Cosmic Ray Sources and Propagation

Some comments about the discussion during this workshop, with apologies for incompleteness ...

Paolo Lipari, INFN Roma “Sapienza”

HAP workshop on CR composition

Karlsruhe 23rd september 2015

Measurements of the Cosmic Ray Fluxes at the Earth:

Interpretation in terms of sources and propagation

$$\phi_p(E,\Omega)\ ,\quad \phi_{\rm He}(E,\Omega)\ ,\quad \ldots\ ,\quad \phi_{\{\rm A,Z\}}(E,\Omega)$$

protons+ nuclei

$$\phi_{e-}(E,\Omega)$$

electrons

$$\phi_{e+}(E,\Omega)$$

$$\phi_{\overline{p}}(E,\Omega)$$

anti-particles

The CR spectra are *nearly perfectly* isotropic.
but the angular distribution carries information
of great importance $\phi(E,\Omega) \simeq \phi(E)$

[of course also when the angular distribution is
consistent with exact isotropy *["The dog that did not bark"]*

The energy spectra

their absolute and relative size,
their *different shapes* for different particle types
carry essential information that we want to understand.

Two topics that we have only discussed little in this workshop but are very important:

1. The electron spectrum

And the relation between the spectra of electrons and protons/nuclei.

[of vital importance for “multi-messenger” studies of the sources]

2. The spectra of positrons and anti-protons.

essential to understand CR propagation.

[In my view] finding the solution to the “positron anomaly” problem is a crucial problem with deep and broad implications.

$$\frac{1}{\beta\, c} \int d\Omega\ \phi_j(E,\Omega) = n_j(E, \vec{x}_\odot, t_{\rm now})$$

The study of the flux of cosmic rays
measure the density of Cosmic Rays
At *one point* (the the vicinity of the solar system)
and *one time* (the present).

Study of the *space dependence* of the CR population
are possible and very important (gamma-ray, radio).

Time variations [on long time scales] are
possible, even if the CR population is
on average stationary.
Common assumption:
[can be violated. M]

$$n_j(E, \vec{x}_\odot, t_{\rm now}) \simeq \langle n_j(E, \vec{x}_\odot) \rangle_{\rm time}$$

Talk of Michael Kachelriess: this morning:

V. Savchenko, M. Kachelrie and D. V. Semikoz,
"Imprint of a 2 Million Year old Source on the Cosmic-ray Anisotropy,"
Astrophys. J. **809**, no. 2, L23 (2015) [arXiv:1505.02720 [astro-ph.HE]].

Formation of the Cosmic Ray flux:
divided into two phases:

Injection

[ASTROPHYSICAL SOURCES]

[in interstellar (or intergalactic) space]

Propagation

[from the injection point to the Sun]

Q: is this division really valid ?
A: in most scenarios this is a good subdivision,
but this is a critical point

Galactic Cosmic Rays:

have their origin in sources inside the Milky Way

Extra-Galactic Cosmic Rays

gave their origin in sources outside the Milky Way

Natural to expect that:

Galactic particles dominate the flux at Low energy

Extra-galactic particles dominate the flux at High energy

$$\phi_{\text{galactic}}(E^*) = \phi_{\text{extra galactic}}(E^*)$$

Transition Energy E*

Galactic Cosmic Rays

Very likely:
Ensemble of astrophysical objects that are (astrophysically) quasi-point-like and transients [active for a limited amount of time] {e.g. SNR's or GRB's}

Source labeled by k: $S_{[k]}$

$$\{\vec{x},\ [t_i, t_f],\ N_p(E),\ N_{\rm He}(E),\ \ldots\ ]\}$$

Position, time of activity, injections of protons, ...

Average injection of protons in the Milky Way [particles/(GeV sec)]
obtained averaging over all sources;

$$\langle Q_p(E) \rangle = \frac{1}{T} \sum_{k \in [t, t+T]} N_p^{[k]}(E)$$

We *know* (!) that this injection spectrum extends to PeV energy (and possibly beyond). So some sources must be capable of doing so.

Relation between the observed flux
and the injection ? [example of protons]

$$\phi_p(E) = \frac{\beta\, c}{4\,\pi} \int dt \int d^3x\; q_p(E, \vec{x}, t_0 - t)\; P(\vec{x}_\odot, \vec{x}, t; E)$$

Flux obtained summing over many sources
In a large volume (the entire Galaxy)
active during a long [Myr] time interval (in the past)

Approximately:

$$\phi_p(E) \simeq \frac{\beta\, c}{4\,\pi}\; \langle Q_p(E) \rangle\; \frac{T_{\rm eff}(E)}{V_{\rm conf}}$$

Spectral shape determined by Injection + Propagation

Natural Questions:

Do different classes of objects contribute
to the observed Cosmic Ray populations ?
[SNR's, GRB's, Galactic Center,....]

What physical mechanisms operate in these potential
classes of sources ?

What is the “average emission”
from sources of the same class ?

Sources of the same class
have emission of the identical (or similar) shape
or there are significant variations
between individual objects:

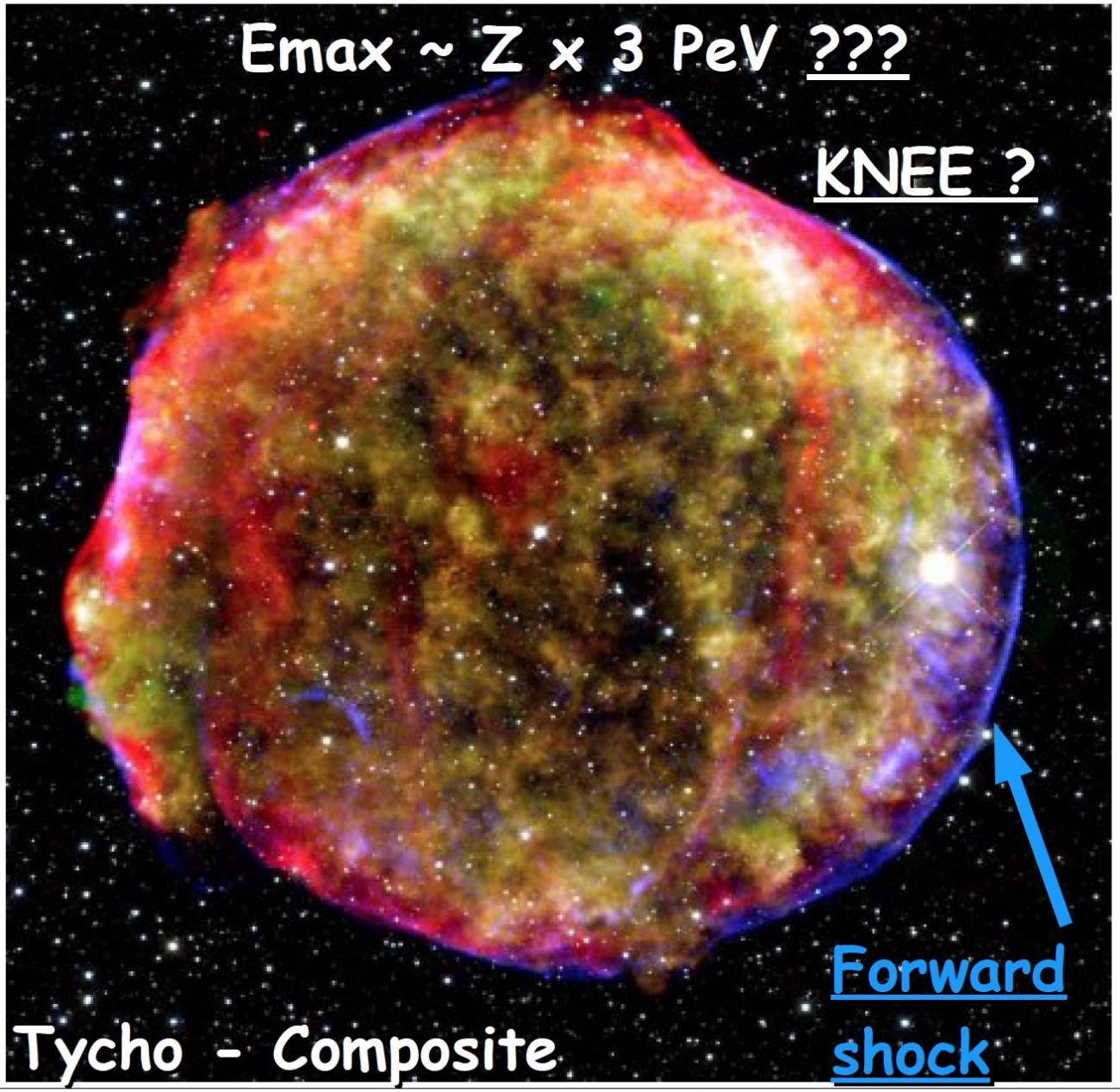
What are the main sources
of the Galactic Cosmic Rays ?

At this meeting we have heard
[strong] arguments in favor of
SuperNova Remnants:

See talks of:
Pasquale Blasi
Gwenael Giacinti

Sources, acceleration mechanism

Supernova remnant



What is the average spectrum
of (for example) protons injected by one object:

Simplest (naïve description):

$$N_p^{[k]}(E) \simeq N_0 \; E^{-\alpha} \; e^{-E/E_{\rm max}^{[k]}}$$

Normalization, slope, E_{max}

Perhaps not exponential cutoff
E^*, E_{max}

Very important (and very “annoying” …) ambiguity:

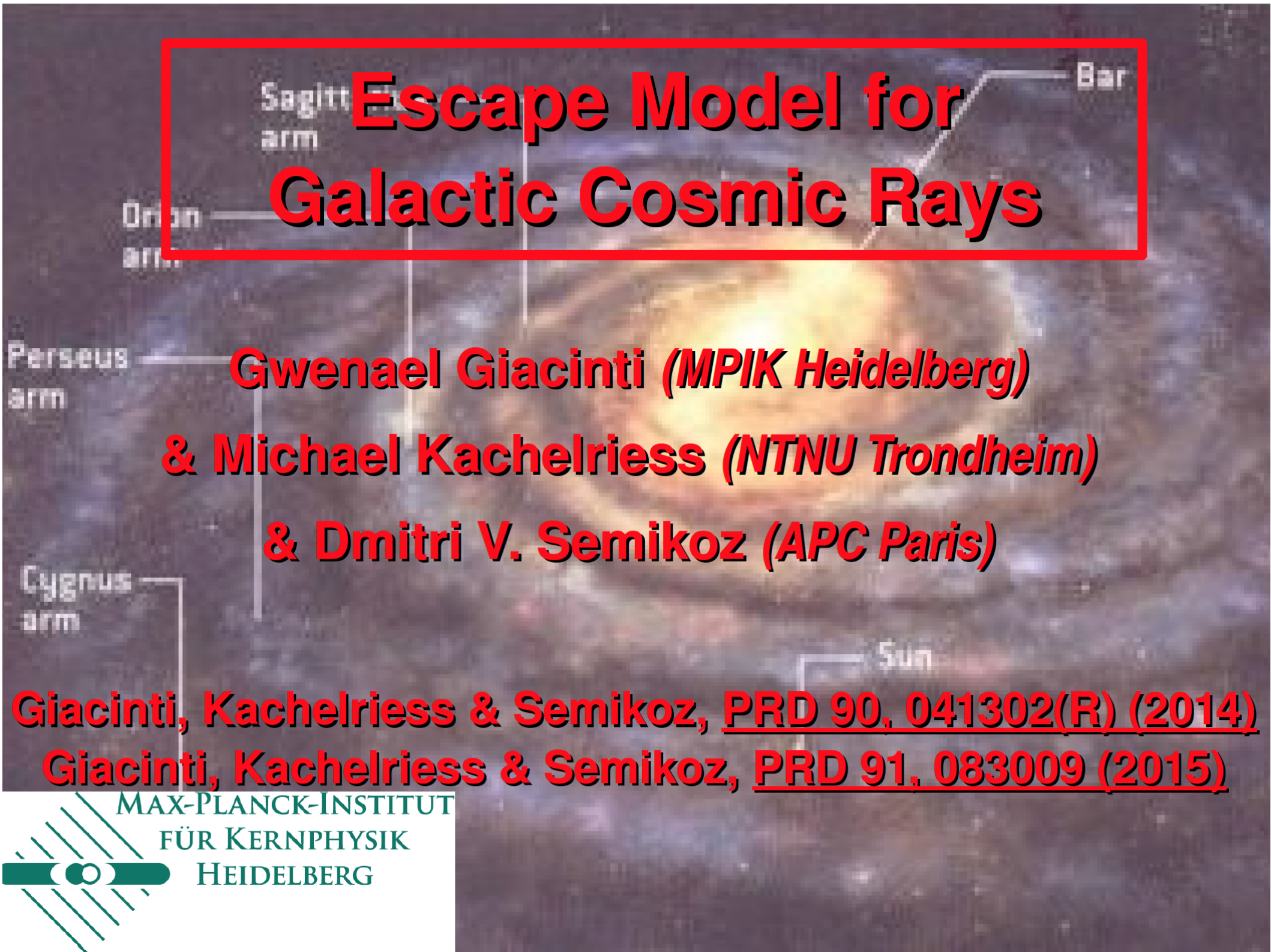
Any feature in the shape of the energy spectrum
can be attributed to the injection or to propagation.

Most prominent spectral feature
the “Knee” [or better the “Knees”]:

Is it created by Injection or Propagation ?

P.Blasi argued for Injection [acceleration]
in a framework where SNR are the CR sources

G.Giacinti argued for the knee as
a signature of Propagation



Escape Model for Galactic Cosmic Rays

Gwenael Giacinti *(MPIK Heidelberg)*

& Michael Kachelriess *(NTNU Trondheim)*

& Dmitri V. Semikoz *(APC Paris)*

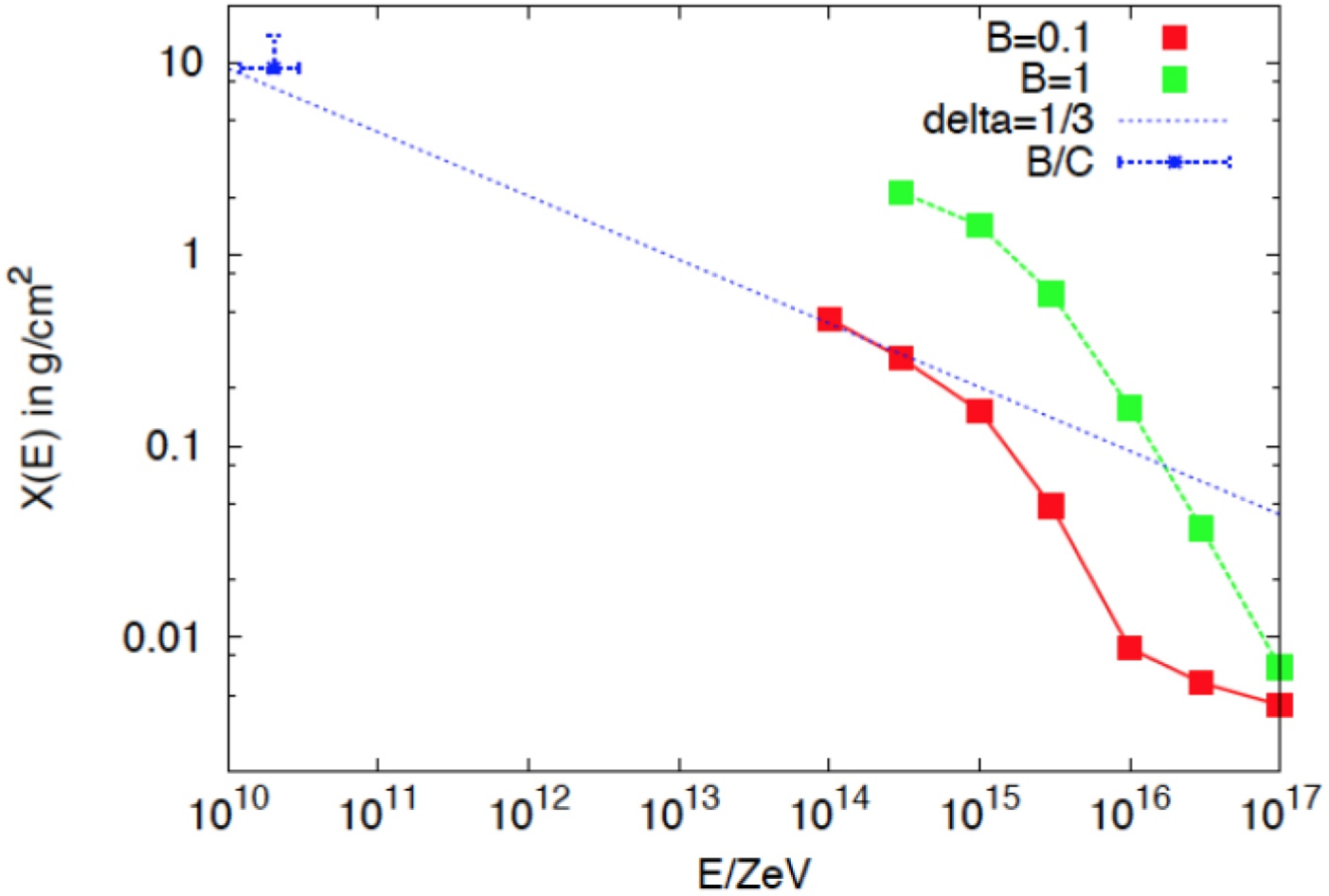
Giacinti, Kachelriess & Semikoz, PRD 90, 041302(R) (2014)

Giacinti, Kachelriess & Semikoz, PRD 91, 083009 (2015)

MAX-PLANCK-INSTITUT
FÜR KERNPHYSIK
HEIDELBERG

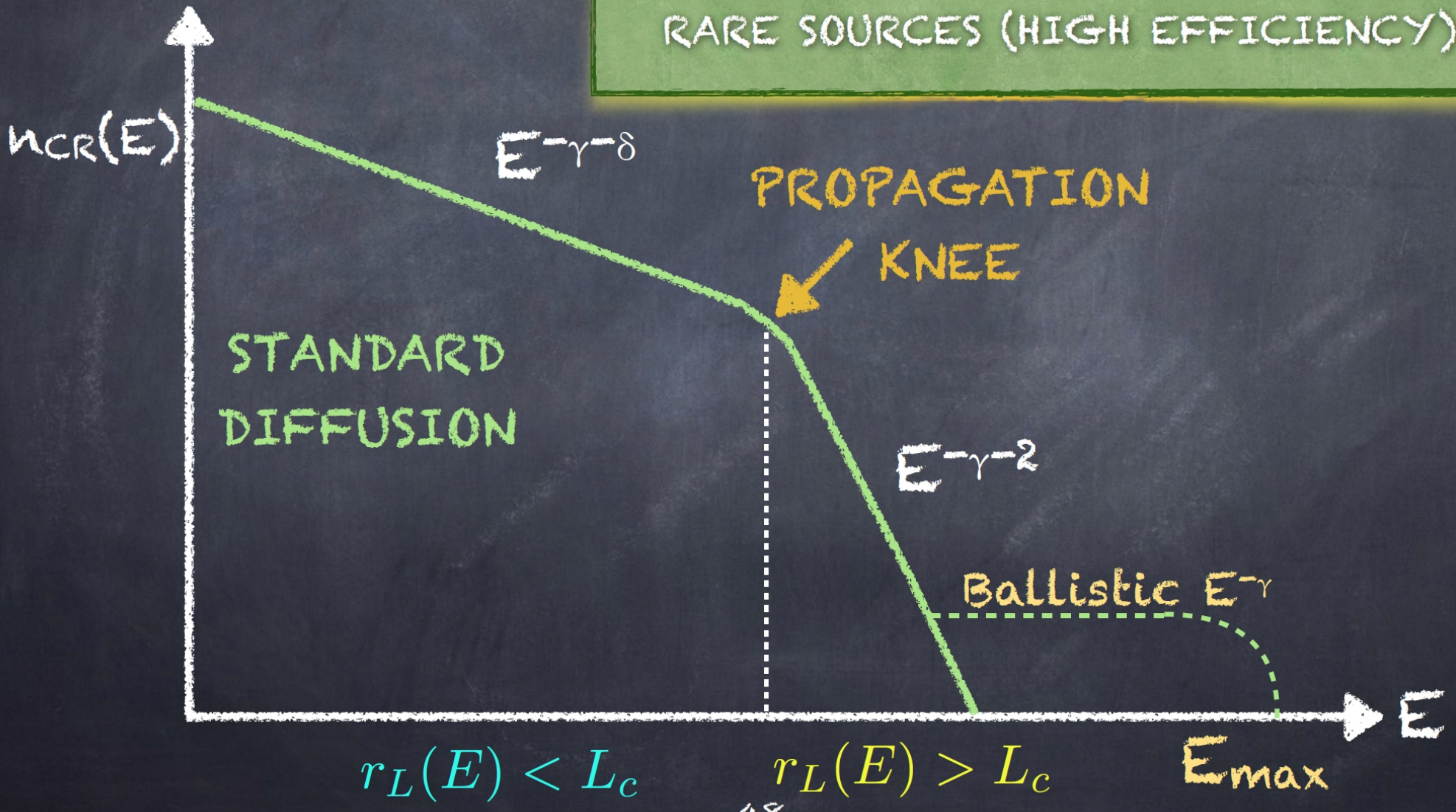
Cosmic Ray Knee

- $l_{\rm coh}$ and regular field $B(x)$ fixed from observations
- determine magnitude of random $B_{\rm rms}(x)$ from grammage $X(E)$



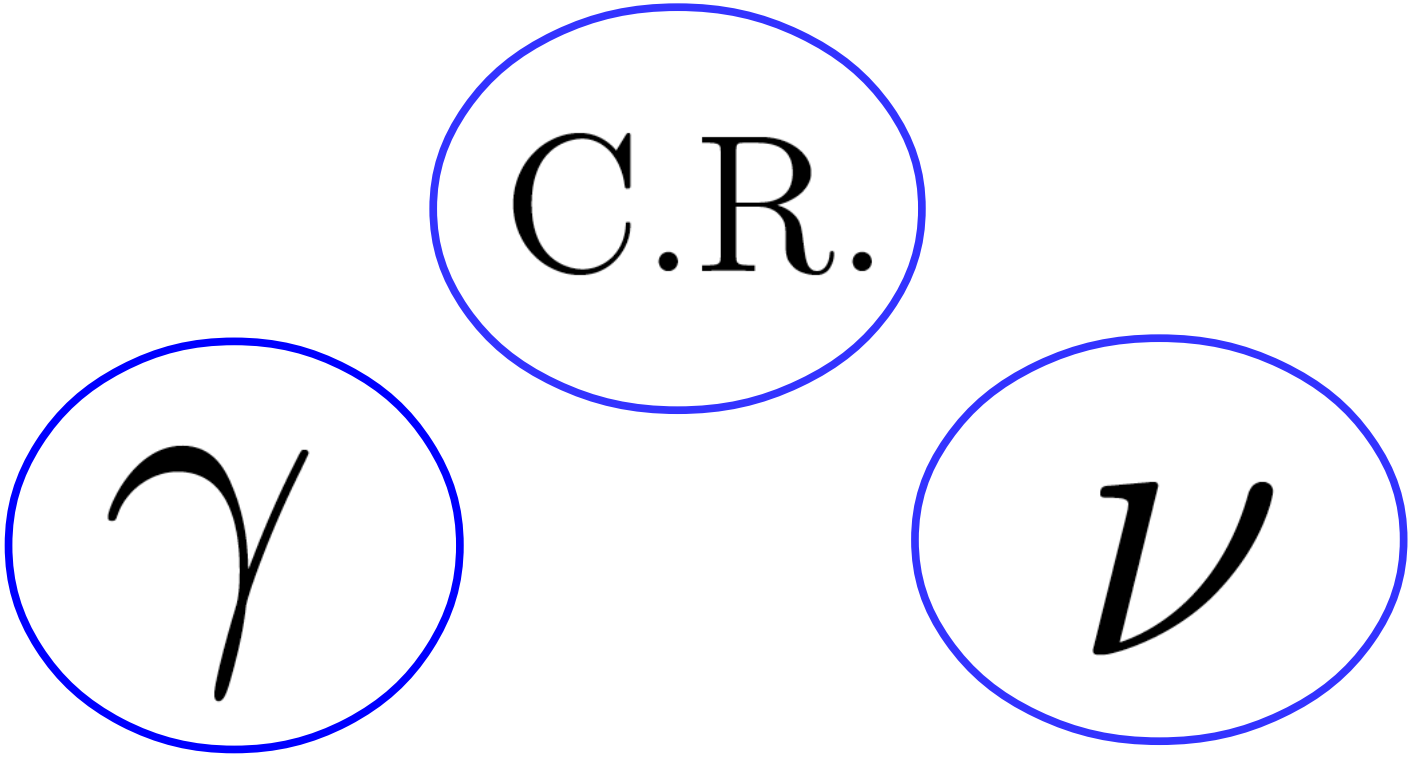
Knee as a propagation effect

IT REQUIRES VERY HIGH E_{MAX} AND RARE SOURCES (HIGH EFFICIENCY)

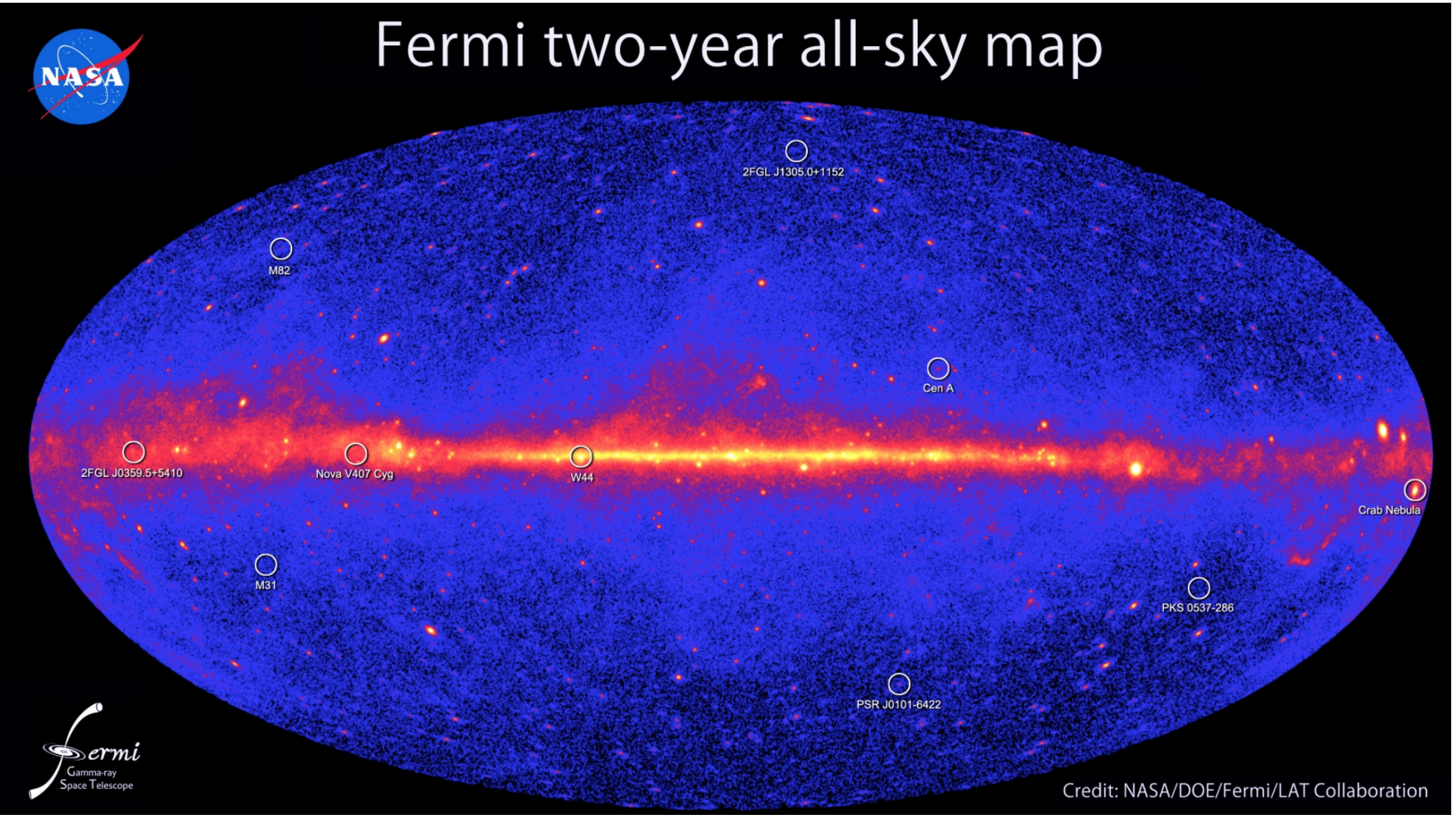


Multi-Messenger Astrophysics

Astrophysical Objects that accelerate Cosmic Rays must be emitters of photons and neutrinos.

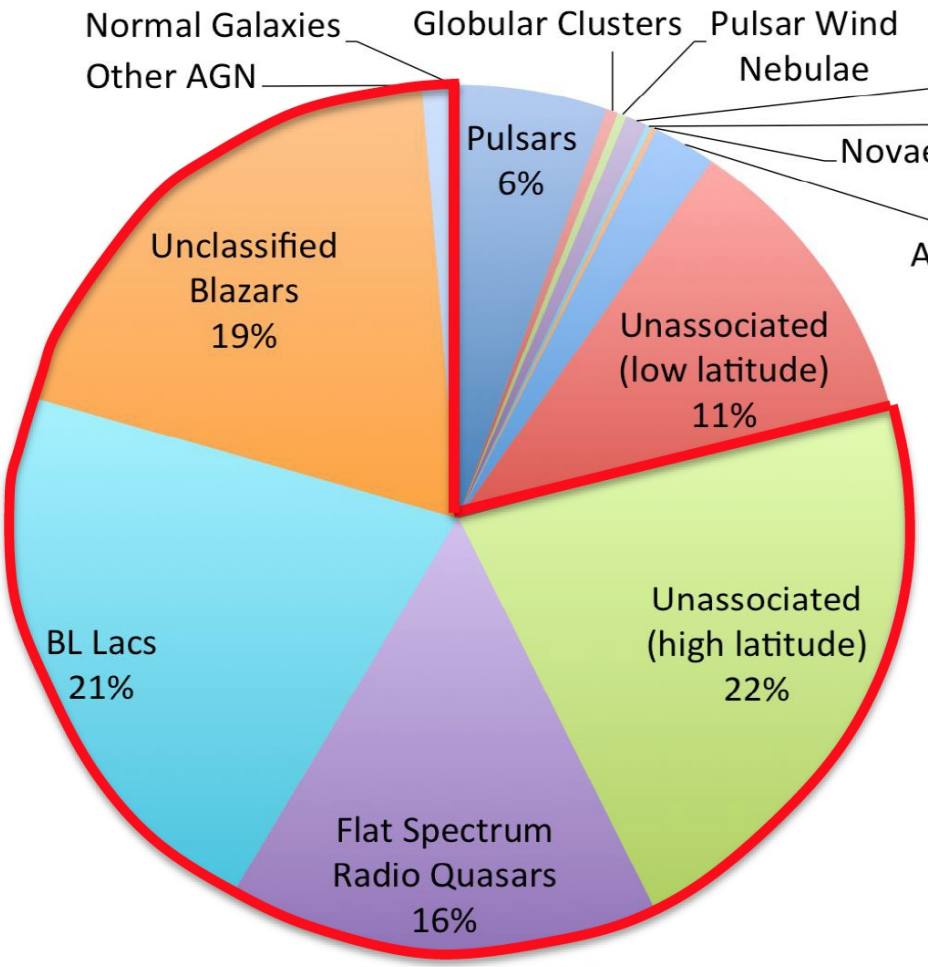


We know know that the Galaxy and the Universe
are full of different classes of sources that contain
(and therefore generate) populations of relativistic particles



Fermi 3rd catalog

Demographics: High Energy



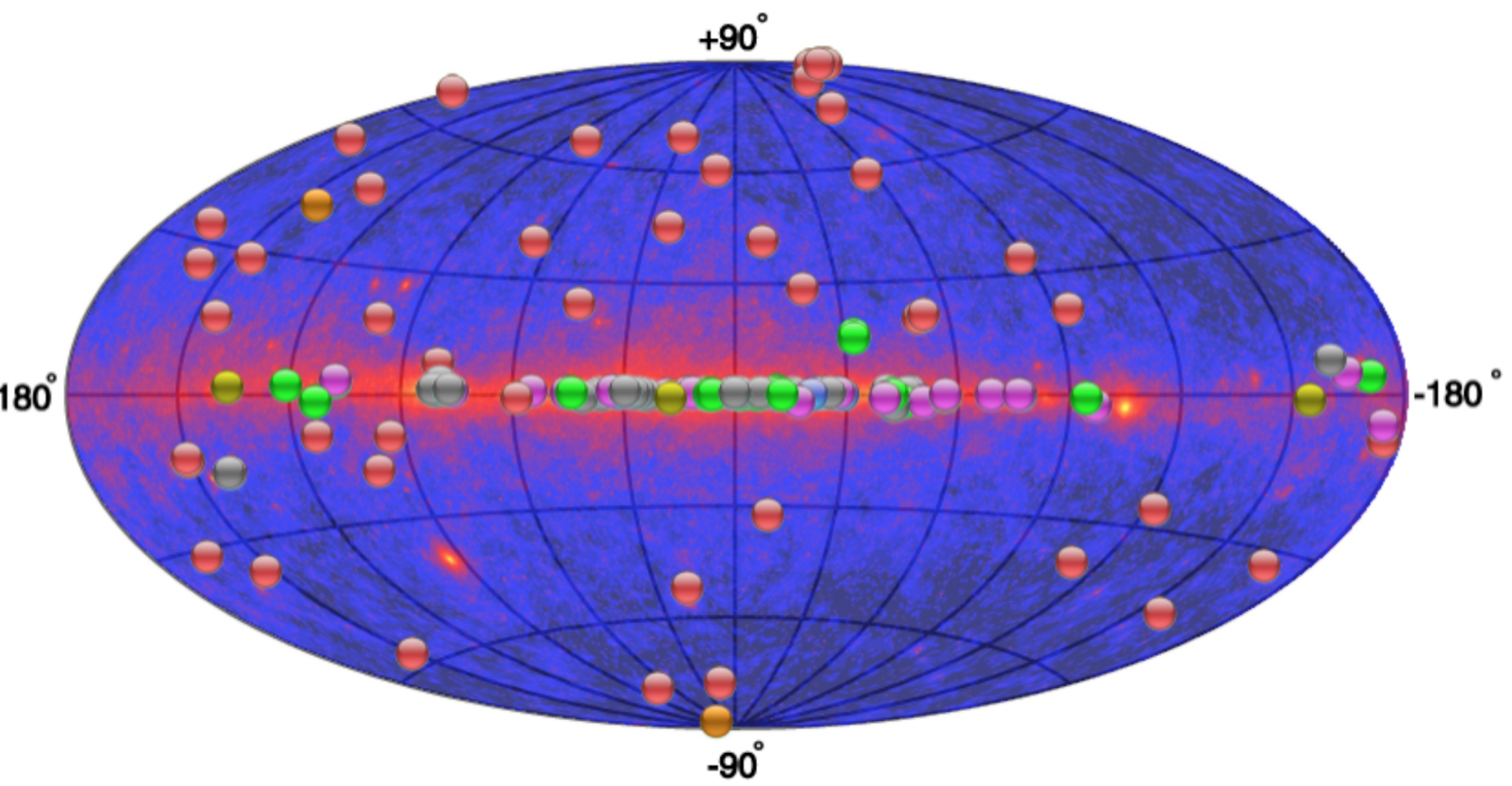
80% extragalactic

>3033 sources
>100 MeV

Based on 3FGL

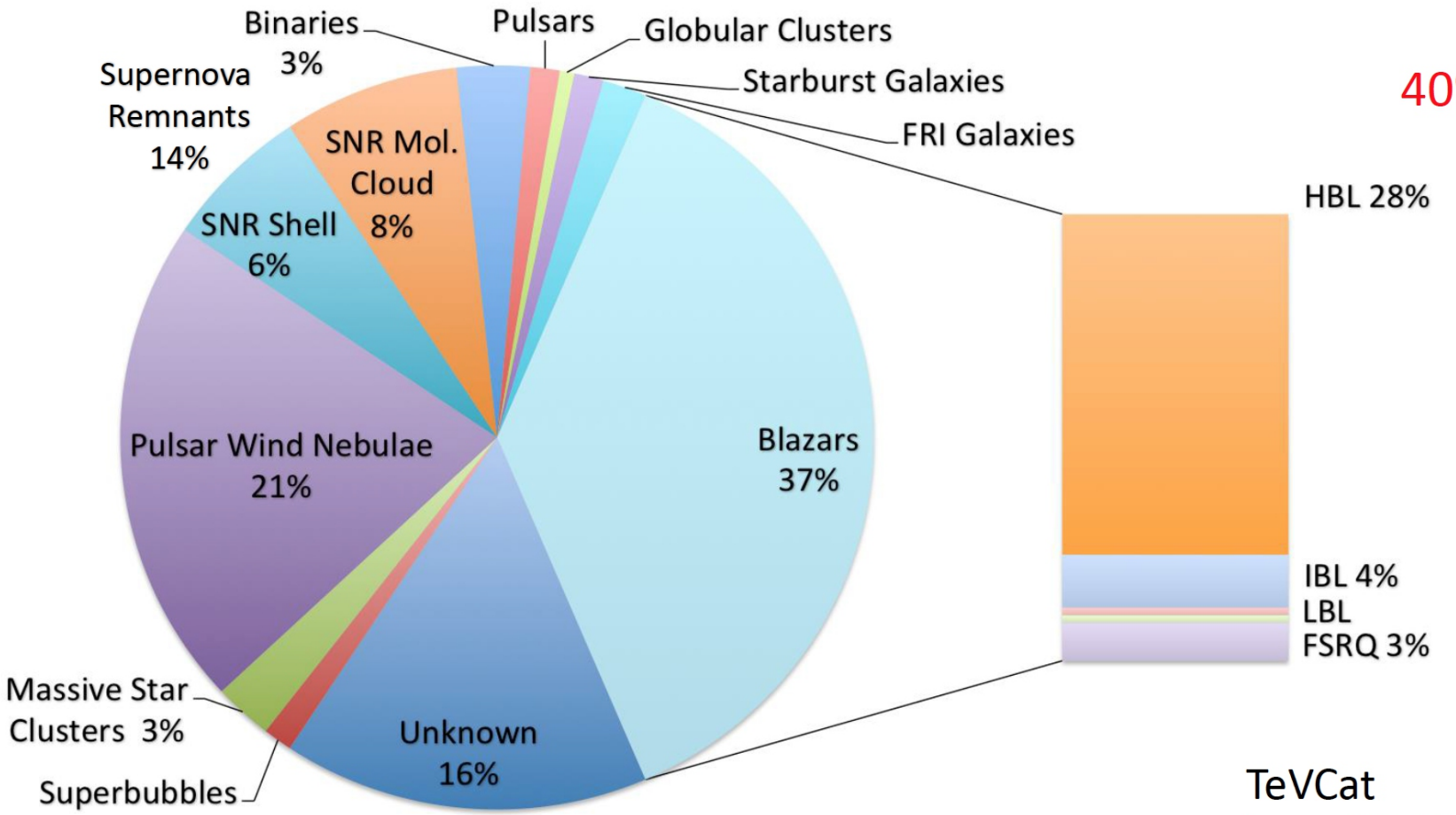
Liz Hays, ICRC 2015

TeV Sky



blue-to-red colors – > 0.1 GeV – Fermi gamma-ray sky

Demographics: Very High Energy



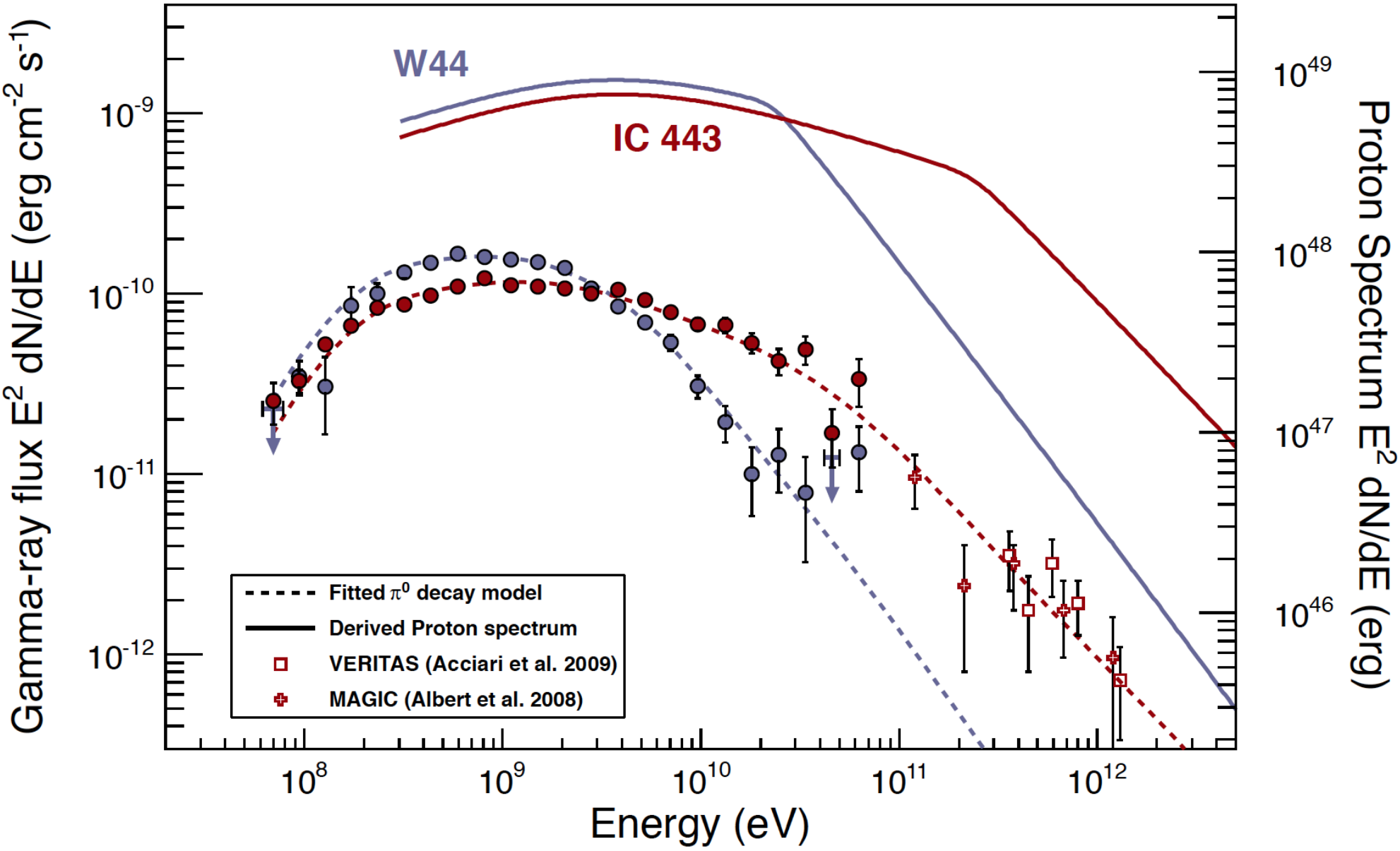
40% extragalactic

>150 sources

>~100 GeV

TeVCat

http://TeVCat.uchicago.edu


W44
IC 443
Fitted π^0 decay model
Derived Proton spectrum
VERITAS (Acciari et al. 2009)
MAGIC (Albert et al. 2008)
Gamma-ray flux E^2 dN/dE (erg cm^{-2} s^{-1})
Proton Spectrum E^2 dN/dE (erg)
Energy (eV)
10^{-9}
10^{-10}
10^{-11}
10^{-12}
10^{49}
10^{48}
10^{47}
10^{46}
10^{8}
10^{9}
10^{10}
10^{11}
10^{12}

Emission from a source
[for example a SuperNova remnant] $[t_i, t_f]$

$N_p^{[k]}(E)$ Total emission of
Relativistic protons from the source

Looking at the source when it is active:
What are the emissions of photons and neutrinos ?

$\dot{N}_\gamma(E,t)$ $\dot{N}_\nu(E,t)$

$N_p^{[k]}(E)$ Total emission of
Relativistic protons from the source

$N_p^{\rm in}(E,t)$ $\dot{N}_p^{\rm out}(E,t)$

$$\int_{t_i}^{t_f} dt\ \dot{N}_p^{\rm out}(E,t) = N_p^{[k]}(E)$$

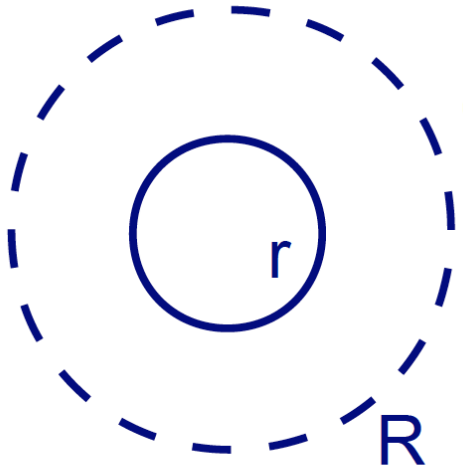
Talk of Martin Pohl this morning

CR acceleration and escape

$$\int \gamma_{\max} \mathrm{d}t \sim 5$$

$$Q_{\mathrm{CR}} = \int j_{\mathrm{CR}} \mathrm{d}t = 10\sqrt{\rho/\mu_0}$$

CR charge through a unit surface, upstream



The CR current density at a radius R is $j_{\mathrm{CR}} = \eta\rho u_s^3 r^2/R^2 T$
(CRs accelerated to energy eT when the shock radius was r)

$$\int_0^R \frac{\eta\rho(r)u_s^2(r)}{T(r)}\, r^2 \mathrm{d}r = 10R^2\sqrt{\frac{\rho(R)}{\mu_0}}$$

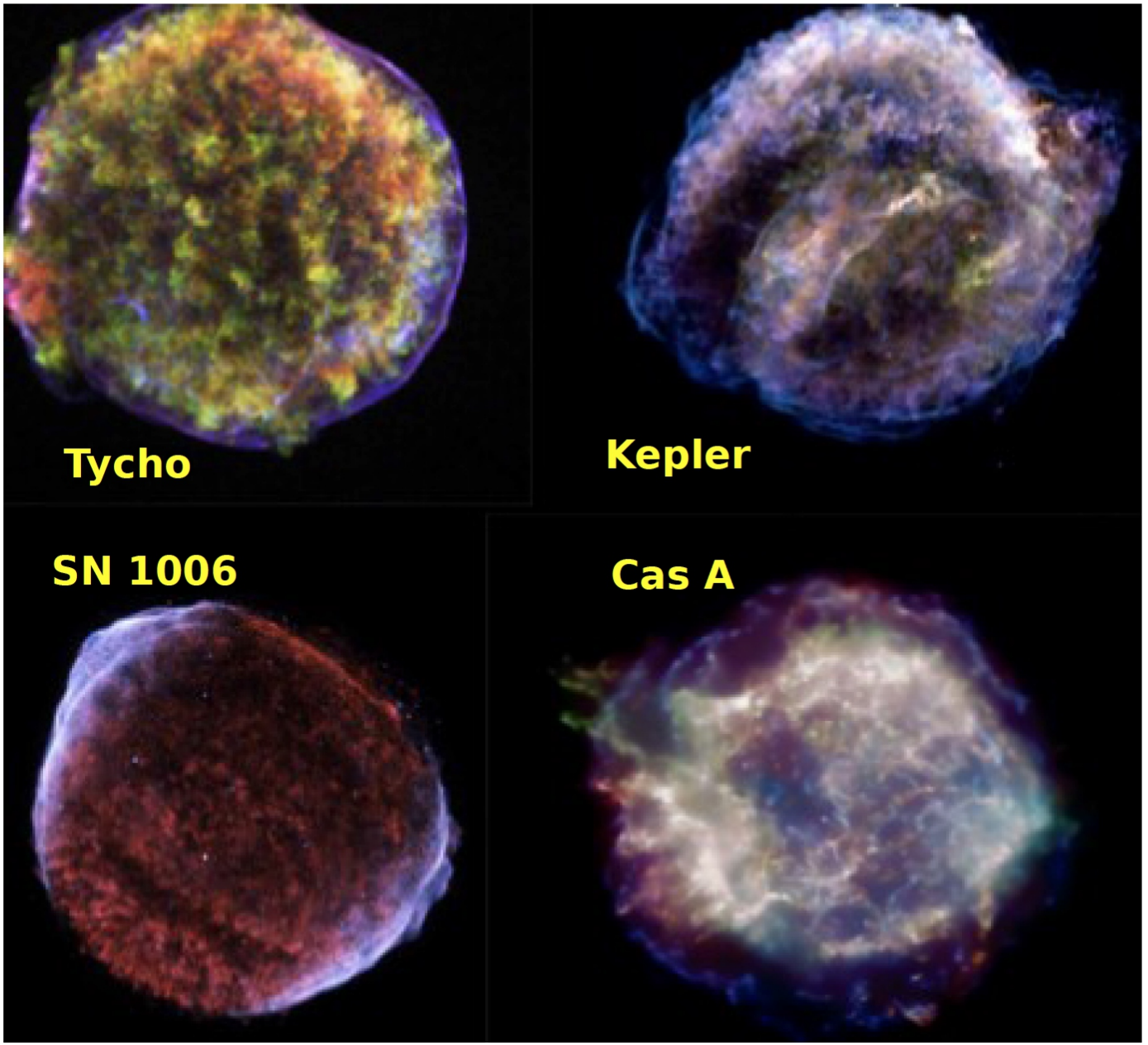
Diff. / R :

ρ = cst →

$$T = 230\eta_{0.03} n_{\mathrm{e}}^{1/2} u_7^2 R_{\mathrm{pc}}\ \mathrm{TeV}$$

Cas A : T ≈ 400 TeV !!!

Nowadays, historical SNRs are <u>not</u> accelerating particles to the knee !



how to find the "missing PeV protons in SNRs?

highest energy particles, E > 100 TeV, are confined in the shell only during a few 100 years => most promising search for PeVatrons?

multi-TeV γ-rays from dense gas clouds in the near neighborhood

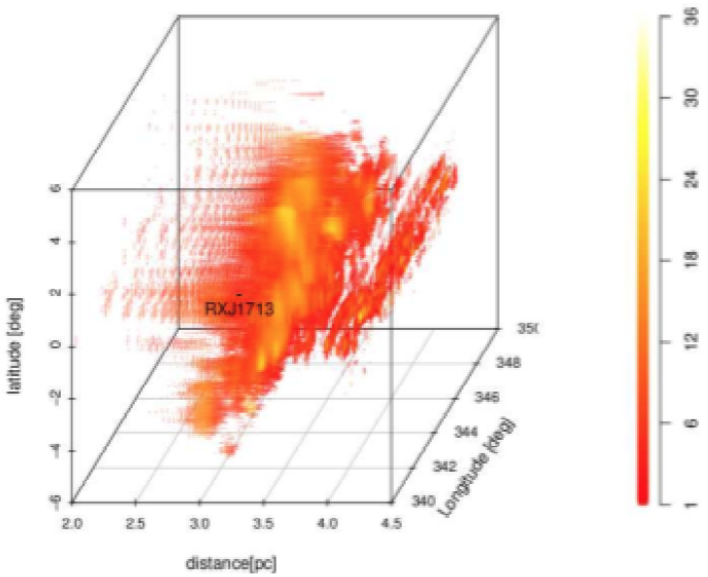
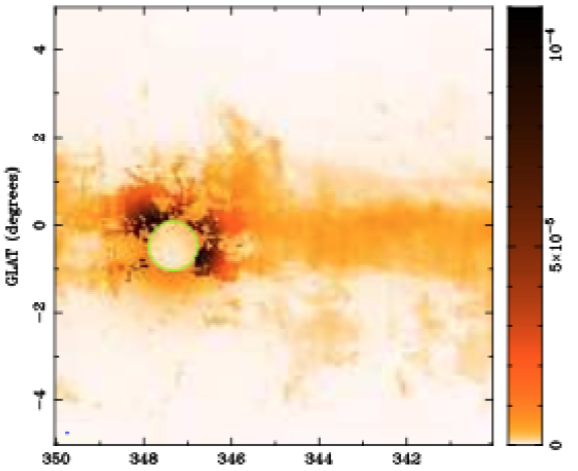


Fig. 1. The gas distribution in the region which spans Galactic longitude $340^\circ < l < 350^\circ$, Galactic latitude $-5^\circ < b < 5^\circ$ and heliocentric distance 50 pc $< l_d <$ 30 kpc, as observed by the NANTEN and LAB surveys, expressed in protons cm^{-3}. The distance axis is logaritmic in base 10. A value for the gas density is given every 50 pc in distance, which is reflected in the apparent slicy structure for distances below 100 pc. For sake of clarity only densities above 1 protons cm^{-3} are shown. Also indicated the position of the historical SNR, RX J1713.7-3946.



surrounding gas density:

NANTEN data

age:

1600 yr

escape of protons:

model of Zirakashvili&Ptuskin 2008

diffusion coefficient outside SNR:

$D=10^{26}\ (E/10GeV)^{0.5}\ cm^2/s$

Are SNRs the only candidate as the main source of the Galactic Cosmic Rays ?

Are there any alternatives ?

Are SNRs the only candidate as the main source of the Galactic Cosmic Rays ?

Are there any alternatives ?

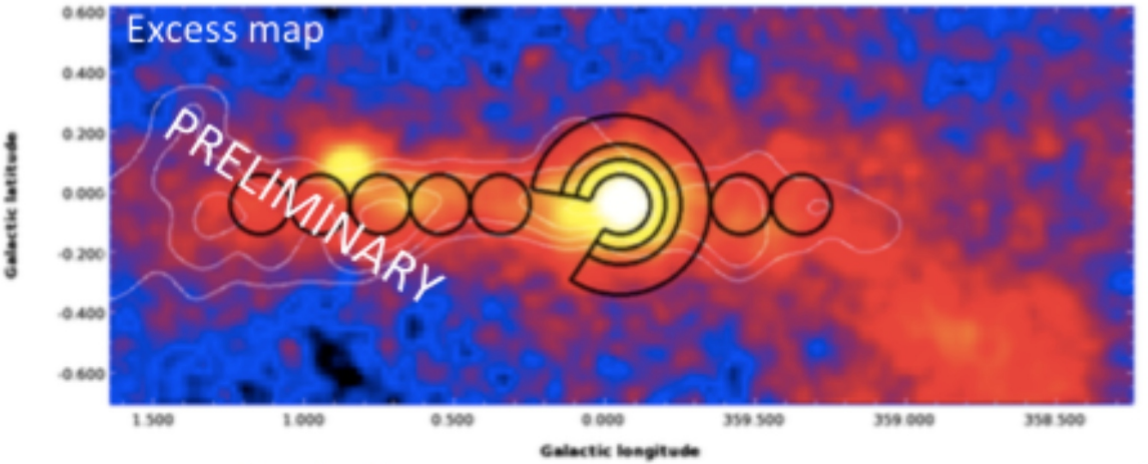
... SNR are the most natural and attractive
(and certainly the most “popular” candidate)
But one should keep an open mind for alternatives
[perhaps unexpected].

GRB's
PWN's
The Galactic Center

new!

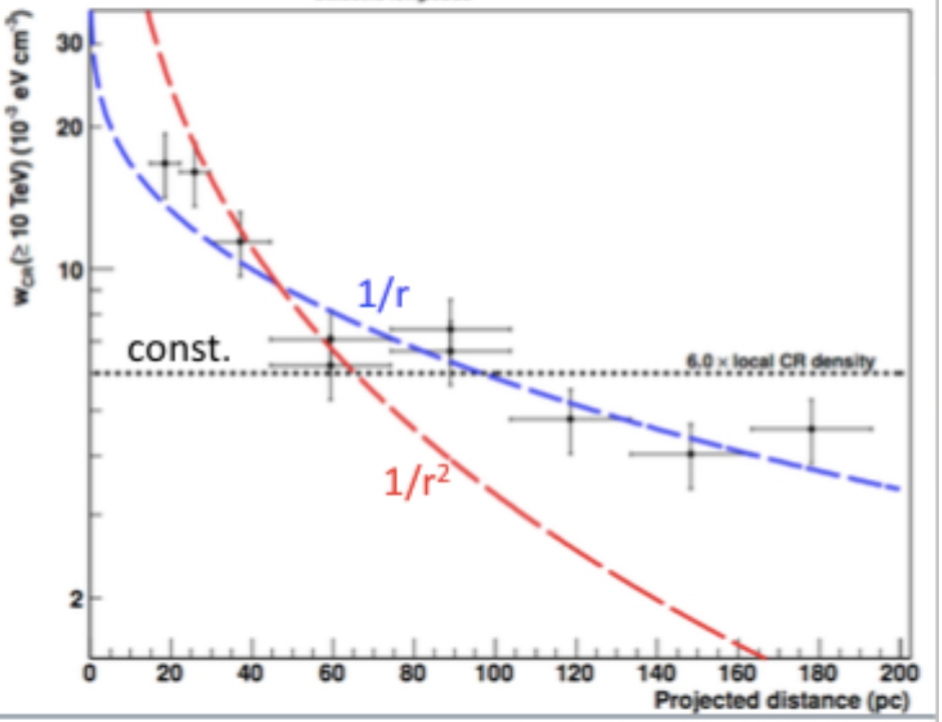
Cosmic-ray density distribution

- Correlation with molecular clouds
  => pp interaction target mass (M)
- Gamma-ray luminosity (L) in several regions
- => CR density $\propto$ L/M



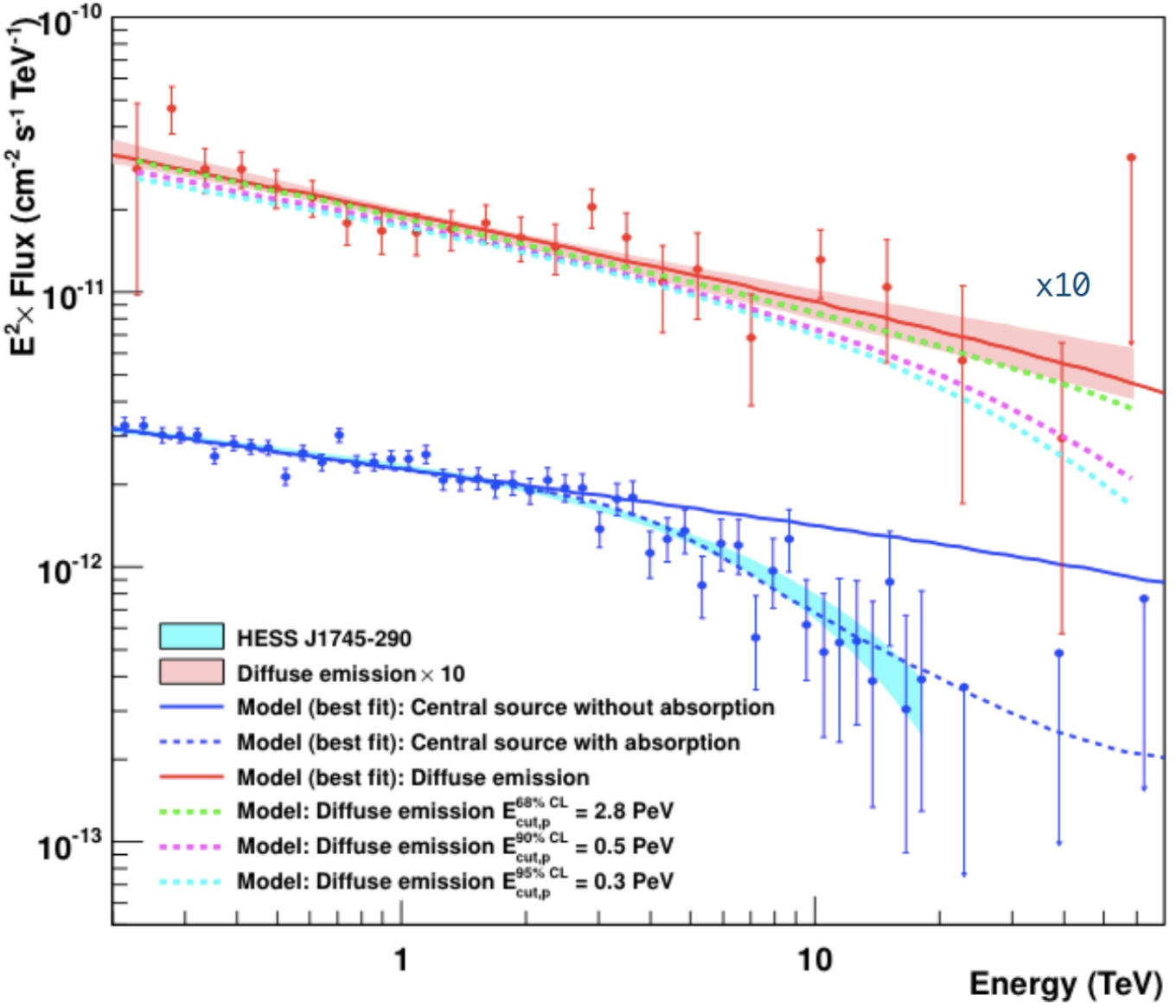
CR density radial distributions:
- Homogeneous => Impulsive injection of CRs and diffusive propagation
- 1/r2 => Wind-driven propagation
- 1/r => continuous injection and diffusive propagation

Central accelerator located within 10 pc and injecting CRs continuously for > 1 kyrs

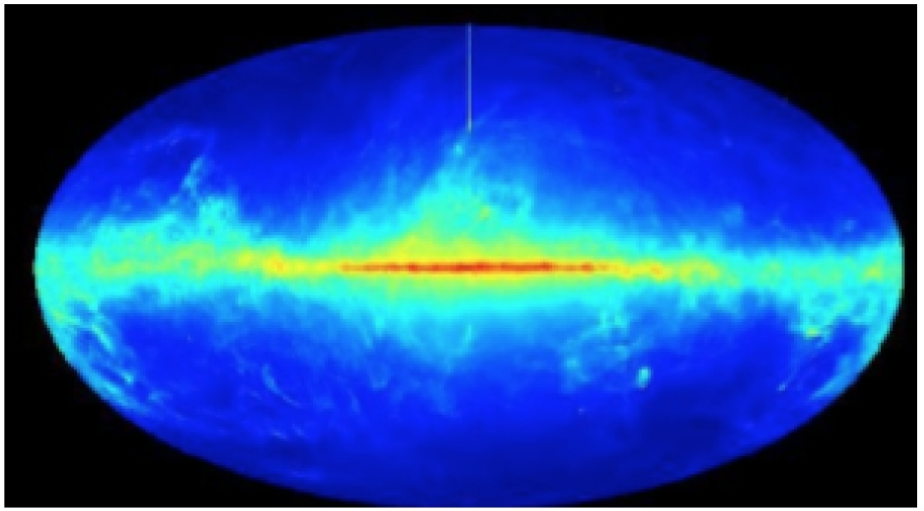


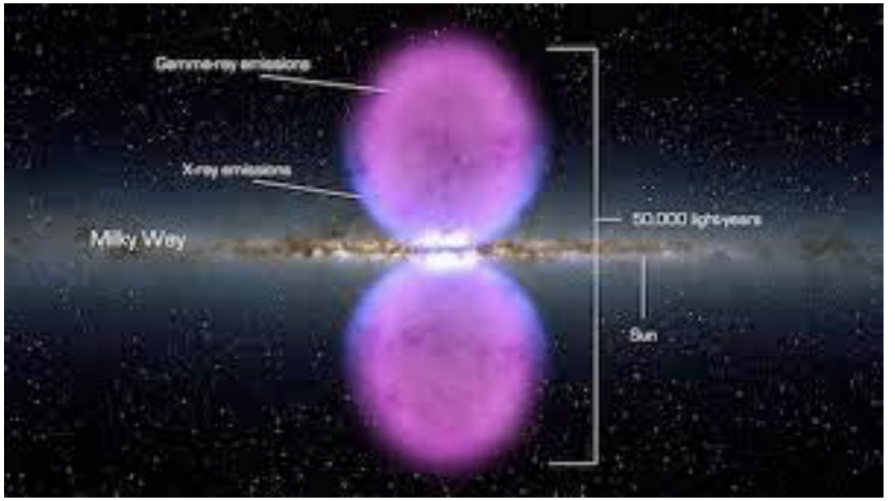
new!

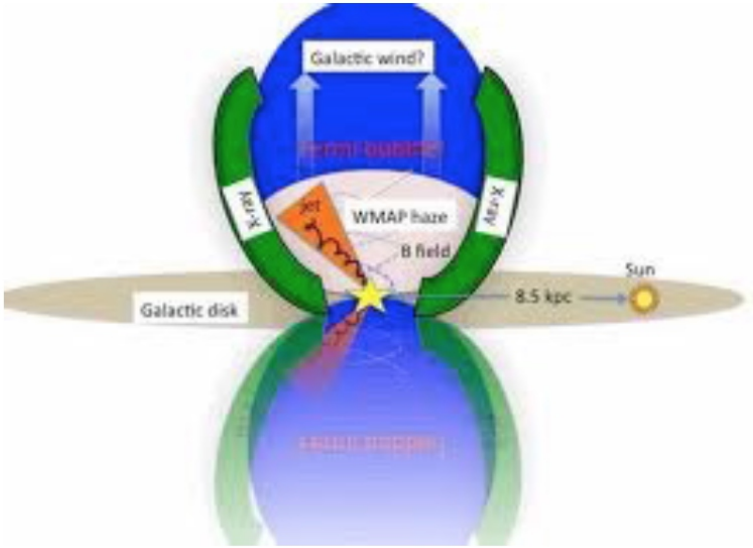
GC: the central source and the diffuse emission of CMZ



CRs from GC responsible for Fermi Bubbles?







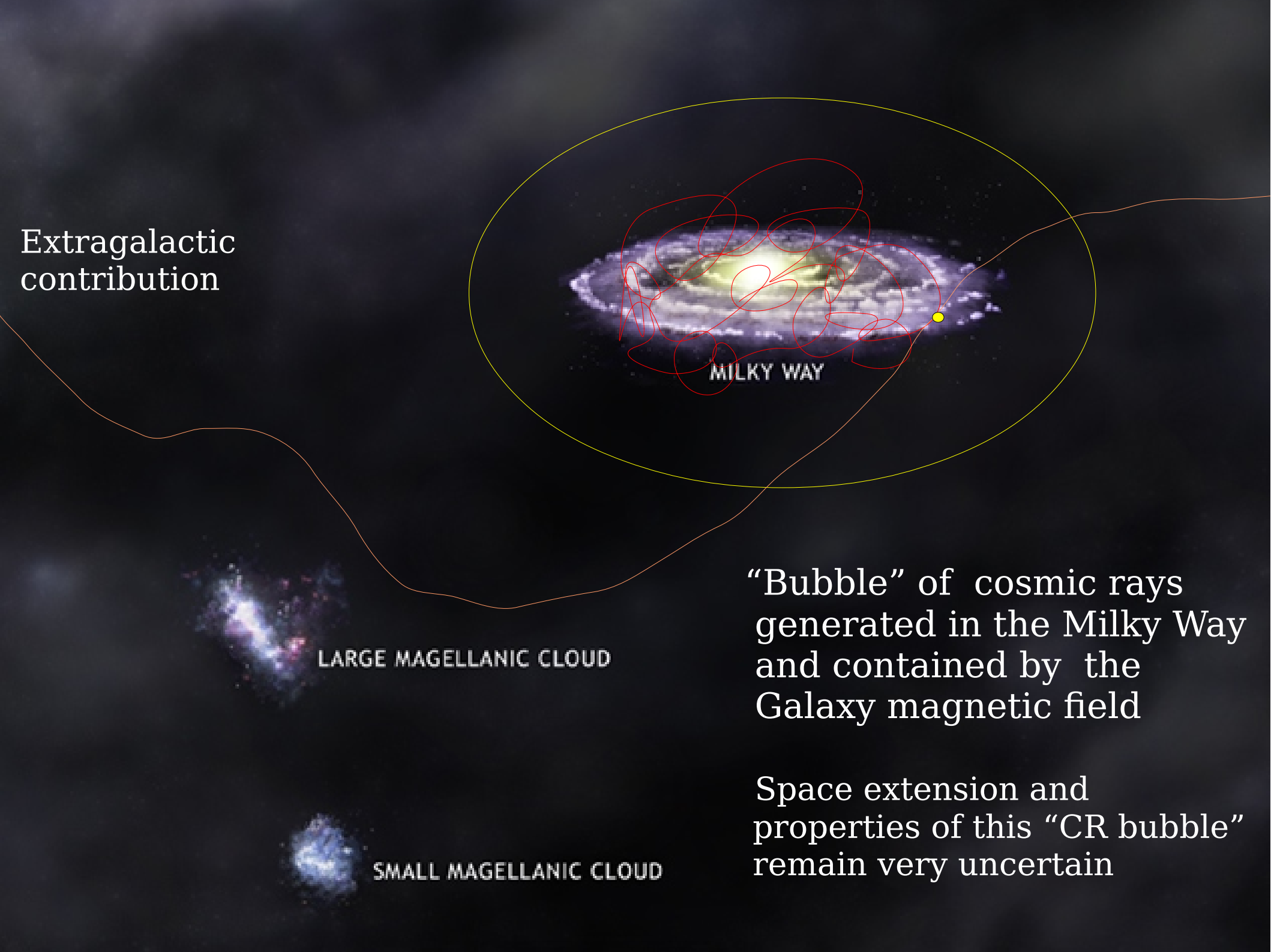
Conclusions:

- Galactic Center (GC) harbors a hadronic PeVatron within a few pc region around Sgr A* a suspected SMBH
- 1/r type distribution of the CR density implies (quasi)continuous regime of operation of the accelerator with a power 10^{38} erg/s (on timescales 1 to 10 kyr) - a non negligible fraction of the current accretion power
- this accelerator alone can account for most of the flux of Galactic CRs around the "knee" if its power over the last 10^6 years or so, has been maintained at average level of 10^{39} erg/s.
- escape of particles into the Galactic halo and their subsequent interactions with the surrounding gas, can be responsible for the sub-PeV neutrinos recently reported by the IceCube collaboration
- the expected >10 TeV neutrino flux is within the range of sensitivity a several km^3 volumee neutrino detector
- perfect target for CTA - to search for the variability of the central source, to measure the spectrum of diffuse (CMZ) gamma-rays up to 100 TeV and beyond

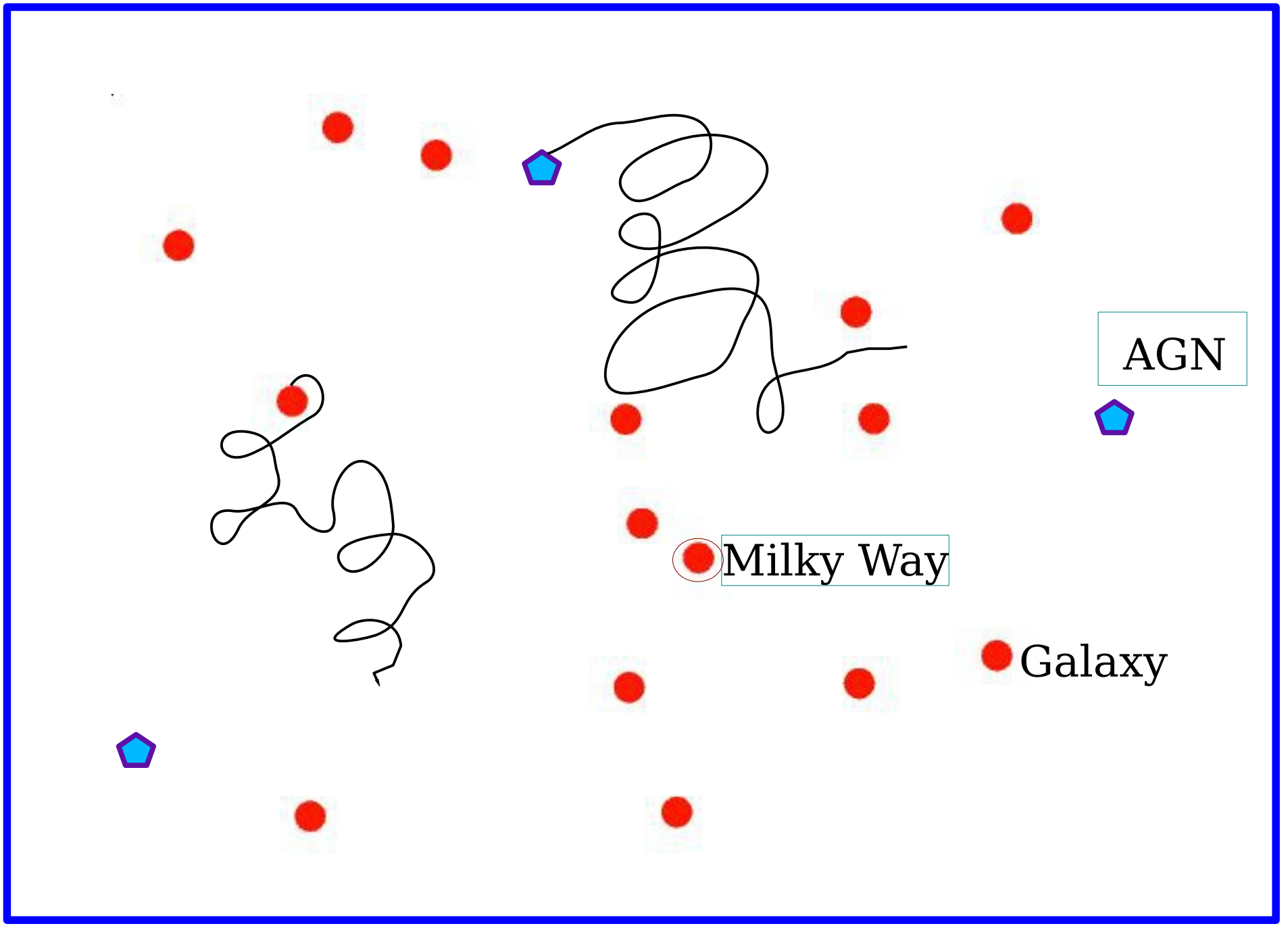
Galactic

versus

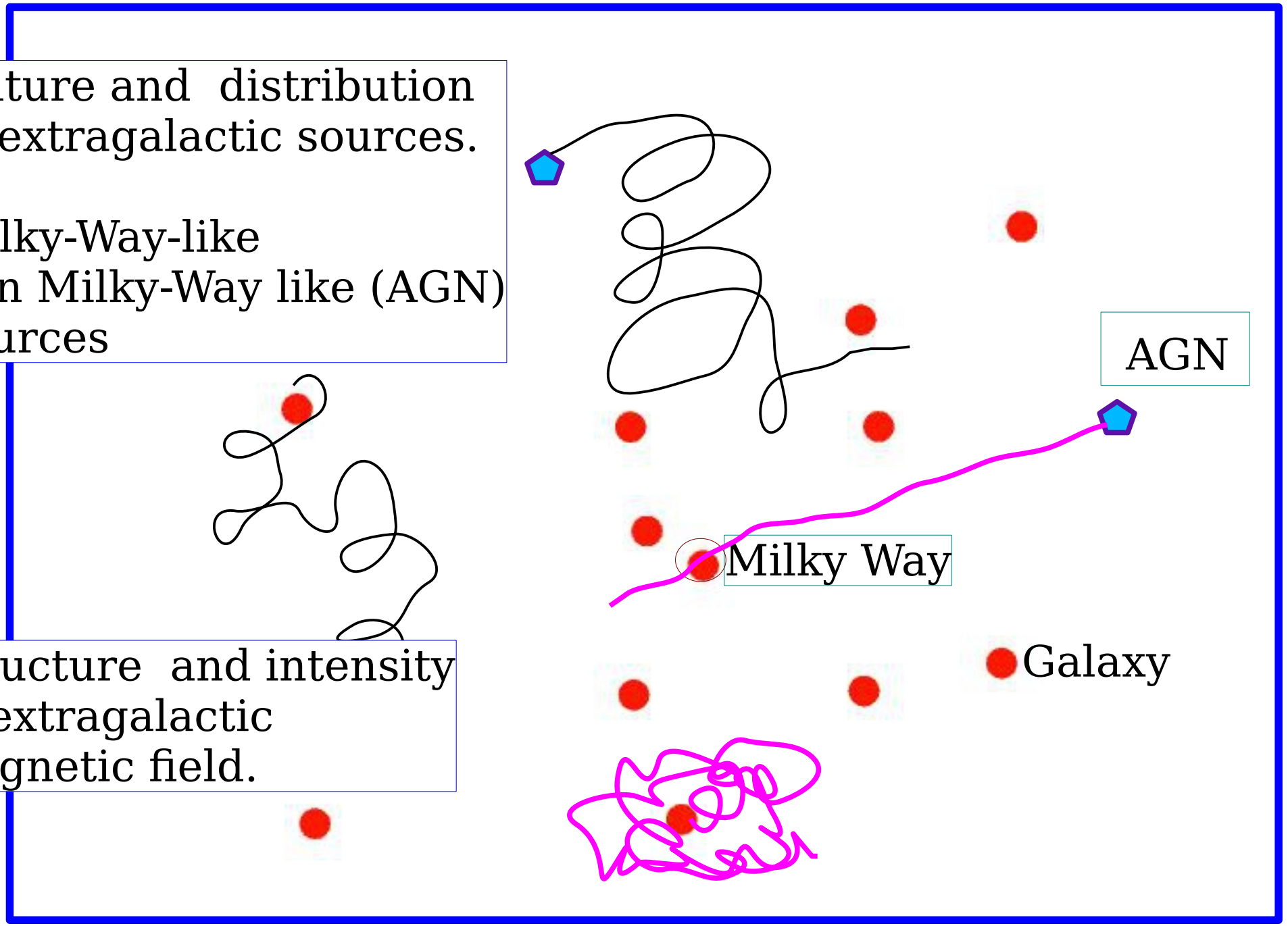
Extra-Galactic


Extragalactic
contribution
MILKY WAY
LARGE MAGELLANIC CLOUD
SMALL MAGELLANIC CLOUD
“Bubble” of cosmic rays
generated in the Milky Way
and contained by the
Galaxy magnetic field
Space extension and
properties of this “CR bubble”
remain very uncertain

Piece of extragalactic space: Non MilkyWay-like sources



Piece of extragalactic space:



The distinction
Galactic / extra-Galactic is conceptually clear.

... but how is it possible experimentally to disentangle the Galactic and extragalactic populations ?

Non trivial

Crucial observation : *ANGULAR DISTRIBUTIONS !*

Galactic CR production most likely from a disk region (with the Sun close to one border)

ISOTROPY :

1. Sufficiently "scrambled" particles produced in the Milky Way

2. Extragalactic particles emitted from a (sufficiently large portion) of an isotropic universe

Simple ideas:

1. At a *sufficiently high magnetic rigidity*
   the angular distribution of the Galactic particles
   will start to show the imprint of the geometry of the
   emission (an confinement volume)

2. At *sufficiently high magnetic rigidity*
   Extragalactic particles will:

   2a. Come from a smaller volume in the universe
   and carry information about the
   non-homogeneity of the local universe.

   2b. "Point" [with smearing + deviations]
   to extragalactic source "Proton Astronomy"

Simple ideas:

What is “sufficiently high” ?

1. At a *sufficiently high magnetic rigidity*
   the angular distribution of the Galactic particles
   will start to show the imprint of the geometry of the
   emission (an confinement volume)

2. At *sufficiently high magnetic rigidity*
   Extragalactic particles will:

   2a. Come from a smaller volume in the universe
   and carry information about the
   non-homogeneity of the local universe.

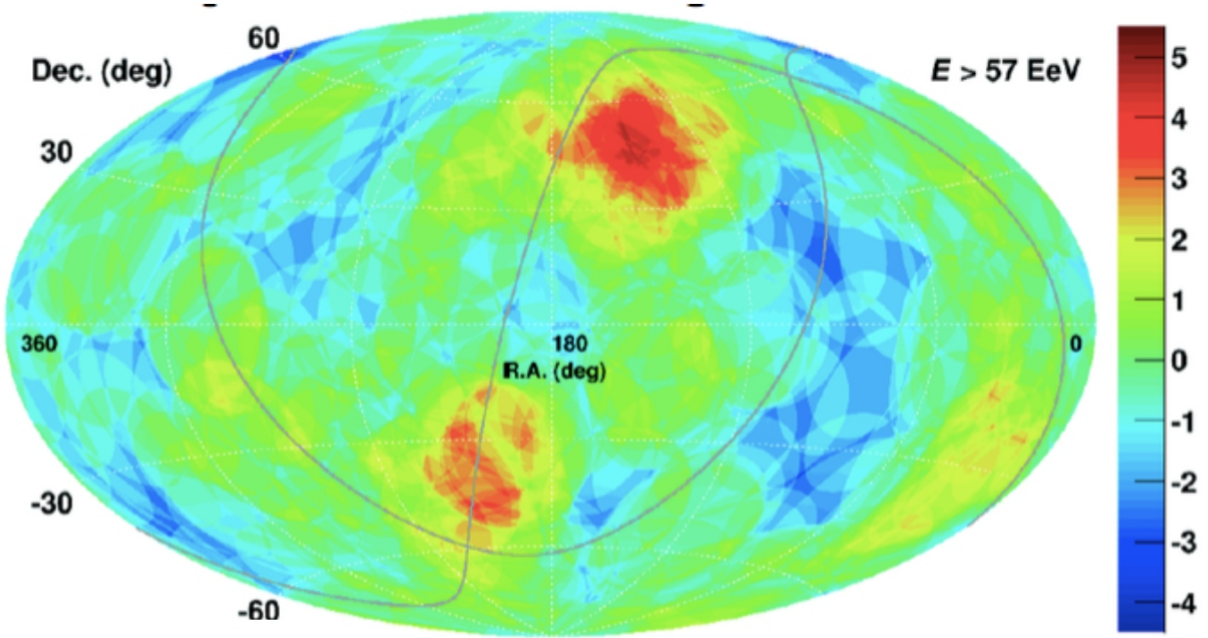
   2b. “Point” [with smearing + deviations]
   to extragalactic source “Proton Astronomy”

Has this been achieved ?

Point source searches

- astrophysical origin of UHE sources (top-down models strongly disfavoured)
- look at highest energies (as deflections proportional to Z/E)
- look close (as cutoff is seen for E> 40 EeV)

- No significant excesses were found
- Two medium scale spots



TA

7 years, 109 Events (> 57 EeV)

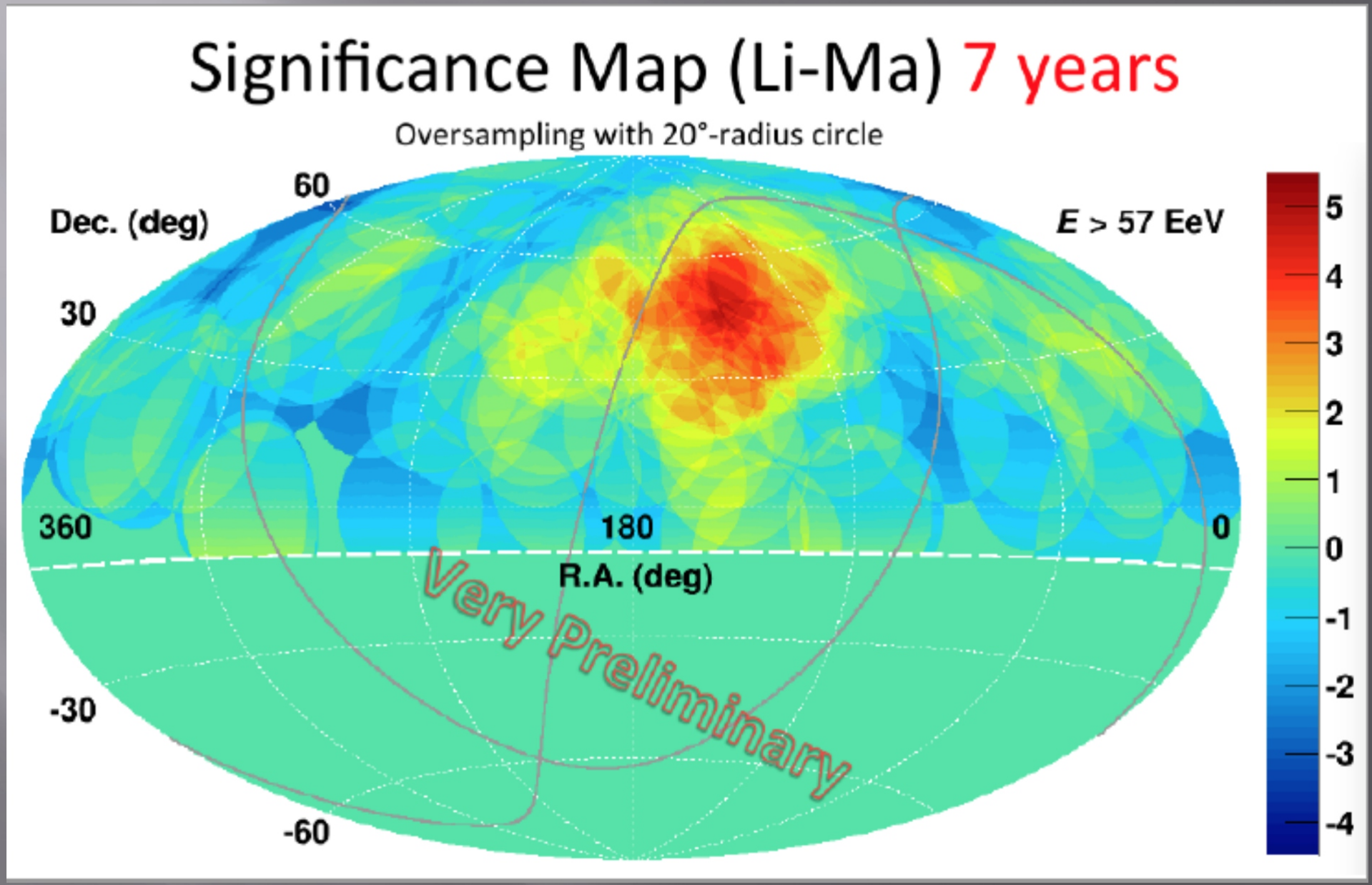
Northern Hemisphere: hot spot seen by TA (3.4 σ) near the Ursa Major cluster

Auger

10 years 157 events (> 57 EeV)

Southern Hemisphere: hot spot seen by Auger (post-trial prob 1.4%) near to Cen A

TA Hotspot


Significance Map (Li-Ma) 7 years
Oversampling with 20°-radius circle
Dec. (deg)
60
30
-30
-60
360
180
0
R.A. (deg)
E > 57 EeV
5
4
3
2
1
0
-1
-2
-3
-4
Very Preliminary

Magnetic Field of the Milky Way

$$\vec{B} = \vec{B}_{\text{regular}} + \vec{B}_{\text{random}}$$

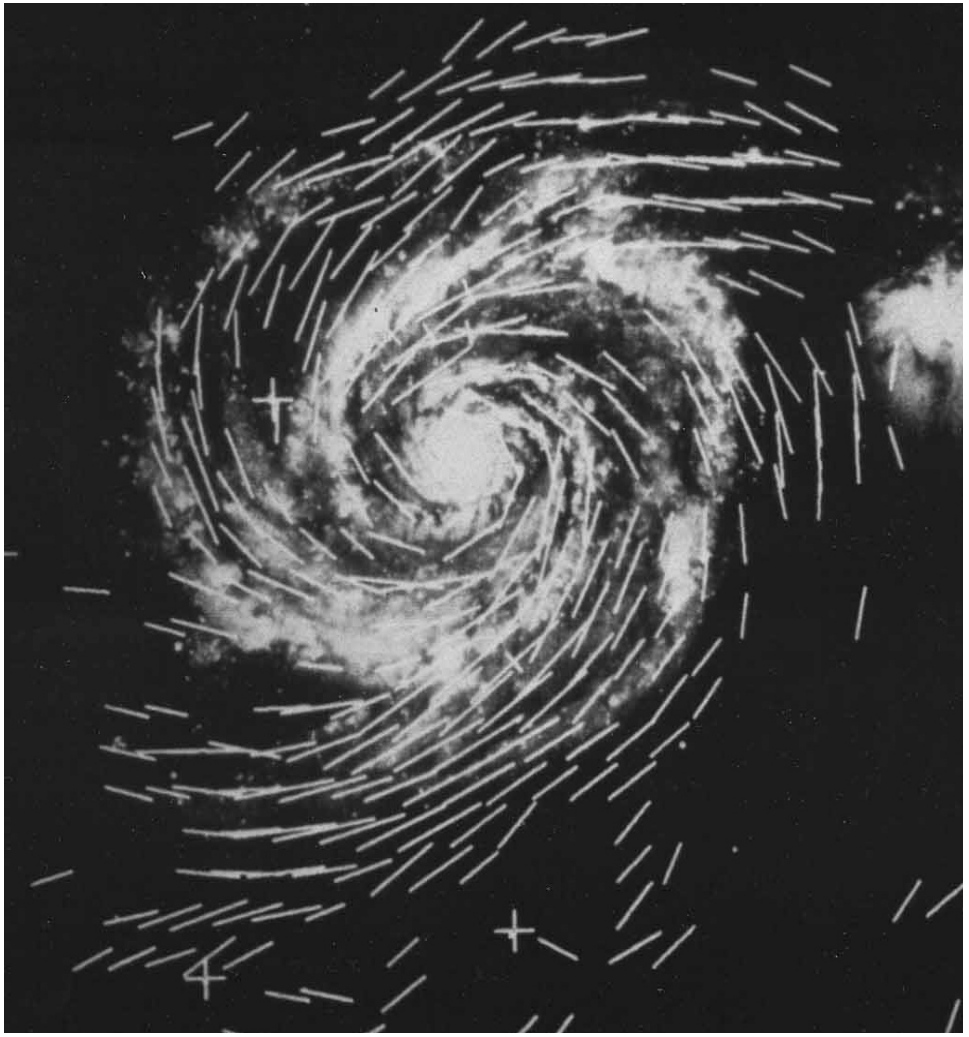
"Regular Field"

(Global structure)

"Random Field"

(associated with turbulent motions in the interstellar plasma)

Magnetic fields of different galaxies

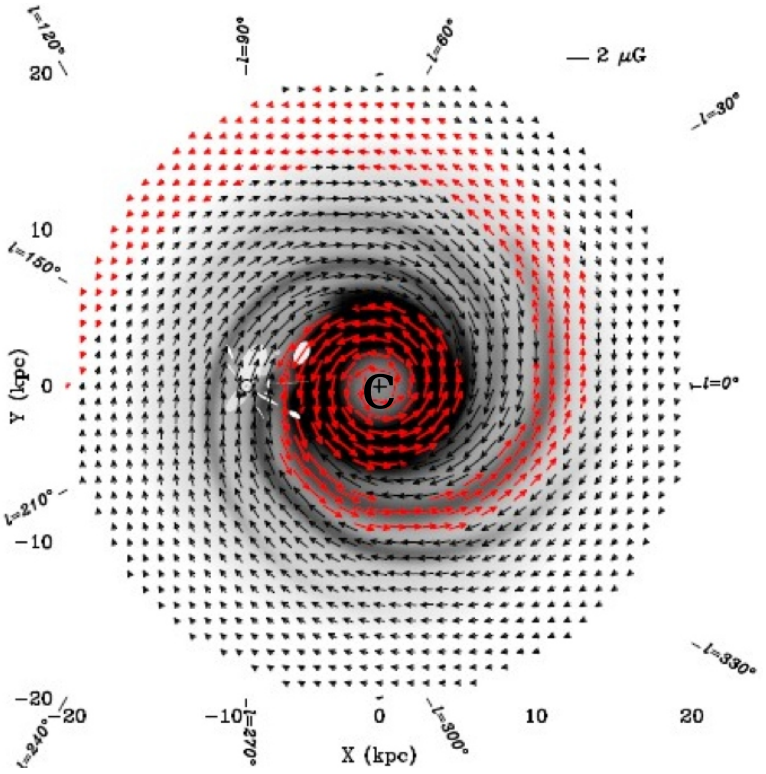


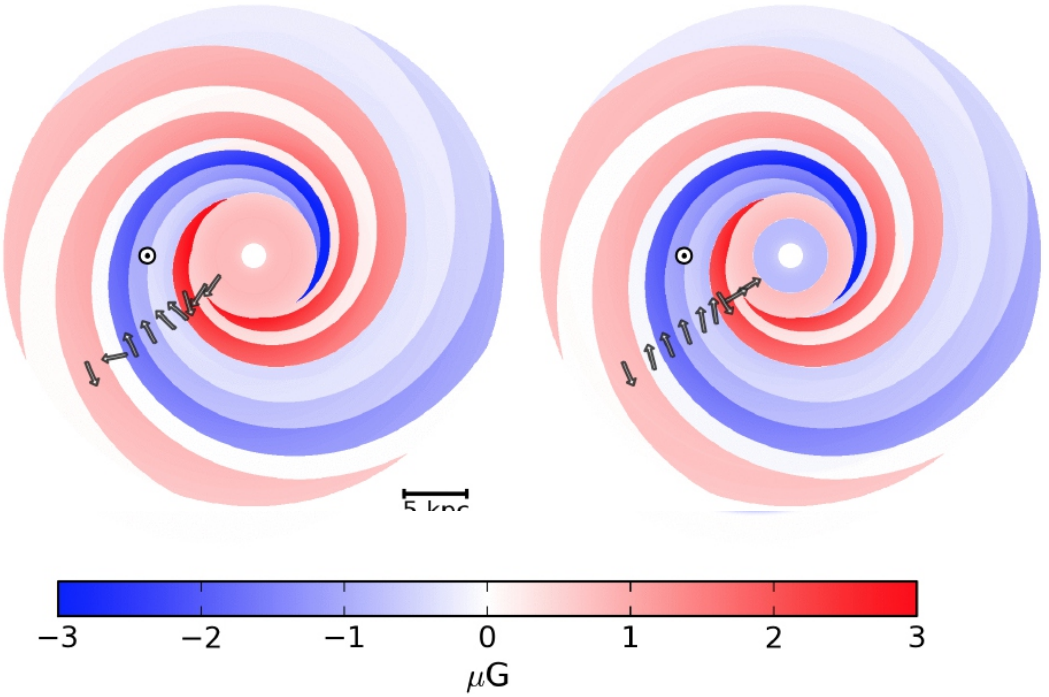
Magnetic field in the galactic plane is of order
<B> = few (5-10) microGauss,
with approximate equal contributions of the
regular and *random* fields.

The regular field in the galactic plane
has a spiral pattern with a pitch angle
similar to what is seen in optical observations.

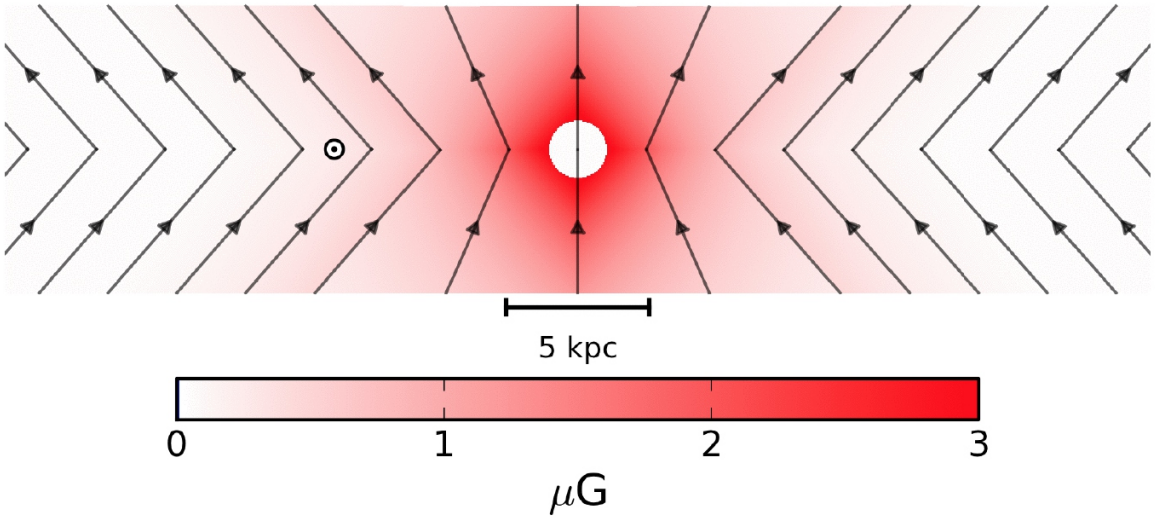
The Field direction reverses
with regions where
the field is “in” and “out”

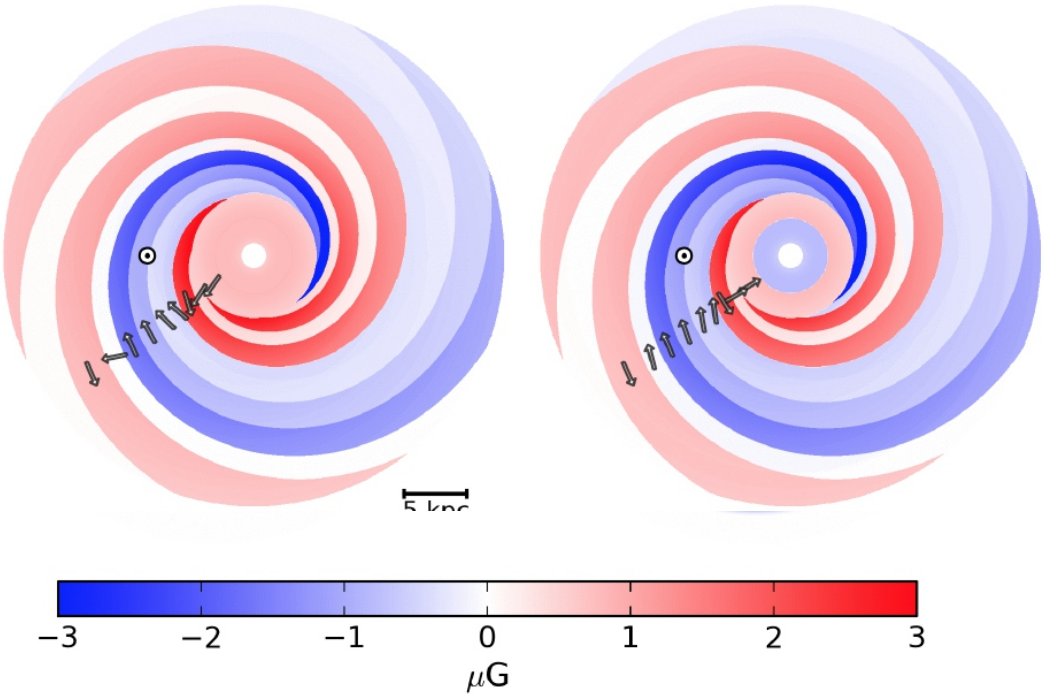
Extended halo with
very poorly known properties.



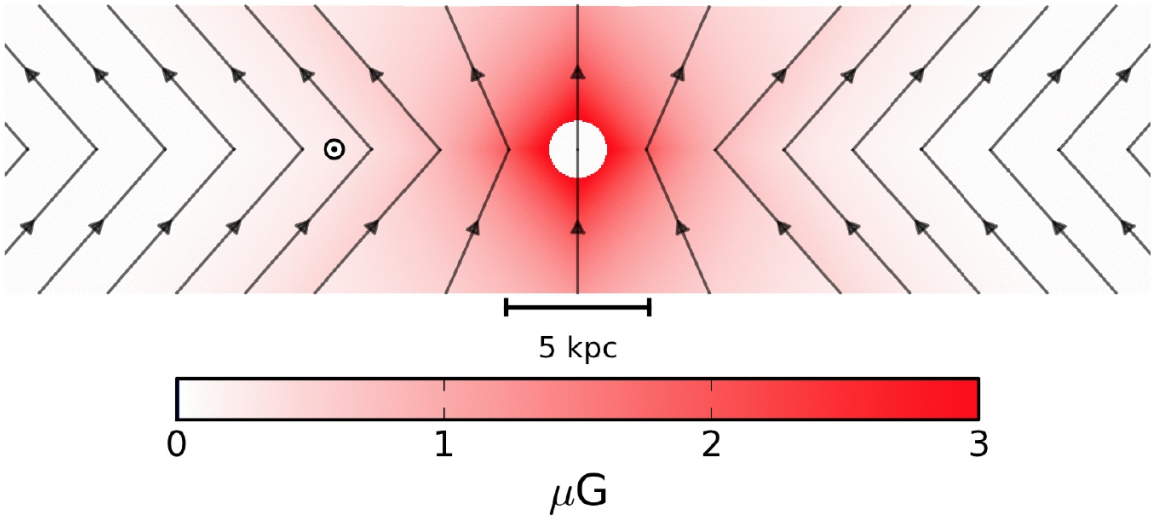


Milky Way magnetic field
Jansson, Farrar
Ap.J. 761 (2012)





Milky Way magnetic field
Jansson, Farrar
Ap.J. 761 (2012)

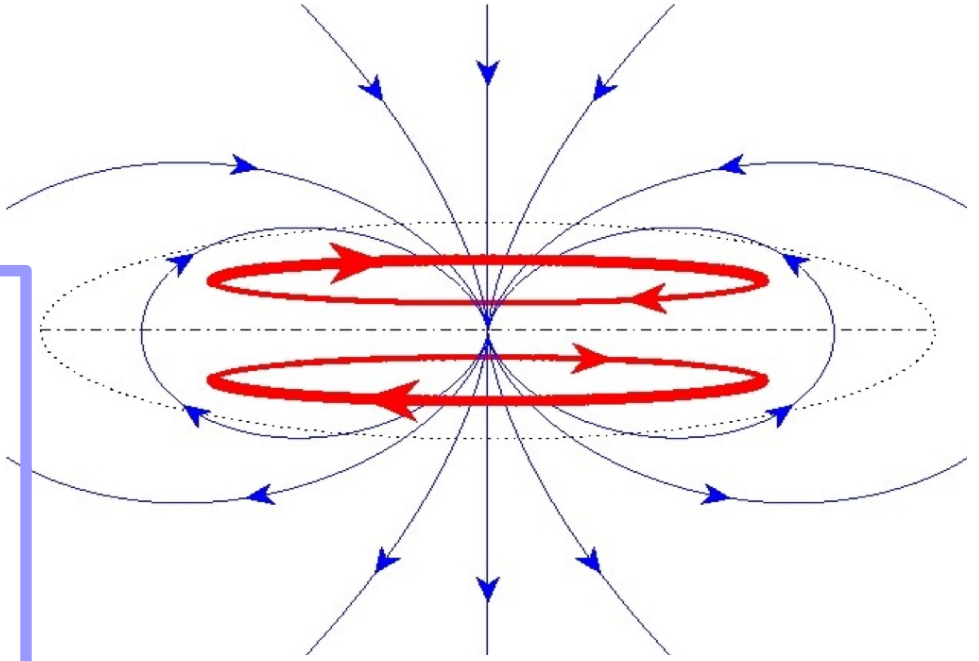


What happens
if the lines “close”

J. L. Han, R. N. Manchester and G. J. Qiao, "Pulsar rotation measures and the magnetic structure of our galaxy," MNRAS **306**, 371, (1999), [astro-ph/9903101].

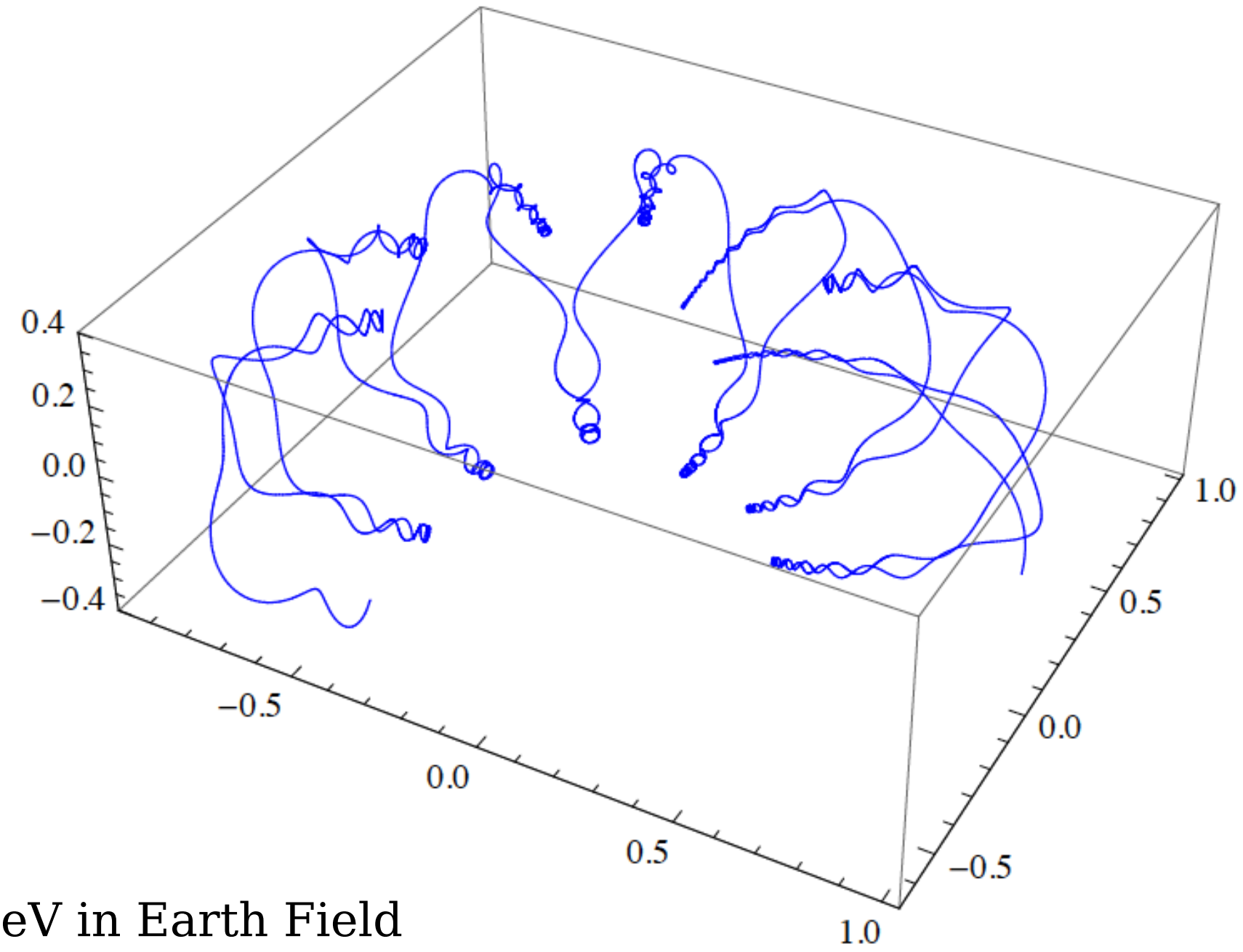
The galactic vertical magnetic field in the vicinity of the Solar System is of order 0.2-0.3 microGauss, and directed from the South galactic Pole to the North Galactic Pole.

"This field could be the manifestation of a global dipolar field"



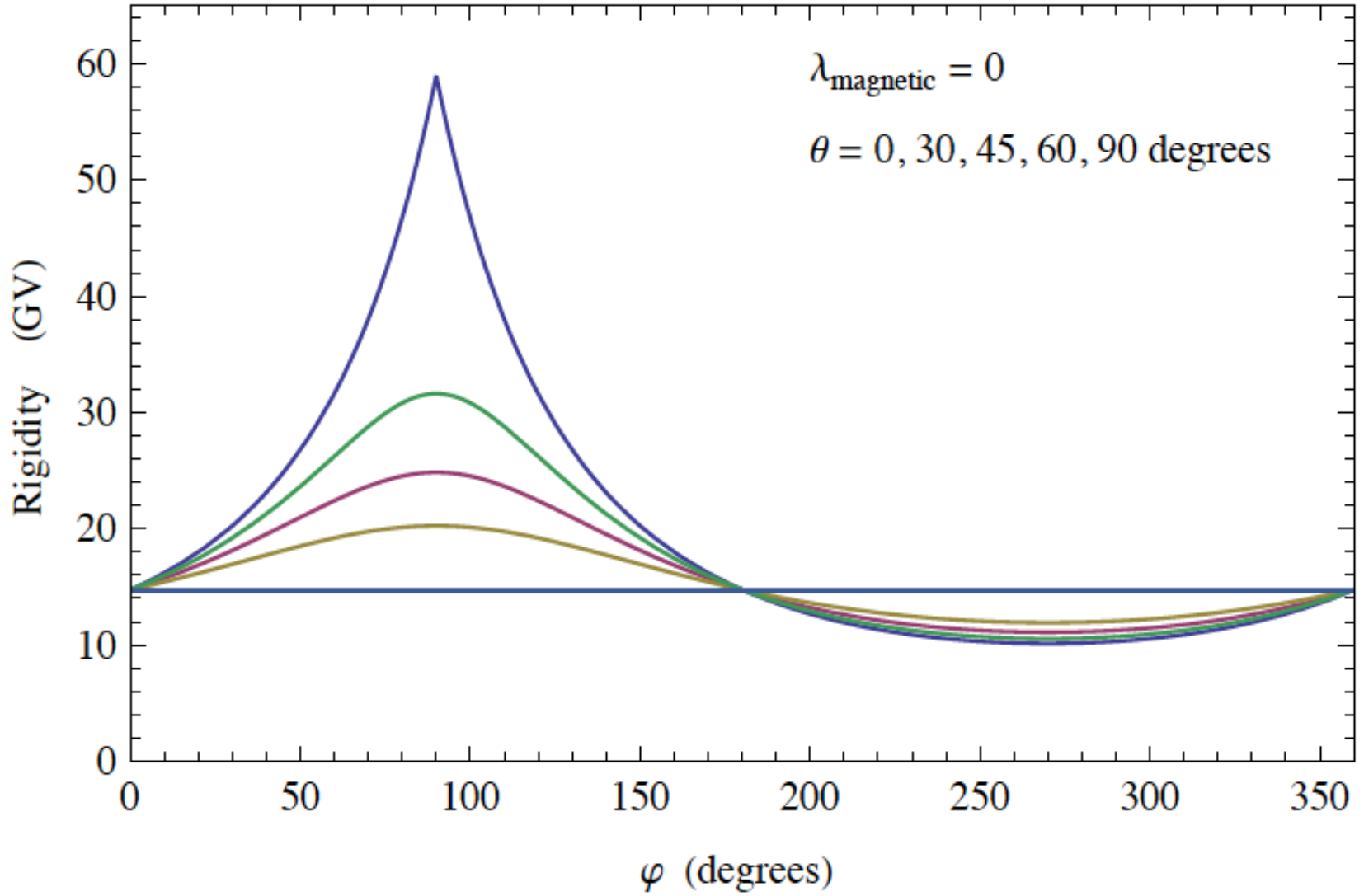
IF the Milky Way
Magnetic field has a dipole
As large as suggested above
What are the consequences ?

Confinement of cosmic rays in the Earth dipole.



7 GeV in Earth Field

$$\left(\frac{p}{q}\right)^{*} = \frac{M}{r^2}\left[\frac{\cos^4\lambda}{(1+\sqrt{1-\cos^3\lambda\,\cos b\,\sin\ell})^2}\right]$$



$$M = B_{\odot z}\, r_\odot^3$$

Dipole Magnetic Moment

$$E^* = q_e\, B_{\odot z}\, r_\odot = q_e\, \frac{M}{r_\odot^2} \simeq 1.57 \times 10^{18}\ \left(\frac{B_{\odot,z}}{0.2\ \mu\mathrm{G}}\right)\ \mathrm{eV}$$

$$e\, B_{\oplus,\mathrm{eq}}\, R_\oplus \simeq 59\ \mathrm{GeV}$$

$$e\, B_{\odot,z}\, r_\odot \sim 1.5 \times 10^{18}\ \mathrm{eV}$$

Can the global structure of the Milky Way magnetic field play (especially dipole, and quadrupole component) play a significant role in the confinement of the highest energy cosmic rays ?

This is (at least for me) an intriguing hypothesis that is interesting to study both theoretically and experimentally.

Extragalactic Contribution

Where is the transition ?

One expects that the transition is associated to a spectral feature:

Extragalactic Contribution

Where is the transition ?

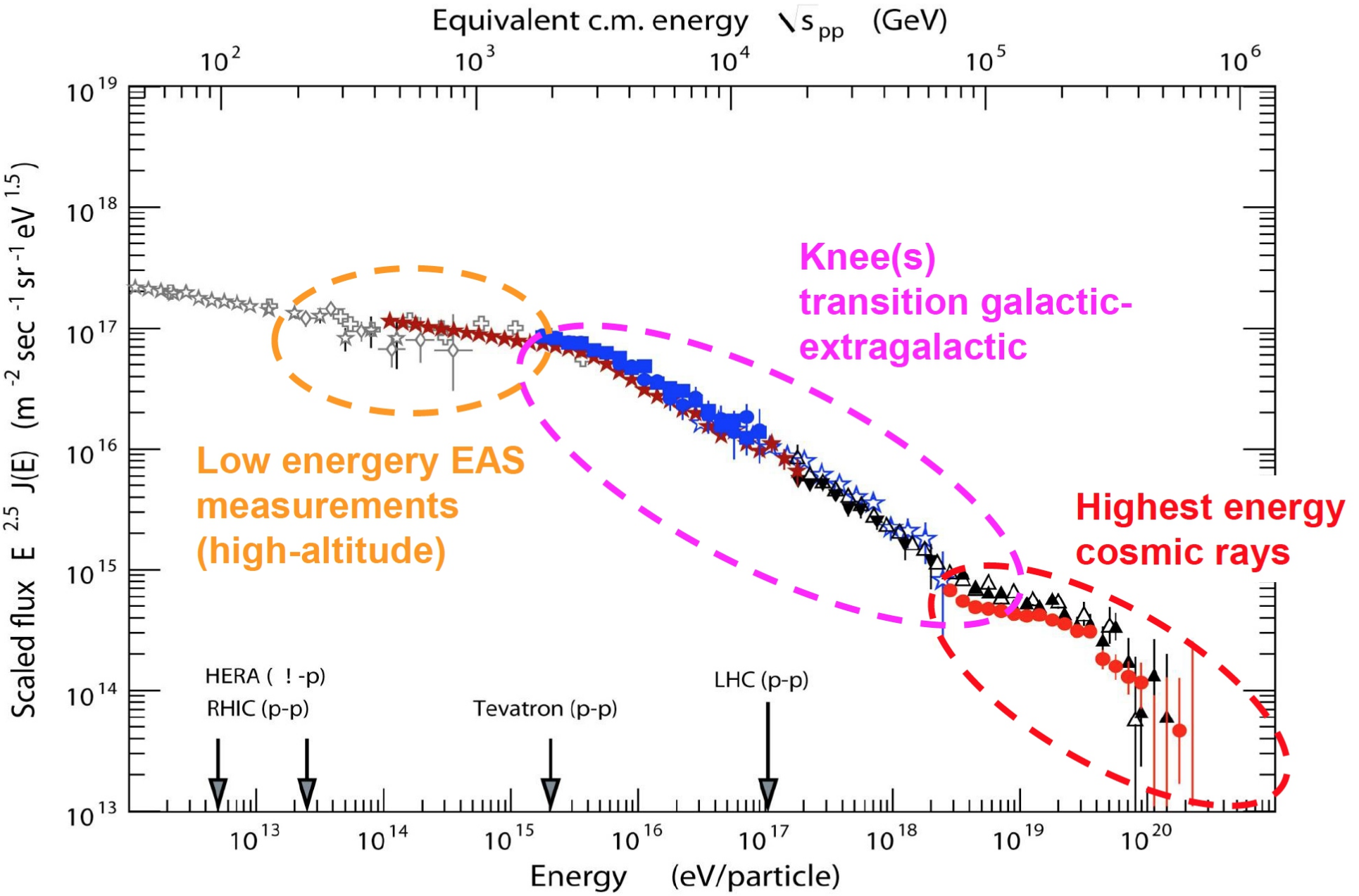
One expects that the transition is associated to a spectral feature:

“Ankle” [hardening]

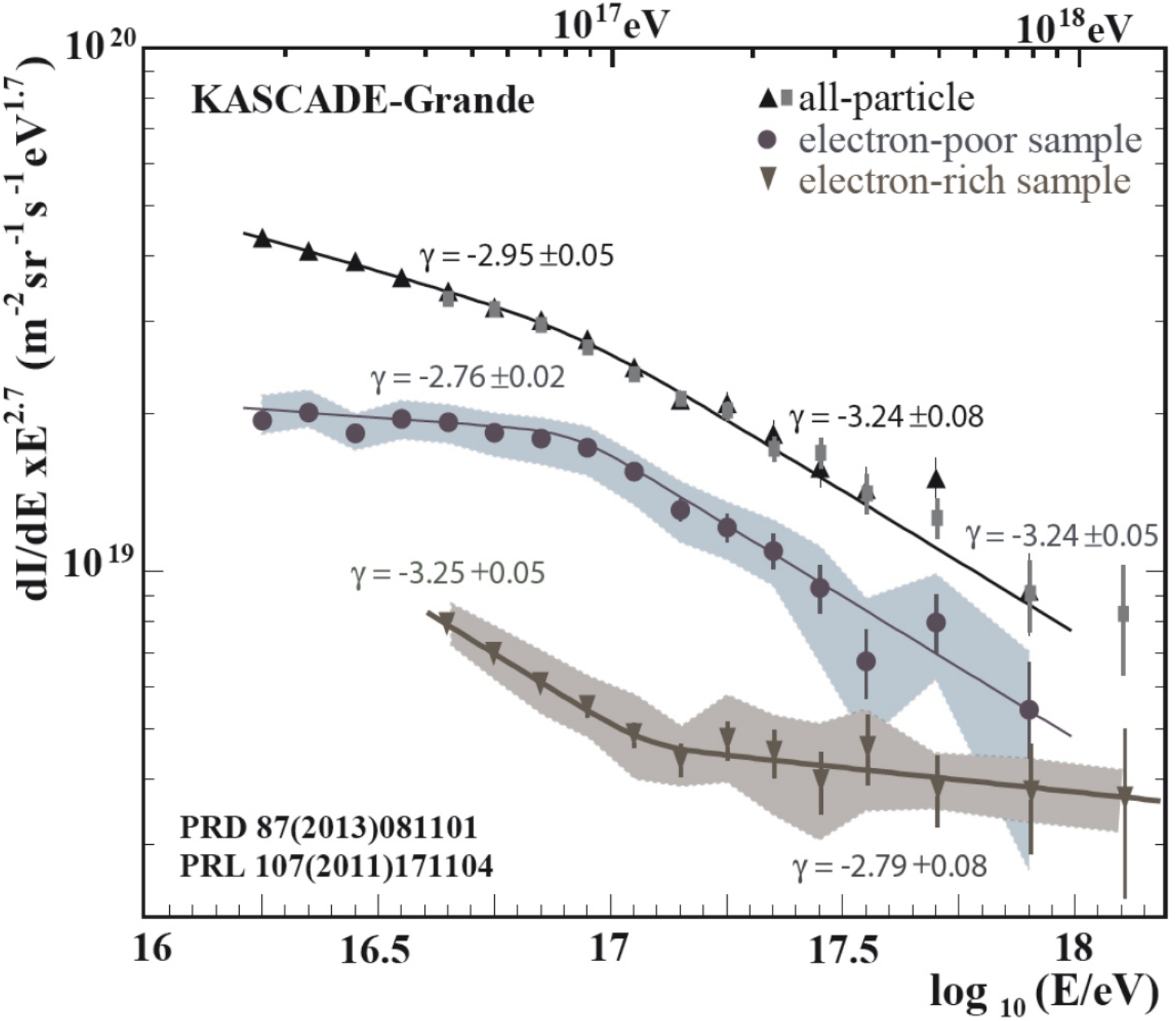
or

“Second Knee” [softening, less marked]

High-energy cosmic ray spectrum

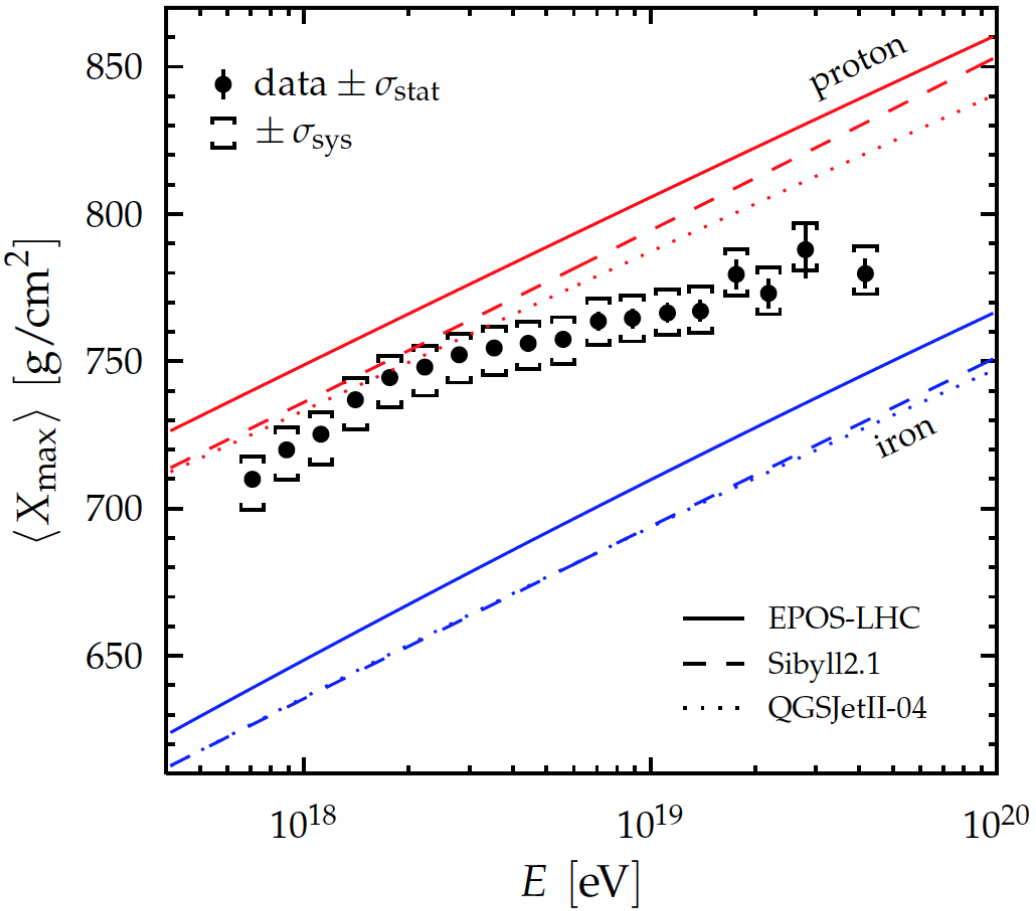


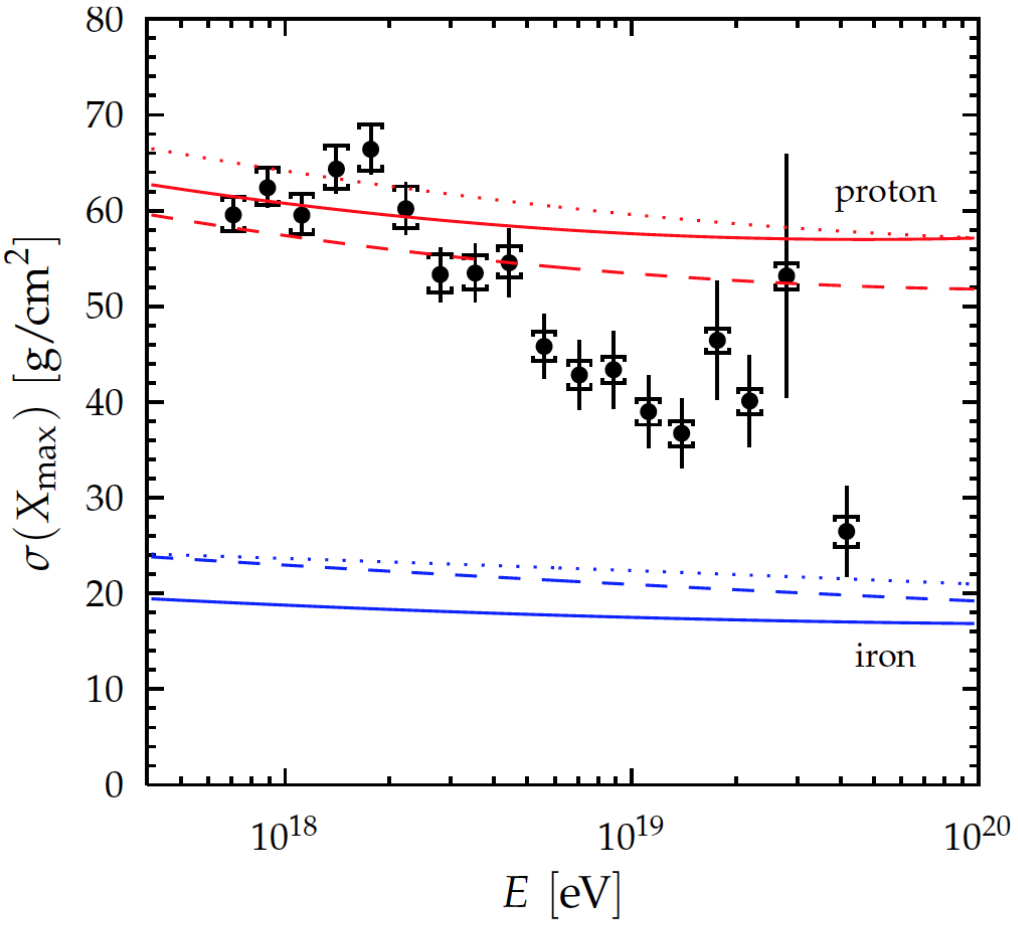
Kascade Grande “ankle” in the light component.



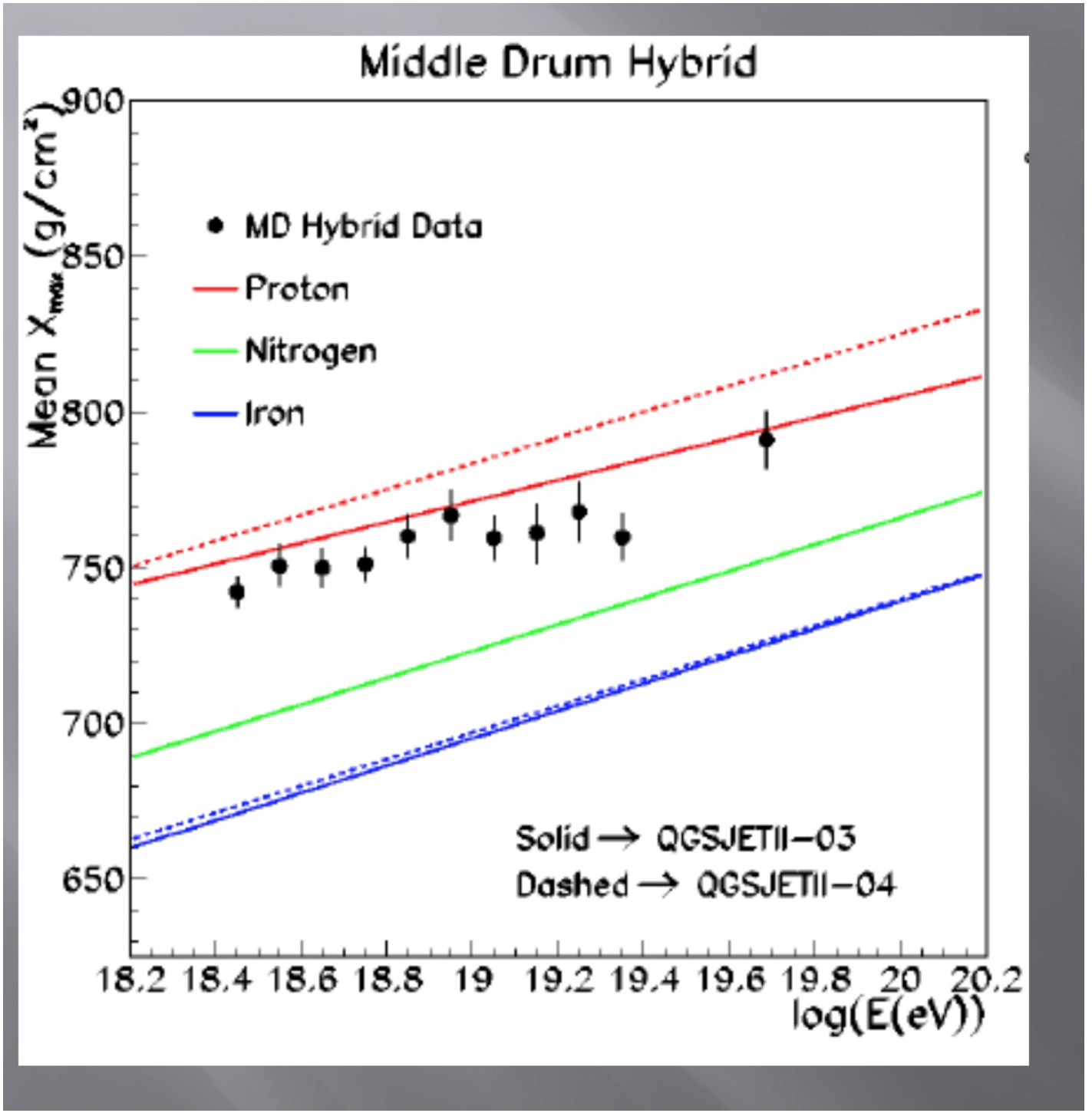
Auger results: Markus Roth

Average Shower Maximum

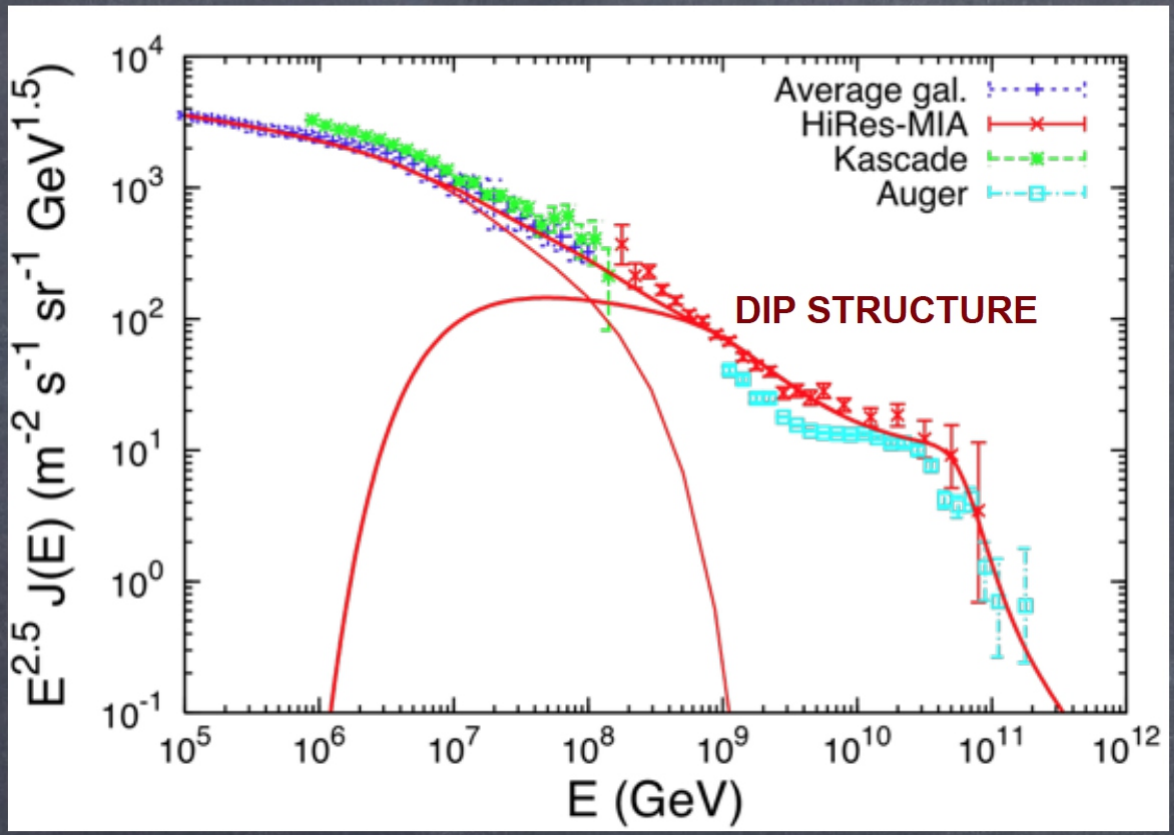




Pierre Auger Collaboration, PRD 90 (2014) 12, 122005


Middle Drum Hybrid
Mean X_{max} (g/cm^2)
900
850
800
750
700
650
MD Hybrid Data
Proton
Nitrogen
Iron
Solid → QGSJETII−03
Dashed → QGSJETII−04
18.2
18.4
18.6
18.8
19
19.2
19.4
19.6
19.8
20
20.2
log(E(eV))

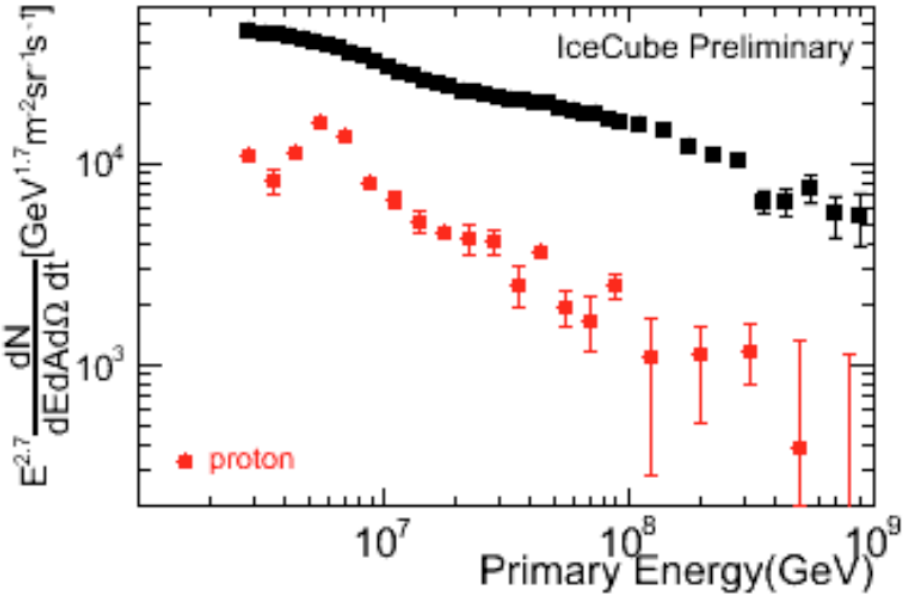
THE DIP

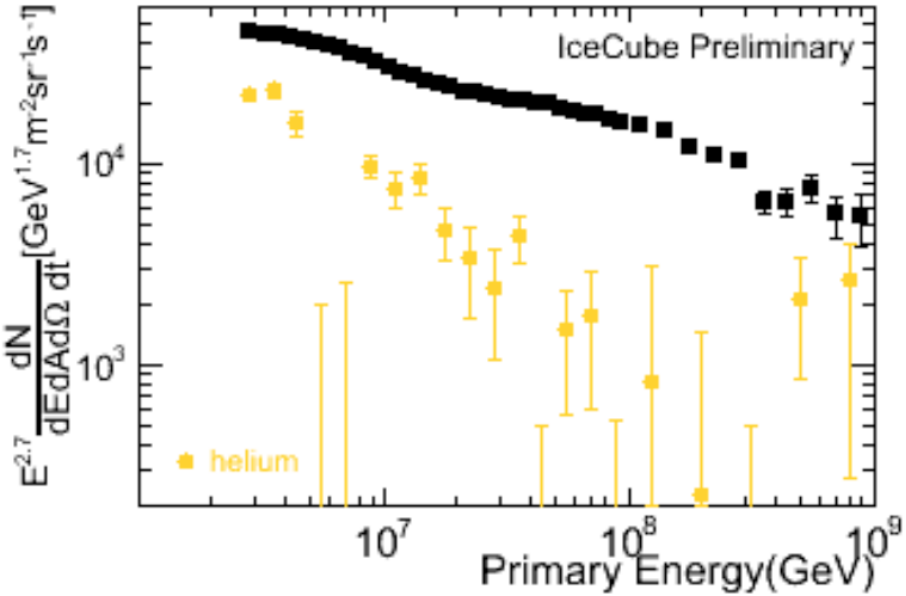


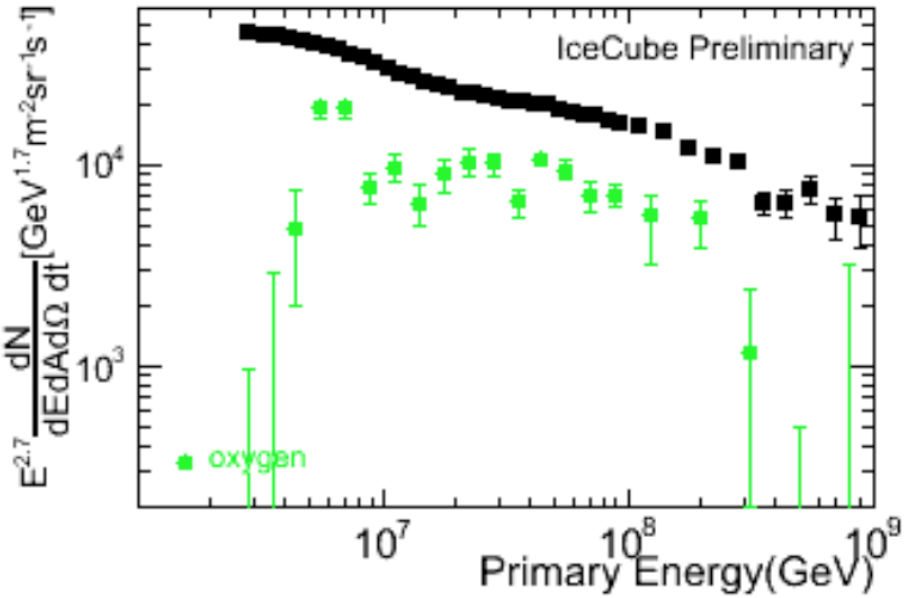
THE BALANCE BETWEEN BETHE-HEITLER PAIR PRODUCTION AND EXPANSION OF THE UNIVERSE NATURALLY CREATES A DIP IN THE CR SPECTRUM

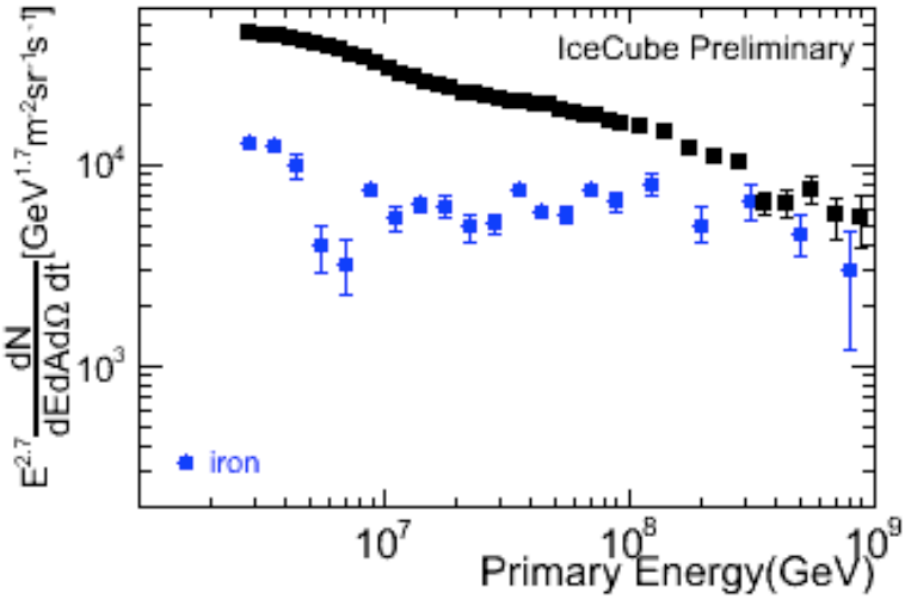
THE DIP IS VISIBLE ONLY IF COMPOSITION IS LIGHT (<15% He)

Spectra of 4 elemental groups









IceCube results: Sam de Ridder

Statistical and fit uncertainties only

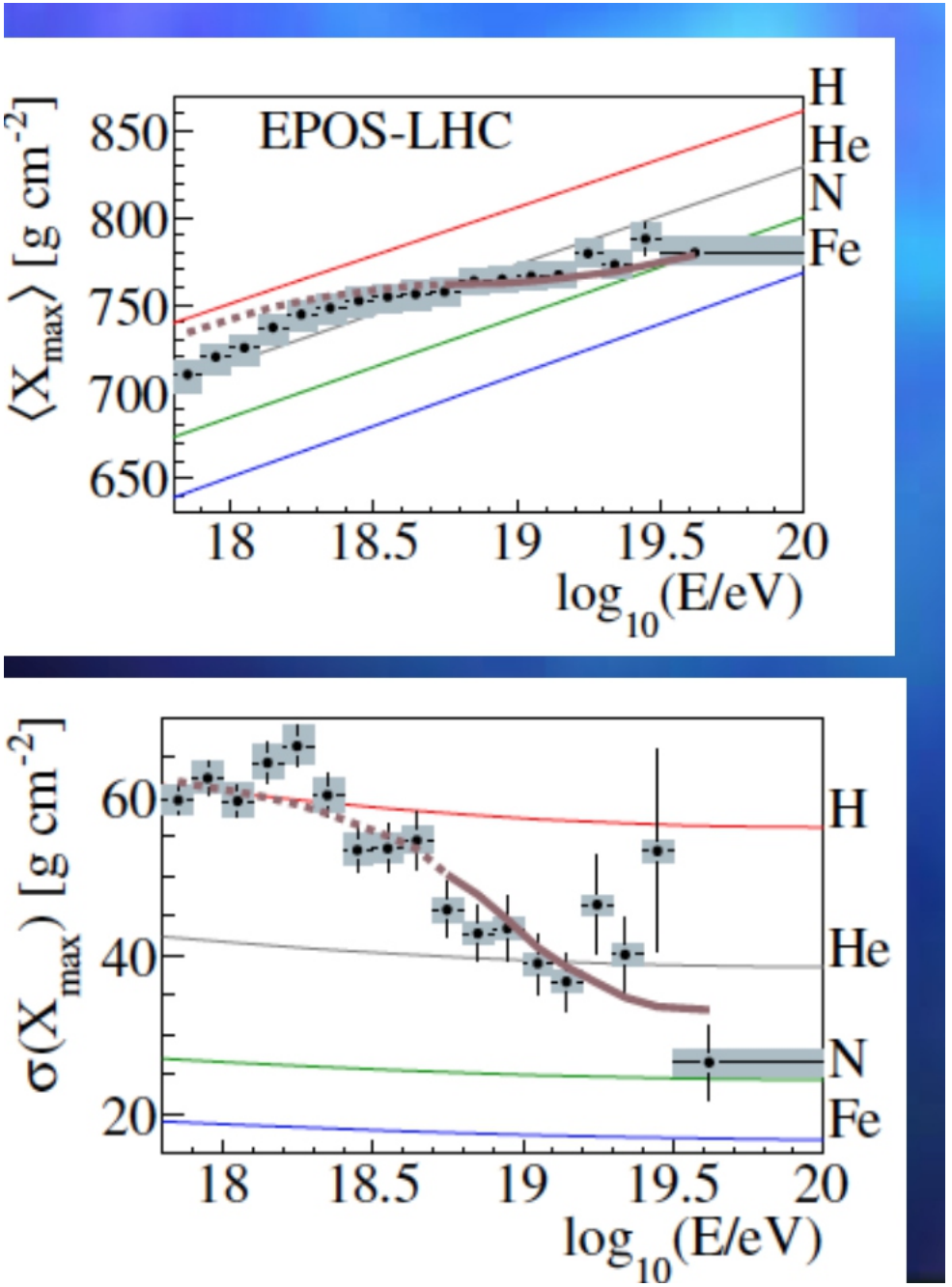
Interpretation of the Auger data

Composition
becomes heavier

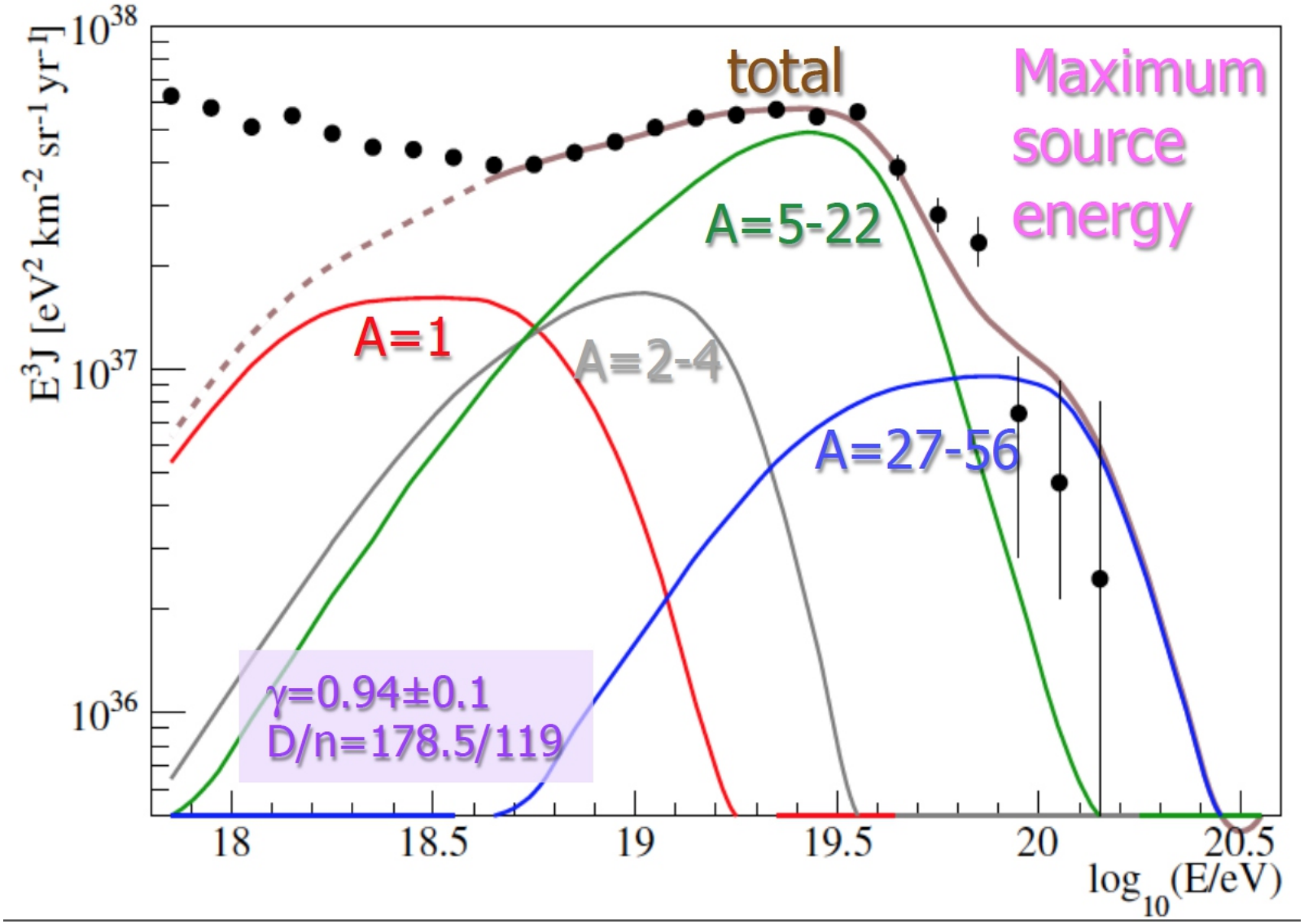
in a very peculiar way

Dispersion also
decreases

At all energies
only a small range
of masses contribute



A. di Matteo et al., Proc. of 34th ICRC, The Hague (2015)



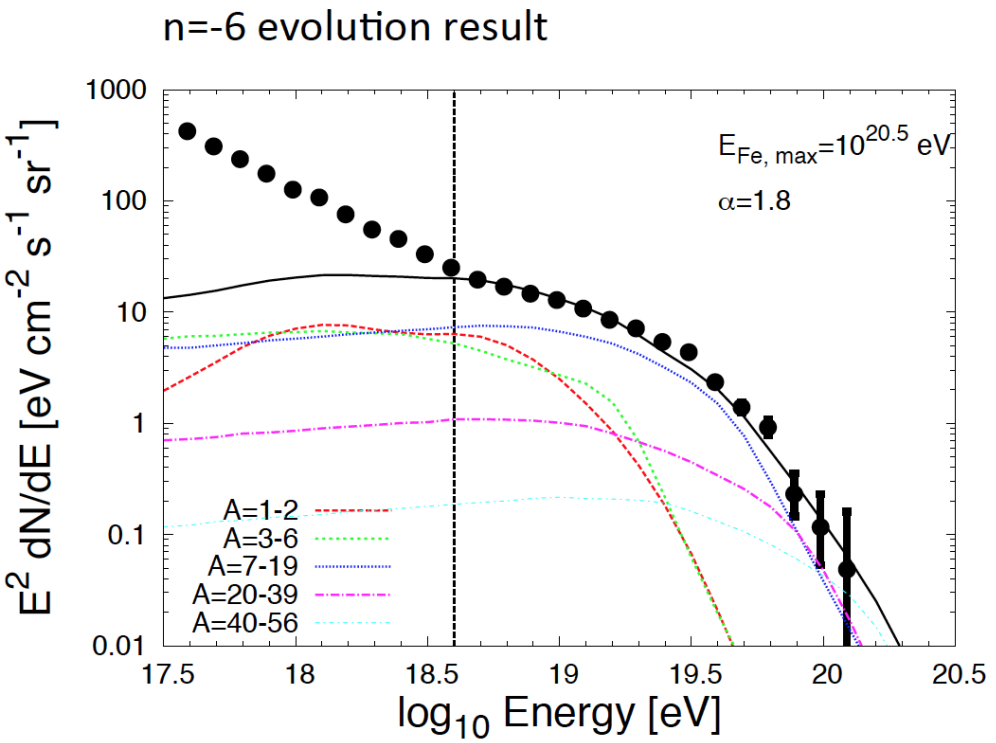
Fit of the Auger composition presented at ICRC2015

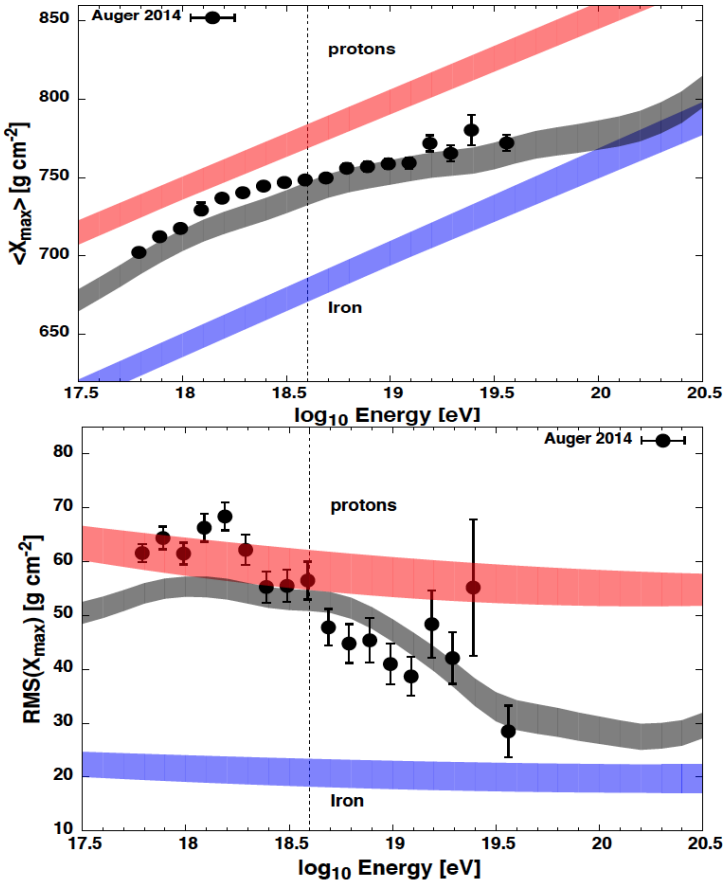
model SPG	best fit	2nd local min
J_0 [$\mathrm{eV}^{-1}\ \mathrm{Mpc}^{-3}\ \mathrm{yr}^{-1}$]	7.17×10^{18}	4.53×10^{19}
γ	$0.94^{+0.09}_{-0.10}$	2.03
$\log_{10}(R_{\mathrm{cut}}/\mathrm{V})$	18.67 ± 0.03	19.84
p_{H}	$0.0^{+29.9}\%$	0.0%
p_{He}	$62.0^{+3.5}_{-22.2}\%$	0.0%
p_{N}	$37.2^{+4.2}_{-12.6}\%$	94.2%
p_{Fe}	$0.8^{+0.2}_{-0.3}\%$	5.8%
D/n	178.5/119	235.0/119
$D\ (J)$, $D\ (X_{\mathrm{max}})$	18.8, 159.8	14.5, 220.5
p	2.6%	5×10^{-4}

Andrew Taylor

MCMC Likelihood Scan: Spectral + Composition Fits

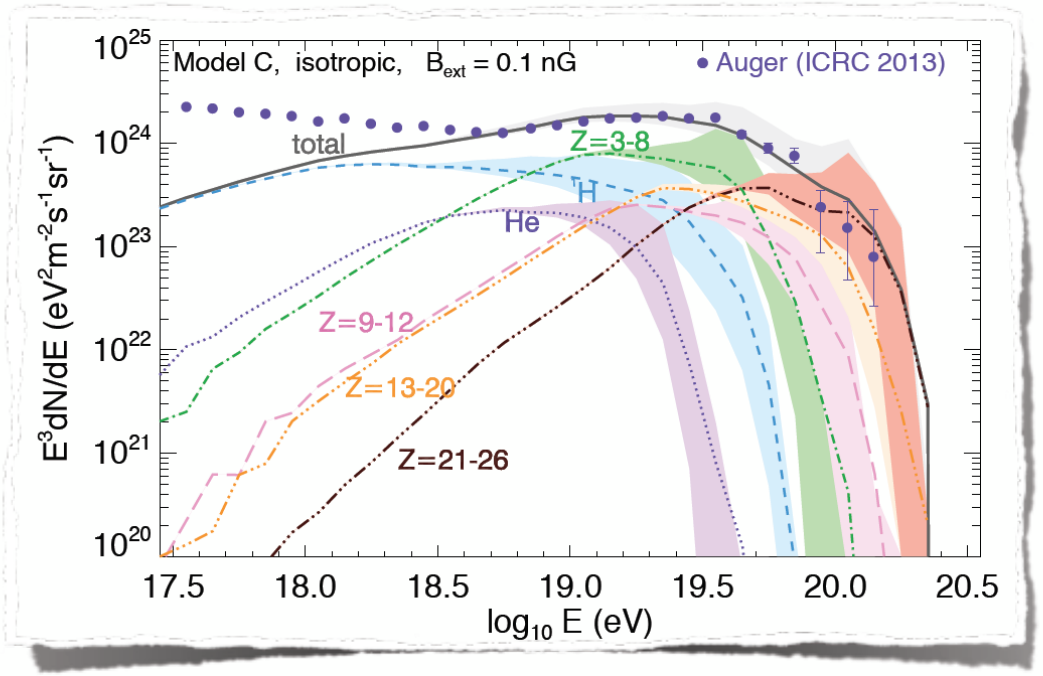
$$\mathbf{L}(\mathbf{f_p}, \mathbf{f_{He}}, \mathbf{f_N}, \mathbf{f_{Si}}, \mathbf{E_{max}}, \alpha) \propto \exp(-\chi^2/2)$$

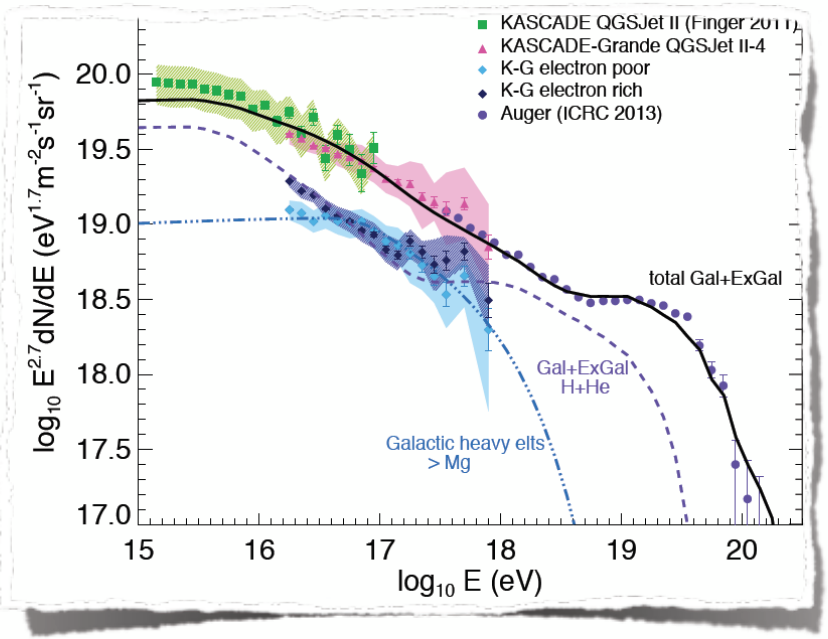




A physical model

Globus et al. and Unger et al. (2015) propose a similar idea: spectra of nuclei appear hard because at low energies photo disintegration inside sources has been at work





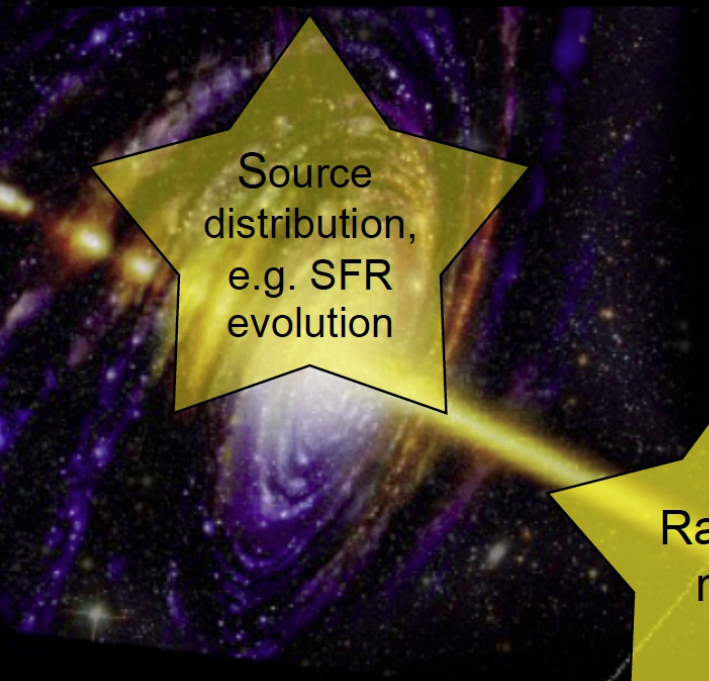
Sources of UHECR
[dominated but extragalactic contribution]

Active Galactic Nuclei
[Andrew Taylor]

Gamma Ray Bursts
[Walter Winter]

...

Combined source-propagation models: ν-γ-UHECRs



Source distribution, e.g. SFR evolution

Key challenge 1: How do cosmic rays escape from the source?

Key challenge 3: Secondary production very sensitive to geometry estimators

Large astrophysical uncertainties

Radiation model

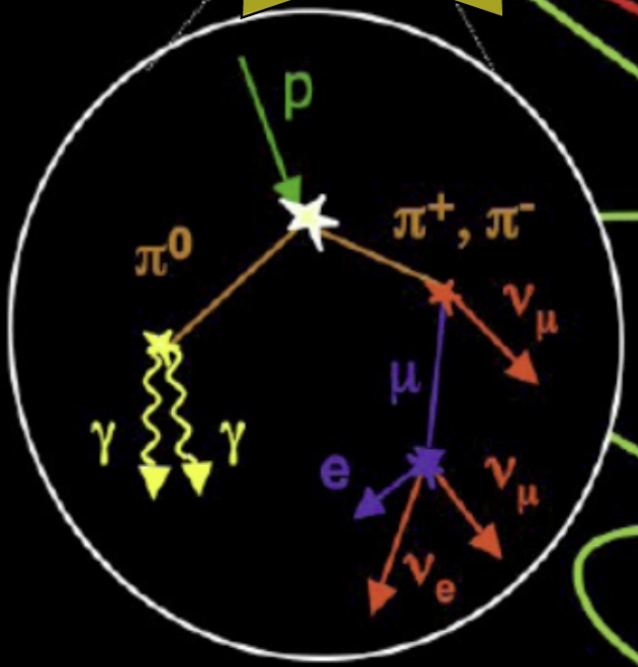
Key challenge 2: Baryonic loading?

γ

ν_μ

Idea: Determine by fit to UHECR data?

Astrophysical beam dump



Propaga-tion effects

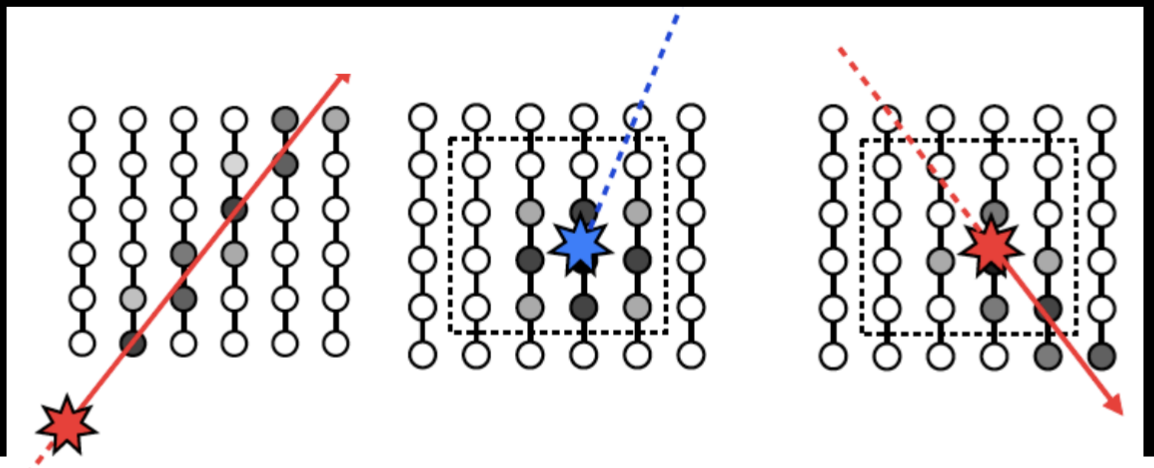
p

Very interesting relation with the flux of Astrophysical Neutrinos detected by IceCube

Elements of discussion in the talks of
Walter Winter
Dmitri Semikoz

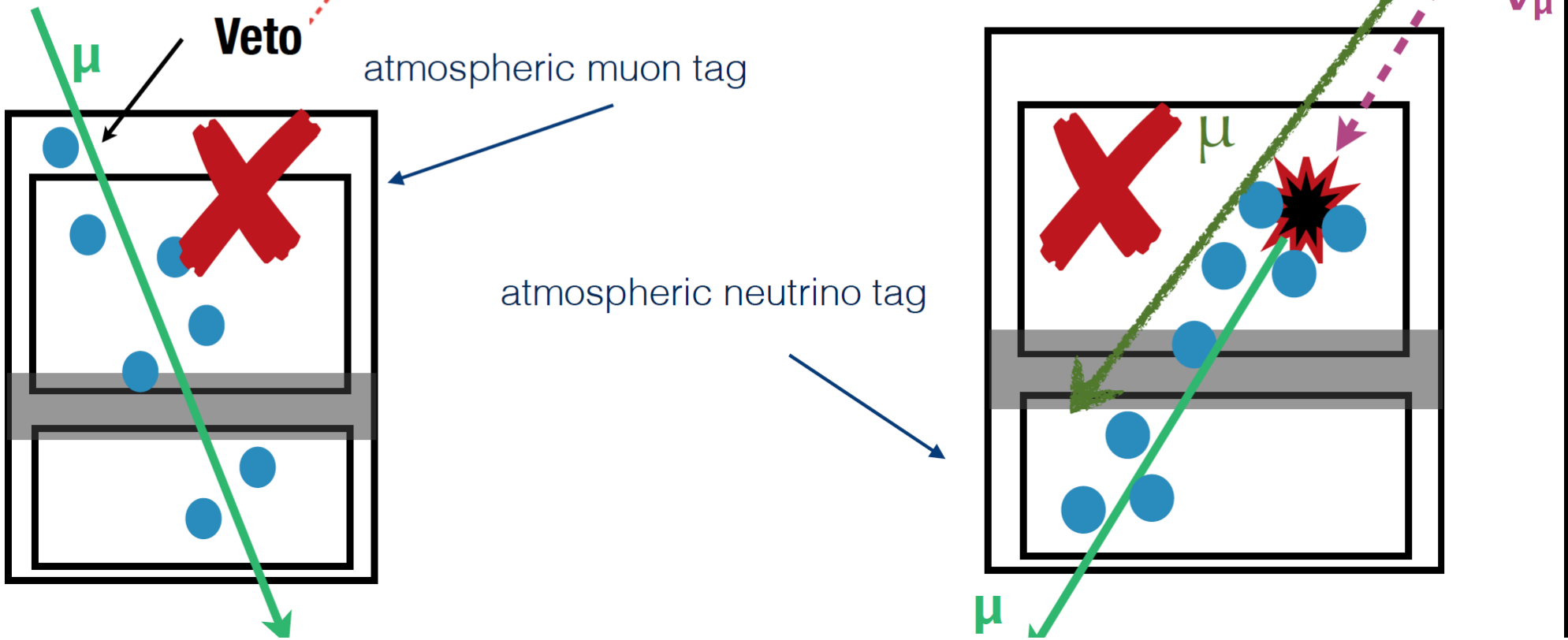
Neutrino selection & background rejection

Upgoing thoroughgoing neutrino induced muons - Earth is a filter - or vertex identification of 'starting events' (tracks and cascades)

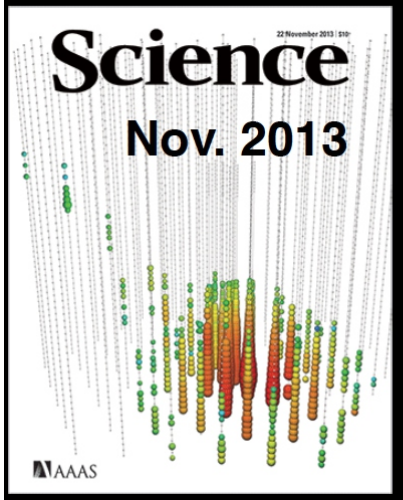


Schönert, Resconi, Schulz, Phys. Rev. D, 79:043009 (2009)

Gaisser, Jero, Karle, van Santen, Phys. Rev. D, 90:023009 (2014)

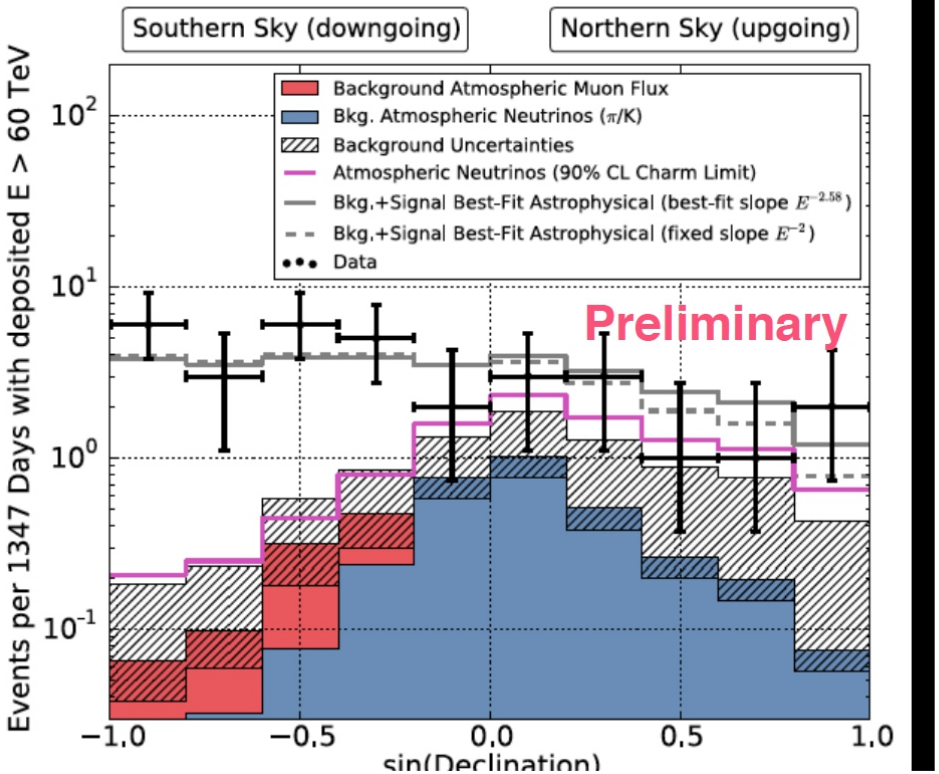


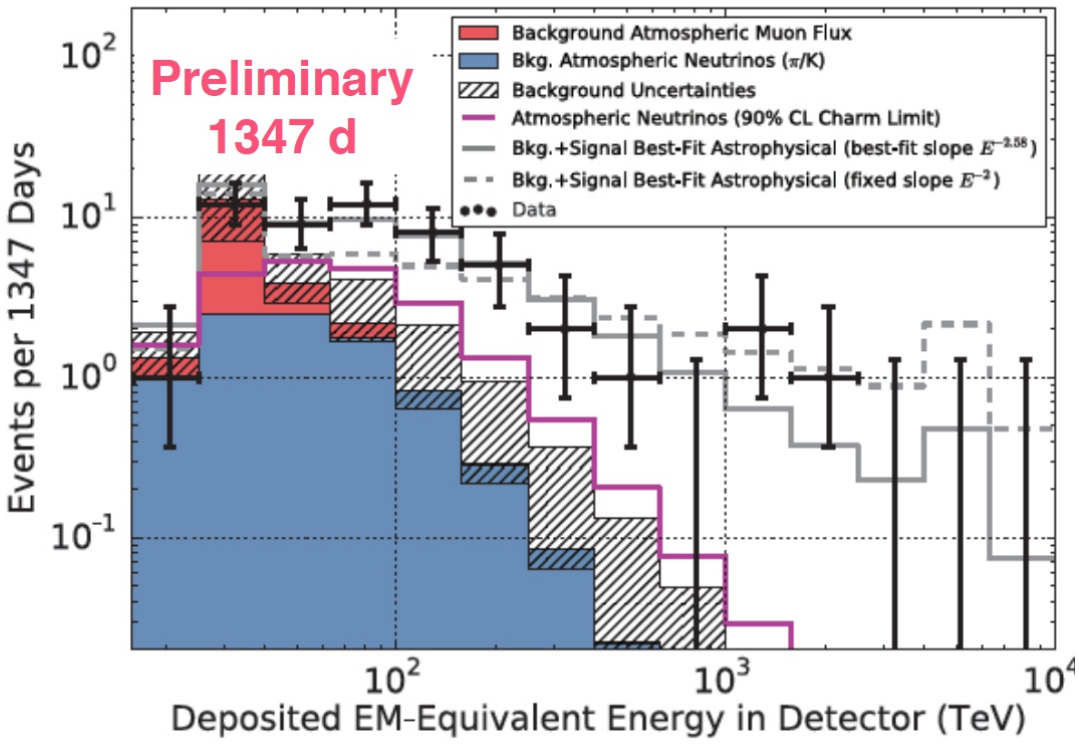
4 yr (2010-14) of HESE



Anti-coincidence veto + >6000 p.e. (>30 TeV)
54 events (17+events in PRL 113 (2014) 101101).
2 are evident background events.
Background:
Measured: 12.6 ± 5.1 atmospheric muon events
Atmospheric prompt component estimated using a previously set limit on atmospheric neutrinos with 59 strings: $9.0^{+8.0}_{-2.2}$

Kopper, Giang, Kurahashi, ICRC 2015, POS 1081, PRL 113 (2014) 101101





Theory versus Experiment in Cosmic Ray astrophysics

The study of Cosmic Rays is a field dominated by the observers where the theorists are always a few steps behind trying to interpret the surprises obtained each time that new instruments allow some progress in the quality of observations.

The observers are guiding the field toward the understanding the physical mechanism, that control high energy astrophysics.

The very existence of CR was not predicted,
The extension to very high energy was not predicted,
.....

It is essential for future progress to have measurements of good quality and systematic uncertainties under control.

Some observations for VHE/UHE Cosmic Rays that have broad and deep consequences for the astrophysical interpretation and that require confirmation/clarification.

1. The shape of the “Knees” (10^{14} eV - 10^{17} eV) (for proton, helium, CNO, …, Fe).

2. Confirmation of the existence of a hardening of the proton (or light) component at 10^{17} eV, leading to a proton dominated spectrum around 10^{18} eV.

3. Evolution of the composition of the CR around the “ankle” and up the highest energy (10^{18} eV - 10^{20} eV).

1. The shape of the “Knees” (10^{14} eV - 10^{17} eV) (for proton, helium, CNO, …, Fe).

   [Argo low energy proton/knee ?]
   [Is it possible to improve after Kascade/EAS TOP]

2. Confirmation of the existence of a hardening of the proton (or light) component at 10^{17} eV, leading to a proton dominated spectrum around 10^{18} eV.

   [Crucial element for all interpretations]
   [What about IceCube ? Discrepancy ? Systematics ?]

3. Evolution of the composition of the CR around the “ankle” and up the highest energy (10^{18} eV - 10^{20} eV).

   [Auger composition versus
   “Dip Model” (pure proton) interpretation]