Determining the fraction of protons in UHECRs with cosmogenic neutrinos

Image: Pierre Auger Observatory

Arjen van Vliet
Rafael Alves Batista
Jörg Hörandel

Madison, 25/07/2019

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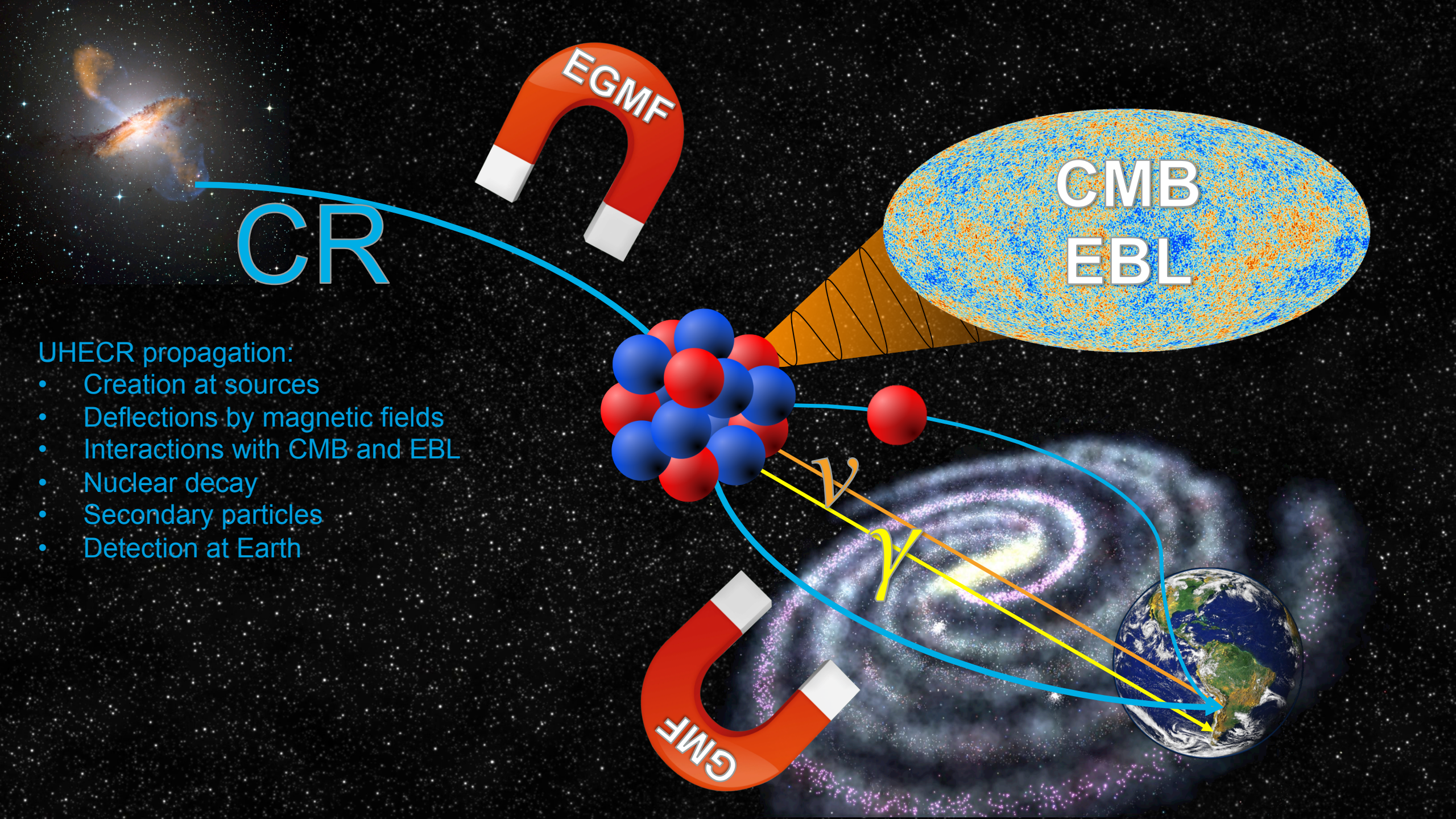


UHECR propagation:

- Creation at sources
- Deflections by magnetic fields
- Interactions with CMB and EBL
- Nuclear decay
- Secondary particles
- Detection at Earth

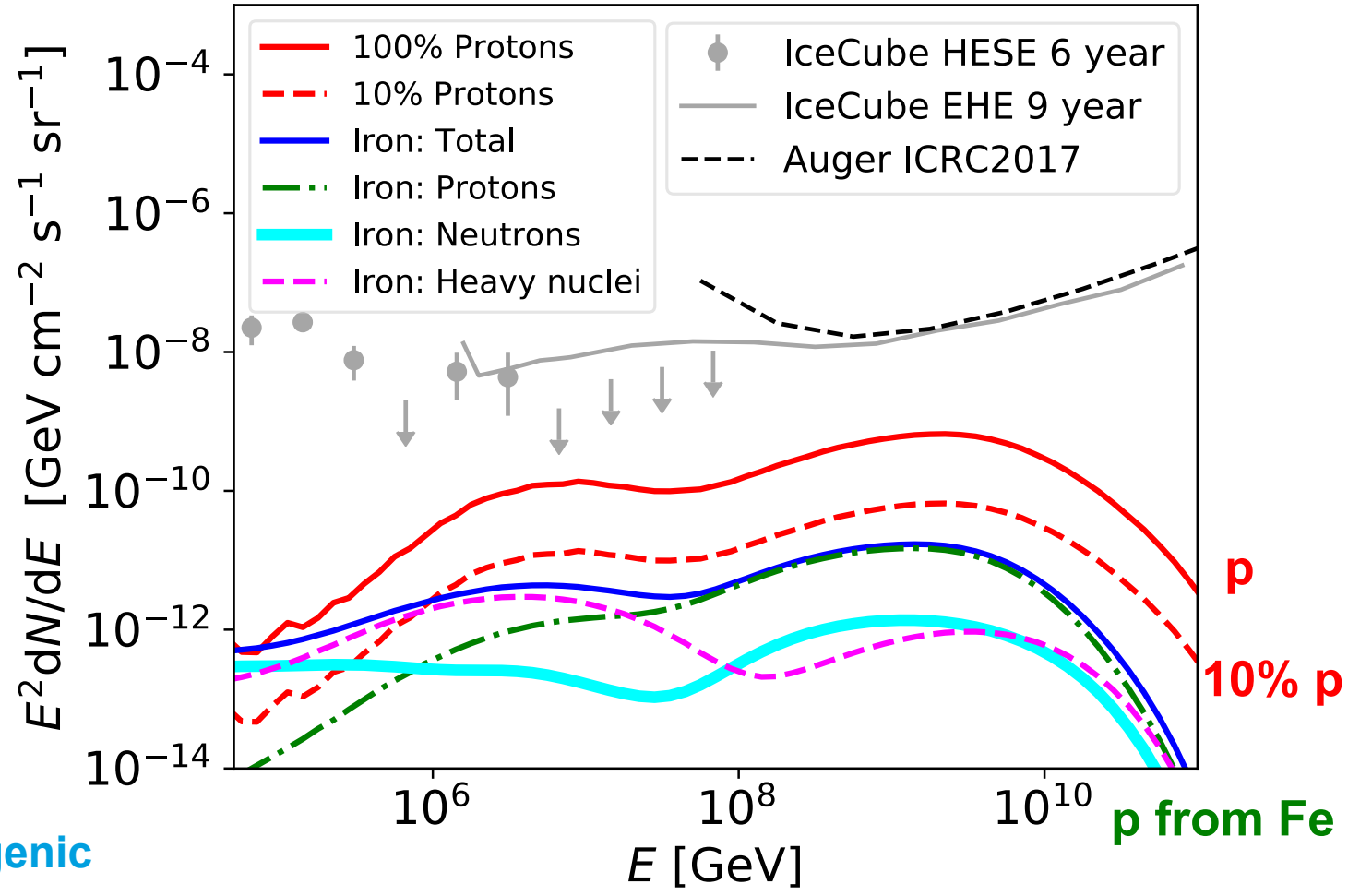
Cosmogenic neutrinos; protons vs. iron

- Continuous distribution of identical sources
- Spectrum at the sources:

  Power law with rigidity-dependent cut-off

  $$\frac{\mathrm{d}N}{\mathrm{d}E} \propto E^{-\alpha} \exp(-E / ZR_{\mathrm{max}})$$
- $\alpha = 2.5$
- $R_{\mathrm{max}} = 200$ EV
- Composition at the sources:

  Pure proton vs. pure iron
- Comoving source evolution
- EBL: Gilmore *et al*. 2012
- **Protons especially important for cosmogenic neutrino production**



Combined fit

- Continuous distribution of identical sources
- Spectrum at the sources:

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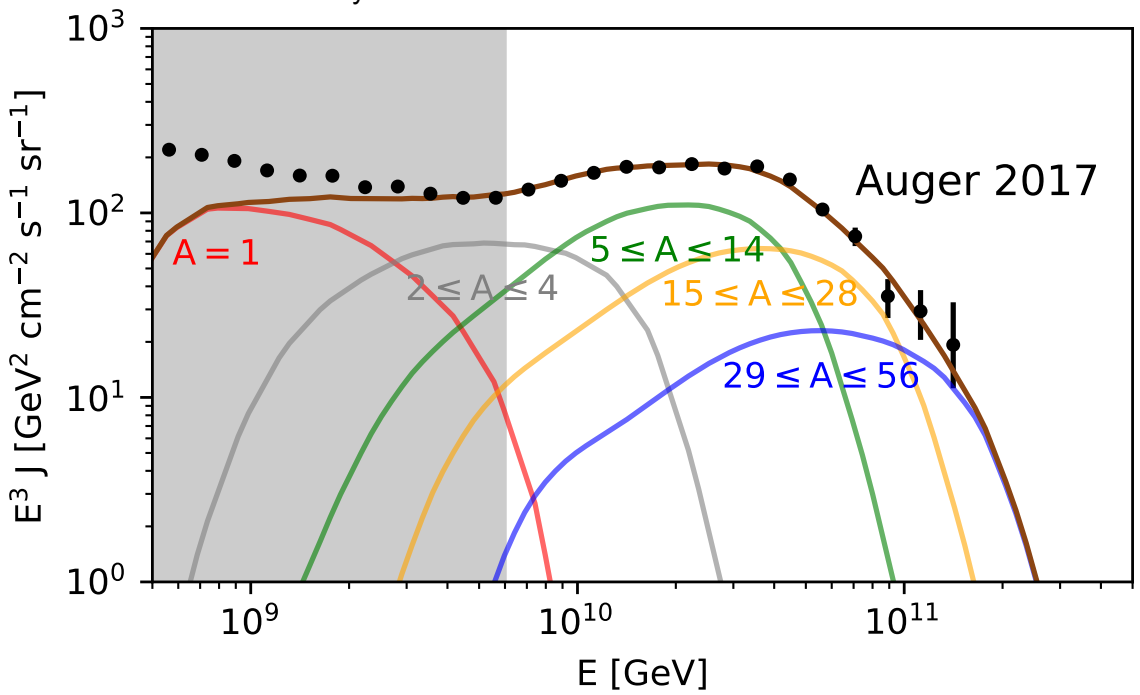
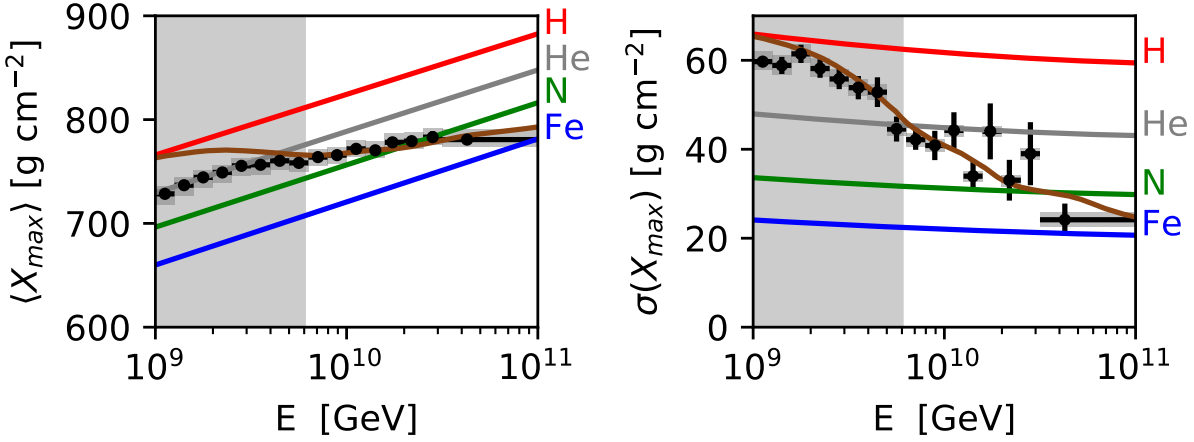
  $$\frac{\mathrm{d}N}{\mathrm{d}E} \propto E^{-\alpha} \exp(-E / ZR_{\mathrm{max}})$$
- $\alpha < 1.3$, hard spectral index
- $R_{\mathrm{max}} < 7$ EV, low max. rigidity
- Composition at the sources:

  Intermediate to heavy ($Z > 5$)
- **No protons at highest *E***

See also: Taylor *et al*. (2015), Auger (2017), Romero-Wolf and Ave (2018), Alves-Batista *et al*. (2019), etc.

Presentation: CRI10a by Anatoli Fedynitch
Monday at 16:30





J. Heinze, A. Fedynitch, D. Boncioli and W. Winter, Astrophys. J. 873 (2019) 88

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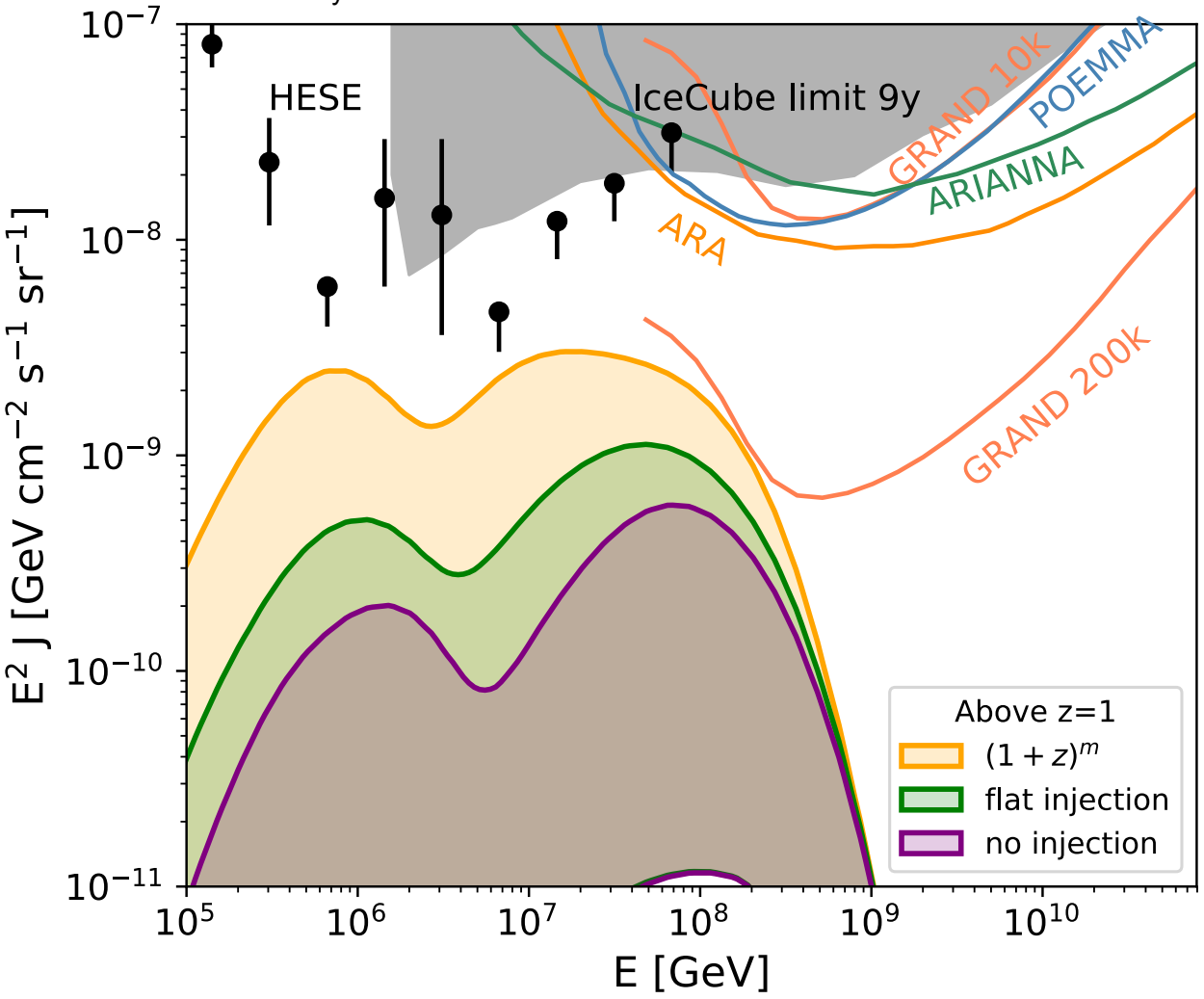

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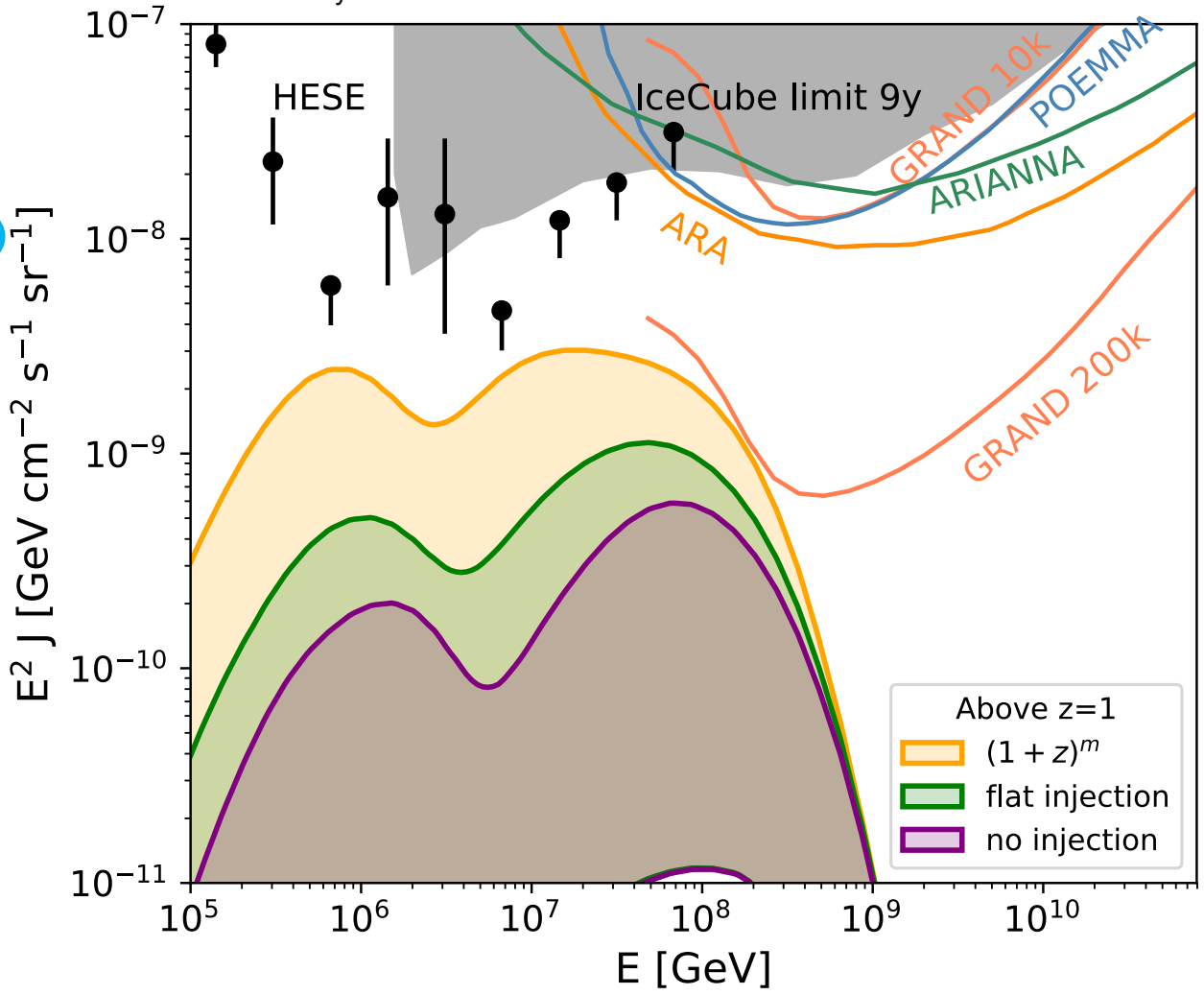
- **Additional proton component can improve fit**

M. S. Muzio, M. Unger and G. R. Farrar, arXiv:1906.06233
See also: CRI10d by Marco Muzio; Monday at 17:15

See also: CRI10a by Anatoli Fedynitch
Monday at 16:30



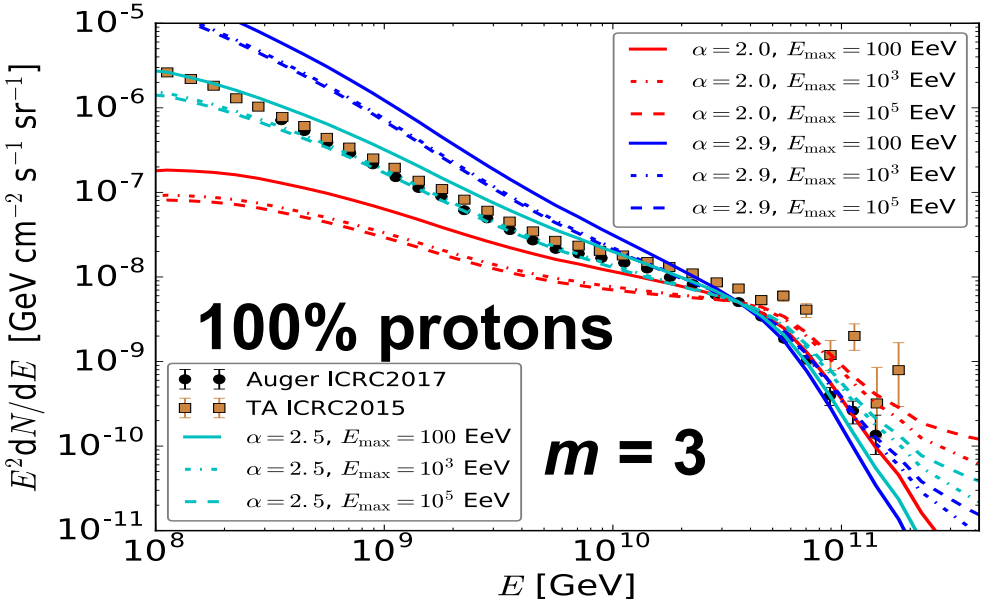
J. Heinze, A. Fedynitch, D. Boncioli and W. Winter,
Astrophys. J. 873 (2019) 88

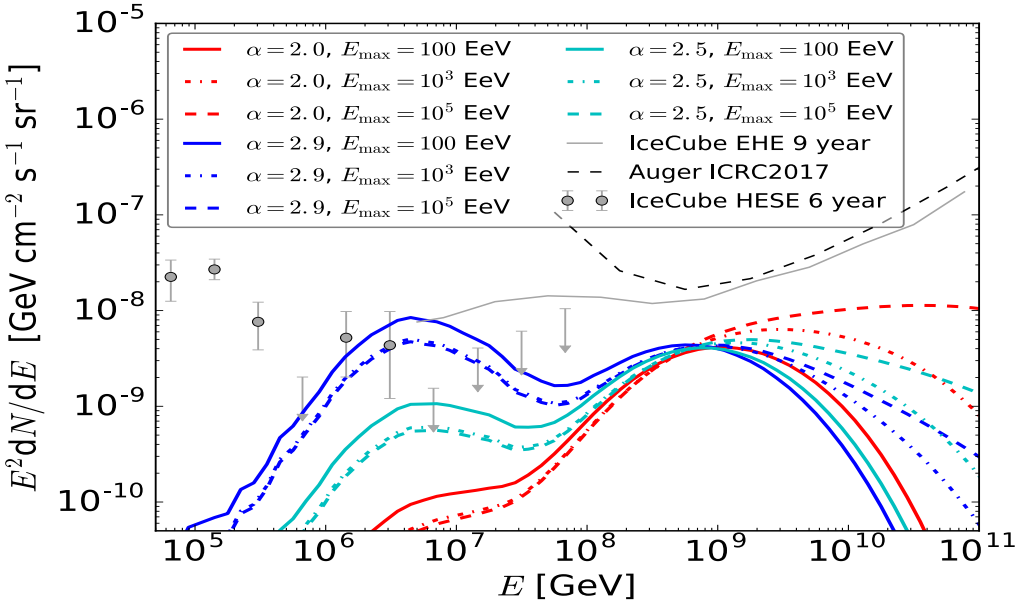
Neutrinos at ~1 EeV

- Cosmogenic neutrino flux depends on:
  - Spectral index α
  - Max. rigidity R_{max}
  - EBL model
  - Composition (proton fraction at Earth, f)
  - Source evolution
- Sweet spot at ~1 EeV, only depends on:
  - Composition (proton fraction)
  - Source evolution (z_{max} = 4)

$$SE = \begin{cases} (1+z)^m & \text{for } m \leq 0 \\ (1+z)^m & \text{for } m > 0 \text{ and } z < 1.5 \\ 2.5^m & \text{for } m > 0 \text{ and } z \geq 1.5 \end{cases}$$

A. van Vliet, J. R. Hörandel and R. Alves Batista, PRD 100 (2019) 021302(R)





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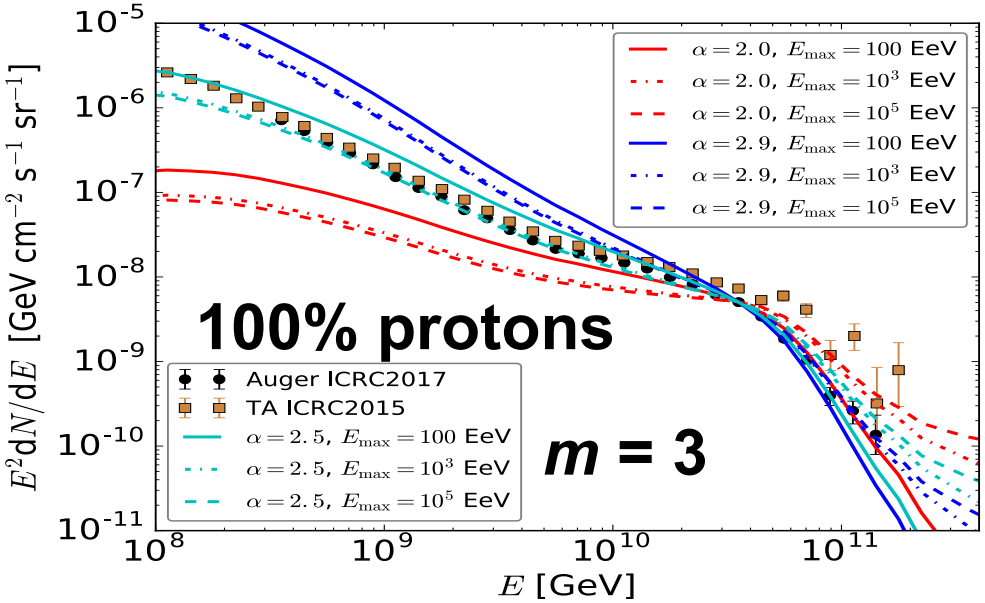
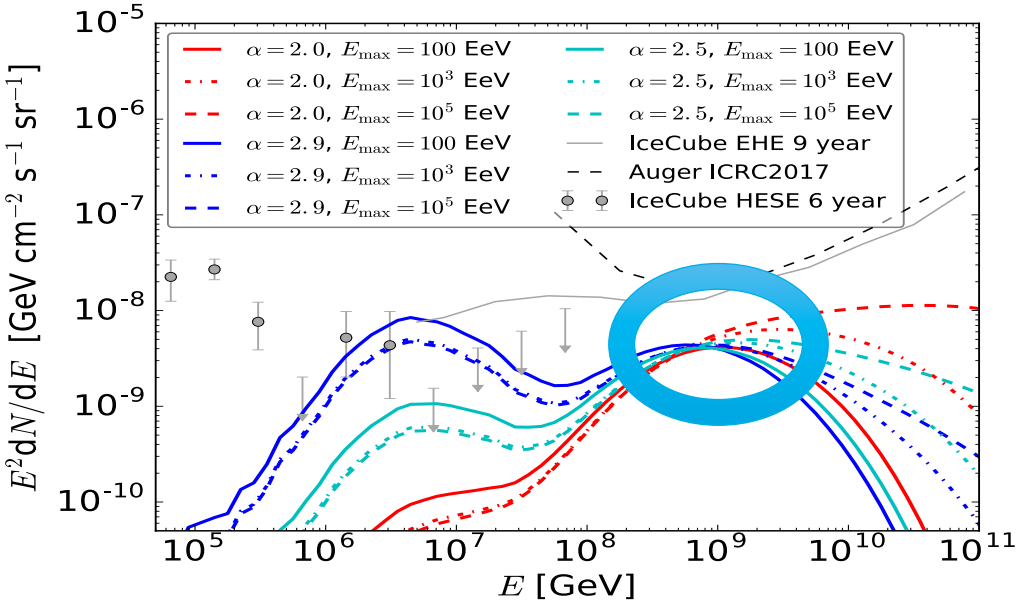
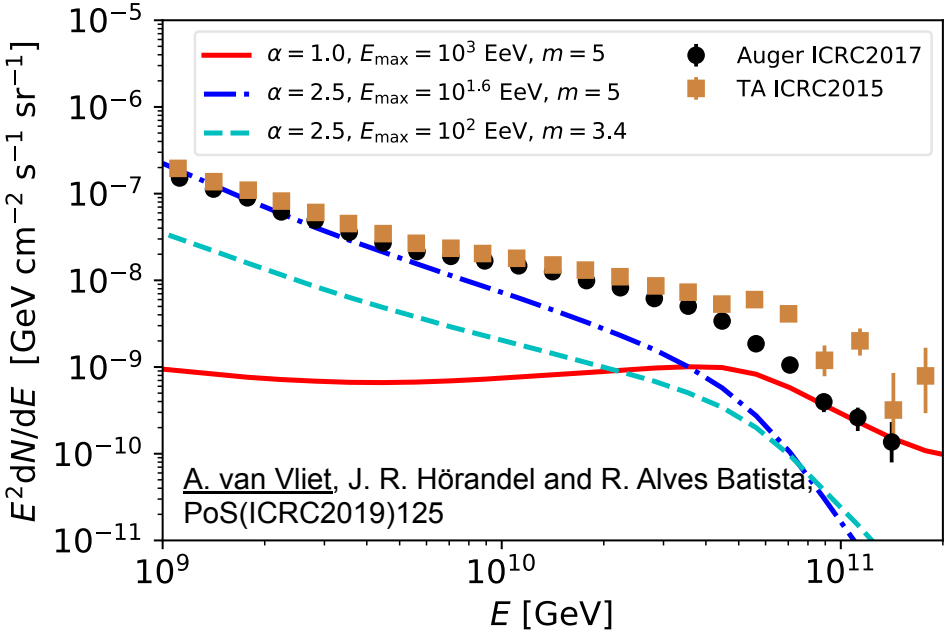


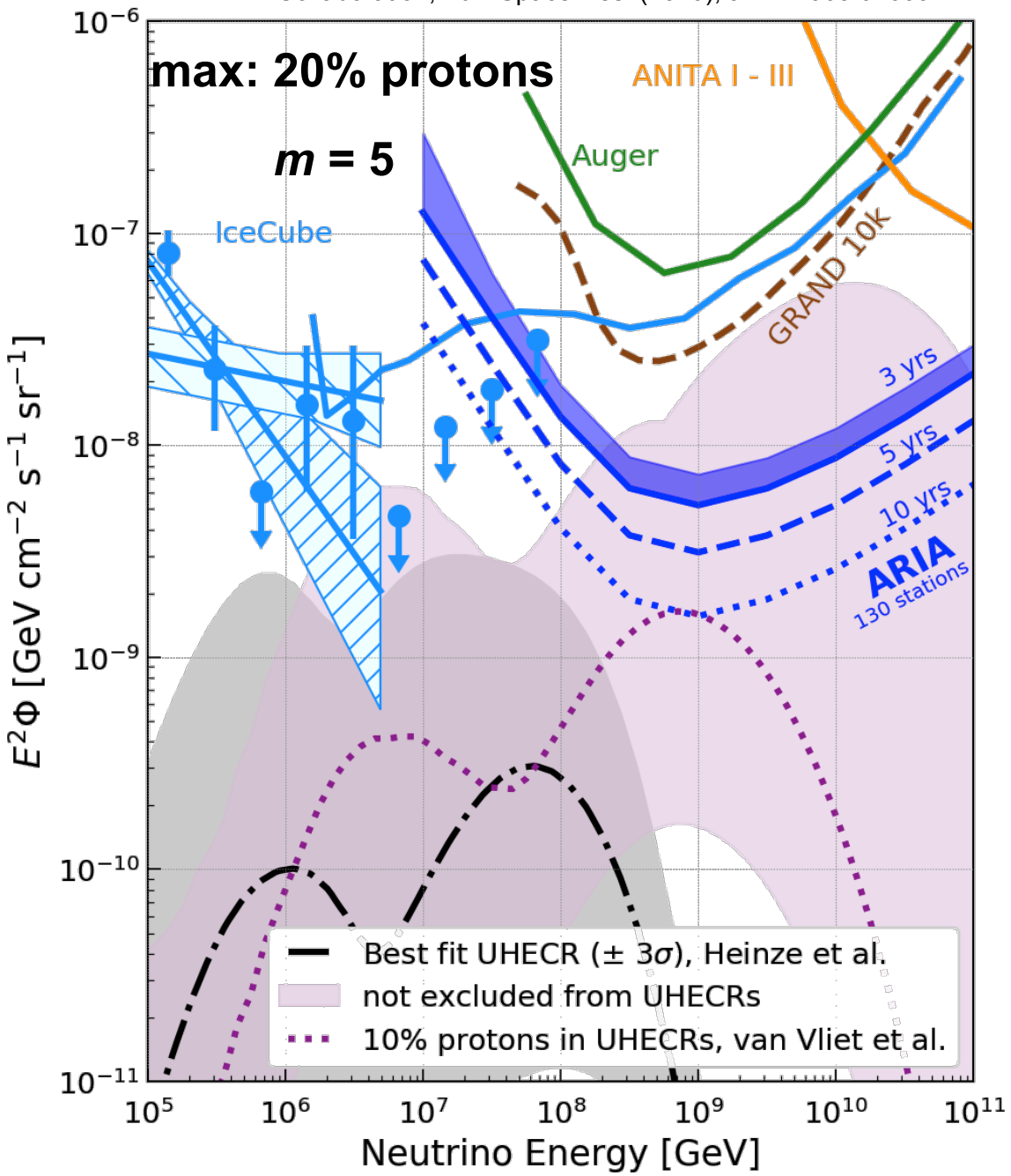


Neutrinos from subdominant proton component

- Cosmogenic neutrino flux for:
  - $1.0 < \alpha < 2.5$
  - $10^{1.6} < E_{max} < 10^3$ EeV
  - EBL model: Franceschini '08
  - proton fraction $f < 0.2$ at $10^{1.6}$ EeV
  - $m < 5$



ARIANNA Collaboration, Adv. Space Res. (2019), arXiv:1903.01609

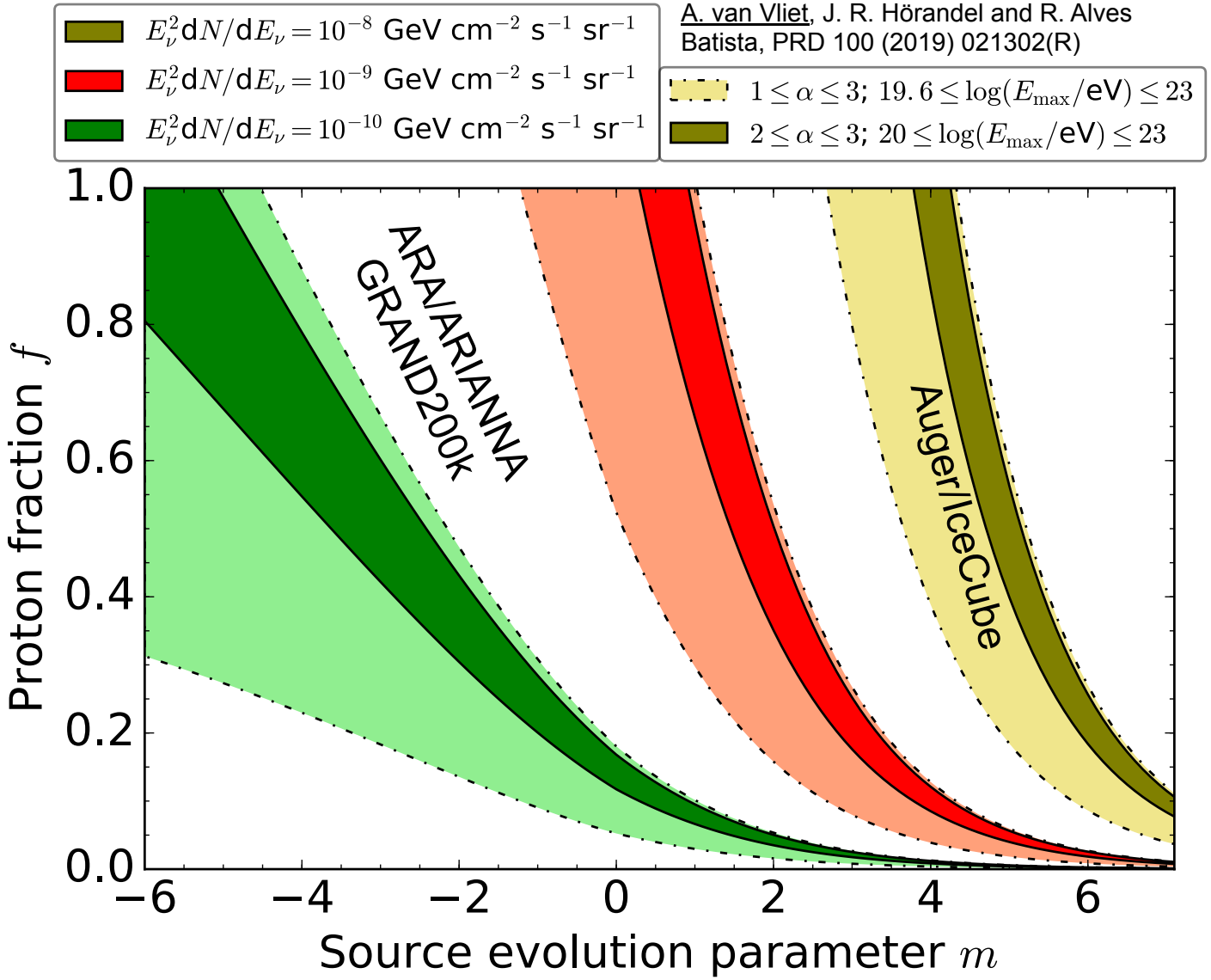


Proton fraction vs. source evolution

- Single-flavour neutrino flux at ~1 EeV
- Auger and IceCube are both close to ~10^{-8} GeV cm^{-2} s^{-1} sr^{-1}
- Top-right part of parameter space already constrained
- Combination of a large proton fraction and strong source evolution ruled out

See also: Pierre Auger Collaboration, arXiv:1906.07422
NU4e by Francisco Pedreira; Friday at 17:30

A. van Vliet, J. R. Hörandel and R. Alves Batista, PRD 100 (2019) 021302(R)



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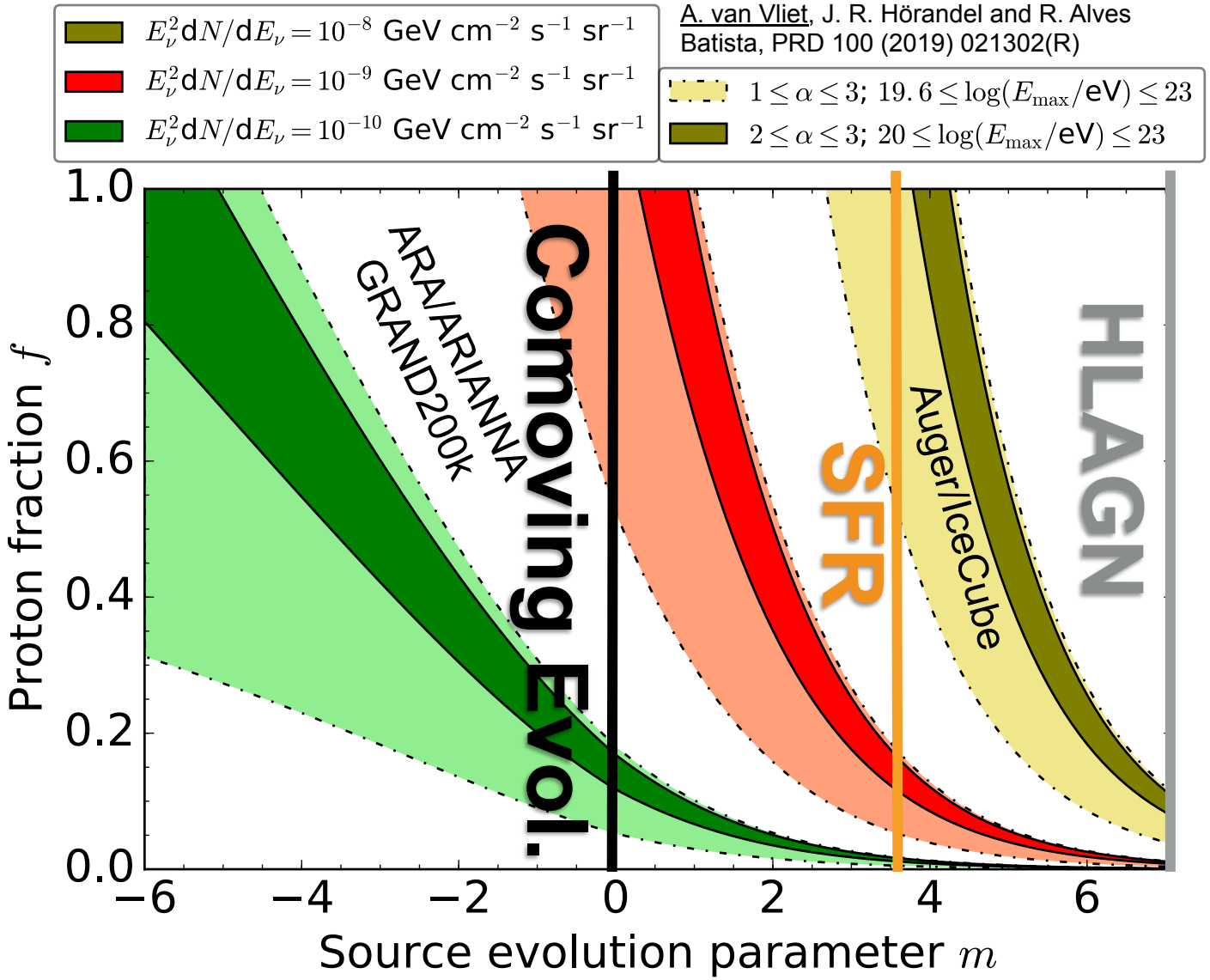

Conclusions

- Neutrino limits at ~1 EeV are able to constrain the proton fraction and source evolution of UHECR sources
- The combination of a large proton fraction and a strong source evolution is already ruled out
- Strong potential for upcoming experiments, to detect cosmogenic neutrinos and to further constrain the parameter space
- Determine proton fraction in UHECRs independent of hadronic interaction models

Backup slides

Current sensitivity

- Single-flavour neutrino flux at ~1 EeV
- Auger and IceCube are both close to

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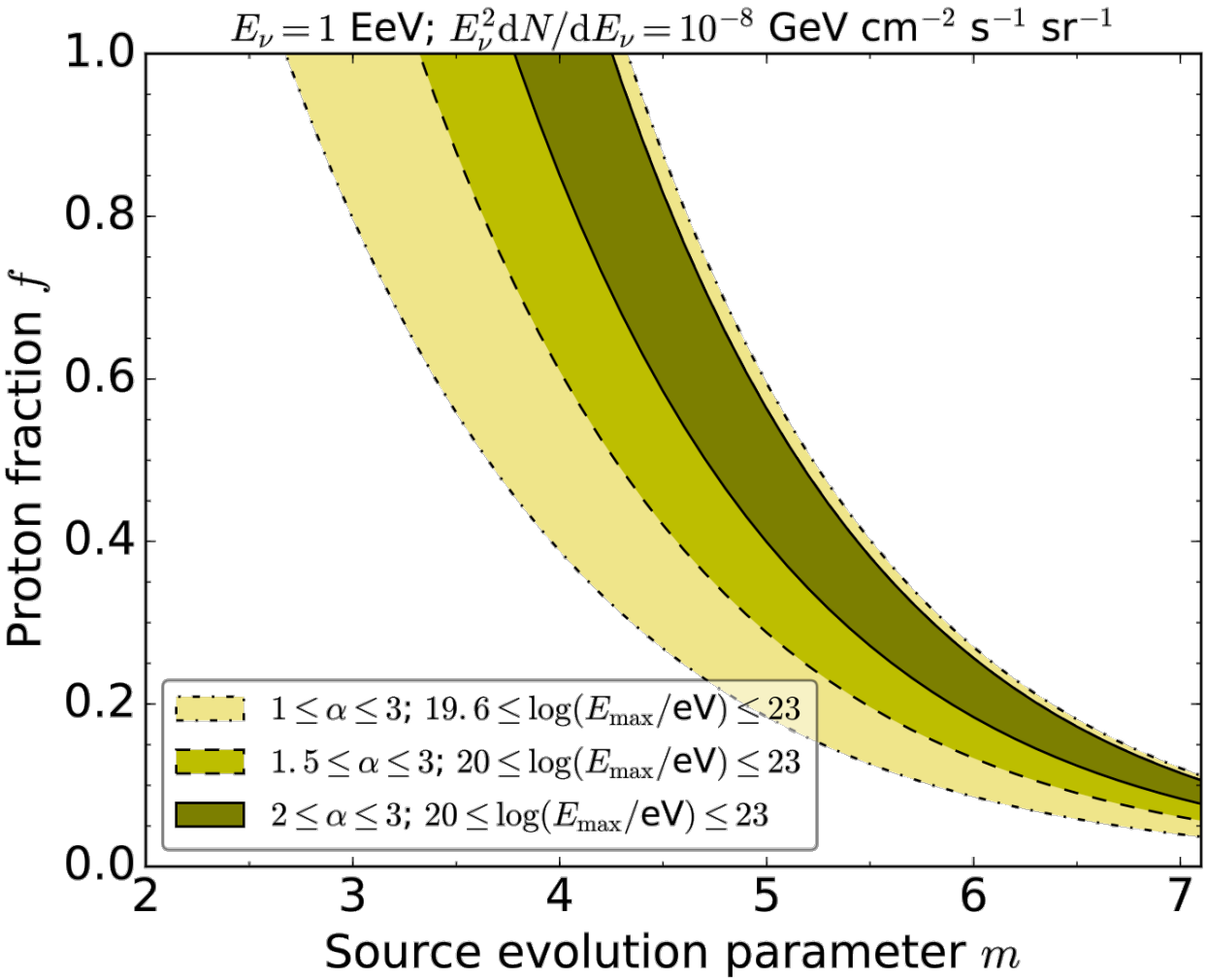

A. van Vliet, J. R. Hörandel and R. Alves Batista, PoS(ICRC2019)125

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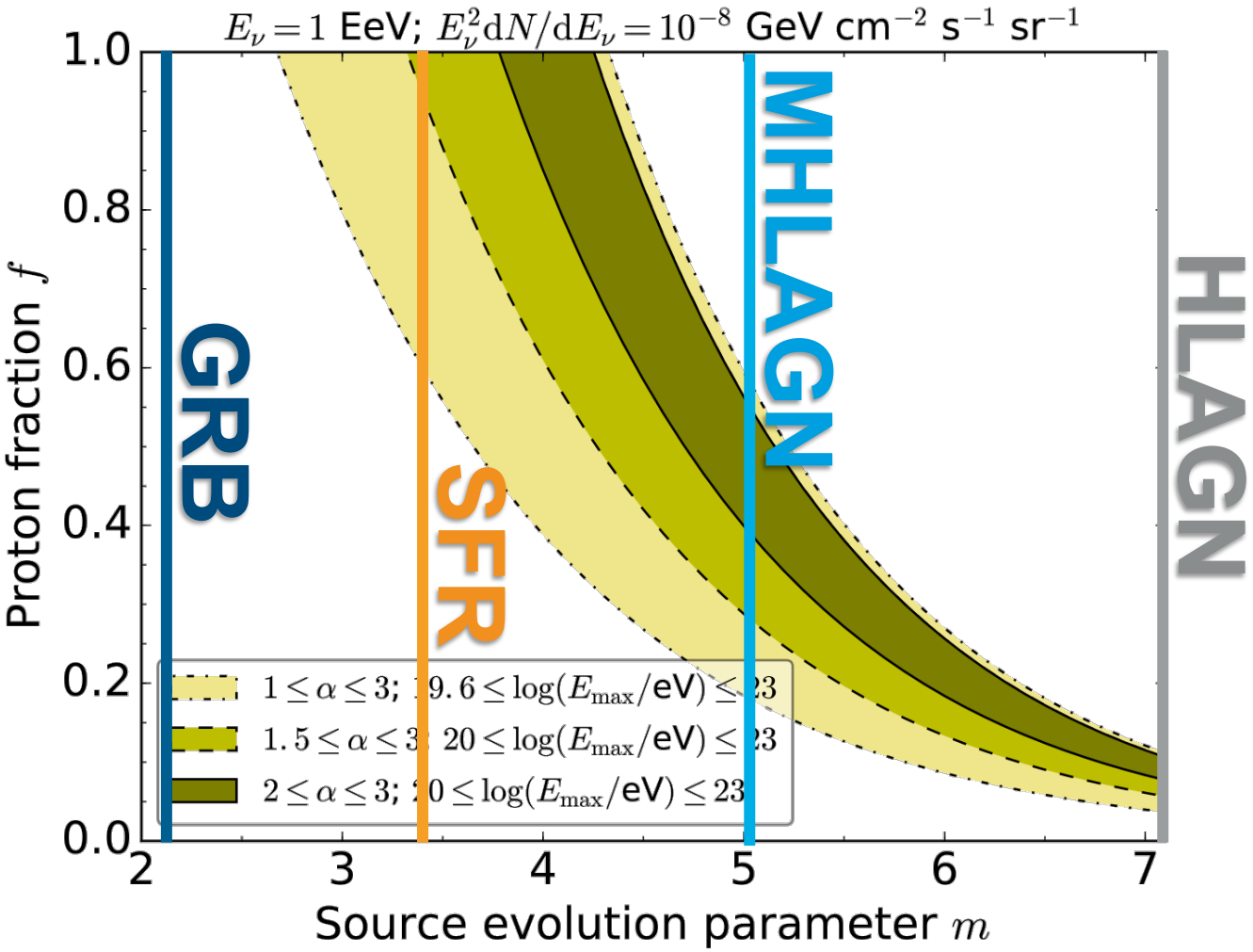


A. van Vliet, J. R. Hörandel and R. Alves Batista, PoS(ICRC2019)125

CRPropa 3.2 - Overview

R. Alves Batista, J. Becker Tjus, A. Dundovic, M. Erdmann, C. Heiter, K.-H. Kampert, L. Merten, G. Müller, A. Saveliev, G. Sigl, A. van Vliet, D. Walz and T. Winchen, in preparation

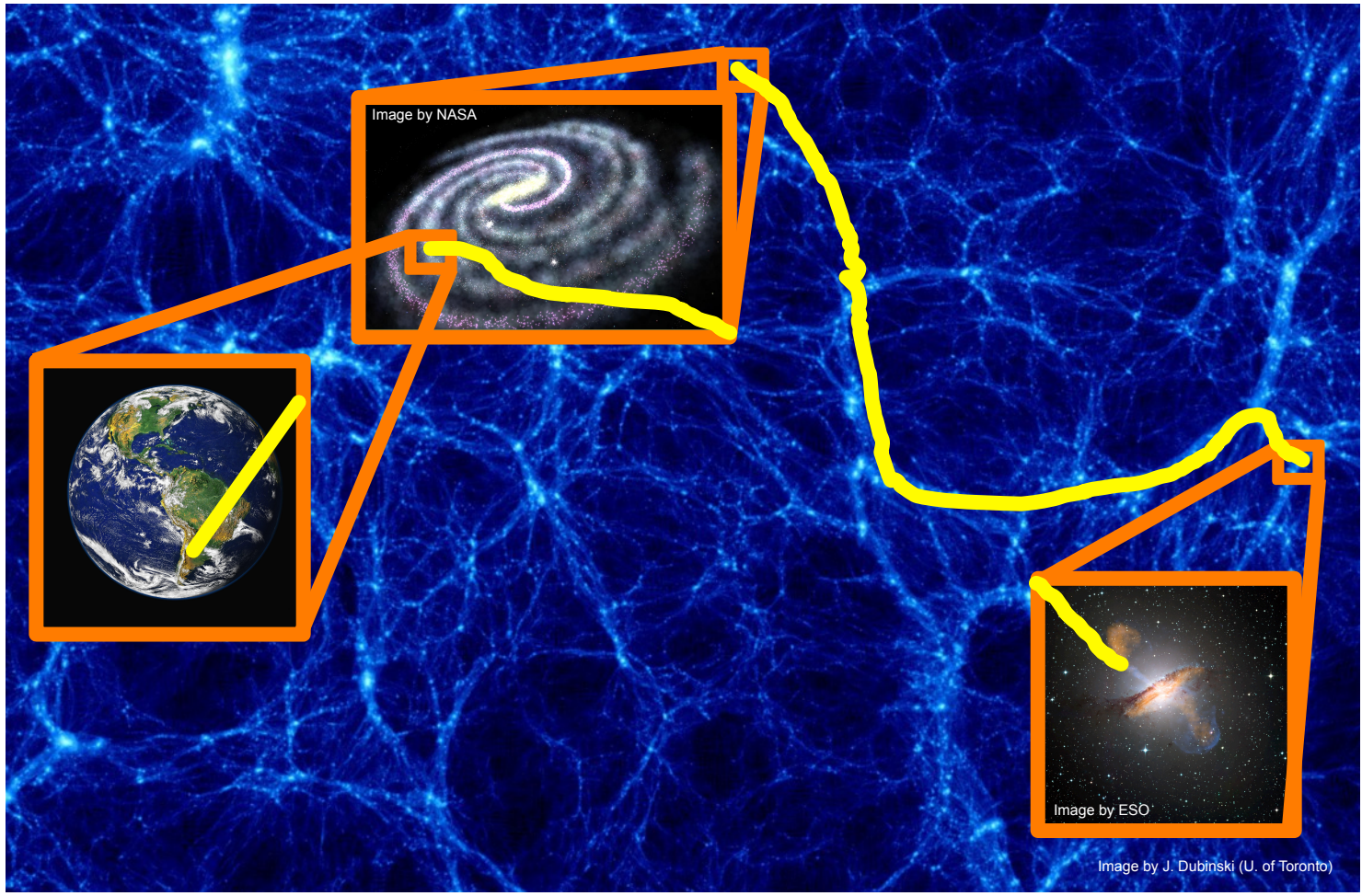
Open-source astroparticle simulation framework from TeV to ZeV energies for:

- Extragalactic propagation
- Galactic propagation
- Acceleration (new in 3.2)

of

- Cosmic rays
- Electromagnetic cascades ($E \geq$ GeV)
- Neutrinos

crpropa.desy.de



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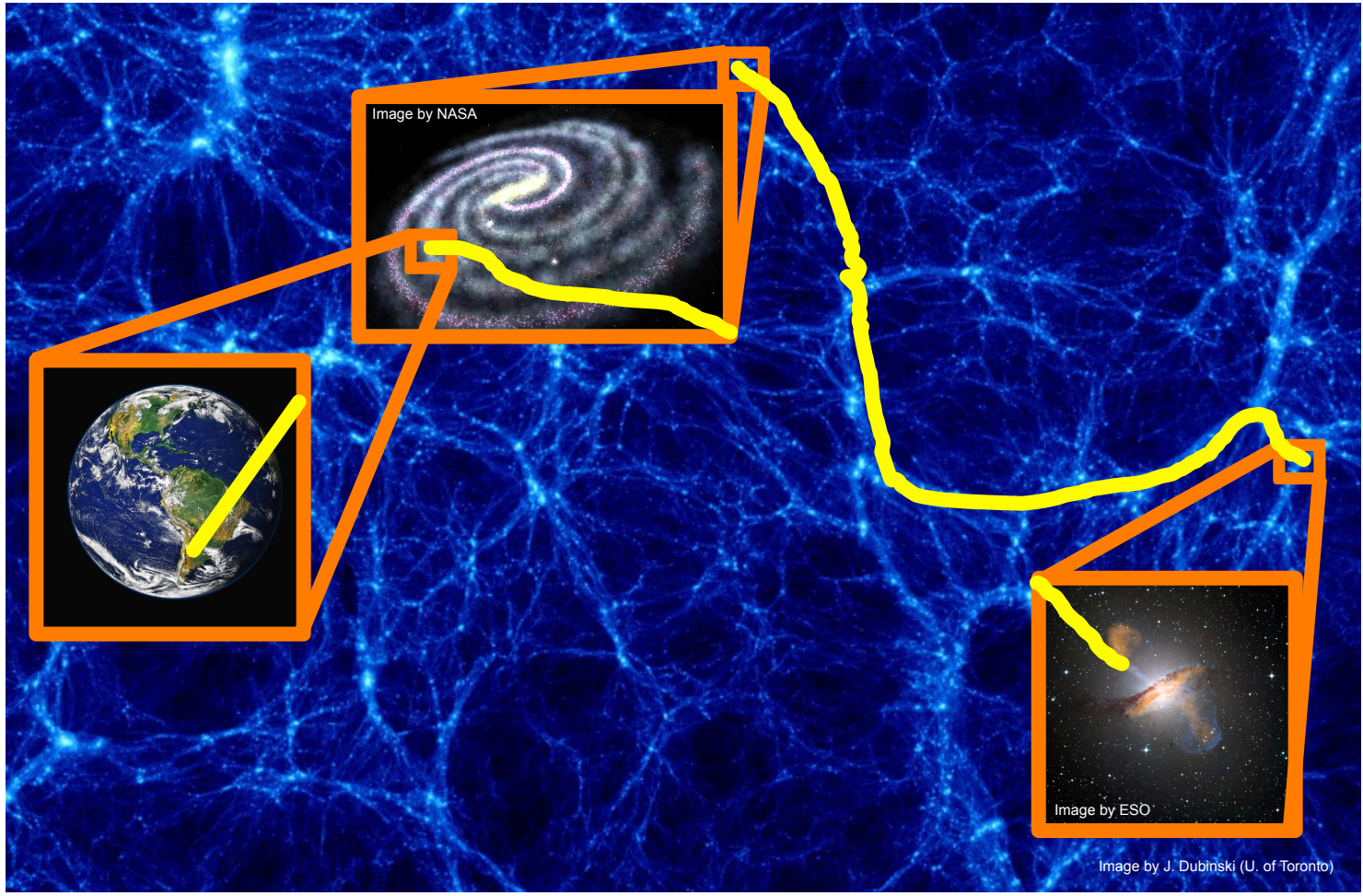
Open-source astroparticle simulation framework from TeV to ZeV energies including:

- All relevant interactions for:
  - Nuclei
  - Electromagnetic cascades
- Deflections in magnetic fields
- Redshift evolution
- Adiabatic cooling



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Open-source astroparticle simulation framework from TeV to ZeV energies, with models provided for:

- Galactic magnetic field (GMF)
  - Jansson and Farrar (Astrophys. J. 761 (2012) L11)
  - JF12 + solenoidal improvements (arXiv:1809.07528)
  - Pshirkov (Astrophys. J. 738 (2011) 192)
  - Toroidal halo / ASS / BSS logarithmic spiral
- Extragalactic magnetic field (EGMF) and large-scale structure (LSS) density field
  - CLUES (Mon. Not. Roy. Astron. Soc. 475 (2018) 2519)
  - Dolag *et al*. (JCAP 01 (2005) 009)
  - Sigl *et al*. (Phys. Rev. D 70 (2004) 043007)
- Extragalactic background light (EBL)
  - 8 different options, see:

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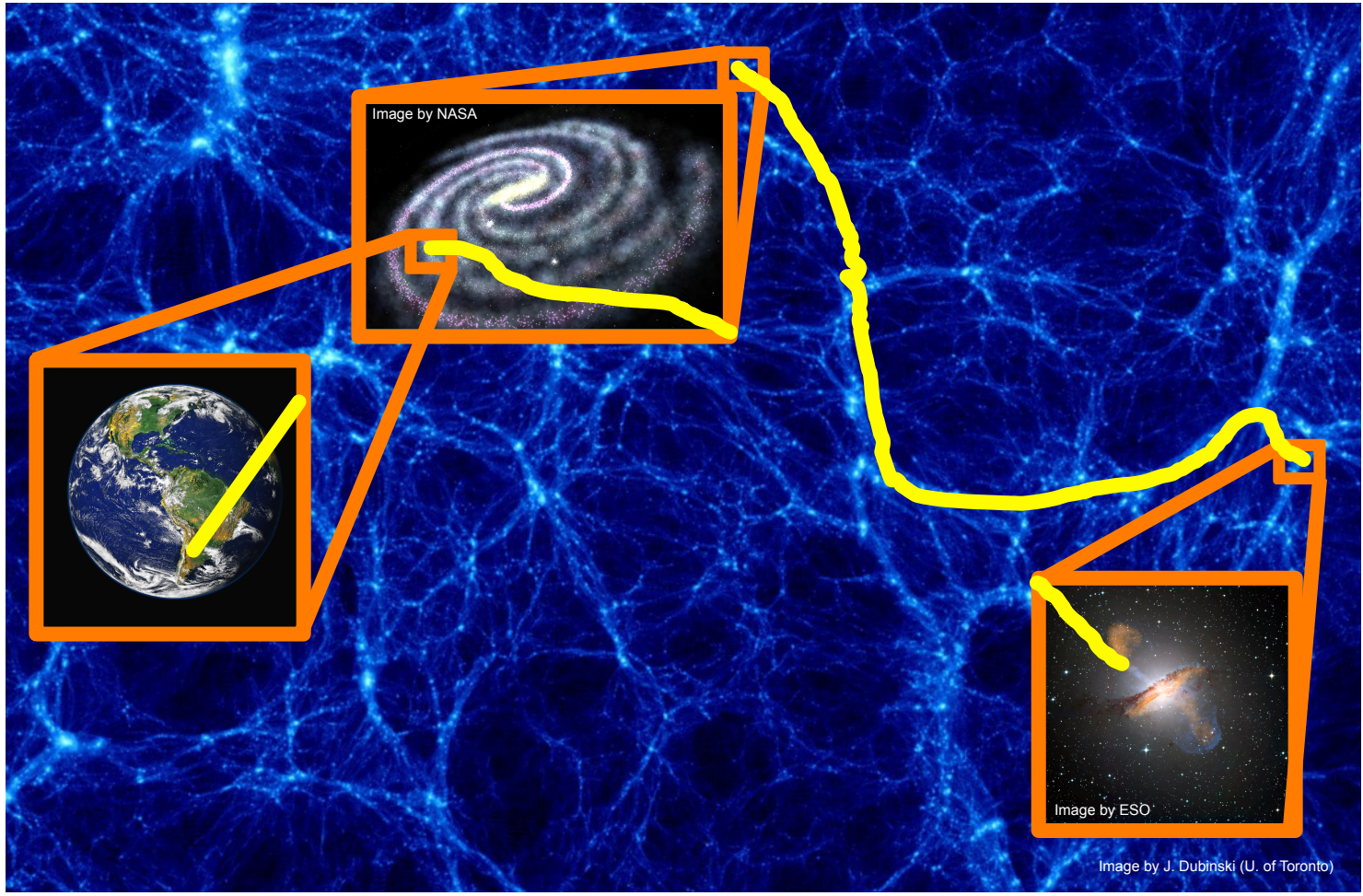
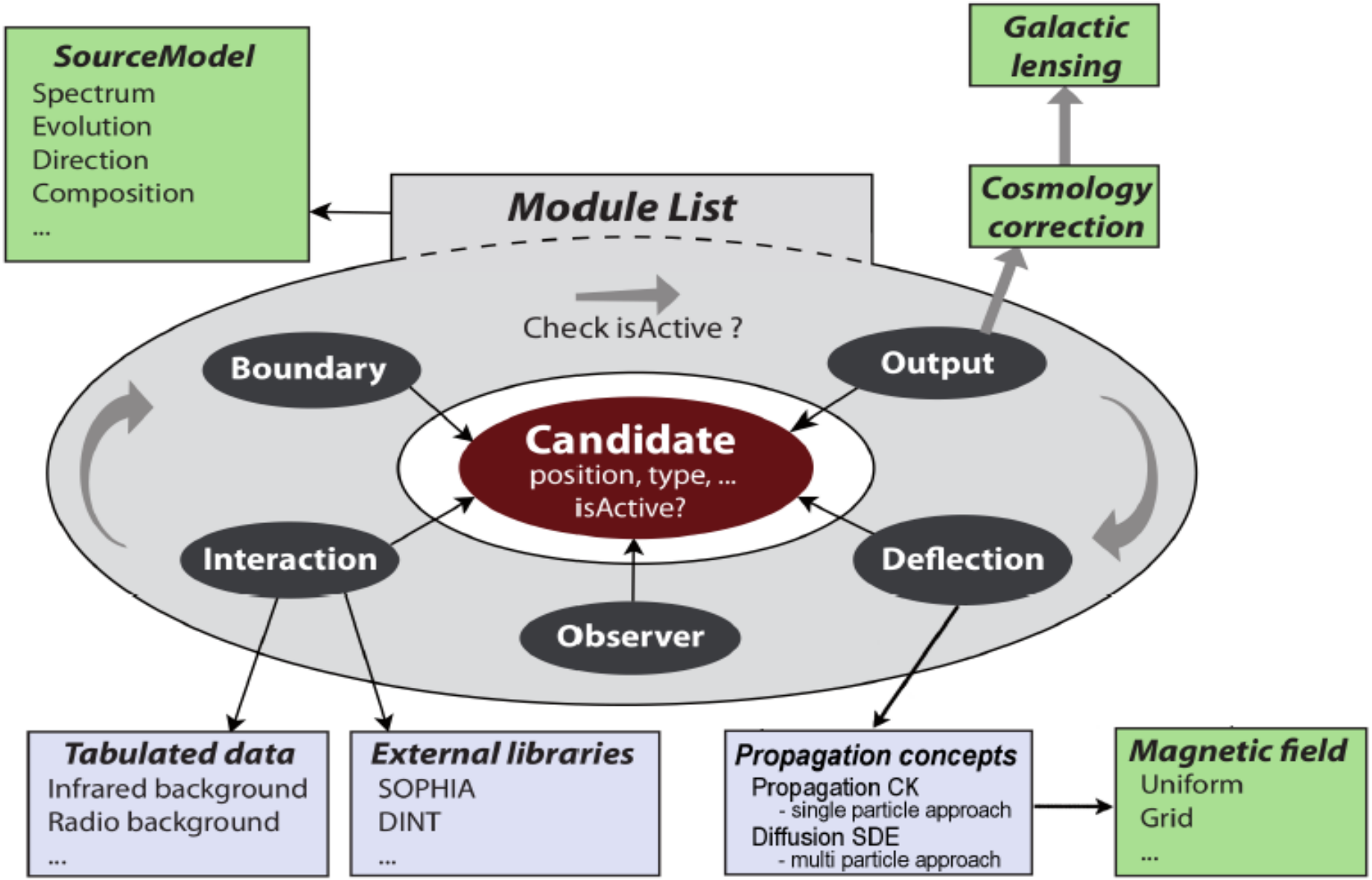


Modular code structure

- Flexible simulation setup
- Pick the modules you need
- Add your own modules
- Test specific modules
- Adjust modules
- Multipurpose simulation framework



R. Alves Batista, A. Dundovic, M. Erdmann, K.-H. Kampert, D. Kümpel, G. Müller, G. Sigl, A. van Vliet, D. Walz and T. Winchen, JCAP 1605 (2016) 038

Extragalactic cosmic rays

Extragalactic cosmic rays

- **1D, 3D and 4D simulation environments**
- Deflections in EGMF
- Sources following the LSS density field
- Energy-loss interactions with CMB and EBL:
  - Pair production
  - Photodisintegration
  - Photo-meson production
- Expansion of the universe
- Nuclear decay
- Deflections in GMF with lensing technique
- Targeting method with learning technique for optimized emission direction (new in 3.2)

- Creation and propagation of secondary particles:
  - Secondary nuclei
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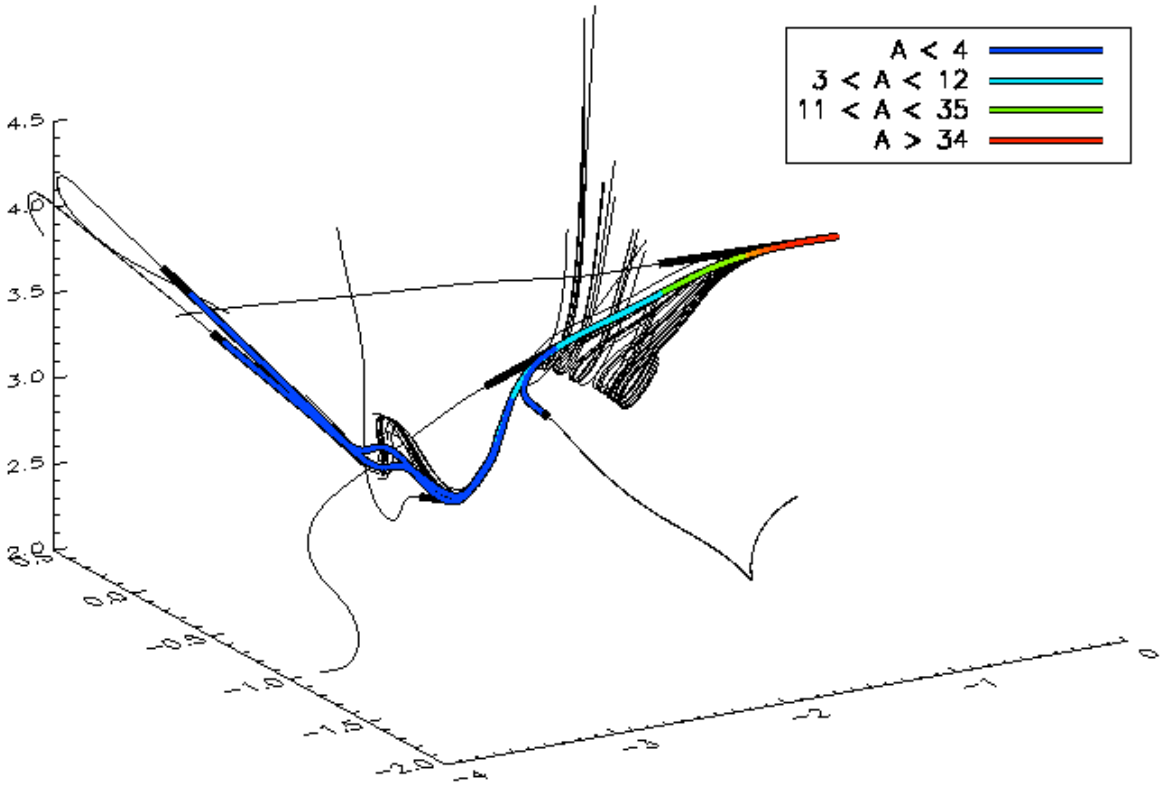

K.-H. Kampert, J. Kulbartz, L. Maccione, N. Nierstenhoefer, P. Schiffer, G. Sigl, A. van Vliet, Astropart. Phys. 42 (2013) 41

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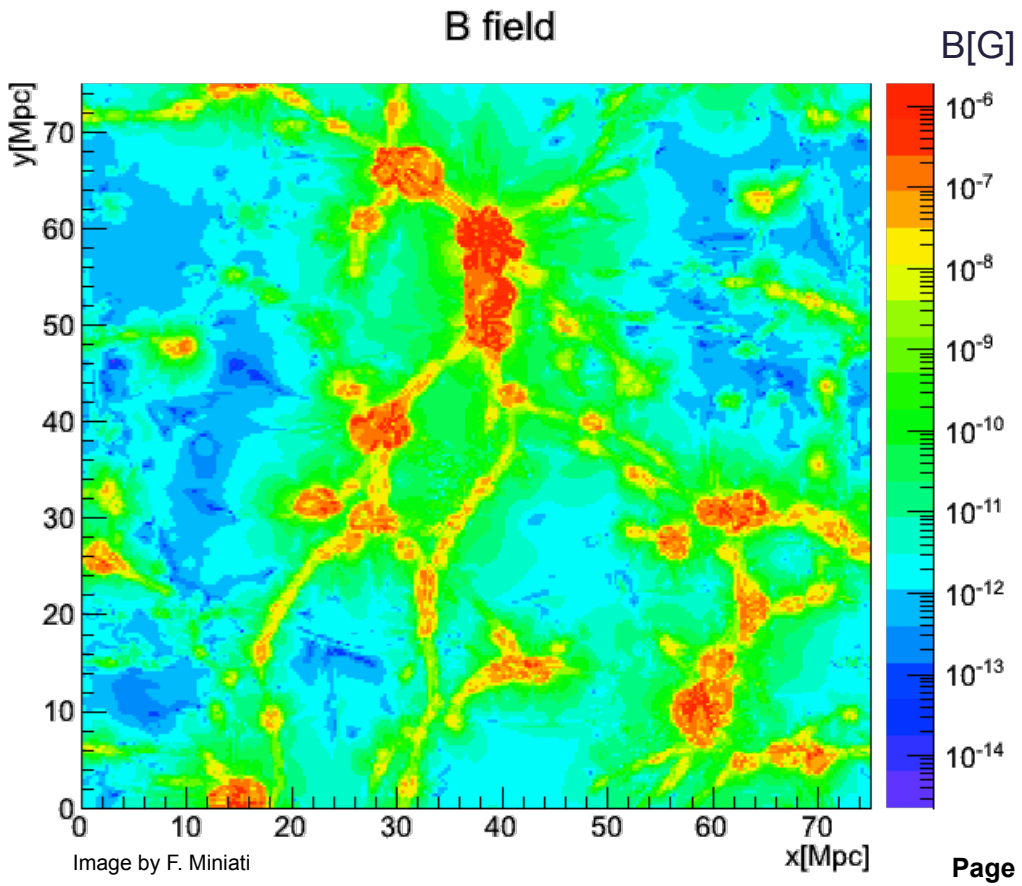

Image by F. Miniati

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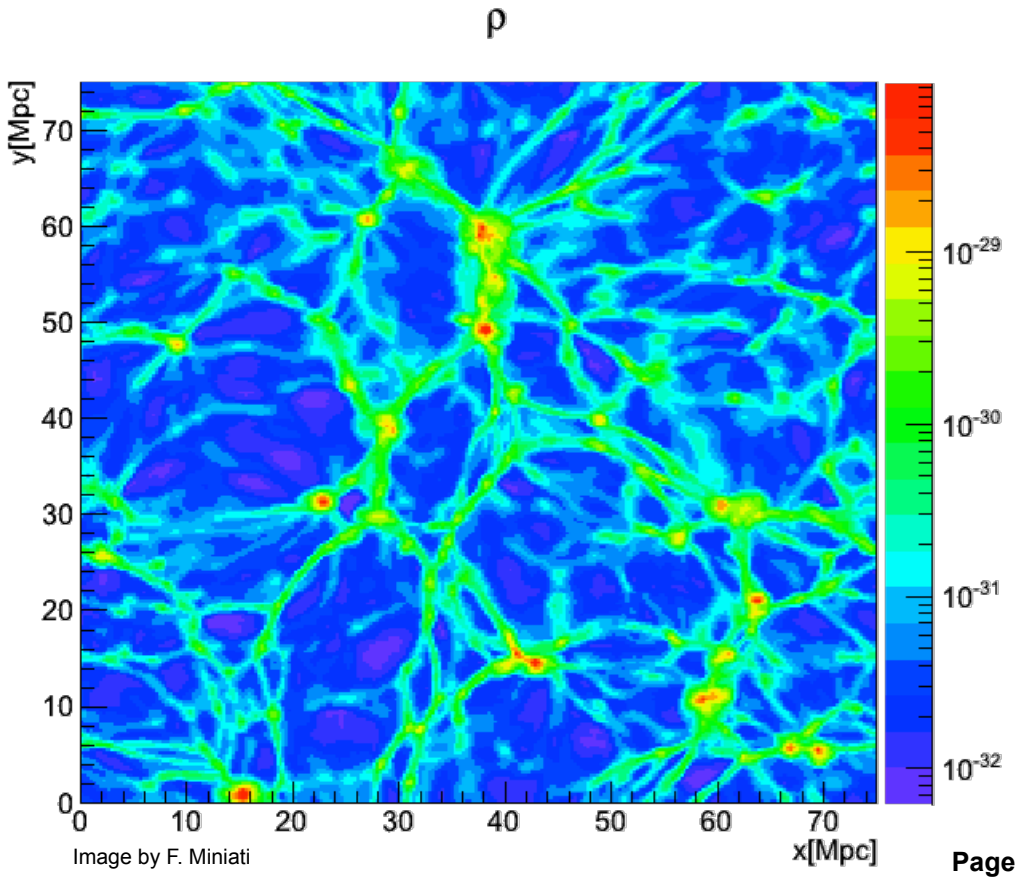

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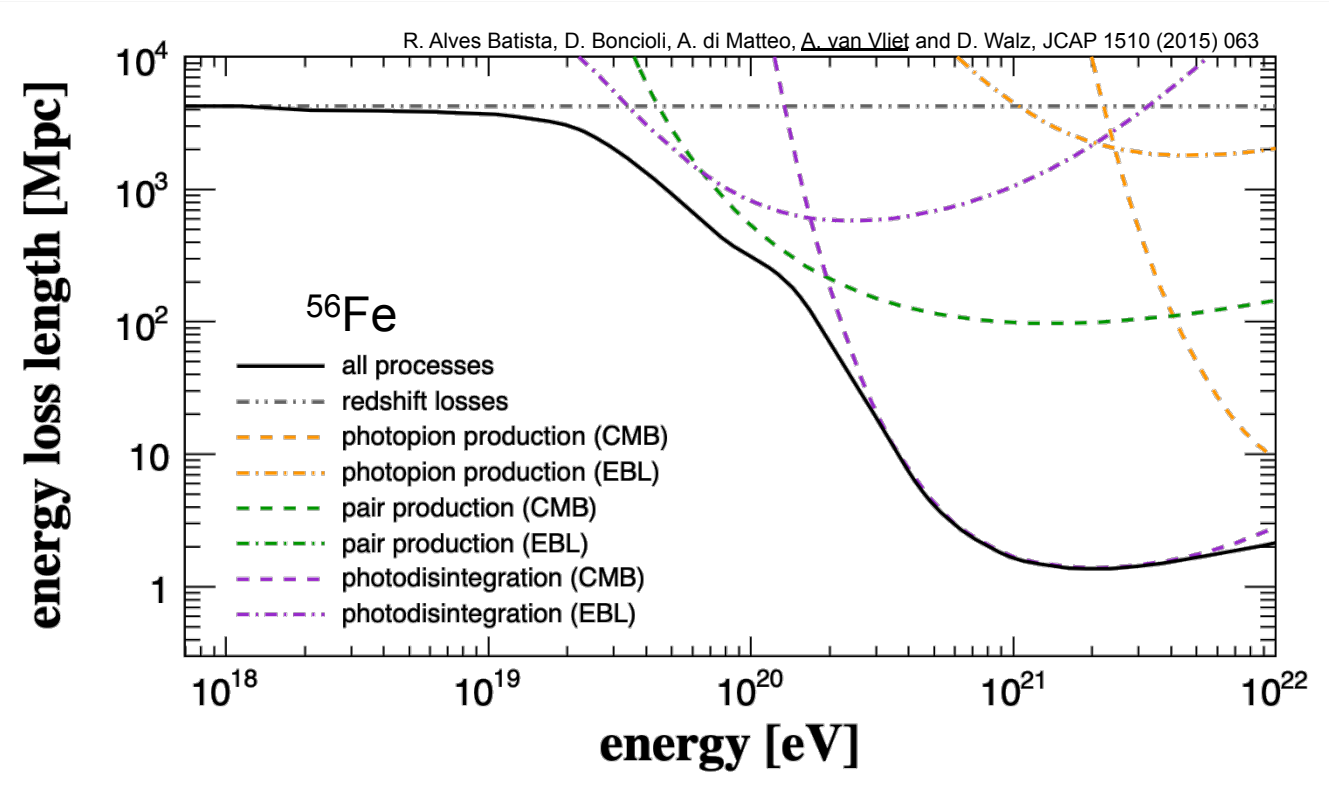

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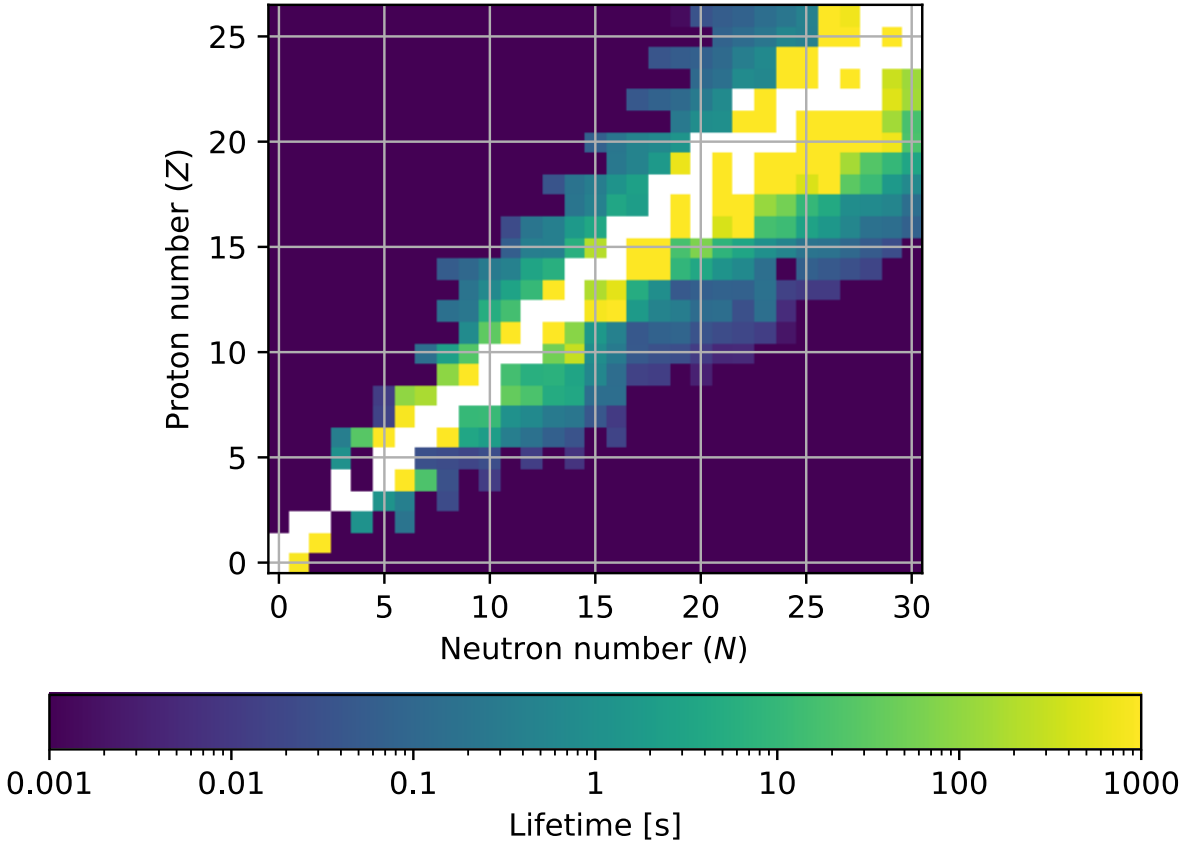

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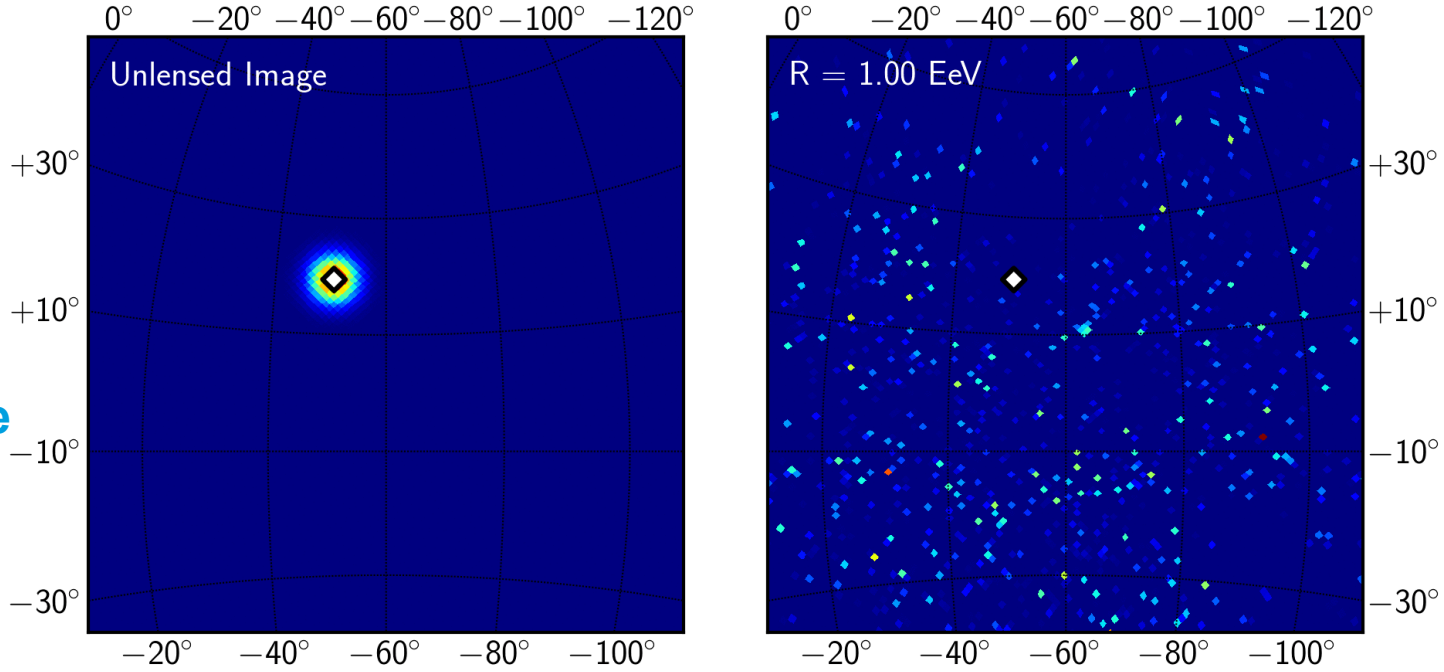

Movie by R. Alves Batista

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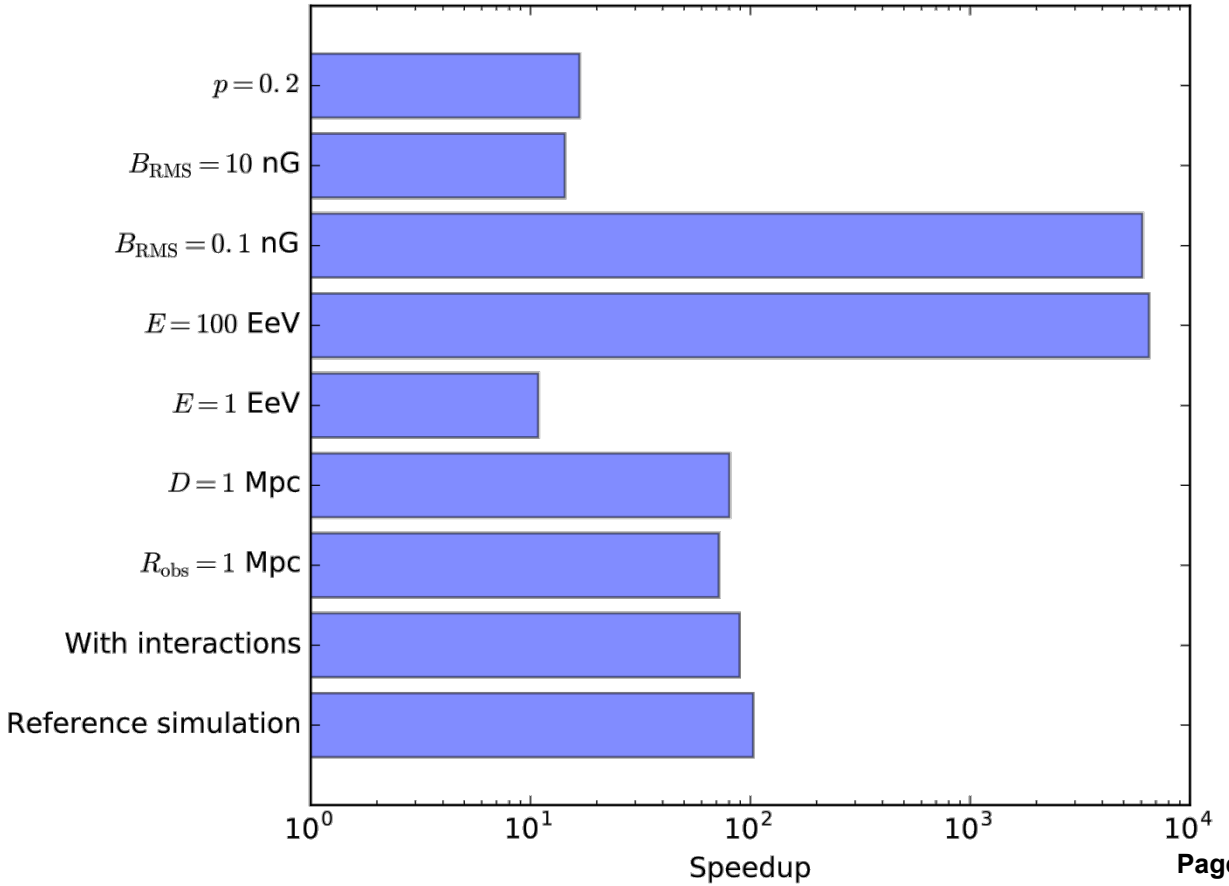

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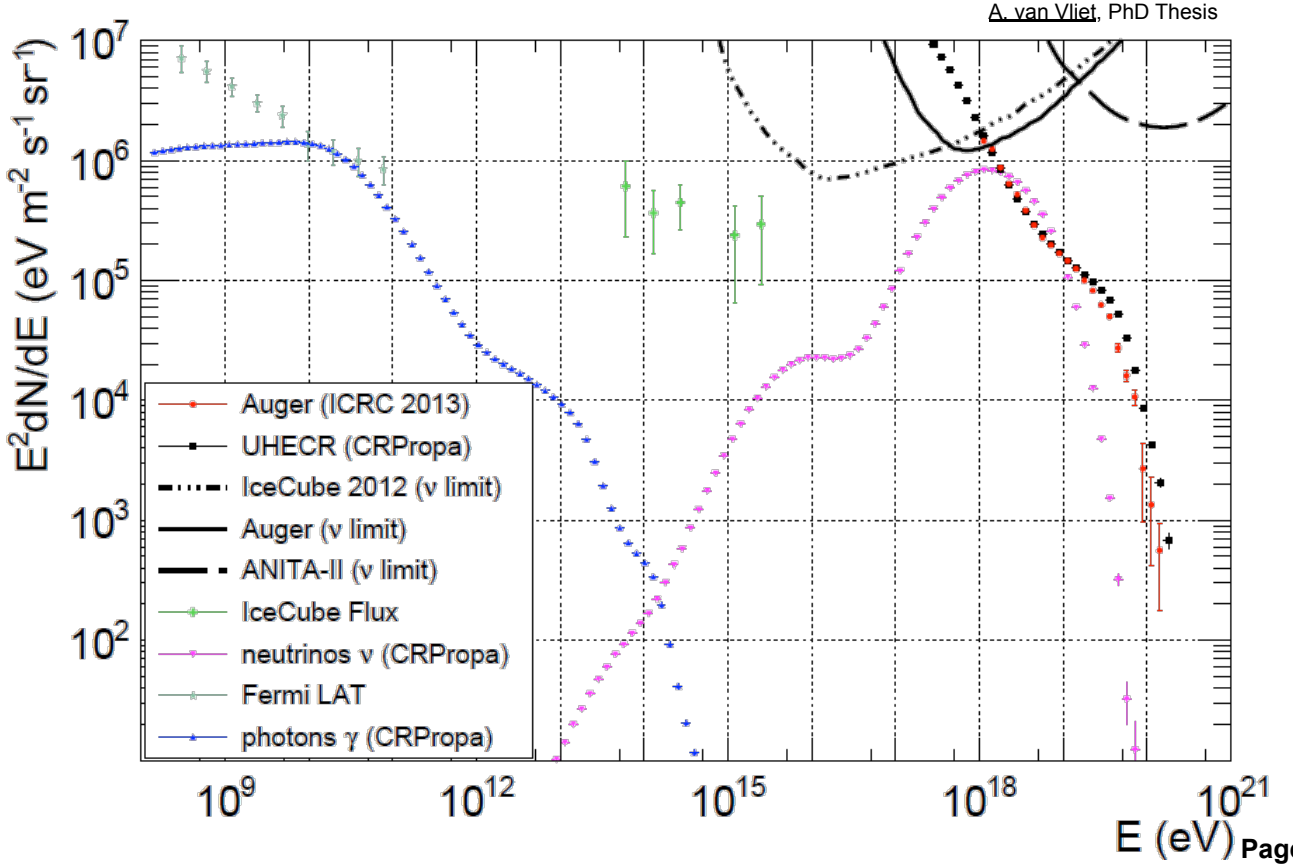
A. van Vliet, PhD Thesis



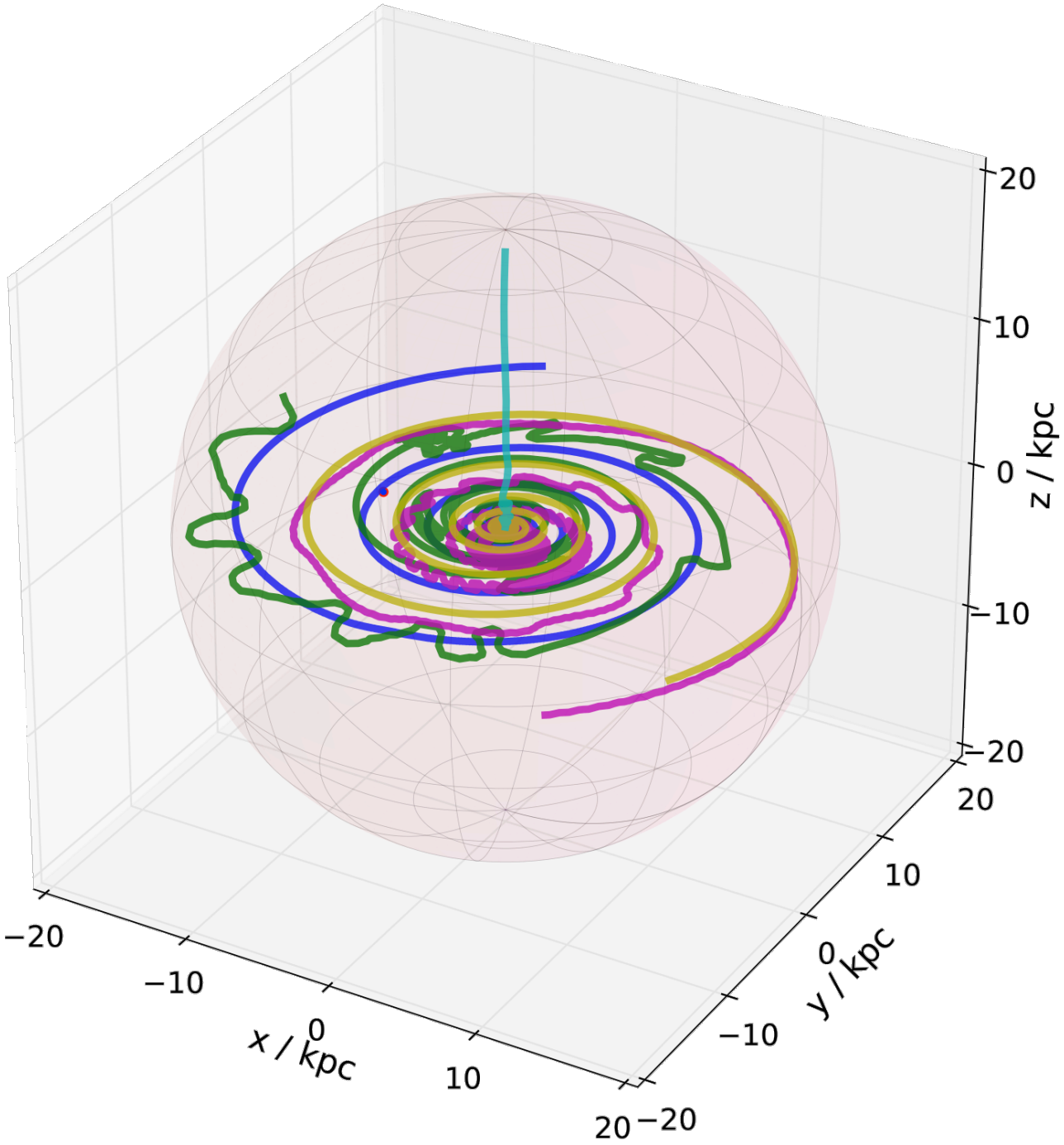
Galactic cosmic rays

Galactic cosmic rays

Single-particle approach

Solve equation of motion

- 5 protons
- $E = 10^{18}$ eV
- Isotropic emission
- Source at Galactic center
- Pshirkov ‘11 GMF



Galactic cosmic rays

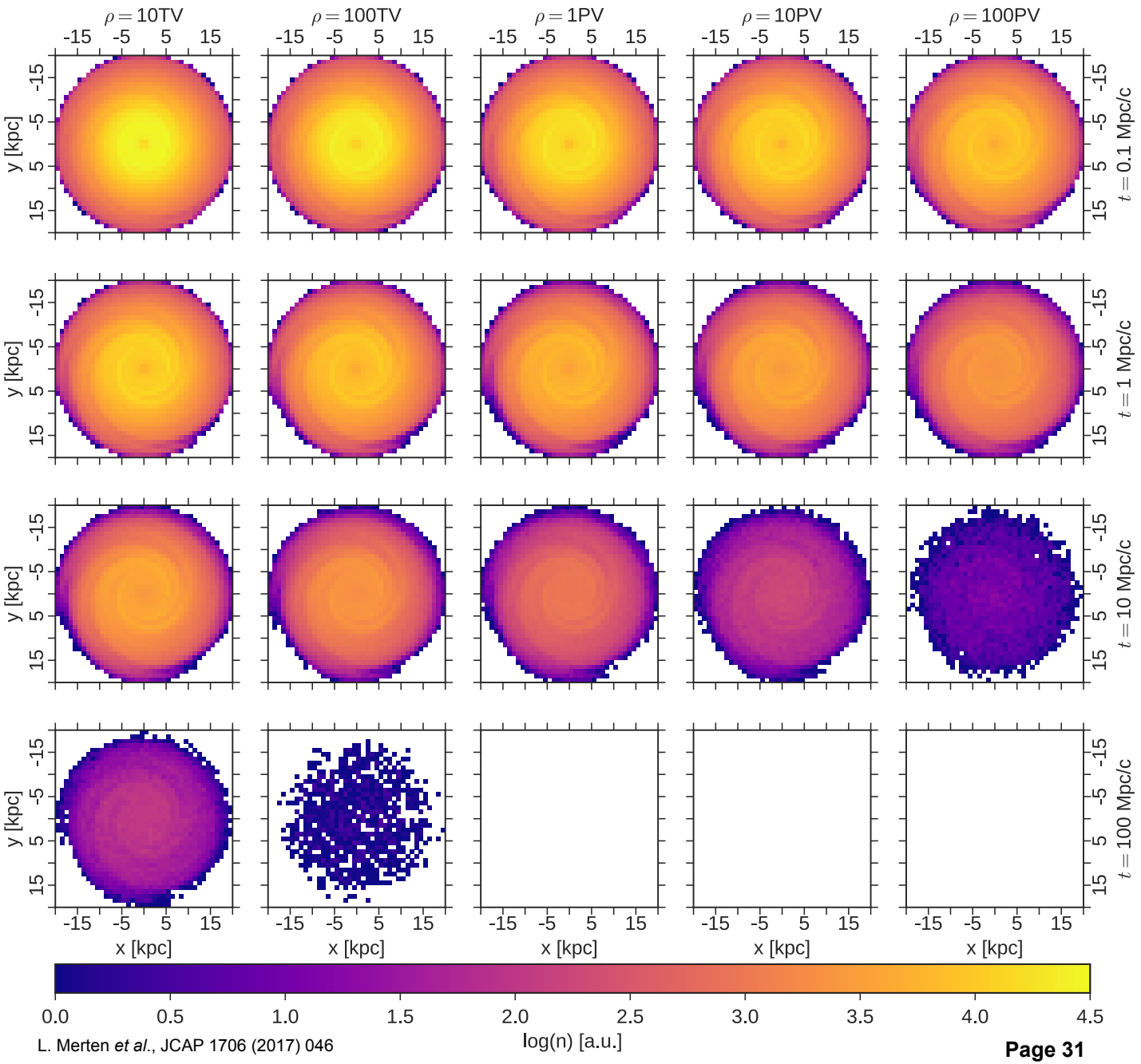
Multi-particle diffusion approach (new in 3.2)

Solve transport equation

- Anisotropic diffusion
- Advection
- Adiabatic cooling
- Momentum diffusion

Example

- Cosmic-ray density
- In Galactic plane
- Homogeneous injection
- Jansson and Farrar ‘12 GMF



L. Merten *et al.*, JCAP 1706 (2017) 046

Electromagnetic cascades

Electromagnetic cascades

Propagation methods

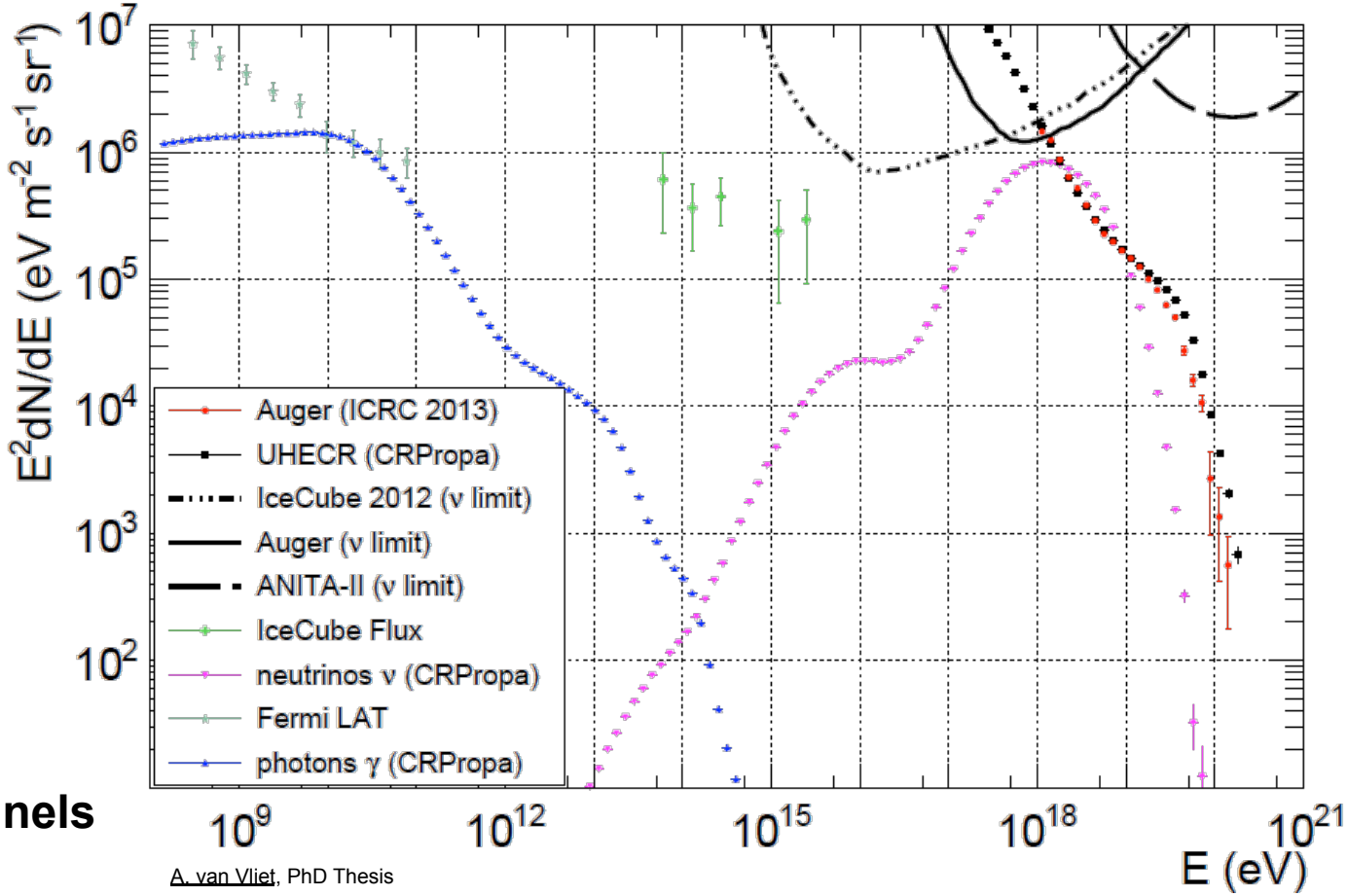
- **DINT**
- EleCa
- Propagation using CRPropa (new in 3.2)
  - Full modular 3D treatment of EM cascades

Interactions

- Pair production
- Double pair production
- Triplet pair production
- Inverse Compton scattering

New in 3.2: additional photon production channels

Cosmogenic photons using DINT



A. van Vliet, PhD Thesis

Electromagnetic cascades

Propagation methods

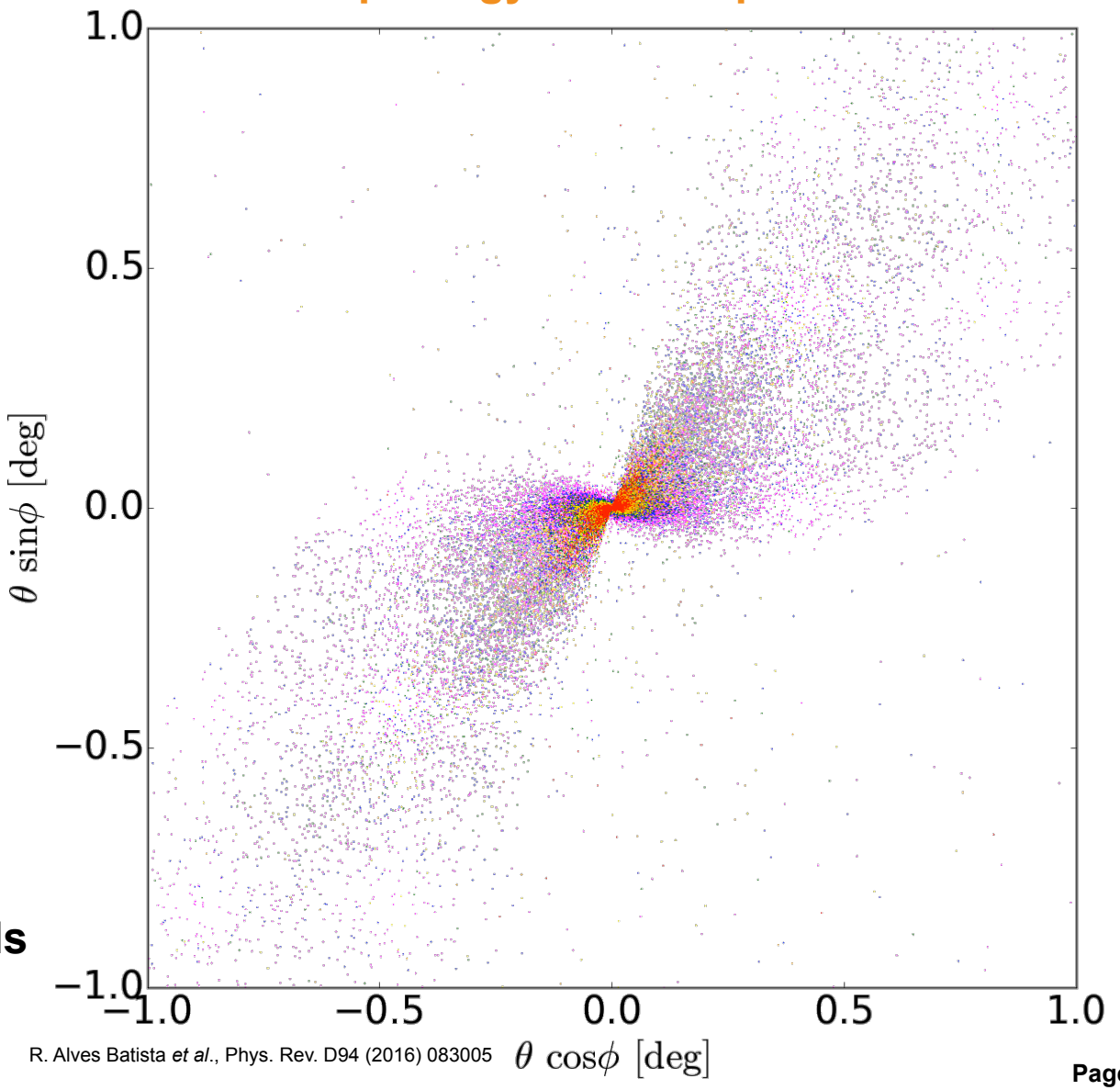
- DINT
- EleCa
- **Propagation using CRPropa (new in 3.2)**
  - **Full modular 3D treatment of EM cascades**

Interactions

- Pair production
- Double pair production
- Triplet pair production
- Inverse Compton scattering

New in 3.2: additional photon production channels

Morphology of blazar pair haloes



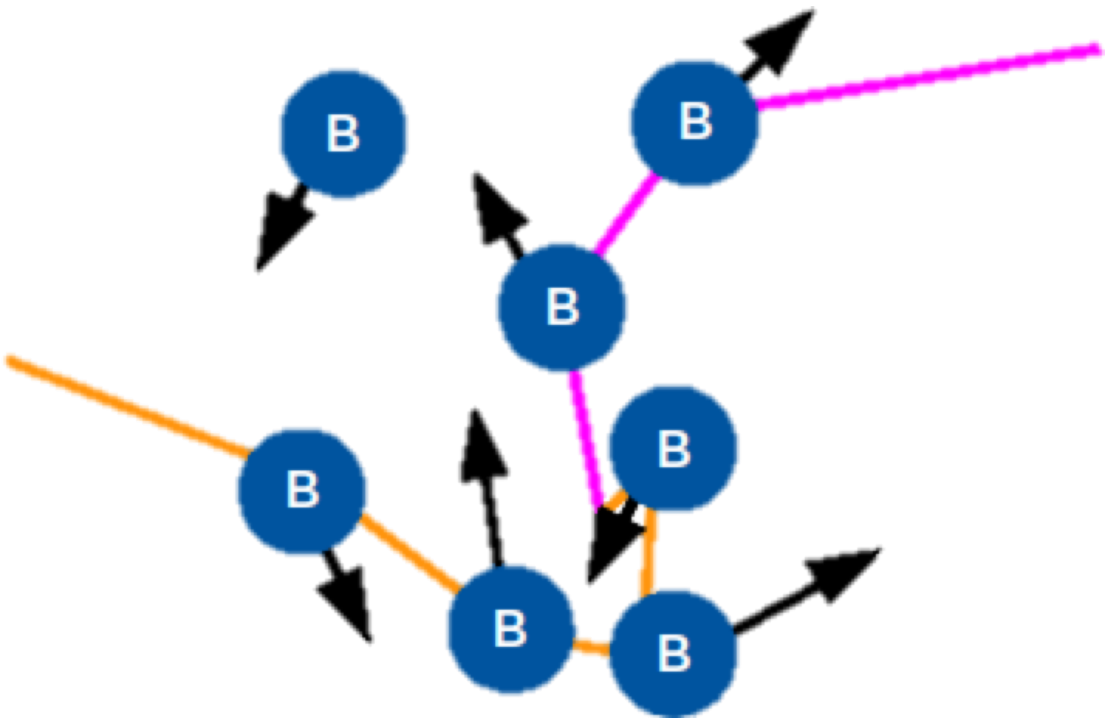
R. Alves Batista *et al.*, Phys. Rev. D94 (2016) 083005

Diffusive shock acceleration (new in 3.2)

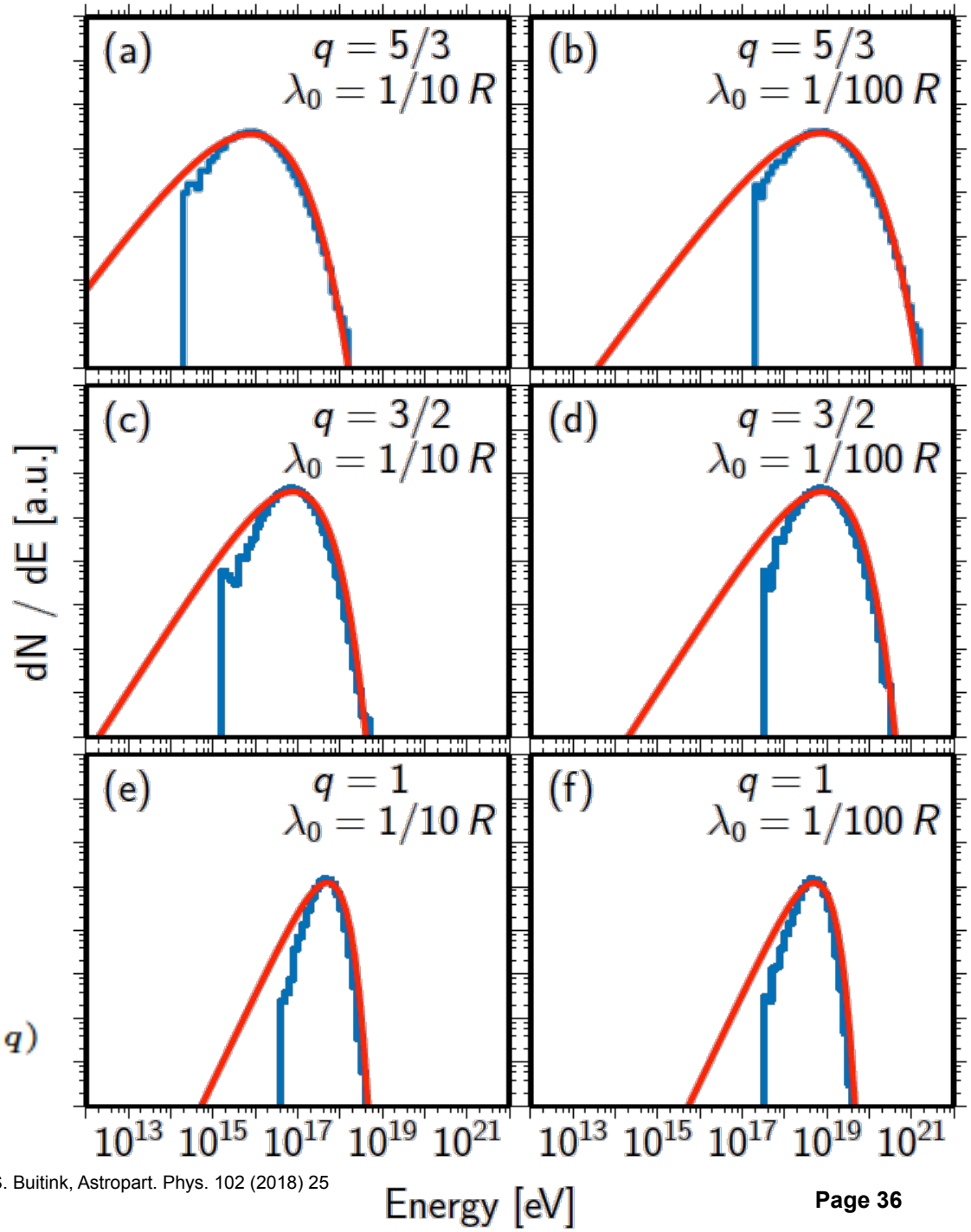
Diffusive shock acceleration

Second order

- Acceleration at random scattering centres



$$\frac{dN}{dE} \propto E^{(3-q)}\, e^{-(E/E_0)^{(2-q)}}$$

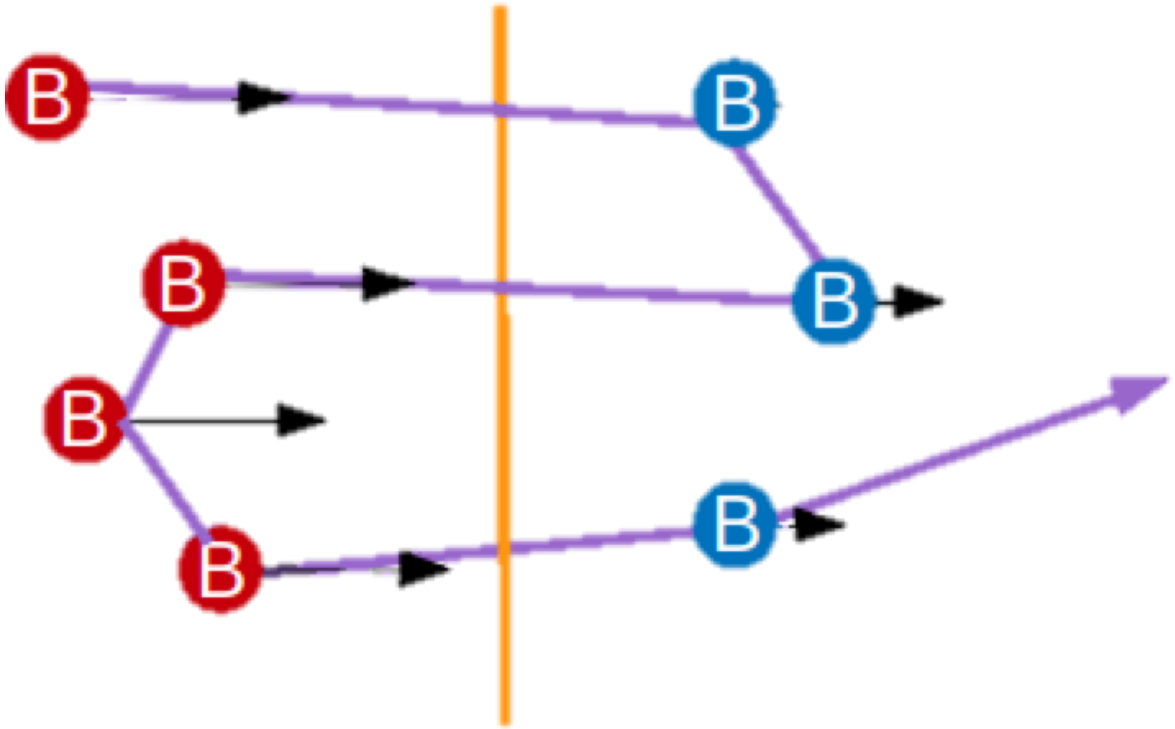


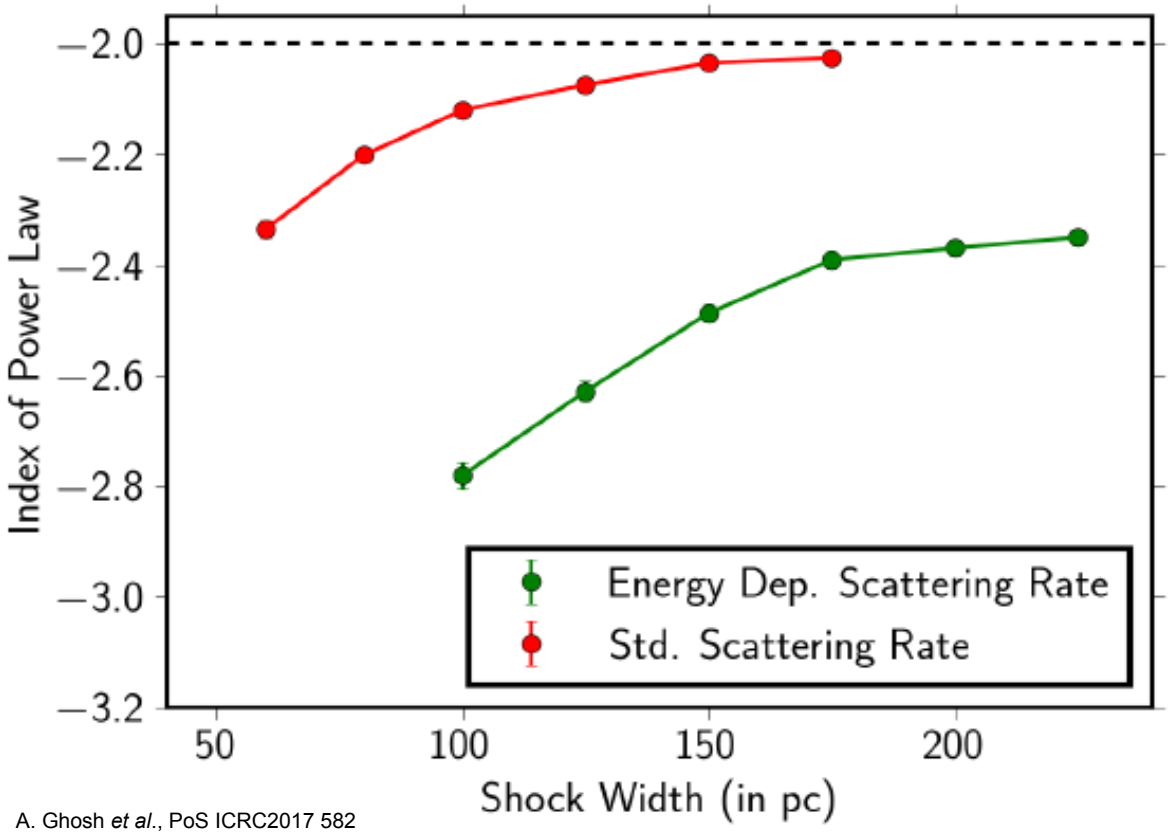
T. Winchen and S. Buitink, Astropart. Phys. 102 (2018) 25

Diffusive shock acceleration

First order

- Acceleration at directed scattering centres





A. Ghosh *et al.*, PoS ICRC2017 582

What is possible with CRPropa

What is possible with CRPropa

- For your favorite source model, EGMF model, GMF model and EBL model:
- Simulate (fit) cosmic-ray spectrum, composition, arrival directions + secondary photon and neutrino spectra
- Or focus on more specific problems, e.g., for IMAGINE:
  - Calculate **expected deflection angle** of extragalactic cosmic rays in GMF model as function of energy / charge / location on the sky; most efficient with **backtracking from Earth to edge of Galaxy**
  - Focus on specific parts of the GMF model / specific energy ranges / specific locations (sources) in the sky
  - Calculate **expected Galactic cosmic-ray density** at intermediate energies for specific GMF models
  - Calculate **effect of GMF on electromagnetic cascades**, depending on energy / location

Summary

- CRPropa: Multi-purpose open-source astroparticle simulation framework
- Available from: crpropa.desy.de
- CRPropa 3.2 under development at the moment with new major features including:
  - Diffusion for Galactic cosmic rays
  - Targeting method for speedup of extragalactic propagation
  - Improved electromagnetic cascade simulations
  - Acceleration at the sources
- Multiple possibly interesting application with IMAGINE

Contact

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