CERN SUMMER STUDENT - LECTURE I

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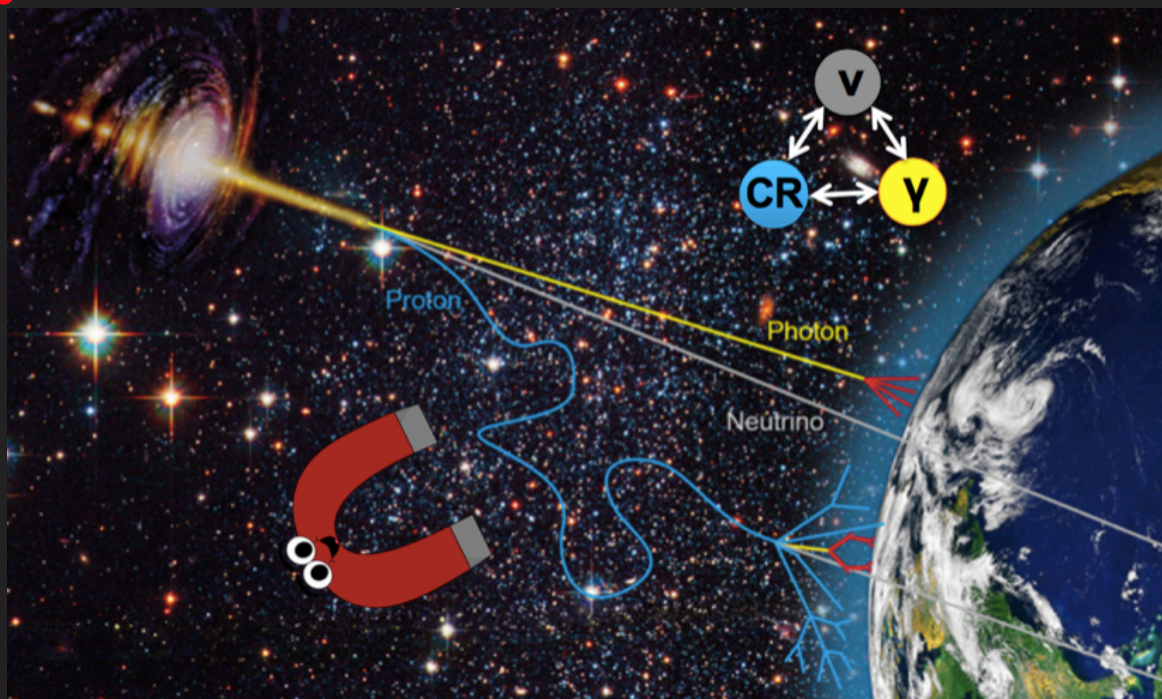
ASTROPARTICLE II

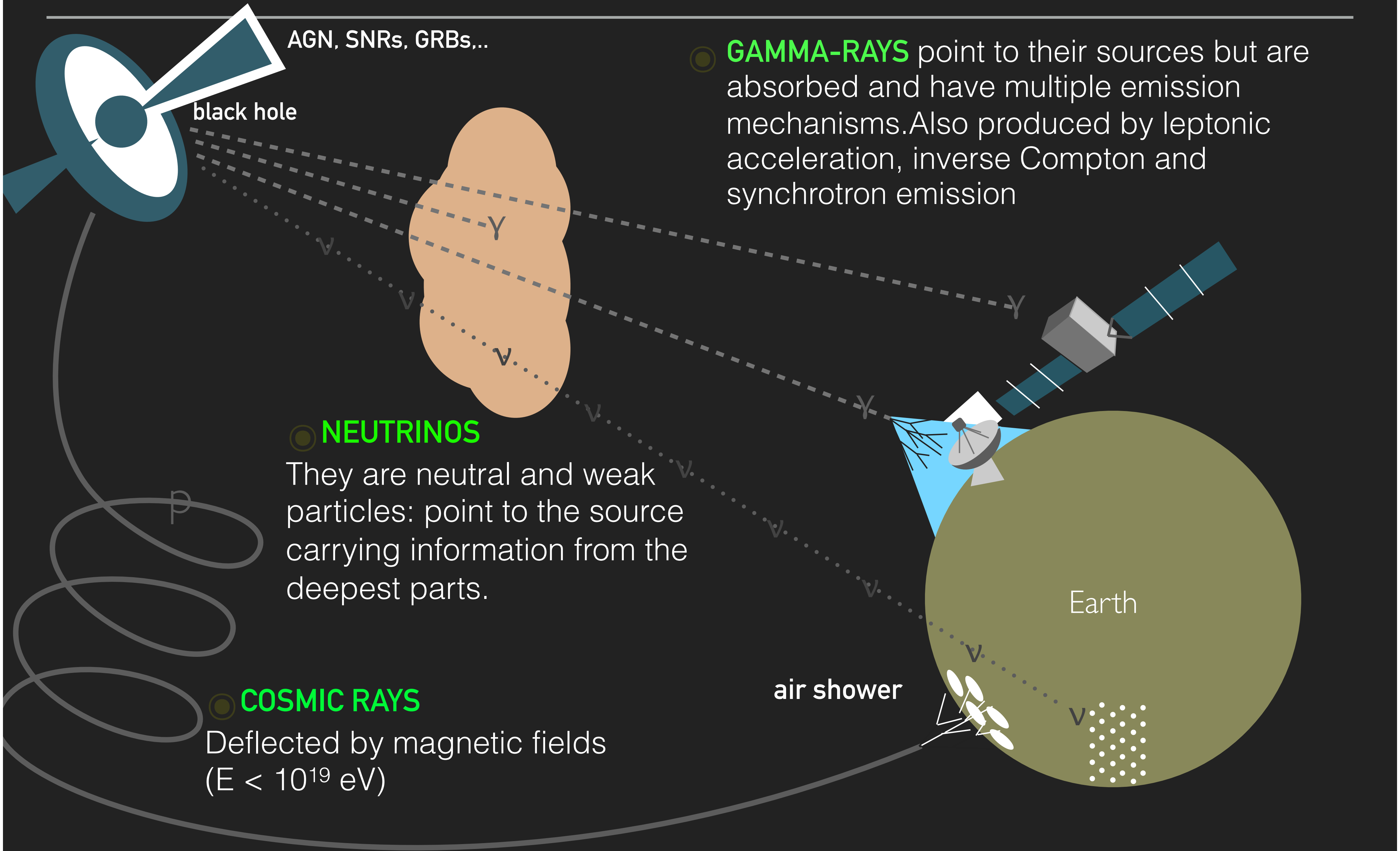
20 JULY 2017

CONTENTS OF TWO LECTURES

- Radiation from the universe and cosmic rays (CR)
- Cosmic ray observables: spectrum and composition
- Propagation and sources of cosmic rays
- The connection of CRs to other messengers :
- CRs with Ultra-High Energy CRs
  - Gamma-Rays
  - Neutrinos



THE MESSENGER PROPAGATION

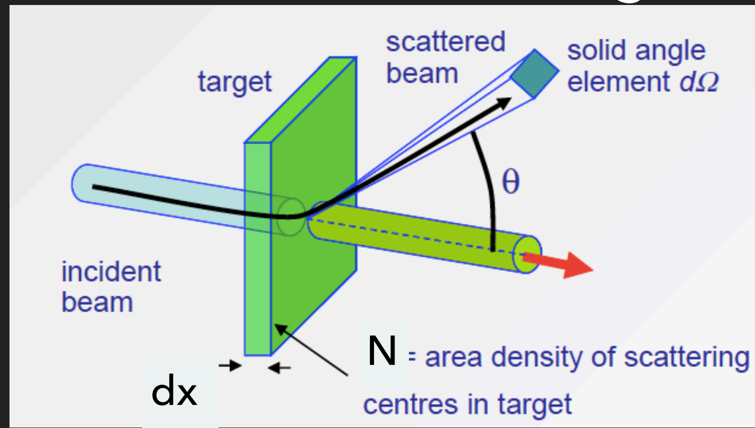


THE INTERACTION LENGTH OF A PARTICLE

- Horizon = messenger mean free path (interaction length) in a medium

- X-section σ: area of the target intercepted by a beam measured as average fraction of scattered particles per unit time in the solid angle dΩ per unity of incident flux

$$\frac{d\sigma(E,\Omega)}{d\Omega} = \frac{1}{\Phi}\frac{dN_s}{d\Omega}$$



- Mean free path :

w = interaction probability = Nσdx, where N = n. of target particles/Volume

P(x) = prob. that a particle does not interact after traveling a distance x

P(x + dx) = P(x) (1-wdx) = prob. that a particle has no interaction between x and x+dx

$$\mathrm{P(x+dx) = P(x) + \frac{dP}{dx}dx = P(x) - P(x)wdx} \quad \Rightarrow \frac{dP}{P} = -w dx \Rightarrow P(x) = P(0)e^{-wx}$$

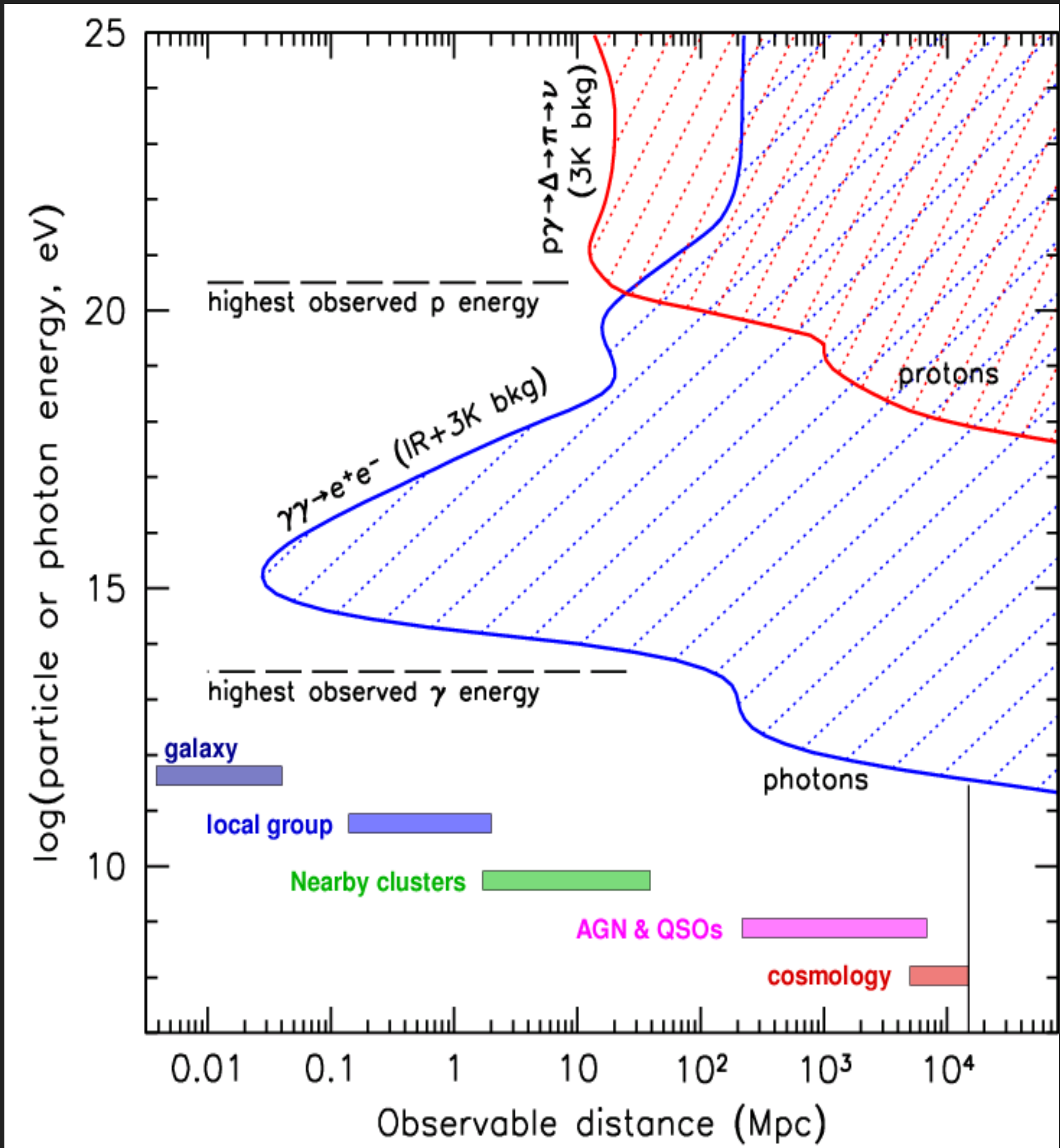
$$\lambda = \frac{\int \mathrm{xP(x)dx}}{\int \mathrm{P(x)dx}} = \frac{1}{\mathrm{w}} = \frac{1}{\mathrm{N}\sigma} = \frac{\mathrm{Am_p}}{\sigma\rho}$$

Target material

P(0) = 1 initially the particle did not interact

Particle properties

THE MESSENGER HORIZON = INTERACTION LENGTH IN THE COSMOS



Proton horizon (GZK cut-off):

$$p\gamma_{2.7K} \rightarrow \Delta^+ \rightarrow \pi^+ n$$

$$L_\gamma = \frac{1}{\sigma_{p-\gamma} n_\gamma} \sim 10 \text{ Mpc}$$

$$\sim \frac{1}{10^{-28}\text{cm}^2 \times 400\text{cm}^{-3}}$$

The neutrino horizon is comparable to the observable universe!

$$\bar{\nu}\nu_{1.95K} \rightarrow Z \rightarrow X$$

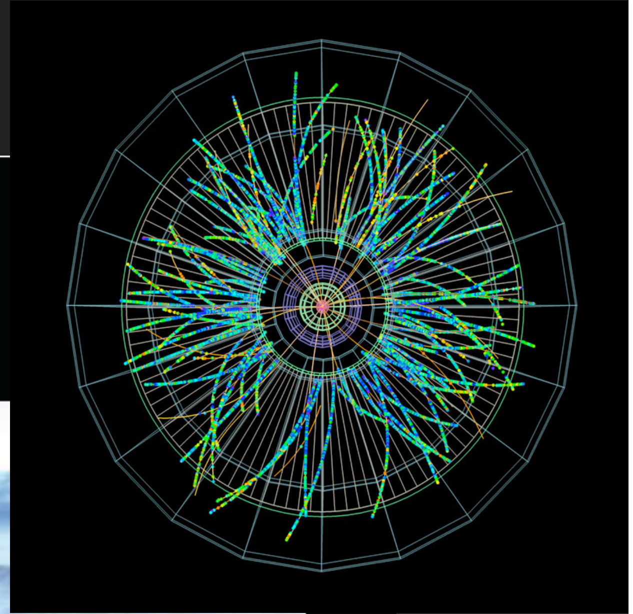
$$L_\nu = \frac{1}{\sigma_{res} \times n} = \frac{1}{5\times 10^{31} cm^2 \times 112 cm^{-3}} \approx 6Gpc$$

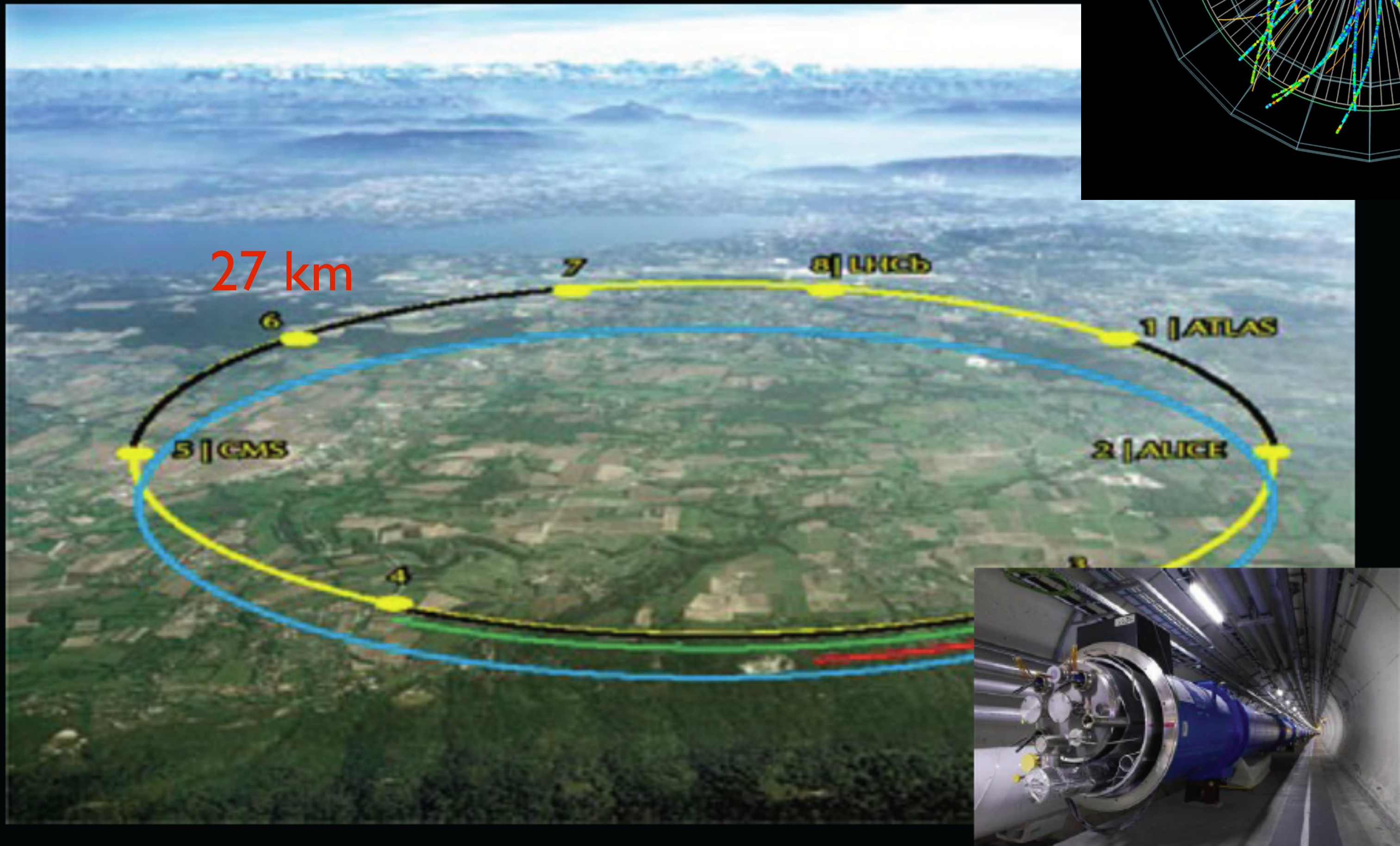
arxiv.org/pdf/0811.1160v2.pdf

ACCELERATORS

Large Hadron Collider:

$E_{max} = c \cdot e \cdot B \cdot R = 7 \times 10^{12}$ eV



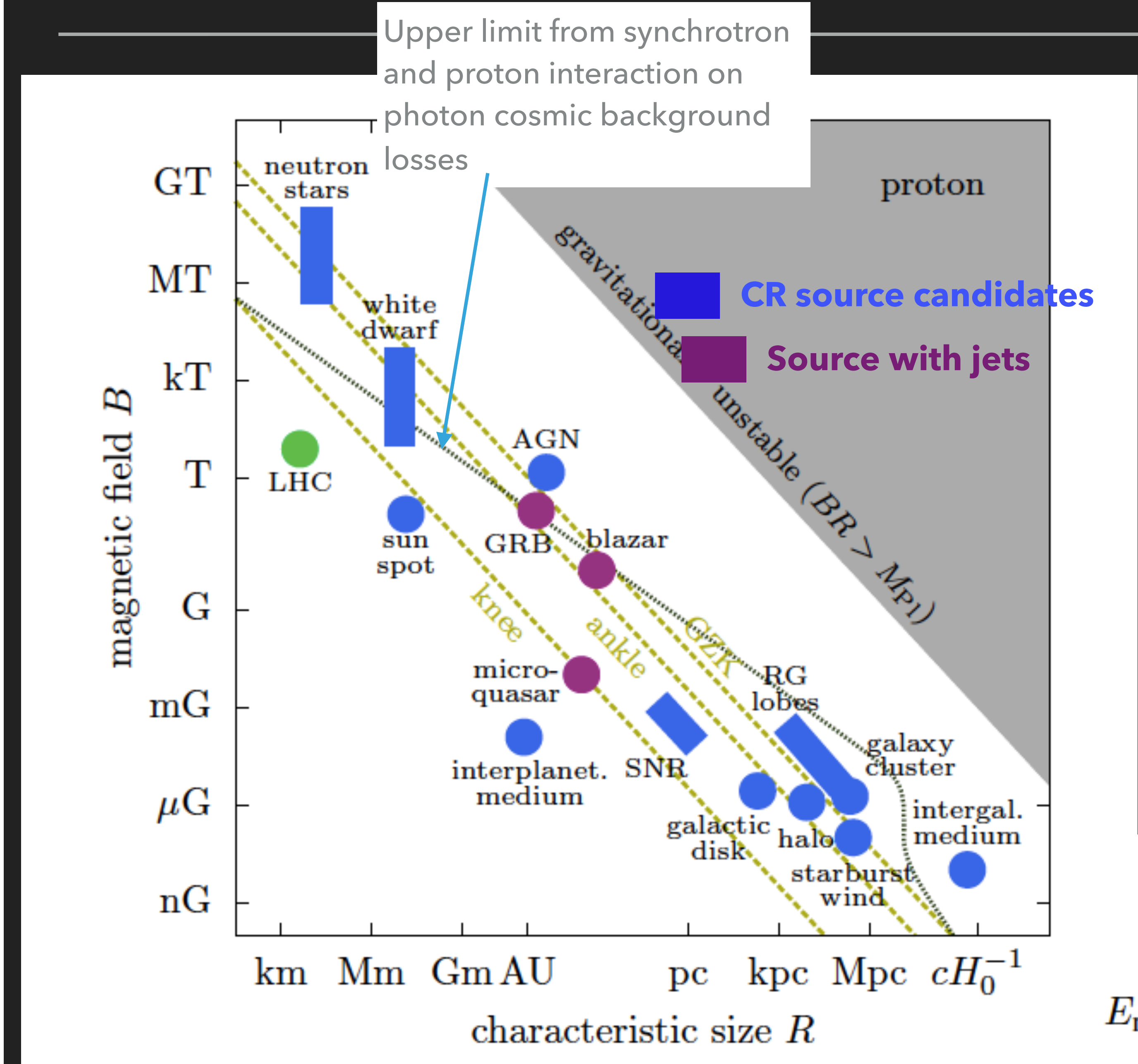


9593 superconducting magnets at -271.3 °C accelerate protons to collide in 4 points instrumented to analyze matter and its constituents in which it decomposes at these extreme conditions similar to 3×10^{-15} seconds after the Big Bang(15 TeV correspond to abt. 10^{17} Kelvin)

COSMIC ACCELERATORS

An LHC with the radius of the Mercury orbit could accelerate protons to 10^{20} eV = 10^7 x LHC!

MESSENGER ACCELERATION: THE HILLAS' PLOT



Lorentz force

$$F_L = qvB = m\frac{v^2}{R}$$

Imposing that the Larmour is equal to the accelerating region

$R = R_{acc}$

We find the maximum energy at which the charged relativistic particle with q = Ze can be accelerated

$$R_L = \frac{cp}{ZeB} \approx 100\,\mathrm{pc}\,\frac{3\mu\mathrm{G}}{B}\,\frac{E}{Z\times 10^{18}\mathrm{eV}}$$

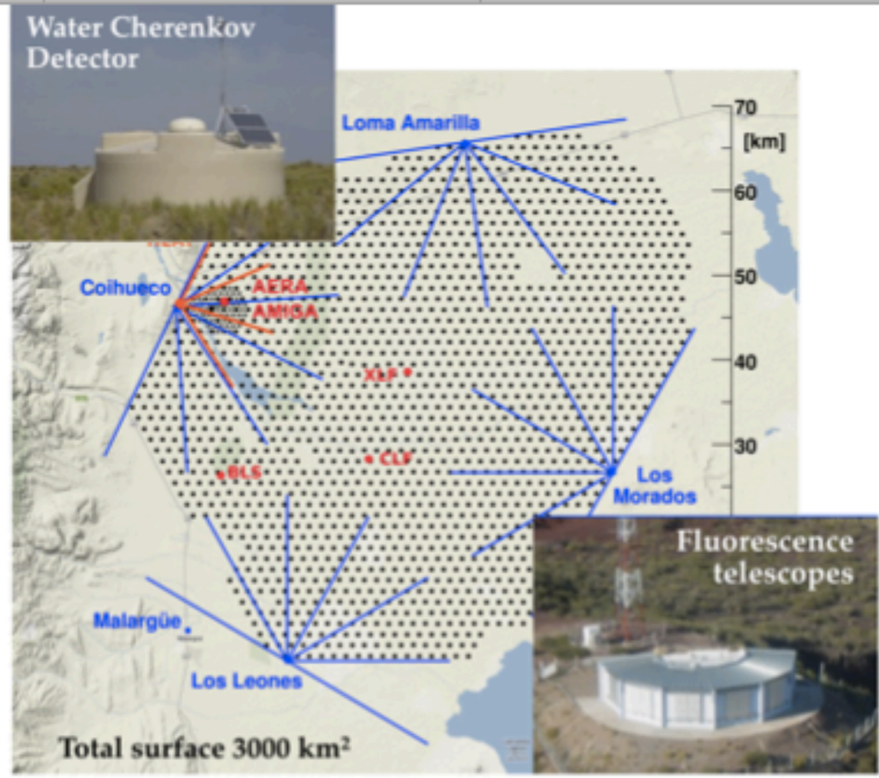
$$E_{\mathrm{max}} \simeq Z\left(\frac{B}{\mu\mathrm{G}}\right)\left(\frac{R_{\mathrm{source}}}{\mathrm{kpc}}\right)\times 10^9\ \mathrm{GeV}$$

For jets with Lorentz factors Γ, $E_{max} \cong \Gamma ZBR$

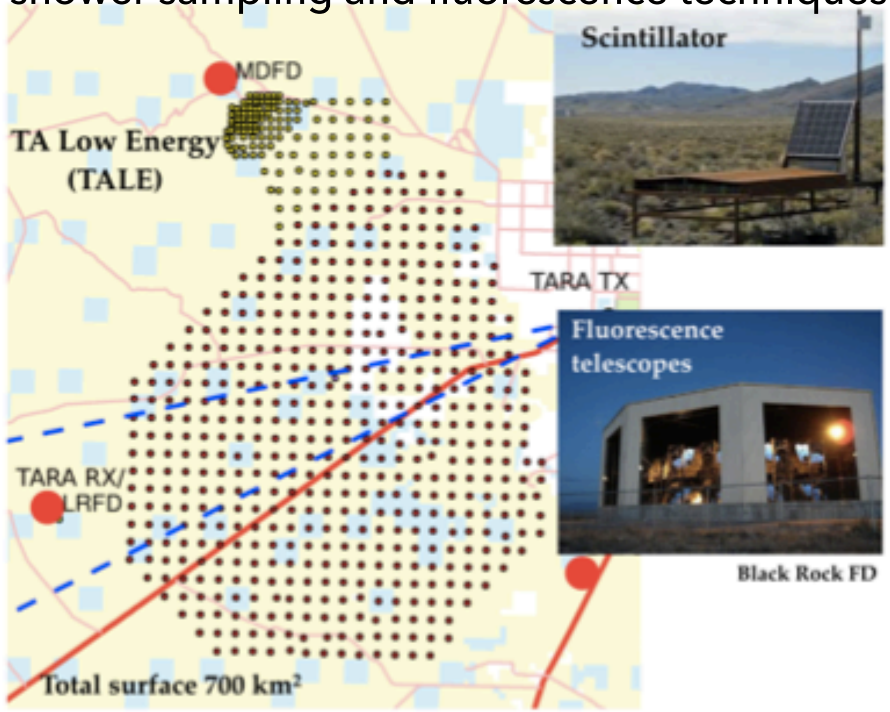
UHECR MESSENGERS

Can UHECR be cosmic messengers?

Yes ! But only in a tiny energy window between the minimum energy at which they are not deflected by B-fields and when they are not absorbed on cosmic radiation (GZK cutoff).



shower sampling and fluorescence techniques



MAGNETIC FIELD DEFLECTIONS OF UHECRS

If UHECR are not protons then astronomy with them will be not easy due to larger magnetic deflections.

$$mv^2/r = pv/r = ZevB/c$$

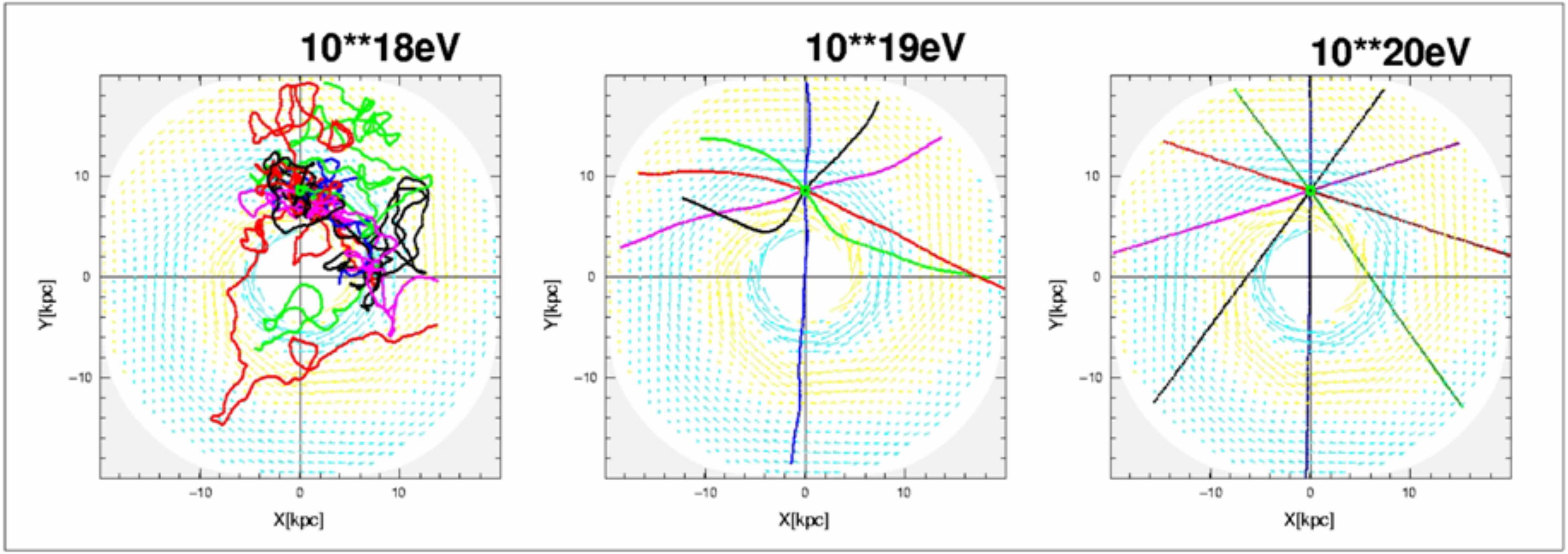
$$r = pc/ZeB$$

$$r(cm) = \frac{1}{300}\frac{E(eV)}{ZB(G)}$$

$$(10^{12}eV) = 10^{15}cm = 3\times10^{-4}pc$$

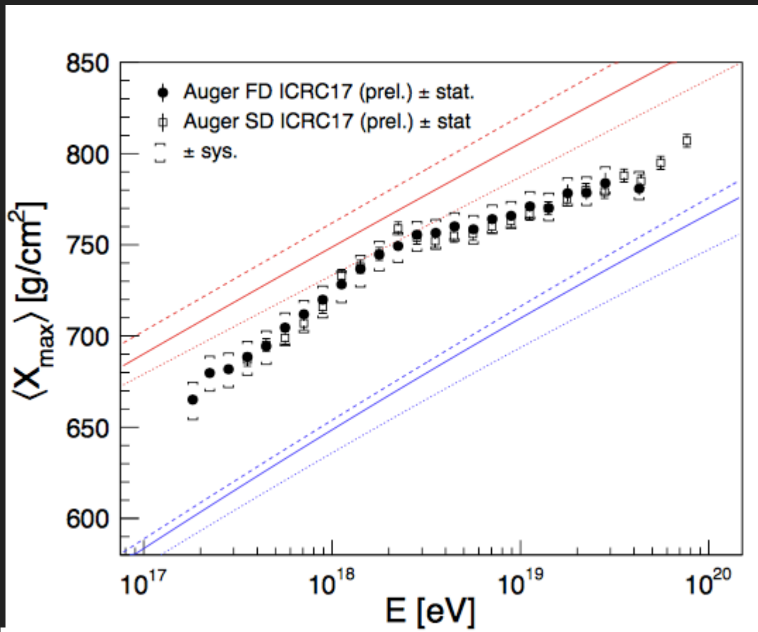
$$r = (10^{15}eV) = 10^{18}cm = 3\times10^{-1}pc$$

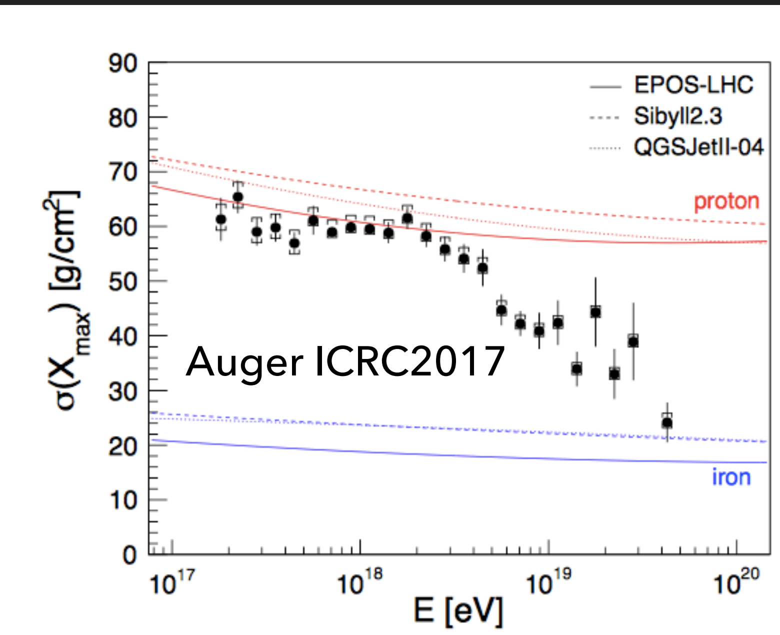
$$(10^{18}eV) = 10^{21}cm = 300\,pc$$

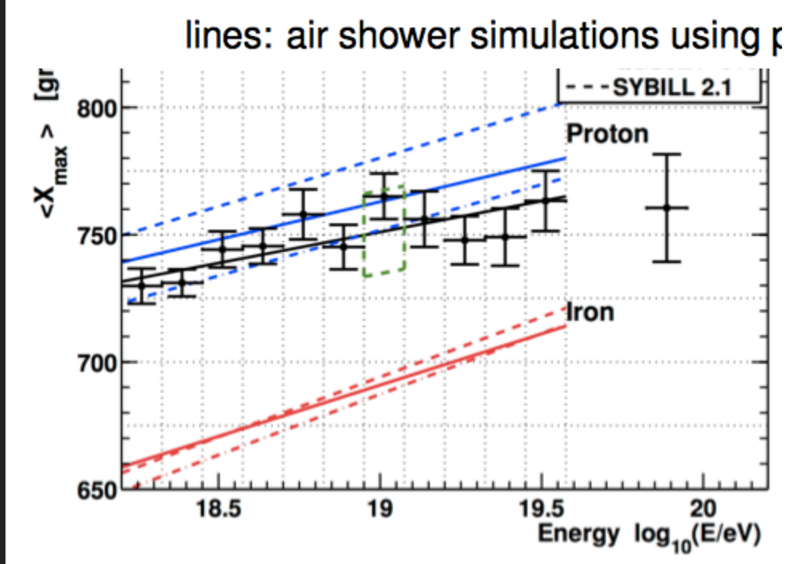


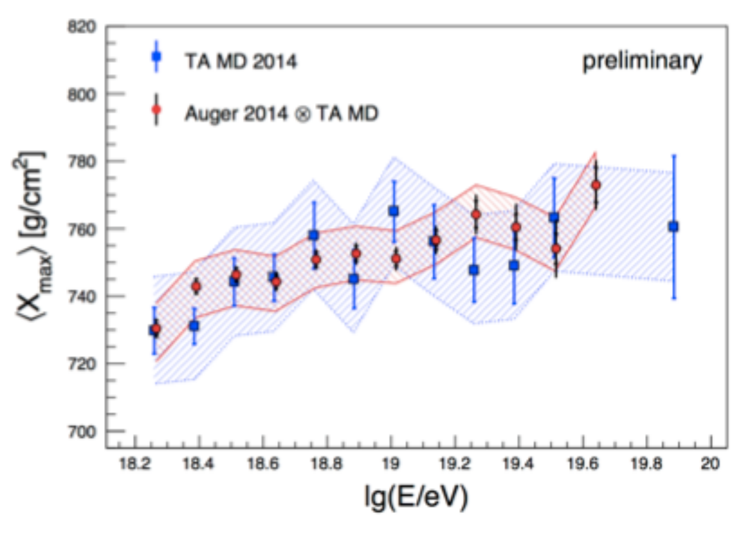
THE UHECR COMPOSITION

X_{max} = depth in the atmosphere where shows maximum occurs. It is an indictor of the composition since Fe showers penetrate less in the atmosphere than proton once principally due to the smaller interaction length.

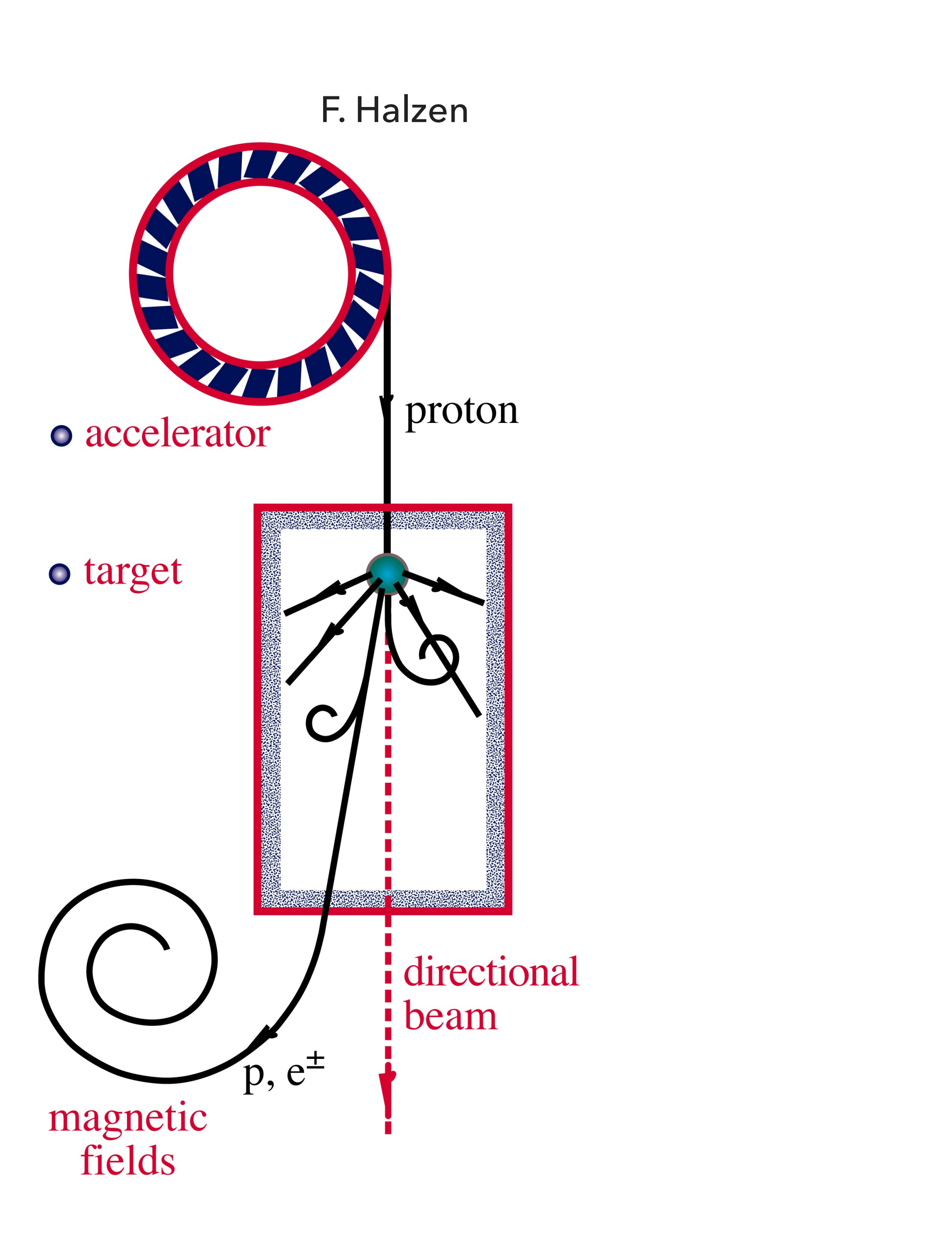


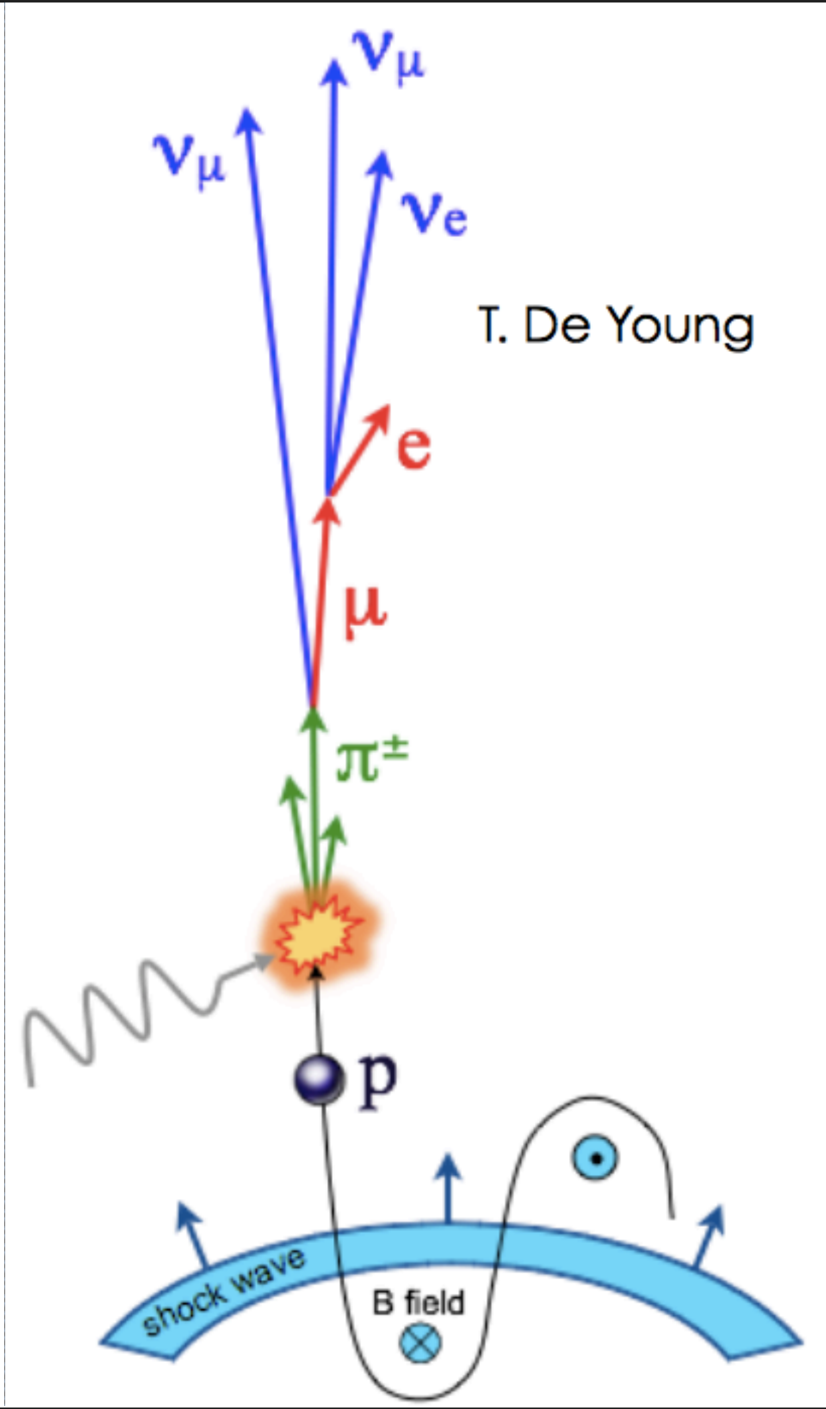




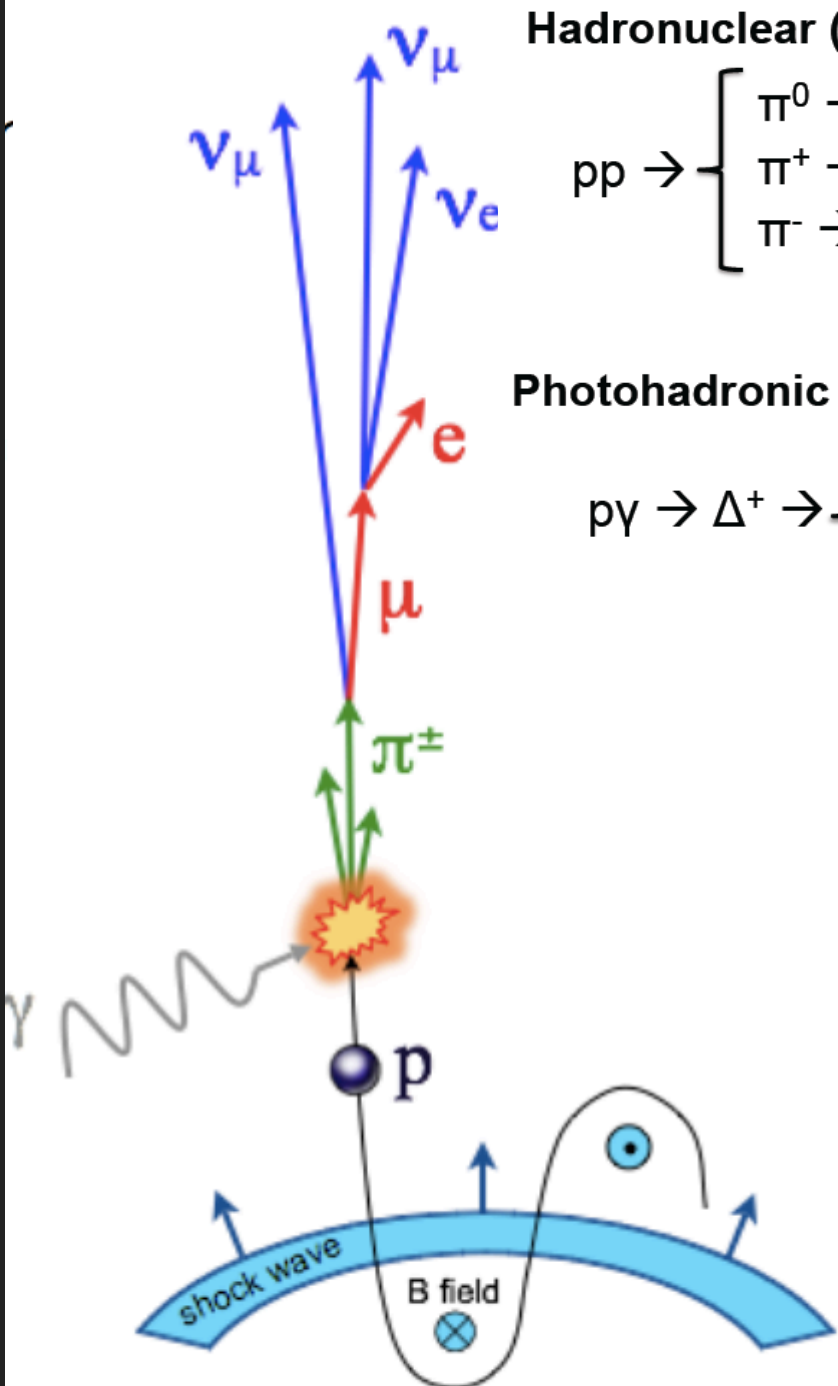


THE GENERIC MESSENGER SOURCE: EARTH & HEAVEN



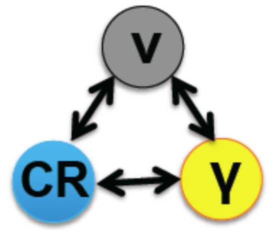


THE GENERIC MESSENGER SOURCE : A COSMIC BEAM DUMP



Hadronuclear (e.g. star burst galaxies and galaxy clusters)

$$pp \rightarrow \begin{cases} \pi^0 \rightarrow \gamma\,\gamma \\ \pi^+ \rightarrow \mu^+ \nu_\mu \rightarrow e^+ \nu_e \nu_\mu \bar{\nu}_\mu \\ \pi^- \rightarrow \mu^- \bar{\nu}_\mu \rightarrow e^- \bar{\nu}_e \bar{\nu}_\mu \nu_\mu \end{cases}$$



Photohadronic (e.g. gamma-ray bursts, active galactic nuclei)

$$p\gamma \rightarrow \Delta^+ \rightarrow \begin{cases} p\,\pi^0 \rightarrow p\,\gamma\,\gamma \\ n\,\pi^+ \rightarrow n\,\mu^+ \nu_\mu \rightarrow n\,e^+ \nu_e \bar{\nu}_\mu \nu_\mu \end{cases}$$

cosmic ray + gamma

cosmic ray + neutrinos

Neutrino flavour ratio at source:

pion-muon decay

$$\nu_e : \nu_\mu : \nu_\tau \sim 1 : 2 : 0$$

Oscillations average out over cosmic baselines

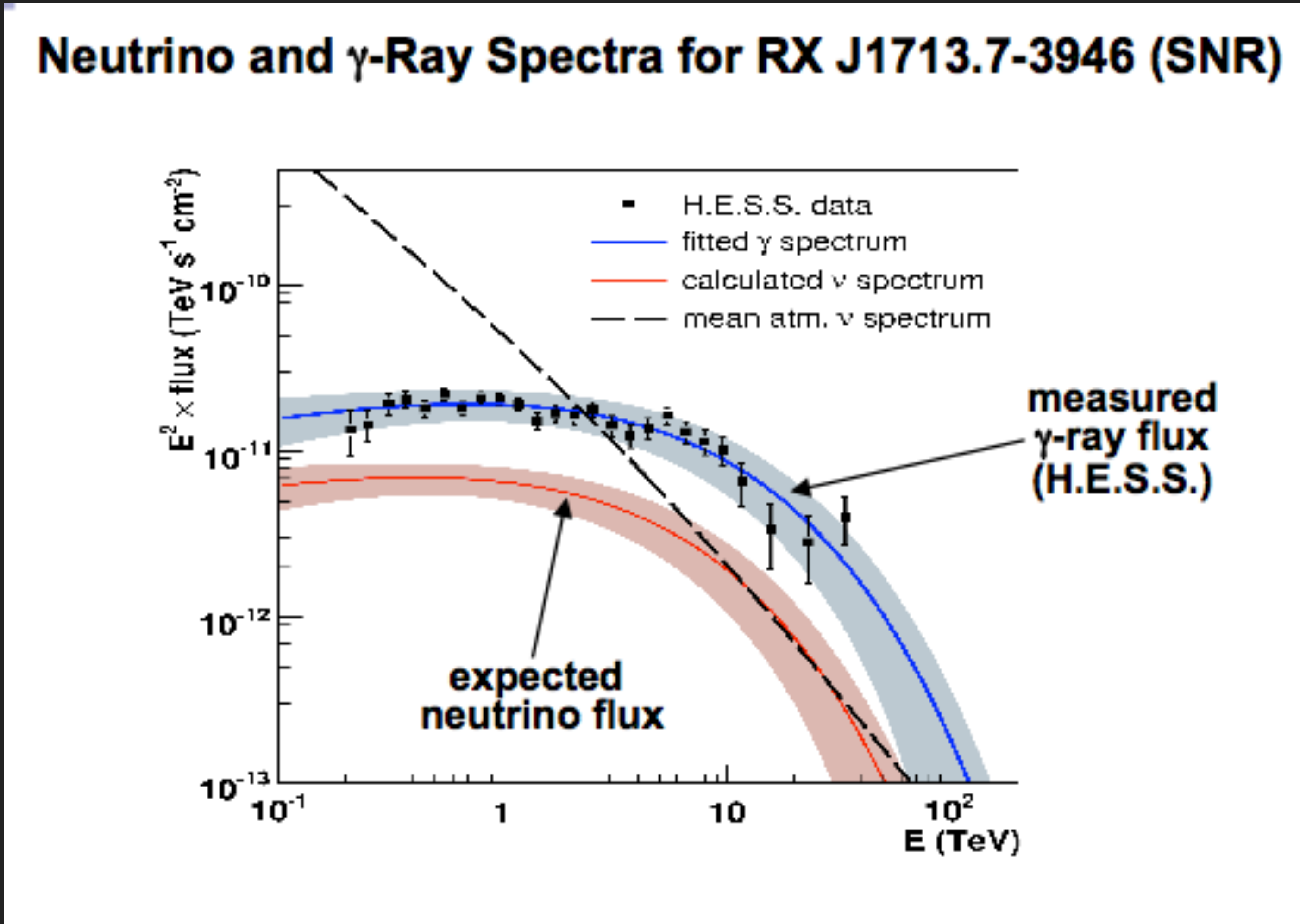
$$\nu_e : \nu_\mu : \nu_\tau \sim 1 : 1 : 1$$

NEUTRINO SPECTRA FROM COSMIC RAY AND GAMMA SPECTRA

Neglecting gamma-ray absorption and including standard neutrino oscillations

$$\frac{dN_\nu}{dE} = \frac{dN_\gamma}{dE} \text{ for p} - \text{p}$$

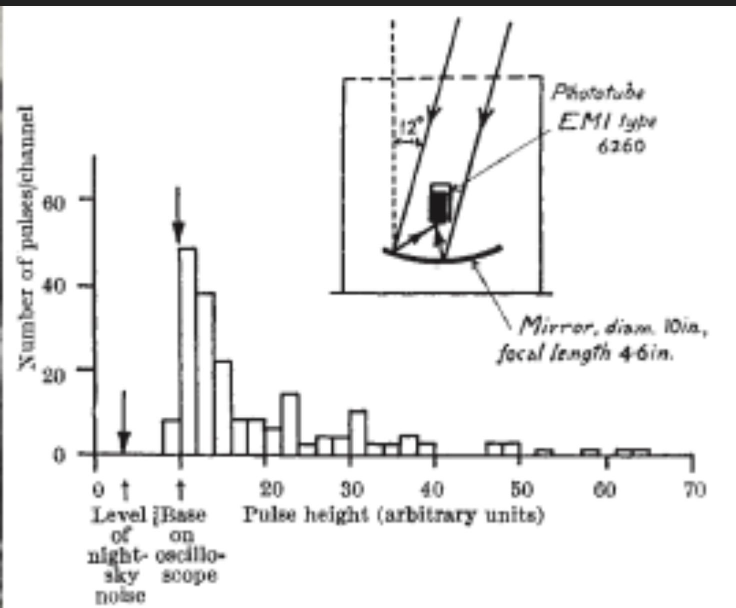
$$\frac{dN_\nu}{dE} = \frac{dN_\gamma}{dE} \; for \, p - \gamma$$

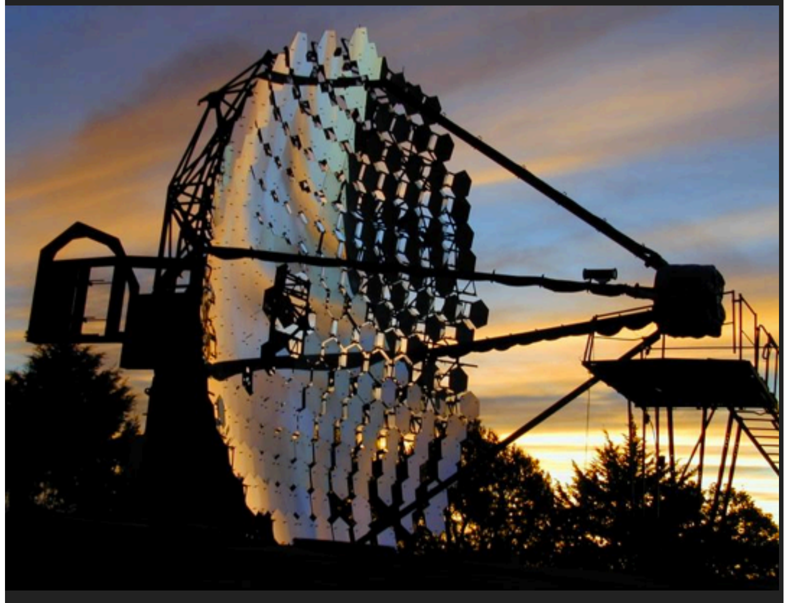


GAMMA-RAY ASTRONOMY : HISTORICAL HINTS

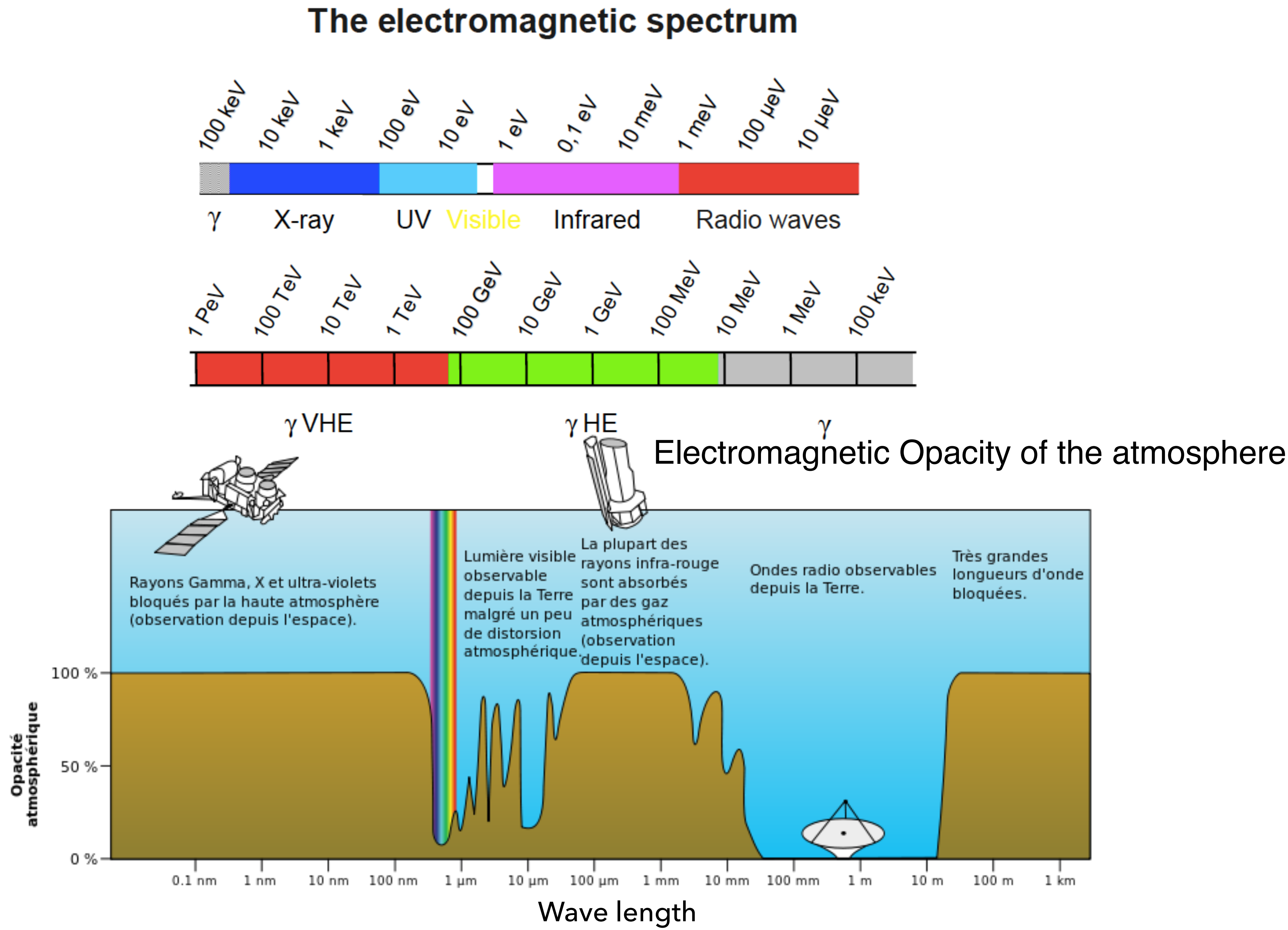
- 2002: Nobel prize to Koshiba-Davis-Giacconi (for birth of X-ray astronomy)
- 1953: Galbraight and Kelley build first rudimental Cherenkov telescope with a garbage can (birth of gamma-ray astronomy)
- Whipple discovers Crab Nebula after about 20 years exploiting the gamma/hadron discrimination of shower images on a 37 PMT camera with 3.5° FoV
- In 1989 Crab was the only TeV source, nowadays …

Lorenz & Wagner, arXiv:1207.6003

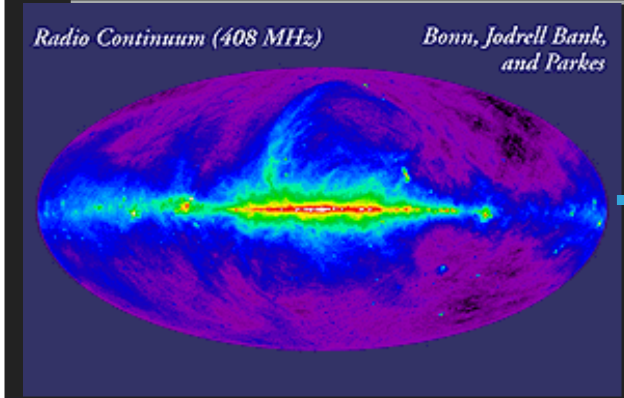


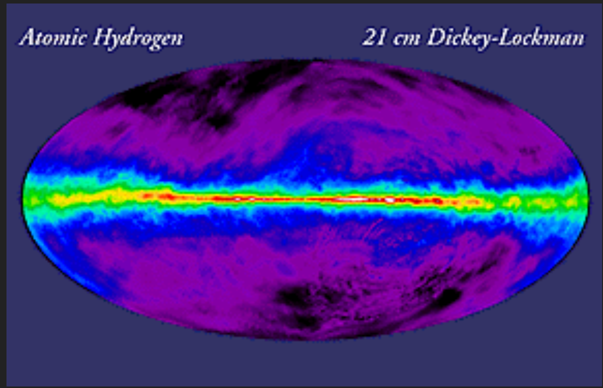


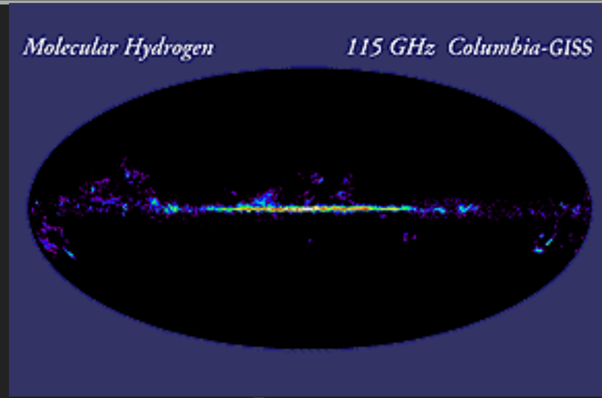
MULTIWALENGTH ASTRONOMICAL OBSERVATIONS



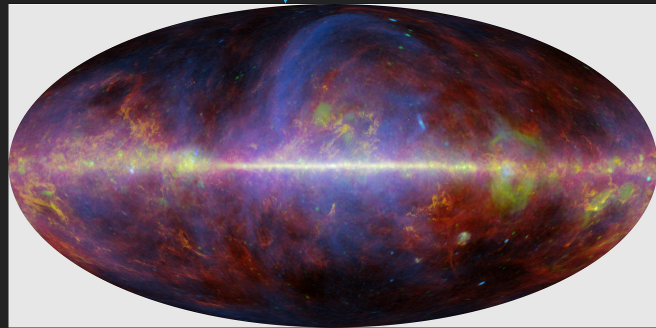
THE MULTIWALENGTH SKY

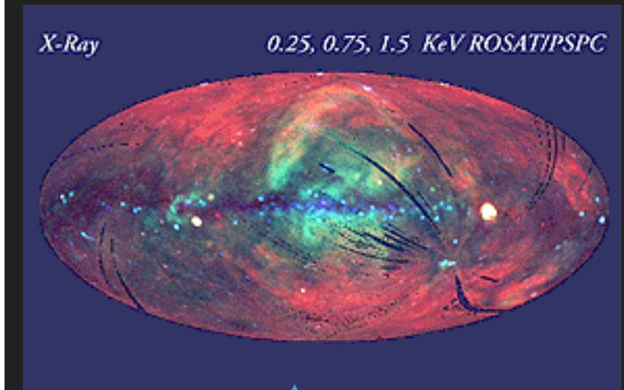


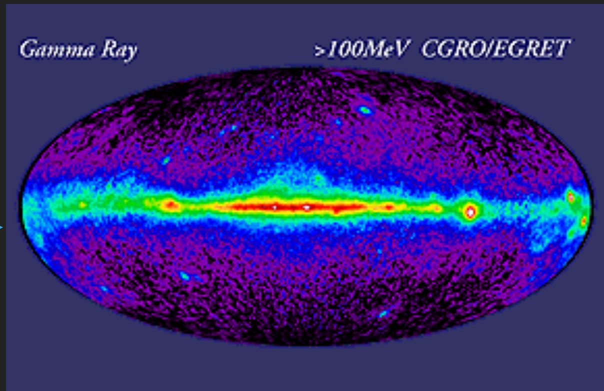




Planck 10-0.3 mm

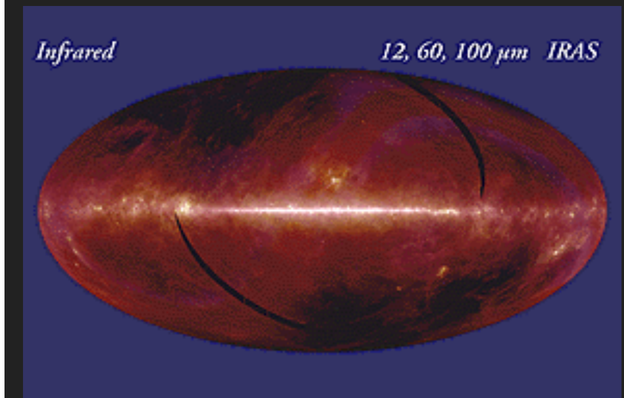


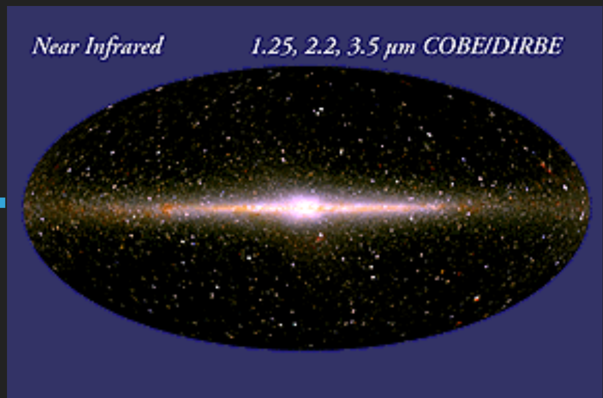




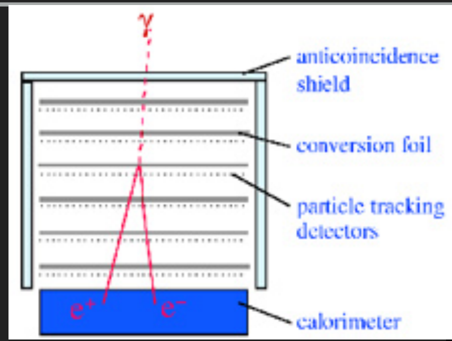
https://mwmw.gsfc.nasa.gov/mmw_allsky.html

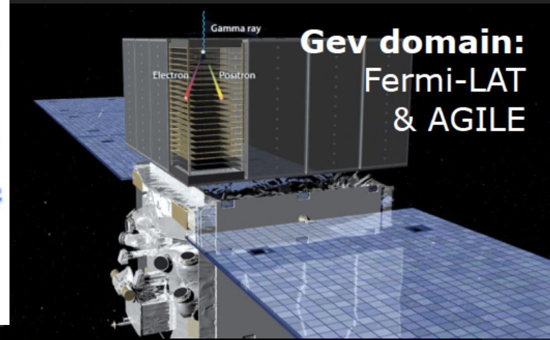
http://www.chromoscope.net



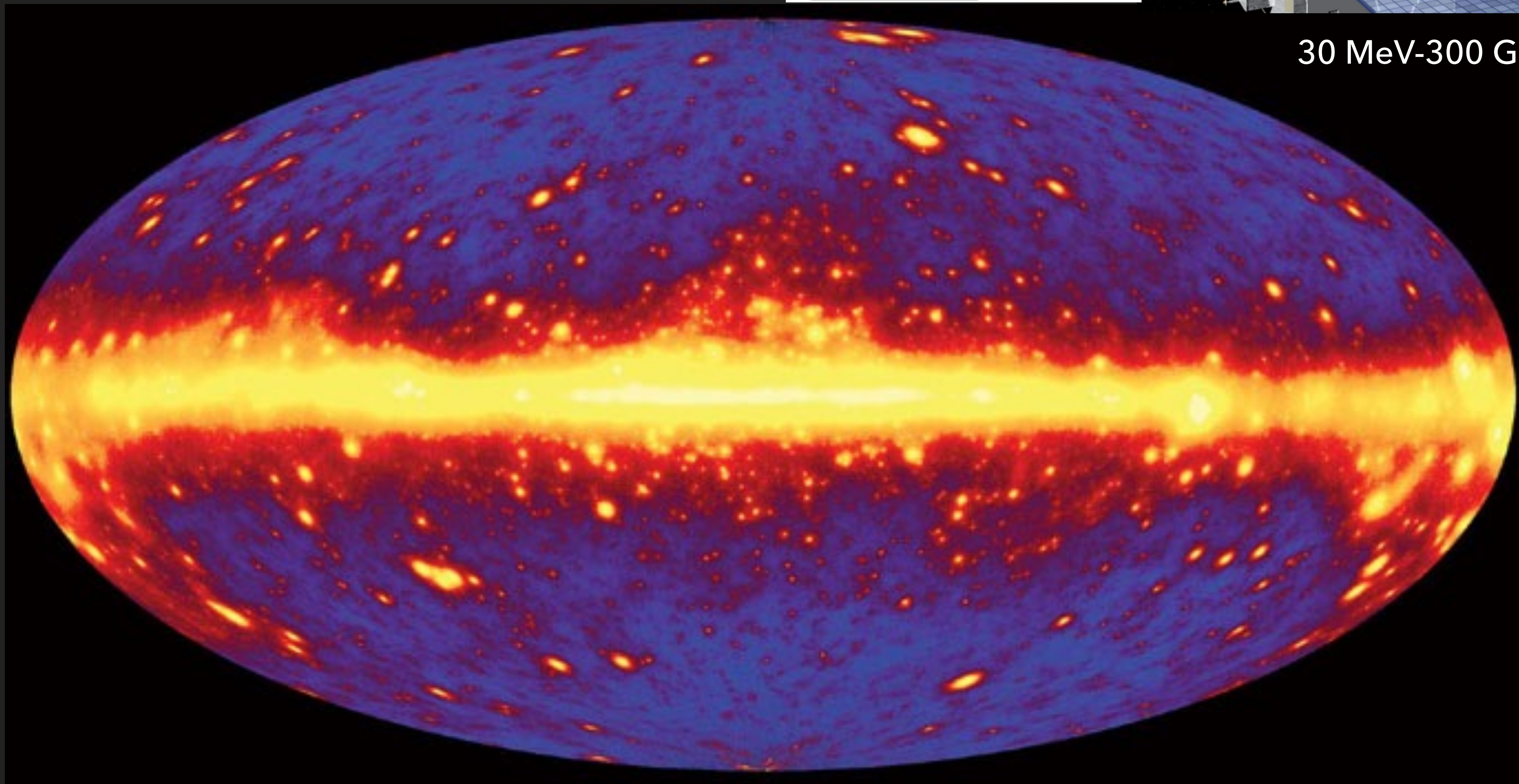


THE ACCELERATORS SKY IN THE TEV SEEN BY FERMI-LAT



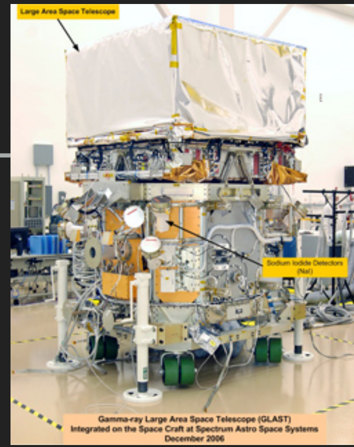


30 MeV-300 GeV

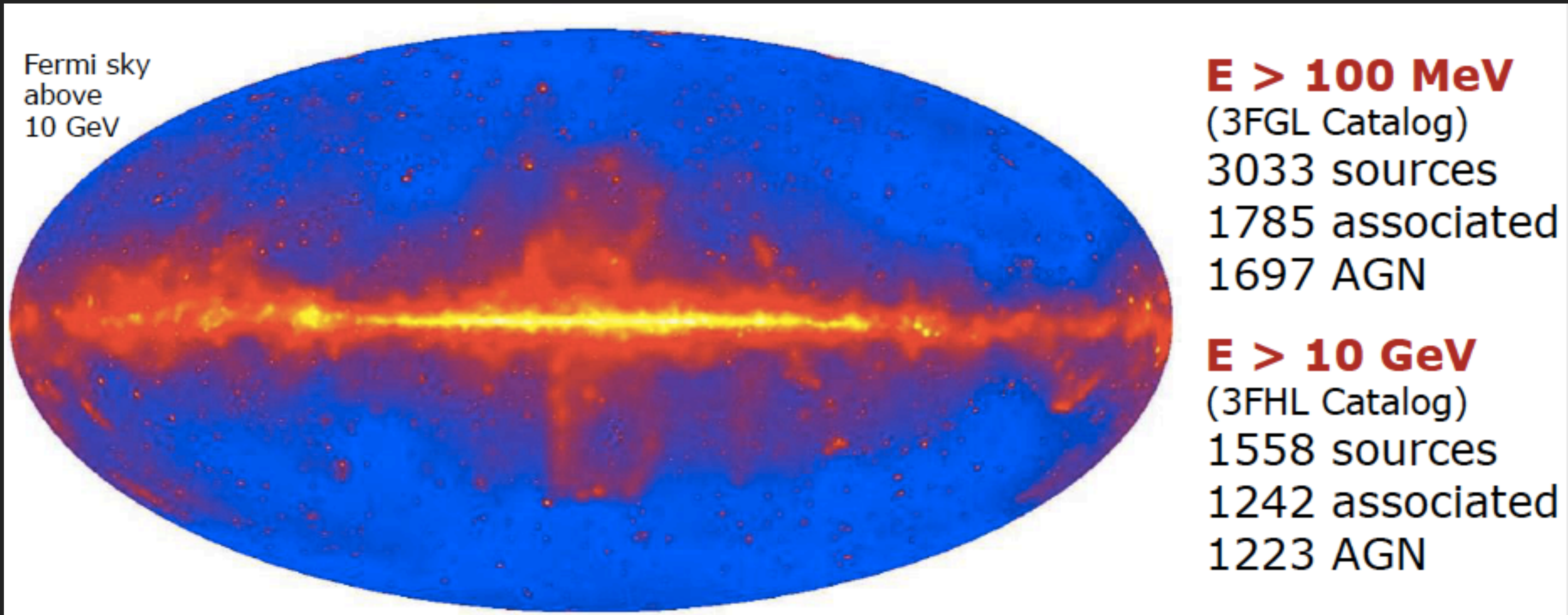


http://www.nasa.gov/mission_pages/GLAST/news/gammaray_best.html

THE SKY > 10 GEV

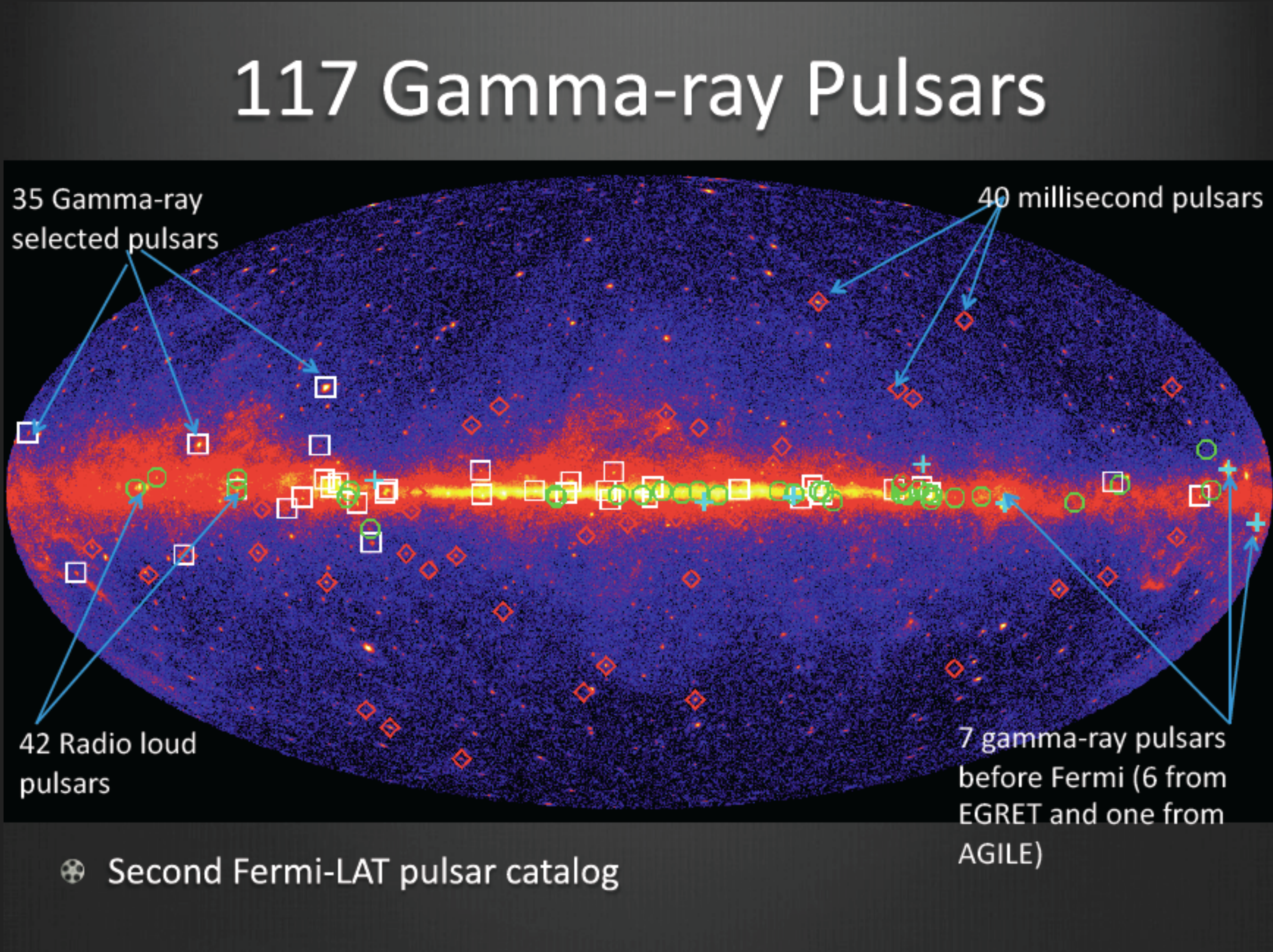


- Plenty of yet unidentified sources!



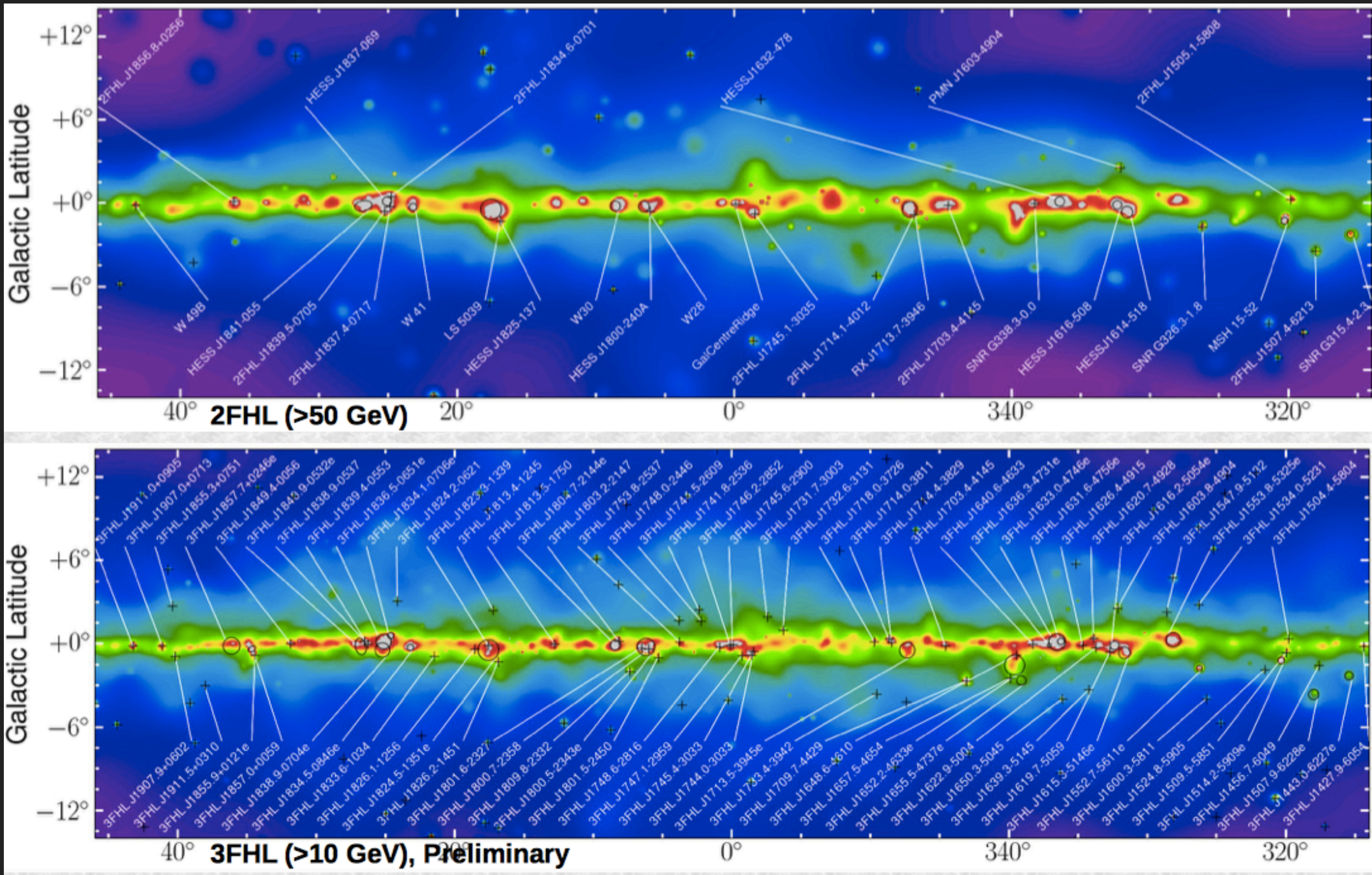
3rd Source Catalog
Fermi-LAT Coll., arXiv:1501.02003
3rd Catalog of Hard Sources
Fermi-LAT Coll., arXiv:1702.0066

GAMMA-RAY PULSARS WITH FERMI

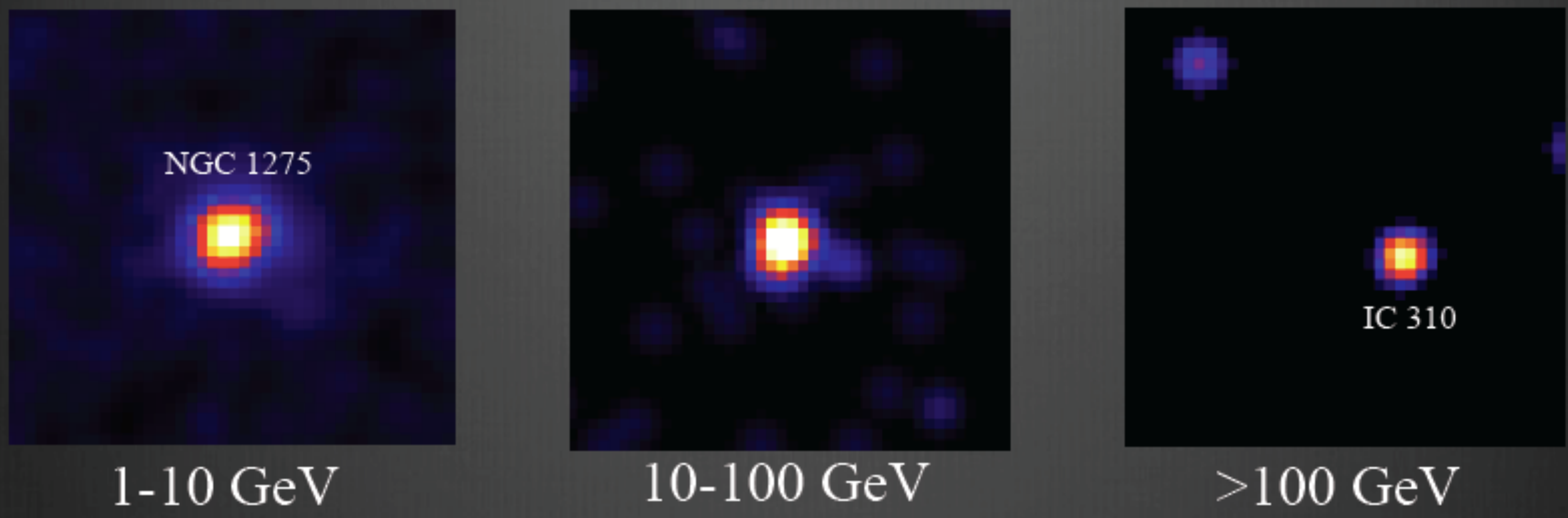


GALACTIC PLANE SURVEYS

1720 sources (54 extended)



NEW SOURCES IN THE TEV REGION

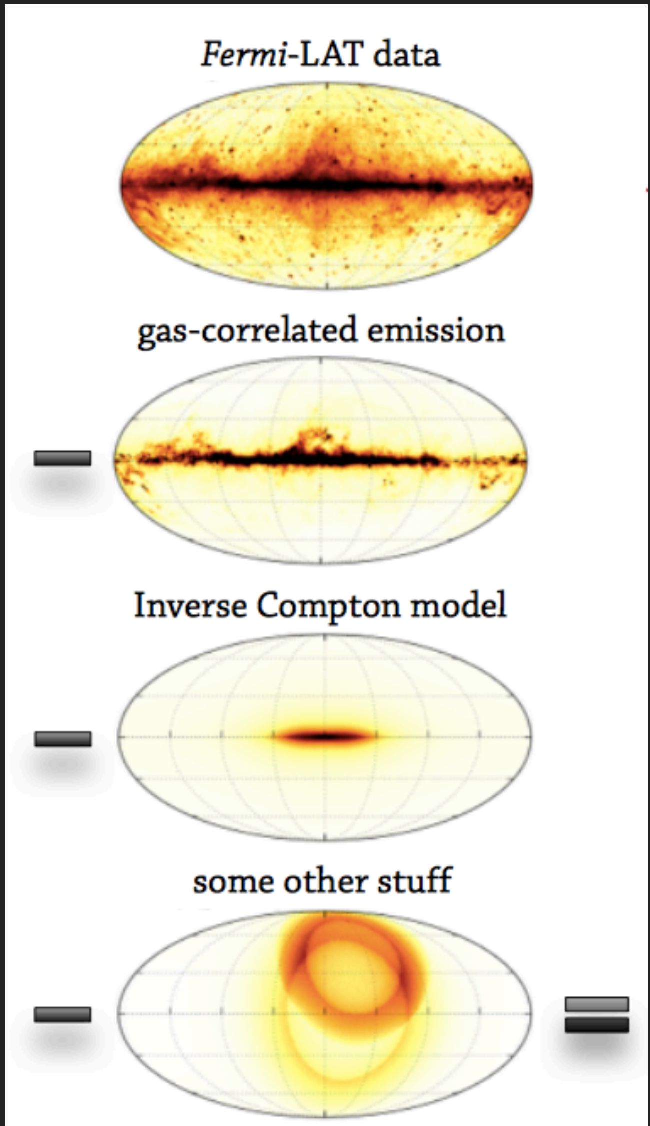


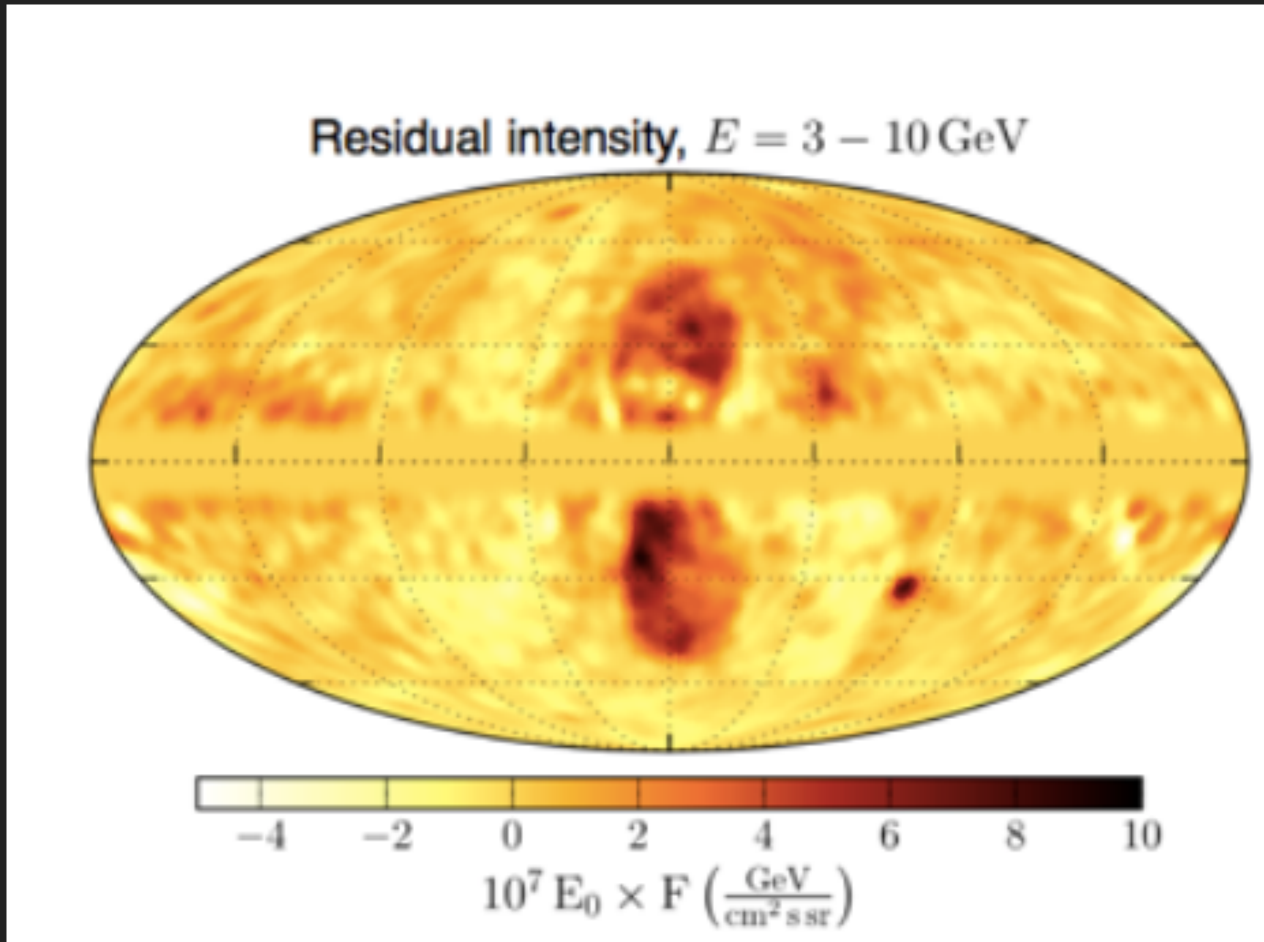
At energies below 10 GeV, only the radio galaxy NGC 1275 (Perseus A) is visible, but above 10 GeV a second source (to the lower right) emerges. Above 100 GeV, only this source, the head-tail galaxy IC 310, remains. From Neronov et al (2010)

New sources and features emerge in the gamma-ray sky with increasing energy

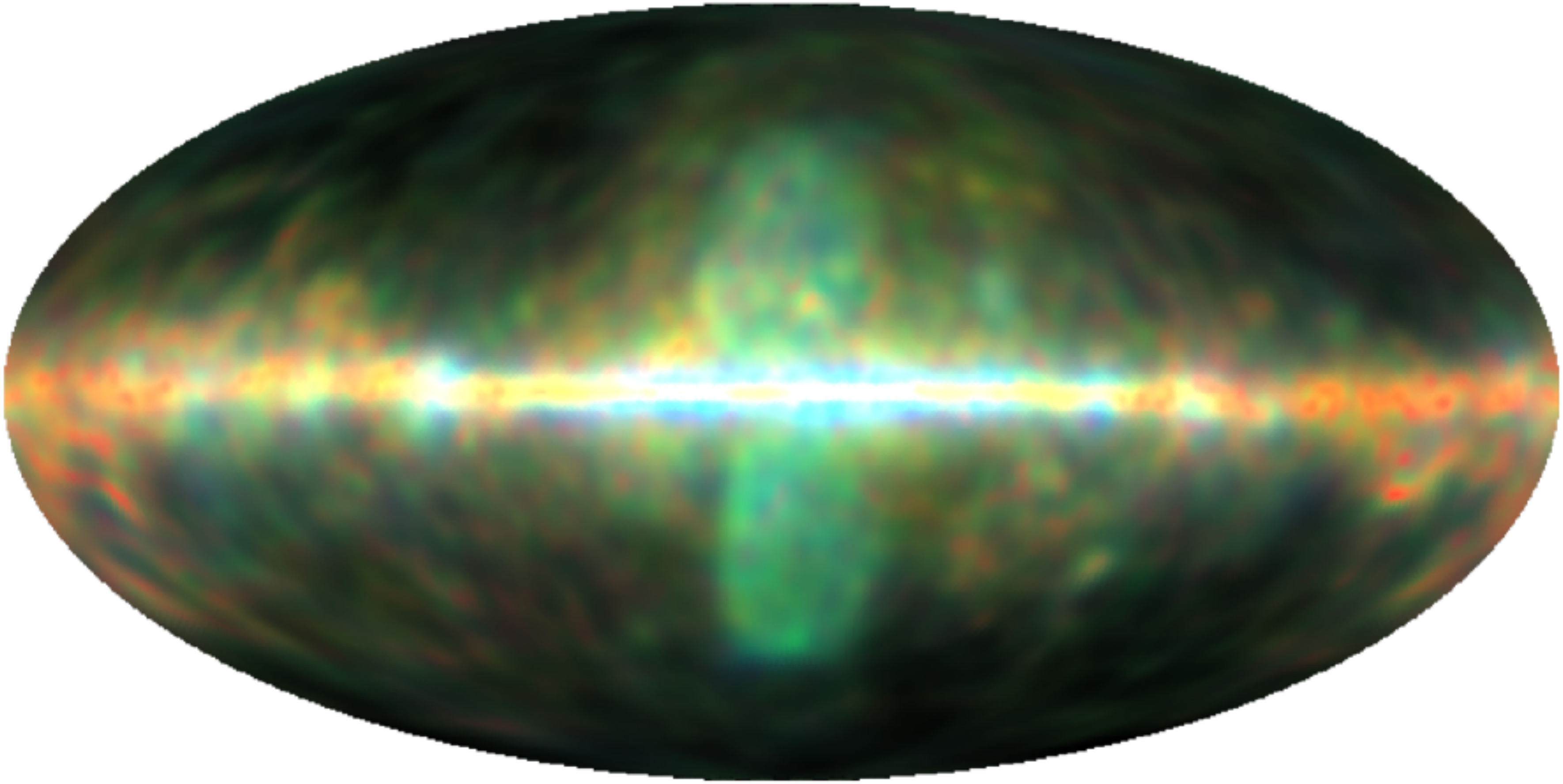
TEXT

Large structures of spectrally hard gamma-ray emission above 100MeV discovered in data from the Fermi-LAT telescope. (Su et al. ApJ 724 2010 and Dobler et al, ApJ 717, 2010)





THE SERENDIPITOUS SKY: THE FERMI BUBBLES

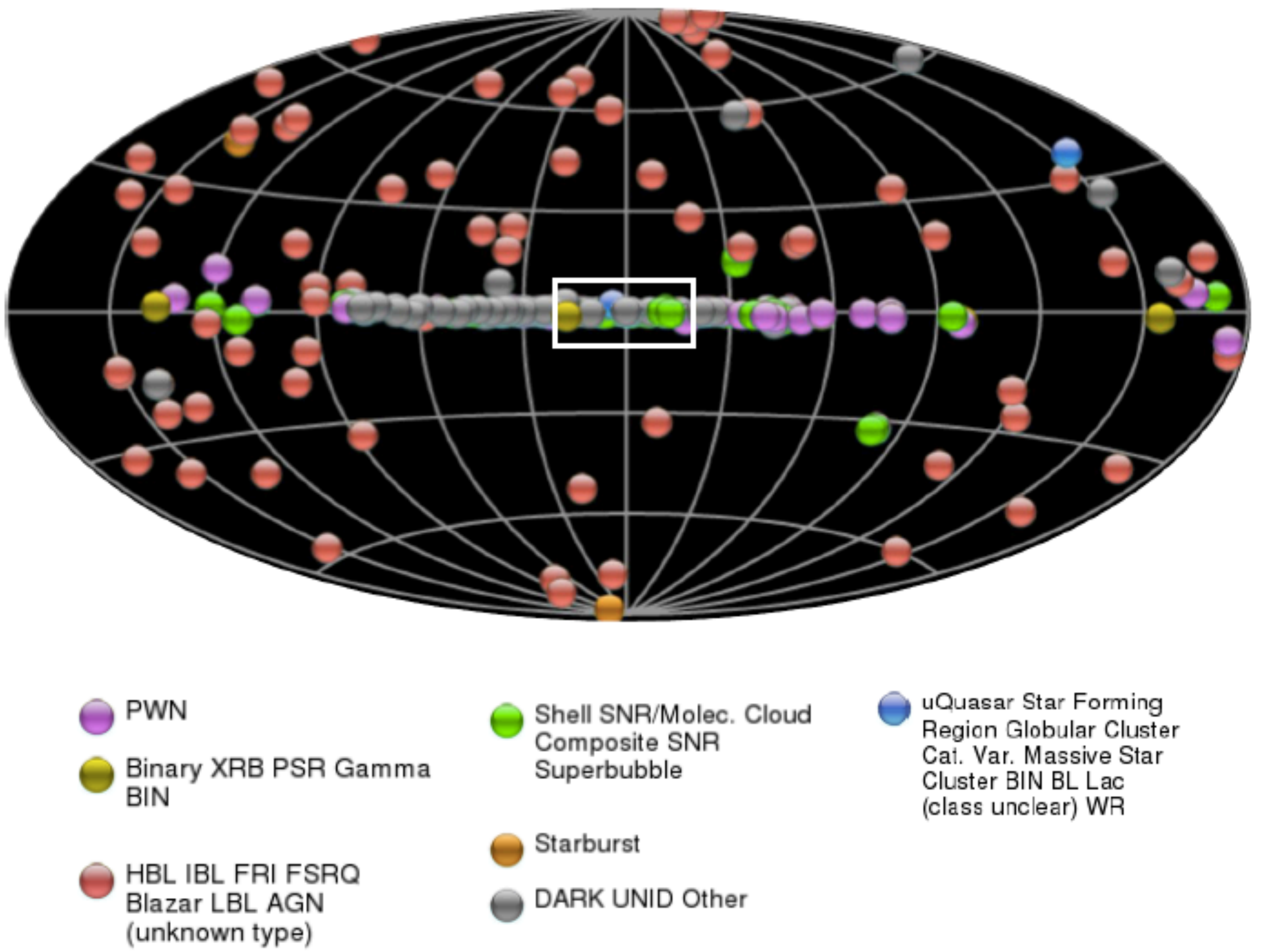


Residual map removing point sources, gas correlated emission,…

Ackermann et al. ApJ 793 2014

THE TEV SKY

tevcat.uchicago.edu

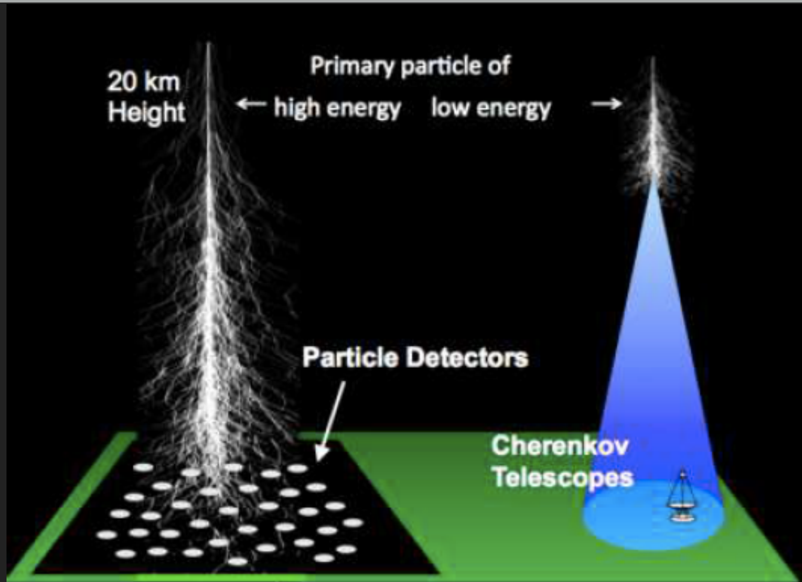


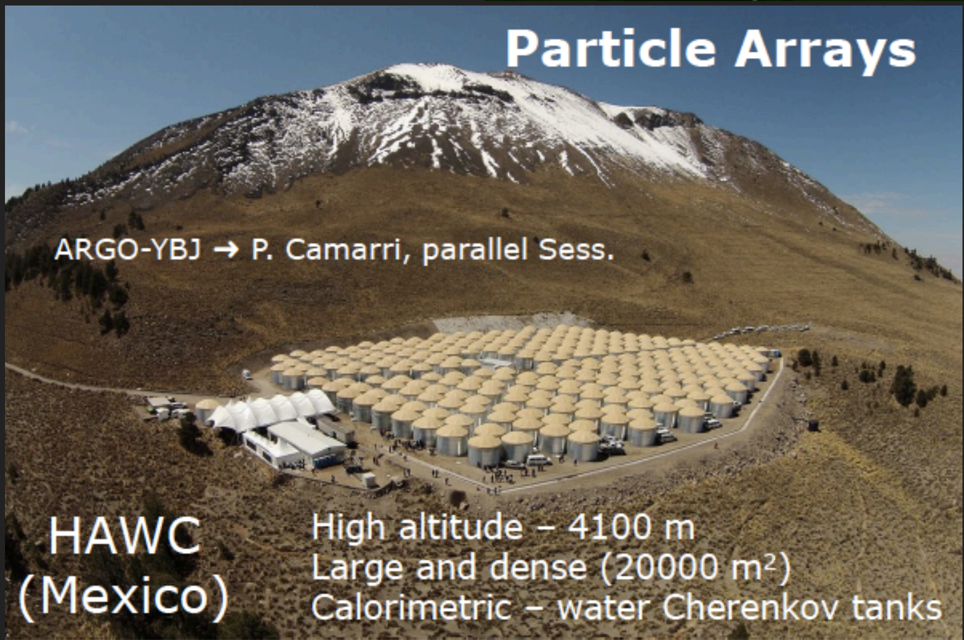
E > 100 MeV
(3FGL Catalog)
3033 sources
1785 associated
1697 AGN

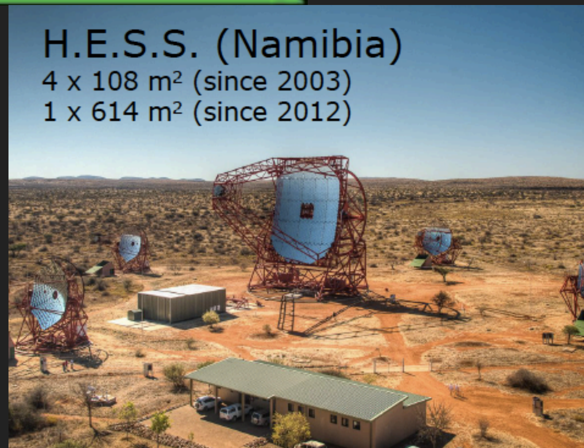
E > 10 GeV
(3FHL Catalog)
1558 sources
1242 associated
1223 AGN

E ~ 1 TeV
198 sources
150 associated
70 AGN

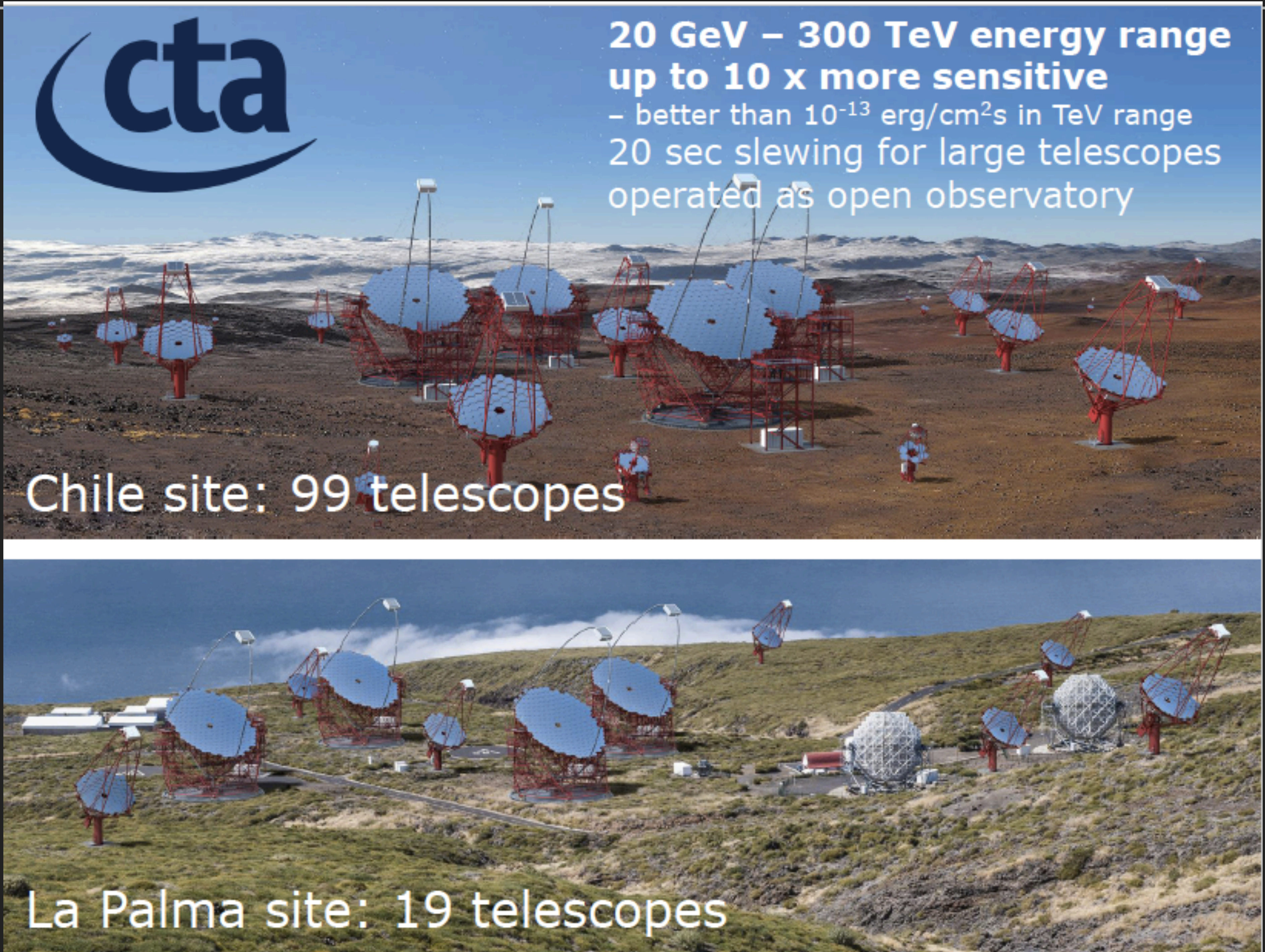
TWO MAJOR TECHNIQUES TO DETECT GAMMA-RAYS AT GROUND

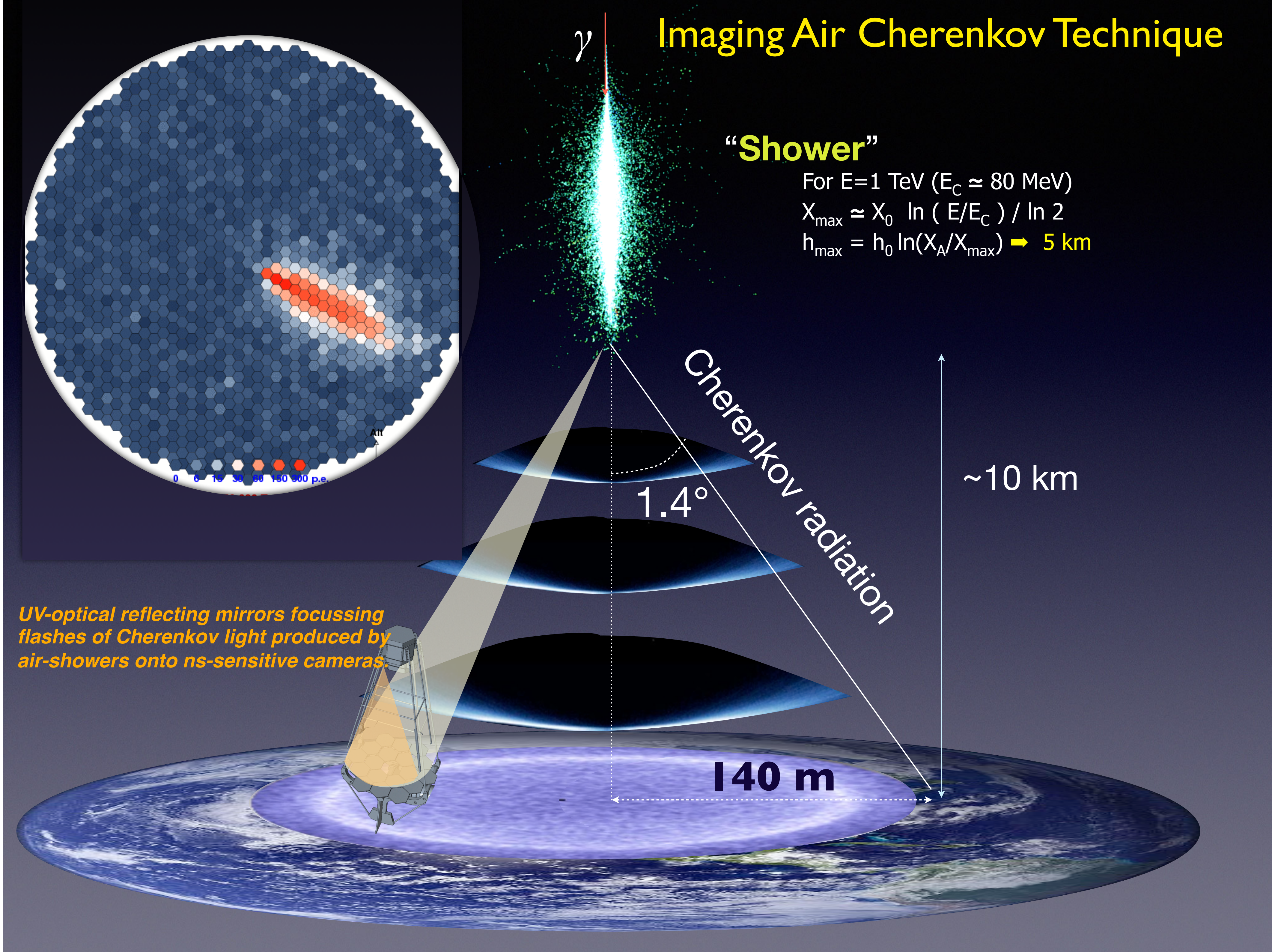




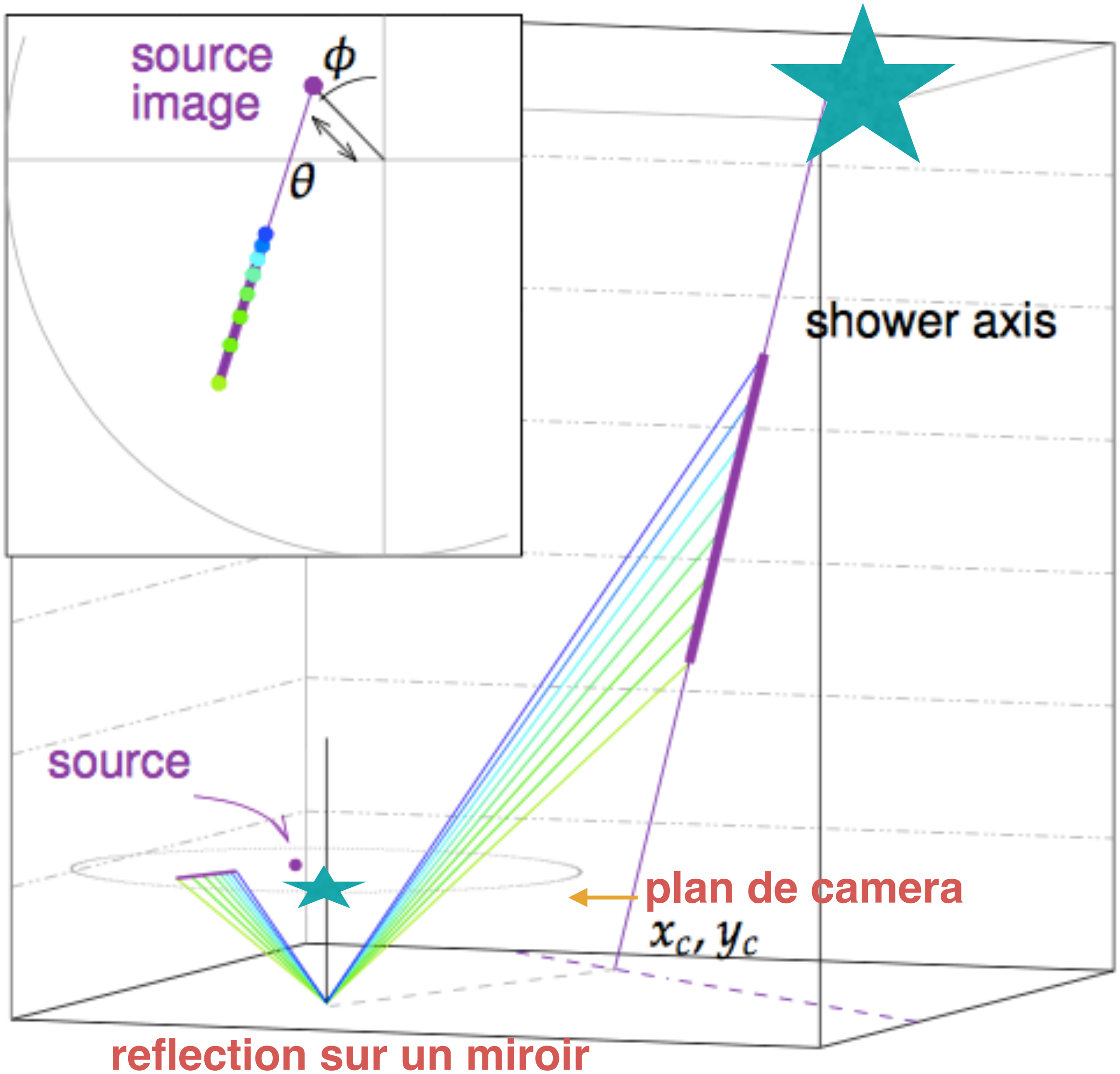


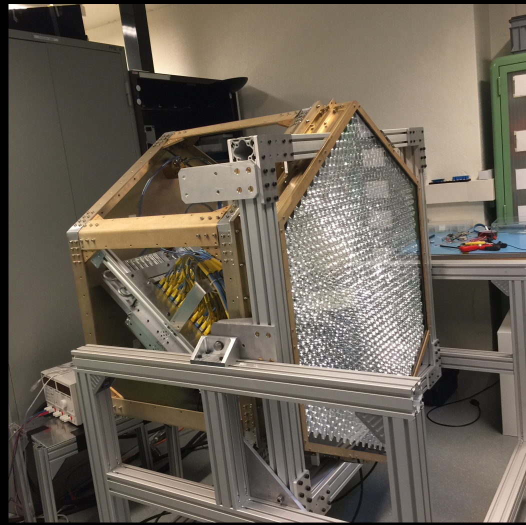
THE NEW GENERATION TEV GAMMA-RAY OBSERVATORY




Imaging Air Cherenkov Technique
γ
"Shower"
For E=1 TeV ($E_C \simeq$ 80 MeV)
$X_{max} \simeq X_0 \ \ln (E/E_C) / \ln 2$
$h_{max} = h_0 \ln(X_A/X_{max})$ ➡ 5 km
Cherenkov radiation
1.4°
~10 km
140 m
0 6 15 30 60 150 300 p.e.
Alt
UV-optical reflecting mirrors focussing flashes of Cherenkov light produced by air-showers onto ns-sensitive cameras.

IACT detection in detail

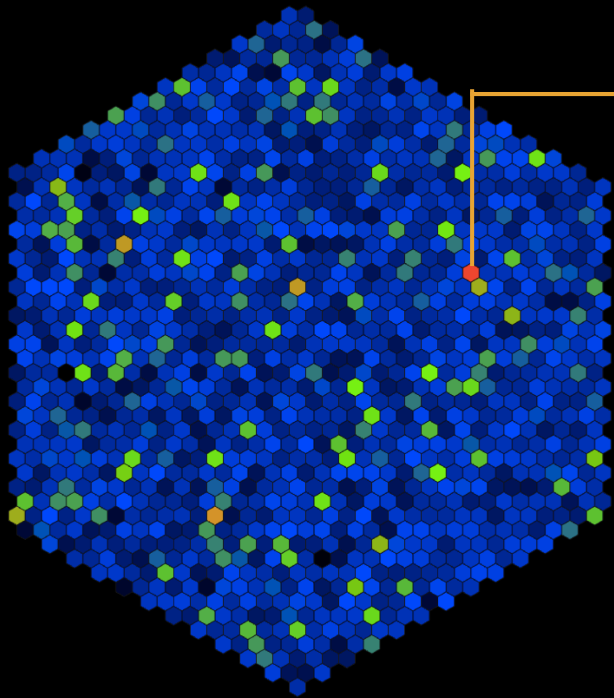




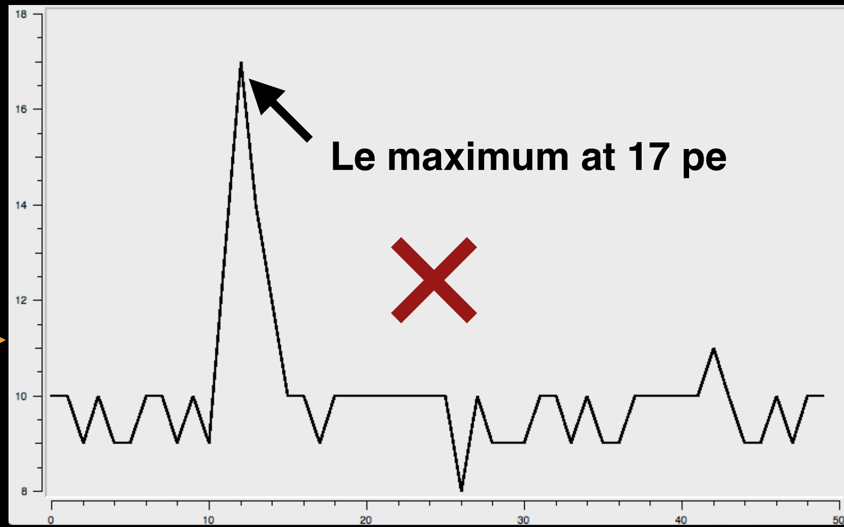
- the camera images the shower piece by piece on hit pixels with ns precision
- we can reconstruct where is the **source of gamma-rays** !
- With more than a telescope, **the precision on the position** of the source improves

A camera at night

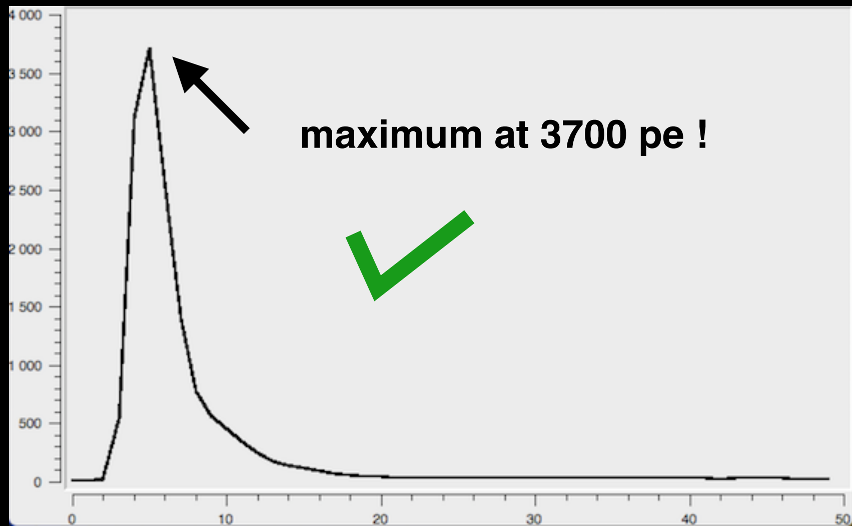
- How we can have a clear signature from gamma-rays on top of the noise?
  - ➡ It is enough to set a threshold on the amplitude of signals

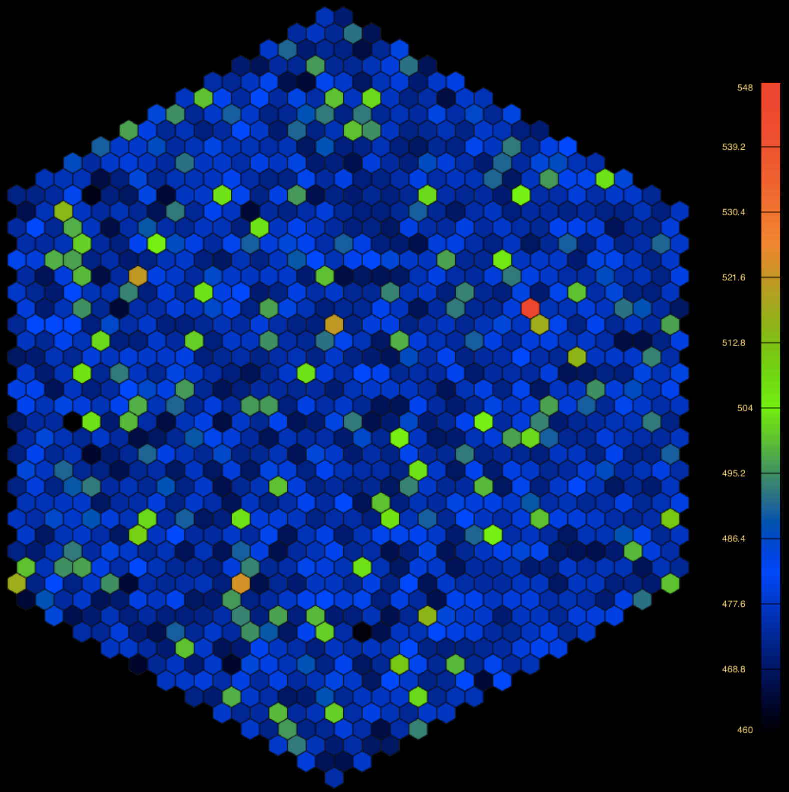


Signal of a pixel during a night with moon

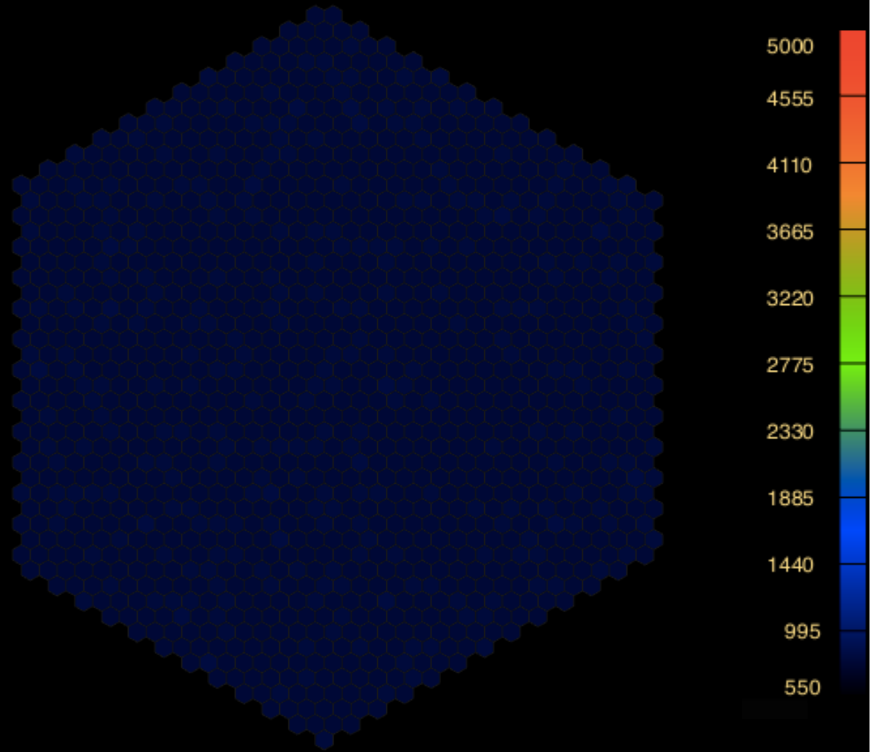


Signal with photons





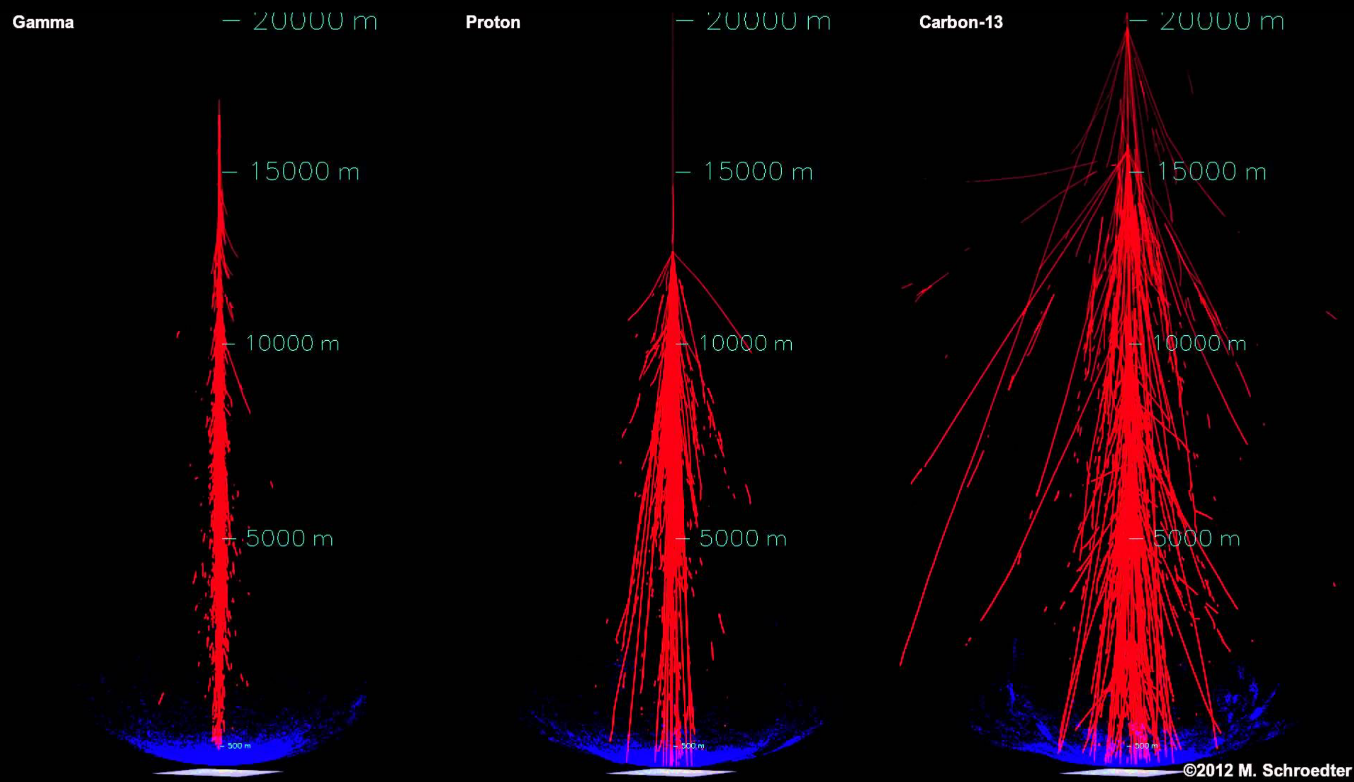
Threshold:
pe> 550



The noise is totally reduced!

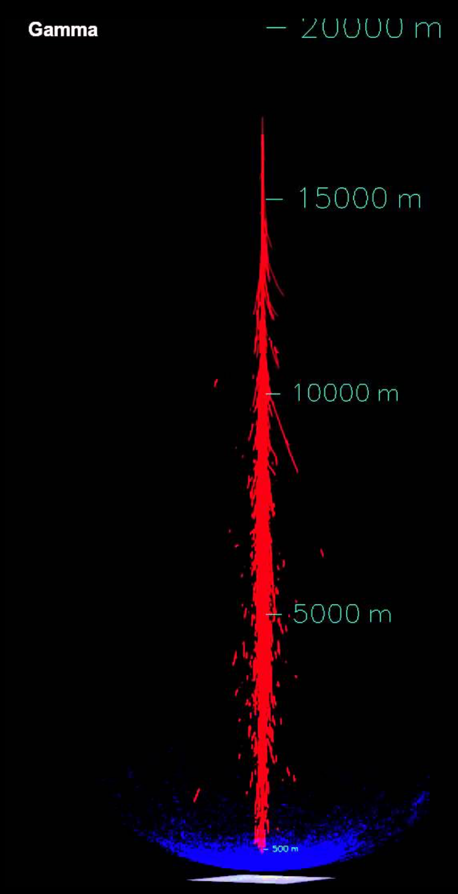
Can we identify gamma-rays?

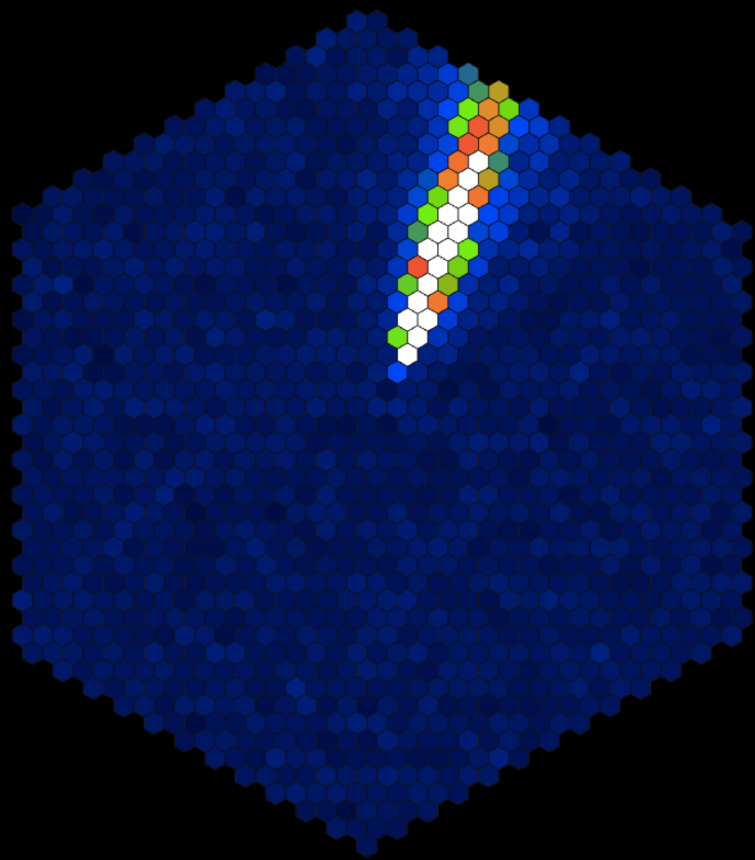
- ➡ It is not so simple….



- ➡ there are about 10^5 more cosmic ray hadronic showers,
- ➡ energy and inclination of showers affect them and when energy is low it is tough to have clear images
- ➡ the core of the shower (the Centre of Mass of the charge) can be close or far from the telescope

The signature of a gamma-ray

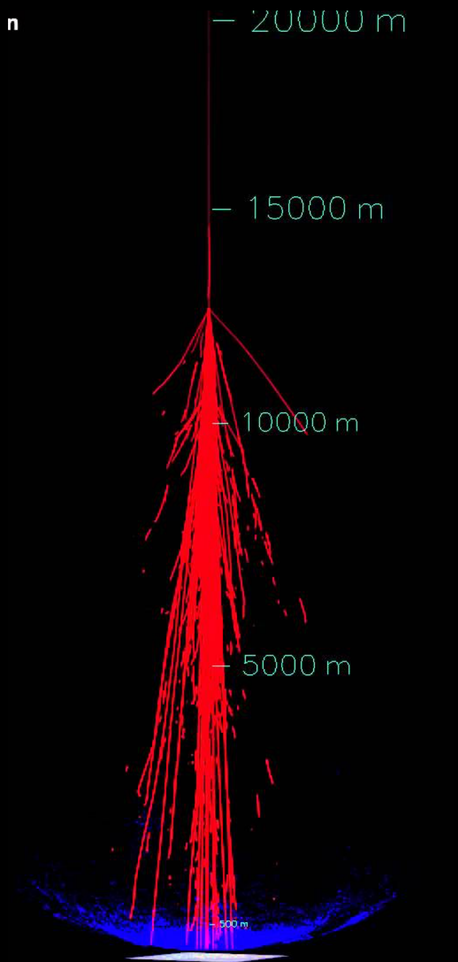


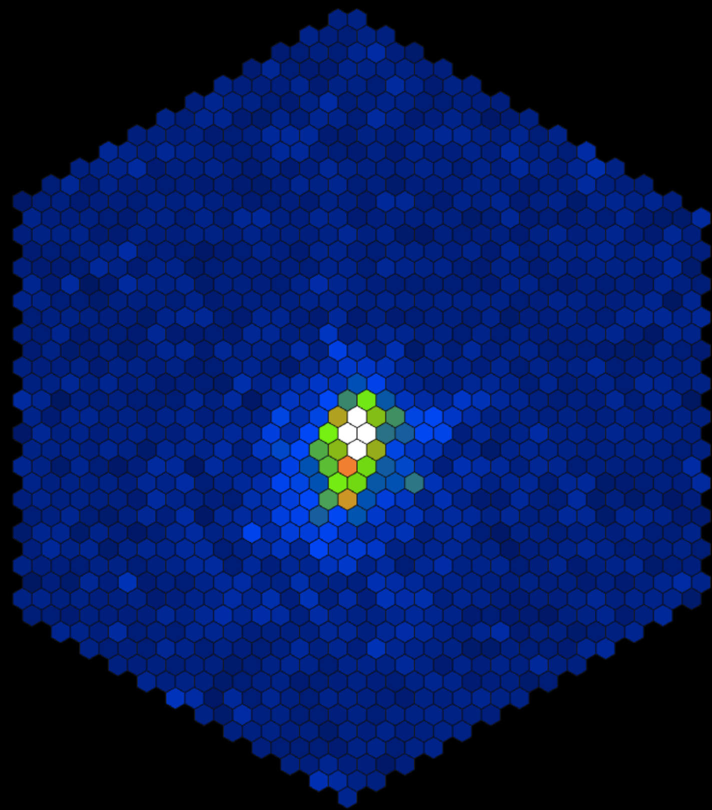


➡elongated shape

➡regular charge development

The signature of an hadron



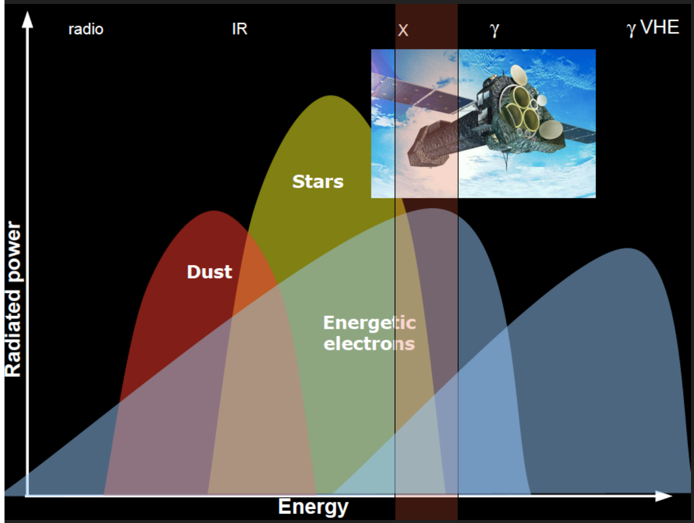


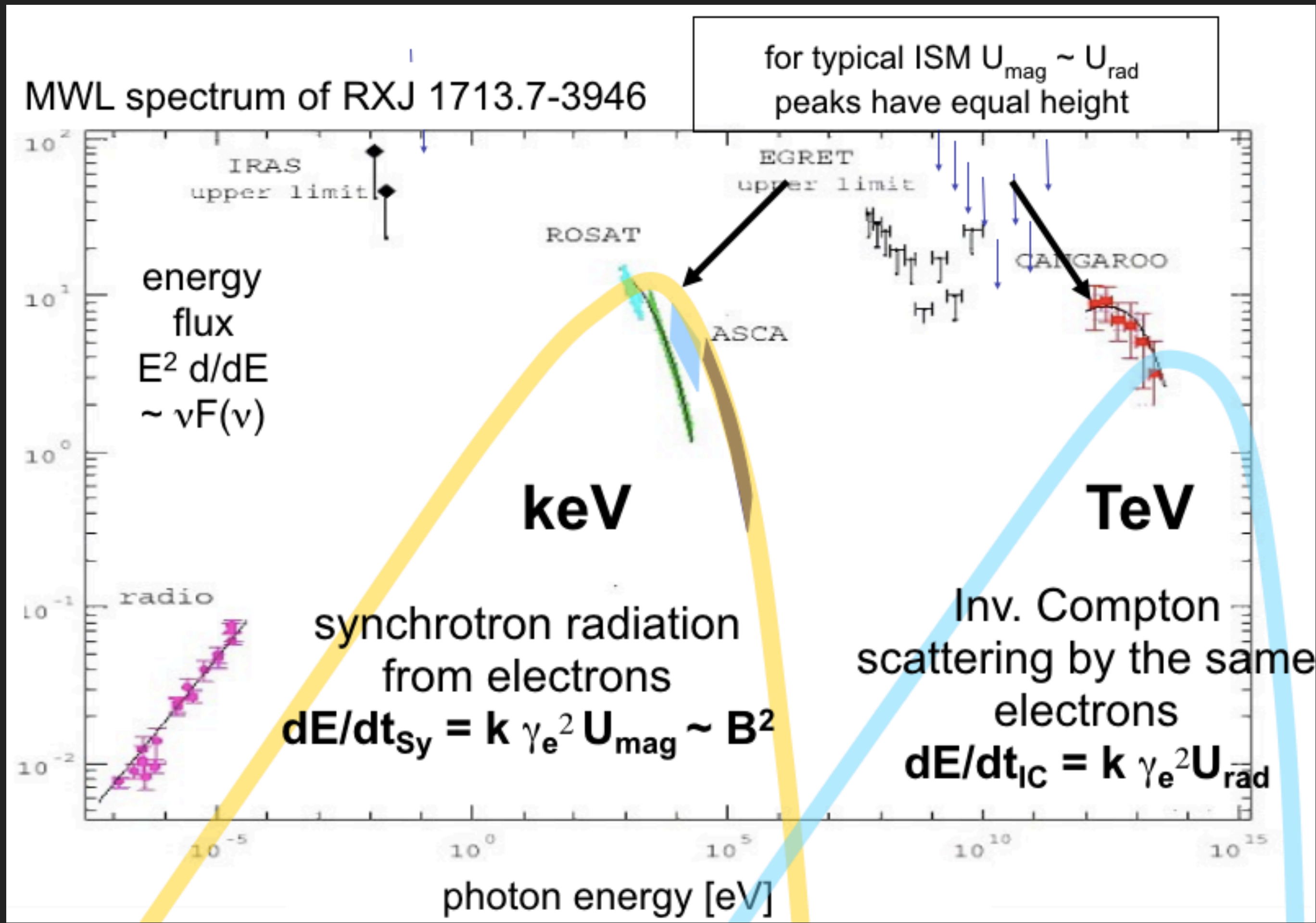
➡The development of the shower is sparse on the plane of te camera

➡The shape is more round and sometimes with sparse charge on far away pixels

➡not a preferential direction

THE SPECTRAL EMISSION FROM A TYPICAL ACCELERATOR: CRAB





THE 1ST ACCELERATION MECHANISM IN SN REMNANTS

- On of the features of the 1st order Fermi accelerator is to produce E^{-2} spectra maximum acceleration energy since the accelerator has finite lifetime T_A the

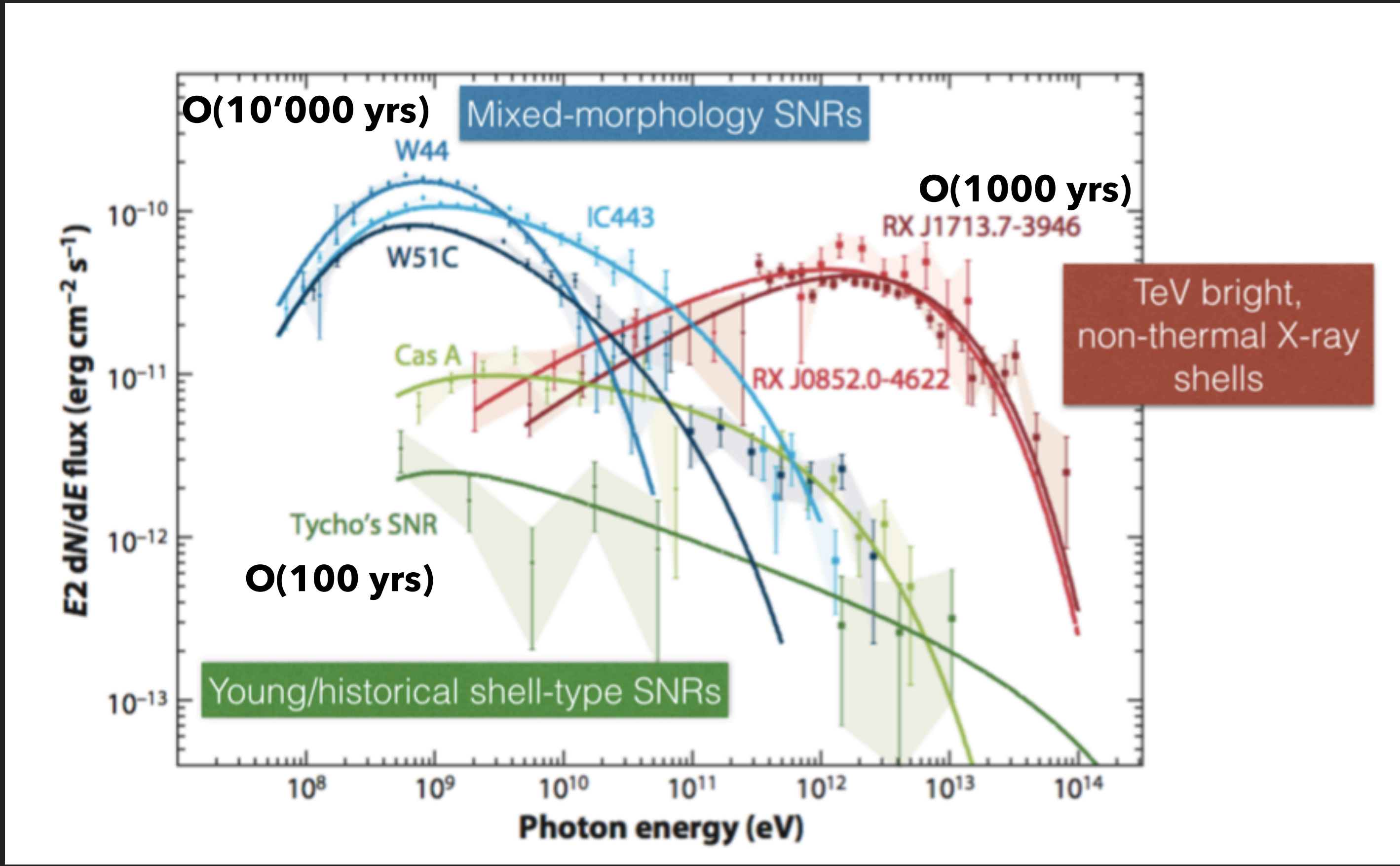
$$E \leq E_0(1+\xi)^{T_A/T_{cycle}}$$

T_{cycle}: time the particle takes to cross back and fourth the shock

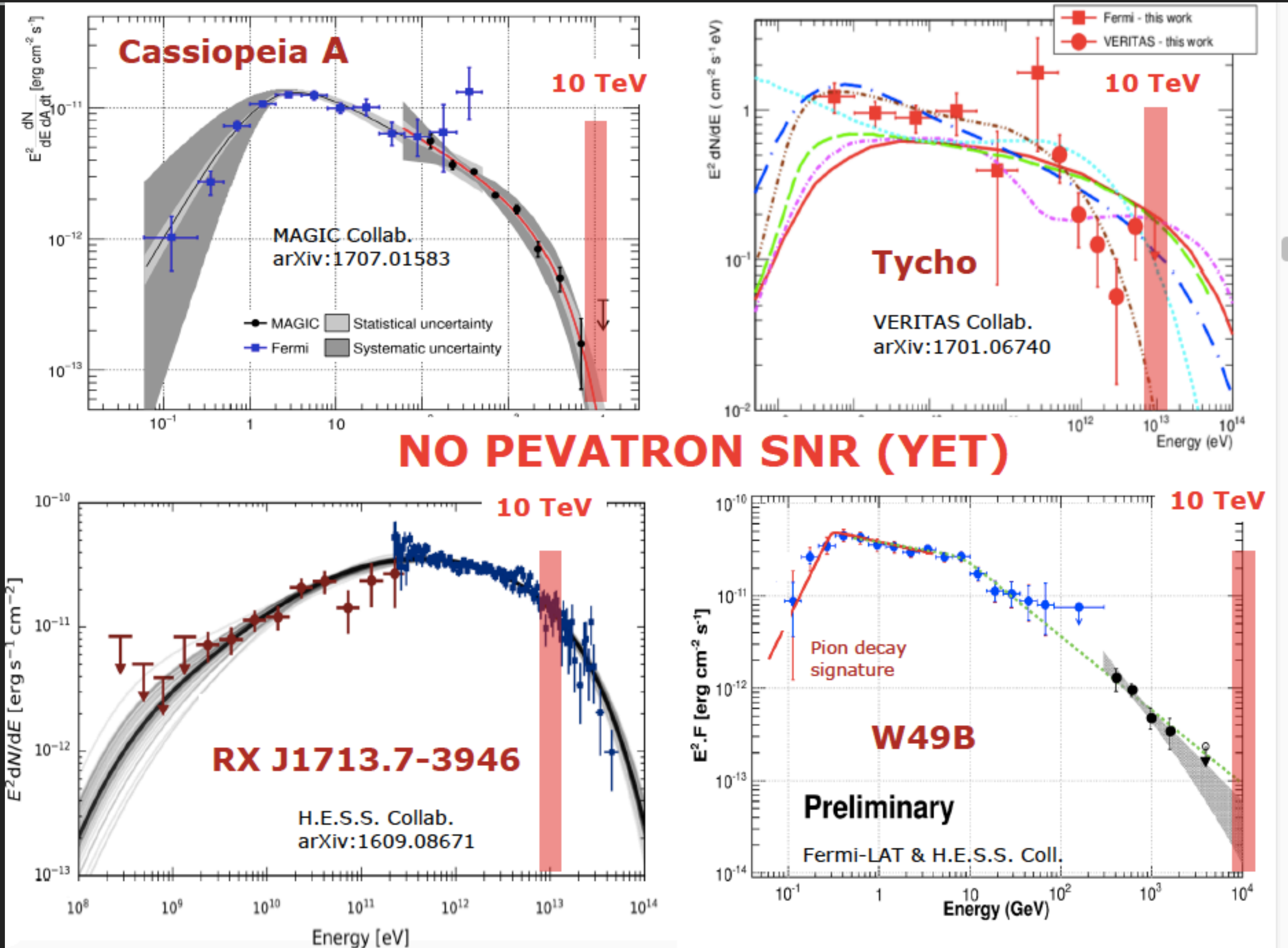
- For a SN the shock is an efficient accelerator until the density of ejecta becomes comparable to the density of ISM in the Galaxy (order of 100-1000 yrs) => E_{max} ~ 100 TeV x Z

- This energy is about an order of magnitude lower than the knee of ~3 PeV x Z… PROBLEM!

- SN efficiency is age dependent



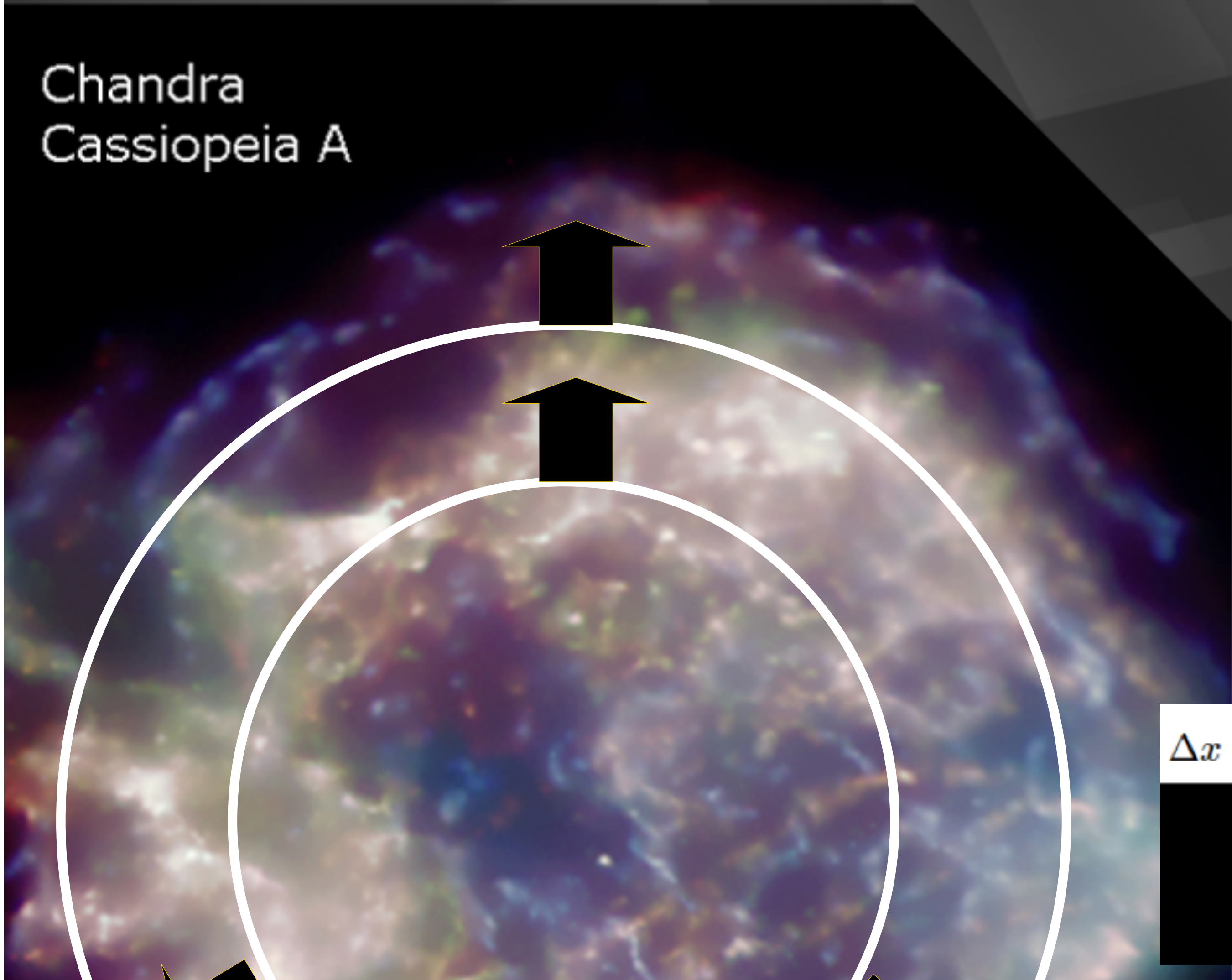
NOT YET A SNR PEVATRON OBSERVED BY GAMMA-RAY EXPERIMENTS

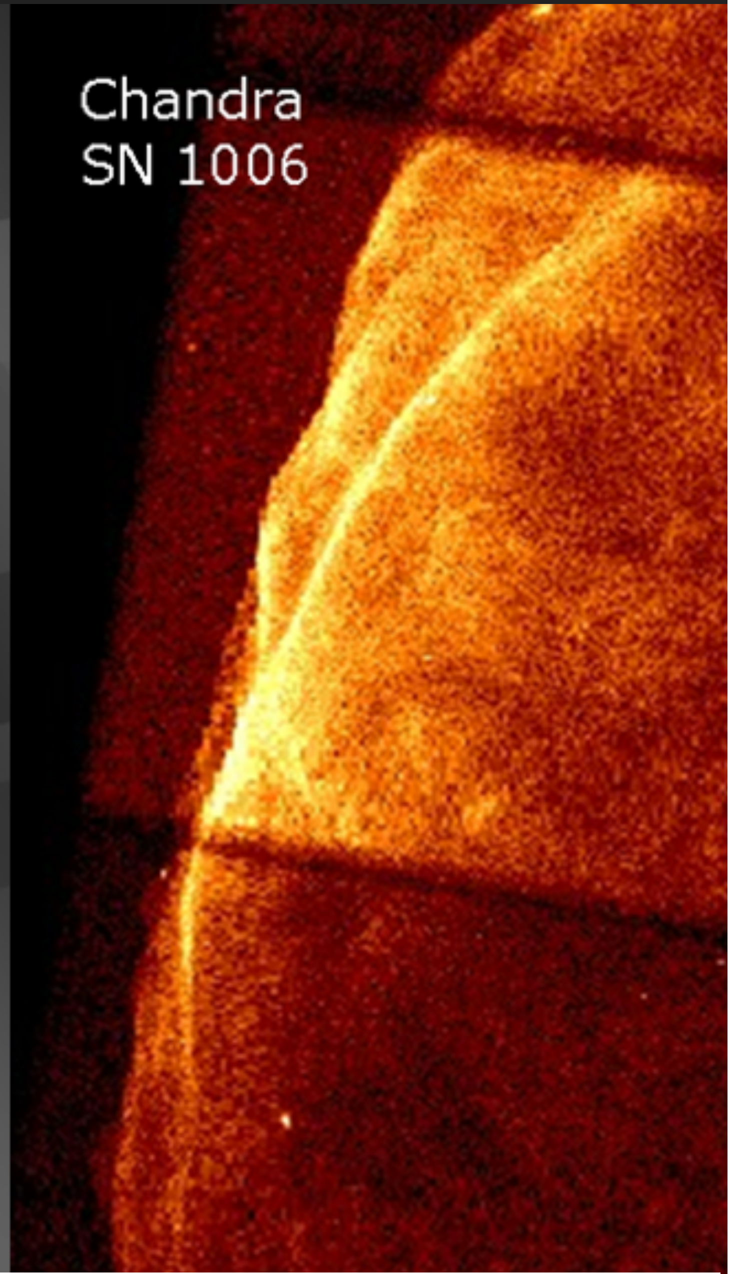


W. Hoffman, HEP-EPS 2017

BEYOND DSA

Non-linear DSA (dynamical connection between CRs being accelerated and the background plasma) is in agreement with observed filaments due to synchrotron emission of electrons of dimensions of 10^{-2} pc. They imply large B-fields of the order of 100 uG



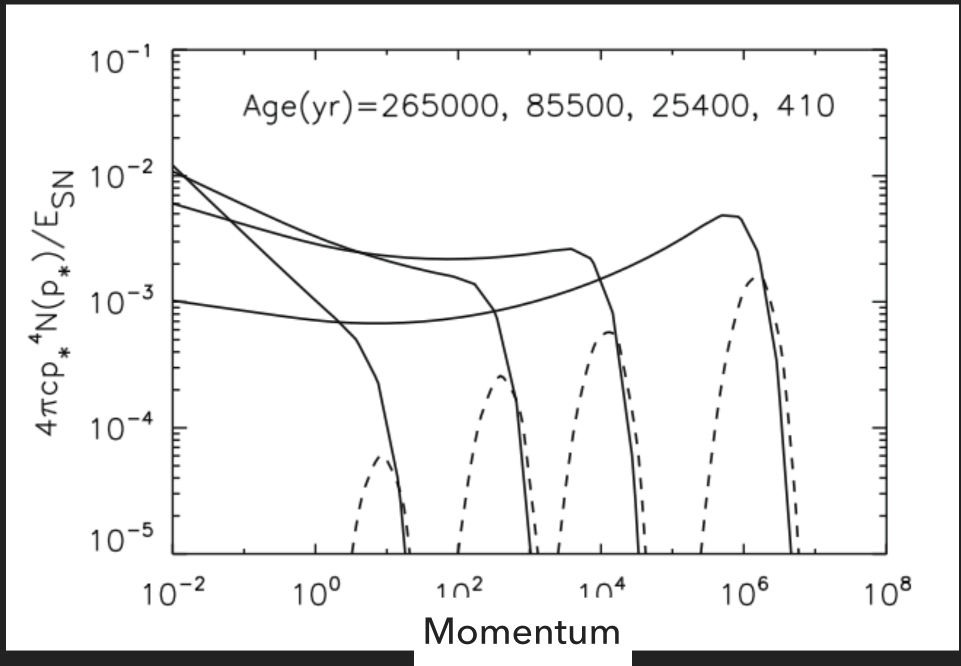


$$\Delta x \approx \sqrt{D(E_{max})\tau_{loss}(E_{max})} \approx 0.04\ B_{100}^{-3/2}\ \mathrm{pc}$$

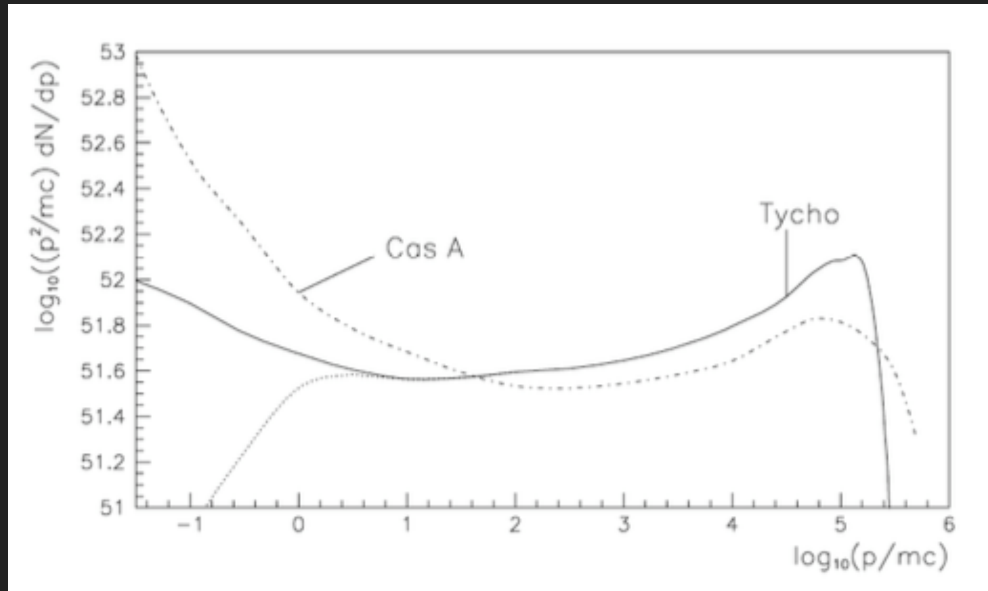
$$B \approx 100\ \mu\mathrm{Gauss}$$

SPECTAL DISAGREEMENT WITH DSA

- Observed spectra are softer than what predicted by DSA (E^{-2}) and on-linear DSA (concave shape)



D. Caprioli et al. / Astroparticle Physics 33 (2010) 160–168



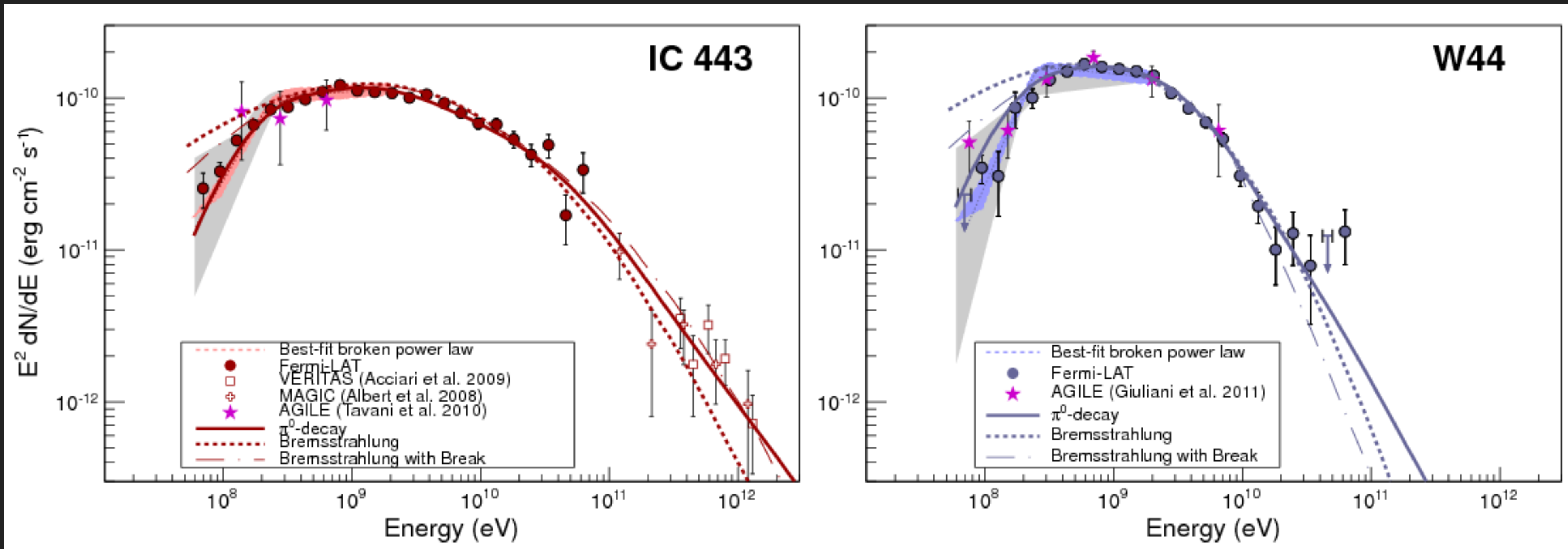
(Voelk *et al*, A&A396:649,2002)

- Alternative source scenarios are possible: BH PeVatron in the Galactic Centre (H.E.S.S. arXiv:1603.07730) being more efficient accelerator or superbubbles

http://www.nature.com/nature/journal/v460/n7256/full/nature08127.html

THE TEV REGION

- In this region it is possible to identify CR acceleration through precise measurements of spectra of cosmic accelerators or the detection of astrophysical neutrinos from a source



$$p\, p_{\mathrm{ISM}} \rightarrow \pi^0 \rightarrow \gamma\gamma$$

Ackermann et al. (Fermi Collaboration), Science, 339, 807 (2013)

SOME NEUTRINO ASTRONOMY HISTORICAL HINTS

1965: F. Reines detects neutrino with Cherenkov technique in South African mine

Neutrino telescope concept birth

Ann.Rev.Nucl.Sci 10 (1960) 63

COSMIC RAY SHOWERS[1]

By Kenneth Greisen

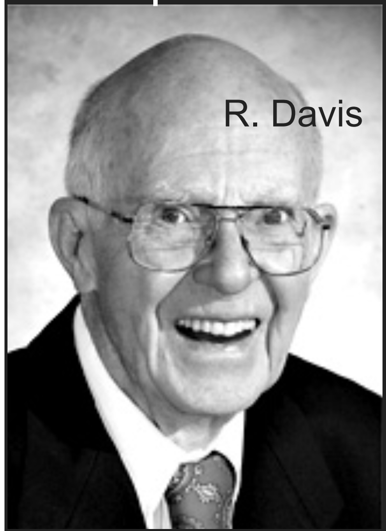
Let us now consider the feasibility of detecting the neutrino flux. As a detector, we propose a large Cherenkov counter, about 15 m. in diameter, located in a mine far underground. The counter should be surrounded with photomultipliers to detect the events, and enclosed in a shell of scintillating material to distinguish neutrino events from those caused by μ mesons. Such a detector would be rather expensive, but not as much as modern ac-

Fanciful though this proposal seems, we suspect that within the next decade, cosmic ray neutrino detection will become one of the tools of both physics and astronomy.

M.Markov,1960: We propose to install detectors deep in a lake or in the sea and to determine the direction of charged particleswith th e help of Cherenkov radiation. Proc. 1960 ICHEP

NOBEL PRIZE WINNERS IN THE NEUTRINO SECTOR

Nobel prize 2002



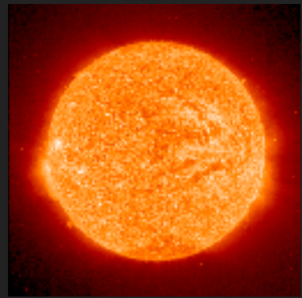
Oscillations with neutrinos from thermonuclear reactions in the Sun

~ 6 x 10^{10} νs per cm^2 per s^1 with E_ν~ 0.1 – 20 MeV

produced in thermonuclear reactions in the Sun

$$4p \rightarrow {}^4\text{He} + 2e^+ + 2\nu_e$$

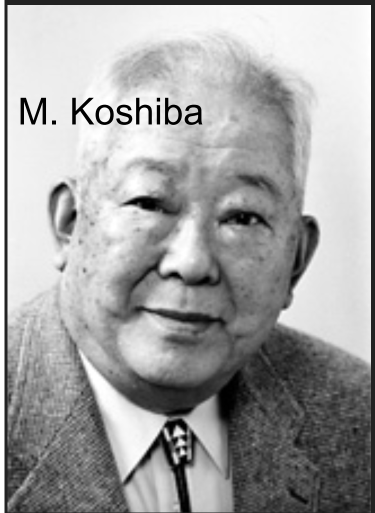
means ~ 100,000 billion solar neutrinos pass through your body/s



Nobel prize 2015

A.B. McDonald

T. Kajita



Supernova 1987A Neutrinos :

~ 10 s bursts of 10 MeV νs from stellar collapse

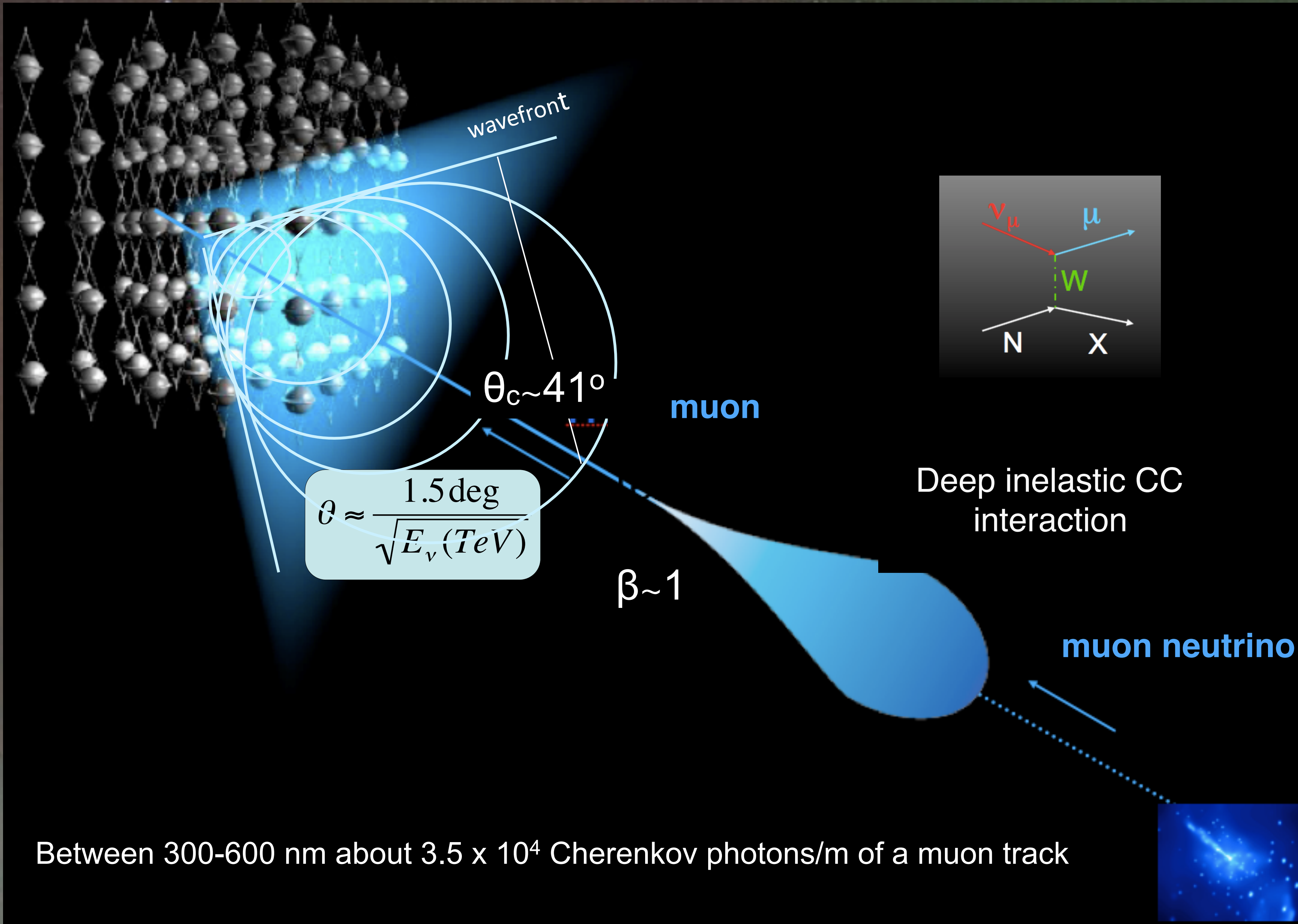
$$e^- + p \rightarrow n + \nu_e$$

$$e^- + e^+ \rightarrow \bar{\nu} + \nu$$

Nobel prize 2016

Oscillations with atmospheric neutrinos

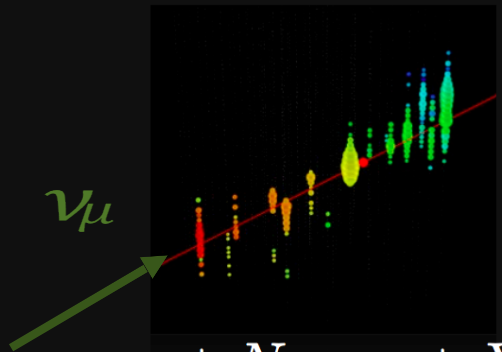
CHERENKOV NEUTRINO TELESCOPE DETECTION PRINCIPLE



Between 300-600 nm about 3.5 x 10^4 Cherenkov photons/m of a muon track

NEUTRINO TOPOLOGIES

CC Muon Neutrino

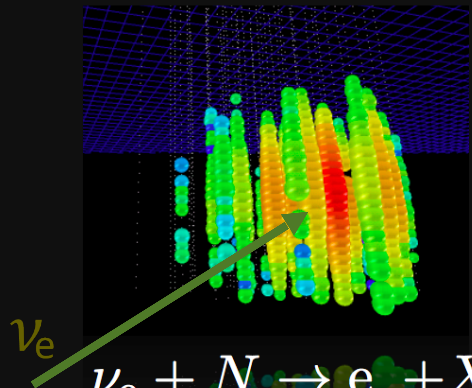


$$\nu_\mu + N \rightarrow \mu + X$$

track (data)

factor of ≈ 2 energy resolution
< 1° angular resolution

Neutral Current /Electron Neutrino



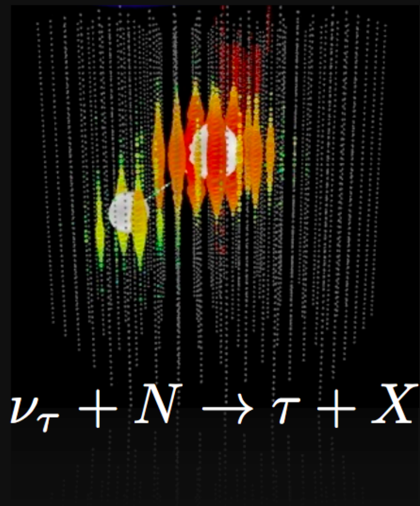
$$\nu_e + N \rightarrow e + X$$

$$\nu_x + N \rightarrow \nu_x + X$$

cascade (data)

≈ ±15% deposited energy resolution
≈ 10° angular resolution
(at energies > 100 TeV)

CC Tau Neutrino



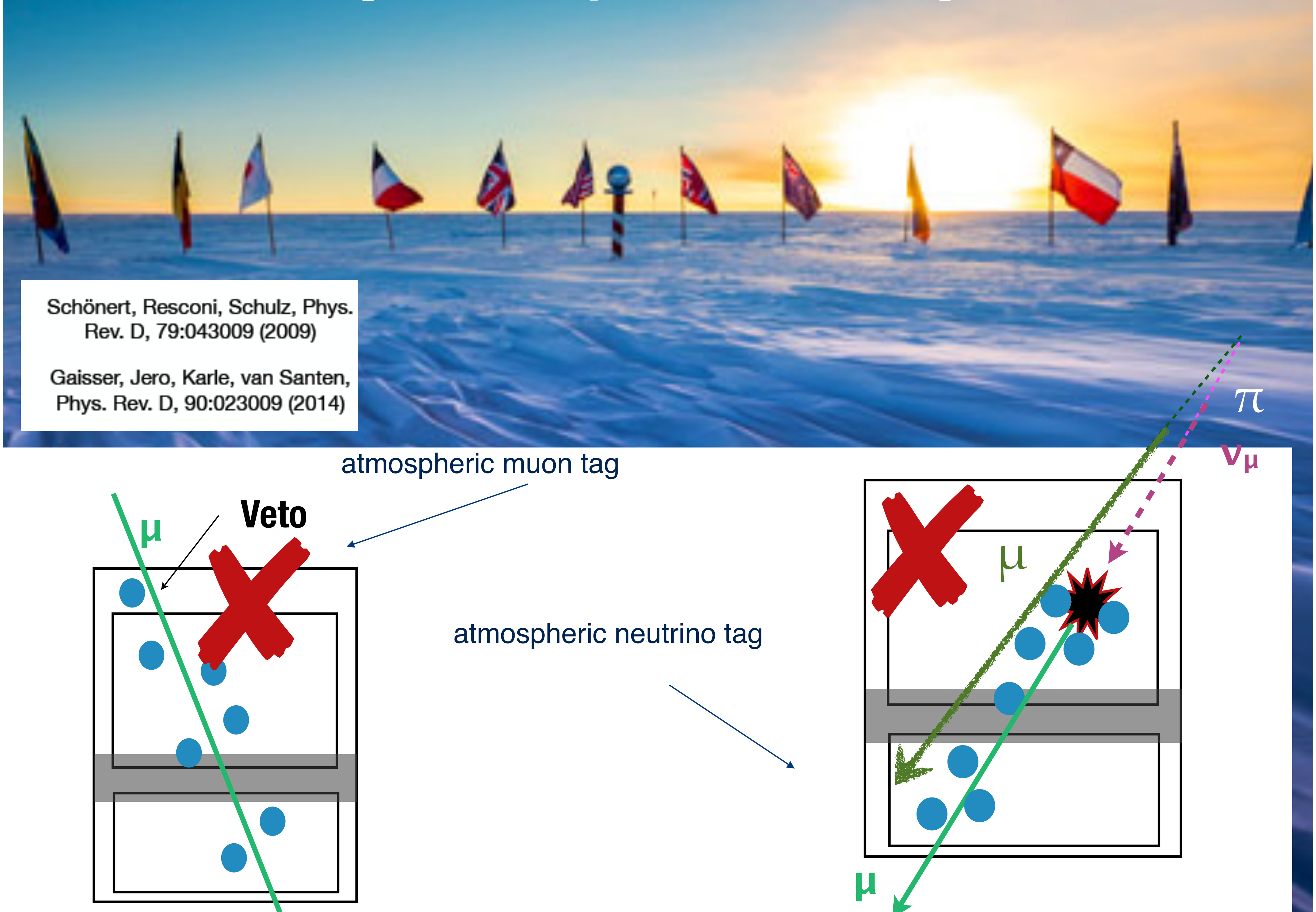
$$\nu_\tau + N \rightarrow \tau + X$$

"double-bang" and other signatures (simulation)

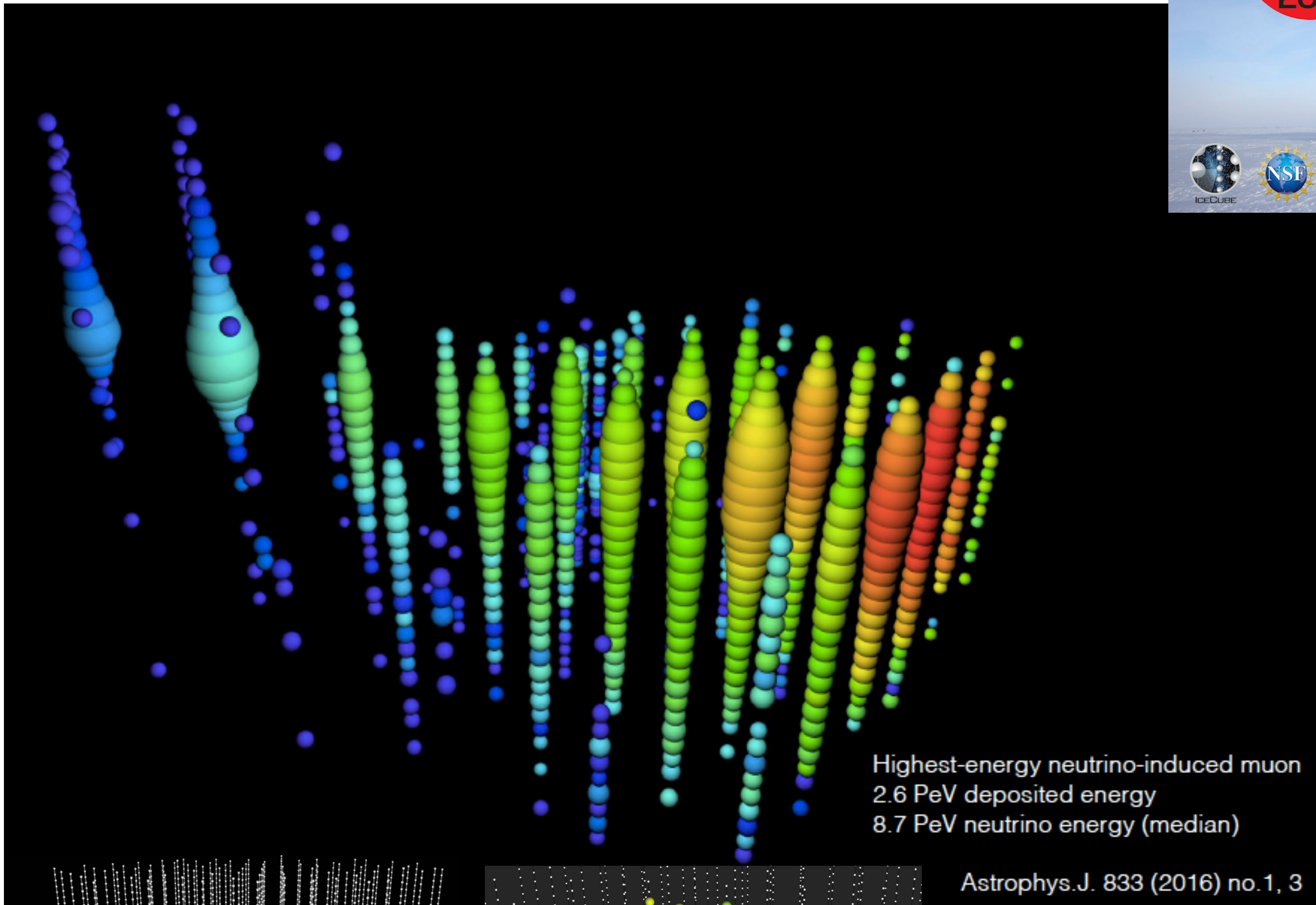
(not observed yet)

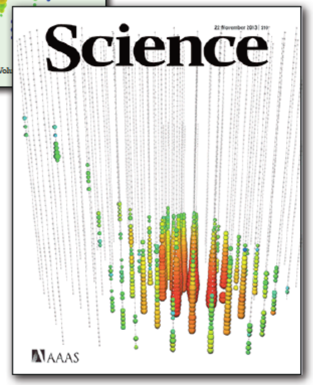
Martin Wolf, IceCube/NSF

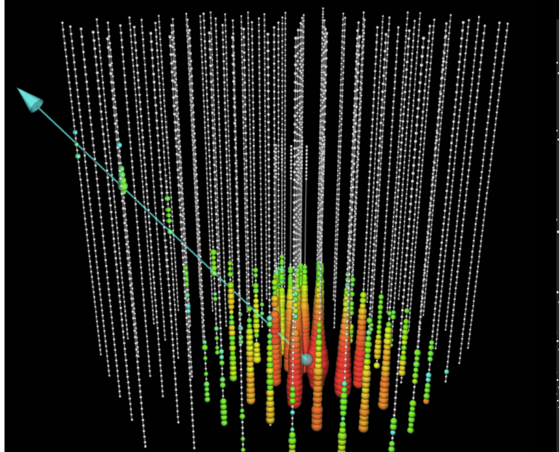
Vetoing atmospheric backgrounds

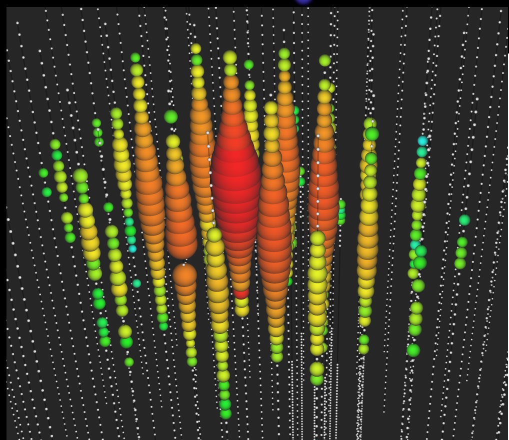


SIGNALS FROM THE HEAVENS







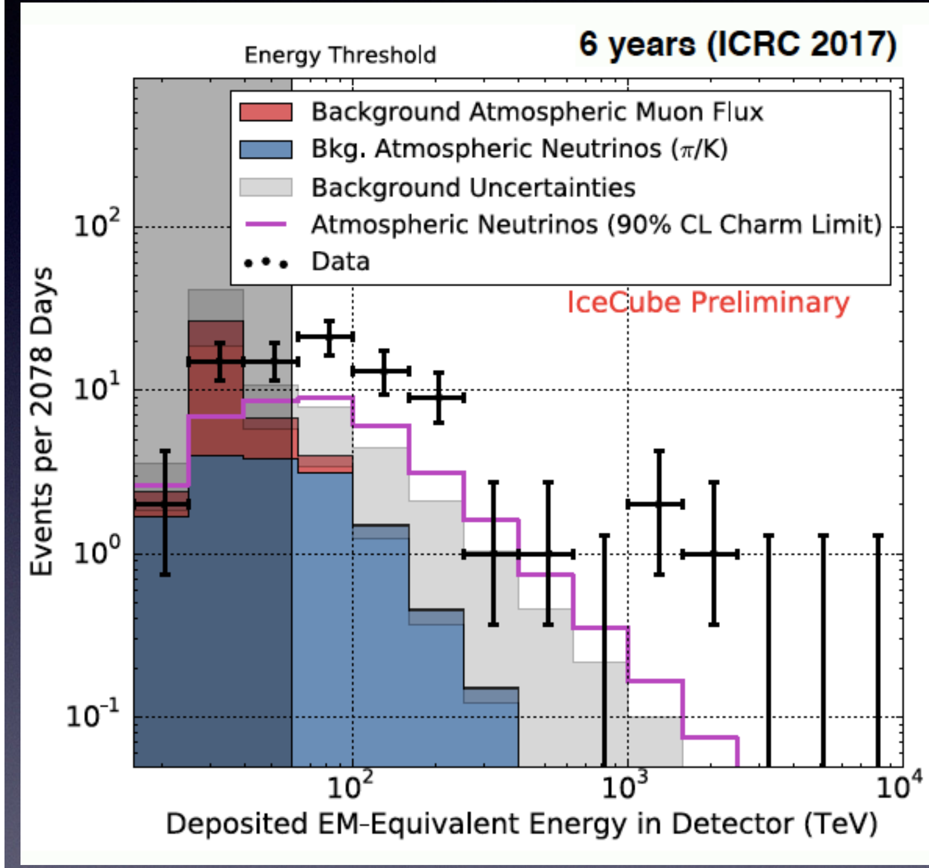


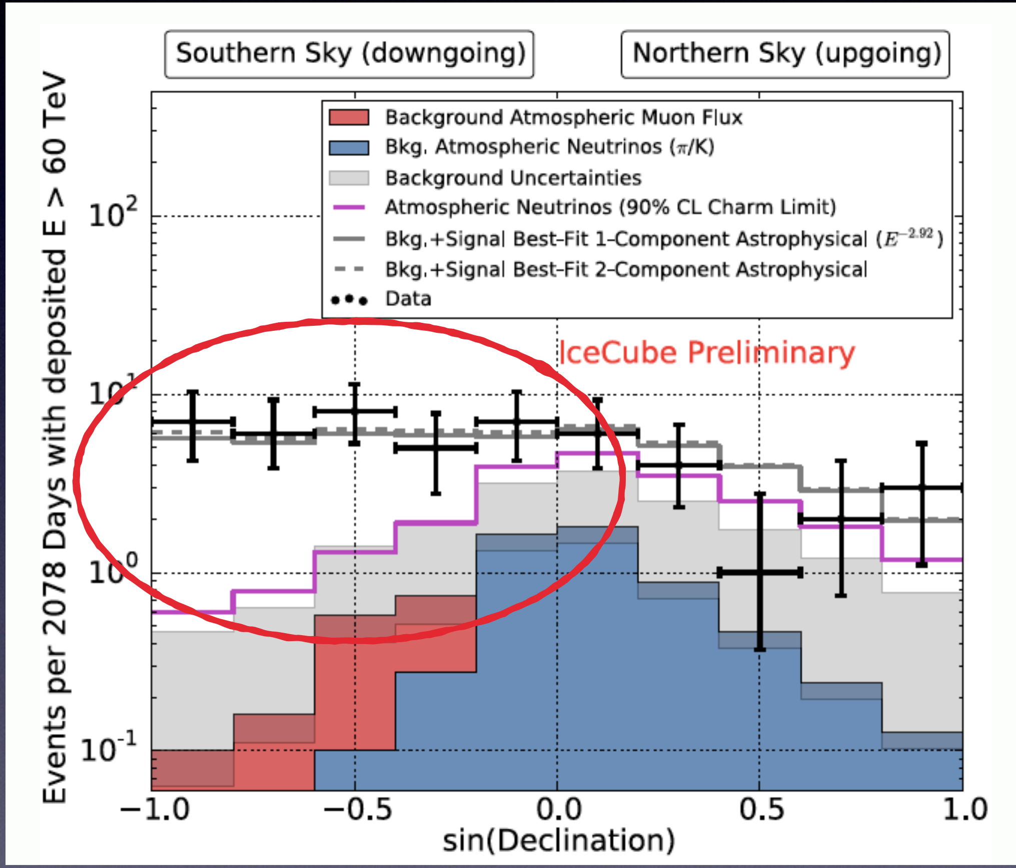
HIGH ENERGY STARTING EVENTS

Zenith distribution is incompatible with atmospheric neutrinos

82 events/6 yrs

Reminder: at south pole zenith = 90° - declination





The real voyage of discovery consists not in seeking new landscapes, but in having new eyes. ***(Marcel Proust)***