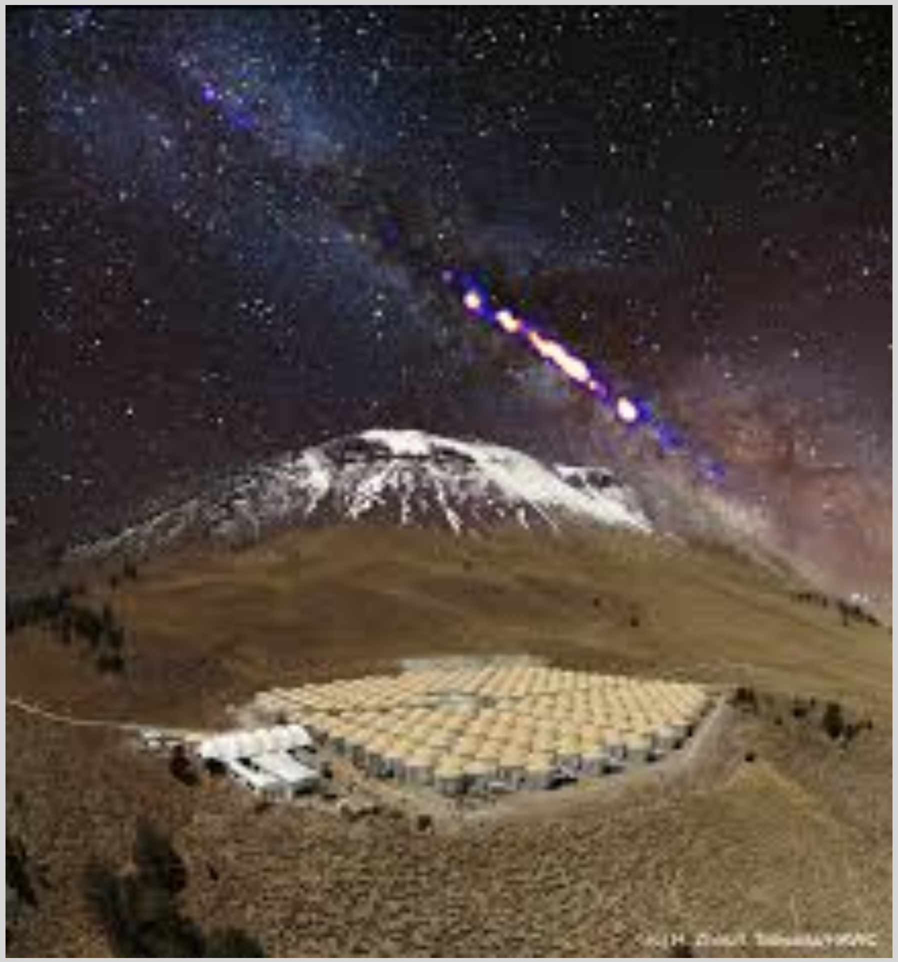
Lectures on Astroparticle physics




IDPASC School 2023

Gabrijela Zaharijas

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Getting to know each other

- **About me**
  - Gamma rays and dark matter search
  - Fermi LAT, CTA
- **You?**
  - PP/Cosmo/Astro partition?
  - How many familiar with
    - Fermi acceleration?
    - Diffusion equation in the Galaxy?

Outline

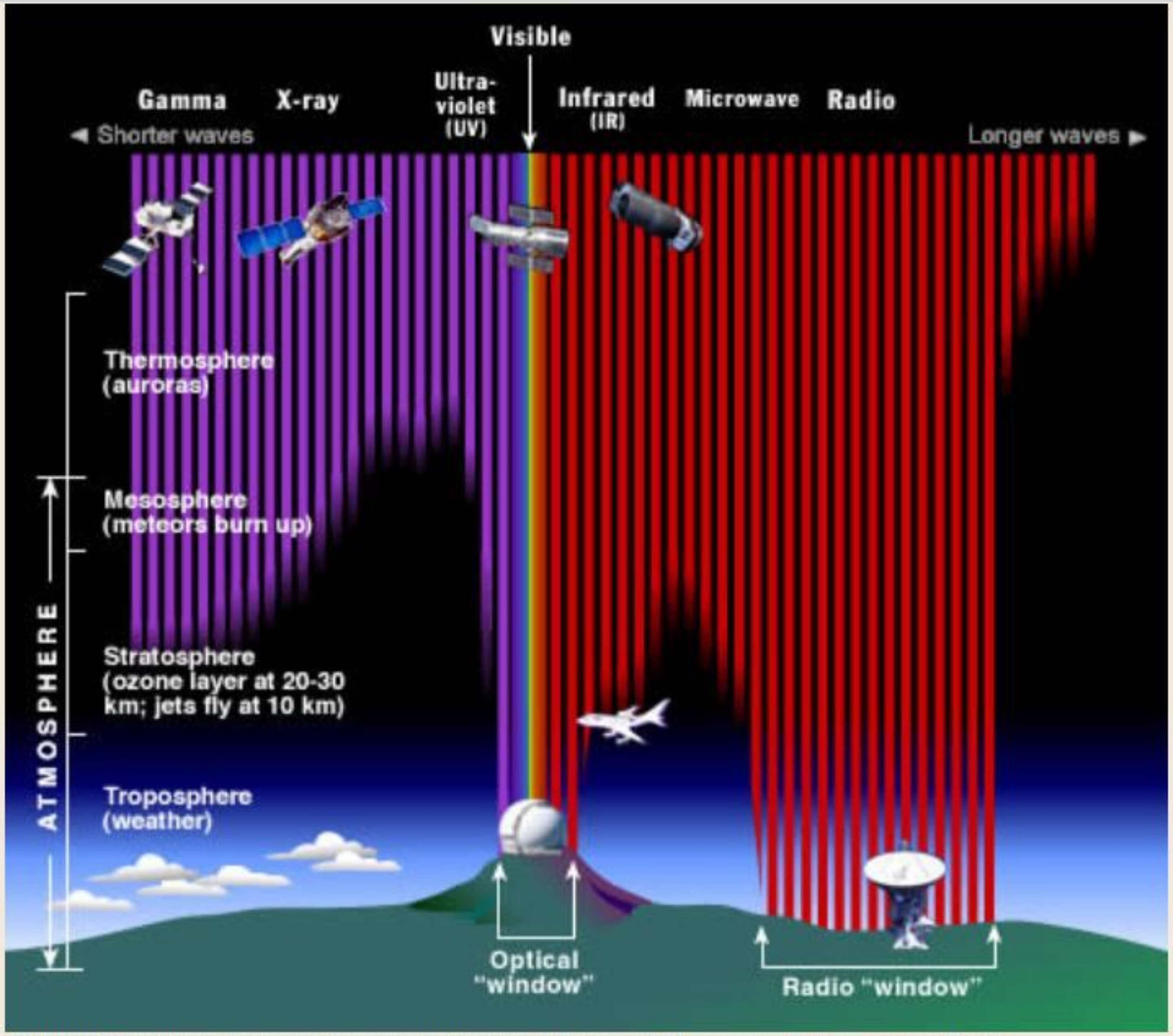
- Bits of history and the ‘big picture’
- **Cosmic rays**:
  - Acceleration and propagation of CRs
  - Observations/measurements
  - State of the art: what we learned and open questions
- **Gamma rays**:
  - ‘Components’ of the high-energy sky
  - What are the observational tools
  - Where are we now - latest results

Literature

- De Angelis, Pimenta “Introduction to Particle and Astroparticle Physics”
- Gabriele Ghisellini, “RADIATIVE PROCESSES IN HIGH ENERGY ASTROPHYSICS”, 1202.5949

Quick history overview: the birth of astroparticle physics / particle astrophysics

Astronomy is an ancient discipline, that started by using our eyes as the main tool



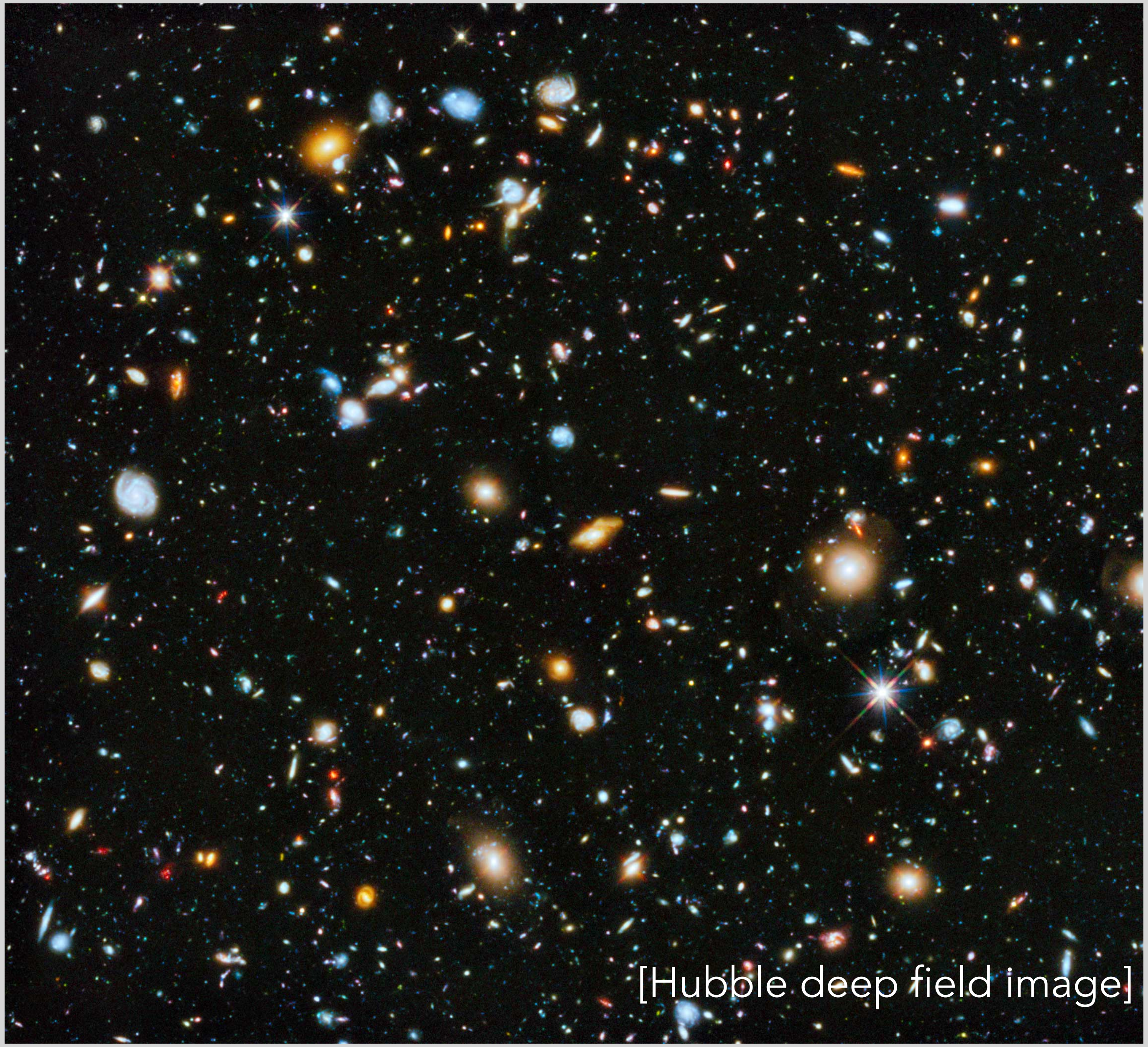
SOURCES: Chandra mission website and Space Telescope Science Institute

Quick history overview: the birth of astroparticle physics / particle astrophysics

Astronomy is an ancient discipline, that started by using our eyes as the main tool

Impressive progress from first Galileo's telescopes (early 17th century), to modern day astronomy

[astro-photography (early 1900) of the Andromeda 'nebula']



[Hubble deep field image]

Quick history overview: the birth of astroparticle physics / particle astrophysics

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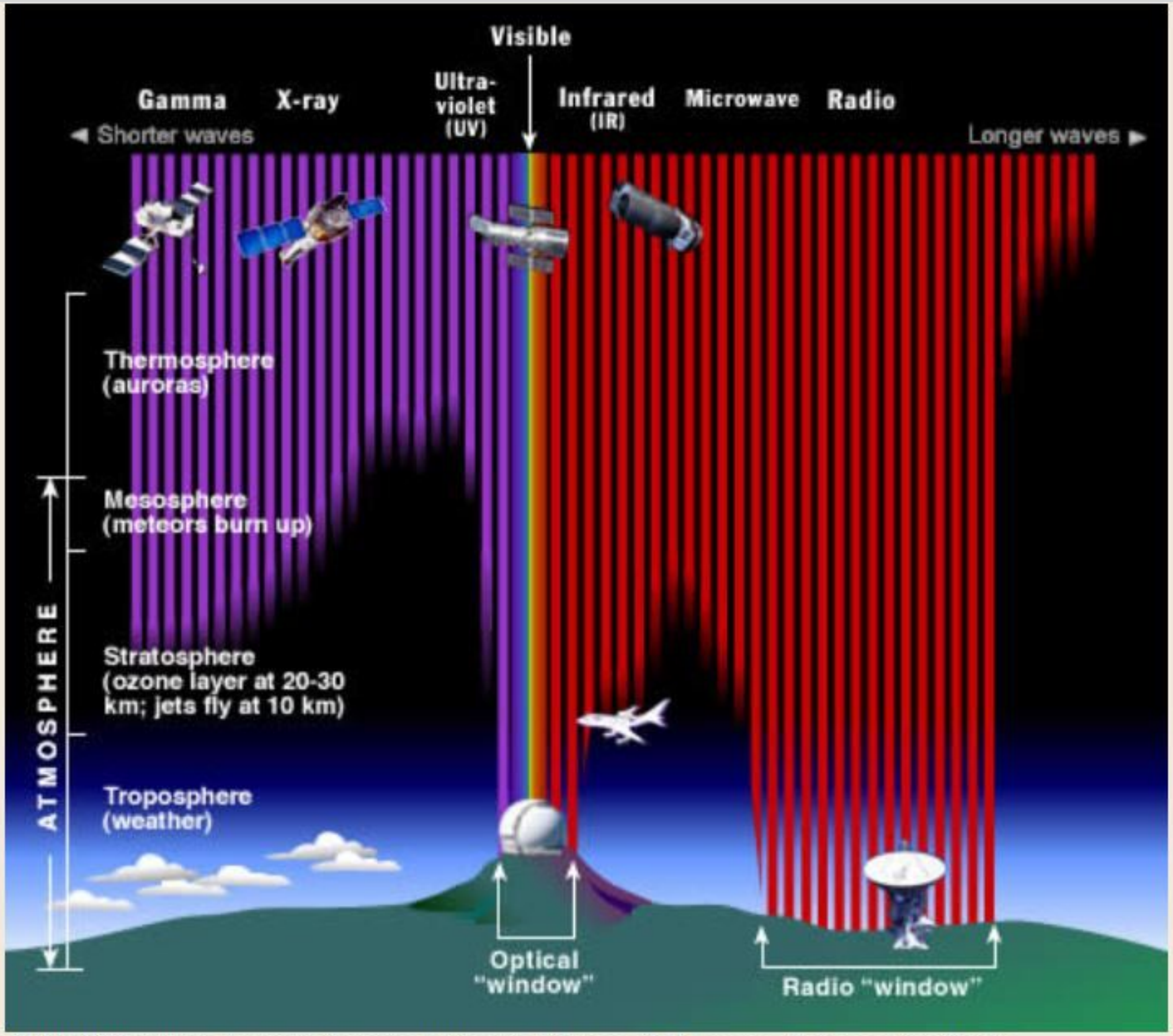

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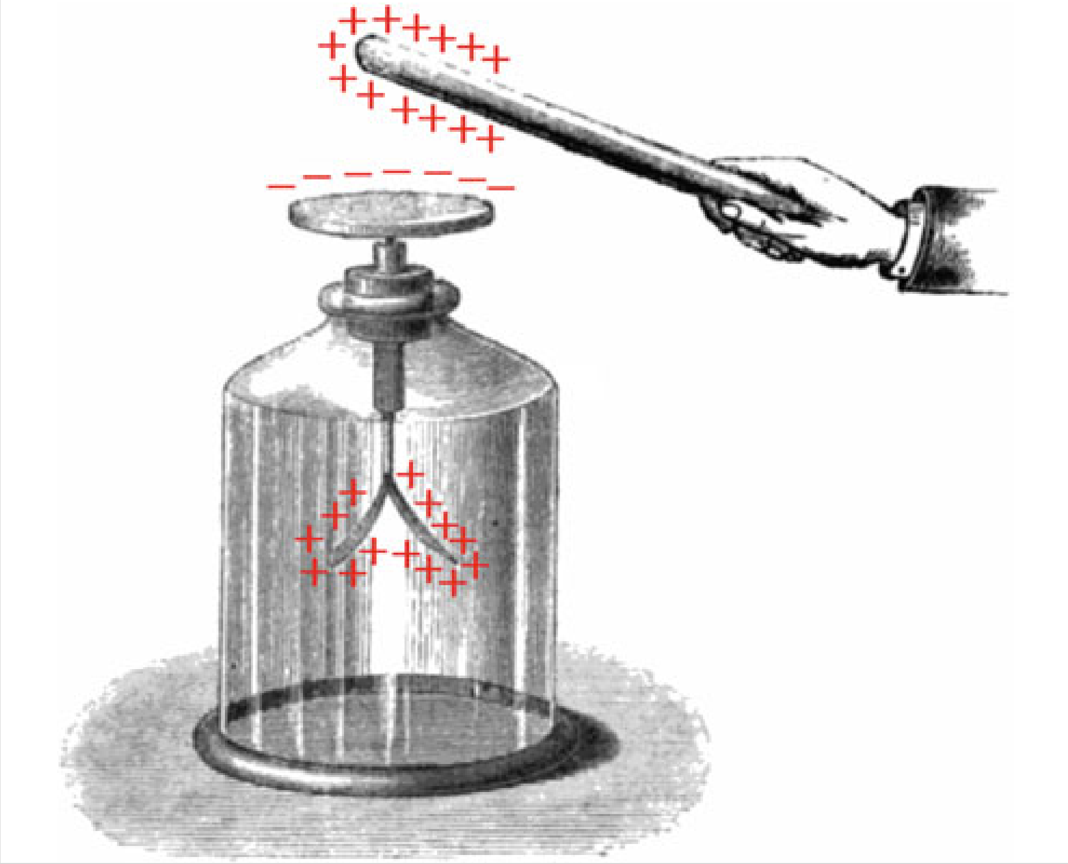
However, it took going to high energies (gamma rays) and discovery & studies of charge CRs to realise the deep intimate connection between the cosmic messengers and fundamental questions of nature

Quick history overview: the birth of astroparticle physics / particle astrophysics

Key events:

- **1785, Coulomb** noticed that **electroscopes discharge** spontaneously
- noticed discharge happens **in the presence of radioactive materials** (1800s) - ions in the air
- **Terrestrial origin** of the radioactivity that discharge electroscopes was a commonplace assumption



Quick history overview: the birth of astroparticle physics / particle astrophysics

Key events:

- **~1900 Wilson** entertained a possibility that this radiation could be of **extraterrestrial origin**.

- He measured discharge in ***tunnels***, with solid rock for shielding overhead, however no reduction in ionization was observed. The hypothesis of an extraterrestrial origin, was dropped.

Quick history overview: the birth of astroparticle physics / particle astrophysics

Key events:

- **1909 - Father Theodor Wulf,** designed highly **precise and portable electroscope** and measured the ionization rate at the top of the Eiffel tower in Paris, about 300 m high.
- he observed that the radiation intensity "**decrease** at nearly 300 m [altitude] was **not even to half of its ground value**," while "just a few percent of the radiation" should remain if it did emerge from ground.

- The idea of extraterrestrial origin of this 'radiation' was back in the game!

Quick history overview: the birth of astroparticle physics / particle astrophysics

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Note how critical are experimental advances

- The idea of extraterrestrial origin of this 'radiation' was back in the game!

Quick history overview: the birth of astroparticle physics / particle astrophysics

Key events:

- **1911-1912** A series of balloon flights by the Austrian physicist **Victor Hess** settled the issue.
- Flew up to 5200 m: the ionization rate first passed through a minimum and then increased considerably with height
- **An unknown radiation from space with extreme penetrating power was causing the ionization.**
- **No mentioning of cosmic rays or particles.**

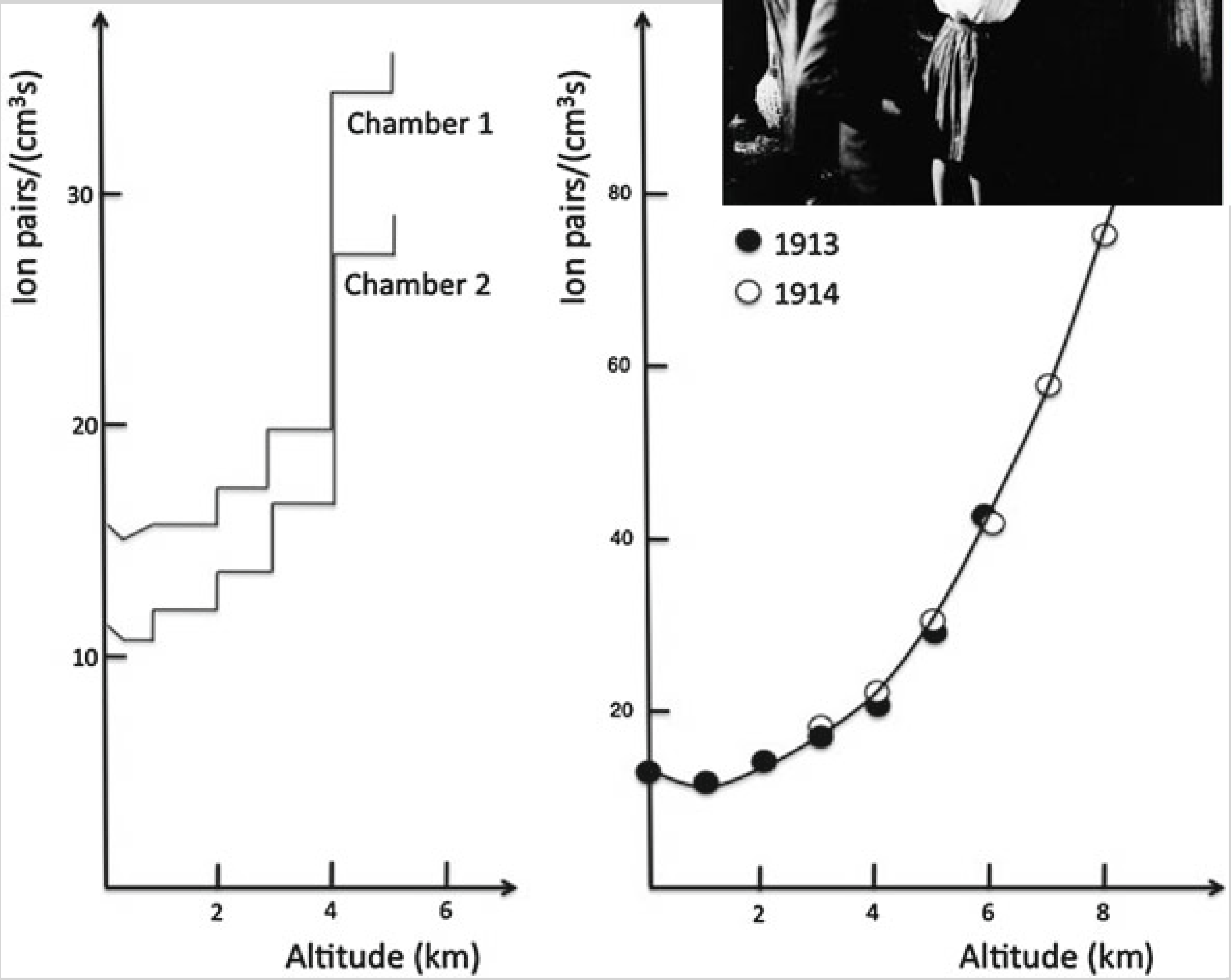


Fig. 3.6 Variation of ionization with altitude. *Left panel* Final ascent by Hess (1912), carrying ion chambers. *Right panel* Ascents by Kolhörster (1913, 1914)

[V. F. Hess (1912). "Über Beobachtungen der durchdringenden Strahlung bei sieben Freiballonfahrten". Physikalische Zeitschrift 13: 1084–1091]

Quick history overview: the birth of astroparticle physics / particle astrophysics

Key events:

- Some scientists were sceptical, especially Millikan in the USA. He could NOT confirm results with an unmanned balloon flight to 15 km over Texas.
- Millikan finally accepted the latitude effect after making measurements from airplanes in 1933.
- He coined the name "cosmic rays."
- In Central Europe, the names ‘Höhenstrahlung’ (high-altitude radiation) and ‘Ultra-Gammastrahlung’ became current.
- It took a long time before the particle nature and composition of cosmic rays were understood.

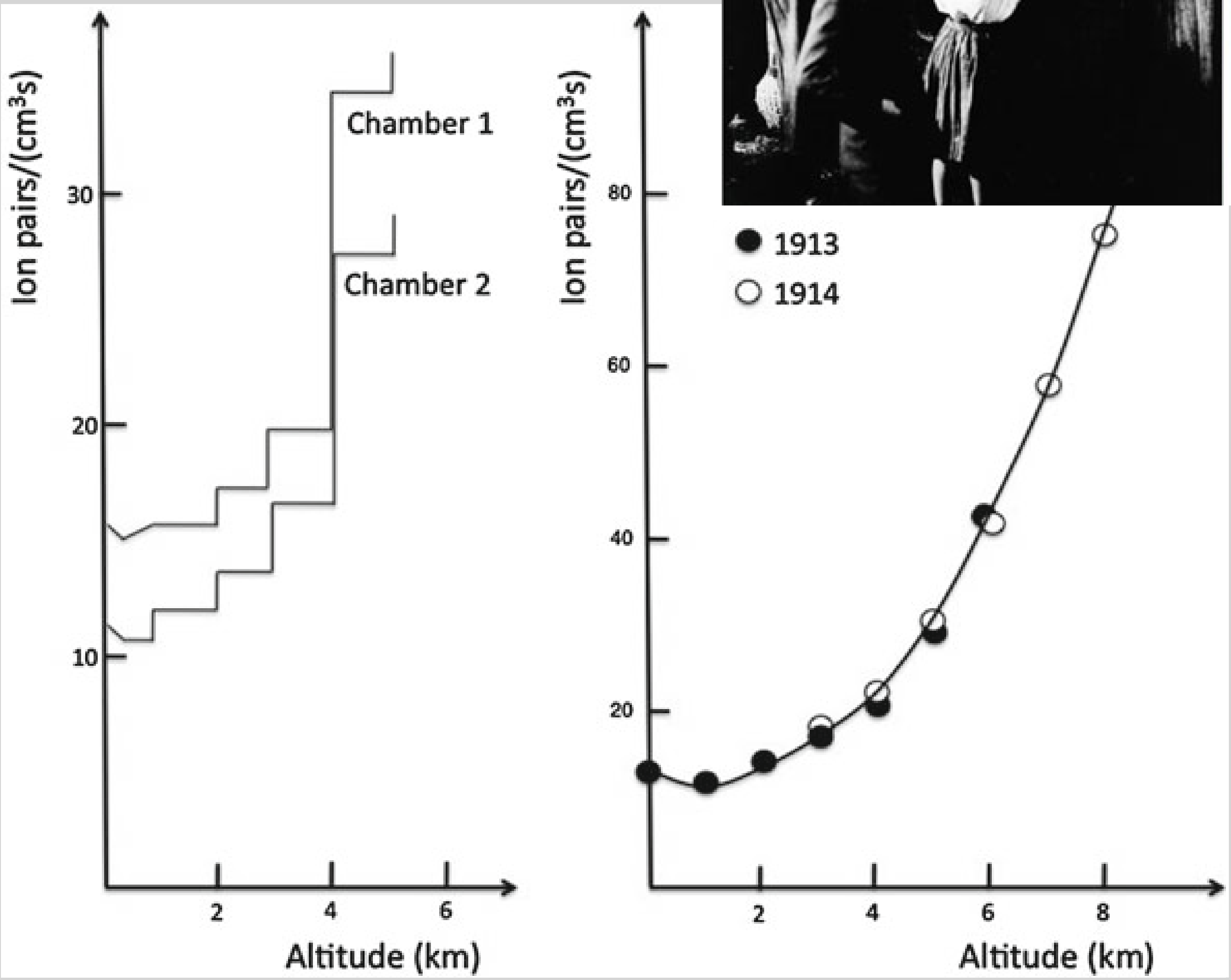
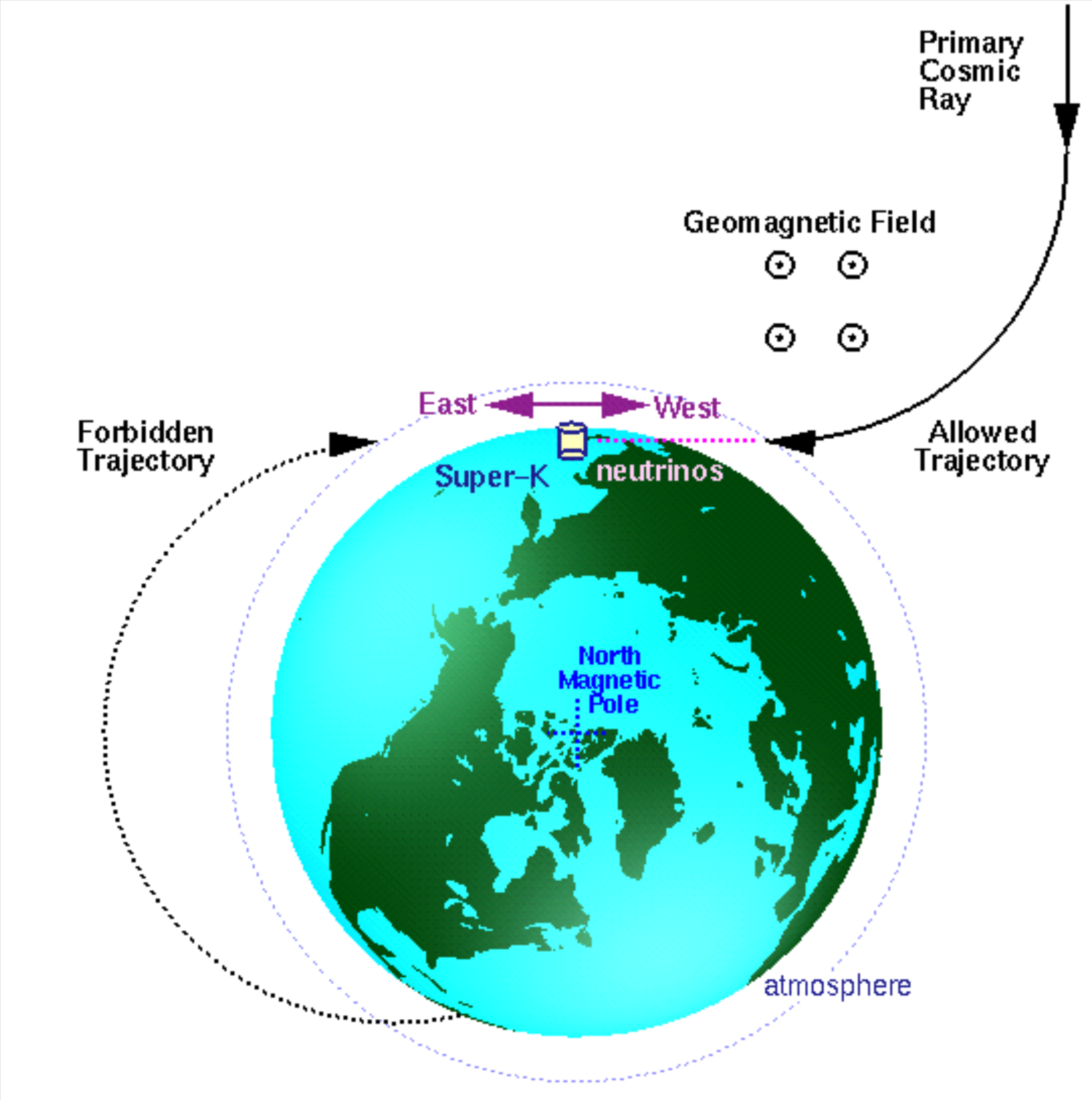


Fig. 3.6 Variation of ionization with altitude. *Left panel* Final ascent by Hess (1912), carrying ion chambers. *Right panel* Ascents by Kolhörster (1913, 1914)

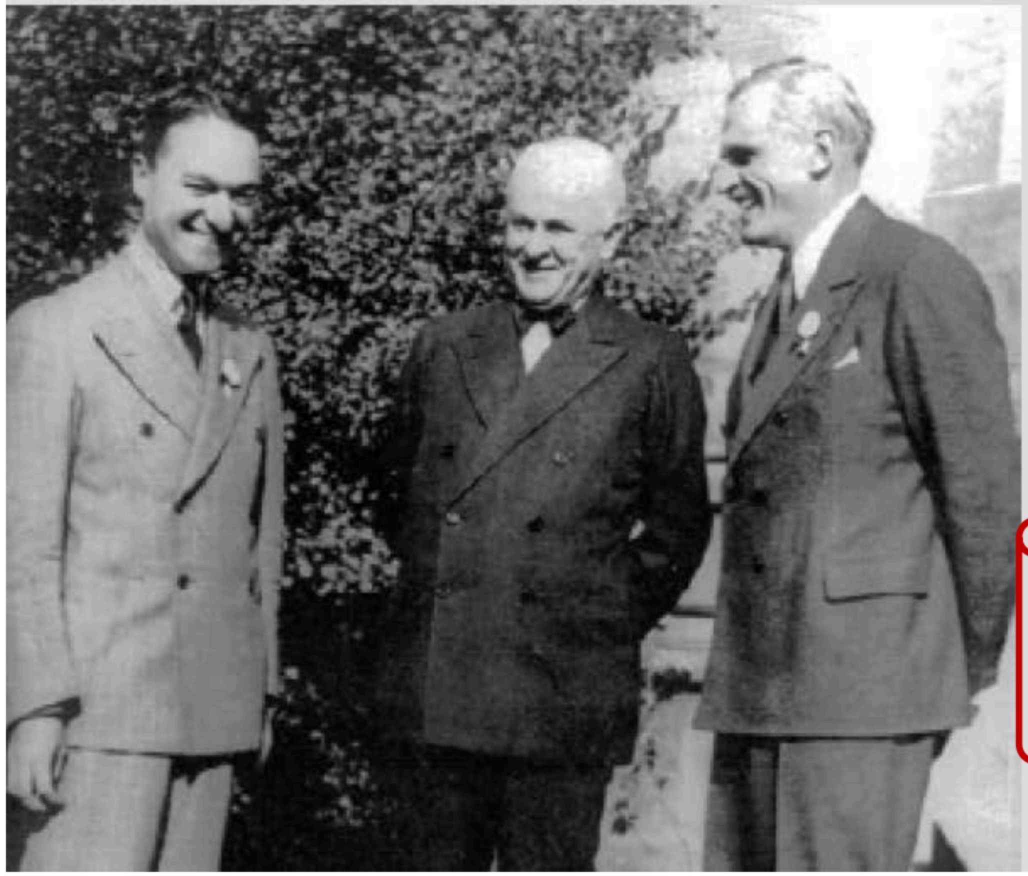
Quick history overview: the birth of astroparticle physics / particle astrophysics

Next steps:

- In **1933**, three independent experiments by Alvarez and Compton, Johnson, and Rossi, discovered that **close to the equator there were more cosmic rays coming from West than from East** —> cosmic rays are mostly **positively charged,** and thus most probably protons.



Quick history overview: the birth of astroparticle physics / particle astrophysics



Bruno Rossi, Robert A. Millikan, and Arthur H. Compton at the Rome conference, October 11–18, 1931.

The Rome conference 1931 ‘‘marked the beginning of the historical debate about the nature of cosmic rays....’’

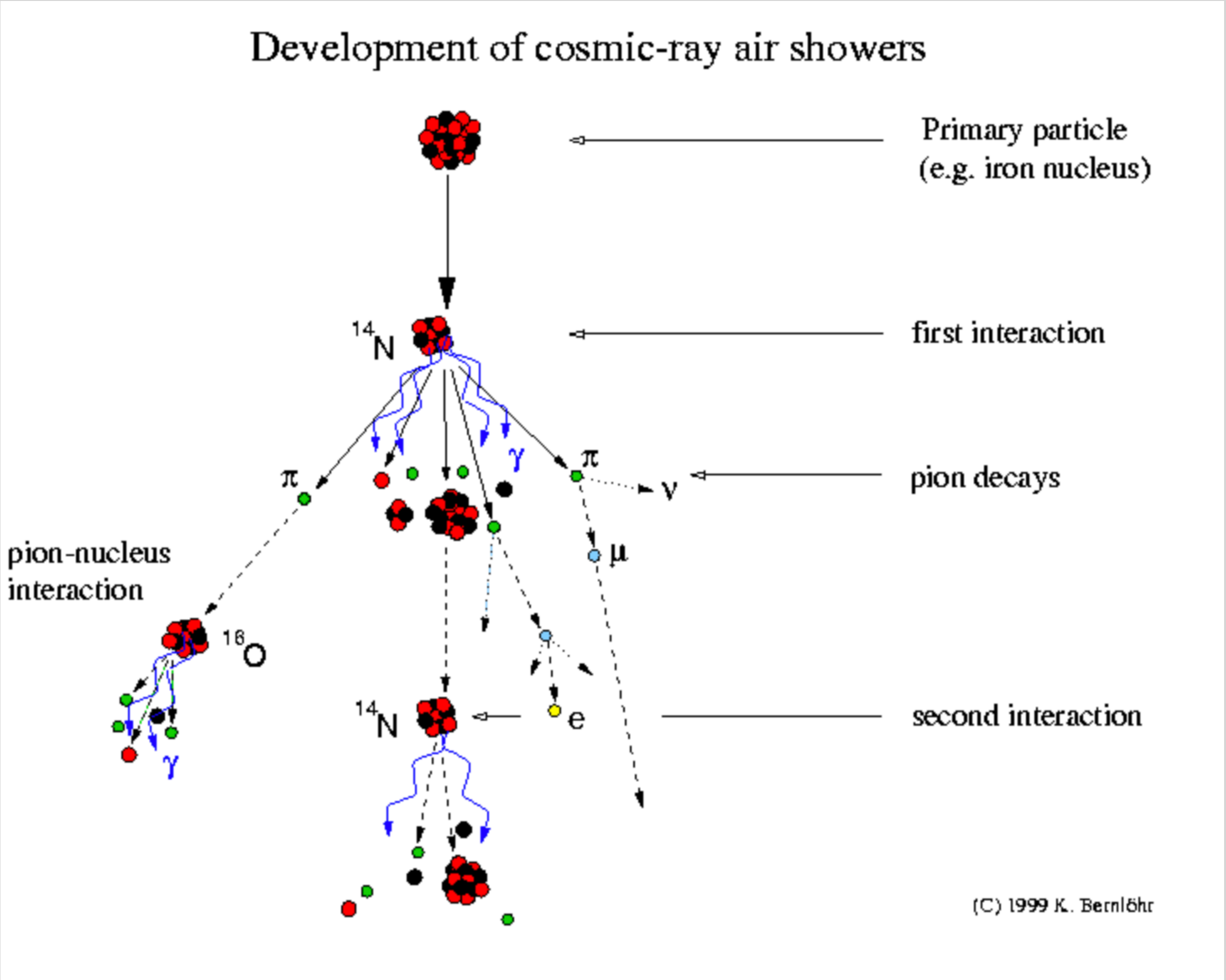
...”At the invitation of Fermi, I gave an introductory speech on the problem of cosmic rays. The main thrust of this talk was to present what, to my mind, were irrefutable arguments against Millikan’s theory of the ”birth cry” of atoms. Such a brash behavior on the part of a mere youngster (I was then 26 years old) clearly did not please Millikan, who for a number of years thereafter, chose to ignore my work altogether.”

Rossi Physics Today October 1981

Quick history overview: the birth of astroparticle physics / particle astrophysics

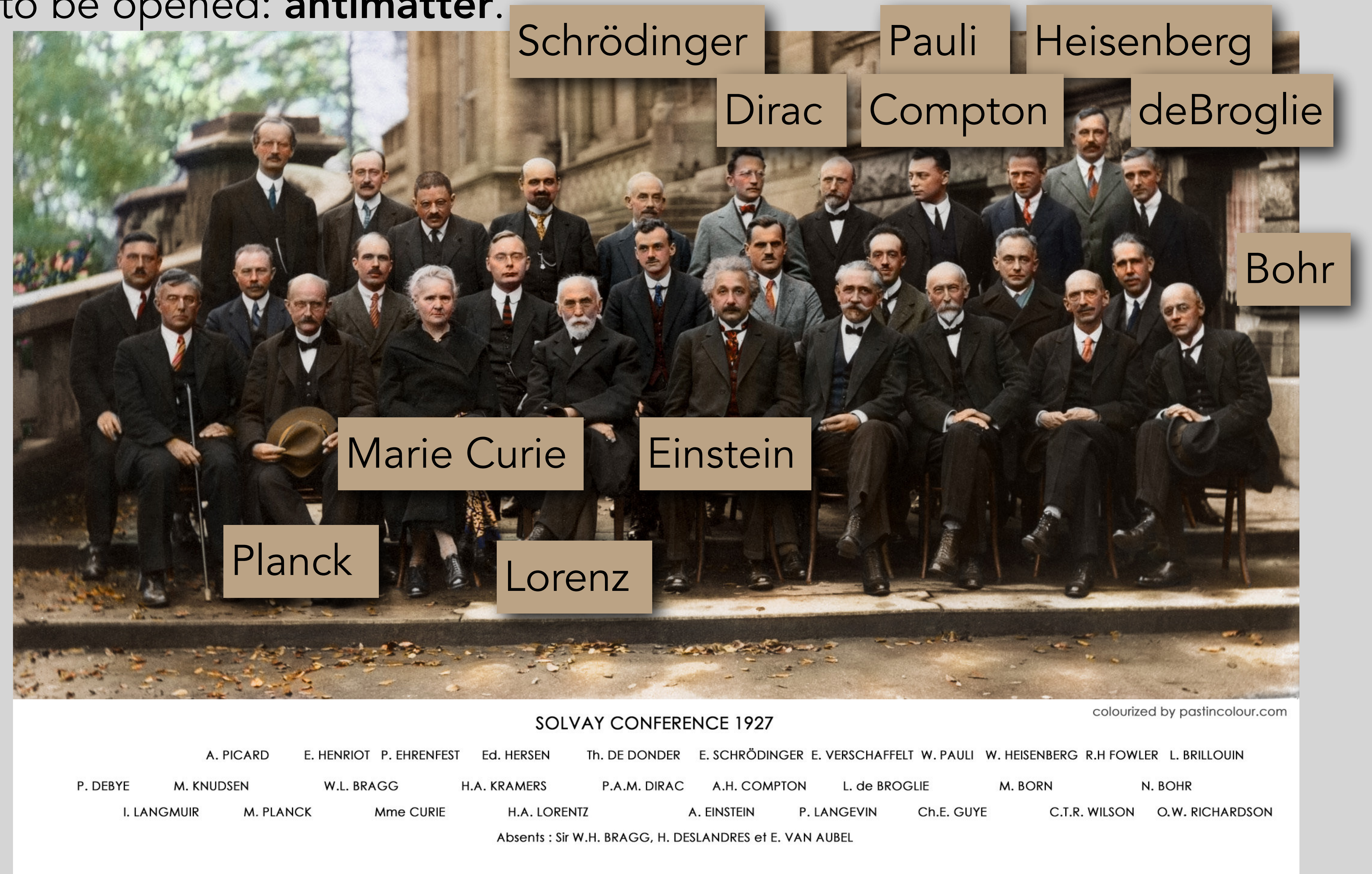
Next steps:

- **1933** Rossi and (later) Pierre Auger observed the coincidence of cosmic ray particle counts between separated counters, and discovered **air showers**.



Quick history overview: the birth of astroparticle physics / particle astrophysics

- Note that **theoretical progress went ‘hand-in-hand’**: at the end of the 1920s, scientists put together **relativity and quantum mechanics**, and the discoveries following these attempts changed completely our view of nature. A new window was going to be opened: **antimatter**.



Quick history overview: the birth of astroparticle physics / particle astrophysics

Just the beginning! Enter the renaissance of (particle) physics

- The obvious next step was to **investigate the nature of such particles**, and to use them to probe matter in detail, much in the same way as in the e.g. Rutherford experiment.

- **Particle physics thus started with cosmic rays, and majority of early fundamental discoveries were made thanks to cosmic rays**.

Quick history overview: the birth of astroparticle physics / particle astrophysics

Just the beginning! Enter the renaissance of (particle) physics

- Fundamental tool - **cloud chamber** (in a magnetic field)

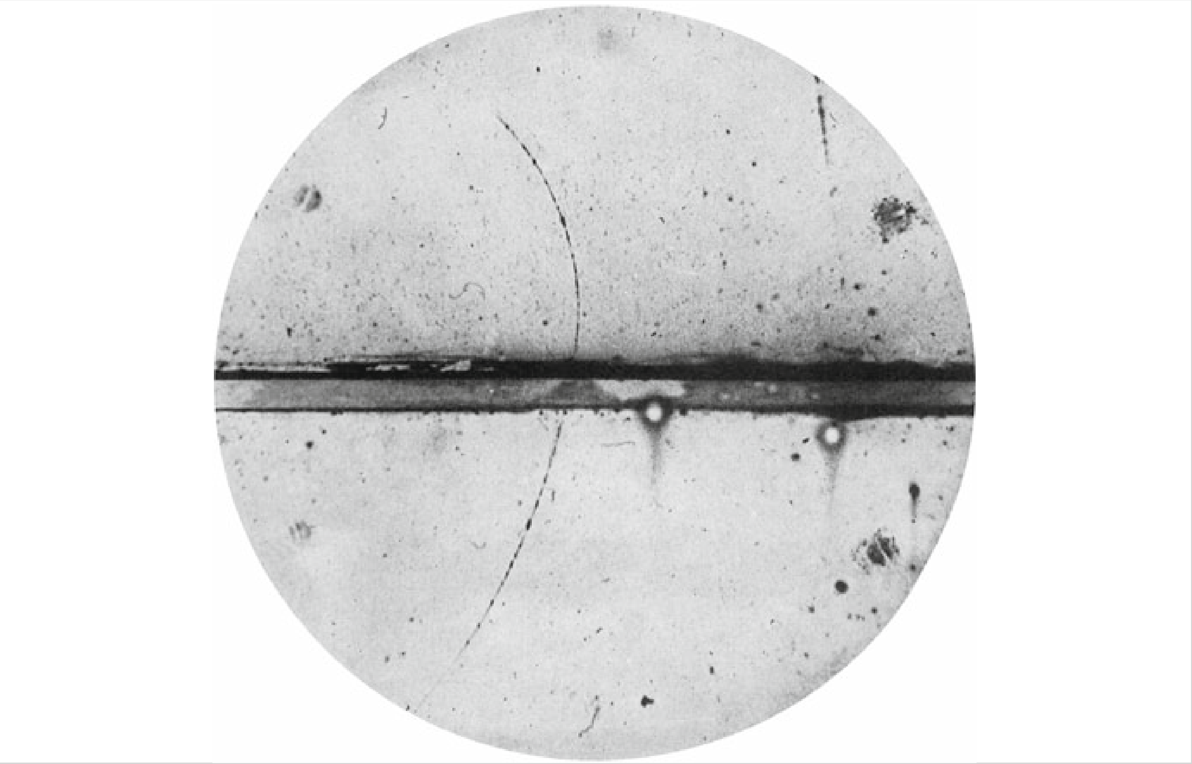


Fig. 3.9 The first picture by Anderson showing the passage of a cosmic antielectron, or positron, through a cloud chamber immersed in a magnetic field. One can understand that the particle comes from the *bottom* in the picture by the fact that, after passing through the sheet of material in the medium (and therefore losing energy), the radius of curvature decreases. The positive charge is inferred from the direction of bending in the magnetic field. The mass is measured by the bubble density (a proton would lose energy faster). Since most cosmic rays come from the *top*, the first evidence for antimatter comes thus from an unconventional event. From C.D. Anderson, "The Positive Electron," Physical Review 43 (1933) 491

1933 - During his doctoral thesis (supervised by Millikan), ***Anderson*** was studying the tracks of **cosmic rays passing through a *cloud chamber in a magnetic field***.

In 1933 he discovered antimatter in the form of **a positive particle of mass consistent with the electron mass**, later called the ***positron***. Dirac's equation (1928) prediction was confirmed - great achievement for cosmic ray physics.

Anderson shared with Hess the Nobel Prize for Physics in 1936.

Quick history overview: the birth of astroparticle physics / particle astrophysics

Just the beginning! Enter the renaissance of (particle) physics

In the first half of the century, elementary particles were discovered in cosmic rays.

- 1932: e^+ Carl Anderson (cloud chamber).
- 1936-37: μ Anderson, Neddermeyer, Street, and Stevenson, the Yukawa particle? "meson".
- 1947: π Lattes, Ochialini, and Powell.
- 1947 – 53: k Rochester, Butler, and Powell
- 1951: Λ
- 1952: Ξ
- 1953: Σ

(1951–1953) Pic du Midi, cloud chamber studies.

Quick history overview: the birth of astroparticle physics / particle astrophysics

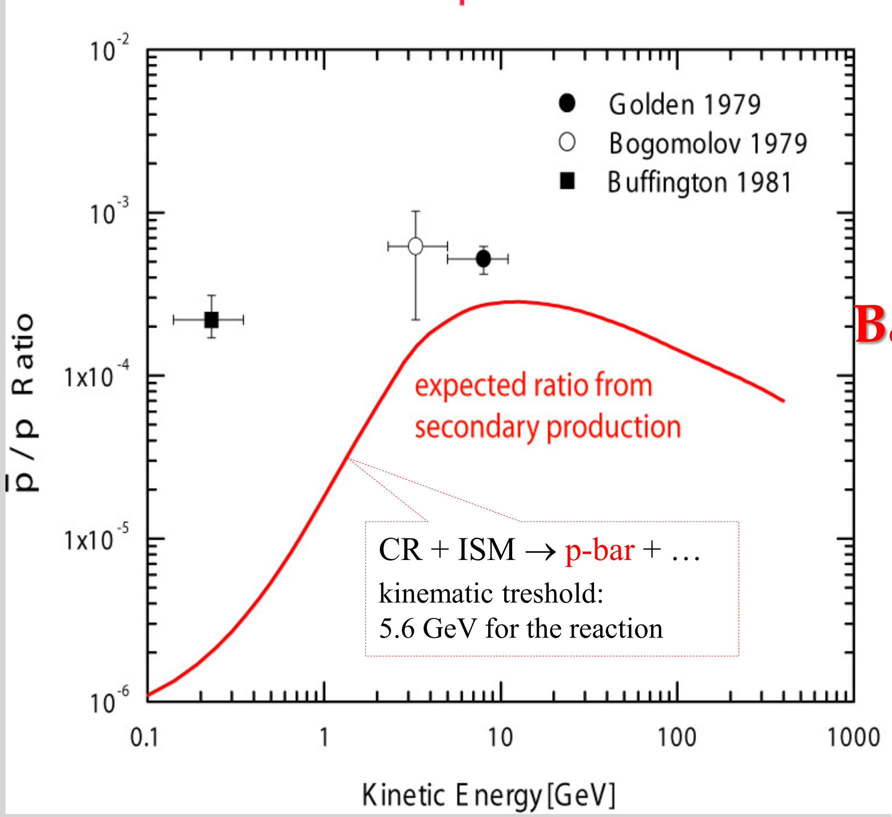
Just the beginning! Enter the renaissance of (particle) physics

- **cosmic rays were the primary tool for particle physics** (‘the natures accelerators’)
- since the advent of particle accelerators in the **1950s**, particle physicists ***went from hunting to farming***.
- despite the great advances of the technology of accelerators, ***the highest energies will always be reached by cosmic rays***.

Quick history overview: the birth of astroparticle physics / particle astrophysics

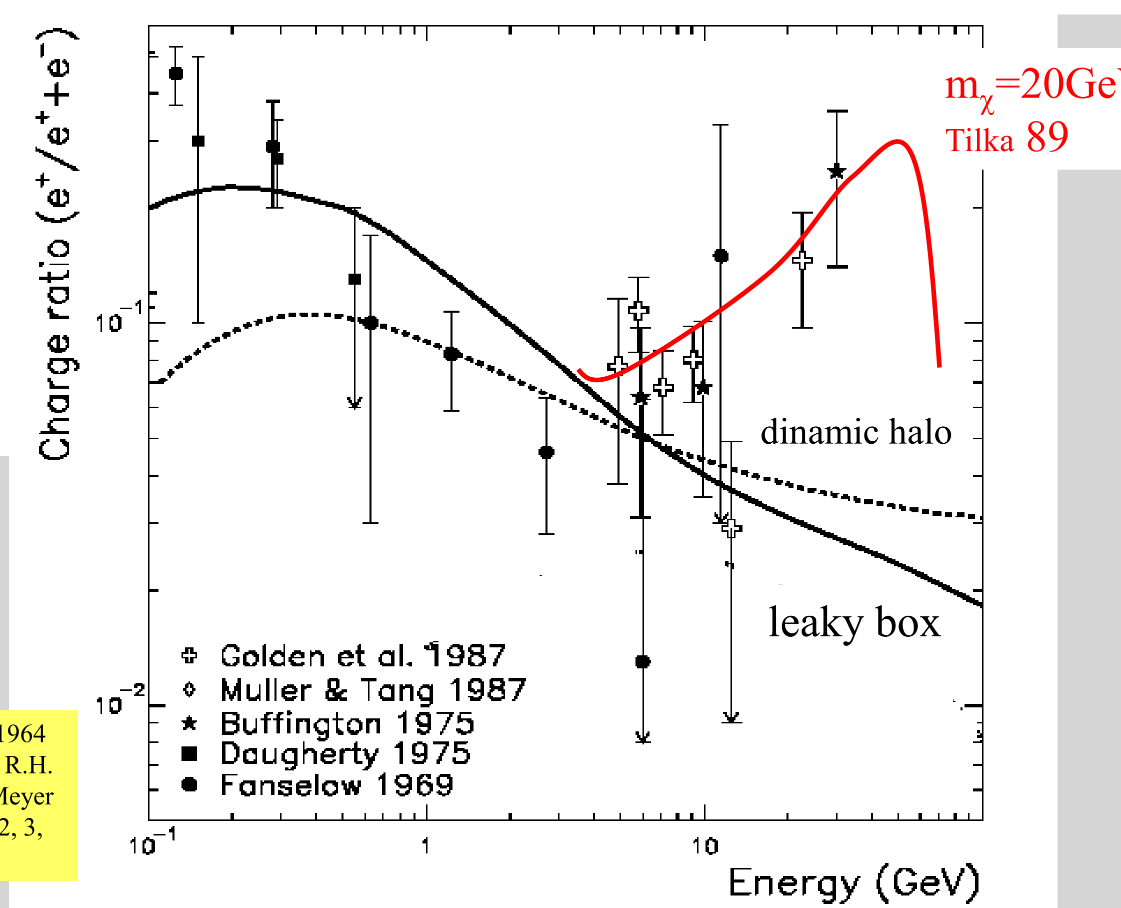
First detections of anti-particle and gamma-ray spectra:

The first historical measurements on galactic antiprotons



First detection in 1964 by J.A. De shong, R.H. Hildebrand & P. Meyer (Phys. Rev. Let. 12, 3, 1964)

Balloon data : Positron fraction before 1990

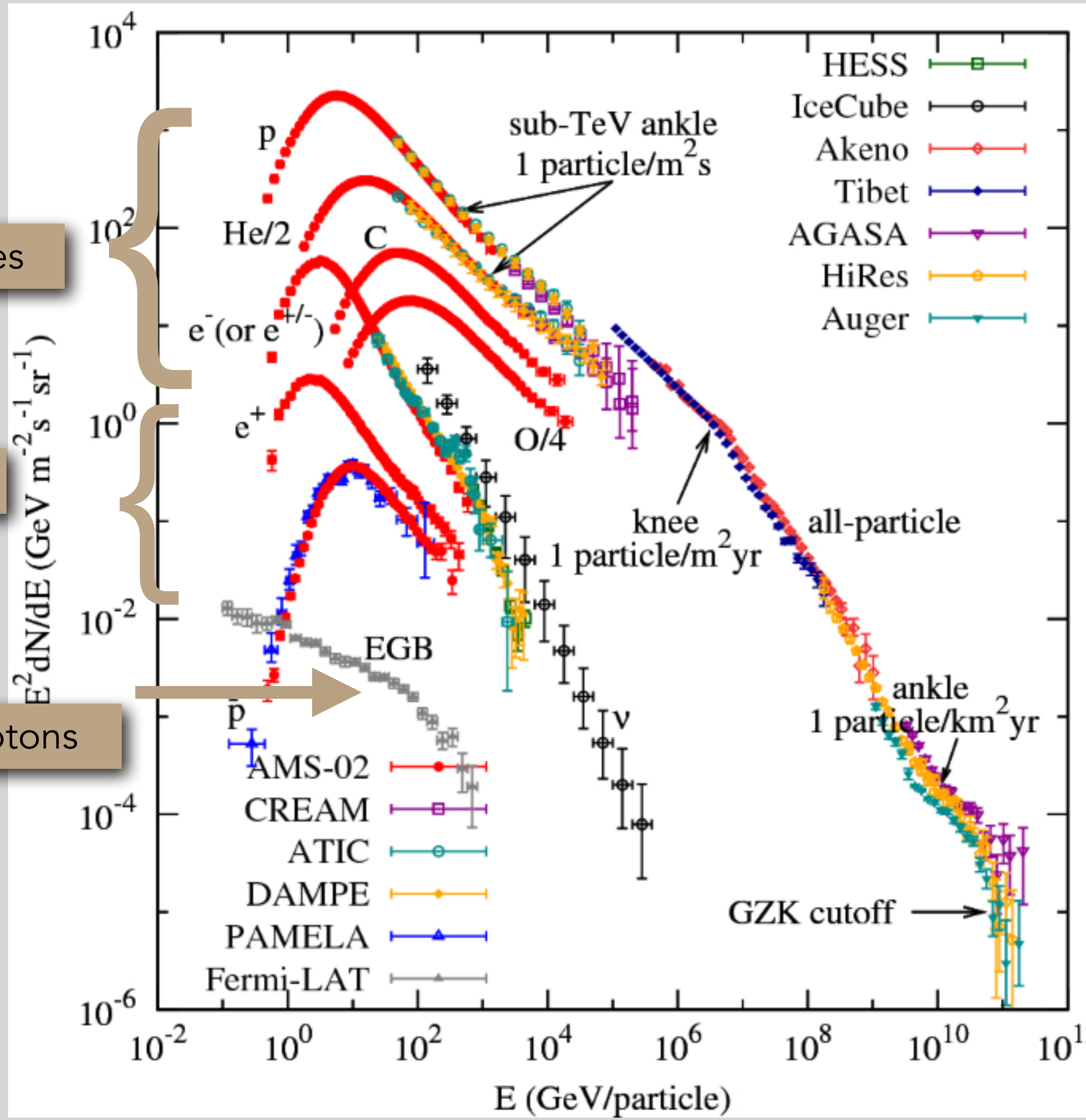


Gamma-rays absorbed by the atmosphere — the first gamma-ray telescope on the Explorer 11 satellite in 1961, less than 100 photons

Explorer 11

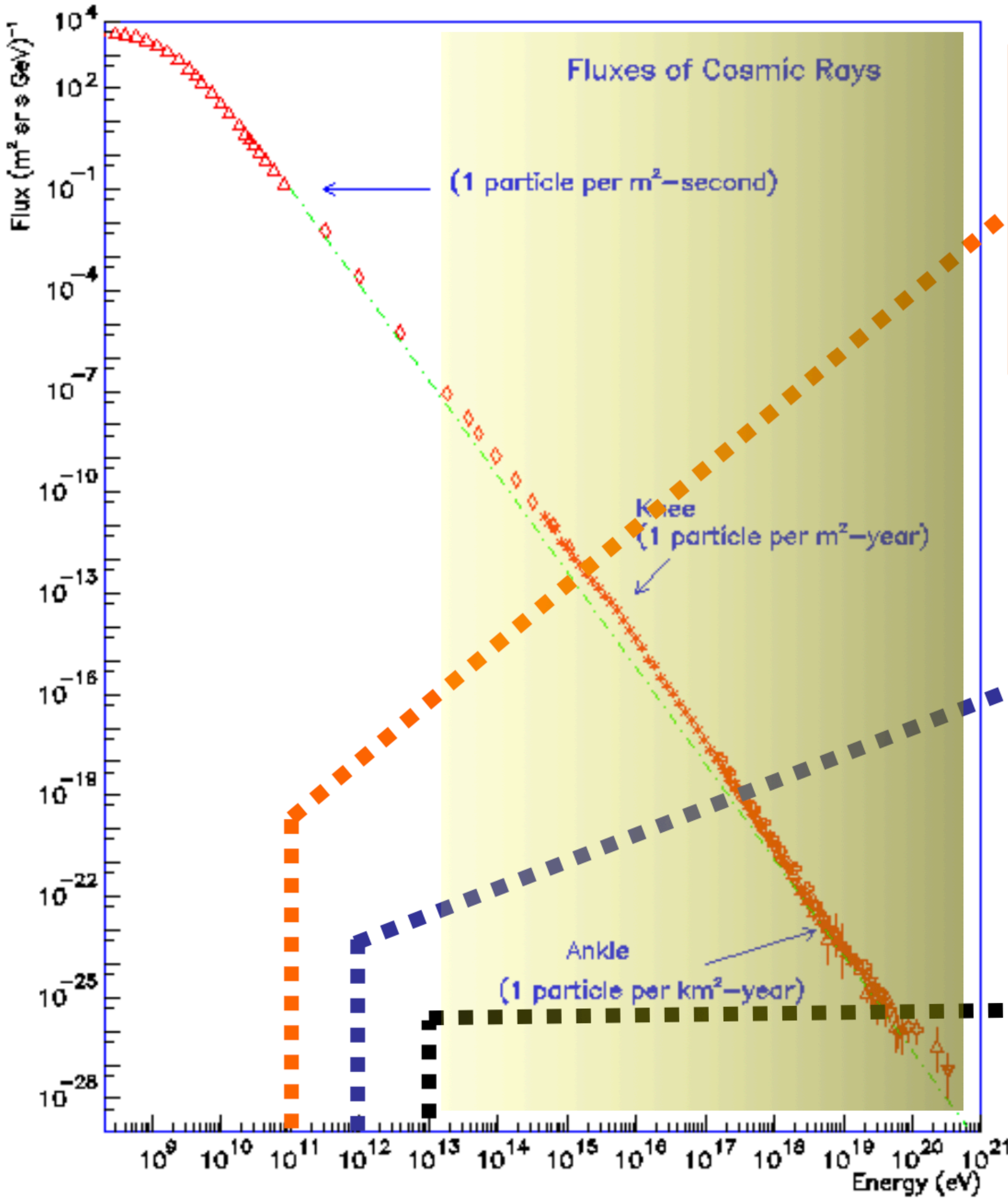
Manufacturer	Goddard Space Flight Center
Launch mass	37.2 kg (82 lb) [1]
Start of mission	
Launch date	27 April 1961, 14:16:38 GMT
Rocket	Juno II (AM-19E)
Launch site	Cape Canaveral, LC-26B

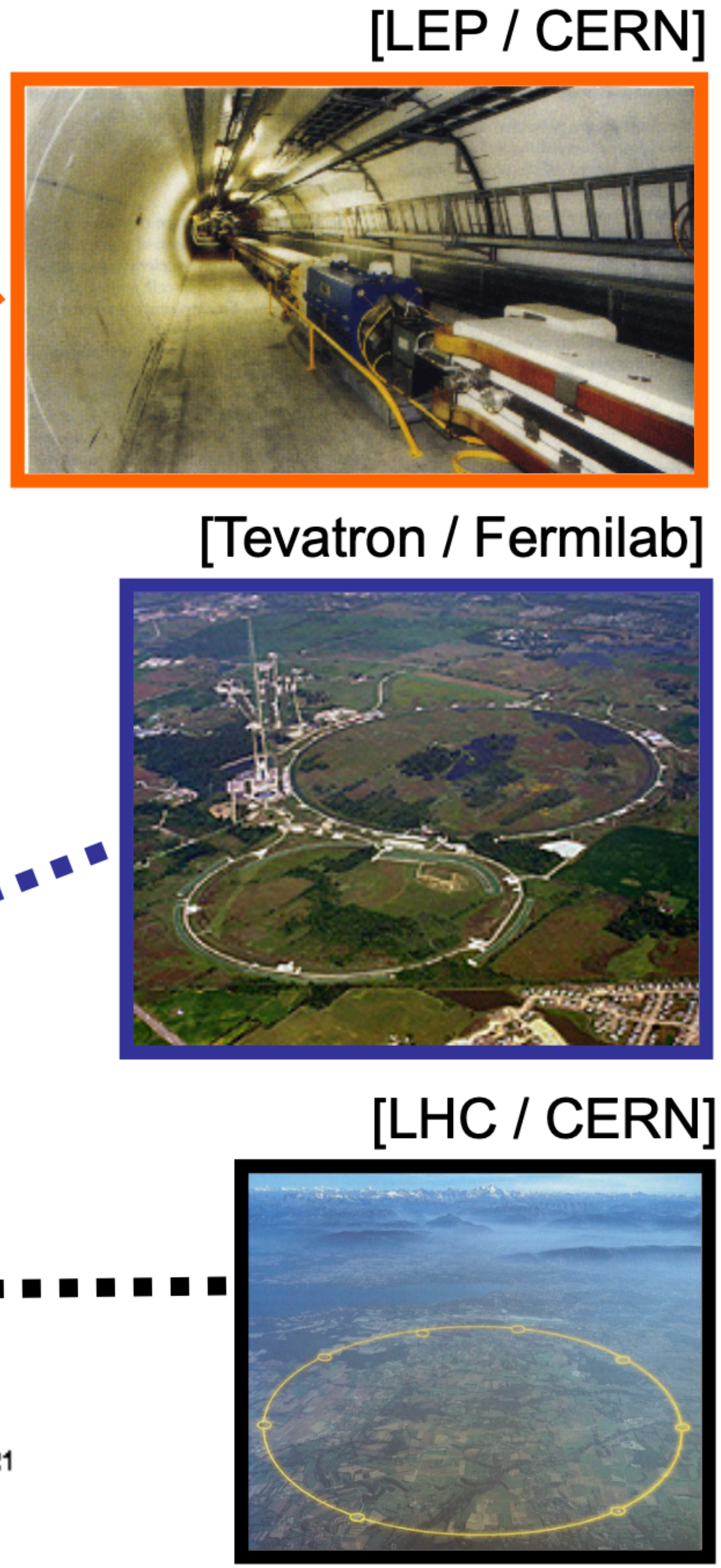
The situation cca 2022



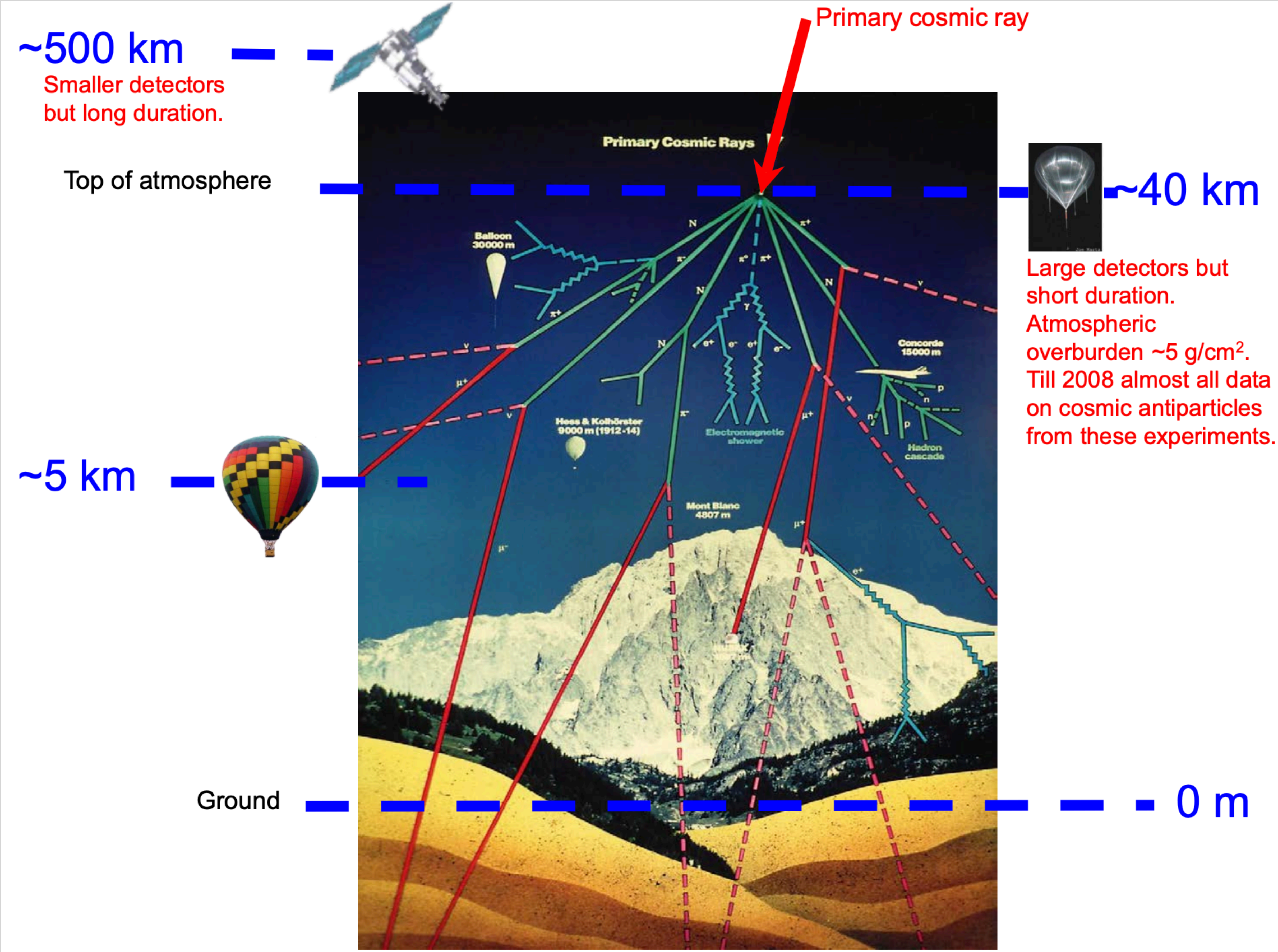
Composition (at ~ 1 GeV):
85% H (p)
12% He (α)
1% heavier nuclei
2% $e^{\pm}$ (> 90% e^-)
10^{-5}-10^{-4} antiprotons.

Note the energy scale

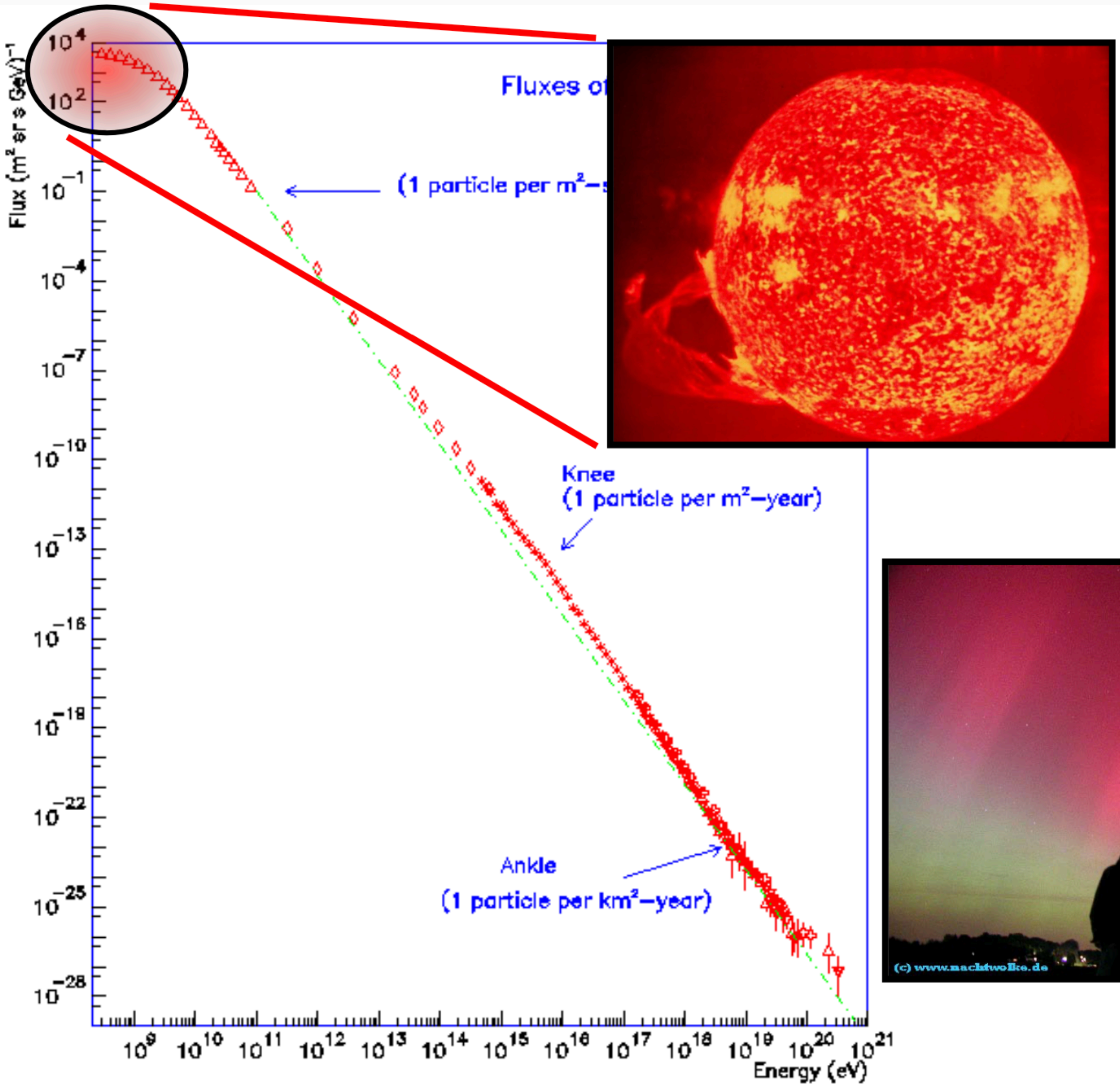




Experimental strategies



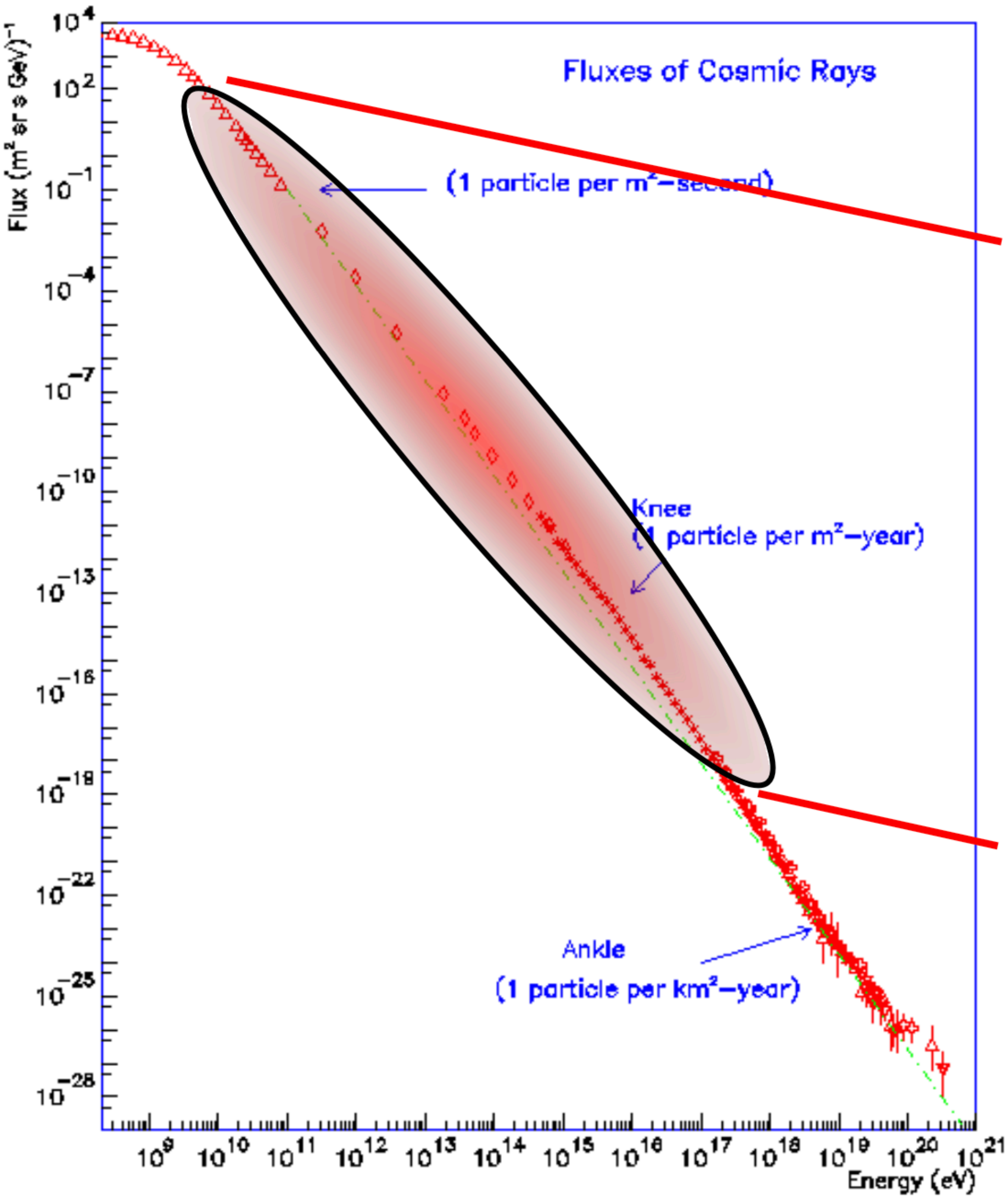
Experimental strategies



Solar Flare

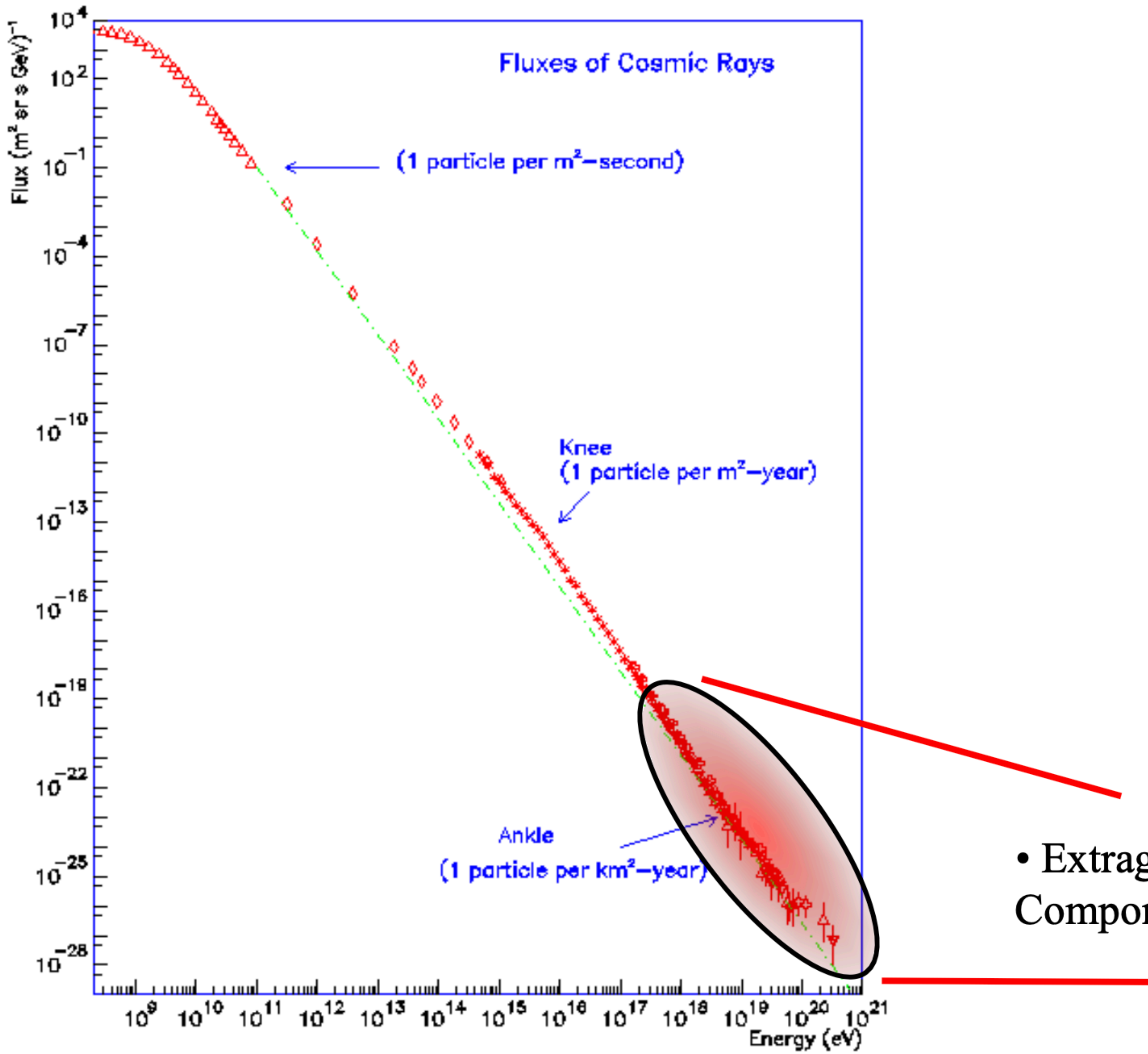
Northern Ligths

Experimental strategies



- SuperNova Explosion

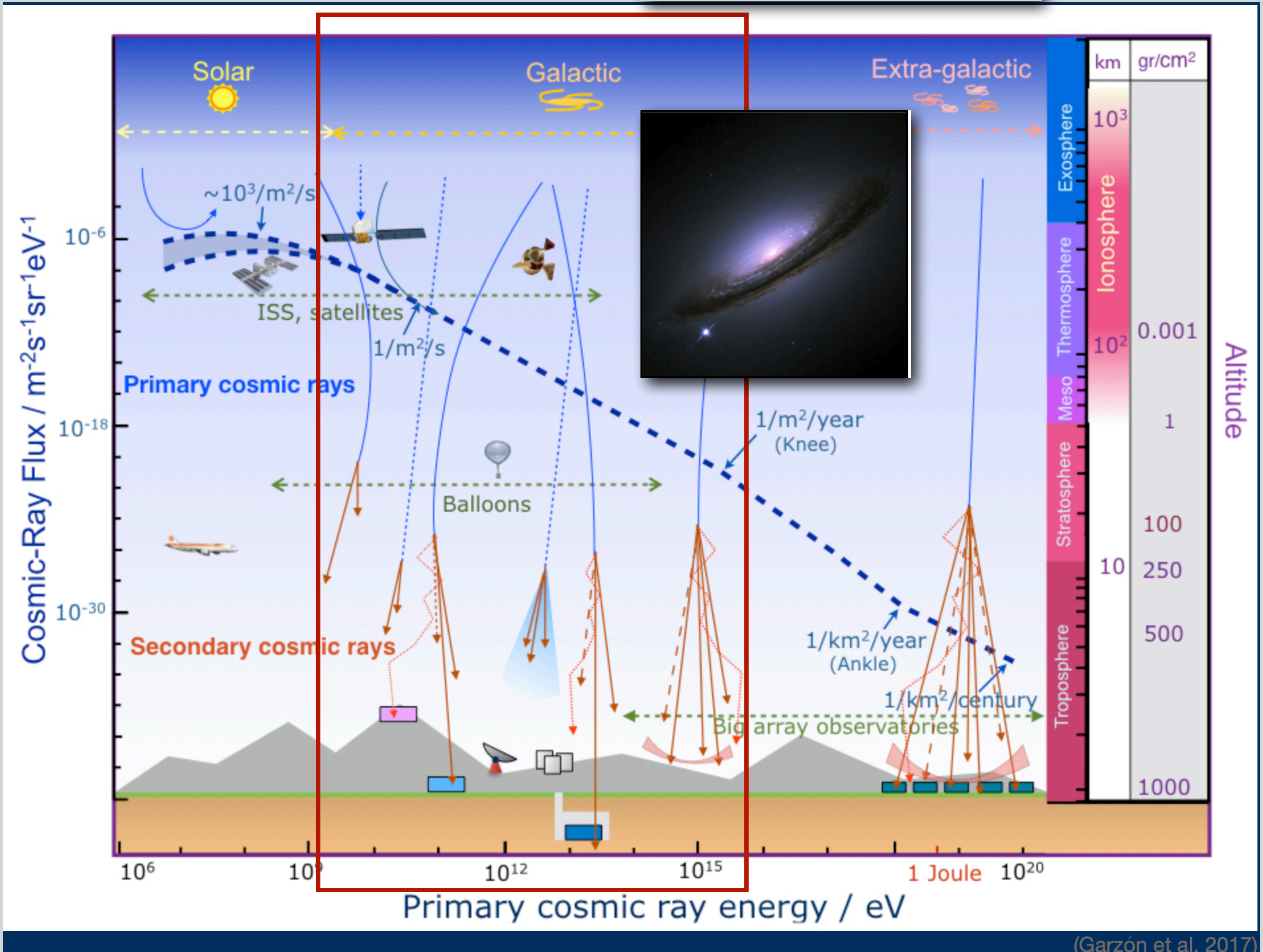
Experimental strategies



- Extragalactic Component: AGNs?

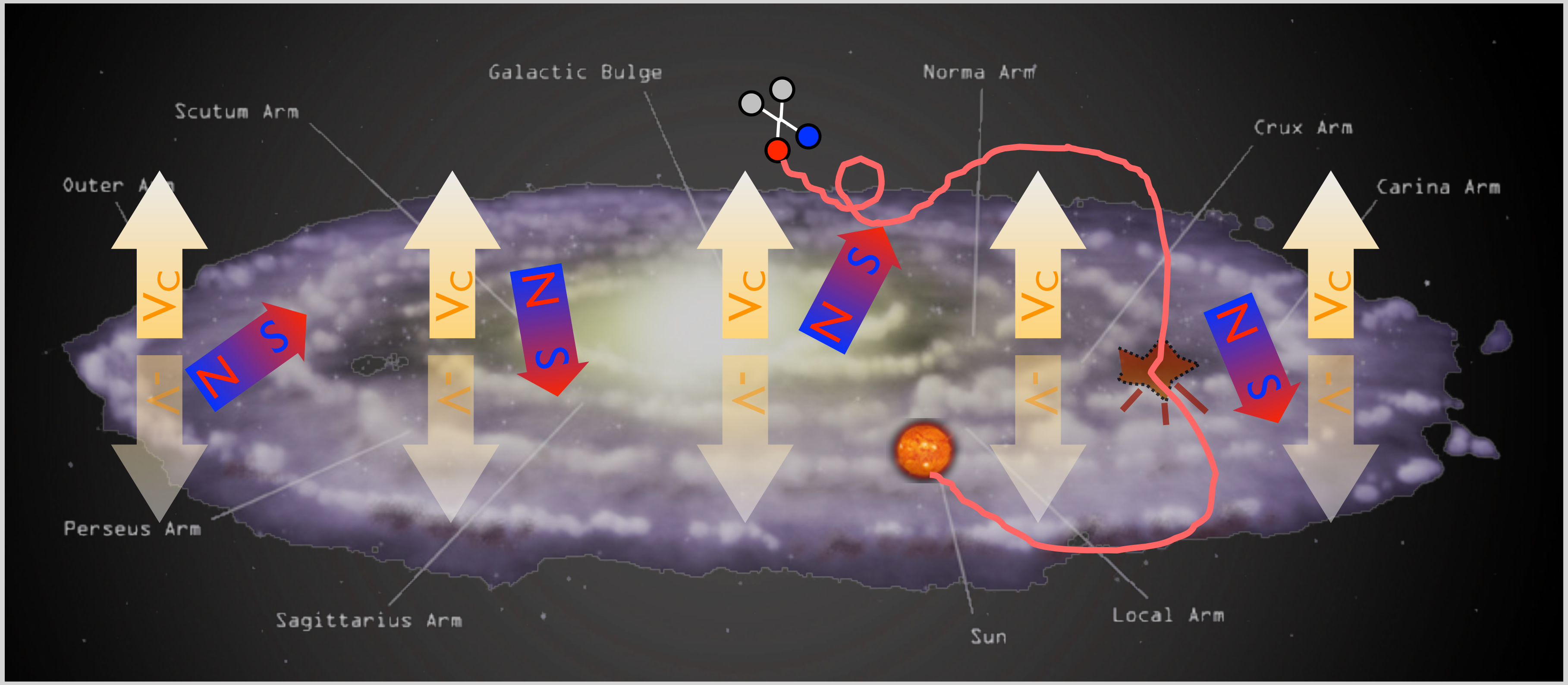
Experimental strategies

Main focus of the lectures



What are the CR (composition)?
Where/how are they produced?

- After being observationally established the big questions for physics was how are such particles produced and how they reach us
- The question can be decomposed in four parts:
  - energetics
  - acceleration
  - energy losses
  - CR diffusion

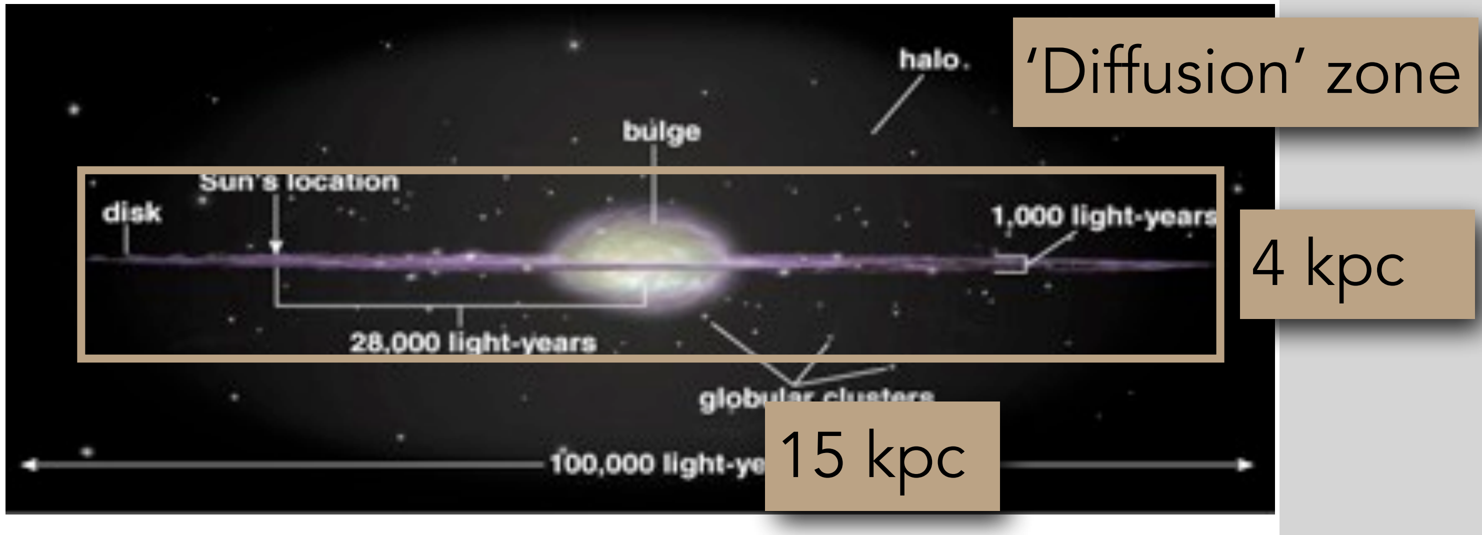


Energetics

The power budget

The integrated E-density in CR is of about ρ_{CR}~0.5 eV/cm^3

The confinement volume of the Milky Way is $V_{conf} \sim \pi R^2 h \sim 8\ 10^{67}$ cm^3 (using h~4 kpc and R~15 kpc)



The total Energy in CR in the Galaxy is of about $W_{CR}=\rho_{CR}V_{conf} \sim 6.7\ 10^{55}$ erg

For a confinement time of 10^7 yr, $L_{CR}=W_{CR}/\tau_{conf} \sim 2\ 10^{41}$ erg/s

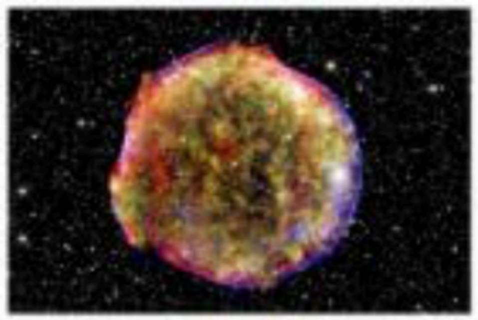
A typical SN releases ~10^{51} erg in kinetic Energy & happens 2-3 times per century, i.e. $L_{kin}=E_{kin}\ \Gamma_{SN} \sim 8\ 10^{41}$ erg/s

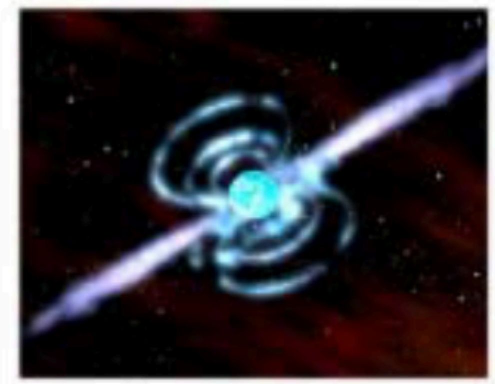
Cosmic Rays could be accounted for with a conversion efficiency of ~20% of the macroscopic kinetic energy into microscopic particle acceleration

Energetics

Galactic cosmic rays - energetics

Ginzburg, 1958, ...





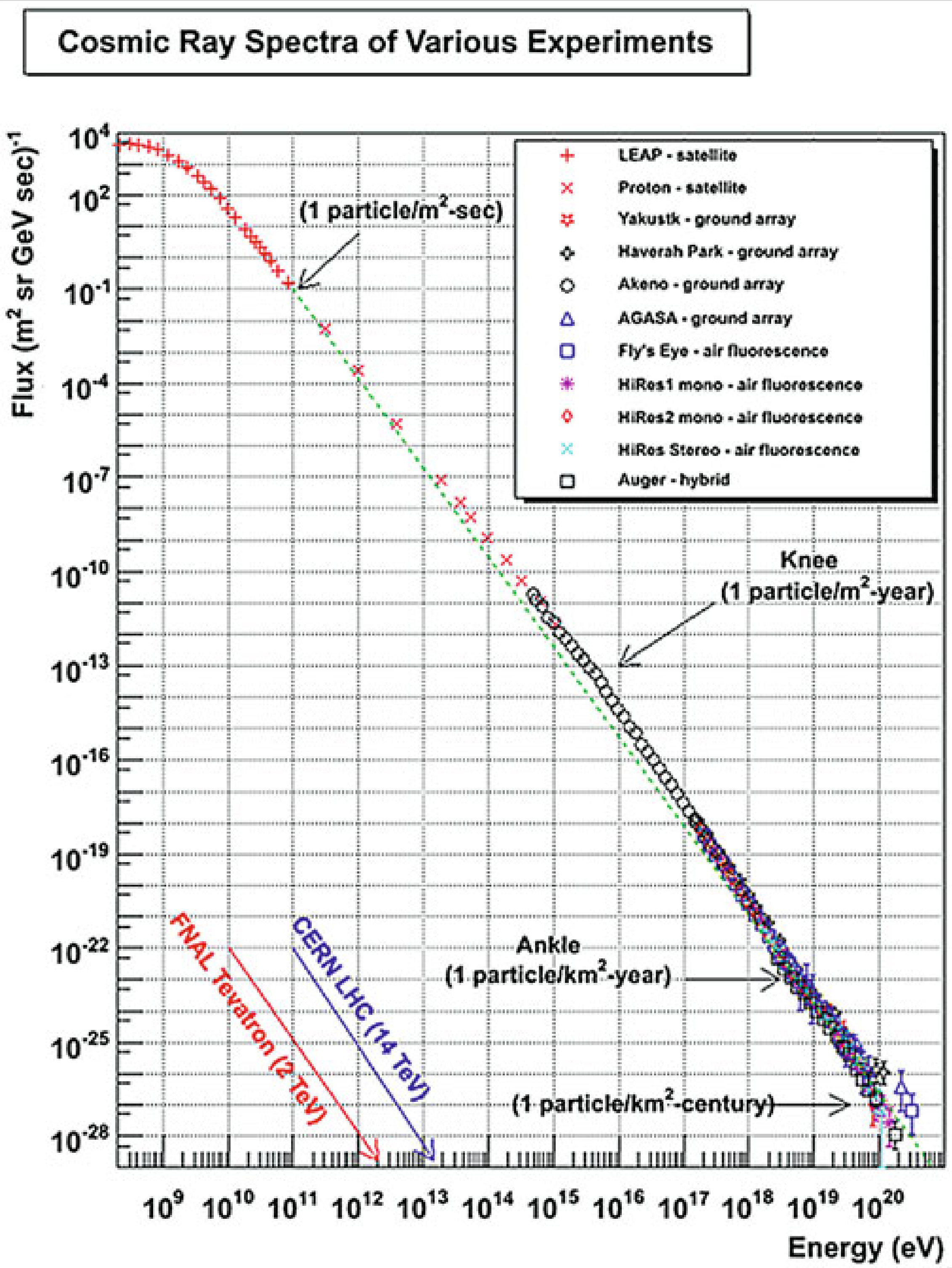

- Cosmic ray power in our Galaxy: ~ **5 x 10^{40} ergs/s**
  - **Supernovae and their remnants:**
    Release 10^{51} ergs, happen 1/30 years. **Q ~ 10^{42} ergs/s**
  - **Novae** (accretion of matter onto white dwarf):
    100/year, release 10^{47} ergs, **Q ~ 10^{42} ergs/s**
  - **Rotating neutron stars:**
    Majority of Galactic Fermi-LAT sources, **Q ~ 10^{41} ergs/s**
  - **Stellar winds from hot O/B stars:**
    Strong winds from rad. pressure (10^{9} $\dot{M}_{sun}$), **Q~10^{41} ergs/s**

Stefan Funk, April 1st 2012, APS Atlanta

CR acceleration

- The main observational inputs:
  - charged CR spectrum is (broken) PL: **acceleration processes are non-thermal**!

<~GeV affected by Solar winds



$$I(E) \propto E^{-\gamma}$$

(Thermal vs non-thermal spectrum)

First striking feature: **the power law spectrum!**
*'The queen of the **non–thermal** particle distribution '* (Ghisellini)

- **Thermal plasma (in equilibrium)** is characterised by a Maxwellian distribution of particles & emits black-body spectra:

$$F(v)dv \;=\; 4\pi v^2 \left(\frac{m}{2\pi kT}\right)^{3/2} e^{-mv^2/2kT} dv$$

- However, In ***rarefied and hot plasmas***, the relaxation time required to go to equilibrium, and allow for sufficient energy exchange among particles is long, compared to the typical timescales of other processes, as *acceleration, cooling and escape* - ***NON THERMAL PROCESSES***.

The emission is then shaped by these other, more efficient, processes and typically results in a power-law.

CR acceleration - mechanism

CR acceleration

Energy provided by gravity, rotation…

Only charged particles!

ALL ACCELERATION MECHANISMS ARE ELECTROMAGNETIC IN NATURE

MAGNETIC FIELD CANNOT MAKE WORK ON CHARGED PARTICLES THEREFORE ELECTRIC FIELDS ARE NEEDED FOR ACCELERATION TO OCCUR

REGULAR ACCELERATION

THE ELECTRIC FIELD IS LARGE SCALE:

$$\langle \vec{E} \rangle \neq 0$$

STOCHASTIC ACCELERATION

THE ELECTRIC FIELD IS SMALL SCALE:

$$\langle \vec{E} \rangle = 0 \quad \langle \vec{E}^2 \rangle \neq 0$$

CR acceleration

REGULAR ACCELERATION

$$\langle \vec{E} \rangle \neq 0$$

Very special conditions are necessary in Astrophysical environments in order to achieve this condition, because of the high electrical conductivity of astrophysical plasmas. Few exceptions:

UNIPOLAR INDUCTOR: this occurs in the case of rotating magnetic fields, such as in pulsars, rotating black holes. An electric potential is established between the surface of the rotating object (neutrons star, BH) and infinity. The potential difference is usable only in places (gaps) where the condition $\vec{E} \cdot \vec{B} = 0$ **is violated. MHD is broken in the gaps.**

RECONNECTION: Locally, regions with opposite orientation of magnetic field merge, giving rise to a net local electric field E~LB, where L is the size of the reconnection region. It occurs in the sun and solar wind, but probably also in the magnetosphere of rotating neutron stars and BHs.

CR acceleration

- **Permanent magnetic fields** are not a good candidate since they cannot accelerate particles,
- **static electric fields** would be quickly neutralized (caveats…)
- while **variable magnetic fields** may induce variable electrical fields and thus accelerate, provided the particles are submitted to many acceleration cycles.

But, how does it work?

In **1933**, **Zwicky and Baade** wrote a joint paper ``**Supernovae and Cosmic Rays**" where they coined a new term - ***Supernova*** and advanced a revolutionary **conjecture**: ***that supernovae represent the collapse of ``ordinary stars into neutron stars,"*** because that gave about the right total energy released in the outburst.

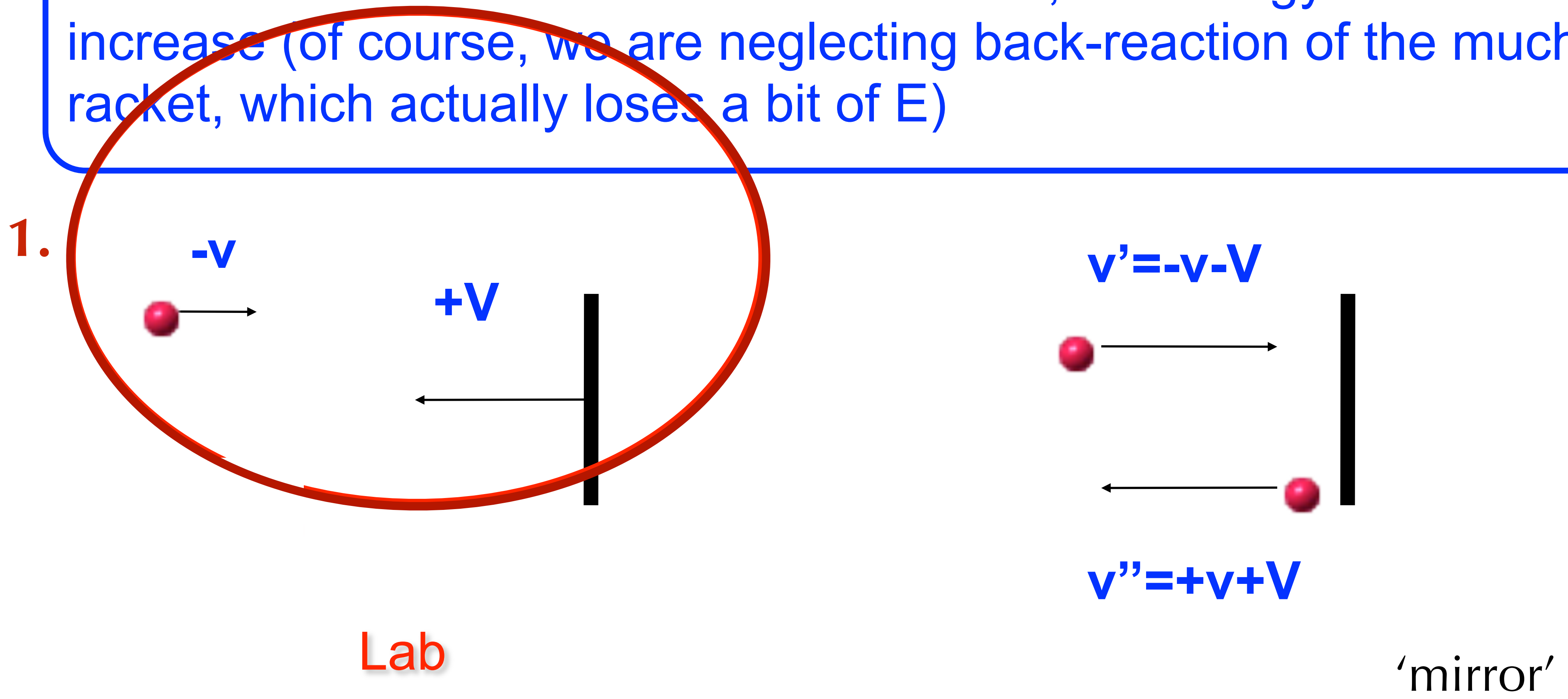
It took **16 years** for **Fermi** to devise **a model** in which this conjecture could be 'testable'; indeed we are convinced nowadays that most of the accelerators of cosmic rays in our galaxy are, indeed, **supernova remnants**.

But how can a SNR or whatever remnant of a gravitational collapse accelerate particles?

CR acceleration

Fermi's proposal: consider 'change of frame' acceleration

Think of a ball bouncing on moving racket: There's no gain of energy… in the frame of the racket! In the lab frame, the energy of the ball does increase (of course, we are neglecting back-reaction of the much larger racket, which actually loses a bit of E)



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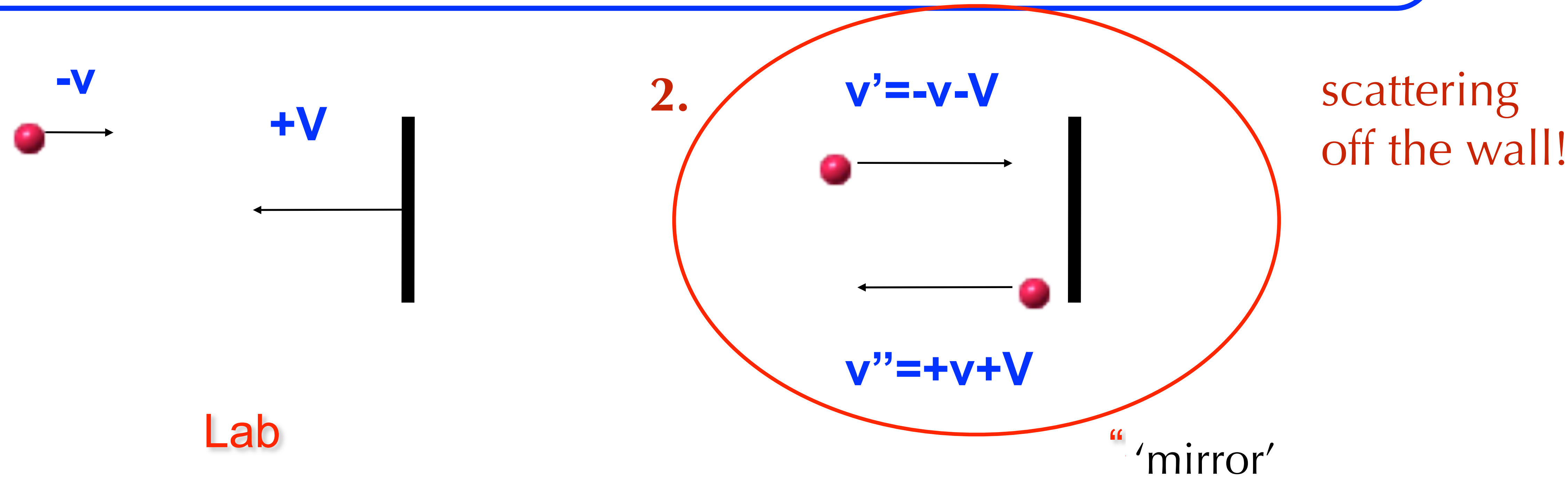

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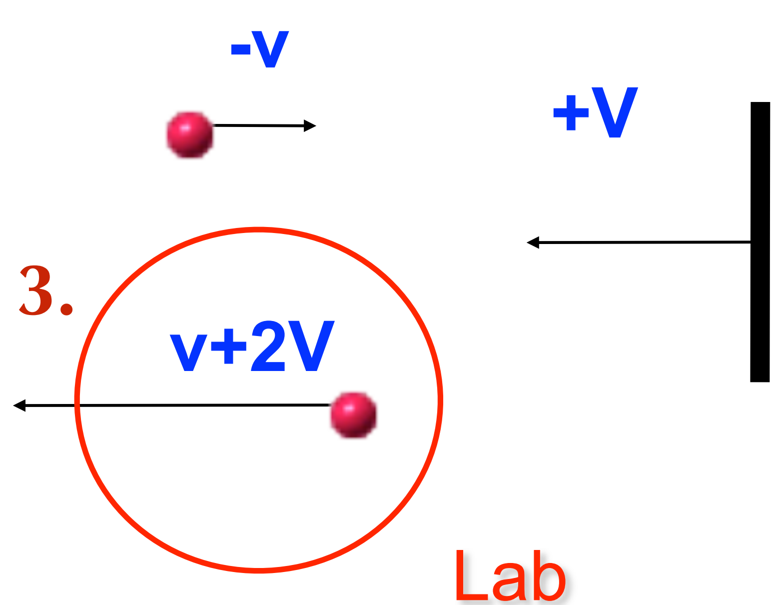
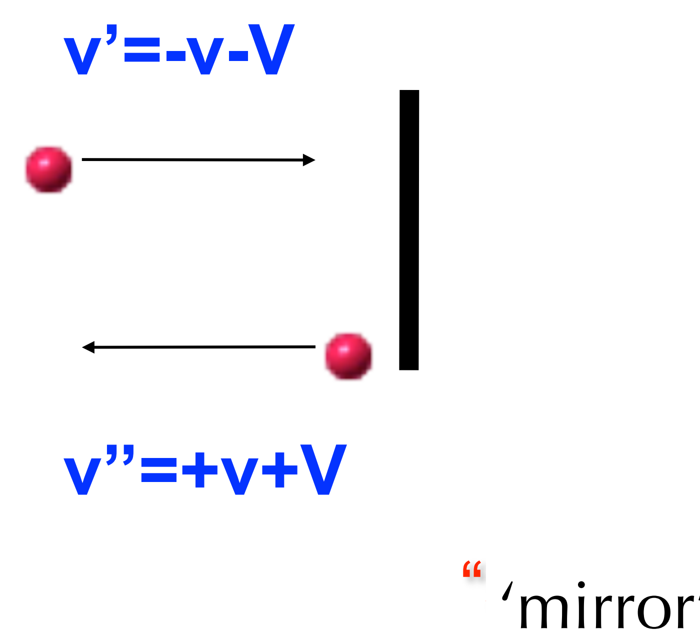




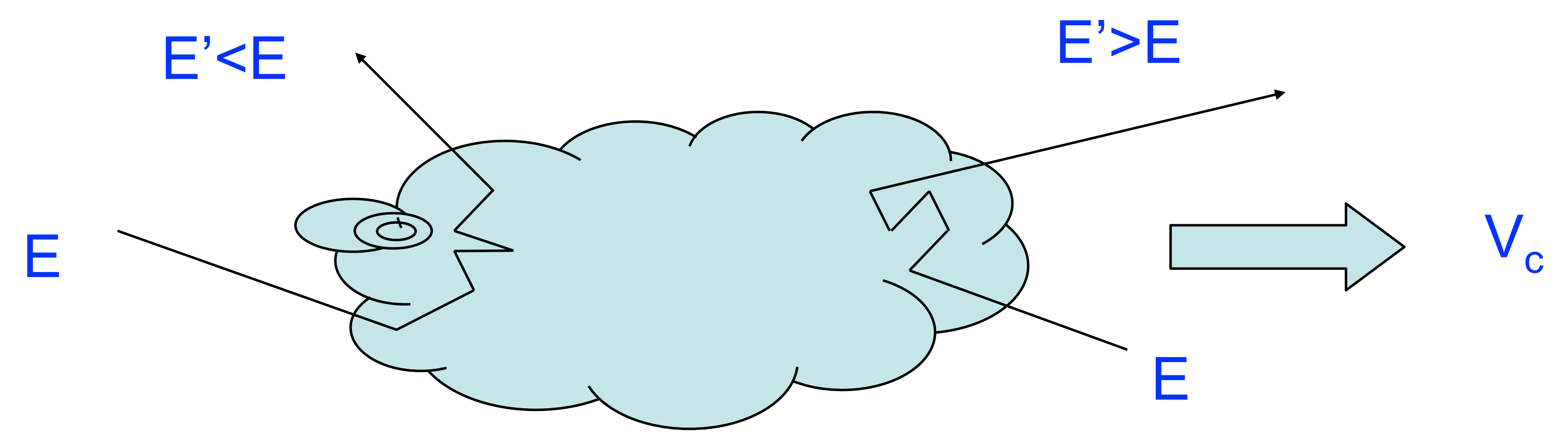
'change of frame' acceleration

NOT an elastic scattering

CR acceleration

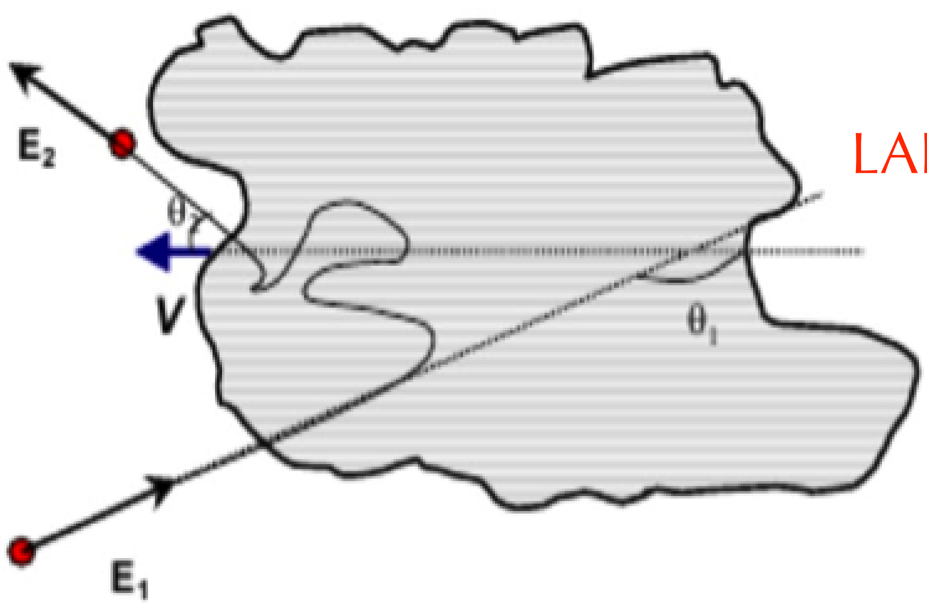
Fermi's conjecture was that a similar processes could be happening in astrophysical systems with magnetic inhomogeneities as 'mirrors'.

Initial proposal: the acceleration happens by scattering off "magnetic inhomogeneity" clouds in the ISM, which act as magnetic mirrors.



2nd order Fermi acceleration a charged particle with energy E_1 in the "laboratory" frame scattering inside a shock wave, i.e., a moving boundary between regions of different density.

See e.g. Alessandro de Angelis and Mario Pimeta "Introduction to Particle and Astroparticle Physics"



LAB frame

The cloud has a velocity $\beta = V/c$, and θ_1 and θ_2 are the angles between, respectively, the initial and final particle momentum and the cloud velocity.

in the cloud reference frame:

$$E_1^* = \gamma E_1(1 - \beta \cos\theta_1)\,.$$

The energy of the particle $E1_*$ in the cloud reference frame

In the cloud reference frame $E2_* = E1_*$ (collisions to a wall!)

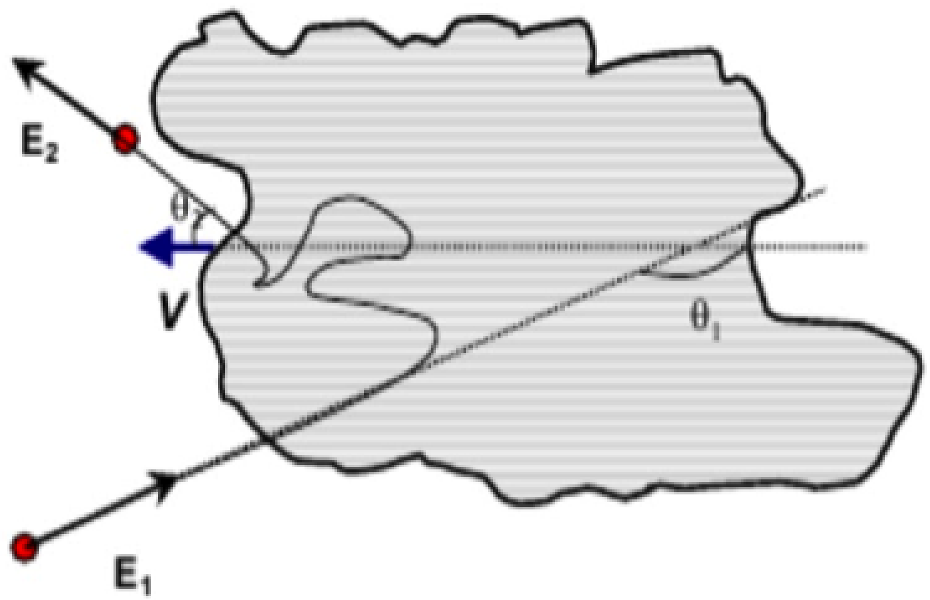
back to the LAB frame:

$$E_2 = \gamma E_2^*(1 + \beta \cos\theta_2)\,.$$

$$\frac{\Delta E}{E} = \frac{1 - \beta\cos\theta_1 + \beta\cos\theta_2 - \beta^2\cos\theta_1\cos\theta_2}{1-\beta^2} - 1\,.$$

relative energy exchange

2nd order Fermi acceleration



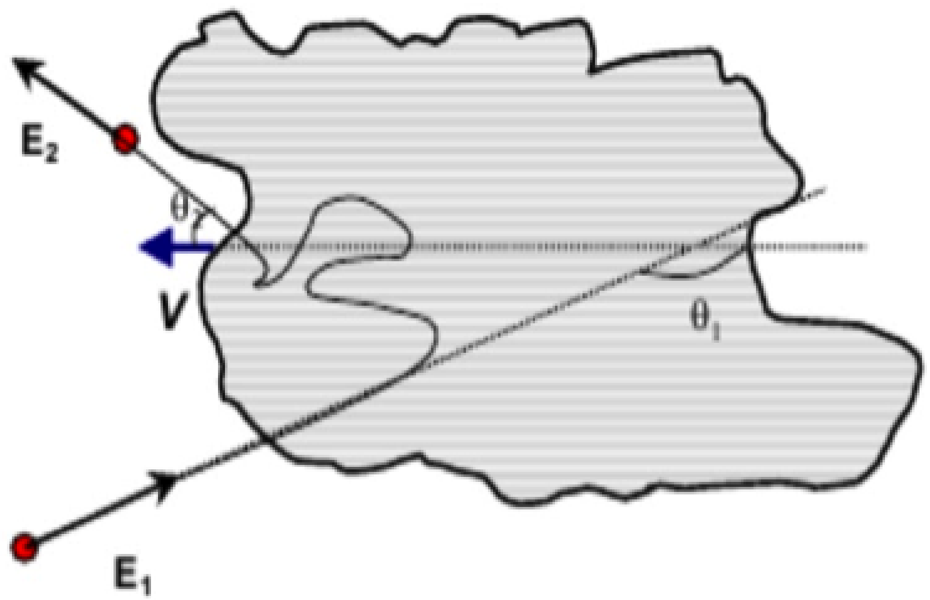
$$\frac{\Delta E}{E} = \frac{1 - \beta\cos\theta_1 + \beta\cos\theta_2 - \beta^2\cos\theta_1\cos\theta_2}{1-\beta^2} - 1\,.$$

$$\langle\cos\theta_2\rangle = 0$$

the particle scatters many times inside of the cloud, exit direction 'random'.

$$\left\langle\frac{\Delta E}{E}\right\rangle = \frac{1 - \beta\langle\cos\theta_1\rangle}{1-\beta^2} - 1\,.$$

2nd order Fermi acceleration



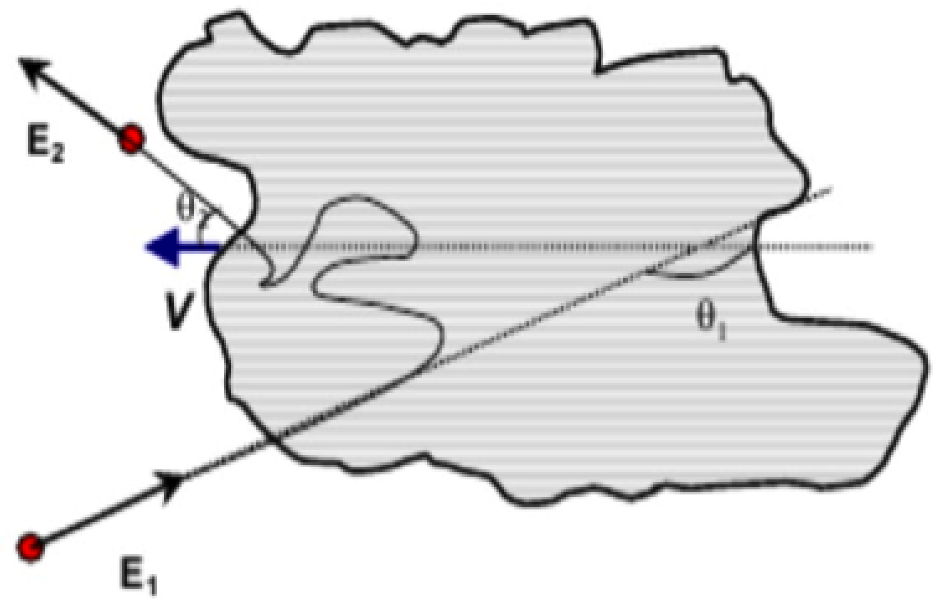
$$P \propto (v - V\cos\theta_1) \simeq (1 - \beta\cos\theta_1)$$

the probability to scatter with the cloud *does* depend on the relative velocity

$$\langle \cos\theta_1 \rangle = \frac{\int_{-1}^{1} \cos\theta_1 (1 - \beta\cos\theta_1) d\cos\theta_1}{\int_{-1}^{1} (1 - \beta\cos\theta_1) d\cos\theta_1} = -\frac{\beta}{3} \, .$$

$$\left\langle \frac{\Delta E}{E} \right\rangle \simeq \frac{4}{3}\beta^2 \, .$$

2nd order Fermi acceleration



Summary:

Each interaction of a test particle with a magnetized cloud results in either an energy gain or an energy loss, depending upon the relative direction of motion at the time of the scattering. On average however, the head-on collisions dominate upon tail-on collisions leading to a net increase in the energy.

$$\left\langle \frac{\Delta E}{E} \right\rangle \simeq \frac{4}{3}\beta^2 .$$

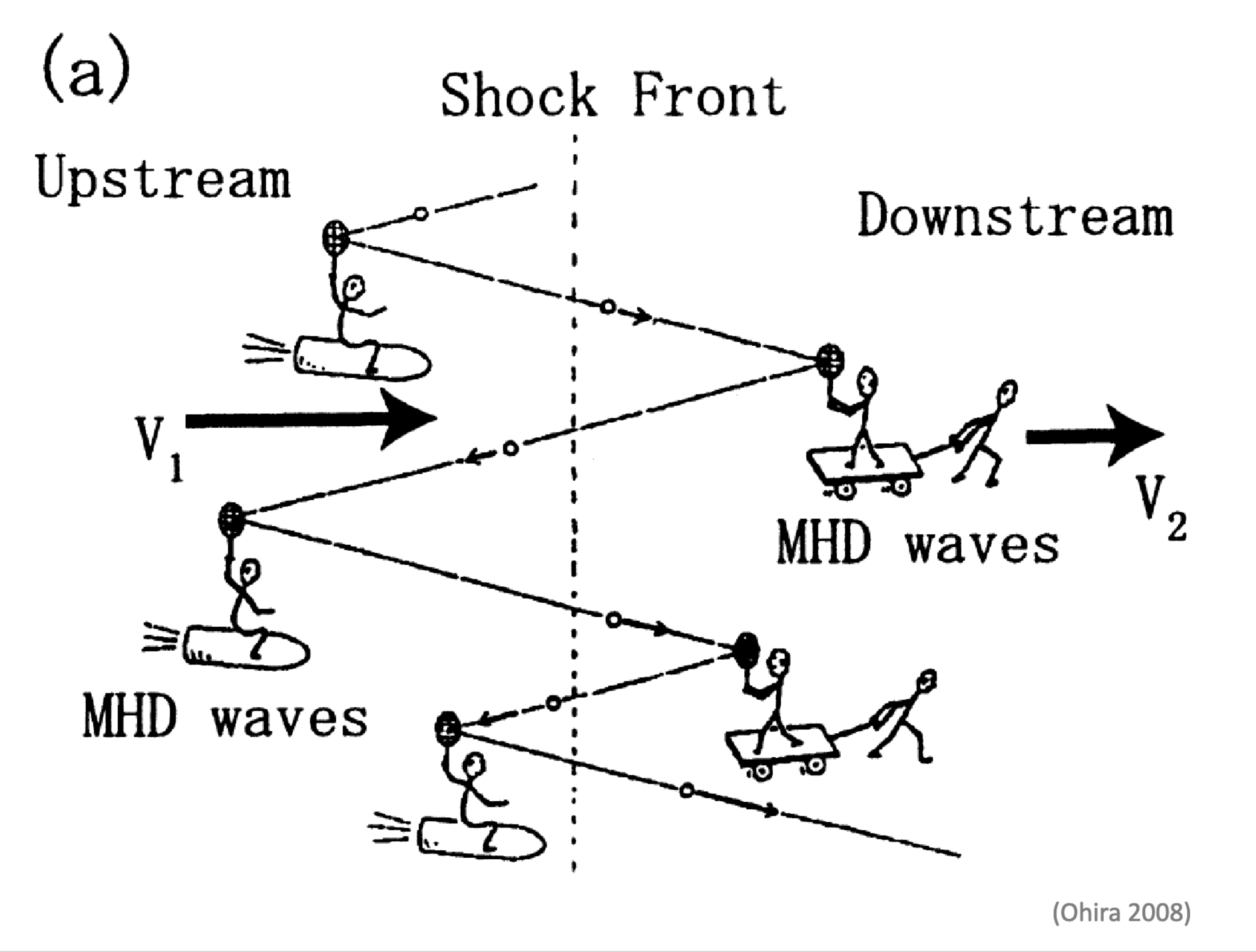
Does it work? **NO…**

The energy gain is quadratic in the cloud velocity and, as this velocity is usually small (β ≃ 10^-4), it is not able to explain the cosmic ray energy spectrum.

Also, does not explain why we observe a power law spectra.

CR acceleration

Fermi's next idea: special geometry is needed, particles need to stay trapped in a geometry where they can experience *repeated* 'ping-pong' acceleration



CR acceleration

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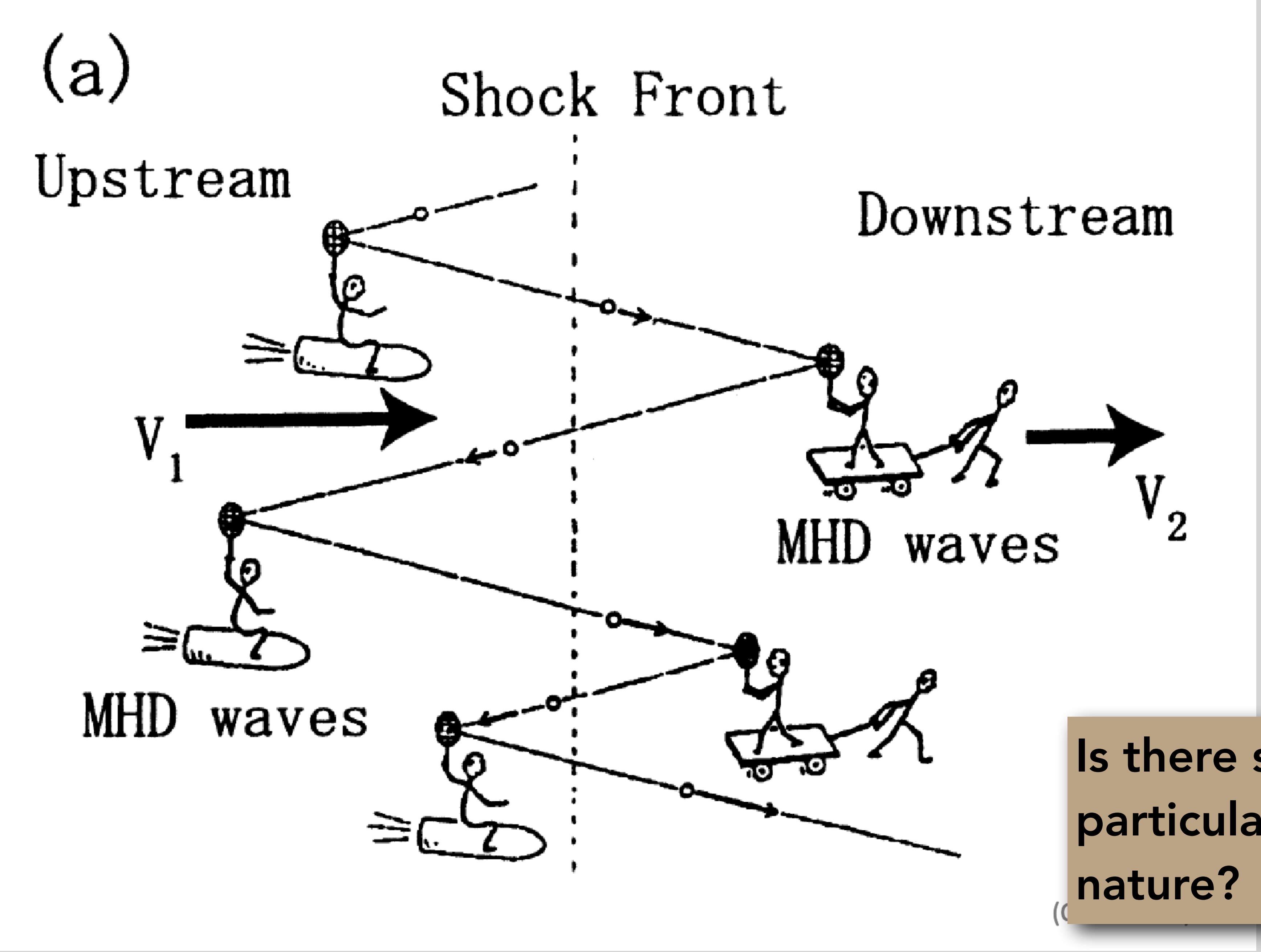
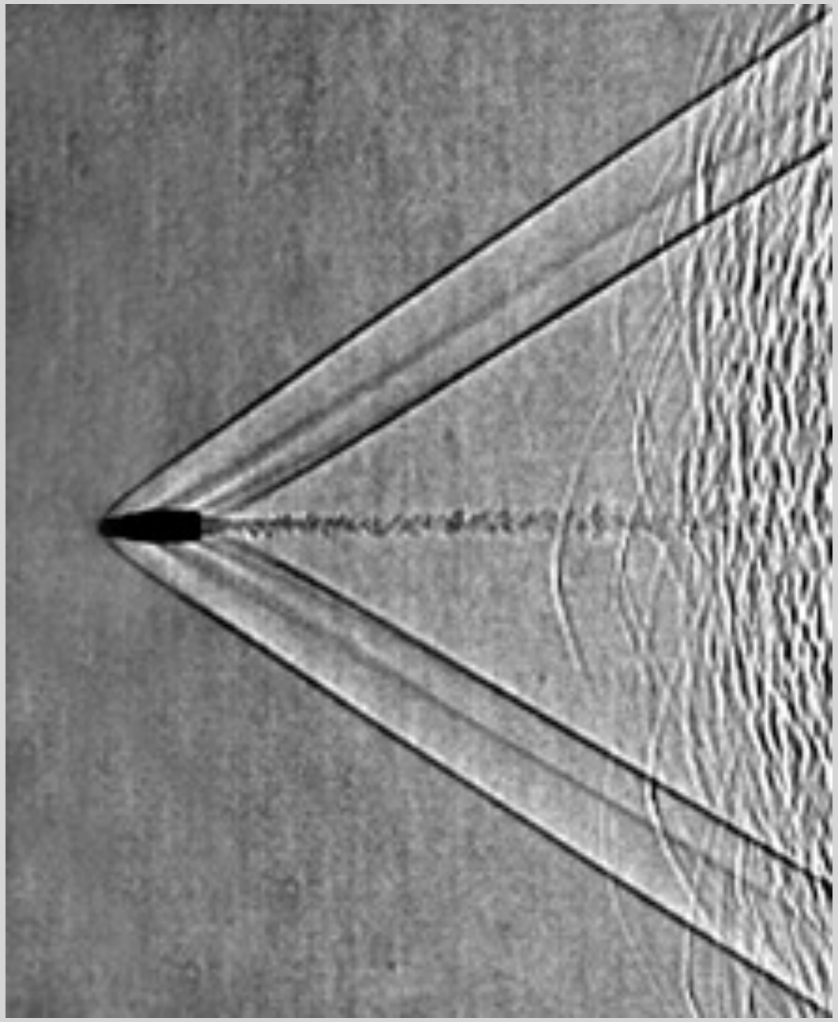


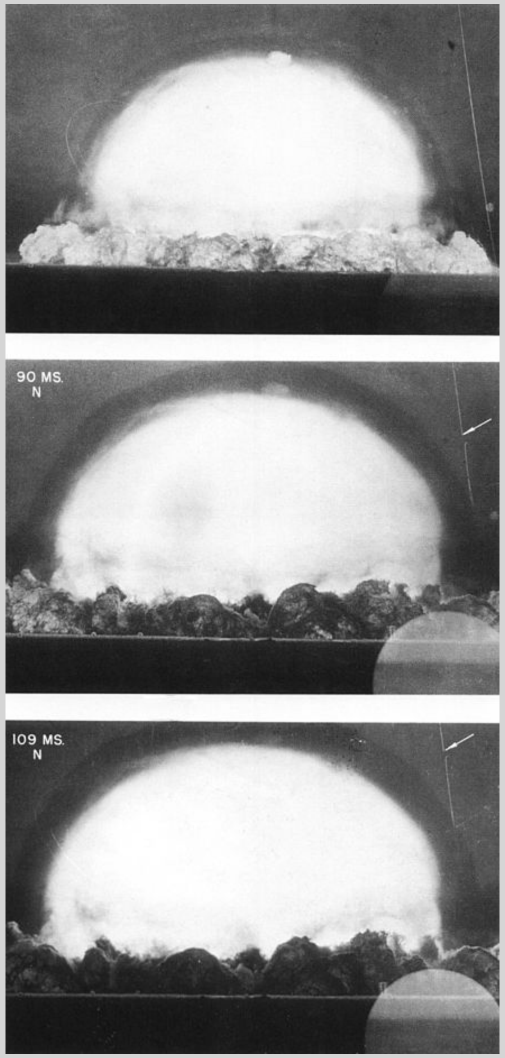
Is there such a particular geometry in nature?

CR acceleration

Shock waves?

In physics, a **shock wave** (also spelled **shockwave**), or **shock**, is a type of propagating disturbance that moves faster than the local speed of sound in the medium. Like an ordinary wave, a shock wave carries energy and can propagate through a medium but is characterized by an abrupt, nearly discontinuous, change in pressure, temperature, and density of the medium.[1][2][3][4][5][6]

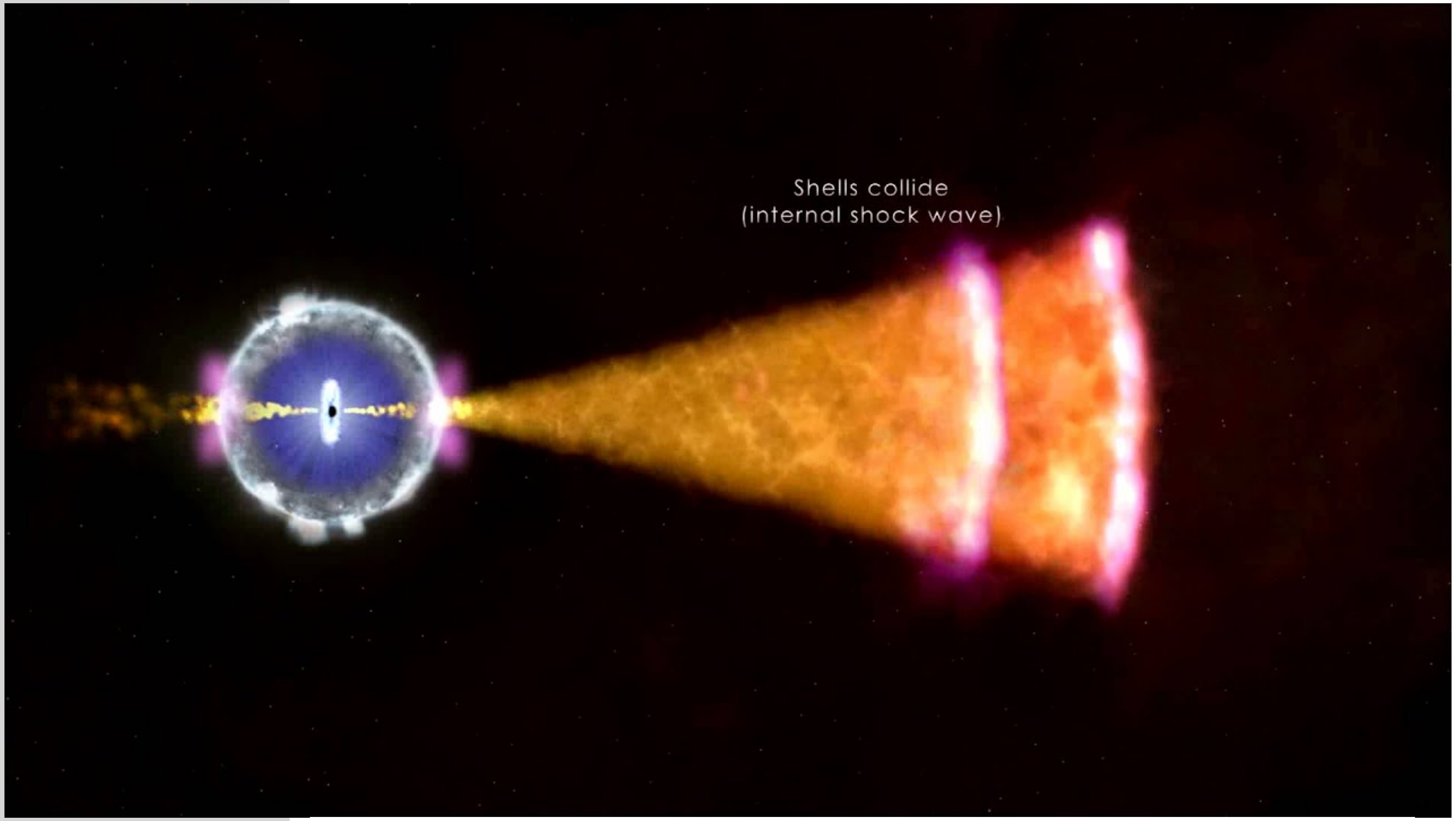




CR acceleration

Plenty of shocks in nature…

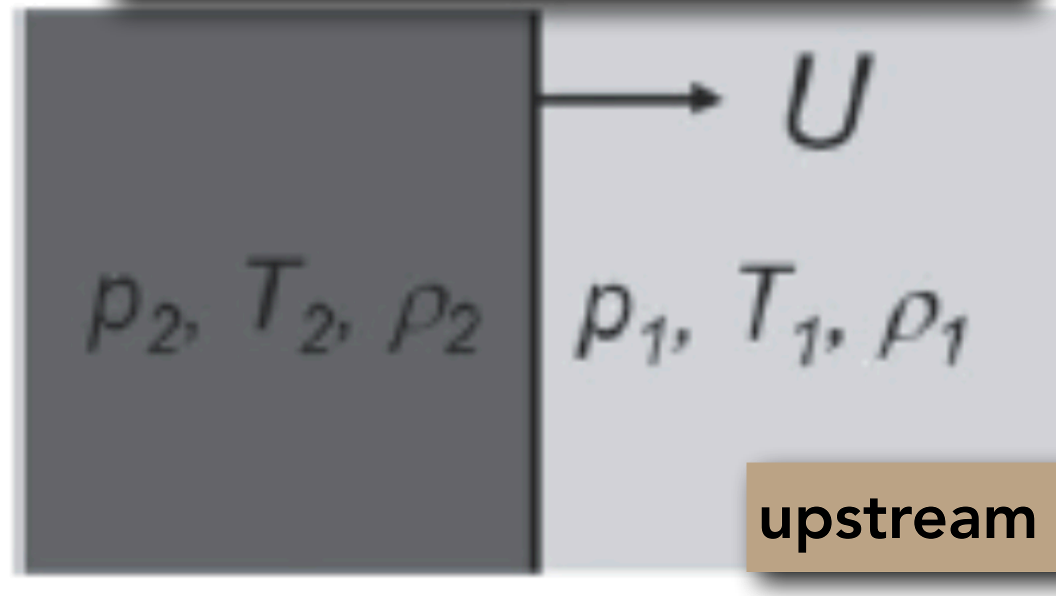
Even on Earth! The main difference is that shock in space are collisionless, i.e. the microscopic physics is not the collision between atoms or ions, rather the scattering onto magnetic inhomogeneities over scales as small as the gyroradius of the particles. In terrestrial Labs, hard to reproduce collisionless shock physics!



Collisionless shocks are formed because of the excitation of electro-magnetic instabilities, namely collective effects generated by groups of charged particles in the background plasma.

What are astrophysical 'shocks'?

Rest frame of interstellar gas

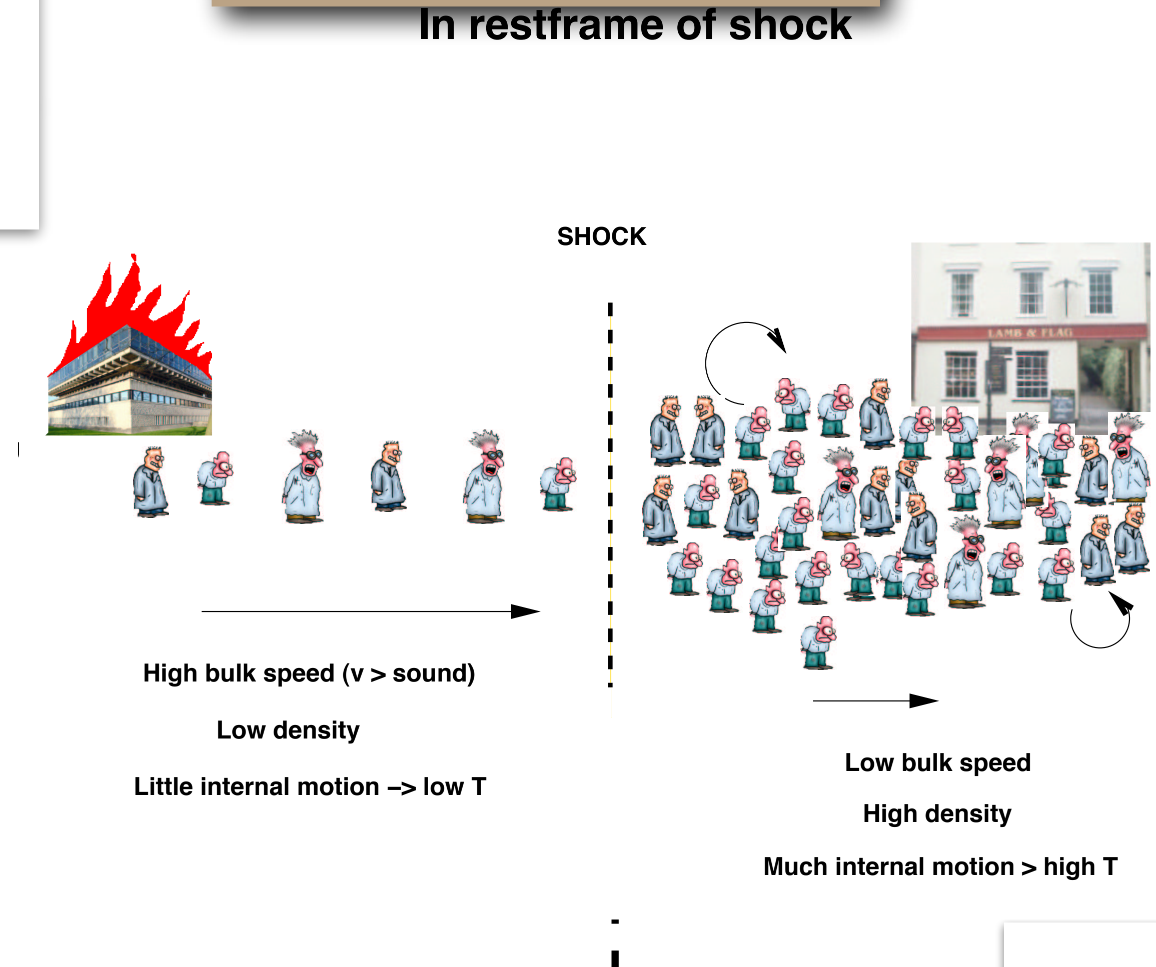


upstream (stationary)

Rest frame of shock

upstream

unshocked ("virgin") gas



downstream

shocked gas

Strong shock jump conditions

$$\frac{\rho_d}{\rho_u} = 4; \frac{v_u}{v_d} = 4$$

Conserve mass: the mass per unit area flowing across the shock is conserved.

$$\rho_u v_u = \rho_d v_d$$

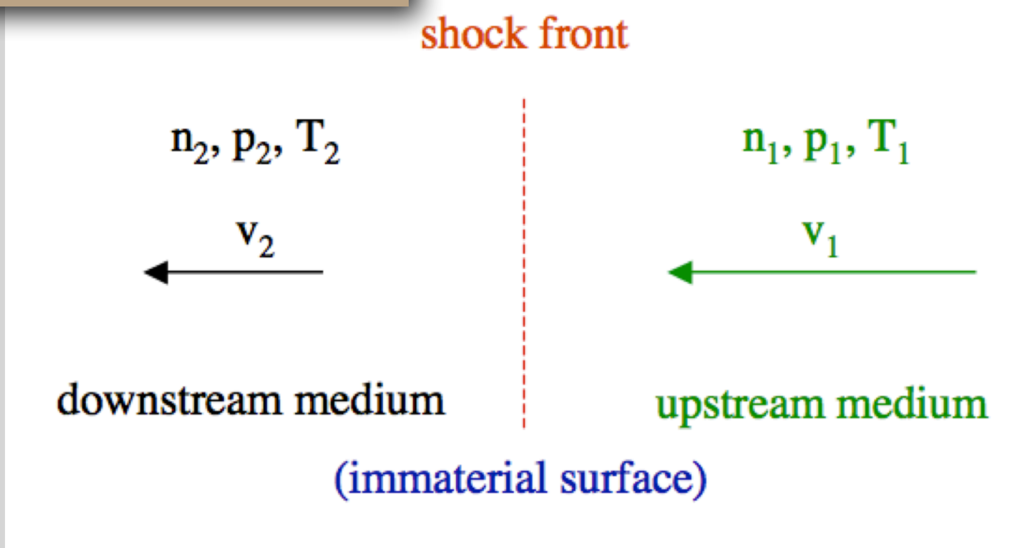
Conserve momentum: the shock does not accelerate in its rest frame. The difference between upstream and downstream ram-pressures must be provided by the gas pressure downstream.

$$\rho_u v_u^2 = P_d + \rho_d v_d^2$$

Conserve energy: PdV work is being done on the gas at the shock. The rate (per unit area) at which this work is done is $v_d P_d$

$$v_u(\frac{1}{2}\rho_u v_u^2) - v_d(\frac{1}{2}\rho_d v_d^2 + \frac{3}{2}P_d) = v_d P_d$$

Higher density and T



When passing through the shock, the fluid is compressed, heated and slows down:

ρ2>ρ1, T2>T1, v2<v1

For strong shocks: ρ2=4ρ1, v2=v1/4

In shocks, there is a large pressure & T jump; also, the Kinetic Energy (partially) heats the gas

Shock waves are huge "heating" machines!

Collisionless shocks

While shocks in the terrestrial environment are mediated by particle-particle collisions, astrophysical shocks are almost always of a different nature. The pathlength for ionized plasmas is of the order of: **rarified plasma!**

$$\lambda \simeq \frac{1}{n\sigma} = 3.2 Mpc\, n_1^{-1} \left(\frac{\sigma}{10^{-25} cm^2}\right)^{-1}$$

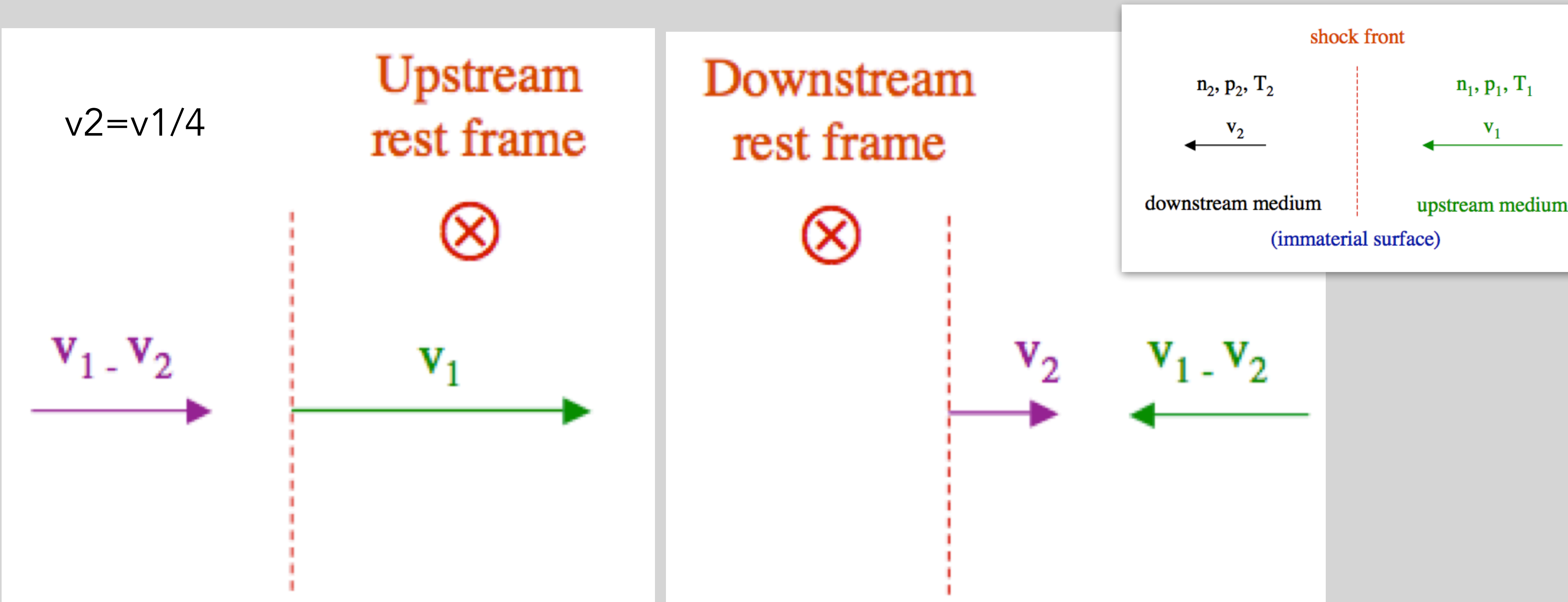
Absurdly large compared with any reasonable length scale. It follows that astrophysical shocks can hardly form because of particle-particle scattering But REQUIRE the mediation of magnetic fields. In the downstream gas the Larmor radius of particles is:

$$r_{L,th} \approx 10^{10} B_\mu T_8^{1/2} \text{ cm} \quad \sim 10^{-9} \text{ pc}$$

The slowing down of the incoming flow and its isotropization (thermalization) Is due to the action of magnetic fields in the shock **region (COLLISIONLESS SHOCKS)**

CR acceleration

Fermi's next idea: special geometry is needed, particles need to stay trapped in a geometry where they can experience repeated 'ping-pong' acceleration



Now consider **electrons initially at rest in the unshocked gas frame**.

They see the shock approaching at v_u but they also see the hot shocked gas approaching at 3/4 v_u.

As they cross the shock they are accelerated to a mean speed of 3/4vu (velocity of shocked gas as viewed from the frame of the unshocked gas), and are also thermalised to a high temperature.

CR acceleration

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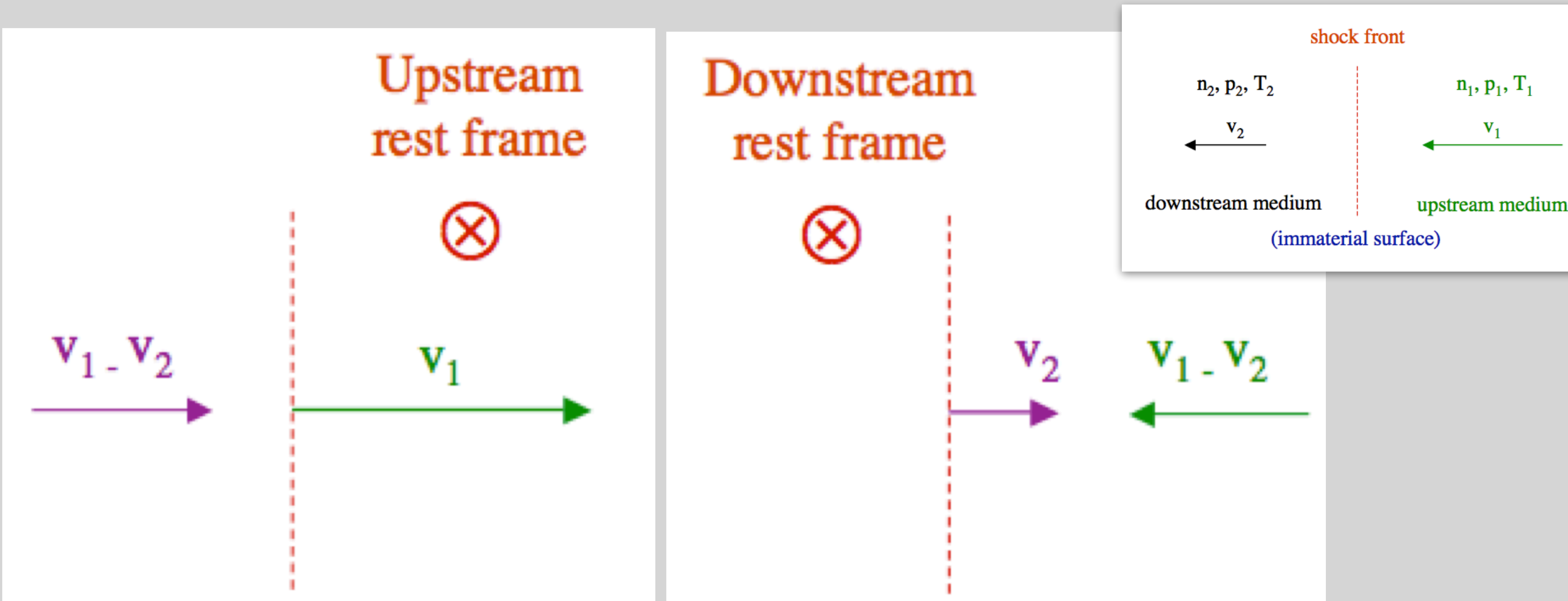
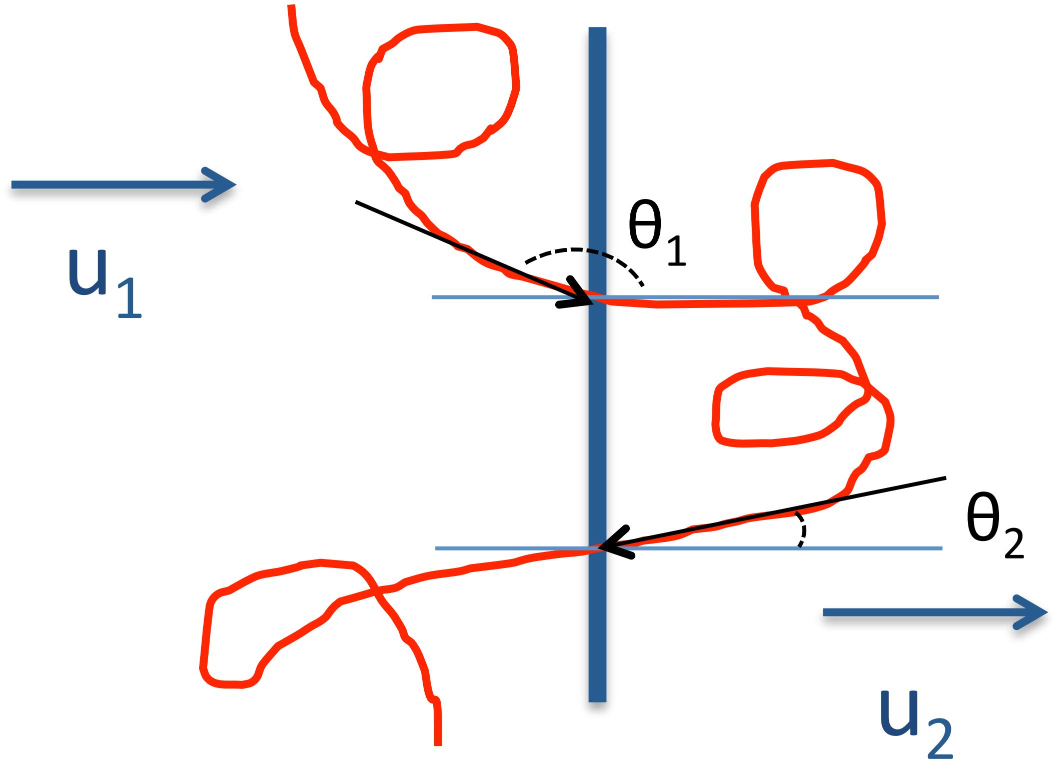


The clever part is this: consider what would happen if, say as a result of its thermal motion, or tangled magnetic field, an electron is carried back over the shock front.

With respect to the frame it has just come from—the shocked gas frame—it is once again accelerated by 3/4vu (mean velocity of the gas in the unschocked frame).

Energy gain in a shock cycle



In the shock wave rest frame the medium ahead of the shock (upstream) runs into the shock front with a velocity *u*1 , while the shocked gas (downstream) moves away with a velocity *u*2

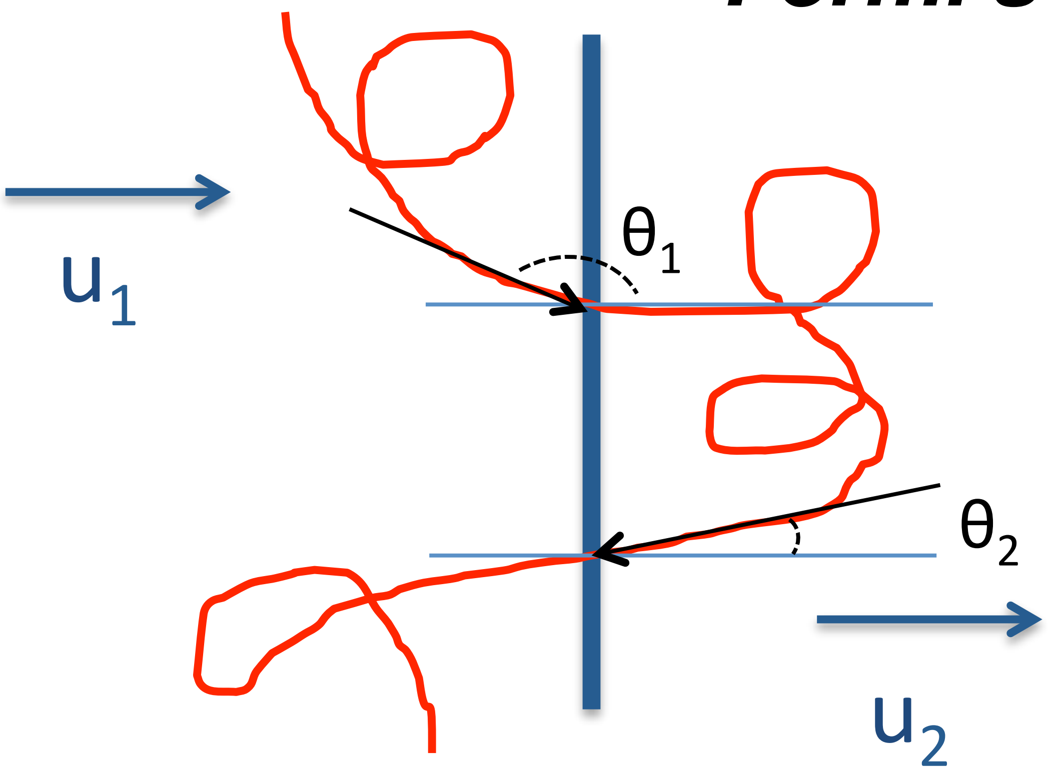
GEOMETRY constrained: The angle θ1(θ2) between the particle initial (final) velocity and the shock **velocity is now constrained to this specific geometry: –1 ≤ cos θ1 ≤ 0 (0 ≤ cos θ2 ≤ 1)**;

$$\langle \cos\theta_1 \rangle = \frac{\int_{-1}^{0} \cos^2\theta_1 d\cos\theta_1}{\int_{-1}^{0} \cos\theta_1 d\cos\theta_1} = -\frac{2}{3}$$

$$\langle \cos\theta_2 \rangle = \frac{\int_{0}^{1} \cos^2\theta_2 d\cos\theta_2}{\int_{0}^{1} \cos\theta_2 d\cos\theta_2} = \frac{2}{3} .$$

probability to scatter with a shock ~cosθ

'Fermi's "ping-pong" acceleration process'



$$\langle\cos\theta_1\rangle = \frac{\int_{-1}^{0}\cos^2\theta_1 d\cos\theta_1}{\int_{-1}^{0}\cos\theta_1 d\cos\theta_1} = -\frac{2}{3}$$

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$$\frac{\Delta E}{E} = \frac{1-\beta\cos\theta_1+\beta\cos\theta_2-\beta^2\cos\theta_1\cos\theta_2}{1-\beta^2} - 1$$

energy gain 'per crossing'!

$$\frac{\Delta E}{E} = \epsilon \simeq \frac{4}{3}\beta\,.$$

A FEW IMPORTANT POINTS:

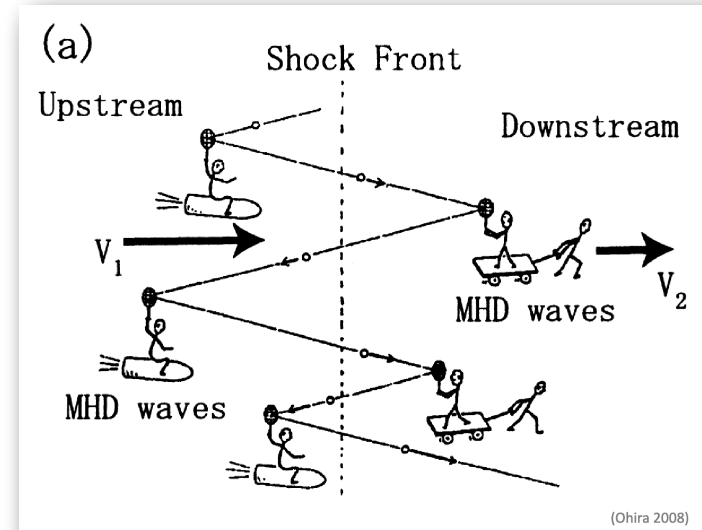
I. There are no configurations that lead to losses

II. The mean energy gain is now first order in b

III. The energy gain is basically independent of any detail on how particles scatter back and forth!

Now that we defined en gain PER CROSSING - how about the final spectrum of accelerated particles?

$$\frac{\Delta E}{E} = \epsilon \simeq \frac{4}{3}\beta\,.$$



in each cycle energy gained ε, after n- crossings

$$E_n = E_0(1+\epsilon)^n$$

or, by solving for n (**number of cycles needed to reach the energy En**):

$$n = \ln\left(\frac{E}{E_0}\right) / \ln(1+\epsilon)$$

Define Pn - probability for particle to ESCAPE from he shock

Then, the **probability P_{En} that a particle reaches energy En**

$$P_{E_n} = (1-P_i)^n$$

~probability for particle to stay for n-cycles, i.e. to reach energy En

$$P_{E_n} = (1 - P_i)^{\ln\left(\frac{E}{E_0}\right)/\ln(1+\epsilon)}$$

$$\ln P_{E_n} = \frac{\ln\left(\frac{E}{E_0}\right)}{\ln(1+\epsilon)} \ln(1 - P_i)$$

$$\ln P_{E_n} = \frac{\ln(1 - P_i)}{\ln(1+\epsilon)} \ln\left(\frac{E}{E_0}\right).$$

$$\frac{N}{N_0} = P_{E_n} = \left(\frac{E}{E_0}\right)^{-\alpha} \qquad \alpha = -\frac{\ln(1 - P_i)}{\ln(1+\epsilon)} \cong \frac{P_i}{\epsilon}$$

or, by differentiating wrt energy:

$$\boxed{\frac{dN}{dE} \propto \left(\frac{E}{E_0}\right)^{-\gamma}} \qquad \gamma = \alpha + 1\,.$$

$$P_{E_n} = (1 - P_i)^{\ln\left(\frac{E}{E_0}\right)/\ln(1+\epsilon)}$$

$$\ln P_{E_n} = \frac{\ln\left(\frac{E}{E_0}\right)}{\ln(1+\epsilon)} \ln(1 - P_i)$$

$$\ln P_{E_n} = \frac{\ln(1 - P_i)}{\ln(1+\epsilon)} \ln(\frac{E}{E_0}) .$$

Predicts a PL spectra, just as observed in nature!
The index predicted to be 2 for supersonic shocks - a softer spectra observed - more later!

$$\frac{N}{N_0} = P_{E_n} = (\frac{E}{E_0})^{-\alpha}$$

or, by differentiating wrt energy:

$$\frac{dN}{dE} \propto \left(\frac{E}{E_0}\right)^{-\gamma}$$

$$\gamma = \alpha + 1 .$$

How about the MAX energy that can be reached?

The maximum energy that a charged particle could achieve in the supernova remnant is then simply the rate of energy gain, times the time T_S spent in the shock. In the Fermi 1st order model,

$$\frac{dE}{dt} \simeq \beta \frac{E}{T_{cycle}} ,$$

$\Delta E/E \sim \beta$

where $T_{cycle} \simeq \lambda_{cycle}/(\beta c)$ is the time between two crossings. Since $\lambda_{cycle} \simeq r_L \simeq E/(ZeB)$ (r_L is the Larmor radius),

$$T_{cycle} \simeq \frac{E}{ZeB\beta c} \Longrightarrow \frac{dE}{dt} \simeq (\beta^2 c)ZeB .$$

Finally

$$E_{max} \simeq T_S \frac{dE}{dt} \simeq ZeBR_S\beta .$$

$$\frac{\Delta E}{E} = \epsilon \simeq \frac{4}{3}\beta .$$

$$E_{max} \simeq \beta\, Ze\, B\, R_S \simeq 300\, Z\, \text{TeV} .$$

Inserting B=4μG and assuming TS ≃RS/(βc), where RS is the radius of the SNR

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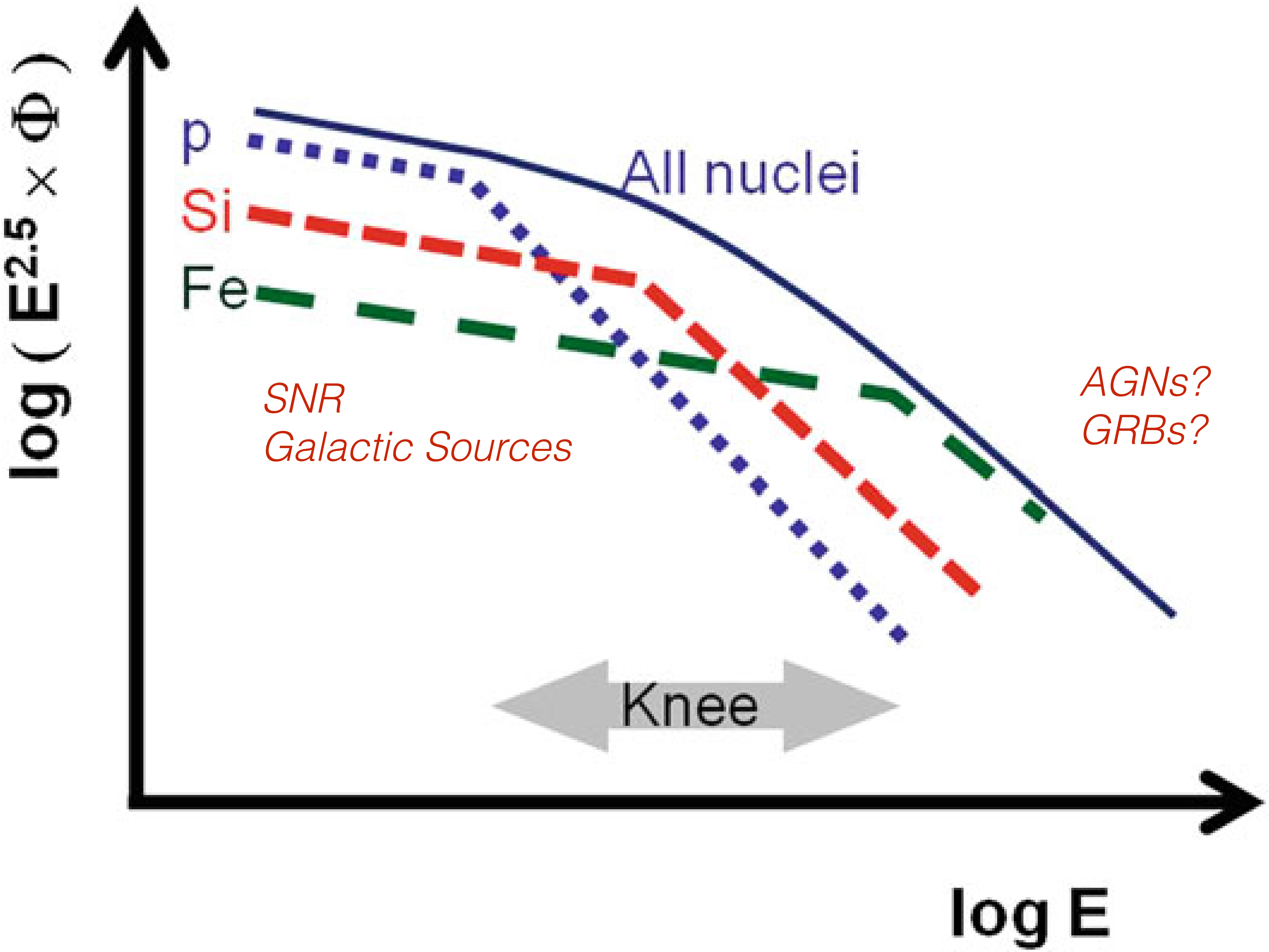
Inserting B=4μG and assuming TS ≃RS/(βc), where RS is the radius of the SNR

Very reasonable too for SNRs, remember the 'knee' in the CR spectrum. Depends on Z!



log ($E^{2.5} \times \Phi$)
p
Si
Fe
All nuclei
SNR
Galactic Sources
AGNs?
GRBs?
Knee
log E

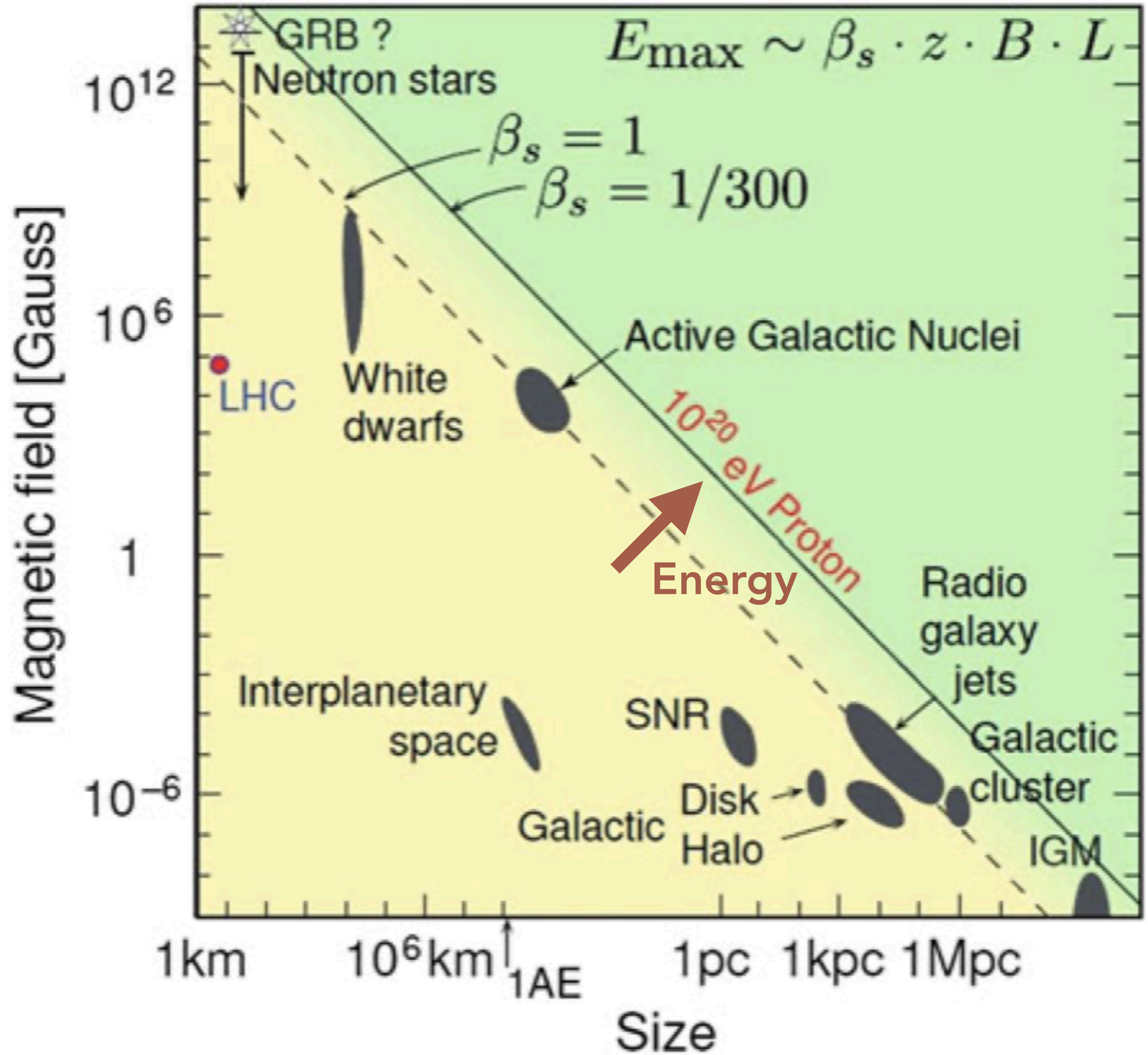
Beyond SNRs - Hillas Plot

The size of the acceleration region must be large enough to contains particles it accelerates - heuristic Hillas criterion

$$E_{\rm max}^{\rm Hillas} \sim Z\, e\, B\, R$$

$$\frac{E}{1\,\rm PeV} \simeq \frac{B}{1\,\mu\rm G} \times \frac{R}{1\,\rm pc}$$

$$\frac{E}{1\,\rm PeV} \simeq 0.2 \frac{B}{1\,\rm G} \times \frac{R}{1\,\rm AU}\,.$$



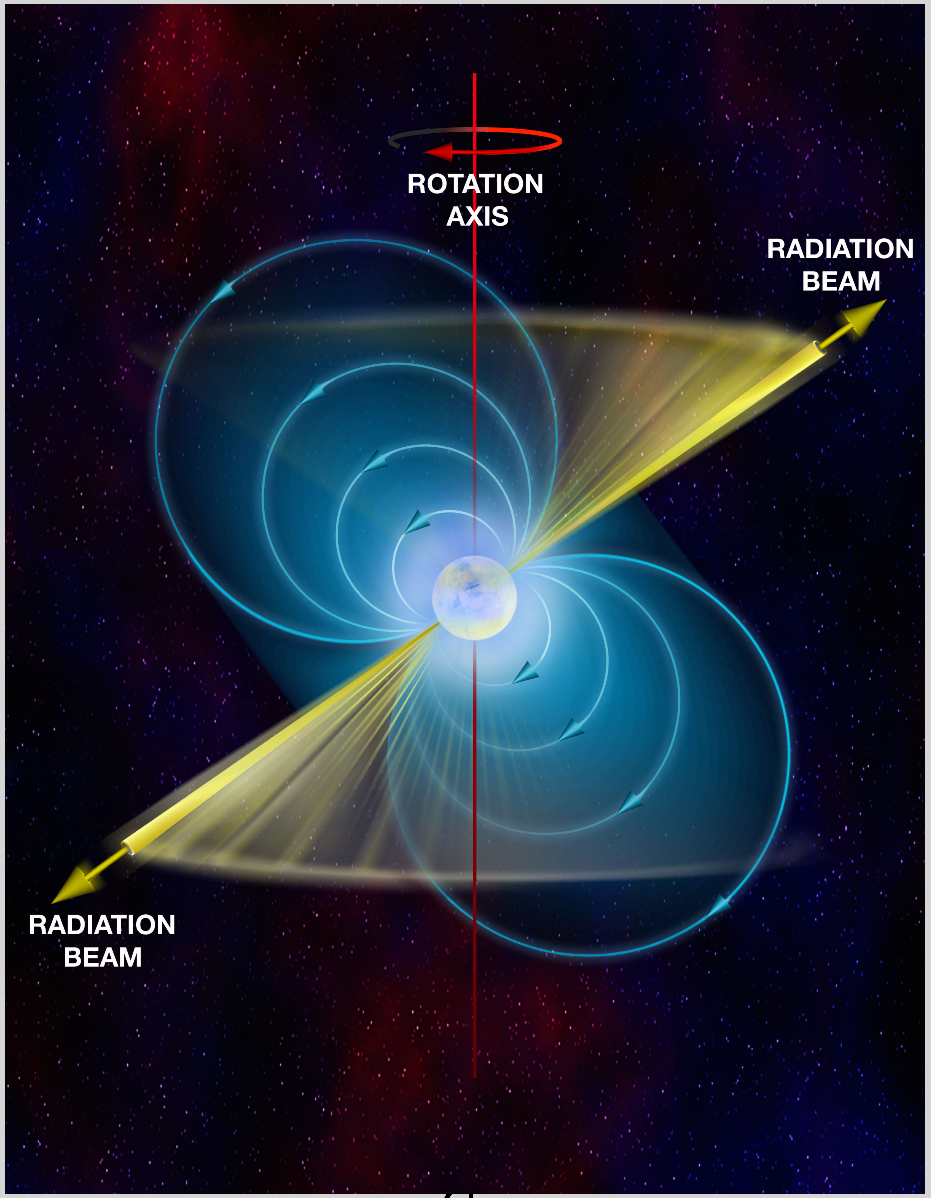
CR acceleration

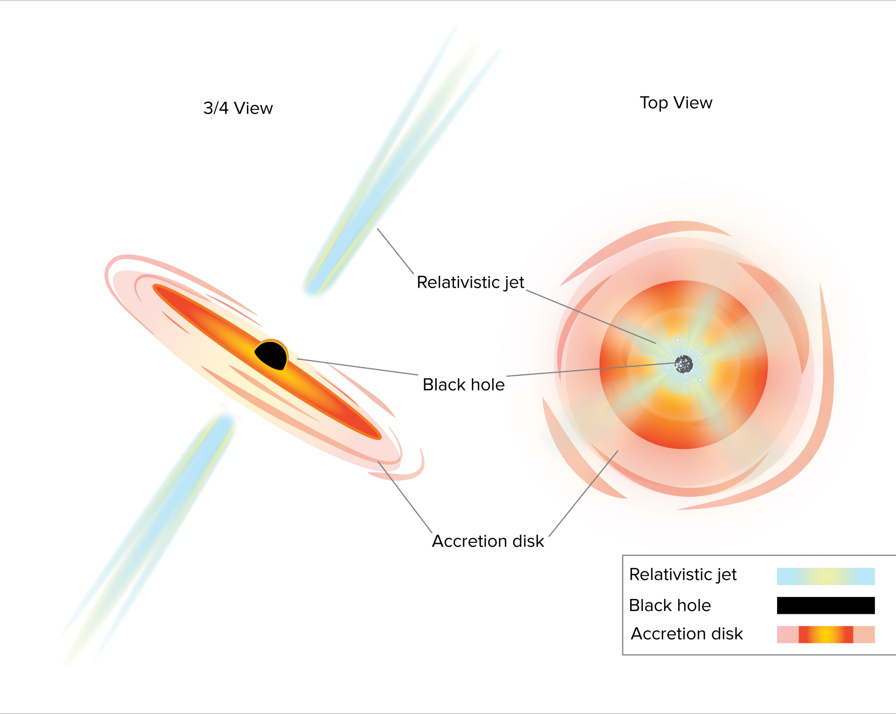
Summary:

- Astrophysical shocks provide prime location for particle **(ping-pong) acceleration**!
- Additional acceleration sites include vicinity of pulsars (rotational energy) and Active Galactic Nuclei (black hole gravity)

This image combines X-ray data from ESA's XMM-Newton and NASA's Chandra X-ray Observatory (combined to form the blue and green colours) with infrared observations from NASA's Spitzer Space Telescope and Wide-Field Infrared Survey Explorer (yellow and red).

The supernova remnant RCW 86 is some 8000 light-years away.





Beyond linear 'test particle' theory...

NON LINEAR THEORY

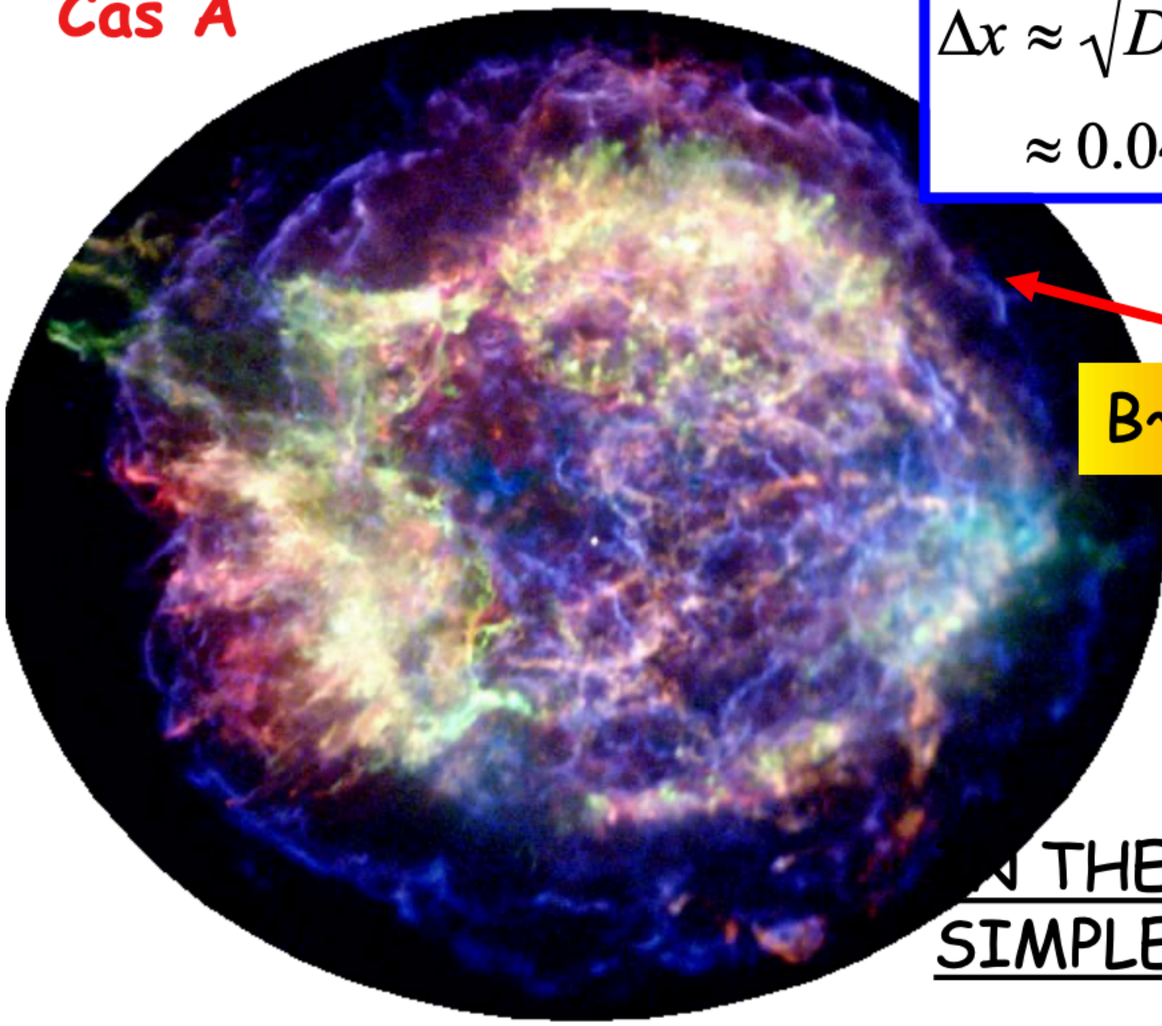
A theory of particle acceleration that allows one to describe:

1. ***Dynamical reaction of accelerated particles***
2. ***Streaming instability CR-induced B-field***
3. ***Dynamical reaction of amplified fields***
4. ***Phenomenological recipe for injection (self-regulation of the system)***
5. ***Escape of particles from boundaries (Cosmic Rays)***

Cortesy of E. Amato & P. Blasi

AMPLIFIED MAGNETIC FIELDS

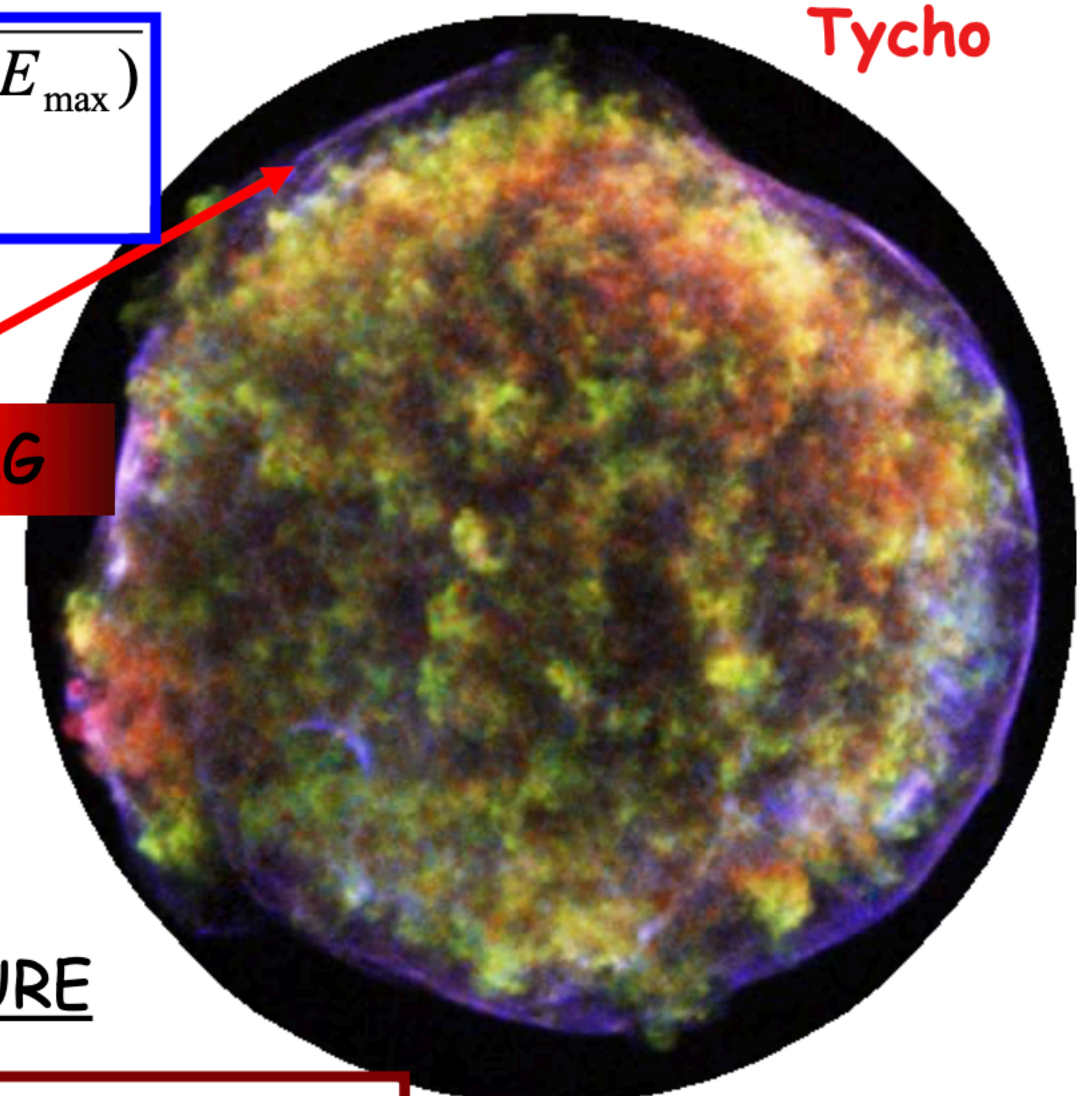
Cas A



$$\Delta x \approx \sqrt{D(E_{\max})\tau_{loss}(E_{\max})}$$
$$\approx 0.04 B_{100}^{-3/2} pc$$

B~100-300μG

Tycho



N THE
SIMPLEST PICTURE

EFFICIENT PARTICLE ACCELERATION BECAUSE OF HIGH B-FIELD

HIGH B-FIELD BECAUSE OF EFFICIENT PARTICLE ACCELERATION

CAVEAT:

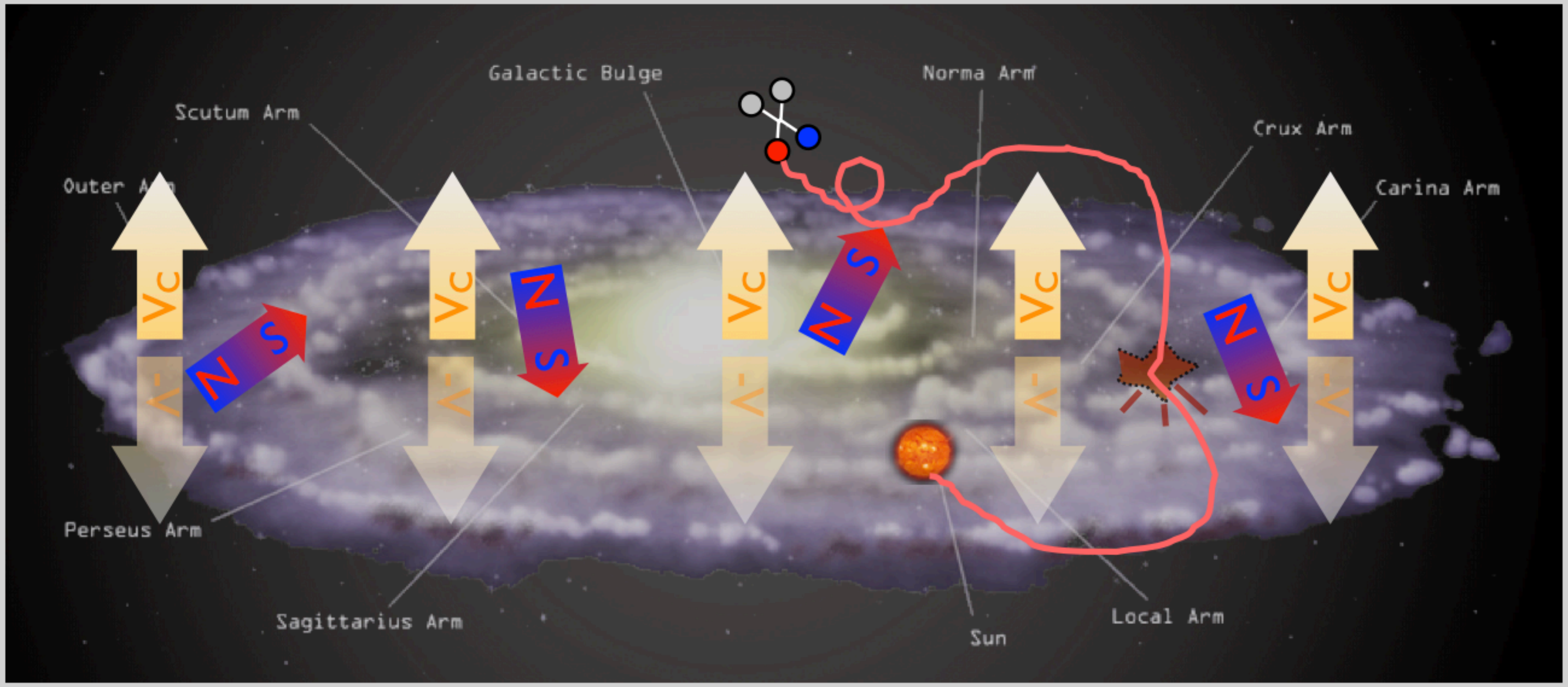
LARGE MAGNETIC FIELDS MIGHT HAVE DIFFERENT ORIGIN AND DO NOT IMPLY EFFICIENT SCATTERING...

Cortesy of E. Amato & P. Blasi

CR energy losses

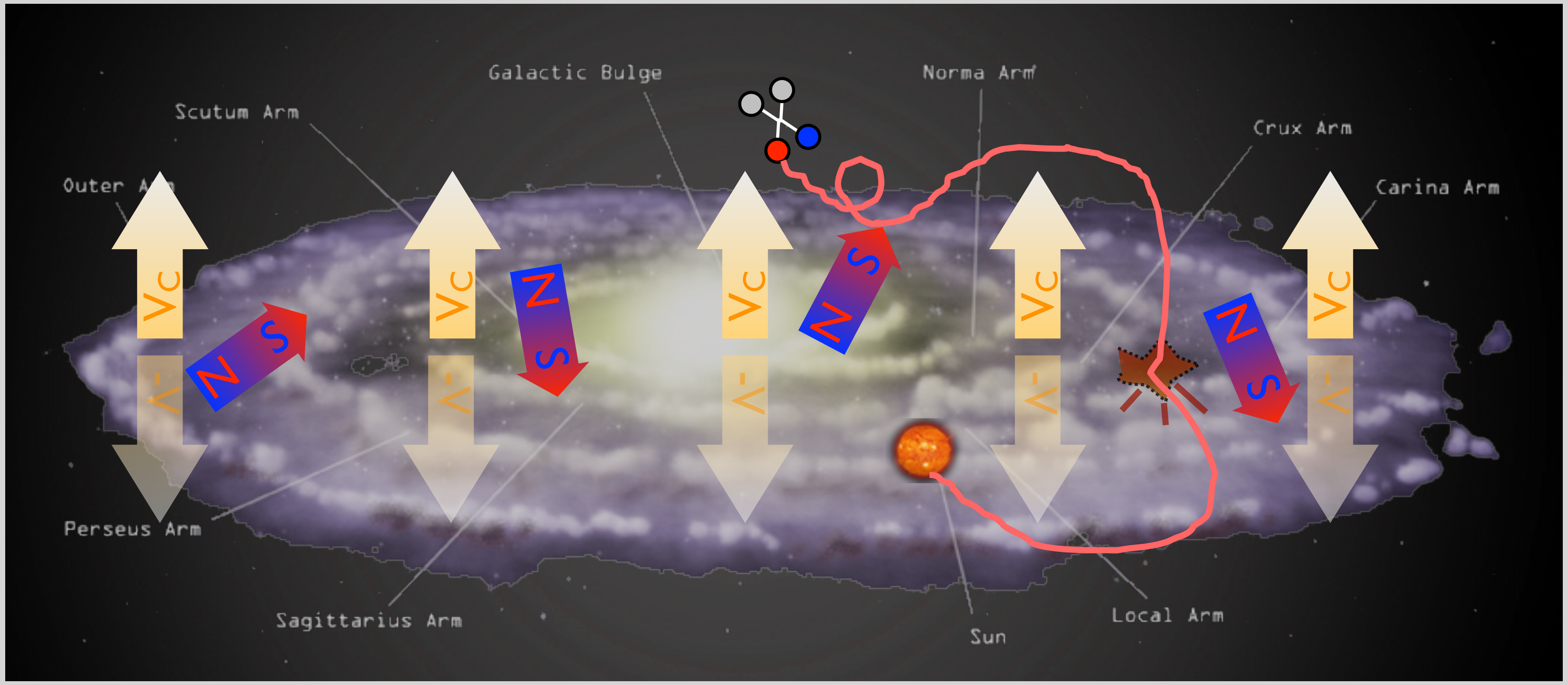
Now we have some idea on how primary CRs are accelerated, but how about their propagation in the medium/energy losses?
Intimately related to the production of 'secondaries' e.g. gamma rays.

- The question can be decomposed in four parts:
  - energetics
  - acceleration
  - energy losses
  - CR diffusion



Big picture: **connection between CRs and neutral messengers** (γ's and ν's)

Charged CRs



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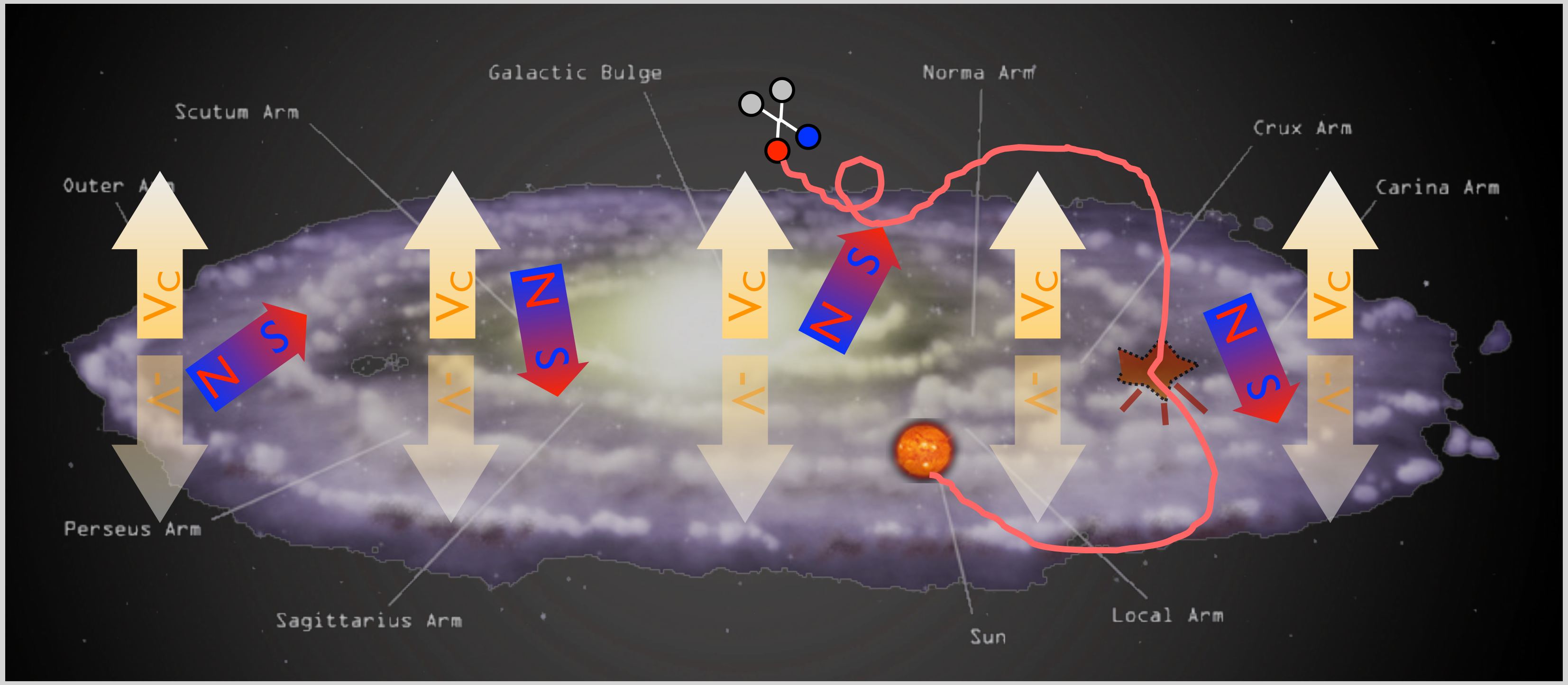
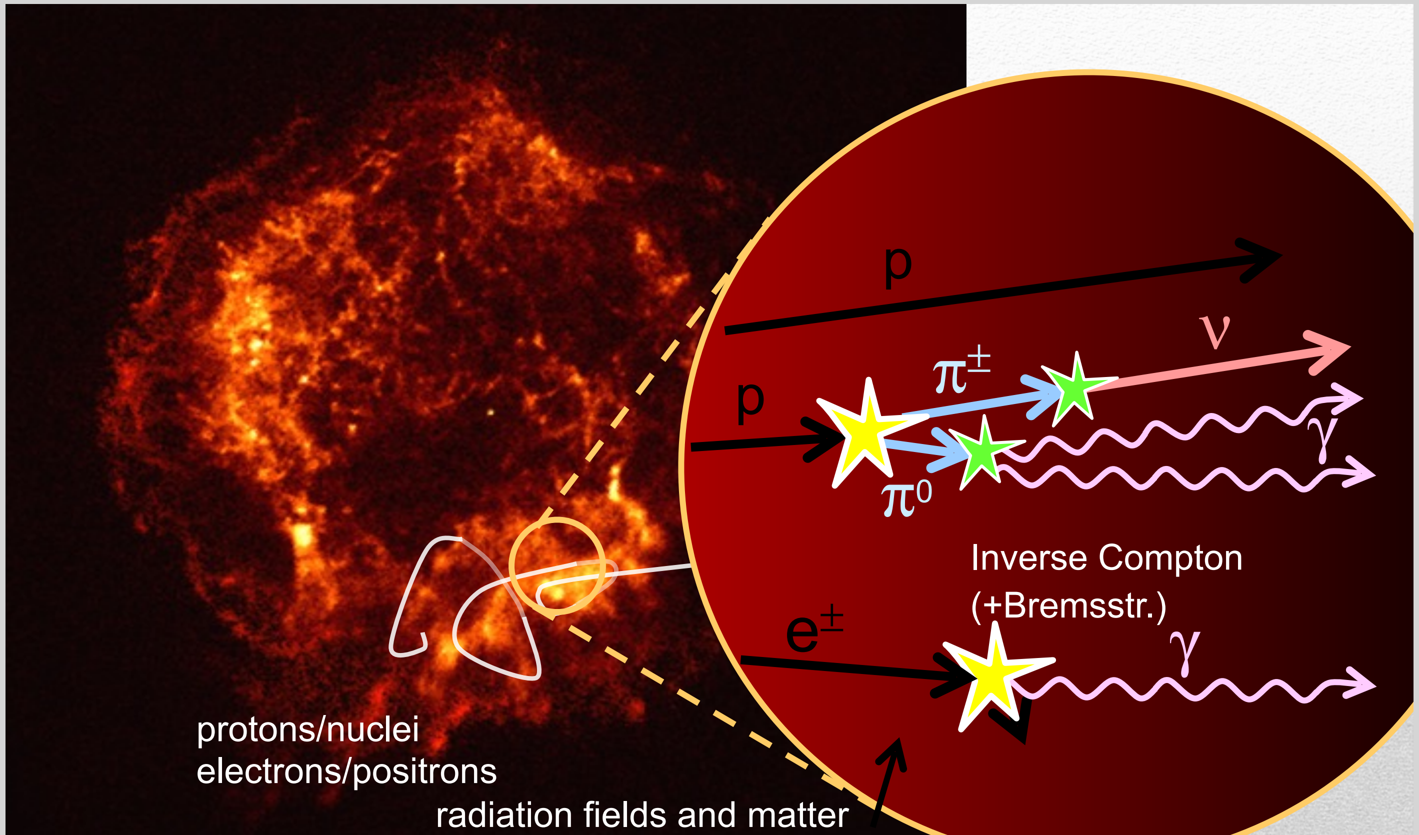


γ's and ν's

- produced in interactions of charged CRs with the medium



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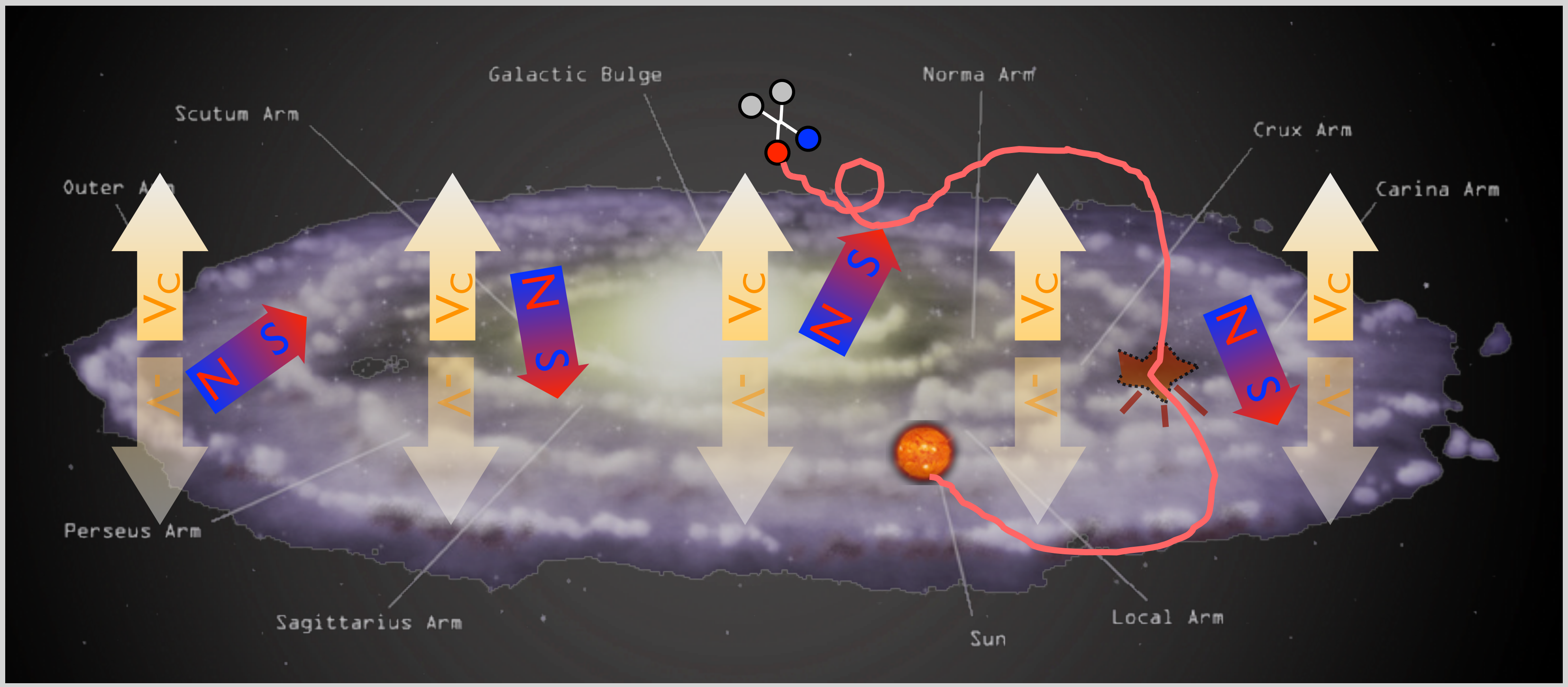
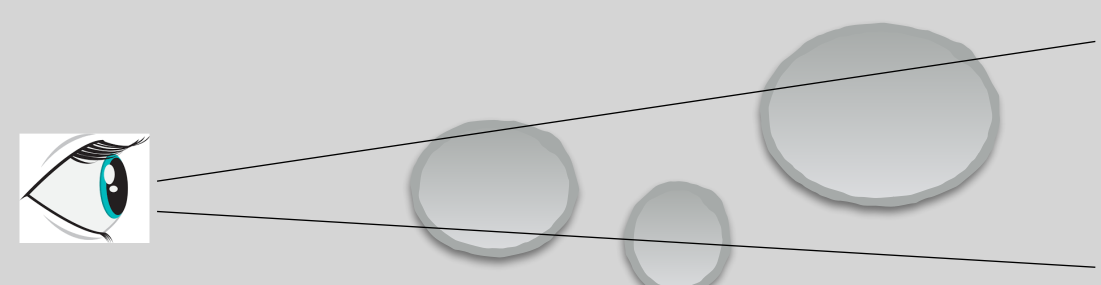


γ's and ν's

- produced in interactions of charged CRs with the medium
- travel in straight lines!



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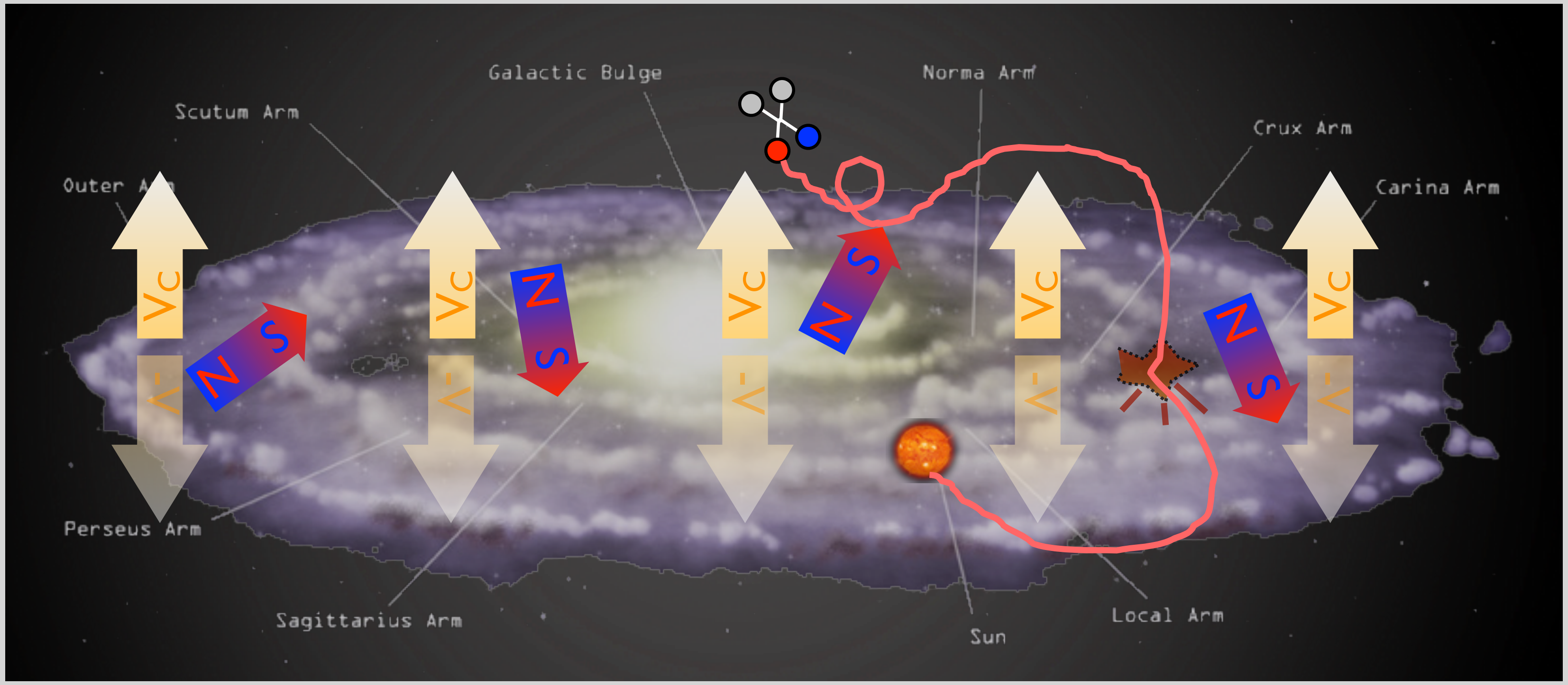

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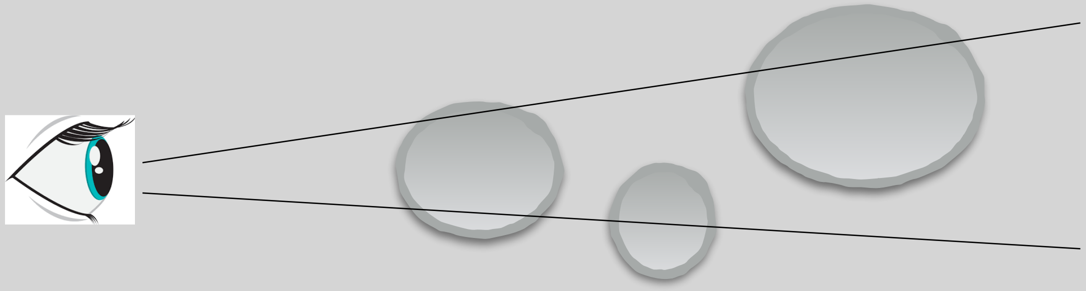
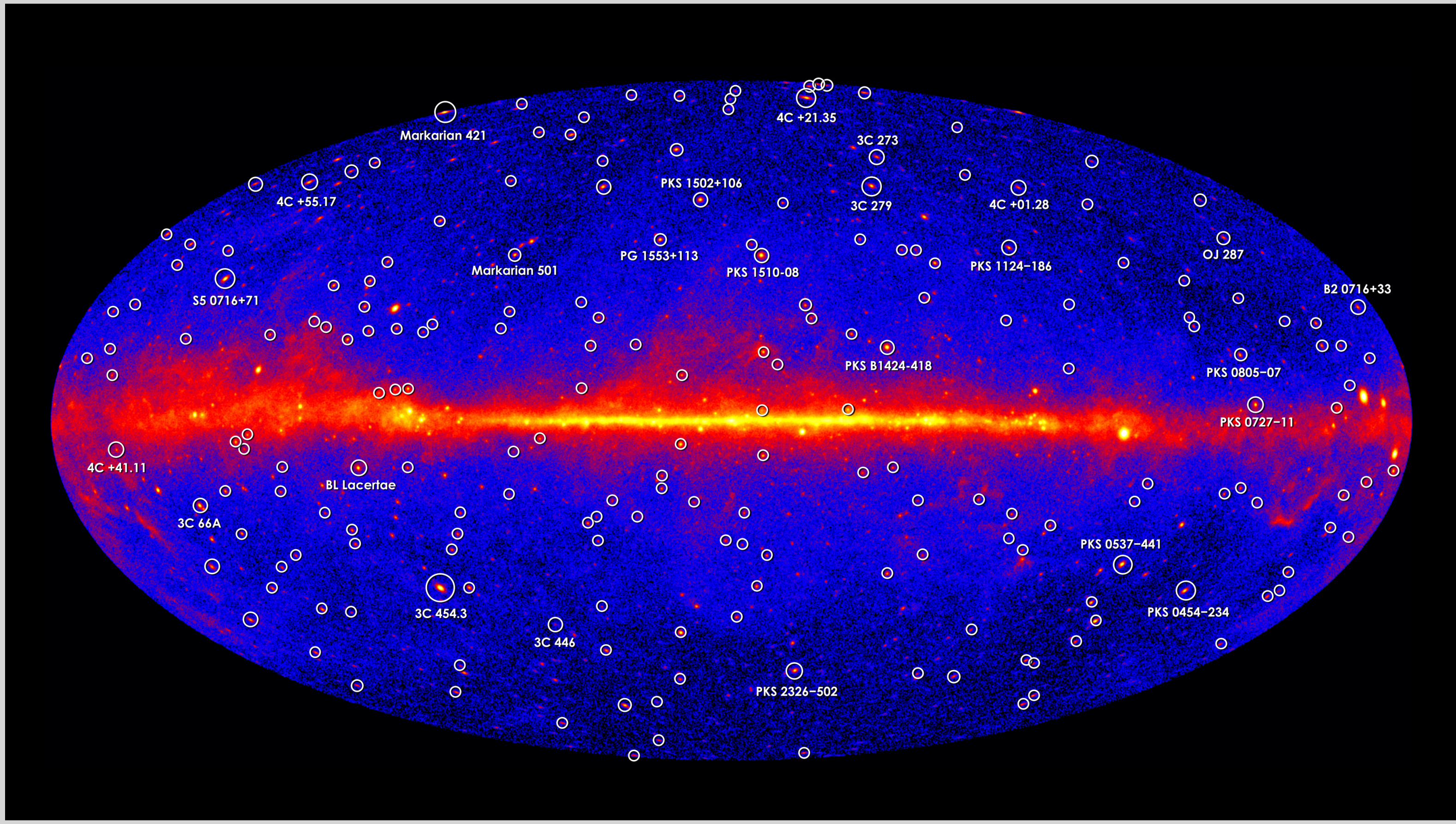


Importance of multi-messenger approach!

Today’s tutorial

Gamma-ray sources with the Cherenkov Telescope Array (CTA)



- We will use gammapy (official CTA tool)
- Tutorial will be given by Judit Perez Romero

1 - We will run the tutorial online with **Google Collab**:

https://colab.research.google.com/drive/185MH2XjbCmMfvXLp5PXkqsoR5-nDkvhj?usp=sharing

2 - Requirements:

- Have a **google account**
- Preferably run on **Google Chrome**
- **Download the file** "cta-prod5-zenodo-fitsonly-v0.1.zip" from https://zenodo.org/record/5499840#.YUya5WYzbUI

Class 2

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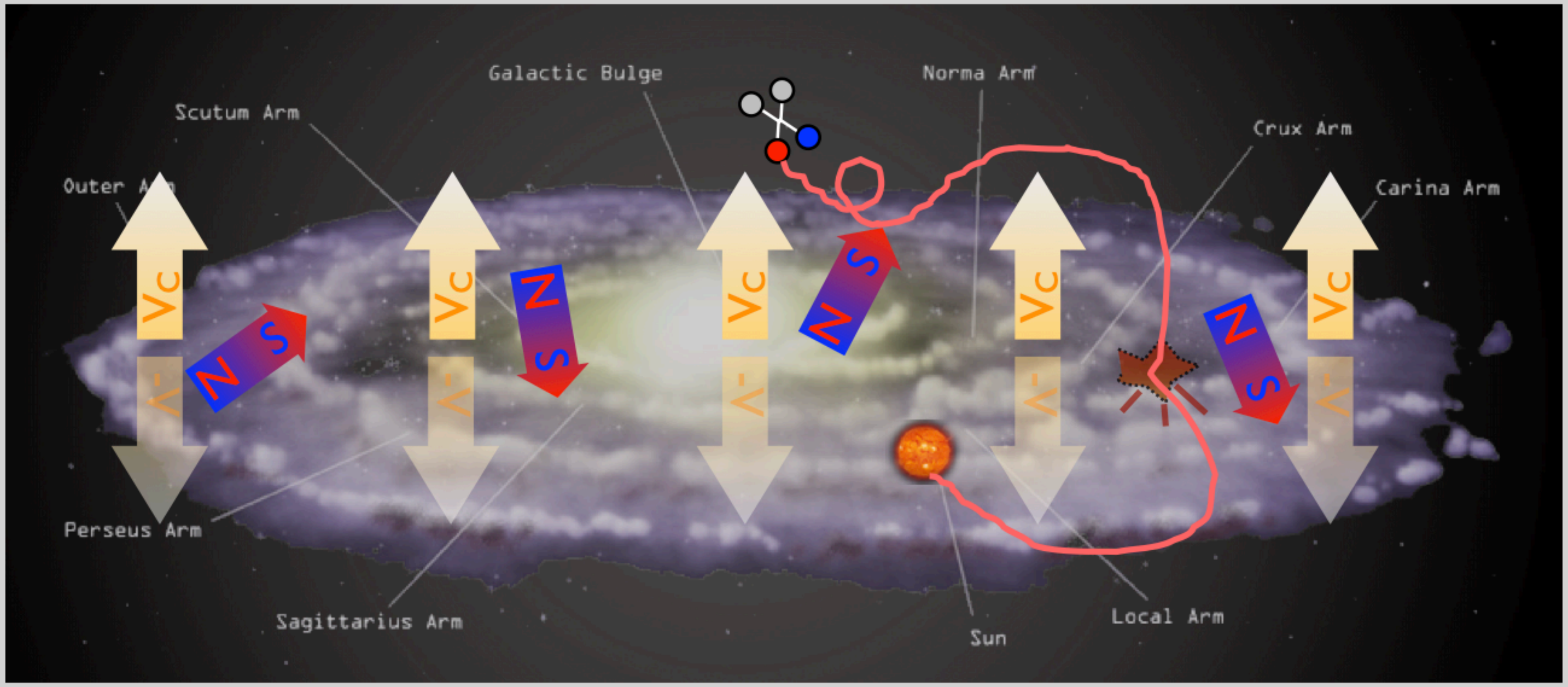
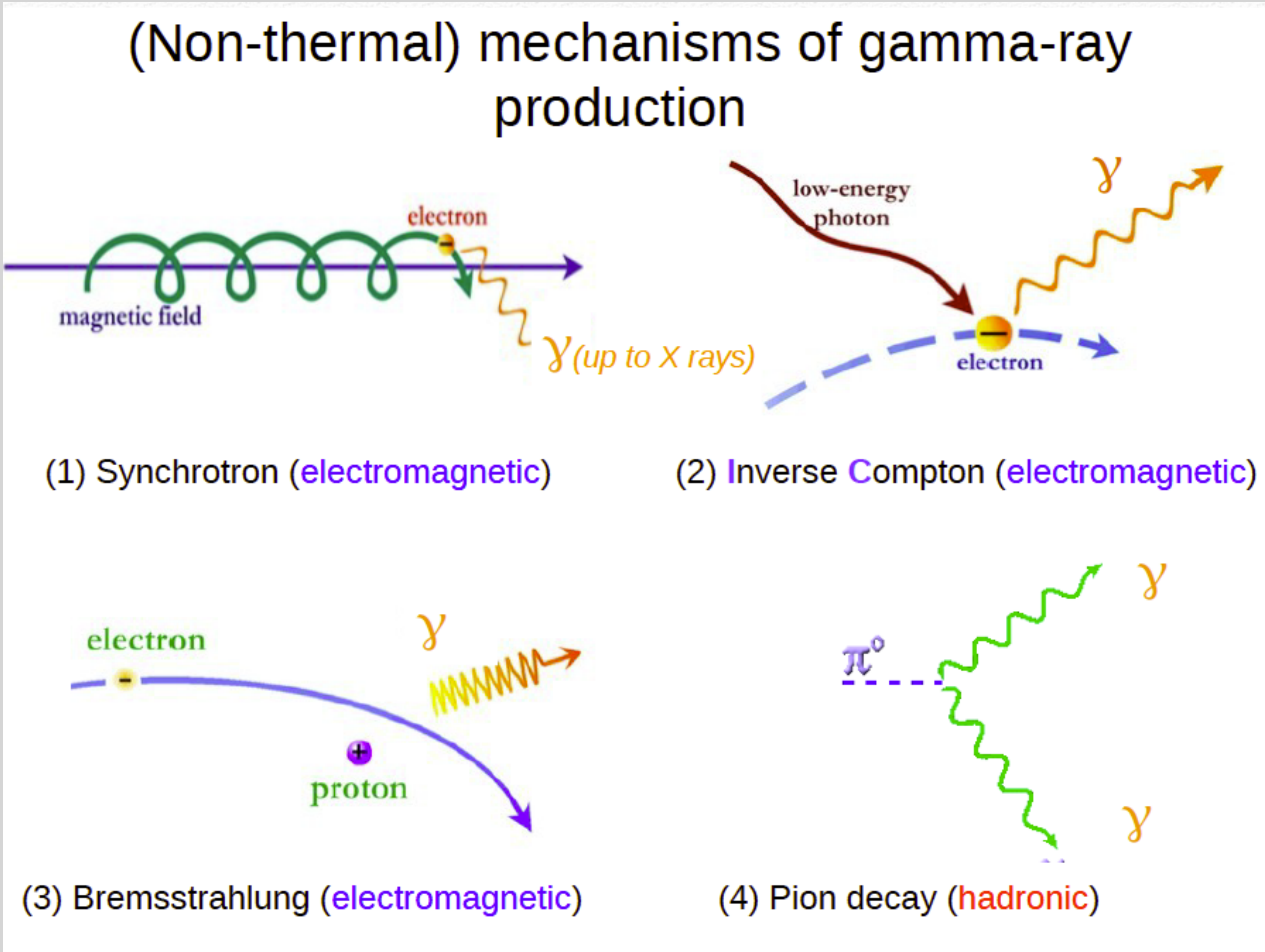
  - CR diffusion



And after that move to γ's (and ν's)

CR energy losses



CR energy losses

Focus on electrons first:

The electron interacts with this medium by means of essentially four processes:

(i) by making elastic and inelastic collisions with the atoms and ions of the gas, (**ionization**)

(ii) by emitting a **bremsstrahlung** photon during these same scatterings,

(iii) by undergoing **Compton scatterings** with the photons of the radiation field,

(iv) by being accelerated by the magnetic field, emitting **synchrotron** radiation or "magnetic bremsstrahlung" in the process.

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CR energy losses

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Reasons for treating the three processes together:
— all three are photon-producing processes and provide information about the interaction of the electrons with the medium through the detection of these photons.
— **each process is essentially a special case of Compton scattering, breams with virtual photons, synch with B field**.

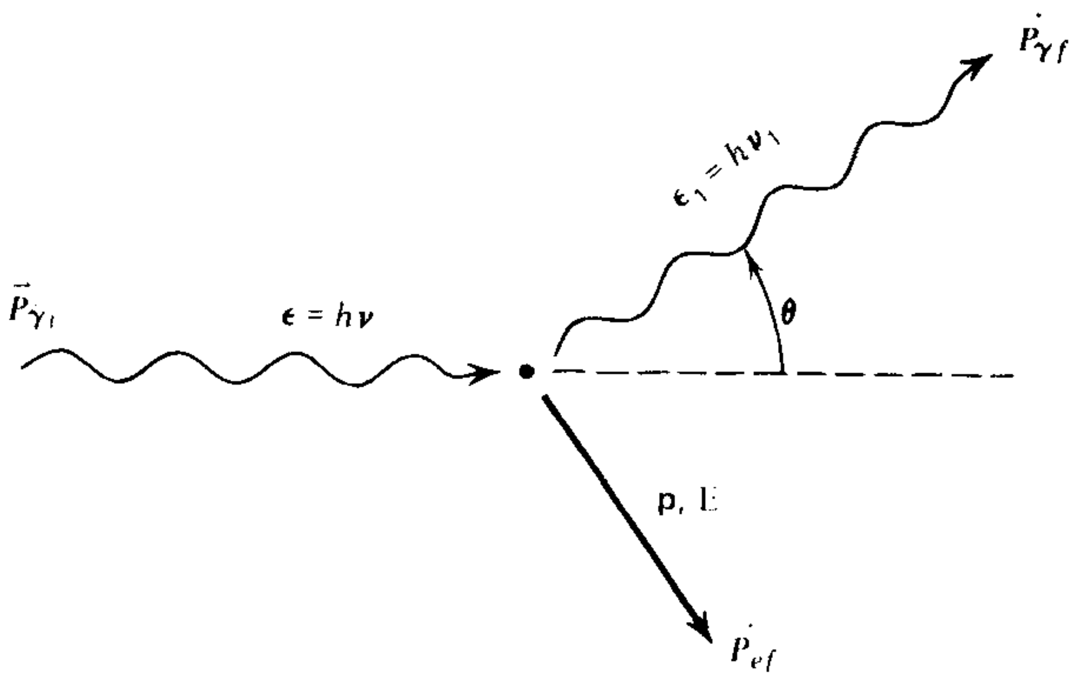
Inverse Compton Scattering

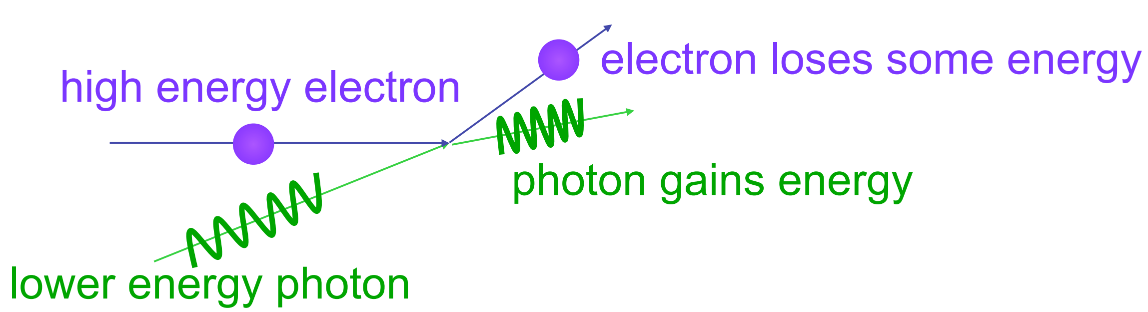
Compton vs inverse-Compton:

Compton scattering - electron initially at rest.

Inverse Compton - moving electrons!

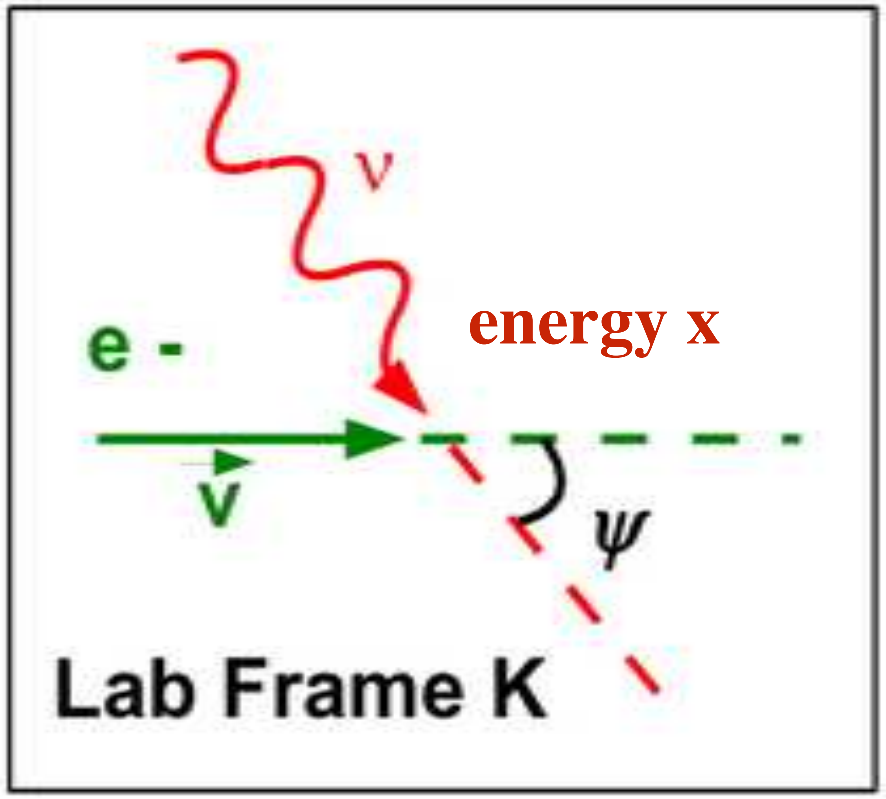
When electrons have sufficient kinetic energy compared to the photon, net energy may be transferred from the electron to the photon

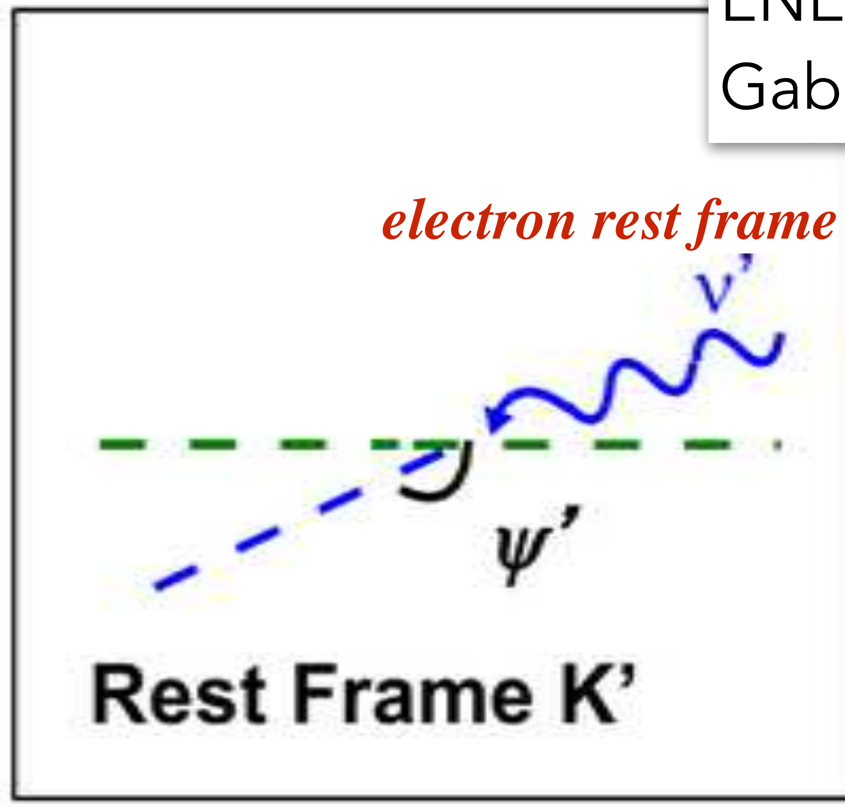




Inverse Compton Scattering

See e.g. “RADIATIVE PROCESSES IN HIGH ENERGY ASTROPHYSICS" Gabriele Ghisellini, 1202.5949





in the electron rest frame:

$$x' = x\gamma(1 - \beta\cos\psi)$$

x is the photon energy in LAB frame

$$x'_1 = x'$$

Then back in the LAB frame:

$$x_1 = x'_1\gamma(1 + \beta\cos\psi'_1)$$

$$\cos\psi'_1 = \frac{\cos\psi_1 - \beta}{1 - \beta\cos\psi_1}$$

$$x_1 = x\,\frac{1 - \beta\cos\psi}{1 - \beta\cos\psi_1}$$

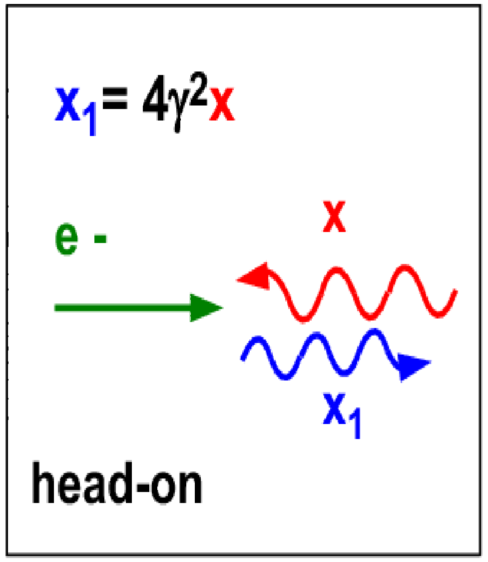
Inverse Compton Scattering

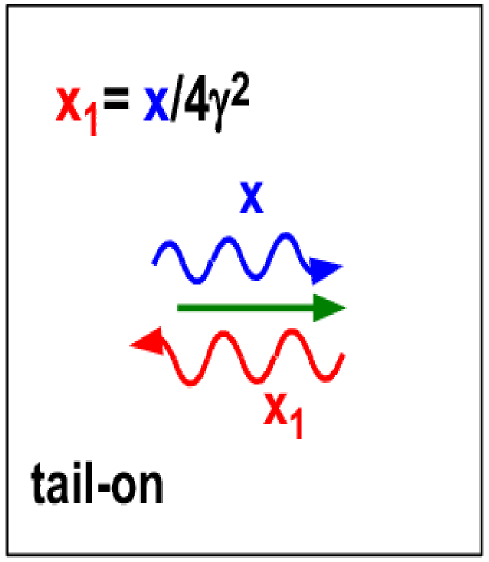
⇒ MAX energy: **ψ = π** (head on collision) and **ψ1 = 0** (the photon along the electron velocity)

$$x_1 = x\frac{1+\beta}{1-\beta} = \gamma^2(1+\beta)^2 x \rightarrow \boxed{4\gamma^2 x;} \quad \mathrm{head-on}$$

⇒ MIN energy: **ψ = 0 and ψ1 = π**

$$x_1 = x\frac{1-\beta}{1+\beta} = \frac{x}{\gamma^2(1+\beta)^2} \rightarrow \boxed{\frac{x}{4\gamma^2};} \quad \mathrm{tail-on}$$





AVERAGE

photon energy
after scattering

$$\boxed{\langle x_1 \rangle = \frac{4}{3}\gamma^2 x}$$

- energy of the photon is greatly enhanced (by gamma>>1)
- electron looses little energy, and all is taken by photons

Inverse Compton Scattering

The energy loss rate of the electron (PER electron !)

$$P_c(\gamma) = \left(\frac{\text{\# of collisions}}{\text{sec}}\right)(\text{average phot. energy after scatt.})$$

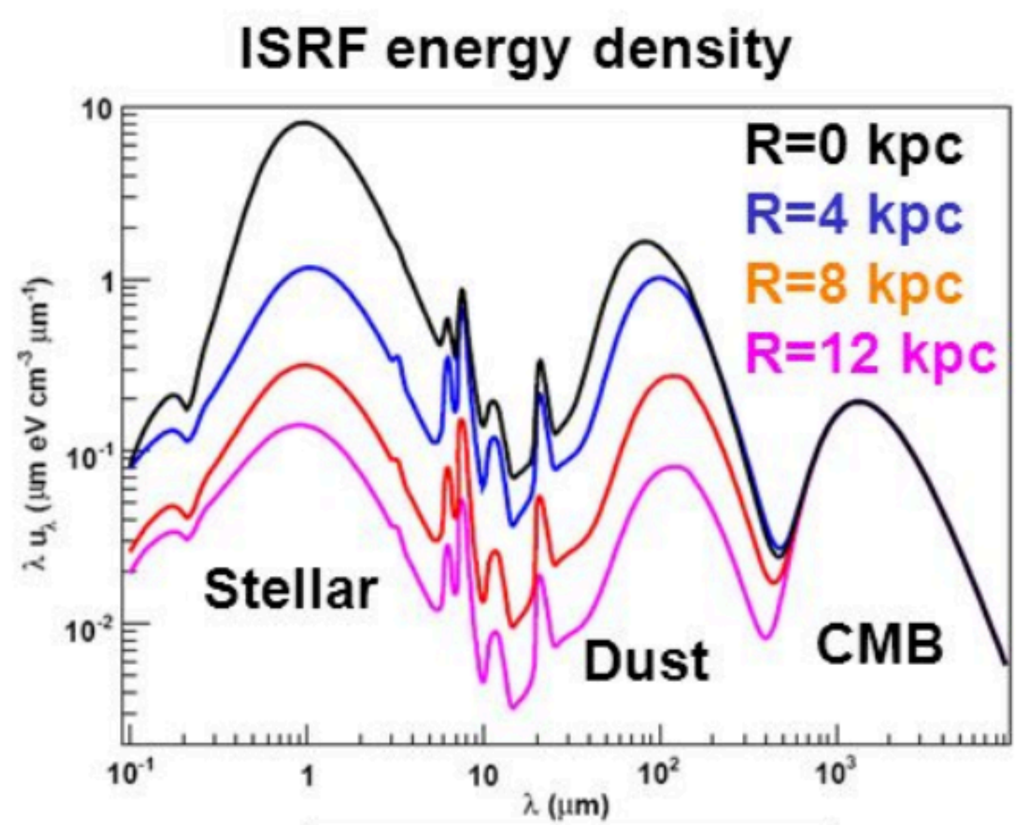
$$= \left(\sigma_T c \frac{U_r}{\langle h\nu\rangle}\right)\left(\frac{4}{3}\langle h\nu\rangle\gamma^2\right)$$

Average energy of a radiated photons per scattering

Thompson x-section

Photon radiation field energy density

$$U_r = \int \epsilon n(\epsilon) d\epsilon$$



Porter et al. 2008

Inverse Compton Scattering

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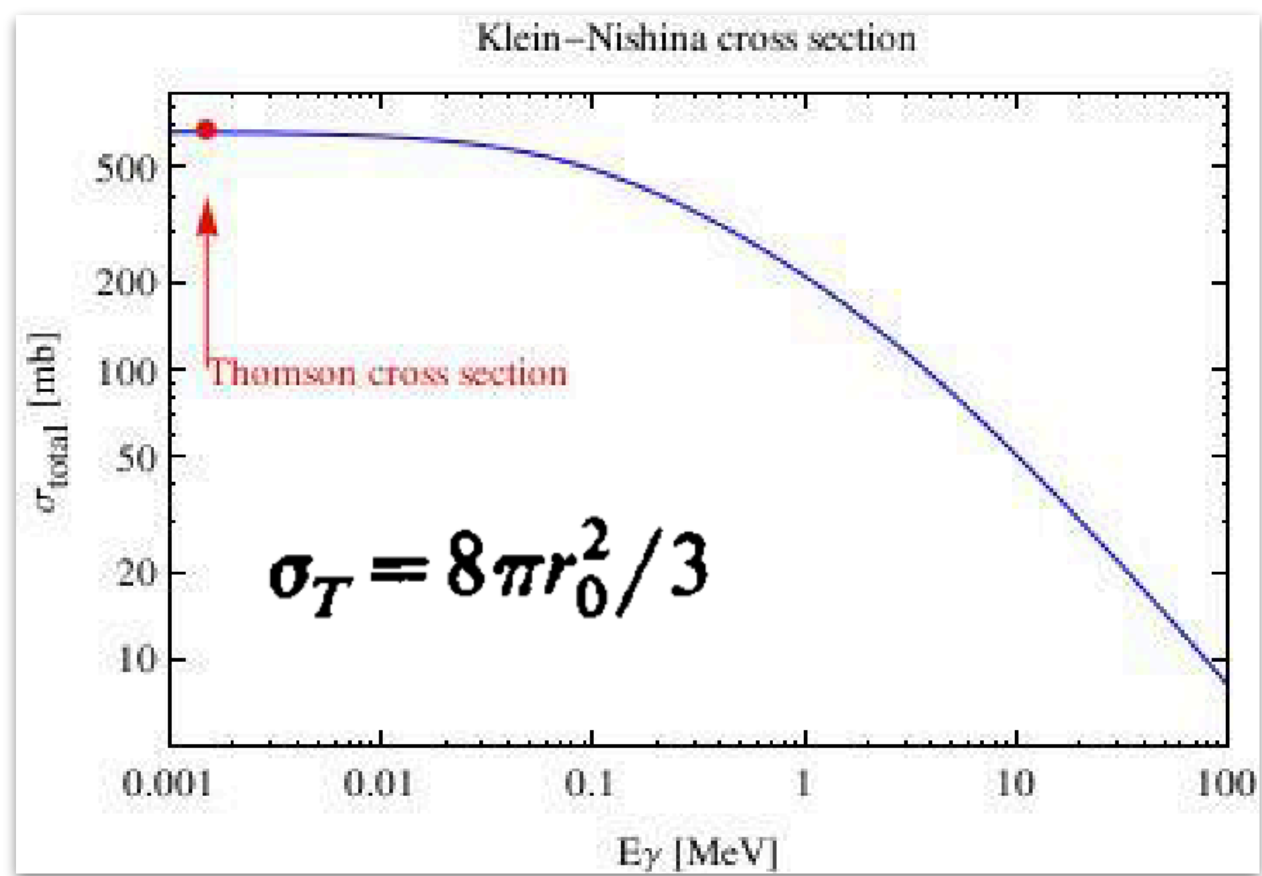
$$= \left(\sigma_T c \frac{U_r}{\langle h\nu \rangle}\right)\left(\frac{4}{3}\langle h\nu \rangle \gamma^2\right)$$

Thompson x-section

If $x' \ll 1$, we are in the Thomson regime.

Relativistic Klein-Nishina regieme ofter relevant!



Inverse Compton Scattering

The spectrum:

the average energy of the photons PER electron: $\langle x_1 \rangle = \frac{4}{3}\gamma^2 x_0;$

Full photon energy spectrum for a DISTRIBUTION of electrons

assume a **power–law energy distribution for the relativistic electrons**:

$$N(\gamma) = K\gamma^{-p}$$

(E=γmc^2)

-> for a power law electron distribution, photon energy spectrum is power law with a related index!

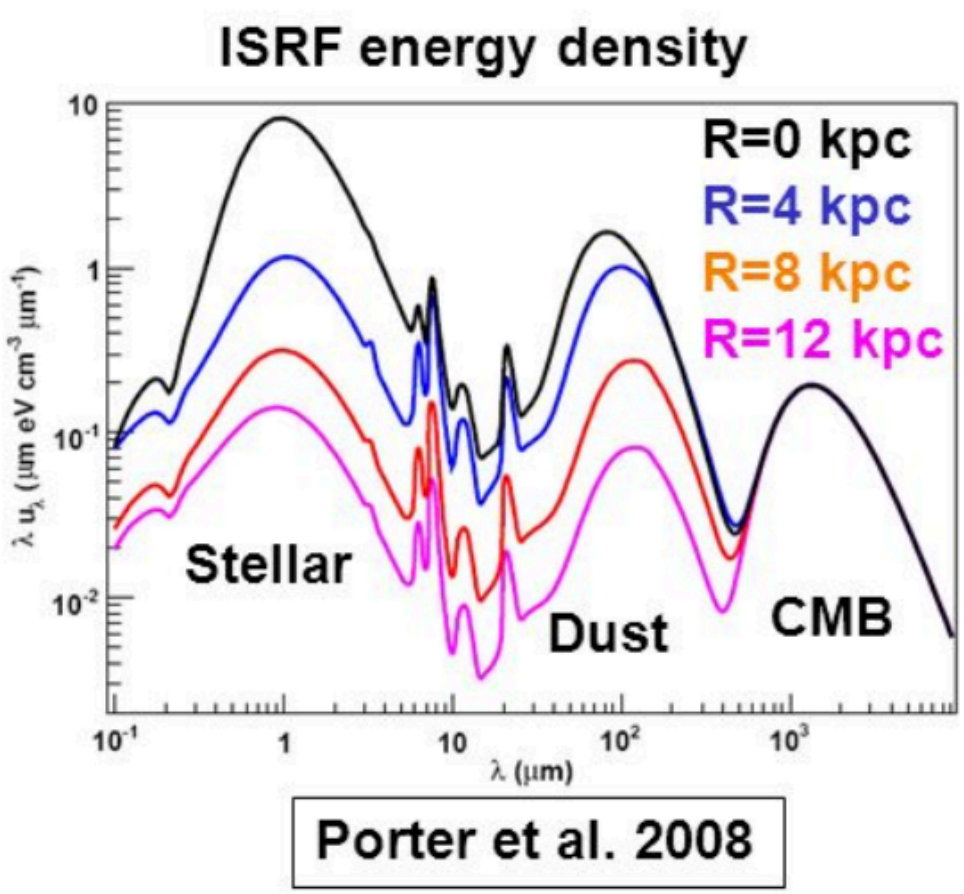
$$\epsilon_c(\nu_c) = \frac{1}{4\pi}\frac{(4/3)^\alpha}{2}\frac{\tau_c}{R/c}\nu_c^{-\alpha}\int_{\nu_{\min}}^{\nu_{\max}}\frac{U_r(\nu)}{\nu}\nu^\alpha d\nu$$

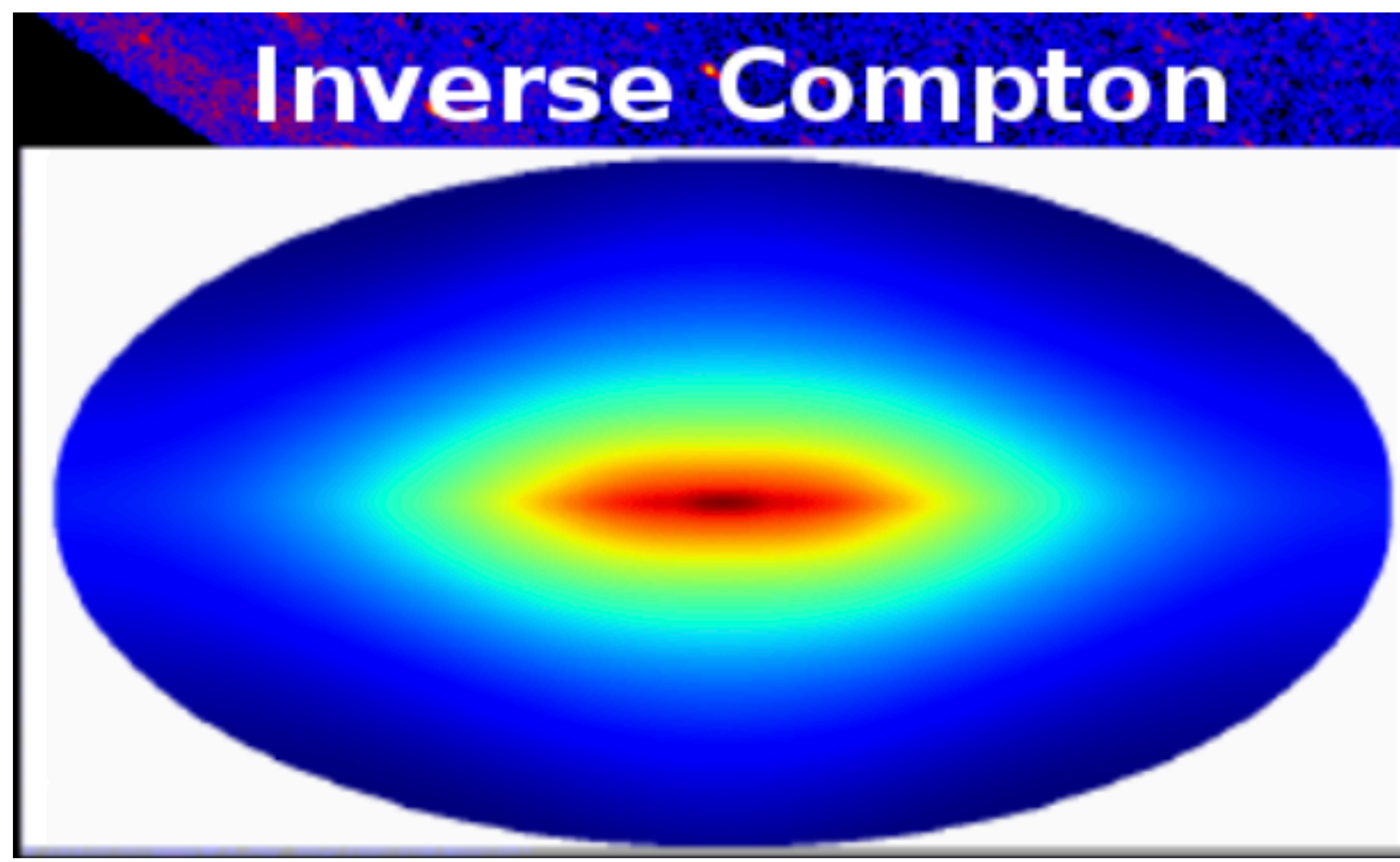
$$\alpha = \frac{p-1}{2}$$

Inverse Compton Scattering

Take home messages:

— for a power law electron distribution, photon energy spectrum is **power law with a related index!**
— typical photon energy after scattering is **boosted by γ^2**
— gamma ray flux follows the energy density of **target photons Ur**





Synchrotron scattering

As for the IC:

— **the losses are proportional to the square of the electron energy**

— **to the cross section, and energy density of the target field!**

$$P = \frac{4}{3}\sigma_T c\beta^2\gamma^2 U_B. \qquad U_B = B^2/8\pi$$

Remember: analogous covariant expression (as seen also in analogy with IC).

$$P_c(\gamma) \equiv \frac{dE_e}{dt} = \frac{4}{3}\sigma_T c\gamma^2\beta^2 U_r$$

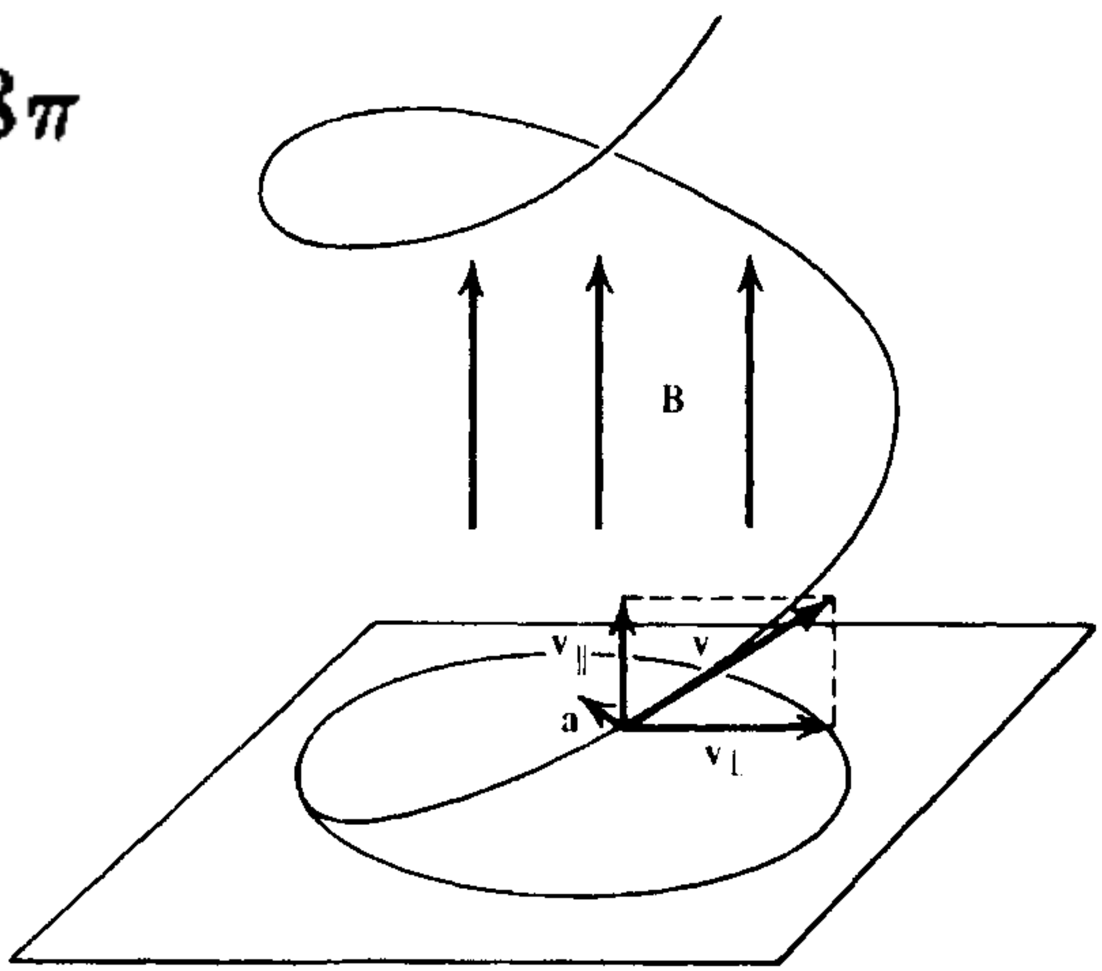


Figure 6.1 Helical motion of a particle in a uniform magnetic field.

Synchrotron scattering

how about the spectrum?

power law electron distribution produces a power law spectrum, and the two spectral indices are related

$$N(\gamma) = K\,\gamma^{-p}$$

$$\begin{aligned}
\epsilon_{\rm s}(\nu) &\propto B^2\gamma^2 K\gamma^{-p}\frac{d\gamma}{d\nu} \\
&\propto B^2 K \left(\frac{\nu}{\nu_{\rm L}}\right)^{(2-p)/2} \frac{\nu^{-1/2}}{\nu_{\rm L}^{1/2}} \\
&\propto K\,B^{(p+1)/2}\,\nu^{-(p-1)/2}
\end{aligned}$$

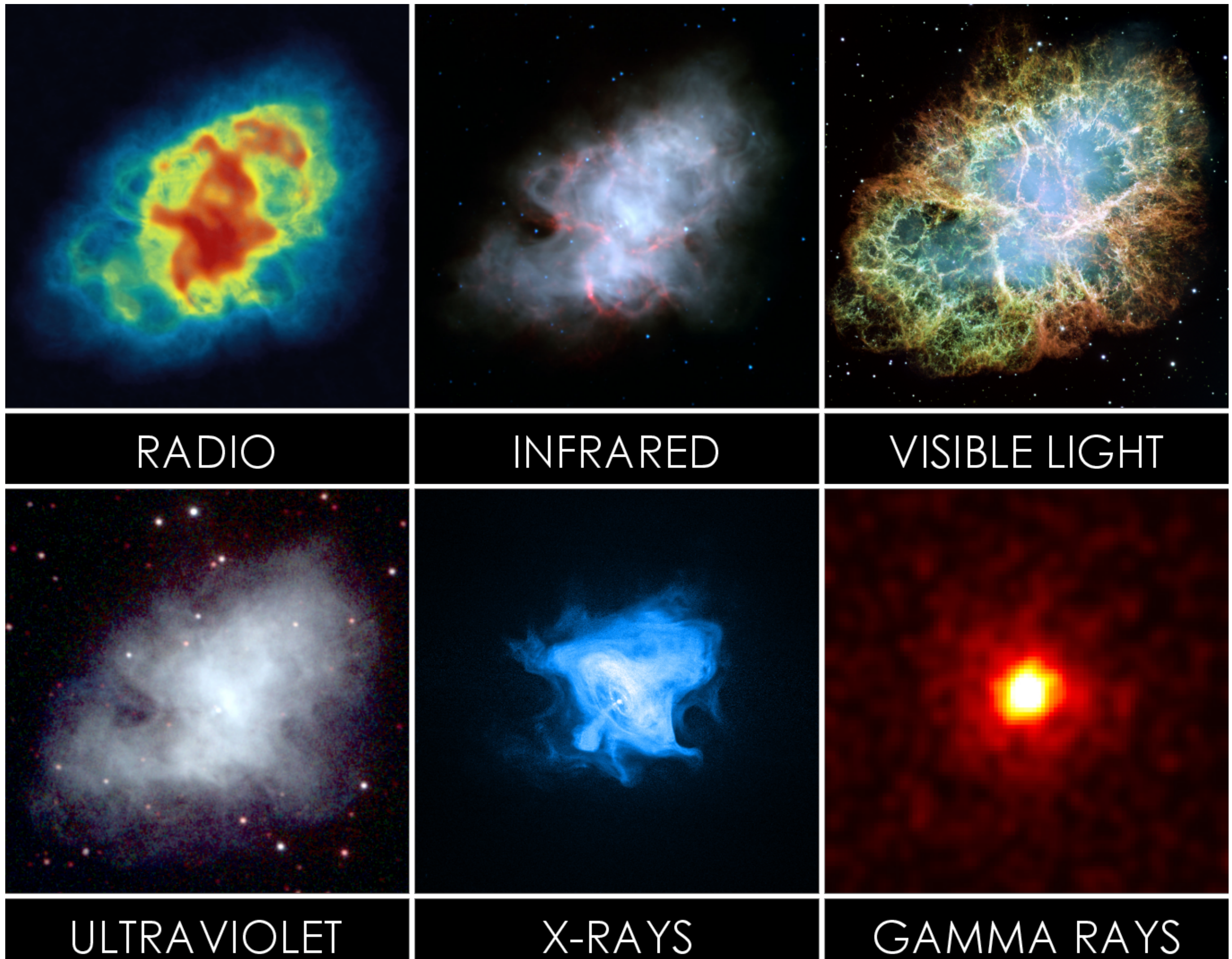
Inverse Compton vs synchrotron scattering

Crab Nebula - an astrophysics ‘darling’

Is a supernova remnant (that went off in 1054 as documented by Chinese astronomers) and pulsar wind nebula (in the inner parts of the nebula).

At the center of it is a Crab pulsar that powers the nebula (discovered in 1968).

~2kpc away.



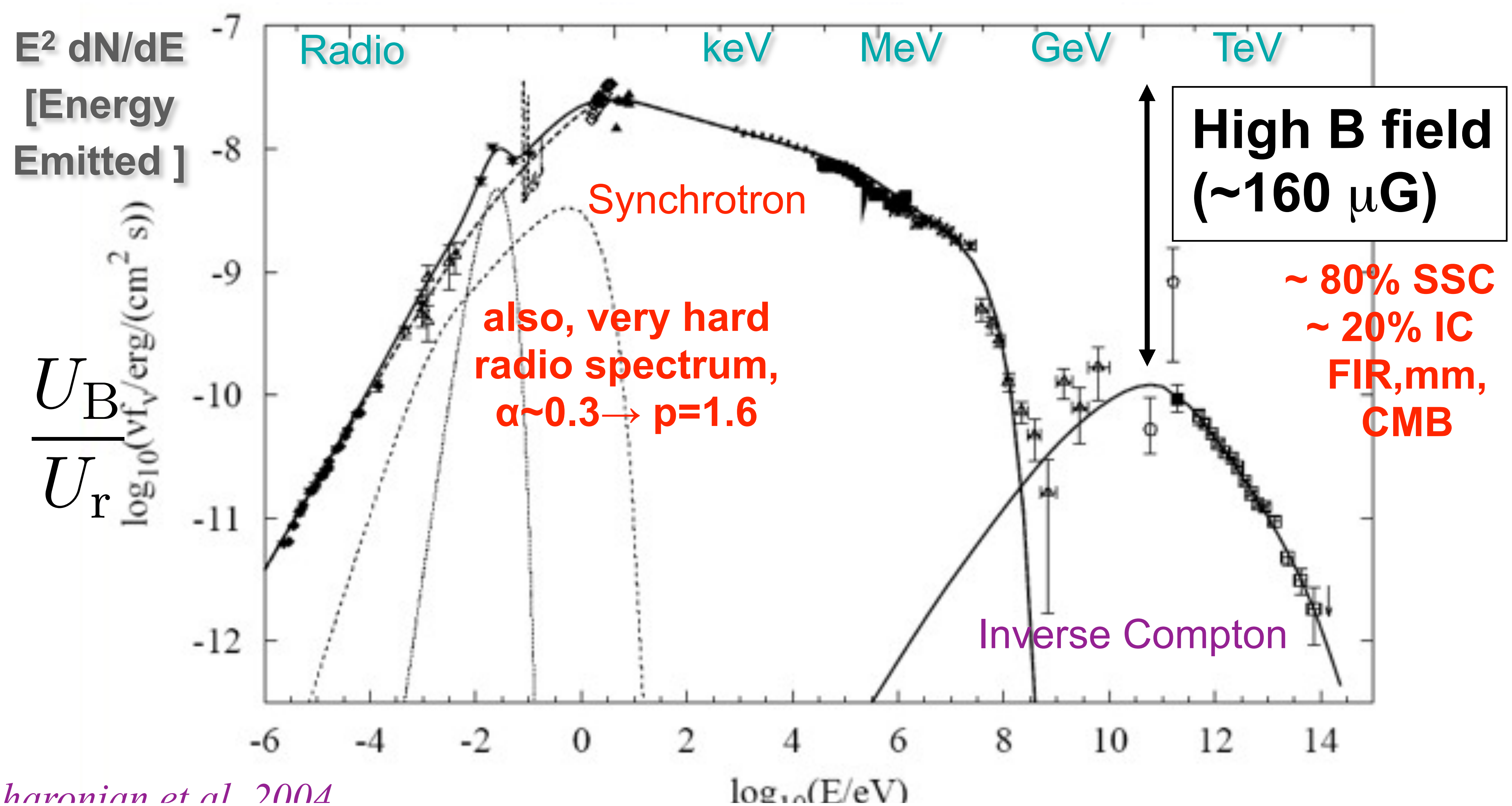
Inverse Compton Scattering - relation with synchrotron scattering

Multiwavelength spectra: Crab Nebula

This object seems to be well explained in a framework where the spinning NS injects leptons, which produce SR on the B-field & mostly the same SR photons are upscattered to produce the second peak (Synchrotron Self-Compton Model)

In SSC, comparing the two peaks allows one to deduce the B-field intensity.

$$\frac{L_{\rm syn}}{L_{\rm IC}} = \frac{P_{\rm syn}}{P_{\rm c}} = \frac{U_{\rm B}}{U_{\rm r}}$$



Aharonian et al. 2004

Inverse Compton Scattering - relation with synchrotron scattering

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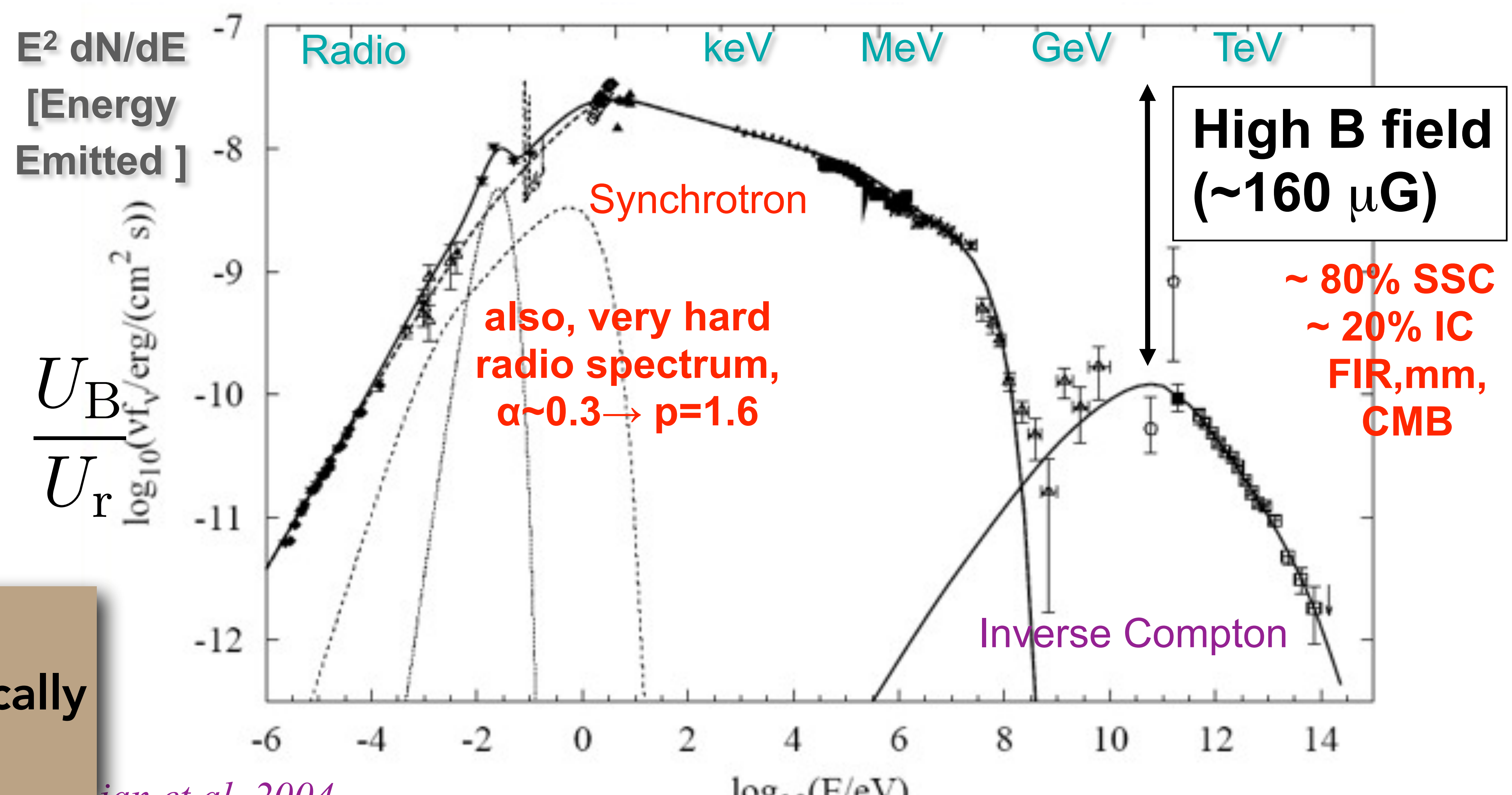
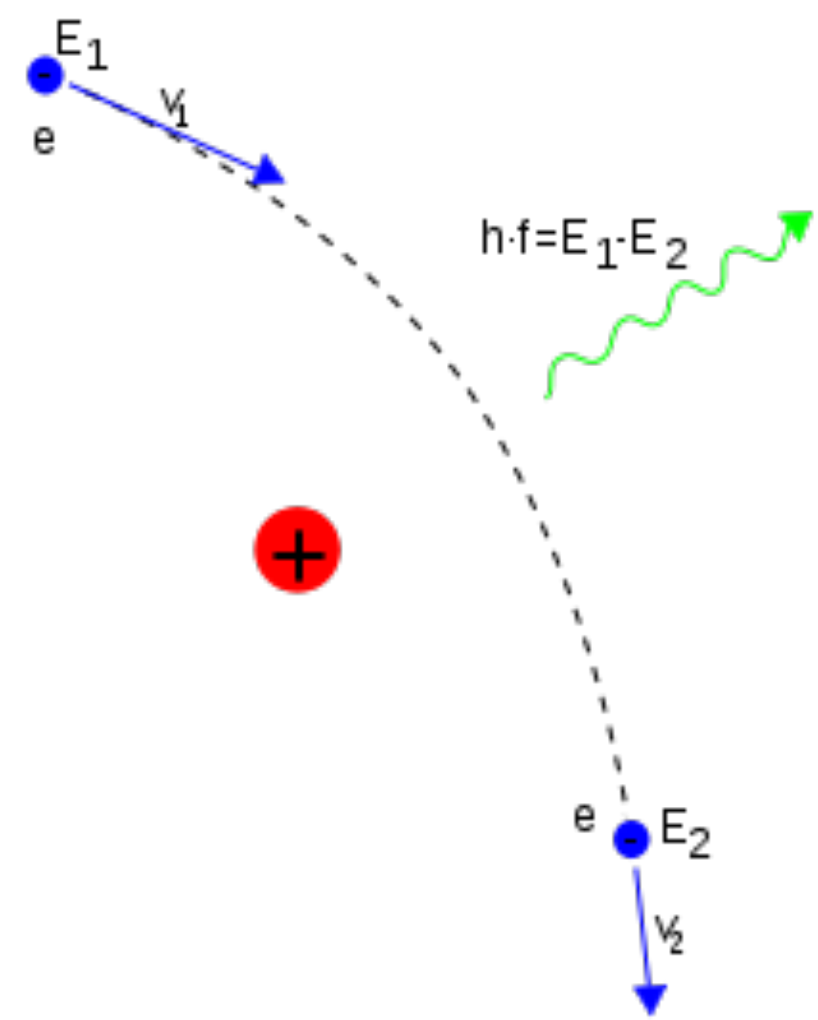


$$\frac{L_{syn}}{L_{IC}} = \frac{P_{syn}}{P_c} = \frac{U_B}{U_r}$$

Note also that synchrotron falls typically In the radio band !

Bremsstrahlung

Bremsstrahlung ("braking radiation") is electromagnetic radiation produced by the deceleration of a charged particle when deflected by another charged particle, typically an electron by an atomic nucleus. The moving particle loses kinetic energy, which is converted into a photon.



Bremsstrahlung

total energy losses

Two regimes (super for relativistic electrons):

weak shielding

$$b^{\rm ion}_{\rm brem} = \alpha_{\rm em} \frac{3\,\sigma_{\rm T}}{2\pi} n_i \, Z(Z+1) \left(\log 2 \, \frac{E_{e^\pm}}{m_e} - \frac{1}{3} \right) E_{e^\pm}$$

electron energy loss parameter, b=-dE/dt

strong shielding

$$b^{\rm neut}_{\rm brem} = \alpha_{\rm em} \frac{3\,\sigma_{\rm T}}{8\pi} n_i \left(\frac{4}{3} \phi^i_{1,\rm ss} - \frac{1}{3} \phi^i_{2,\rm ss} \right) E_{e^\pm}$$

Main features -- electron energy losses (and photon energy spectrum) are:

- **linear function of the electron energy**
- **linear function of gas density**

Remember, it was **square** for IC&synch!

Bremsstrahlung

$$b_{\rm brem}^{\rm ion} = \alpha_{\rm em} \frac{3\,\sigma_{\rm T}}{2\pi} n_i \, Z(Z+1) \left(\log 2 \, \frac{E_{e^\pm}}{m_e} - \frac{1}{3} \right) E_{e^\pm}$$

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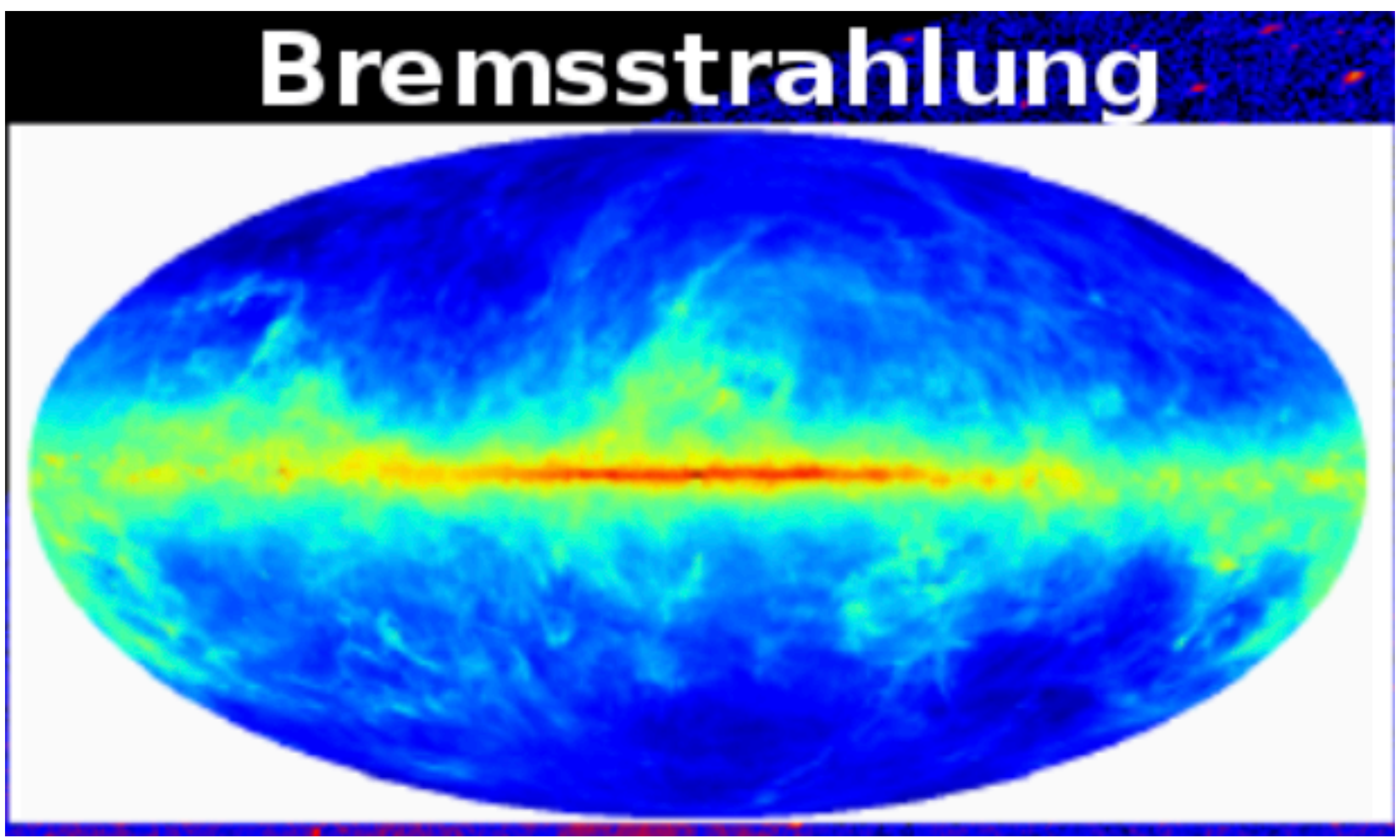
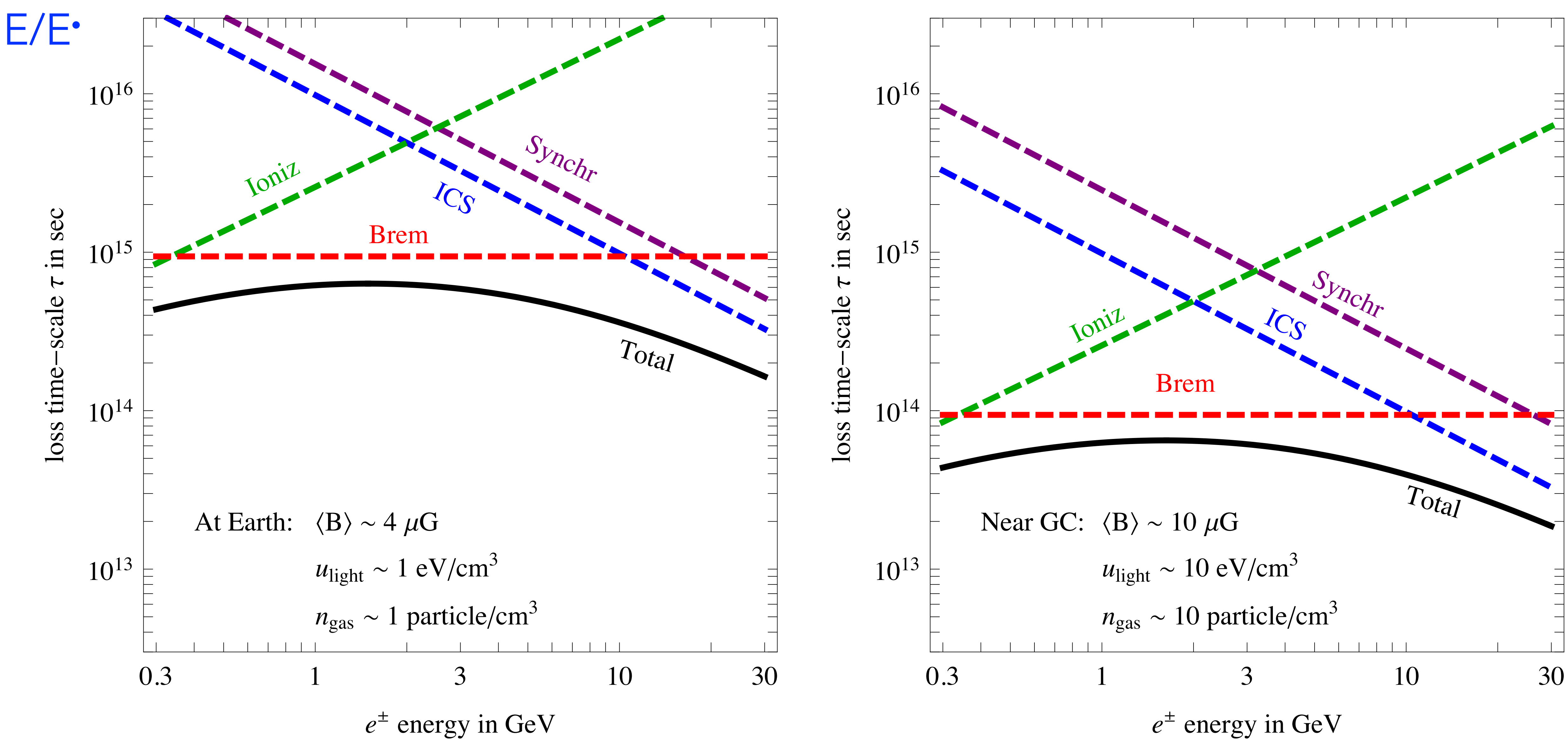


gamma ray flux follows the energy density of **target gas!**

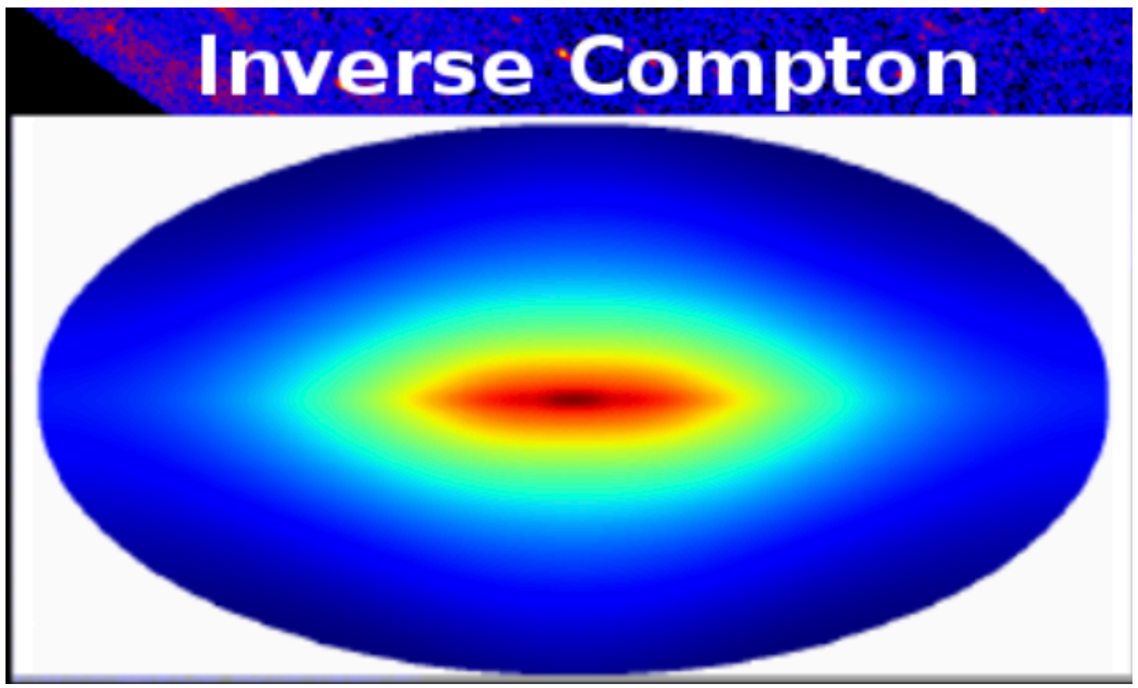
Bremsstrahlung vs IC vs Synch

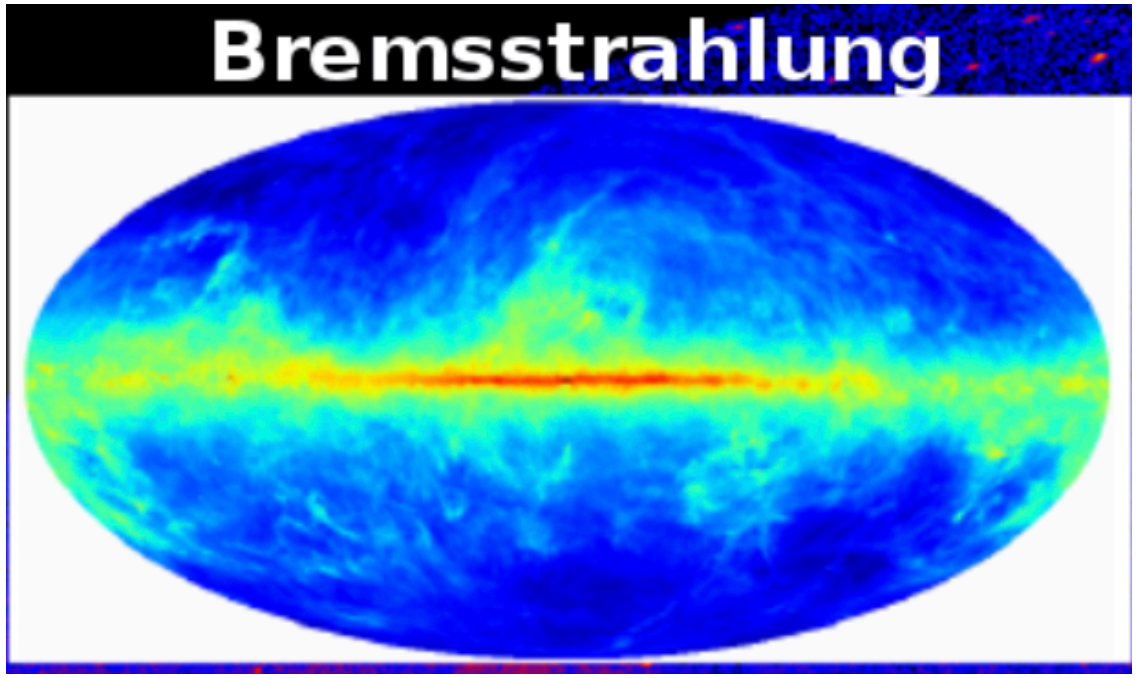
energy-loss time-scale: in our Galaxy breams dominates for energies 0.1 - 10 GeV



So far we talked about ELECTRON energy losses:

- IC
- Synchrotron
- Bremsstrahlung





How about PROTONS?

The most relevant HE process is **collision of protons with the gas atoms, and subsequent decays of the produced neutral pions (π 0 s).**

Inelastic collisions of energetic protons with ambient matter, e.g.,

$$\begin{aligned} p+p &\rightarrow p+p+\pi^0 \\ p+p &\rightarrow p+n+\pi^+ \\ p+p &\rightarrow p+p+\pi^+ + \pi^- \ldots \end{aligned}$$

Pions decay very quickly via main channels (probability $\geq 98.8\%$):

$$\begin{aligned} \pi^0 &\rightarrow \gamma+\gamma \\ \pi^+ &\rightarrow \mu^+ + \nu_\mu \quad \text{and} \quad \mu^+ \rightarrow e^+ + \bar{\nu}_\mu + \nu_e \\ \pi^- &\rightarrow \mu^- + \bar{\nu}_\mu \quad \text{and} \quad \mu^- \rightarrow e^- + \nu_\mu + \bar{\nu}_e \end{aligned}$$

$\Rightarrow$ Neutrinos as *smoking gun* of hadronic processes.

Energy threshold for pp interaction (pion production):

The s variable is the square of the center-of-mass energy. In the center-of-mass reference frame S^*: $s = (p_1 + p_2)^2$

$$s = \left((E_1^*, \vec{p}^*) + (E_2^*, -\vec{p}^*)\right)^2 = E_{CM}^2 = (E_1^* + E_2^*)^2. \qquad (2.110)$$

In the laboratory reference frame S:

$$s = \left((E_{\text{beam}}, \vec{p}_{\text{beam}}) + (M_{\text{target}}c^2, 0)\right)^2 = E_{CM}^2$$
$$= M_{\text{beam}}^2 c^4 + M_{\text{target}}^2 c^4 + 2E_{\text{beam}} M_{\text{target}} c^2 .$$

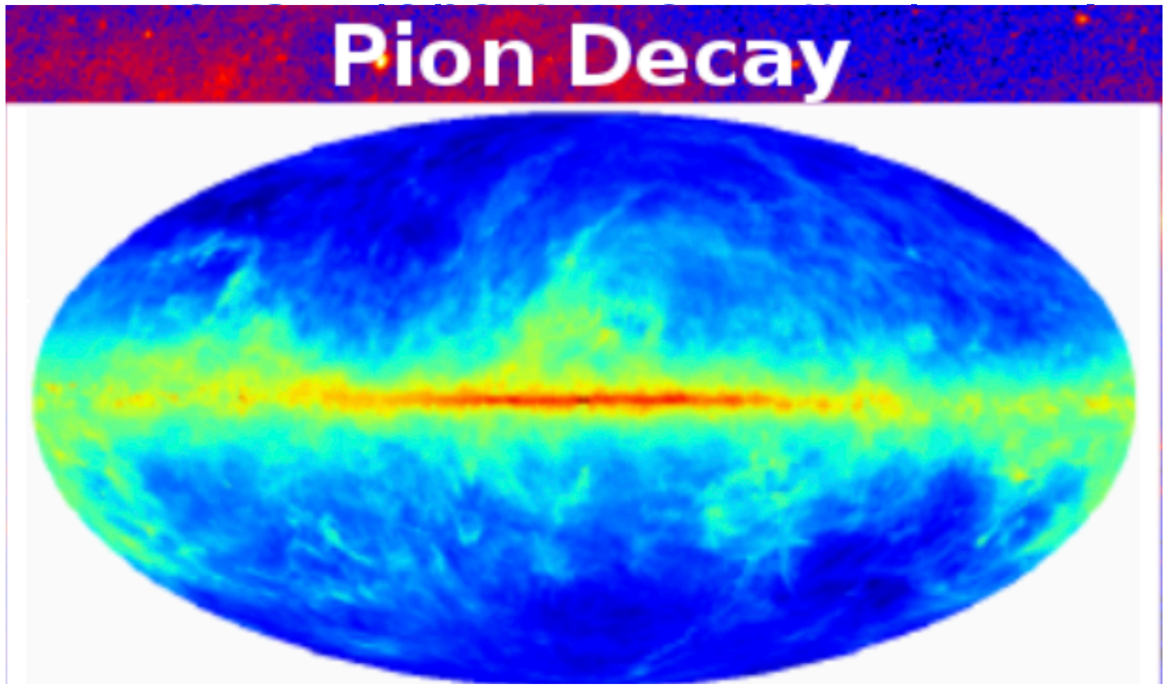
Assuming $s \sim (2m_p + m_\pi)$ one gets:

$$E_{\text{Lab}}^{\text{thr}} = \frac{(2\,m_p + m_\pi)^2 - 2m_p^2}{2\,m_p} \simeq 1.2\,\text{GeV}$$

Hadronic losses: in matter - Protons

Main characteristics:

- flux of pions follows that of a parent proton population
- average energy of photons is half of the pion energy **(for neutrons 1/4th!)**



Direct link with the parent population energy distribution

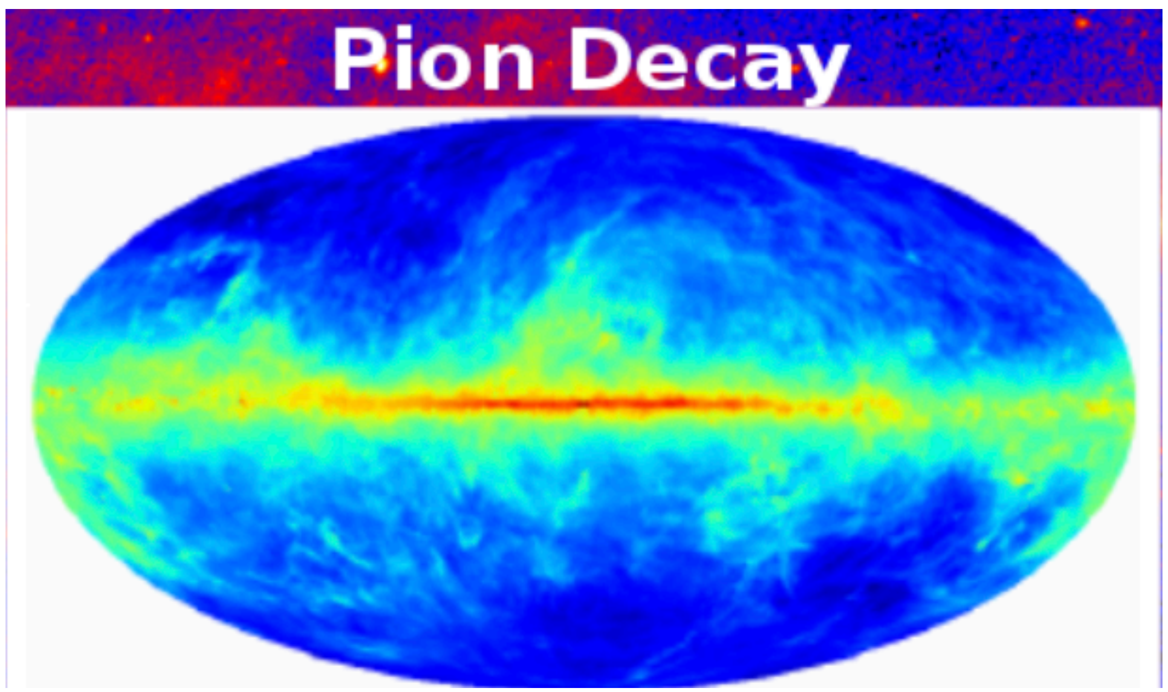
$$\langle E_\pi \rangle = \frac{\kappa_{pp} E_p}{N_\pi^{pp}} \qquad \langle E_\gamma \rangle \simeq \langle E_\pi \rangle / 2 \qquad \langle E_\nu \rangle \simeq \langle E_\pi \rangle / 4$$

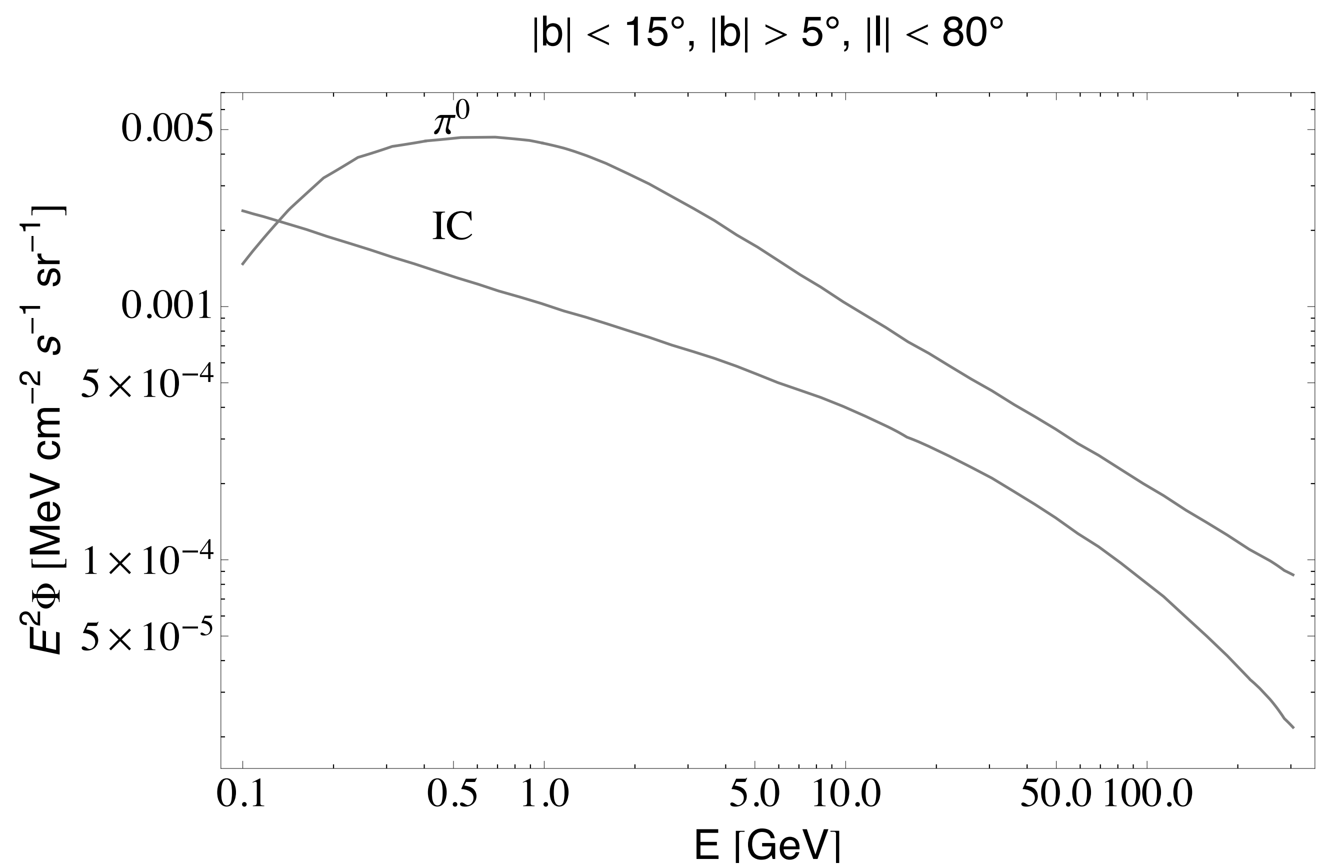
γ' & ν's as diagnostics of hadronic accelerators and/or of propagation

$$\pi^0 \rightarrow \gamma\gamma \qquad \pi^+ \rightarrow \mu^+ \nu_\mu \rightarrow e^+ \nu_e \bar{\nu}_\mu \nu_\mu$$

Take home messages:

- pion emission traces target gas
- it has a cut-off below 1.2 GeV (threshold energy)





Take home messages

IC & Synch:

— electron energy loss rate/emitted power **proportional to the energy density of target photons Ur and to the square of electron energy**!
— for a power law electron distribution, photon energy spectrum is **power law with a related index**!
— typical **photon energy after a scatter with an electron with energy γ is boosted by γ^2**

bremss:

— electron energy loss rate/emitted power proportional to the gas density
— in our Galaxy relevant in the <10 GeV range

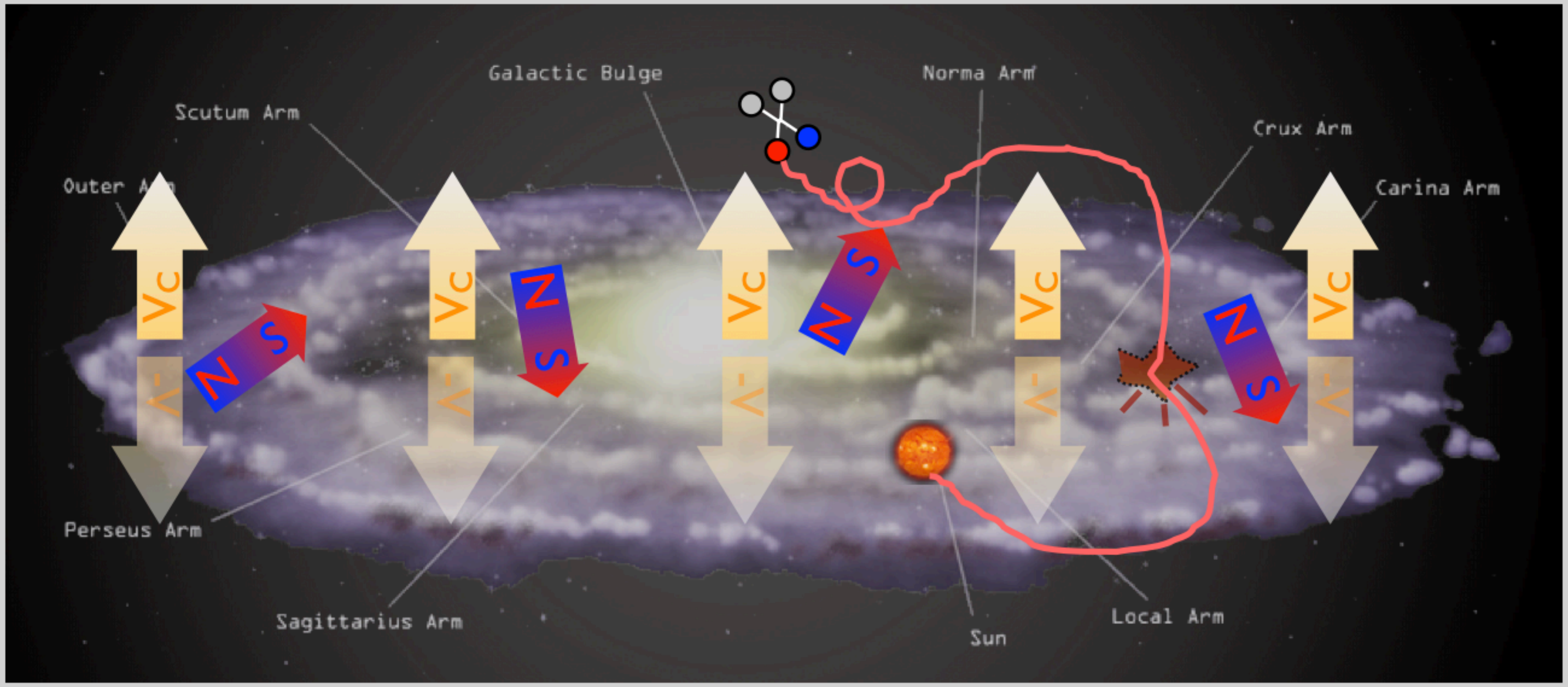
pi0 decay:

— proton energy loss rate/emitted power proportional to the gas density
— cut-off below ~1 GeV
— photons (neutrinos) take 1/2 (1/4) of the pion energy

CR confinement

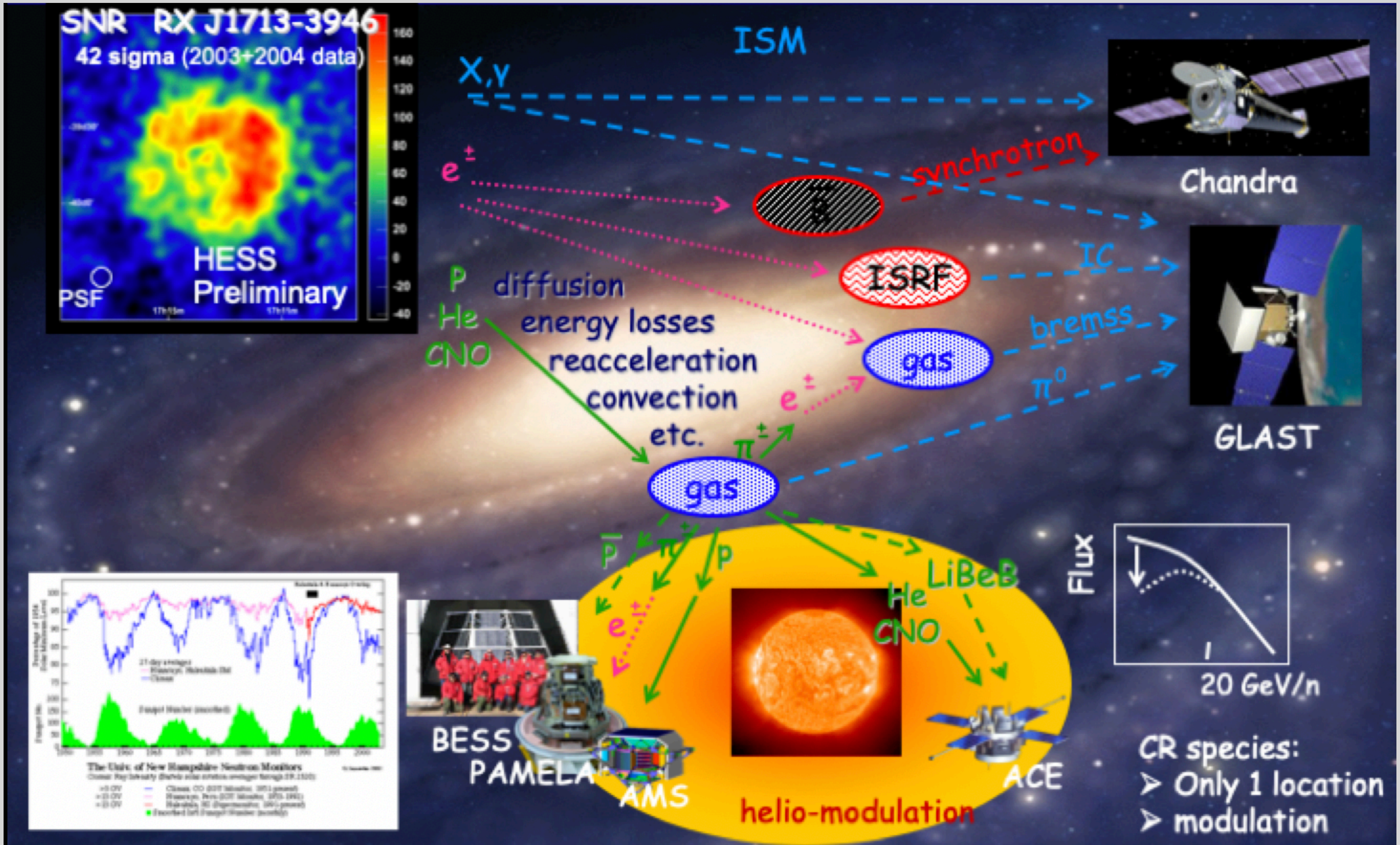
Now we have some idea on how primary CRs are accelerated, but how about their propagation in the medium/energy losses?
Intimately related to the production of 'secondaries' e.g. gamma rays.

- The question can be decomposed in four parts:
  - energetics
  - acceleration
  - energy losses
  - CR diffusion

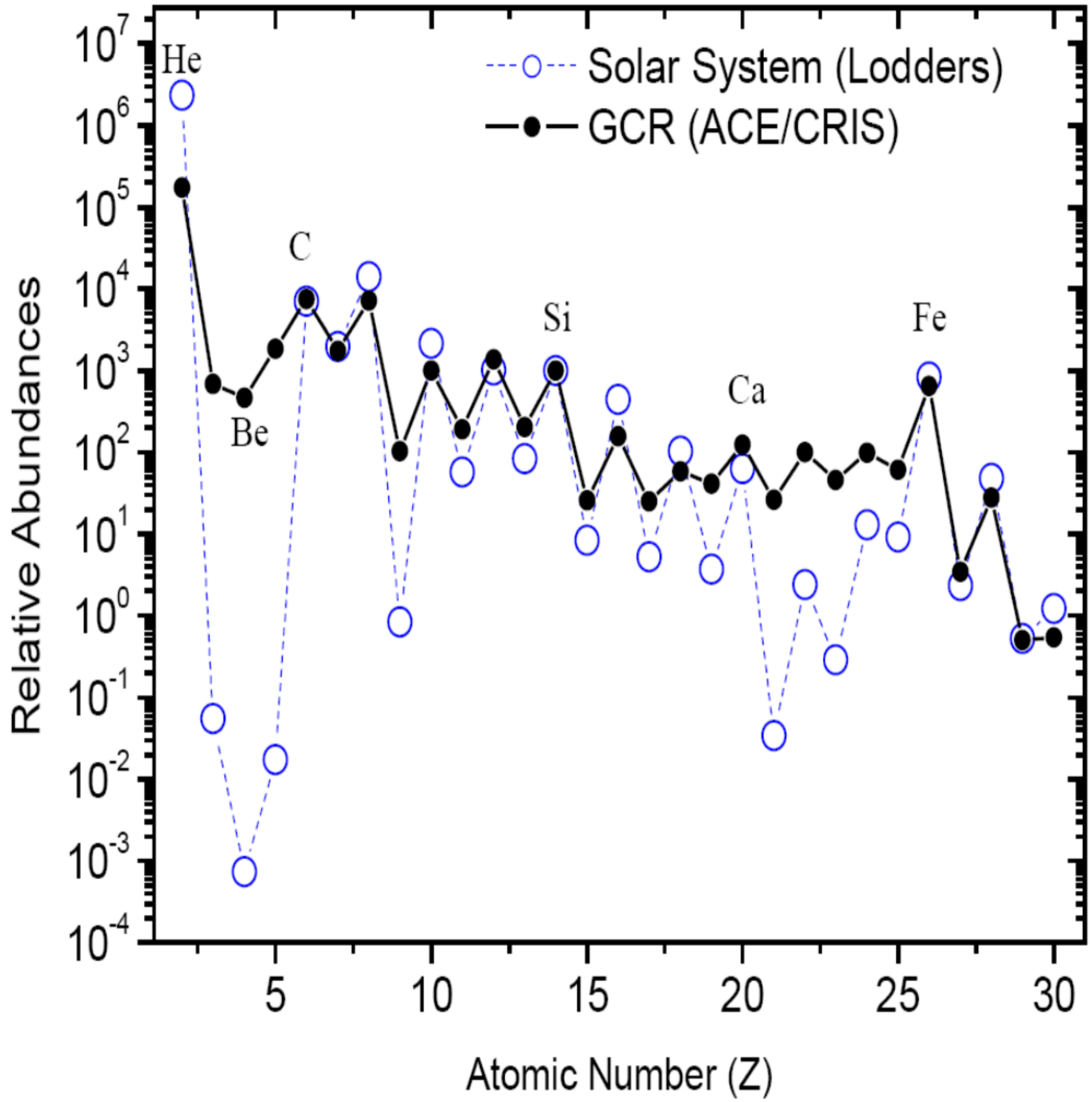


CR diffusion

- Energy losses do not occur only AT sources!
- The medium of our galaxy for example is magnetised and inhomogeneities keep CRs 'entangled' in the galaxy



Evidence of CRs confinement in the Galaxy



Solar System: Lodders, ApJ 591 (2003) 1220
GCR: Israel, ECRS 2004

the main features are the
— agreement on the "peaks" (more tightly bounded even-Z nuclei) and
— higher abundances for cosmic rays on the "valleys"

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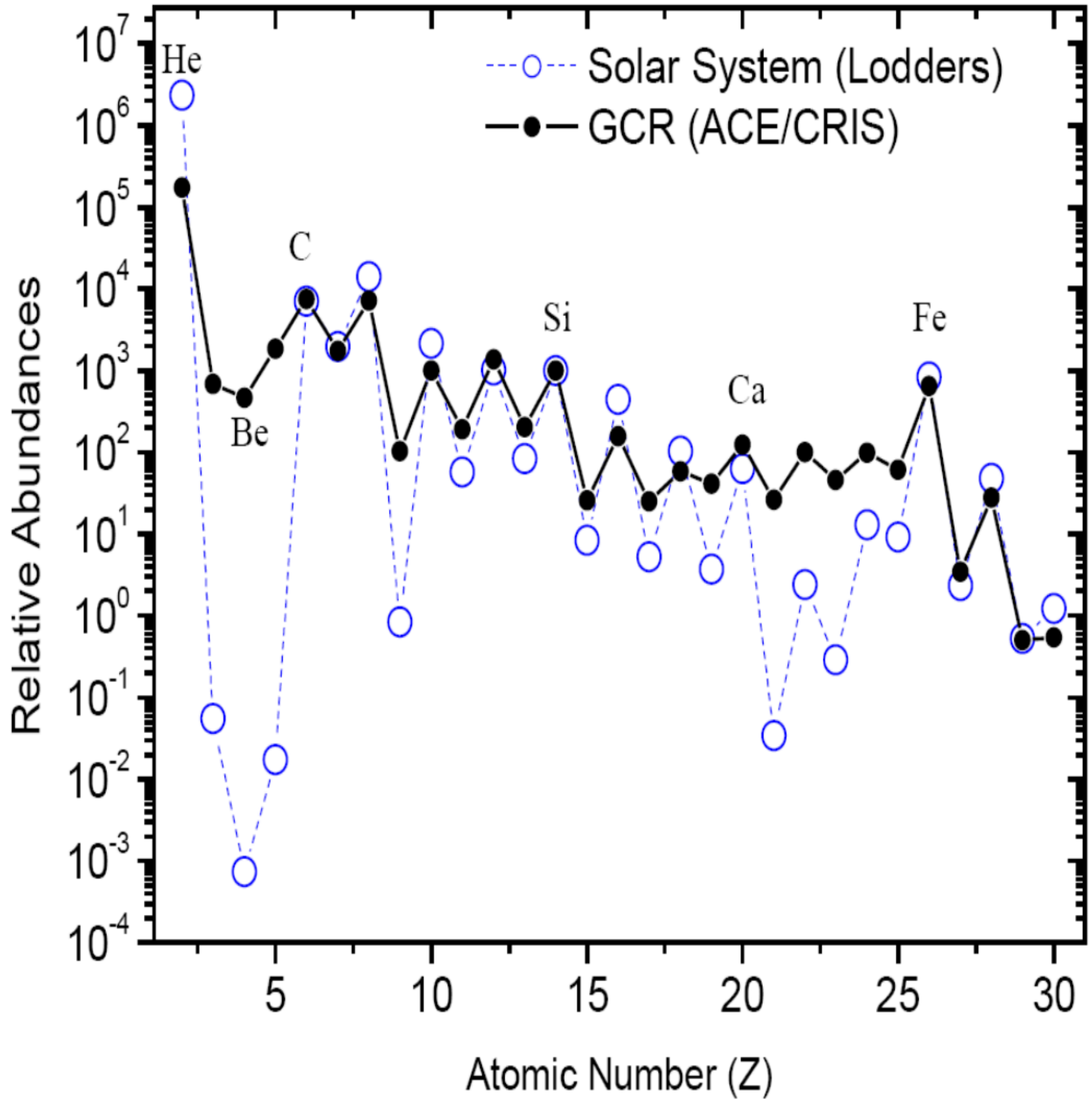

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the main features are the
— agreement on the "peaks" (more tightly bounded even-Z nuclei) and
— higher abundances for cosmic rays on the "valleys"

Points to a scenario where:
— primary cosmic rays are produced in stellar endproducts,
— the "valley" elements are mainly secondaries produced in the interaction of the primaries cosmic rays with the interstellar medium ("spallation")

Evidence of CRs confinement in the Galaxy

Lets take a closer look at secondary/primary ratio:

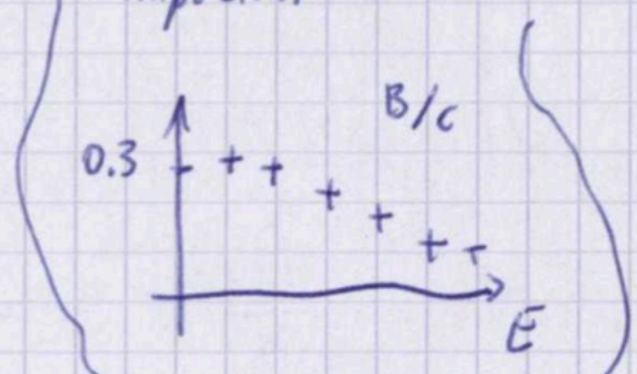
$$p \longrightarrow S + X$$

$$\begin{bmatrix} C \\ N \\ O \end{bmatrix} \qquad \begin{bmatrix} Li \\ Be \\ B \end{bmatrix}$$

$$\begin{cases} \dfrac{dn_p}{dX} = -n_p \dfrac{\sigma_{tot}}{m} \Rightarrow n_p = n_p(0)\, e^{-\frac{\sigma_{tot} X}{m}} \\ \dfrac{dn_s}{dX} = n_p \dfrac{\sigma_{spall}}{m} \Rightarrow n_s = \left(n_p(0)\, e^{-\frac{\sigma_{tot} X}{m}}\right) \cdot X \dfrac{\sigma_{spall}}{m} \end{cases}$$

$$\left[n_s / n_p \sim X \frac{\sigma_{spall}}{m} \right]$$

⇒ This is why secondary / primary ratios are important



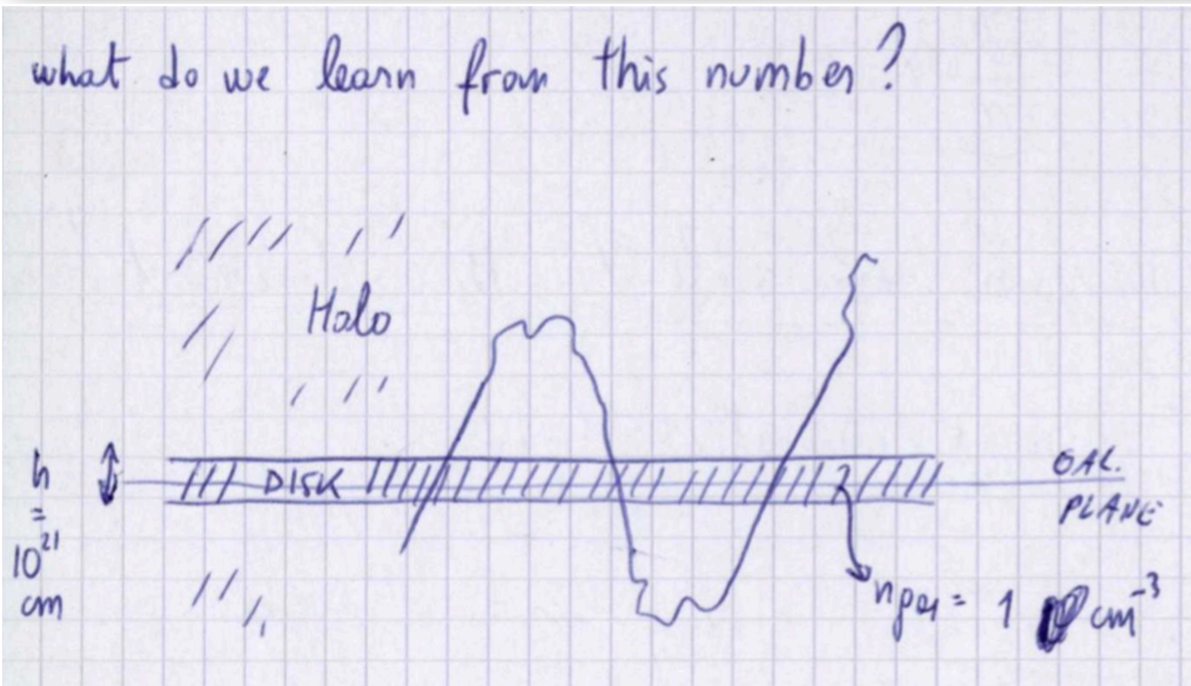
$$1\,\mathrm{GeV}: \quad 0{,}3 \sim \frac{X}{\left(m/\sigma = 10\ g/cm^2\right)}$$

$$\Rightarrow \boxed{X \sim 3\ g/cm^2} \quad [\mathrm{GRAMMAGE}]$$

Ratio of S/P gives us the grammage!

Evidence of CRs confinement in the Galaxy

Lets take a closer look at secondary/primary ratio:



$$X_{disk} = m_p \, n_{gas} \, h \sim 10^{-3} \ g/cm^2$$

($m_p \approx 10^{-24}$, $n_{gas} \approx 1$, $h \approx 10^{21}$)

⇓

CRs must cross the disk many times to accumulate the grammage

$$\tau = \left(\frac{X}{X_{disk}}\right)\left(\frac{h}{c}\right) = 1{,}4 \cdot 10^{14}\ s = 5 \cdot 10^{6}\ y$$

($h \approx 10^{21}$, $c = 3 \cdot 10^{10}$)

average time spent by CRs in the Galaxy

Evidence of CRs confinement in the Galaxy

That number is inconsistent with the Galaxy crossing timescale:

✦ a CR following a straight line ⊥to the disc crosses $X \sim m_p\, n_H\, h \sim 10^{-3}\ g/cm^2$.
(h=300 pc~10^{21} cm as Galactic disc thickness, $n_H \sim 1\ cm^{-3}$ as ISM density)

✦ The residence time of cosmic rays in the galaxy follows as
$t_{prop} \sim (X/10^{-3}\ g/cm^2)(h/c) \sim 5 \times 10^6\ yr$.

A similar timescale of ~ 10^7 yr follows from the relative abundances of

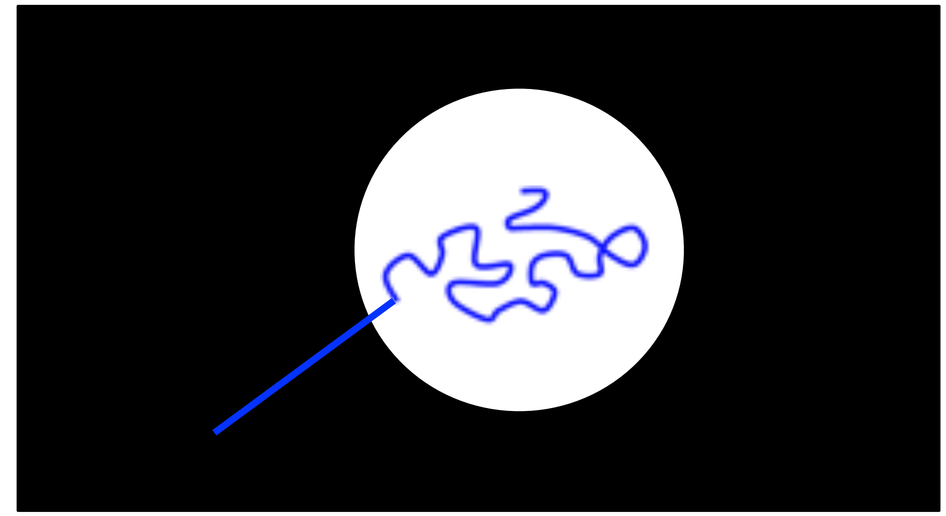
radioactive isotopes, like $^{10}Be/^{9}Be$ ($\tau_{10Be} \sim 1.5 \times 10^6$ yr)

The comparison of the isotopic ratio at the production in spallation events in the Lab wrt what measured in CR provides a measure of their "age".

How to model diffusion?

Leaky box approximation

For stationary, homogeneous & isotropic problems, the diffusion operator can be effectively replaced by an effective "diffusive confinement" time τ_{diff}



Diffusion operator

$$\frac{\partial \Phi}{\partial t} - D\nabla^2\Phi = Q \Rightarrow \frac{\partial \Phi}{\partial t} - \frac{\Phi}{\tau_{\rm diff}(E)} = Q$$

Effective diffusion confinement time

At steady state

$$\Phi = Q(E)\tau_{\rm diff}(E)$$

Note that, if diffusion dominates, we can also infer that the source spectra are in general different than those CR observed at the Earth

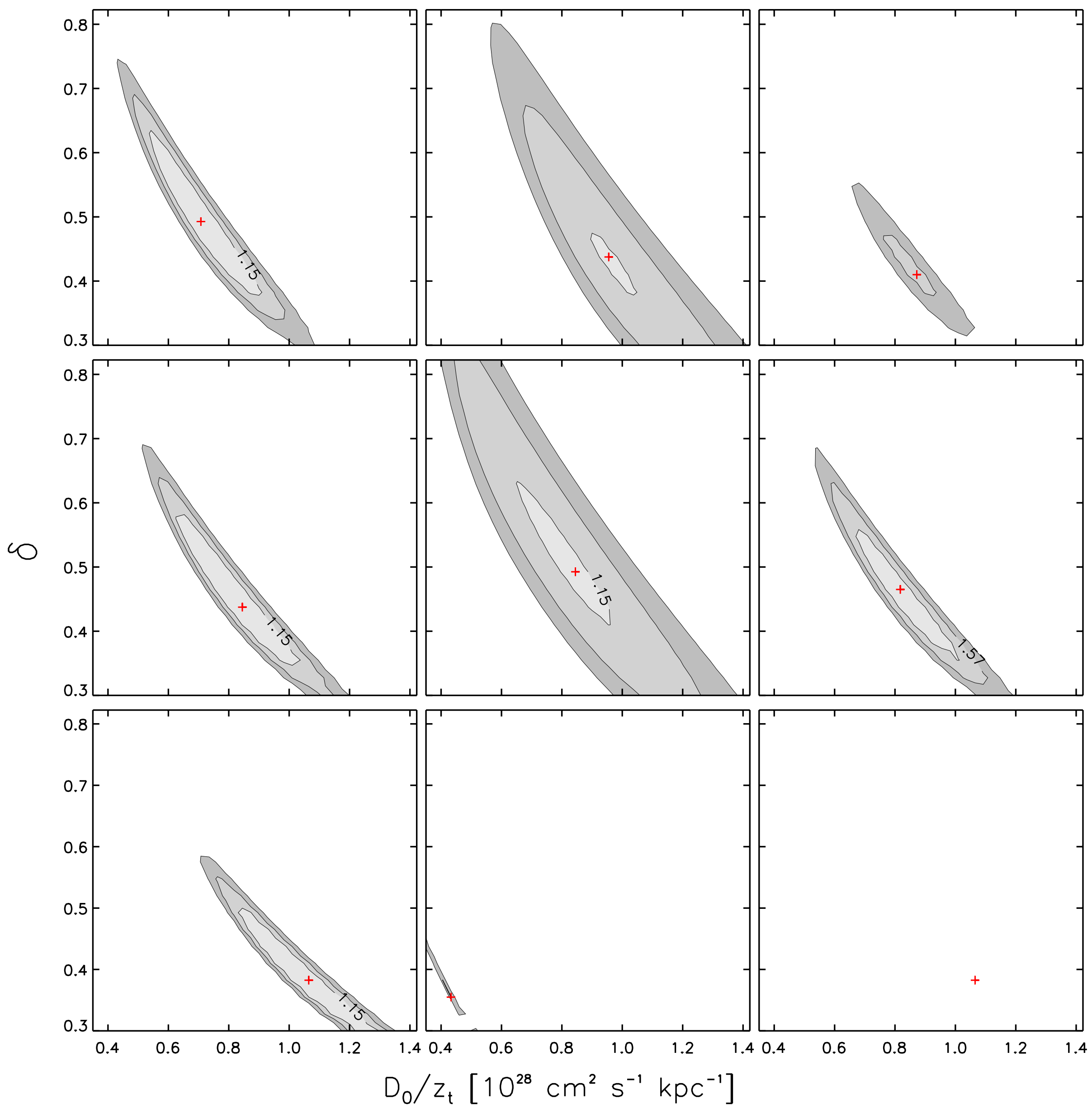
Secondary/Primary CR as diagnostics

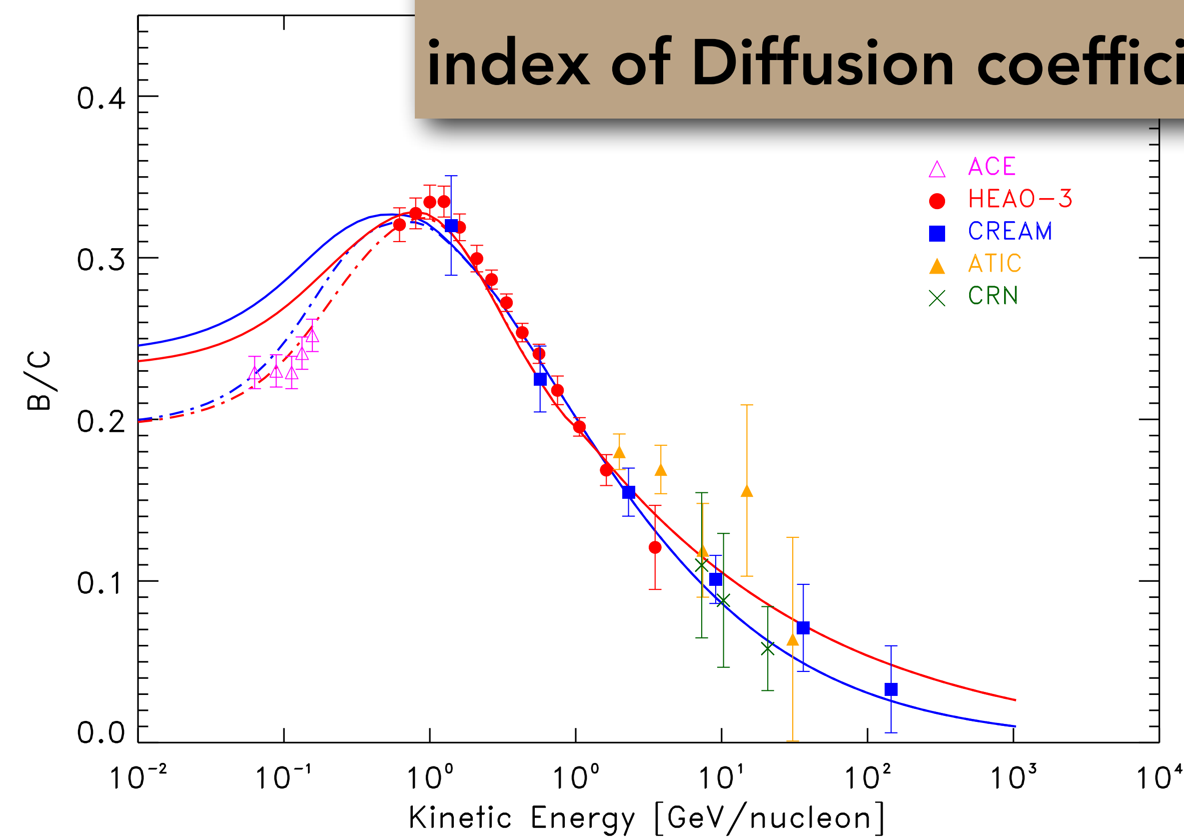
If a type of nucleus is not present as primary, but only produced as secondary via collisions (this includes e.g. antiprotons), then

$$\Phi_s = Q_s\, \tau_{\rm diff} \propto \sigma_{p\to s} \Phi_p \tau_{\rm diff}$$

$$\frac{\Phi_s}{\Phi_p} \propto \tau_{\rm diff}(E) \propto D(E)^{-1} \propto E^{\delta}$$

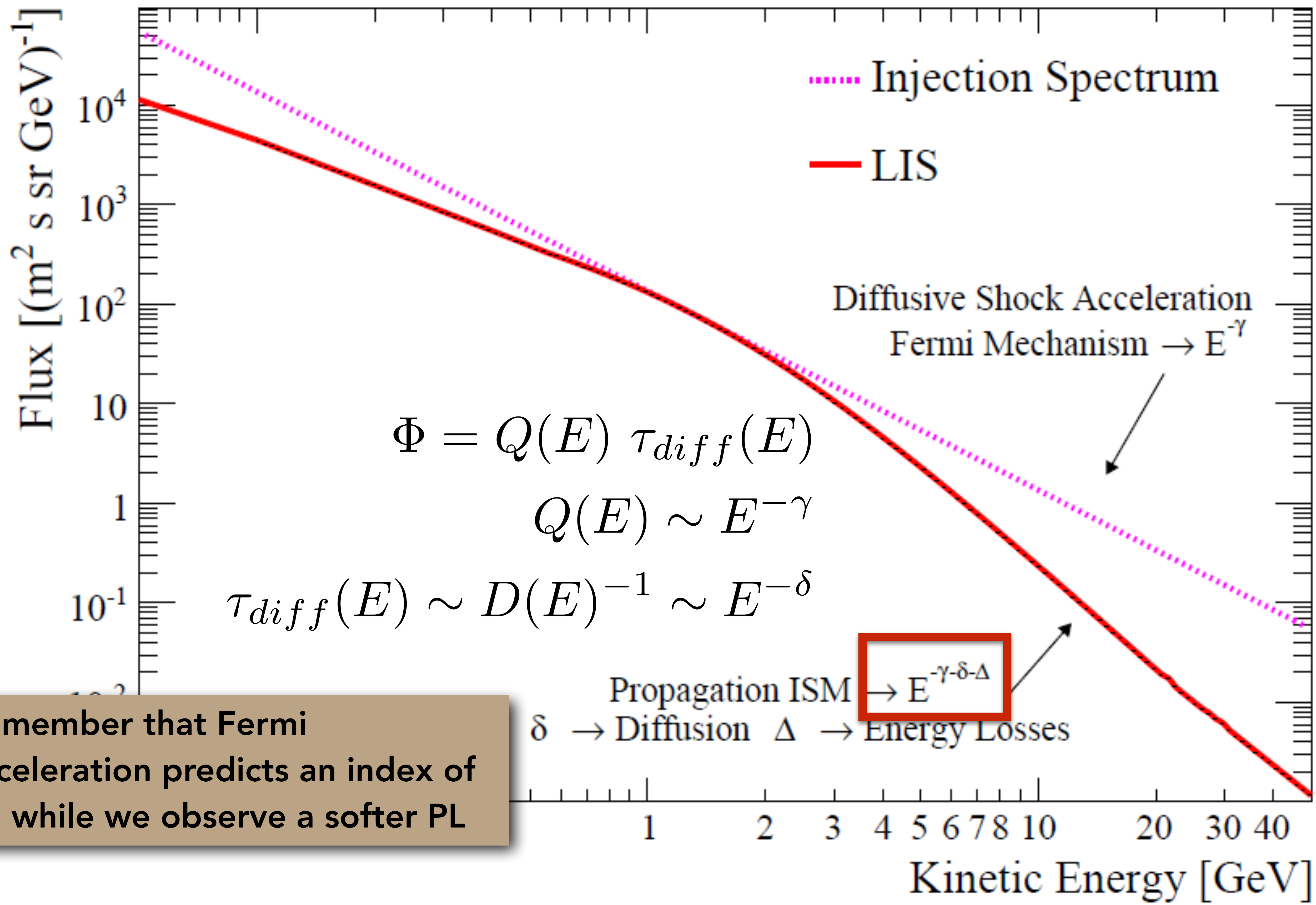
Possible to determine the index of Diffusion coefficient!





$D \approx 10^{29}\ \mathrm{cm}^2/\mathrm{s} \iff \delta B/B \sim 10^{-6}$

$$D(R) \simeq 10^{28} \div 10^{29} \left(\frac{R}{3\,\mathrm{GV}}\right)^{0.5} \mathrm{cm}^2/\mathrm{s}$$

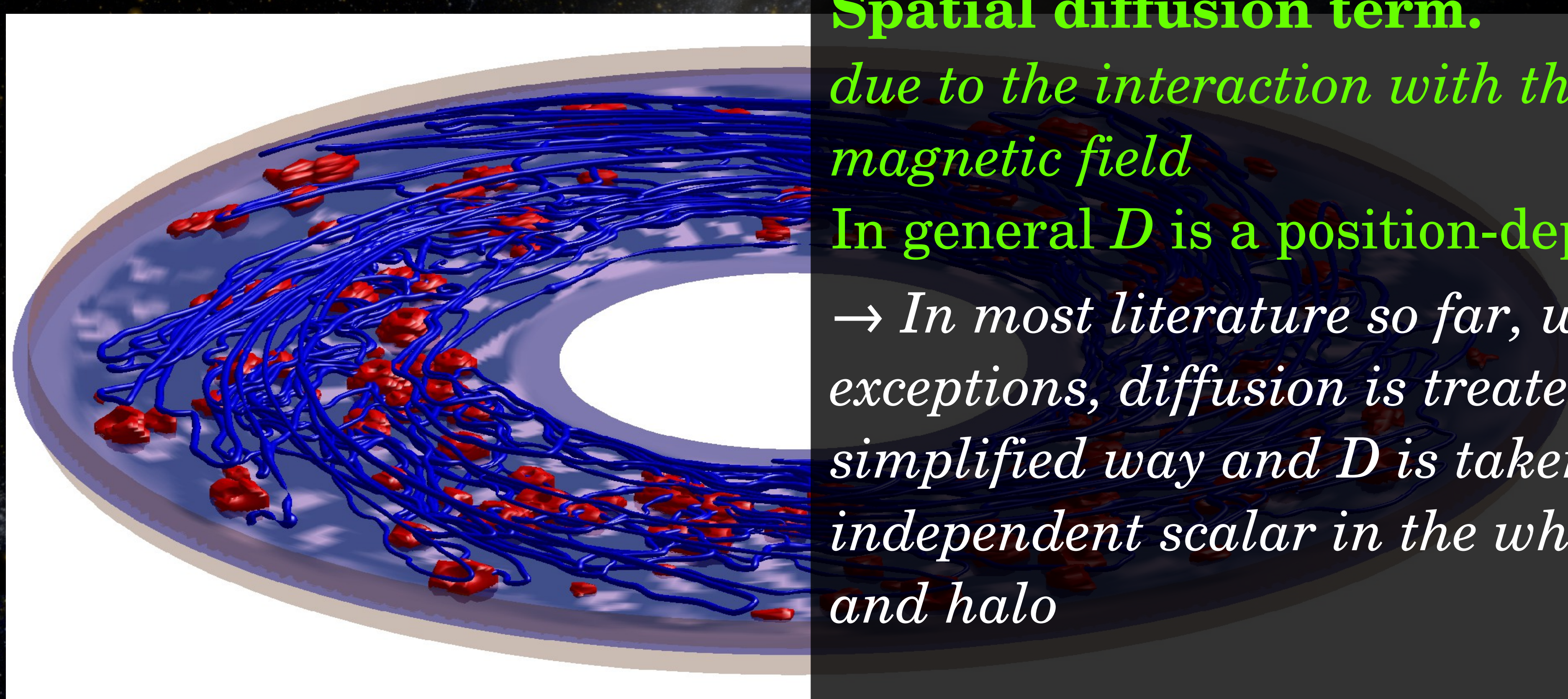


Remember that Fermi acceleration predicts an index of -2, while we observe a softer PL

The basic picture

The complete equation describing CR propagation is the following:

$$\frac{\partial N^i(\vec{x},p,t)}{\partial t} = \nabla\cdot(D\nabla N^i - \mathbf{v_C})N^i(\vec{x},p,t) + \frac{\partial}{\partial p}\left(\dot{p} - \frac{p}{3}\cdot\mathbf{v_C}\right) - \frac{\partial}{\partial p}p^2 D_{pp}\frac{\partial}{\partial p}\frac{N^i(\vec{x},p,t)}{p^2} + Q^i(\vec{x},p,t) + \sum_{j>i} c\beta n_{\mathrm{gas}}\sigma_{ij}N^j - c\beta n_{\mathrm{gas}}\sigma_{\mathrm{in}}N^i(\vec{x},p,t)$$



Spatial diffusion term.

due to the interaction with the Galactic magnetic field

In general D is a position-dependent tensor D_{ij}

→ *In most literature so far, with only very few exceptions, diffusion is treated in a over-simplified way and D is taken as a spatial-independent scalar in the whole Galactic disk and halo*

The basic picture

The equation describing CR propagation is the following:

$$\frac{\partial N^i(\vec{x},p,t)}{\partial t} = \nabla \cdot (D\nabla N^i - \mathbf{v_C})N^i(\vec{x},p,t) + $$
$$+ \frac{\partial}{\partial p}\left(\dot{p} - \frac{p}{3}\cdot \mathbf{v_C}\right) - \frac{\partial}{\partial p}p^2 D_{pp}\frac{\partial}{\partial p}\frac{N^i(\vec{x},p,t)}{p^2}$$
$$+ Q^i(\vec{x},p,t) + \sum_{j>i} c\beta n_{\rm gas}\sigma_{ij}N^j - c\beta n_{\rm gas}\sigma_{\rm in}N^i(\vec{x},p,t)$$

Energy losses due to the interaction with the ISM: gas, magnetic fields, diffuse radiation field in the IR, optical, UV

→ this term is important for low-energy hardons and high-energy leptons (IC scattering, synchrotron emission)

The basic picture

The equation describing CR propagation is the following:

$$
\begin{aligned}
\frac{\partial N^i(\vec{x},p,t)}{\partial t} &= \nabla\cdot(D\nabla N^i - \mathbf{v_C})N^i(\vec{x},p,t) + \\
&+ \frac{\partial}{\partial p}\left(\dot{p} - \frac{p}{3}\cdot\mathbf{v_C}\right) - \frac{\partial}{\partial p}p^2 D_{pp}\frac{\partial}{\partial p}\frac{N^i(\vec{x},p,t)}{p^2} \\
&+ Q^i(\vec{x},p,t) + \sum_{j>i} c\beta n_{\rm gas}\sigma_{ij}N^j - c\beta n_{\rm gas}\sigma_{\rm in}N^i(\vec{x},p,t)
\end{aligned}
$$

Reacceleration

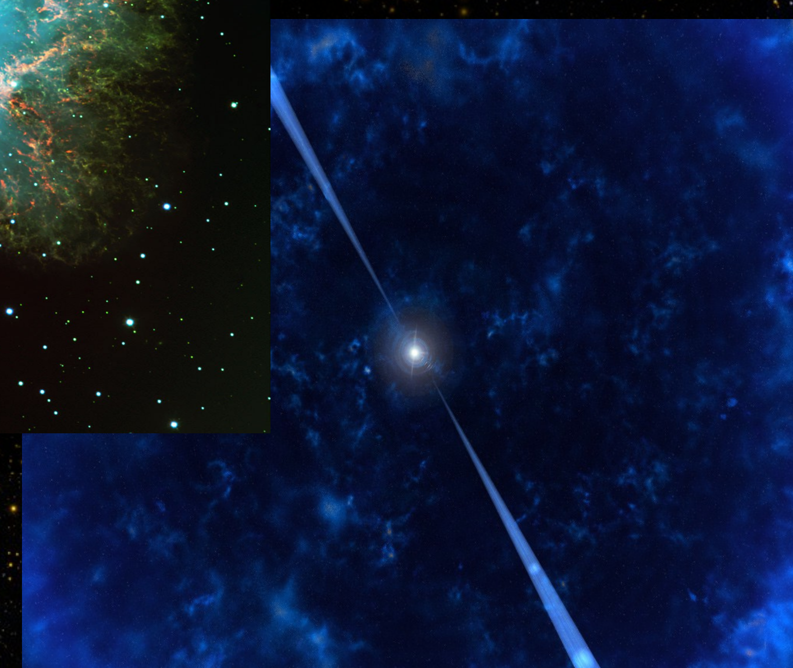
The basic picture

The equation describing CR propagation is the following:

$$\frac{\partial N^i(\vec{x},p,t)}{\partial t} = \nabla\cdot(D\nabla N^i - \mathbf{v_C})N^i(\vec{x},p,t) + \\ + \frac{\partial}{\partial p}\left(\dot{p} - \frac{p}{3}\cdot\mathbf{v_C}\right) - \frac{\partial}{\partial p}p^2 D_{pp}\frac{\partial}{\partial p}\frac{N^i(\vec{x},p,t)}{p^2} \\ + Q^i(\vec{x},p,t) + \sum_{j>i} c\beta n_{\rm gas}\sigma_{ij}N^j - c\beta n_{\rm gas}\sigma_{\rm in}N^i(\vec{x},p,t)$$

Primary source term.

Protons, nuclei, electrons are accelerated by SNR shocks



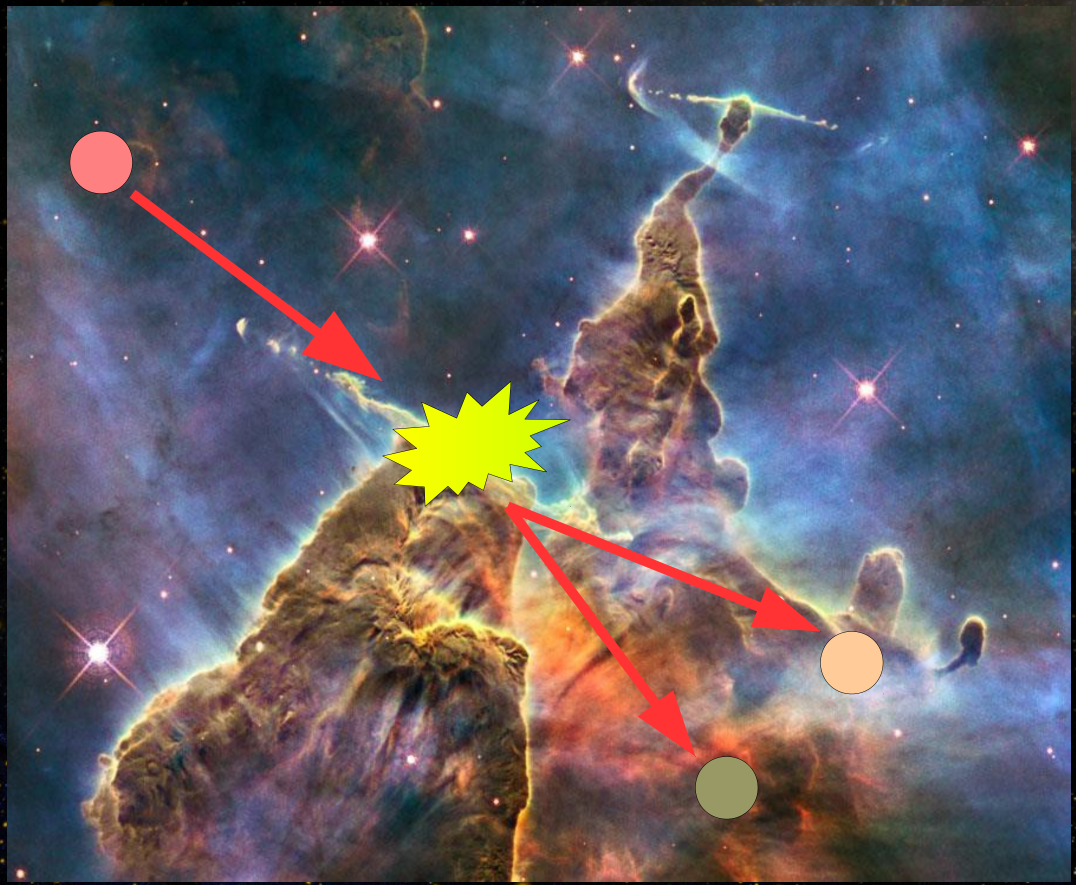
→ Other classes of CR accelerators? (maybe pulsars?)

→ *CRs coming from DM annihilation/decay?*

The basic picture

The equation describing CR propagation is the following:

$$\frac{\partial N^i(\vec{x},p,t)}{\partial t} = \nabla\cdot(D\nabla N^i - \mathbf{v_C})N^i(\vec{x},p,t) + \\ + \frac{\partial}{\partial p}\left(\dot{p} - \frac{p}{3}\cdot\mathbf{v_C}\right) - \frac{\partial}{\partial p}p^2 D_{pp}\frac{\partial}{\partial p}\frac{N^i(\vec{x},p,t)}{p^2} \\ + Q^i(\vec{x},p,t) + \sum_{j>i} c\beta n_{\mathrm{gas}}\sigma_{ij}N^j - c\beta n_{\mathrm{gas}}\sigma_{\mathrm{in}}N^i(\vec{x},p,t)$$



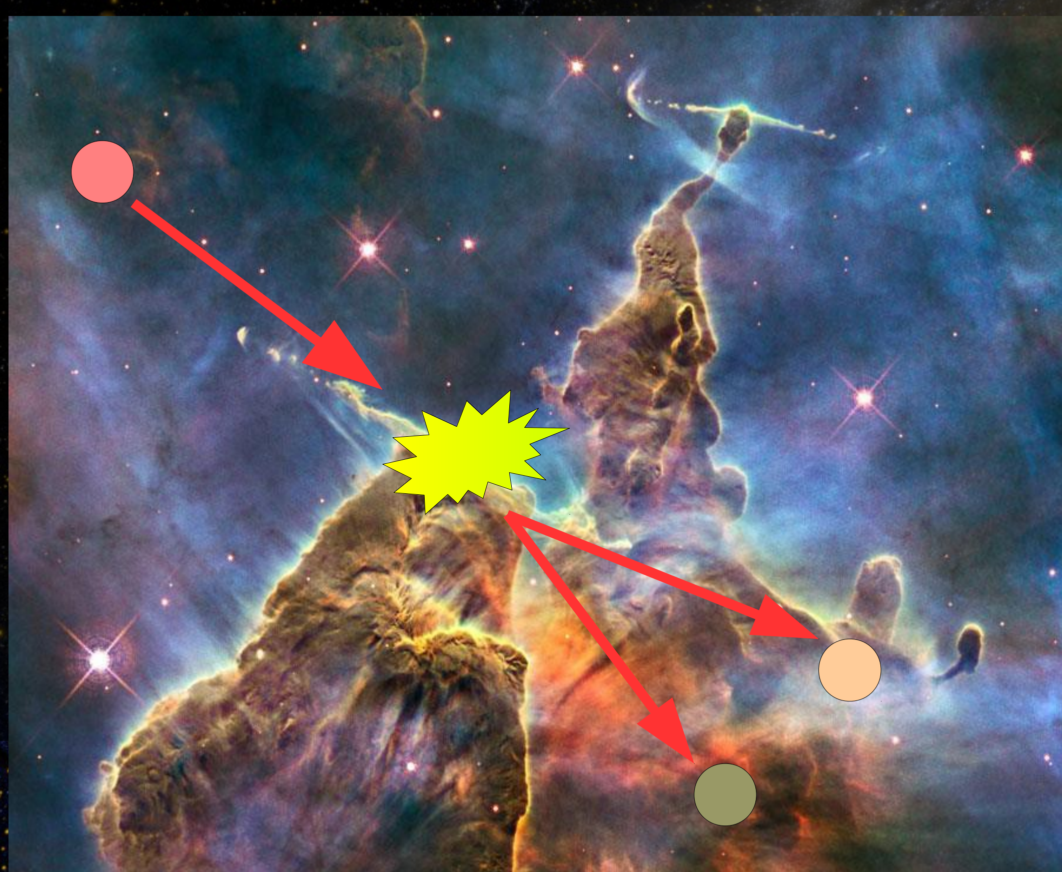
Spallation source term from heavier nuclei interacting with interstellar gas.

For Li, Be, B and antiparticles (positrons, antiprotons) this is the dominant source term.

The basic picture

The equation describing CR propagation is the following:

$$\begin{aligned}\frac{\partial N^i(\vec{x},p,t)}{\partial t} &= \nabla\cdot(D\nabla N^i - \mathbf{v_C})N^i(\vec{x},p,t) + \\ &+ \frac{\partial}{\partial p}\left(\dot{p} - \frac{p}{3}\cdot\mathbf{v_C}\right) - \frac{\partial}{\partial p}p^2 D_{pp}\frac{\partial}{\partial p}\frac{N^i(\vec{x},p,t)}{p^2} \\ &+ Q^i(\vec{x},p,t) + \sum_{j>i} c\beta n_{\rm gas}\sigma_{ij}N^j - c\beta n_{\rm gas}\sigma_{\rm in}N^i(\vec{x},p,t)\end{aligned}$$

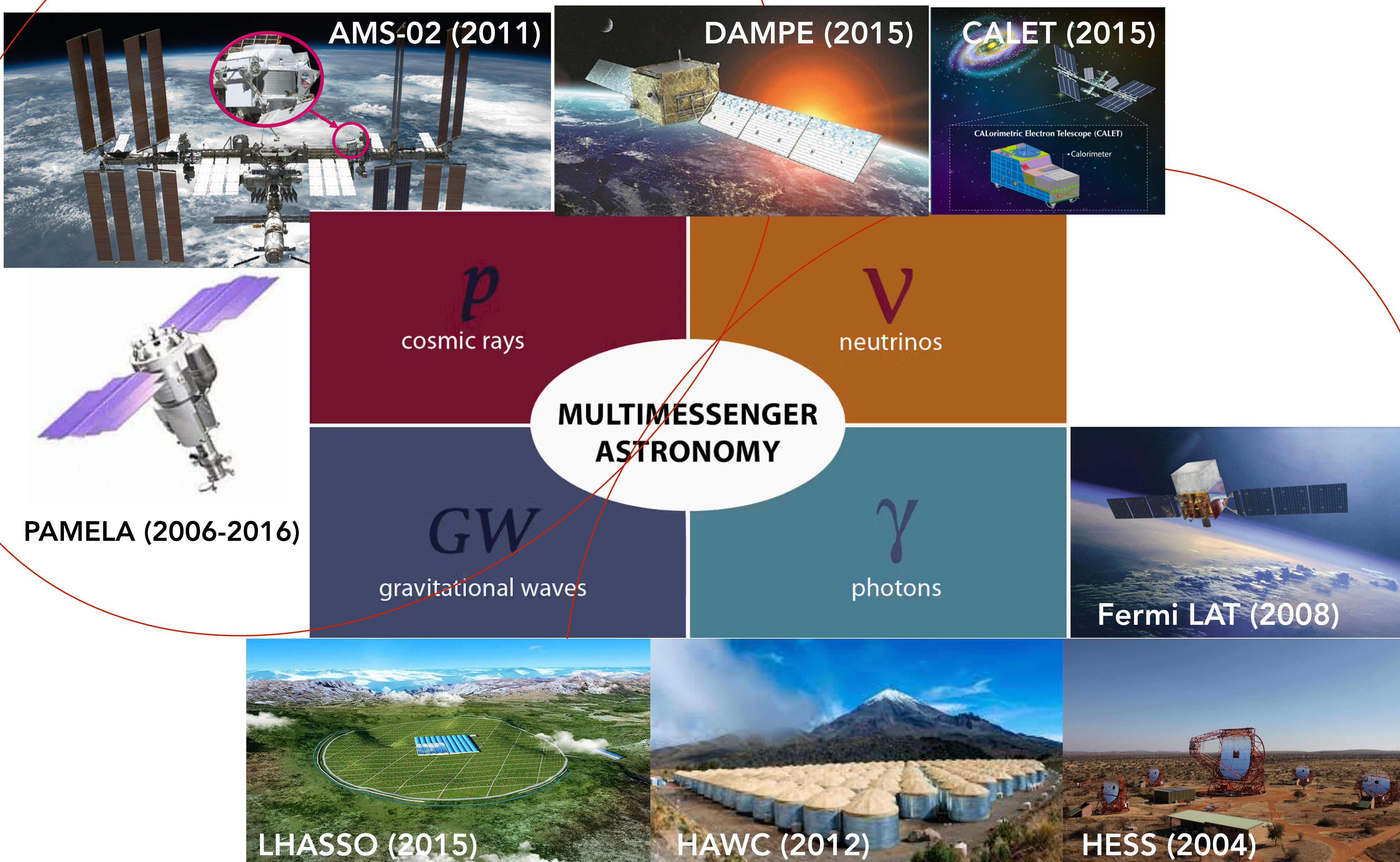


Spallation loss term

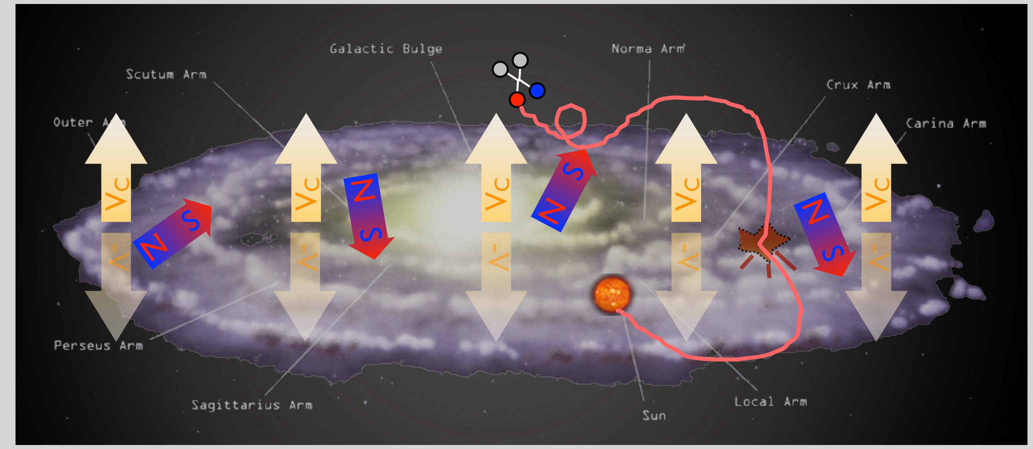
$$\overbrace{\frac{\partial N^j}{\partial t}}^{\text{Variation}} + \overbrace{\left(-\vec{\nabla}\cdot\left(K(E,\vec{r})\vec{\nabla}\right)+\vec{\nabla}\cdot\vec{V}(\vec{r})\right)}^{\text{Spatial transport: diffusion+convection}} N^j + \overbrace{\left(\Gamma_{\rm rad}+\Gamma_{\rm inel}\right)}^{\text{Catastrophic losses}} N^j + \overbrace{\frac{\partial}{\partial E}\left(b^j N^j - c^j\frac{\partial N^j}{\partial E}\right)}^{\text{E gains/losses}} = \overbrace{Q^j(E,\vec{r}) \quad + \sum_{m_i>m_j}\Gamma^{i\rightarrow j}N^i}^{\text{Source term: prim.+sec.}}$$

	(Semi-)analytical	*Numerical*	*Monte Carlo*
Approach	Simplify the problem: • keep dominant effects only • simplify the geometry	Finite difference scheme: • discretise the equation • scheme (e.g., Crank-Nicholson)	Follow each particle: • N particles at t=0 • evolve each of them to t+1 $1\text{D} : \Delta z = \pm\sqrt{2D\Delta t}$
Tools	• Green functions, • Fourier/Bessel expansion • Differential equations	• Numerical recipes/solvers (NAG, GSL libraries)	• Stochastic differential equations (Markov process) + MPI
Pros	• Useful to understand the physics • Fast (MCMC analyses "simple")	• Very simple algebra • Any new input easily included	• Statistical properties (along path) • No grid but t step (for/back)-ward
cons	• Only solve approximate model • New solution for new problem	• Slower, memory for high res. • "Less" insight in the physics	• Even slower (+ statistical errors) • Massively parallel problem
Codes and/or references	Webber (1970+) Ptuskin (1980+) Schlickeiser (1990+) USINE (2000+)	GALPROP (Strong et al. 1998) DRAGON (Evoli et al. 2008) PICARD (Kissmann et al., 2013)	Webber & Rockstroh (1997) Farahat et al. (2008) Kopp, Büshing et al. (2012)

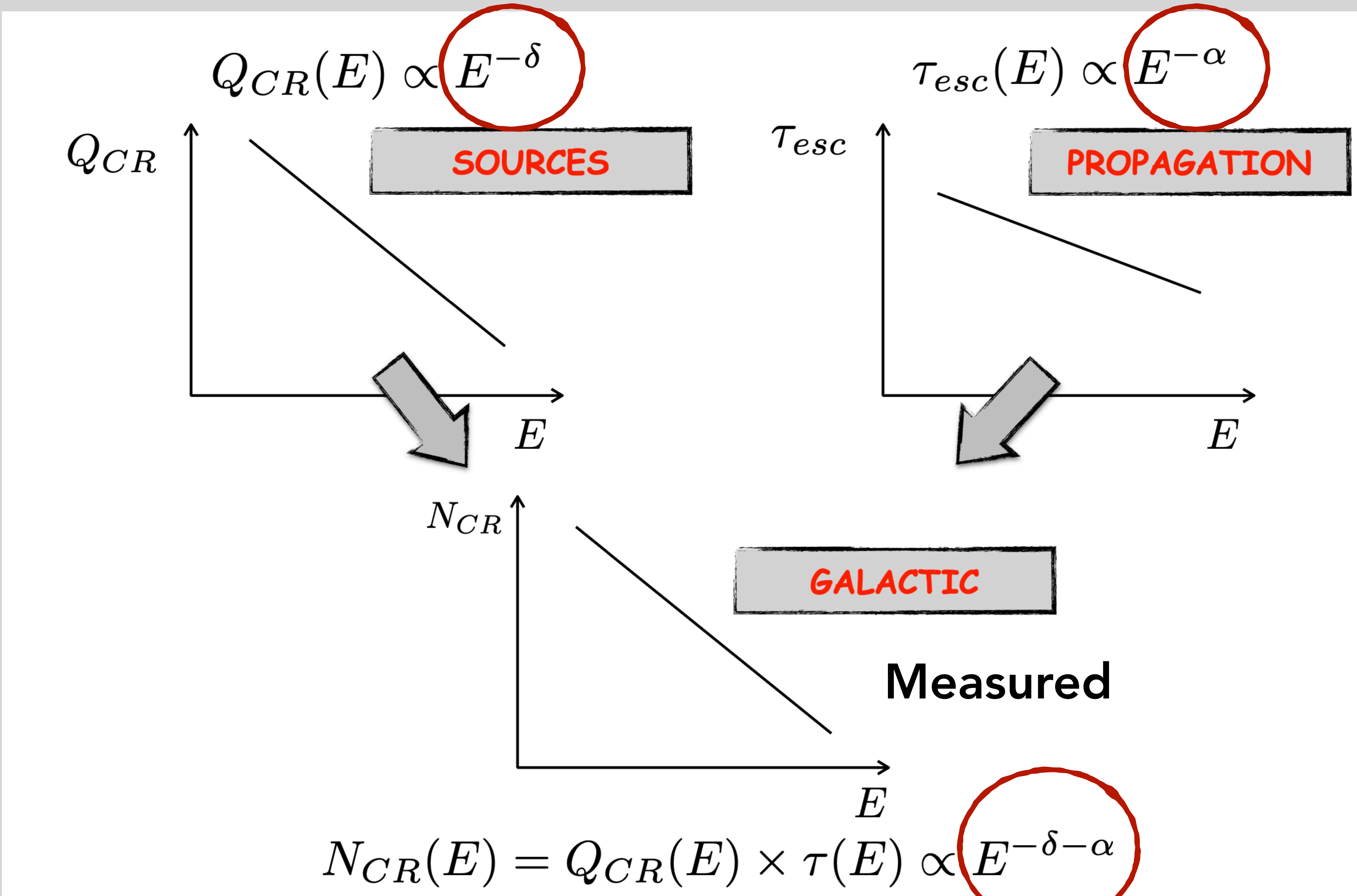
Current experiments - golden era



State of the art



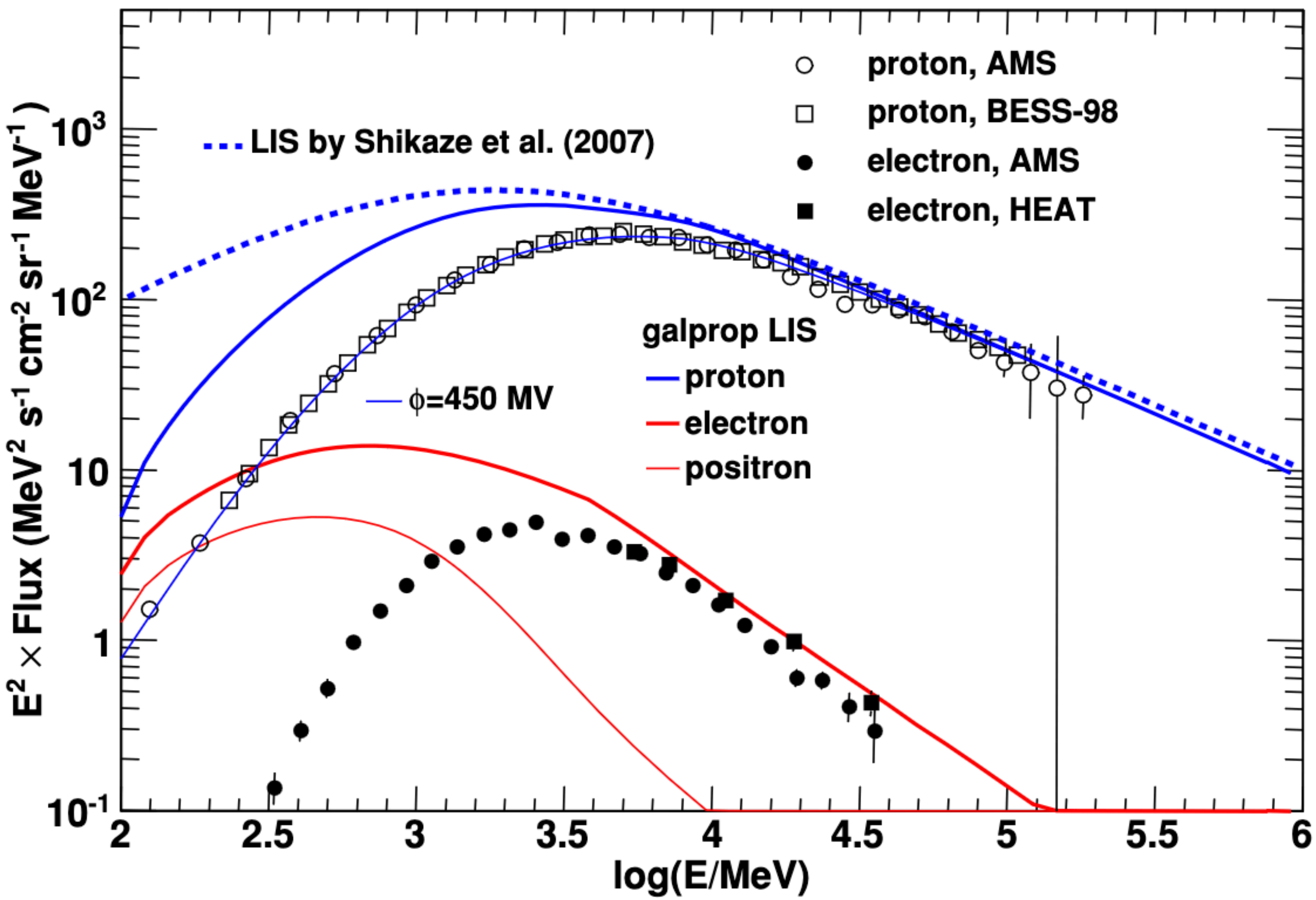
General wisdom



[Credit: S. Gabici, ICRC23]

Life was good, in the old days…

Protons

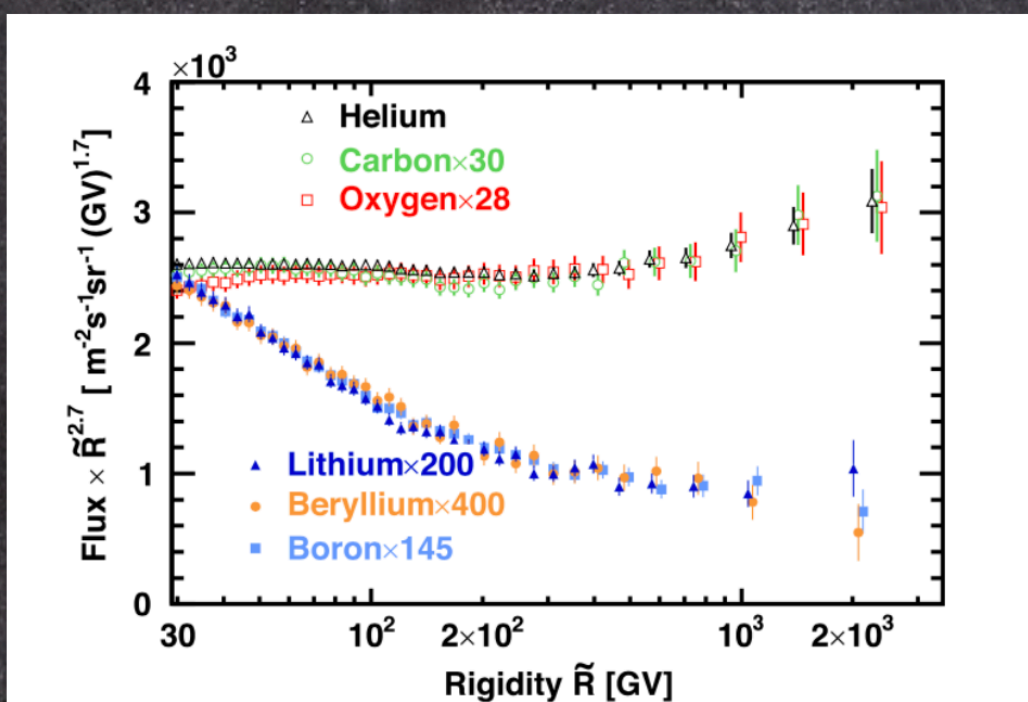


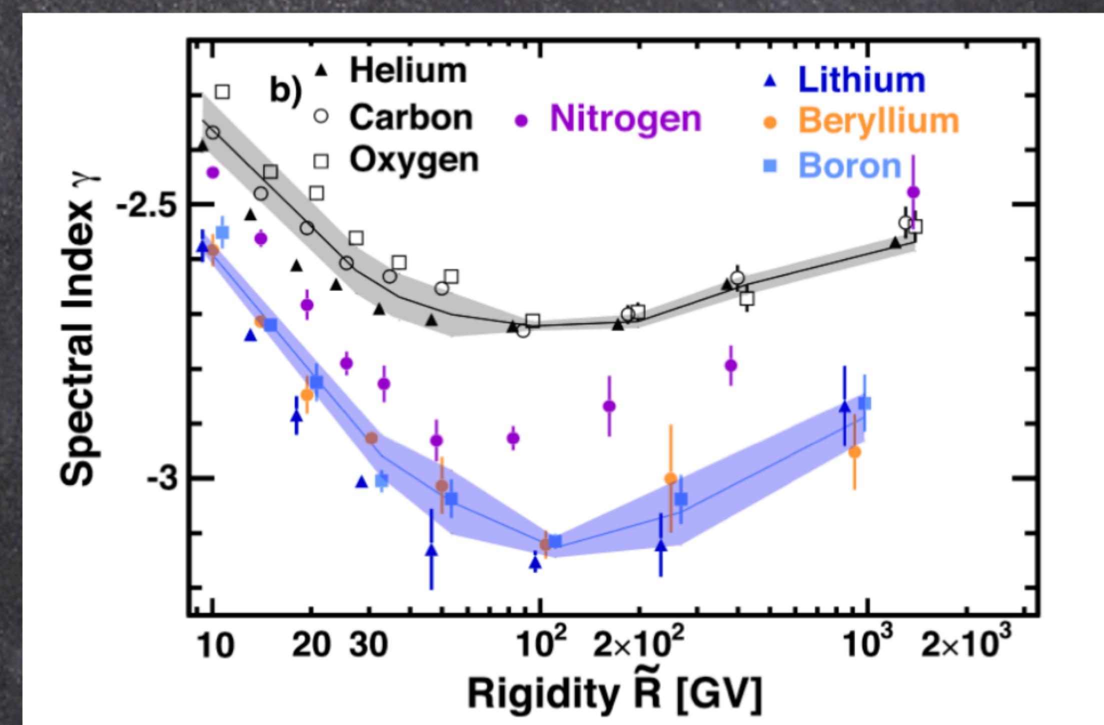
[Astrophys. J., 703:1249–1256, 2009]

With more data taking…

Hardening of nuclear spectra

PAMELA Coll. Science 2011; AMS Coll Phys Rept 2021; PRL2017; PRL2018

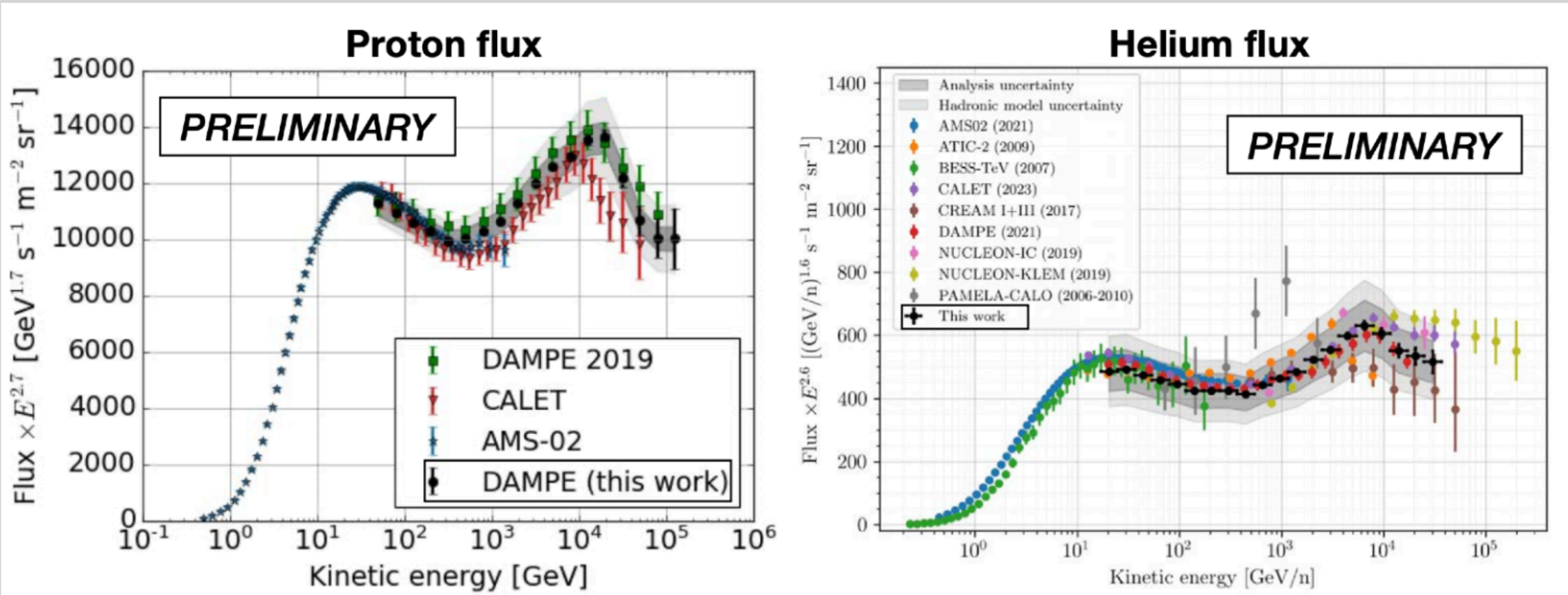




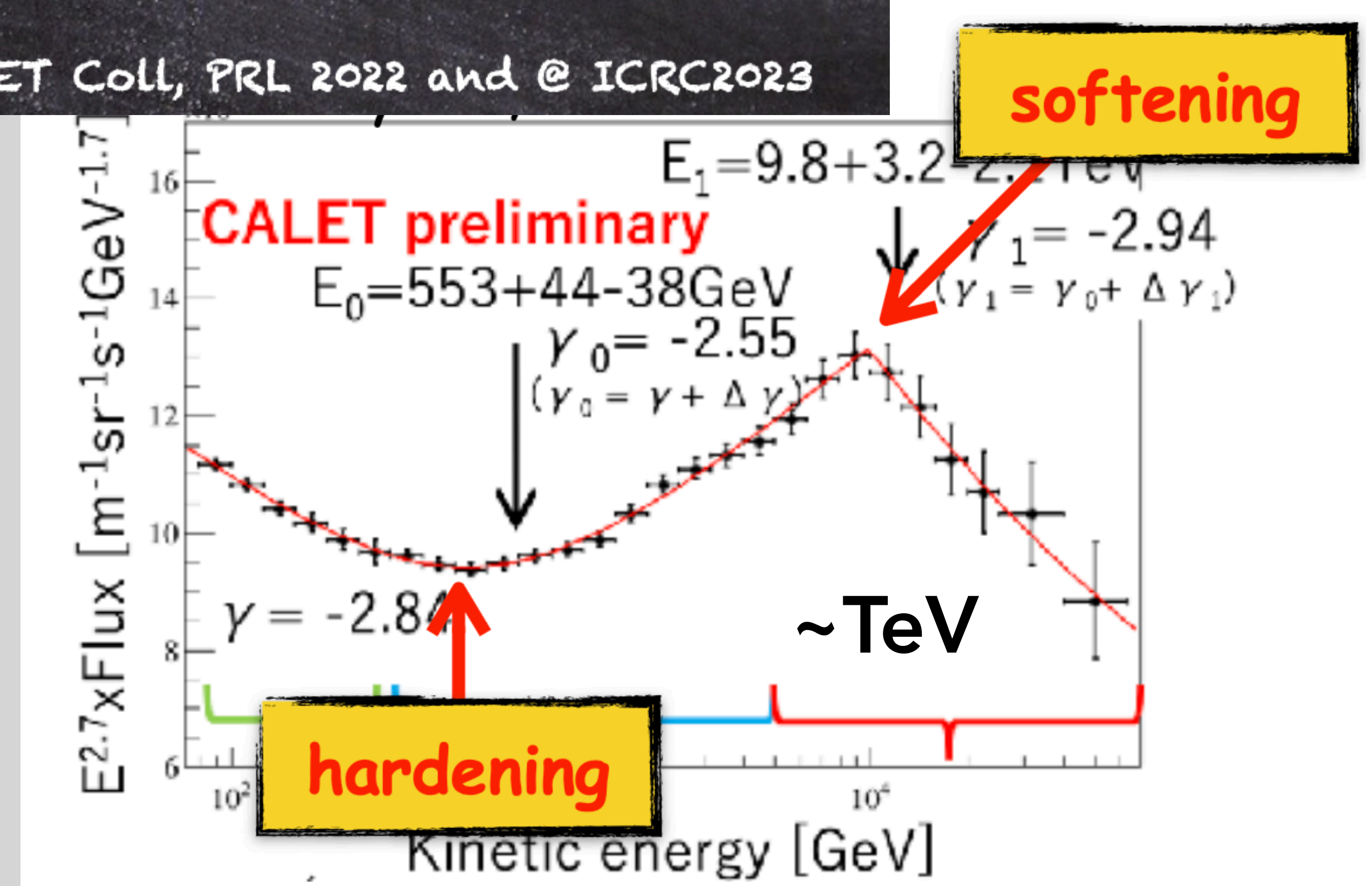
A general hardening is observed at ~ 300 GV

[Credit: F. Donato, TAUP23]

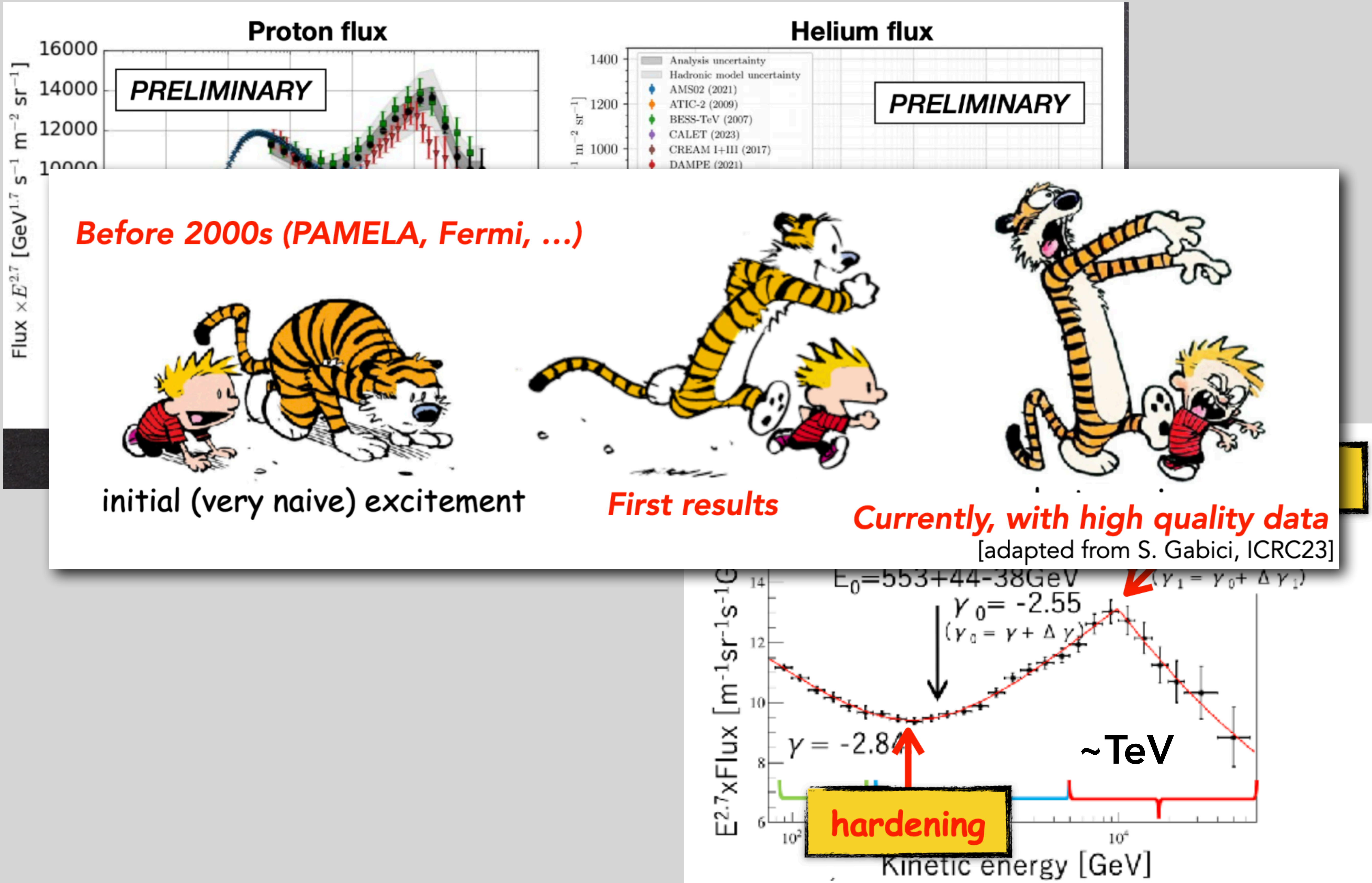
With more data taking…



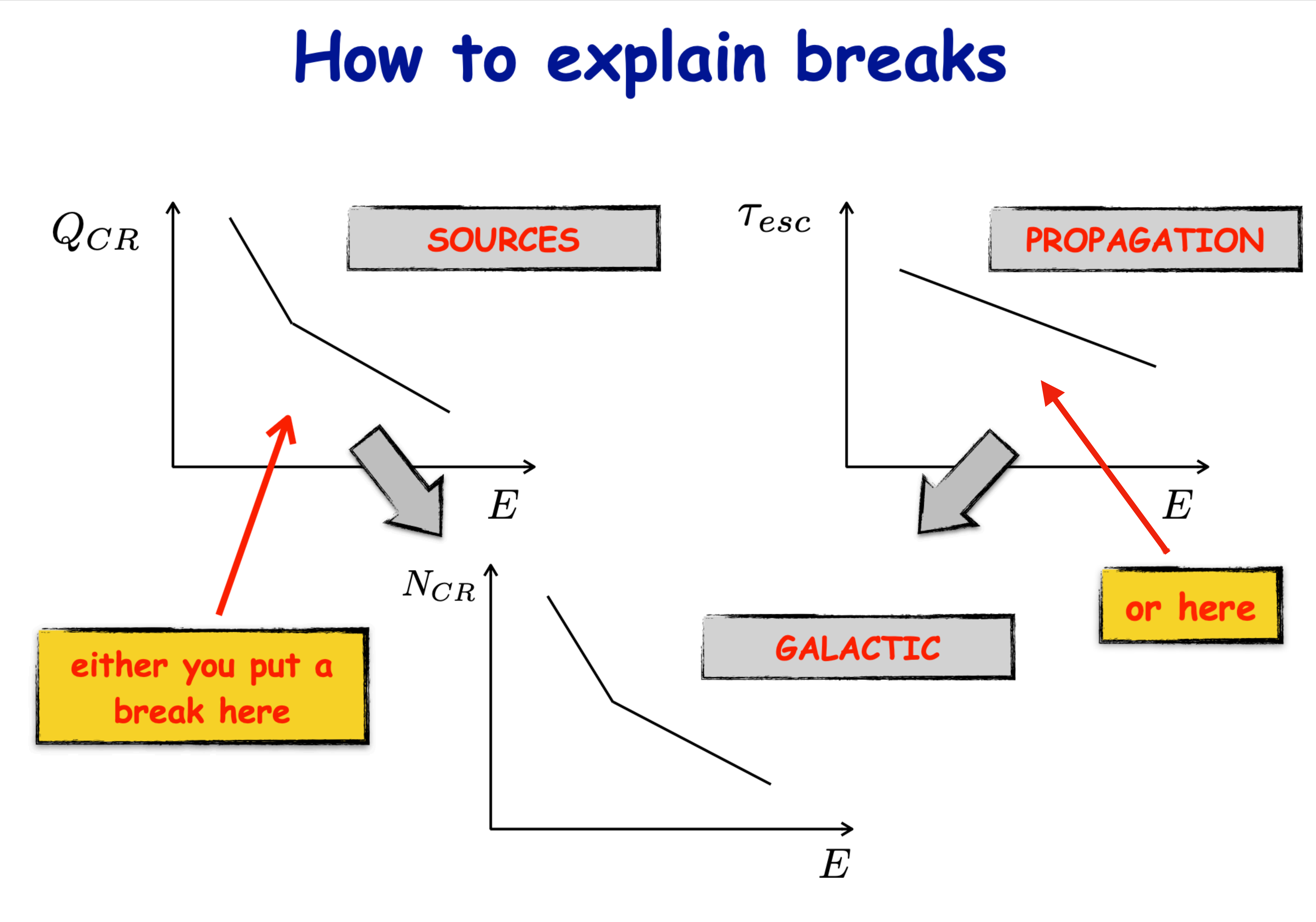
Dampe Coll See also CALET Coll, PRL 2022 and @ ICRC2023



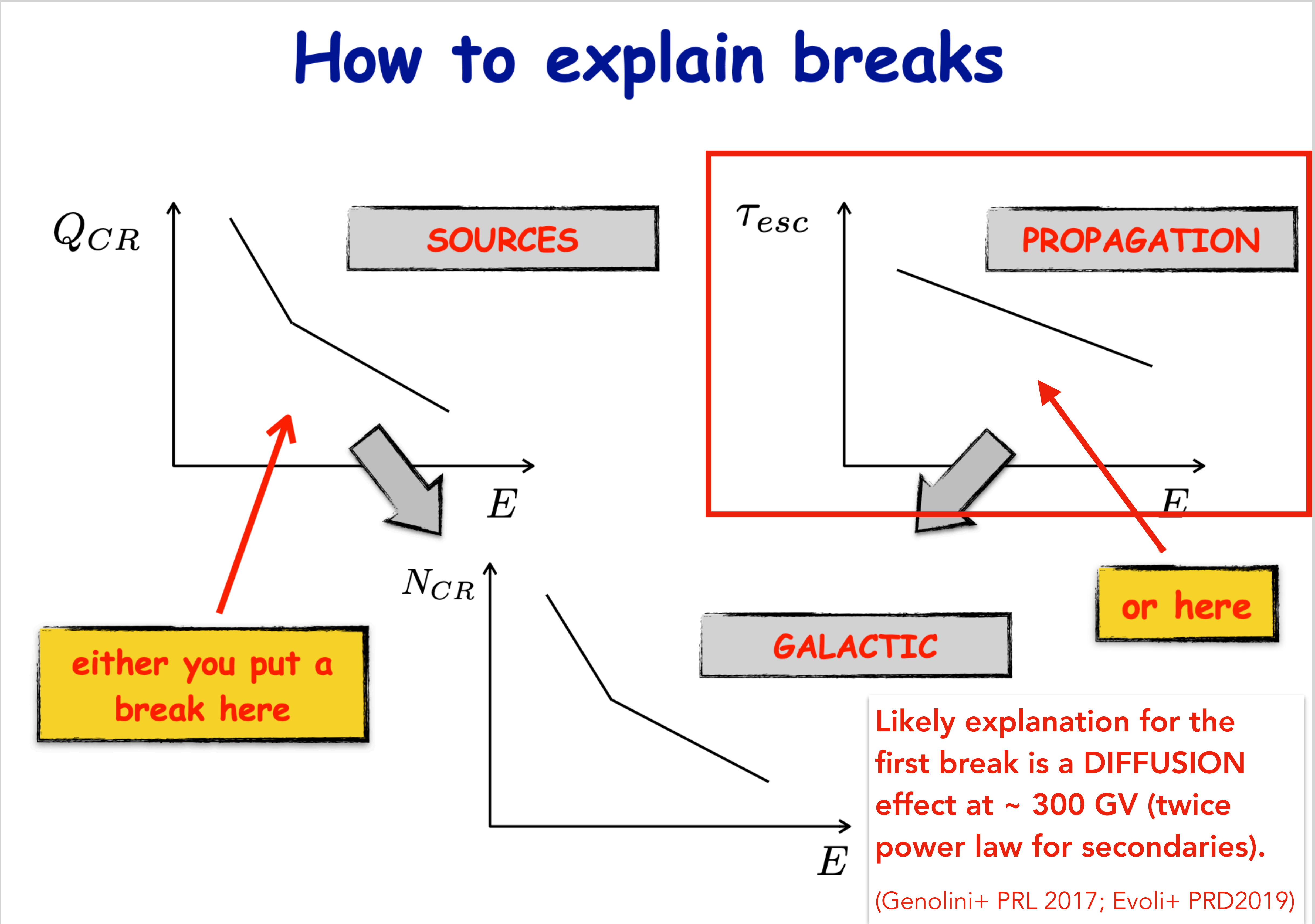
With more data taking…



Brief status of CRs



Brief status of CRs

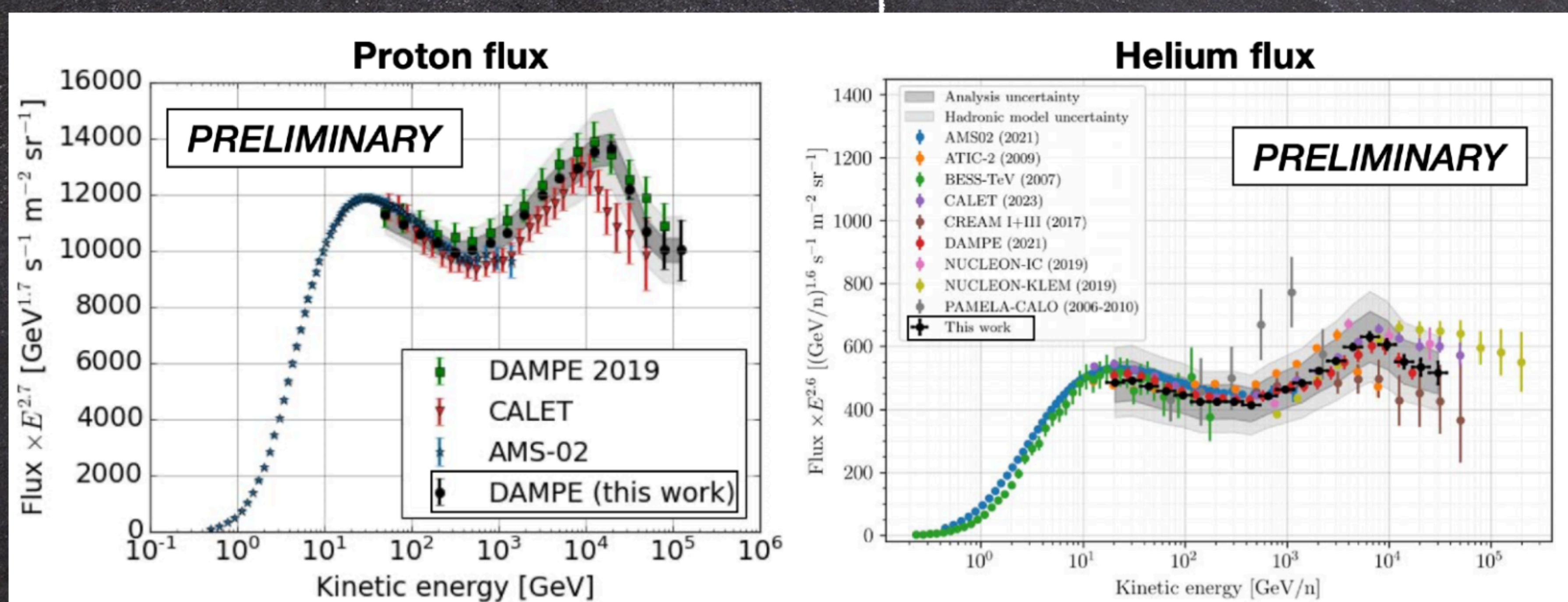


Brief status of CRs

P and He spectra: shifts, breaks and bumps

1. p spectrum is distinctly softer ($\Delta\gamma \sim 0.1$) than He at all energies (shift): Not understood yet
2. R dependence of He, C, O are very similar, all (also p) break at 300 GV: ~ understood
3. The p and He spectra > TeV show a bump: suggestions

Dampe Coll - see Ivan De Mitri's talk



See also CALET Coll, PRL 2022 and @ ICRC2023

Bump: probably an effect in acceleration or escape from the sources

[Credit: F. Donato, TAUP23]

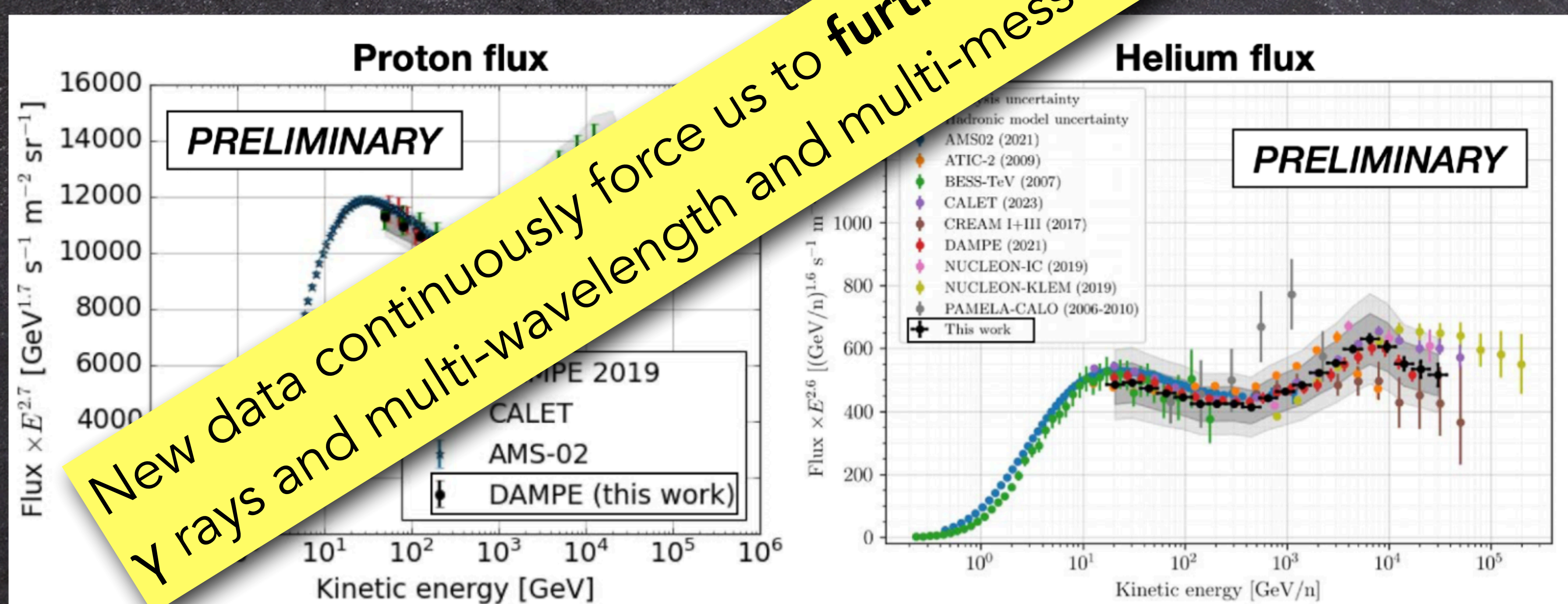
Evoli+ PRD2019; Di Mauro, FD+ 2023

Brief status of CRs

P and He spectra: shifts, breaks and bumps

1. p spectrum is distinctly softer (Δγ ~ 0.1) than He at all energies (shift): Not understood yet
2. R dependence of He, C, O are very similar, all ... break at 300 GV: ~ understood
3. The p and He spectra > TeV show a b... ...ations

Da... ...Ivan De Mitri's talk



New data continuously force us to further theoretical efforts.
γ rays and multi-wavelength and multi-messenger data critical.

See also CALET Coll, PRL 2022 and @ ICRC2023

Bump: probably an effect in acceleration or escape from the sources

Evoli+ PRD2019; Di Mauro, FD+ 2023

[Credit: F. Donato, TAUP23]

Class 3

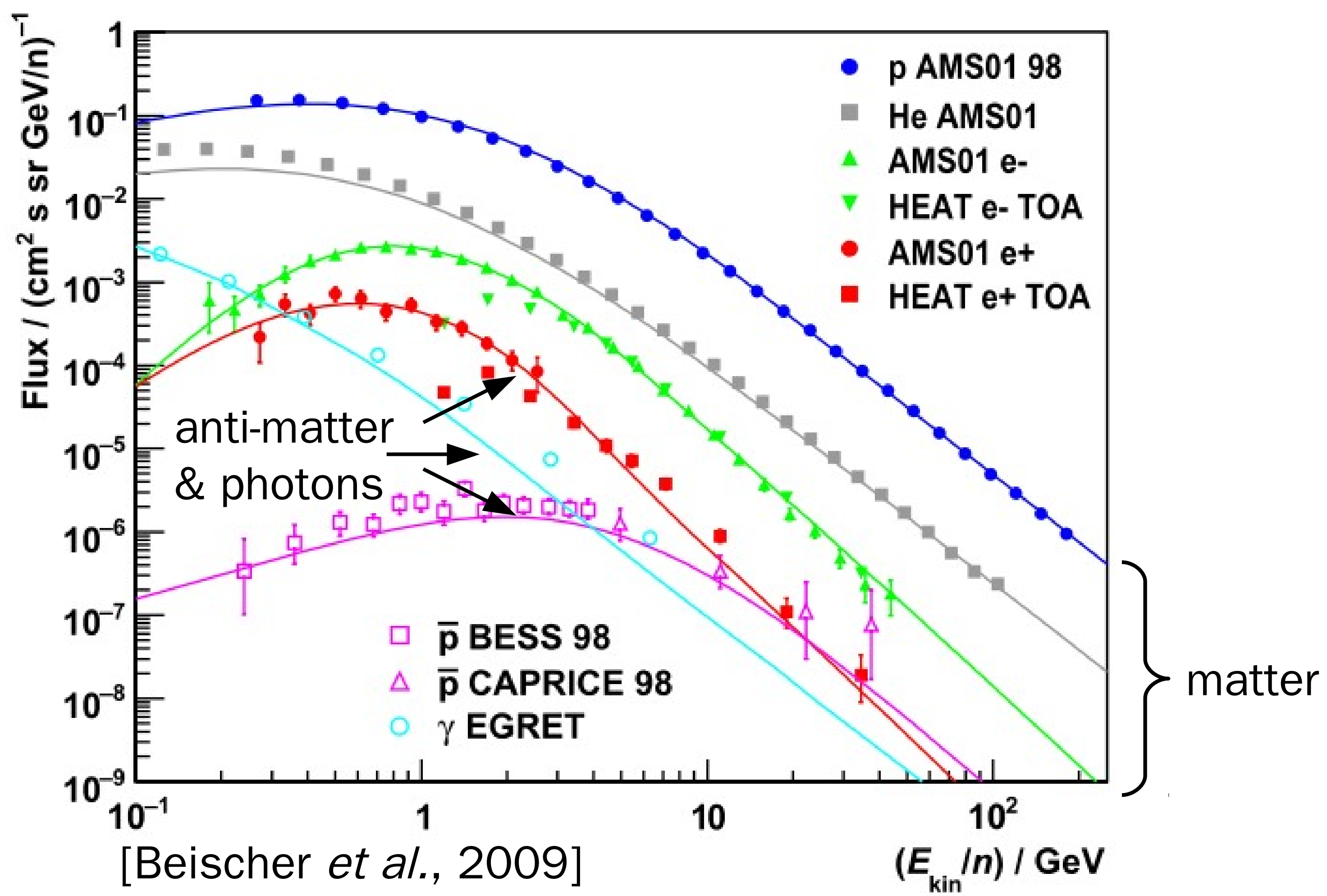
Observations: The gamma-ray sky

PROs:

- **neutral! point back to their source**
- Easier to catch than neutrinos (higher statistics)
- => ***with gamma-rays one can study individual identified sources and different sources classes***

CONs:

Gamma rays are rare (high CR backgrounds)!



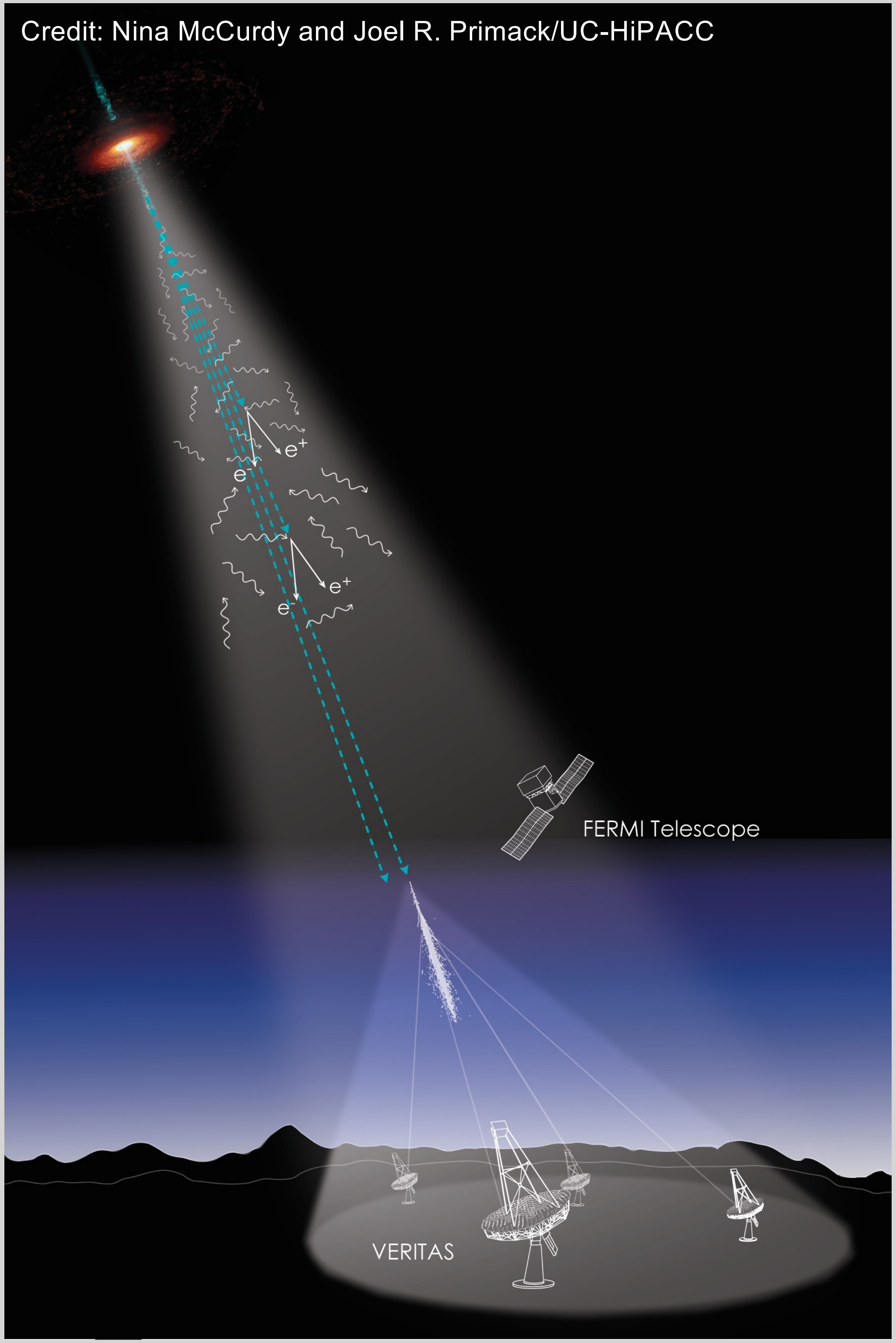
[Beischer *et al.*, 2009]

What tools?

γ's 'blocked' by the atmosphere

→ ***satellites***

(EGRET (1991- 2001), AGILE (2007-), Fermi LAT (2008-))



What tools?

γ's 'blocked' by the atmosphere

→ ***satellites***

(EGRET (1991- 2001), AGILE (2007-), Fermi LAT (2008-))

or ground based

Imaging Atmospheric Cherenkov Telescopes

(…,H.E.S.S. (2002 -), MAGIC (2004 -), VERITAS (2007 -))

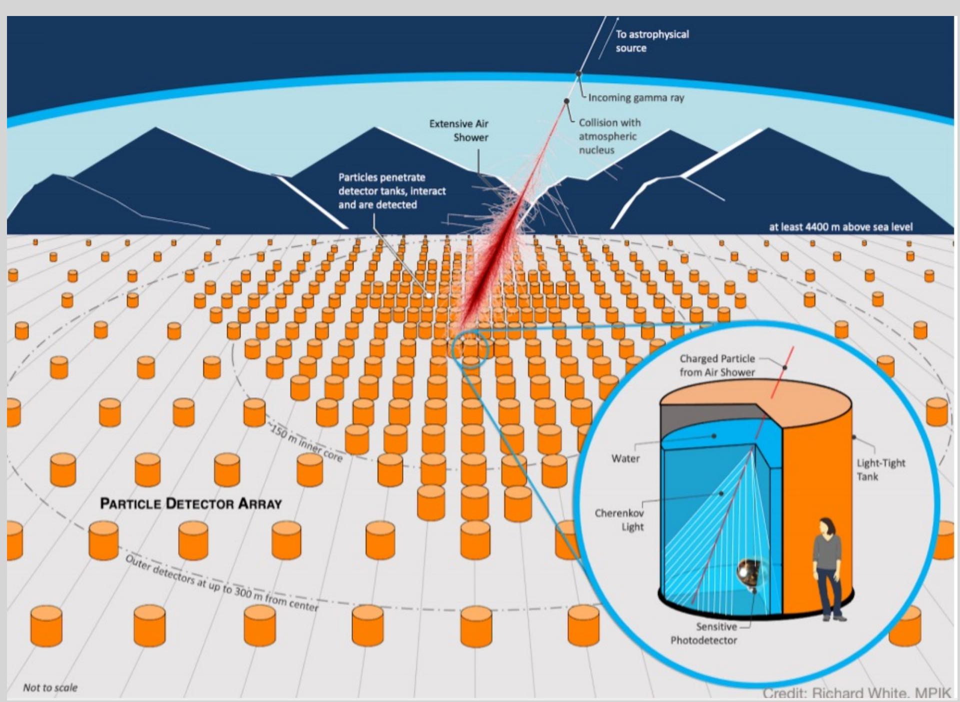
Water Cherenkov detectors

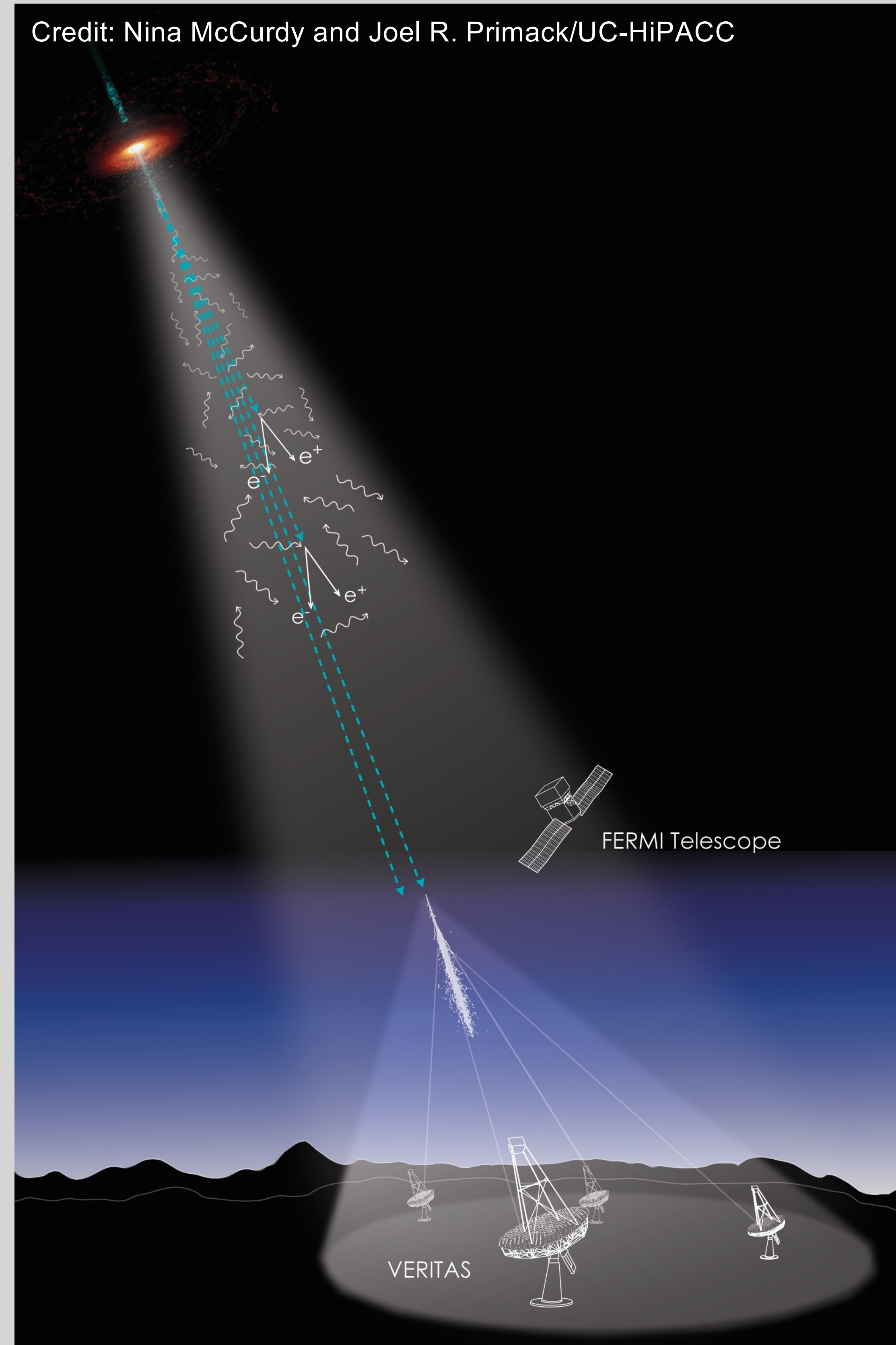
('observing Universe with a bucket of water')

(…, HAWC (2011 -))

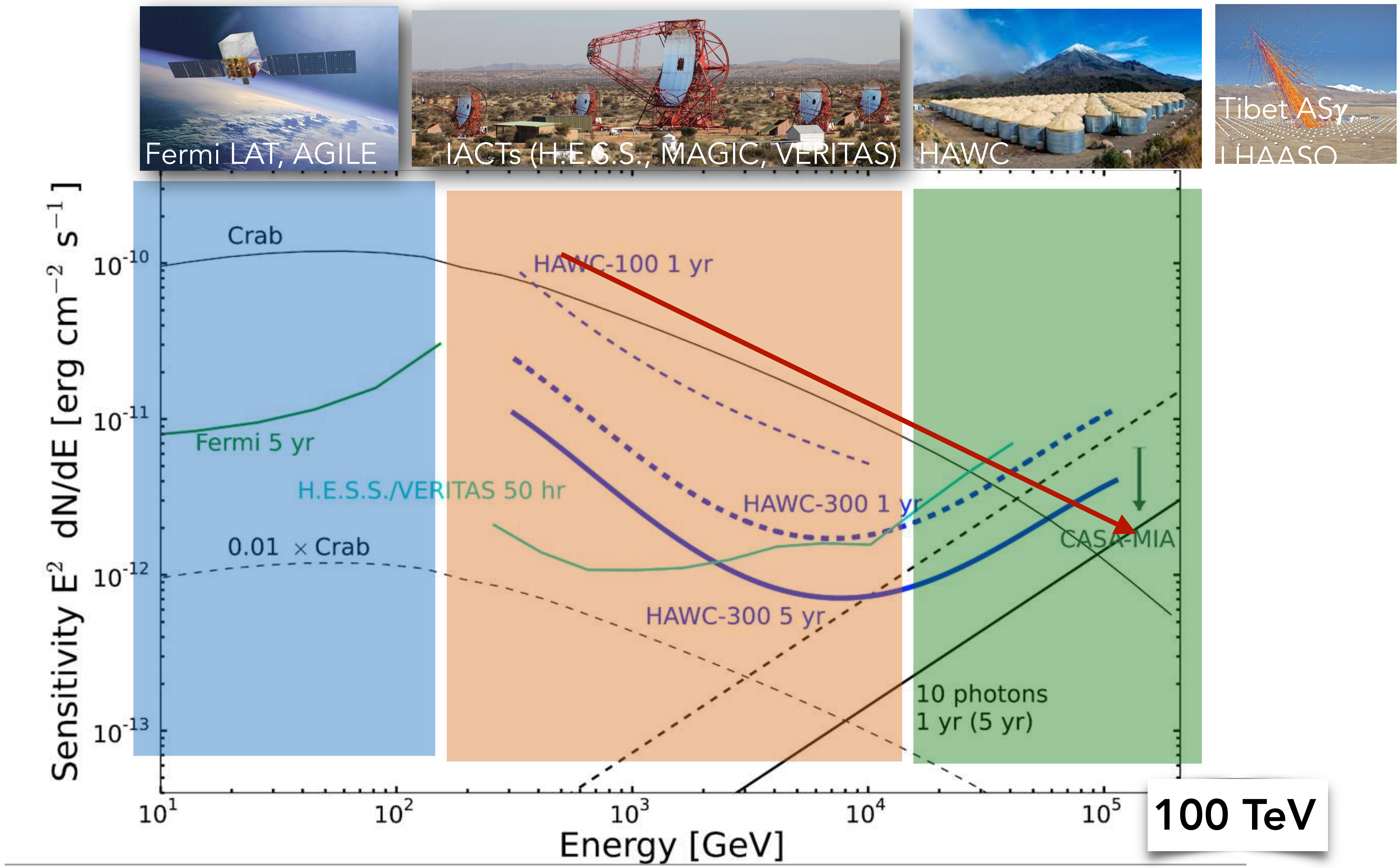
Other techniques (scintilators) + combinations

(Tibet AS**γ** (1990-), LHASSO (2021 -))



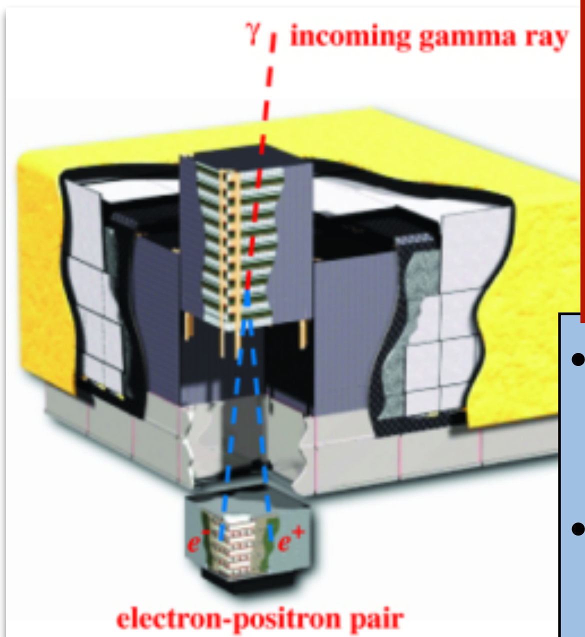


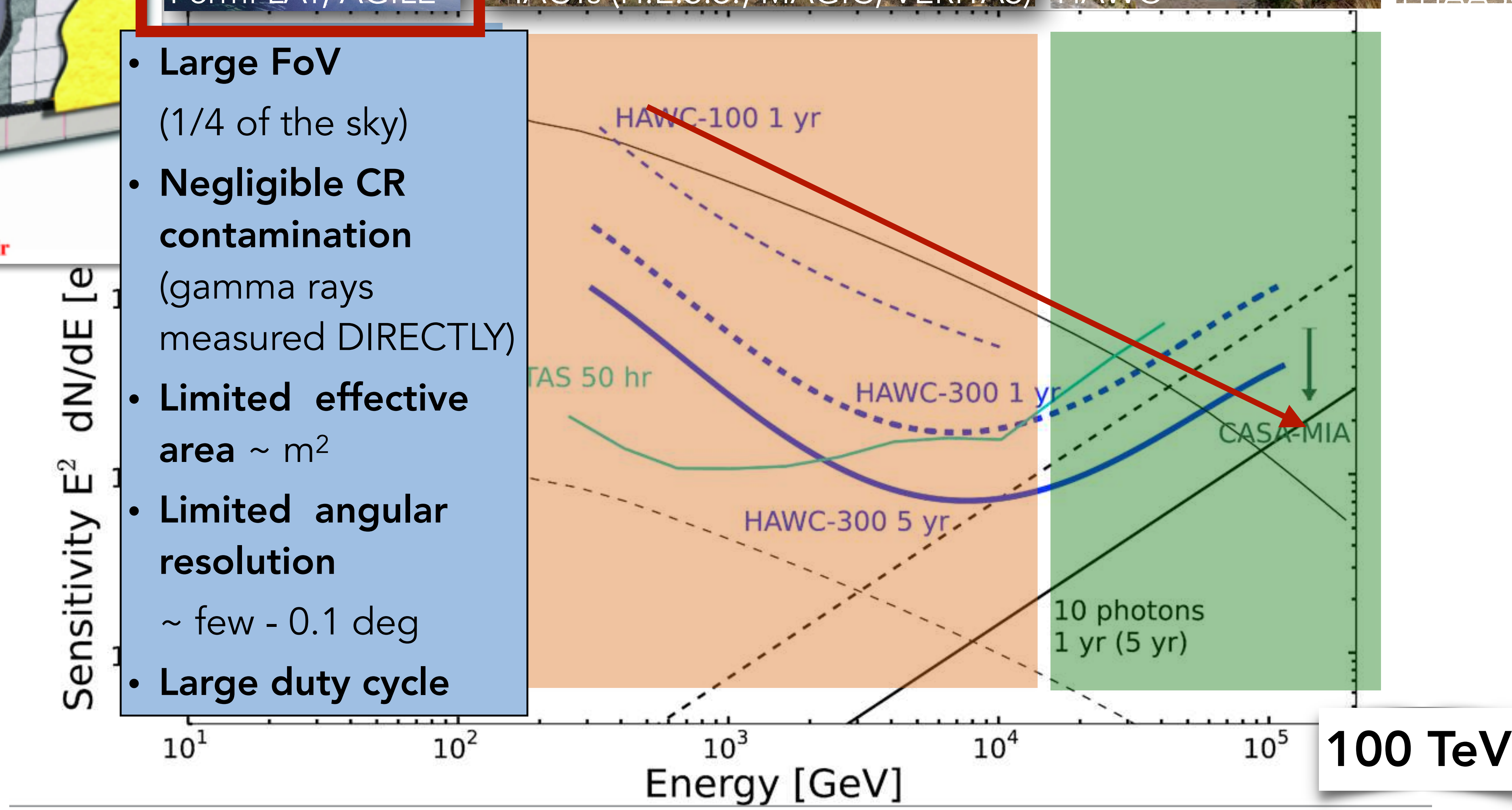
What tools?



Fermi LAT, AGILE
IACTs (H.E.S.S., MAGIC, VERITAS)
HAWC
Tibet ASγ,
LHAASO
Sensitivity E² dN/dE [erg cm⁻² s⁻¹]
Crab
HAWC-100 1 yr
Fermi 5 yr
H.E.S.S./VERITAS 50 hr
HAWC-300 1 yr
0.01 × Crab
CASA-MIA
HAWC-300 5 yr
10 photons
1 yr (5 yr)
Energy [GeV]
100 TeV

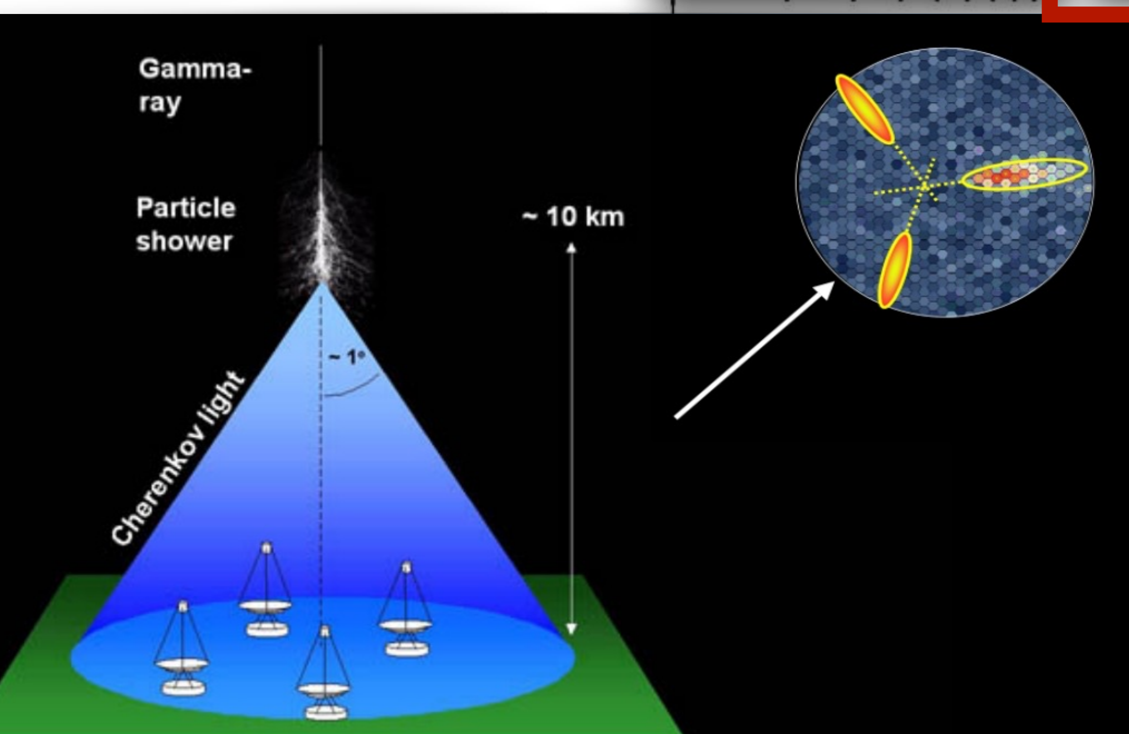
What tools?



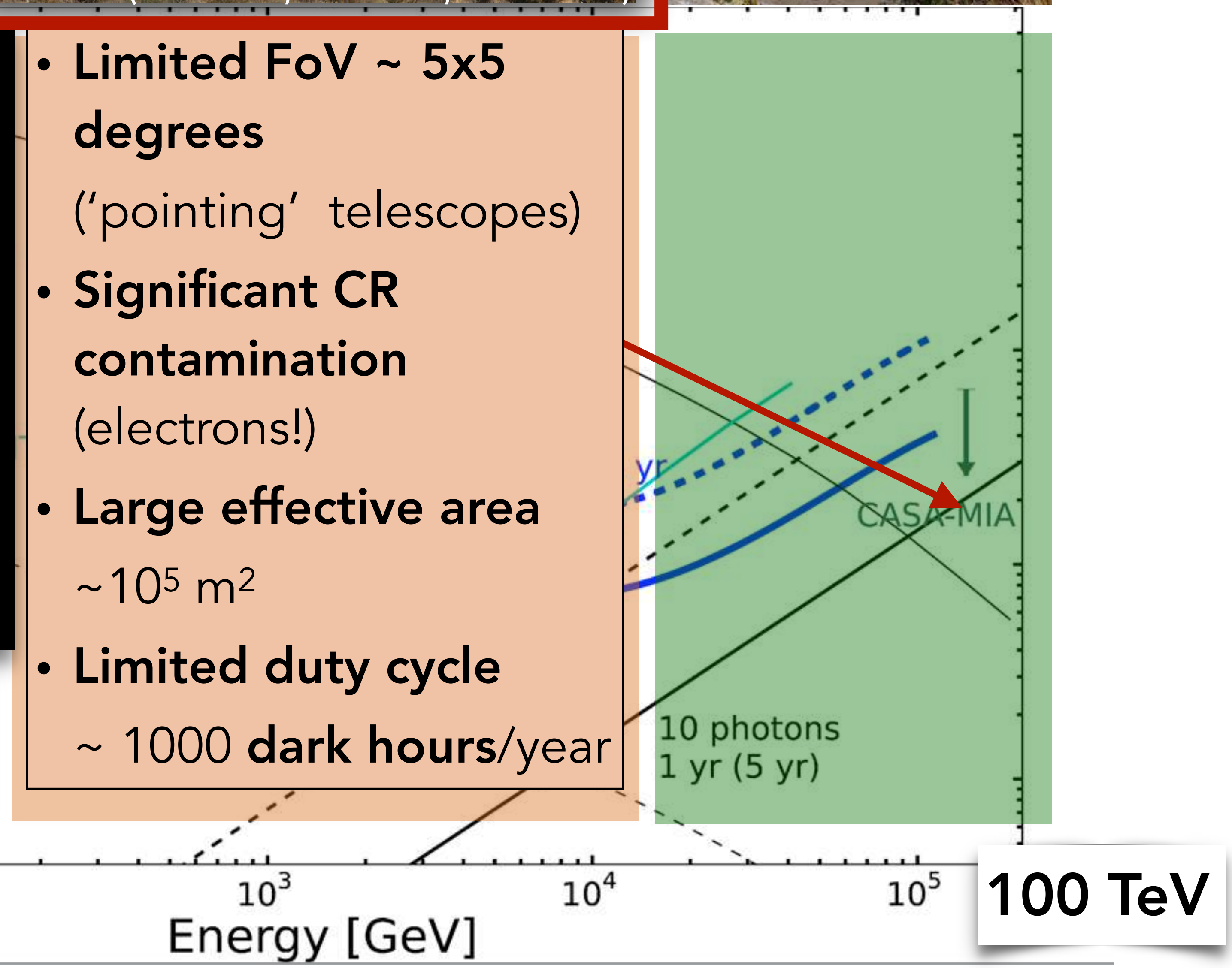


- **Large FoV**
  (1/4 of the sky)
- **Negligible CR contamination**
  (gamma rays measured DIRECTLY)
- **Limited effective area** ~ m²
- **Limited angular resolution**
  ~ few - 0.1 deg
- **Large duty cycle**

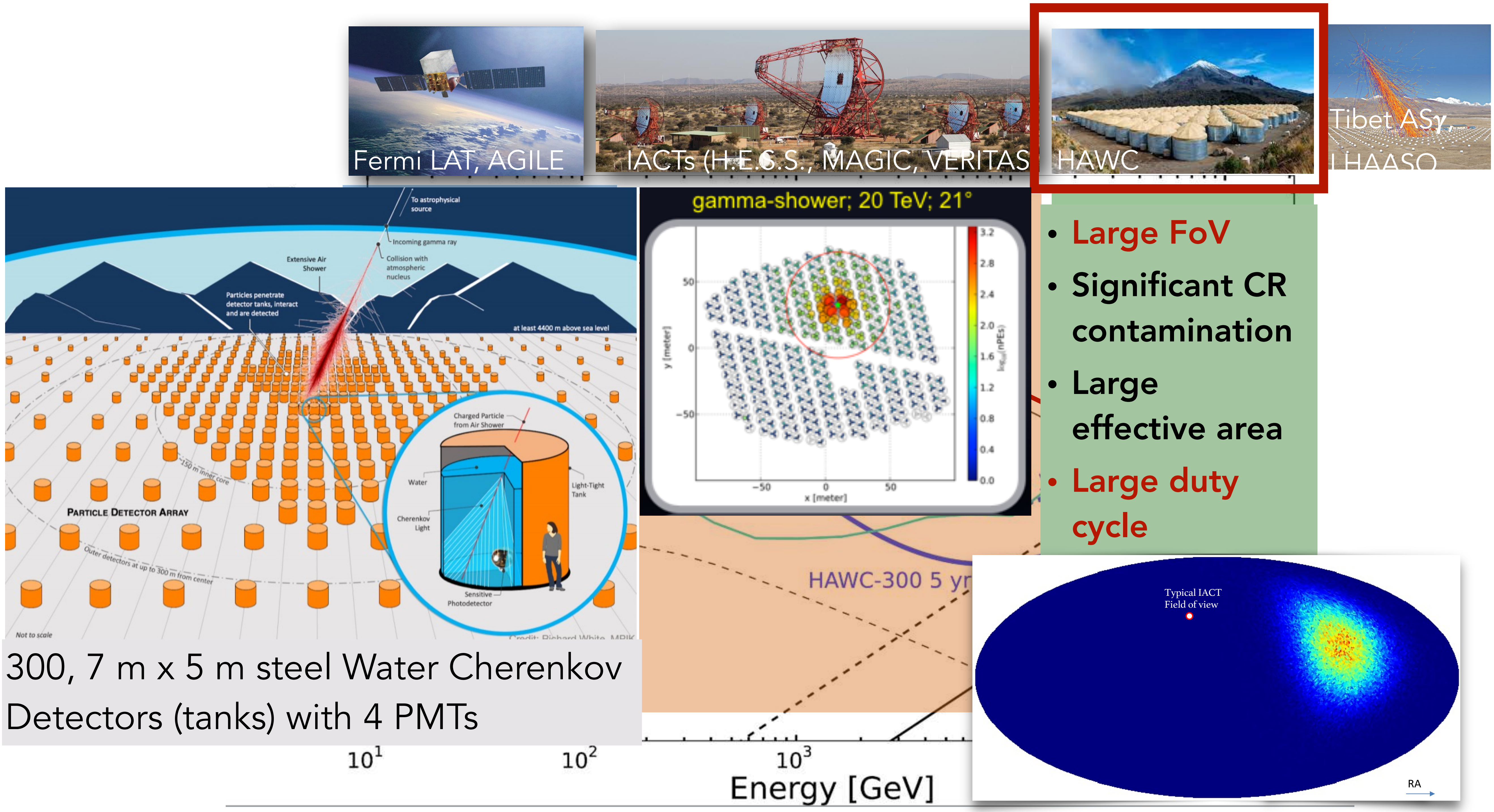
What tools?



- **Limited FoV ~ 5x5 degrees** ('pointing' telescopes)
- **Significant CR contamination** (electrons!)
- **Large effective area** ~10^5 m^2
- **Limited duty cycle** ~ 1000 **dark hours**/year

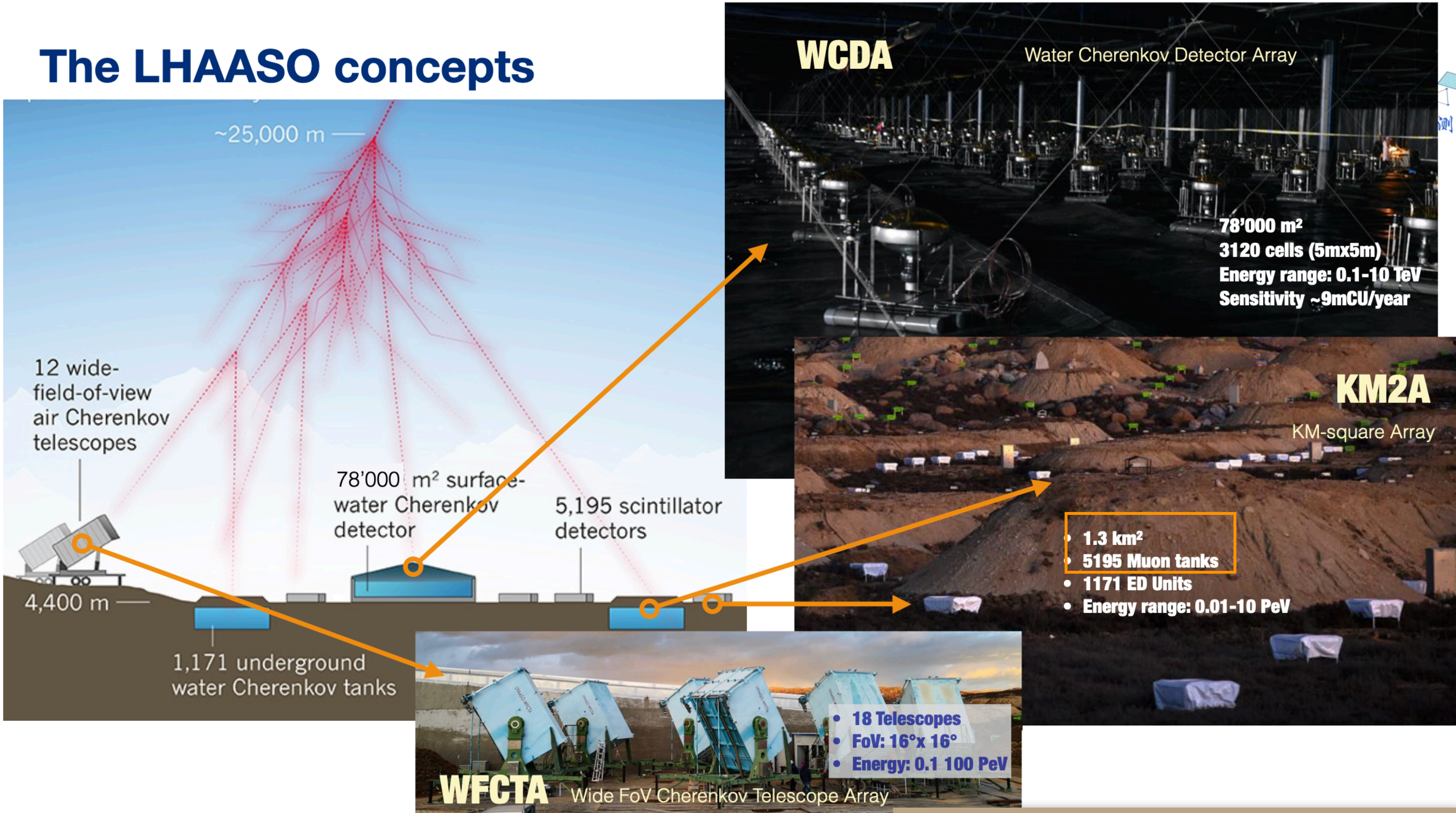


What tools?



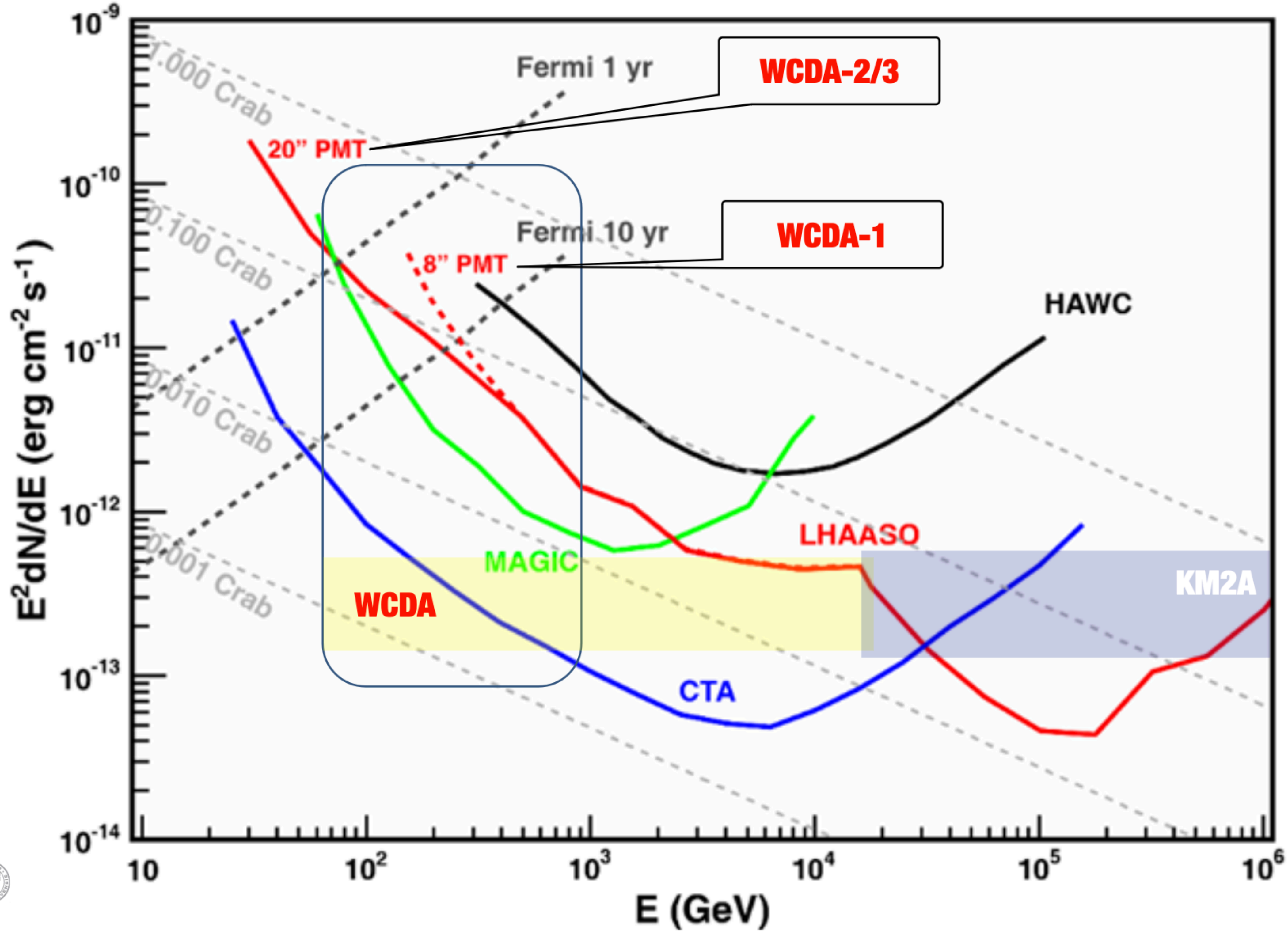
Fermi LAT, AGILE
IACTs (H.E.S.S., MAGIC, VERITAS
HAWC
Tibet ASγ,
LHAASO
To astrophysical source
Incoming gamma ray
Extensive Air Shower
Collision with atmospheric nucleus
Particles penetrate detector tanks, interact and are detected
at least 4400 m above sea level
Particle Detector Array
150 m inner core
Outer detectors at up to 300 m from center
Charged Particle from Air Shower
Water
Cherenkov Light
Light-Tight Tank
Sensitive Photodetector
Not to scale
300, 7 m x 5 m steel Water Cherenkov Detectors (tanks) with 4 PMTs
gamma-shower; 20 TeV; 21°
y [meter]
x [meter]
• Large FoV
• Significant CR contamination
• Large effective area
• Large duty cycle
HAWC-300 5 yr
Typical IACT Field of view
RA
10^1
10^2
10^3
Energy [GeV]

The LHAASO concepts

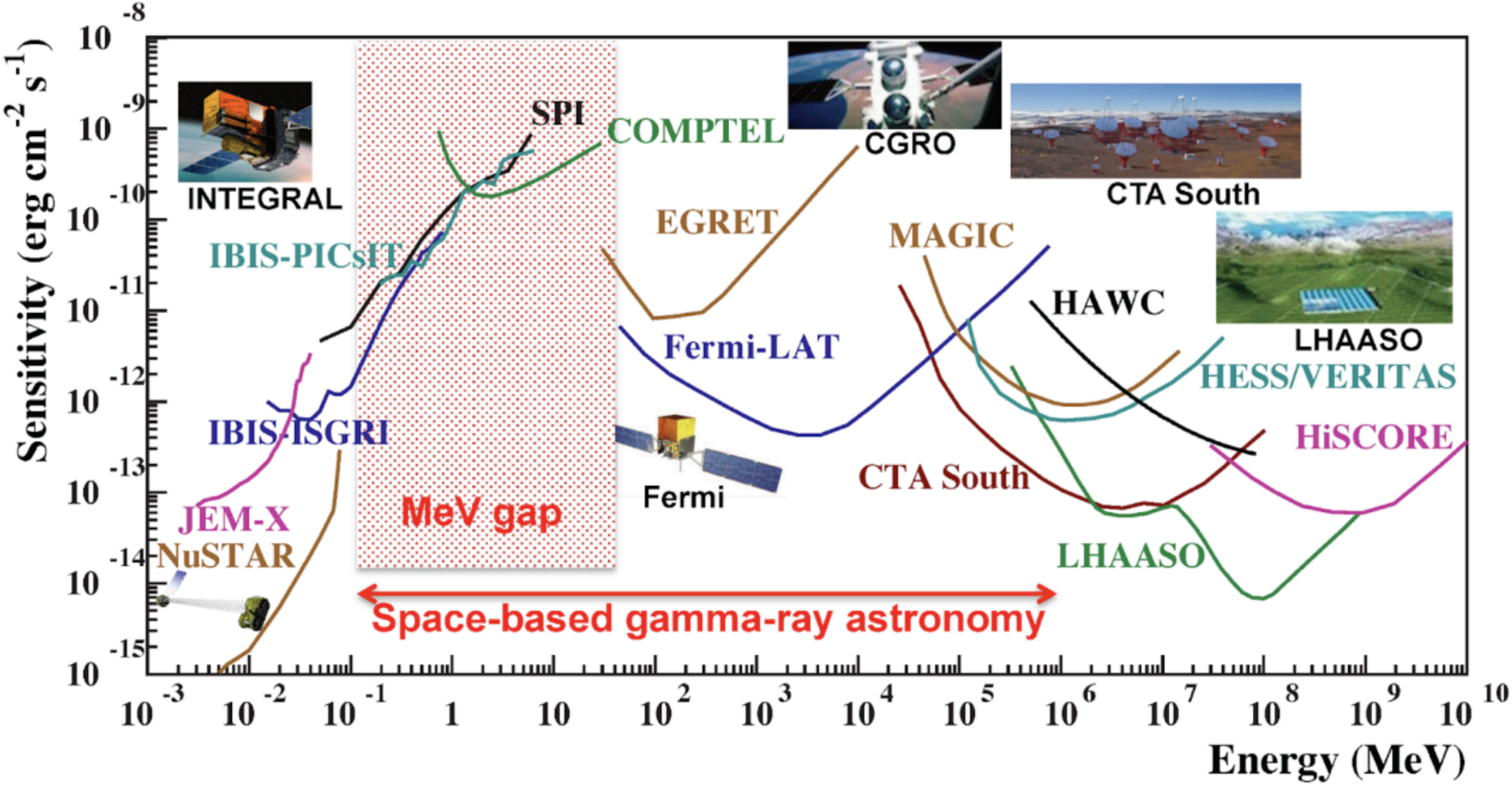


km2A —> PeV
essentially a background-free sample of gamma rays above 50 TeV

LHAASO Expected Sensitivity



Future?

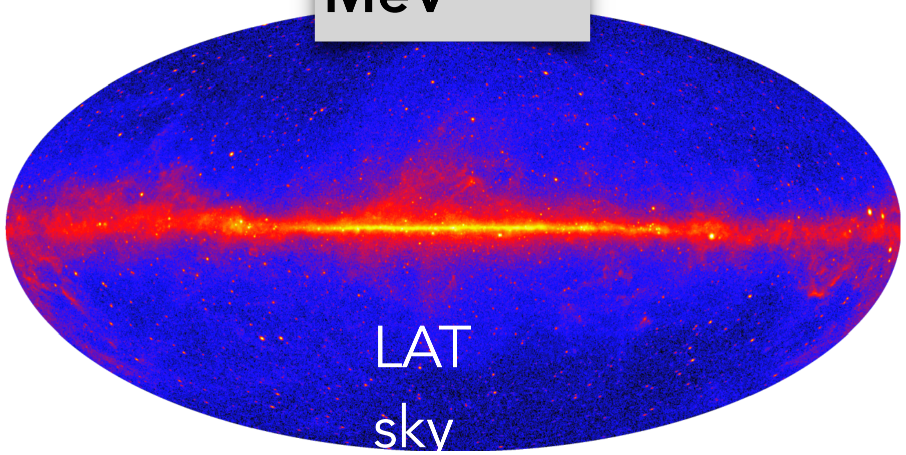


Astrogam?

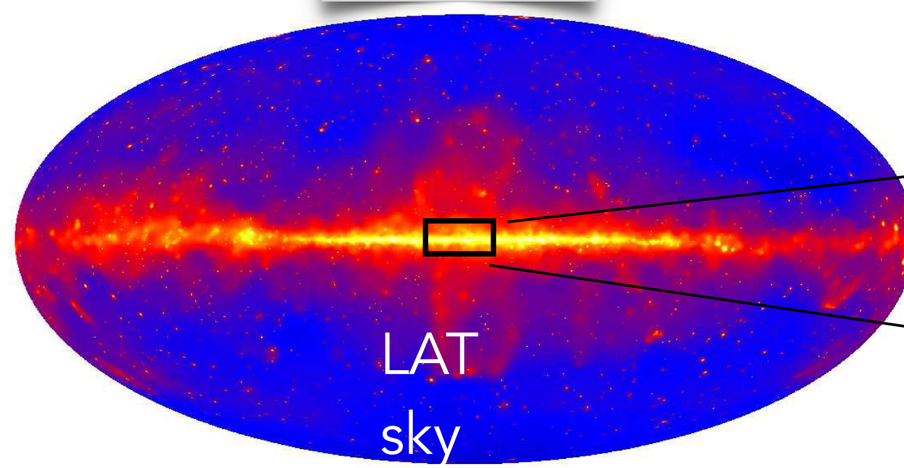
CTA

GeV vs TeV sky

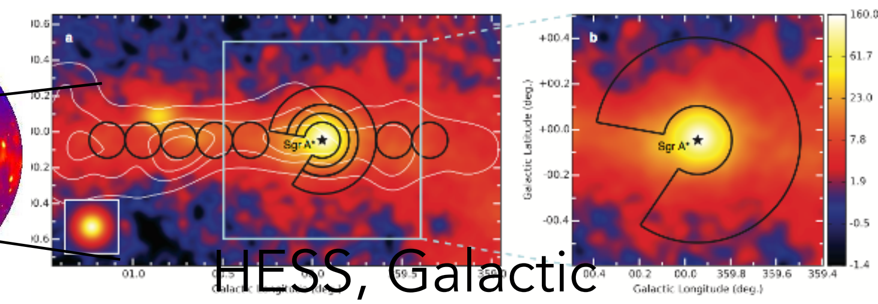
>300 MeV



>10 GeV

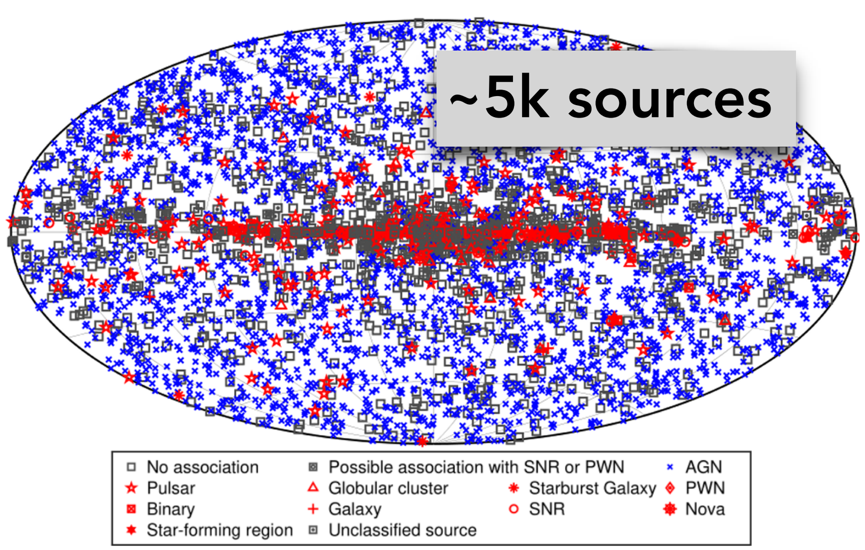


>~100 GeV



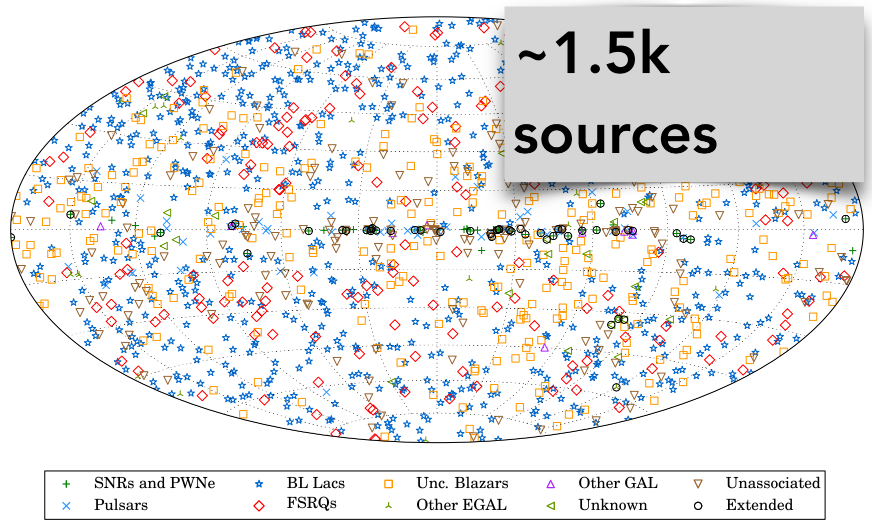
HESS, Galactic center Ridge

~5k sources



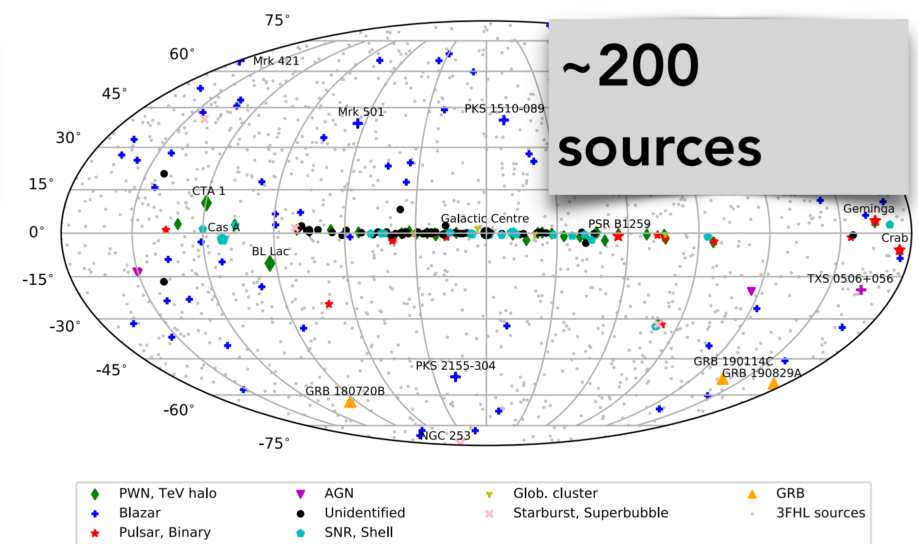
LAT source catalogue, >300 MeV (4FGL)

~1.5k sources



LAT source catalogue, **>10 GeV** (3FHL)

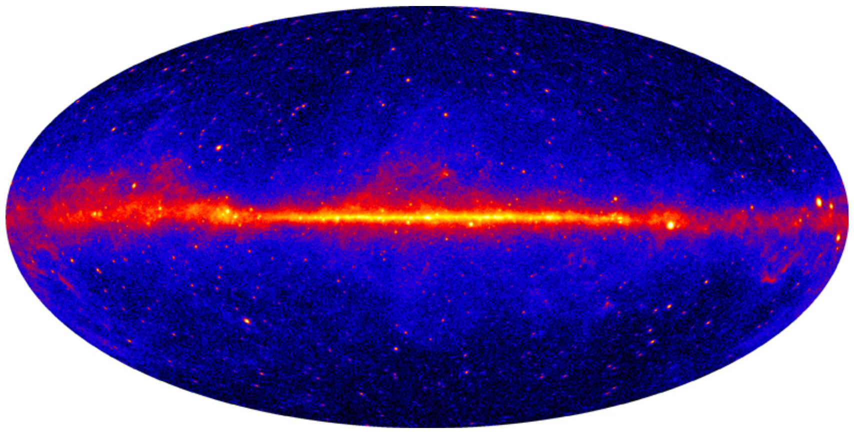
~200 sources



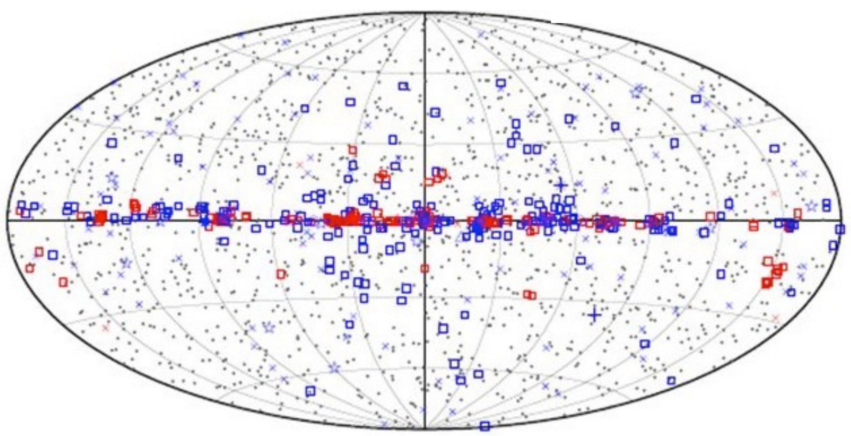
TeVCat, 2019

The 'GeV' sky

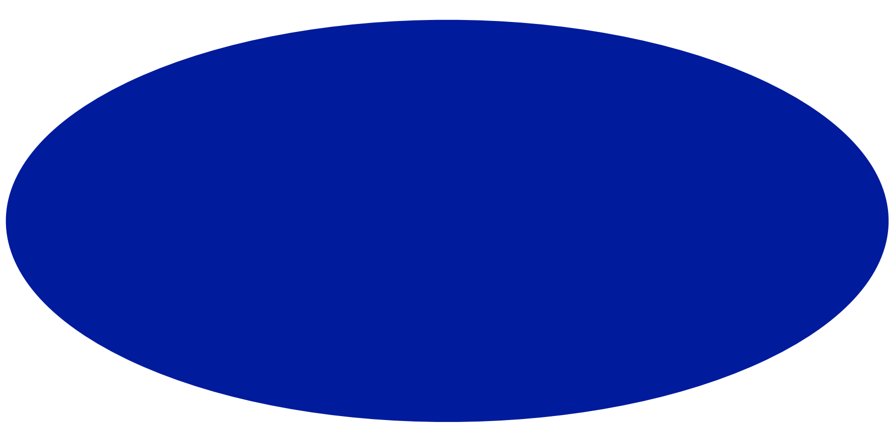
Diffuse emission from our Galaxy



Point sources



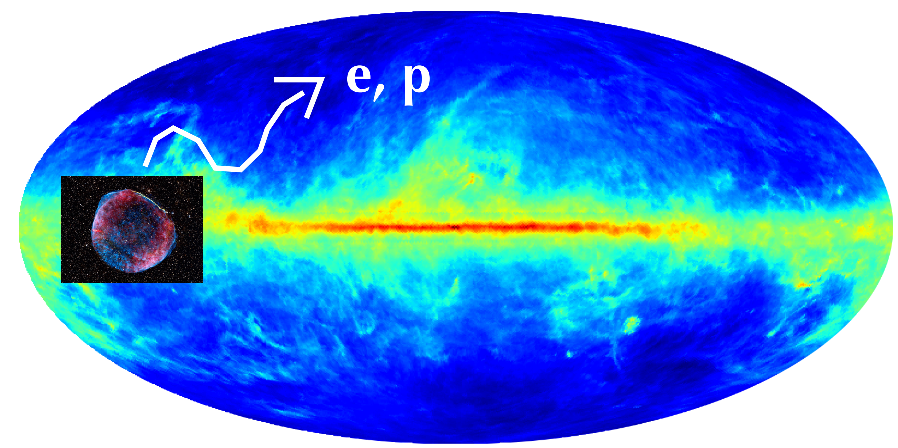
Isotropic emission

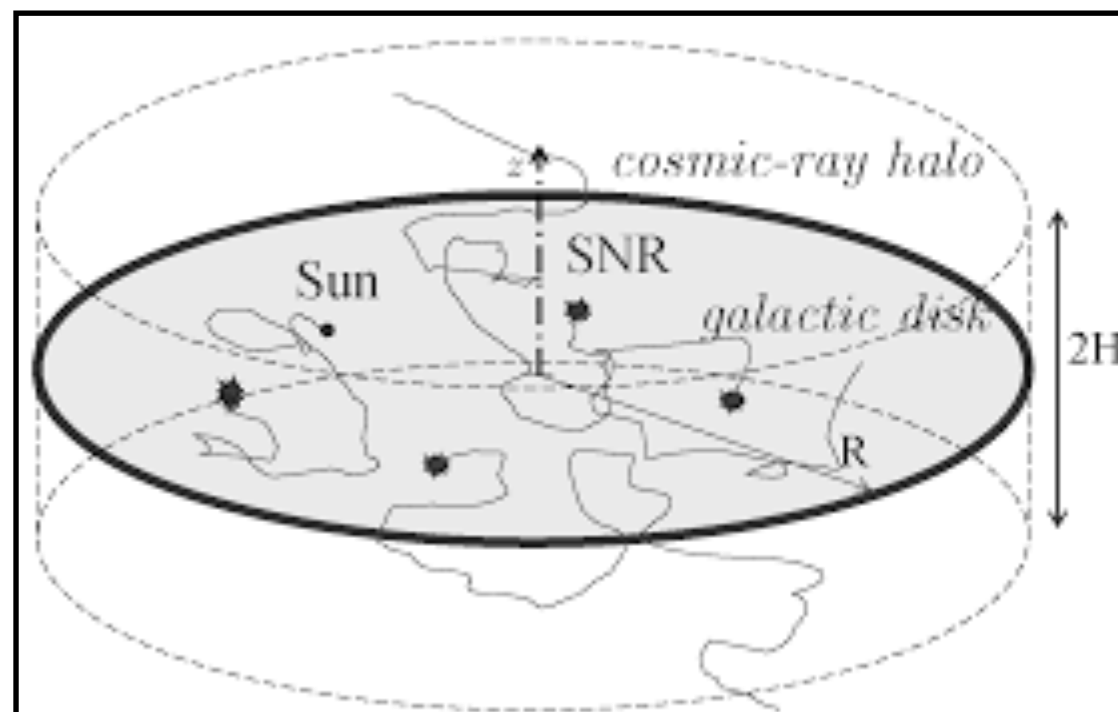


90% of the LAT photons!

cosmic rays+interstellar medium

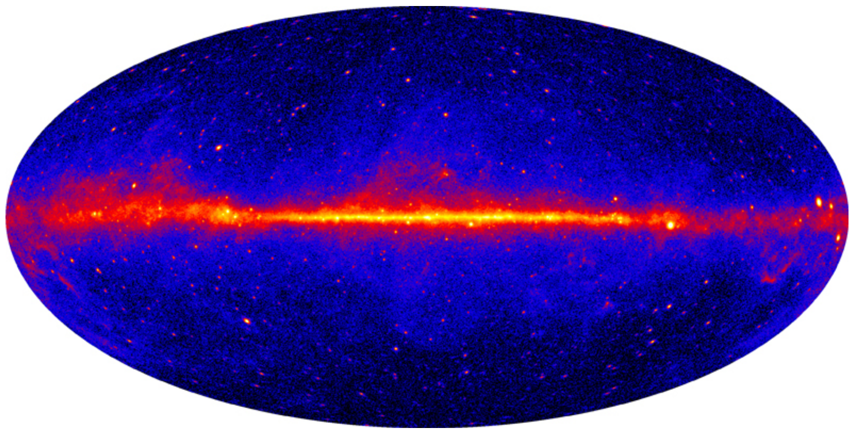
Allow us to probe CR distribution in 2D/3D!



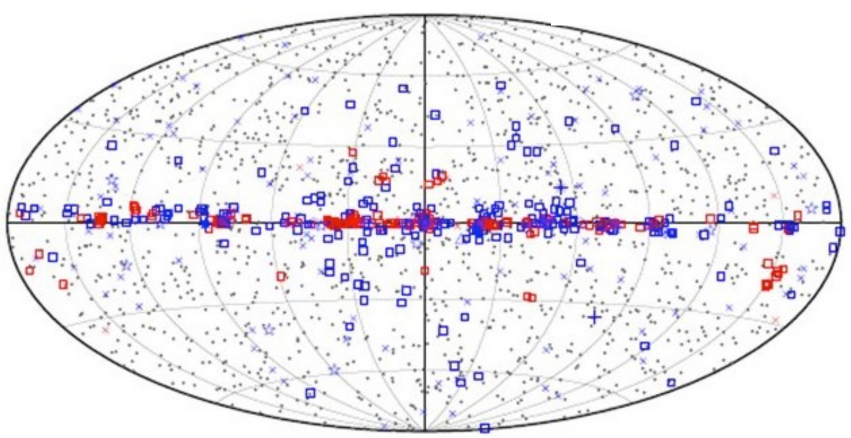


The ‘GeV’ sky

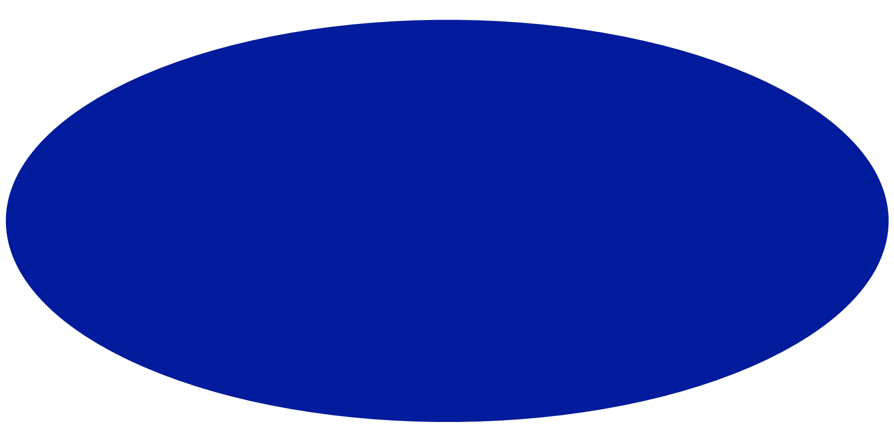
Diffuse emission from our Galaxy



Point sources



Isotropic emission



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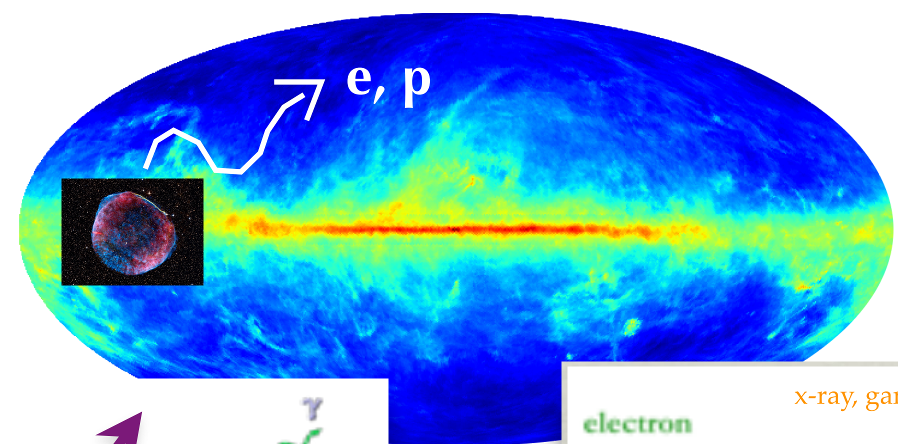
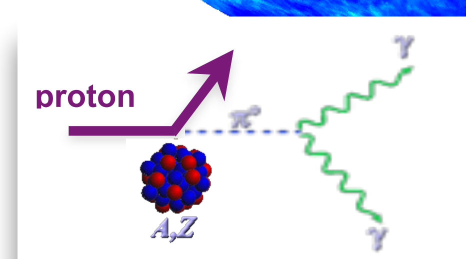
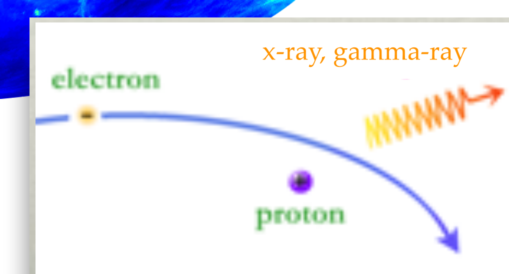


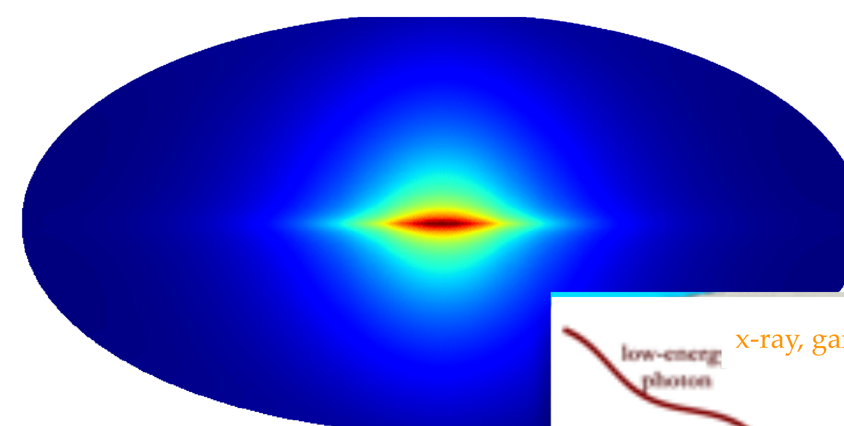


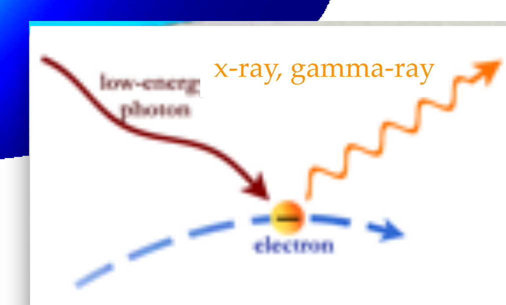
π^0 decay



bremsstrahlung

+

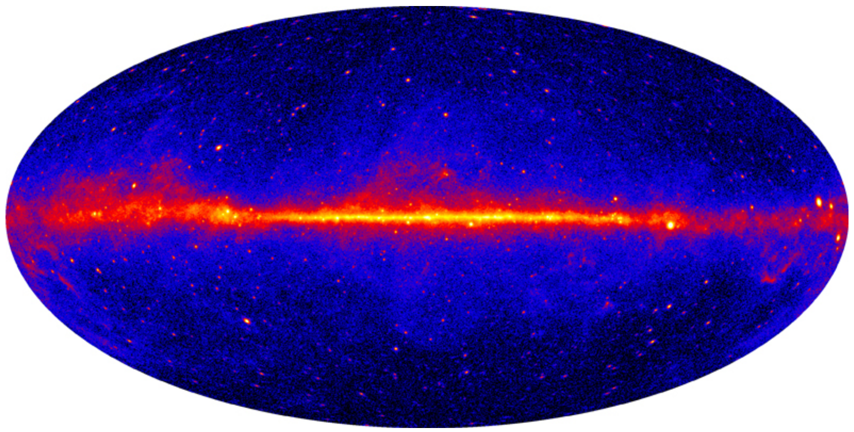




inverse Compton

The 'GeV' sky

Diffuse emission from our Galaxy



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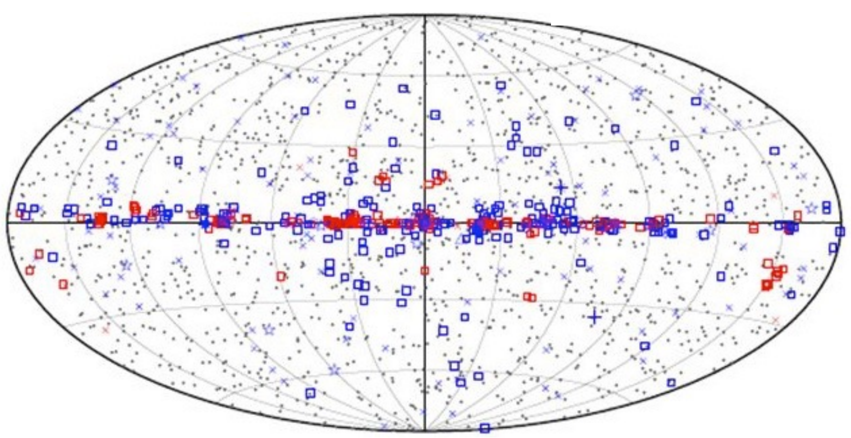
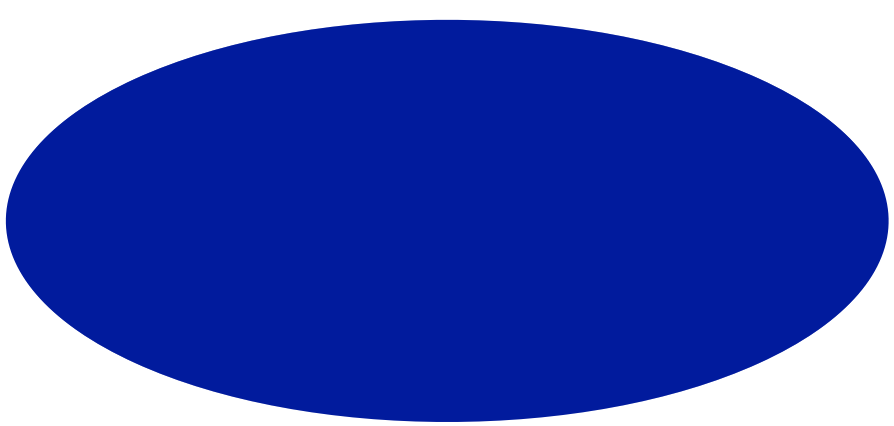


Isotropic emission



90% of the LAT photons!

cosmic rays+interstellar medium

→Challenges: need to be model:

— source distribution from tracers of gamma ray sources (SNRs, PSRs)

— gas densities from atomic transition lines - 3D reconstructions needed

— IC: need to model ISRF

— Galactic magnetic fields…

$$\frac{\partial \psi(\vec{r},p,t)}{\partial t} = q(\vec{r},p)$$ sources (SNR, nuclear reactions…)

diffusion $$+\vec{\nabla}\cdot[D_{xx}\vec{\nabla}\psi - \vec{V}\psi]$$ convection

diffusive reacceleration $$+\frac{\partial}{\partial p}\left[p^2 D_{pp}\frac{\partial}{\partial p}\frac{\psi}{p^2}\right]$$

E-loss $$-\frac{\partial}{\partial p}\left[\frac{dp}{dt}\psi - \frac{1}{3}p\vec{\nabla}\cdot\vec{V}\psi\right]$$ convection

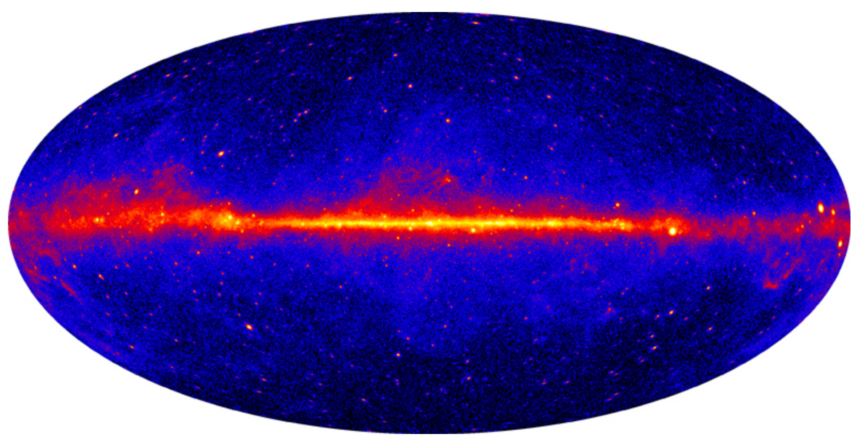
fragmentation $$-\frac{\psi}{\tau_f} - \frac{\psi}{\tau_d}$$ radioactive decay

$\psi(\mathbf{r},p,t)$ – density per total momentum

Sophisticated numerical solvers: GALPROP, DRAGON.

The 'GeV' sky

Diffuse emission from our Galaxy



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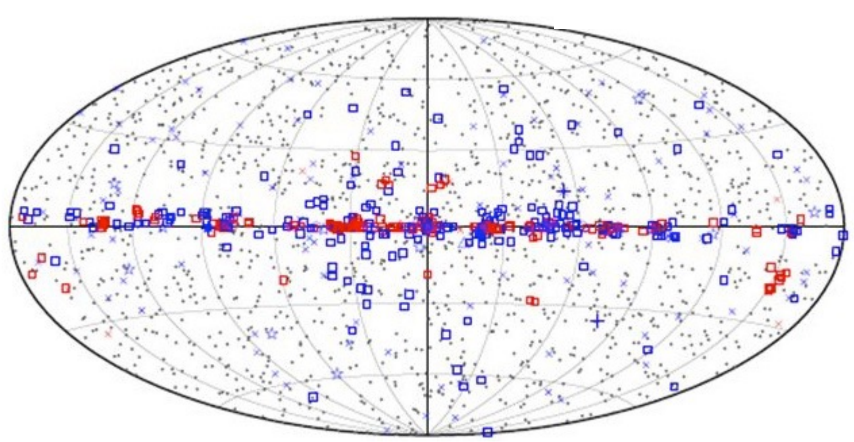
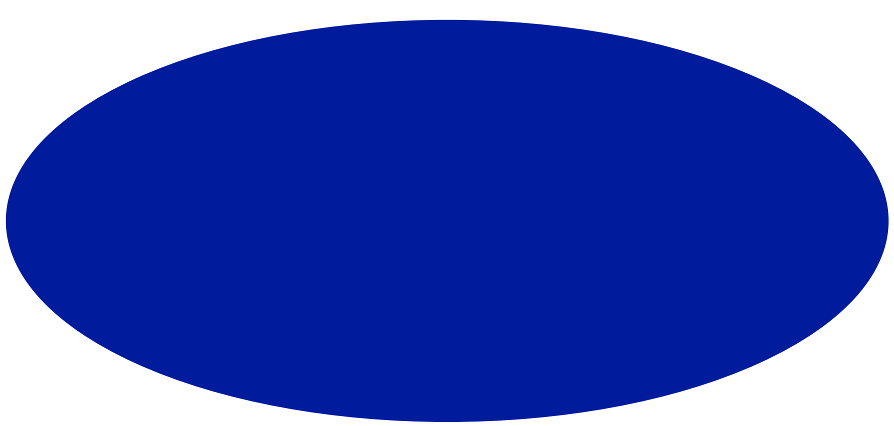


Isotropic emission



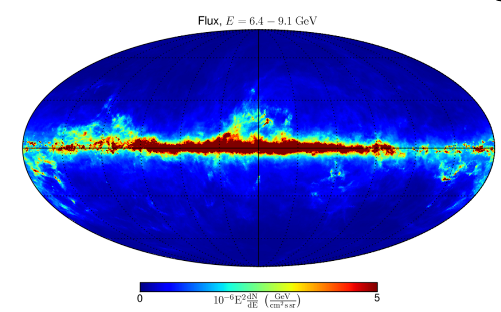
90% of the LAT photons!

cosmic rays+interstellar medium

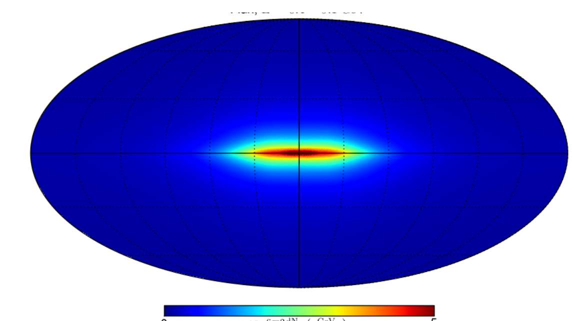
— Note pion and bremsstrahlung emission follow gas distribution

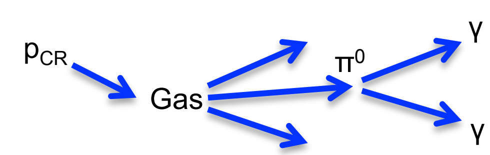
— IC is distributed as interstellar radiation field

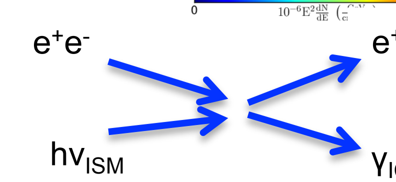
π^0 and bremsstrahlung

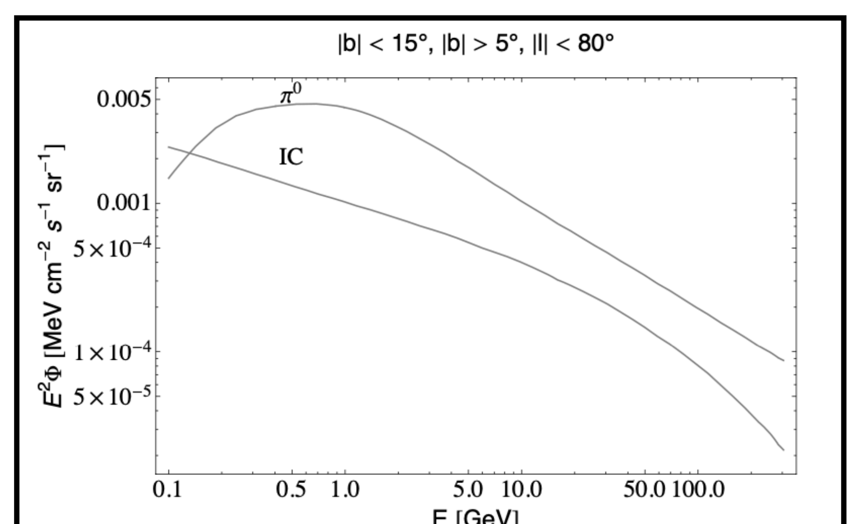


Inverse Compton



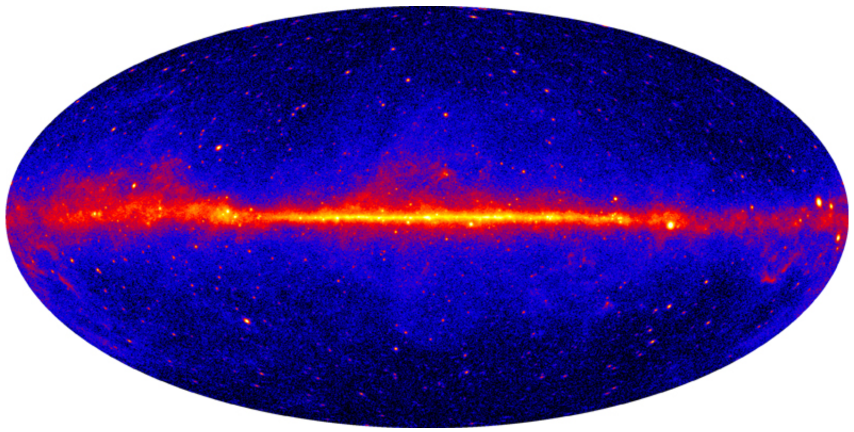






The 'GeV' sky

Diffuse emission from our Galaxy



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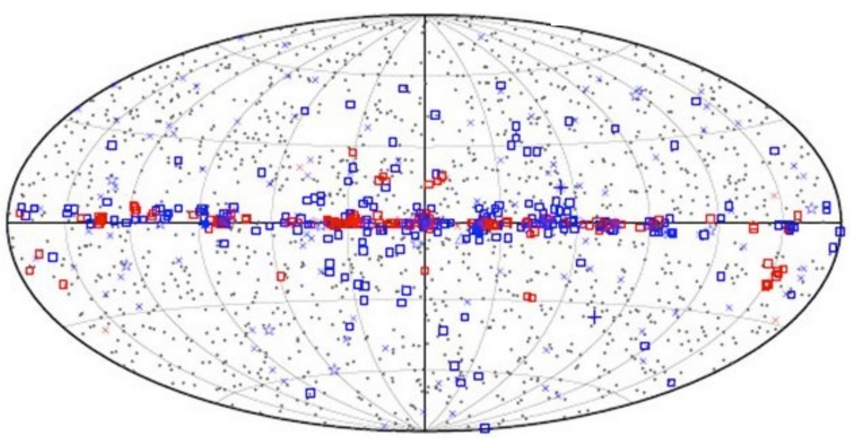
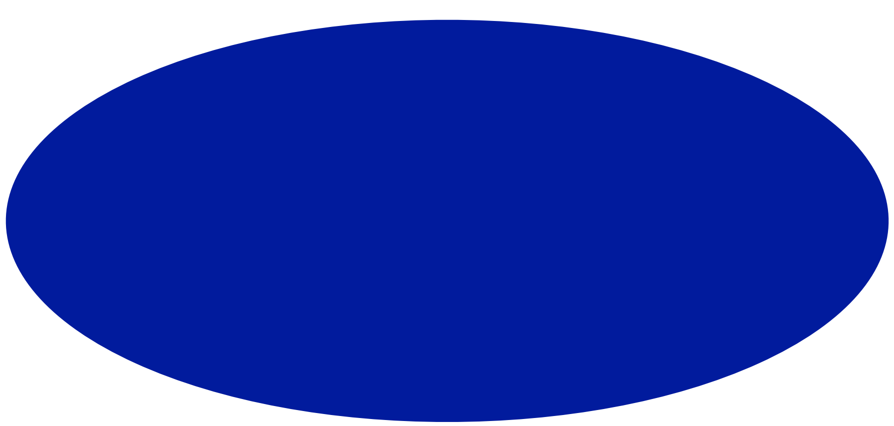


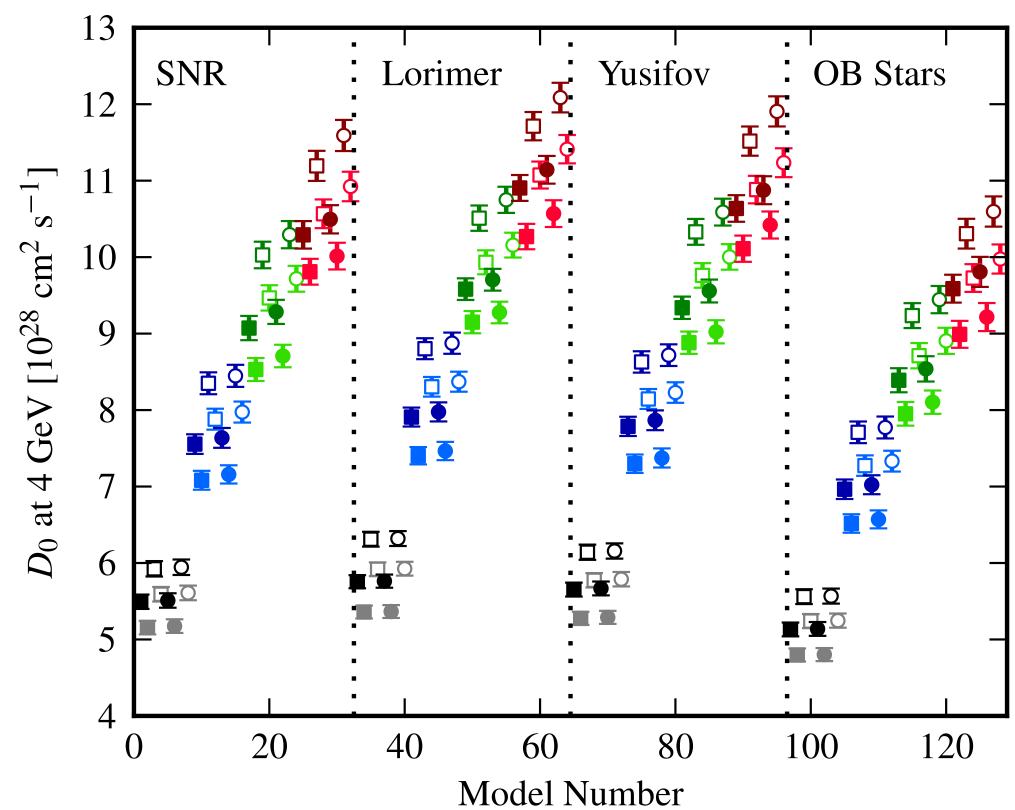
Isotropic emission



90% of the LAT photons!

cosmic rays+interstellar medium

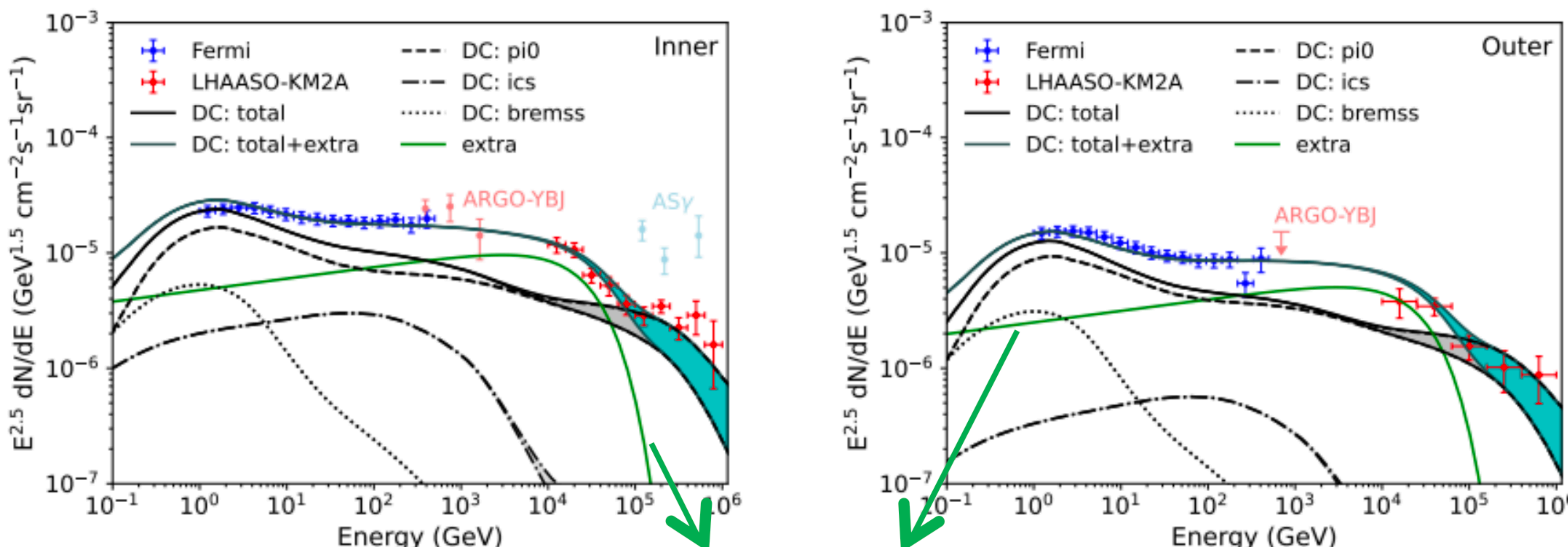
— can be used (together with direct CR measurement) to constrain parameters of the CR distribution and interstellar medium



Use gamma-rays to constrain CR diffusion equation parameters

Having large field of view beneficial for detection of diffuse emission

- Fermi LAT
- **LHAASO recently claimed detection in the TeV range**



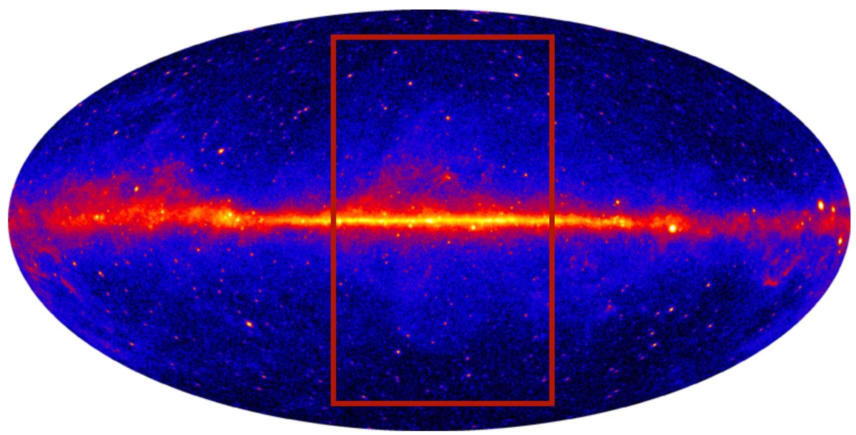
$\propto E^{-2.40} \exp\left(-E/30\ \mathrm{TeV}\right)$

- SEDs of GDE in two regions
- Higher than prediction, contamination of sources?

[Credit: Z. Cao, TAUP23]

The 'GeV' sky

Diffuse emission from our Galaxy



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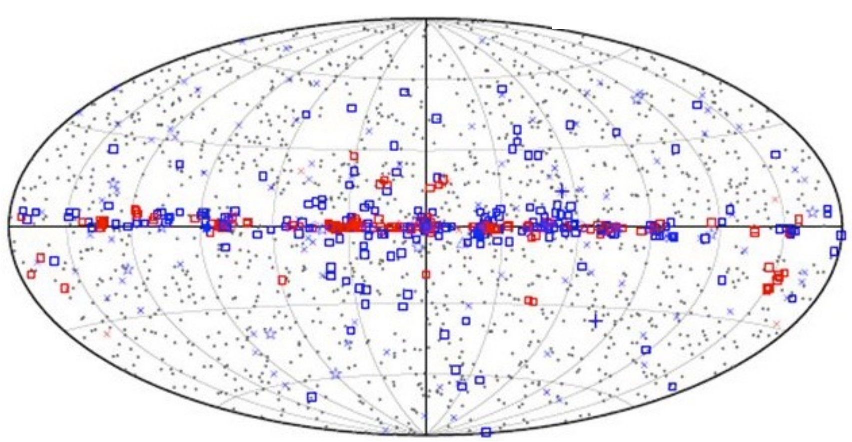

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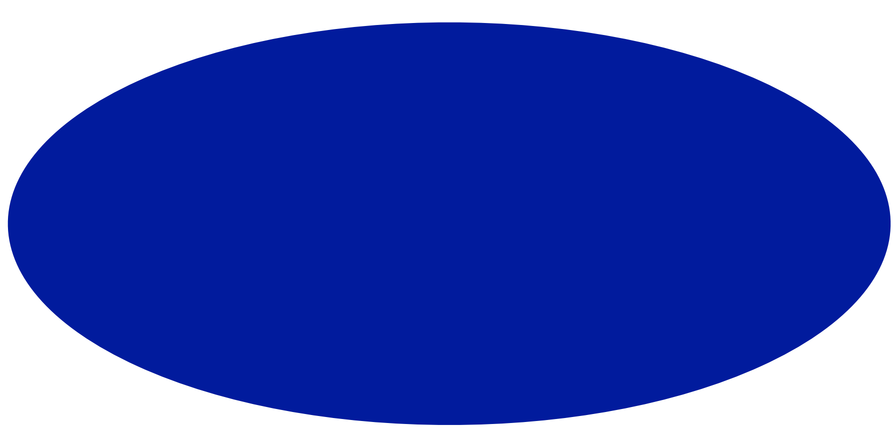
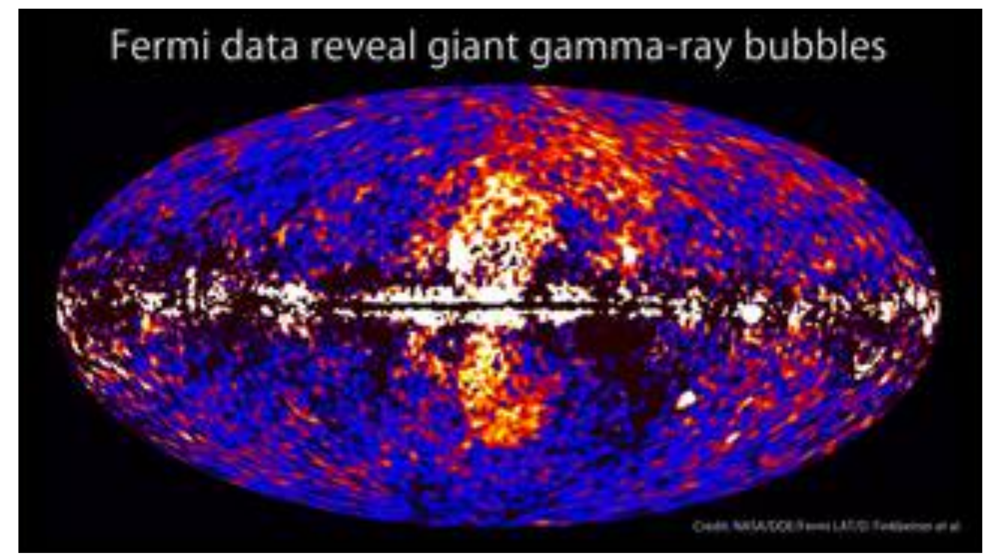
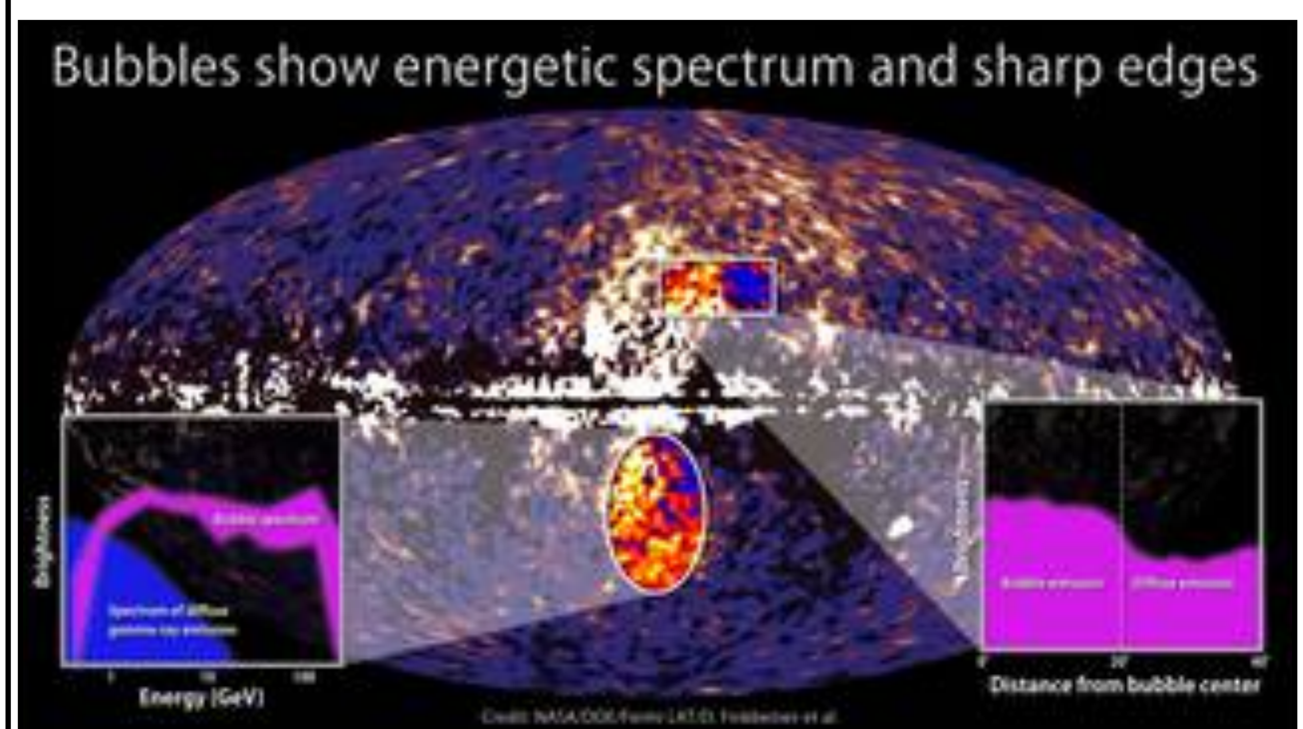


The Fermi bubbles

After removing the interstellar emission background, large structured emanating from the Galactic center with hard spectrum.





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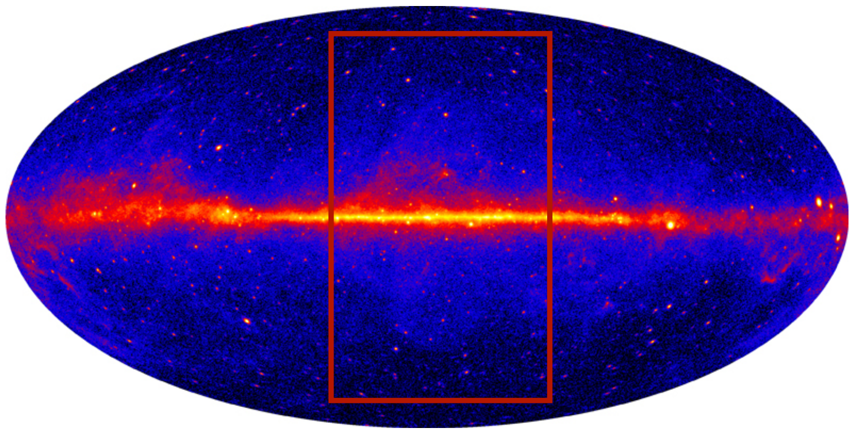

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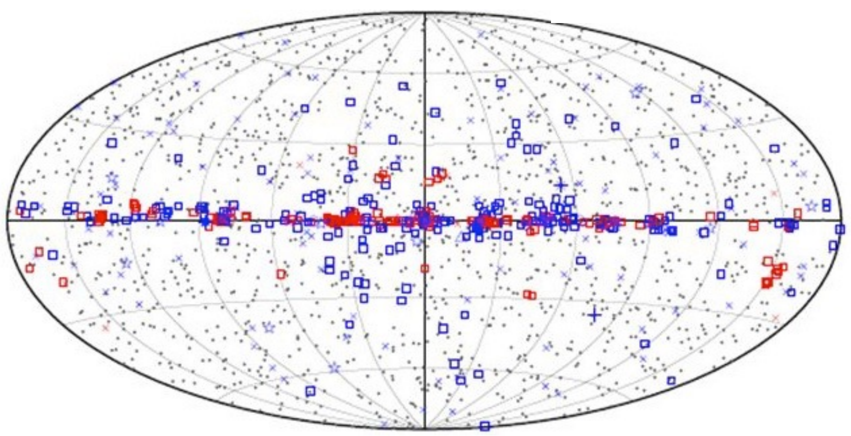

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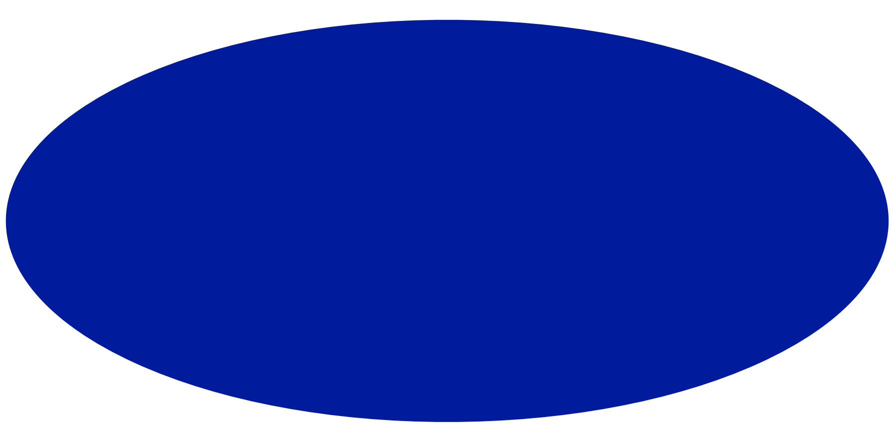

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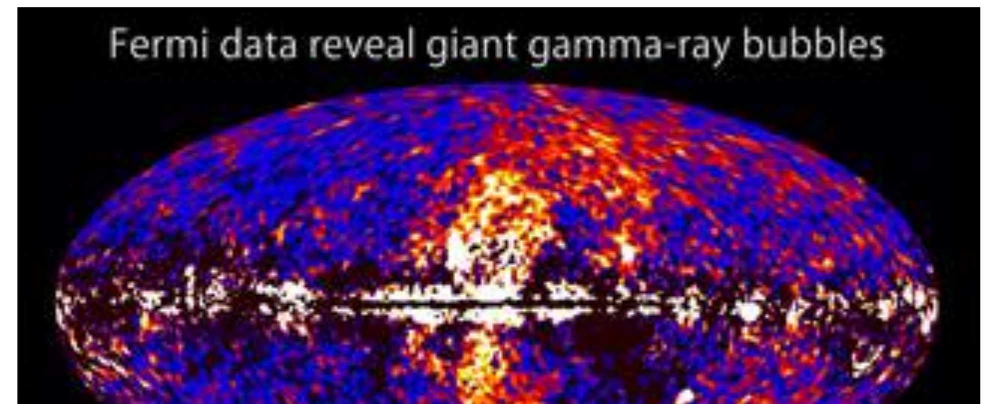
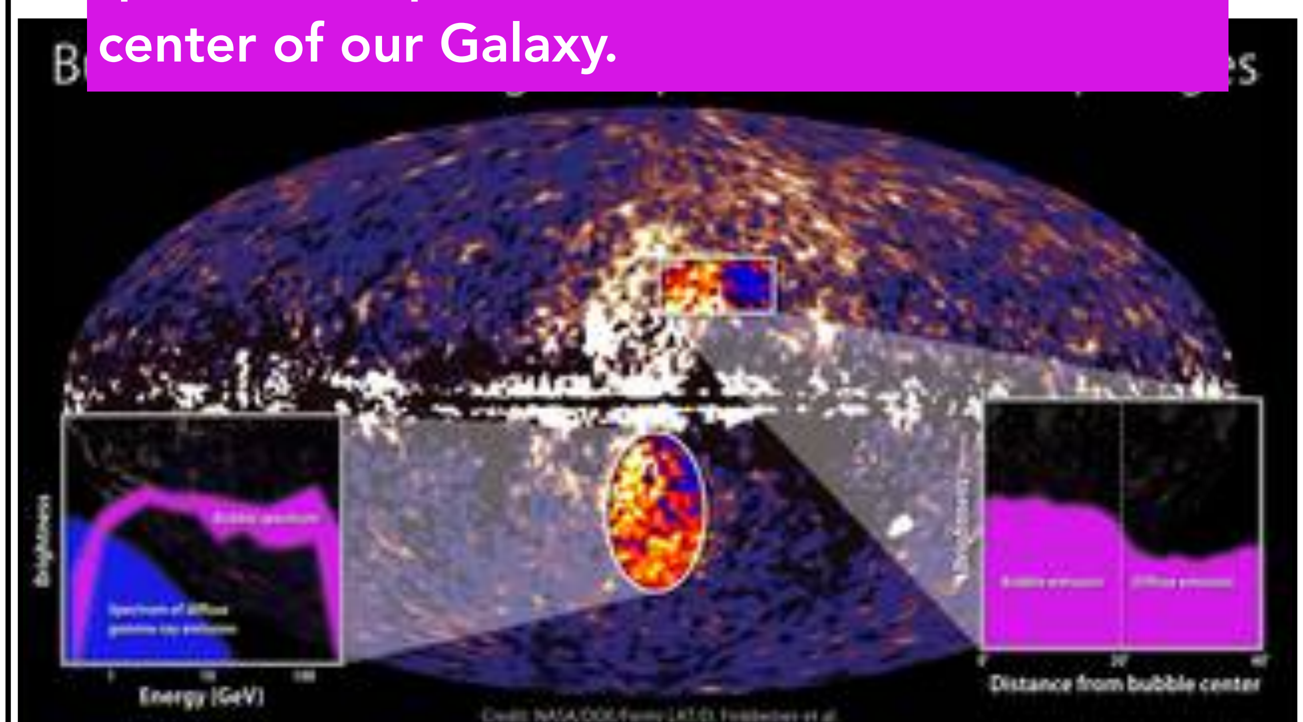
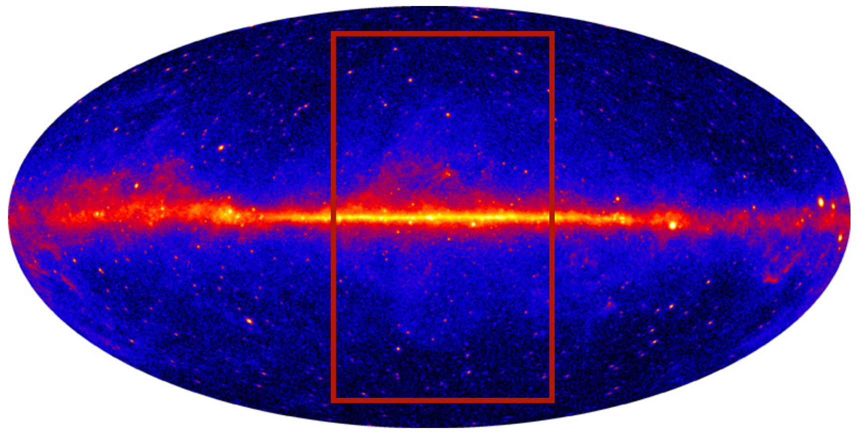


A breakthrough! Origin unclear but likely linked to the past activity of the currently quiescent super massive black hole at the center of our Galaxy.



The 'GeV' sky

Diffuse emission from our Galaxy



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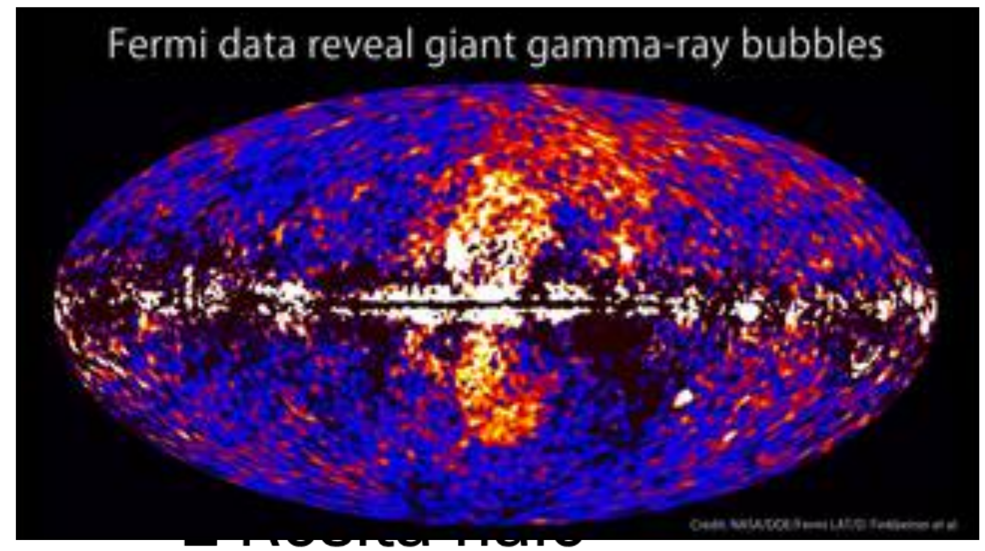

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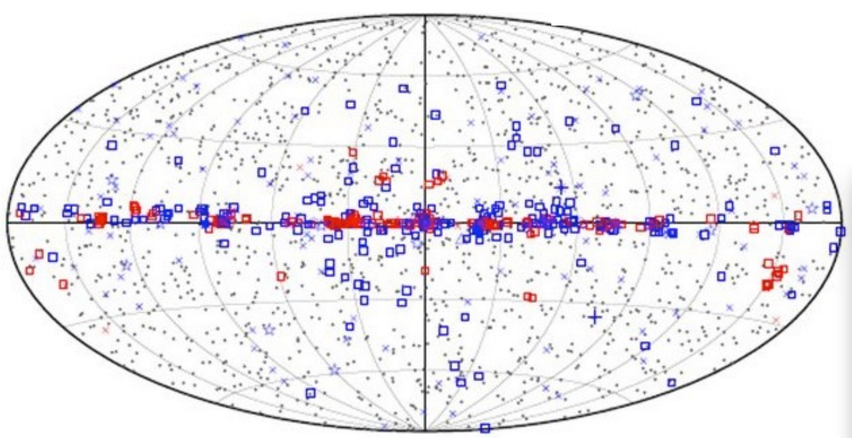
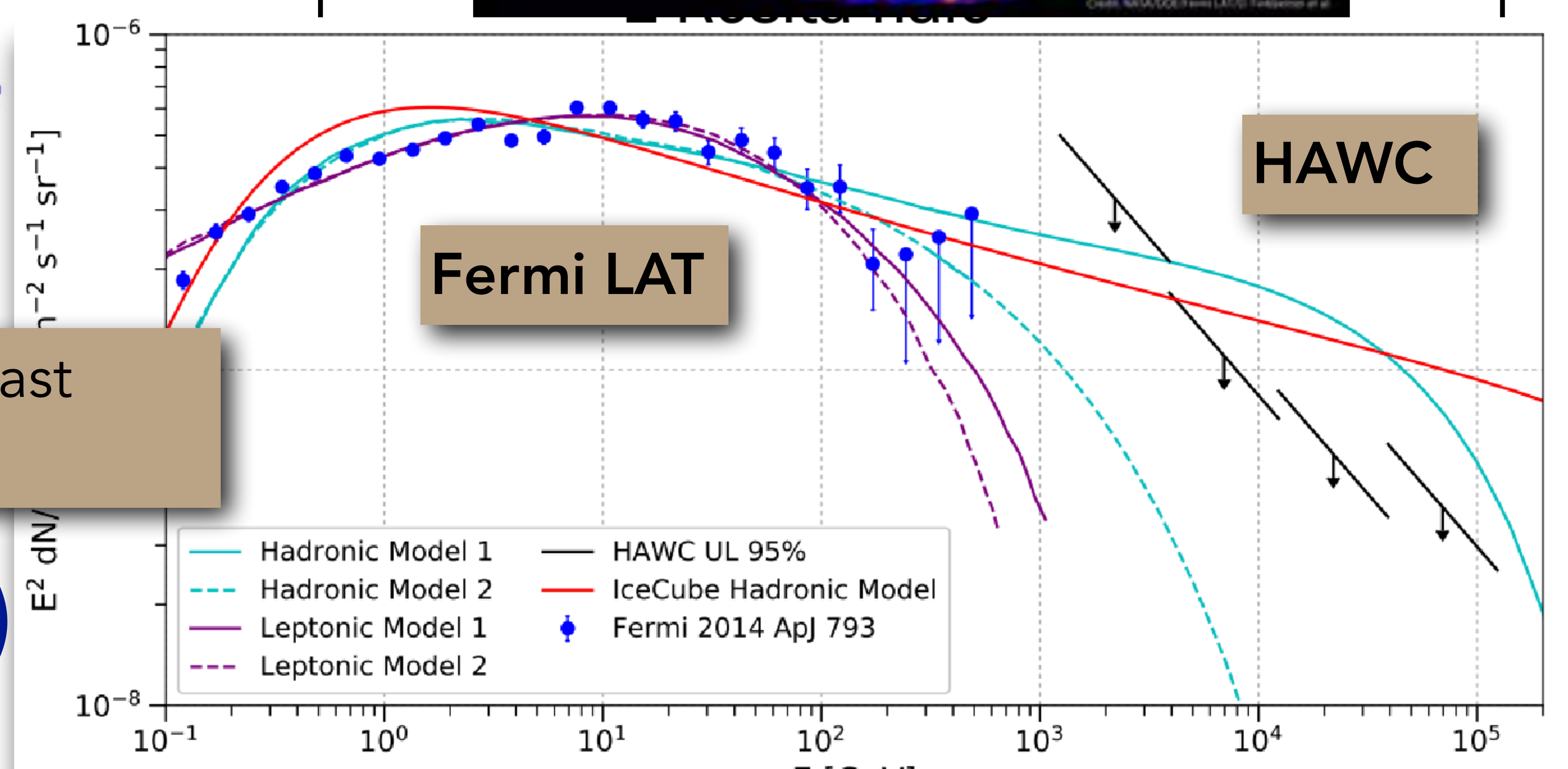
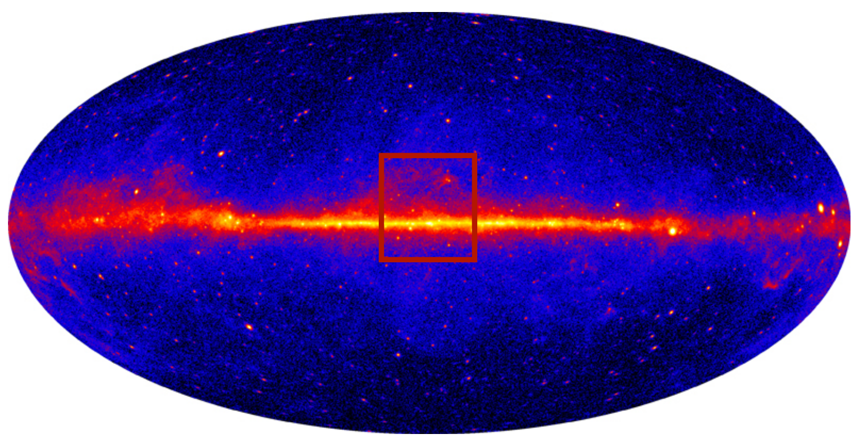




Telling us something about the past activity at the Galactic center?

The 'GeV' sky

Diffuse emission from our Galaxy



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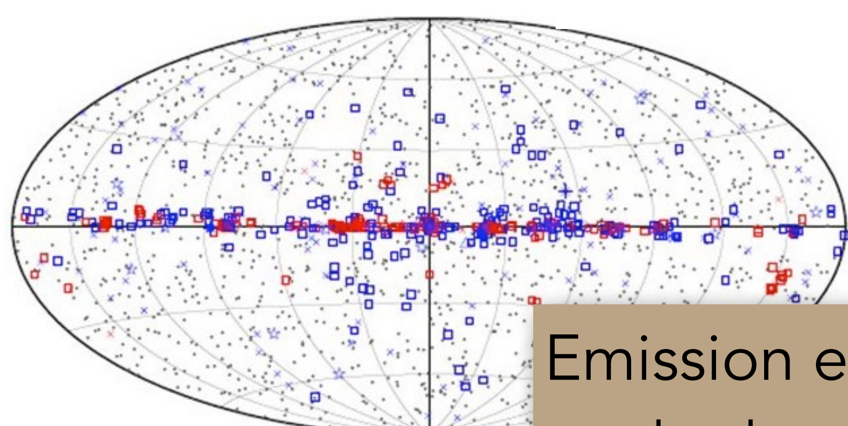
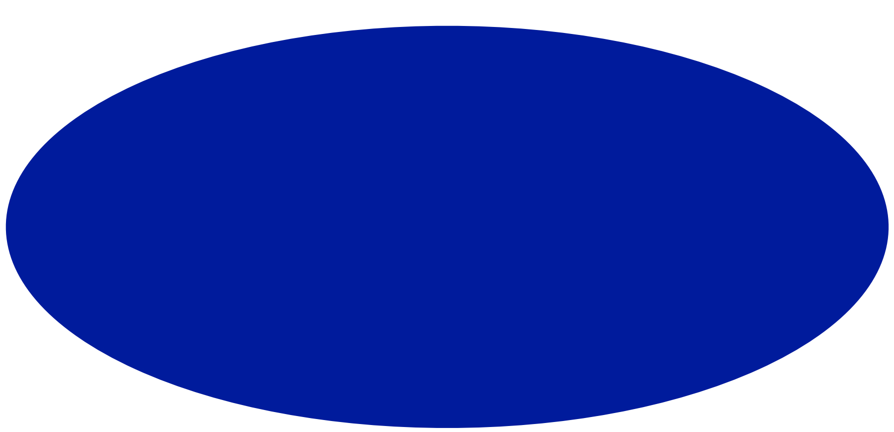
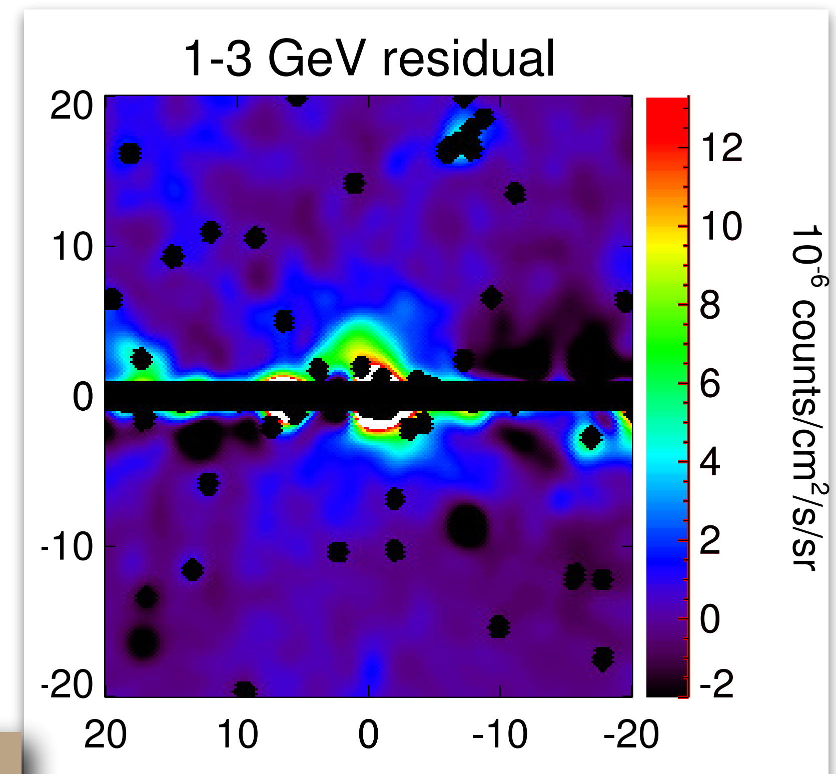


Isotropic emission

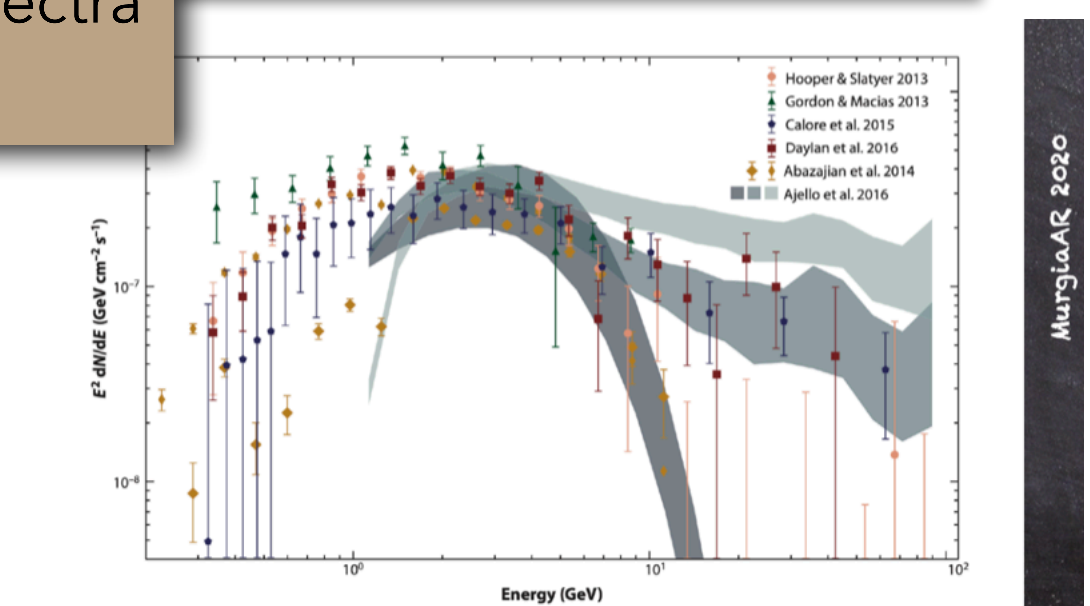


The Galactic Center Excess

After IEM and FB templates removed, persistent excess!

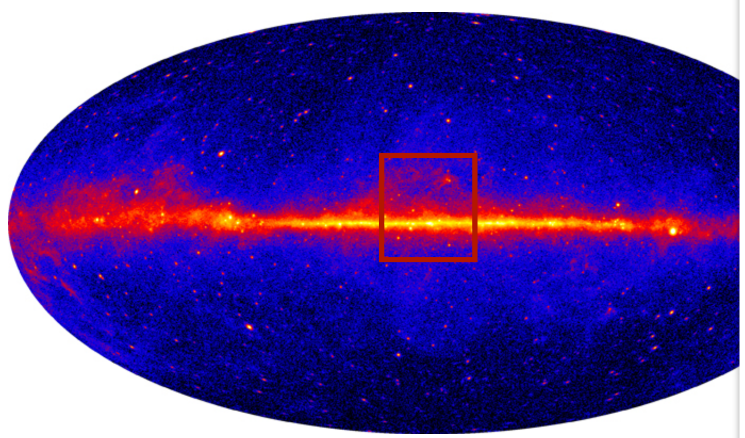


Emission extended and spectra peaked around 3-10 GeVs



The ‘GeV’ sky

Diffuse emission from our Galaxy



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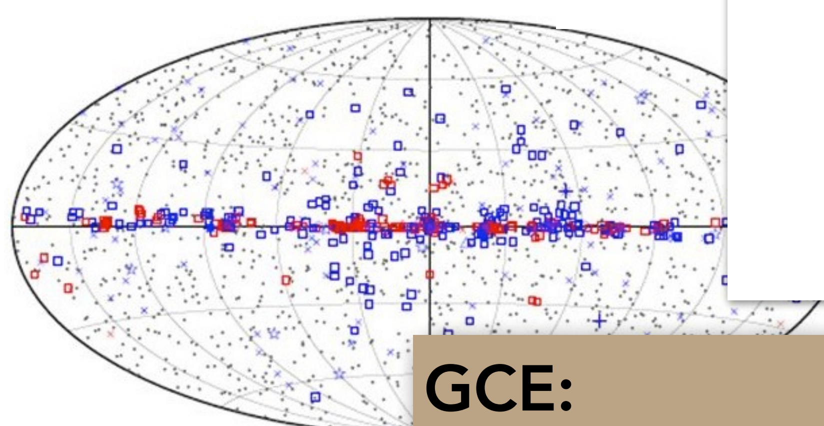

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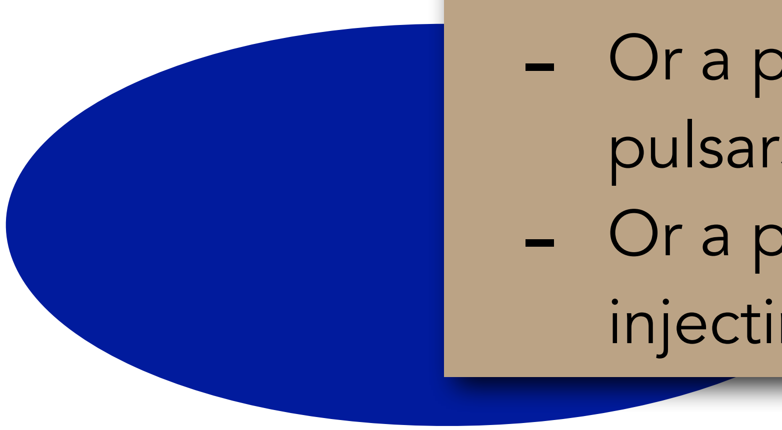
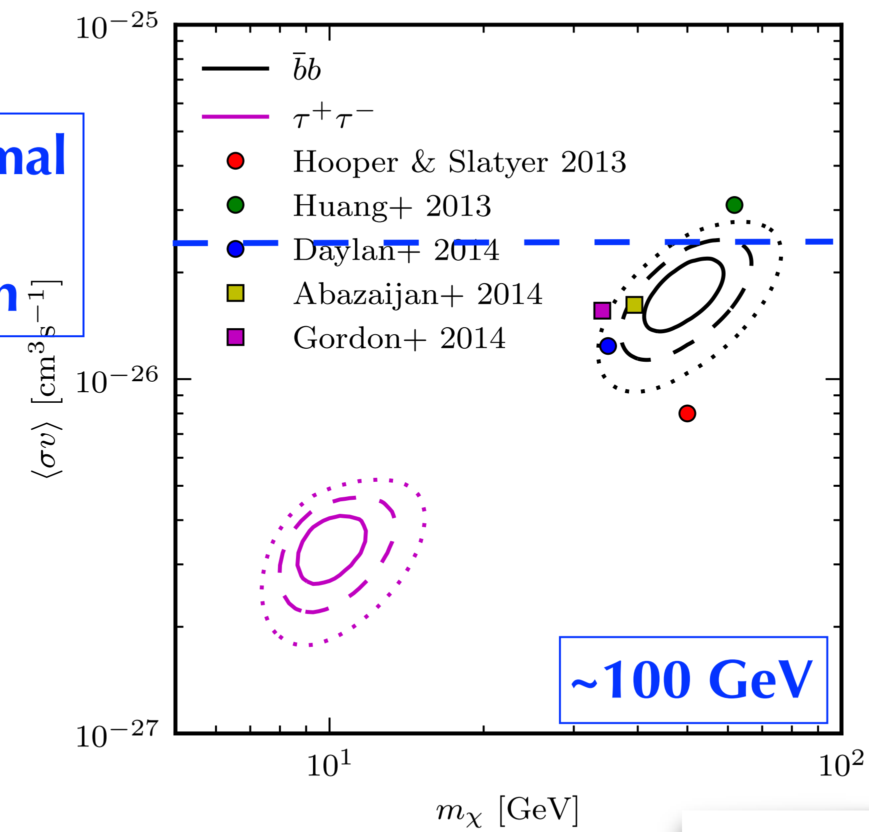


The Galactic Center Excess

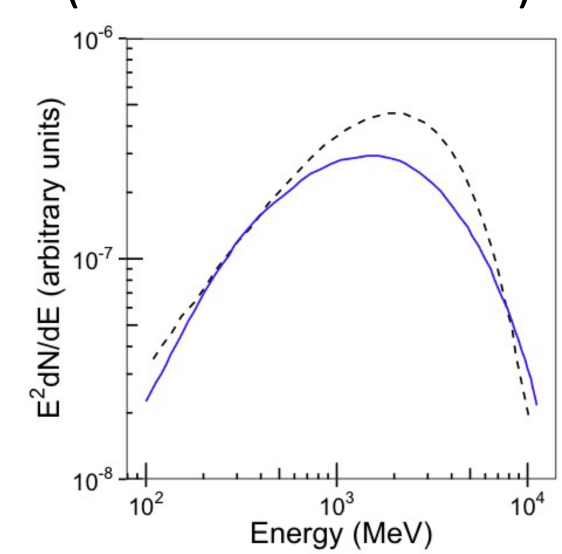
Right on the spot where WIMP DM is supposed to be!



GCE:

- it could be your perfect thermal DM
- Or a population of unresolved pulsars
- Or a past transient event injecting energy at the GC

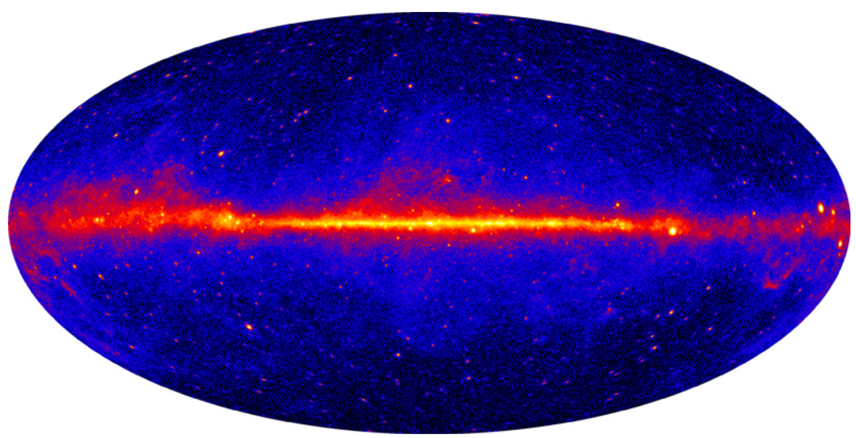
Spectral twins: Pulsar/DM Annihilation (30 GeV bb channel)



Baltz et al (2007)

The 'GeV' sky

Diffuse emission from our Galaxy



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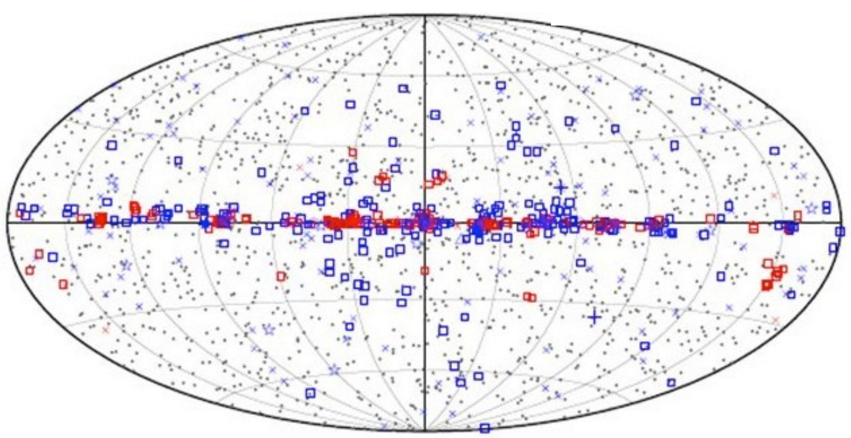

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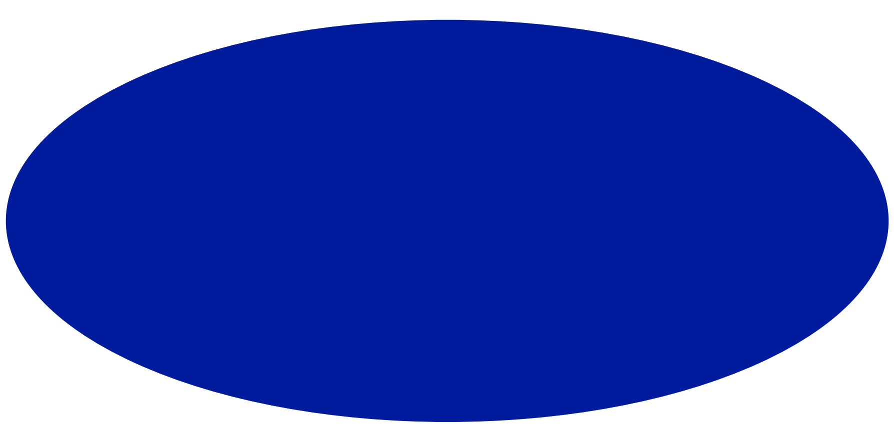
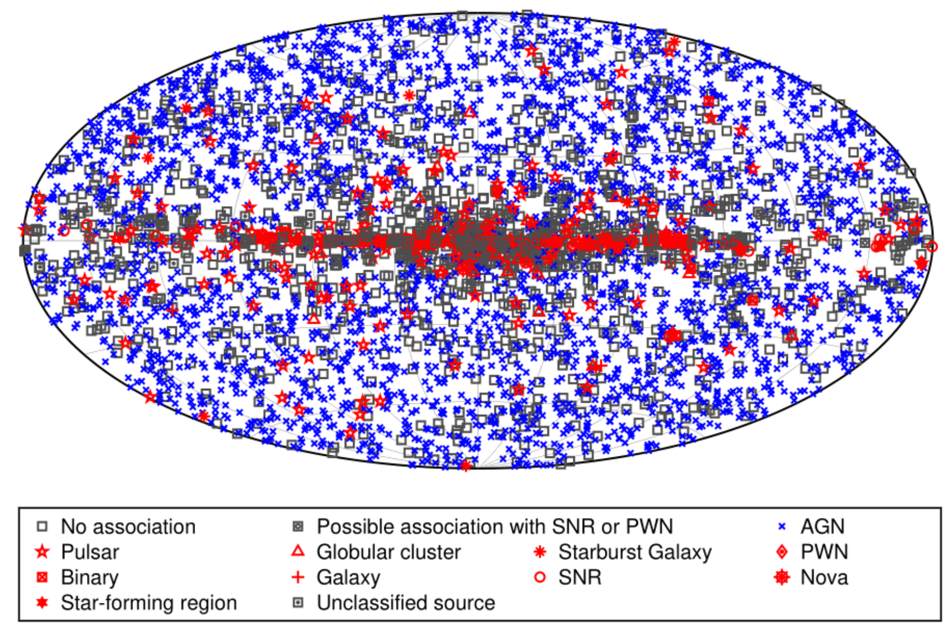
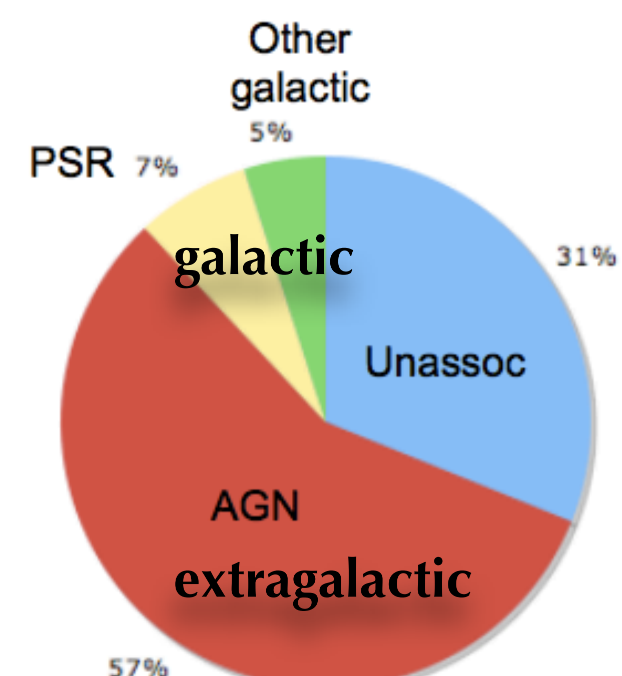


Fermi 4FGL catalog
>~5000 sources!



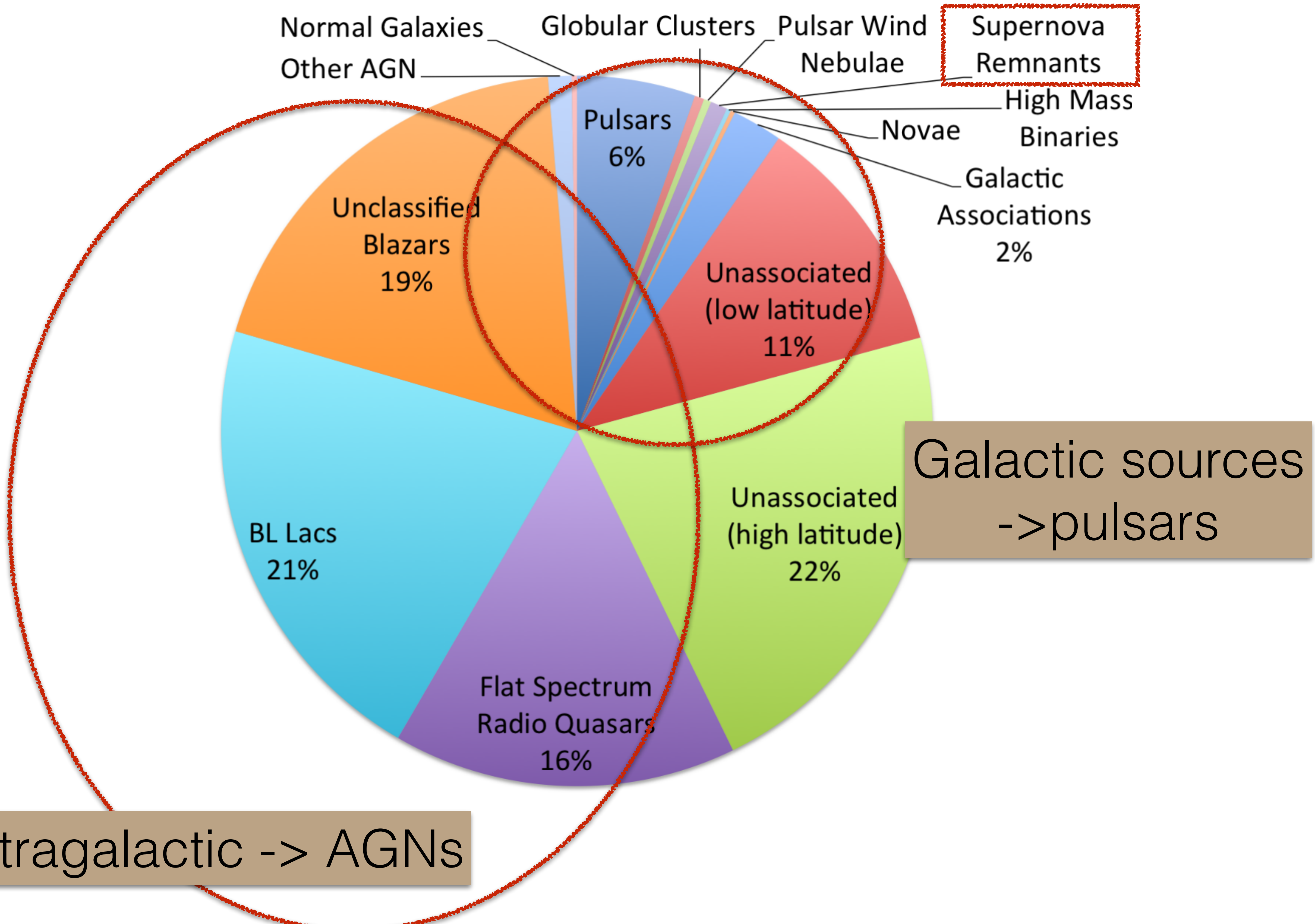
https://fermi.gsfc.nasa.gov/ssc/data/access/lat/8yr_catalog/

galactic: PSRs, PWNs, SNR, Nova, Globular clusters…



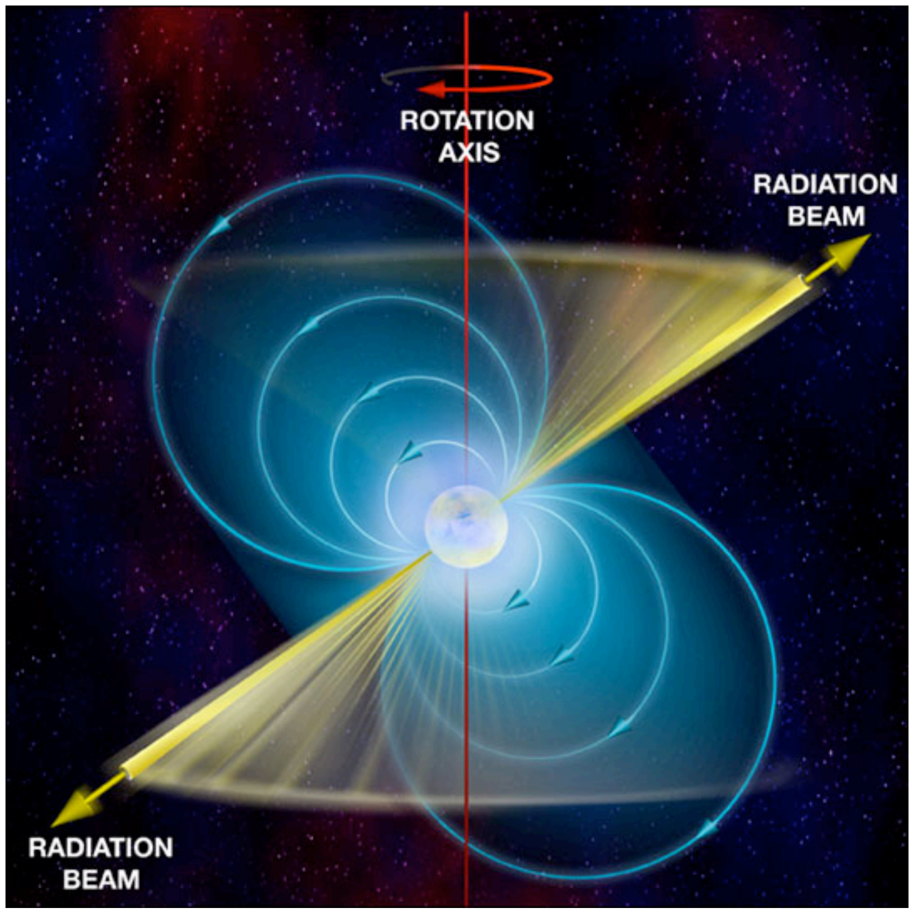
extragalactic: AGNs (BLLacs, FSRQs), star forming galaxies

HE astro sources



Pulsars

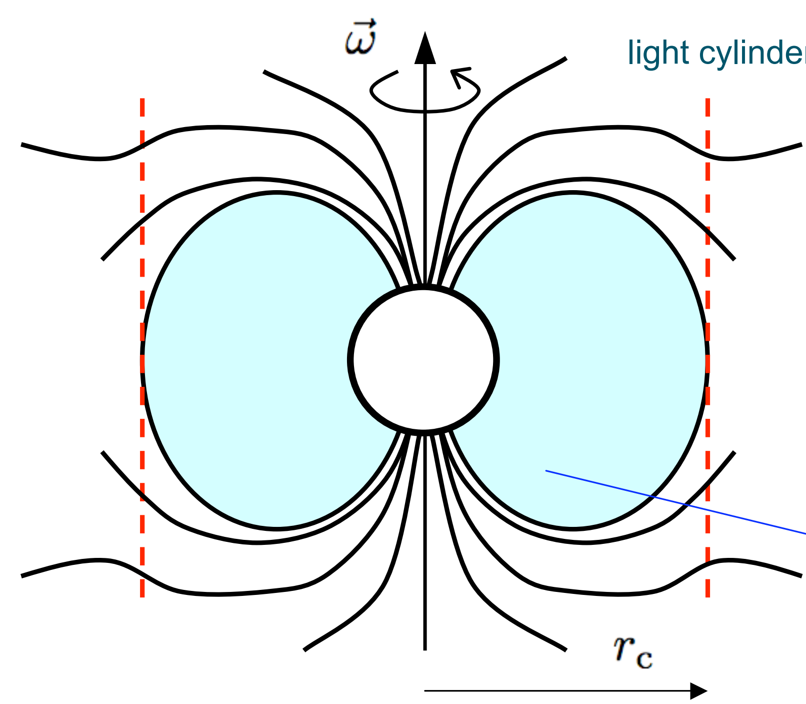
What are they?



‘the lighthouse' model

- fast spinning magnetic star
- magnetic dipole axis not aligned
  with the spinning axis
- beamed emission (neutron stars)

Neutron star magnetosphere (V)



at the light cylinder

$$v(r_c) = r_c\ \omega = c$$

co-rotating plasmas are on the magnetic-field lines closed inside the light cylinder

+ particles can escape along the open field lines

Standard formulae

For many pulsars, all we know is the period (P) and period derivative (Pdot)

$$\dot{E} = 4\pi^2 I \dot{P} P^{-3}$$
$$= 3.95 \times 10^{31}\ \mathrm{erg\ s^{-1}} \left(\frac{\dot{P}}{10^{-15}}\right) \left(\frac{P}{s}\right)^{-3}$$

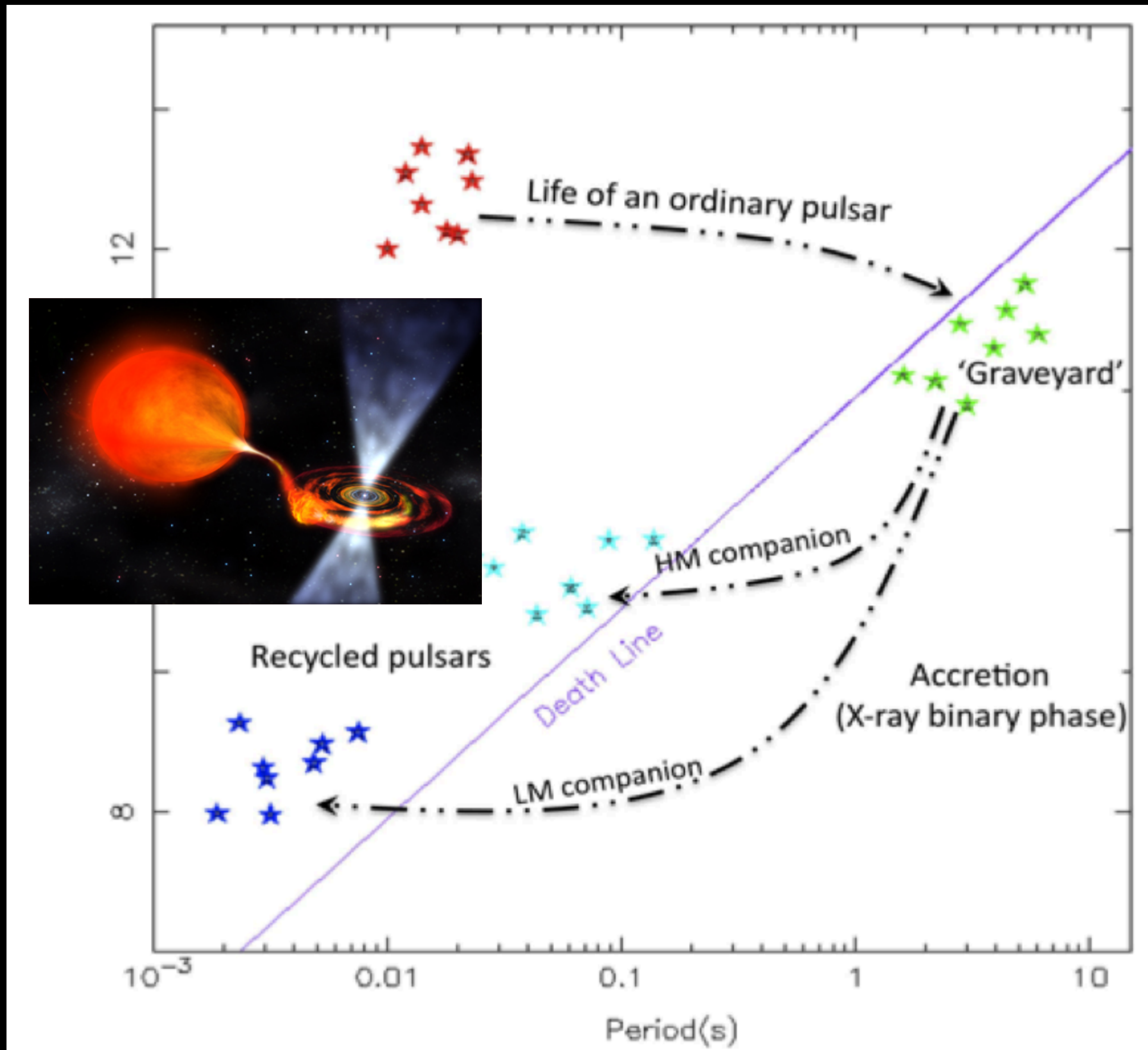
$$\tau = \frac{P}{2\dot{P}}$$
$$= 15.8\ \mathrm{Myr} \left(\frac{P}{s}\right) \left(\frac{\dot{P}}{10^{-15}}\right)$$

$$B = 3.2 \times 10^{19}\ \mathrm{G} \sqrt{P\dot{P}}$$
$$= 10^{12}\ \mathrm{G} \left(\frac{\dot{P}}{10^{-15}}\right)^{1/2} \left(\frac{P}{s}\right)^{1/2}$$

Assumptions

$M = 1.4 M_{\odot}$
$R = 10$ km
$I = 10^{45}$ g cm^2
Pure dipole spin-down

MSP Formation



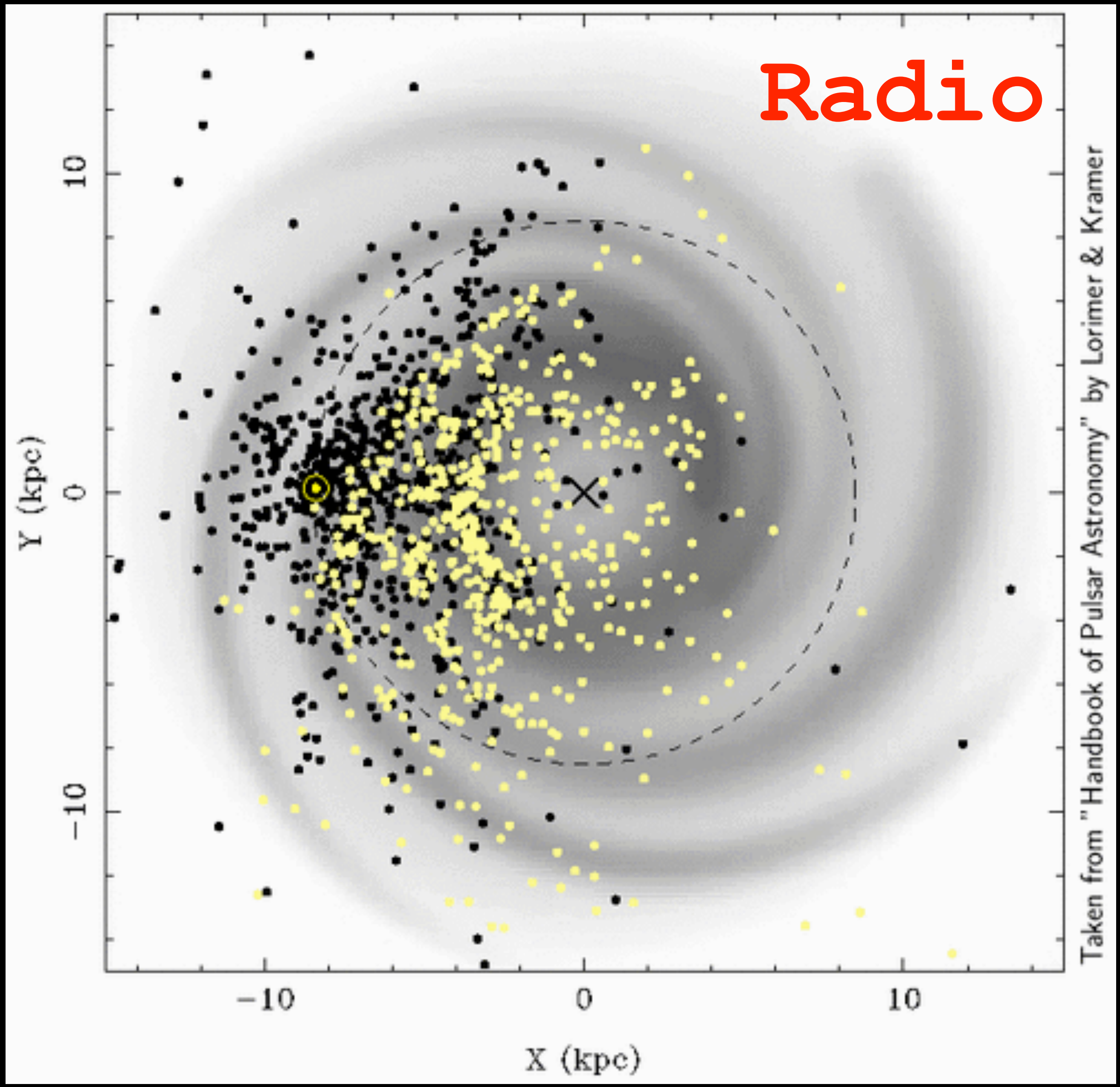
Stairs

Mass transfer from the primary star to the neutron star transports angular momentum, resulting in spin-up of the neutron star.

A weak pulsar magnetic field is an advantage because the magnetic pressure determines the accretion radius about the star and, if this is weak, angular momentum transfer can occur close to the surface of the neutron star resulting in a large spin-up.

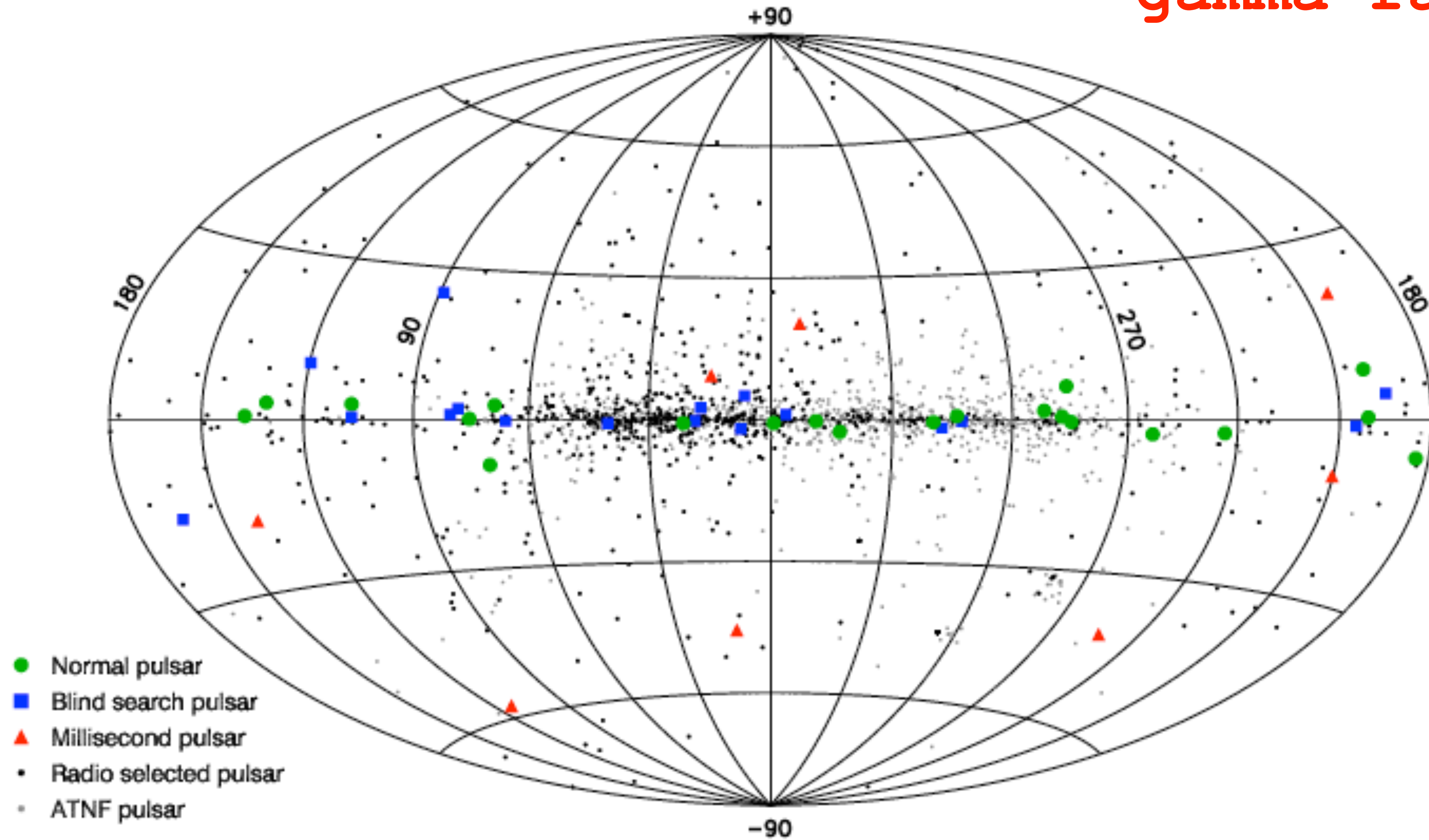
Although the magnetic fields are weak, this is more than *compensated for by the fast rotation speeds* of the millisecond pulsars.

Know Galactic Population



Space velocities of 10 - >1000 km/s

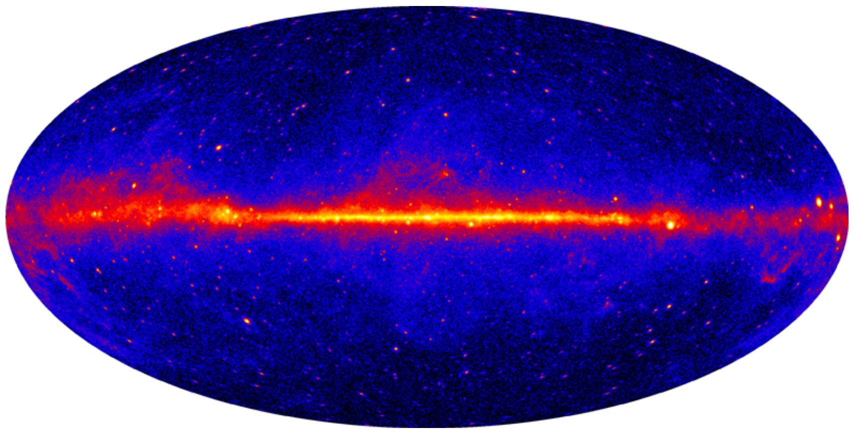
gamma ray



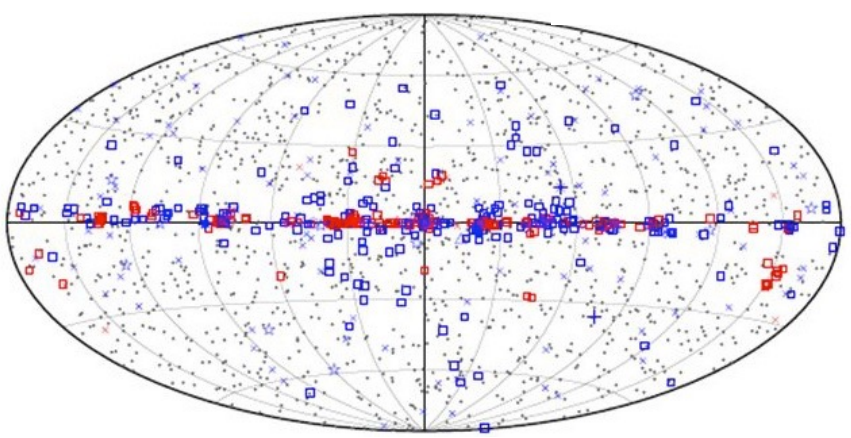
Milli-second pulsars are much older -> distributed more uniformly on the sky!

The 'GeV' sky

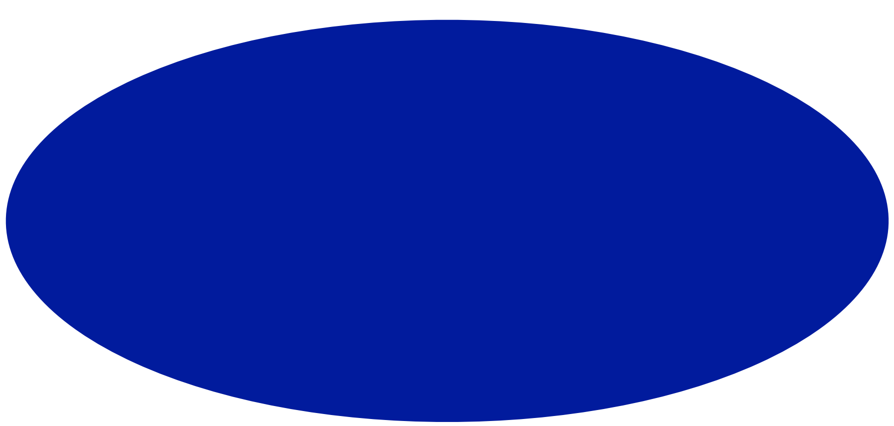
Diffuse emission from our Galaxy



Point sources

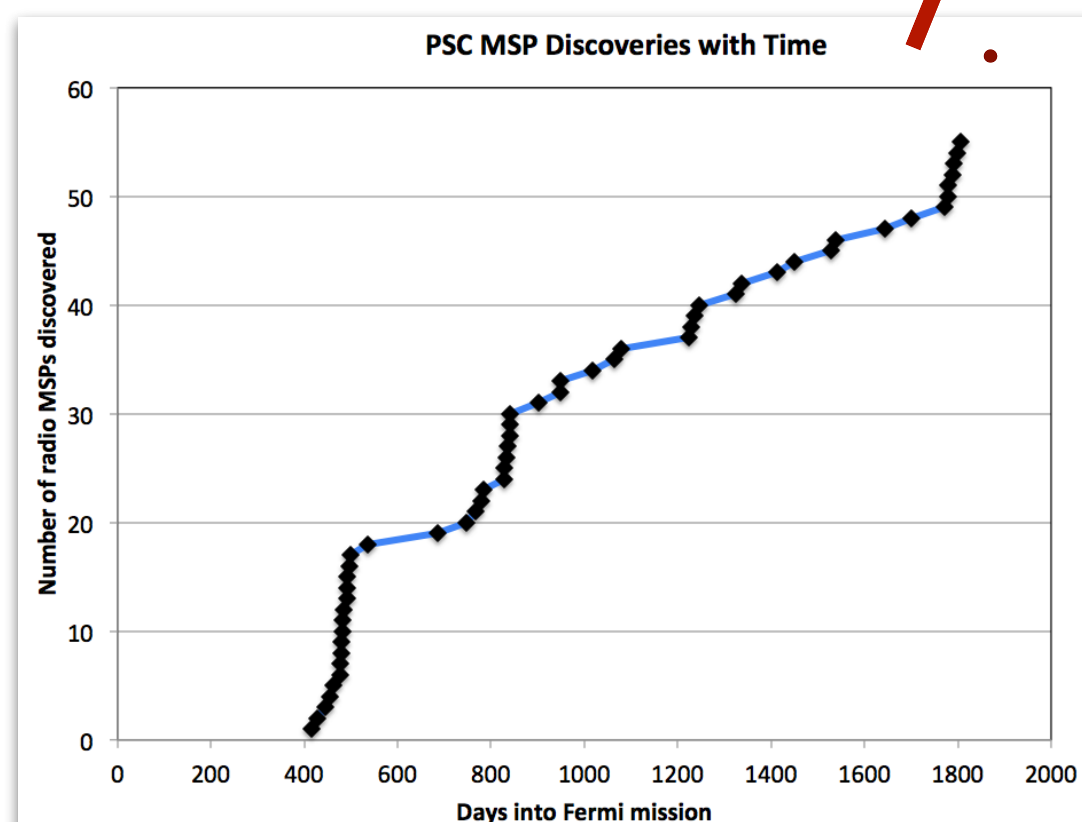


Isotropic emission

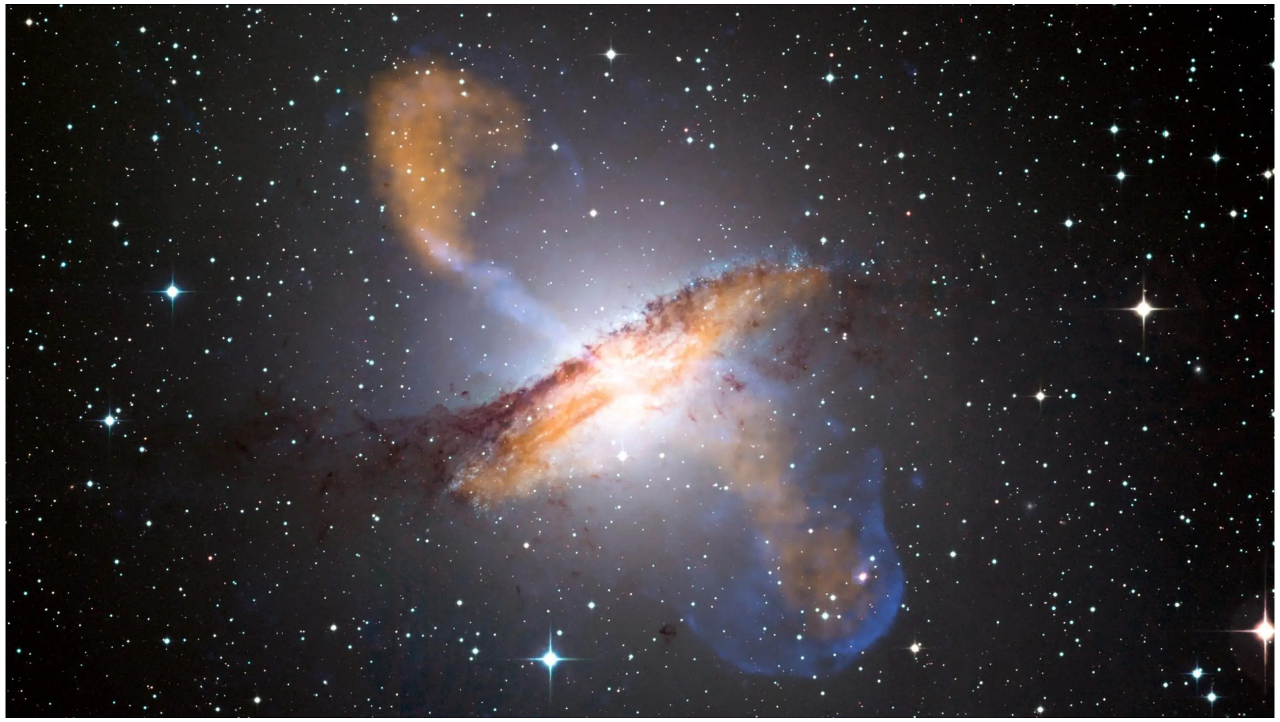


The Fermi LAT pulsar 'revolution'

~250PSRs



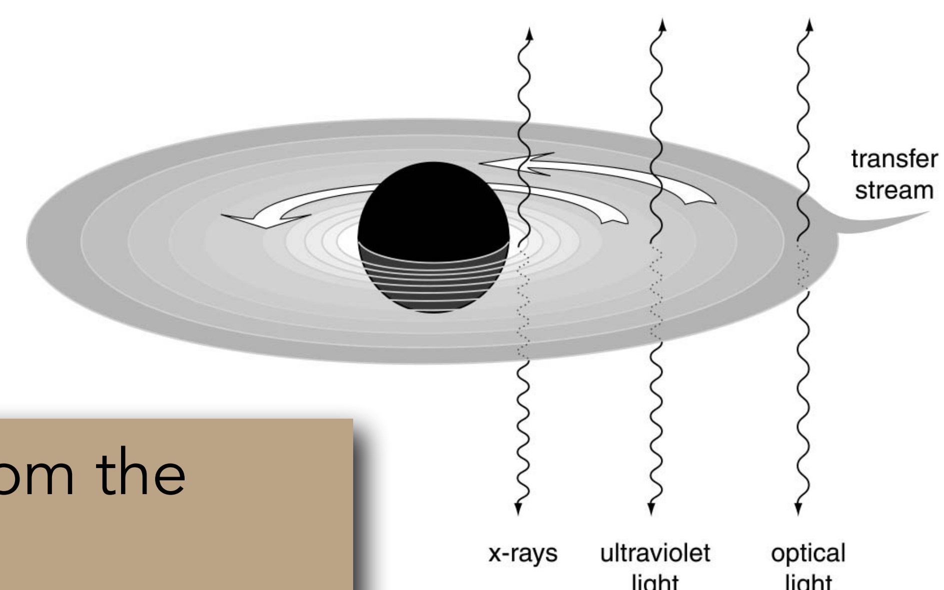
Active Galactic Nuclei



Nuclei 'active' —> **brighter than the host Galaxy**

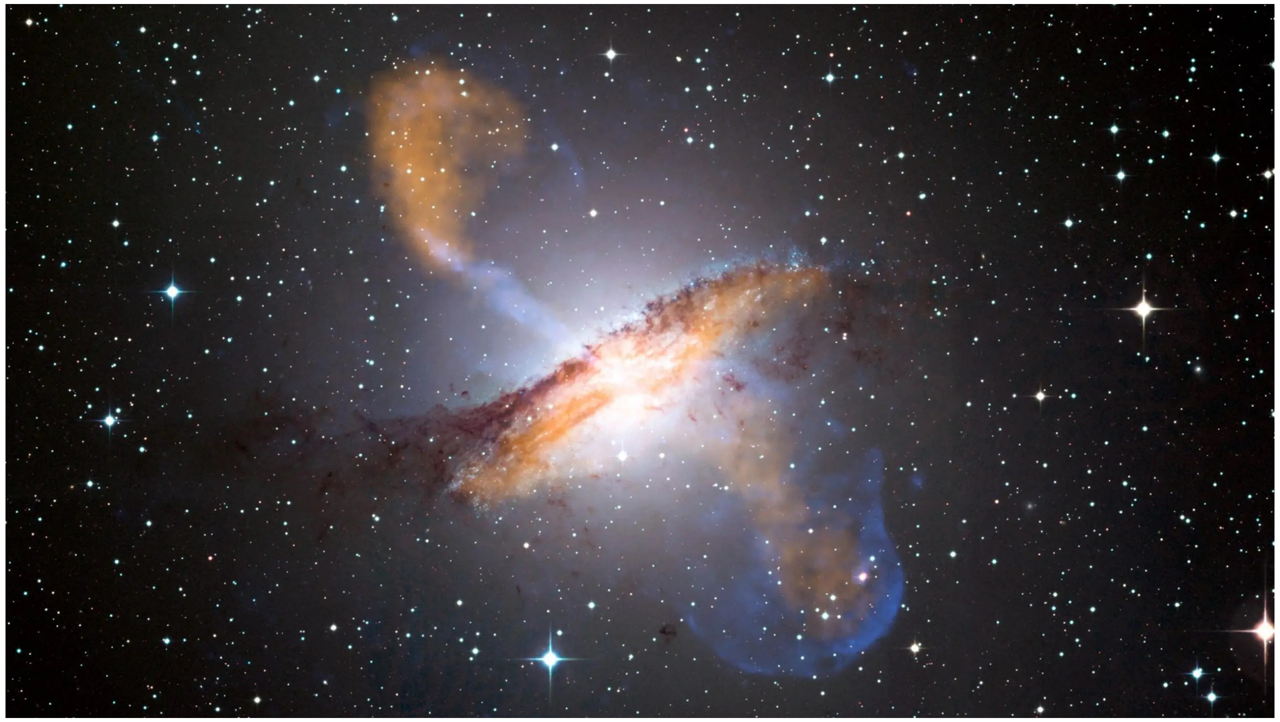
Energy Release From Central Engines

Some of it will emerge as a mix of ***thermal emission*** from various parts of the accretion disk; some emerges as a ***non-thermal synchrotron emission*** from particles accelerated by the magnetic fields embedded in the accretion disk or the BH itself



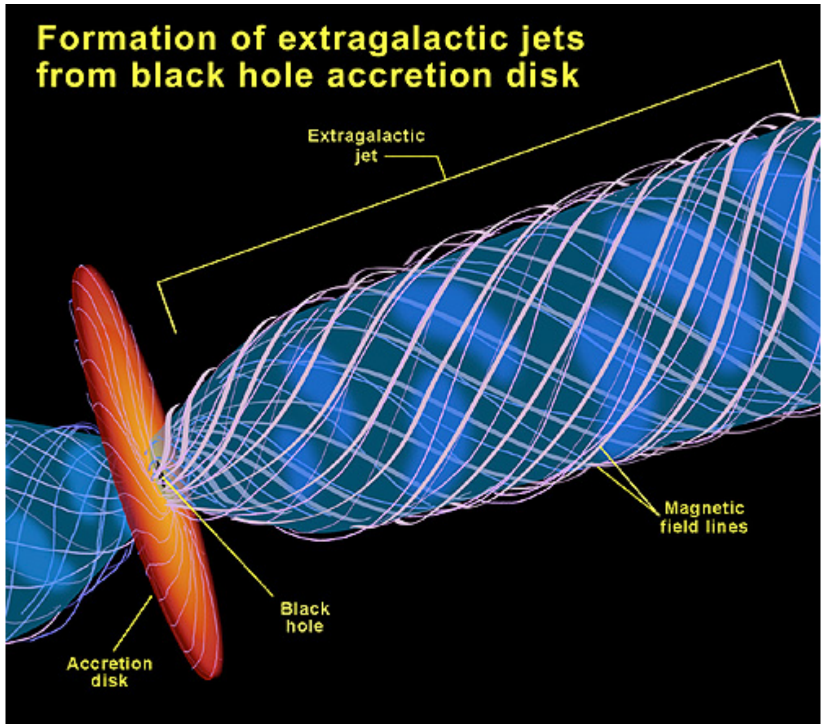
Thermal emission from the accretion disk…

Active Galactic Nuclei



Nuclei 'active' —> **brighter than the host Galaxy**

The Origin of AGN Jets



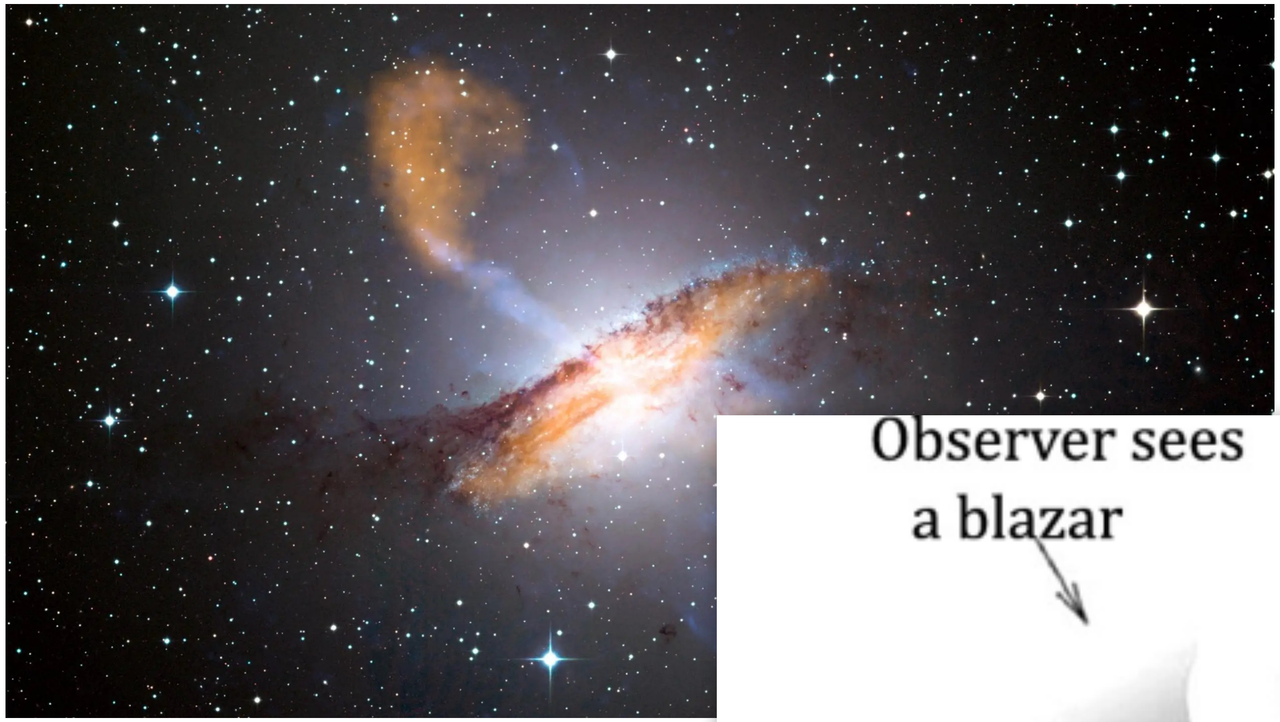
Magnetic fields are threaded through the accretion disk, and/or the spinning black hole itself

The spin turns the magnetic lines of force into well-defined and tightly wound funnels, along which charged particles are accelerated

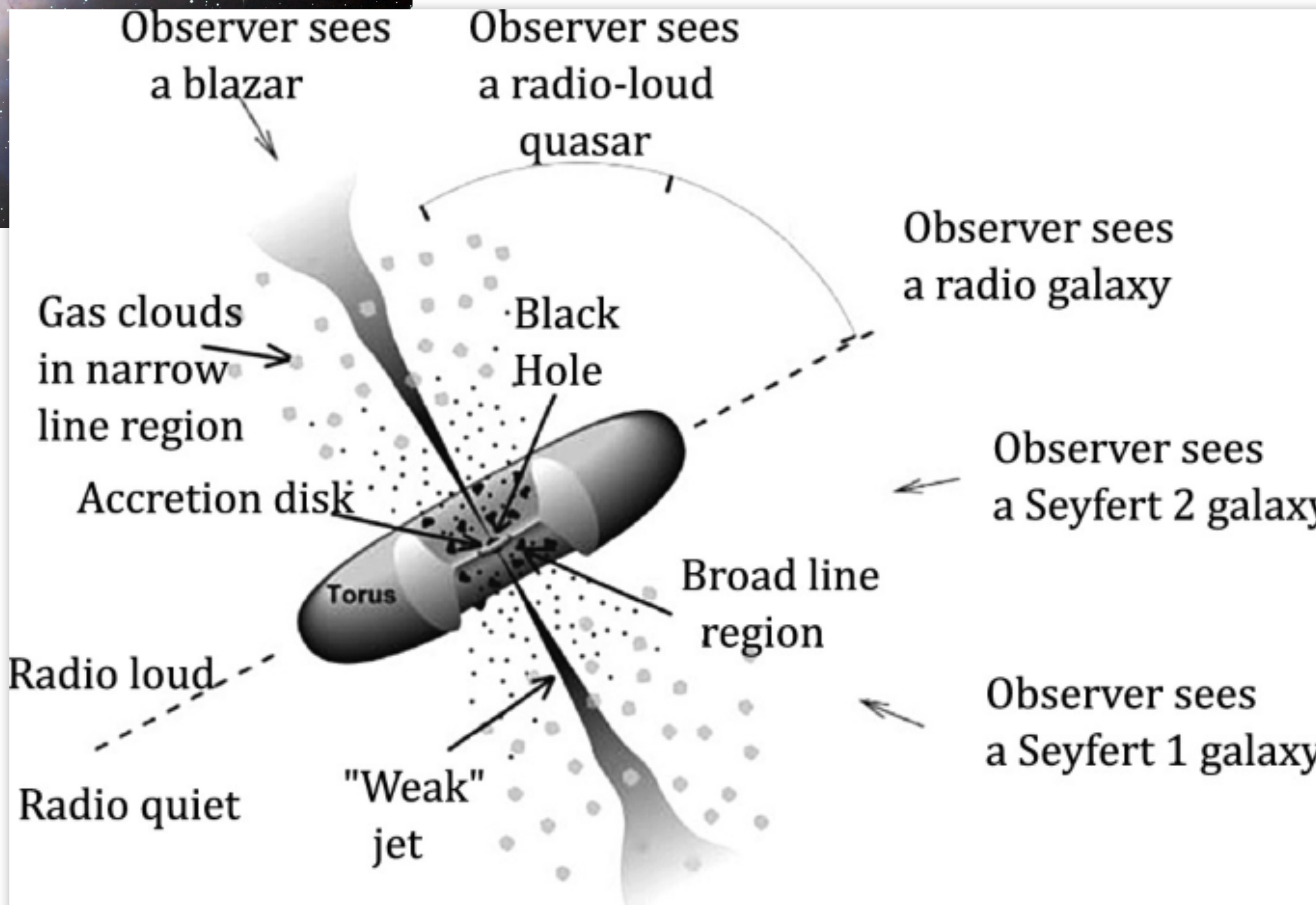
This saps the rotational energy of the disk and/or the BH itself; aside from radiation, mechanical energy is carried by the jets to lobes

and non-thermal from the jets!…

Active Galactic Nuclei

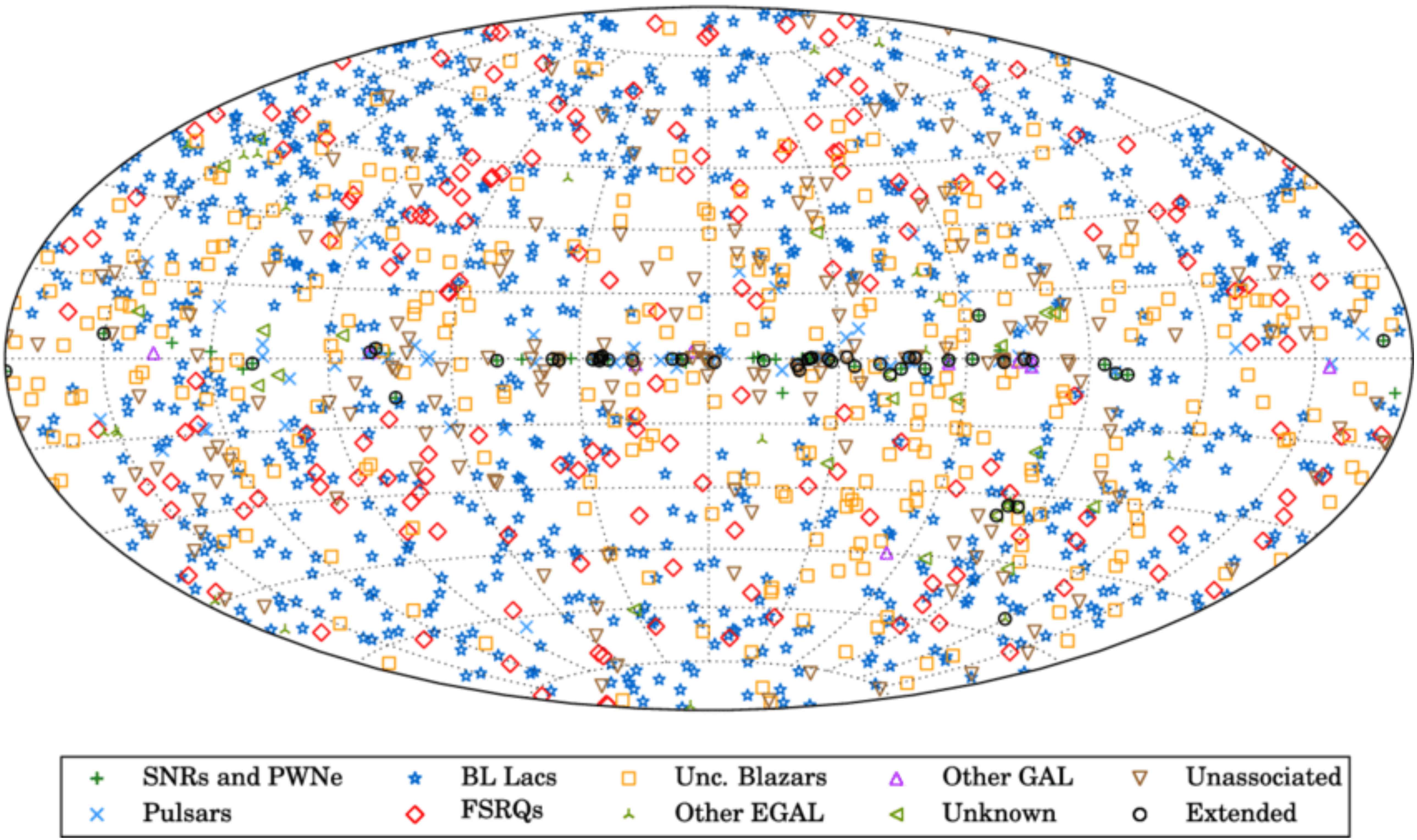


Nuclei 'active' —> **brighter than the host Galaxy**



Complex geometry:
- Accretion disk
- Dust torus
- Jets

- Thousands AGNs (**blazars!**) populate the gamma ray (Fermi LAT) sky



Non thermal spectrum of Blazars

- The overall spectral energy distribution (SED), once plotted in νF_ν, shows **two broad peaks**.

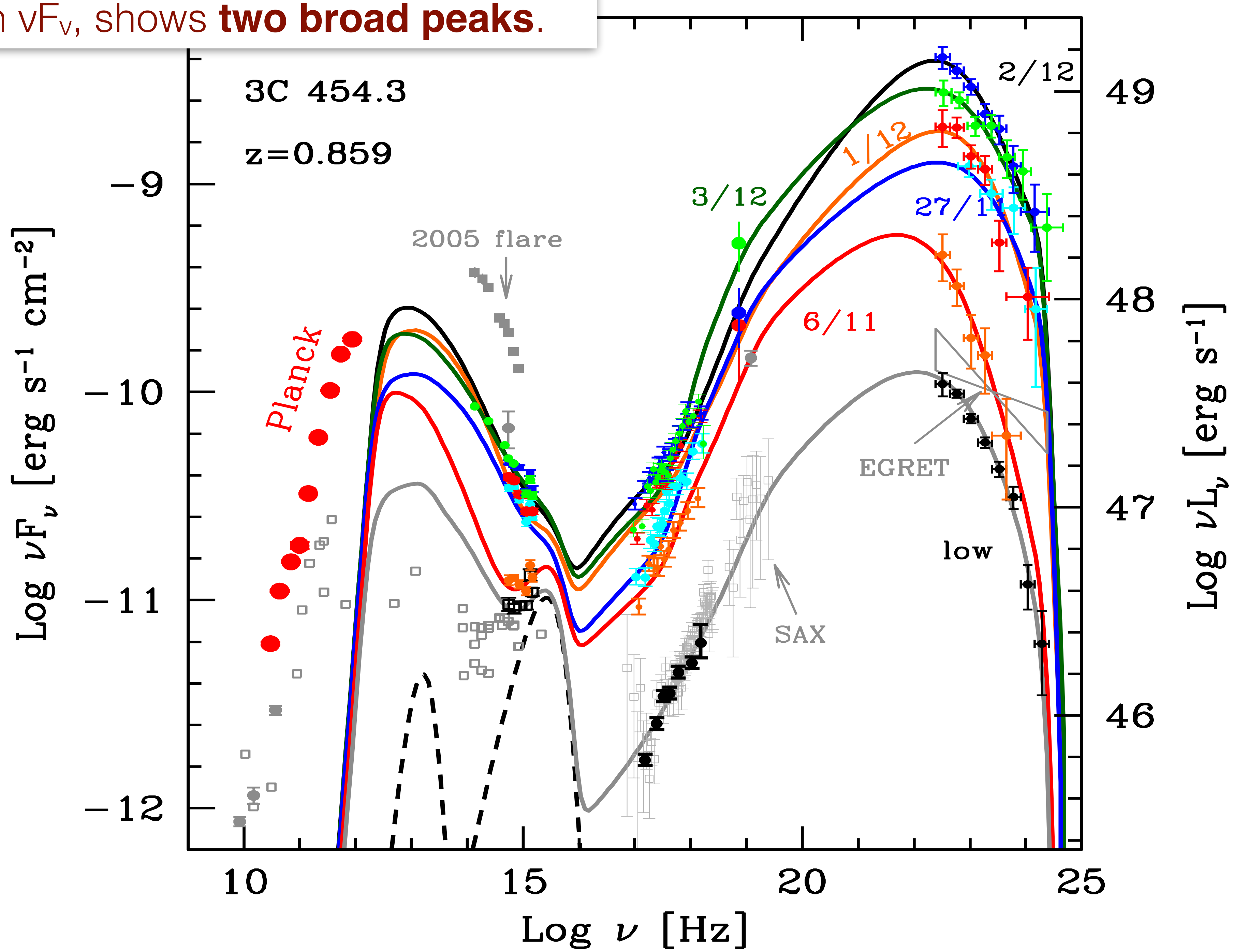
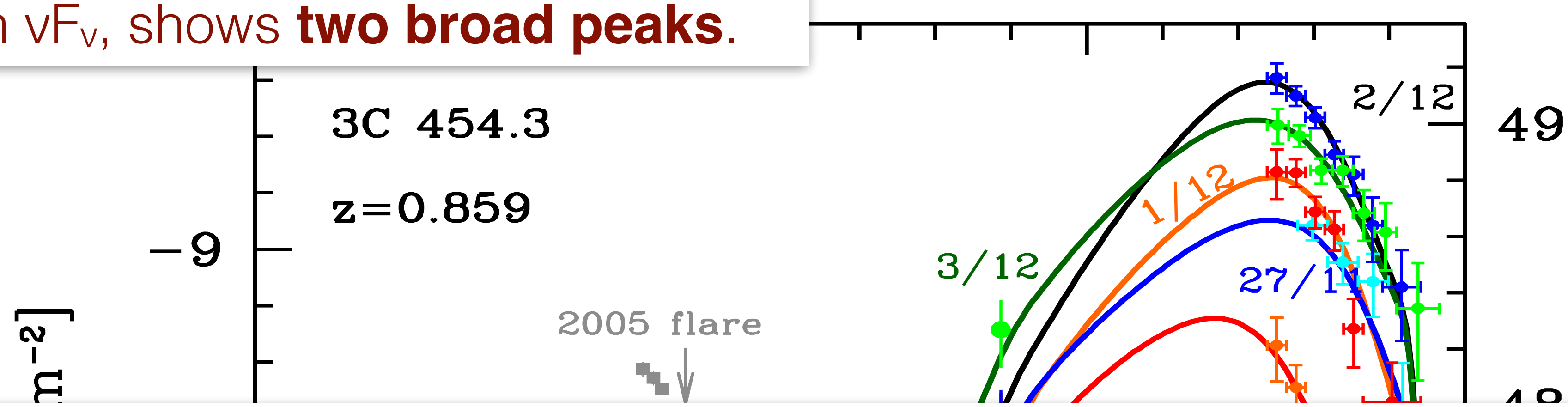


Figure 8.12: The overall electromagnetic spectrum of 3C 454.3, the most luminous γ–ray source up to now. Note the large amplitude variability, even day–by–day. Dates refer to the year 2009. Lines correspond to fitting models. See Bonnoli et al. (2011, MNRAS, 410, 368).

Non thermal spectrum of Blazars

- The overall spectral energy distribution (SED), once plotted in νF_ν, shows **two broad peaks**.



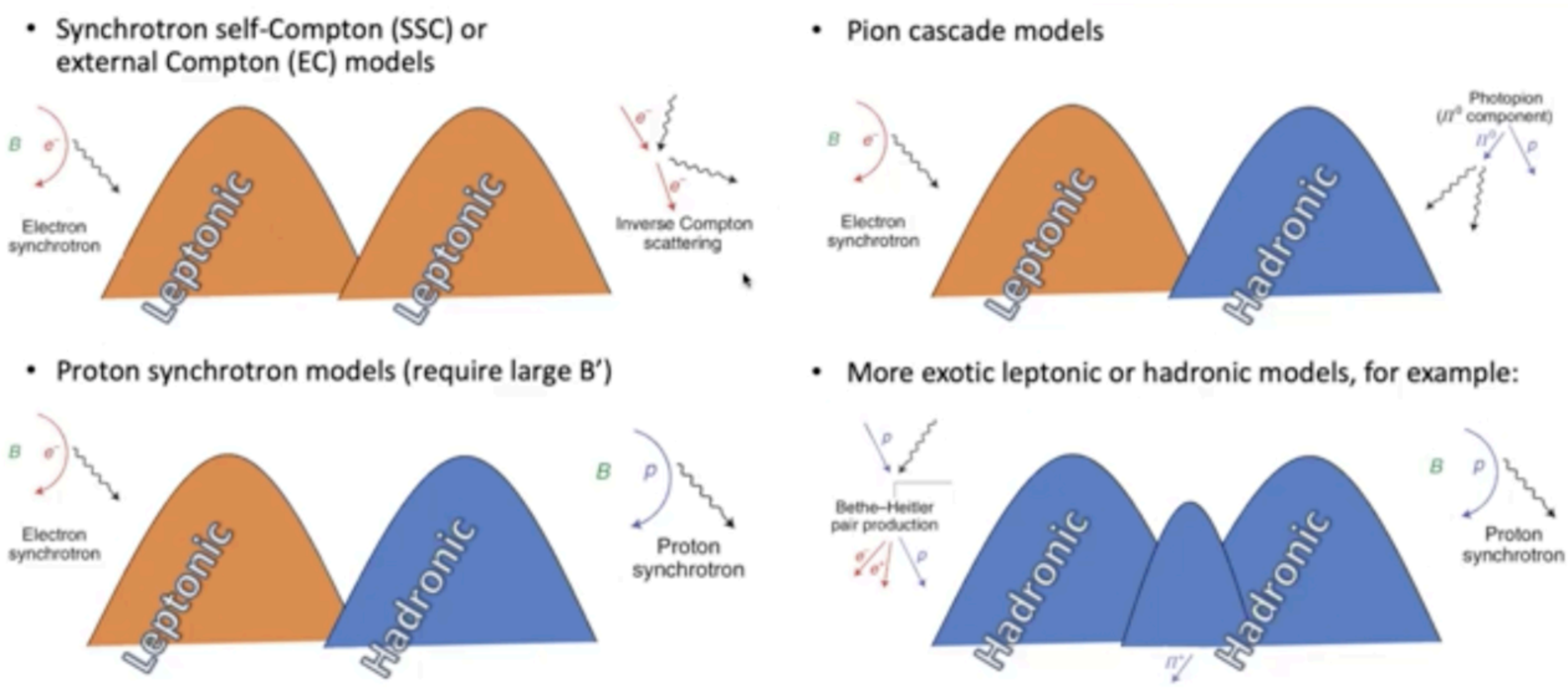
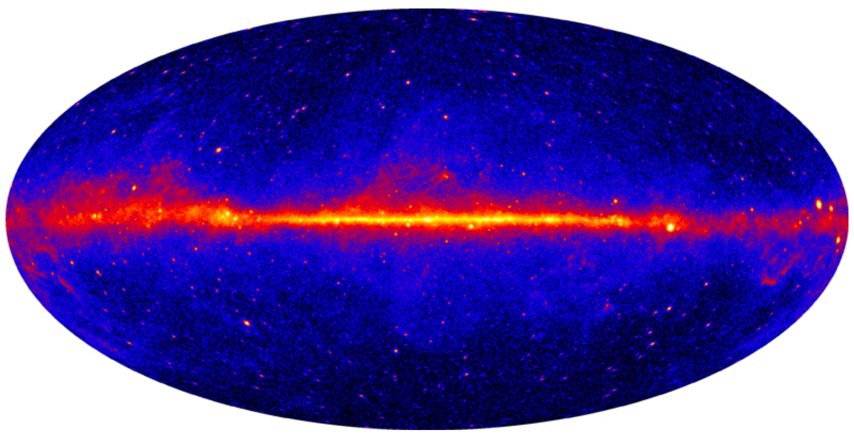


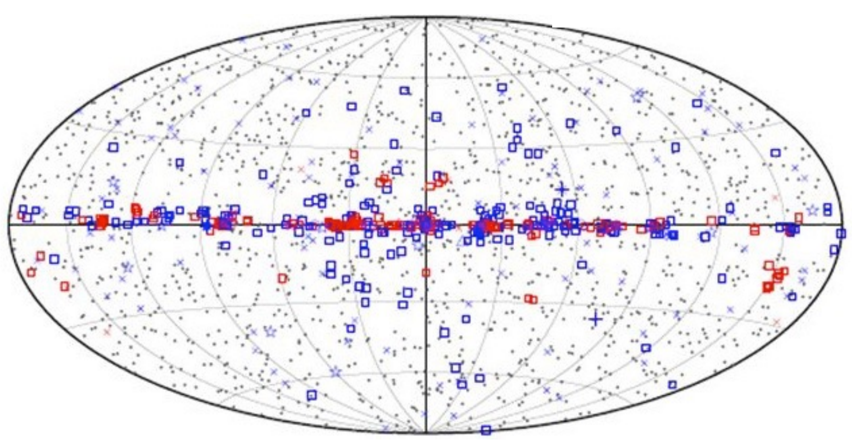
Figure 3: Models of AGN emission

The ‘GeV’ sky

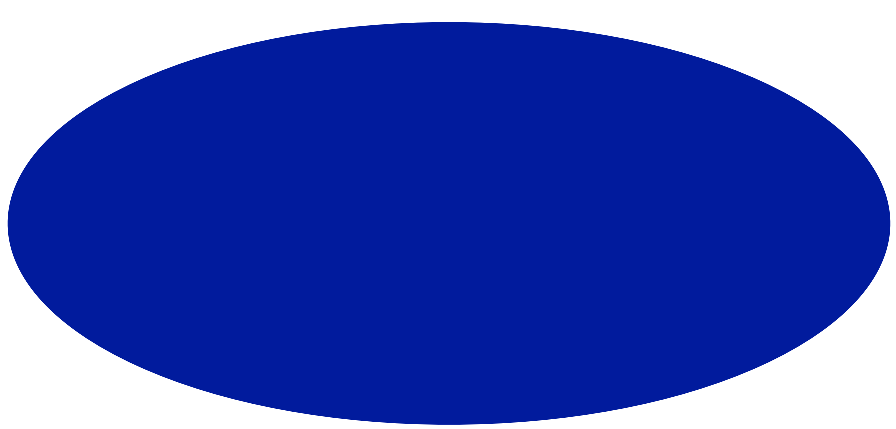
Diffuse emission from our Galaxy



Point sources

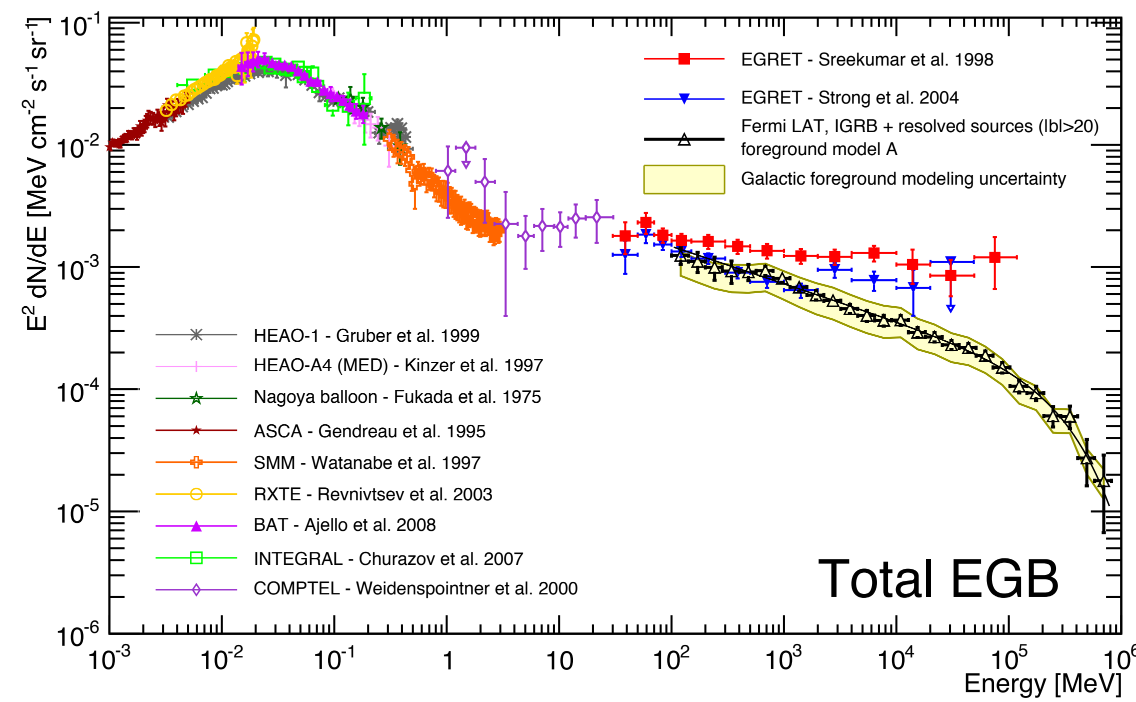


Isotropic emission



dominates at high latitudes

origin not yet fully understood

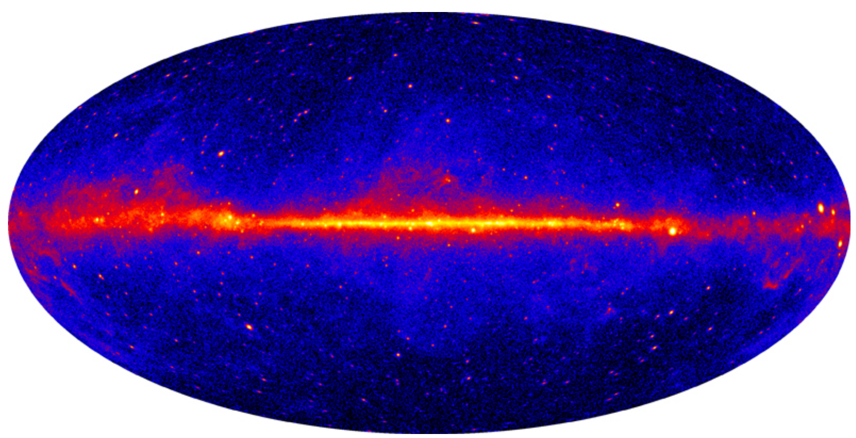


guaranteed contribution: faint (not individually resolved) extragalactic sources

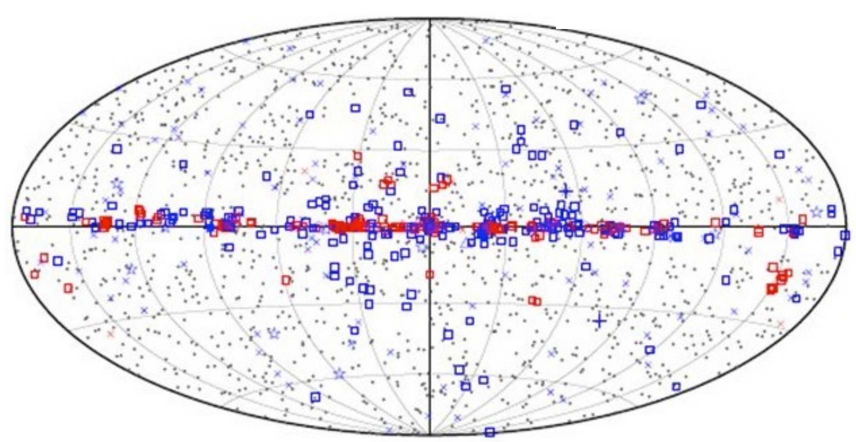
[Ackermann+, ApJ799, 2015)]

The 'GeV' sky

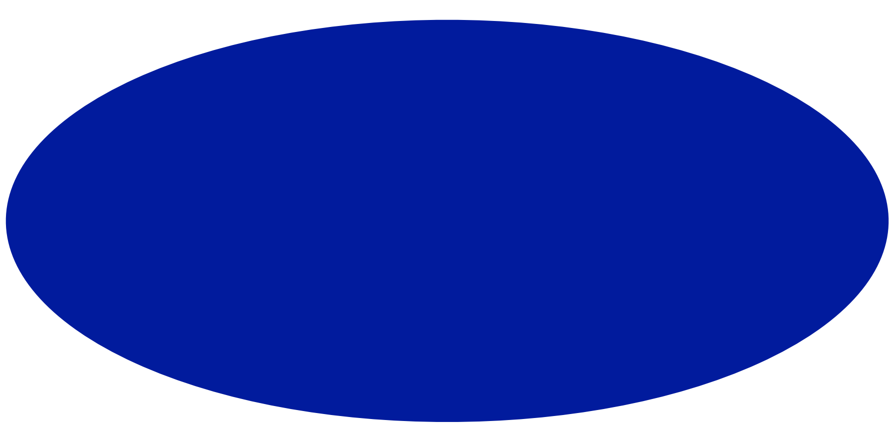
Diffuse emission from our Galaxy



Point sources

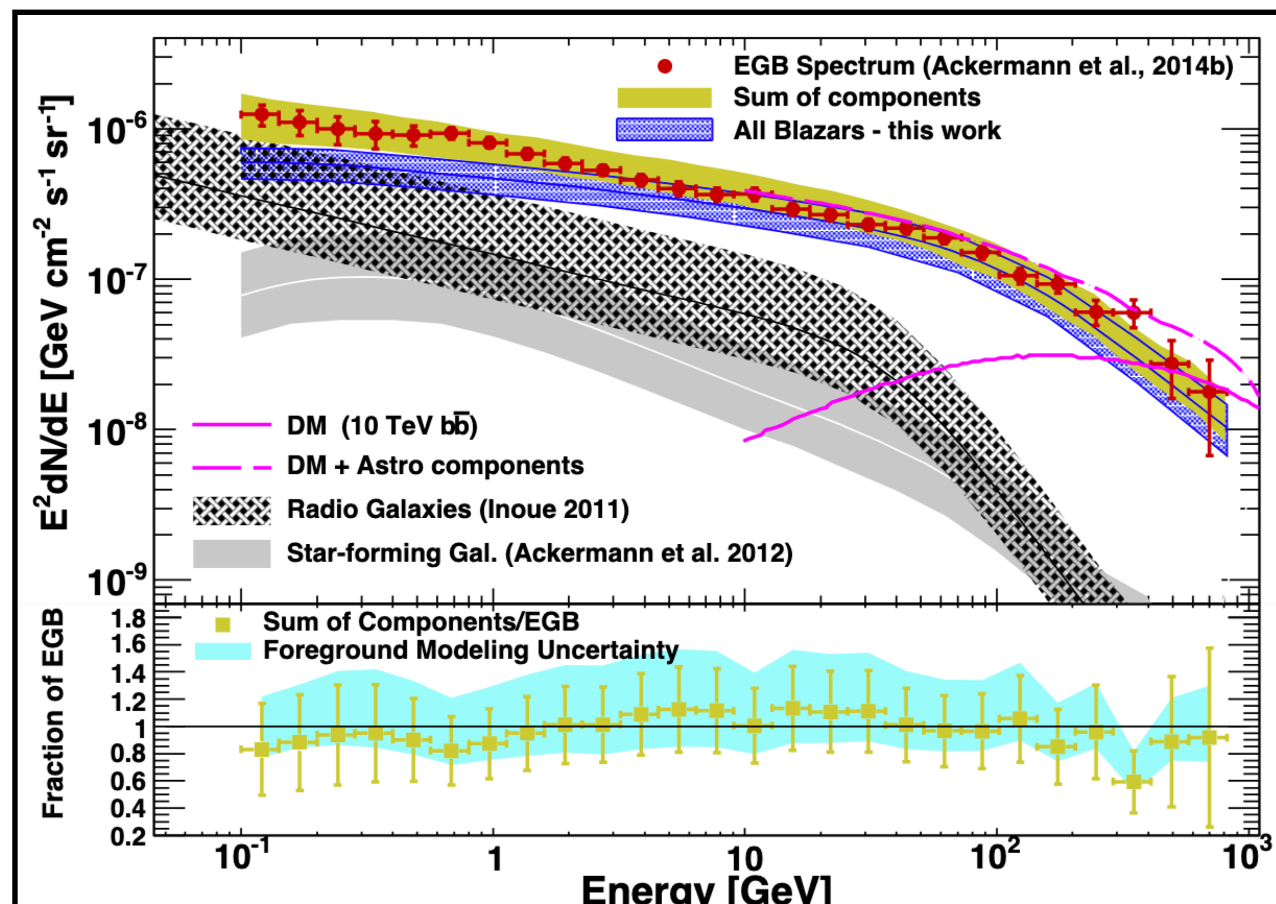


Isotropic emission



dominates at high latitudes

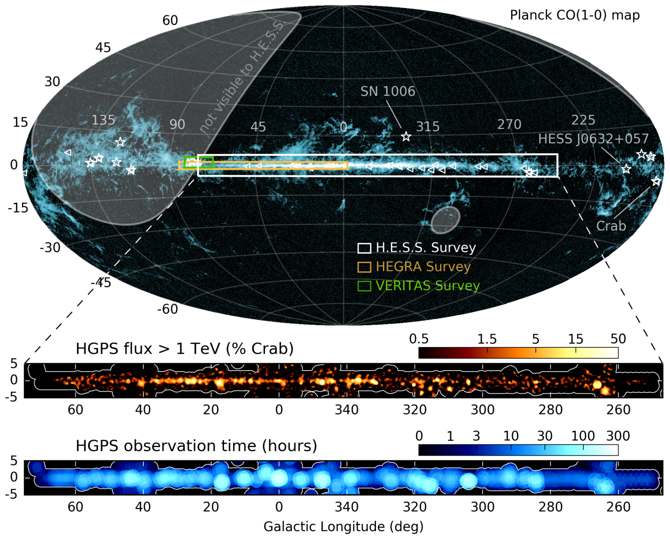
Cumulative emission from all individually unresolved sources



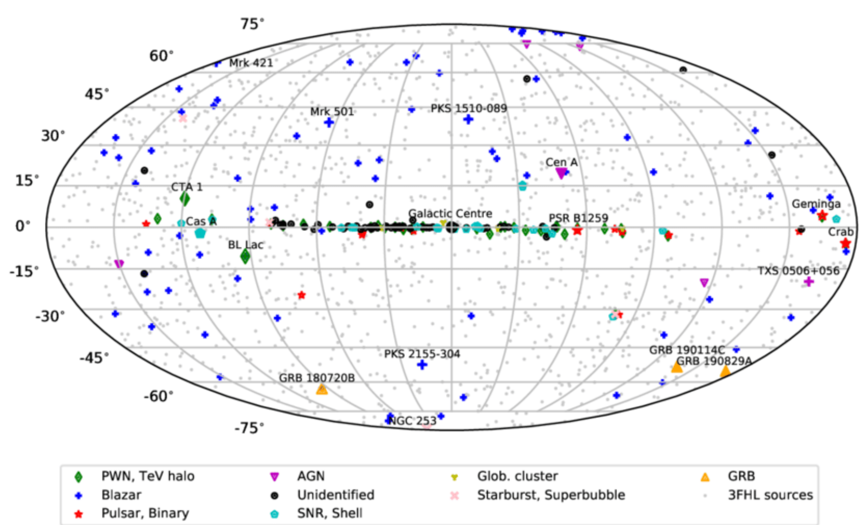
[Ackermann+, ApJ799, 2015)]

The TeV sky

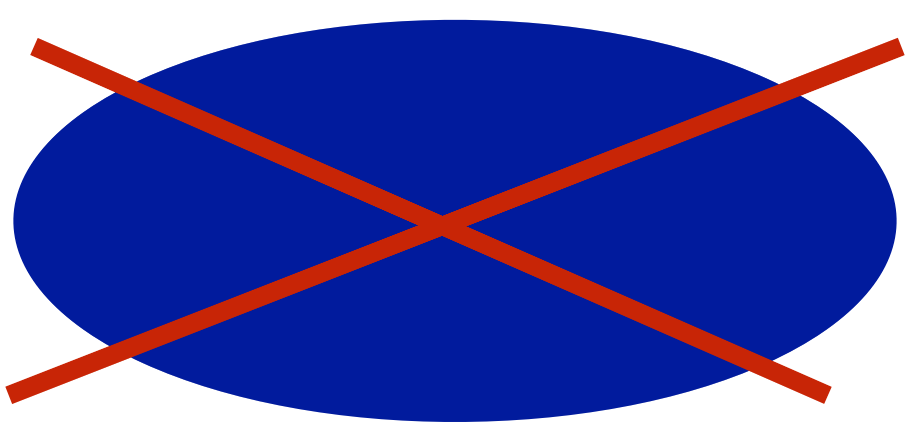
Diffuse emission from our Galaxy

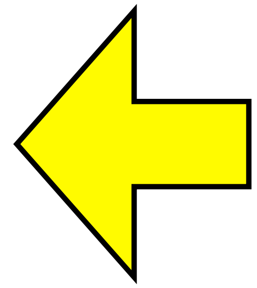


Point sources

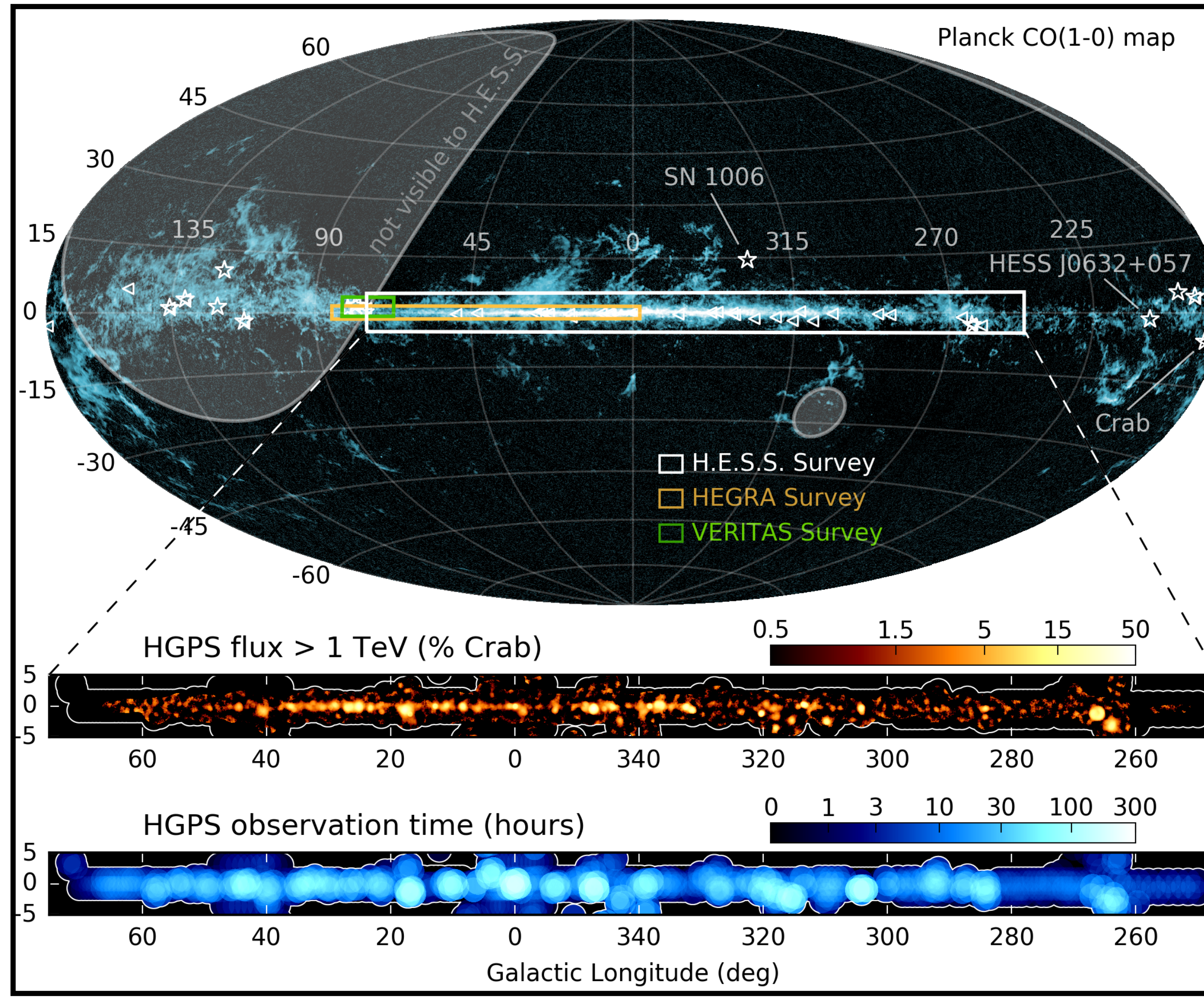


Isotropic emission





Ground based telescopes performed survey observations of extended regions:



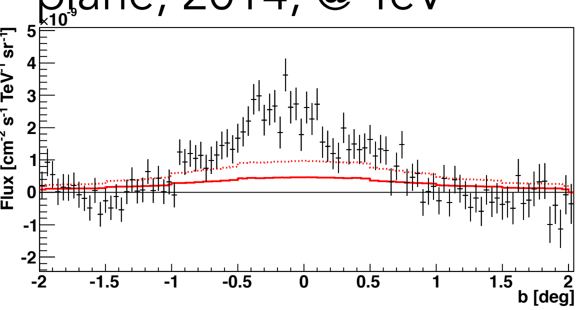
Cumulative diffuse emission detected along the plane

[H.E.S.S. Galactic Plane Survey]

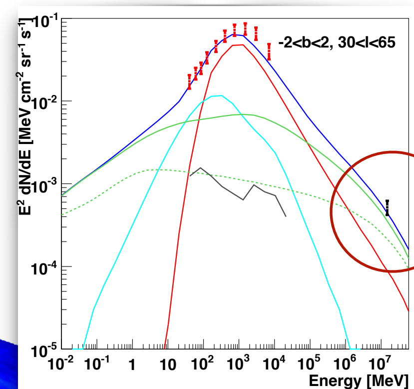
Galactic interstellar emission at TeV?

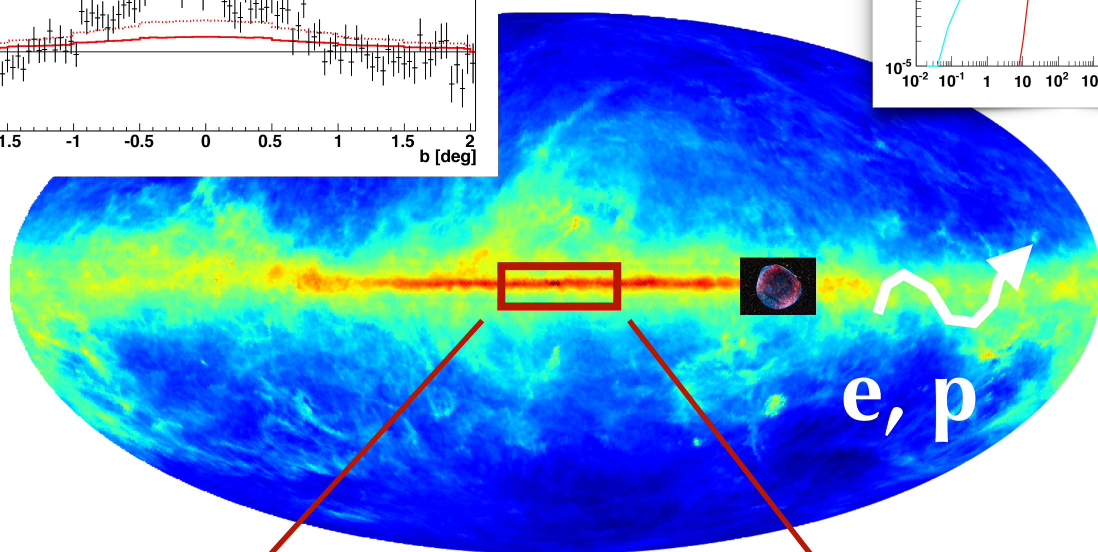
Gamma-ray IE allows us to (indirectly) probe Galactic CR distribution, IS medium (gas density) and fields (ISRF, B) and to constrain the CR transport properties

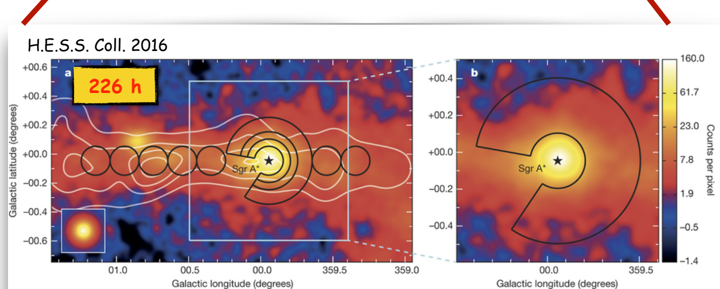
HESS cumulative emission from the plane, 2014, @ TeV

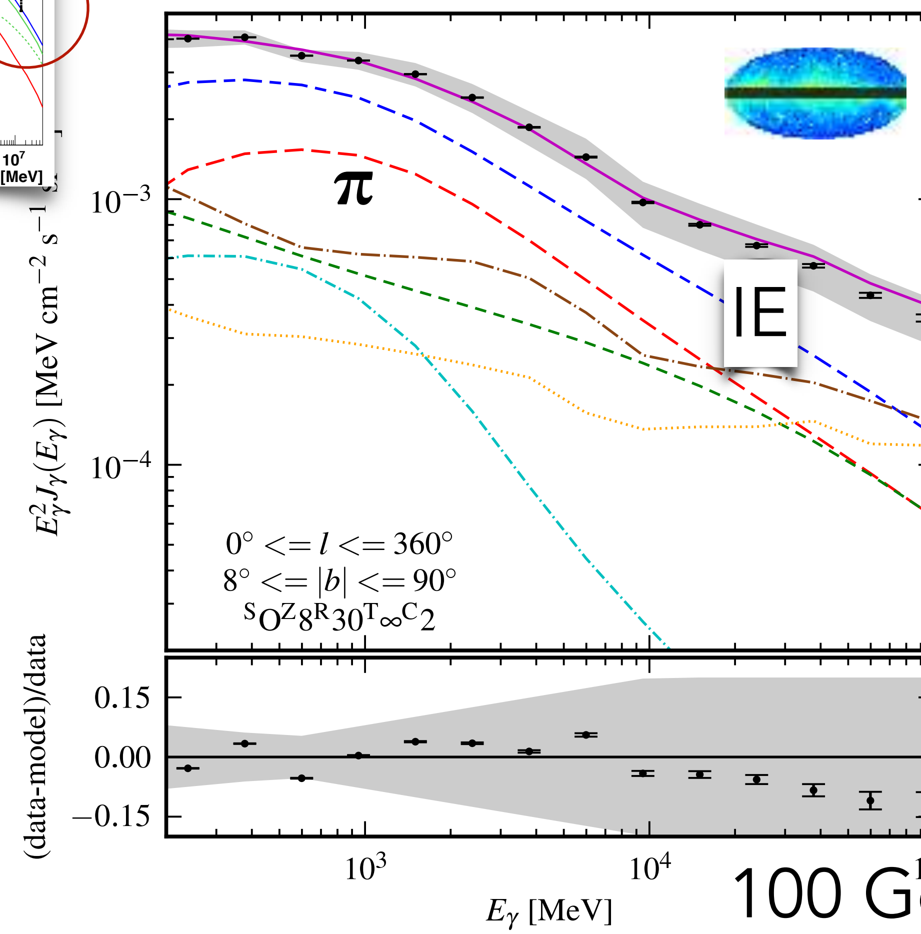


MILAGRO, 2008 30<l<65, lbl <2, @15 TeV







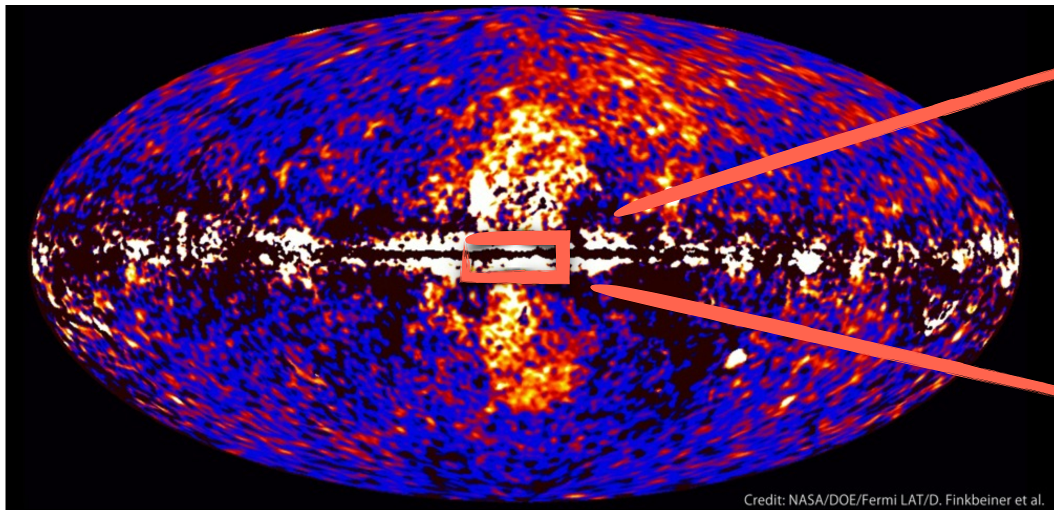


...?

100 GeV

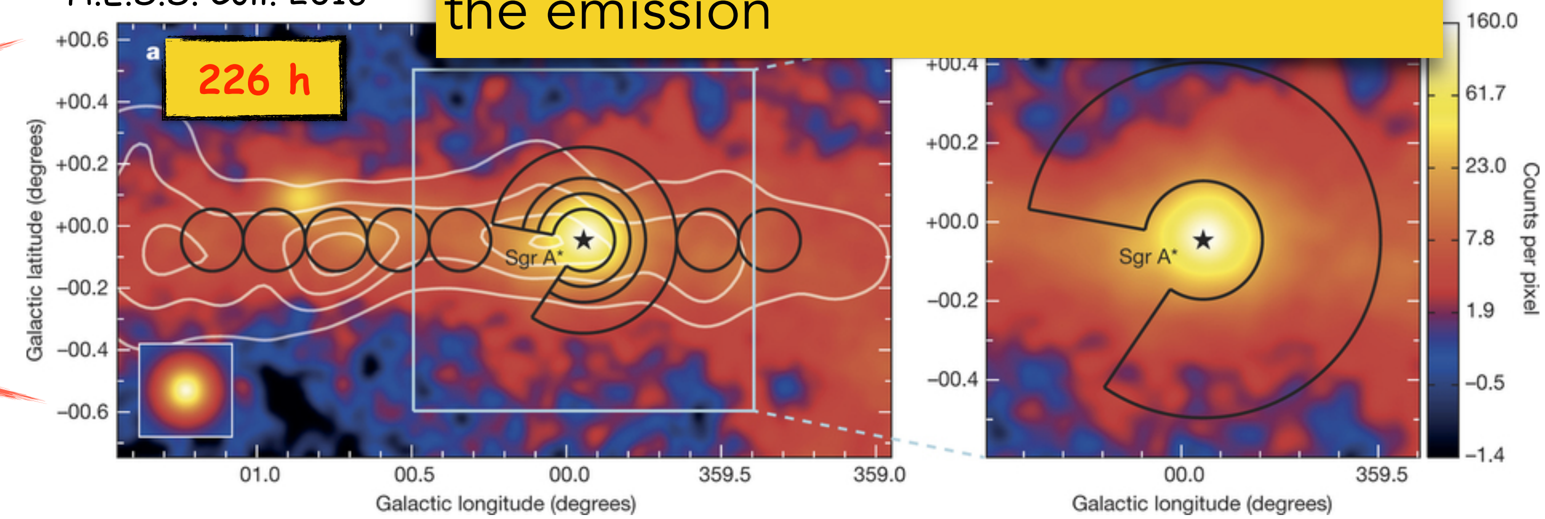
TeV

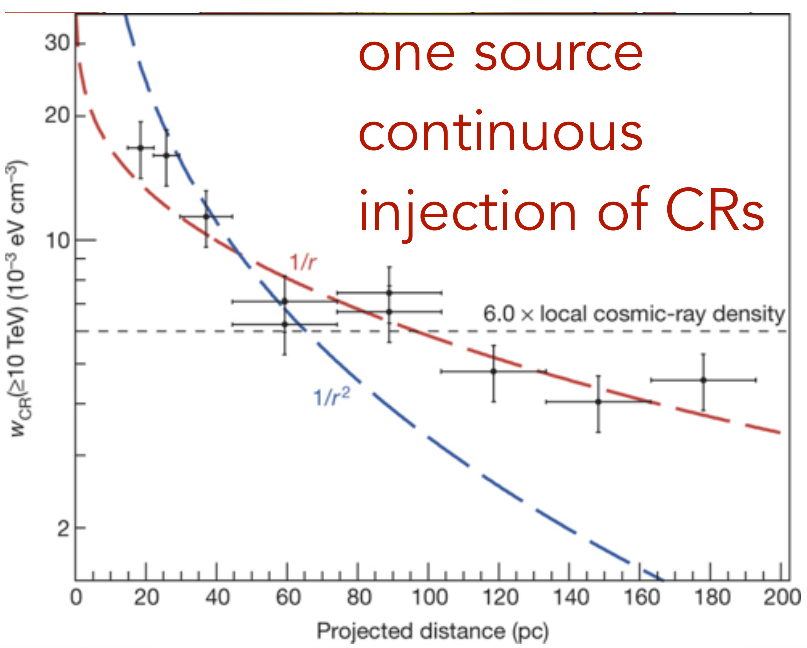
Galactic
PeVatrons ?



H.E.S.S. Coll. 2016

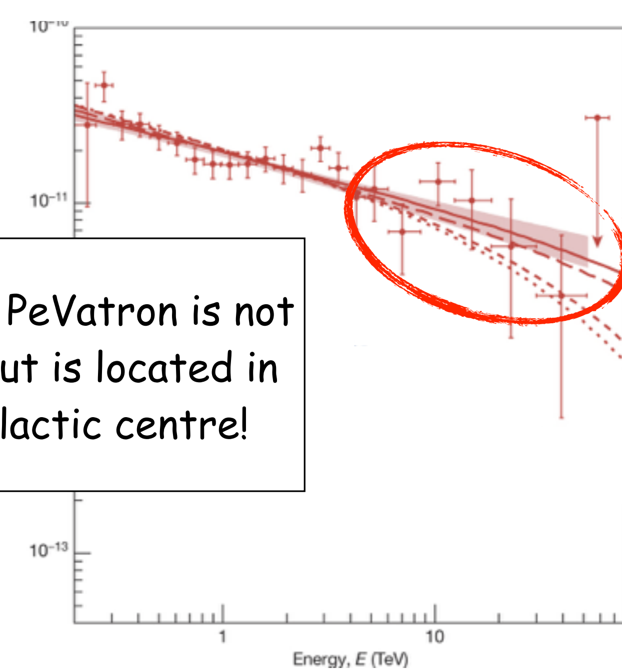
Protons most likely responsible for the emission





one source continuous injection of CRs

The source likely related to the SMBH activity!



the first PeVatron is not a SNR but is located in the Galactic centre!

diffuse emission from the GC

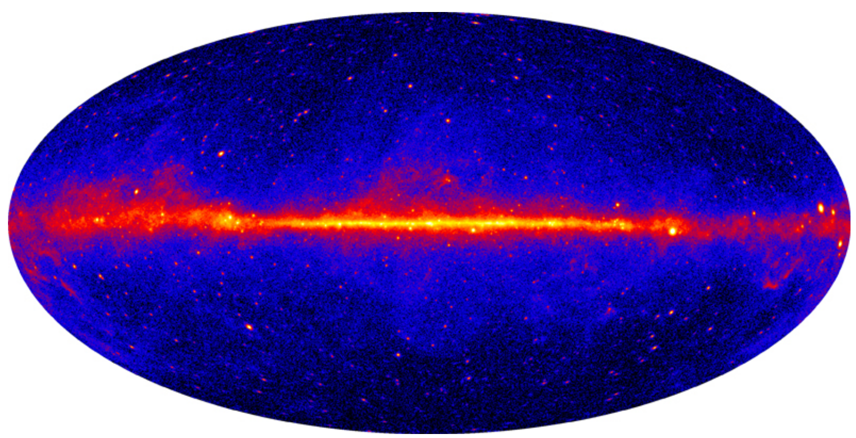
no cutoff!

a cutoff @ ...	deviates from data @
2.9 PeV	68%
0.6 PeV	90%
0.4 PeV	95%

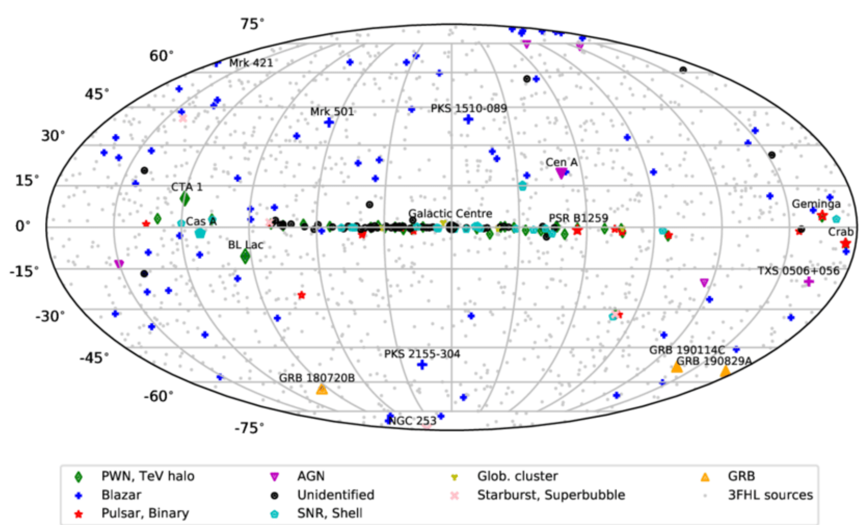
H.E.S.S. Coll. 2016

The TeV sky

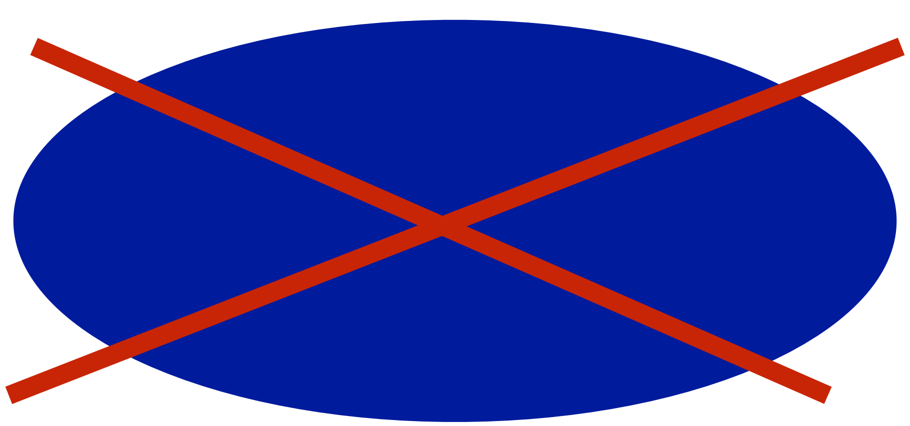
Diffuse emission from our Galaxy



Point sources

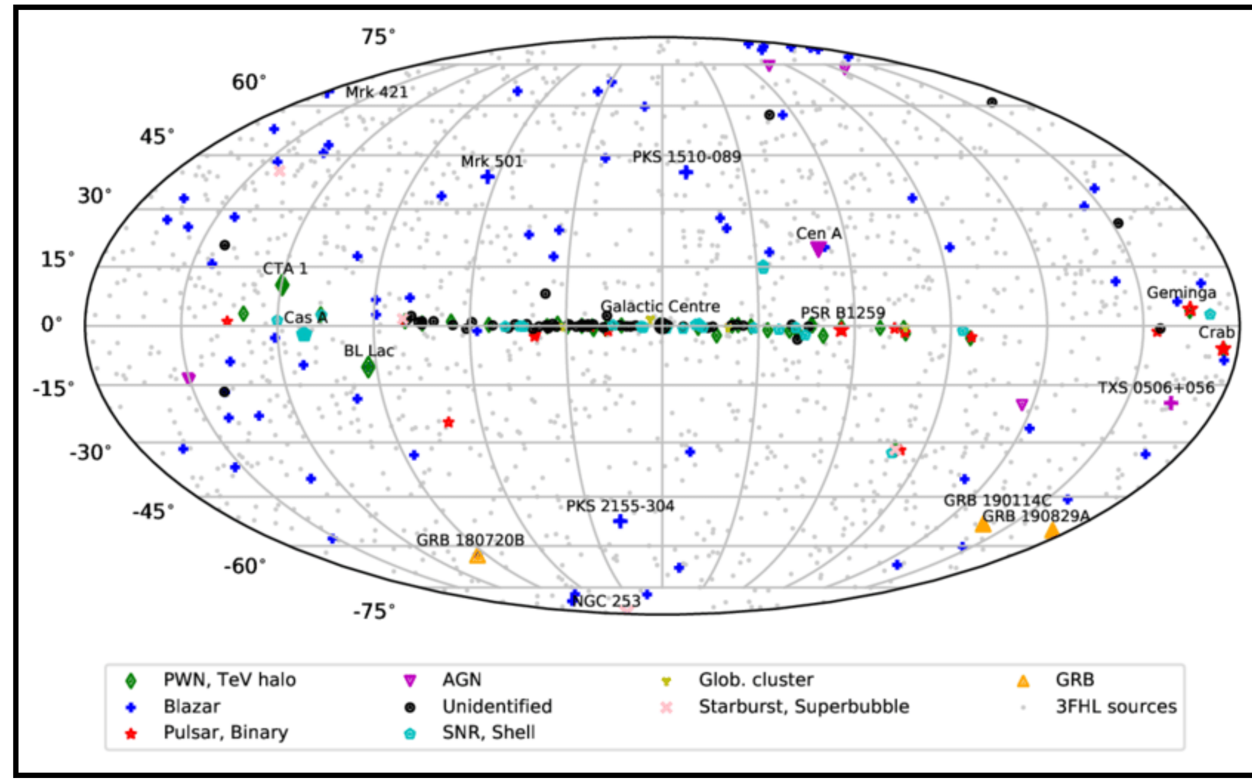


Isotropic emission



Hundreds of sources

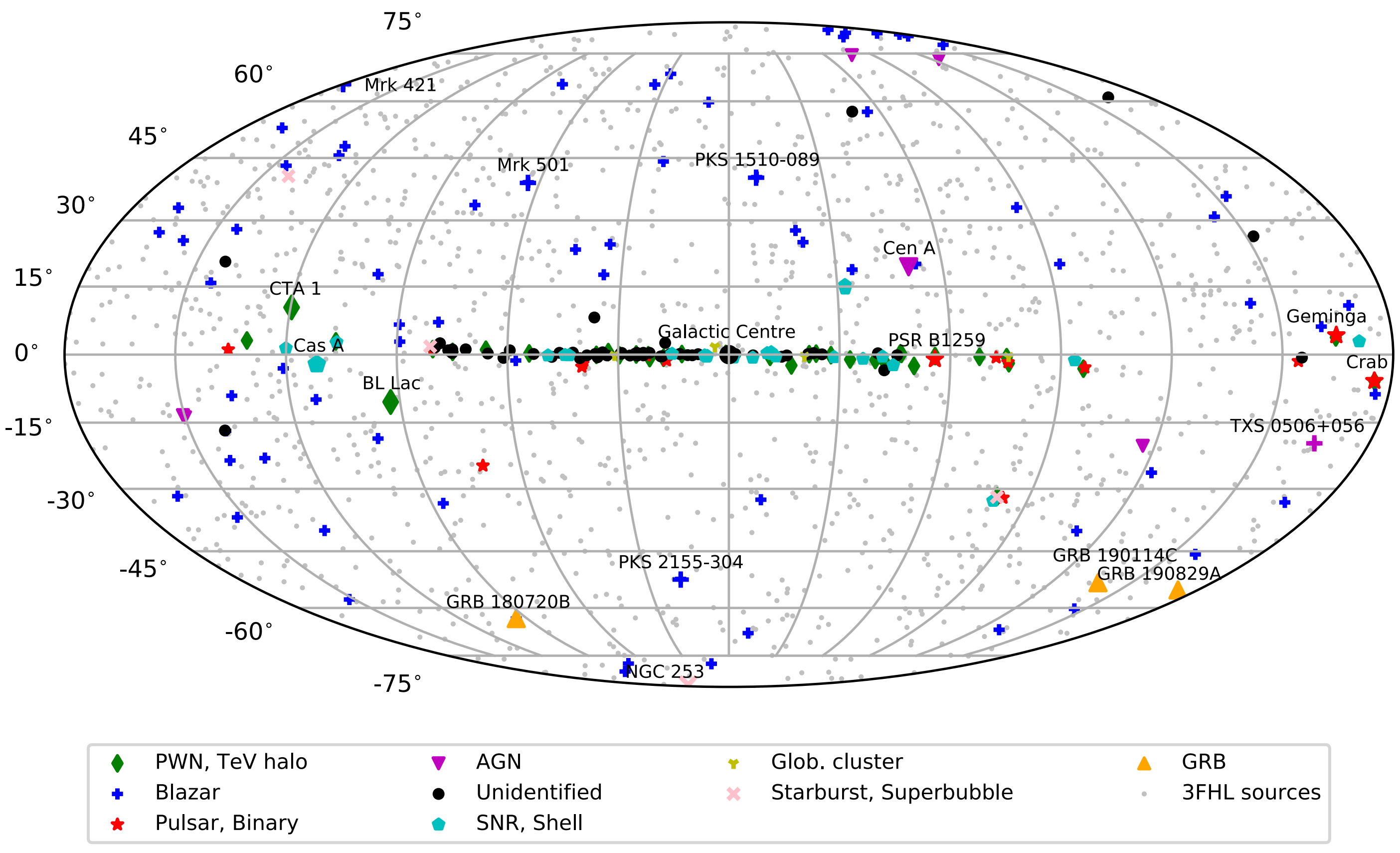
Significant portion of galactic sources is extended (PWNs, SNRs etc)



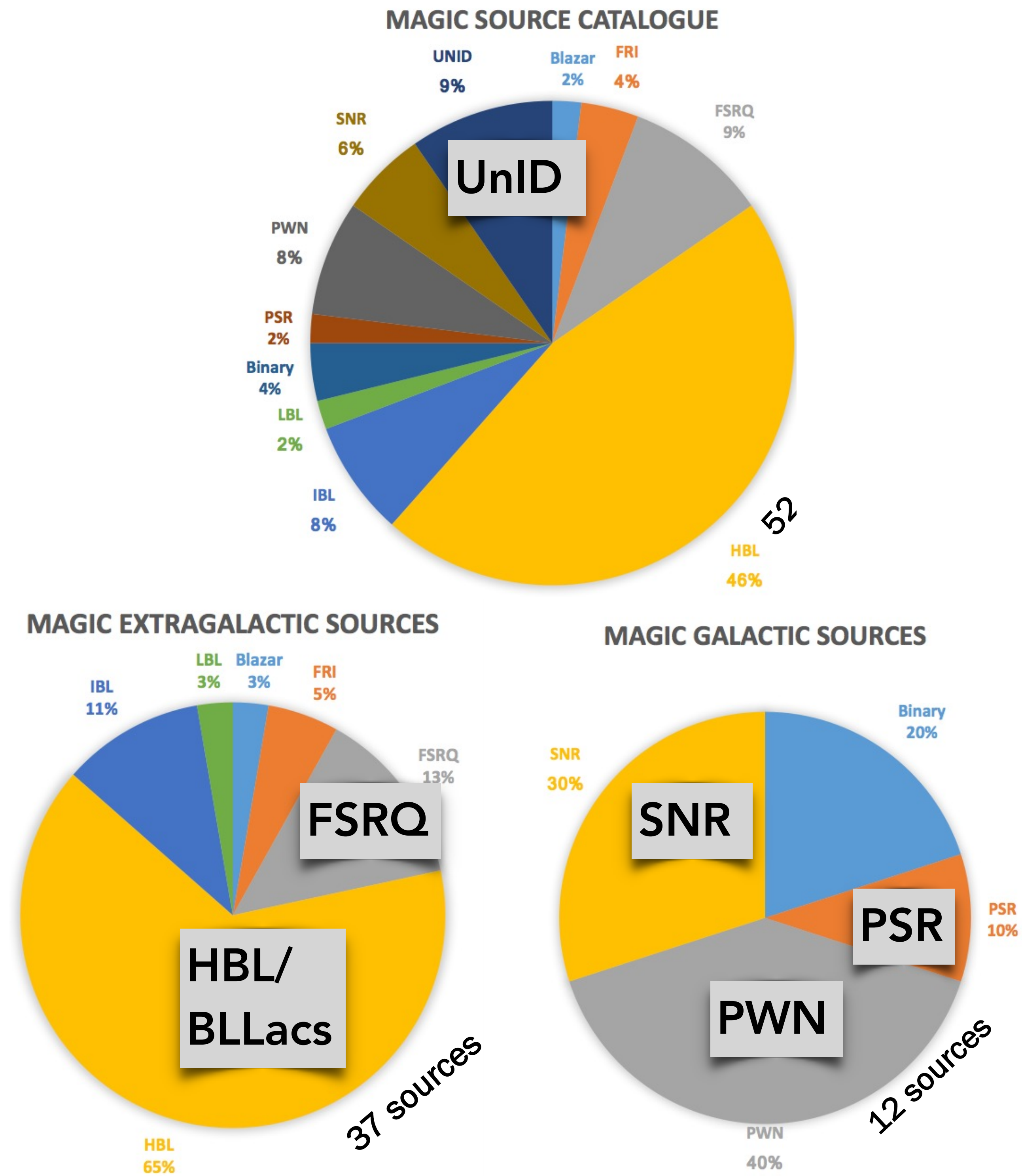
[TeVCat, mid 2019]

TeVCat, what sources?

The TeV sky (mid-2019) overlayed with the 3FHL



[Hinton & Ruiz-Velasco, 2019]

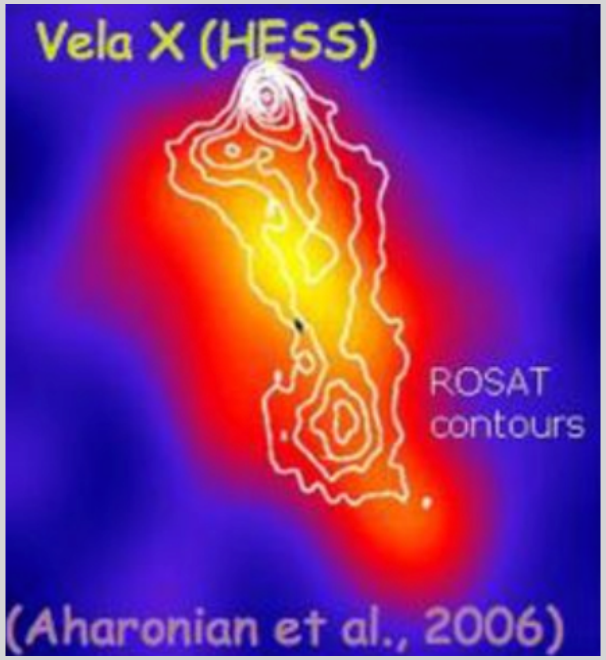


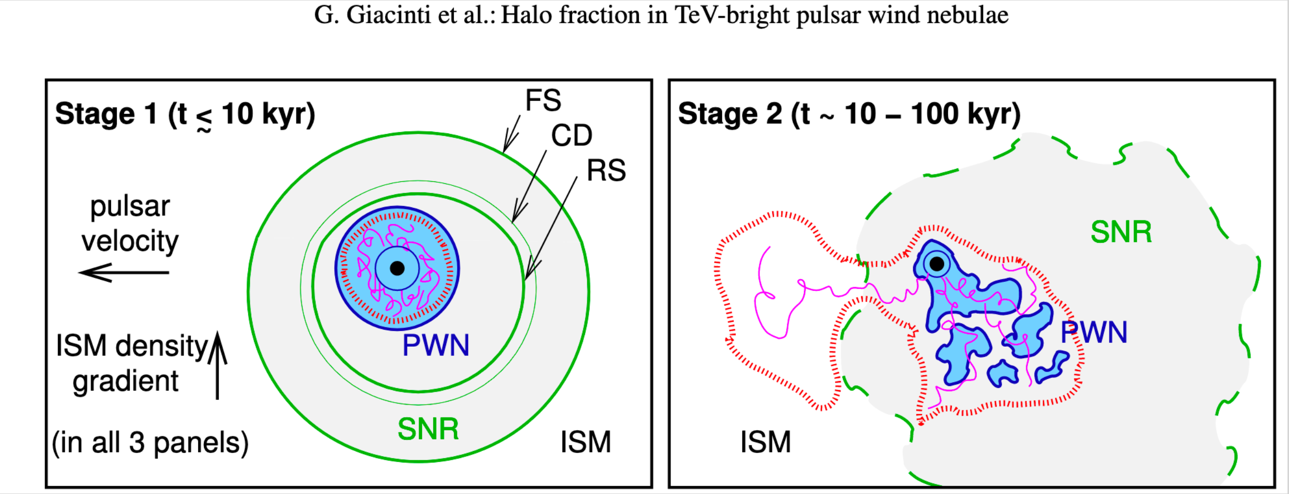
[M. Doro, ISAPP school 2021]

TeVCat, Galactic sources

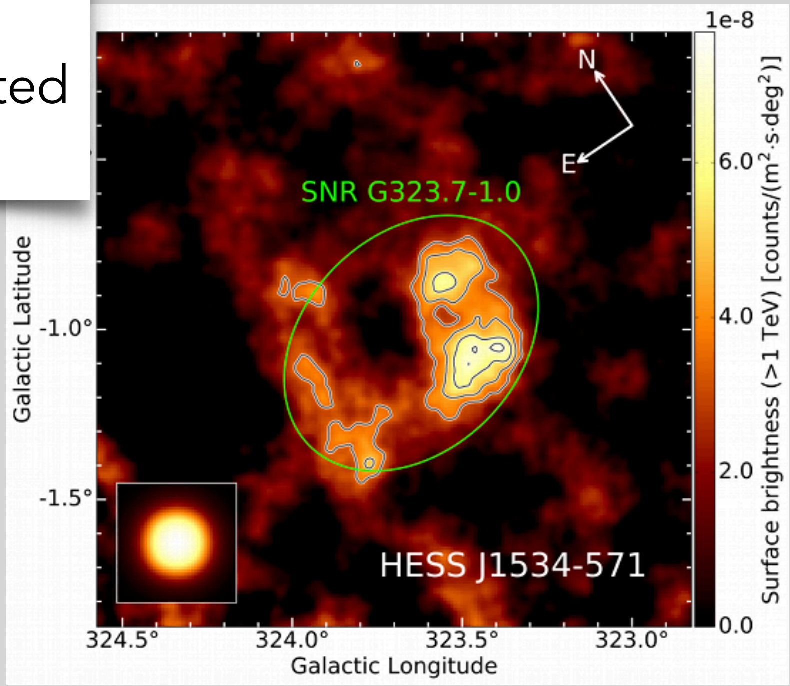
A large fraction of sources **PWNs**

Recall: @ LAT energies (related) pulsars are the most dominant source class



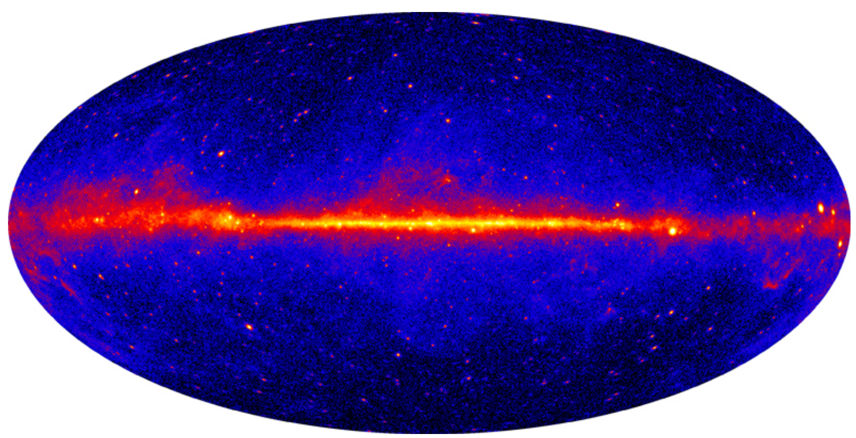


PWN: emission in a zone where a pulsar's influence is dominant, particle propagation ~ dominated by advection

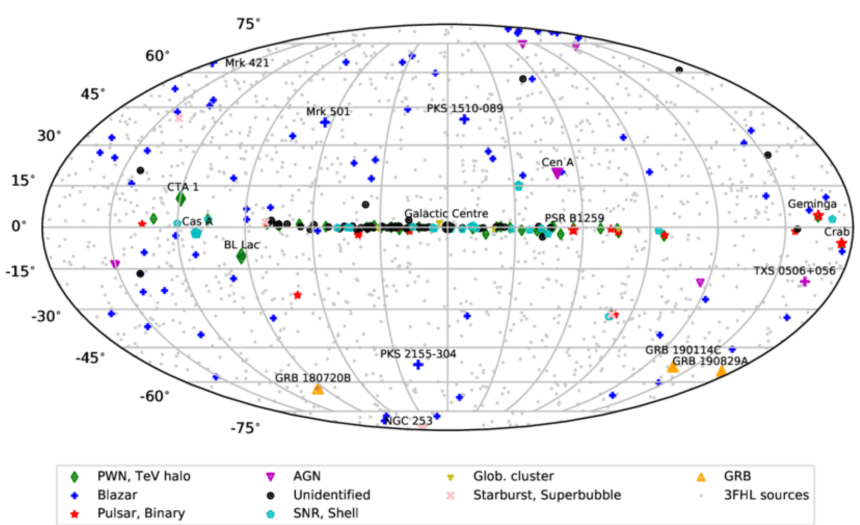


The TeV sky

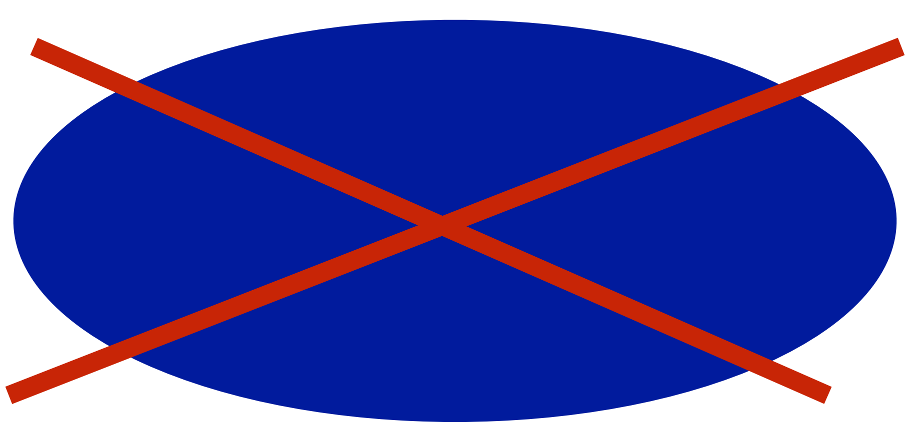
Diffuse emission from our Galaxy



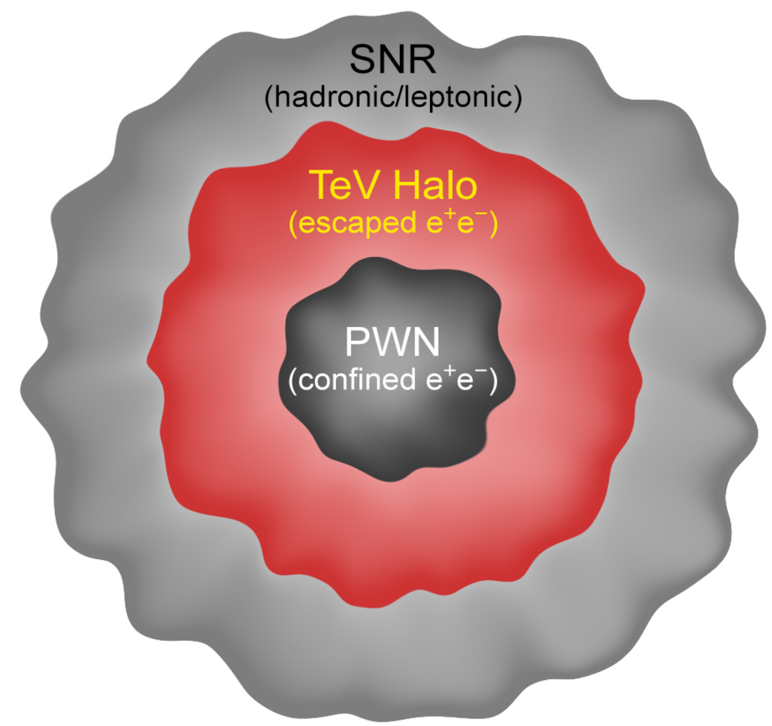
Point sources



Isotropic emission



New source classes discovered (HAWC)- pulsar halos

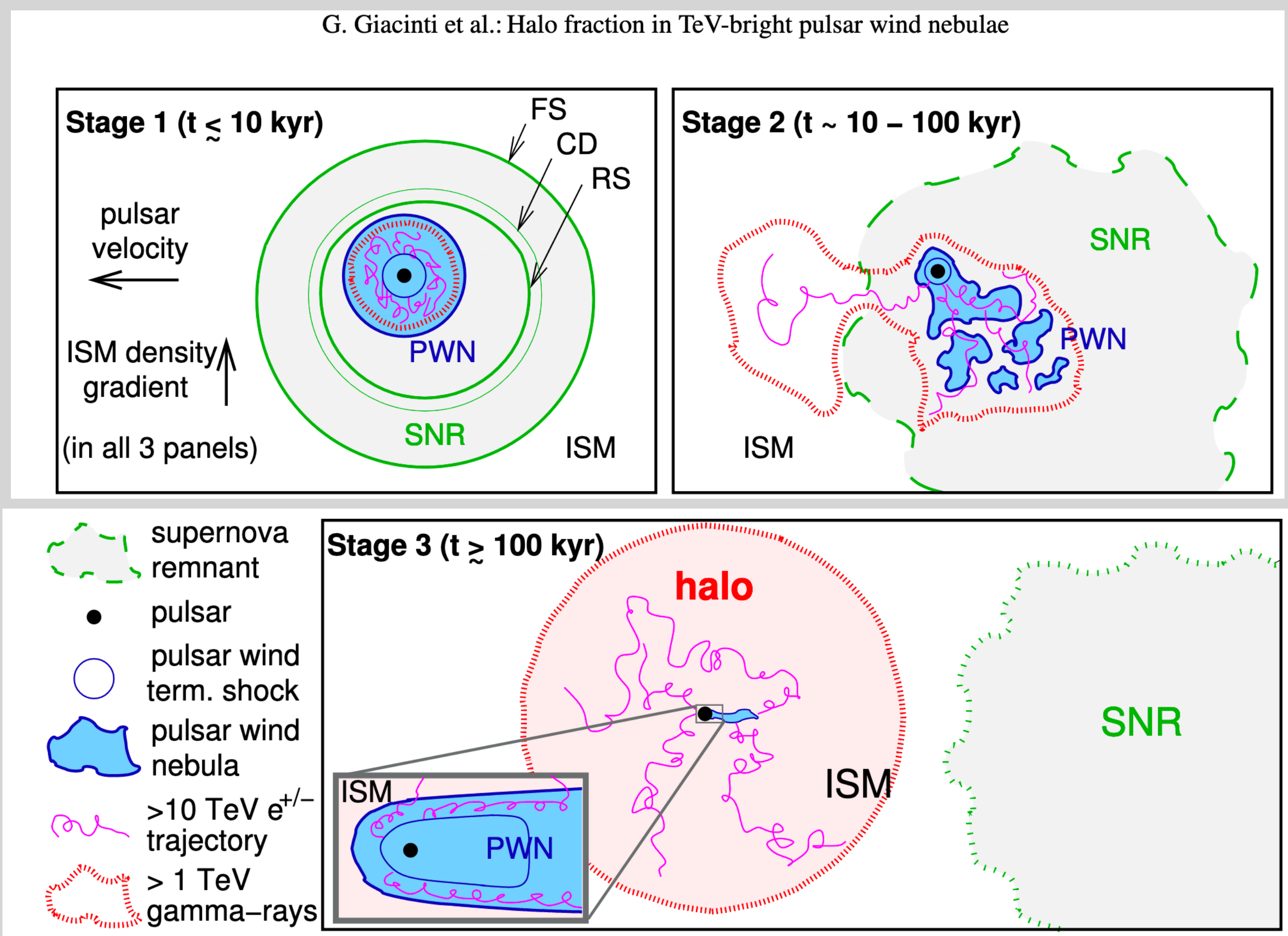


[Sudoh+, 2019]

New powerful ways to probe electron population in our galaxy and the CR diffusion properties!

TeVCat, Galactic sources

New source class, **TeV halos**, also related to pulsars!



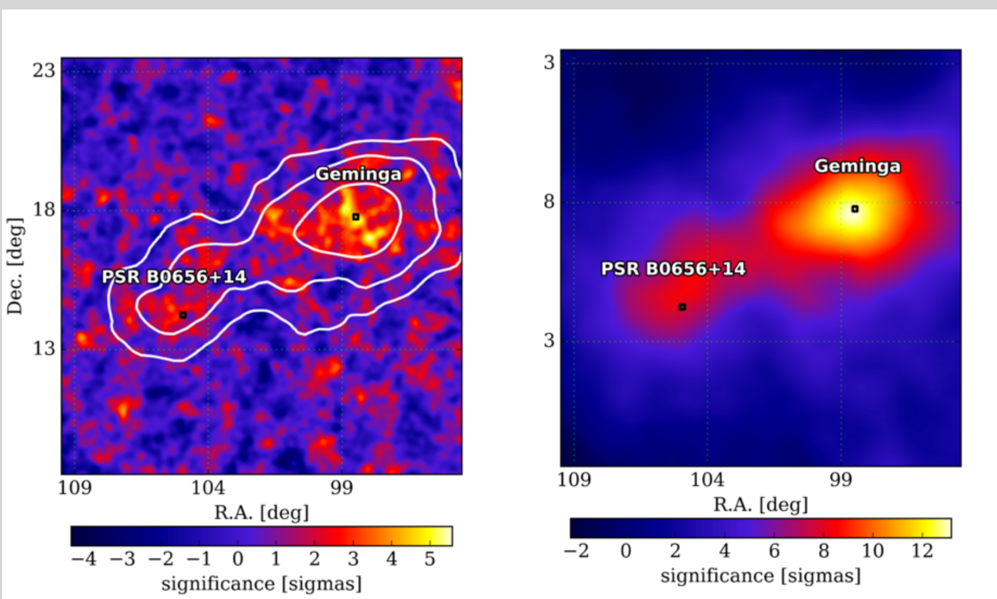
TeV halos: larger zone (>~middle aged pulsars) in which the PSR does not dominate the environment. diffusion >~ than advection

TeVCat, Galactic sources

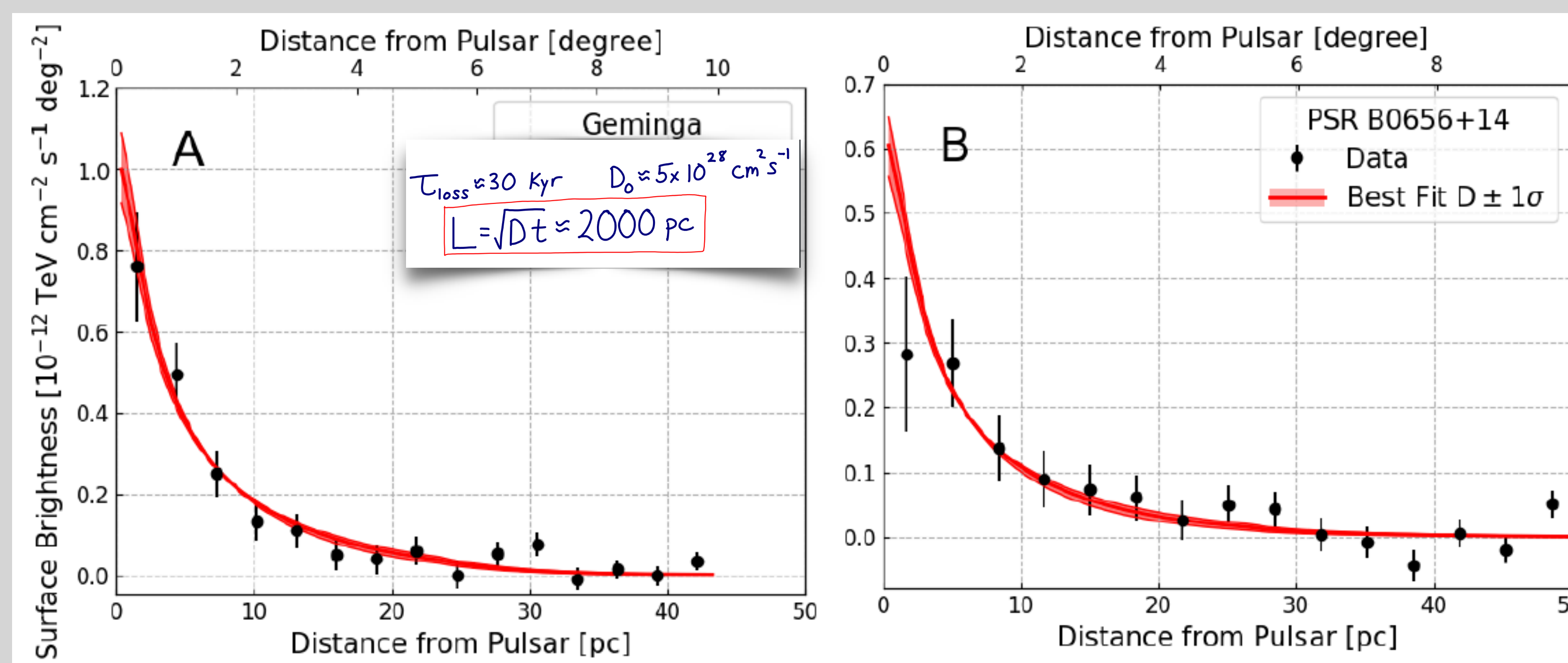
New source class: Geminga and Monogem pulsars are surrounded by a spatially extended region (~25 pc) emitting multi - TeV gamma-rays: ***pulsar TeV halos (HAWC)!*** (Note Geminga halo detected by Milagro 2007)

Implied diffusion coefficient TWO ORDERS OF MAGNITUDE lower than the one in the Galaxy.

The HAWC Collaboration, *Science* 358, 911 (2017)



➡ γ rays between 5−40 TeV, e+e- (IC) of ~TeV energies

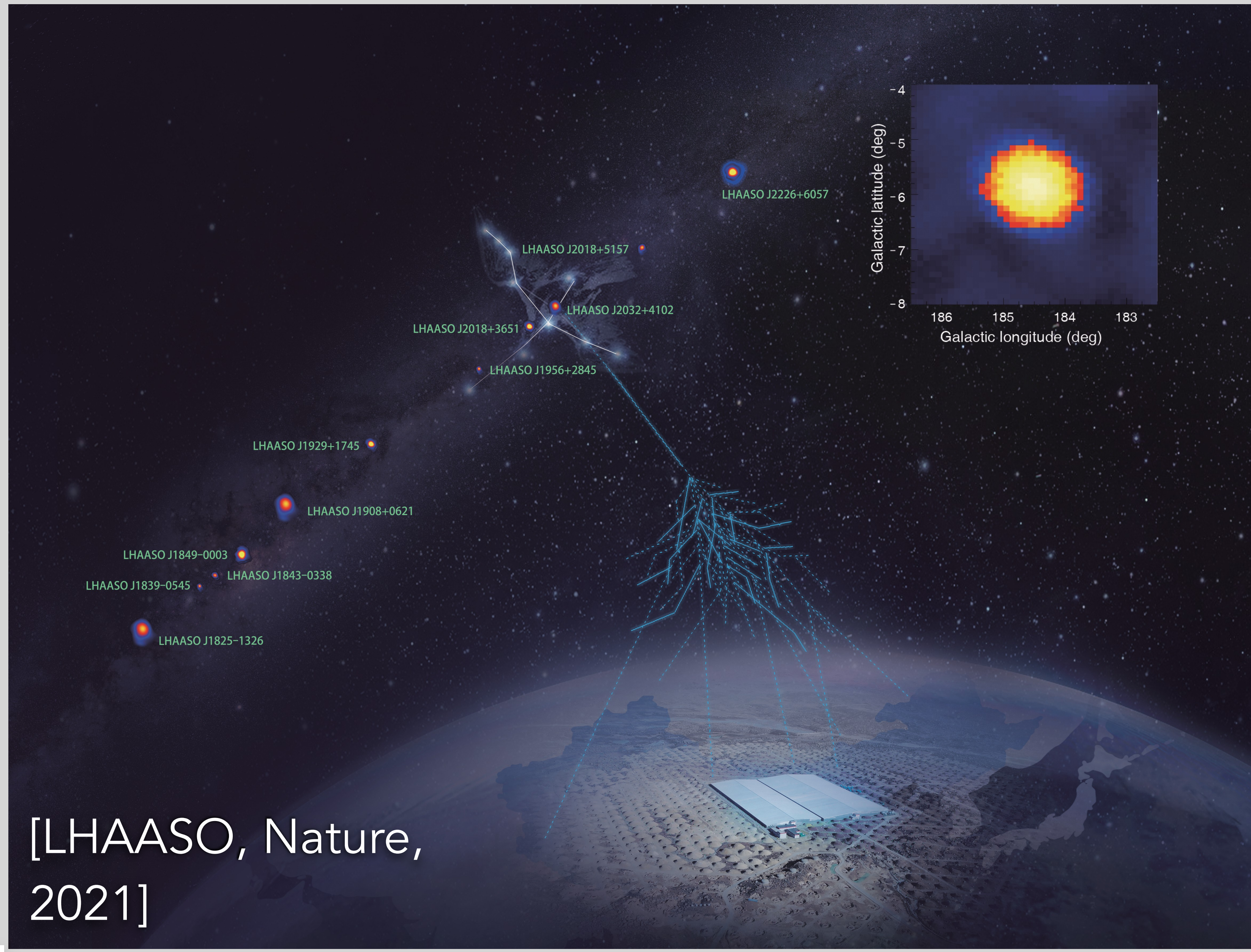


Galactic PeVatrons ?

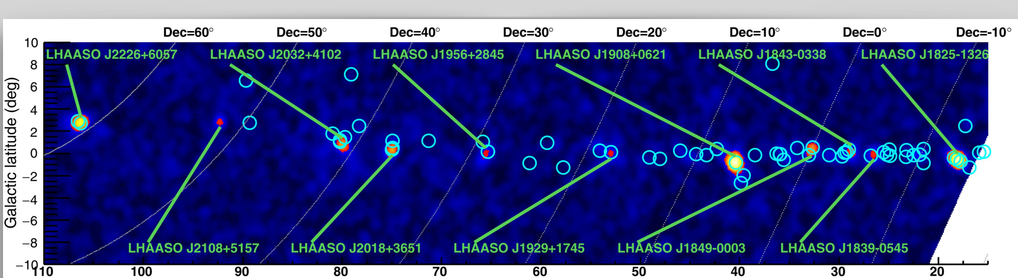
Galaxy is full of PeVatrons!

LHAASO detected **12 sources at > 0.1 PeV**, based on more than **530 photons** (including photons up to **1.4 PeV**)!

In the proximity of known gamma ray emitters, ***PWNe, SNRs and star-forming regions (+Crab nebula)***



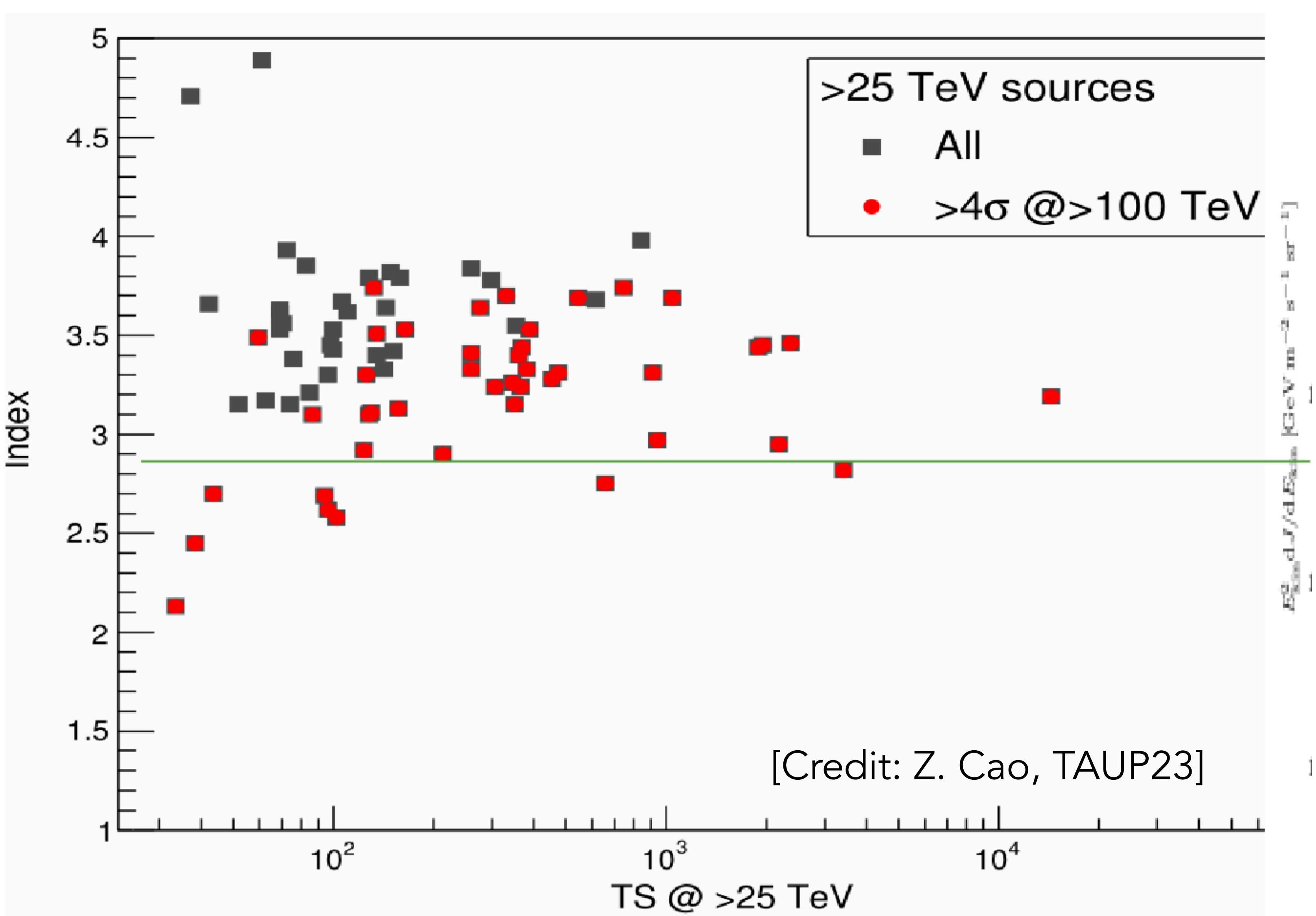
[LHAASO, Nature, 2021]

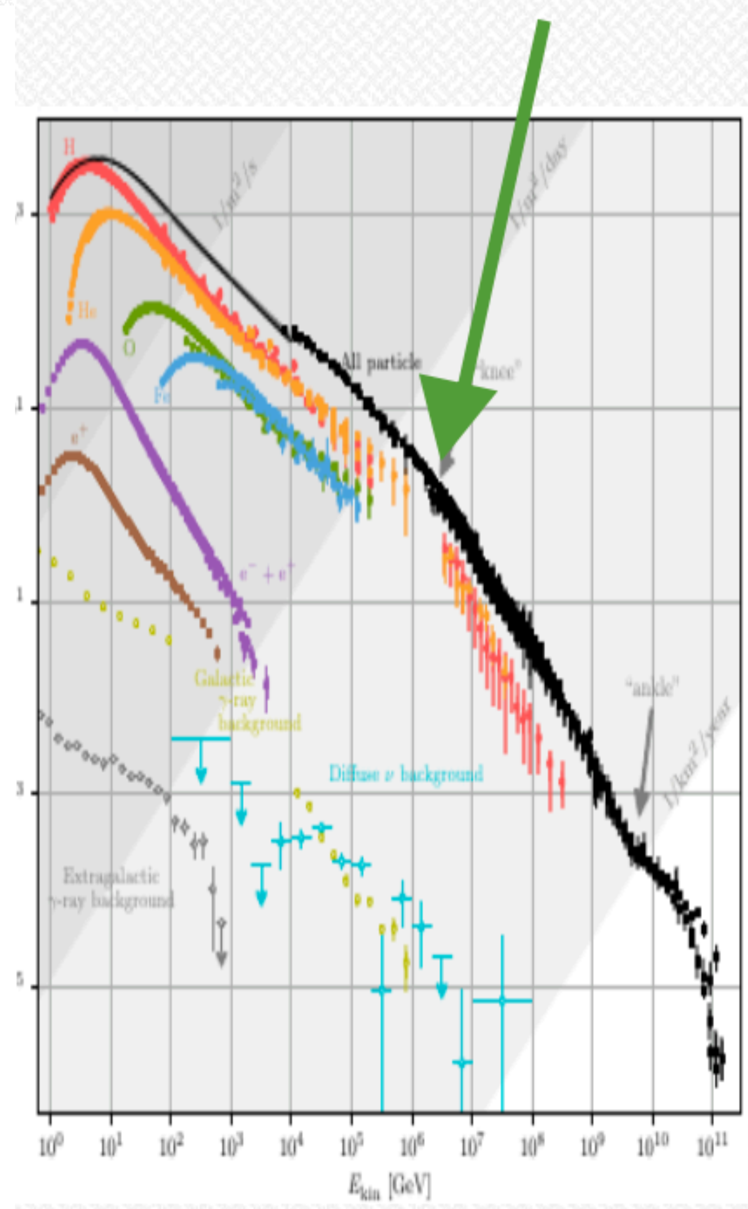


43 PeVatrons are discovered

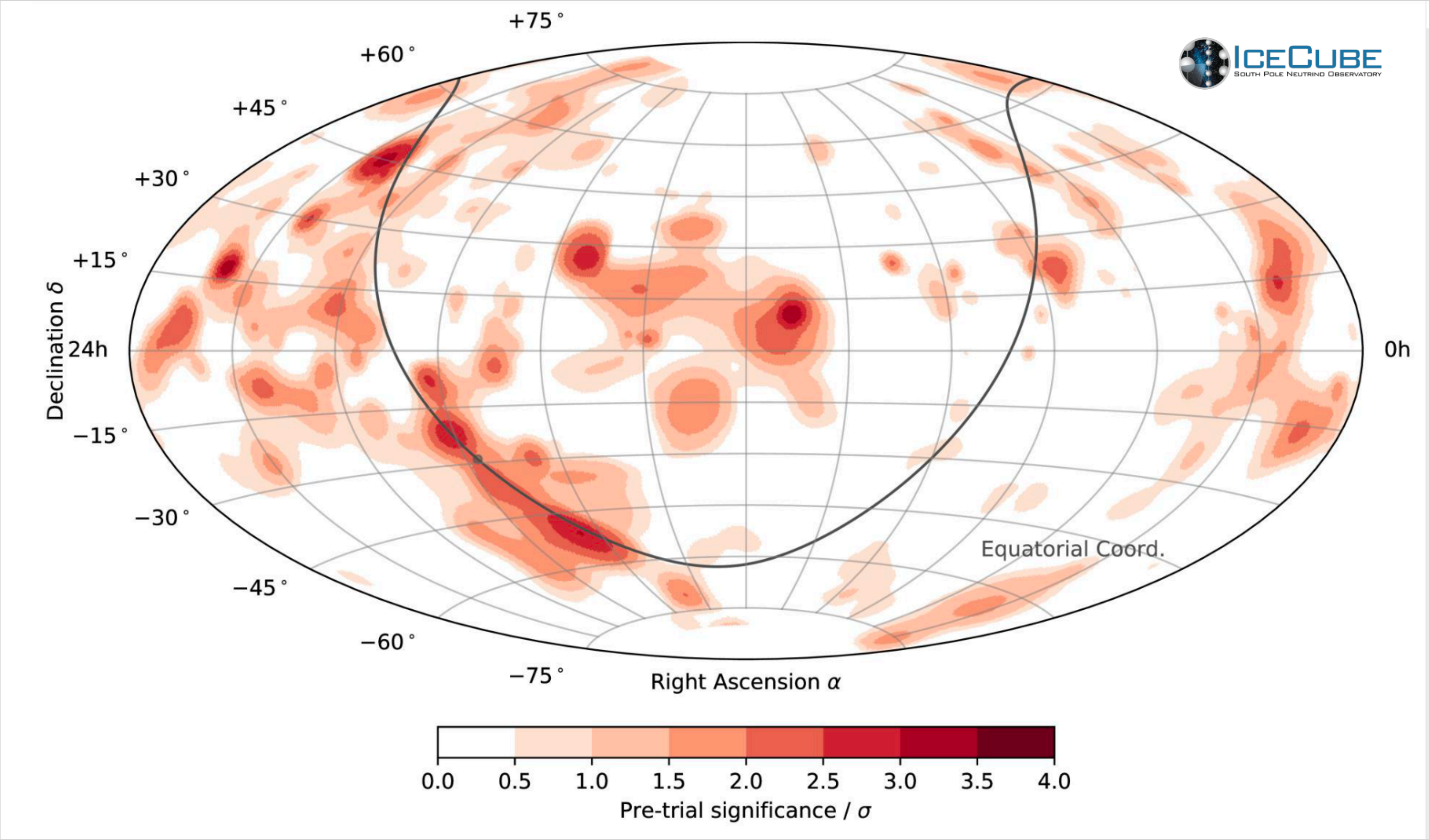
- Photons having E_γ>100 TeV are detected in the 43 sources significantly (>4σ)
- The spectra of the PeVatrons are typically soft, w/ spectral index > 3.
- 8 of them have hard spectra so that there is no emission detected in 1-10 TeV band

Implication: **Our Galaxy is full of PeVatrons, the candidates of the origin of cosmic rays around/above the knee**

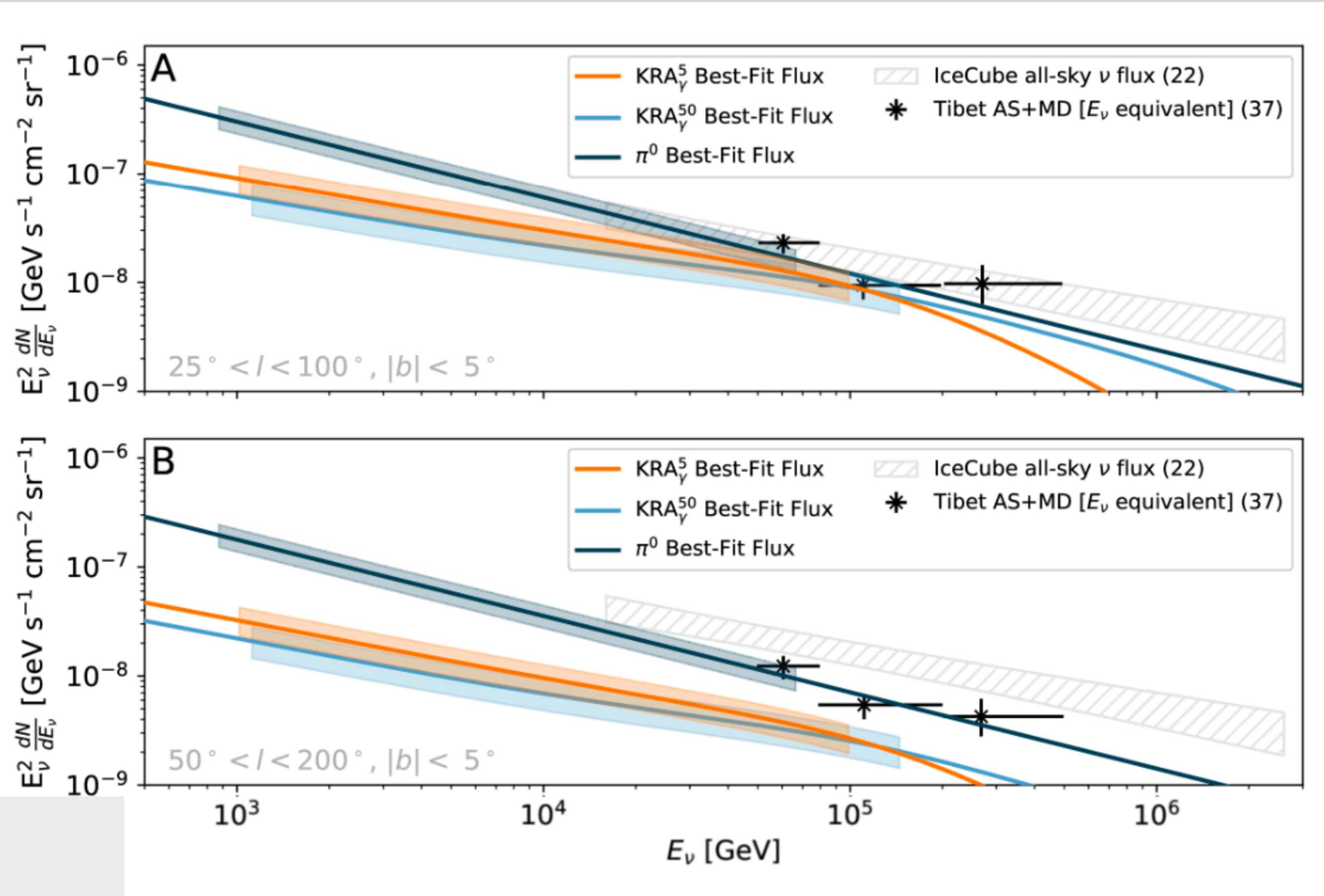
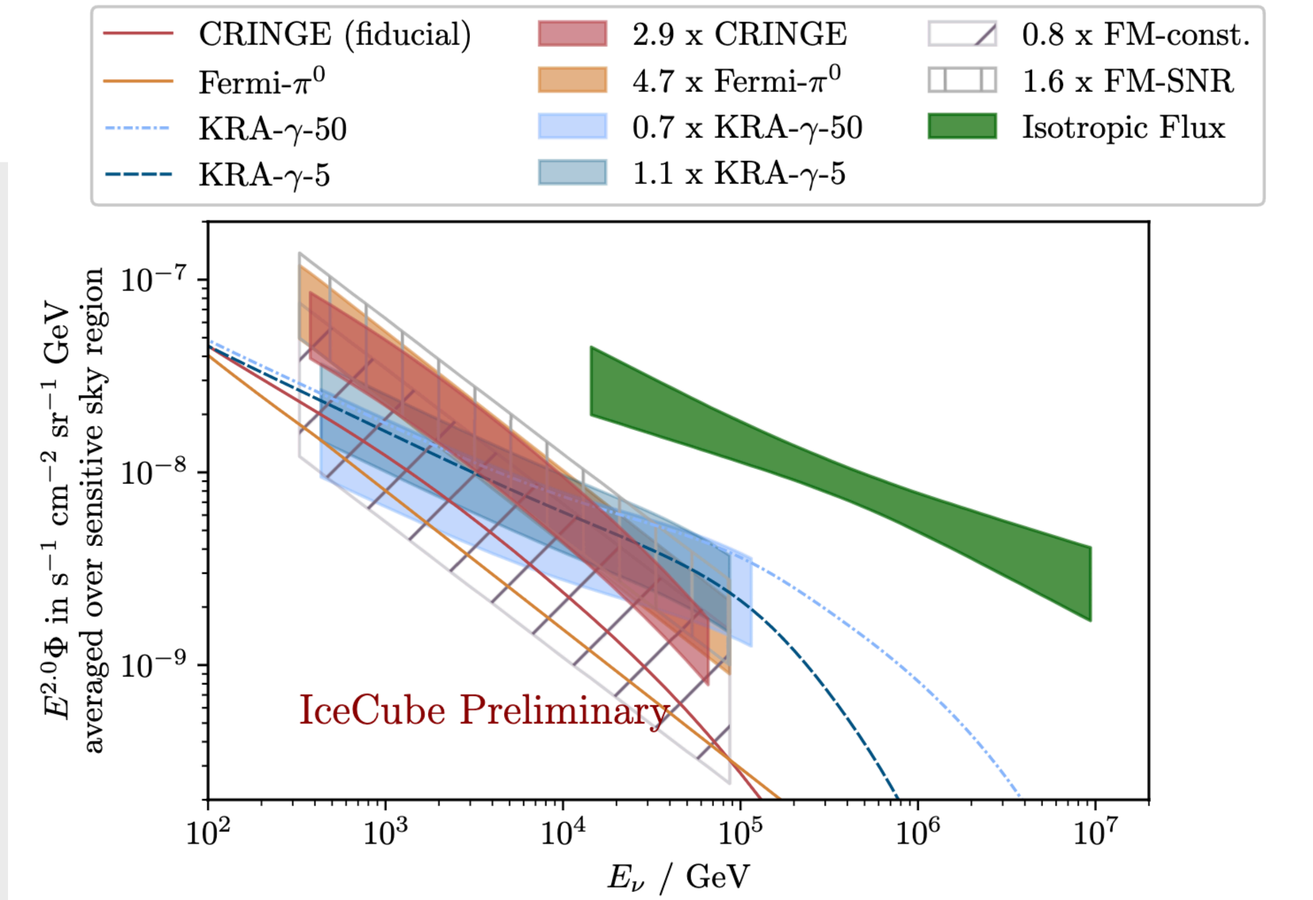
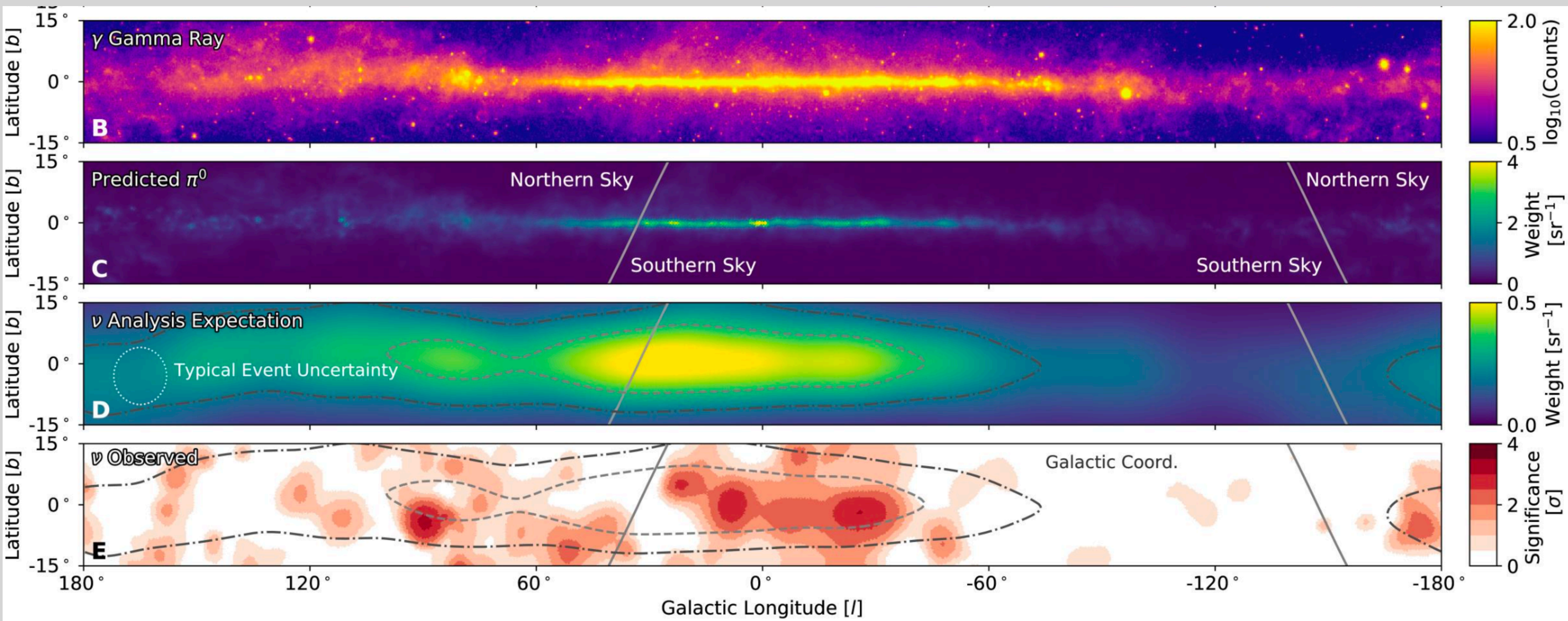




Brief status of neutrinos

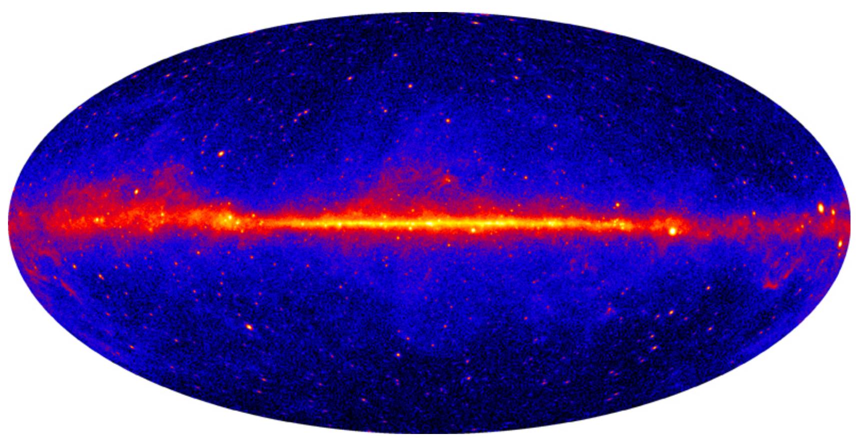


[IceCube Collaboration PoS ICRC2023 (2023) 1046]

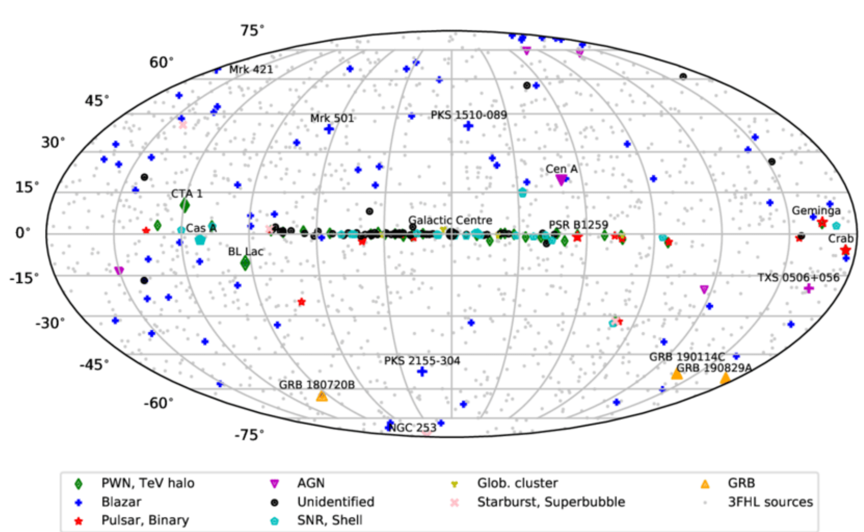

A
KRA_γ^5 Best-Fit Flux
KRA_γ^{50} Best-Fit Flux
π^0 Best-Fit Flux
IceCube all-sky ν flux (22)
Tibet AS+MD [E_ν equivalent] (37)
$25^\circ < l < 100^\circ$, $|b| < 5^\circ$
B
$50^\circ < l < 200^\circ$, $|b| < 5^\circ$
$E_\nu^2 \frac{dN}{dE_\nu}$ [GeV s^{-1} cm^{-2} sr^{-1}]
E_ν [GeV]

CRINGE (fiducial)
Fermi-π^0
KRA-γ-50
KRA-γ-5
2.9 x CRINGE
4.7 x Fermi-π^0
0.7 x KRA-γ-50
1.1 x KRA-γ-5
0.8 x FM-const.
1.6 x FM-SNR
Isotropic Flux
IceCube Preliminary
$E^{2.0}\Phi$ in s^{-1} cm^{-2} sr^{-1} GeV
averaged over sensitive sky region
E_ν / GeV

γ Gamma Ray
B
log$_{10}$(Counts)
Predicted π^0
Northern Sky
Southern Sky
C
Weight [sr^{-1}]
ν Analysis Expectation
Typical Event Uncertainty
D
ν Observed
Galactic Coord.
E
Significance [σ]
Latitude [b]
Galactic Longitude [l]

The TeV sky

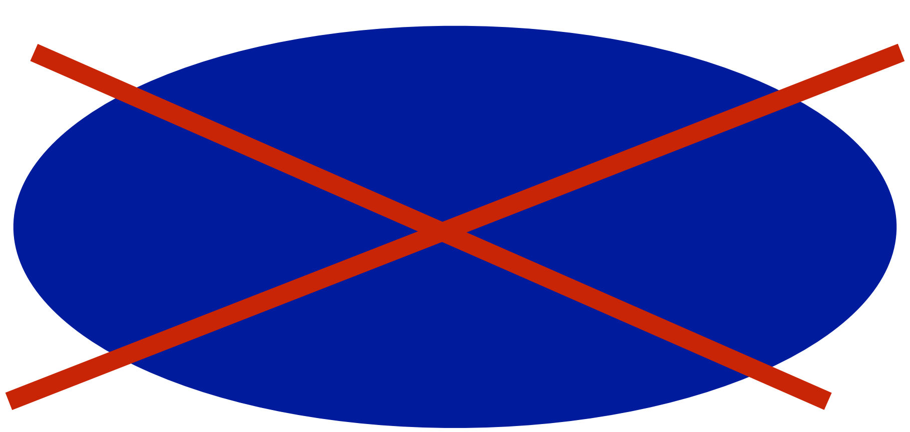
Diffuse emission from our Galaxy



Point sources

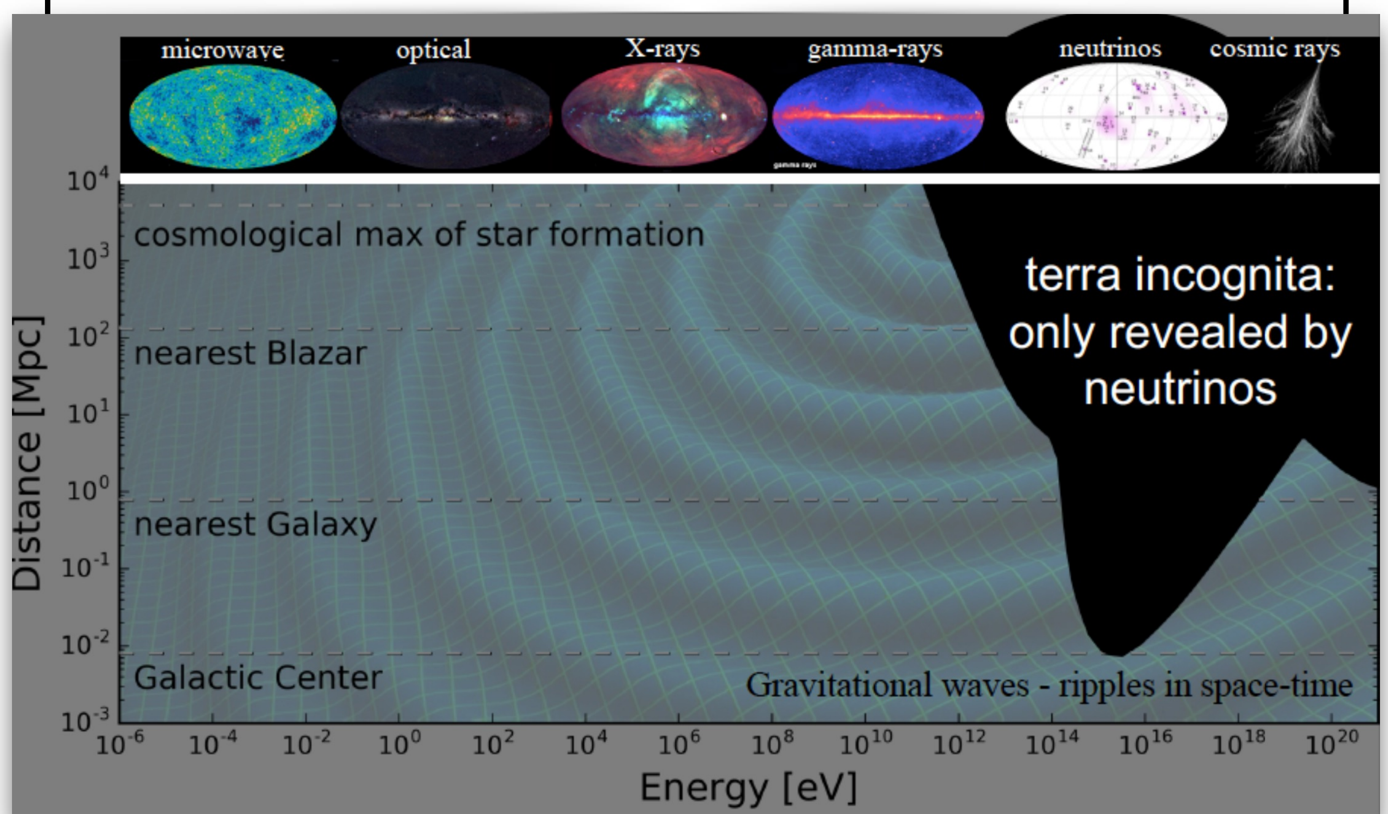


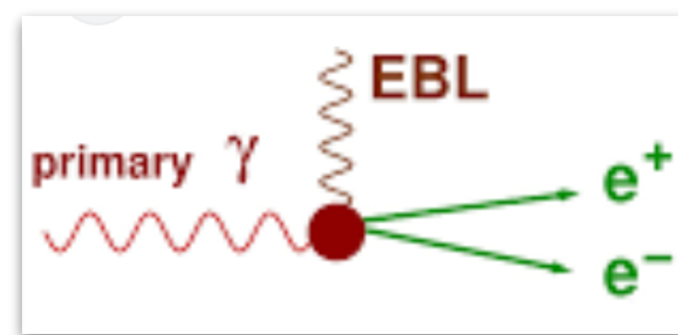
Isotropic emission



Extragalactic TeV sources

Note: 'near-by' Universe!





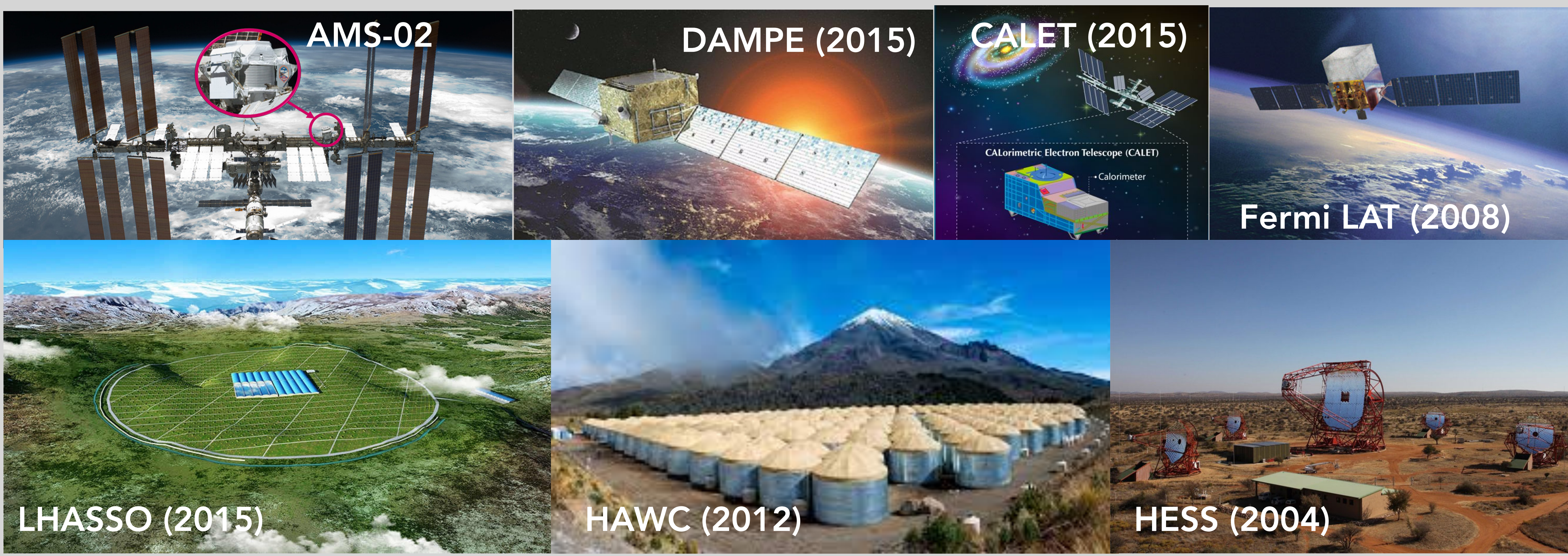
Neutrinos needed @>TeV

Summary

"More telescopes… more data… more questions…"

The field is vibrant with continuing discoveries + entering the 'PeV-era'

Next generation experiments well on the way… ***Stay tuned!***



Today’s tutorial

Gamma-ray sources with the Cherenkov Telescope Array (CTA)

- Vaguely inspired by the Galactic center excess: extended emission at the GC:
  - You will be asked to use likelihood fitting to determine weather the source in your data is point-like or extended