Numerical Modeling of Ultra-High Energy Cosmic Ray Propagation

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HELMHOLTZ | GEMEINSCHAFT

Allianz für Astroteilchenphysik

RWTH AACHEN UNIVERSITY

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DER FORSCHUNG | DER LEHRE | DER BILDUNG

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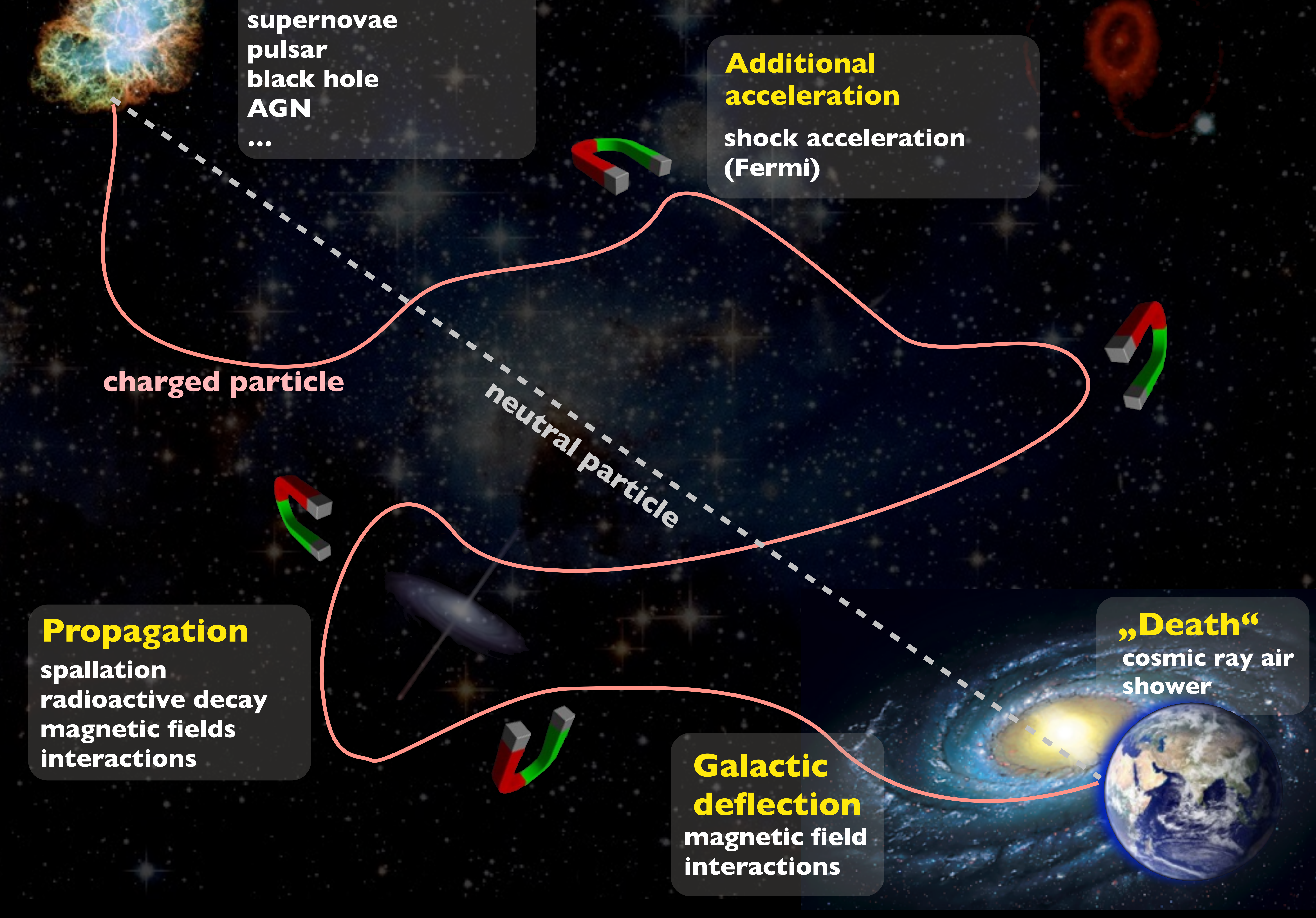
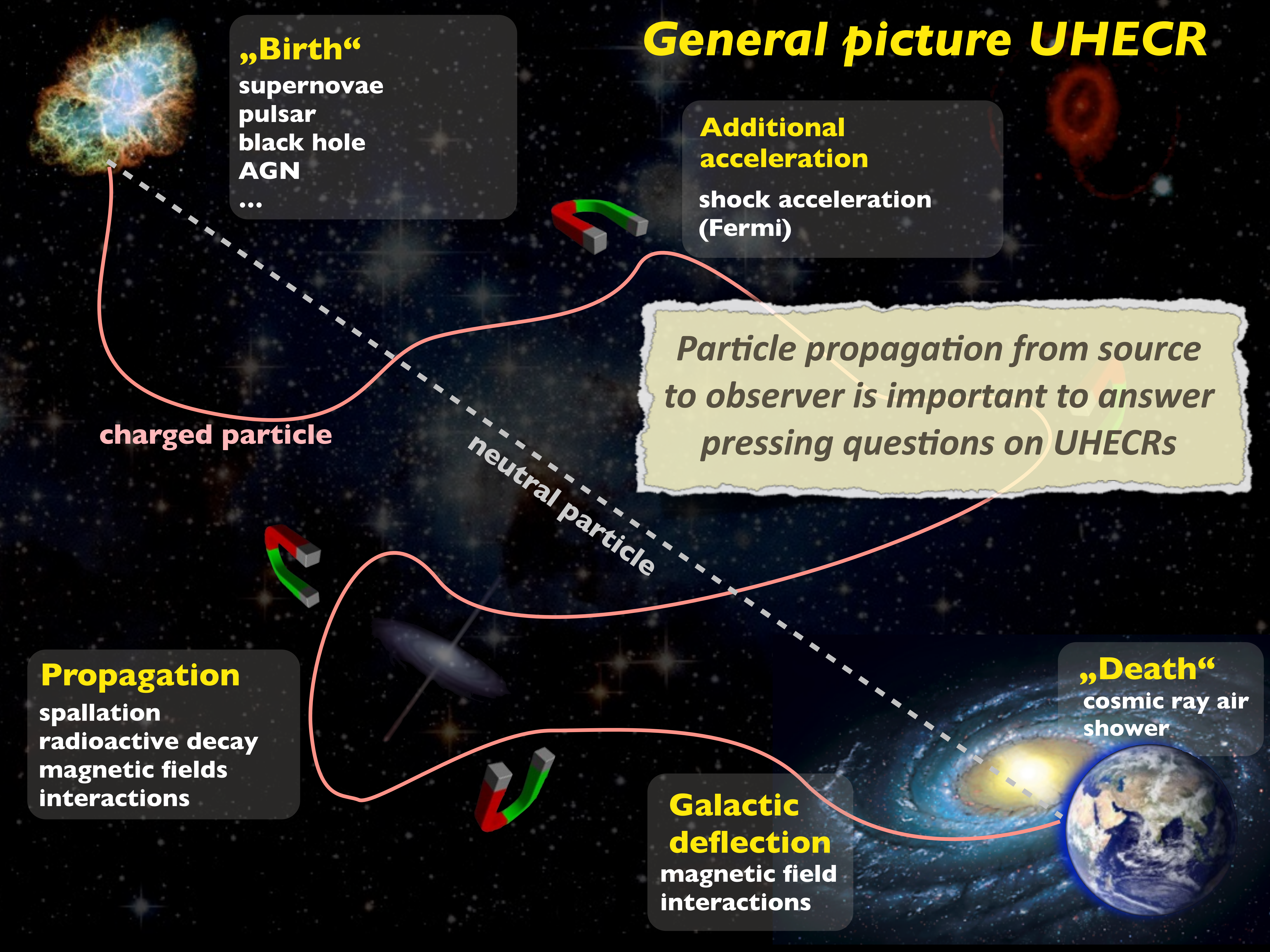
Astroteilchenphysik

Großgeräte der physikalischen Grundlagenforschung

General picture UHECR



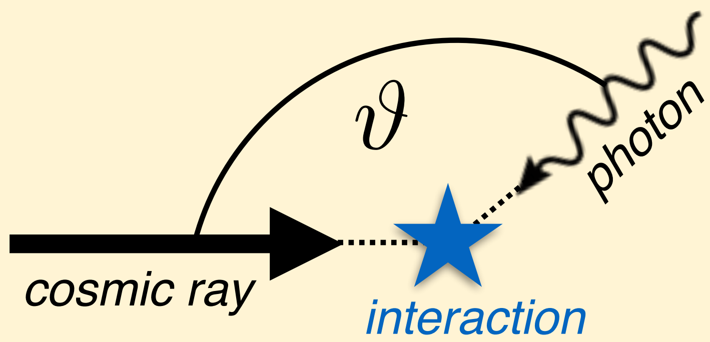

General picture UHECR
„Birth“
supernovae
pulsar
black hole
AGN
...
Additional acceleration
shock acceleration (Fermi)
Particle propagation from source to observer is important to answer pressing questions on UHECRs
charged particle
neutral particle
Propagation
spallation
radioactive decay
magnetic fields
interactions
Galactic deflection
magnetic field
interactions
„Death“
cosmic ray air shower

Propagation features

Extra-galactic energy density

- Cosmic rays can interact with background photons:

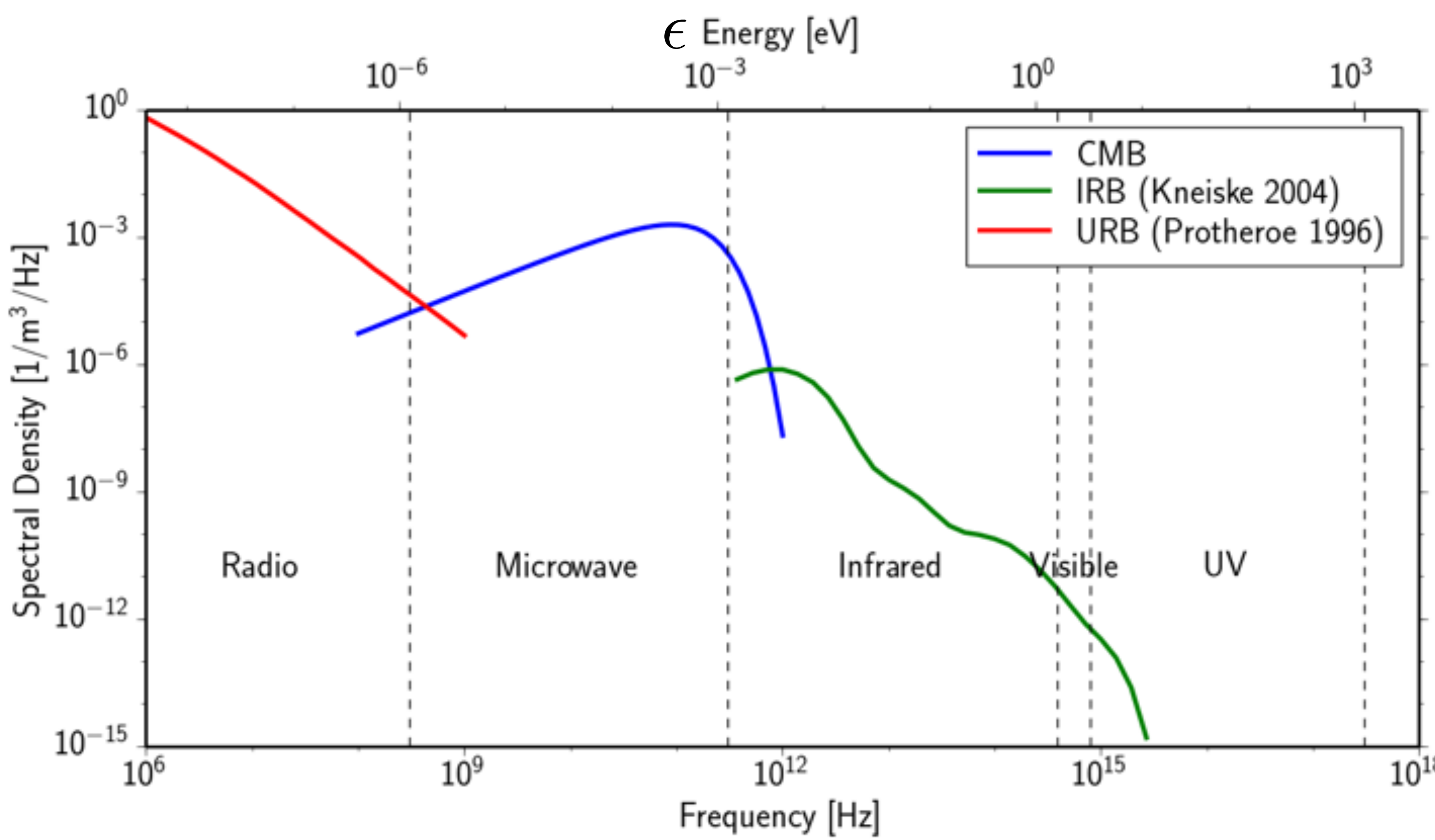
$$\Gamma = \frac{E}{m}$$



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

photon energy in nucleus rest frame

ϵ' is the relevant energy scale for interaction

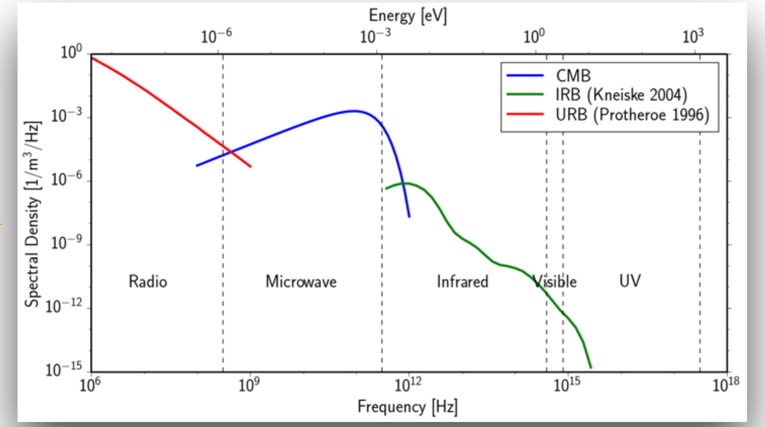


Interactions

- **Pion production**

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

$$N + \gamma \rightarrow N + \pi$$



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

$$p + \gamma \rightarrow \Delta^+ \rightarrow \begin{cases} n + \pi^+ & \text{with branching ratio } 1/3 \\ p + \pi^0 & \text{with branching ratio } 2/3 \end{cases}$$

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

$\pi^0 \rightarrow \gamma + \gamma$ — main channel of high energy photons by hadronic cosmic rays

GZK-effect

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

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

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

Interactions

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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

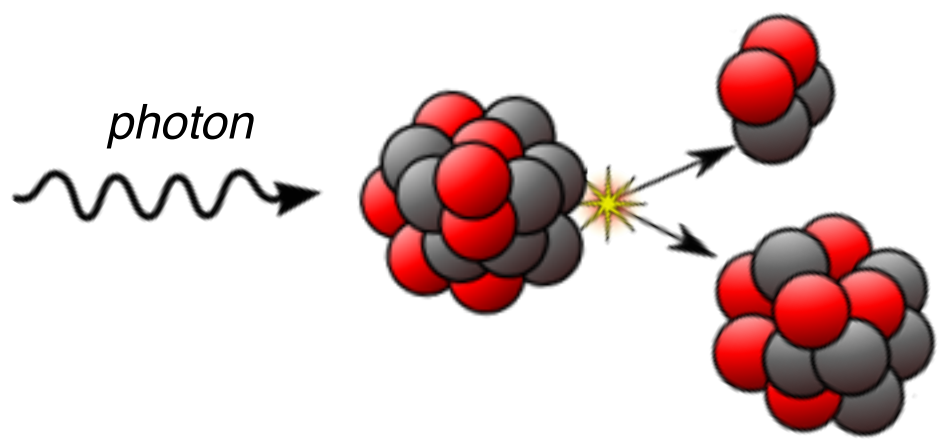
with the threshold energy

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

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

- **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:

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

emission rate of *i* nucleons from a nucleus of mass *A*

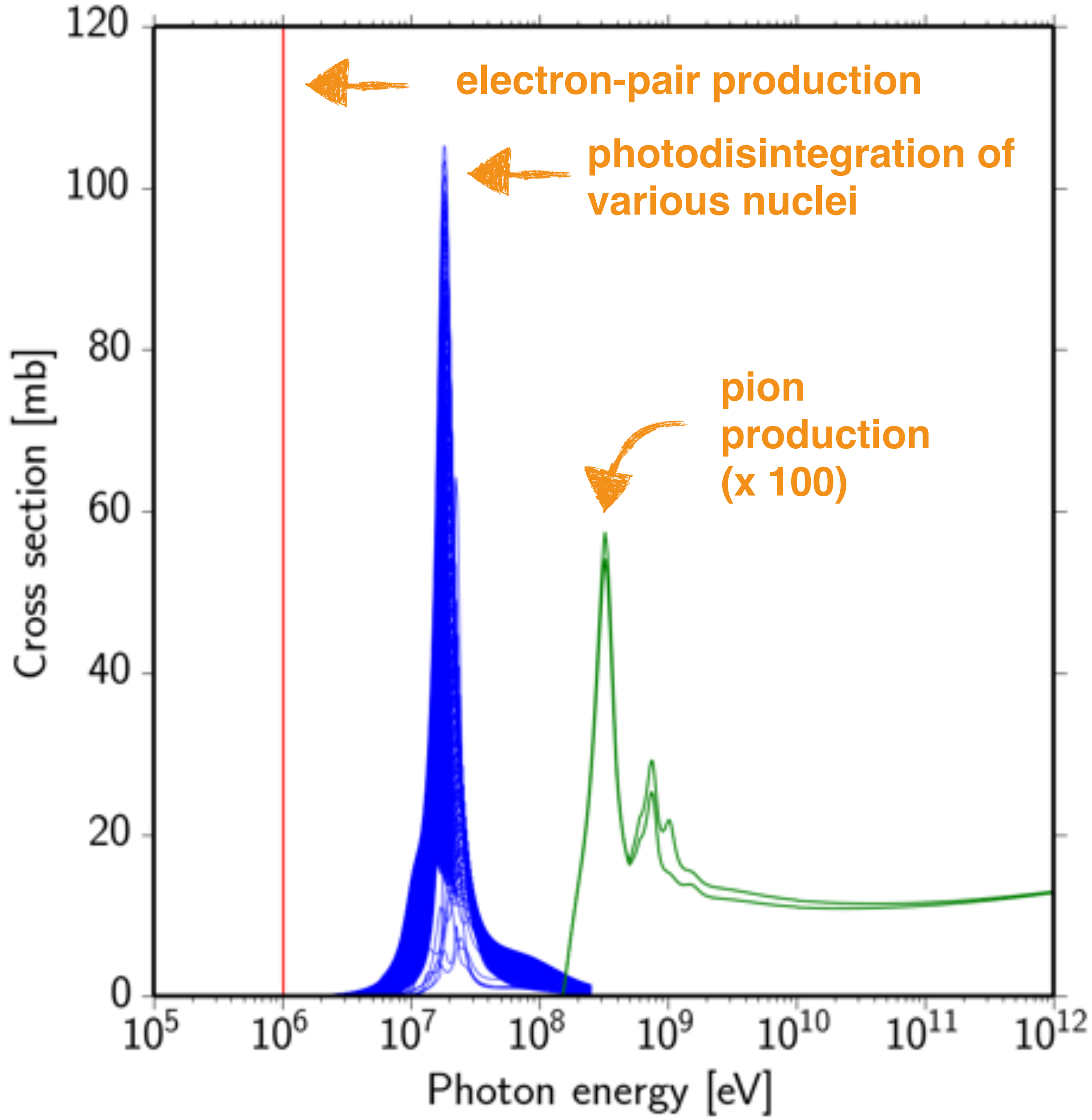
Interaction rate

Interaction rate can be calculated as

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

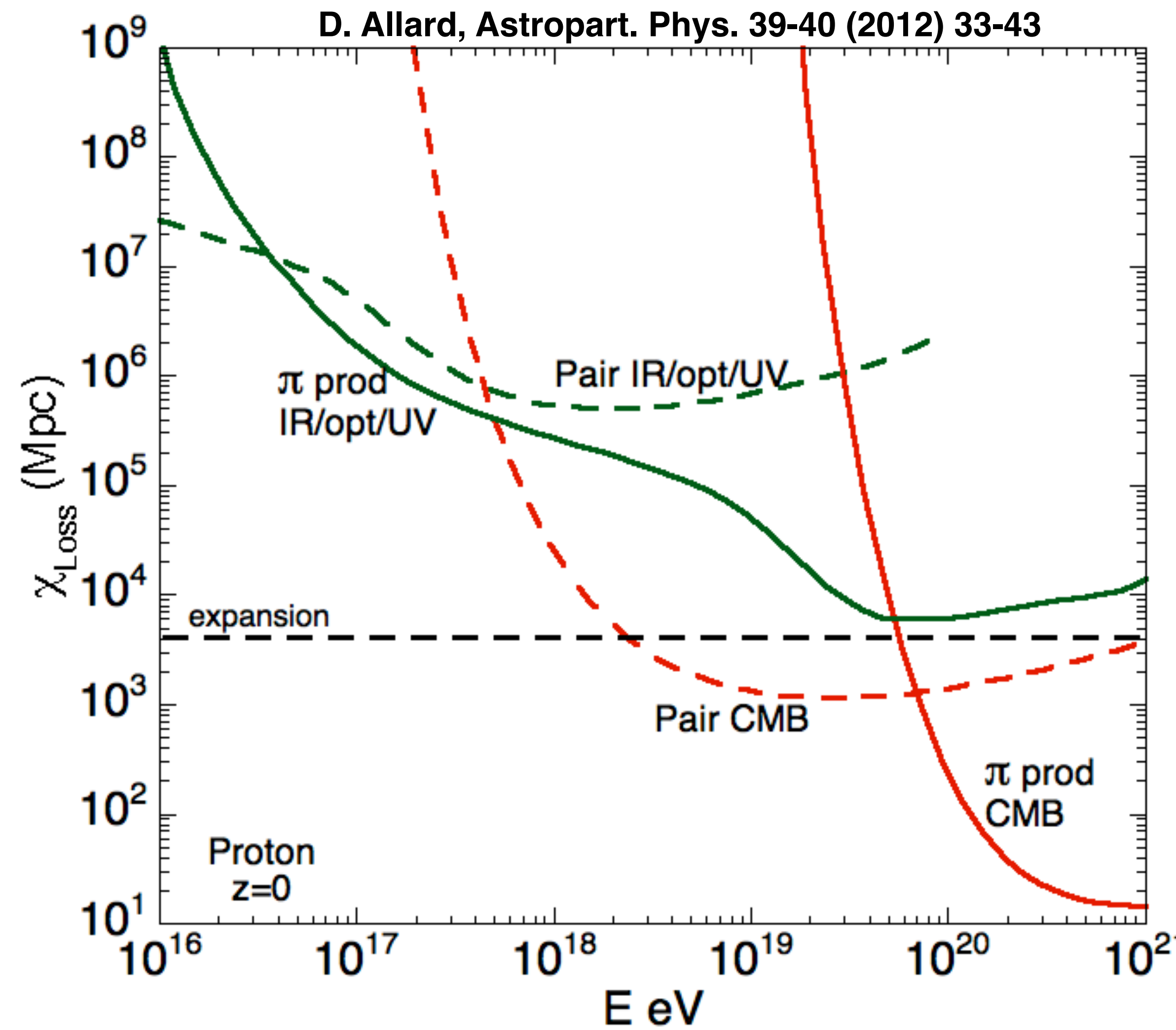
photon number density

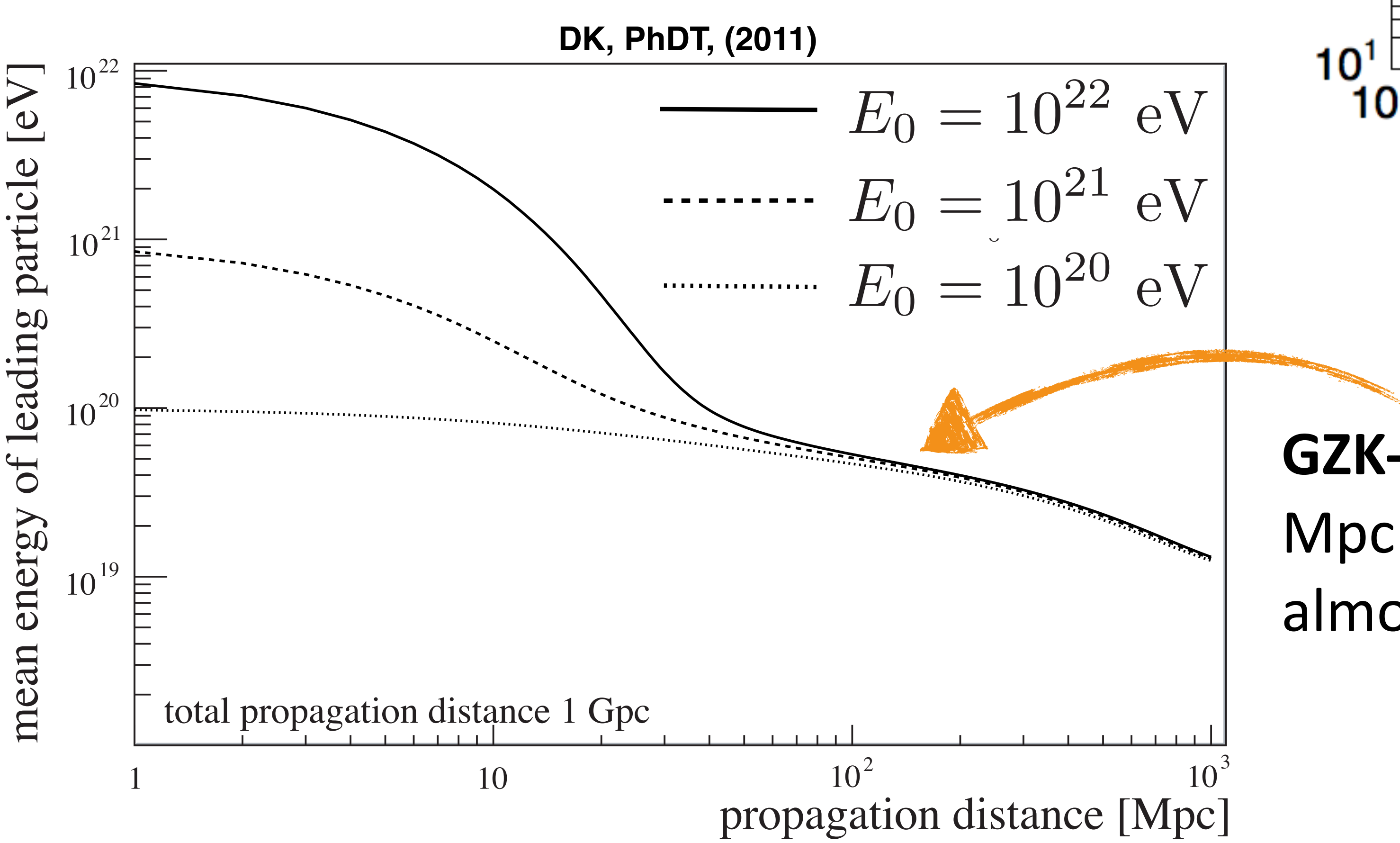
collision angle averaged cross section



Attenuation length for protons

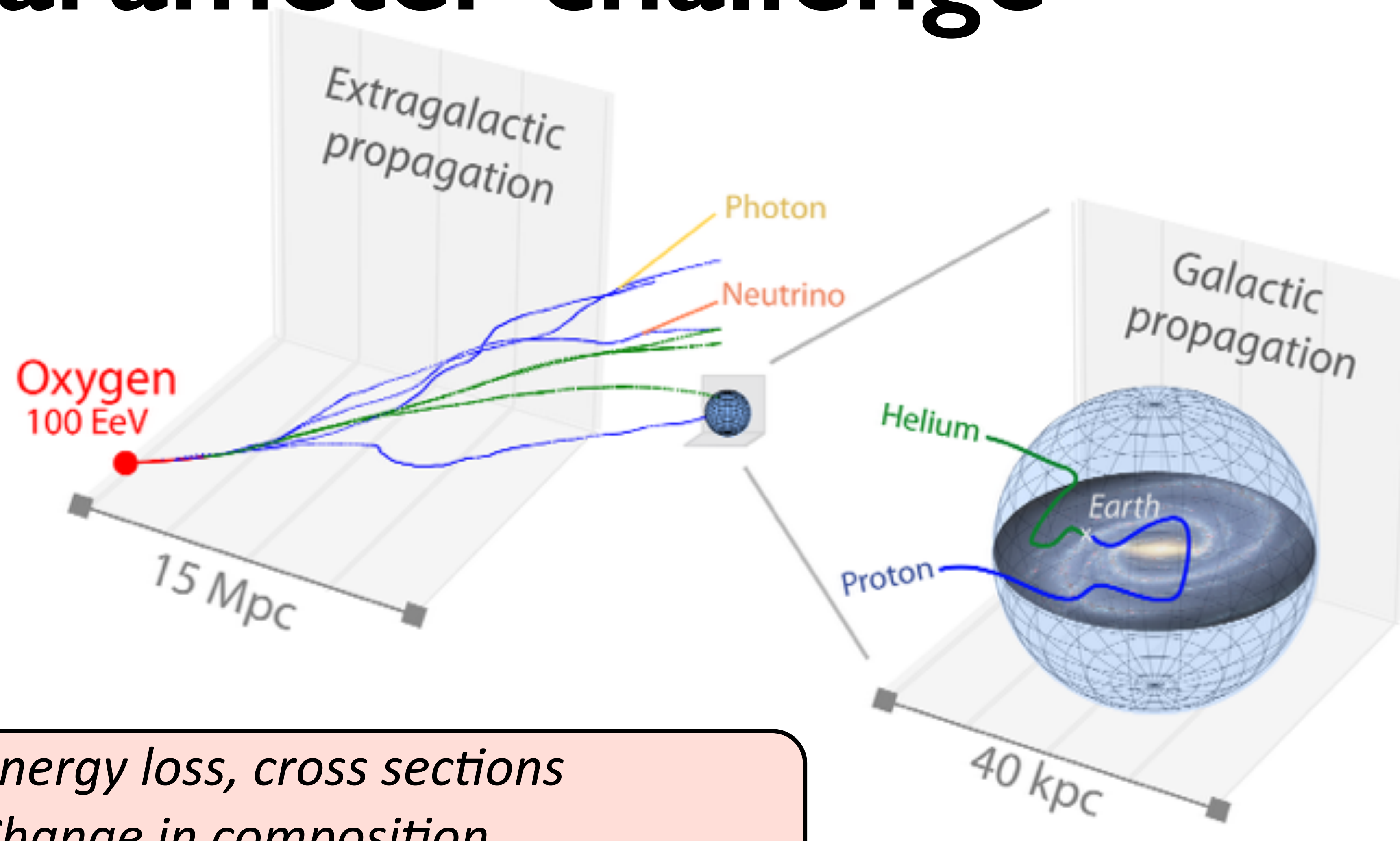
- **Low energies:**
  energy loss dominated by expansion of the universe
- **Intermediate energies:**
  Most important loss length is pair production on CMB
- **High energies:**
  Most important loss length is pion production on CMB





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

Multiparameter challenge



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

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

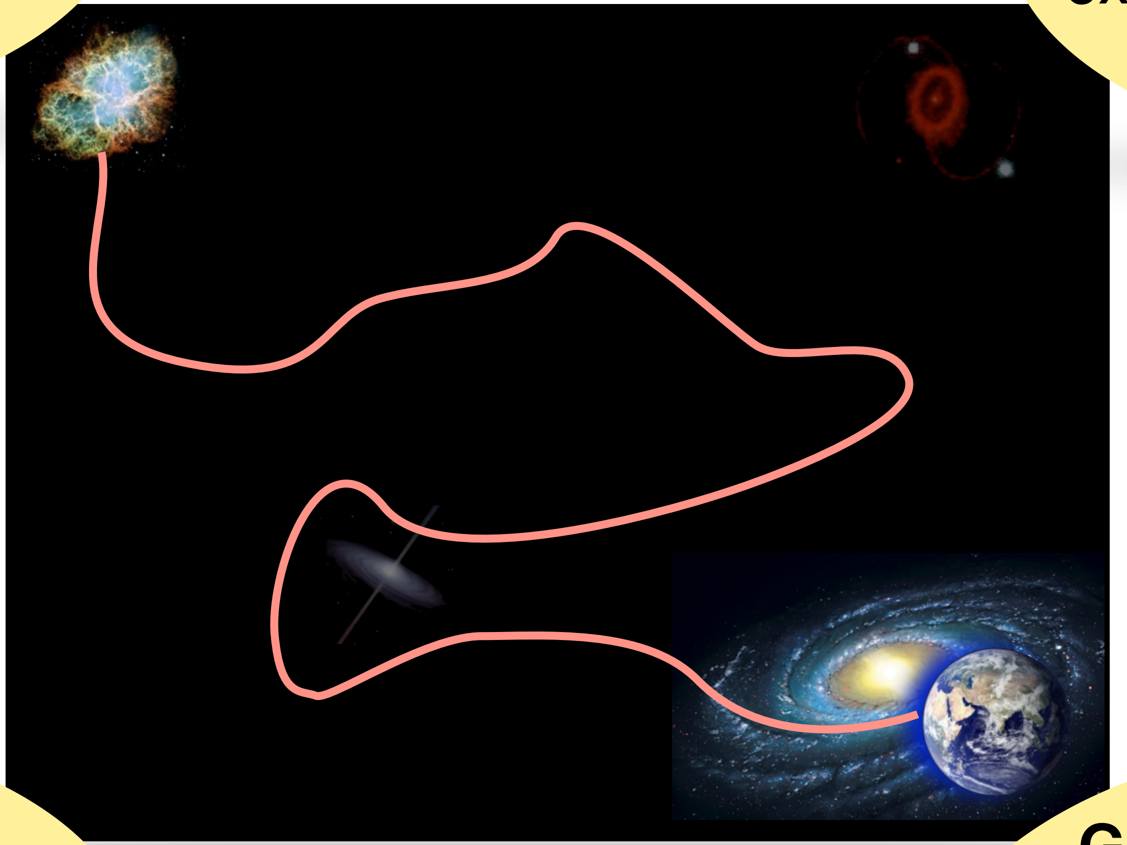
→

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

Simulation Challenge

Flexibility and speed
Large parameter space, large statistics needed, multiple use cases

4D simulations
3D simulations including expansion of the universe



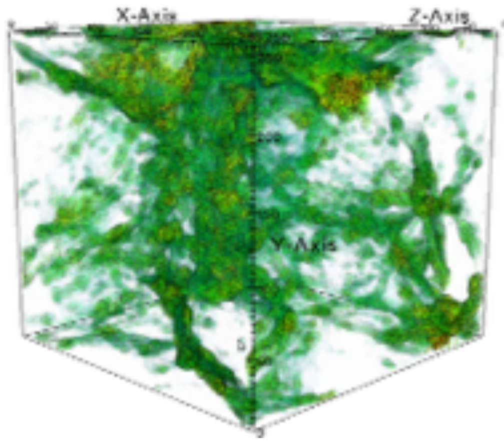
High resolution fields
Large volume, fast lookup

Galactic Propagation
Milky Way tiny (~ 30 kpc) compared to extragalactic distances (~ Mpc) Earth tiny compared to Galaxy

Simulations

- Much progress in recent years

Numerical 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

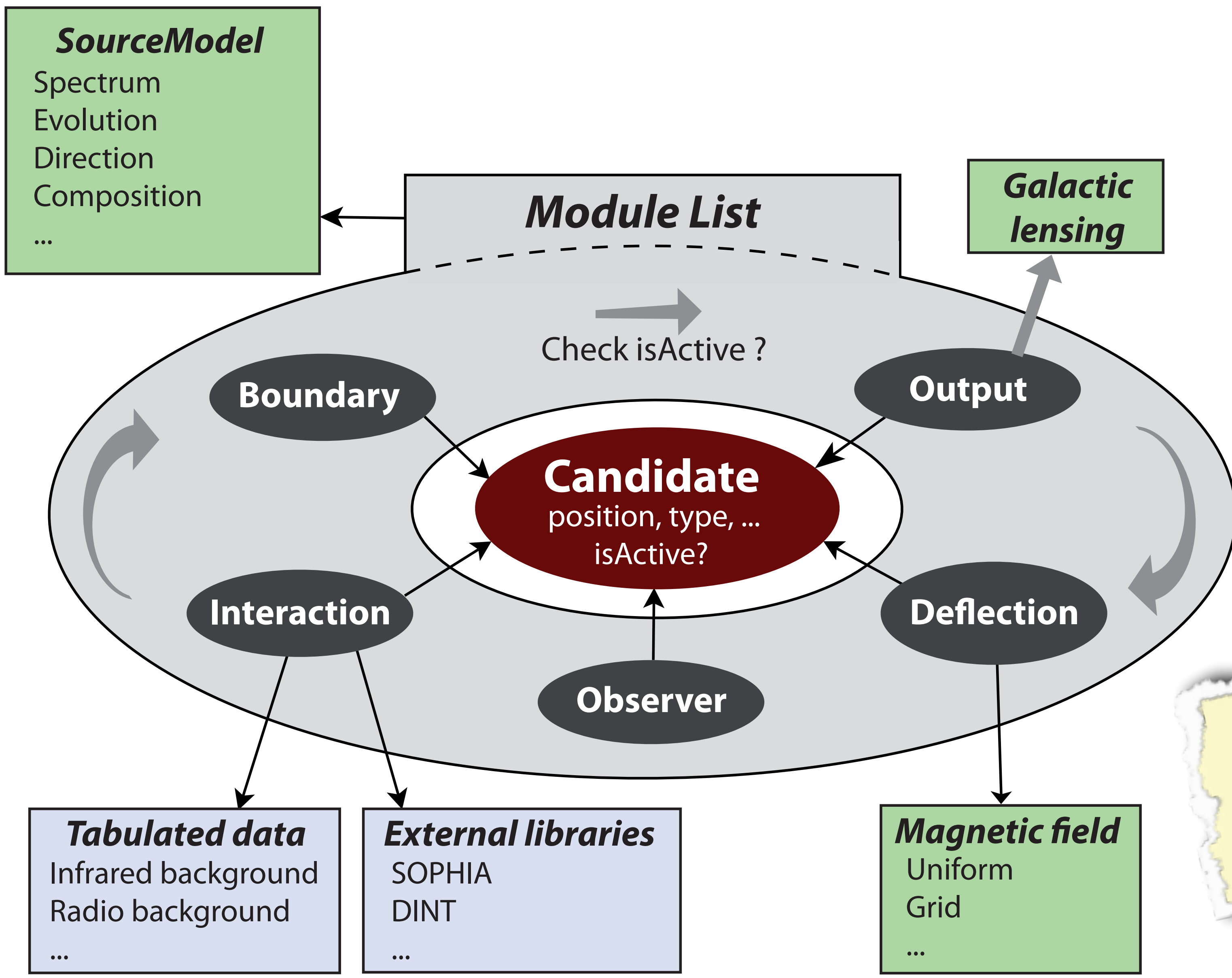
Using high statistic experimental data in combination with sophisticated propagation tools and powerful computing clusters we are entering a **new phase of data / MC comparison**

CRPropa 3

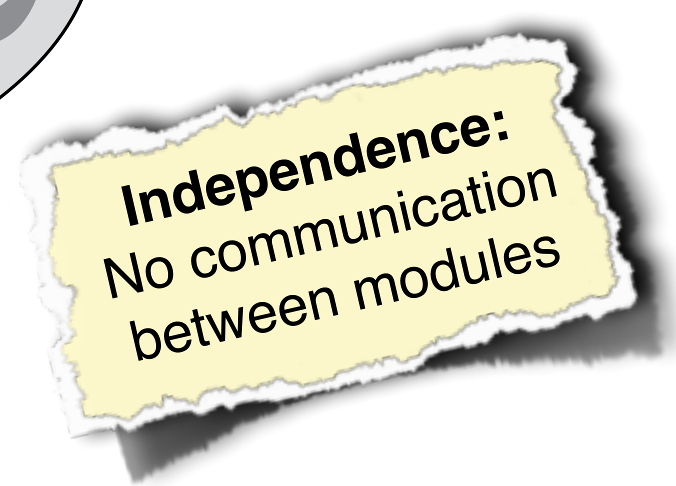
R.A. Batista et al. ICRC 2013
https://crpropa.desy.de

➡ **CRPropa** in a nutshell:

- Publicly available numerical tool to **propagate UHECR nuclei** and its secondaries
- Takes into account **nuclear decay** and interaction with ambient photon fields such as **pion production, photo-disintegration, and pair-production**
- Model deflection of galactic and extra-galactic **magnetic fields**



- **One, three and four dimensional** simulations
- Able to predict **spectra**, **composition** and **arrival direction** of UHECR

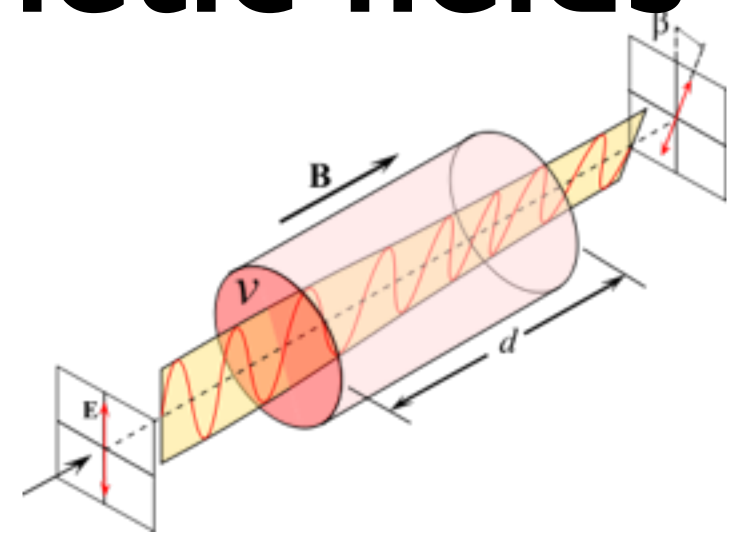


Implement galactic magnetic fields

- 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

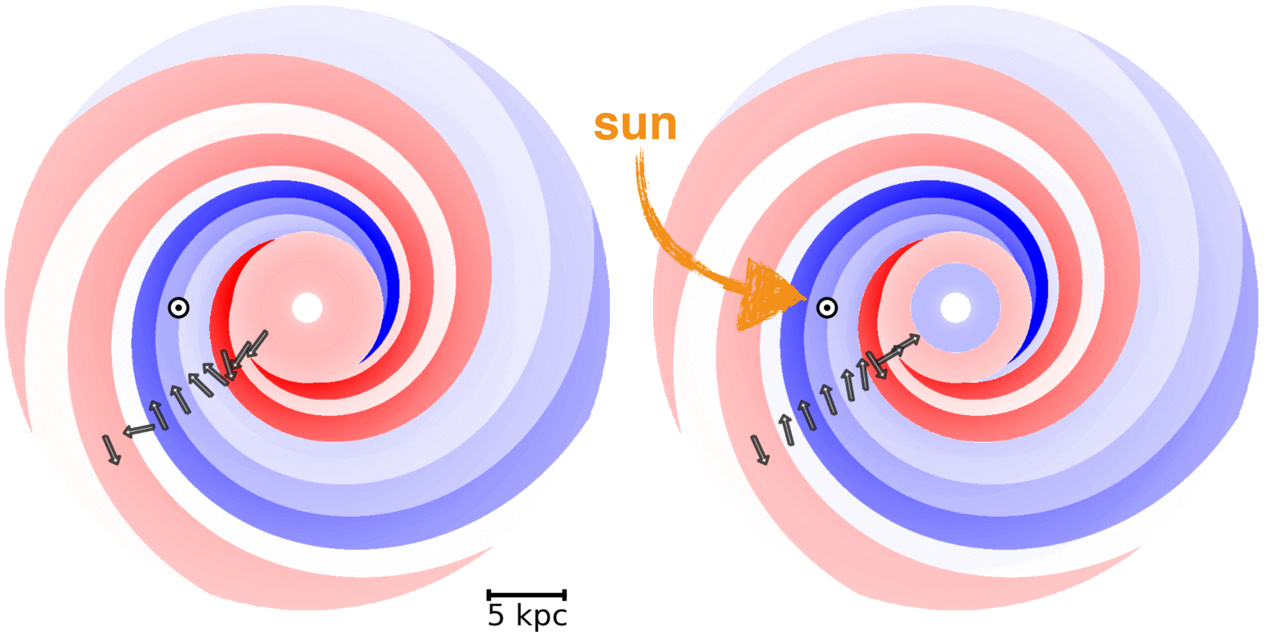
  R. Jansson and G. R. Farrar, ApJL 761 (2012) L11
- Field strength of order micro-Gauss

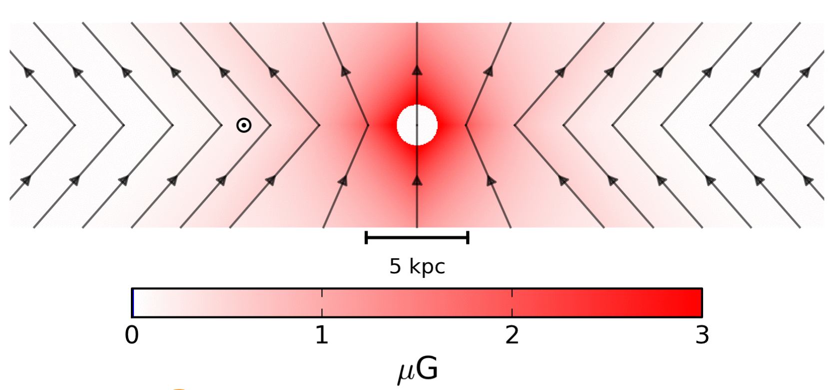


Slices in *x-y* plane

z = 10 pc

z = -10 pc

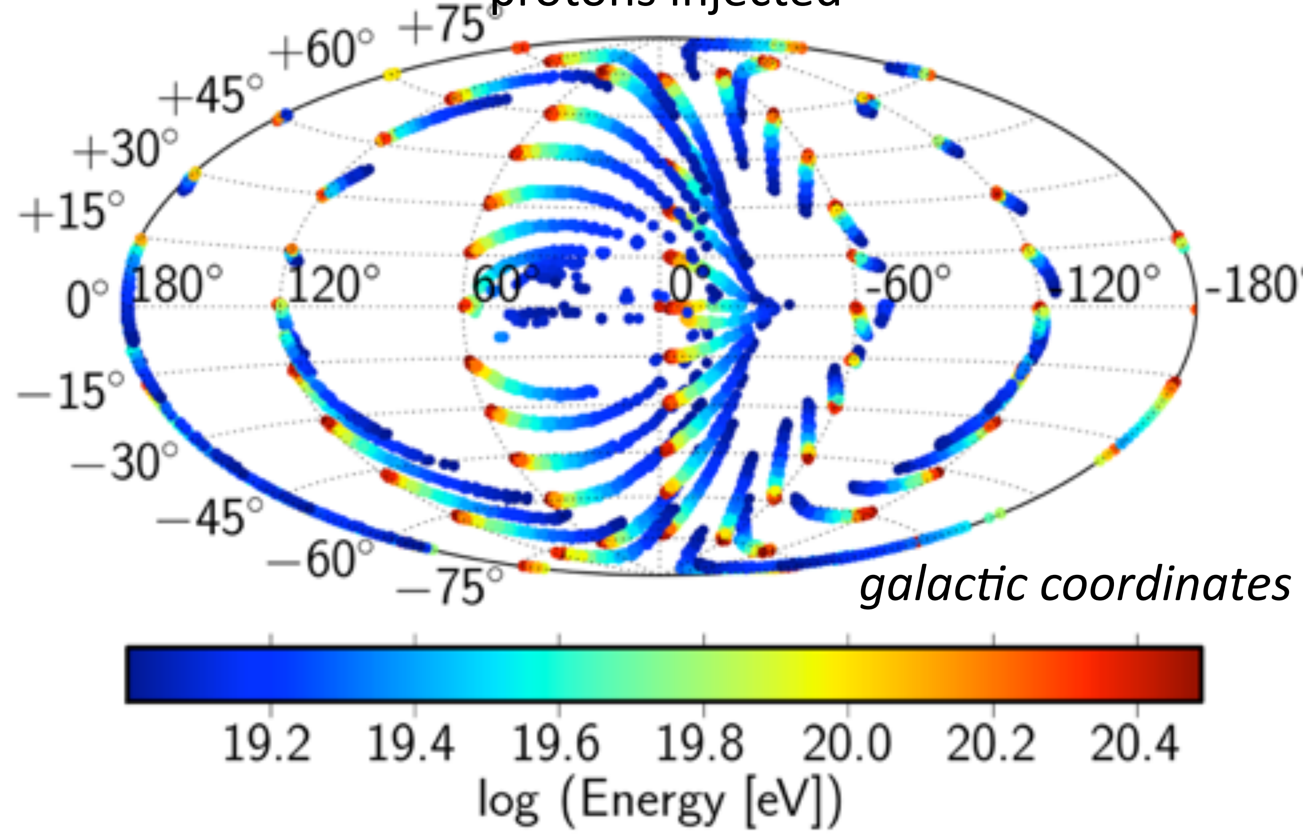




Slices in *x-z* plane

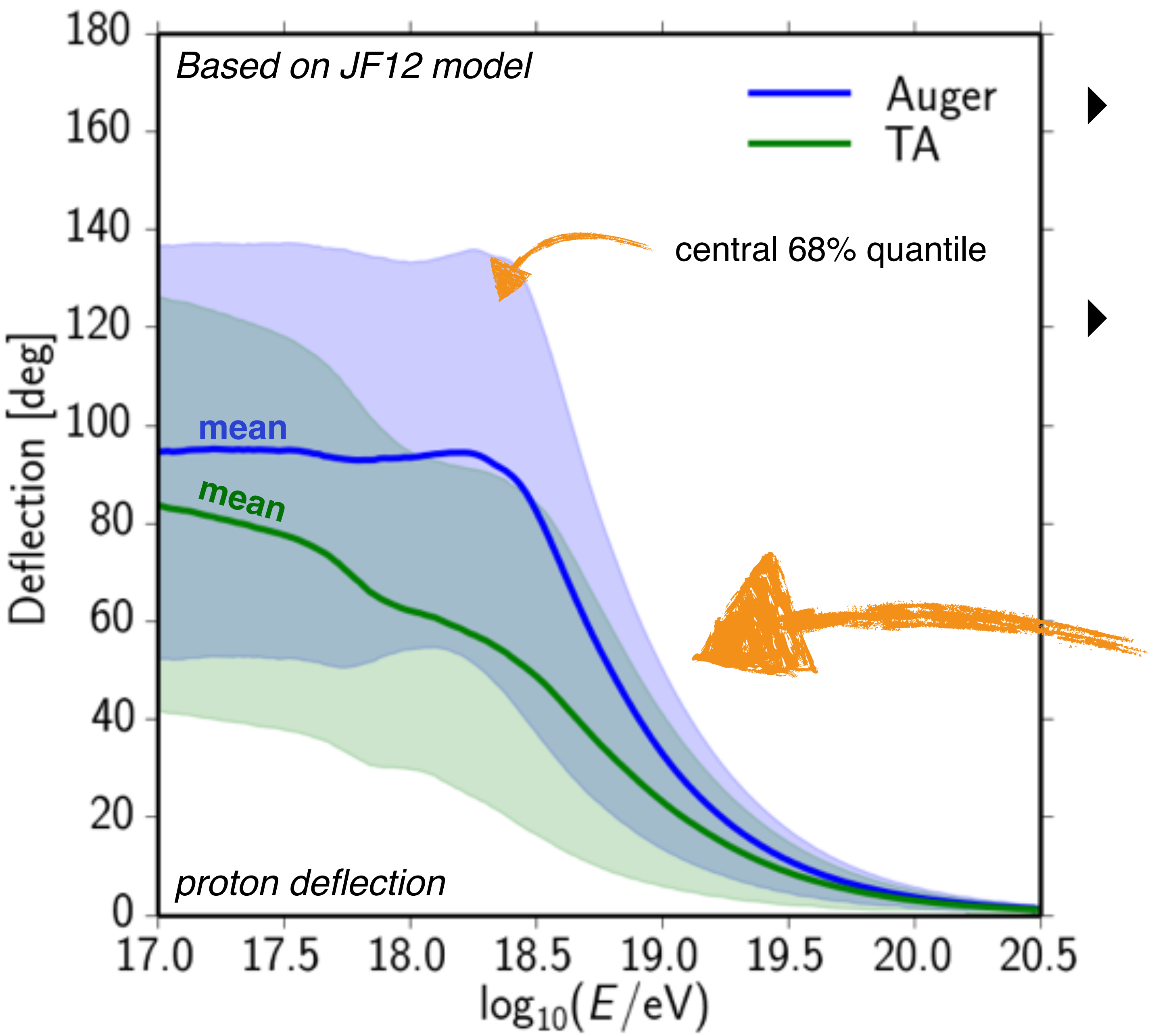
out of the plane component

protons injected



Deflections important in anisotropy studies

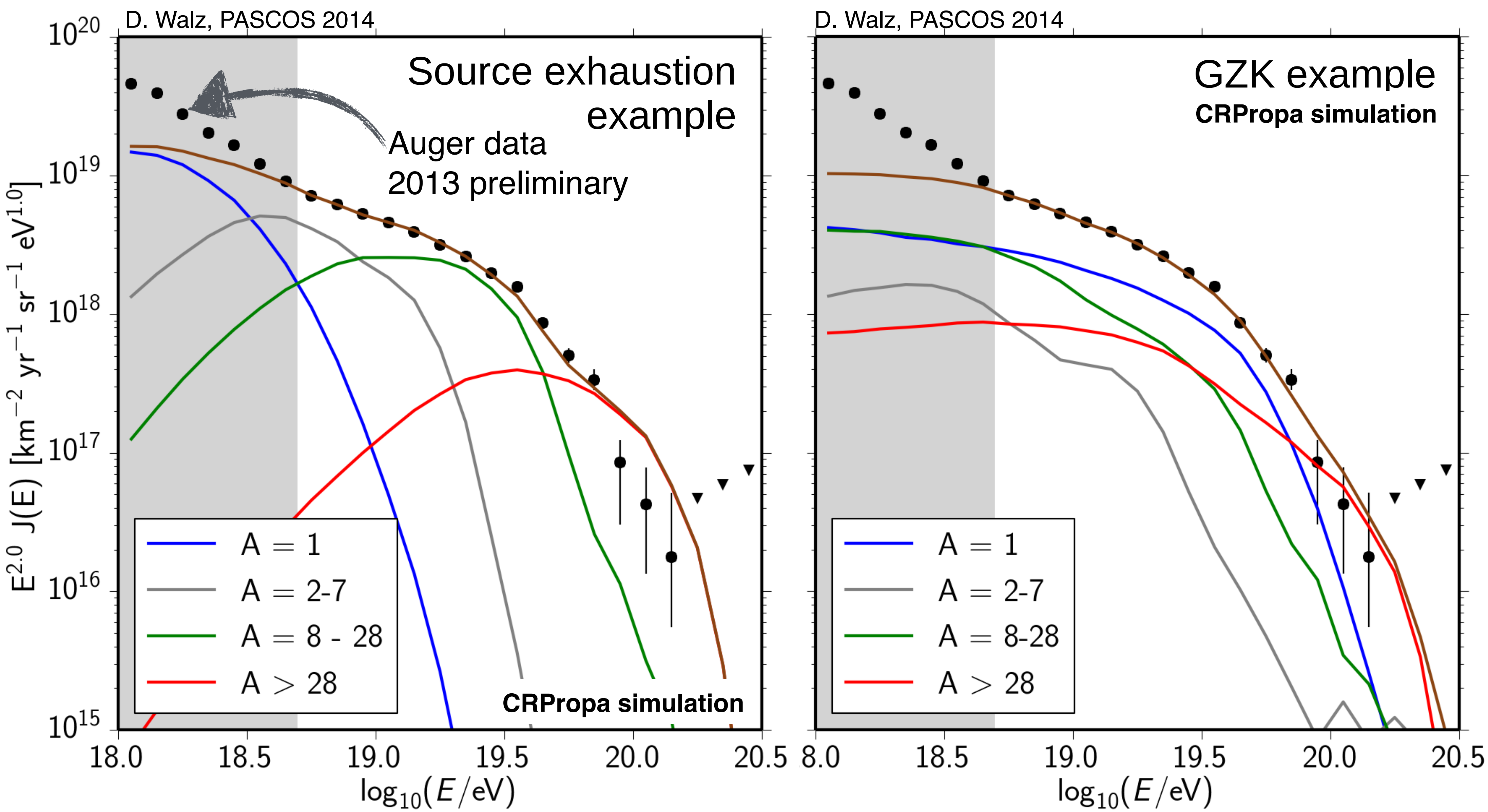
Mean deflection for Auger and TA site



- 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

GZK vs. source exhaustion



- ► Differentiation via measurement of mass composition in suppression region
- ► **Need high statistic data and particle identification!**

3D including EGMF and GMF

Simulation setup:

- **Sources**:
  - Mixed composition injection with relative abundances

H	4	14	56
1	0.5	0.3	0.1

  - Power low injection spectrum

$$\frac{\mathrm{d}N_i}{\mathrm{d}E} \propto A_i^{\alpha-1} E^{-\alpha} e^{-E/(Z_i E_{\max})}$$

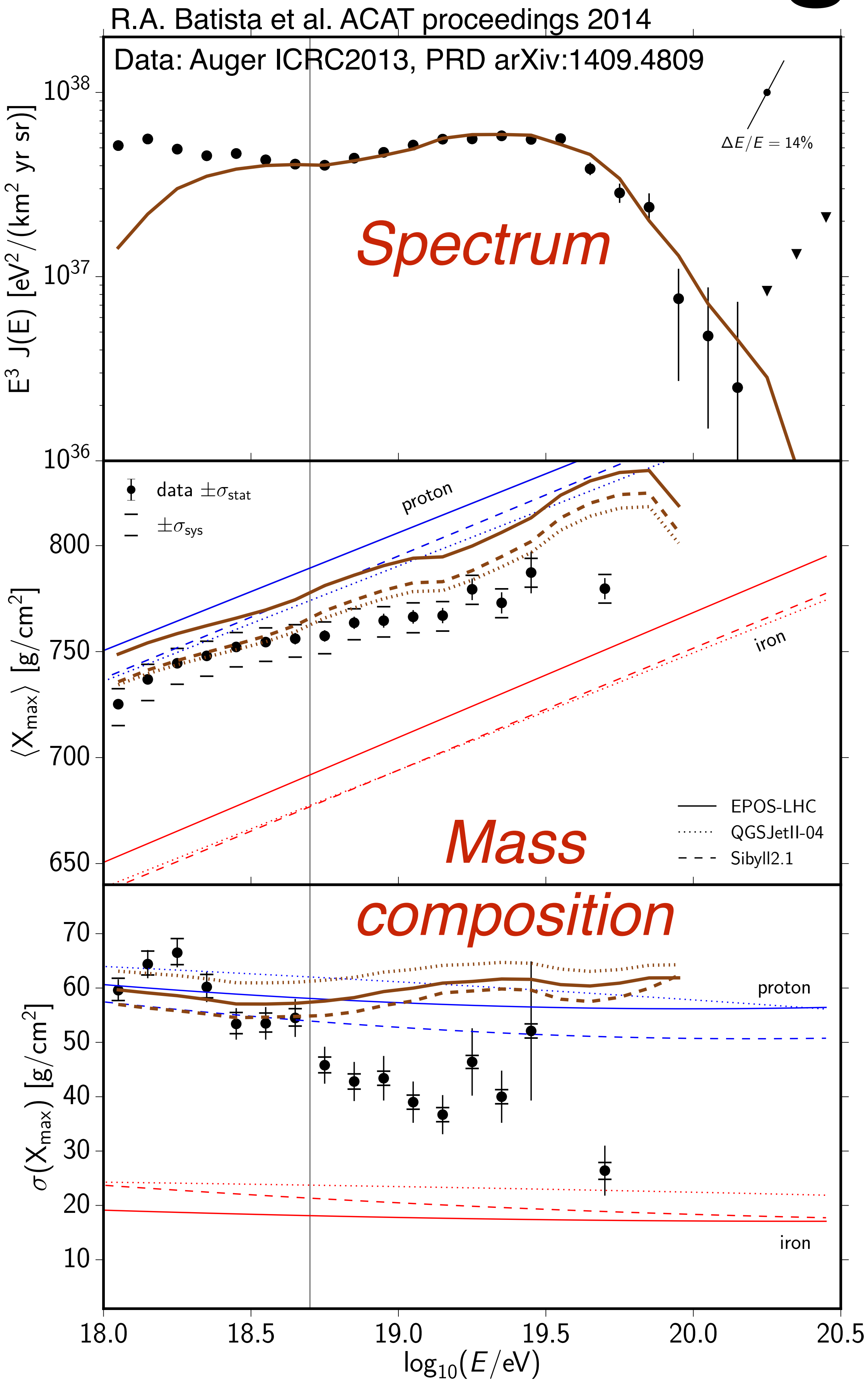
$\alpha = 1.8$

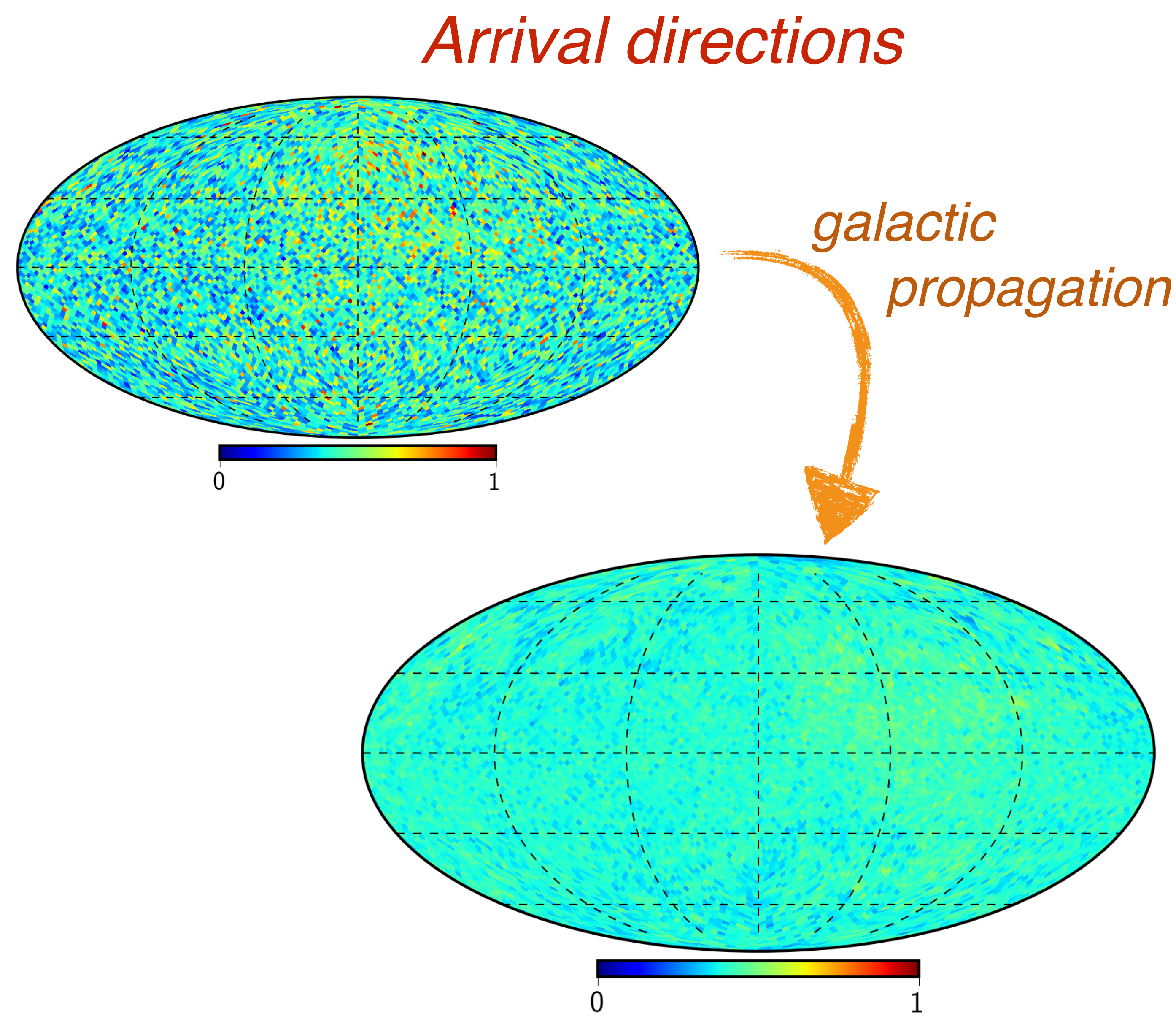
$E_{\max} = 10^{19.8}$ eV

  - Continuous source density following the large-scale-structure (LSS) baryon density of the Dolag et al. simulation up to 4 Gpc distance

- **Magnetic fields**
  - **Extragalactic**: Combination of Dolag et al. field structure and Miniati et al. strength
  - **Galactic**: JF12 model including regular, striated and turbulent component

3D including EGMF and GMF

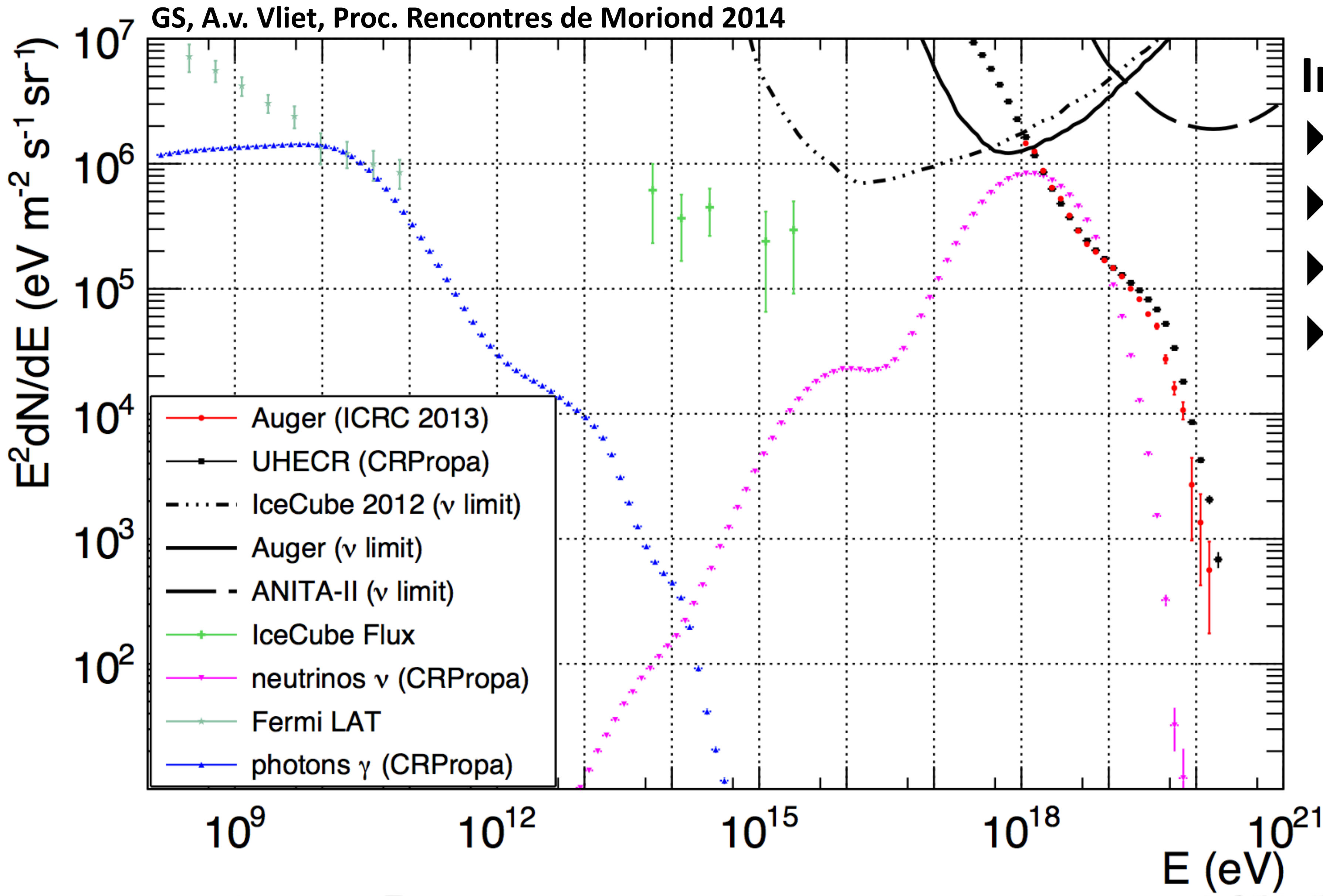




- Reasonable fit to **spectrum** above $10^{18.7}$ eV
- Measured **mass** composition not reproduced
- Small scale **anisotropy** decreases but still anisotropic features.

Multi-messenger approach

- IceCube PeV neutrino events from extragalactic UHECRs?



In this example:

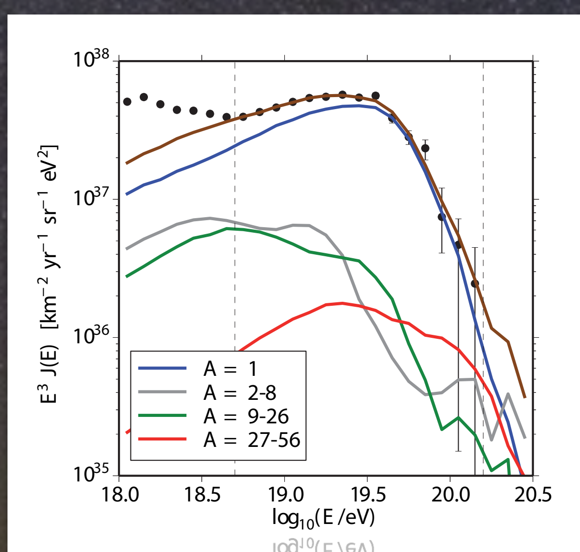
- pure proton injection
- source spectral index 2.2
- E_{max} = 200 EeV
- Relatively strong source evolution model

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

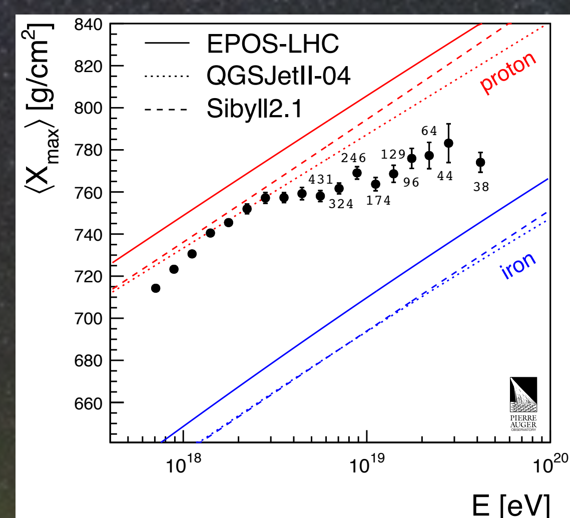
Conclusion

- Numerical propagation of UHECRs plays an important role constraining astrophysical parameters
- Modern simulation tools enable 1D, 3D and 4D simulations in structured (extra)galactic environments including secondaries
- Too early to draw decisive conclusions on astrophysical parameters
  ➡ Use more observables and more experimental data

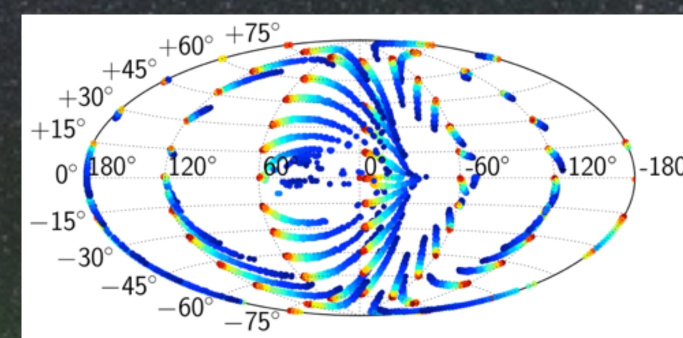
spectrum



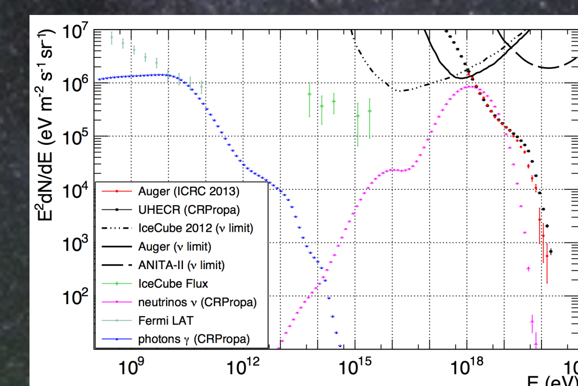
composition



arrival direction



photons, neutrinos

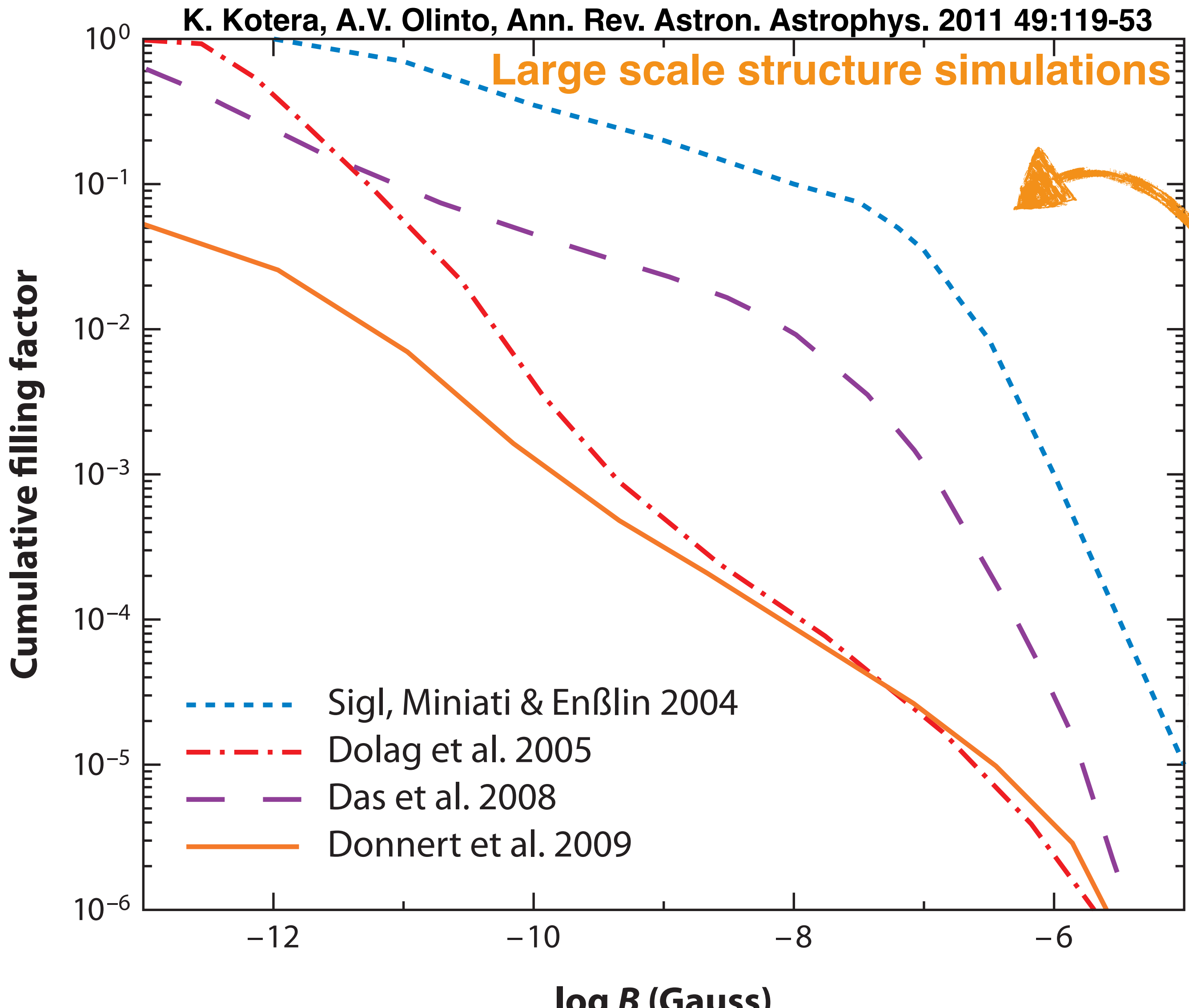


- Secondaries as messengers may further constrain astrophysical parameters, e.g. by comparing with TeV observations
- Vibrant field of MC / data comparison. More results to come…

Backup...

Extragalactic magnetic fields

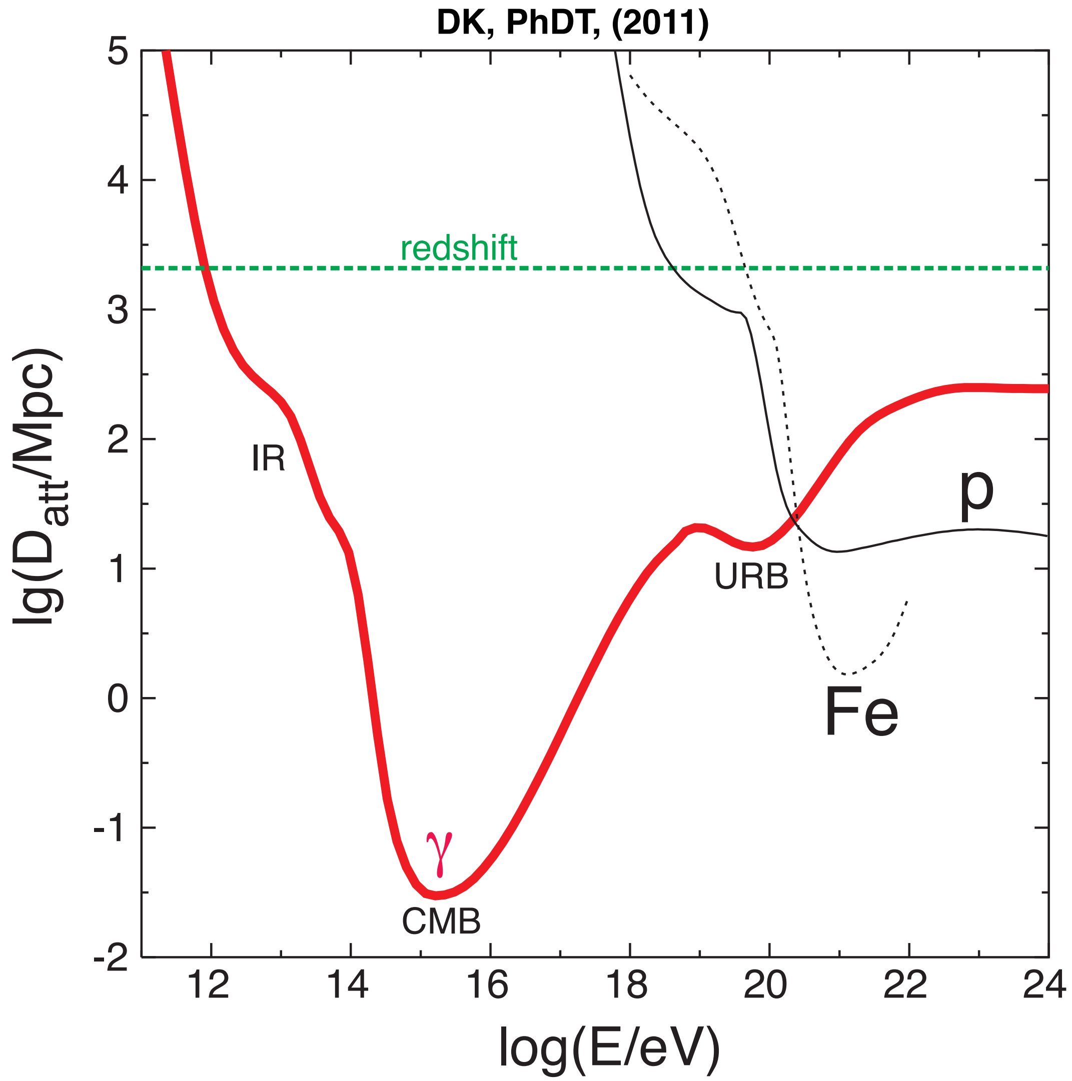
- **Some words of caution**: **Extragalactic** magnetic fields are currently poorly constrained.
- Their origin is not well understood (primordial Universe, magnetic pollution from astrophysical sources, e.g. jets from radio galaxies, …)
- Typical strength of the field varies:
  - **1-40 μG** with coherence 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

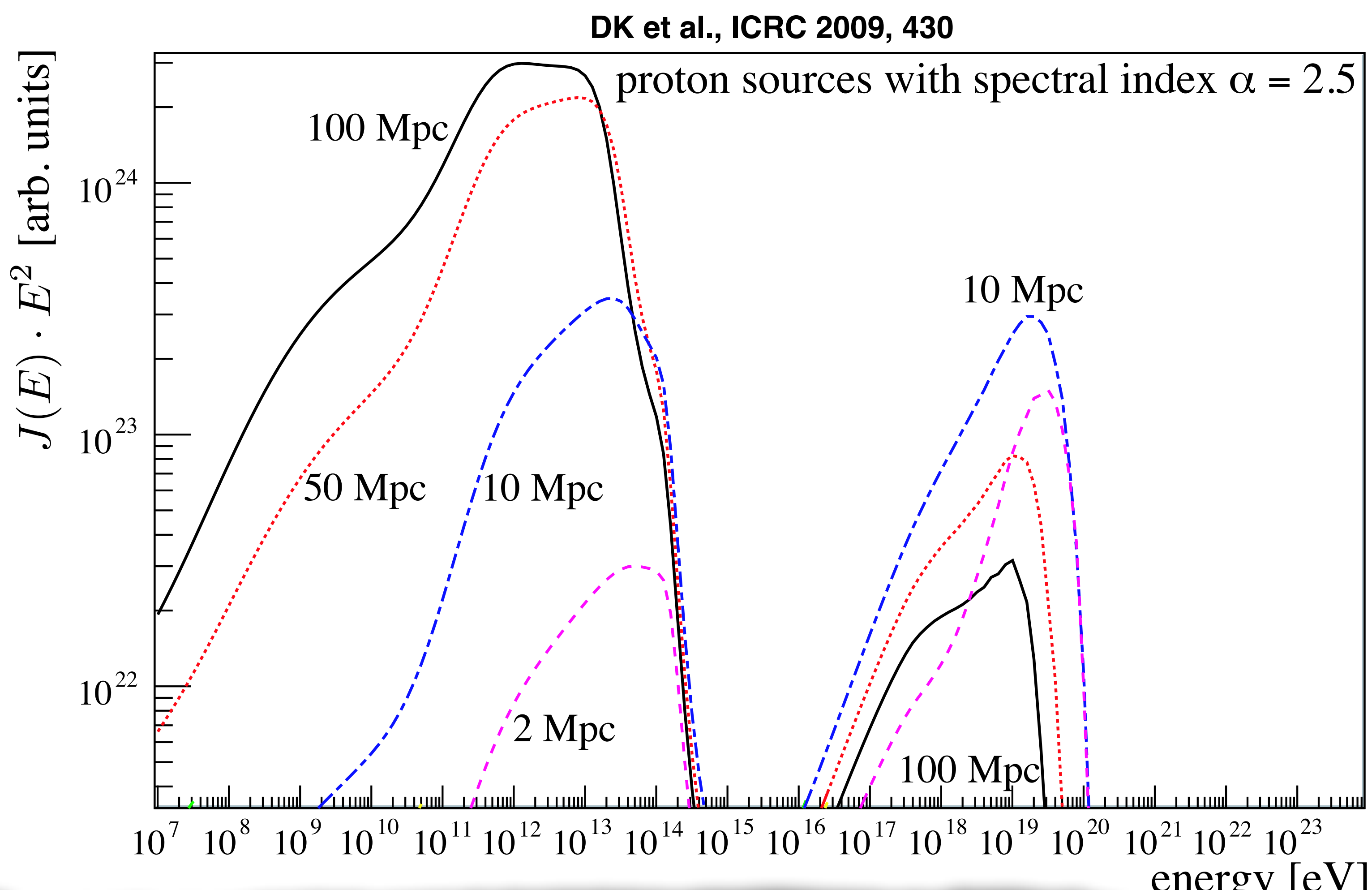
Secondary photons



- 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

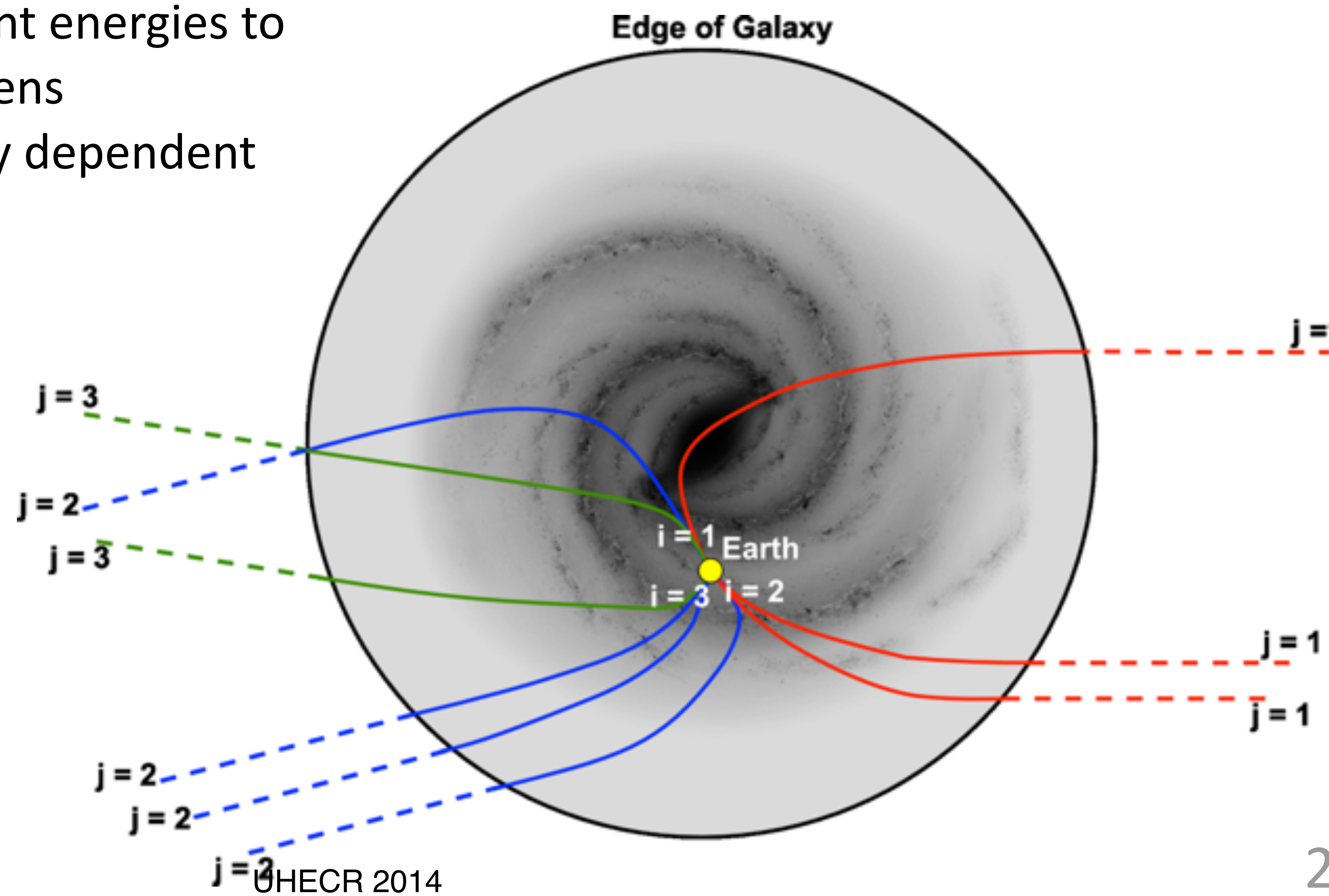
Current status: No photons above ~TeV energies observed

Galactic magnetic field lensing

Neglect energy loss during relatively short galactic propagation
-> Effect of magnetic field can be addressed as magnetic lensing:

For a specific energy bin:

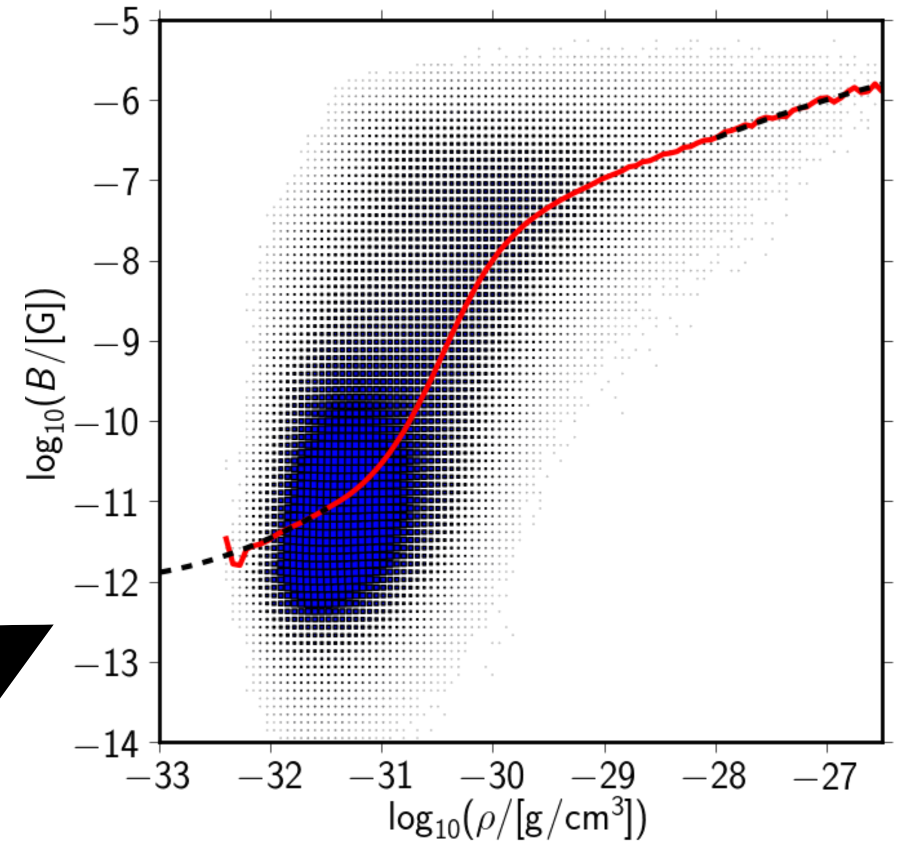
- Backtrack protons starting isotropically at Earth
- Departure direction and exit direction of galaxy binned with 1° resolution
- Calculate probability matrix for a particle entering the galaxy from direction *n* to observe at Earth from direction *m*
- Repeat procedure for different energies to produce energy dependent lens
- Particle with $Z > 1$ use rigidity dependent deflection



3D magnetic field

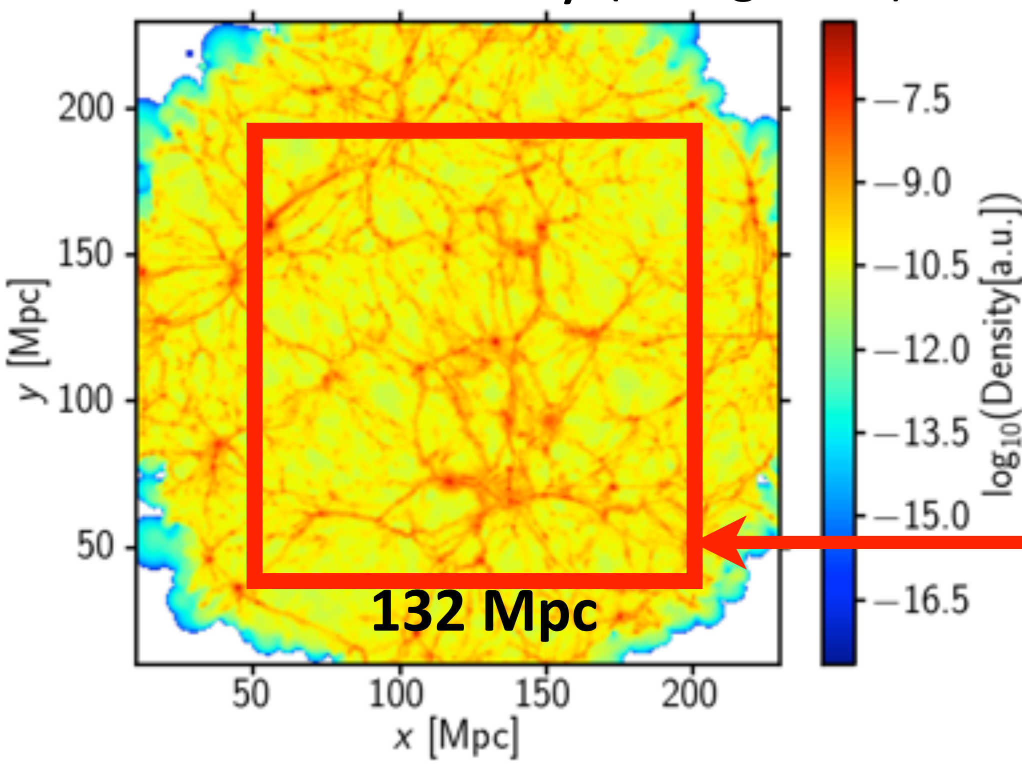
Extragalactic magnetic field:

Obtain field strength from mass density using *B-rho* profile (Miniati *et al.*)



Resulting *B*-strength

LSS mass density (Dolag *et al.*)



Select largest cube that fits inside