The 2013 CERN Summer Student Programme

Astroparticle Physics (1-3/3)

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Outline

- Introduction:
  - The beginnings: 100+ years of cosmic rays
  - Basic concepts
- Detection of cosmic rays and neutrino astronomy
- Dark Matter: a multiparticle and multiwavelength search
- Outlook

Definition according to Wikipedia:

Astroparticle physics, the same as **particle astrophysics**, is a branch of particle physics that studies elementary particles of astronomical origin and their relation to astrophysics and cosmology. It is a *relatively new* field of research emerging at the intersection of particle physics, astronomy, astrophysics, detector physics, relativity, solid state physics, and cosmology. Partly motivated by the historic discovery of neutrino oscillations, the field has undergone remarkable development, both theoretically and experimentally, over the last decade.

Astroparticle physics was originally mostly concerned with **charged particles,** but nowadays a large part of the activities concerns also neutral particles, i.e. **neutrinos, photons** (mostly not optical range), **Dark Matter** and also **Gravity waves**...

Multiparticle and Multiwavelength Approach !

A bit of HIstory

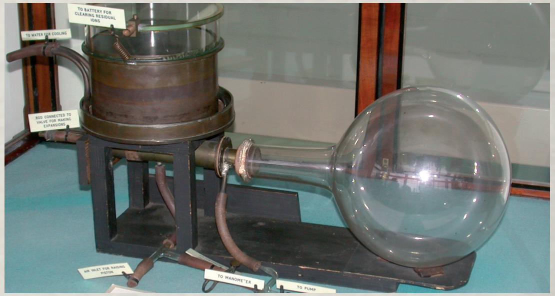
100 Years of Cosmic Rays

1912 Discovery by Victor Hess

1911

CTR Wilson: Development of the cloud chamber and publication of the first pictures

In 1895 CTR Wilson started investigating cloud formation in dust-free air. He discovered that condensed bubbles appear when air molecules are ionised by X-rays. In 1911 Wilson demonstrated with a cloud chamber that alpha and beta rays could be visualised. Two of the published pictures contained straight tracks which were probably the first photographs of cosmic particles. One year before their discovery, Wilson misinterpreted these tracks as beta rays.



Original Wilson cloud chamber (Cavendish Museum)

1911—1912

VF Hess: Calibration measurements with gamma rays

VF Hess in his lab in 1915

In 1910 Hess became an assistant at the just-founded Radium Institute of the Imperial Academy of Sciences in Vienna. He performed absorption measurements in air with the strongest gamma source available at the institute and experimentally confirmed the absorption coefficient predicted by Eve.
He improved the electrometer's construction and developed a calibration method for electrometers using gauge radium sources of different strengths. For calibrated detectors from the company Günther & Tegetmeyer (Braunschweig), the accuracy when measuring the strength of unknown sources was about 5 per mil; uncalibrated instruments achieved 3% accuracy.

1911

VF Hess: First three balloon flights

In August and October of 1911, Hess performed three balloon flights reaching altitudes of 200m to 1000m and confirmed the findings of Wulf, Bergwitz and Gockel. To prepare for a new series of flights, Hess designed and ordered improved instruments, two for gamma-ray detection and one with thin detector walls to measure beta rays.

Victor F Hess in the balloon's basket sometime between 1911 and 1912

1912

VF Hess: Six balloon flights from the Prater in Vienna at lower altitudes

Six new flights were financed by the Imperial Academy of Sciences and supported with balloons from the Royal Imperial Austrian Aeronautical Club in Vienna. Hess measured the ionisation mainly with two or three electrometers:

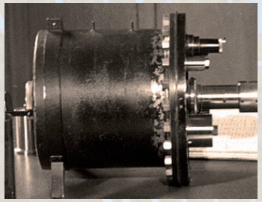
1 17 April, during an eclipse of the sun at 1900m—2750m of altitude
2 26—27 April, at night for six hours at 300m—350m of altitude
3 20—21 May, at night at 150m—340m of altitude
4 3—4 June, at night at 800m—1100m of altitude
5 19 June, in the afternoon at 850m—950m of altitude
6 28 June, at night at 280m—360m of altitude

Seven flight routes of VF Hess in 1912

7 Aug 1912

VF Hess: Seventh balloon flight, reaching an altitude of 5350m Discovery of cosmic rays

With the hydrogen-filled balloon Bohemia, provided by the German Aero Club in Bohemia, Hess, together with W Hoffory and E Wolf, reached an altitude of 5350m and landed at noon in Bad Saarow/Pieskow in Brandenburg. All three detectors measured a strong increase in ionisation.



Electrometer used by VF Hess in 1912

Physik. Zeitschr. XIII, 1912. Hess, Durchdringende Strahlung bei sieben Freiballonfahrten. 1089

Tabelle der Mittelwerte.

Mittlere Höhe über dem Erdboden m	Beobachtete Strahlung in Ionen pro ccm und sec.			
	Apparat 1	Apparat 2	Apparat 3	
	Q_1	Q_2	Q_3 (reduziert)	Q_3 (nicht reduziert)
0	16,5 (18)	11,8 (20)	19,6 (9)	19,7 (9)
bis 200	15,4 (13)	11,1 (12)	19,1 (8)	18,5 (8)
200—500	15,5 (6)	10,4 (6)	18,8 (5)	17,7 (5)
500—1000	15,6 (3)	10,3 (4)	20,8 (2)	18,5 (2)
1000—2000	15,9 (7)	12,1 (8)	22,2 (4)	18,7 (4)
2000—3000	17,3 (1)	13,3 (1)	31,2 (1)	22,5 (1)
3000—4000	19,8 (1)	16,5 (1)	35,2 (1)	21,8 (1)
4000—5200	34,4 (2)	27,2 (2)	—	—

Mean values of all measurements during the seven flights at different altitudes (the number of ionisation values in brackets)

VF Hess summarised the results of these seven flights as follows:

- At altitudes of less than 1000m, the results are in general agreement with previous measurements.
- A radiation of high penetration power hits the atmosphere from above, which cannot be caused by radioactive emanations.
- This radiation contributes to the total amount of observed ionisation at lower altitudes as well.
- Assuming gamma radiation, the sun is not the source of the extraterrestrial radiation.
- There is no difference between ionisation measured during the day and at night.

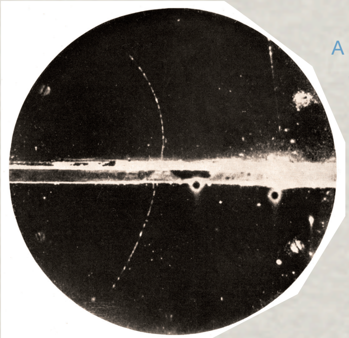
DESY ASPERA Durham University

http://www.desy.de/2012vhess

1933—1947 Birth of Particle Physics

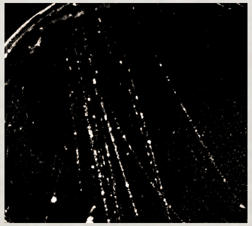
1932 — CD Anderson: Discovery of the positron

In 1931, with a cloud chamber operating in a strong magnetic field, Anderson observed cosmic ray tracks with negative and positive charges, which were interpreted as electrons and protons. Since many positive tracks had the same ionisation as the electrons, Anderson introduced a 6mm-thick lead plate into the chamber. In photographs from 1932, he found tracks with the ionisation and track length observed for electrons, but with a positive charge. This anti-electron (positron) had been predicted two years earlier by PAM Dirac.



A positron with an energy of 63MeV entering the lead plate from below and leaving the plate with an energy of 23MeV. For a proton, the track length would be ten times shorter.

1933—1935 — B Rossi, PMS Blackett, G Occhialini: Particle showers



Cloud chamber photograph of a particle shower with about 16 tracks. The divergence of the tracks points to an interaction in the magnet coil.

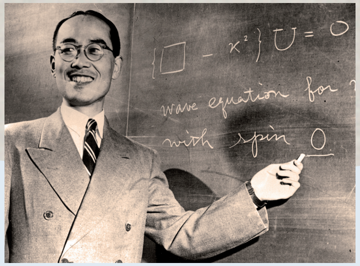
Rossi performed measurements with three Geiger-Müller counters in coincidence with and without lead shielding on top. The coincidence rate increased with the shielding, even though the opposite had been expected. The explanation was the shower production by an incoming cosmic particle.
Blackett and Occhialini demonstrated the shower production visually with cloud chamber photographs.

1934 — W Baade, F Zwicky: Supernovae as possible sources of cosmic rays

By investigating photographic plates taken over the past 30 years, about 13 short flaring, extremely bright objects were identified. Zwicky and Baade called them supernovae. Based on the estimated energy release, they concluded that supernovae are sources of cosmic rays. This hypothesis is still valid, but not completely confirmed.

1935 — H Yukawa: Prediction of the pion

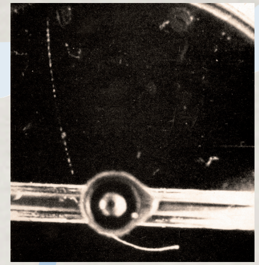
Yukawa formulated a theory to explain the dense packing of protons and neutrons in the nucleus of an atom. The short-ranged field needed a carrier with a mass inversely proportional to the range. He estimated a particle mass of about 100MeV and predicted that these particles could be produced in cosmic particle interactions.



H Yukawa, 1949

1936

SH Neddermeyer, CD Anderson: Discovery of the muon



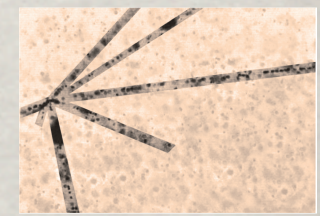
Stereographic photograph of a cloud chamber exposure. A muon enters the chamber from above and comes to rest below.

In a cloud chamber exposure with a 1cm-thick platinum plate in the centre, 6000 photographs were taken. Anderson and Neddermeyer found about 25 events where the energy loss in the platinum absorber was much smaller than measured for electrons or positrons. Since the mass should be between the electron and proton masses, they first called it the mesotron.
For several years, it was assumed that this particle was the predicted Yukawa particle.

1937

M Blau, H Wambacher: First cosmic ray nuclear interaction in a photo emulsion

The photo-emulsion technique was developed by M Blau. In 1937 a five-month exposure to cosmic particles was performed at Hess's Hafelekar cosmic ray station at an altitude of 2300m. The discovery of a so-called star was a breakthrough of this detection technique. A cosmic particle interacted with an atom of the emulsion, producing eight tracks.



A "star" produced in a photo emulsion by a cosmic particle

1938

P Auger: Extensive air showers

With two Geiger-Müller counters in coincidence, Auger and his colleagues, Maze and Robley, detected extensive air showers. They measured the rate at up to 300m of counter distance and estimated the energy of the primary cosmic particles to be about 10^{15}eV.

1942

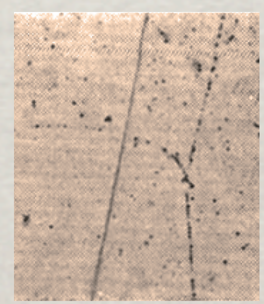
I Lange, SE Forbush: Solar cosmic particles

In February 1942, a large solar flare appeared. Lange and Forbush measured an increase in the cosmic particle rate of about 15%. They concluded that this additional fraction is caused by charged particles emitted by the solar flare.

1947

DH Perkins, GPS Occhialini, CF Powell: Discovery of the pion

The pion event identified by Perkins. Tracks B and C are protons; D is a tritium nucleus. The short track E is a recoil nucleus. The grain density and scattering of track A correspond to a particle with a mass of about 100MeV.



In 1938 Yukawa and Sakata predicted the lifetime of the Yukawa particle to be about 10^{-8} seconds, which was 100 times shorter than the measured lifetime of the muon.
The problem was solved with the discovery of the pion in photographic emulsions in 1947. Perkins found one event, and two months later Occhialini and Powell identified 25 pion interactions.
In Britain, the emulsion technique was improved by Powell, Perkins and others, in cooperation with the Ilford company.

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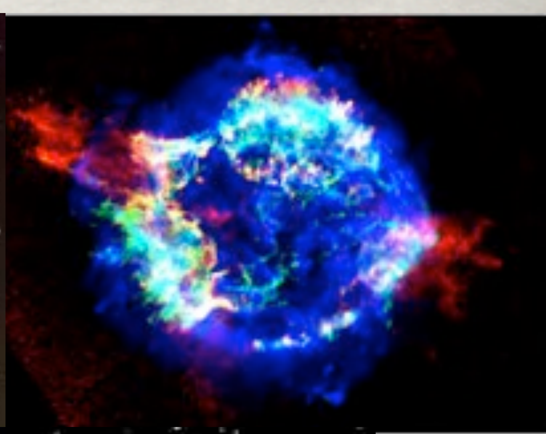
Basics: sources and acceleration

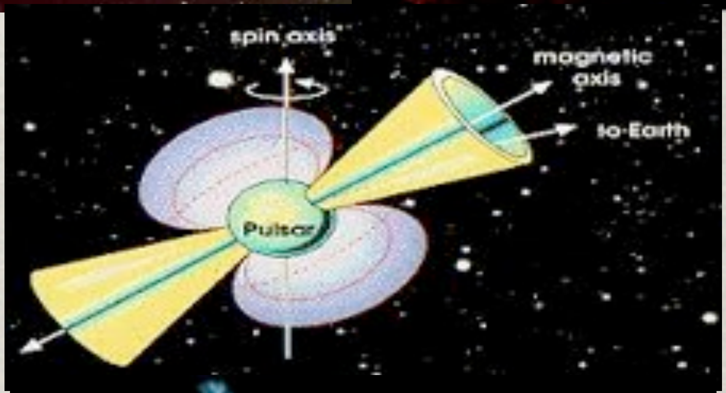
Galactic Sources

In the universe there are many violent processes that can act as particle's sources, i.e.

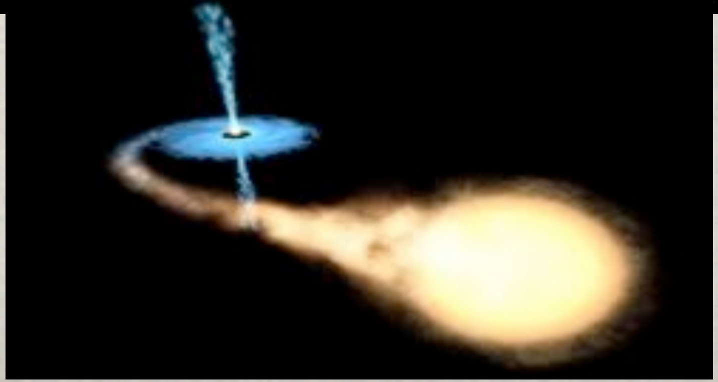
- SuperNova Remnants (SNR)
  (Fermi shock mechanism)



- Neutron stars/Pulsars:
  (high magnetic field)



- Microquasars (Binary systems with an accreating Black Hole)



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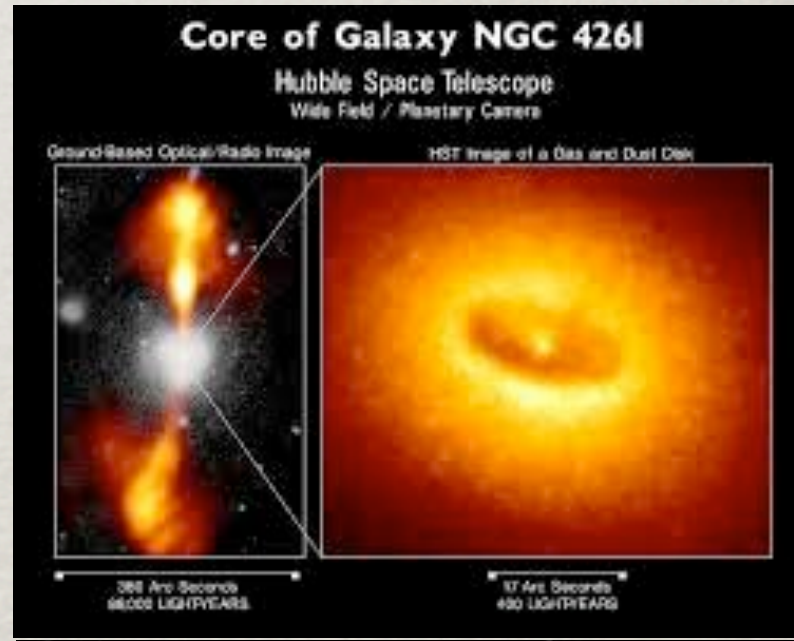
Extragalactic Sources

In the universe there are many violent processes that can act as particle's sources, i.e.

- Active Galactic Nuclei (AGN) Blazars: Supermassive BH at centre of galaxy emitting relativistic jets



- Gamma-ray bursts (GRB): narrow beam of intense EM radiation

High energy Cosmic rays

In general one of the main problems in astrophysics is not to produce particles, but how to give them large energy !
In general there have been two approaches:

- Bottom-up: particles of low energies are accelerated via SM physics, e.g. magnetic/electric fields within the astrophysical objects

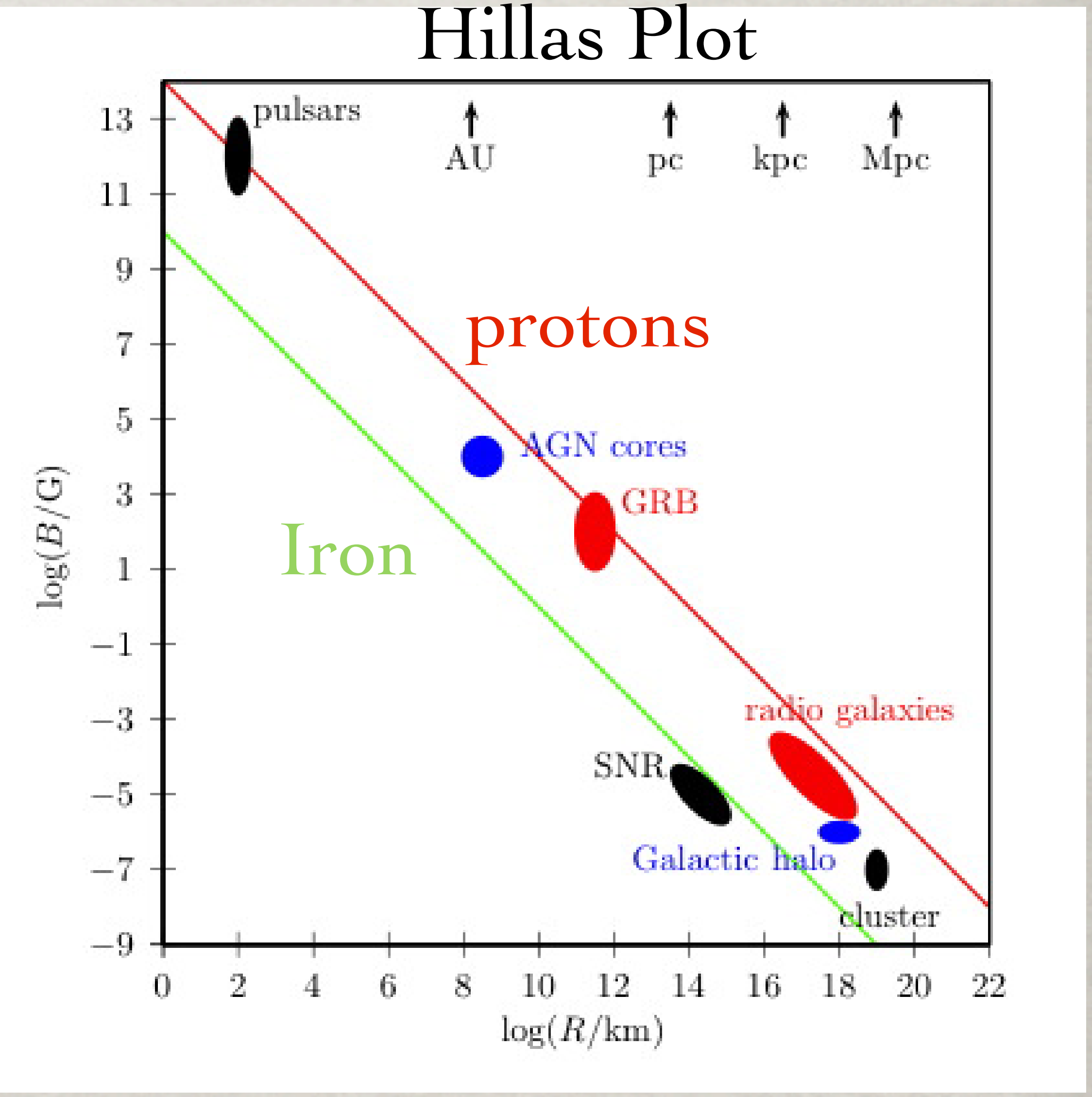
- Top-down: particles are already generated with very high energies, usually via non-SM processes, e.g. decay of a very heavy (exotic) particles

Acceleration

Hillas criterion (geometrical requirement): the maximal energy reachable within an astrophysical body is such that the corresponding Larmor radius is equal to the size of the object...

$$R \sim 2R_L = \frac{2E}{ZeB}$$

$$E_{max} = \frac{1}{2} ZeBR$$



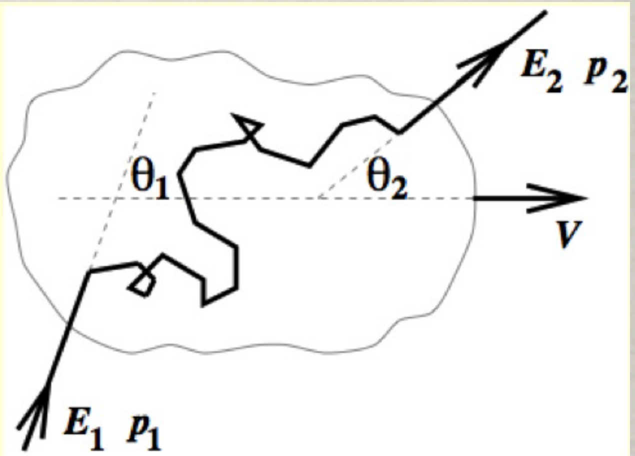
Similar maximal energy ?

FERMI ACCELERATION I

Already long ago Enrico Fermi tried to answer the question of how to accelerate particles in astrophysics. He considered the collision of a particle with a moving magnetized cloud:

$$E_1' = \gamma E_1 (1 - \beta \cos\theta_1)$$

Cloud frame "Lab" frame



After elastic deflection: $E_2' = E_1'$

$$E_2 = \gamma E_1' (1 + \beta \cos\theta_2)$$

"Lab" frame Cloud frame

Energy gain: $\dfrac{\Delta E}{E} = \gamma^2 (\beta^2 - \beta(\cos\theta_1 - \cos\theta_2) - \beta^2 \cos\theta_1 \cos\theta_2)$

On average:

$\langle \cos\theta_1 \rangle = -\beta/3$

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

$$\frac{\Delta E}{E} = \gamma^2 (\beta^2 + \beta^2 \frac{1}{3}) \sim \frac{4}{3}\beta^2$$

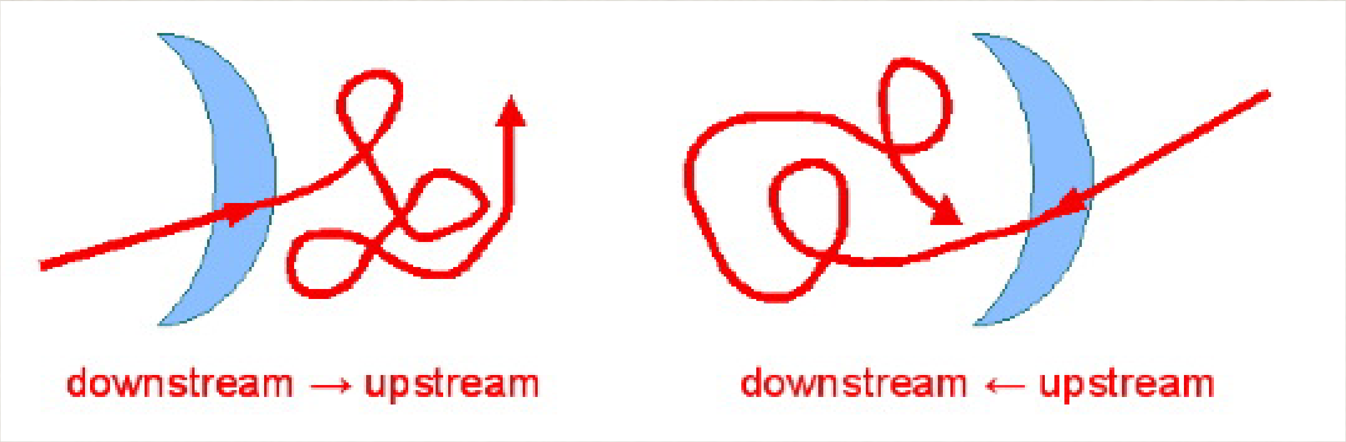
2nd Order

FERMI ACCELERATION II

The second order Fermi acceleration is not sufficient to explain the high energies in the CRs...
Actually possible to gain more by crossing a shock front (first order Fermi acceleration) or exploiting relativistic velocities and large γ

Shock front

Shock front



$$\frac{\Delta E}{E} \sim \frac{4}{3}\beta$$

Power-law spectrum

Any mechanism like the Fermi one generates a power-law particle spectrum. Indeed assuming the source produces particles with energy E_0 and that the energy increases by the factor α after each shock-crossings, we have after many such crossings: $E = E_0\alpha^n$.

Moreover given a probability P_{esc} to escape the accelerating region after each shock crossing, we also have

$$N = N_0(1 - P_{esc})^n$$

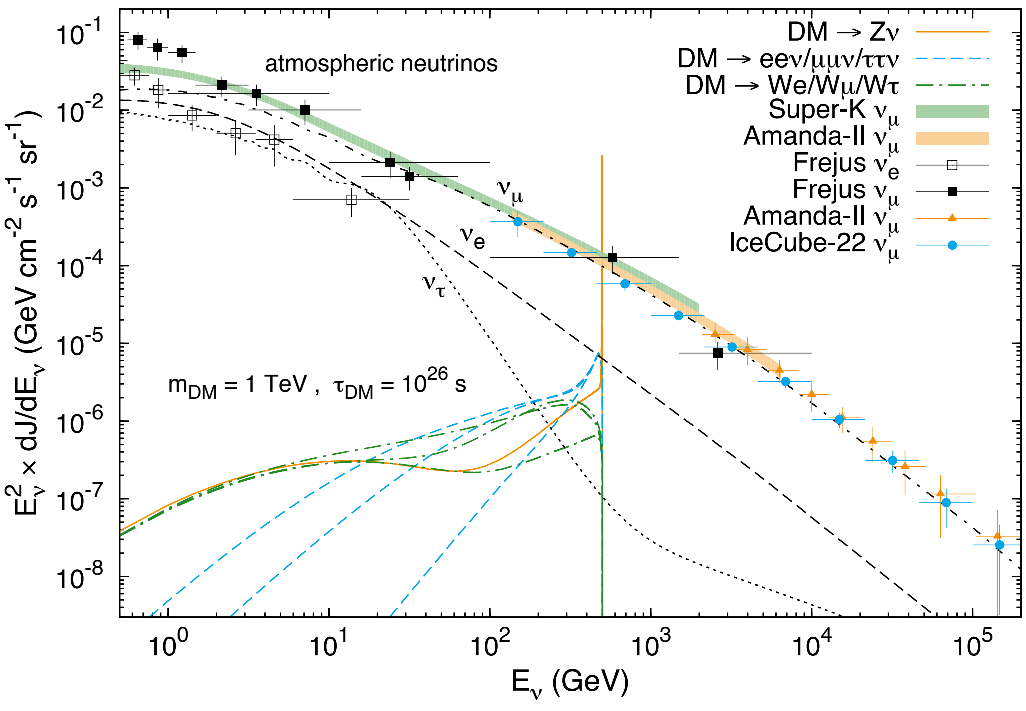
$$\frac{dN}{dE} \propto E^{-1+\frac{\ln(1-P_{esc})}{\ln \alpha}} \sim E^{-1-\frac{P_{esc}}{\alpha-1}}$$

Observed spectrum goes like $E^{-2.7}$

Exotic particle decay

Depending on the number of particles in the final state, a non-relativistic particle decay can produce different daughter particles spectra...

[LC, Grefe, Ibarra & Tran 09]



In general no power-law, but "bump-like" spectrum..., at least before propagation !

Basics: Propagation

Propagation

In general propagation of the cosmic rays from the source to the Earth can change their energy spectrum and if the particles are charged also their direction...

- Scatterings with the intergalactic/interstellar medium: they can change the energy spectrum of the particles
- Deflection due to magnetic fields and energy loss due to synchrotron emission

Neutral particles like photons and neutrinos are less affected, but still not completely safe...

The GZK Cut-off

[Greisen '66, Zatsepin & Kuzmin '66]

Since the universe is not completely empty, interactions that stop or slow down the CR may happen !

The particles with highest density are the CMB photons...

$$\gamma_{CMB} + p \to \Delta \to n + \pi^+, p + \pi^0$$

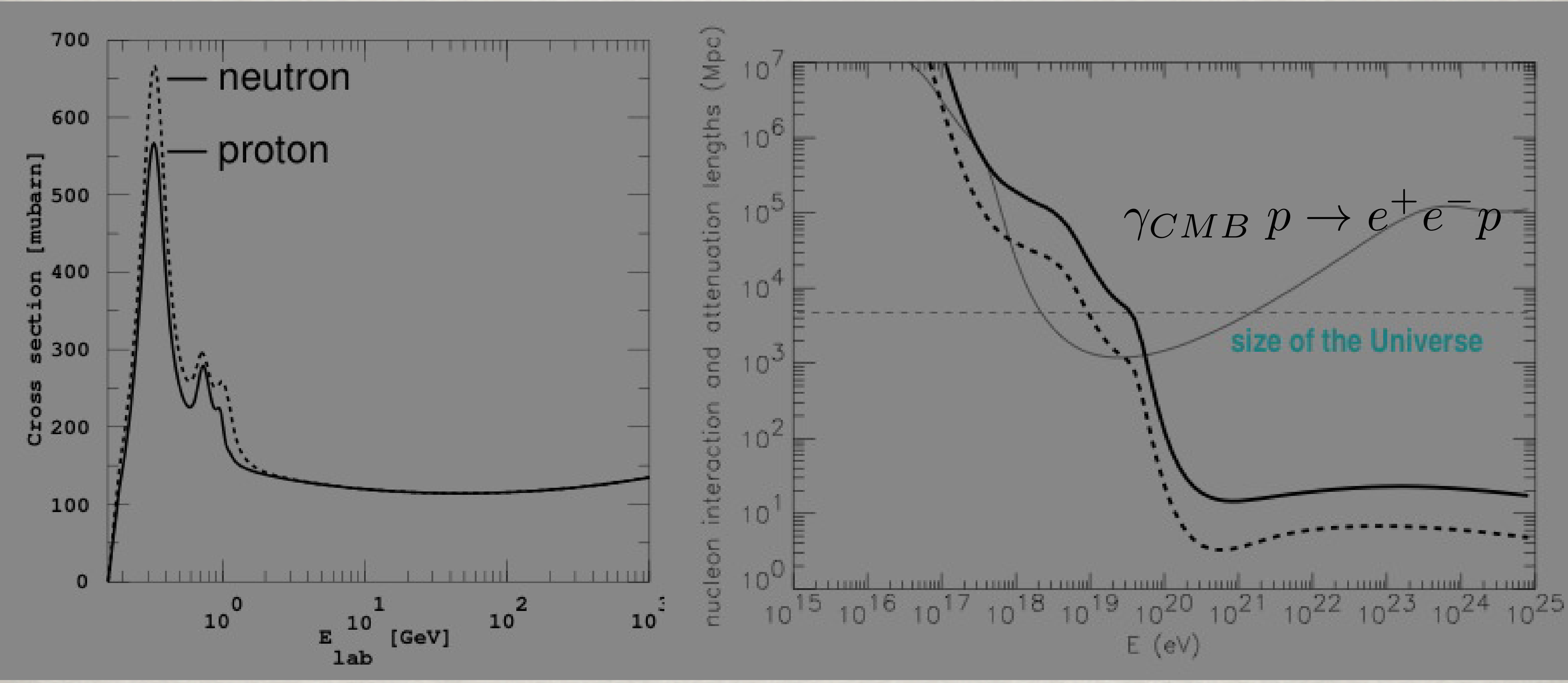
This process has a threshold, since sufficient energy should be present to produce a pion of mass

$$E_p \geq \frac{m_\pi^2}{4E_\gamma} \sim 3 \times 10^{20} eV$$

If allowed, the scattering causes an energy loss of about 20% and cuts off the energy spectrum of protons above threshold.

The GZK Cut-off

[Greisen '66, Zatsepin & Kuzmin '66]



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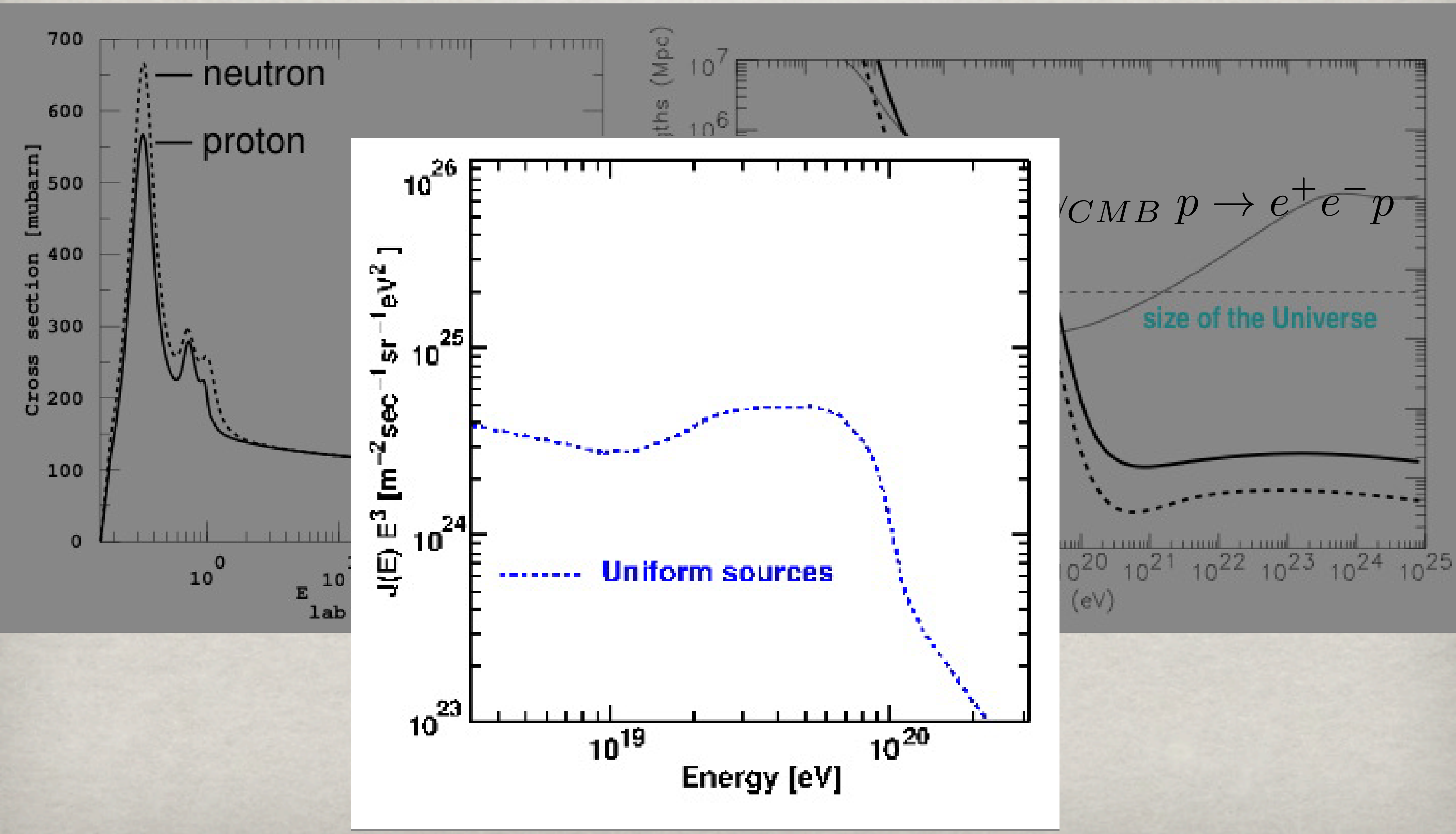


Magnetic fields

The deflection of a charged particle in a magnetic field is just given by the Lorentz force:

$$\vec{F} = q\vec{v} \times \vec{B}$$

In the relativistic limit we have for constant B field:

$$\theta \sim 0.52^o \, q \left(\frac{E}{10^{20} eV} \right)^{-1} \left(\frac{R}{1kpc} \right) \left(\frac{B_\perp}{10^{-6} G} \right)$$

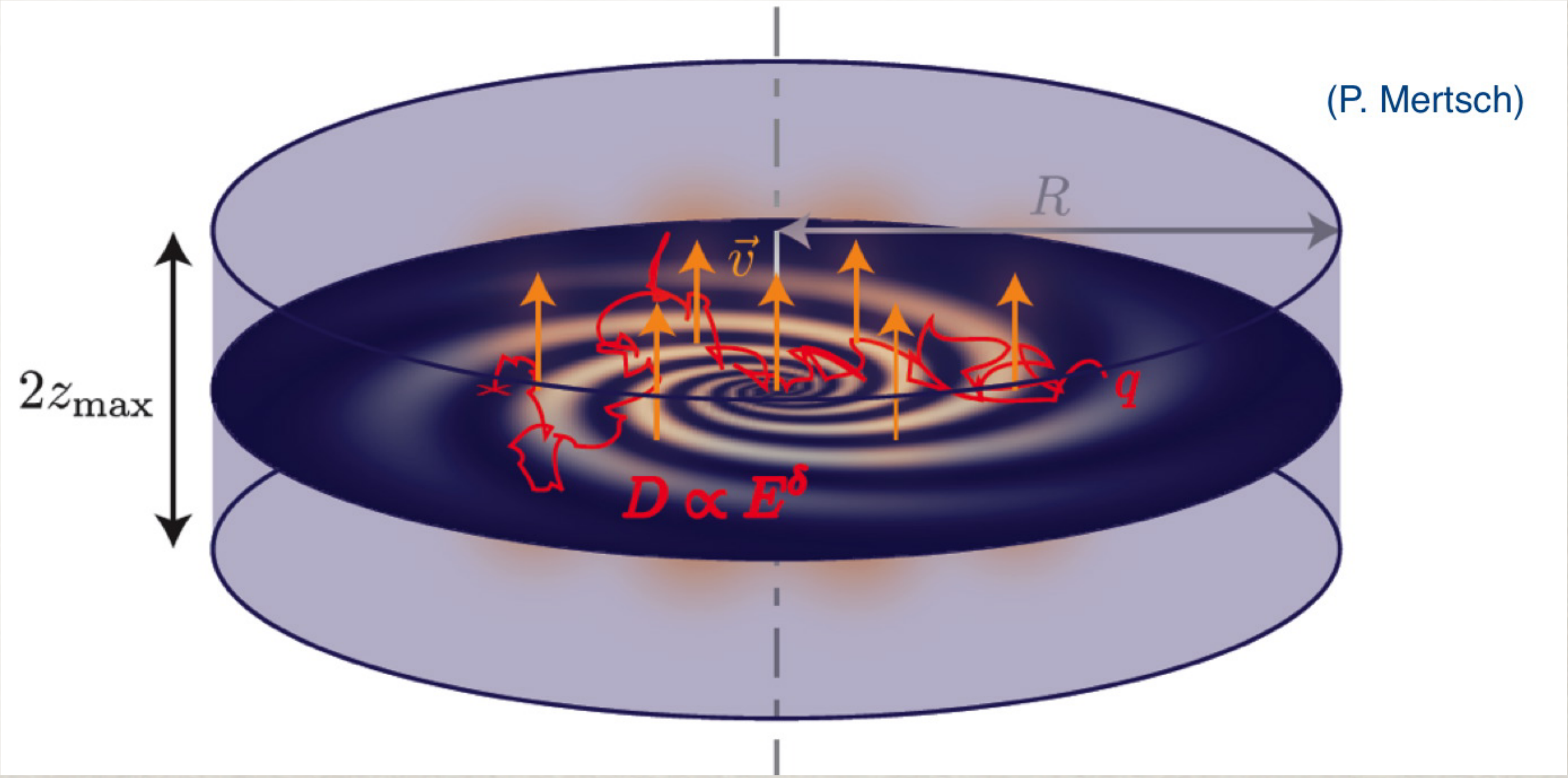
For random B field coherent over a distance ℓ_c:

$$\theta \sim 1.8^o \, q \left(\frac{E}{10^{20} eV} \right)^{-1} \left(\frac{\ell_c R}{50 Mpc^2} \right)^{1/2} \left(\frac{B_\perp}{10^{-9} G} \right)$$

Crucial to know the magnetic fields !!!

Propagation in our galaxy

Charged particles travel in the galaxy along complex paths:



To obtain the spectrum need to solve a complicated diffusion equation including energy losses, spallation, convective winds and possibly sources...

Propagation in our galaxy

Diffusion equation for the charged particles:

$$\frac{\partial f}{\partial t} - K(E)\vec{\nabla}^2 f - \frac{\partial}{\partial E}(b(E)f) + \frac{\partial}{\partial z}(v_c f) = Q_s - 2h\delta(z)\Gamma_{spall} f$$

Diffusion | Energy loss | Convective Wind | Source | Spallation

The equation is not easy to solve... Usually try to obtain the steady state solution for different species at the same time to compare with the data !

Usually the solution for secondaries (no source !) is a (negative) powerlaw.

Basics: detection

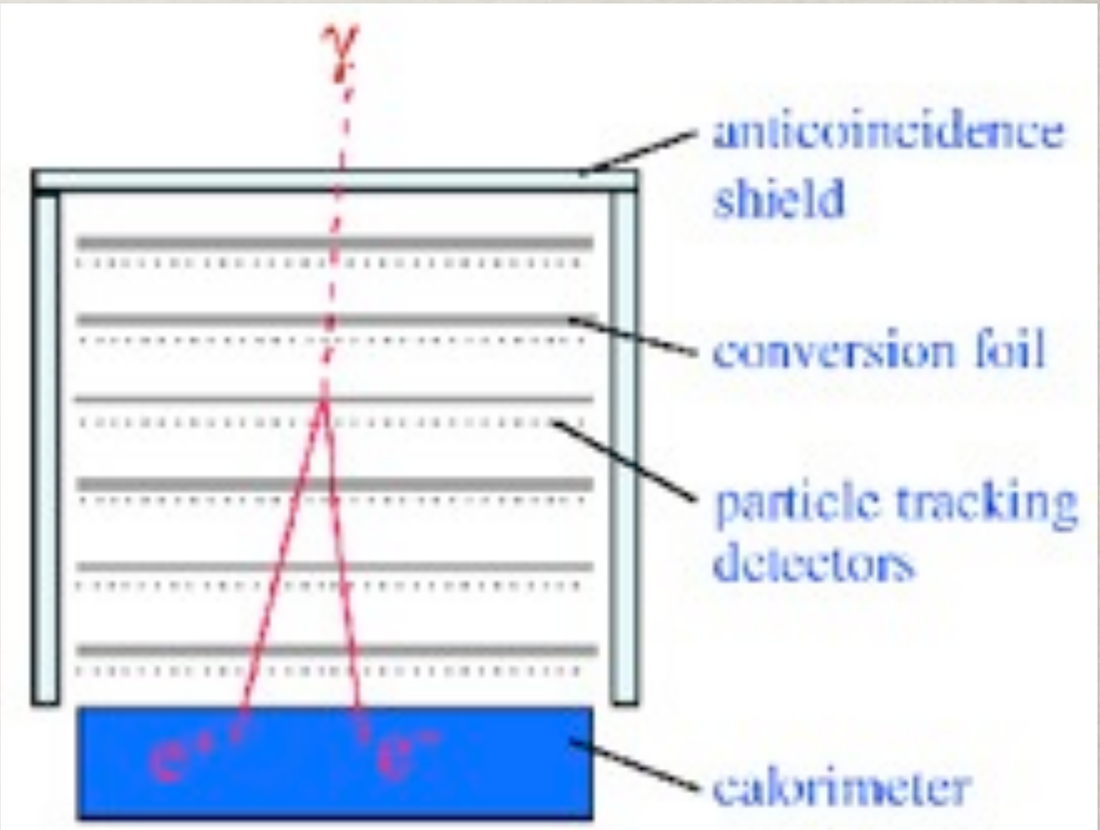
How to detect Cosmic rays

The basic ideas for cosmic rays detectors are the same as any particle physics detector: → Detector lectures by D. Bortoletto

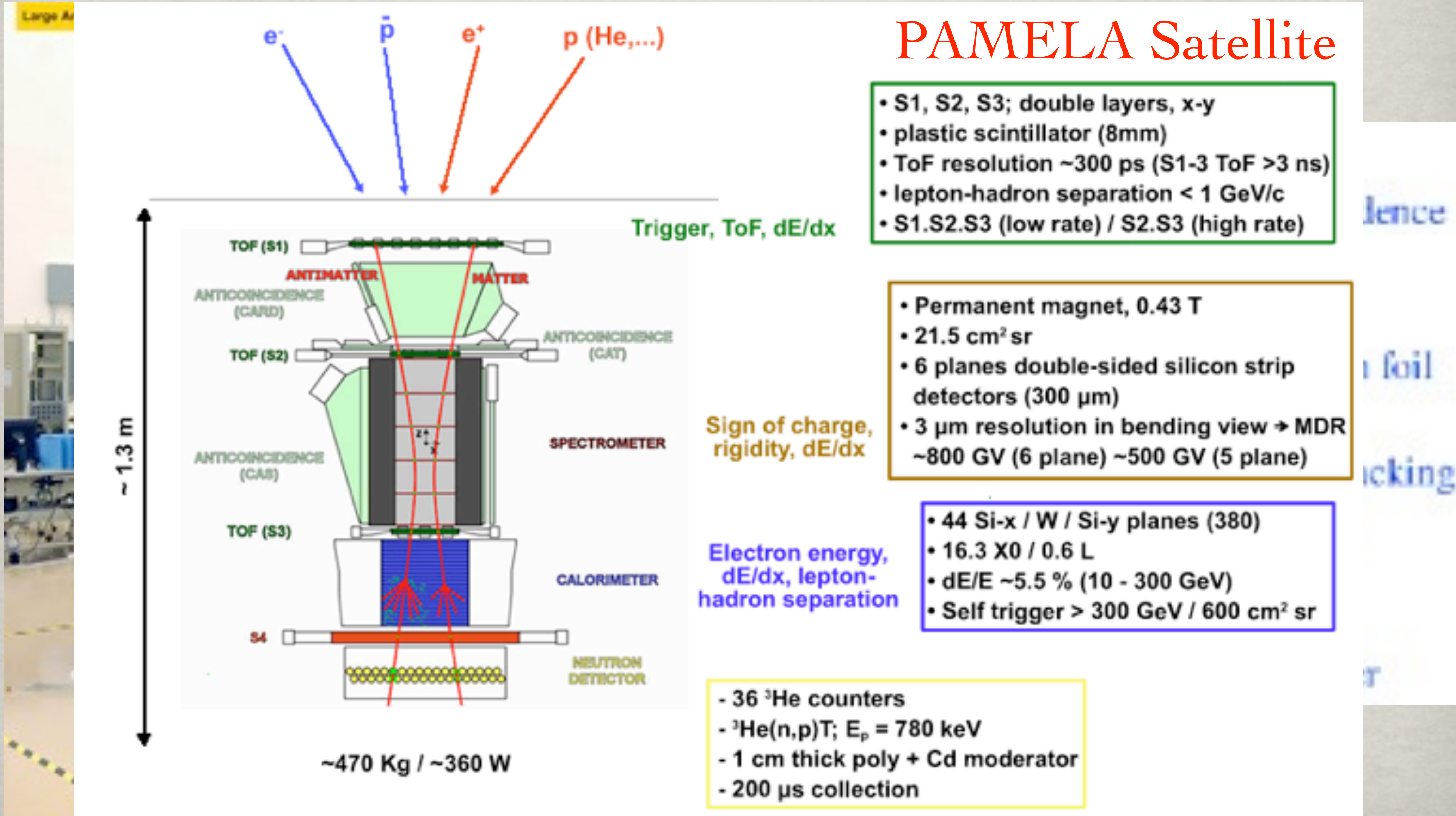
- Charged Particles: To reconstruct charge/mass by spectrometry need a magnetic field !
- Charged Particles: since they are highly relativistic, one can exploit Cherenkov light !
- Neutral Particles (gamma-rays and neutrinos): turn them into charged ones and measure those...
- Neutral Particles (DM): look for energy deposited by elastic scattering with matter.

PARTICLE DETECTORS IN SPACE !

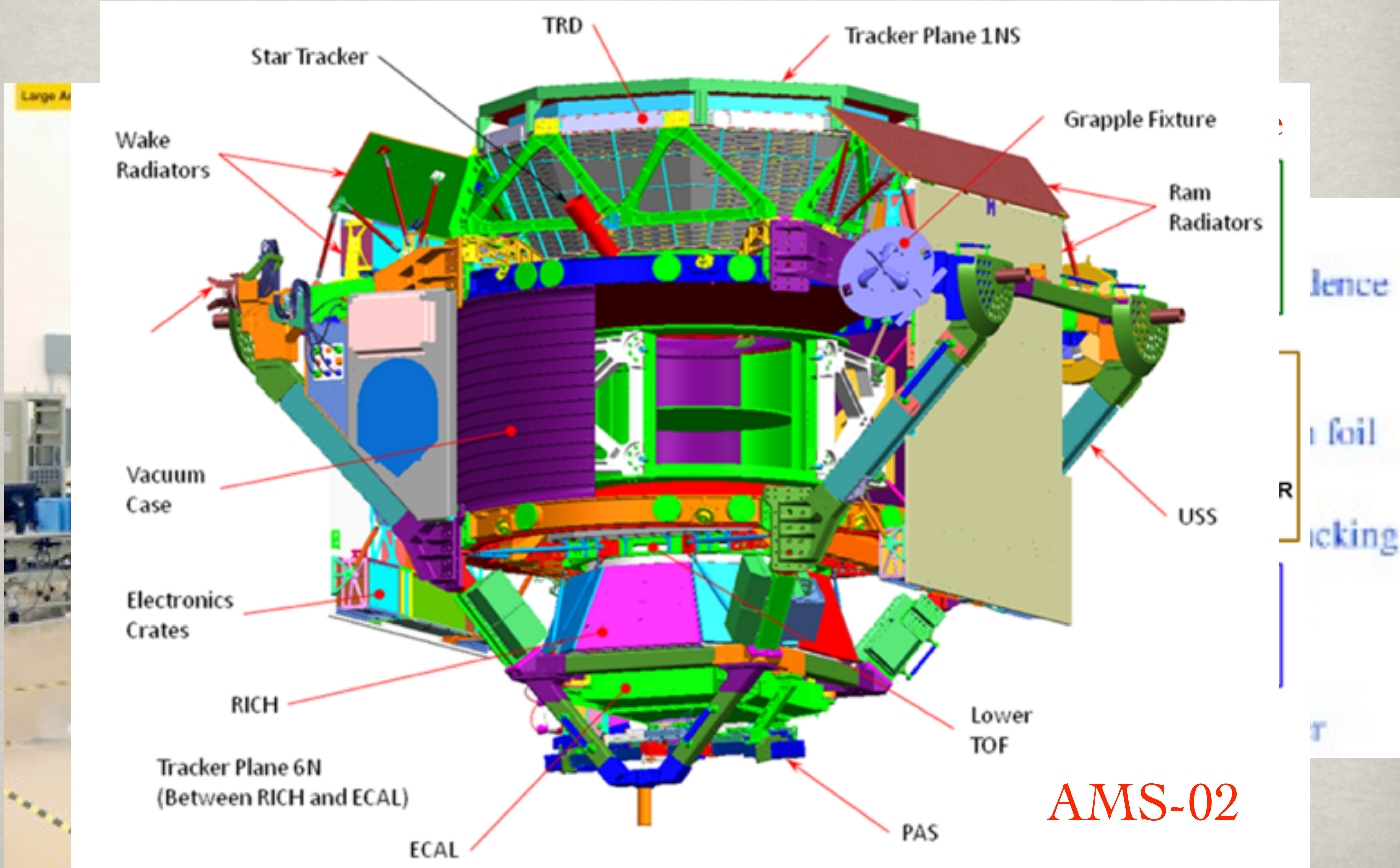
FERMI-LAT



PARTICLE DETECTORS IN SPACE !

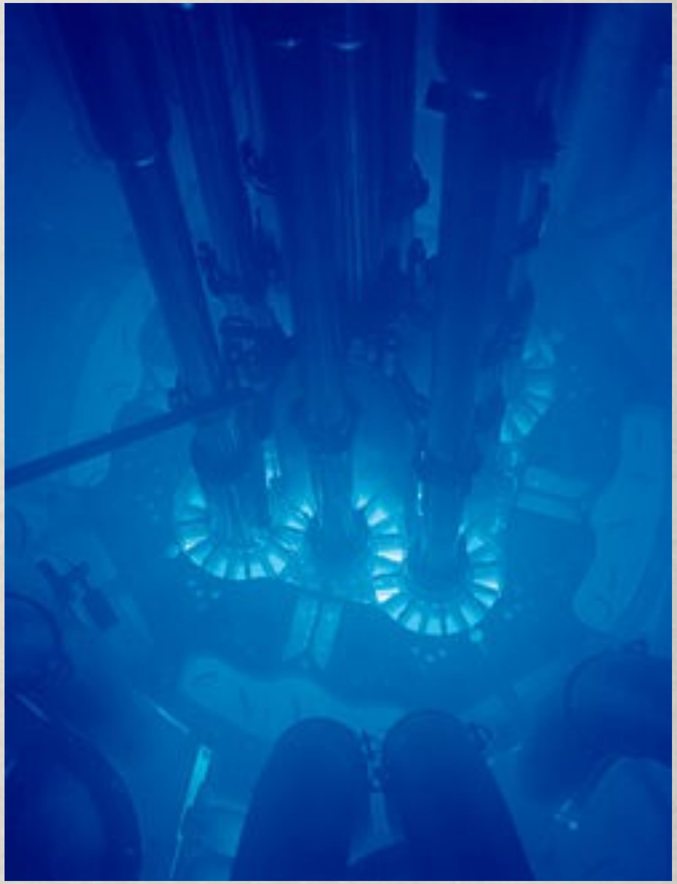


PARTICLE DETECTORS IN SPACE !



Cherenkov radiation I

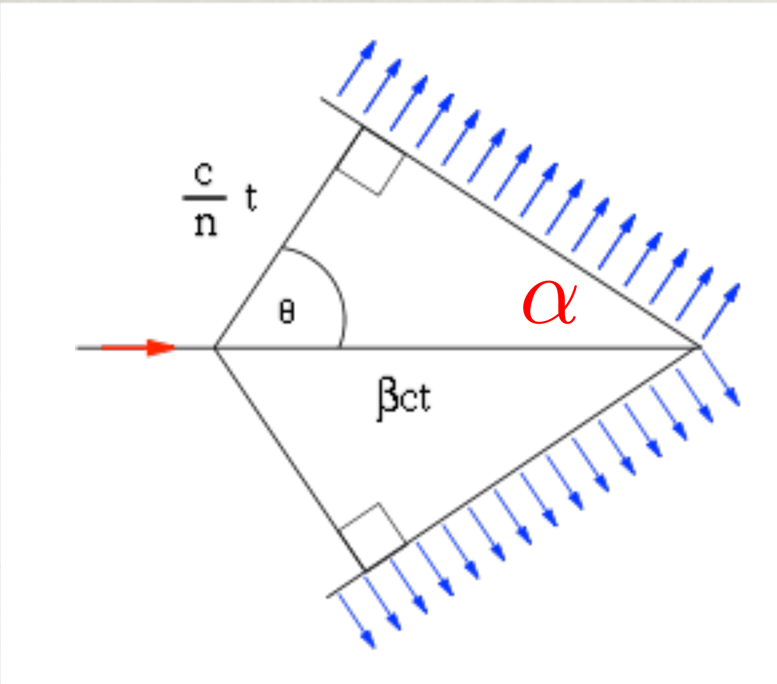
Blue light first observed by P. Cherenkov in liquids under radiation in 1934. I can be seen also as glow around nuclear reactors as shown here...



I. Frank and I. Tamm explained the phenomenon already in 1937:
the effect is analogous to the sonic boom of an aircraft travelling faster than the sound speed, only for electromagnetic waves instead of sound waves !

Every particle travelling in a dielectricum with velocity larger than the speed of light produces Cherenkov light from the medium ionization

Cherenkov radiation II



Cherenkov radiation is emitted with a wavefront forming an angle $\alpha = 90^o - \theta$ with the direction of motion of the particle where

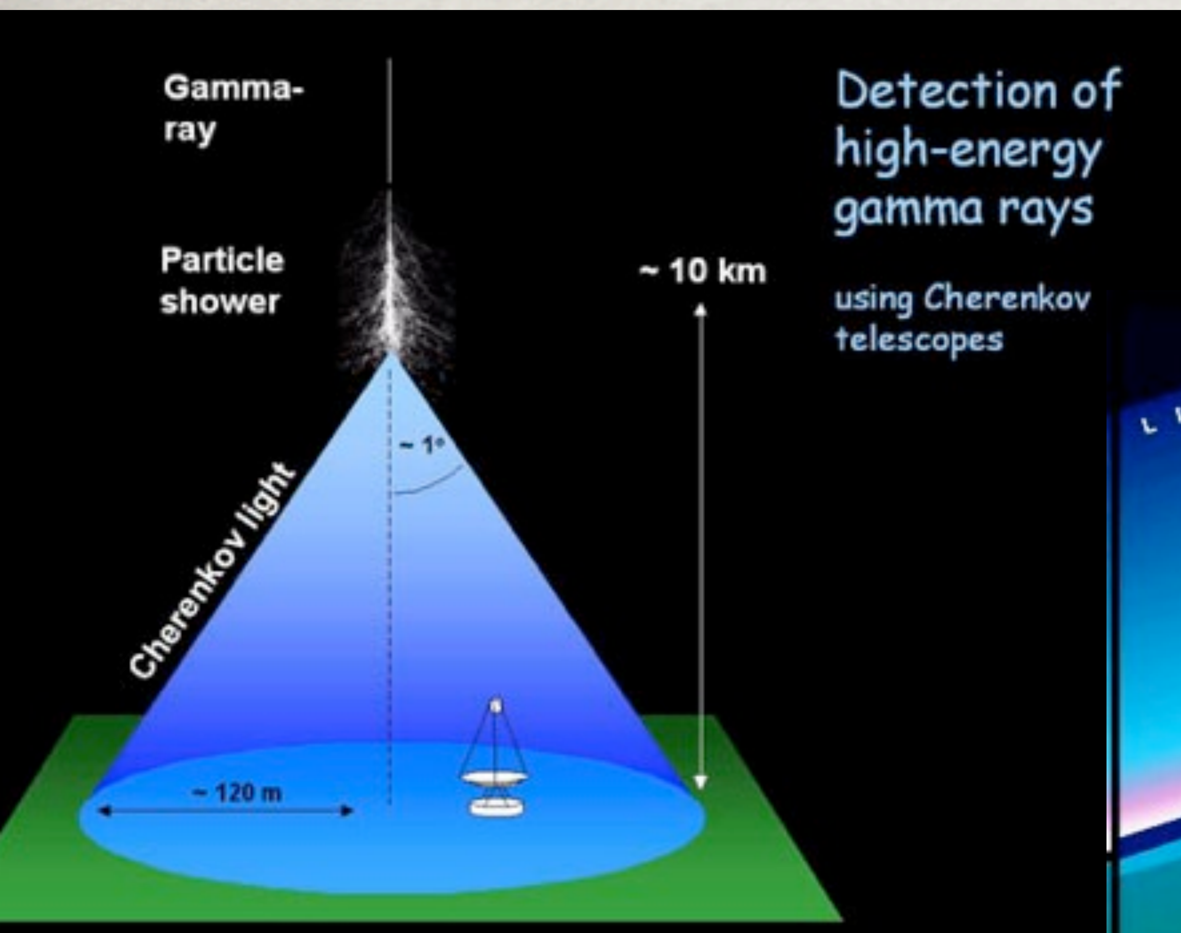
$$\cos\theta = \frac{1}{\beta n}$$

Different angles depending on *n*, i.e. the medium:

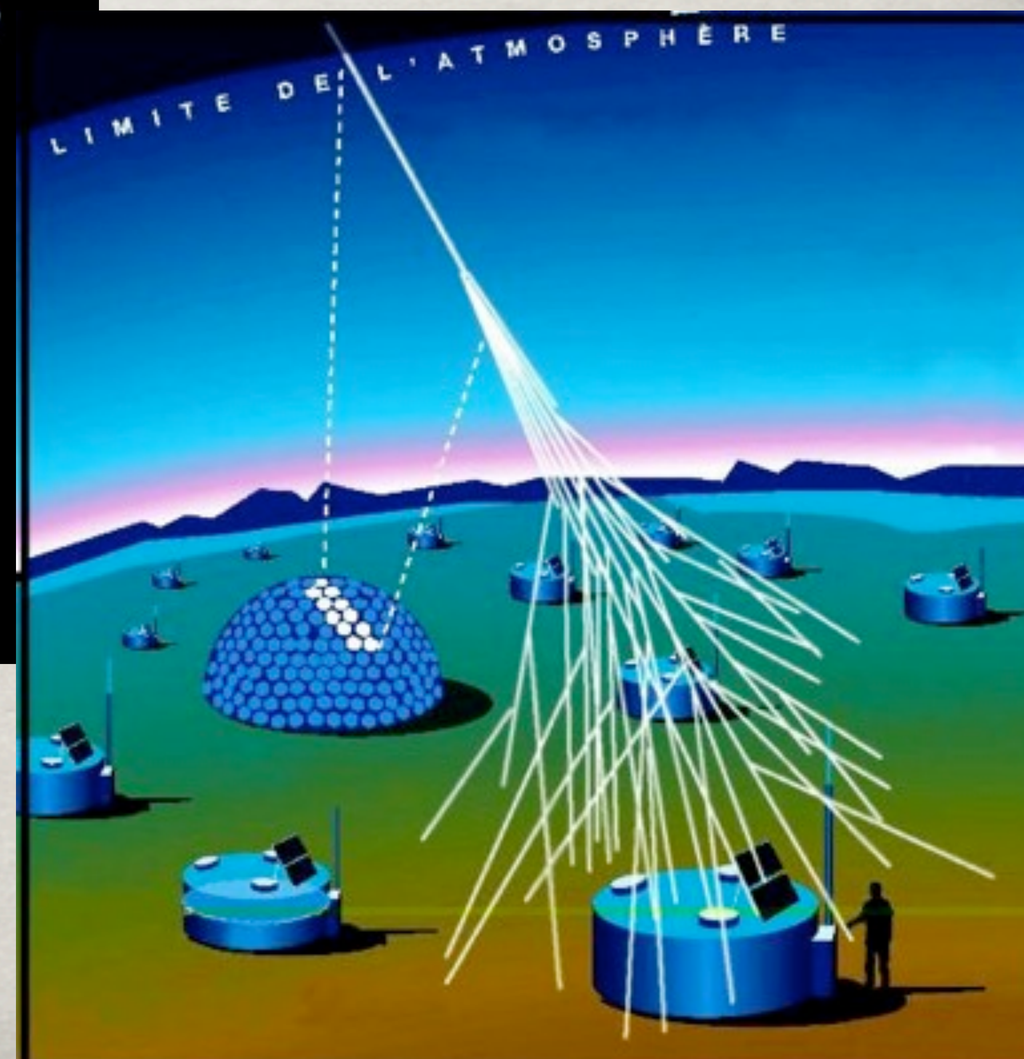
Air: $n \sim 1,0003$ $\alpha \sim 1^o$

Water: $n \sim 1,33$ $\alpha \sim 42^o$

Cherenkov detectors



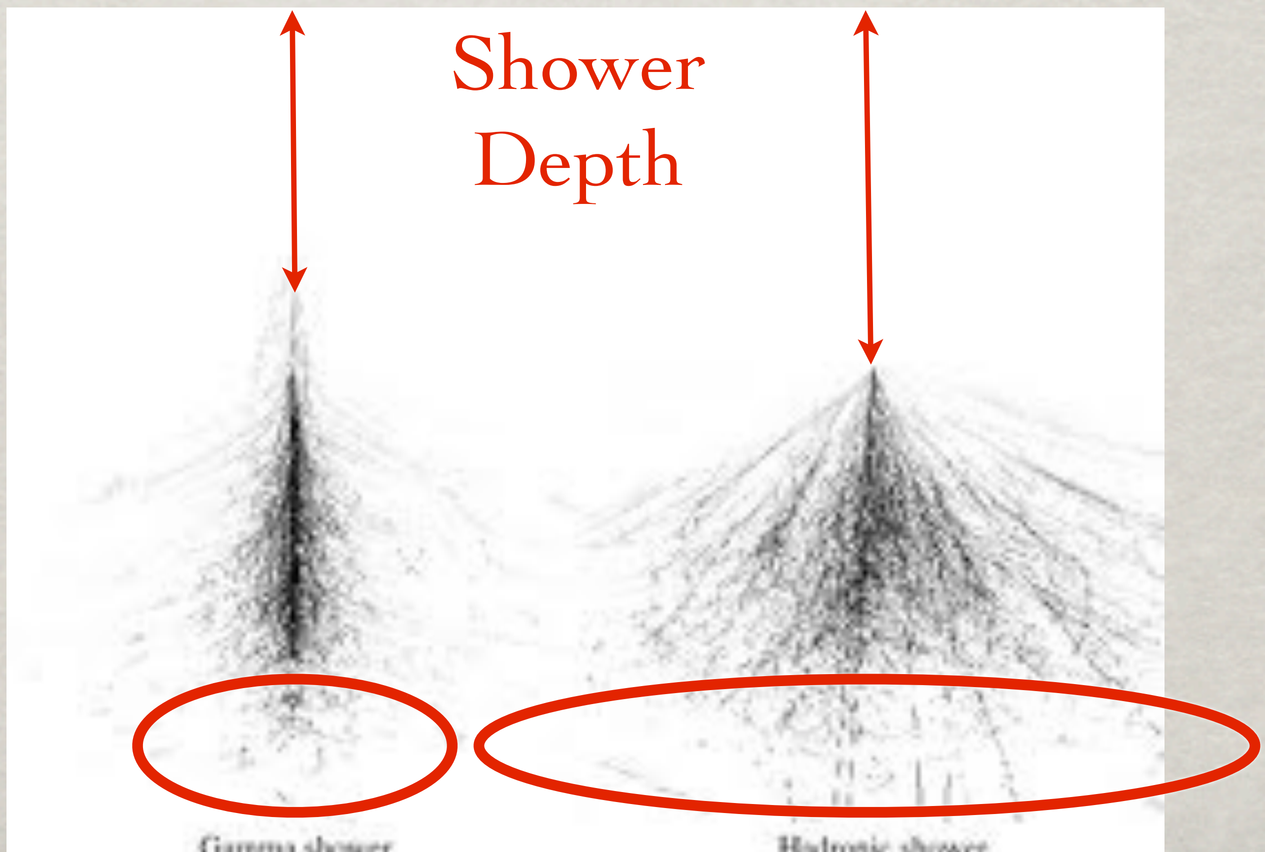
The atmosphere as a calorimeter !



Extended air showers (EAS) produce Cherenkov light in air or water...

Cherenkov detectors

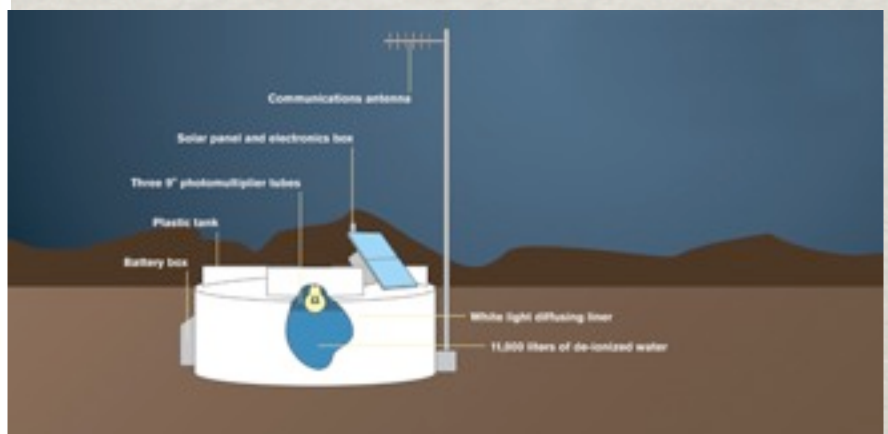
At high enough energy practically ANY (SM) particle produces a shower in the atmosphere.
How to distinguish between them ?
Through the Shape and Depth of the shower !



Spread of
EAS

DETECTORS ON EARTH !

Cherenkhov Telescopes

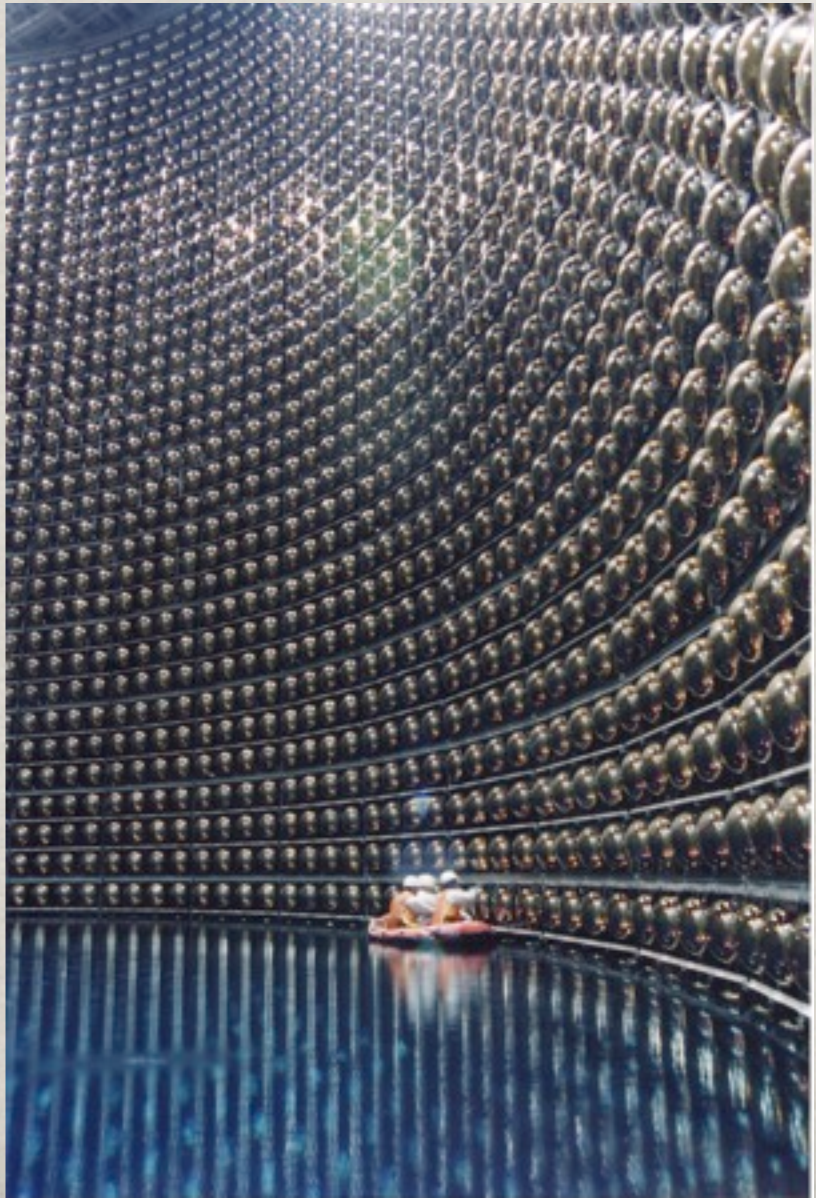


Cosmic rays Observatory

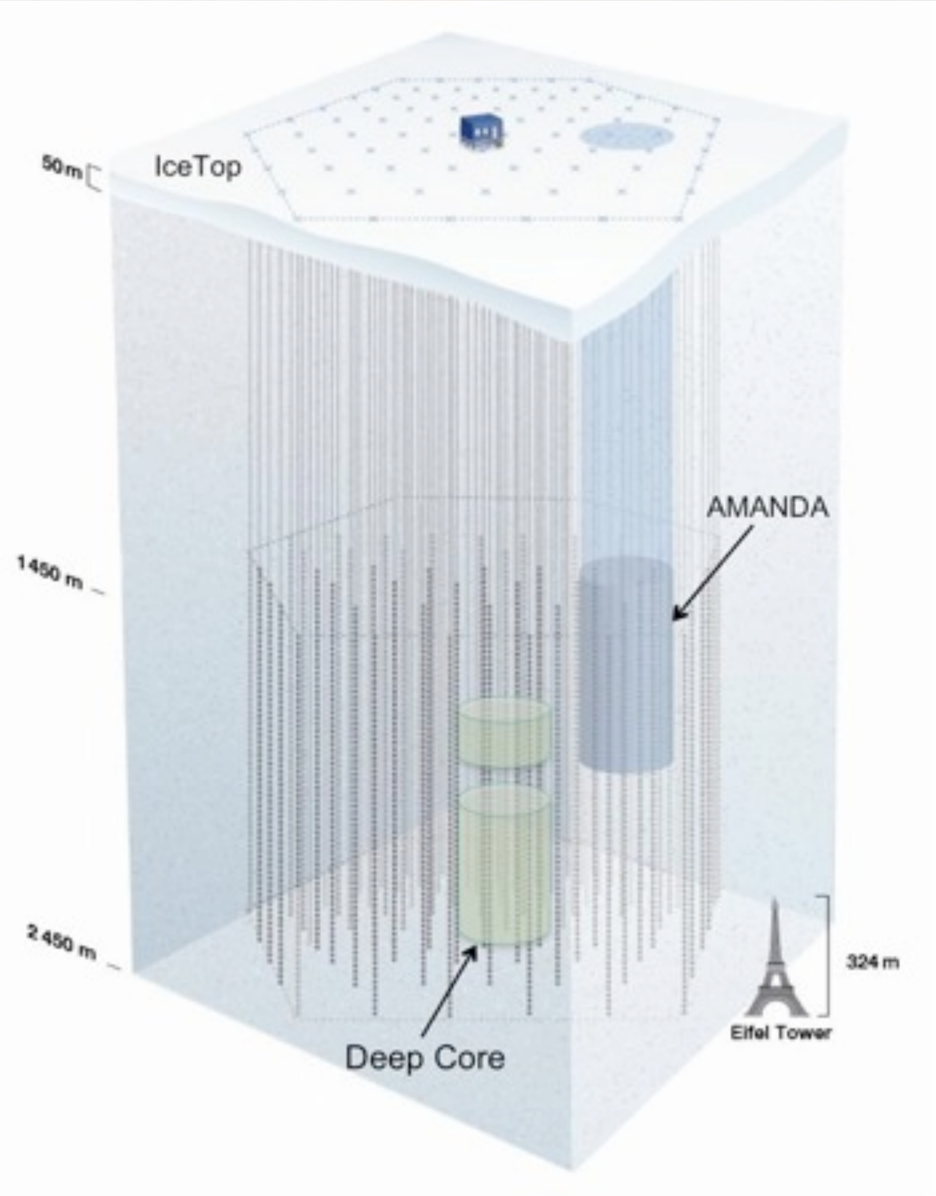
http://www.auger.org

DETECTORS UNDERGROUND !

SuperKamiokande

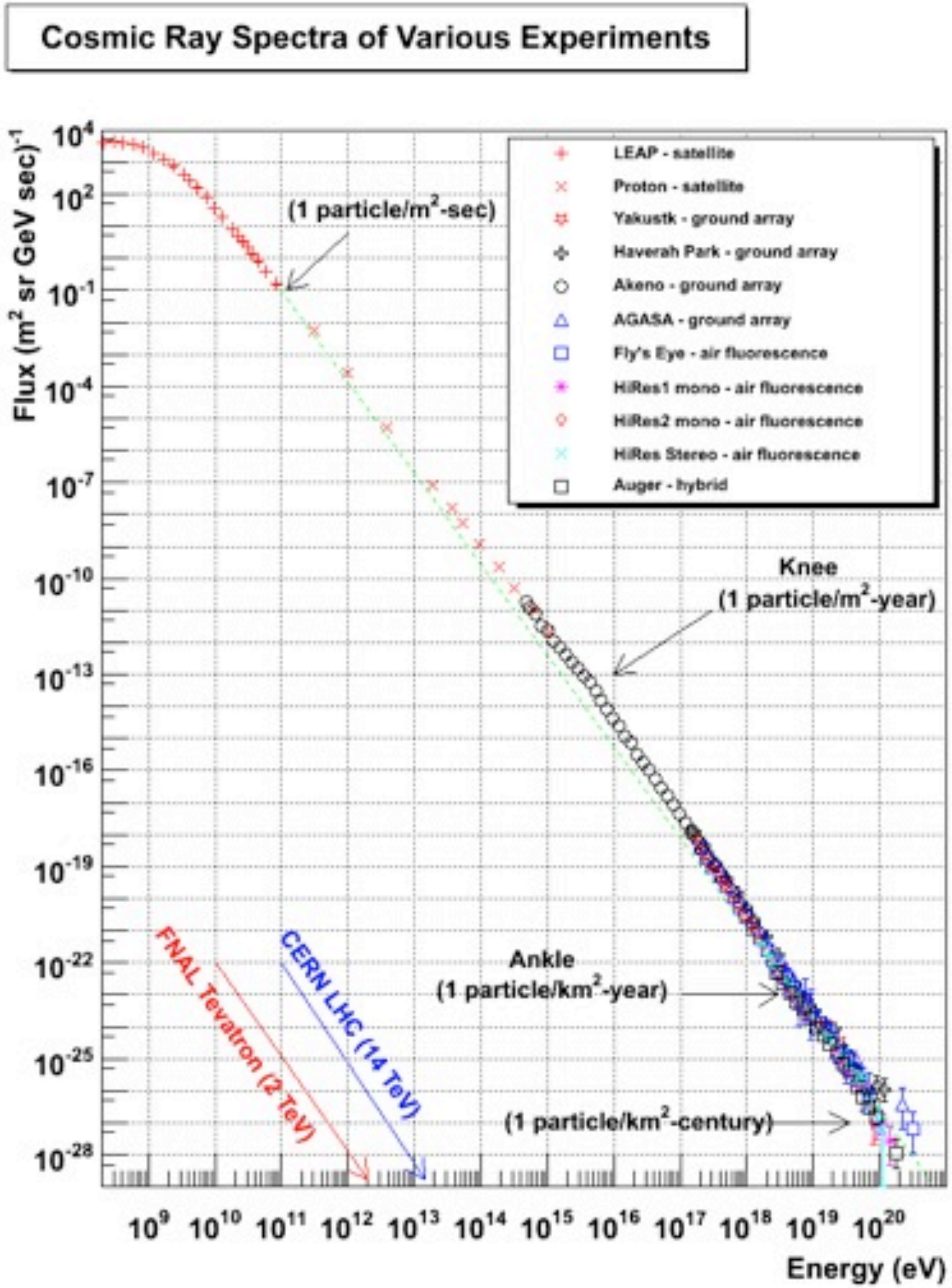


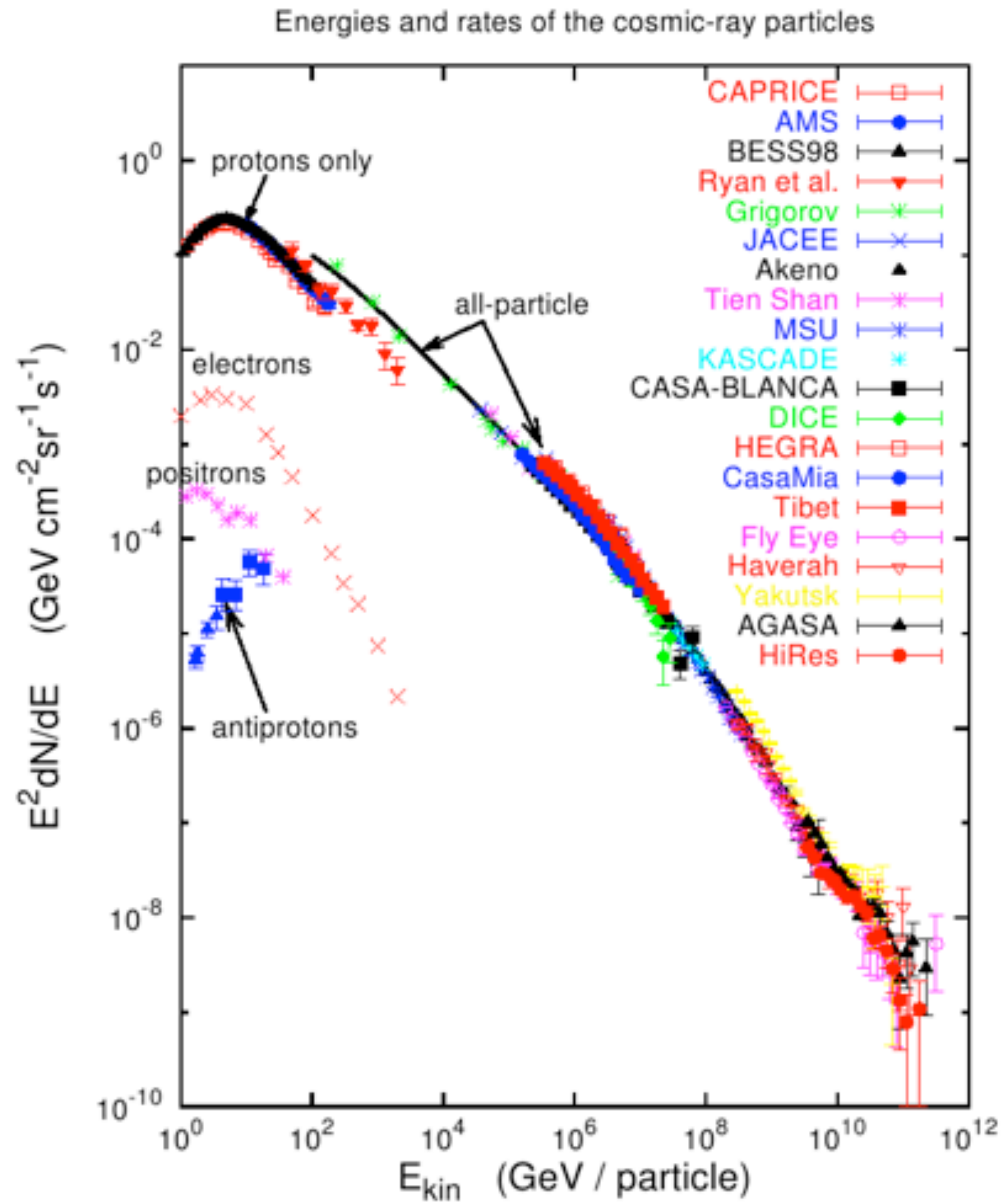
Icecube



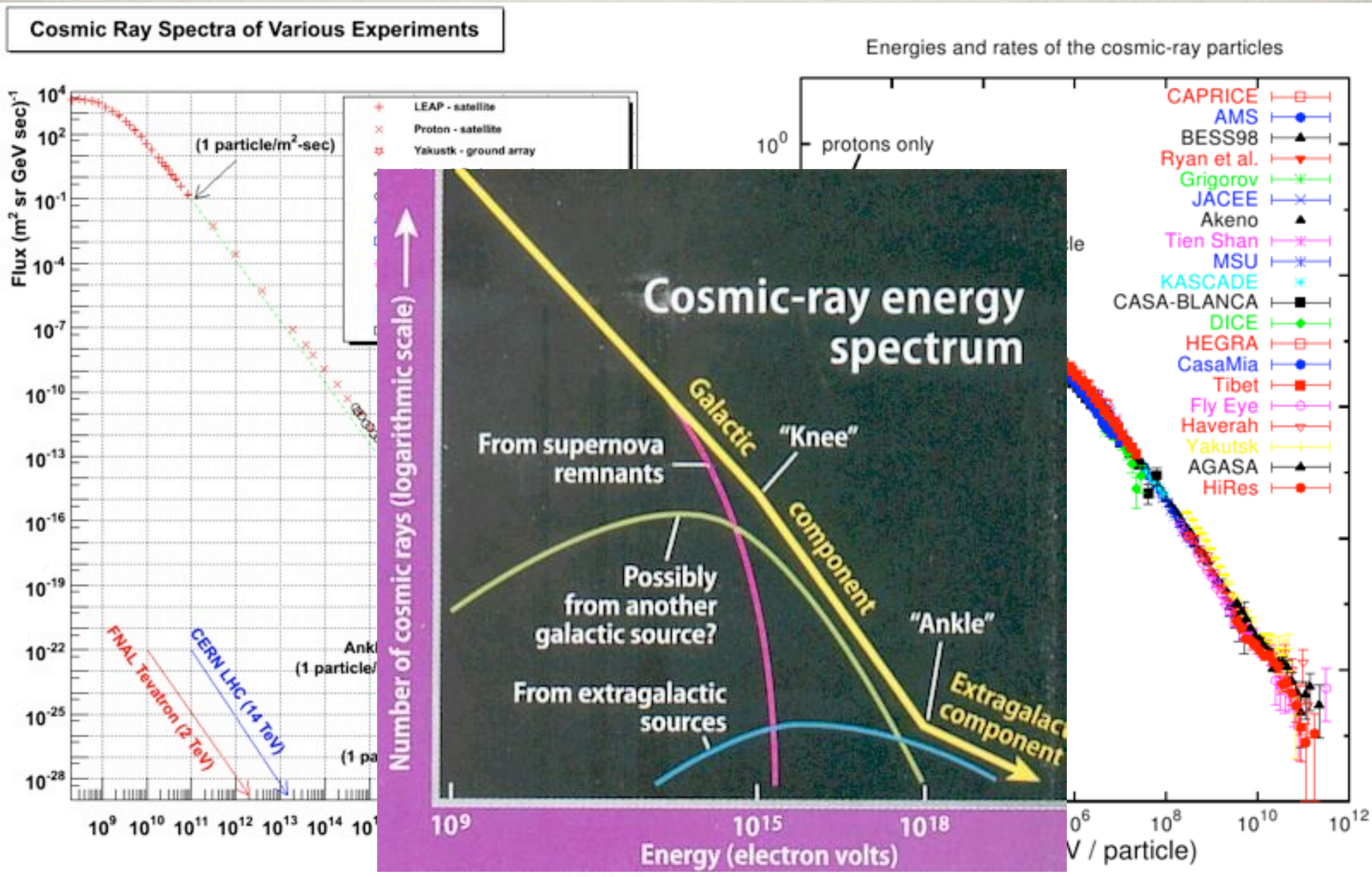
Cosmic Rays
data

Cosmic Rays spectrum



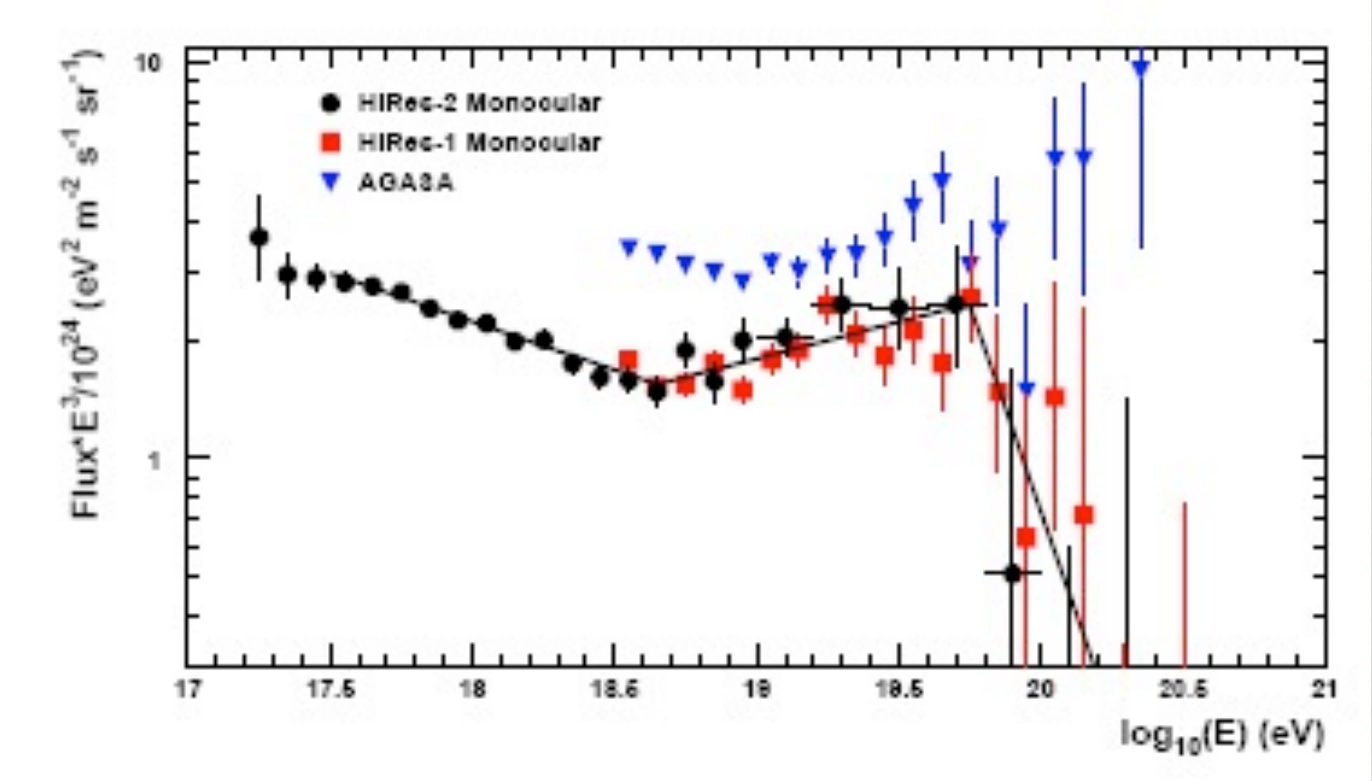


Cosmic Rays spectrum



UHECR & THE GZK CUT-OFF

Long controversy between AGASA and Hires experiments: is there a GZK cut-off or not ???

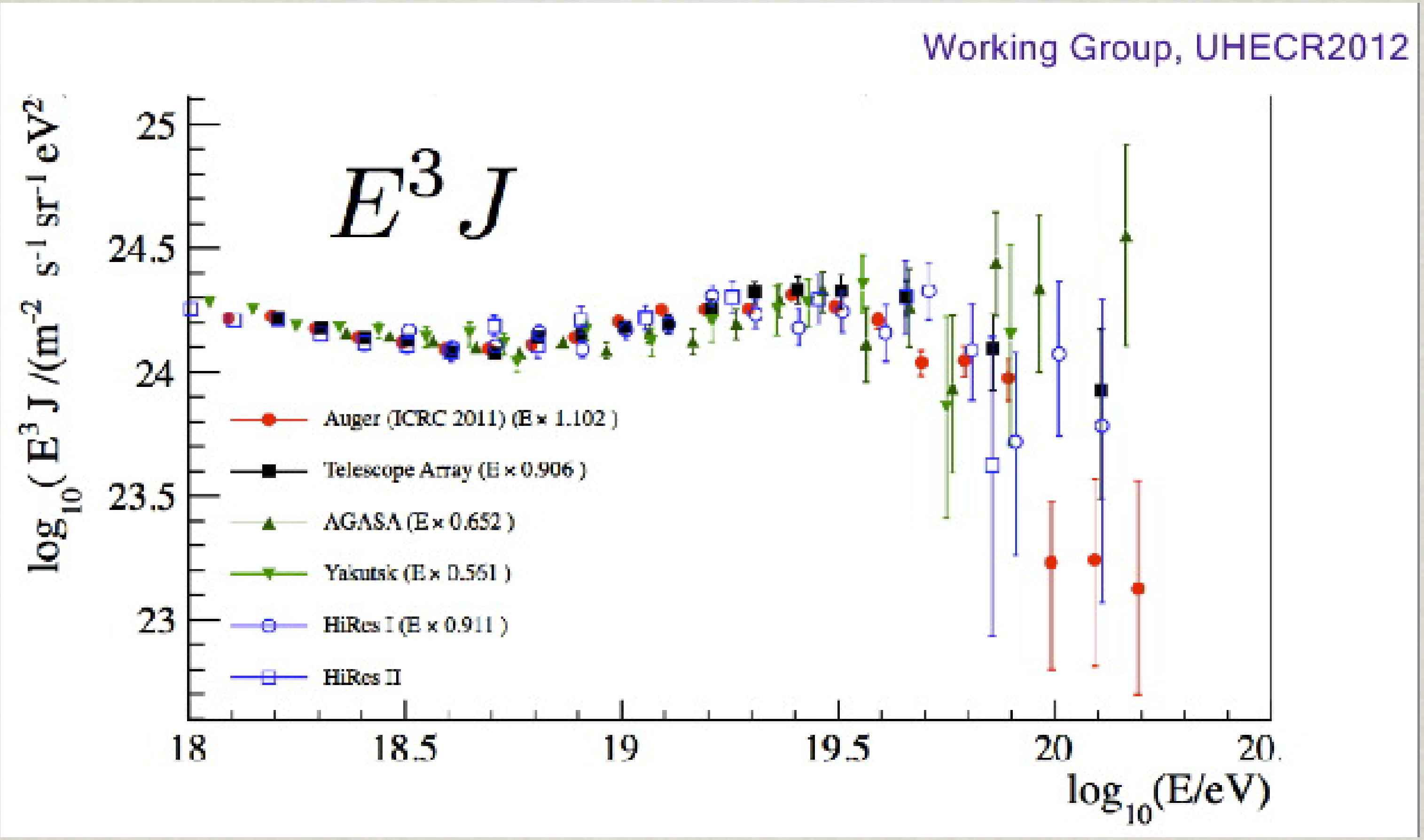


NO

YES

But they are not using the same technique: AGASA is a surface array (SA), while HIRes a fluorescence detector (FD)...

Auger & the GZK cut-off

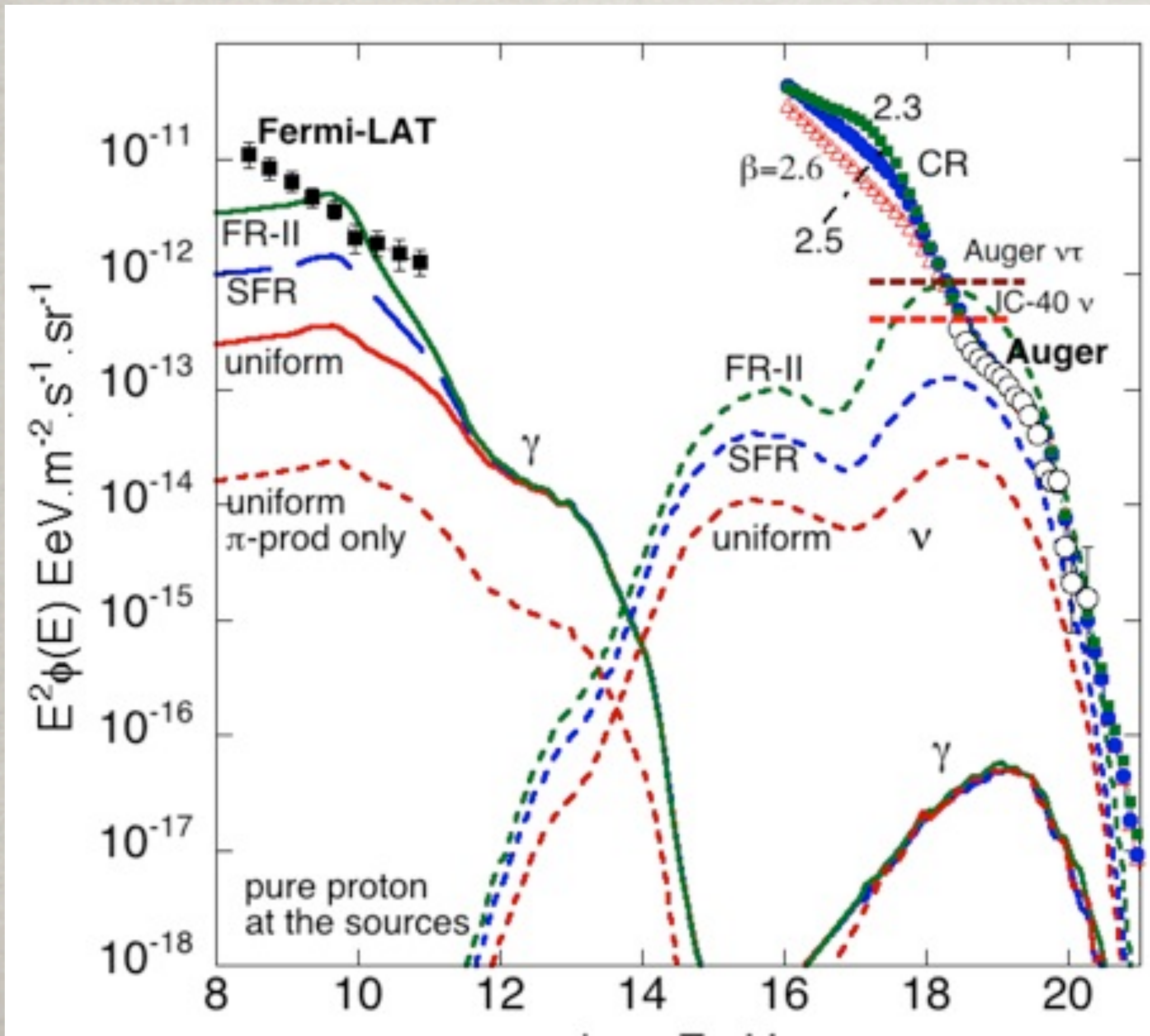


Controversy now solved by AUGER & TA , hybrid detectors with both SA and FD: the energy measured by the two methods differ ! Calibrating SA with FD one obtains good agreement between the experiments and sees a cut-off...

But absolute energy scale is still unclear !

But is it the GZK cut-off ?

Still not proved if the suppression of the flux is really due to the GZK process... It may also be the rarity of such high energy accelerators (recall the Hillas plot !).



How is it possible to disentangle the two ?

With neutrinos and gammas !

In fact the GZK pions decay and produce either neutrinos or gammas.

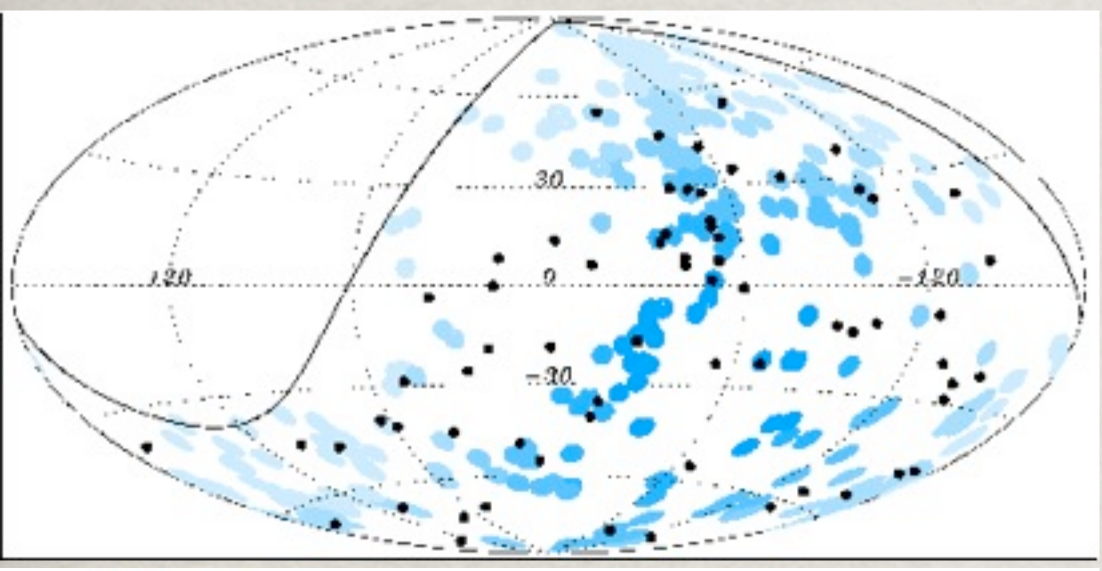
At the moment no neutrinos found yet...

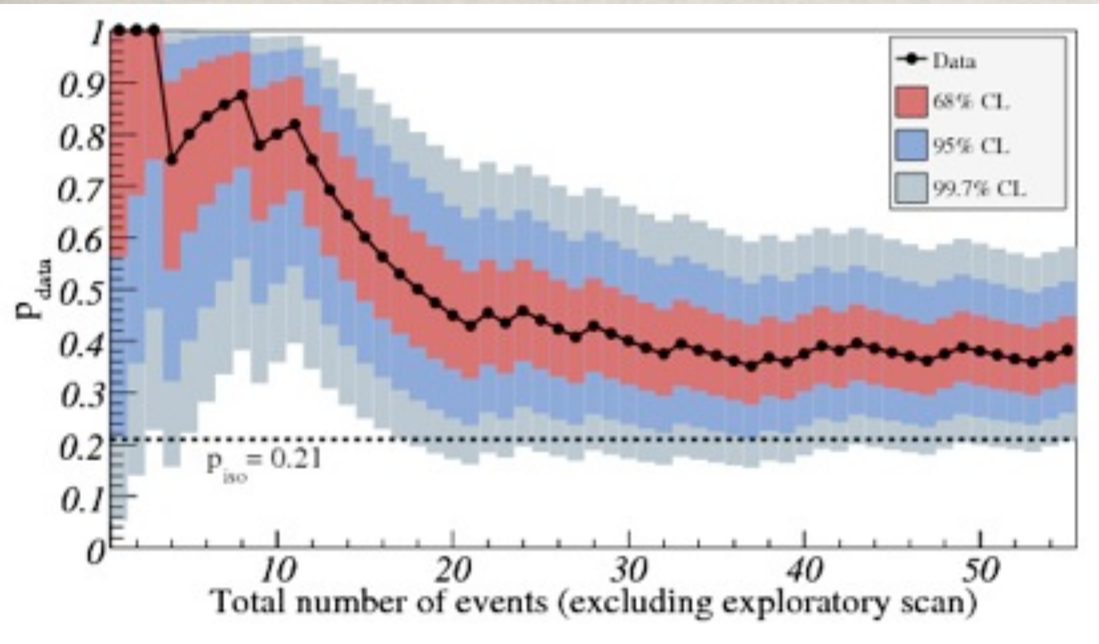
Sources of UHECR ?

We have seen that different astrophysical object are candidates for the UHECR acceleration. Two informations could help to pinpoint the sources:

- Directional information: is the arrival direction of UHECR correlated with a particular type of source ? For so large energies protons are only weakly deflected by the magnetic fields, especially for nearby sources !
- Composition: are the UHECR protons (H) or heavier nuclei like iron (Fe) instead ? The depth of the first interaction in the atmosphere allows to distinguish (Fe interacts earlier than H but with large fluctuations !)

Correlation with AGNs





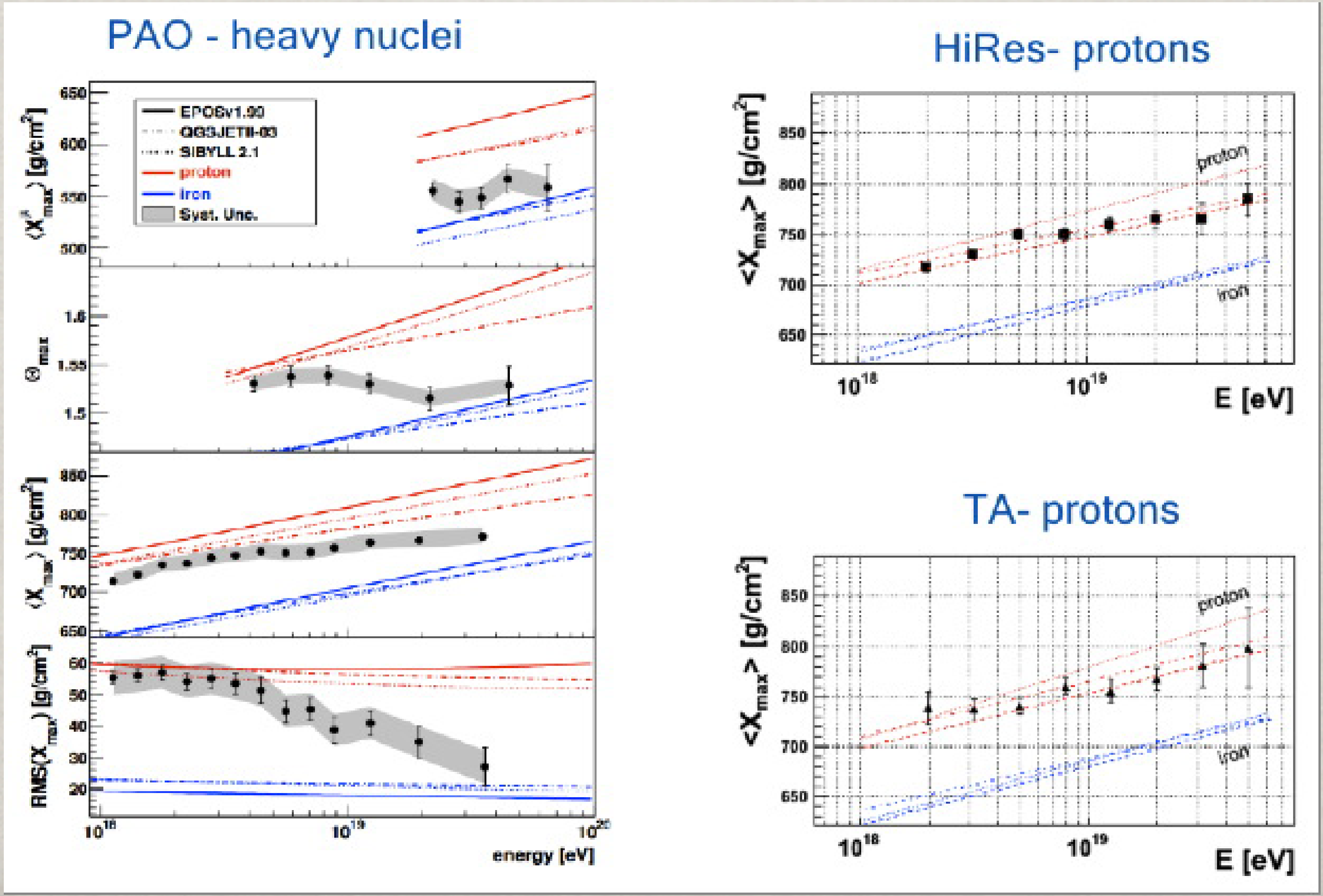
AUGER announced already in 2007 the detection of a possible correlation between UHECR and AGNs. Unfortunately the statistics became worse in the later years, but the signal is not completely lost... $\sim 3\sigma$

But is the correlation with AGNs or only with large scale structure ?

[Auger, arXiv:1009.1855 [astro-ph.HE]]

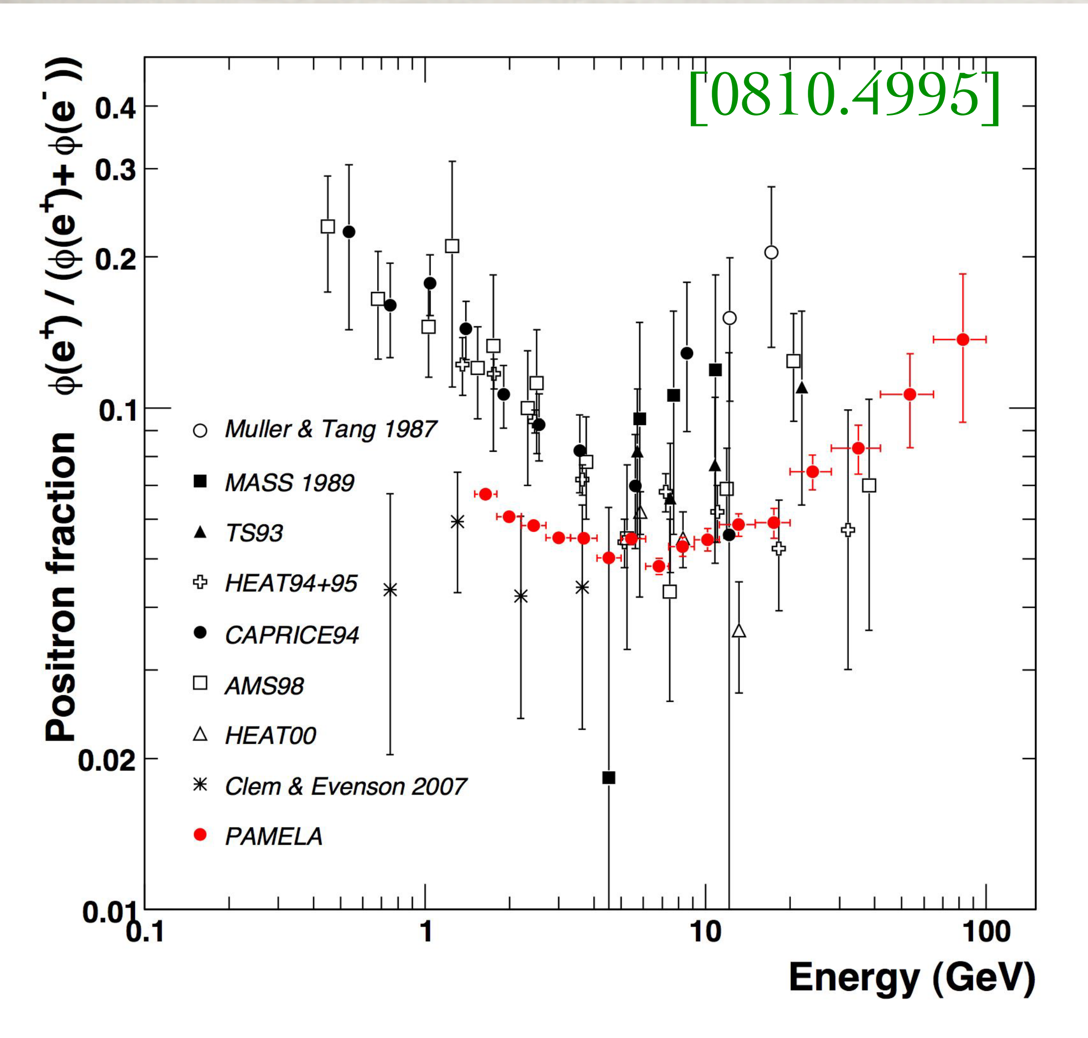
UHECR composition

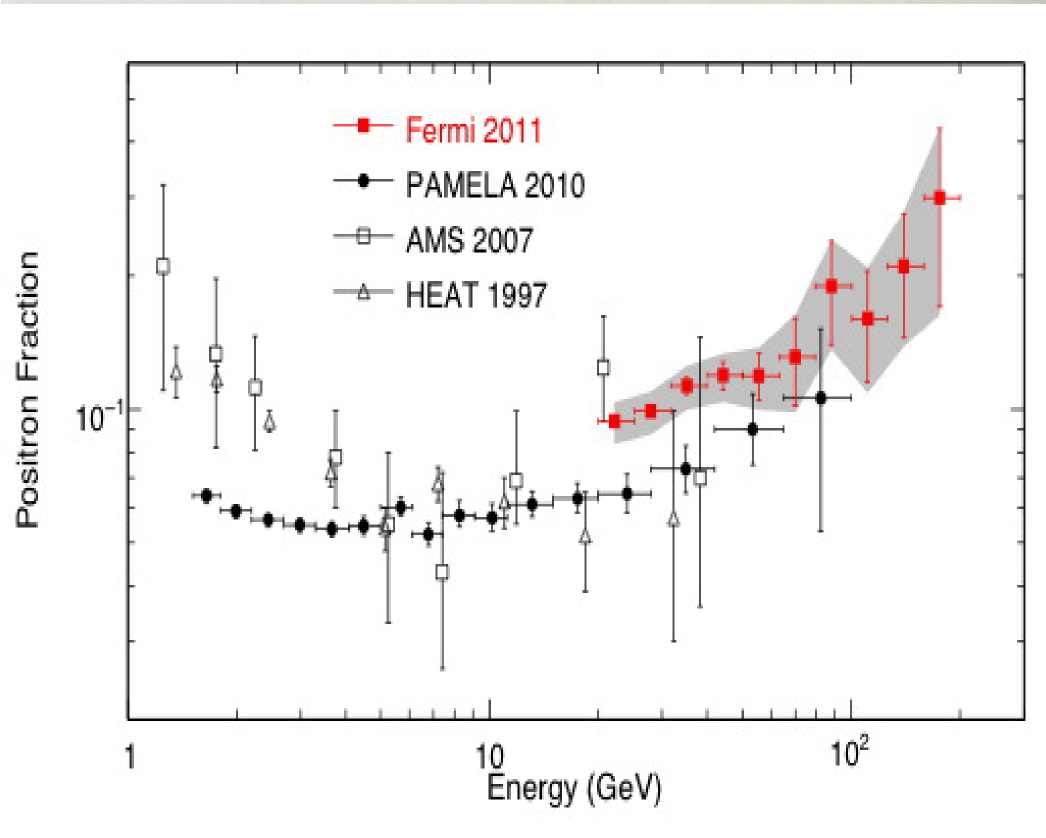
Open question: the different experiments are not in agreement...



Antimatter in CR: positrons

In 2008 PAMELA observes a rising positron fraction, later confirmed by FERMI (exploiting Earth magnetic field !):





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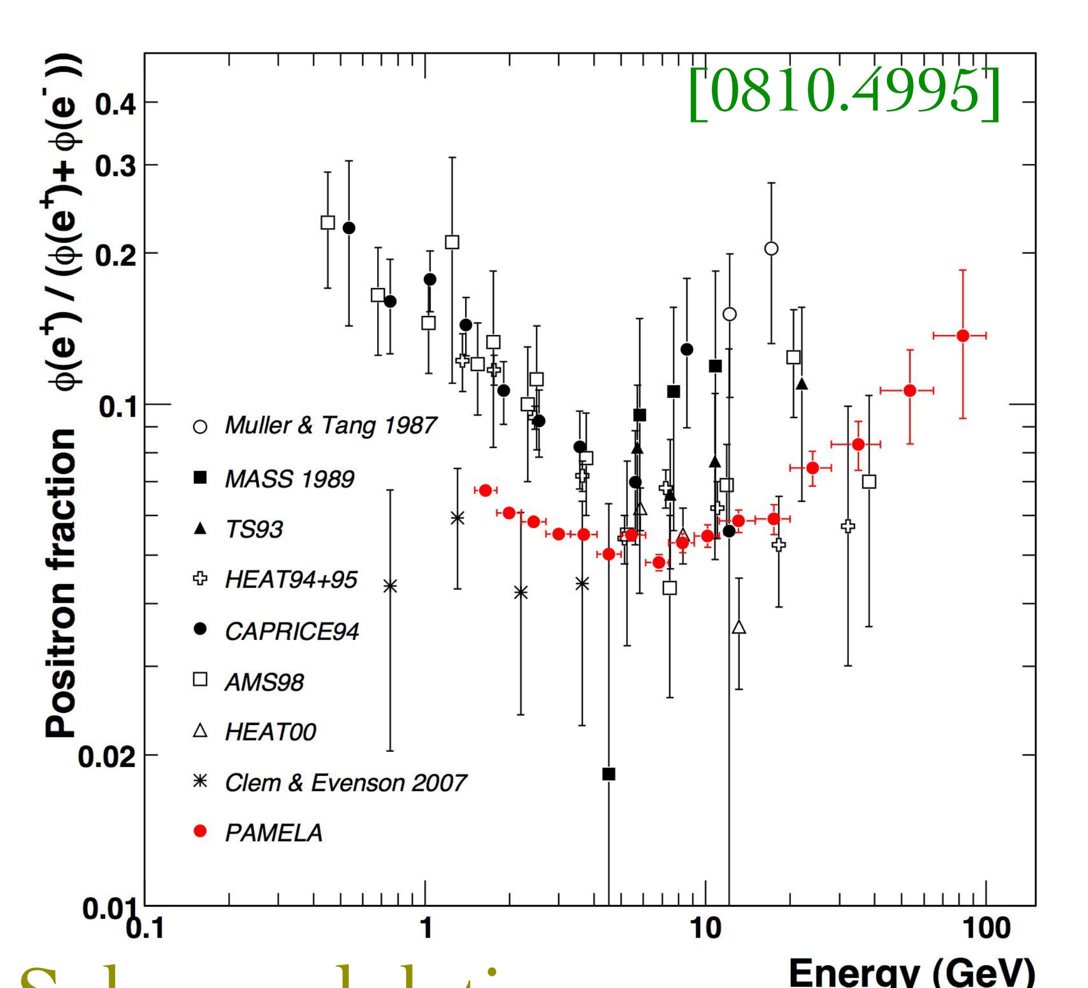
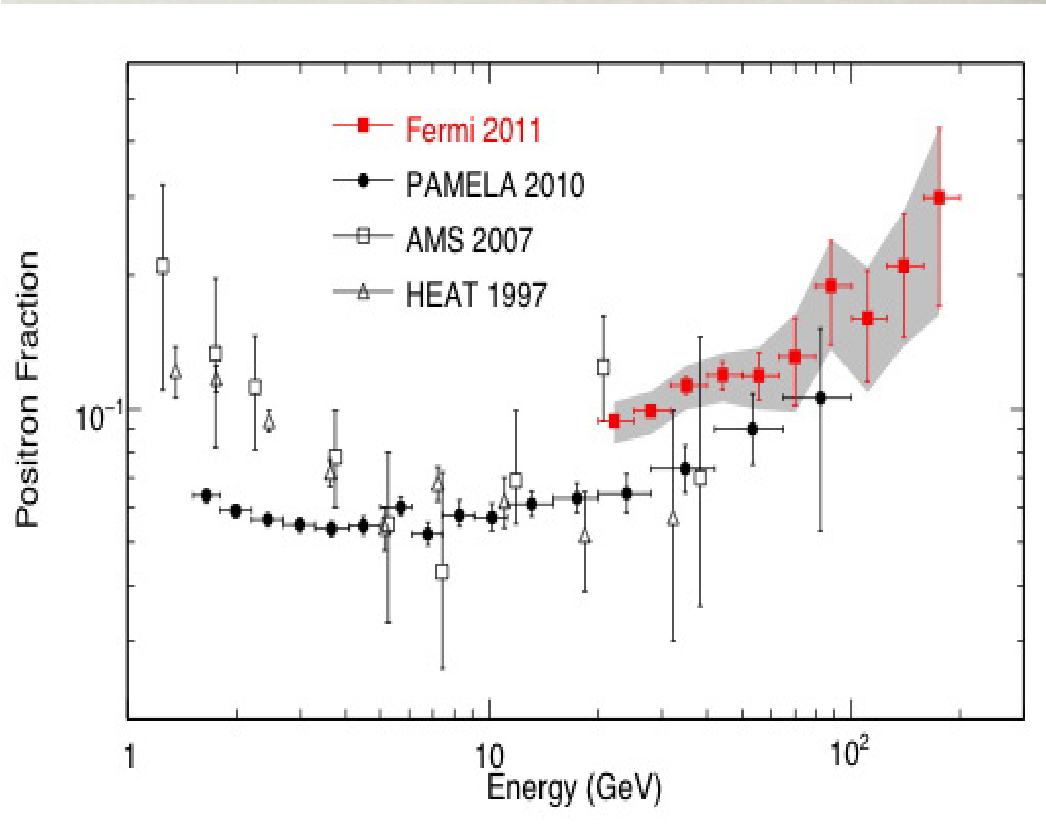


Solar modulation



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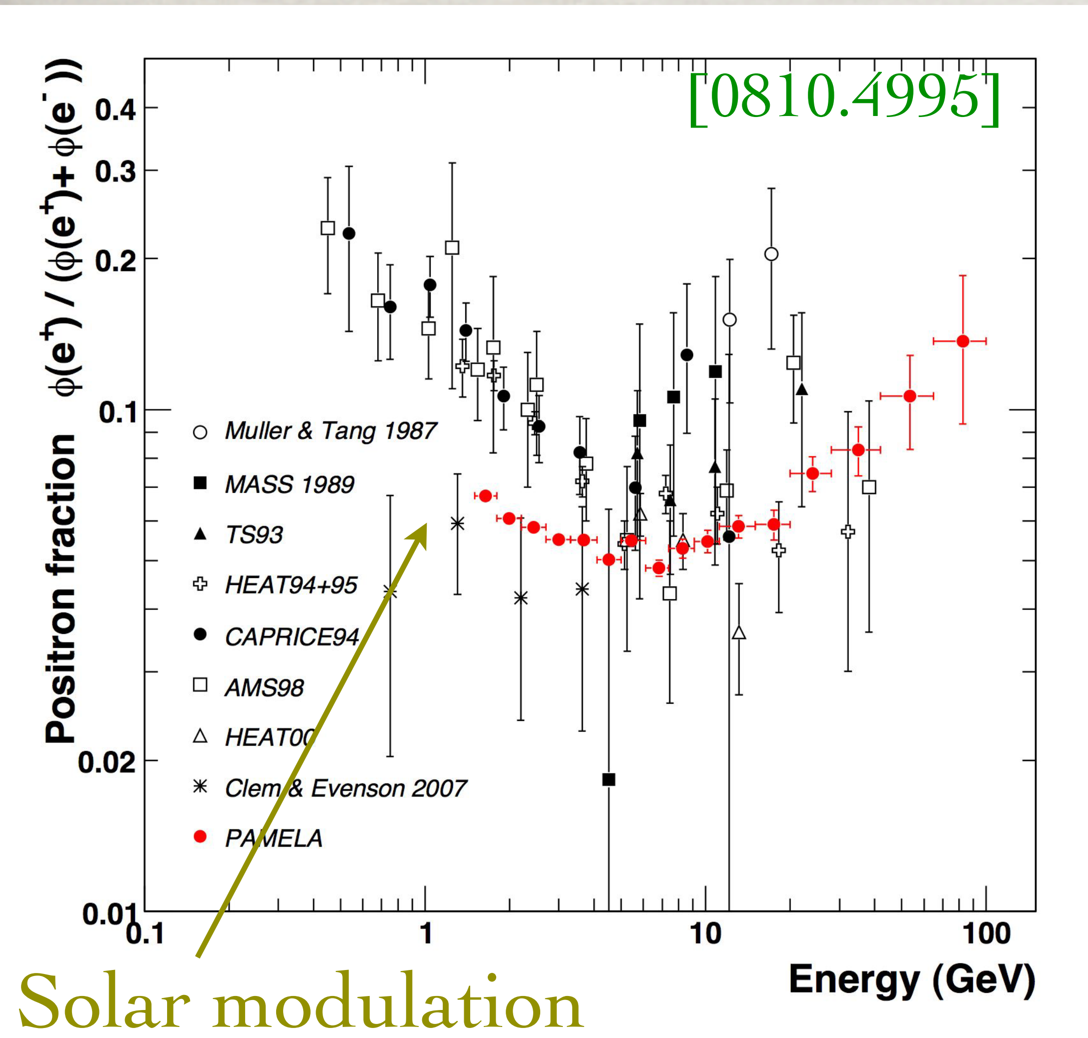
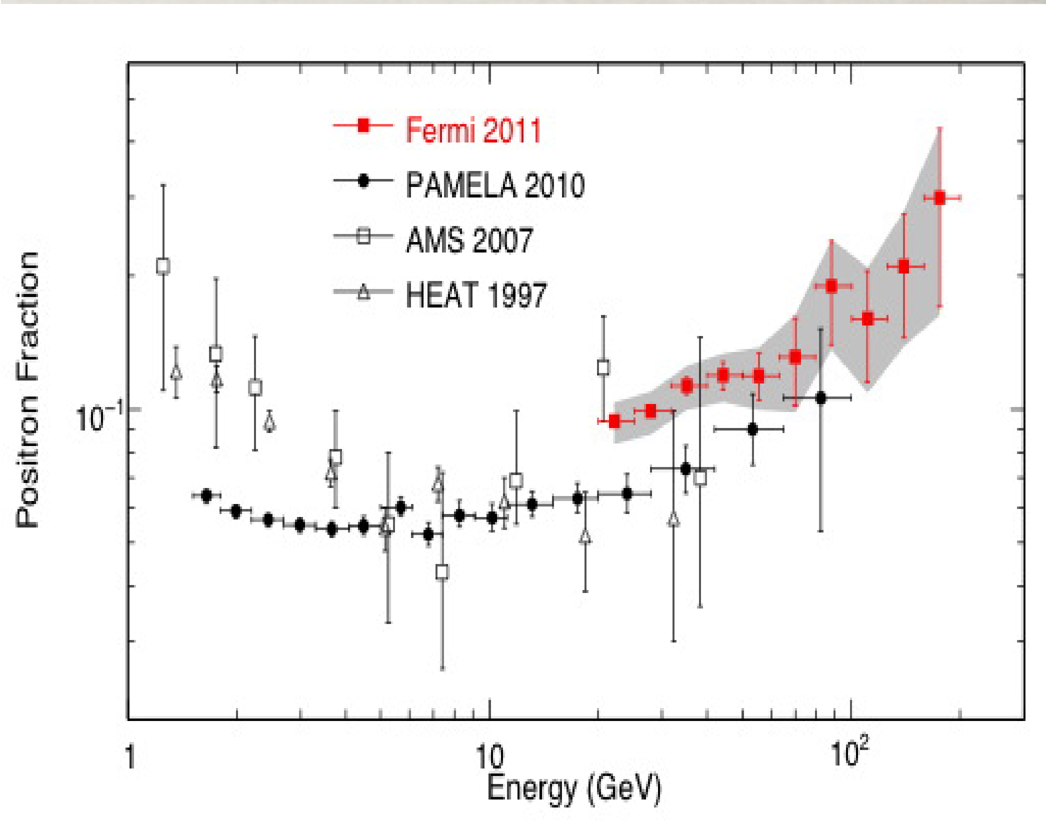
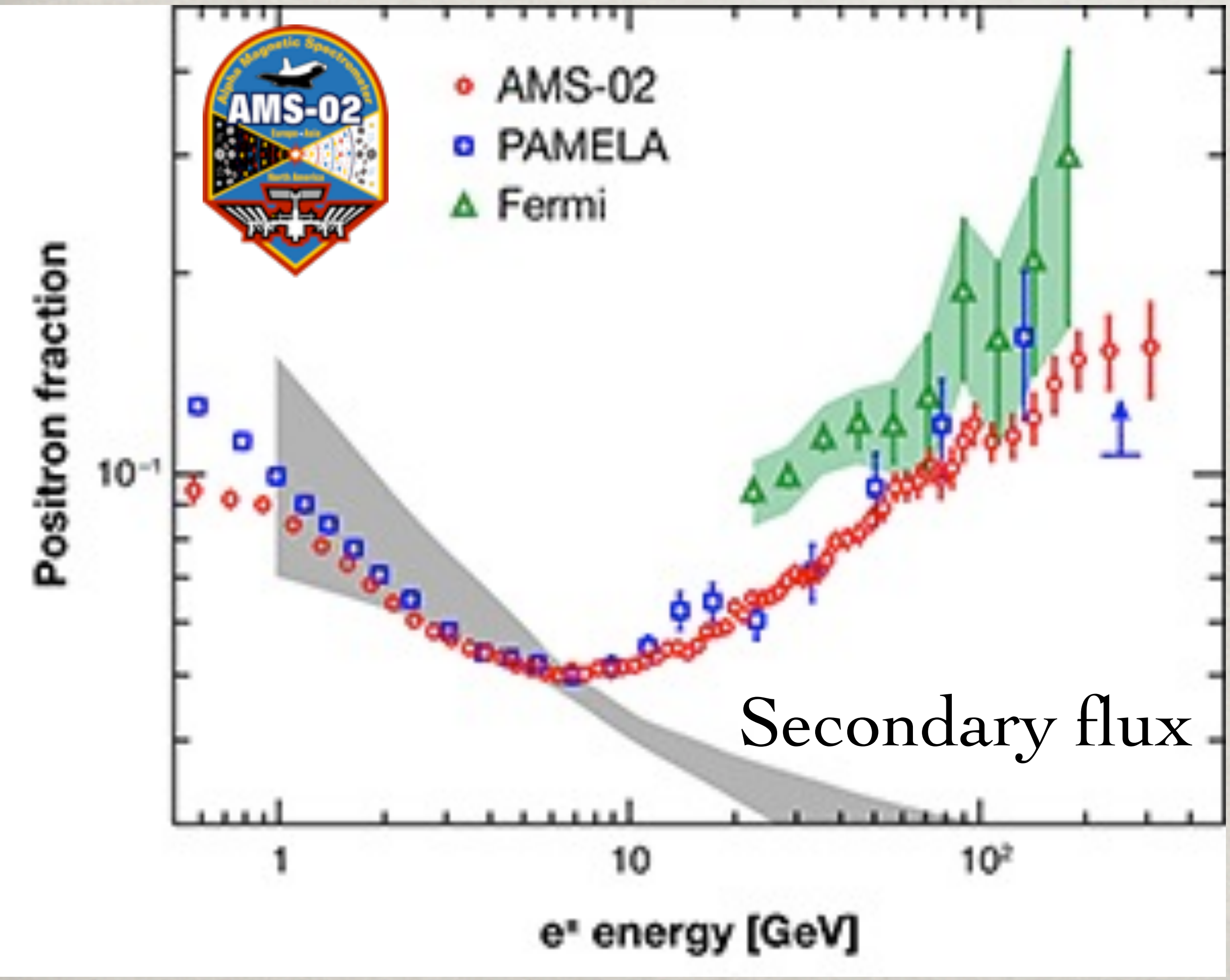




Antimatter in CR: positrons

News: AMS-02 confirms PAMELA and FERMI !



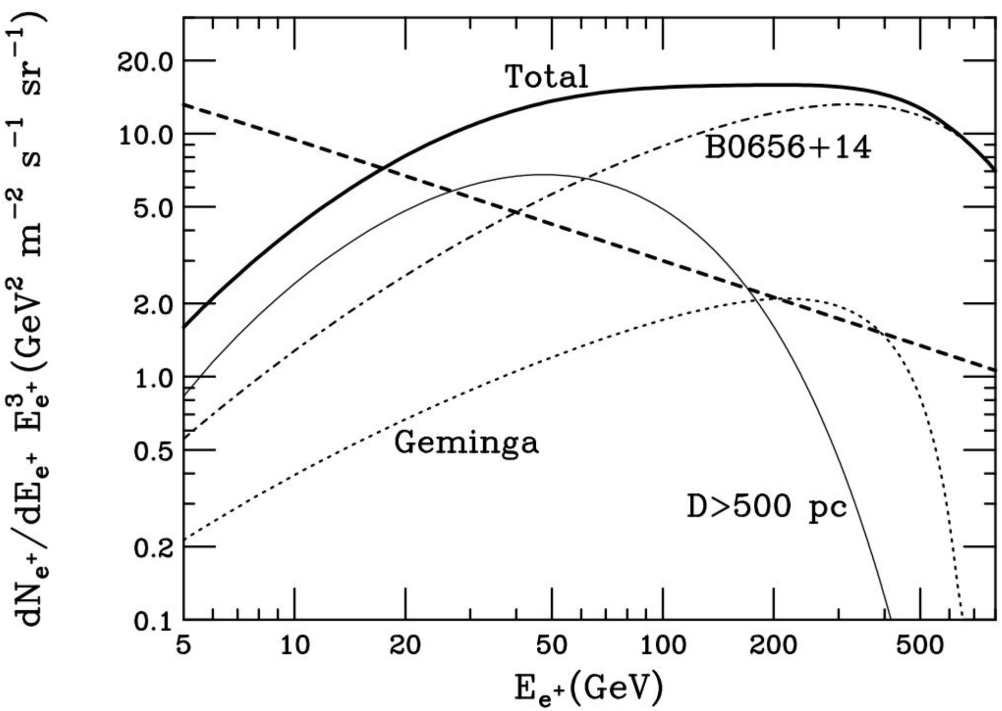
Such a rising spectrum is not explainable by "secondary" positrons produced by CR propagation !

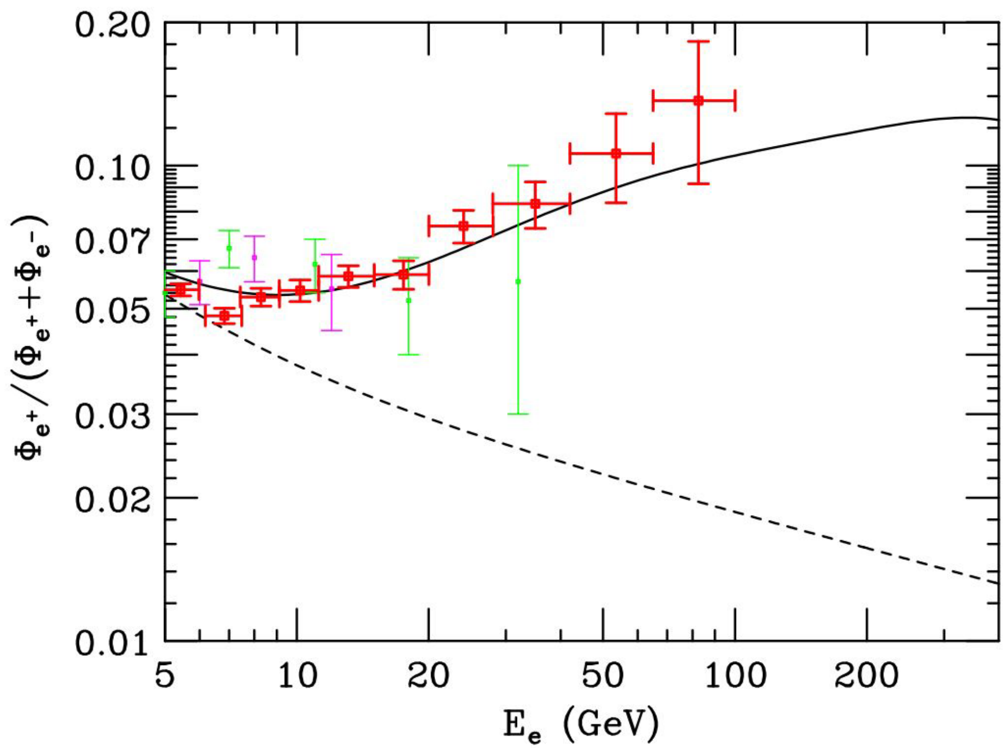
Need a positron source and not too far away...
Dark Matter or astrophysics ?

Maybe it is a pulsar

One or more local pulsars may also be a source of positrons, producting e^+e^- pairs from their energetic gammas

[Hooper, Blasi & Serpico 08]



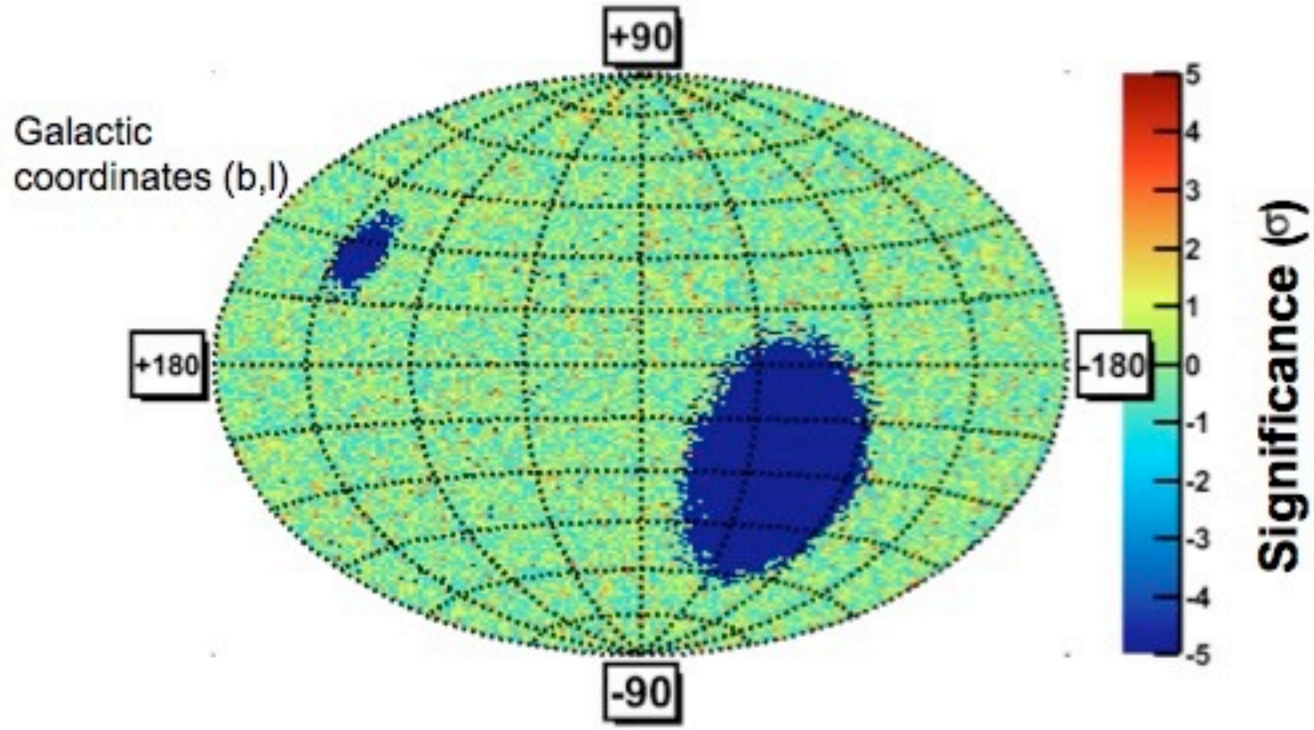


Differences from DM signal: exponential cut-off and some small anisotropy, but of the order 0.05-0.1 %

Anisotropy in positrons

ICRC2013: on the origin of excess positrons

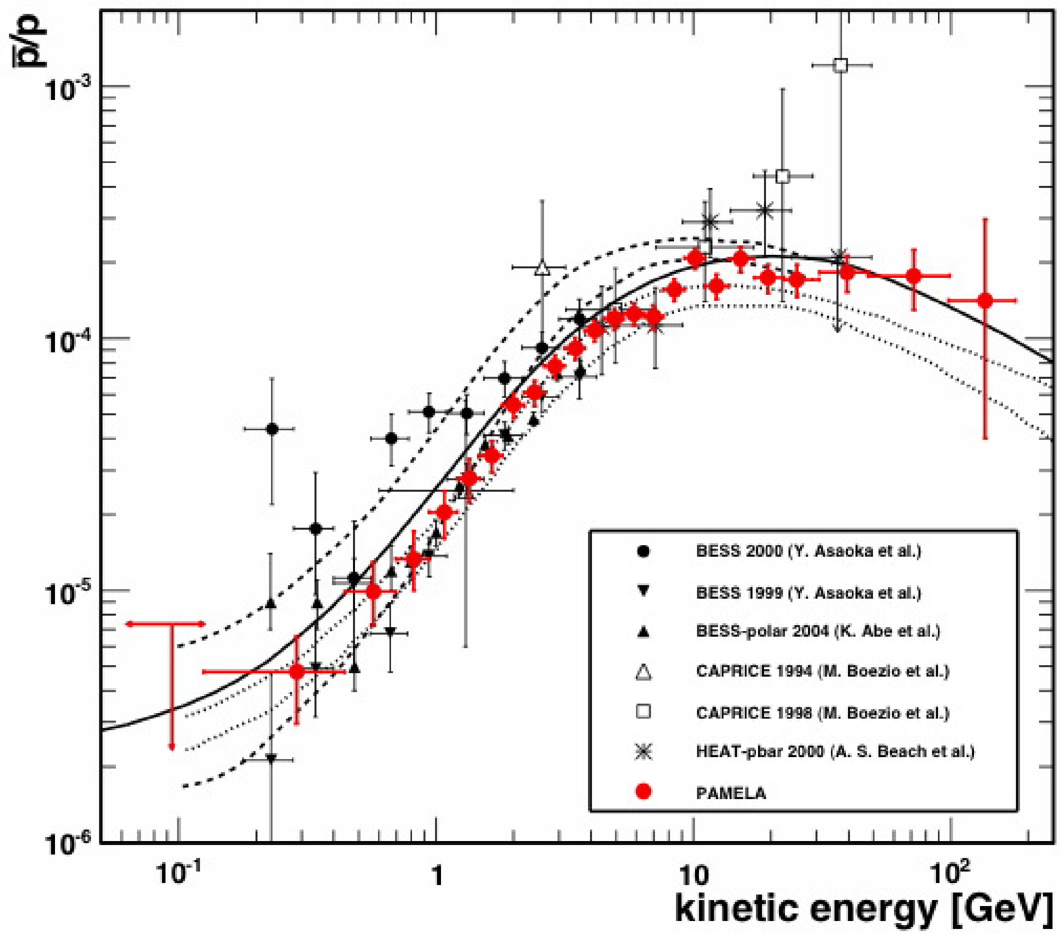
If the excess has a particle physics origin, it should be isotropic



The fluctuations of the positron ratio e^+/e^- are isotropic

Antimatter in CR: antiprotons

[PAMELA, 1007.0821]



Antiproton fraction is instead consistent with spallation production from cosmic rays...
We are waiting for the AMS-02 data!

Neutrinos

Atmospheric Neutrinos

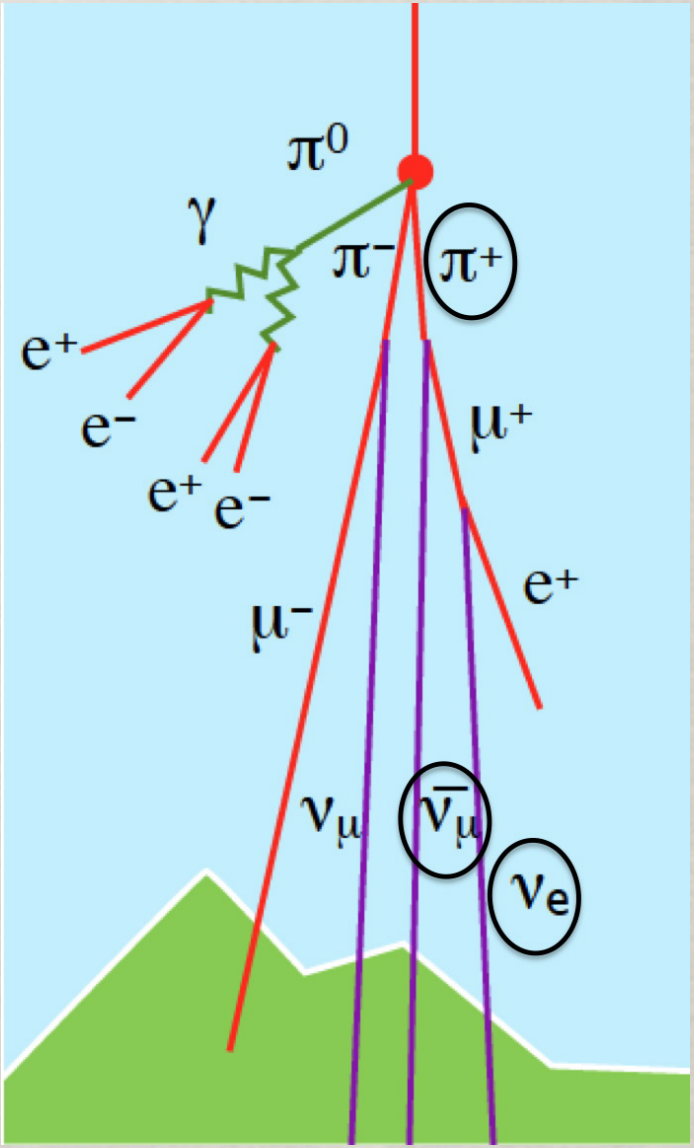
Cosmic rays interacting in the atmosphere produce as usual pions and therefore neutrinos in the ratio

$$\nu_\mu : \nu_e = 2$$

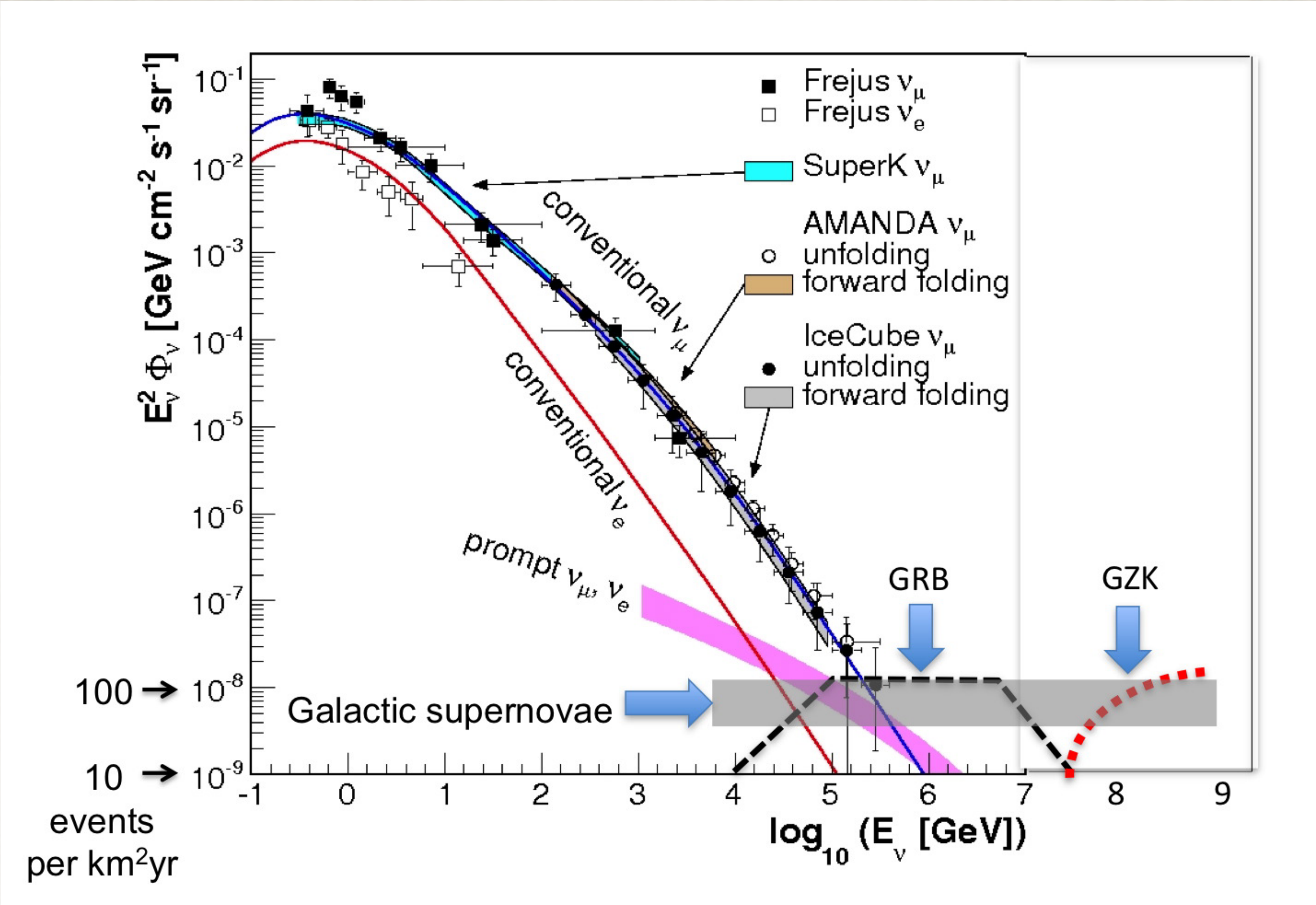
Lower ratio is measured:
neutrino flavour oscillation

→ Neutrino lectures by B. Kayser

For us they are background...

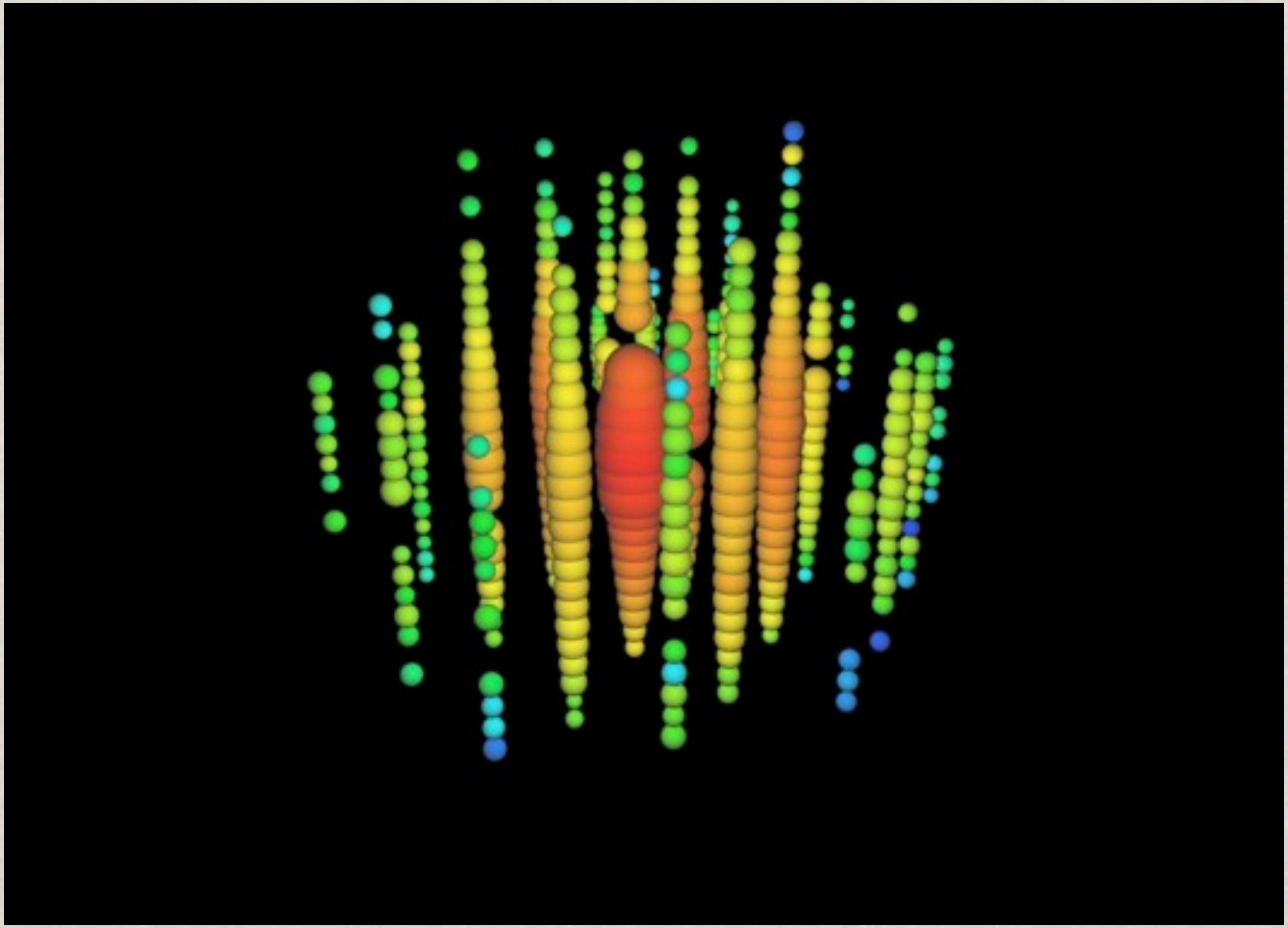


Neutrino Flux



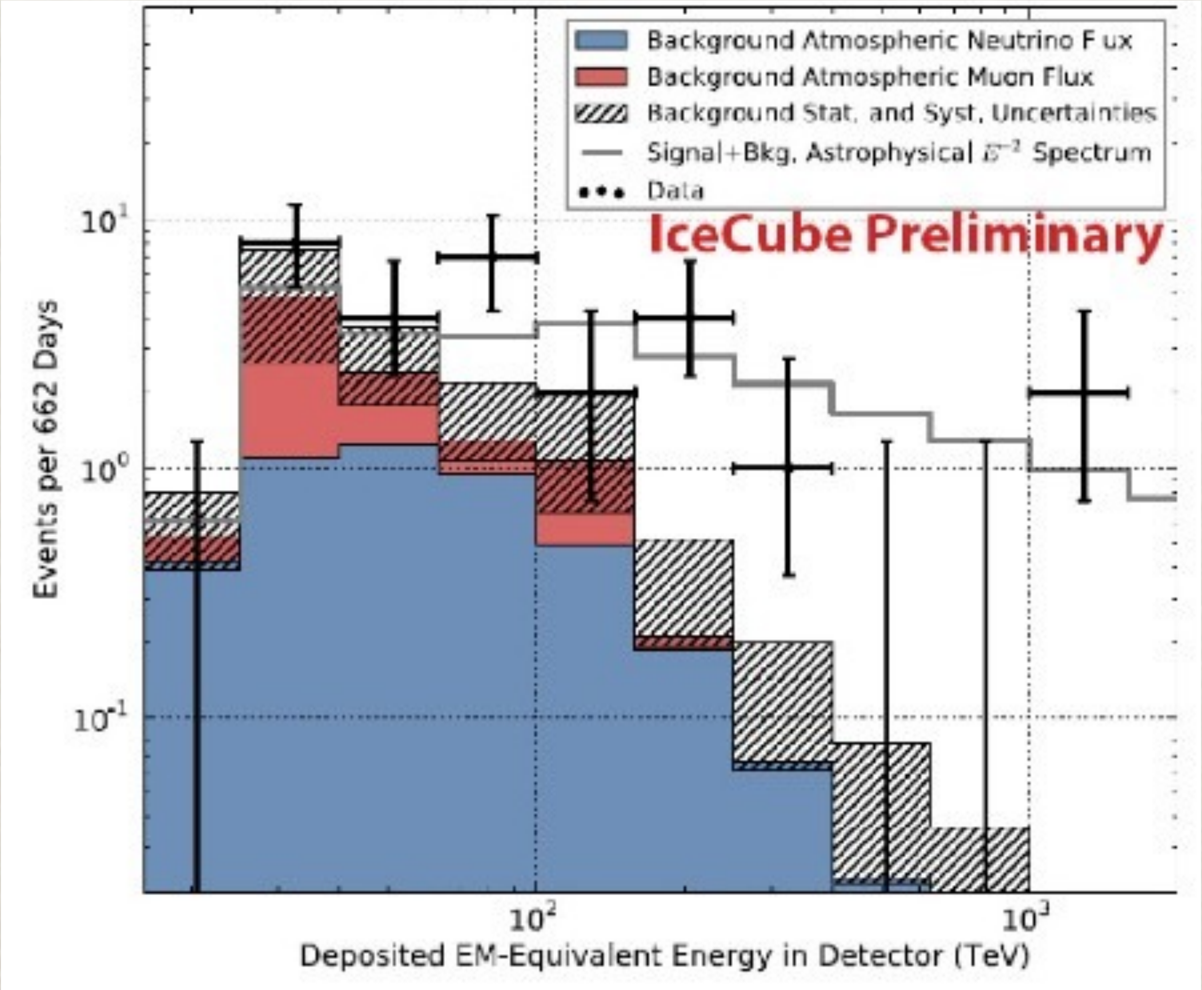
Low Energy part dominated by atmospheric neutrinos, at higher energy different signals are expected...

Neutrino News



First events in PeV energies announced this year !

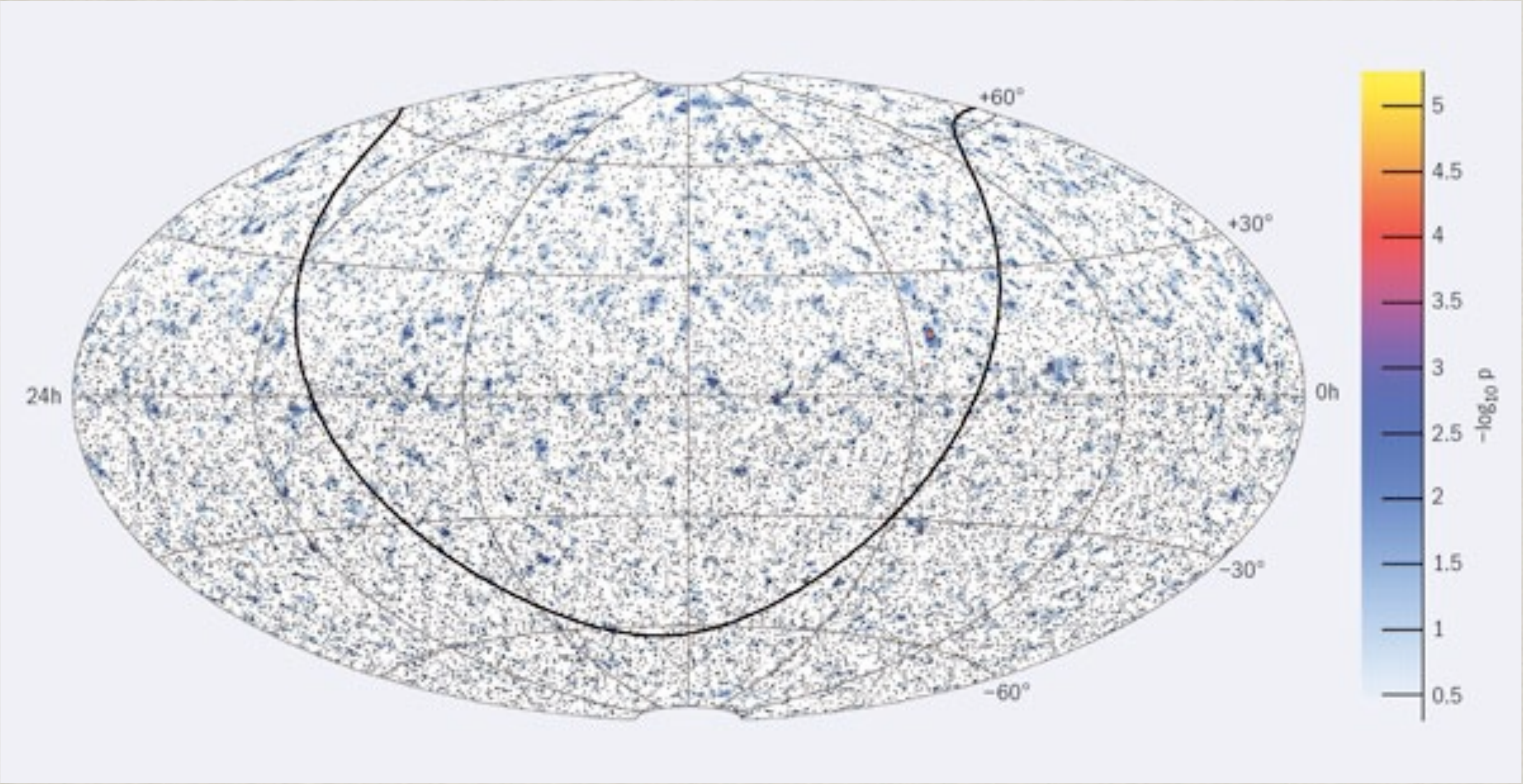
Neutrino News



Two events seen above 100 TeV !

Not compatible with atmospheric neutrino background, but too low energy for the GZK neutrinos...

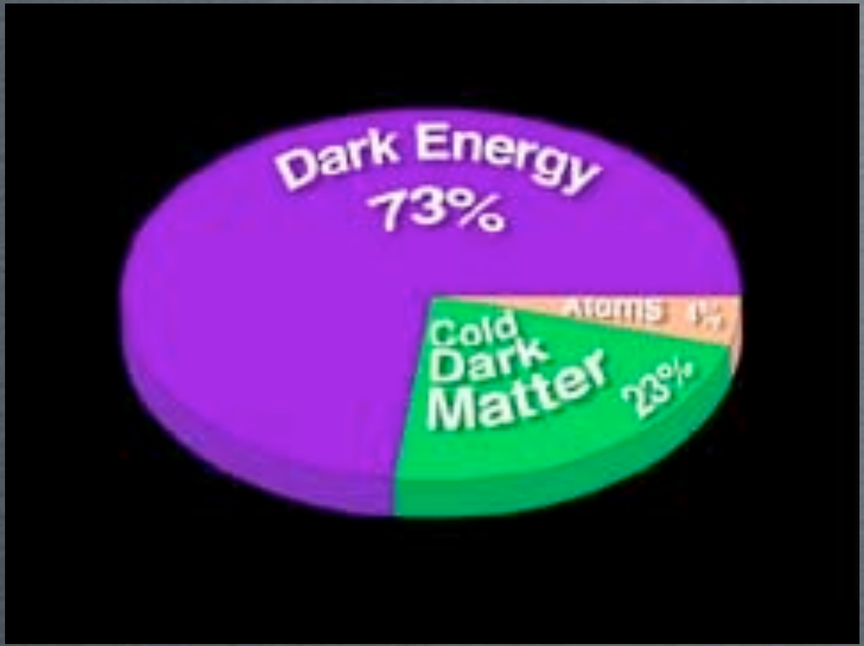
Neutrino Astronomy



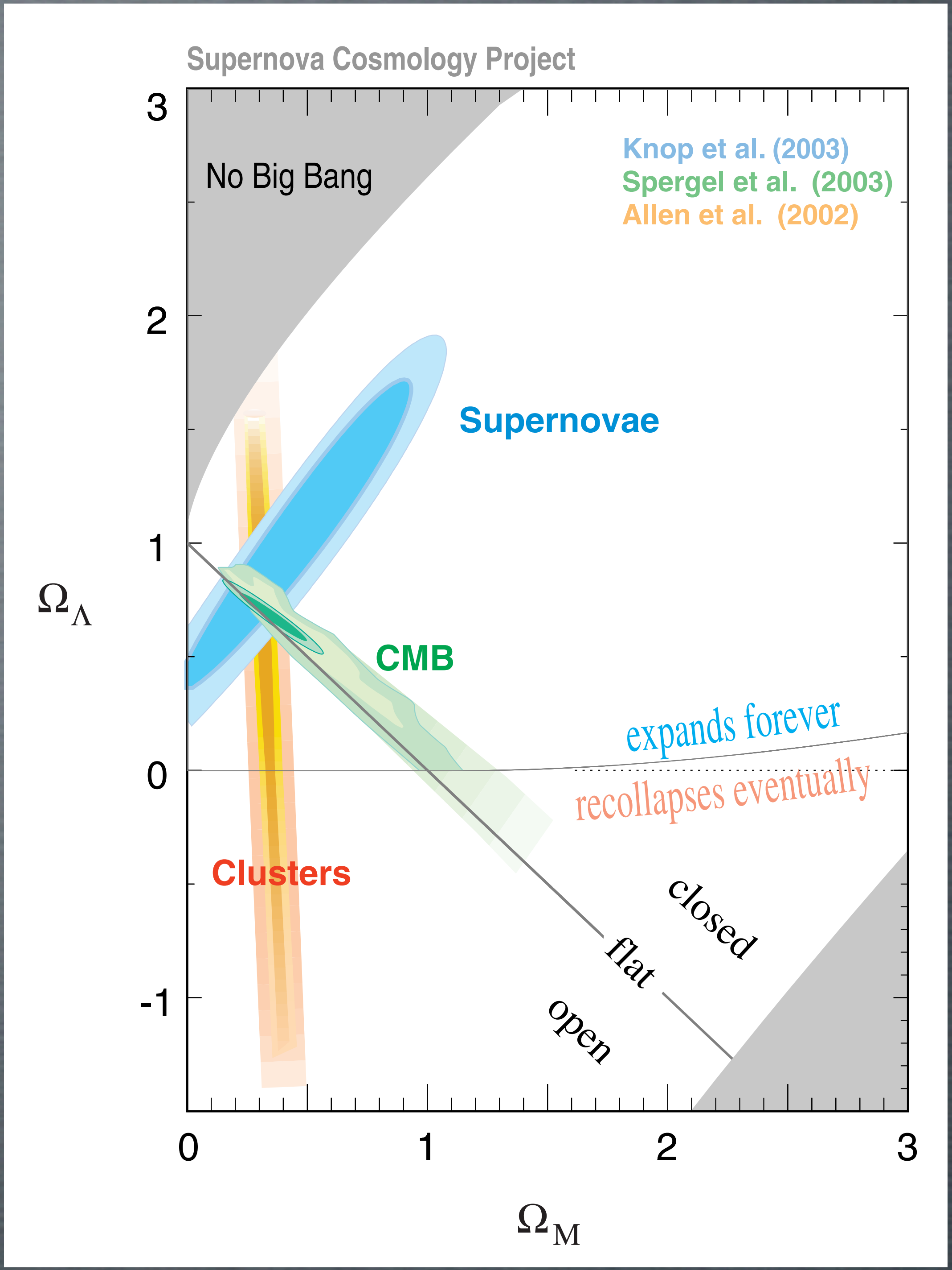
Neutrino sky map so far... The hope is to obtain the same for high energy neutrino and find correlation with sources... No deflection on magnetic field for neutrinos !

Dark Matter

ENERGY CONTENT



with traces of photons, neutrinos & ... ?



DARK MATTER EVIDENCE

→ Cosmology lectures by L. Verde

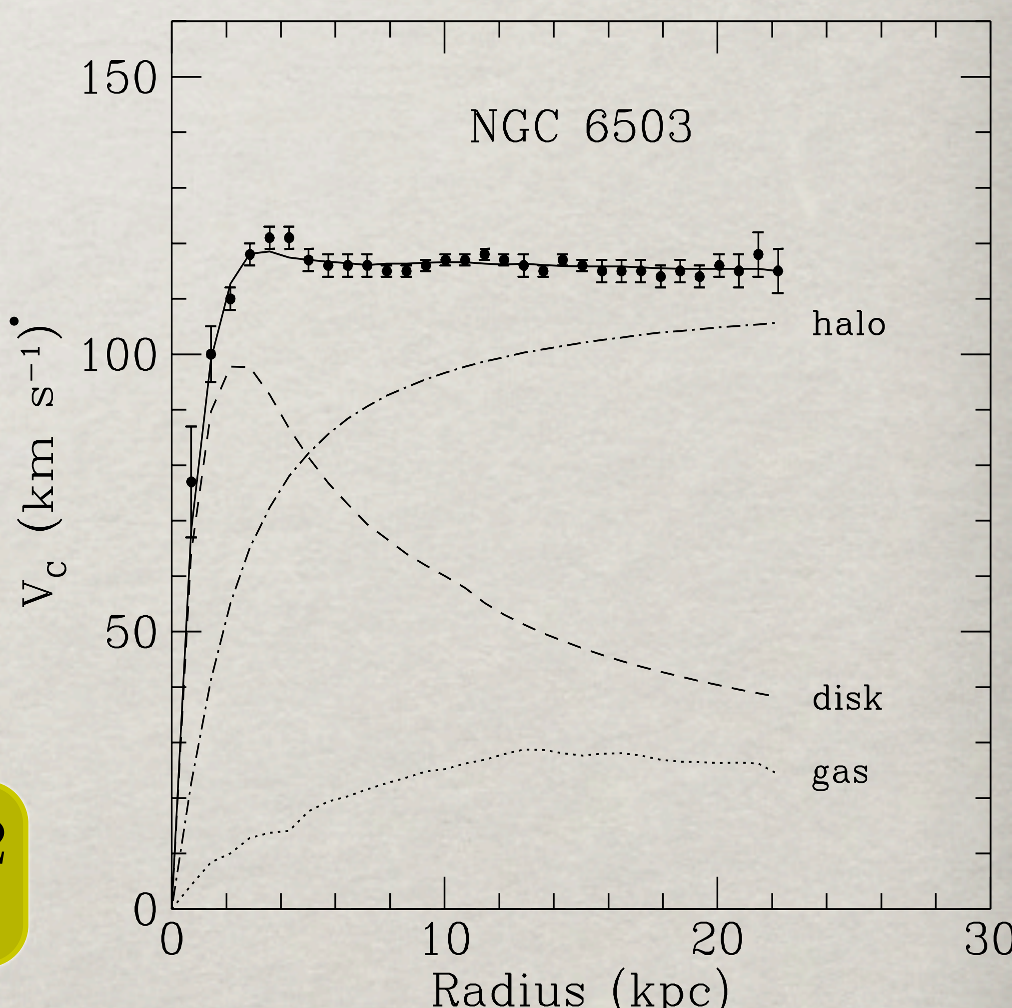
GALACTIC SCALES:

the stars in the outer part of galaxies are faster than expected...

$$v_c^2 \propto G_N \frac{M(r)}{r} \propto \frac{M_{tot}}{r}$$

But instead it is constant ! Need

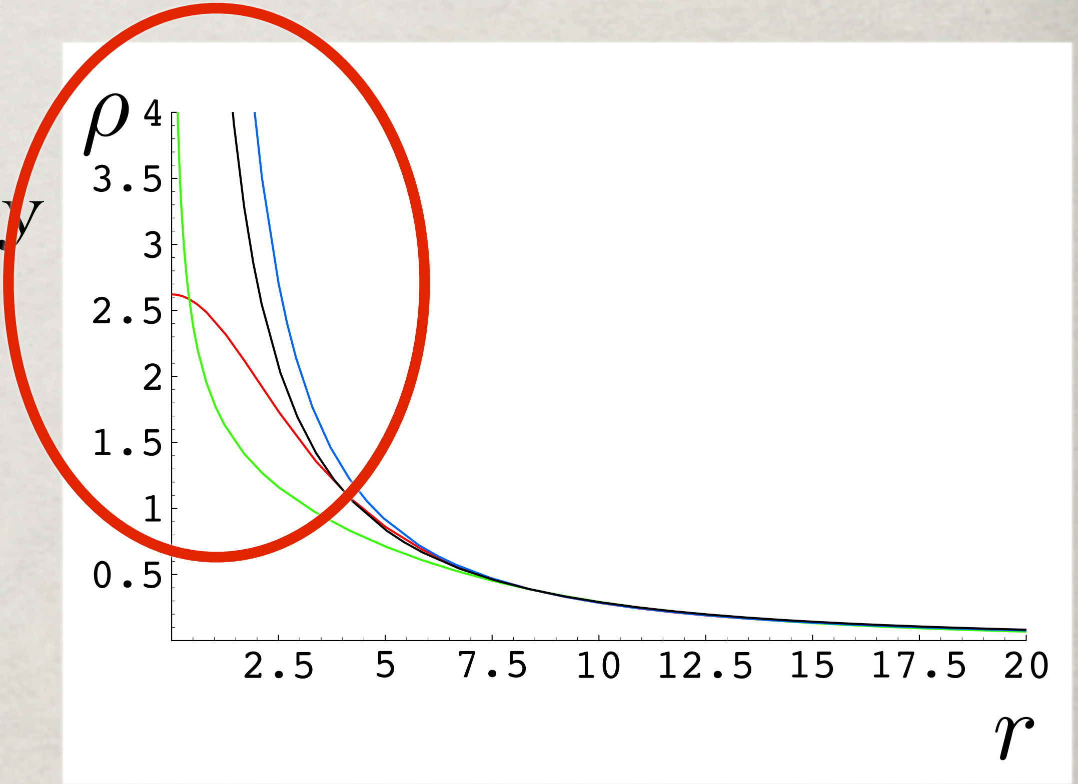
$$M(r) \propto r, \text{ i.e. } \rho_{DM} \propto r^{-2}$$



DARK MATTER EVIDENCE

GALACTIC SCALES:

Many density profiles, inpired by data or numerical simulations: Isothermal, NFW, Moore, Kratsov, Einasto, etc.... They mostly differ in the behaviour at the centre, either cusped or cored !



$$\rho(r) = \frac{\rho_0}{(r/R)^\gamma[1+(r/R)^\alpha]^{(\beta-\gamma)/\alpha}}$$

Critical for indirect detection !

THE WIMP MECHANISM

Primordial abundance of stable massive species

[see e.g. Kolb & Turner '90]

The number density of a stable particle X in an expanding Universe is given by the Bolzmann equation

$$\frac{dn_X}{dt} + 3Hn_X = \langle\sigma(X + X \to \text{anything})v\rangle \left(n_{eq}^2 - n_X^2\right)$$

Hubble expansion　　Collision integral

The particles stay in thermal equilibrium until the interactions are fast enough, then they freeze-out at $x_f = m_X/T_f$

defined by $n_{eq}\,\langle\sigma_A v\rangle_{x_f} = H(x_f)$ and that gives

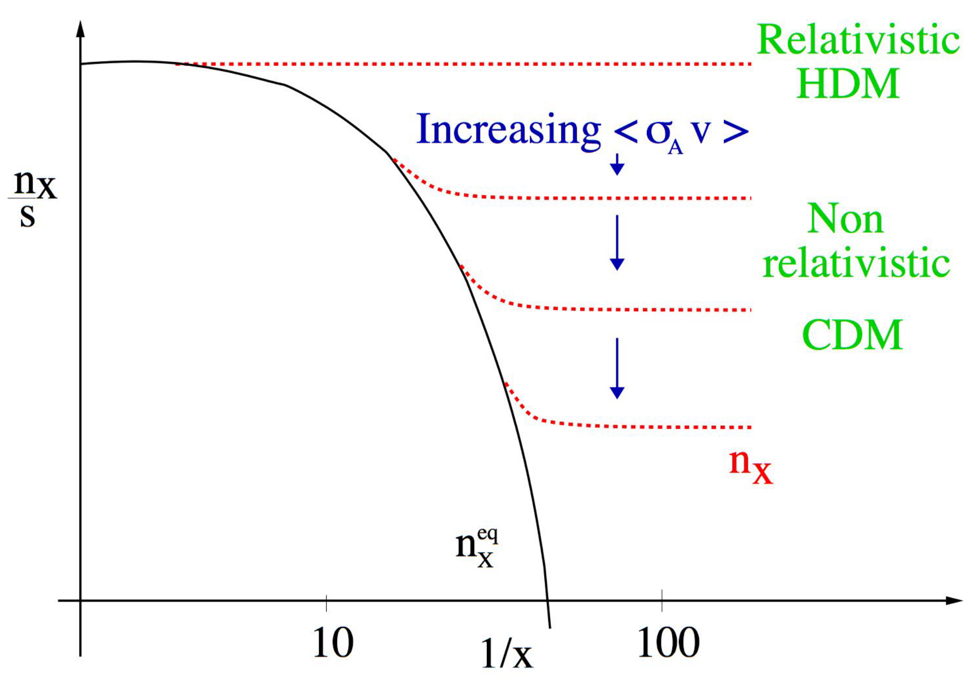
$$\Omega_X = m_X n_X(t_{now}) \quad \propto \quad \frac{1}{\langle\sigma_A v\rangle_{x_f}}$$

Abundance $\Leftrightarrow$ Particle properties

For $m_X \simeq 100$ GeV a WEAK cross-section is needed !

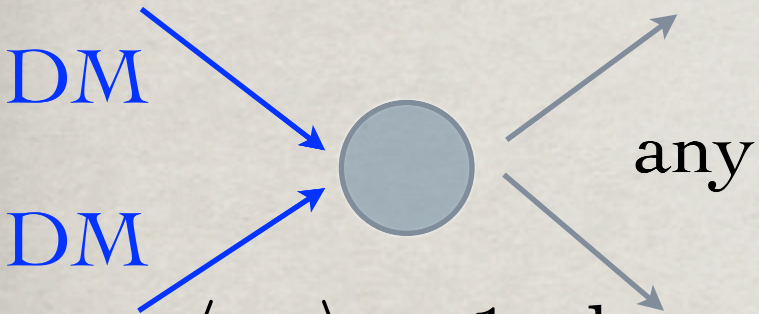
Weakly Interacting Massive Particle

For weaker interactions need lighter masses HOT DM !



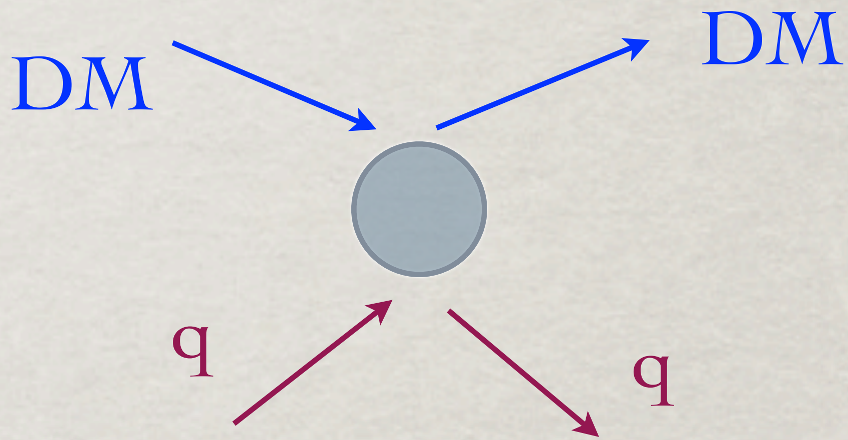
THE WIMP CONNECTION

Early Universe: $\Omega_{CDM}h^2$

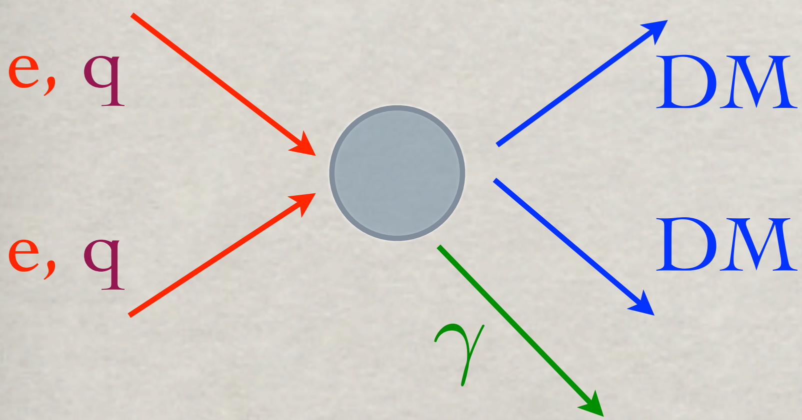


$\langle \sigma v \rangle \sim 1\ \mathrm{pb}$

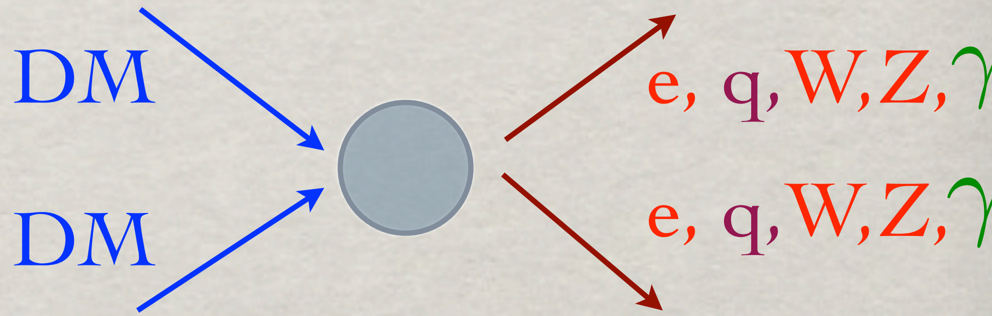
Direct Detection:



Colliders: LHC/ILC



Indirect Detection:



3 different ways to check this hypothesis !!!

THE WIMP CONNECTION

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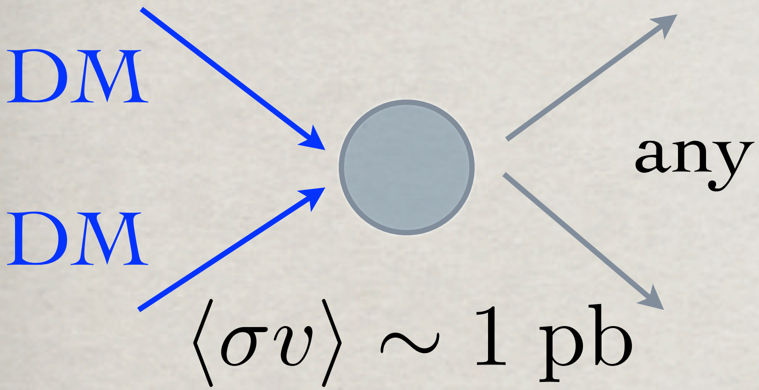

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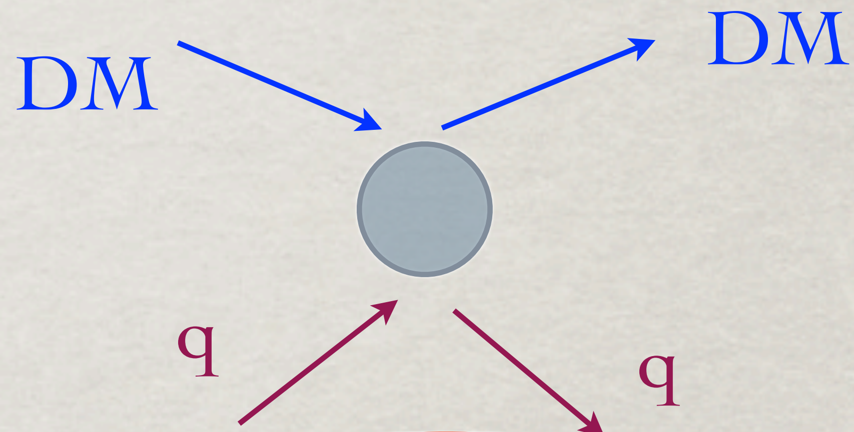

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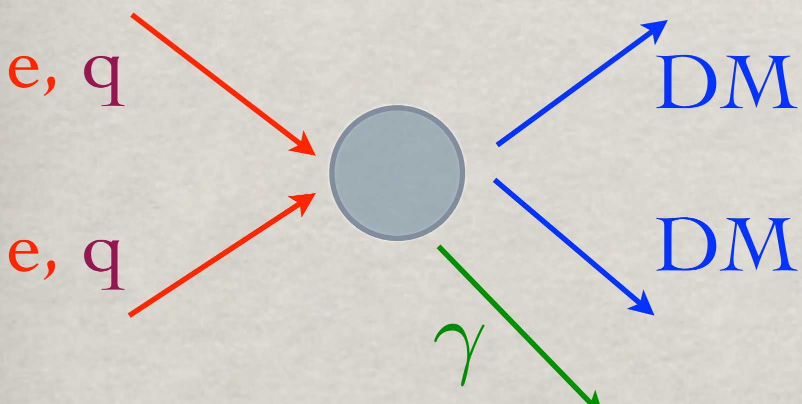
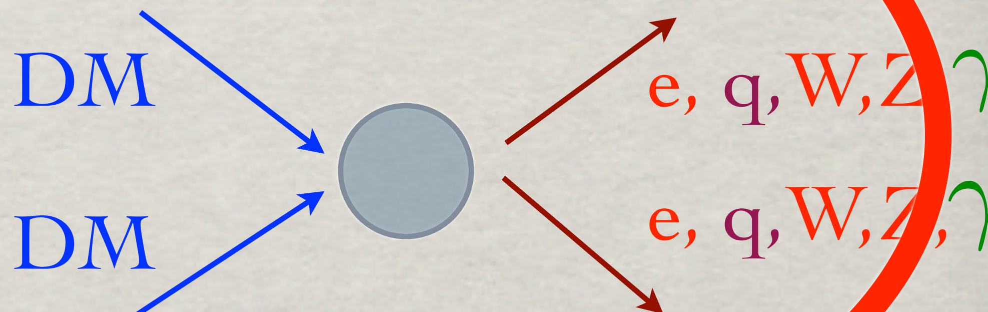


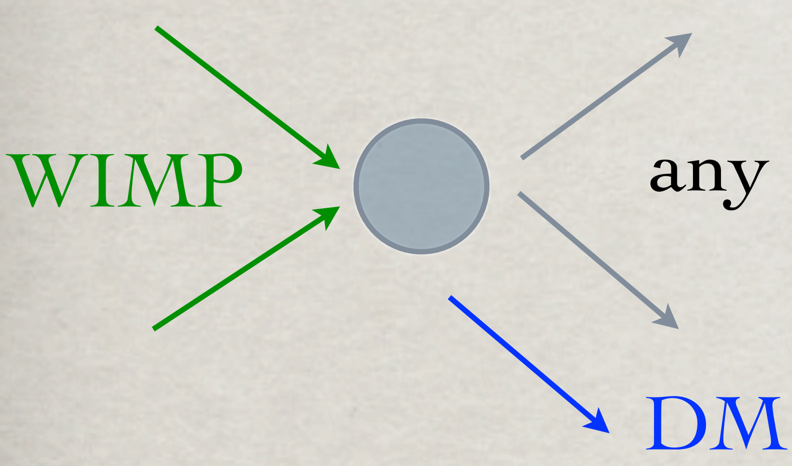
Indirect Detection:



3 different ways to check this hypothesis !!!

Decaying DM connection

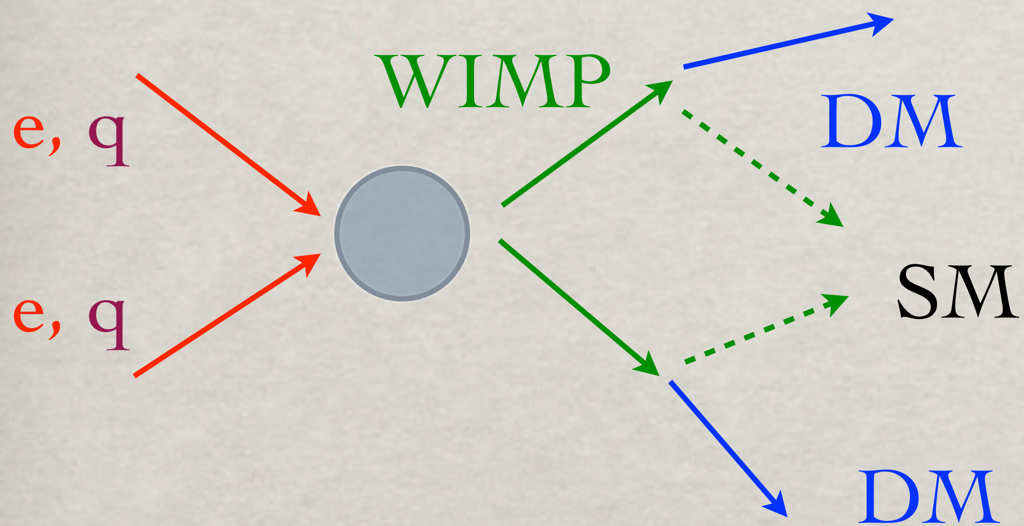
Early Universe: $\Omega_{CDM} h^2$



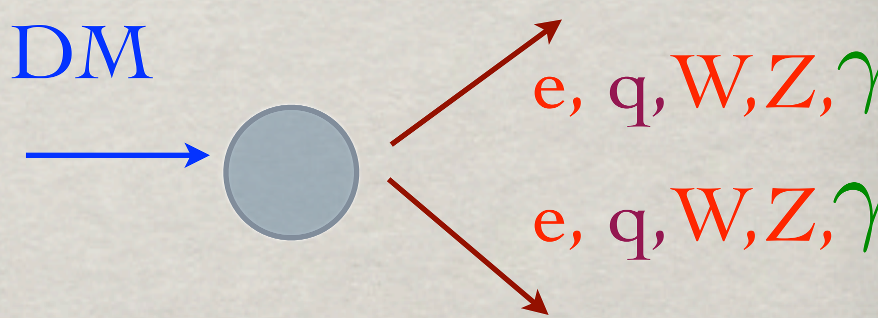
Direct Detection:

NONE...

Colliders: LHC/ILC



Indirect Detection:

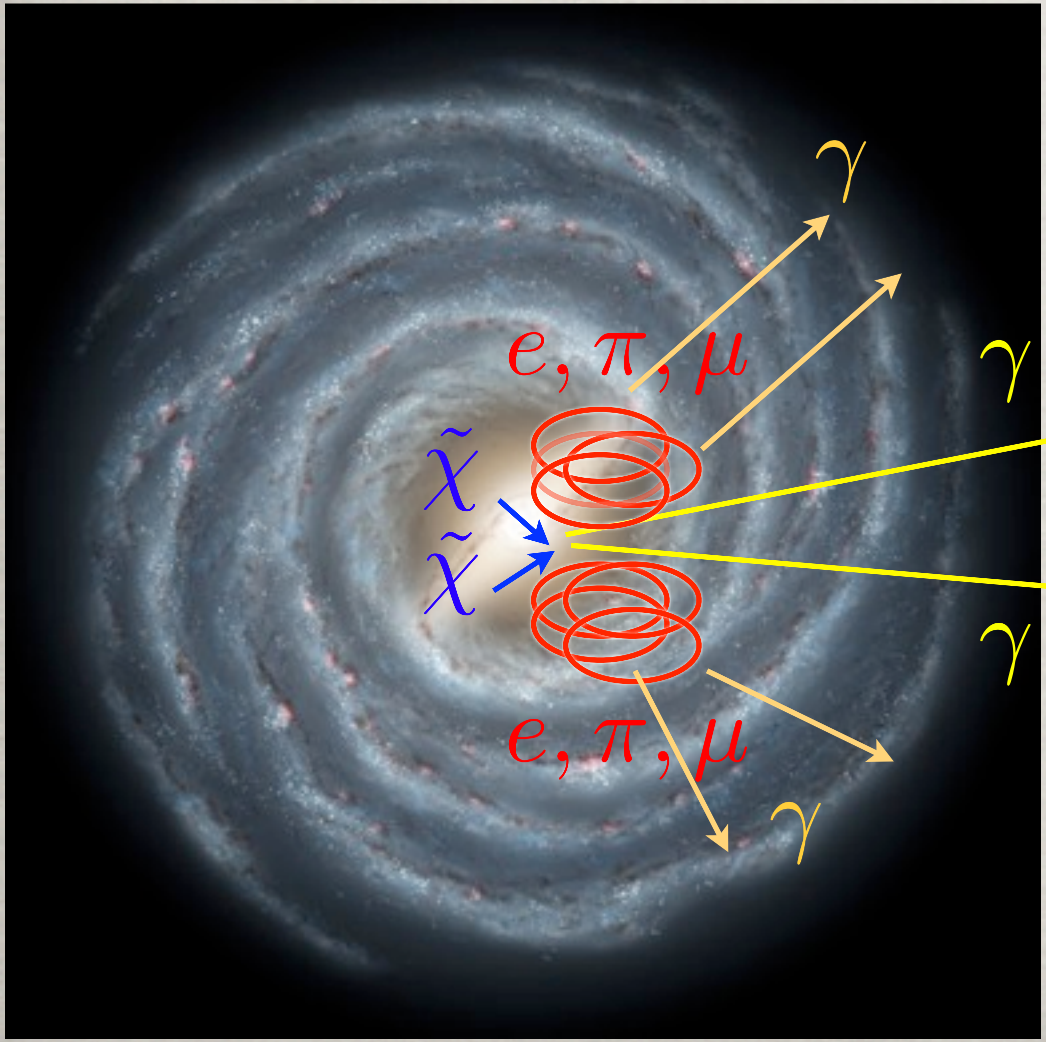


decaying DM !

2 different ways to check this hypothesis !!!

THE HOPE: DETECT DM !

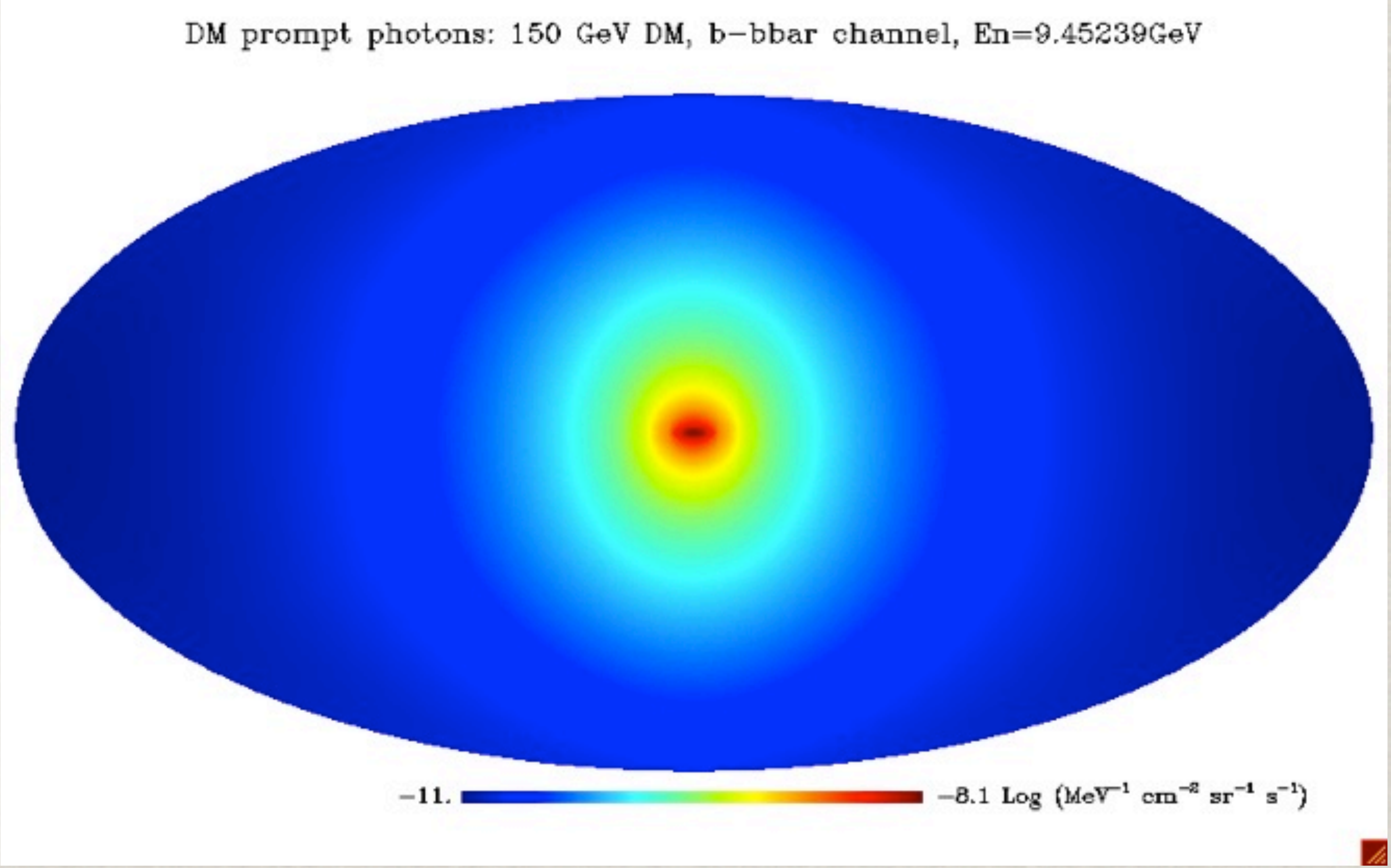
- Look for annihilation signals from the region where the density is large: centre of the Milky Way, other galaxies, clumps of DM, etc...



Measure the decay products!

FERMI, PAMELA, AMS-02, HESS, MAGIC, CTA...

THE HOPE: DETECT DM !



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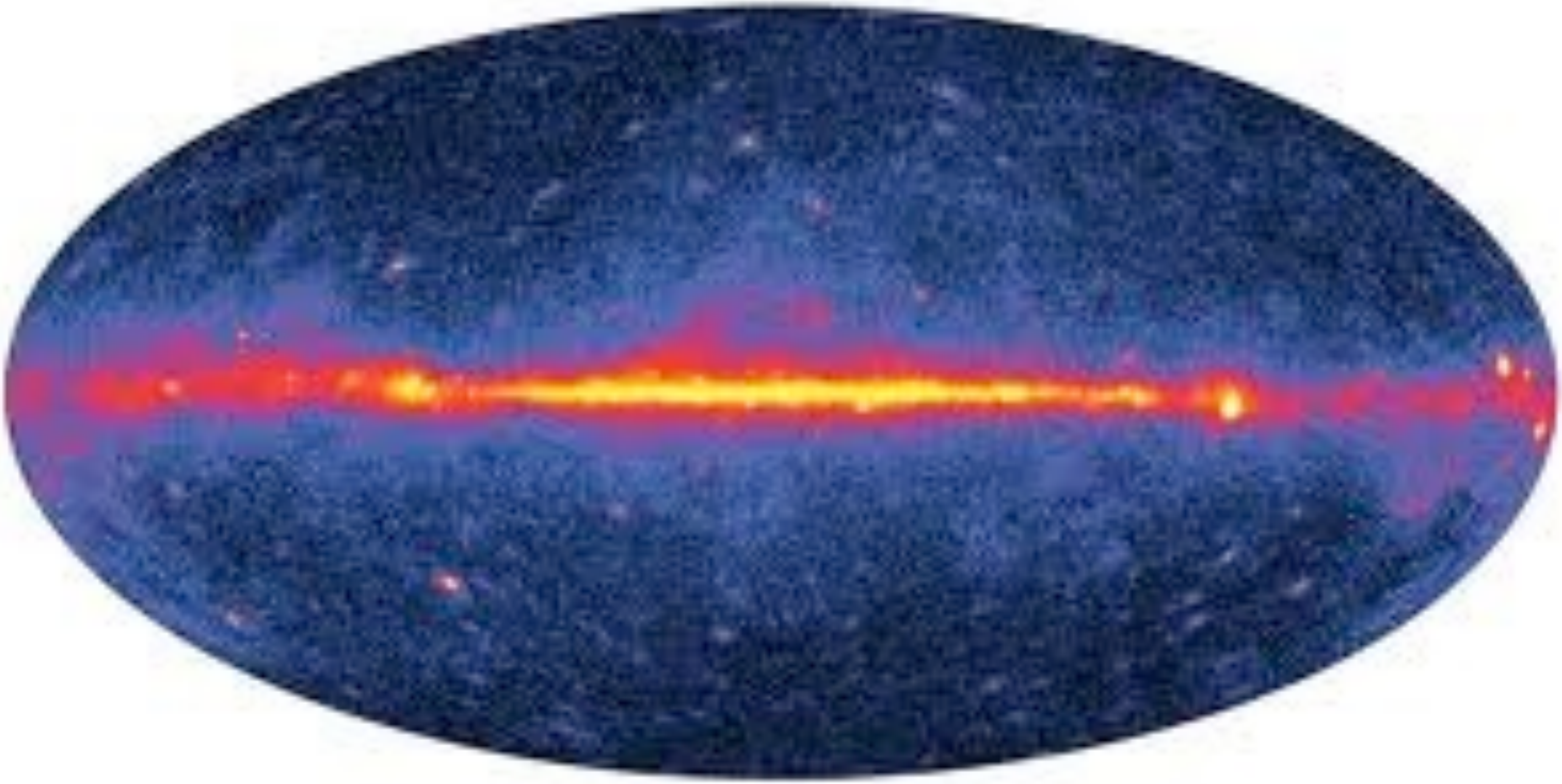


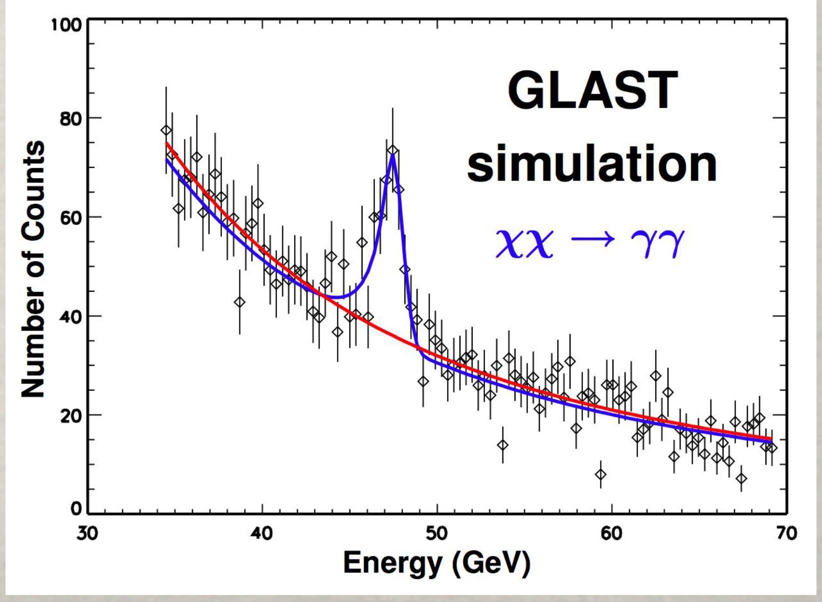
THE HOPE: DETECT DM !

- The flux in a species i is given by

$$\Phi(\theta, E) = \sigma v \, \frac{dN_i}{dE} \, \frac{1}{4\pi m_{DM}^2} \int_{l.o.s.} ds \, \rho^2(r(s,\theta))$$

Particle Physics — Halo property

- Strongly dependent on the halo model/density and the DM clumping: BOOST factor !
- Spectrum in gamma-rays determined by particle physics ! Smoking gun: gamma line...
- For other species also the propagation plays a role.



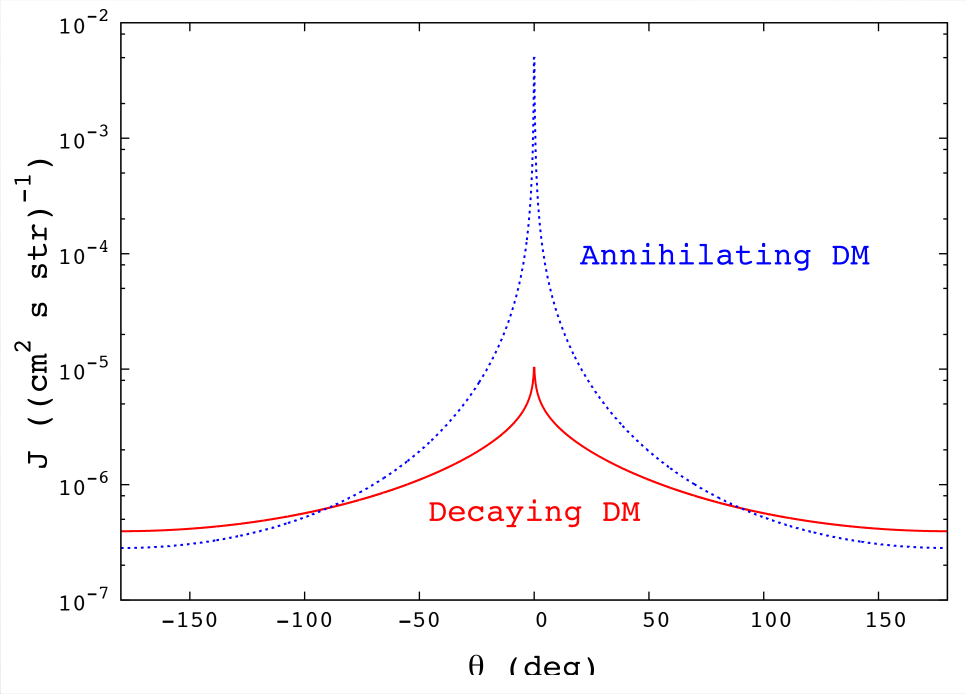
DECAYING DM

- The flux from DM decay in a species i is given by

$$\Phi(\theta, E) = \frac{1}{\tau_{DM}} \frac{dN_i}{dE} \frac{1}{4\pi m_{DM}} \int_{l.o.s.} ds\, \rho(r(s,\theta))$$

Particle Physics Halo property

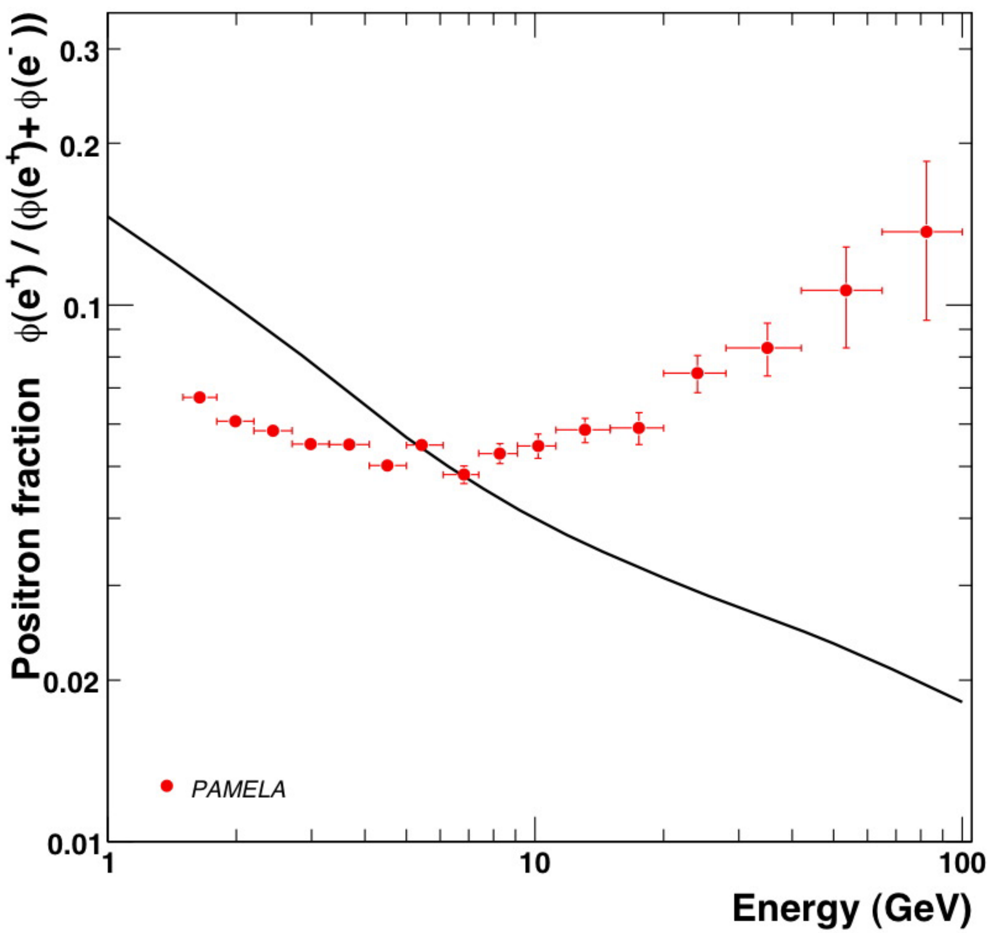
- Very weak dependence on the Halo profile; what matters is the DM lifetime...
- Spectrum in gamma-rays given by the decay channel! Smoking gun: gamma line...
- Galactic/extragalactic signal are comparable...



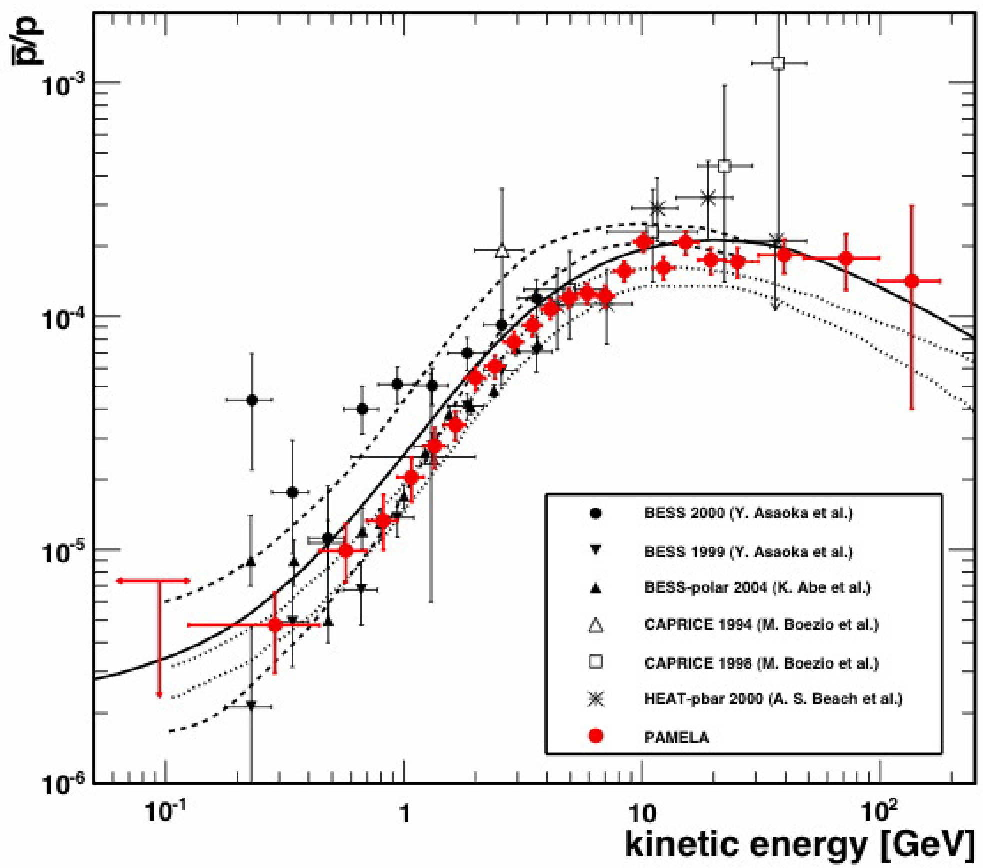
News from the sky

The PAMELA satellite measures antimatter and released data of positron fraction & antiprotons 4 years ago:

[0810.4995]



[1007.0821]



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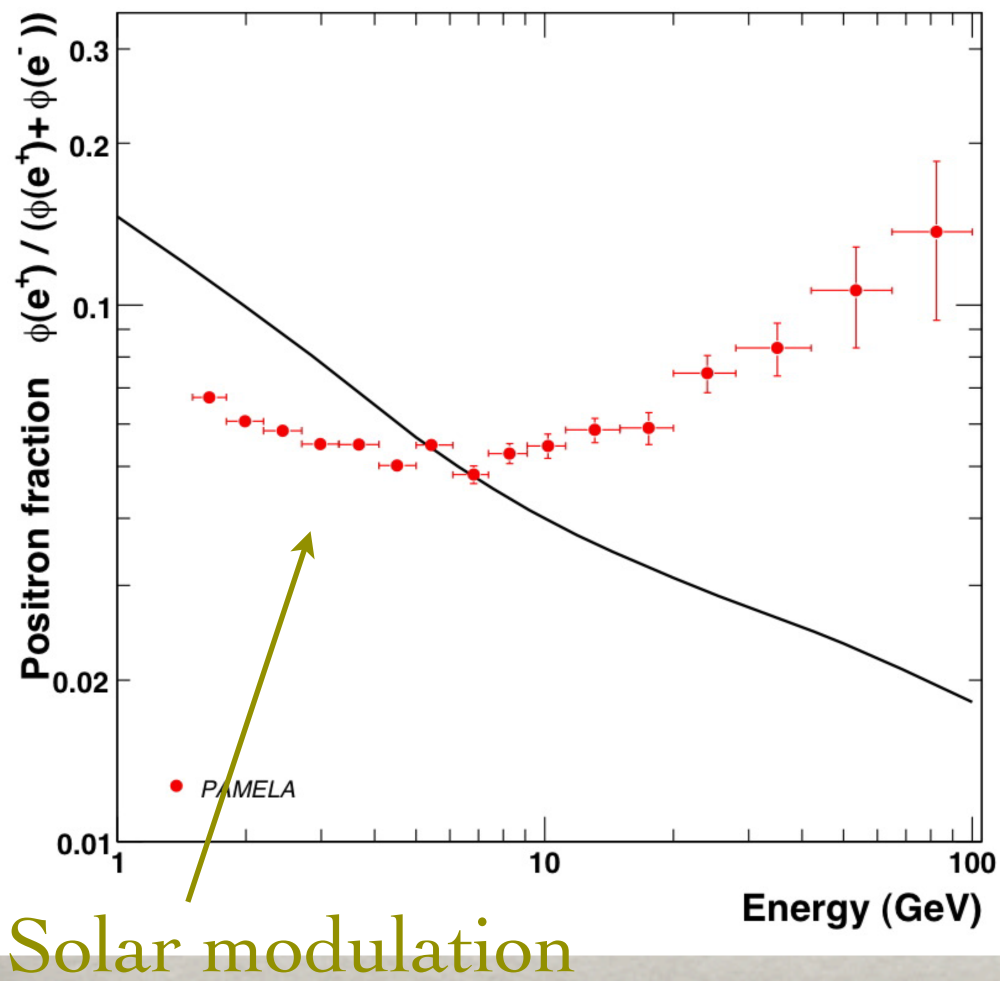

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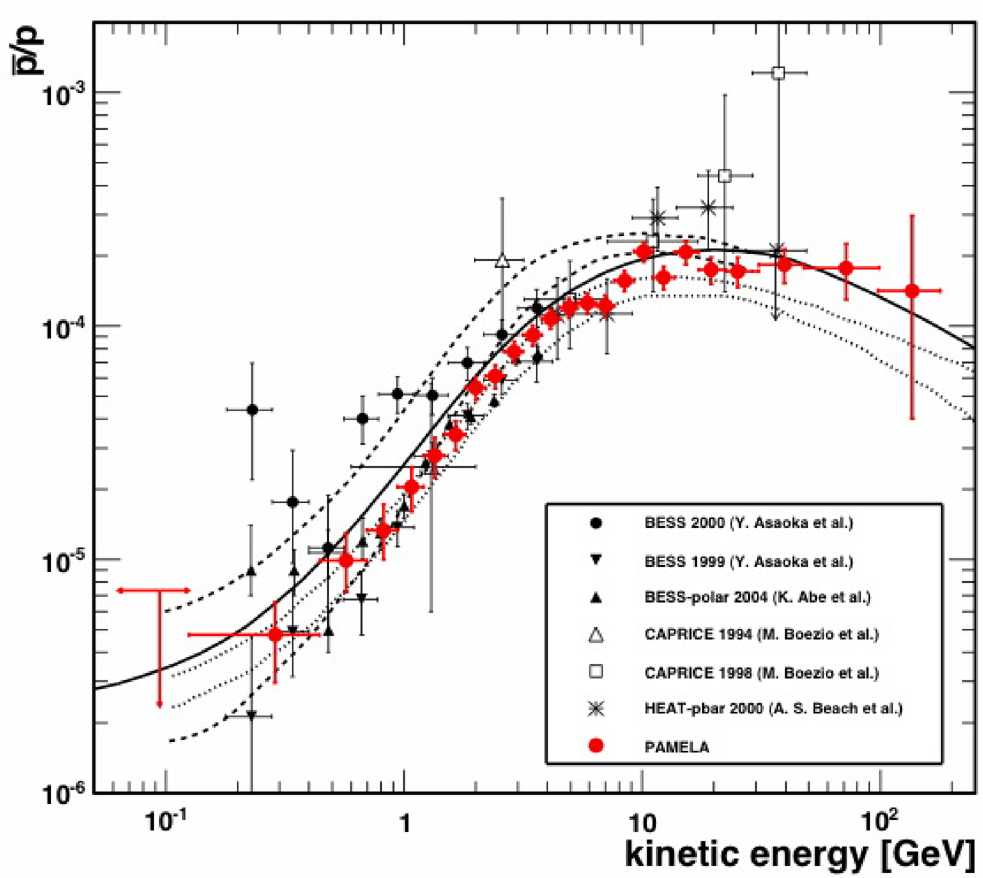

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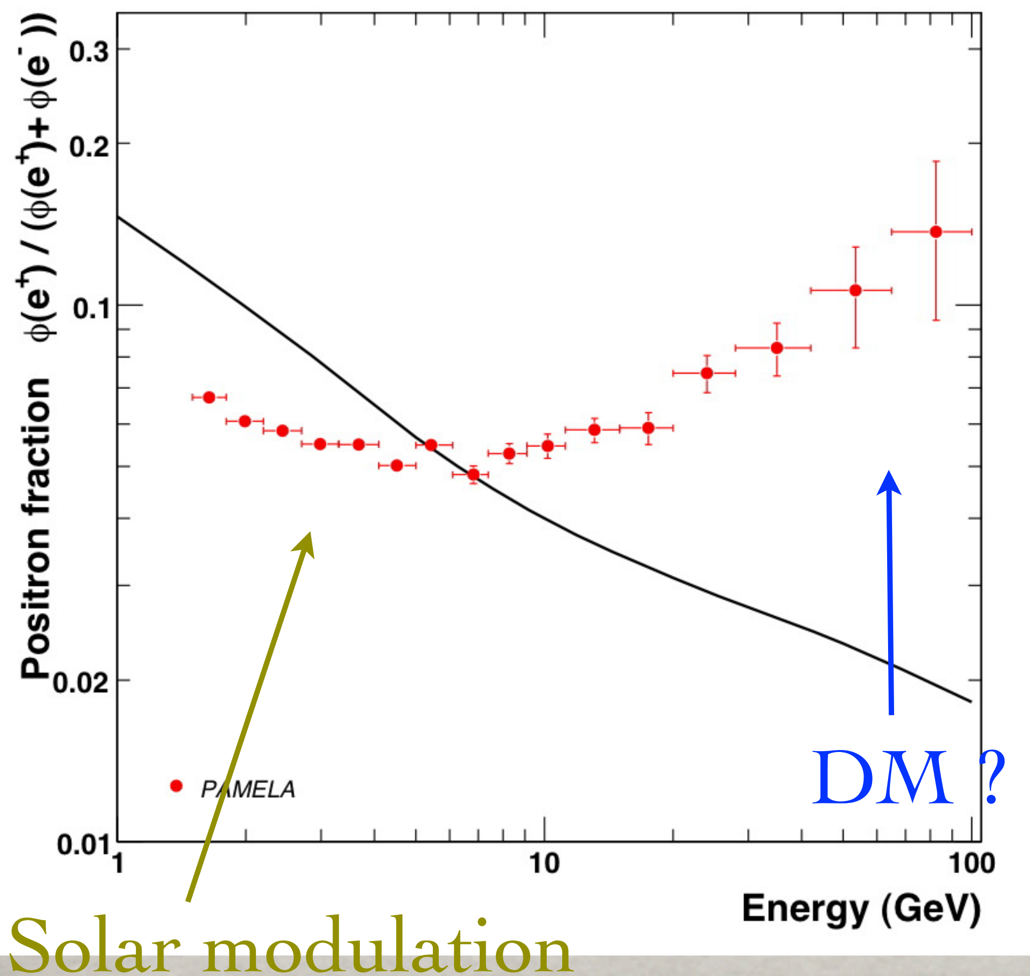

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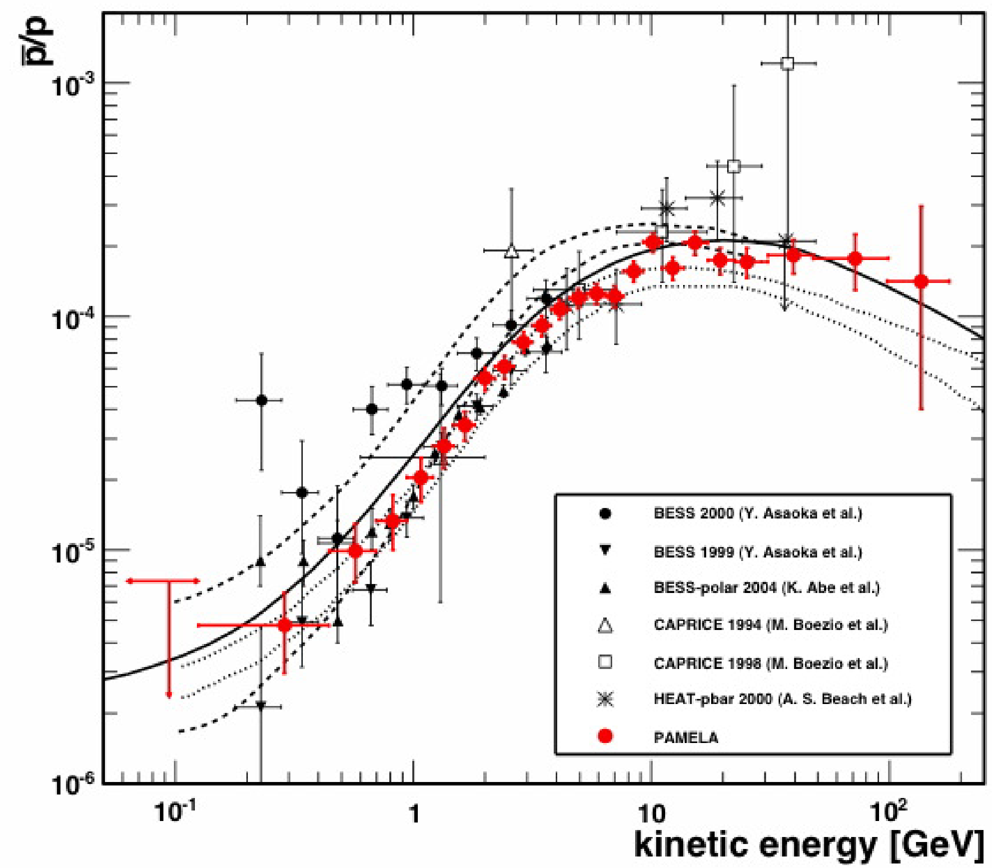

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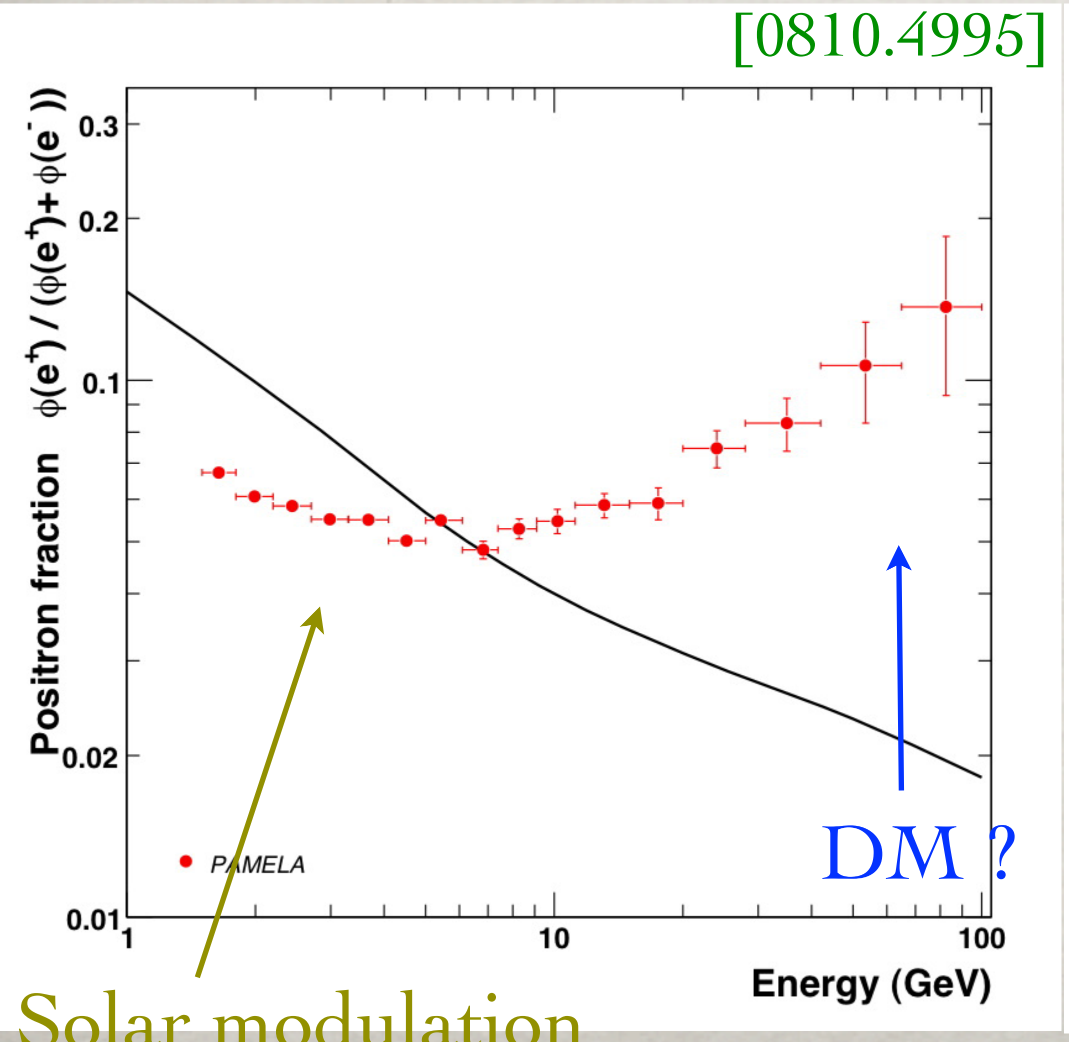
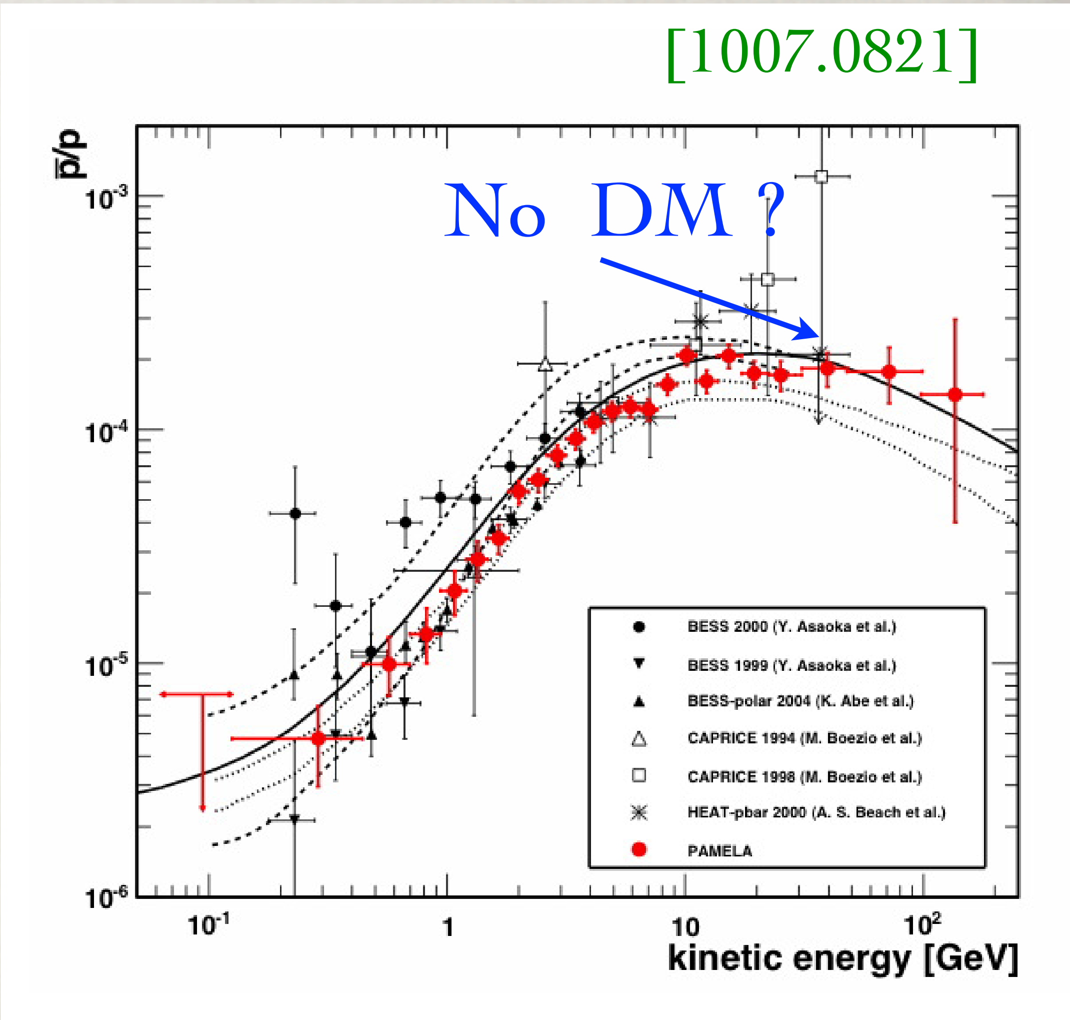
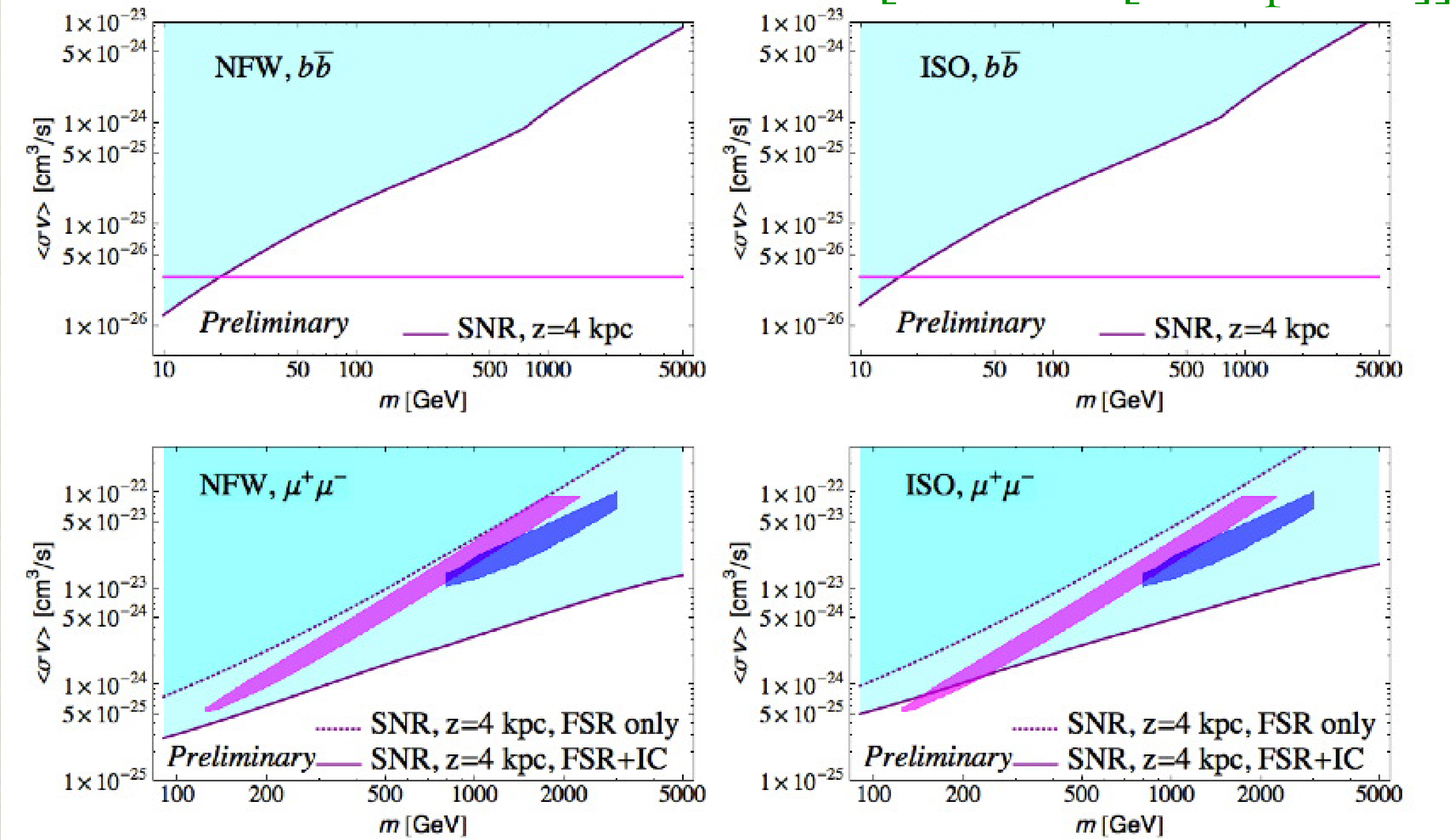




WIMP annihilation ???

The FERMI galactic flux gives bounds on the annihilation cross-section, depending on the channels/DM profile:

[1012.0588[astro-ph.HE]]

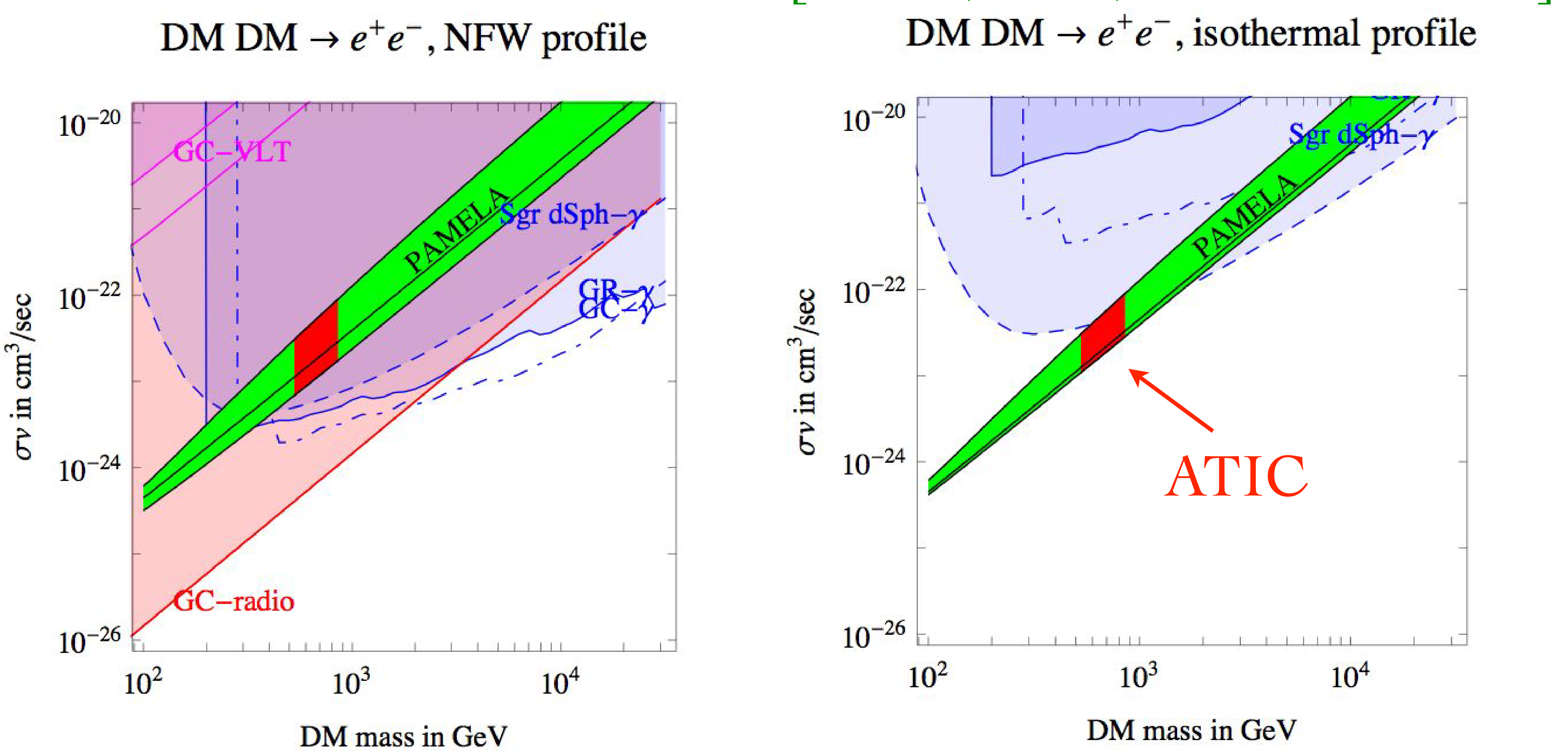


Weaker bounds from other targets: Dwarf galaxies, extragal, ...

WIMP ANNIHILATION ???

Need a very large boost factor ~ 1000 to fit the PAMELA signal but then the rate seems in contrast with the radio signal from the galactic centre for a NFW profile

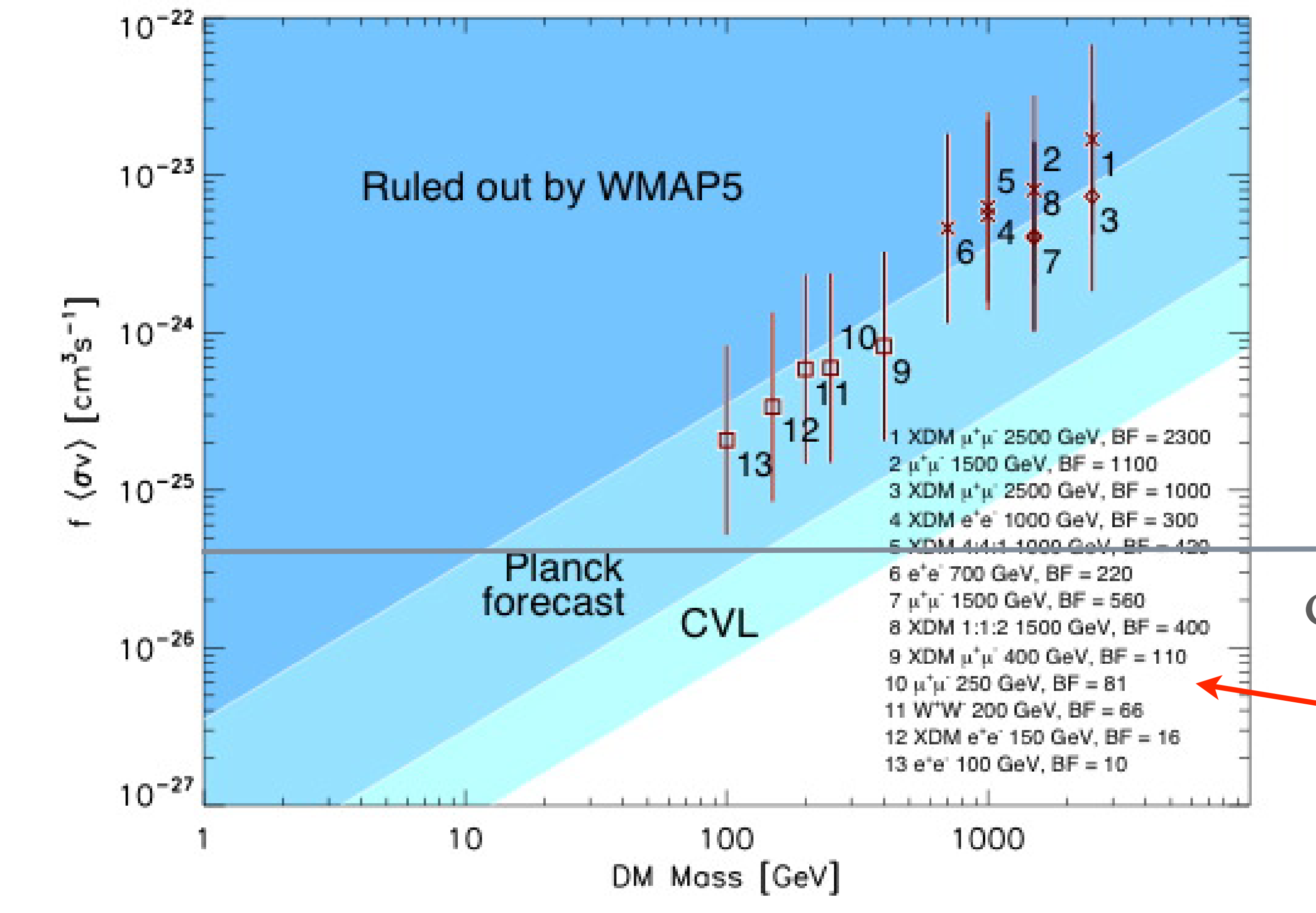
[Bertone, Cirelli, Strumia & Taoso 08]



PLANCK: DM ANNIHILATION

WIMP annihilation also modifies the epoch of recombination due to the release of energy in the primordial plasma and leave imprints into the CMB ! WMAP already puts some constraints, but Planck will reach cross sections needed by PAMELA

[Slatyer, Padmanabhan& Finkbeiner 0906.1197]



But, without polarization data the limit is weaker than WMAP limit !

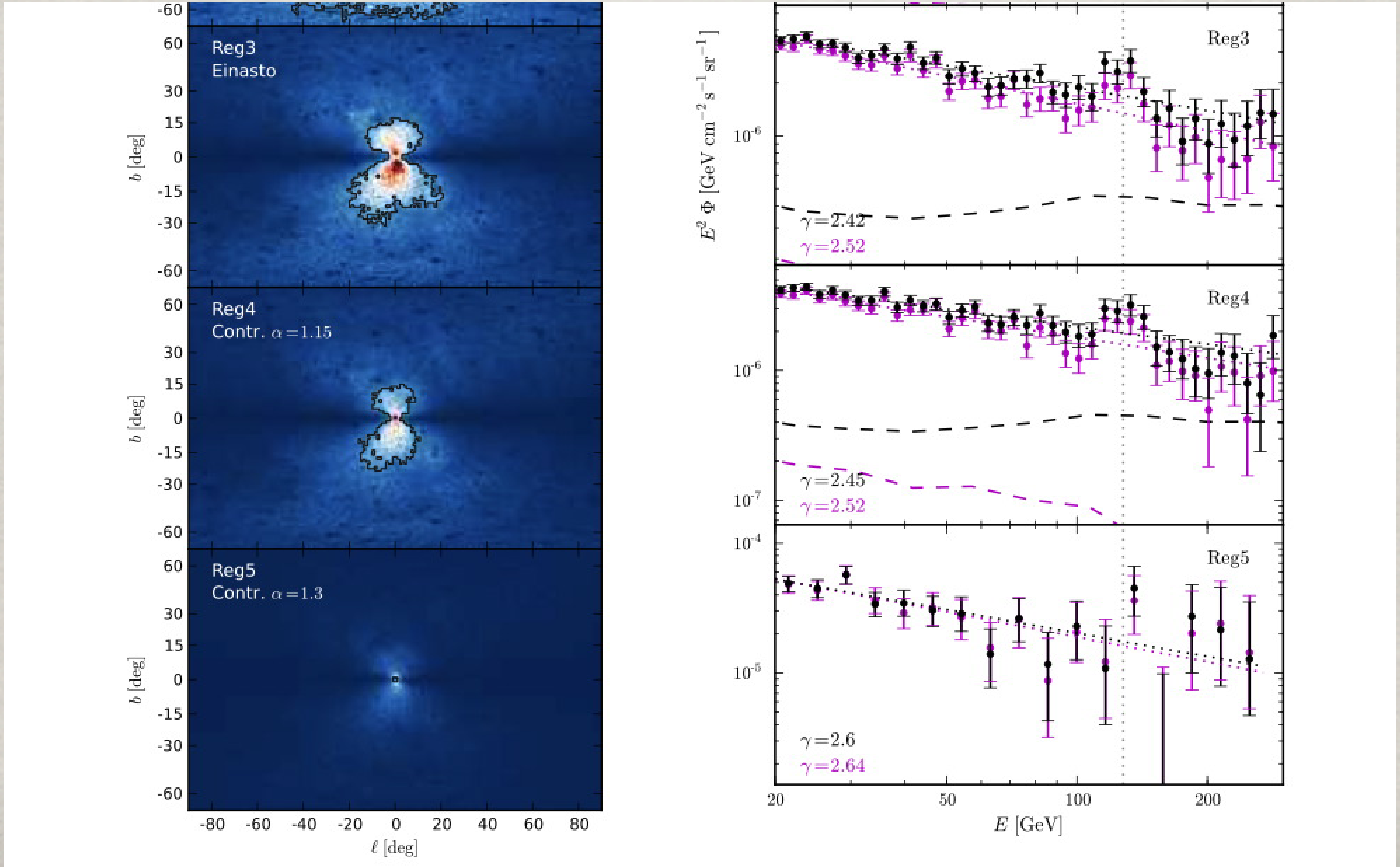
Thermal cross-section

Pamela-inspired DM models

News from the sky II

Possible line hidden in the FERMI data ?

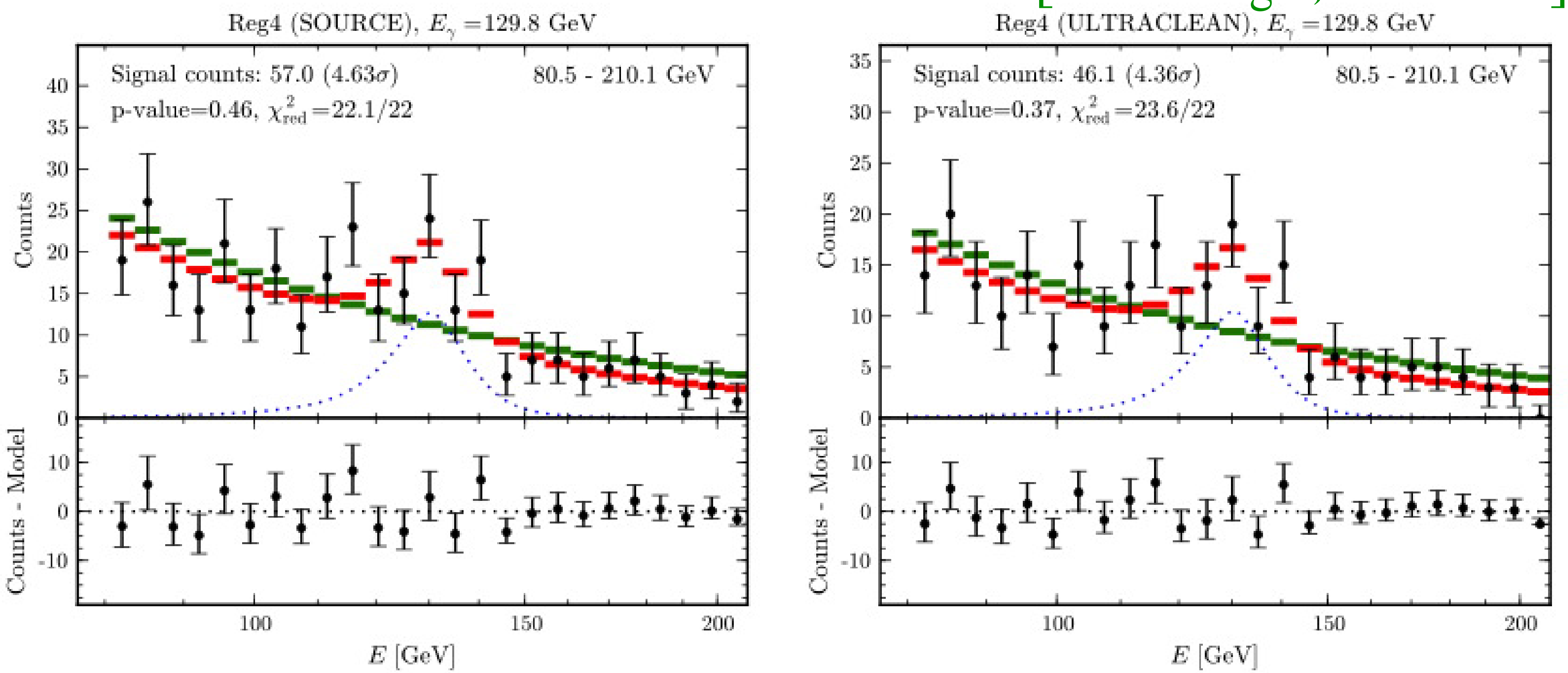
Choose optimized regions in the sky: [Ch. Weniger, 1204.2797]



News from the sky III

In regions 3-4 the best significance in both FERMI data sets

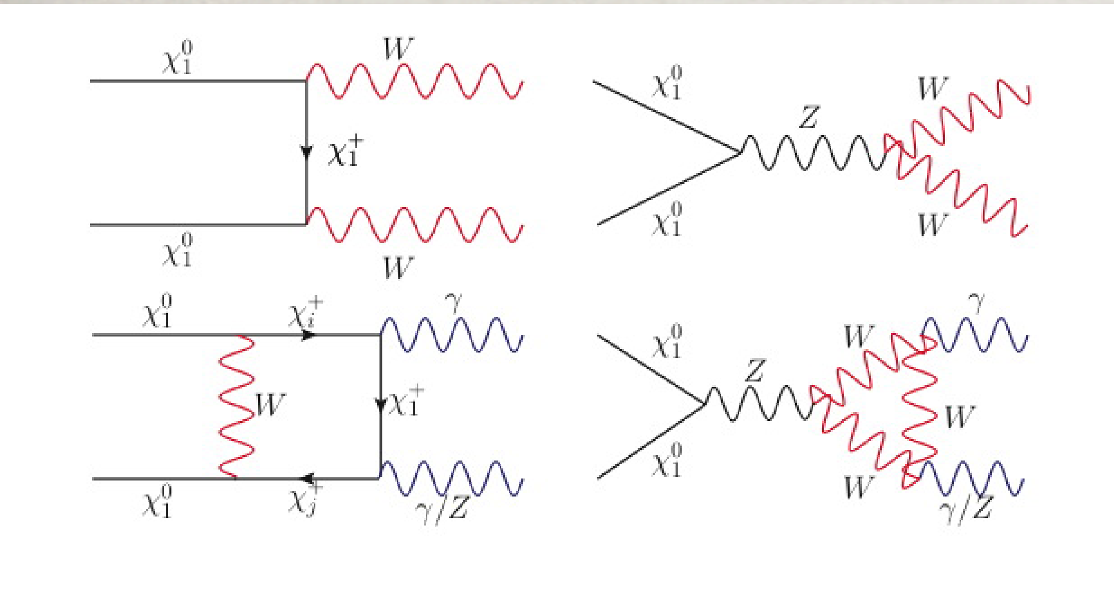
[Ch. Weniger, 1204.2797]



Local significance more than 4 sigma, taking into account the look elsewhere effect it gives 3.2 sigma

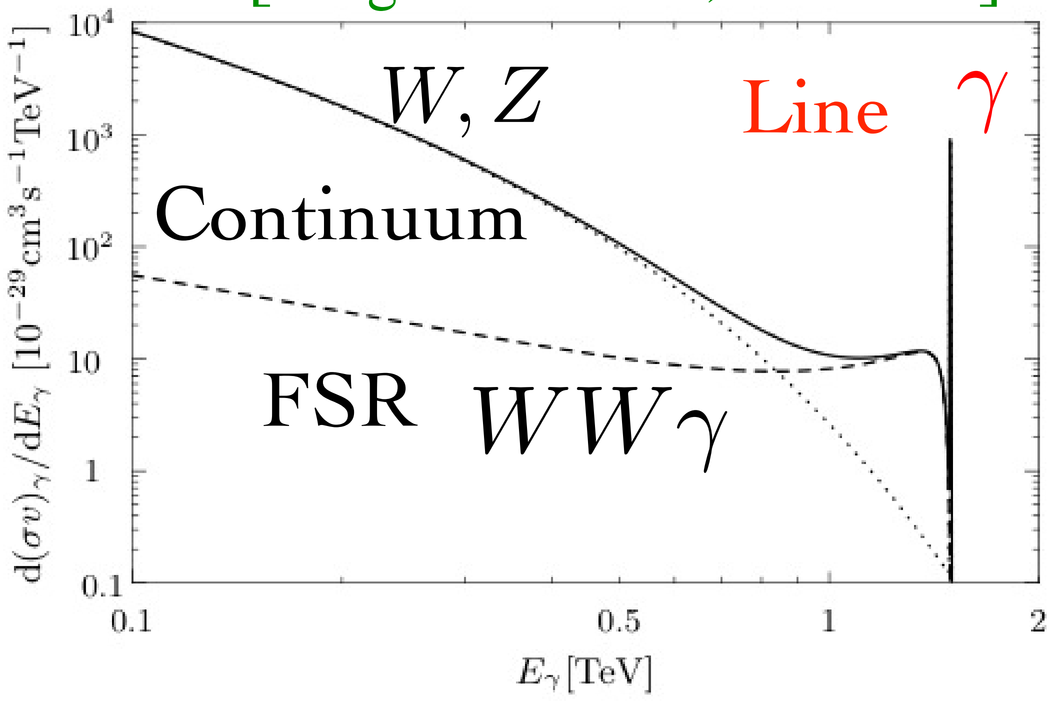
But recently FERMI analysis gives only 1.6 σ significance...

Indirect detection lore



Annihilation into two photons appears only at one loop, while the channel into EW gauge boson is at tree-level

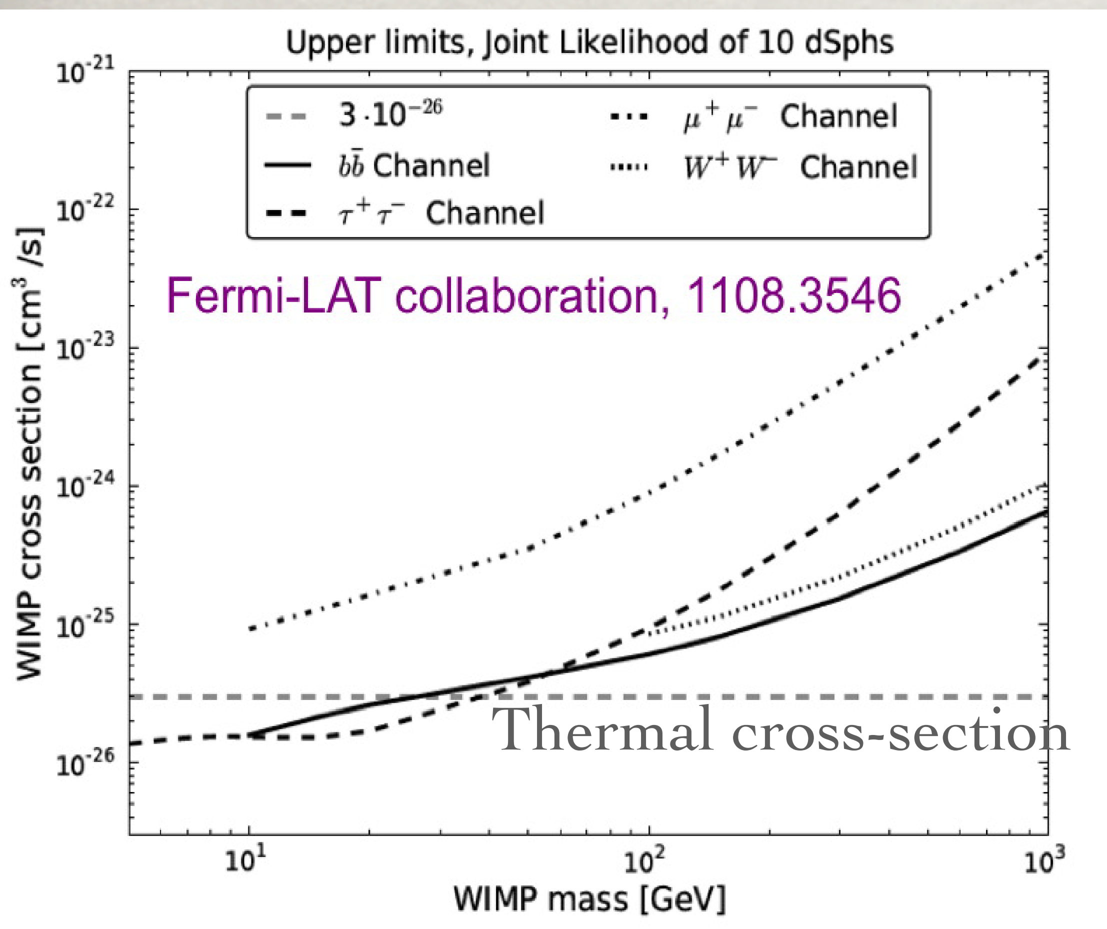
[Bergstroem et al, 0609.510]

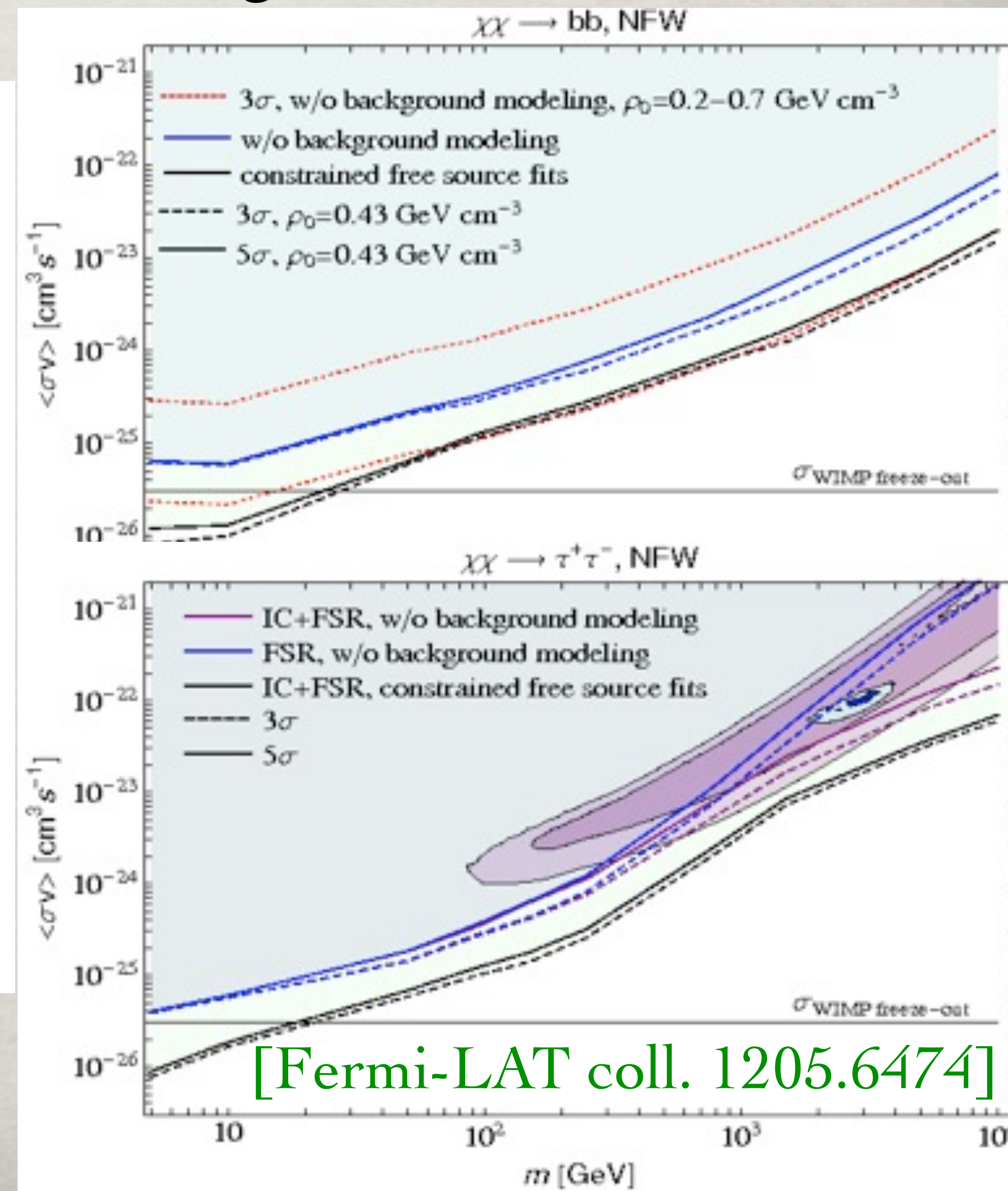


The line signal is therefore suppressed compared to the continuum from EW gauge bosons.
It may be enhanced by Final State Radiation, but that also gives a continuum

Bounds on the continuum

FERMI gives bounds on the gamma-ray emissions from satellite dwarf-galaxies and the galactic centre

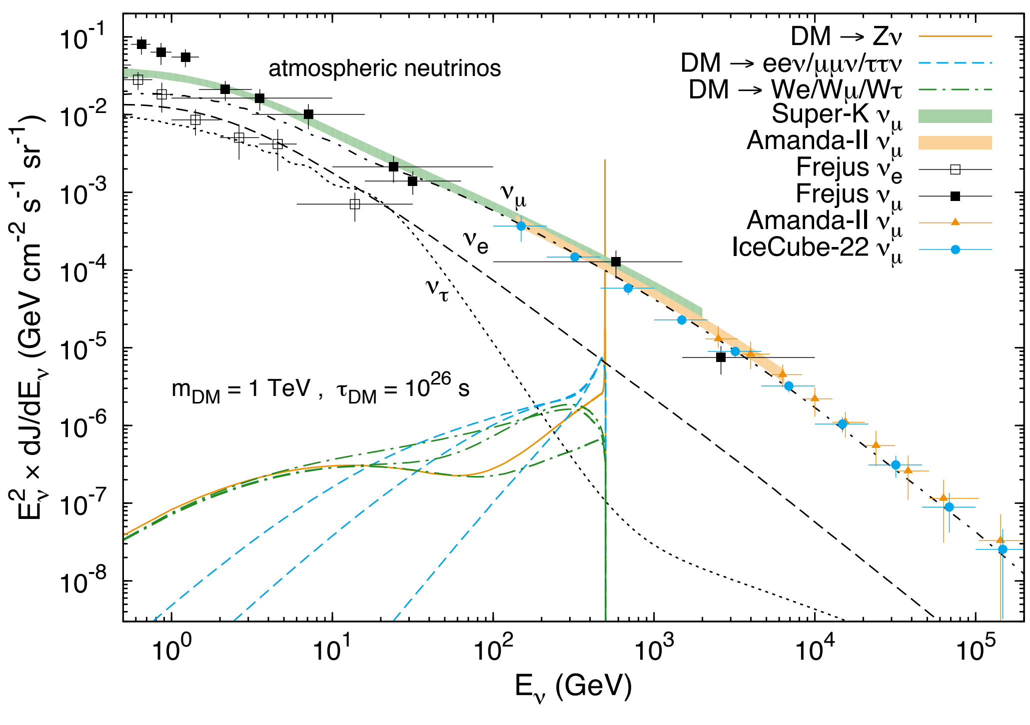


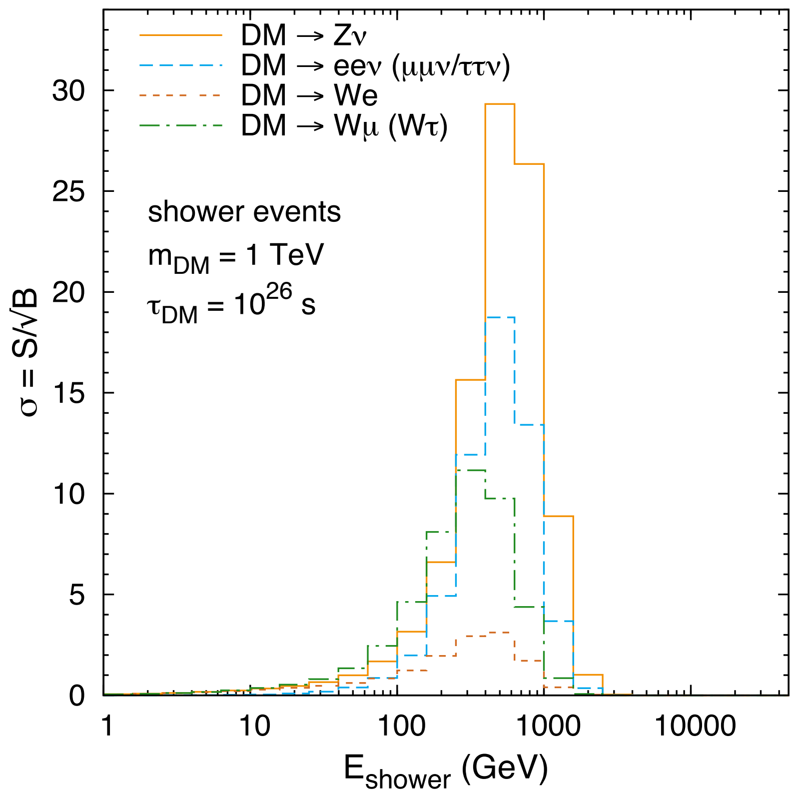


Heavy decaying DM

For heavy decaying DM, the atmospheric neutrino background is large, but still the signal is detectable at km3 detectors like IceCube, esp. if showers may be measured:

[LC, Grefe, Ibarra & Tran 09]

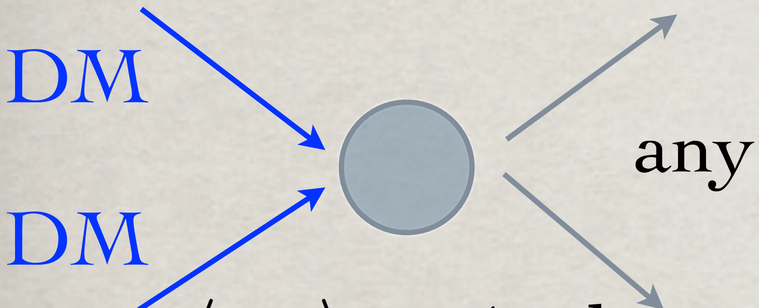




Best significance for cascade/shower events
Possible to detect in IceCube ?

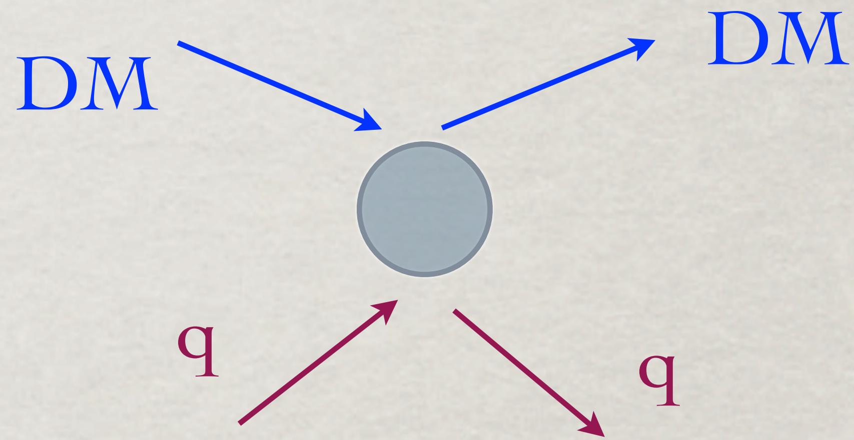
THE WIMP CONNECTION

Early Universe: $\Omega_{CDM} h^2$

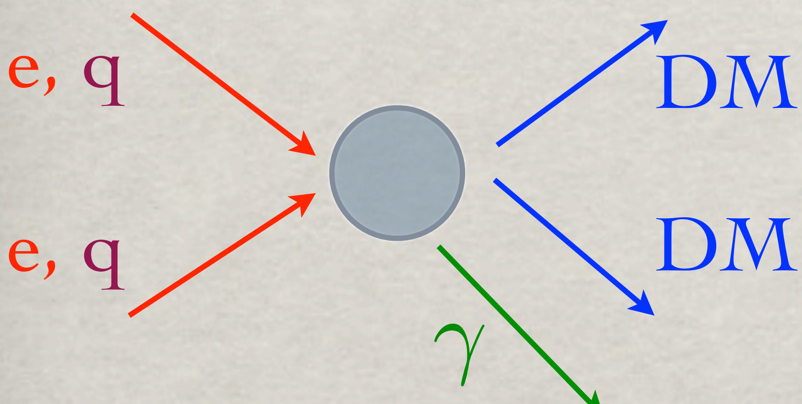


$\langle \sigma v \rangle \sim 1$ pb

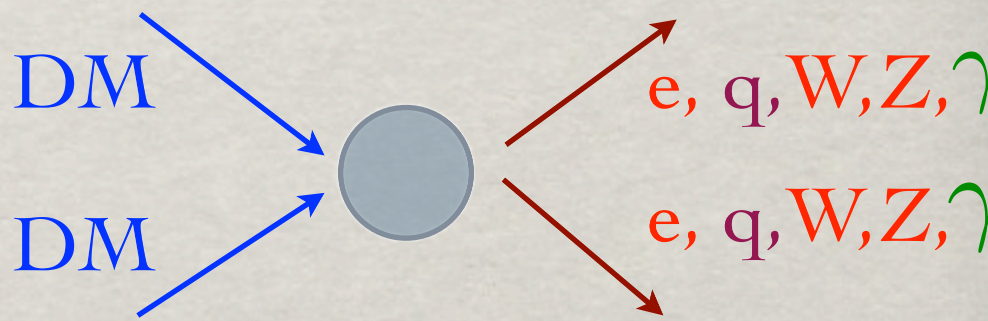
Direct Detection:



Colliders: LHC/ILC



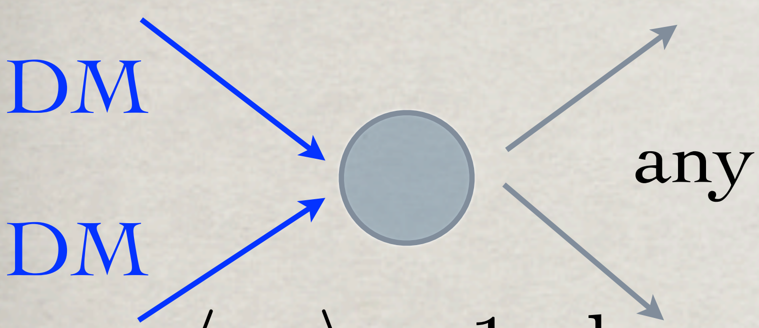
Indirect Detection:



3 different ways to check this hypothesis !!!

THE WIMP CONNECTION

Early Universe: $\Omega_{CDM} h^2$



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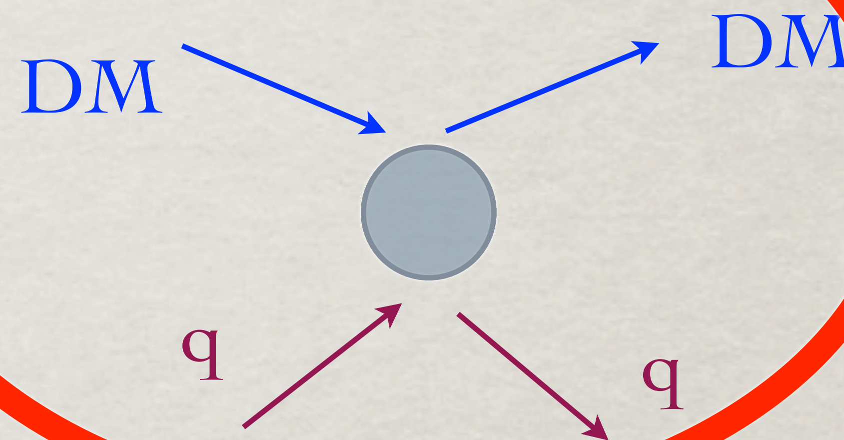

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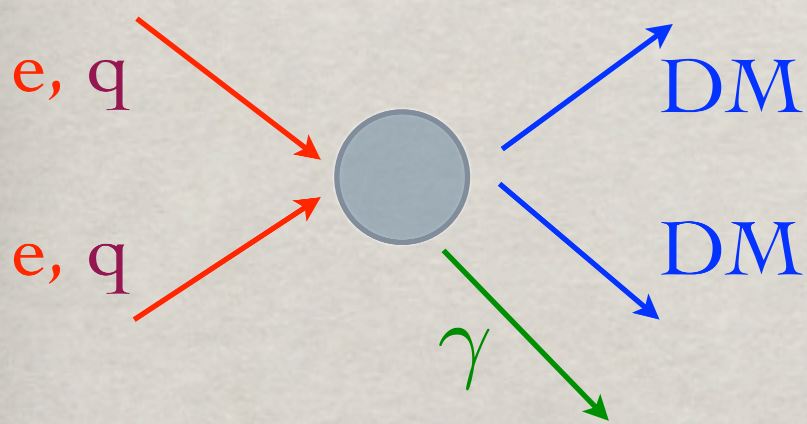
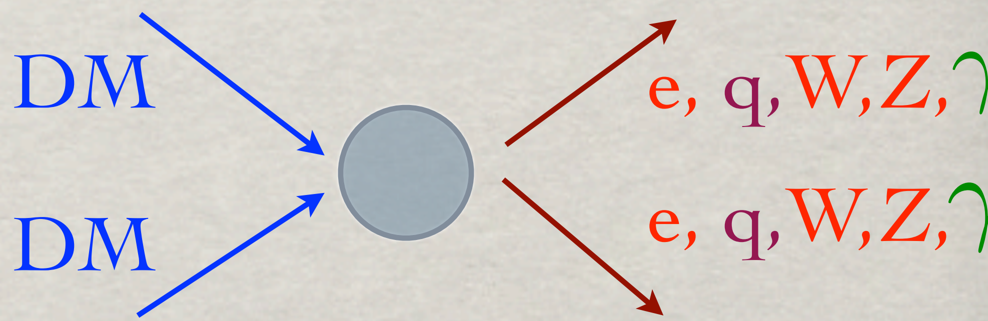
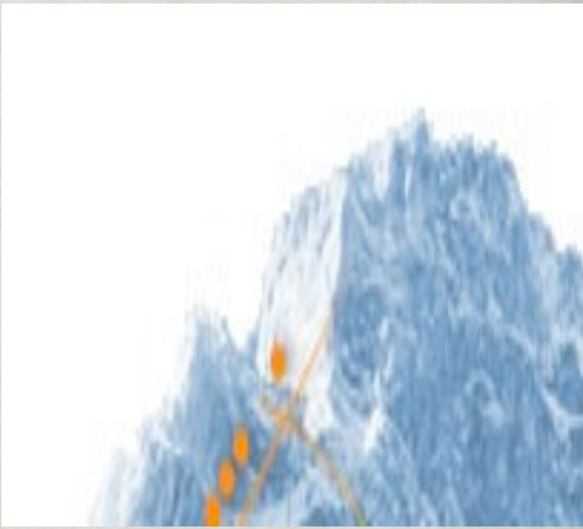


Indirect Detection:

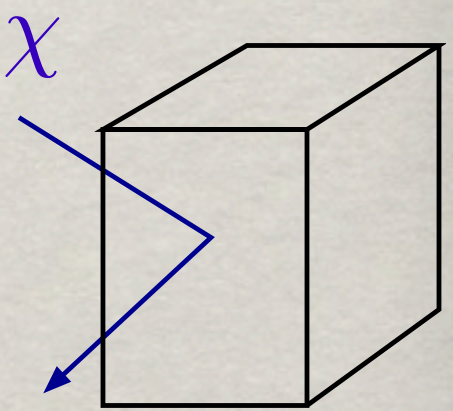


3 different ways to check this hypothesis !!!

THE HOPE: DETECT DM !

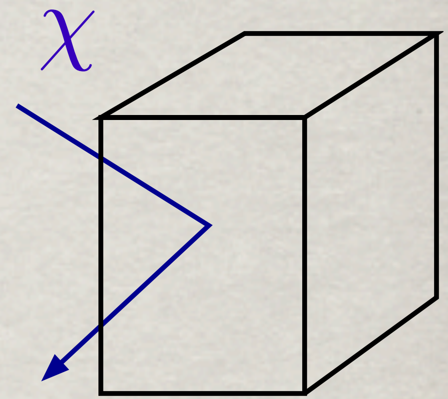


- In direct DM searches in various underground laboratories measuring the "wind" of DM crossing the Earth...
- A WIMP scatters with the nuclei like neutrons, so it is necessary to suppress very strongly the background due to cosmic rays and radioactivity
- To veto electrons/photons the detectors usually measure two different signals, e.g. ionization+phonons (cryogenic detectors) ionization+light (noble gas/liquid detectors)



Direct WIMP detection

- Elastic scattering of a WIMP on nuclei. The recoil energy is in the keV range:



$$\Delta E = \frac{4 m_{DM} m_N}{(m_{DM} + m_N)^2} \, E_{kin}^{DM}$$

with

$$E_{kin}^{DM} \sim \frac{1}{2} m_{DM} v^2 \sim 50 \text{ keV} \frac{m_{DM}}{100\text{GeV}}$$

Need very low threshold !

- The rate is given by

$$\frac{dR}{dE_R} \propto \; \sigma_n F^2(E_R) \; \frac{\rho_{DM}}{m_{DM}} \int_{v_{min}}^{\infty} \frac{dv}{v} f(v)$$

Particle Physics Halo physics

Rate depends on v in lab frame → annual modulation !

Direct WIMP detection

How large are the cross-sections that we expect from thermal consideration or the exchange of (known) EW particles ?

- Thermal relic cross-section to give $\Omega_{DM} h^2 \sim 0.1$

$$\langle \sigma v \rangle \sim 3 \times 10^{-26} cm^3/s \rightarrow \sigma \sim 10^{-36} cm^2 = 1 \text{ pb}$$

- Exchange of Z boson:

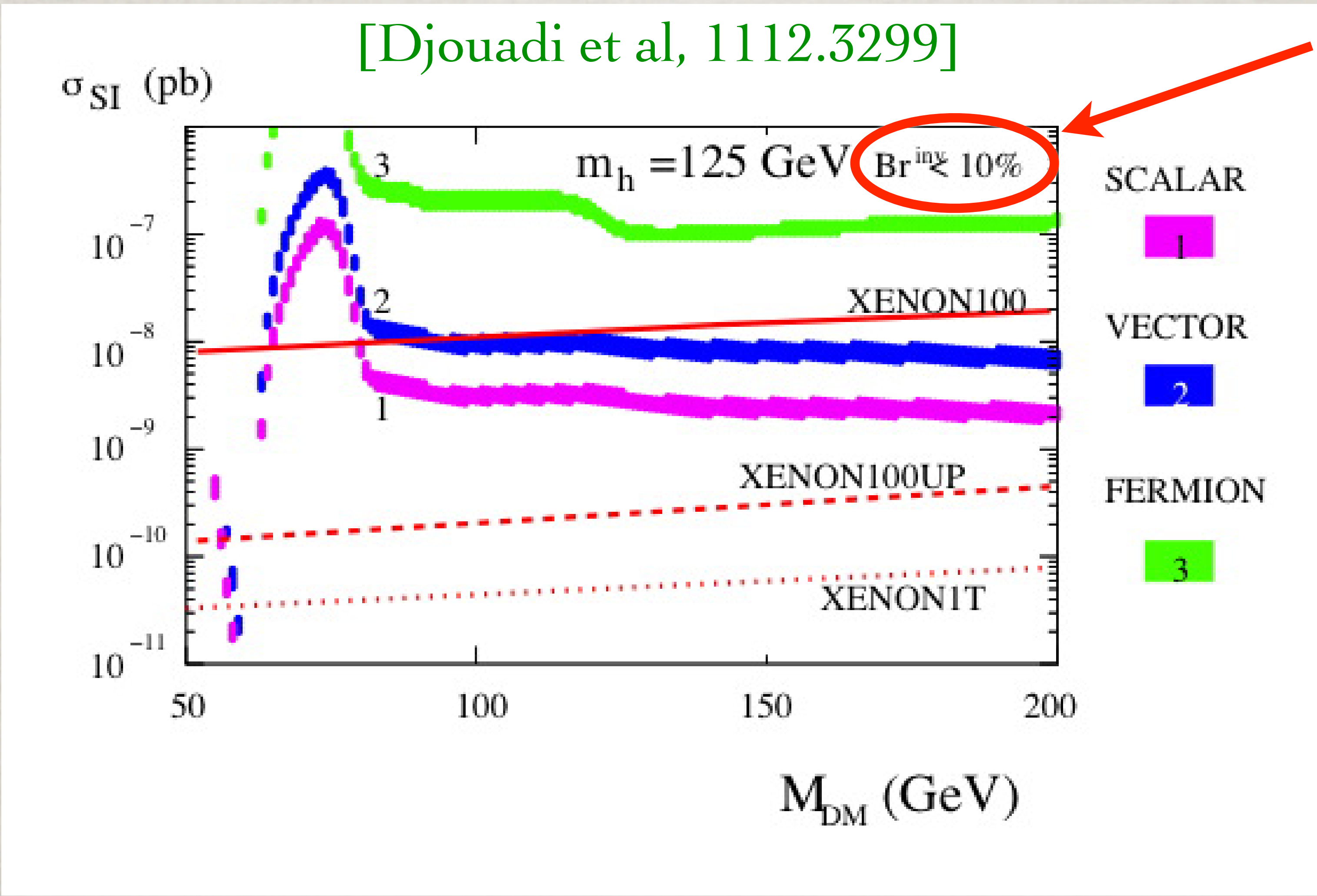
$$\sigma \sim \lambda_{Z\chi}^2 G_F^2 m_p^2 \sim 10^{-38} \lambda_{Z\chi}^2 cm^2 = 10^{-2} \, \lambda_{Z\chi}^2 \text{ pb}$$

- Exchange of Higgs boson:

$$\sigma_p \sim \lambda_{h\chi}^2 m_p^2 / m_h^4 \sim 10^{-44} \lambda_{h\chi}^2 cm^2 = 10^{-8} \, \lambda_{h\chi}^2 \text{ pb}$$

HIGGS PORTAL DM

If the DM interacts with Higgs via portal interaction, it is already under siege by DD & LHC:



Invisible Higgs decay

BOUNDS ON WIMP DM

Spin independent:

CDMS (Ge/Si crystal)

XENON-10 (noble gas/liquid)

Super CDMS

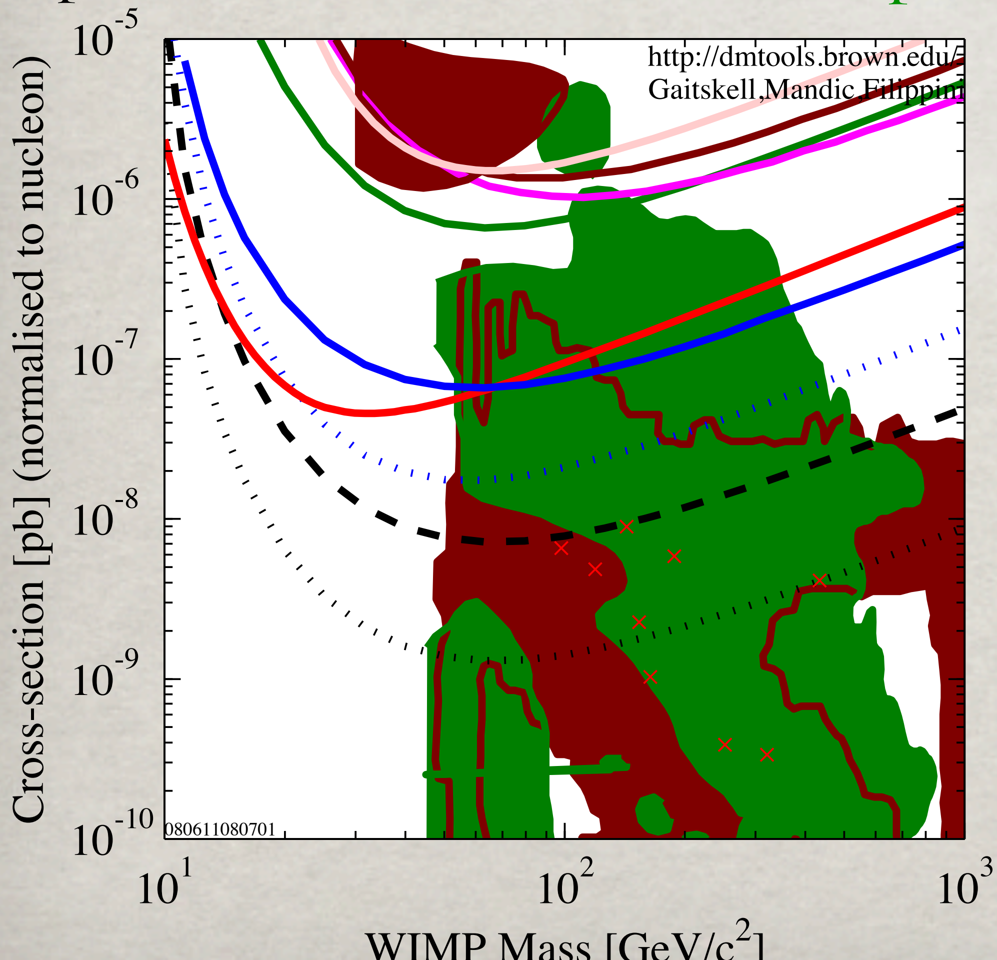
WARP, Zeplin II

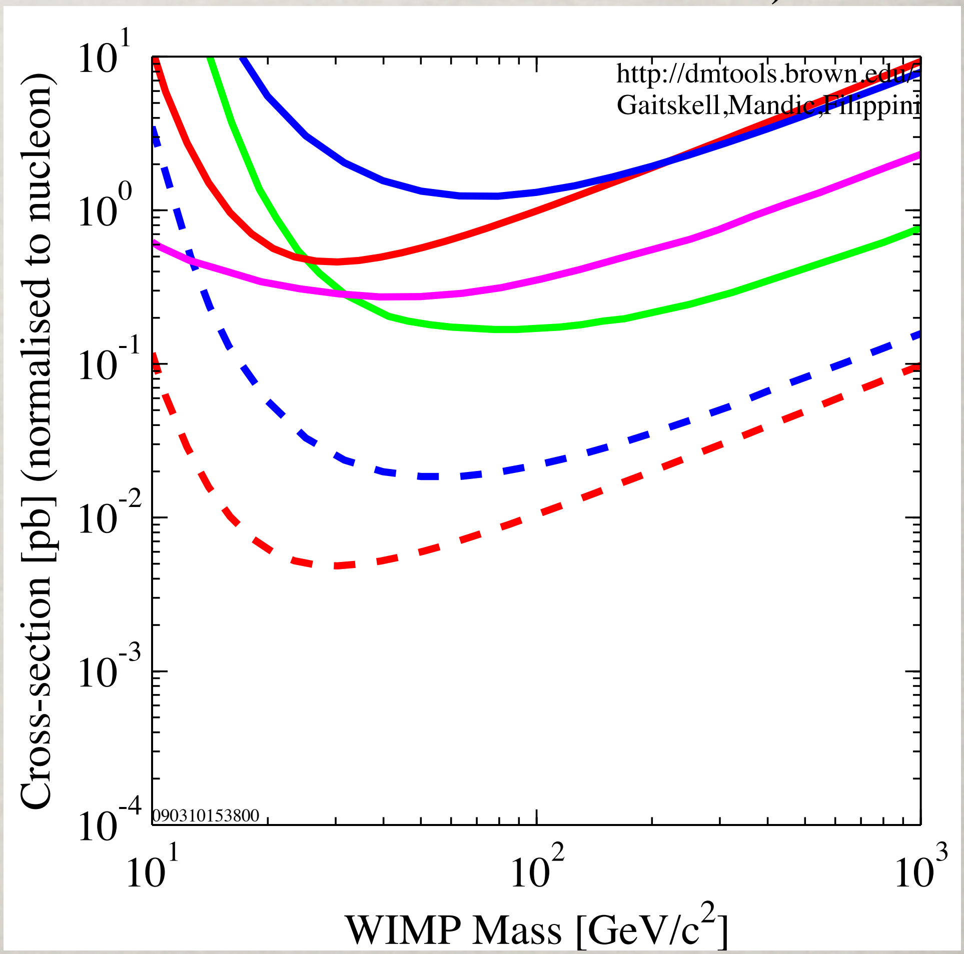
Spin dependent:

proton:

neutron:

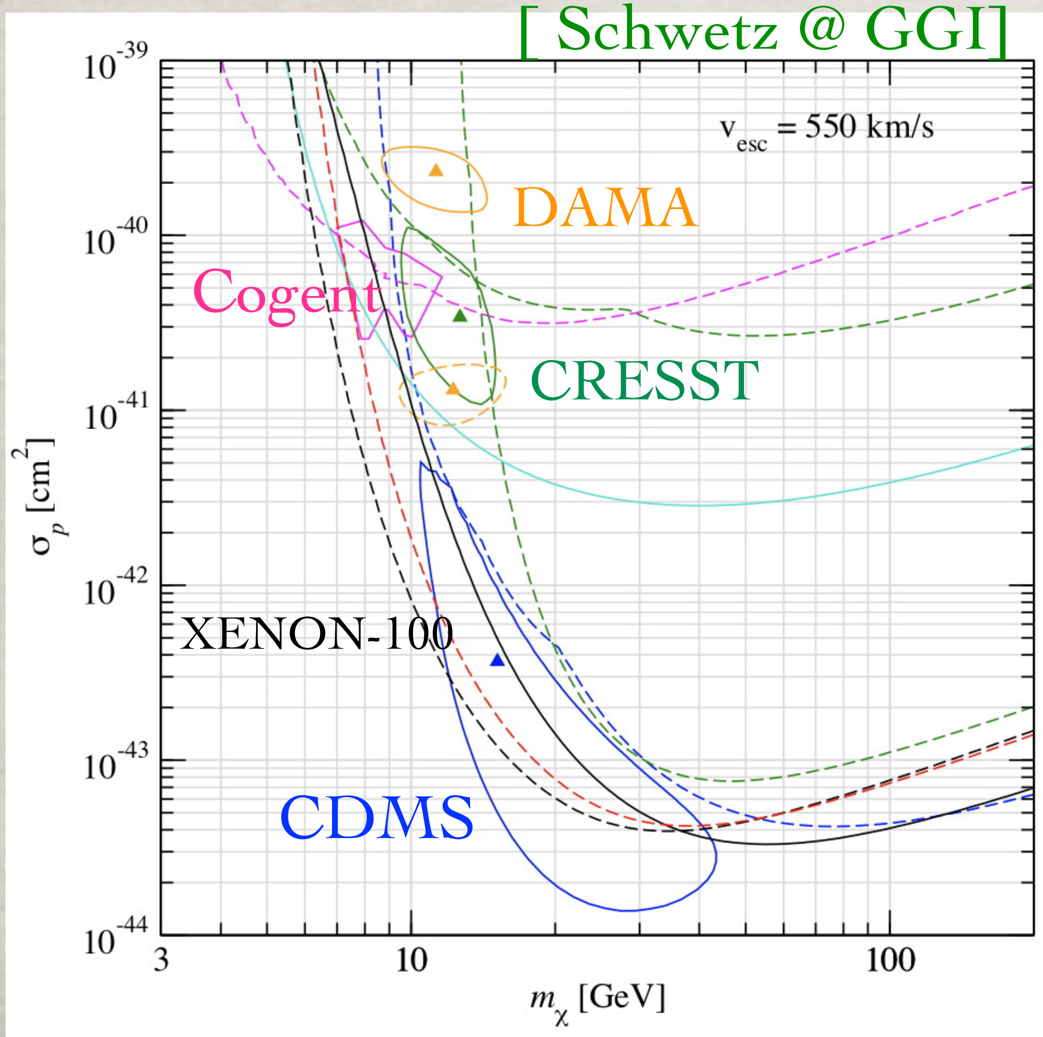
COUPP, KIM





NEWS: SIGNAL(S) OF DM ?

In the last couple of years quite a number of hints appeared in the low mass region... Unfortunately difficult to fit all together and moreover the region is excluded by XENON-100.



DAMA: annual modulation @ ~9 sigma

Cogent: excess+ann. mod.

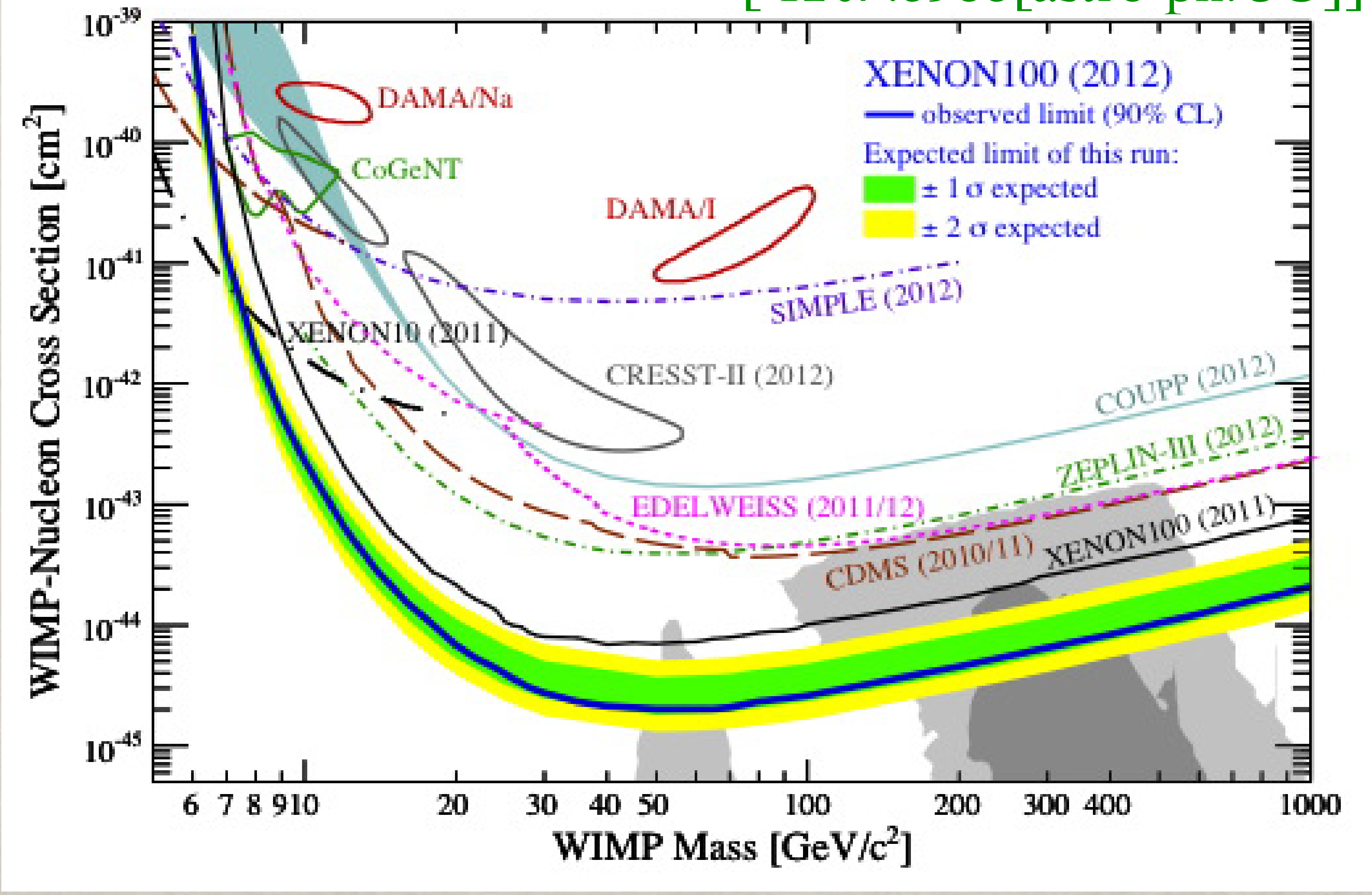
CRESST: 67 events vs 38 bg

CDMS: 2 events vs 0.8 bg no annual modulation

NEWS: SIGNAL(S) OF DM ?

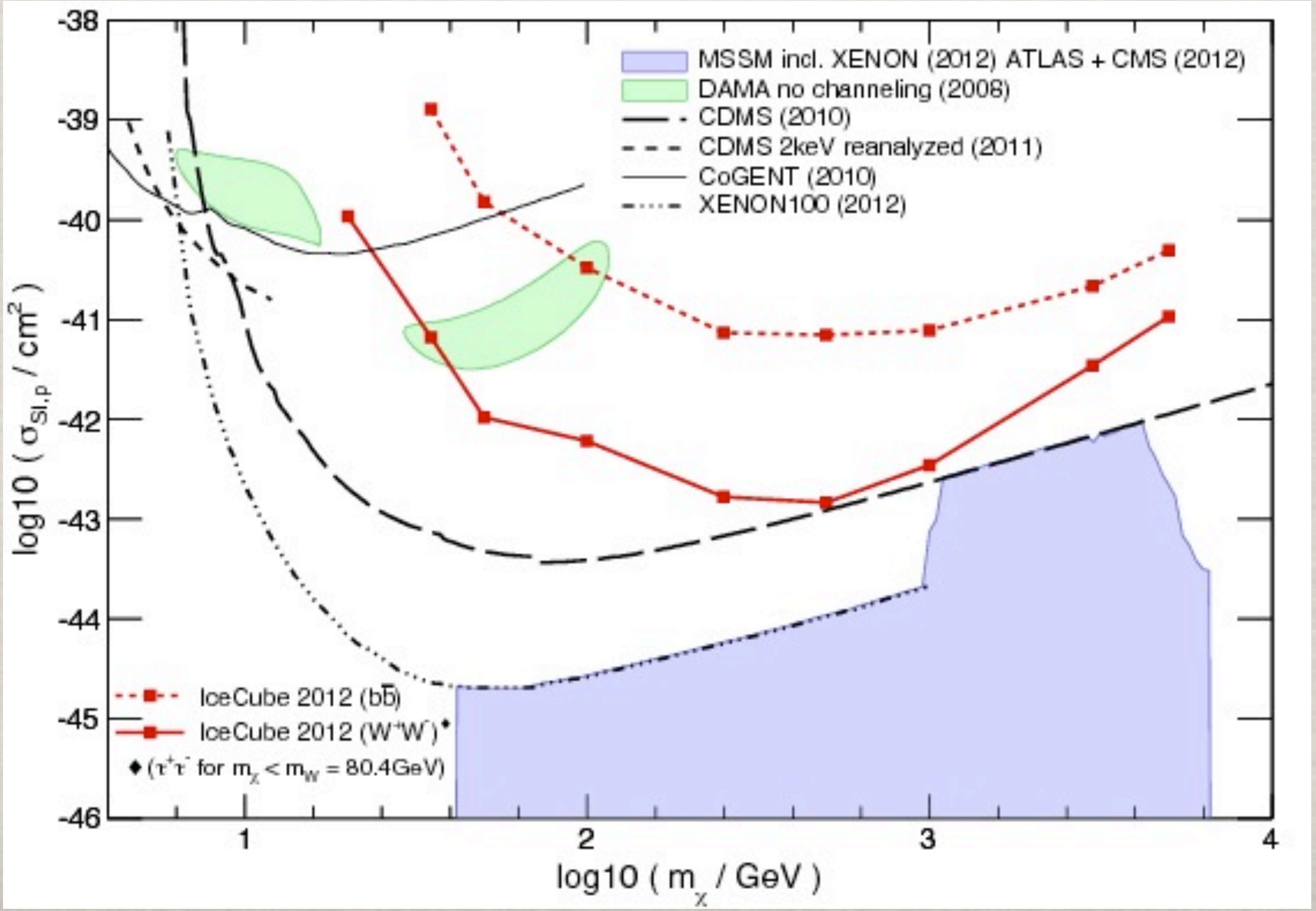
Latest results by XENON-100: two events, but compatible with background, giving the exclusion region:

[1207.5988[astro-ph.CO]]



DM signal in neutrinos

DM can accumulate and annihilate in the sun, if it interacts sufficiently strongly with protons; the only particles that can escape the sun environment are neutrinos: Limits from neutrino detectors



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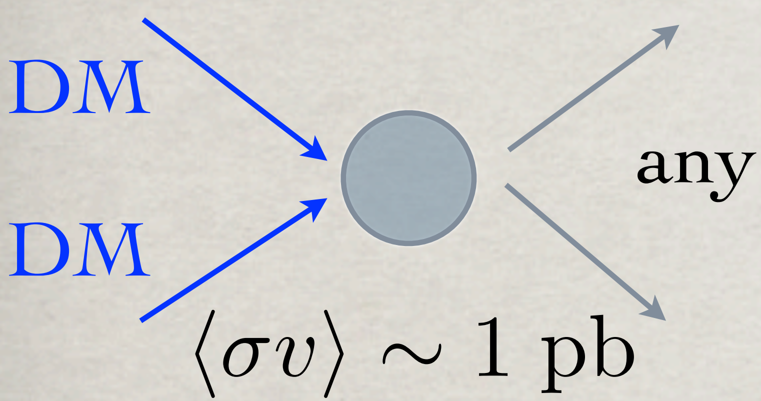
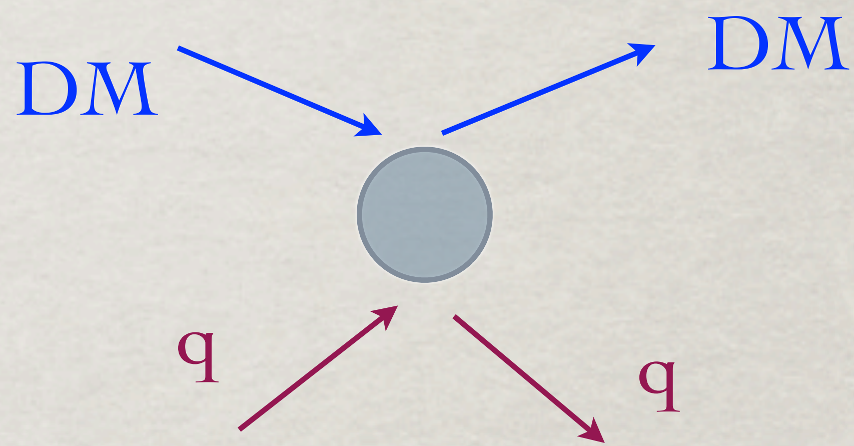
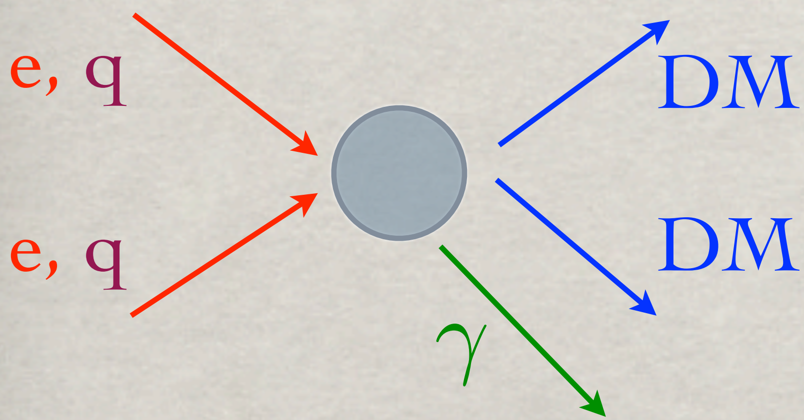


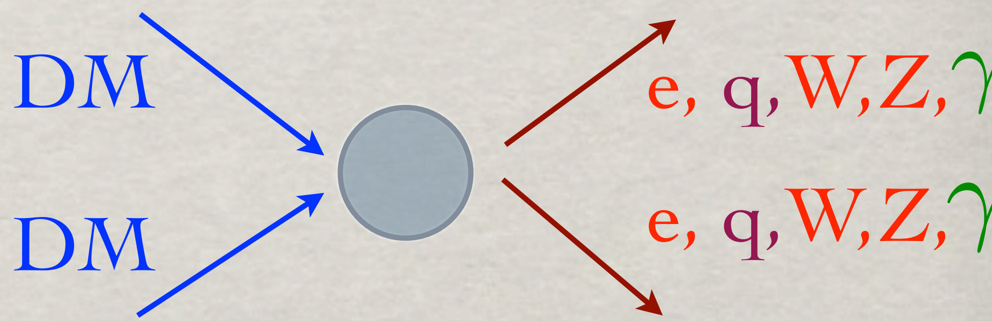
Direct Detection:



Colliders: LHC/ILC



Indirect Detection:



3 different ways to check this hypothesis !!!

THE WIMP CONNECTION

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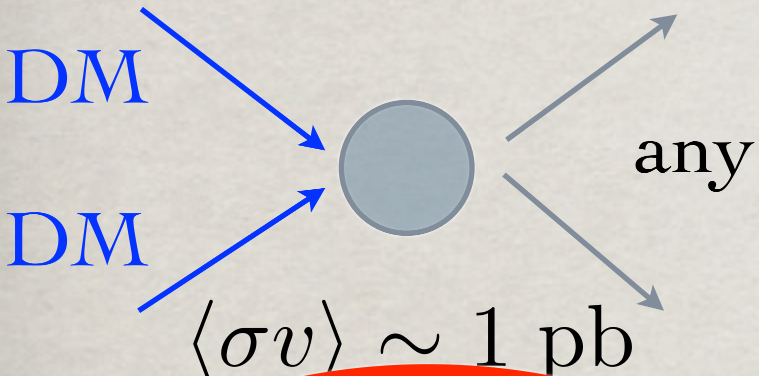
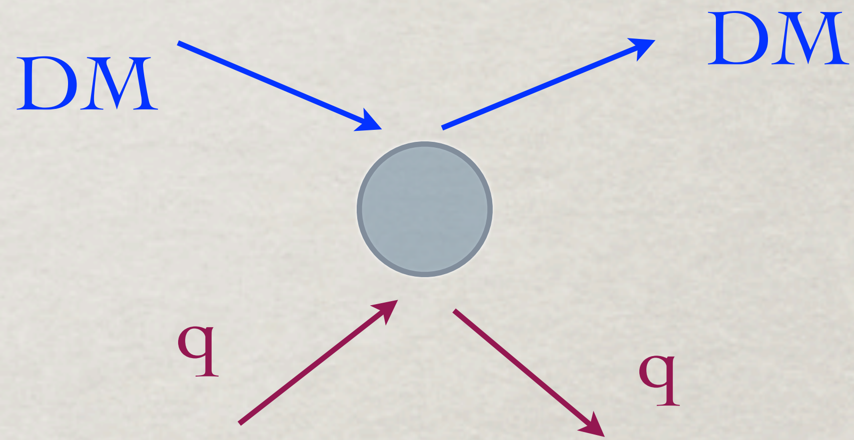
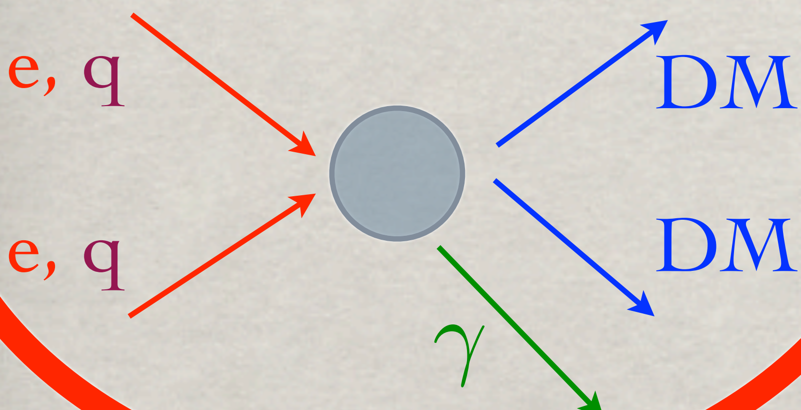


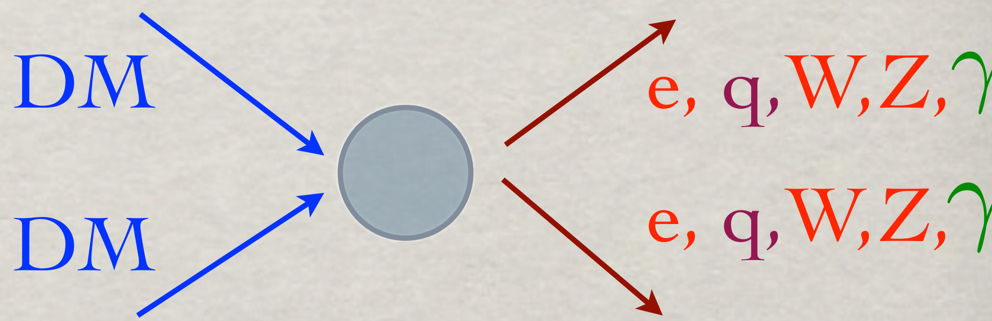
Direct Detection:



Colliders: LHC/ILC



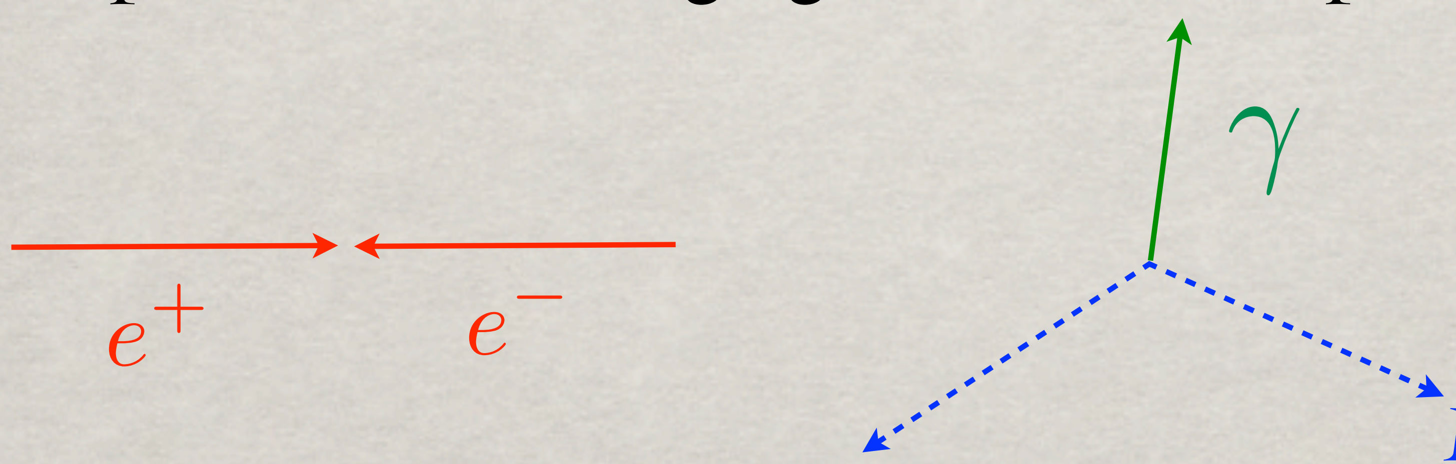
Indirect Detection:



3 different ways to check this hypothesis !!!

Missing energy signature

- The direct production of two DM particles in a collider gives unfortunately no signal ! The energy just disappears without trace...
- How is it possible to tag such events: Thanks to Initial State Radiation ! i.e. either a single photon or a gluon emitted by the initial partons, recoiling against the DM particle(s)

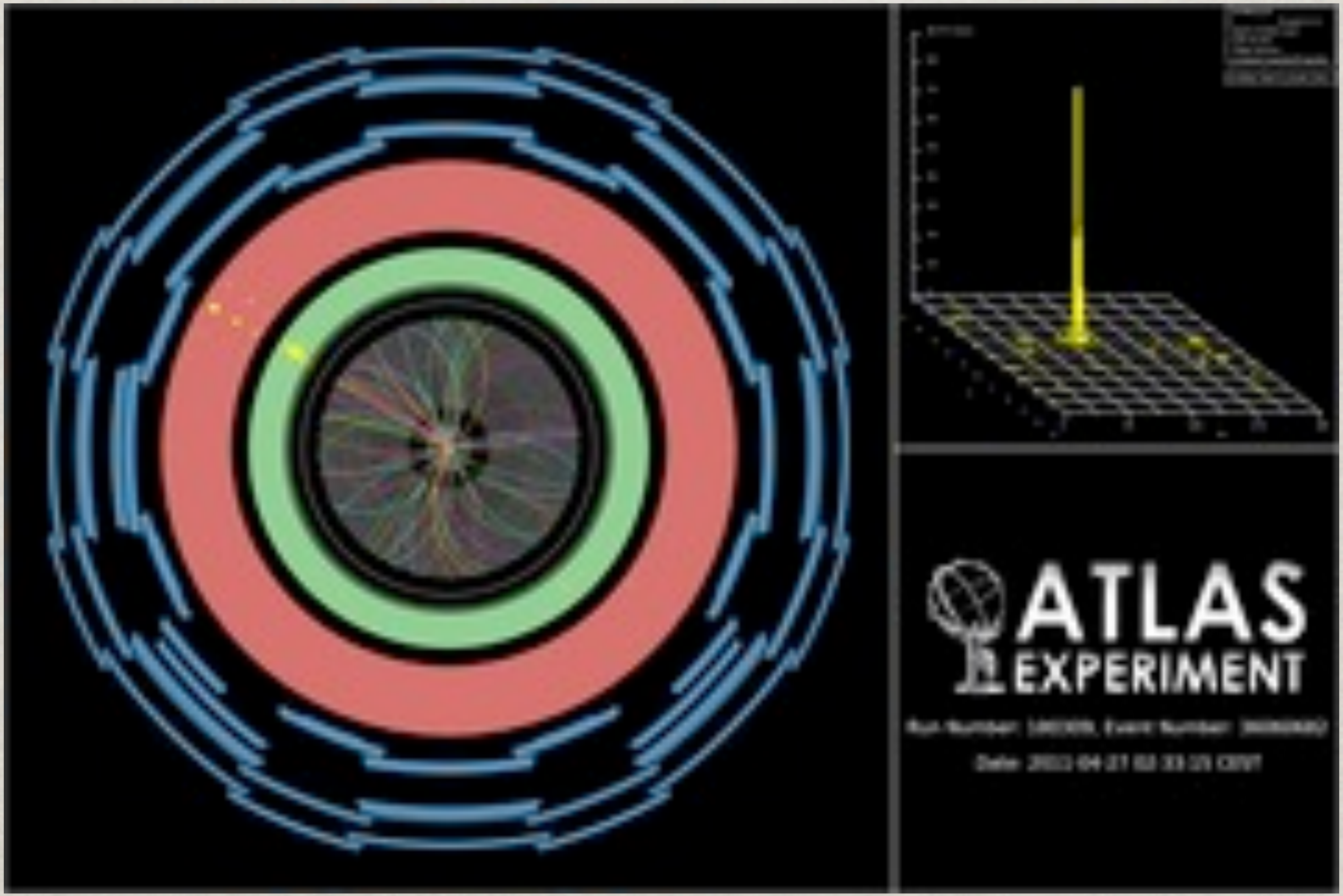


Dark Matter: Missing energy signature

Trouble: need sufficient rate of DM production...

LHC: Monojets ?

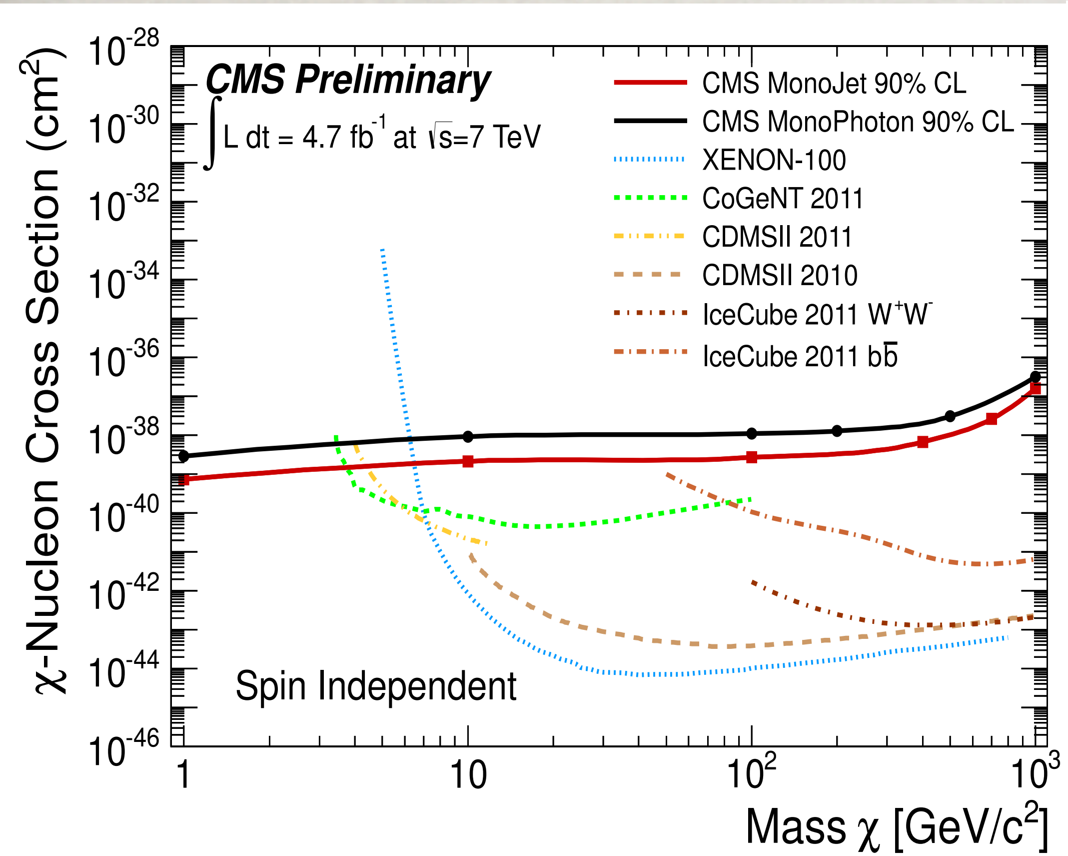
The gluon ISR channel is already being tested at the LHC...

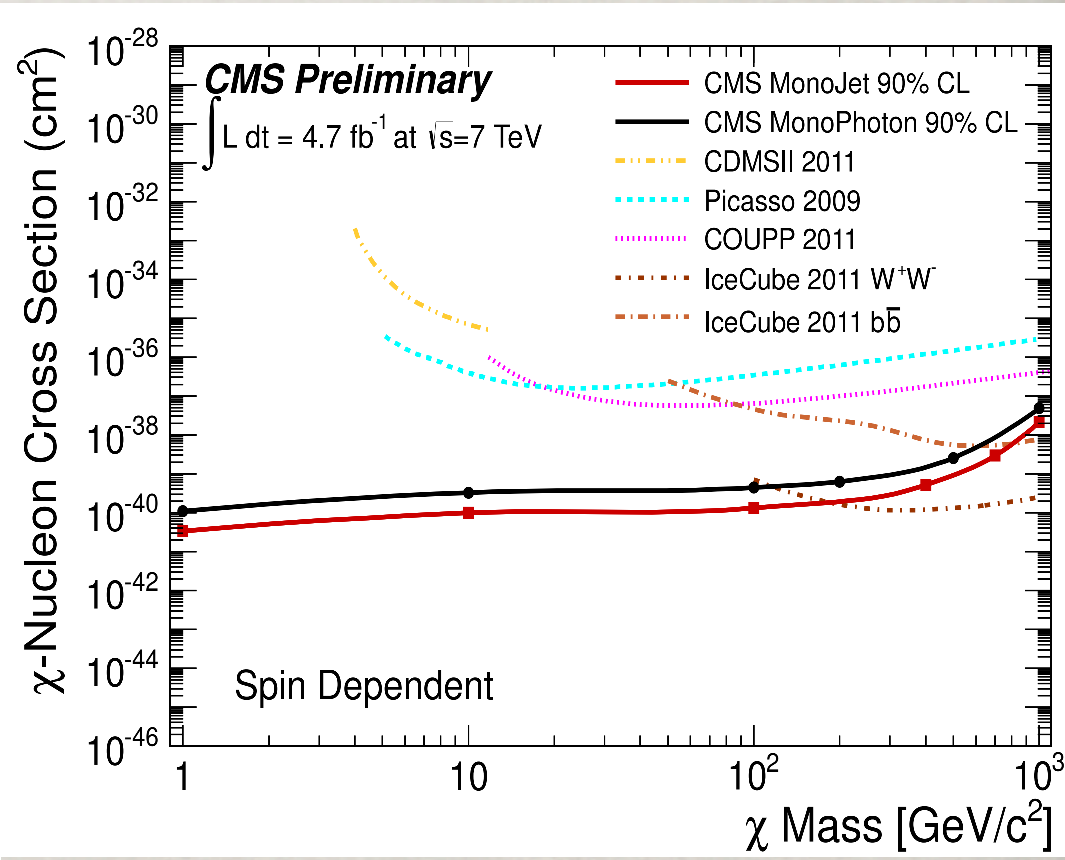


Monojet candidate event !

COLLIDER BOUNDS

Now CMS has performed a monojet/monophoton analysis for DM:

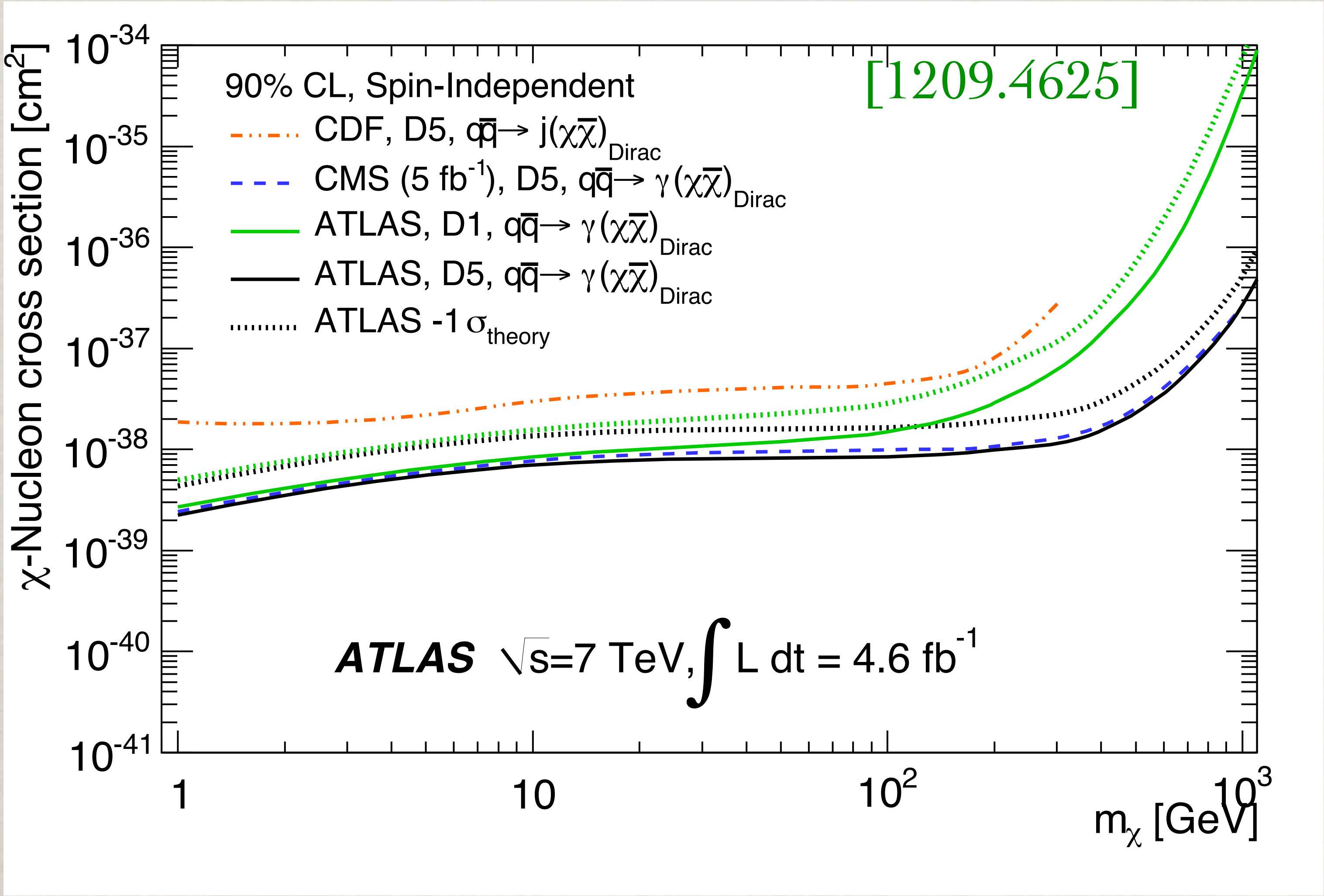




Strongest bound for low mass and for spin dependent case !

COLLIDER BOUNDS

ATLAS has also recently performed a monojet/monophoton analysis for DM:



Strongest bound for low mass and for spin dependent case !

Outlook

Outlook

- Origin of UltraHigh-Energy Cosmic Rays still unclear, but a cut-off in the spectrum is now found: is it the GZK cut-off ?
- Dark Matter is a WIMP, we should see it at colliders, in direct detection experiments and in indirect detection... There are tantalizing hints in Indirect Detection and Direct Detection, more data are expected soon !
- Astroparticle physics offers lots of data and open questions: still lots to do !

References

- Reviews on cosmic rays:
  - A. Olinto Phys.Rept 333 (2000) 329 (astro-ph/0002006)
  - G. Sigl arXiv:1202.0466
- Reviews on Dark Matter, especially Indirect Detection:
  - G. Bertone, D. Hooper, J. Silk Phys.Rept. 405 (2005) 279 (hep-ph/9404175)
  - A. Ibarra, D. Tran, C. Weniger arXiv:1307.6434
- Latest results:
  Talks at the ICRC2013 conference, see http://www.cbpf.br/~icrc2013/