propagation of high energy cosmic rays, gamma rays and neutrinos

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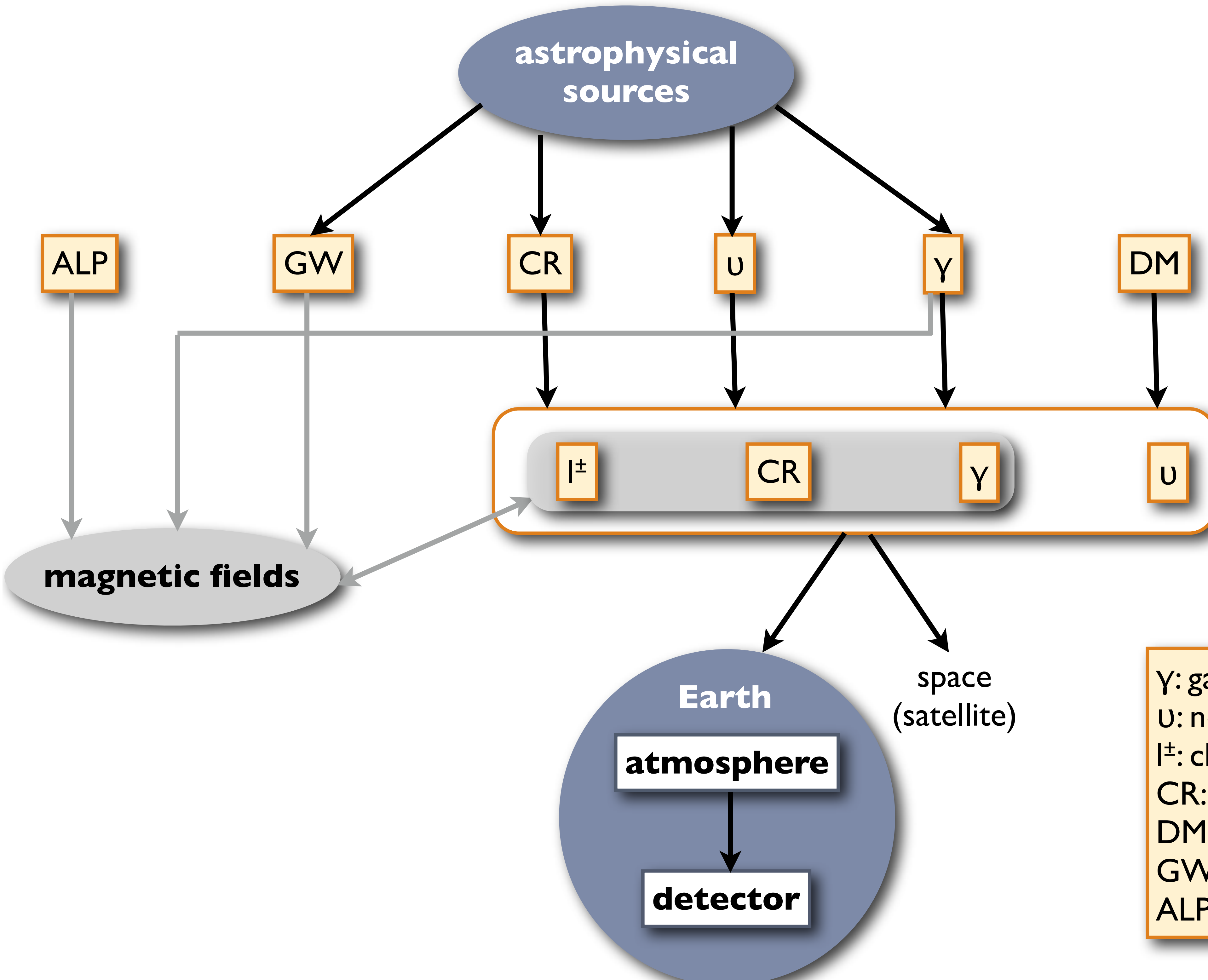
outline of this talk

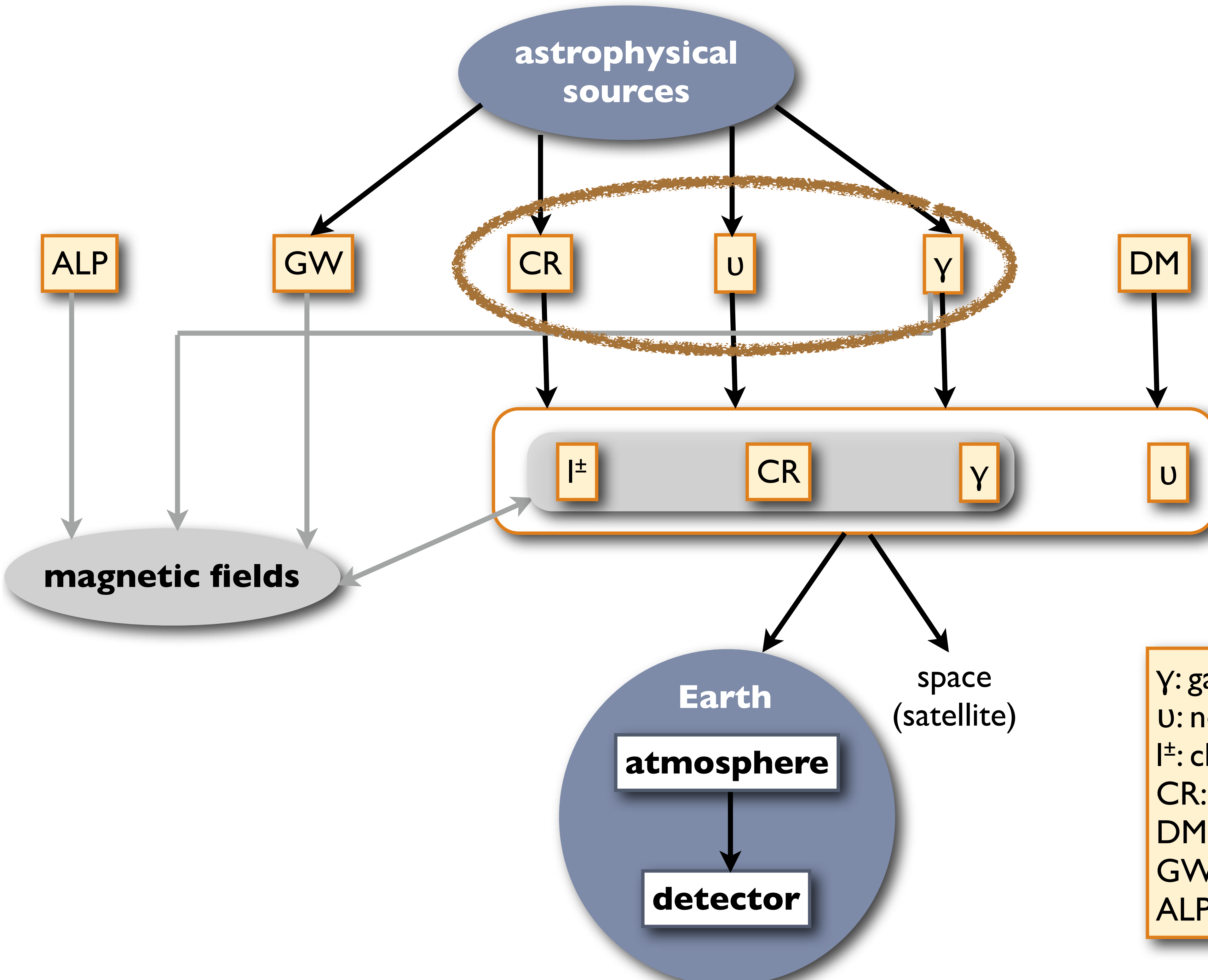
- multimessenger approach
- ultra-high energy cosmic rays
- gamma rays
- neutrinos
- CRPropa

multimessenger astroparticle physics



γ: gamma rays
ν: neutrinos
$l^{\pm}$: charged leptons
CR: cosmic rays
DM: dark matter
GW: gravitational waves
ALP: axion-like particles

multimessenger astroparticle physics



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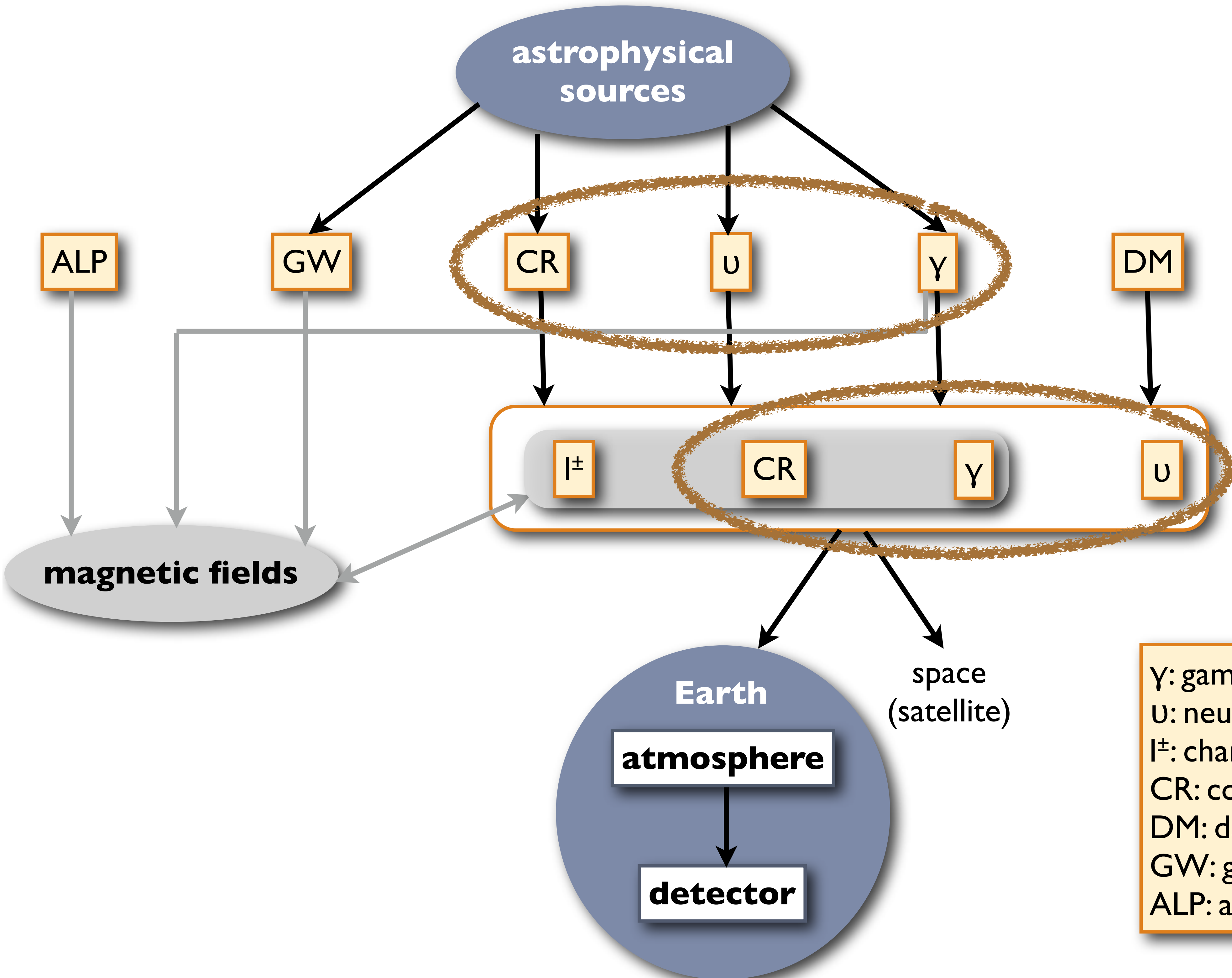

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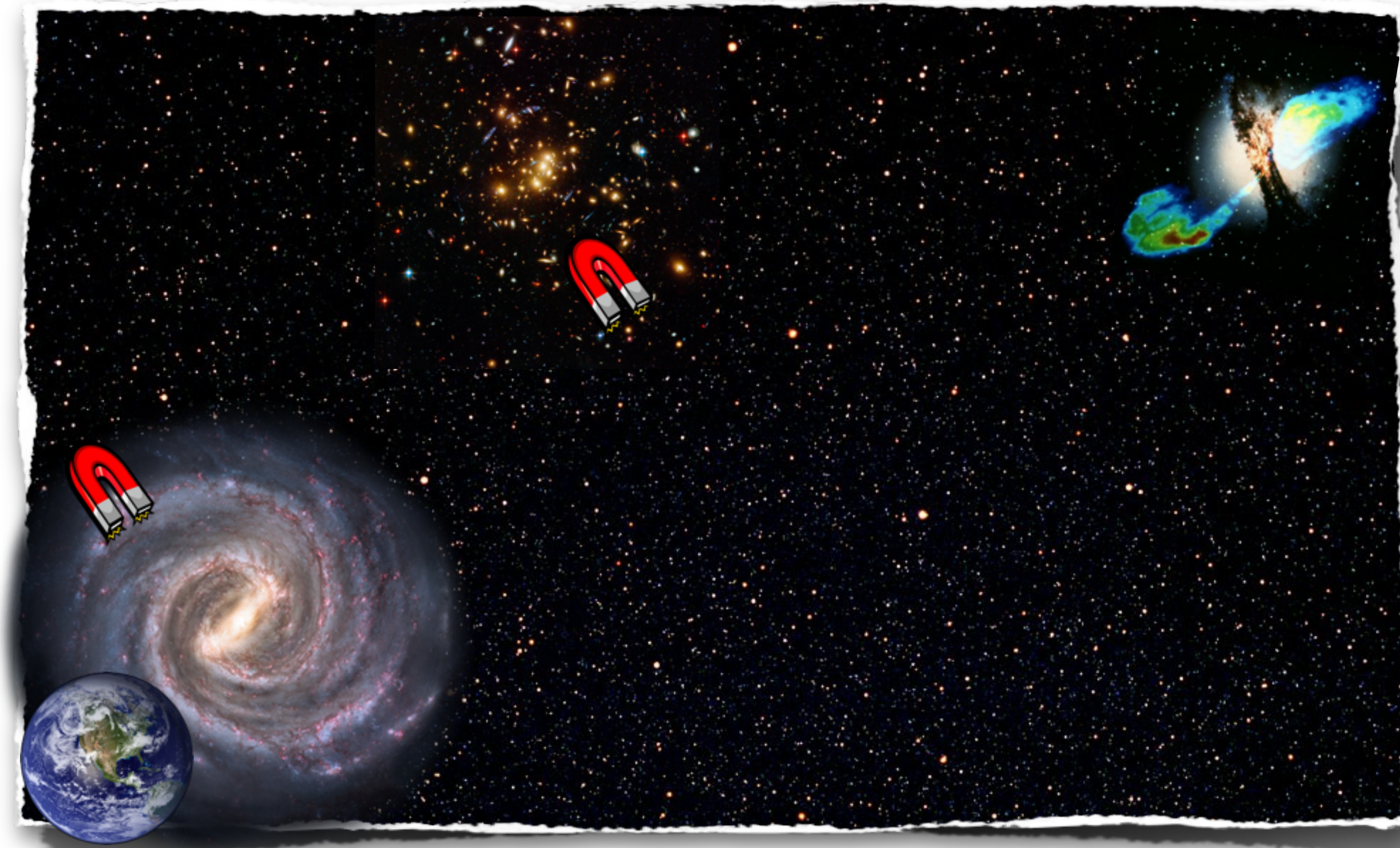

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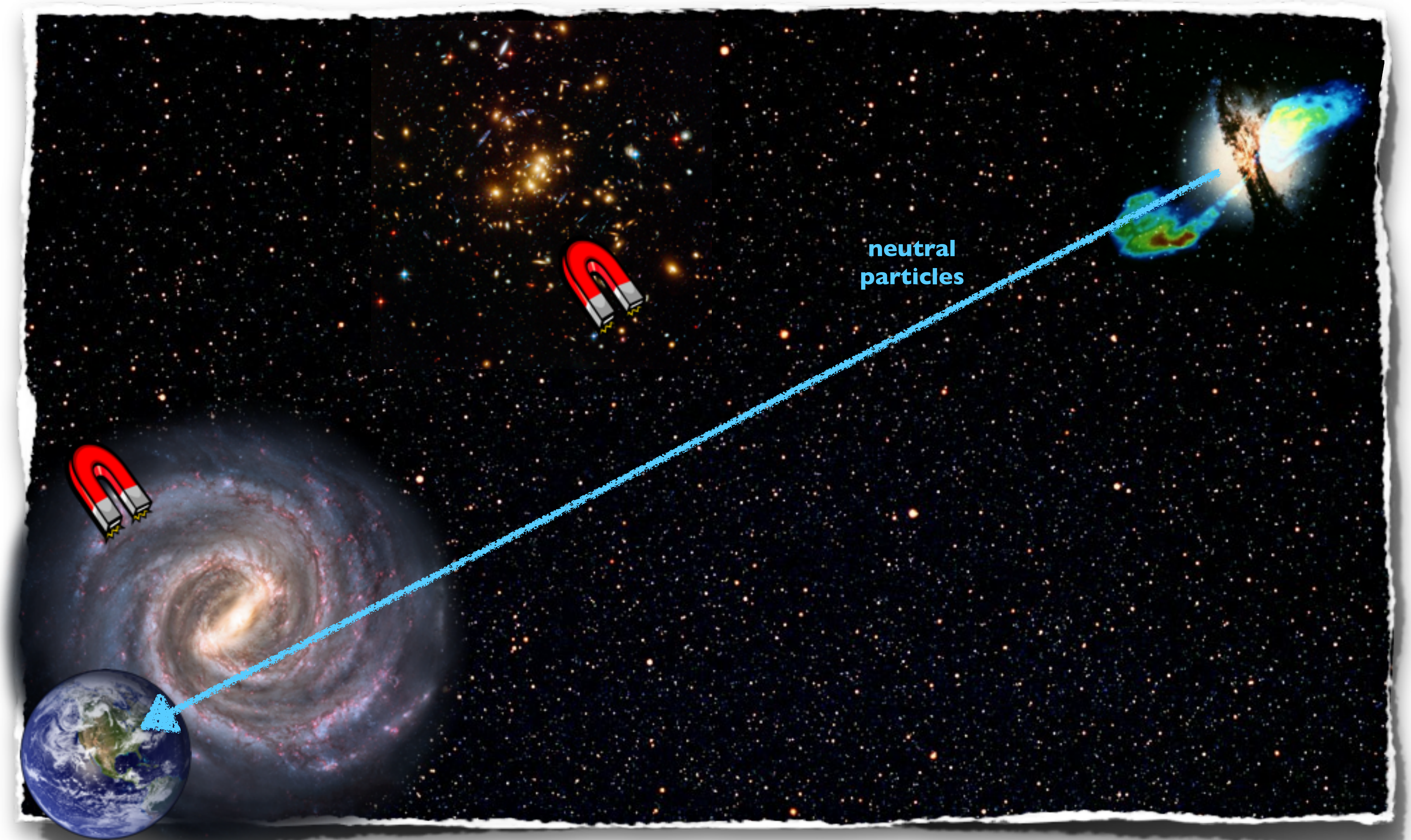

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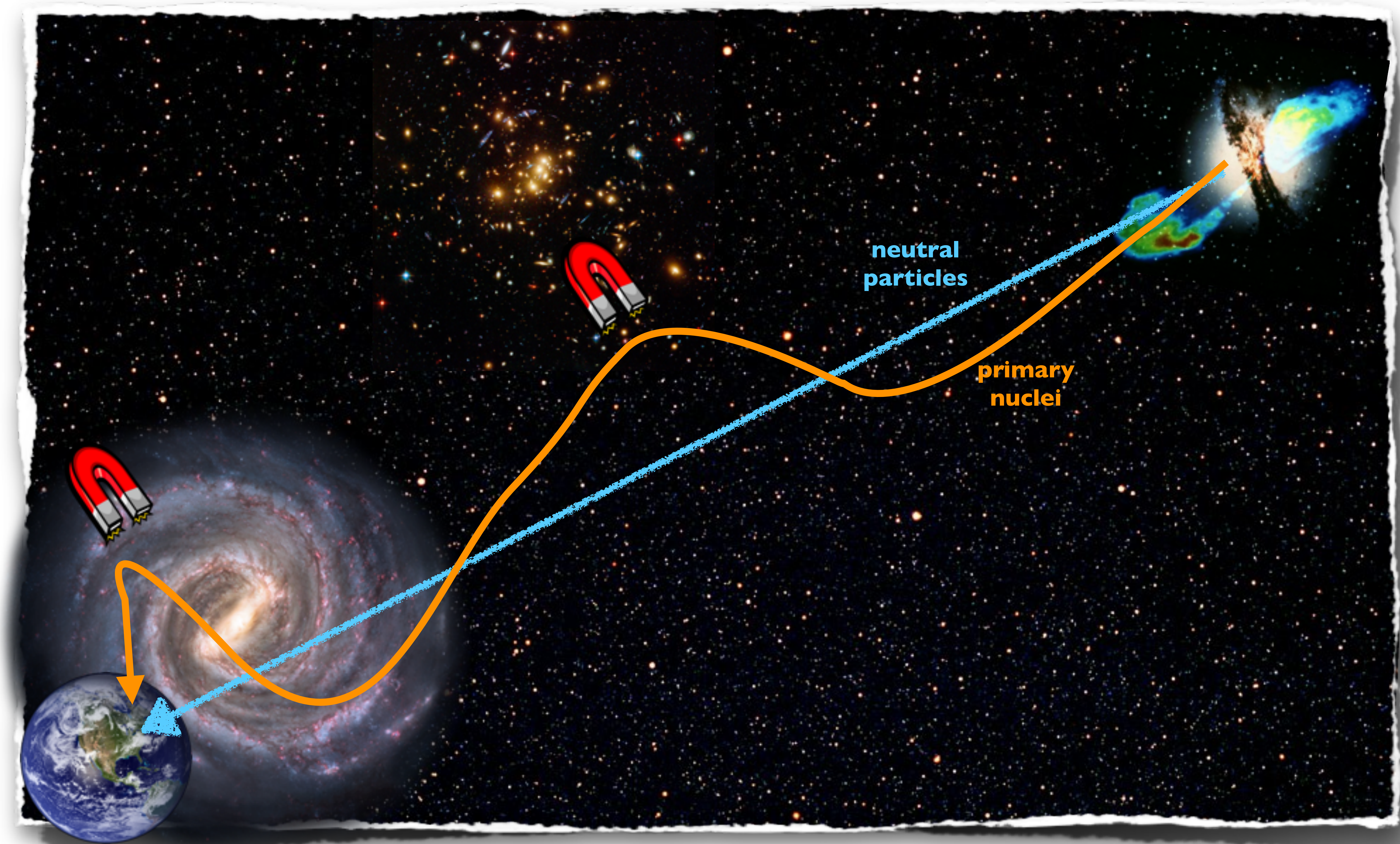

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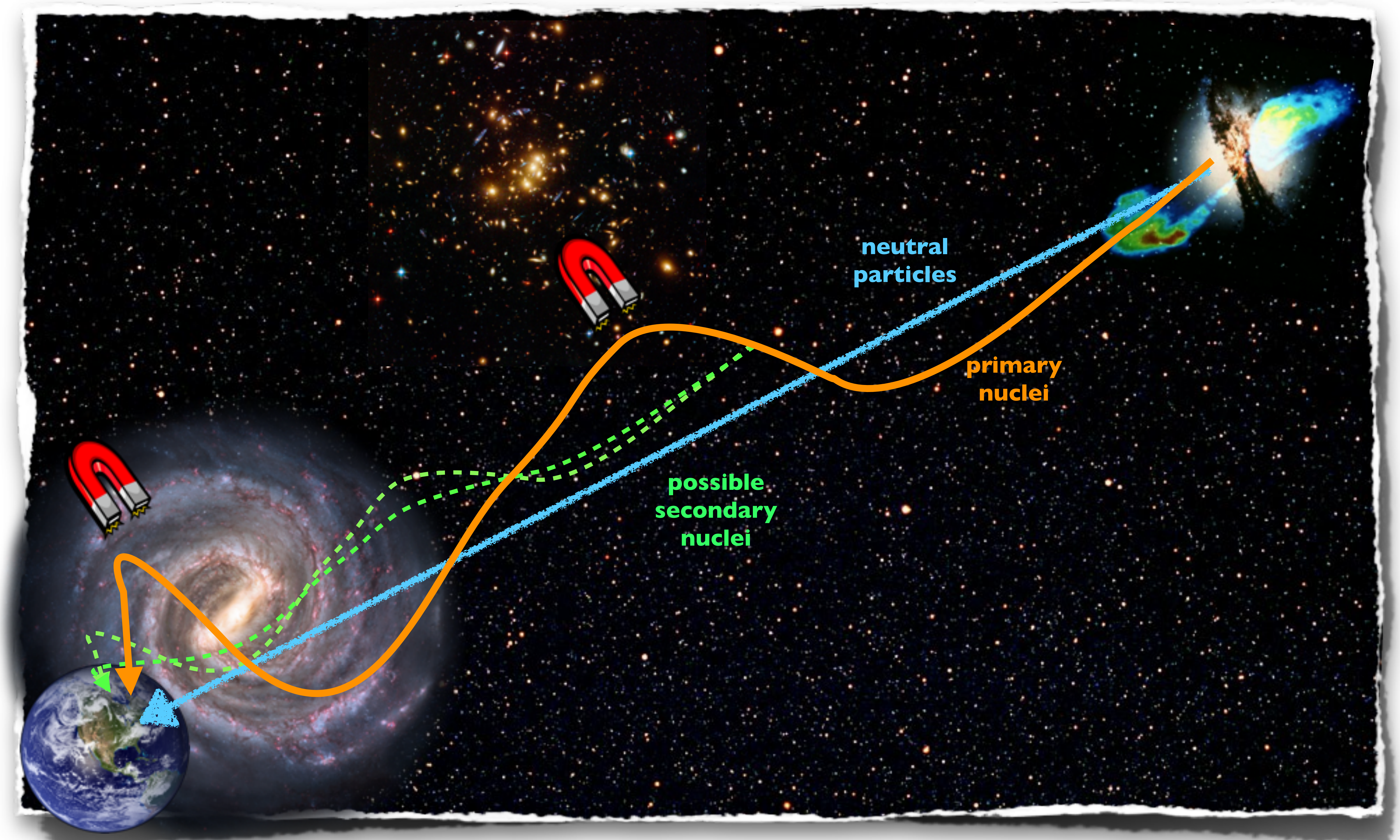

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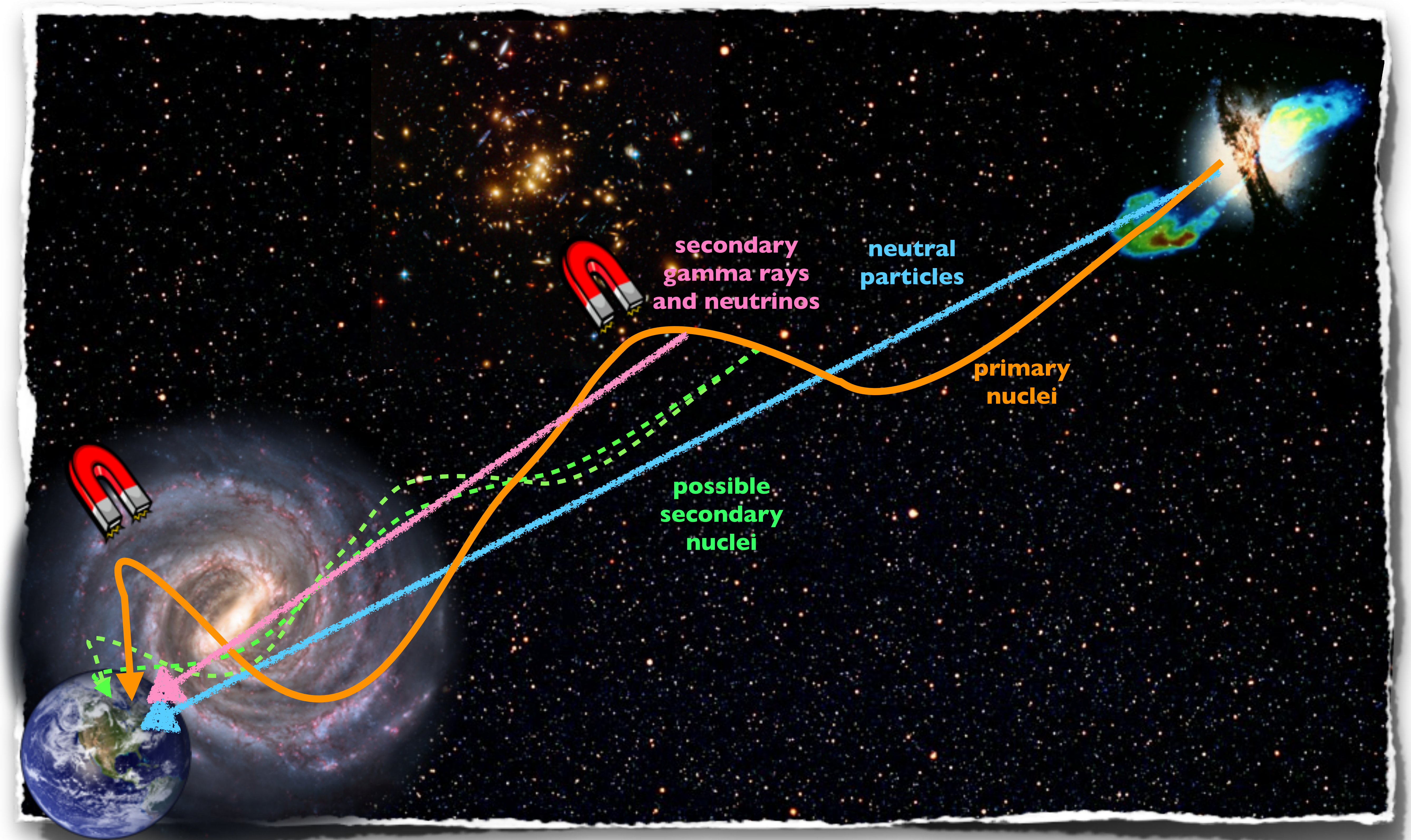
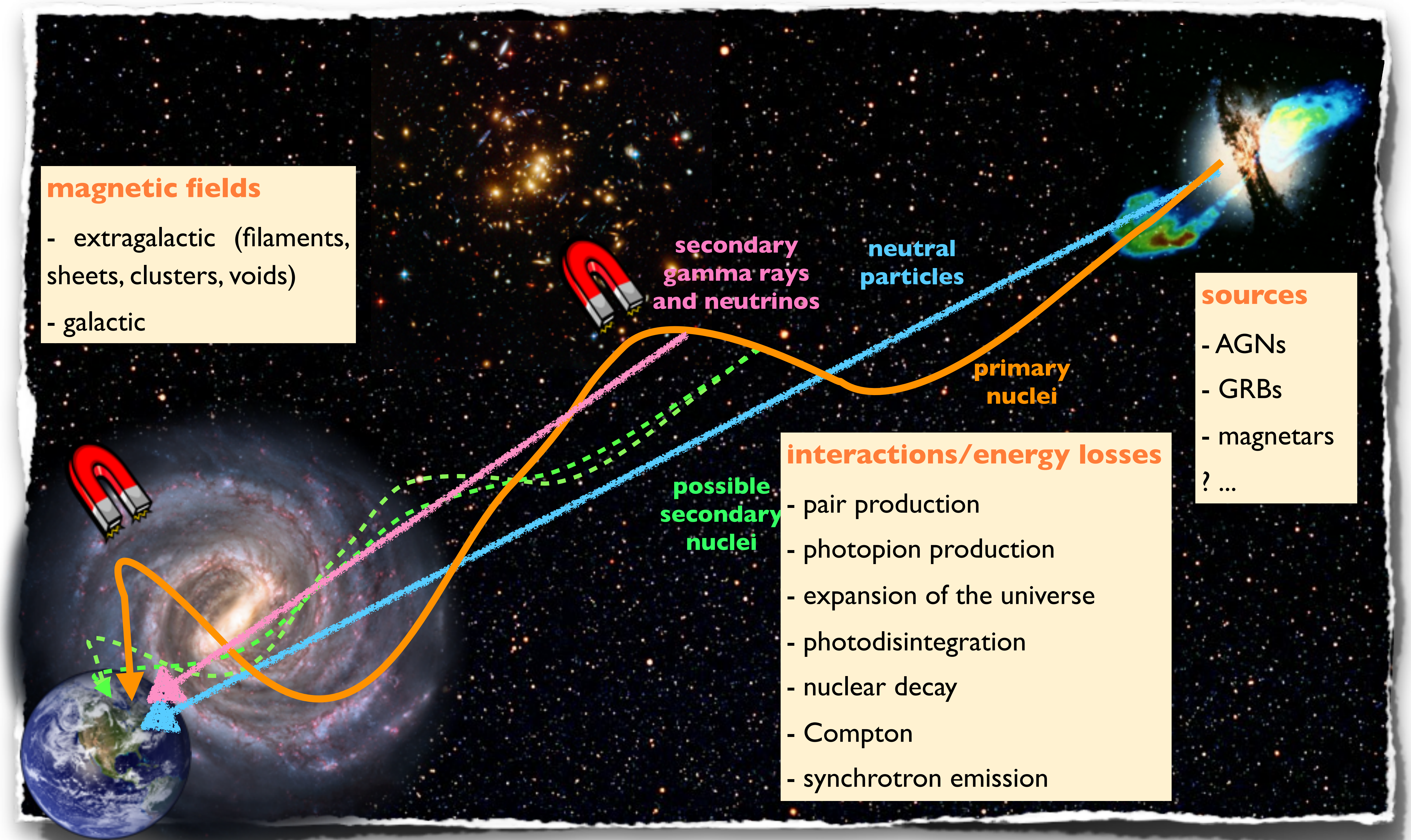


multimessenger astroparticle physics



multimessenger astroparticle physics

- sources of some particles are not known
- sources may be related to the matter distribution in the universe
- the presence of photon backgrounds (e.g. CMB, CIB, ...) permeating the universe provide a medium where interactions will take place
- cosmic magnetic fields (galactic and extragalactic) can affect the trajectory of particles (cosmic rays and gamma rays)

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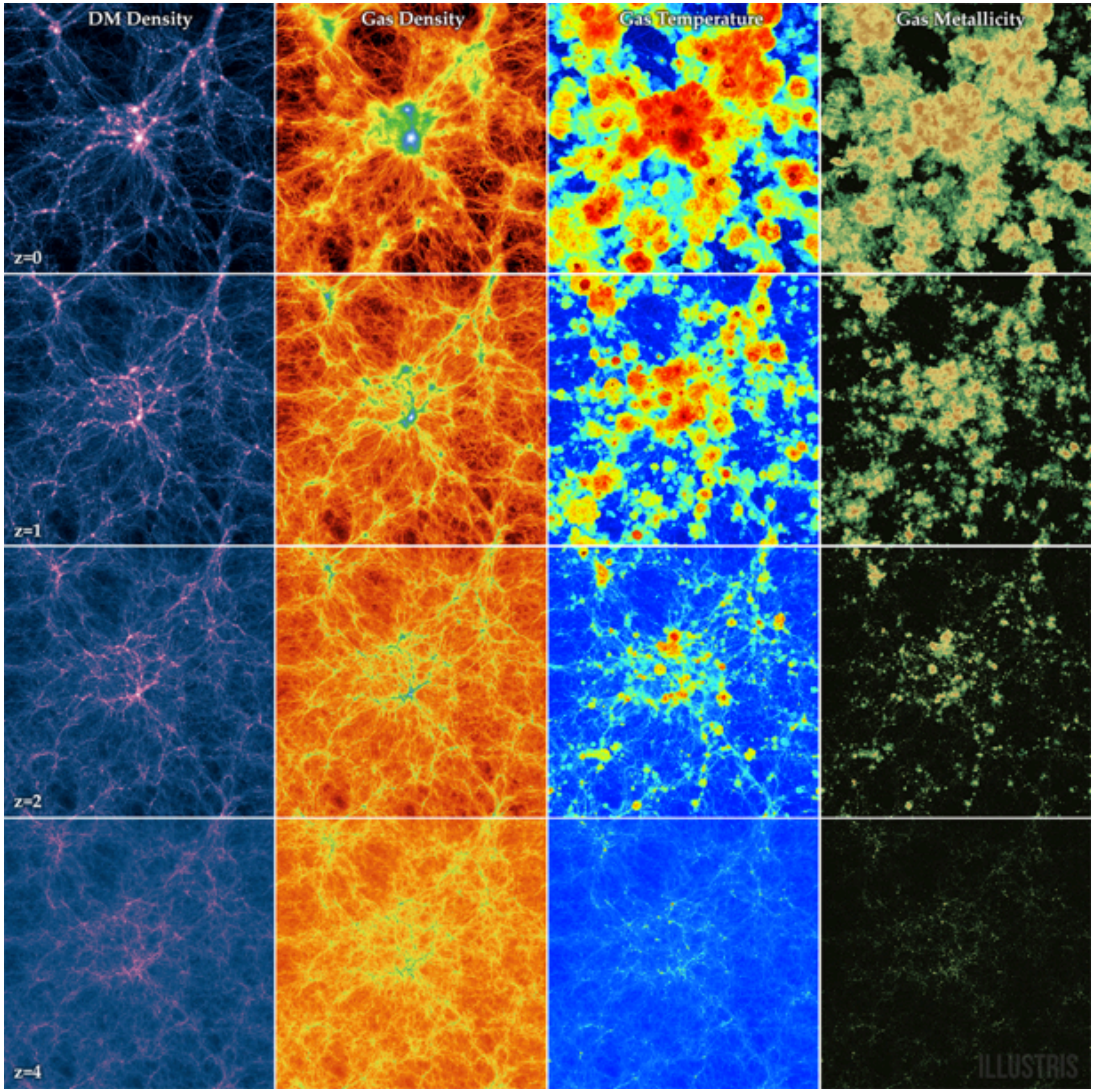
matter distribution

photon backgrounds

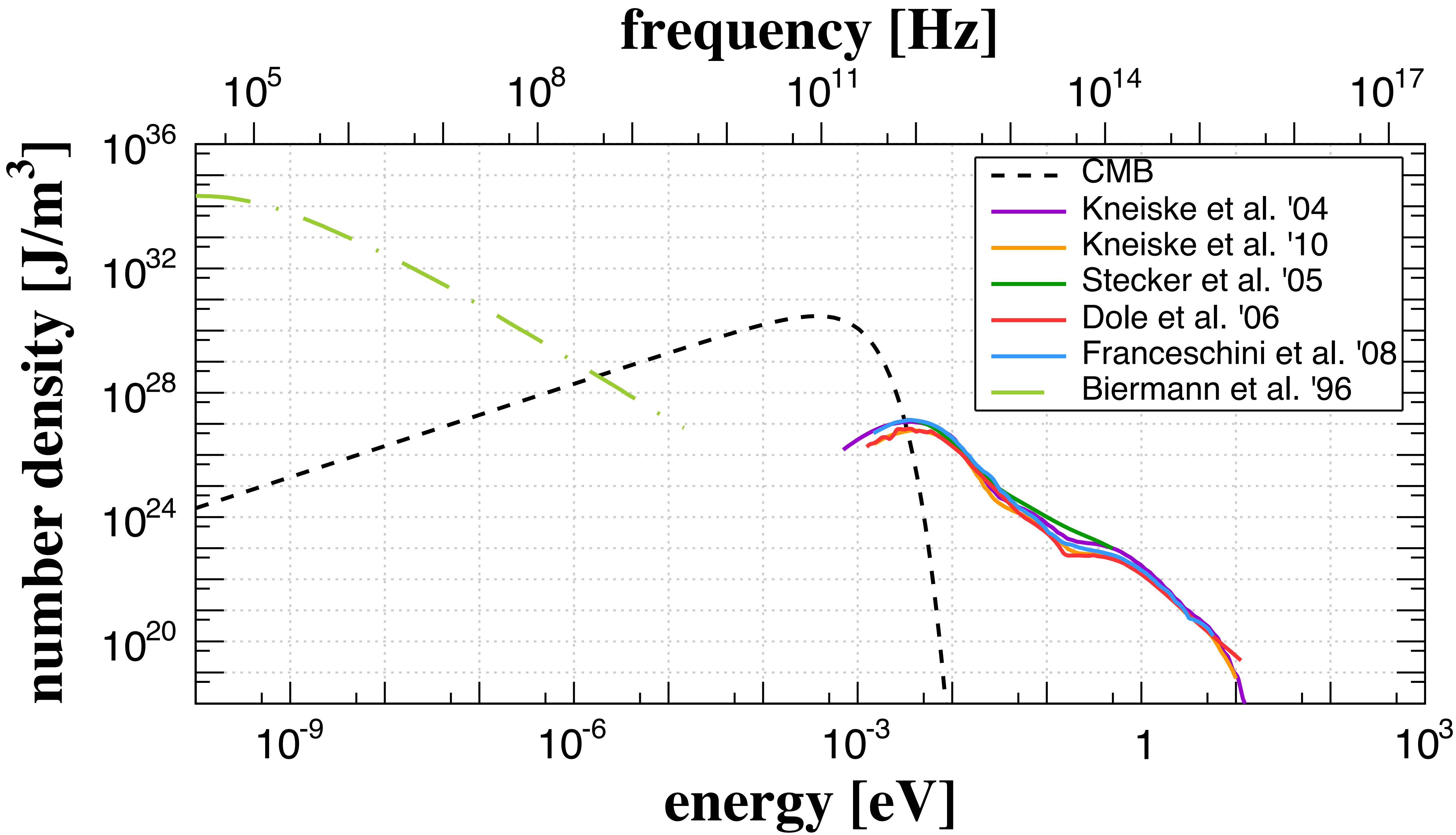
magnetic fields

matter distribution in the universe

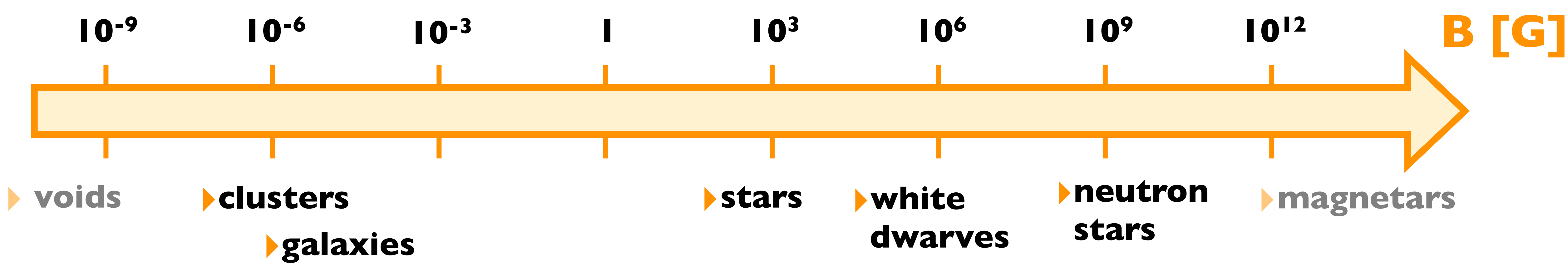


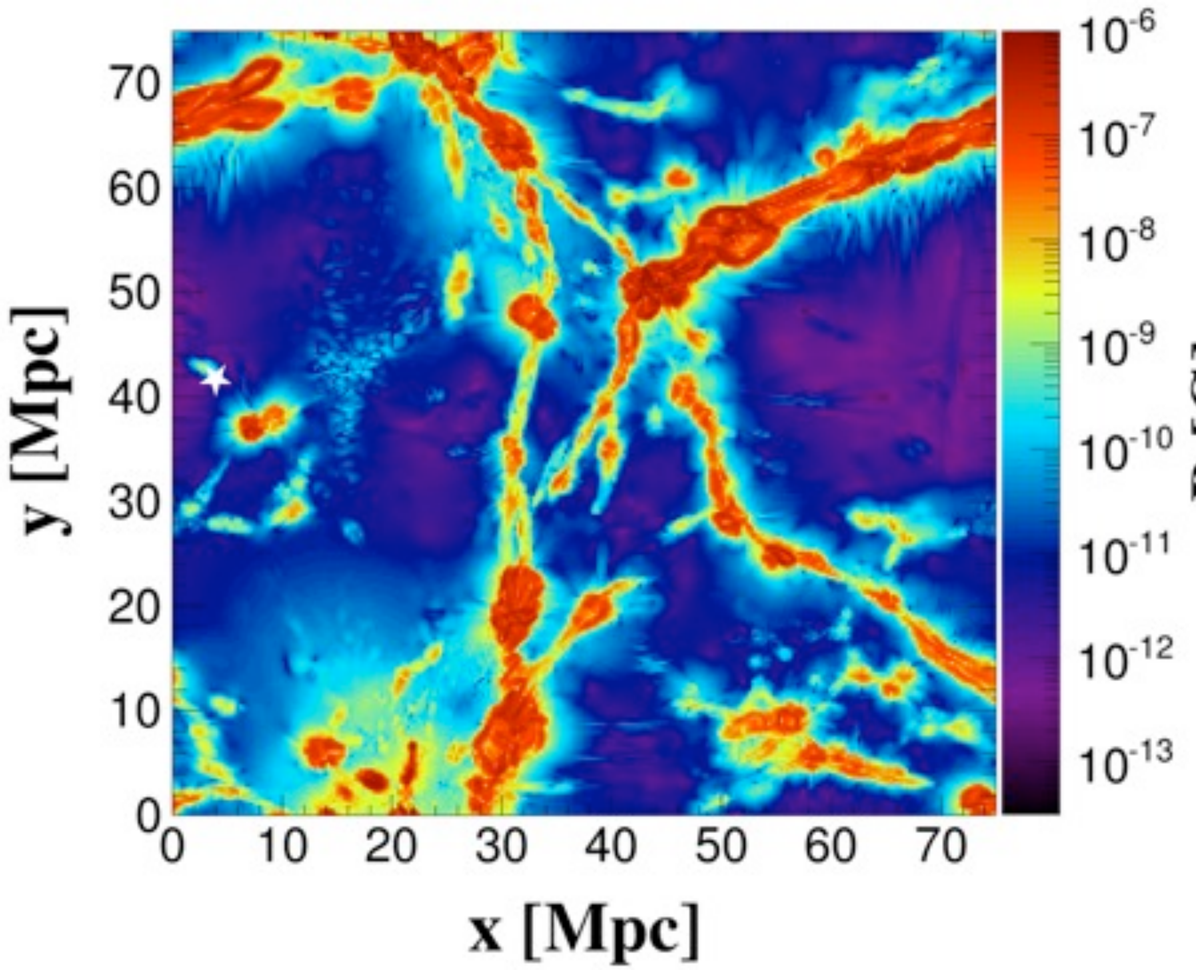
Credits: Illustris Collaboration

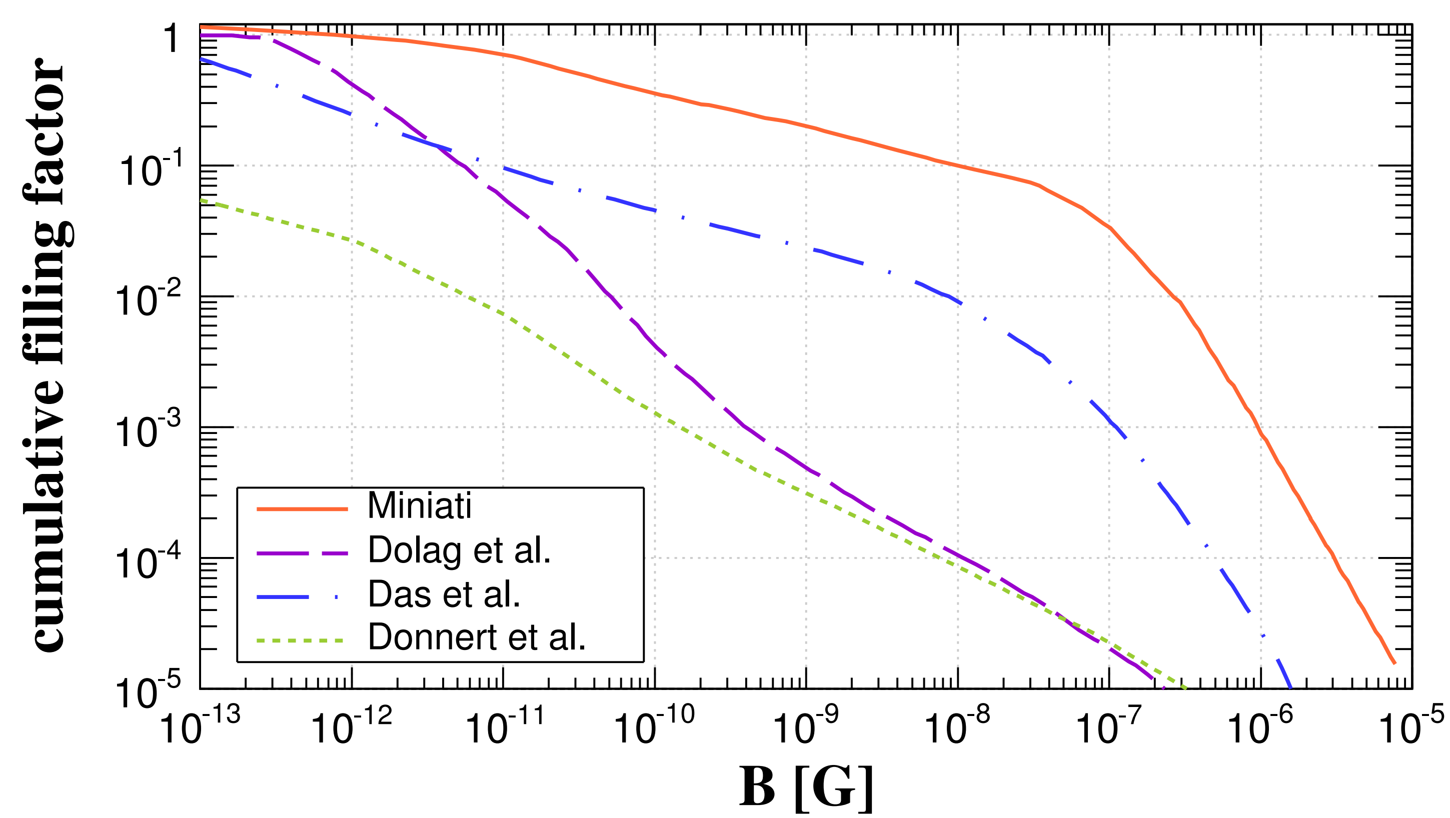
photon backgrounds



cosmic magnetic fields: extragalactic







Miniati, MNRAS 337 (2002) 199

Dolag et al. JCAP 01 (2005) 09

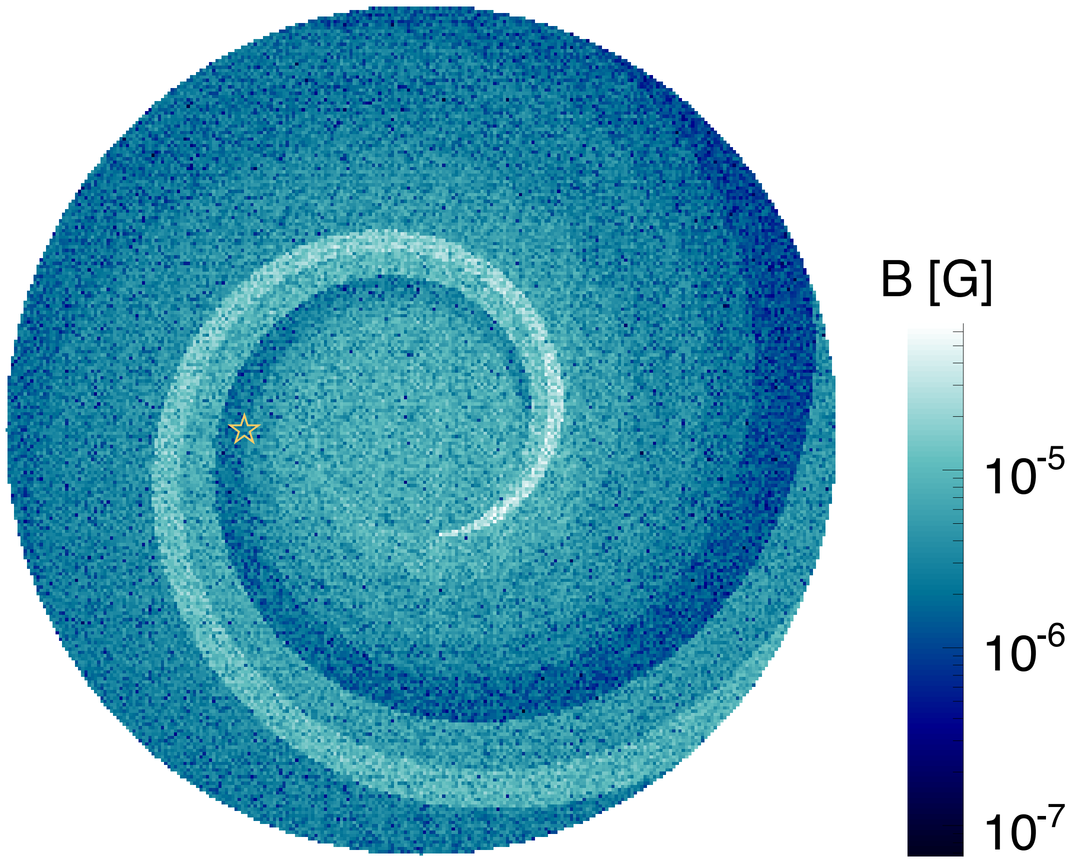
Das et al. ApJ 682 (2008) 29

Donnert et al. MNRAS 392 (2009) 1008

cosmic magnetic fields: galactic

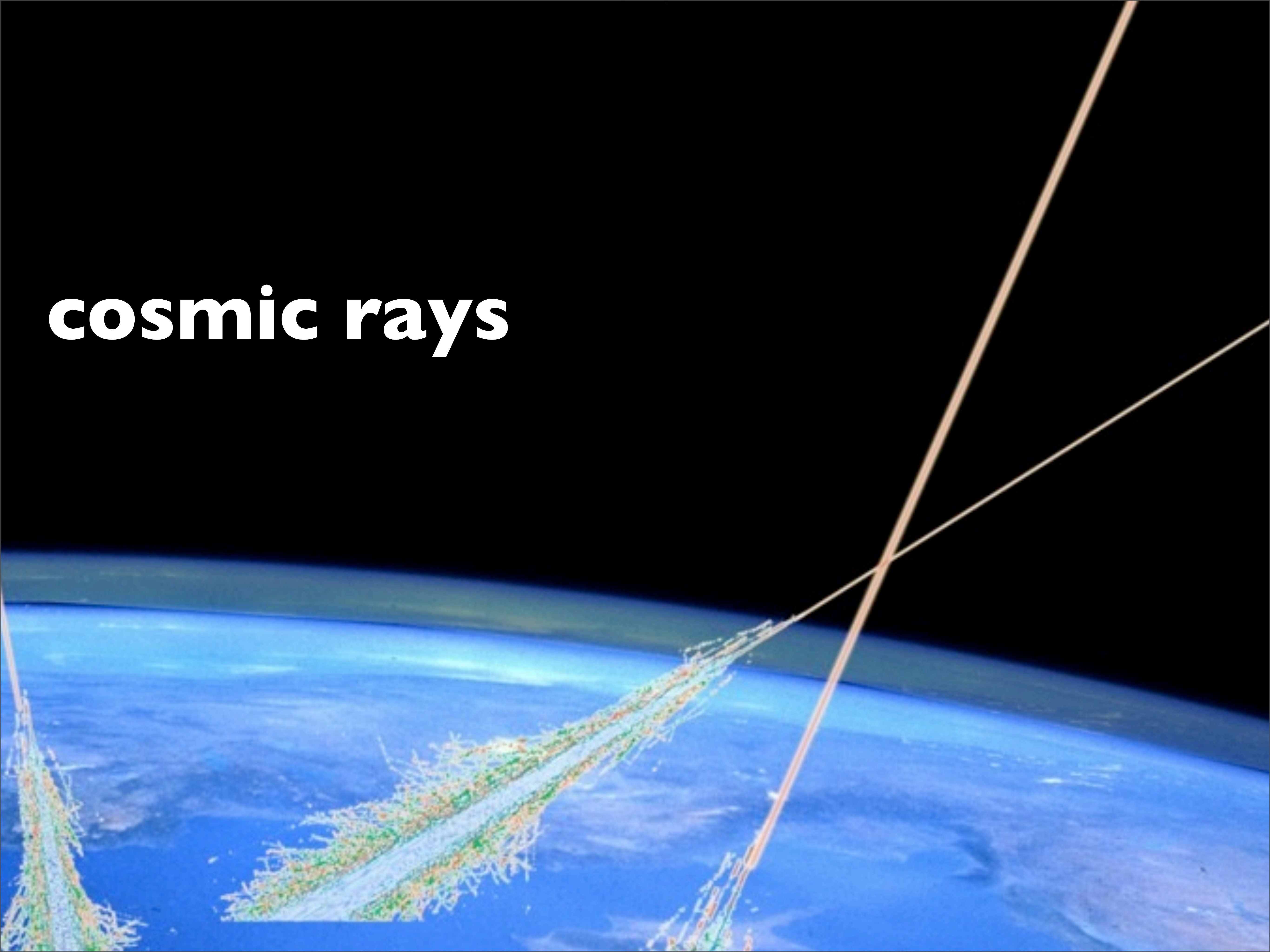
Jansson & Farrar model - regular component

Jansson & Farrar model - total field



Jansson & Farrar, ApJ 757 (2012) 14

Jansson & Farrar ApJL 761 (2012) L11


cosmic rays

ultra-high energy cosmic rays (UHECRs)

fundamental questions

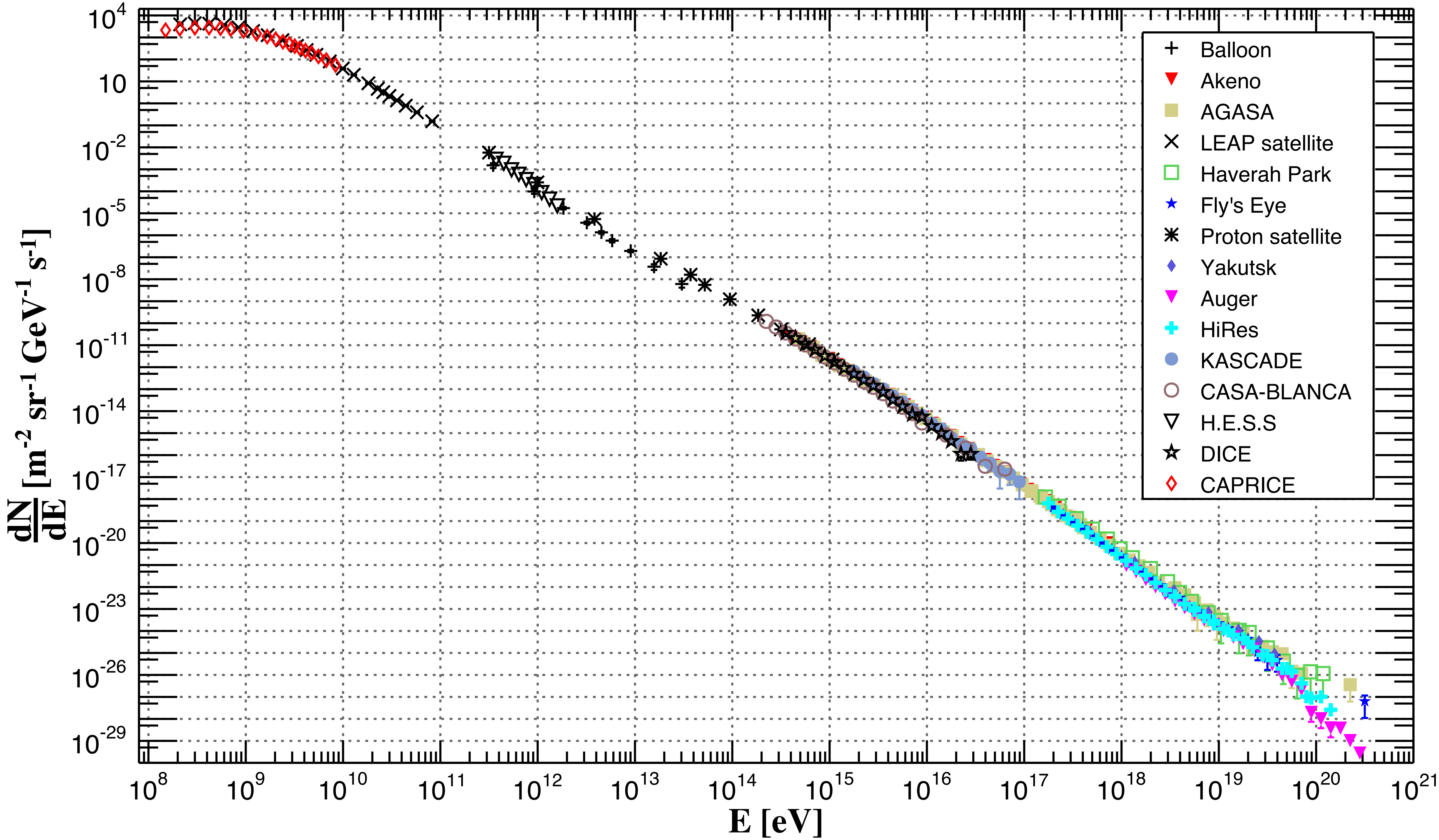
- where do they come from?
- what are they made of?
- how are they accelerated?

some problems

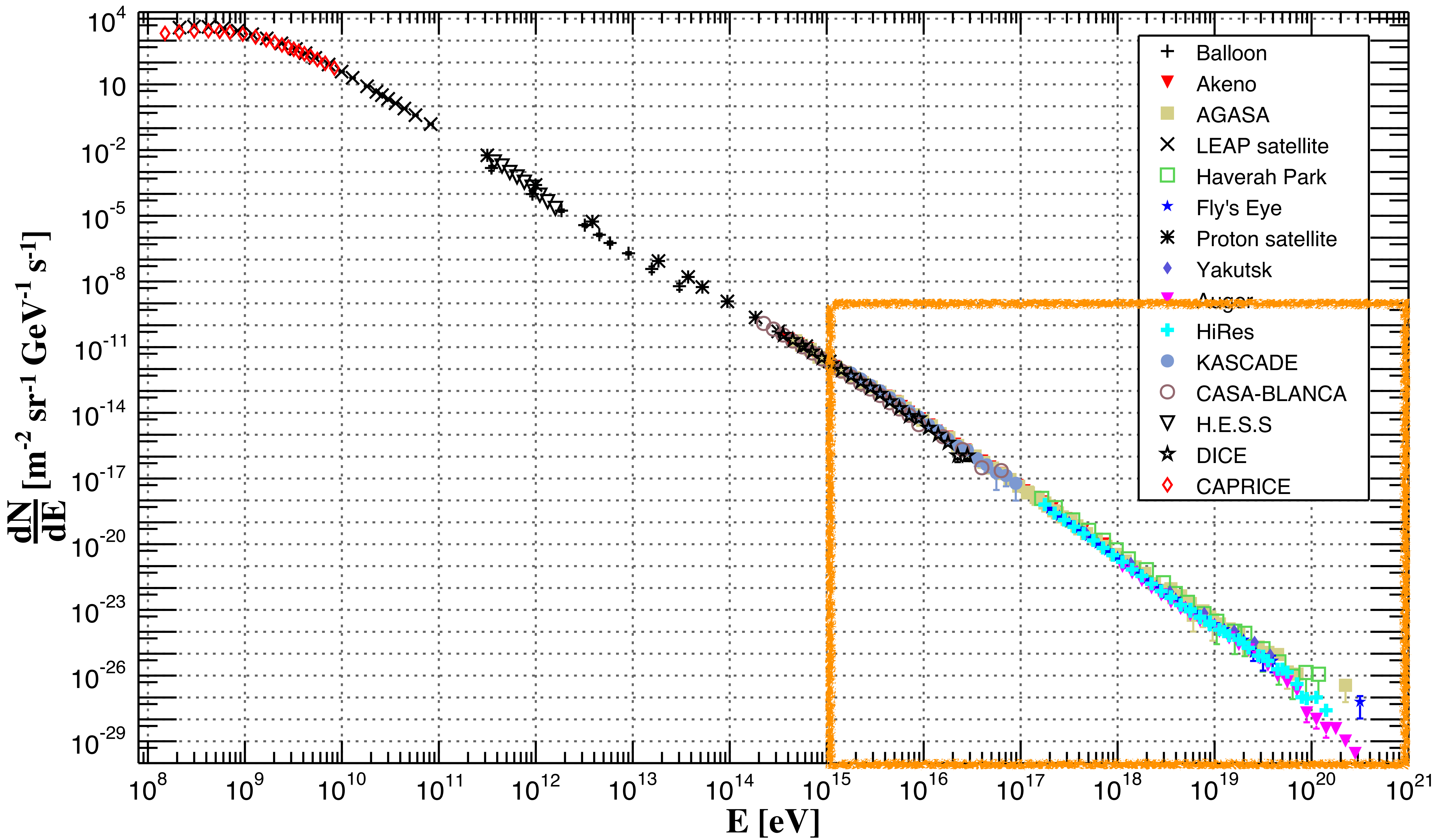
- what is the maximum energy they can reach?
- do we see a GZK cutoff
- where does the transition between galactic and extragalactic cosmic rays take place?
- where does the transition between diffusive and ballistic regimes happen?

- observables from CR experiments: spectrum, composition, anisotropy
- cosmic magnetic fields (galactic and extragalactic) are important
- test new physics scenarios using UHECRs

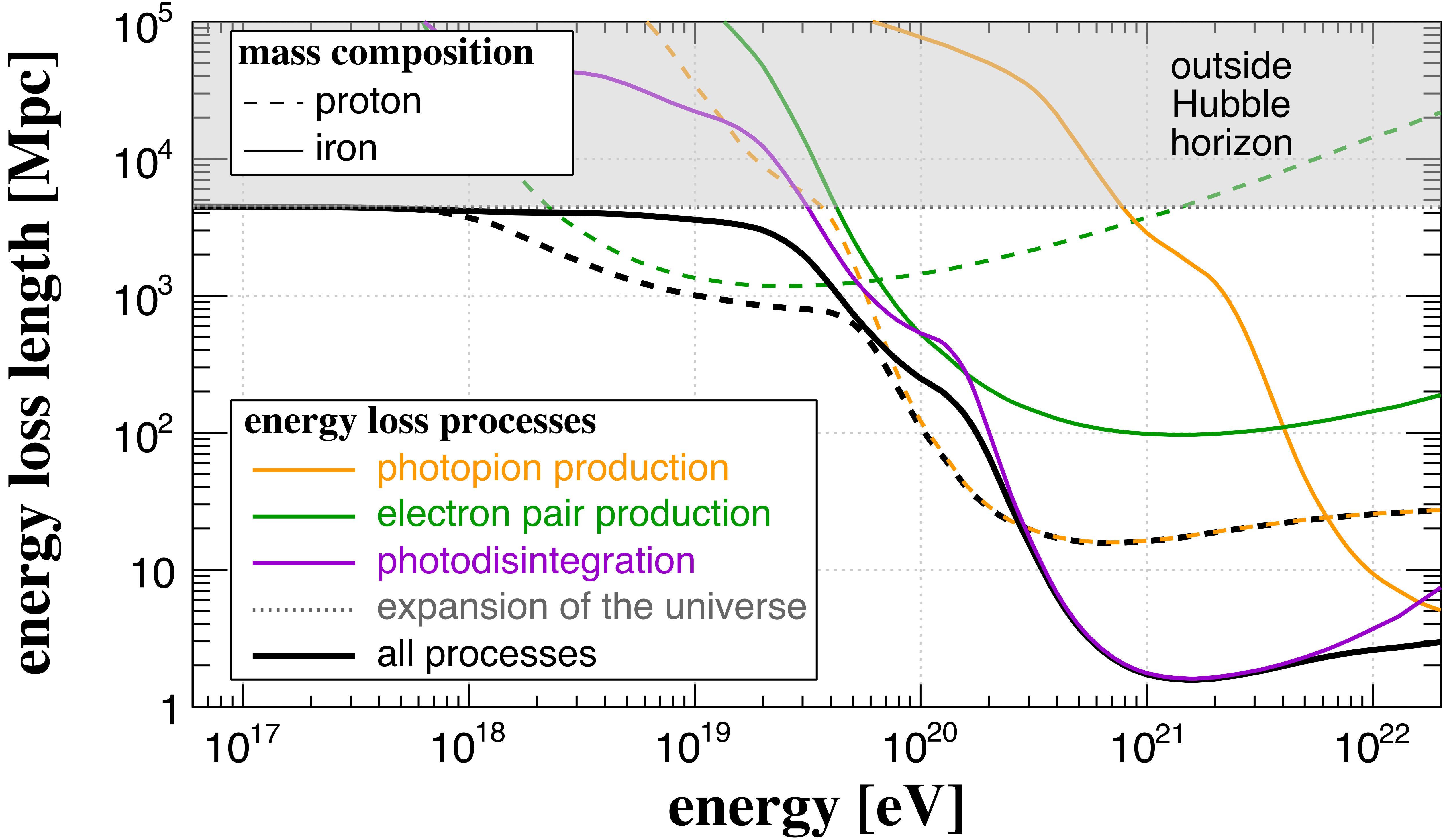
the cosmic ray spectrum



the cosmic ray spectrum



interactions and energy loss processes



interactions and energy loss processes

photopion production

$$p + \gamma \rightarrow \Delta^+ \rightarrow \begin{cases} p + \pi^0 \\ n + \pi^+ \end{cases}$$

mean free path for nuclei written as a function of the mfp for protons and neutrons

expansion of the universe

$$\frac{dt}{dz} = \frac{1}{H_0}\frac{1}{1+z}\frac{1}{\sqrt{\Omega_m(1+z)^3 + \Omega_\Lambda}} \qquad E = \frac{E_0}{1+z}$$

ΛCDM cosmology

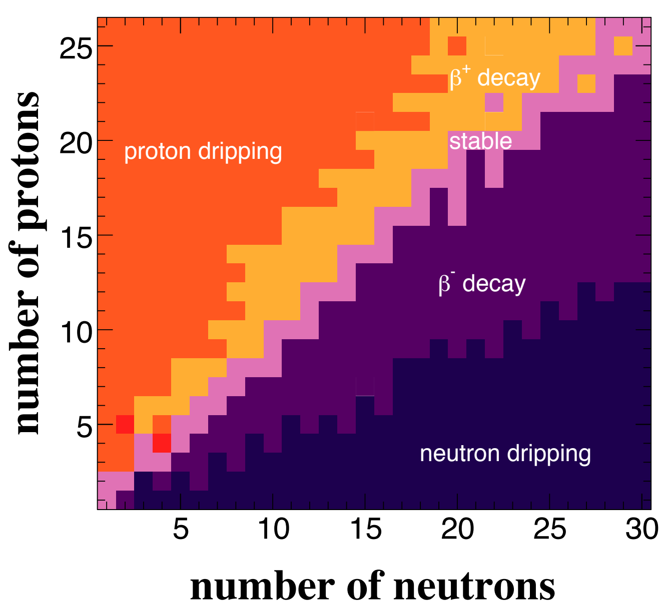
pair production

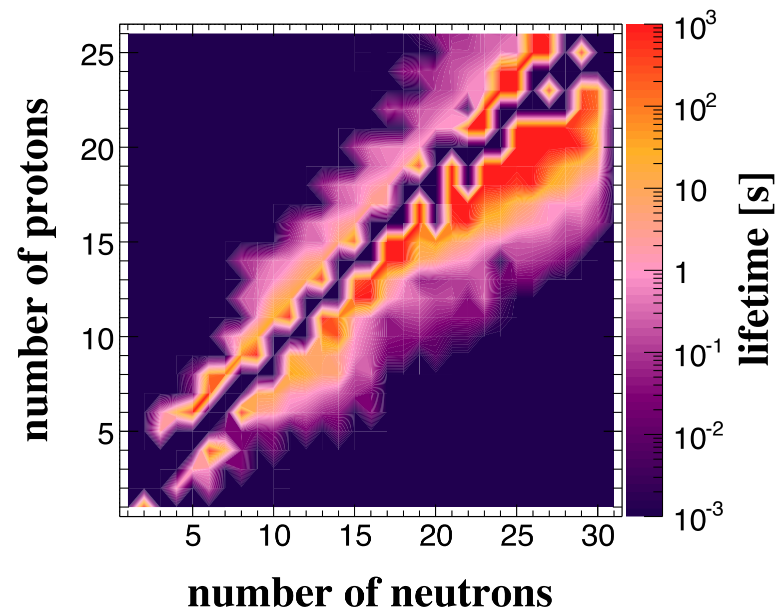
$$-\frac{dE_{A,Z}}{dt} = 3\alpha\sigma_T h^{-3} Z^2 m_e c^2 k_B T f(\Gamma)$$

photodisintegration

$$\frac{1}{\lambda(\Gamma)} = \int_{E_{min}}^{E_{max}} n(\epsilon, z)\bar{\sigma}(\epsilon'_{max} = 2\Gamma\epsilon)d\epsilon$$

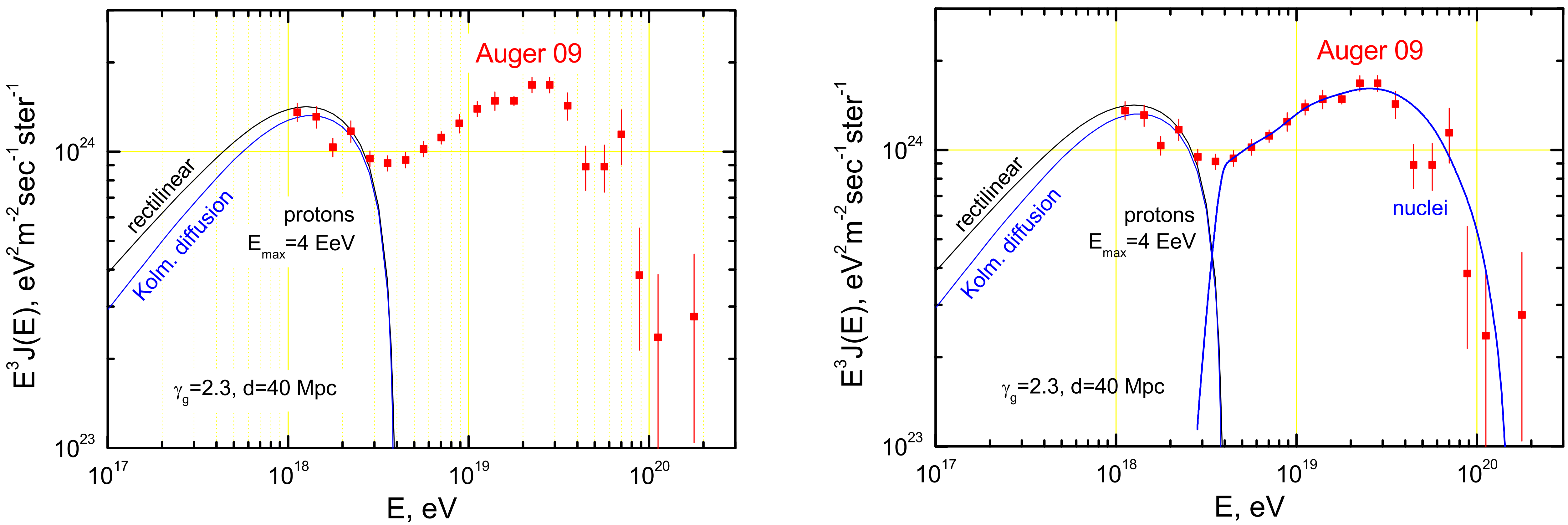
nuclear decay





the “disappointing” model

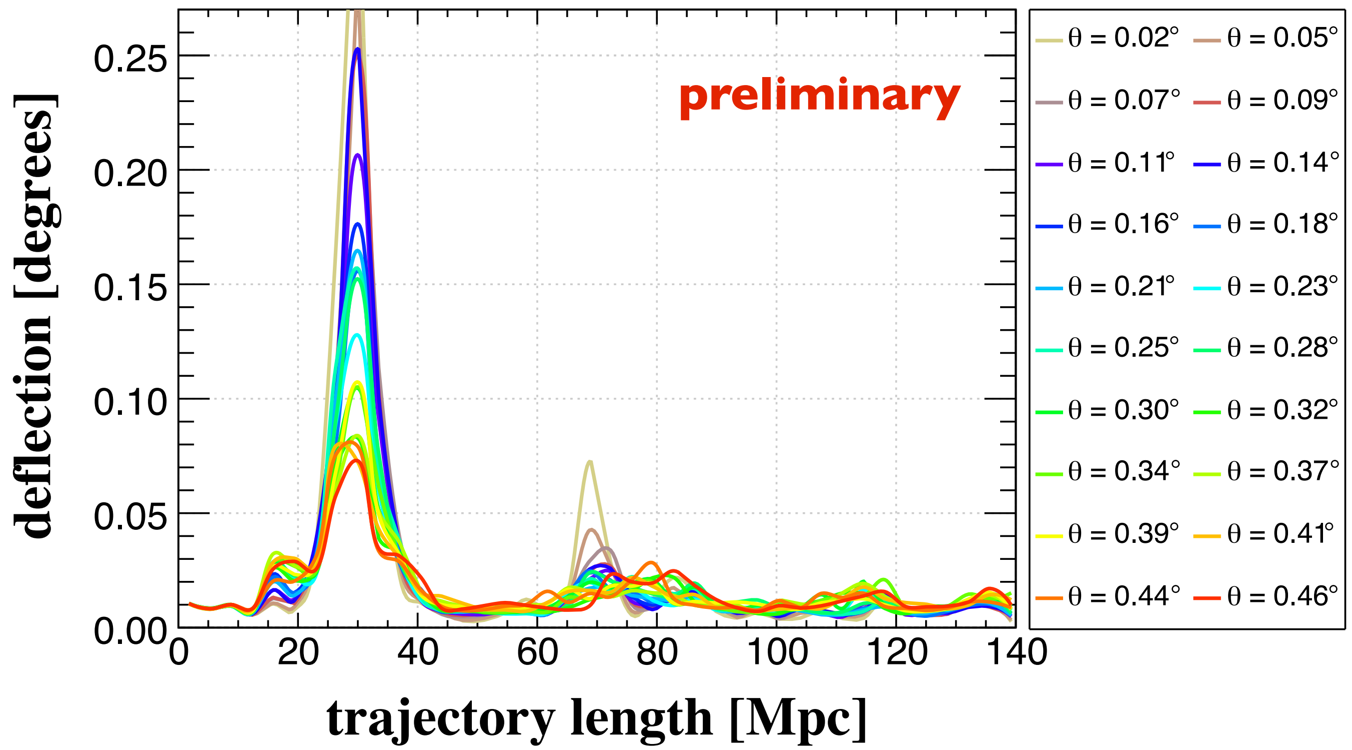
Aloisio et al., Astropart. Phys. 34 (2011) 620

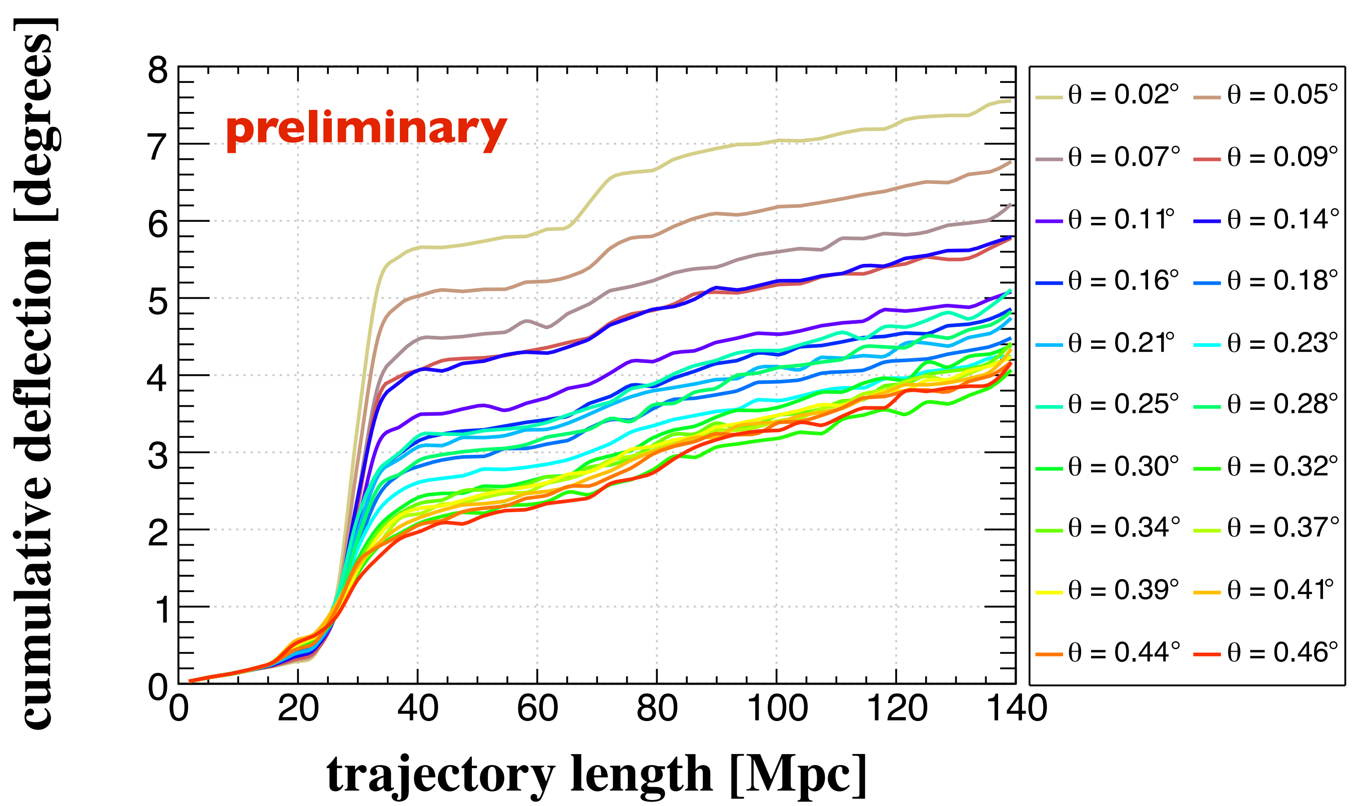


- highest energy cutoff due to maximum acceleration of sources
- no GZK effect

deflections in extragalactic magnetic fields

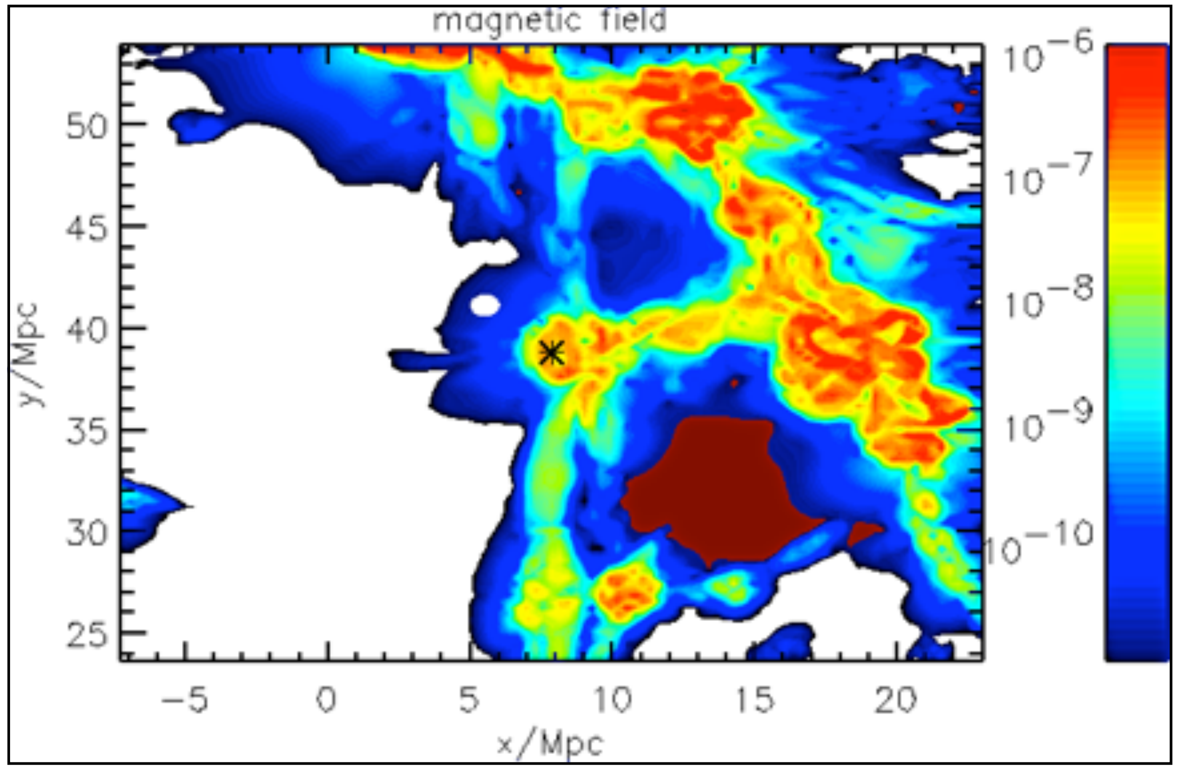
RAB, J. Devriendt, D. Semikoz, M.-S. Shin, G. Sigl. In preparation.



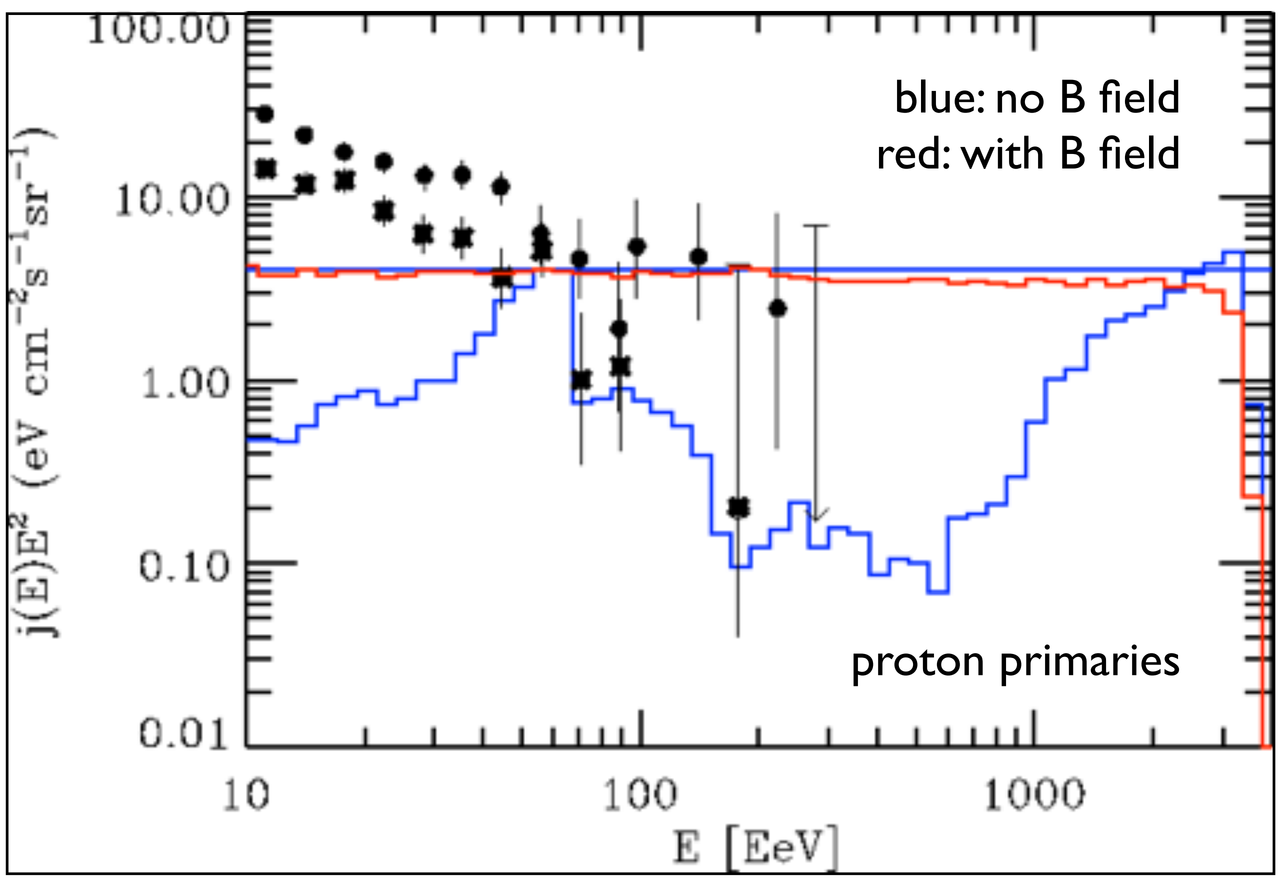


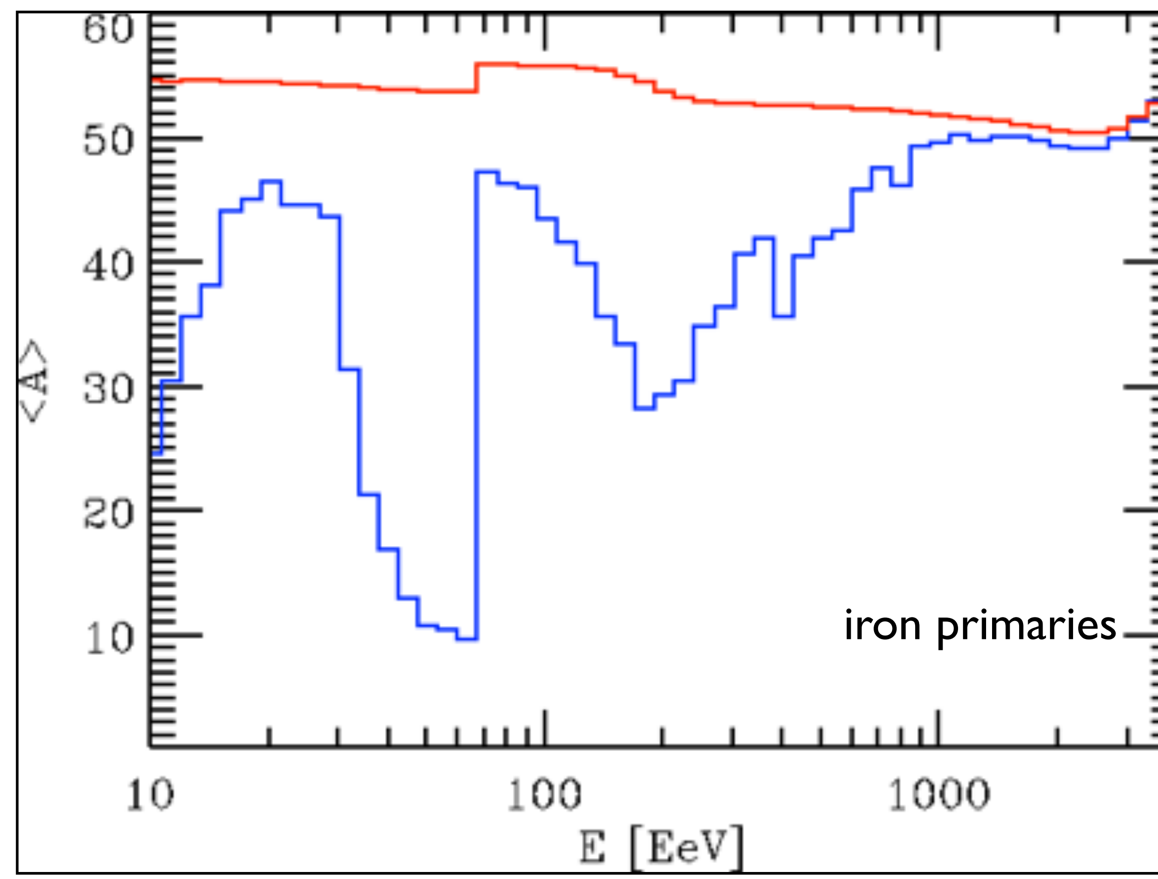
- UHECR “tomography”
- simulation of events recording its full trajectory, changing its initial angle within a cone of θ
- the average over 100 realization for each angle is plotted
- high deflections observed when particles cross structures
- useful for cross checks
- size of the structure is given by the angle of the cone in which the deflections start to become small, and the size (trajectory length) around peaks

UHECRs from individual sources

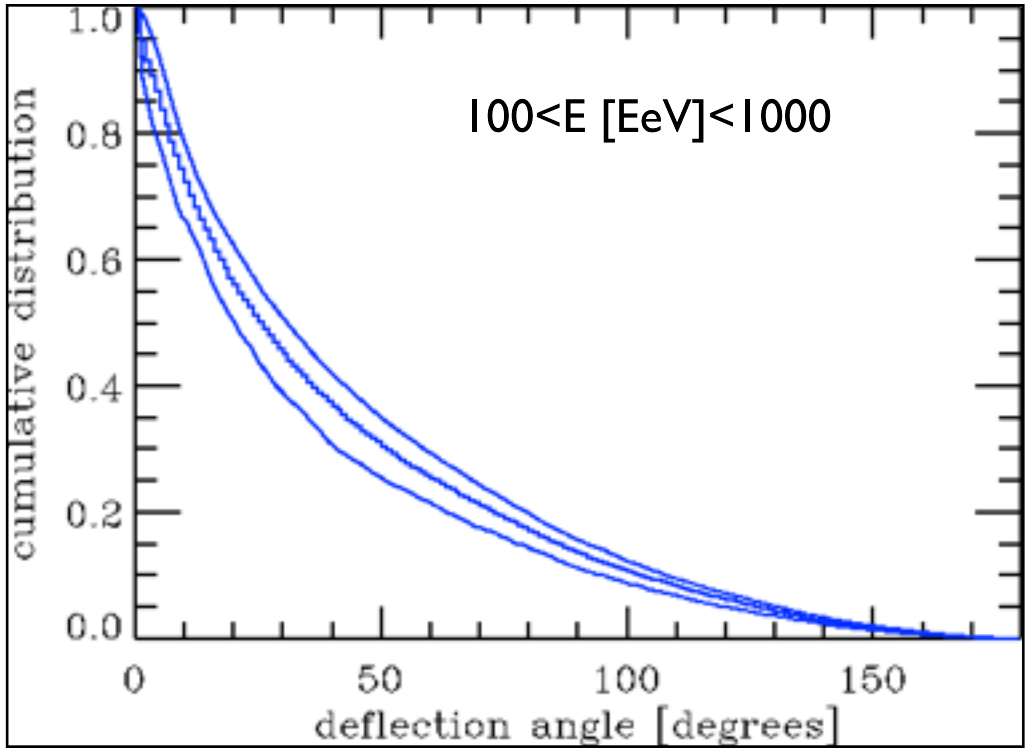


Sigl. JCAP 08 (2004) 012



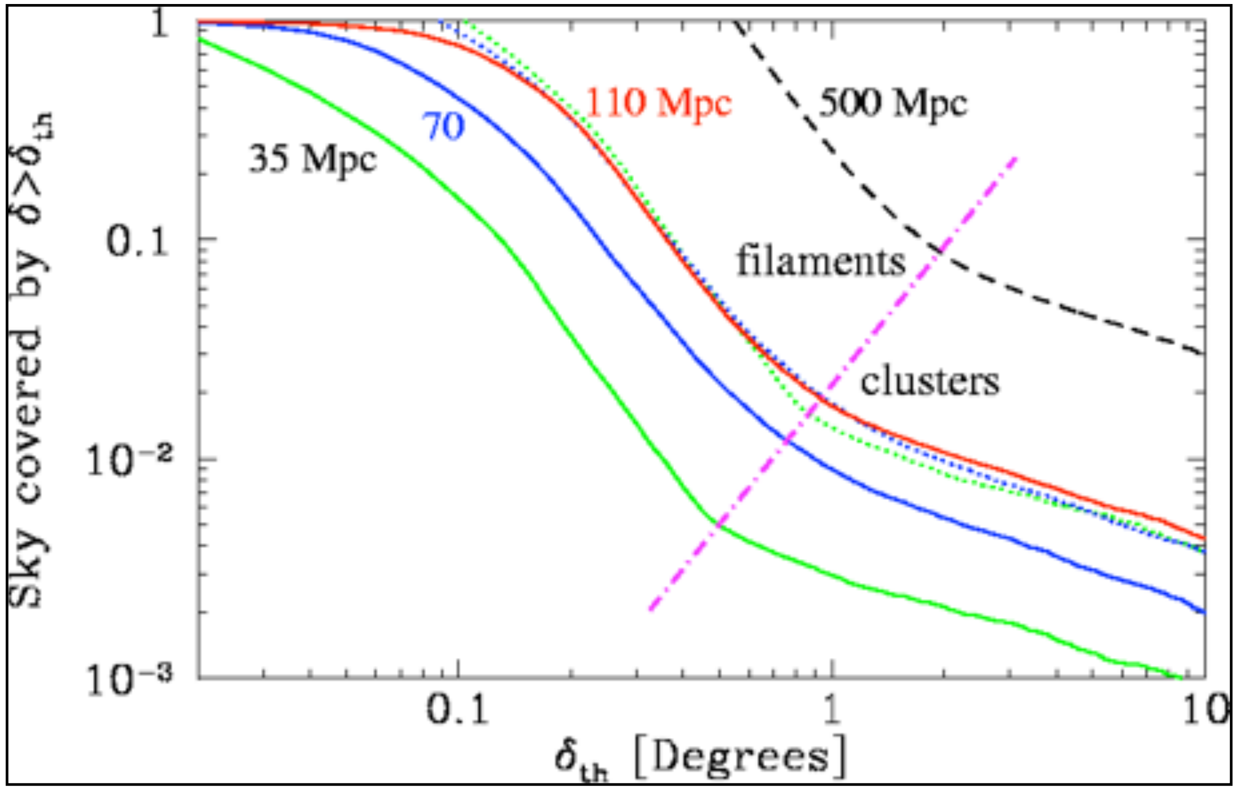


UHECR astronomy?



Sigl, Miniati, Ensslin. PRD 70 (2004) 043007

- cumulative deflections displayed are for protons
- Sigl+: deflections are high
- Dolag+: deflections are small
- for heavy nuclei deflections can be even higher
- UHECR astronomy may be possible in the later but not in the former scenario



Dolag et al. JETP 79(2004) 583

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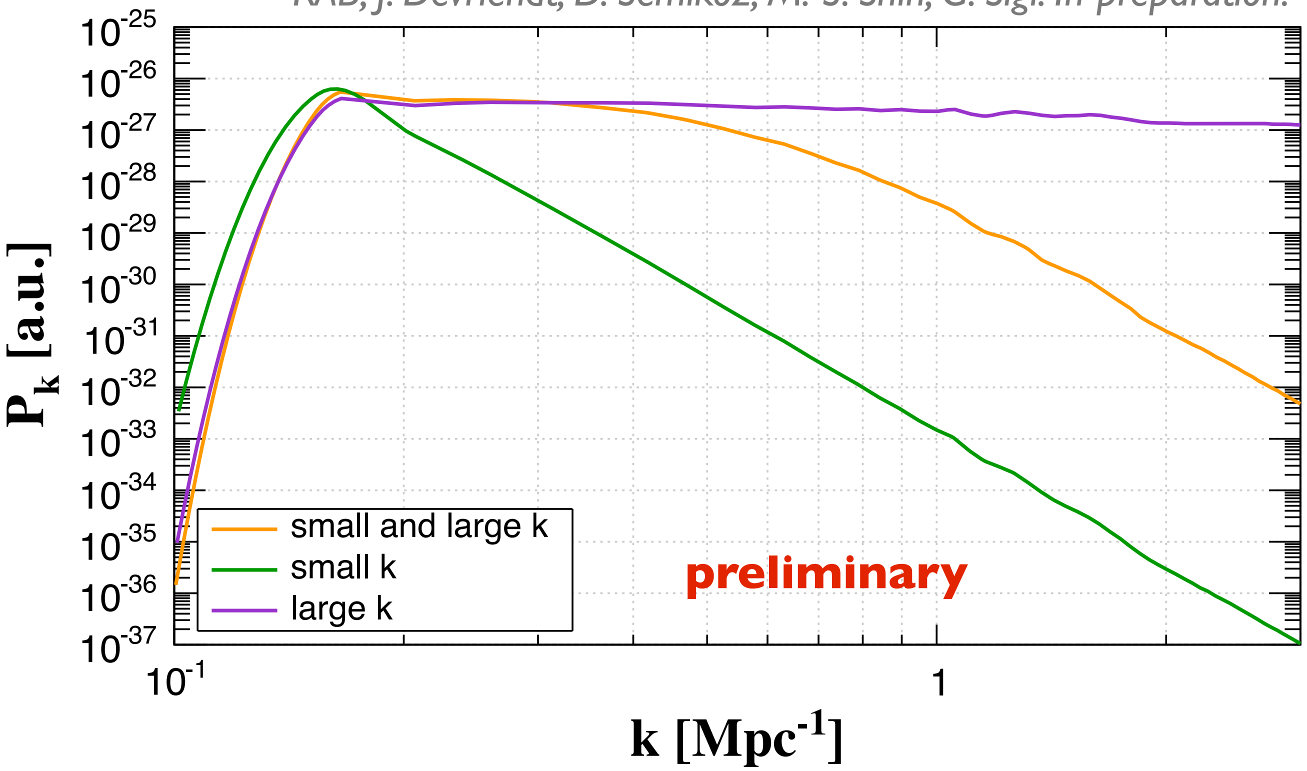
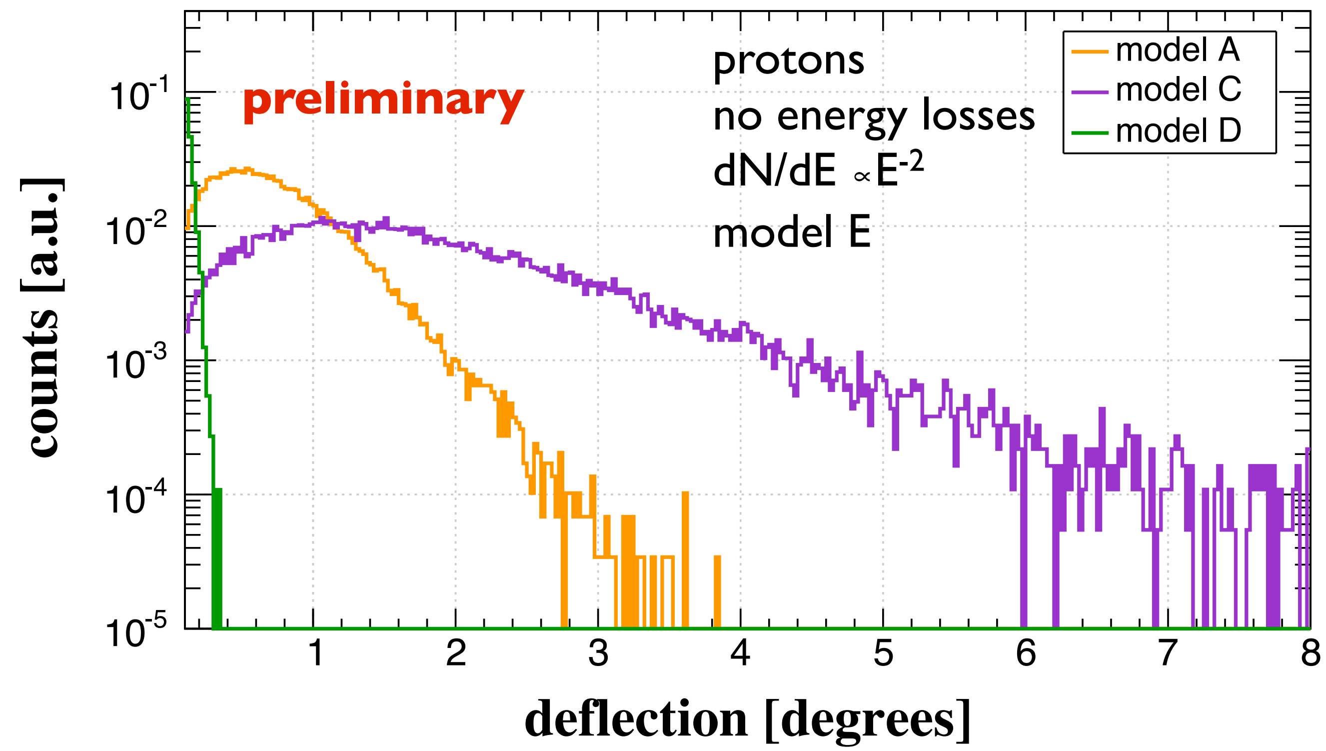
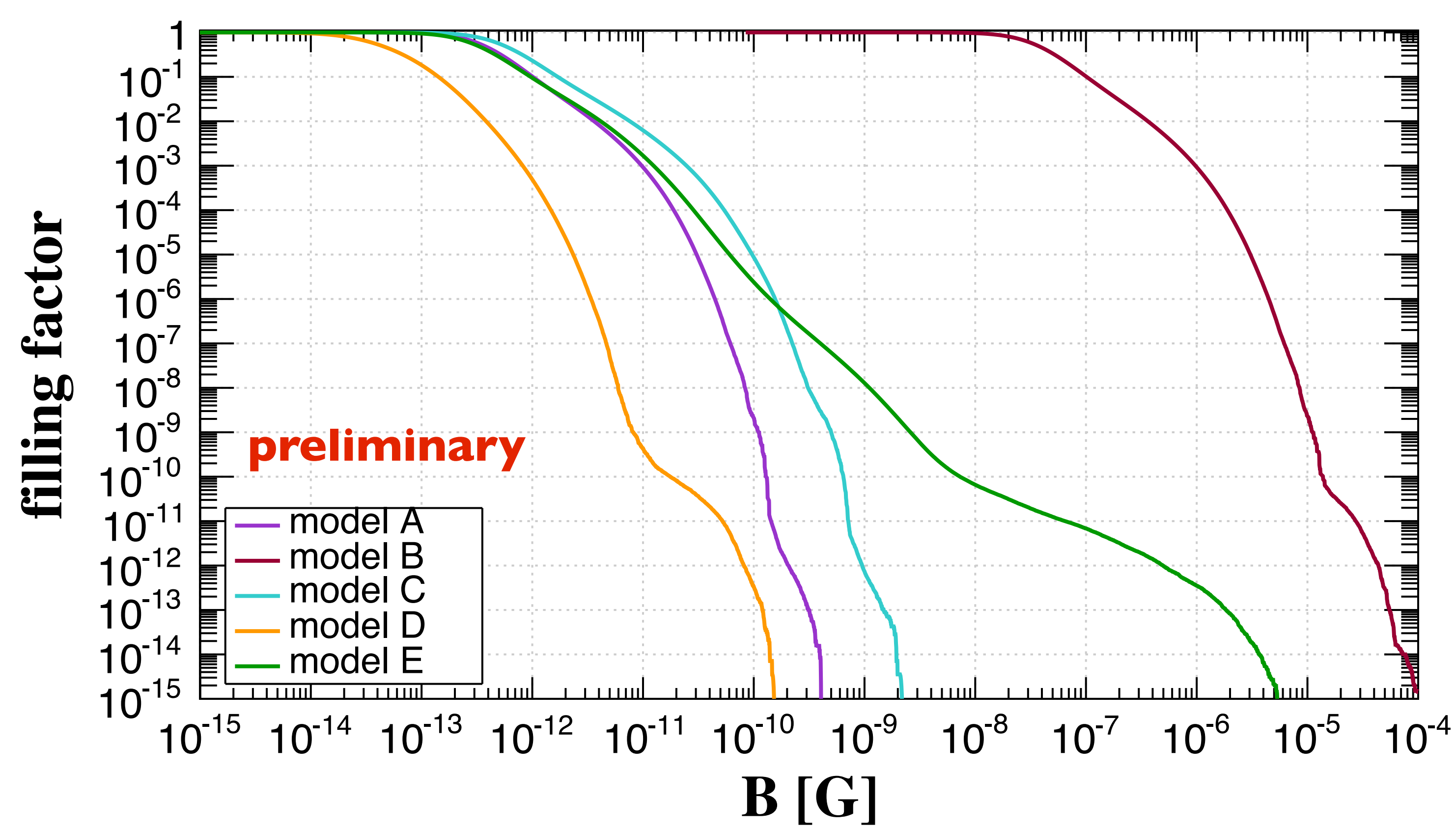




- 200 Mpc/h box
- simulations being done by M.-S. Shin, J. Devriendt, ...
- adaptative mesh refinement (AMR) using the RAMSES code [Teyssier '02]
- 10 levels of refinement



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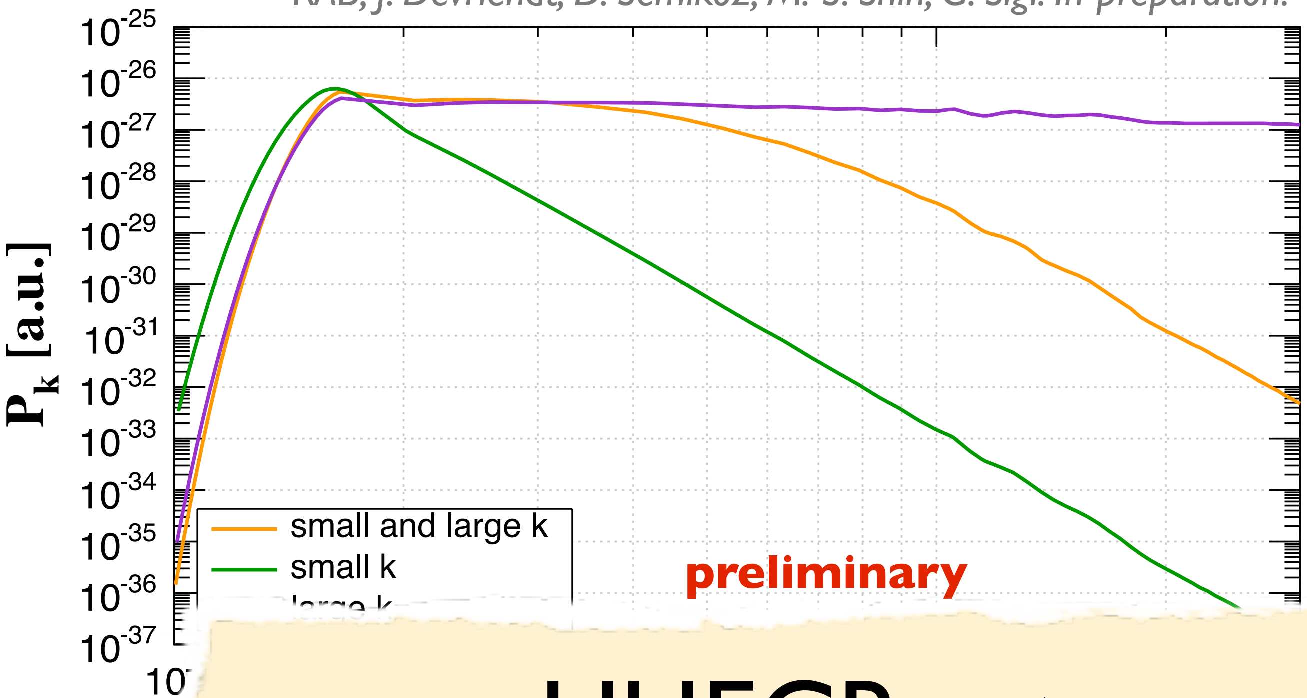
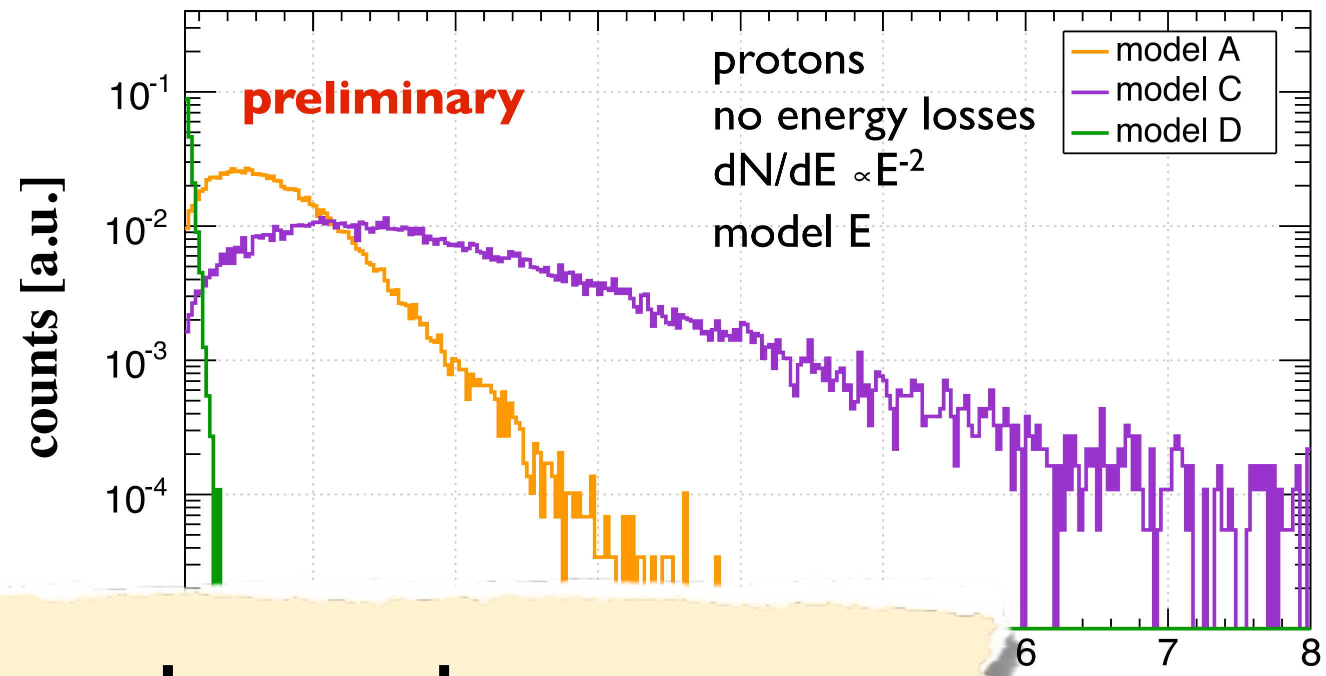
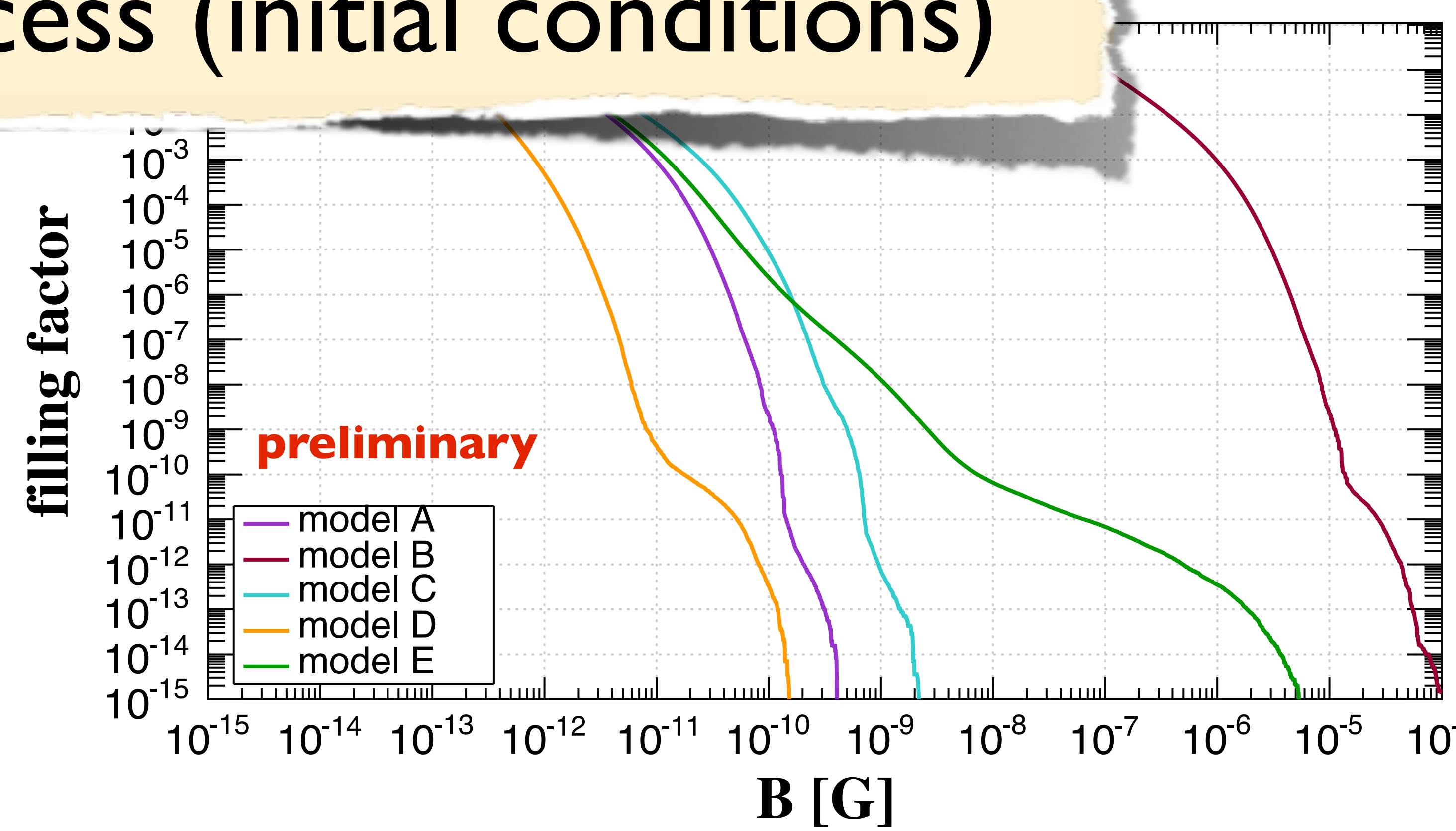


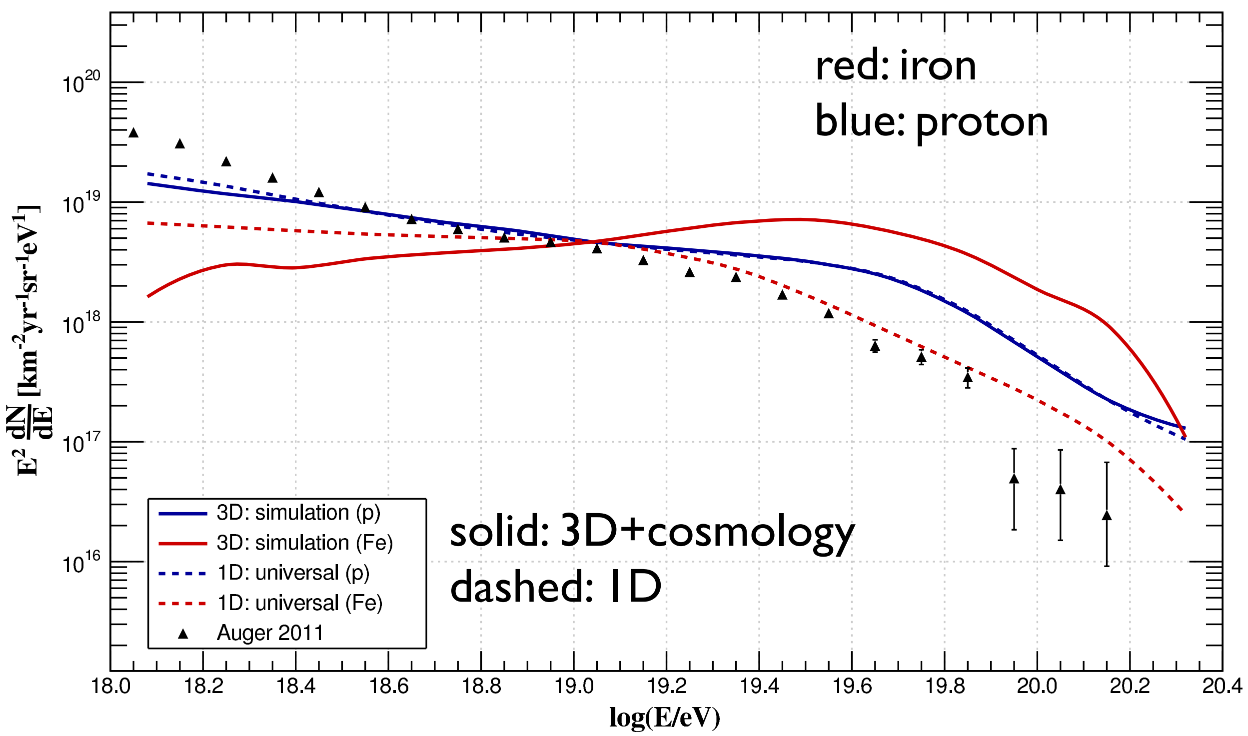


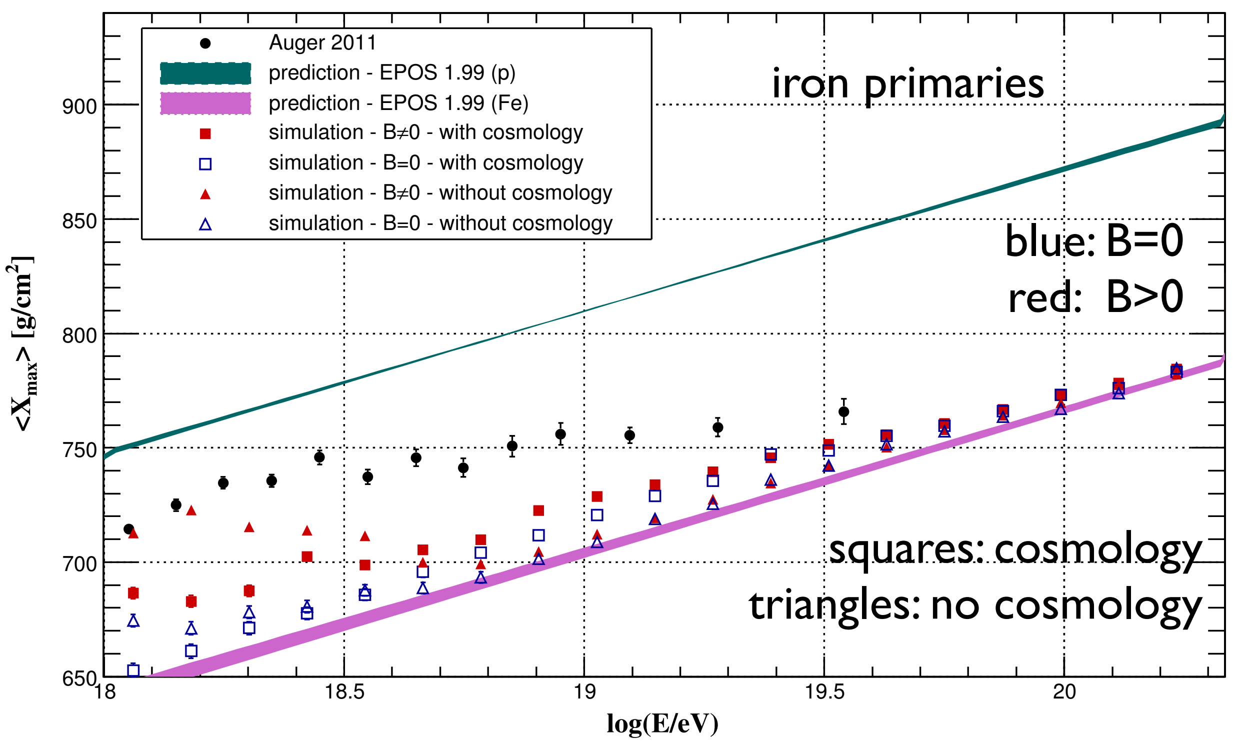
UHECR astronomy depends on magnetogenesis process (initial conditions)

- 200 Mpc/h box
- simulations being done by M.-S. Shin, J. Devriendt, ...
- adaptative mesh refinement (AMR) using the RAMSES code [Teyssier '02]
- 10 levels of refinement



cosmological effects + magnetic fields



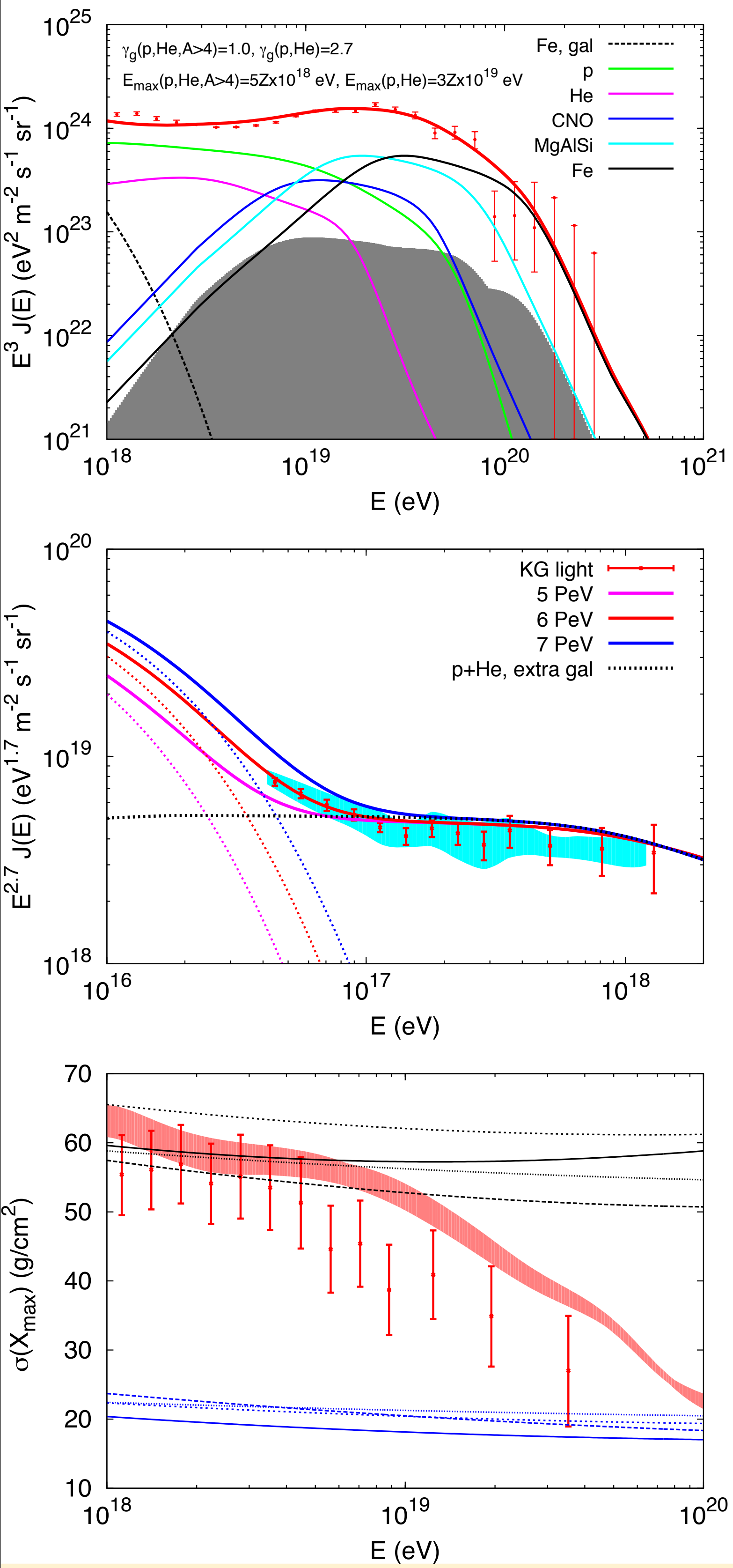


RAB, Schiffer, Sigl. NIM A 742 (2014) 245

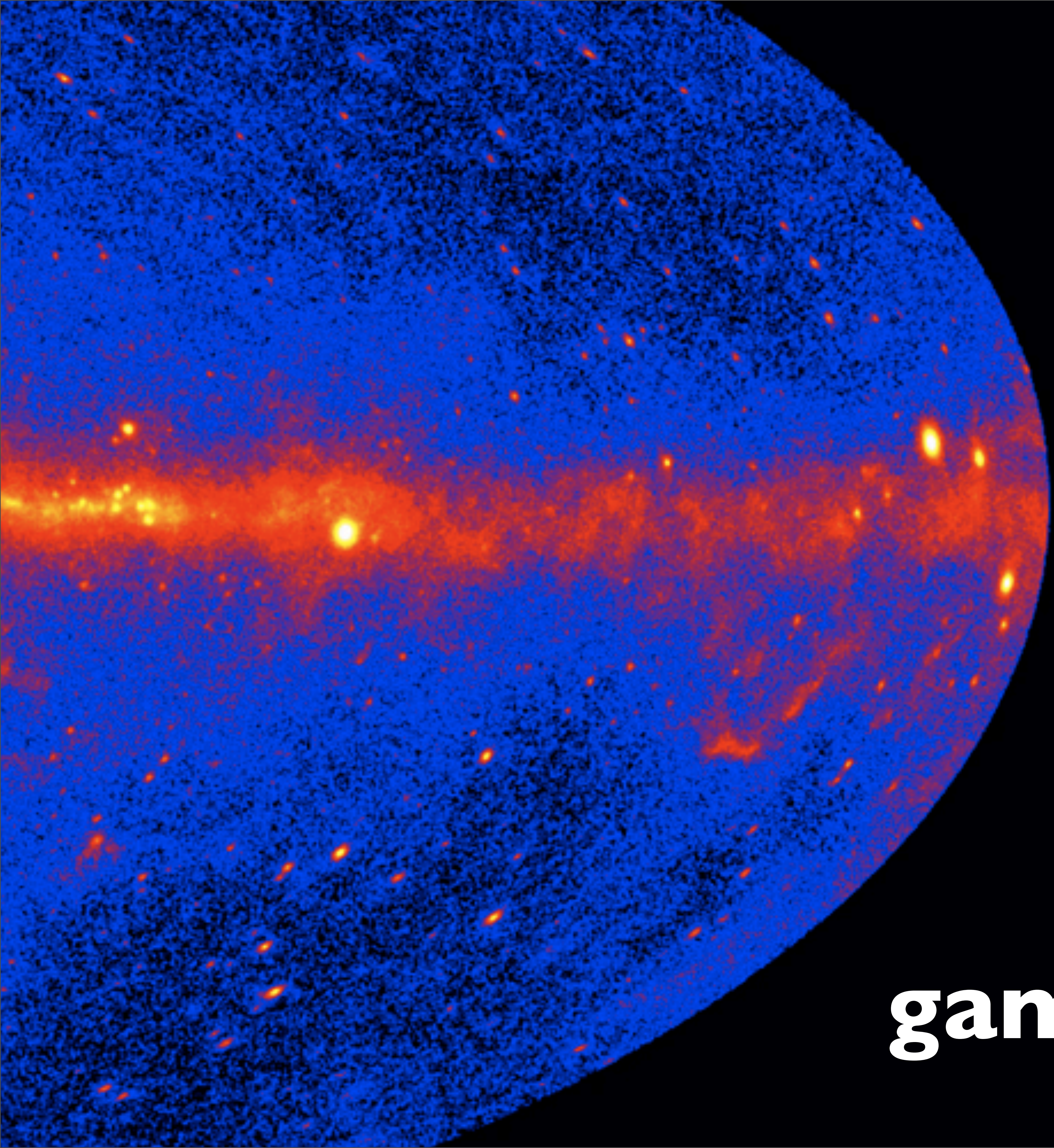
- magnetic fields can affect the shape of the spectrum, so they should be taken into account when performing simulations text for one column no picture slide
- universal spectrum → expected for a uniform source distribution (separation << propagation lengths) → no magnetic field effects
- deviations from universal spectrum for pure iron composition
- large scale structures (magnetic field) + cosmological effects + energy losses → realistic simulations
- cosmological effects may be relevant, mainly at energies ~ EeV
- need to include cosmological effects in 3D simulations → 4D simulations

spectrum-composition fits

Aloisio, Berezinsky, Blasi arXiv:1312.7459

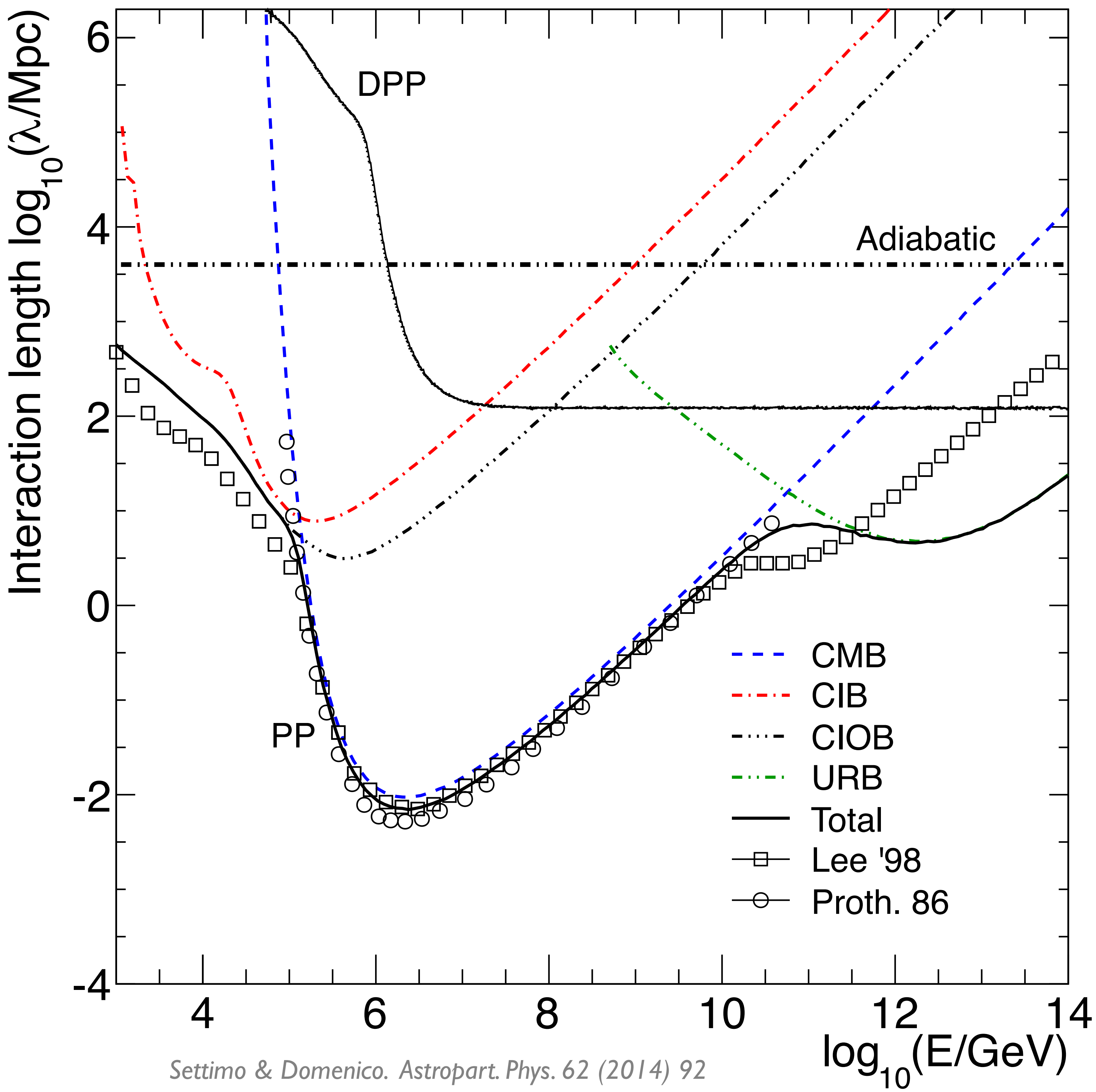


- combined spectrum-composition (1D) fits of the Auger spectrum/ composition *[Aloisio+ '13, Taylor '13]*
- mixed composition; maximum source acceleration cutoff (no GZK)
- results suggest an extra (light) class of sources below the ankle might be needed → Auger + KASCADE-Grande data
- hard spectra "problem" *[Taylor '13]*: these fits seem to suggest that the sources have spectral indexes harder than expected ($\gamma \approx 1.0$-1.6); expected $\gamma \approx 2.0$-2.2 for Fermi acceleration
- magnetic horizon effects might soften the hard spectra, making it again compatible with Fermi shock acceleration *[Mollerach & Roulet '13]*
- magnetic horizon effects do not play a role at EeV energies in realistic extragalactic magnetic field models *[RAB & Sigl '14]*
- caveat I: hadronic interaction models can fail to describe interactions at the highest energies (e.g. muon problem *[Auger '14]*)
- caveat II: source distribution, magnetic field model, nearby sources, etc → shape of the spectrum is sensitive to these parameters



gamma rays

interactions and energy losses



Settimo & Domenico. Astropart. Phys. 62 (2014) 92

main interactions

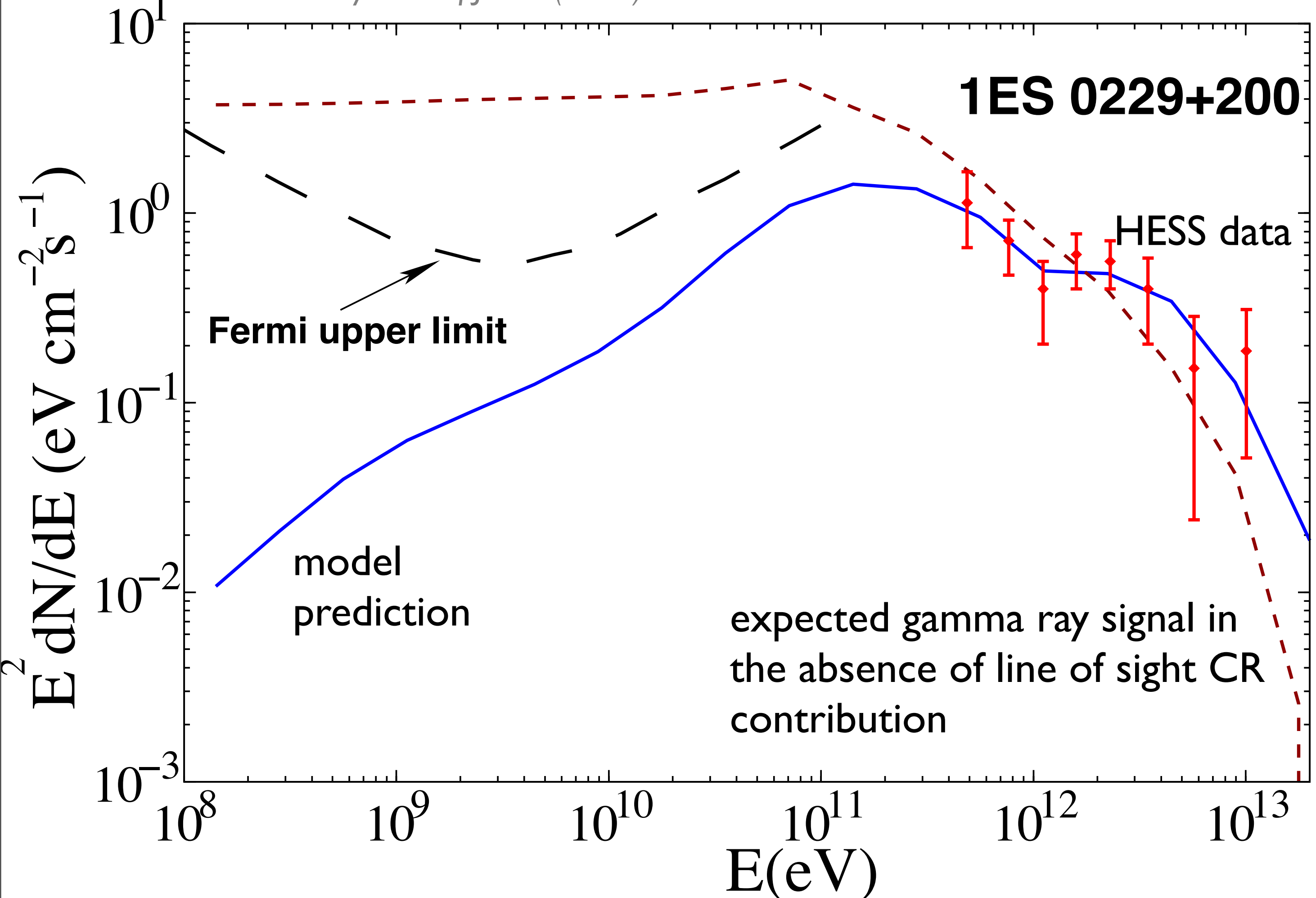
- cosmic microwave background (CMB)
- cosmic infrared background (CIB)
- cosmic infrared and optical background (CIOB)
- universal radio background (URB)

energy losses

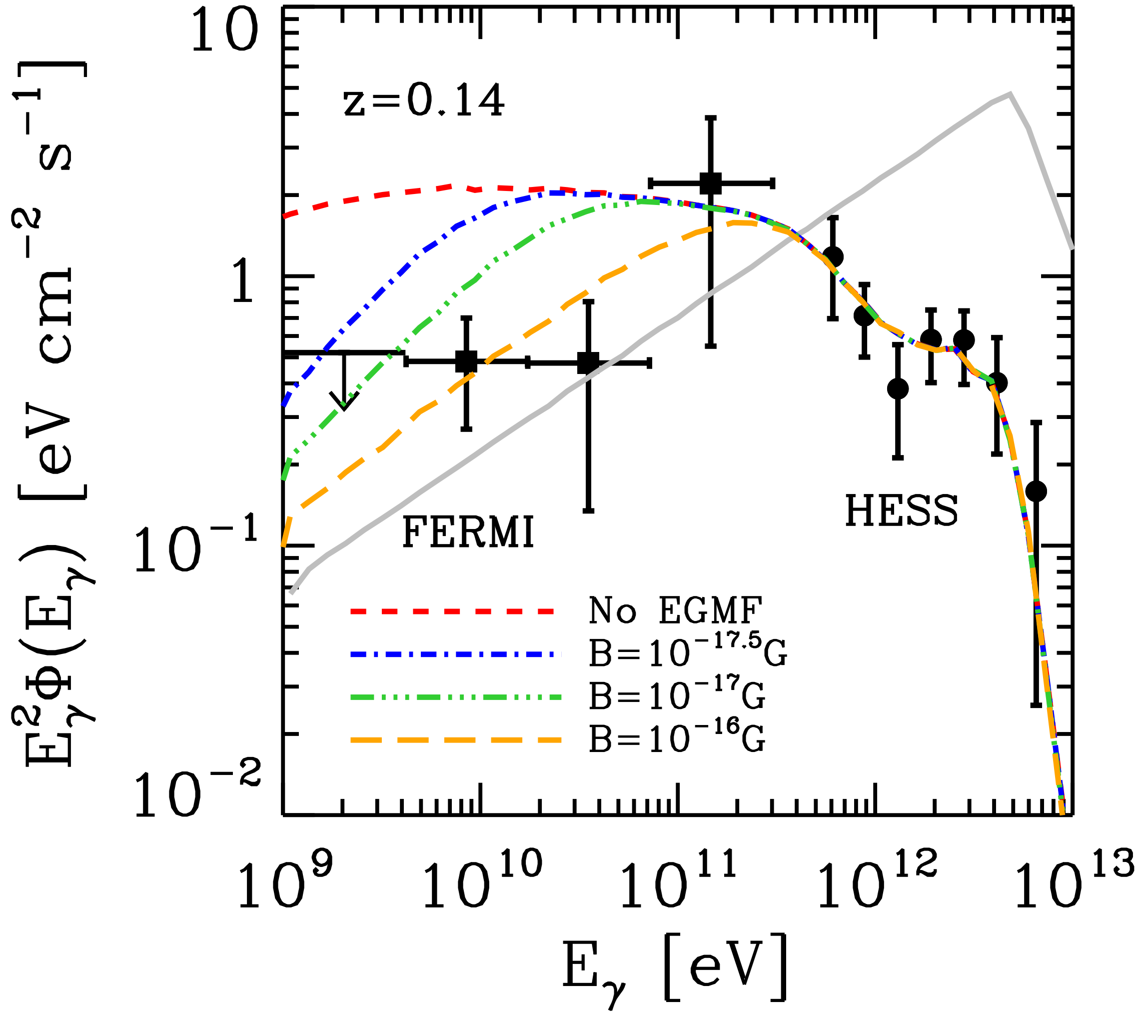
- pair production
- double pair production
- adiabatic expansion of the universe

TeV-GeV flux "problem"

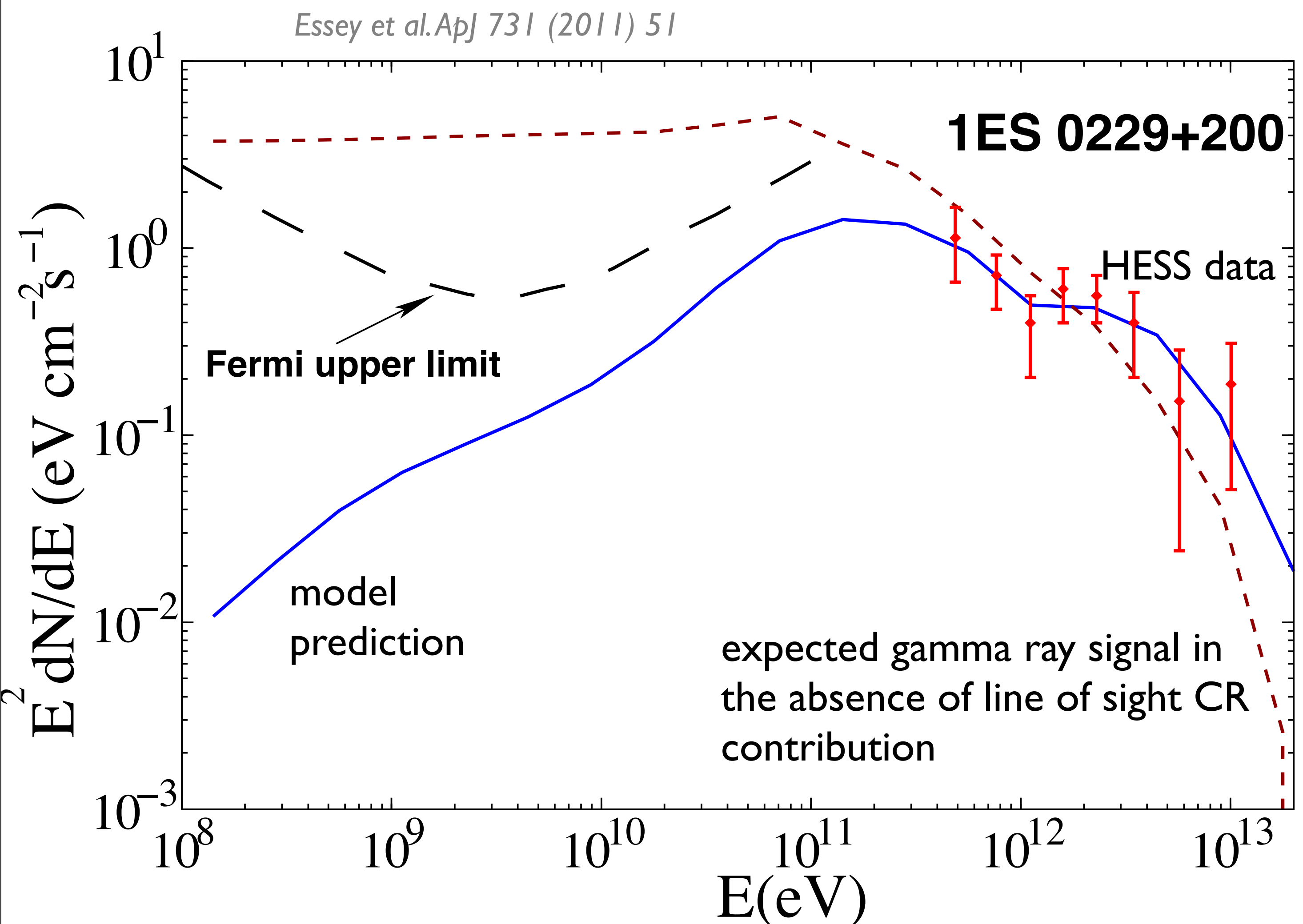
Essey et al. ApJ 731 (2011) 51

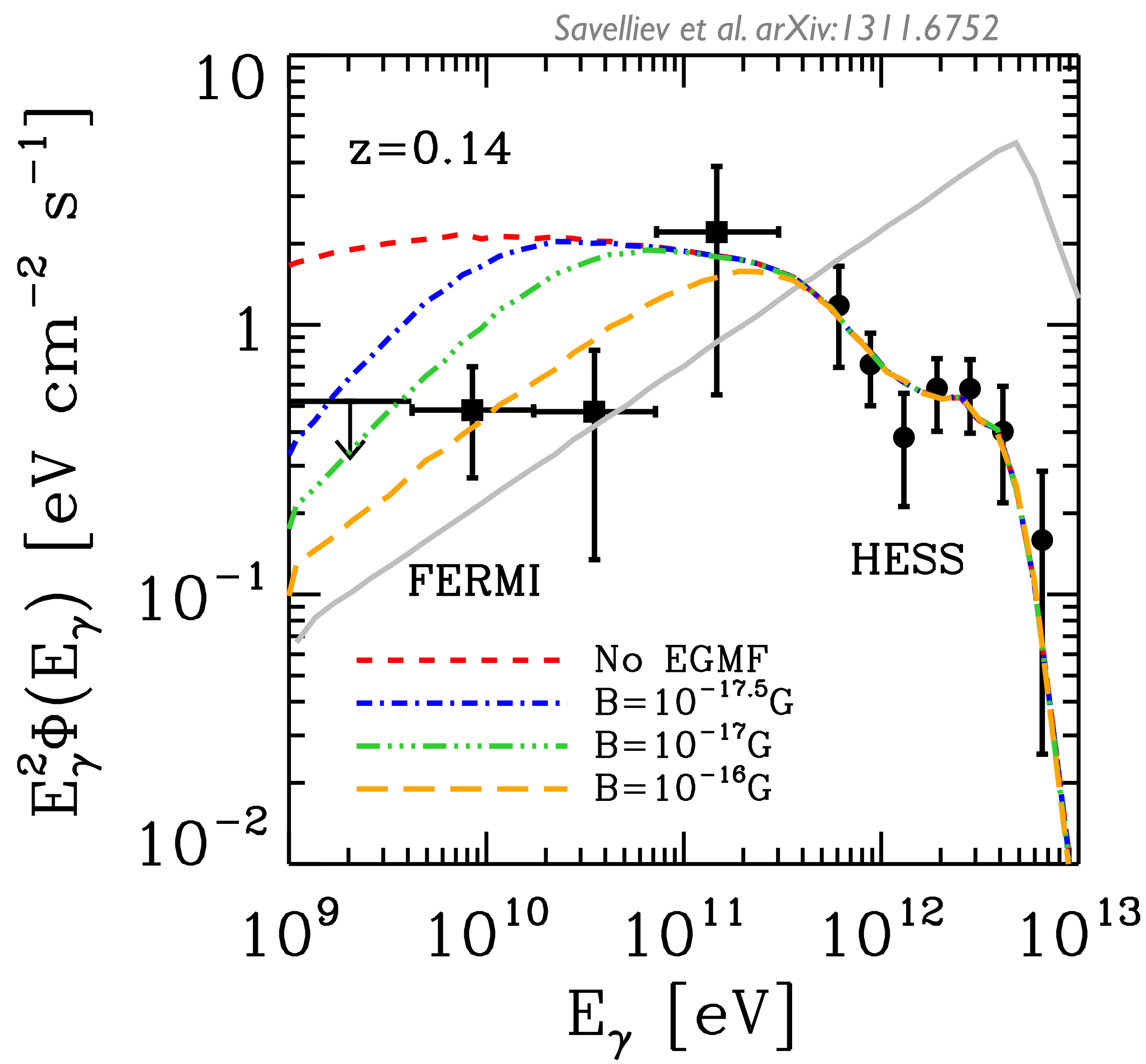


Savelliev et al. arXiv:1311.6752



TeV-GeV flux “problem”



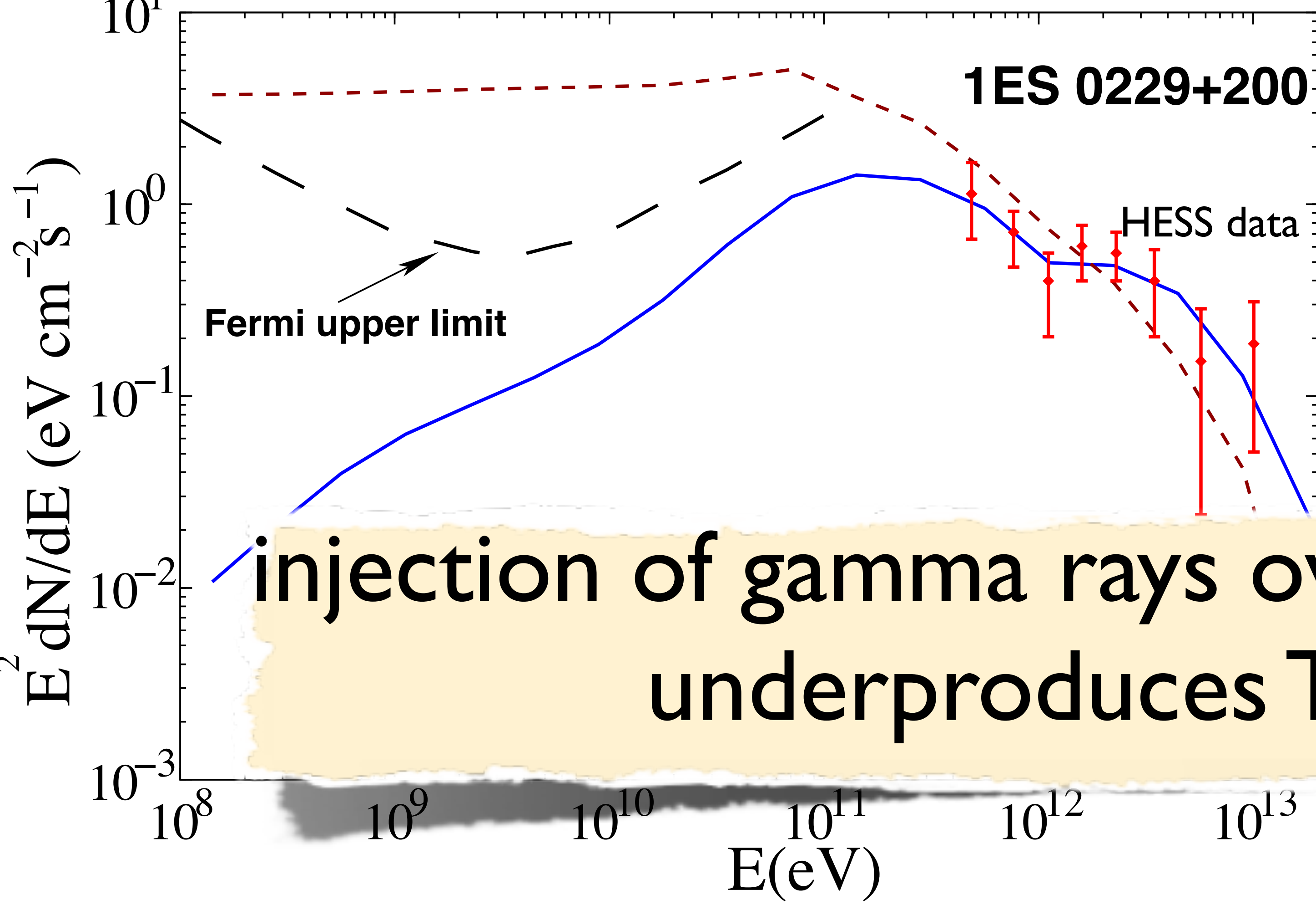


solutions

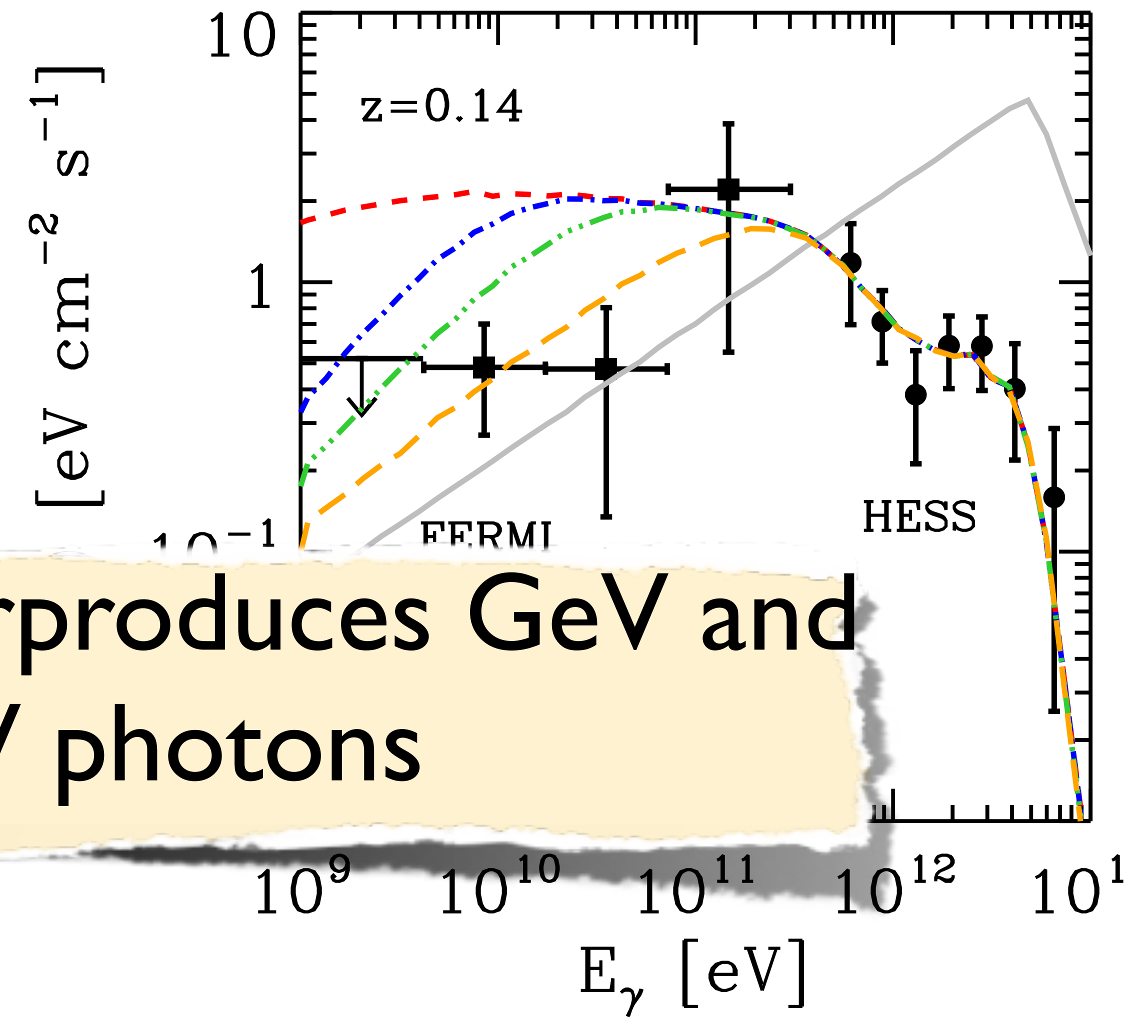
- $B > 10^{-17}$ G disperses the GeV cascade *[Neronov & Vovk ’10, Taylor+ ’11]*
- plasma instabilities suppresses the development of the cascades *[Broderick+ ’11]*
- primary CRs continuously produces TeV gamma rays *[Essey+ ’11]*
- Lorentz invariance violation *[Mavromatos ’10]*
- gamma ray mixing with ALPs or hidden photons *[Horns+ ’12]*

TeV-GeV flux "problem"

Essey et al. ApJ 731 (2011) 51



Savelliev et al. arXiv:1311.6752



injection of gamma rays overproduces GeV and underproduces TeV photons

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electromagnetic cascades

- time delayed photons from primary gamma rays *[Plaga '94, Murase+ '08]*
- gamma rays emitted by blazars
- gamma rays produce e^+e^- pairs → scatter background photons via inverse Compton
- point-like sources will appear extended *[Plaga '94]*
- cascades → lower limits on the extragalactic magnetic field *[Neronov & Semikoz '09]*
- flux suppression at E~GeV *[Neronov & Semikoz '09, Vovk+ '12]*
- controversial issue: plasma instabilities may play a role and suppress the development of the cascades *[Saveliev+ '13]*
- can be induced by gamma rays and high energy cosmic rays

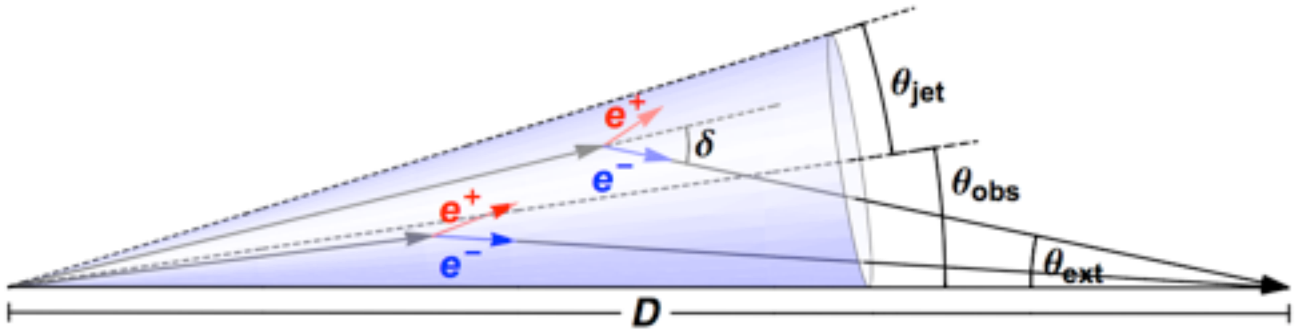
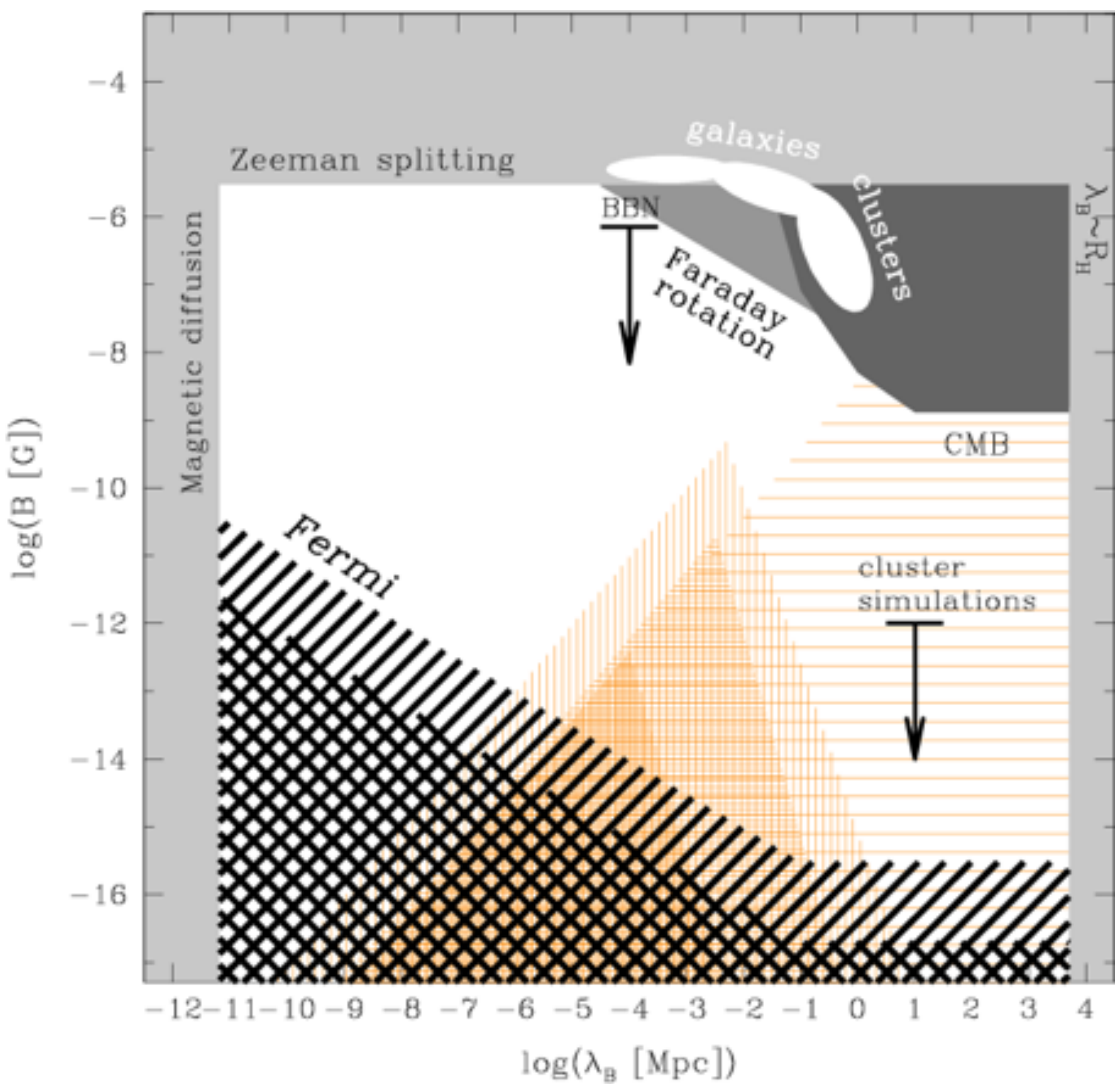
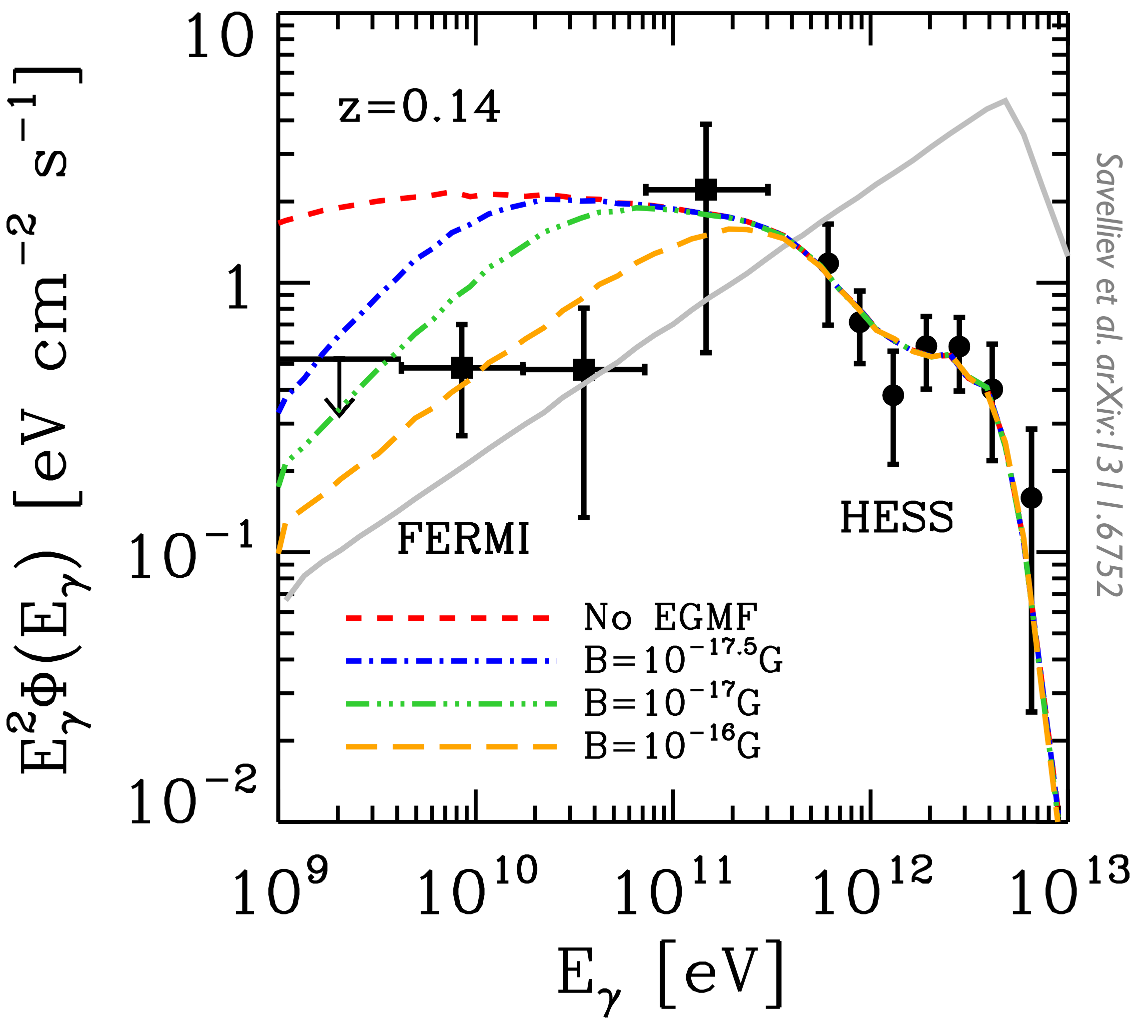


Figure by Andrey Saveliev



Neronov, Vovk. Science 328 (2010) 73

electromagnetic cascades



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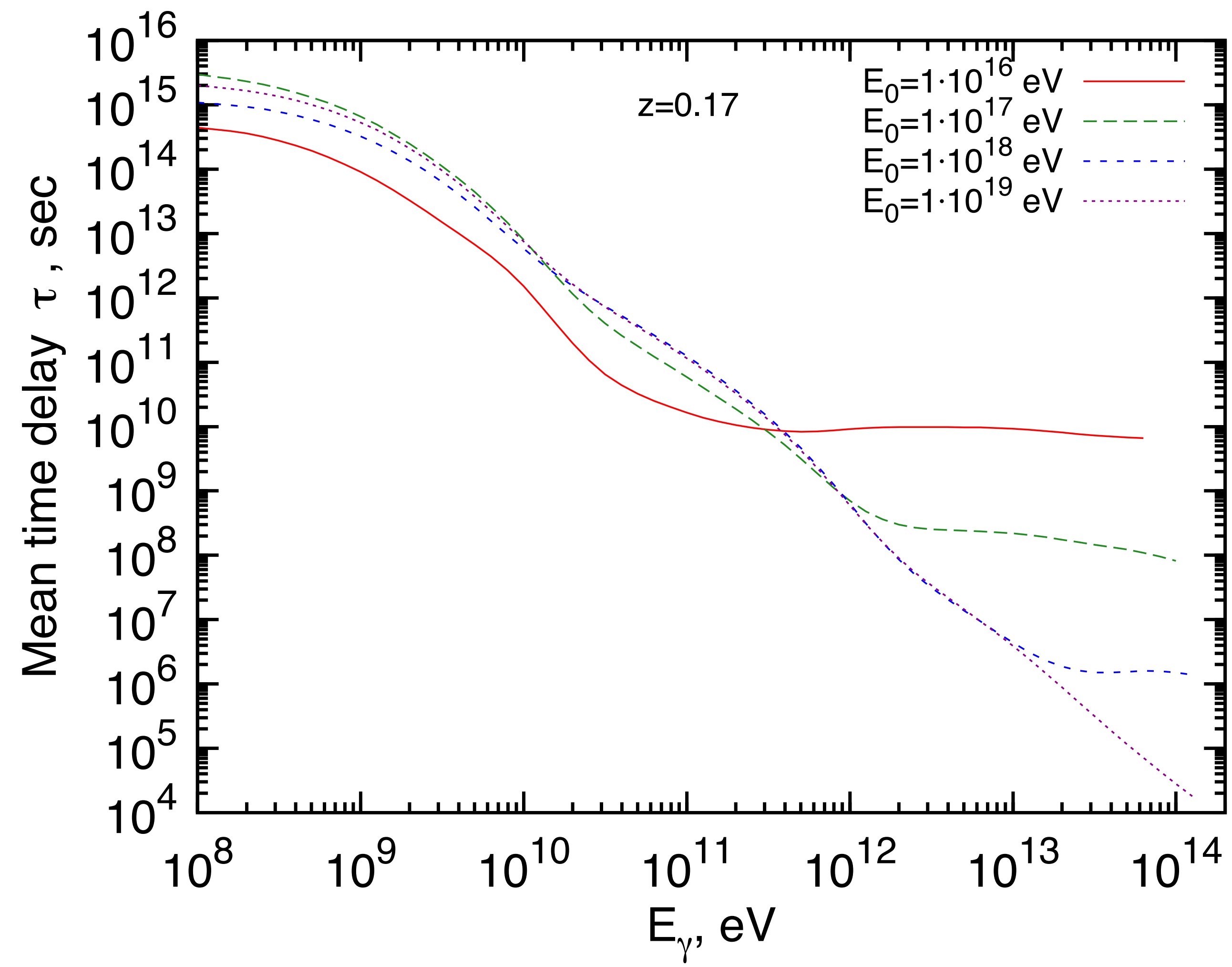
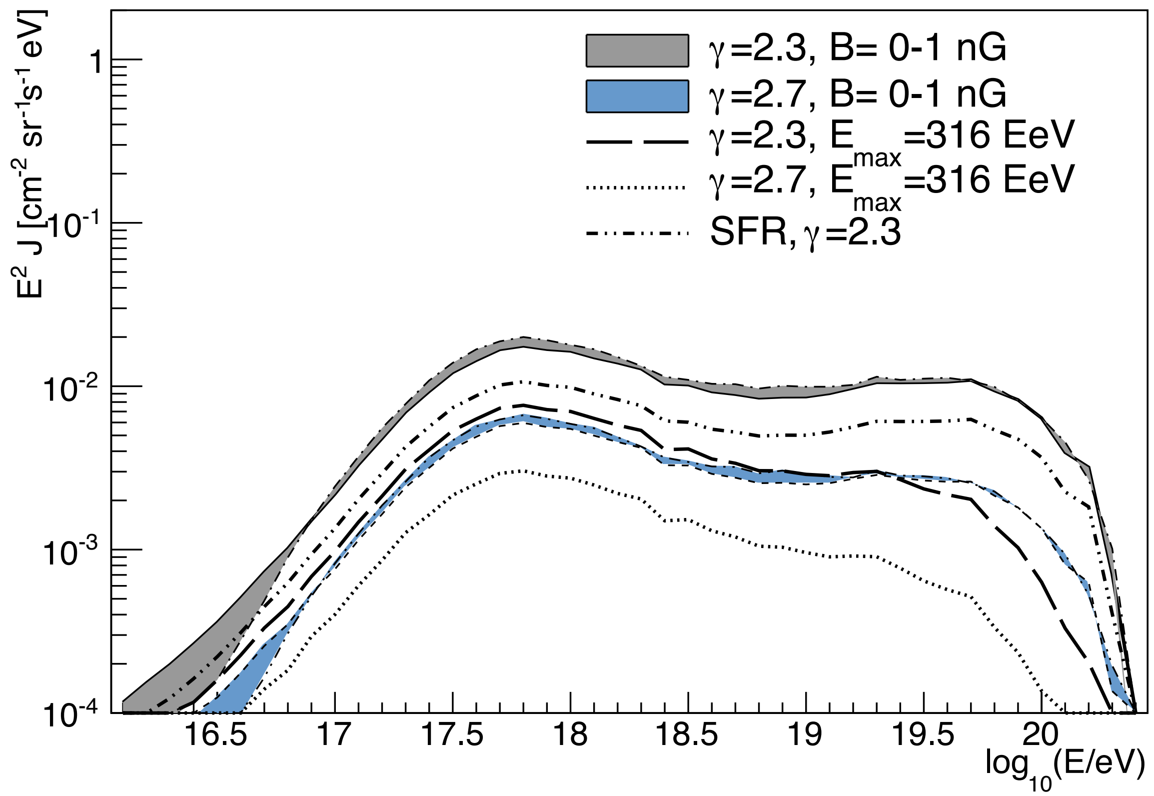
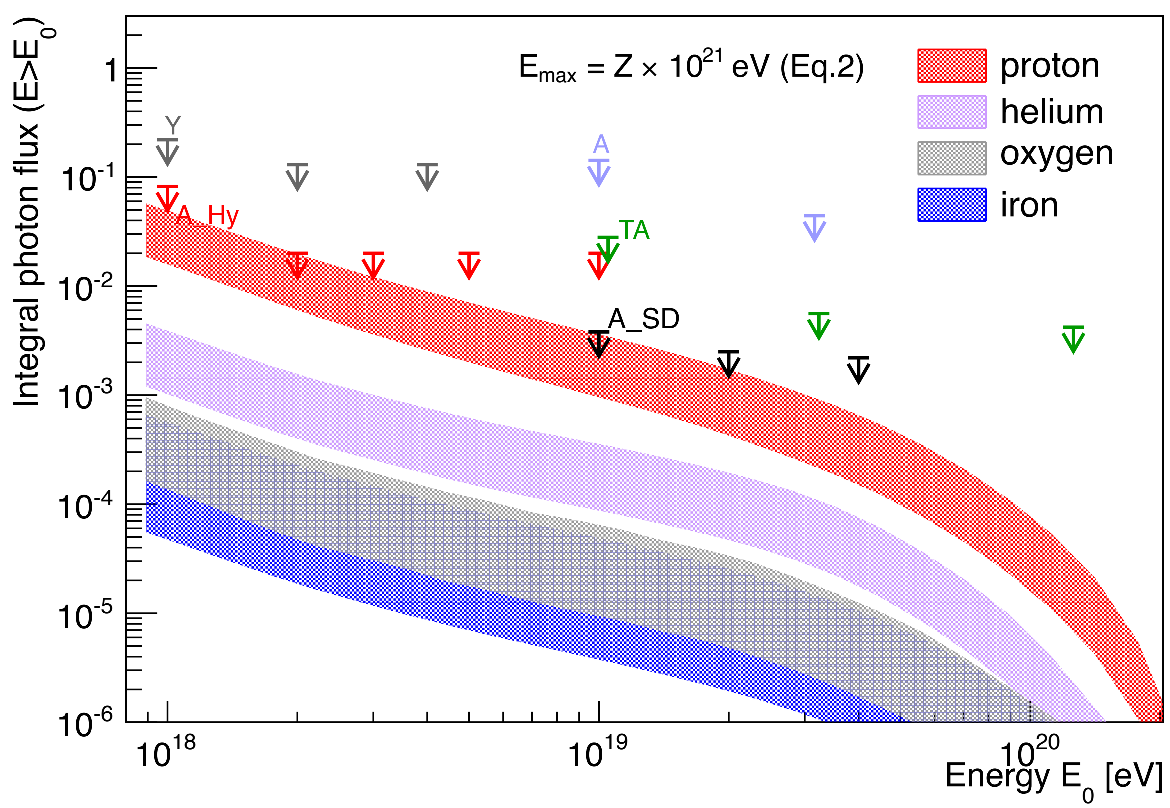
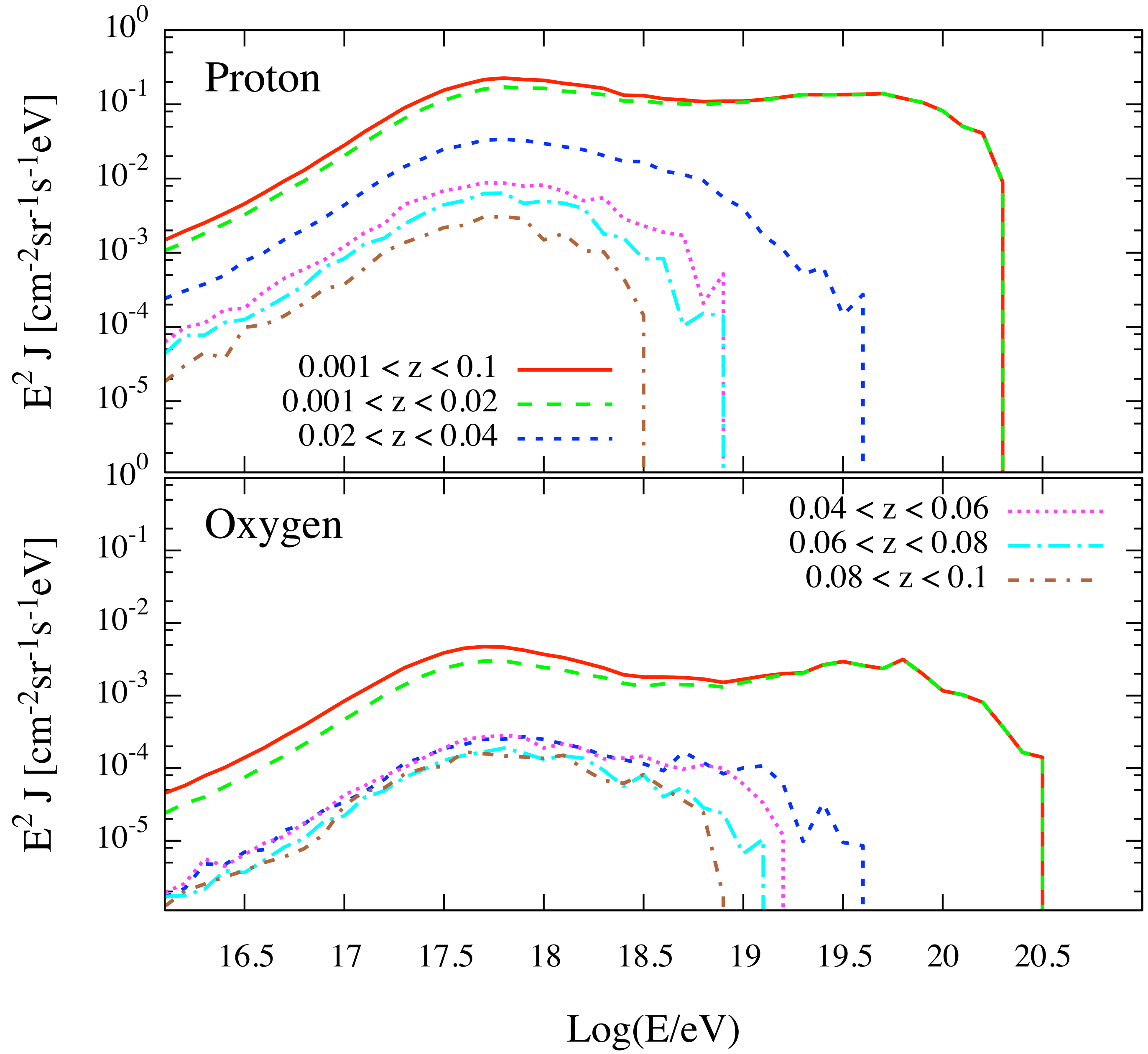


A. Kusenku. Mod. Phys. Lett.A 28 (2013) 1340001

ultra-high energy photons







Settimo & De Domenico, Astropart. Phys 62 (2014) 92

results obtained with the EleCa code

[Settimo & De Domenico '14]


neutrinos

pion production and neutrinos

proton-gamma

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

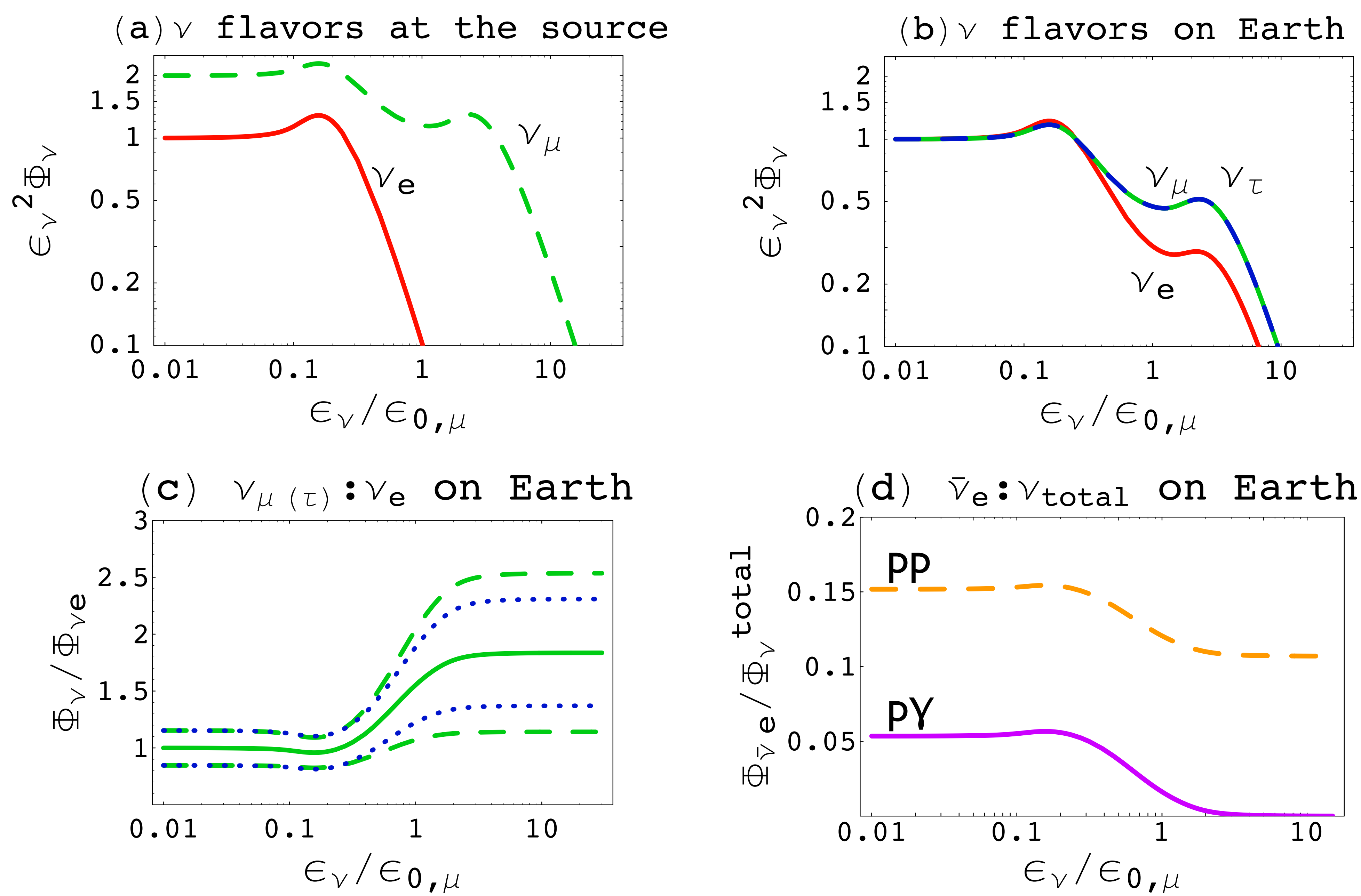
proton-proton

$$p + p \rightarrow p + p + \pi^0$$
$$p + p \rightarrow p + n + \pi^+$$

pion decay

$$\pi^+ \rightarrow \mu^+ + \nu_\mu$$
$$\pi^- \rightarrow \mu^- + \bar{\nu}_\mu$$
$$\pi^0 \rightarrow 2\gamma$$

- injection of pions with energy E_π
- energy loss: $dE/dt \sim E_\pi^2$ $E_{0,\mu}$ (energy at which decay equals energy losses)



Kashti & Waxman. PRL 95 (2005) 111801

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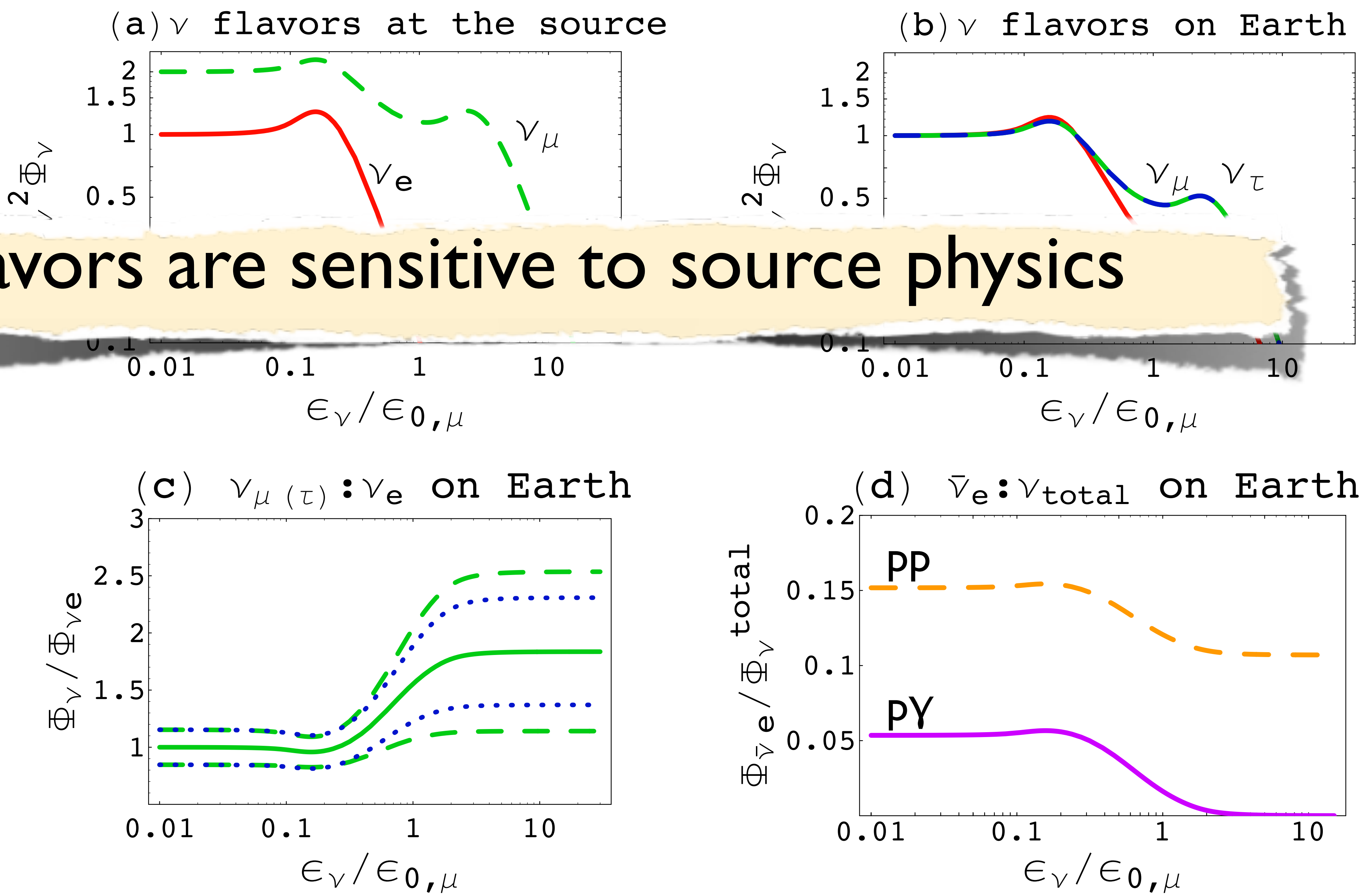
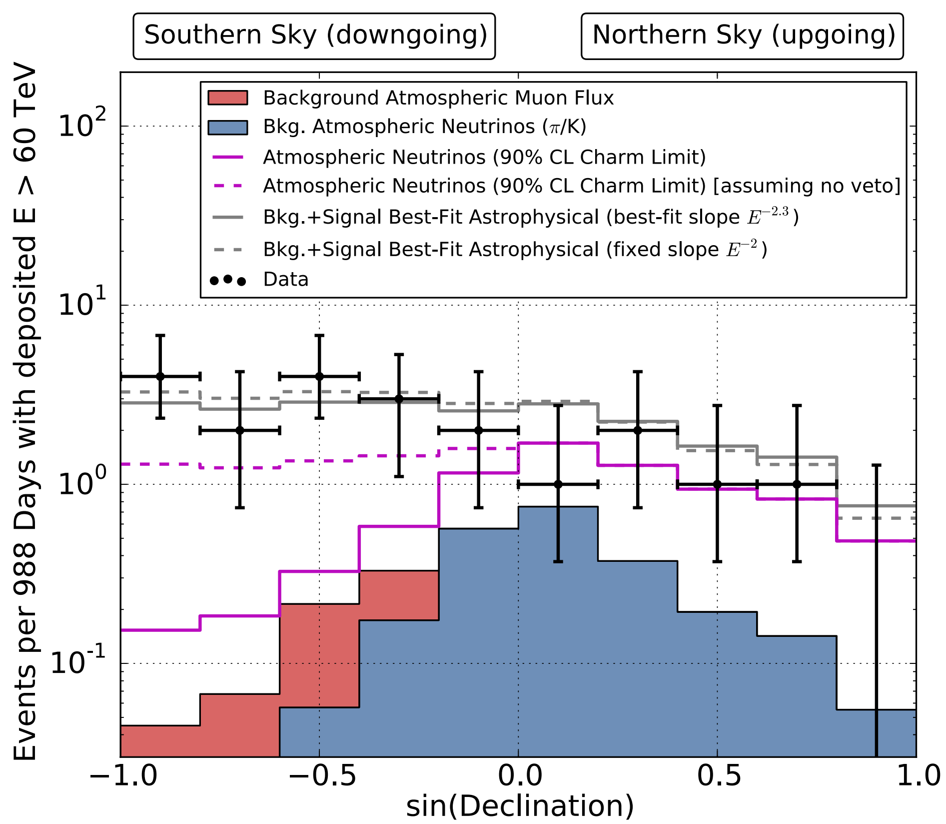
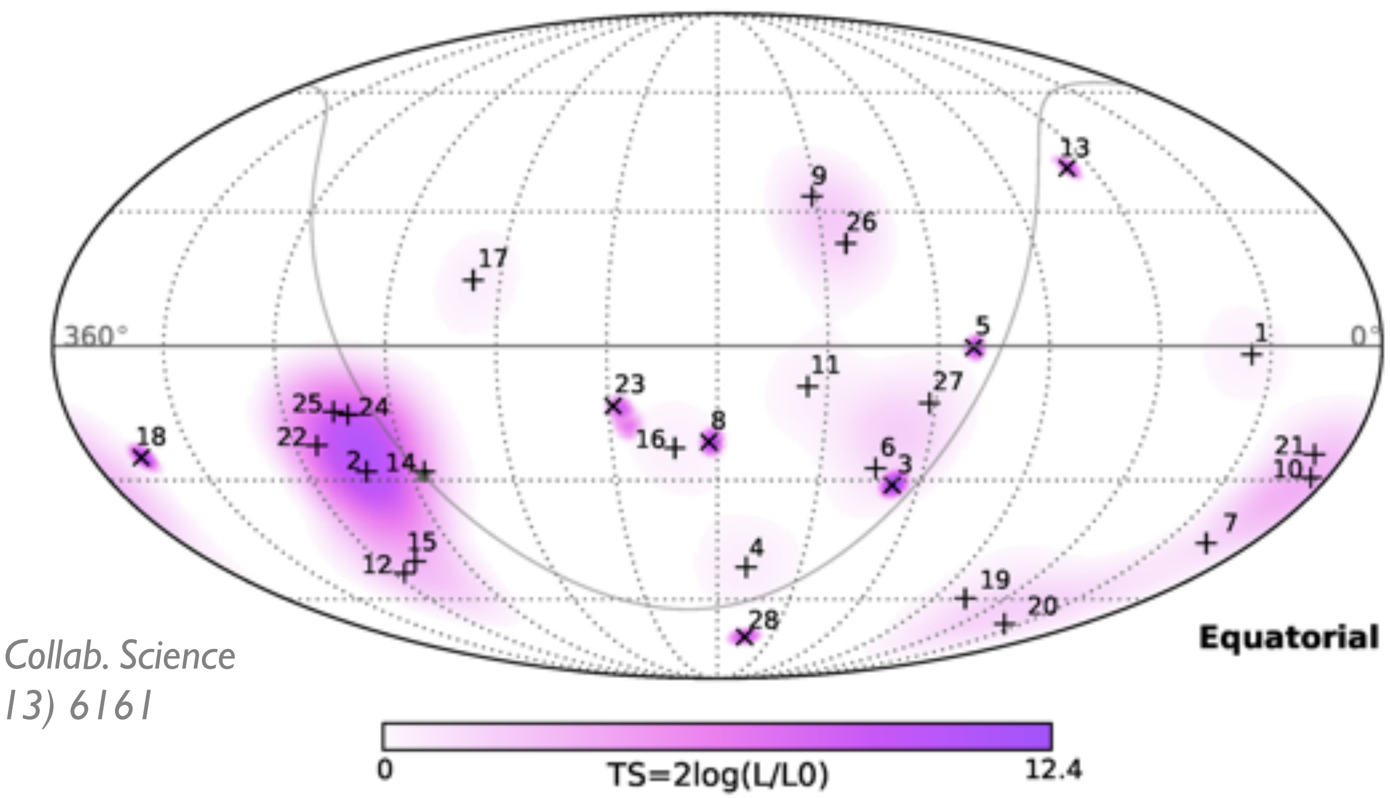


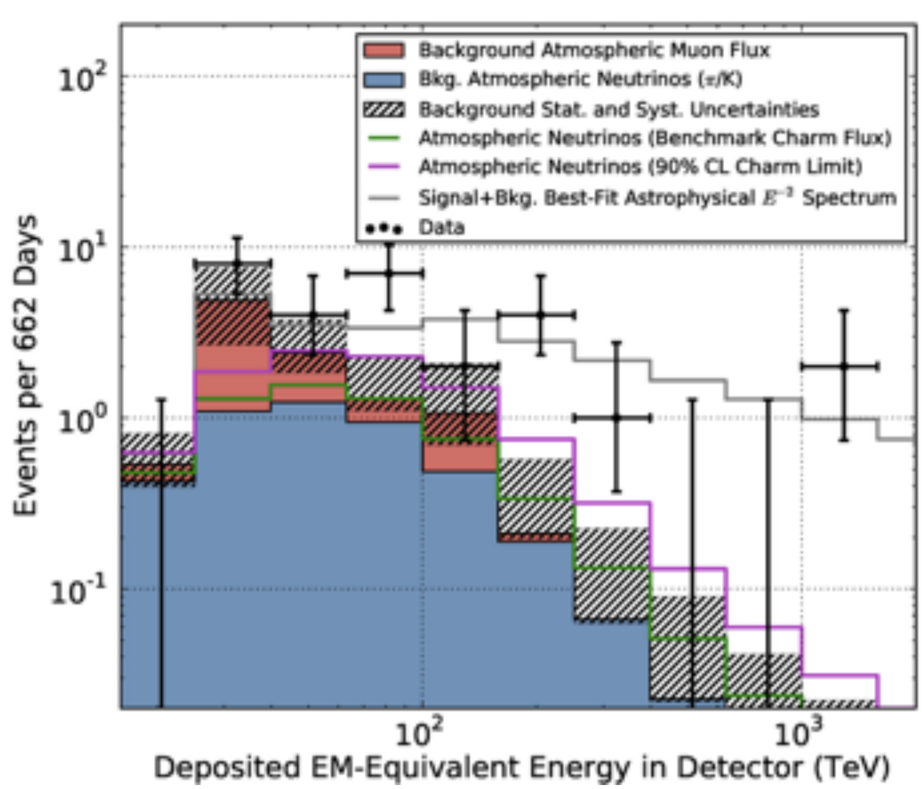
flavors are sensitive to source physics

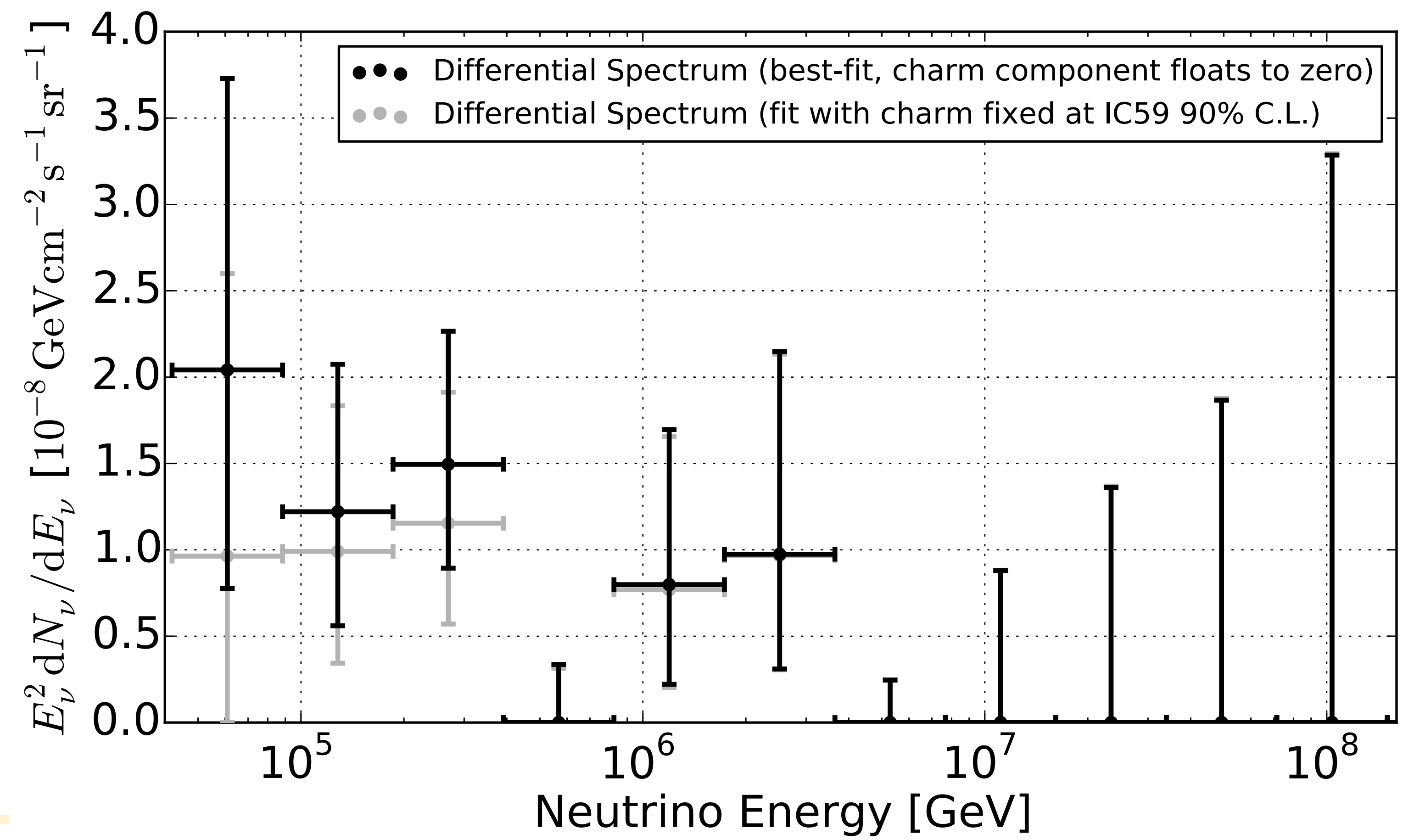
Kashti & Waxman. PRL 95 (2005) 111801





IceCube Collab. Science 342 (2013) 6161





origin of high energy neutrinos

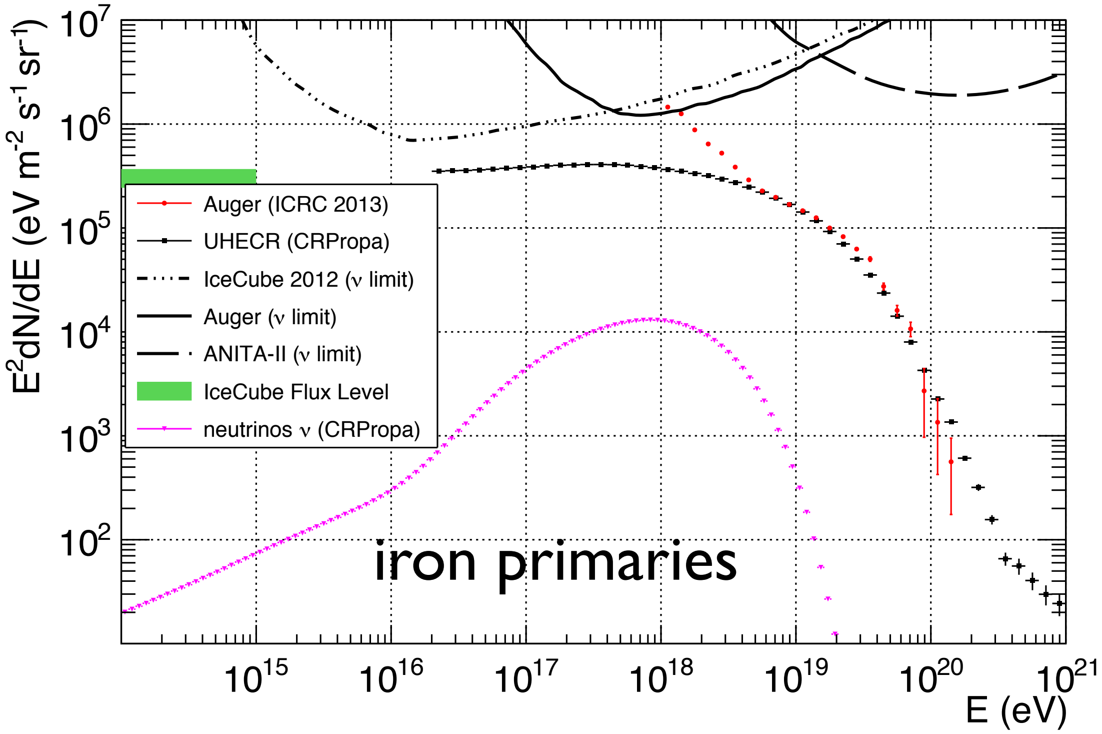
galactic sources

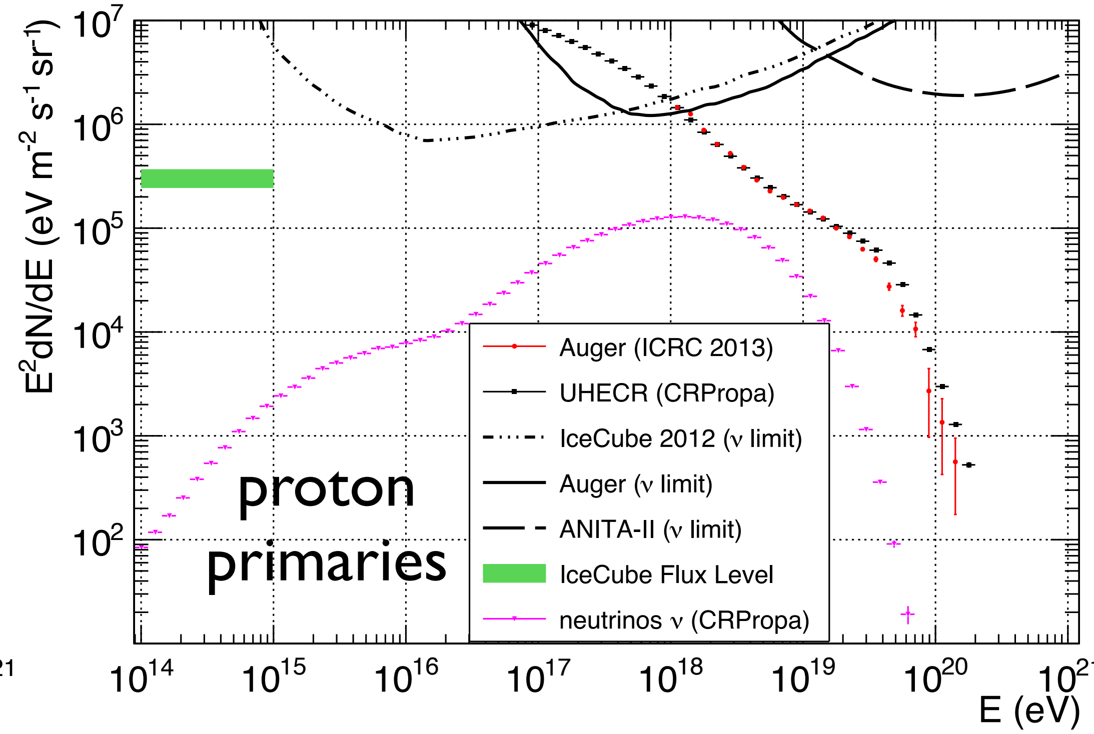
- hypernovae *[Fox+ '13, Ahlers & Murase '14]*
- diffusive galactic emission *[Ahlers & Murase '14, Neronov+ '14]*
- unidentified galactic gamma ray sources *[Fox+ '13]*

extragalactic sources

- galaxy clusters *[Berezisnky+ '97, Murase+ '13]*
- starburst galaxies *[Loeb & Waxman '06, Murase+ '13]*
- AGNs *[Stecker+ '91]*
- GRBs *[Murase & Ioka '13]*
- extragalactic hypernovae *[Liu+ '14]*

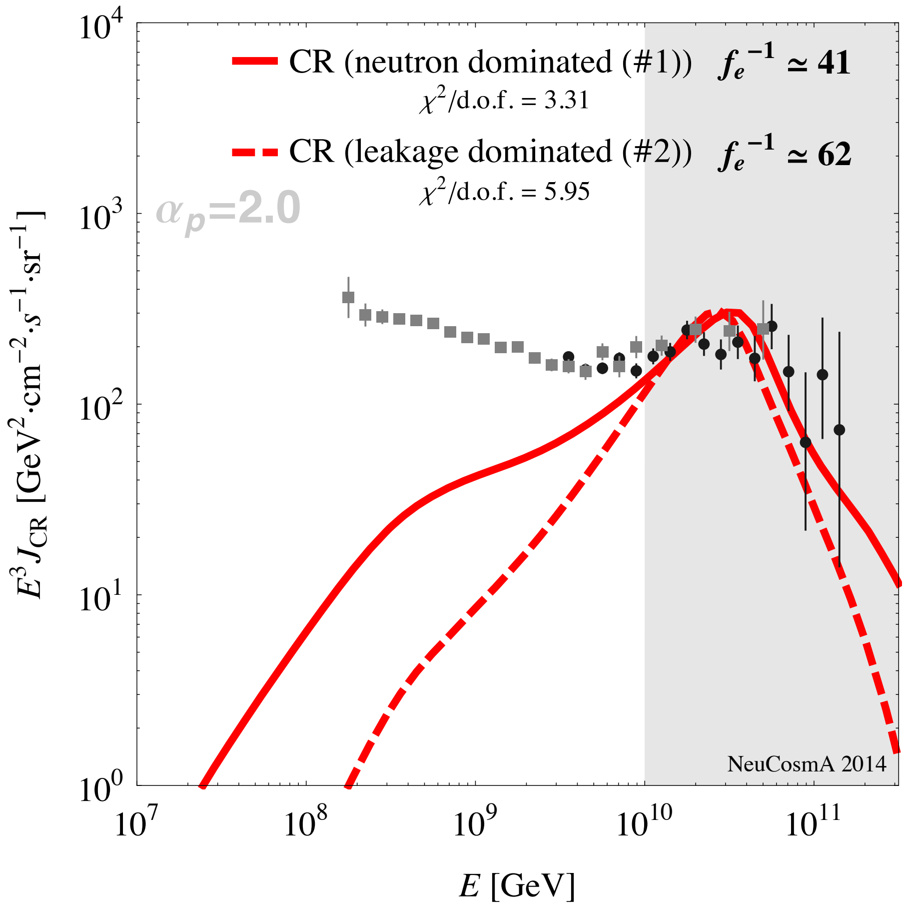
origin of high energy neutrinos

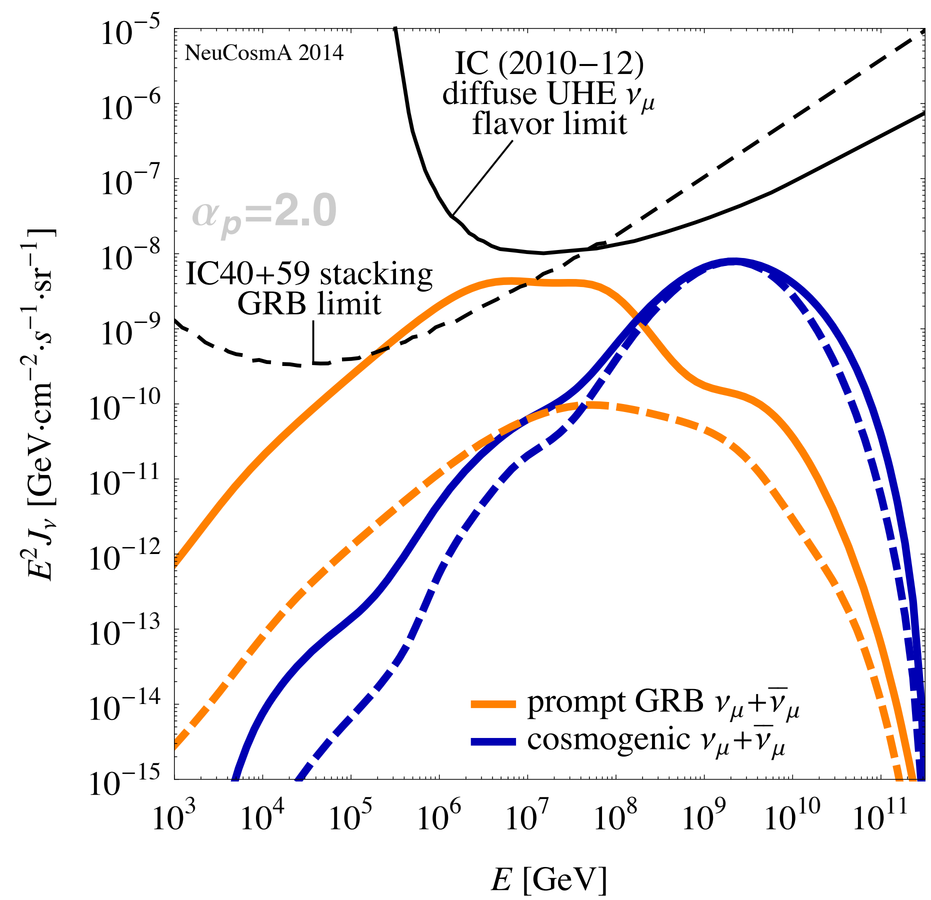




cosmogenic origin

[Sigl & van Vliet '14]

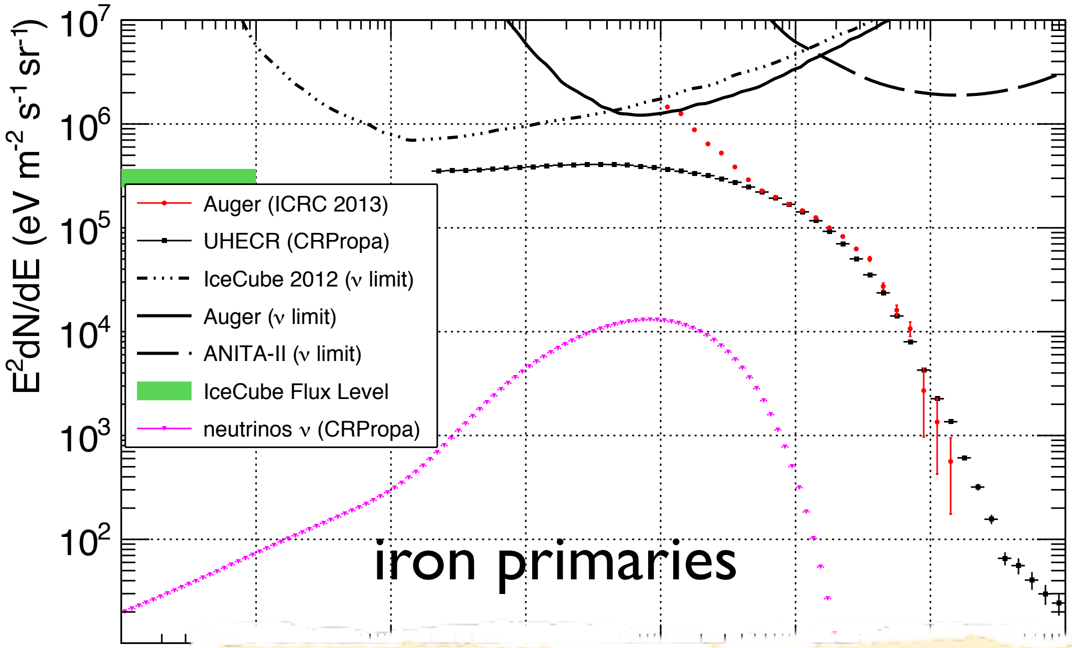


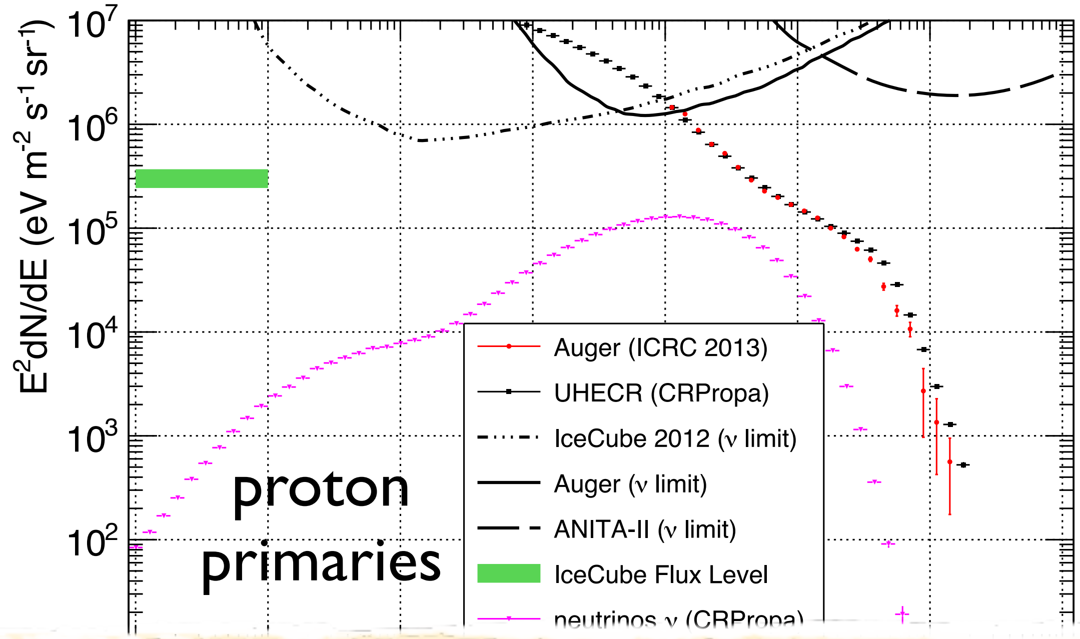


GRB origin

[Baerwald+ '14]

origin of high energy neutrinos

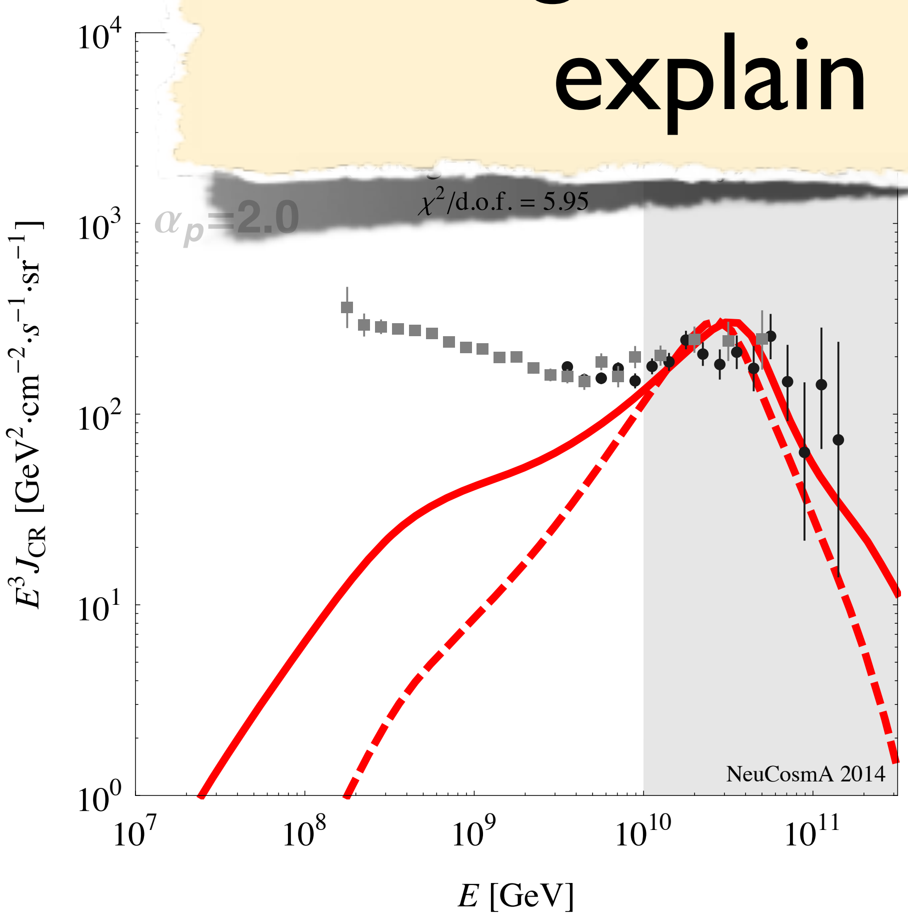


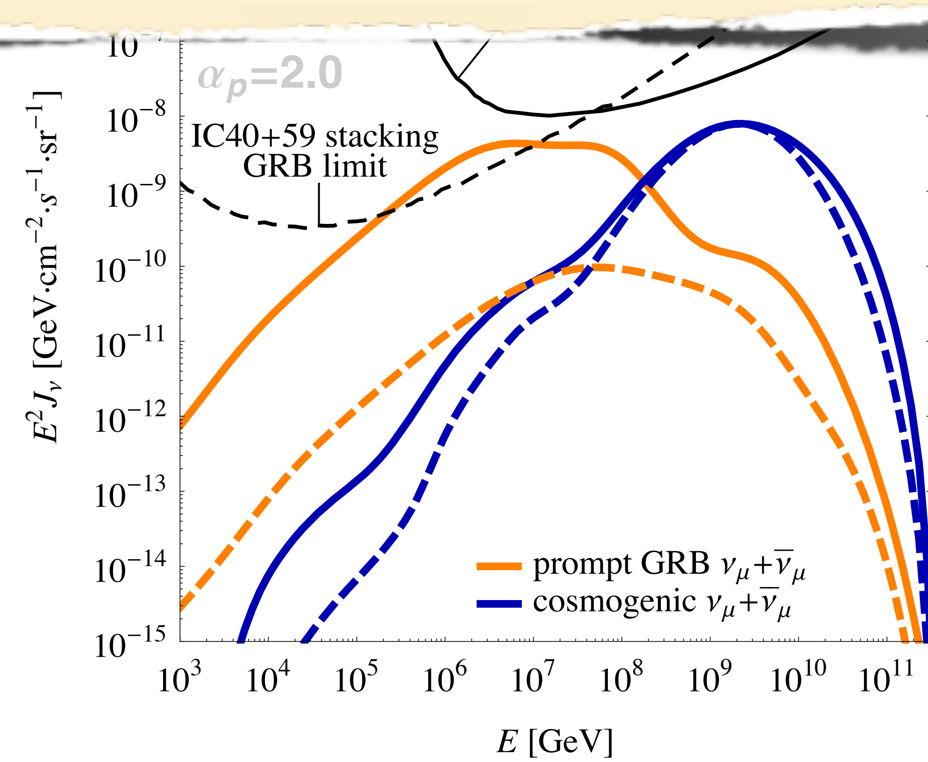


cosmogenic origin

[Sigl & van Vliet '14]

cosmogenic and GRB neutrinos cannot easily explain IceCube PeV neutrinos

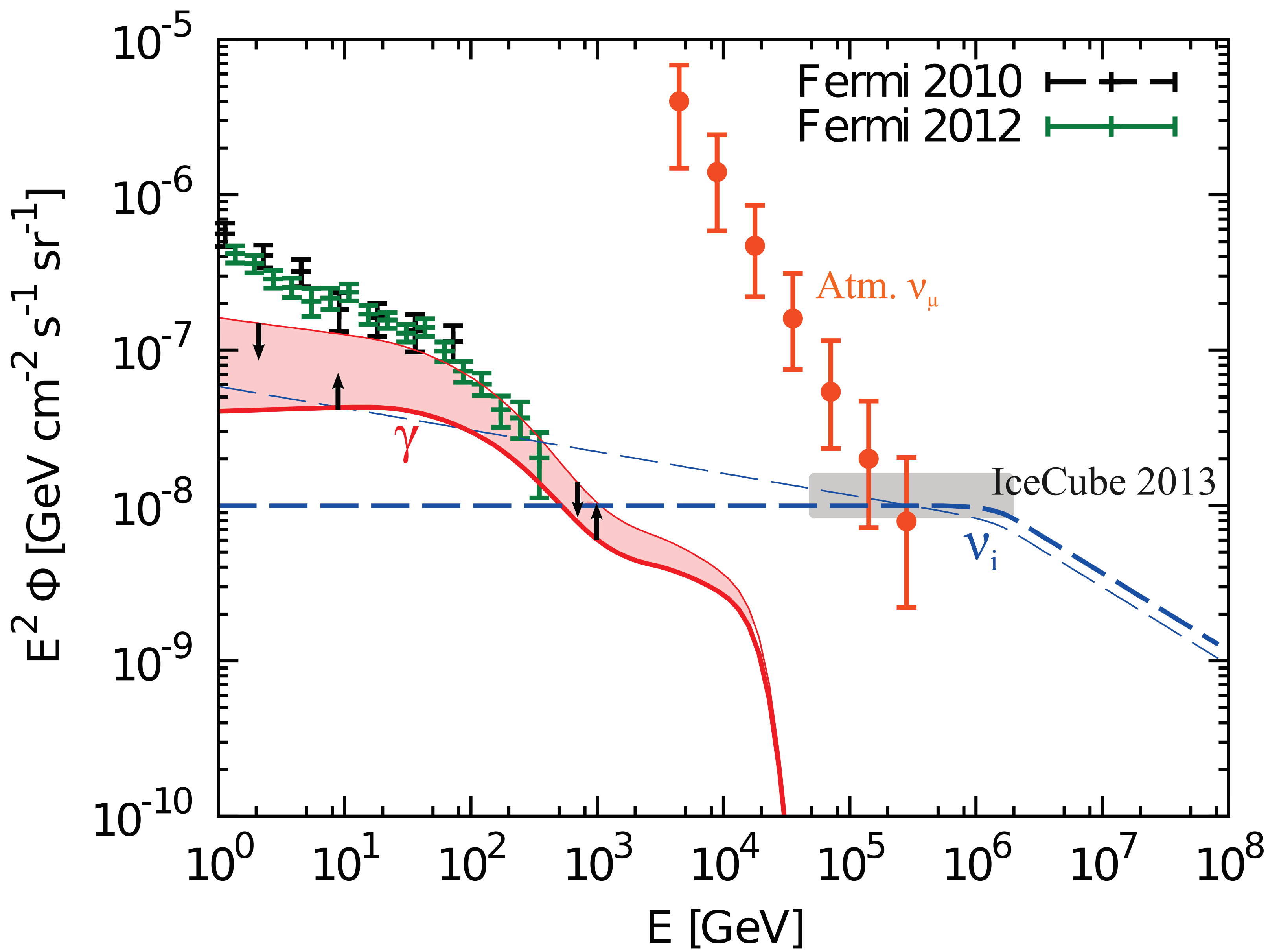




origin of high energy neutrinos

cosmic ray reservoirs

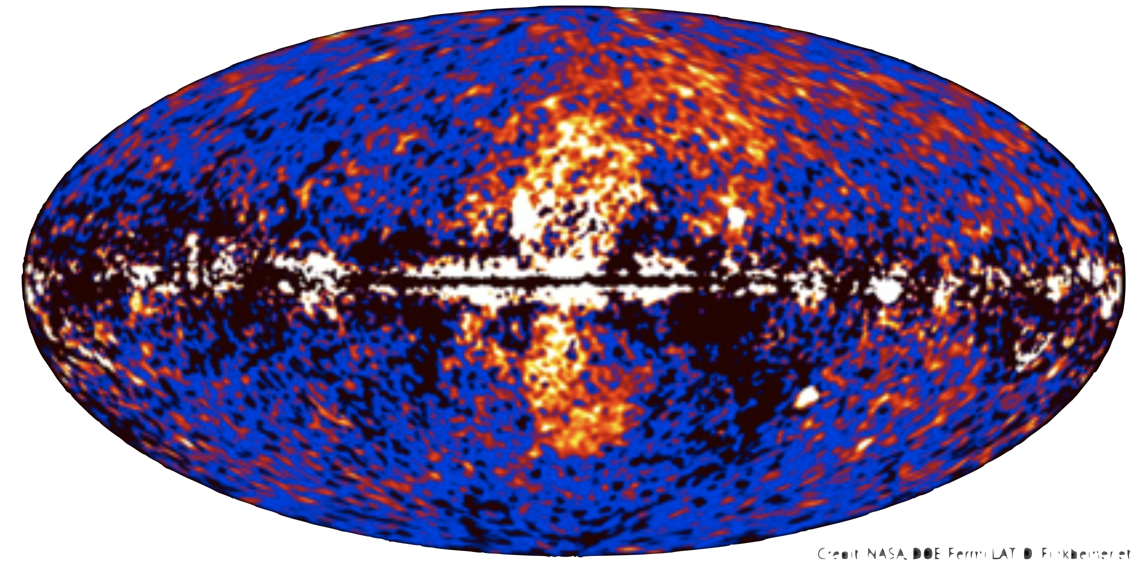
- cosmic ray reservoir (e.g.: starburst galaxies, clusters, etc)
- hadronuclear origin (pp scenario)
- escape of cosmic rays generate neutrinos
- explain simultaneously Fermi and IceCube data



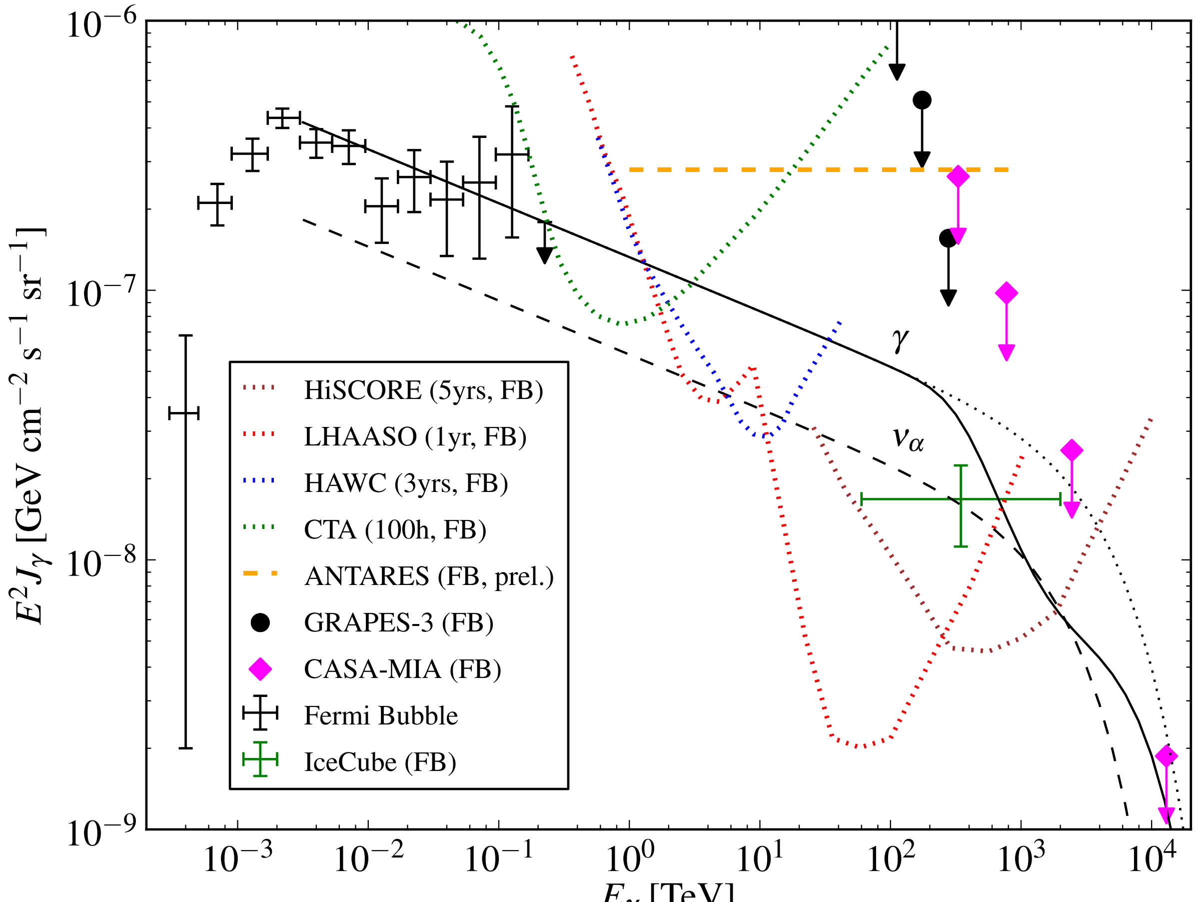
Murase et al. PRD 90 (2014) 023010

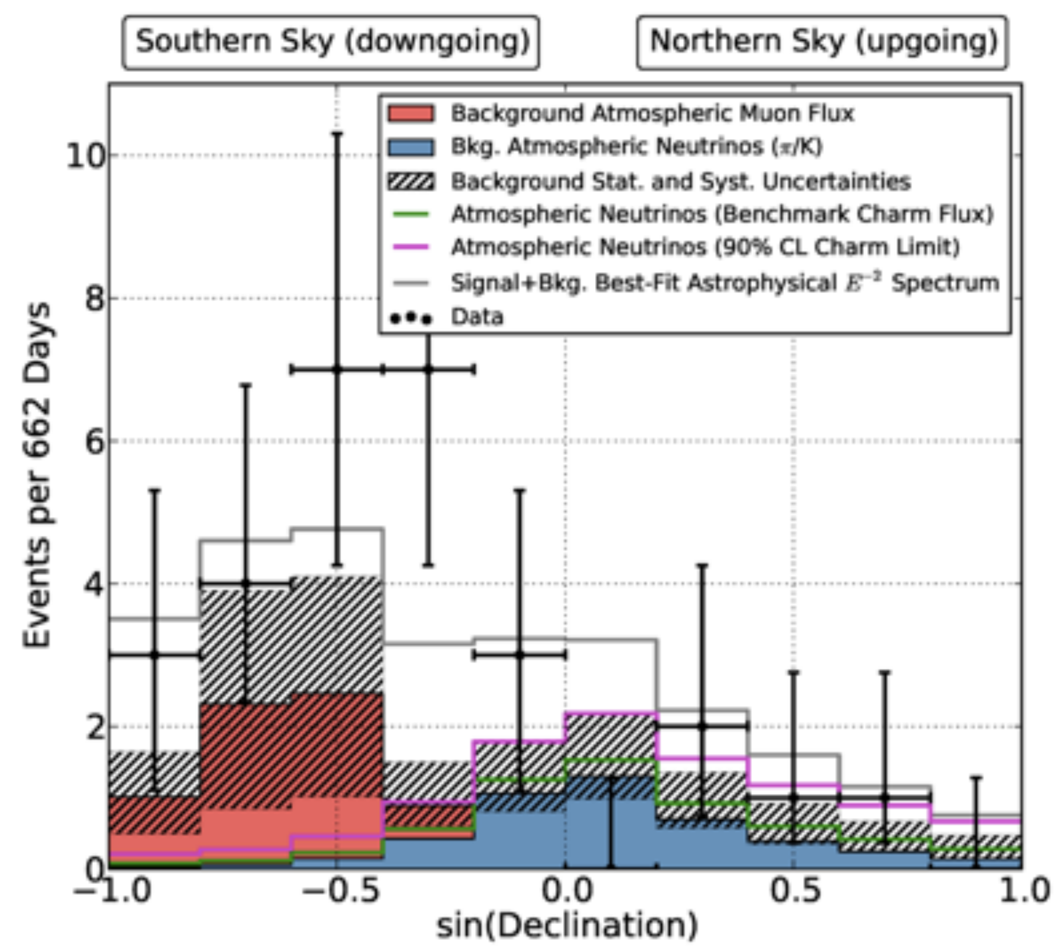
Fermi Bubbles and neutrinos

- Fermi bubbles origin still unknown → can produce associated neutrinos
- small extended excess in IceCube data → galactic center or Fermi bubbles? (not significant)



Ahlers & Murase, PRD 90 (2014) 023010

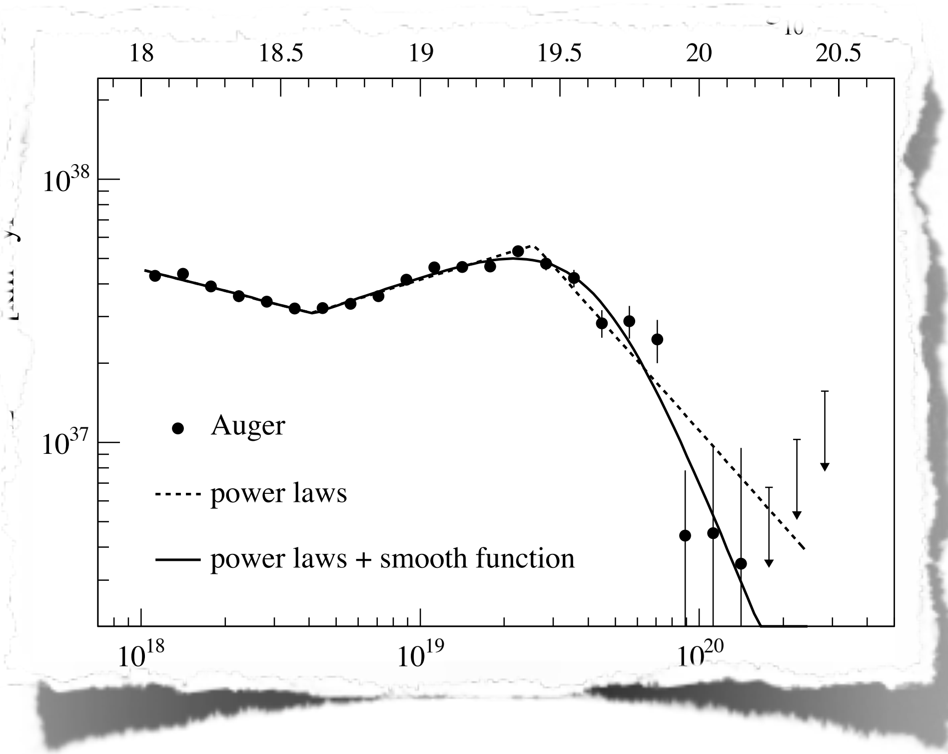




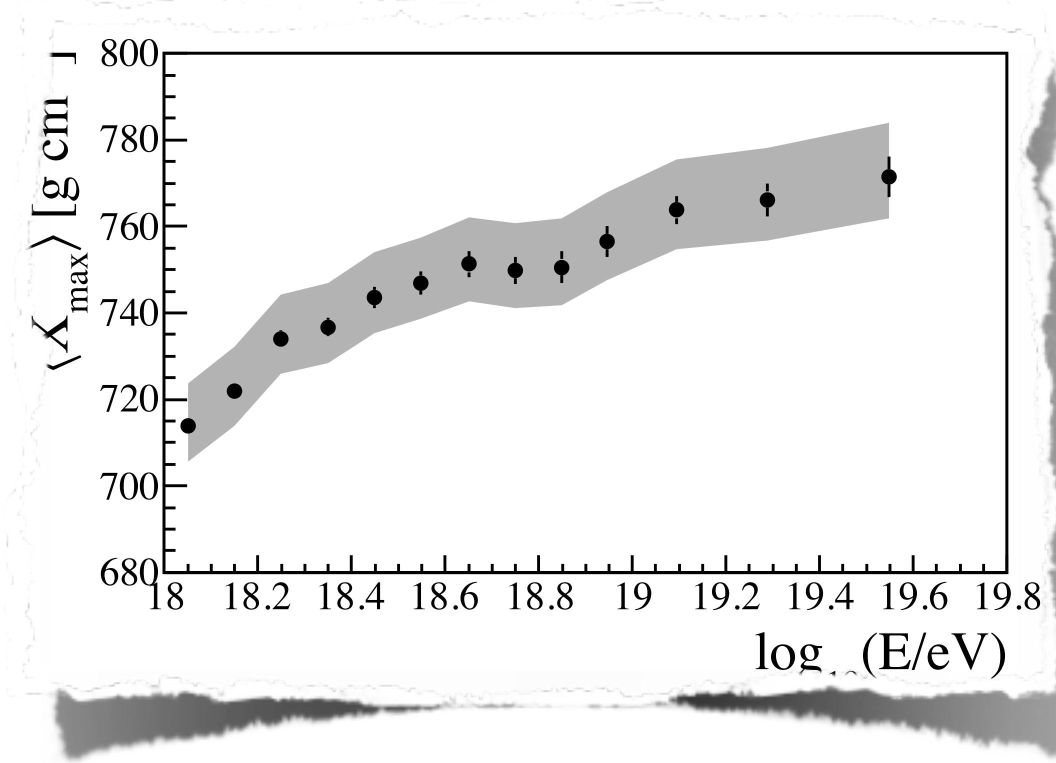
IceCube Collab. Science 342 (2013) 6161

CRPropa: simulating the propagation of high energy particles

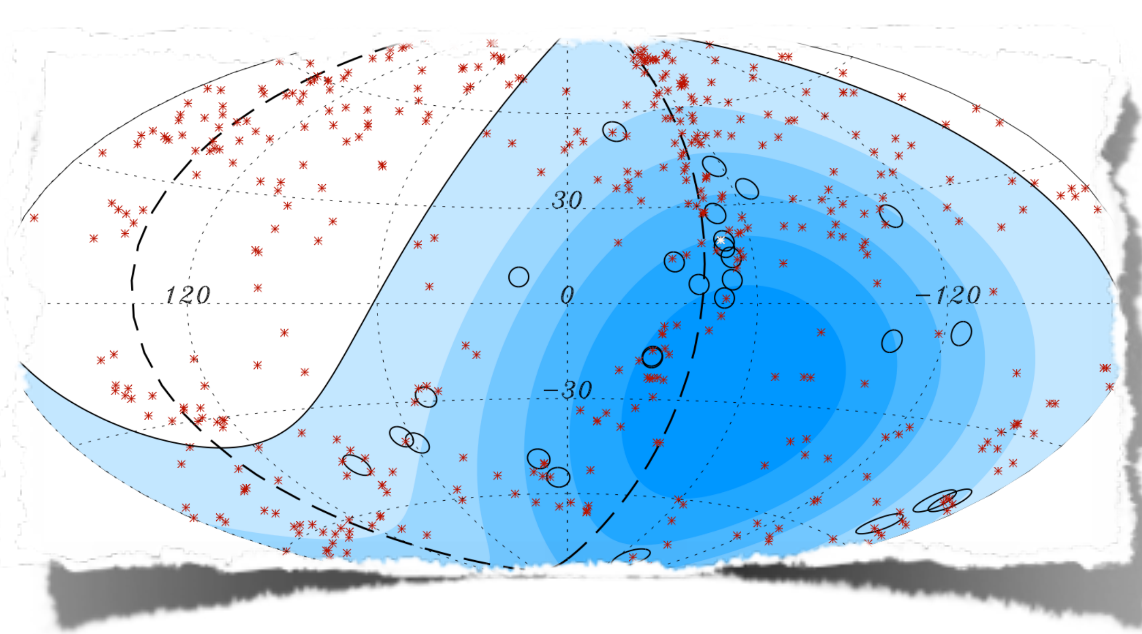
cosmic ray observables



Pierre Auger Collaboration. ICRC 2011.



Pierre Auger Collaboration. JCAP 02 (2013) 026.



Pierre Auger Collaboration. Science 318 (2007) 938.

- explain these three observables
- explain also gamma ray and neutrino counterparts
- magnetic fields and source distribution may affect spectrum and composition, and certainly affect anisotropy
- 3D simulations are needed
- large parameter space → fast simulations

CRPropa code

CRPropa 2

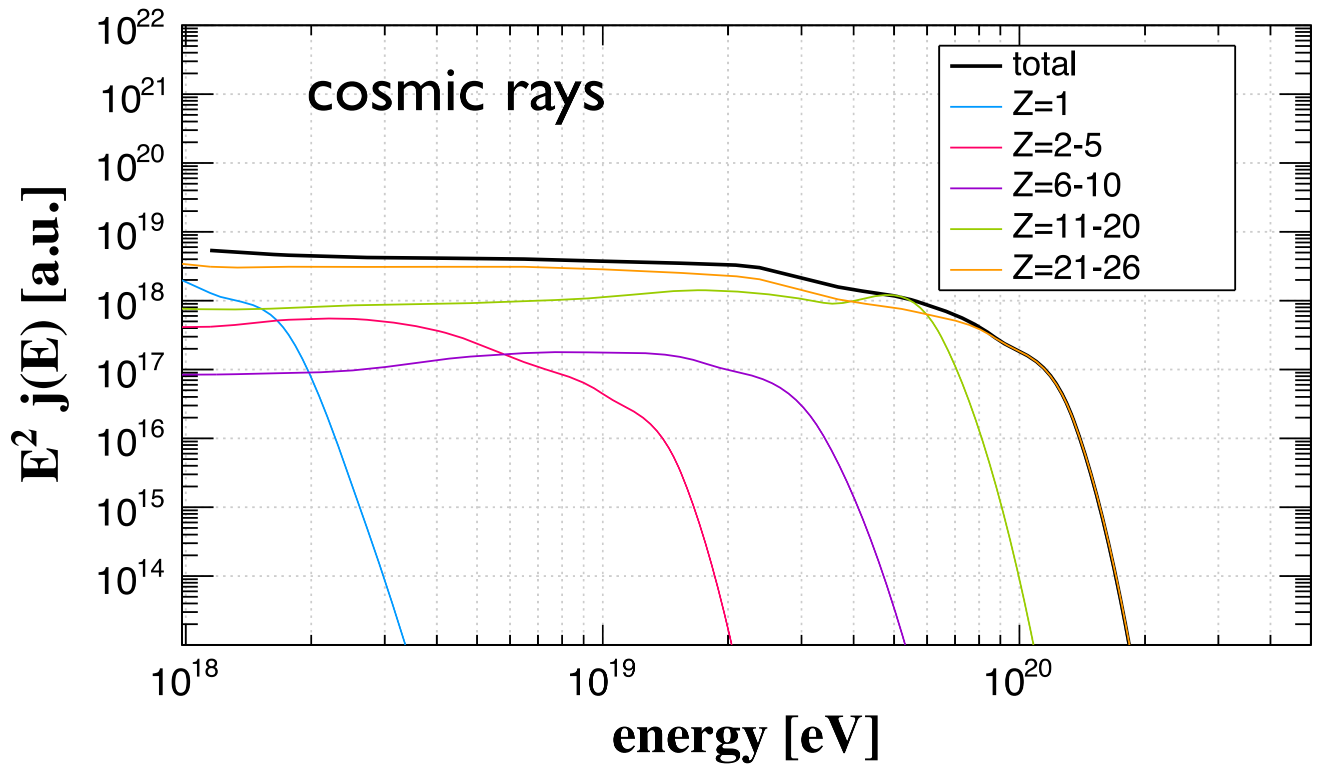
- "official" release
- see *Kampert et al. Astropart. Phys. 42 (2013) 41*
- 1D simulations with cosmology (e.g. source evolution, adiabatic losses, etc)
- 3D simulations in cosmic magnetic fields (uniform B, turbulent B, uniform grid)
- source (point sources, uniform distribution, density grid)
- interaction of particles with background photons (CMB, CIB, URB)
- secondary gamma rays (kinetic equations - DINT package)
- secondary neutrinos
- some improvements suggested by *Kalashev & Kido arXiv:1406.0735*

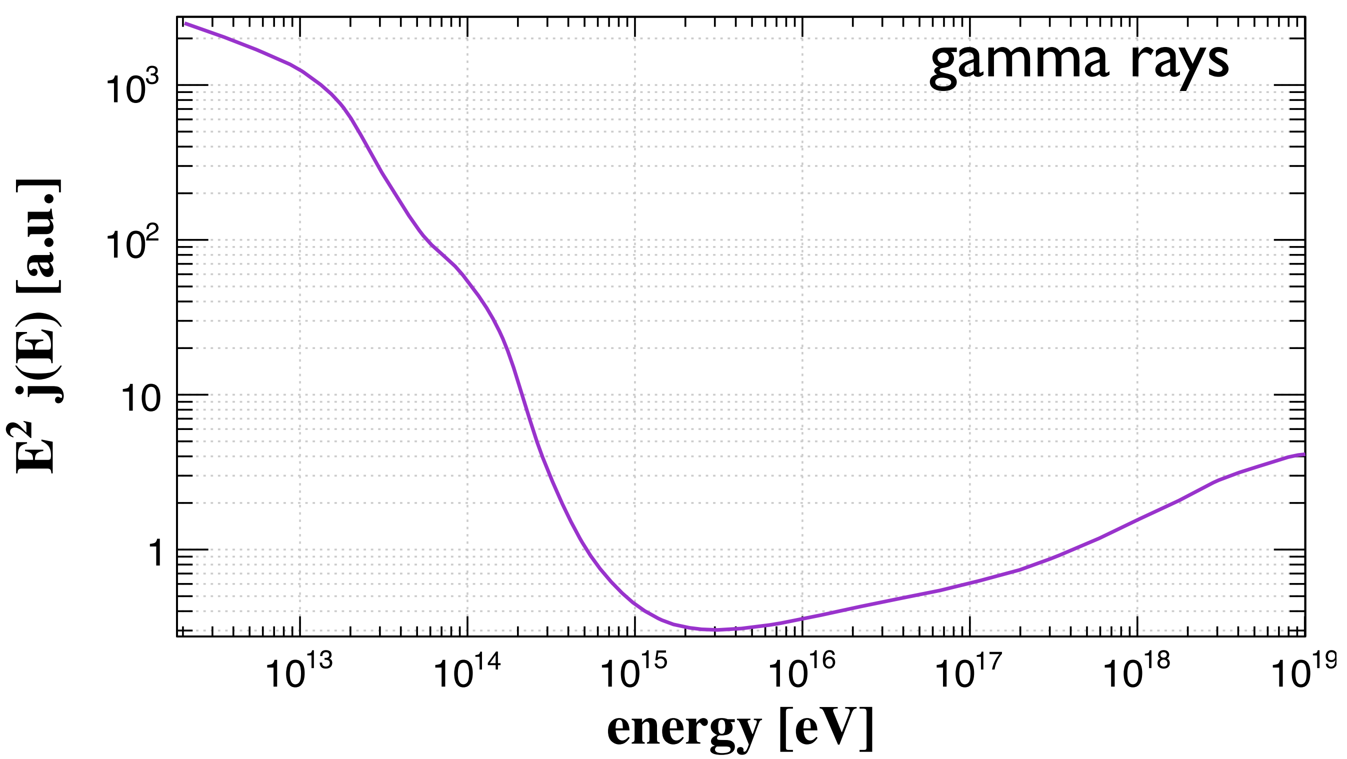
CRPropa 3

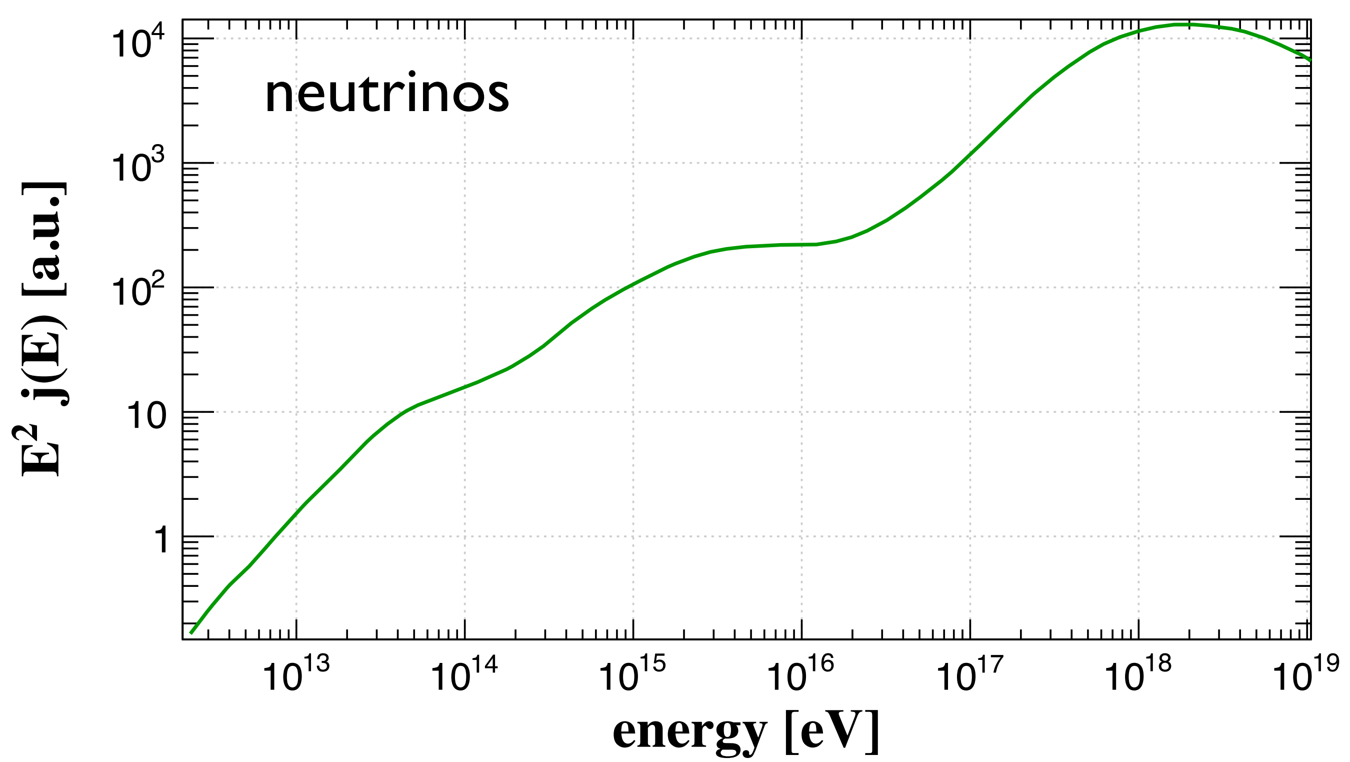
- development version
- see *RAB et al. arXiv:1307.2643*
- complete redesign of the code
- modular structure and python steering
- parallel processing
- 3D simulations with cosmology ("4D mode")
- galactic magnetic field through lenses
- MC photon propagation (EleCa code)
- large scale magnetic fields through smooth particle formalism
- updated photodisintegration cross sections
- more IRB models
- improved interaction rate tables

http://crpropa.desy.de

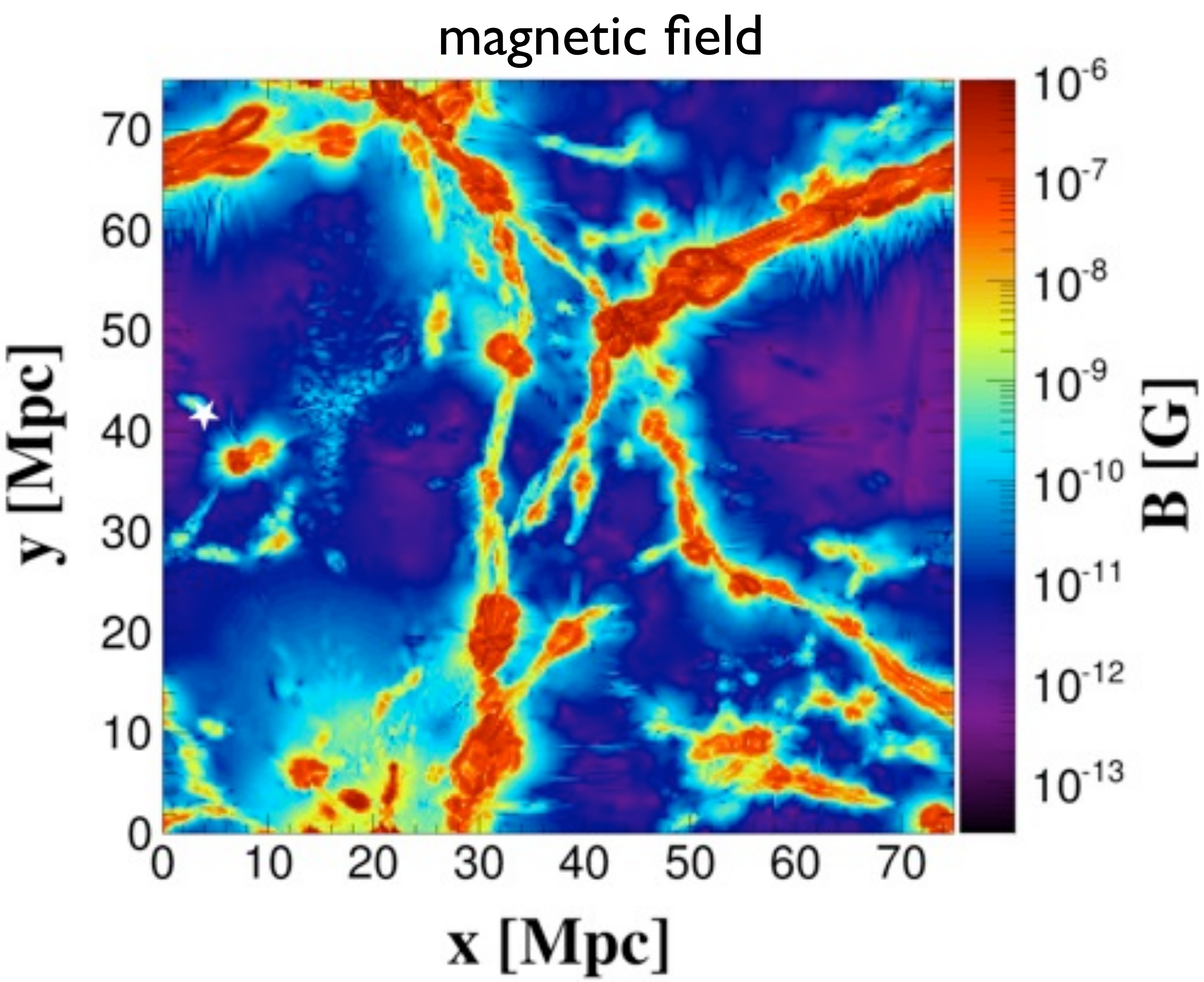
1D example: UHECRs + secondaries

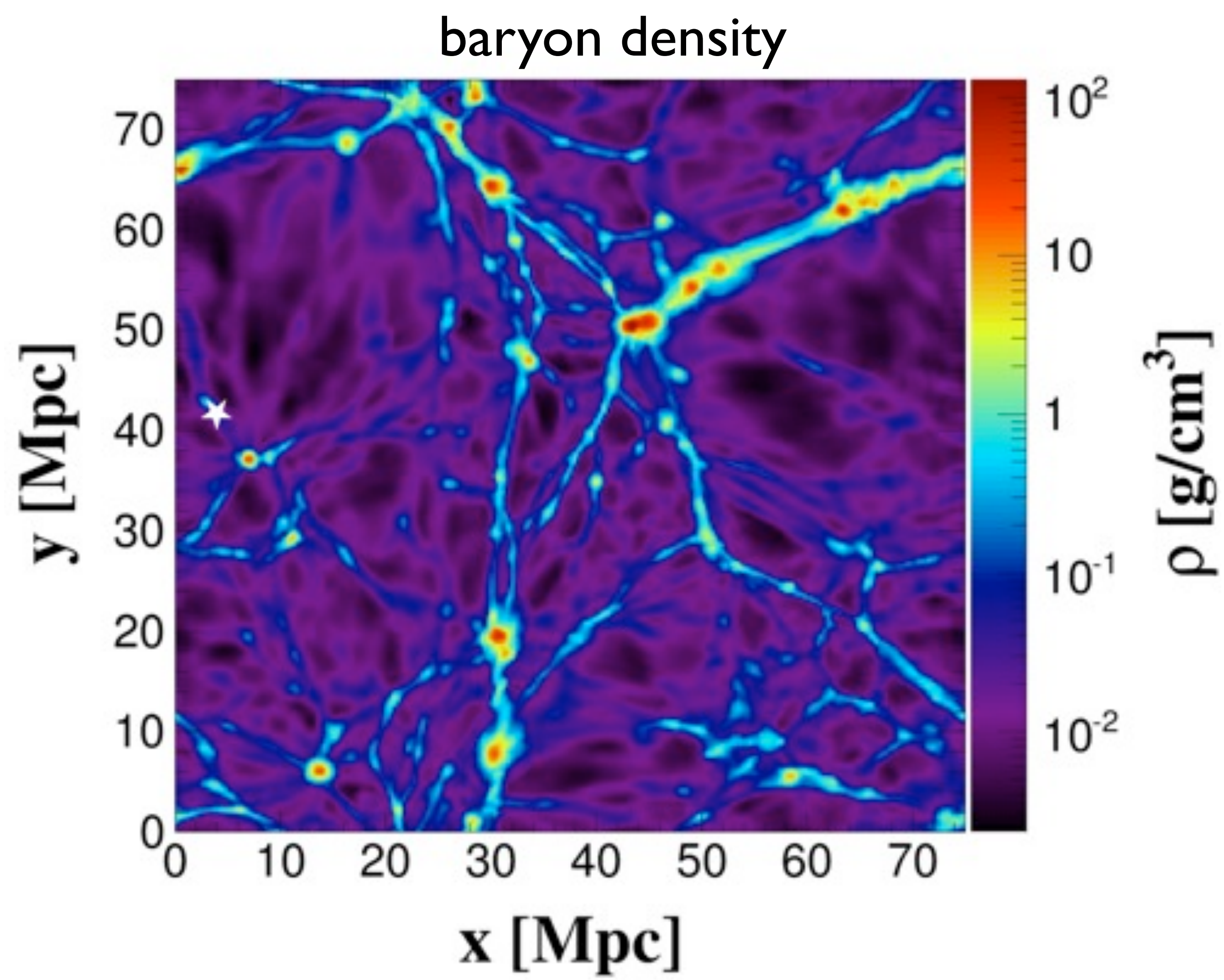






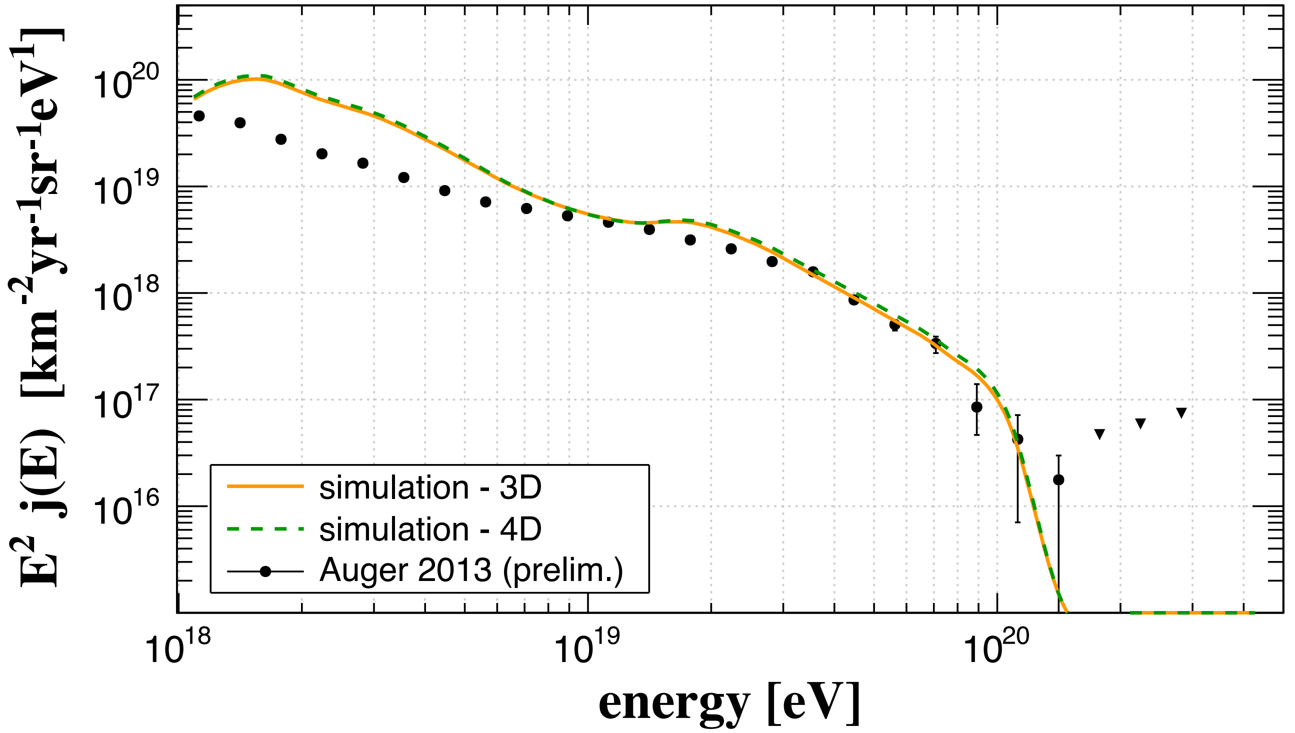
3D simualtion setup: large scale structure



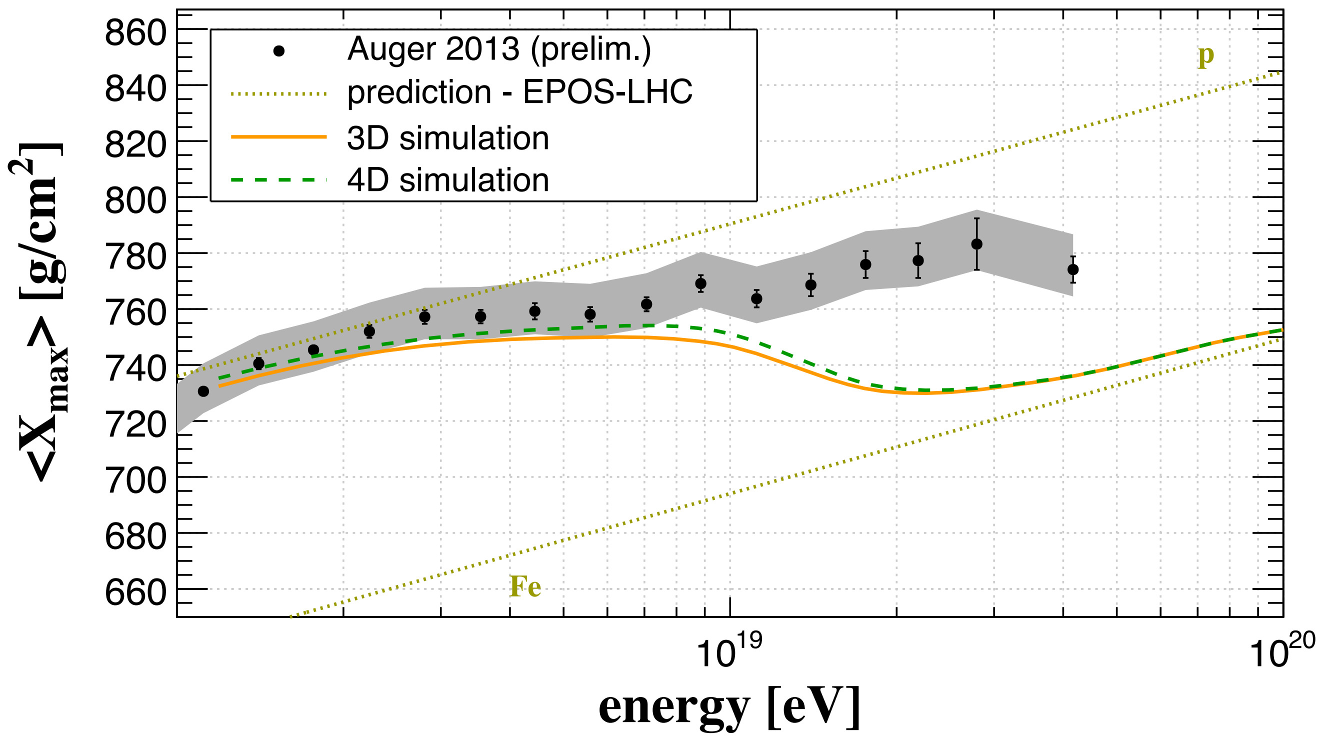


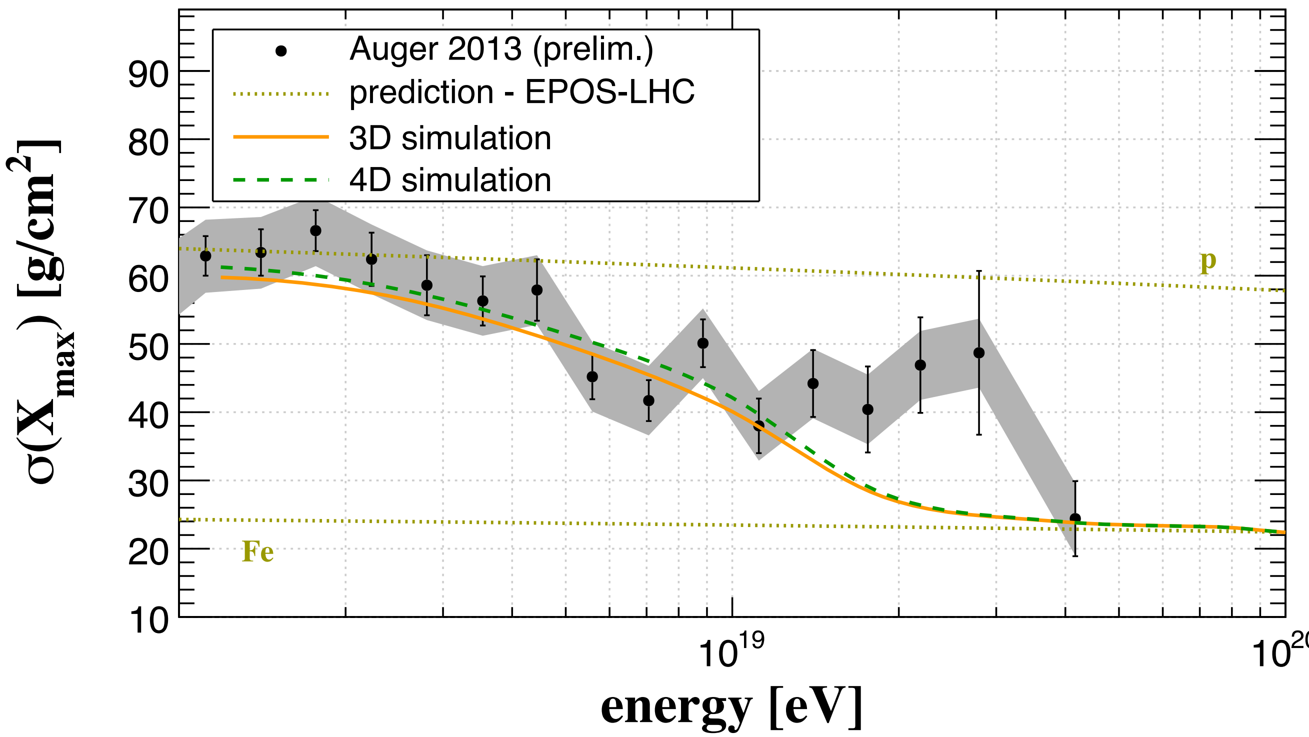
- MHD simulation: Miniati '02
- maximum rigidity = 1000 EeV
- maximum source distance = 4 Gpc
- sources following LSS baryon density
- magnetic field from the grid
- composition: 52% proton, 27% helium, 13% nitrogen, 8% iron
- minimum energy = 1 EeV

3D + 4D example: spectrum and composition



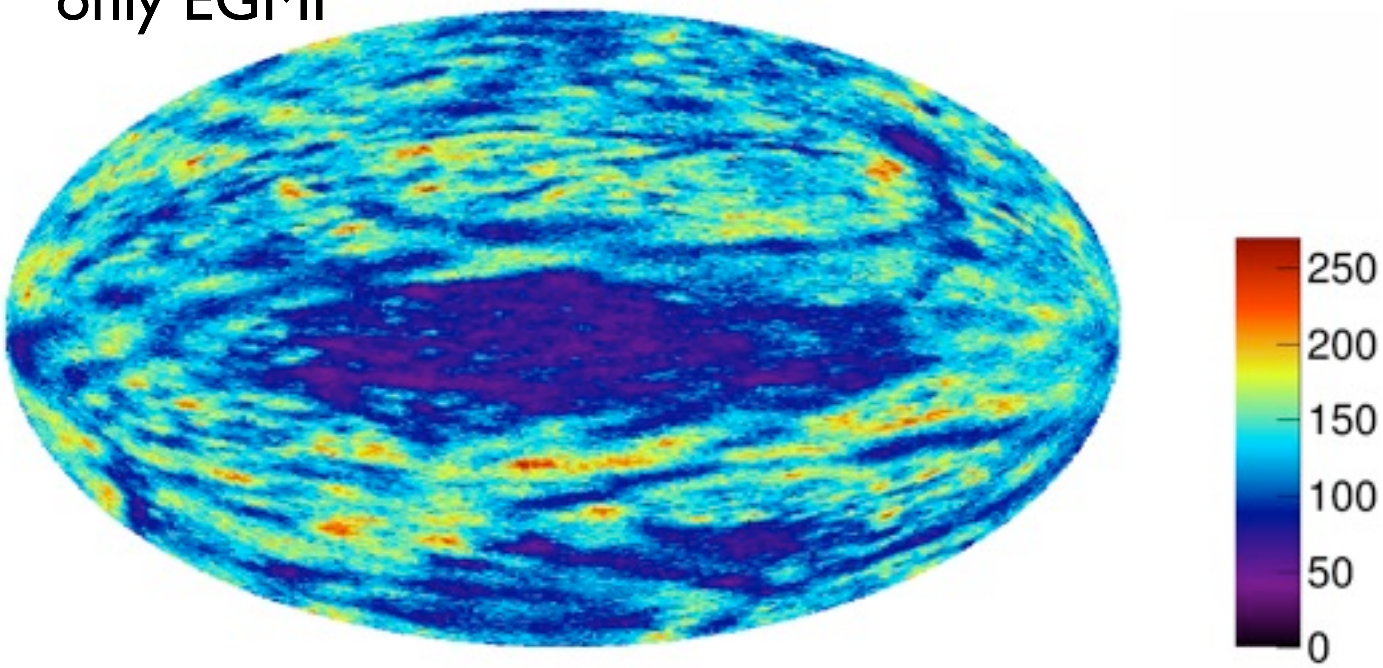
- adiabatic losses + source evolution + magnetic fields → realistic description
- 4D mode drawback: slow compared to 3D; particles are detected when its coordinates are within a hypervolume (3 spatial coordinates + time) around the observer



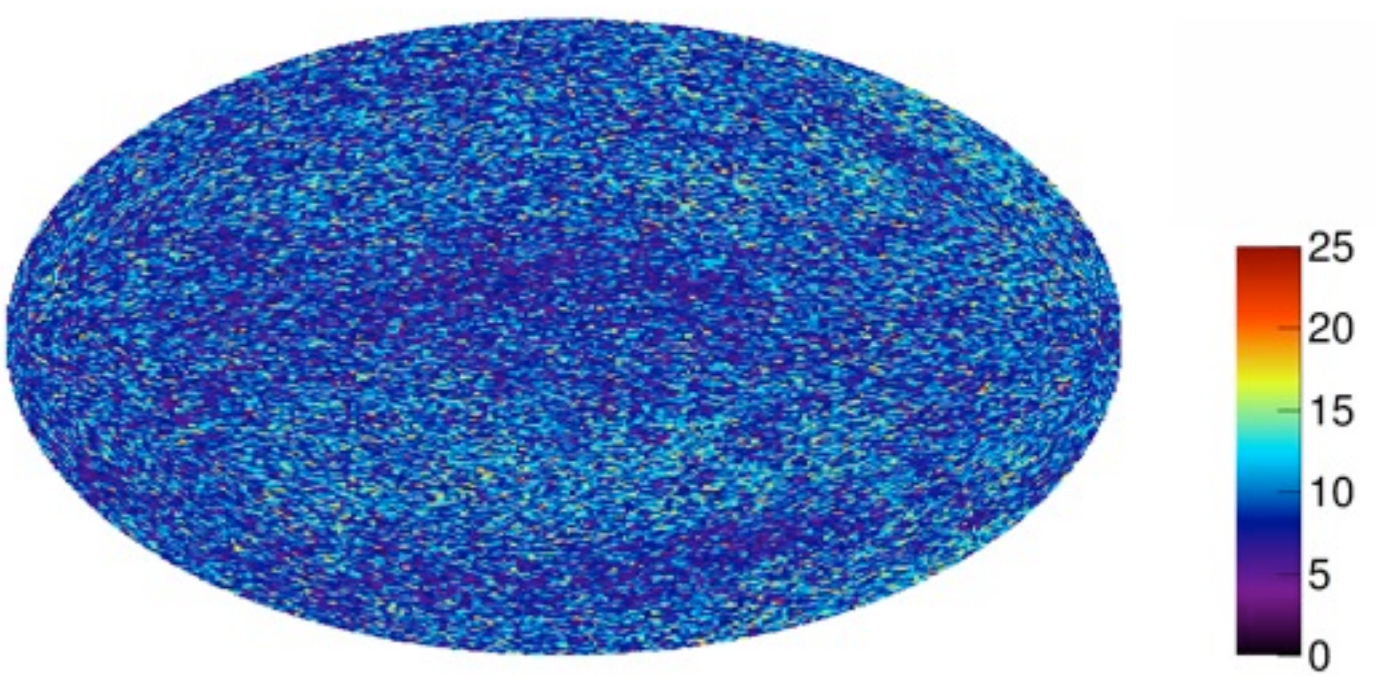


3D example: anisotropies

only EGMF

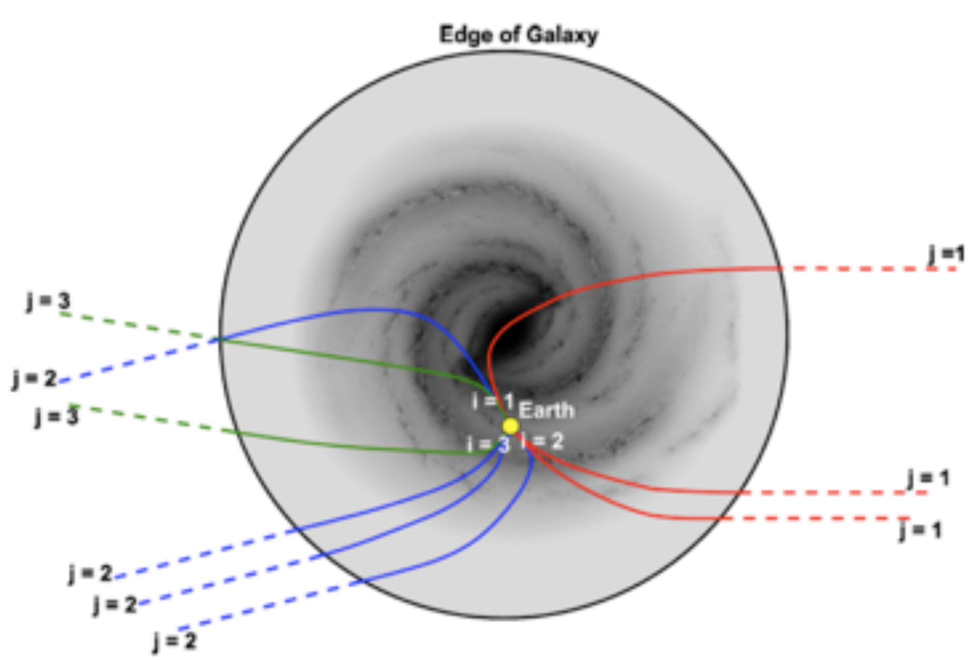


EGMF + GMF



galactic lensing

- assumes no energy losses
- each lens corresponds to a different energy bin
- lenses generated by backtracking protons to the galactic border
- nuclei have deflection Z times higher
- technique based on the PARSEC code *[Bretz+ '14]*
- lenses are applied a posteriori



summary and outlook

- difficult to construct model to explain main observables (spectrum, composition and anisotropies)
- understanding cosmic magnetic fields is crucial for particle astronomy
- status:
  - UHECRs can have mixed composition
  - highest energy cutoff may be due to maximum source acceleration
  - "local" sources may be needed
  - extra light component below the ankle
- cosmogenic neutrino and photon fluxes depend on cosmic rays composition, maximum acceleration and distribution of sources
- IceCube results represent the dawn of the era of neutrino astronomy
- multimessenger studies are now essential to explore all dimensions of the same problem
- future multimessenger studies: cosmic rays + gamma rays + neutrinos + gravitational waves

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Thank you!