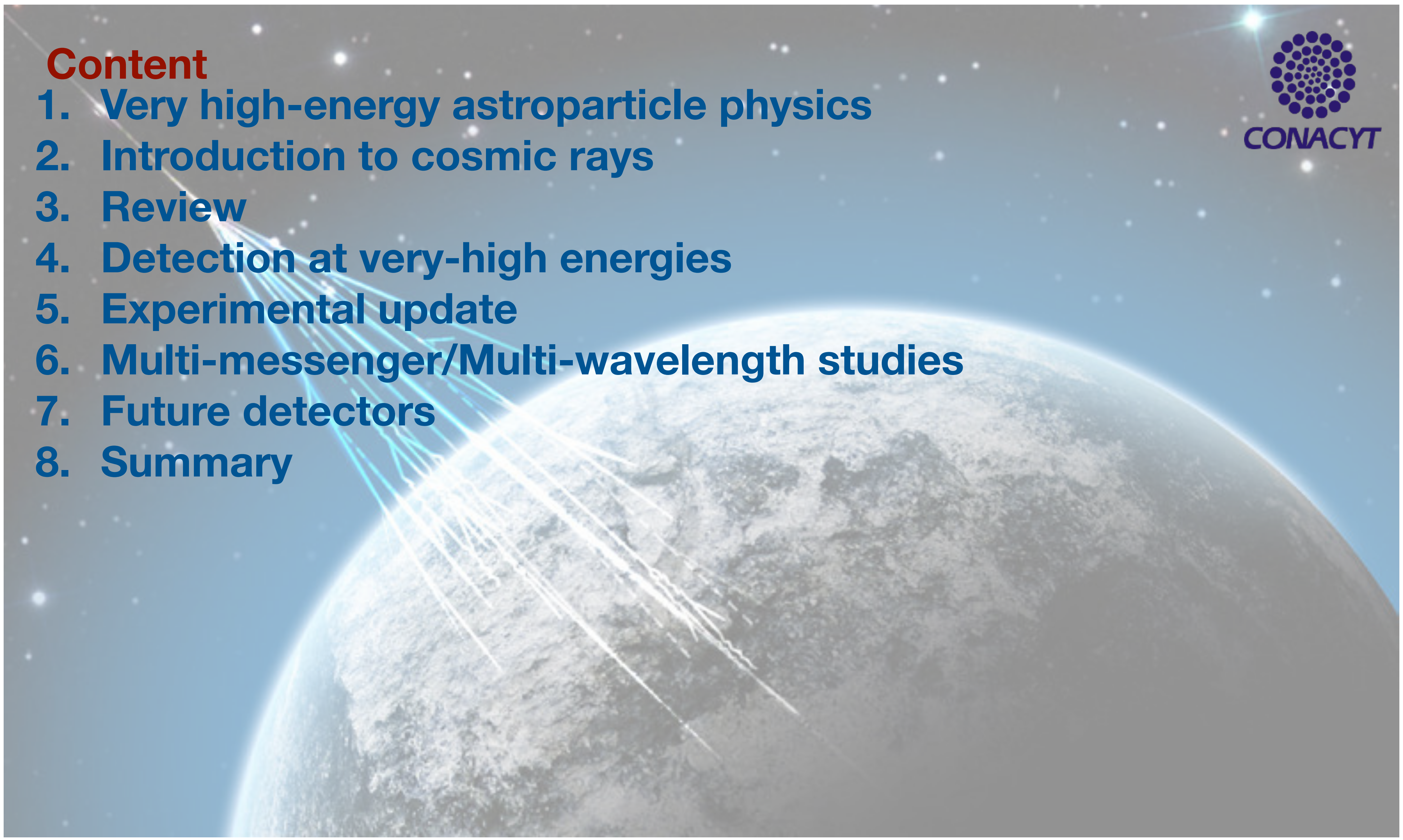
Cosmic rays from 100 TeV up to the EeV regime: a review

J.C. Arteaga-Velázquez

Instituto de Física y Matemáticas, Universidad Michoacana
Morelia, Michoacan, Mexico

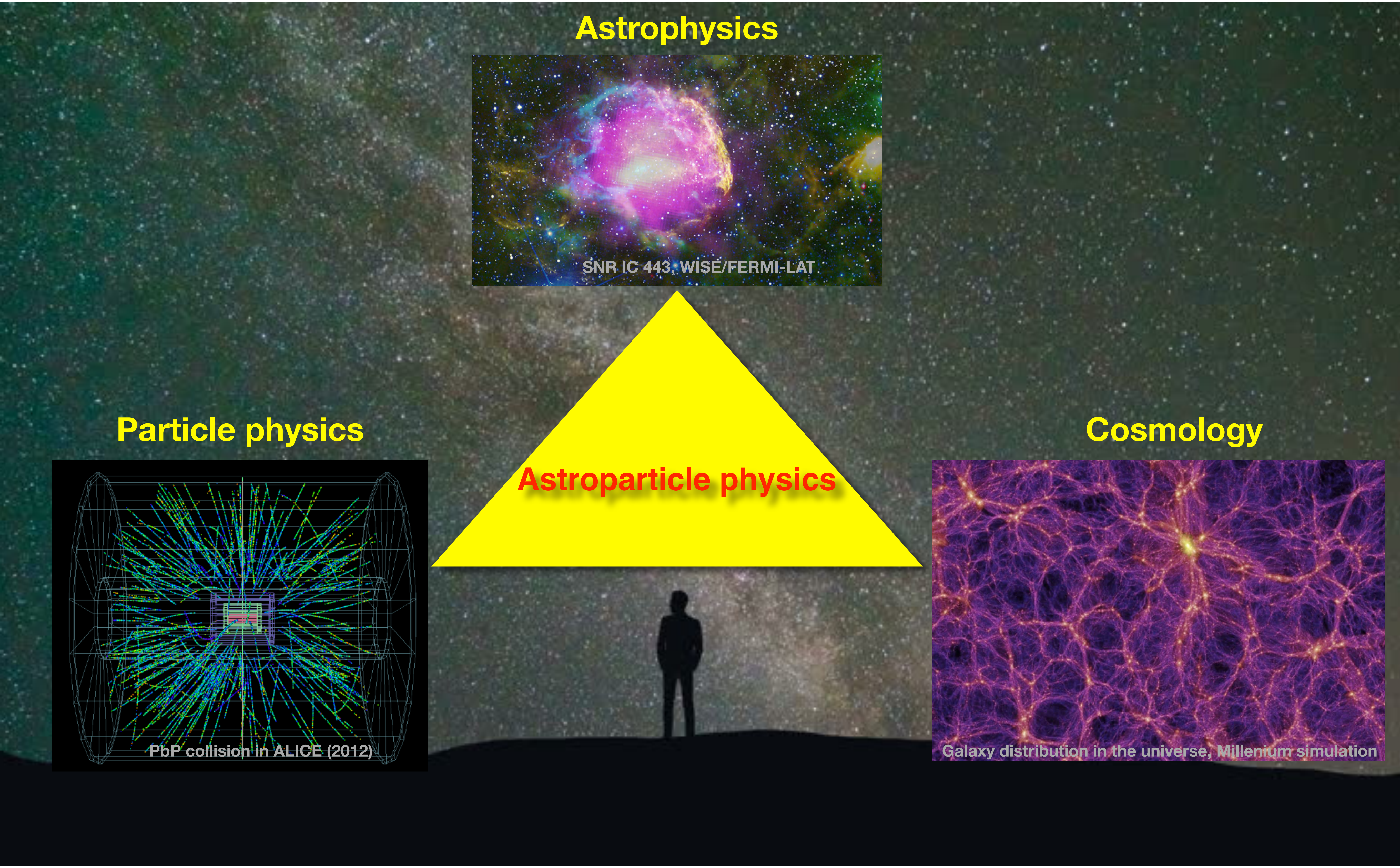


Content

1. Very high-energy astroparticle physics
2. Introduction to cosmic rays
3. Review
4. Detection at very-high energies
5. Experimental update
6. Multi-messenger/Multi-wavelength studies
7. Future detectors
8. Summary

1. Very-high energy astroparticle physics

The astroparticle physics field



Areas of research

High energy (> 10^6 eV) astroparticle physics:

Windows to the most energetic phenomena in the universe

Particle cosmology

Cosmic rays

High-/low-energy neutrinos

Gamma-ray astronomy

Cosmic abundances

Dark matter

Dark energy

Gravitational waves

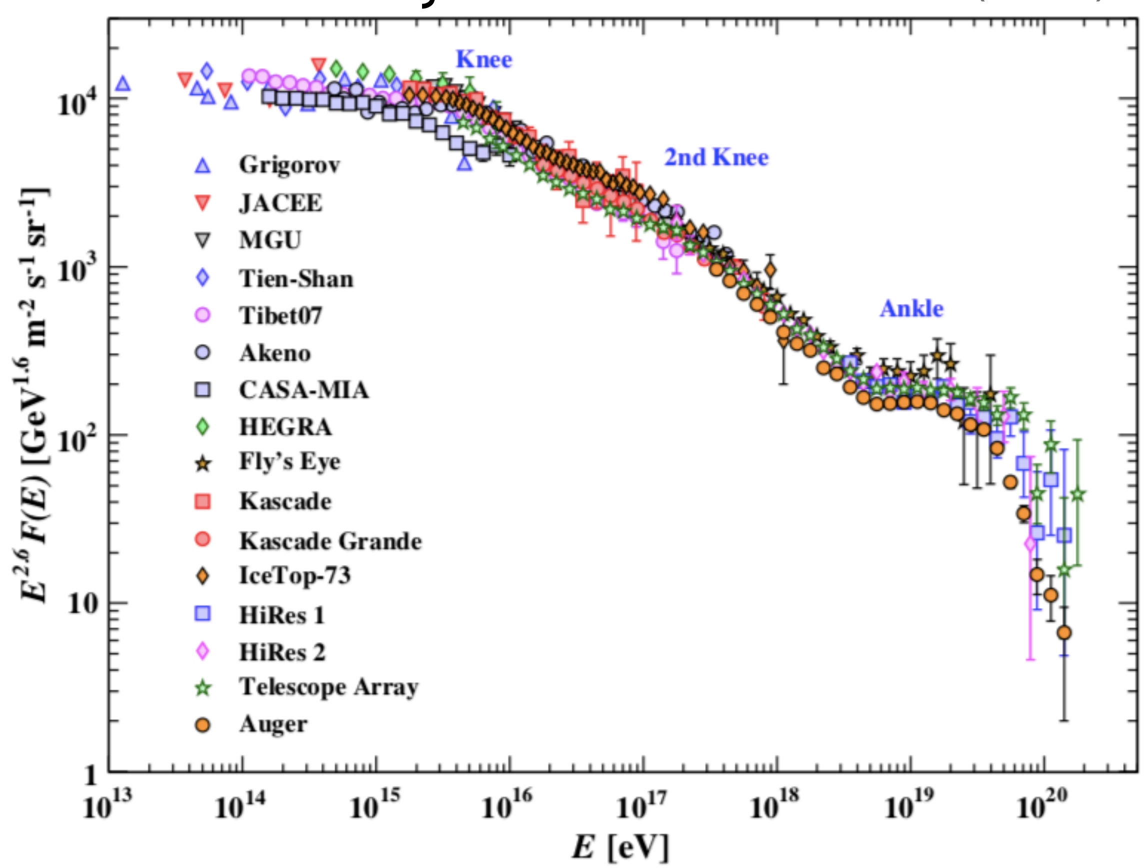
Structure of the universe

Nonthermal sources (Supernova, AGN, GRB,…)

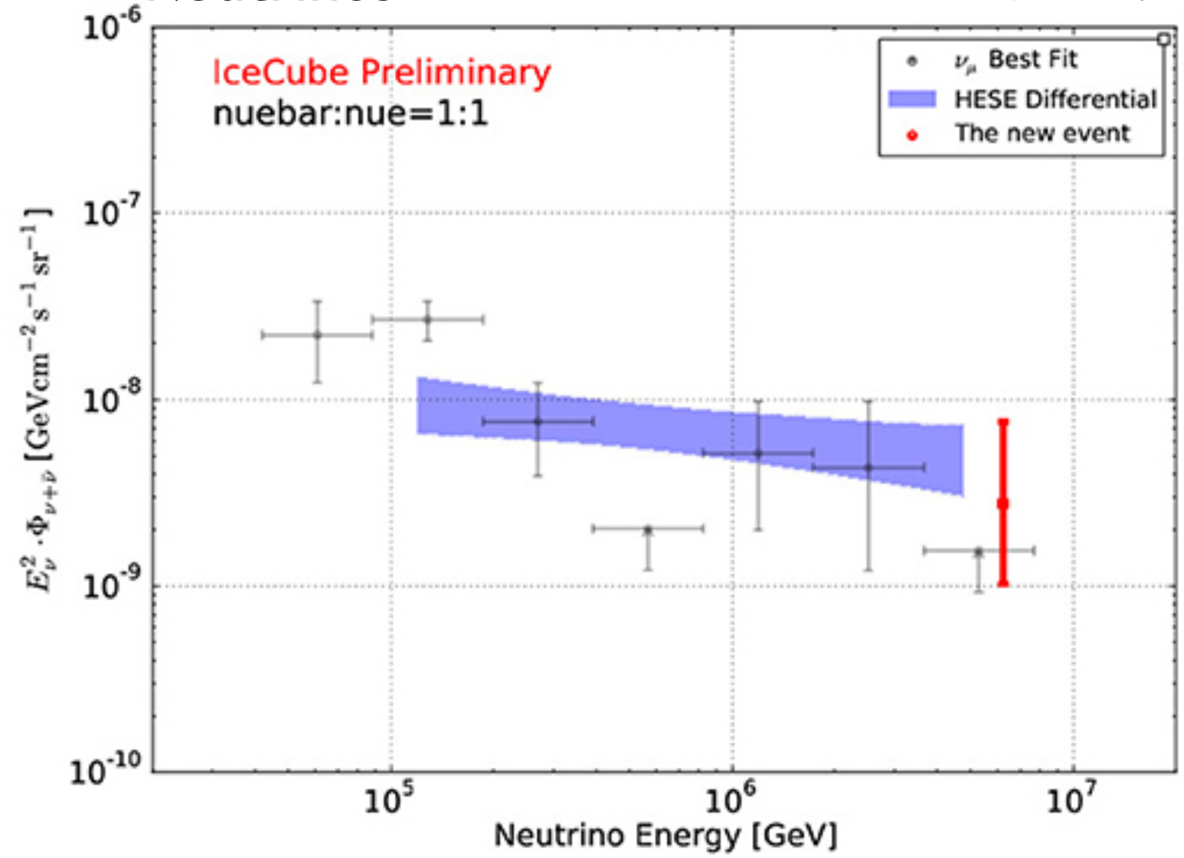
Beyond standard model

Very-high energy astroparticle physics

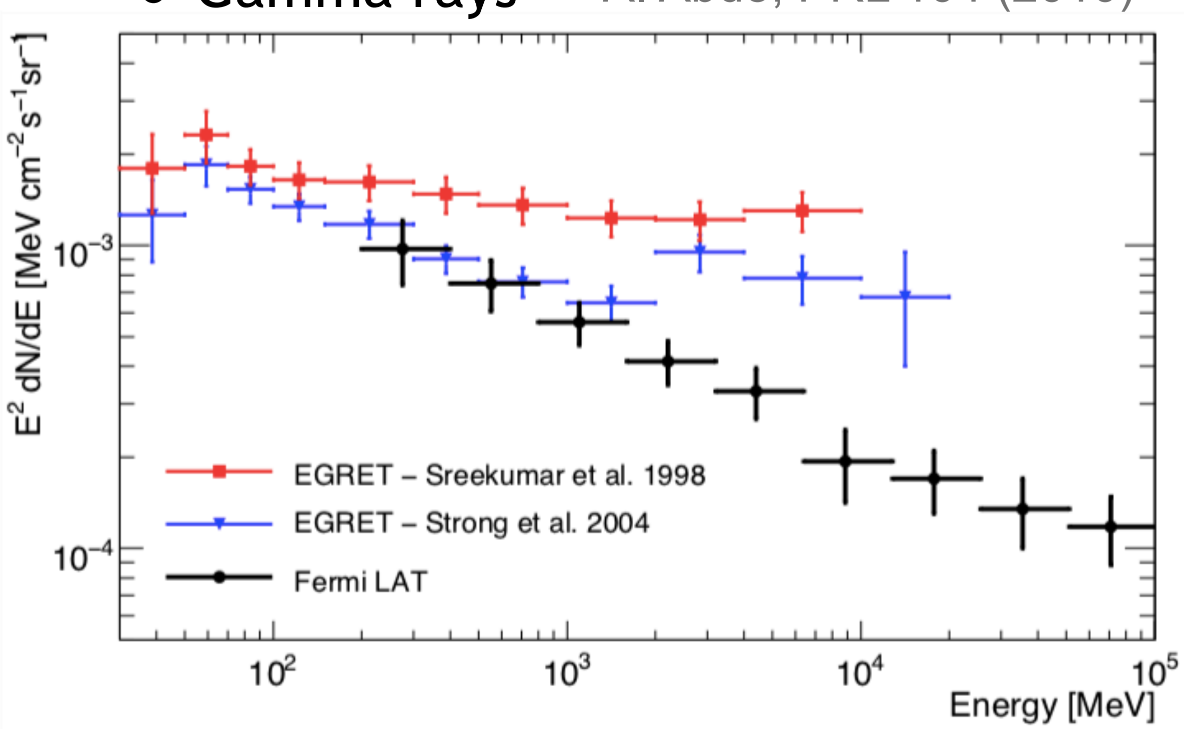
- Cosmic rays PDG (2018)



- Neutrinos F. Halzen et al., Front. Astro. Sp. Sci. (2019)



- Gamma rays A. Abdo, PRL 104 (2010)

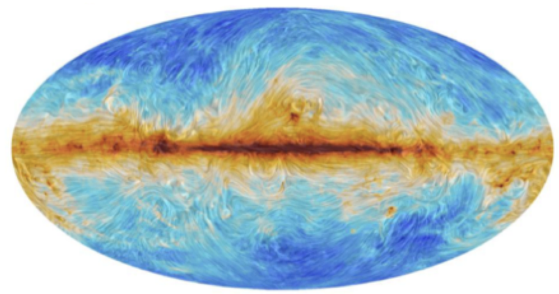


- Spectra of high energy cosmic rays, gamma rays and neutrinos follow power-law functions.

Spectra are not of thermal origin

Very-high energy astroparticle physics

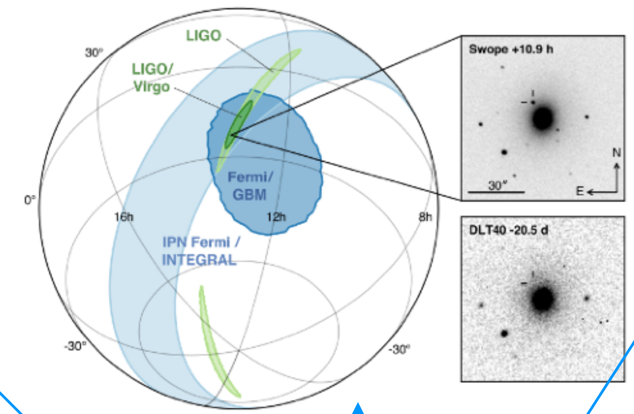
- Constrain models of the galactic and local magnetic field



Cabral&Leedom(1993)

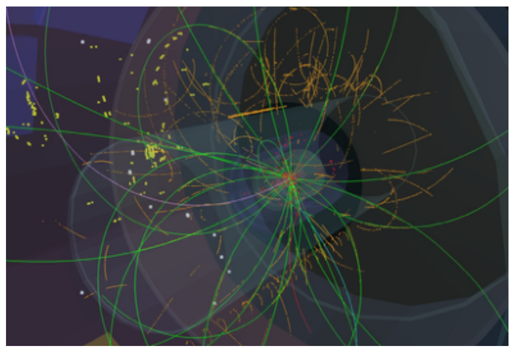
All-sky view of the magnetic field and total intensity of dust emission measured by Planck (ESA)

- Search for HE counterparts.



LIGO/VIRGO/FERMI-LAT

- Test hadronic interactions at energies and regions of phase space not available to current particle accelerators

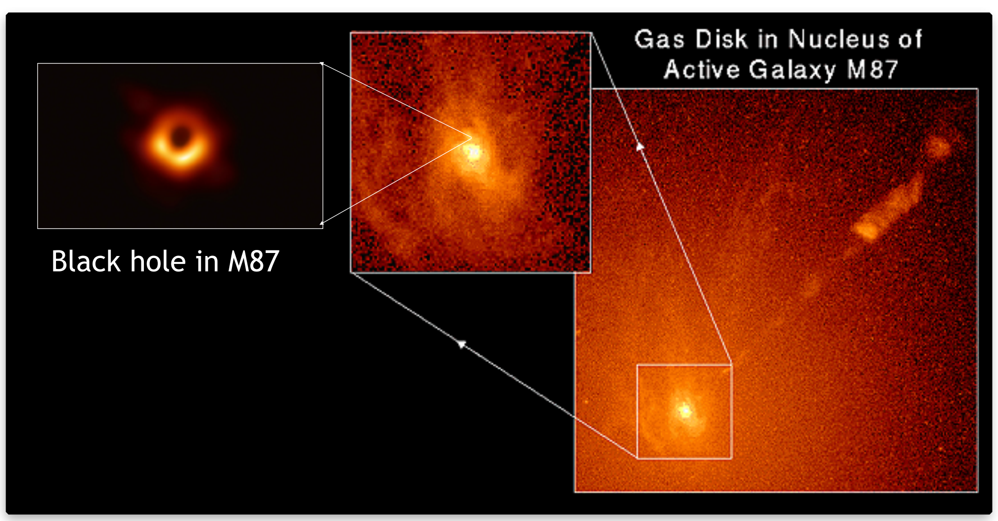


CERN

p-p collision ($\sqrt{s_{cm}}$ = 7 TeV) in ALICE

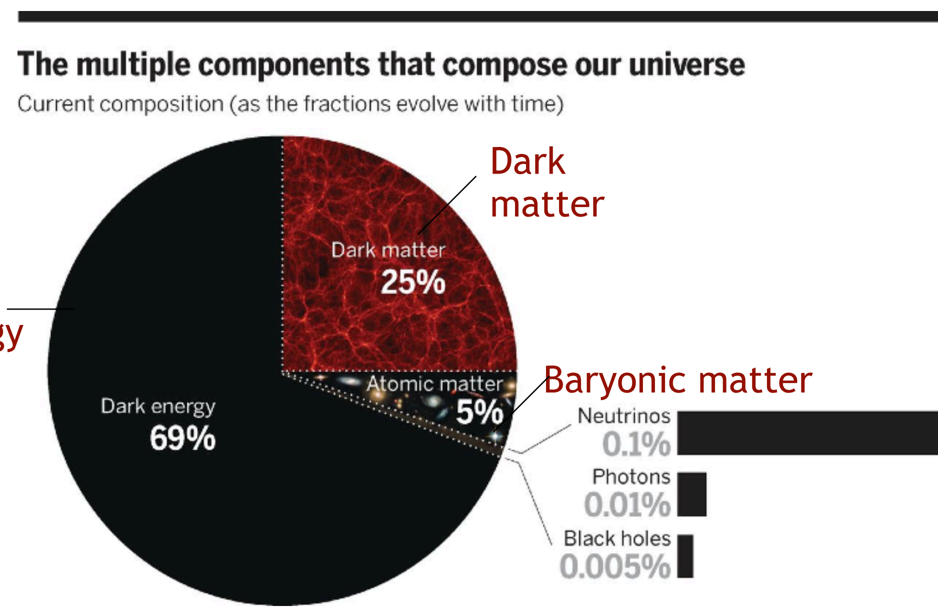
VHE astroparticle physics

- Find and understand the high-energy processes that occur in astrophysical environments



NASA/EHT

- Put limits on physics beyond the standard model



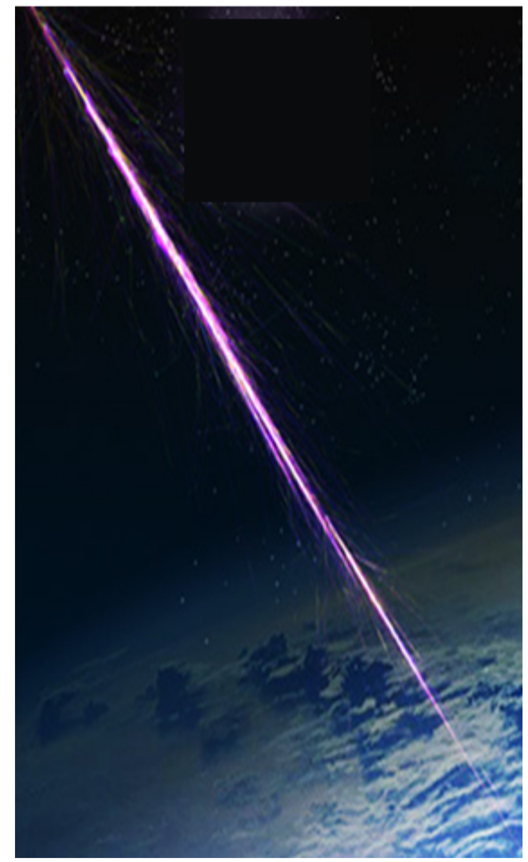
- Probe matter and radiation of the inter-stellar/-galactic medium.

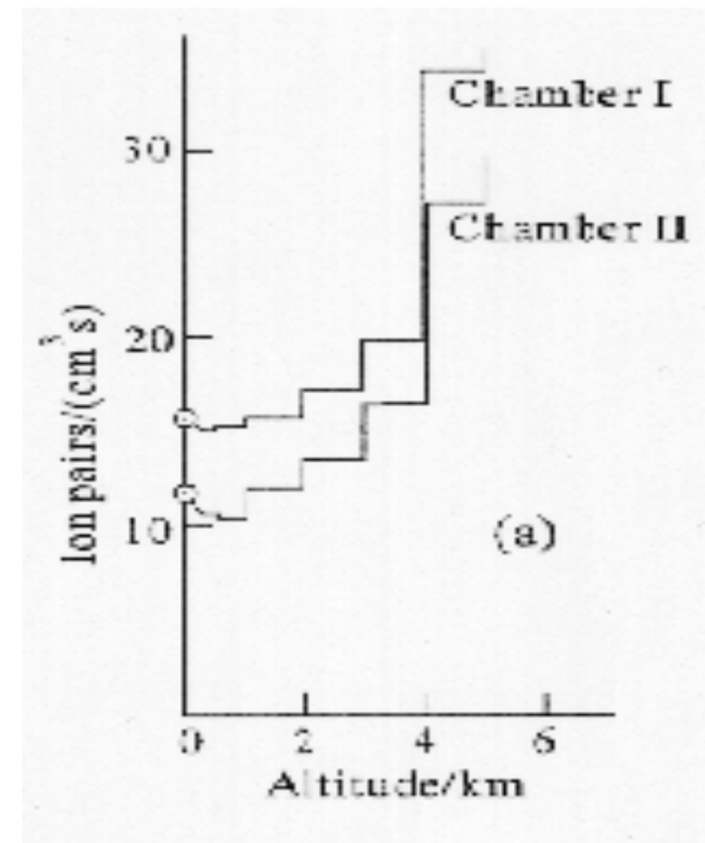
2. Introduction to cosmic rays

Brief historical background

Discovery: 1911-1912

V. F. Hess





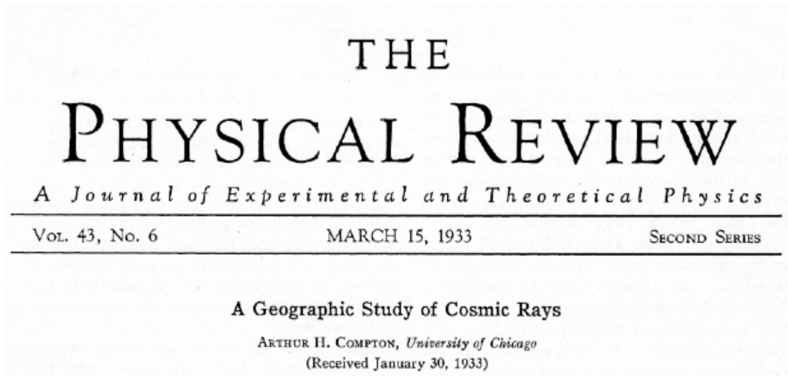
"a radiation of very high penetrating power enters our atmosphere from above"

V. F. Hess, Phys. Z. 13, (1912) 1084

Brief historical background

Nature of the radiation: 1927-1936

A. Compton



THE

PHYSICAL REVIEW

A Journal of Experimental and Theoretical Physics

Vol. 43, No. 6 MARCH 15, 1933 Second Series

A Geographic Study of Cosmic Rays

Arthur H. Compton, *University of Chicago*

(Received January 30, 1933)

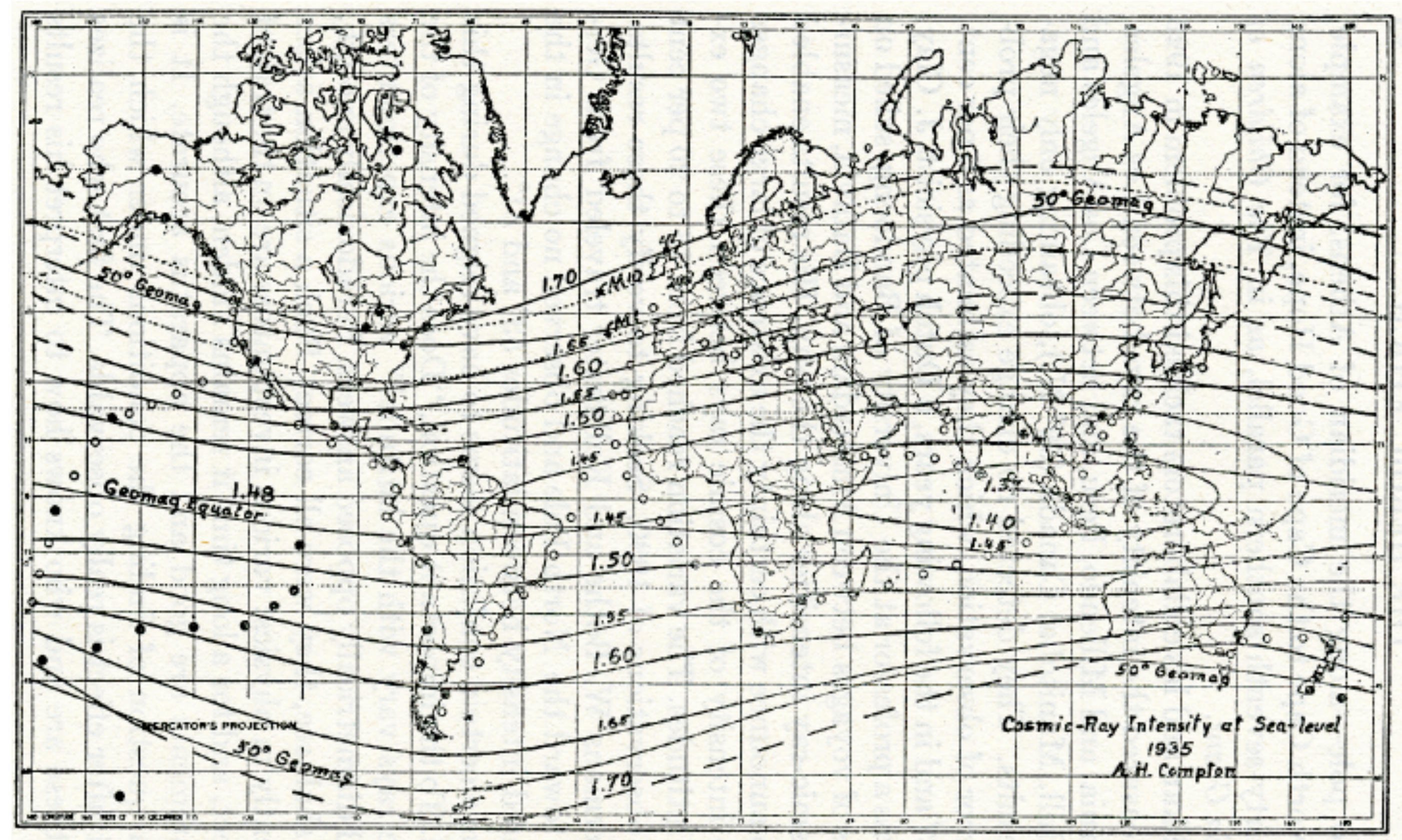
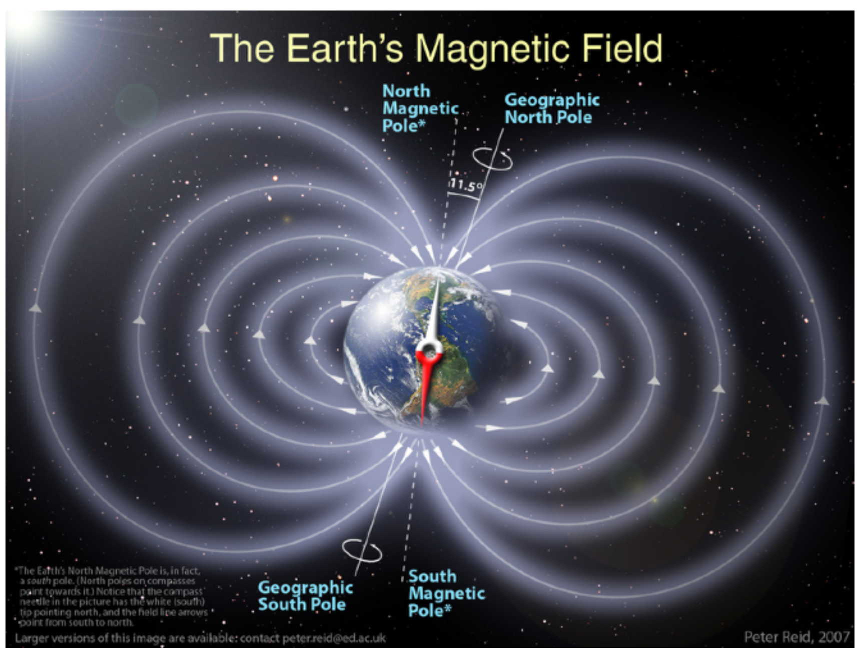


Fig. 6.—Compton's world map of isocosms. Note the parallelism of these lines of equal cosmic-ray intensity and the dotted curves of geomagnetic latitude (50° N. and S.).



CR's are charged particles.

J. Clay, A. Compton, R. Millikan, et al. observed dependence of CR intensity with latitude.

Brief historical background

Composition: 1940-1941

Fig. 1. Inflation of balloon of polyethylene just after dawn. The balloon has a total length of about 120 ft. and most of the fabric is on the ground. Such a balloon can in favourable conditions give level flight at about 90,000 ft. for many hours with a load of 40 kg.

M. Schein

The Nature of the Primary Cosmic Radiation and the Origin of the Mesotron

MARCEL SCHEIN, WILLIAM P. JESSE AND E. O. WOLLAN
Ryerson Physical Laboratory, University of Chicago, Chicago, Illinois

March 13, 1941

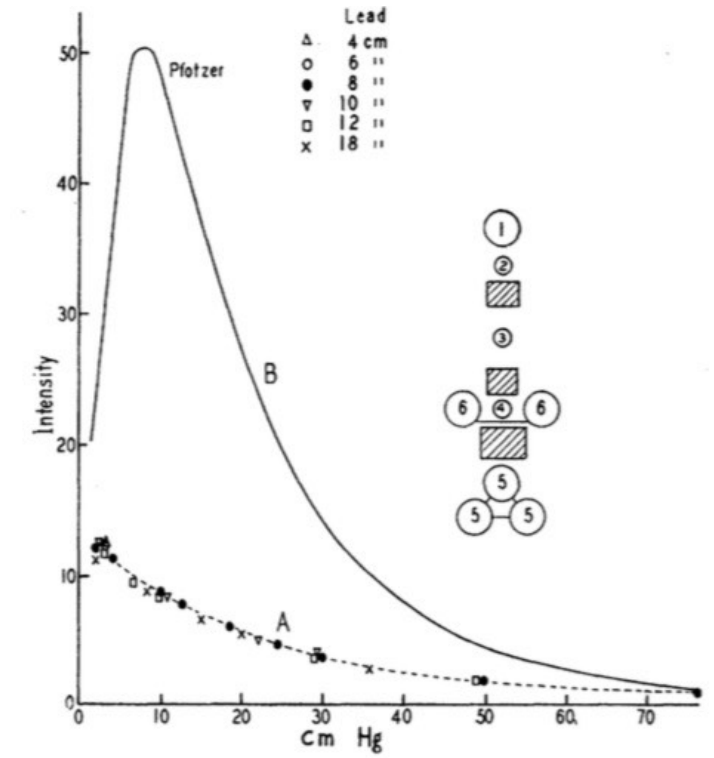


FIG. 1. Curve *A*: Intensity of the hard component for various lead thicknesses as a function of pressure in cm Hg. Curve *B*: Total vertical intensity of cosmic rays obtained by Pfotzer as a function of pressure.

Direct measurements in non-tripulated balloons carried out by M. Schein et al. at altitudes up to 20 km.

Cosmic rays are dominated by protons

M. Schein et al., Phys. Rev. 59, (1941) 615

Cosmic ray known properties

- One of the most energetic and enigmatic form of radiation from outer space

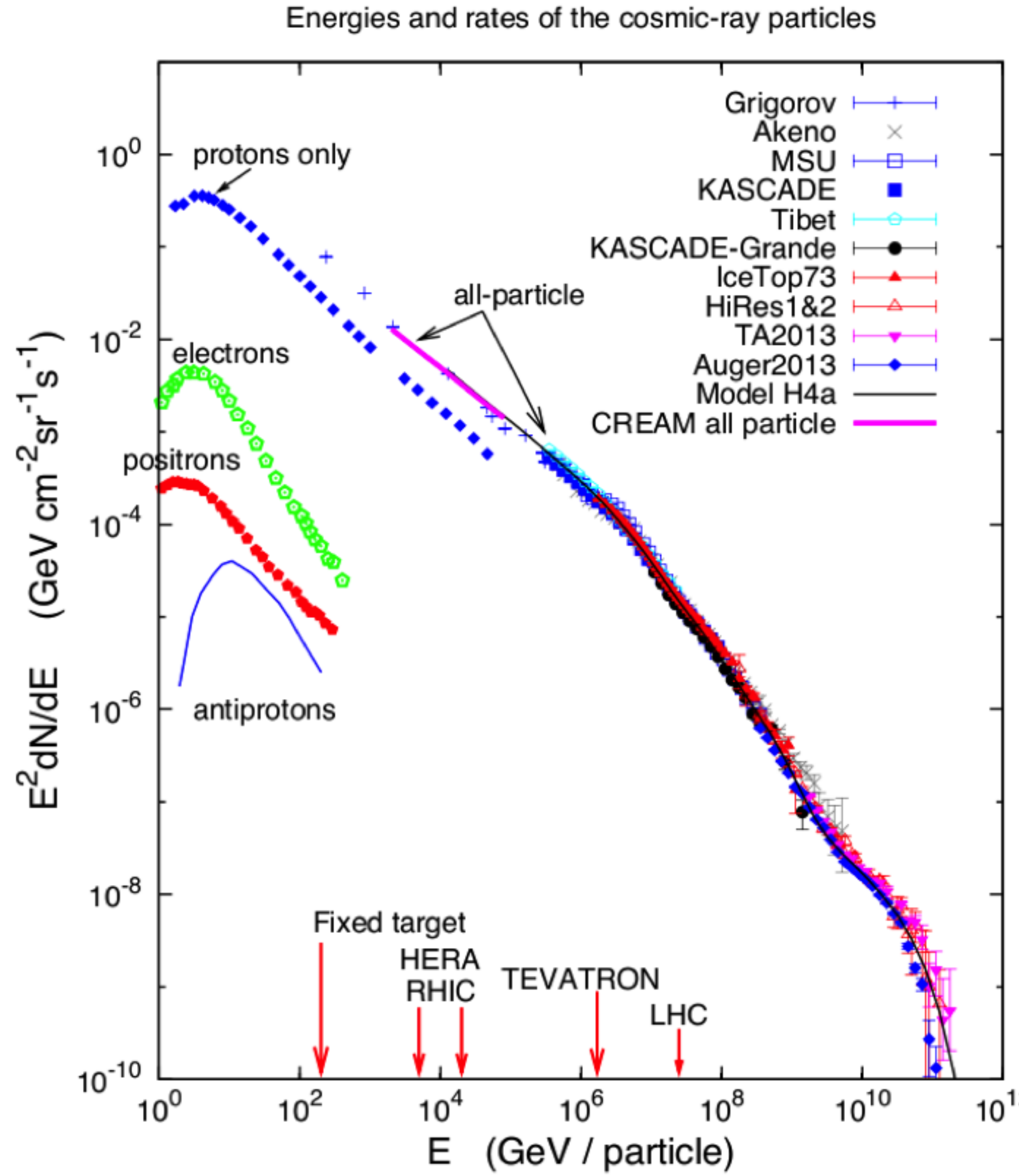
- **Composed** by atomic nuclei:
  - Atomic nuclei (99 %) :
    H (85%), He (3%), Z ≥3 (3%)
  - Electrons (1 %)
  - Traces of antiparticles

- **Energy** ranges from 100 MeV to 10^{20} eV

- **Spectrum** follows roughly a power law
  $F(E) = E^{-\gamma}$

- **Origin** is galactic and extragalactic:
  - Sun (E < 10 GeV),
  - Supernova remnants (E~TeV),
  - Extragalactic sources (E > 1 EeV).

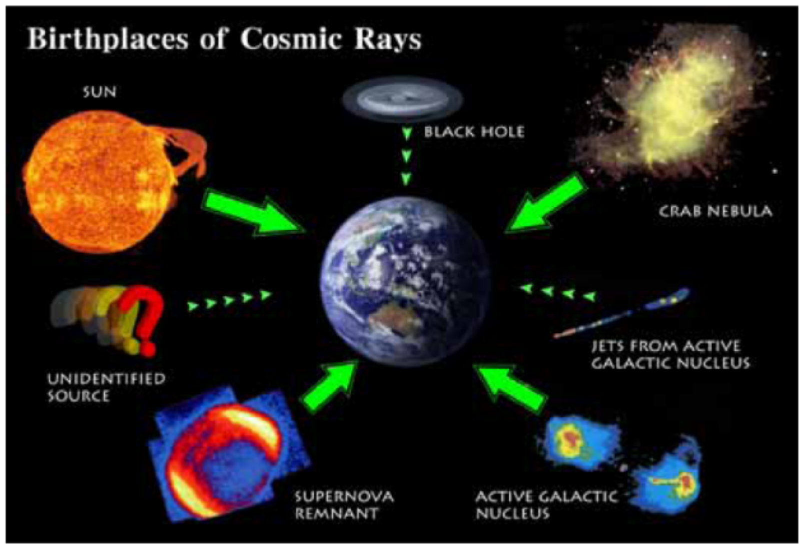
- Diffusive **propagation** in space:
  Age ~ $\mathcal{O}(10^7$ yr) at HE's



Cosmic ray open questions

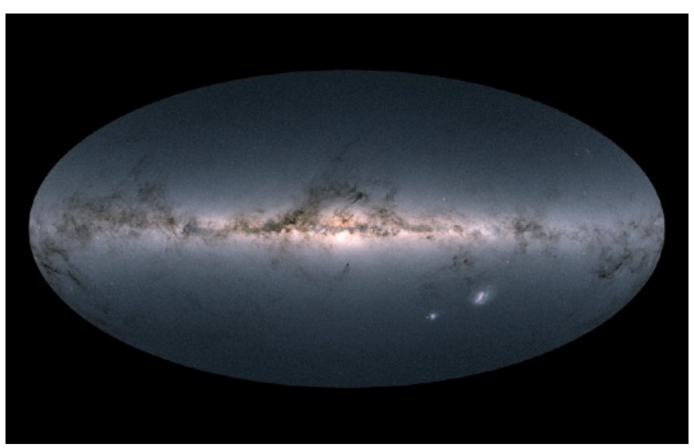
Open questions

- What are the sources of cosmic rays?



<Sources: Sun, Earth - NASA; Crab Nebula - Hale Observatories; Jets from Active Galactic Nucleus, Active Galactic Nucleus - National Radio Astronomy Observatory; Supernova Remnant - ISAS/JAXA>

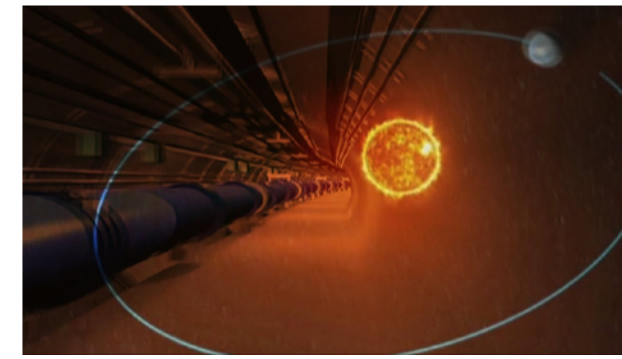
- Where are they accelerated



GAIA's star map of our galaxy (ESA)

- What is the origin of the features in their energy spectrum?

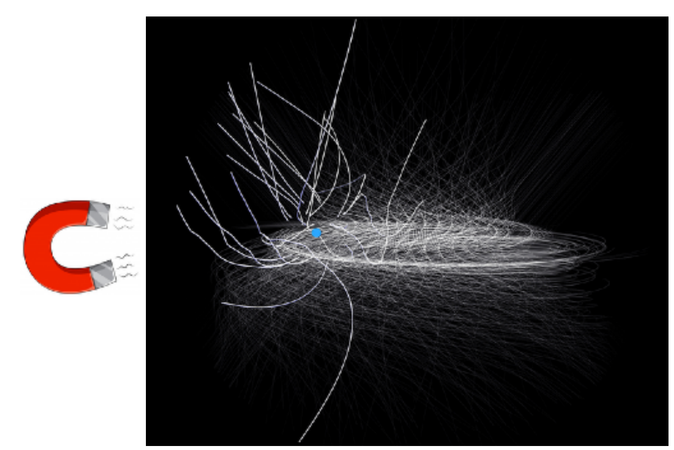
- How are they accelerated?



LHC (CERN)

- What are they made of?

- How do they propagate in the space?



NASA/Modelo JF

Propagation of 10^{18} eV CR 's in the galaxy

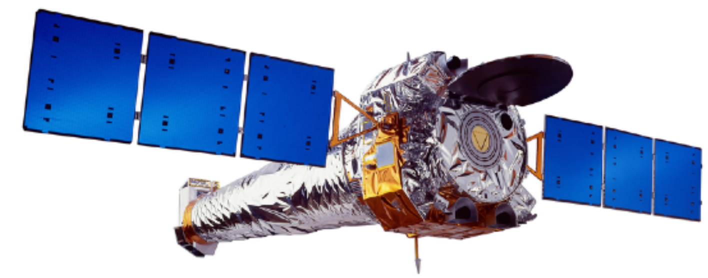
What do we need?

- Cosmic ray measurements on:
  - Composition,
  - energy,
  - arrival direction.

KASCADE-Grande detector

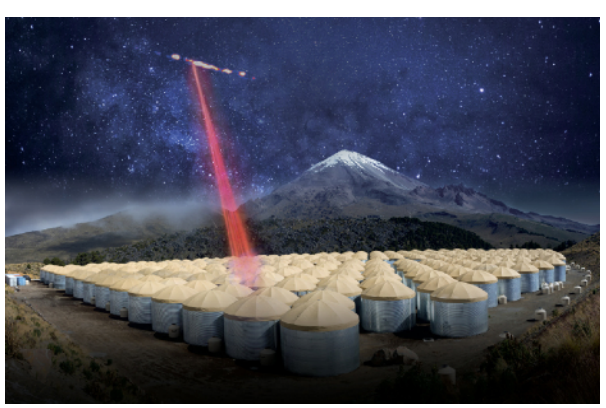
Addressing the mystery of cosmic rays

- Multi-wavelength observations (E < MeV's):
  - radio, microwave, infrared, visible, UV, X-rays.

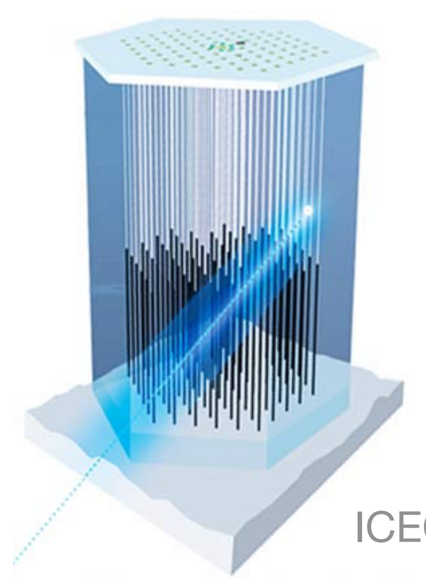


Chandra X-ray telescope

- Multi-messenger measurements:
  - Gamma rays (E > MeV's)
  - Neutrinos (E > GeV's)



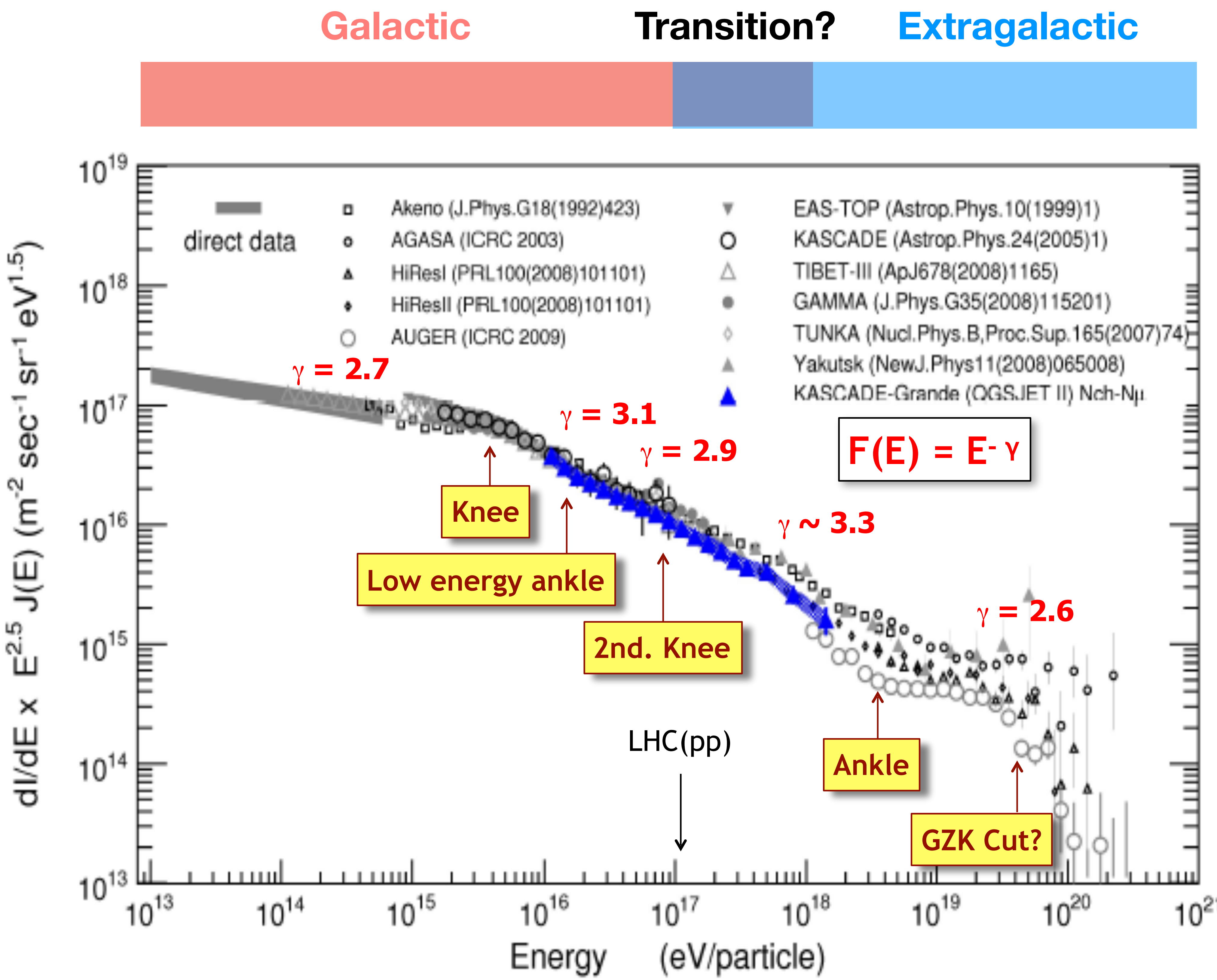
HAWC γ-ray observatory



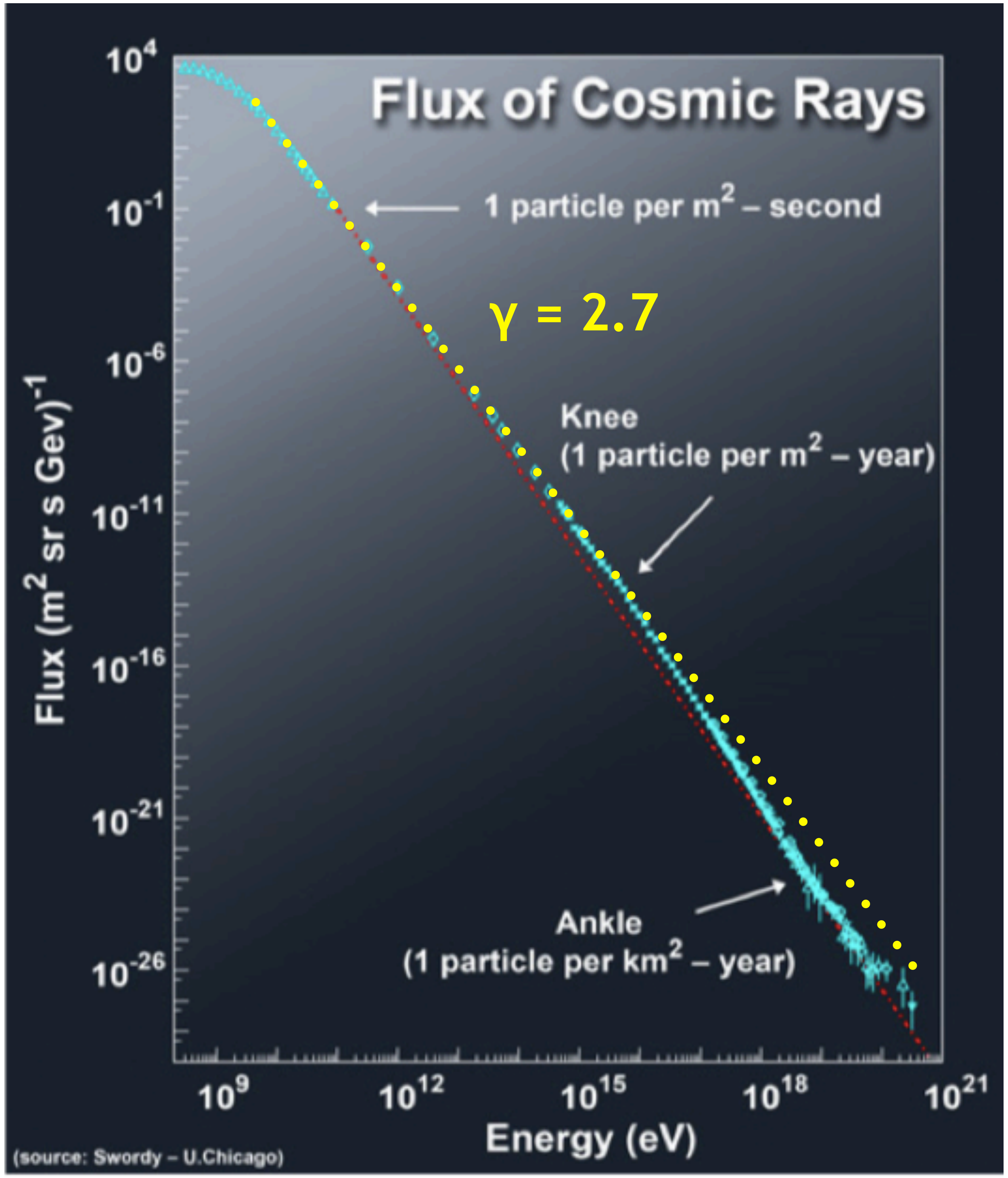
ICECUBE ν observatory

3. Review

Energy spectrum



Origin



Spectrum:

$$\Phi(E) = \frac{dN}{dE\,d\Omega\,dt\,dA} = 1.8\,E^{-2.7}\,\frac{\text{nucleons}}{cm^2\,s\,sr\,GeV}$$

Particle density:

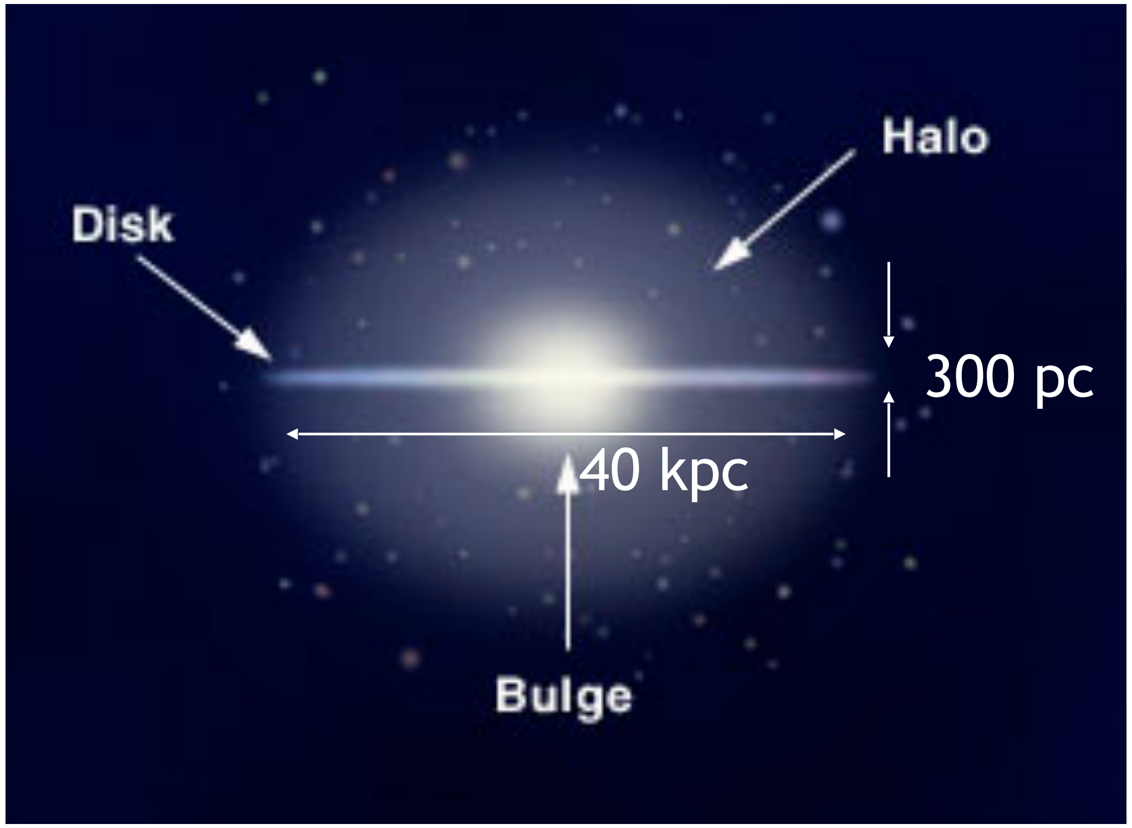
$$\frac{4\pi}{c}\,\Phi(E) = \frac{dN}{dE\,dV}$$

Energy density:

$$\int_{1GeV} E\,\frac{dN}{dE\,dV}\,dE = \int_{1GeV} E\,\frac{4\pi}{c}\,\Phi(E)\,dE$$

$$\approx \frac{1\,eV}{cm^3}$$

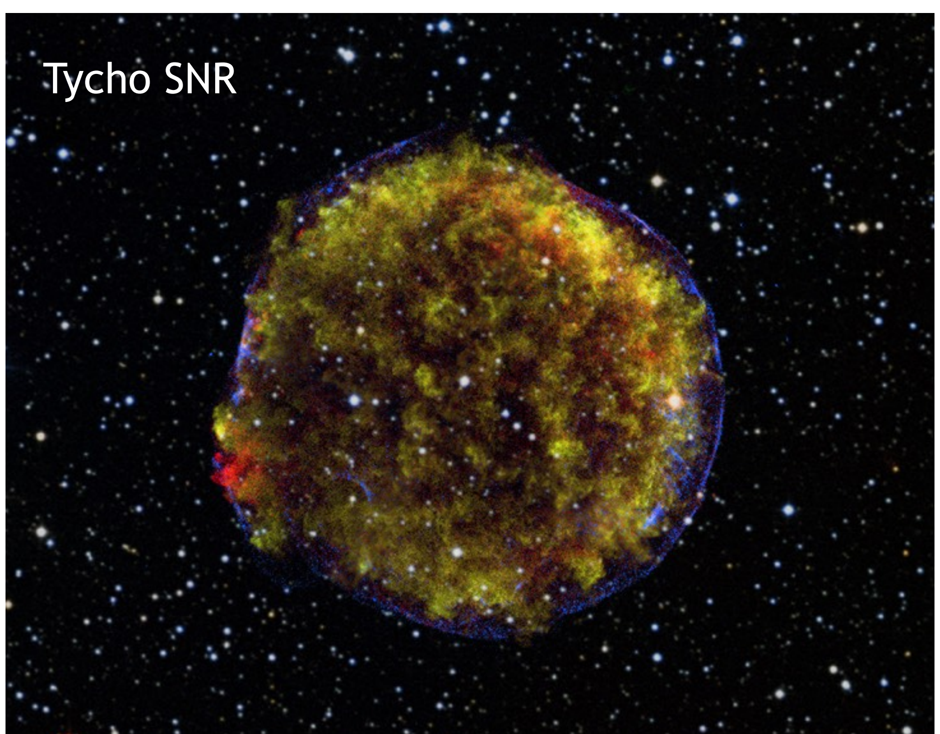
Origin



Galactic cosmic rays:

$\rho_{RC} = 1 \text{ eV/cm}^3$
$V_{DG} = \pi \, (20 \text{ kpc})^2 (300 \text{ pc}) = 10^{66} \text{ cm}^3$
$\tau_{escape} = 10^7 \text{ years}$

$L_{RC} = V_{DG} \, \rho_{RC} \, / \, T_{DG} \sim 10^{41} \text{ erg/s}$



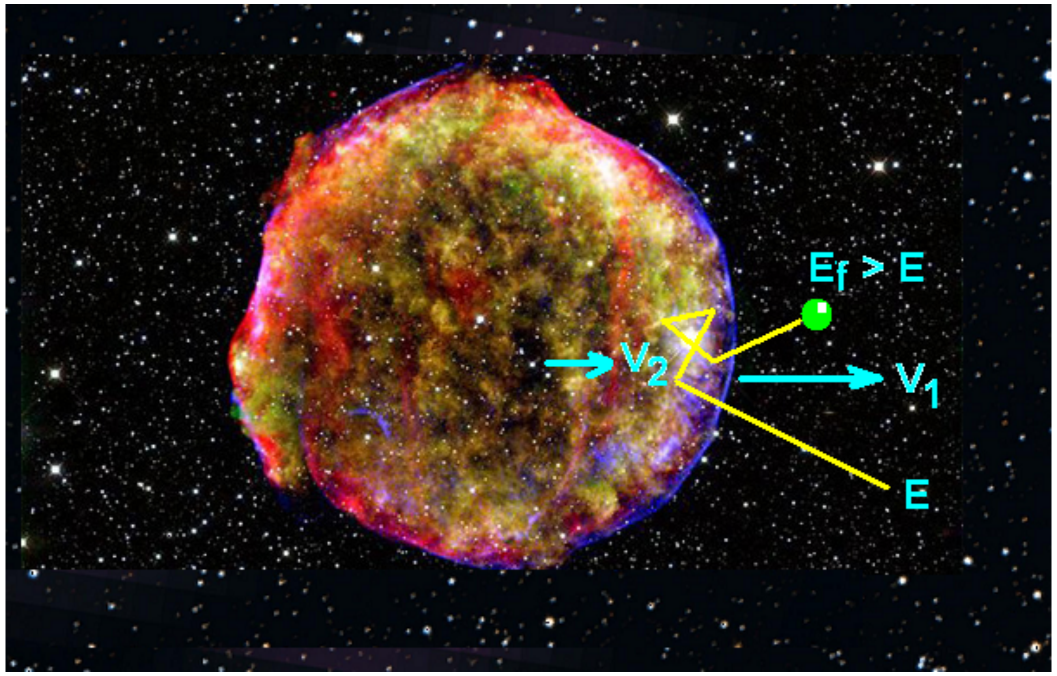
Chandra X-ray Observatory

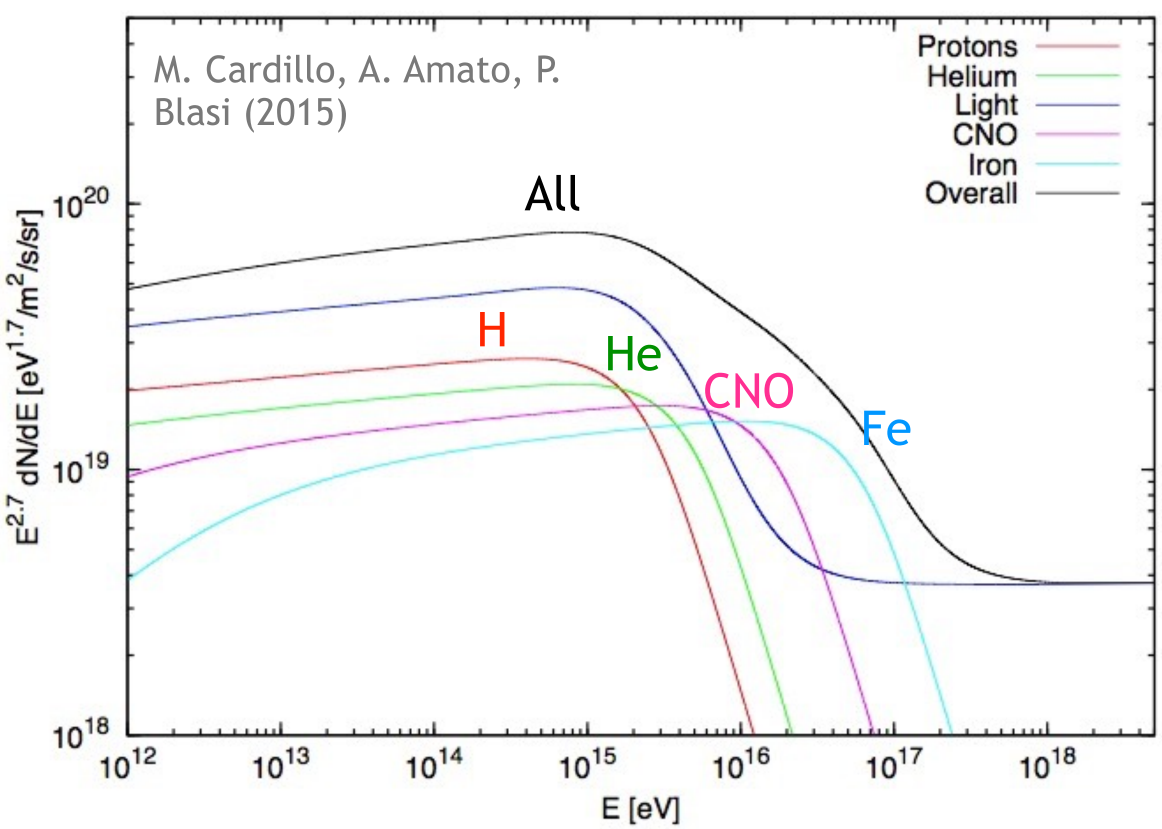
Supernova remnants

$K_{SNR} = 10^{51} \text{ erg}$
$L_{SNR} = K_{SNR} \text{ x } 3 \text{ SN/Siglo} \sim 10^{42} \text{ erg/s}$

$L_{RC} \sim 10\% \, L_{SNR}$

Acceleration mechanism





Diffusive magnetic acceleration in shock fronts:

- Fermi's 1st order mechanism

$$\Delta E/E \sim (v_2/c) = \beta$$

Effects at source:
- Non lineal
- Late phase of SNR
- Different kinds of SNR's

- Spectrum of shape

$$dN/dE \sim E^{-(\gamma_o + \varepsilon)}$$

where $\gamma_o = 2$ y $\varepsilon < 1$

- Maximum energy — B. Peters, Nuovo Cimento 22 (1961) 800

$$E^Z_{cut} \sim Ze \times B \times R$$

$$= Ze\, E^H_{cut}$$

Prediction of cuts/knees in spectra

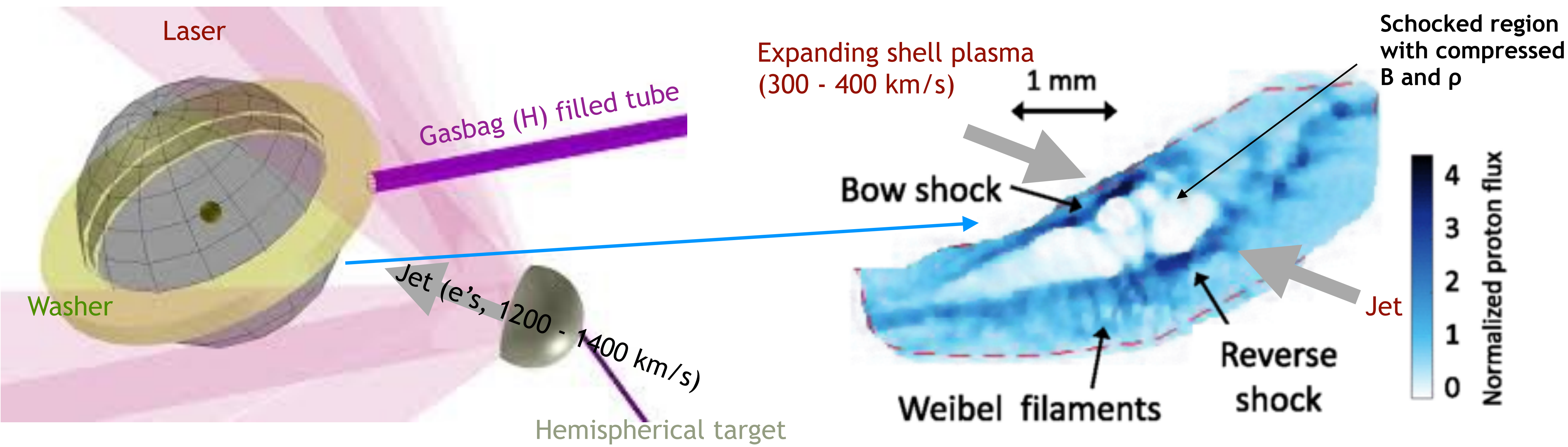
- With magnetic field amplification or in very young SNR's, then E^H_{cut} up to 10^{15} eV!

A.R. Bell, Astrop. Phys. 43 (2013)
S. Gabici et al., ApJ 665 (2007) L131

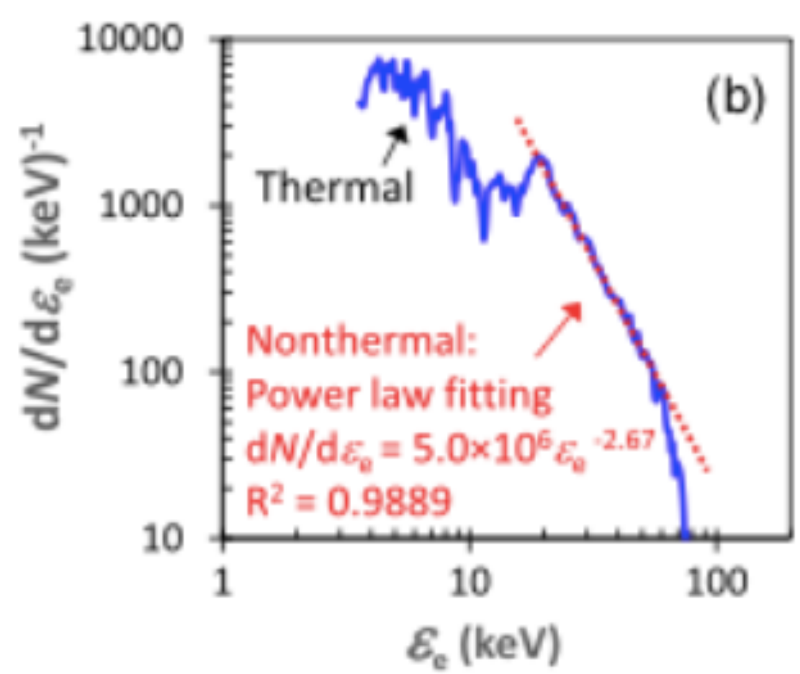
Acceleration mechanism

Production in the laboratory of astrophysical shocks by using supersonic plasmas

C. K. Li et al., PRL 123, 055002 (2019)



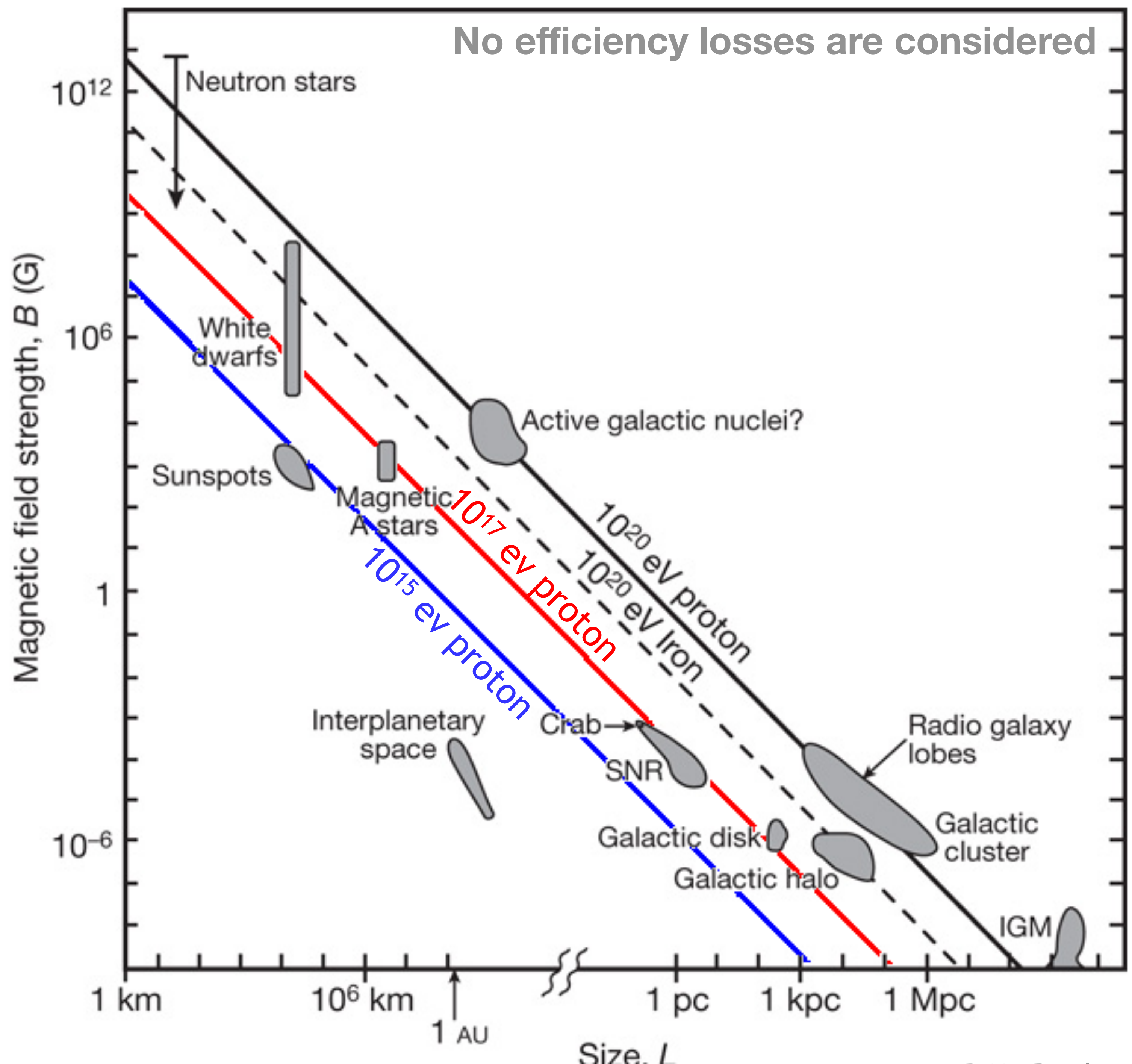
- Electromagnetic shockwave
- Magnetic turbulence
- Electron acceleration in shocked region and in Weibel's turbulences:
  - Spectrum follows a power-law
  - Consistent with 1st order Fermi acceleration



Sources

Hilla's plot: Size (L) vs magnetic field (B) of potential cosmic ray accelerators:

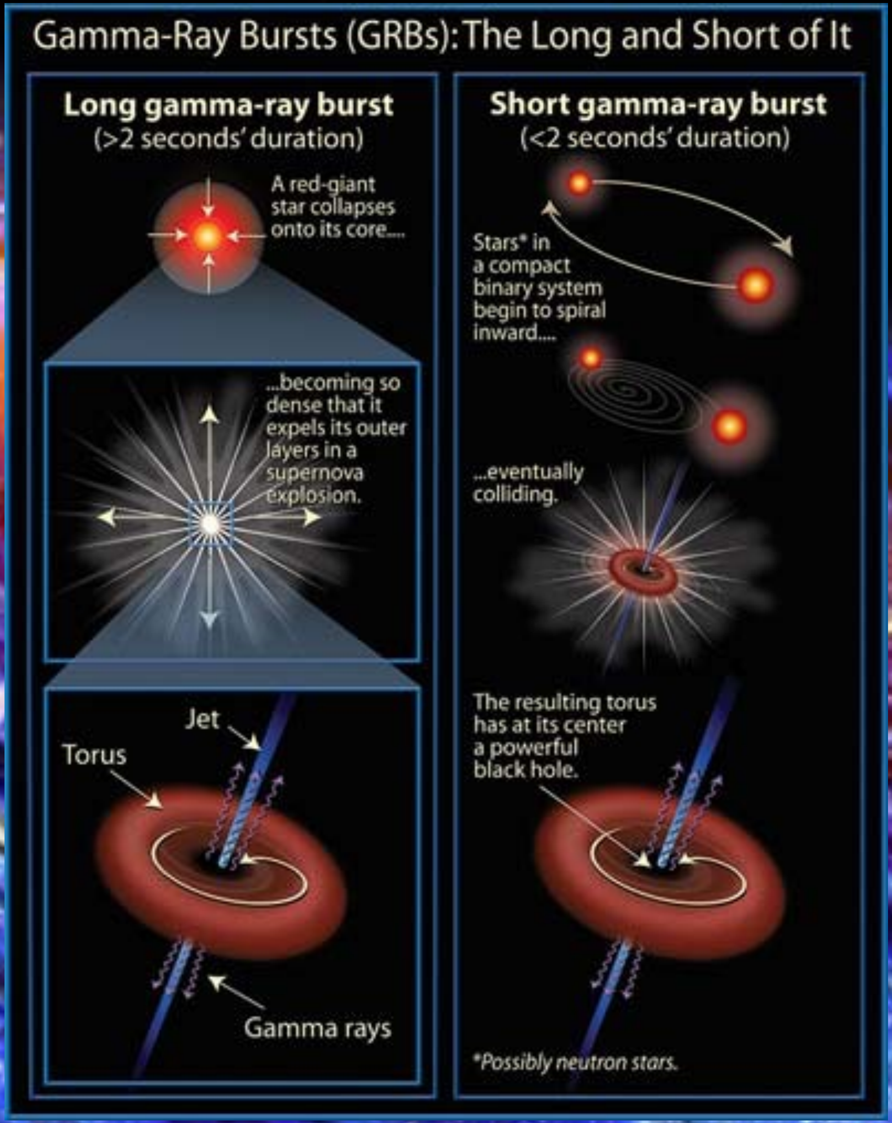
$$E_{max} \sim Ze \cdot B \cdot R$$



P.M. Bauleo et al, Nature 458 (2009)

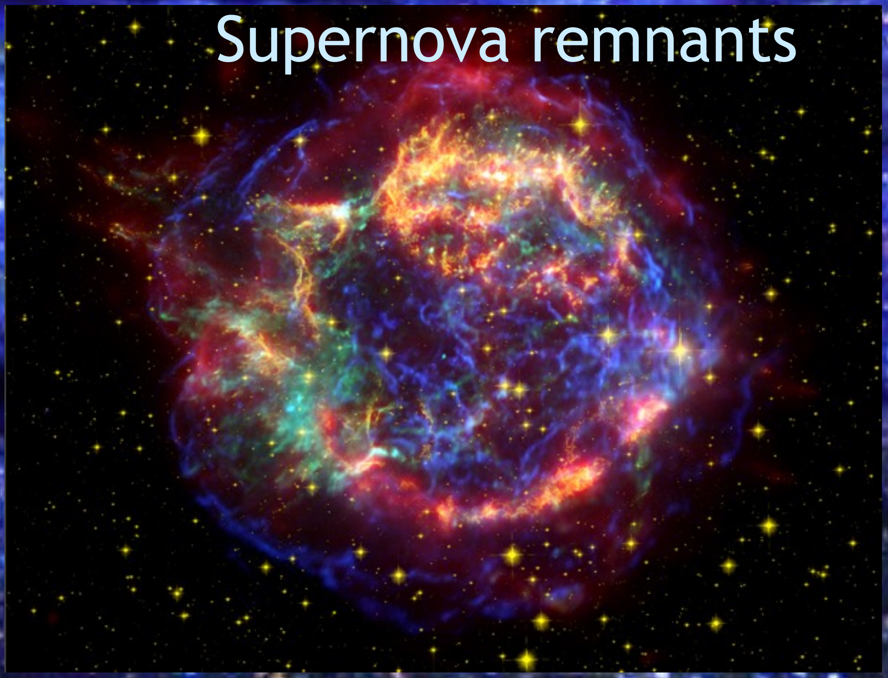
Sources


Galactic center


Gamma-Ray Bursts (GRBs): The Long and Short of It
Long gamma-ray burst
(>2 seconds' duration)
A red-giant star collapses onto its core....
...becoming so dense that it expels its outer layers in a supernova explosion.
Jet
Torus
Gamma rays
Short gamma-ray burst
(<2 seconds' duration)
Stars* in a compact binary system begin to spiral inward....
...eventually colliding.
The resulting torus has at its center a powerful black hole.
*Possibly neutron stars.


Magnetars


Superbubbles

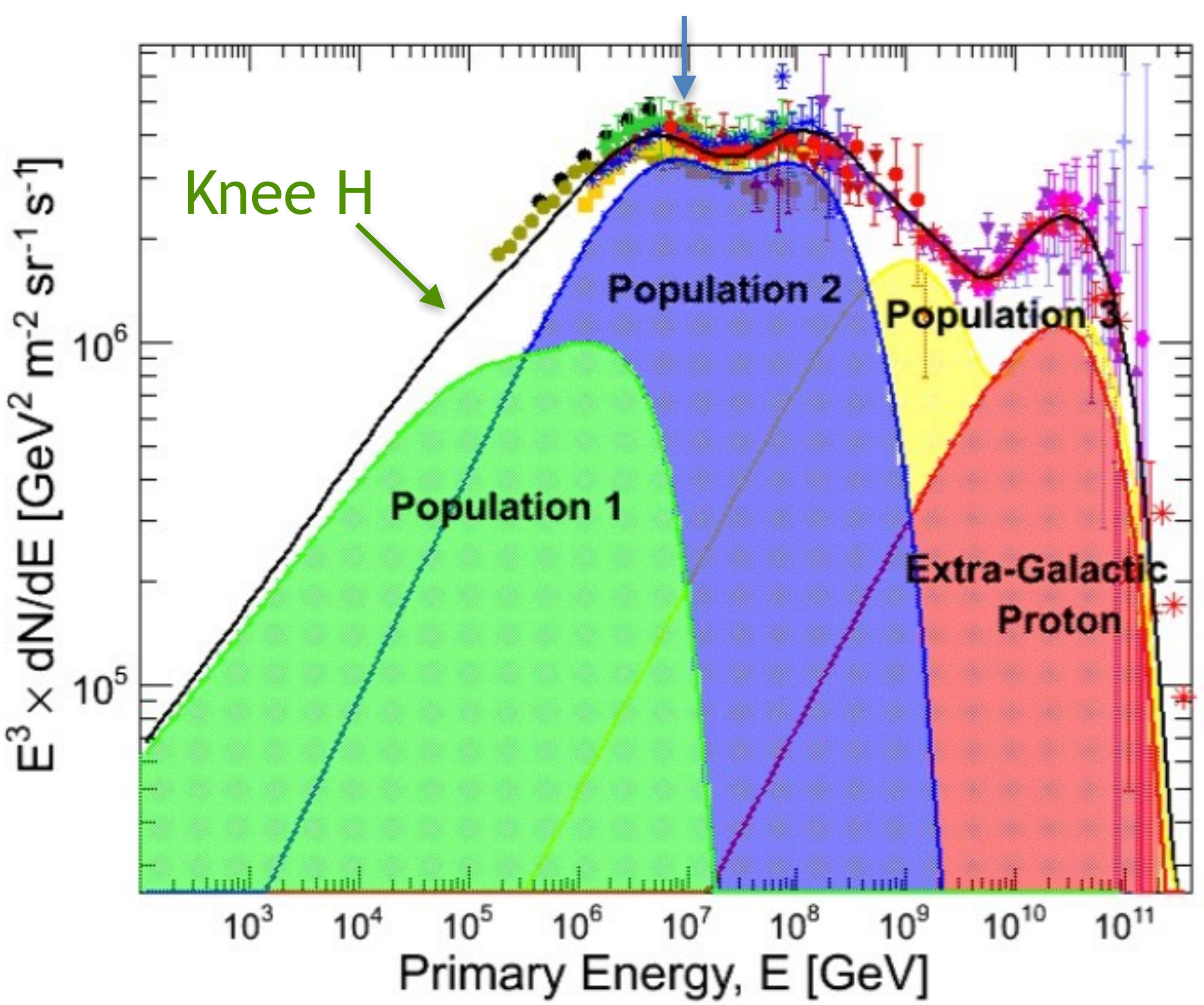

Supernova remnants

Sources

Hilla's model

- Knee's are the result of loss of magnetic confinement at the source.
- Four types of sources to describe all-particle energy spectrum

Knee H



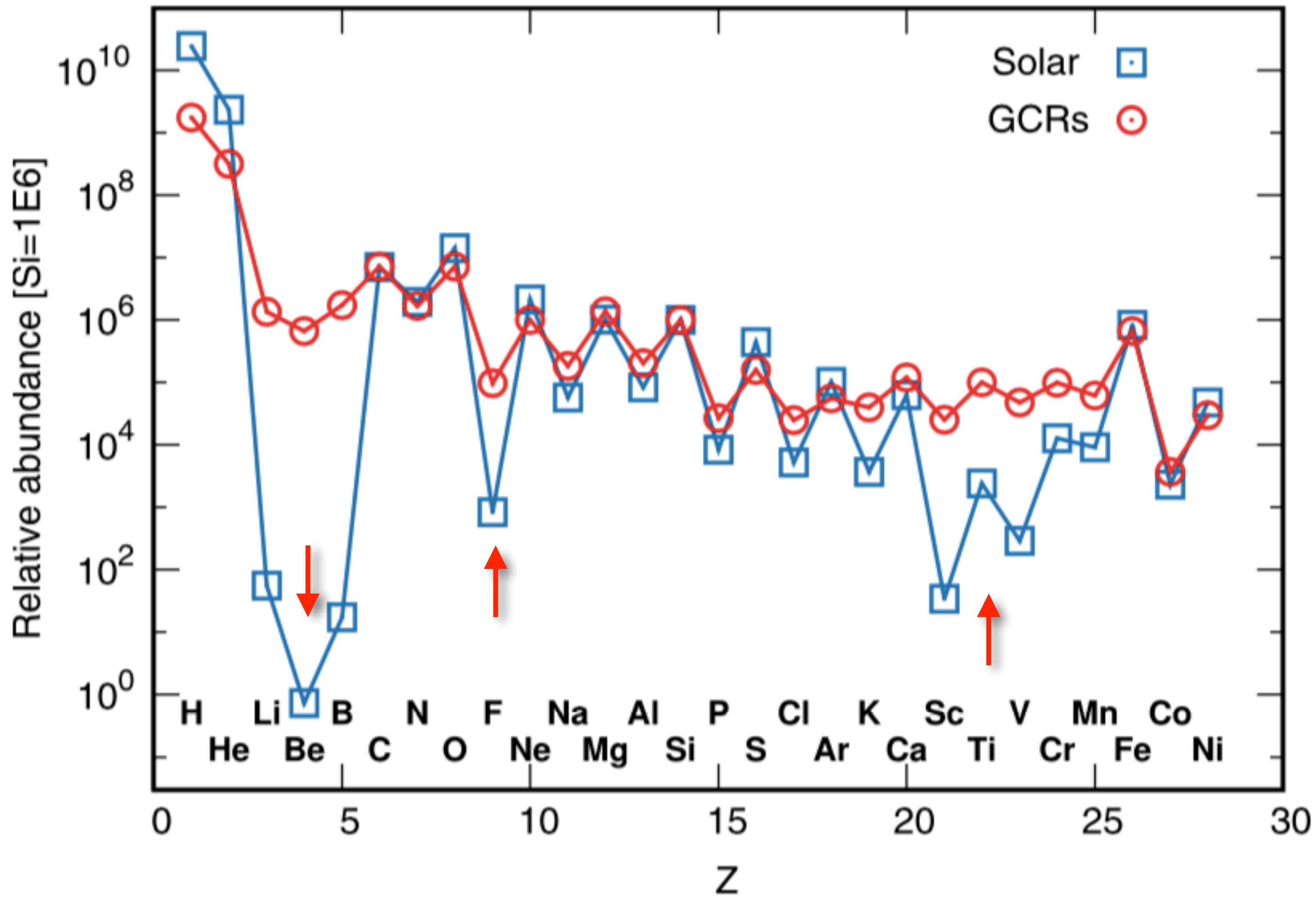
$$\phi_i(E) = \Sigma_{j=1}^{3} a_{i,j}\, E^{-\gamma_{i,j}} \times \exp\left[-\frac{E}{Z_i R_{c,j}}\right].$$

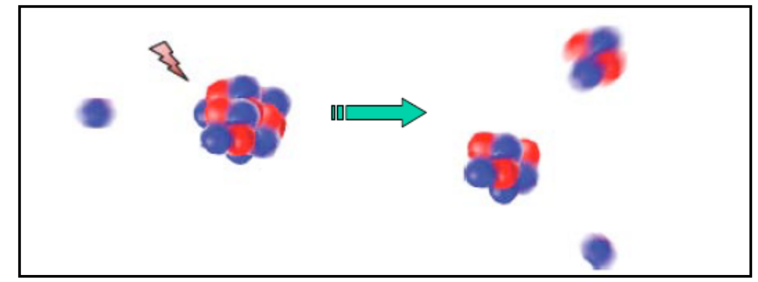
- Population 1: SNR (E_{max} ~ 100 TeV)
- Population 2: Galactic Pevatron PWN, SNR (E_{max} ~ 1 PeV), galactic center, etc.
- Population 3: Galactic Eevatron past Hypernovae/GRB's.
- Population 4: Extragalactic.

S. Tilav, ISVHECRI (2014)
T.K.Gaisser et al., Frontiers of Phys. 8 (2013)

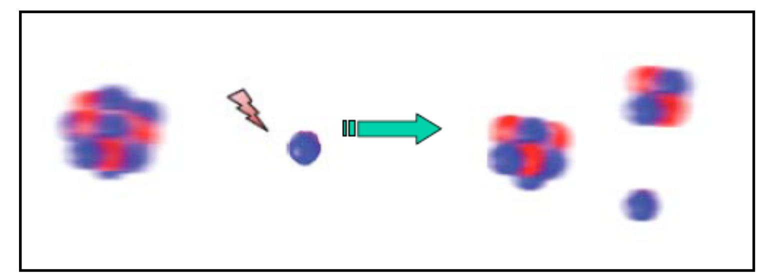
Propagation

S. Mollerach, E. Roulet, Prog. in Part. and Nuc. Phys. 98 (2018) 85





Spallation



Fragmentation

- At **low energies** (GeV's) **CR composition** is similar to that of our **solar system**.
- But abundances of some rare elements in solar system are larger in CR's:
  - Effect of spallation/fragmentation of primaries in space.

- These secondary nuclei:
  - Li, Be, B, F,
  - Sc, Ti, V, Cr, Mn,

can be used as **cosmic clocks,** using primary-to-secondary **ratios**

Propagation

Cosmic ray transport equation:

Source — Collisions with medium — Decay

$$\frac{dn_i}{dt} = Q_i - n_i\left(\frac{1}{\tau_e} + \frac{1}{\tau_i} + \frac{1}{\gamma\tau_{d,i}}\right) + \sum_{j>i} B_{j\to i}\frac{n_j}{\tau_j}$$

Galactic confinement — Spallation

n_i: $[part/Vol \cdot energía]$

Q_i: $Source\ [part/Vol\ .\ time\ .\ energy]$

$\tau_i = 1/\rho_H c \sigma_{iH}$

τ_e: $Escape\ time$

$\gamma\tau_{d,i}$: $Particle\ lifetime$

$B_{j\to i}$: $Branching\ ratio$

It is not considering:
- Ionization
- Reacceleration
- Convection
- Radiative losses.

Propagation

Stationary state

$$\frac{dn_i}{dt} = 0$$

Consider ^{11}B:

- No primary sources.
- Stable product of C and O fragmentation.

  $1/\tau_{d,11} \rightarrow 0$

  $Q_{11} = 0$

Experiment and observations

$$\left(1 + \frac{1}{\tau_e n_H c \sigma_{11}}\right) = \frac{1}{\sigma_{11}} \sum_{A>11} B_{A\to 11} \frac{n_A}{n_{11}} \sigma_A$$

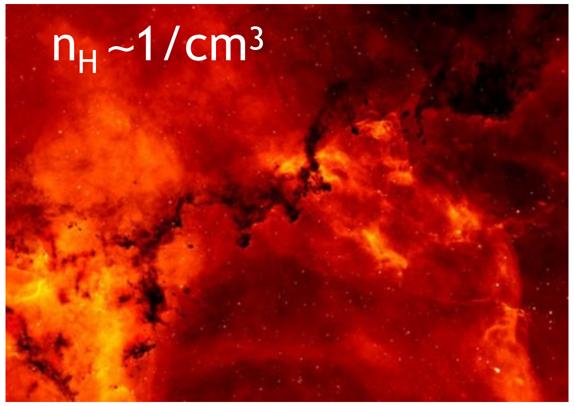
then

$$\tau_e \, n_H(cm^3) \sim 10^7 \; years$$

taking $n_H \sim 1/cm^{-3}$ for the mean *p* density in the galaxy

$$\tau_e \sim 10^7 \, years > Size \; of \; Milky \; Way$$

Evidence of diffusion?



Propagation in the galaxy

Cosmic rays do not point to their source: They are deviated by magnetic fields in the space.

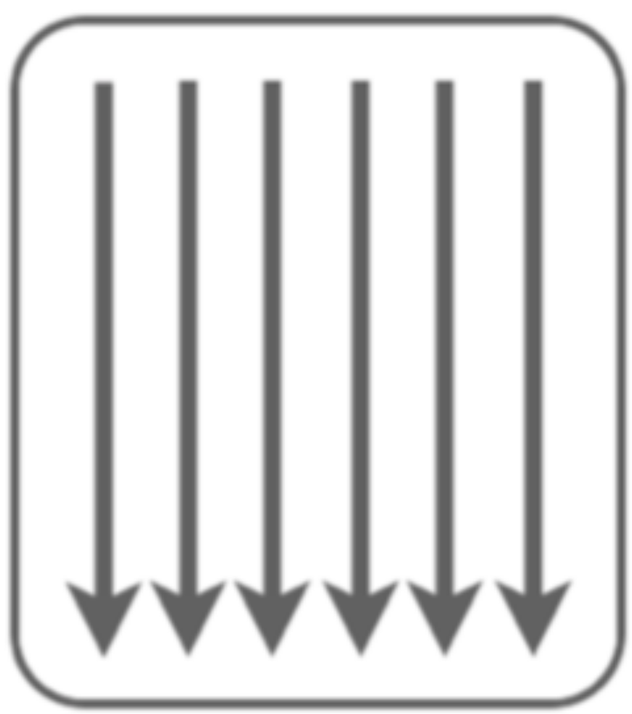
- Diffusion in interstellar/galactic magnetic fields:
  - Random walk type
  - Arrival direction is highly isotropic

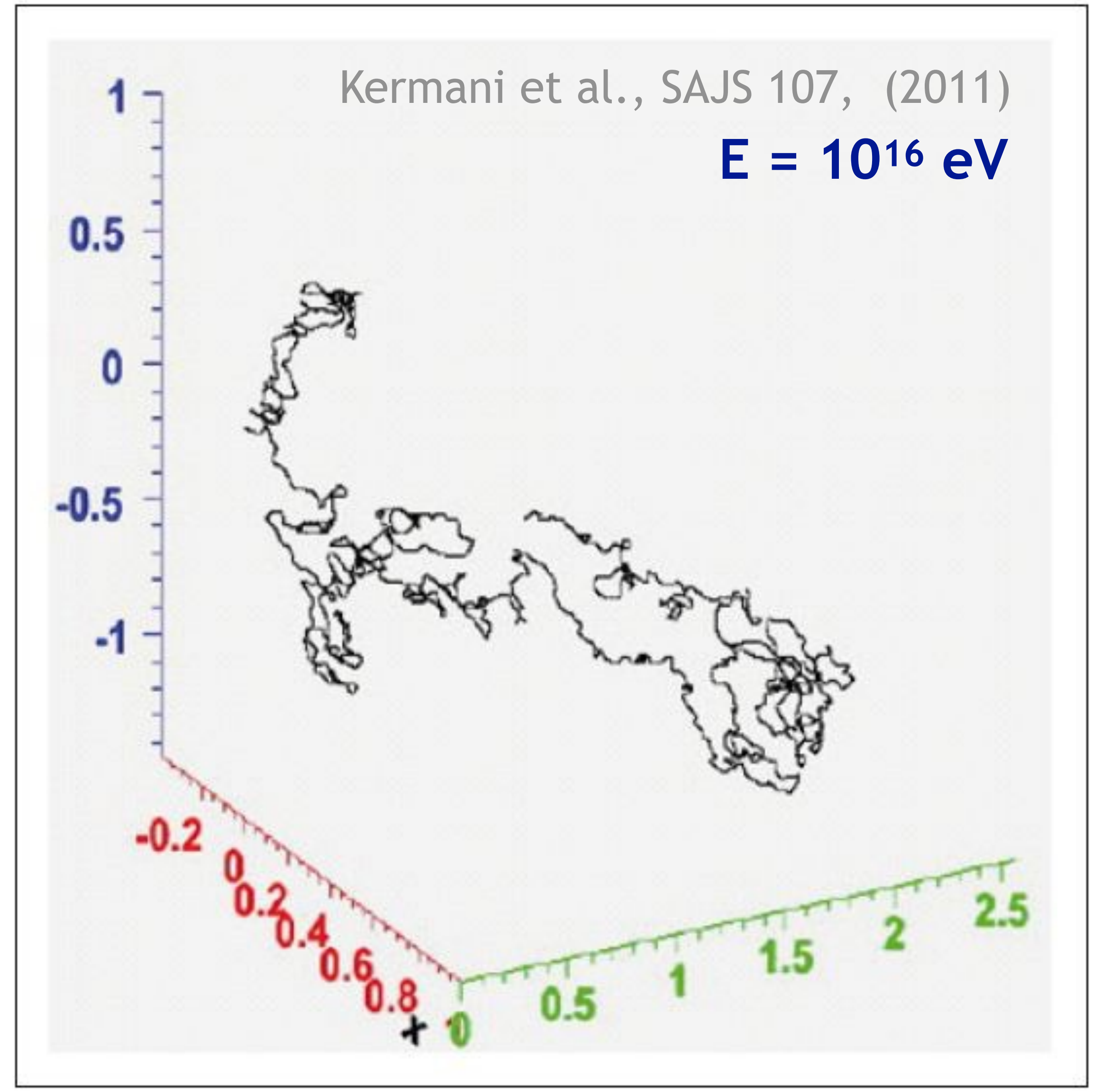
- Components of galactic magnetic field:

Random (small scale) + regular (large scale)

B_{rand} = (0.5 – 2) B_{reg} B_{reg} = μG

$Size_{rand}$ = 50 – 100 pc





Note: Distance scales are in units of kpc.

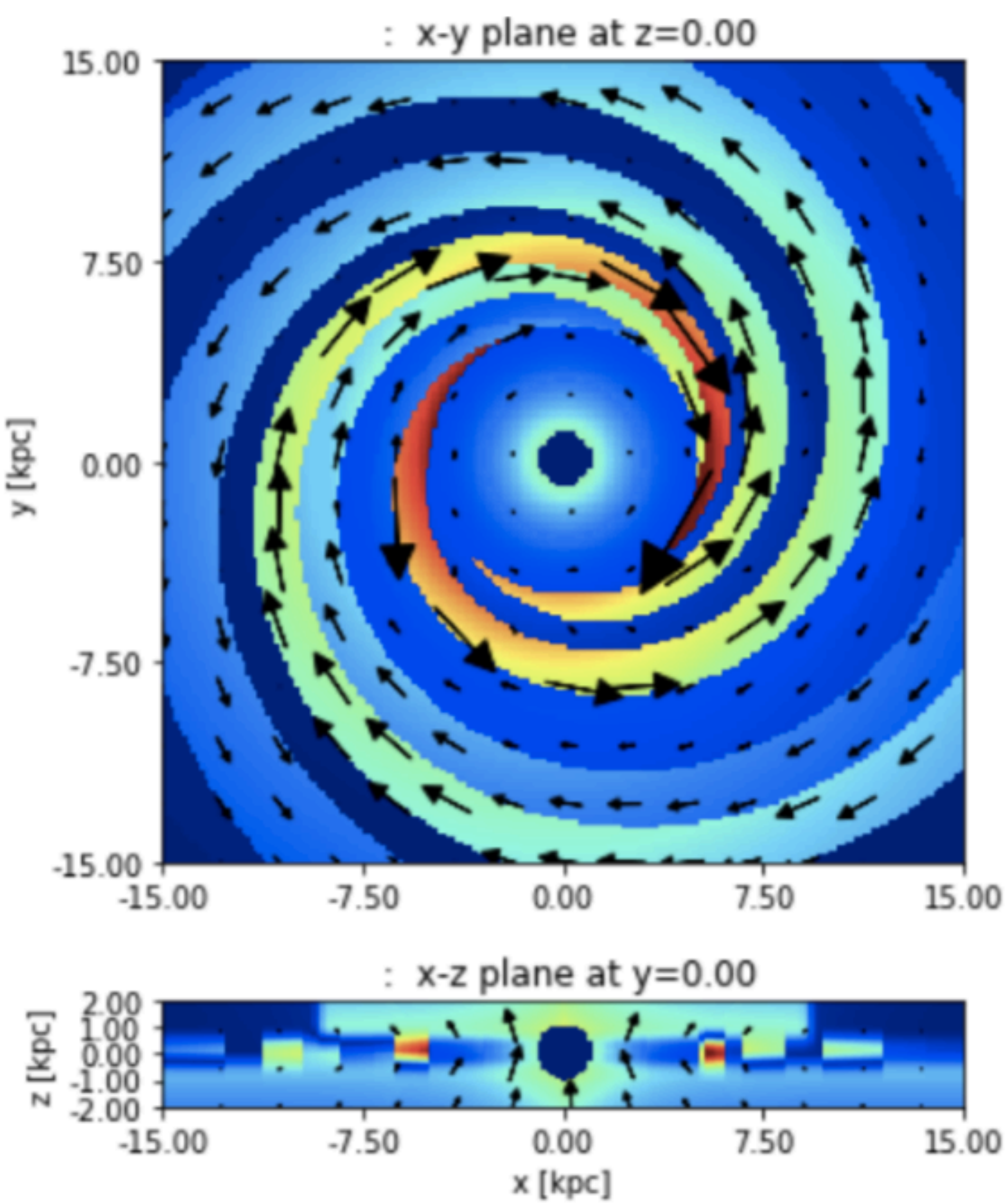
FIGURE 2: A cosmic ray trajectory in a 1 μG turbulent magnetic field as might be found in our galaxy. This track is modelled by following a 10 PeV proton through Kolmogorov turbulence (equivalent to a conventional diffusion model). Super-diffusion models have occasional long straighter paths between major changes of direction.

Propagation in the galaxy

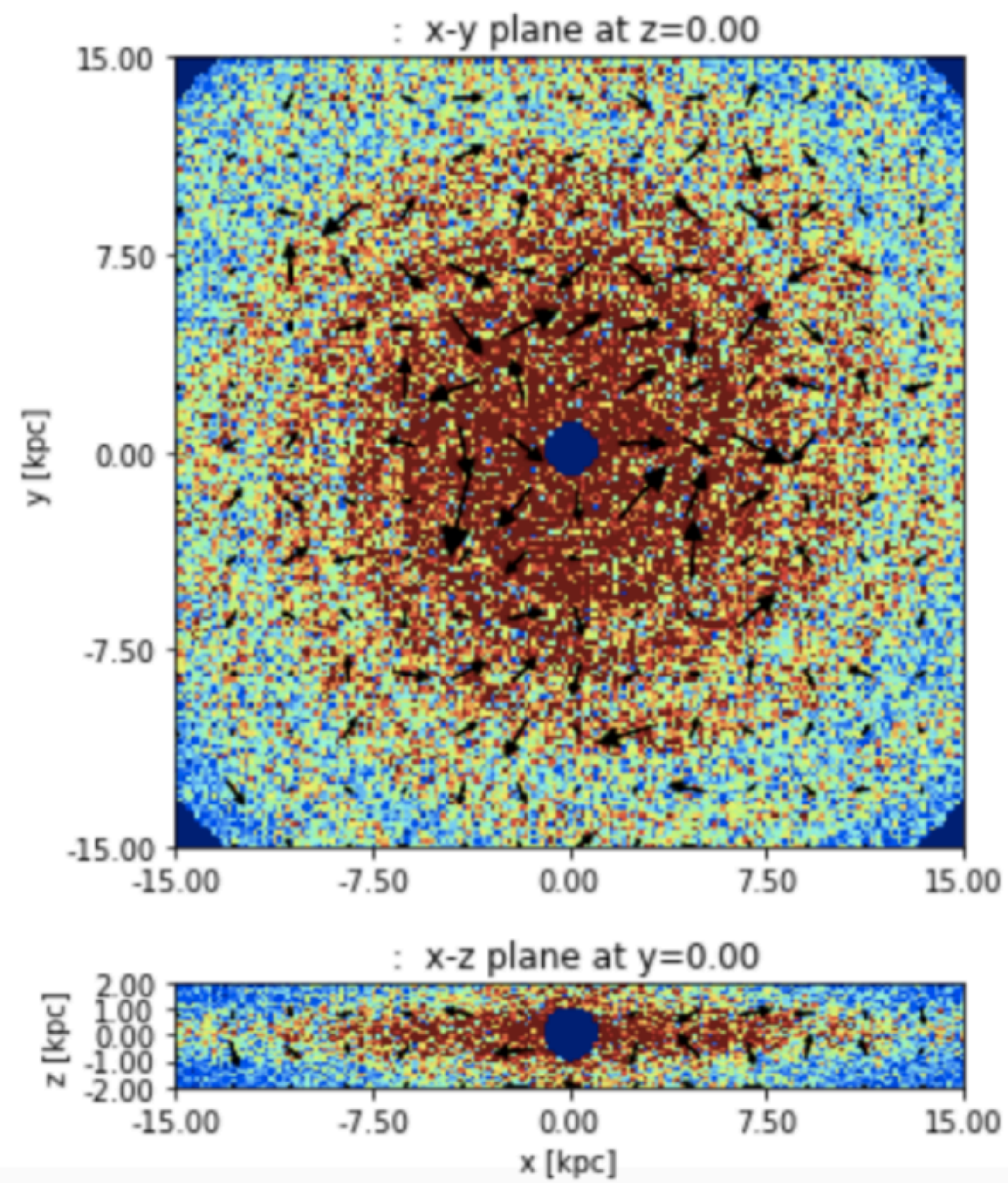
Jansson and Farrar model for the **regular** (left) and **random** (right) galactic magnetic field

Color   : Intensity of B
Arrows: Direction of B

T.R Jaffe, Galaxies **2019**, *7*, 52



Regular component

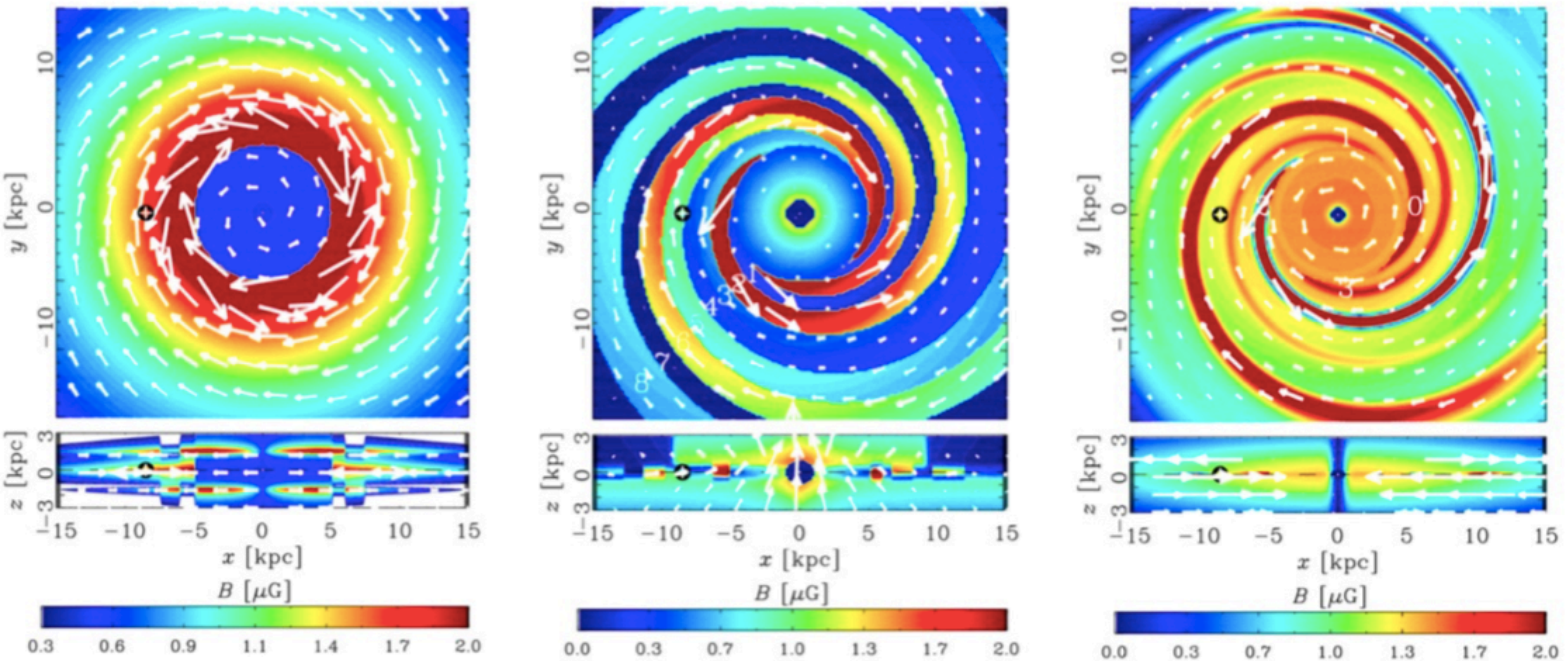


Random component

Propagation

- Problem to understand the propagation of cosmic rays: Magnetic field in the galaxy is not known with precision

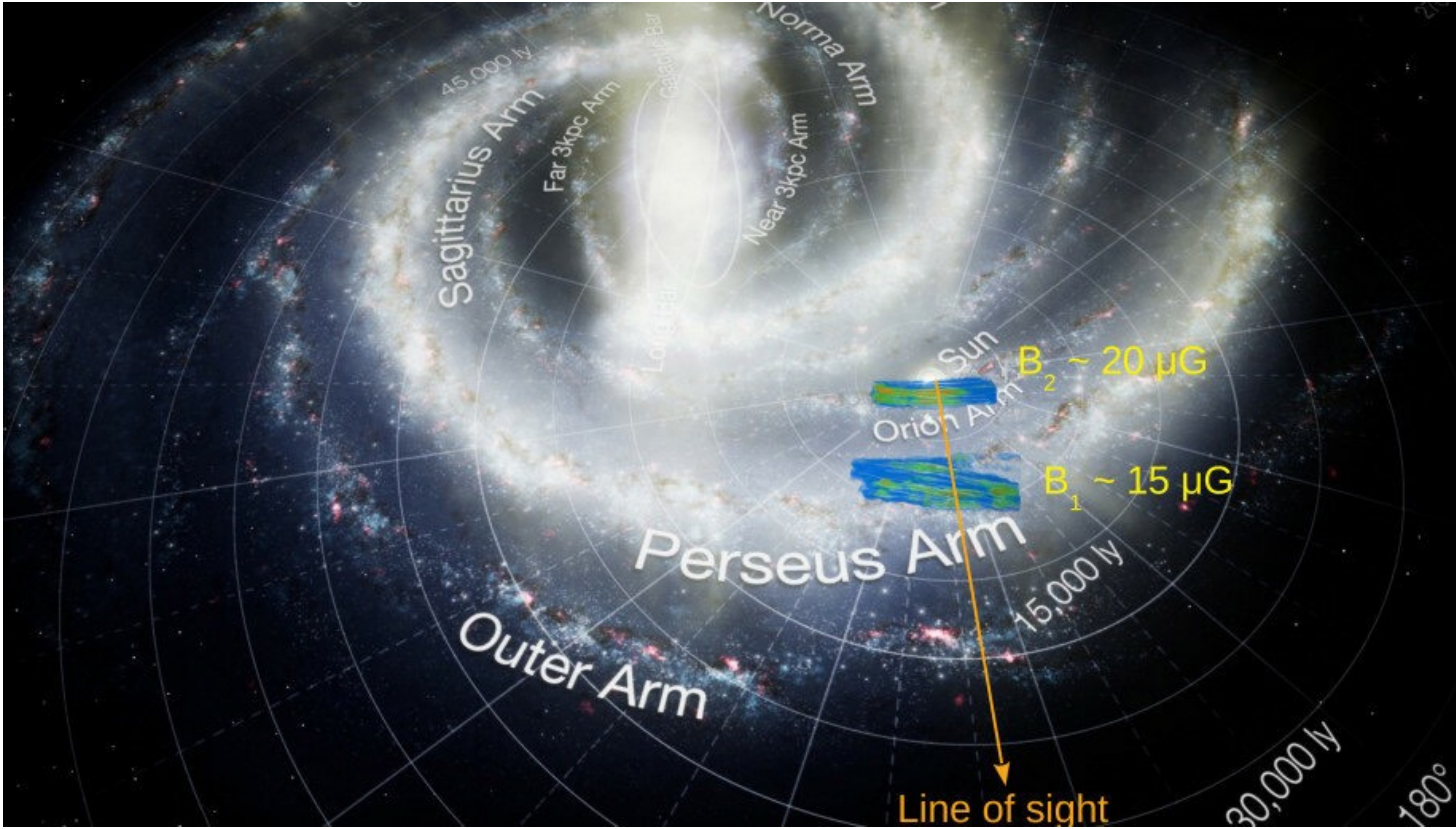
Sun **Jansson & Farrar** **Jaffe**



Three models for the regular component of the galactic B

F. Boulanger et al., JCAP08(2018)049

Propagation

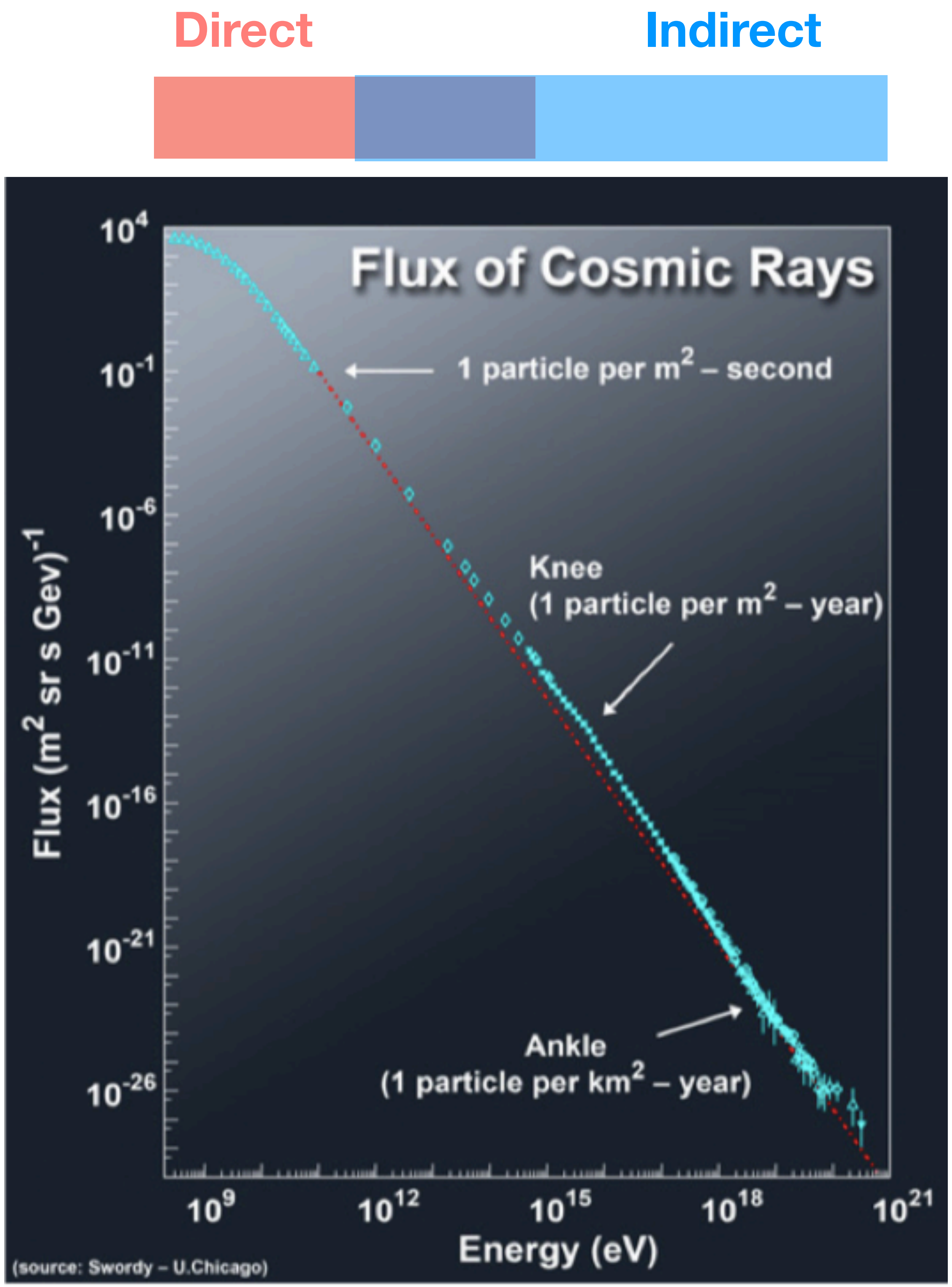


ANU webpage

First steps towards a 3D map of the magnetic field in the Milky Way

A. Tristes et al., ApJ 873 (2019)

4. Detection at very high energies



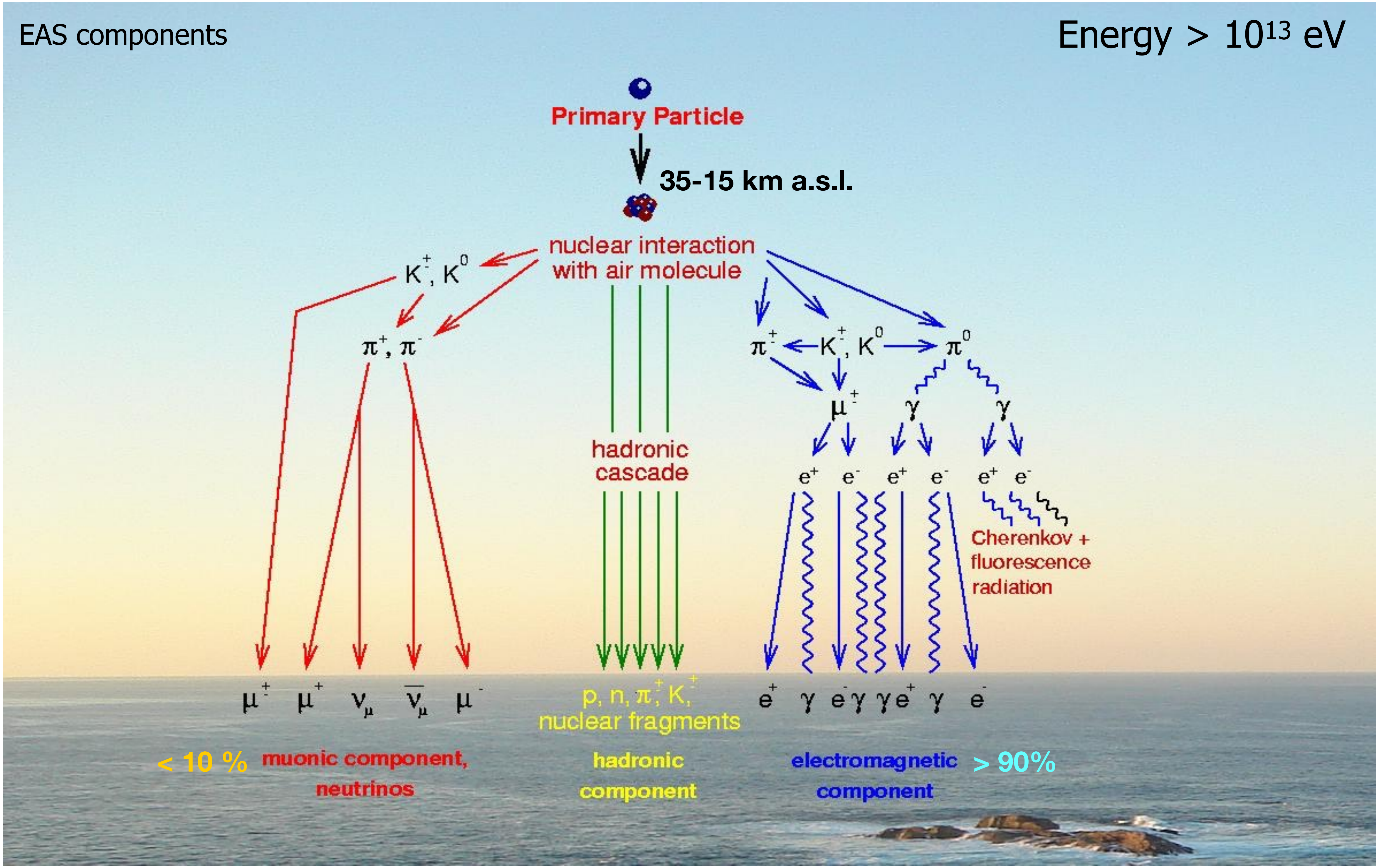
Cosmic ray detection

Direct measurements:
- Small areas
- E_{CR} < 1 PeV
- Direct determination of composition/energy.

Indirect measurements:
- Use **extensive air showers**
- Large collection areas
- E_{CR} > TeV's
- Indirect study of composition: Dependence on hadronic interaction models.

Extensive air showers

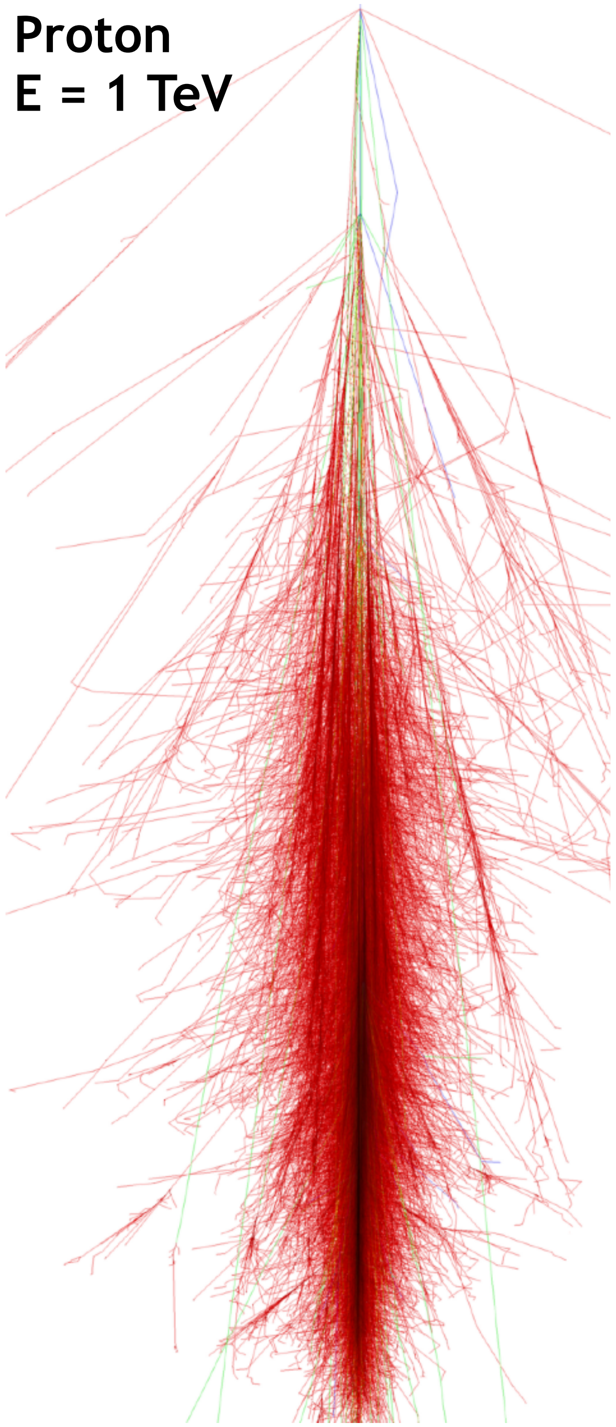
Indirect detection of cosmic rays through **extensive air showers** (EAS)



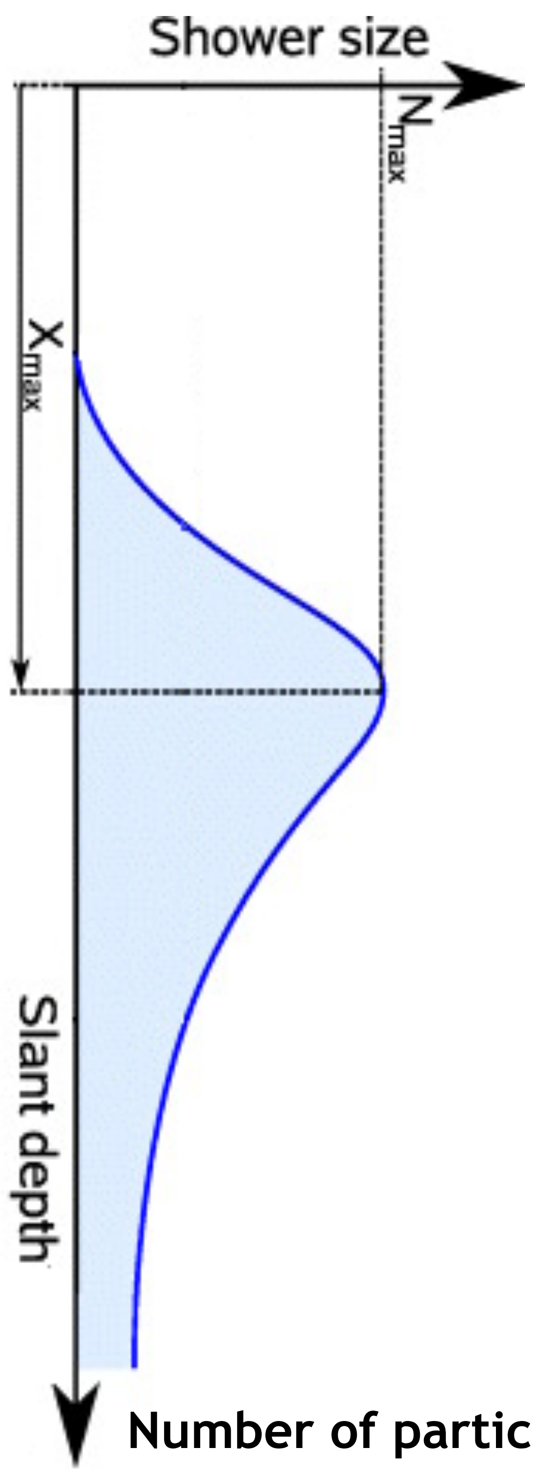
Extensive air showers

Longitudinal development

Proton
E = 1 TeV



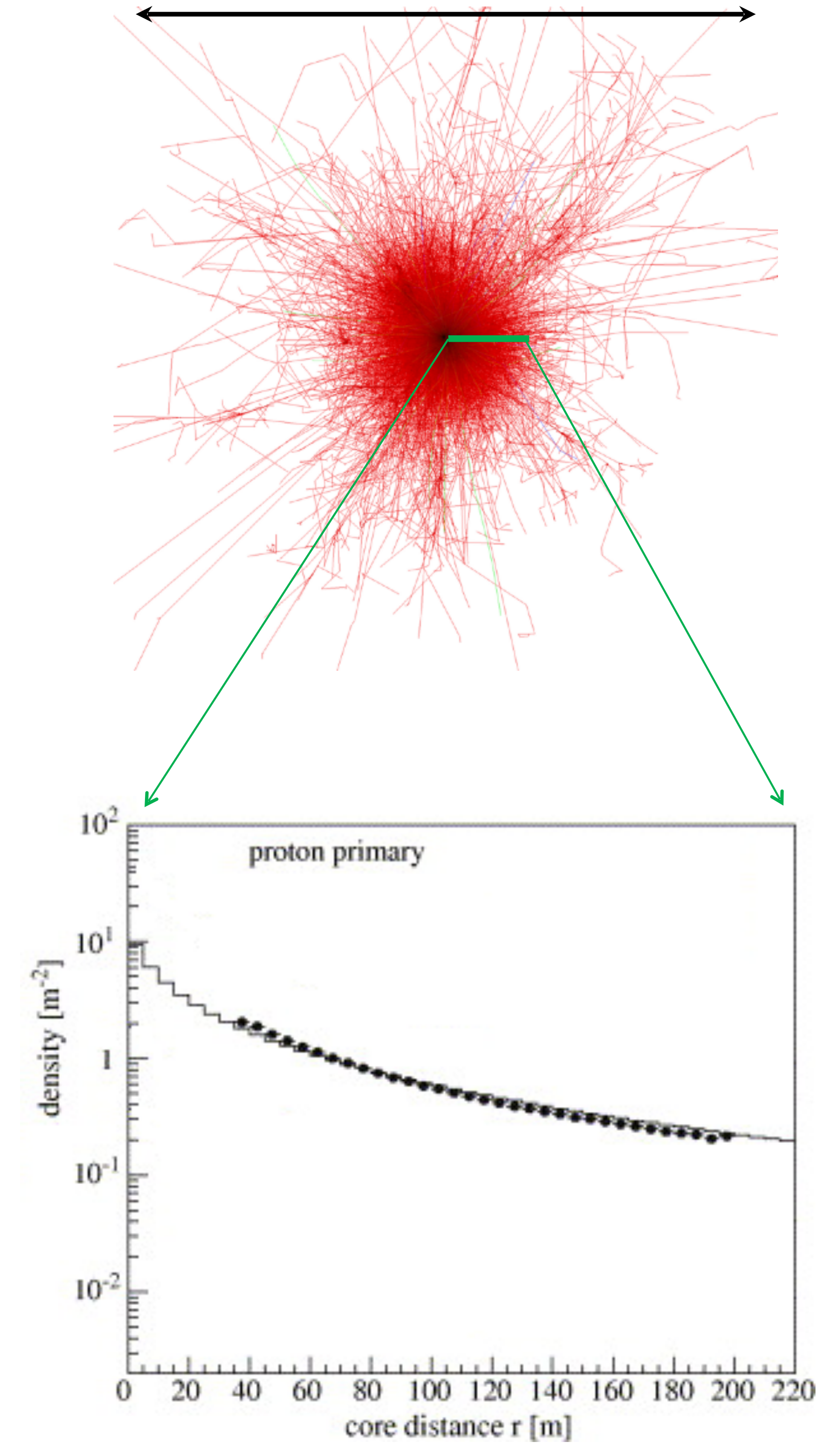
CORSIKA webpage



Number of particles at ground: $N \sim E^{\alpha}$

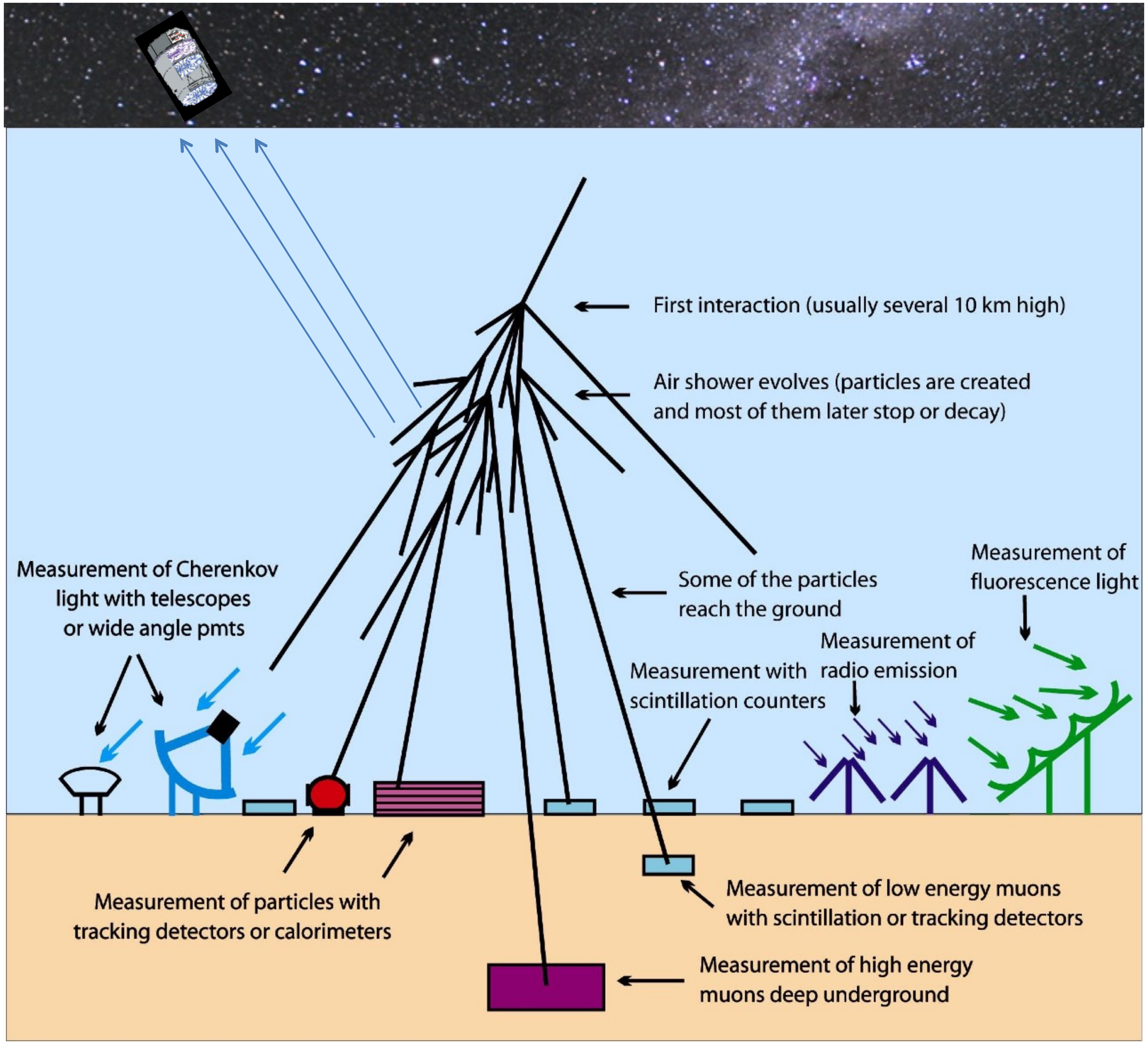
Lateral development

$\mathcal{O}$(0.1 - 1 km)



Extensive air showers

EAS detection from Earth and space



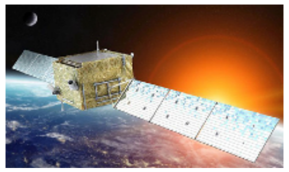
CR detectors E = 100 TeV - 1 EeV

Energy (eV/particle)

10^{13} 10^{14} 10^{15} 10^{16} 10^{17} 10^{18} 10^{19} 10^{20}

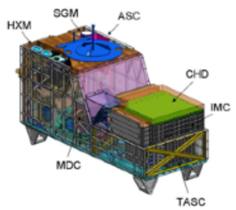
Knee

GZK cut-off

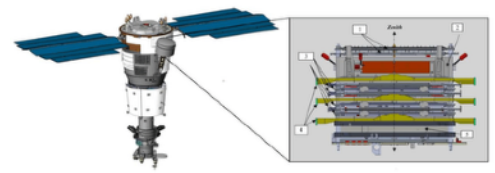


DAMPE

KASCADE-Grande



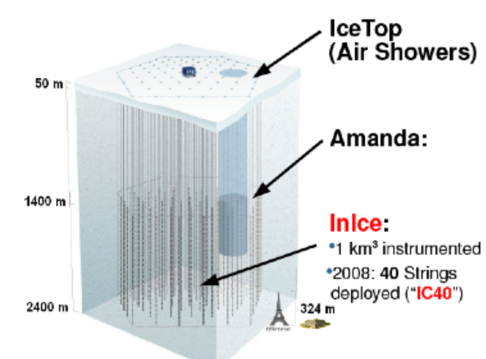
CALET / NUCLEON



Tibet As-γ

HAWC

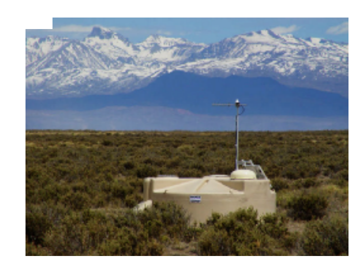
LHAASO

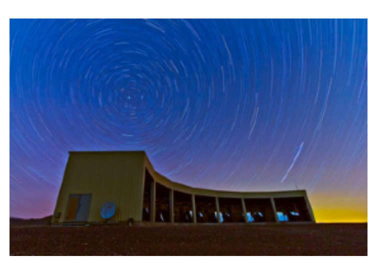


ICETOP/ICECUBE

Grapes-3

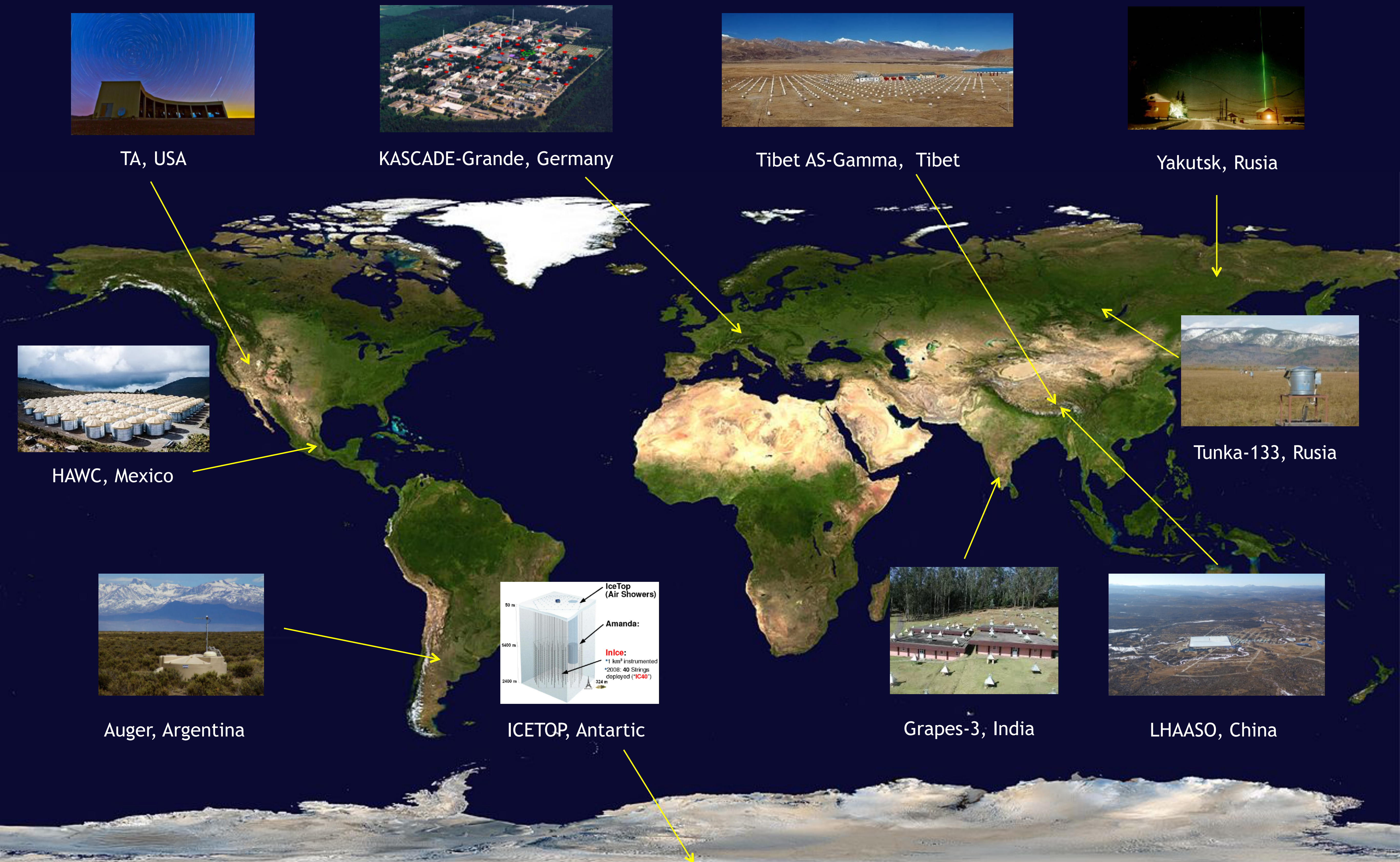
Pierre Auger





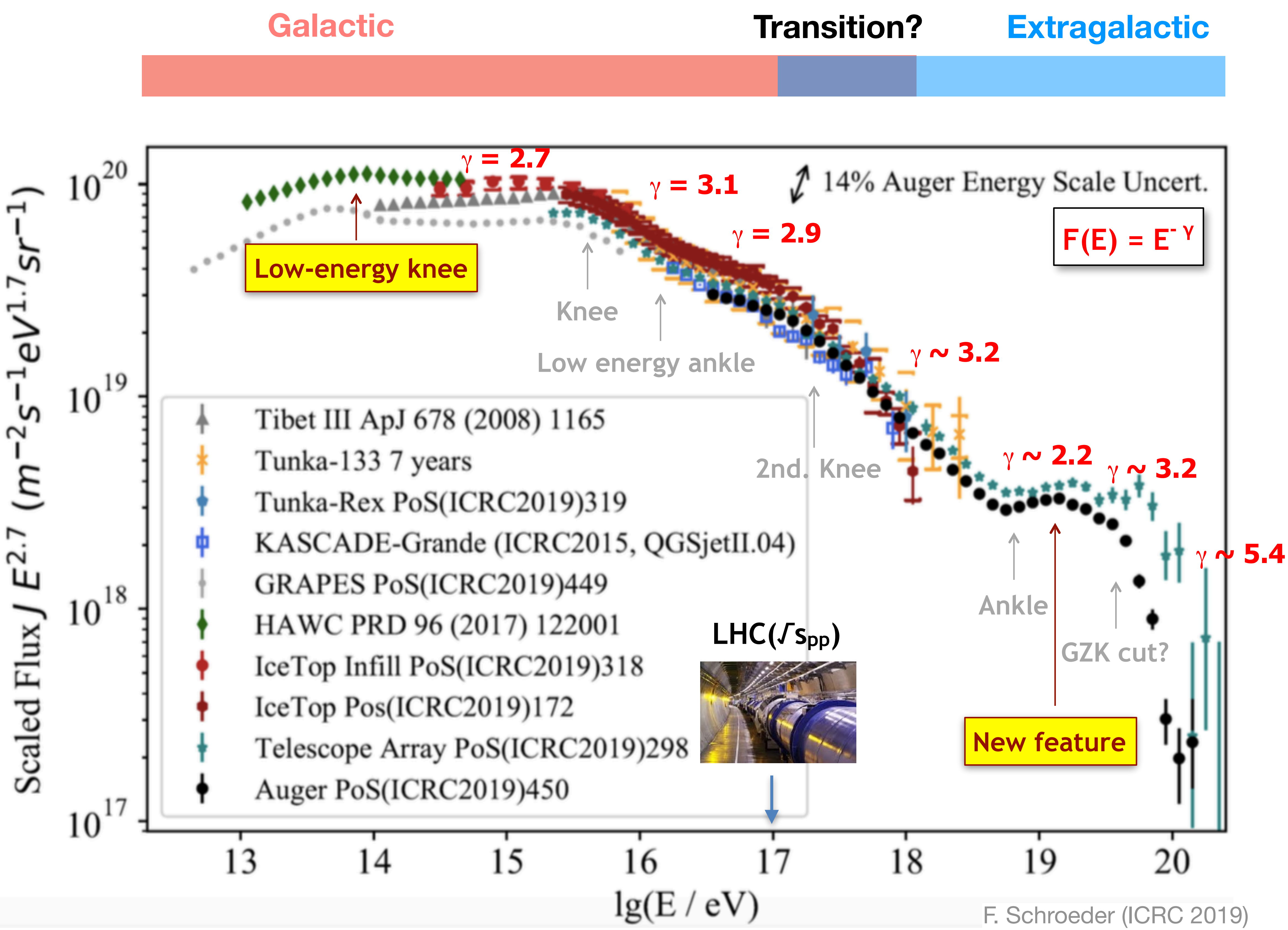
Telescope array

EAS experiments E = 100 TeV - 1 EeV

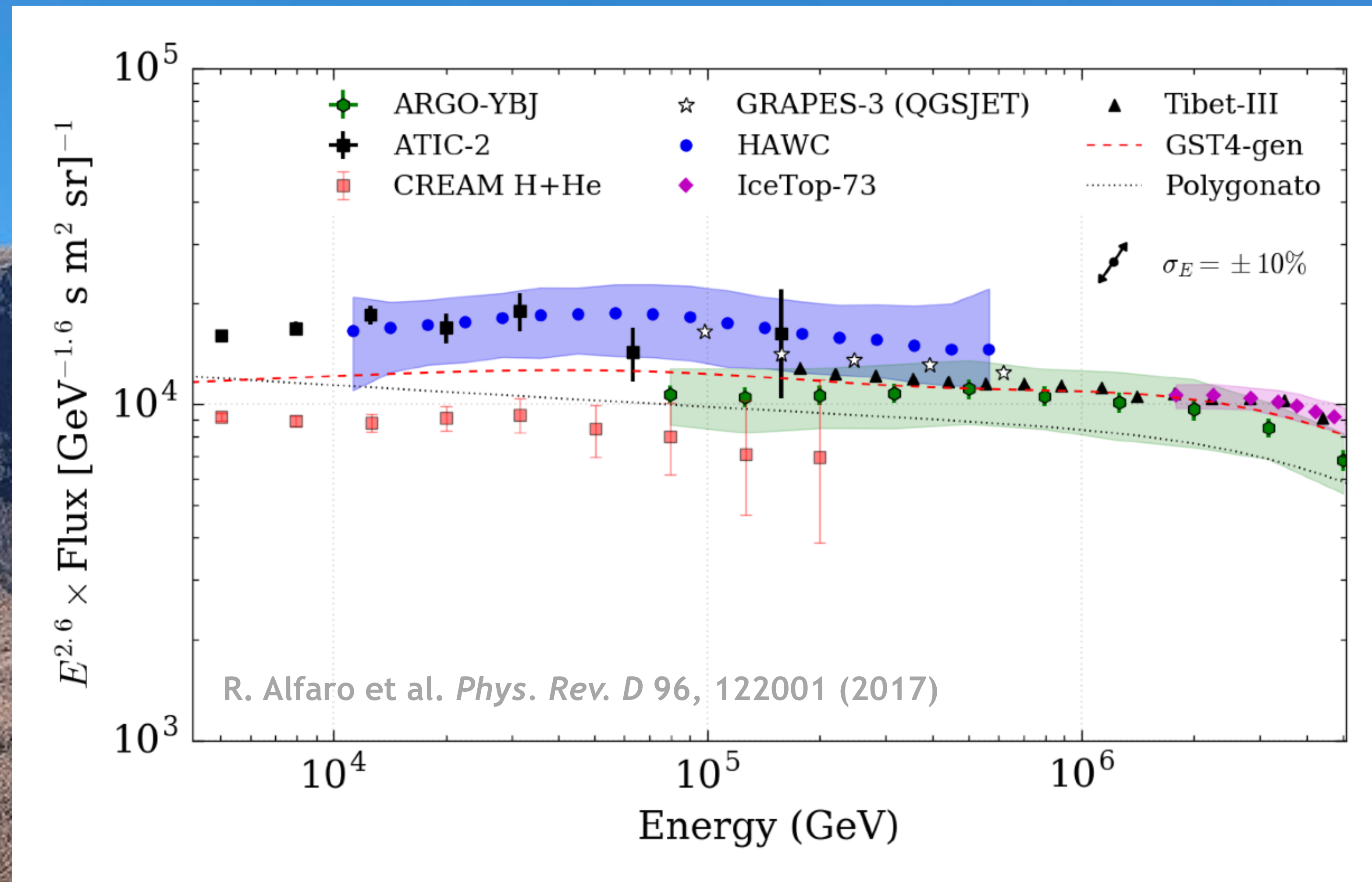


5. Experimental update

Energy spectrum



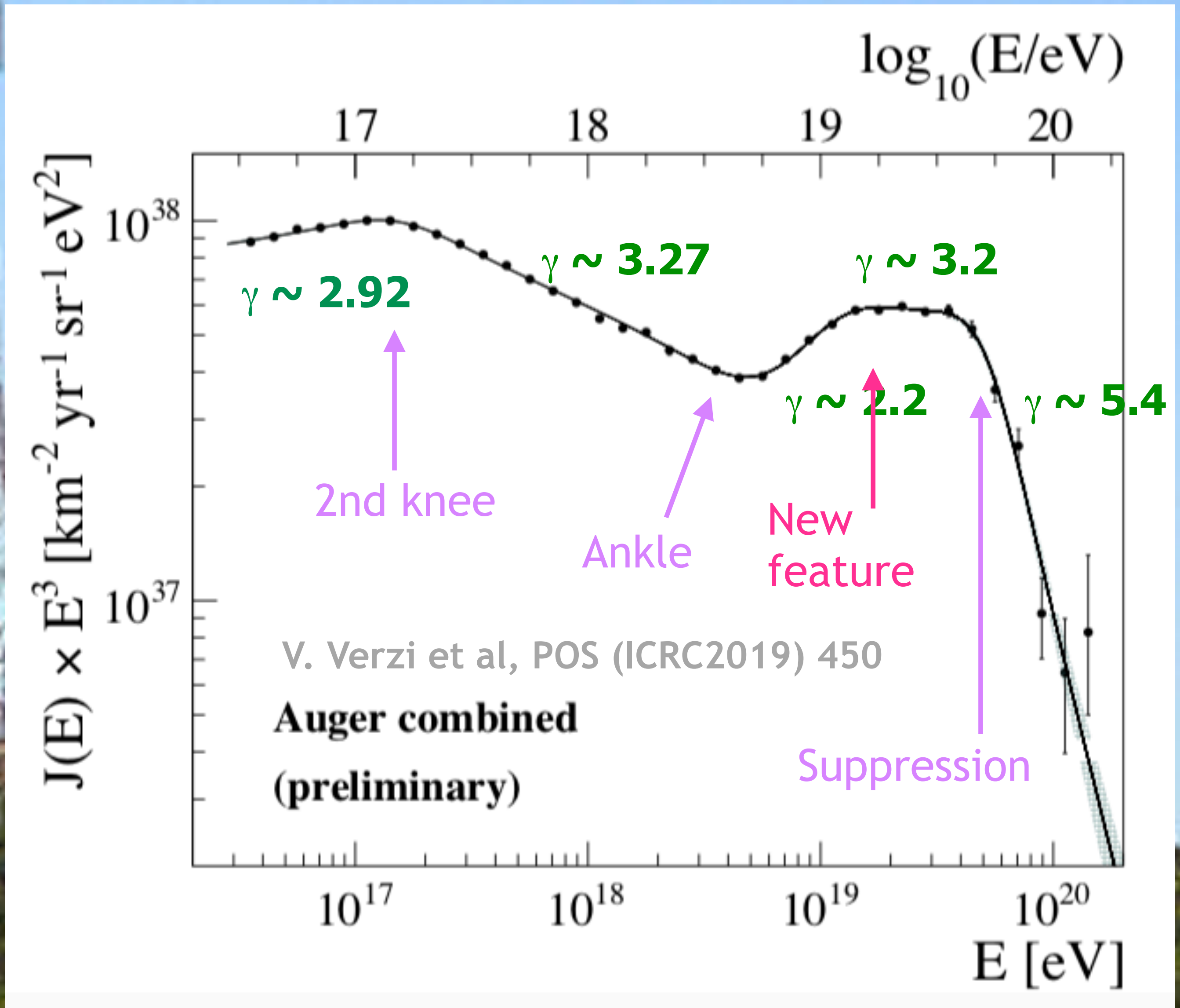
All-particle spectrum measured by the HAWC observatory



- First precision cosmic ray measurements at energies of $\mathcal{O}$(100 TeV).
- Discovery of a new knee @ E ~ 45 TeV.

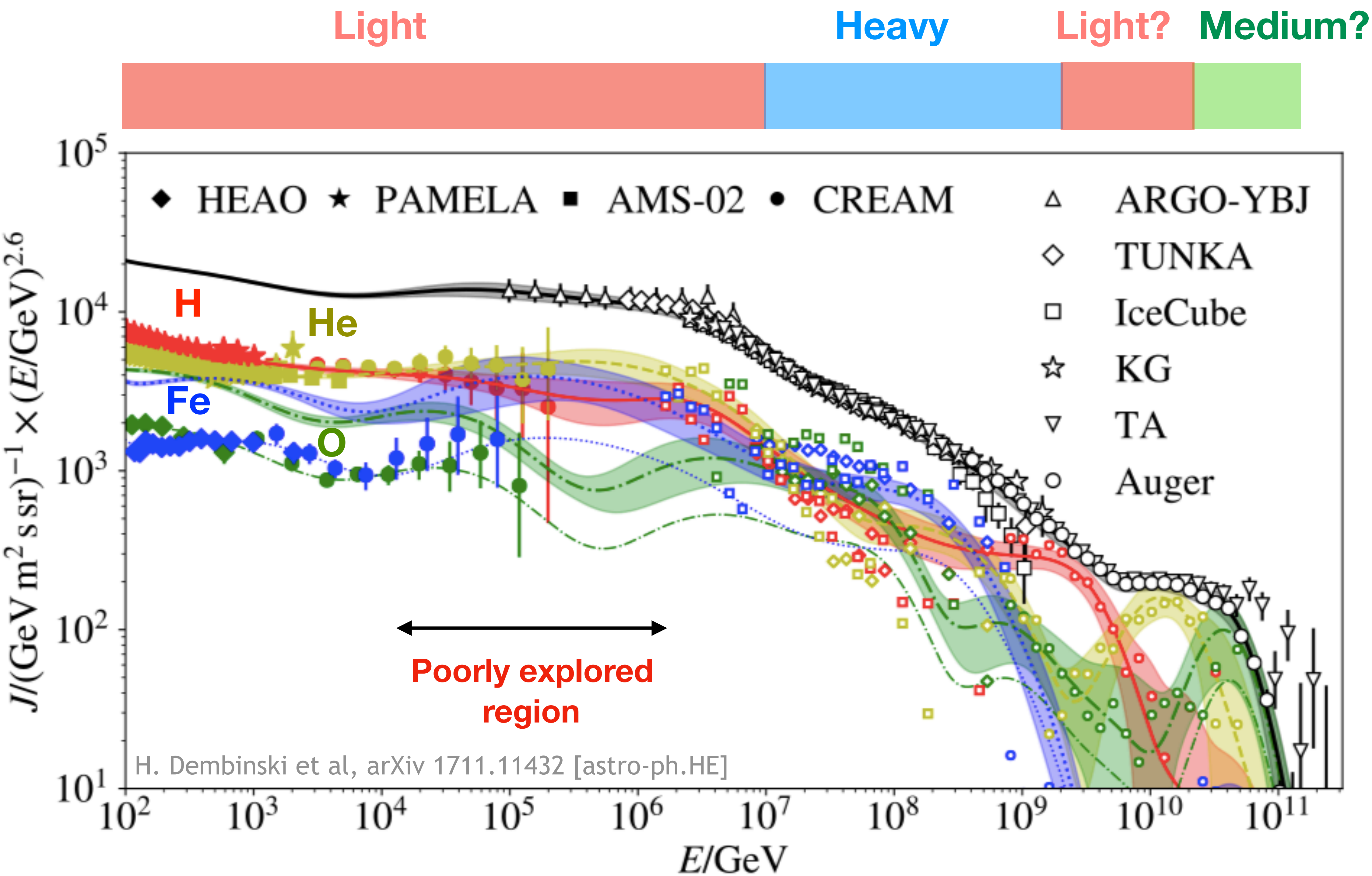
All-particle spectrum measured by the Pierre Auger observatory

- 2nd knee @ E ~ 0.15 EeV
- Ankle @ E ~ 6.2 EeV
- New feature @ E ~ 12 EeV
- Suppression @ E ~ 50 EeV



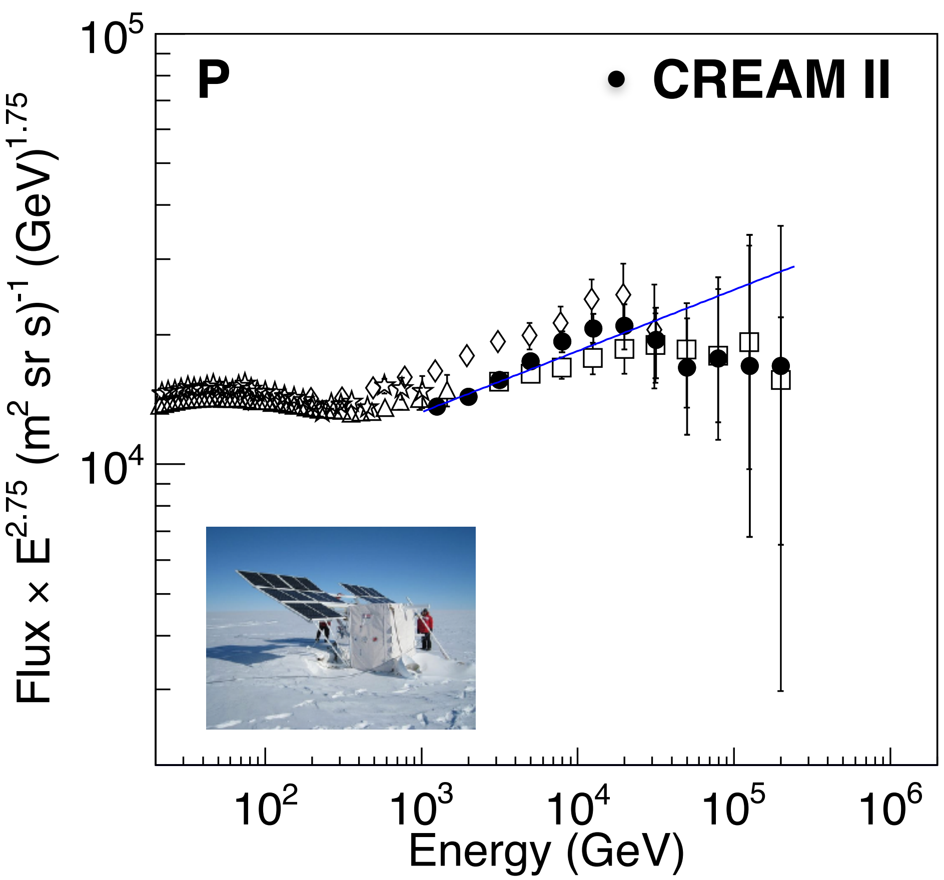
Composition

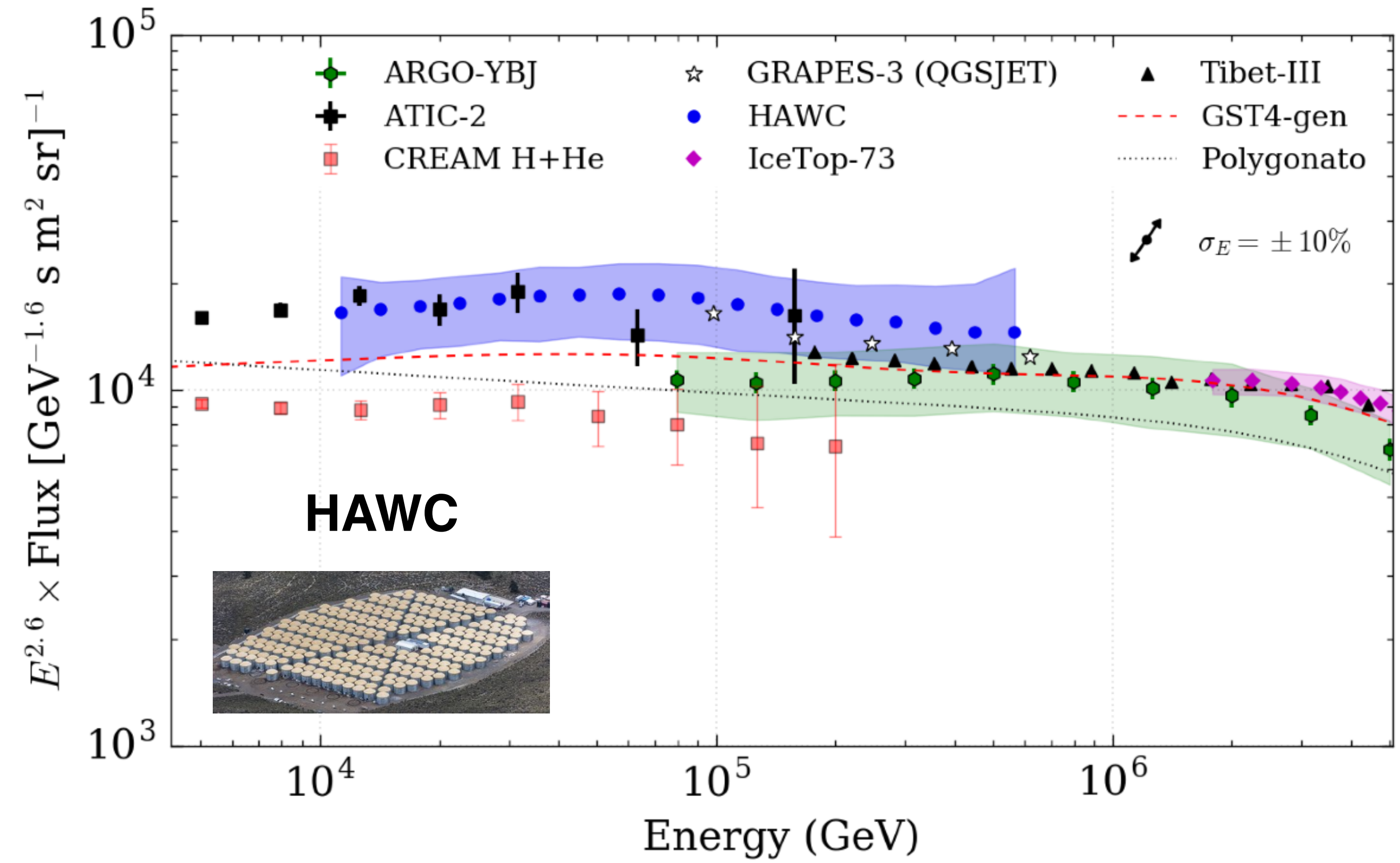
Dominated by:

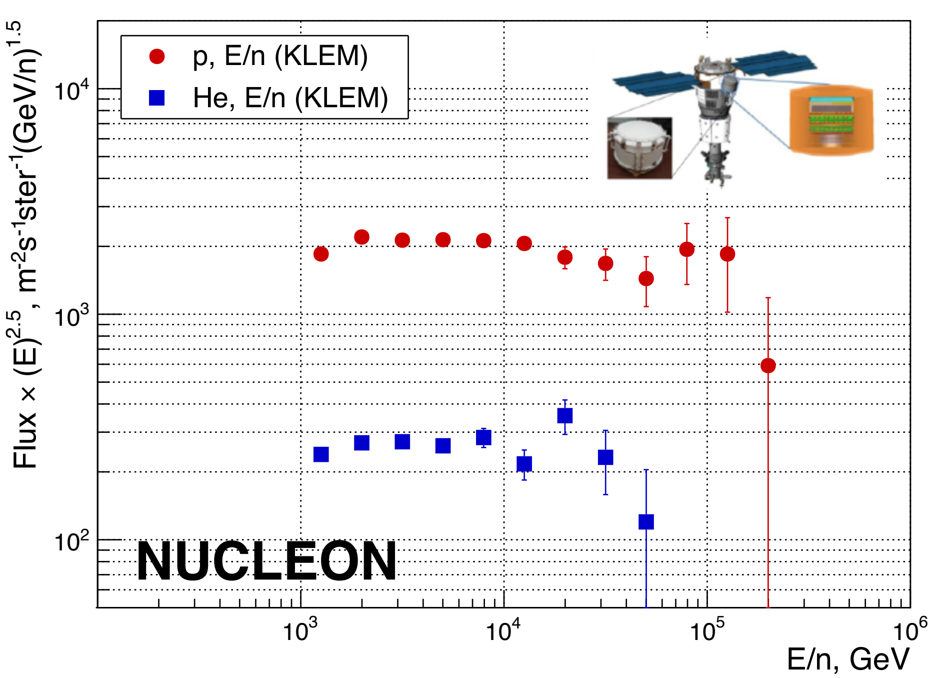


- Relative abundances of atomic nuclei in CR's change with energy
- Changes in spectral index related with evolution of CR composition.

Spectrum of H and He cosmic ray nuclei at TeV's







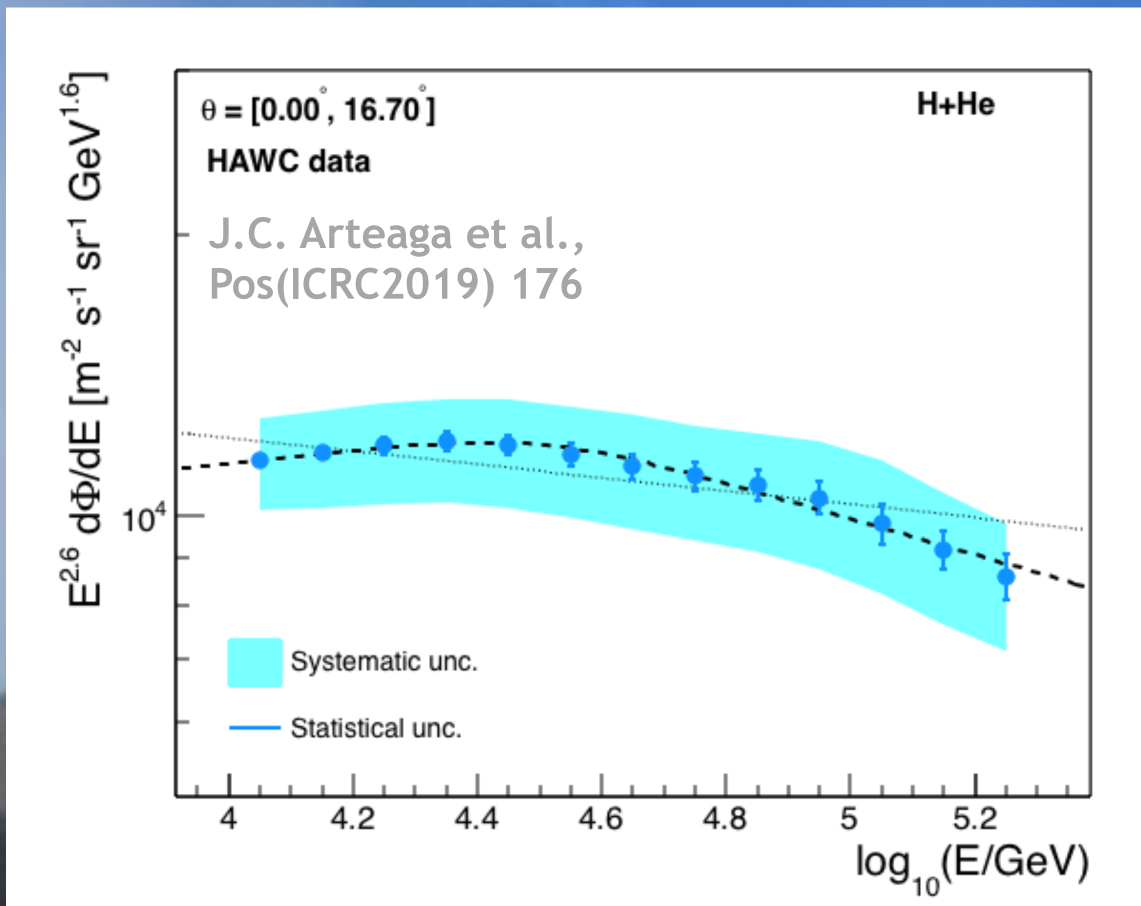
- **CREAM II:** Suggests existence of a break @ 10 TeV's, but low statistics. CREAM Coll., ApJ 839 (2017) 5

- **NUCLEON:** Claims that it confirms CREAM II result, but low statistics. NUCLEON Coll., JCAP 7 (2017)

- **HAWC:** Observation of a break @ 45 TeV in the all- particle spectrum, **is it caused by the light component of CR's?**

HAWC Coll., PRD 96 (2017) 122001

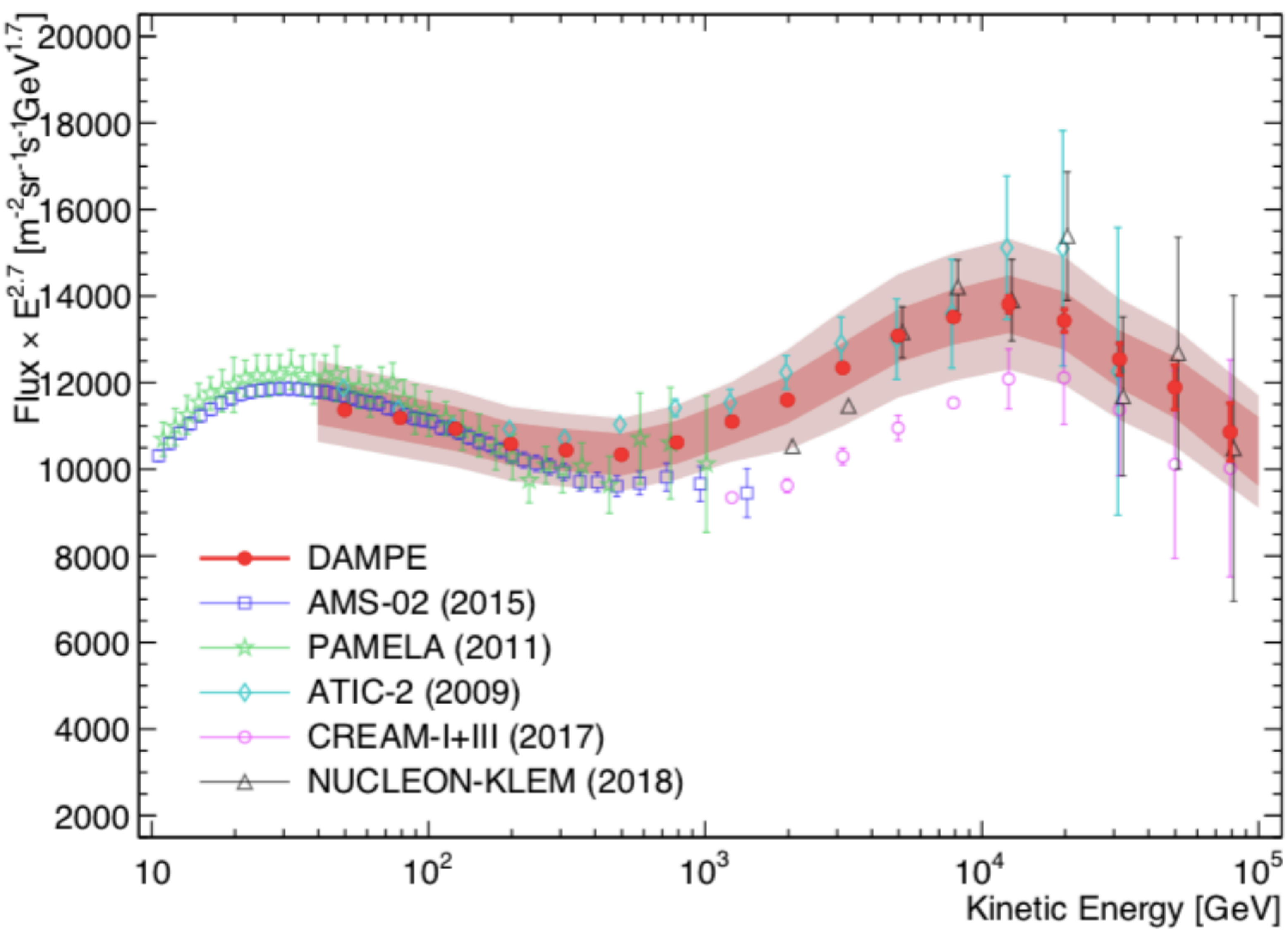
H+He spectrum measured by the HAWC observatory

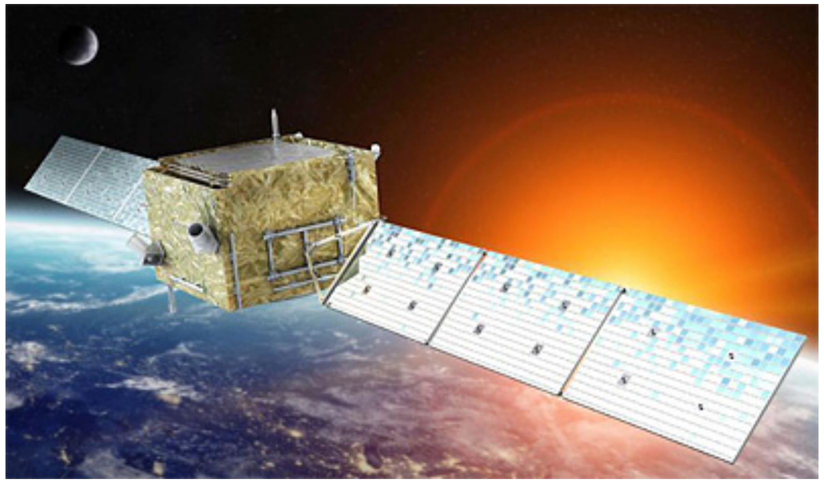


- First high-statistics measurements at energies of $\mathcal{O}$(100 TeV) for the mass group of light cosmic ray primaries.
- Discovery of a knee @ E ~ 32 TeV

H spectrum measured by the HAWC observatory

DAMPE: Observation of a cut in the spectrum of H close to 14 TeV.





DAMPE (Chinese academy of science)

Q. An et al., Science Advances, Vol. 5, no. 9, eaax3793 (2019)

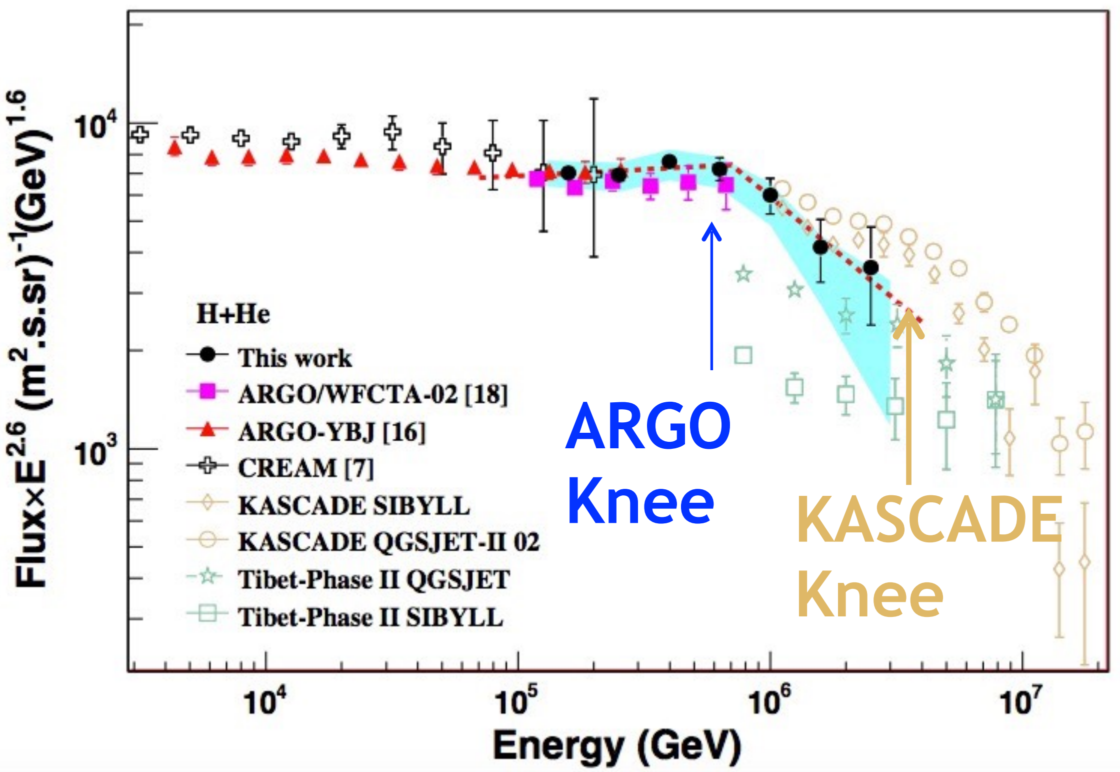
New population of CR sources?
CR Propagation issues?
What is the relation with the features seen by HAWC?

ARGO: A light knee below 1 PeV?

Argo-YBJ/LHAASO CTA: P+He spectrum (3 x 10^{12} - 3 x10^{15} eV)

- Argo-YBJ: 6700 m², 1836 Resistive Plate chambers (RPC's)
- Cherenkov telescope: 256 pixels, 1° x 1° each

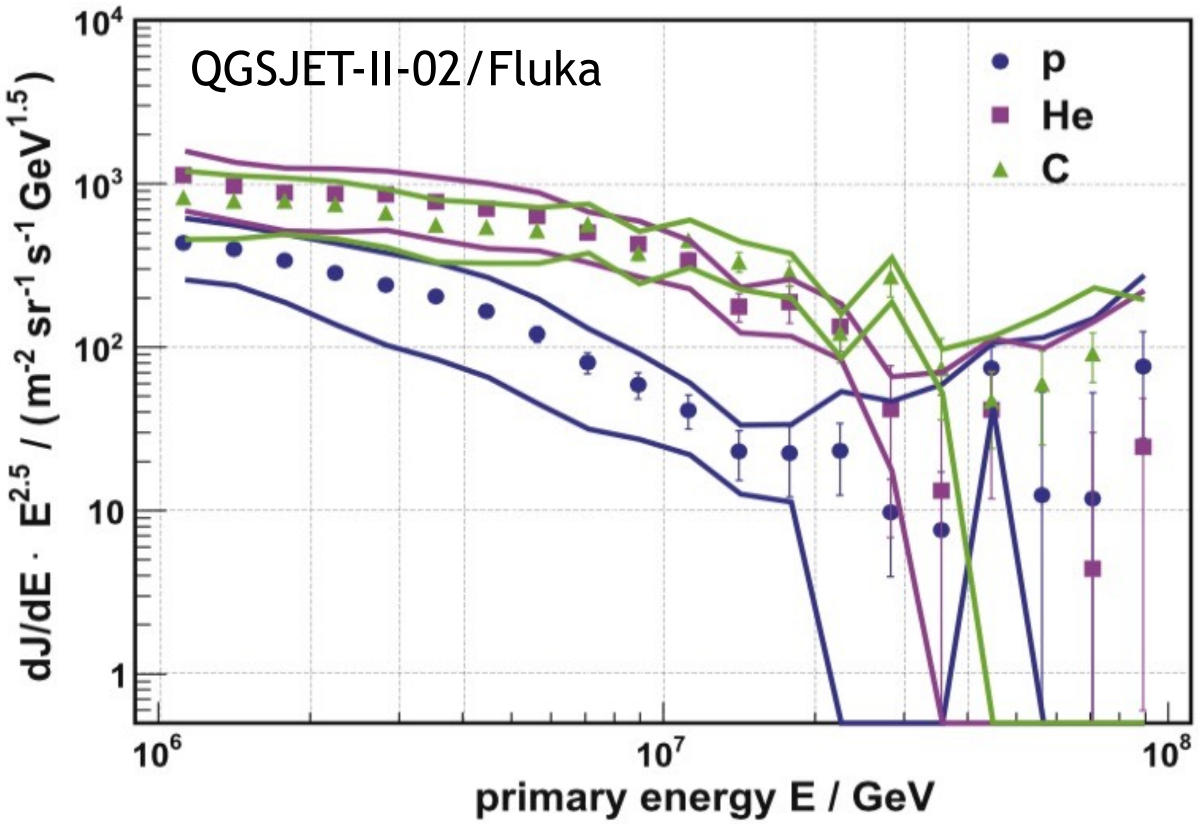
Argo-YBJ, PRD 92, 092005 (2015)

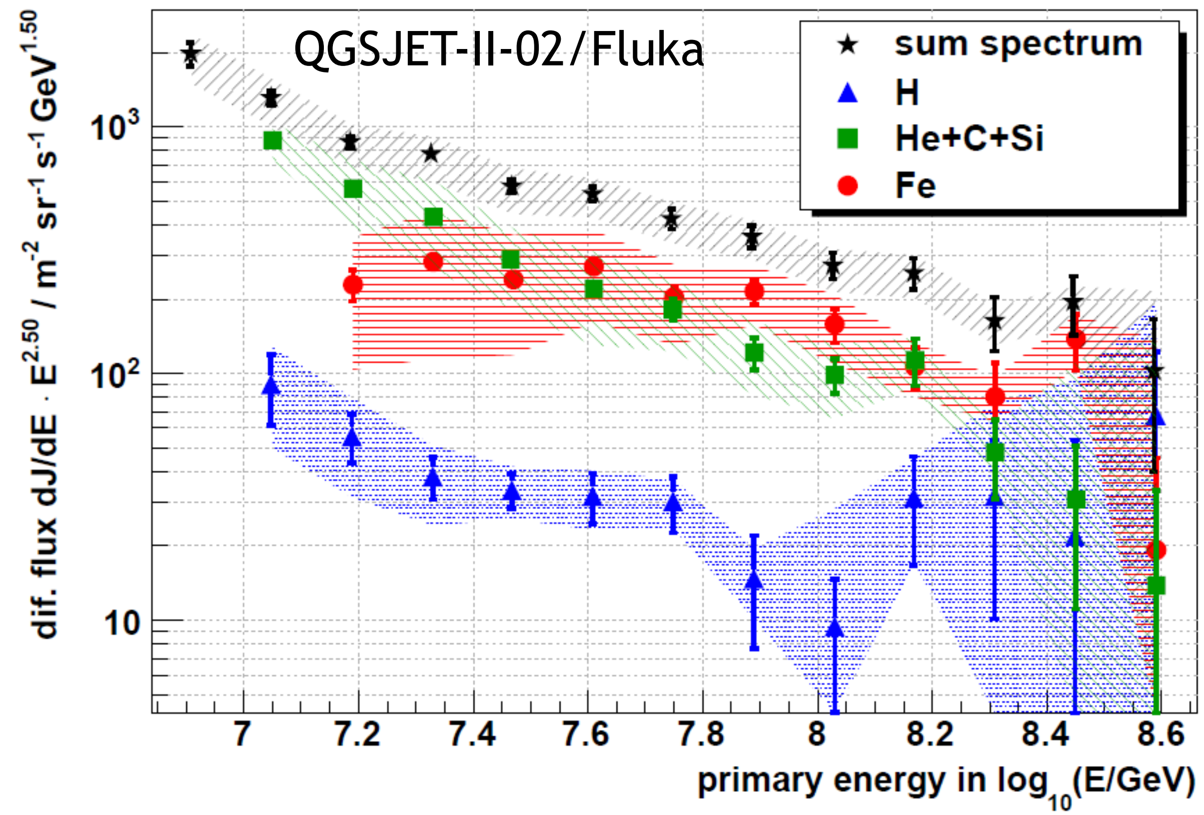


Location of light knee from ARGO (700 TeV) in disagreement with KASCADE

- One feature, but effect of systematic errors, or two different knees?
- If both features exist, are they related with different type of sources?

KASCADE-Grande: Composition around the knee





Results:

- Separation into elemental mass groups.

- PeV region is dominated by light nuclei.
- 100 PeV region is dominated by heavy nuclei.

- Knee: result of **breaks** in spectra of light components.
- 2nd Knee: result of **break** in spectrum of heavy mass group.

Position of individual knees:

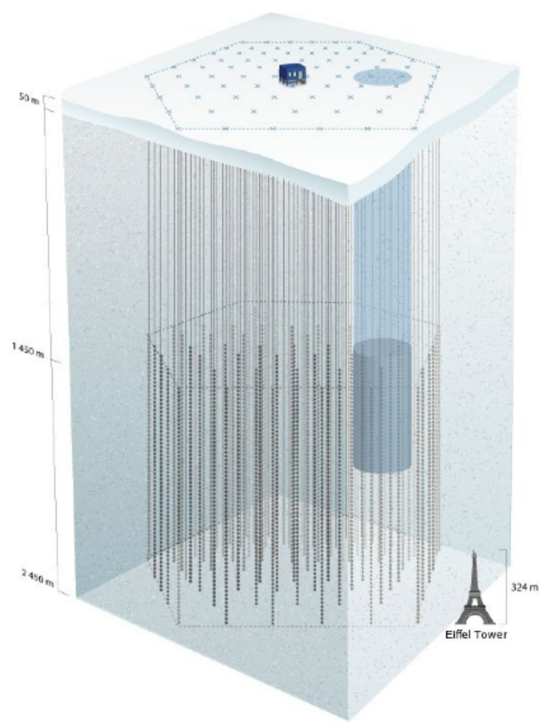
- H. : E_k = 4 PeV
- He: E_k = 7 PeV
- C : E_k = 20 PeV
- Fe: E_k = 80 PeV

$E^Z_k \propto Z$ → **Influence of magnetic field in acceleration/ propagation of CRs**

KASCADE Coll., Astrop. Phys. 24 (2005) 1; Astrop. Phys. 47 (2013) 54

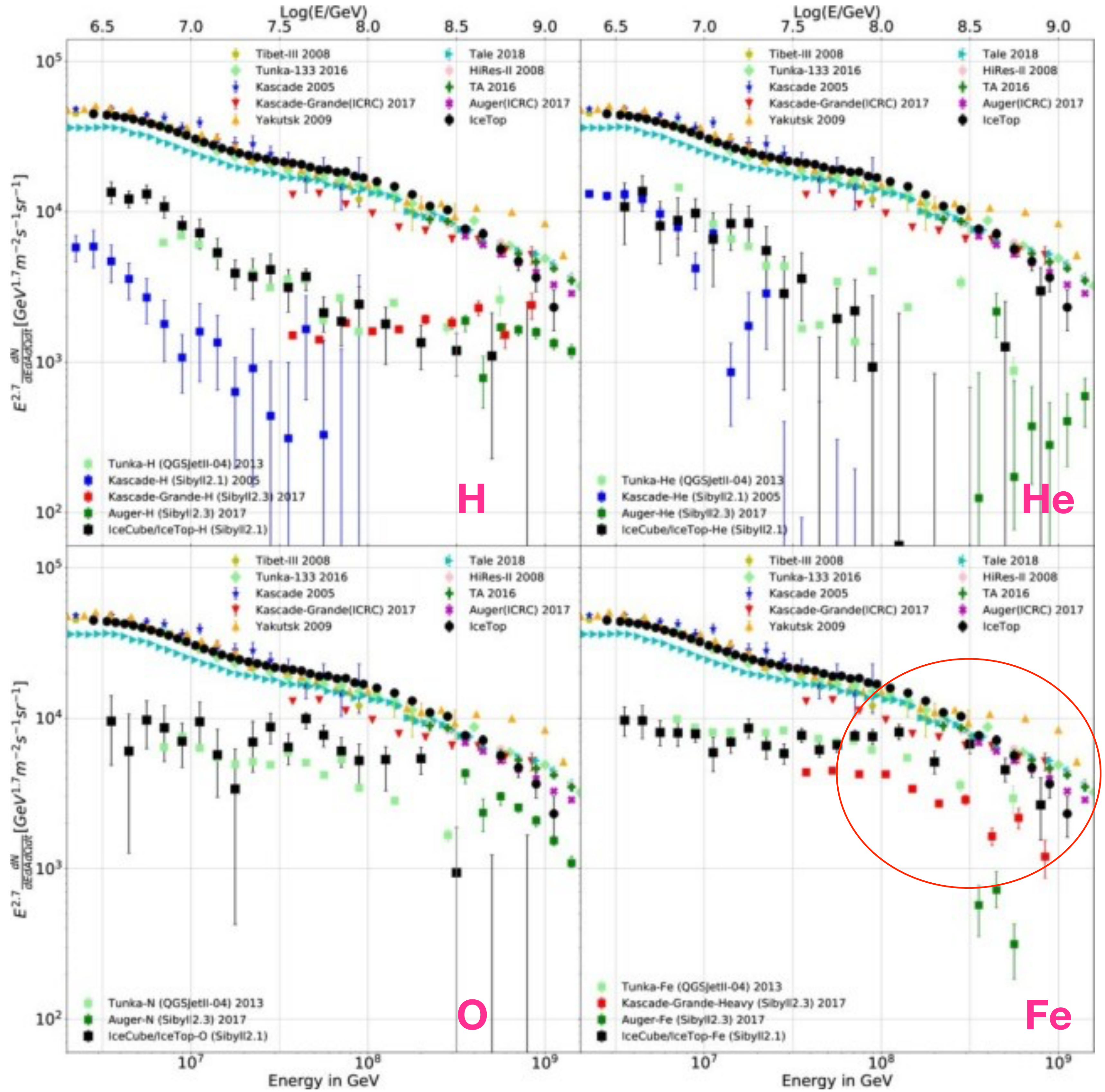
ICETOP: Spectra of mass groups

ICECUBE, PRD 100, 082002 (2019)

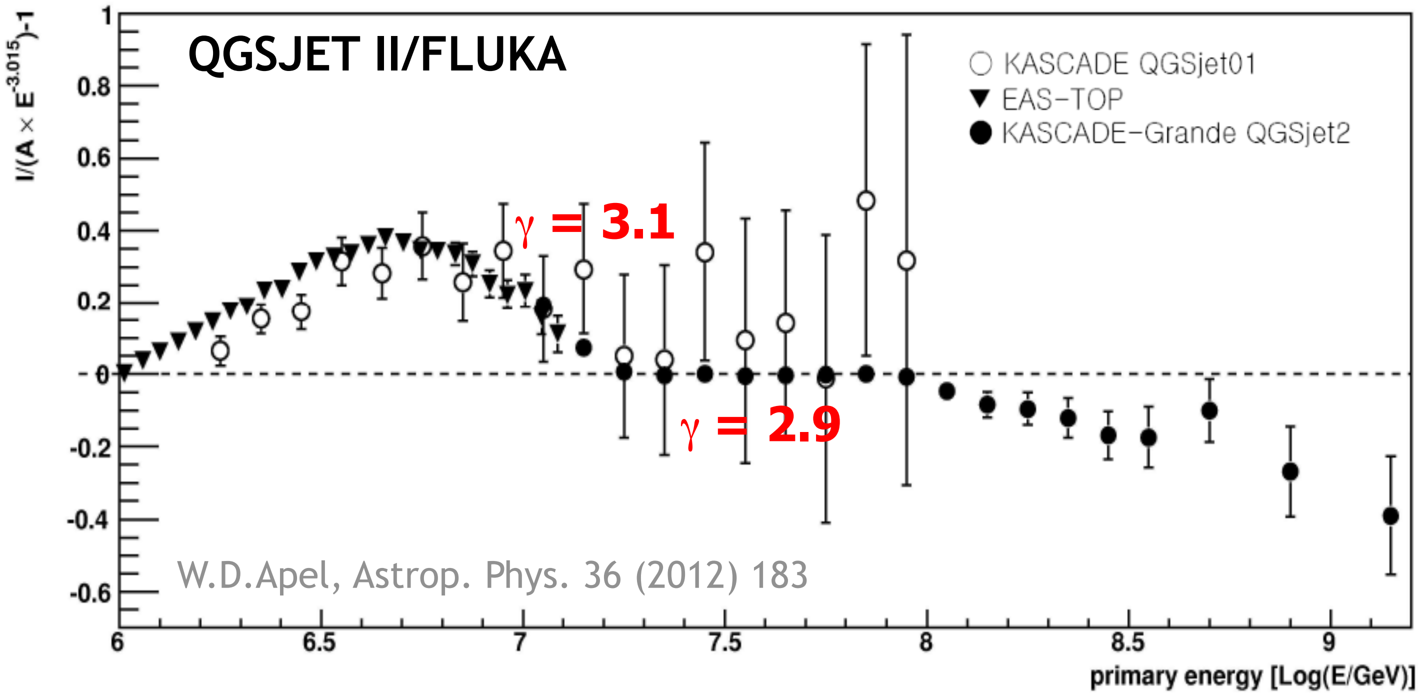


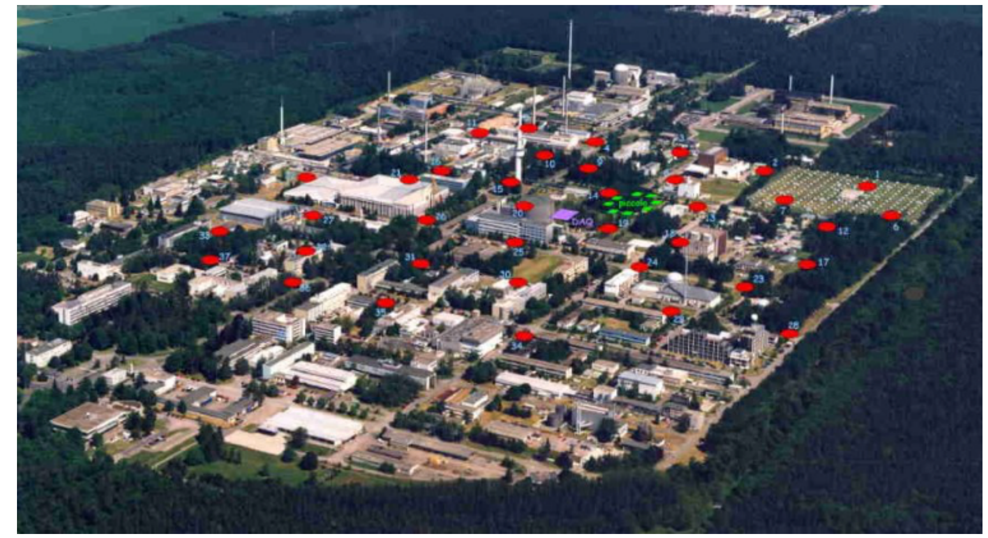
- At 100 PeV the dominant component is the heavy one.

- **ICETOP**'s iron spectrum shows a break at higher energies than observed by **KASCADE-Grande**.



Low energy ankles: all-particle spectrum

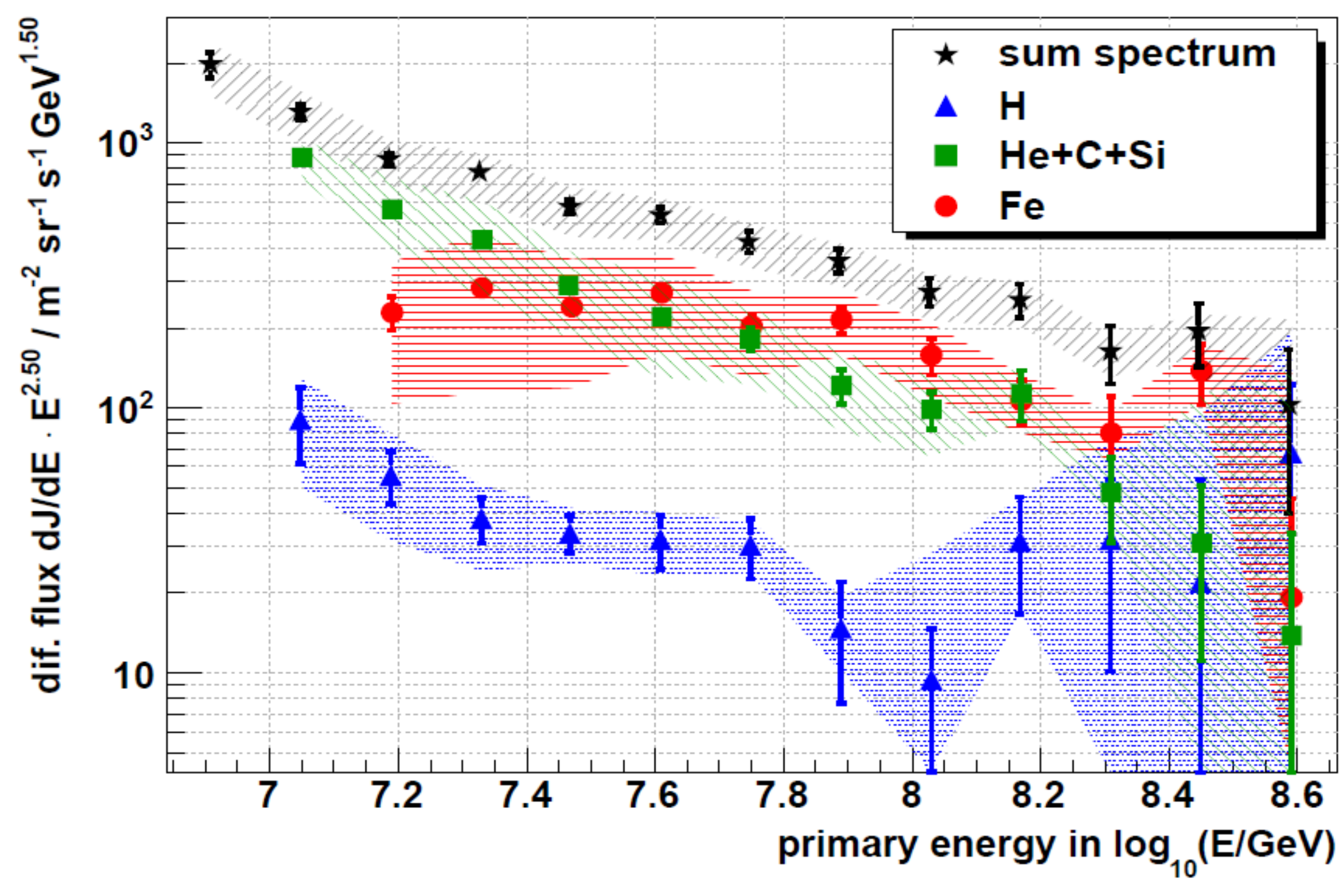




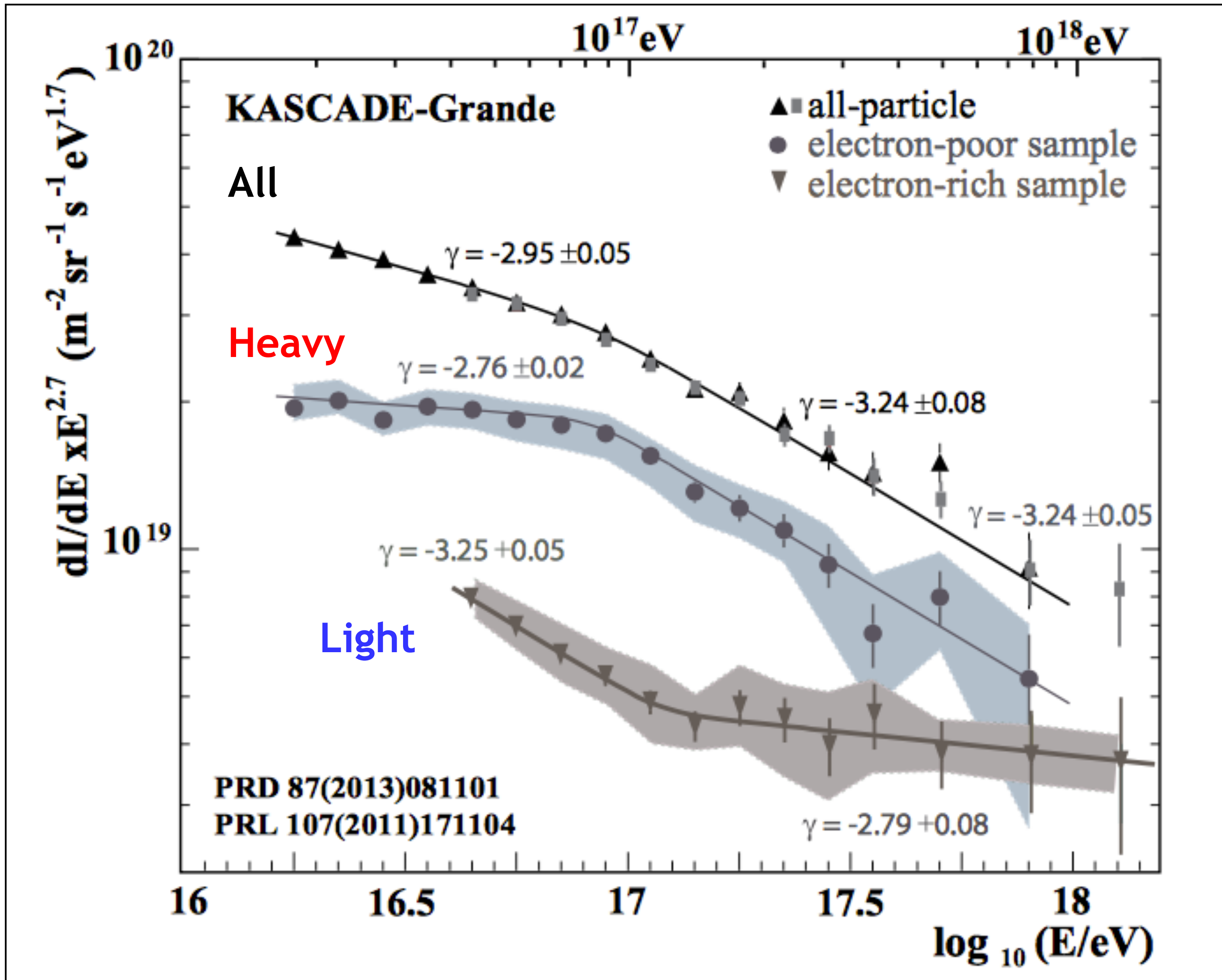
KASCADE-Grande

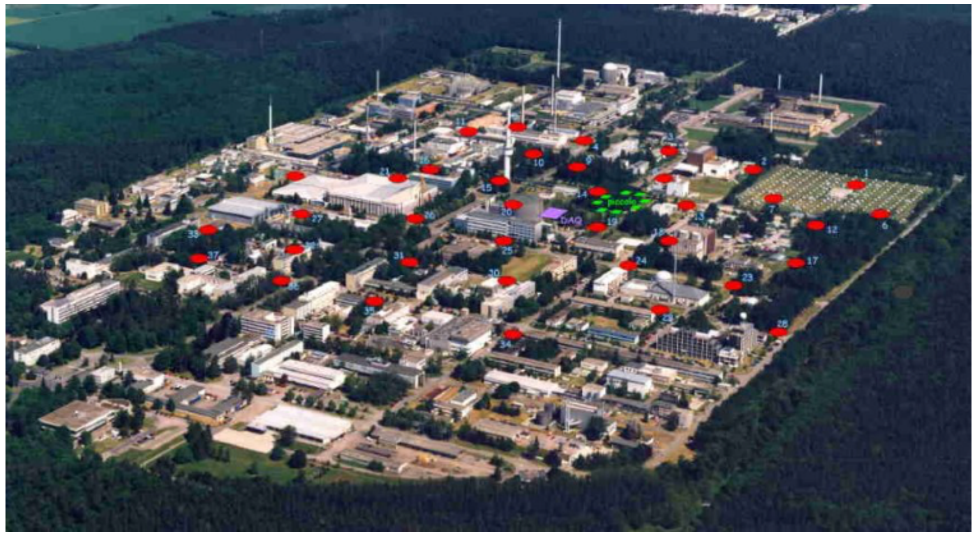
KASCADE coll., Astrop. Phys. 47 (2013) 54

- **Low energy ankle in all-particle spectrum** at **2 x 10^{16} eV** due to transition from intermediate to heavy component.



Low energy ankles: spectrum of light mass group





KASCADE-Grande

No correction for migration effects

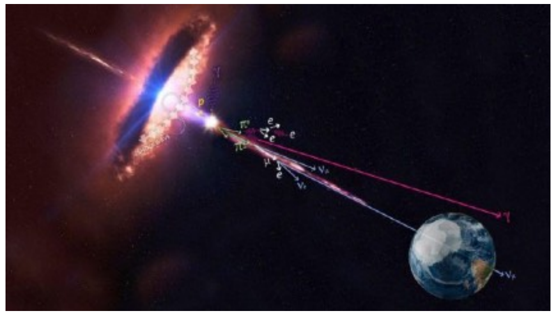
- **Low energy ankle in spectrum of light mass group** at **$10^{17.1}$eV**

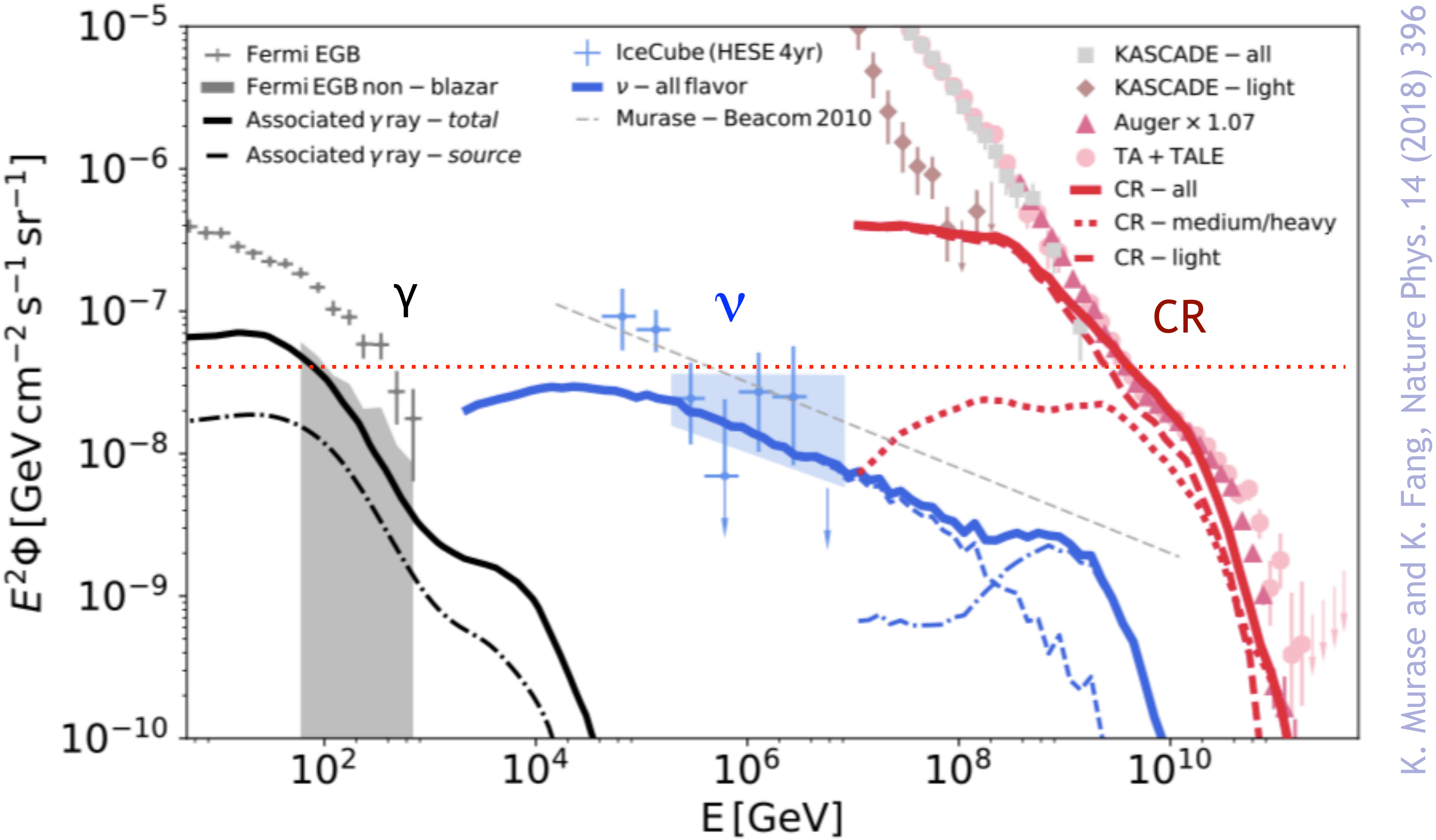
Galactic-extragalactic transition?

Low energy ankles: spectrum of light mass group

Icecube/NASA

Energy generation rate of **isotropic sub-TeV γ-rays**, diffuse PeV ν's and ultra-HE cosmic rays is of the same order: Common origin?





- CR's (E > 100 PeV) : produced in **jets of AGN's** inside cluster of galaxies.
- HE γ-rays and PeV ν's : created by interactions of CR's with hot cluster.

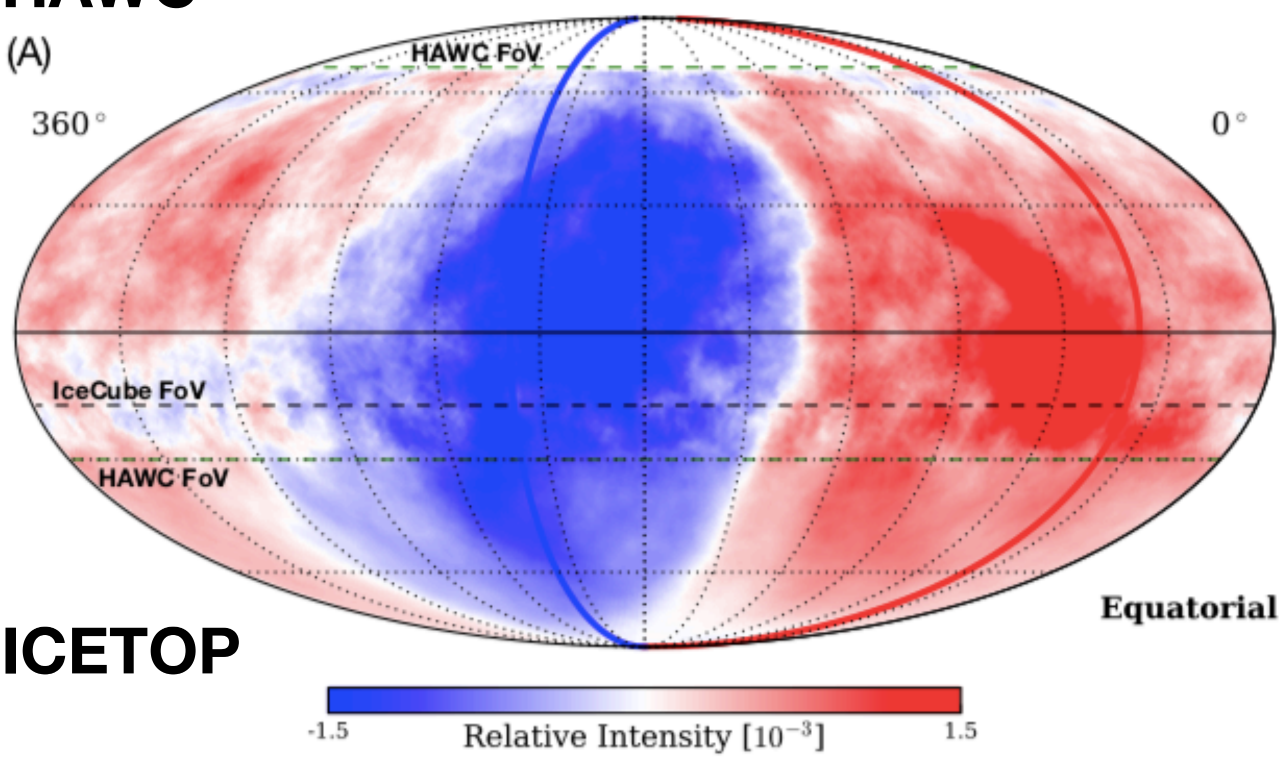
Anisotropies in arrival directions

- Anisotropies of order 10^{-3} - 10^{-4} have been observed in sky map of arrival directions of cosmic rays (Tibet, ARGO-YBJ, Milagro, HAWC, ICECUBE, etc)
  - Large scale: dominated by a dipole (expected from diffusion theory)
  - Small scale: hot spots (unexpected, heliosphere? local turbulence/source? non-diffusive propagation?)

First combined all-sky map of CR anisotropies from HAWC/ICECUBE data

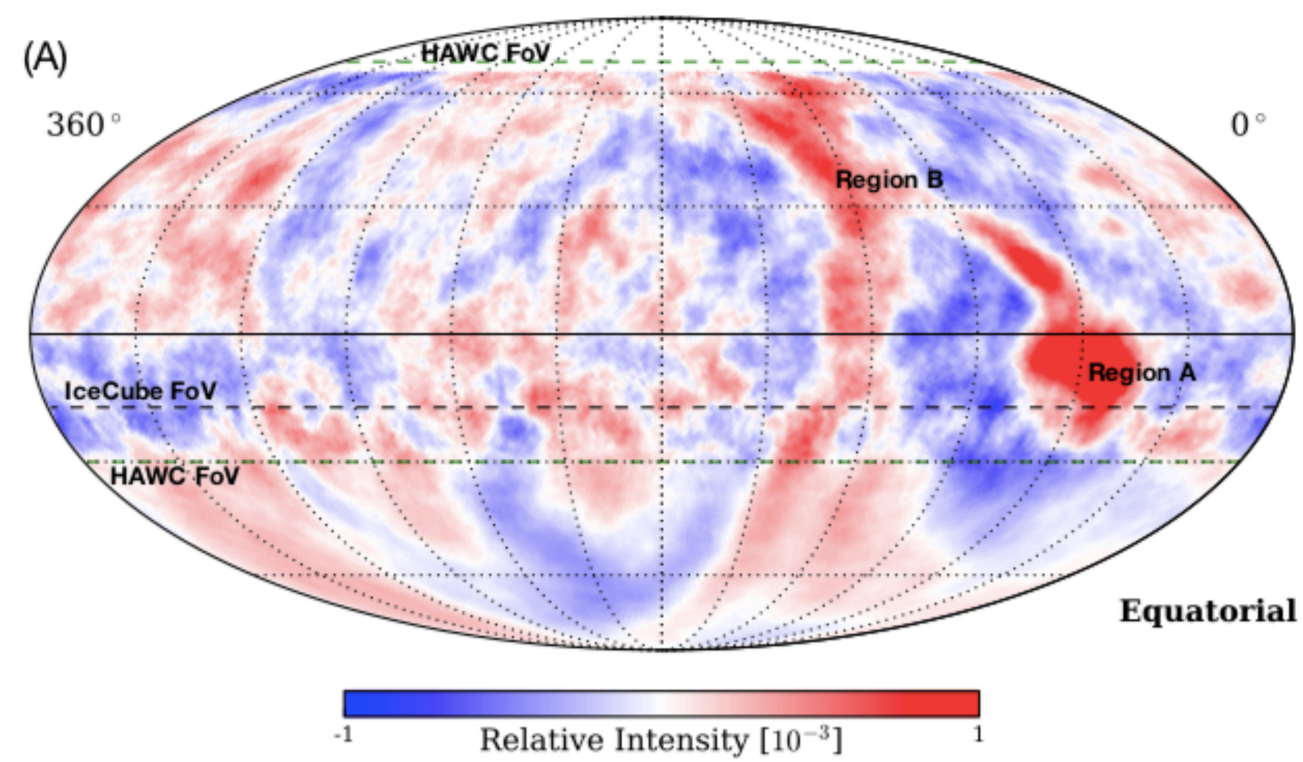
E = 10 TeV

HAWC



ICETOP

Large scale > 60^o



Small scale < 60^o

ICETOP/HAWC, ApJ 871 (2019) 96

Anisotropies in arrival directions

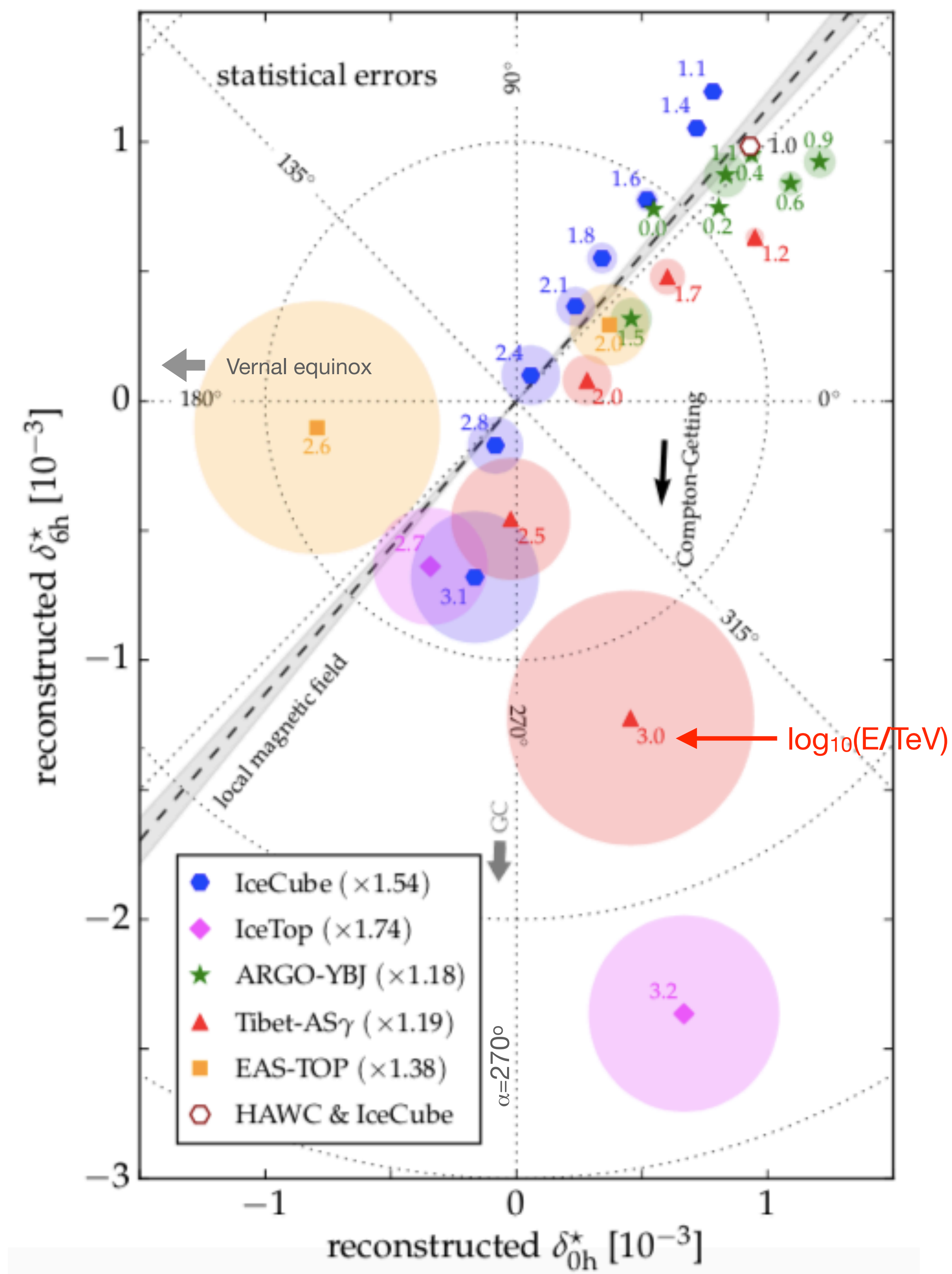
- Arrival maps are sensitive to:
  - Intensity and configuration of magnetic fields
  - Details of propagation of CR's in space
  - Spatial/temporal distribution of sources

- Dipole ($\boldsymbol{\delta}$):

$$\boldsymbol{\delta} \equiv (\delta_{0h}, \delta_{6h}, \delta_N)$$

$$\delta I_{\text{dipole}}(\alpha, \delta) = \boldsymbol{\delta} \cdot \mathbf{n}(\alpha, \delta)$$

- Proportional to CR gradient density.

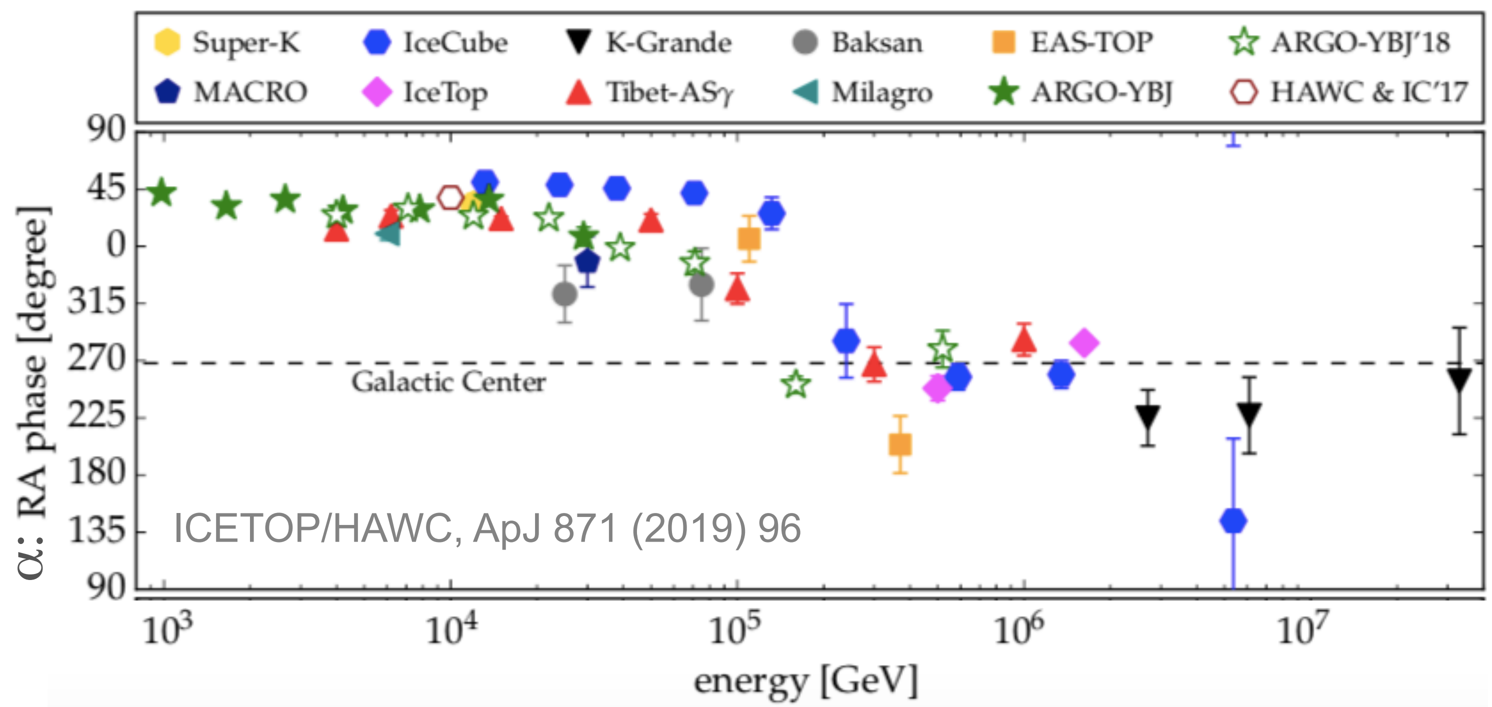


Dipole projection on the equatorial plane

M. Ahlers, arXiv: 1811.08136 [astro-ph.HE]

Anisotropy in arrival directions

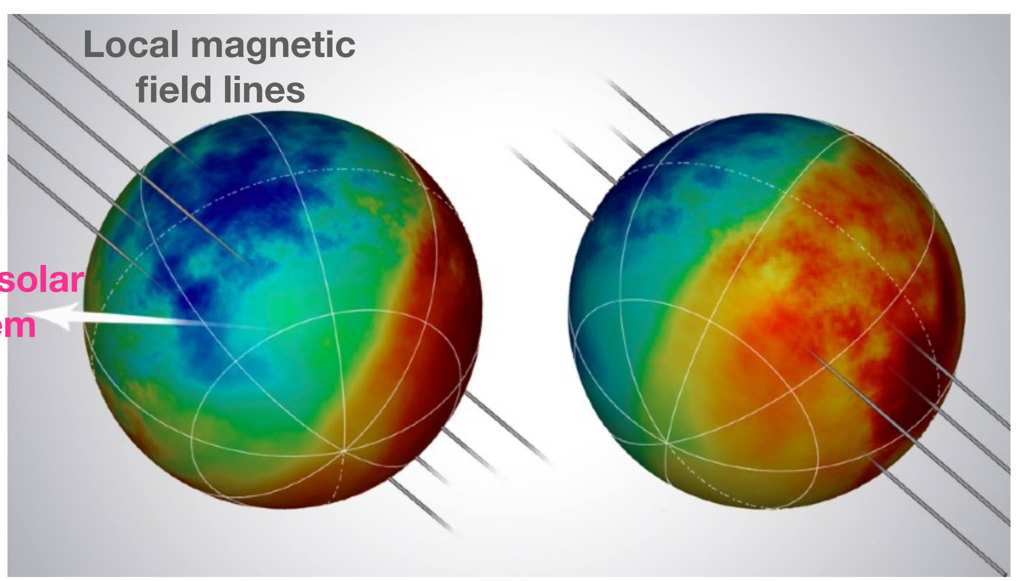
- Dipole phase:



- LE : Agreement with local magnetic field
  Local effect?

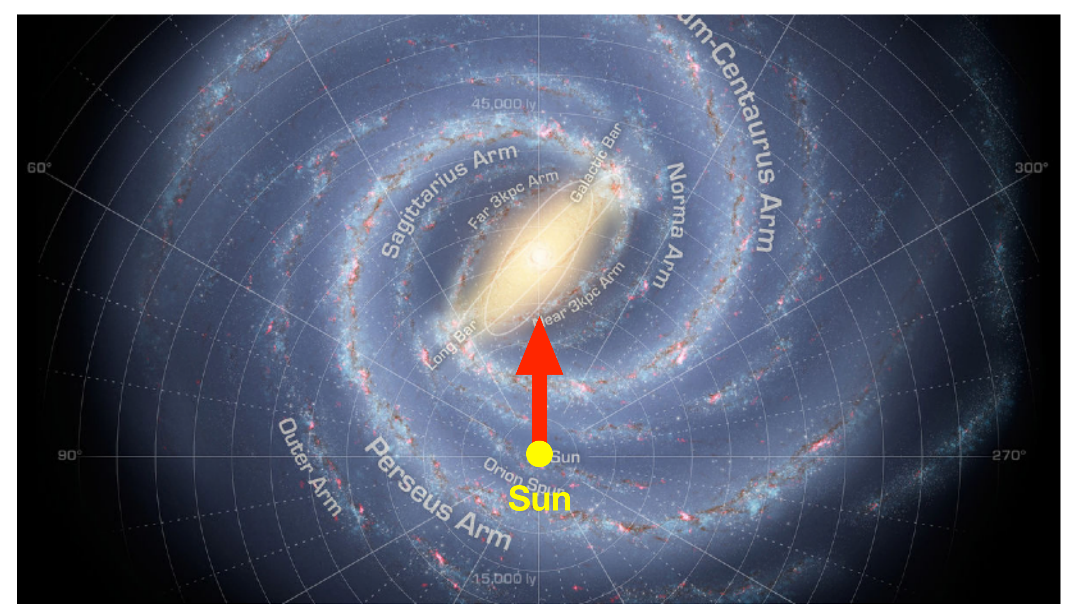
- HE: Seems to point towards galactic center.
  Consistent with isotropic diffusion with
  smooth CR source distribution

S. Mollerach et al., Prog. in Part. and Nuc. Phys. 98 (2018) 85



HAWC/ICECUBE data on 10 TeV CR arrival directions

https://icecube.wisc.edu/news/view/621



Projected dipole direction around 100 TeV

6. Multi-messenger/ Multi-wavelength studies

Multimessenger approach

Interaction of cosmic rays with material and radiation at the source produces γ's and ν's.

$p + p\ (\gamma) \rightarrow \pi^{\pm} + X$

$\quad \rightarrow \mu^{\pm} + \nu_{\mu}$

$\quad\quad \rightarrow e^{\pm} + \nu_{e} + \nu_{\mu}$

$\rightarrow \pi^{o} + X$

$\quad \rightarrow 2\gamma$

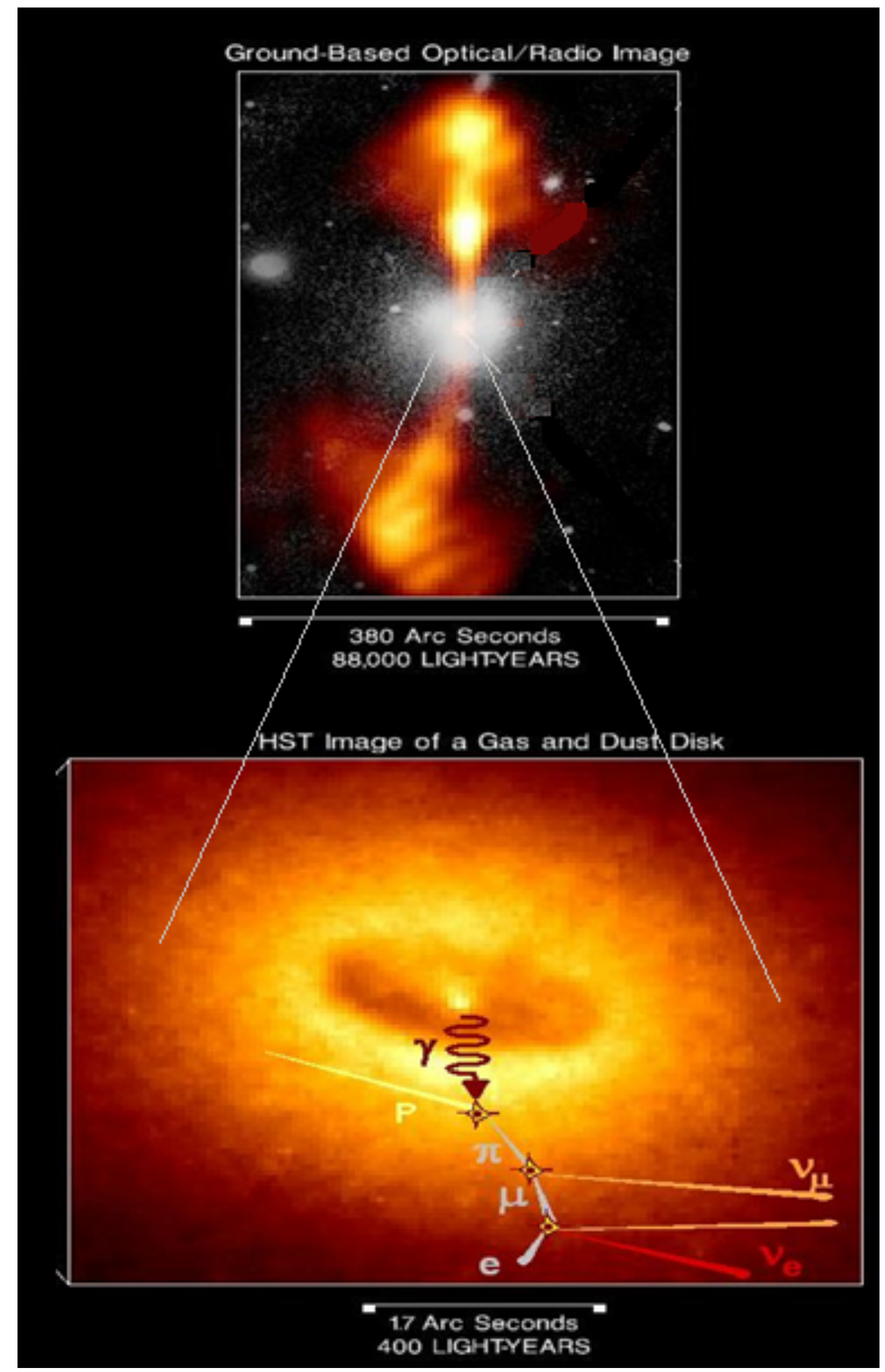
Prob. Production π± — prob. interaction — CR flux

$$\frac{dN_\nu}{dE}(E) = 3 \times \frac{2}{3} \times \frac{1}{x_\nu} \times R_p \frac{dN_p}{dE}\left(\frac{E}{x_\nu}\right)$$

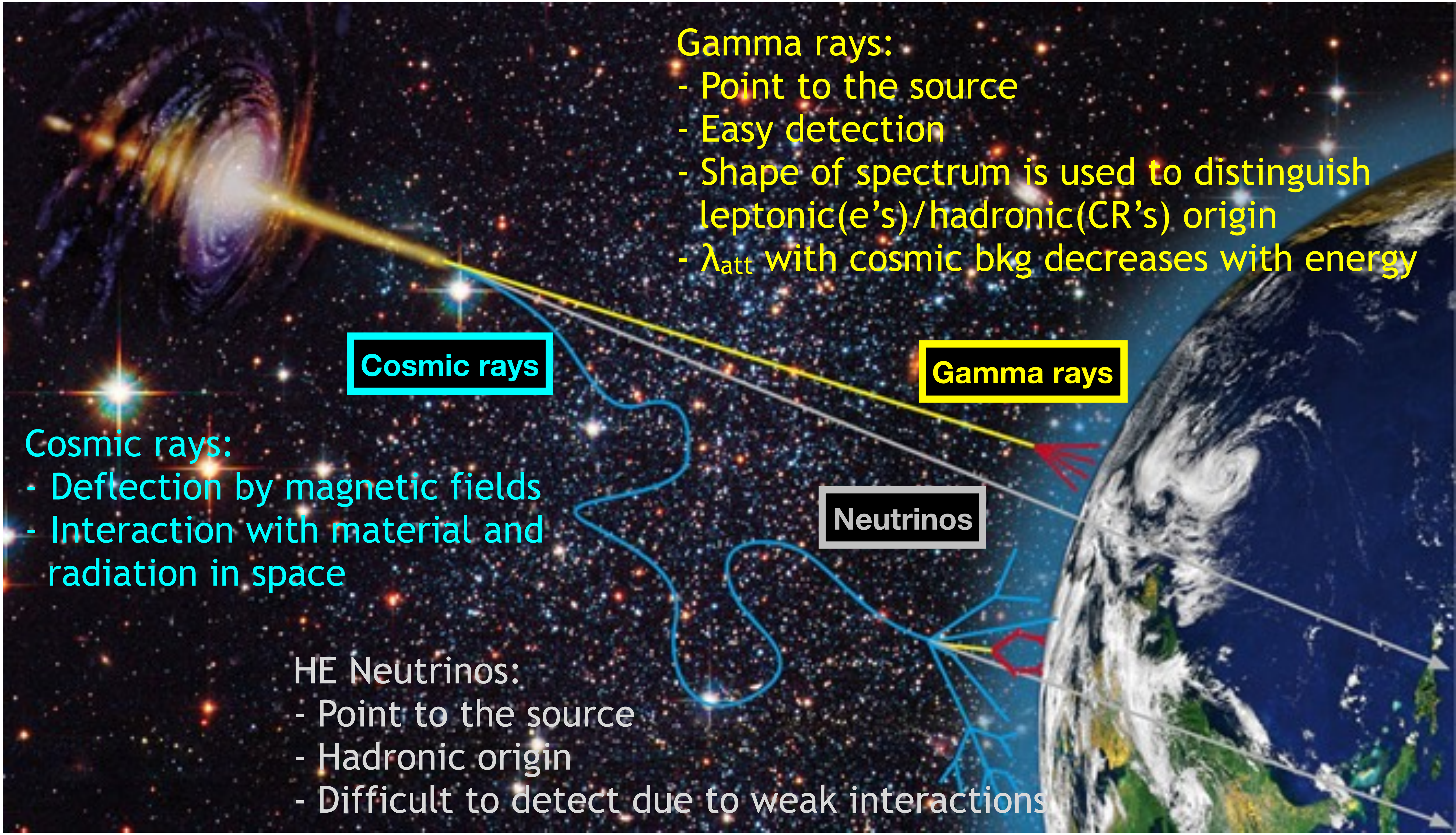
Number of produced neutrinos — $x_\nu = E_\nu / E_{CR} = 0.05$

$$\frac{dN_\gamma}{dE}(E) = 2 \times \frac{1}{3} \times \frac{1}{x_\gamma} \times R_p \frac{dN_p}{dE}\left(\frac{E}{x_\gamma}\right)$$

$x_\gamma = E_\gamma / E_{CR} = 0.1$

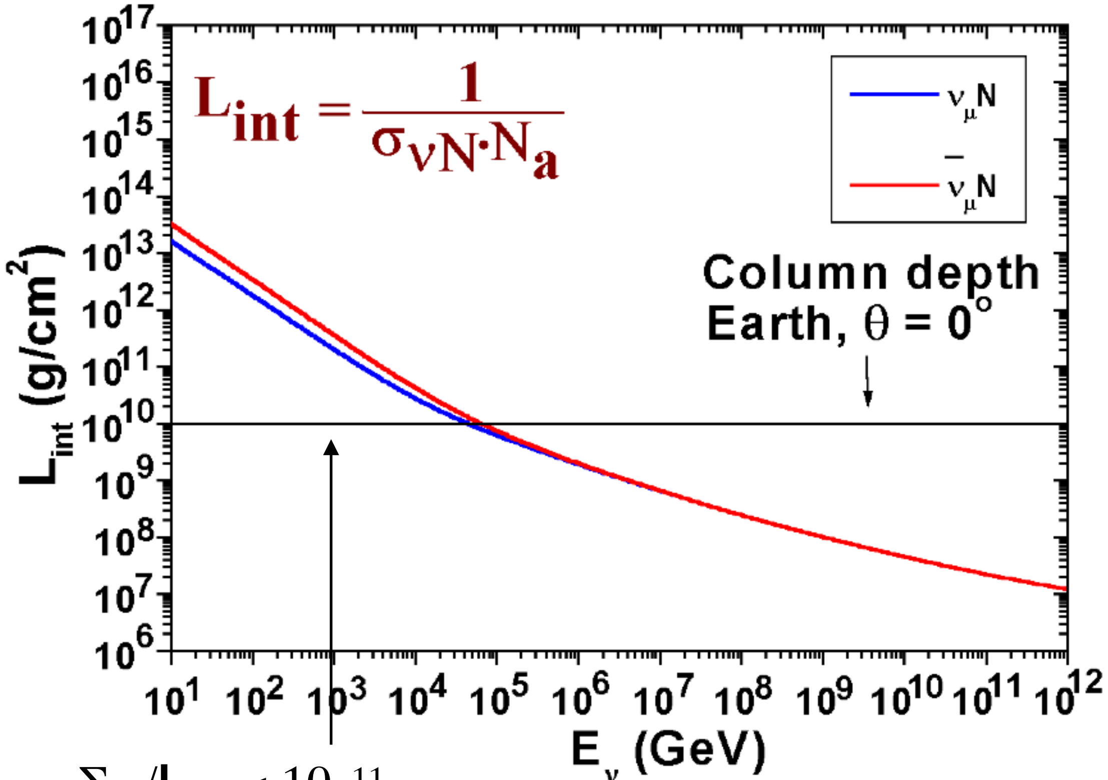


Multimessenger approach



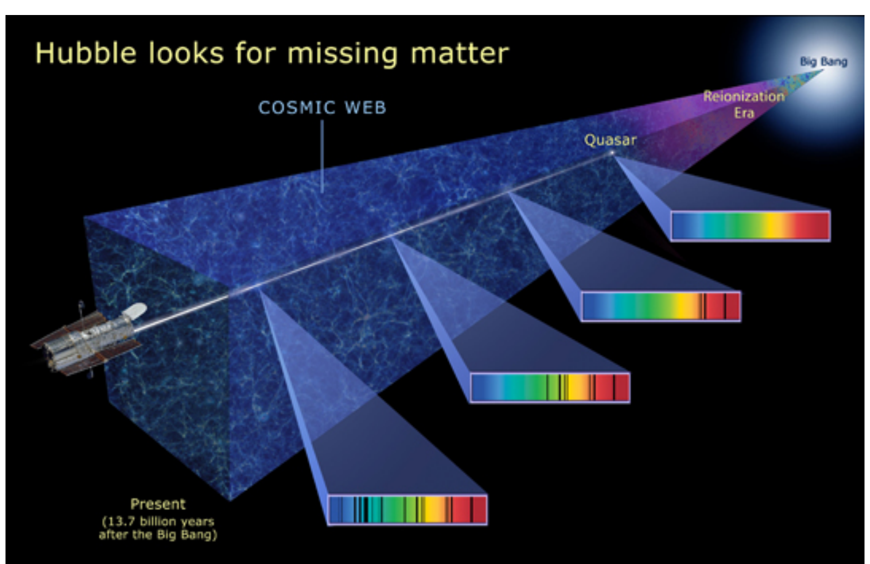
Multimessenger approach

Interaction length of neutrinos with nucleons



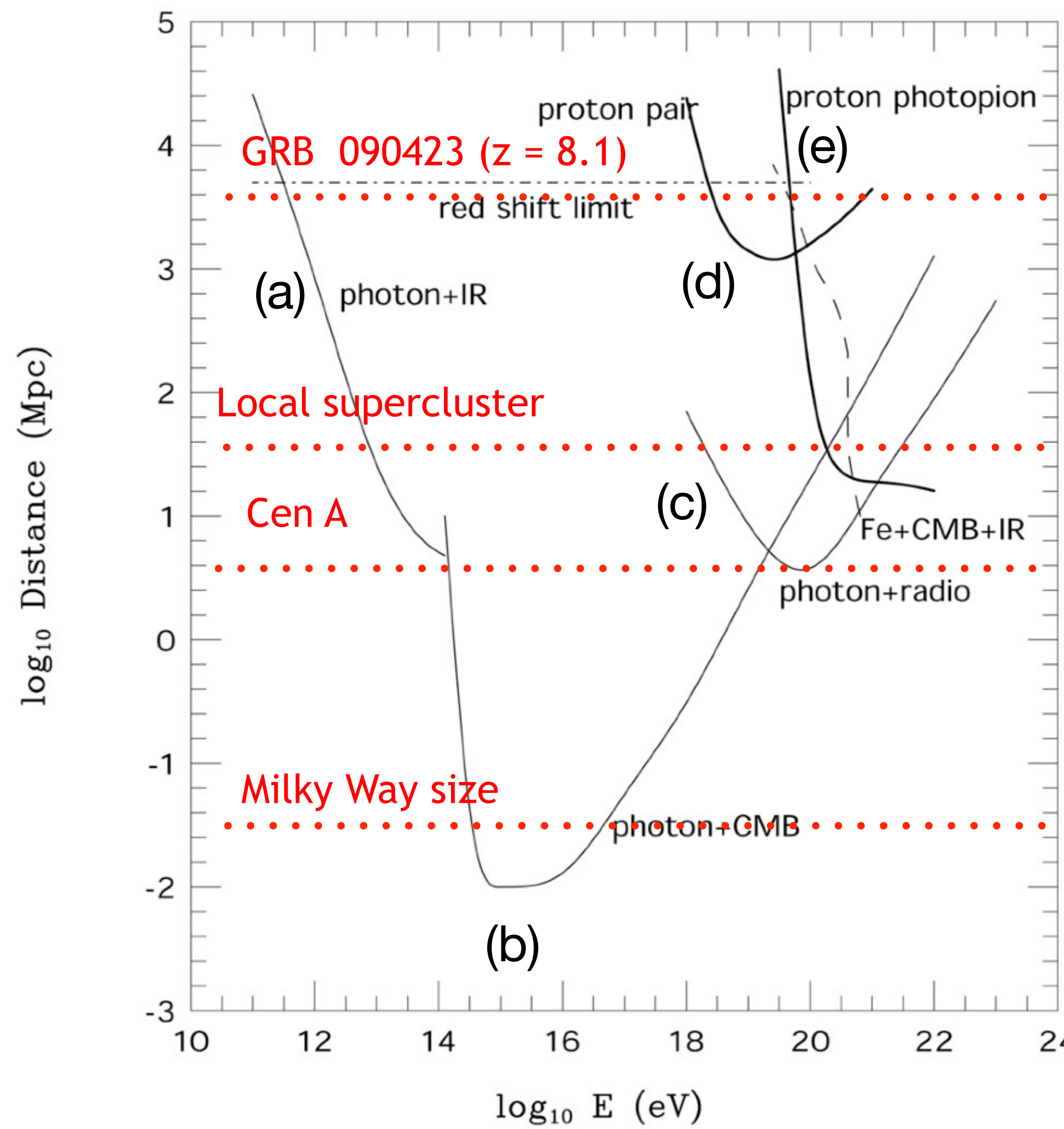
$\Sigma_{HI}/L_{\nu N} < 10^{-11}$

Σ_{HI}: H1 column density of intergalactic medium from Quasar absorption spectra



NASA/Modelo JF

Interaction length of γ and cosmic rays with background radiation



D. F. Torres et al., Rep. On Prog. In Phys. 67, 1663 (2004)

(a) $\gamma + \gamma_{IR}$

(b) $\gamma + \gamma_{CMB}$

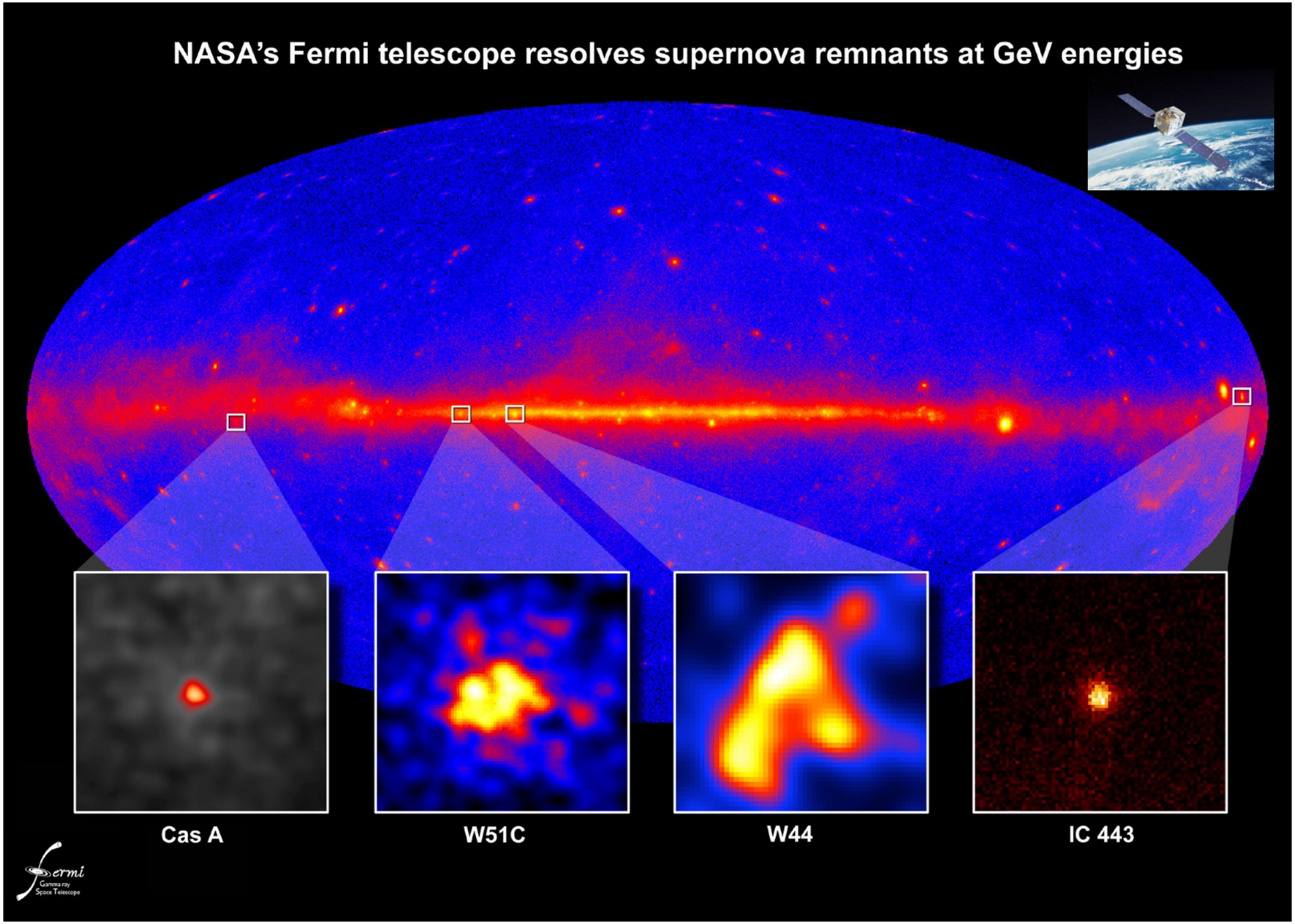
(c) $\gamma + \gamma_{radio}$

(d) $P + \gamma_{CMB} \rightarrow e^+e^-$

(e) $P + \gamma_{CMB} \rightarrow \pi$

Looking for supernova candidates

FERMI-LAT space telescope for γ-rays



Fermi-LAT: Compelling evidence of hadronic acceleration at three SNR's (W51C, W44, IC 443)

Looking for supernova candidates

FERMI-LAT space telescope for γ-rays

- Identification of CR production in SNR's (W51C, W44, IC 443) by observation of the π^0 bump.

- Observed SNR's
  - SNRII (core collapse progenitor)
  - Middle-aged (4-30 kyr)
  - Maximum CR acceleration < few TeV's

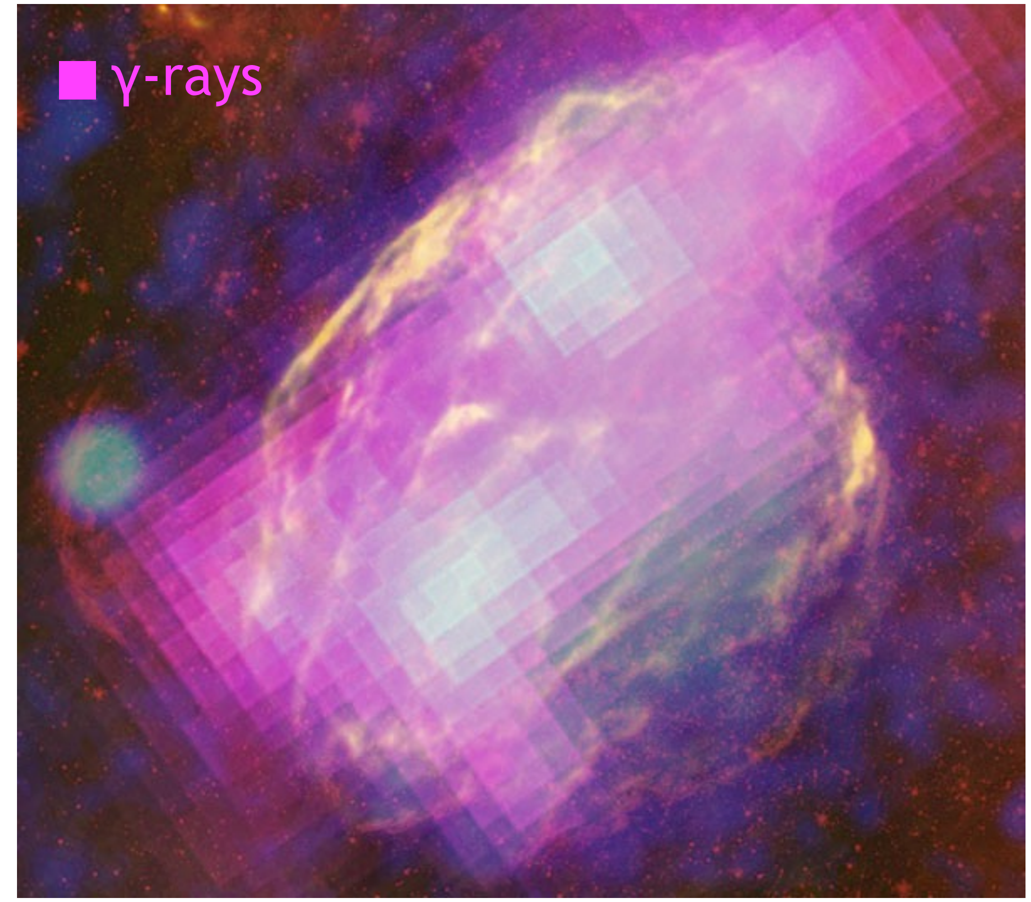
CR prob. interaction　　CR flux

$$\frac{dN_\gamma}{dE}(E) = 2 \times \frac{1}{3} \times \frac{1}{x_\gamma} \times R_p \frac{dN_p}{dE}\left(\frac{E}{x_\gamma}\right)$$

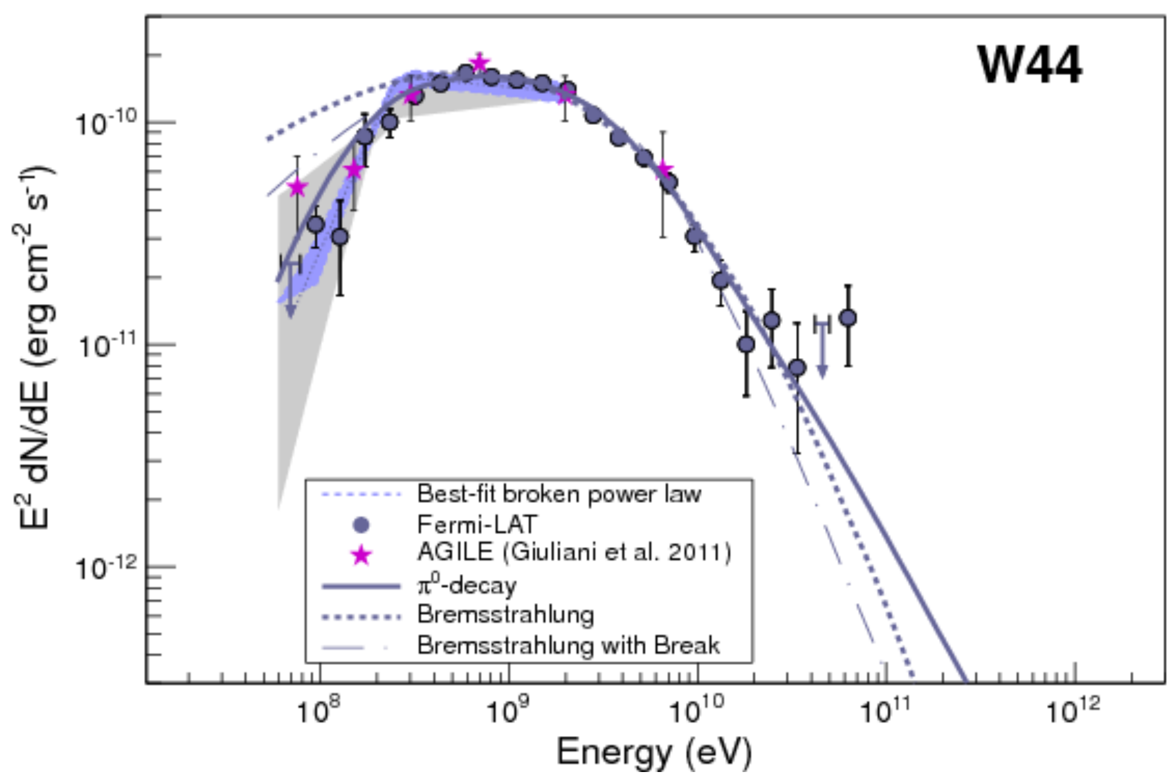
$\pi^0 \rightarrow \gamma + \gamma$

Prob. Production π^0

$x_\gamma = E_\gamma / E_{CR} = 0.1$



FERMI-LAT, Science, 339, 807 (2013)



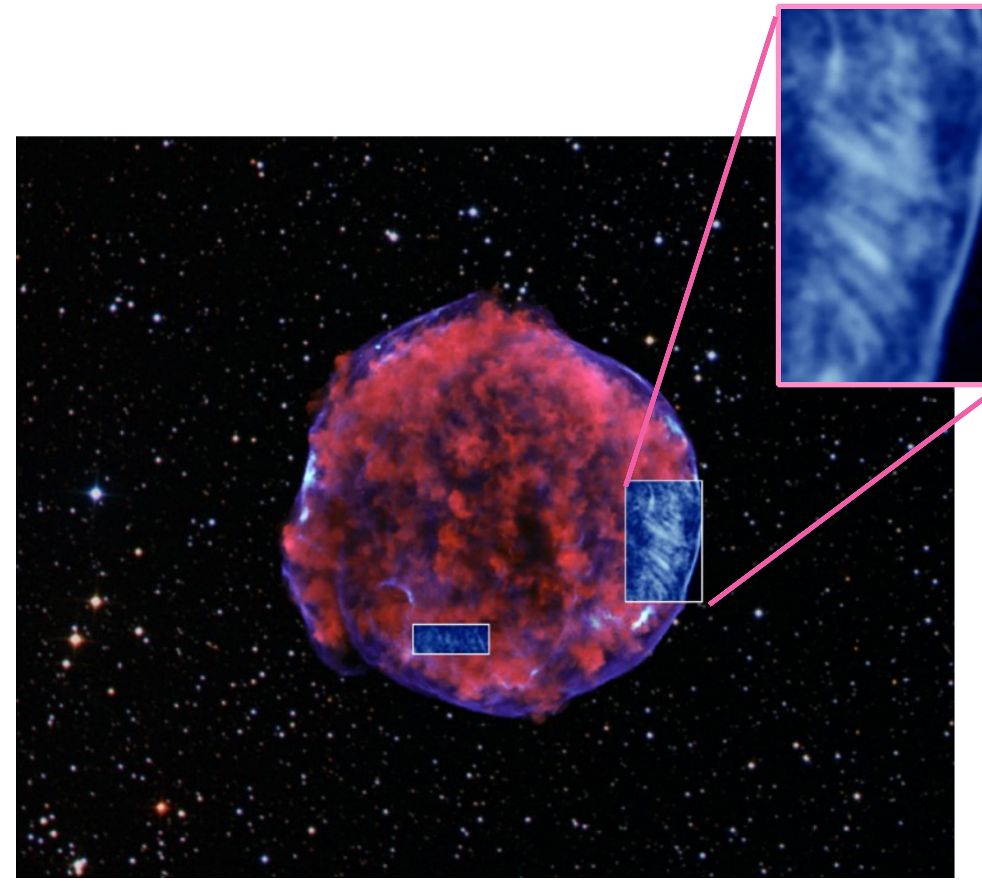
NASA Press Release Feb. 14, 2013

Where are the PeV SNR's?

- Very young SNR's (< 10^2 -10^3 yr) are pevatron candidates.
  - Dozen of pevatrons are expected in Milky Way.

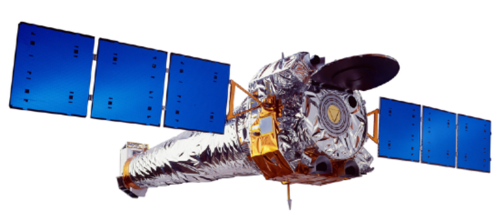
  J. W. Hewitt, (astro-ph.HE) arXiv:1510.01213,
  S. Gabici et al., ApJ 665 (2007) L131

Non observation of PeV SNR's yet

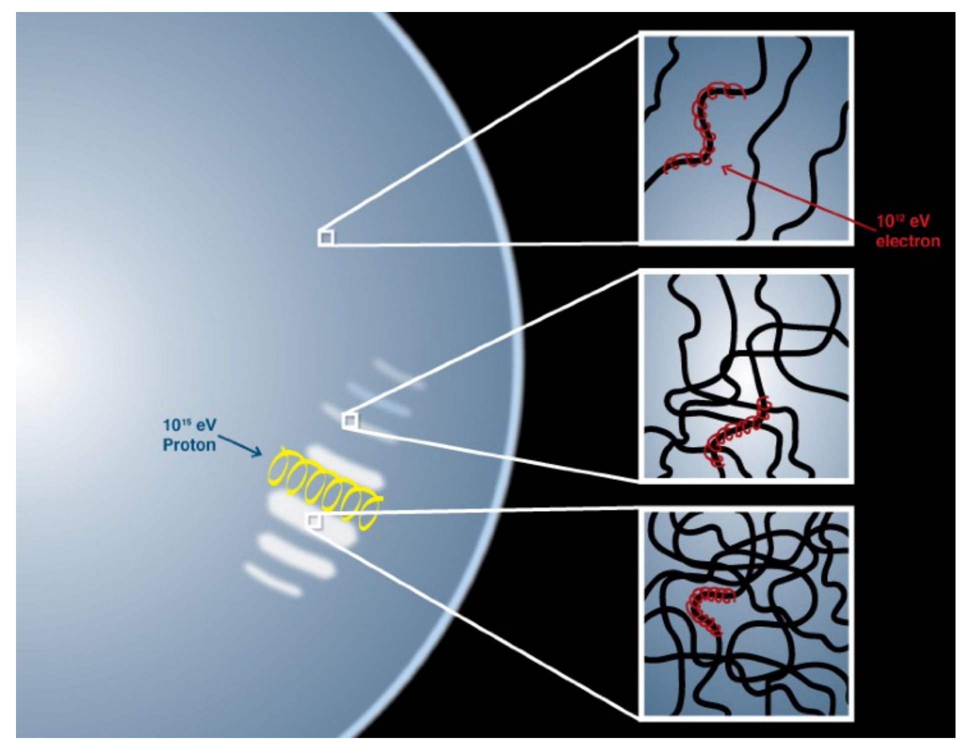


X-ray: NASA/CXC/Rutgers/K.Eriksen et al.; Optical: DSS

- Tycho SNR is a pevatron candidate
  - SNRIa (binary system)
  - X-ray data from Chandra telescope: Observation of strips and gaps with non-thermal origin.
  - Indirect evidence of acceleration up to PeV's in gaps.

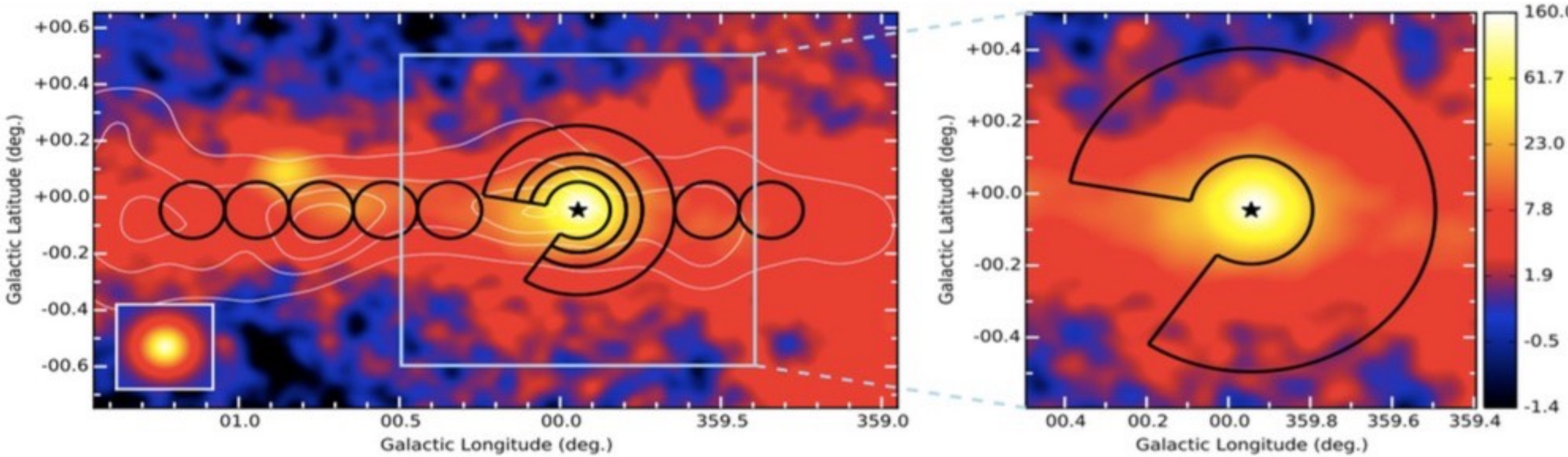


Chandra



Chandra web page

A cosmic ray accelerator in the galactic center?



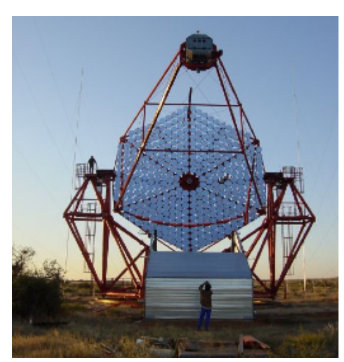
Diffuse TeV γ-emission from interactions of molecular zone with cosmic rays?

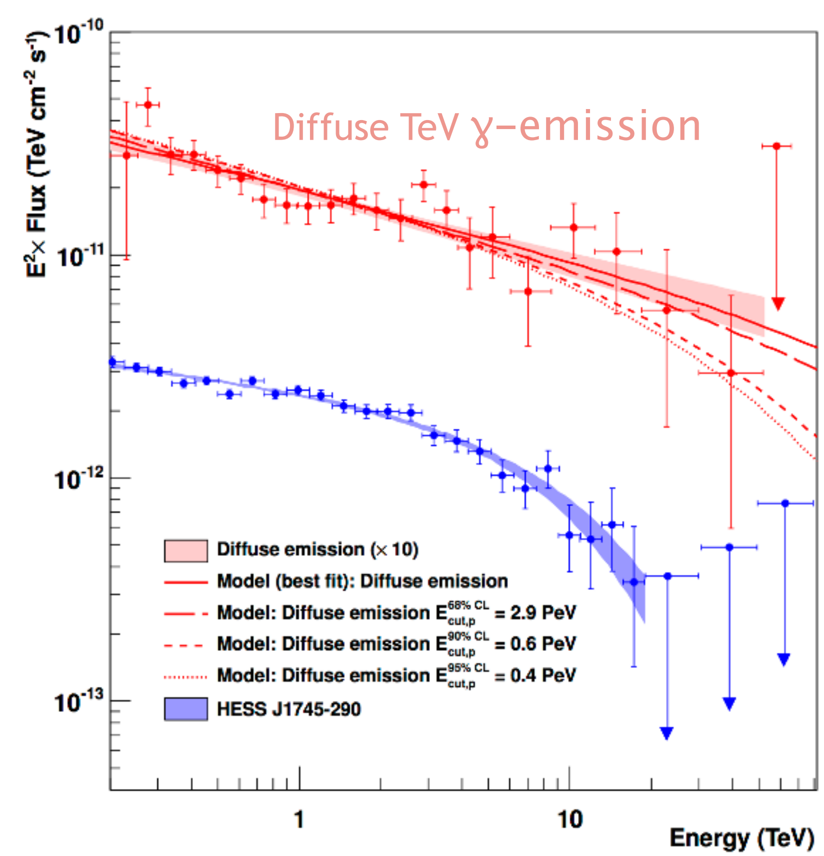
- Source of CR's is a mystery:
  - Spherically distribution (1/r) of CR density.
  - Source within 10 pc of galactic centre.

  HESS, Nature 531, 476-479 (2016);
  HESS, Nature 439, 695-698 (2006)

- TeV Pulsar wind nebulae? Pevatron?

HESS

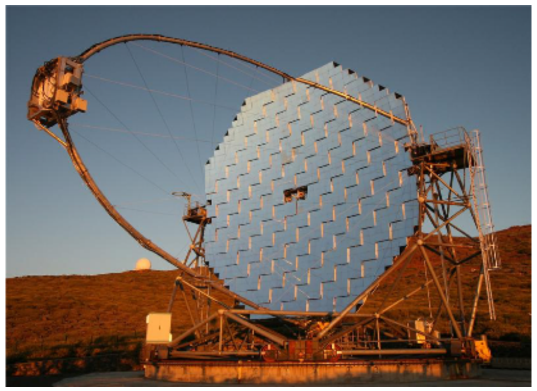




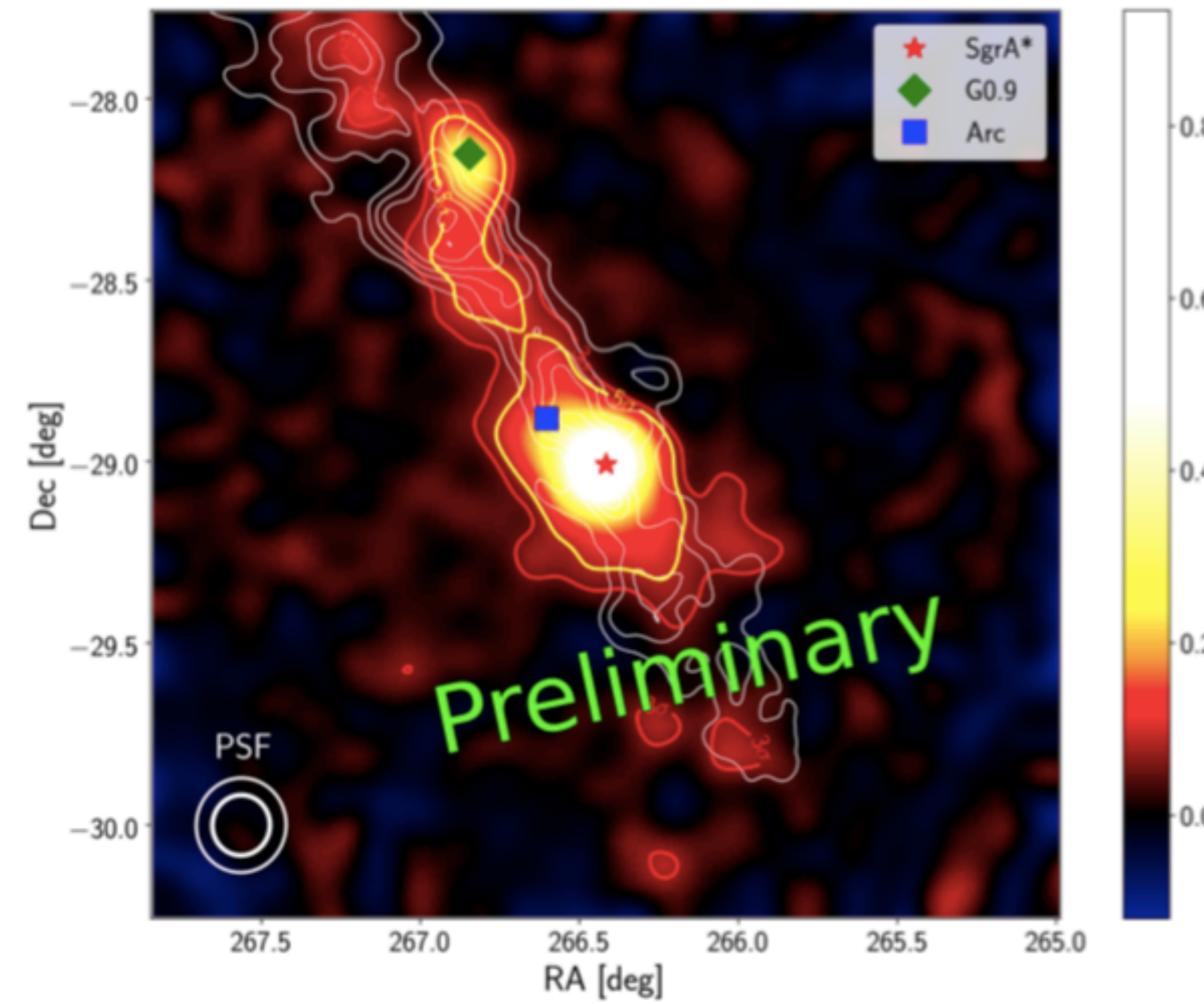
A cosmic ray accelerator in the galactic center?

Diffuse TeV γ-emission from interactions of molecular zone with cosmic rays?

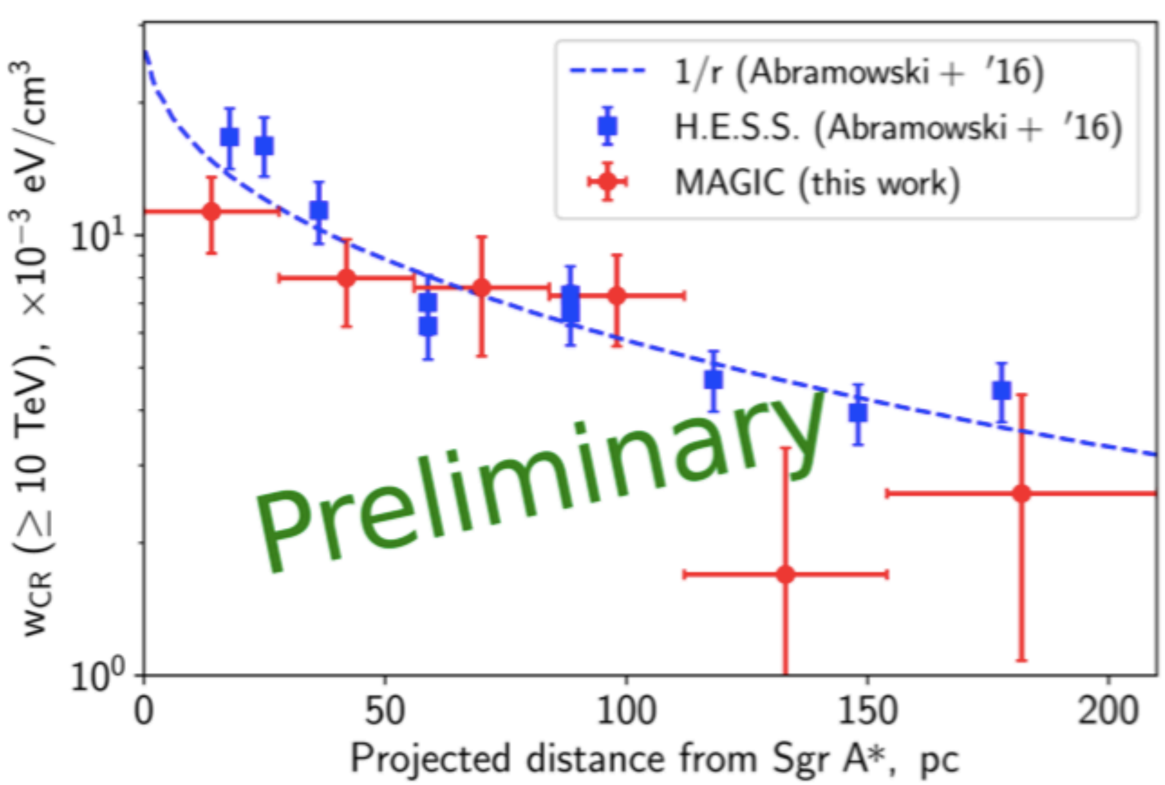
MAGIC

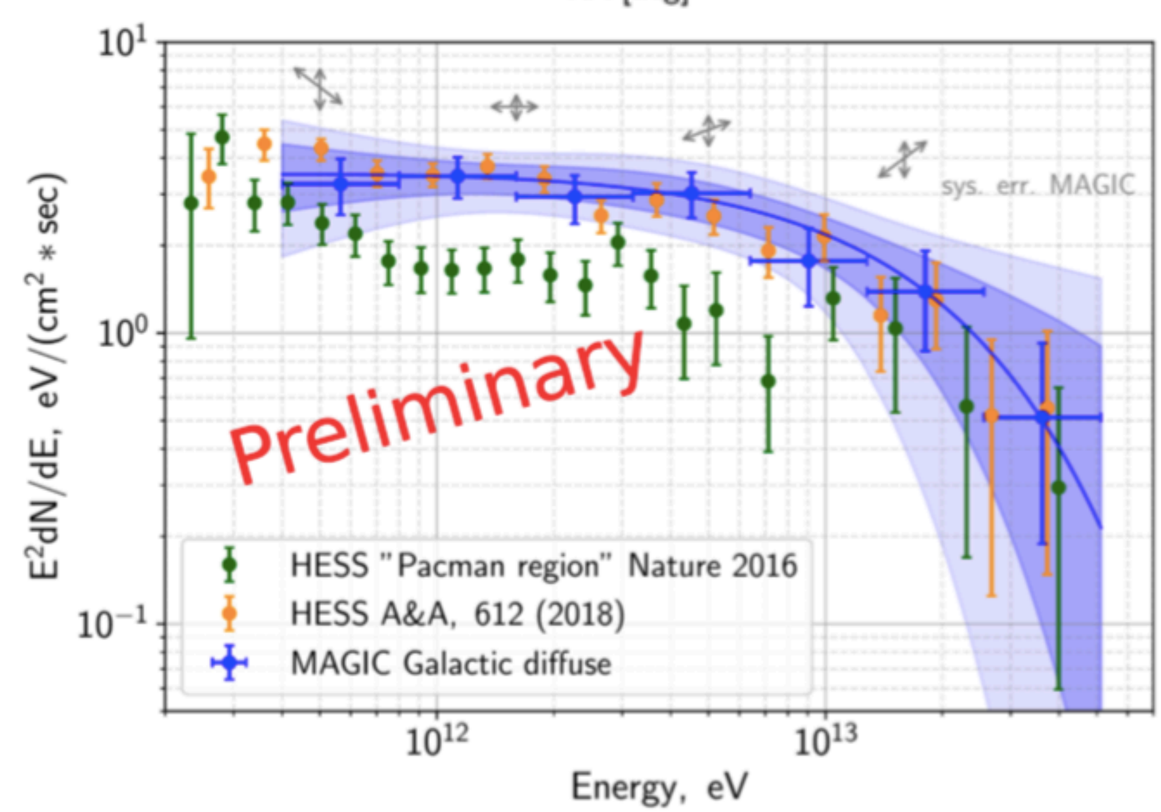


MAGIC, POS (ICRC2019) 680



- MAGIC observations of the galactic center are consistent with HESS results
- CR radial density: Peak at center, diffusion outwards?

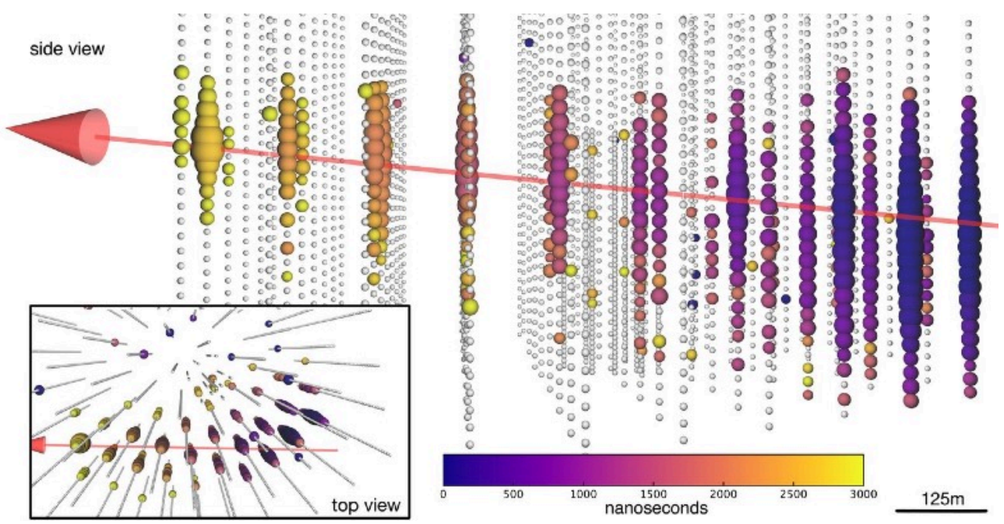


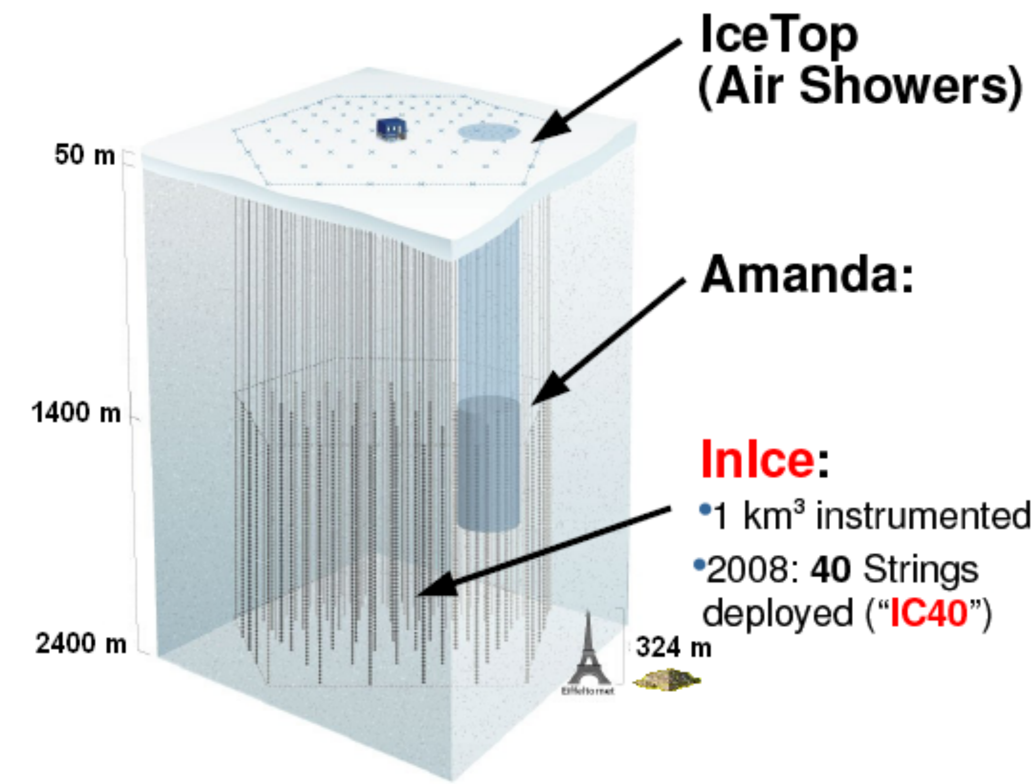


Enter the neutrinos

ICECUBE telescope of neutrinos

- ICECUBE detection of ν's from blazar TXS 0506+056 during *gamma-ray flare*
  - μ signal from 290 TeV ν.

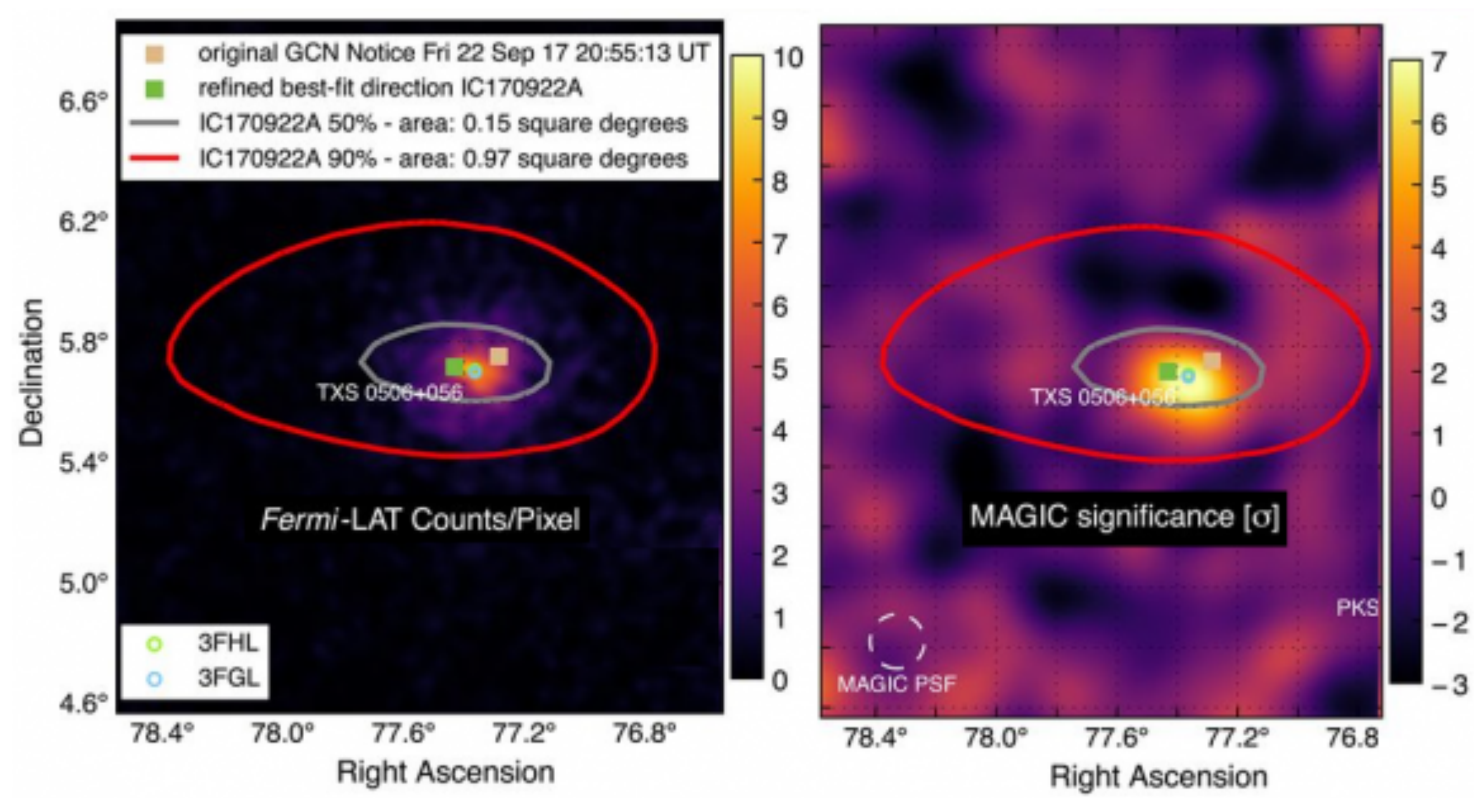




IceCube-170922A event: September 22, 2017.

- Blazars accelerate cosmic rays at least up to PeV energies

$$x_\nu = E_\nu / E_{CR} = 0.05$$



ICECUBE/Fermi-LAT, Science 361 (2018)

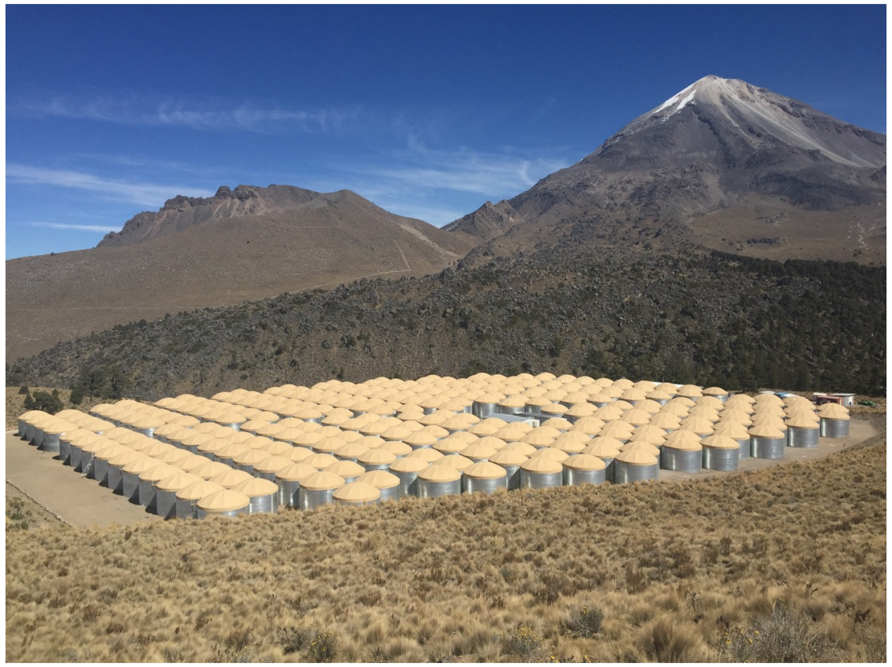
Hunting CR sources with HAWC

HE γ-rays:

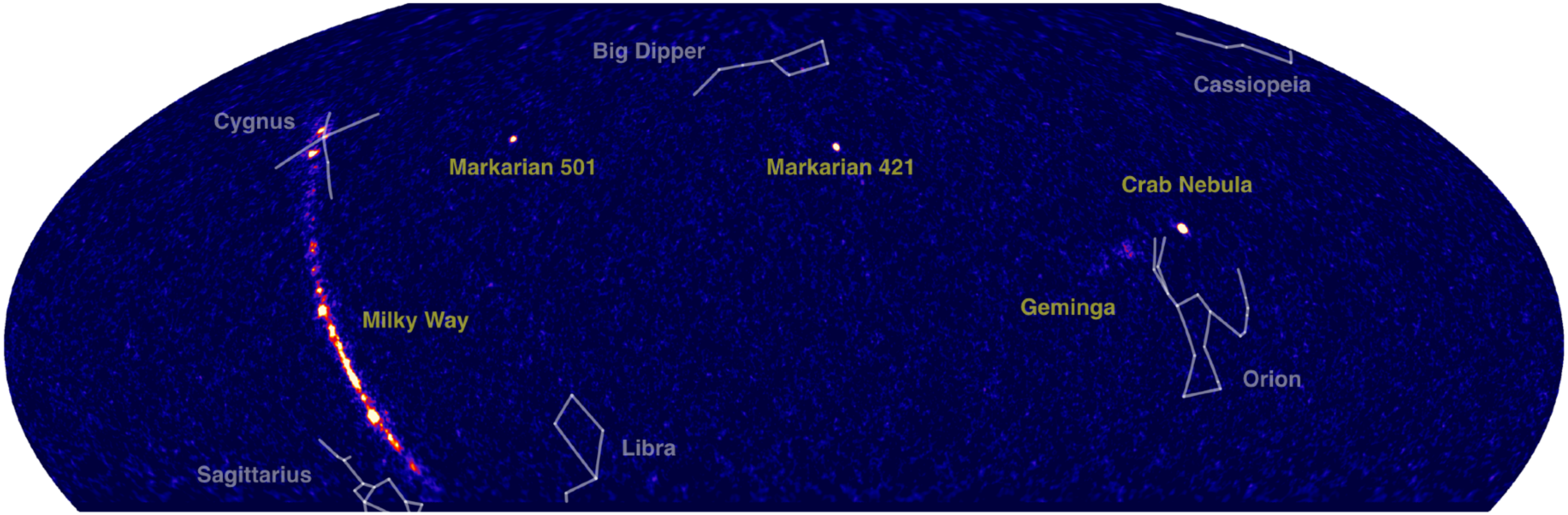
- $\mathcal{O}$(100 TeV) γ-ray observations:
  - leptonic scenario: cut-off
  - hadronic scenario: no cut-off

- HAWC is opening the $\mathcal{O}$(100 TeV) γ-ray region.

HAWC observatory



TeV γ-ray sky map measured from HAWC

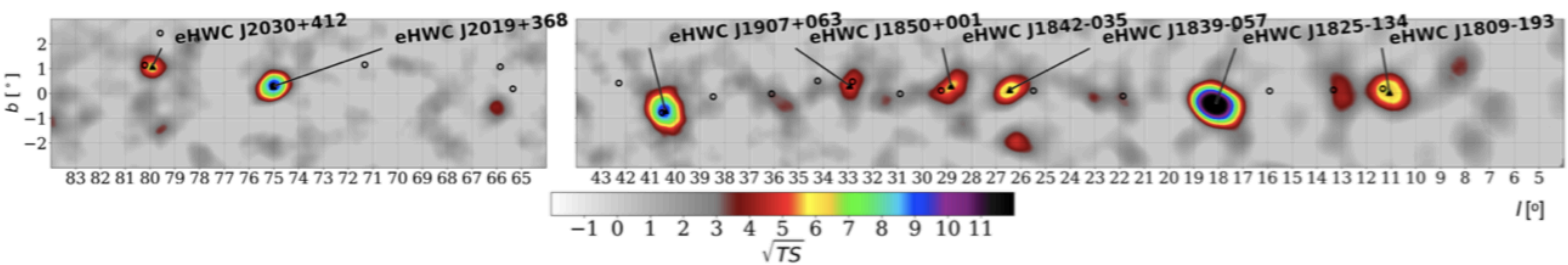


Equatorial coordinates

HAWC, APJ 843 (2017)

Hunting CR sources with HAWC

- Nine sources with γ-ray above 56 TeV.
- All of them have at least one pulsar within 0.5^0 of HAWC location.
- These pulsars are fairly young with age ≈ [1, 200] yr



Galactic coordinates

E > 56 TeV

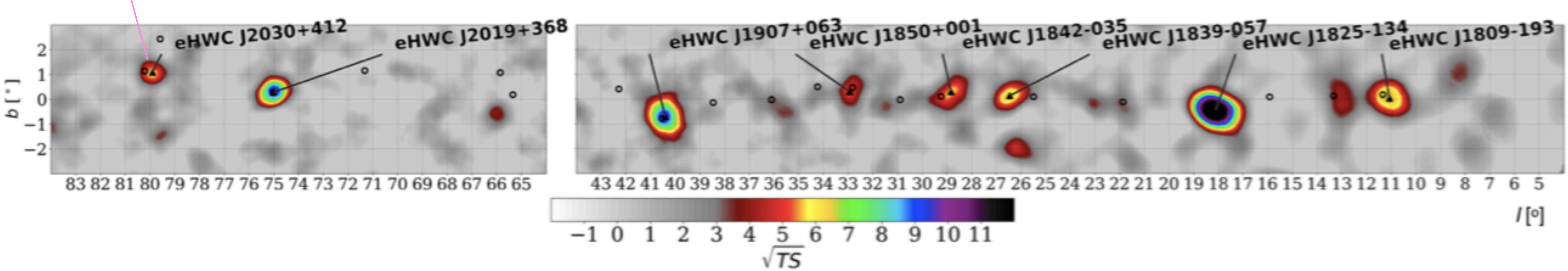
arXiv:1909.08609v1 [astro-ph.HE]

Hunting CR sources with HAWC

- Nine sources with γ-ray above 56 TeV.
- All of them have at least one pulsar within 0.5^0 of HAWC location.
- These pulsars are fairly young with age ≈ [1, 200] yr

Coincident with Cygnus OB2 young massive star cluster

NASA



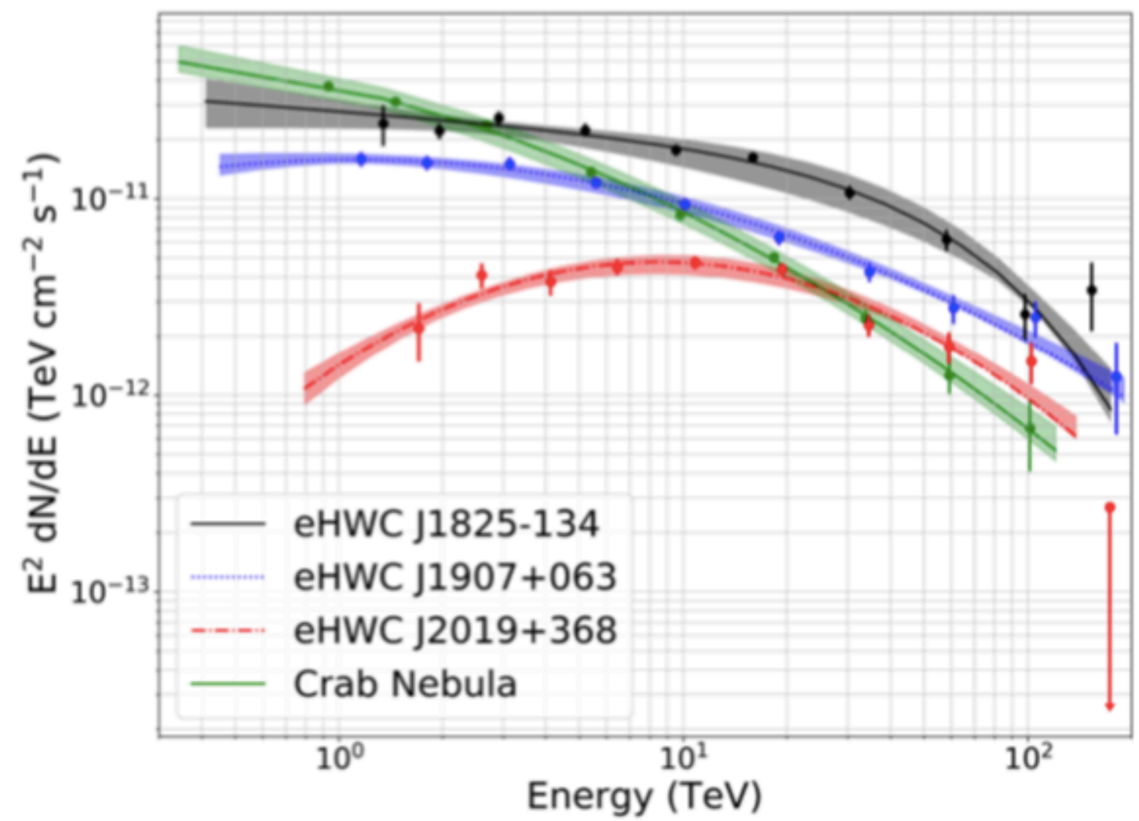
Galactic coordinates

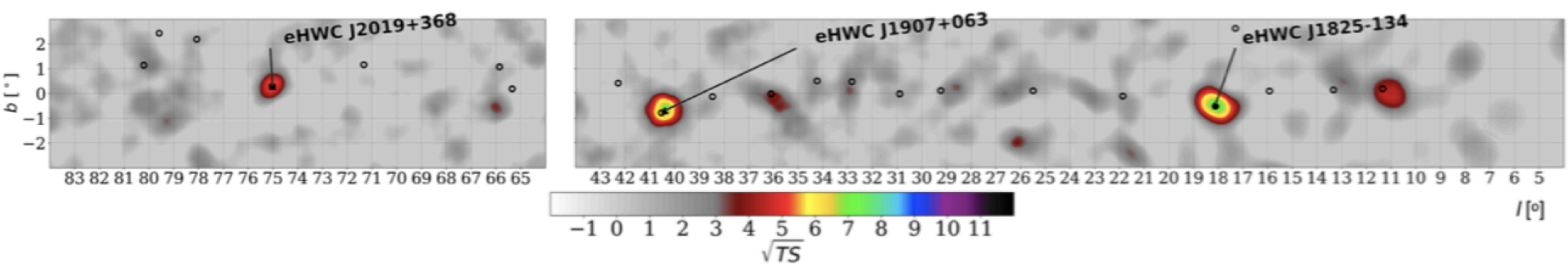
E > 56 TeV

arXiv:1909.08609v1 [astro-ph.HE]

Hunting CR sources with HAWC

- Three sources with γ-ray above 100 TeV.
- Emission mechanism is not yet clear.
- eHWC J1825-134 and J1907+063 exhibit hard spectra with extension to HE's.





Galactic coordinates

E > 100 TeV

arXiv:1909.08609v1 [astro-ph.HE]

Hunting CR sources with HAWC

- Three sources with γ-ray above 100 TeV.
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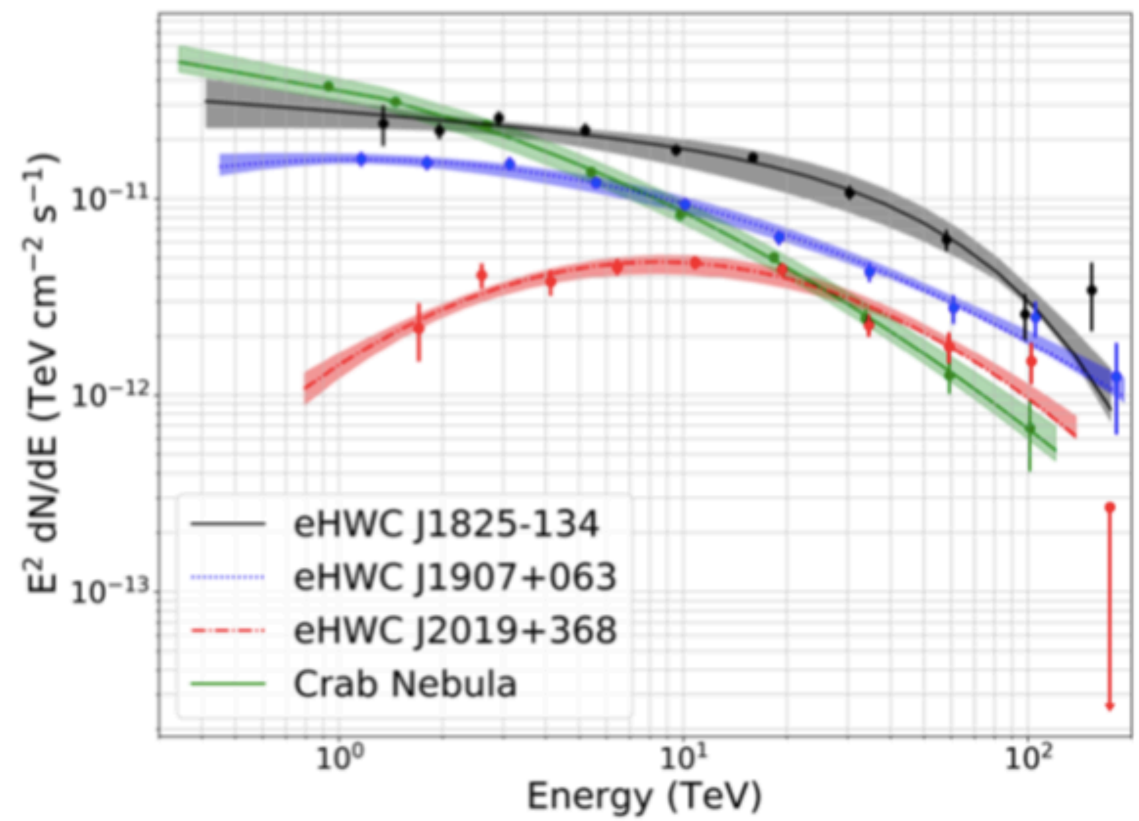
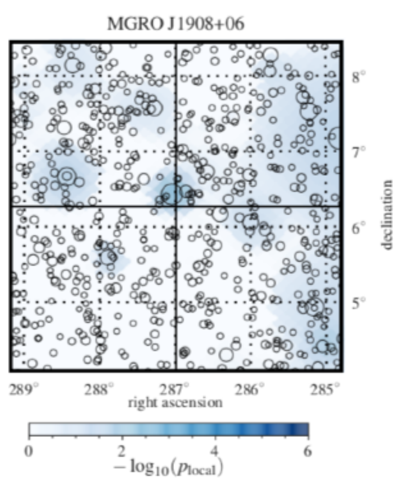
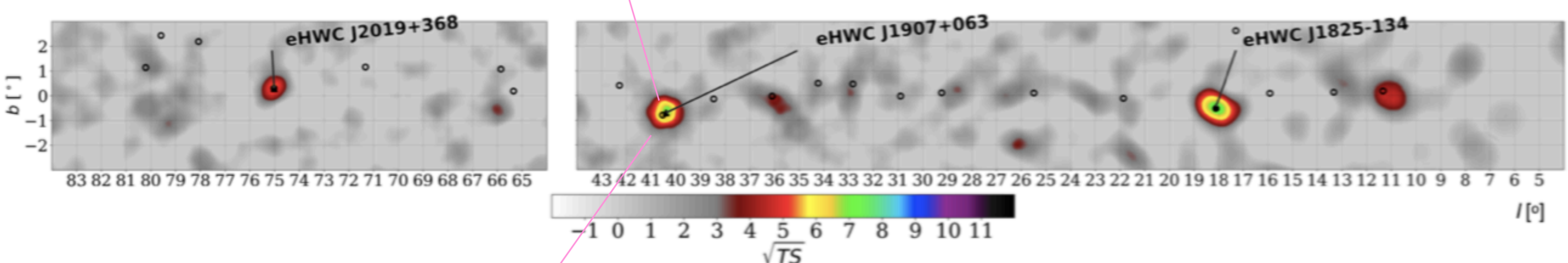




ICECUBE, Eur. Phys. J. C 79 (2019)

Second best p-value in a search for neutrino point like sources with ICECUBE in TeV γ-ray sources



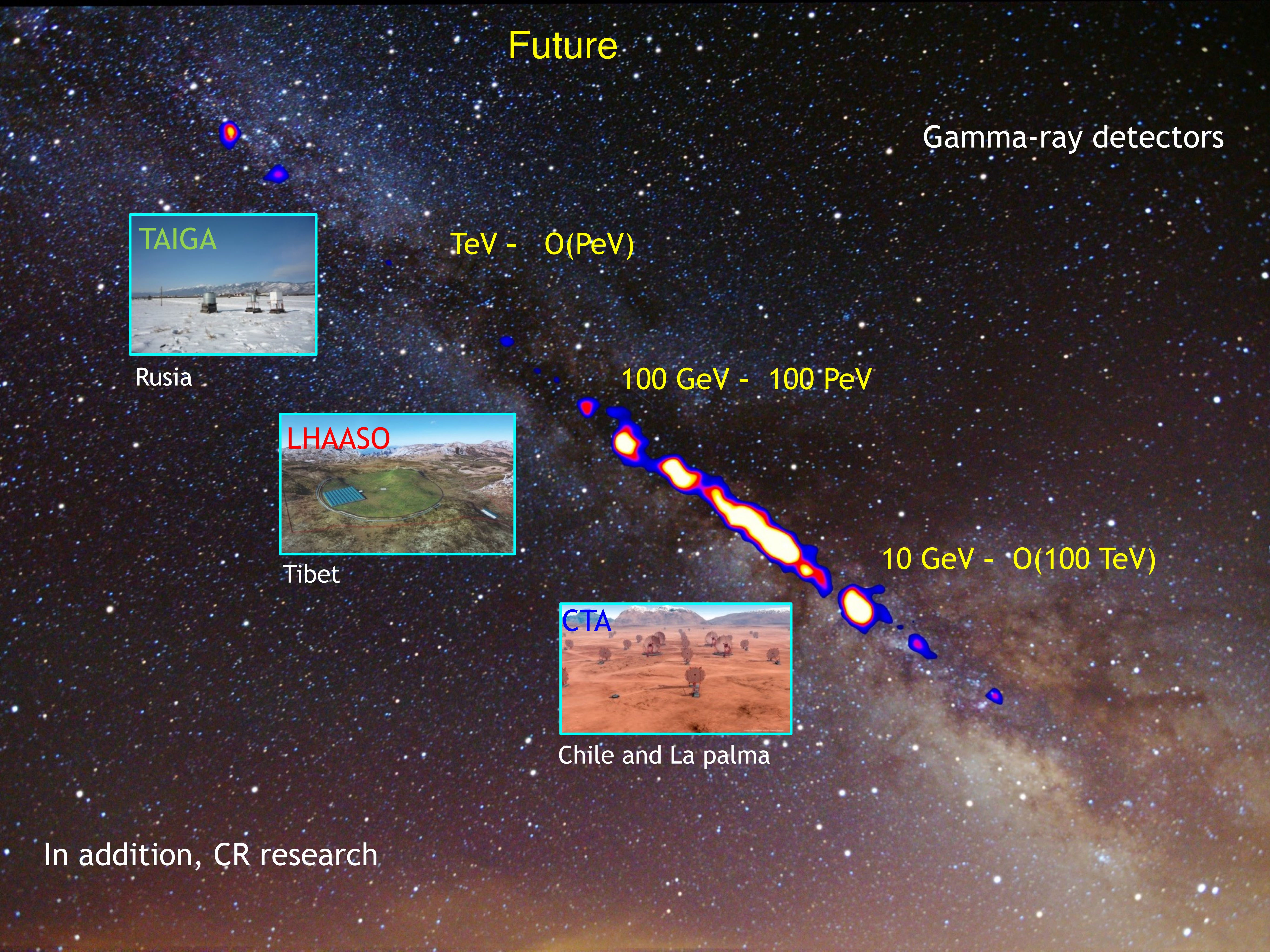
Galactic coordinates

MILAGRO J1908+06

E > 100 TeV

arXiv:1909.08609v1 [astro-ph.HE]

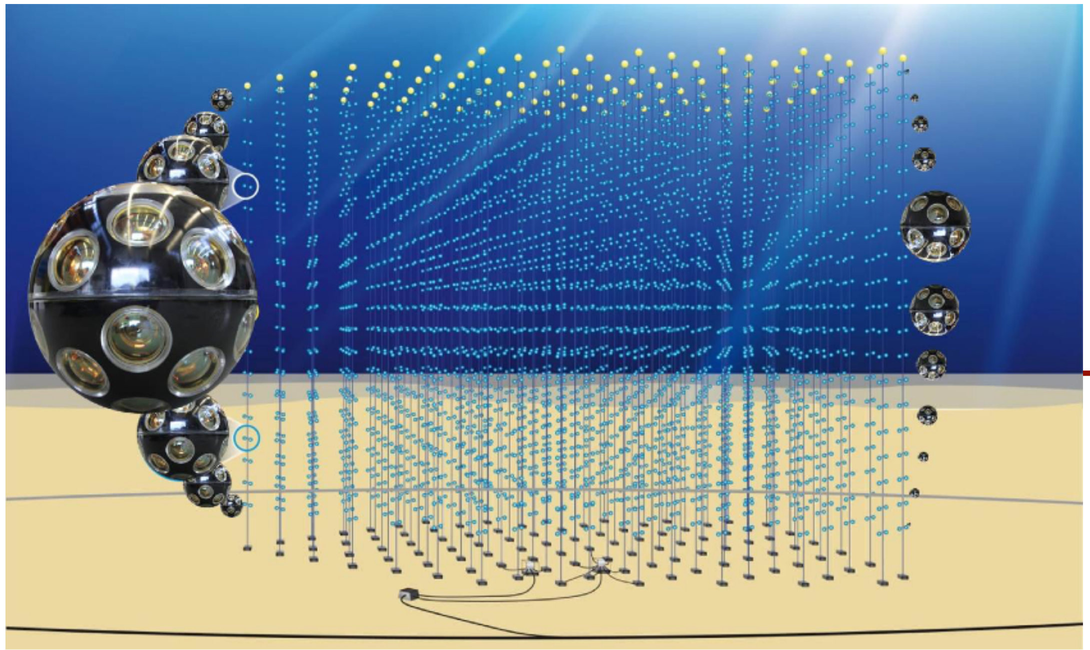
7. Future detectors


Future
Gamma-ray detectors
TAIGA
Rusia
TeV - O(PeV)
LHAASO
Tibet
100 GeV - 100 PeV
10 GeV - O(100 TeV)
CTA
Chile and La palma
In addition, CR research

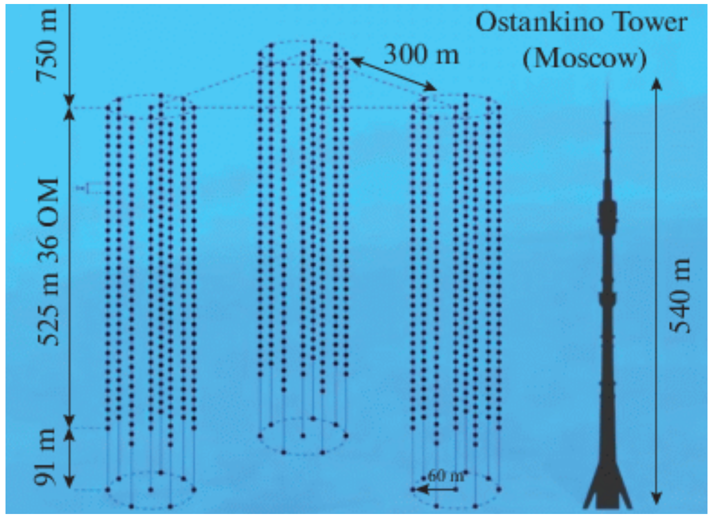
Future

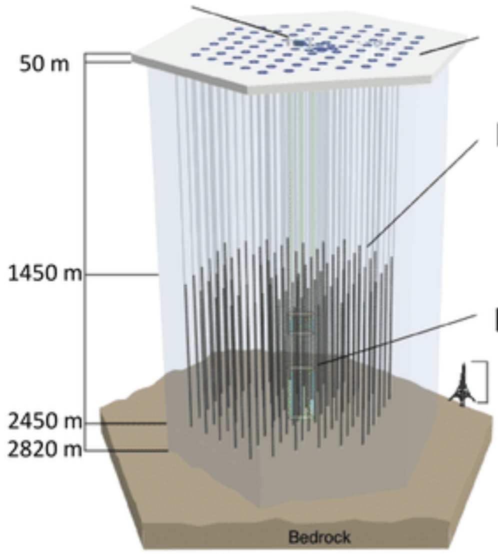
Neutrino detectors

KM3Net (1 km³)



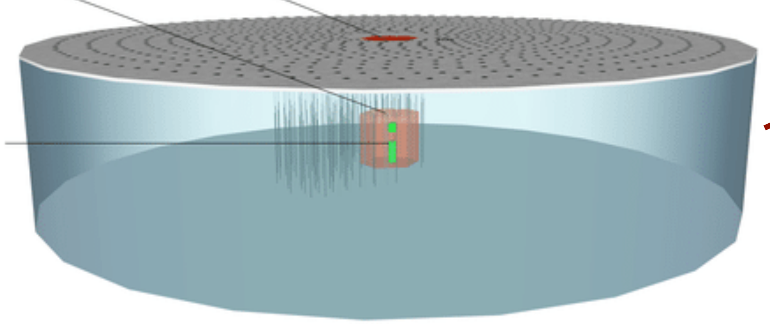
Baikal GVD (1 km³)



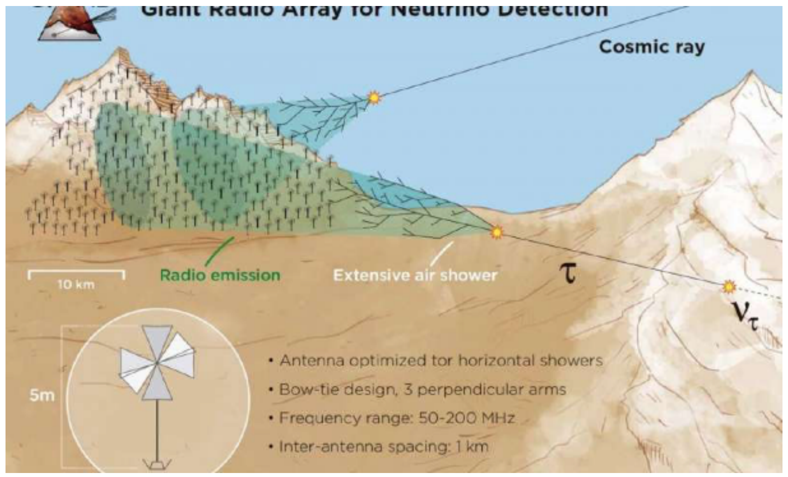


ICECUBE
(1 km³)

ICECUBE-Gen2 (10 km³)



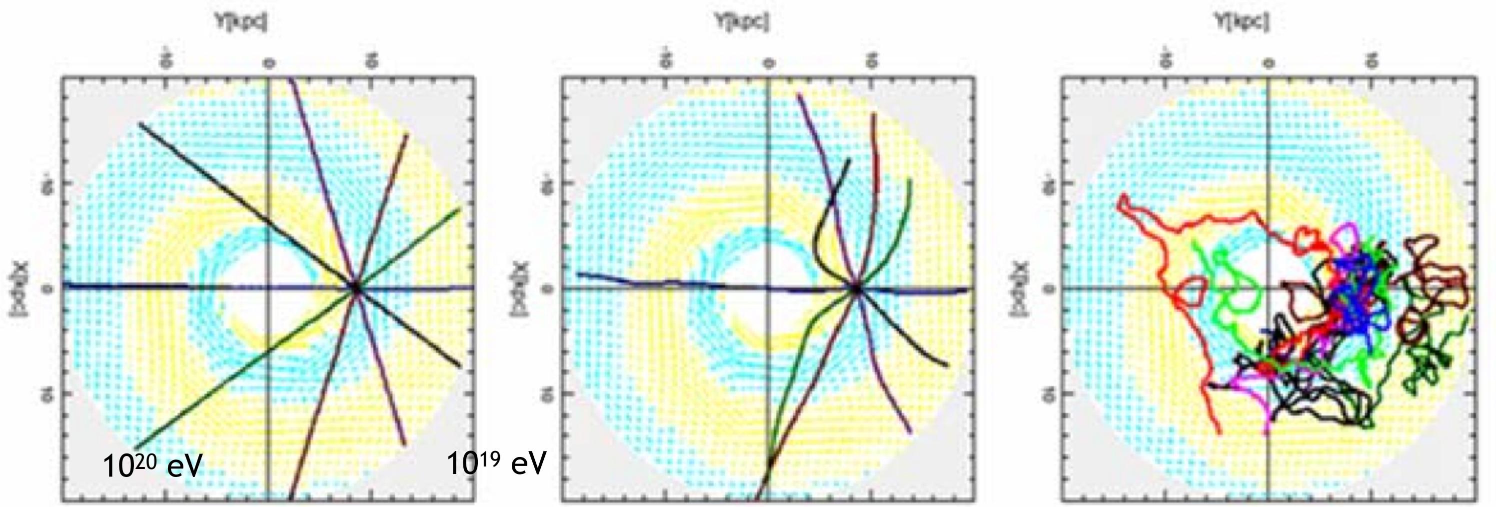
ICECUBE collaboration



Grand (200,000 km²)

Future

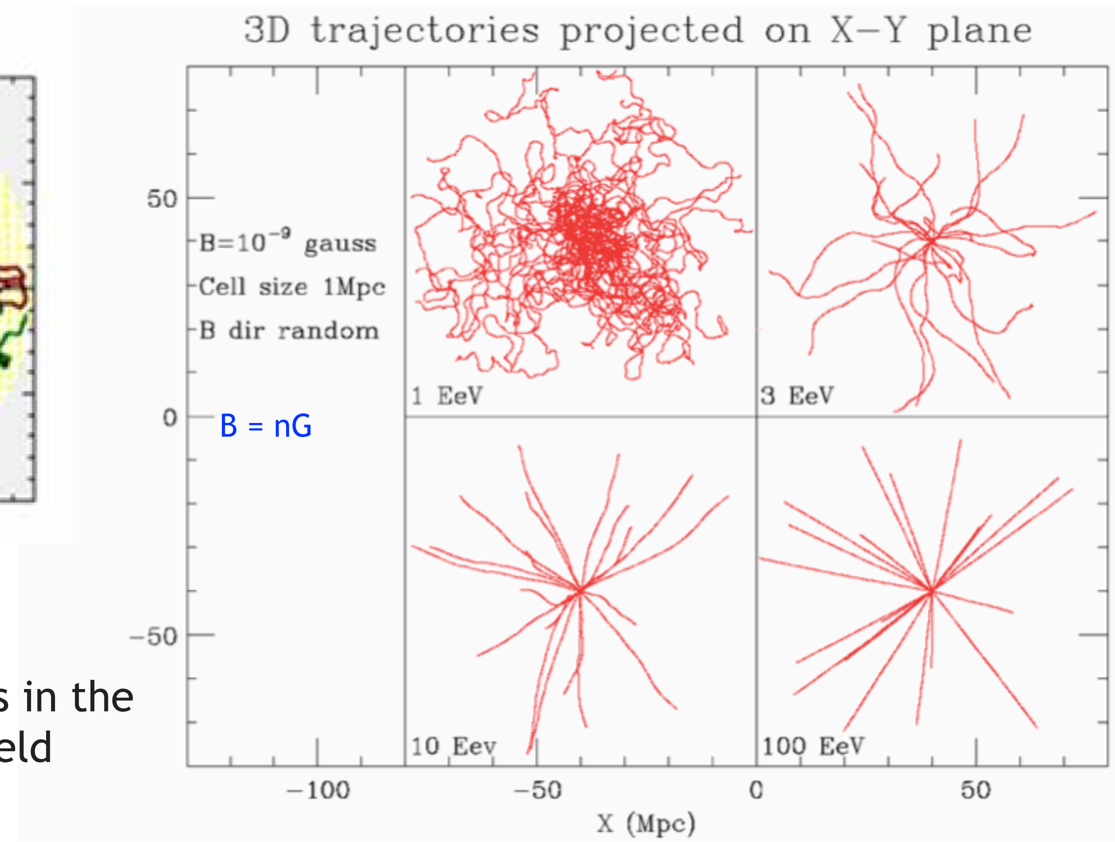
A. Calvez, 2004



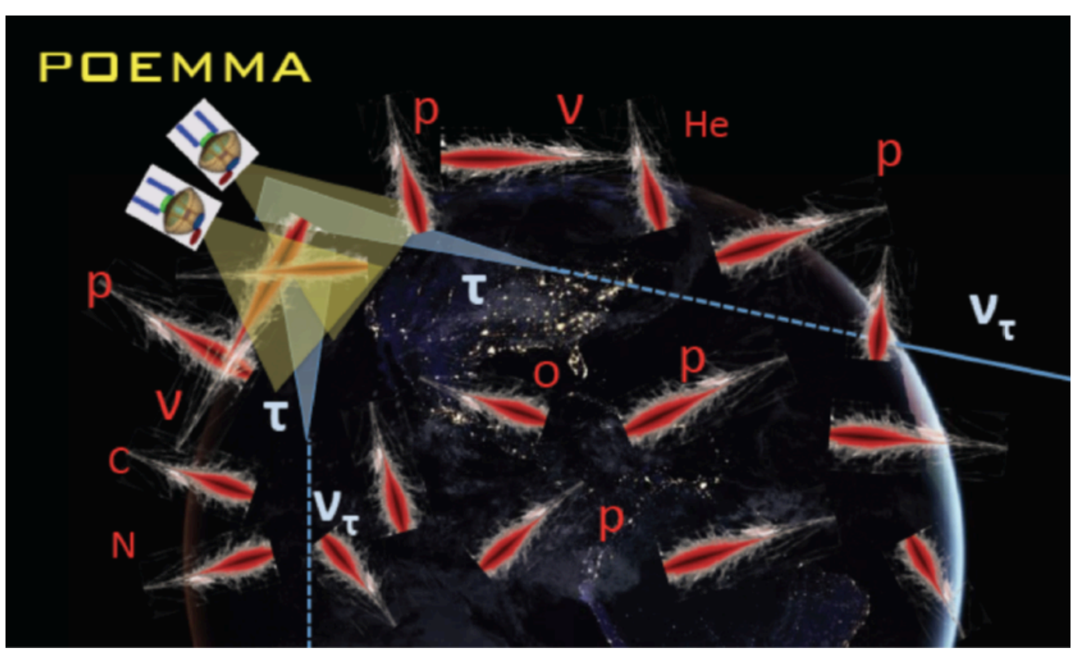
B = μG

Deflection of UHE protons in the galactic magnetic field

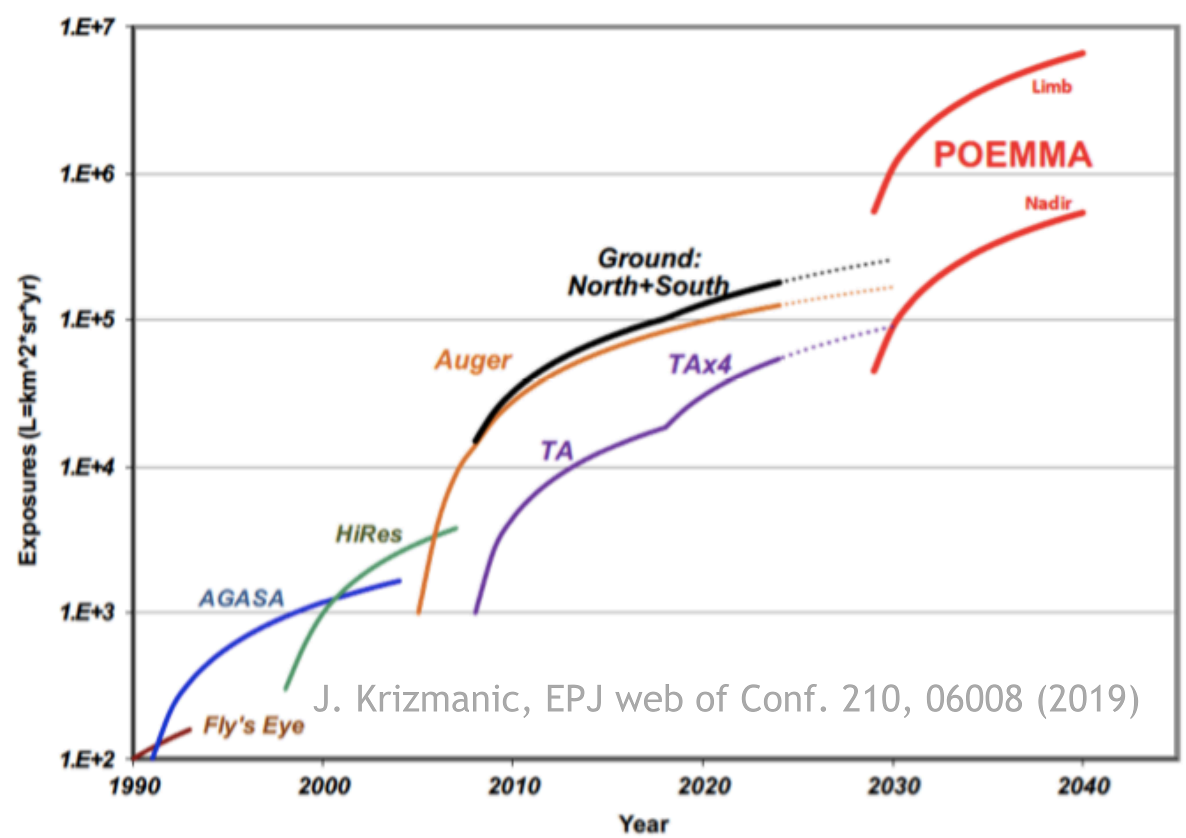
J. Cronin, arXiv: astro-ph/0402487



Deflection of UHE protons in the extragalactic magnetic field



A. Olinto, PoS(ICRC2019) 378



J. Krizmanic, EPJ web of Conf. 210, 06008 (2019)

8. Summary

- The questions about the origin, acceleration, composition, propagation of high-energy cosmic rays are still unsolved.
  - Is there a galactic source of PeV CR’s at the galactic center?
  - What is the origin of the features in the cosmic ray spectrum?
  - Are there new features in the CR spectrum in the poor explored range from 10 TeV to 1 PeV?
  - What are the relative abundances of chemical elements of CR’s above 10 TeV’s?
  - Is there a Pevatron at the galactic center? Where are the Pevatrons?
  - What is the origin of the anisotropies observed in the sky maps of CR arrival directions?

- Important:
  - To reduce uncertainties in hadronic interaction models
  - New precision/high-statistics CR data
  - To measure anisotropies as a function of composition
  - To extend γ-ray measurements up to 100 TeV range.
  - More precision/high-statistics ν data

Thank you for your attention

1519

1509

2019