expectations for cosmogenic neutrinos from cosmic-ray data

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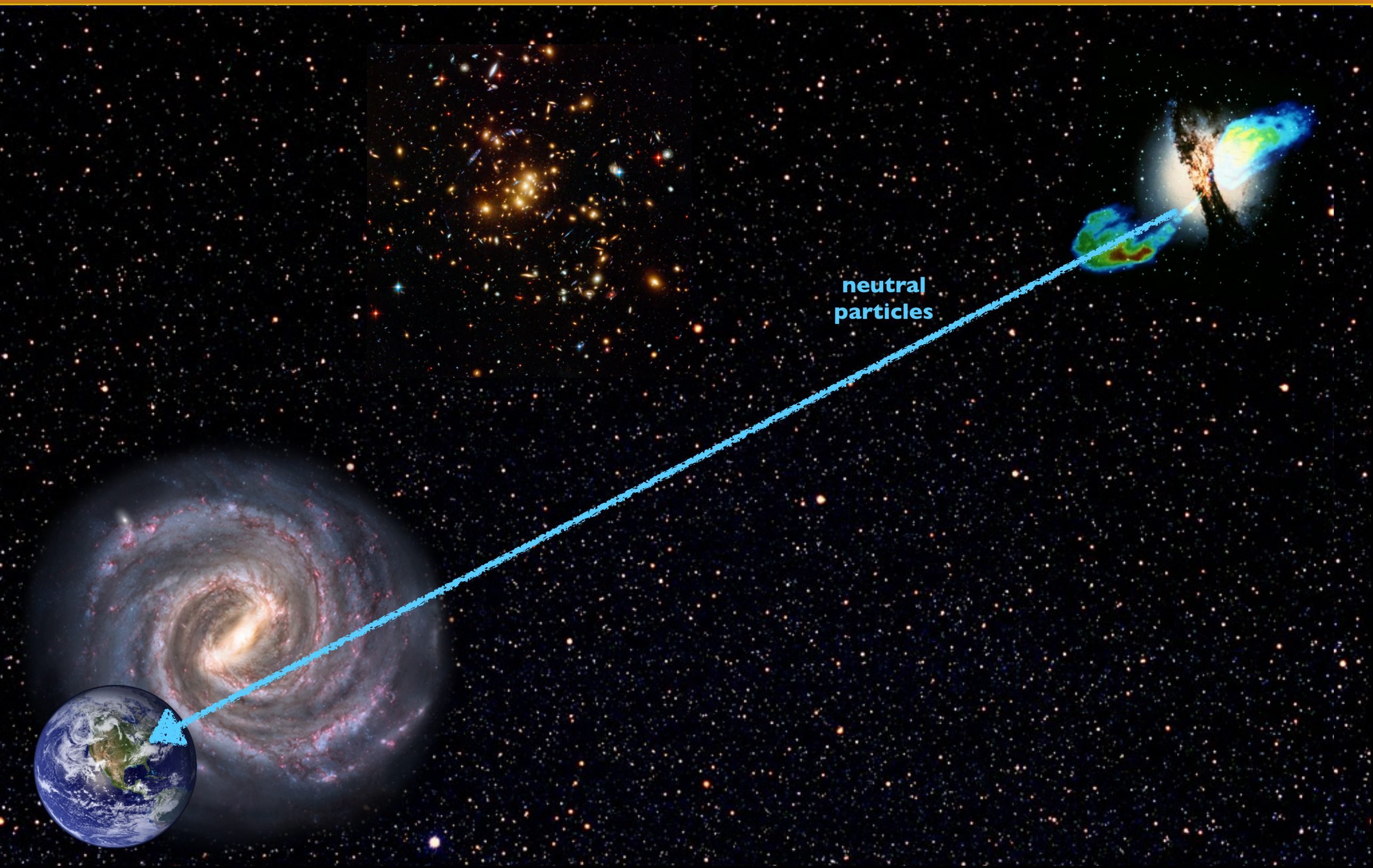
PAHEN
Berlin
26/Sep/2019

UHECR propagation picture

UHECR propagation picture



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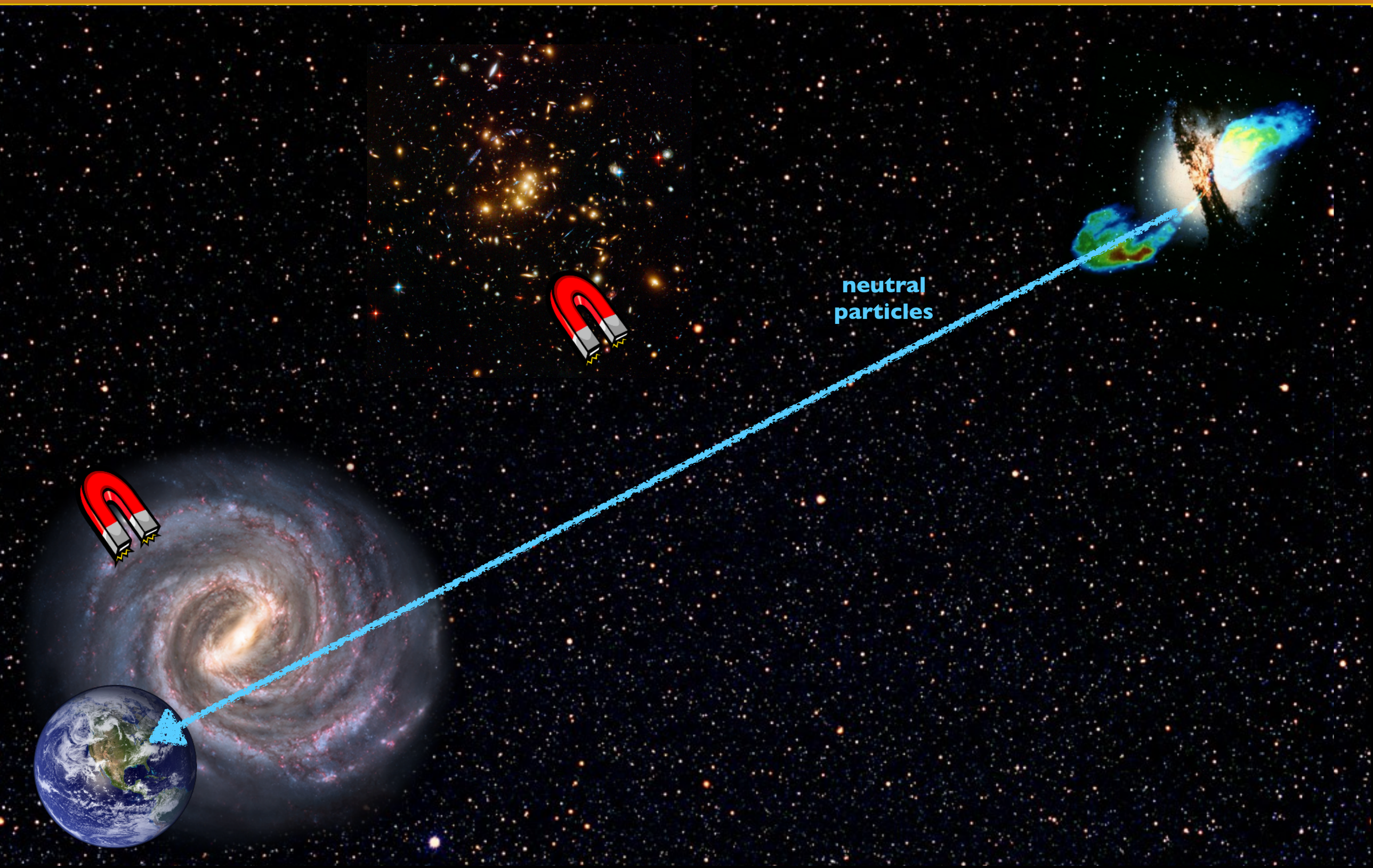

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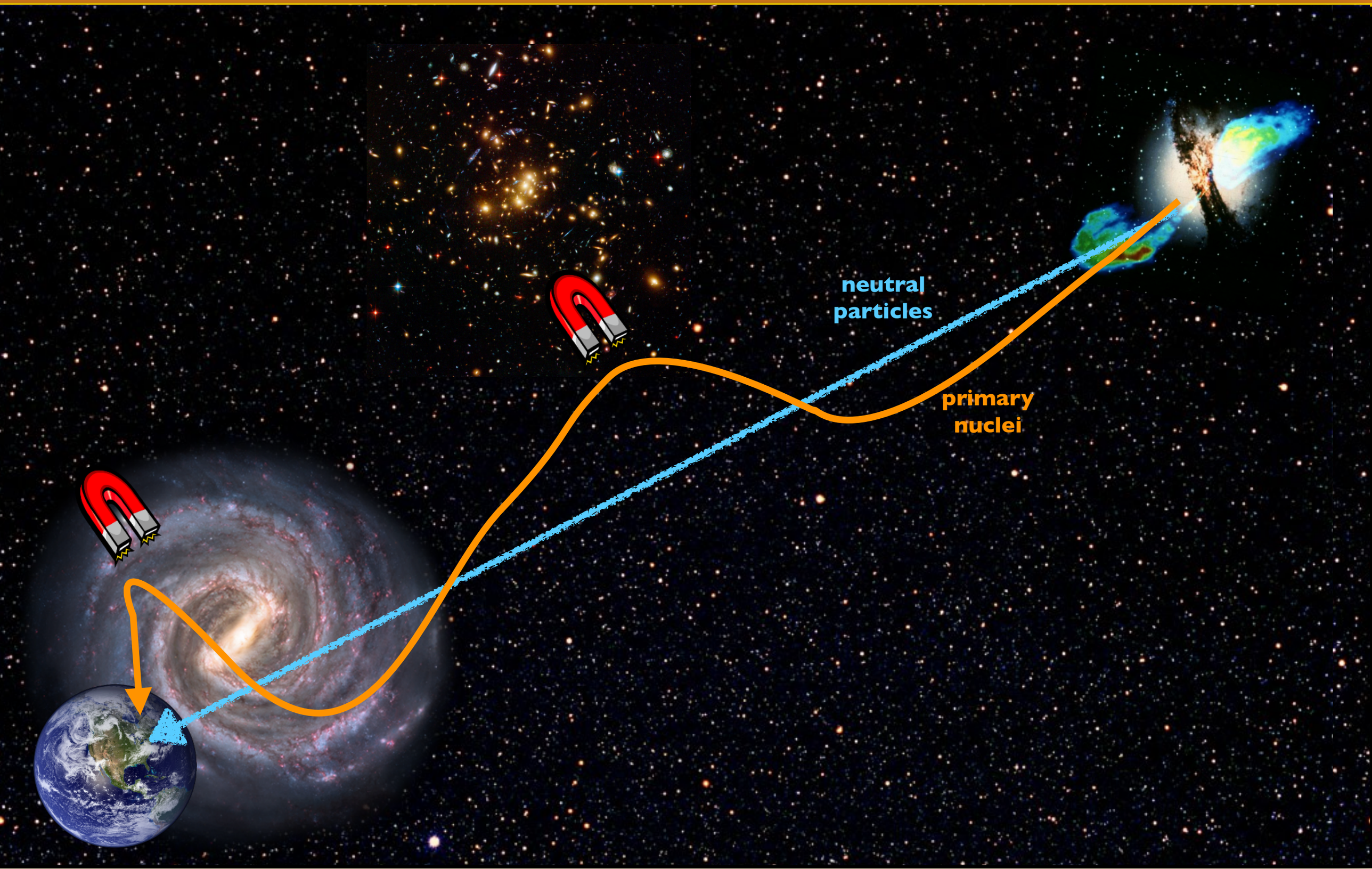

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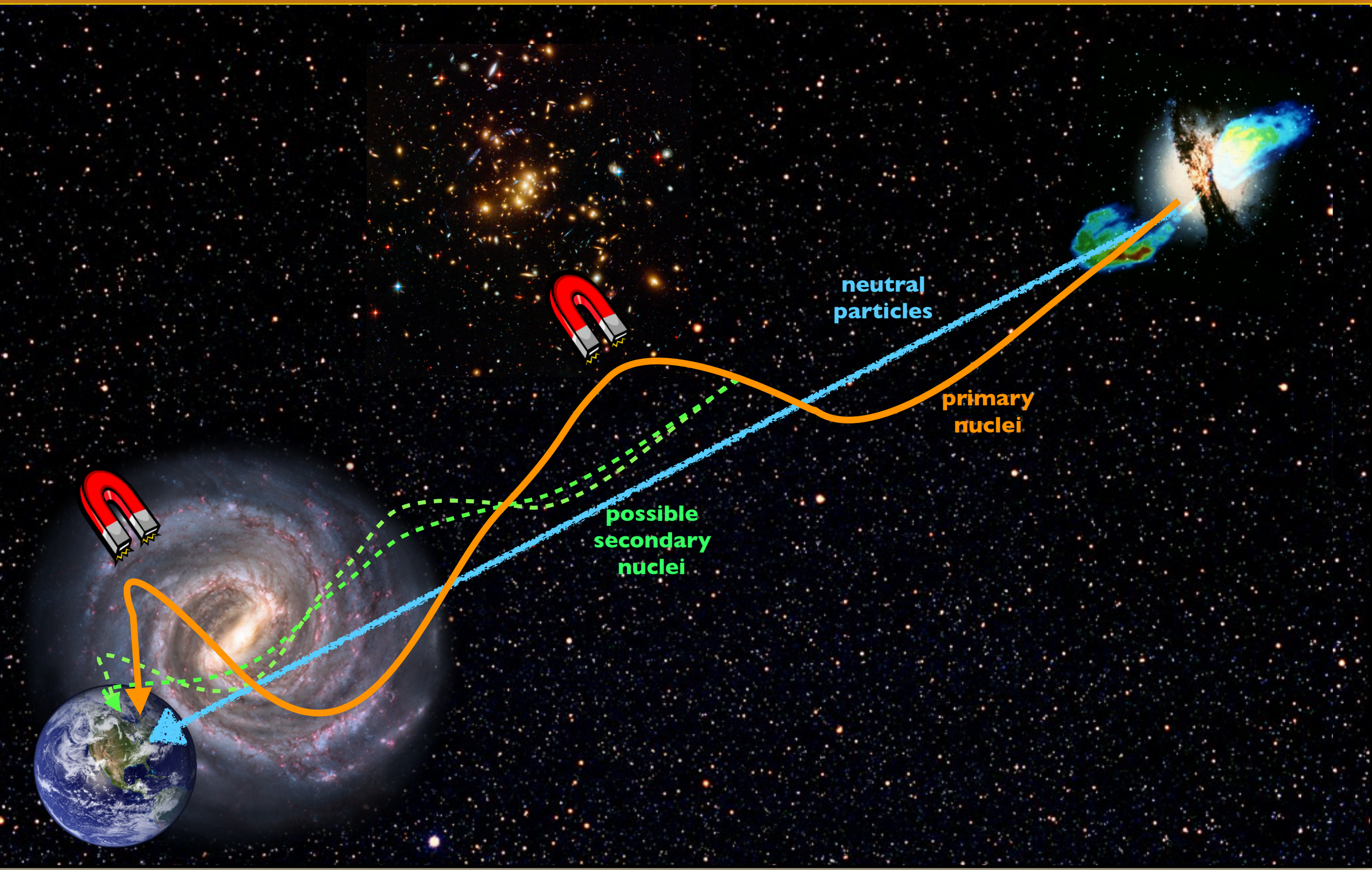

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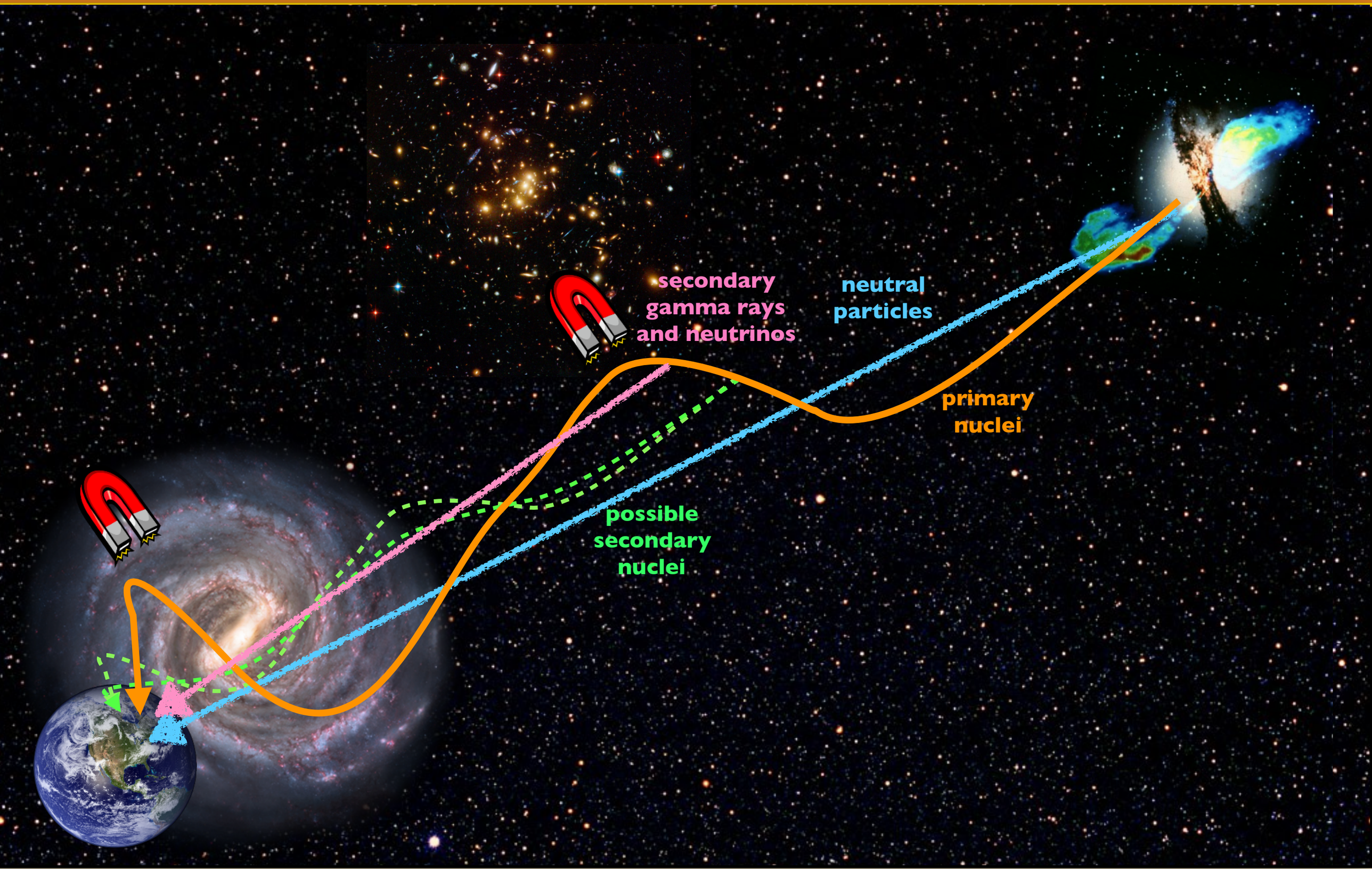

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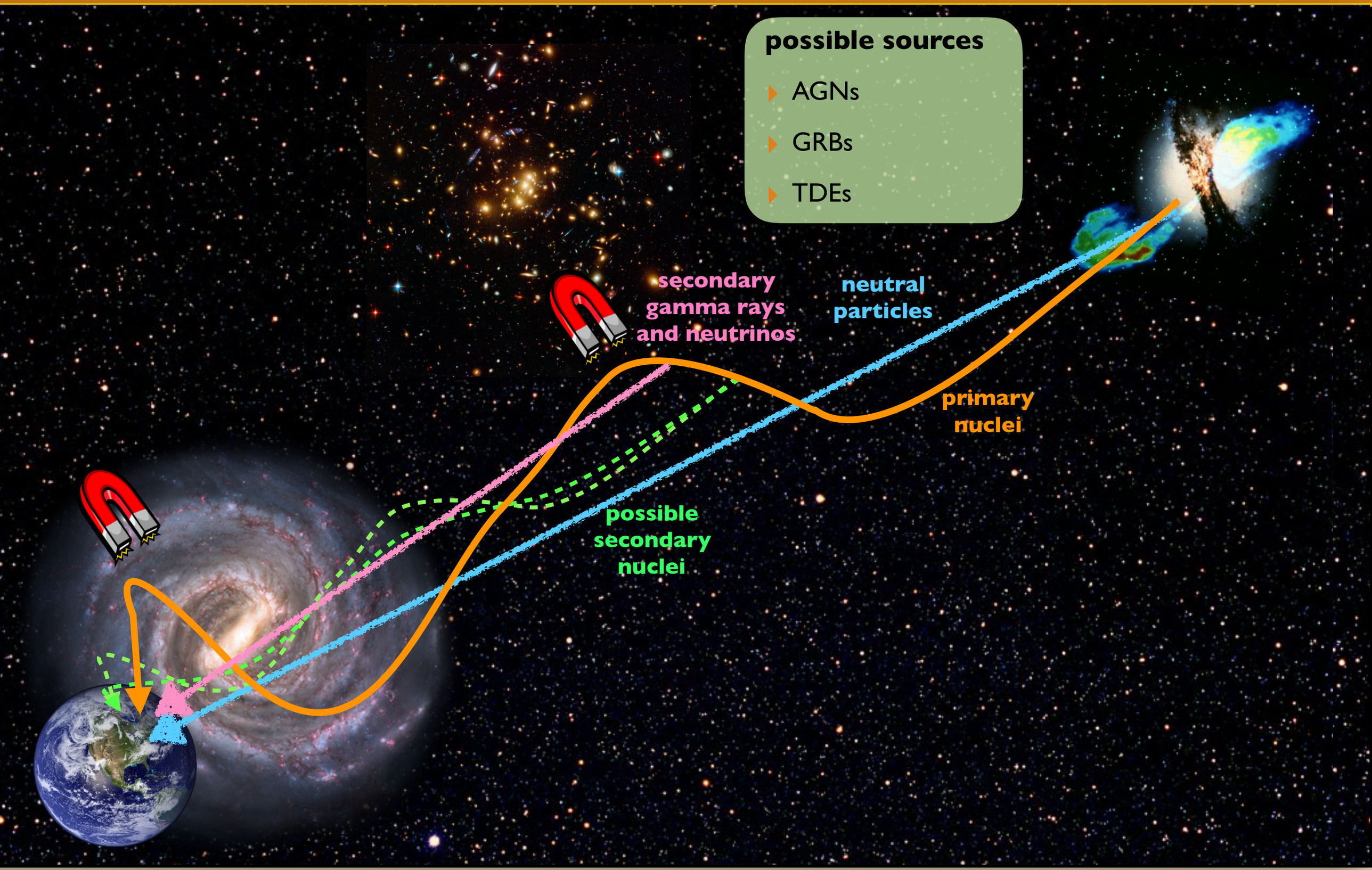

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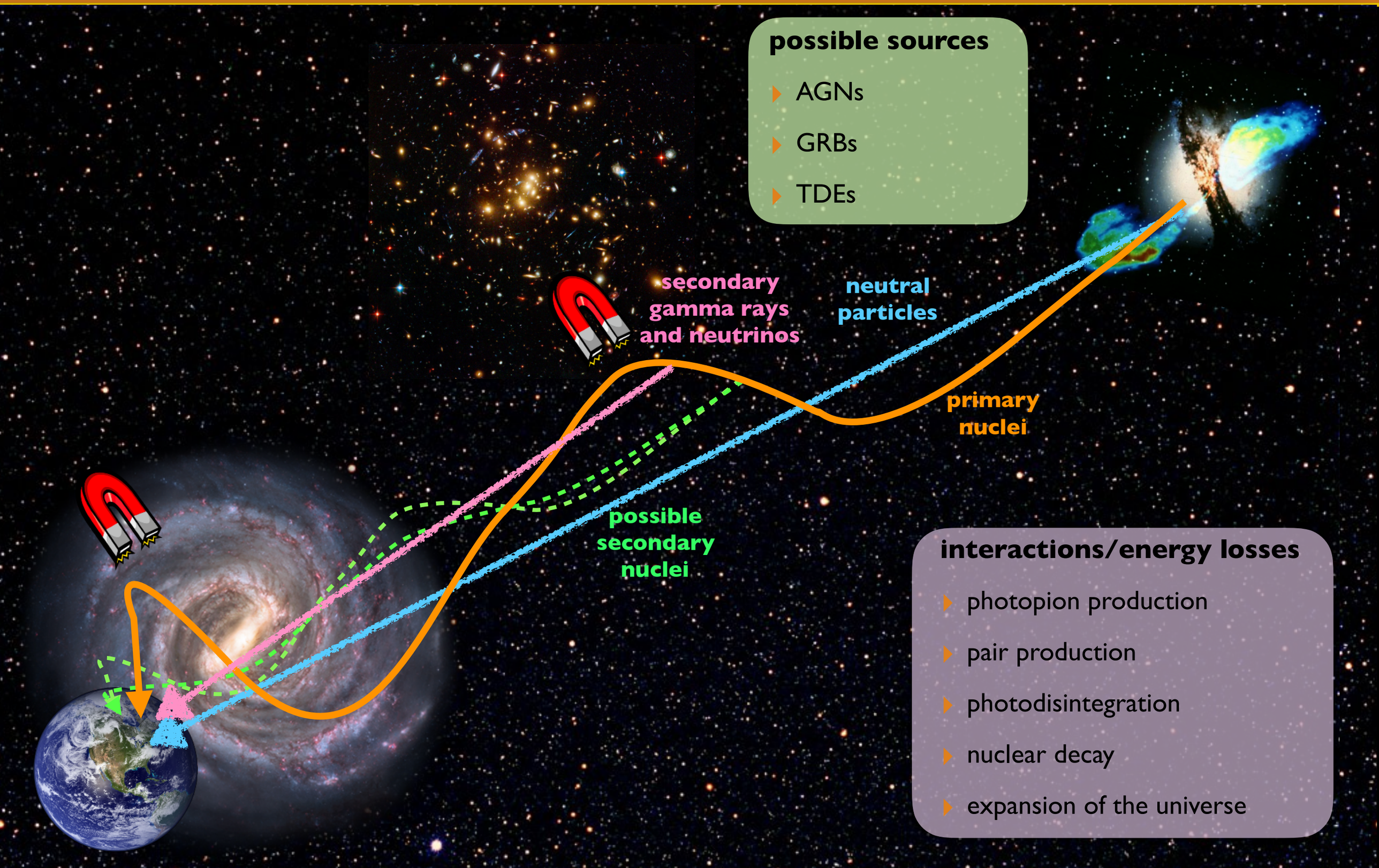


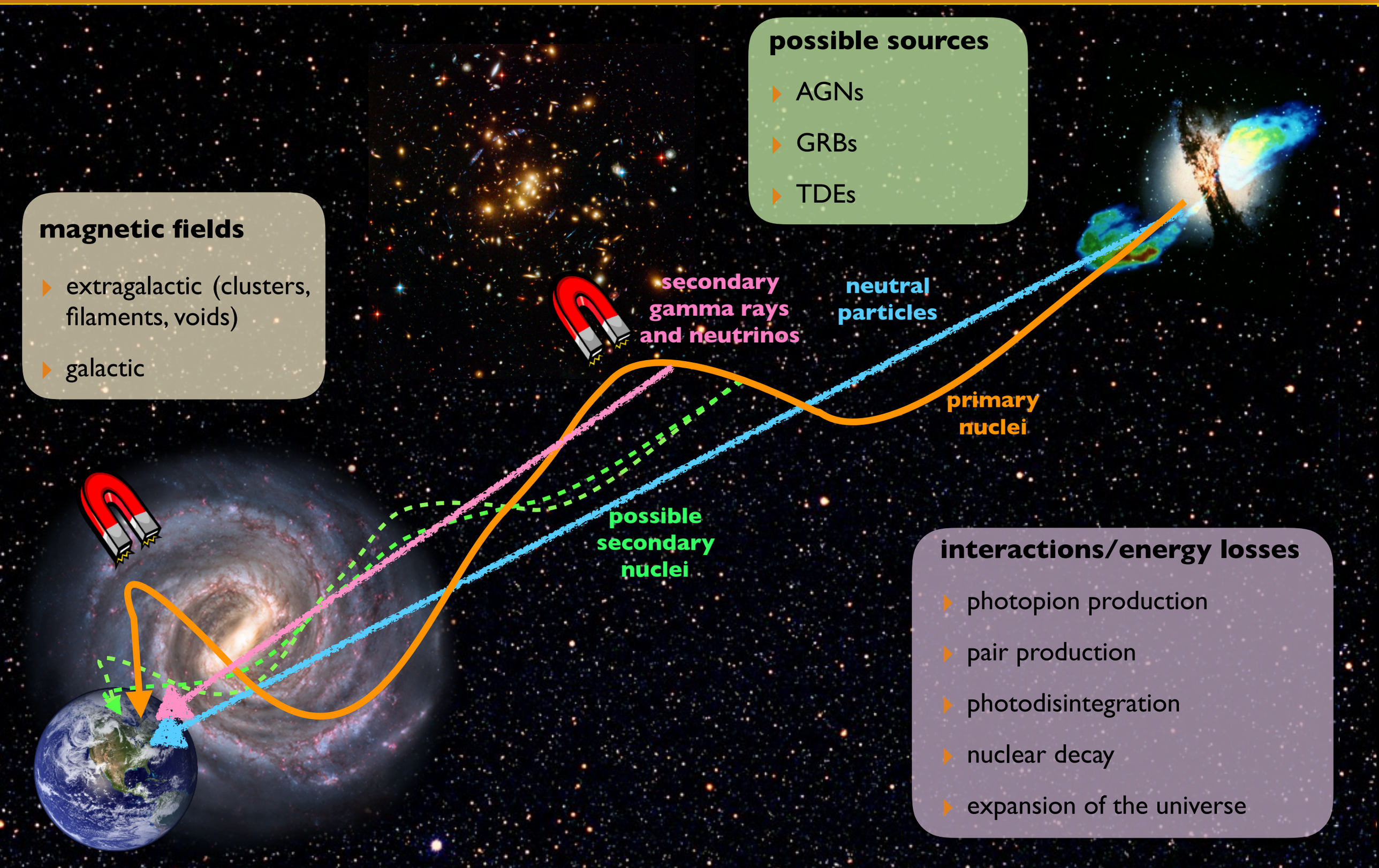
possible sources

- AGNs
- GRBs
- TDEs

interactions/energy losses

- photopion production
- pair production
- photodisintegration
- nuclear decay
- expansion of the universe

UHECR propagation picture



producing cosmogenic particles

producing cosmogenic particles

photopion production

$$p + \gamma \rightarrow \begin{cases} p + \pi^0 \\ n + \pi^+ \end{cases} \qquad \begin{aligned} &\pi^0 \rightarrow 2\gamma \\ &\pi^+ \rightarrow \nu_\mu + \mu^+ \\ &\qquad\qquad \mu^+ \rightarrow e^+ + \nu_e + \bar{\nu}_\mu \end{aligned}$$

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Bethe-Heitler pair production

$$^{A}_{Z}X + \gamma_{bg} \rightarrow ^{A}_{Z}X + e^+ + e^-$$

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photodisintegration

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

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

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

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nuclear decays

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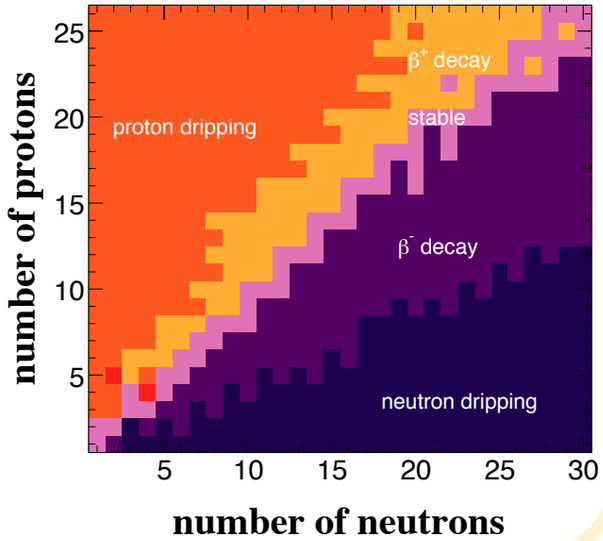

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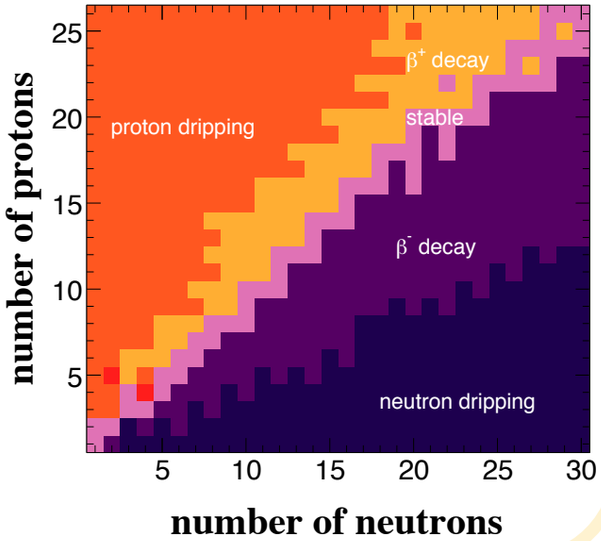

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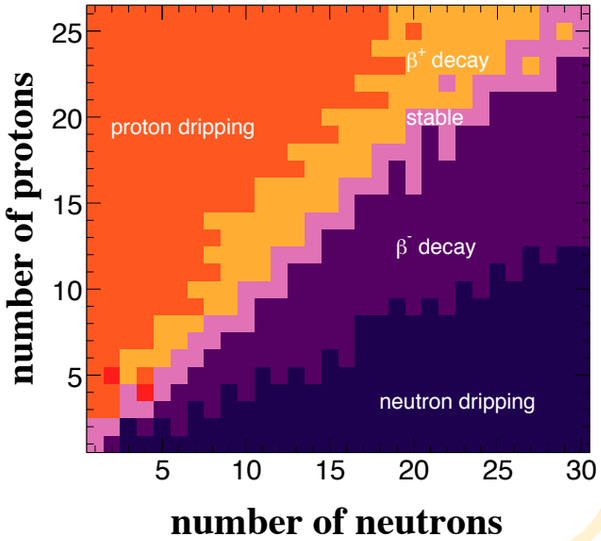

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electromagnetic interactions

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

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

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

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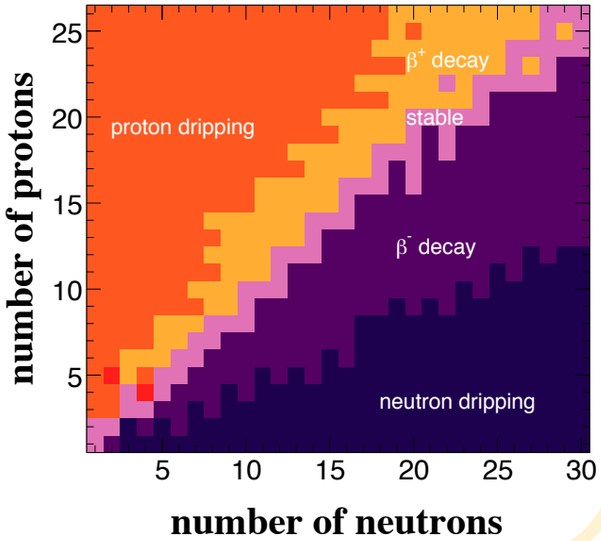

interpreting the UHECR data

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astrophysical inputs

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injection spectrum

initial composition

astrophysical inputs

source distribution

emissivity evolution

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propagation

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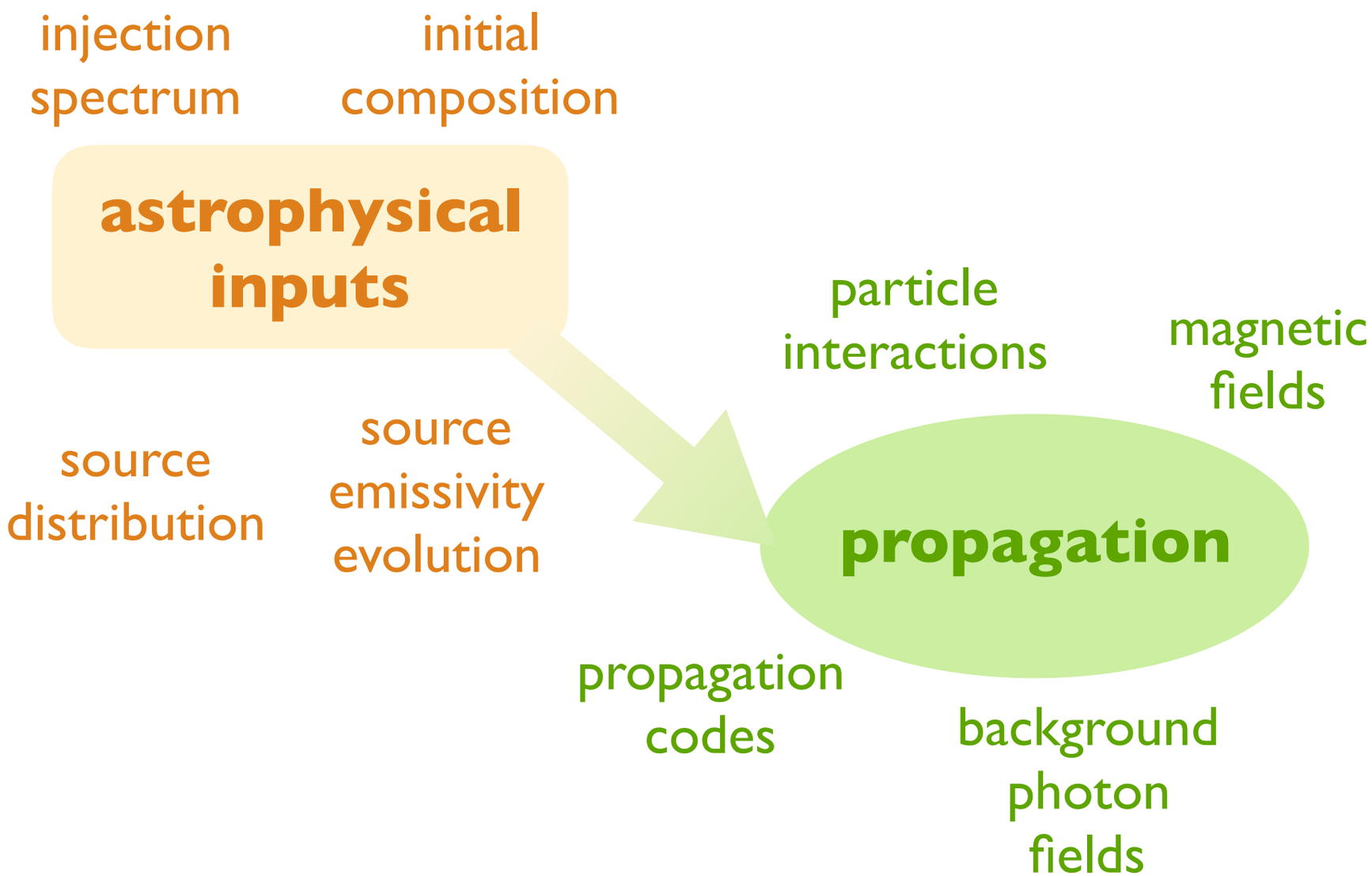

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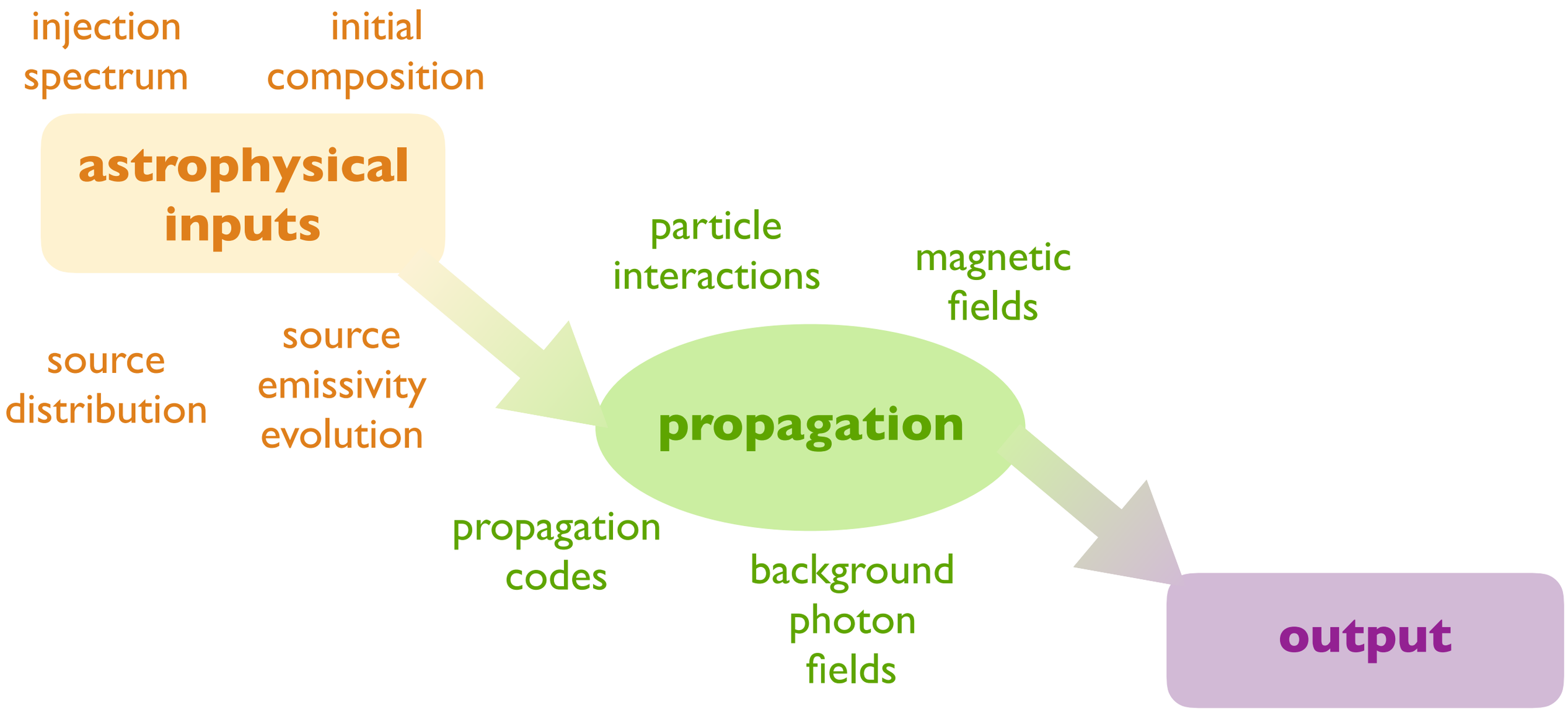

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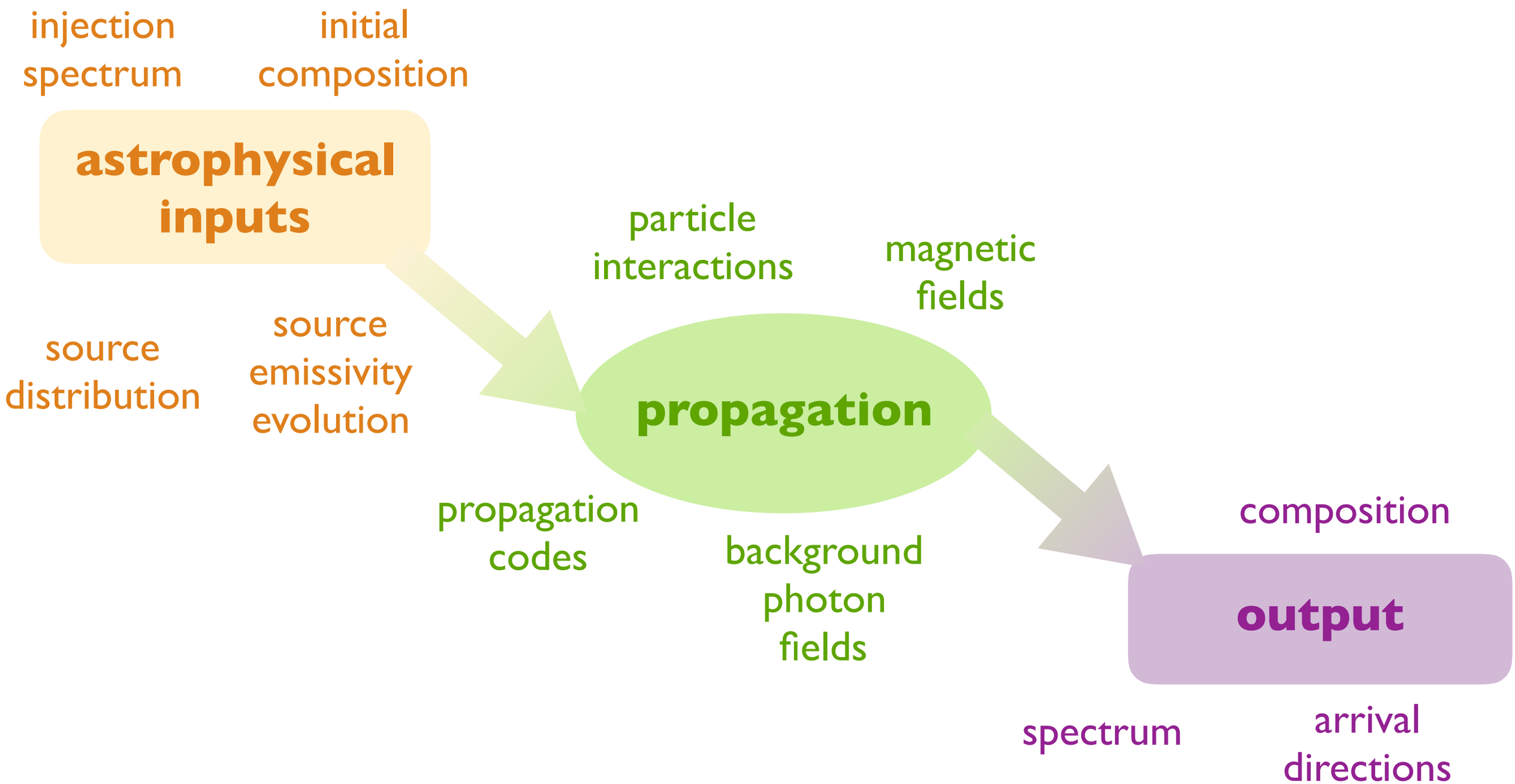


fitting the UHECR data

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)

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

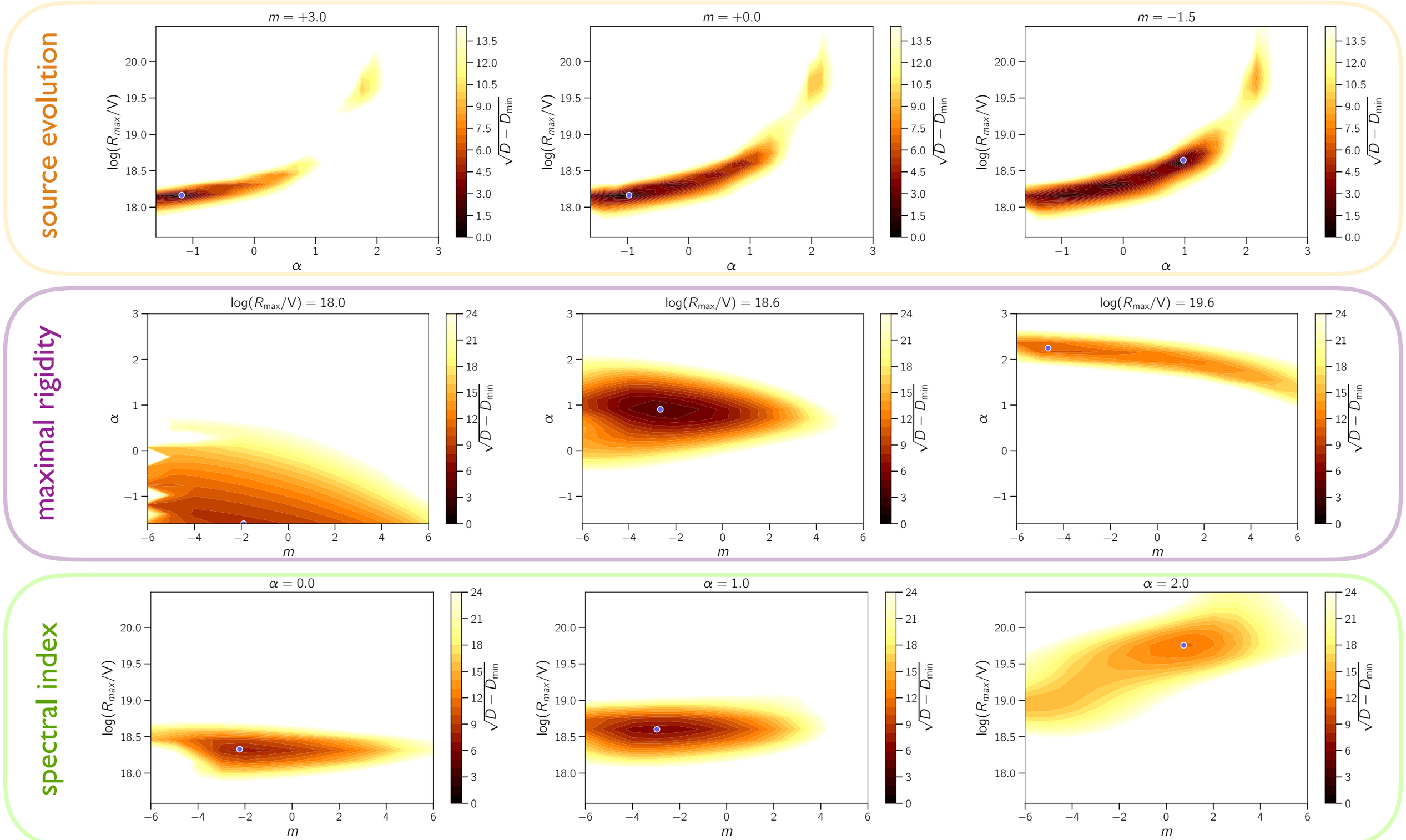
composition: X_{max} distributions

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

spectrum: vertical + inclined events

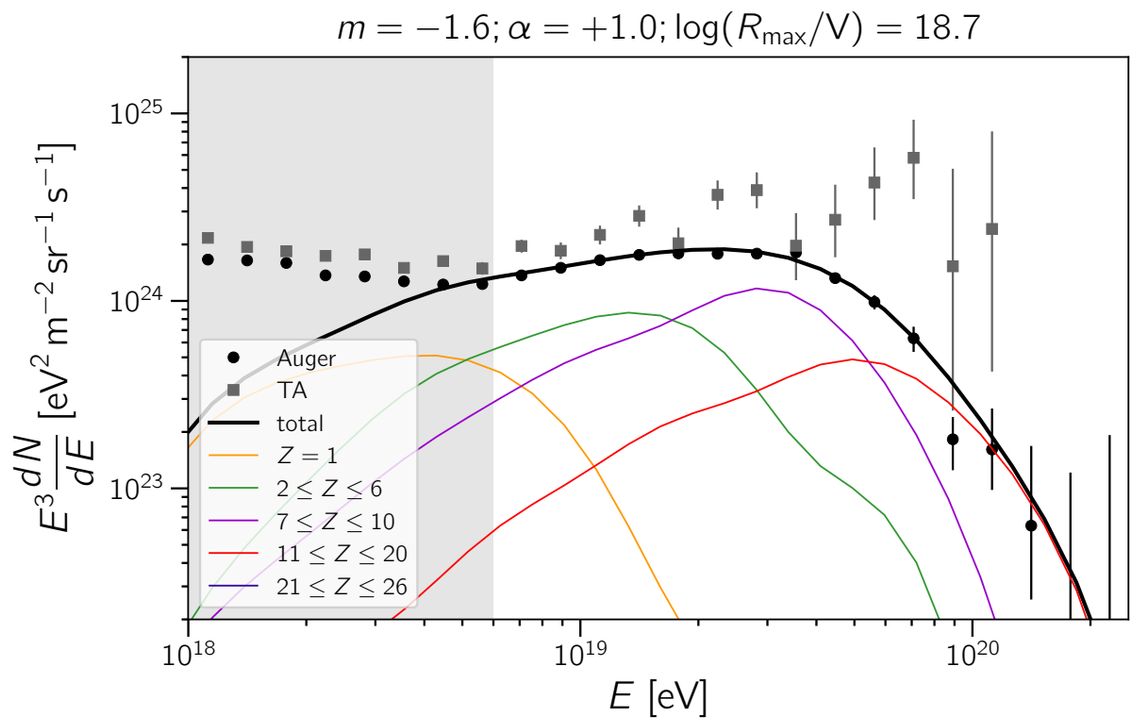
fit results: parameter dependences

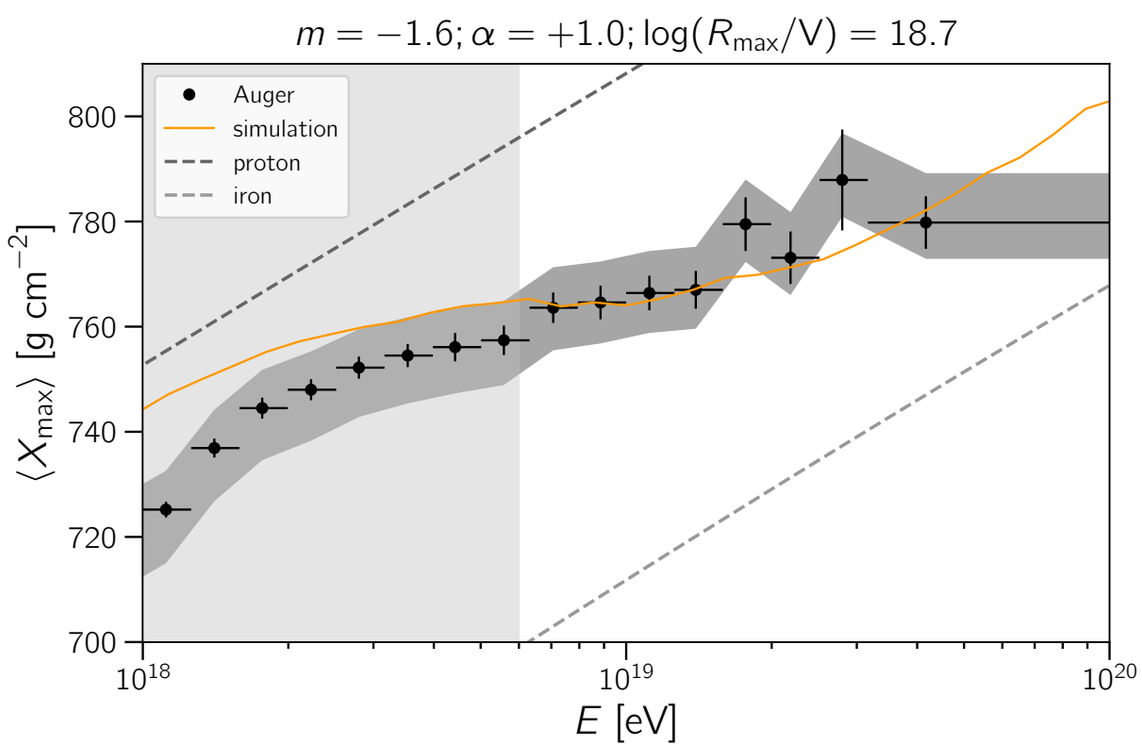
Alves Batista, de Almeida. Lago, Kotera. JCAP 01 (2019) 002. arXiv:1806.10879

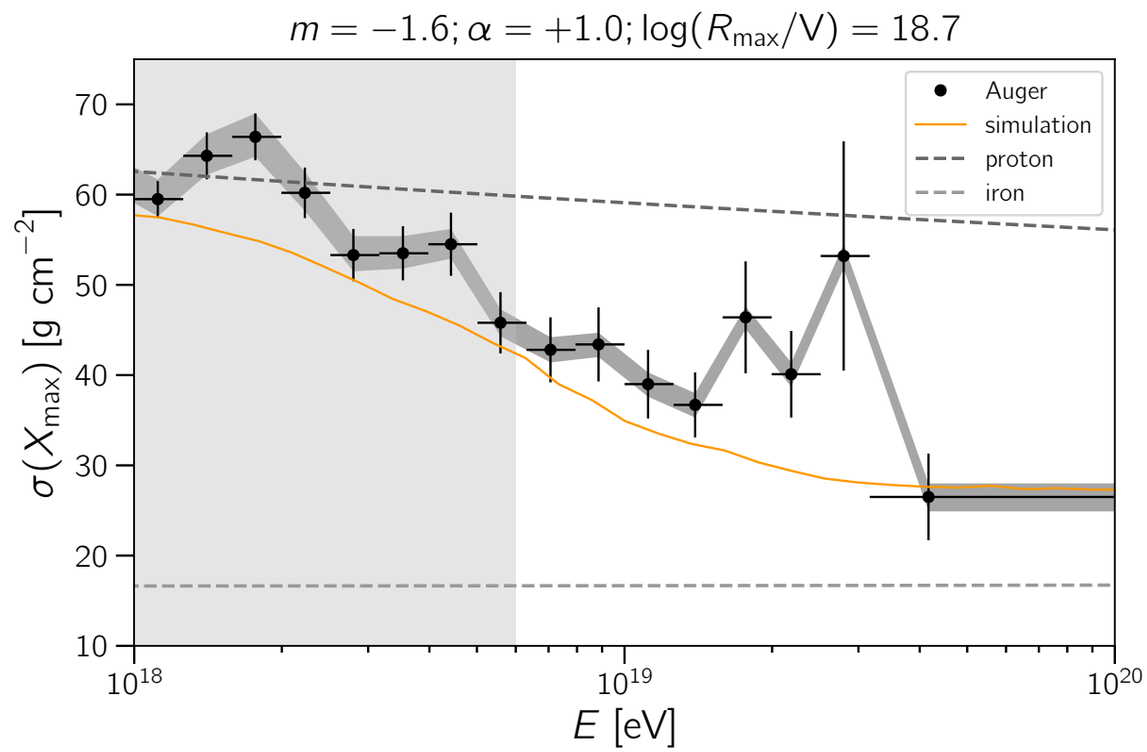


the best-fit

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

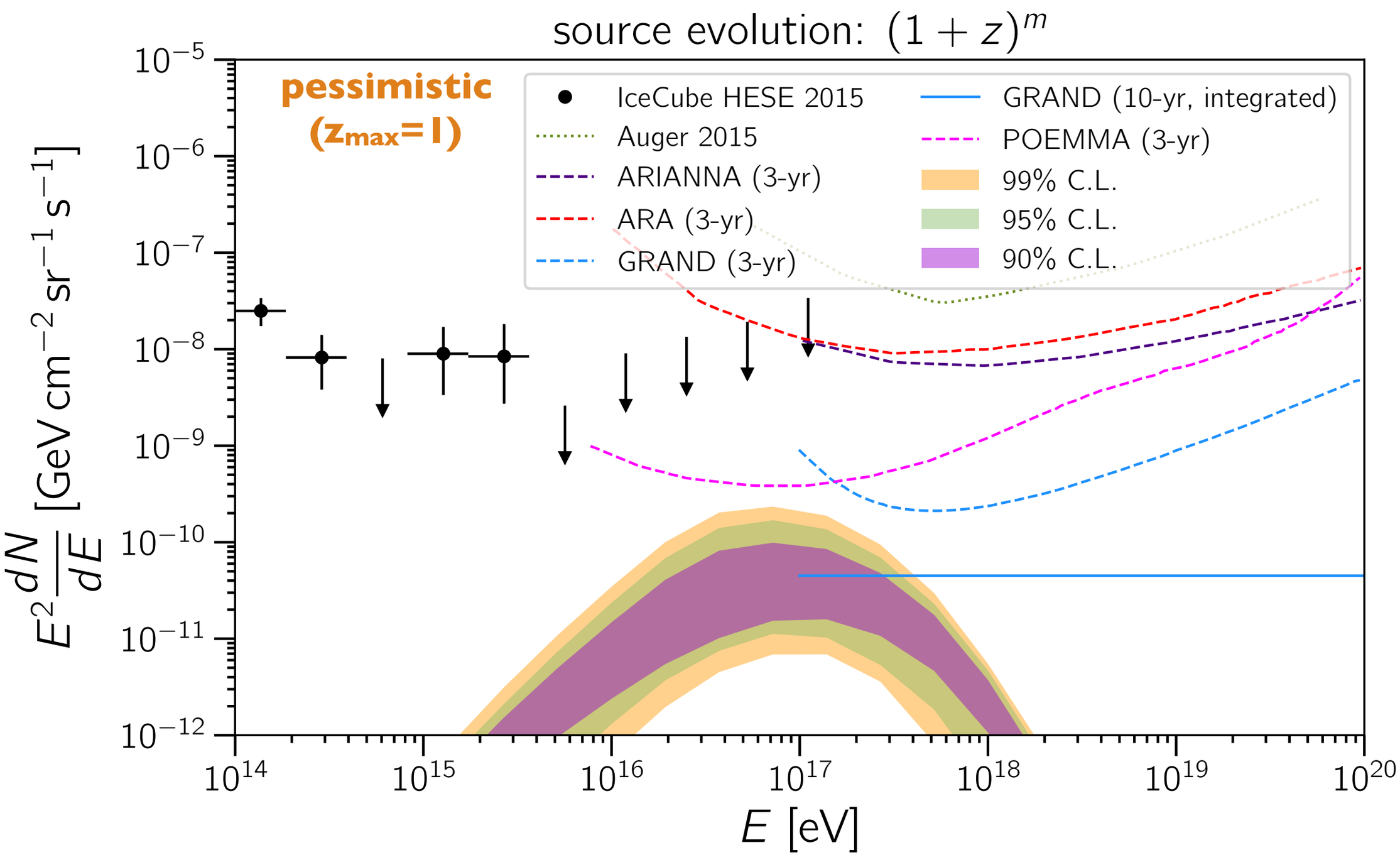






cosmogenic neutrinos

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



cosmogenic photons

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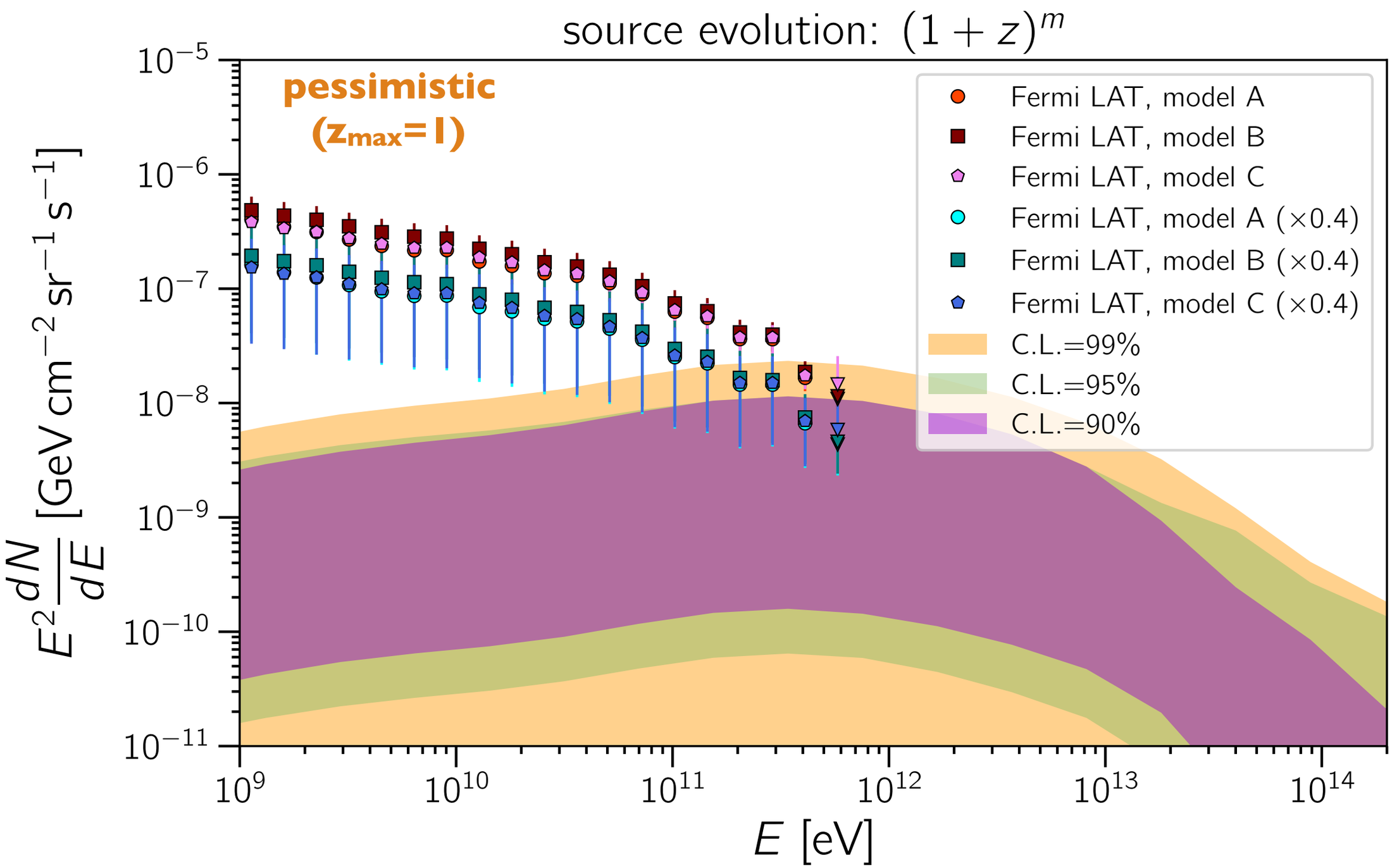
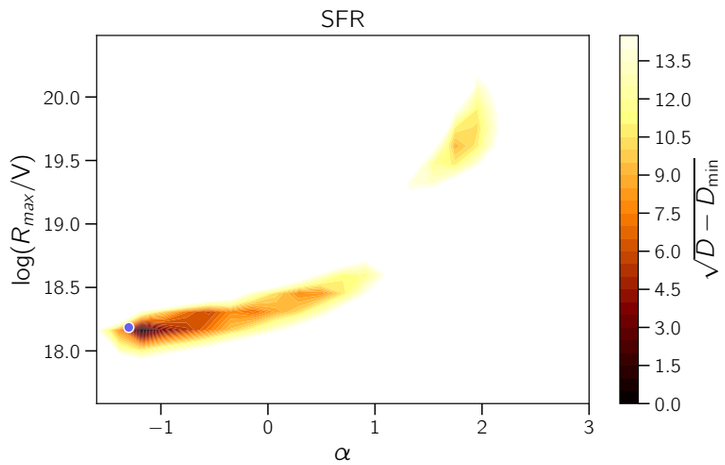
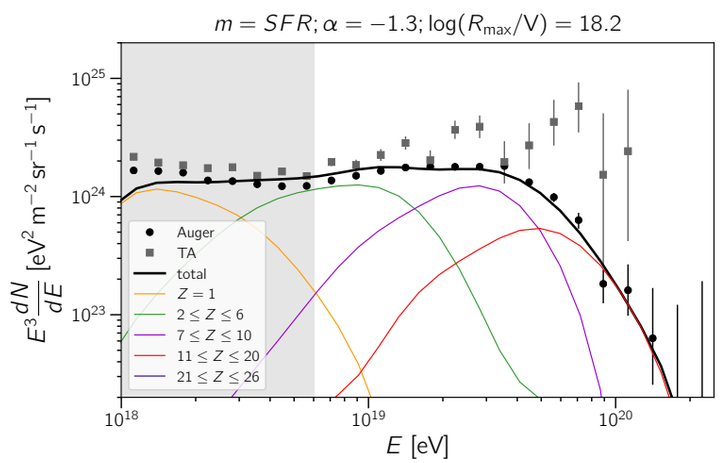
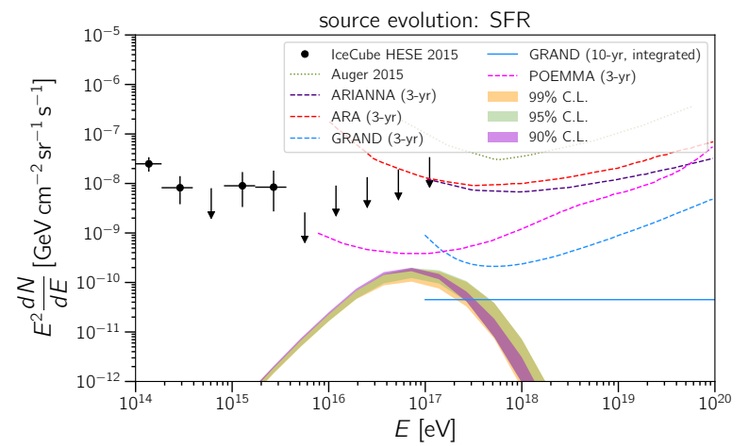


predictions for specific source populations

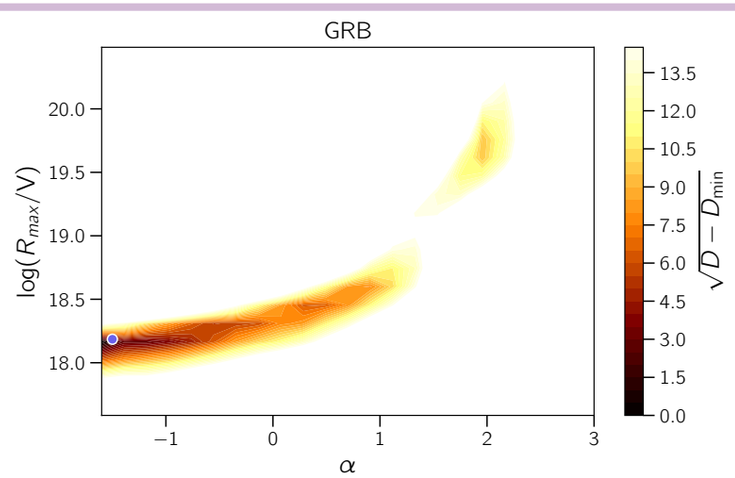
SFR

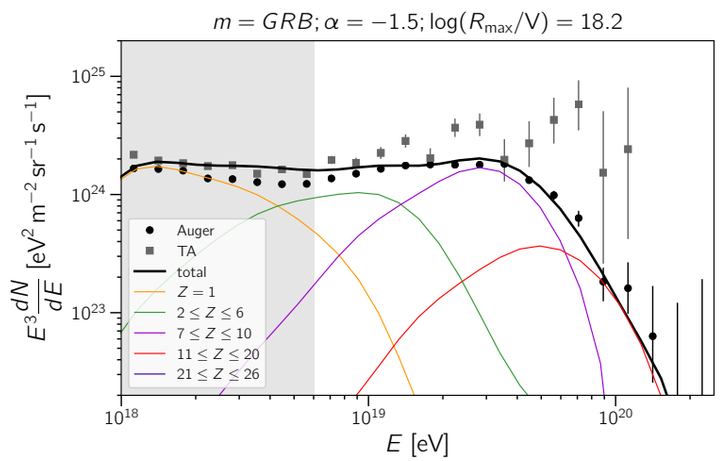


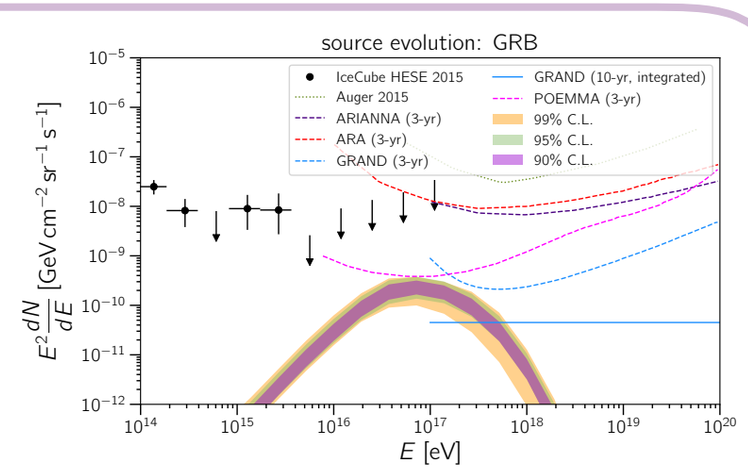




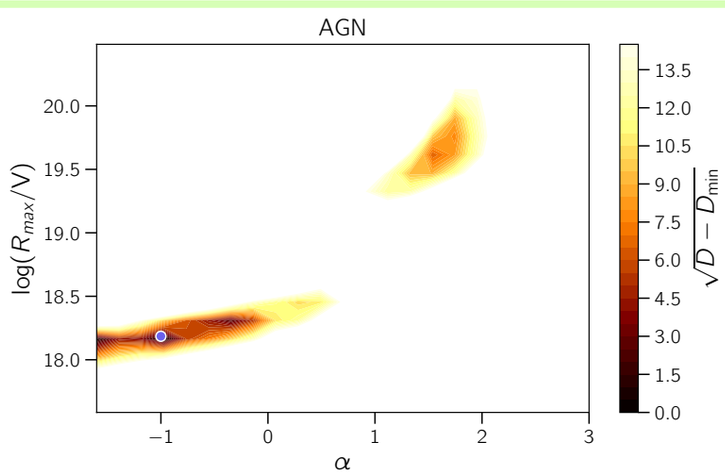
GRB

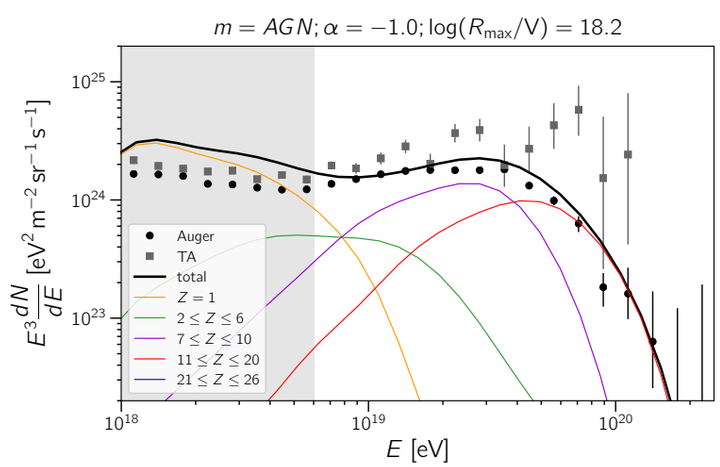


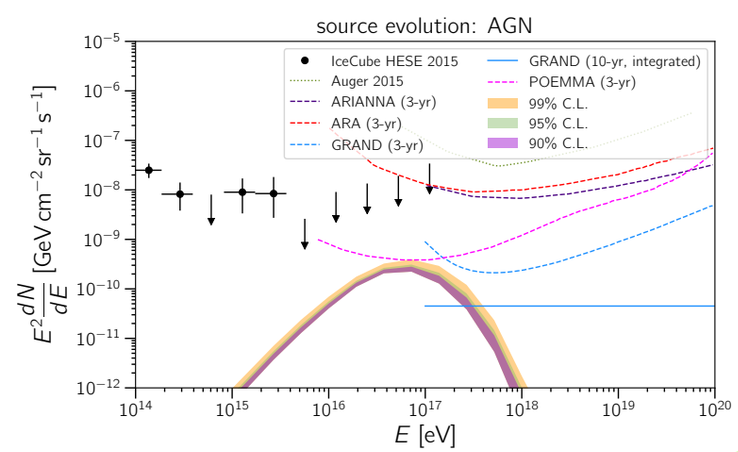




AGN

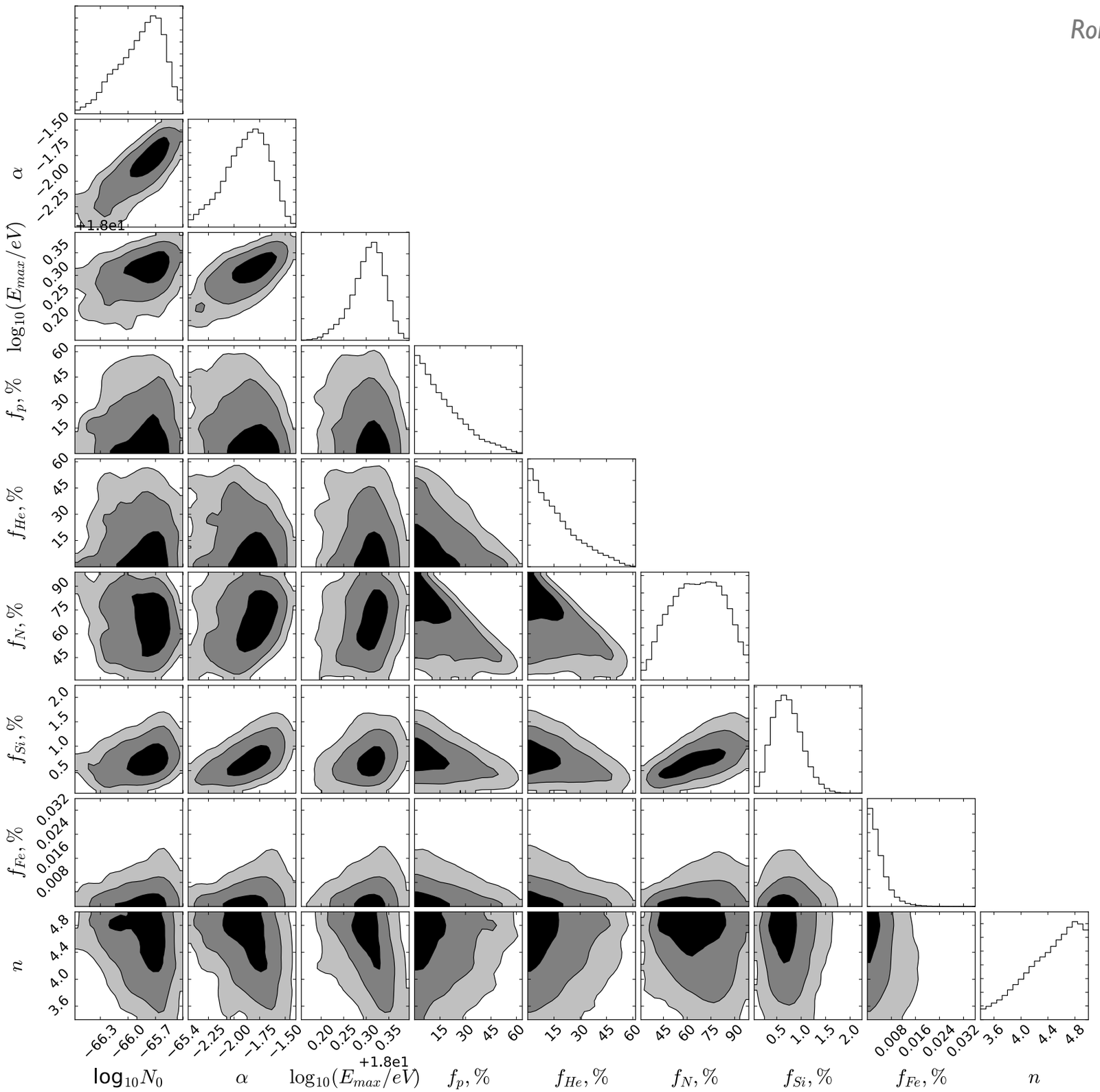






composition degeneracy

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



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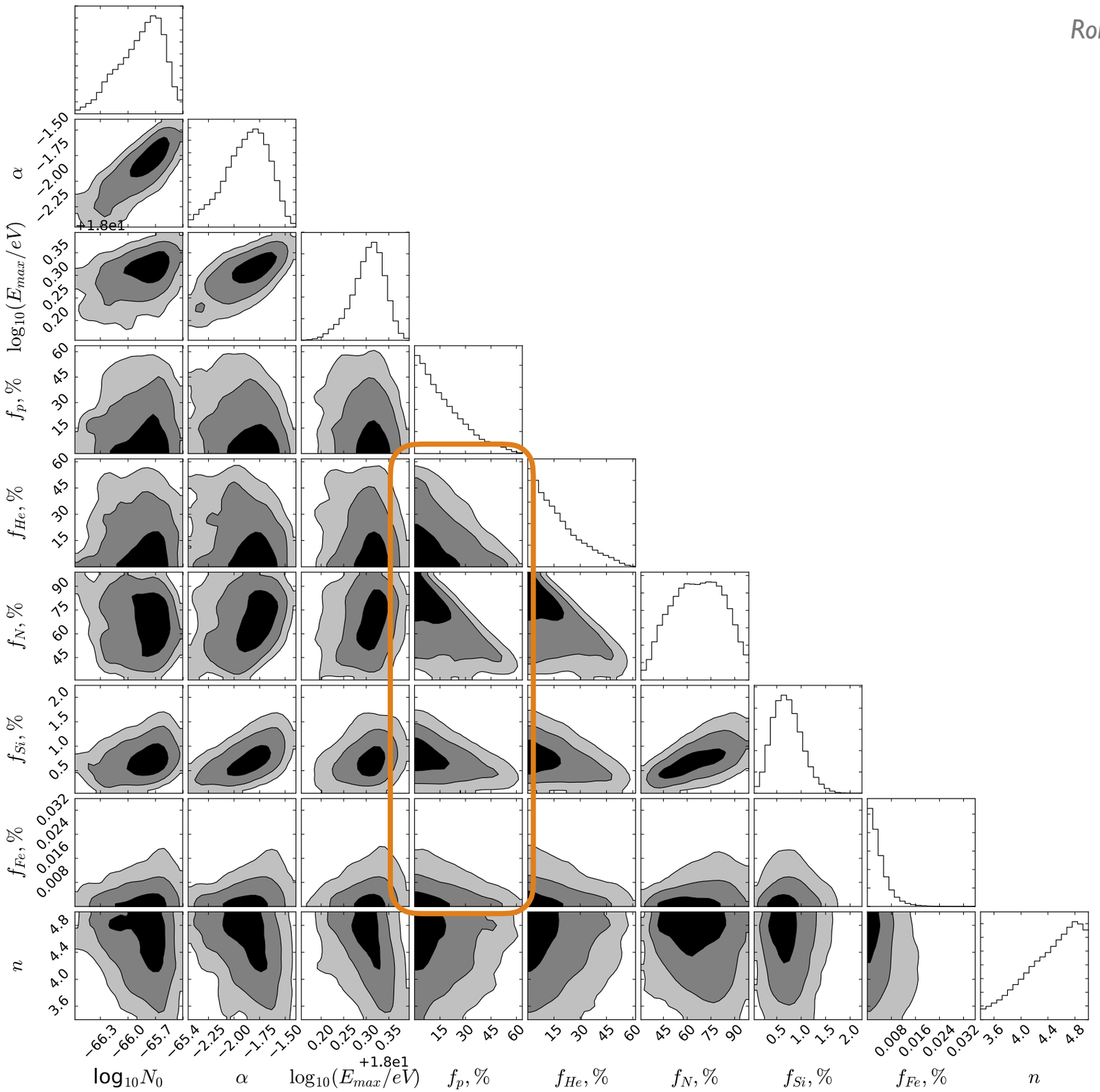

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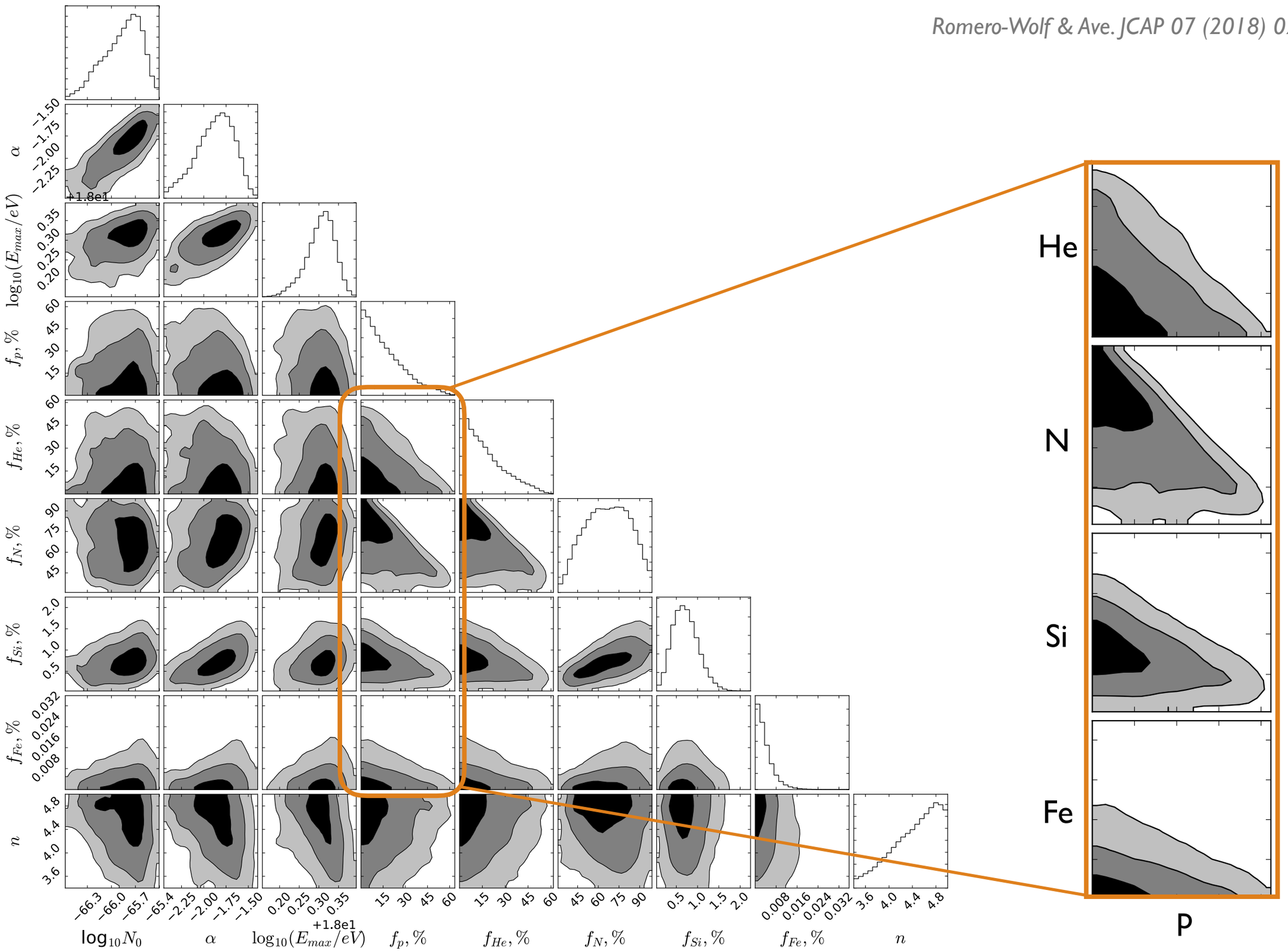
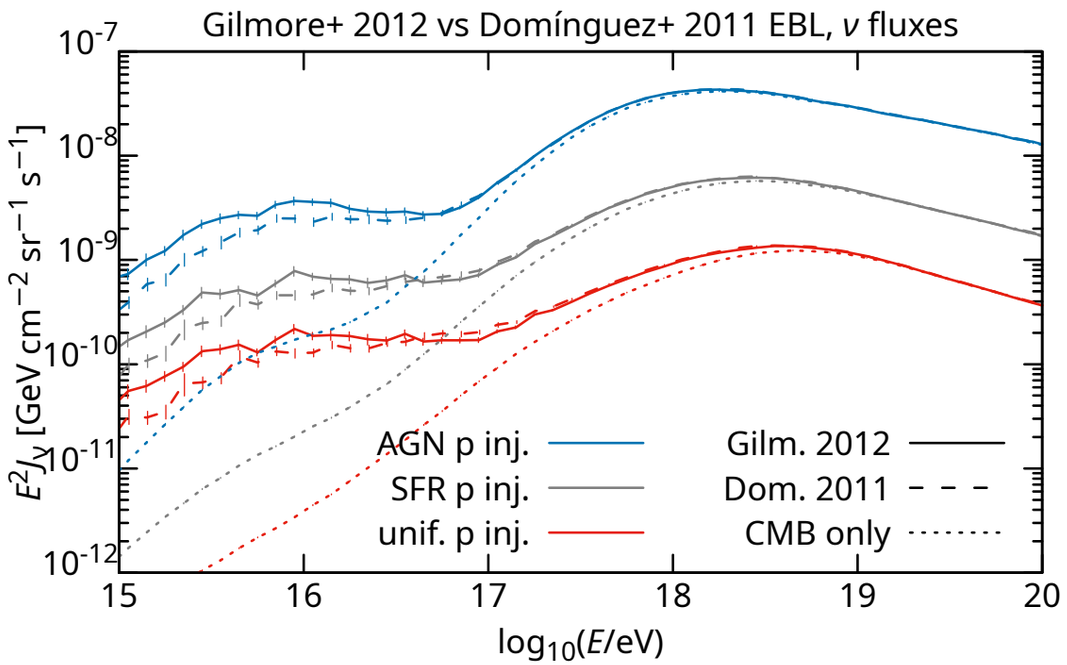
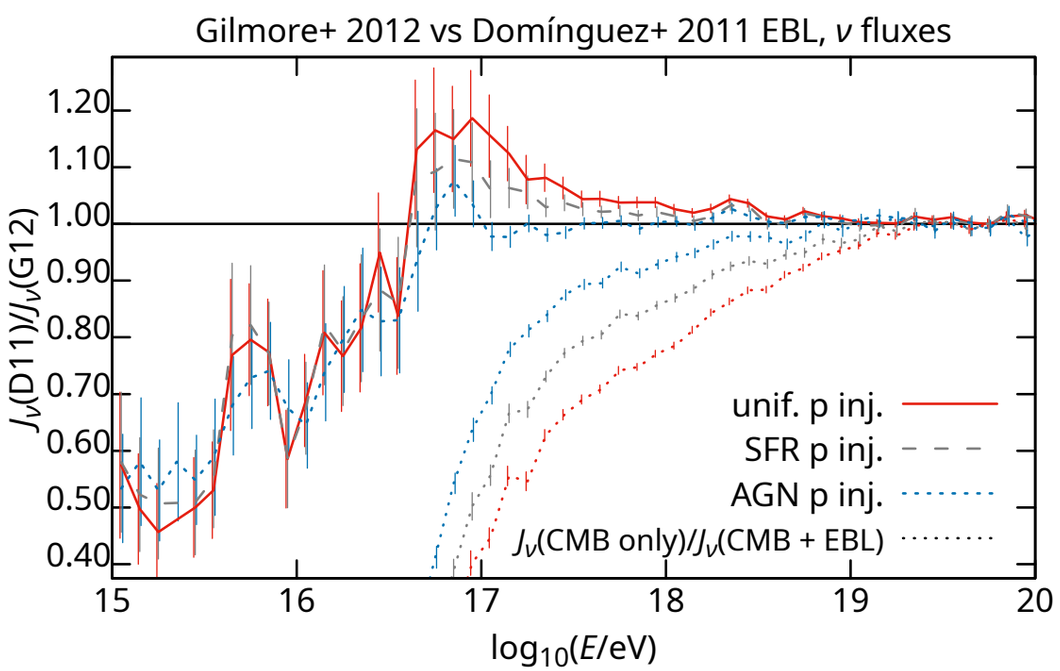


uncertainties: EBL models

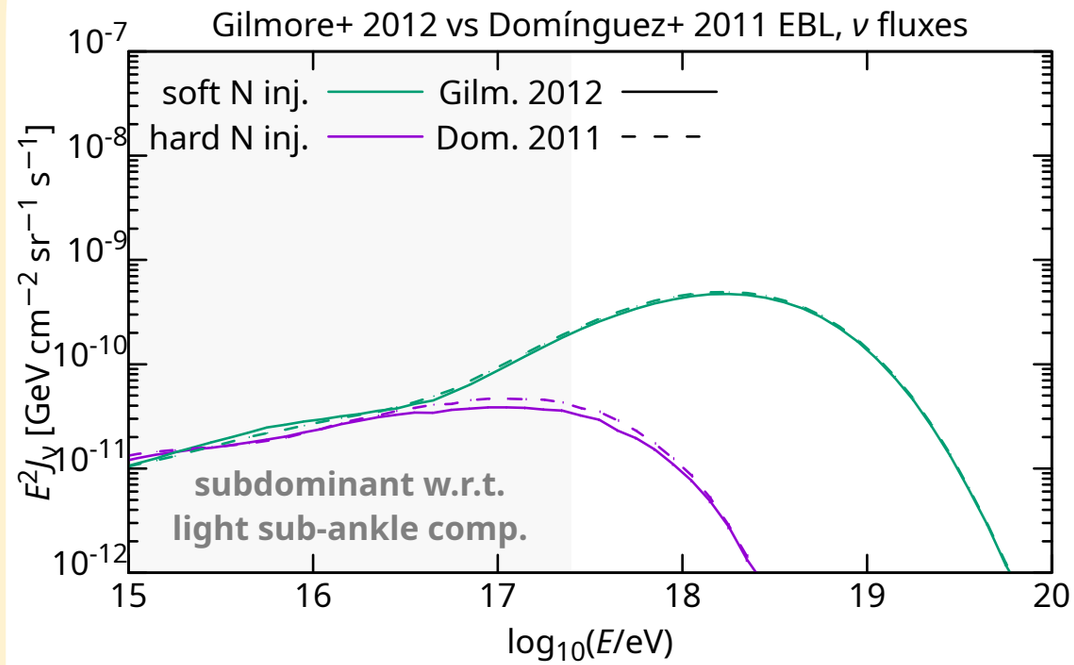
Alves Batista, Boncioli, di Matteo, van Vliet. JCAP 05 (2019) 006. arXiv:1901.01244

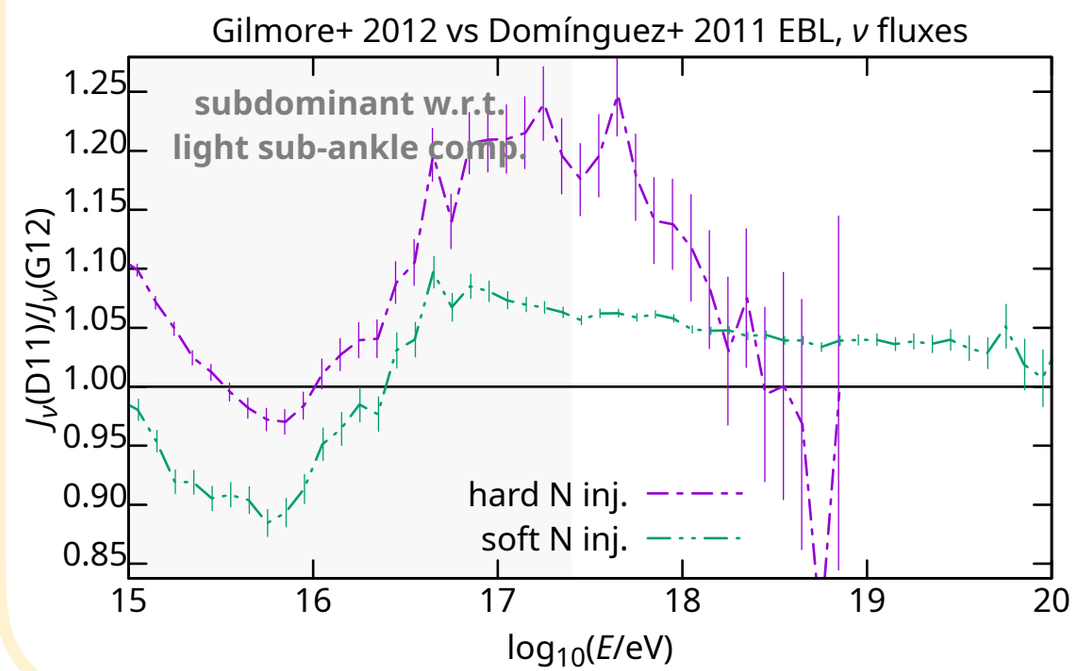
proton





nitrogen





uncertainties: photodisintegration

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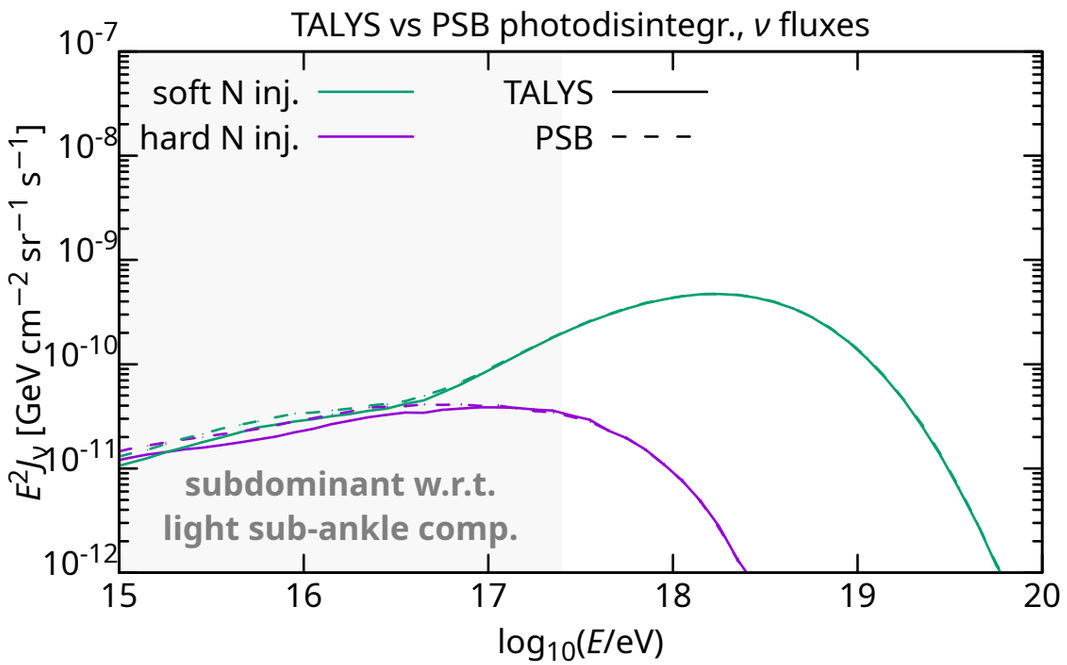
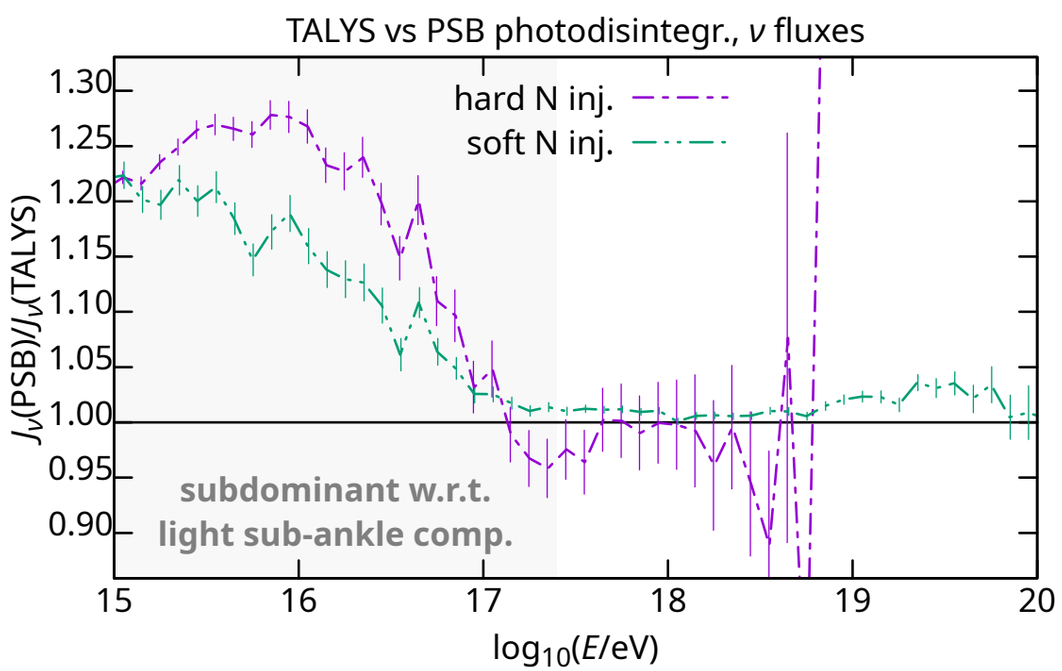
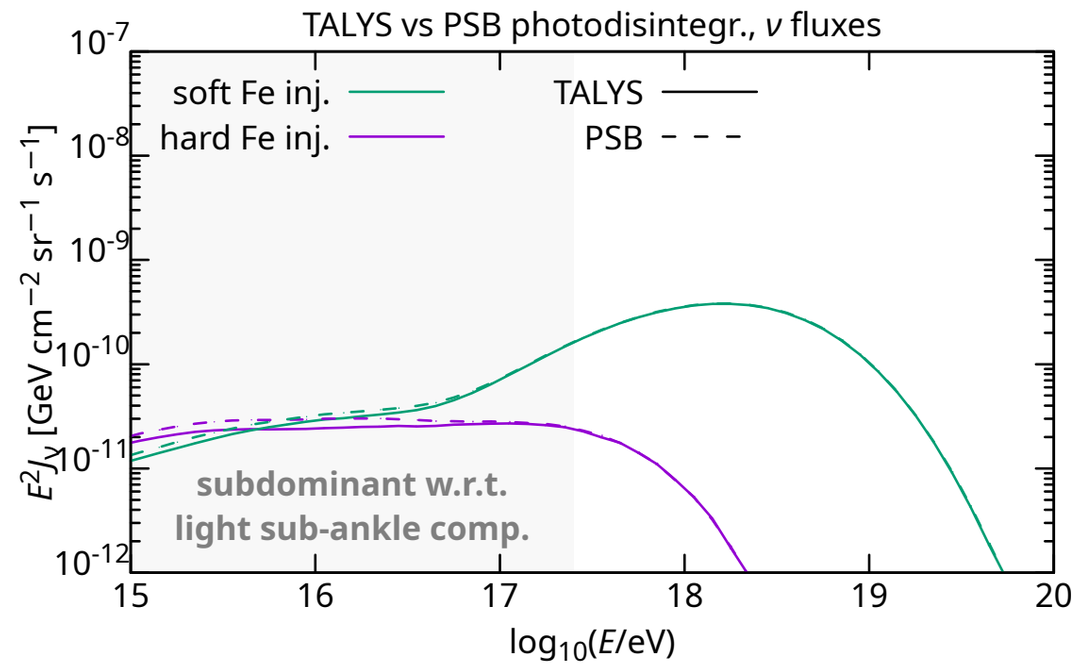
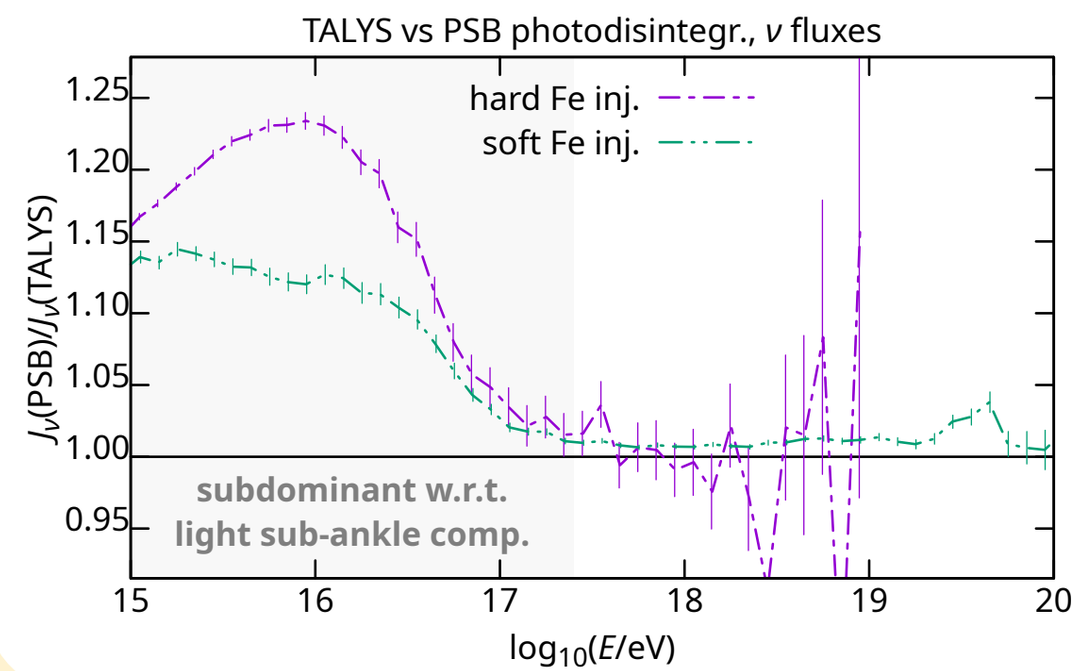




iron

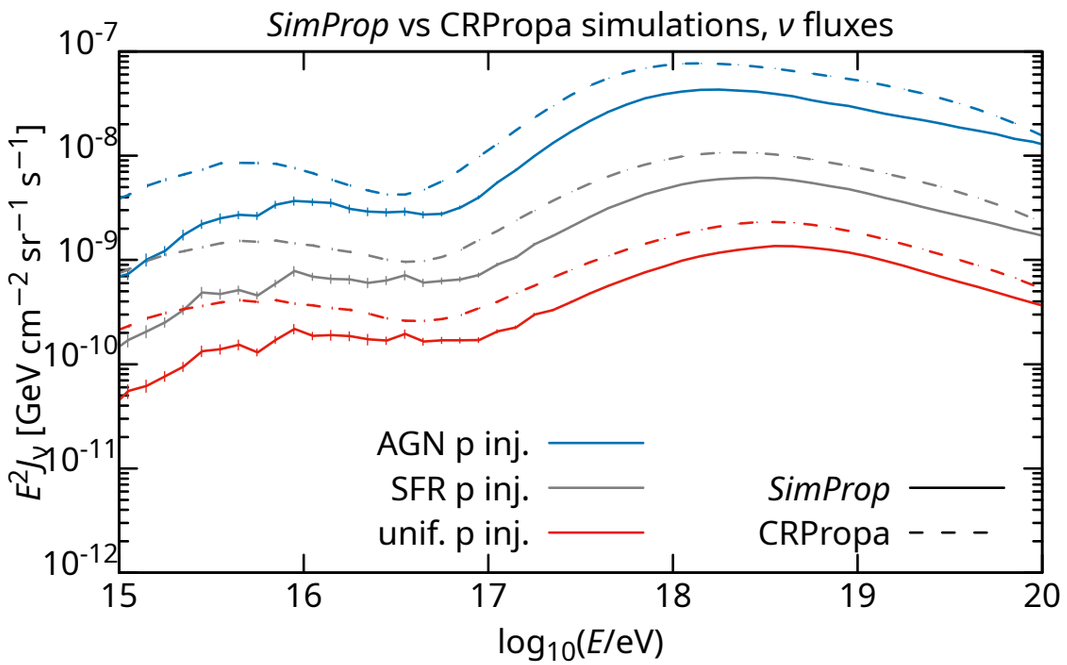


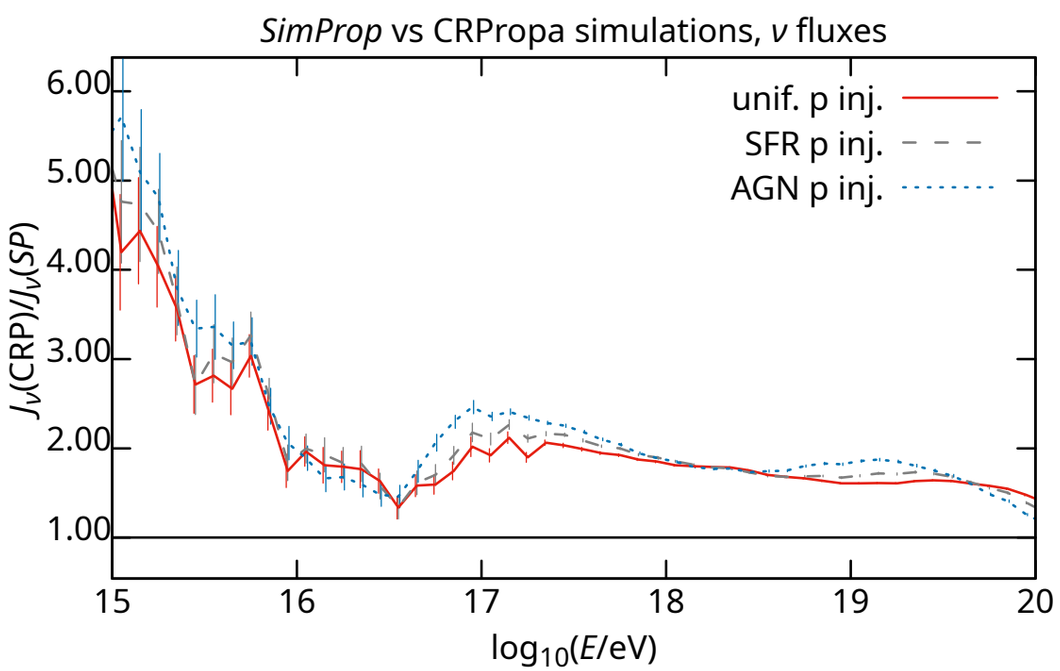


uncertainties: propagation codes

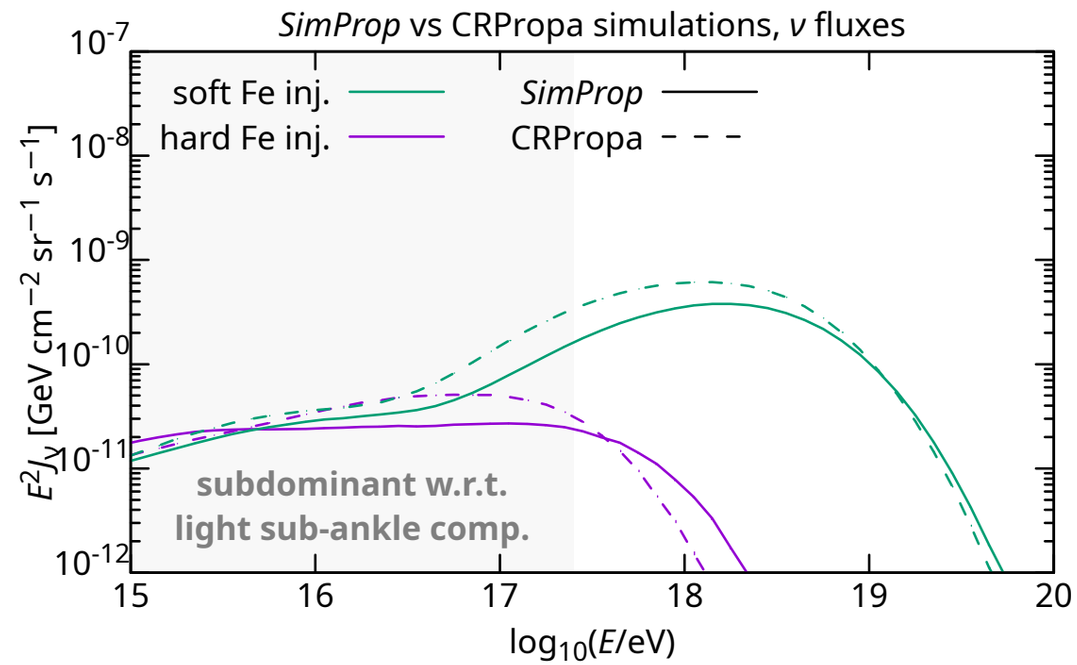
Alves Batista, Boncioli, di Matteo, van Vliet. JCAP 05 (2019) 006. arXiv:1901.01244

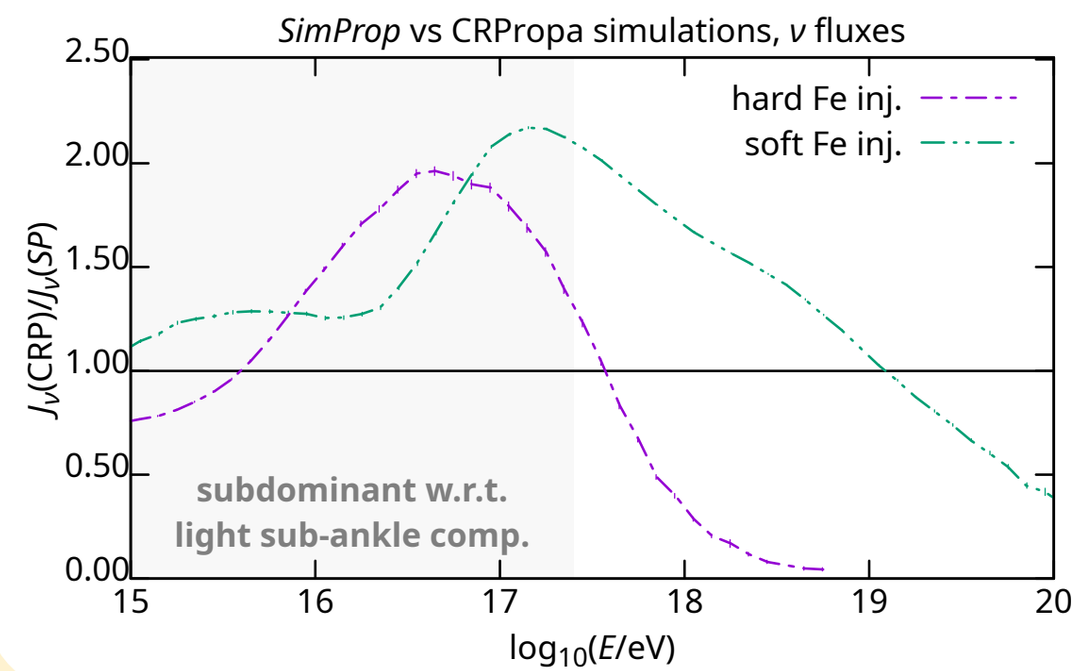
proton





iron





combined fit of the Auger data

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

model	γ	$\log_{10}(R_{\rm cut}/{\rm V})$	D	$D(J)$	$D(X_{\rm max})$
SPG	$+0.96^{+0.08}_{-0.13}$	$18.68^{+0.02}_{-0.04}$	174.3	13.2	161.1
STG	$+0.77^{+0.07}_{-0.13}$	$18.62^{+0.02}_{-0.04}$	175.9	18.8	157.1
SPD	$-1.02^{+0.31}_{-0.26}$	$18.19^{+0.04}_{-0.03}$	187.0	8.4	178.6
CTG	$-1.03^{+0.35}_{-0.30}$	$18.21^{+0.05}_{-0.04}$	189.7	8.3	181.4
	$+0.87^{+0.08}_{-0.06}$	$18.62_{\pm 0.02}$	191.9	29.2	162.7
CTD	$-1.47^{+0.28}_{*}$	$18.15^{+0.03}_{-0.01}$	187.3	8.8	178.5
CGD	$-1.01^{+0.26}_{-0.28}$	$18.21_{\pm 0.03}$	179.5	7.9	171.6

*This interval extends all the way down to -1.5, the lowest value of γ we considered.

model	$f_{\rm H}$	$f_{\rm He}$	$f_{\rm N}$	$f_{\rm Si}$	$\frac{\mathcal{L}_{\rm H}}{\mathcal{L}_0}$	$\frac{\mathcal{L}_{\rm He}}{\mathcal{L}_0}$	$\frac{\mathcal{L}_{\rm N}}{\mathcal{L}_0}$	$\frac{\mathcal{L}_{\rm Si}}{\mathcal{L}_0}$
SPG	0%	67%	28%	5%	0%	33%	50%	17%
STG	0%	7%	85%	8%	0%	1%	81%	17%
SPD	63%	37%	0.6%	0.03%	9%	45%	30%	15%
CTG ($\gamma = -1.03$)	68%	31%	1%	0.06%	7%	26%	50%	18%
CTG ($\gamma = +0.87$)	0%	0%	88%	12%	0%	0%	77%	23%
CTD	45%	52%	3%	0.06%	1%	15%	70%	14%
CGD	90%	5%	4%	0.09%	5%	2%	79%	14%

C: CRPropa
S: SimProp

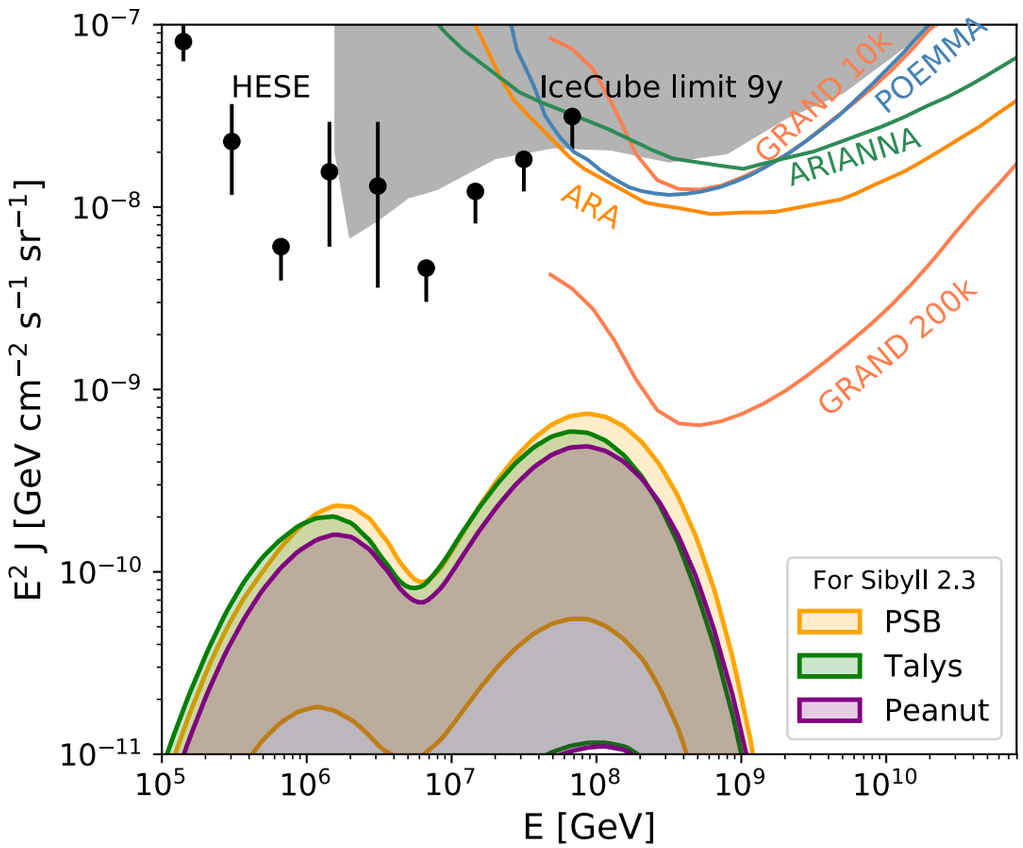
G: EBL Gilmore et al. 2012
D: EBL Domínguez et al. 2011

P: PSB photodisintegration
T: TALYS 1.6 photodisintegration

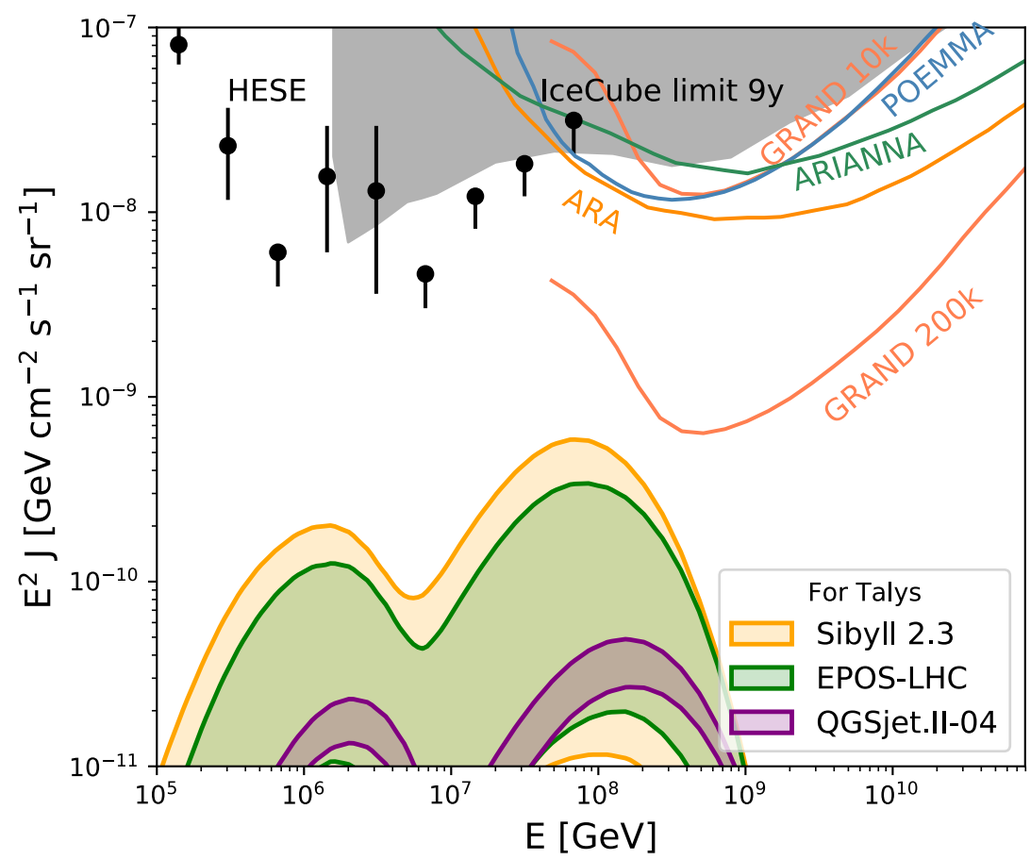
including more uncertainties...

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

photodisintegration models

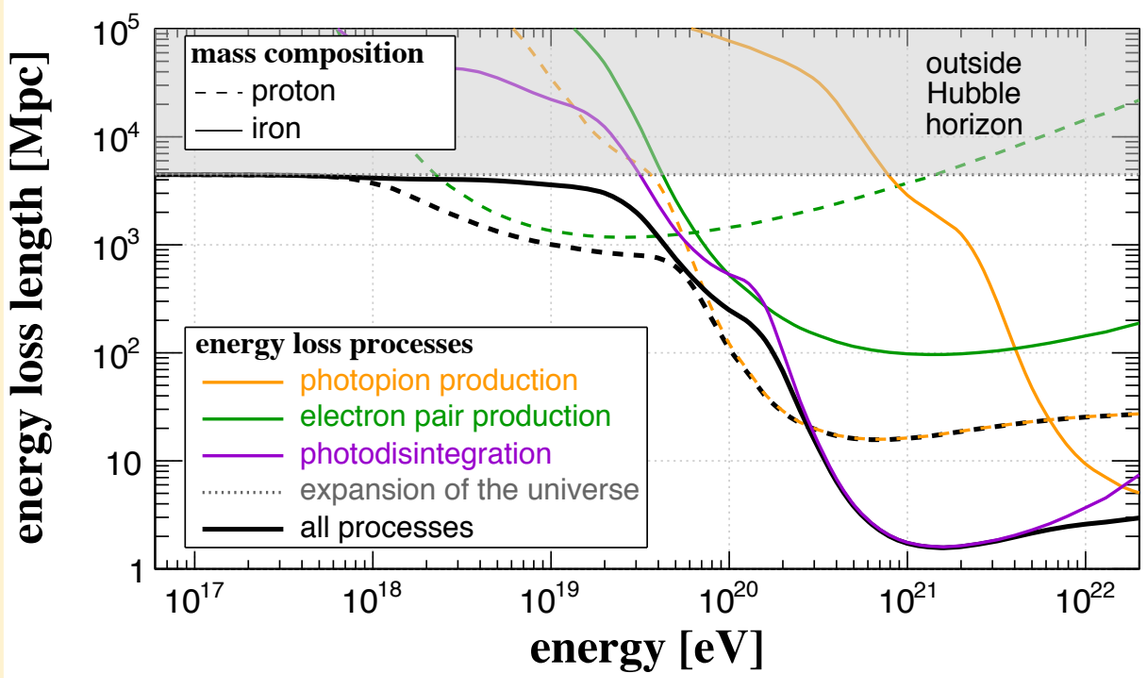


hadronic interaction models



cosmogenic neutrinos & proton fraction

interaction rates



- protons tend to produce more neutrinos than heavier nuclei

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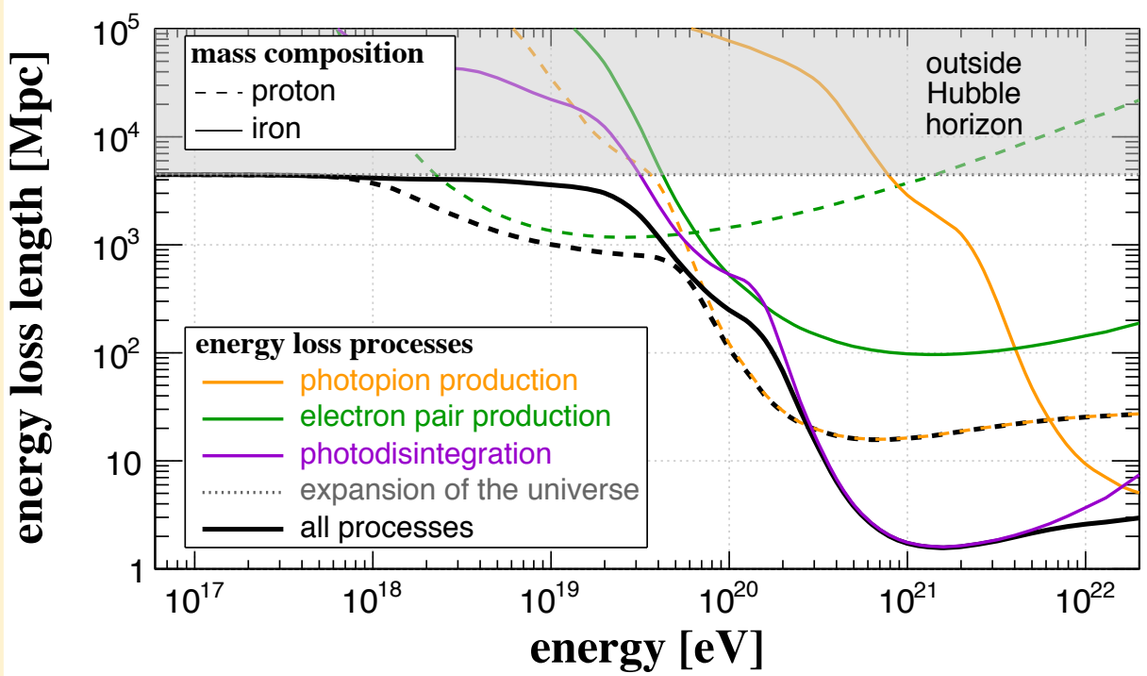

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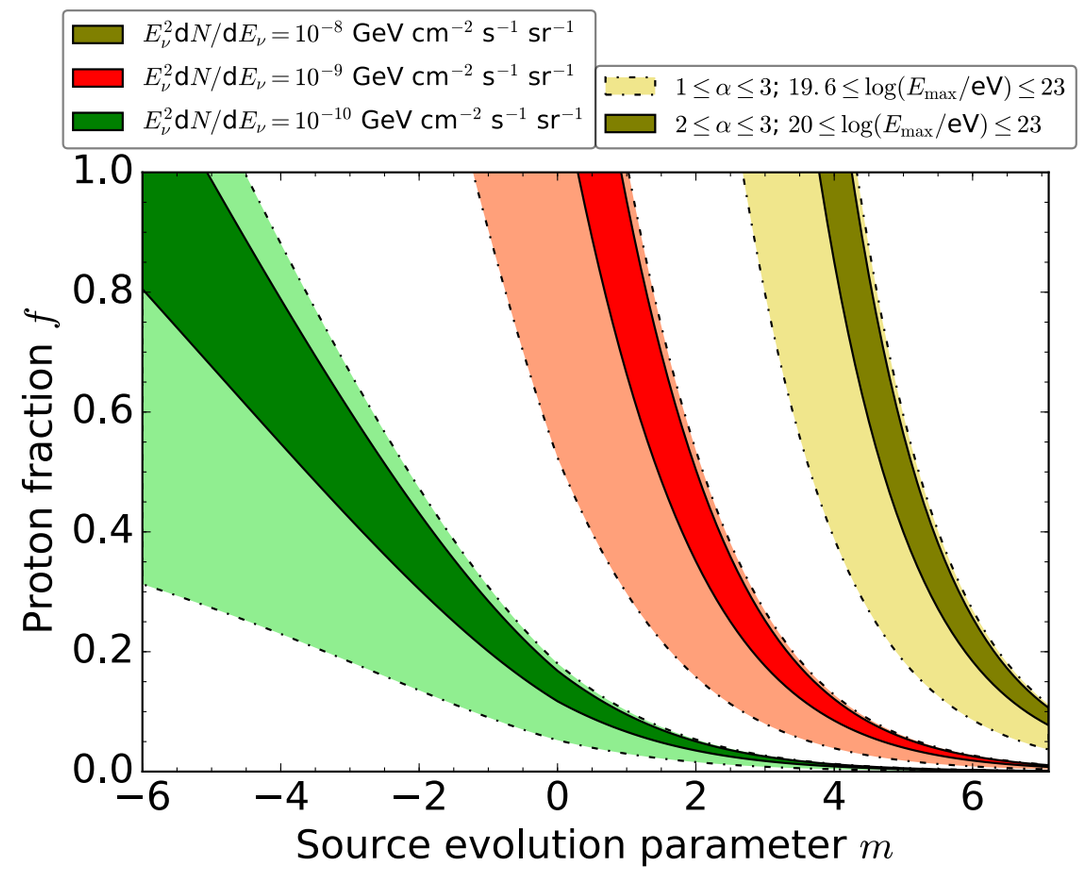
proton fraction

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



- we can use cosmogenic neutrinos to constrain the proton fraction at ultra-high energies!

what about magnetic fields?

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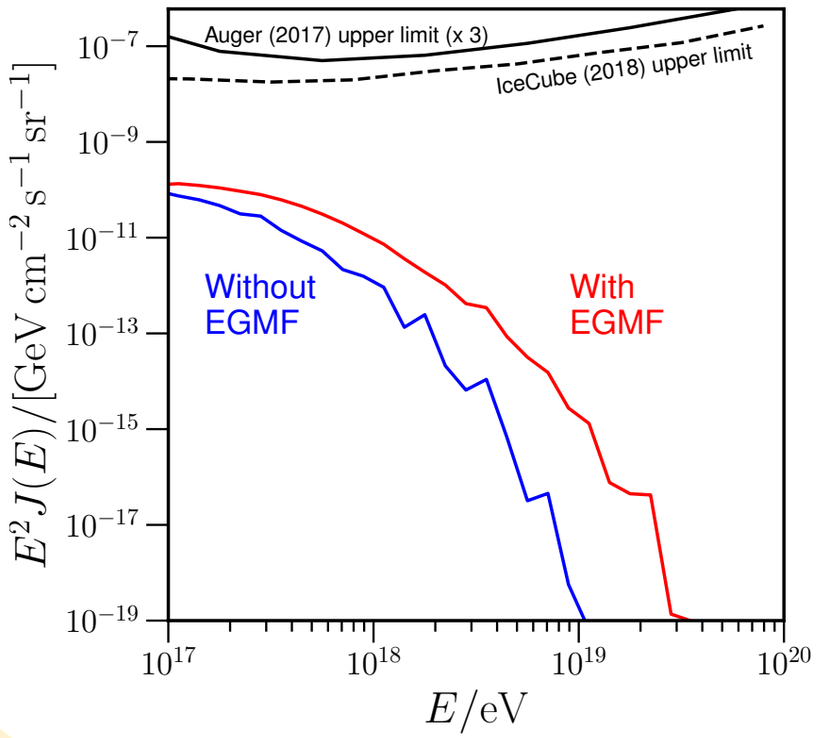
Wittkowski & Kampert. MNRAS 489 (2019) L118. arXiv:1810.03769



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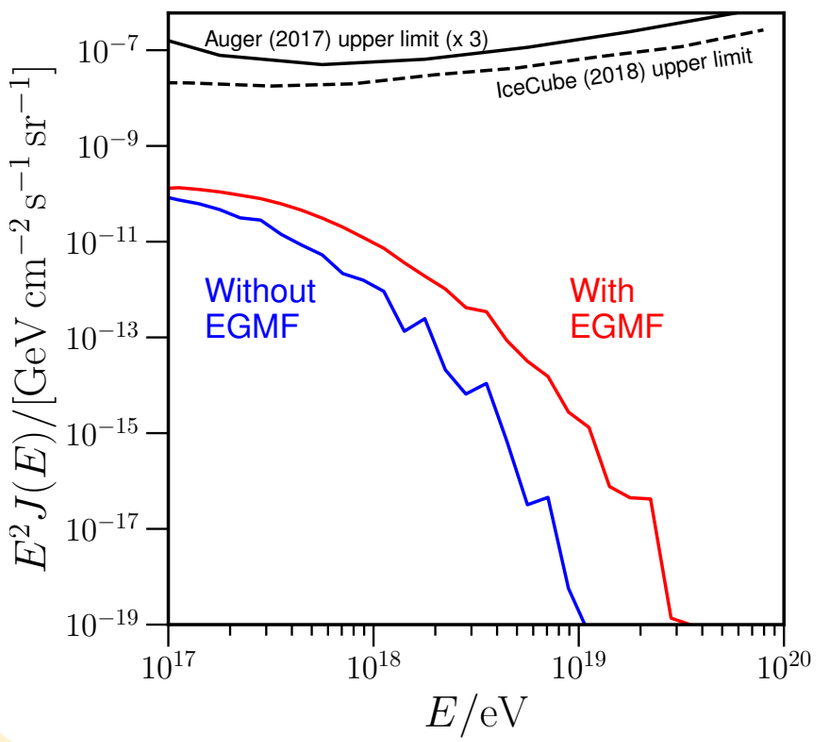

- cosmogenic neutrino fluxes *may* increase in the presence of magnetic fields
- fits *may* soften when EGMFs are included
- source distribution or magnetic fields? (both?!)
- EGMFs are very poorly known

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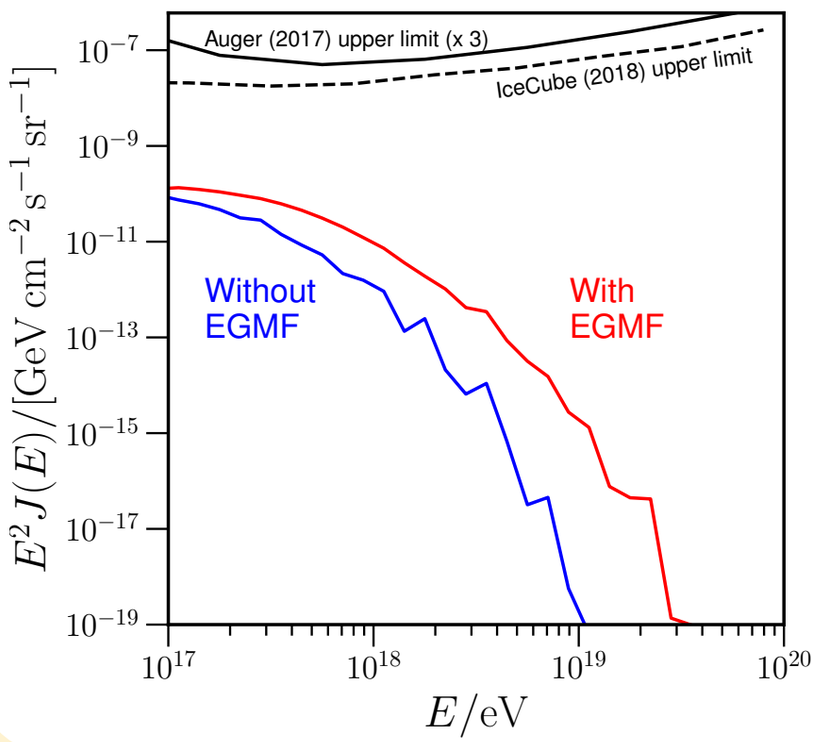

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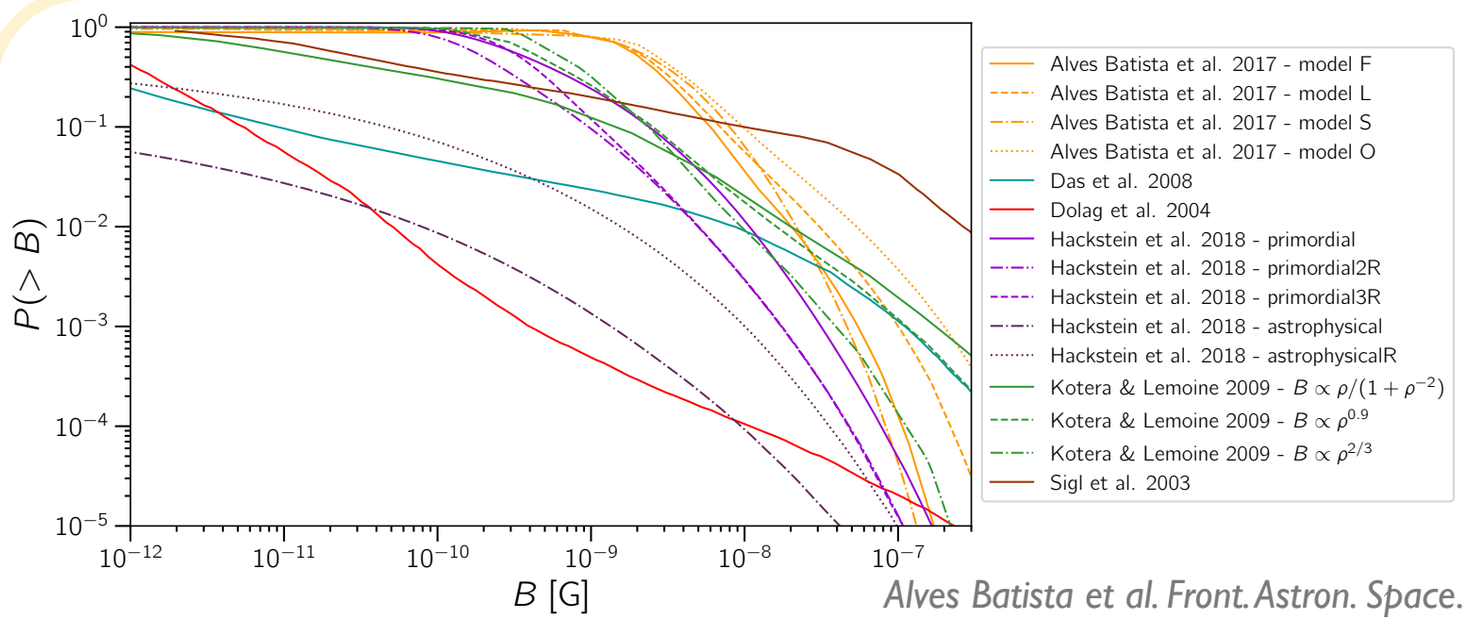

Alves Batista et al. Front. Astron. Space. Sci. 6 (2019) 23. arXiv:1903.06714

where do we stand?

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- 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

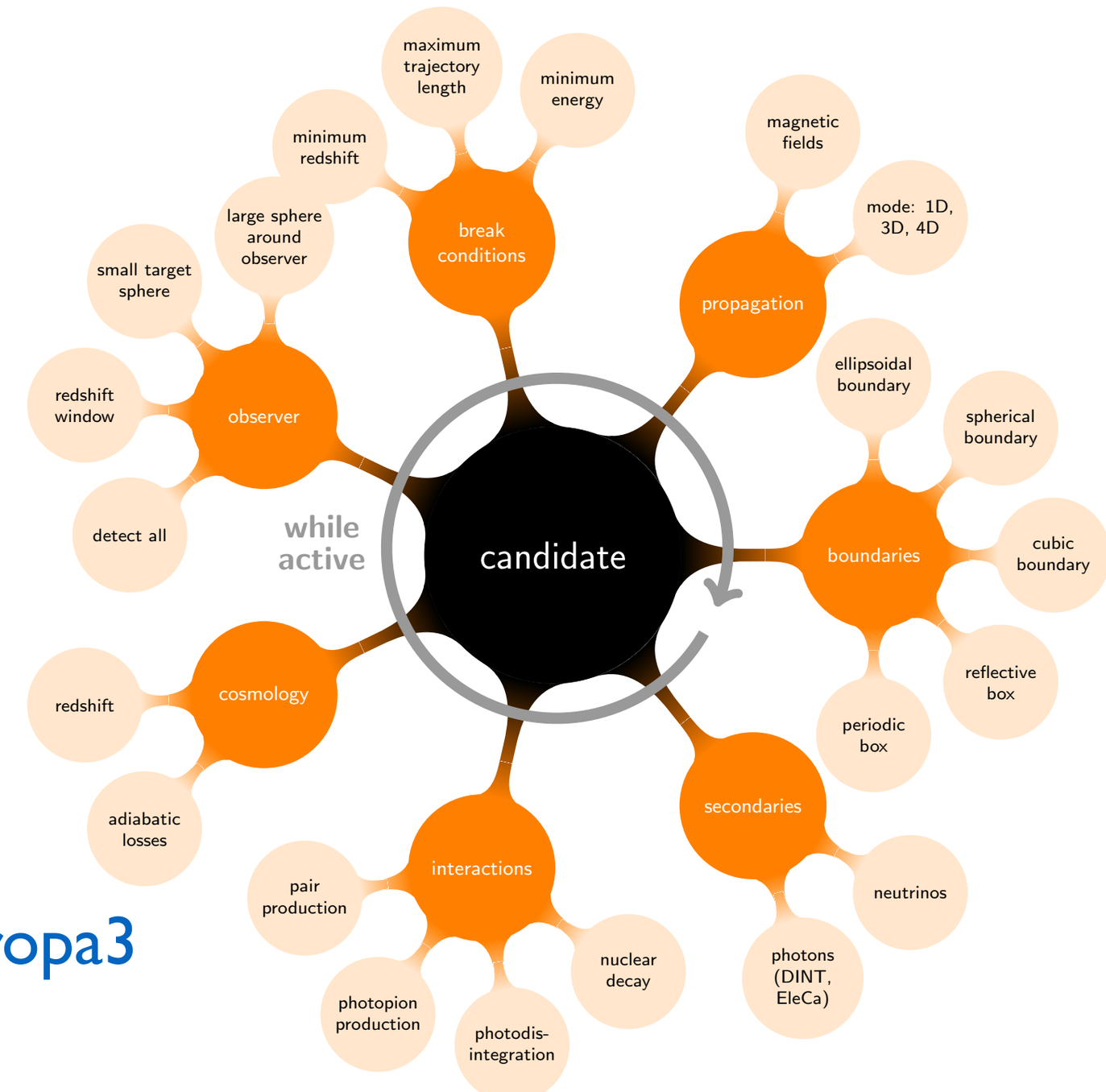
back-up slides

modelling the propagation of UHECRs: CRPropa

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

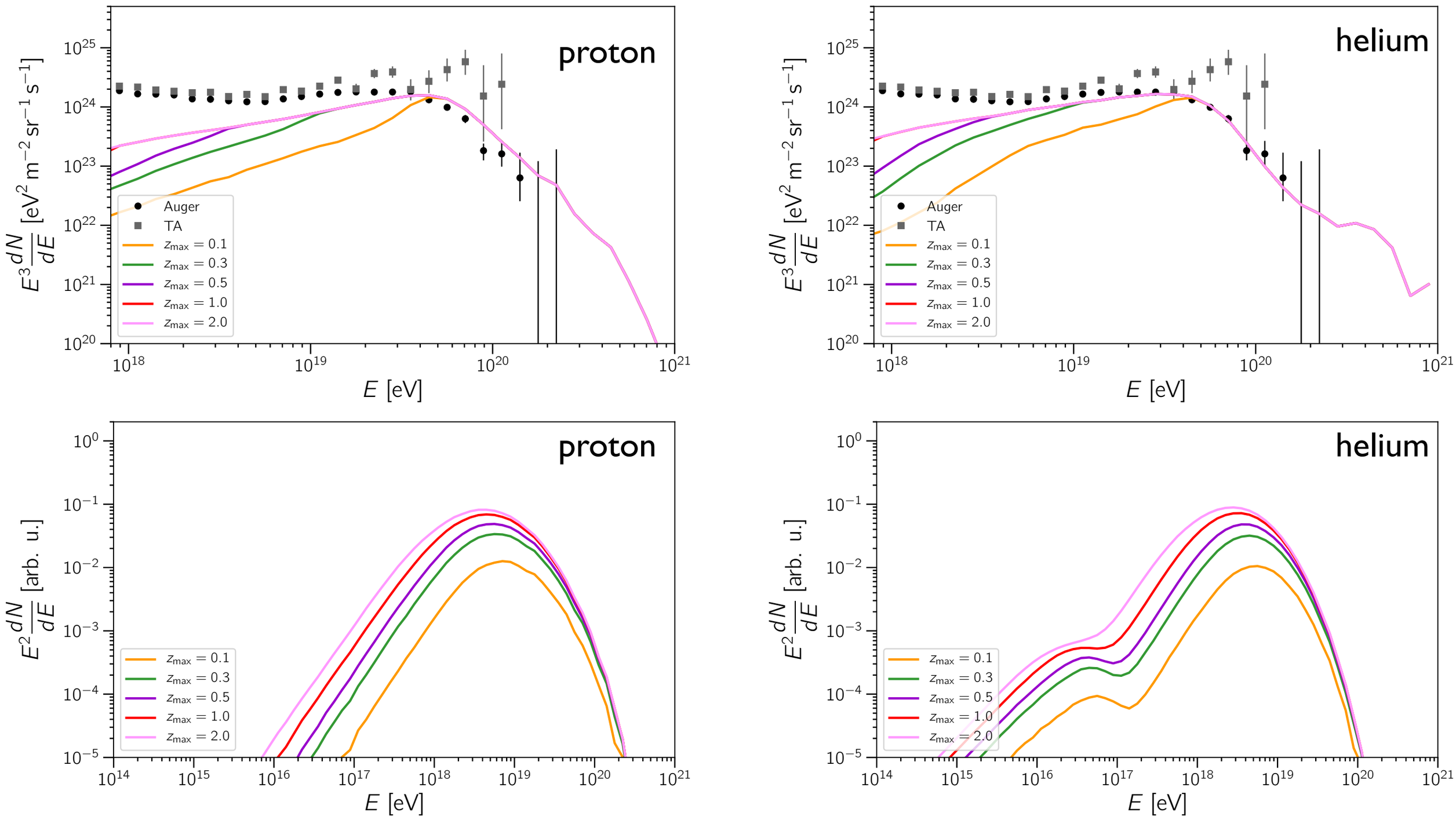
- publicly available Monte Carlo code for propagating UHECRs and their secondaries in the intergalactic space
- modular structure
- parallelisation with OpenMP
- 1D, 3D and "4D" simulations
- relevant energy losses implemented
- variety of tools to handle custom magnetic field models
- predict spectrum, composition, and anisotropies simultaneously
- several models of EBL available
- possible to compute secondary **gamma** and **neutrino** fluxes

https://github.com/CRPropa/CRPropa3



maximum redshift

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

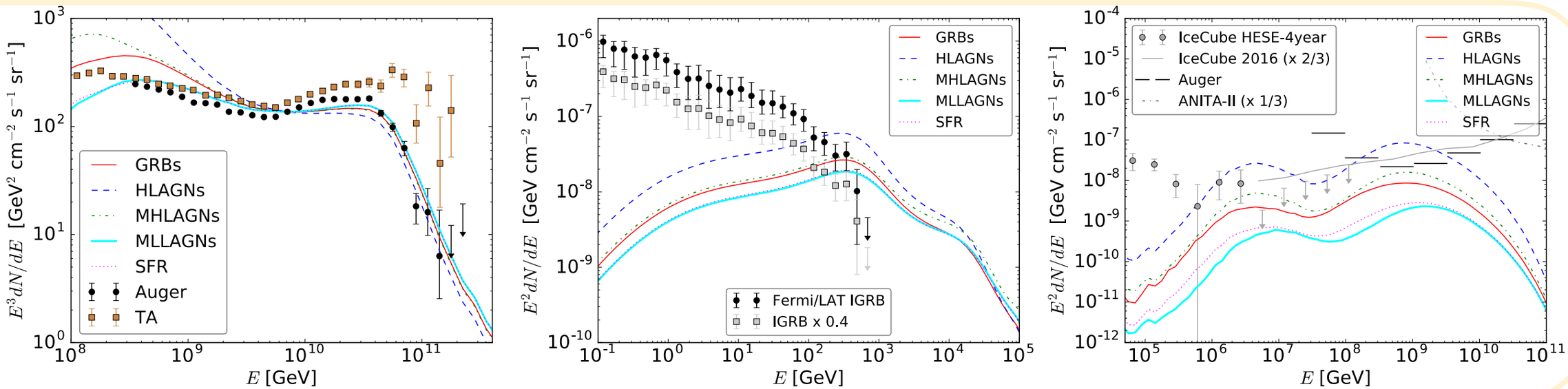


UHECR constraints with cosmogenics

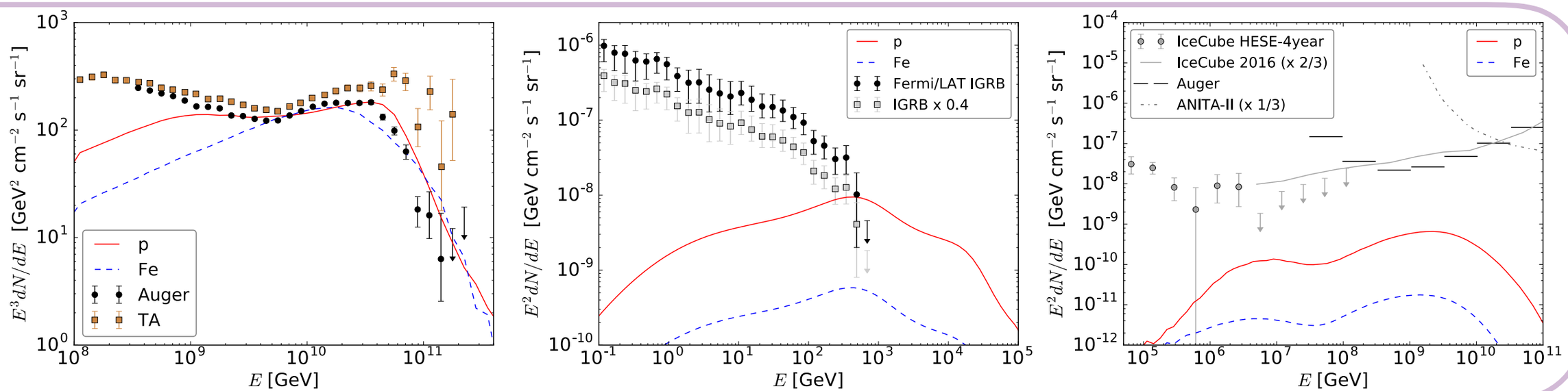
van Vliet, Hörandel, Alves Batista. Proc. of Science (ICRC2017) 562. arXiv: 17017.04511

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

theoretical uncertainties in the modelling

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

main sources of uncertainties

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

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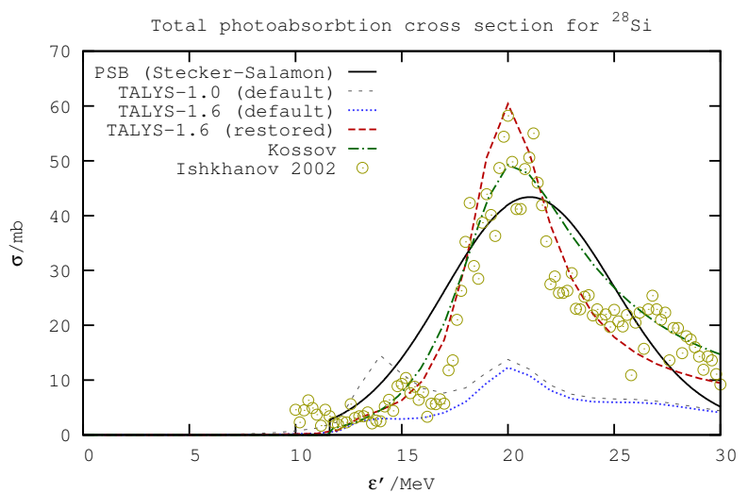

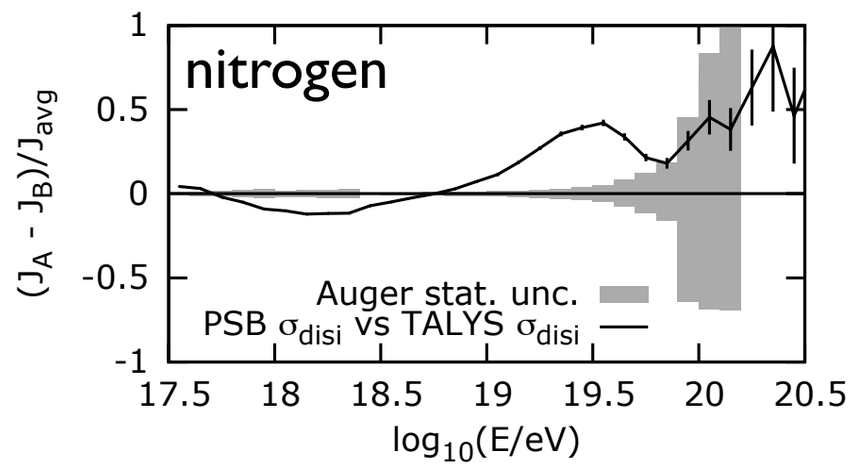

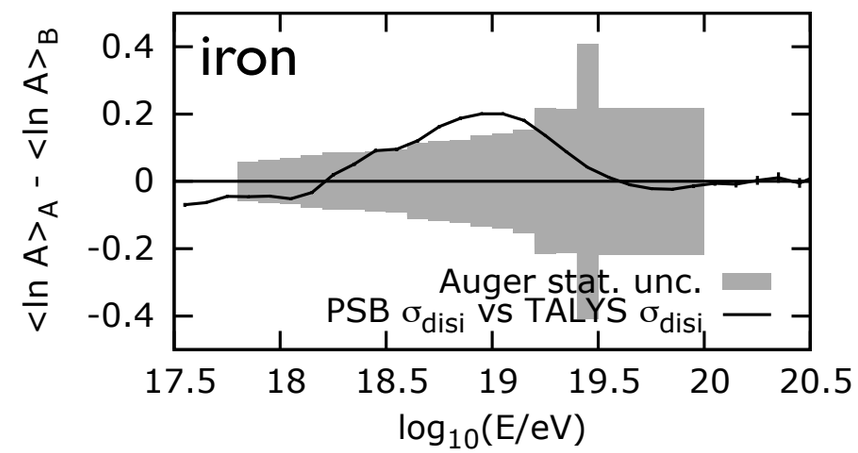

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