Extragalactic Propagation of Ultra-High Energy Cosmic Rays

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10th Rencontres du Vietnam
Very High Energy Phenomena in the Universe
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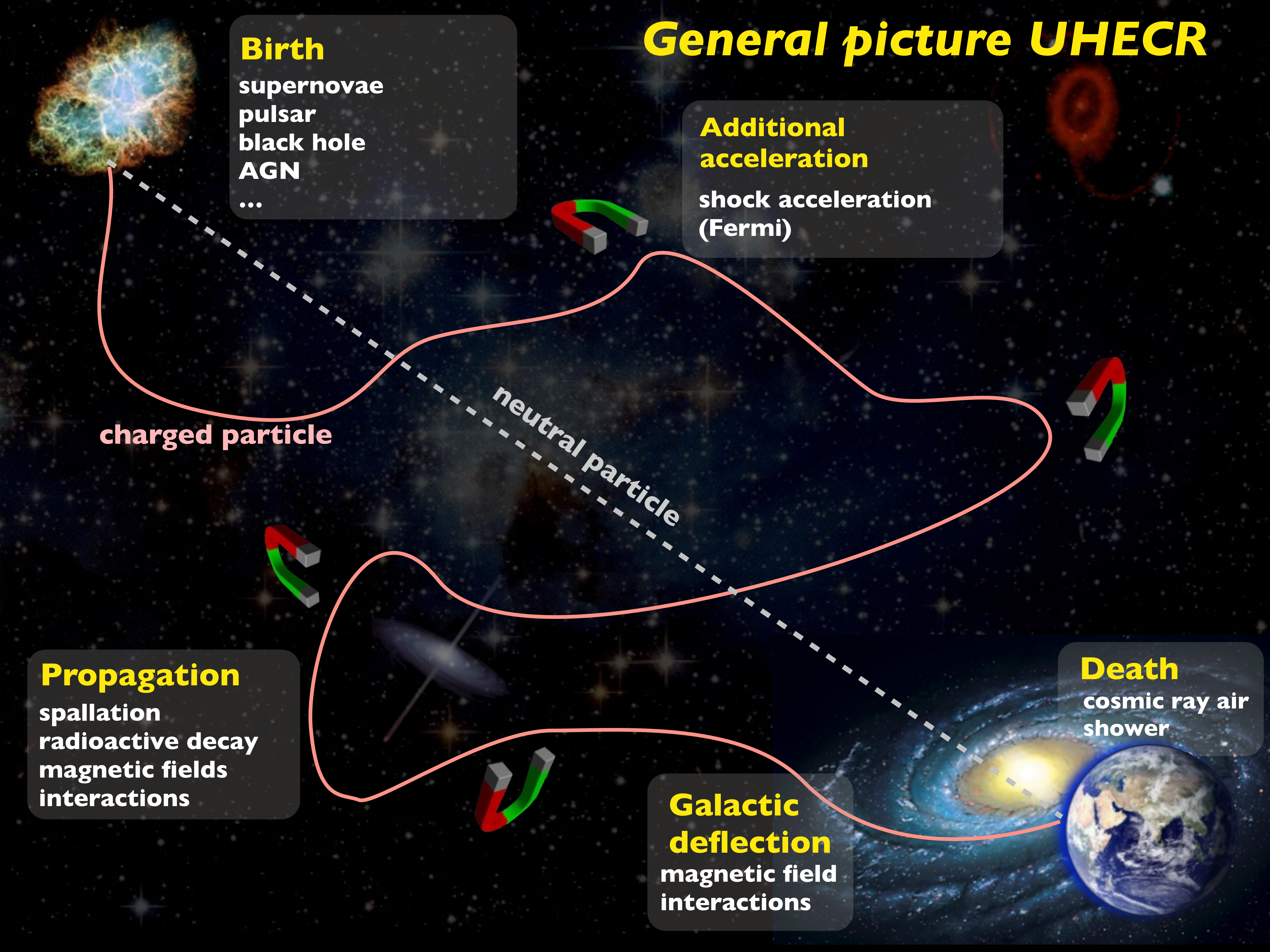
Ultra-high energy cosmic rays

$E > 10^{17}$ eV

Pressing questions:

1. Where do they come from?
2. What are they made of?
3. How are they accelerated?
4. What can they tell us about fundamental and particle physics?
5. Is there a maximal energy?

Particle propagation from source to observer is important to answer these questions

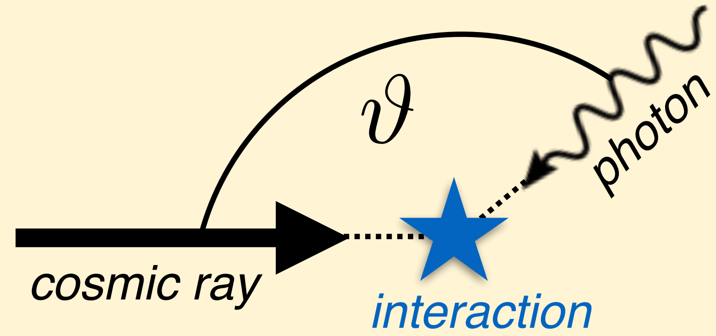

General picture UHECR
Birth
supernovae
pulsar
black hole
AGN
...
Additional acceleration
shock acceleration (Fermi)
charged particle
neutral particle
Propagation
spallation
radioactive decay
magnetic fields
interactions
Galactic deflection
magnetic field
interactions
Death
cosmic ray air shower

Propagation features

Extra-galactic energy density

- Cosmic rays can interact with background photons:

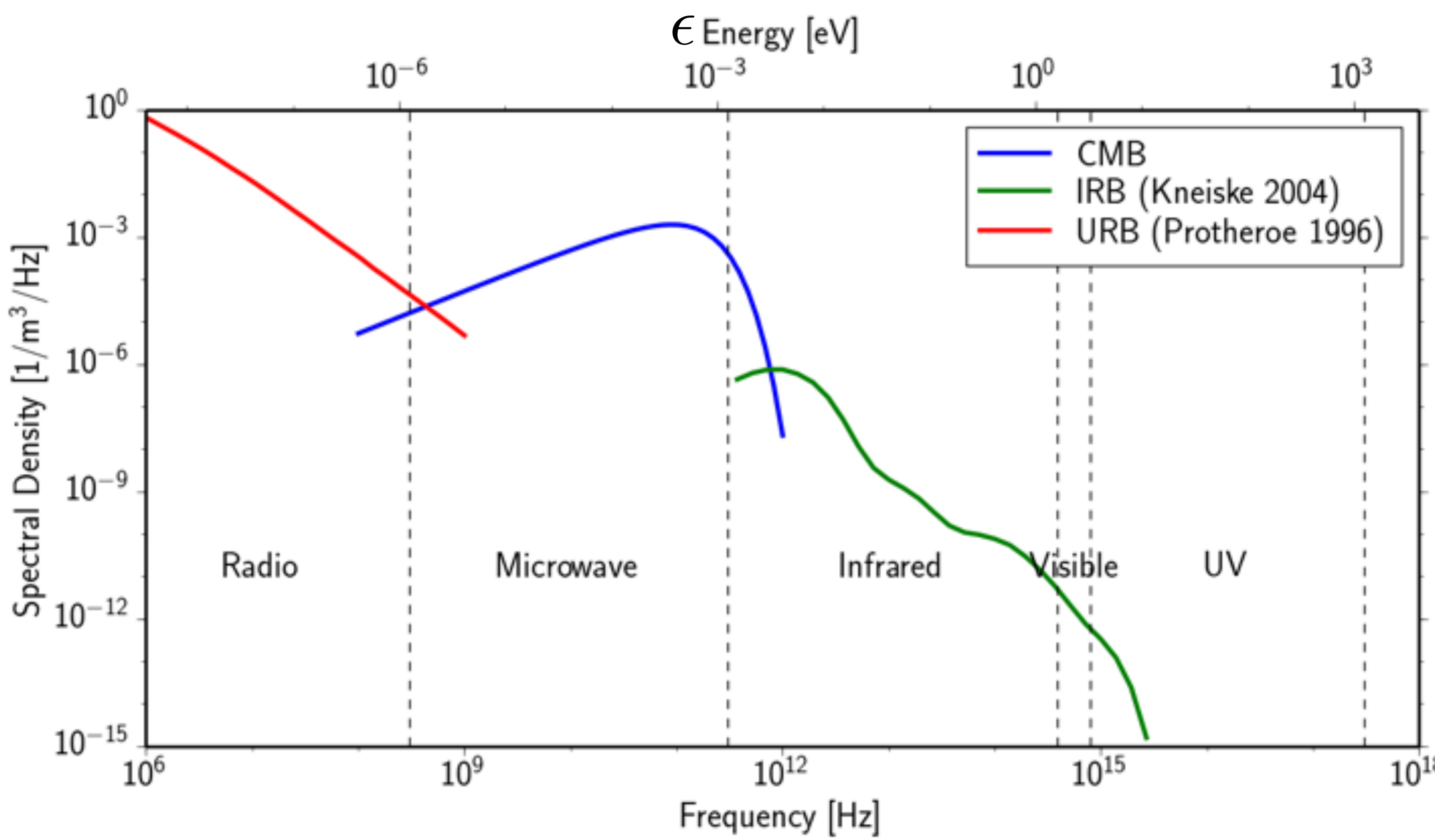
$$\Gamma = \frac{E}{m}$$



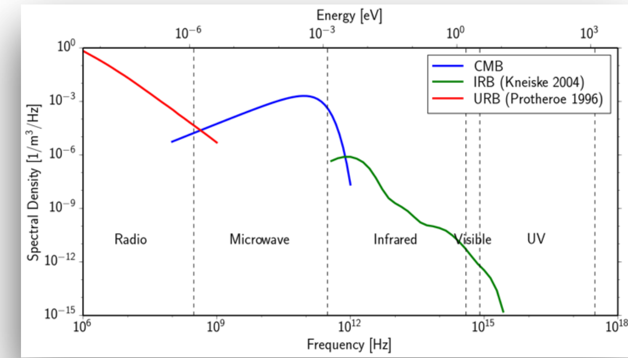
$$\epsilon' = \epsilon\Gamma(1 - \cos(\vartheta))$$

photon energy in nucleus rest frame

ϵ' is the relevant energy scale for interaction



Interactions



- **Pion production**

Pion production for a head-on collision of a nucleon *N*:

$$N + \gamma \to N + \pi$$

with the threshold energy

$$E_{\mathrm{thres}} = \frac{m_\pi (m_N + m_\pi/2)}{2\epsilon} \approx 6.8 \cdot 10^{19} \left(\frac{\epsilon}{10^{-3}\ \mathrm{eV}} \right)^{-1} \mathrm{eV}$$

where $\epsilon \sim 10^{-3}\ \mathrm{eV}$ represents a typical target photon such as a CMB photon.
Both the electromagnetic and the strong interaction play a role.
Example: Pion production by protons via delta resonance:

EM interaction — strong interaction

$$p + \gamma \to \Delta^+ \to \begin{cases} n + \pi^+ & \text{with branching ratio } 1/3 \\ p + \pi_0 & \text{with branching ratio } 2/3 \end{cases}$$

$n + \pi^+$: $\to \mu^+ + \nu_\mu$ — main production channel of neutrinos by hadronic cosmic rays

$p + \pi_0$: $\to \gamma + \gamma$ — main channel of high energy photons by hadronic cosmic rays

After the discovery of the CMB (1965) people realized:

Universe gets opaque for cosmic rays at ultra-high energies: GZK-effect

first realized by Greisen, Zatsepin and Kuzmin in 1966

K. Greisen, PRL 16 748 (1966), G.T. Zatsepin and V.A. Kuzmin Sov. Phys. JETP Lett. 4 78 (1966)

Interactions

- **Pair production**

Pair production by a nucleus with mass number *A* and charge *Z* on a photon:

$$^{A}_{Z} + \gamma \rightarrow ^{A}_{Z} + e^{+} + e^{-}$$

induces electromagnetic cascades via inverse Compton scattering

with the threshold energy

$$E_{\text{thres}} = \frac{m_e(m + m_e)}{\epsilon} \approx 4.8 \cdot 10^{17}\ A\ \left(\frac{\epsilon}{10^{-3}\ \text{eV}}\right)^{-1} \text{eV}$$

where $\epsilon \sim 10^{-3}\ \text{eV}$ represents a typical target photon such as a CMB photon.

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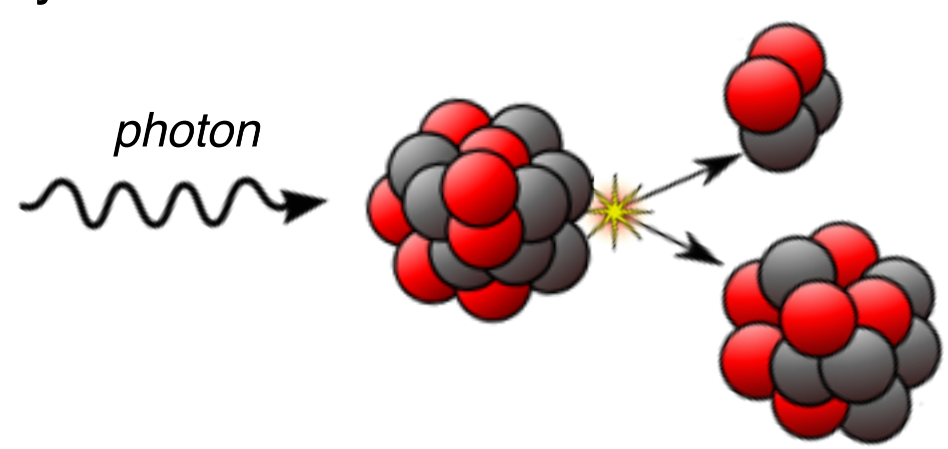
where $\epsilon \sim 10^{-3}\ \mathrm{eV}$ represents a typical target photon such as a CMB photon.

- **Photodisintegration of nuclei**

Gamma ray is absorbed by nuclei and causes it to enter excited state before splitting in two parts.



Changes in energy ΔE, and atomic number ΔA, are related by $\Delta E/E = \Delta A/A$
Thus, effective energy loss rate is given by:

$$\frac{1}{E}\frac{\mathrm{d}E}{\mathrm{d}t}\bigg|_{\mathrm{eff}} = \frac{1}{A}\frac{\mathrm{d}A}{\mathrm{d}t} = \sum_i \frac{i}{A} l_{A,i}(E)$$

mean free path for the emission of *i* nucleons

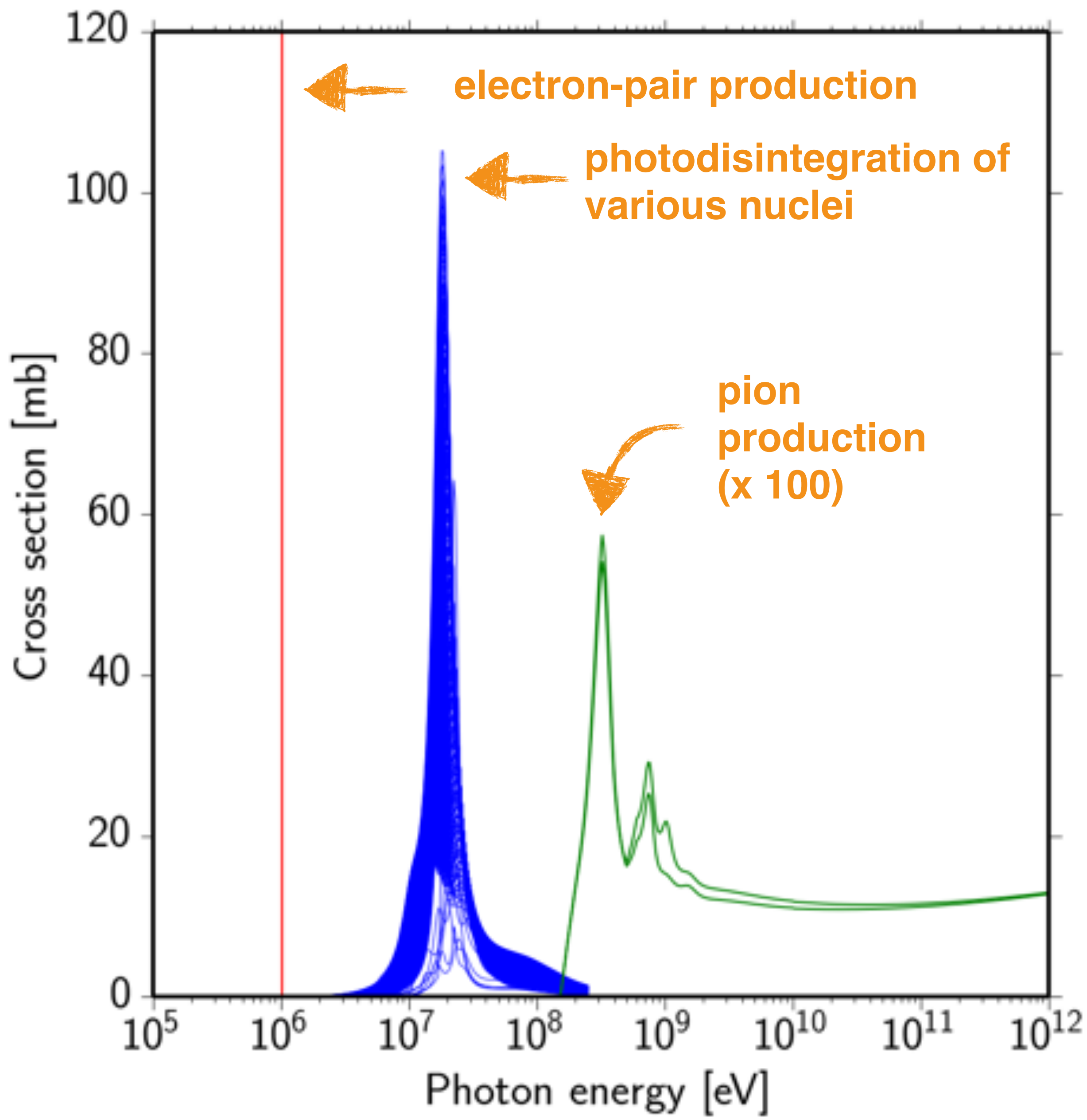
Interaction rate

Interaction rate can be calculated as

$$\lambda^{-1} = \int_0^\infty n(\epsilon)\sigma_{\text{avg}}(\epsilon)\ \mathrm{d}\epsilon$$

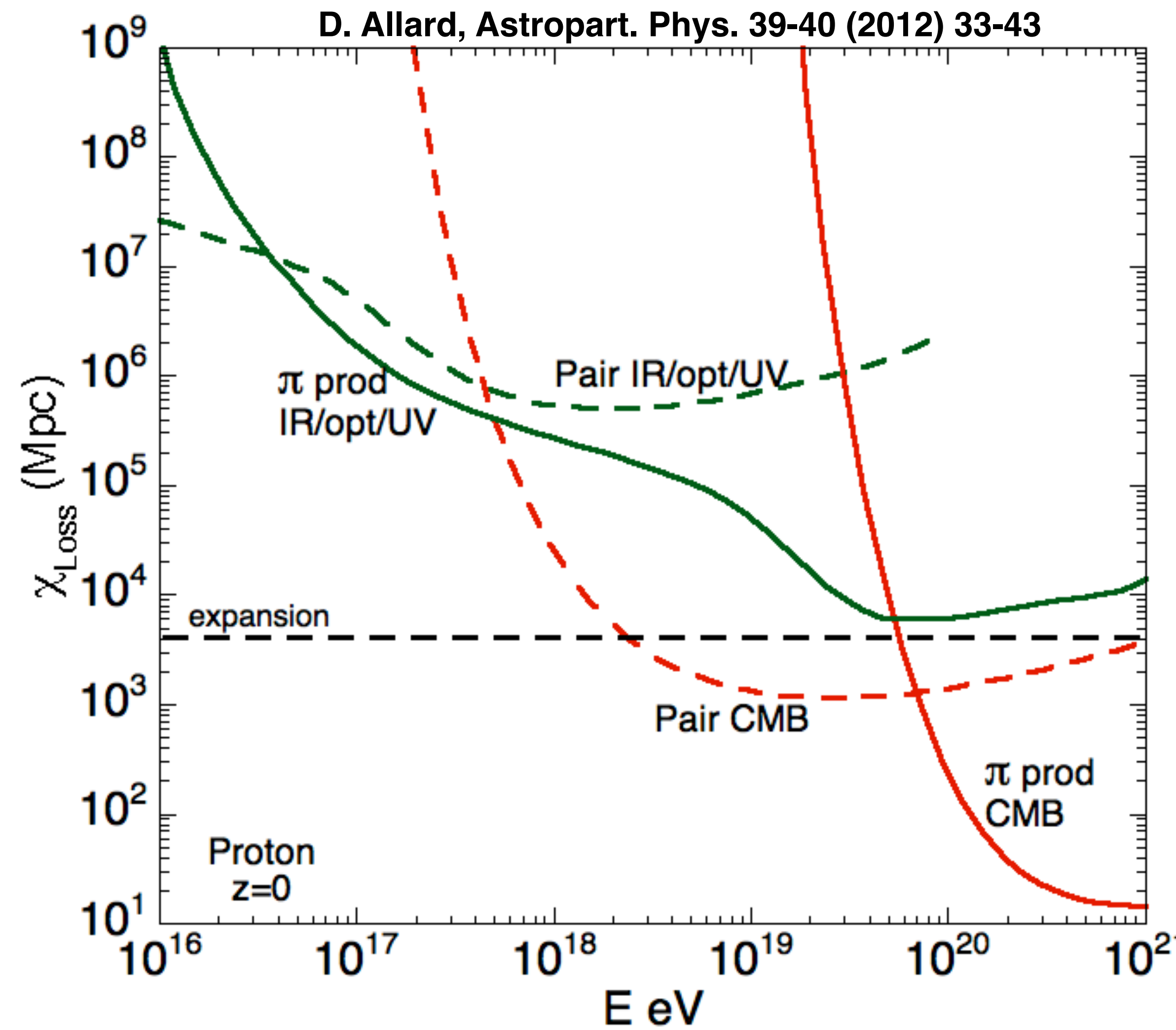
photon number density

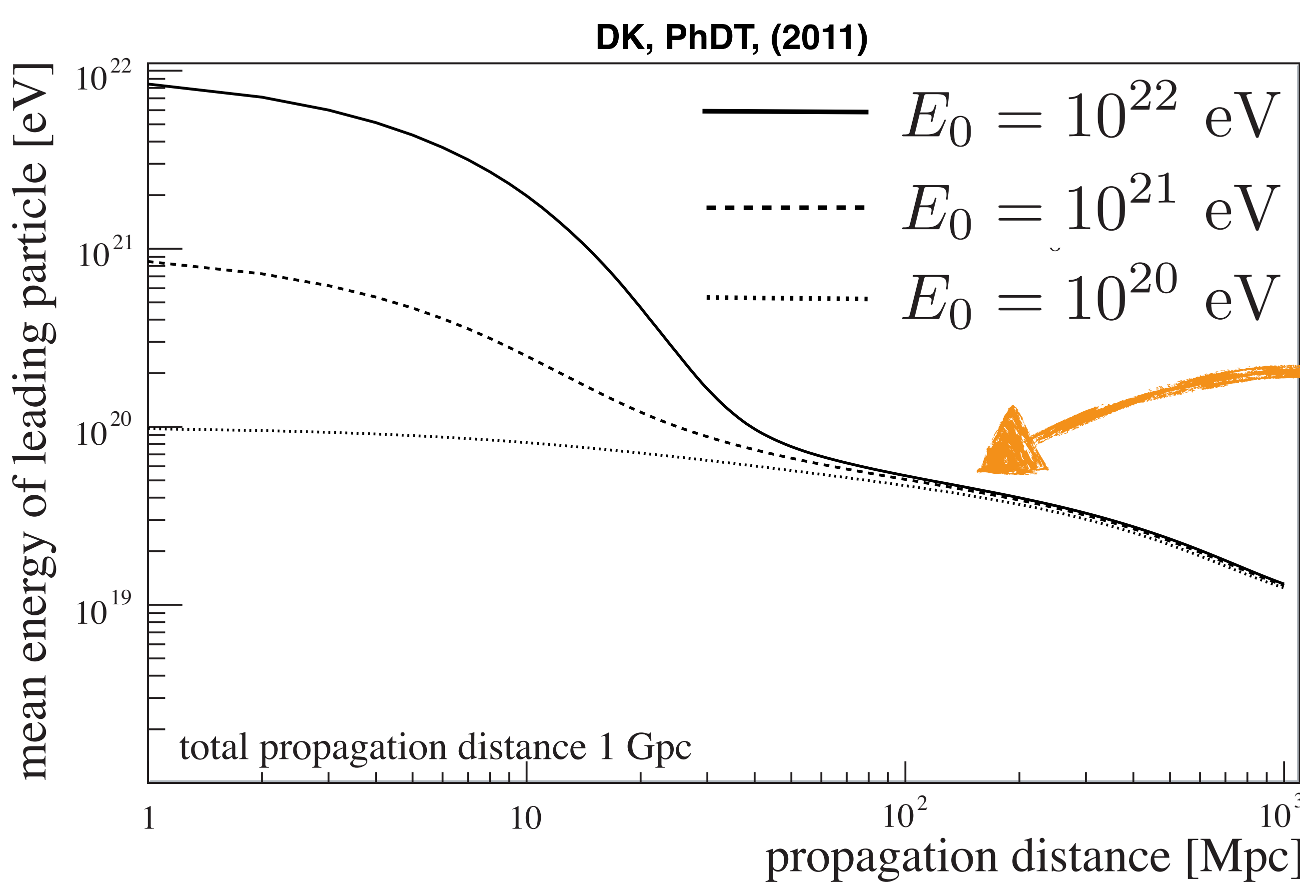
collision angle averaged cross section



Attenuation length for protons

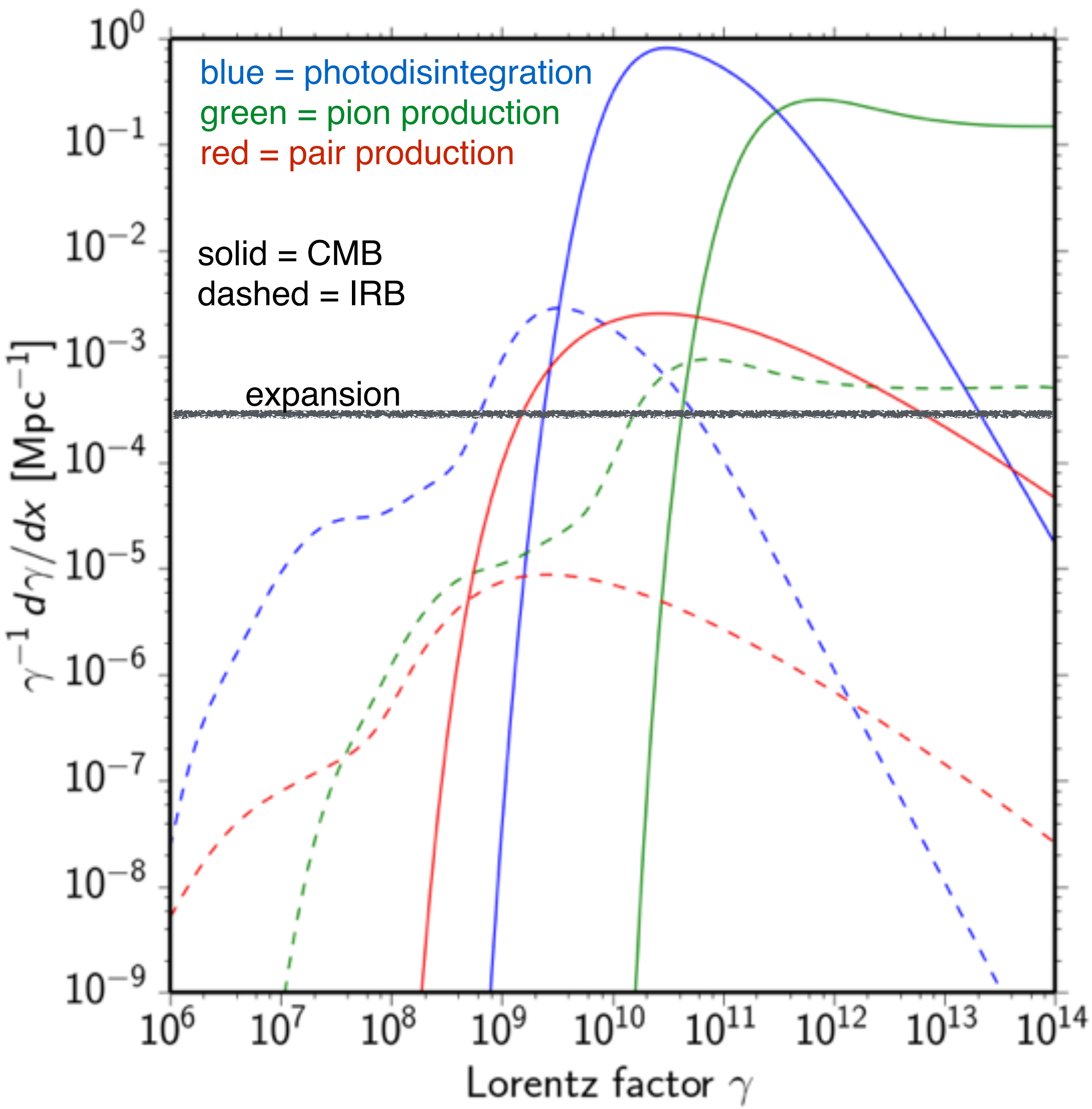
- **Low energies:**
  energy loss dominated by expansion of the universe
- **Intermediate energies:**
  Most important loss length is pair production on CMB
- **High energies:**
  Most important loss length is pion production on CMB





GZK-effect: For propagation distances > 100 Mpc the primary energy is attenuated to almost the same value

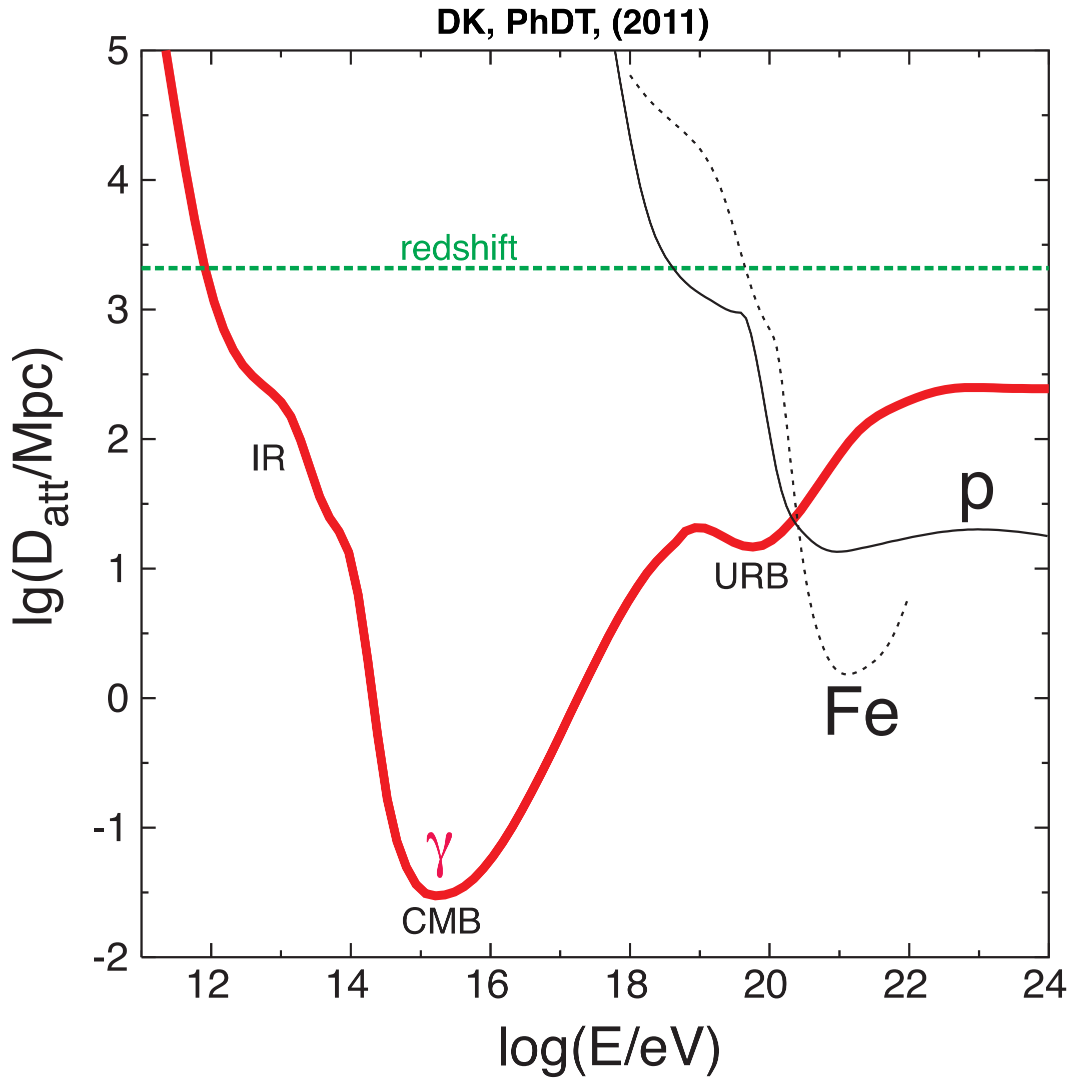
Energy loss rate for Carbon-12



$$E \sim \Gamma\ A\ 10^9\ \mathrm{eV}$$

- **Low energies:**
  energy loss dominated by expansion of the universe
- **Intermediate energies:**
  Most important energy loss is photodisintegration
- **High energies:**
  Pion production on CMB

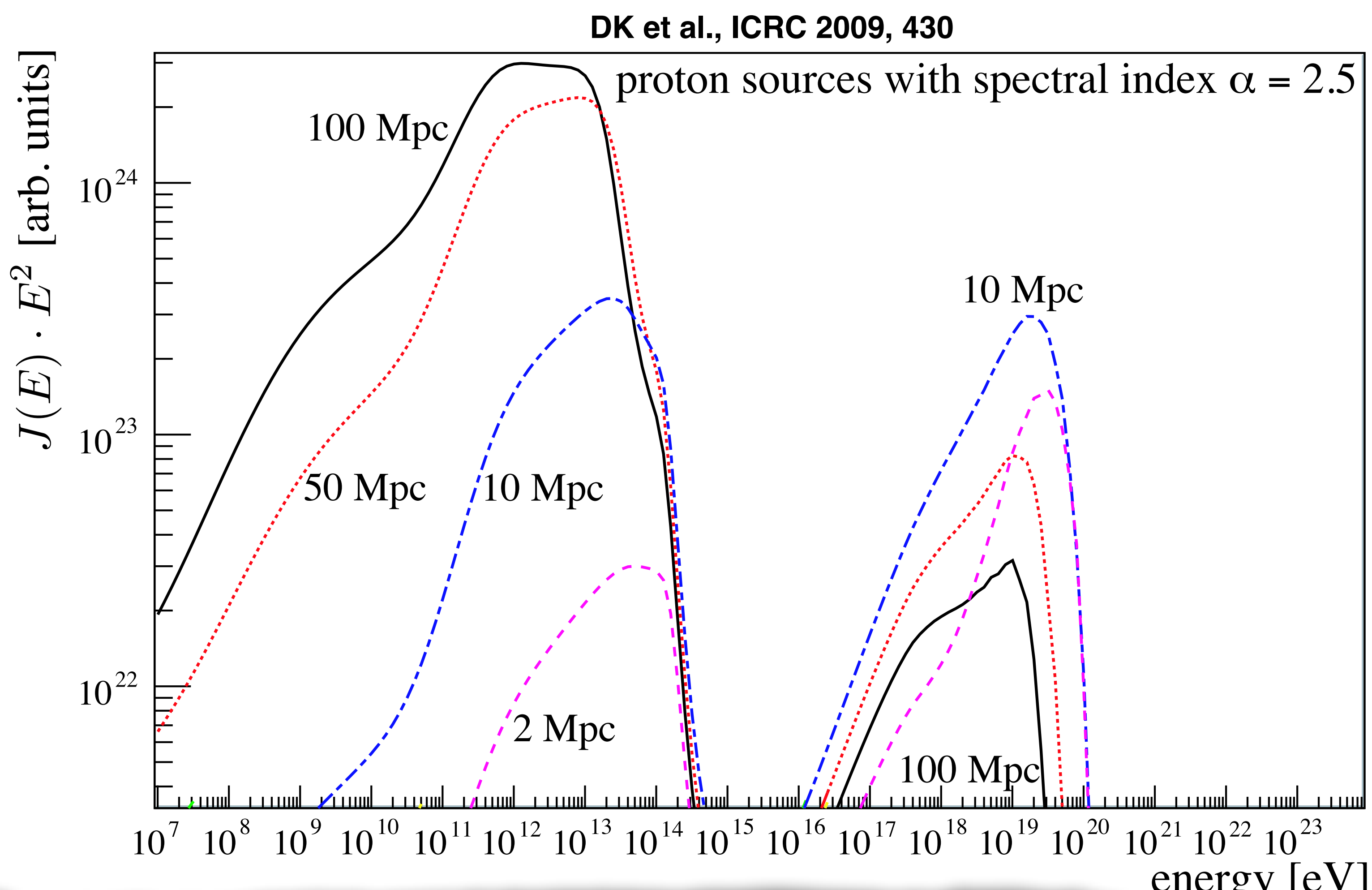
Secondary photons



- Dominant interaction process is pair production:

$$\gamma_{\mathrm{UHE}} + \gamma_b \rightarrow e^+ + e^-$$

- Strong attenuation in PeV regime by CMB photons



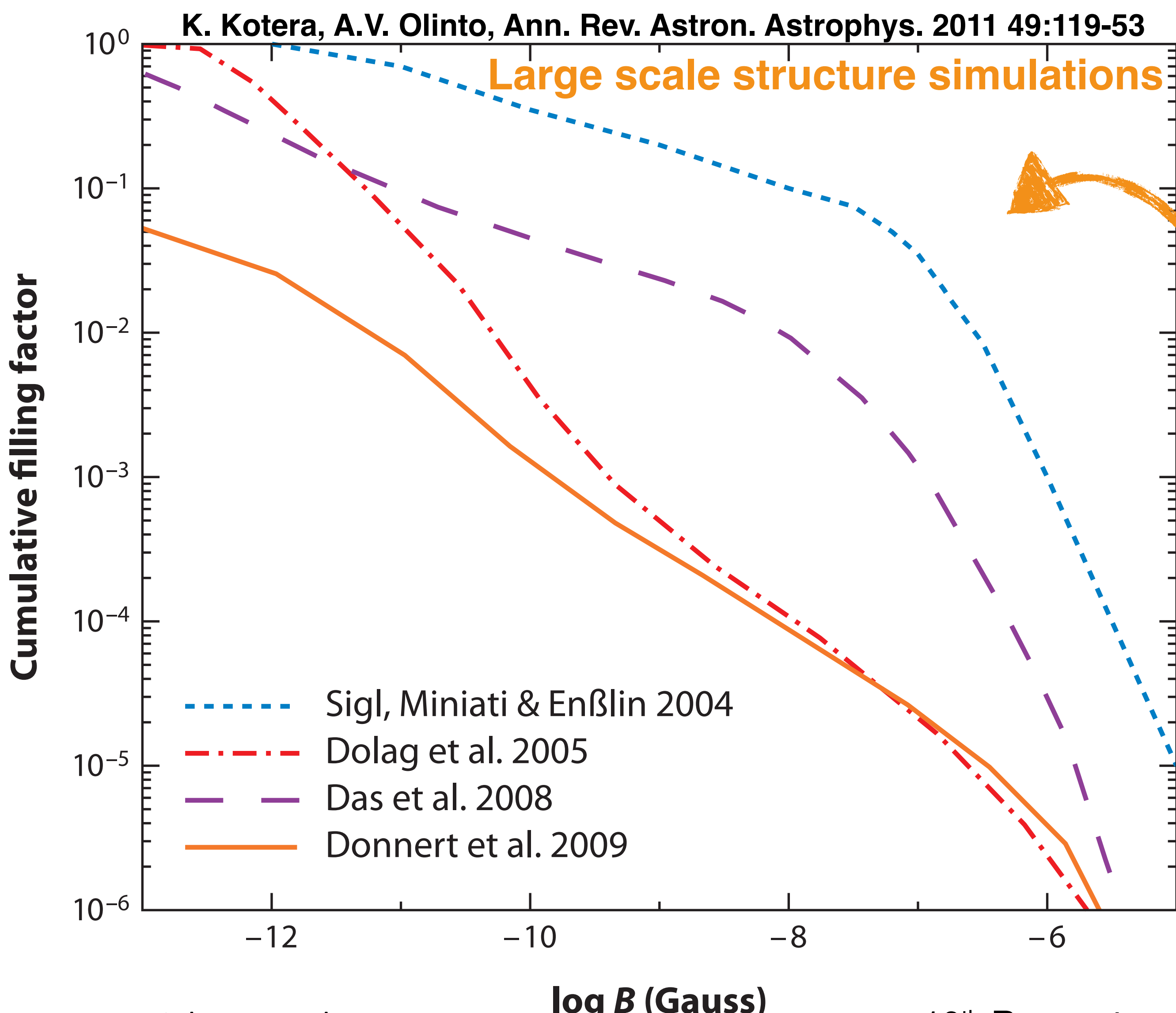
- Typical energy loss length:
  - 7-15 Mpc at 10^{19} eV
  - 5-30 Mpc at 10^{20} eV

observation of galactic and nearby extragalactic sources may be possible

Current status: No photons above ~TeV energies observed

Extragalactic magnetic fields

- **Some words of caution**: **Extragalactic** magnetic fields are currently poorly constrained.
- Their origin is not well understood (primordial Universe, magnetic pollution from astrophysical sources, e.g. jets from radio galaxies, …)
- Typical strength of the field varies:
  - **1-40 μG** with coherence length of about 10 kpc *(clusters of galaxies)*
  - **10^{-16} - 10^{-6} G** with coherence length between 1-10 Mpc *(in filaments)*
- Field strength probably related to matter density in this environment

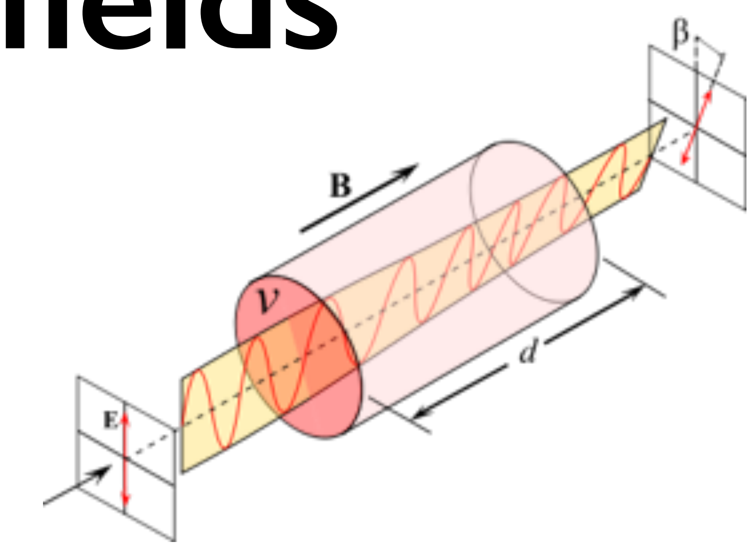


- Absence of powerful counterparts in the arrival direction of UHECRs is probably related to magnetic fields

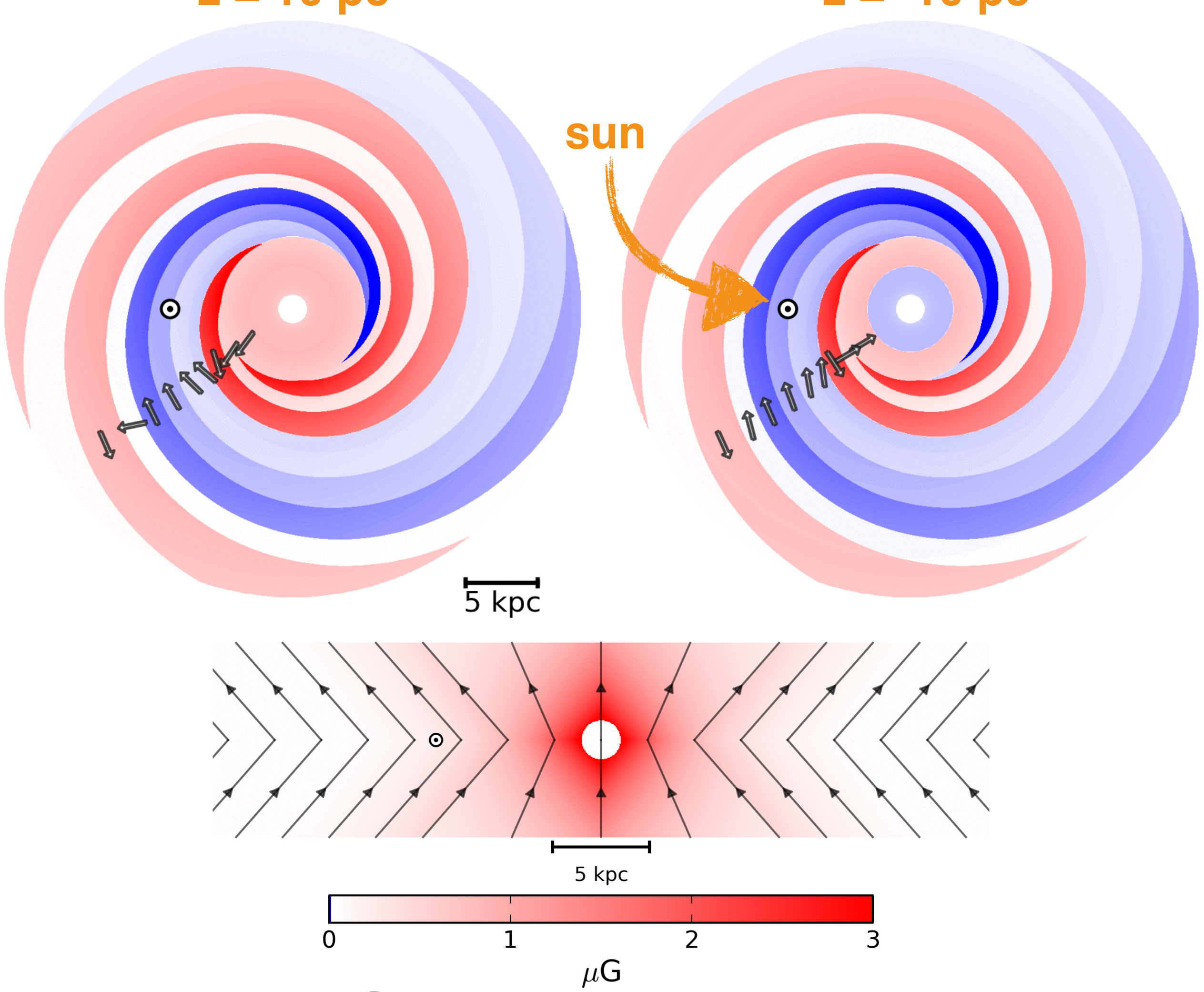
- Simulations lead to **very discrepant results**
- Illustrates **variety of assumptions** made
- E.g. Sigl, Miniati & Enßlin estimate proton deflection with energy > 100 EeV by **10-20°**, whereas Dolag et al. **< 1°** of the same energy

Galactic magnetic fields

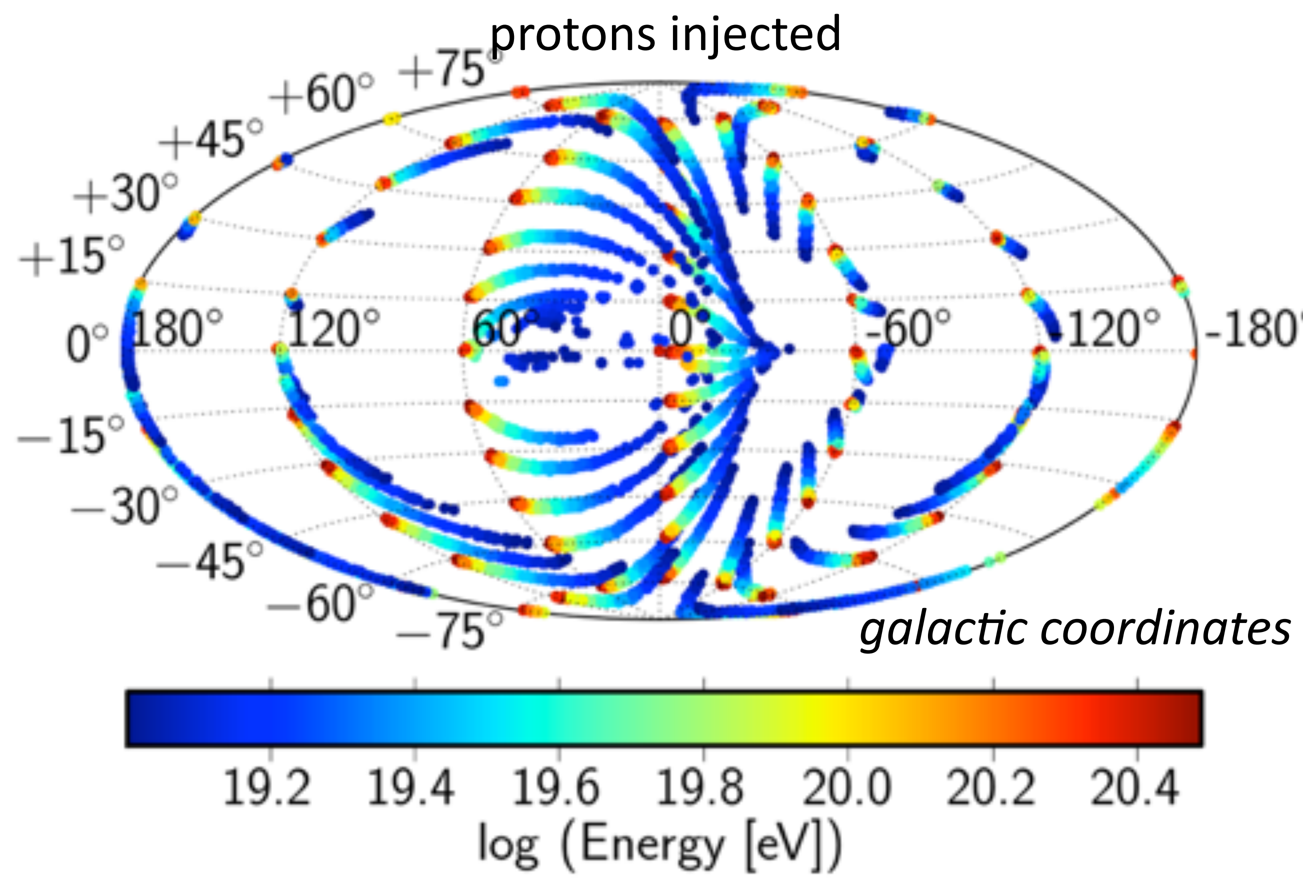
- Much progress in recent years
- Models based on Faraday rotation measurements and polarized and unpolarized synchrotron emission
- Concentrate on field from Jannson & Farrar: **JF12**
  R. Jansson and G. R. Farrar, ApJ 757 (2012) 14
  R. Jansson and G. R. Farrar, ApJL 761 (2012) L11
- Field strength of order micro-Gauss



Slices in *x-y* plane



Slices in *x-z* plane
out of the plane component



Deflections important in anisotropy studies

TA hotspot

Science AAAS July 8 2014


Physicists spot potential source of 'Oh-My-God' particles

Tweet 151 Share 2.4k 8+1 54

By Adrian Cho | 8 July 2014 1:00 am | 40 Comments

40 Comments

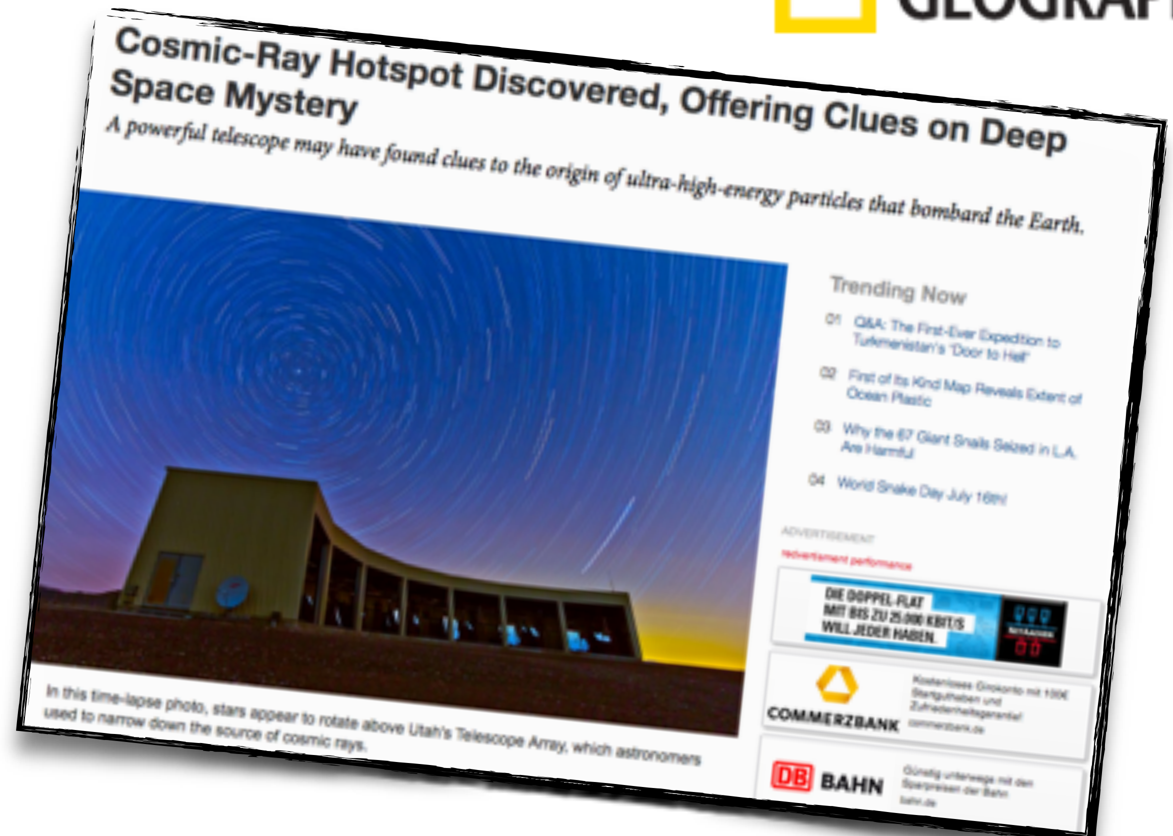
Staff Writer

Email Adrian

For decades, physicists have sought the sources of the most energetic subatomic particles in the universe—cosmic rays that strike the atmosphere with as much energy as well-thrown baseballs. Now, a team working with the Telescope Array, a collection of 507 particle detectors covering 700 square kilometers of desert in Utah, has observed a broad "hotspot" in the sky in which such cosmic rays seem to originate. Although not definitive, the observation suggests the cosmic rays emanate from a distinct source near our galaxy and not from sources spread all over the universe.

Physicists have been down a similar road before. In 2007, researchers with the Pierre Auger

July 9 2014 NATIONAL GEOGRAPHIC


Cosmic-Ray Hotspot Discovered, Offering Clues on Deep Space Mystery

A powerful telescope may have found clues to the origin of ultra-high-energy particles that bombard the Earth.

In this time-lapse photo, stars appear to rotate above Utah's Telescope Array, which astronomers used to narrow down the source of cosmic rays.

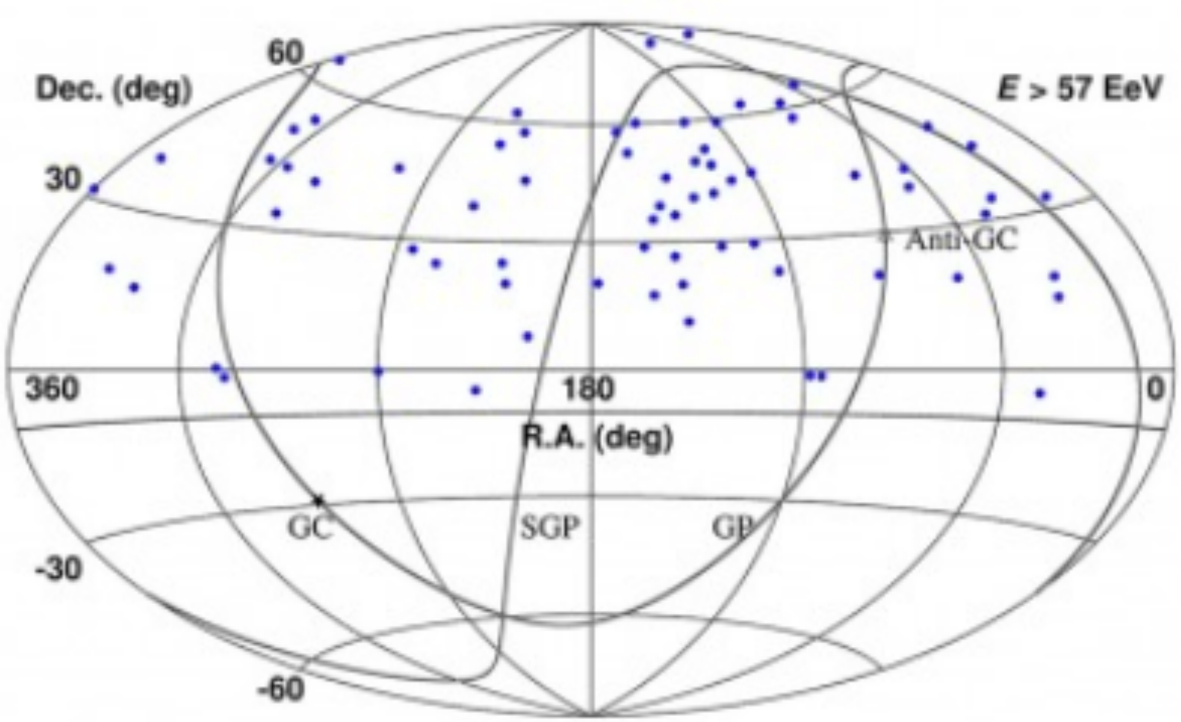
Trending Now

01 Q&A: The First-Ever Expedition to Turkmenistan's 'Door to Hell'

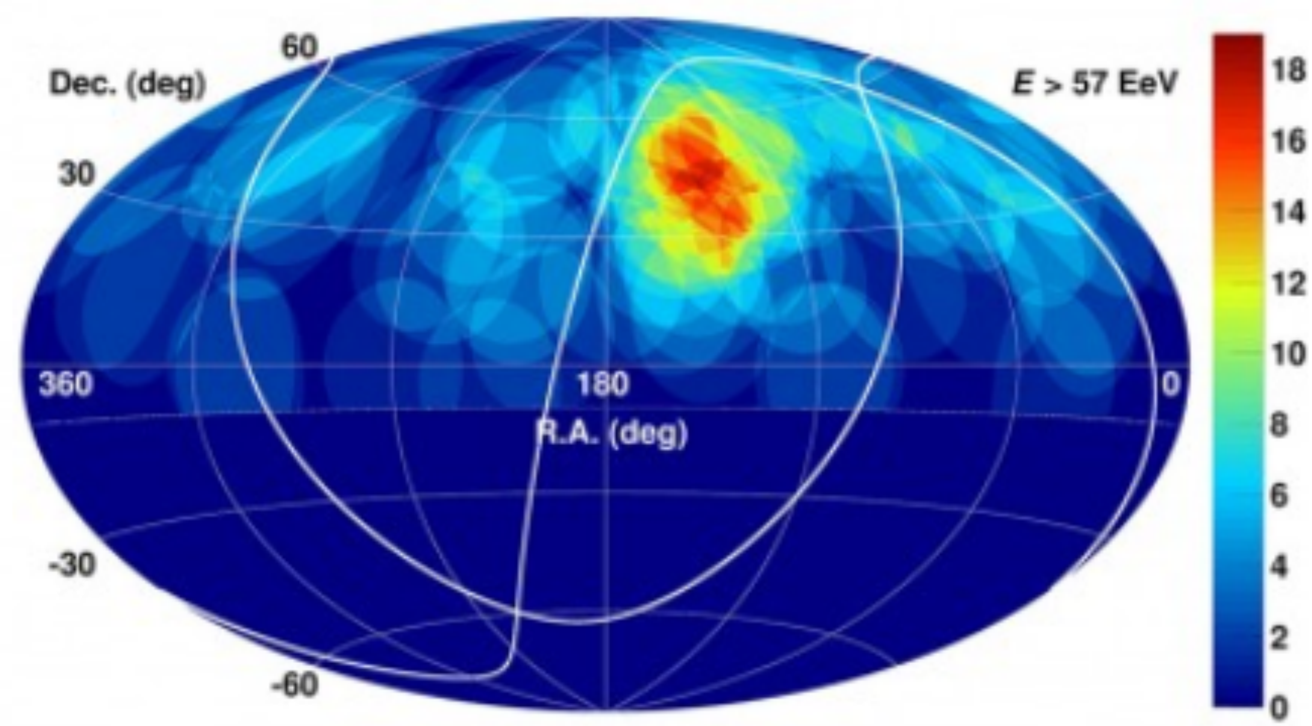
02 First of its Kind Map Reveals Extent of Ocean Plastic

03 Why the 67 Giant Snails Seized in L.A. Are Harmful

04 World Snake Day July 16th!

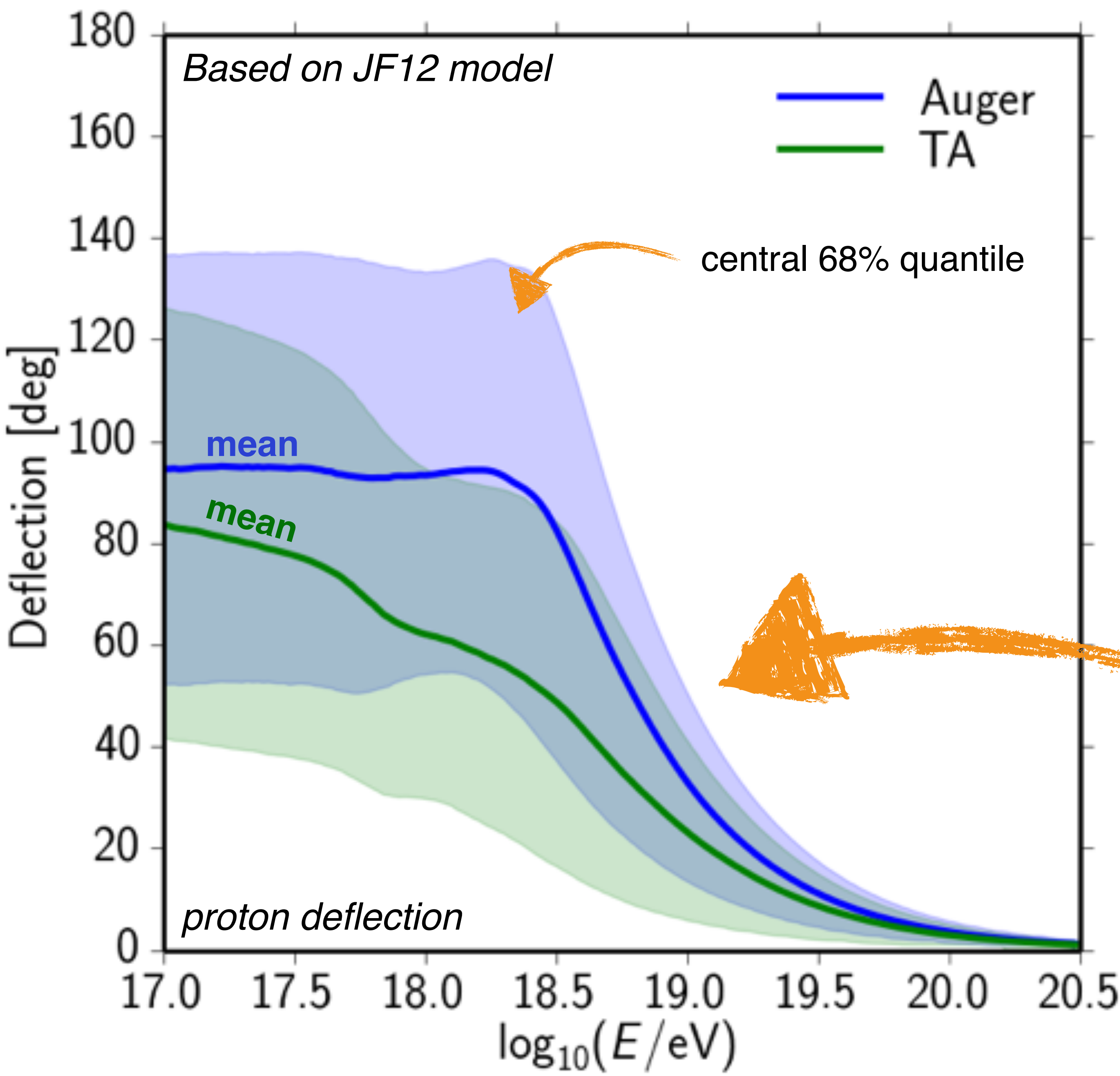


equatorial coordinates



equatorial coordinates

Mean deflection for Auger and TA site

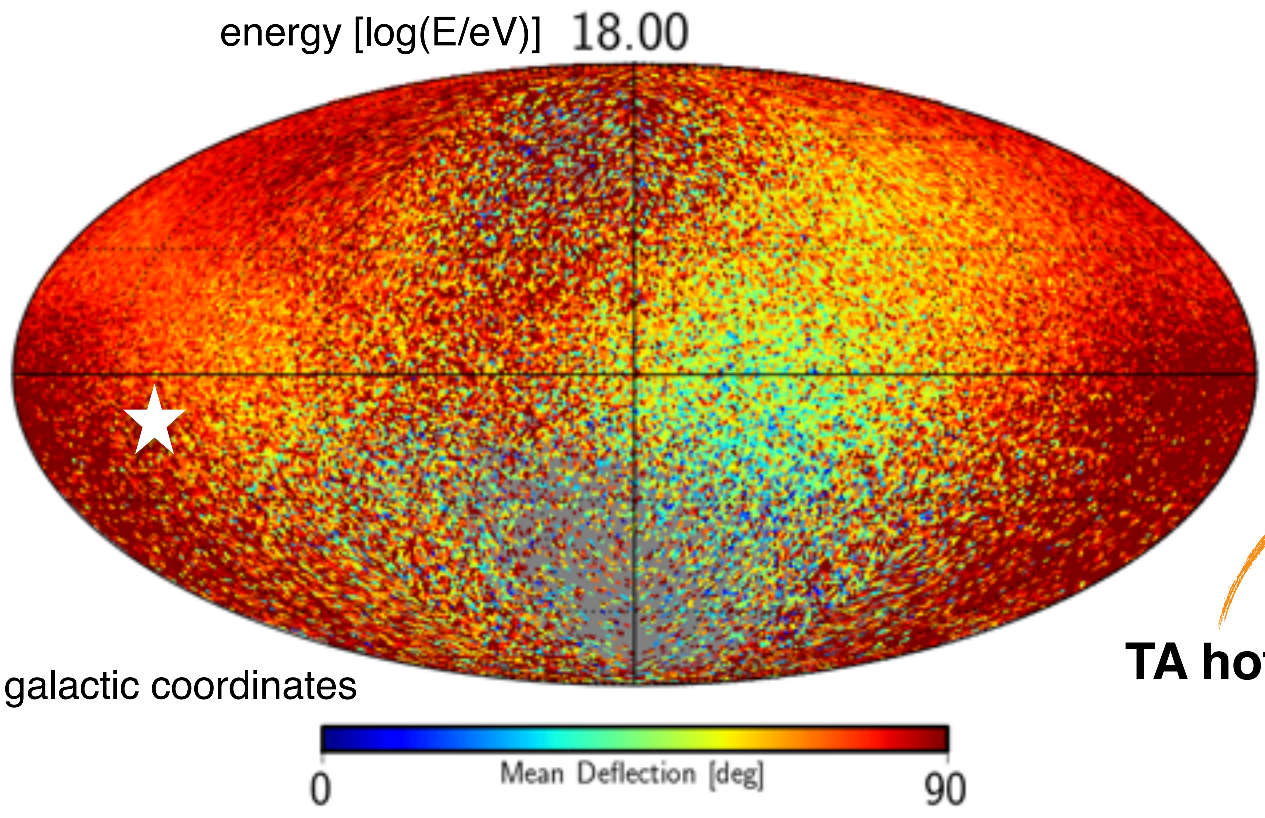


- Mean deflection assuming that particles arrive isotropically at the edge of the galaxy
- Events recorded at each site up to 60° in zenith angle

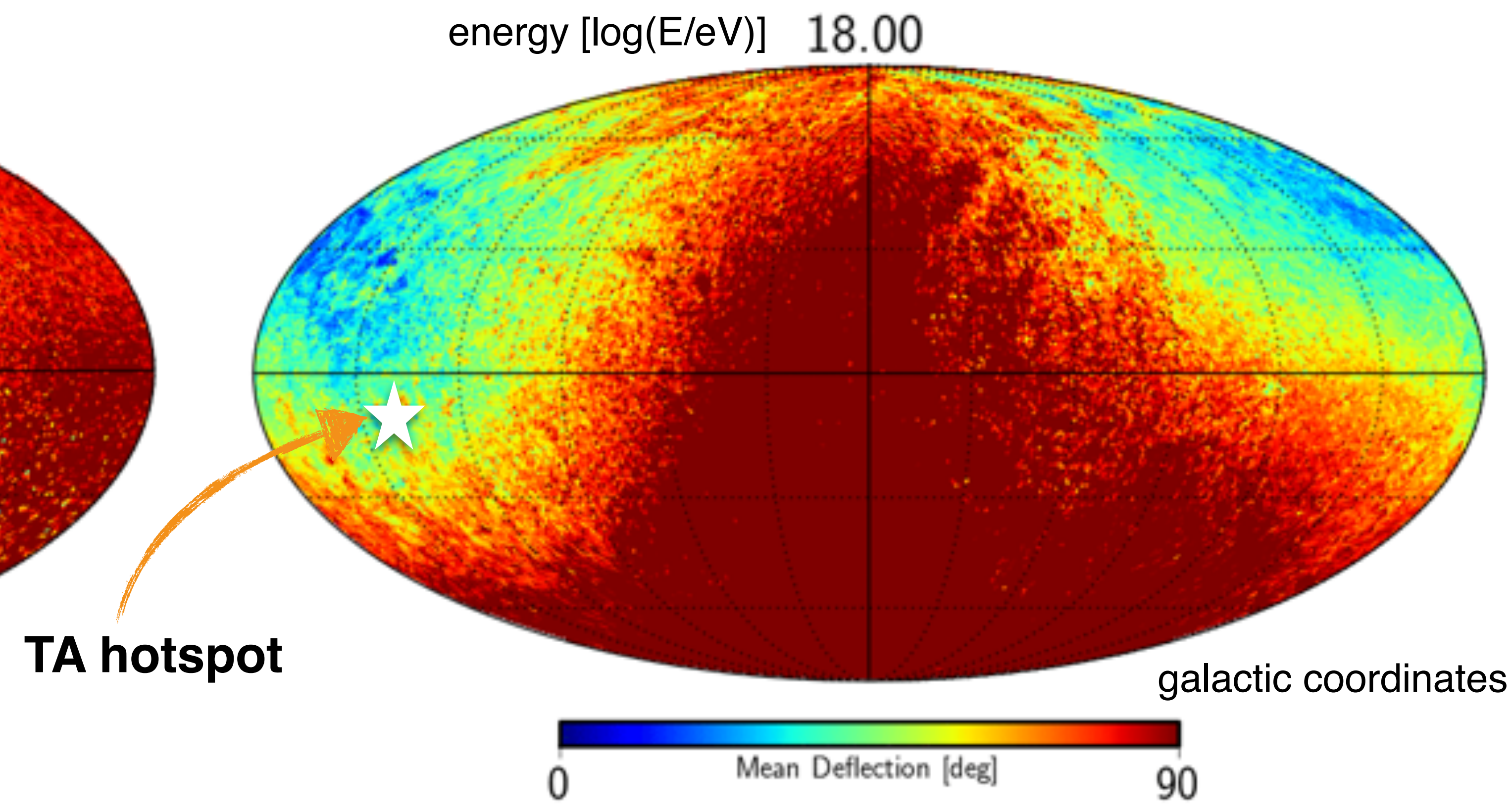
TA and Auger observe different deflections. Important when comparing Auger and TA measurements

Mean galactic deflection

Mean deflection of protons arriving at the edge of the galaxy

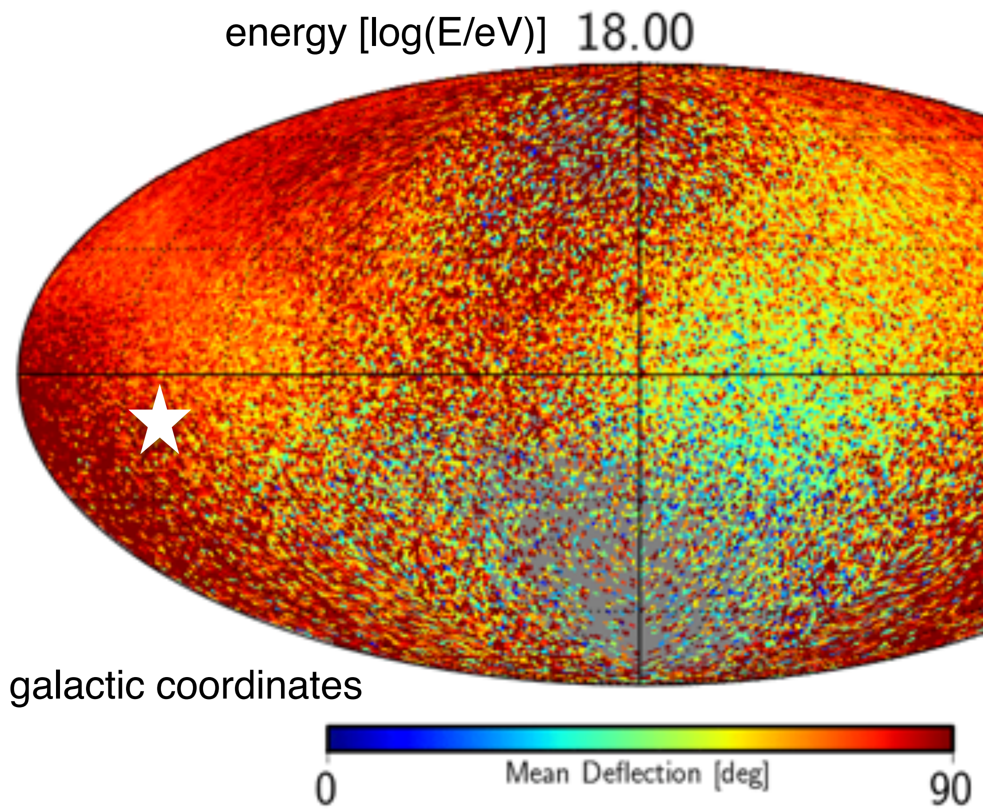


Mean deflection of protons as seem from Earth

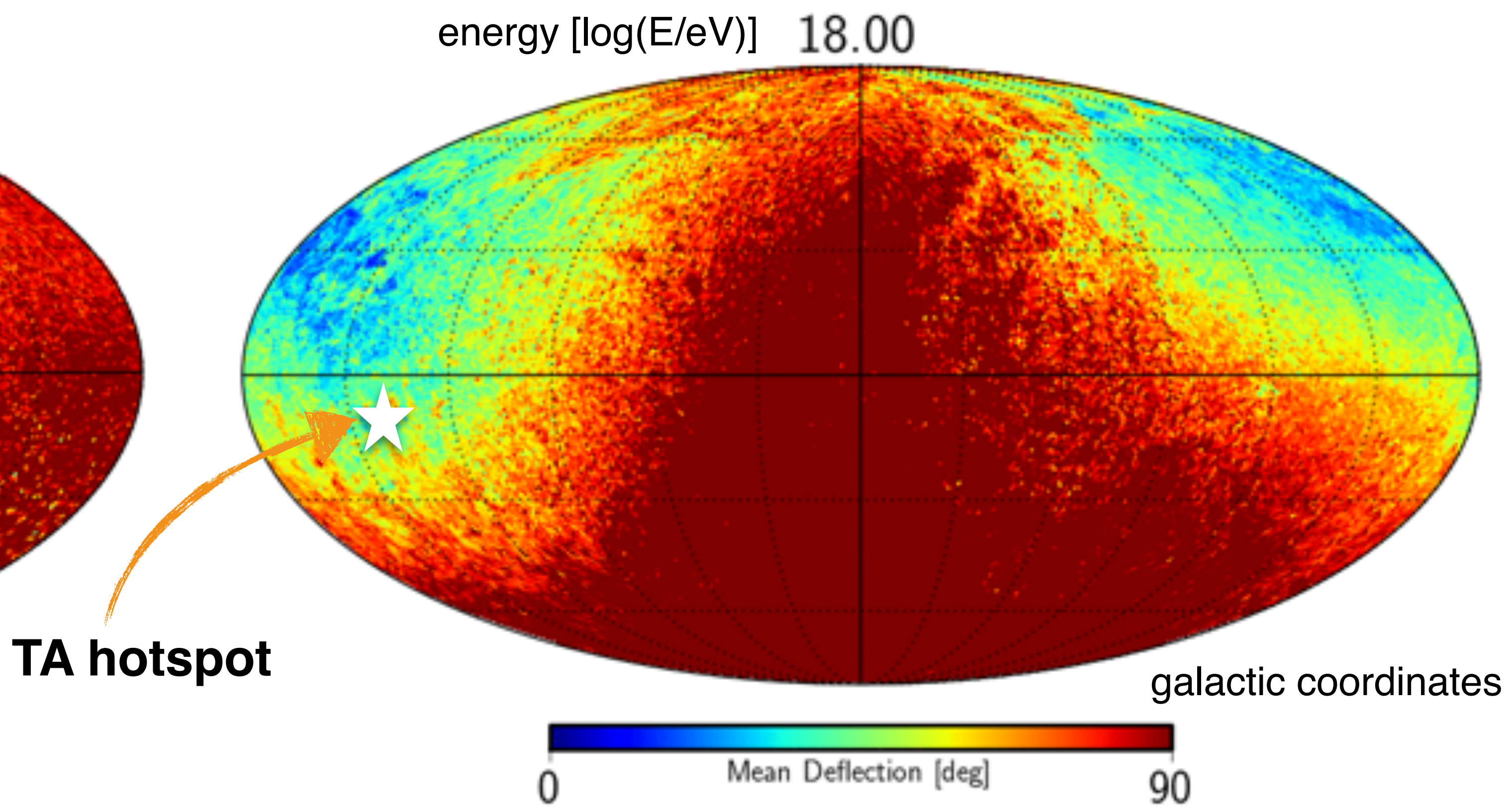


Mean galactic deflection

Mean deflection of protons arriving at the edge of the galaxy



Mean deflection of protons as seem from Earth

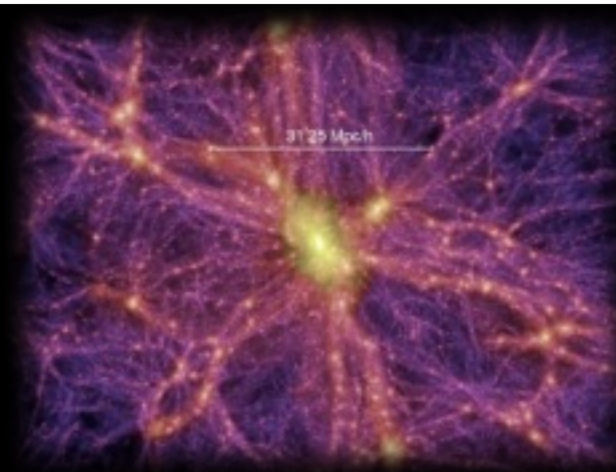


Multiparameter challenge in simulations

Multiparameter challenge

Aim: Constrain / determine astrophysical parameters
Challenge: Many unknown/uncertain parameters

Sources



Propagation

Observation

Number
Position
Size
Luminosity
Spectrum
Composition
Evolution
Transient sources
Emission patterns

→

Energy loss, cross sections
Change in composition
Background radiation model
Redshift effects

Extragalactic Mag. Field
Strength, coherence length,
structure (filaments, voids, cluster)

Galactic Mag. Field
Model and strength
scale heights, turbulence

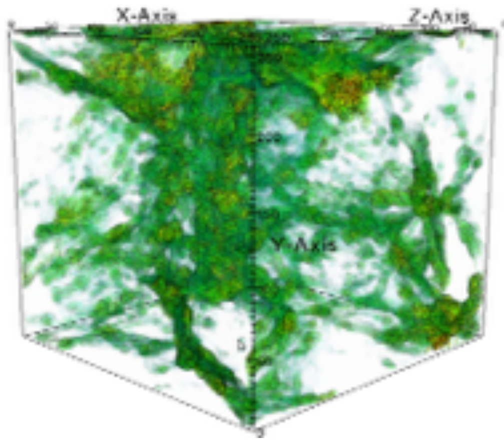
→

Direction *(direct)*
Energy *(direct)*
Composition
(indirect e.g. X_{max}*)*

Simulations

- Much progress in recent years

Propagation codes



CRPropa
R.A. Batista et al. ICRC 2013
https://crpropa.desy.de
SimProp
R. Aloisio et al. JCAP 10 007 (2012)

Experimental data

PIERRE AUGER OBSERVATORY

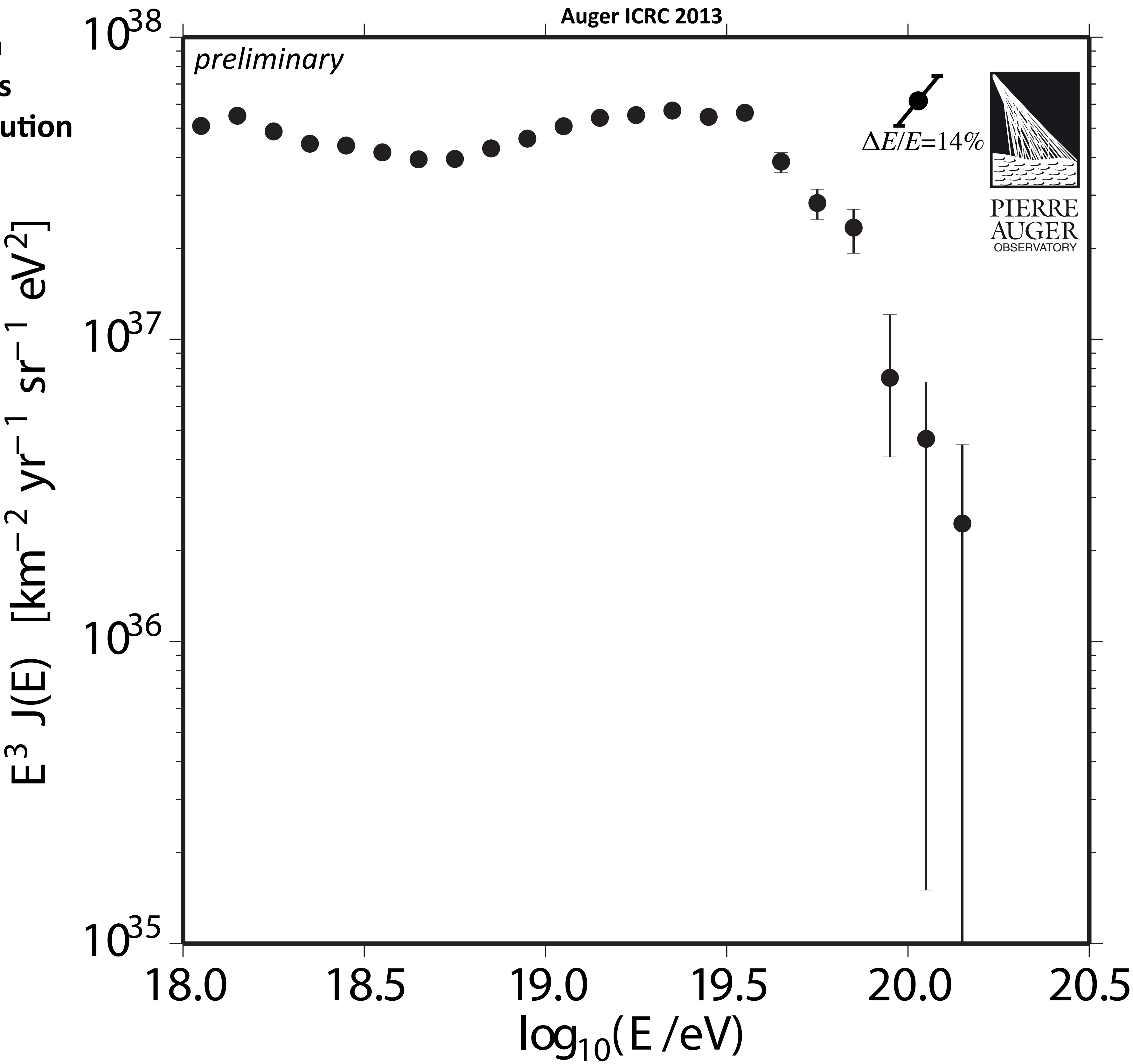
TELESCOPE ARRAY PROJECT

Computing power

Using high statistic experimental data in combination with sophisticated propagation tools and powerful computing clusters we are entering a **new phase of data / MC comparison**

Simple example data comparison

- **1D simulation**
- **Homogeneous source distribution**
- ***m*=0**



Simple example data comparison

- 1D simulation
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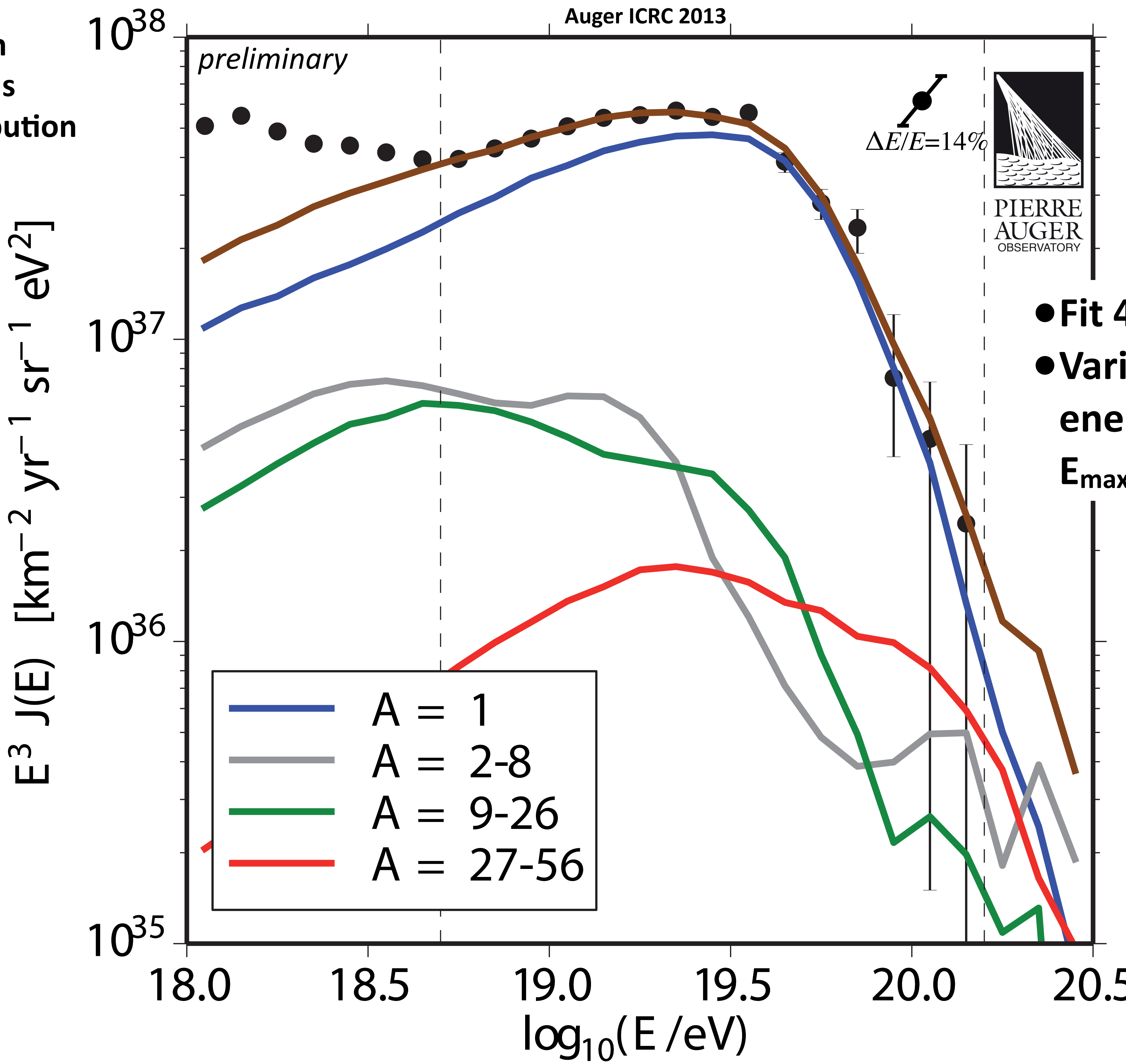
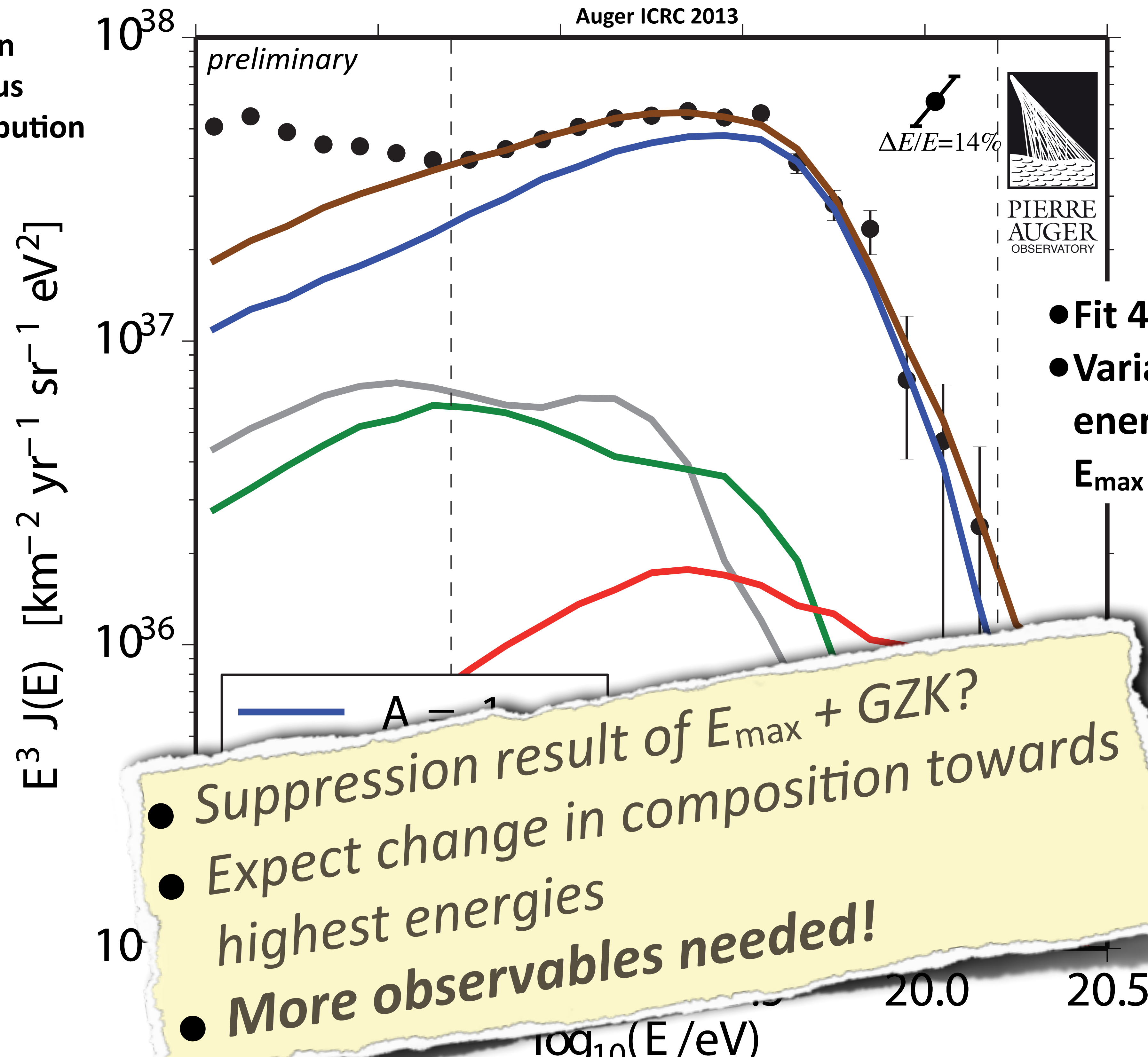


- Fit 4 masses at source
- Variable maximum energy. Best fit: $E_{max} = 10^{19.73}$ x Z eV

Simple example data comparison

- 1D simulation
- Homogeneous source distribution
- *m*=0

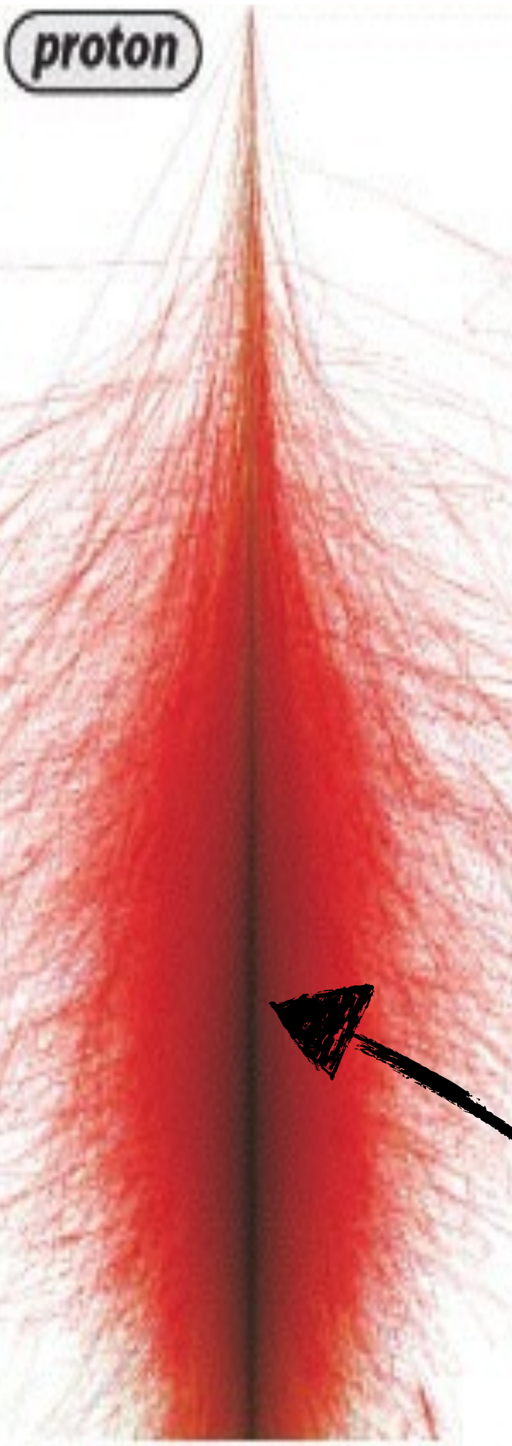


- Fit 4 masses at source
- Variable maximum energy. Best fit: $E_{max} = 10^{19.73} \times Z$ eV

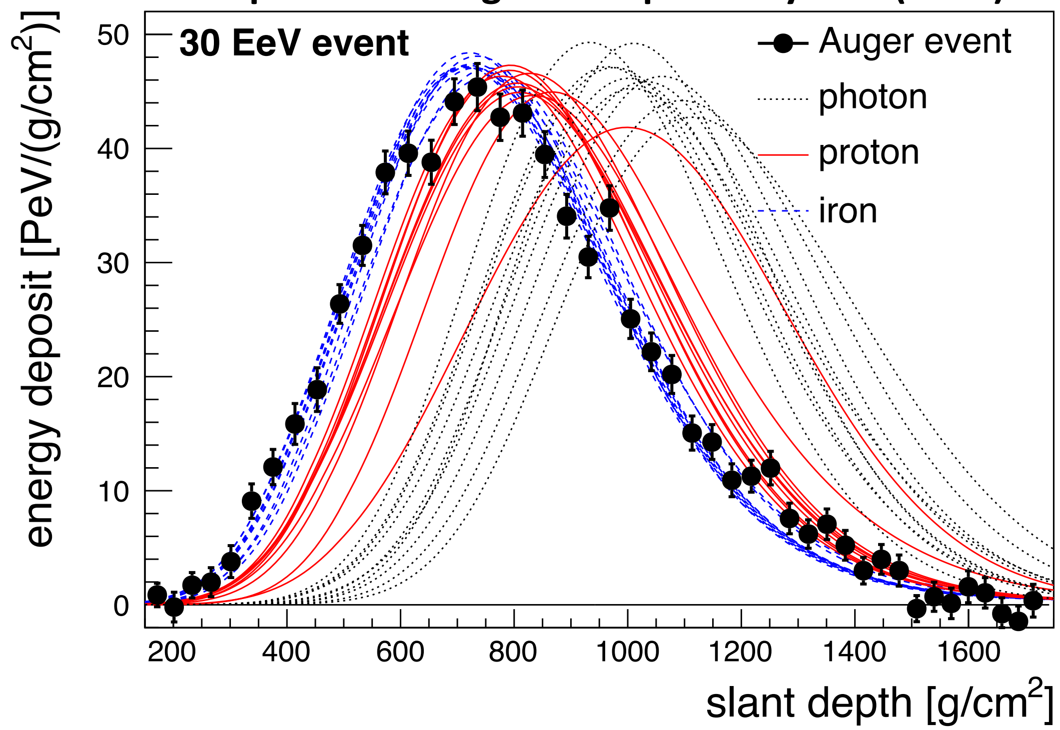
- *Suppression result of E_{max} + GZK?*
- *Expect change in composition towards highest energies*
- ***More observables needed!***

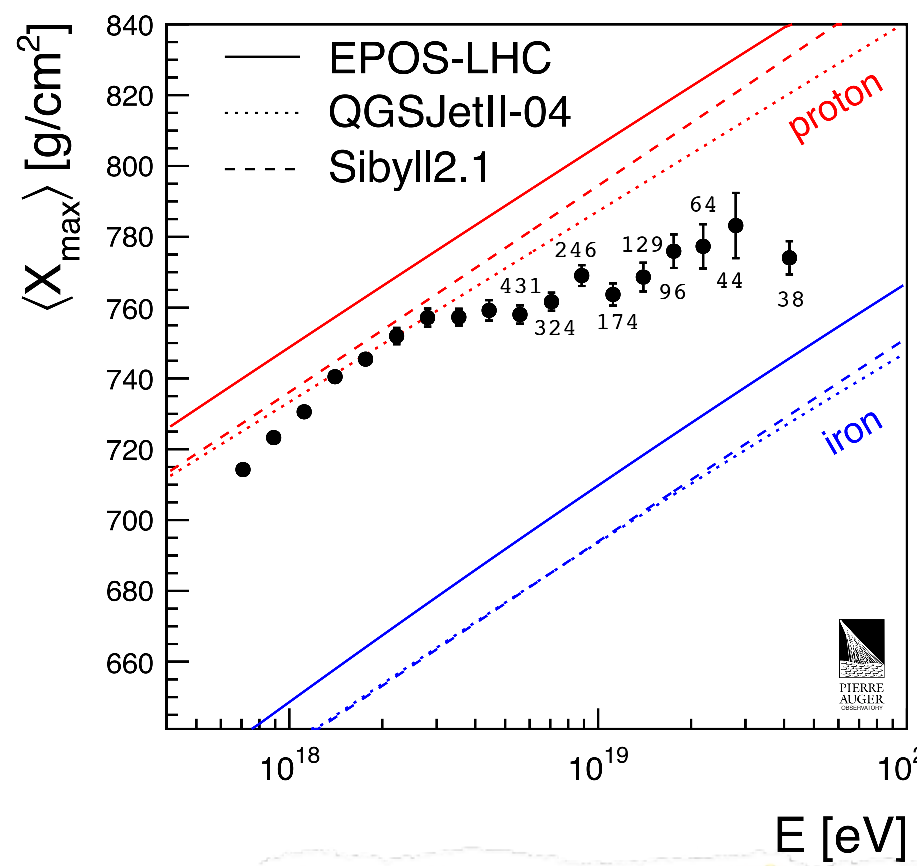
Composition observable

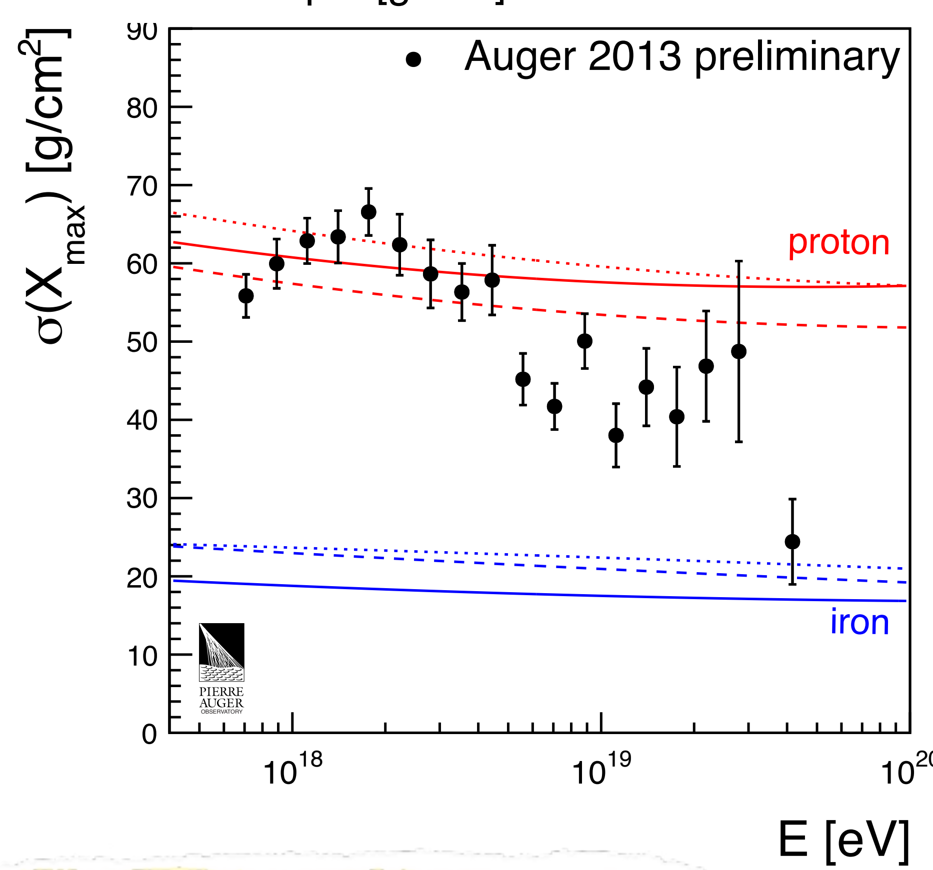
Primary cosmic ray



K.-H. Kampert & M. Unger Astropart. Phys. 35 (2012) 10





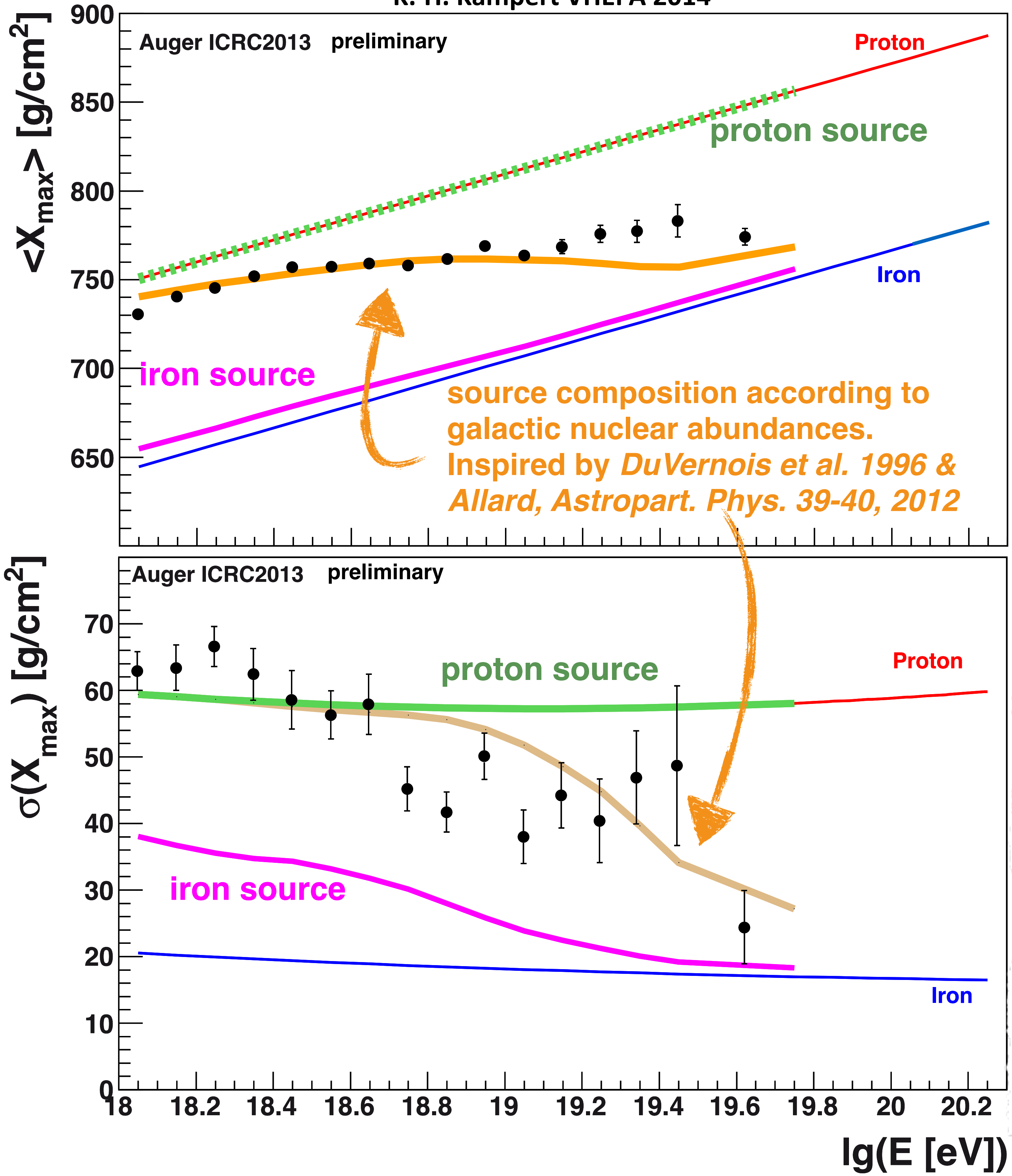


Depth of shower maximum X_{max}

Use composition as additional observable

Example with composition observable

K.-H. Kampert VHEPA 2014



- **In this example:**
  - $E_{max,p} = 10^{18.9}$ eV
    $E_{max,Fe} = 26\ E_{max,p}$
  - Source spectral index = 1.55 (very hard)
  - No source evolution

- **Here limiting energy of sources combined with GZK describes composition data best**
- **Additional (proton) component may be needed to describe composition at highes energies**
- **Pure proton composition can not describe Auger data**

Many other papers on this subject

Astroparticle Physics 39–40 (2012) 33–43
Astroparticle Physics
journal homepage: www.elsevier.com/locate/astropart

Extragalactic propagation of ultrahigh energy cosmic-rays

Denis Allard
Laboratoire Astroparticule et Cosmologie (APC), Université Paris 7/CNRS, 10 rue A. Domon et L. Duquet, 75205 Paris Cedex 13, France

Astroparticle Physics 54, 48 (2014)
Astroparticle Physics
journal homepage: www.elsevier.com/locate/astropart

UHECR composition models

Andrew M. Taylor
Dublin Institute for Advanced Studies, 31 Fitzwilliam Place, Dublin 2, Ireland

Astroparticle Physics 33 (2010) 151–159
Astroparticle Physics
journal homepage: www.elsevier.com/locate/astropart

On the heavy chemical composition of the ultra-high energy cosmic rays

Dan Hooper [a,b], Andrew M. Taylor [c,d,*]

PHYSICAL REVIEW D 84, 105007 (2011)

Need for a local source of ultrahigh-energy cosmic-ray nuclei

Andrew M. Taylor,[1] Markus Ahlers,[2] and Felix A. Aharonian[3,4]

Frontiers of Physics
December 2013, Volume 8, Issue 6, pp 748-758

Cosmic ray energy spectrum from measurements of air sh...

T. K. Gaisser, T. Stanev, S. Tilav

Ultra high energy cosmic rays: implications of Auger data for source spectra and chemical composition

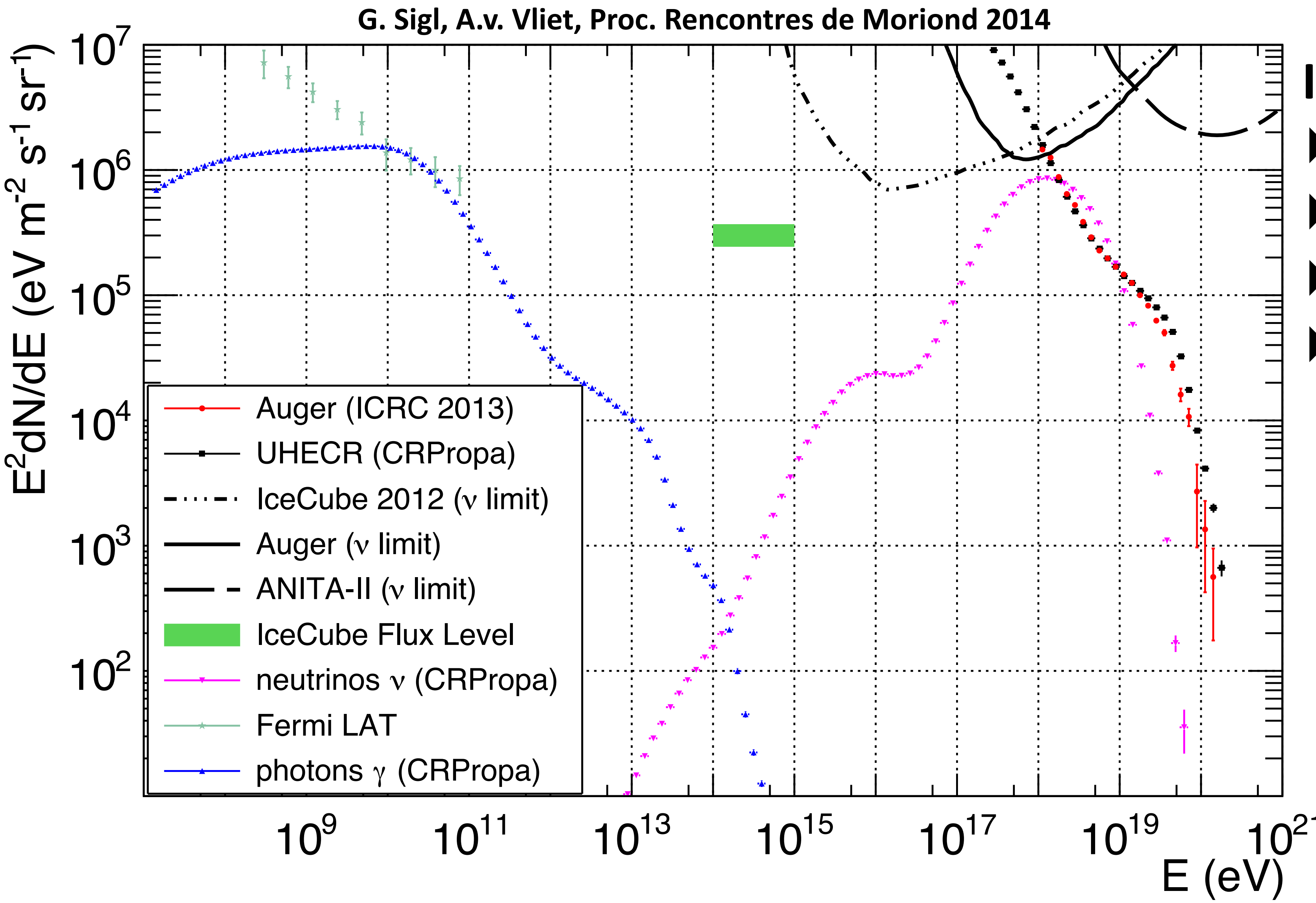
Subm. to JCAP 2013

Bottom line:

- **Hard source spectral index** needed, unless **nearby source** (additional component) is assumed
- **Too early to draw decisive conclusions** (large parameter space and big uncertainties)

Multi-messenger approach

- IceCube PeV neutrino events from extragalactic UHECRs?



In this example:

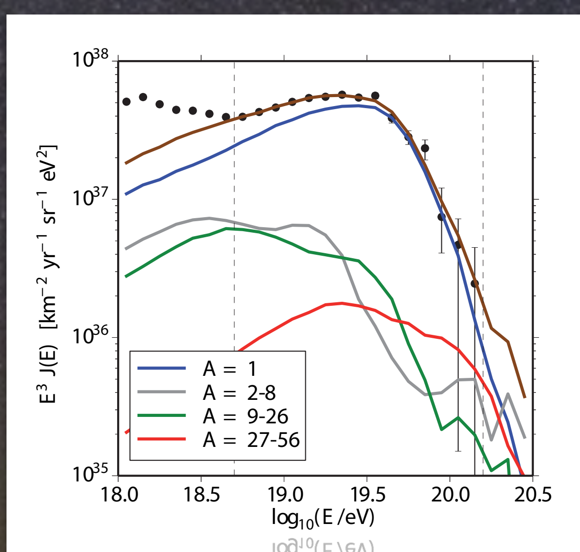
- pure proton injection
- source spectral index 2.2
- E_{max} = 200 EeV
- Relatively strong source evolution model

- Difficult to interpret IceCube events in terms of cosmogenic neutrino flux
- Gamma ray flux of the order of Fermi diffuse level

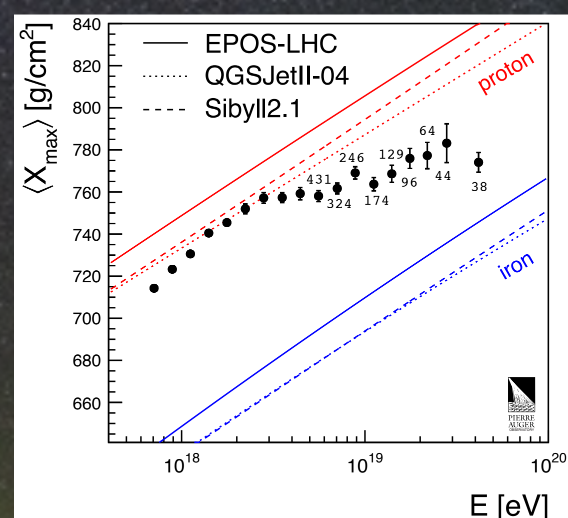
Conclusion

- Propagation of UHECRs plays an important role constraining astrophysical parameters
- Modern simulation tools enable 1D and 3D simulations in structured (extra)galactic environments including secondaries
- Too early to draw decisive conclusions on astrophysical parameters
  ➡ Use more observables and experimental data

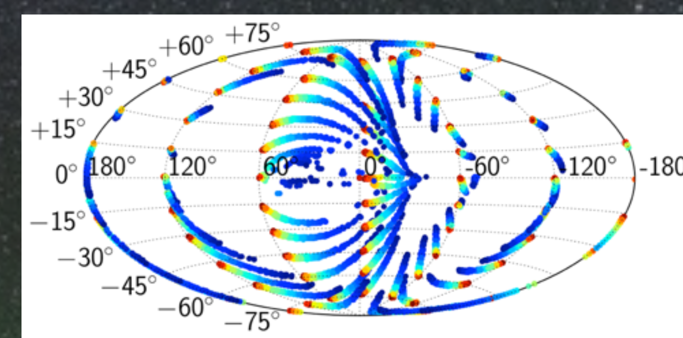
spectrum



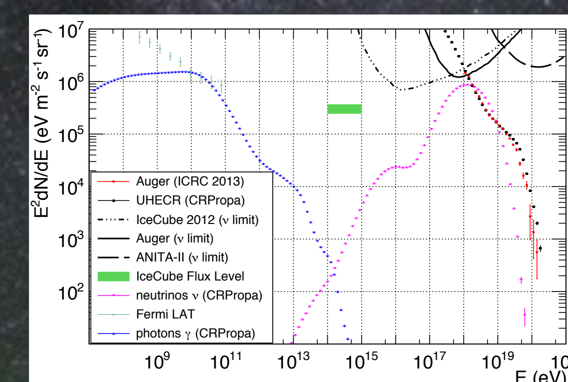
composition



arrival direction



photons, neutrinos



- Secondaries as messengers may further constrain astrophysical parameters, e.g. by comparing with TeV observations
- Vibrant field of MC / data comparison. More results to come…

… the future is bright