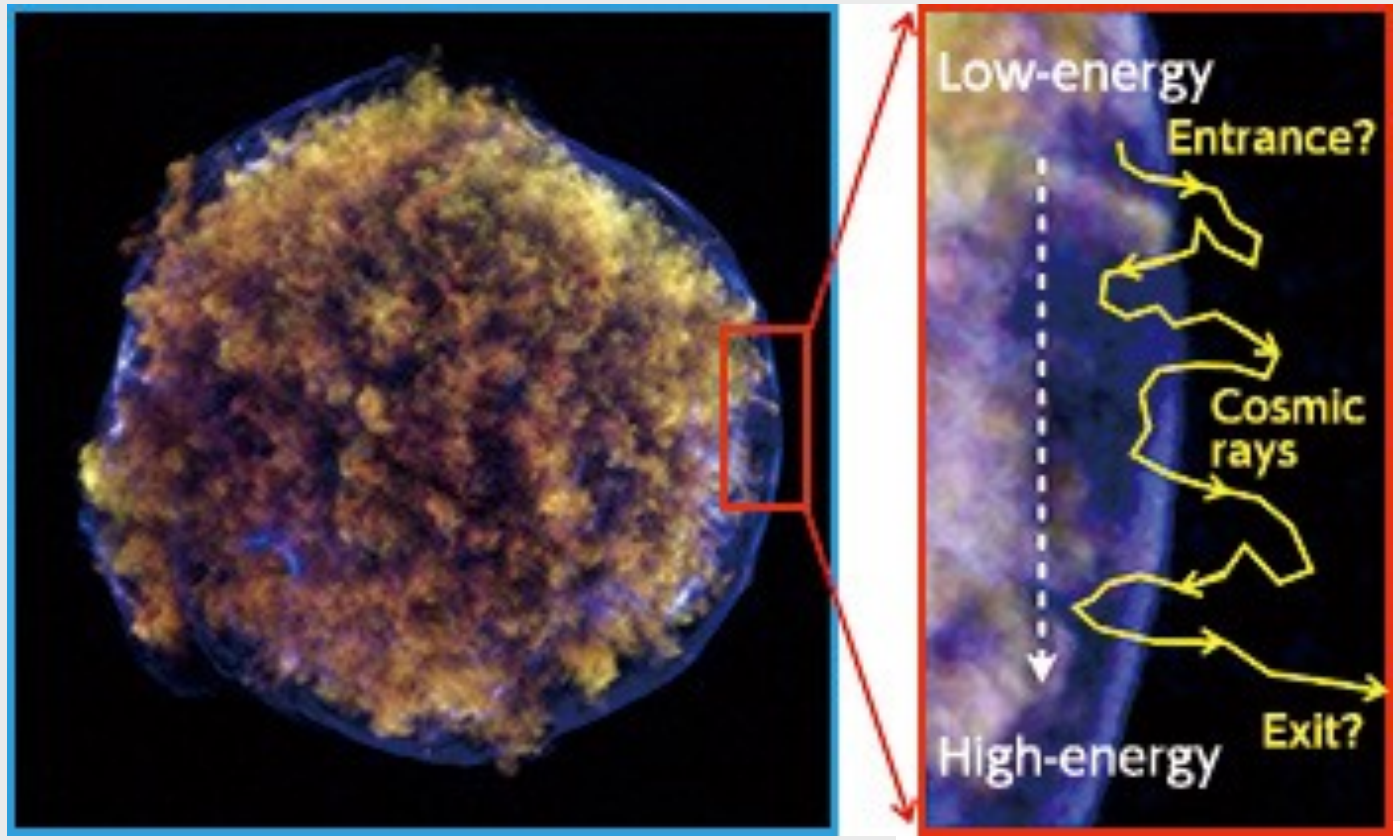
Cosmic rays and air shower physics III

Ralph Engel

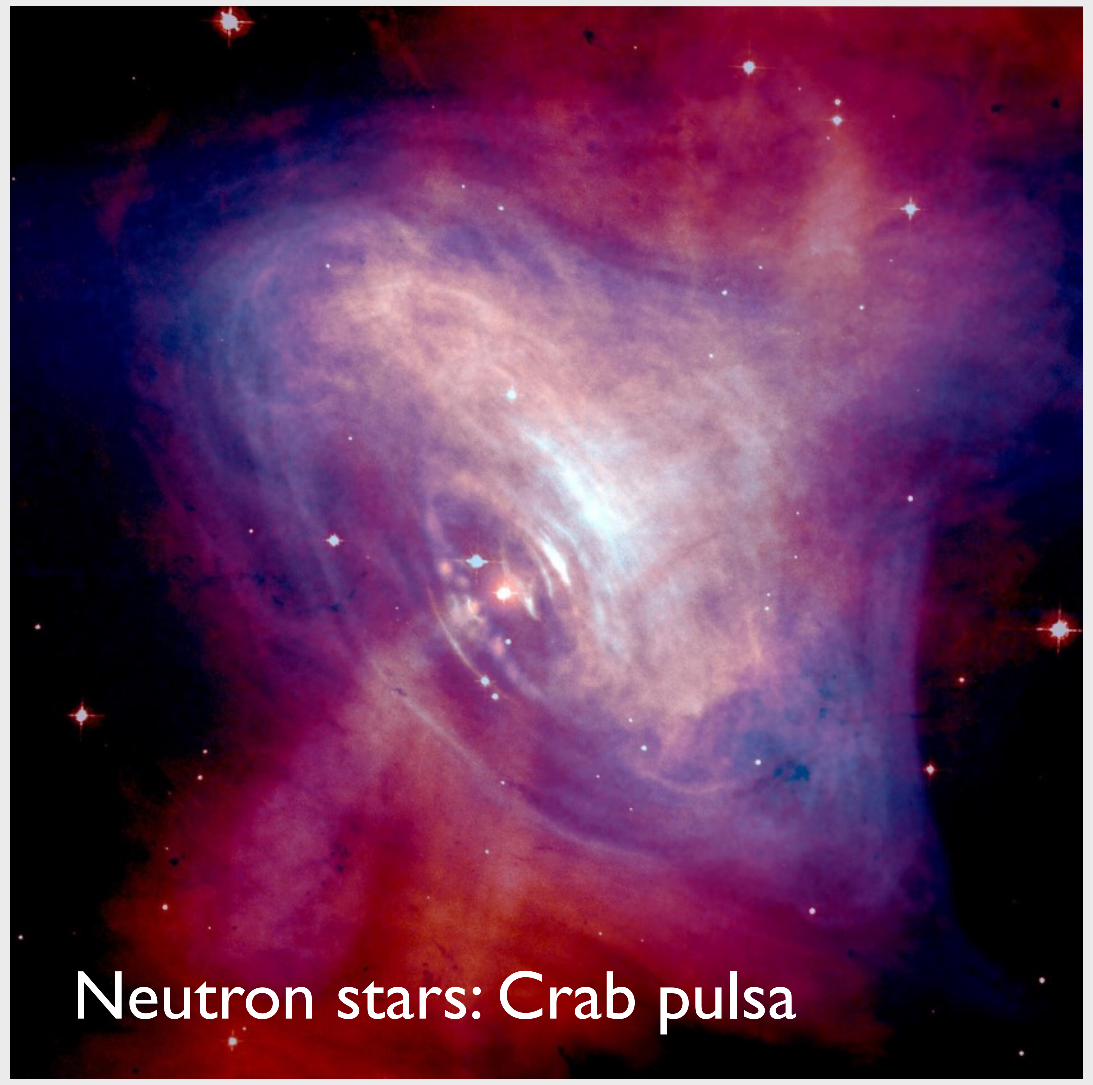
Karlsruhe Institute of Technology (KIT)

(photograph by S. Saffi)

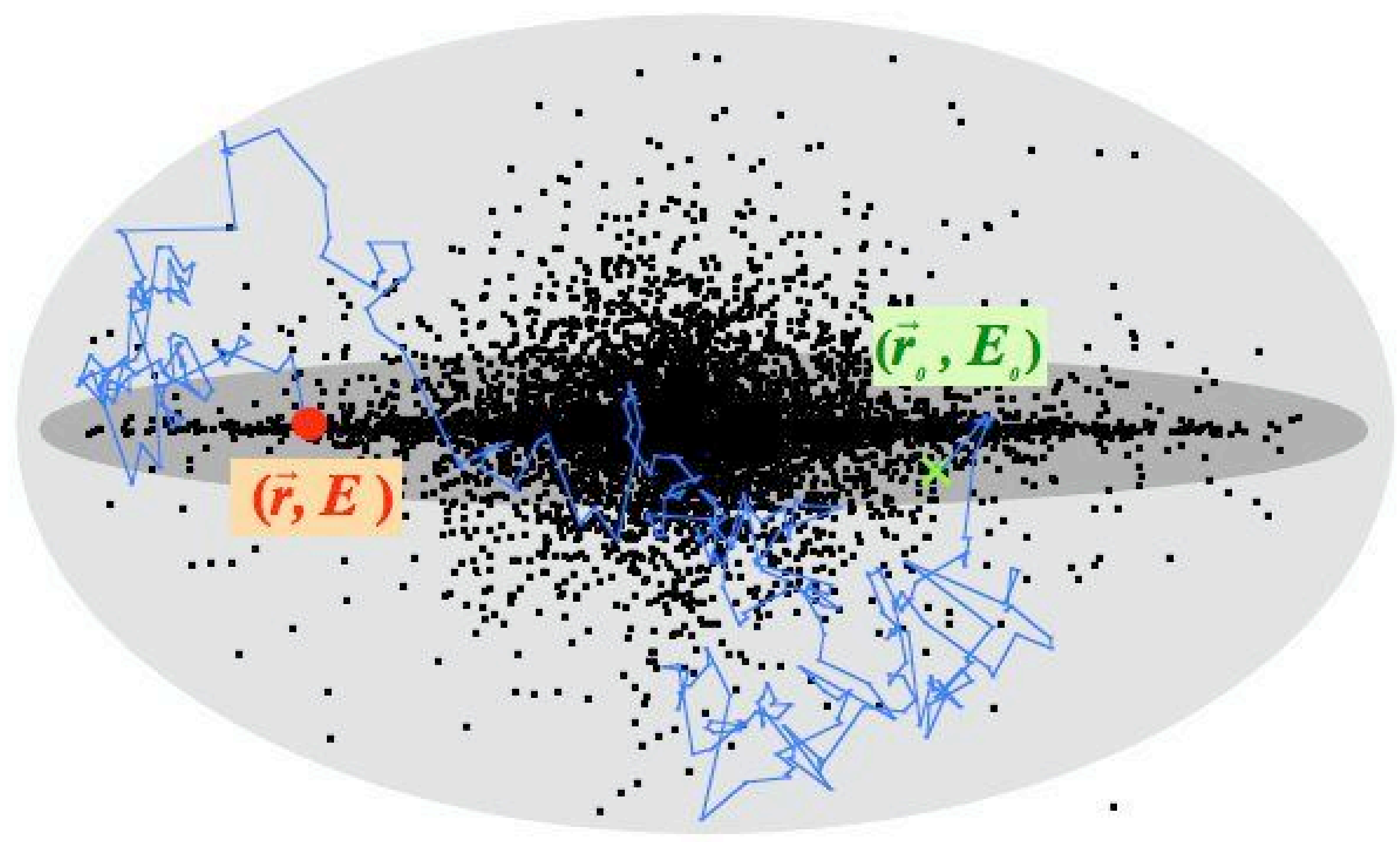
Many known accelerators in our Galaxy



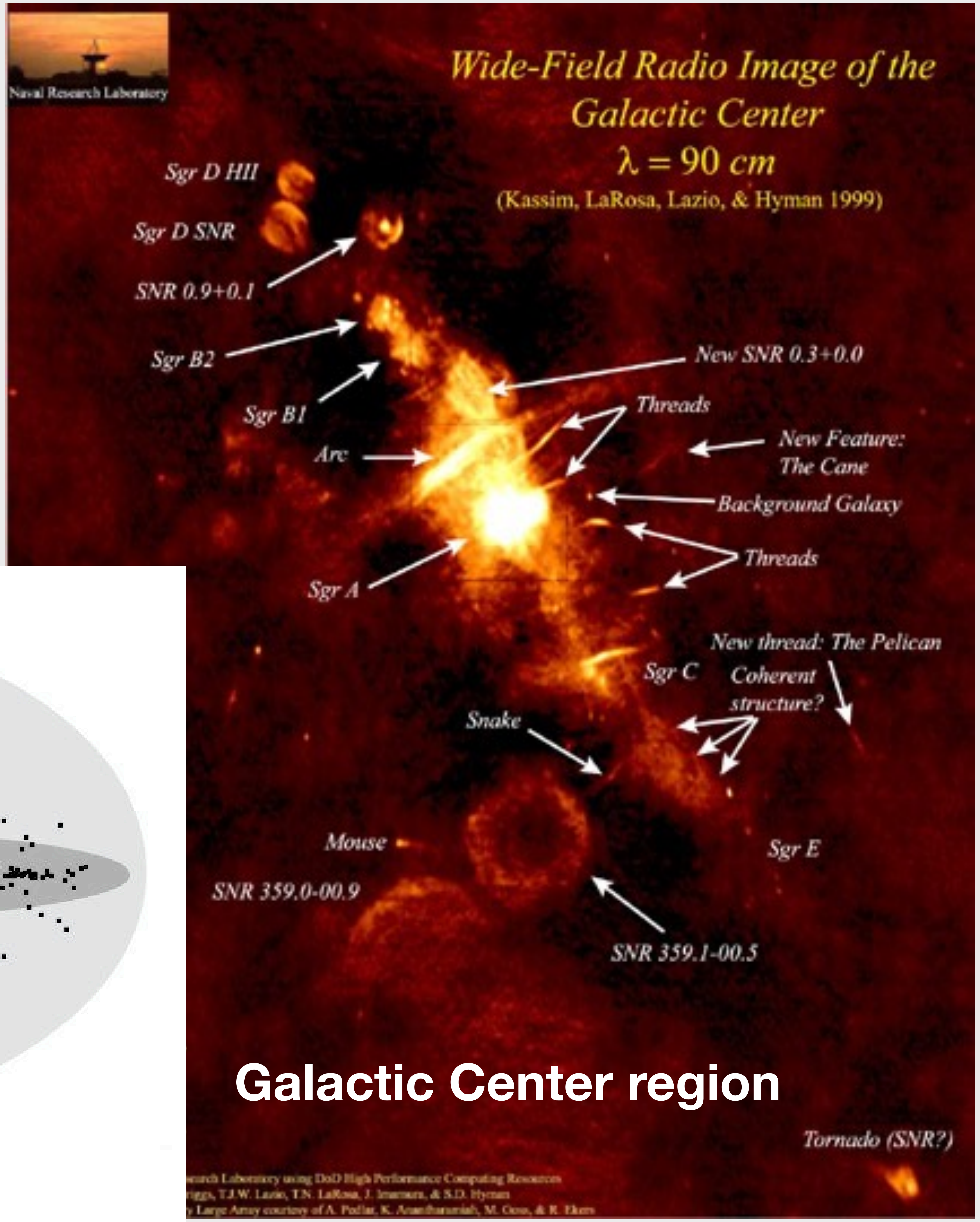
Supernove remnants: Tychos SN 1573



Neutron stars: Crab pulsa

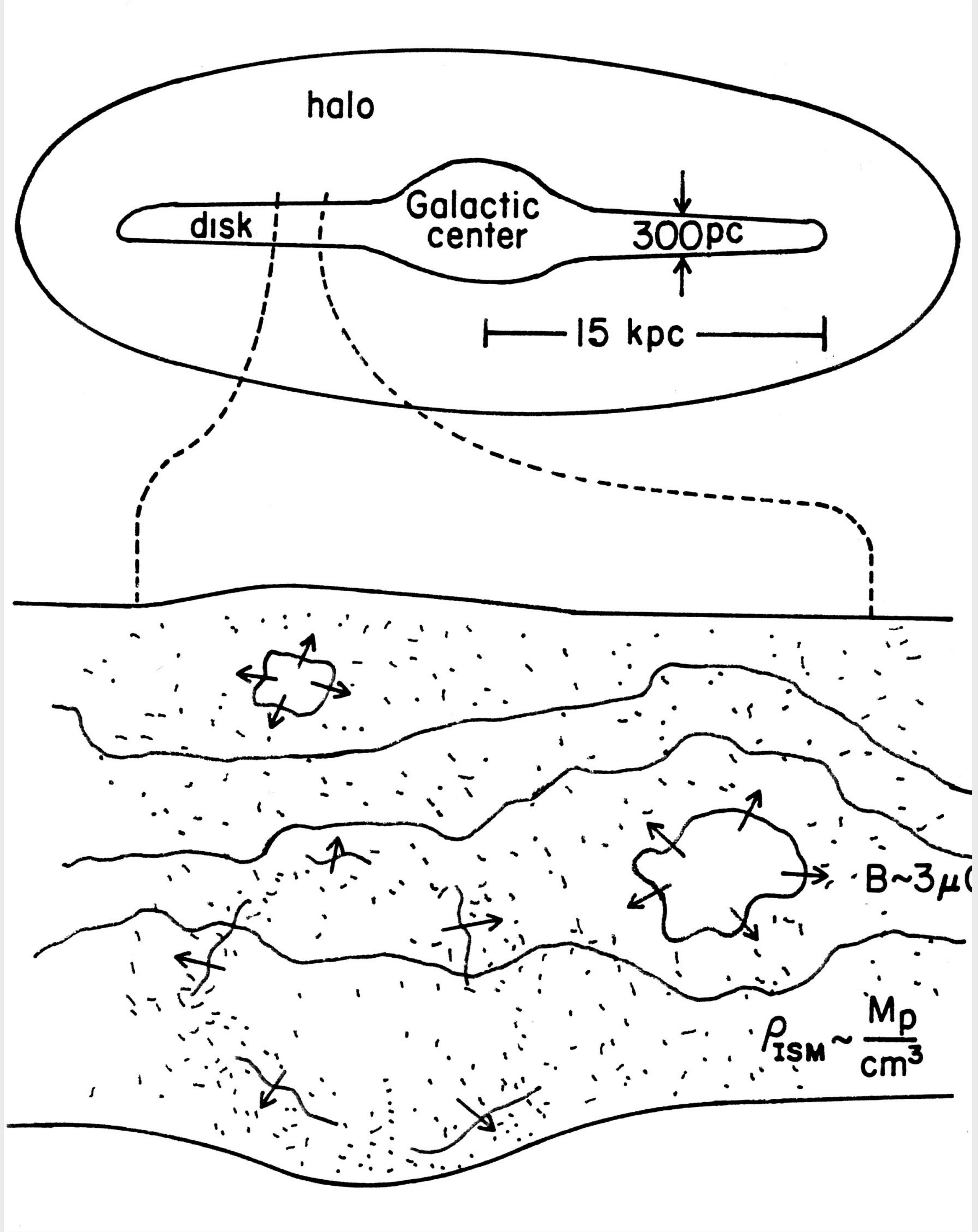


Magnetic confinement in Galaxy



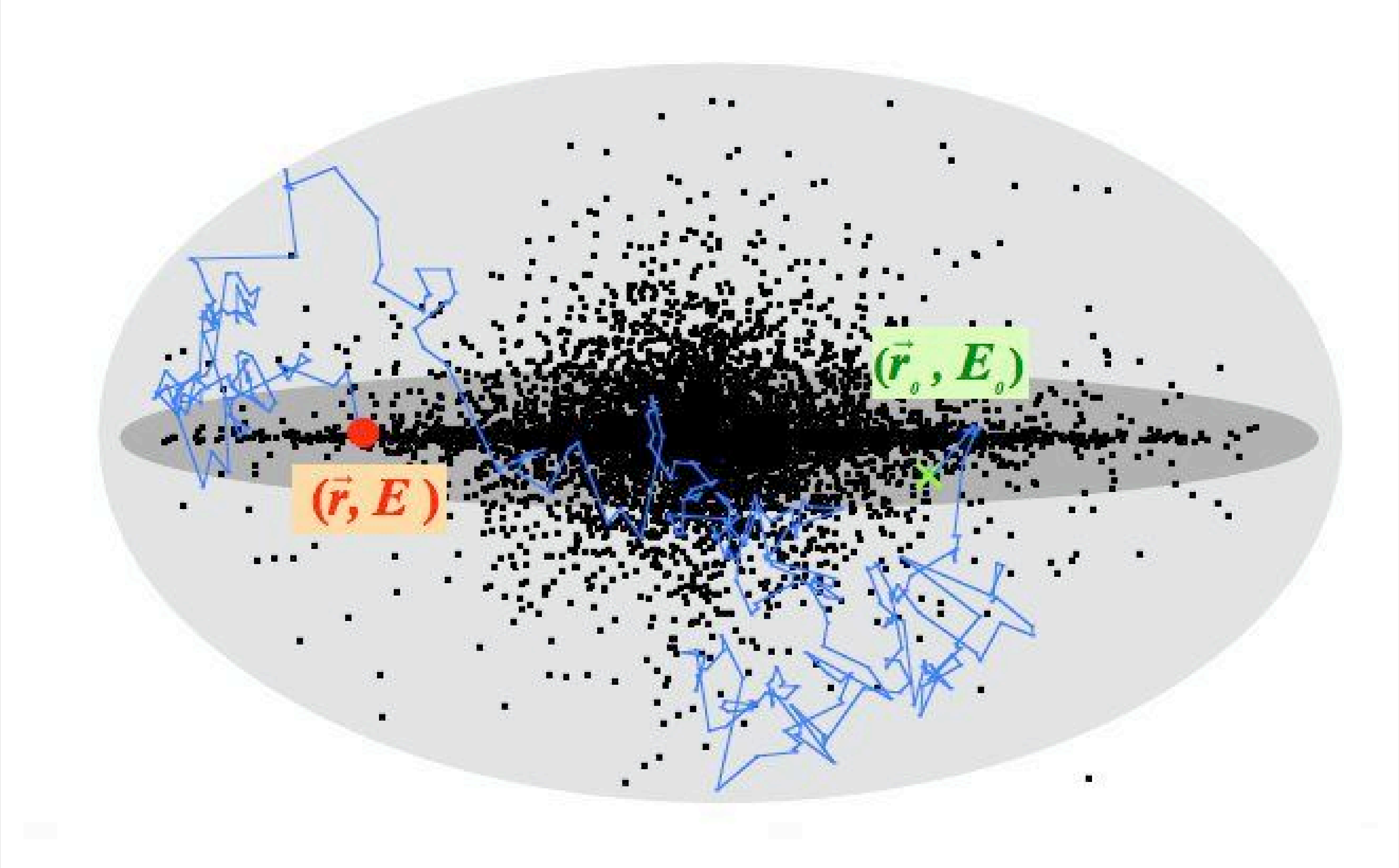
Galactic Center region

Standard model of galactic cosmic rays

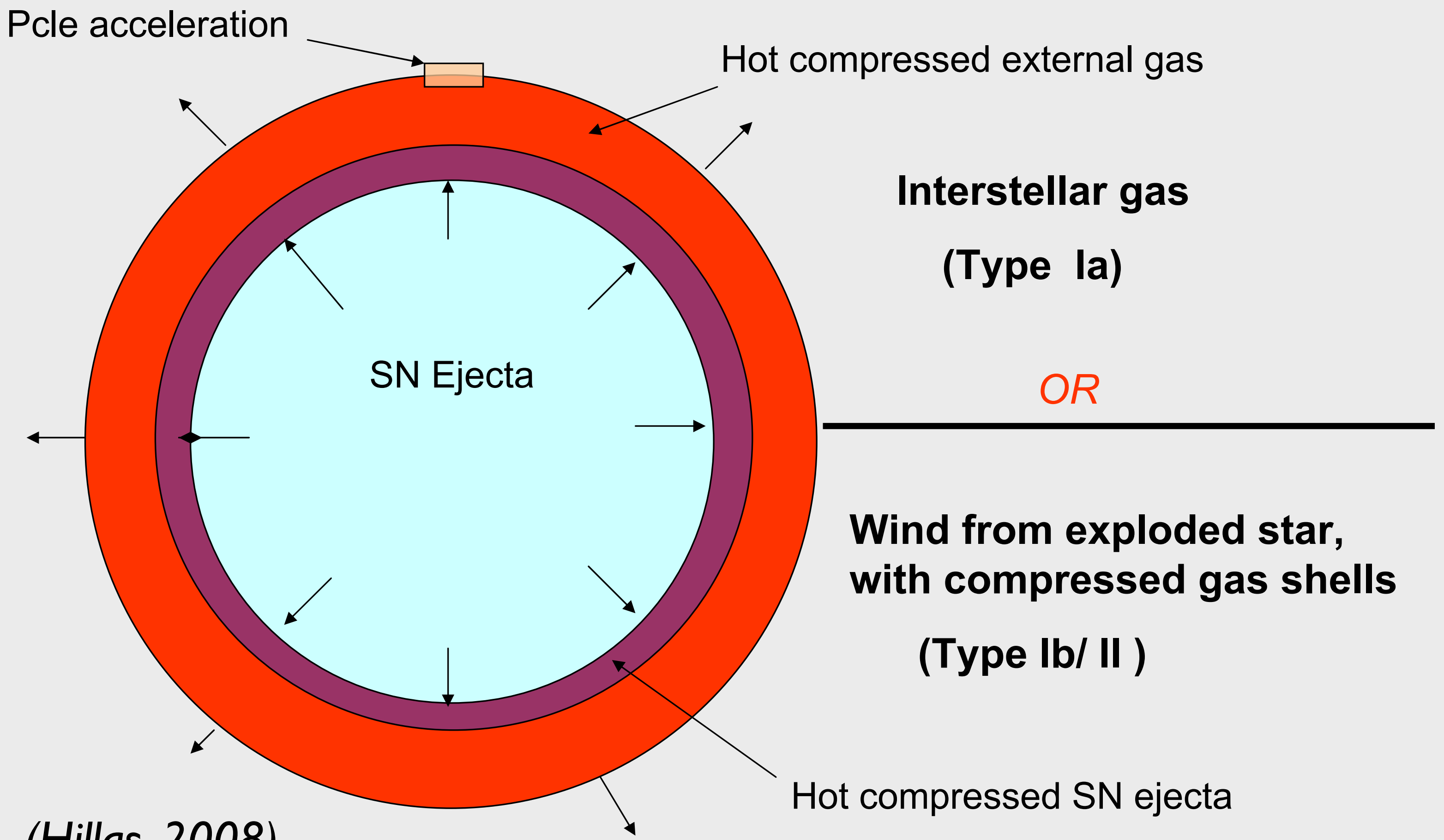


Argument of energy balance: SNR

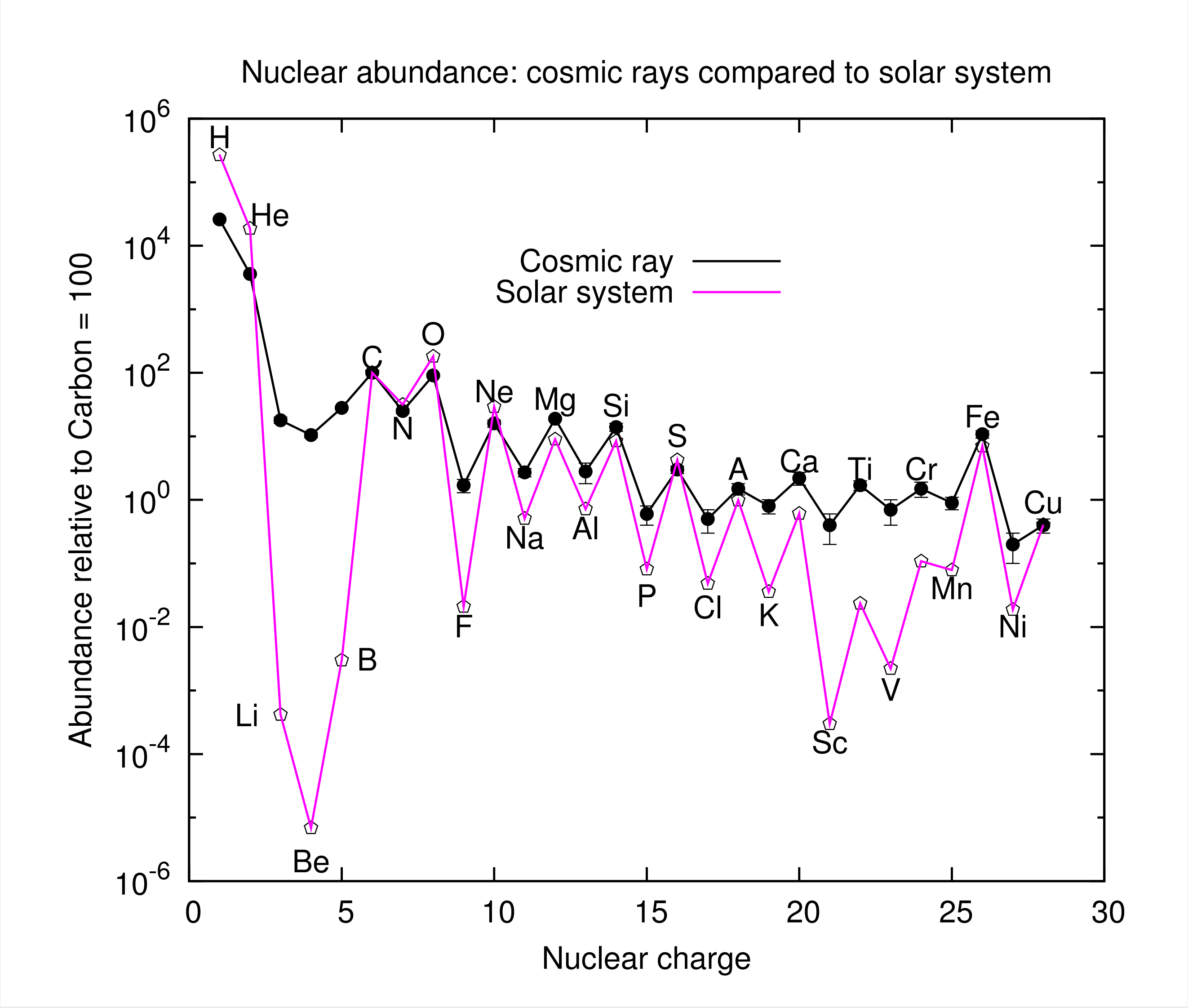
Fermi shock acceleration on shocks ~ $E^{-2.4}$



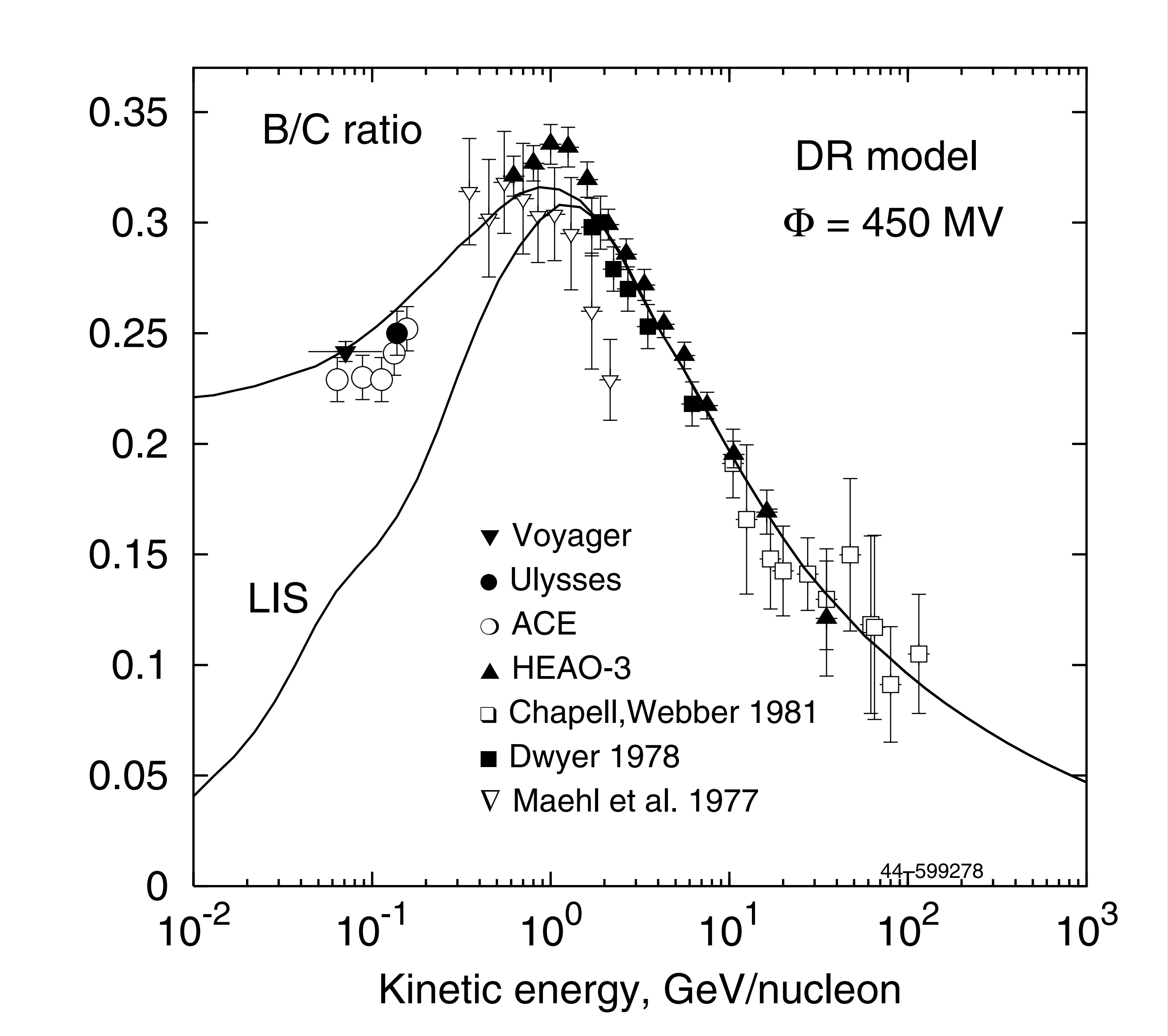
Magnetic diffusion in disk and halo



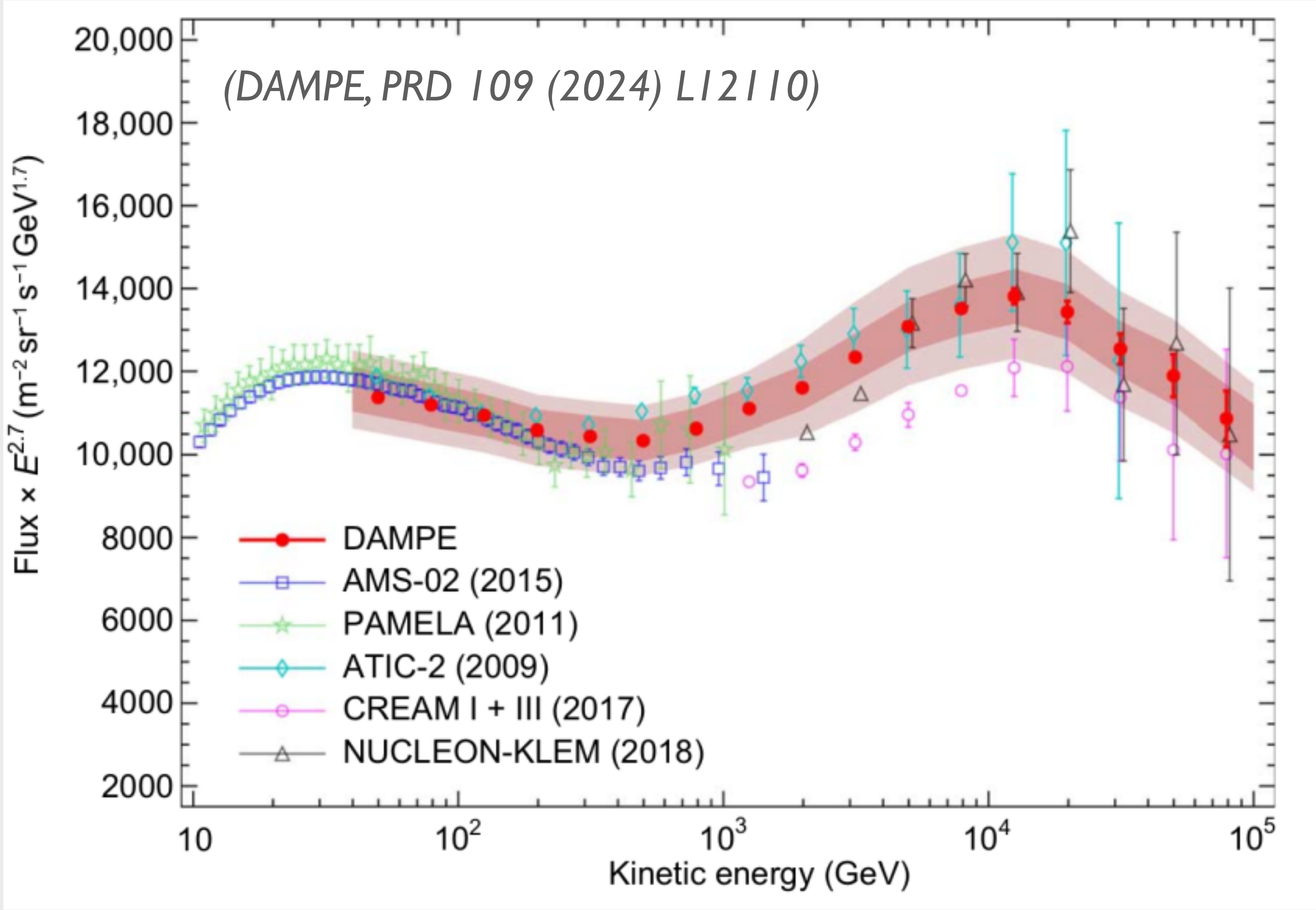
(Hillas, 2008)



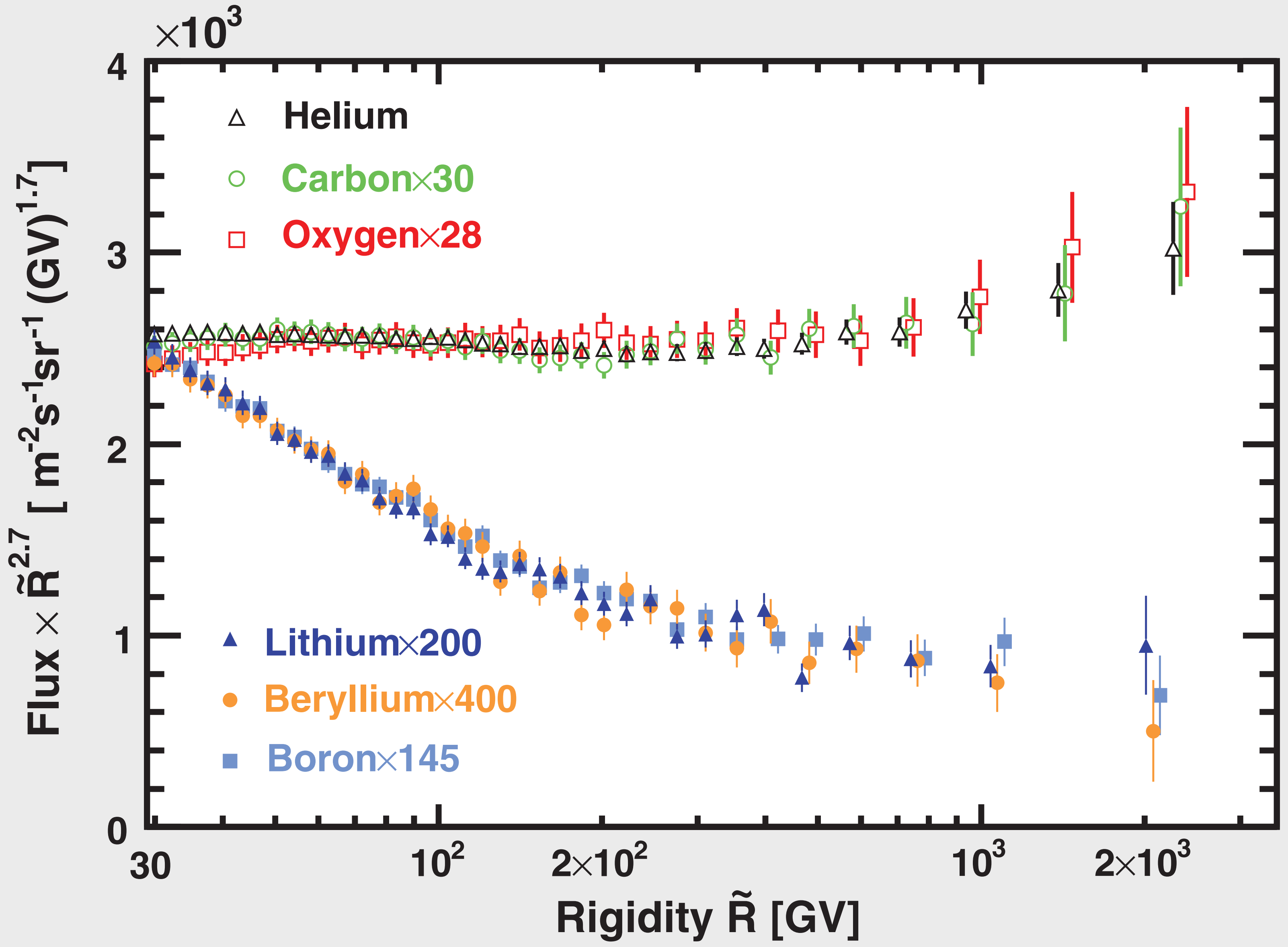
Production of secondary particles



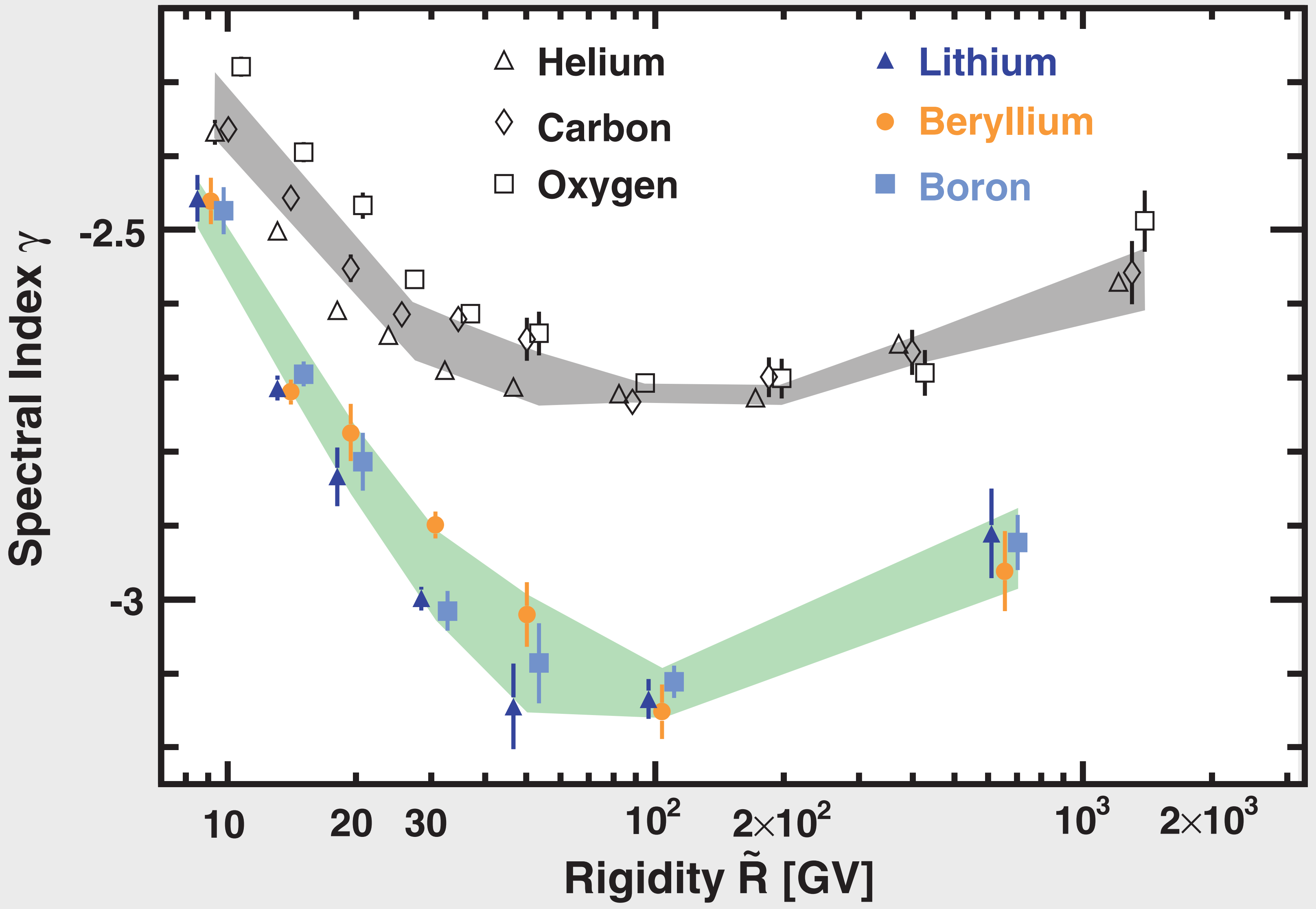
Unexpected structure – check with secondaries



(AMS, PRL 120 (2018) 021101)



Data indicate propagation effect causing hardening



$$N_{\rm C}(E) \quad \sim \quad \tau_{\rm C,esc}(E)\, Q_{\rm C}(E)$$

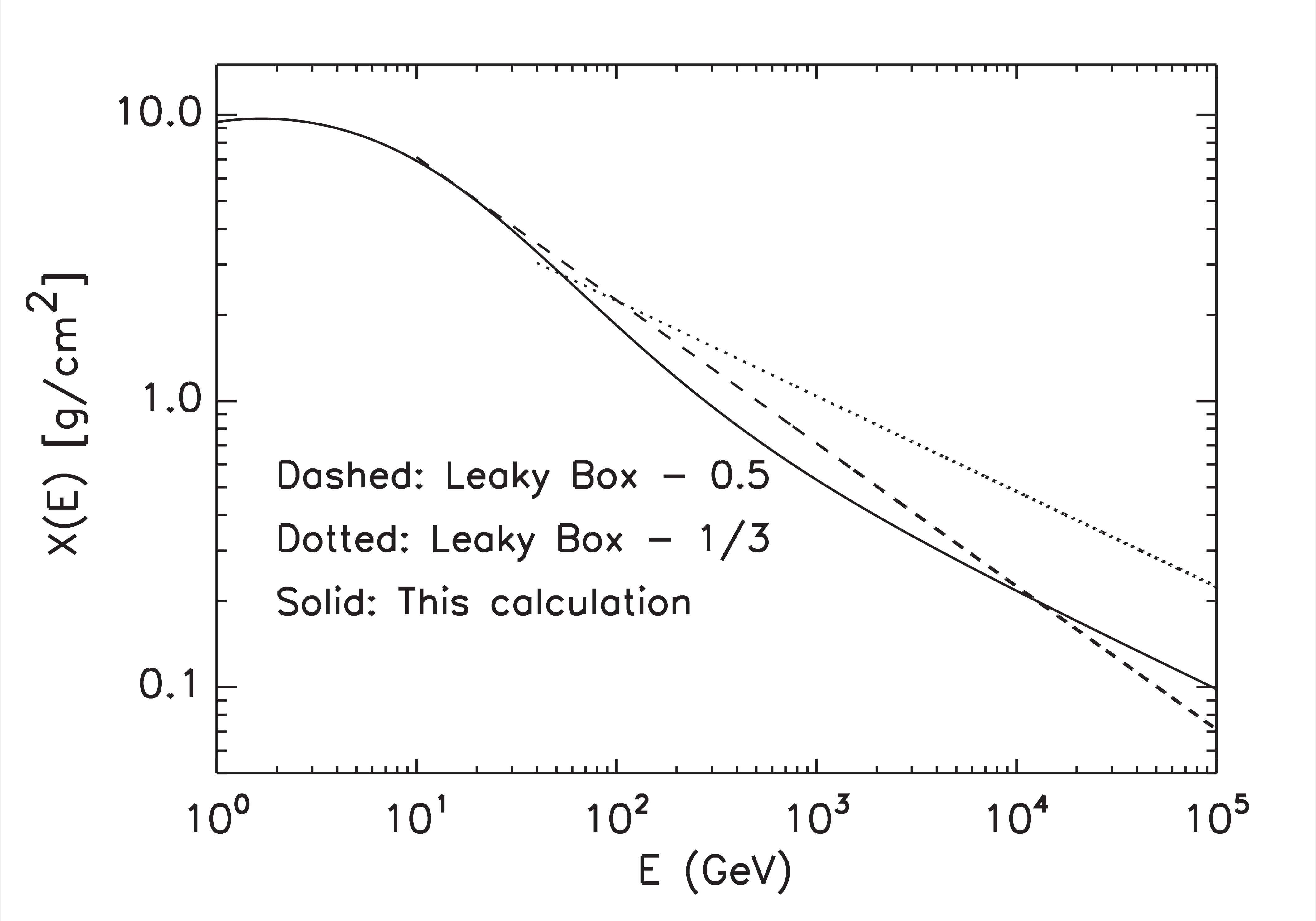
Escape time: diffusion coefficient

Source

$$N_{\rm B}(E) \quad \sim \quad \tau_{\rm B,esc}(E)\, \frac{N_{\rm C}(E)}{\tau_{\rm C,int}}$$

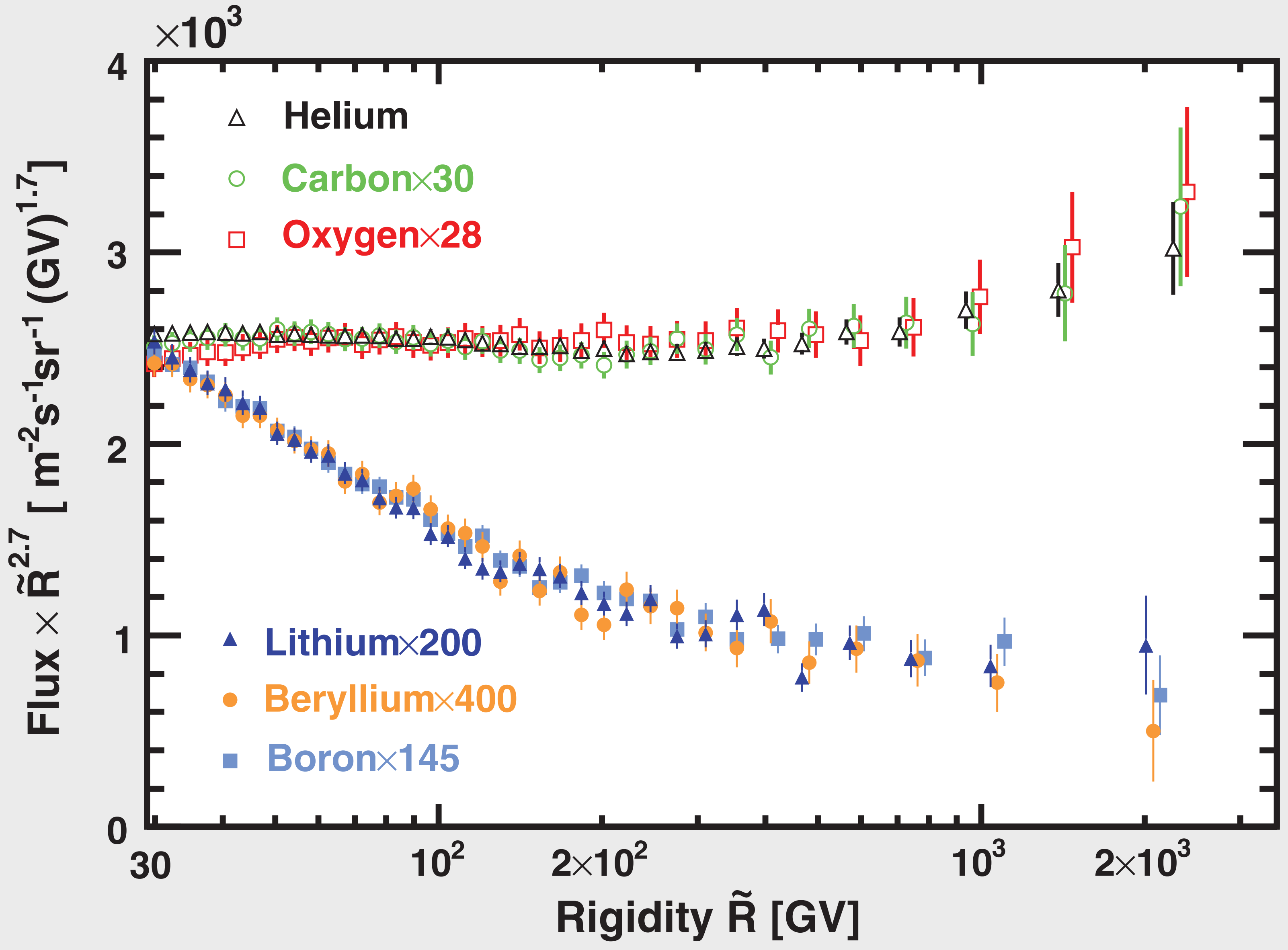
$$\sim \quad \frac{\tau_{\rm B,esc}(E)\, \tau_{\rm C,esc}(E)}{\tau_{\rm C,int}}\, Q_{\rm C}(E)$$

Unexpected structure – check with secondaries

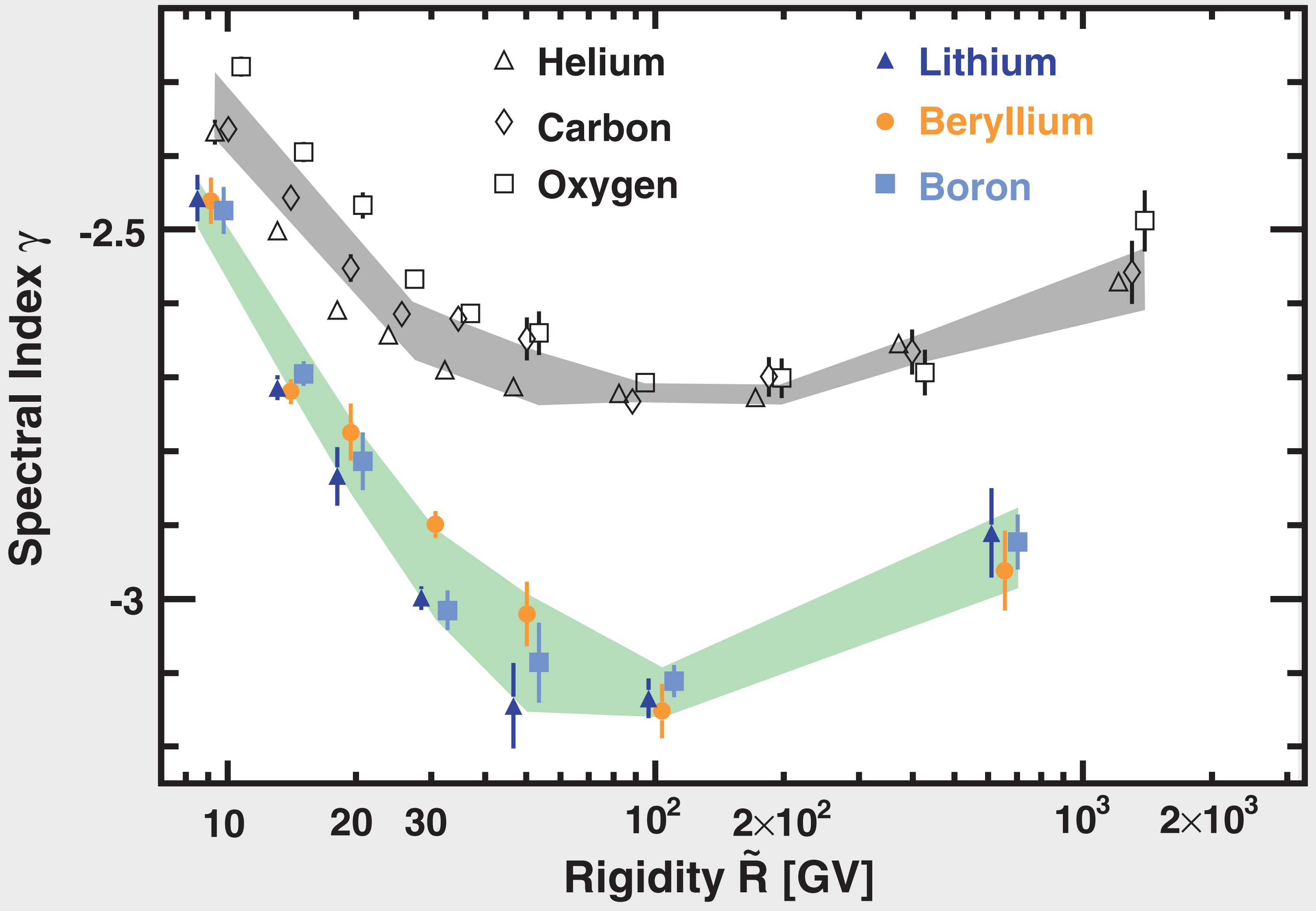


(Balsi, Amato, Serpico, PRL 109 (2012) 061101)

(AMS, PRL 120 (2018) 021101)



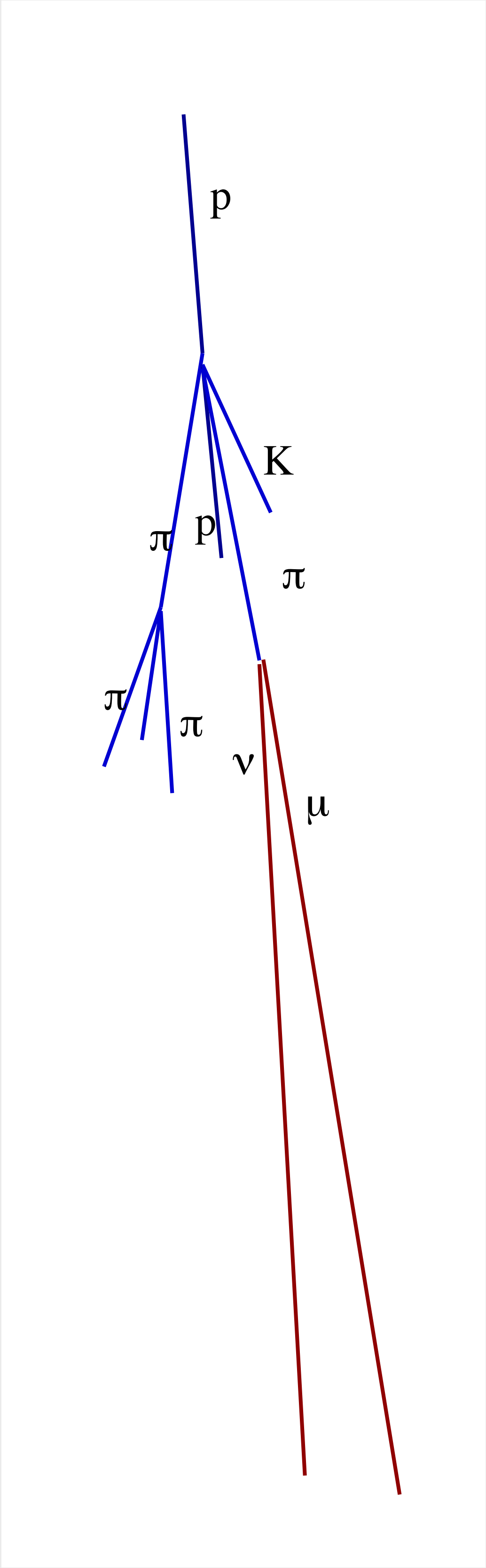
Change predicted
from δ ~ 0.6 at low energy
to δ ~ 0.33 at high energy

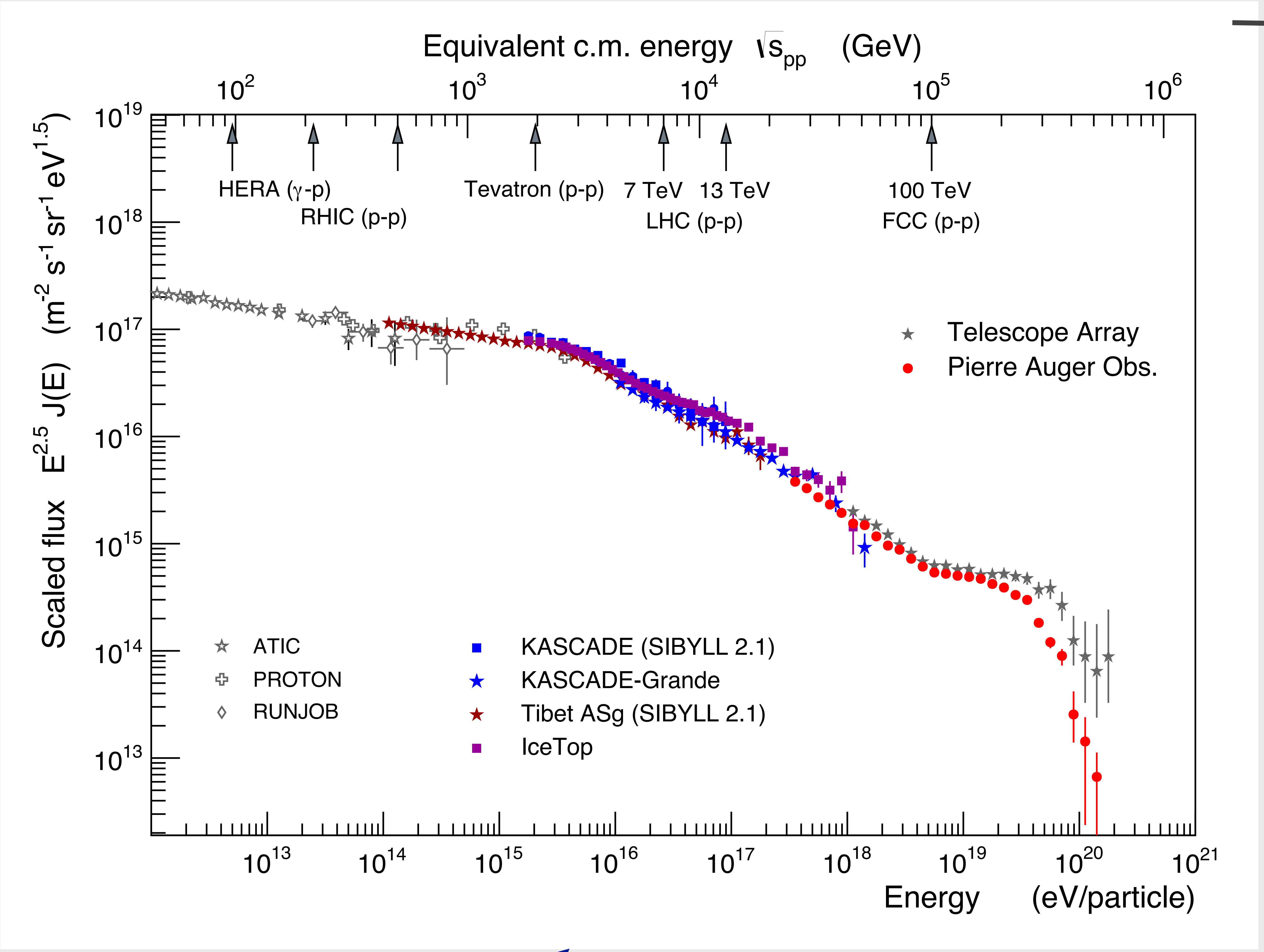


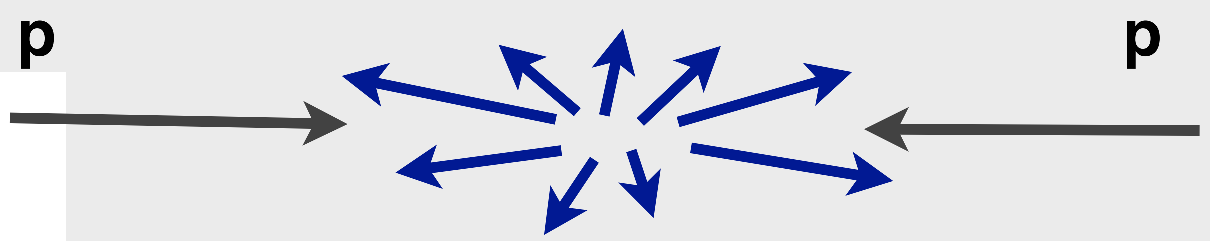
Transition from self-generated turbulence of mag. fields to externally generated turbulence

$$N_B(E) \sim \tau_{B,esc}(E)\,\frac{N_C(E)}{\tau_{C,int}} \sim \frac{\tau_{B,esc}(E)\,\tau_{C,esc}(E)}{\tau_{C,int}}\,Q_C(E)$$

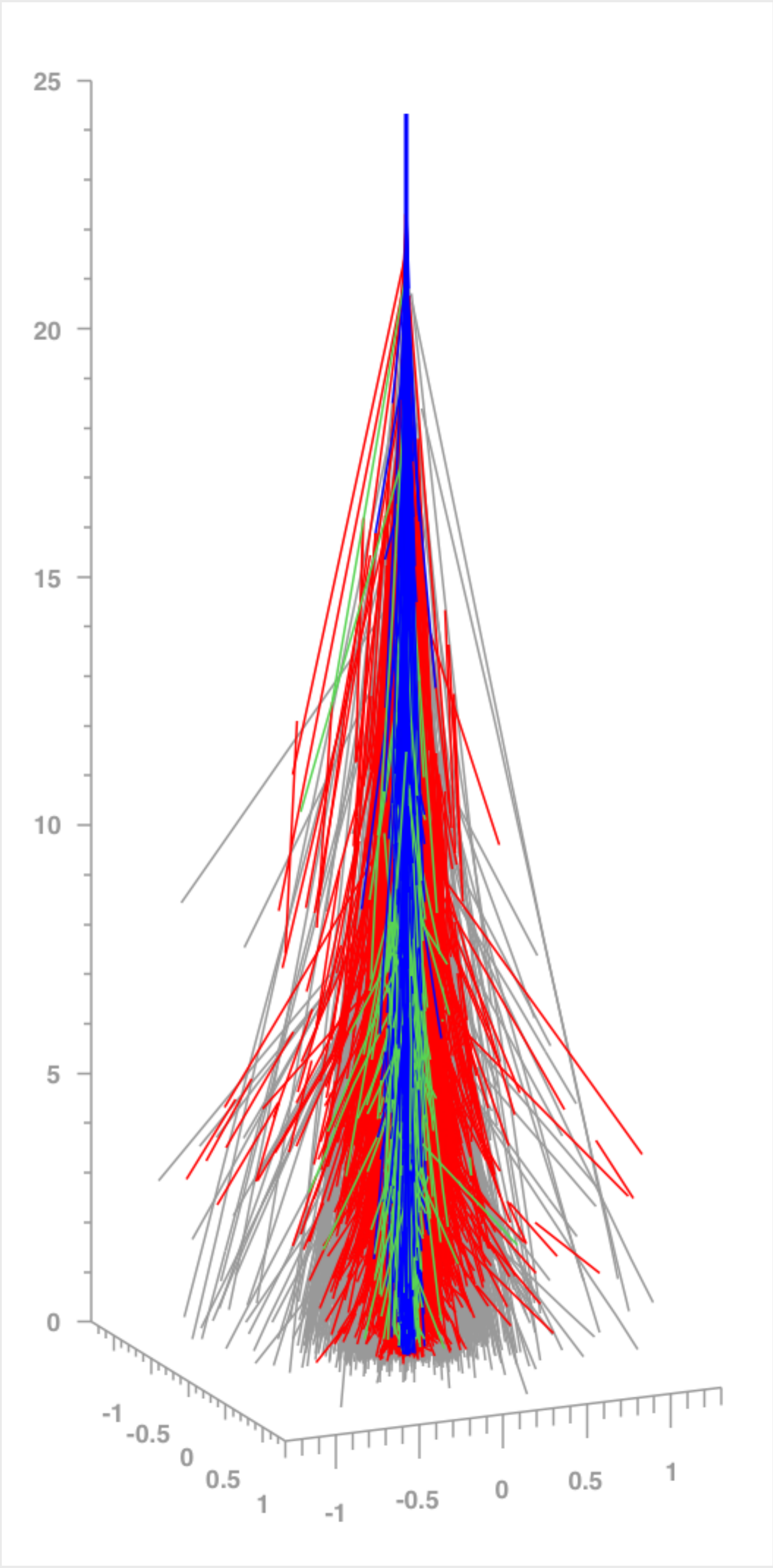
Cosmic ray flux and interaction energies



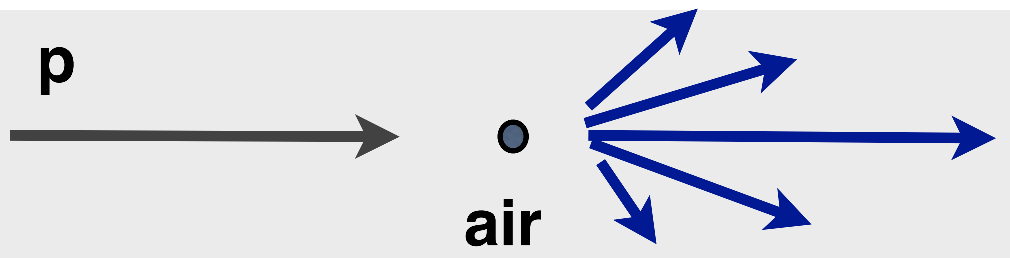




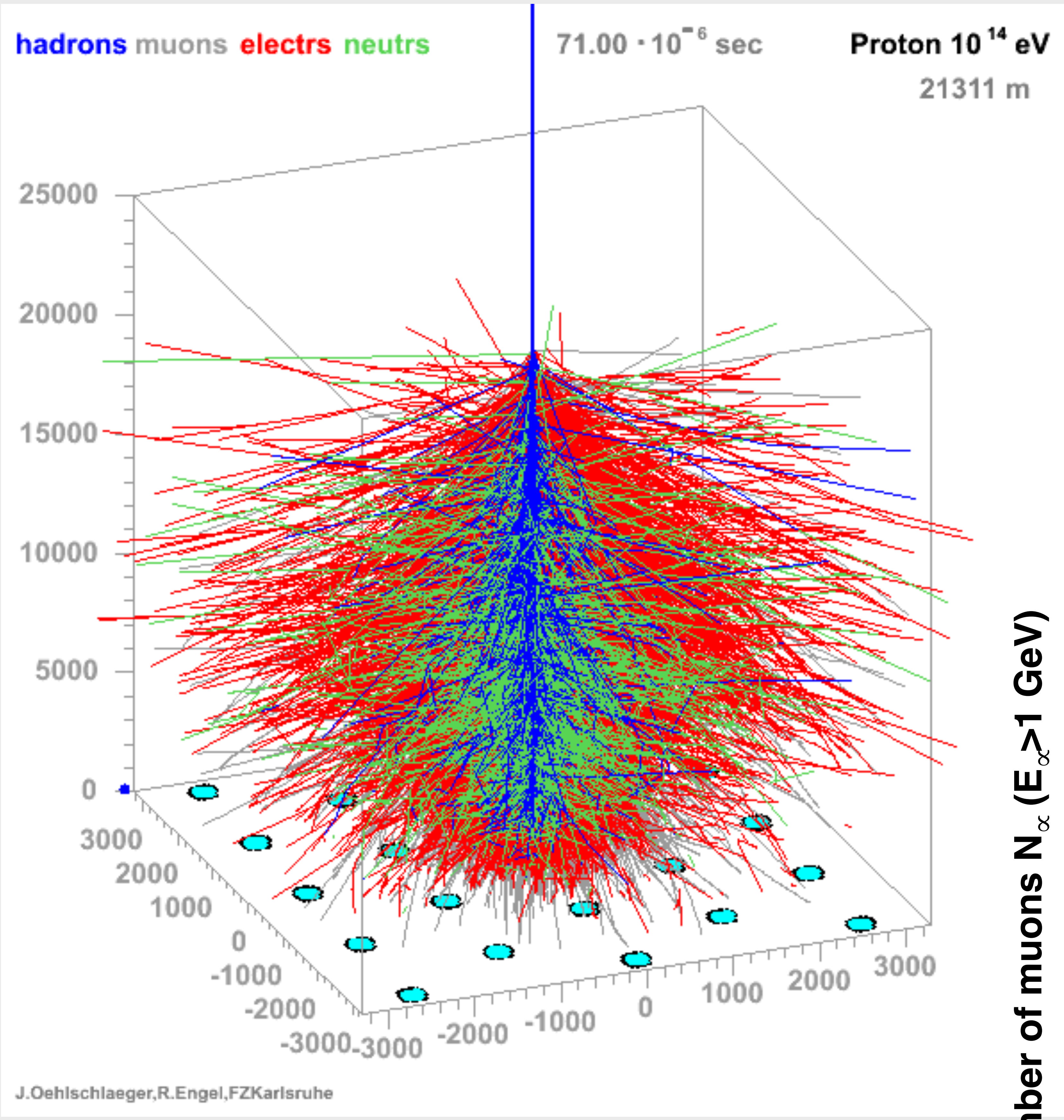
Center-of-mass energy

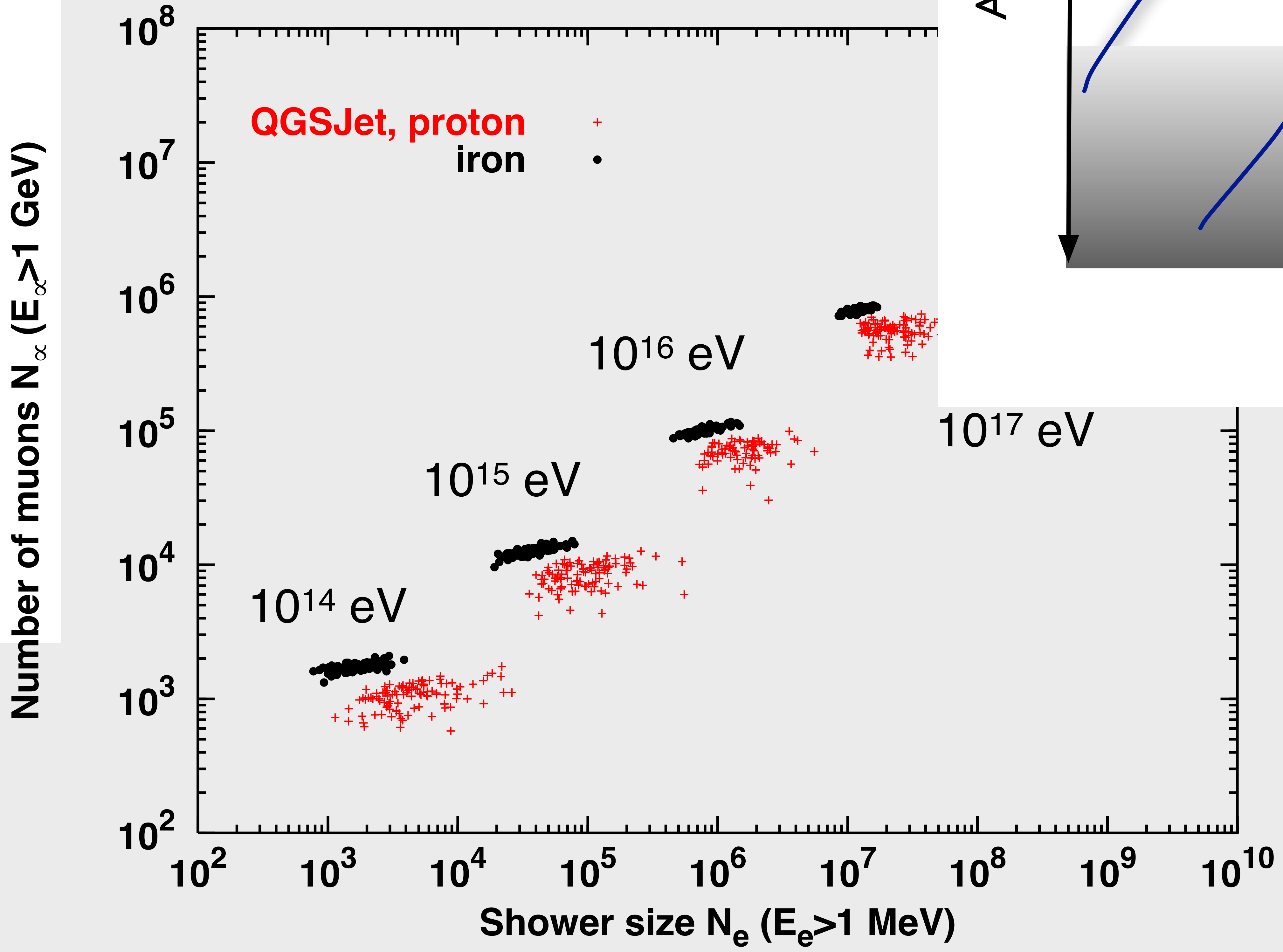


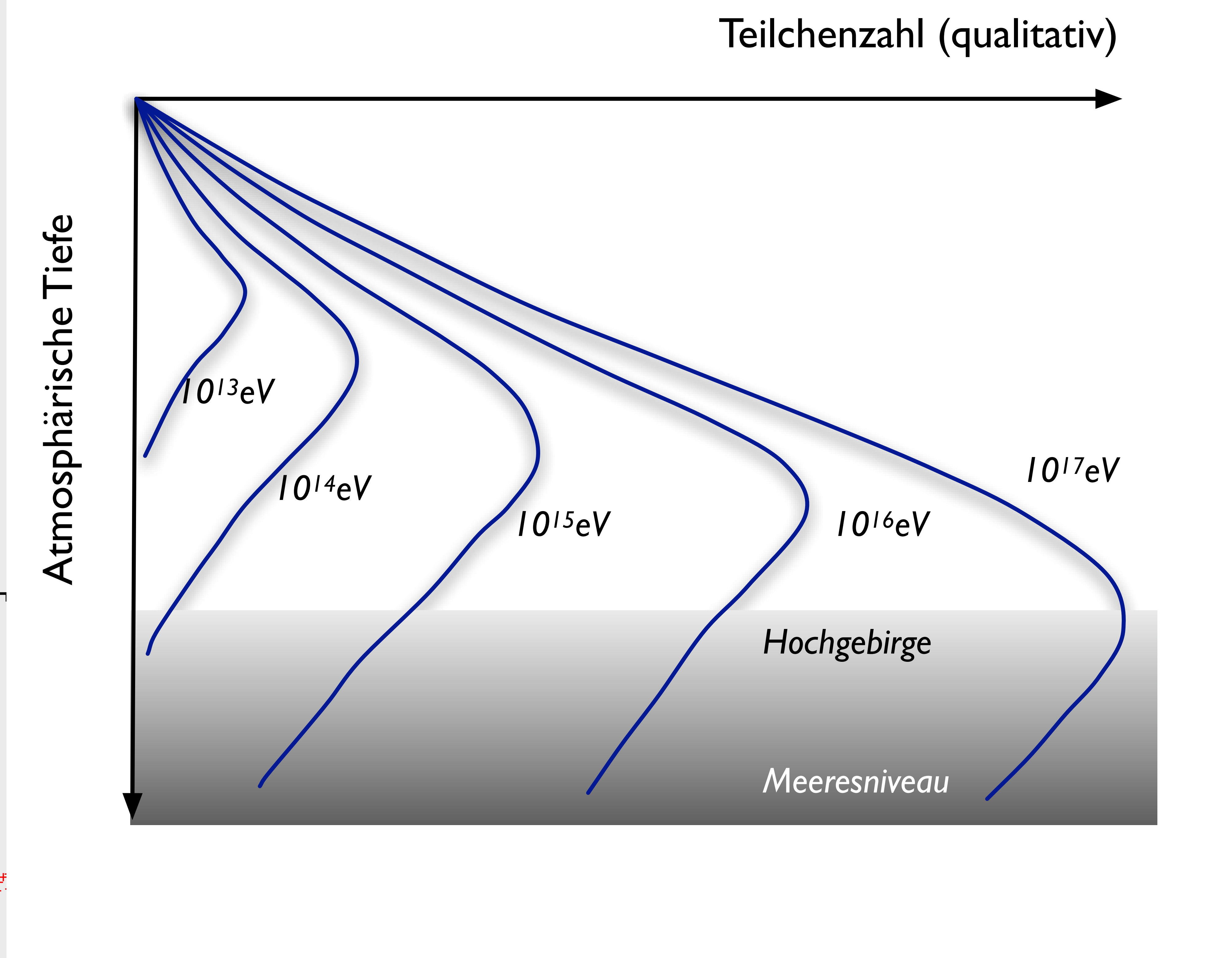
Laboratory energy



Air shower ground arrays: N_e and N_μ





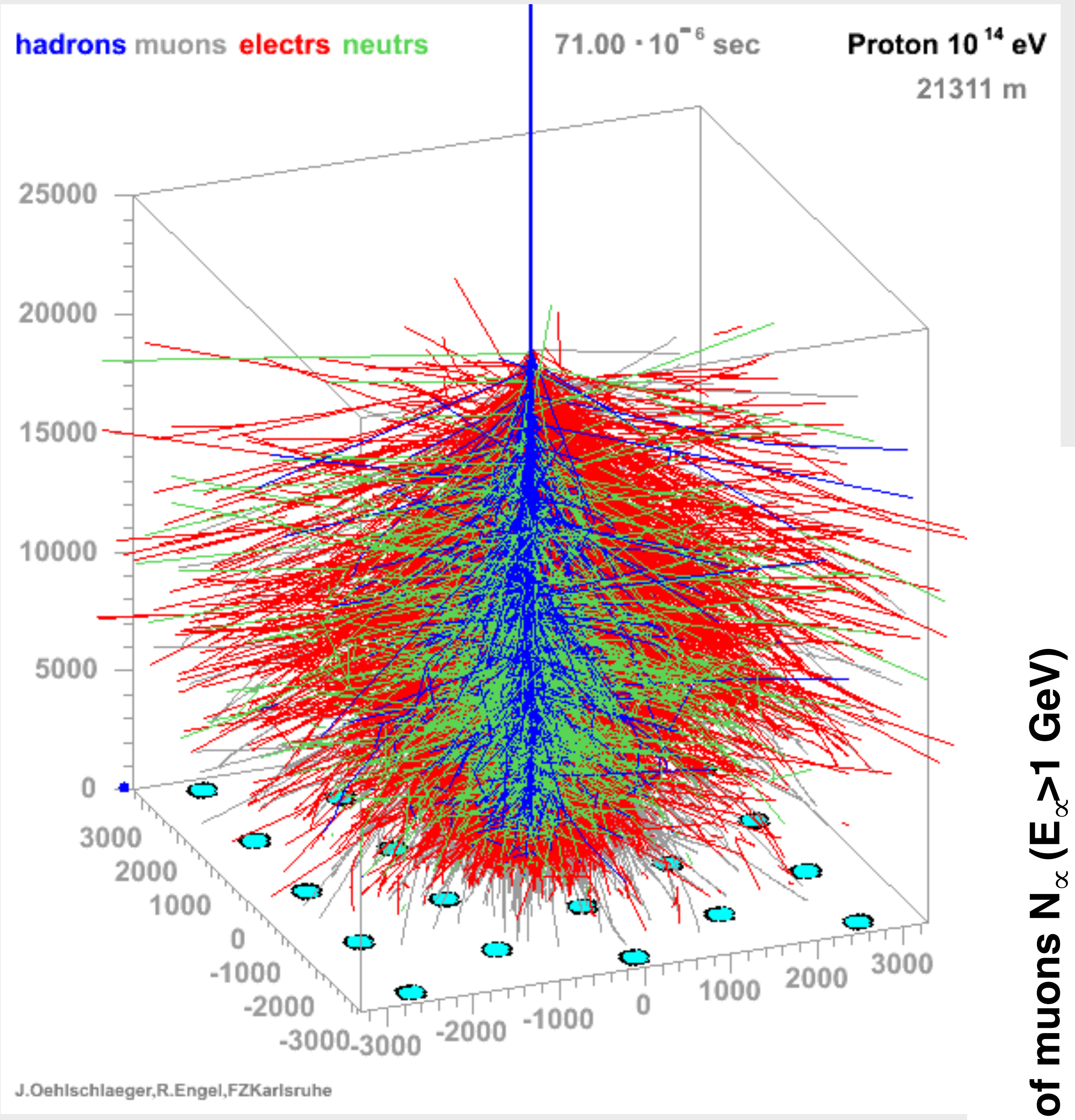


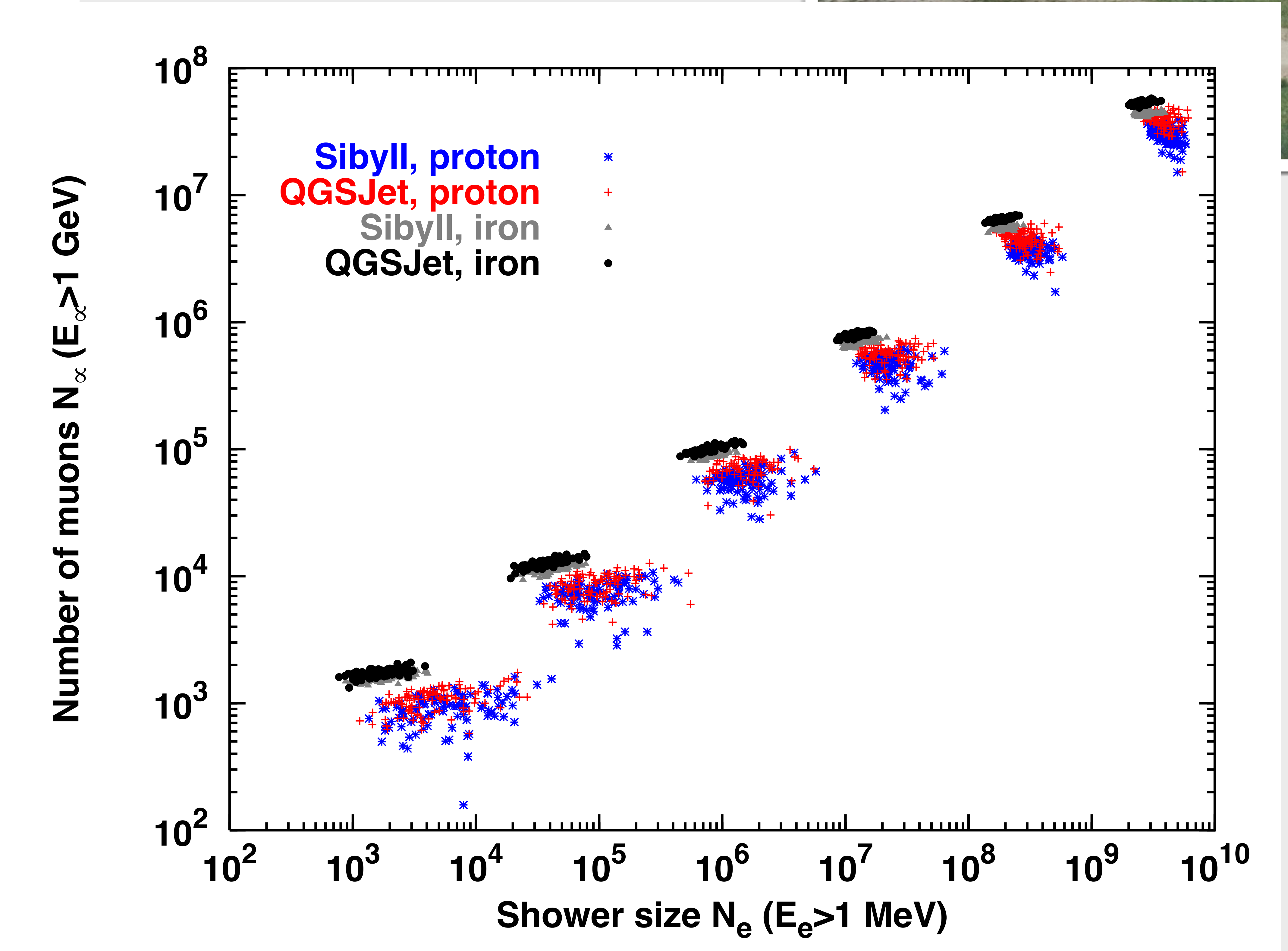
KASCADE and KASCADE-Grande

KASCADE und KASCADE-Grande
(KArlsruhe Shower Core and Array DEtector)

Fläche ~ 0.04 km^2,
252 Teilchendetektoren

Air shower ground arrays – model dependence





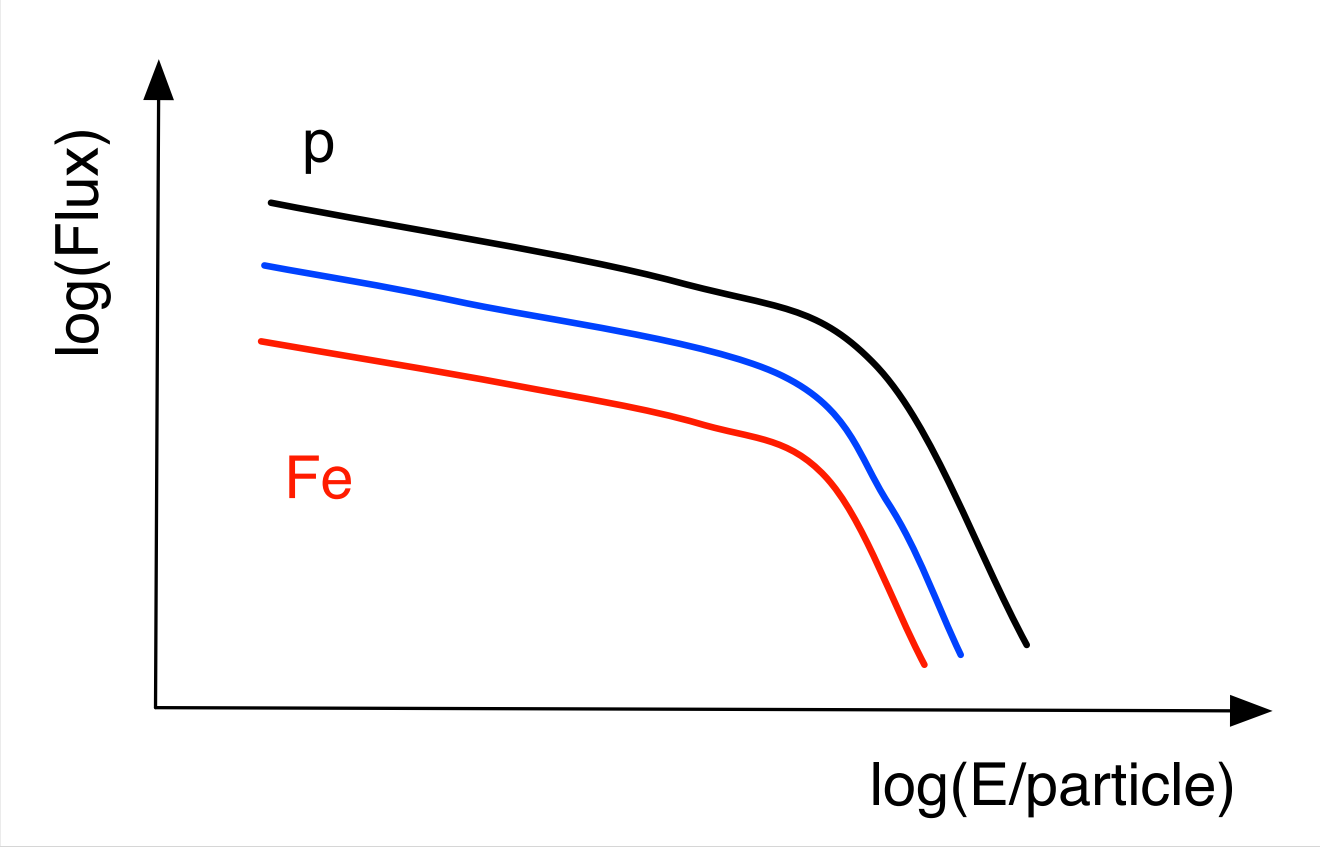
Energy estimate: energy conservation

$$\ln E = a \cdot \ln N_e + b \cdot \ln N_\mu$$

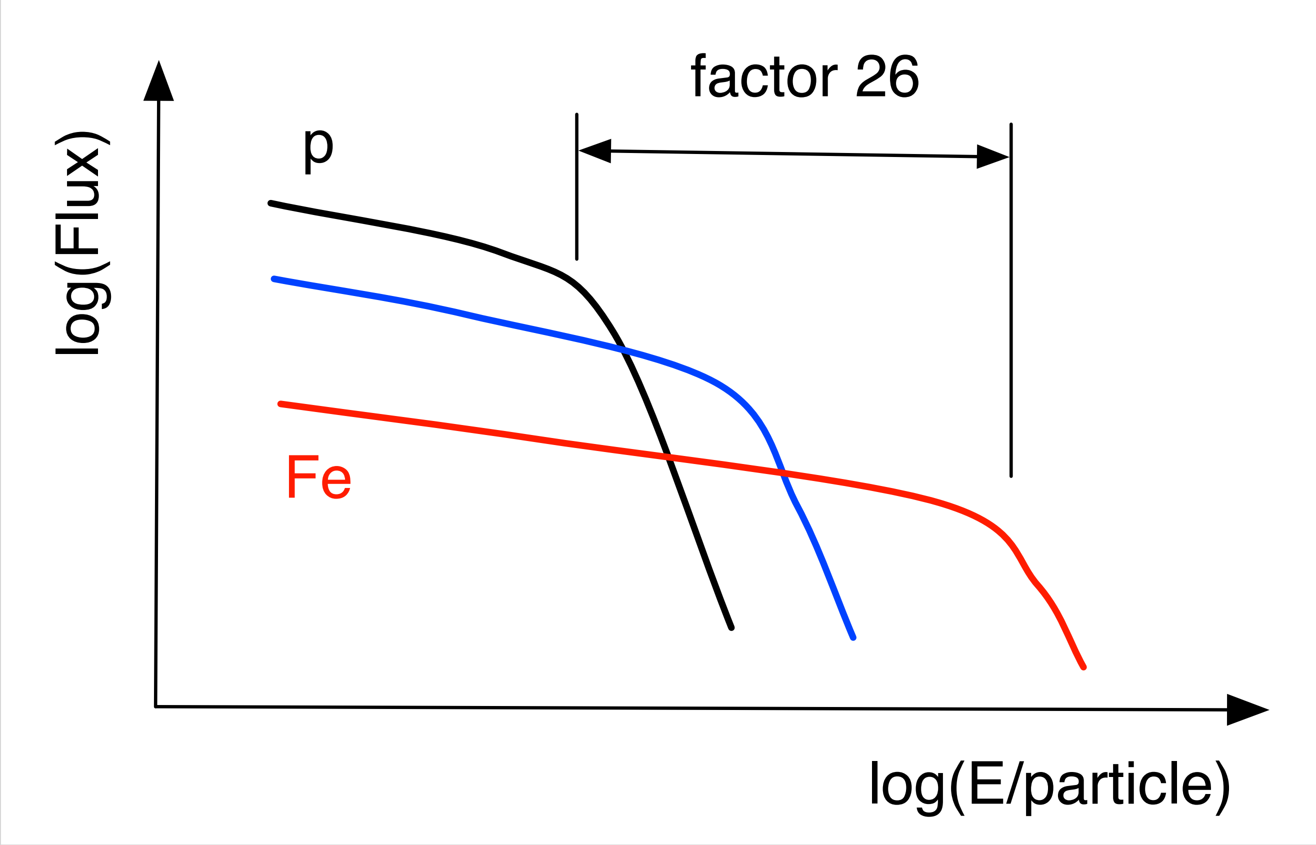
Mass estimate: strong dependence on used hadronic interaction model

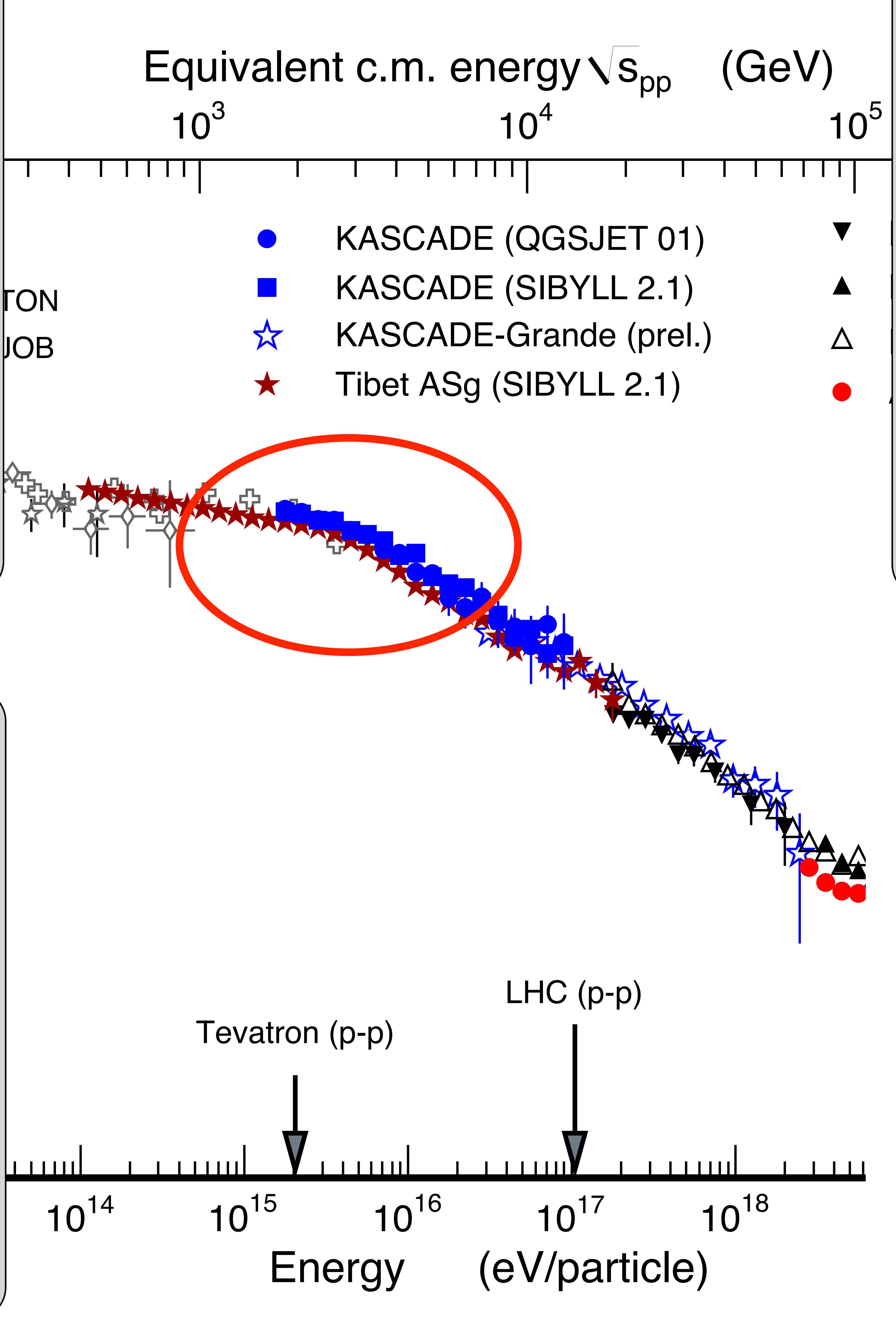
Possible interpretation of knee in spectrum

Nothing special (fine tuning?):

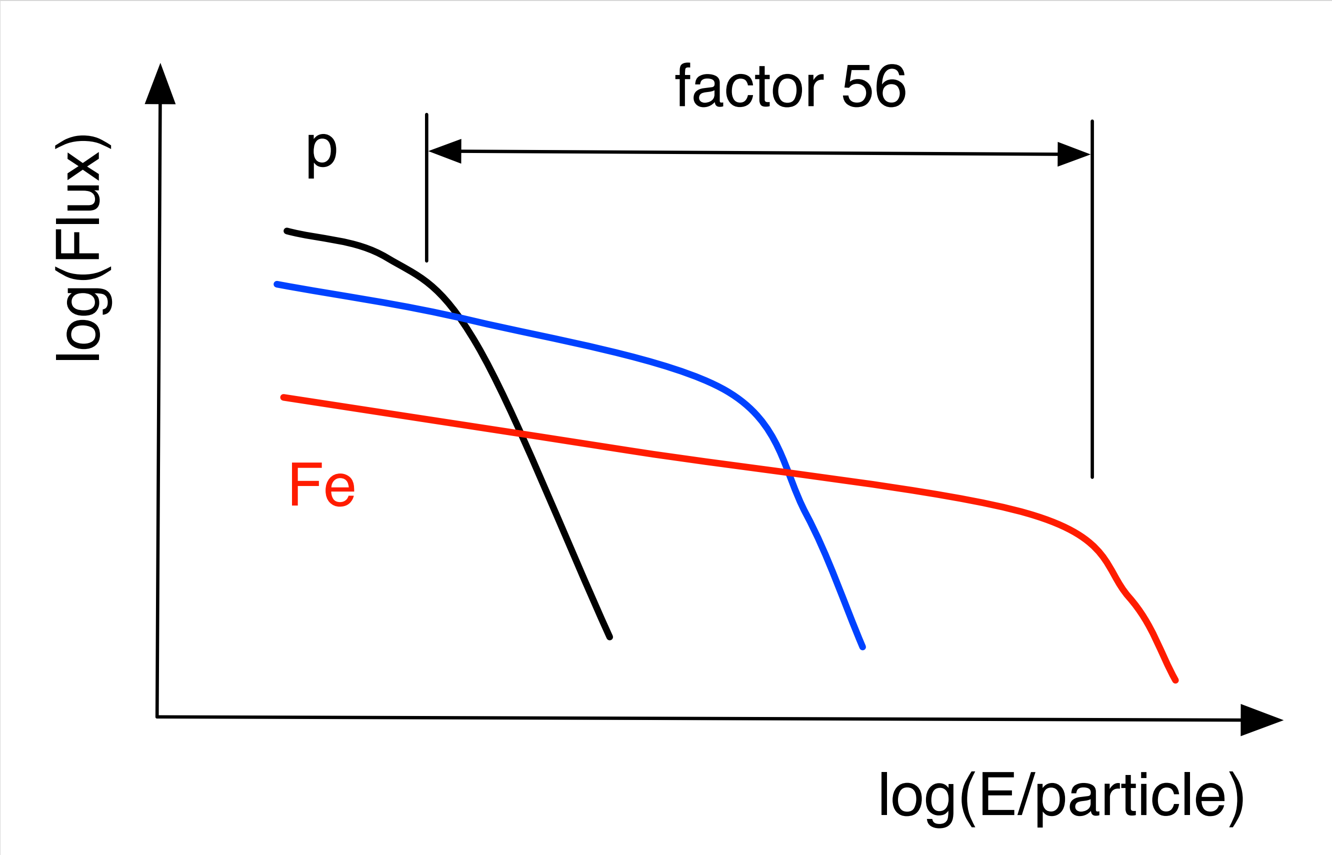


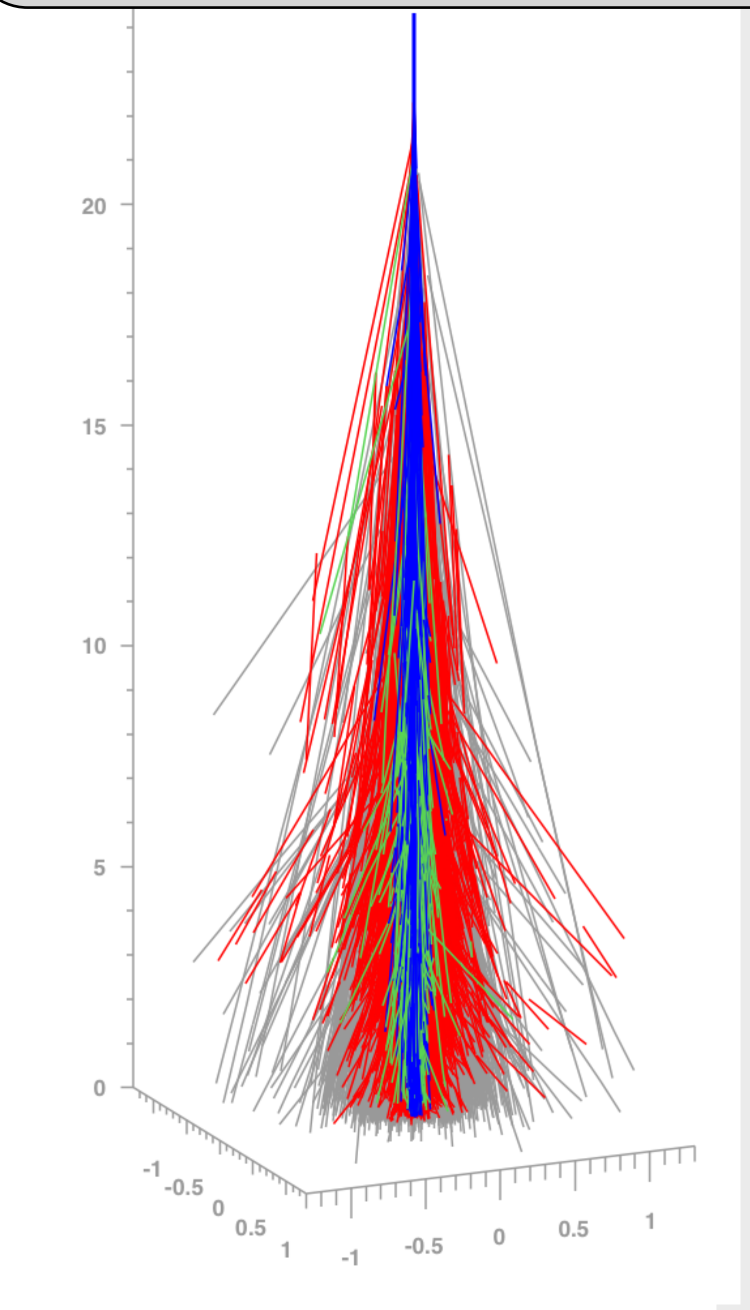
Acceleration/propagation (rigidity):





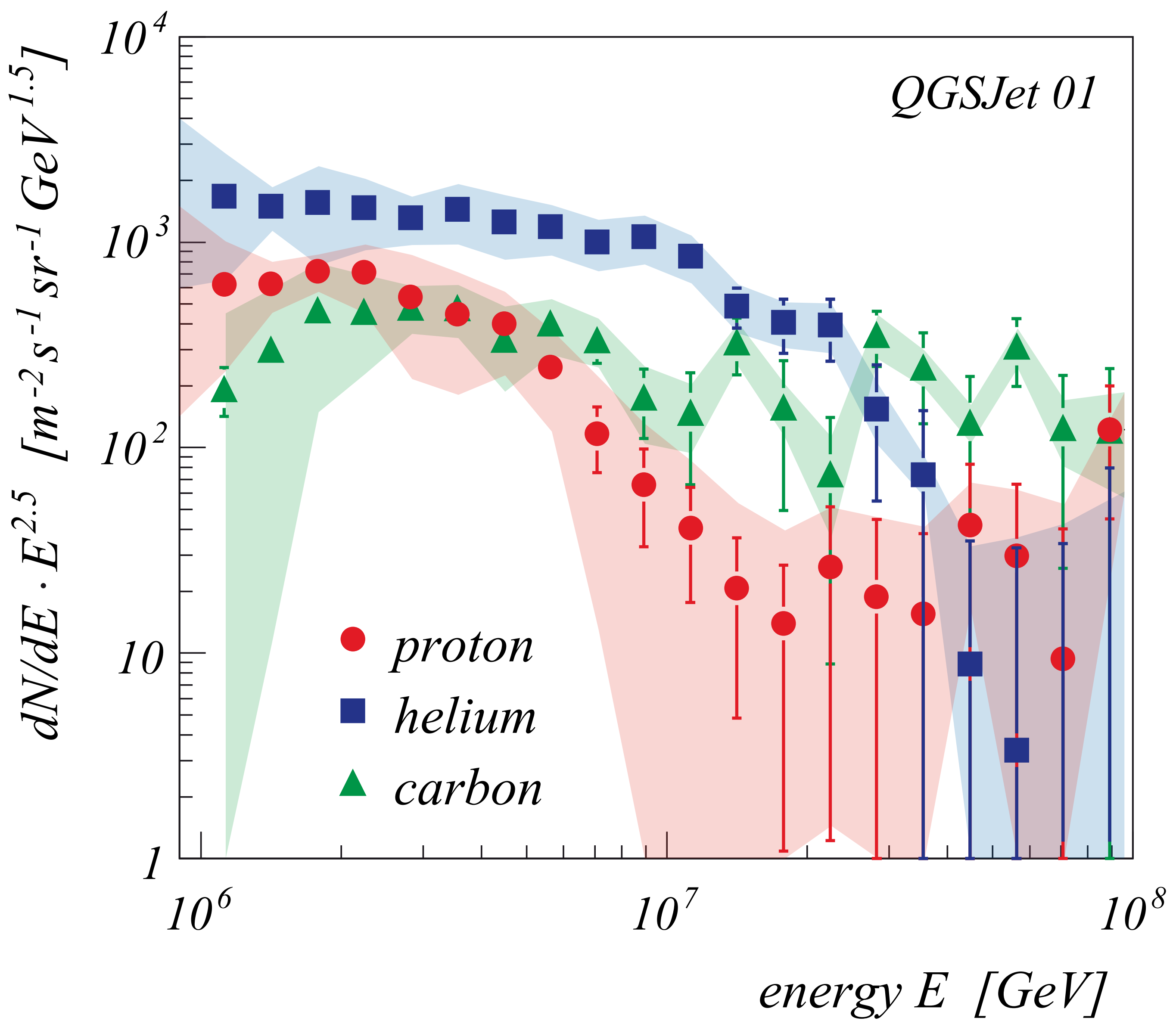
Particle physics (energy per nucleon):

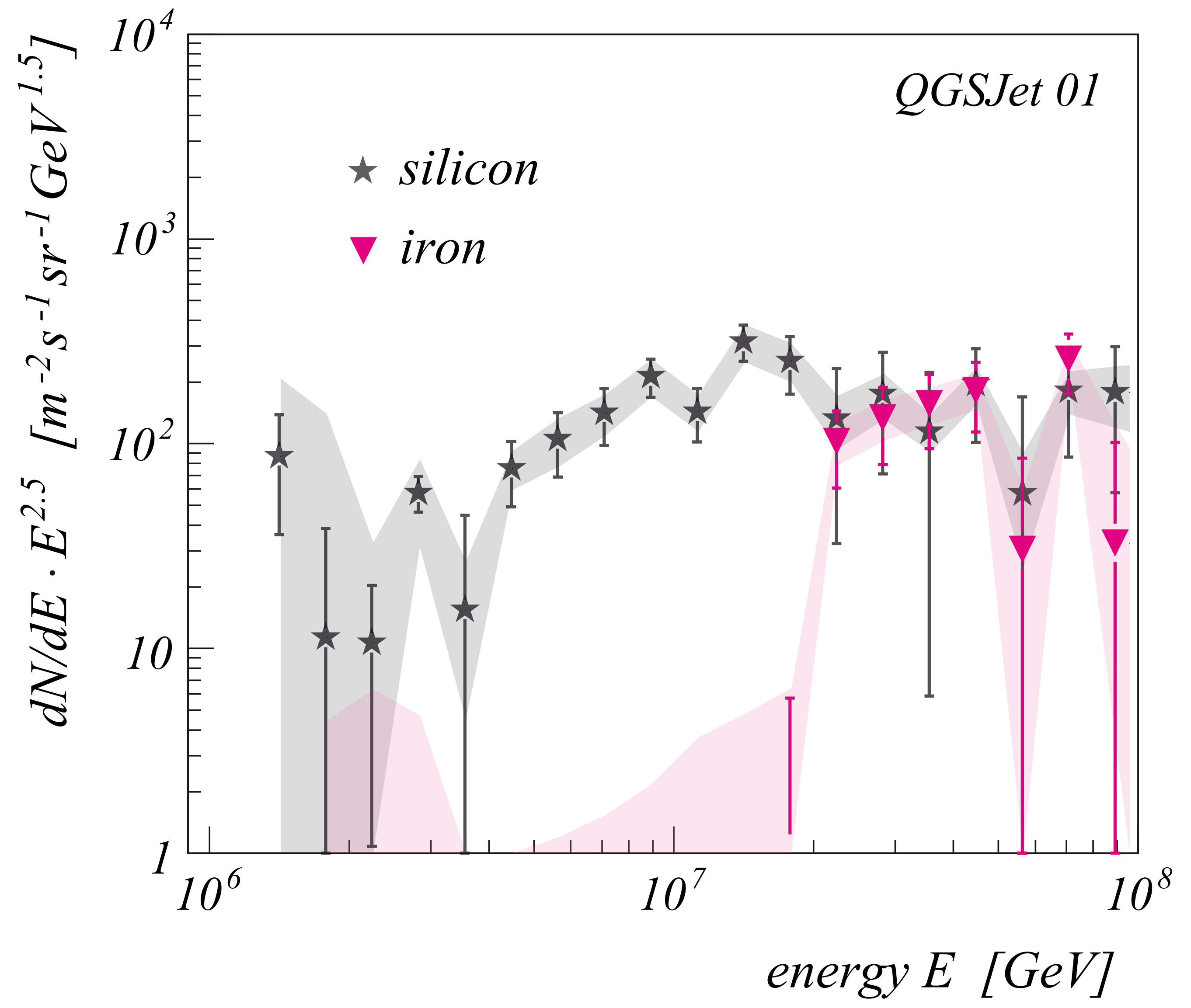


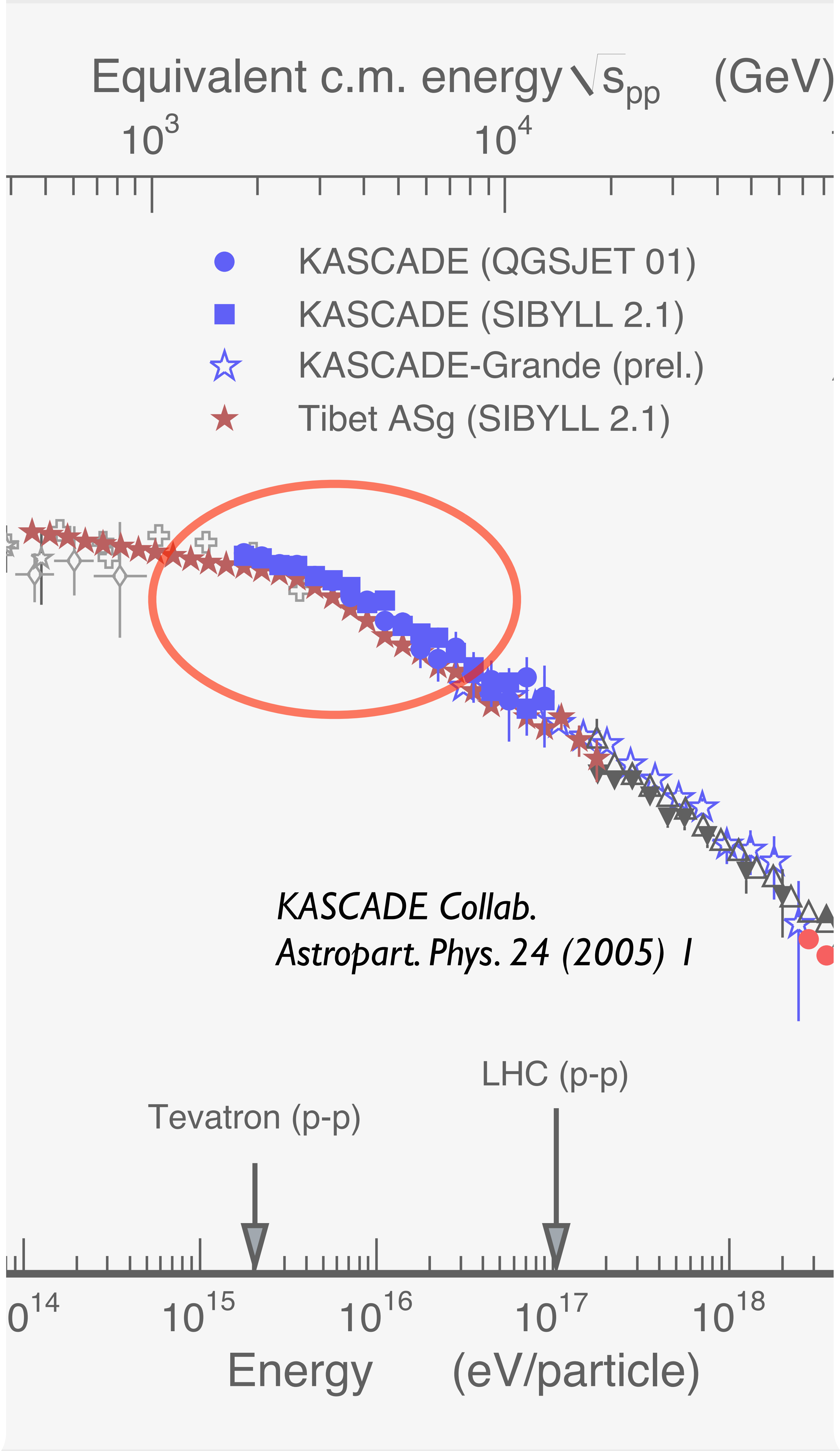


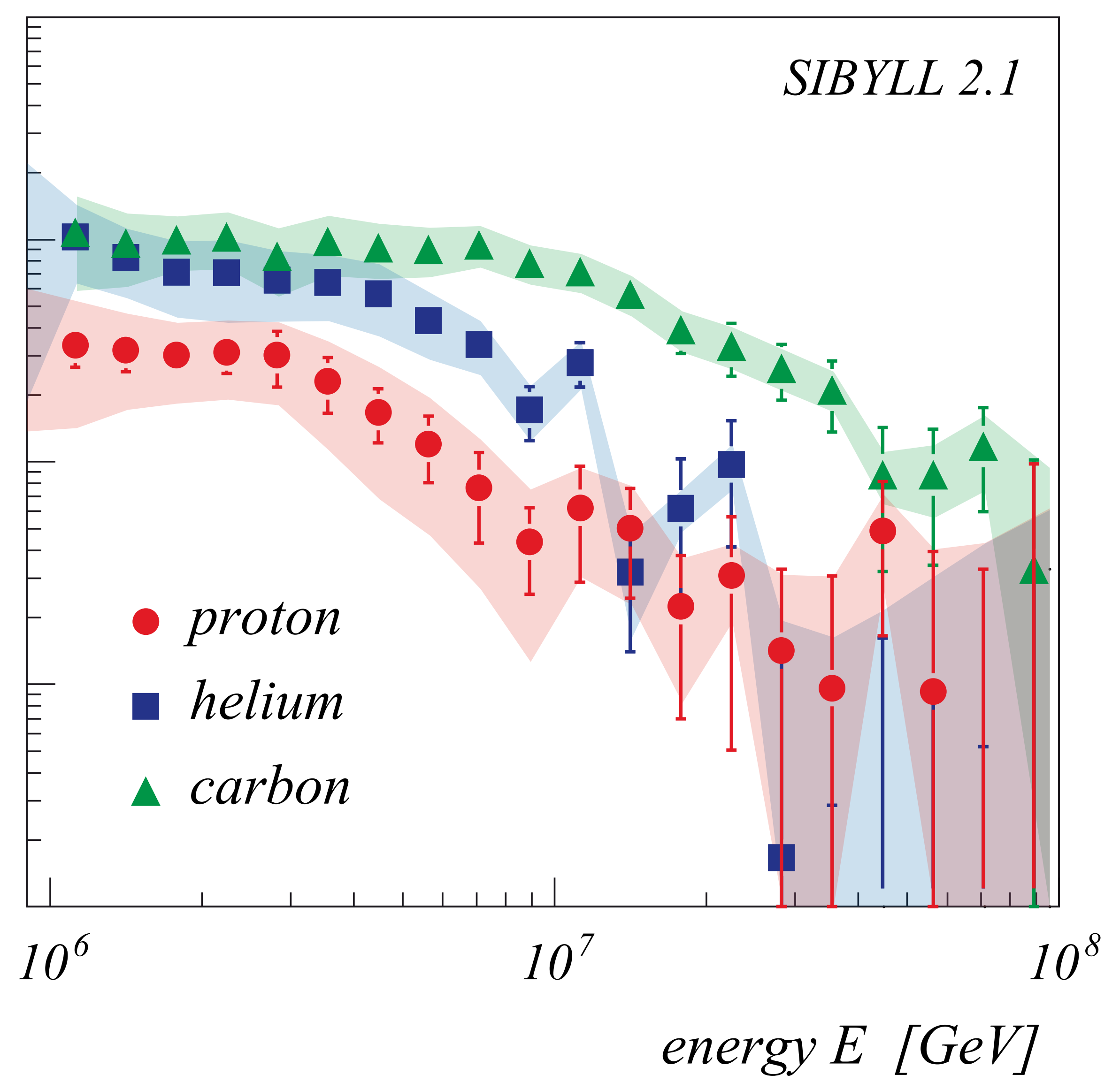
Shower energy wrongly reconstructed due to new particle physics setting at knee energy

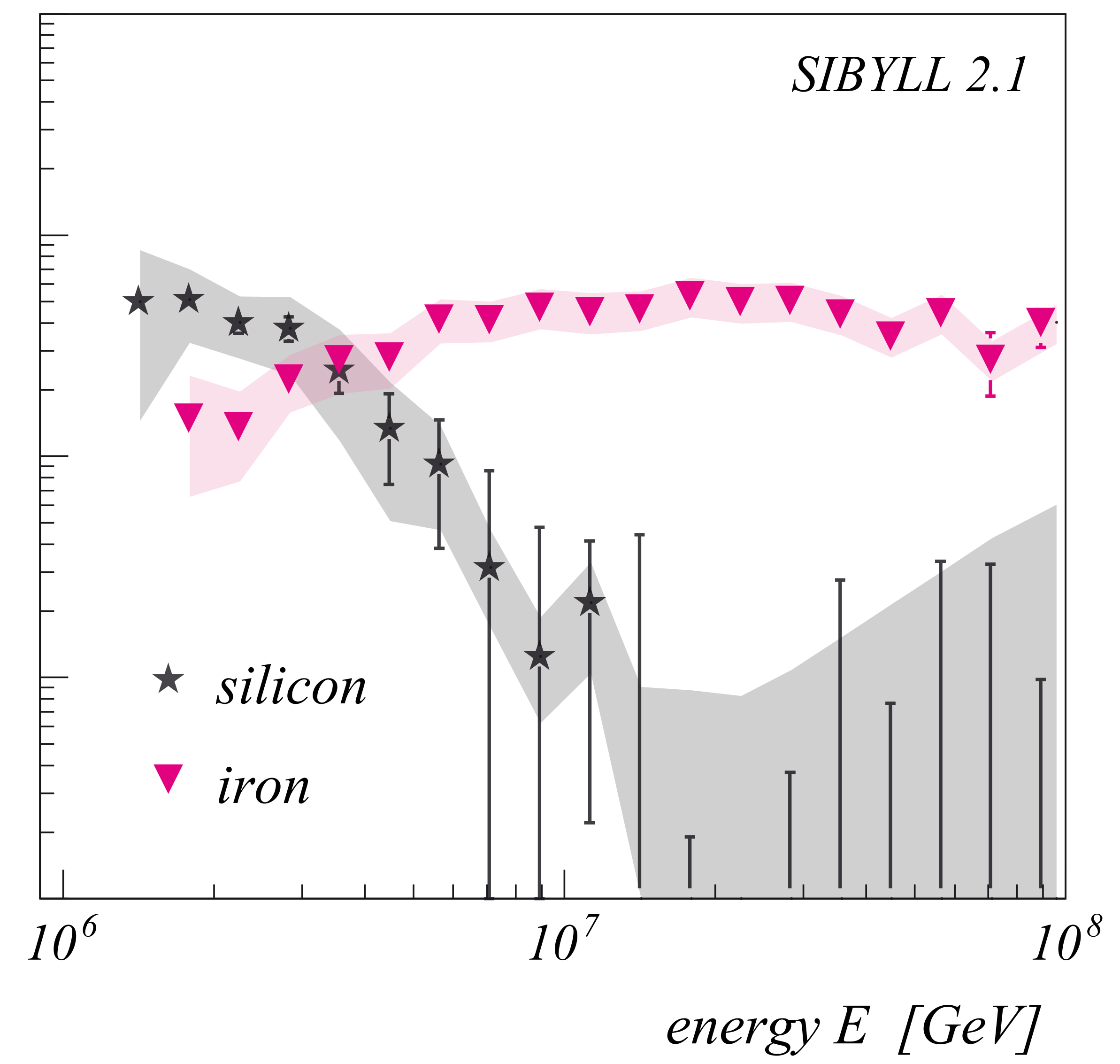
Mass composition at the knee: KASCADE data



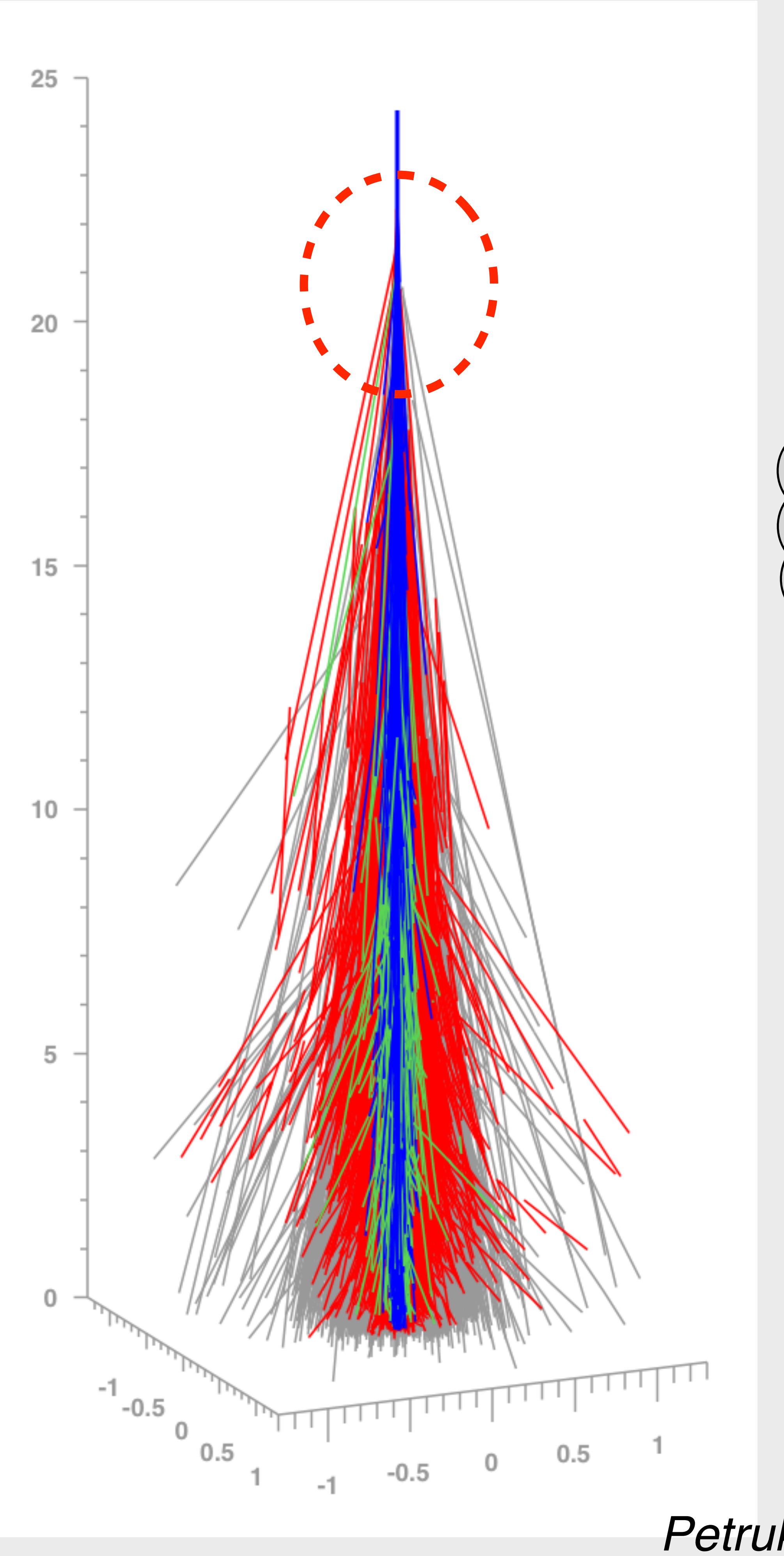


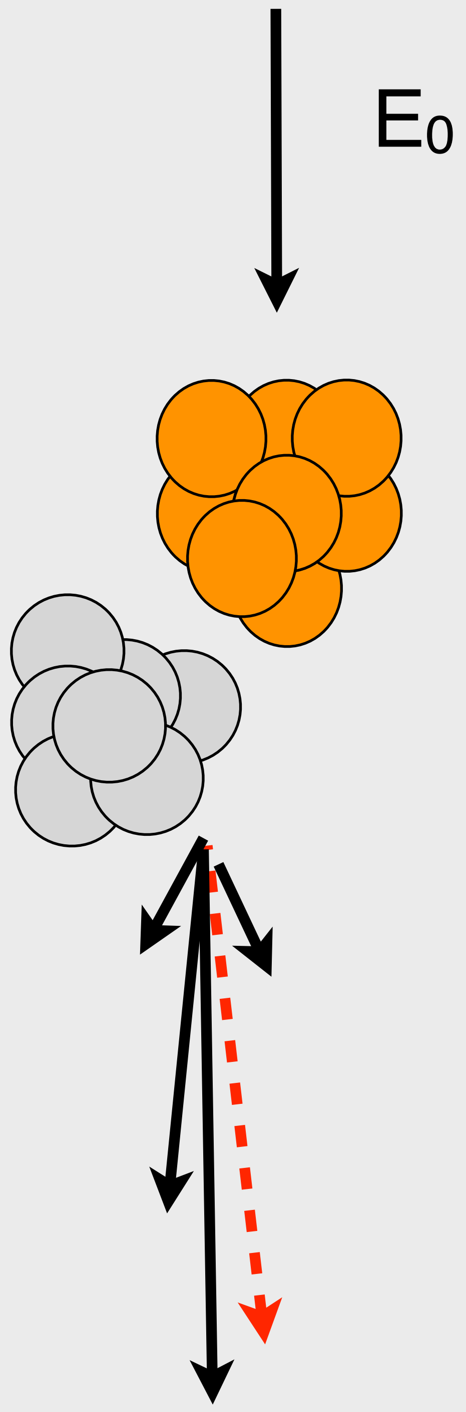






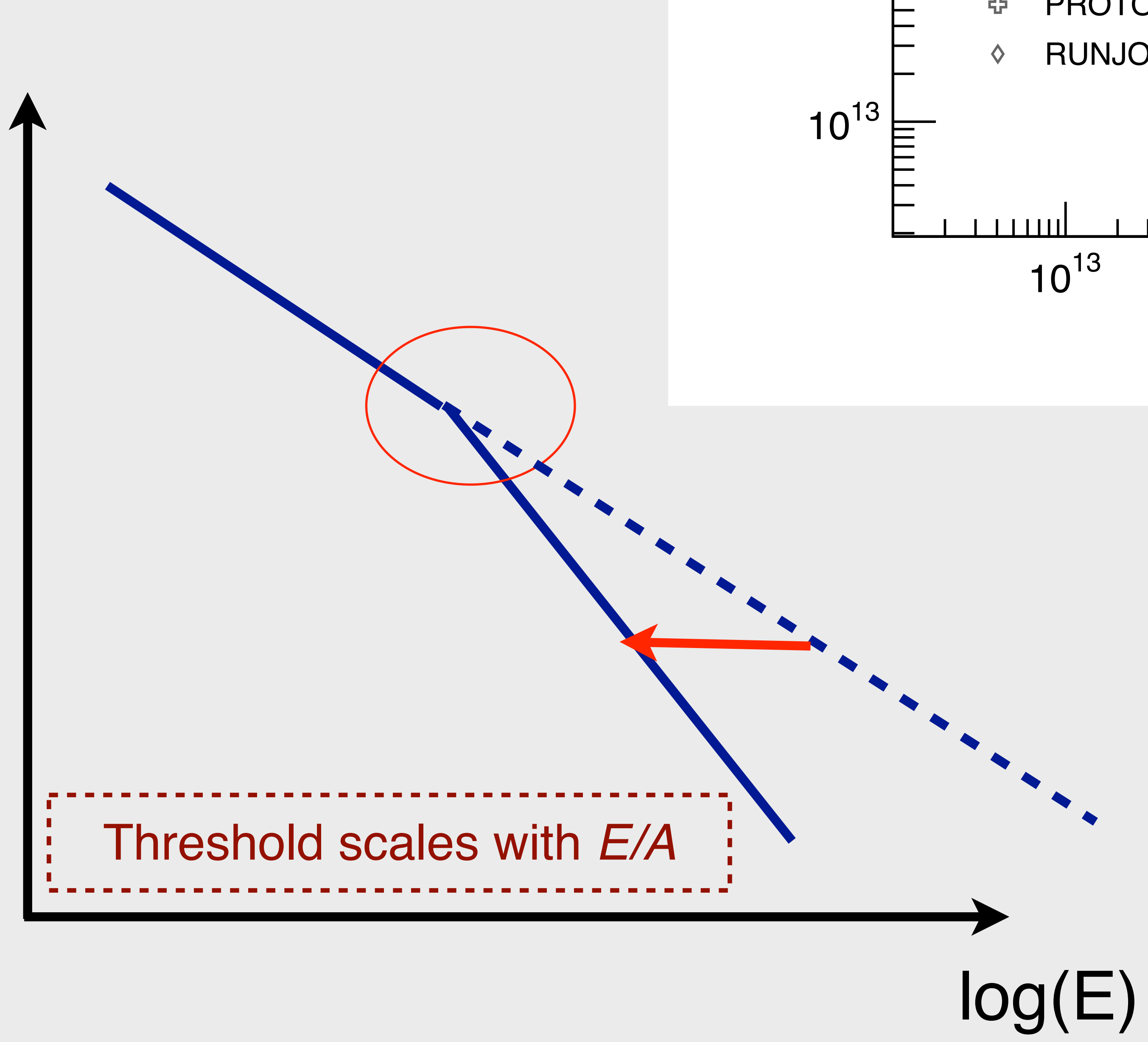
LHC data and interpretation of knee



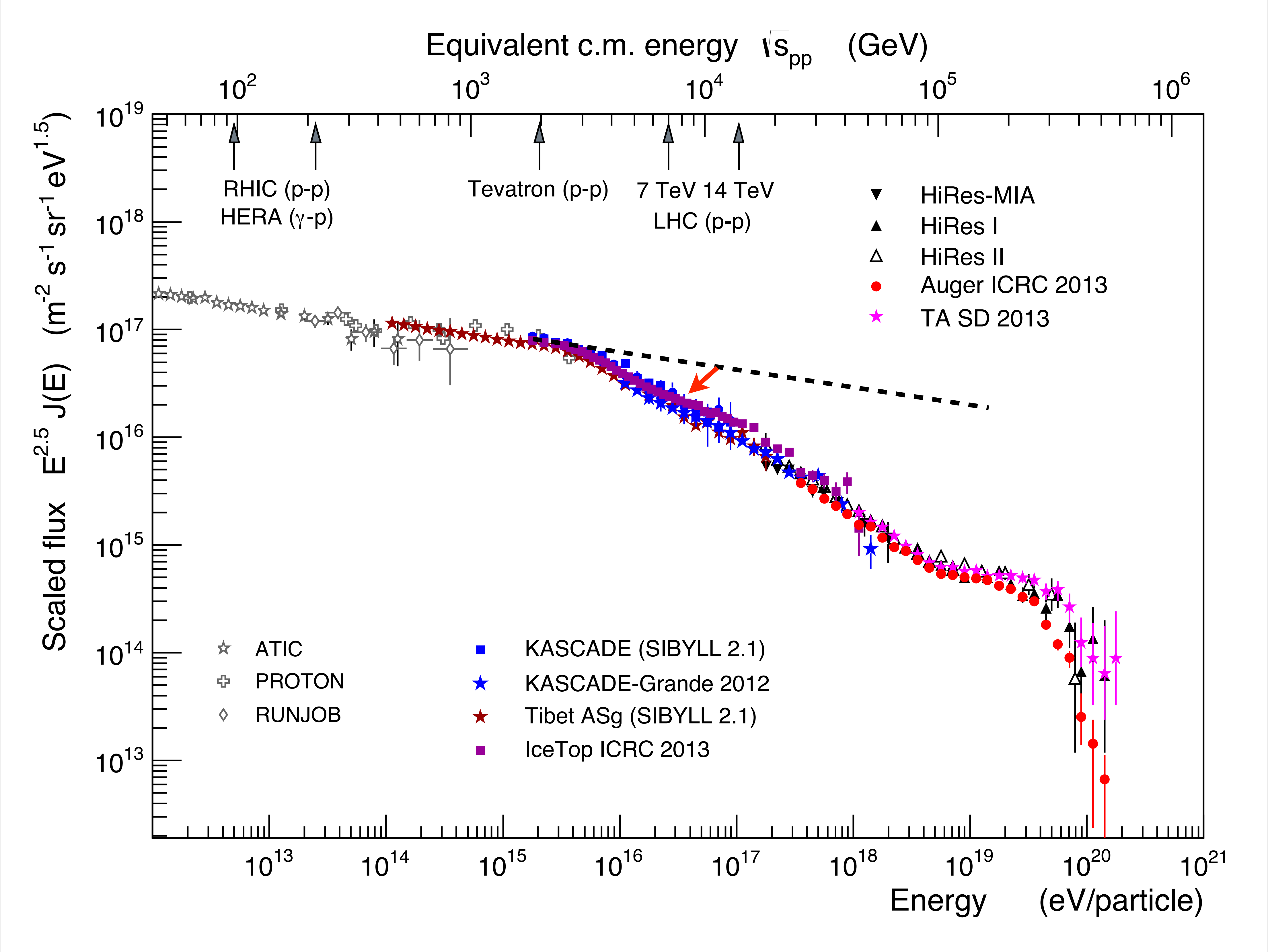


Knee due to wrong energy reconstruction of showers?

E_X ~100 TeV



Petrukhin, NPB 151 (2006) 57
Barcelo at al. JACP 06 (2009) 027
Dixit et al. EPJC 68 (2010) 573
Petrukhin NPB 212 (2011) 235

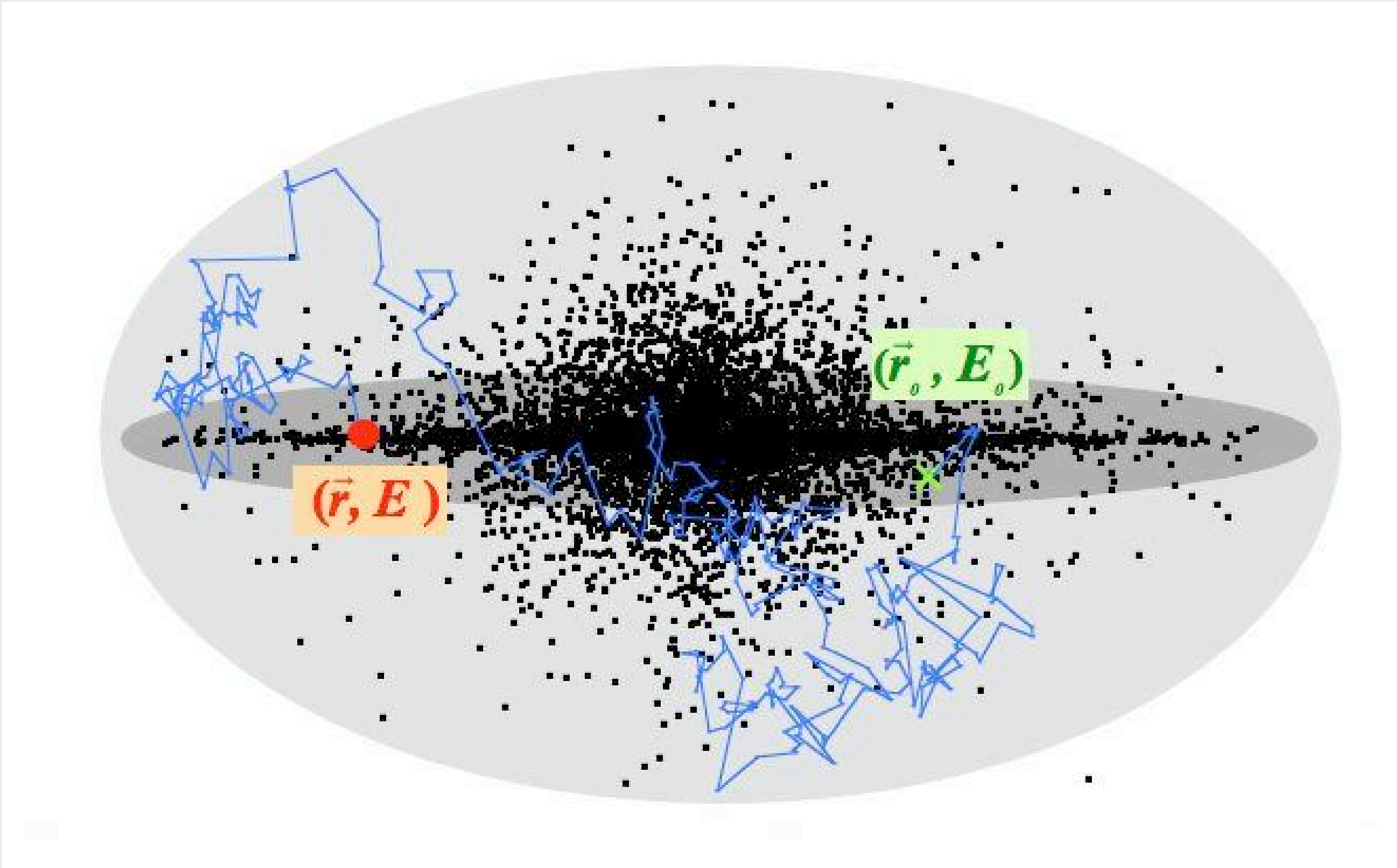


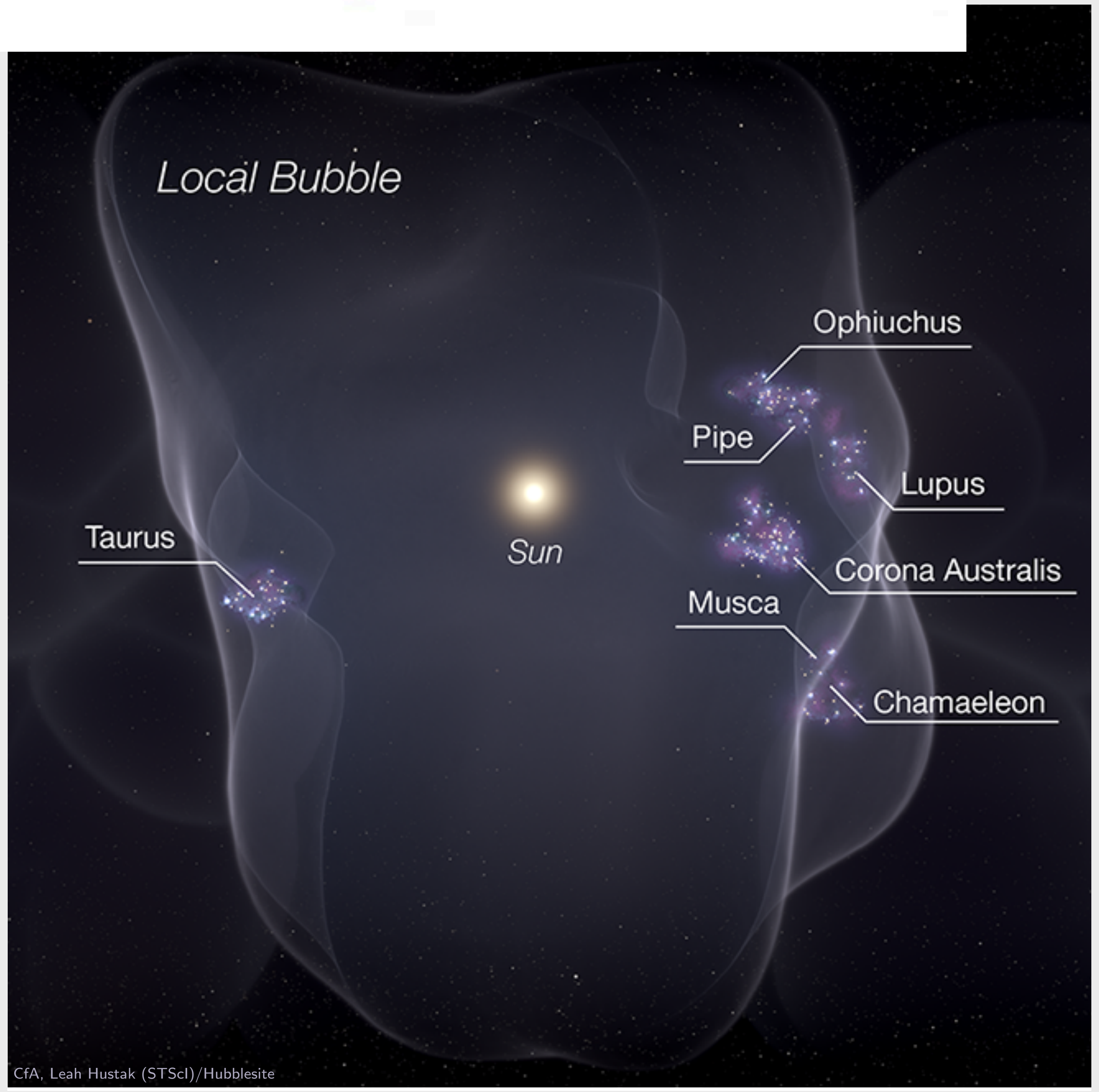
~50% of energy needs to be transferred to invisible channel

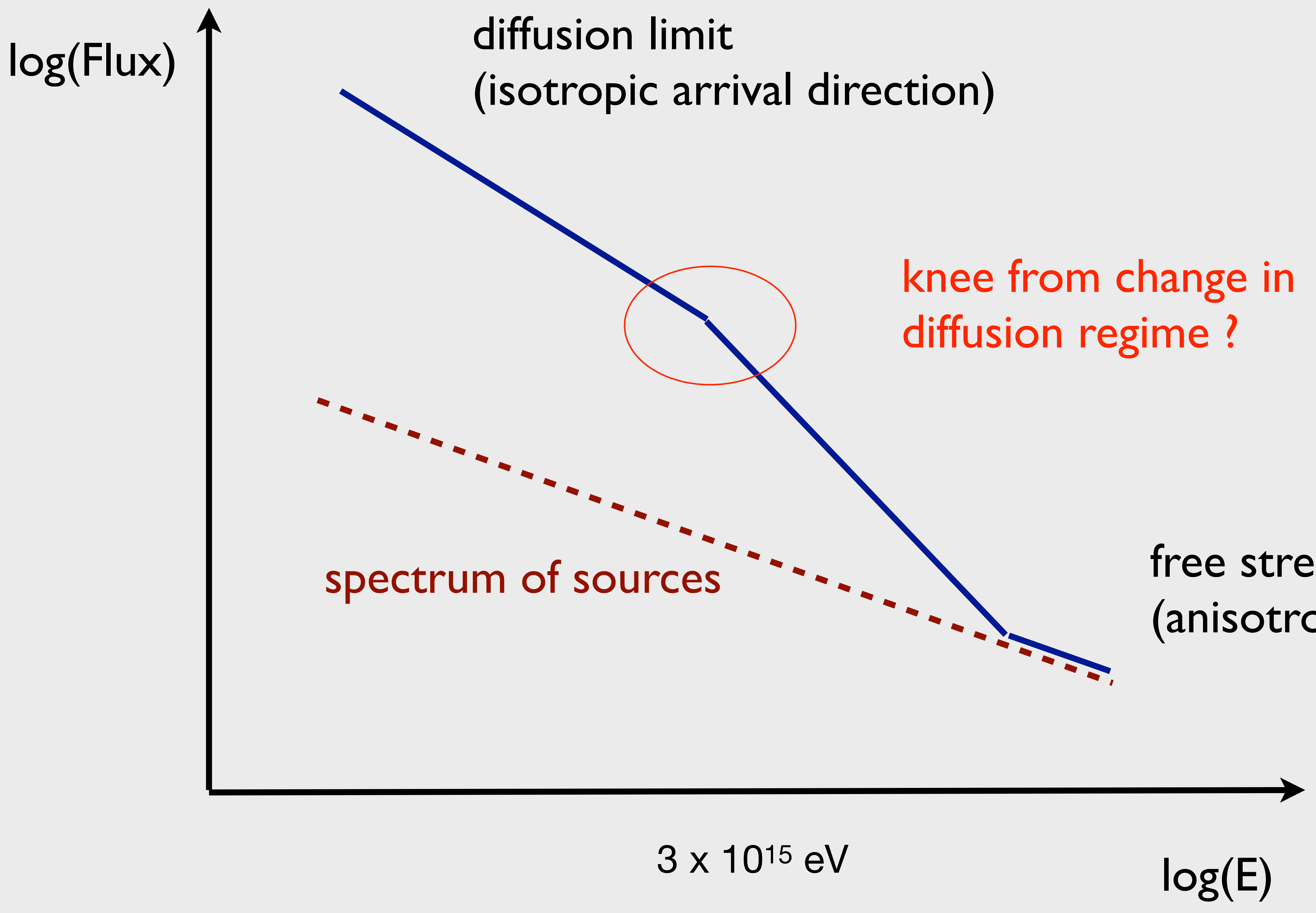
No indications for missing energy processes at LHC

(d'Enterria et al., Astropart. Phys. 35, 2011)

Knee due to diffusion / escape from Glaxy





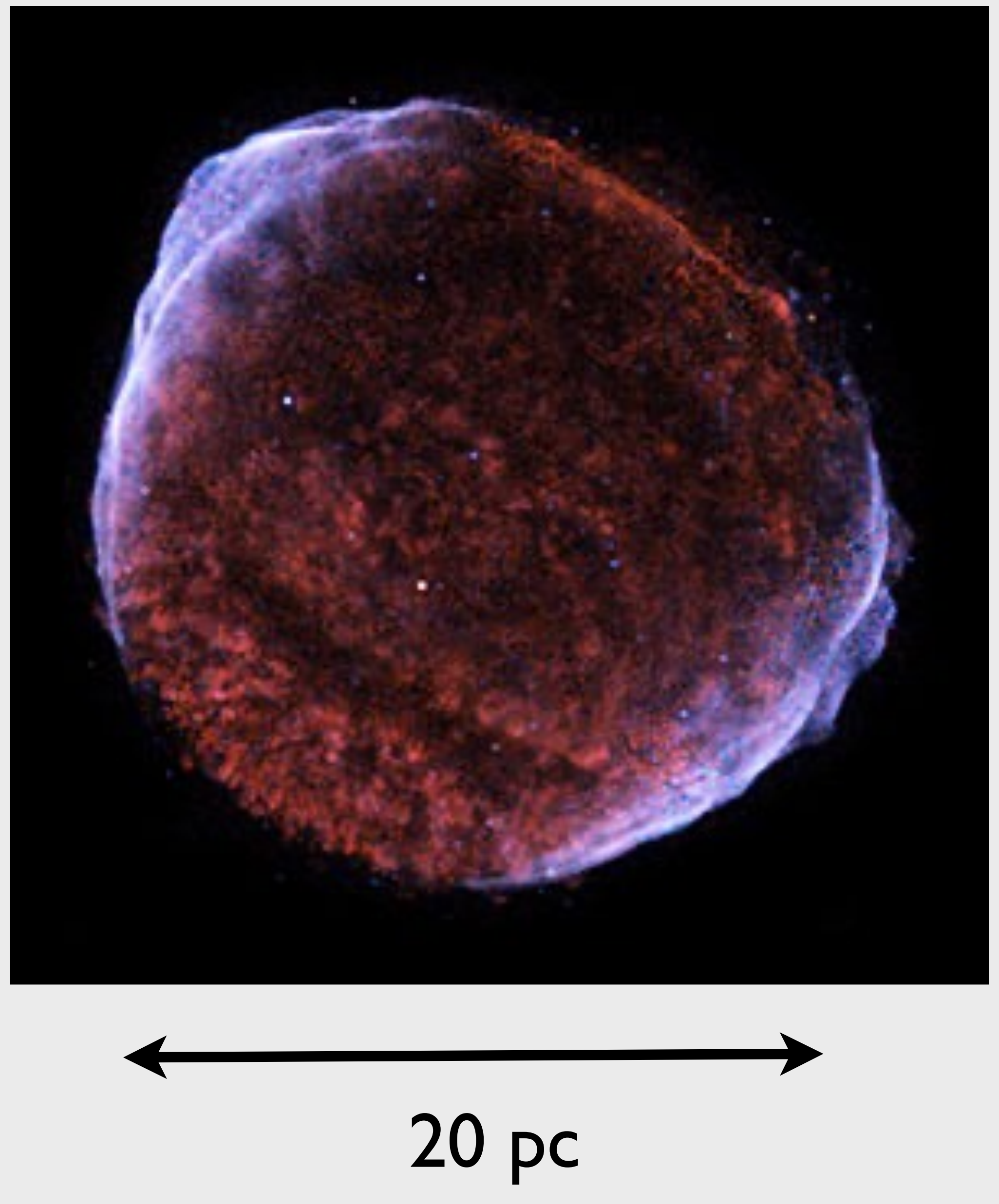


Diffusion: same behaviour for different elements at same rigidity $p/Z \sim E/Z$

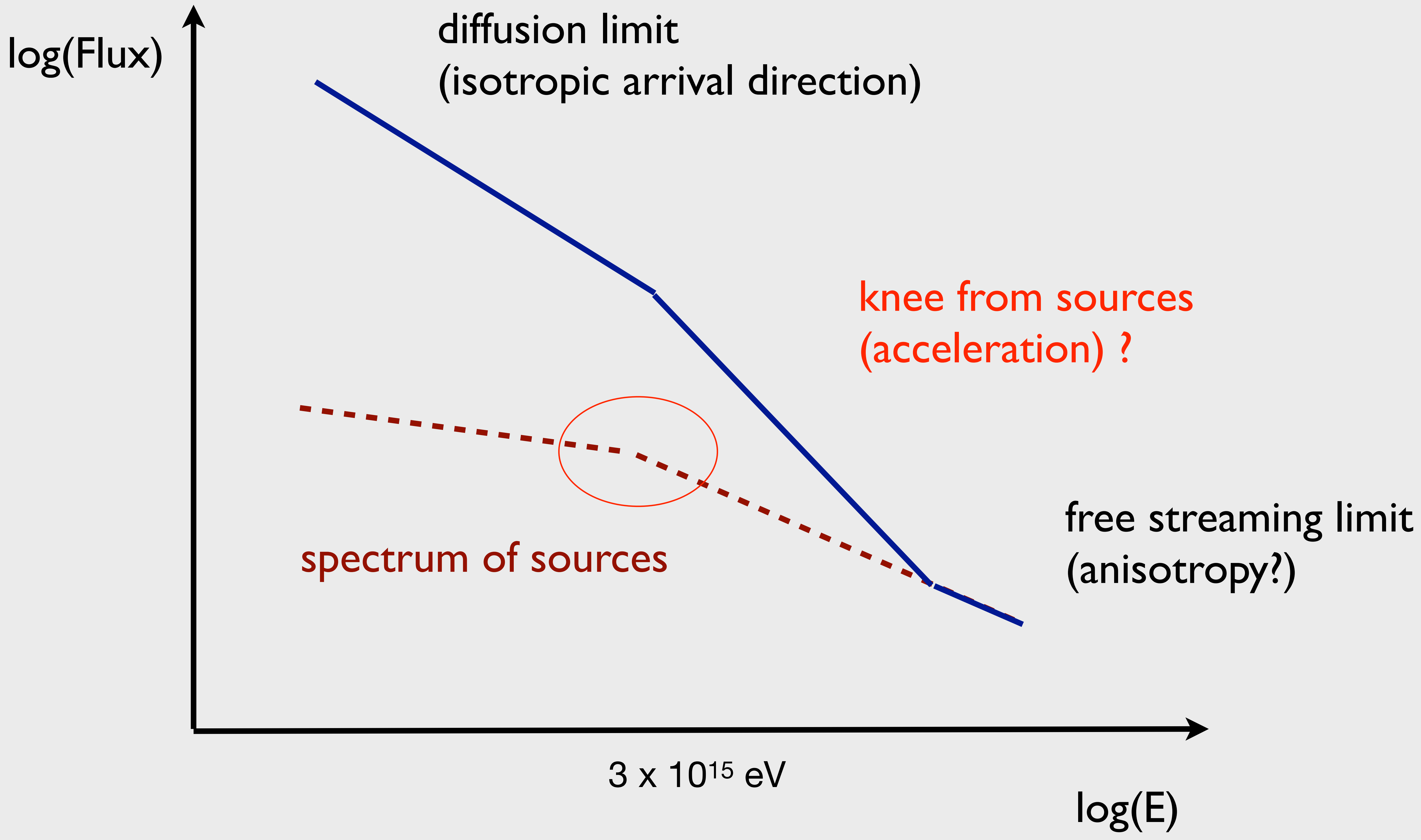
Knee due to features of acceleration processes

SN remnant 1006

Distance ~ 2.2 kpc



8000 km/s

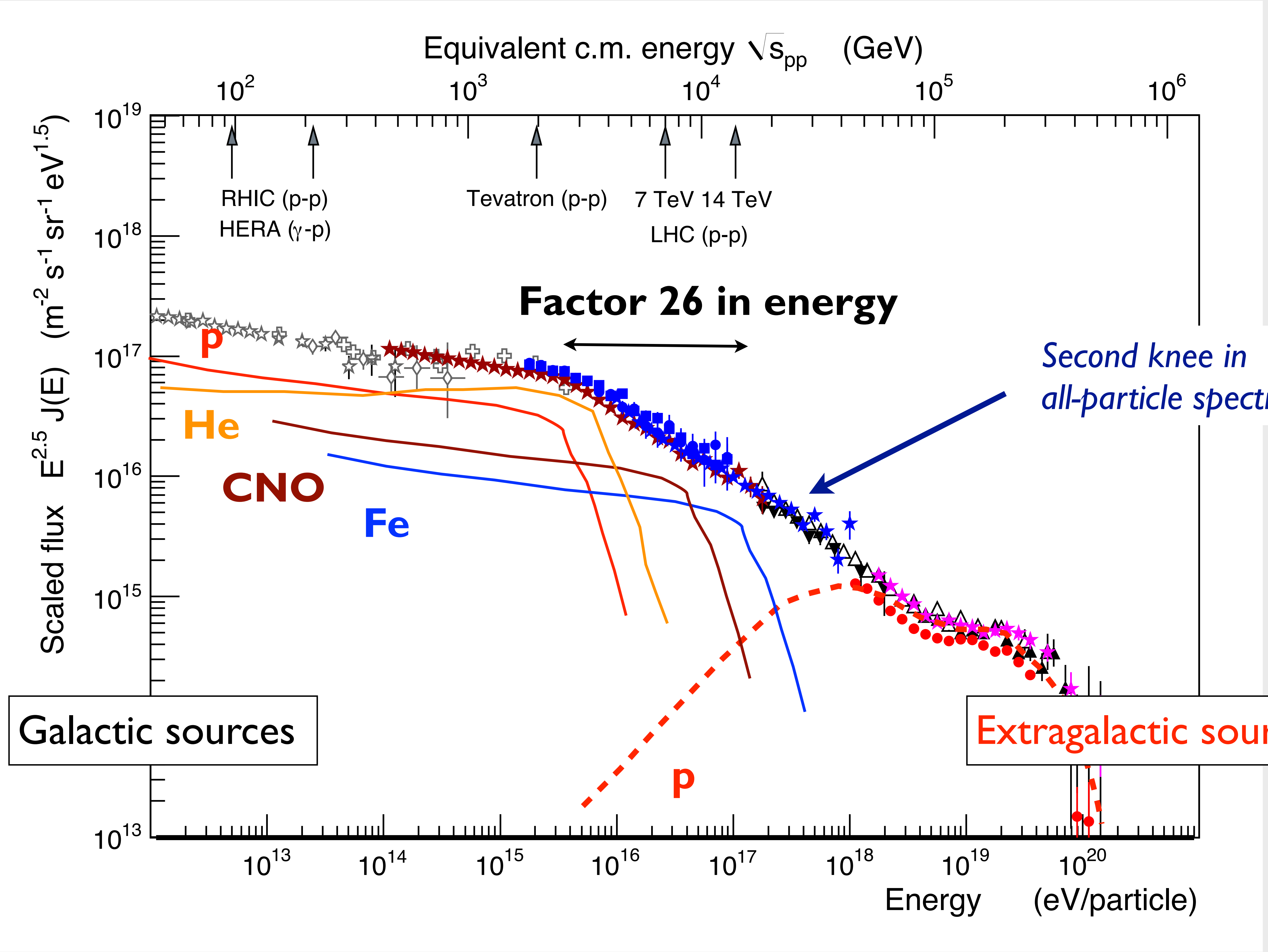


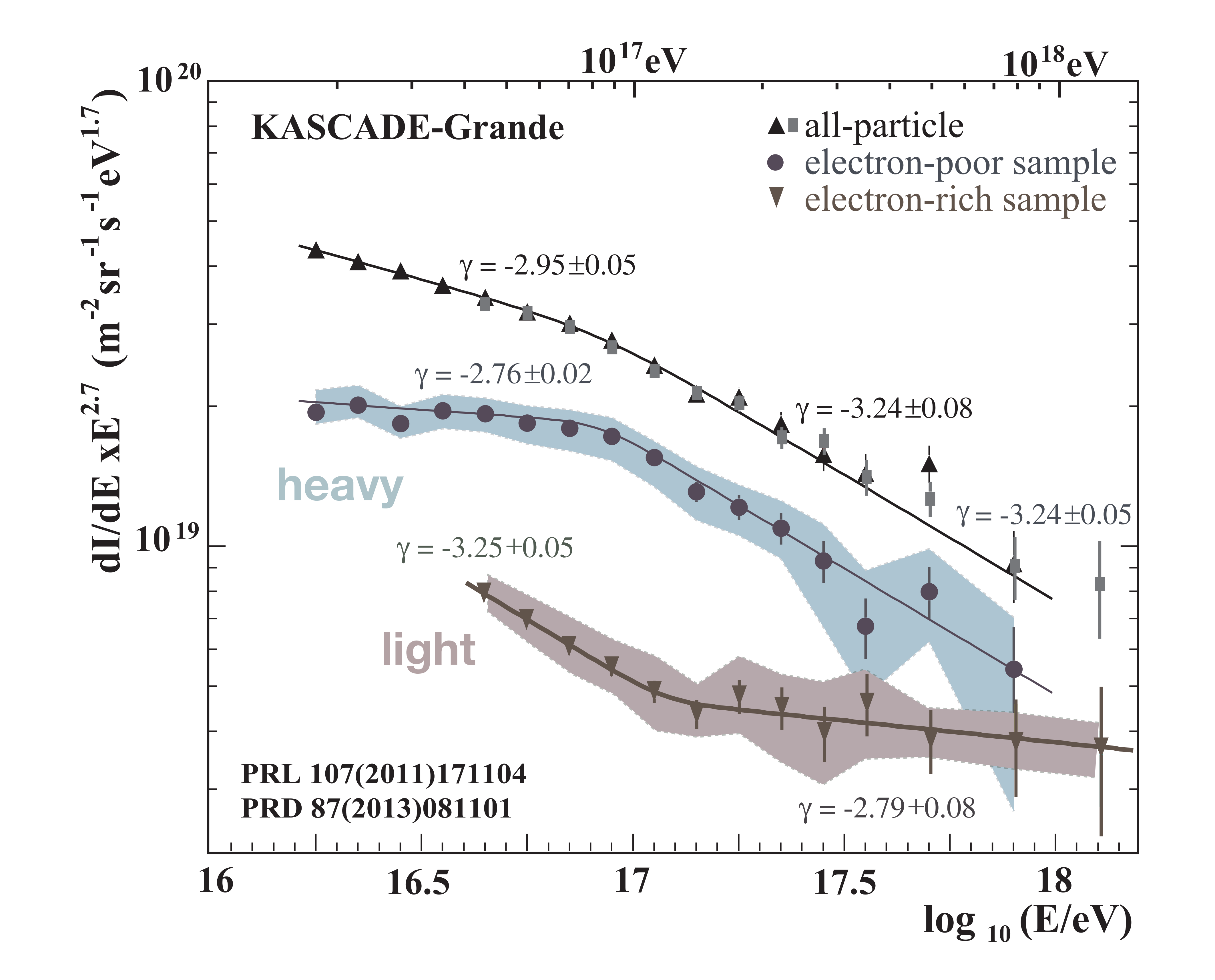
$$E_{p,\max} = 3 \times 10^{12} Z \left(\frac{B}{\mu\mathrm{G}}\right) \left(\frac{u}{1000\,\mathrm{km/s}}\right) \left(\frac{L}{\mathrm{pc}}\right) \mathrm{eV}$$

Acceleration: same behavior for different elements at same rigidity *p*/*Z* ~ *E*/*Z*

Emerging model of high-energy cosmic rays

- **Knee as feature of either maximum particle energy of a source class or propagation**
- Dominance of helium flux observed (and expected from low-energy extrapolation), but not understood
- Acceleration scenario: sources don't reach energy of transition to free steaming
- Diffusion scenario: mass groups should show ~20% anisotropy beyond the knee





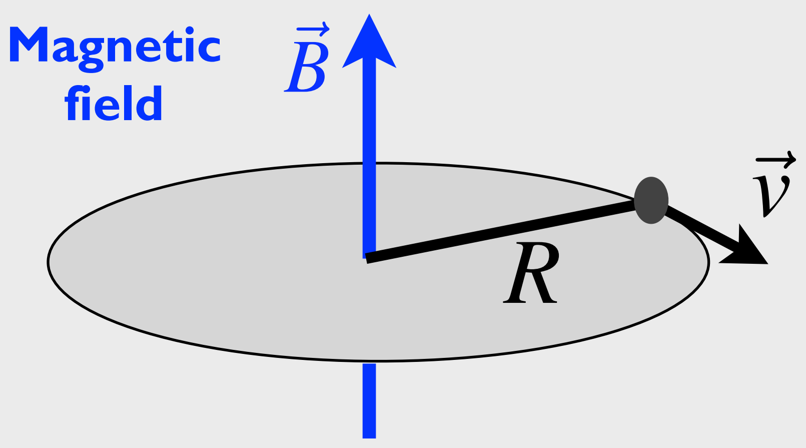
Knee of heavy particles found

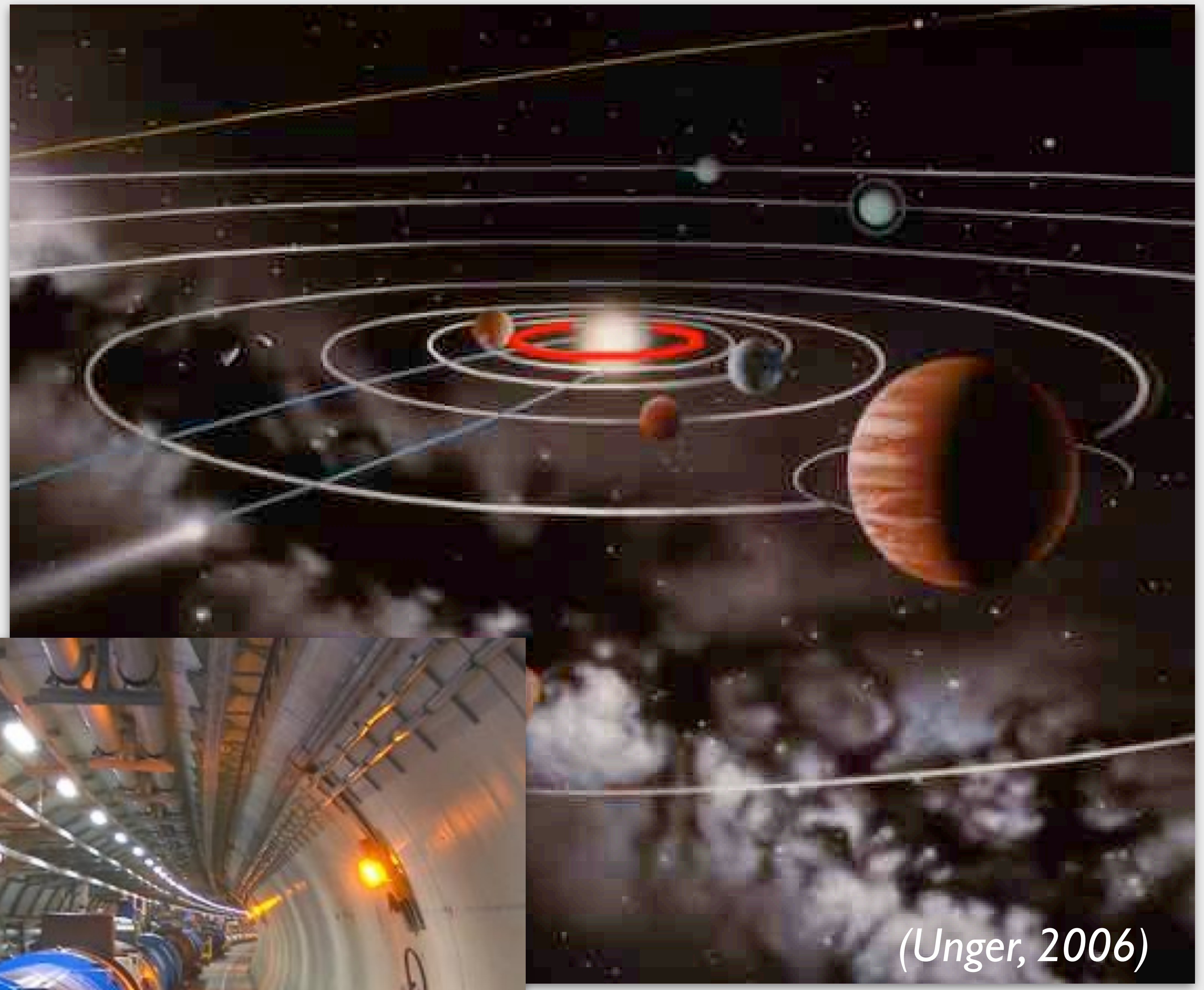
New light (proton, extragalactic?) component

Physics of extragalactic cosmic rays

Sources have to produce particles reaching 10^{20} eV

Particle on circular orbit

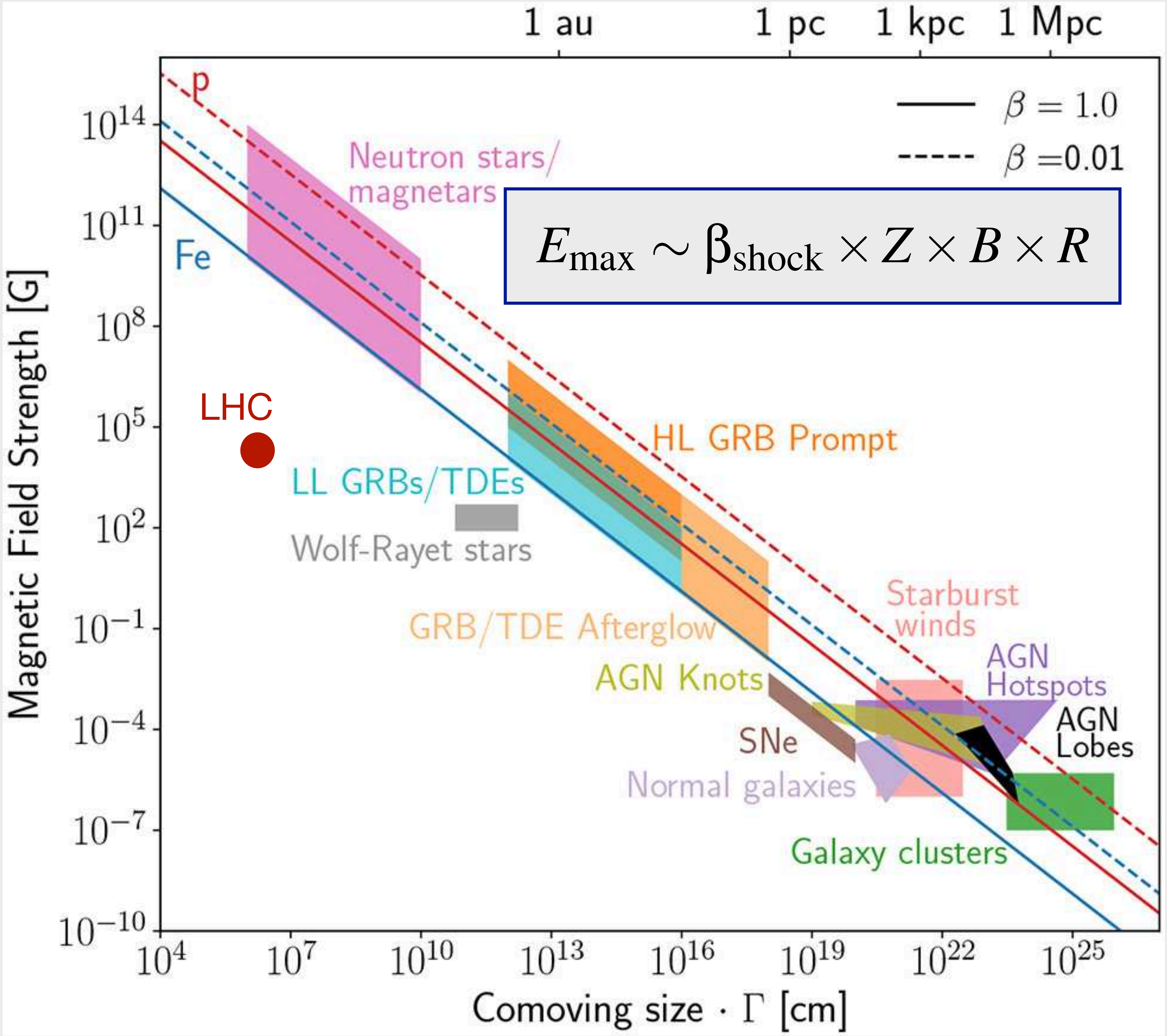




Need accelerator of size of the orbit of the planet Mercury to reach 10^{20} eV with LHC technology

Hillas plot (1984)

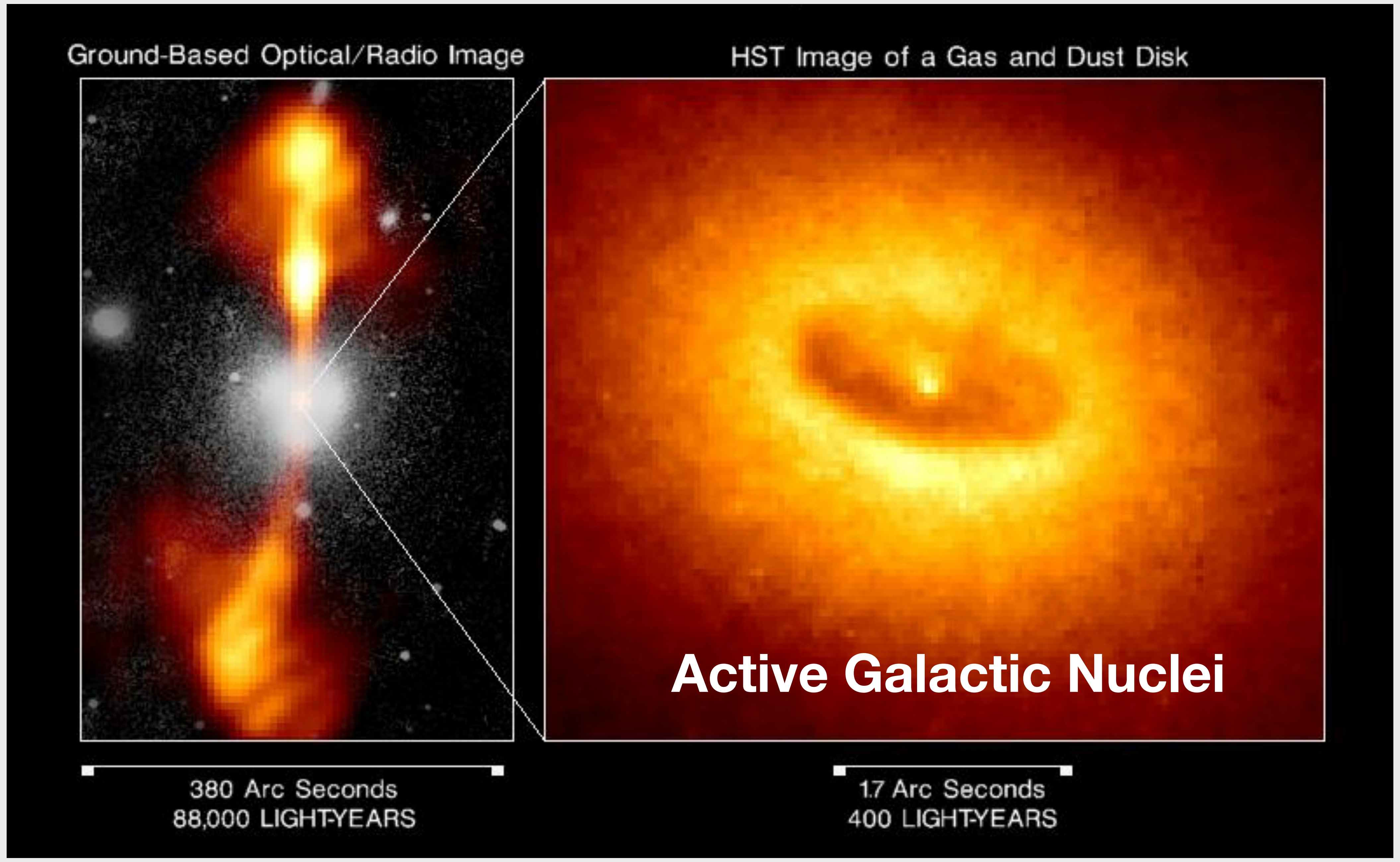
(MIAPP review, Front.Astron.Space Sci. 6 (2019) 23)

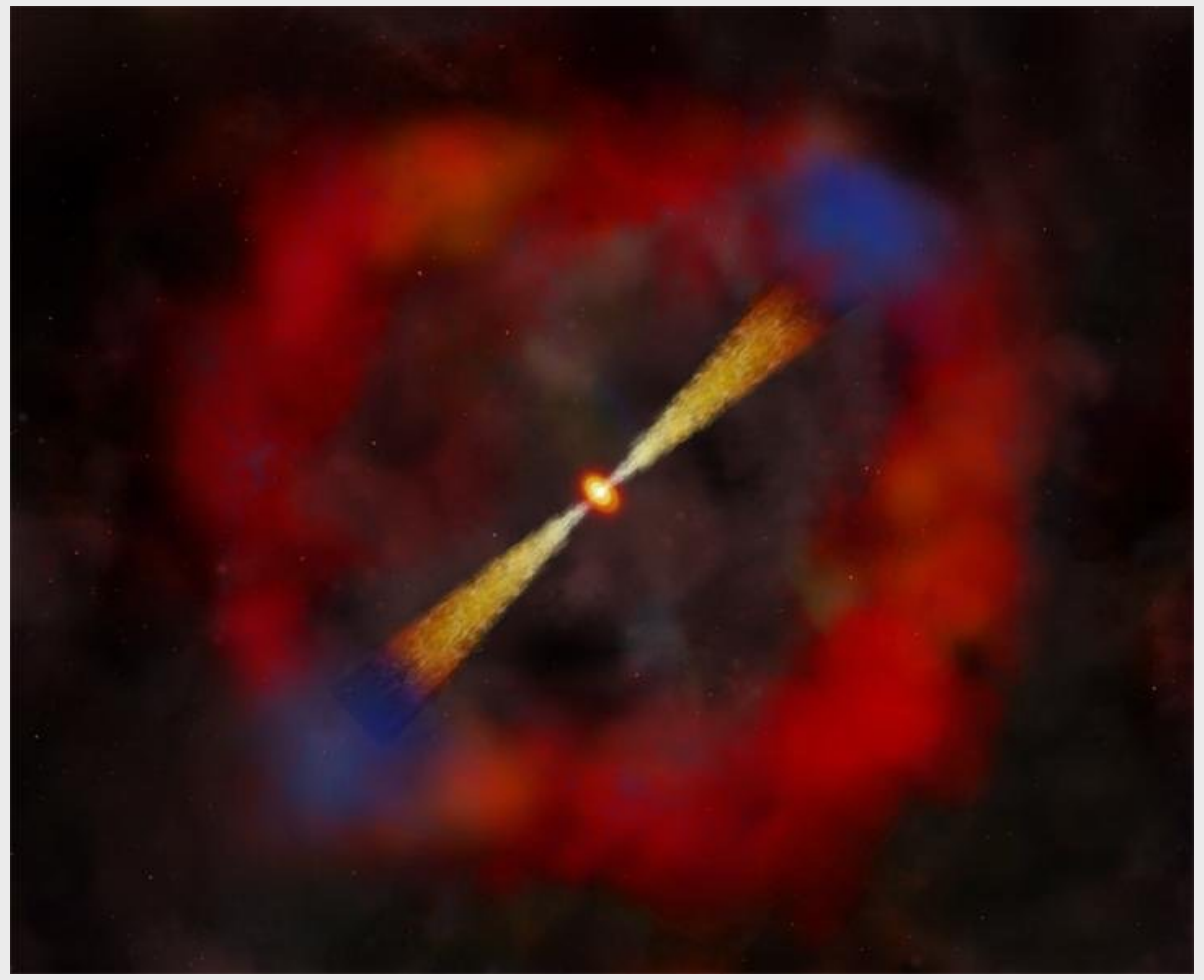


Hardly any source expected to accelerate protons to 10^{20} eV

Examples of astrophysical source candidates

Diffusive shock acceleration

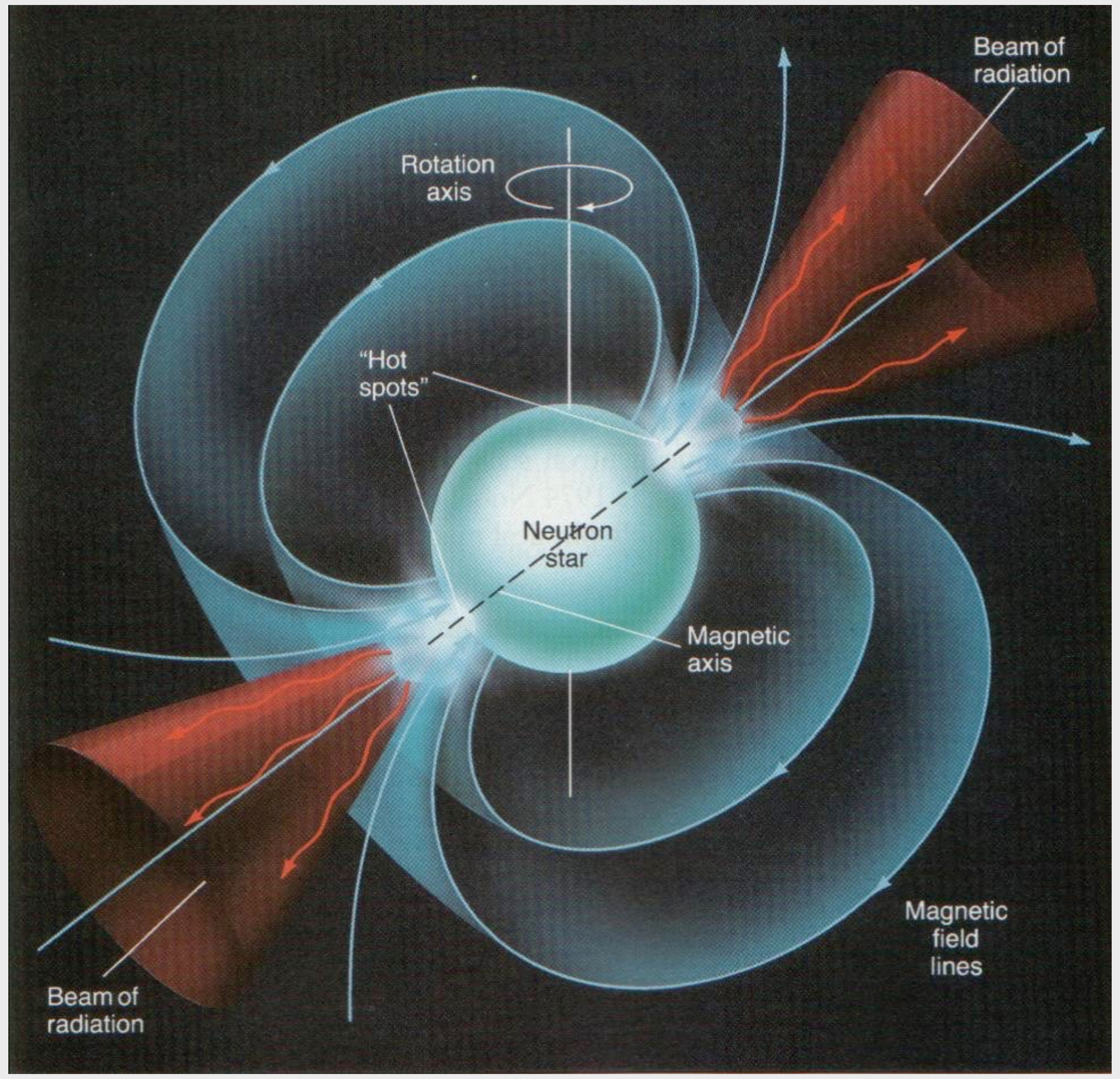




$$\frac{\mathrm{d}N_{\mathrm{inj}}}{\mathrm{d}E} \sim E^{-2}$$

Gamma ray bursts (GRBs)

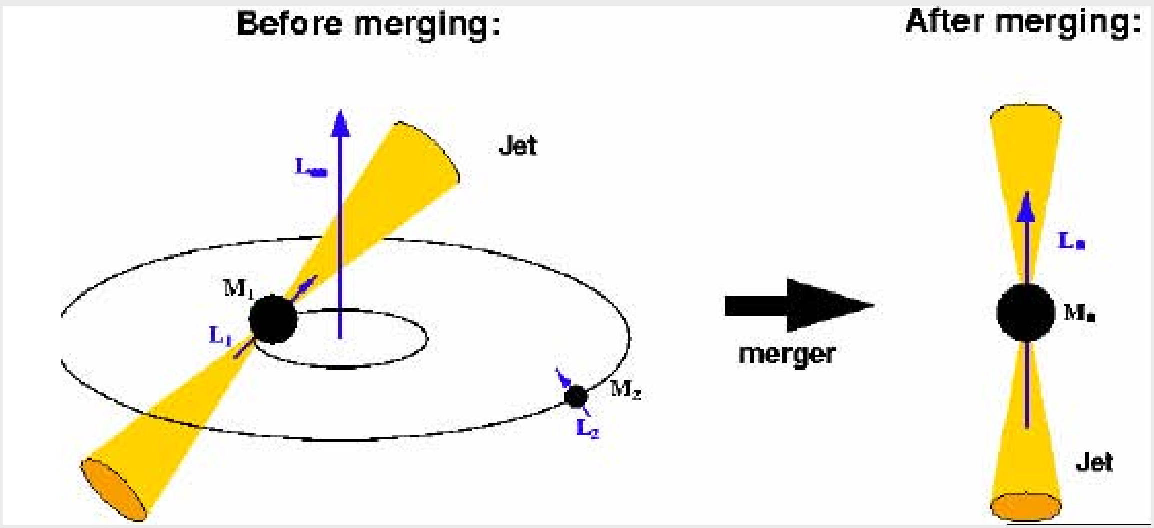
Inductive acceleration

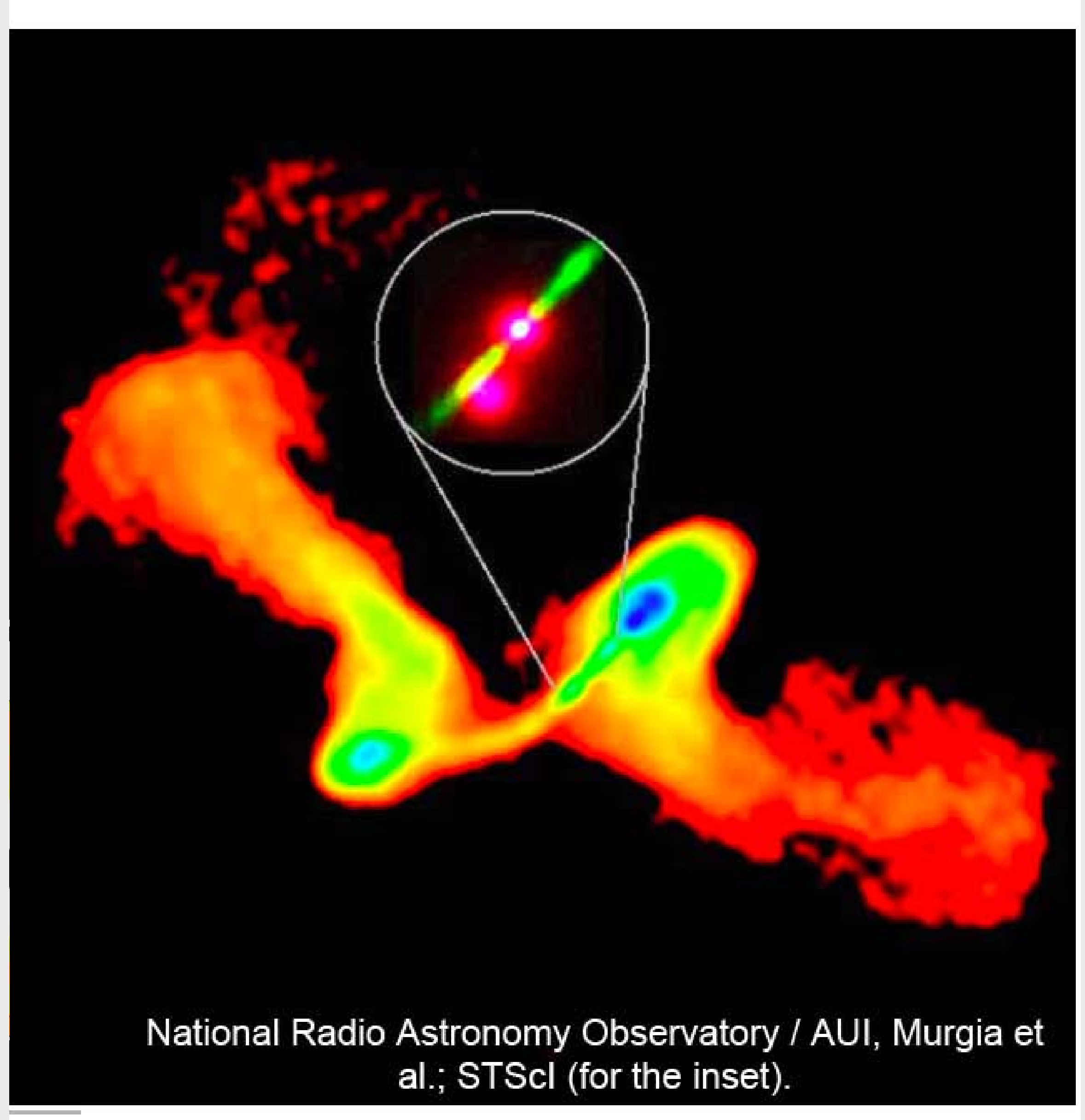


Rapidly spinning neutron stars

$$\frac{\mathrm{d}N_{\mathrm{inj}}}{\mathrm{d}E} \sim E^{-1}\left(1+\frac{E}{E_g}\right)^{-1}$$

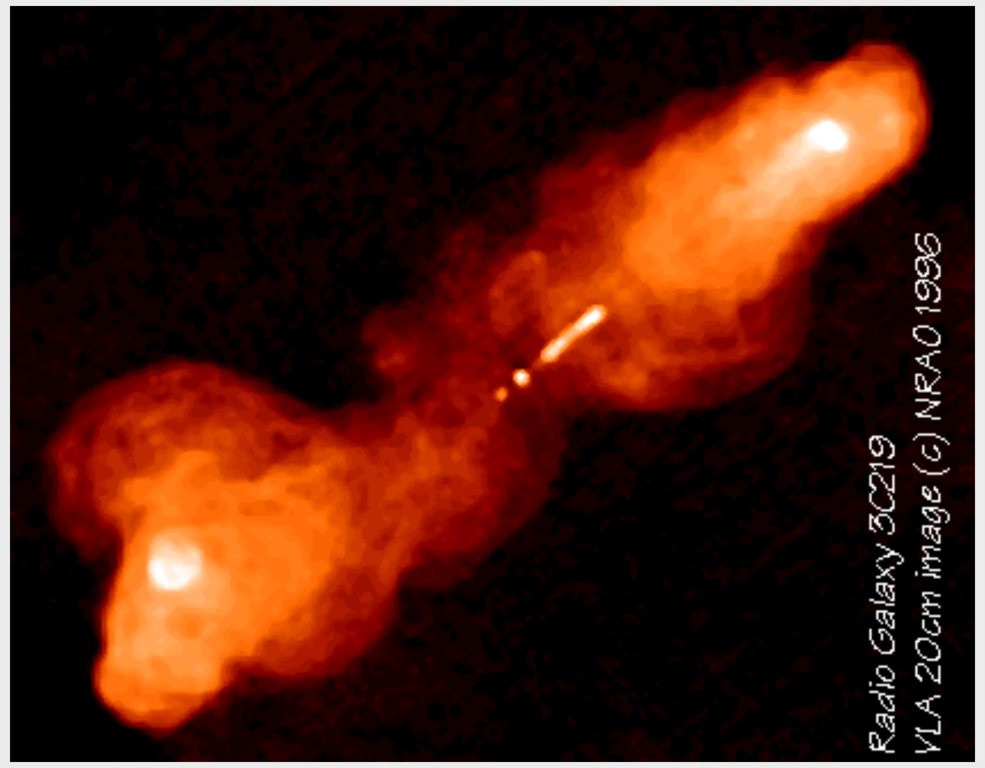
Single (relativistic) reflection





Tidal disruption events (TDEs)

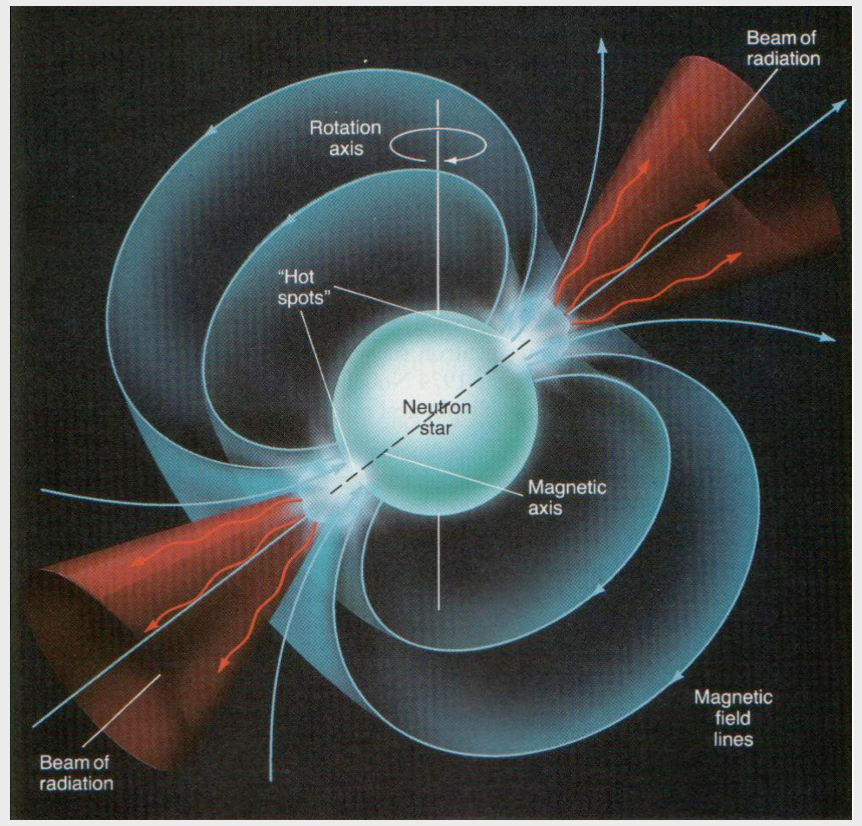
Acceleration (bottom-up) or exotic (top-down) scenarios?



Active Galactic Nuclei (AGN):
Black Hole of ~10^9 solar masses

	Process	Distribution	Injection flux
AGNs, GRBs, … (☆)	Diffuse shock acceleration	Cosmological	p … Fe
Young pulsars (☆☆)	EM acceleration	Galaxy & halo	mainly Fe
X particles (☆☆☆)	Decay & particle cascade	(a) Halo (SHDM) (b) Cosmological	ν, γ-rays and p
Z-bursts (☆☆☆☆)	Z^0 decay & particle cascade	Cosmological & clusters	ν, γ-rays and p

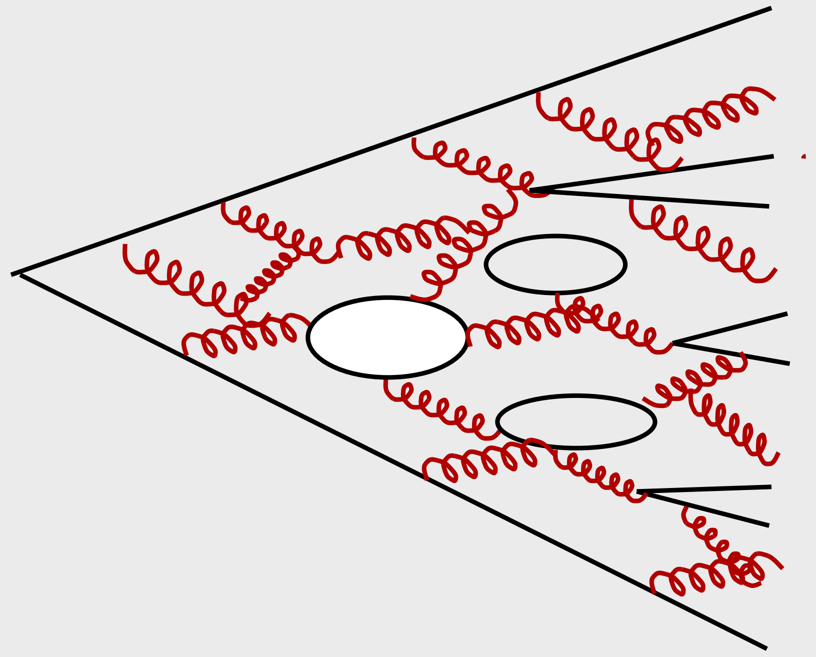
Magnetars:
magnetic field
up to ~10^{15} G



X particles from:

- topological defects
- monopoles
- cosmic strings
- cosmic necklaces
- .....

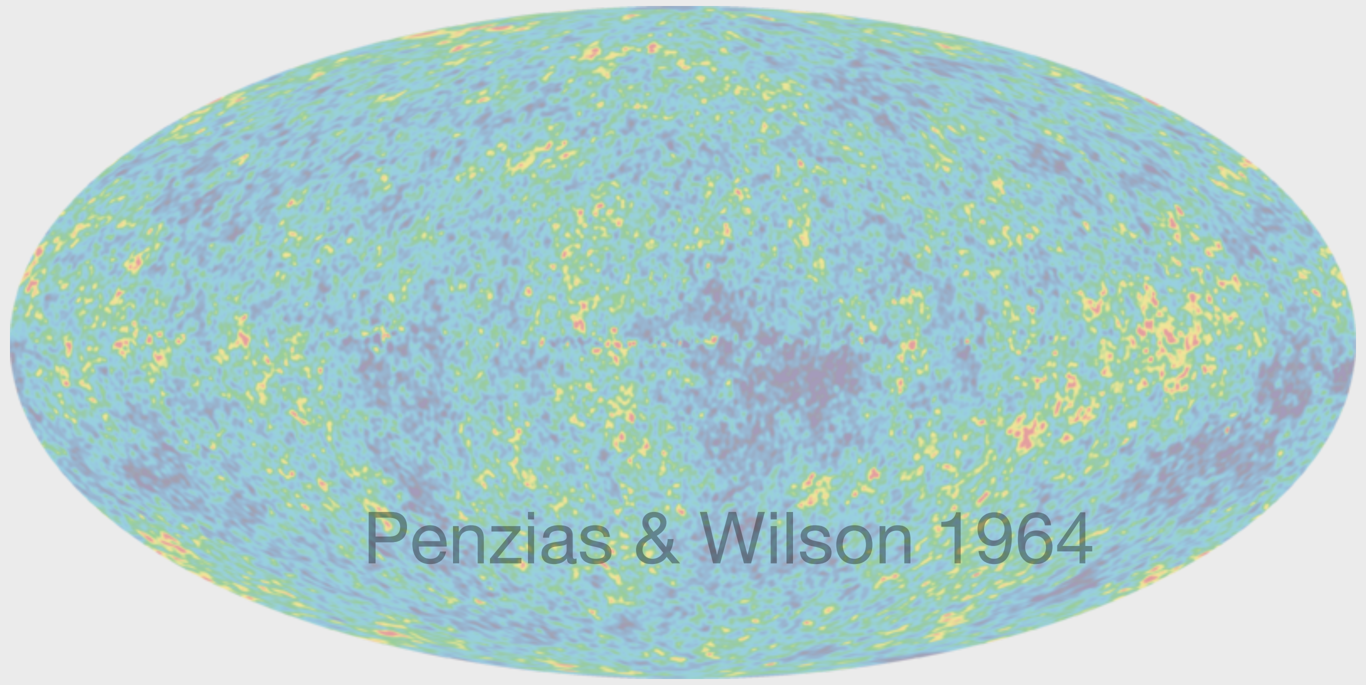
Big Bang:
super-heavy particles,
topological defects:
M_X ~ 10^{23} - 10^{24} eV



large fluxes of photons and neutrinos

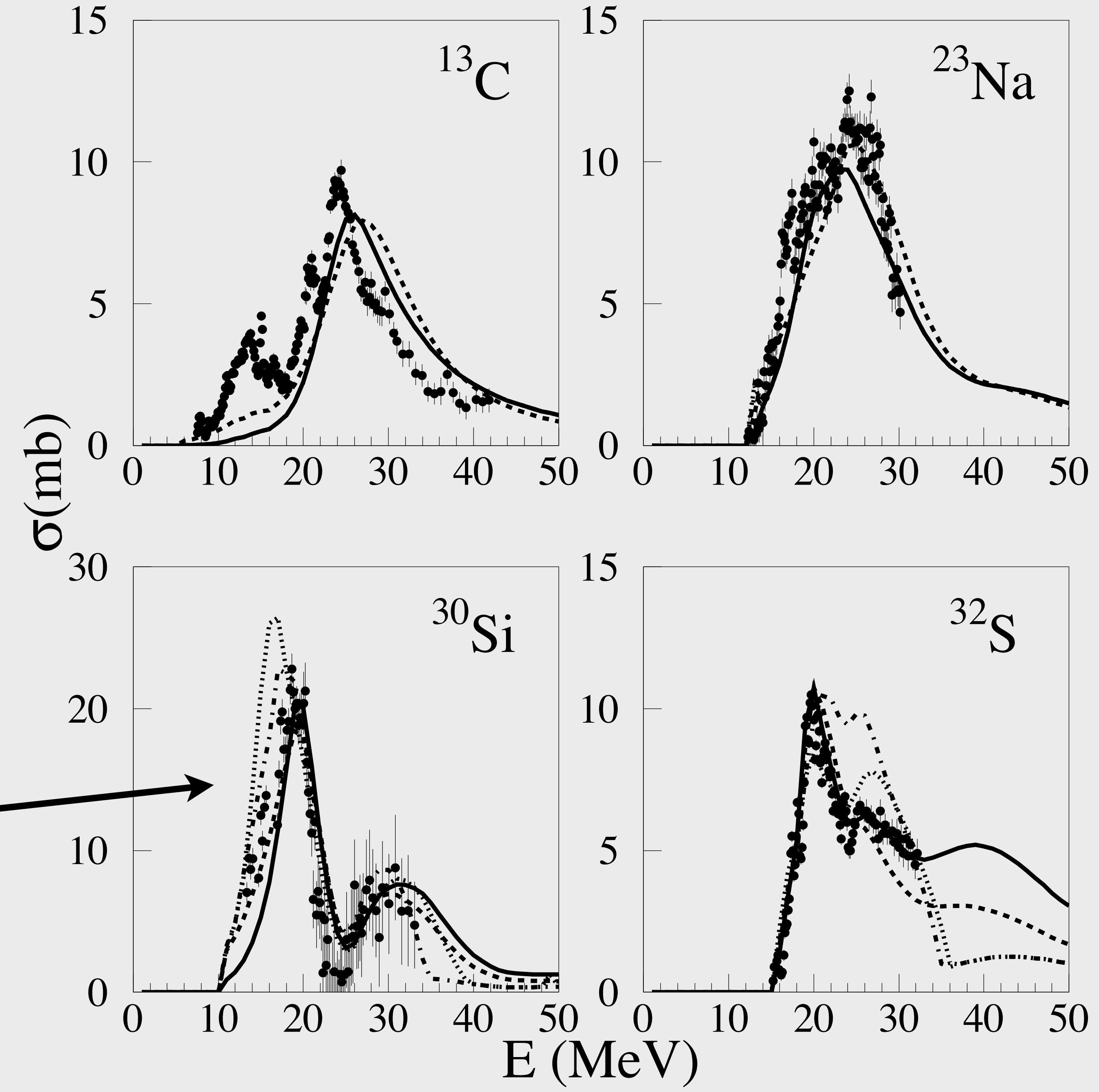
(RE, Nijmegen Summer School, 2006)

Propagation of ultra-high energy particles



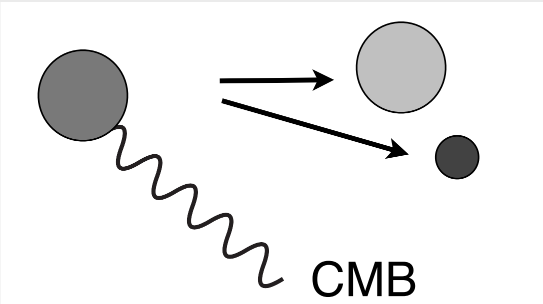
Greisen, Zatsepin & Kuzmin (GZK) effect, 1966

$\gamma A \rightarrow X$



Giant dipole resonance

Protons →

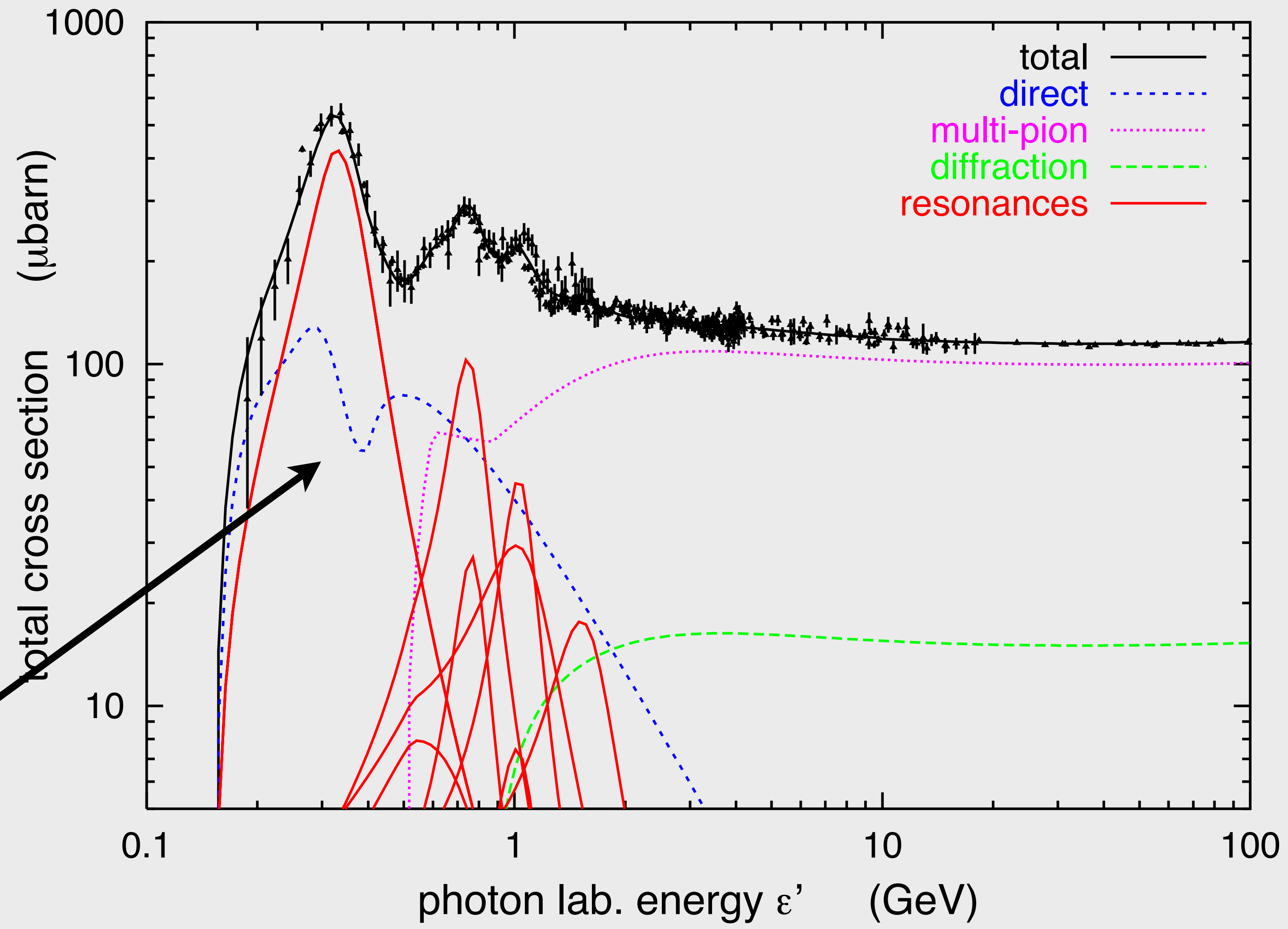


$n \quad p$

$\pi^{+} \quad \pi^{0}$

Photo-pion production
(mainly Δ resonance)

$\gamma p \rightarrow X$



Delta resonance
(m=1.232 GeV)

Nuclei →

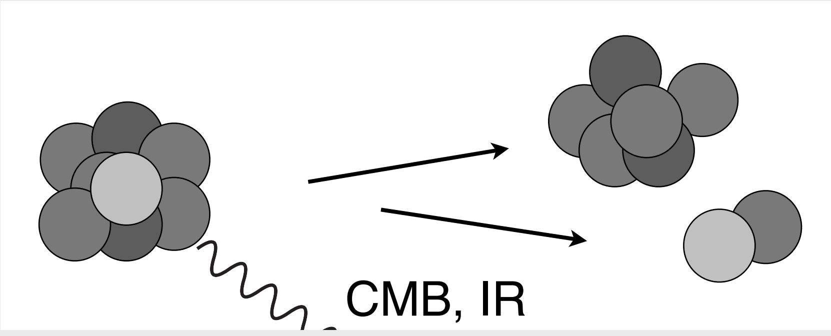


Photo-dissociation
(giant dipole resonance)

Energy loss due to propagation in CMB

Proton

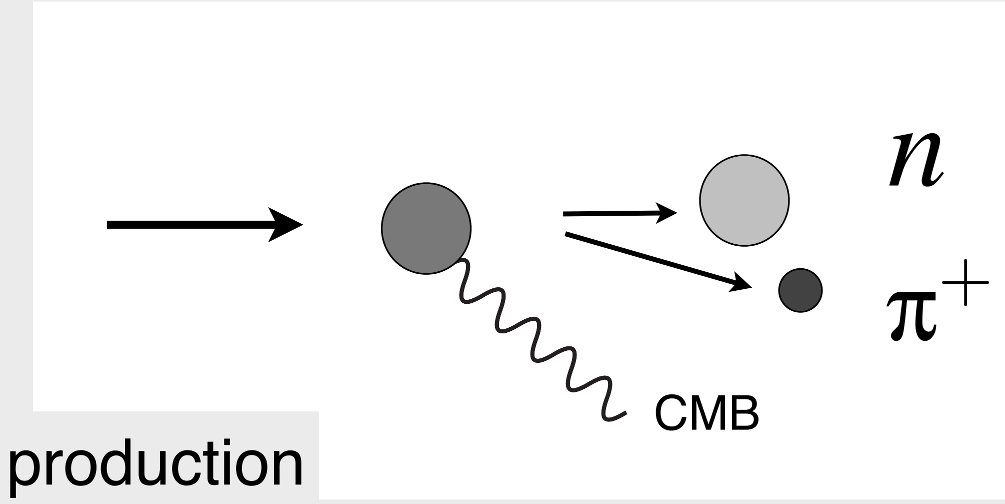


Photo-pion production
(mainly Δ resonance)

Nuclei

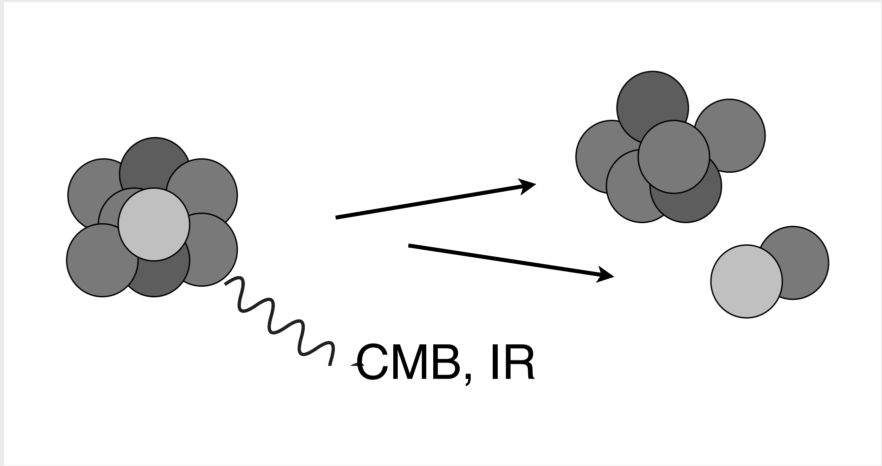
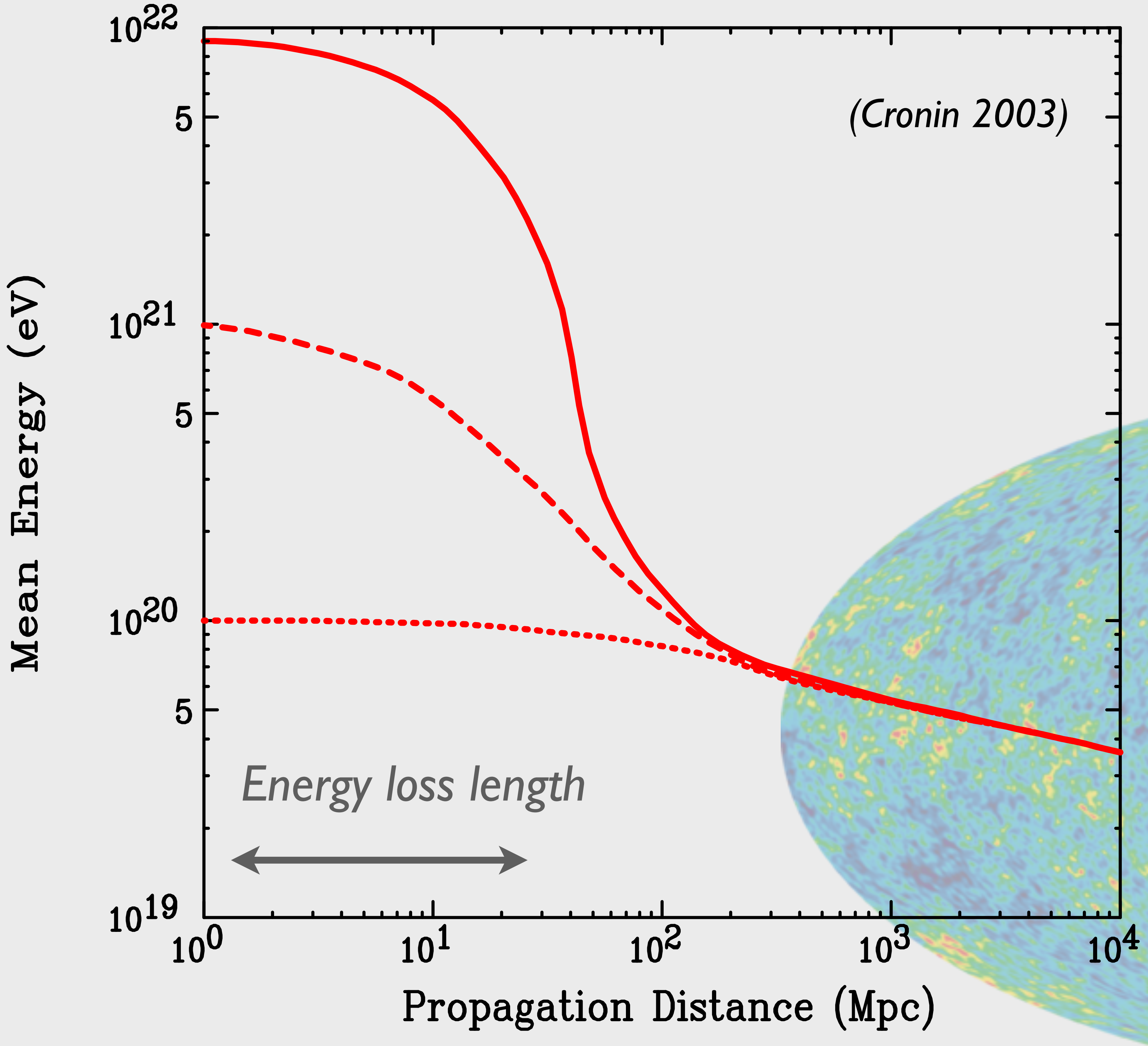
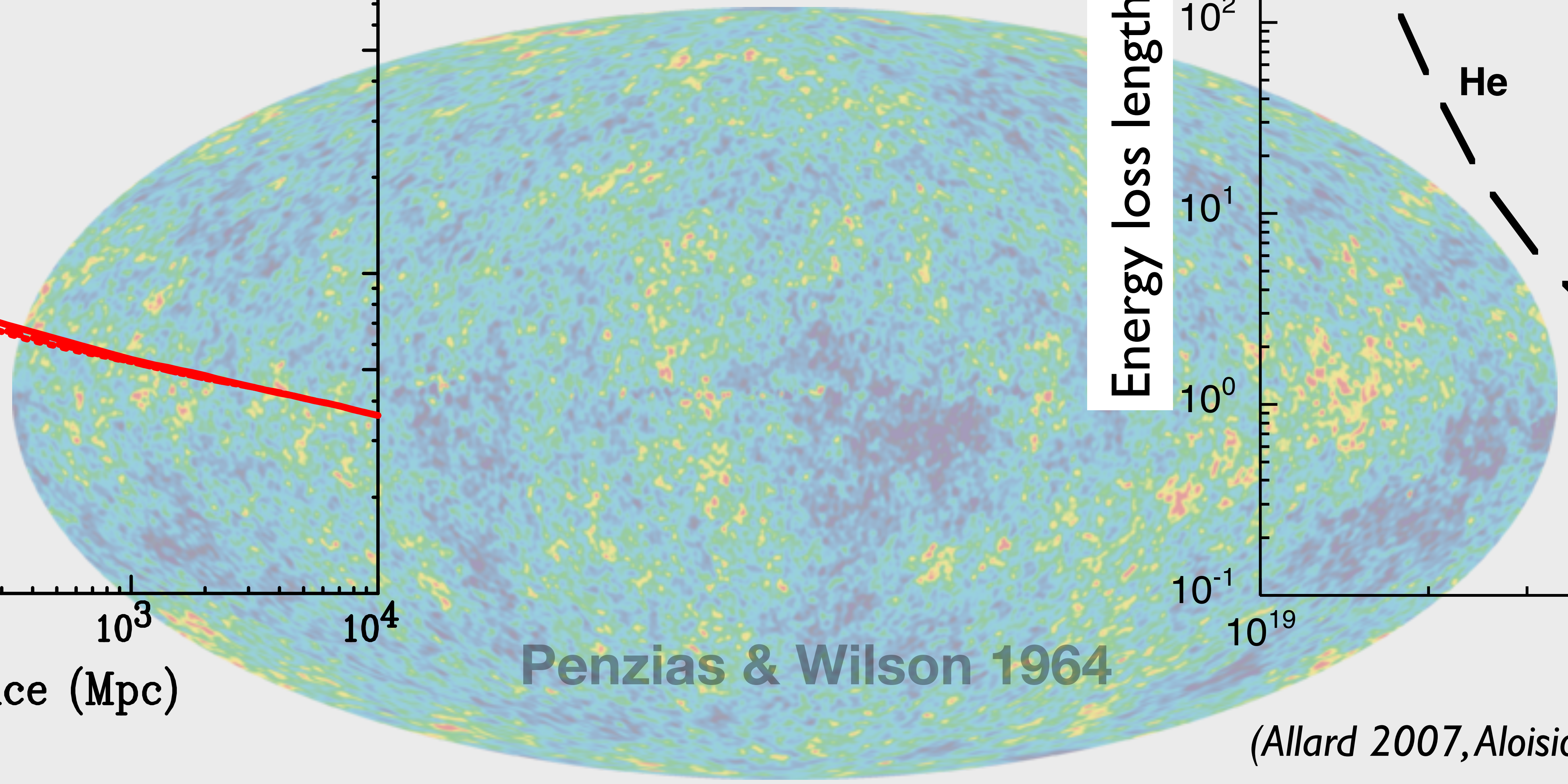
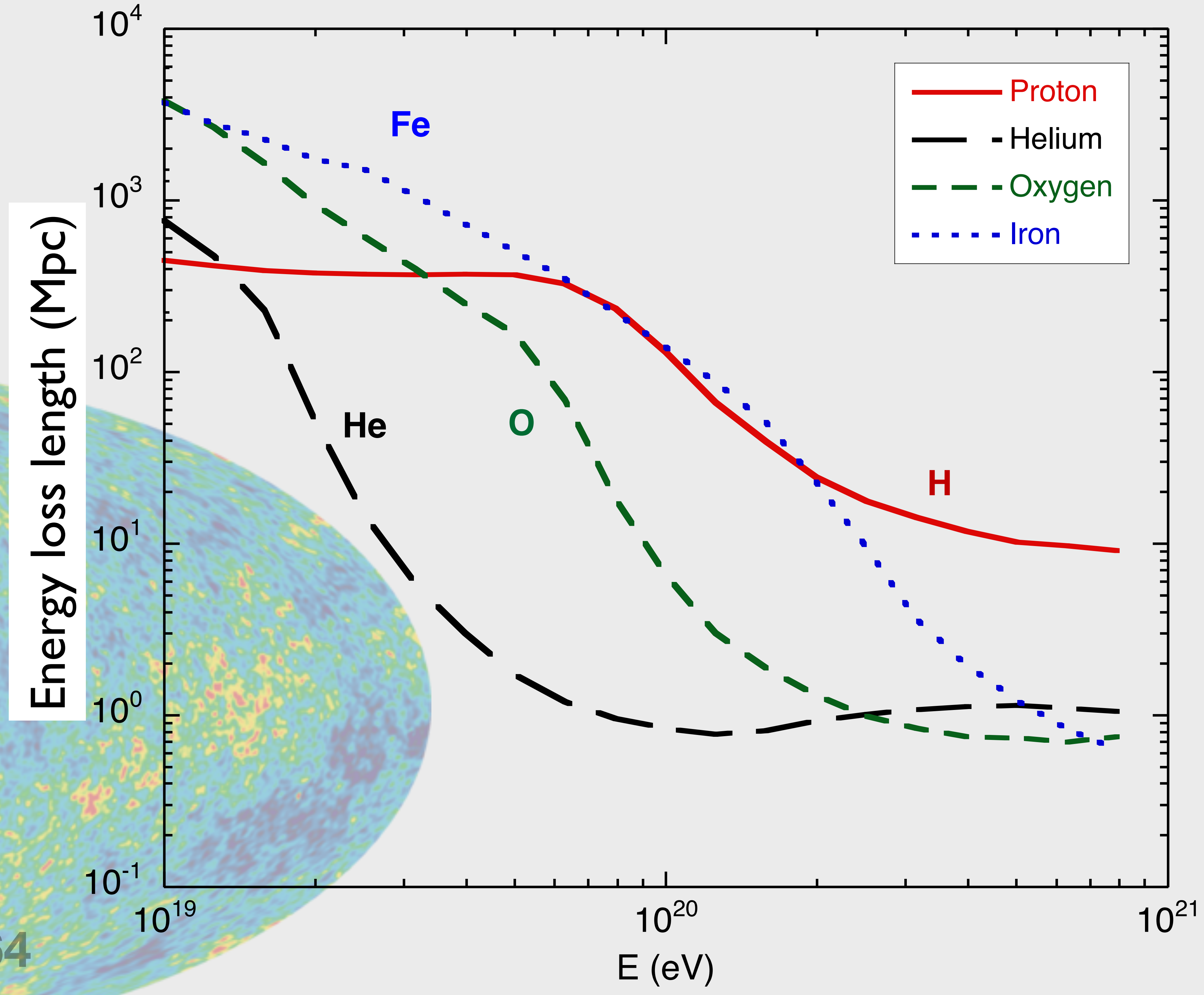


Photo-dissociation
(giant dipole resonance)



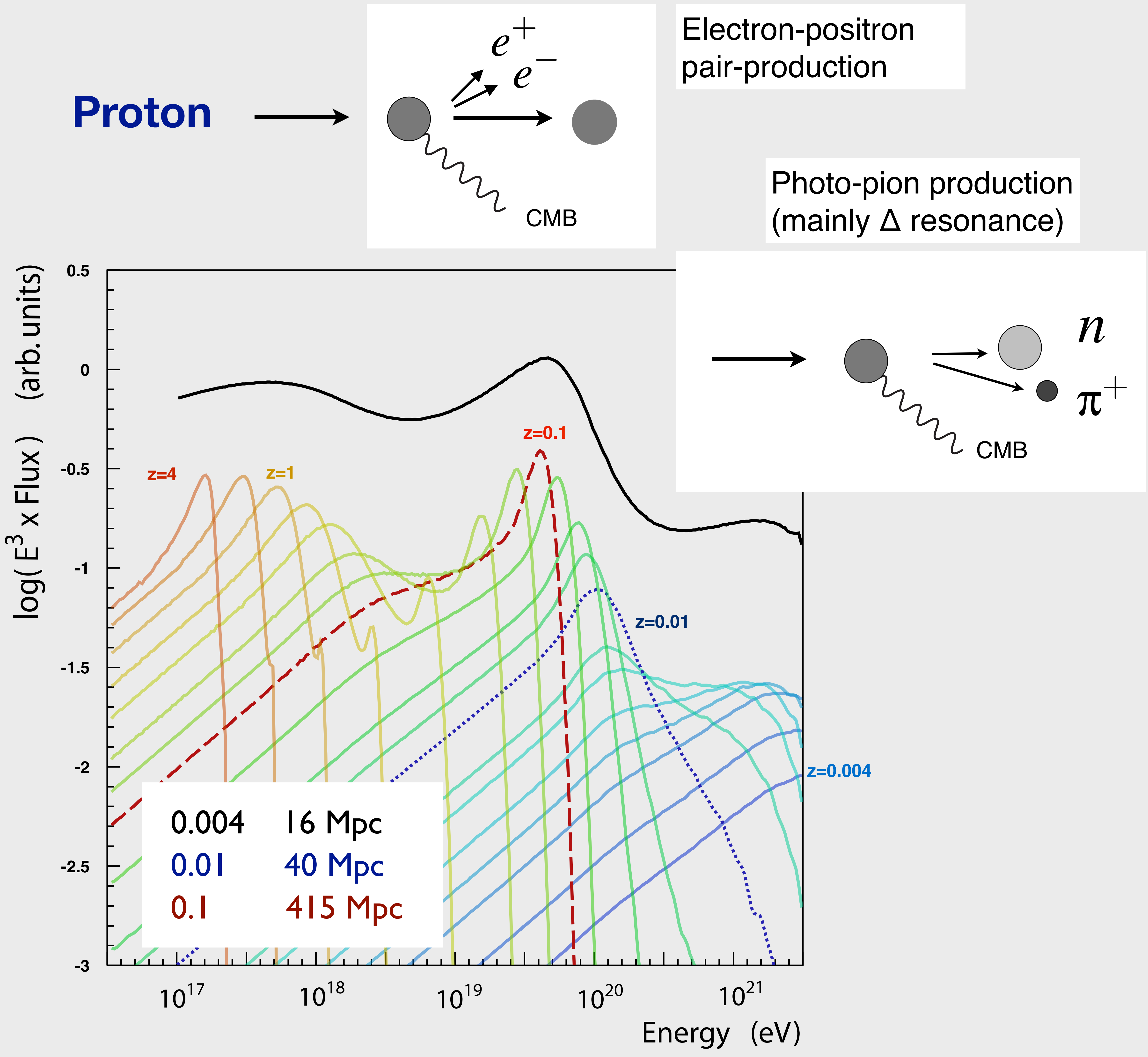
Greisen,
Zatsepin & Kuzmin
(GZK) effect, 1966



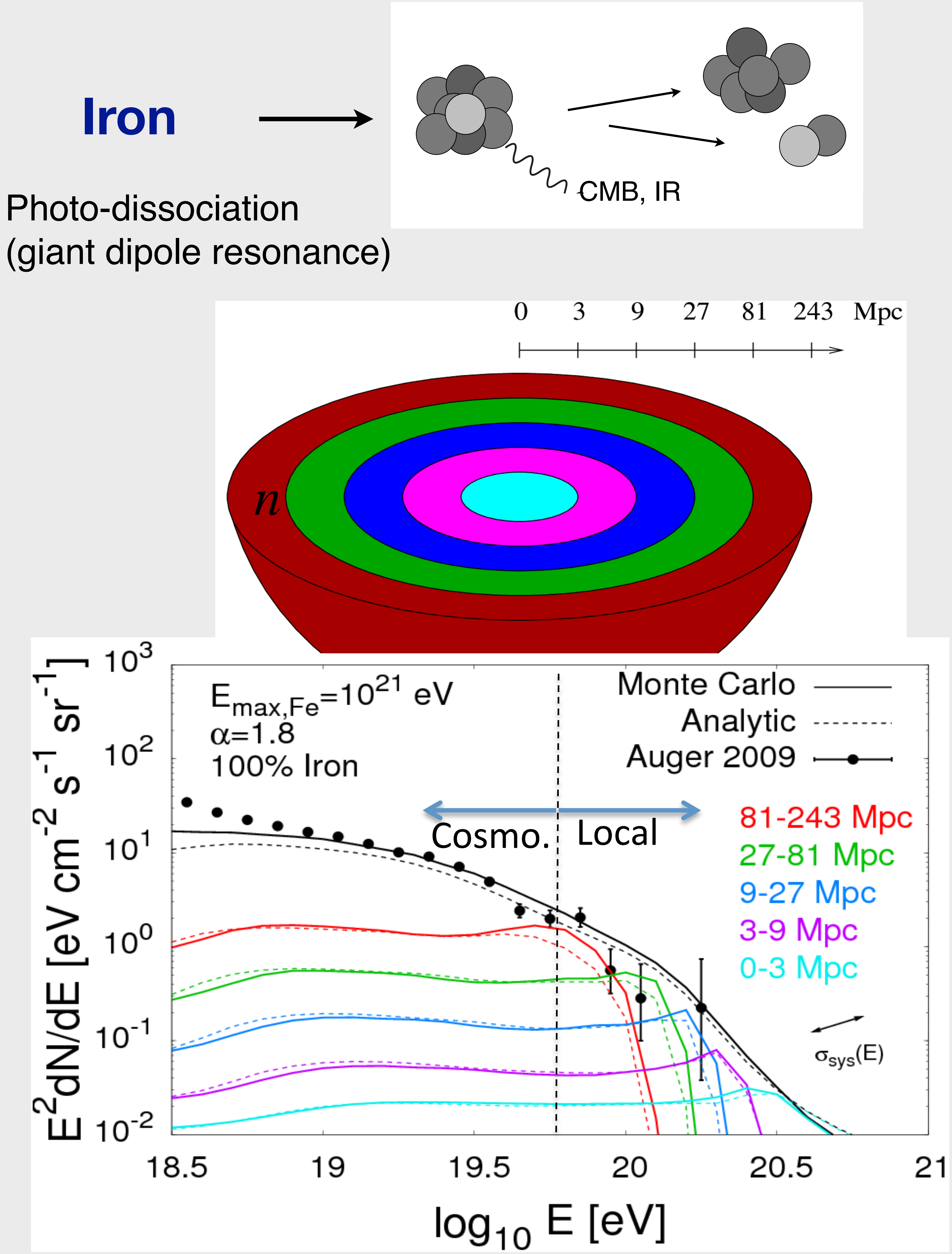


(Allard 2007, Aloisio 2017)

Typical production distances – GZK sphere



(Bergmann et al., PLB 2006)

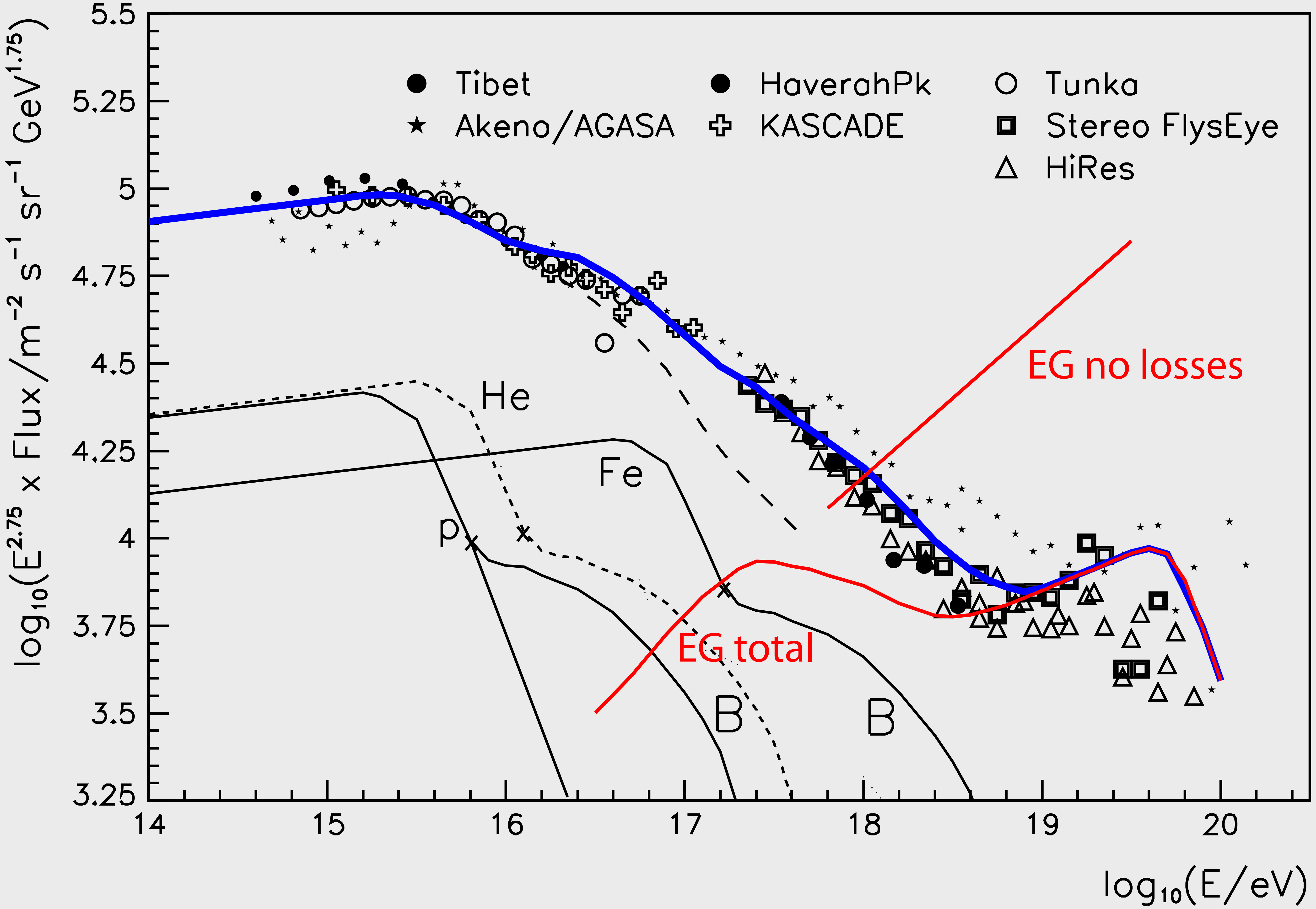


(Hooper, Taylor et al., PRD 2008)

Greisen-Zatsepin-Kuzmin (GZK) effect, 1966

Hillas´ model of cosmic ray flux

Scaled all-particle spectrum



Mainly protons as UHECR

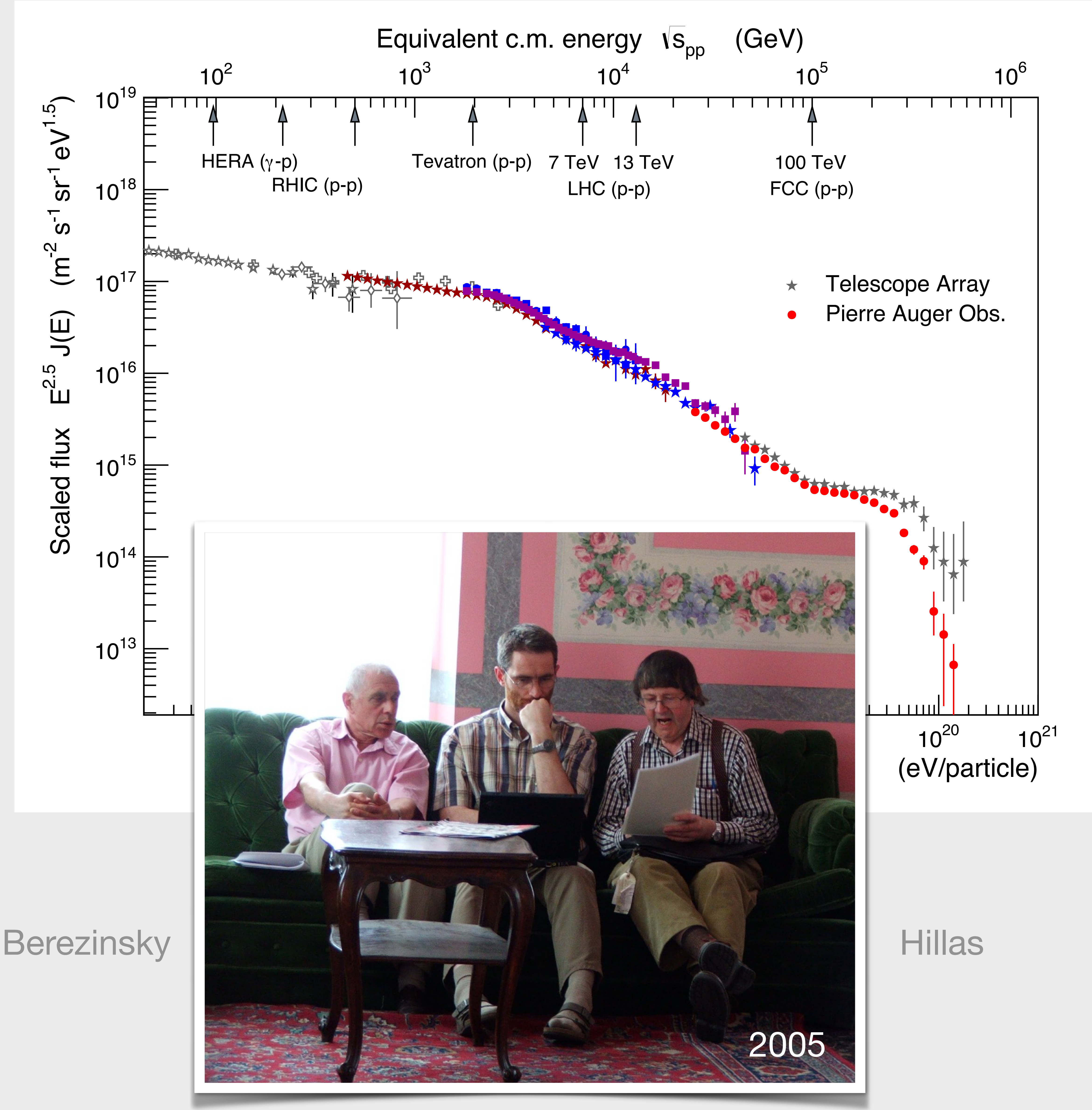
$$\frac{dN_{\text{inj}}}{dE} \sim E^{-2.3}$$

Deformation of injected spectrum fully understood

Need additional "component B"

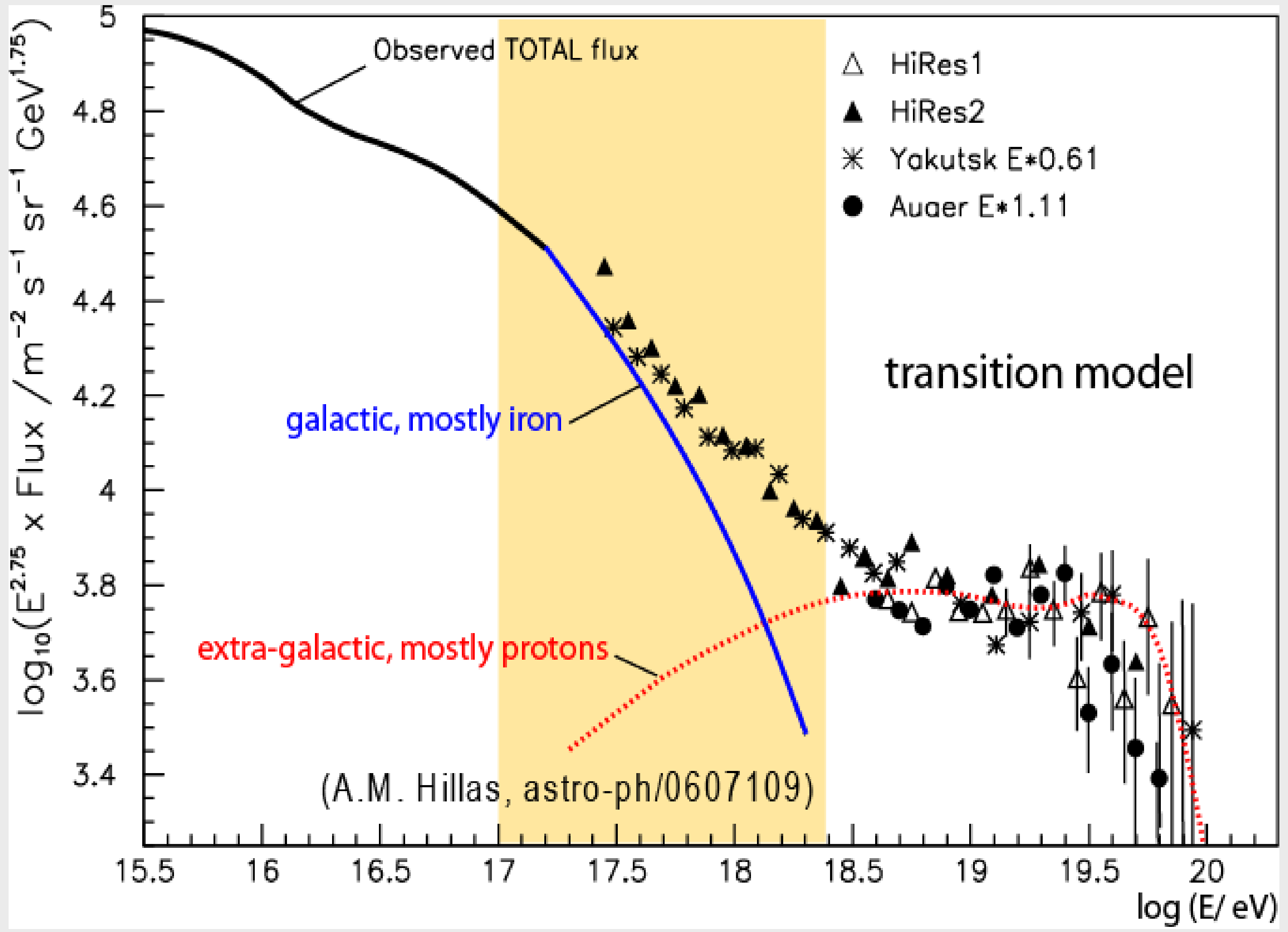
(Hillas J. Phys. G31, 2005)

Standard models of ultra-high energy cosmic rays (2005)



Berezinsky

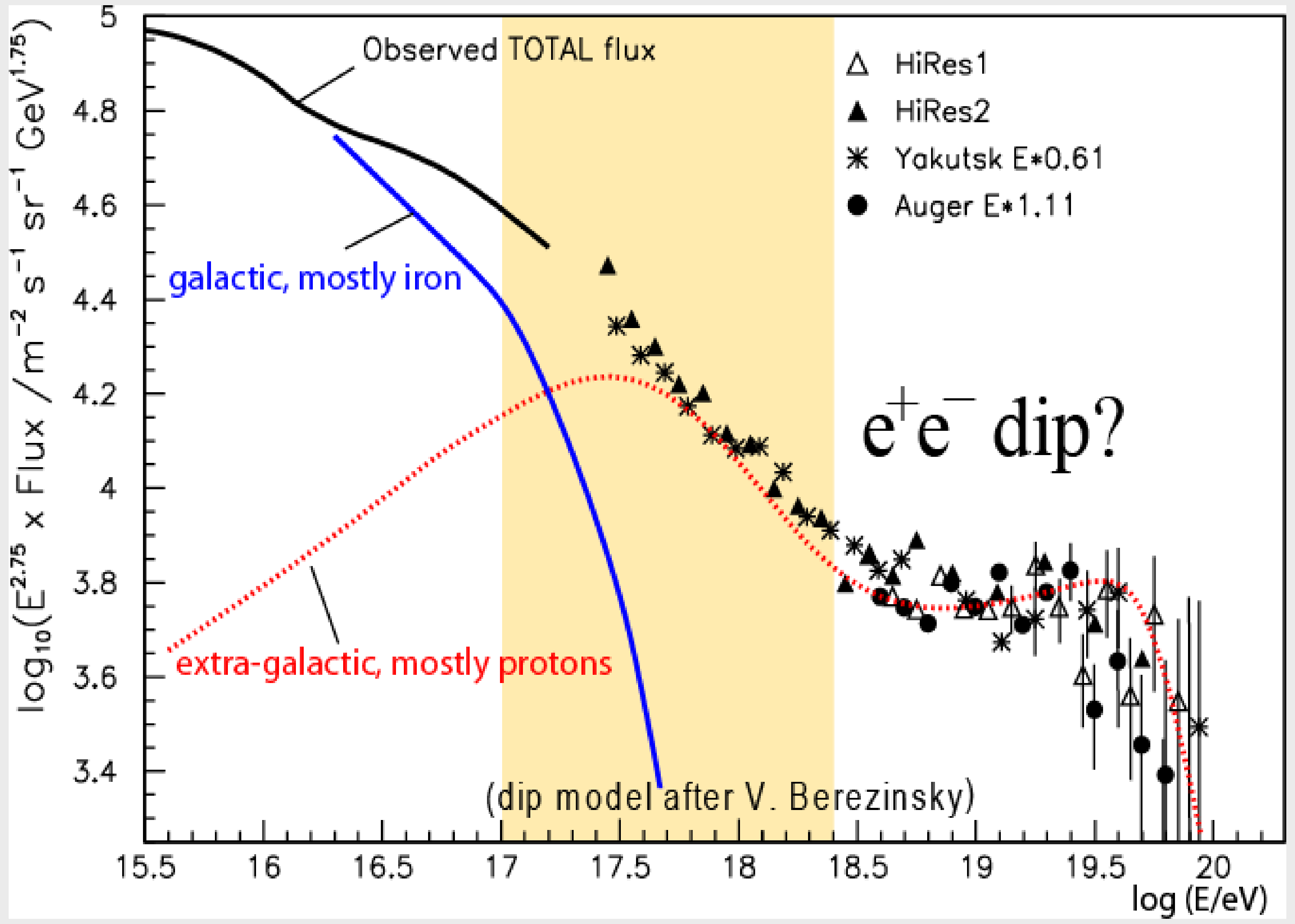
Hillas



Ankle model:
Hillas, Wolfendale et al.

$$\frac{dN_p}{dE} \sim E^{-2.3}$$

(J. Phys. G31 (2005) R95)



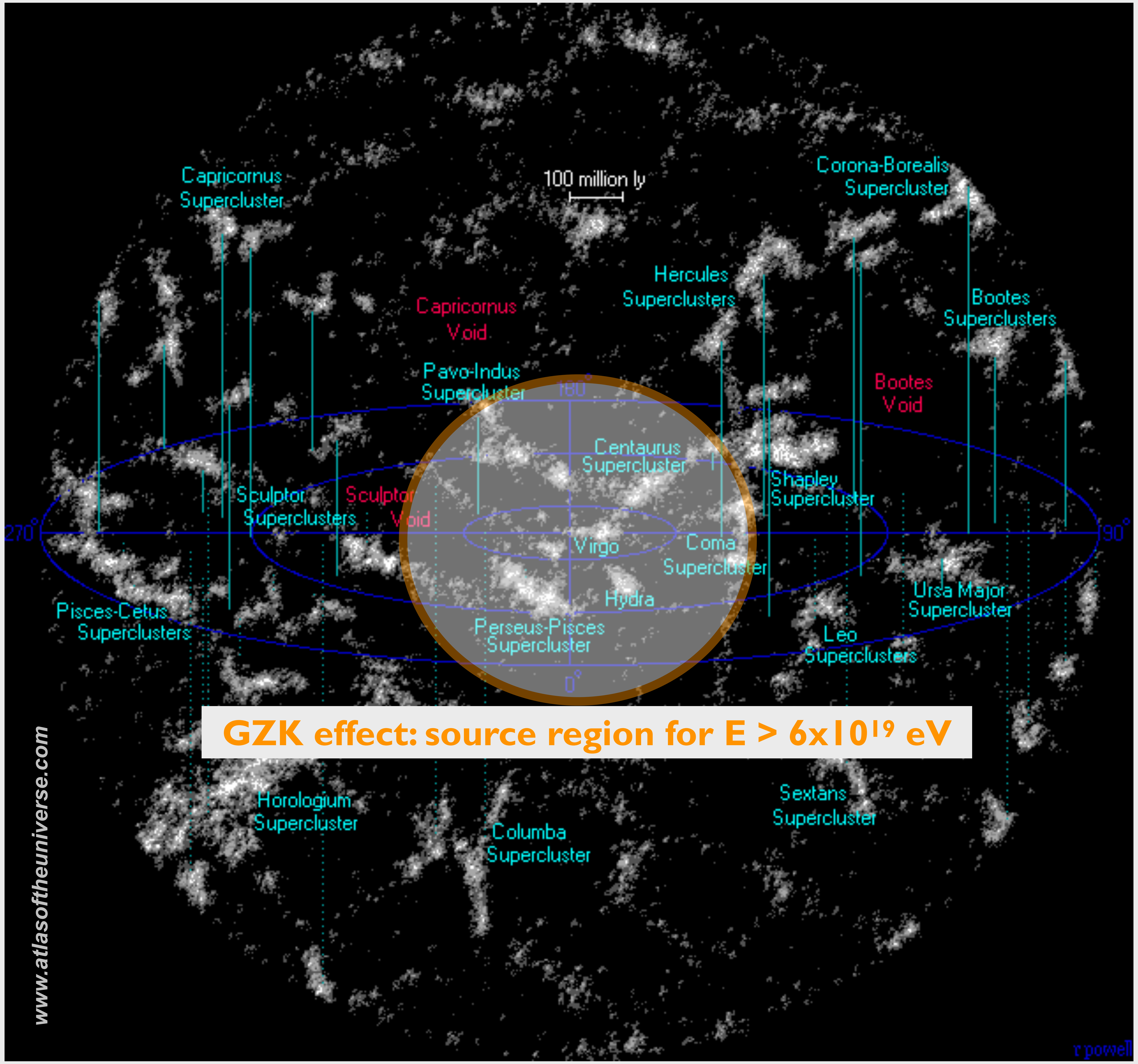
Dip model:
Berezinsky et al.

$$p\,\gamma_{CMB} \to p\,e^+ e^-$$

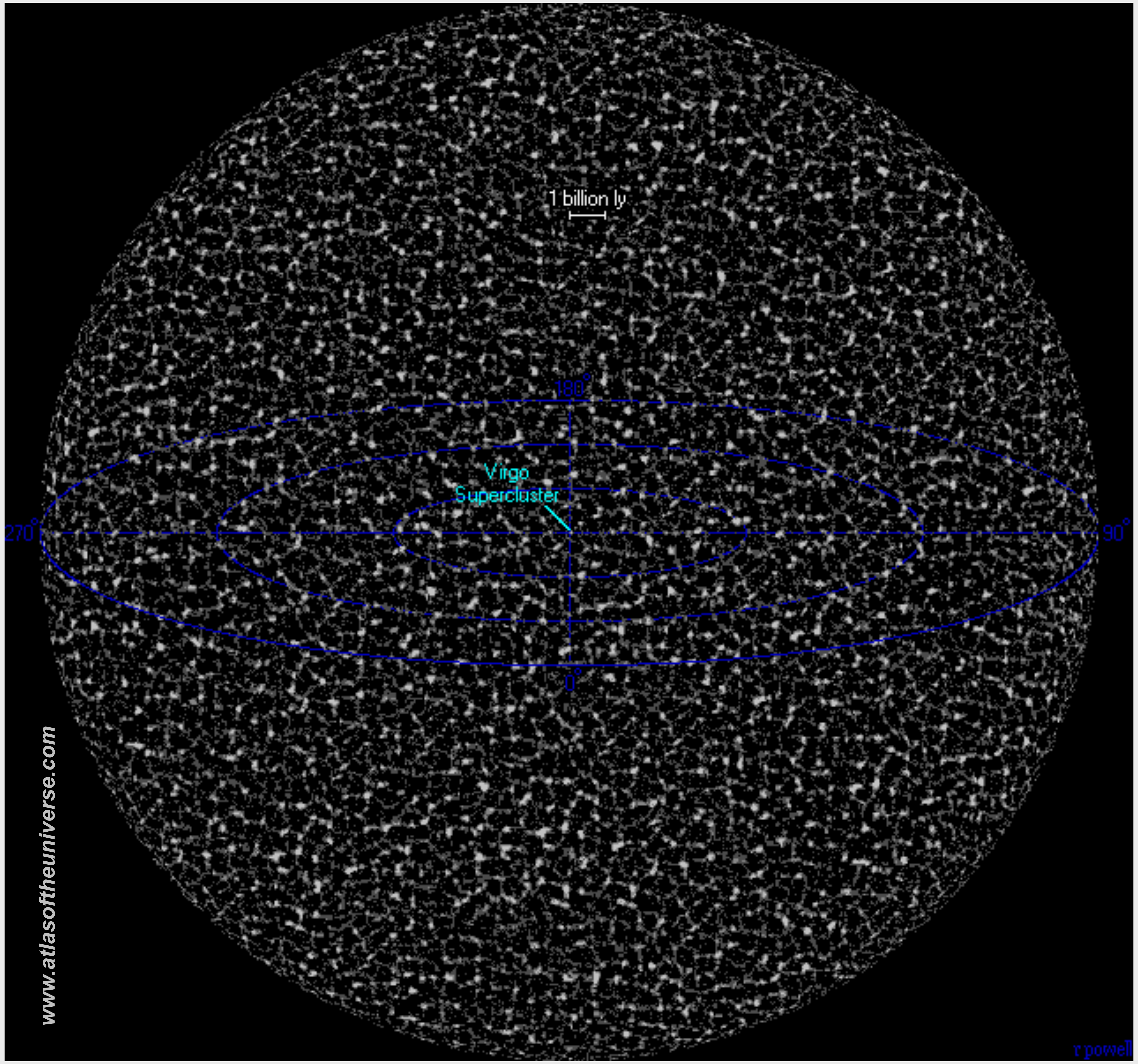
$$\frac{dN_p}{dE} \sim E^{-2.7}$$

(PRD 74 (2006) 043005)

Matter/source distribution in the Universe



Cosmic rays, gamma-rays



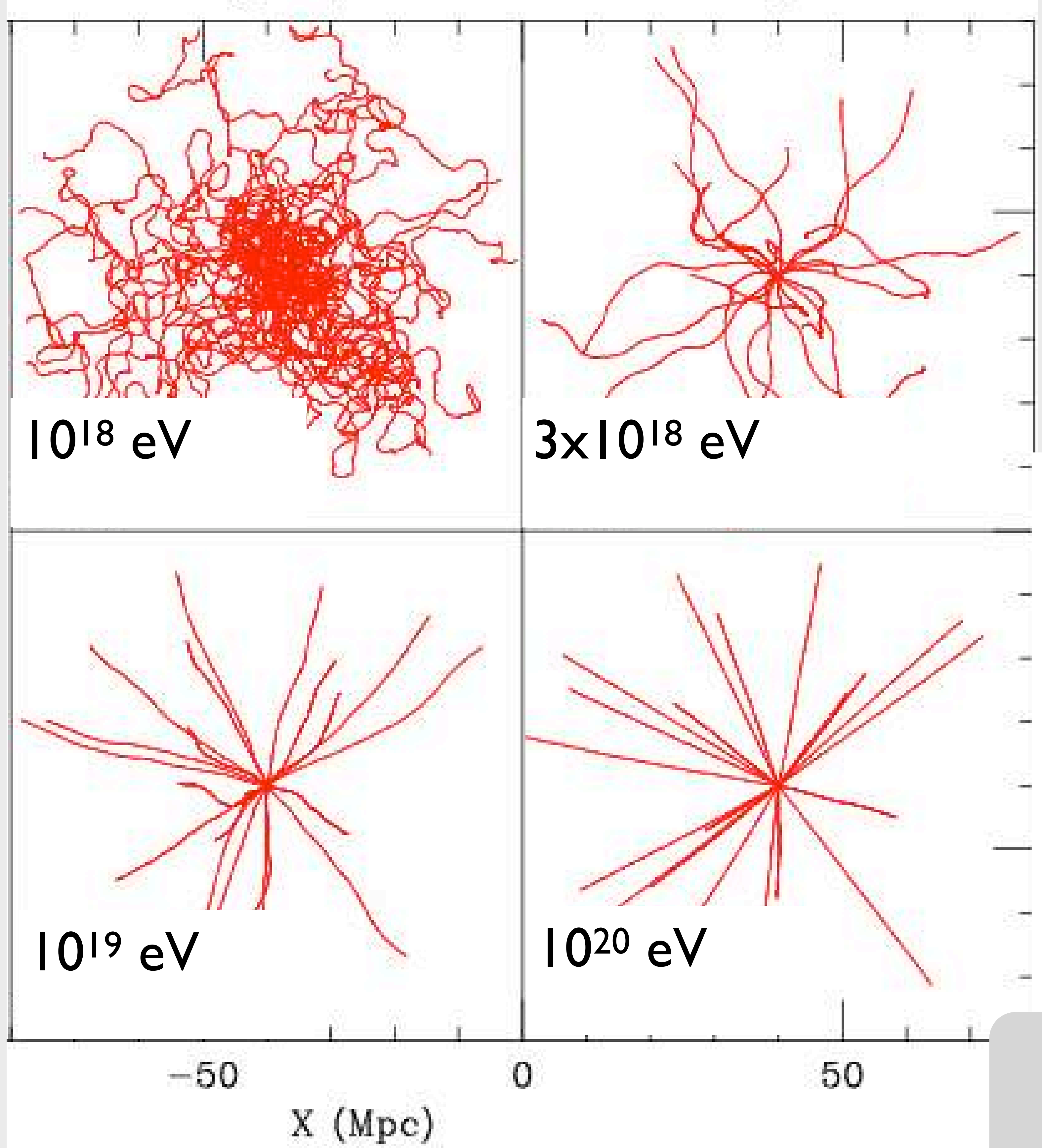
Neutrinos

Defection by magnetic fields

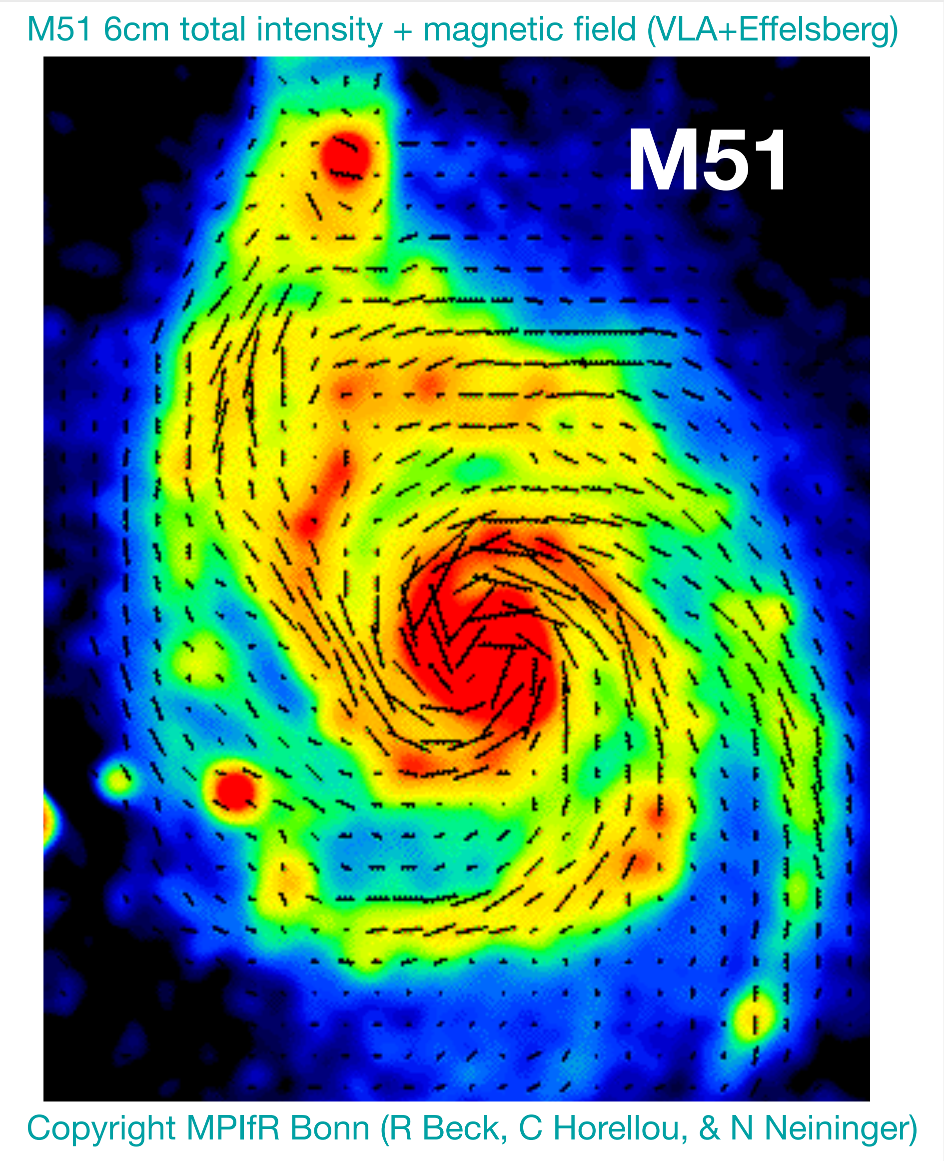
Deflection in extragalactic mag. fields (~1nG)

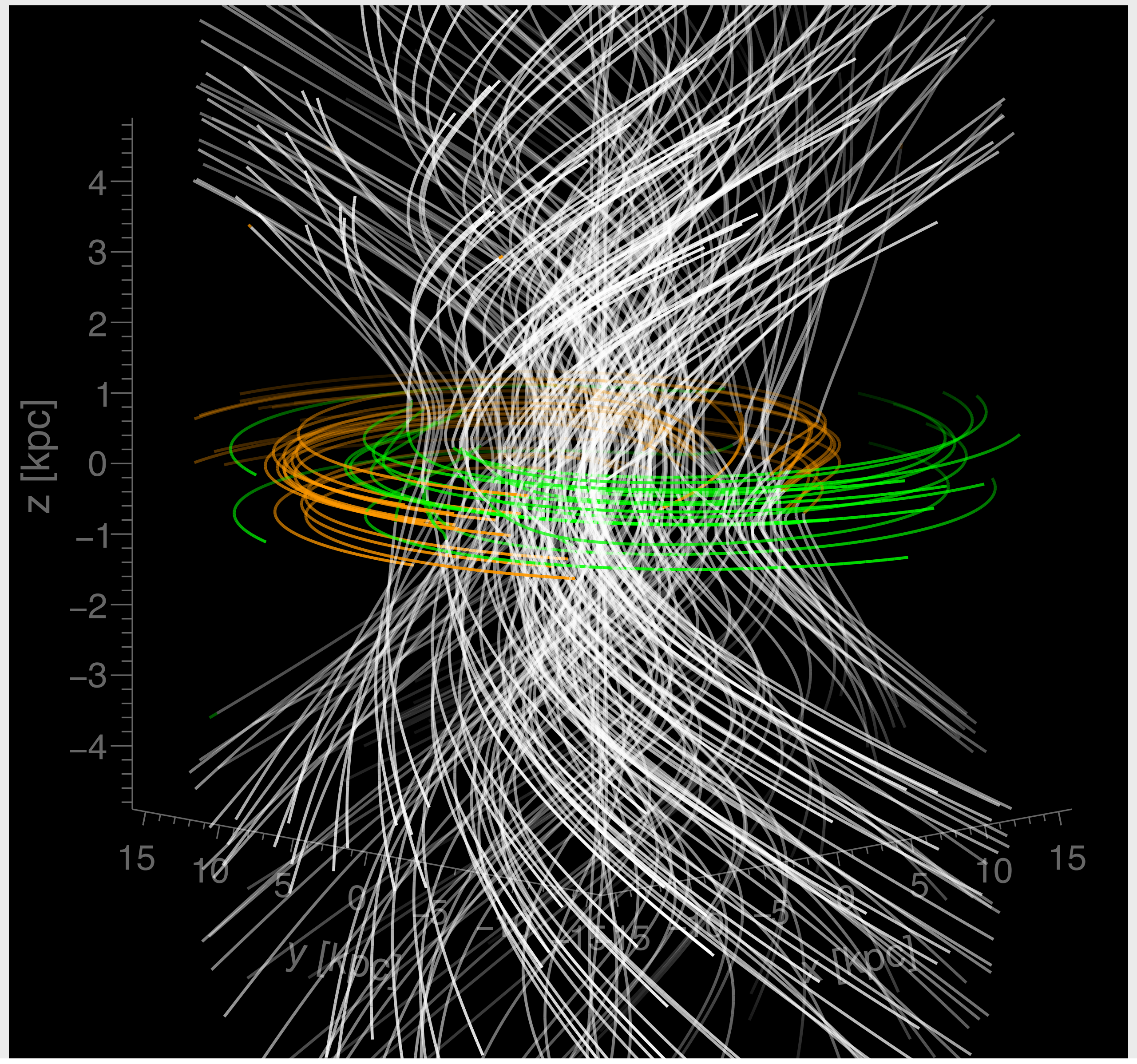
(Cronin, NPB 2003)

protons

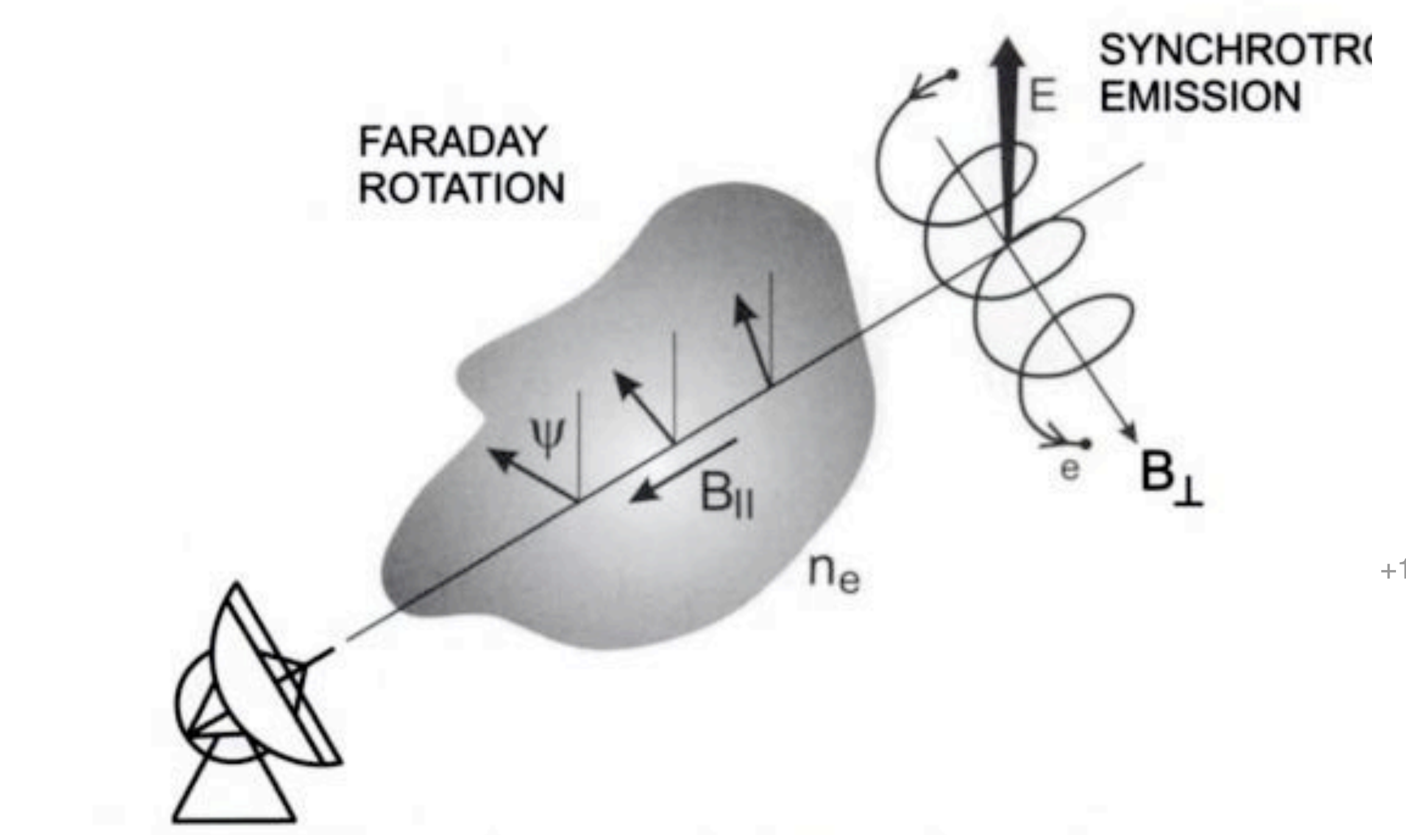


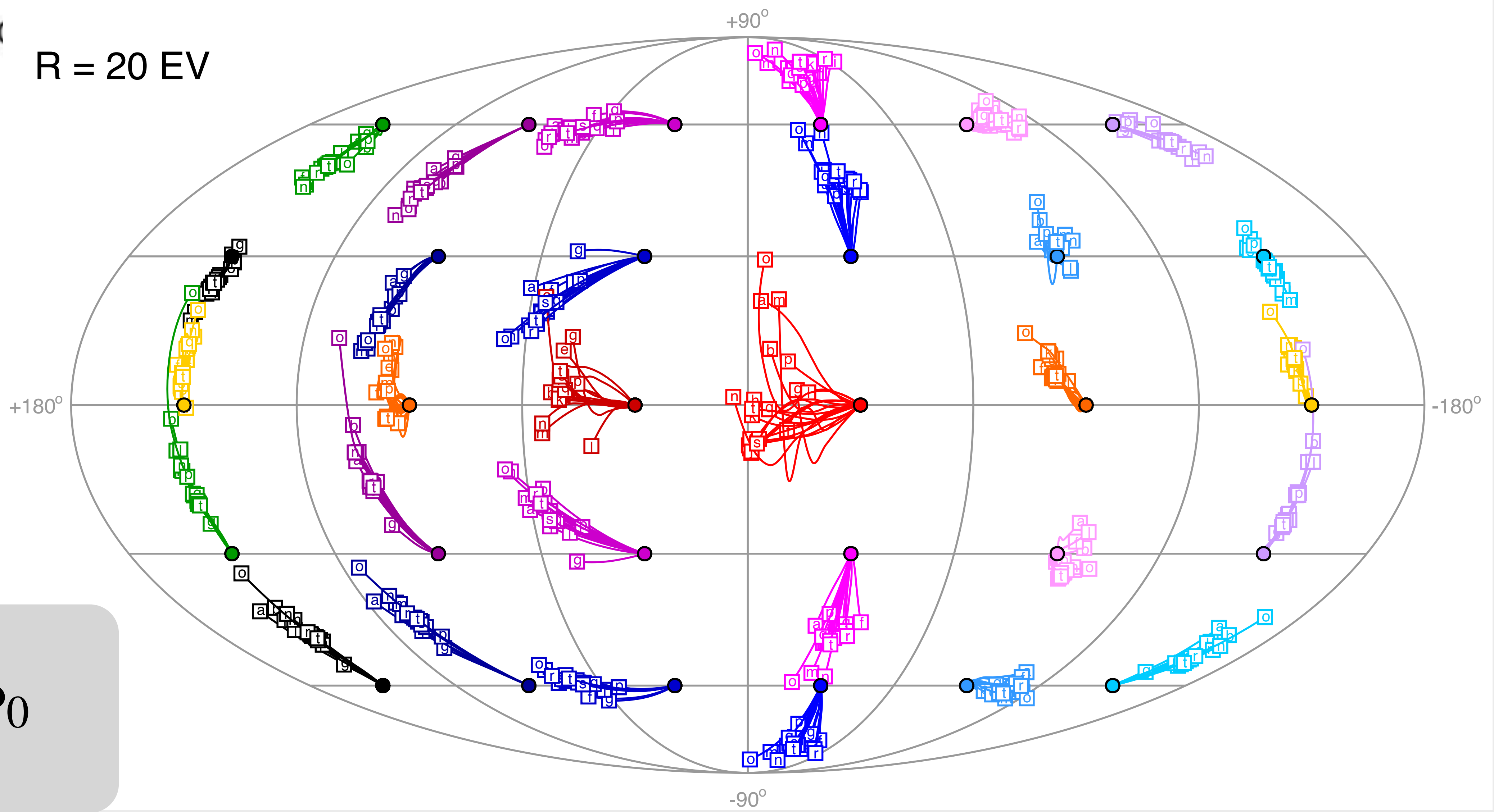
Deflection in Galactic mag. fields (~3μG)





(Unger & Farrar, ApJ 970 (2024) 1, 95)

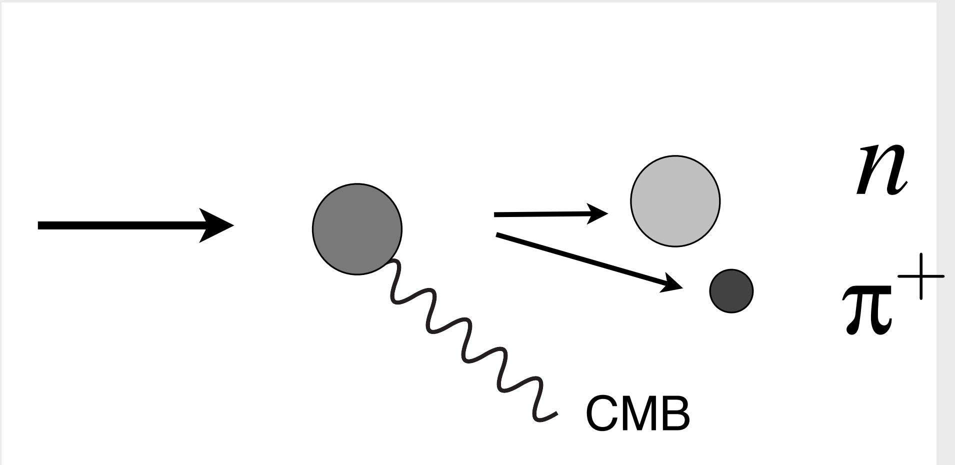




$$\Phi = \frac{e^3}{2\pi m_e^2 c^4}\,\lambda^2 \int n_e(l)\, B_{||}(l)\, dl \,+\, \Phi_0$$

Physics of ultra-high energy cosmic rays – protons

Energy loss (GZK effect)

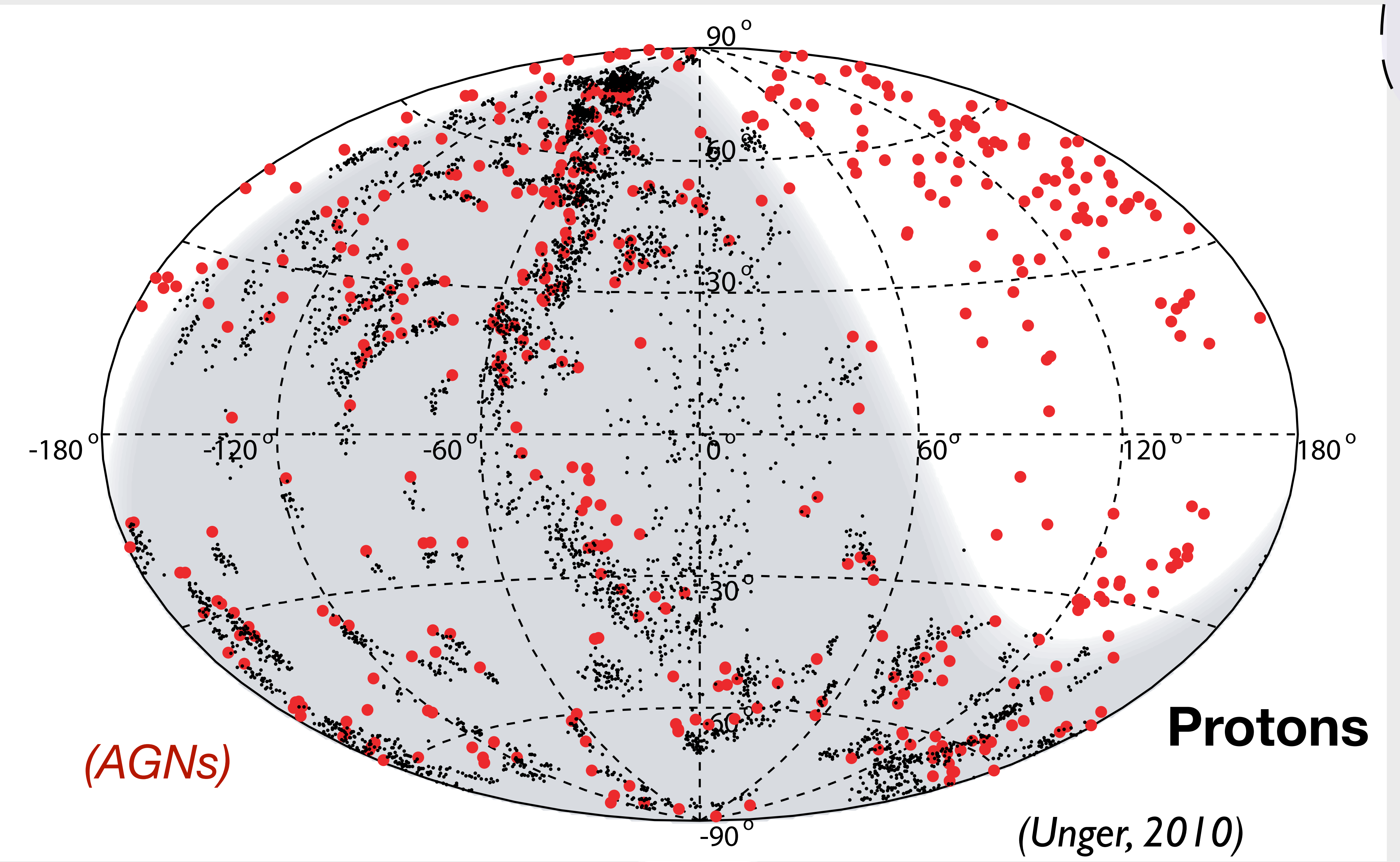


$$n$$
$$\pi^+ \to \mu^+ \nu_\mu$$
$$\to e^+ \bar{\nu}_\mu \nu_\mu \nu_e$$

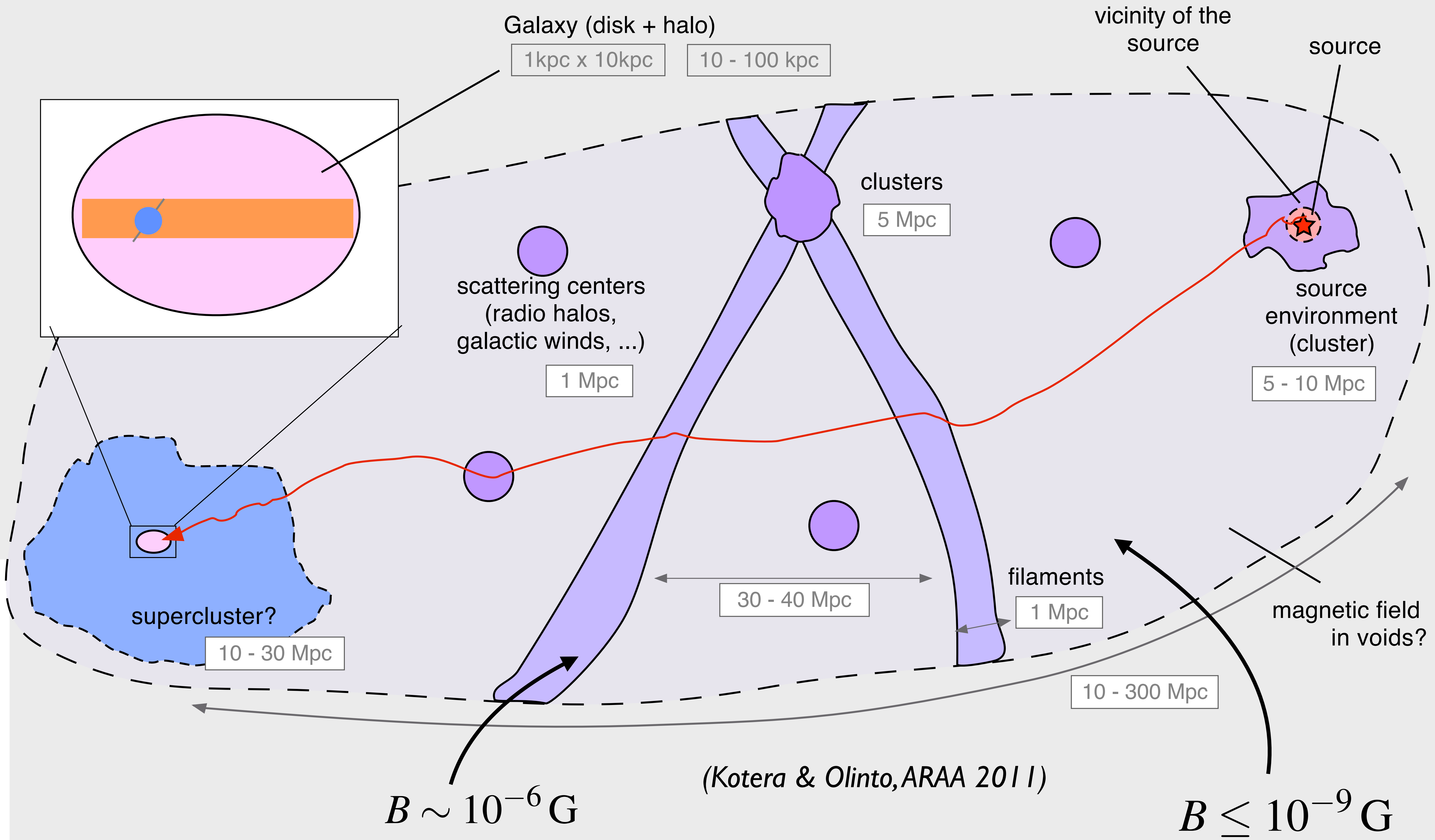
Photo-pion production
(mainly Δ resonance)

$$p$$
$$\pi^0 \to \gamma\gamma$$

Magnetic deflection



(Unger, 2010)



(Kotera & Olinto, ARAA 2011)

Protons accelerated or product of decay of super-heavy particles

Escape from source regions as neutrons or by diffusion

Guaranteed cosmogenic UHE neutrino flux (1/20 E_0)

Physics of ultra-high energy cosmic rays – nuclei

Energy loss (GZK effect)

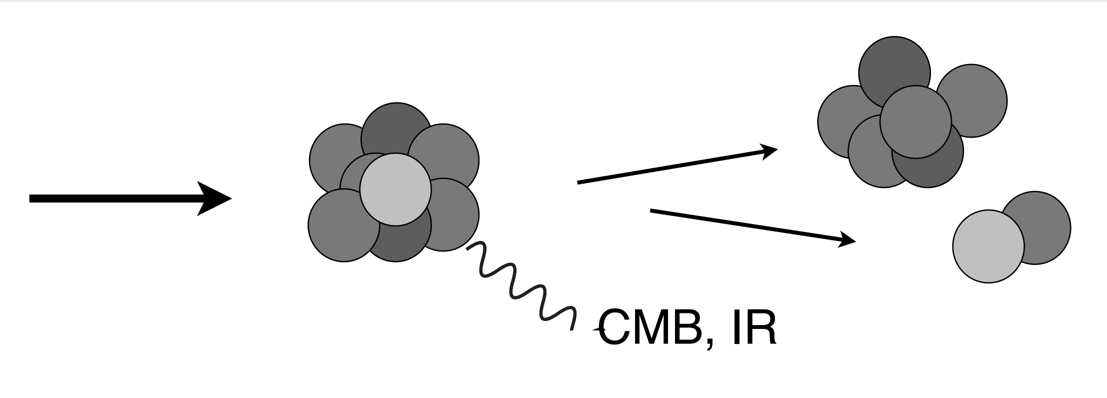
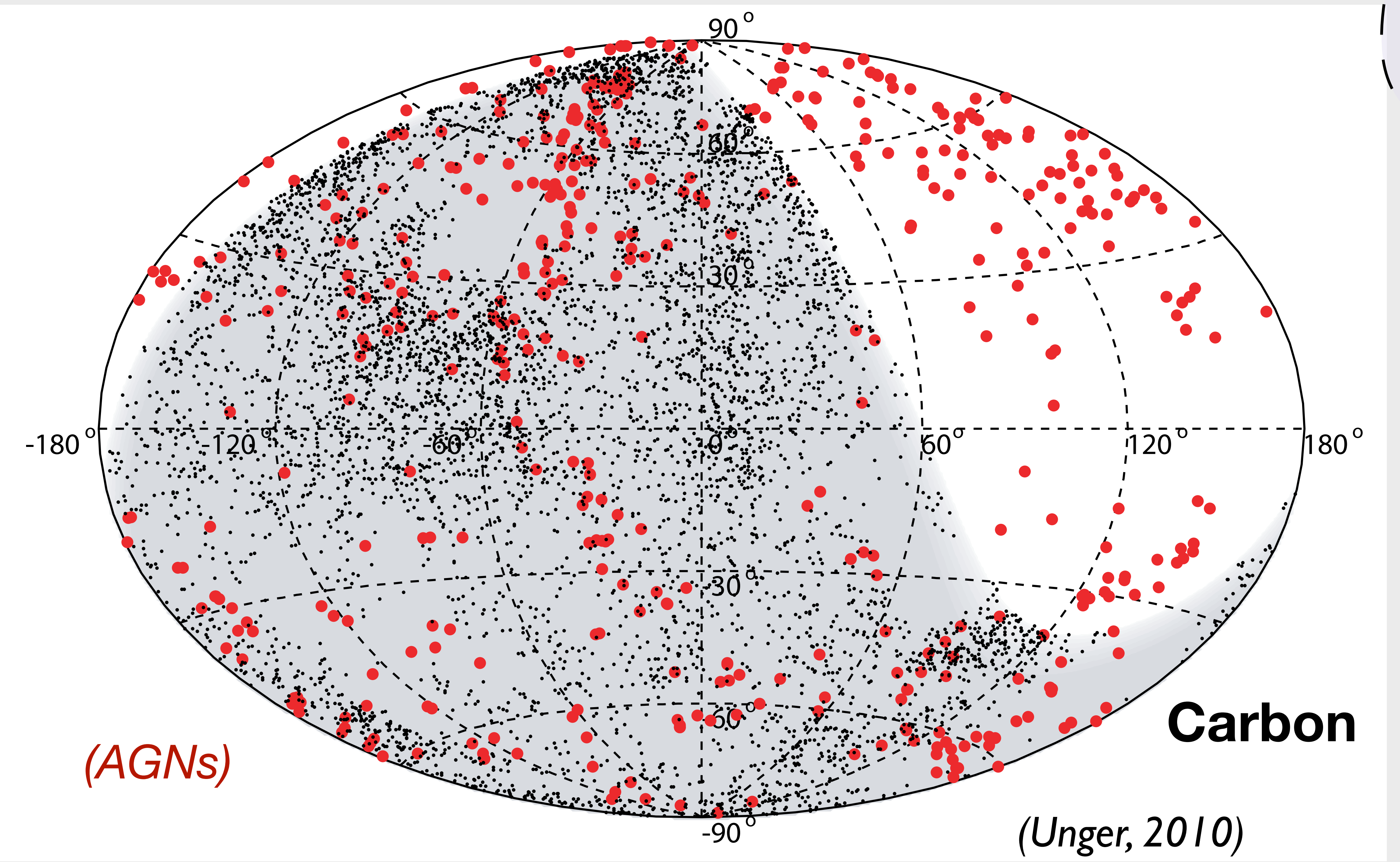
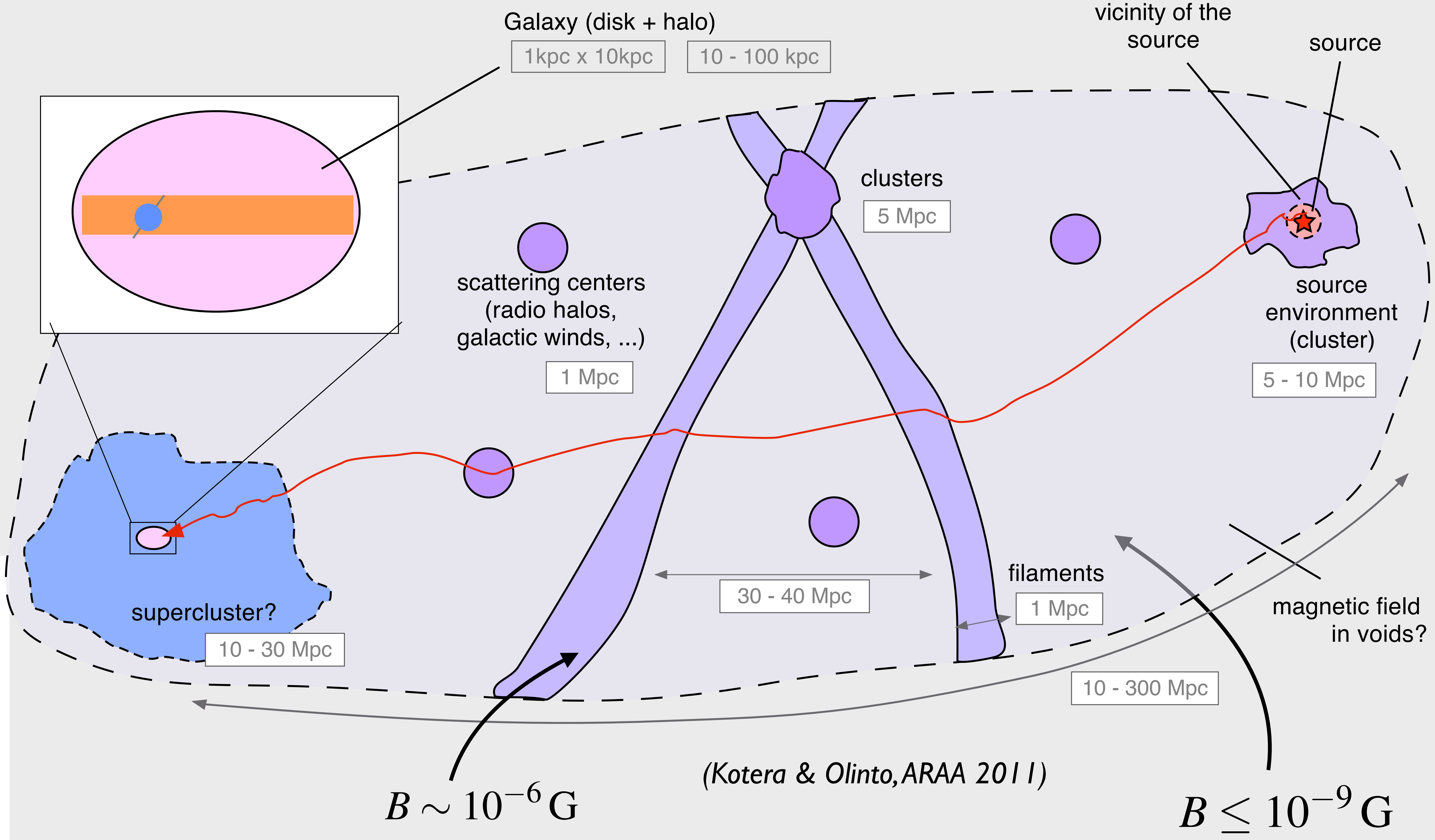


Photo-dissociation
(giant dipole resonance)

$$n \rightarrow p\, e^- \,\bar{\nu}_e$$

Magnetic deflection





Nuclei accelerated in sources with weak background fields

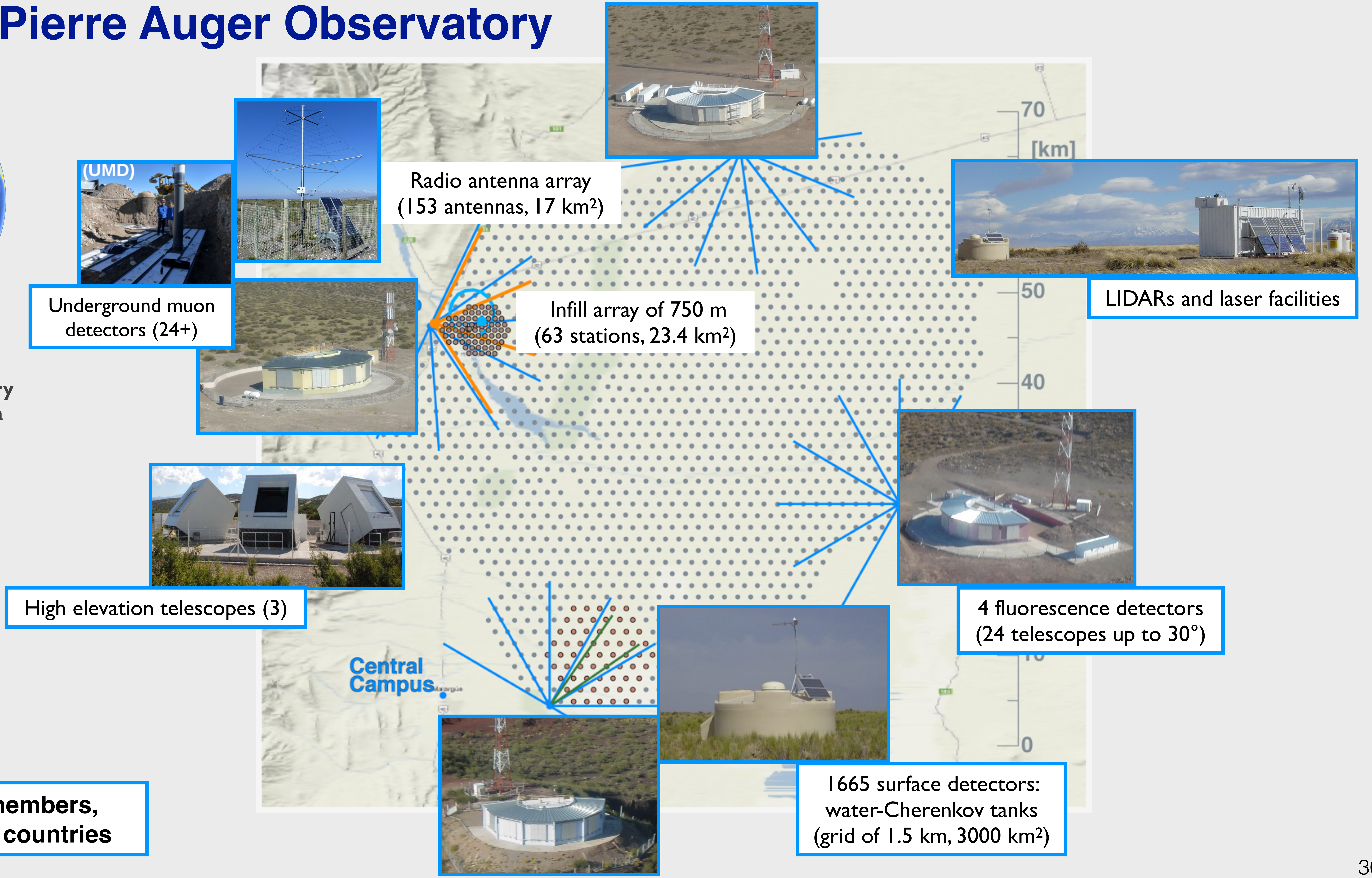
Interplay of spallation in source and escape by diffusion

Mainly electron anti-neutrinos from neutron decay (10^{-5} E_0/A)

Ultra-high energy cosmic ray observations

The Pierre Auger Observatory

Pierre Auger Observatory
Province Mendoza, Argentina



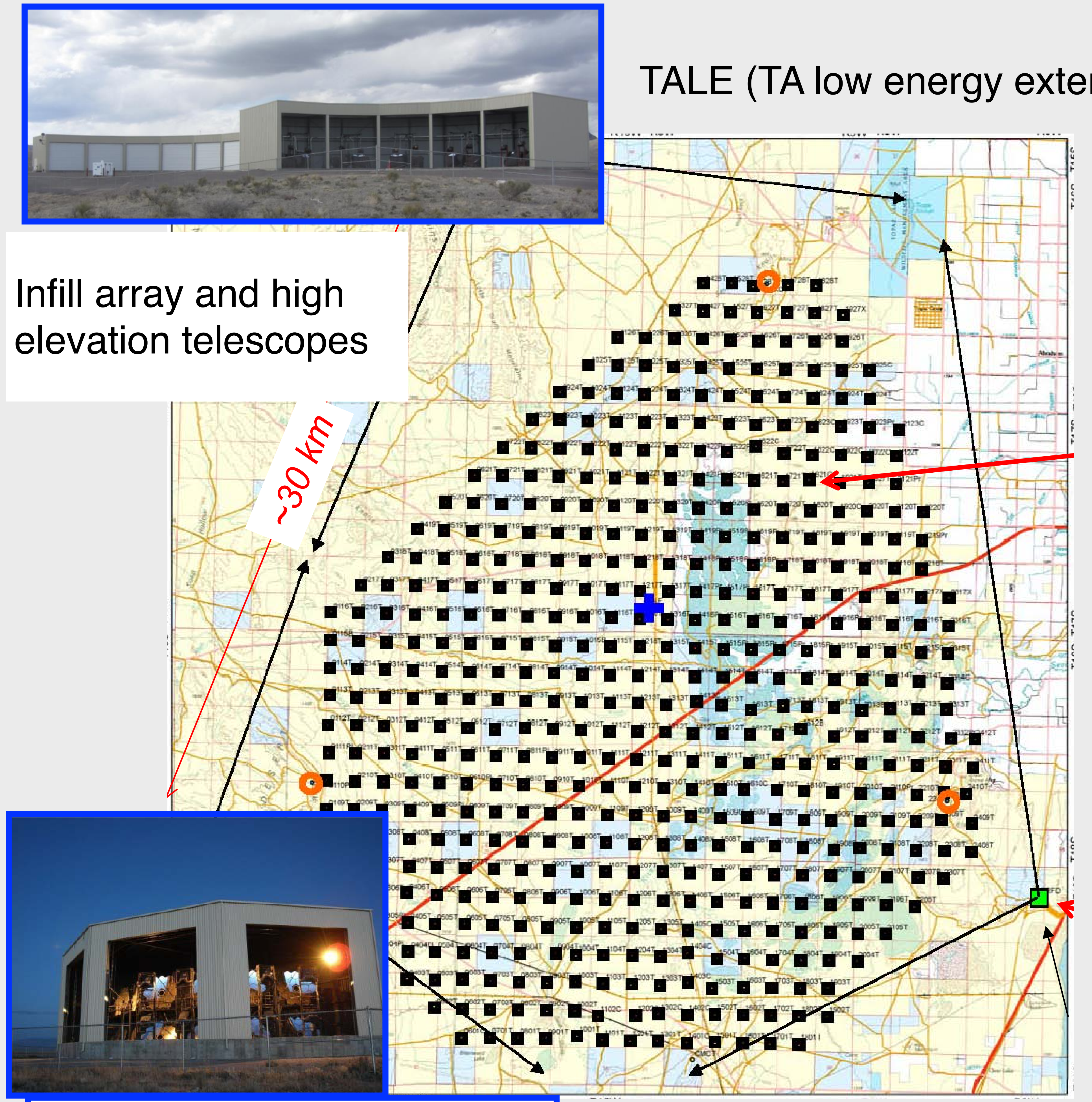
More than 400 members, 95 institutes, 18 countries

Telescope Array (TA)

Middle Drum: based on HiRes II

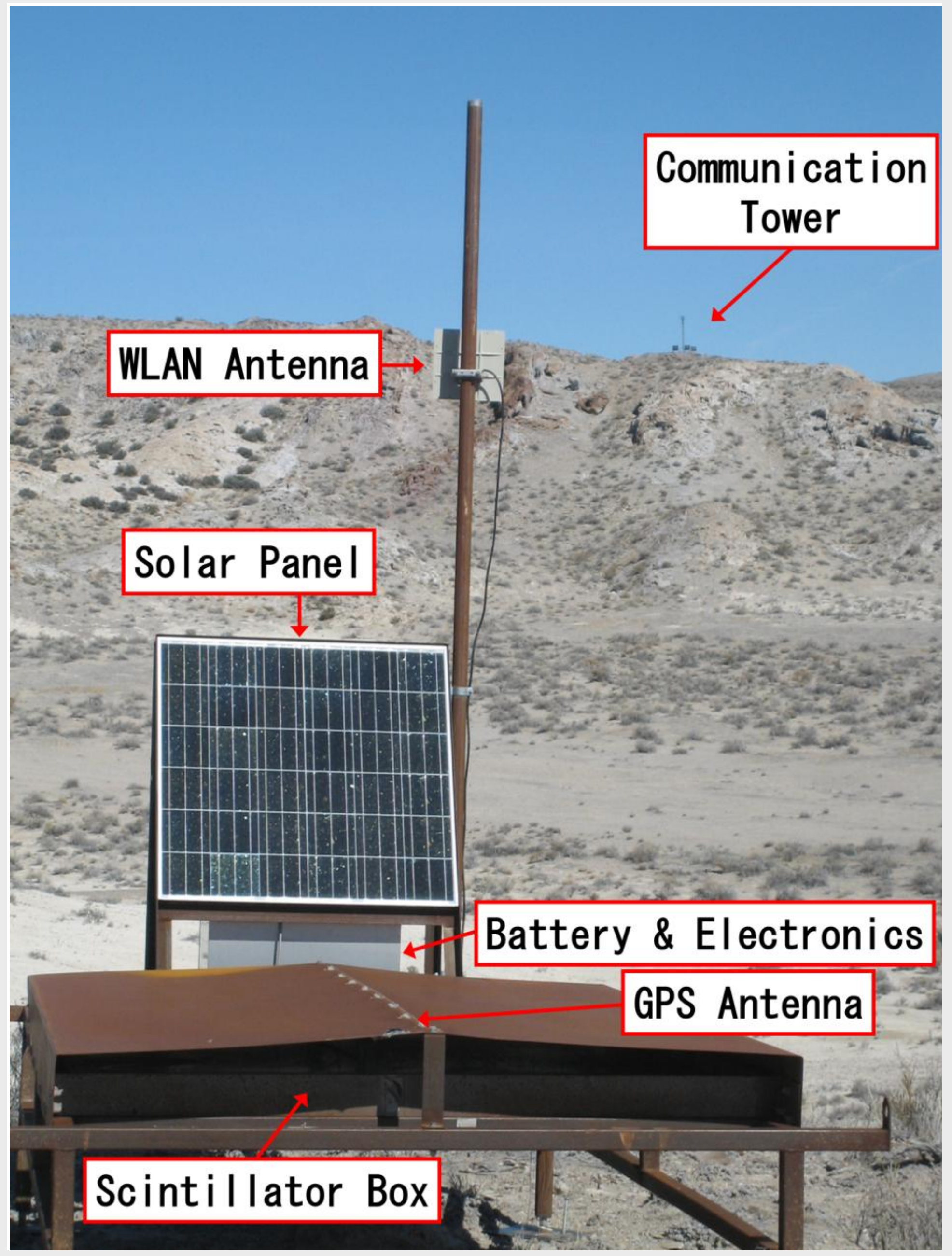
TALE (TA low energy extension)

Infill array and high elevation telescopes

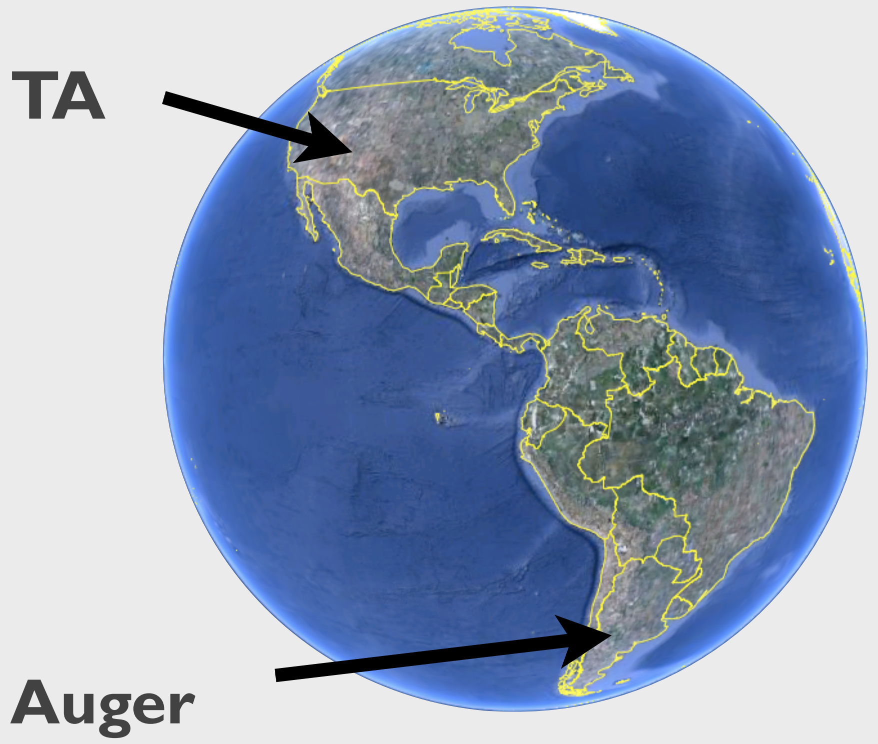


3 fluorescence detectors
(2 new, one station HiRes II)

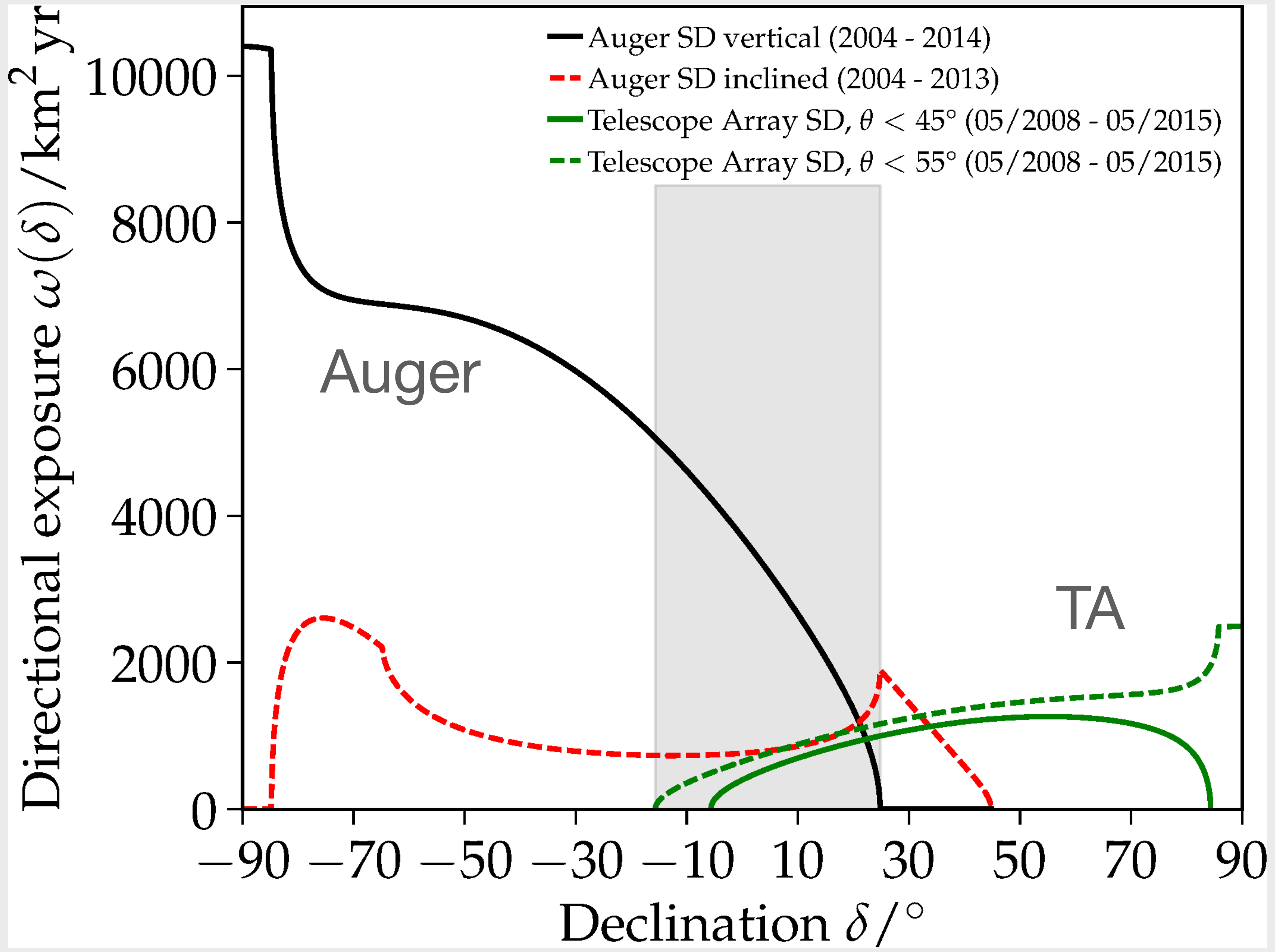
507 surface detectors:
double-layer scintillators
(grid of 1.2 km, 680 km²)



Extension to TAx4 in progress

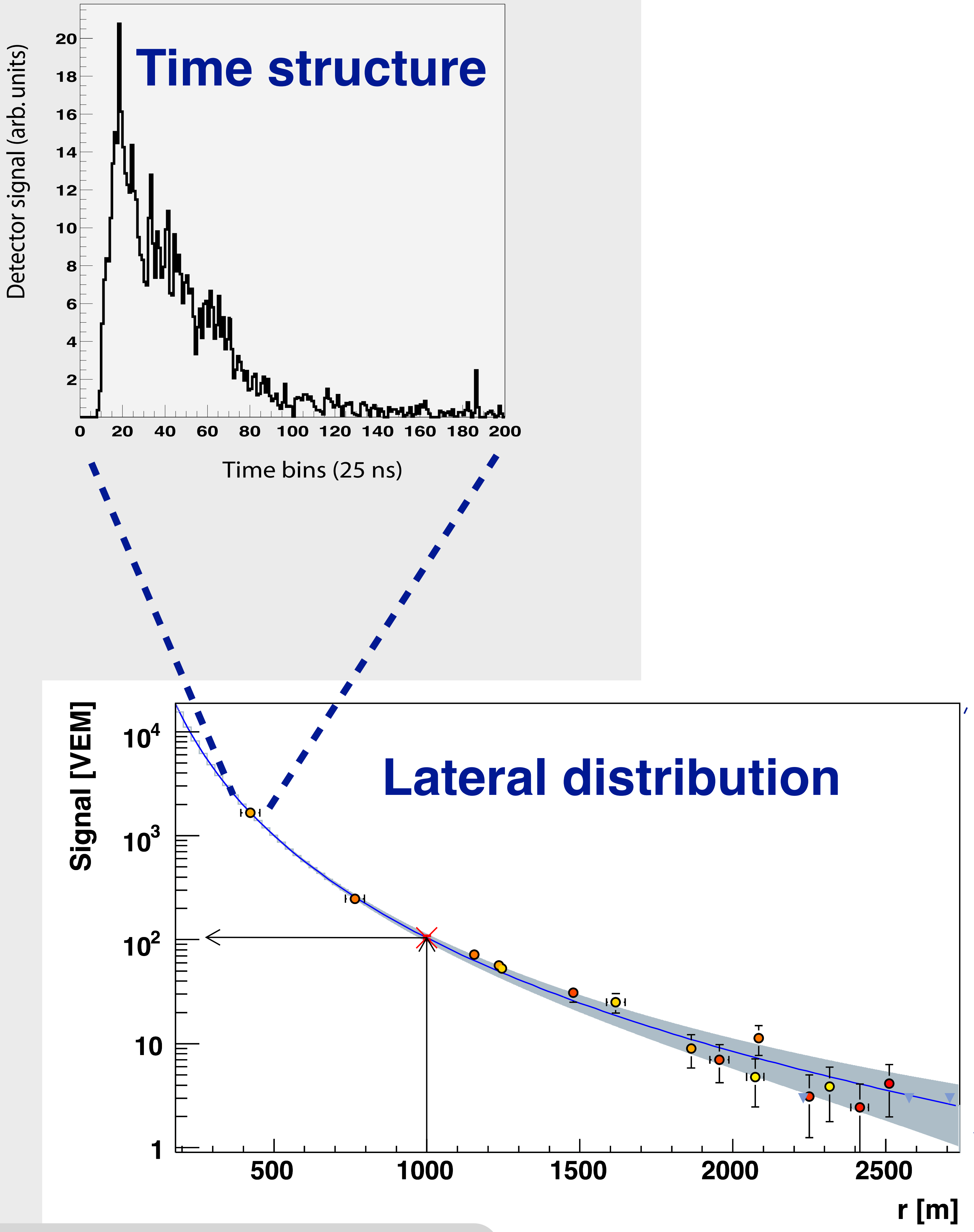


Exposure of observatories

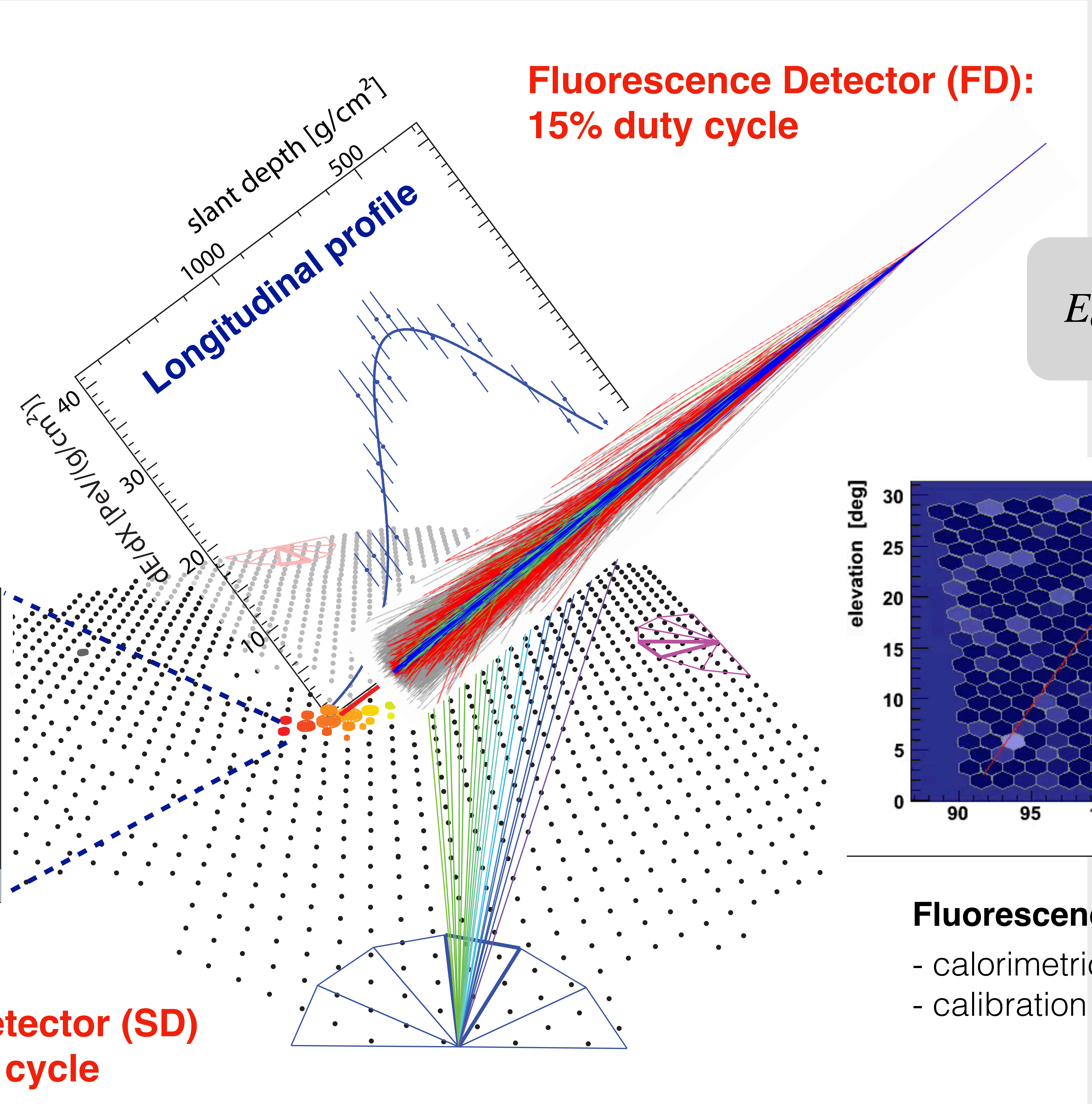


Northern hemisphere: Delta, Utah, USA

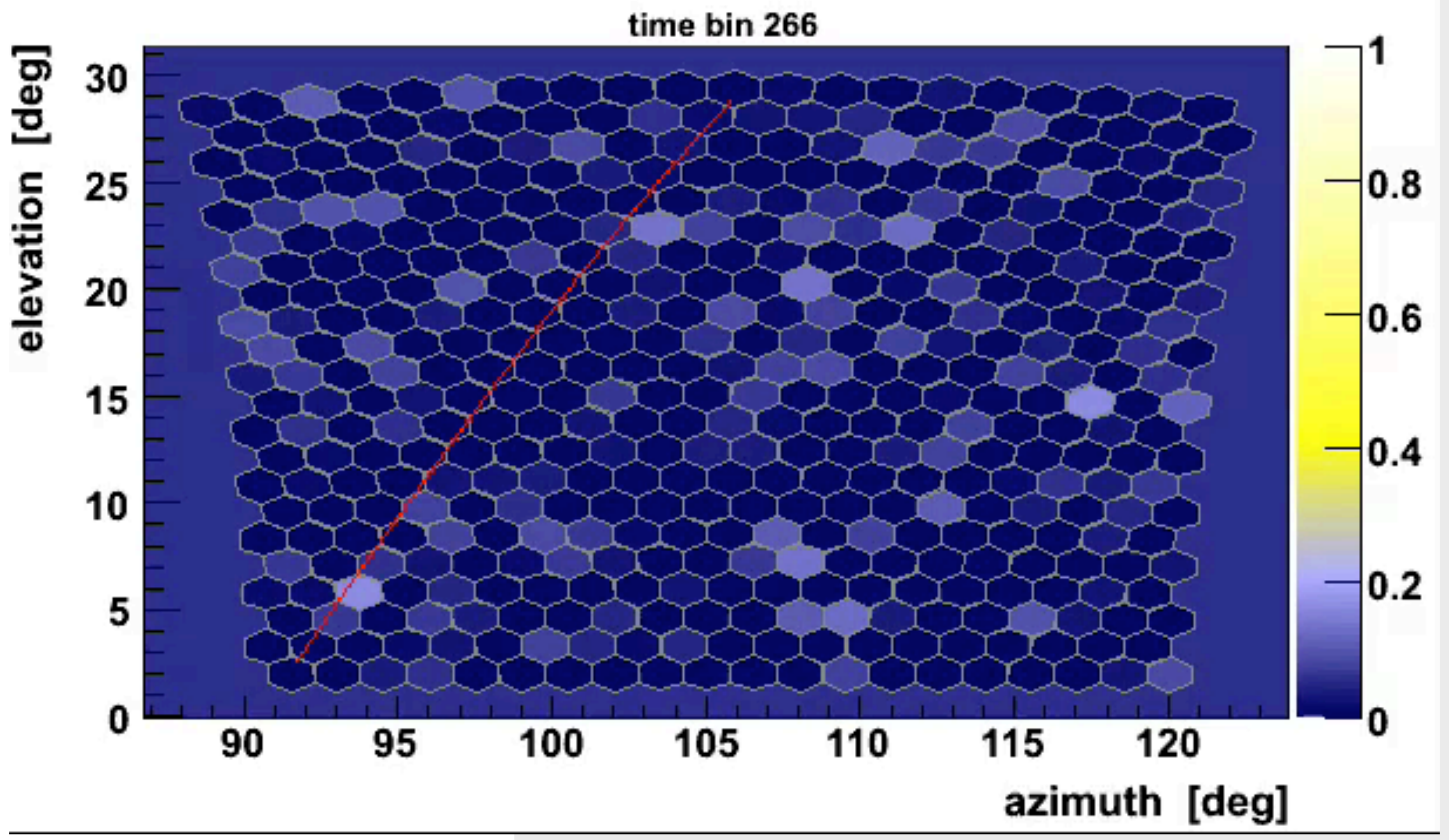
Measurement principles (hybrid observation)



$$E_{\mathrm{rec}} = f(S_{1000}, \theta)$$



$$E_{\mathrm{cal}} = \int_0^\infty \left(\frac{\mathrm{d}E}{\mathrm{d}X}\right)_{\mathrm{obs}} \mathrm{d}X$$

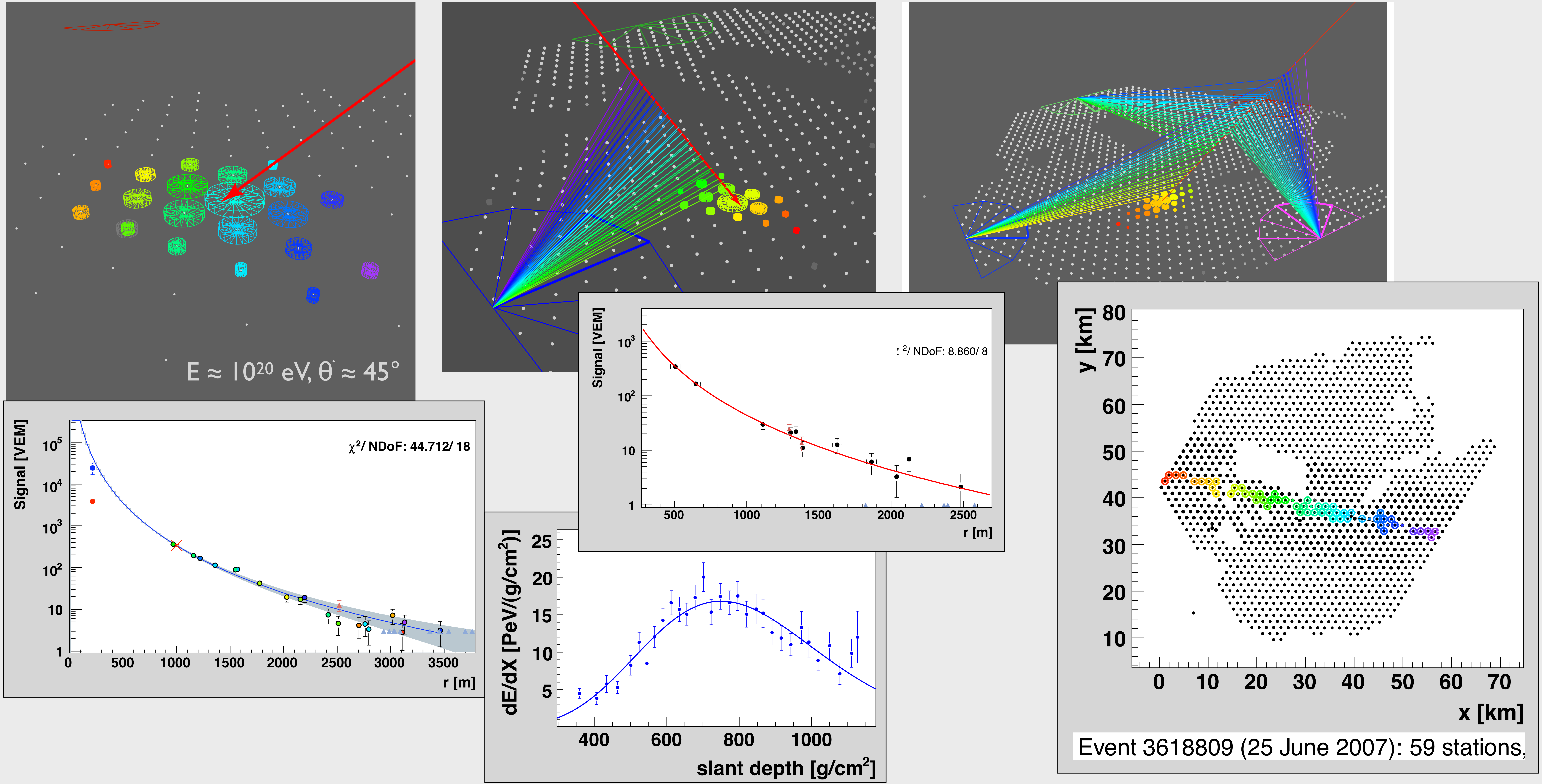


Fluorescence signal:

- calorimetric in shower energy
- calibration of surface detector array

Measurement principles (hybrid observation)

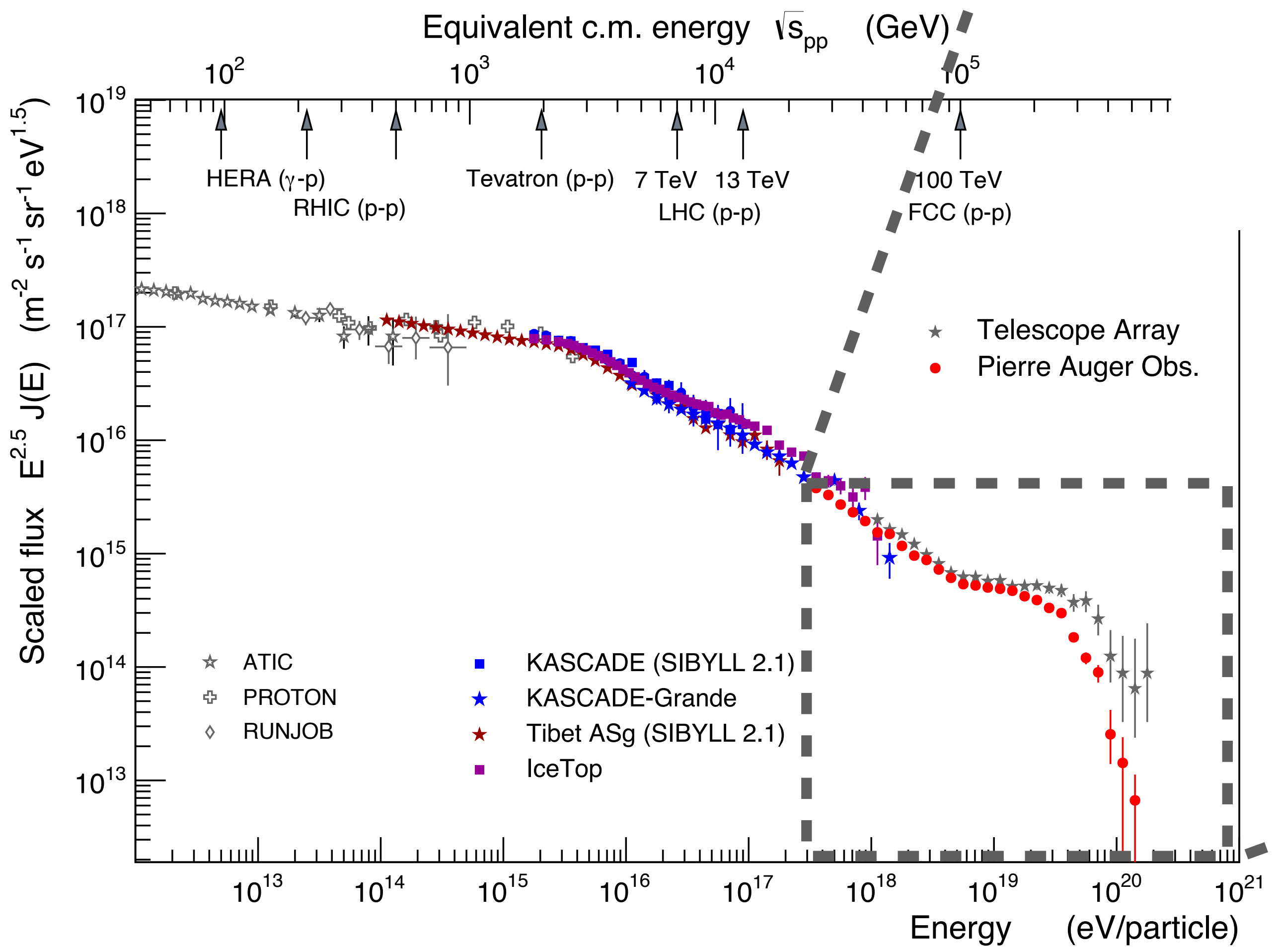
Examples of observed events

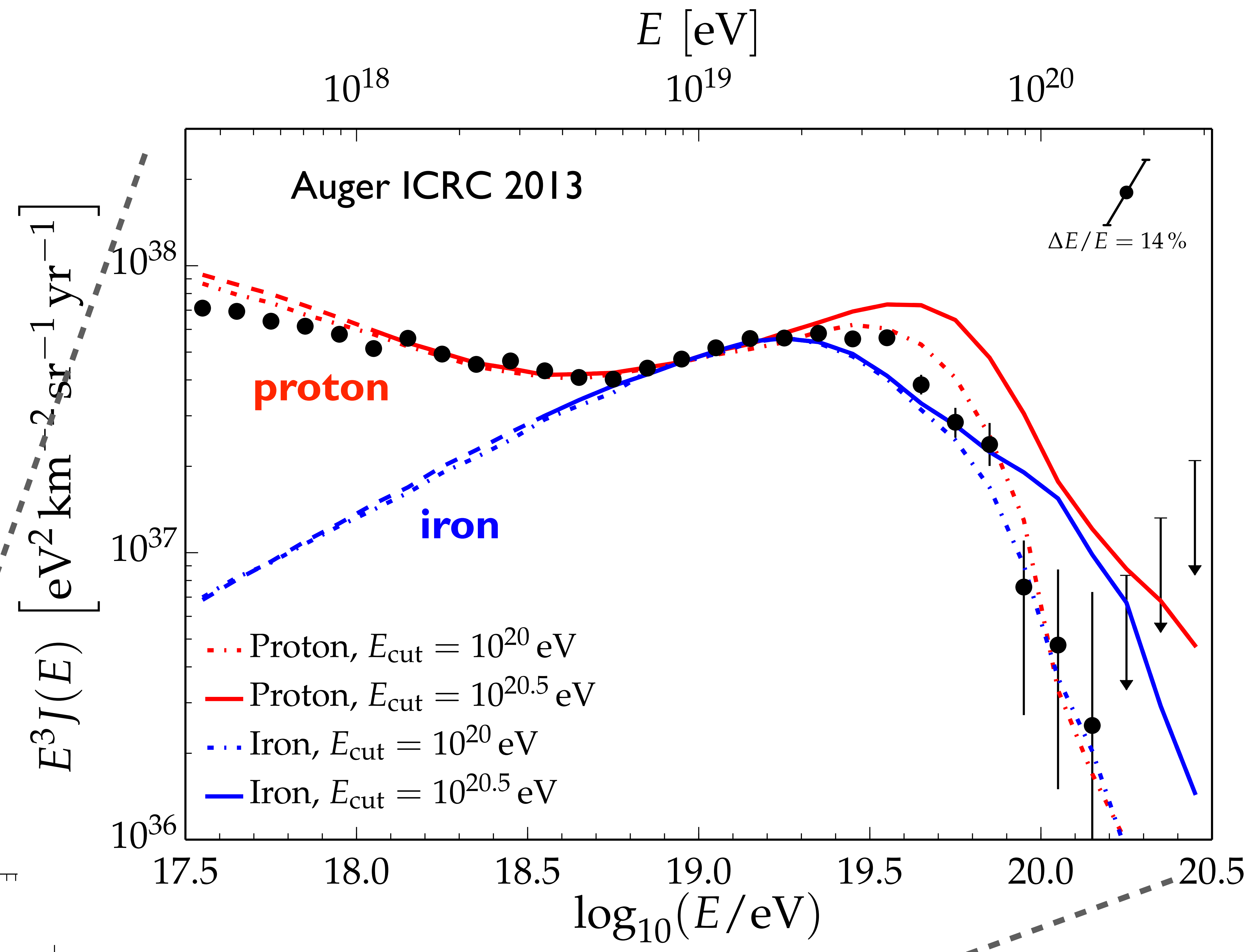


Energy spectrum 2013 and GZK expectation

Source spectrum

$$\frac{dN_{inj}}{dE} \sim E^{-\gamma} \exp\left(-\frac{E}{E_{cut}}\right)$$





Greisen-Zatsepin-Kuzmin (GZK) effect

Photo-pion production (mainly Δ resonance) and e^+e^- pair production

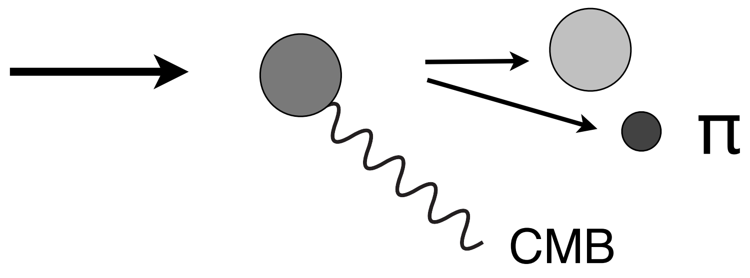
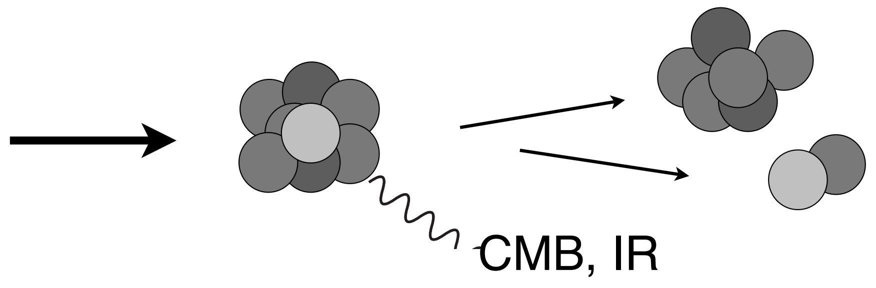


Photo-dissociation (giant dipole resonance)

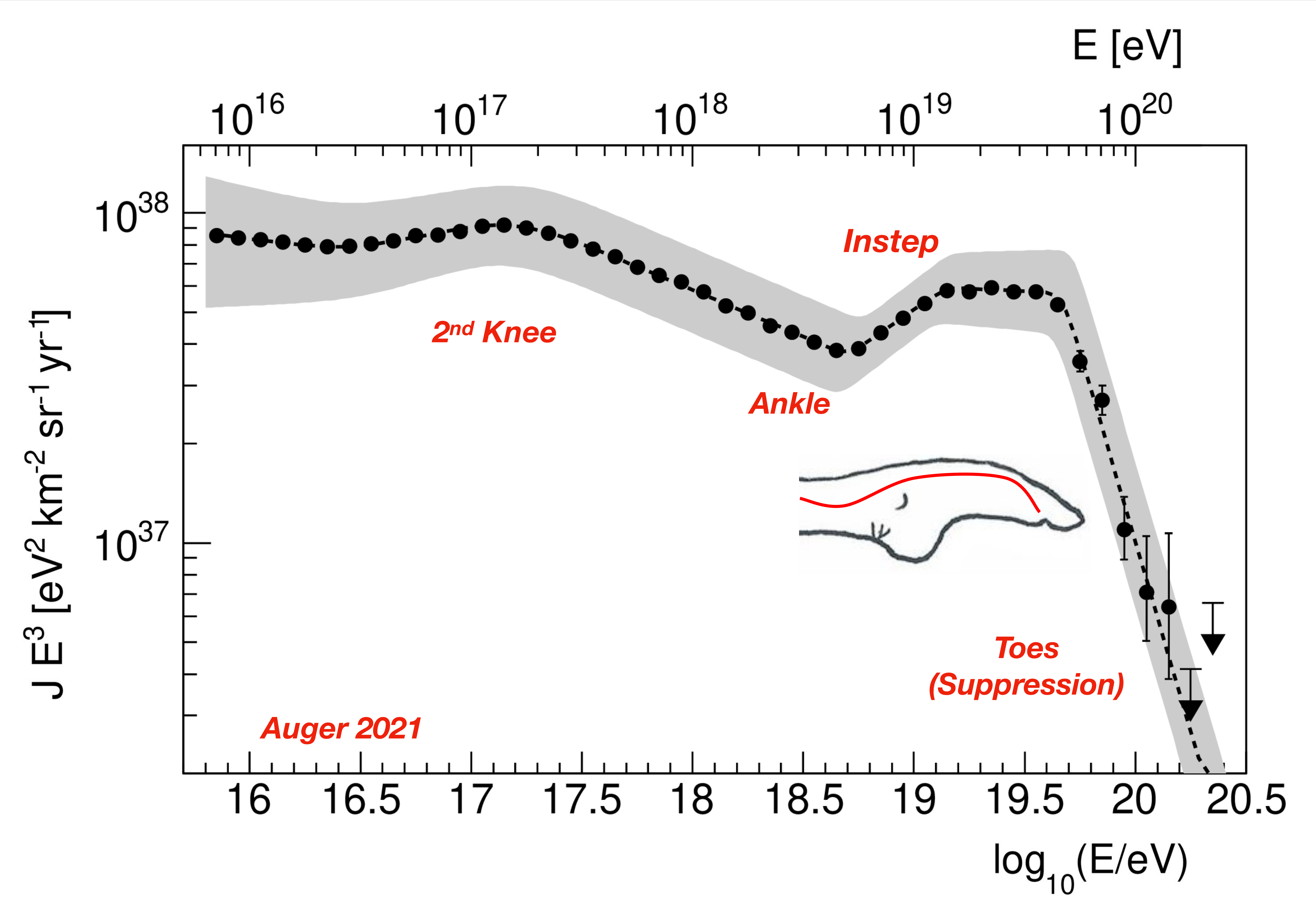


Iron dominated flux

Suppression: giant dipole resonance

Ankle: transition to galactic sources

Energy spectrum of Auger Observatory

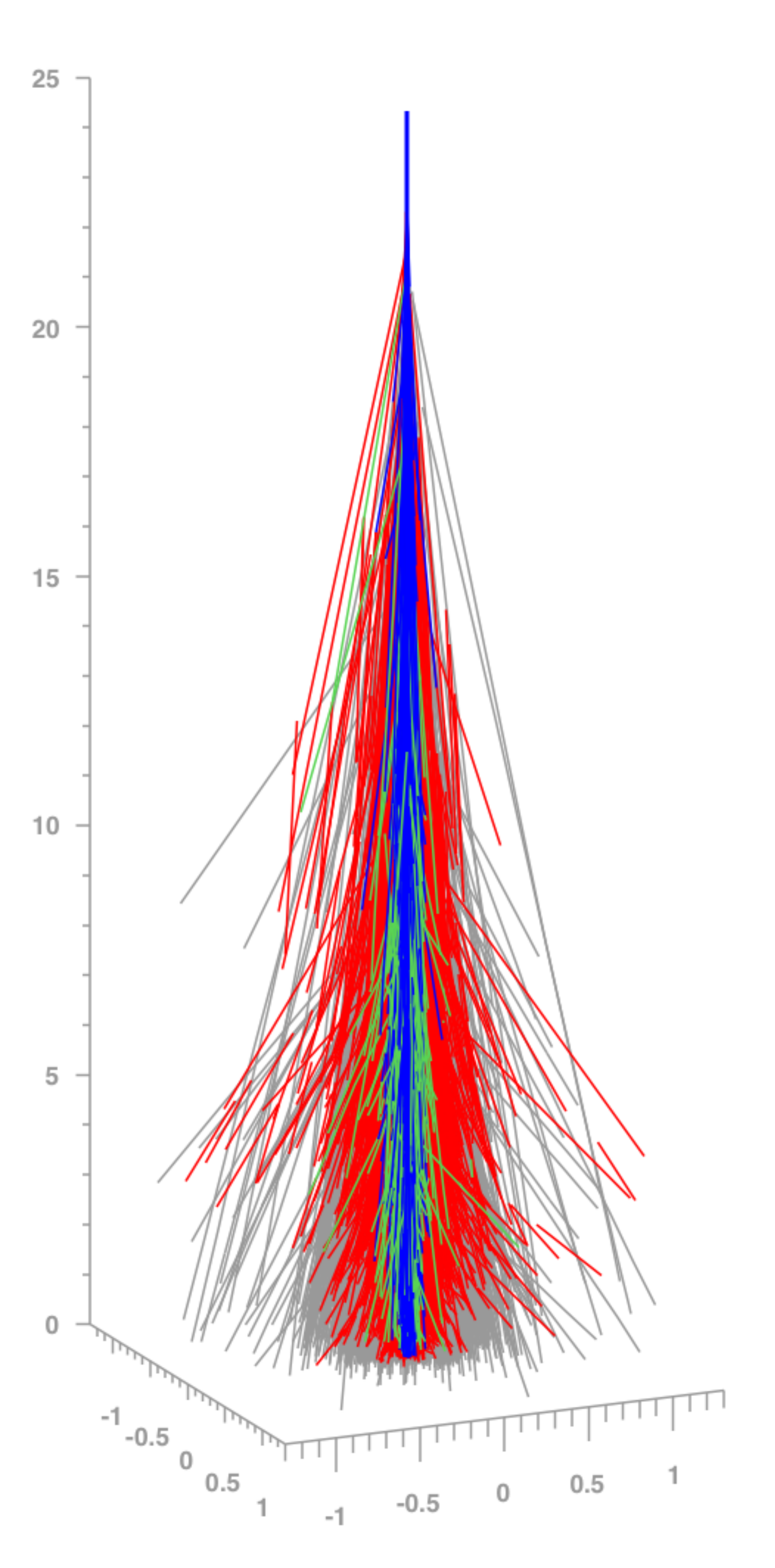


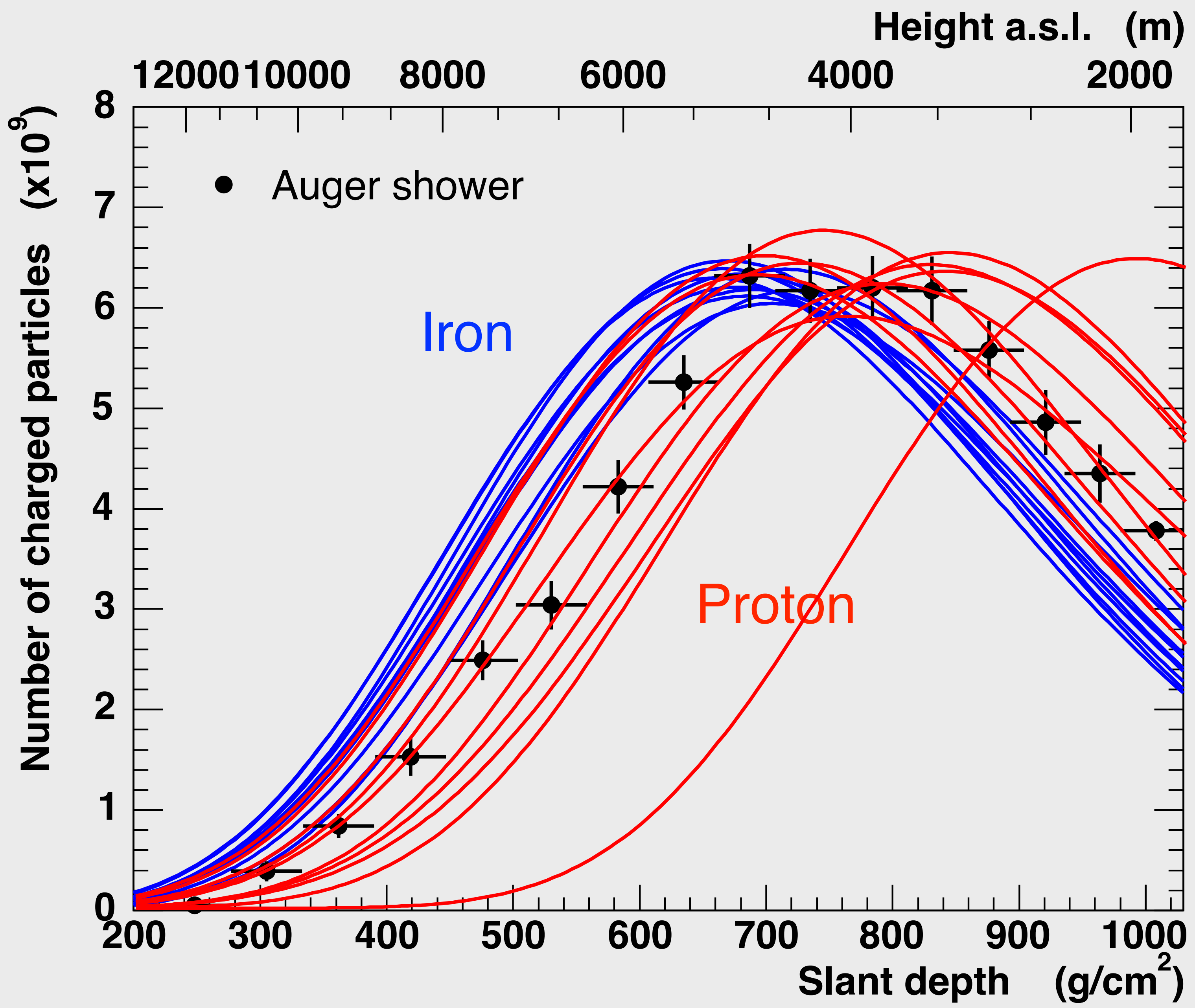
Phys. Rev. Lett. 125 (2020) 121106
Phys. Rev. D102 (2020) 062005
Eur. Phys. J. C81 (2021) 966

Band: uncertainty,
mainly 14% sys. energy scale

Spectrum shape and Instep not compatible with source models of single mass group (p, ..., Fe)

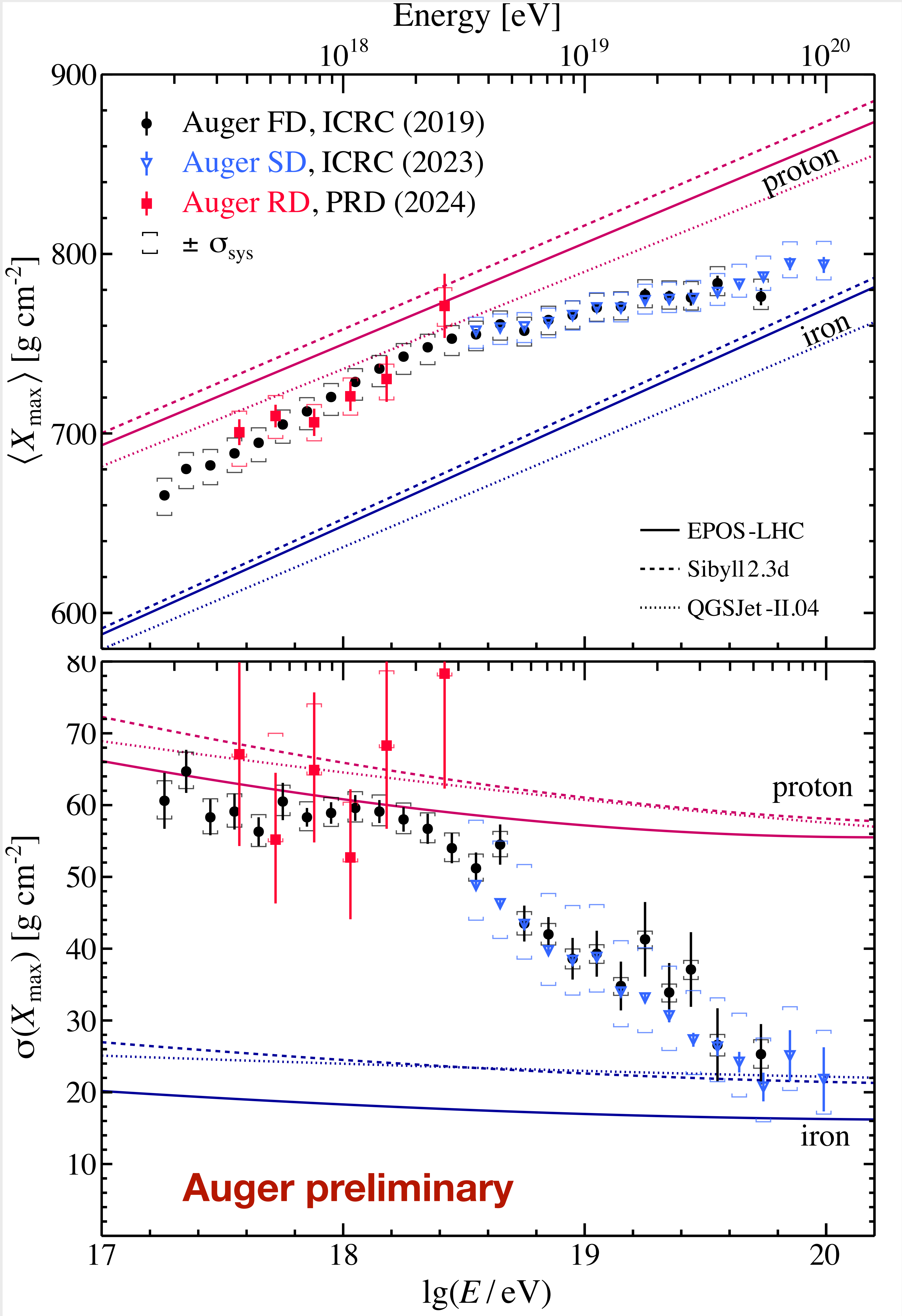
Depth of shower maximum





Example: event measured by Auger

Average X_{max}



Shower-by-shower fluctuations

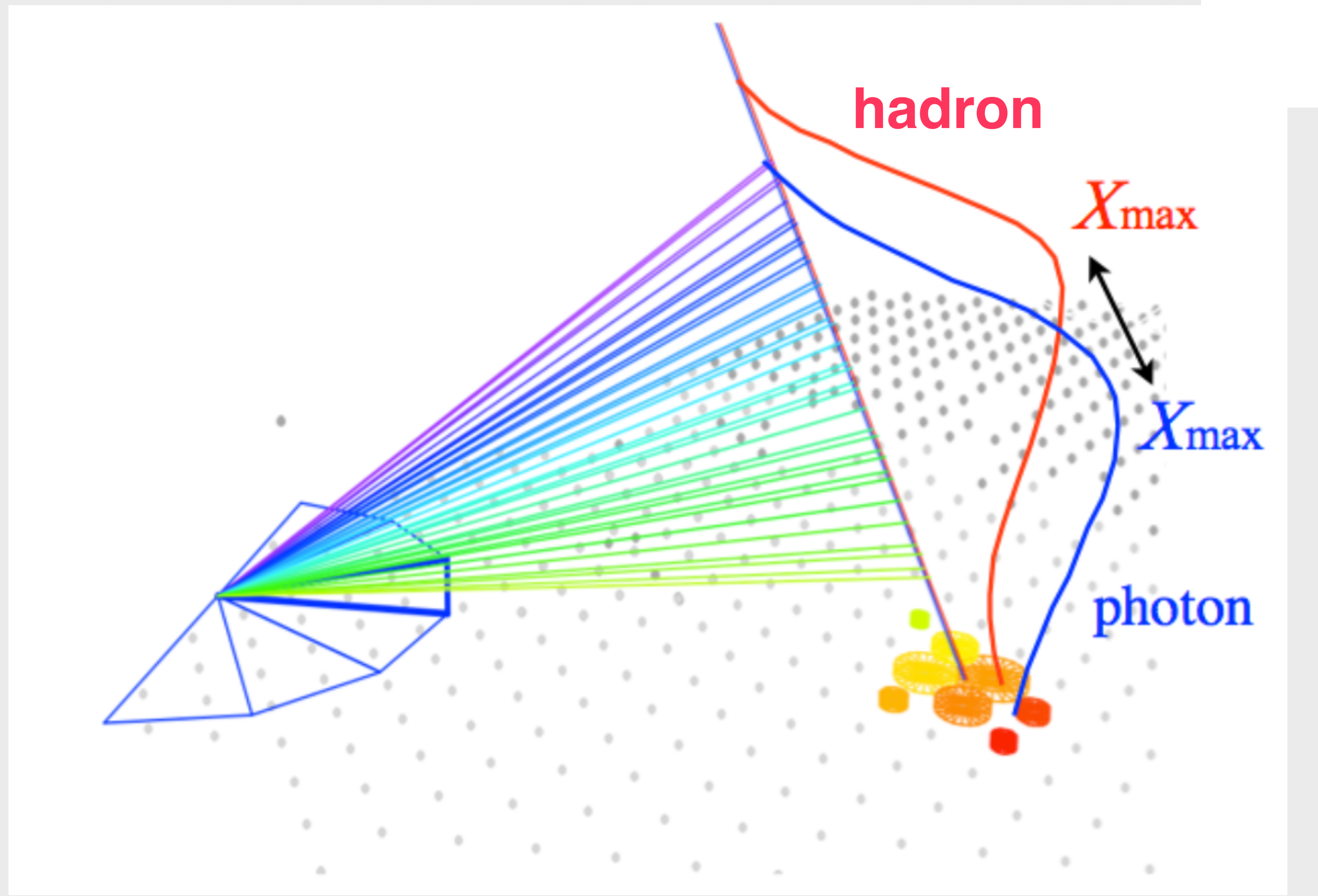
(FD telescopes: PRD 90 (2014), 122005 & 122005, updated ICRC 2023)

(SD risetime: Phys. Rev. D96 (2017), 122003)

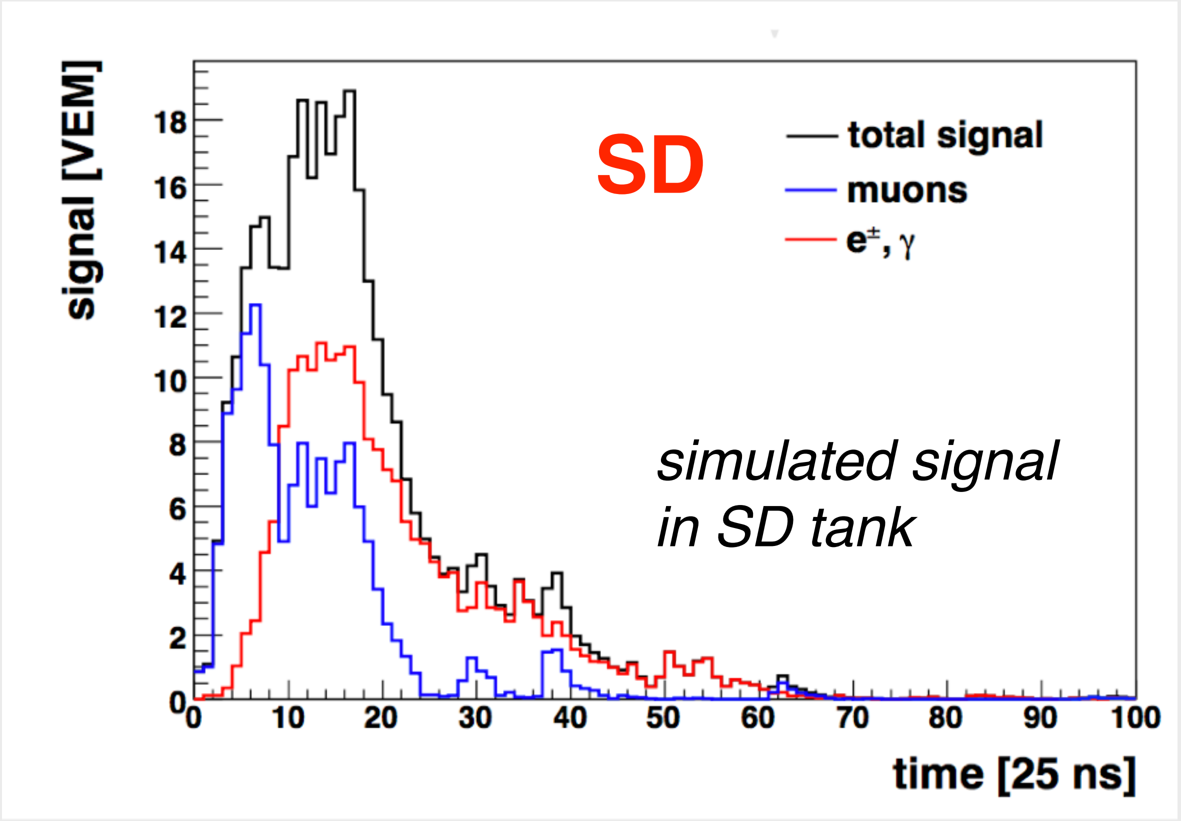
(AERA/radio: Phys. Rev. Lett. 132 (2024) 021001 & PRD 2024)

(SD DNN: ICRC 2023, to be published)

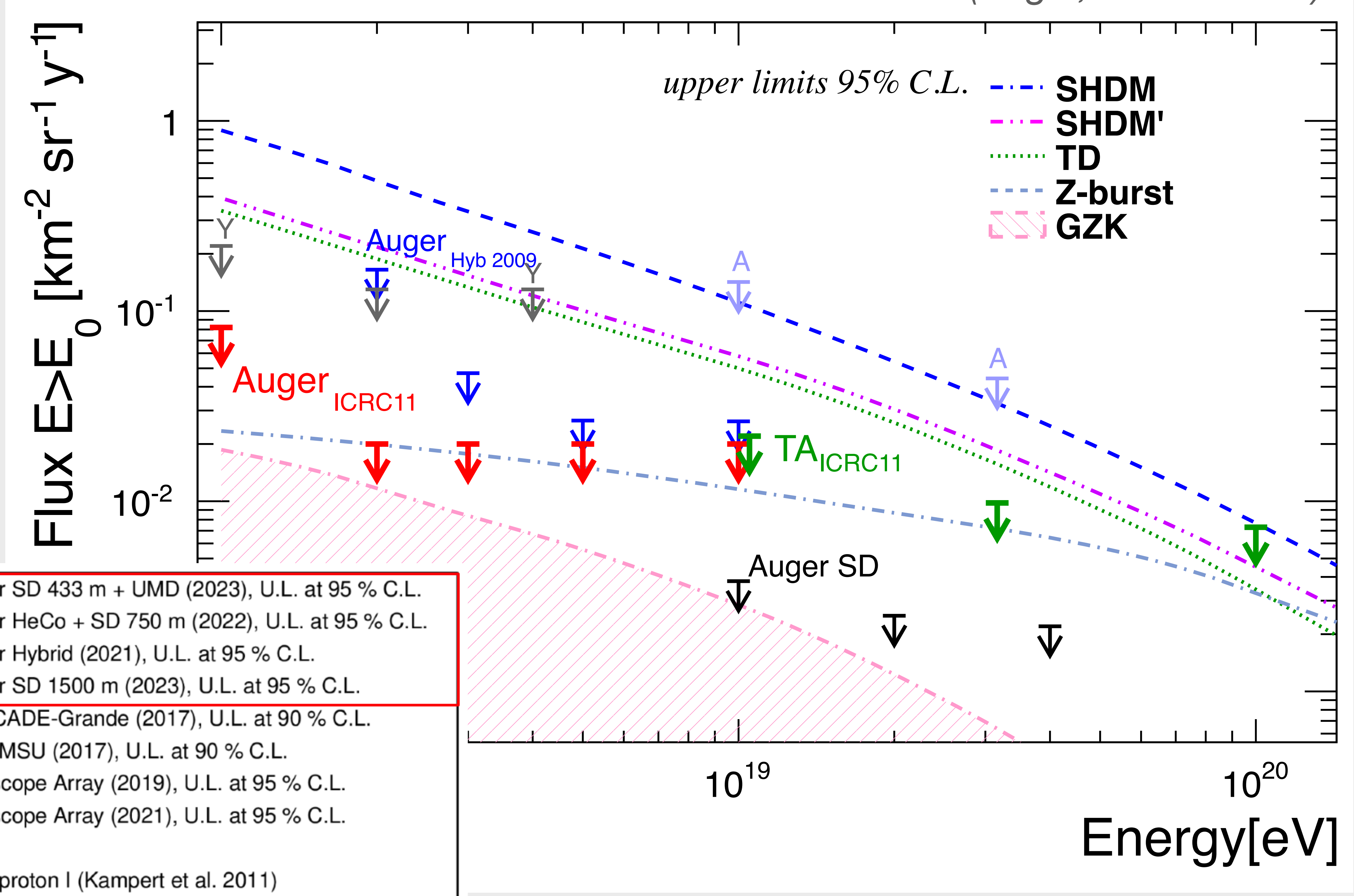
Multi-messenger searches: photons



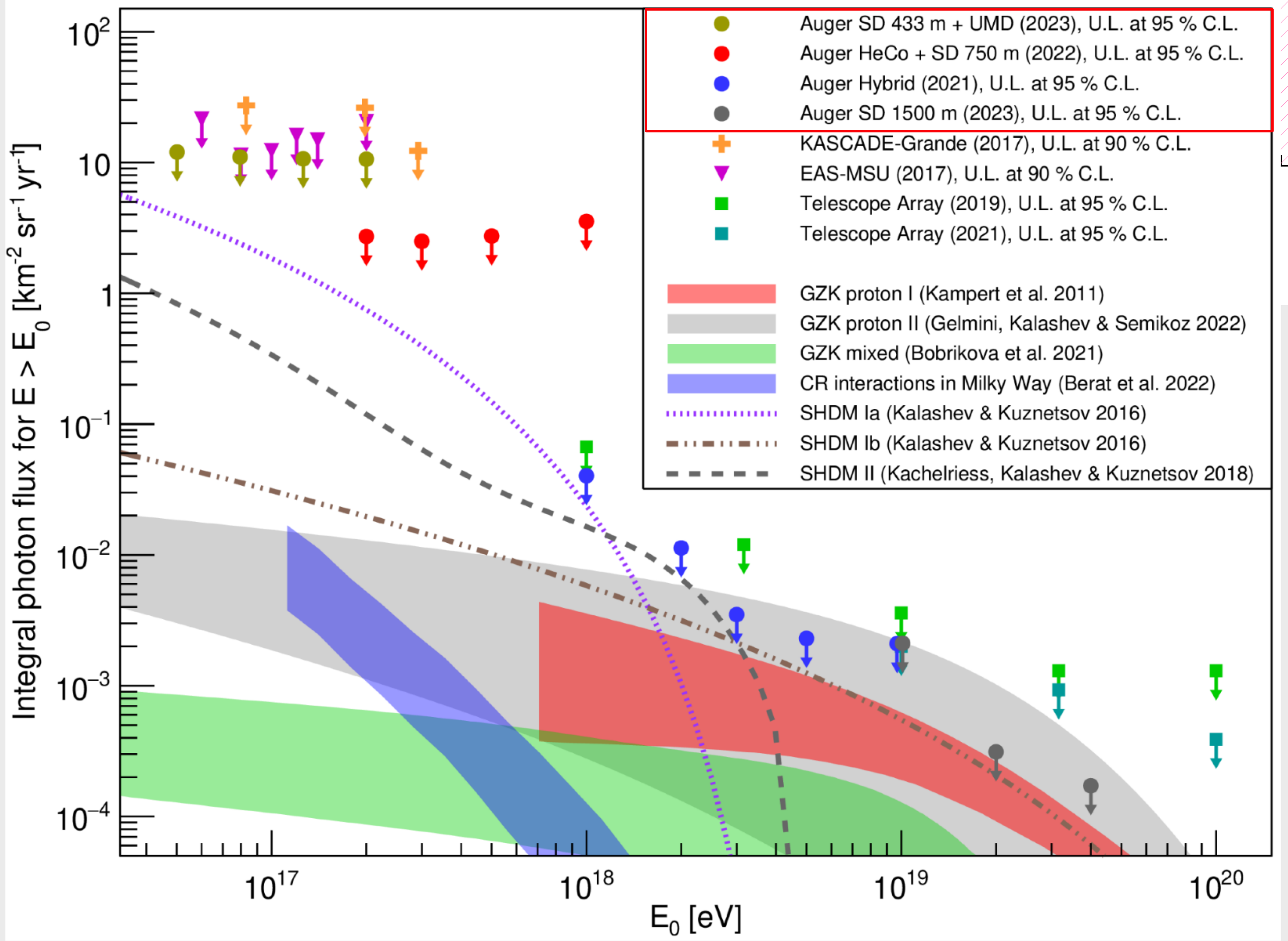
Photons interact deeper (larger X_{max}), fewer muons (rise time, lateral slope)



(Auger, 2006 – 2011)



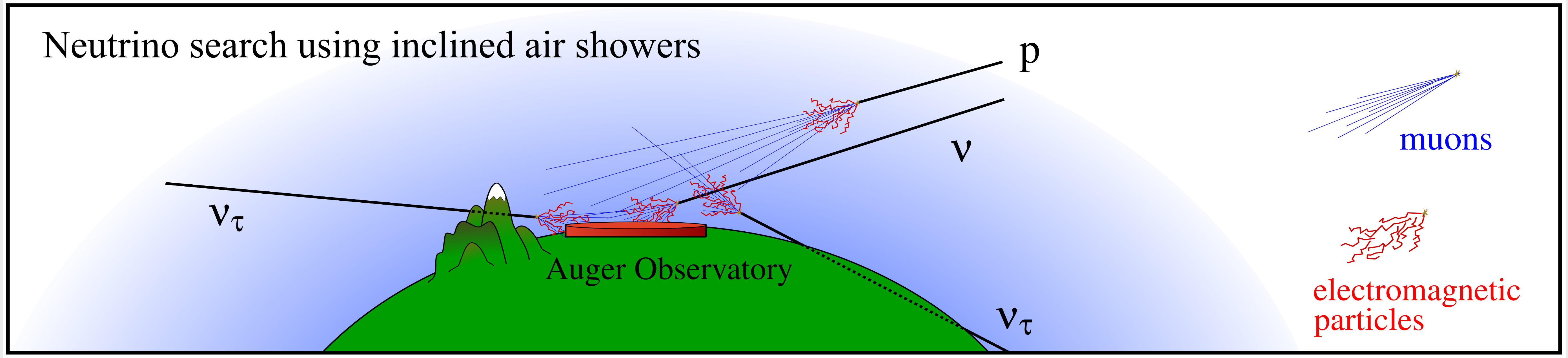
(Auger, ICRC 2023)

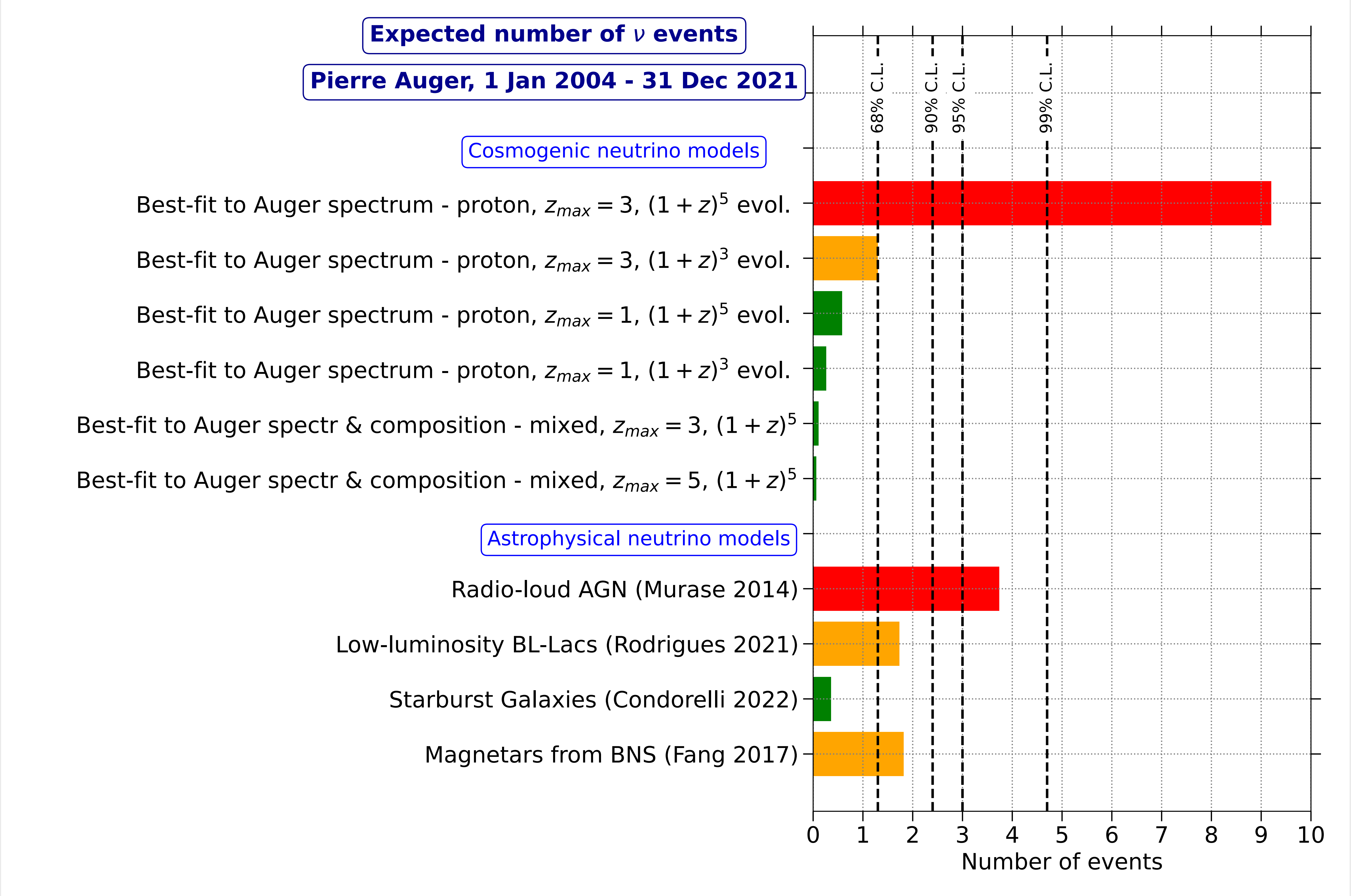


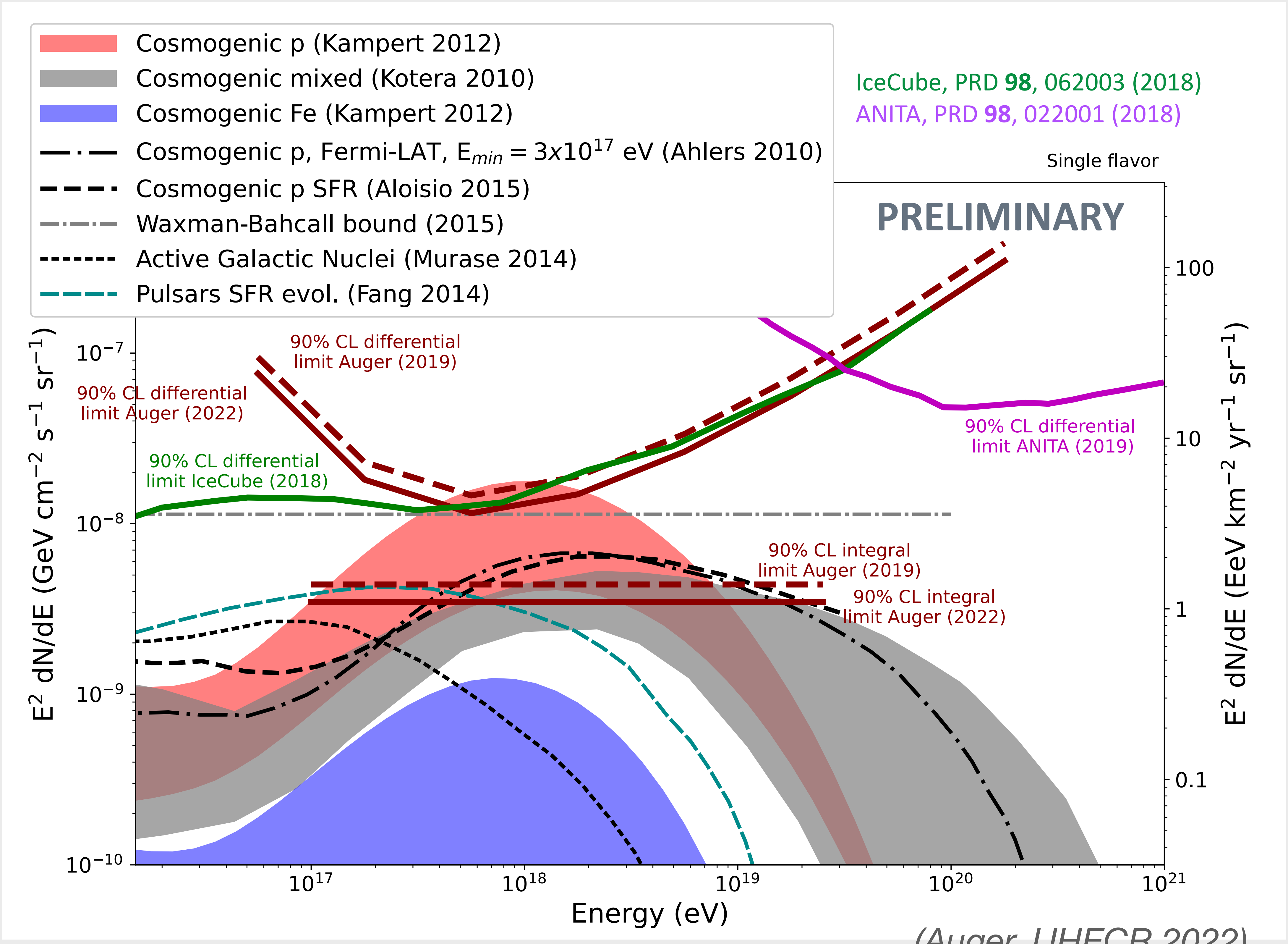
Exotic processes as dominant sources excluded

Sensitivity reaches GZK predictions

Multi-messenger searches: neutrinos





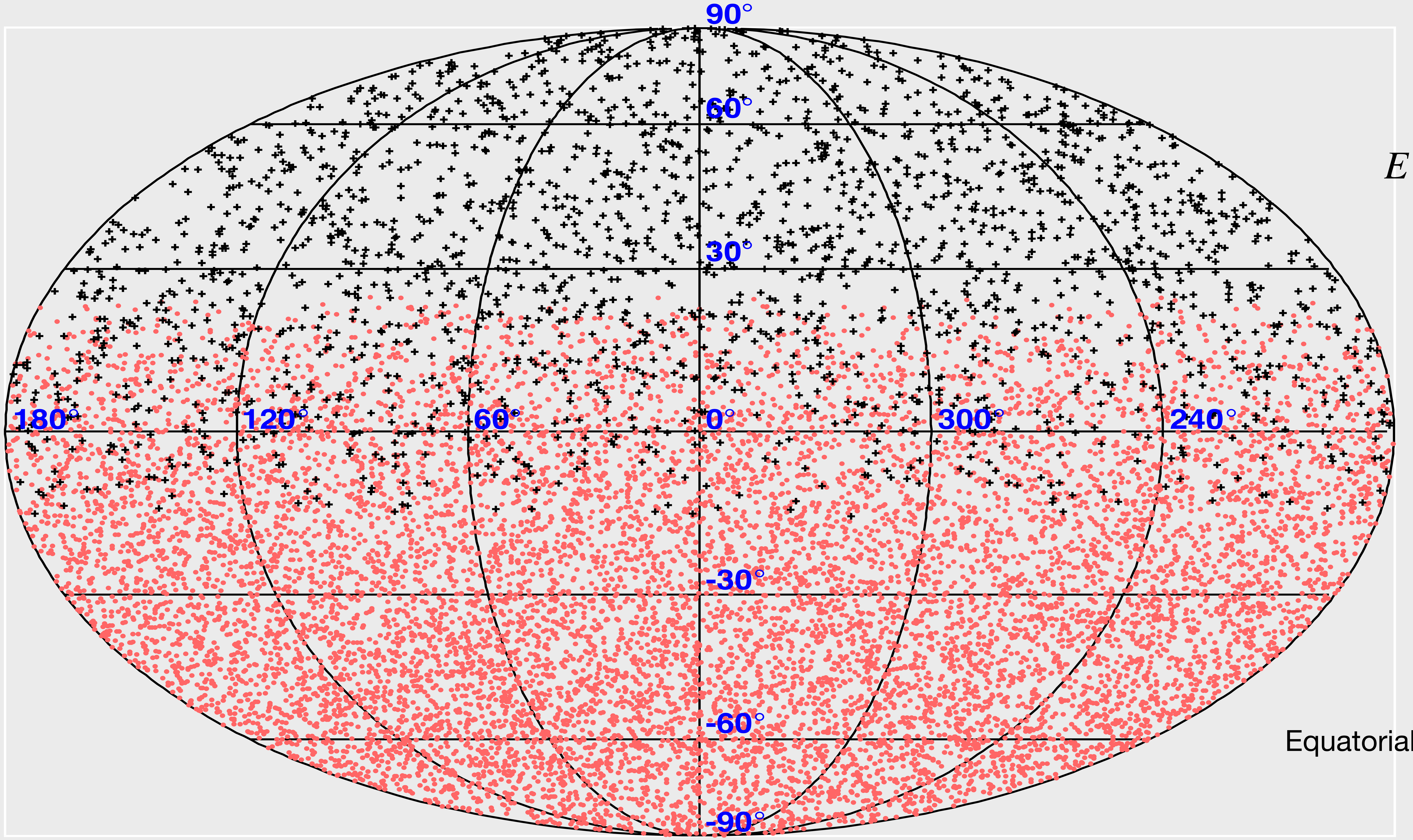


(Auger, UHECR 2022)

Neutrino sensitivity better than Waxman-Bahcall bound
Limits constrain GZK & astrophysical neutrino models

Arrival direction distribution surprisingly isotropic

TA data



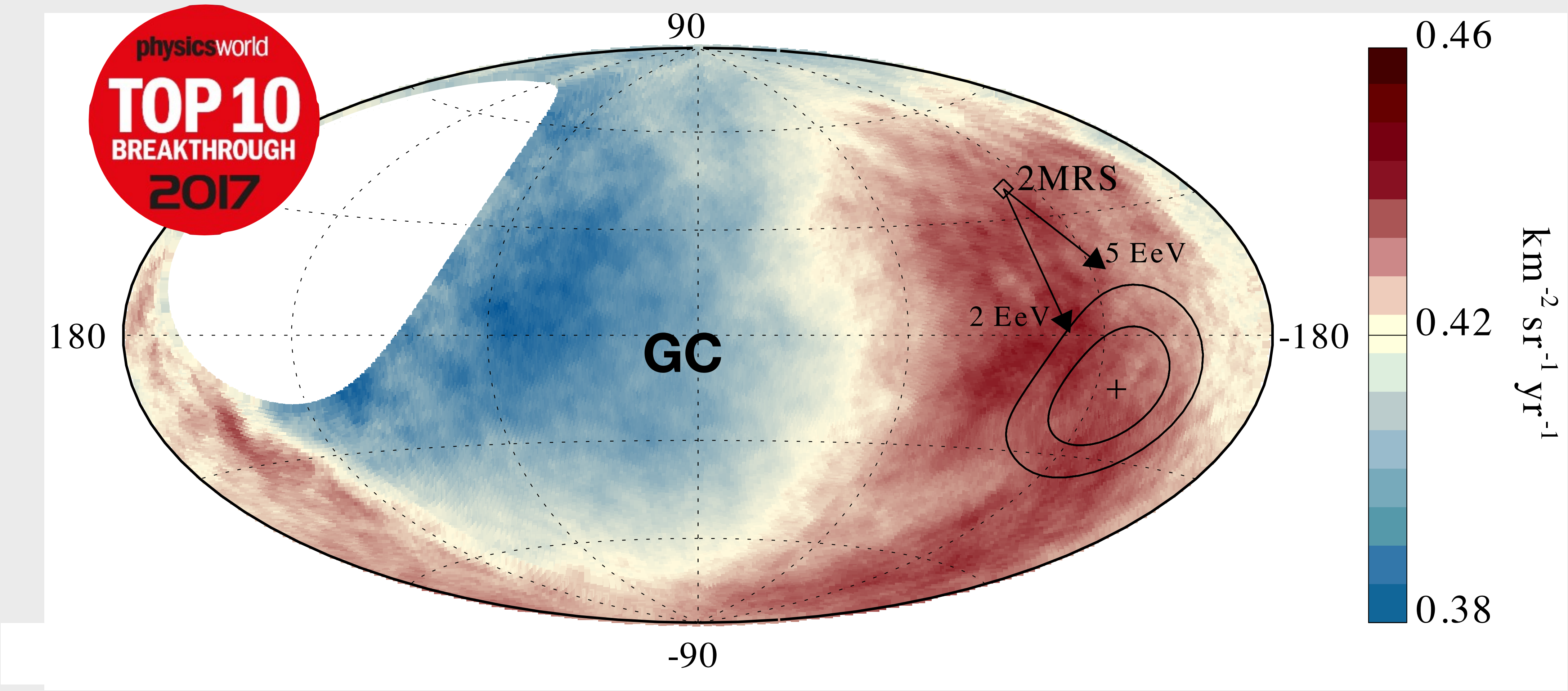
Auger data

$E > 10^{19}\,\mathrm{eV}$

Equatorial coordinates

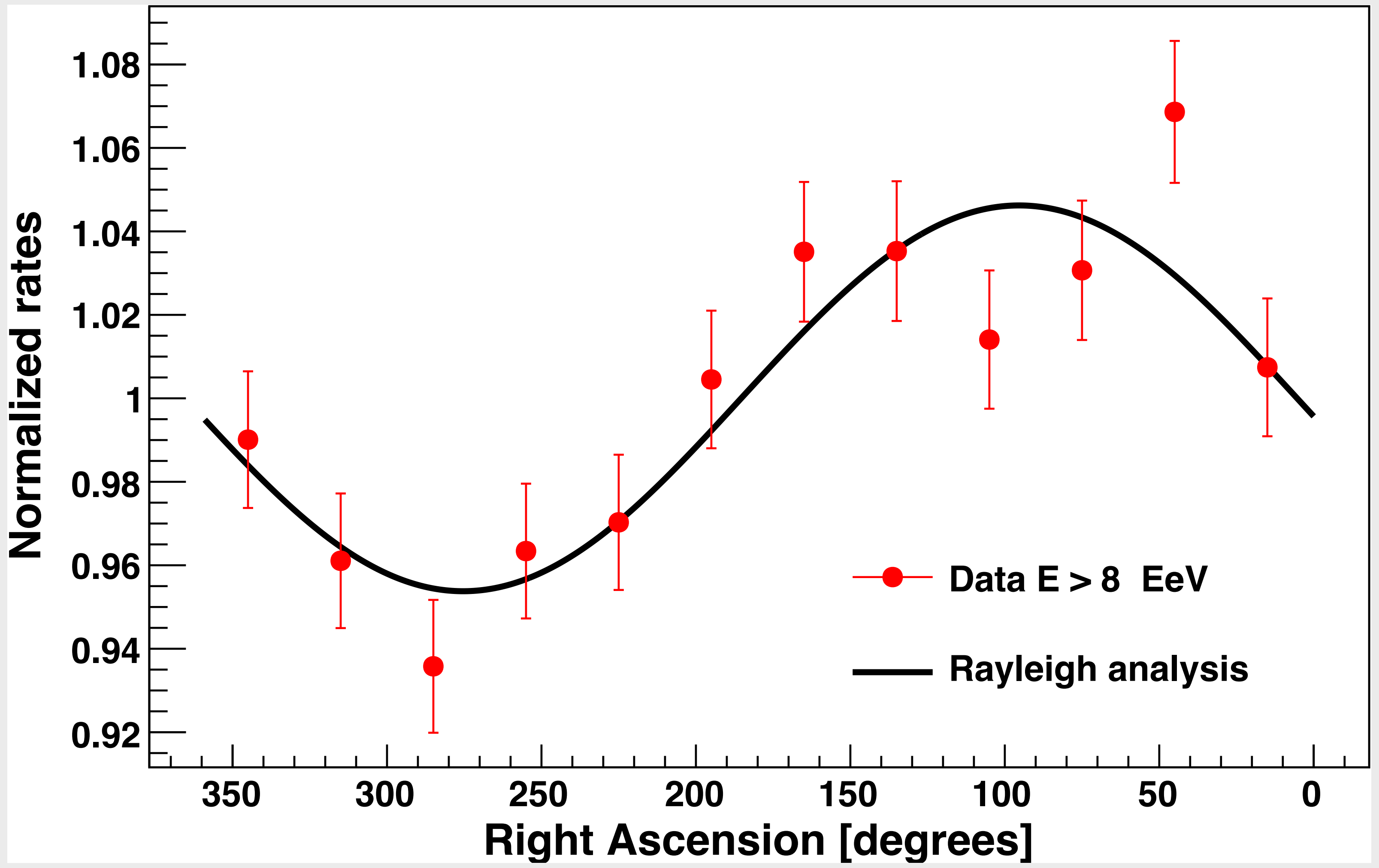
Pierre Auger and TA Collaborations, ApJ **794** (2014) 2, 172

Arrival directions – large angular scales

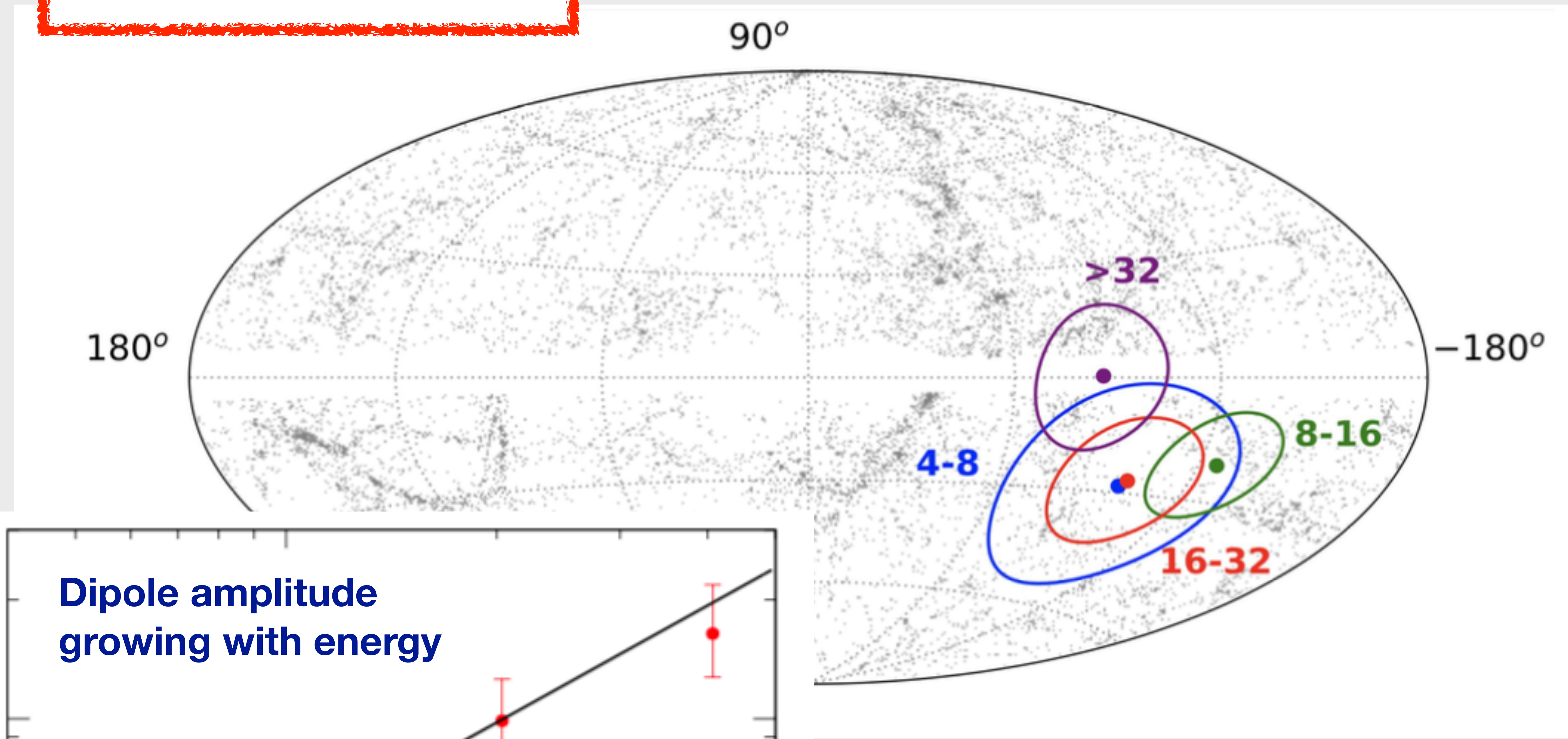


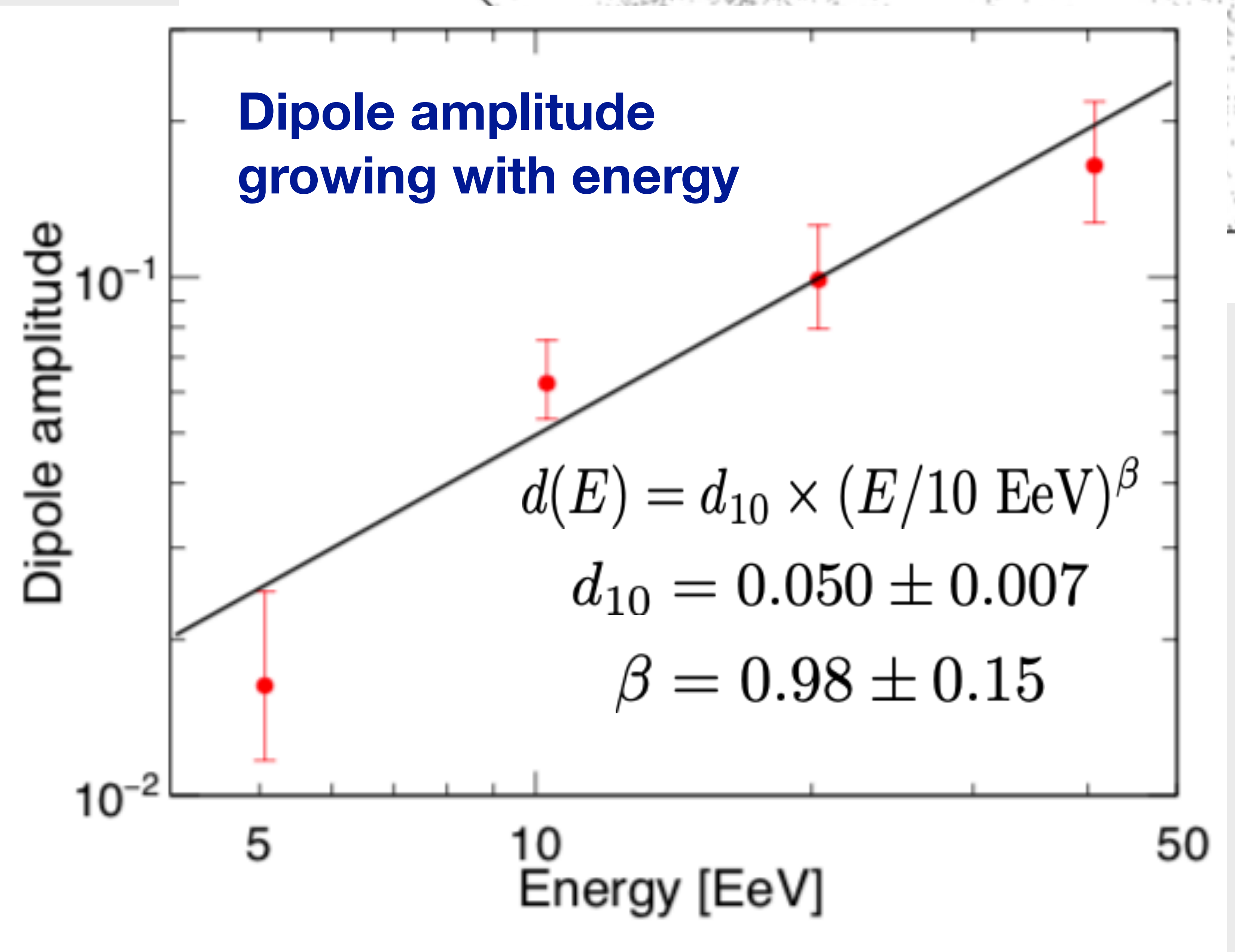
6.5% dipole at 6.9 σ (post rial)

(Science 357 (2017) 1266, update ICRC 2023)



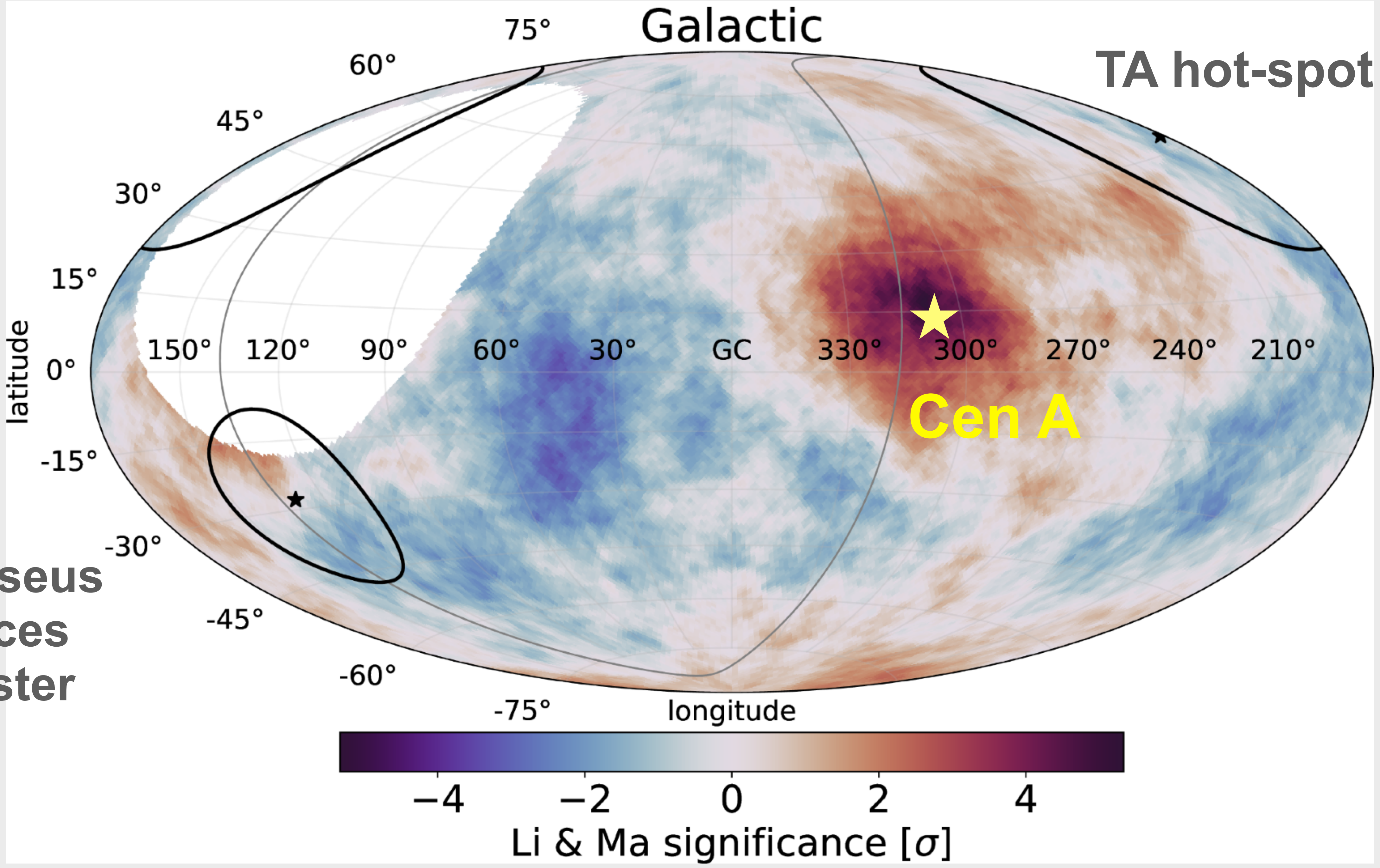
$$E > 8 \times 10^{18}\,\mathrm{eV}$$

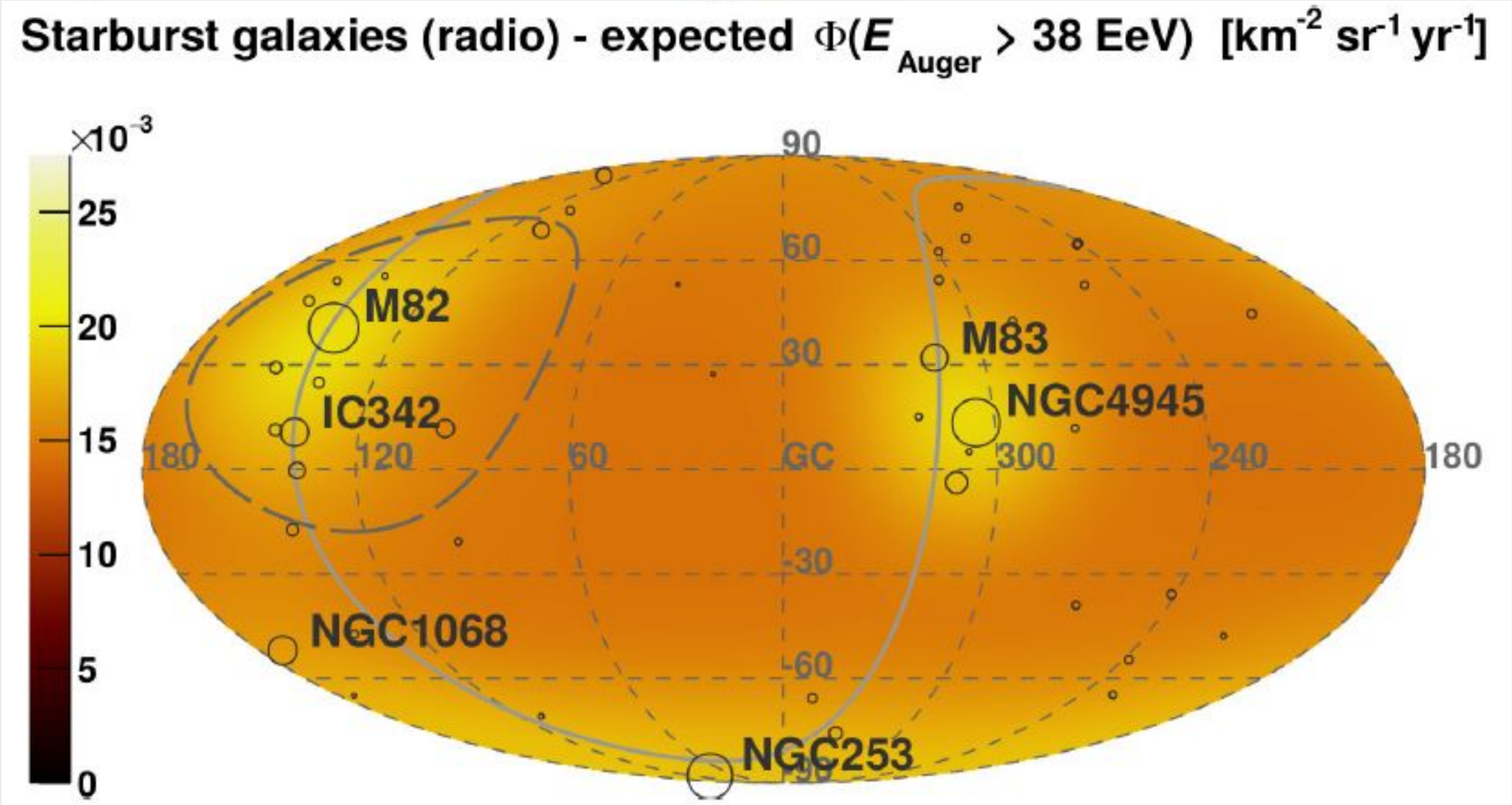


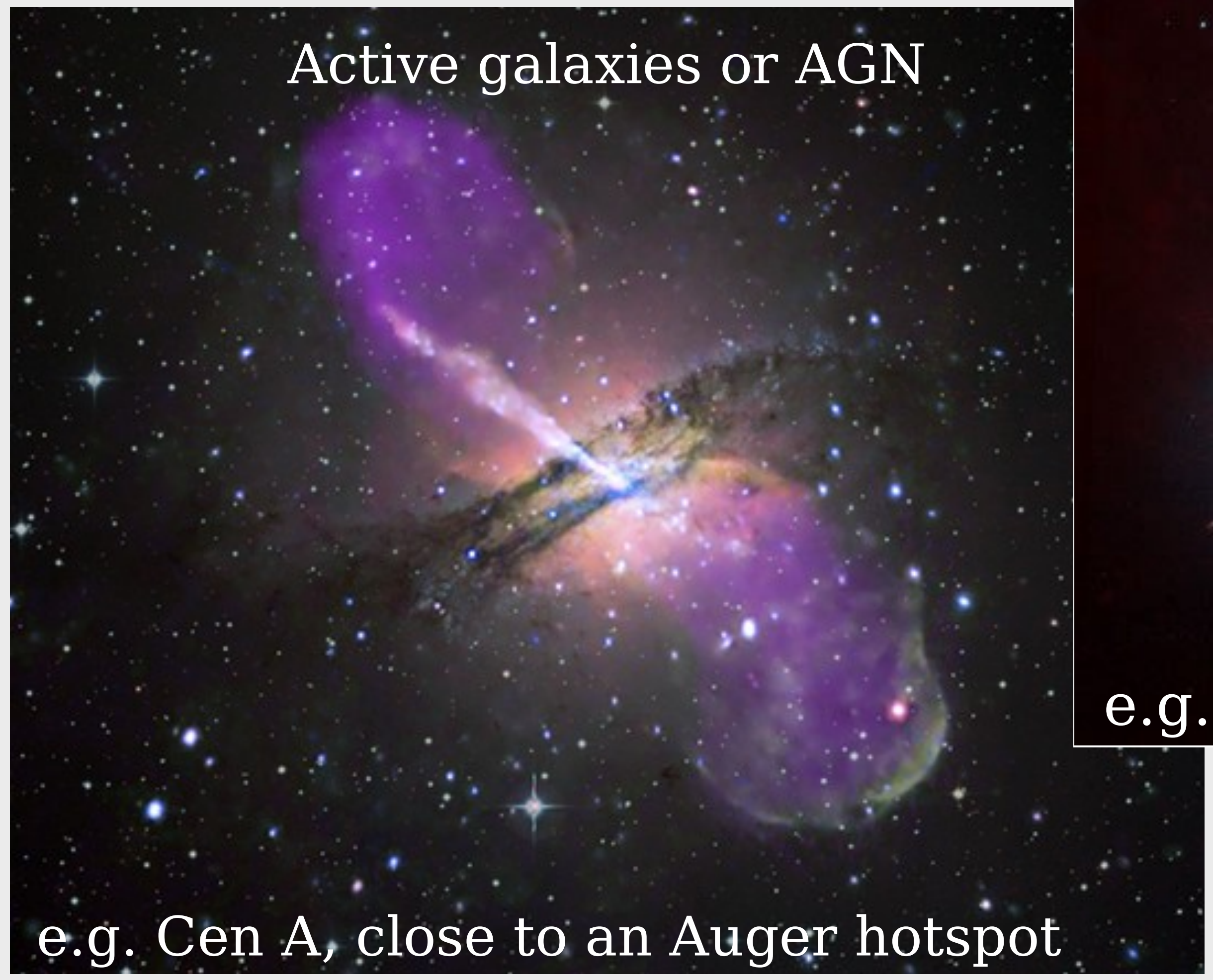


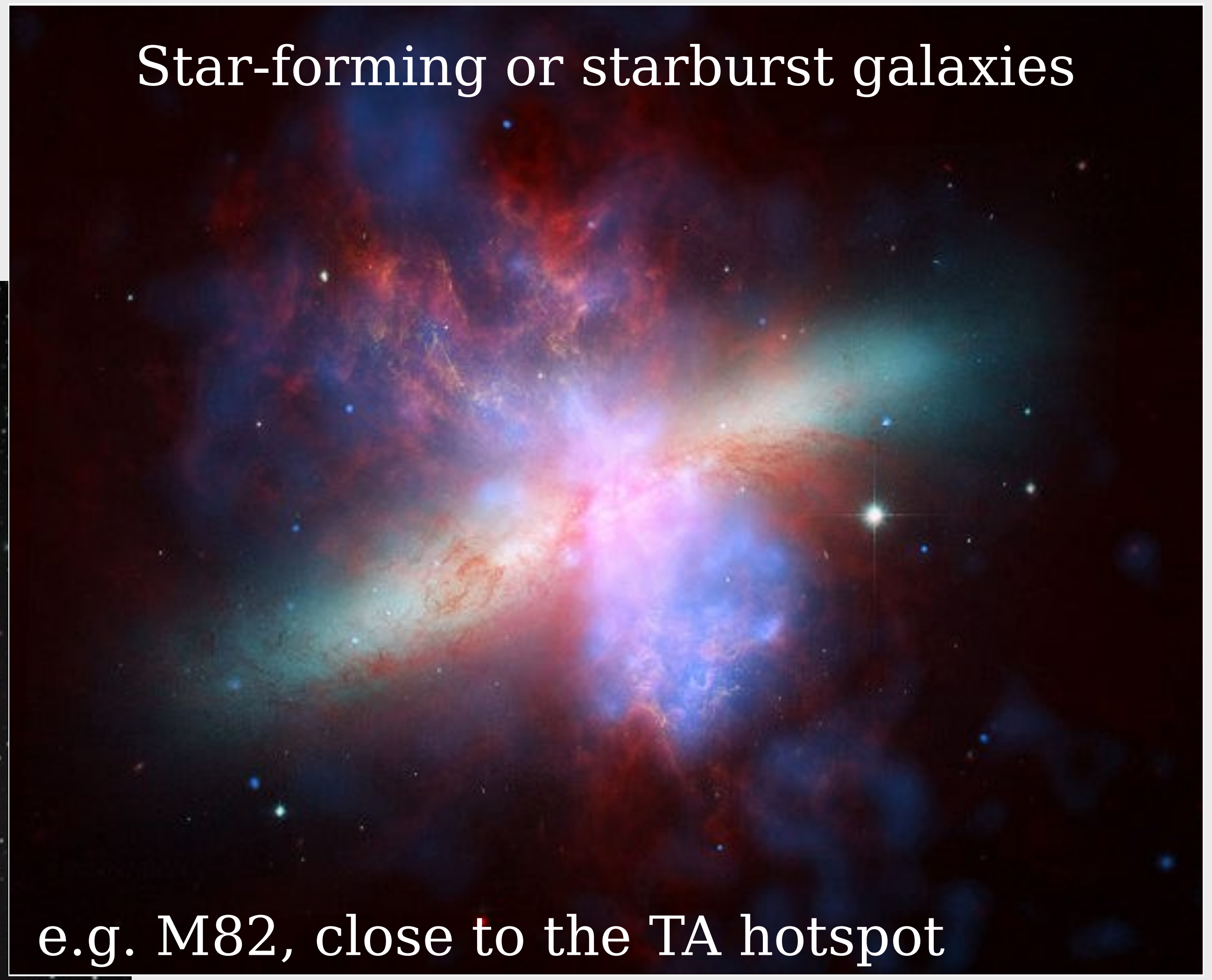
Dipole points away from Galactic Center: extragalactic origin

Arrival directions – high-energy anisotropy searches









Centaurus A: E > 3.8 10^{19} eV, ~27° radius, 4.0 σ (post trial)

Starburst galaxies: E > 3.8 10^{19} eV, ~25° radius, 3.8 σ (post trial)

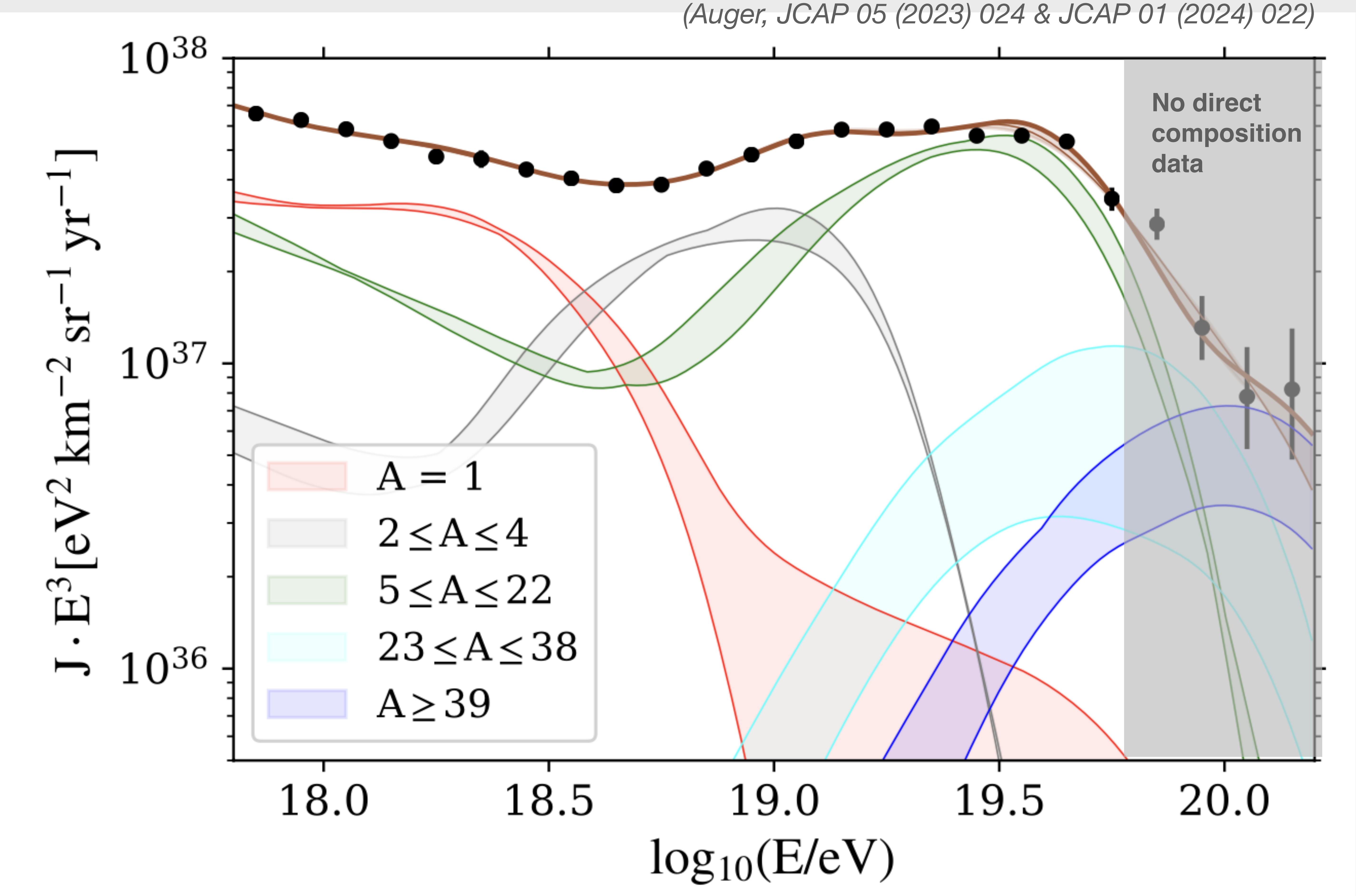
Discovery level of 5σ expected only after 2025

First probe of TA over-densities thanks to inclined showers

(Astrophysical Journal, 935:170, 2022, update ICRC 2023)

Interpretation of data

Model calculations for mass composition and flux



Assumption: source injection spectra universal in rigidity *R* = *E*/*Z* (acceleration, scaling with charge *Z*)

Transition to heavier nuclei

$$E_{\mathrm{p,cut}} = 1.4 \ldots 1.6 \times 10^{18}\,\mathrm{eV}$$

Exceptionally hard injection spectrum

$$\frac{\mathrm{d}N}{\mathrm{d}E} \sim E^{1.5\ldots2}$$

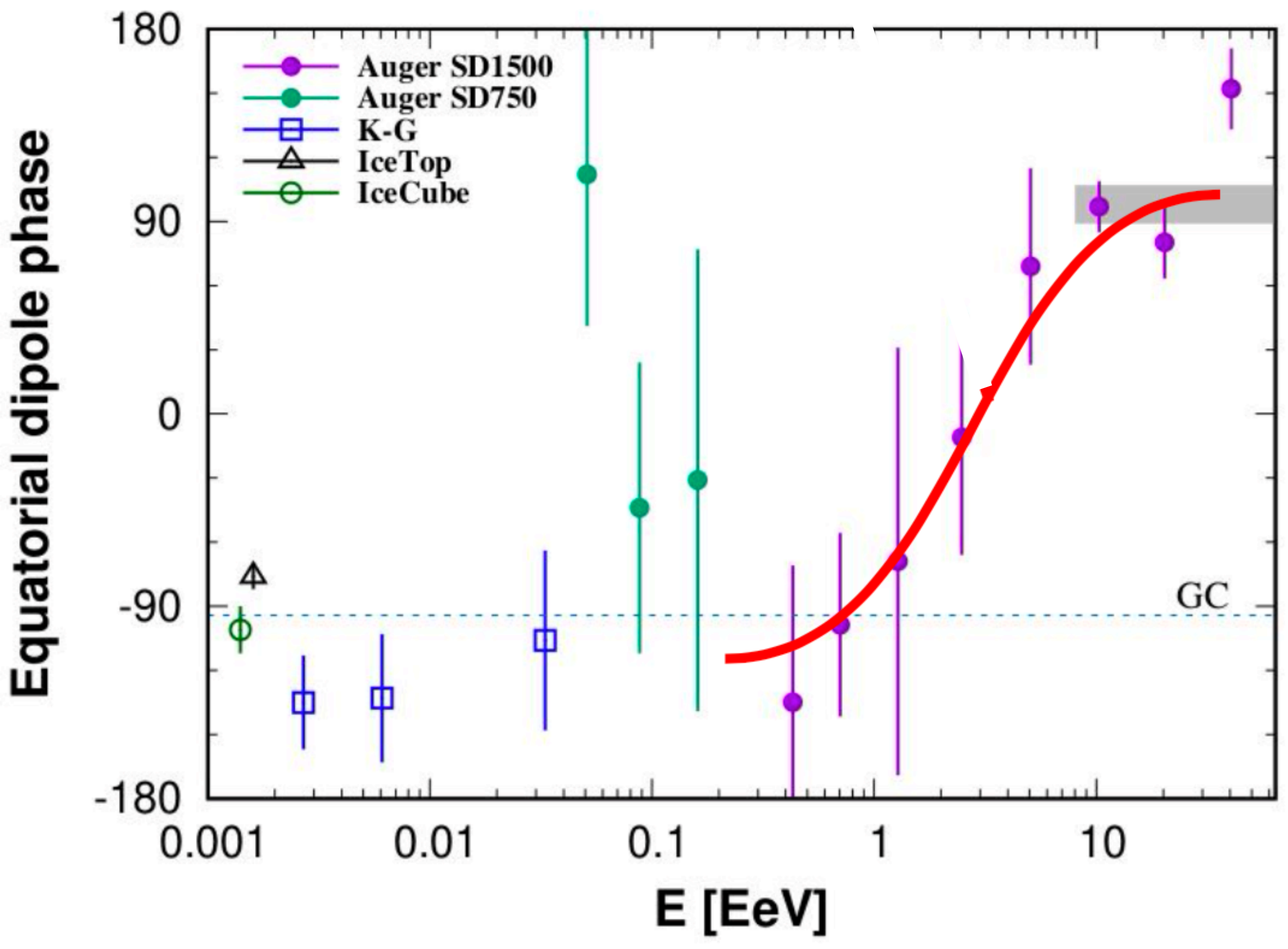
Fermi acceleration

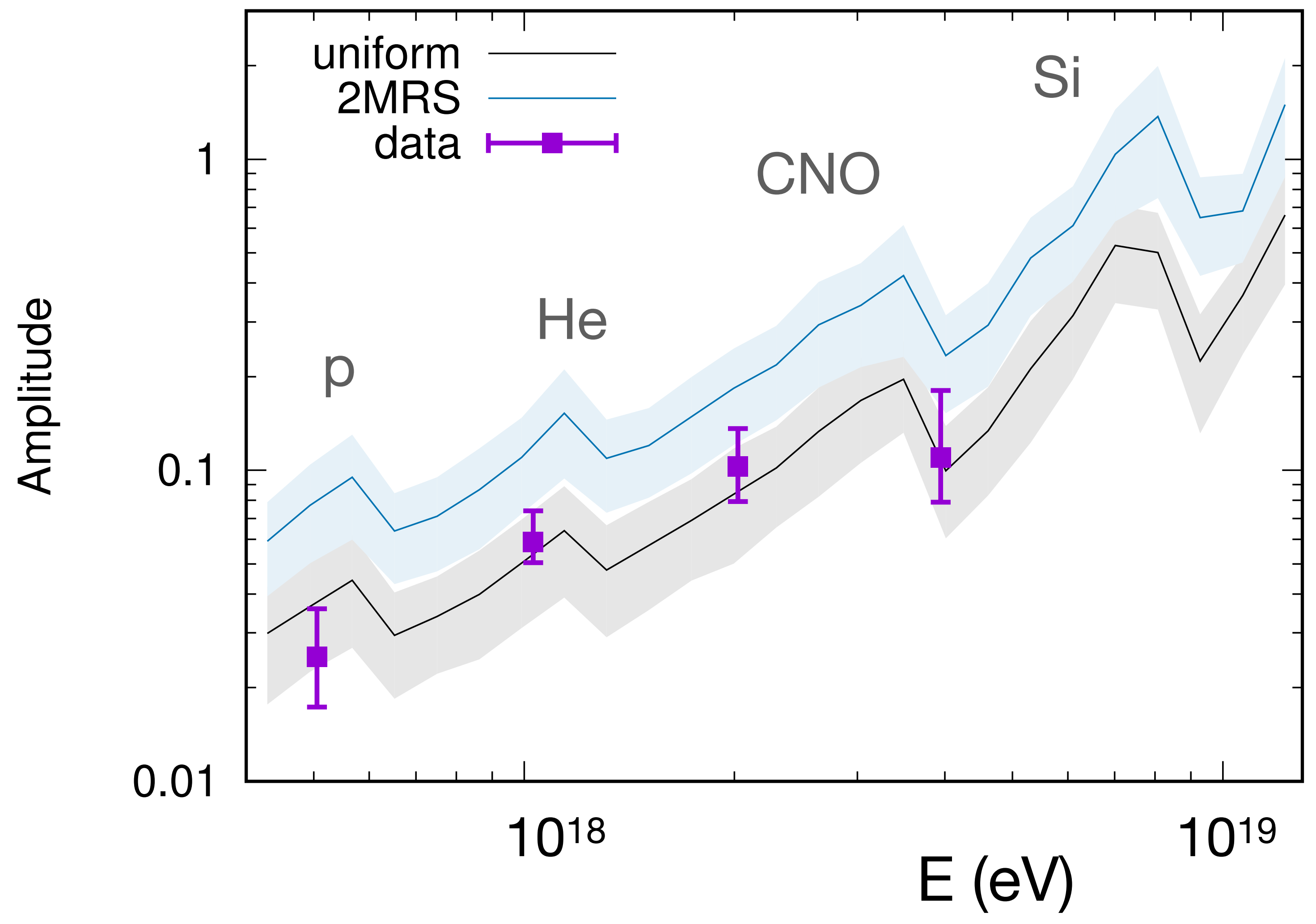
$$E^{-2\ldots-2.3}$$

Flux suppression due mainly to limit of injection energy of sources

Extragalactic origin of dipole anisotropy

Direction and energy dependence of extragalactic dipole



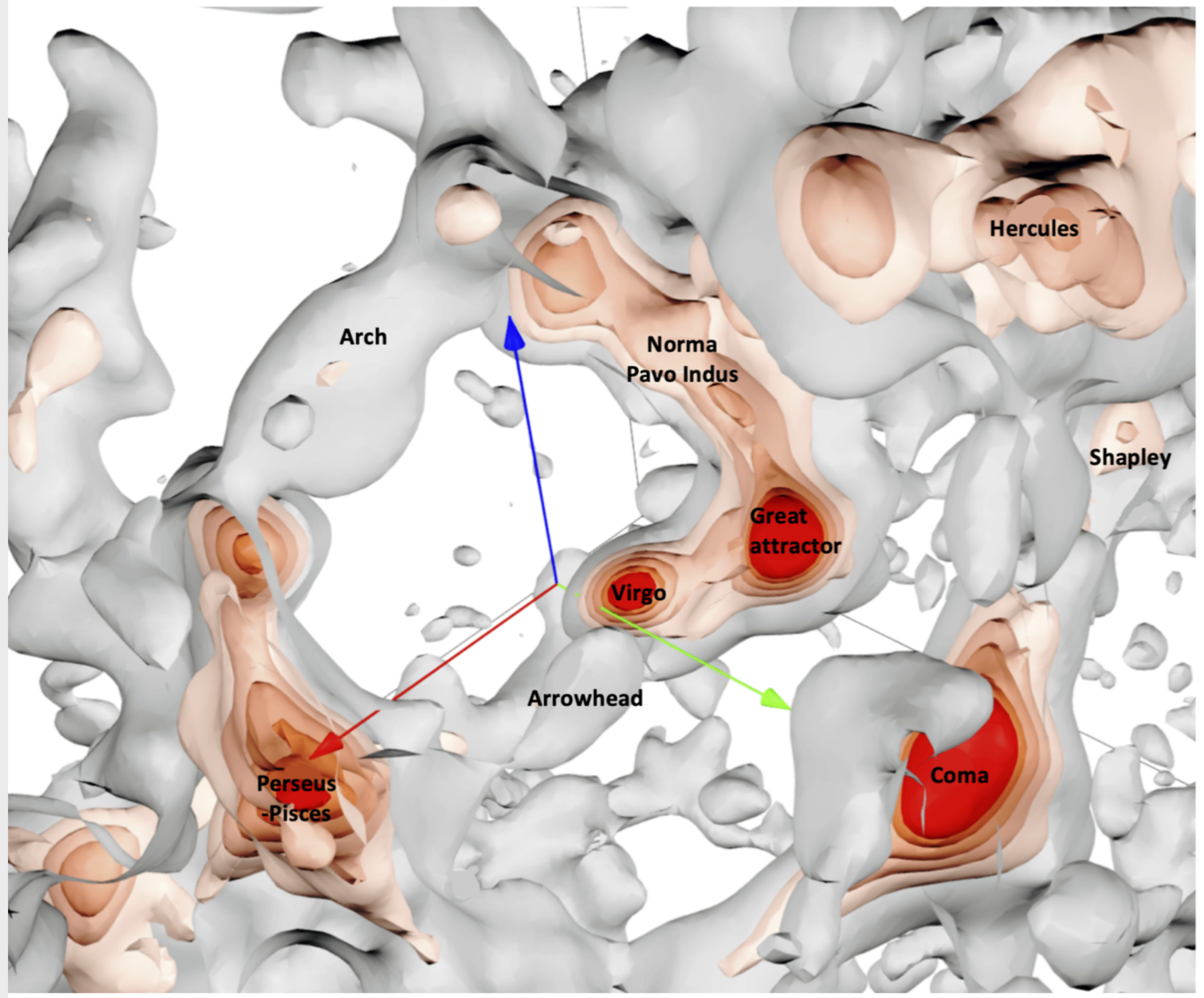


(Auger, ApJ 868 (2018) 1)

(Auger, ApJ 203, 2012,
Giacinti et al. JCAP 2012, 2015)

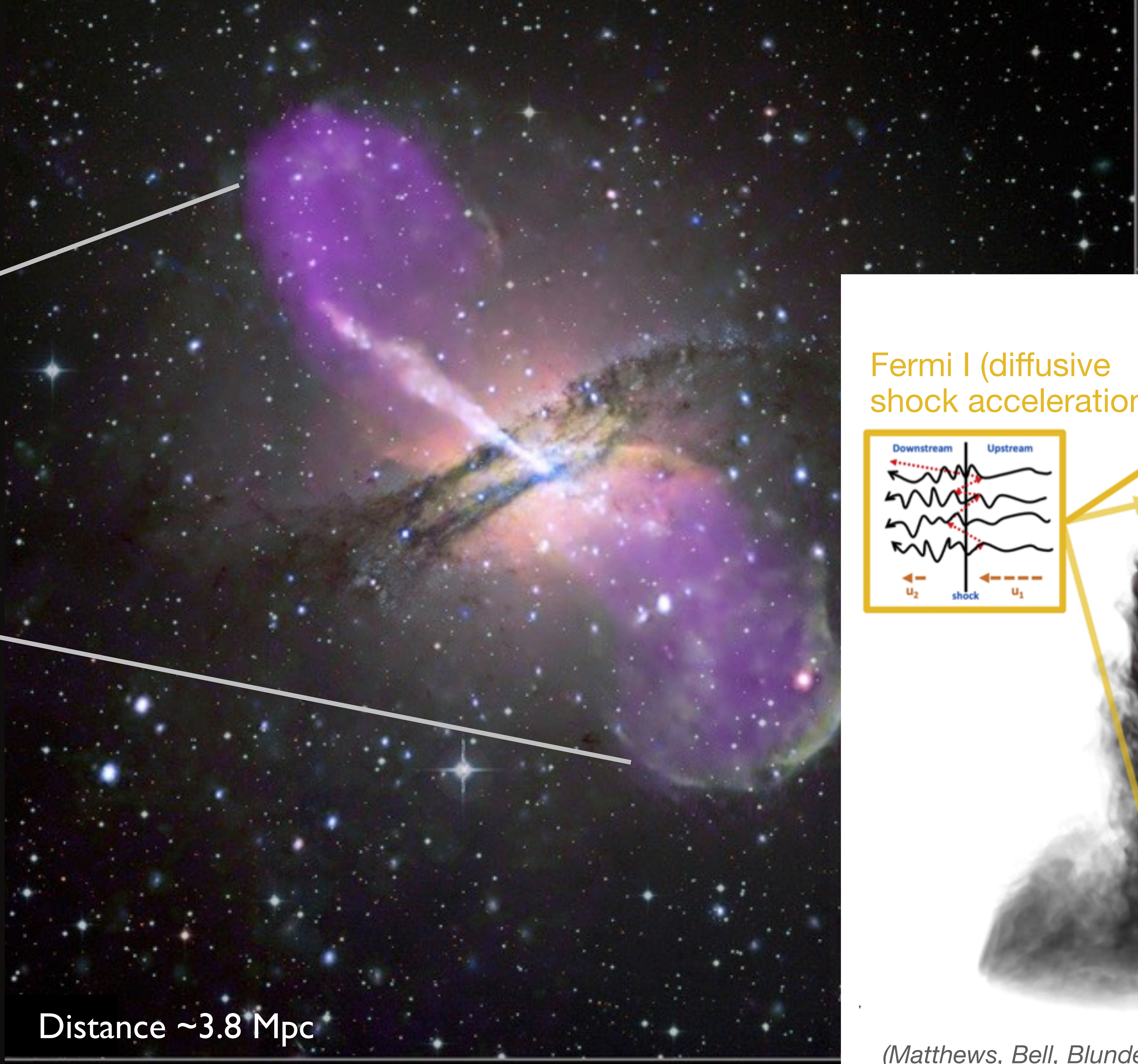
(Bister & Farrar, 2312.02645)

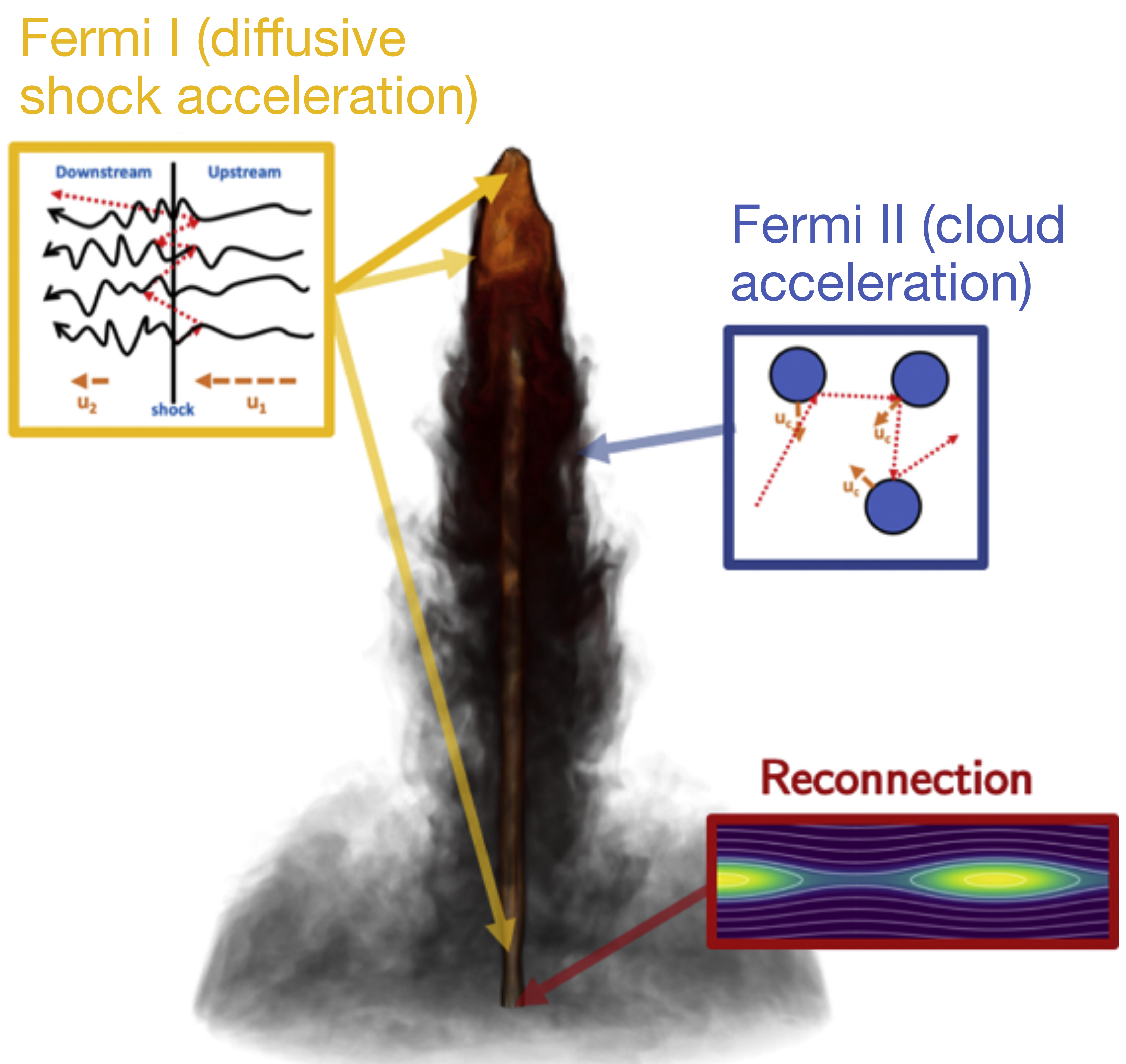
(Ding, Globus & Farrar ApJ 913 (2021) L13)



Protons below ankle energy are of extragalactic origin
Dipole anisotropy indicates transition to extragalactic sources
Interplay of source distribution, composition, and mag. horizon

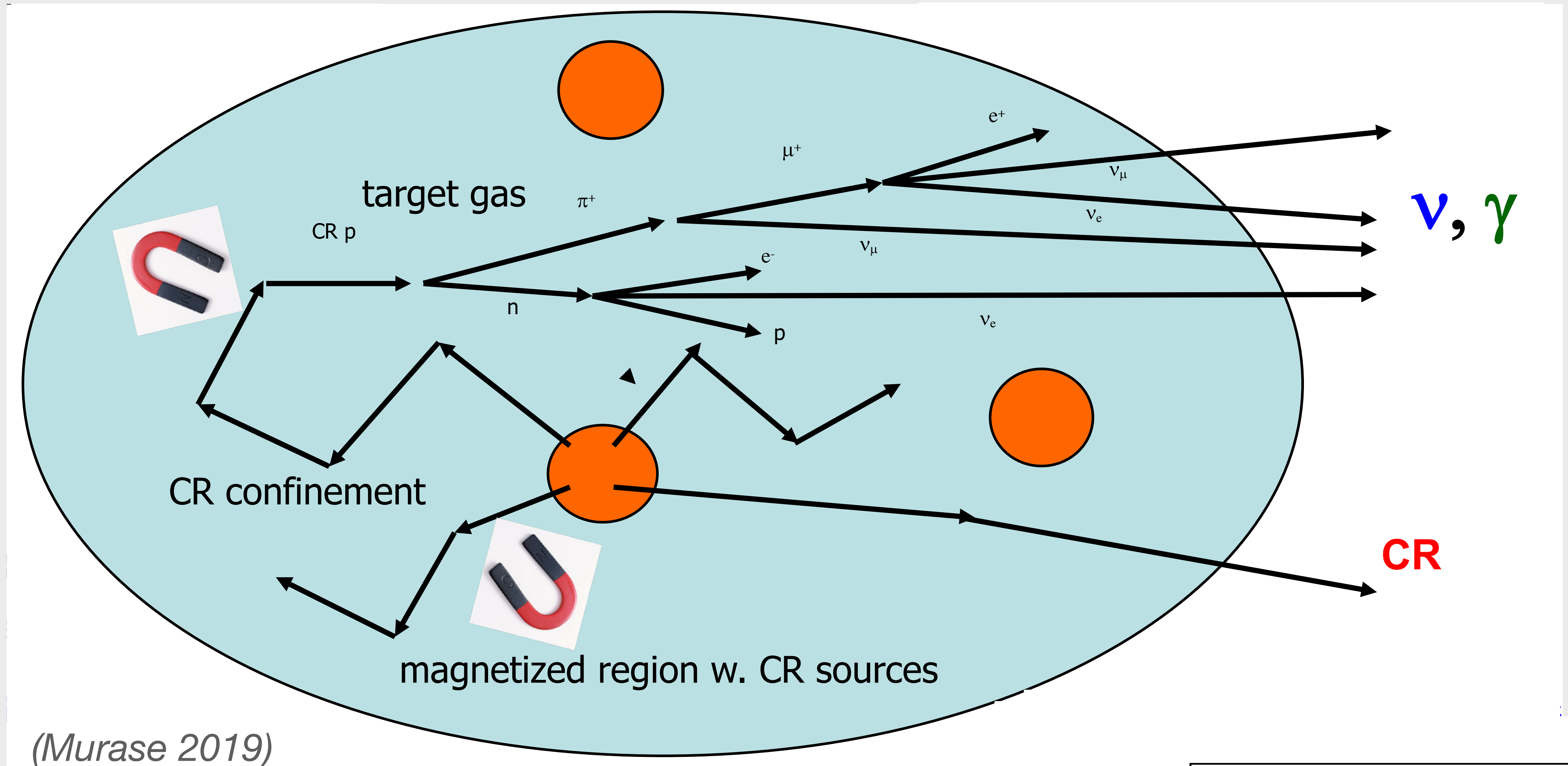
Closest Active Galactic Nucleus: Centaurus A





(Matthews, Bell, Blundel New Ast. Rev. 89 (2020) 101543)

Source models and challenges

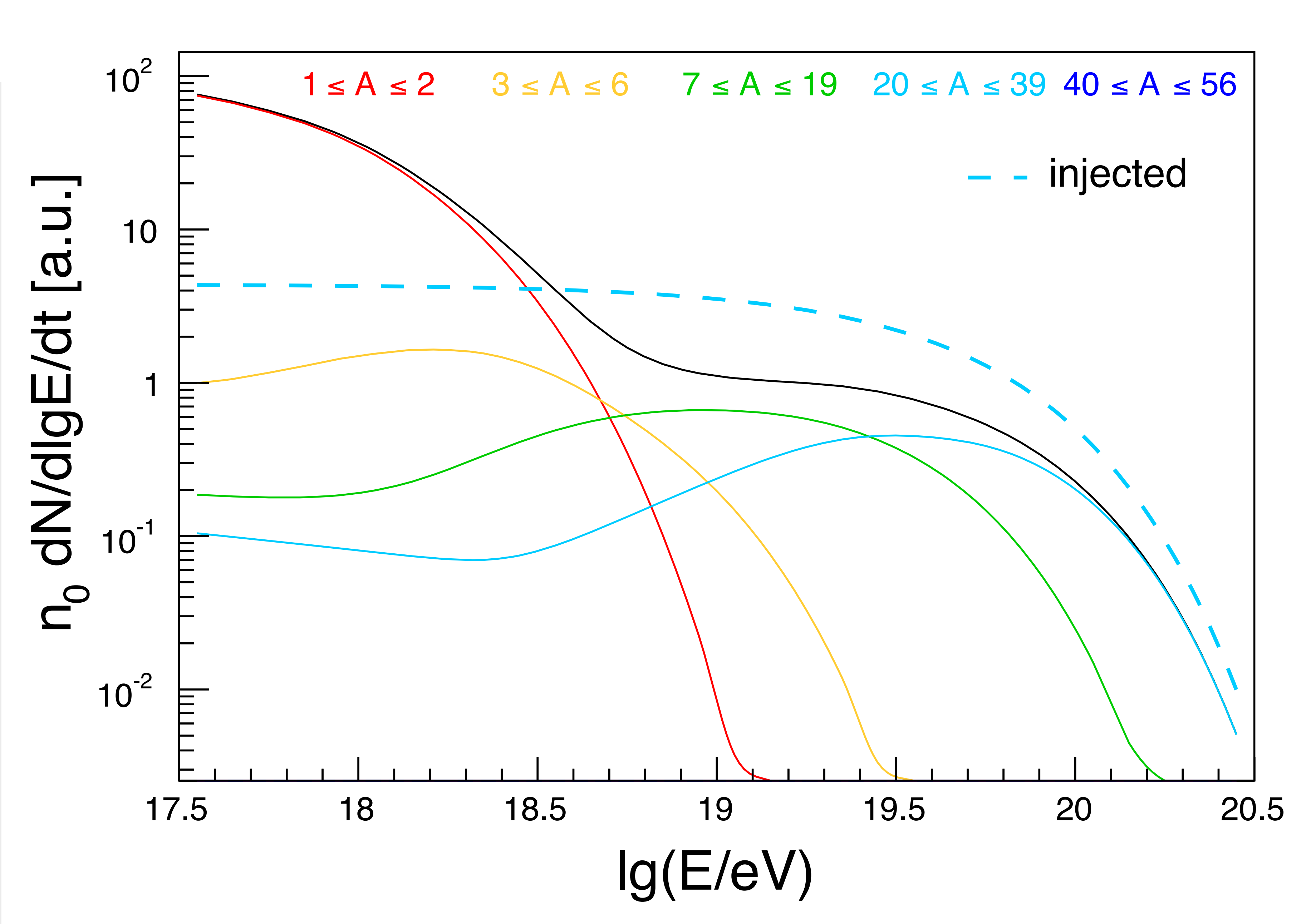


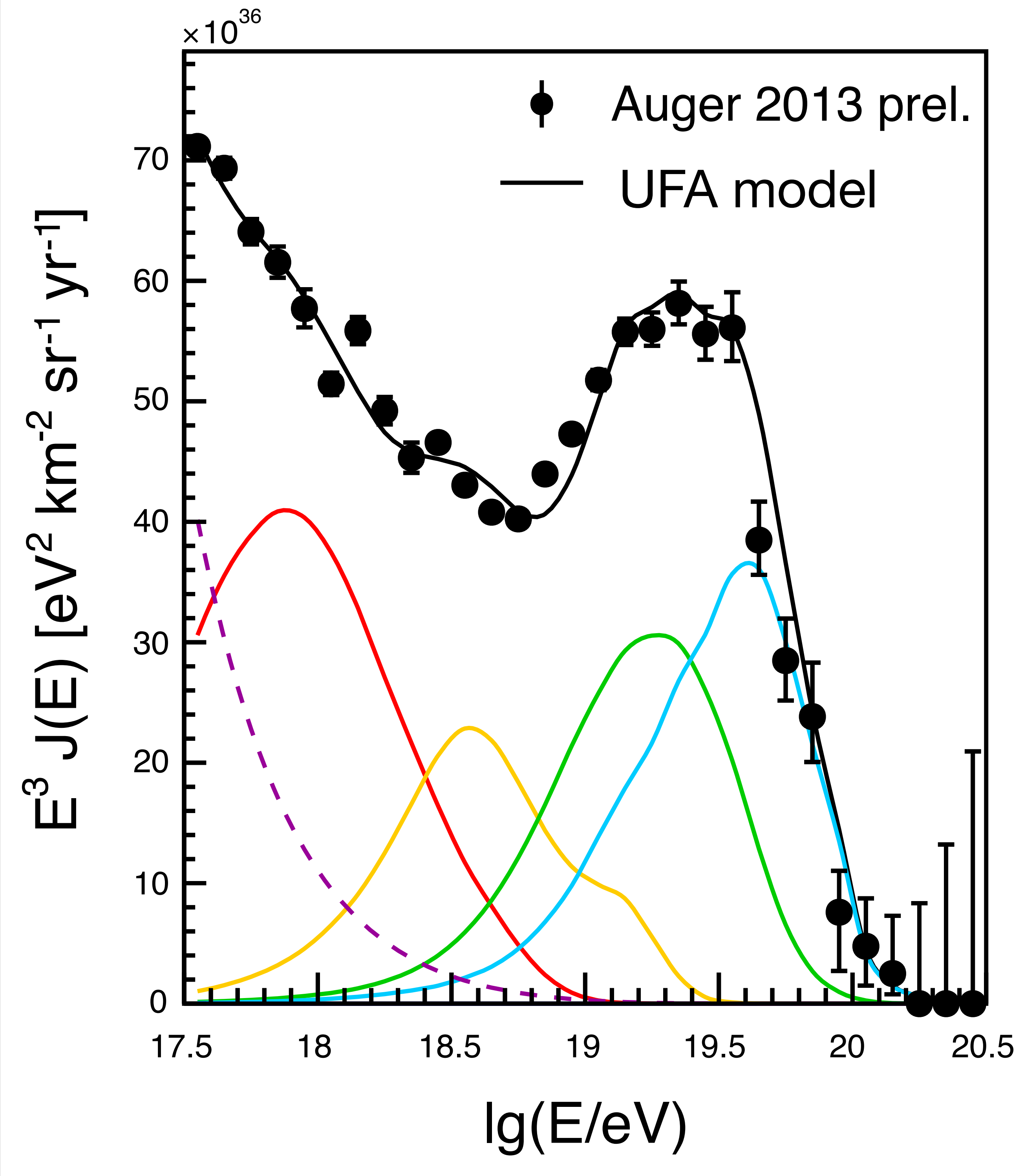
(Murase 2019)

Problem 1: injection of mainly heavy elements
Problem 2: ions have to leave source
Problem 3: hard source spectrum
Problem 4: source population diversity
Problem 5: large degree of isotropy

(Unger, Farrar, Anchordoqui, PRD 92, 2015)

$$\frac{dN_{\text{ini}}}{dE} \sim E^{-1}$$

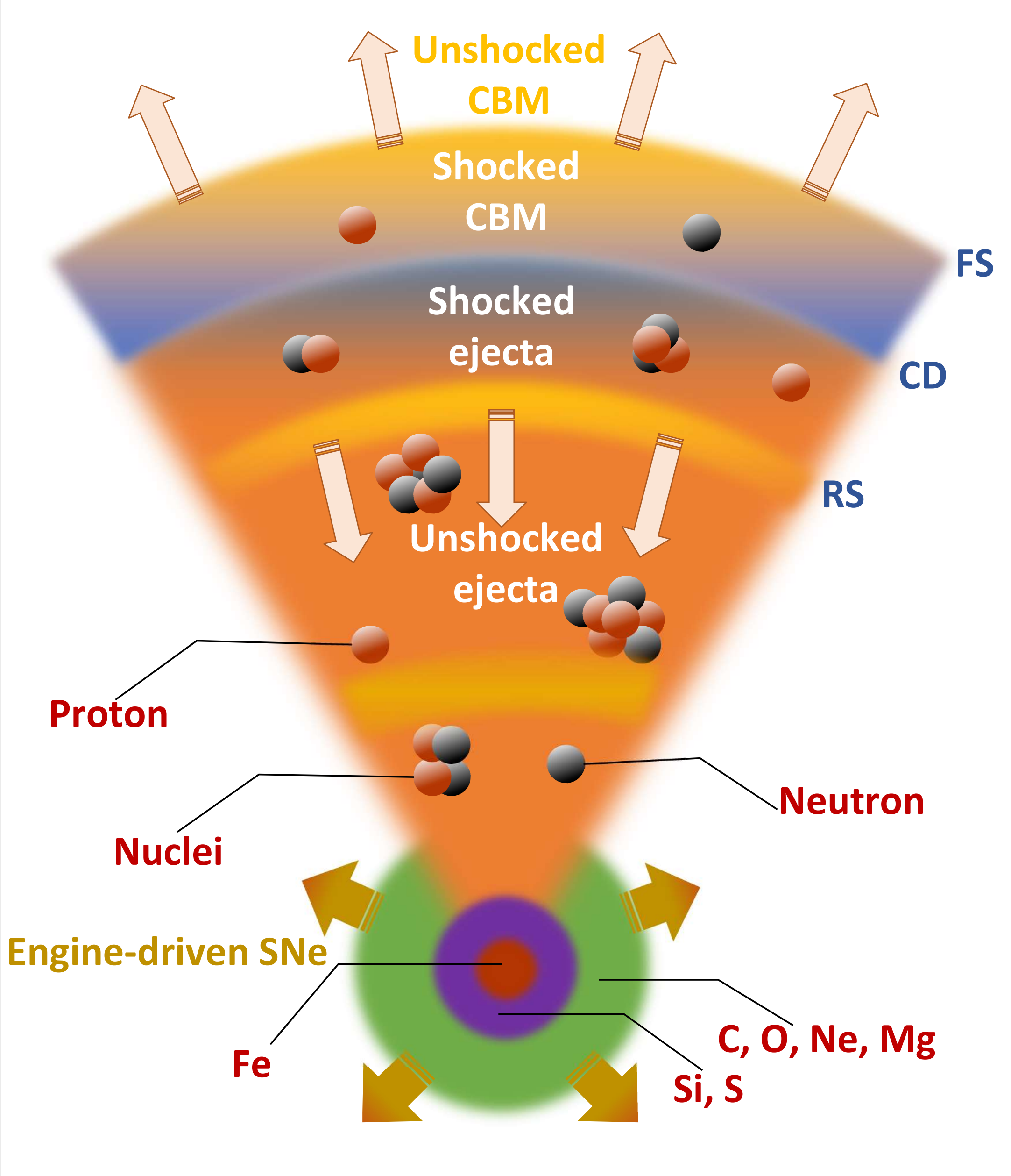


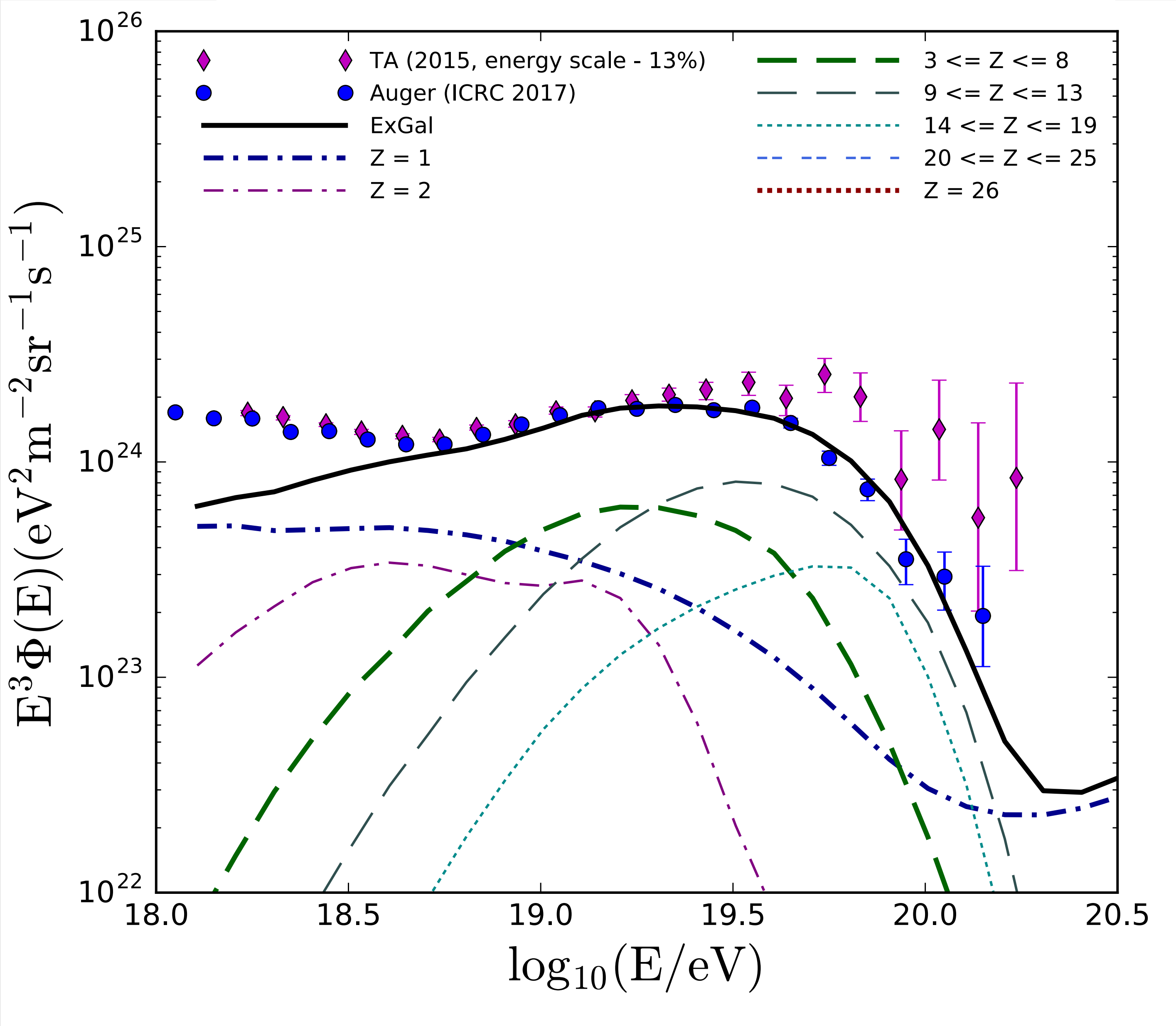


Nuclear disintegration in source region (scaling with mass *A*)

(Globus et al. 2015, Unger et al. 2015, Fang & Murase 2017)

New generation of complex model scenarios



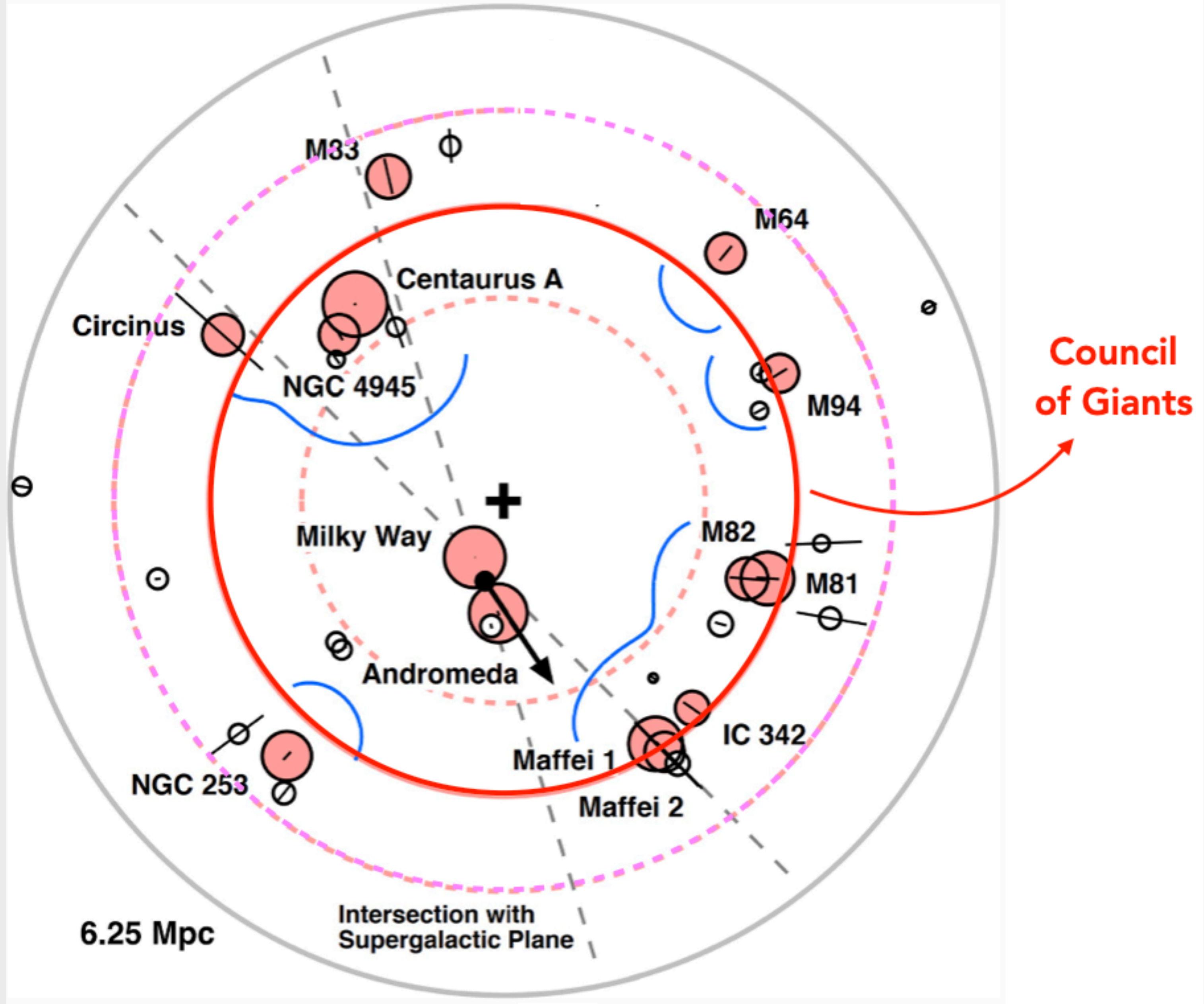


Interplay between
confinement in source
and disintegration of nuclei:
hard energy spectra
(Aloisio et al. 2014, Taylor et al. 2015, Globus et al. 2015, Unger et al. 2015, Fang & Murase 2017)

Reverse shock scenario in
low-luminosity long GRBs
(Zhang, Murase et al 2019+)

Tidal disruption events (TDEs)
of WD or carbon-rich stars
(Farrar, Piran 2009, Pfeffer et al. 2017, Zhang et al 2017)

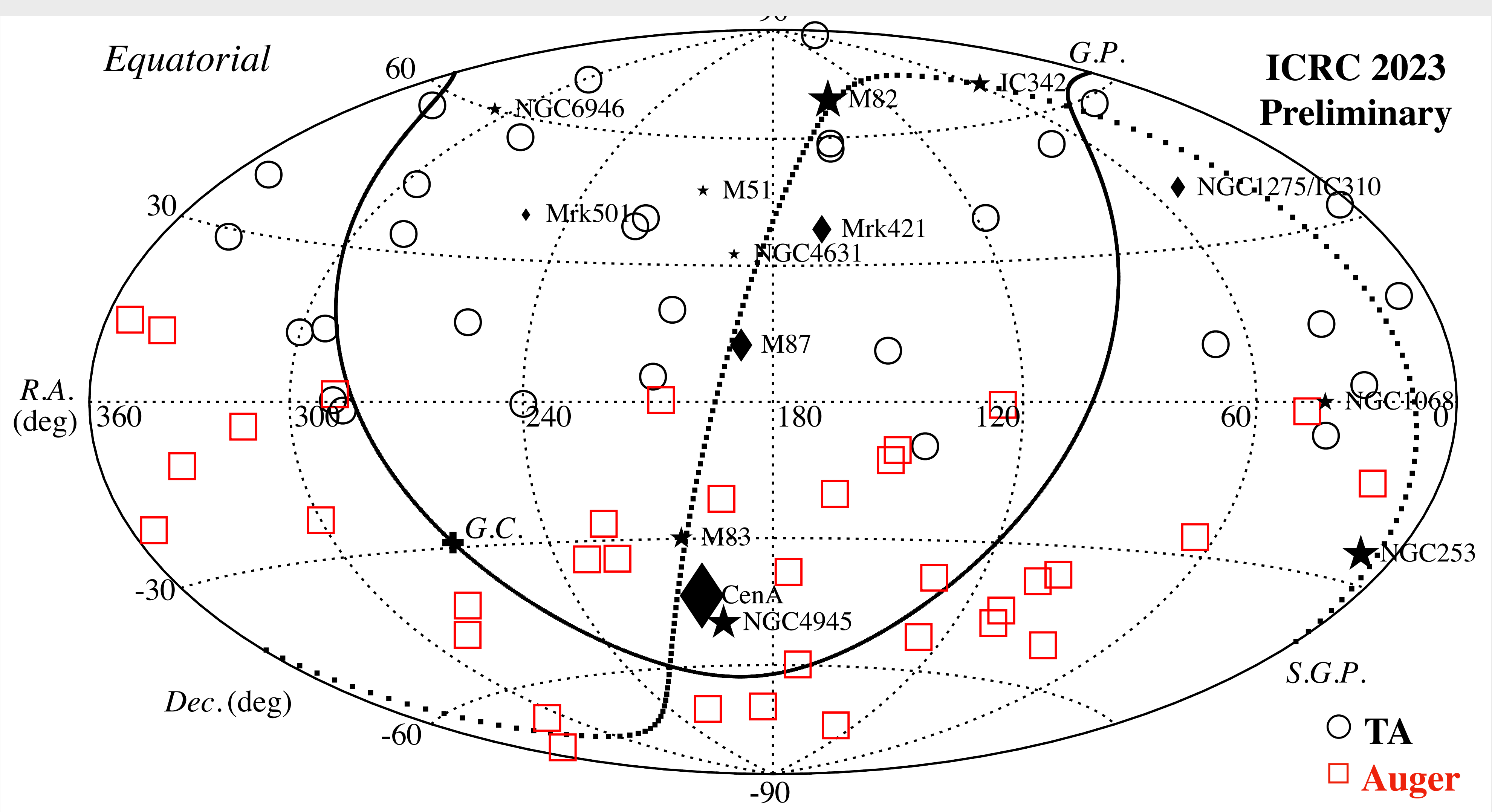
One-shot acceleration in
rapidly spinning **neutron stars**
(Arons 2003, Olinto, Kotera, Feng, Kirk …)



Cen-A bust & **deflection on Council of Giants**, solving isotropy and source diversity problem
(Taylor et al. 2023)

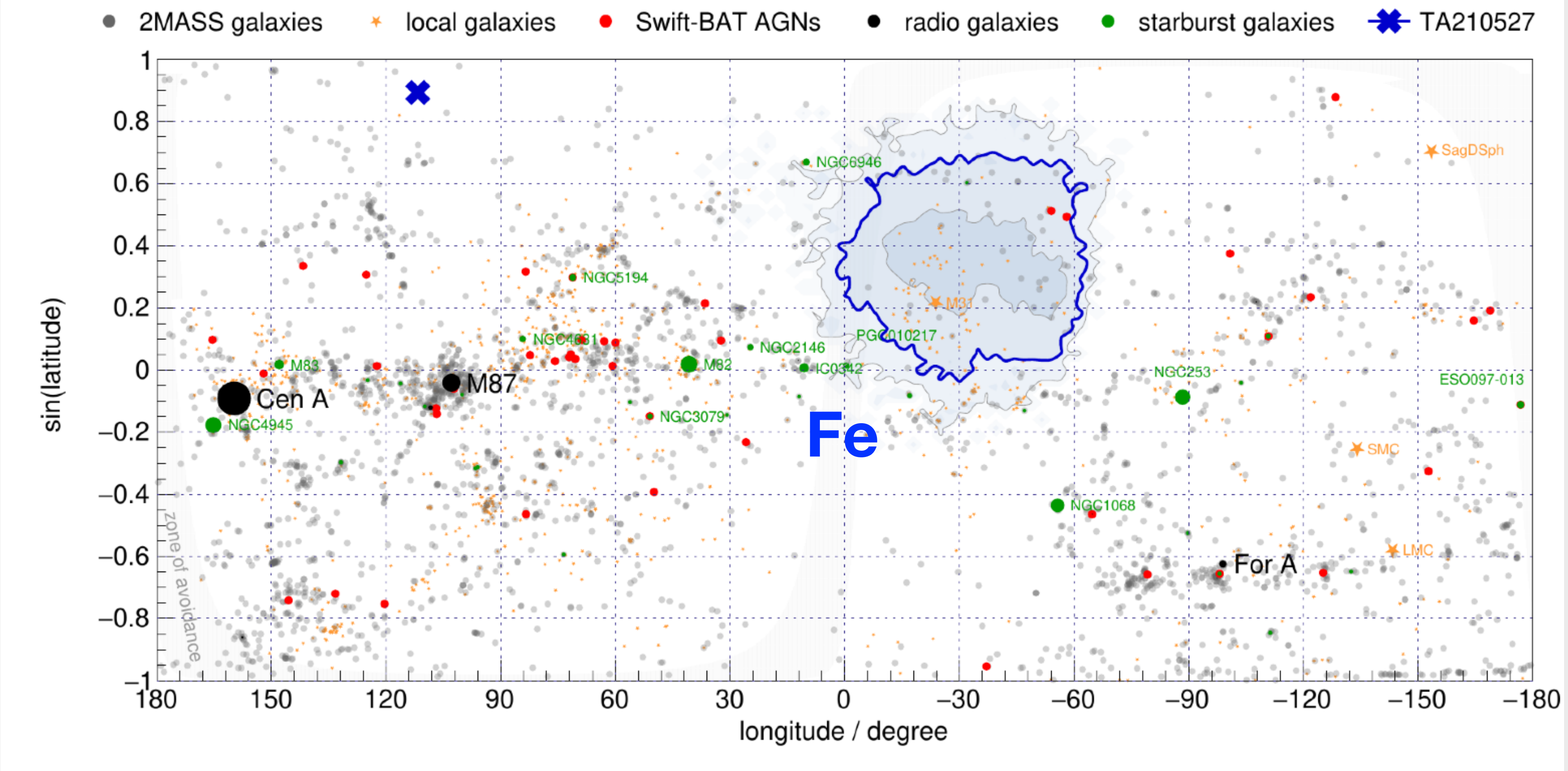
Relativistic reflection of
existing CR population
(Biermann, Caprioli, Wykes, 2012+, Blandford 2023)

Searching for sources at the highest energies



$E > 10^{20}$ eV

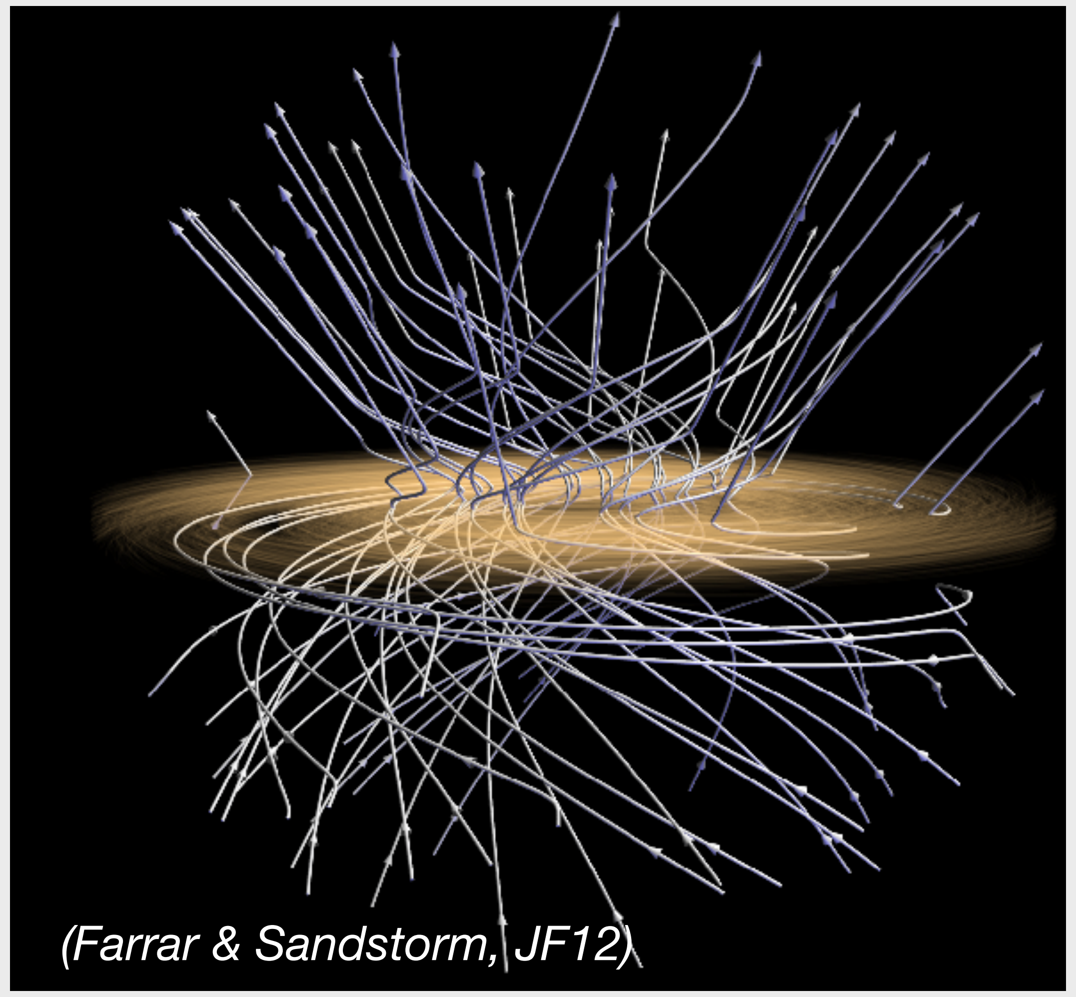
(Fujii, rapporteur talk ICRC 2023)



Amaterasu event (~2.4x10^{20} eV)

(TA, Science 382 (2023) 903)

(Unger & Farrar, ApJ 962 (2024) L5)



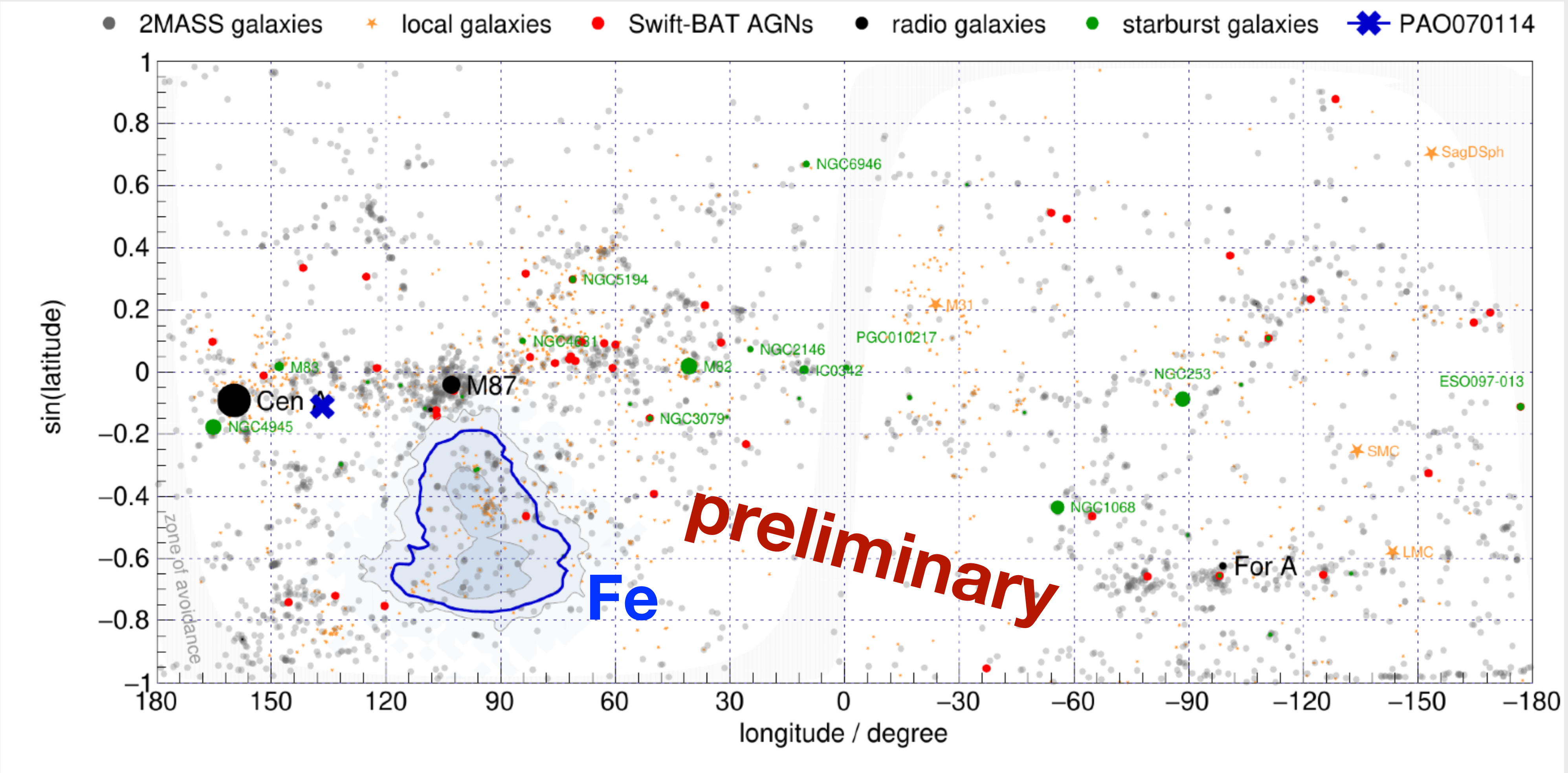
(Farrar & Sandstorm, JF12)

Transient sources?

Backtracking of particles through Galactic mag. field

New mag. field model UF24

(Unger & Farrar, 2311.12120)



Auger high energy event (~1.6x10^{20} eV)

(Unger 2024)

Upgrade of the Observatory – AugerPrime

Physics motivation

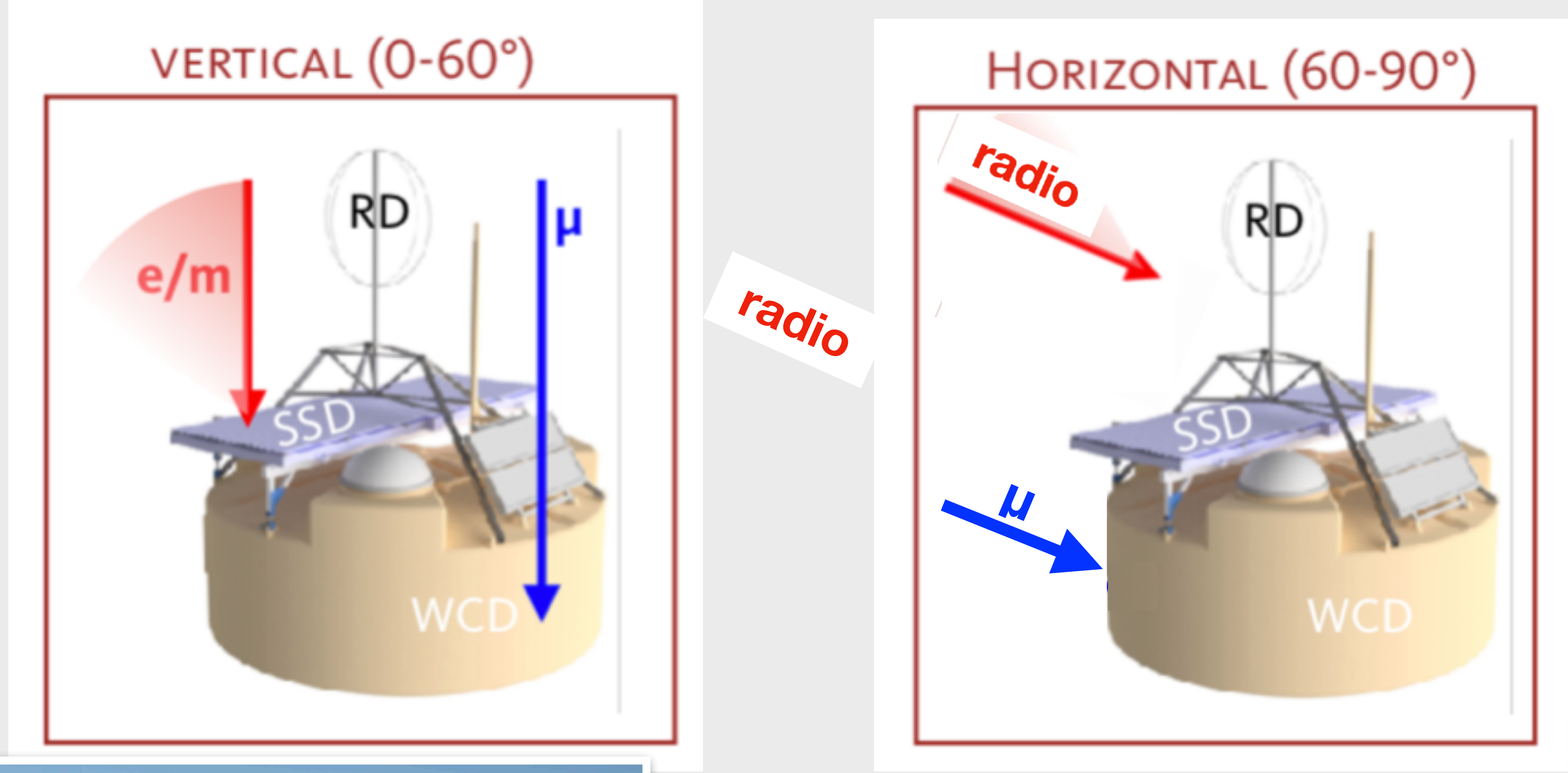
- Composition measurement up to 10^{20} eV
- Composition selected anisotropy
- Particle physics with air showers
- Much better understanding of **new and old** data

Components of AugerPrime

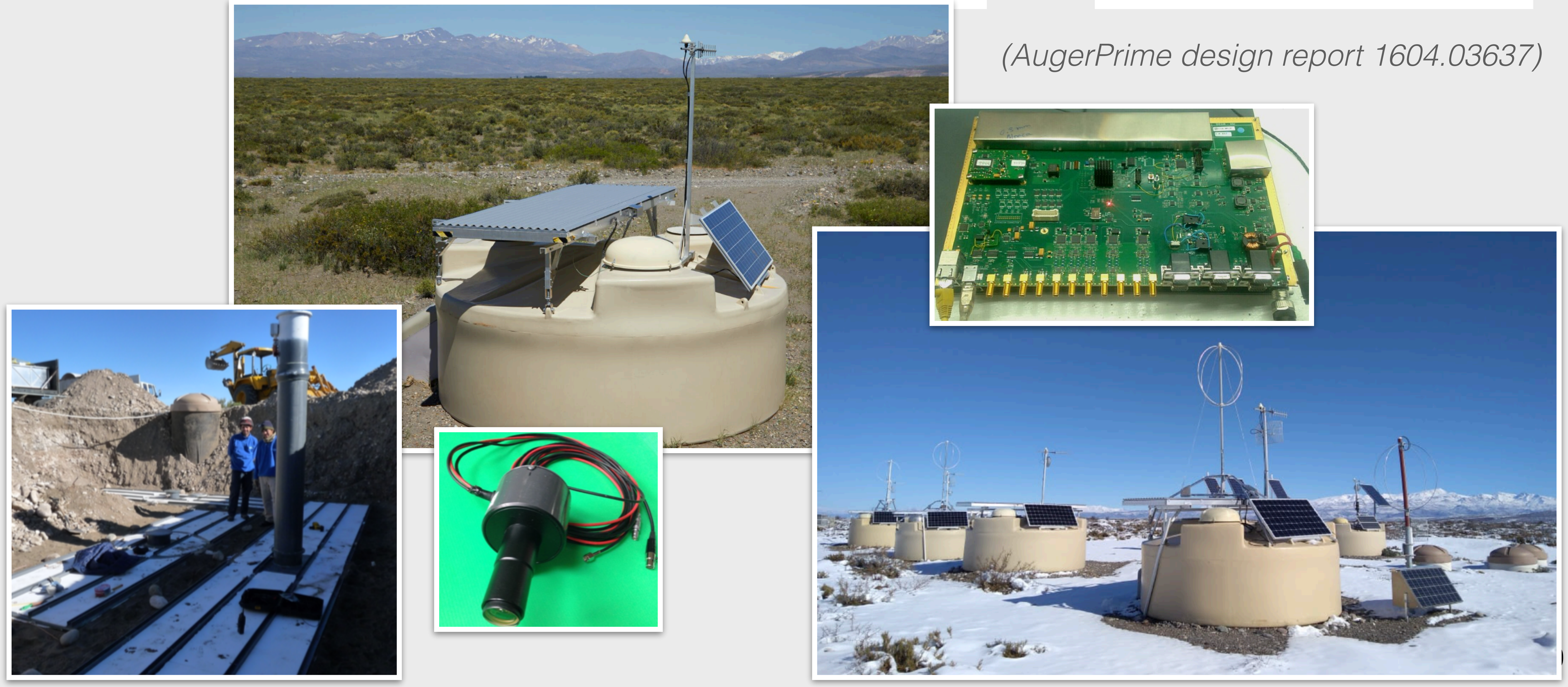
- 3.8 m^2 scintillator panels (SSD)
- New electronics (40 MHz -> 120 MHz)
- Small PMT (dynamic range WCD)
- Radio antennas for inclined showers
- Underground muon counters (750 m array, 433 m array)

Auger Observatory Phase II:
10 more years of data taking

Composition sensitivity with 100% duty cycle



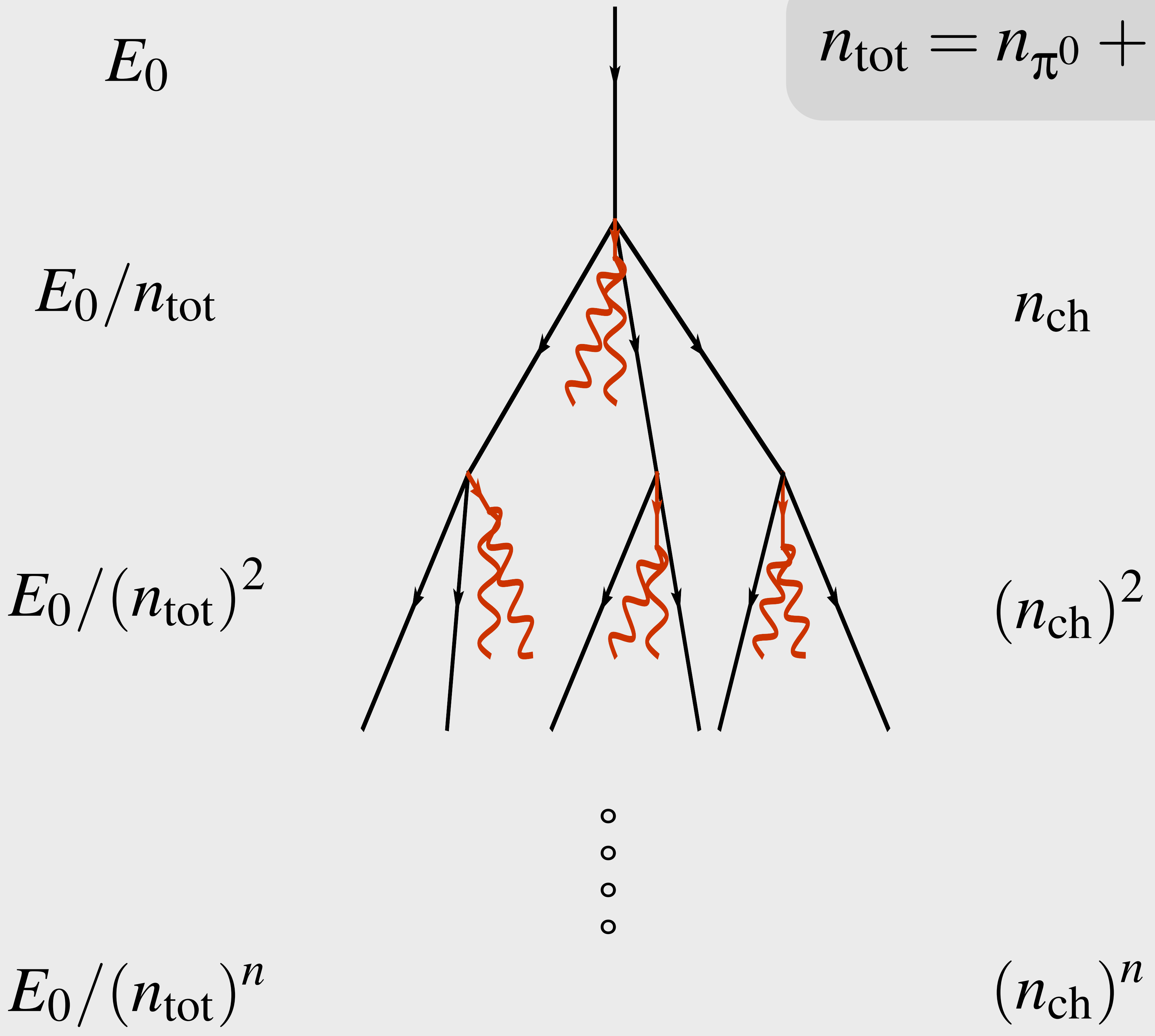
(AugerPrime design report 1604.03637)



Backup slides

Qualitative approach: Heitler-Matthews model

$$n_{\rm tot} = n_{\pi^0} + n_{\rm ch}$$



Primary particle proton

π^0 decay immediately

$\pi^\pm$ initiate new hadronic cascades

$$N_\mu = \left(\frac{E_0}{E_{\rm dec}}\right)^\alpha$$

$$\alpha = \frac{\ln n_{\rm ch}}{\ln n_{\rm tot}} \approx 0.85 \ldots 0.95$$

Assumptions:

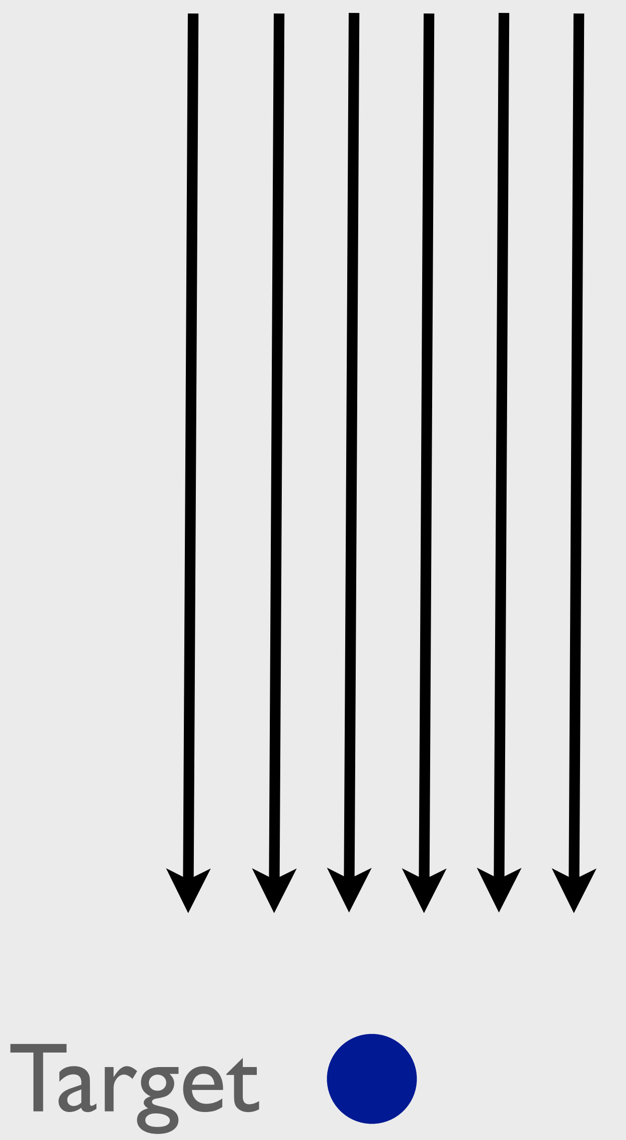
- cascade stops at $E_{\rm part} = E_{\rm dec}$
- each hadron produces one muon

(Matthews, Astropart.Phys. 22, 2005)

Superposition model – particle numbers

Nucleus
(binding energy ~5 MeV/nuc)

$$E_i = E_0/A$$



Proton-induced shower

$$N_{\max} \sim E_0/E_c$$

$$N_\mu = \left(\frac{E_0}{E_{\mathrm{dec}}}\right)^\alpha \qquad \alpha \approx 0.9$$

Assumption:
nucleus of mass *A* and energy E_0 corresponds to *A* nucleons (protons) of energy $E_n = E_0/A$

$$N^A_{\max} \sim A\left(\frac{E_0}{AE_c}\right) = N_{\max}$$

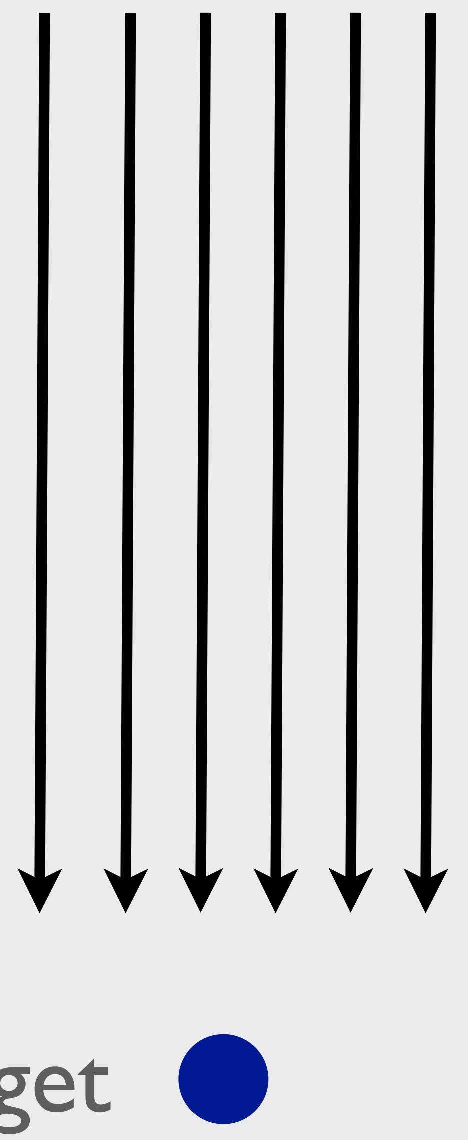
$$N^A_\mu = A\left(\frac{E_0}{AE_{\mathrm{dec}}}\right)^\alpha = A^{1-\alpha} N_\mu$$

Iron showers ~40% more muons than proton showers

Superposition model – depth of shower maximum

Nucleus
(binding energy ~5 MeV/nuc)

$$E_i = E_0/A$$

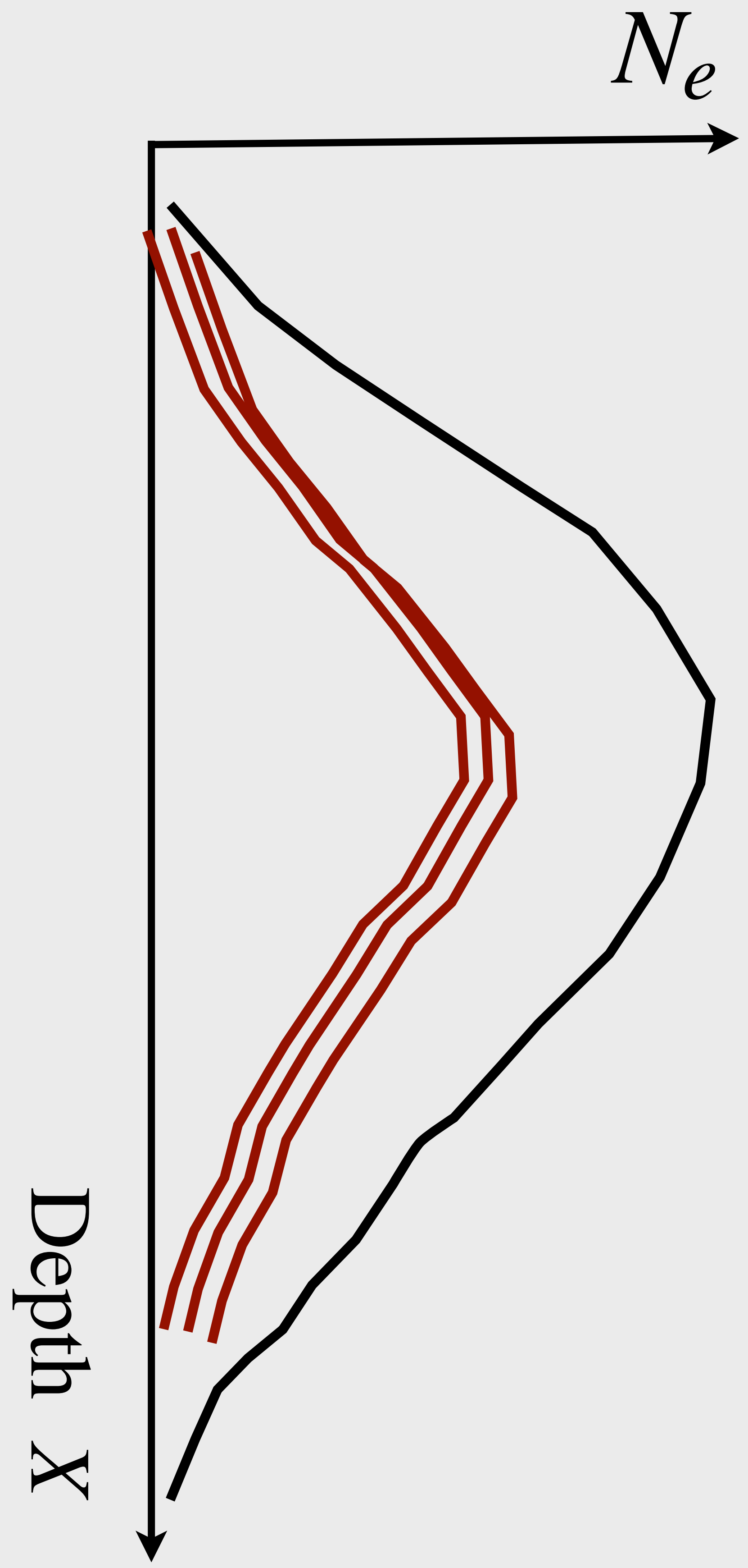


Target

Proton-induced shower

$$X_{\max} \sim \lambda_{\text{eff}} \ln(E_0)$$

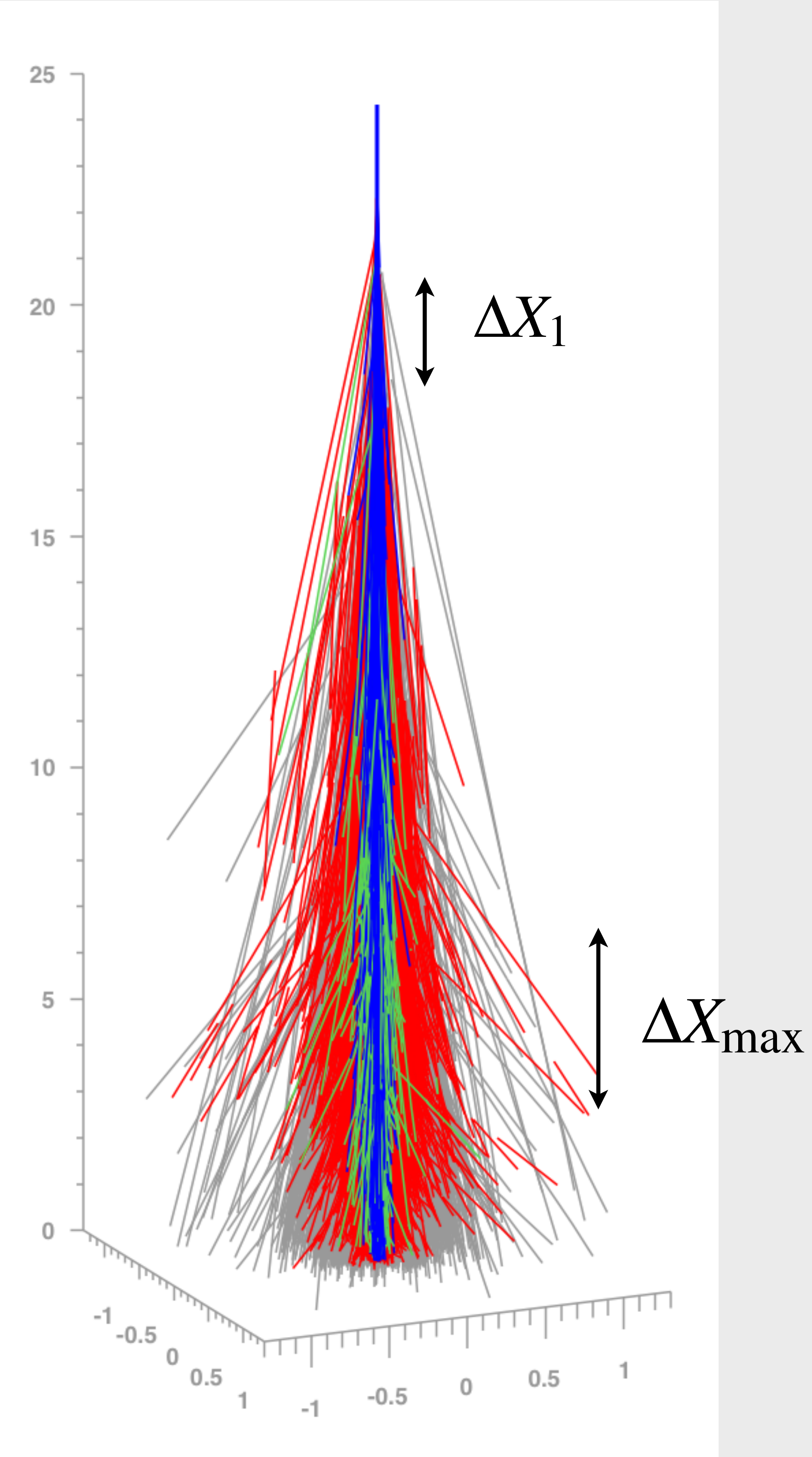
Assumption:
nucleus of mass *A* and energy E_0 corresponds to *A* nucleons (protons) of energy $E_n = E_0/A$



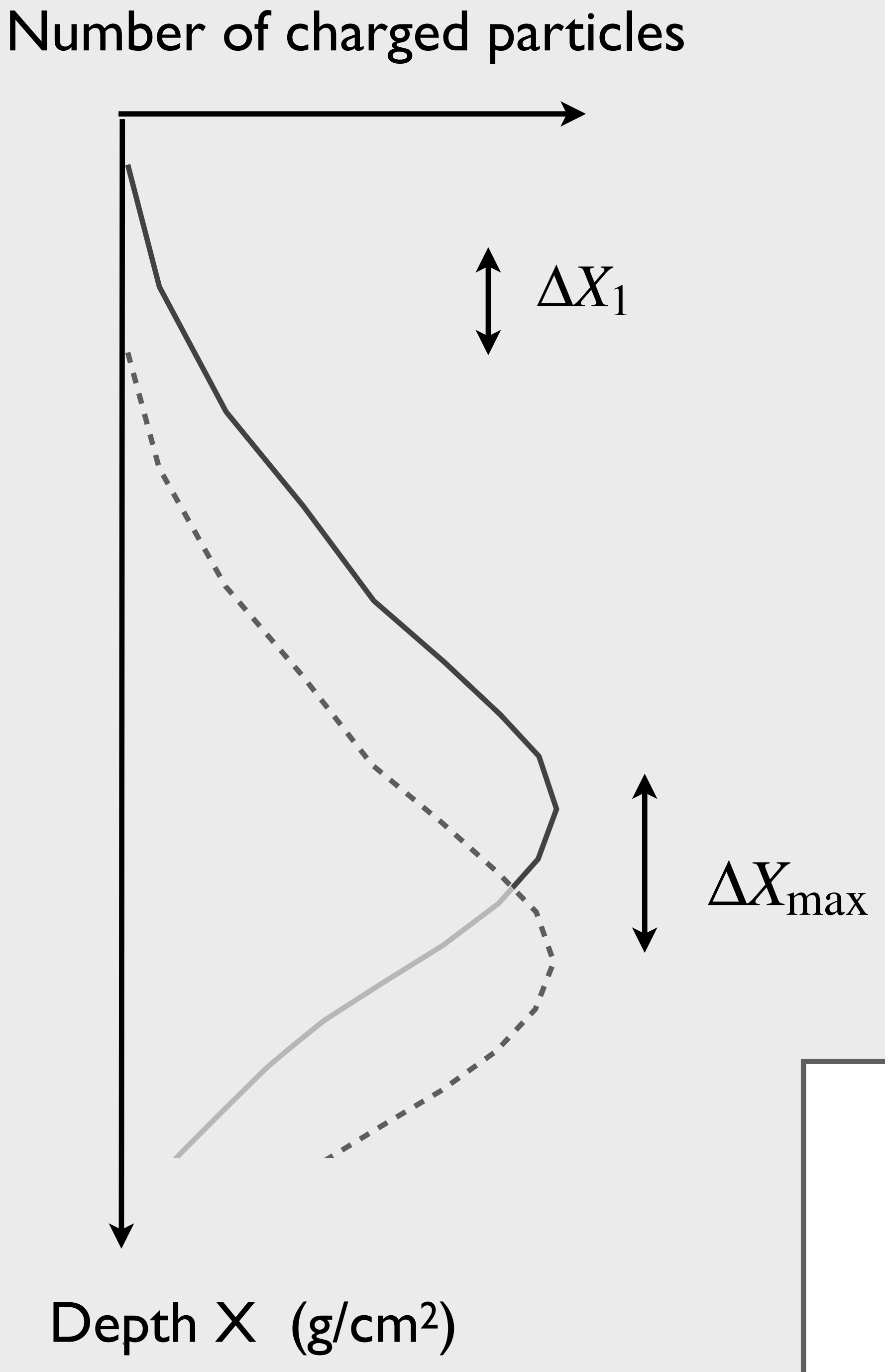
Proton showers penetrate deeper than iron showers ~ ln(A)

$$X_{\max}^{A} \sim \lambda_{\text{eff}} \ln(E_0/A)$$

Hadronic interactions – cross section measurement

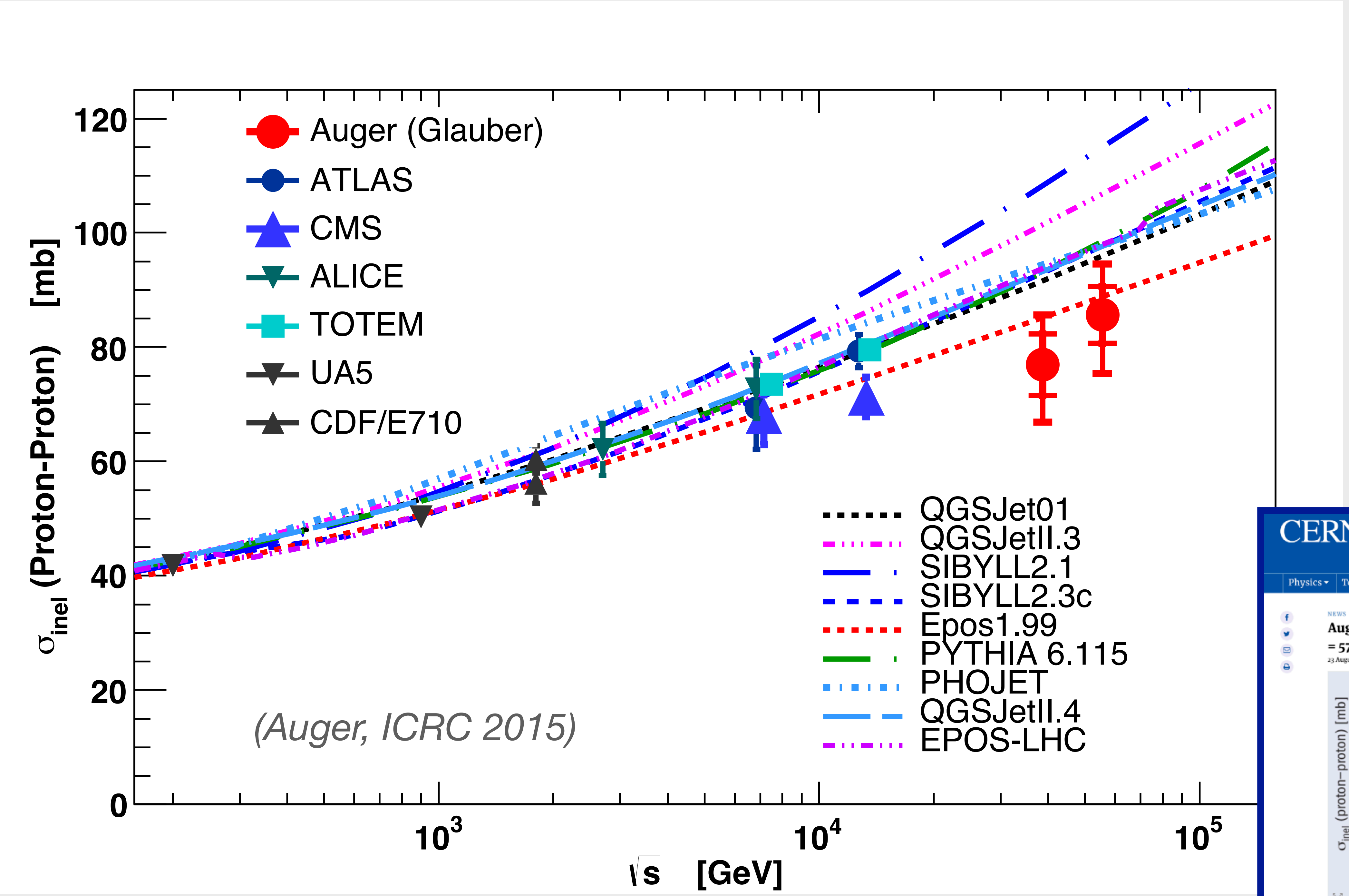


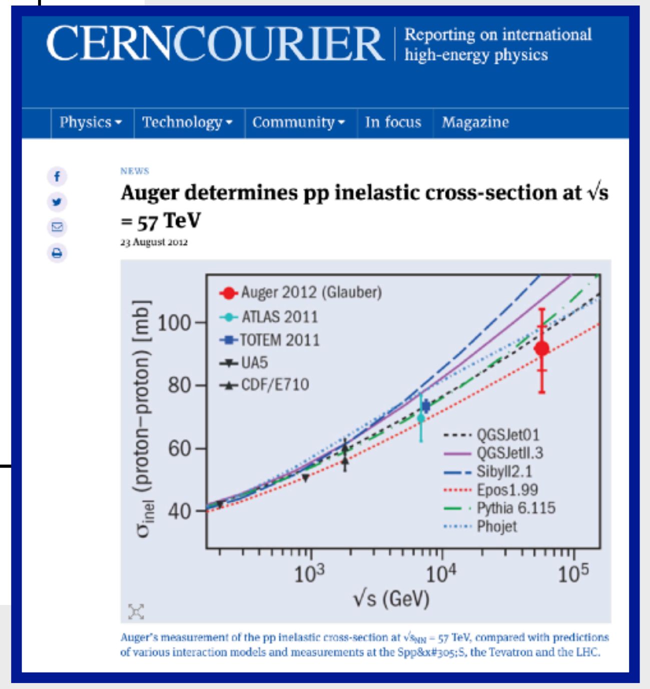
(Auger, PRL 109 (2012) 062002)



$$\frac{dP}{dX_1} = \frac{1}{\lambda_{int}} e^{-X_1/\lambda_{int}}$$

$$\sigma_{p-air} = \frac{\langle m_{air} \rangle}{\lambda_{int}}$$

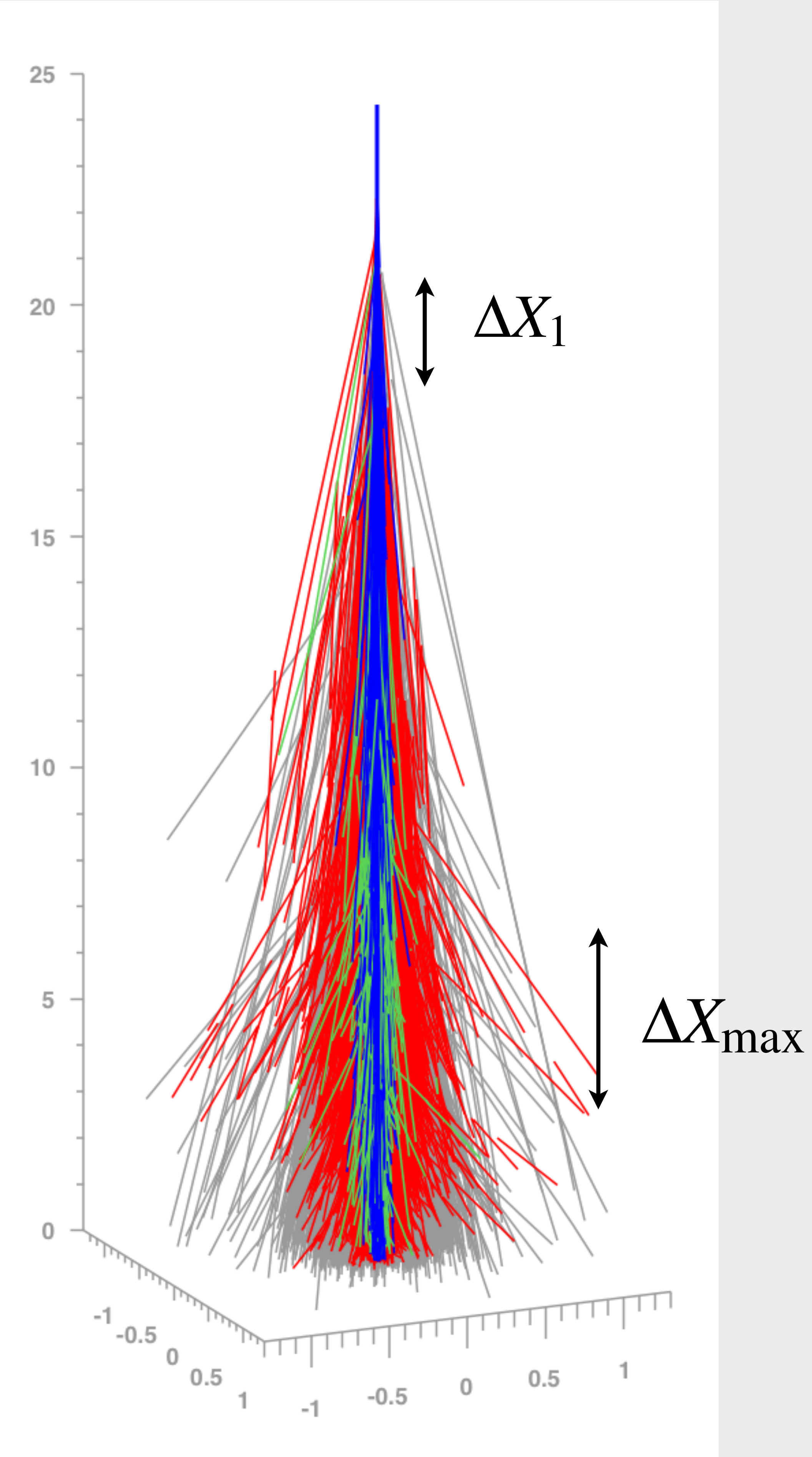




Challenges in analysis

- mass composition
- fluctuations in shower development (model needed for correction)
- conversion from p-air to p-p

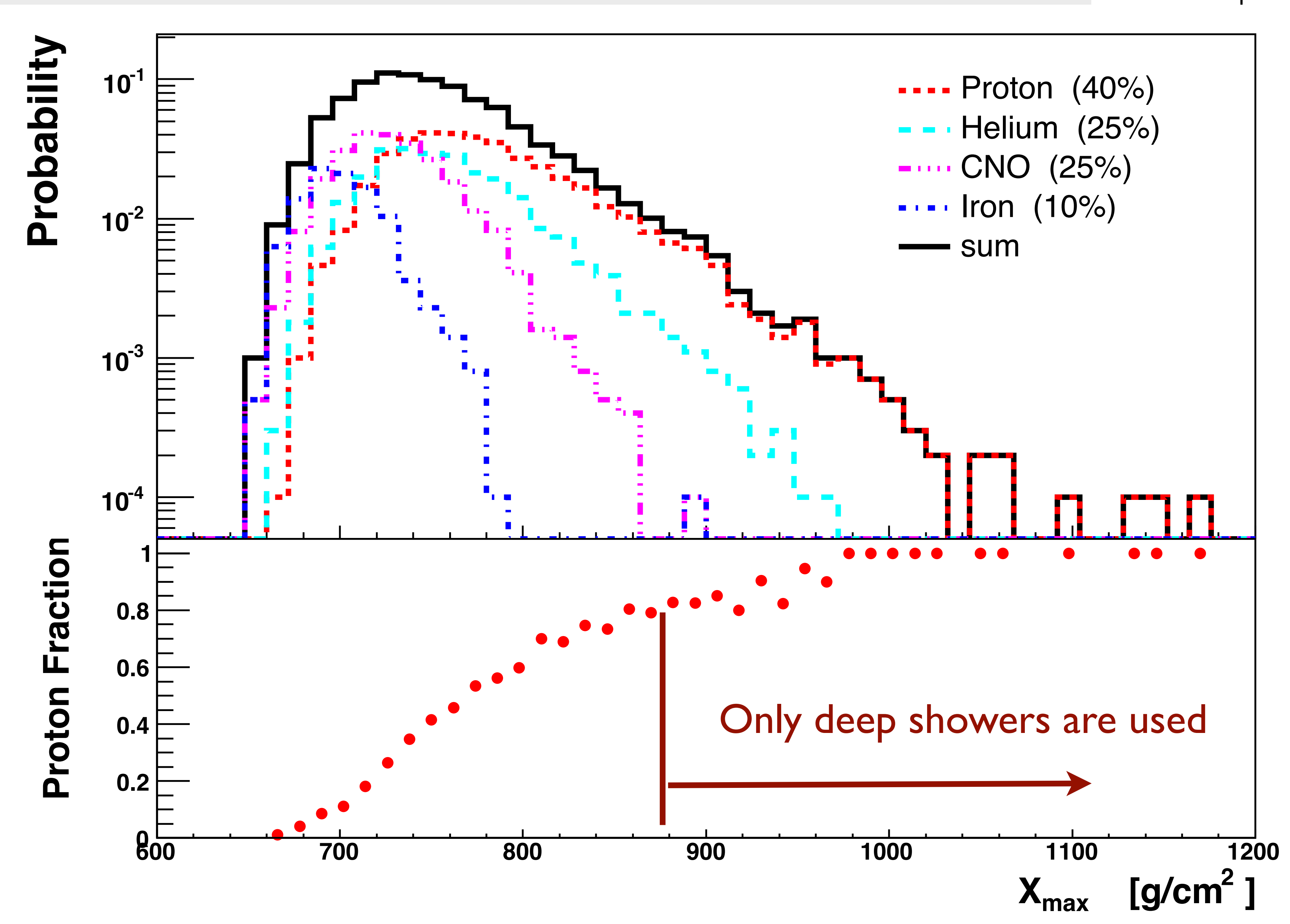
Hadronic interactions – cross section measurement

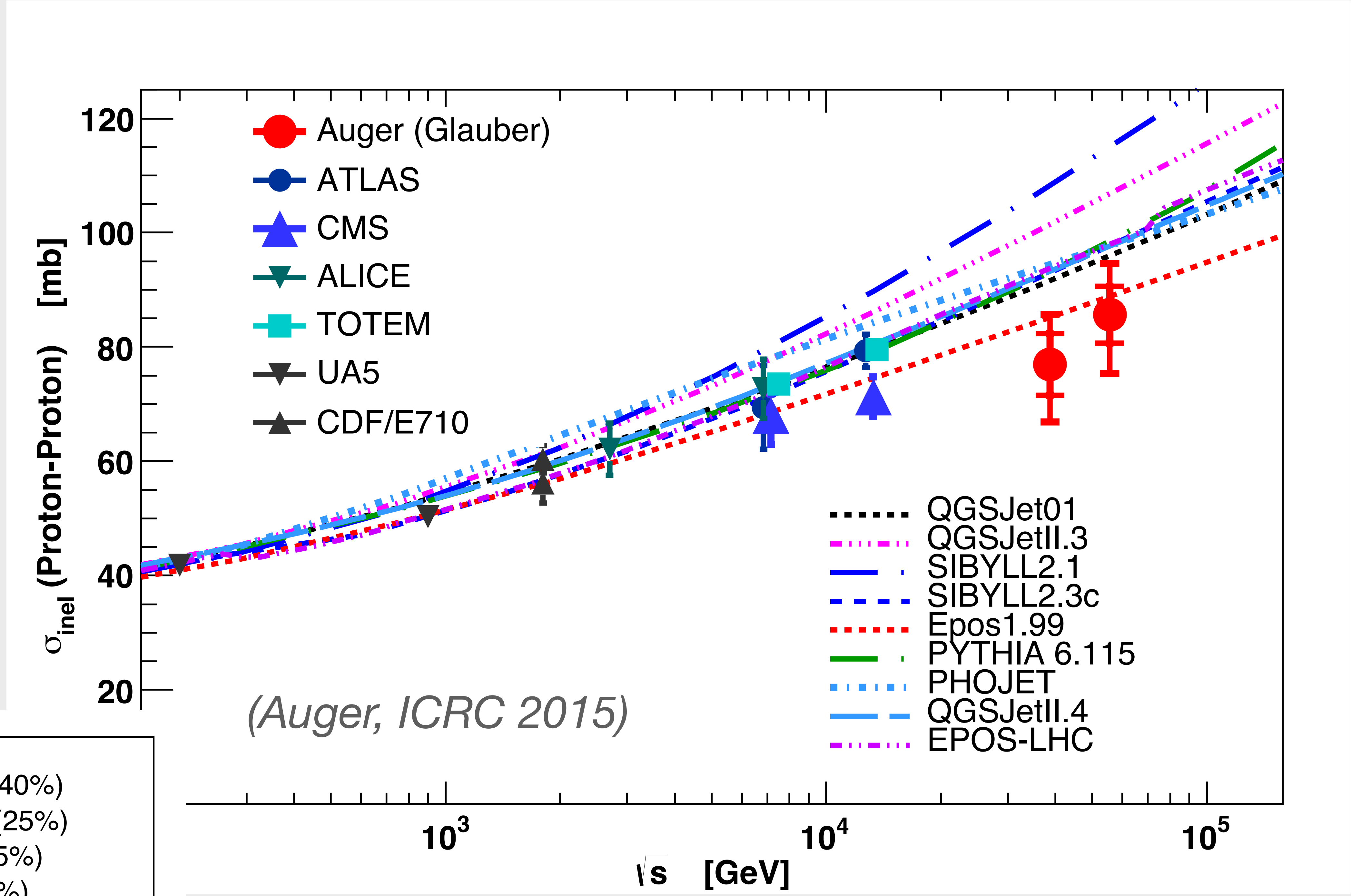


(Auger, PRL 109 (2012) 062002)

$$\frac{dP}{dX_1} = \frac{1}{\lambda_{int}} e^{-X_1/\lambda_{int}}$$

$$\sigma_{p-air} = \frac{\langle m_{air} \rangle}{\lambda_{int}}$$

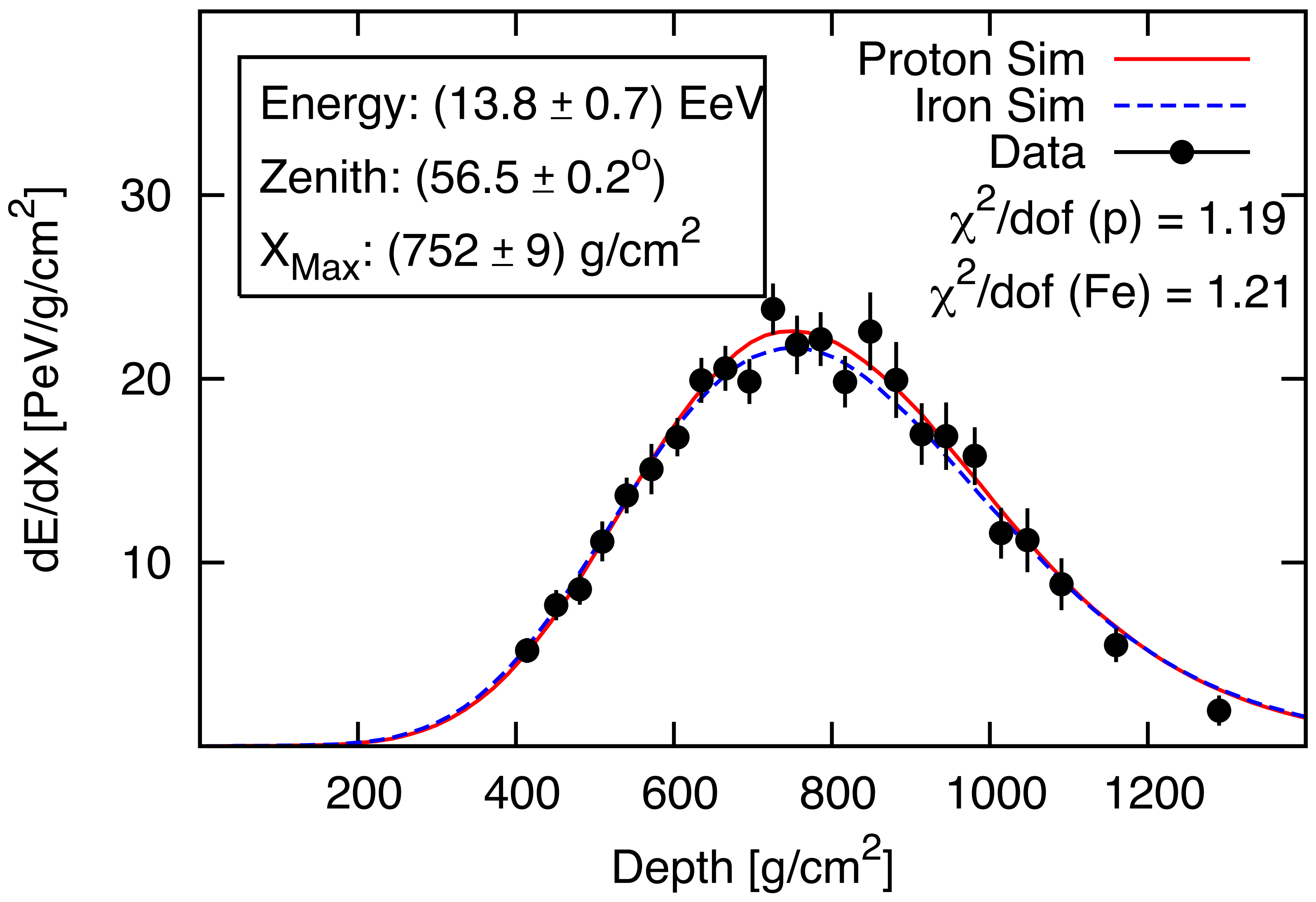


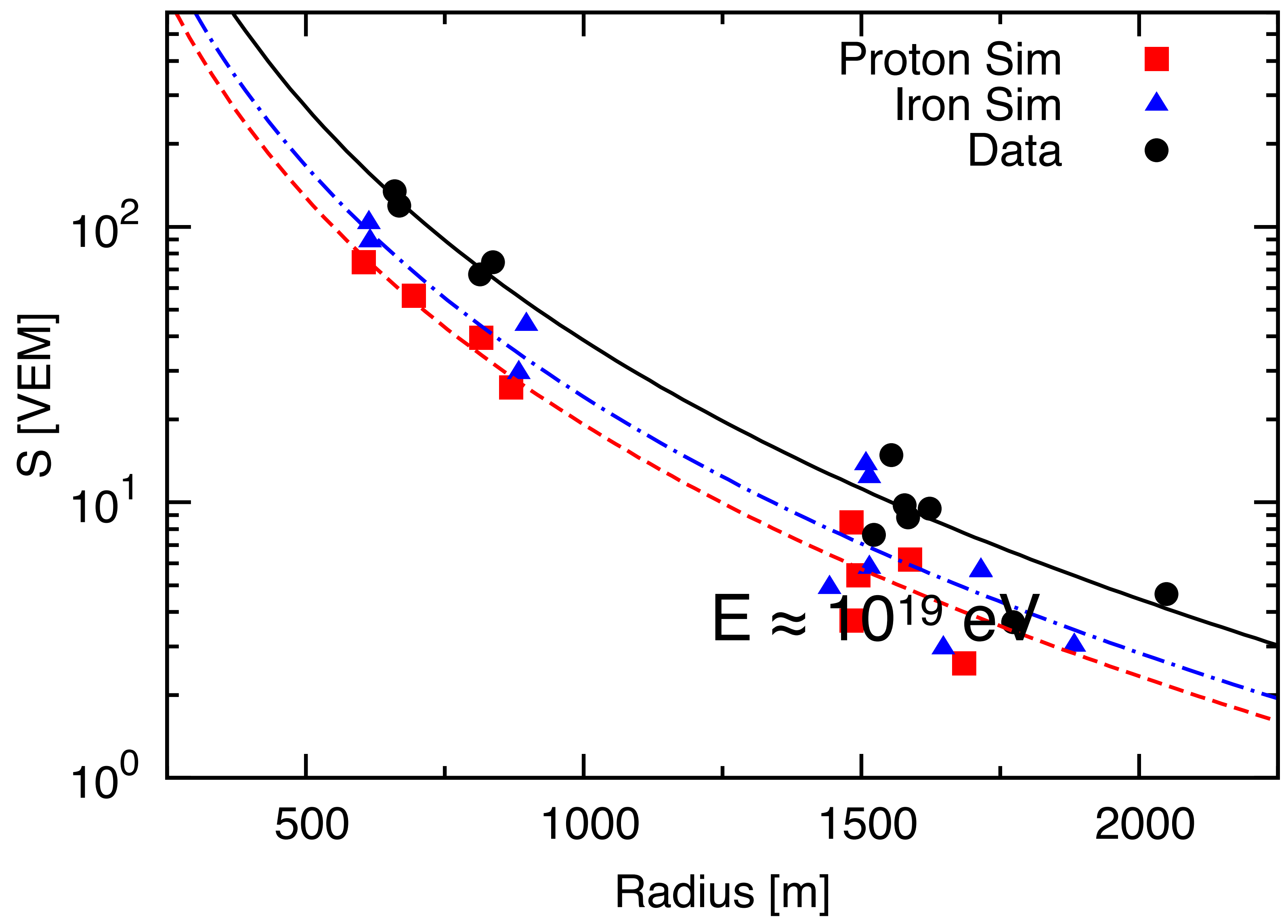


Challenges in analysis

- mass composition
- fluctuations in shower development (model needed for correction)

Auger muon measurement – vertical showers



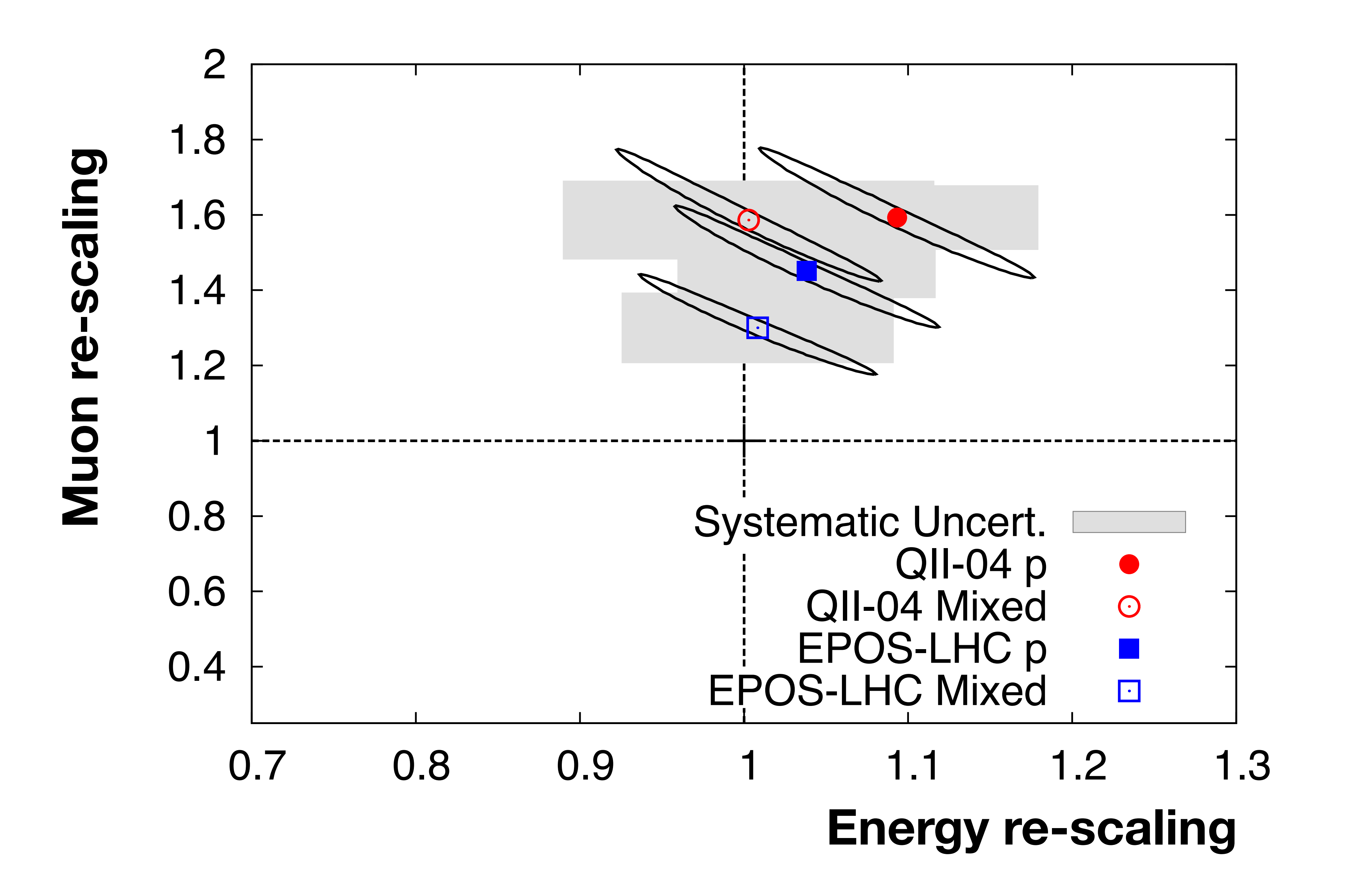


(Auger, PRL 117, 2016)

Energy scaling: em. particles and muons

Muon scaling: hadronically produced muons and muon interaction/decay products

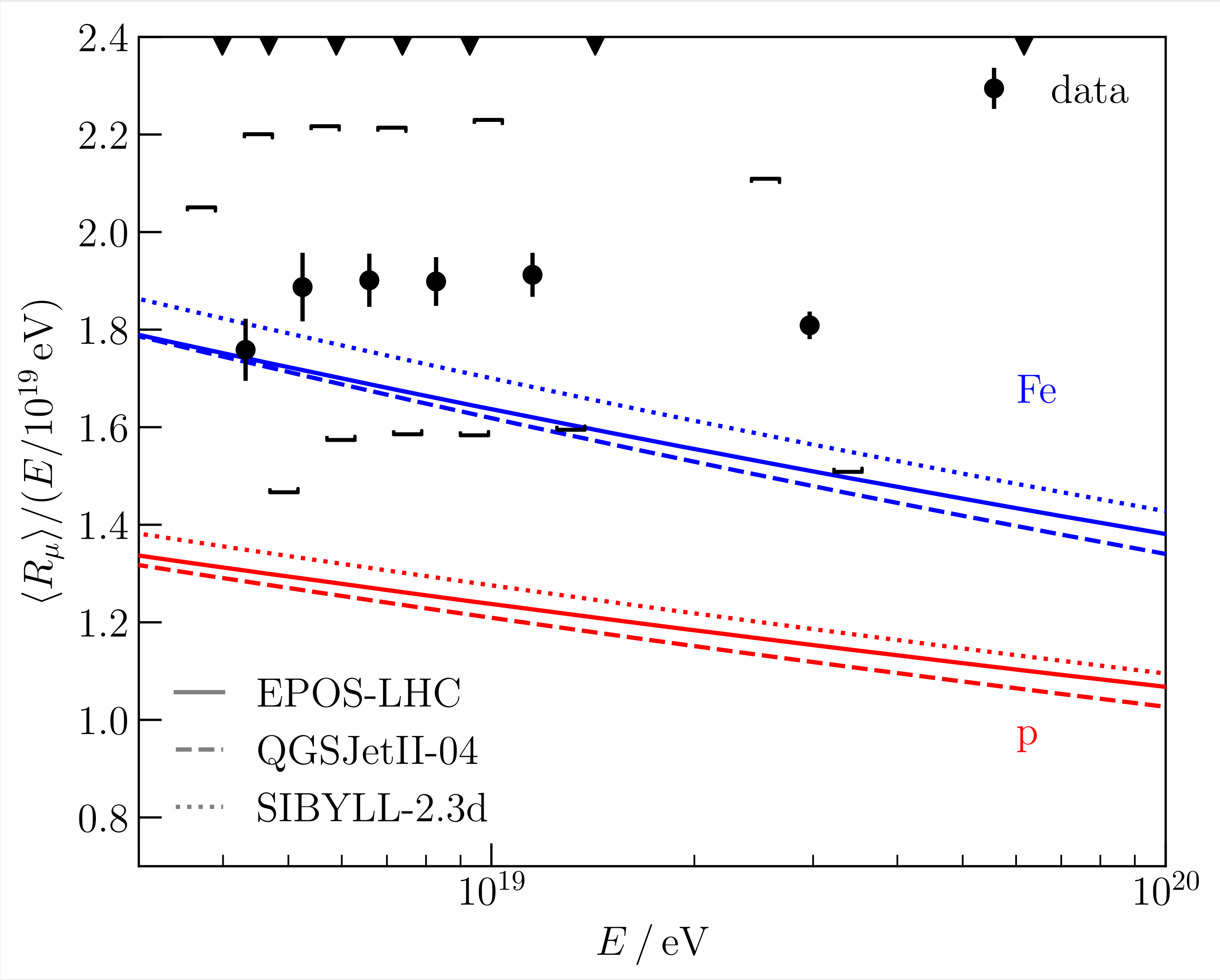
Use showers of different zenith angles



Consistently more muons in data than predicted

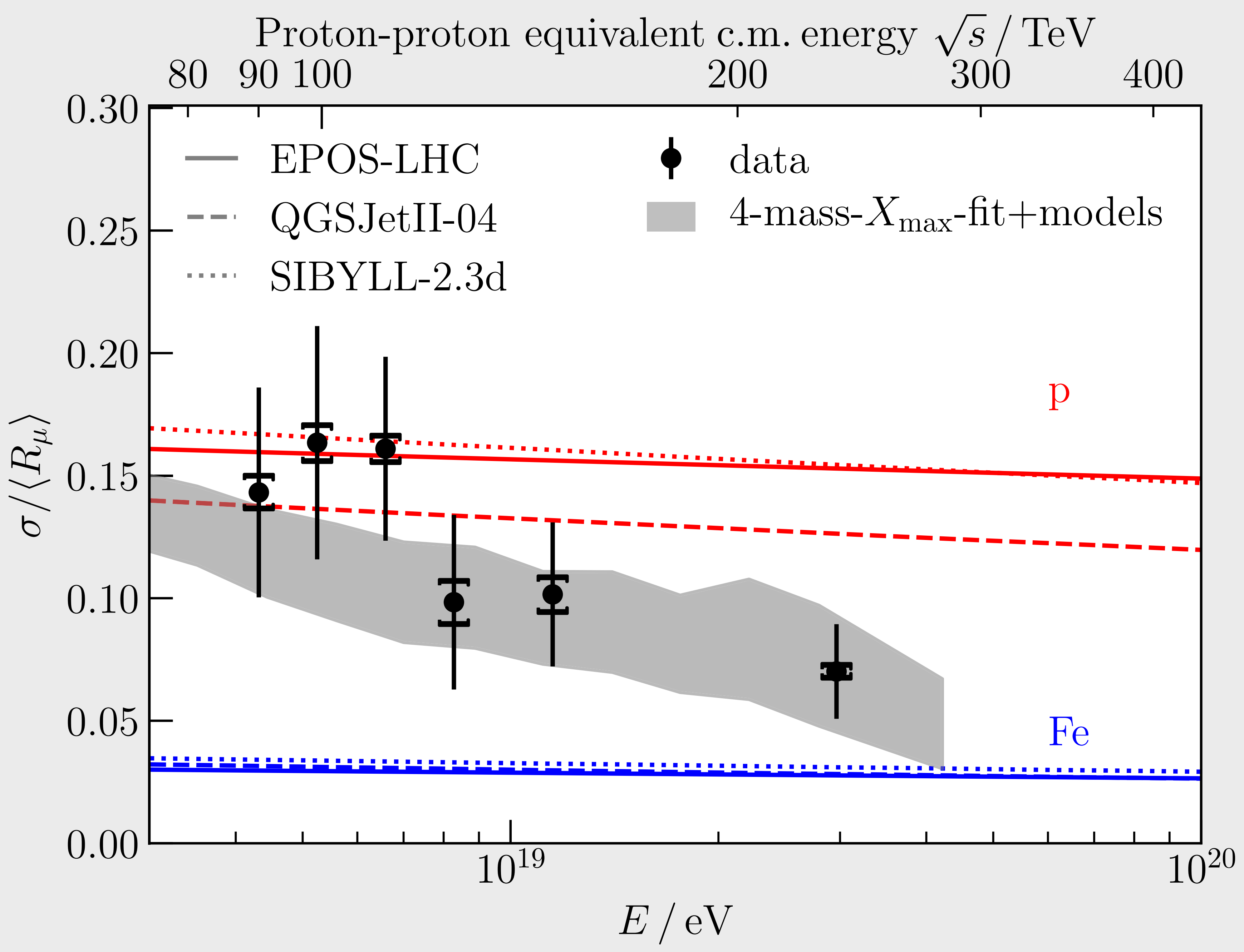
Auger muon measurement – inclined showers

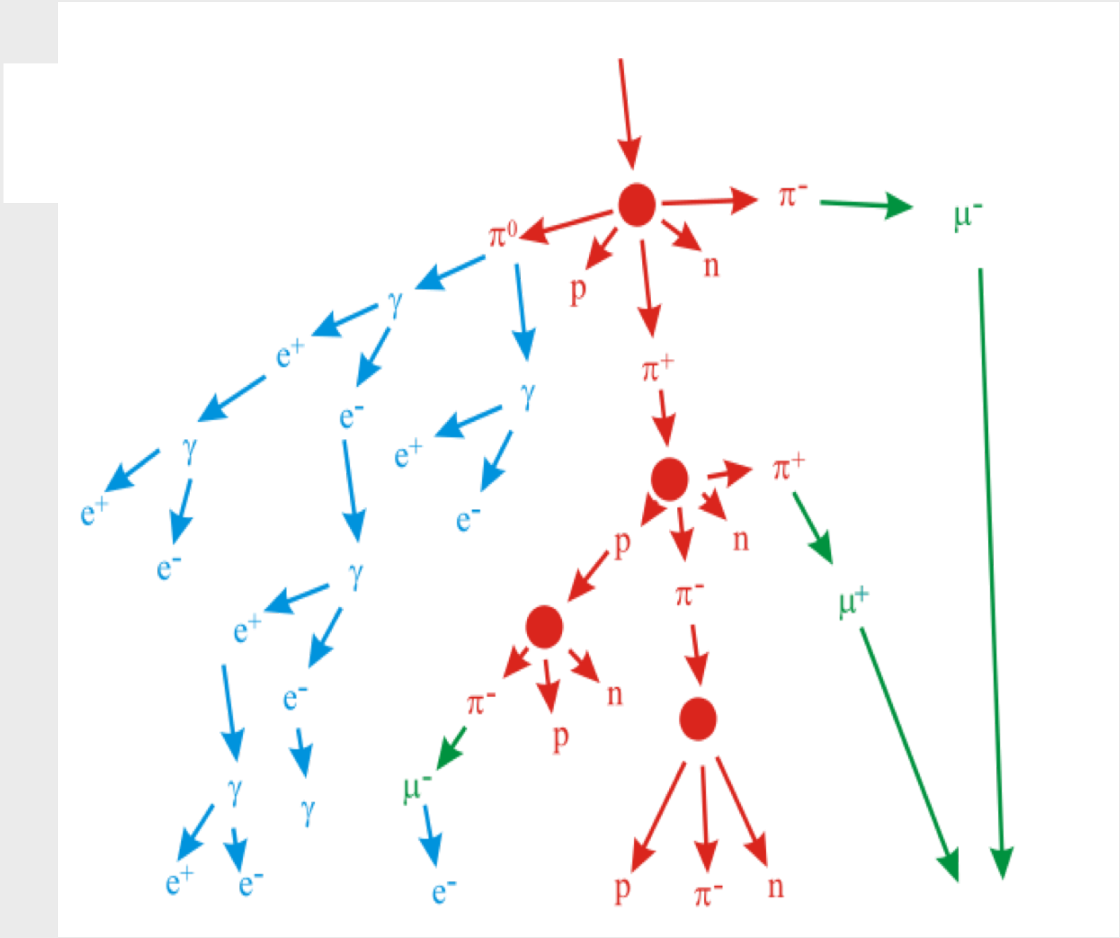
Number of muons in showers with θ>65°

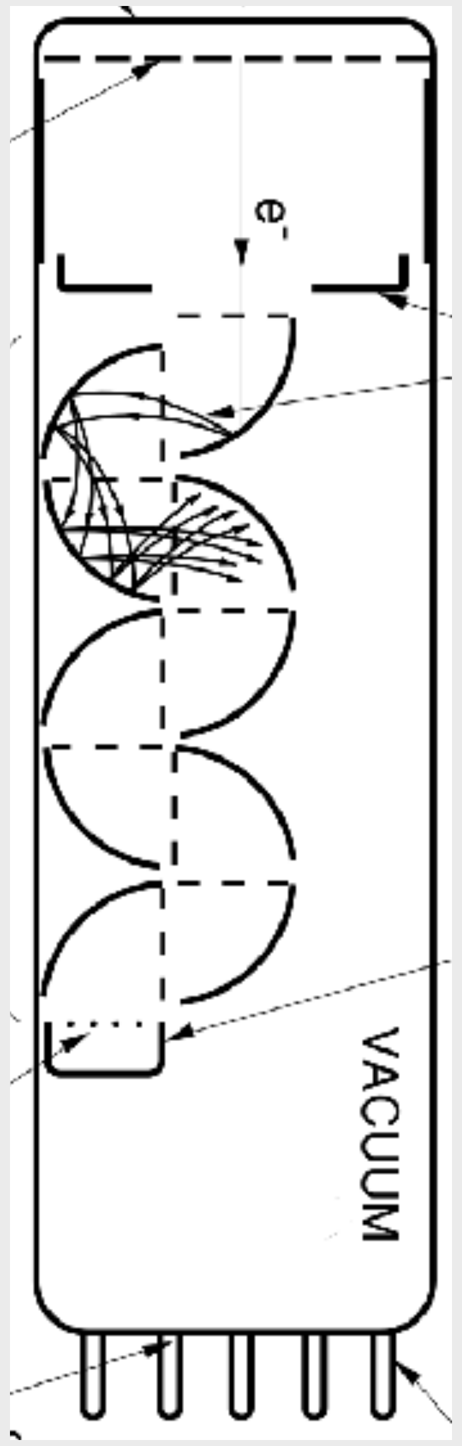


(Auger PRD 2015, PRL 2021)

Shower-to-shower fluctuations





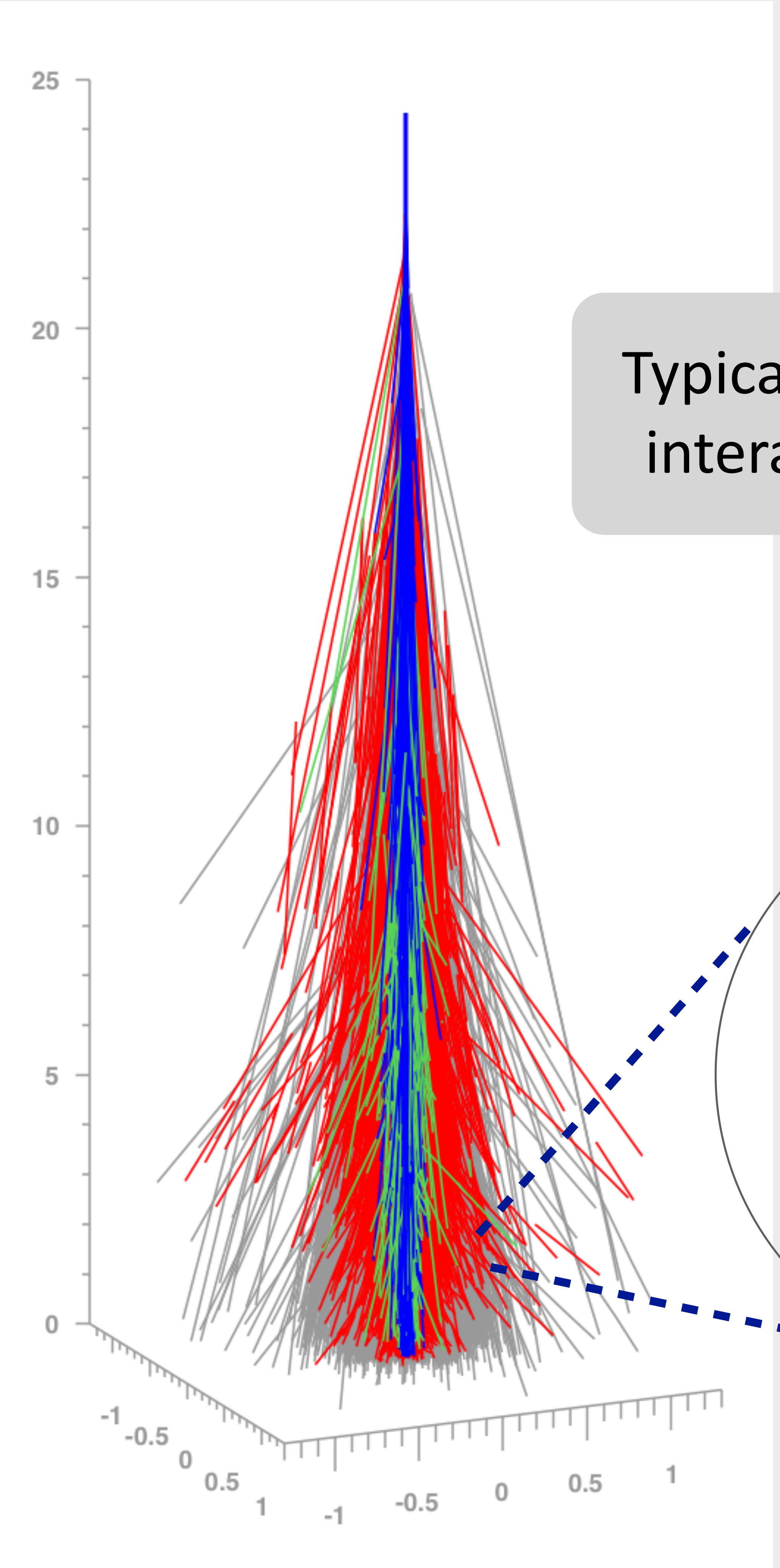


Lorenzo Cazon et al.
Astropart. Phys. 36 (2012) 211
Phys. Lett. B784 (2018) 68
Phys. Rev. D103 (2021) 022001

70% of fluctuations from first interaction

Discrepancy of muon number (20–30%), but no in relative shower-to-shower fluctuations

Muon production at large lateral distance



Typically 8-10 interactions

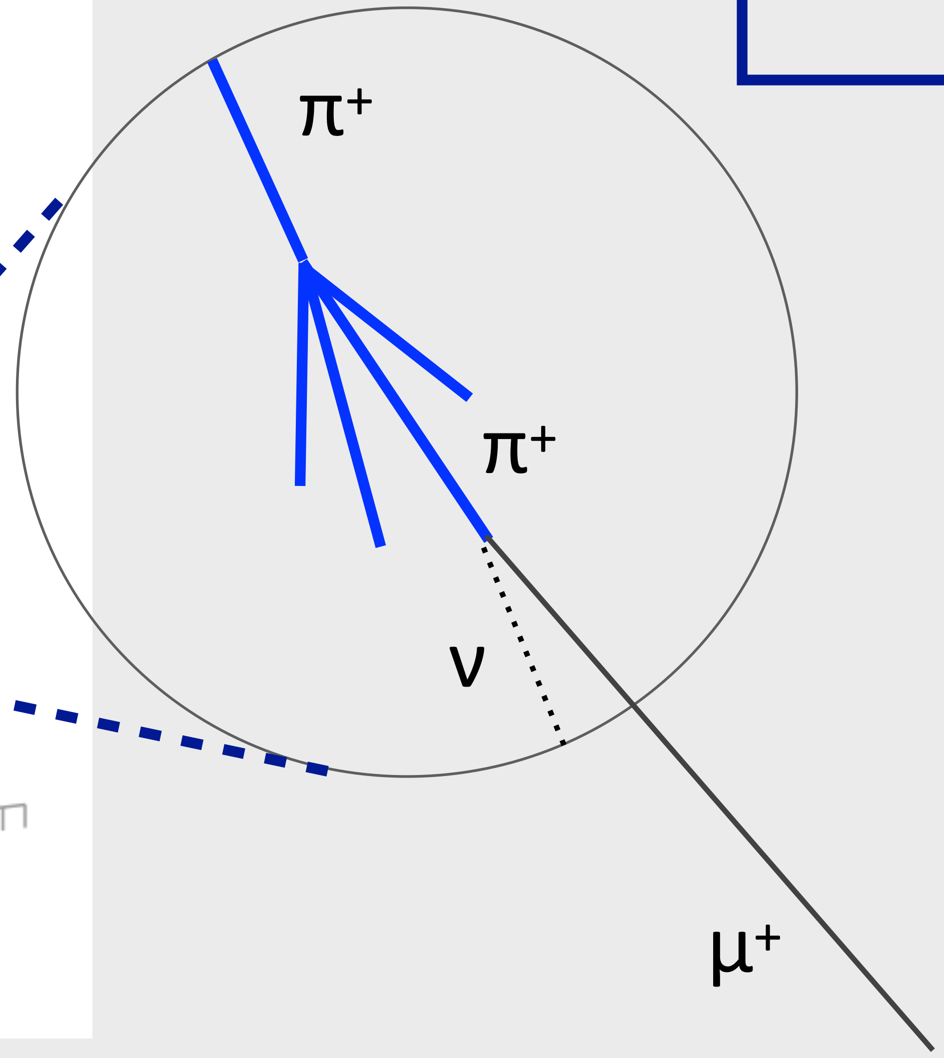
$$\pi^0 \rightarrow \gamma\gamma$$

$$c\tau_{\pi^0} = 25.1\,\mathrm{nm}$$

$$\pi^+ \rightarrow \mu^+ \nu_\mu$$

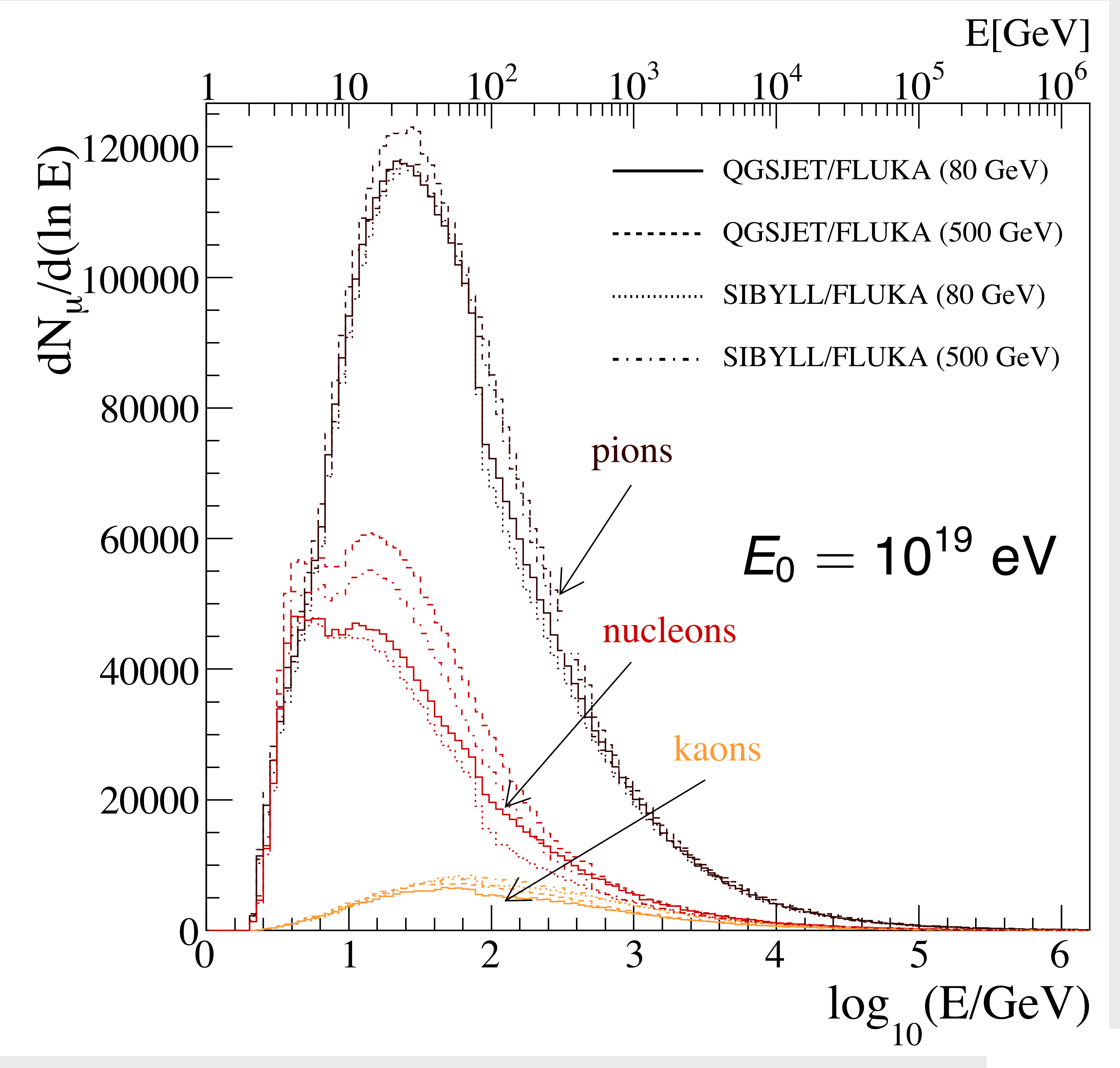
$$c\tau_{\pi^\pm} = 7.8\,\mathrm{m}$$

$$E_{\pi^\pm,\mathrm{dec}} \sim 30\,\mathrm{GeV}$$



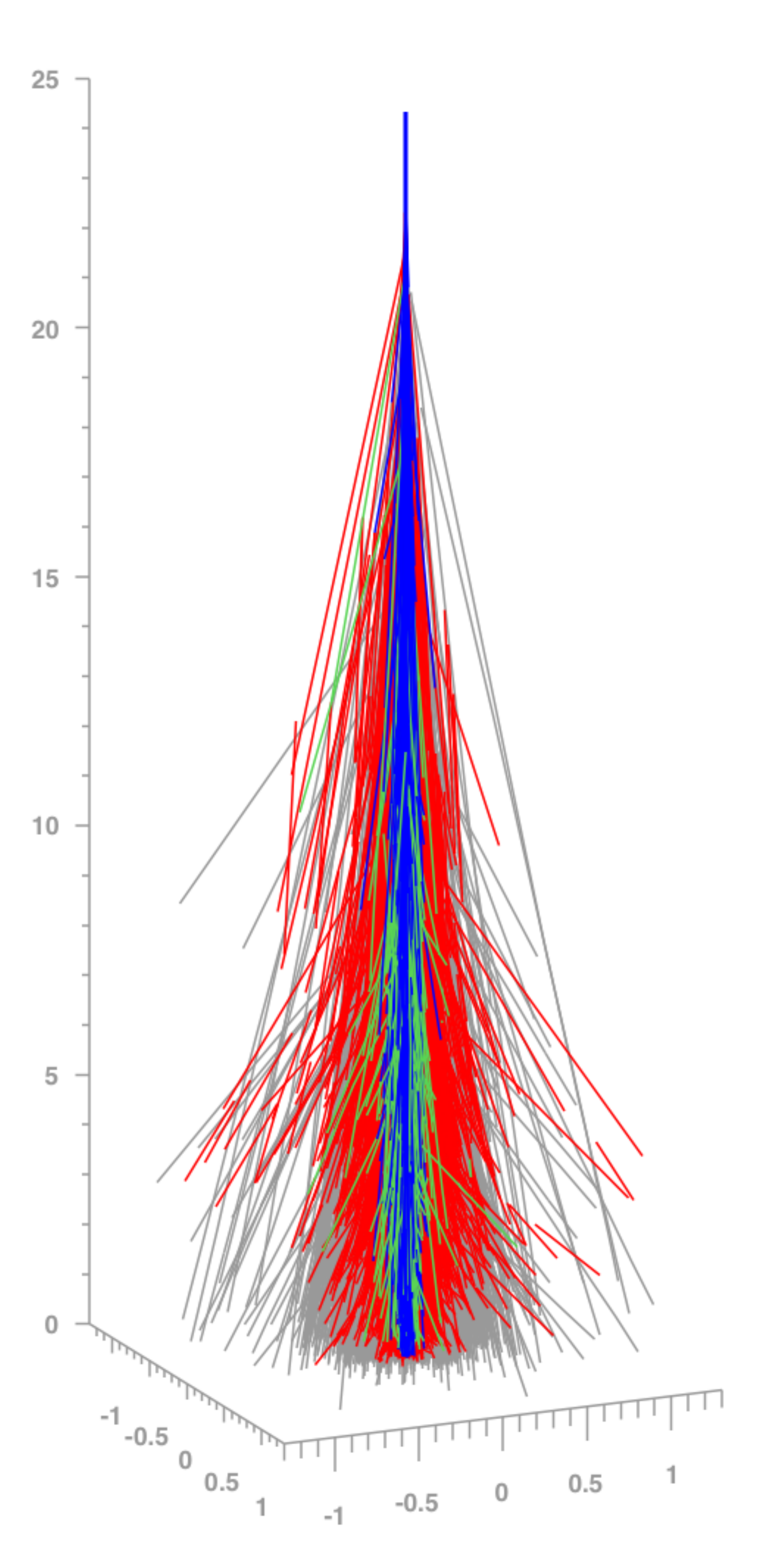
Muon observed at 1000 m from core

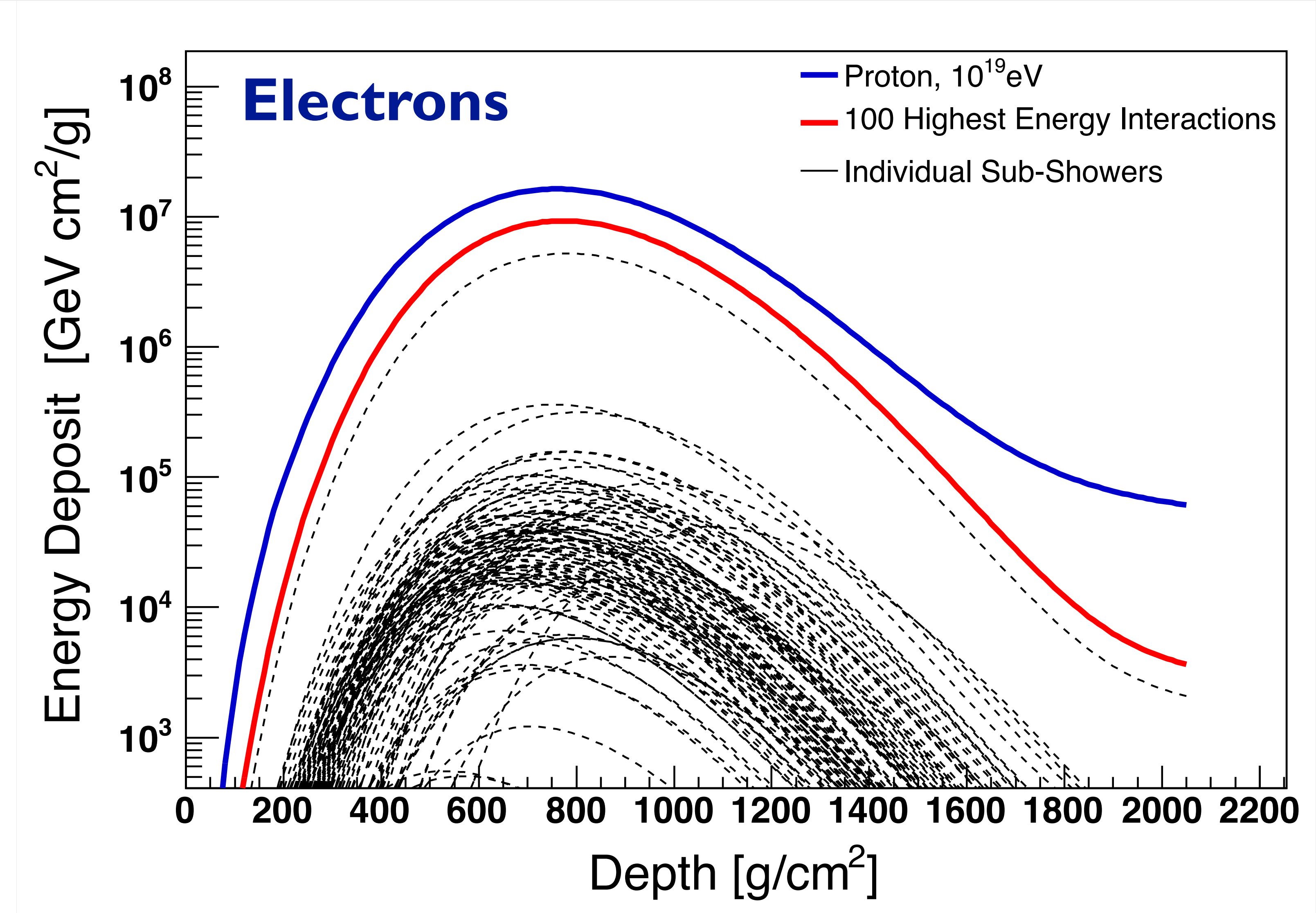
Energy distribution of **last interaction** that produced a detected muon

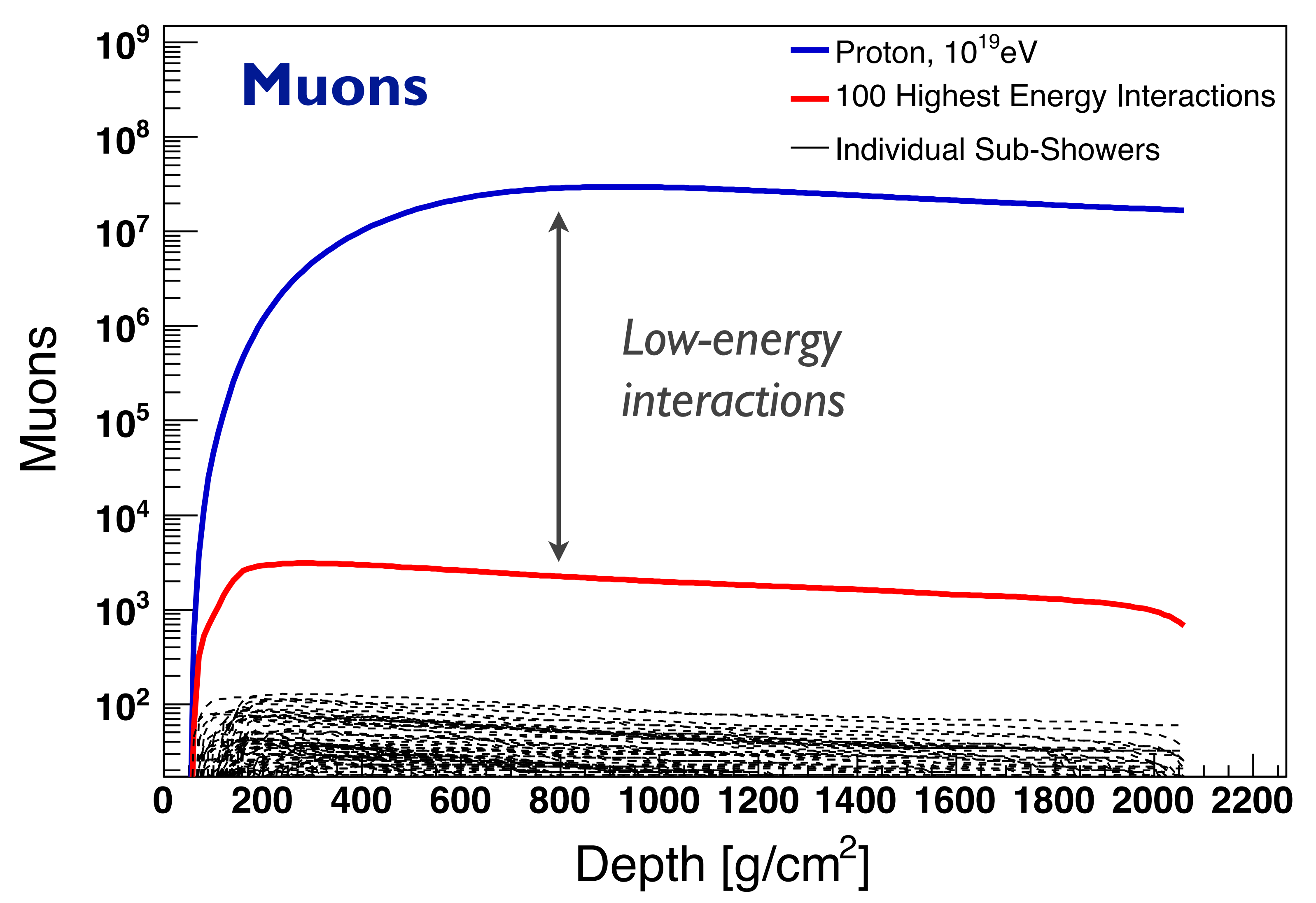


(Maris et al. ICRC 2009)

Importance of hadronic interactions at different energies







Shower particles produced in 100 interactions of highest energy

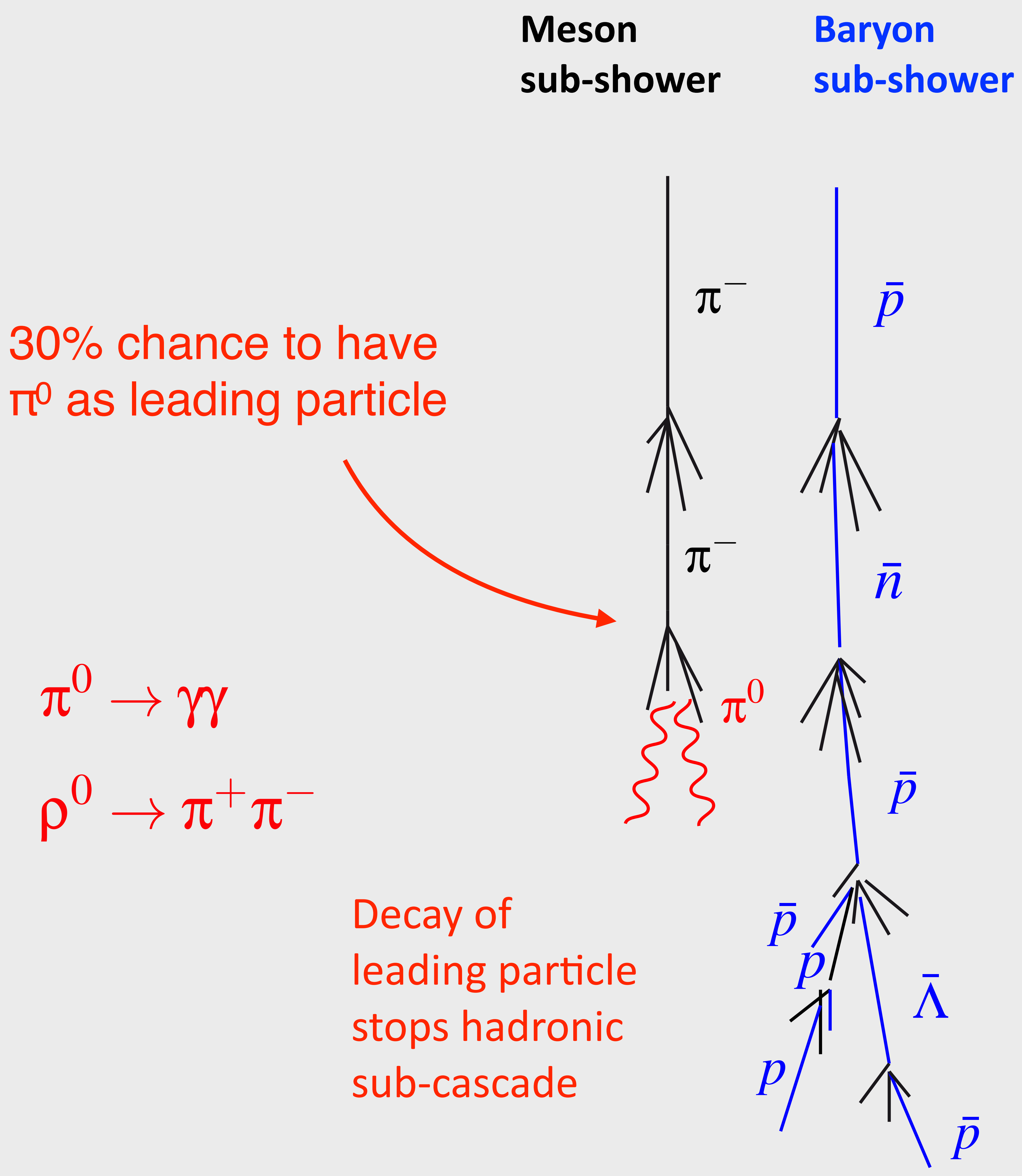
Electrons/photons:
high-energy interactions

Muons/hadrons:
low-energy interactions

Muons: 8 – 12 generations, majority of muons produced in ~30 GeV interactions

(Ulrich APS 2010)

Muon production depends on hadronic energy fraction



1 Baryon-Antibaryon pair production *(Pierog, Werner 2008)*

- Baryon number conservation
- Low-energy particles: large angle to shower axis
- Transverse momentum of baryons higher
- Enhancement of mainly **low-energy** muons

(Grieder ICRC 1973; Pierog, Werner PRL 101, 2008)

2 Enhanced kaon/strangeness production *(Anchordoqui et al. 2022)*

- Similar effects as baryon pairs
- Decay at higher energy than pions (~600 GeV)

3 Leading particle effect for pions *(Drescher 2007, Ostapchenko 2016)*

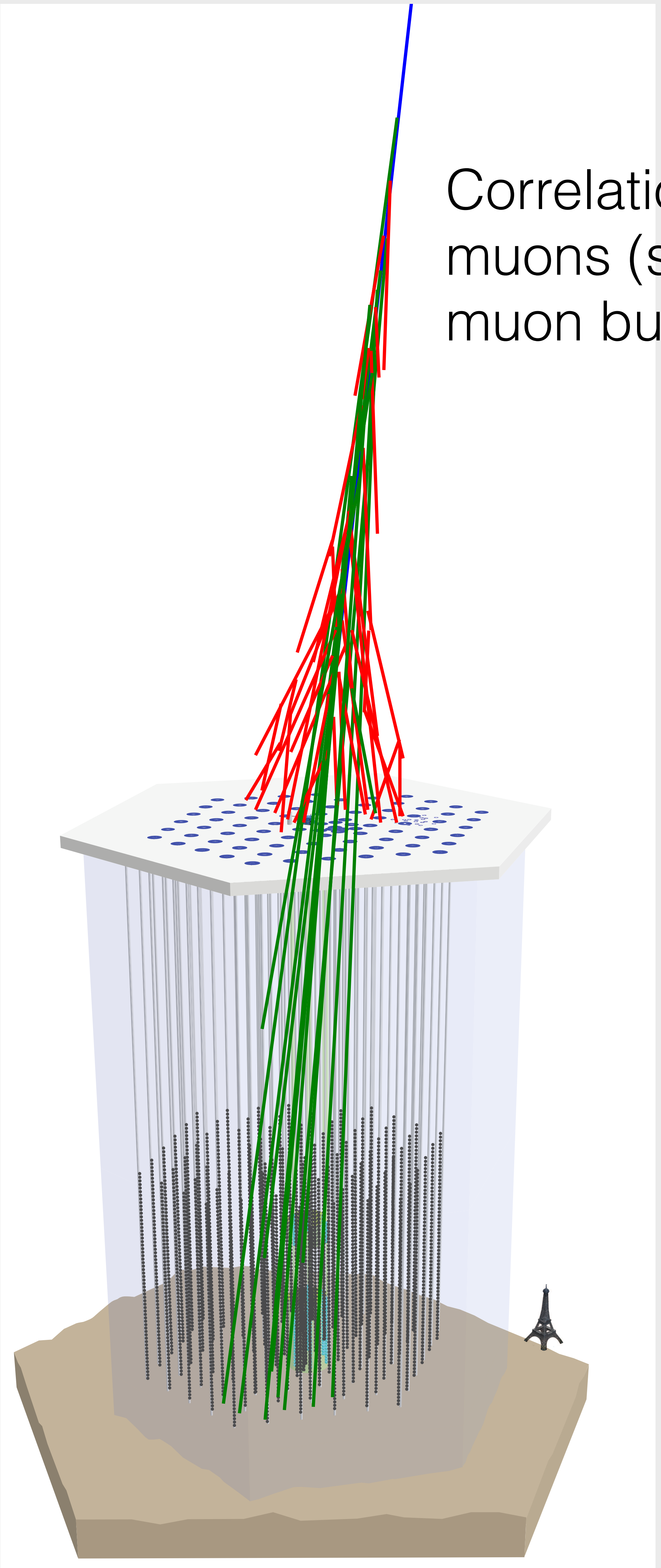
- Leading particle for a π could be ρ^0 and not π^0
- Decay of ρ^0 to 100% into two charged pions

4 New hadronic physics at high energy *(Farrar, Allen 2012, Salamida 2009)*

- Inhibition of π^0 decay (Lorentz invariance violation etc.)
- Chiral symmetry restauration

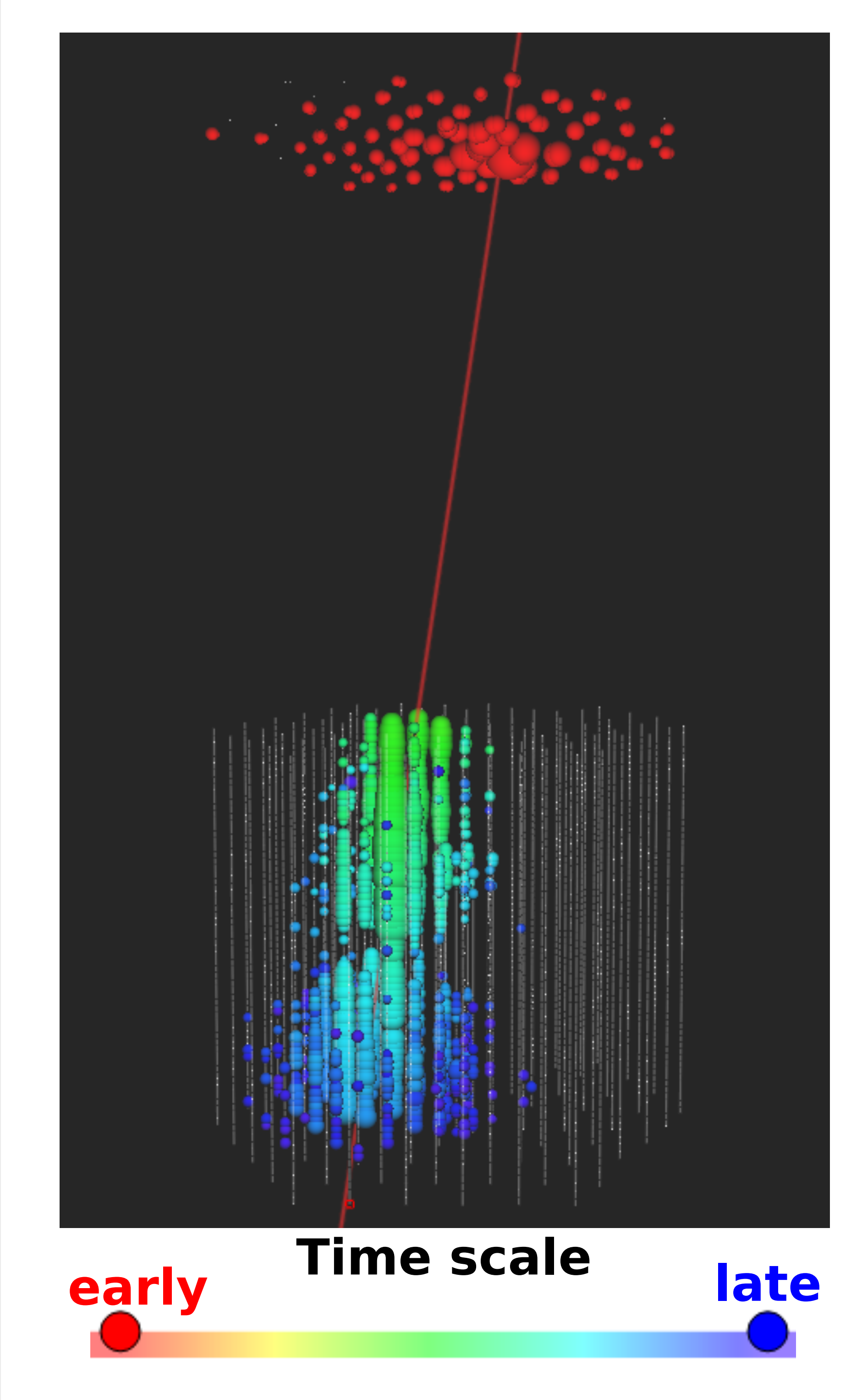
Several of these effects: Core-Corona model (Pierog et al.)

IceCube: discrimination of enhancement scenarios?

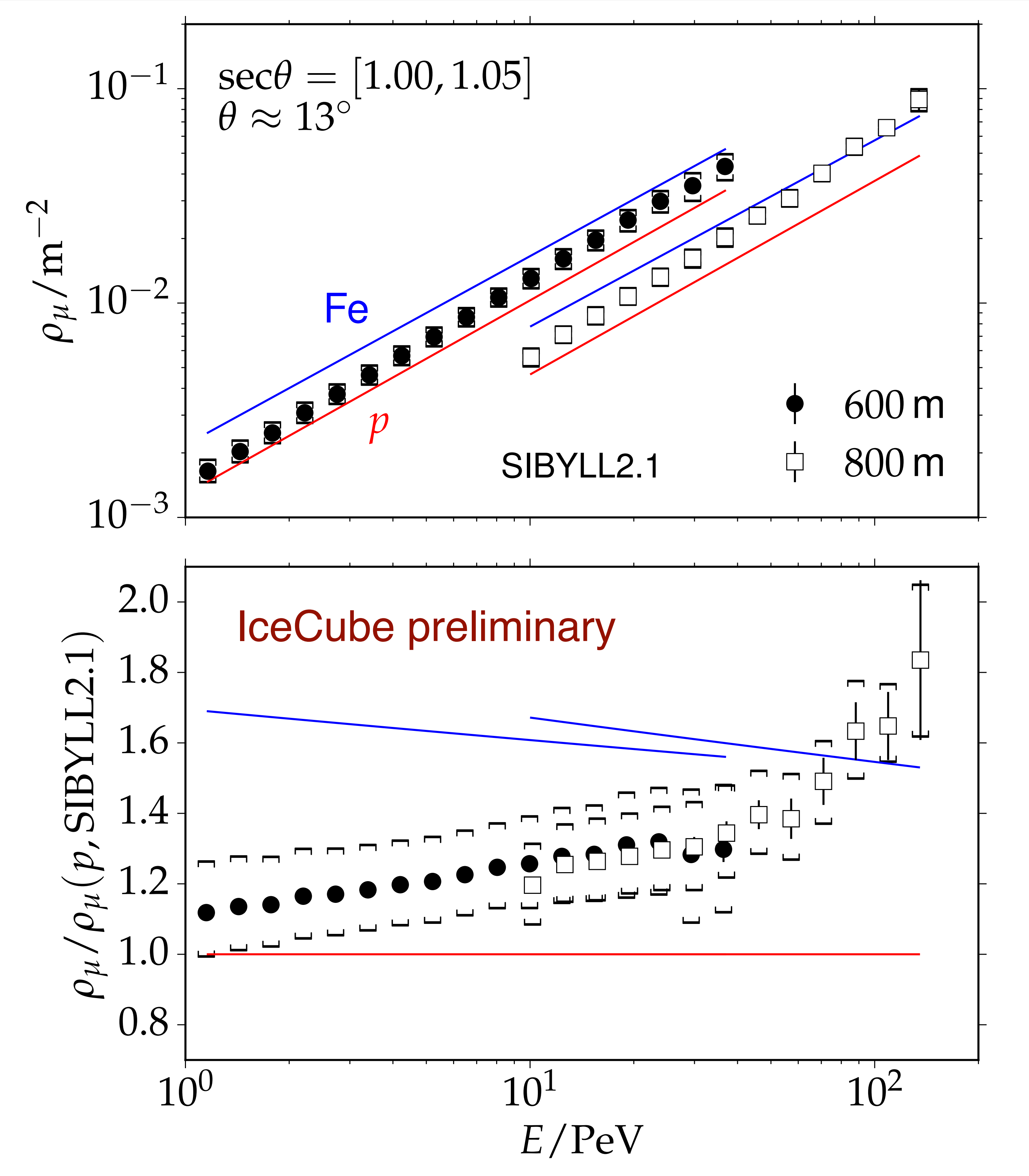


Correlation of low energy muons (surface) and in-ice muon bundles

IceTop: E_μ ~1 GeV



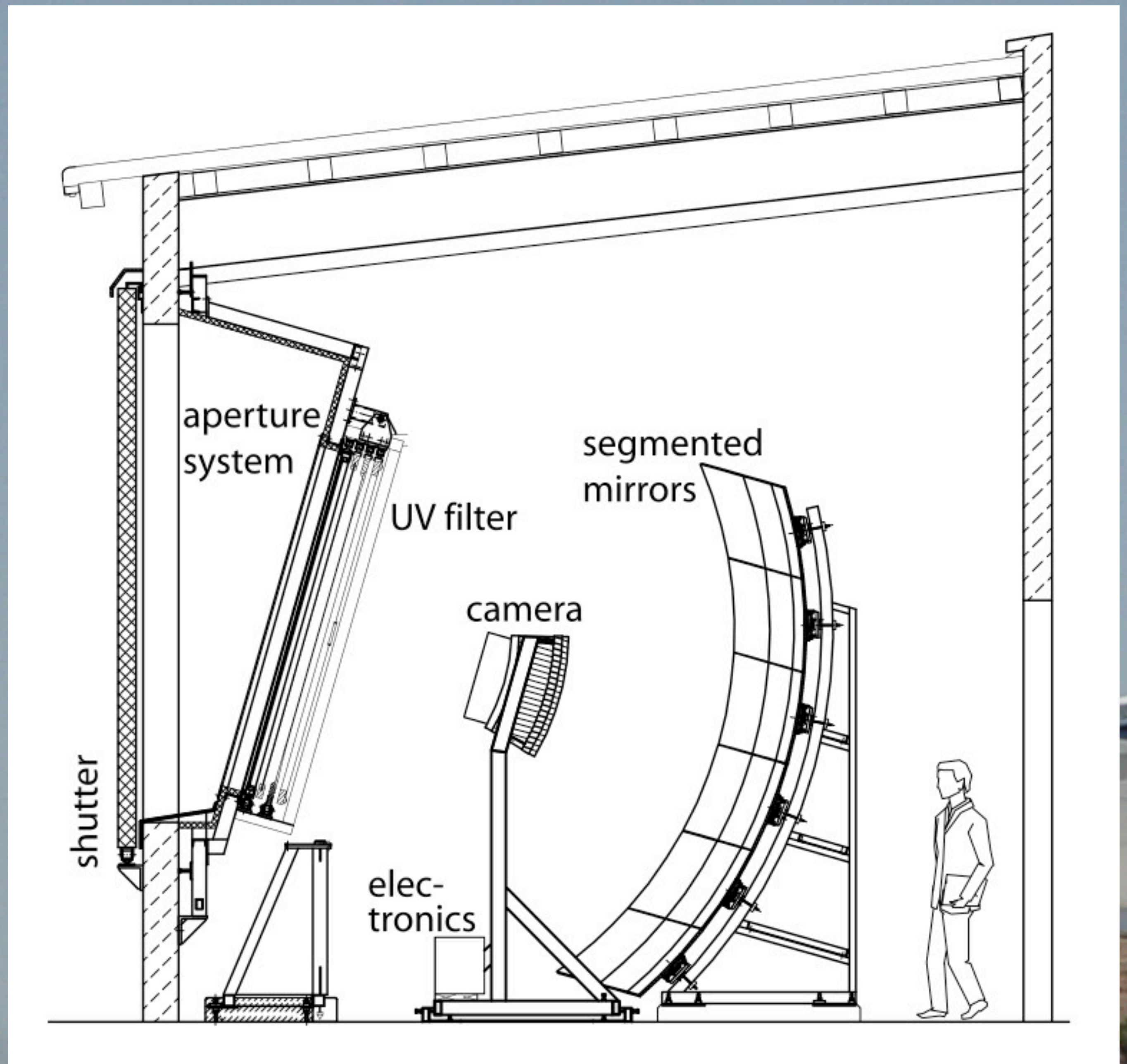
(IceCube, Gonzalez & Dembinski et al. 2016)



IceCube: E_μ >300 GeV


Malargue, Province Mendoza, Argentina


Malargue, Province Mendoza, Argentina
1.5 km

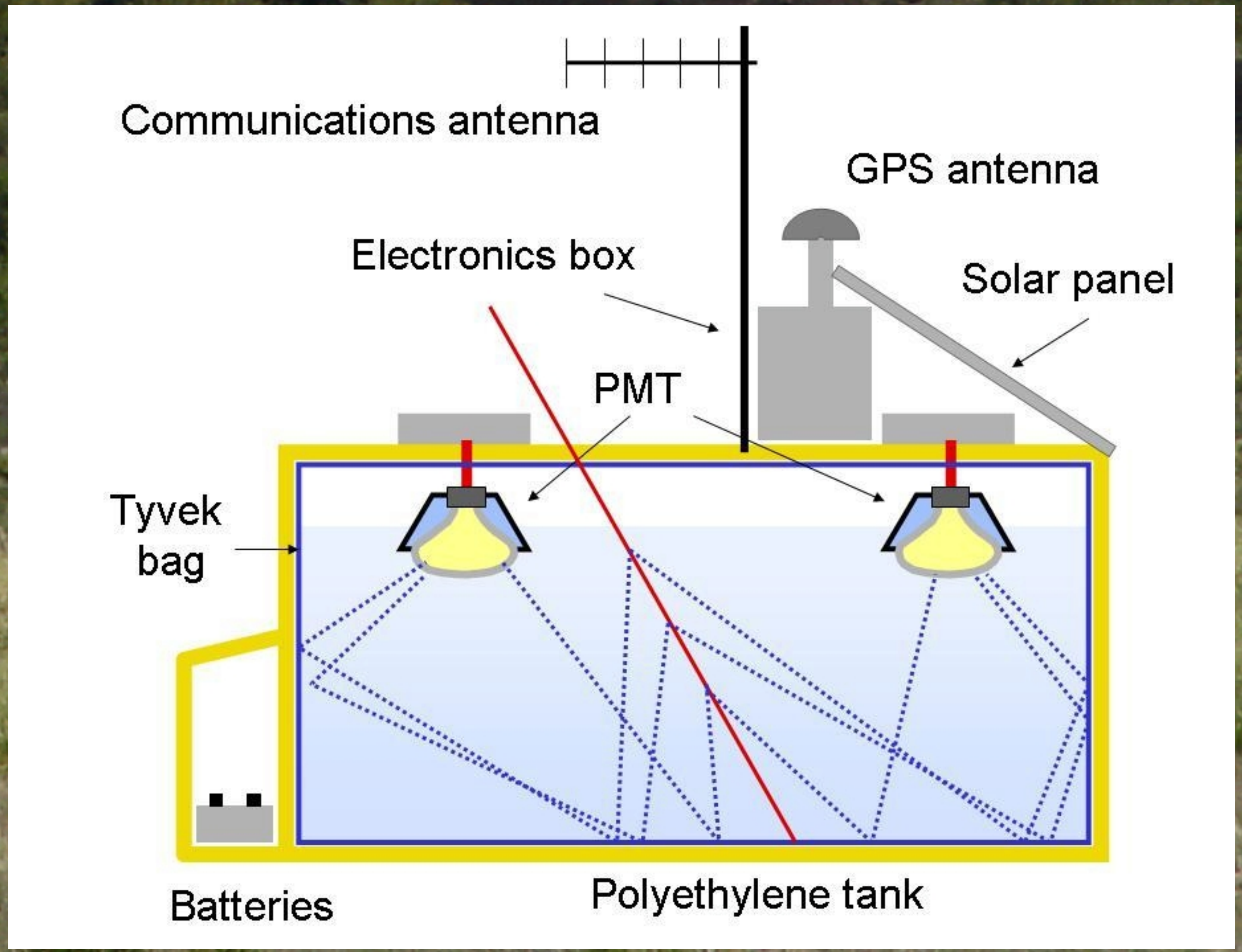


Fluorescence telescopes

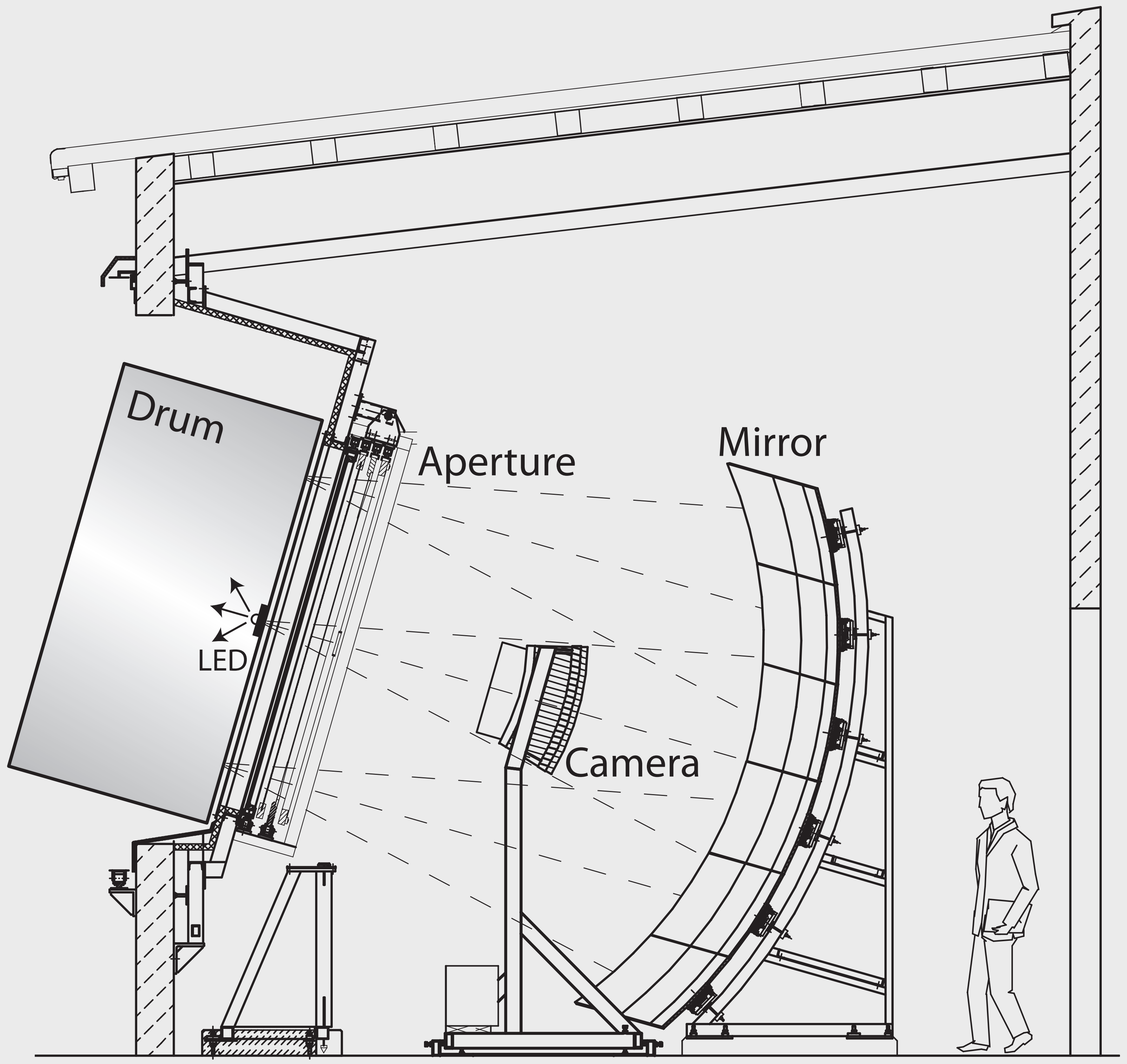
PMT camera with 440 pixels, 1.5° FoV per pixel, 10 MHz, 3.4 m segmented mirror

Particle detectors

10 m^2 area, 1.20 m high, 12 tons of water, 3 PMTs (9 inch), 40 MHz

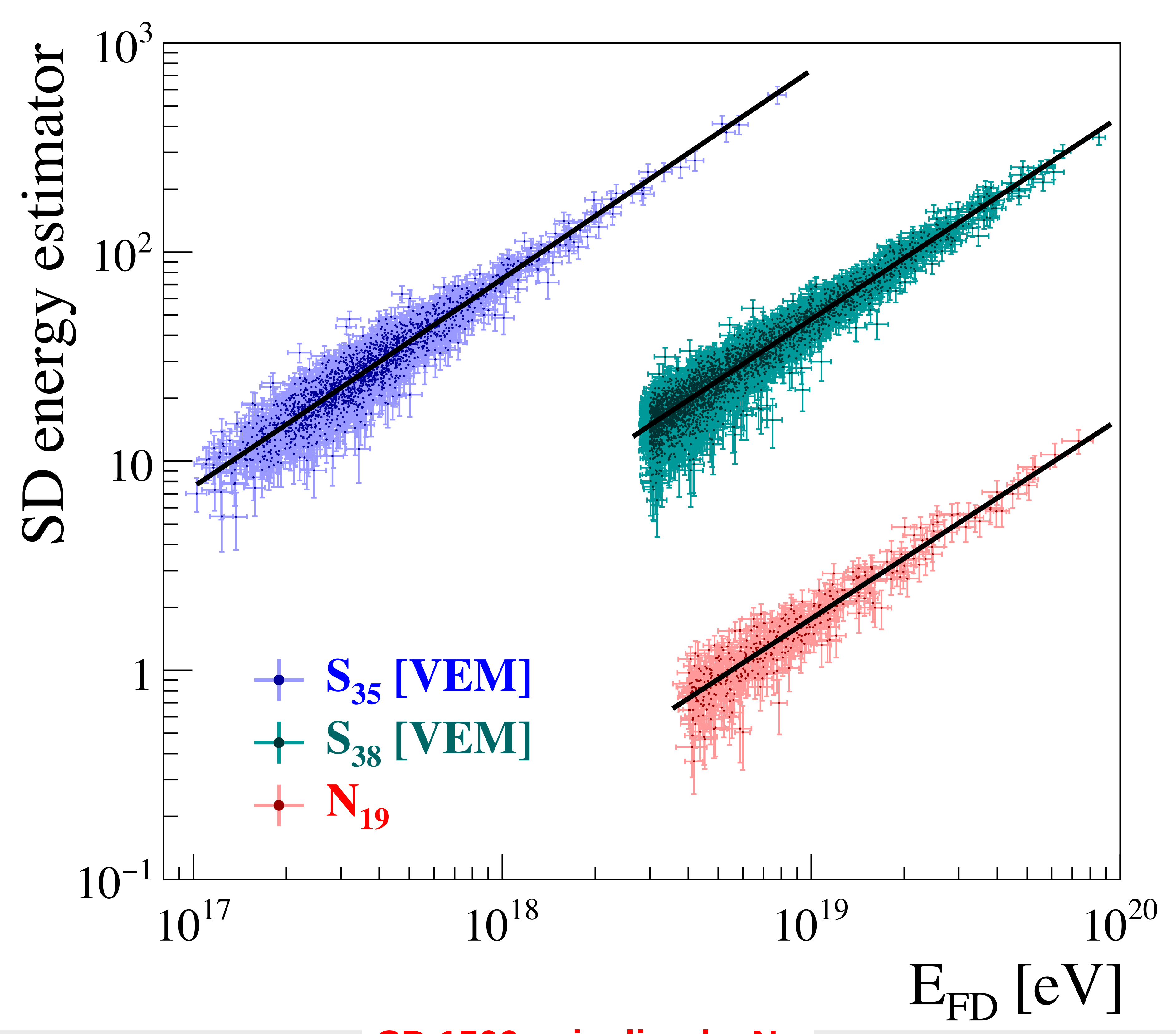


Energy calibration with fluorescence telescopes



SD 750 m – S_{35}
- S(450)+CIC
- threshold 0.1 EeV

SD 1500 m vertical – S_{38}
- S(1000)+CIC
- threshold 2.5 EeV



SD 1500 m inclined – N_{19}
- scaling parameter
- threshold 4 EeV

Drum: very precise end-to-end calibration

Cal-A: hourly relative calibration of camera only

$UHECR + matter \rightarrow \pi^{\pm} + \pi^{0} + X$
$\hookrightarrow \gamma + \gamma$
$\hookrightarrow \mu + \nu_\mu + \nu_e$
SHOCK WAVE
γ
p
π°
π±
e
e
e
μ
ν_μ
ν_e
γ
ν_μ
Auger: A 4π MM Observatory
1 Neutrons and charged CRs: Θ ≤ 80°
2 UHE Photons: 30° ≤ Θ ≤ 60°
3 Down-Going Neutrinos: 60° ≤ Θ ≤ 90°
4 Earth Skimming Neutrinos: 90° ≤ Θ ≤ 95°
5 HE BSM Particles: Θ > 95°

Waxman

Bahcall

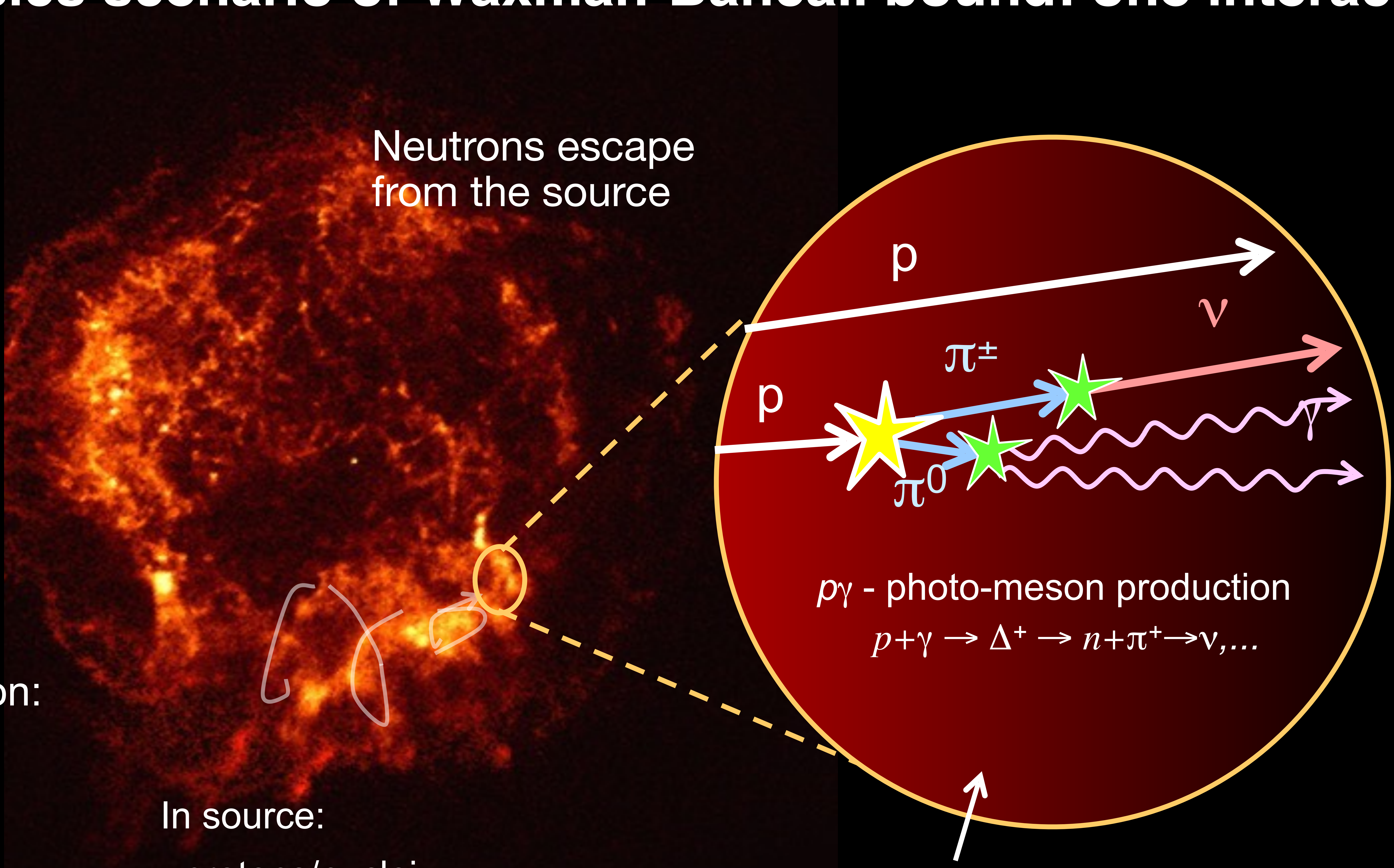
Use cosmic ray flux to estimate neutrino flux:

The Waxman-Bahcall upper bound (1998)

(Waxman & Bahcall, Phys. Rev. D59 (1999) 023002)

(Bahcall & Waxman, Phys. Rev. D64 (2001) 023002)

Physics scenario of Waxman-Bahcall bound: one interaction



Fermi acceleration:

dN/dE ~ E^{-2}

In source:

- protons/nuclei
- electrons/positrons

Target: radiation fields and matter

Assumptions and resulting bound

Sources inject only protons, luminosity normalized to CR data in range 10^{19} – 10^{20} eV

$$Q_p(E_p) = A\, E_p^{-2}$$

(Fermi acceleration of protons)

For each proton escaping the source exactly one interaction is assumed

$$p + \gamma \longrightarrow n\, \pi^+ \longrightarrow n\, \mu^+\, \nu_\mu \longrightarrow n\, e^+\, \nu_e\, \bar{\nu}_\mu\, \nu_\mu$$

(single interaction)

branching ratio 0.33

20% of p energy

each particle has 25% of the energy of the π^+

Neutrino flux

$$\Phi_{\nu_\mu}(E_{\nu_\mu}) = 0.33 \times 0.2 \times 0.25 \times A\, E_{\nu_\mu}^{-2}$$

Correction factors related to

- cosmological evolution of sources
- neutrino oscillations

$$\Phi_{\nu_\mu}(E_{\nu_\mu}) < 2 \times 10^{-8}\, \mathrm{GeV/cm^2\, s\, sr}$$

(Waxman & Bahcall, PRD59, 1998)

Assumptions and normalization of WB upper bound

(Waxman & Bahcall, Phys. Rev. D59 (1999) 023002)

- Extragalactic cosmic-ray protons extending to the highest energies

- One interaction with photon field per proton in source or source region

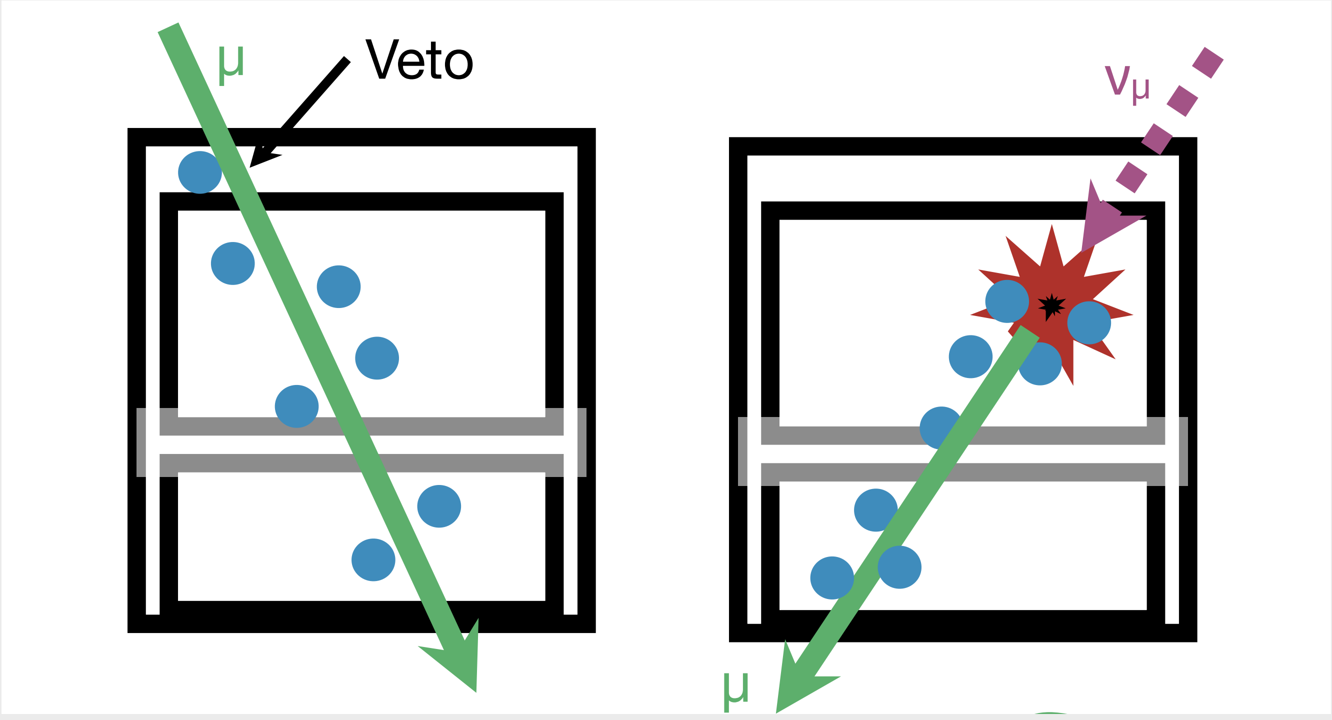
- Source production spectrum similar to Fermi acceleration

$$\frac{\mathrm{d}N}{\mathrm{d}E} \sim E^{-\gamma} \qquad \gamma = 1.8 \ldots 2.3$$

- **Energy production rate** (normalization) of 4 x 10^{44} erg Mpc^{-1} yr^{-1} *(Waxman, ApJ 452 (1995) L1)*

Size of neutrino detector (water, ice) for observing this flux has to be V ~ 1 km^3

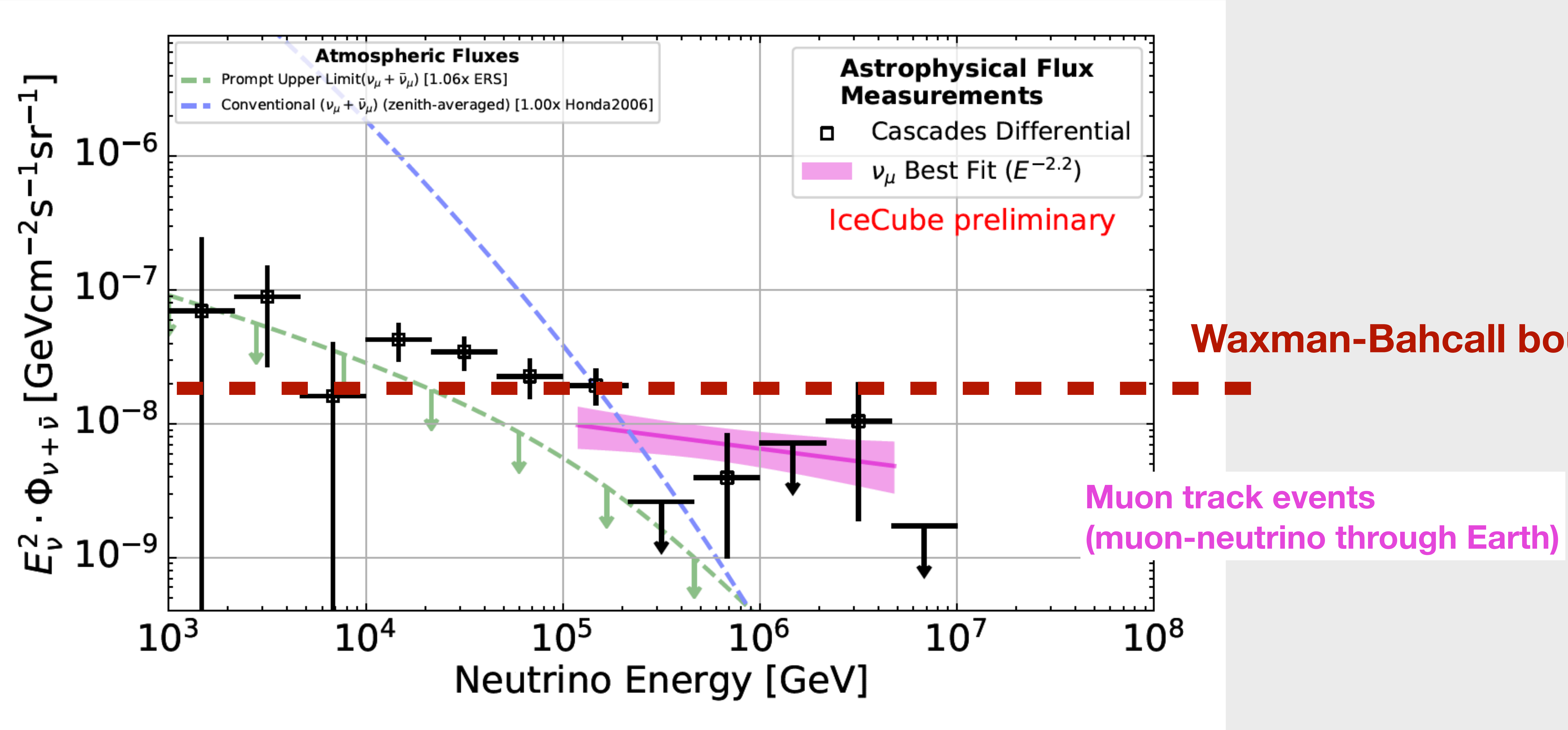
Neutrino flux found at level of Waxman-Bahcall bound



Veto technique

High energy starting events (HESE)

(IceCube, Science 342 (2013) 1242856)



Summary of assumption of WB upper bound

(Waxman & Bahcall, Phys. Rev. D59 (1999) 023002)

- Extragalactic cosmic-ray protons extending to the highest energies ✗
- One interaction with photon field per proton in source or source region
- Source production spectrum similar to Fermi acceleration ✗

$$\frac{\mathrm{d}N}{\mathrm{d}E} \sim E^{-\gamma} \qquad \gamma = 1.8 \ldots 2.3$$

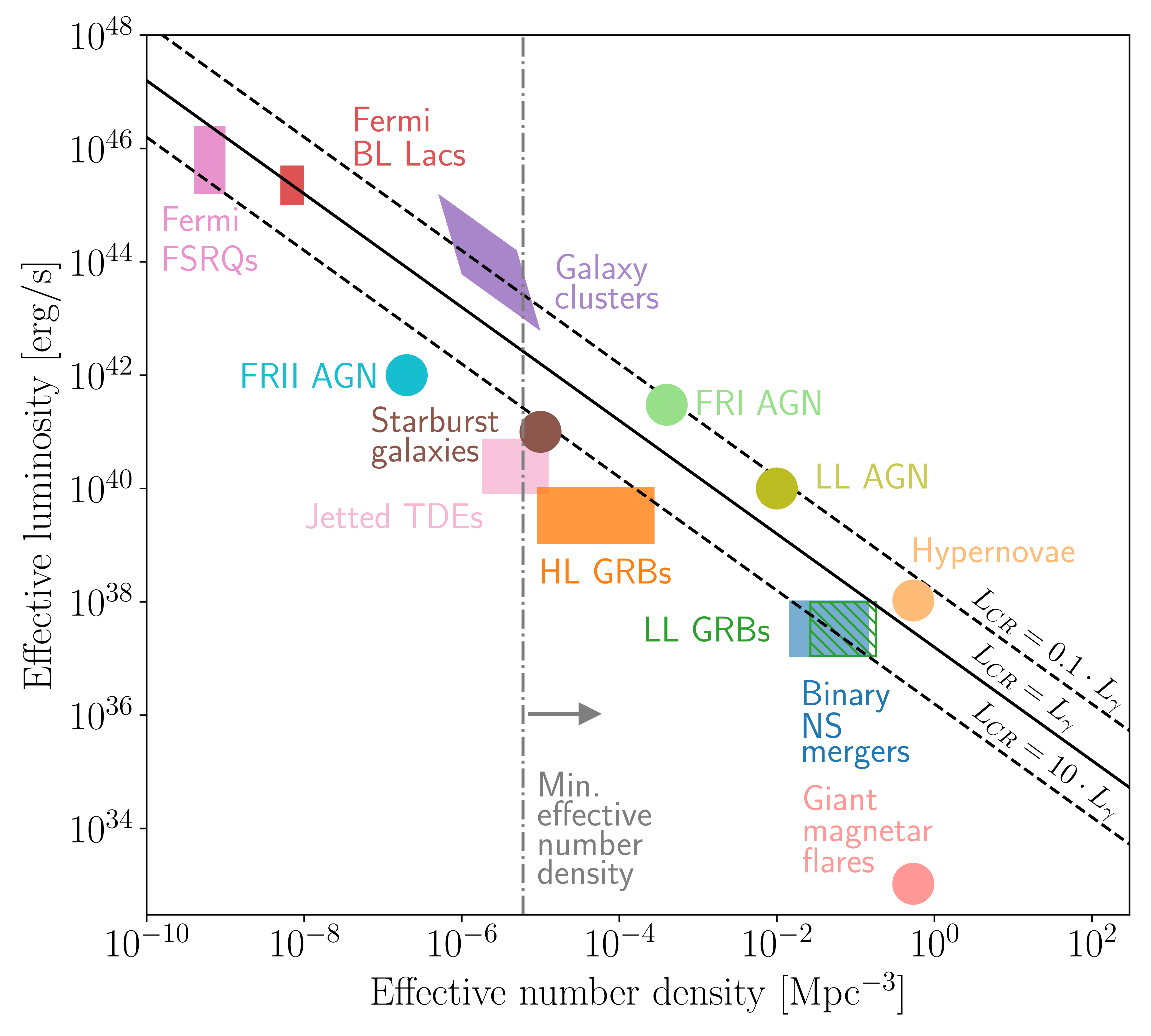
PIERRE AUGER OBSERVATORY

- Energy production rate (normalization) of 4 x 10^{44} erg Mpc^{-1} yr^{-1} ✓

(Waxman, ApJ 452 (1995) L1)

Size of neutrino detector (water, ice) for observing this flux has to be V ~ 1 km^3

Constraints on source models – luminosity density



(MIAPP review, Front.Astron.Space Sci. 6 (2019) 23)

Integral of cosmic ray flux observed by Auger

$$\varepsilon_{CR} = 4\pi/c \int_{E_{ankle}}^{\infty} E \cdot \mathrm{Flux}(E)\ \mathrm{d}E$$

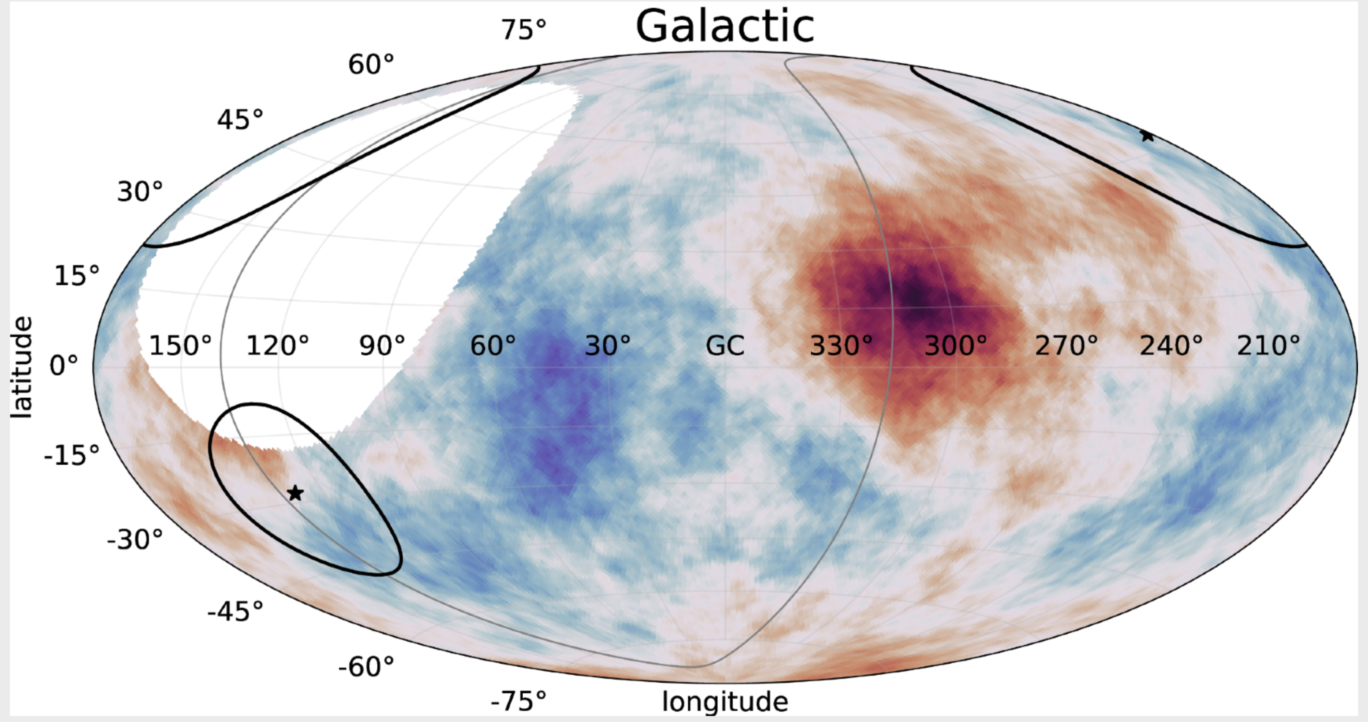
$$= (5.66 \pm 0.03 \pm 1.40) \cdot 10^{53}\ \mathrm{erg\ Mpc^{-3}}$$

$$\mathscr{L} \sim \varepsilon_{CR}/t_{\mathrm{loss}} = 2 \cdot 10^{44}\ \mathrm{erg\ Mpc^{-3}\ yr^{-1}}$$

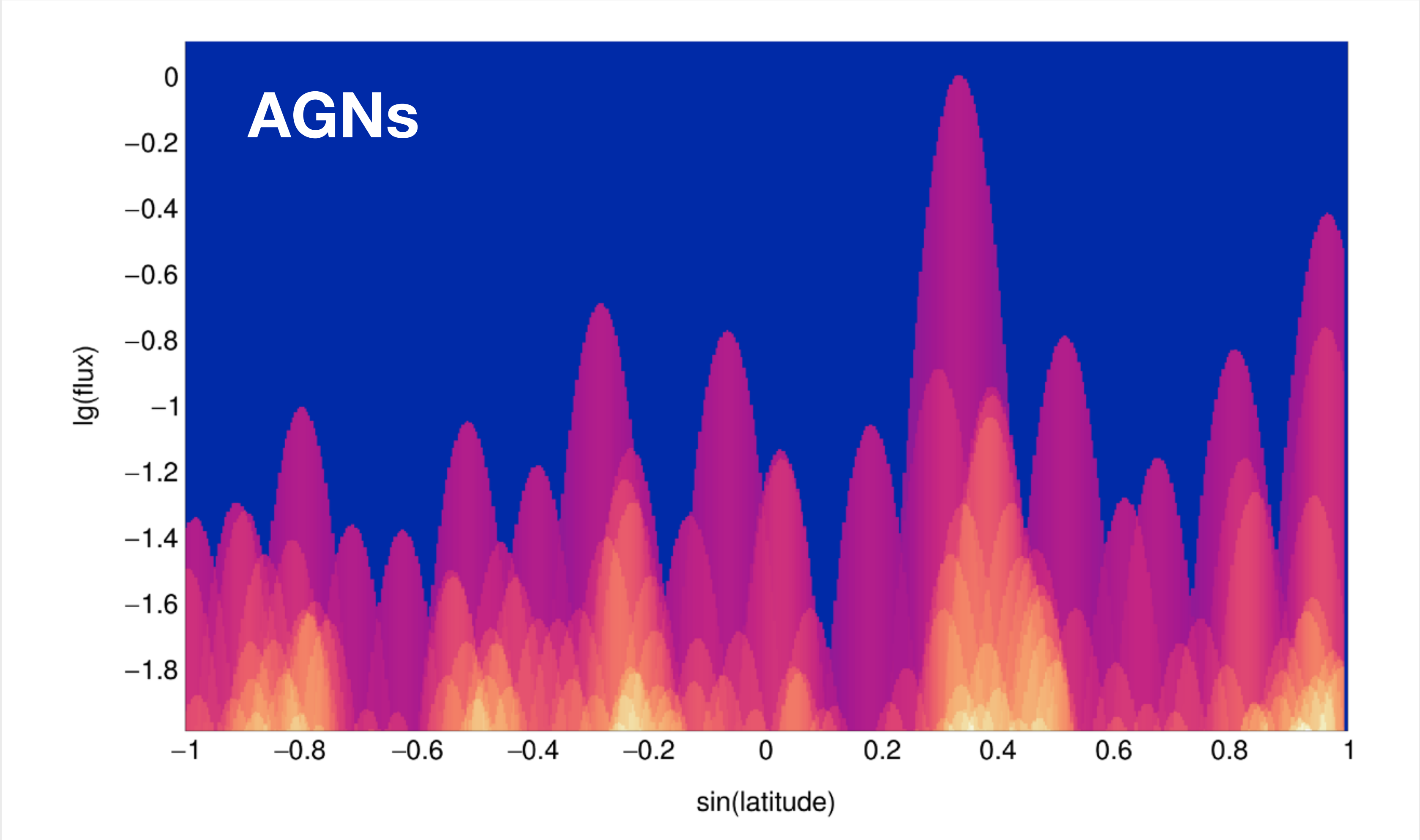
Full calculation with SimpProp: $\mathscr{L} \simeq 6 \cdot 10^{44}\ \mathrm{erg\ Mpc^{-3} yr^{-1}}$

Like WB bound: gamma rays produced in sources (direct e± acceleration and CR interactions)

Increase of statistics at highest energies

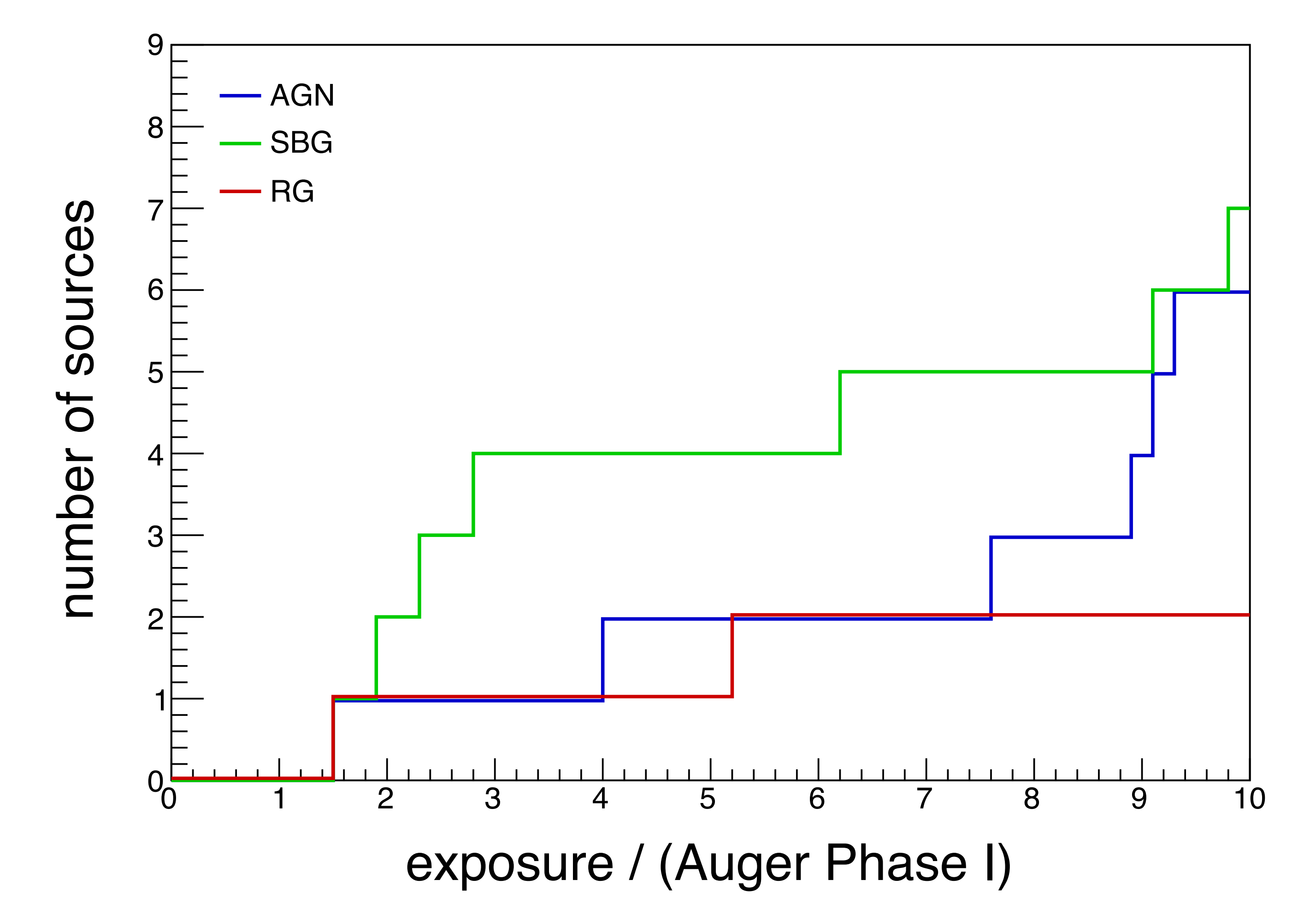


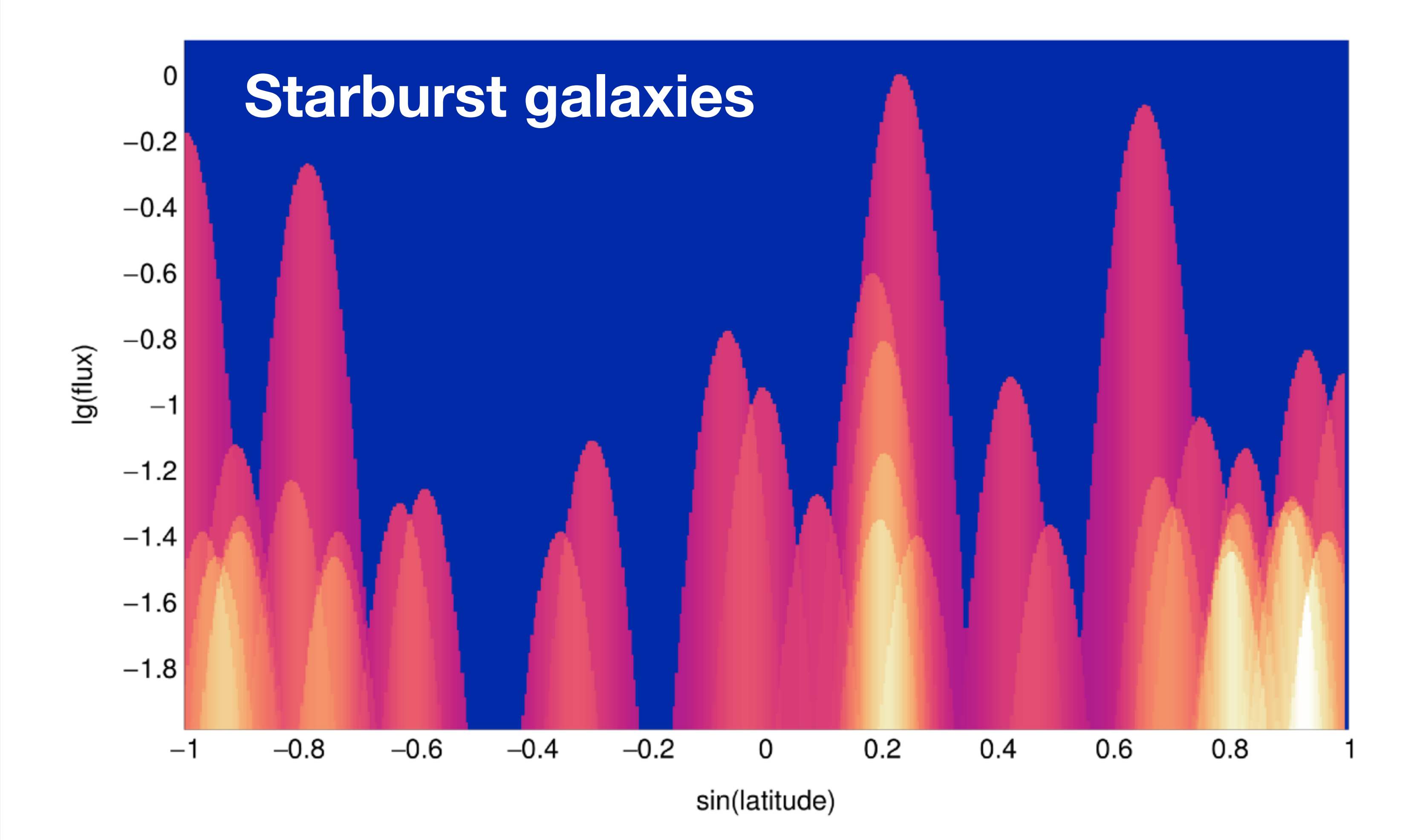
(Unger, RE et al., work in progress)

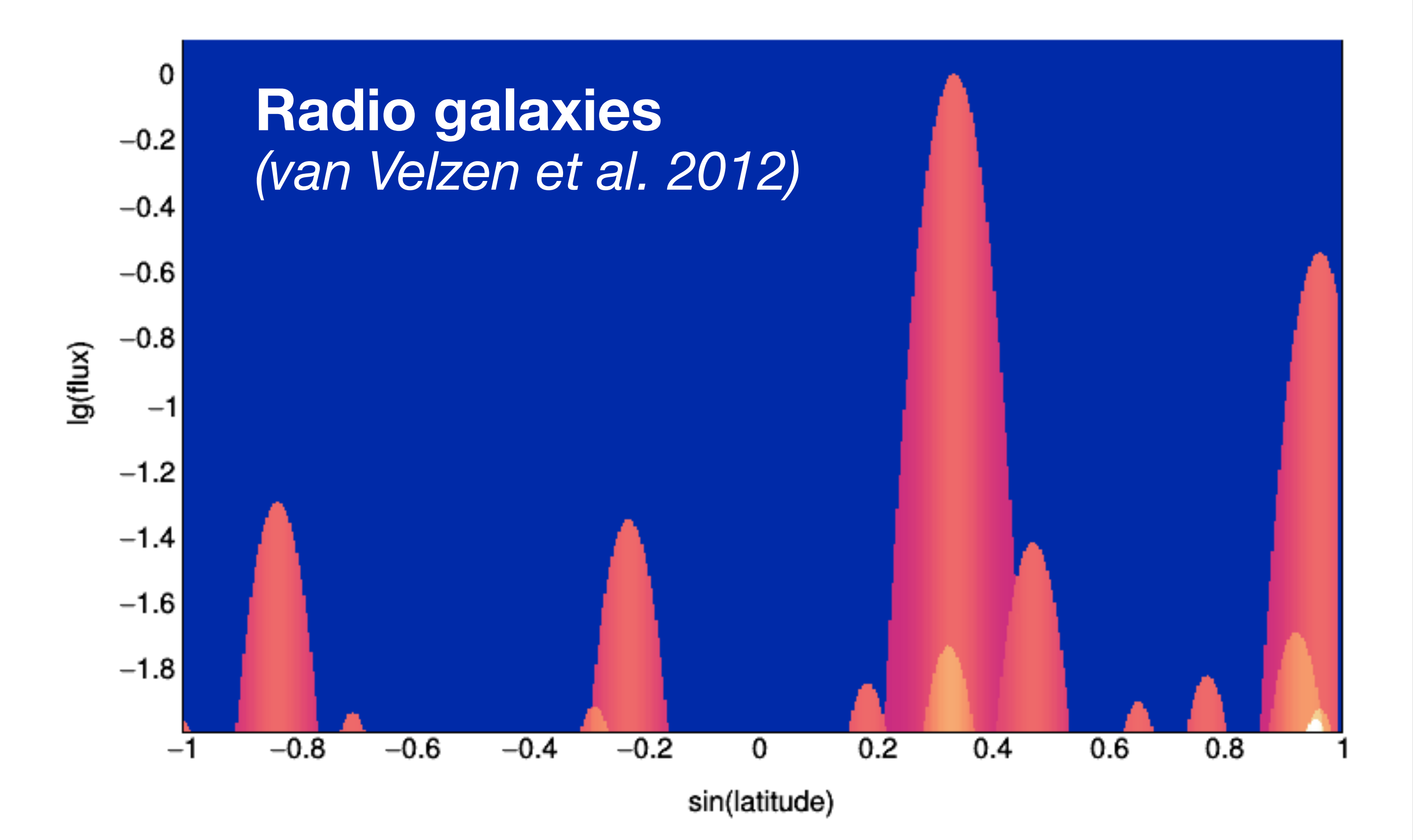


Interpretation of hotspot with different catalogs

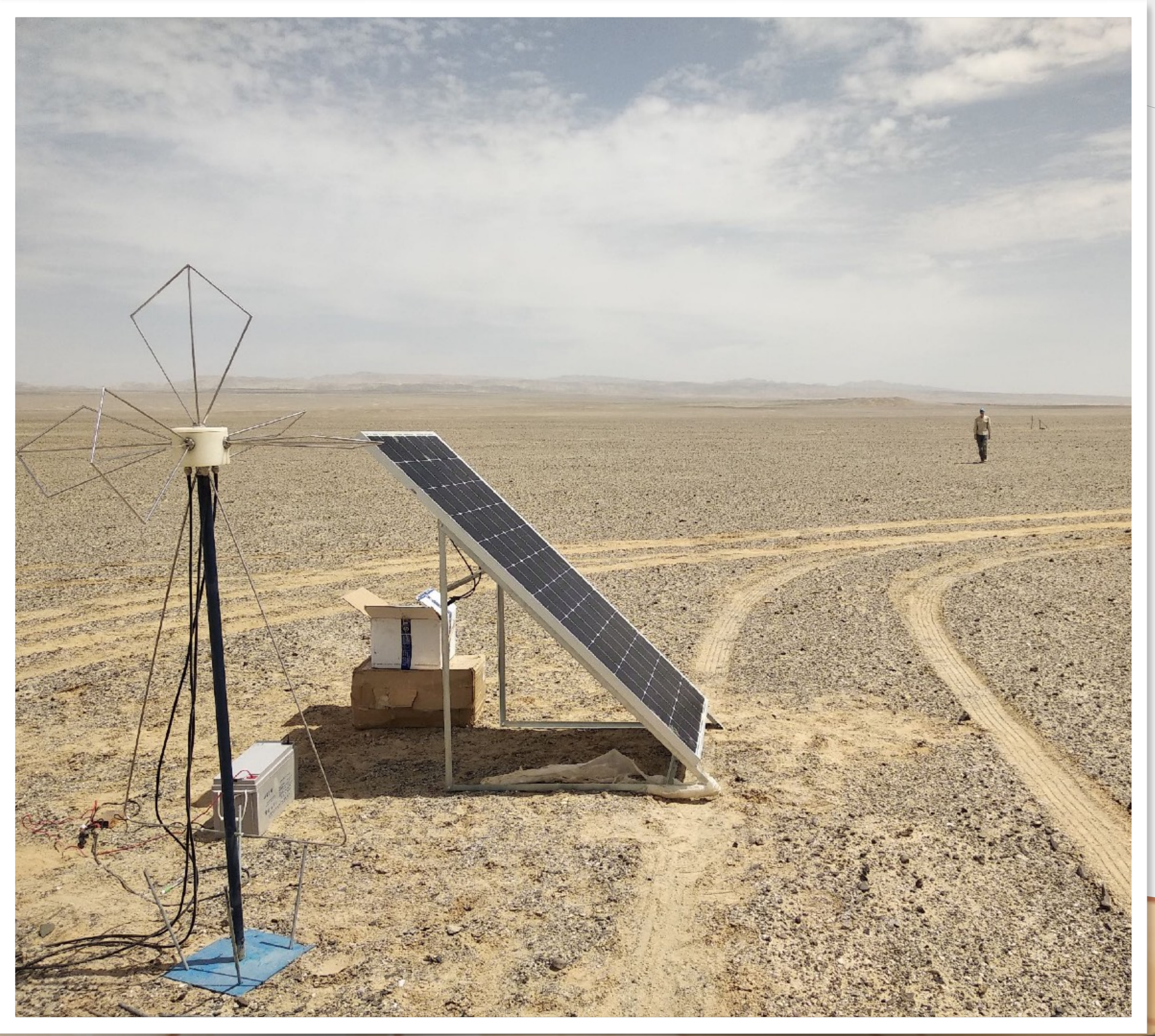
Second hotspot will break degeneracy

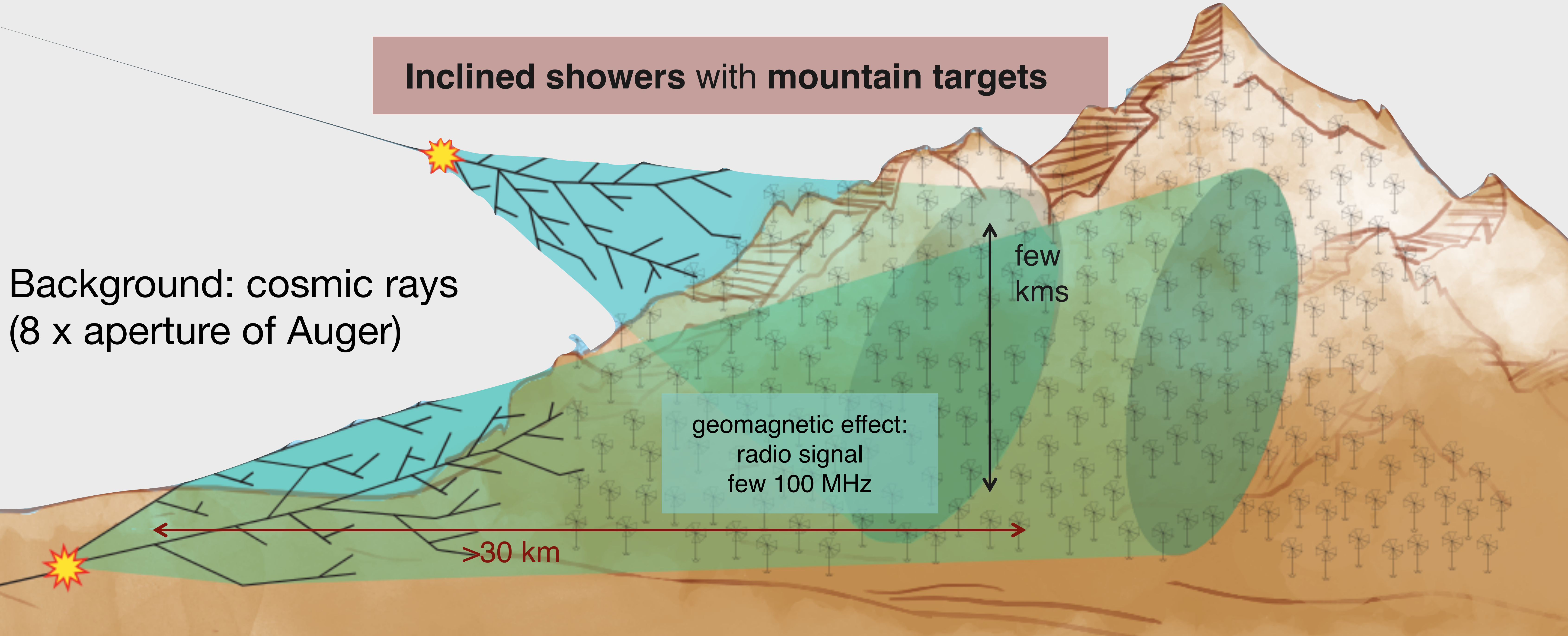






GRAND (Giant Radio Array for Neutrino Detection)



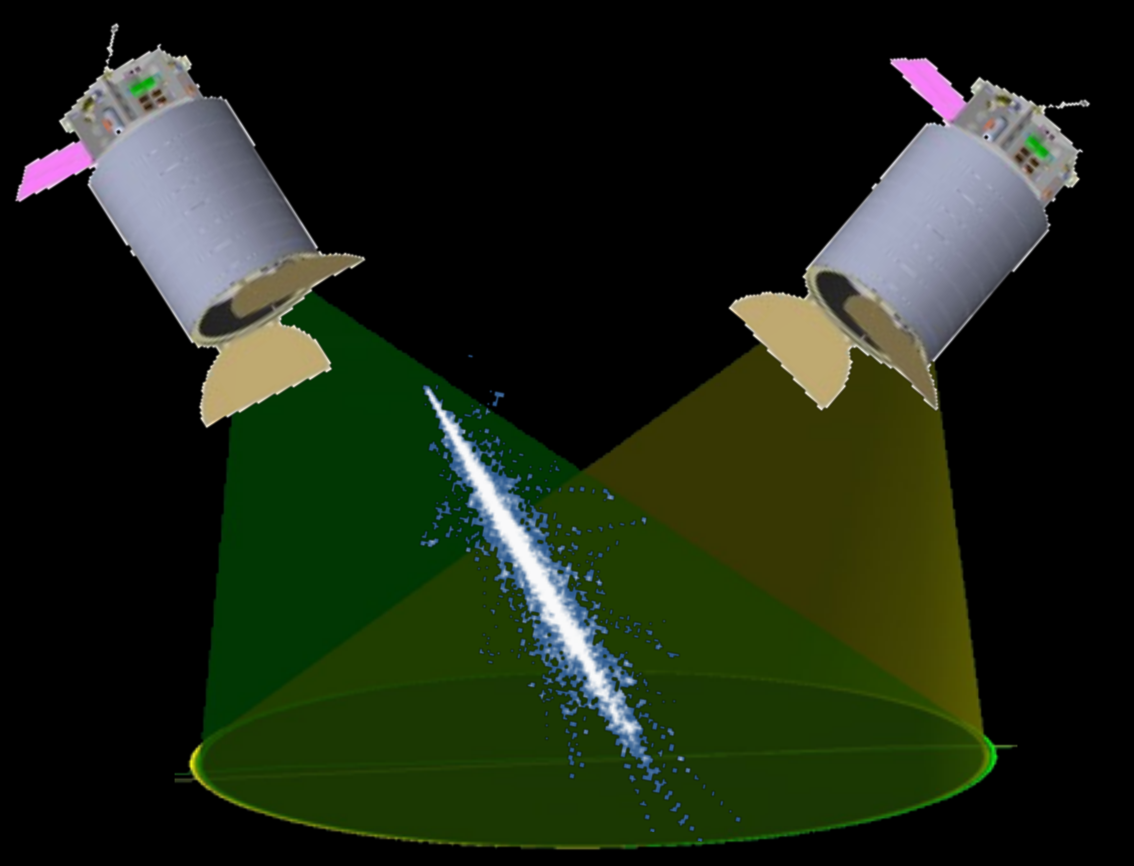


GRANDProto300	GRAND10k	GRAND200k
202x	202x+5	203x
• 300 antennas over 200 km² • autonomous radio detection of very inclined air-showers • cosmic rays $10^{16.5\text{-}18}$ eV • 1.3 M€ (fully funded, China)	• 10^4 antennas over 10^4 km² • 1st GRAND subarray • discovery of EeV neutrinos for optimistic fluxes • 13 M€ (mostly China)	• 200k antennas over 200k km² • 20 sub-arrays of 10k antennas on different continents • 1st EeV neutrino detection and/or neutrino astronomy! • 150 M€

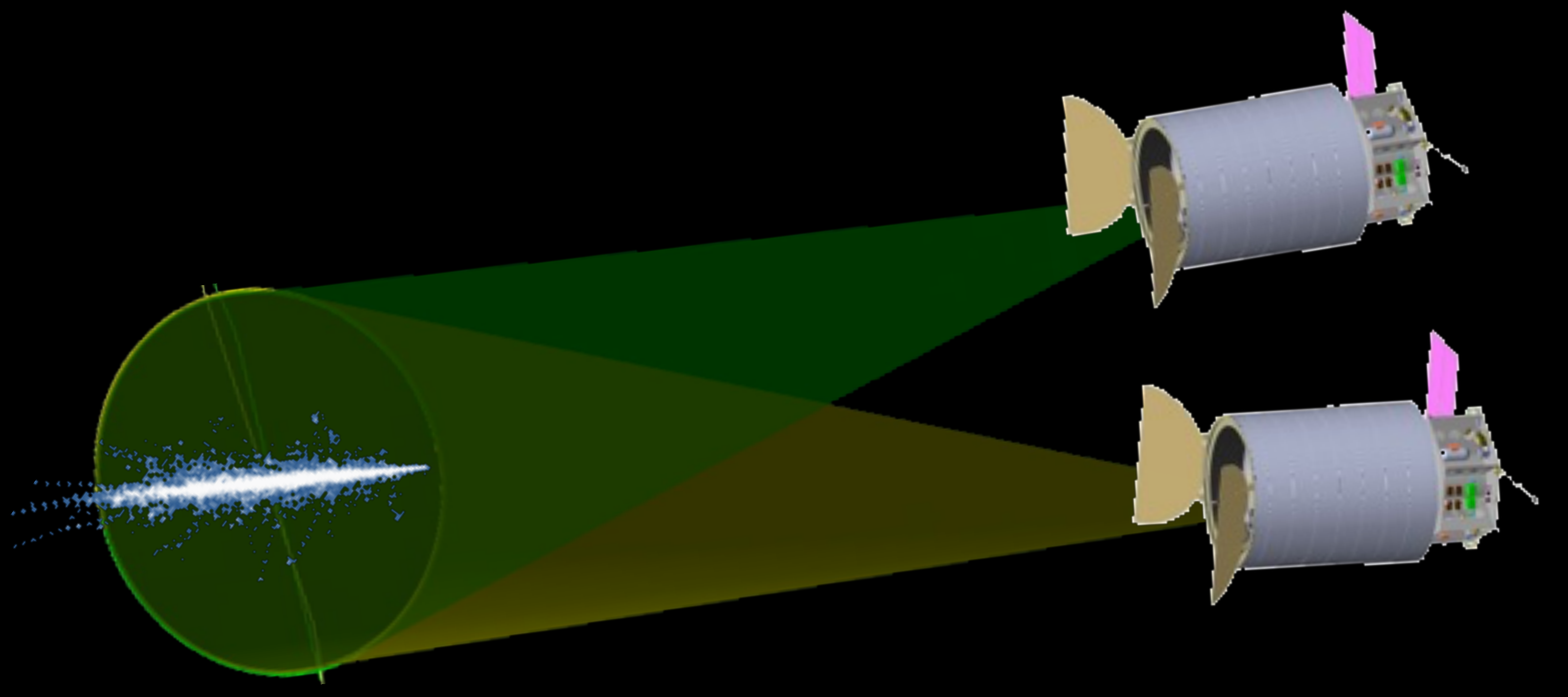
(slides by
K. Kotera)

POEMMA

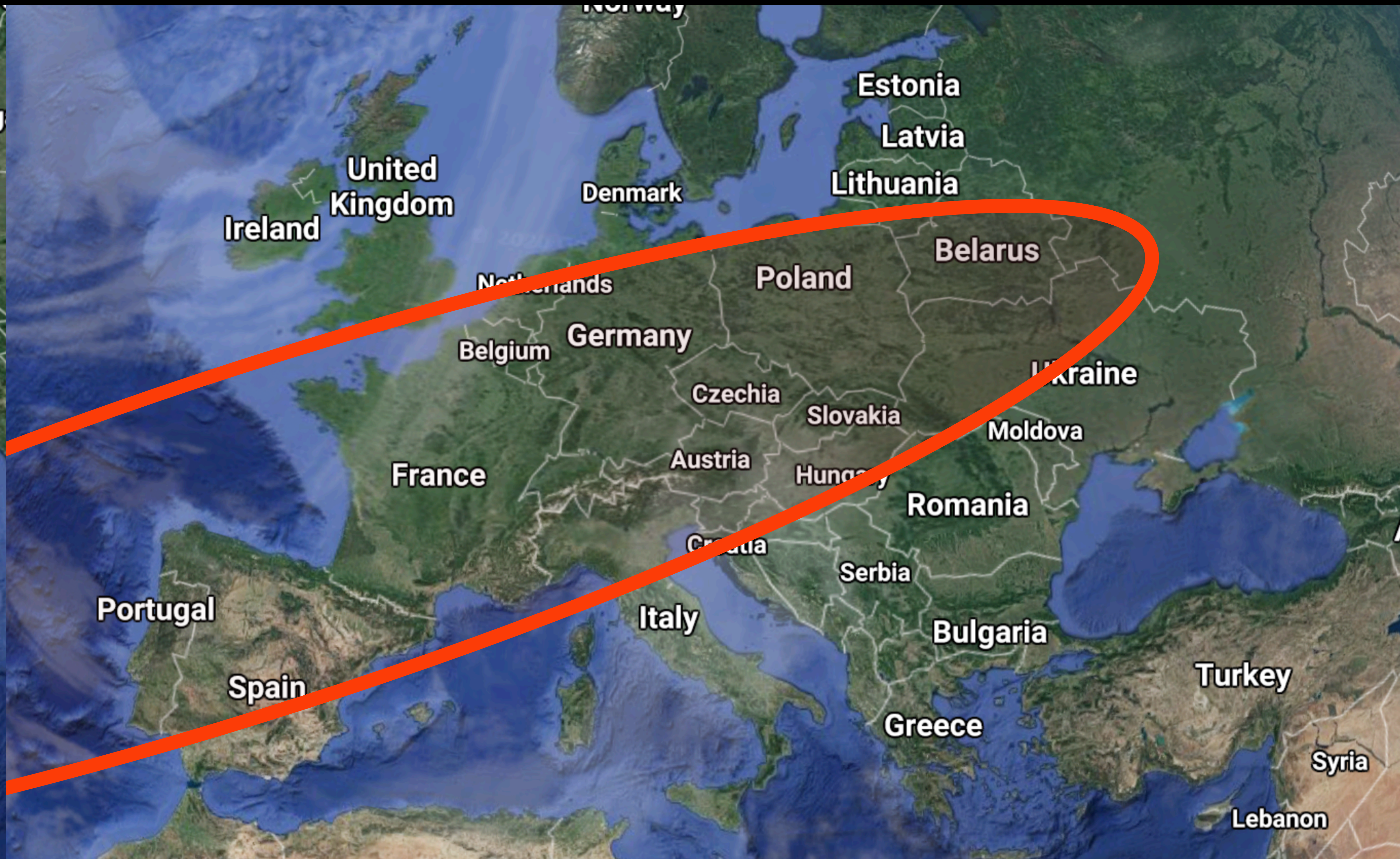
Observing Modes



Nadir for UHECR:
Radius 200-400 km



Limb for Neutrinos & UHECRs
Radius 2.6-3.7 10^3 km



(slides by A. Olinto)

Extension of Telescope Array – TAx4

TELESCOPE ARRAY

TA x 4

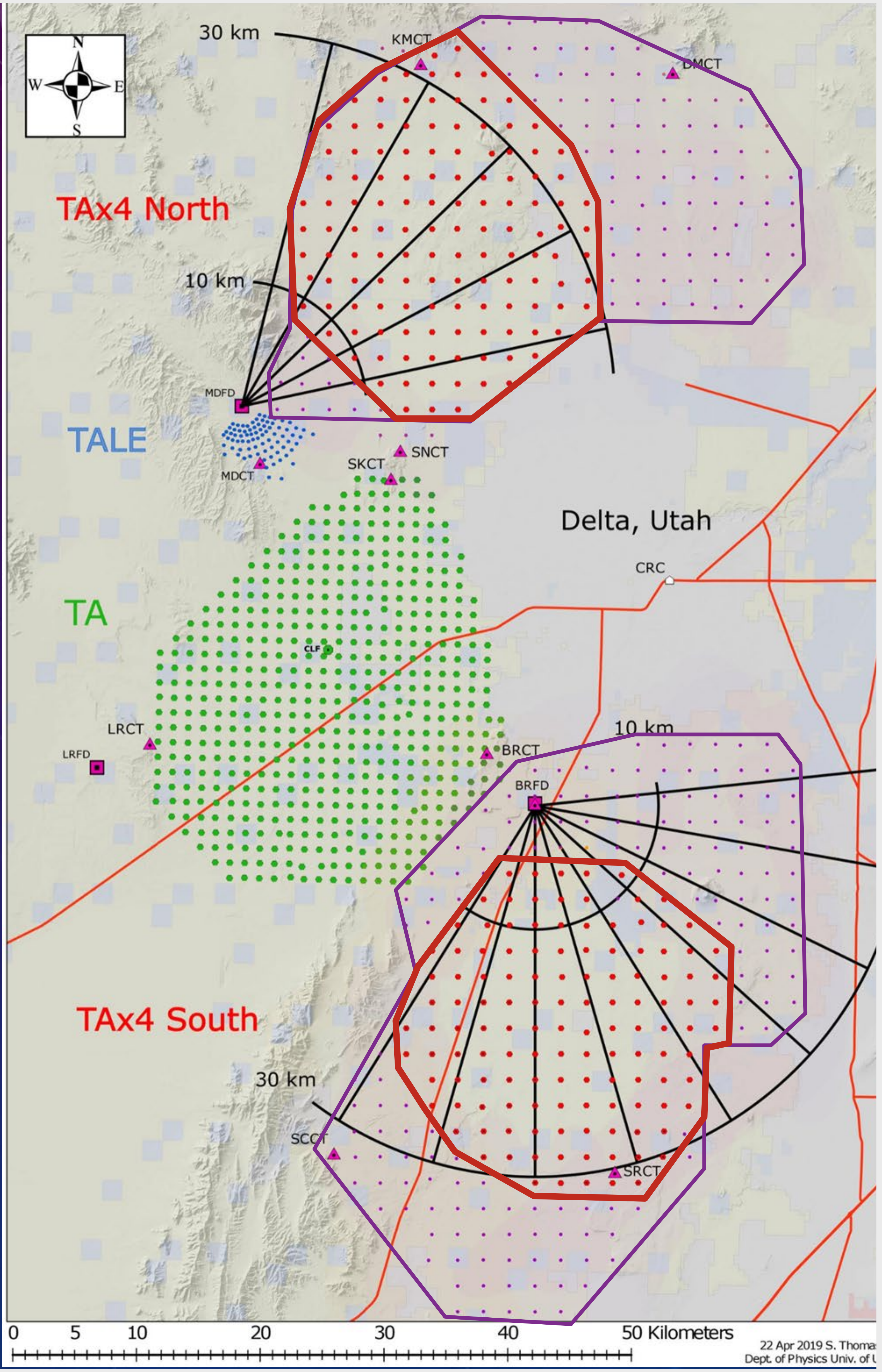
Expanded Surface Array

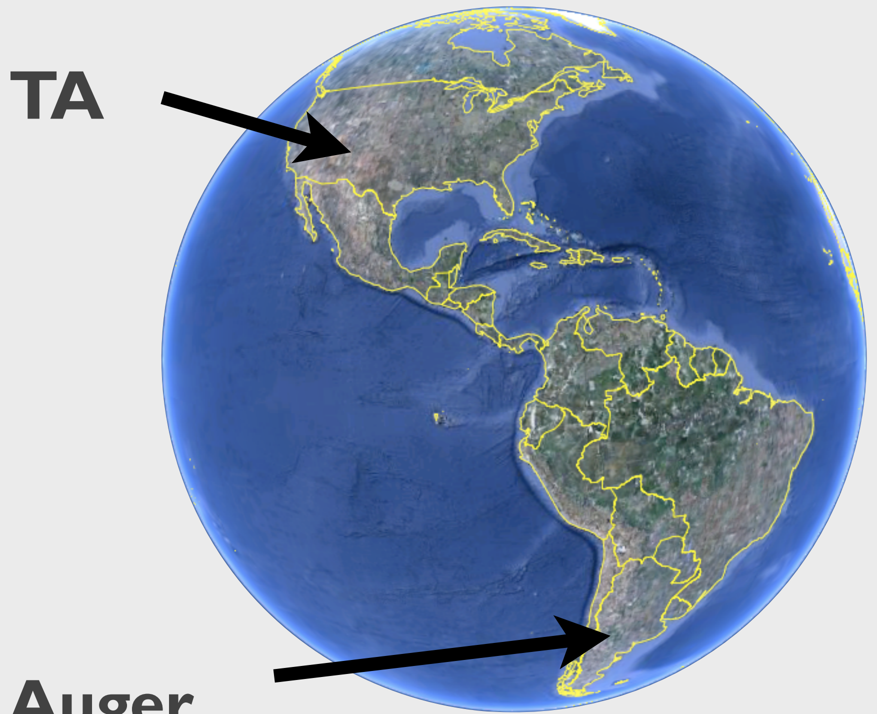
- 2.08-km spacing
- SDs similar design as TA
- 257 of planned 500 deployed (operational since 11/2019)

Fluorescence Telescopes

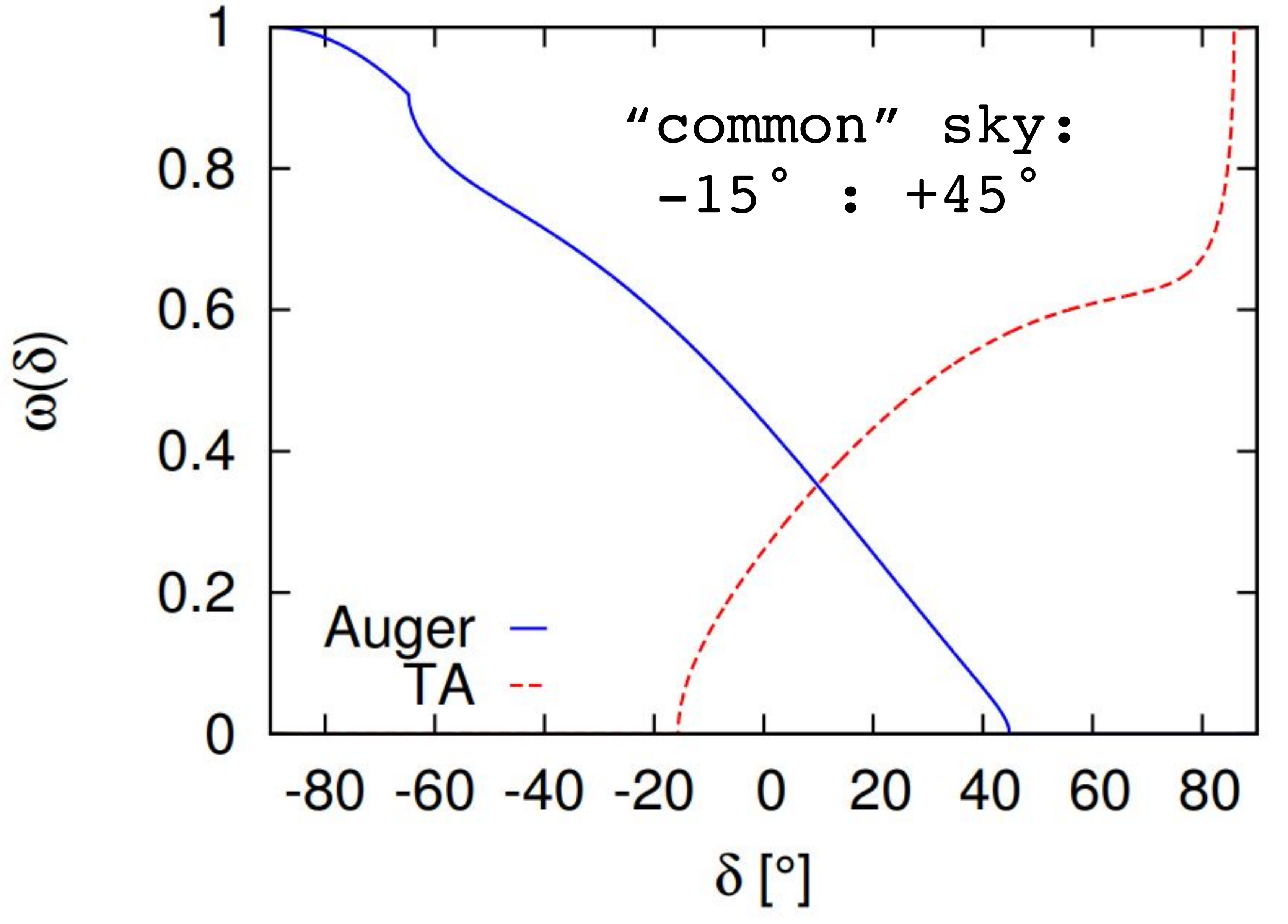
- 4 telescopes viewing NE lobe (since 06/2019)
- 8 telescopes viewing SE lobe (since 08/2020)
- 3˚–17˚ elevation

Slide by John Matthews





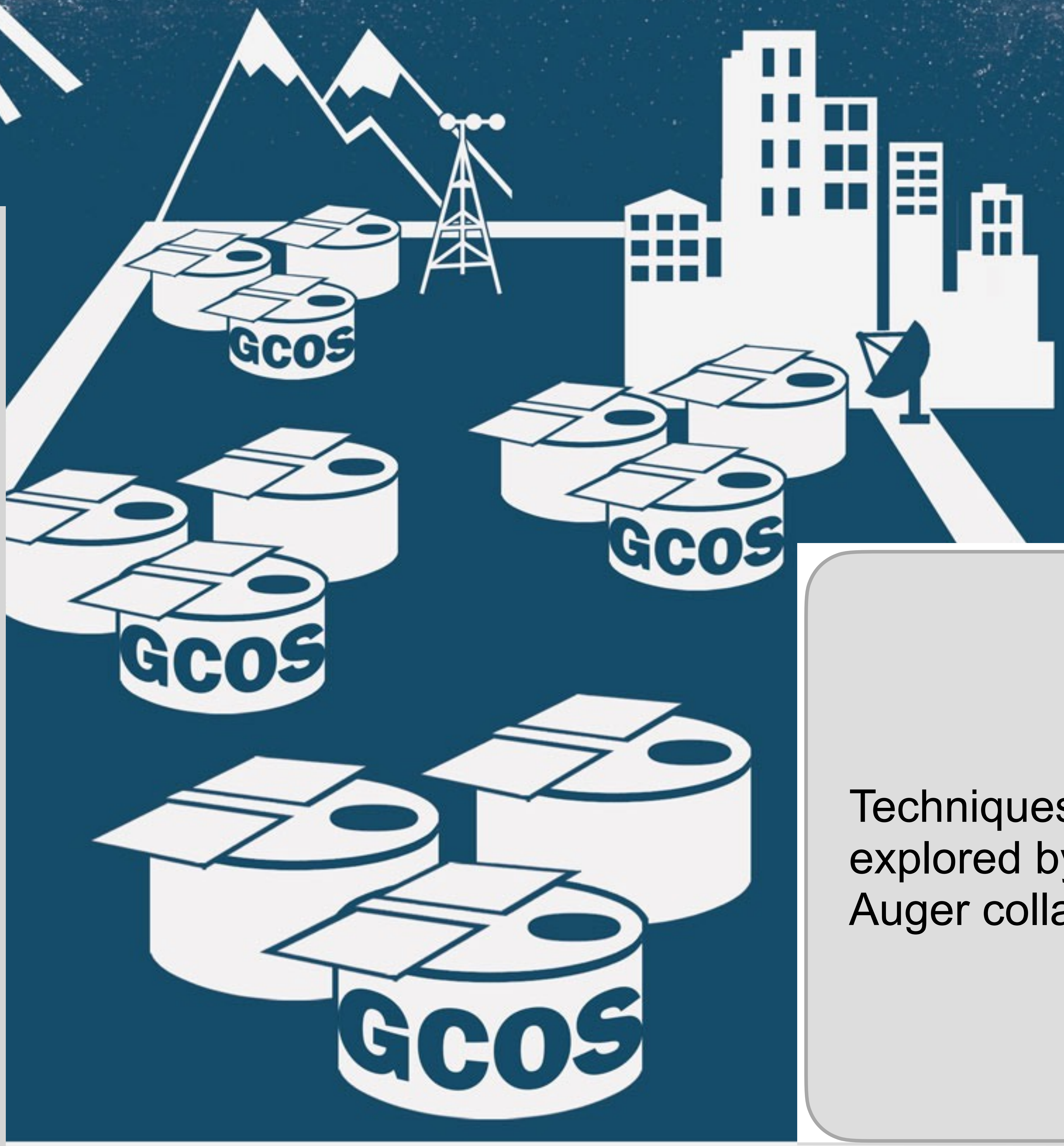
TA after upgrade to TAx4



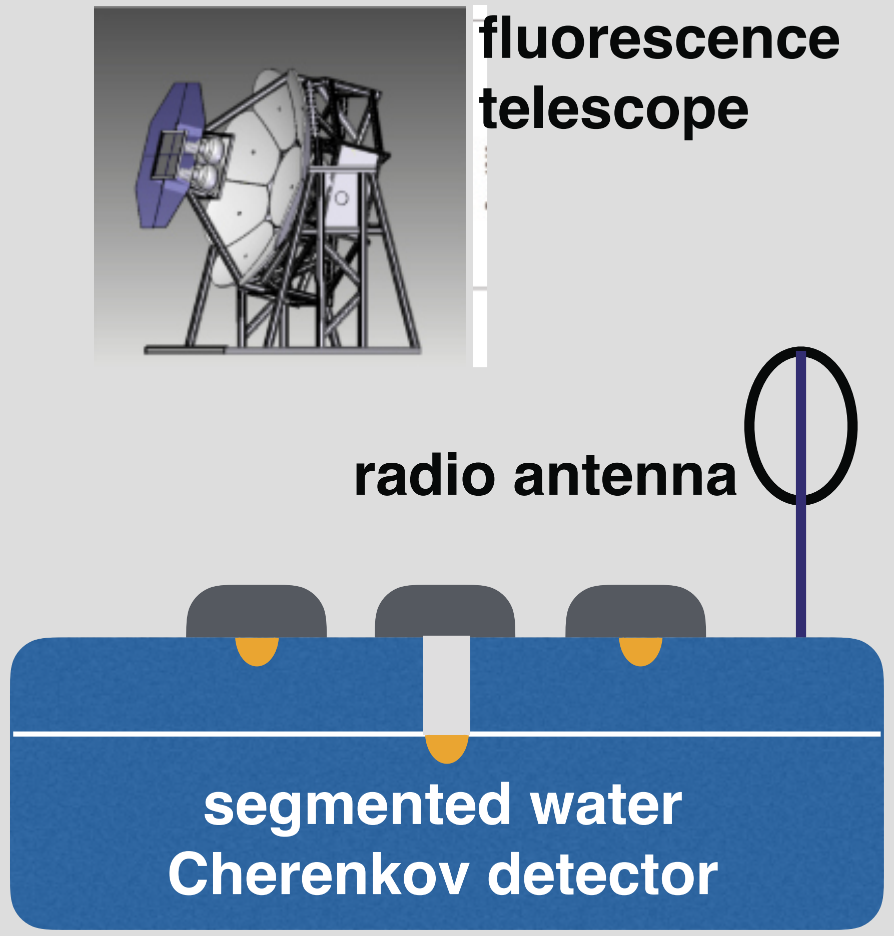
Towards a Global Cosmic Ray Observatory (GCOS)

- Ultra-large aperture (~100,000 km sr)
- Composition sensitivity essential
- Good energy resolution (~20%)

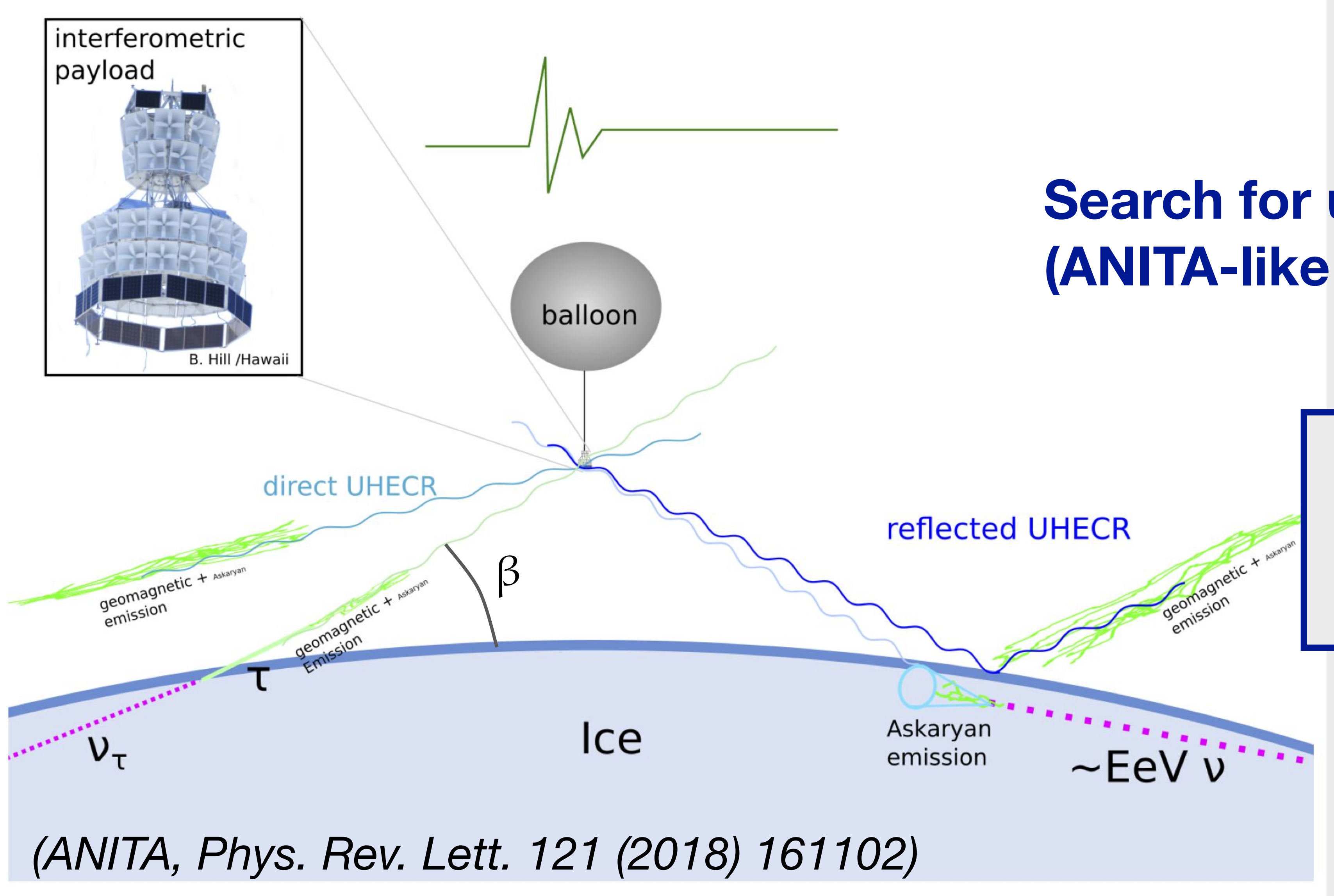
- Multi-messenger instrument
- Full-sky observation (several observatory sites, different technologies)
- Include atmosphere and geo-sciences etc.



Techniques currently explored by TA and Auger collaborations



Fundamental physics studies

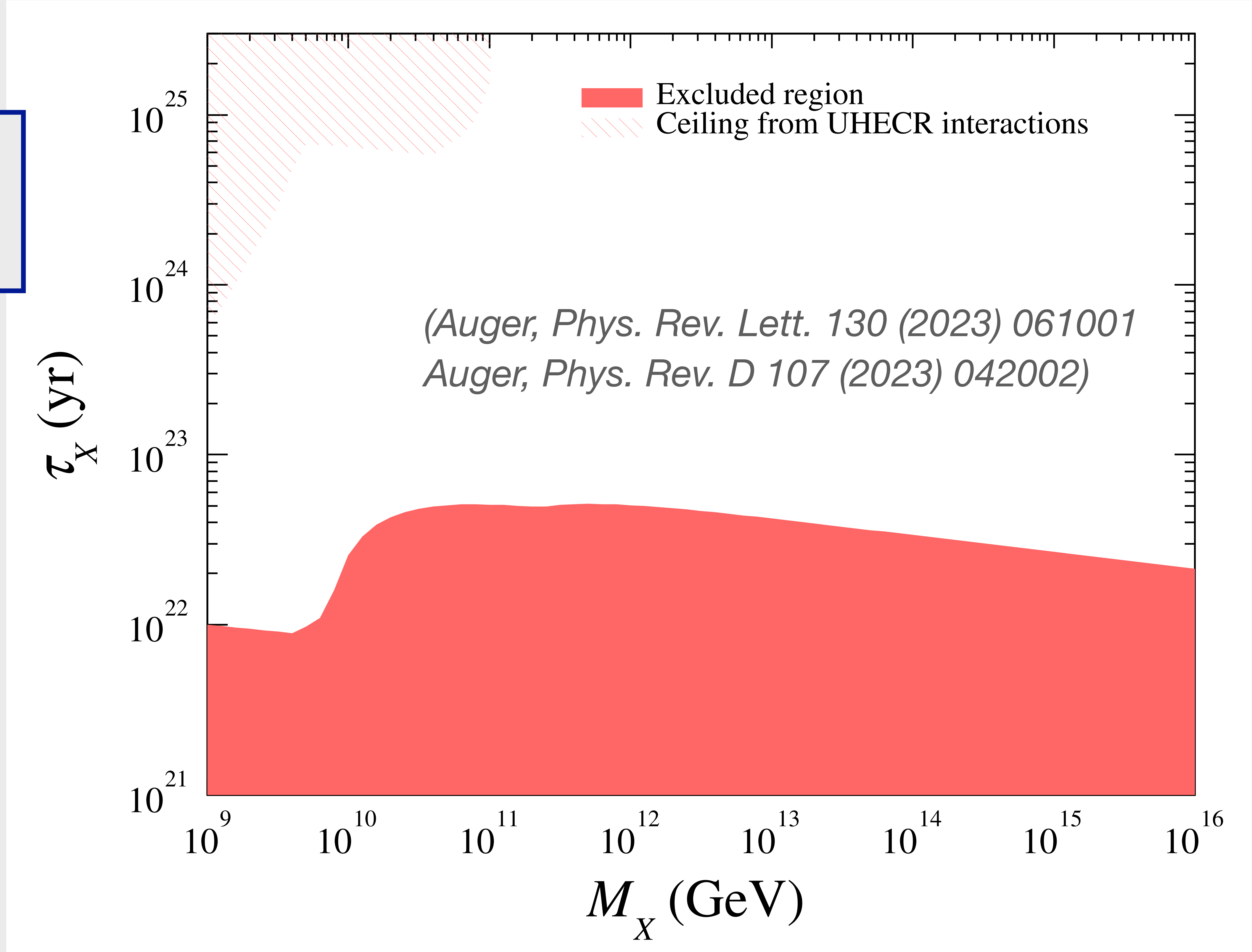


(ANITA, Phys. Rev. Lett. 121 (2018) 161102)

Search for upward going showers (ANITA-like events)

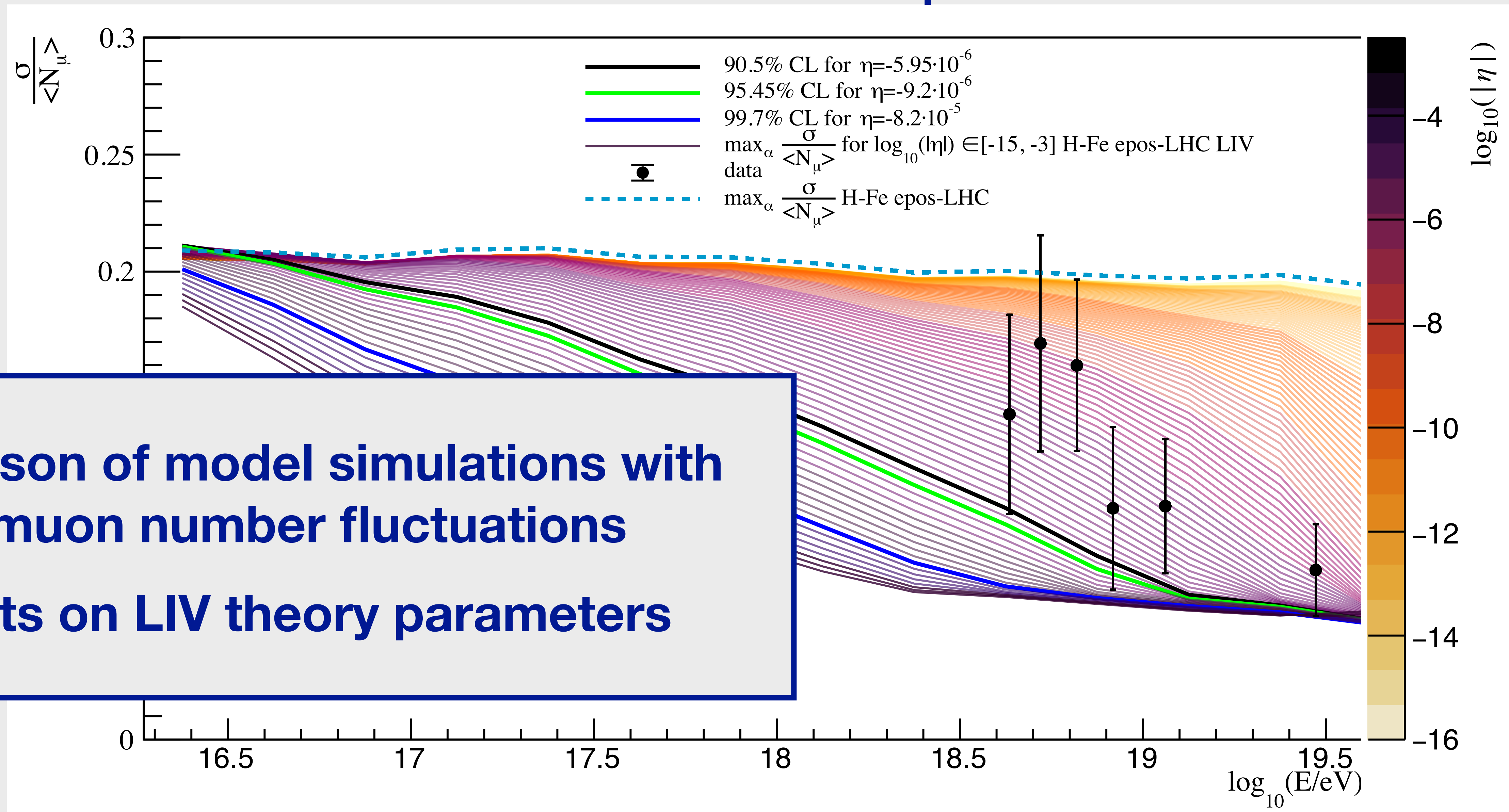
No ANITA-like events seen
~10x exposure of ANITA

Photon and neutrino limits at ultra-high energy



(Auger, Phys. Rev. Lett. 130 (2023) 061001
Auger, Phys. Rev. D 107 (2023) 042002)

Lorentz-dilated lifetime of neutral pions

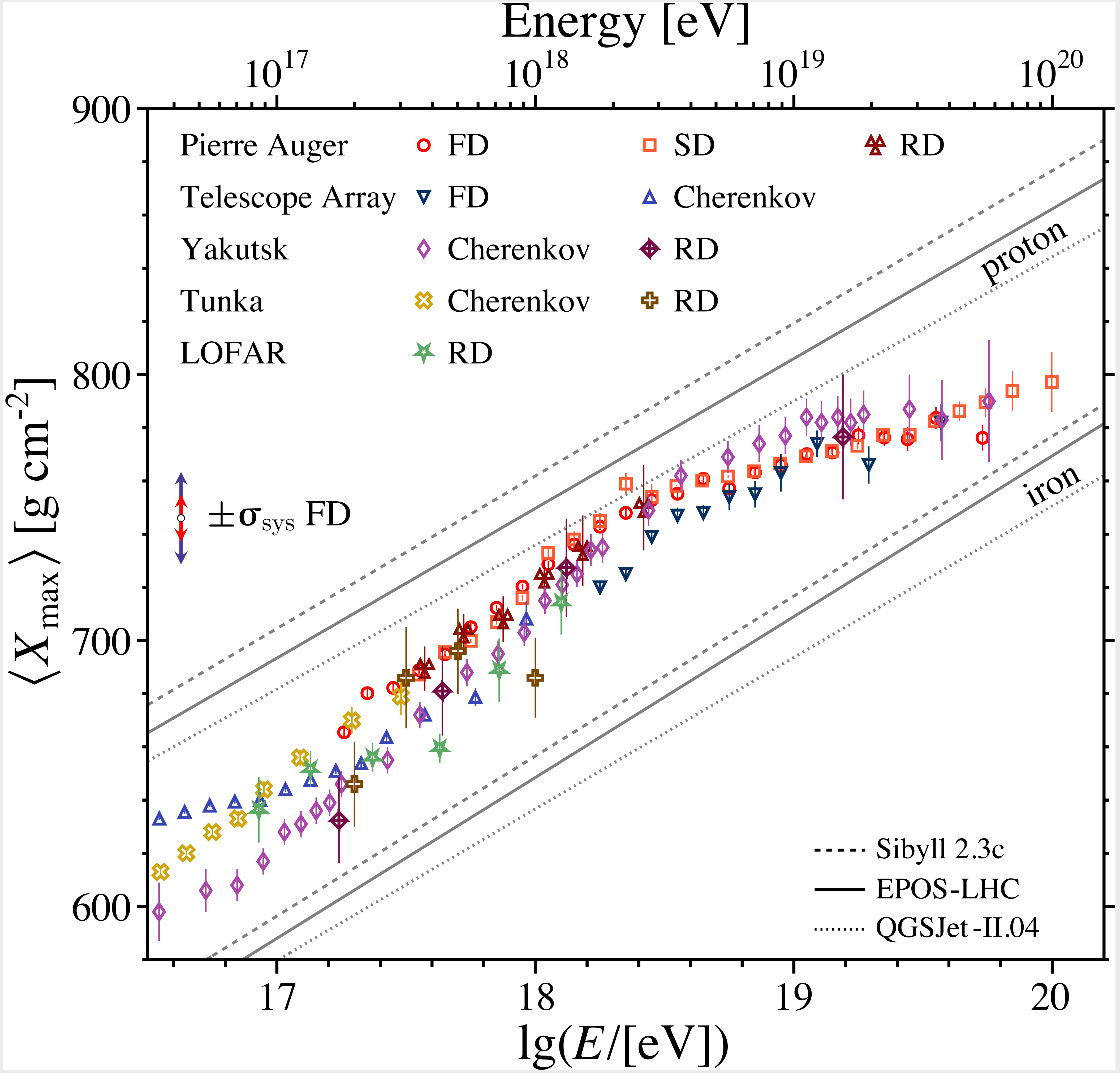


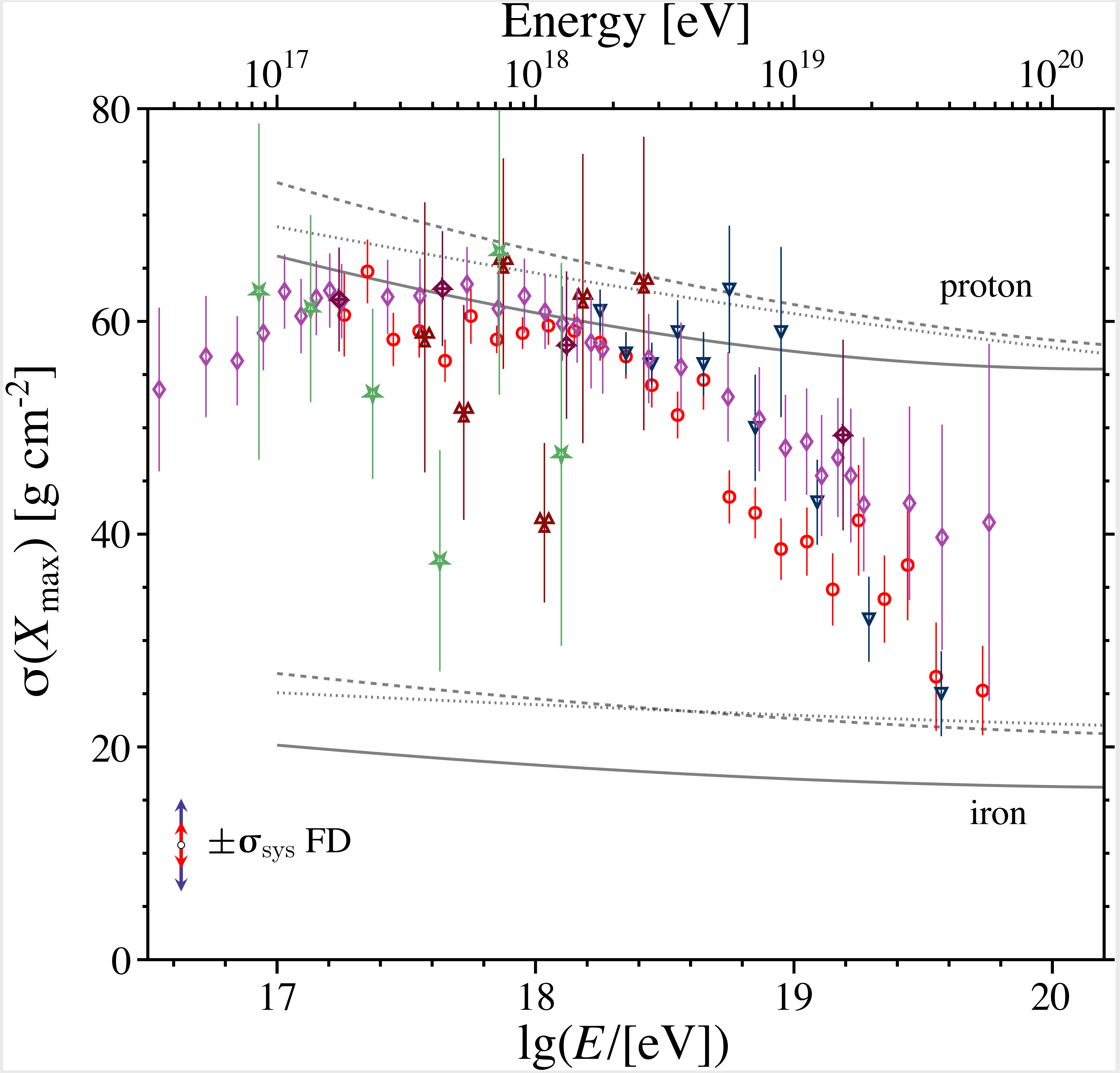
Comparison of model simulations with data on muon number fluctuations

New limits on LIV theory parameters

Limits on parameters of SHDM models (mass, lifetime, decay through instanton processes)

World data set on depth of shower maximum (X_{max})

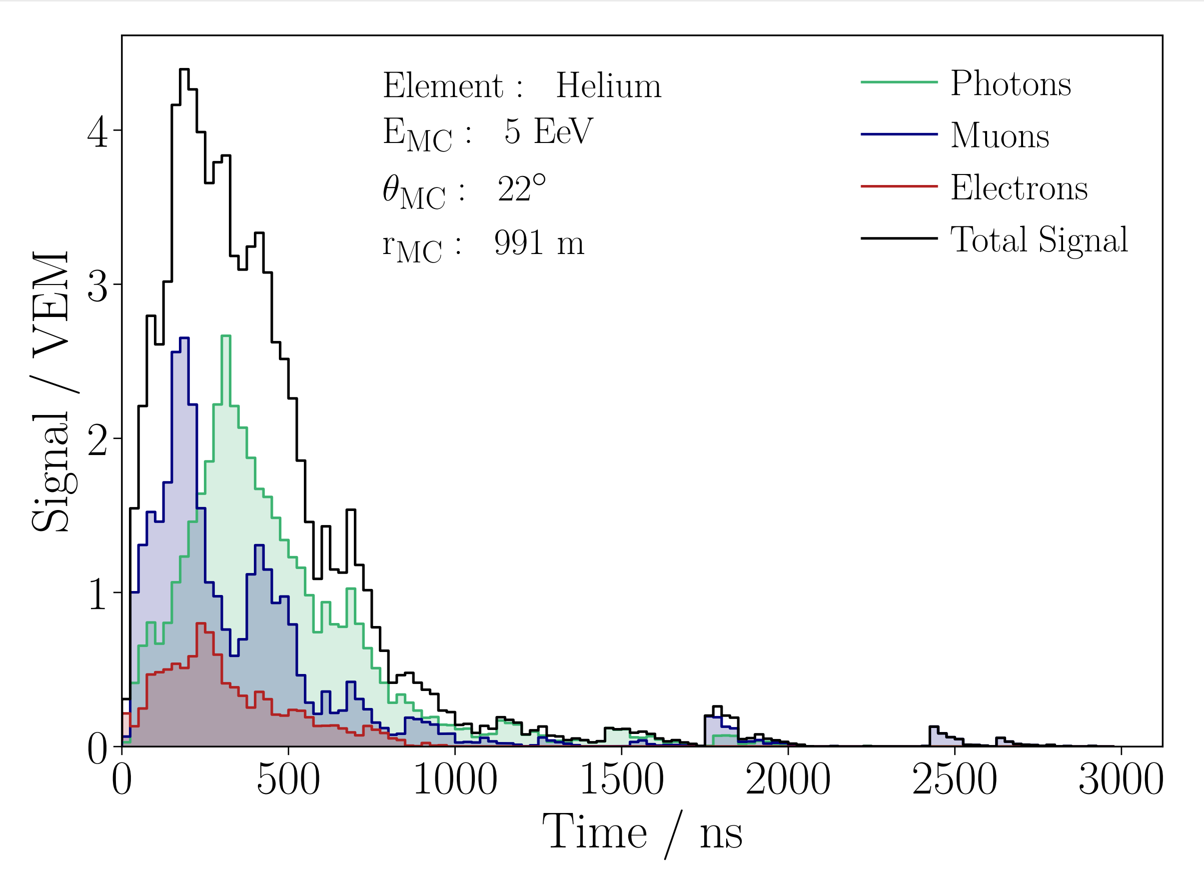


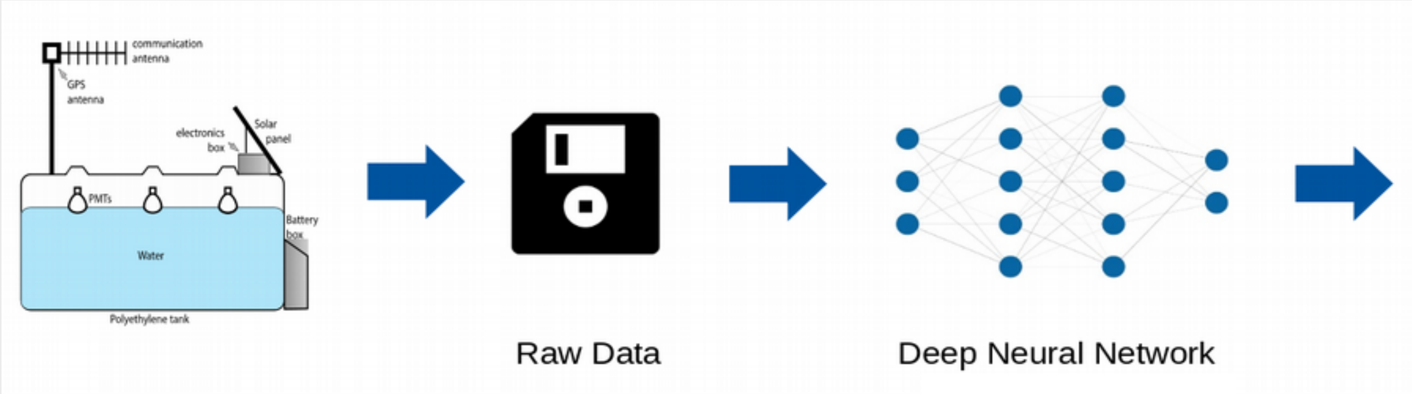


(Coleman et al. Snowmass, Astroparticle Physics 147 (2023) 102794)

Surface detector data and machine learning

Simulated signal of one surface station

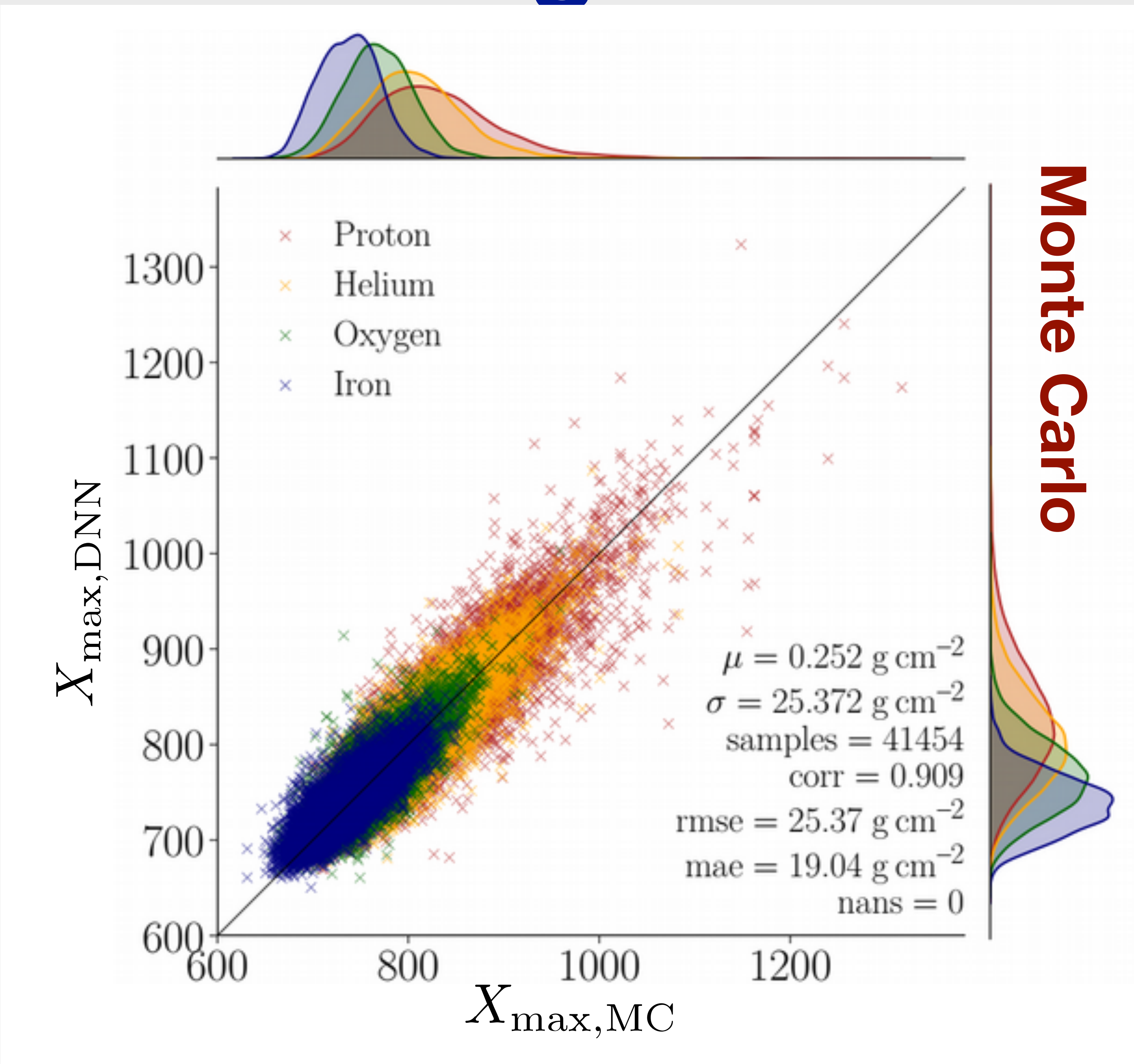


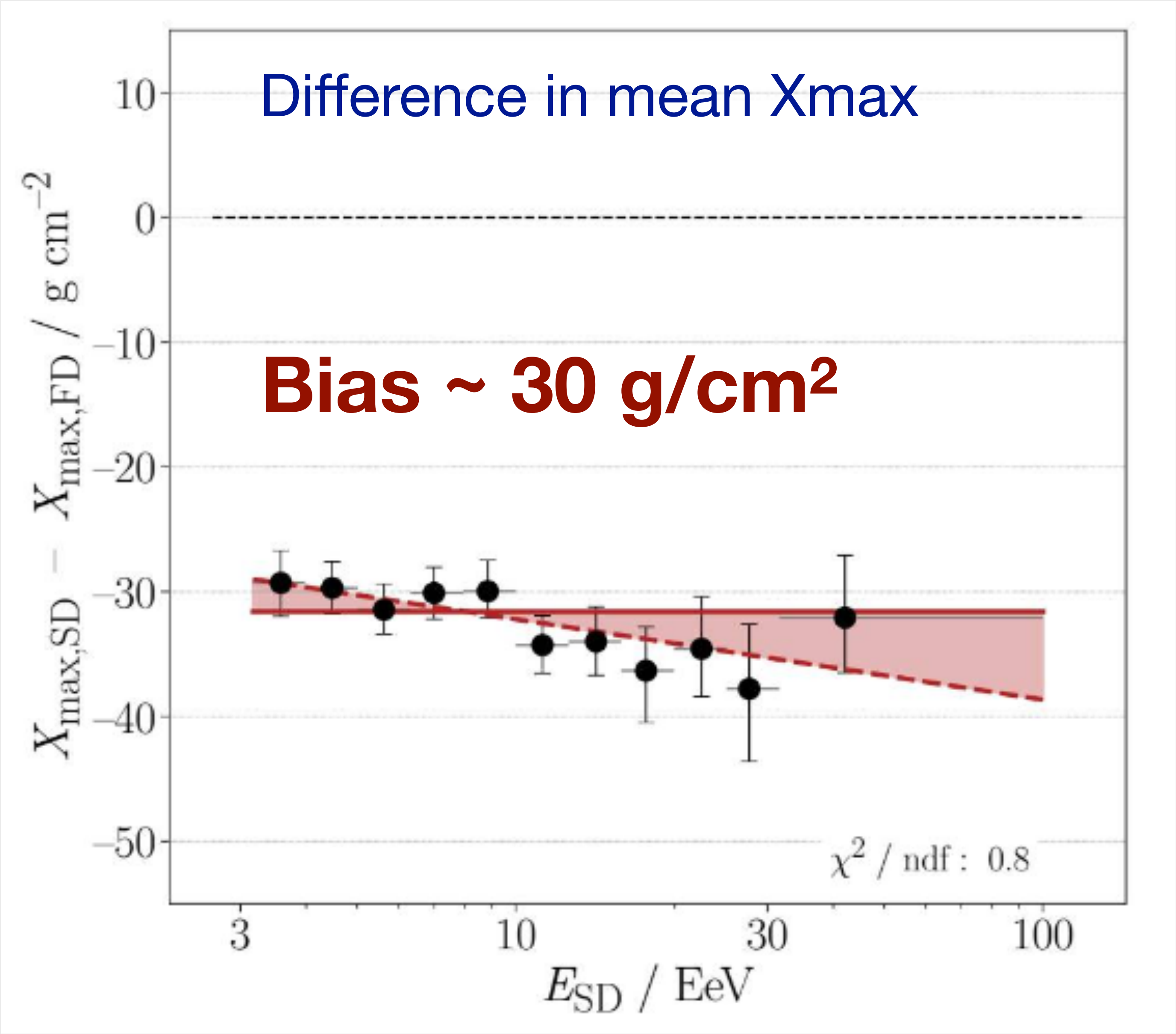


Reconstructing Xmax with DNNs: ultimate check with hybrid data

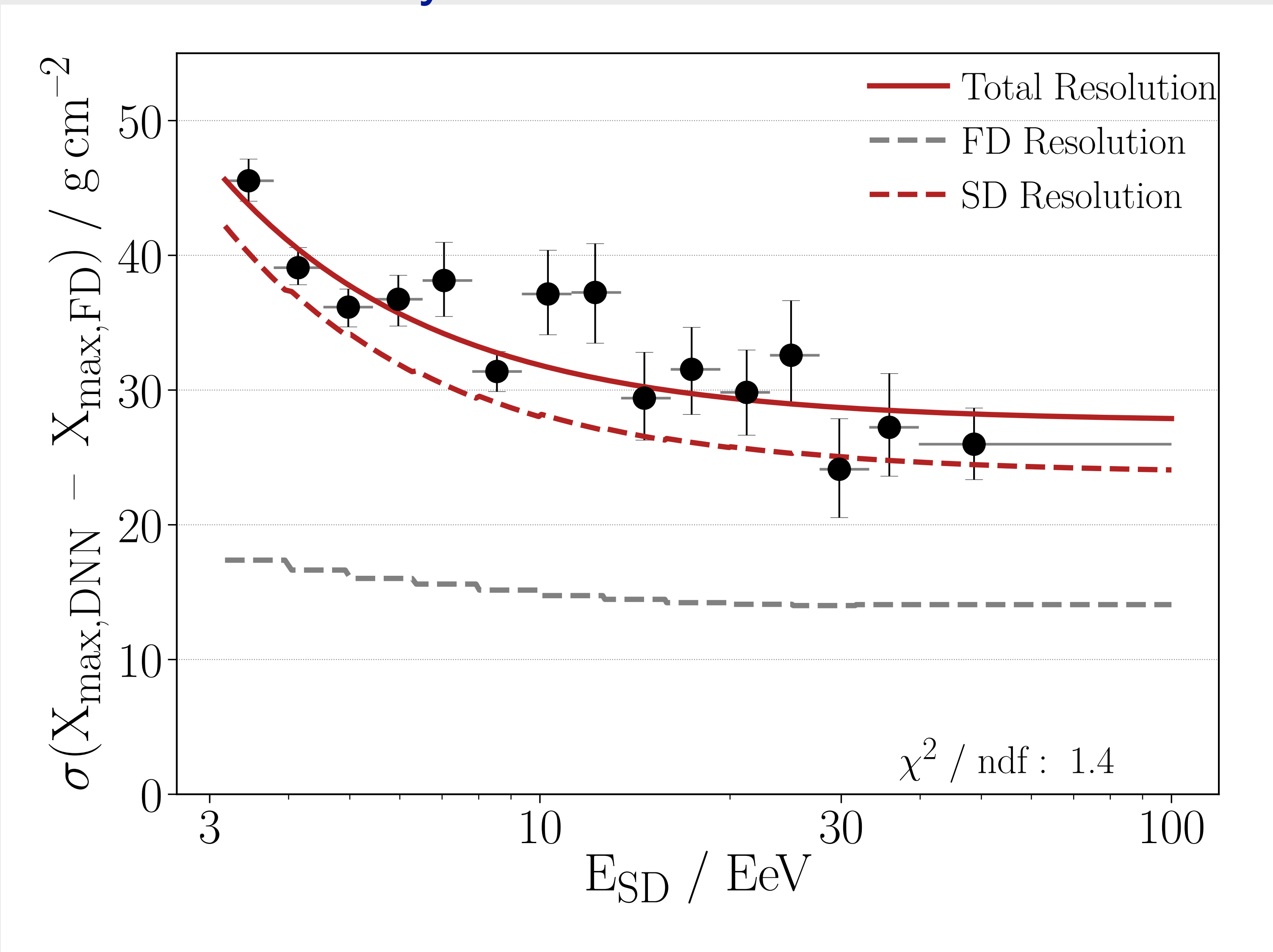
(Auger, JINST 16 (2021) P07019)

Monte Carlo

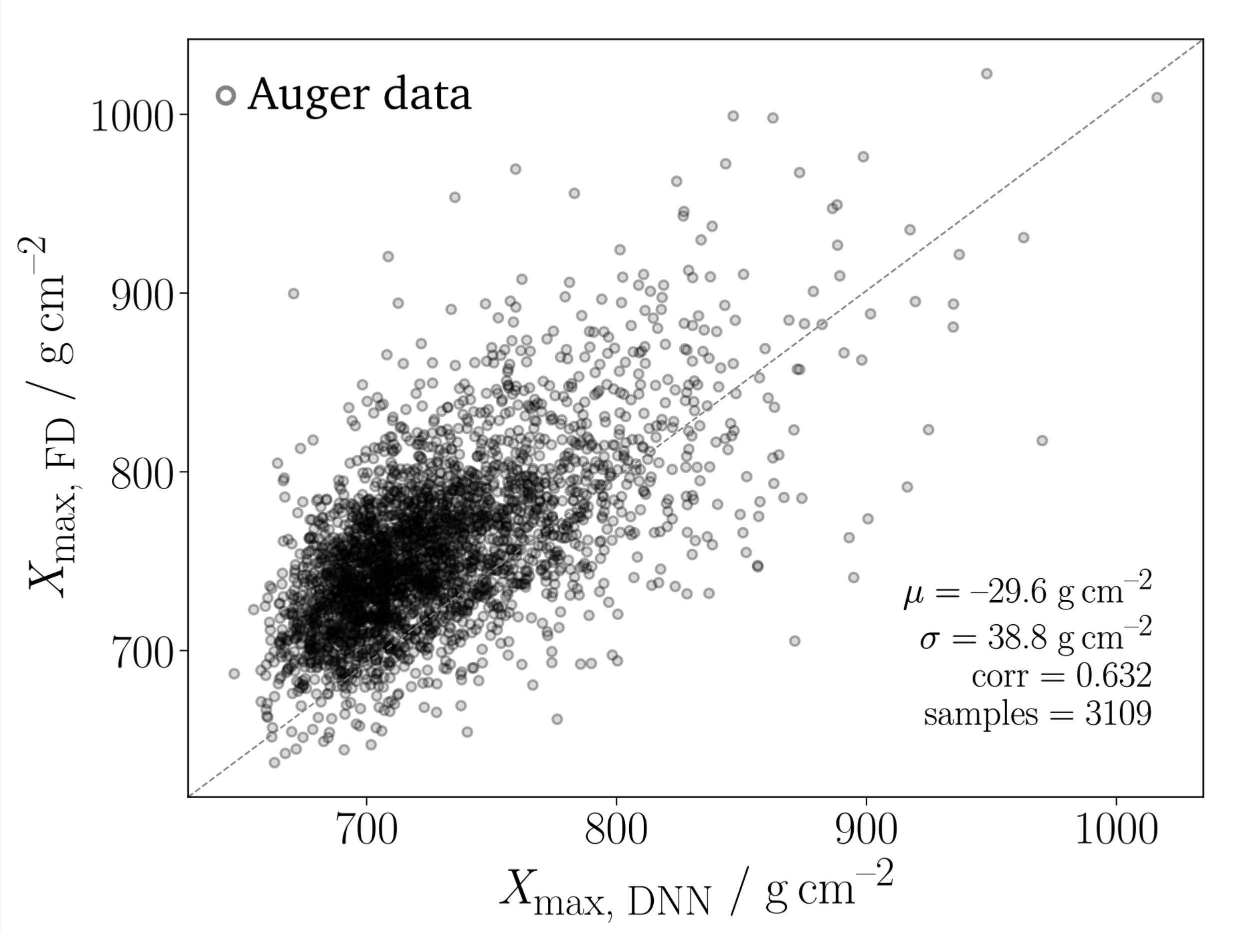




Shower-by shower Xmax resolution



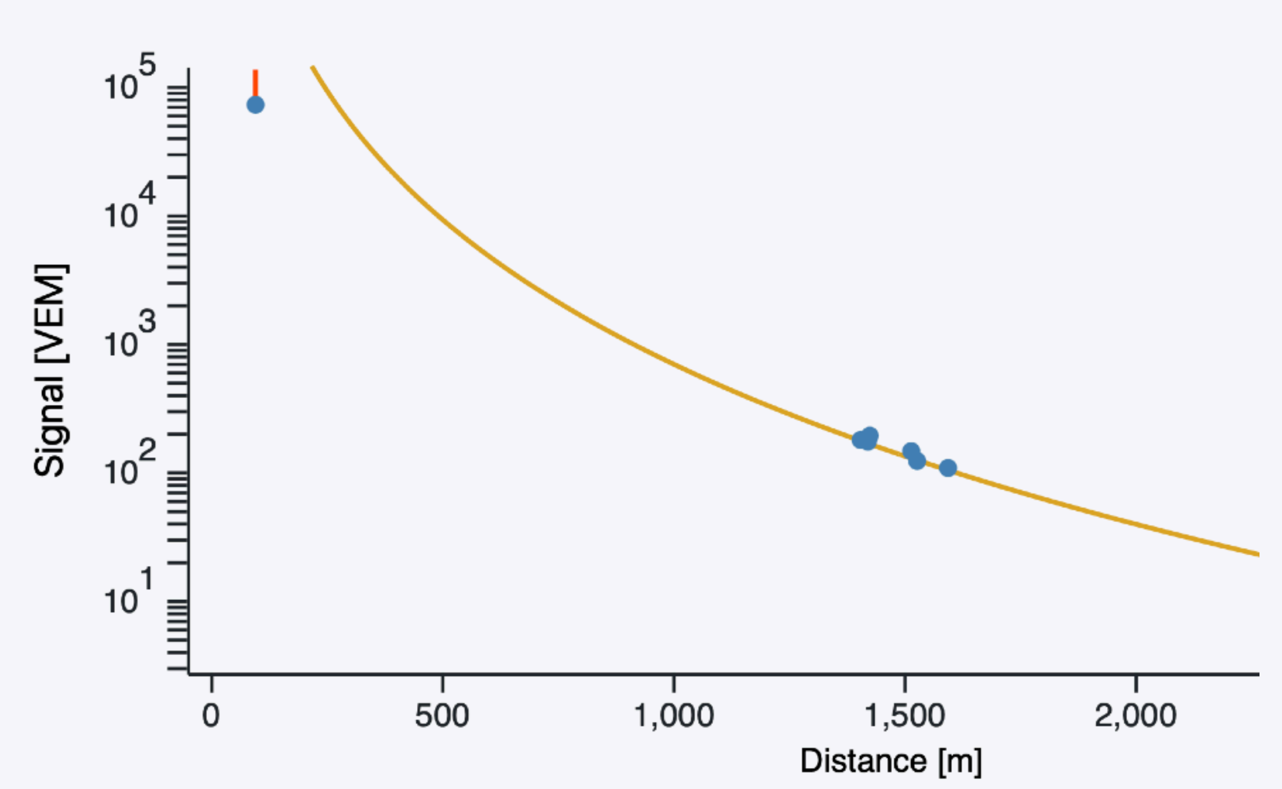
Hybrid data

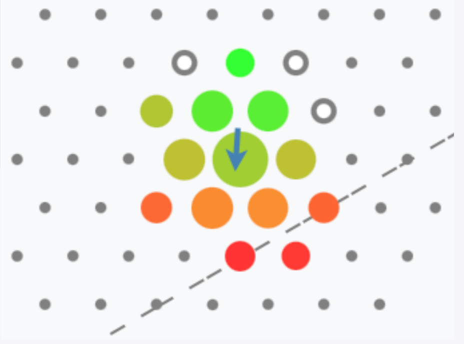


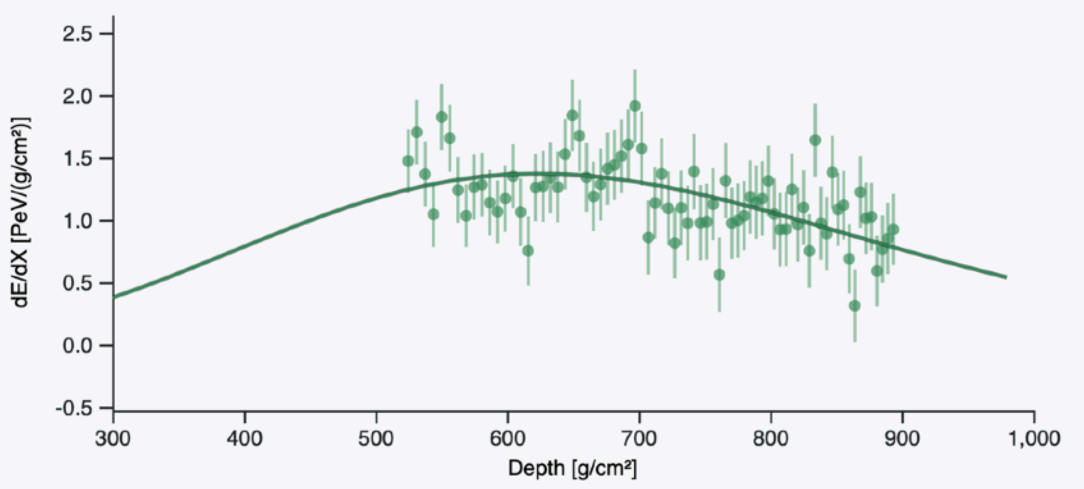
An invitation: Auger open data

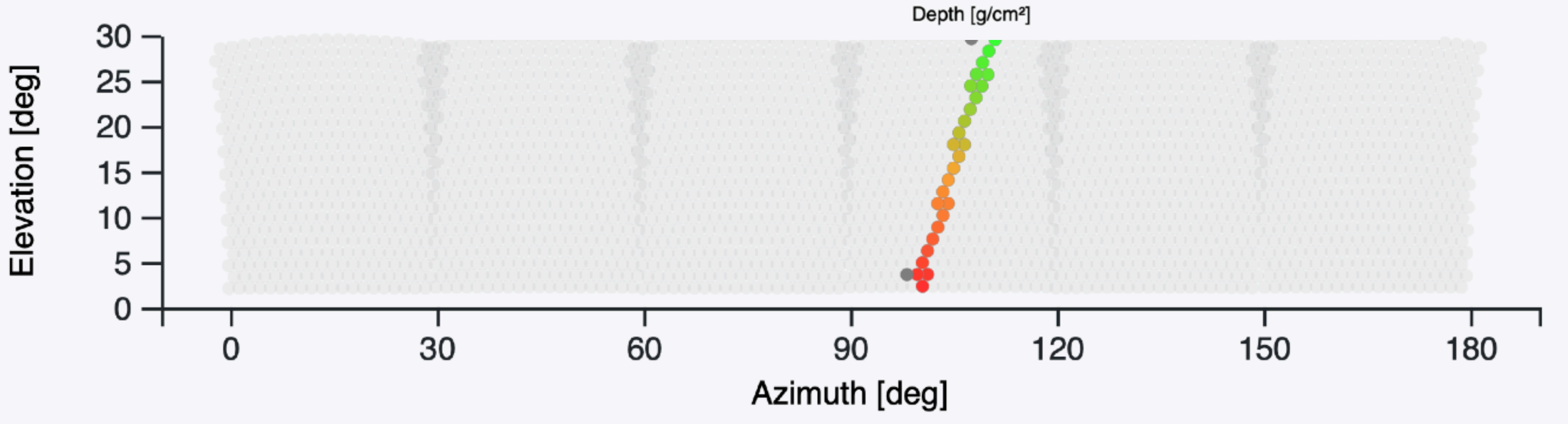
opendata.auger.org

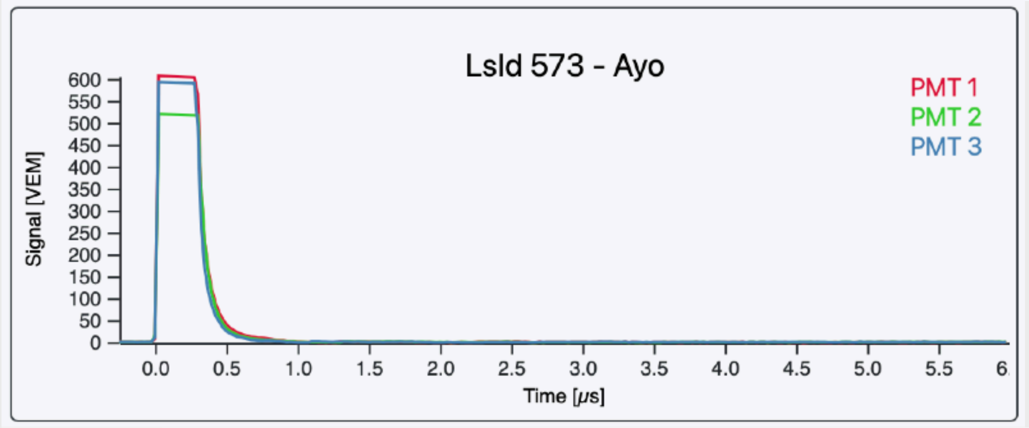
DOI:10.5281/zenodo.4487613

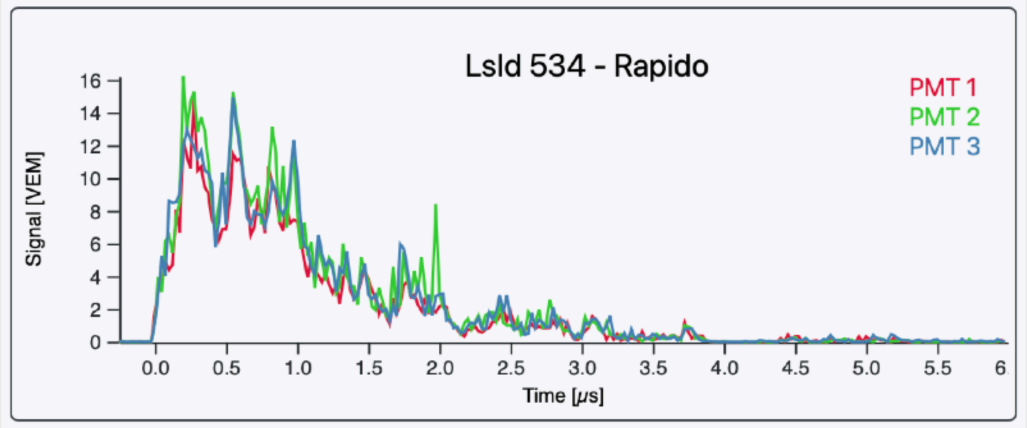


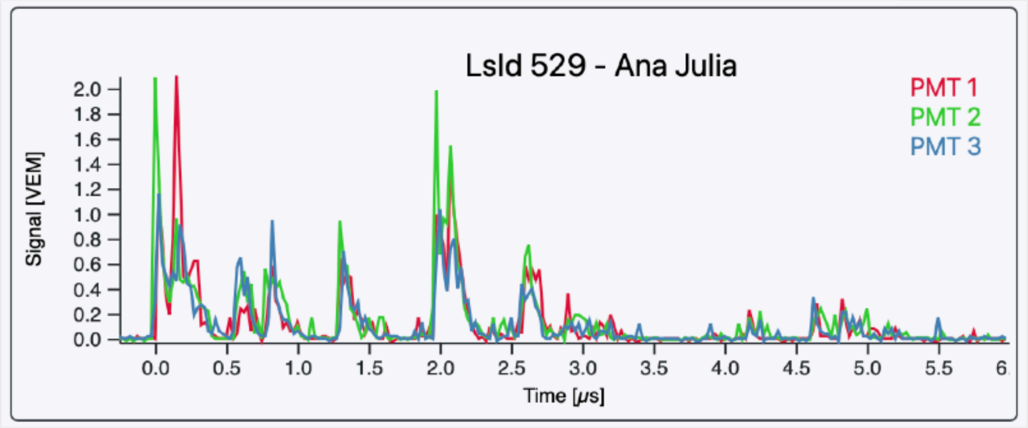












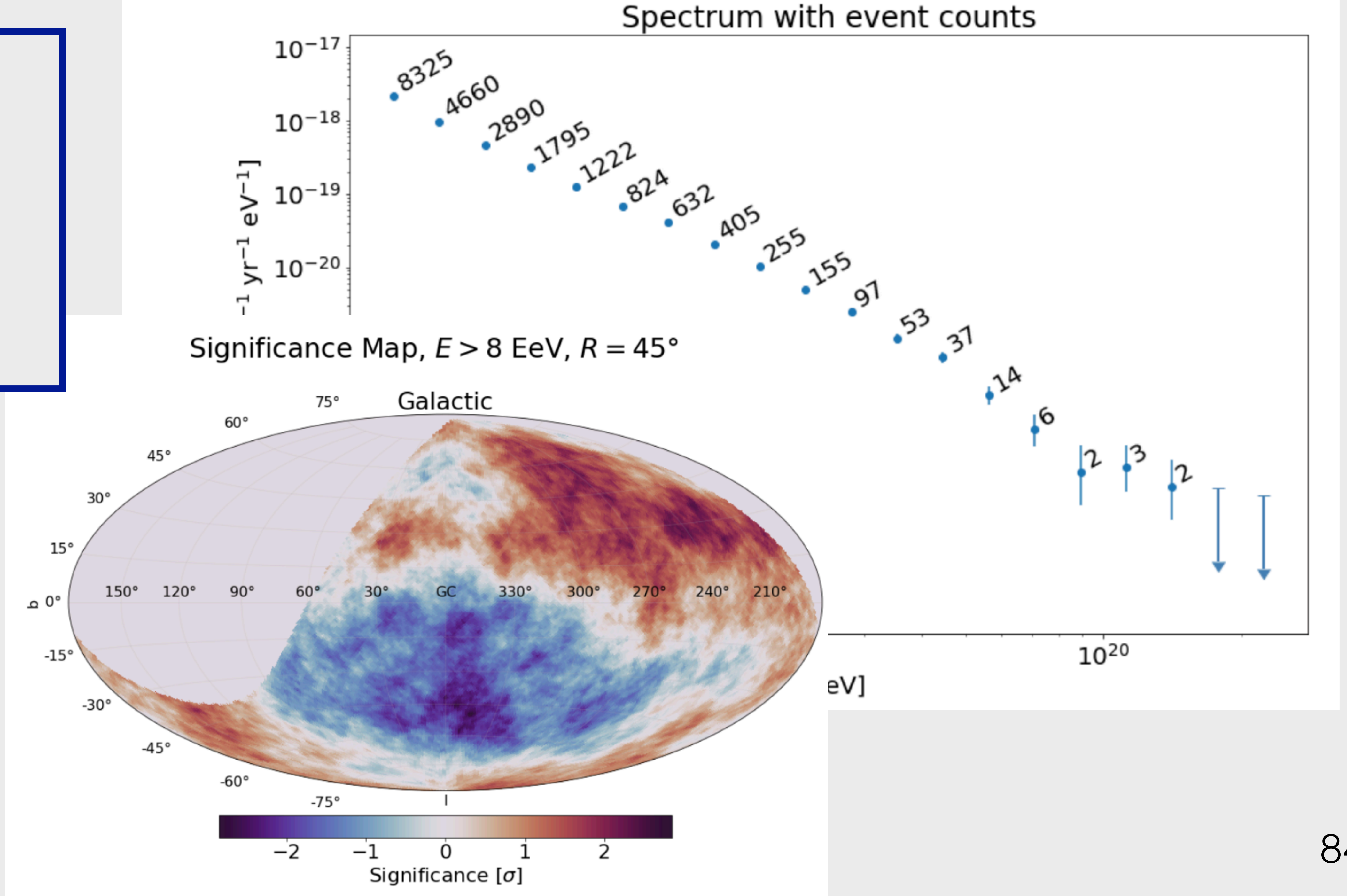
Currently 10% of Auger vertical data
Research-level data in JSON format
Online visualization of events
Data analysis scripts for science plots

You are welcome to use this data

If you have a great idea what to look for we can work with you to apply your analysis also to the full data set

In [19]:

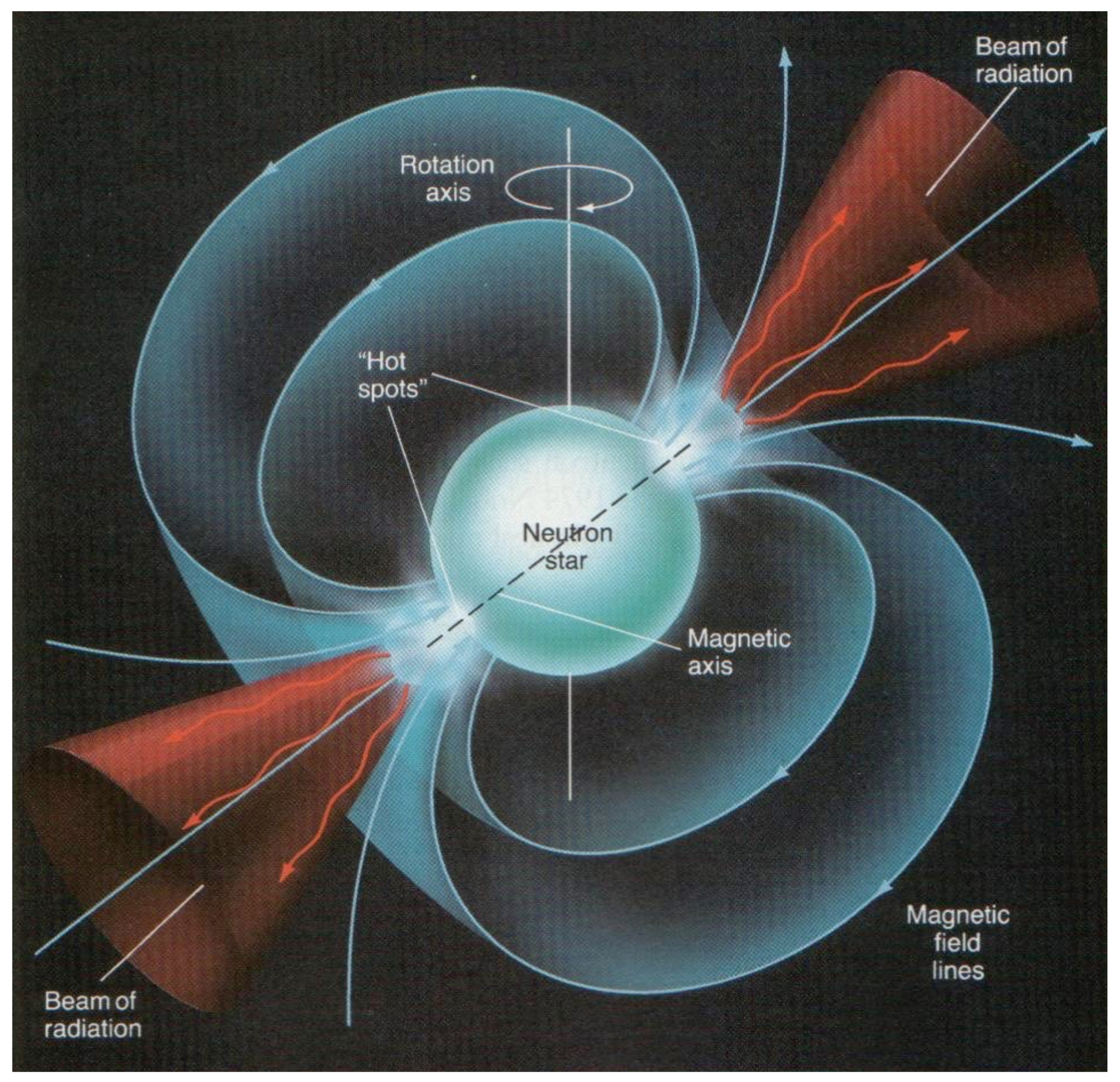
```
Y_0val = FC_CL * 0.9

plt.title("Spectrum with event counts")
plt.errorbar(bin_energy18[cut_nz], flux, [flux_lower, flux_upper], fmt="o")
plt.errorbar(bin_energy18[cut_z], FC_CL, Y_0val, uplims=True, marker="None", color="steelblue",
             markeredgecolor="r", markerfacecolor="r", linewidth=2.0, linestyle="None", capsize
=5)
plt.xscale("log")
plt.yscale("log")
plt.xlabel('E [eV]')
plt.ylabel(r'J$^{Raw}$(E) [km$^{-2}$ sr$^{-1}$ yr$^{-1}$ eV$^{-1}$]')

# expand the range in y to have space for the labels and upper limits
plt.ylim(flux[flux > 0].min()*0.01, flux.max()*7)

# add the counts to the points
for E, J, count in zip(bin_energy18, flux, h):
    if count > 0:
        plt.annotate(count, (E, J), rotation=30, va='bottom')
```

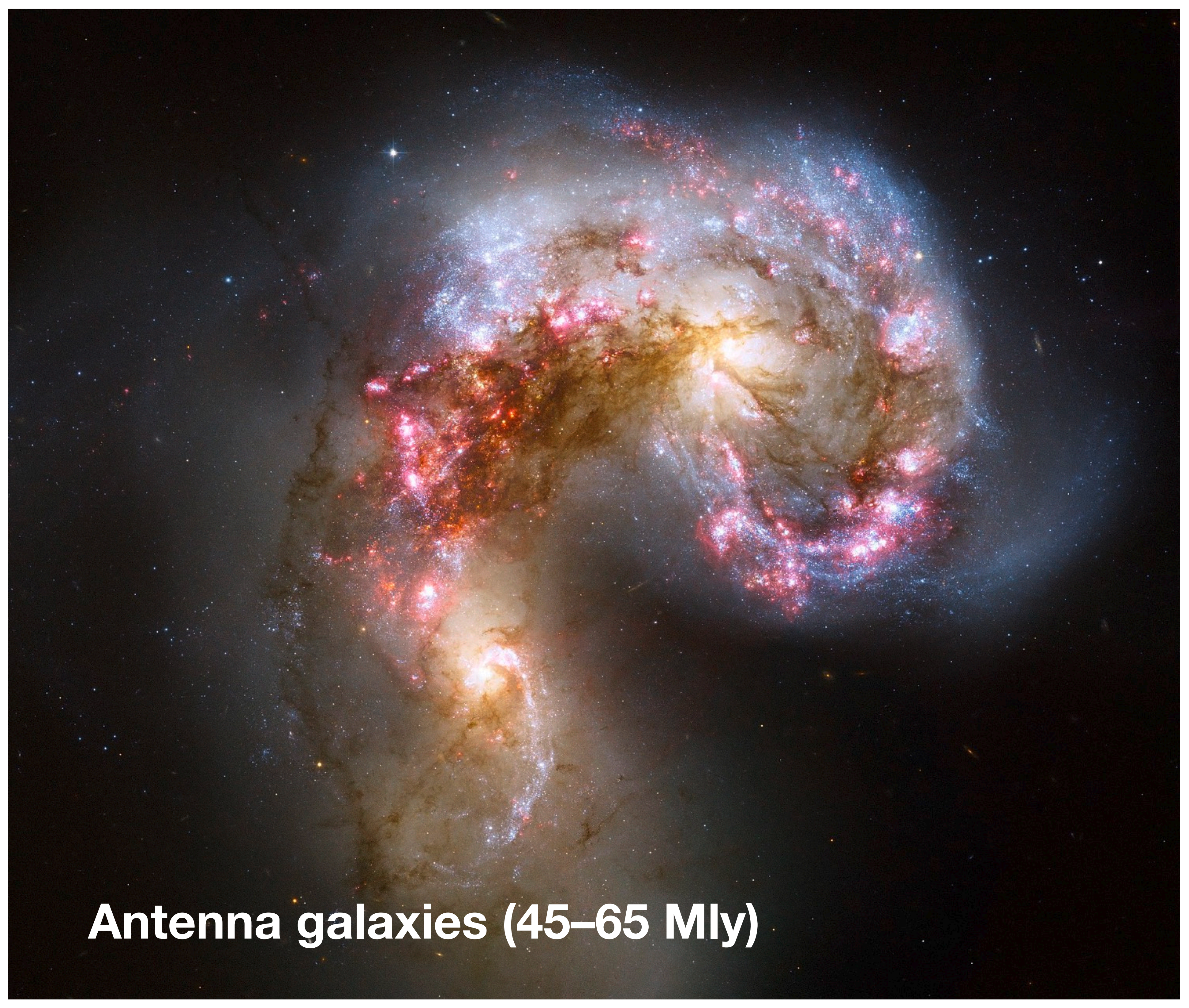


Correlation with star burst galaxies

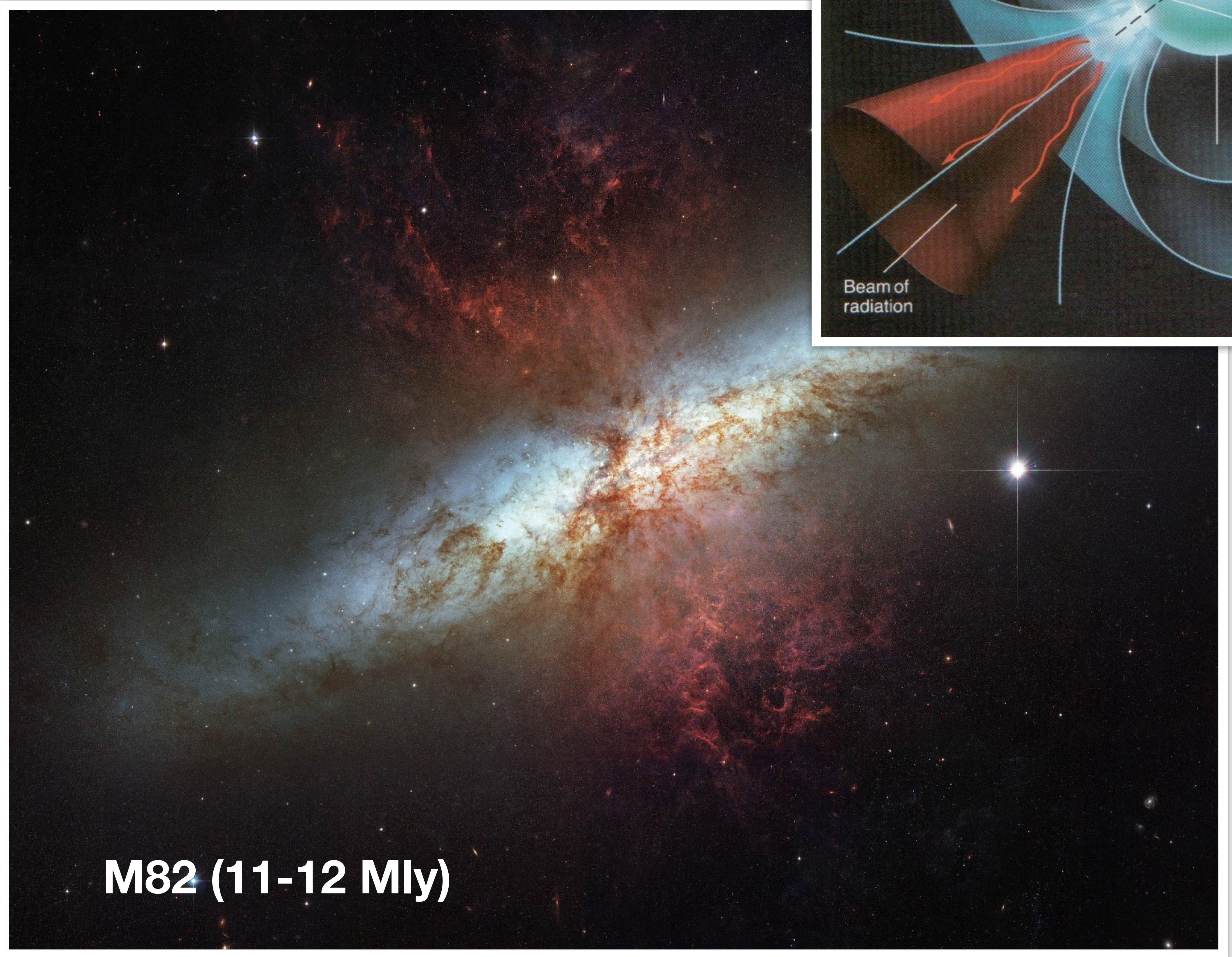
Gamma ray bursts or rapidly spinning neutron stars as sources?

Data taking needed until 2035 to solve this question



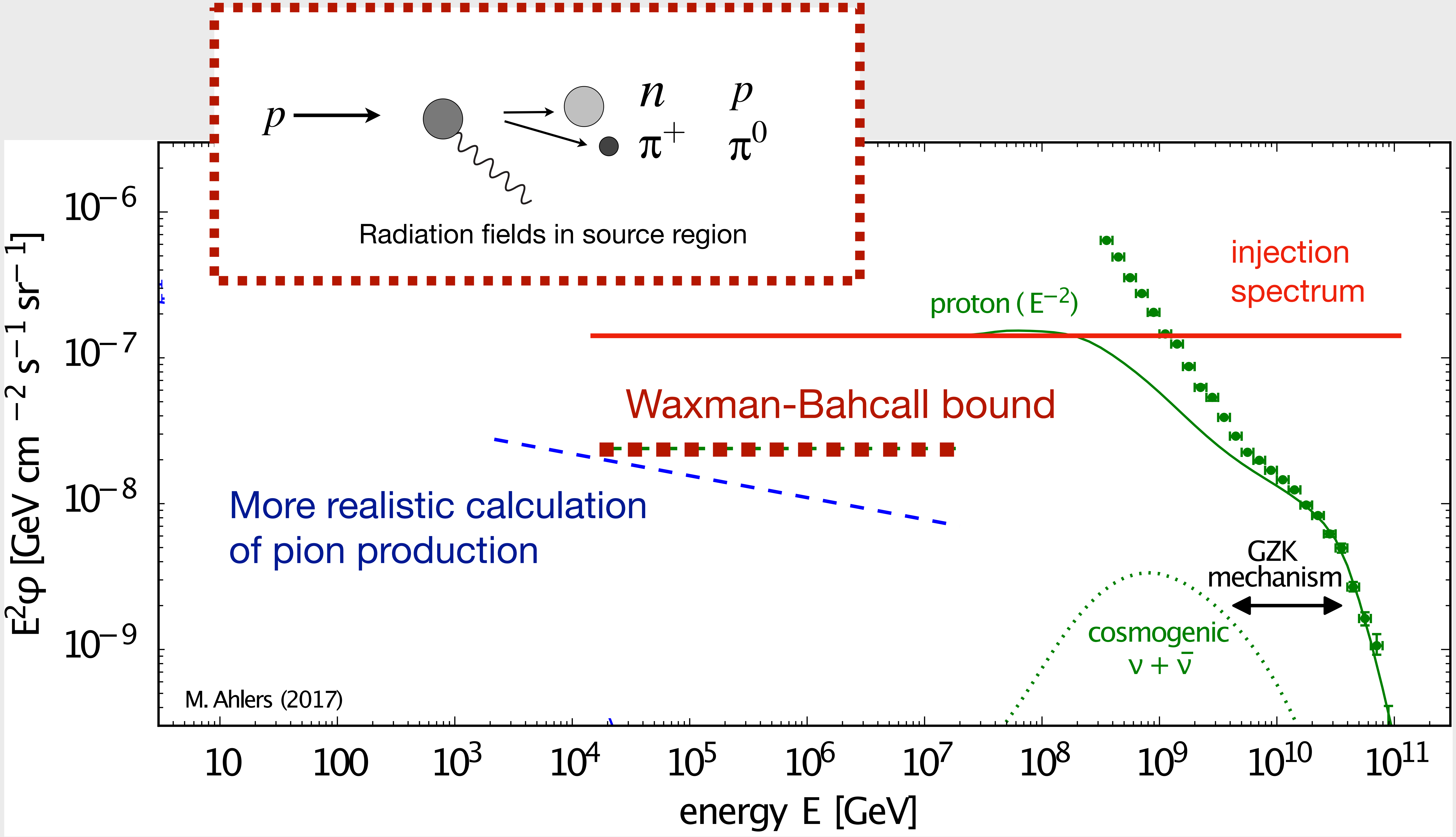


(NASA/ESA)

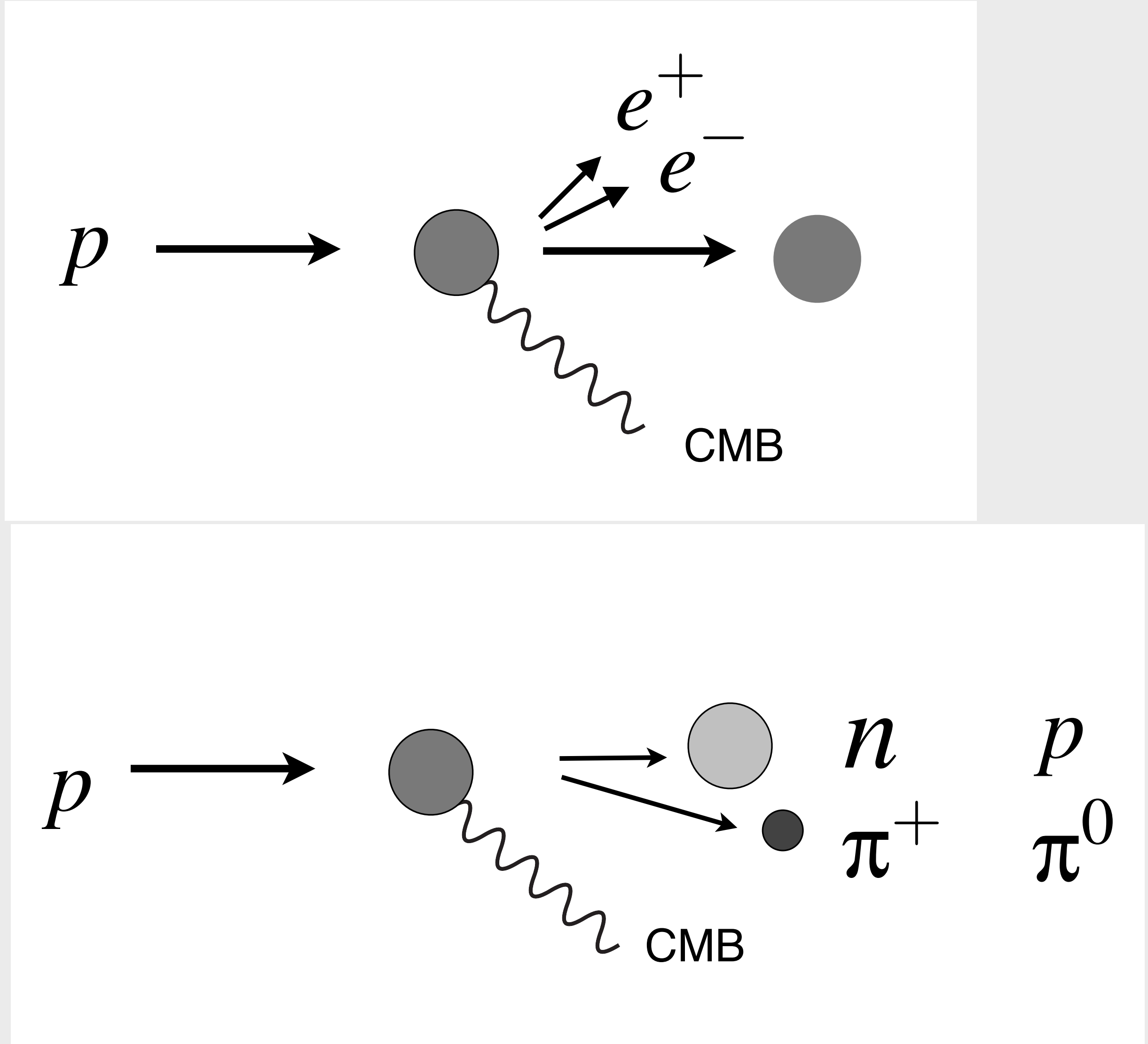


(NASA/ESA)

Graphical representation of WB bound



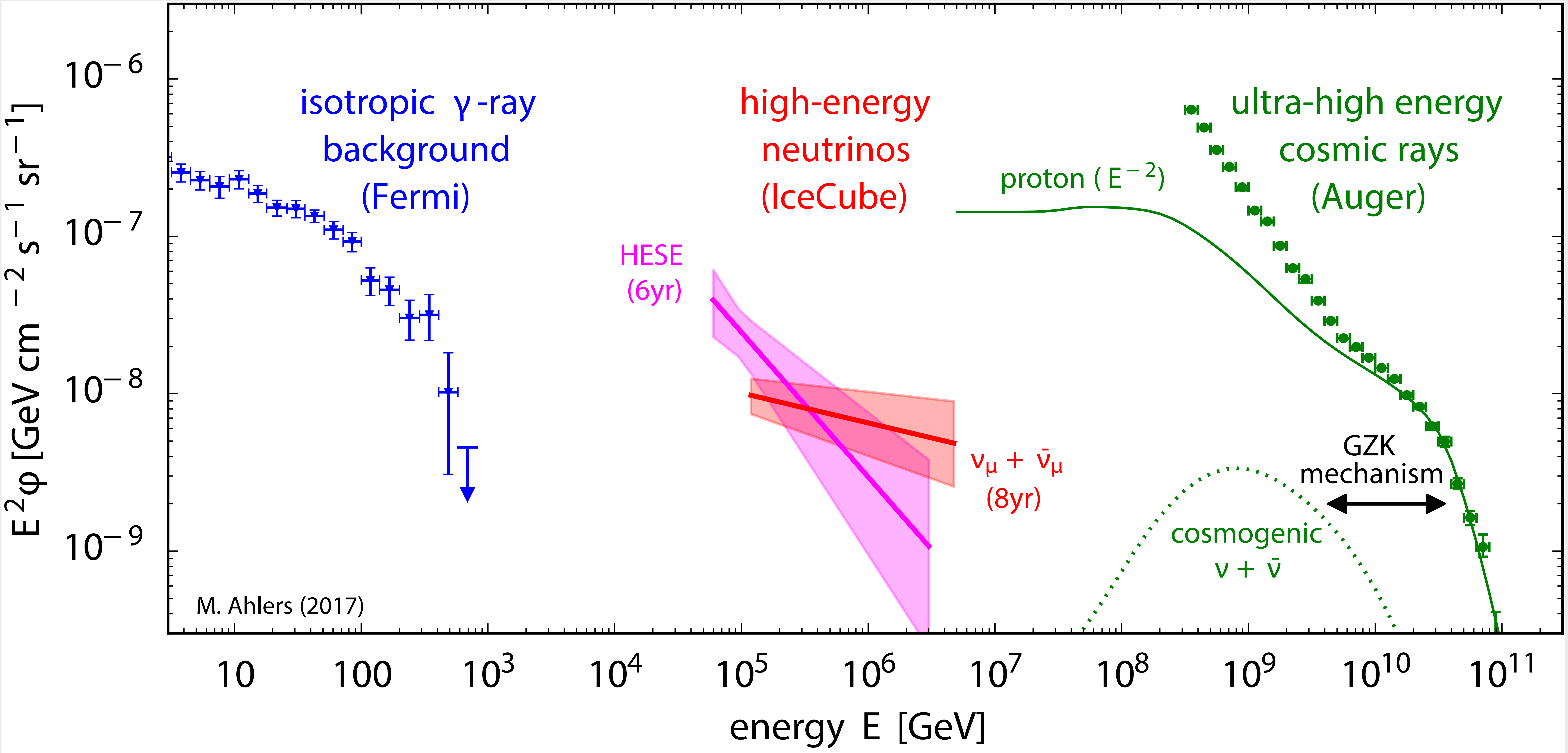
No data to support assumptions at the time the bounds was developed



GZK mechanism

Estimate of size of required neutrino detector based on this type of calculation (V ~ 1 km³)

Secondary particles – Propagation and sources



Energy spectrum of protons injected by sources

$$\frac{dN_{inj}}{dE} \sim E^{-2}$$

$$\pi^0 \longrightarrow \gamma\,\gamma$$

Gamma rays

$$\pi^+ \longrightarrow \mu^+\,\nu_\mu \longrightarrow e^+\,\nu_e\,\nu_\mu\,\bar{\nu}_\mu$$

Neutrinos

GZK effect:
Photo-pion production (mainly Δ resonance)