on the detectability of cosmogenic neutrinos

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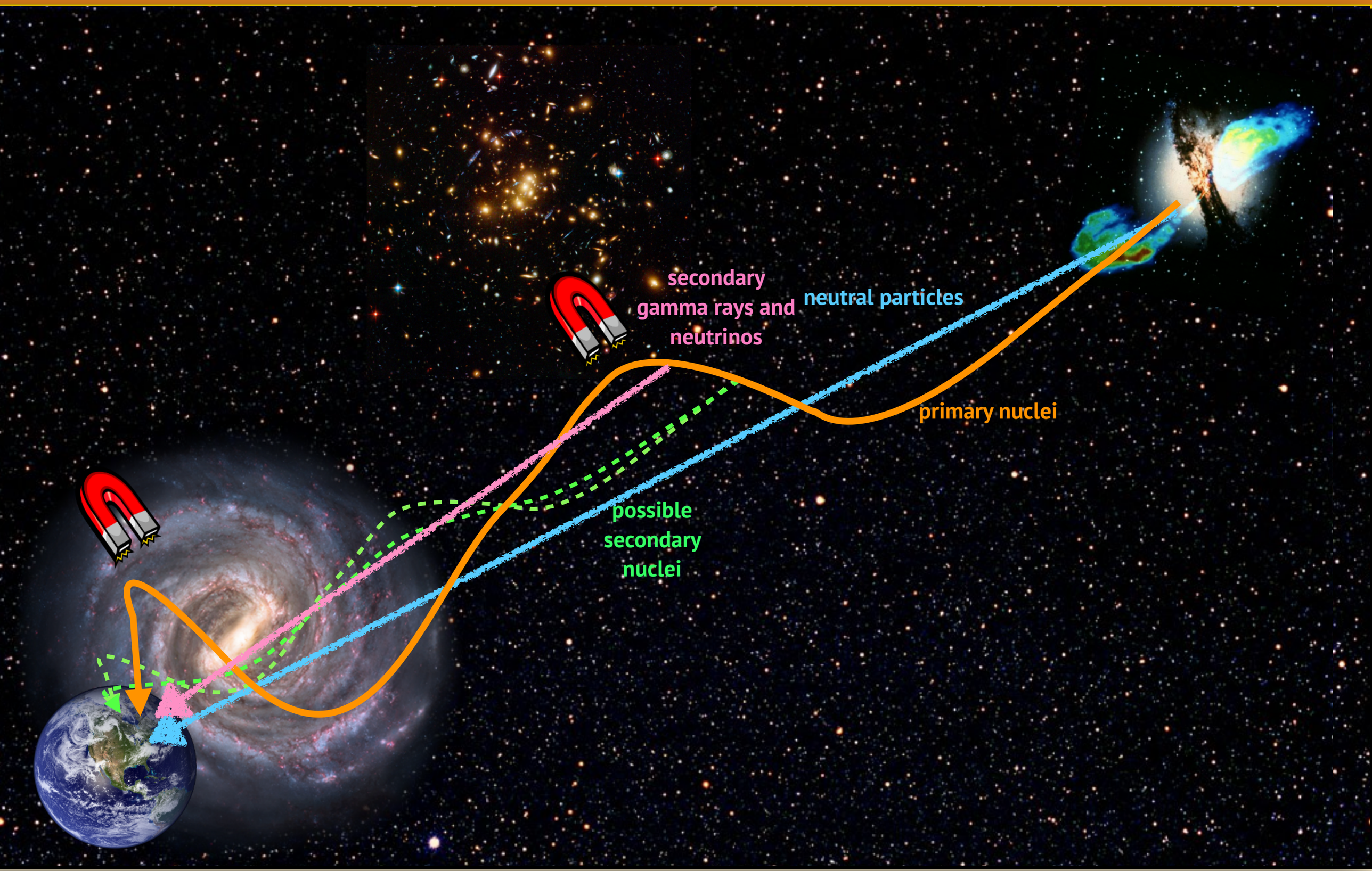
propagation picture



producing cosmogenic particles

photopion production

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

$$\pi^0 \rightarrow 2\gamma$$

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

$$\mu^+ \rightarrow e^+ + \nu_e + \bar{\nu}_\mu$$

Bethe-Heitler pair production

$${}^A_Z X + \gamma_{bg} \rightarrow {}^A_Z X + e^+ + e^-$$

photodisintegration

$${}^A_Z X + \gamma_{bg} \rightarrow {}^{A-1}_{Z} X + n$$

$${}^A_Z X + \gamma_{bg} \rightarrow {}^{A-1}_{Z-1} X + p$$

$${}^A_Z X + \gamma_{bg} \rightarrow {}^{A-4}_{Z-2} X + \alpha$$

electromagnetic interactions

$$\gamma + \gamma_{bg} \rightarrow e^- + e^+$$

$$\gamma + \gamma_{bg} \rightarrow e^- + e^+ + e^+ + e^-$$

$$e^\pm + \gamma_{bg} \rightarrow e^\pm + \gamma$$

$$e^\pm + \gamma_{bg} \rightarrow e^\pm + e^+ + e^-$$

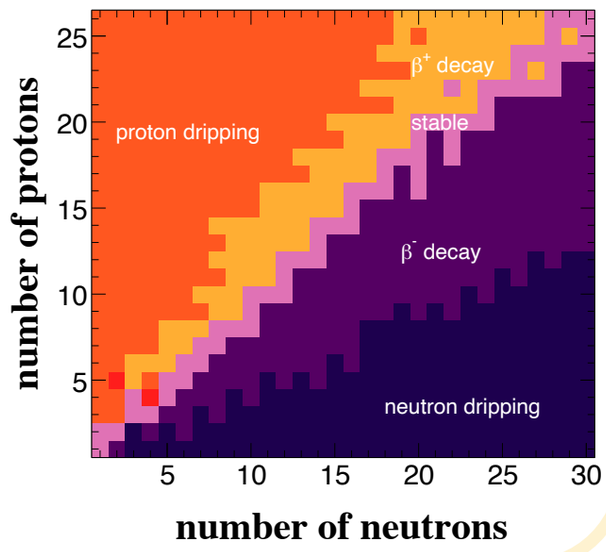
nuclear decays

$${}^A_Z X \rightarrow {}^{A-4}_{Z-2} X + \alpha$$

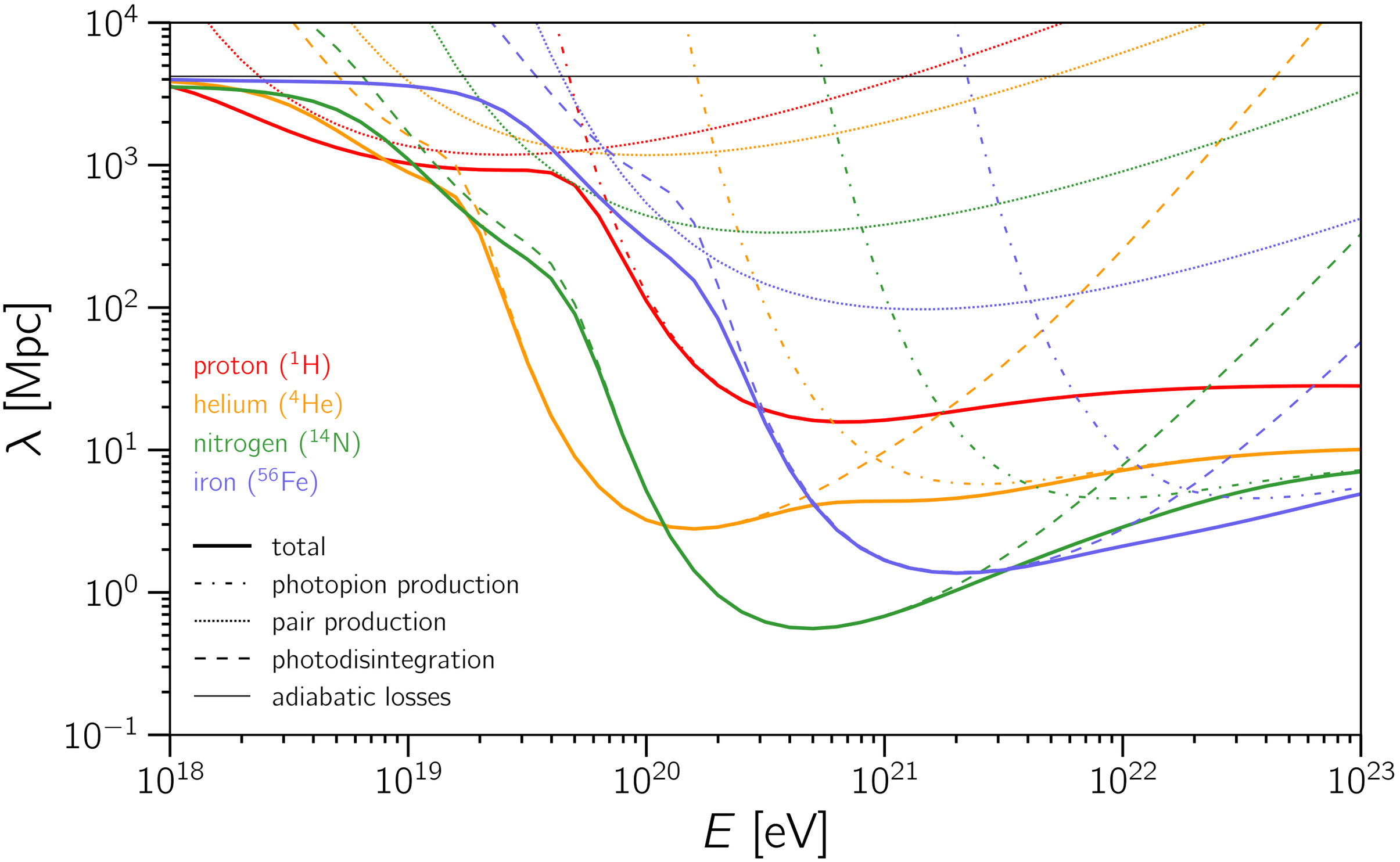
$${}^A_Z X \rightarrow {}^{A}_{Z+1} X + e^- + \bar{\nu}_e$$

$${}^A_Z X \rightarrow {}^{A}_{Z-1} X + e^+ + \nu_e$$

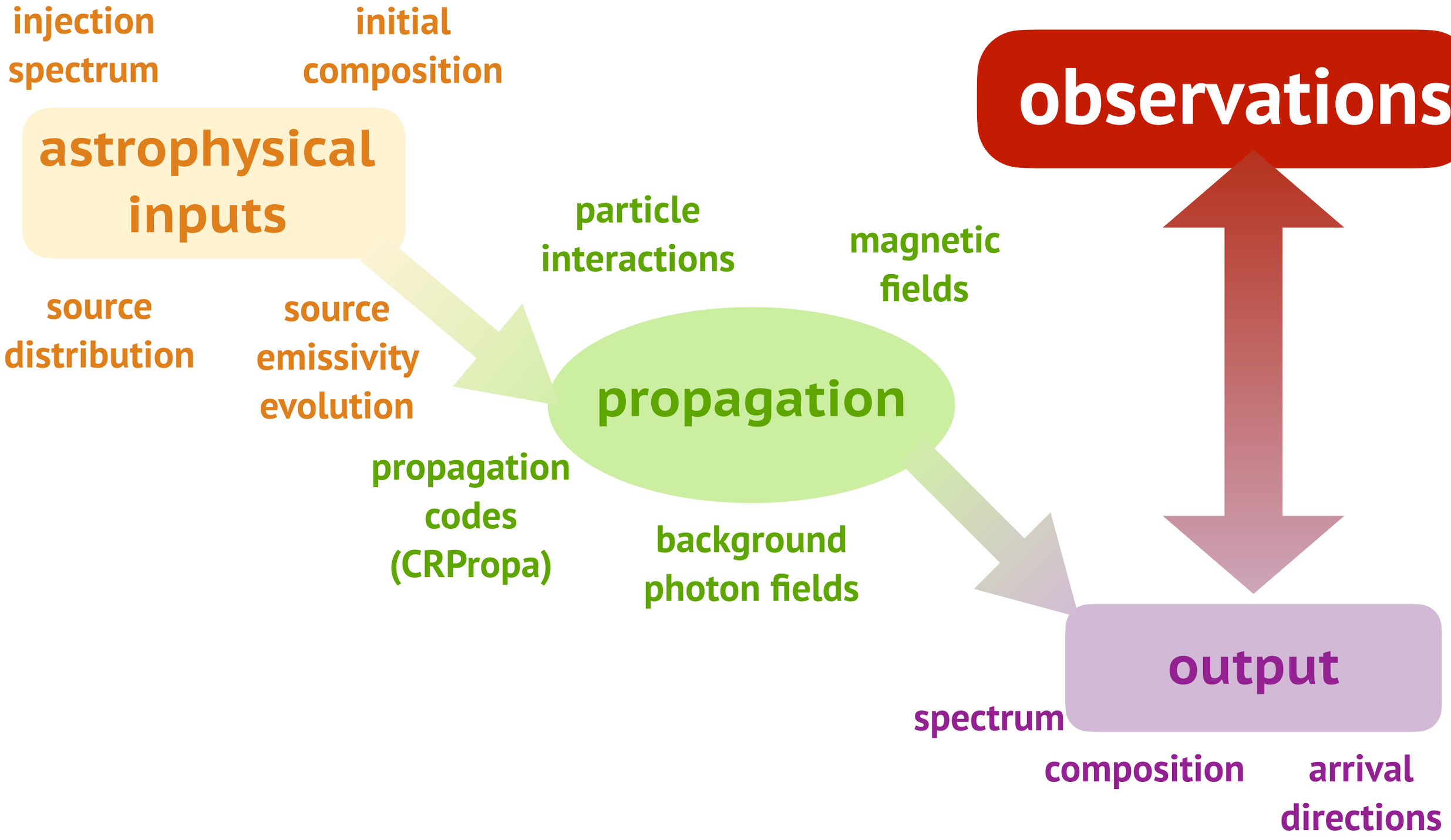
$${}^A_Z X^* \rightarrow {}^A_Z X + \gamma$$



mean free paths at ultra-high energies



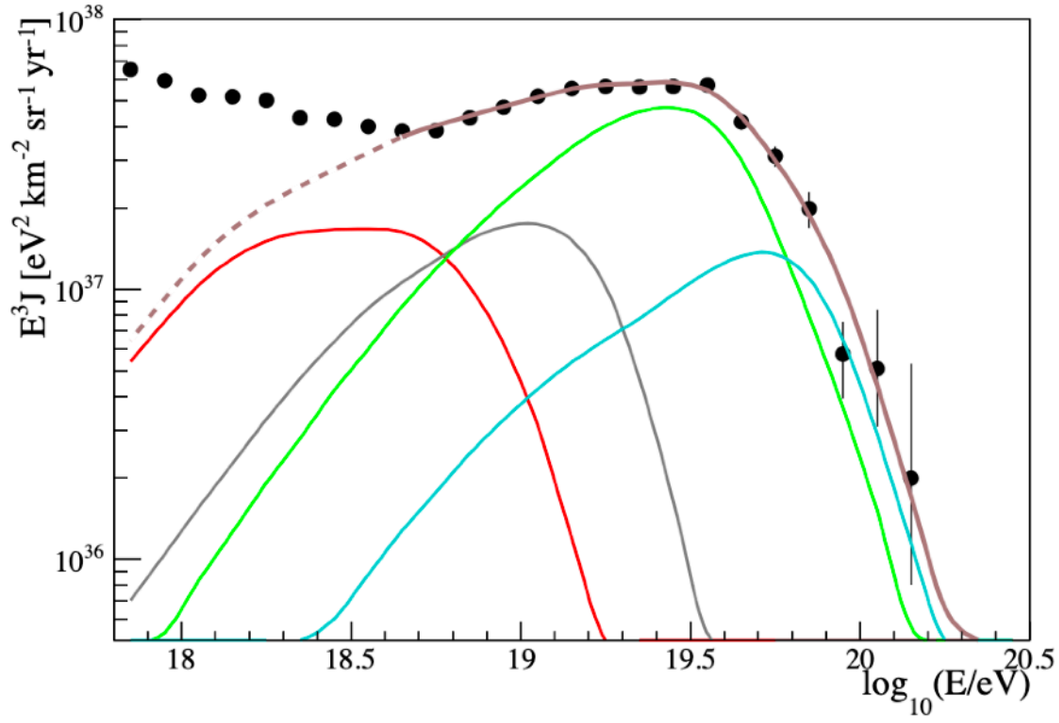
interpreting the UHECR data

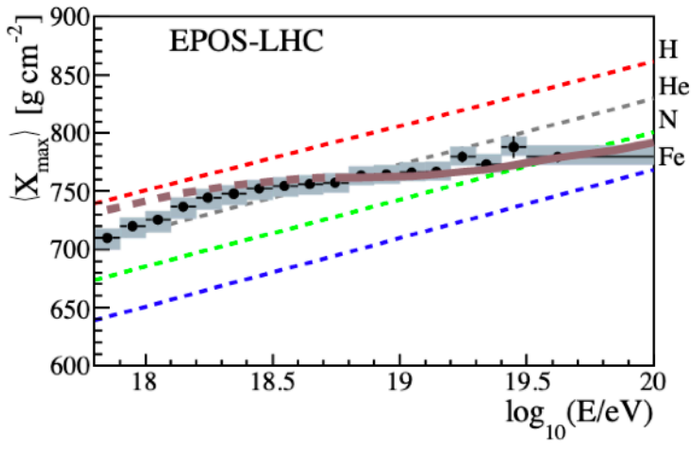


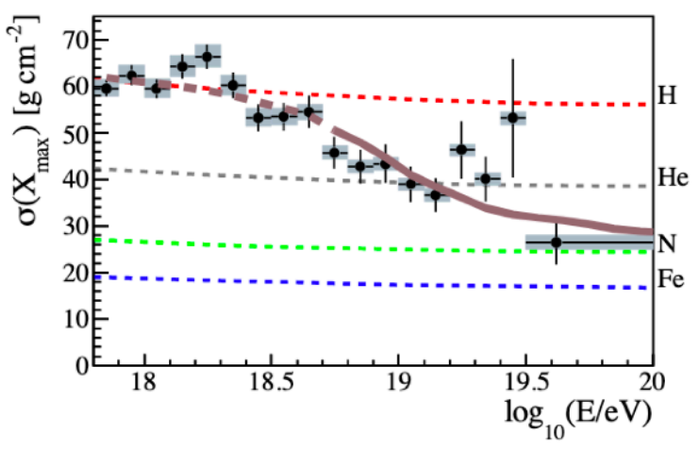
combined fit of the Auger data

Pierre Auger Collaboration. . JCAP 04 (2017) 038. arXiv:1612.07155

spectral index = 0.87
maximum rigidity = $10^{18.62}$ V
composition: 88% nitrogen + 12% silicon







fitting the UHECR data

astrophysical inputs

- five compositions: p, He, N, Si, Fe
- α=[-1.6, 3.1] in steps of 0.1
- log(R_{max}/V)=[17.5, 20.5] in steps of 0.1
- source evolution: $(1+z)^m$
- m=[-6,6] in steps of 0.1
- one-dimensional model
- sources uniformly distributed (0<z<1)
- injected spectrum:

$$\frac{dN}{dE} \propto E^{-\alpha} \begin{cases} 1 & E < ZR_{max} \\ \exp\left(-\frac{E}{ZR_{max}}\right) & E \geq ZR_{max} \end{cases}$$

fitting procedure

model likelihood

$$D = D(J) + D(X_{max}) = -2\ln\frac{\mathscr{L}_J}{\mathscr{L}_J^{sat}} - 2\ln\frac{\mathscr{L}_{X_{max}}}{\mathscr{L}_{X_{max}}^{sat}}$$

saturated model
(matches data)

$$\mathscr{L}_{X_{max}} = \prod_i n_i! \prod_j \frac{1}{k_{ij}!} (G_{ij}^{model})^{k_{ij}}$$

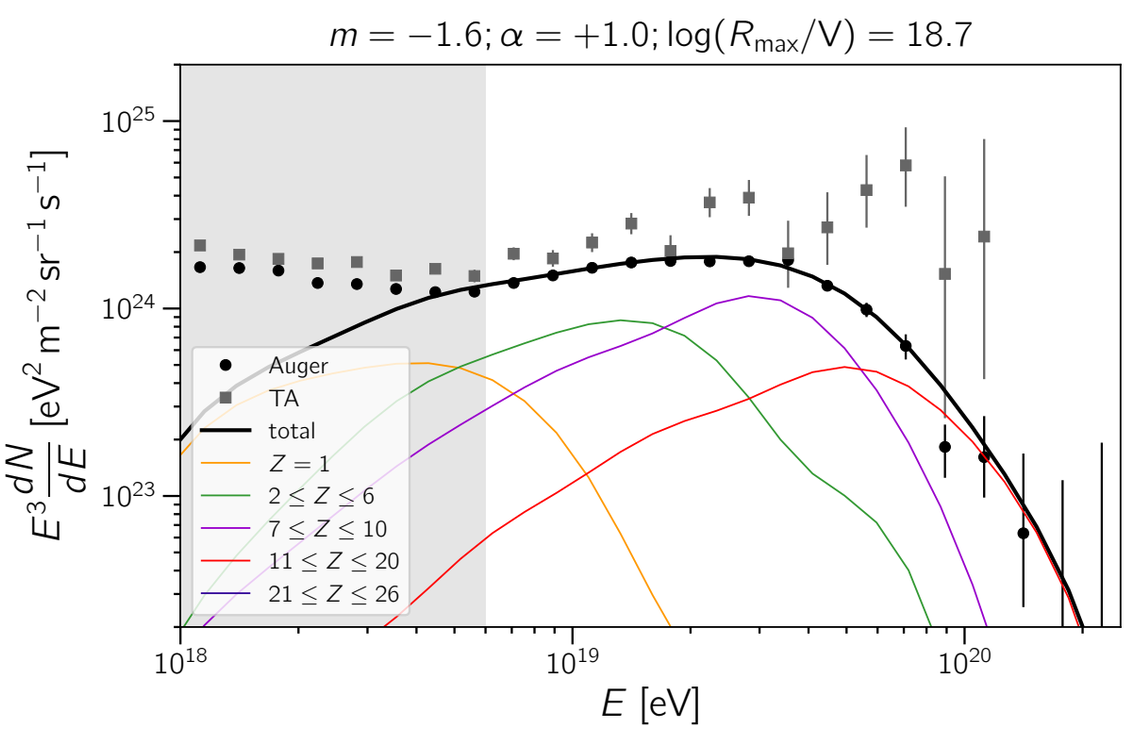
composition: X_{max} distributions

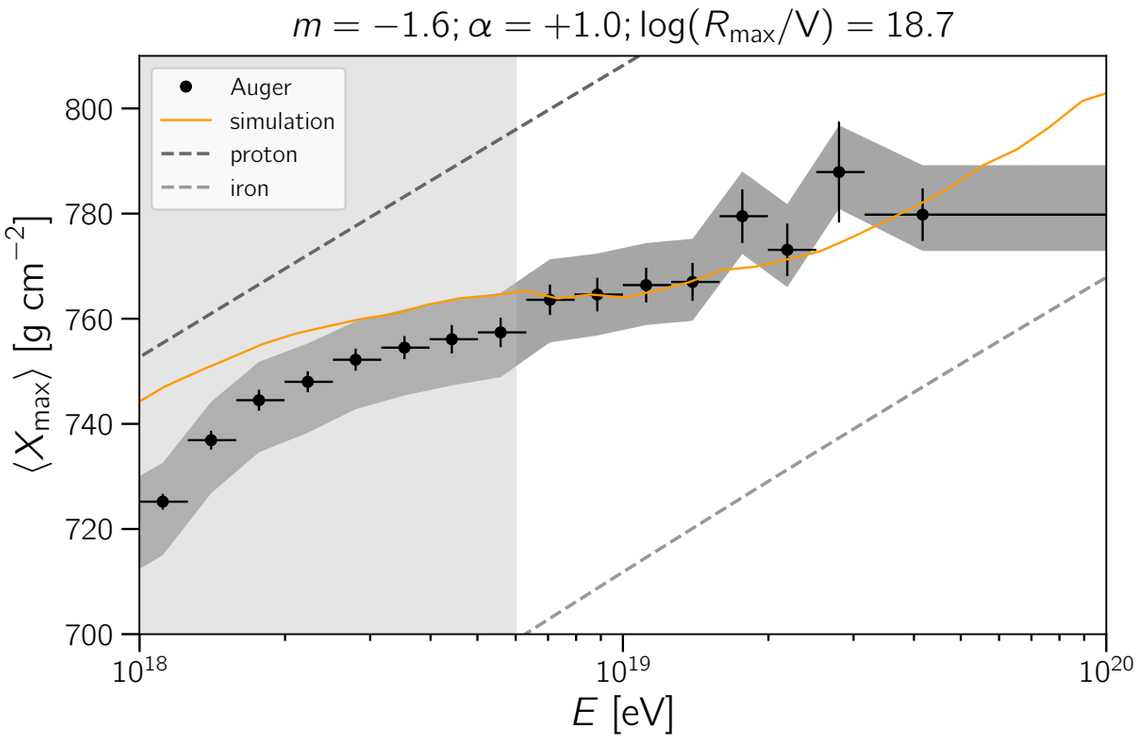
$$D = -2\sum_i \mu_i - n_i + n_i \ln\frac{n_i}{\mu_i}$$

spectrum: vertical + inclined events

the best-fit

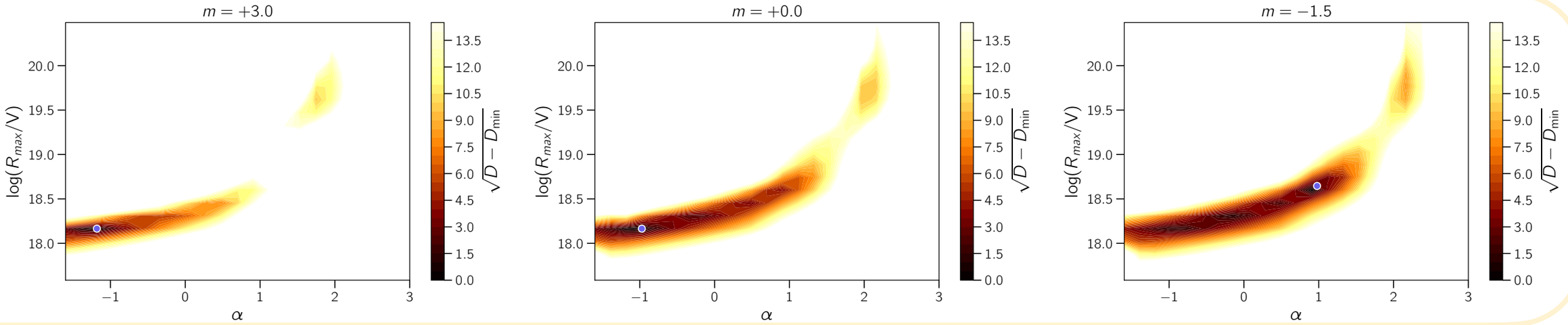
Alves Batista, de Almeida. Lago, Kotera. JCAP 01 (2019) 002. arXiv:1806.10879



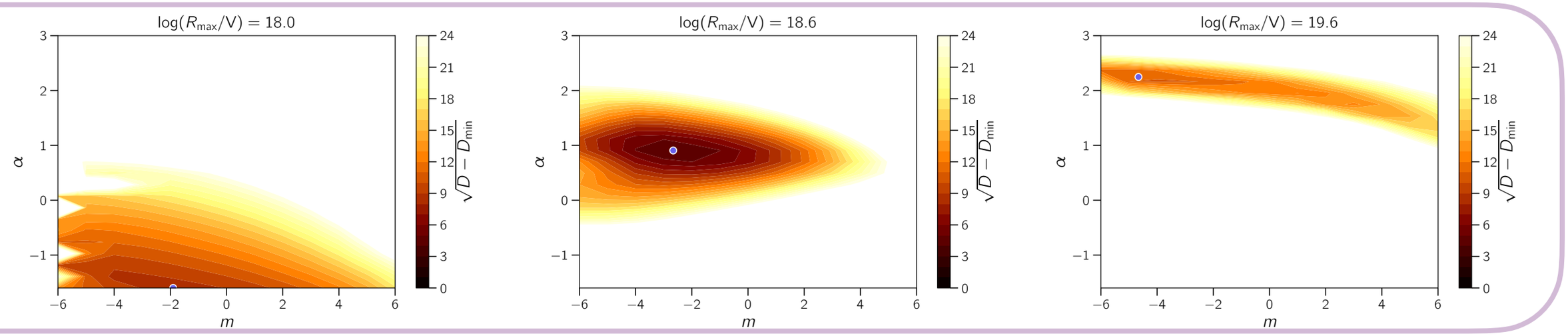


fit results: parameter dependences

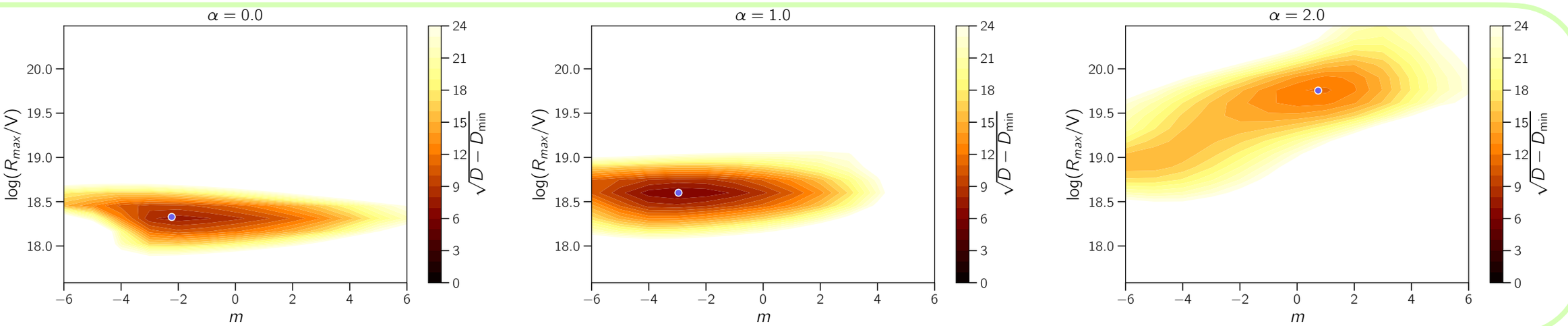
source evolution



maximal rigidity

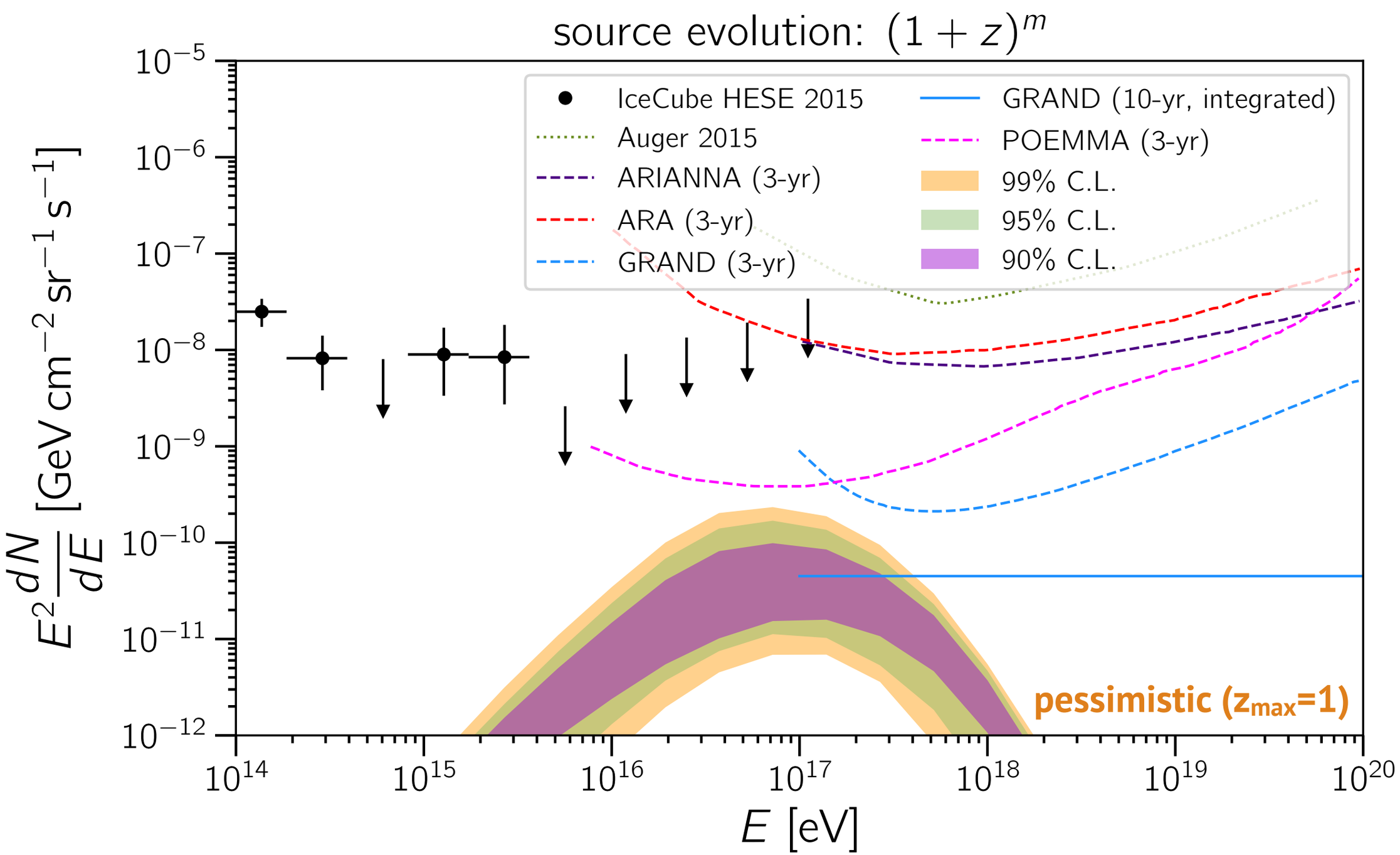


spectral index



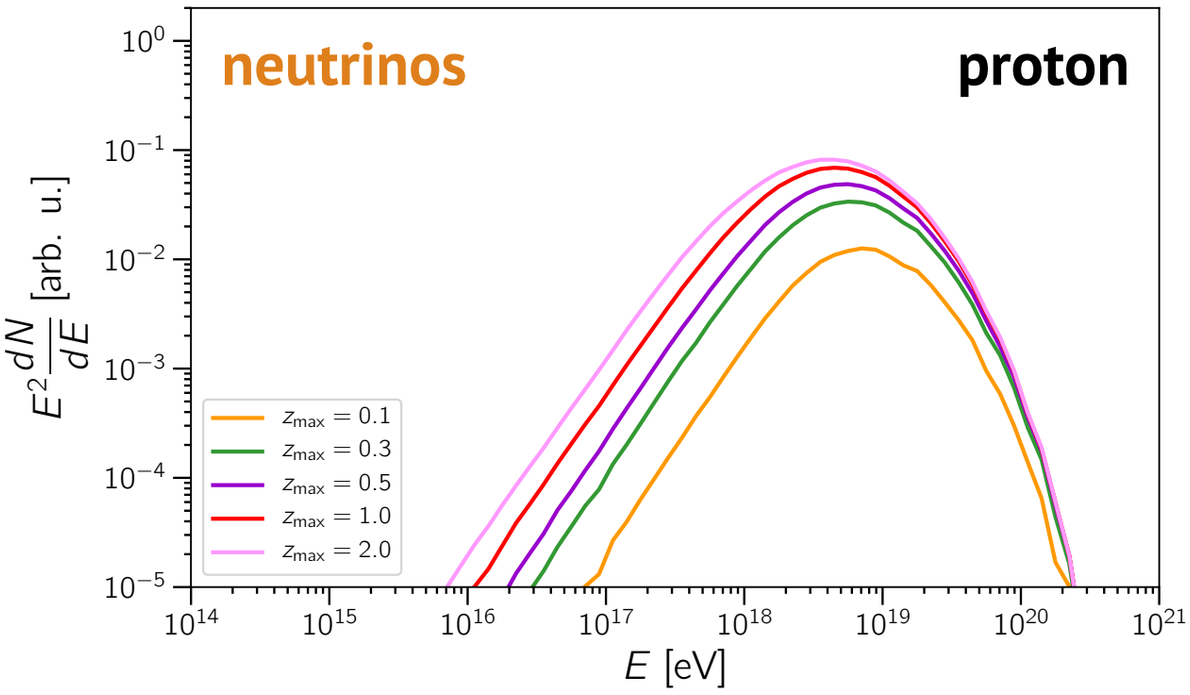
cosmogenic neutrinos

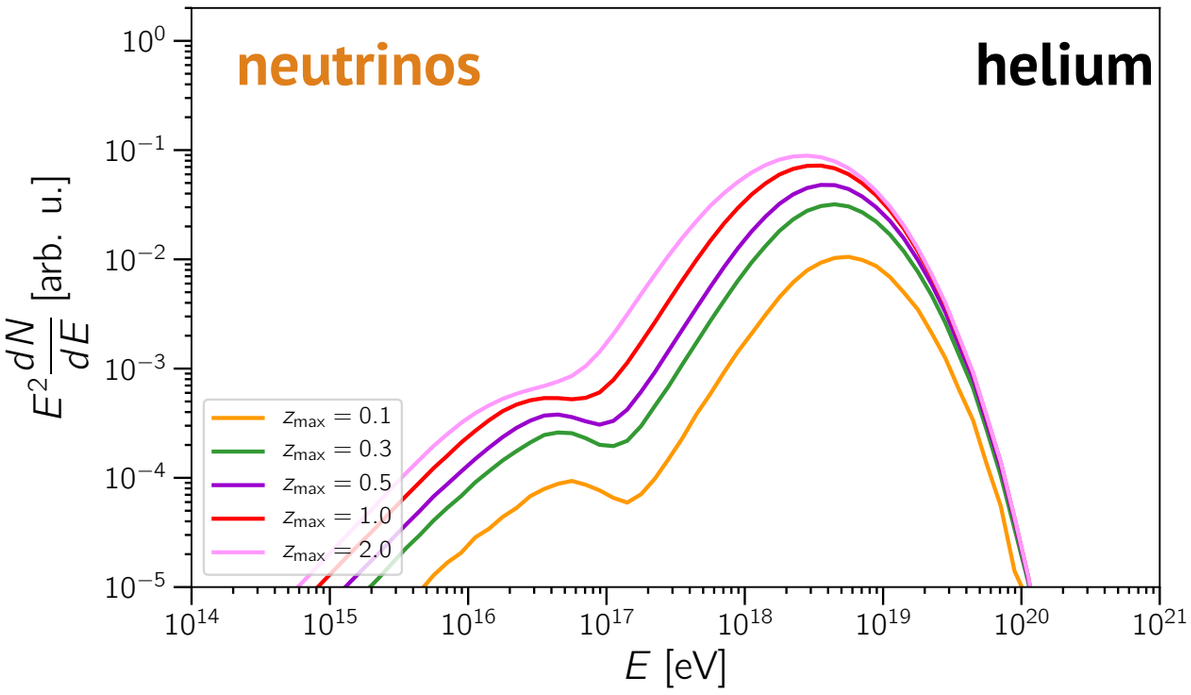
Alves Batista, de Almeida. Lago, Kotera. JCAP 01 (2019) 002. arXiv:1806.10879



maximum redshift

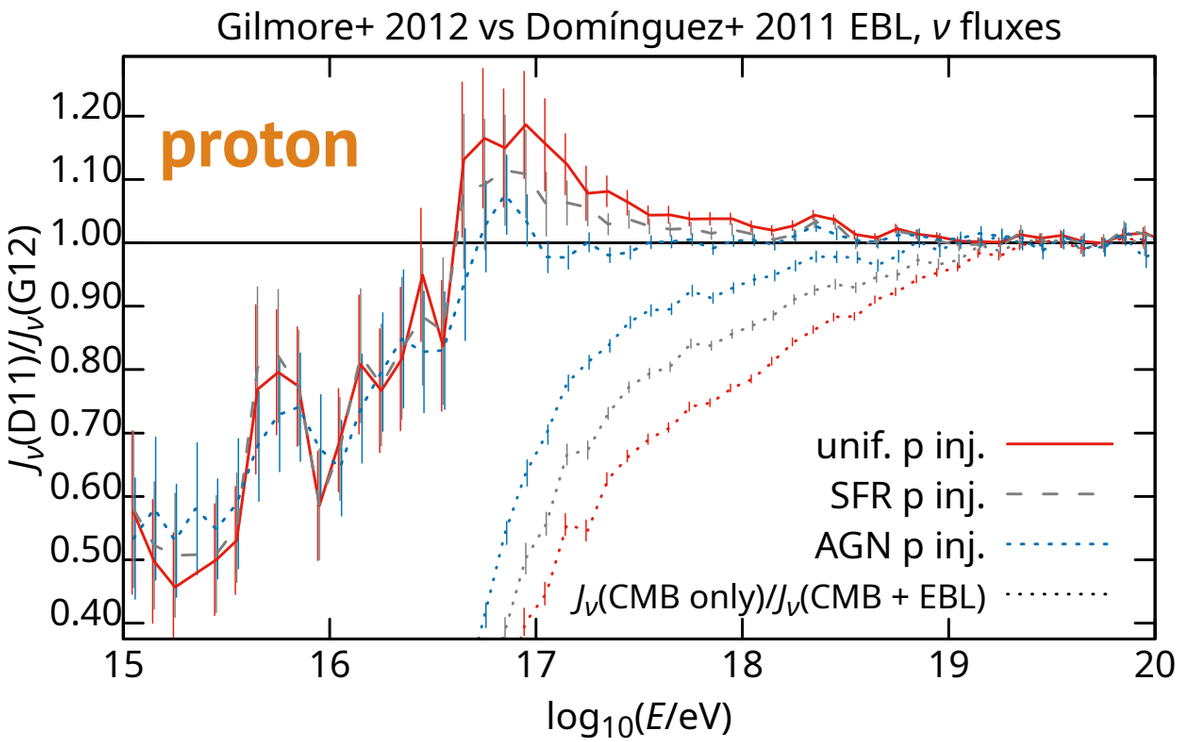
Alves Batista, de Almeida. Lago, Kotera. JCAP 01 (2019) 002. arXiv:1806.10879

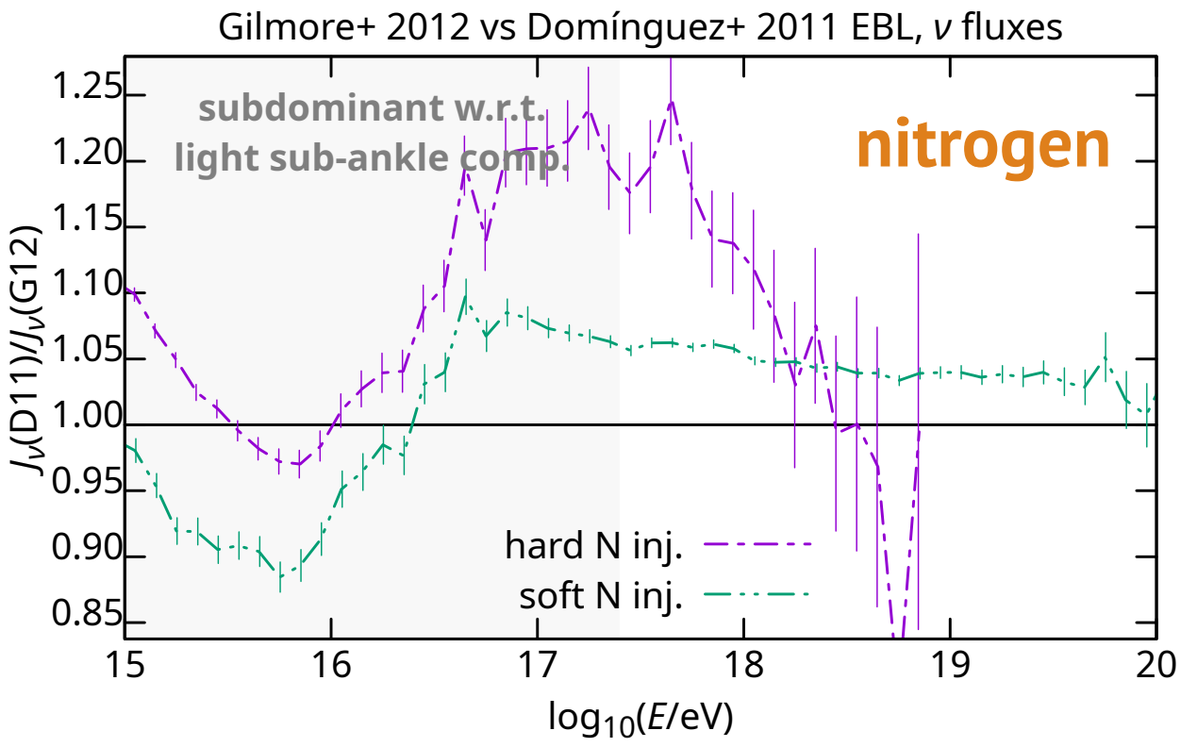




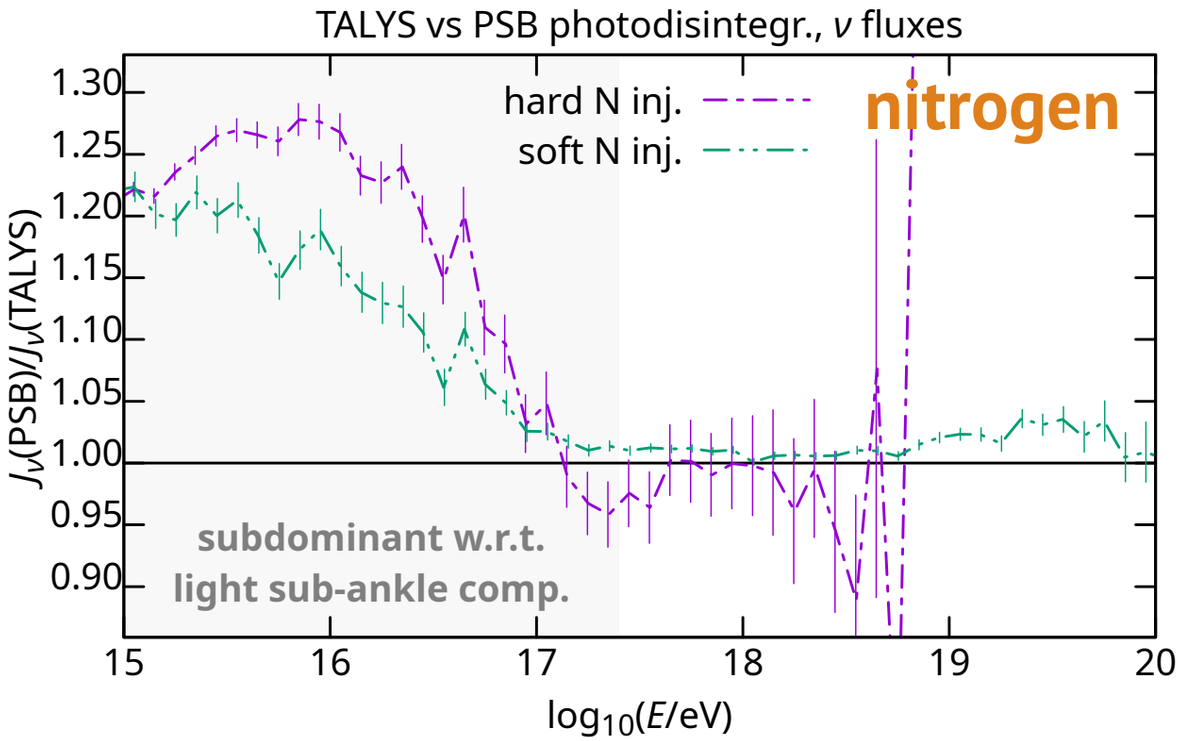
uncertainties: EBL models

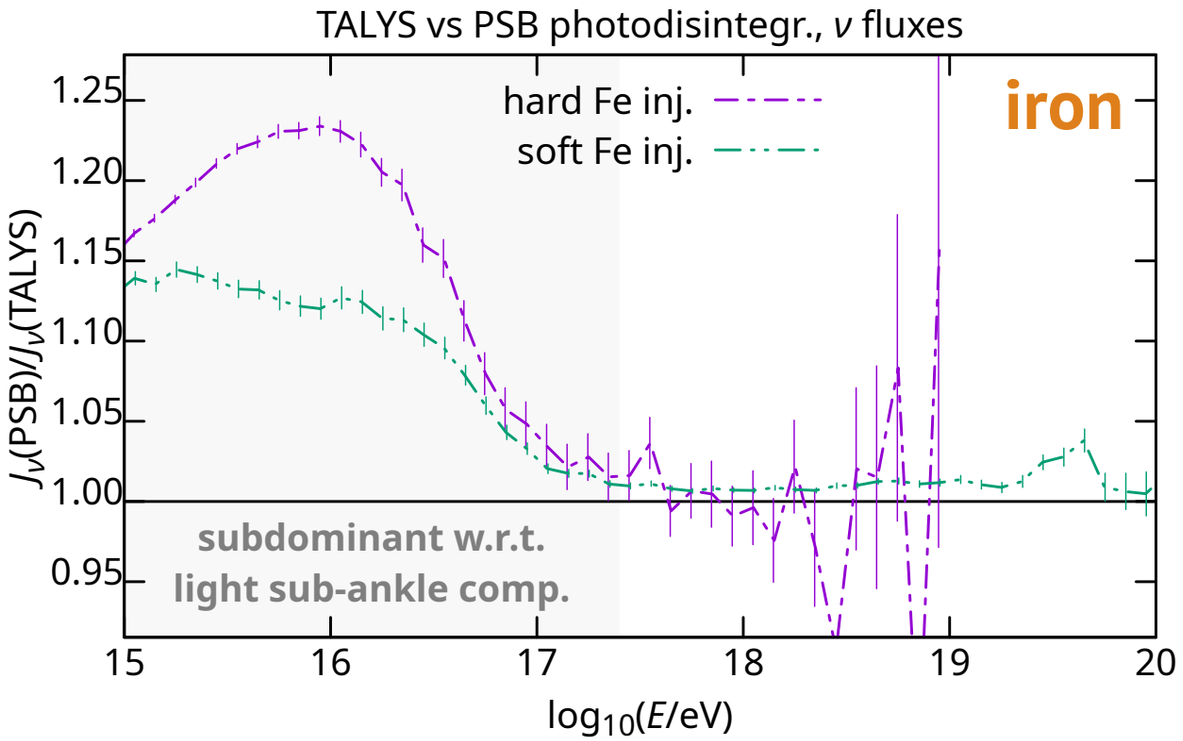
Alves Batista, Boncioli, di Matteo, van Vliet. JCAP 05 (2019) 006. arXiv:1901.01244





uncertainties: photodisintegration

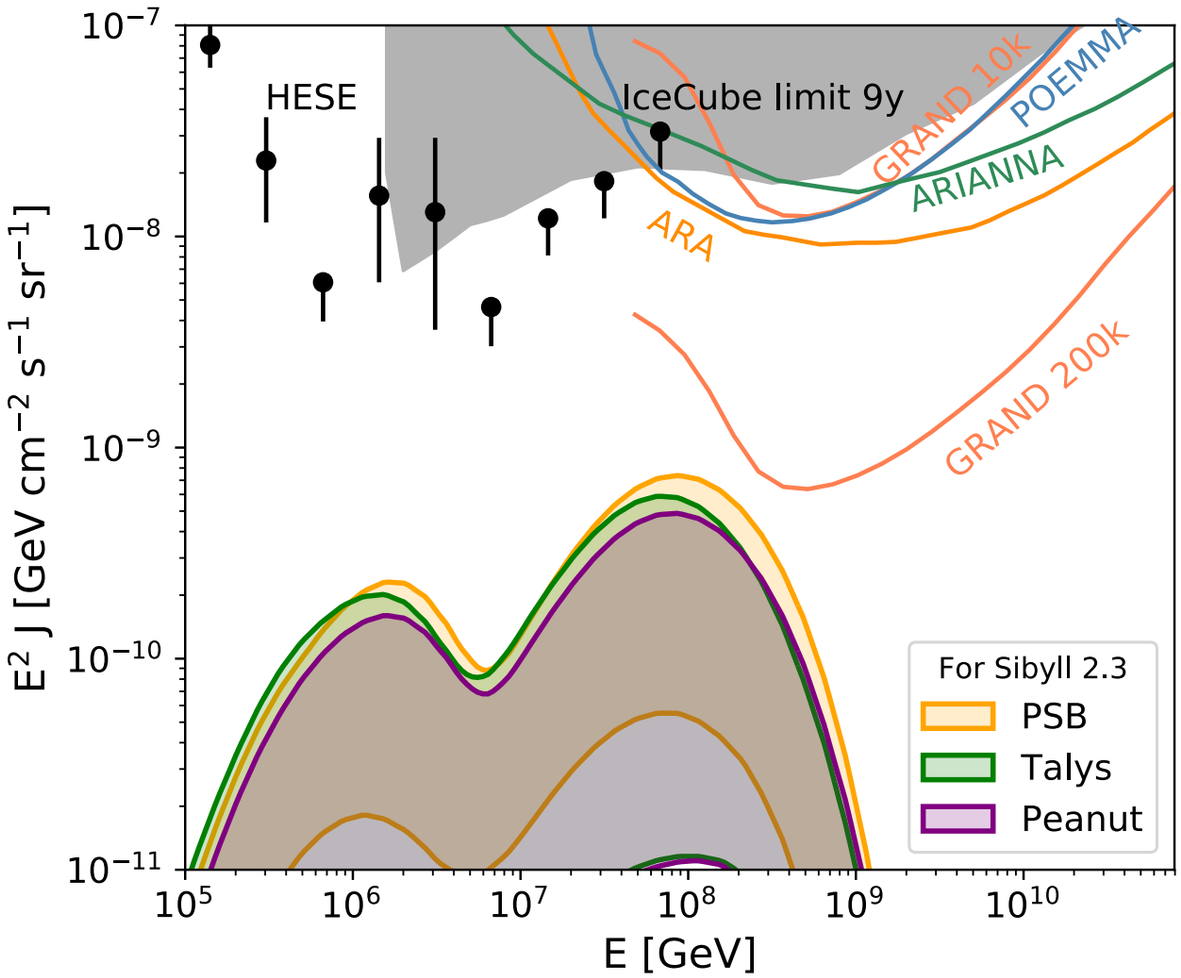




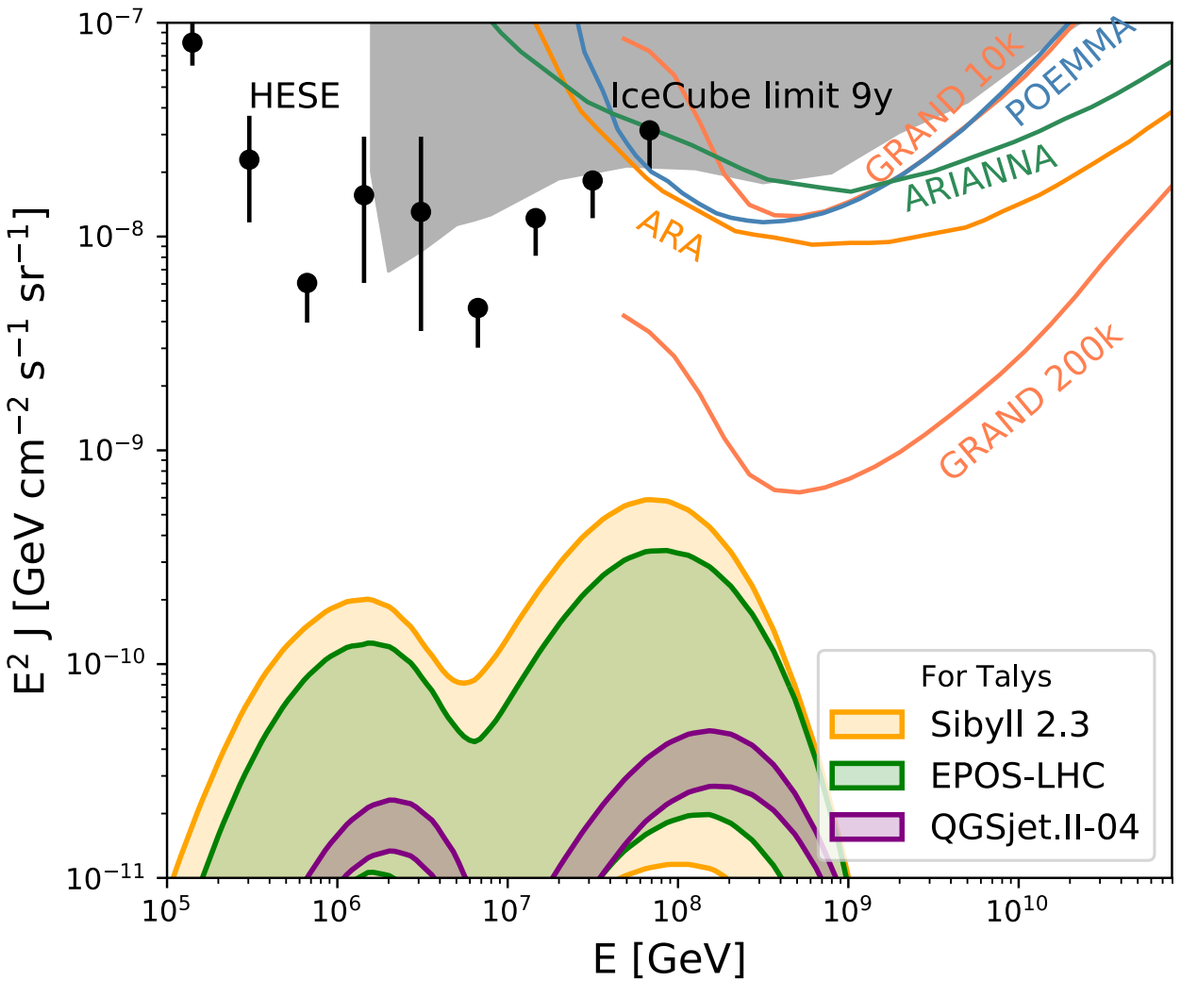
including more uncertainties...

Heinze, Fedynitch, Boncioli, Winter. ApJ 873 (2019) 88. arXiv:1901.03338

photodisintegration models

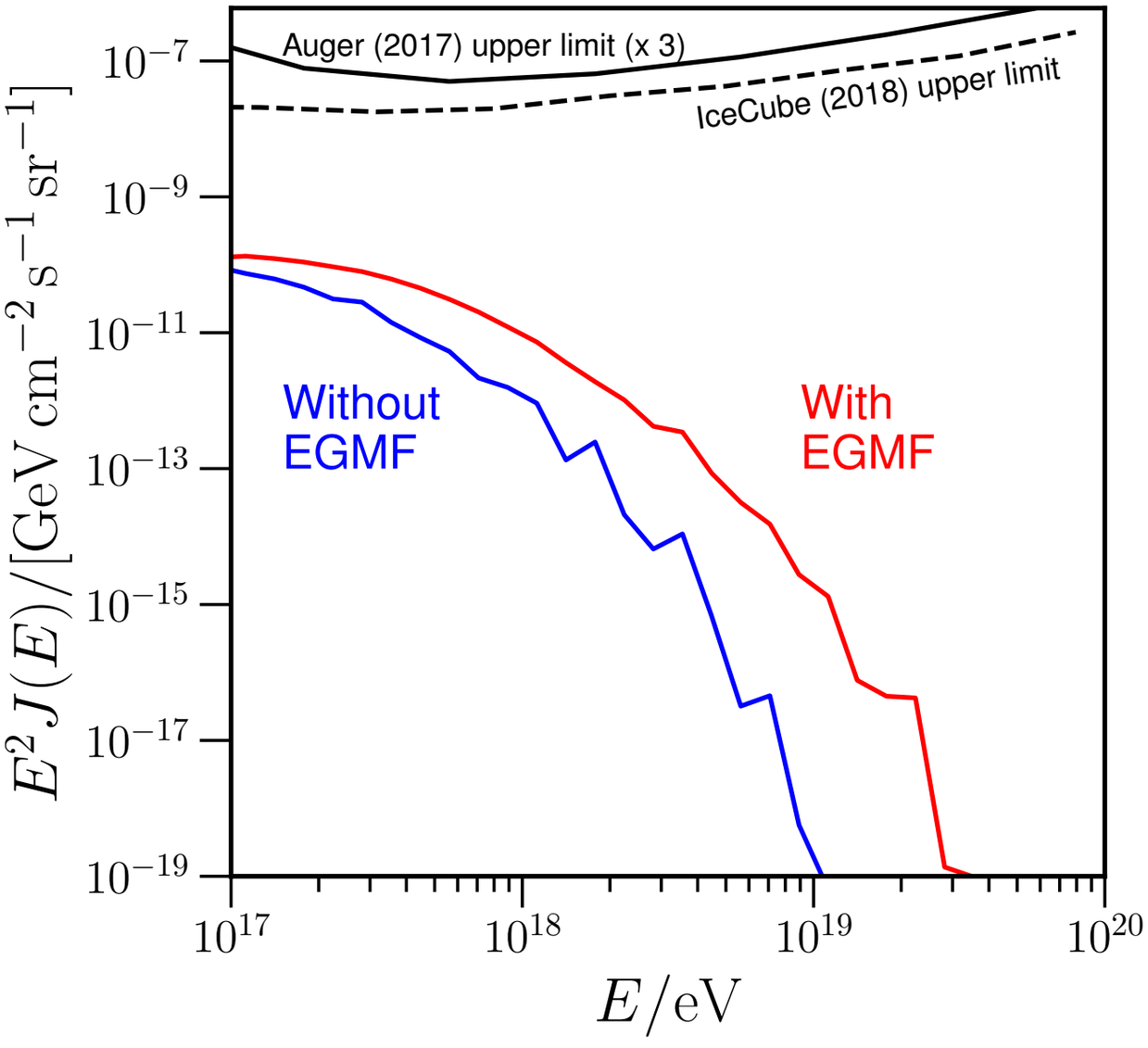


hadronic interaction models



what about magnetic fields?

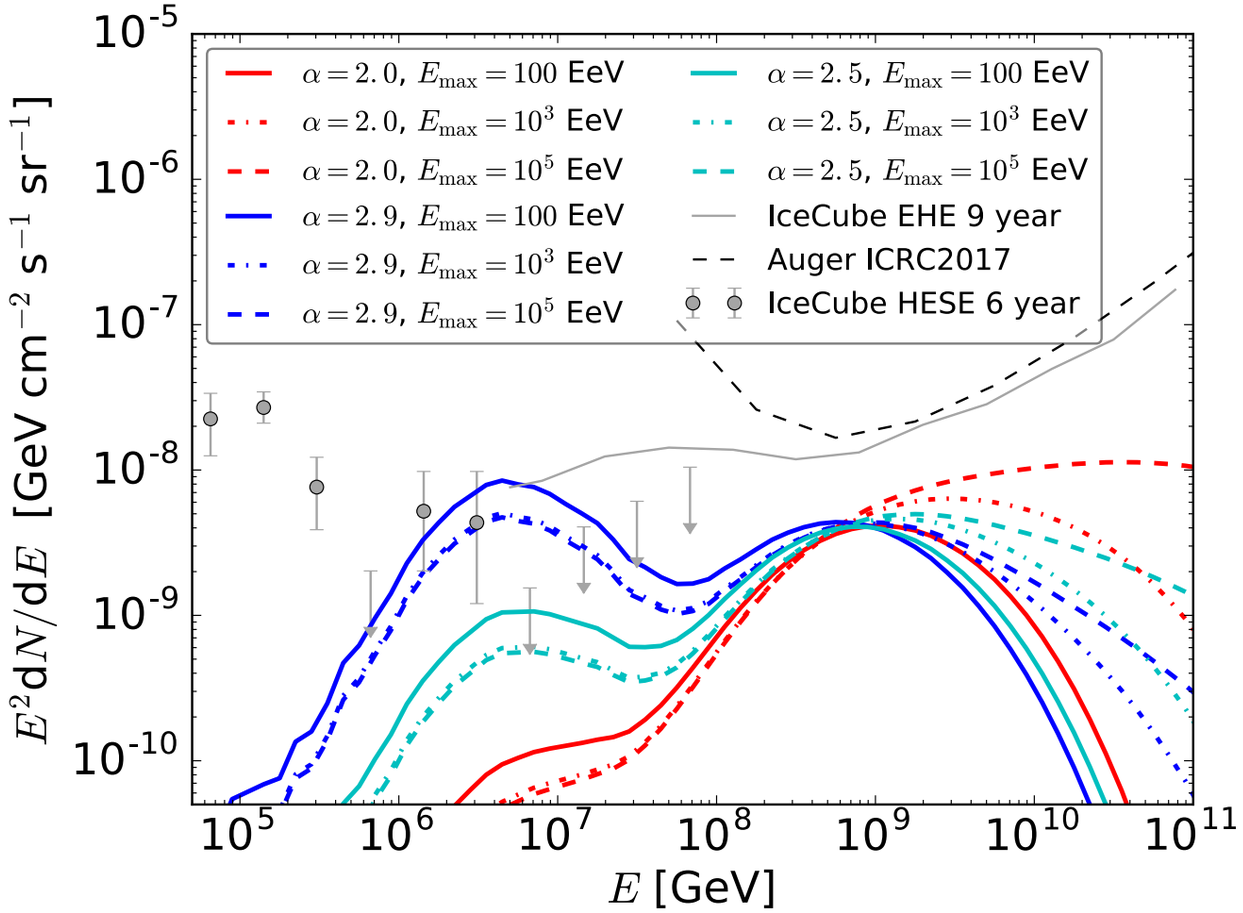
Wittkowski & Kampert. MNRAS 489 (2019) L118. arXiv:1810.03769

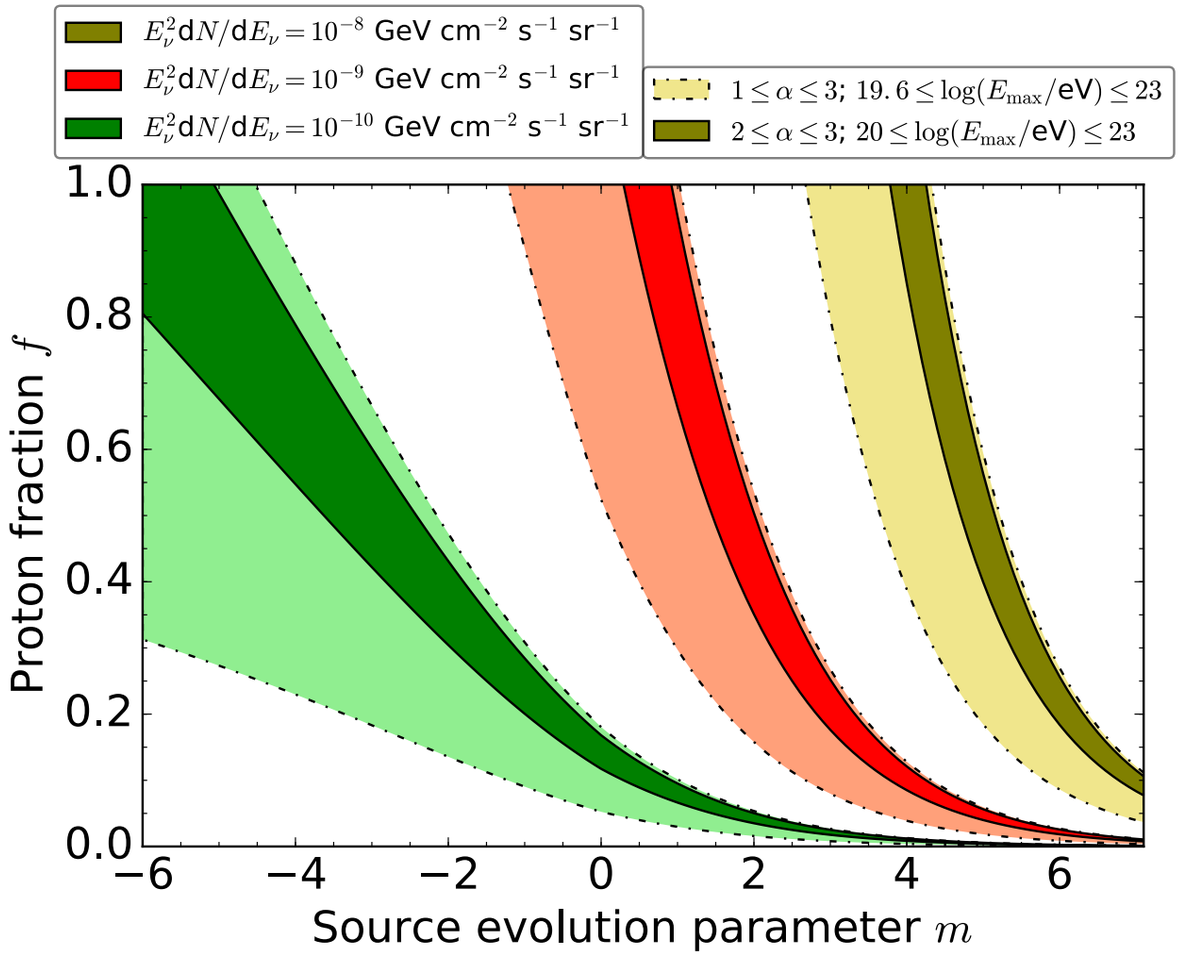


- cosmogenic neutrino fluxes *may* increase in the presence of magnetic fields
- when magnetic fields are included in the fit, softer spectra may be obatained
- source distribution or magnetic fields? (both?!)
- EGMFs are very poorly known

cosmogenic neutrinos & proton fraction

van Vliet, Alves Batista, Hörandel. Physical Review D 100 (2019) 02312. arXiv:1901.01899



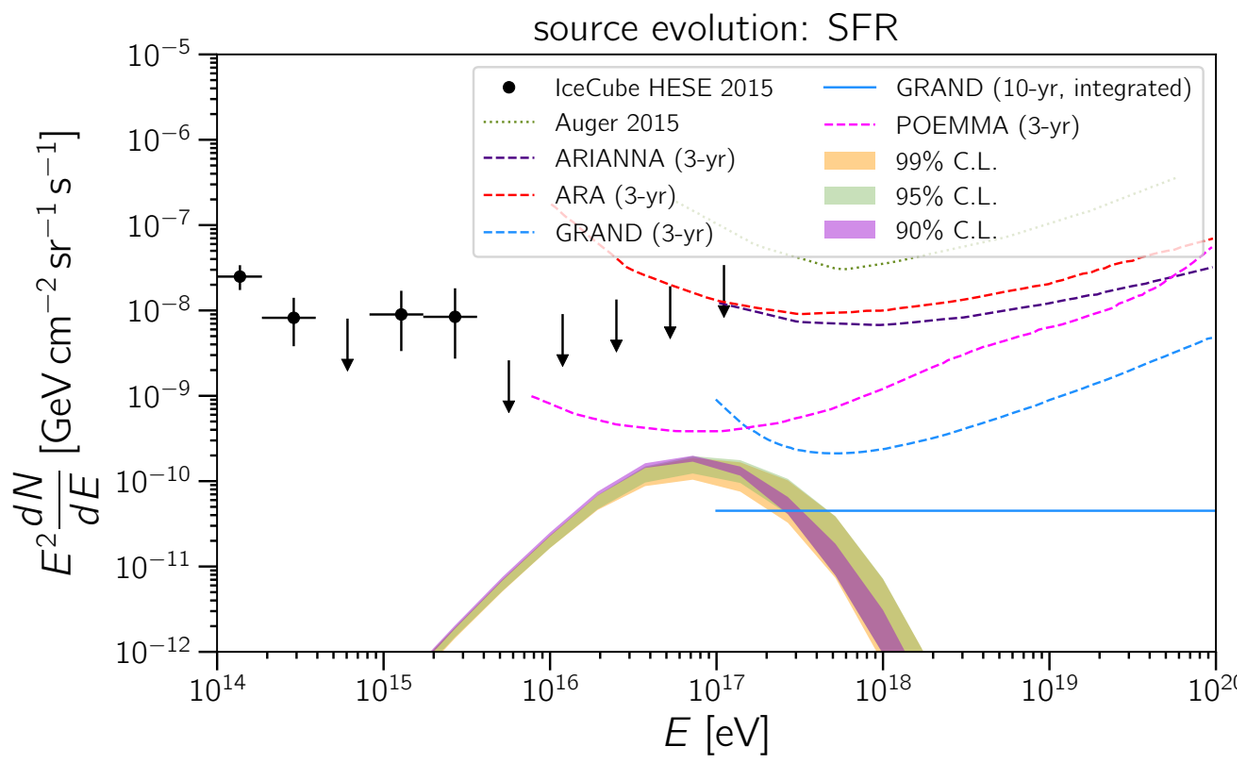


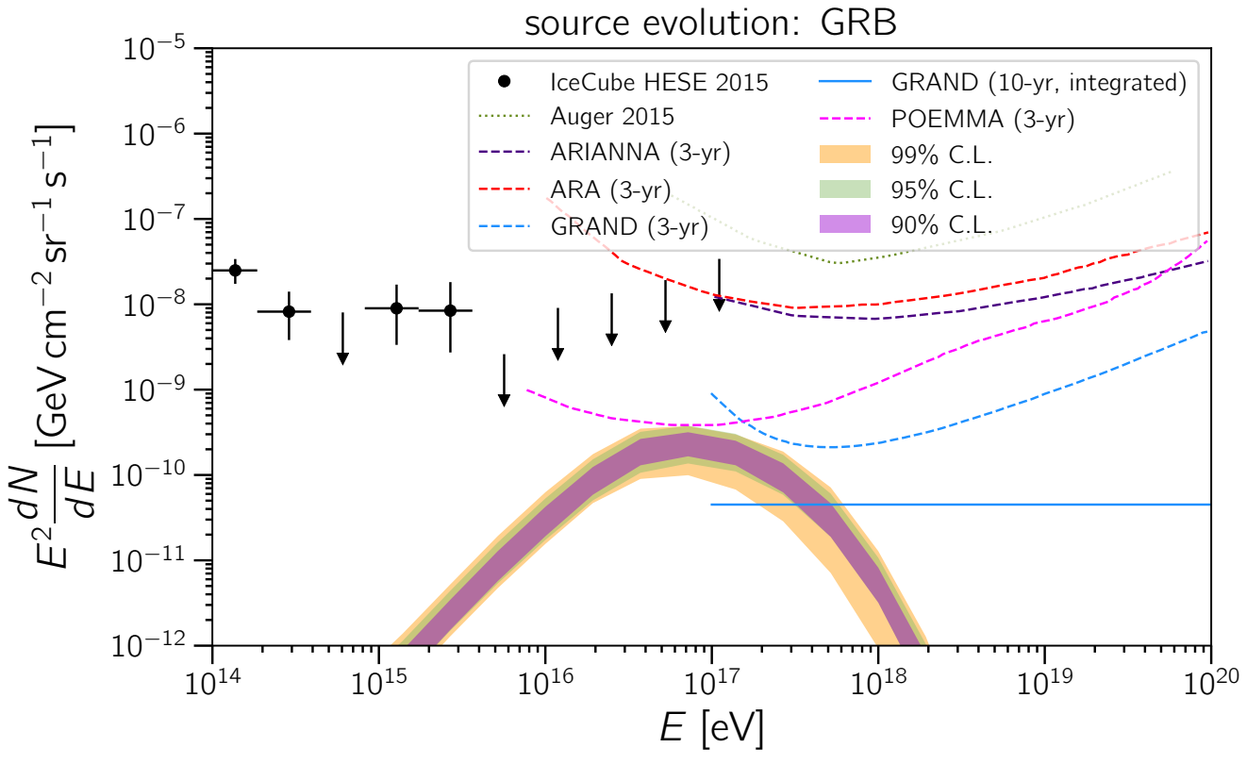
where do we stand?

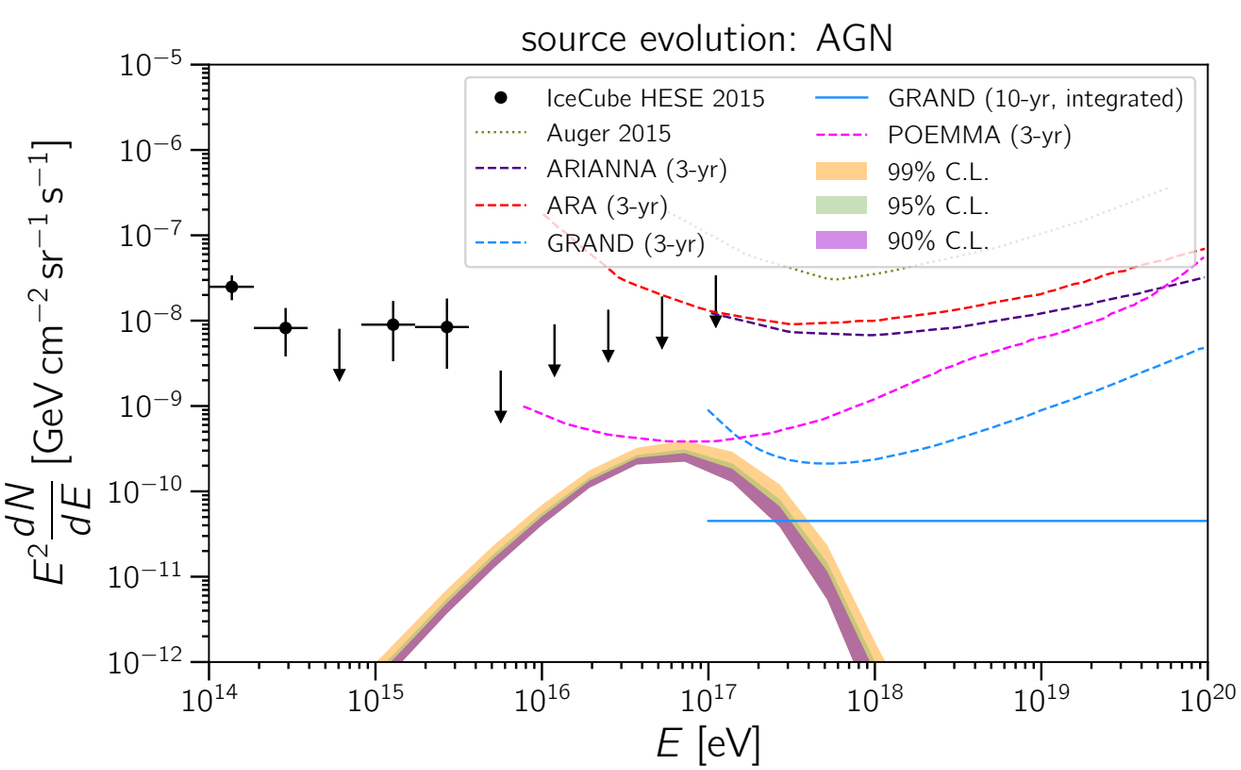
- combined spectrum-composition fits suggest UHECR sources with hard spectra with intermediate composition
- EBL spectrum, photonuclear cross sections, magnetic fields → sources of uncertainty in the modelling of UHECR propagation
- cosmogenic fluxes computed are pessimistic
- the flux of cosmogenic neutrinos strongly depends on UHECR-related parameters → many uncertainties
- the (non-)observation of cosmogenic neutrinos may tell us something about the UHECR composition
- the picture may change if improved models with more realistic source distributions and magnetic fields are considered

back-up slides

predictions for specific source populations

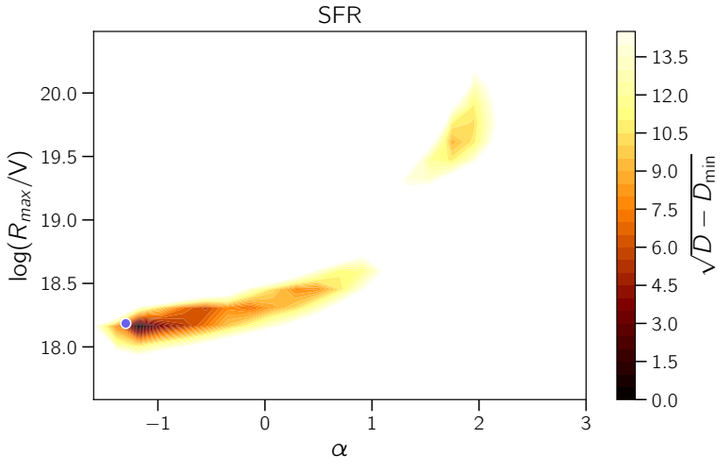


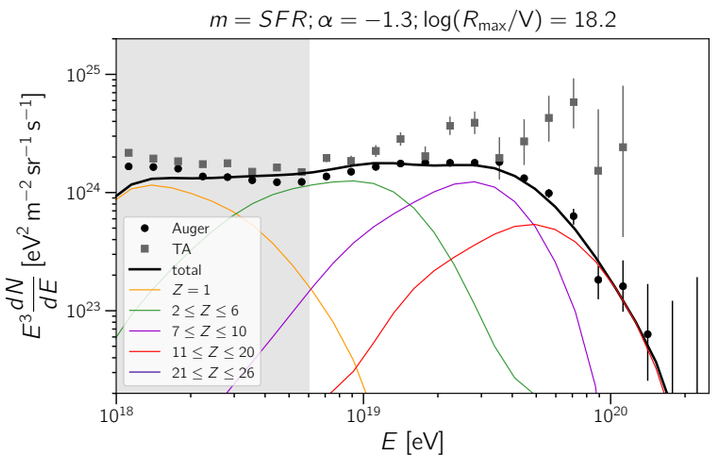


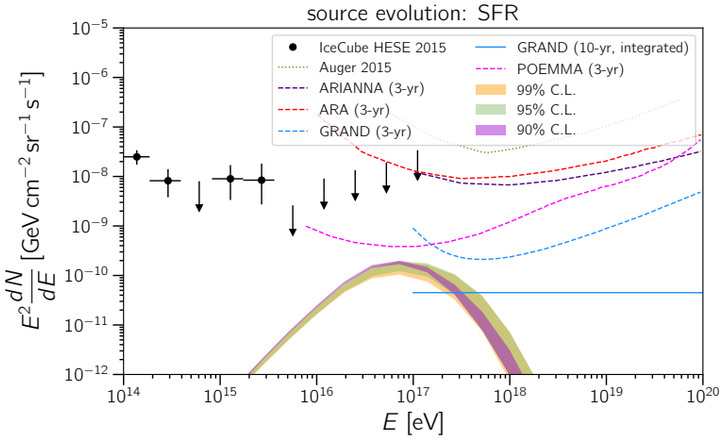


predictions for specific source populations

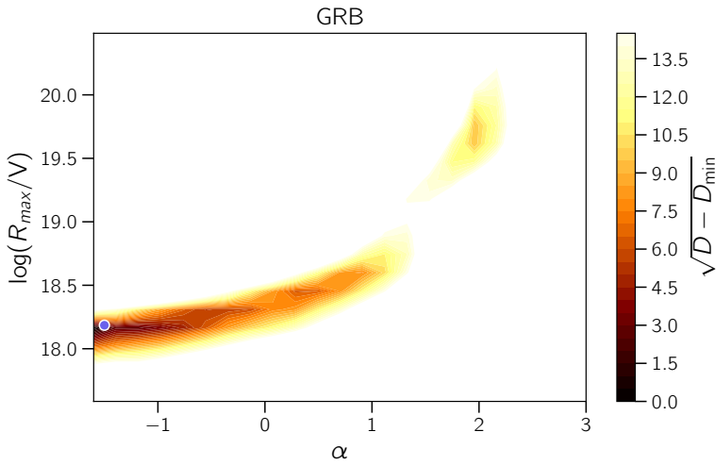
SFR

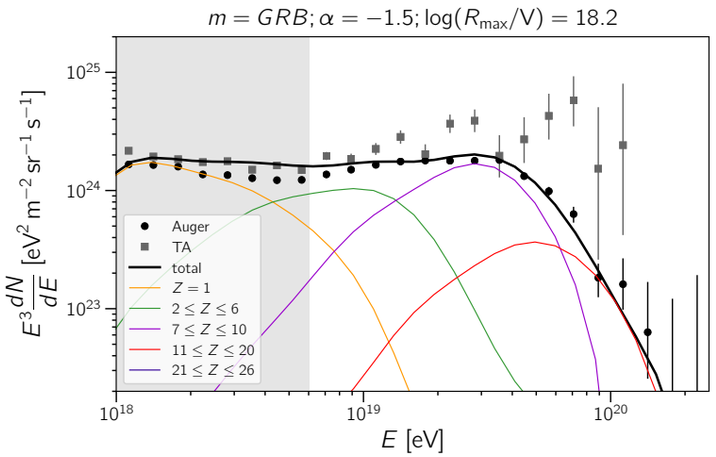


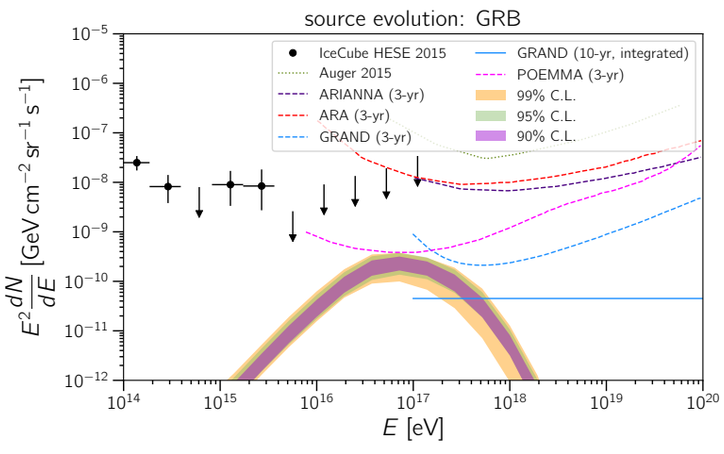




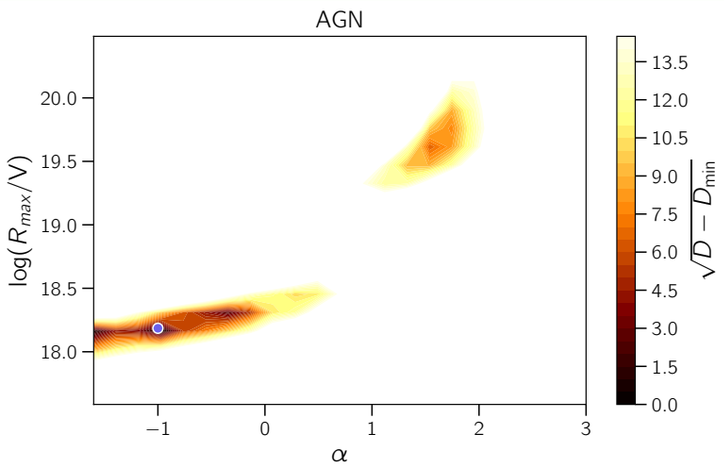
GRB

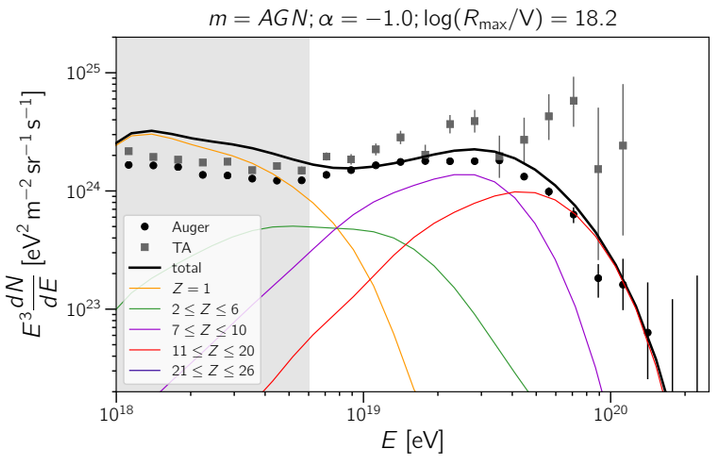


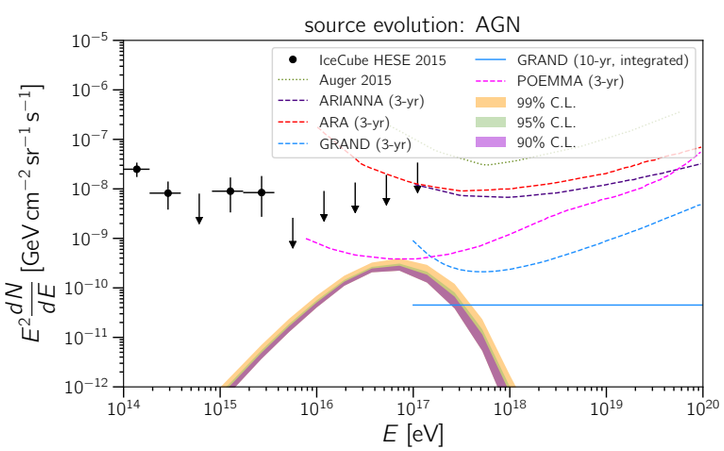




AGN

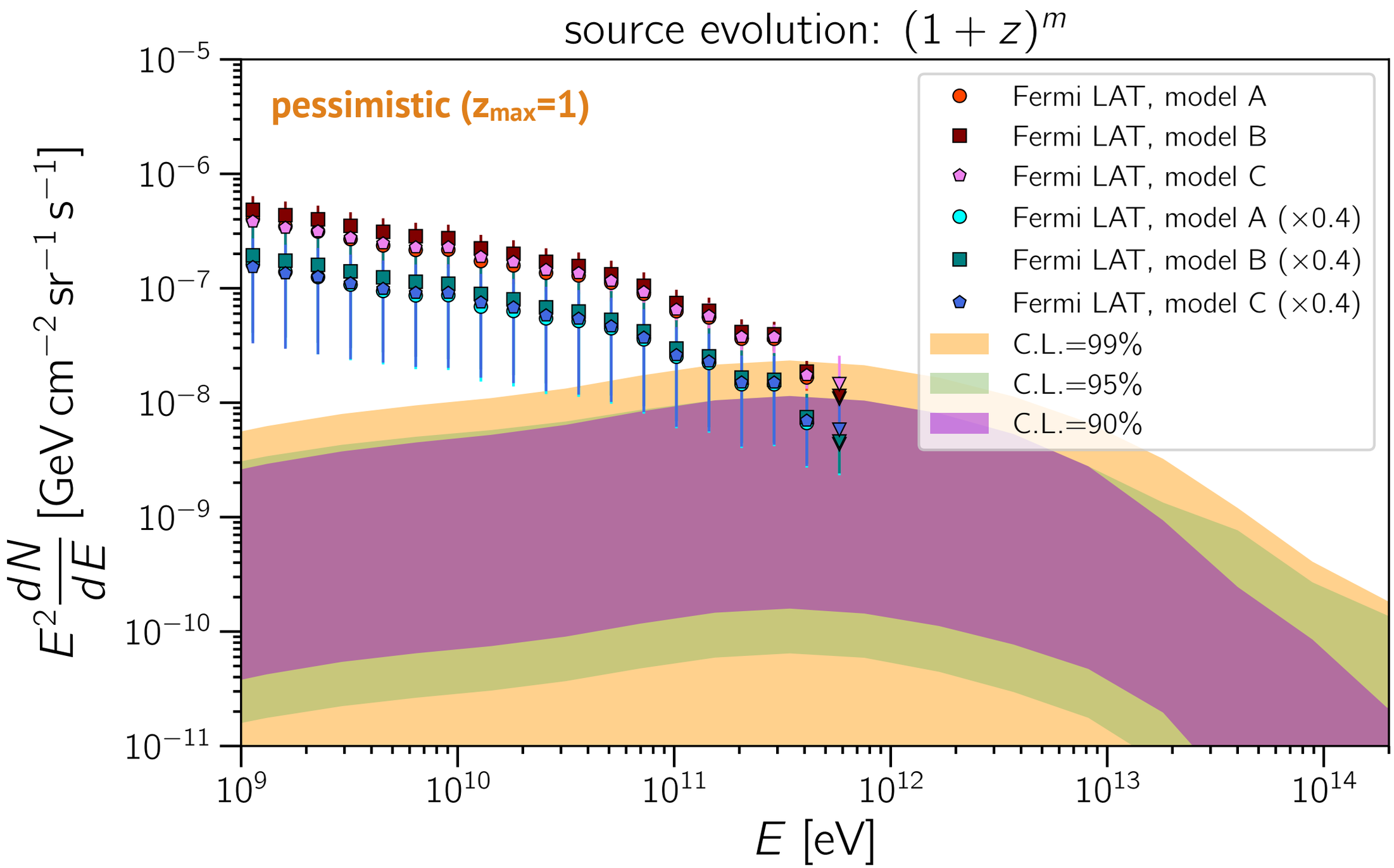




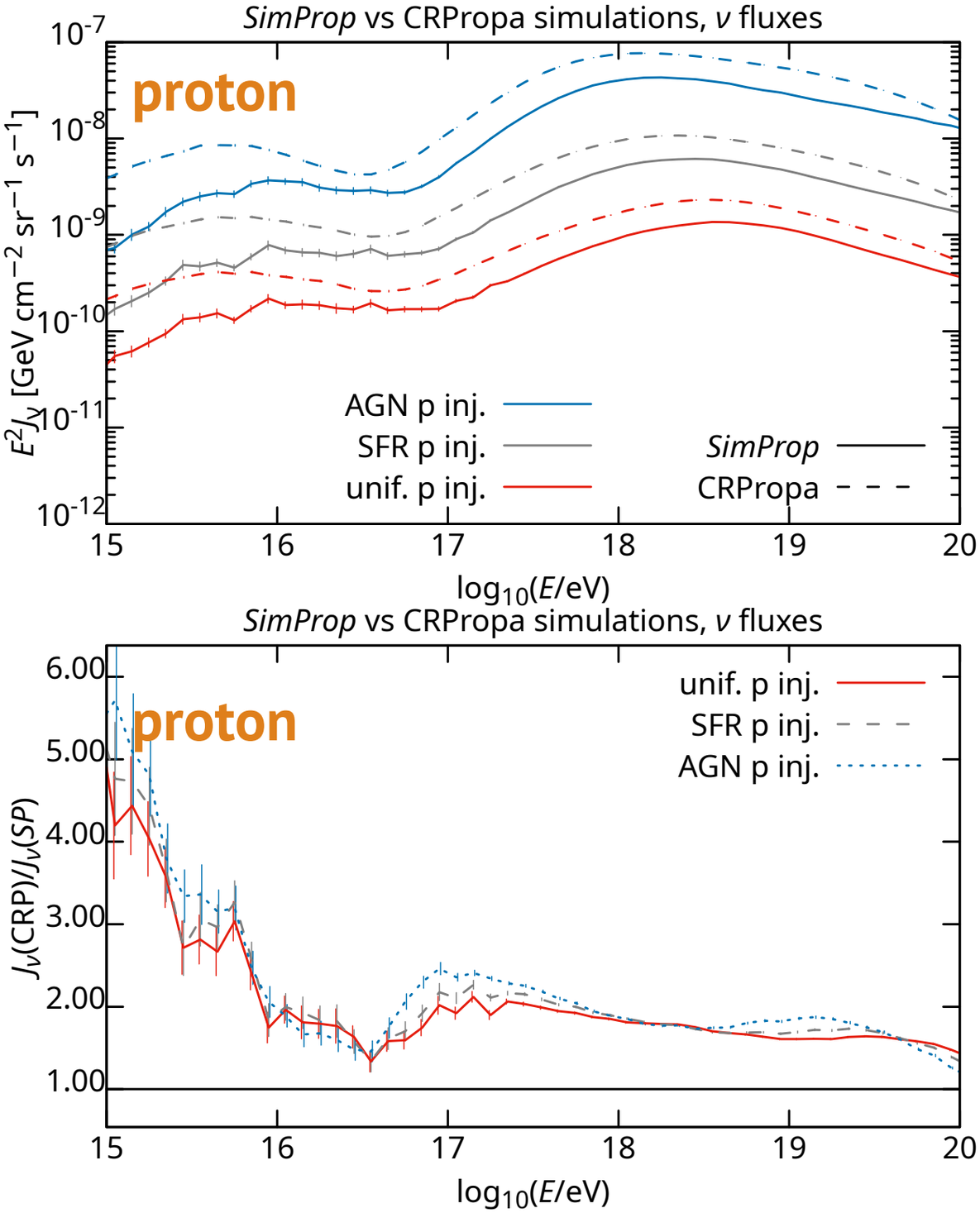


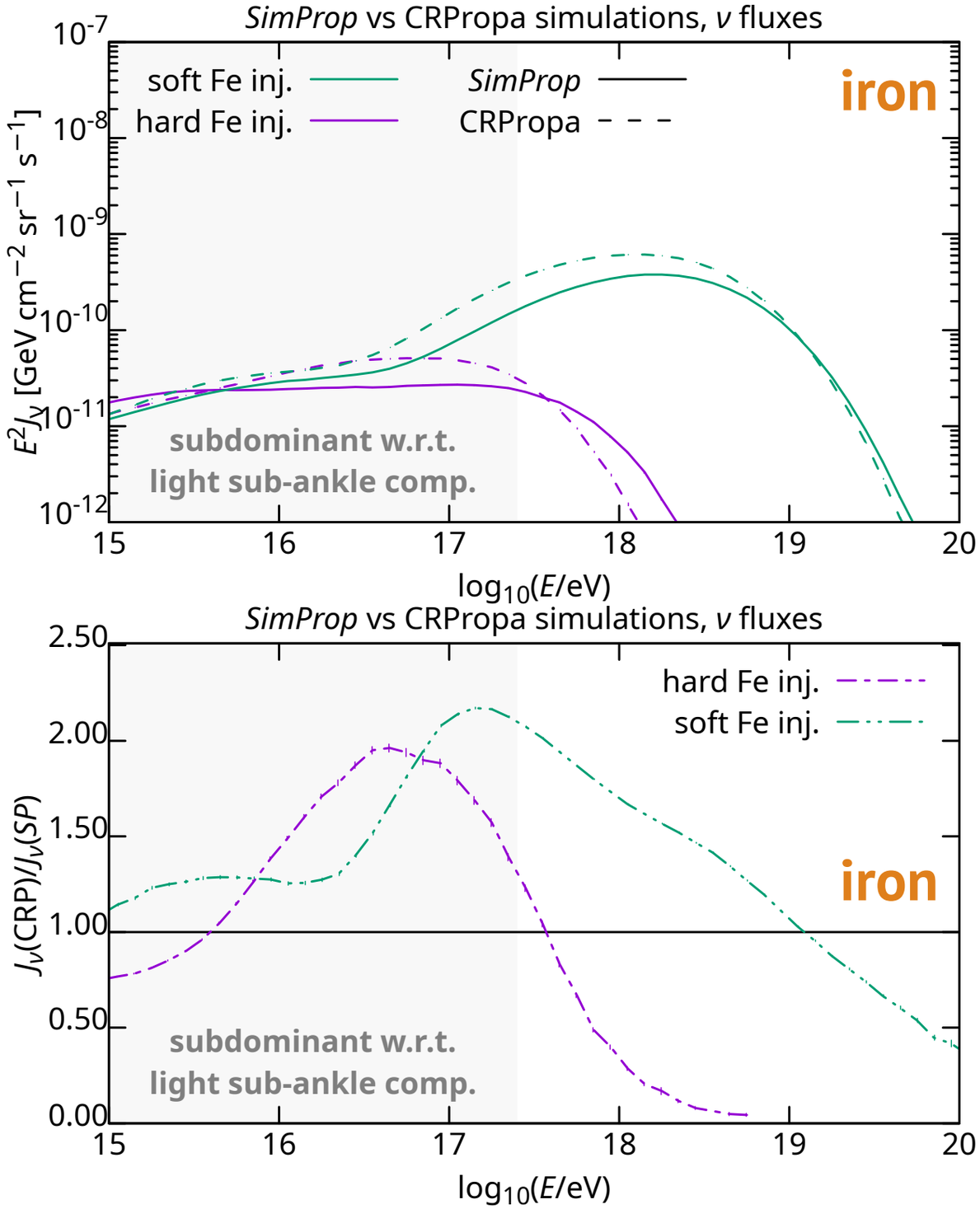
cosmogenic photons

Alves Batista, de Almeida. Lago, Kotera. JCAP 01 (2019) 002. arXiv:1806.10879



uncertainties: propagation codes



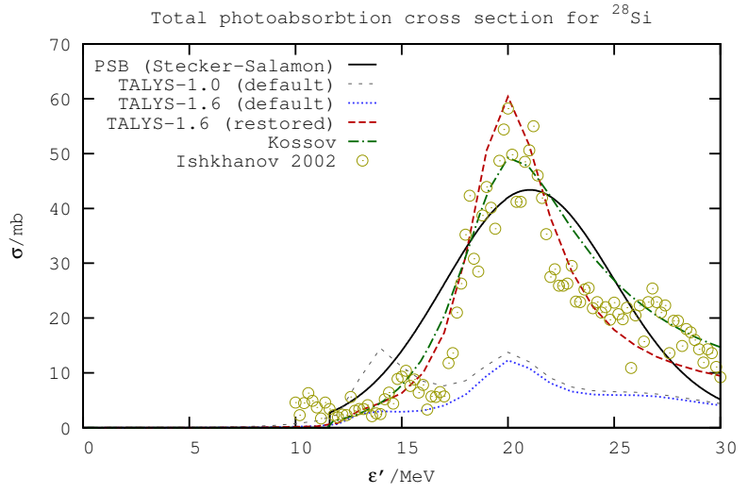


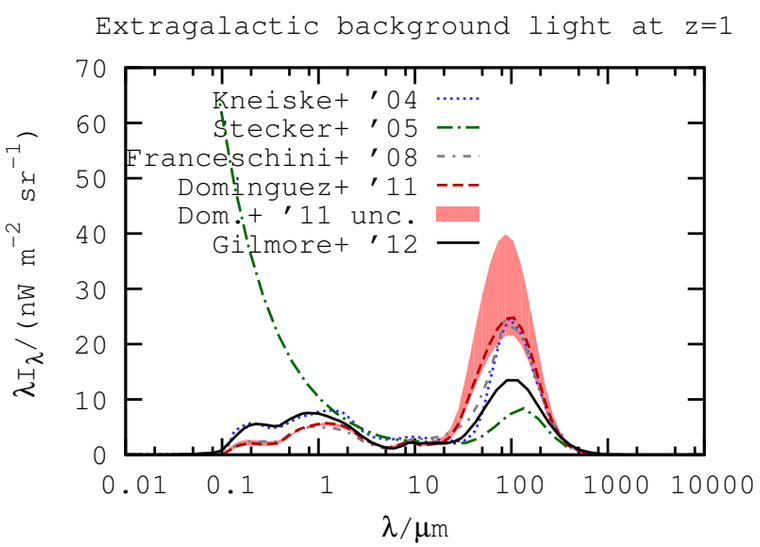
theoretical uncertainties in the modelling

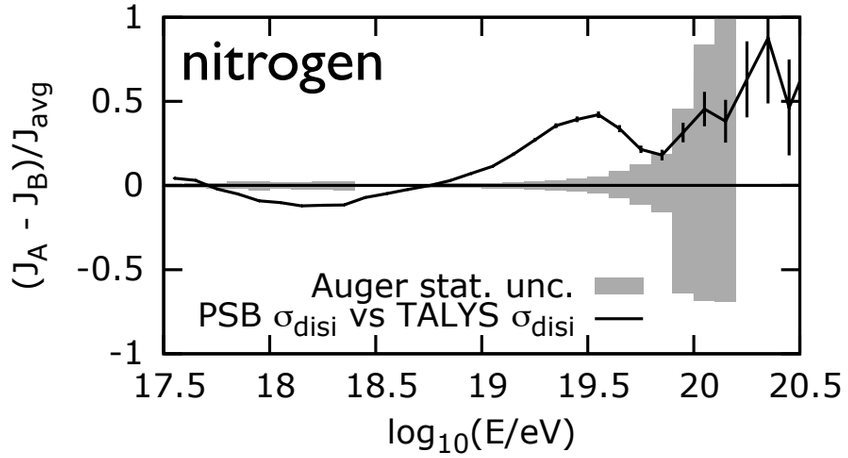
Alves Batista, Boncioli, di Matteo, van Vliet, Walz. JCAP 1510 (2015) 063. arXiv:1508.01824

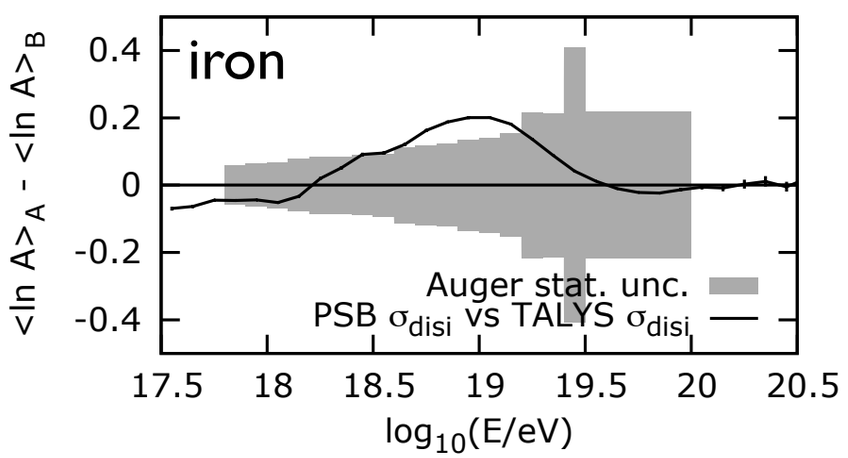
sources of uncertainty

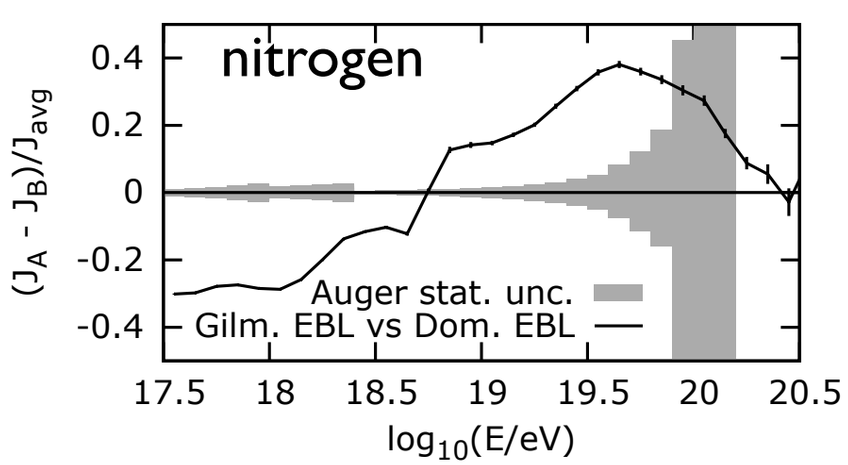
- photodisintegration cross sections
- EBL model
- propagation codes (e.g. CPropa, SimProp, ...)

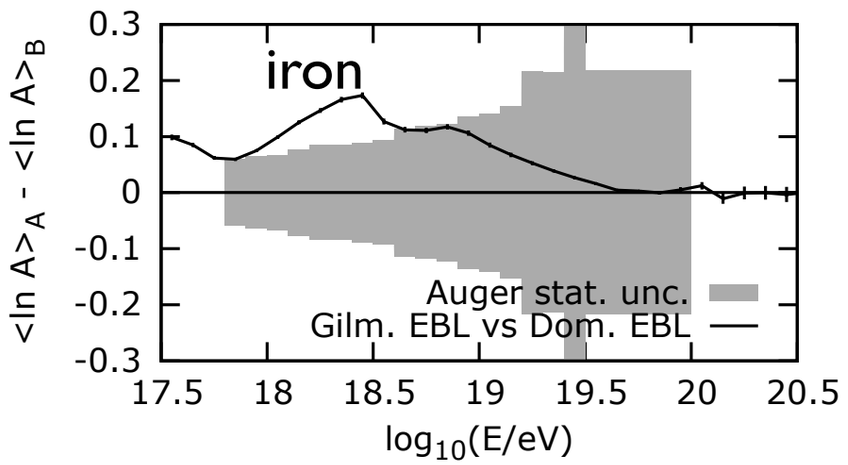






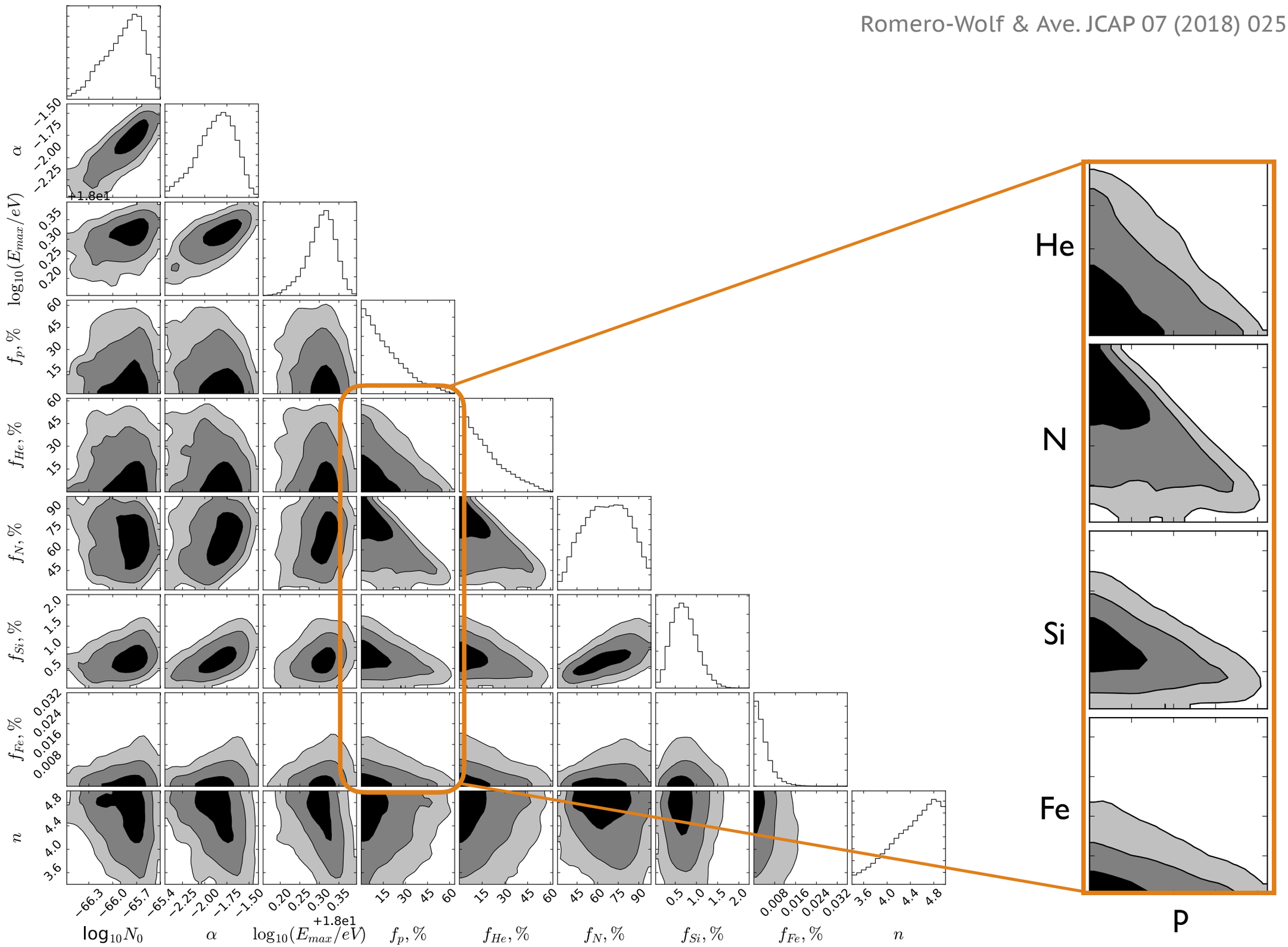






composition degeneracy

Romero-Wolf & Ave. JCAP 07 (2018) 025. arXiv:1712.07290

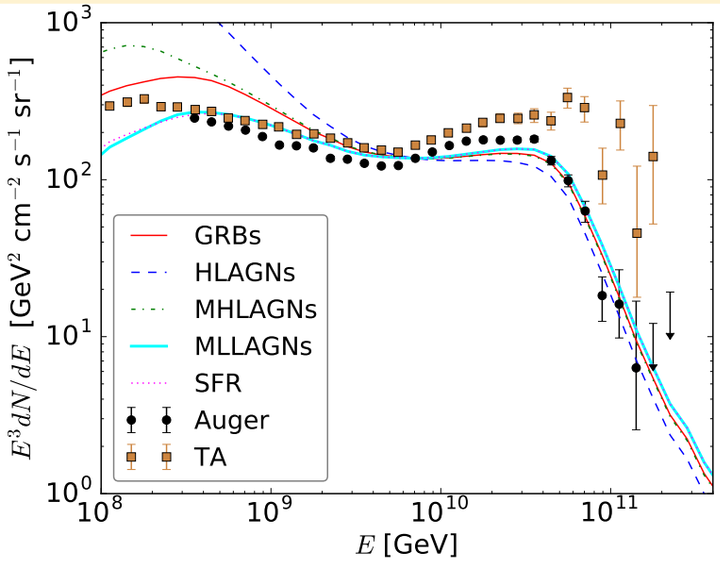


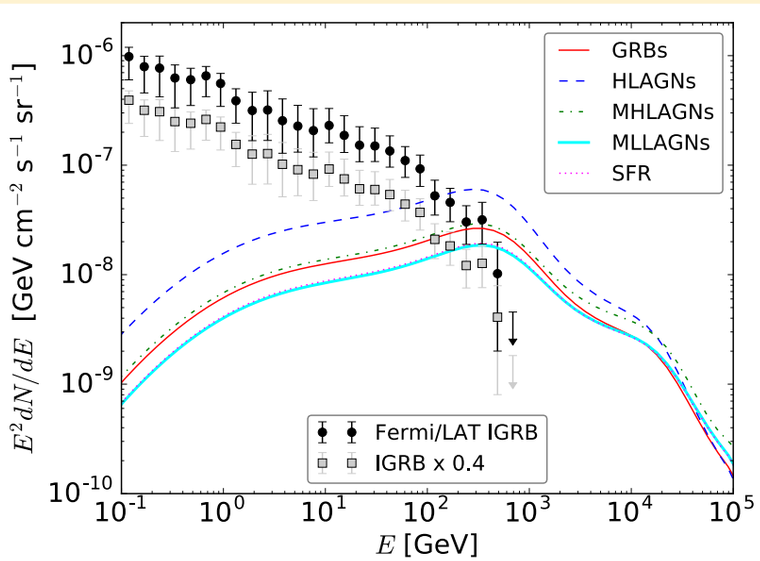
UHECR constraints with cosmogenics

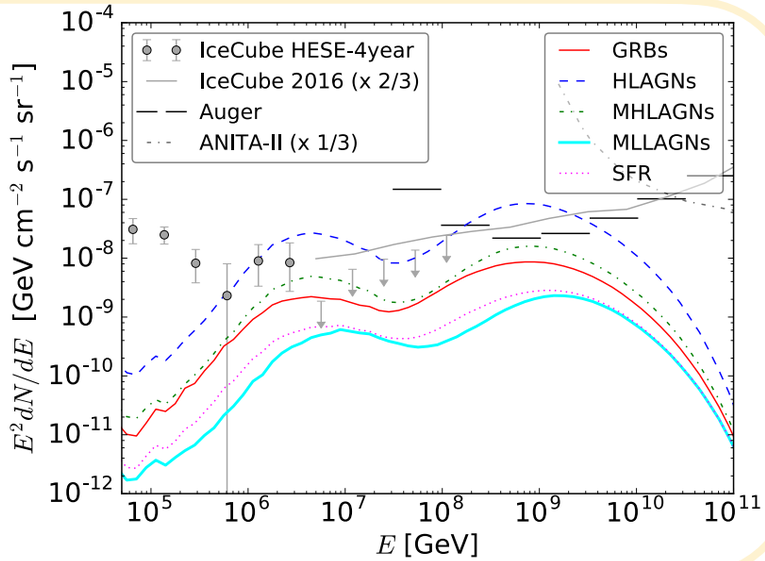
van Vliet, Hörandel, Alves Batista. Proc. of Science (ICRC2017) 562. arXiv: 17017.04511

UHECRs | **gamma rays** | **neutrinos**

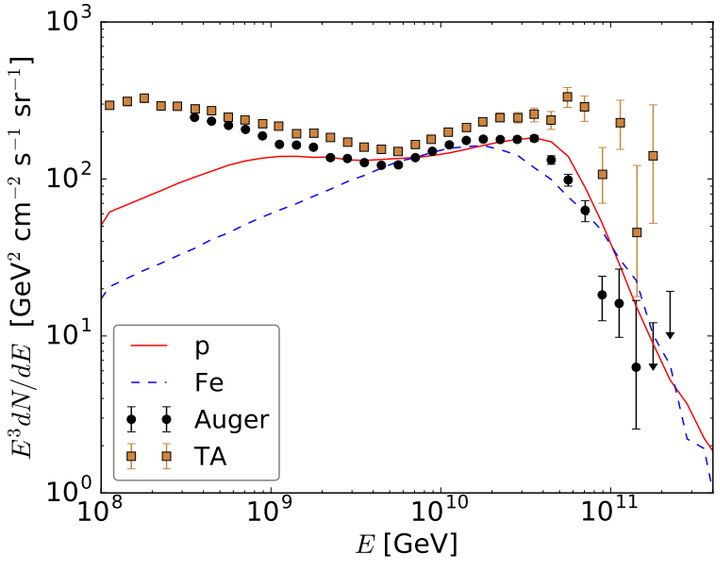
constraining sources

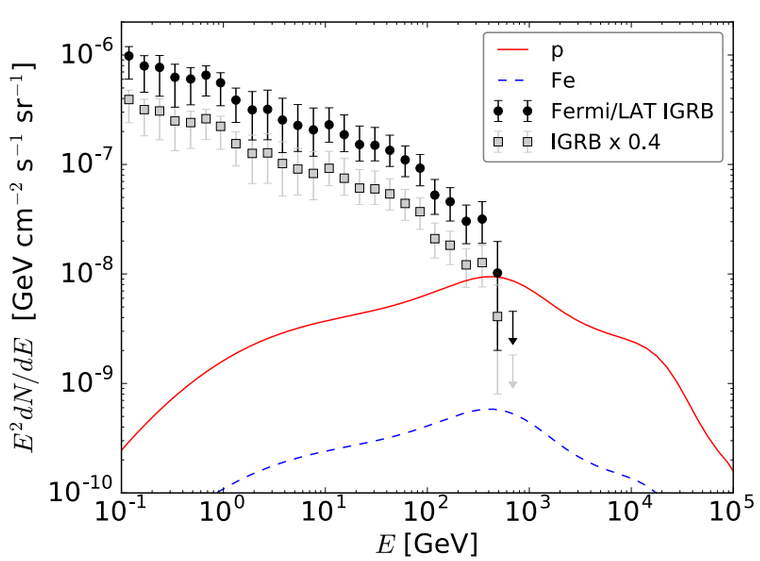


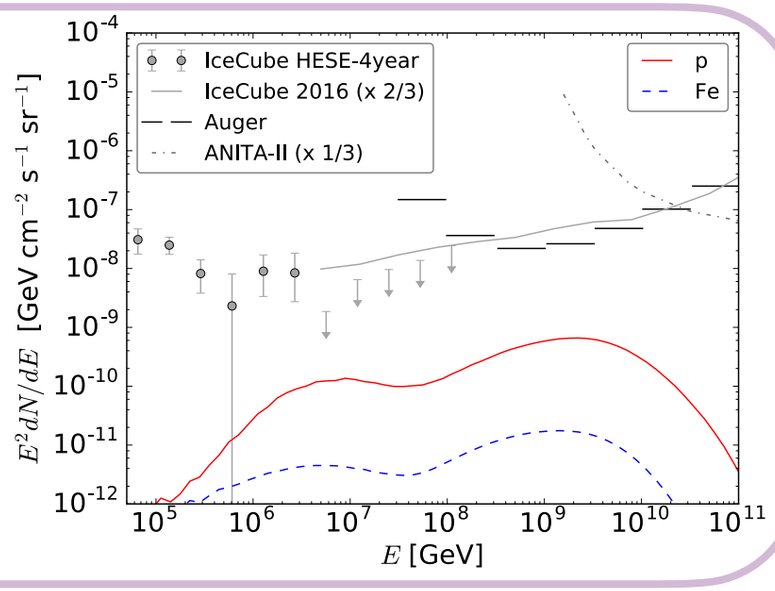




constraining composition



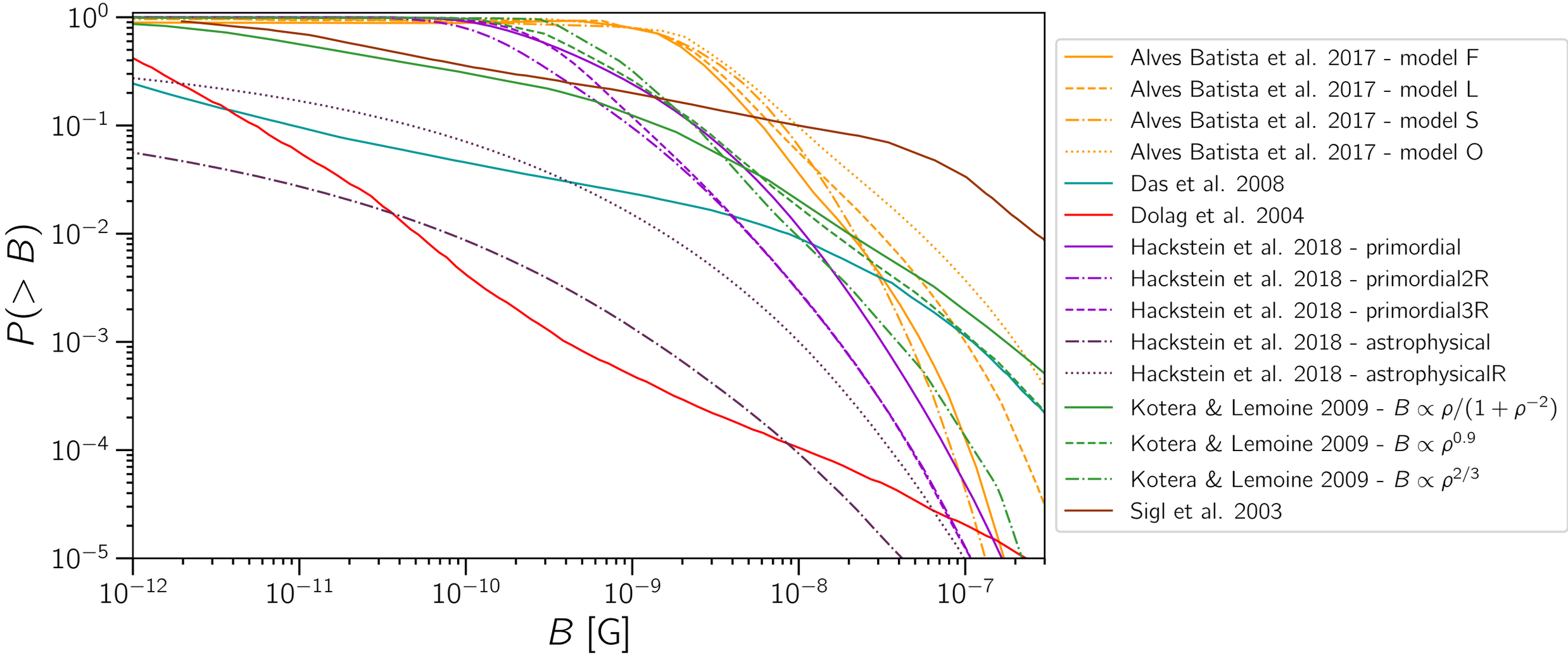




first row: pure proton, spectral index = 2.5, source evolutions indicated, maximal rigidity = 200 EV
second row: pure proton/iron, spectral index = 2.5, no source evolution, maximal rigidity = 200 EV

what about magnetic fields?

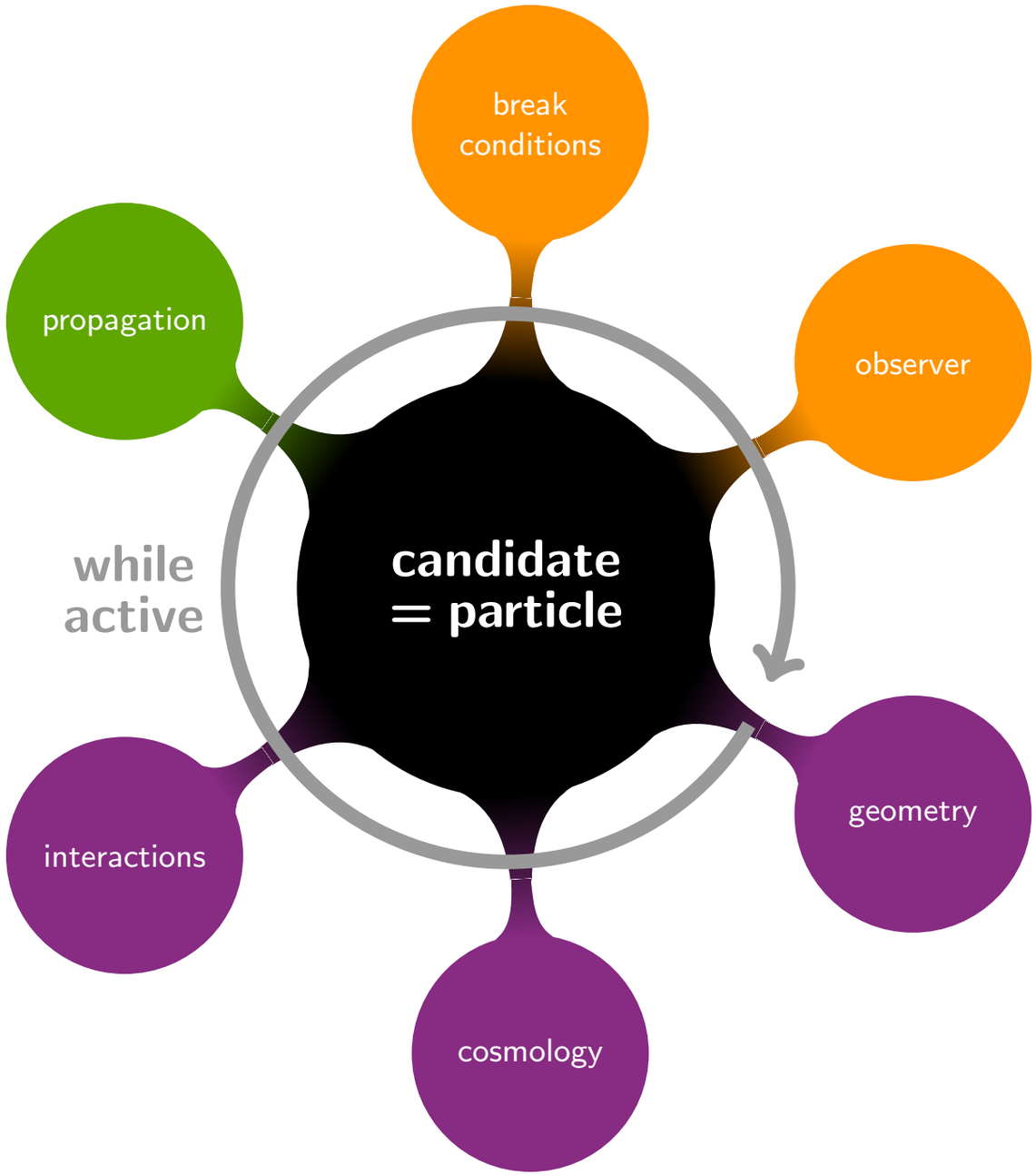
Alves Batista et al. Front. Astron. Space. Sci. 6 (2019) 23. arXiv:1903.06714



the CRPropa code

Alves Batista et al. JCAP 05 (2016) 038. arXiv:1603.07142

- publicly available Monte Carlo code
- **modular** structure
- propagation of cosmic rays, gamma rays, neutrinos
- galactic and extragalactic propagation
- modular structure
- parallelisation with OpenMP
- development on Github: https://github.com/CRPropa/CRPropa3
- CRPropa 3.2 coming out soon!



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