

CRPropa 2.0

Public Software to Model Extra-Galactic Propagation
of Ultra-High Energy Nuclei

K.H. Kampert

J. Kulbartz

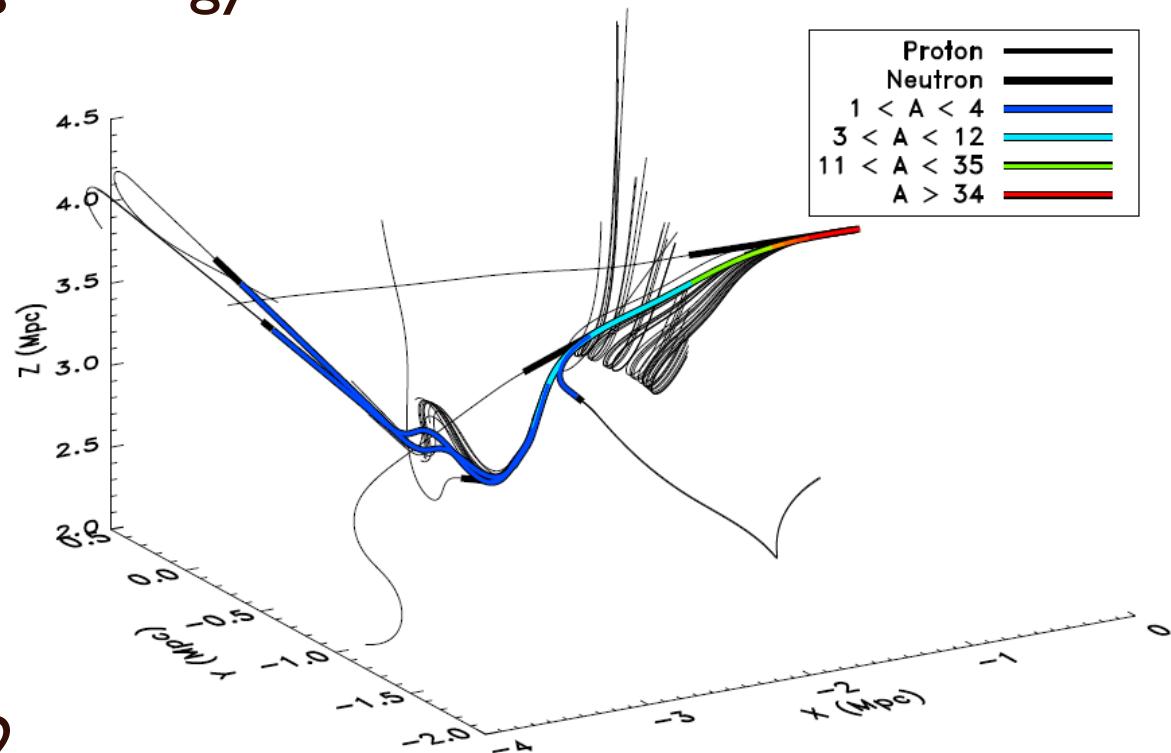
L. Maccione

N. Nierstenhoefer

P. Schiffer

G. Sigl

A. van Vliet



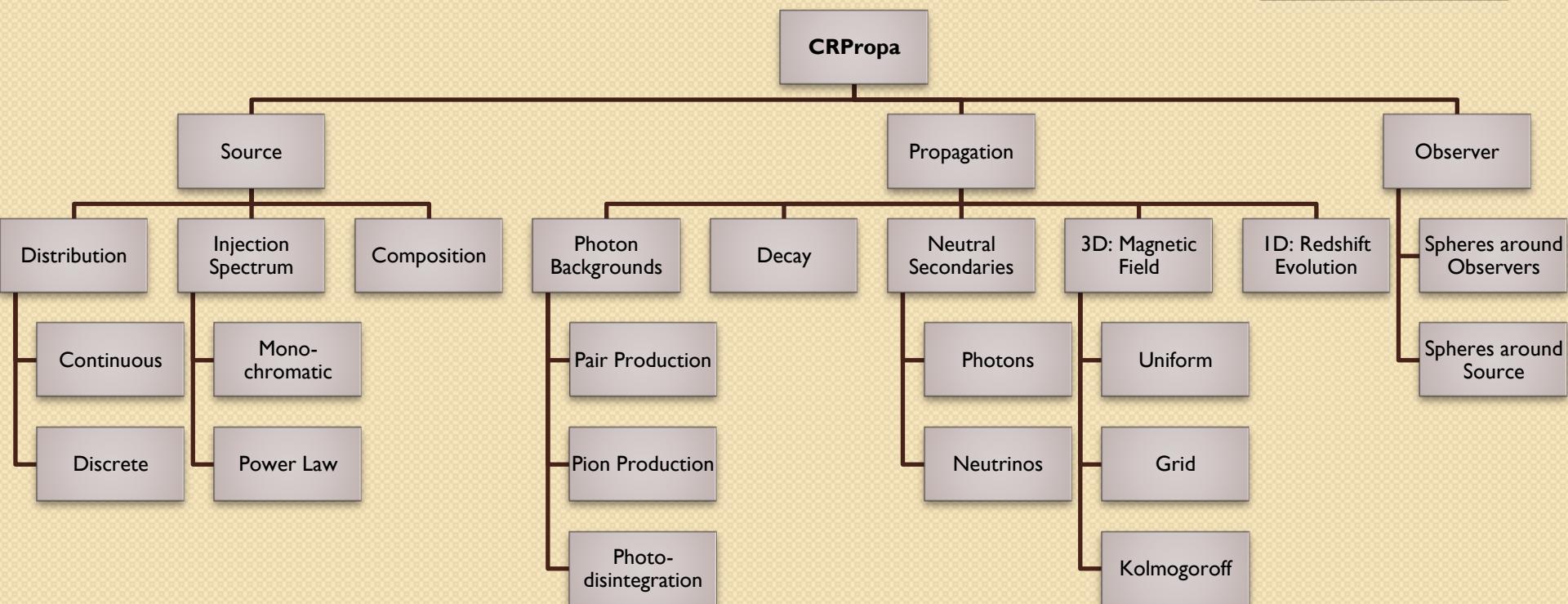
ISVHECRI 2012

Outline

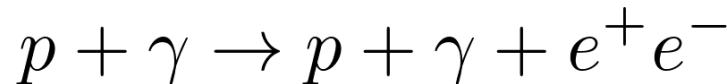
- Introduction to CRPropa
- Interactions
- Propagation Algorithm
- Future Developments
- Examples
 - 1D Simulation
 - 3D Simulation

CRPropa 2.0 released

- Available at: <https://crpropa.desy.de>
- Accompanying paper arXiv: 1206.3132, to appear in Astropart. Phys.
- For news and discussion please join the mailing list crpropa-user@desy.de
- For user support/bug reports write to crpropa-support@desy.de

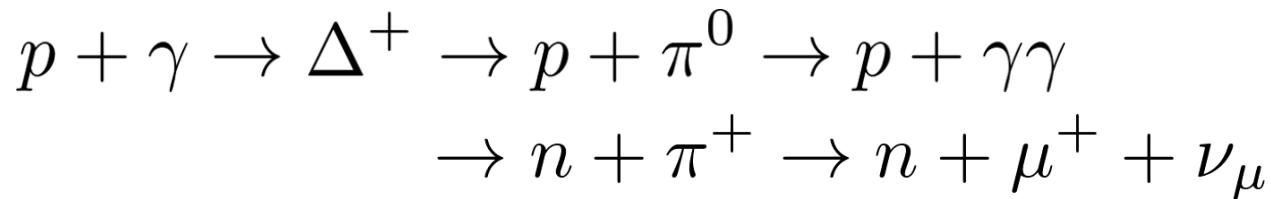


Pair Production



- Energy loss per interaction
 $\sim 2m_e/m_p \approx 0.1\%$
→ continuous energy loss
- Most important reaction for creation of secondary photons in the TeV range

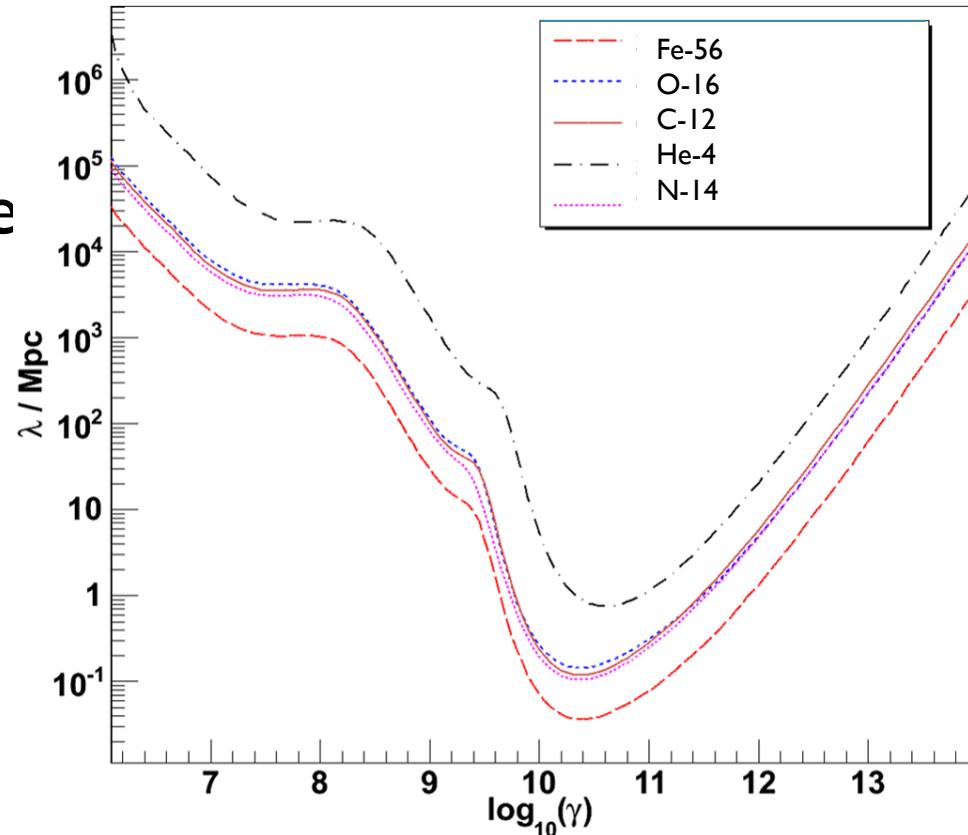
Photopion Production



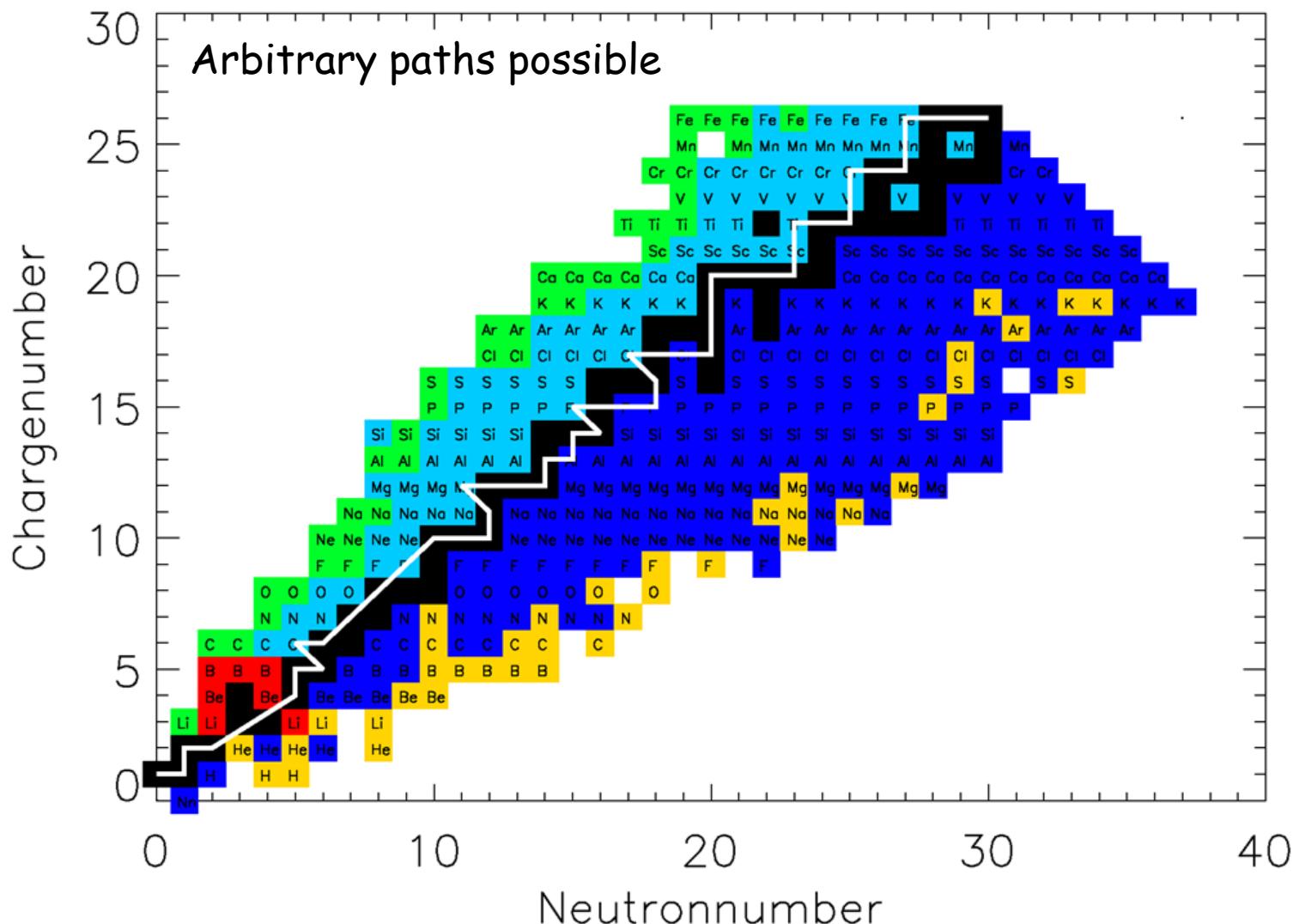
- Energy loss per interaction
 $\sim m_\pi/m_p \approx 15\%$
→ stochastic process, interaction from SOPHIA
- Interaction behind the GZK cut-off

Photodisintegration and Decay

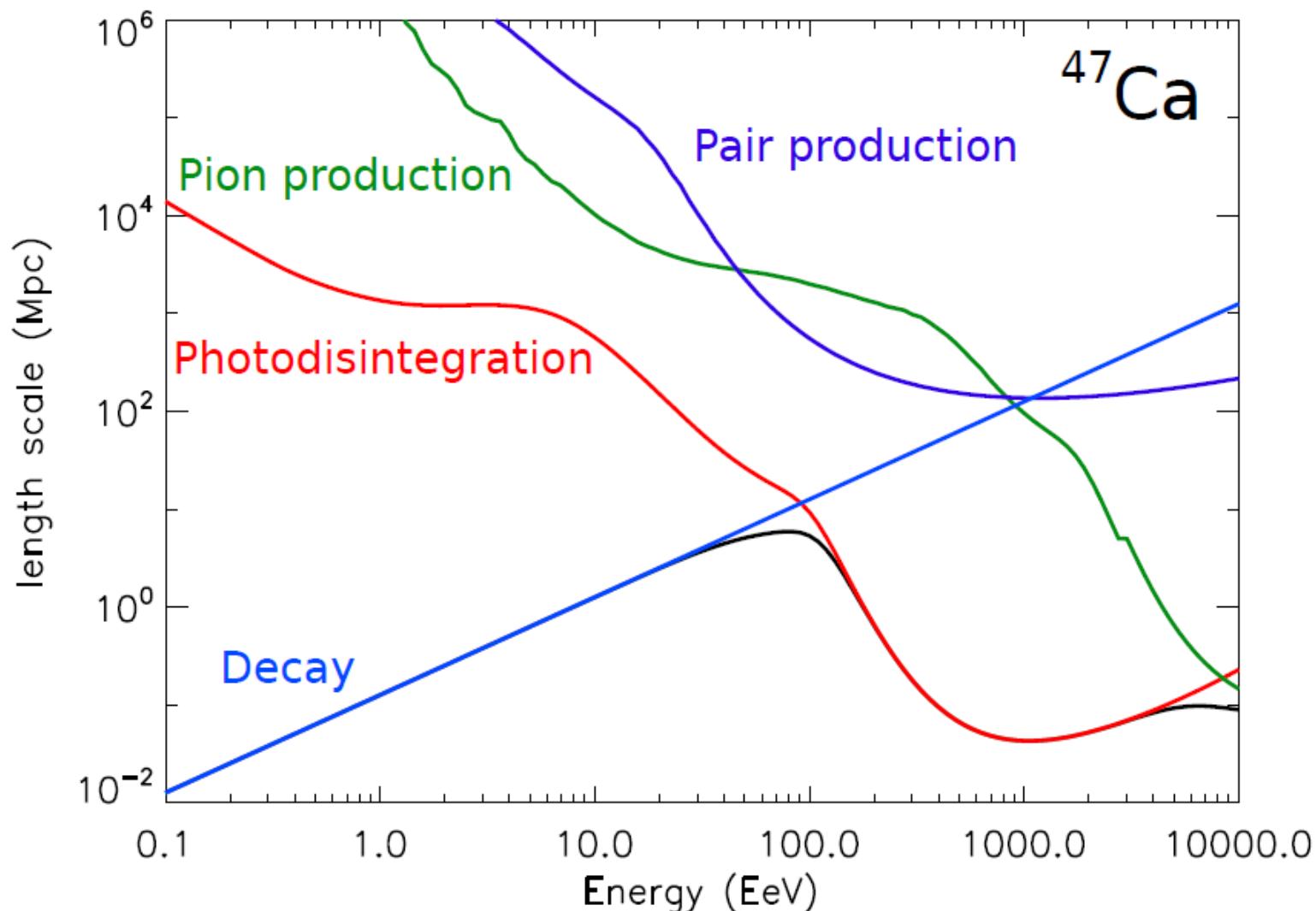
- PD cross sections for 287 isotopes from TALYS + some extensions (~80,000 exclusive channels)
- Decay for 434 isotopes from NuDat2 + some extensions



Photodisintegration and Decay

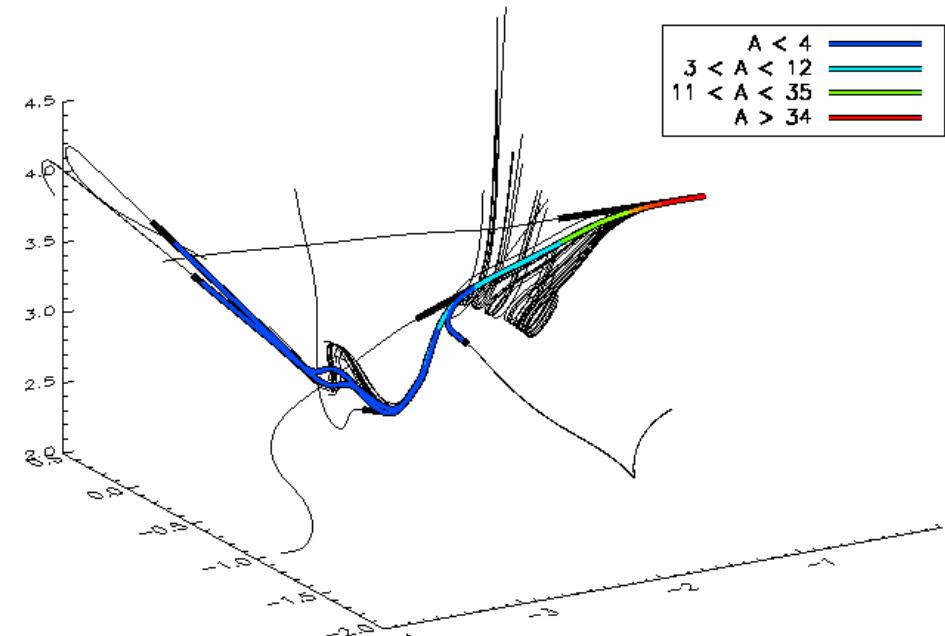


Interaction Length Scales



Propagation Algorithm

- Dial next interaction
- Propagate up to this interaction or D_{\max} (record detection)
- If reached, execute interaction (add secondaries to queue)
- Apply continuous energy loss
- If still over threshold, dial next interaction



Future Developments

- CRPropa is constantly under development
- Improvement of the code
 - Modular Propagation Code
- Improvement of the physical model
 - Cosmology for 3D propagation
 - More options for magnetic fields (adaptive grid)
 - Interface to galactic propagation
 - Allow use of more general infrared background models
 - ...

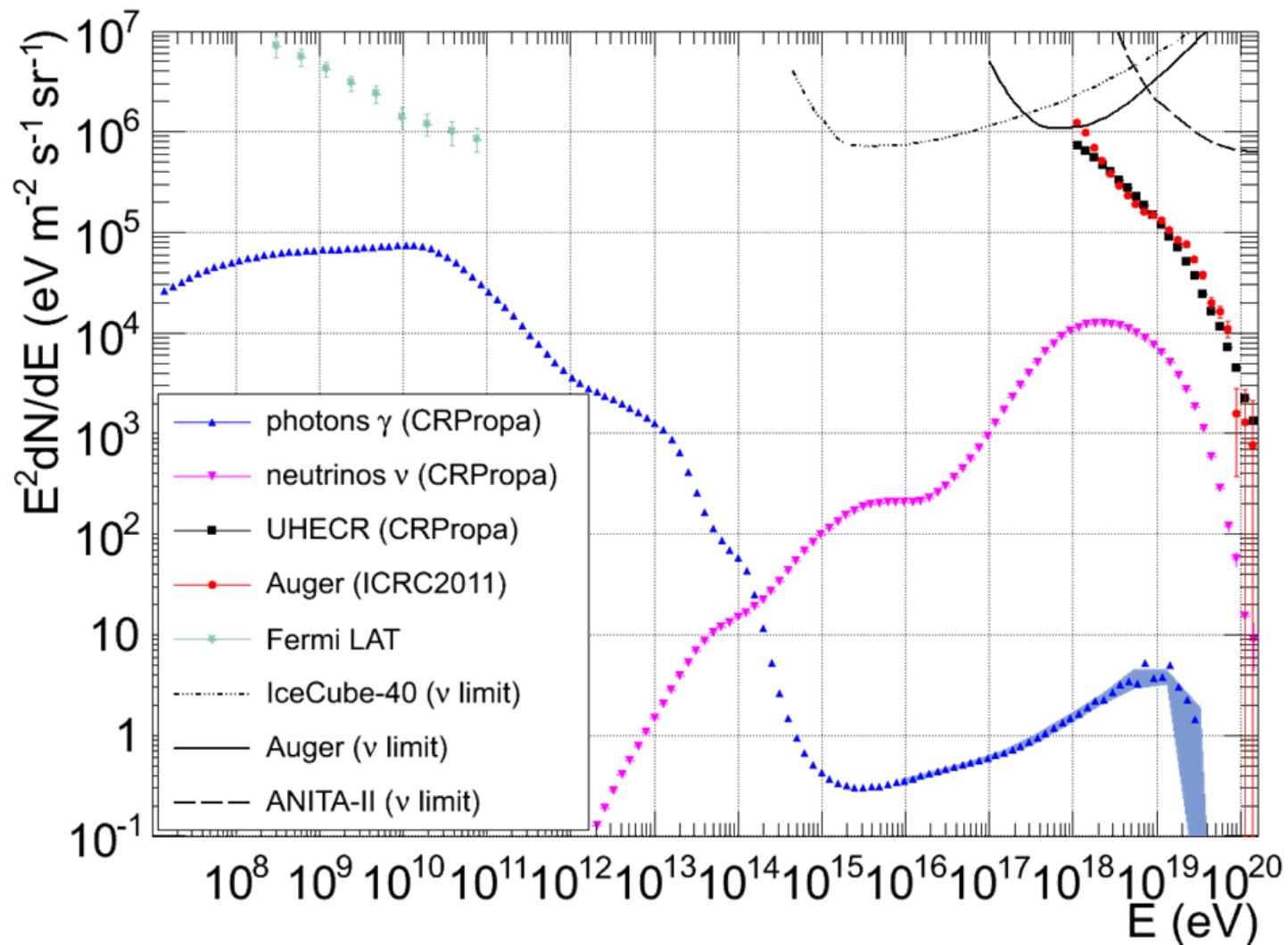
Examples

- 1D Simulation
 - Including cosmological and source evolution as a function of the redshift
 - Showing secondary neutrinos and photons
- 3D Simulation
 - Effects of a source density and extragalactic magnetic field (EGMF) following the Large Scale Structure (LSS) baryon density

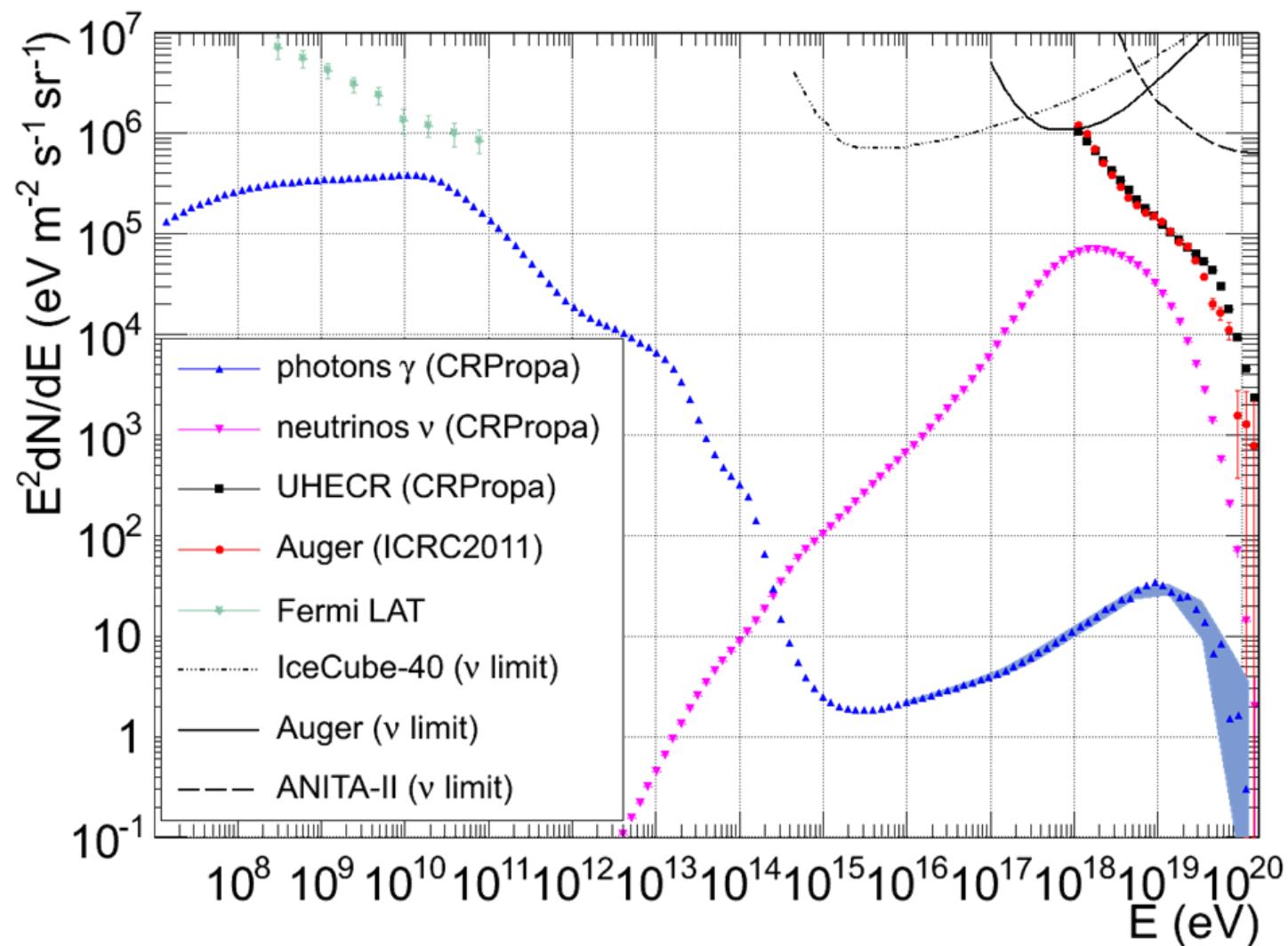
1D Simulation

- Cosmological Expansion
- Λ CDM Universe ($\Omega_m=0.3$, $\Omega_\lambda=0.7$, $H_0=72 \text{ km s}^{-1} \text{ Mpc}^{-1}$)
- Comoving source evolution $(1+z)^4$, $z_{max}=2$
- Injection spectrum: $dN/dE \propto E^{-2.2}$
- Max. rigidity: $R=E/Z=384.6 \text{ EeV}$
- Min. energy: $E_{min}=1 \text{ EeV}$
- Normalized to Auger spectrum at 10 EeV
- Neutrino limits and spectra: Single flavor, I:I:I ratio

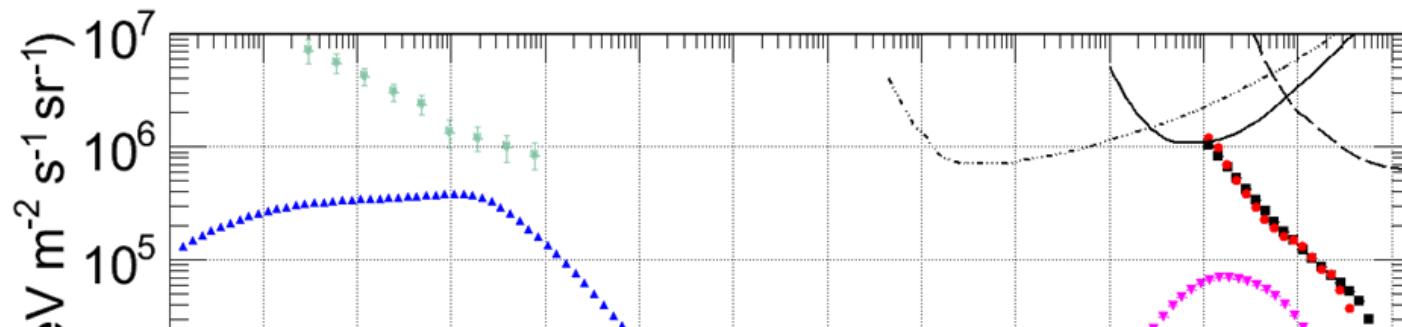
Pure Iron Injection



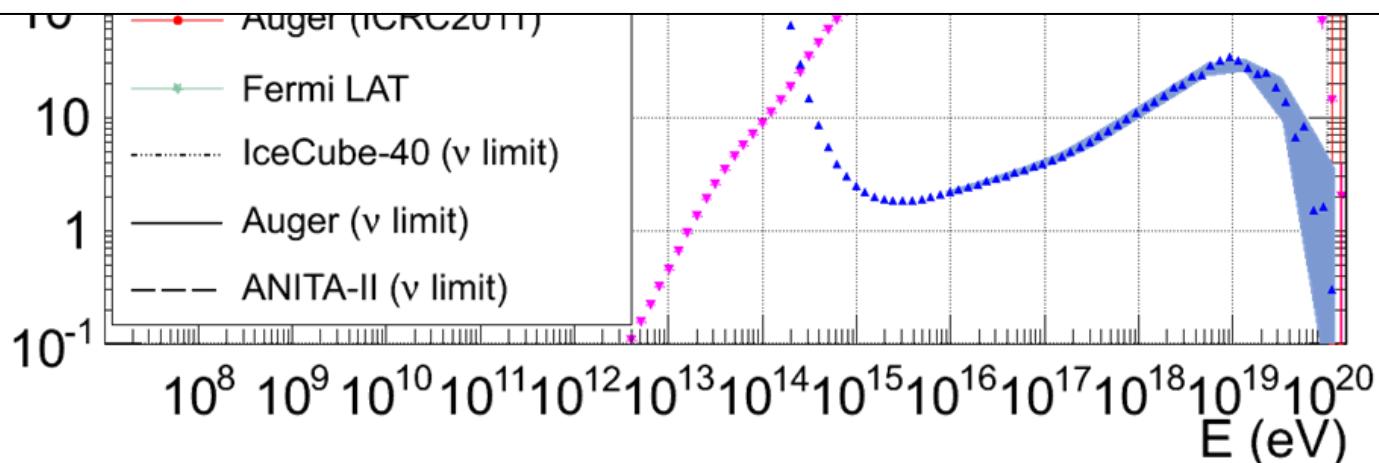
Mixed Galactic Composition



Mixed Galactic Composition



- Conclusion: A lighter source composition increases the fluxes of secondaries (photopion production dominates w.r.t. photodisintegration).

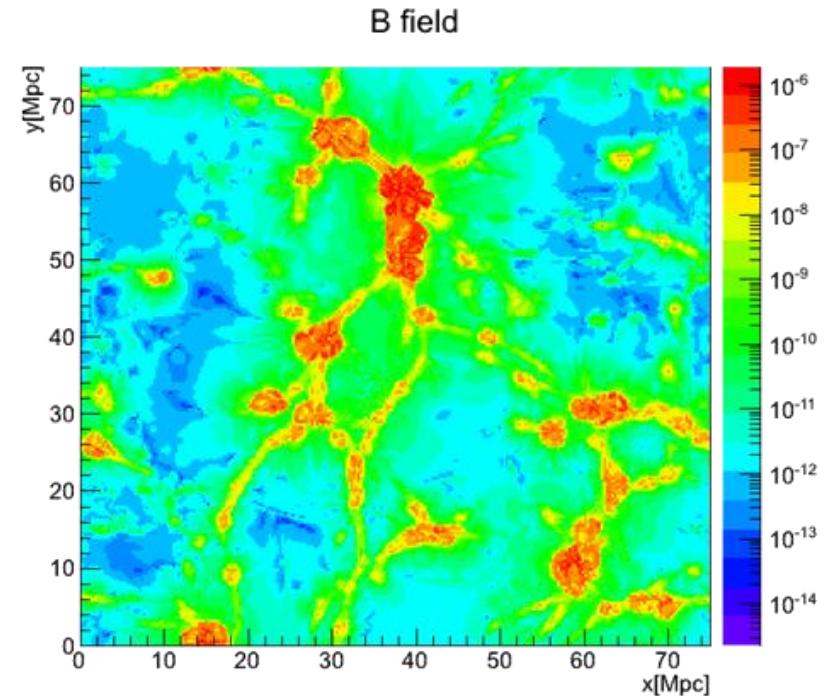
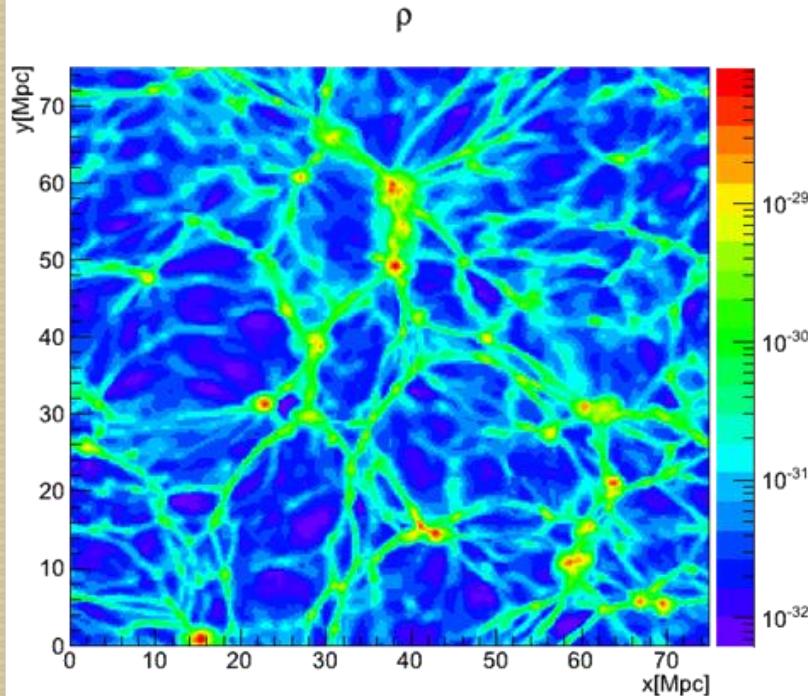


3D Simulation

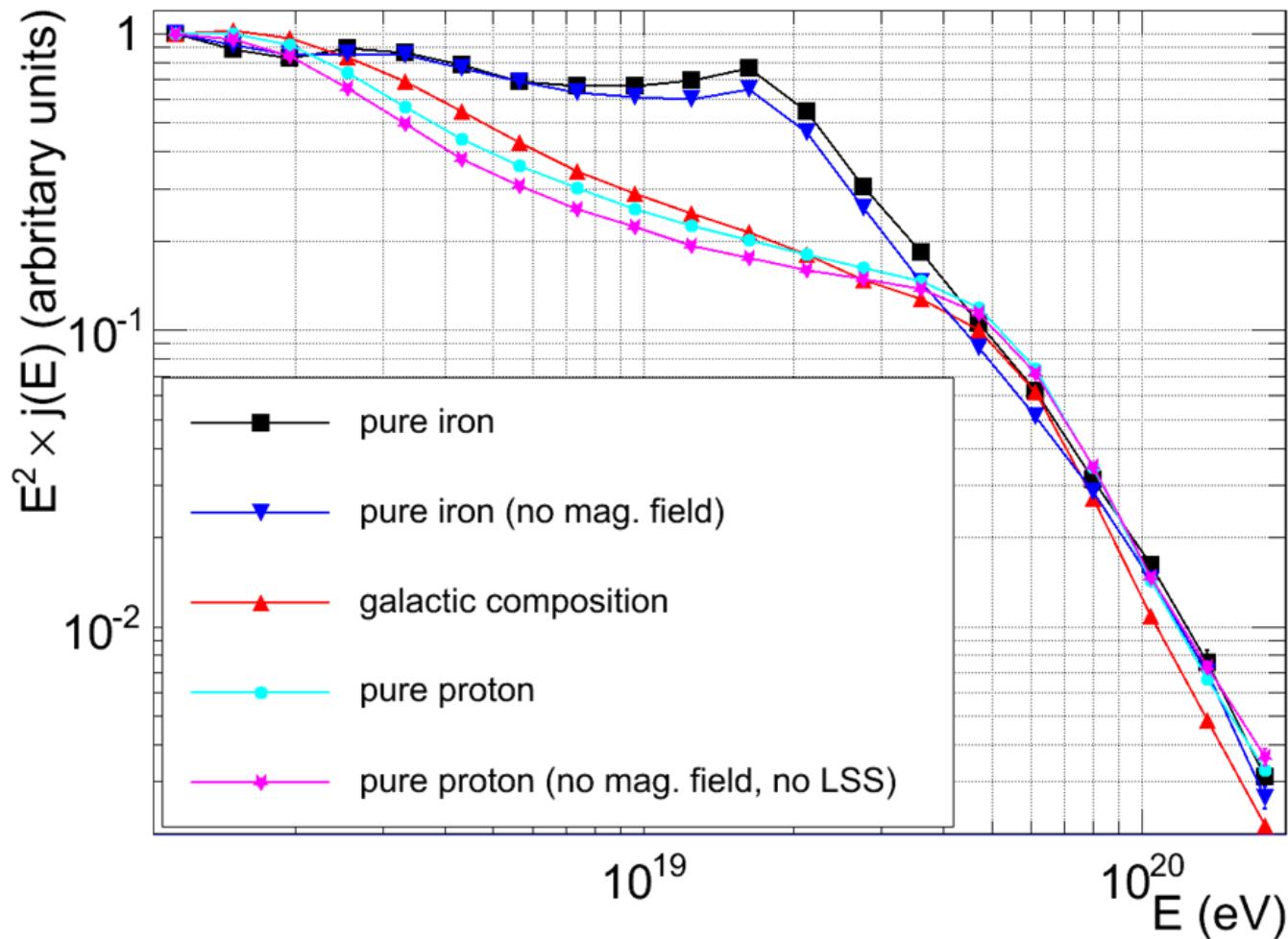
- Max. time: 3000 Mpc ($z \approx 1.9$)
- Injection spectrum: $dN/dE \propto E^{-2.2}$
- Max. rigidity: $R = 384.6$ EeV
- Min. energy: $E_{min} = 1$ EeV
- Detection: Sphere around observer;
 $r = 1$ Mpc
- Spectrum normalized to 1 in the first bin

Cosmological Environment

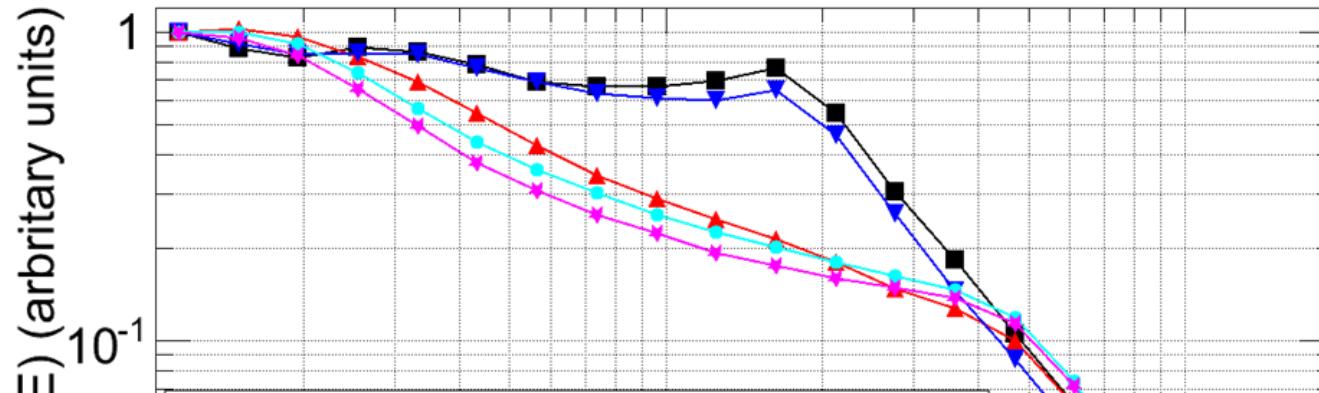
- Grid based source density and EGMF by F. Miniati



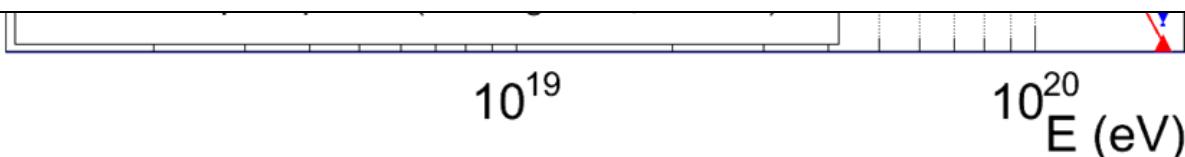
Energy Spectra



Energy Spectra

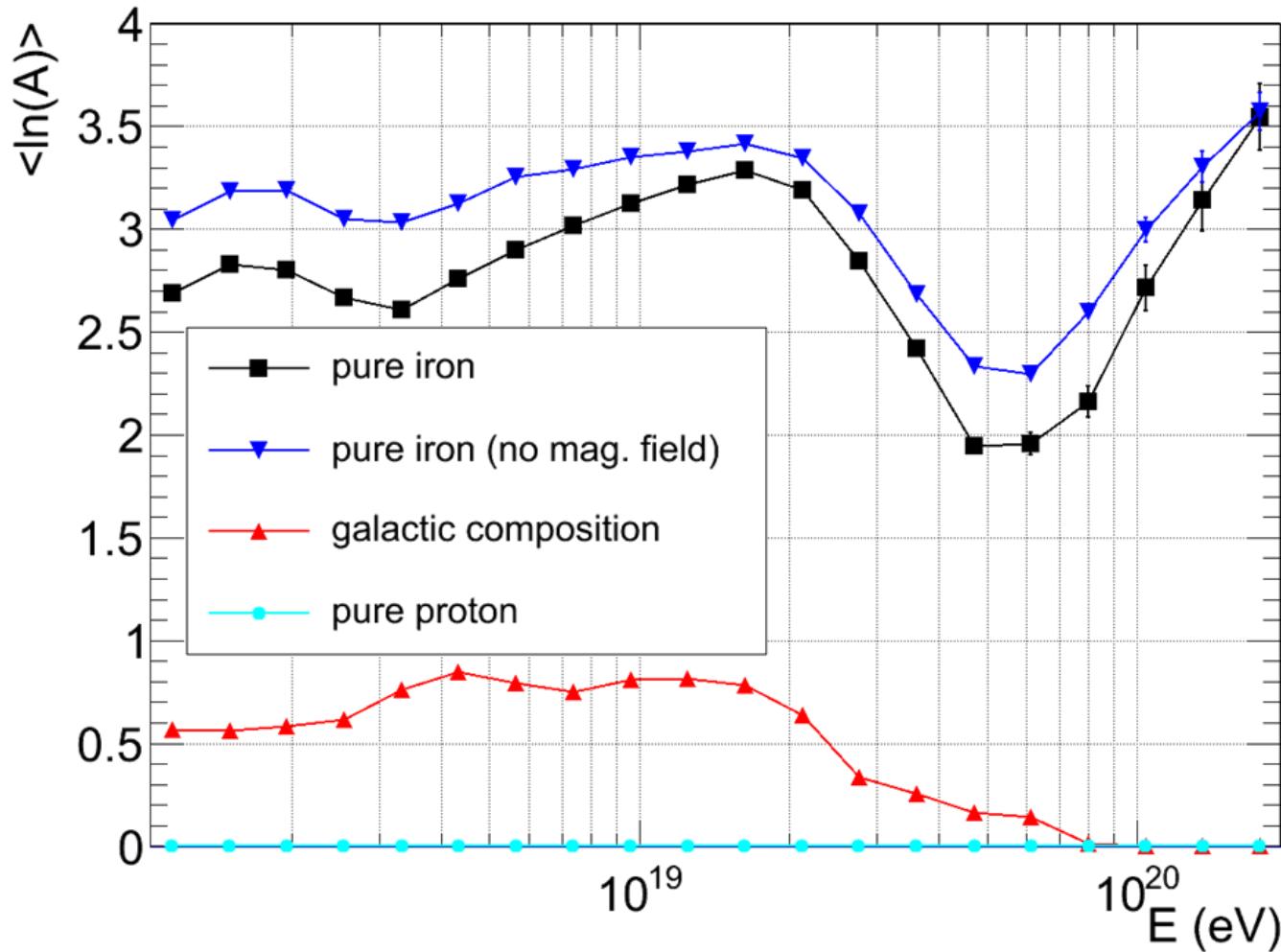


- Conclusions:
 - The shape of the spectrum changes for heavy vs. light injected compositions.
 - No strong effect from LSS-EGMF or LSS-source density.



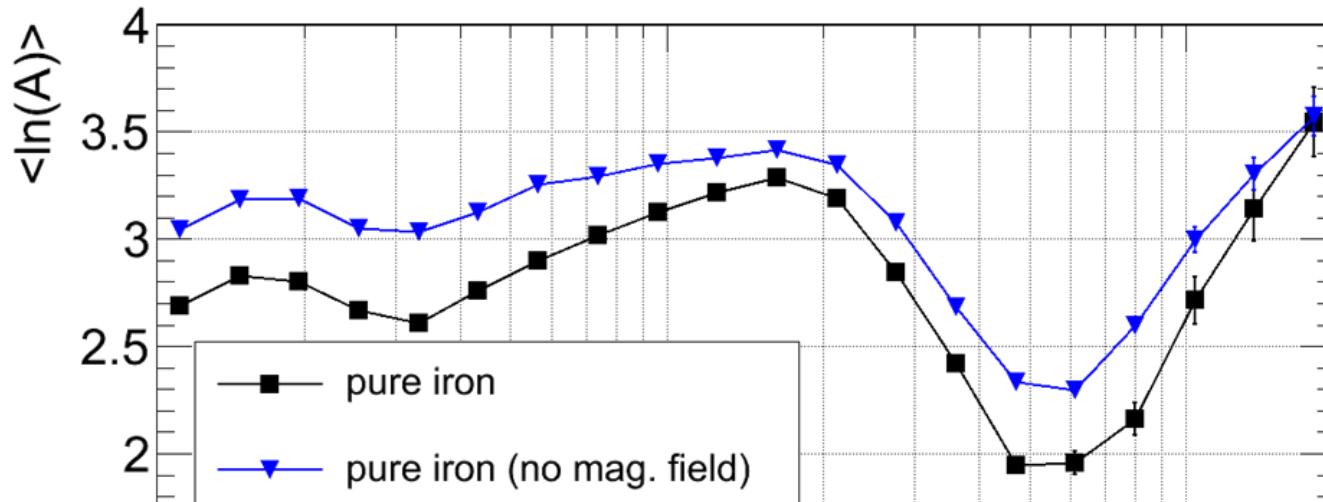
Observed Mass Spectra

$$\ln(55) \approx 4.0$$

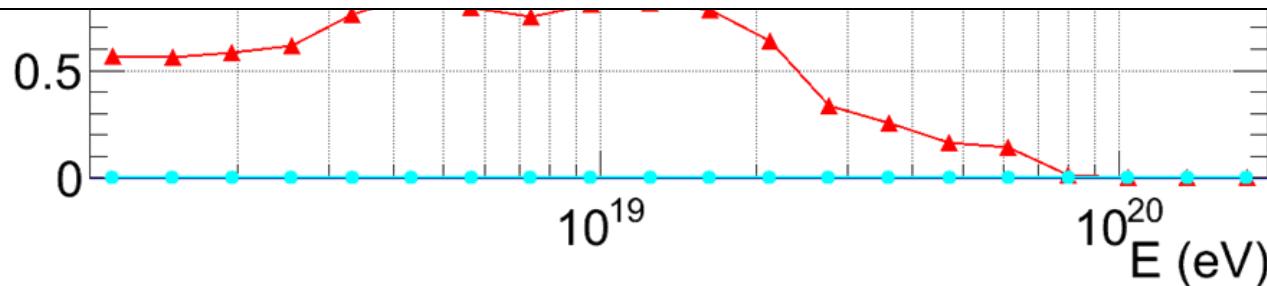


Observed Mass Spectra

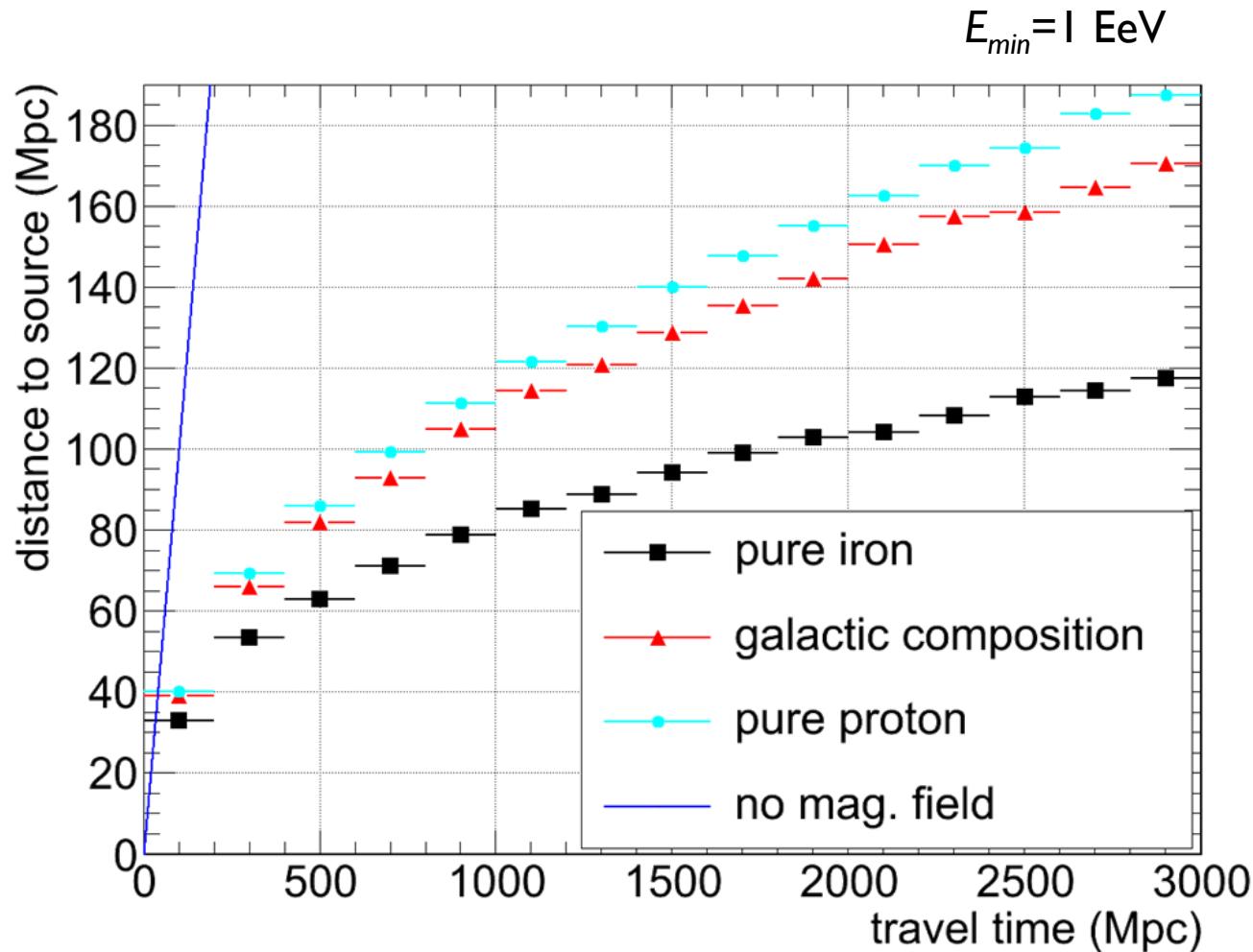
$$\ln(55) \approx 4.0$$



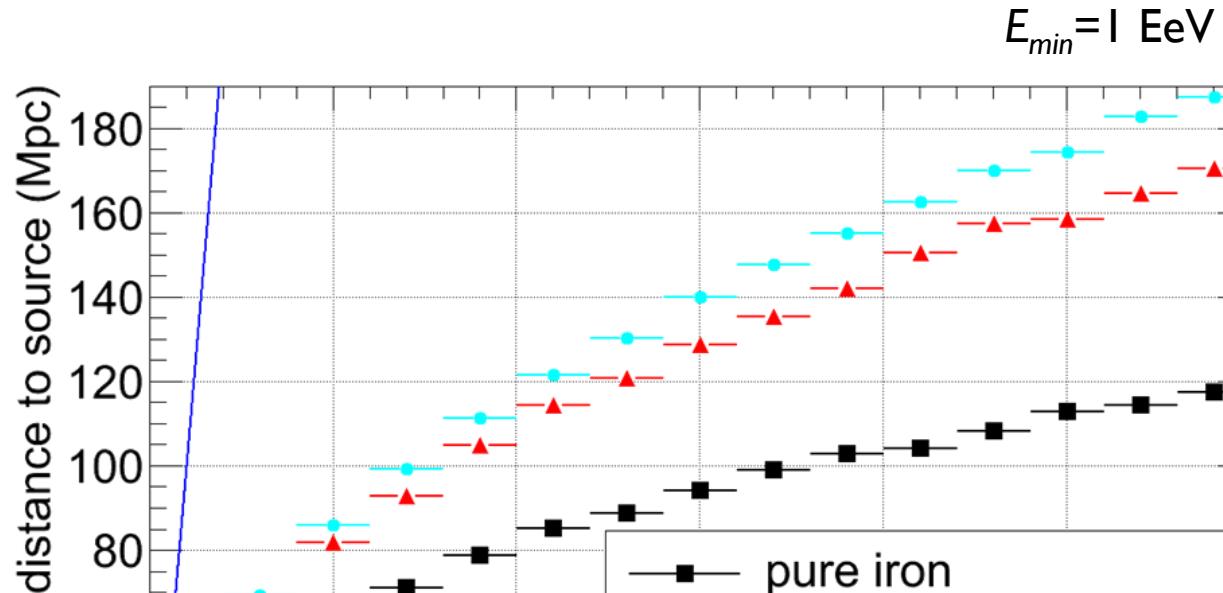
- Conclusion: Observed composition of pure iron injection affected by deflections.



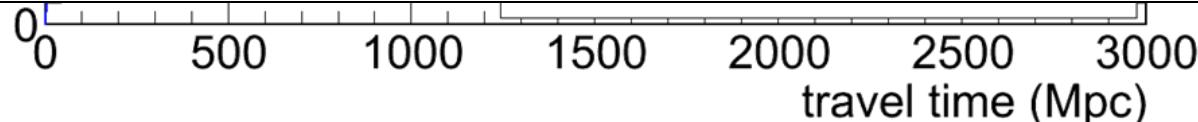
Travel Time vs. Source Distance



Travel Time vs. Source Distance



- Conclusions:
 - Strong effect of EGMF on the horizon.
 - Smaller horizon for heavier injected composition.



Conclusions from Examples

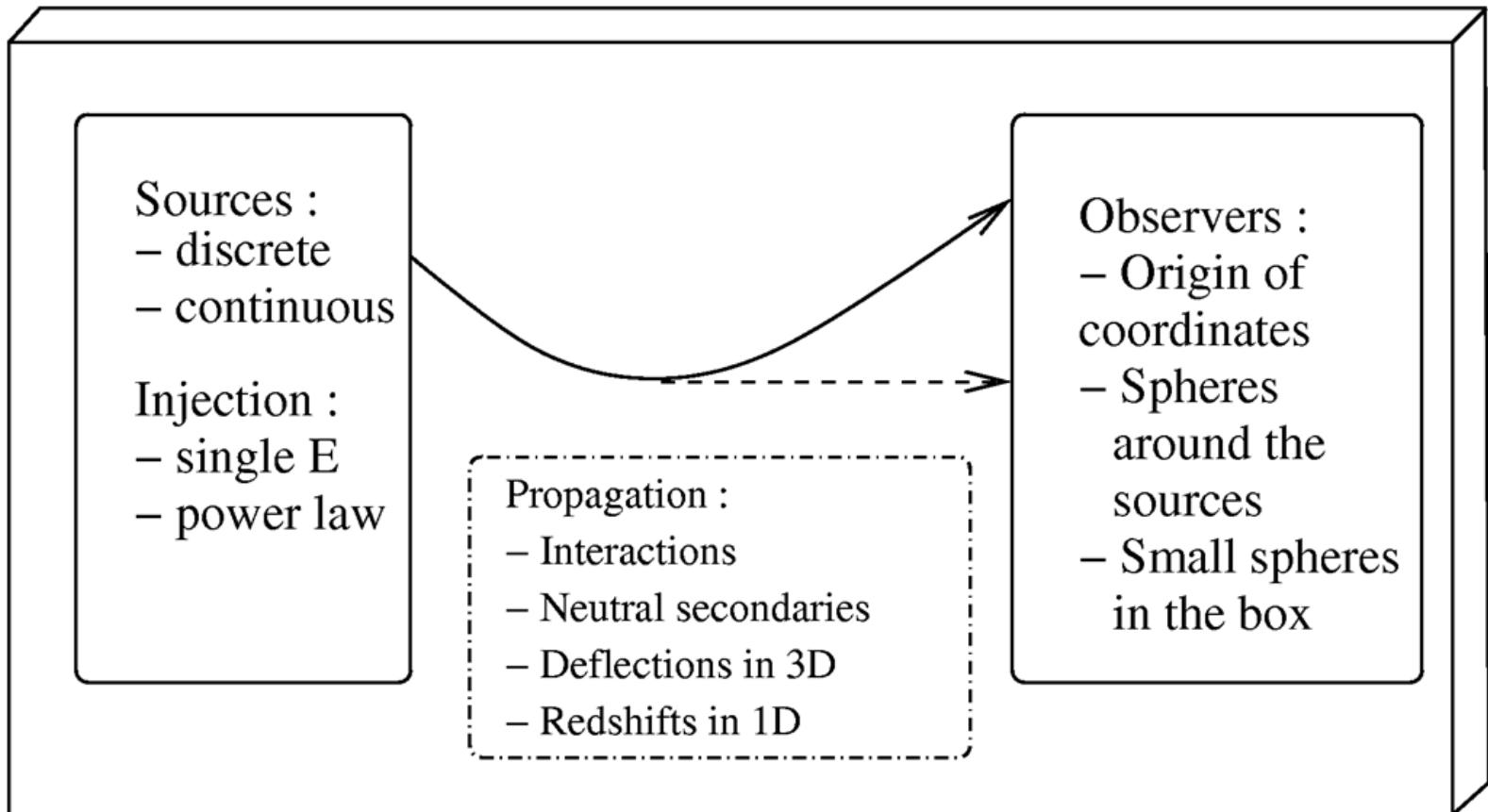
- A lighter source composition increases the fluxes of secondaries.
- The shape of the UHECR spectrum:
 - changes for light vs. heavy injected compositions.
 - not strongly affected by the LSS-EGMF or LSS-source density.
- The average mass decreases due to interactions with the EGMF.
- The LSS-EGMF strongly affects the horizon of the source.

Summary CRPropa 2.0

- Publically available at <https://crpropa.desy.de>
- Accompanying paper arXiv: 1206.3132, to appear in Astropart. Phys.
- Can handle all relevant interactions for UHECR propagation and their neutral secondaries.
- Will be improved further in the future, suggestions and/or help are welcome.

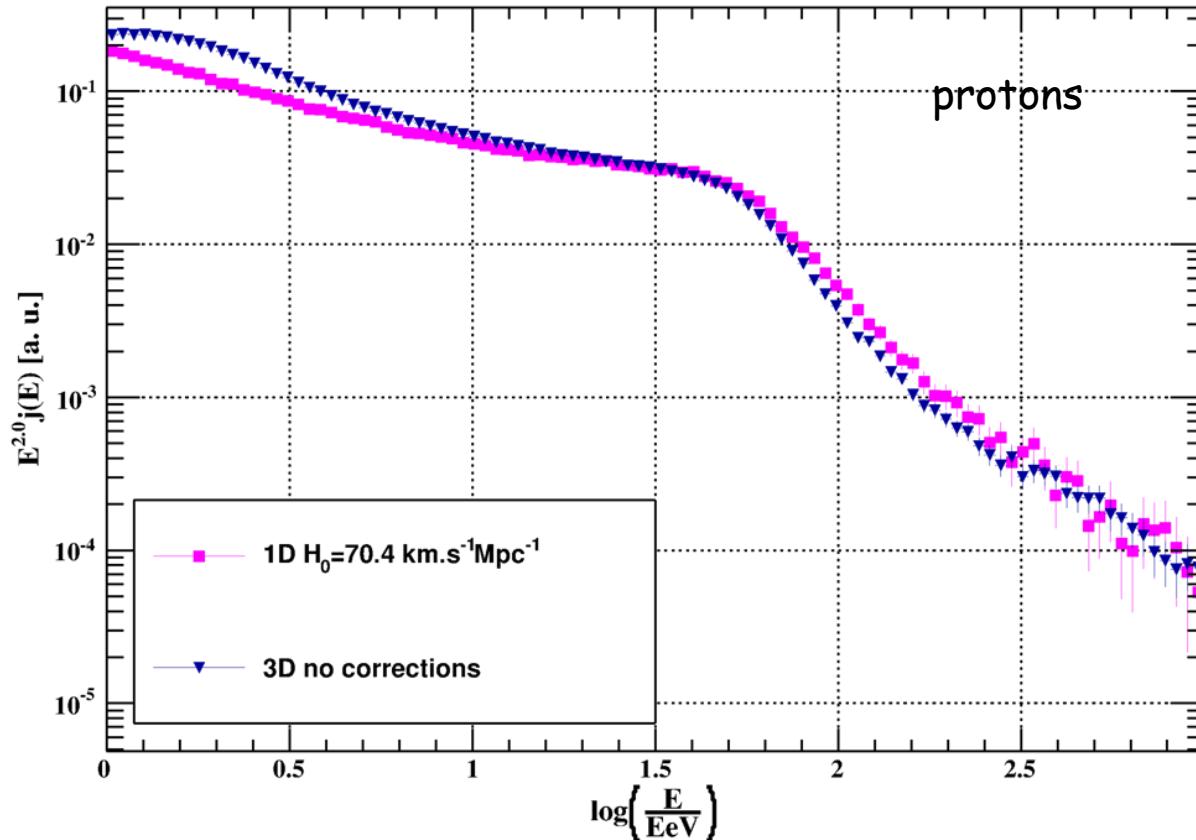
Backup Slides

Overview



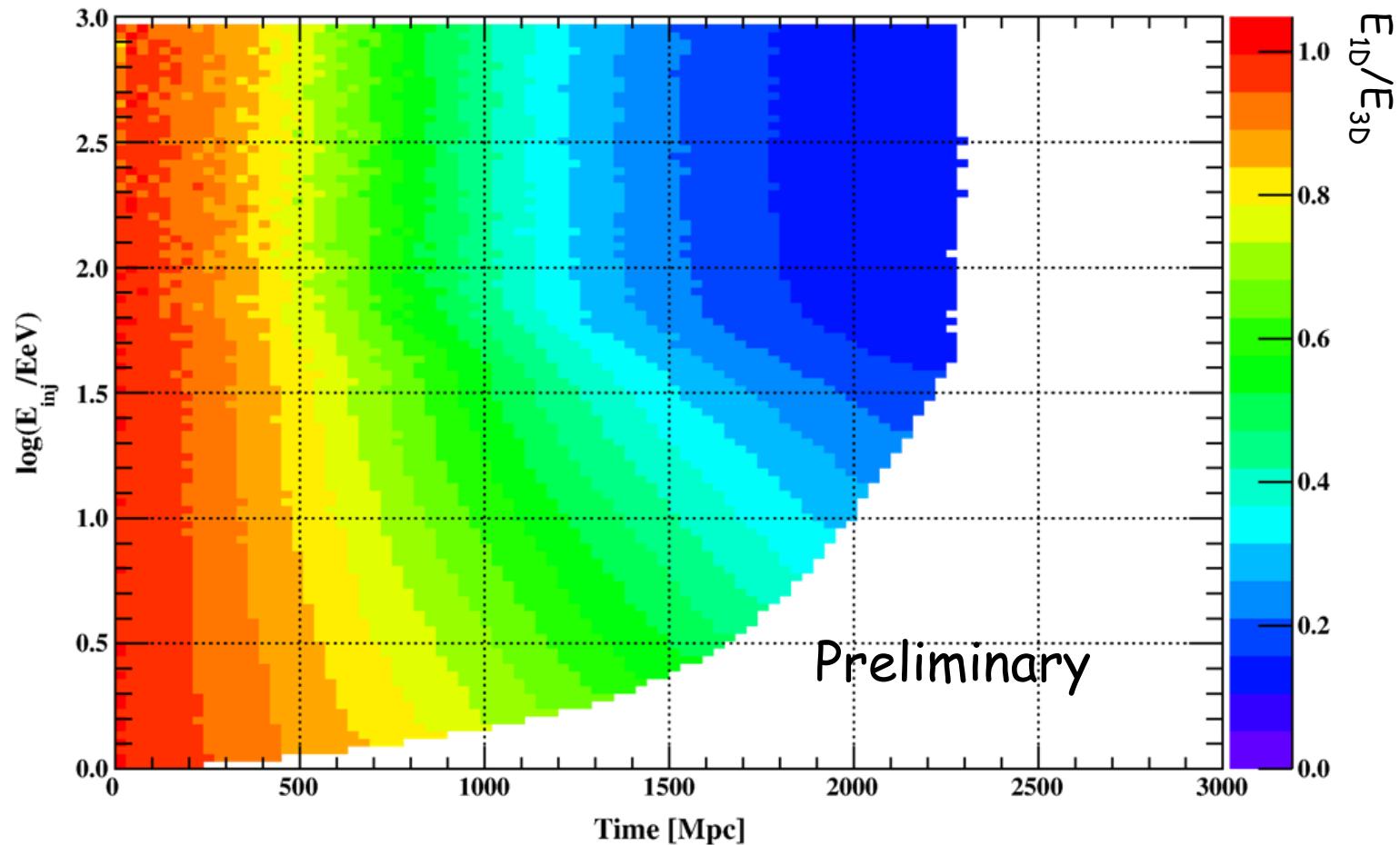
Cosmology in 3D propagation

- Injection redshift unknown (periodic boundary conditions, deflections)
- Simulation is done at $z=0$



Cosmology in 3D propagation

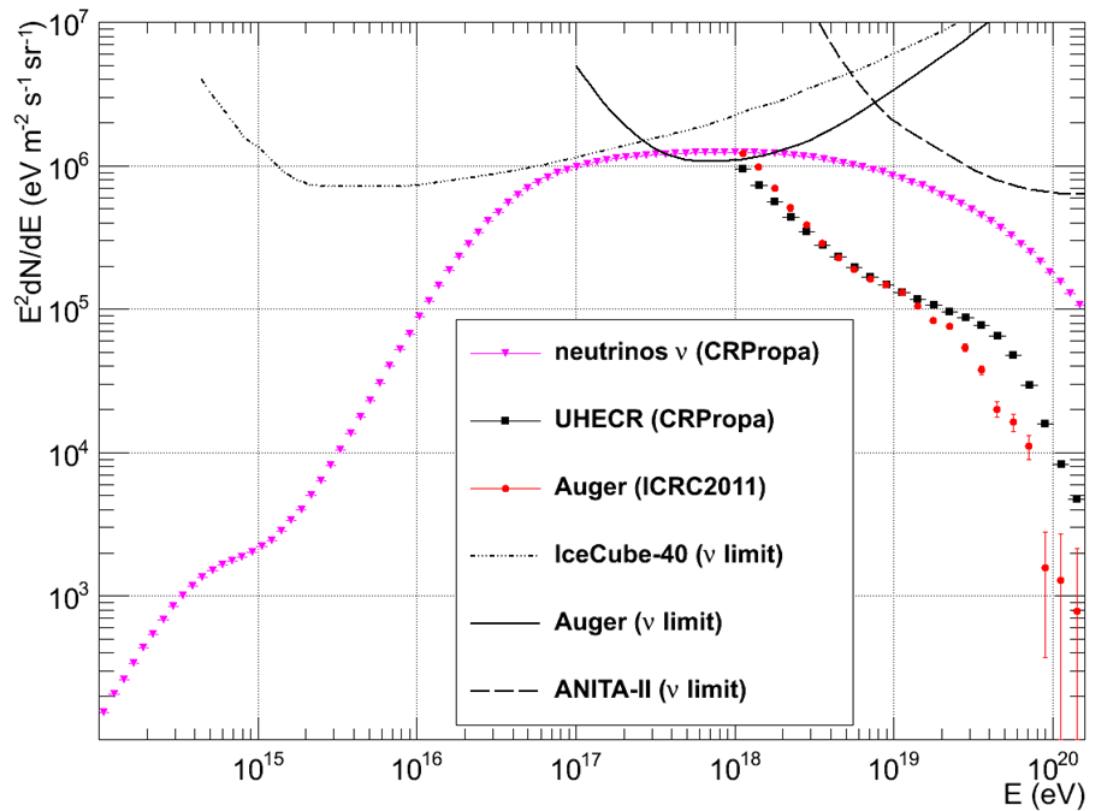
Compare observed energy for 1D and 3D propagation



Could be used as a correction for 3D propagation

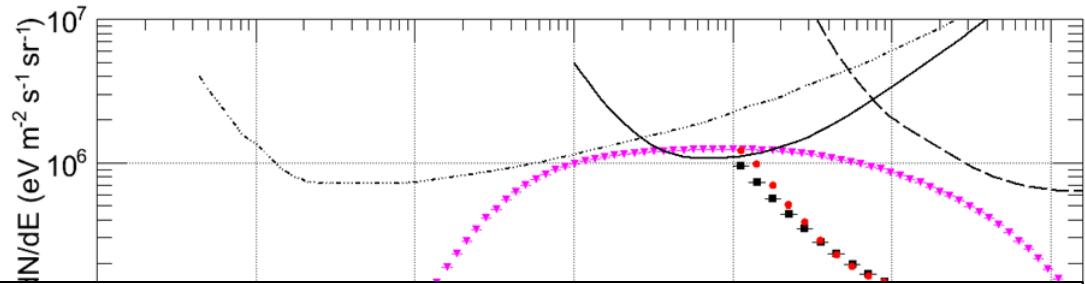
Violating Neutrino Limits

- Pure proton injection
- Comoving source evolution $(1+z)^4$, $z_{max}=11$ (was $z_{max}=2$)
- Max. rigidity: $R=10^4$ EeV (was $R=384.6$ EeV)



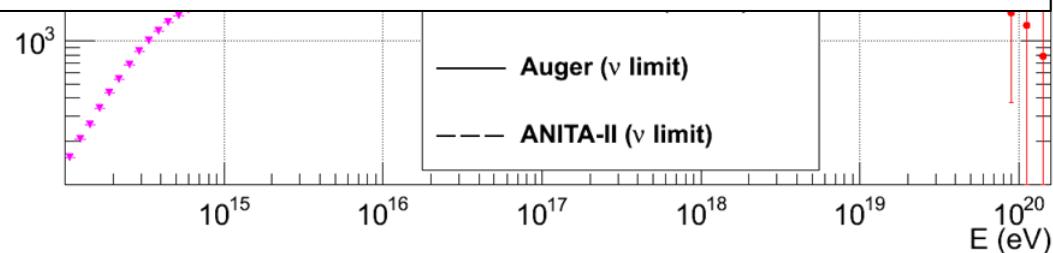
Violating Neutrino Limits

- Pure proton injection
- Comoving source evolution $(1+z)^4$.

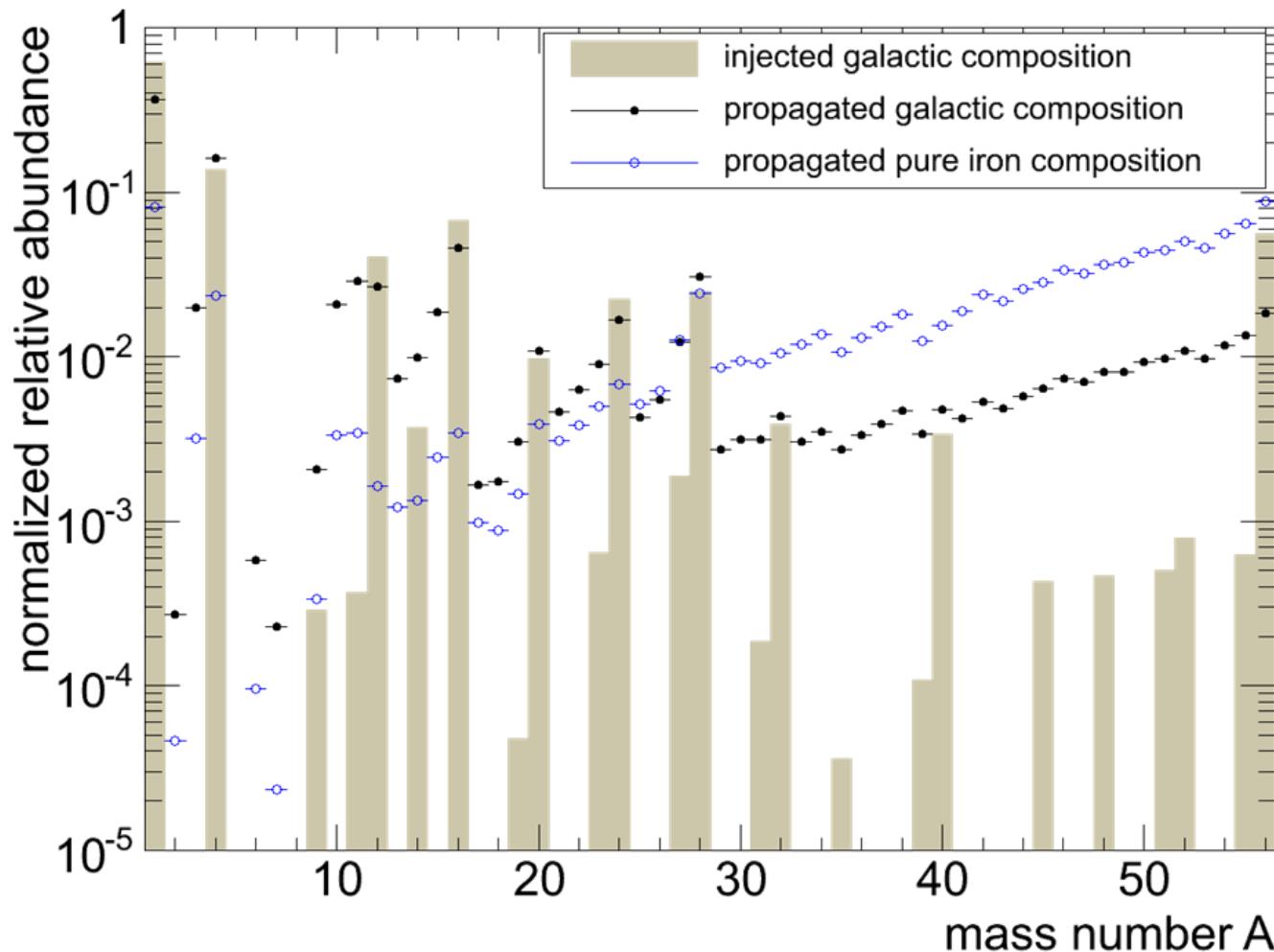


► Conclusion: Physically an unrealistic model, but we might not be so far away from detecting the neutrino flux for realistic models.

$R=10^+$ EeV
(was $R=384.6$ EeV)

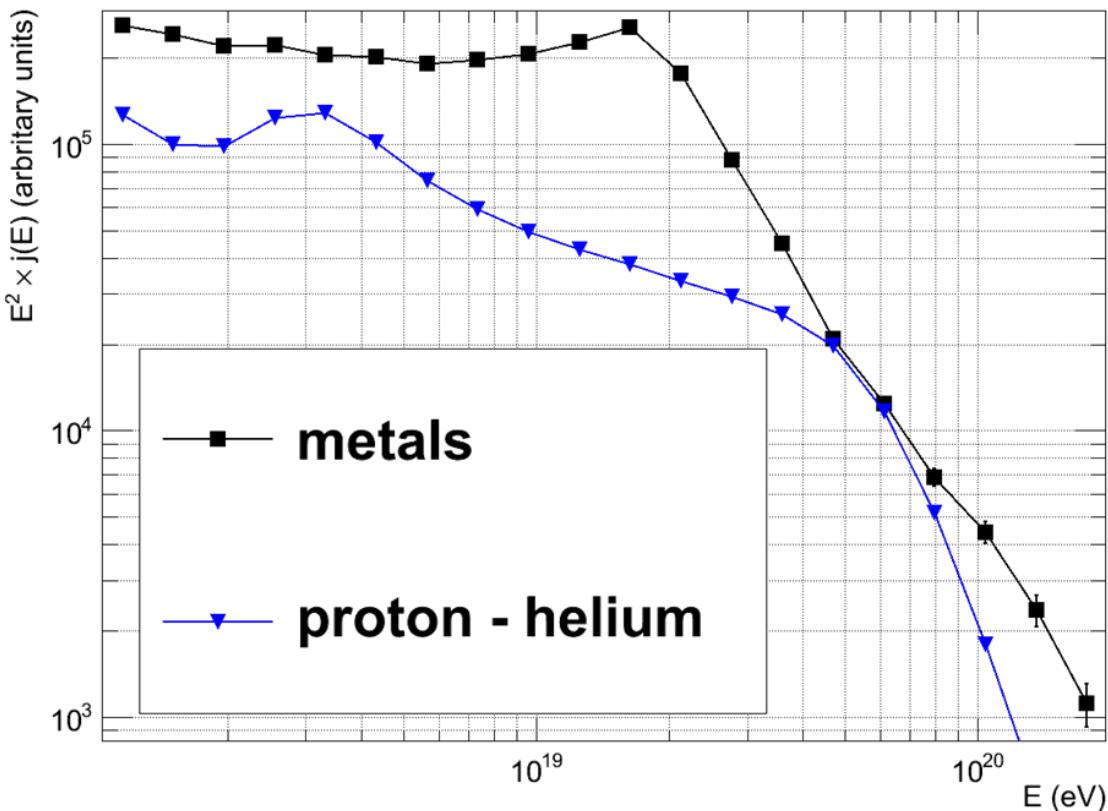


Atomic Mass Distribution



Iron Injection with LSS-EGMF

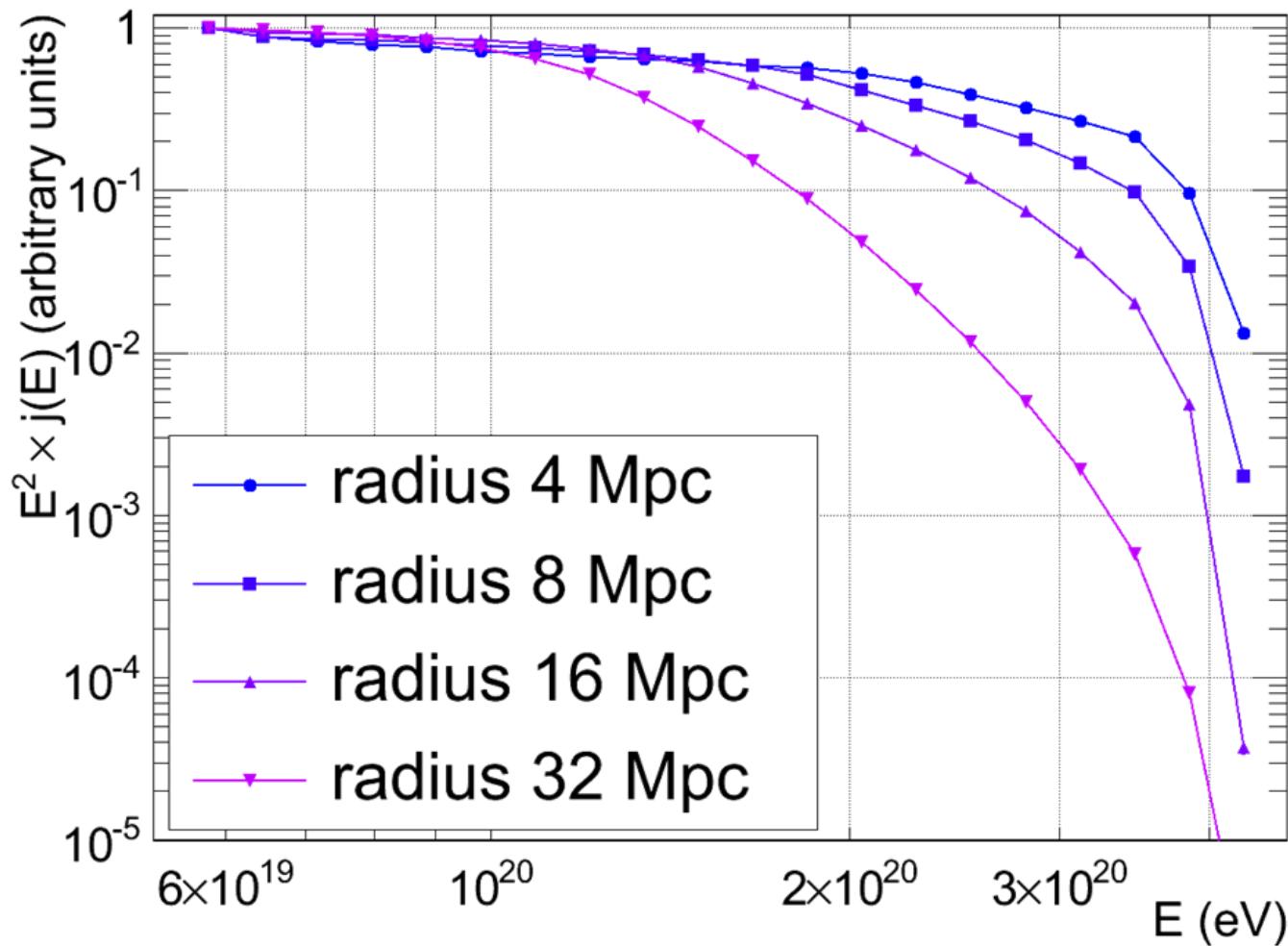
- Continuous Source Distribution following Large Scale Structure (LSS)
- Injection spectrum: $dN/dE \propto E^{-2.2}$
- Max. rigidity: $R=384.6$ EeV
- Detection: Sphere around observer; $r=1$ Mpc



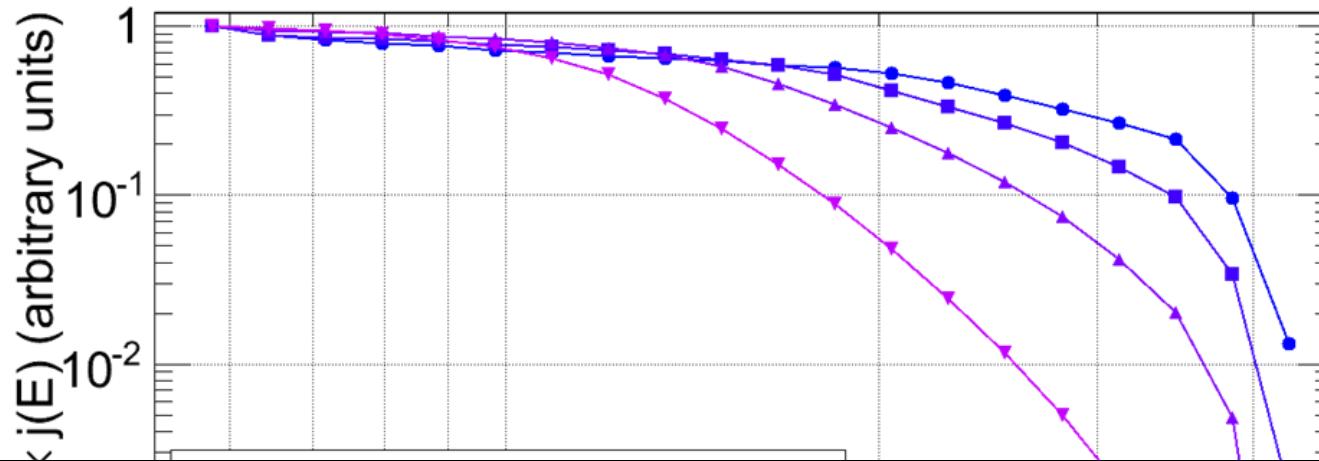
3D Simulation

- Continuous Source Distribution and EGMF following the LSS
- Injection spectrum: $dN/dE \propto E^{-2.2}$
- Max. rigidity: $R=384.6$ EeV
- Min. energy: $E_{min}=55$ EeV
- Detection: Sphere around Source
- Spectrum normalized to 1 in the first bin

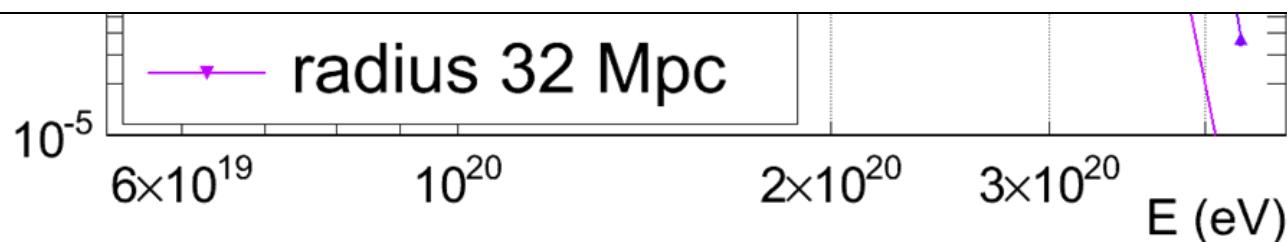
Energy Spectra



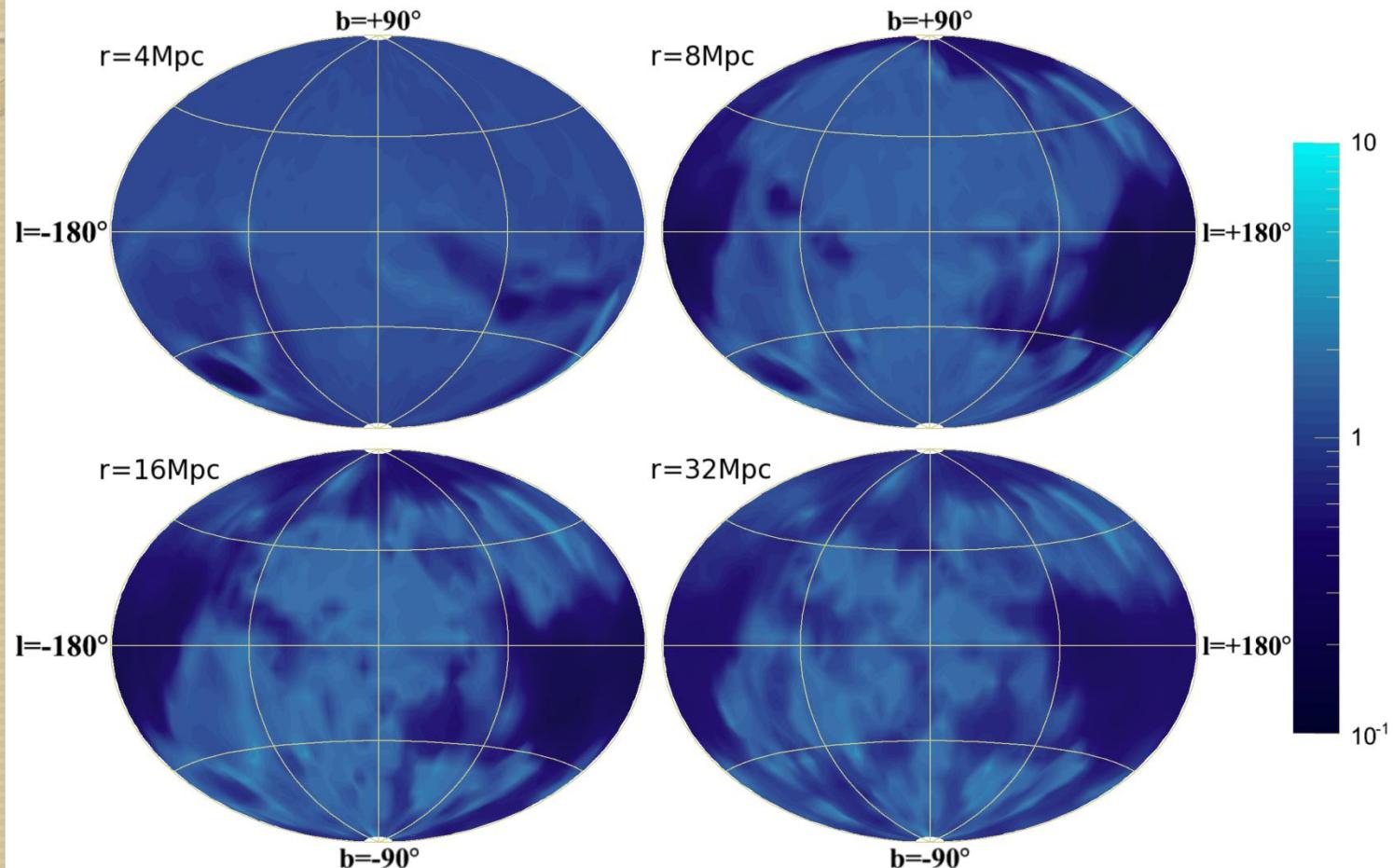
Energy Spectra



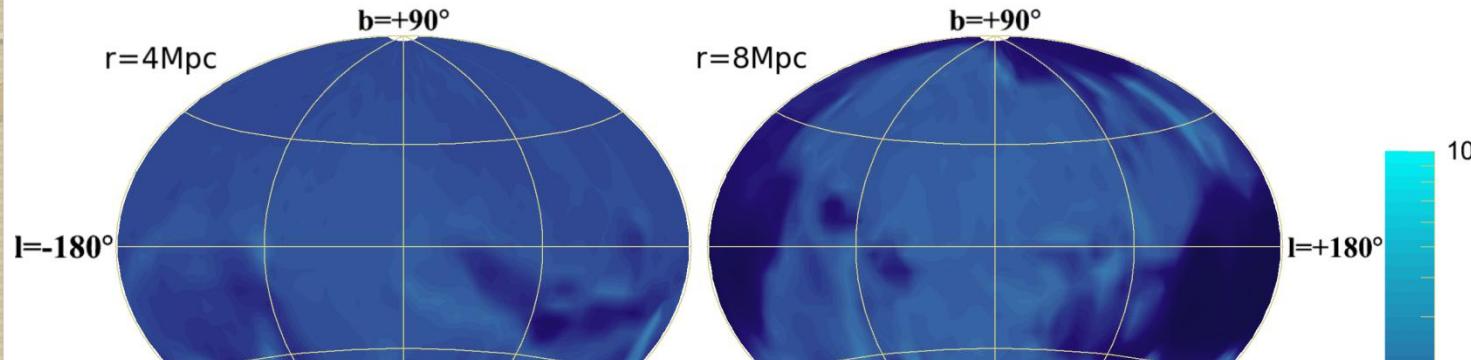
- ▶ Conclusion: Flux of cosmic rays at the highest energies suppressed by particle interactions as the distance to the source increases.



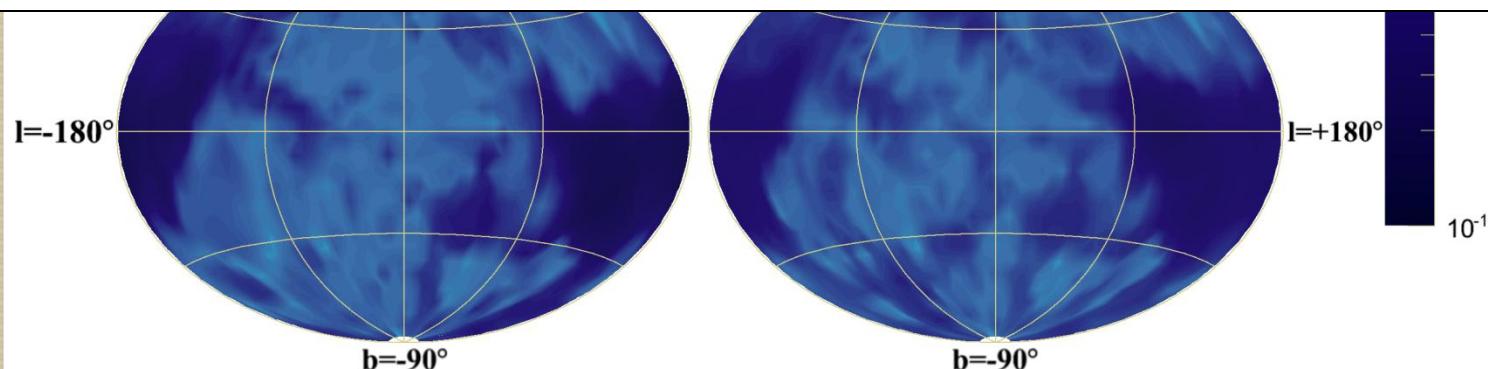
Sky Maps



Sky Maps

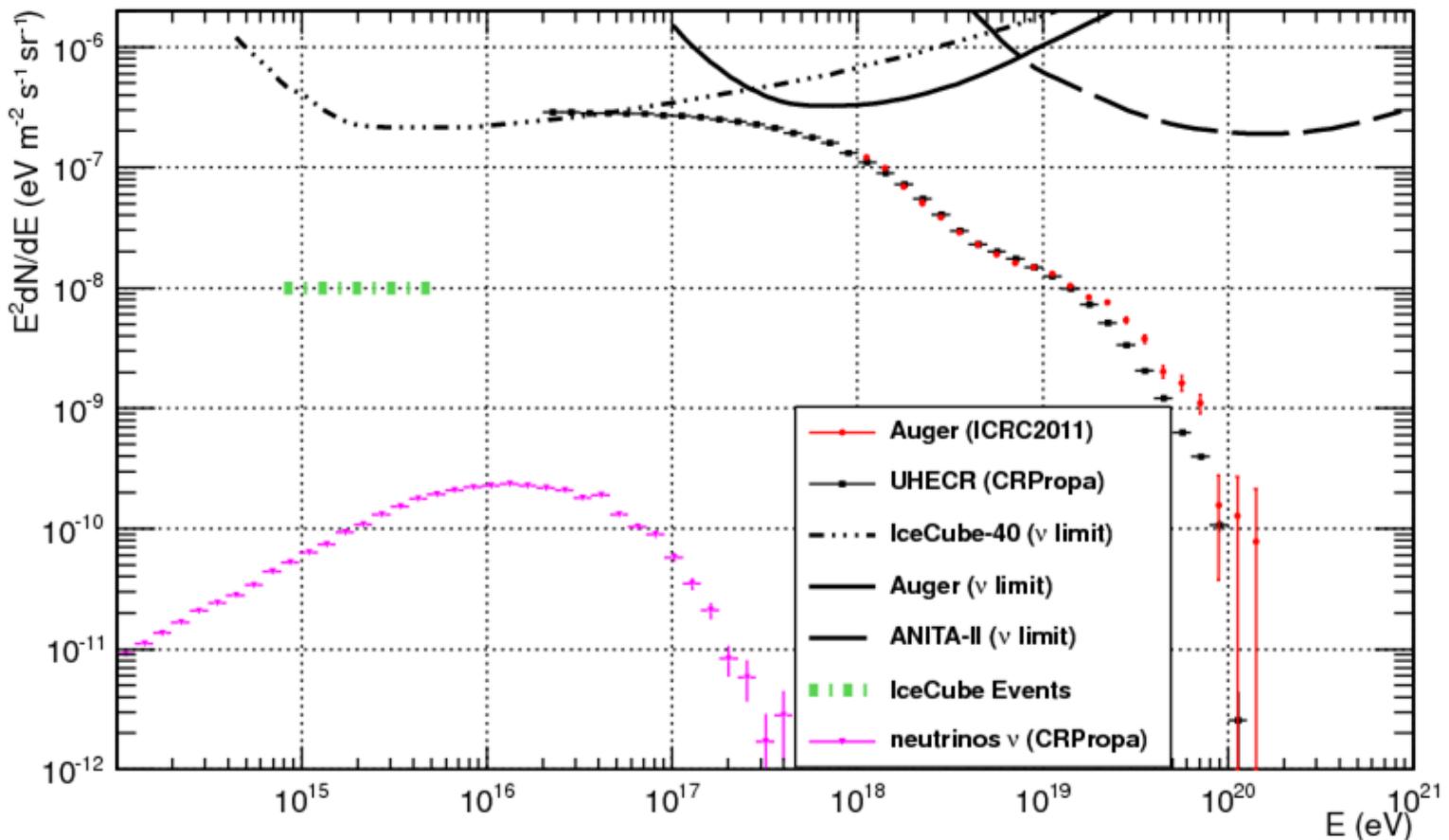


- Conclusion: The UHECR distribution becomes more anisotropic with increasing distance to the source (increased deflections in the LSS-EGMF).

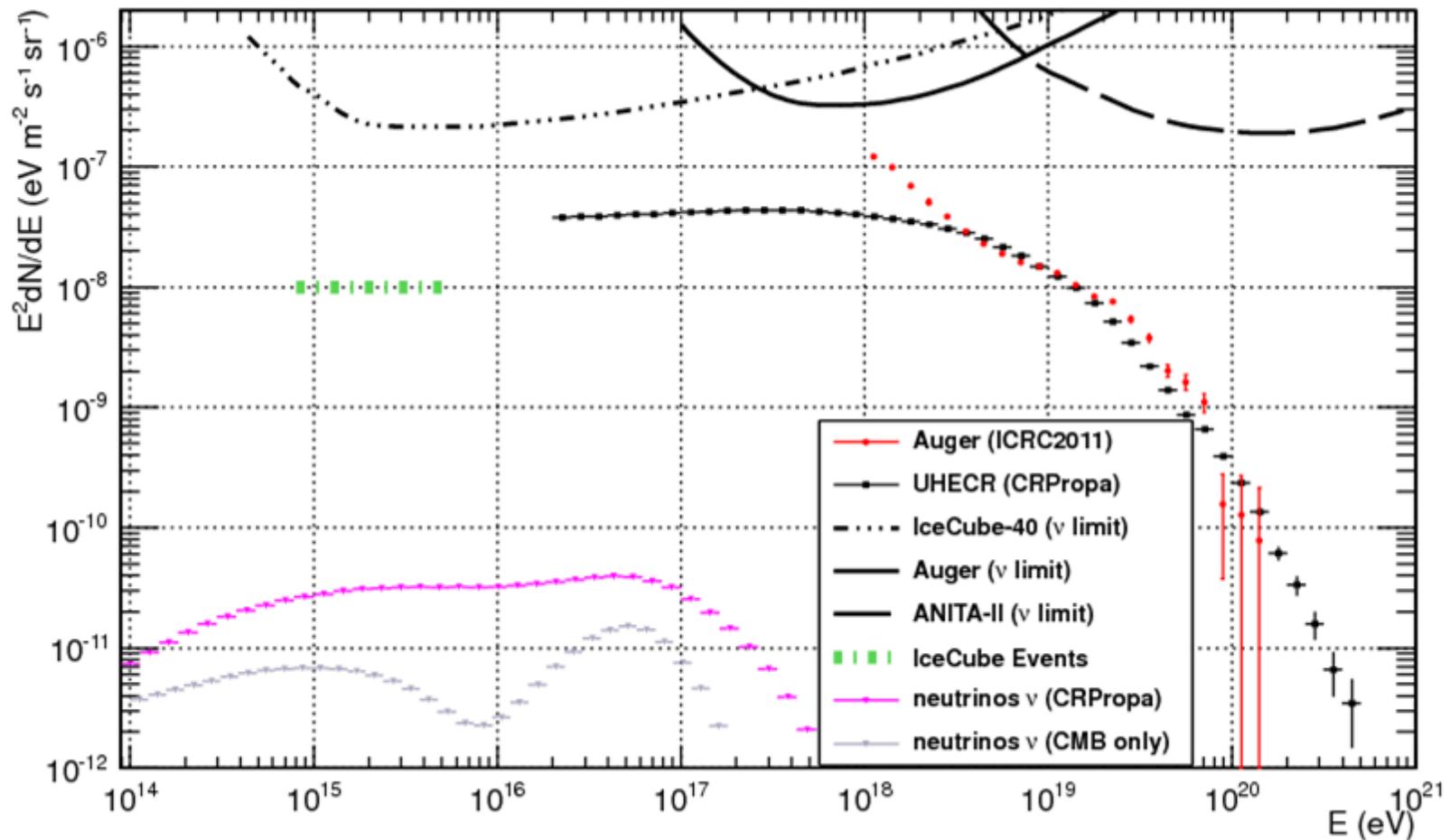


IC_GRB2_400pFe_Kneiske_0_8_4

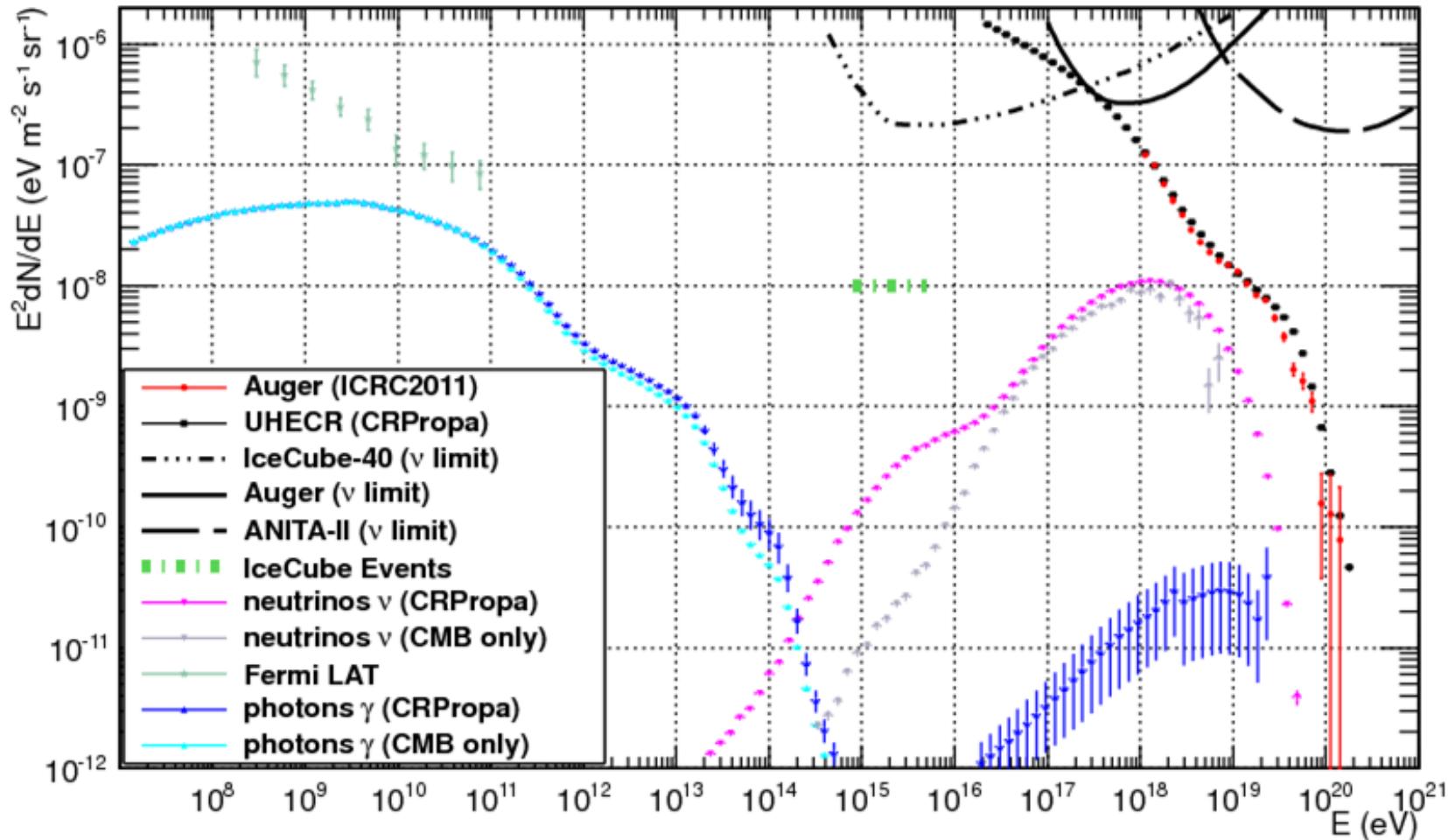
_20



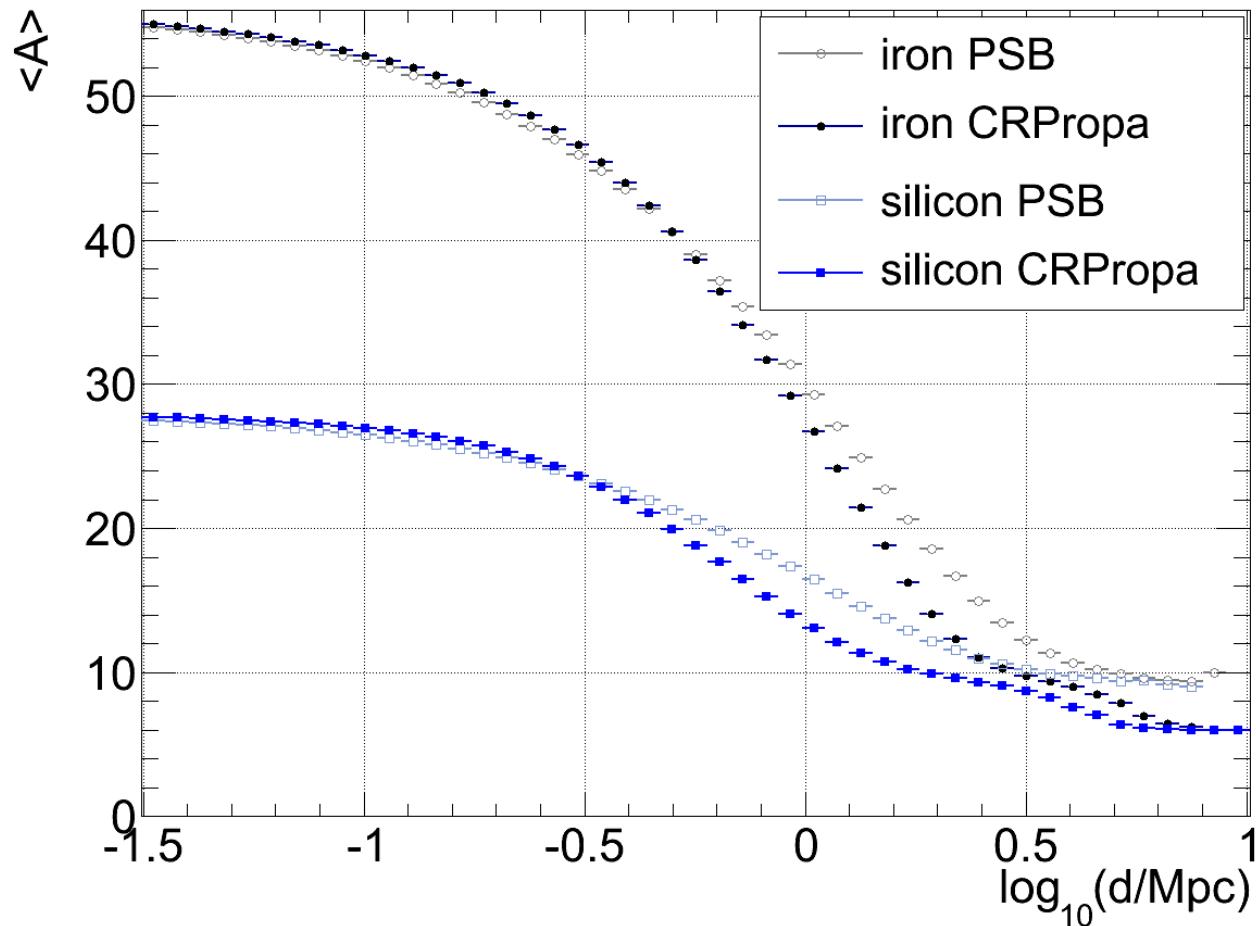
IC_GRB2_Fe_Kneiske_0_8_20_20



IC_GRB2_p_Kneiske_0_8_200_24



PSB primary comparison



PSB secondary comparison

