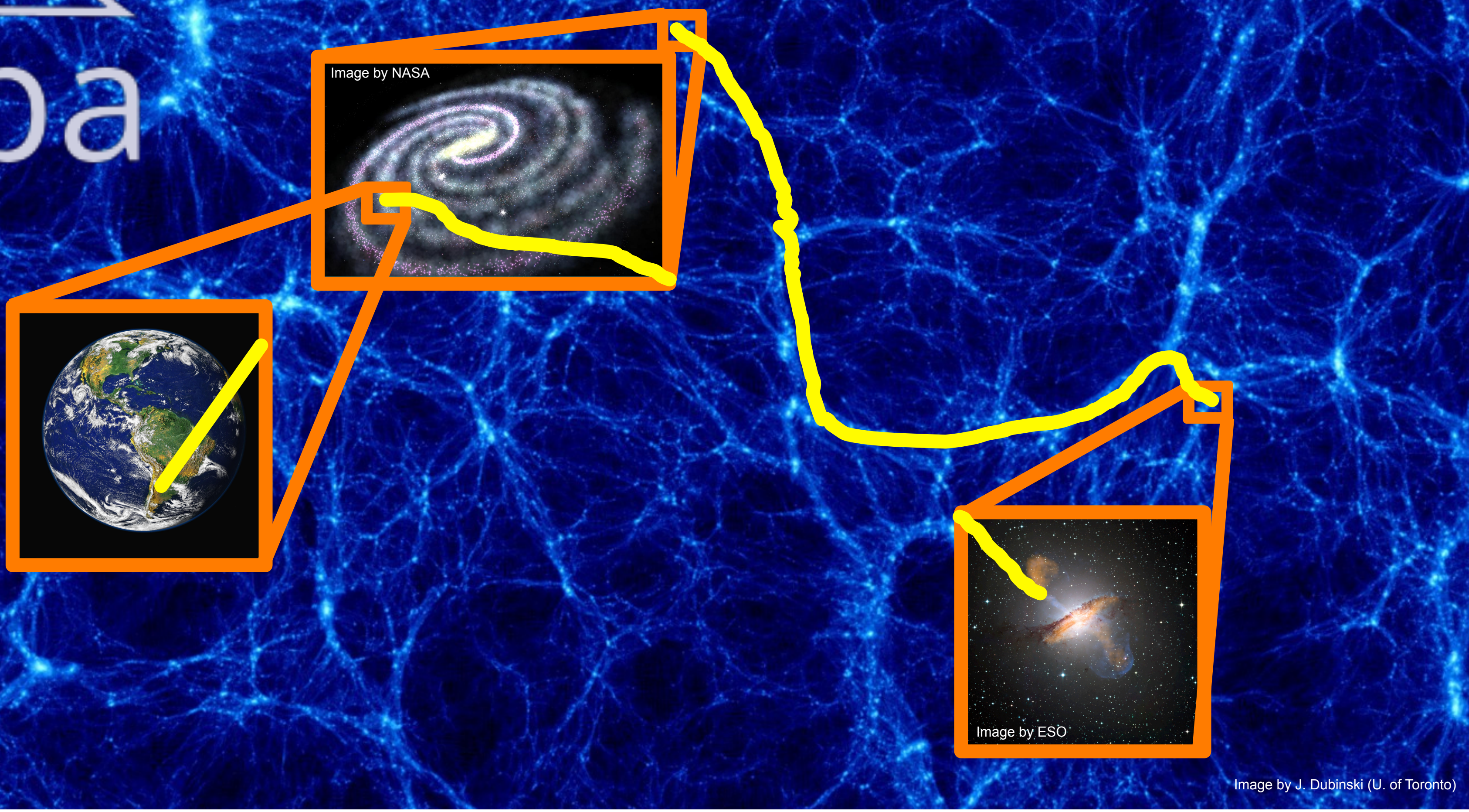
# CRPropa

## An open-source astroparticle propagation framework from TeV to ZeV energies





Arjen van Vliet

Zeuthen, 15.03.2019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# Outline

**CRPropa 3.2 - Overview**
- Purpose
- Includes
- External models provided

**Modular code structure**

**Extragalactic cosmic rays**
- 1D, 3D and 4D
- EGMF and LSS
- Interactions
- GMF lensing
- Targeting
- Secondary particles

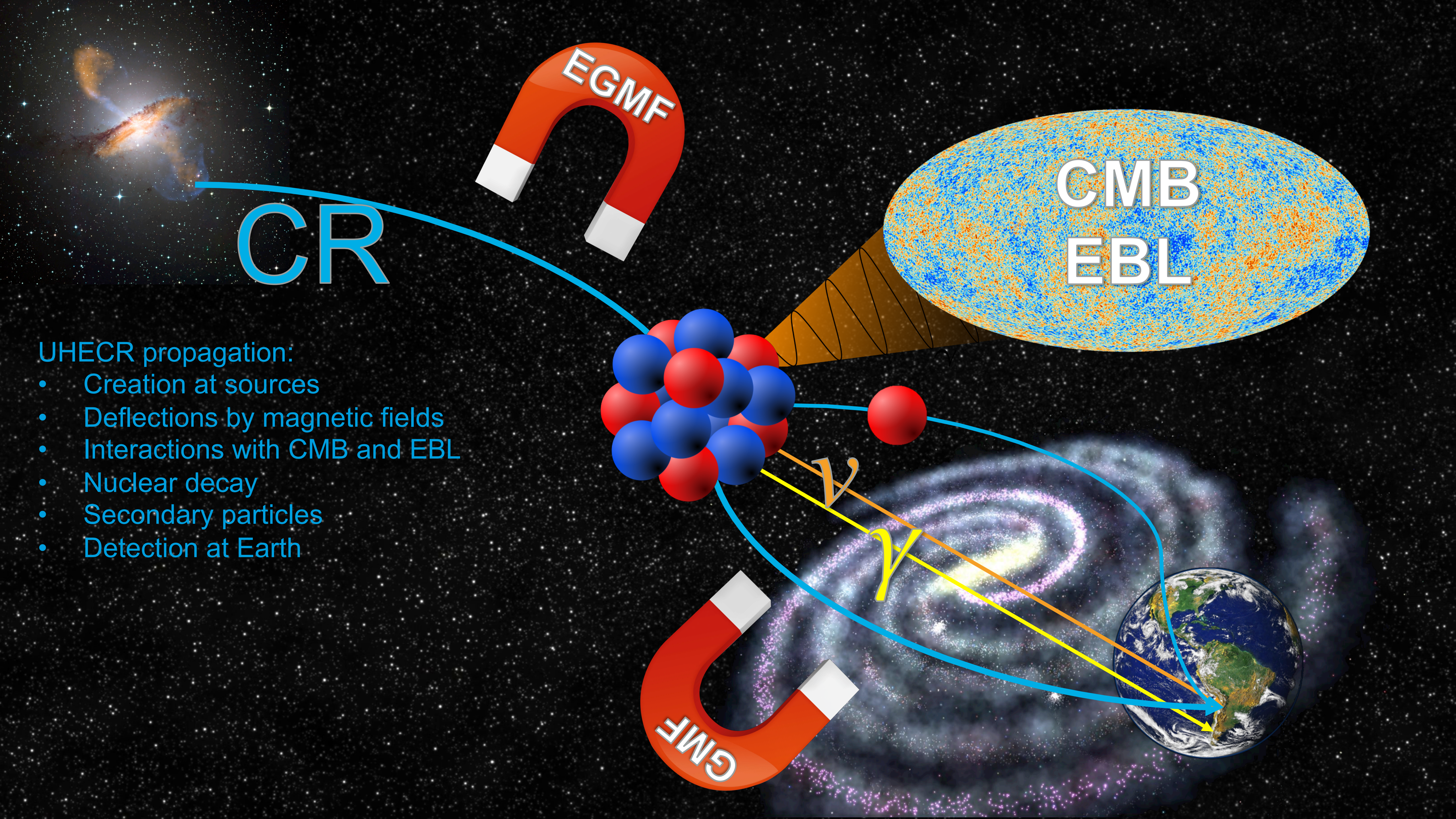
**Galactic cosmic rays**
- Single-particle propagation
- Diffusion

**Electromagnetic cascades**

**Diffusive shock acceleration**
- 1$^{st}$ and 2$^{nd}$ order

**Example: Cosmogenic neutrinos**

**Example: UHECRs from radio galaxies**


EGMF
CMB
EBL
CR
UHECR propagation:
• Creation at sources
• Deflections by magnetic fields
• Interactions with CMB and EBL
• Nuclear decay
• Secondary particles
• Detection at Earth
ν
γ
GMF

# 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

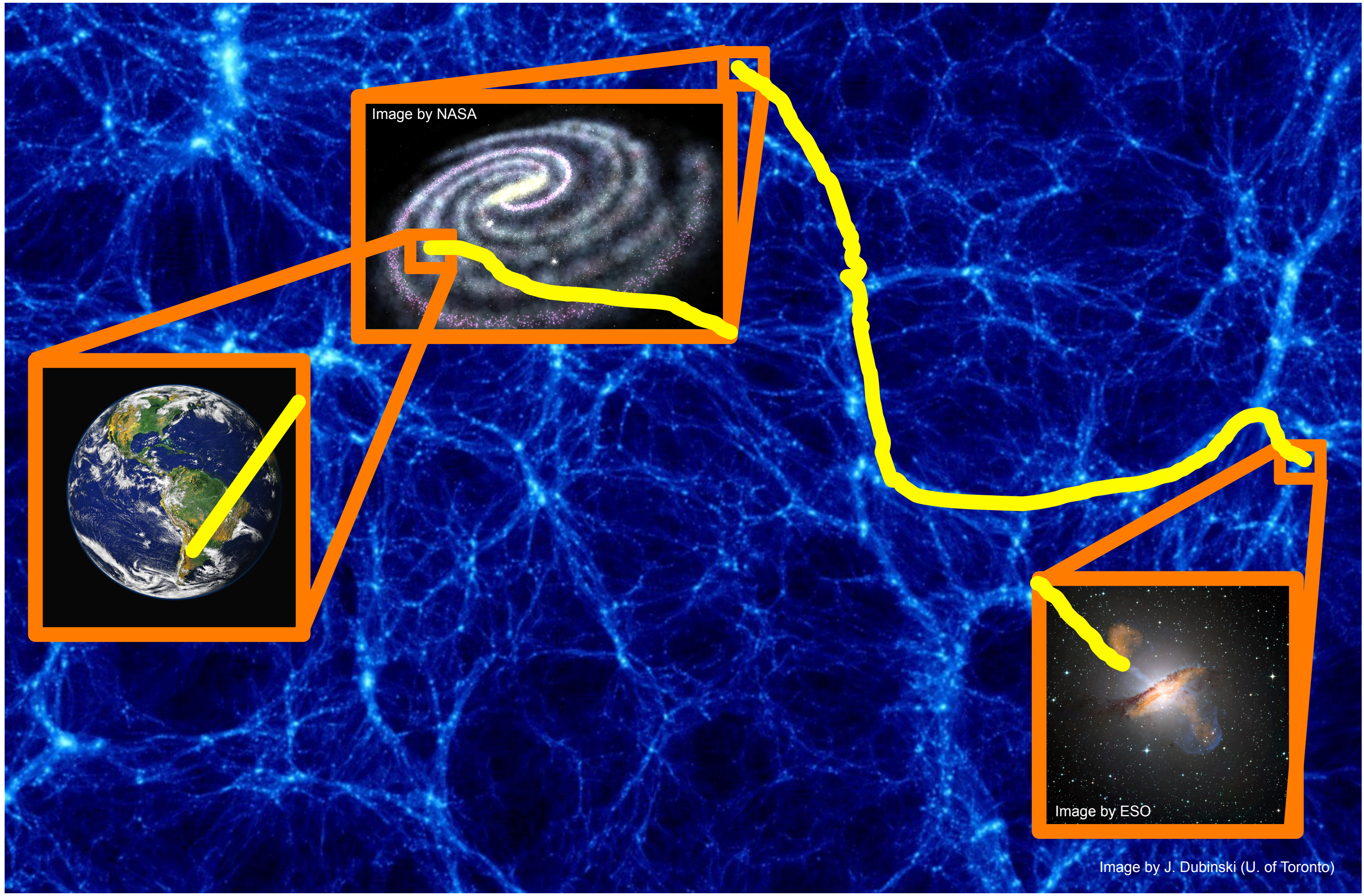
**Open-source astroparticle simulation framework from TeV to ZeV energies for:**

- 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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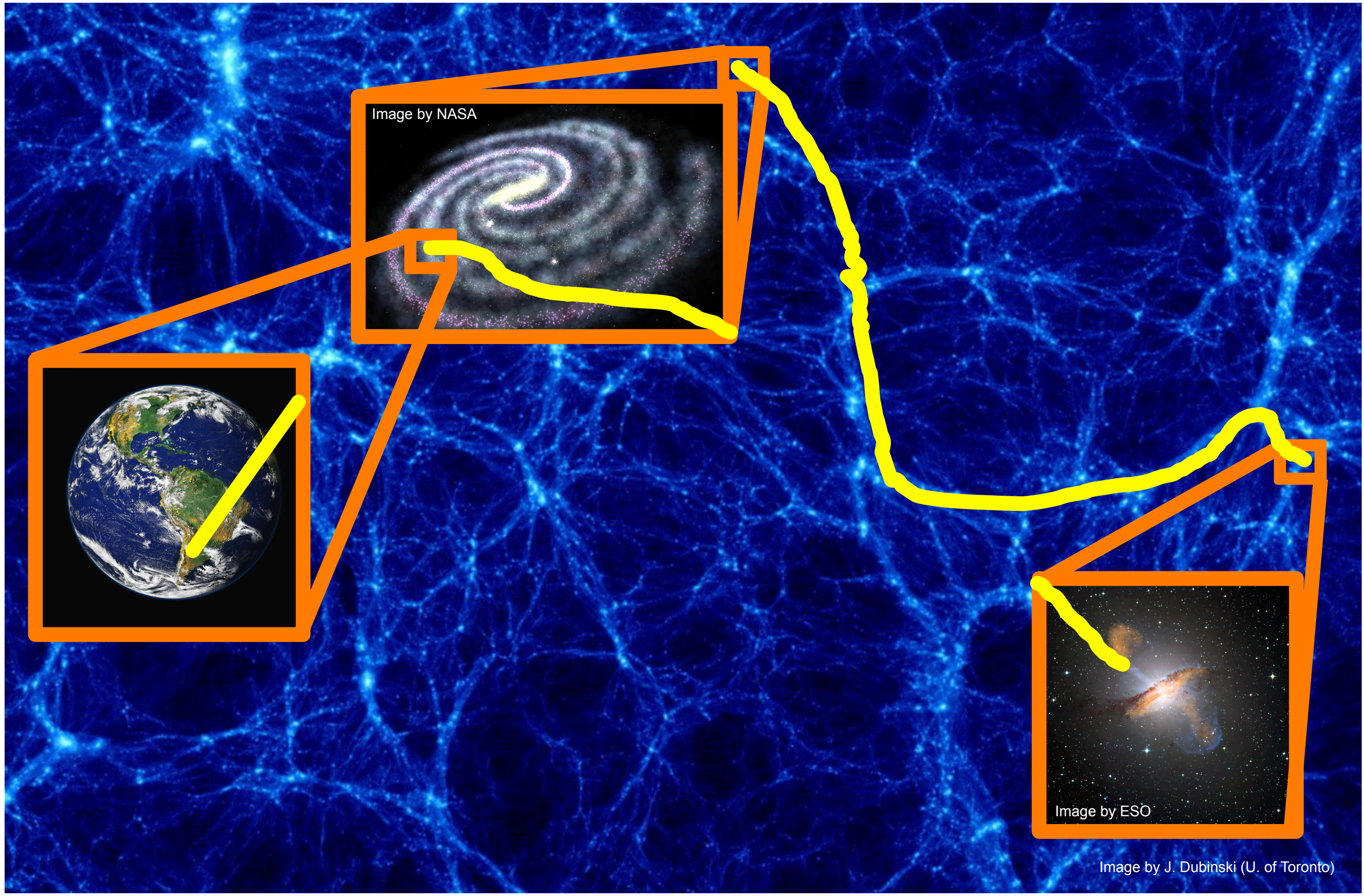

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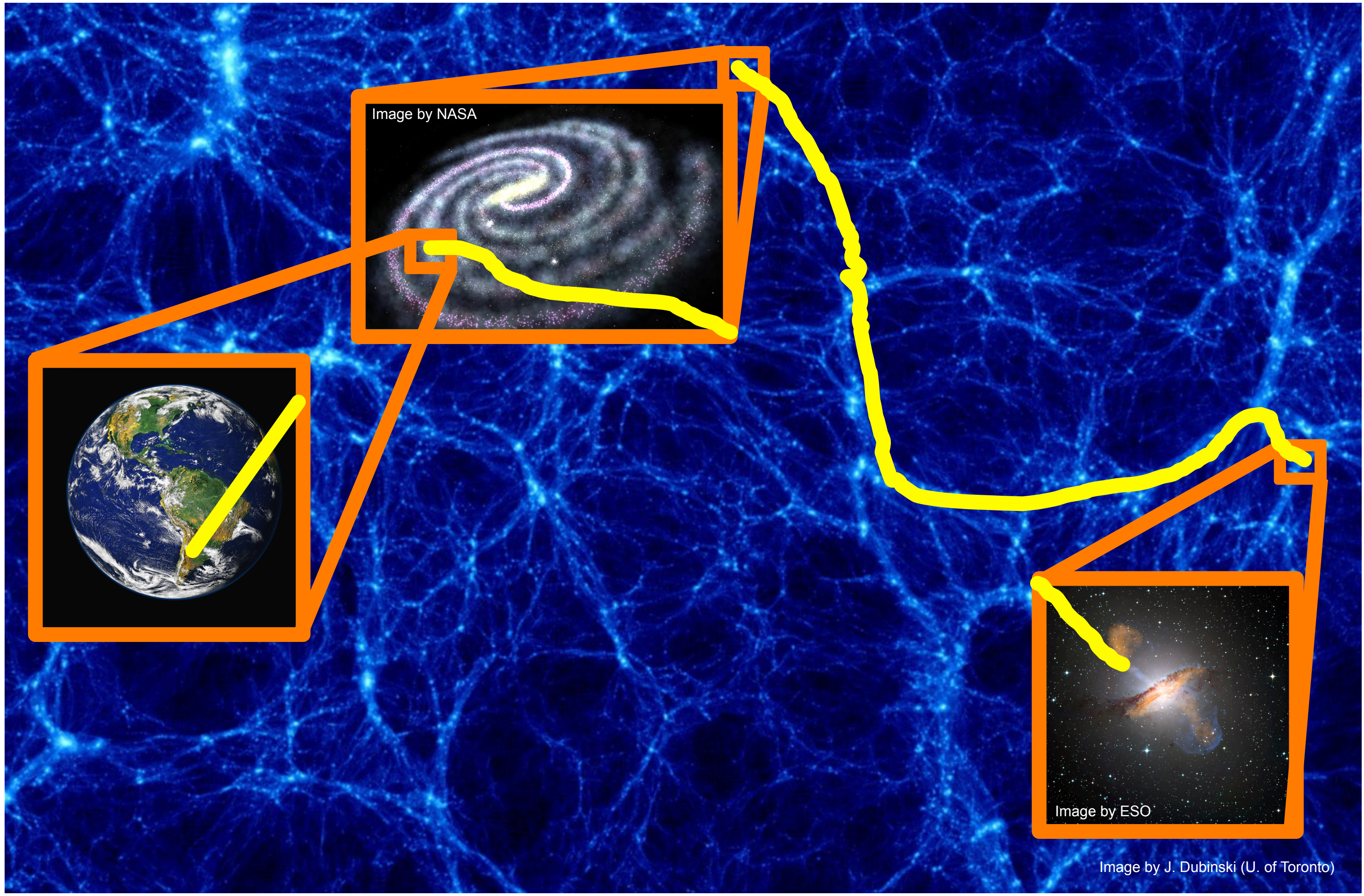
**Open-source astroparticle simulation framework from TeV to ZeV energies, with models provided for:**

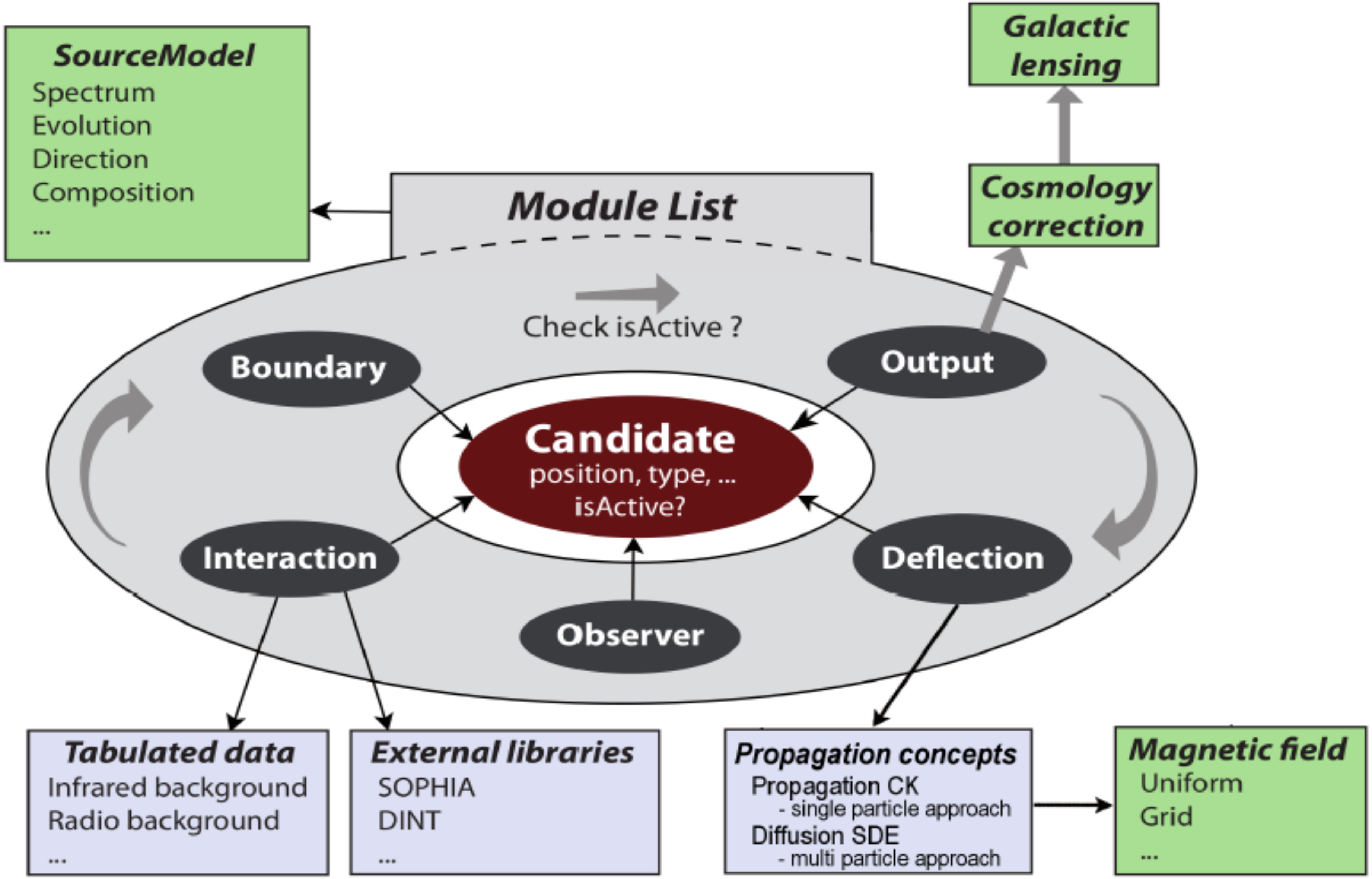
- Galactic magnetic field (GMF)
  - Jansson and Farrar (Astrophys. J. 761 (2012) L11)
  - Pshirkov (Astrophys. J. 738 (2011) 192)
- Extragalactic magnetic field (EGMF) and large-scale structure (LSS) density field
  - CLUES (Mon. Not. Roy. Astron. Soc. 475 (2018) 2519)
  - Dolag *et al*. (JCAP 01 (2005)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

crpropa.desy.de



# 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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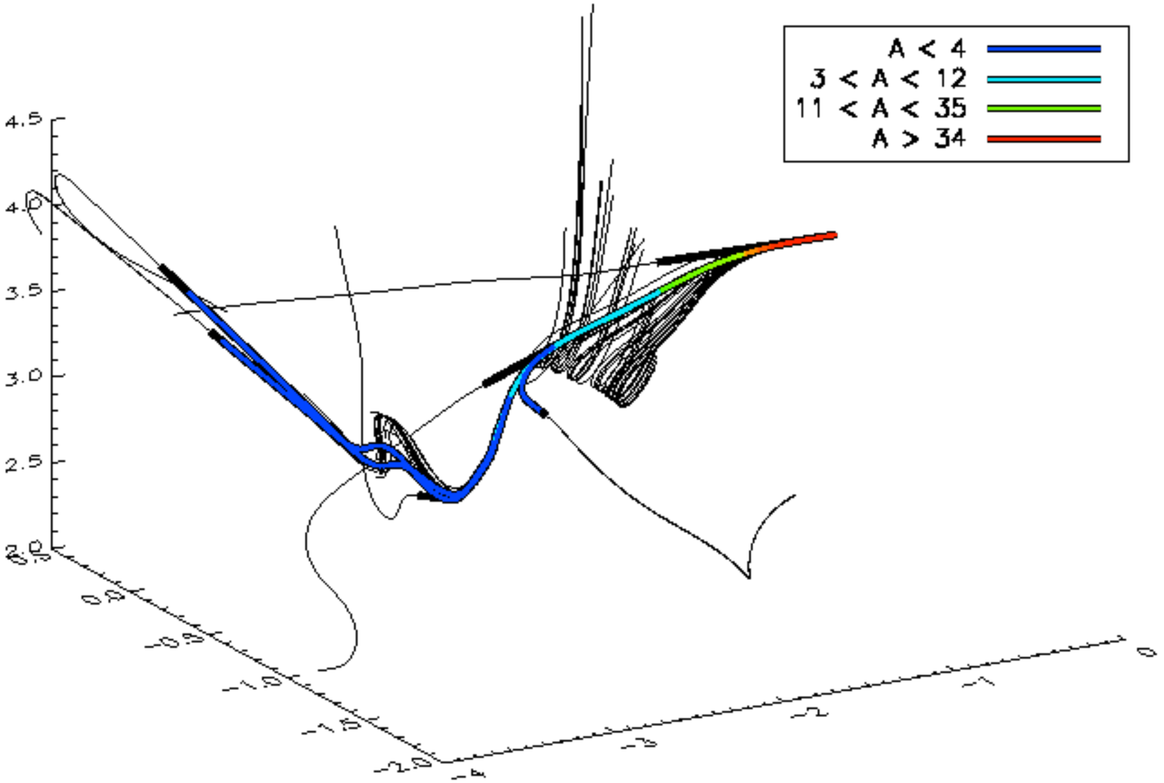


K.-H. Kampert, J. Kulbartz, L. Maccione, N. Nierstenhoefer, P. Schiffer, G. Sigl, A. van Vliet, Astropart. Phys. 42 (2013) 41

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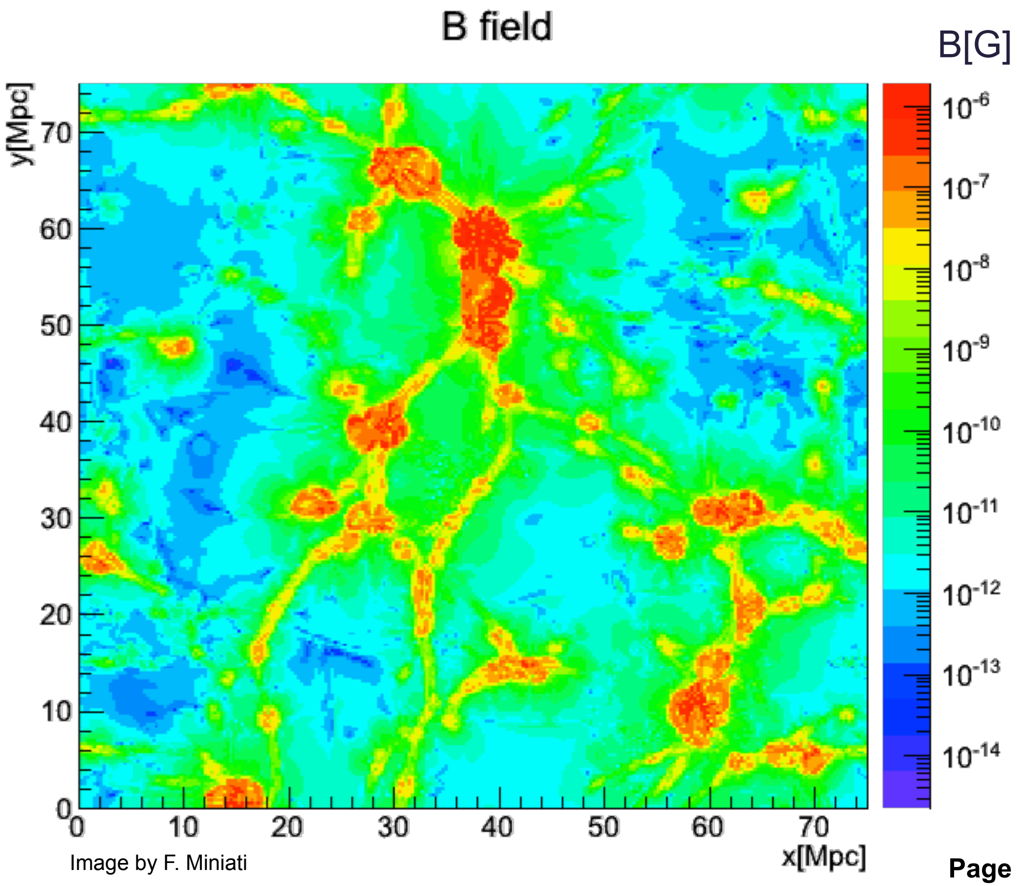


Image by F. Miniati

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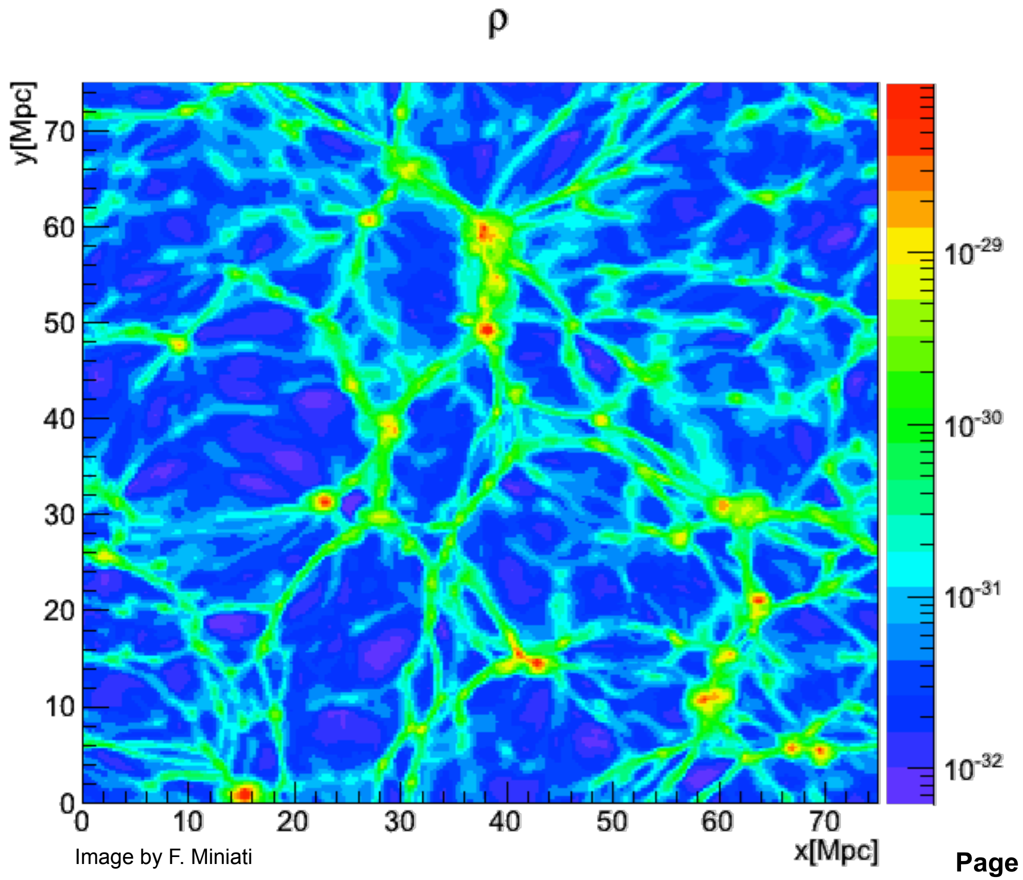


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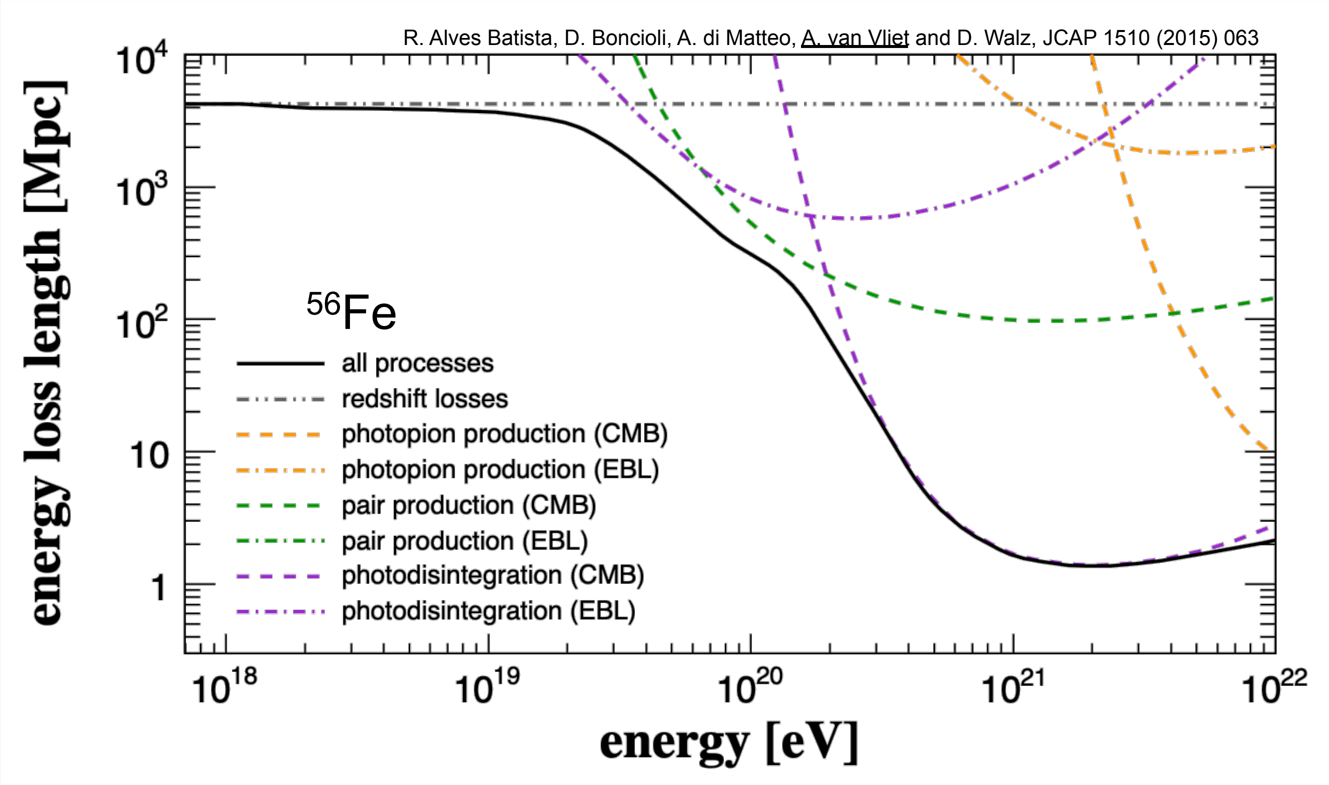

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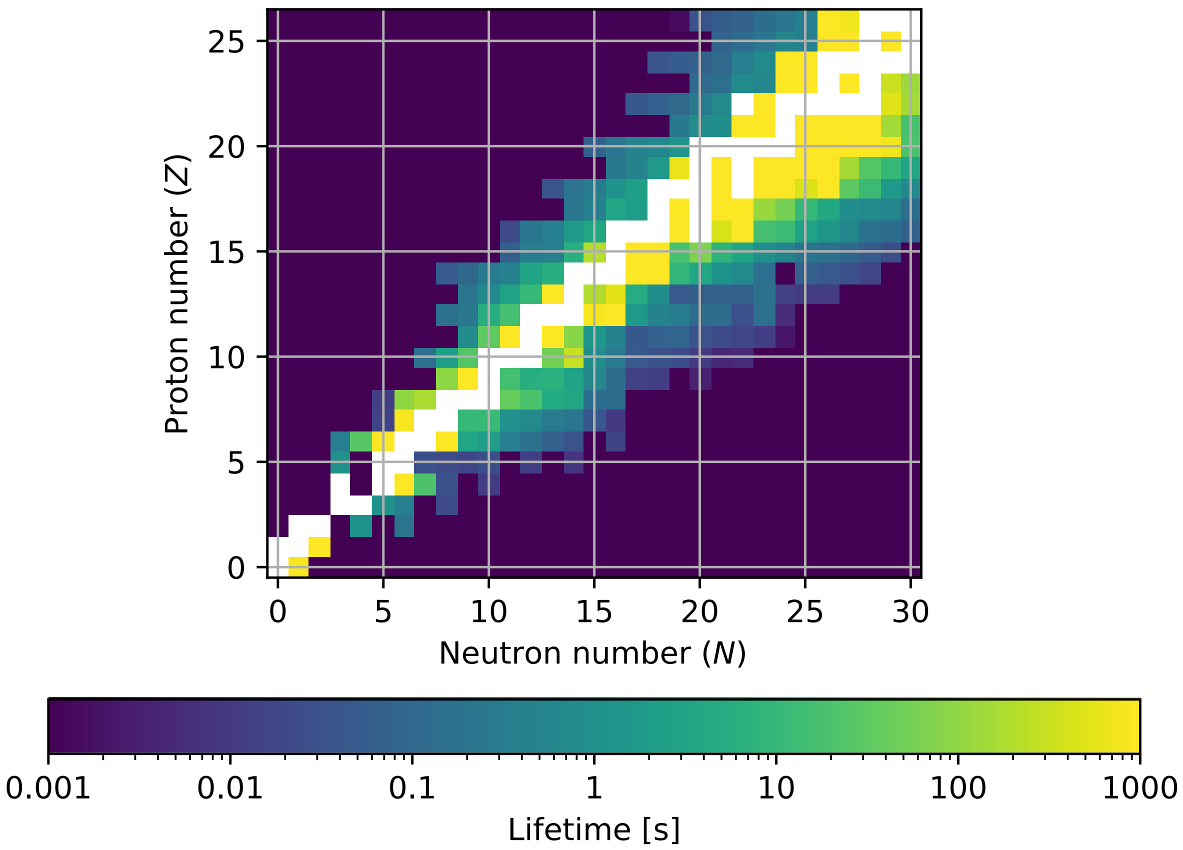

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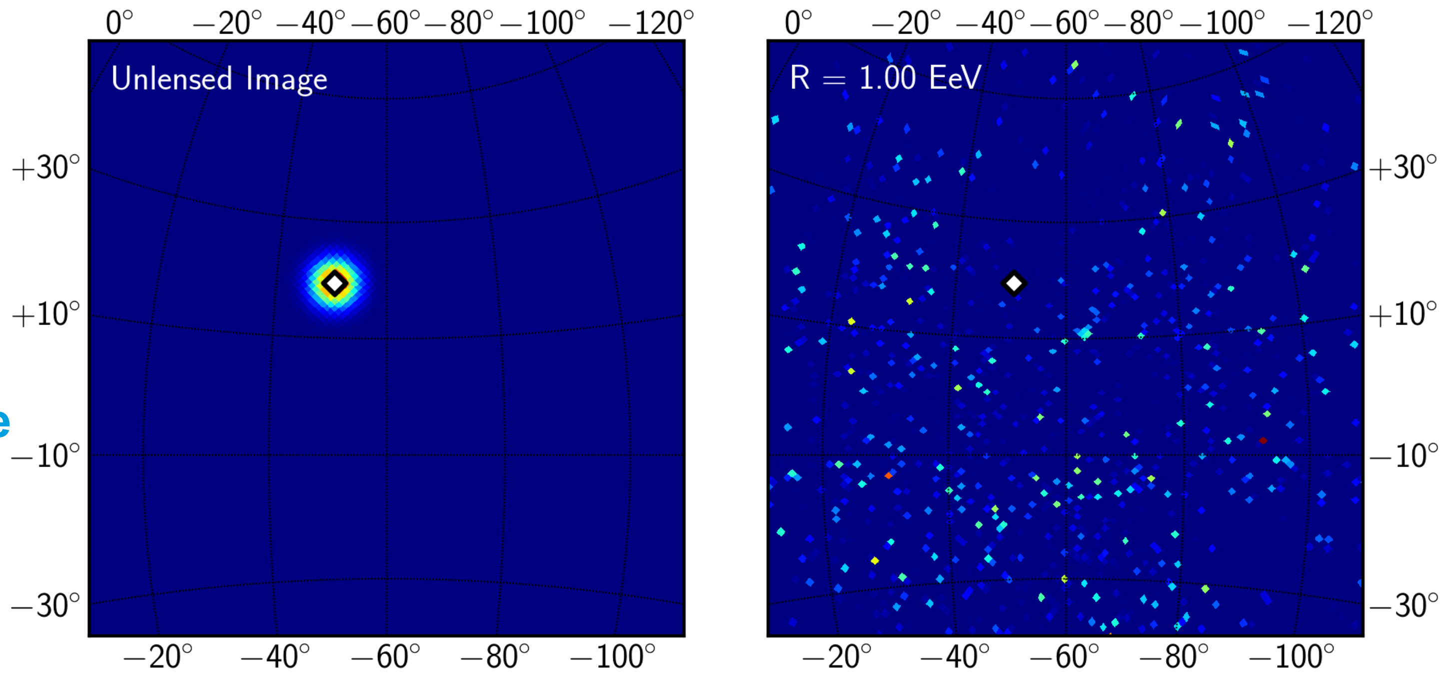


Movie by R. Alves Batista

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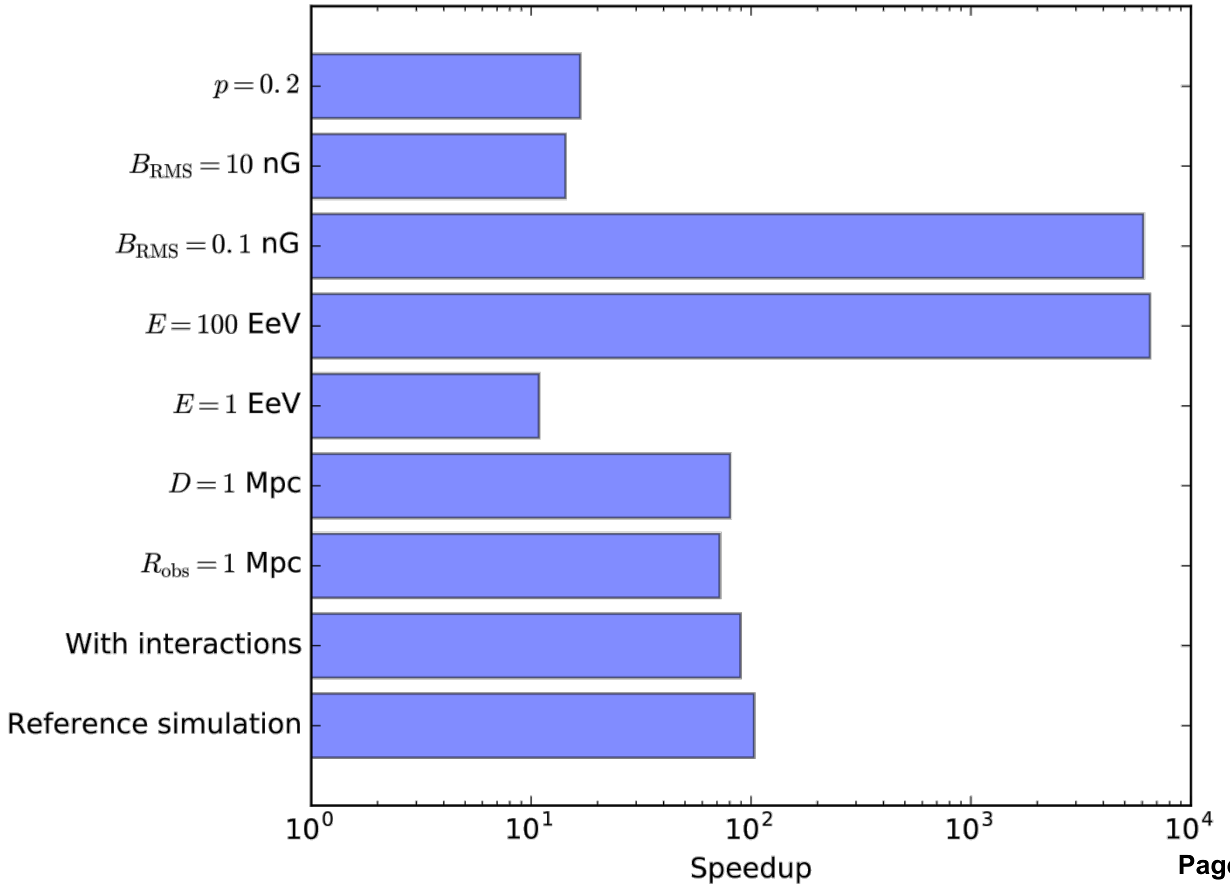

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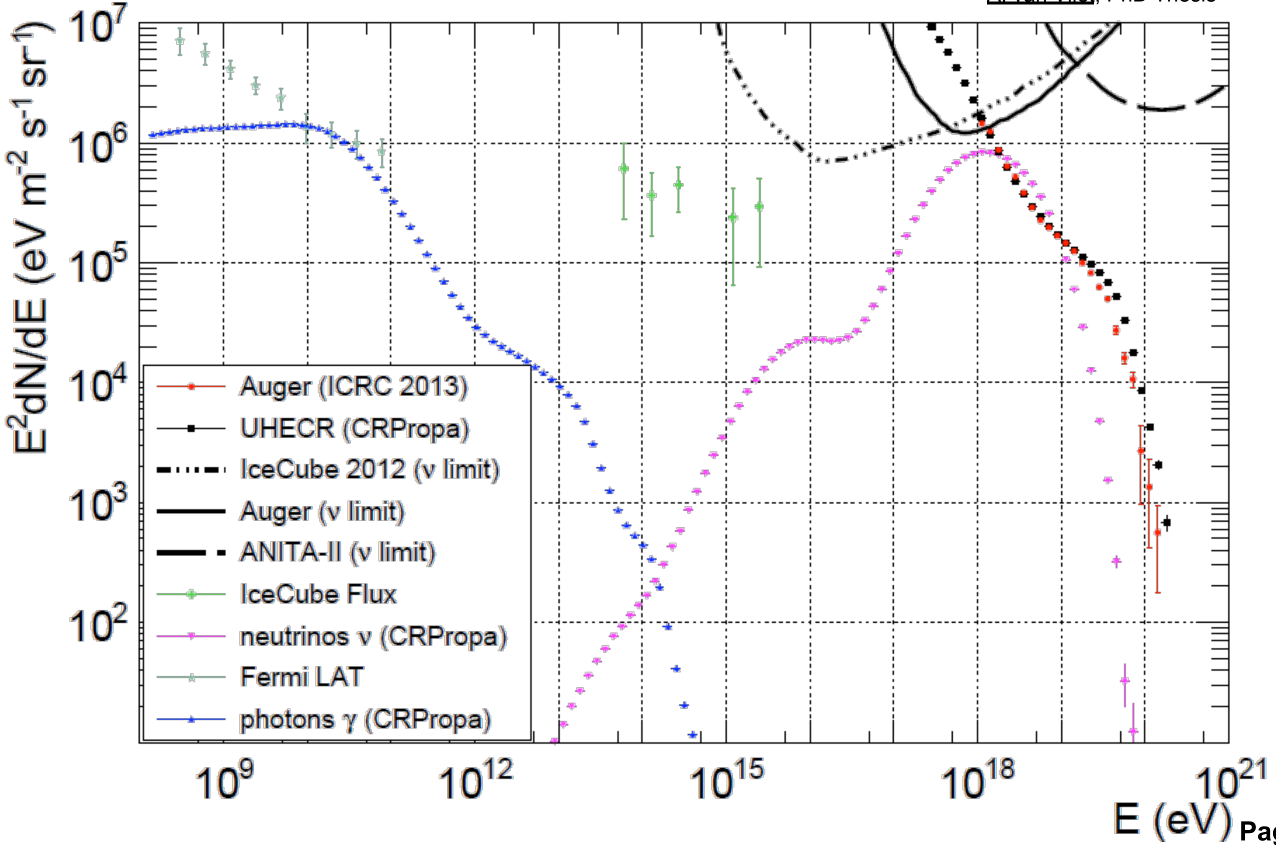
A. van Vliet, PhD Thesis



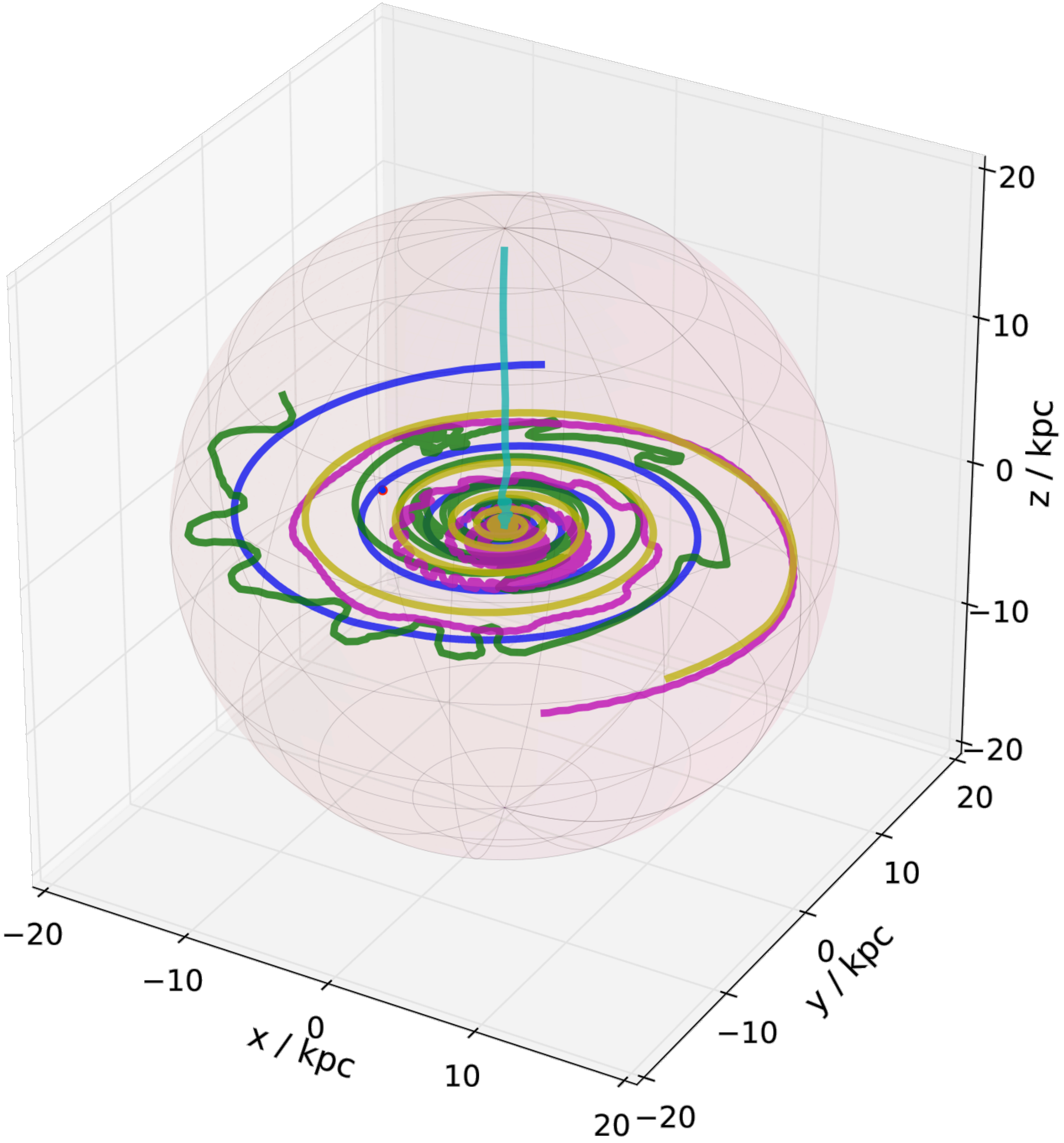
# Galactic cosmic rays

# 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

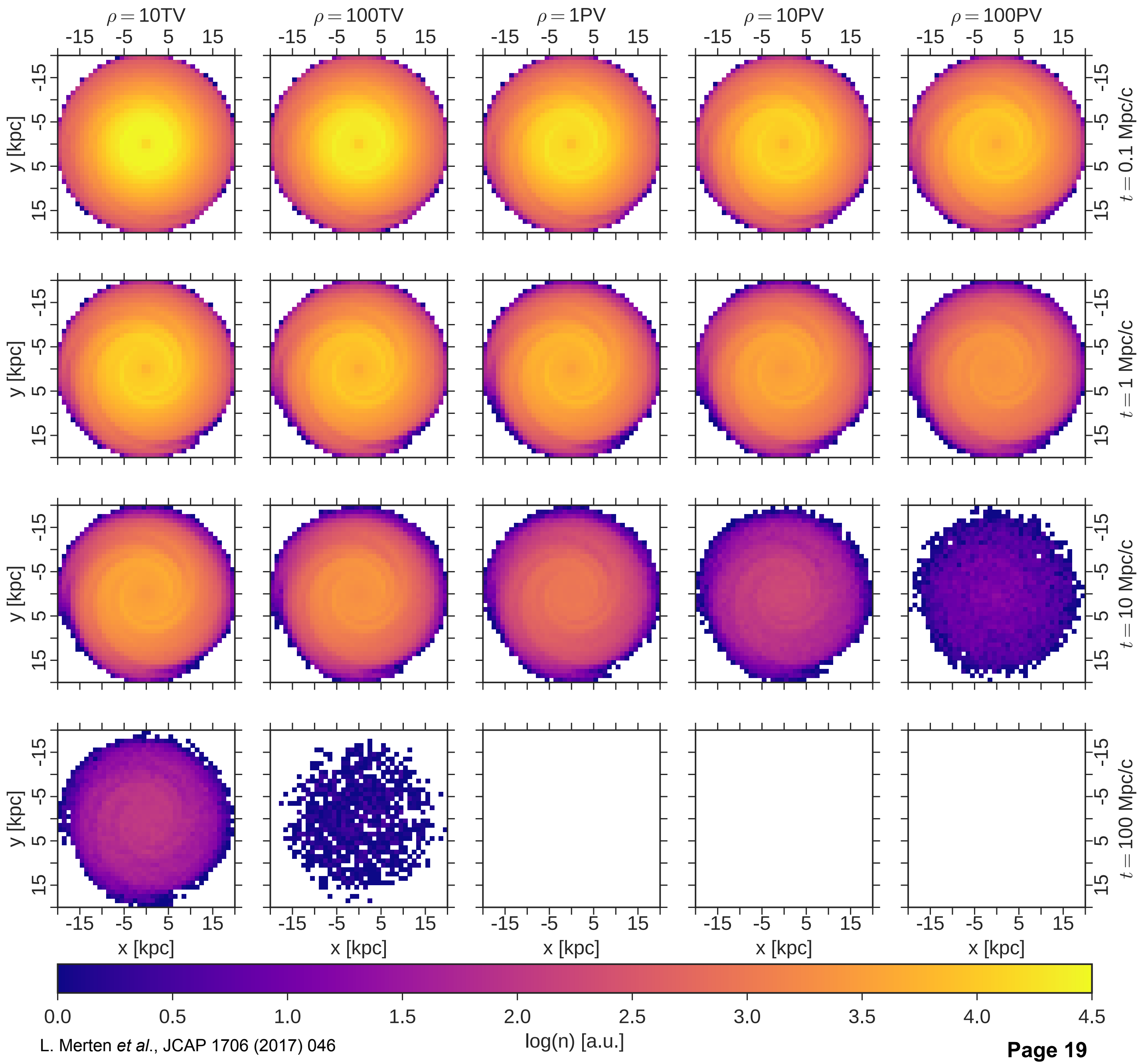
## Multi-particle diffusion approach (new in 3.2)

### 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

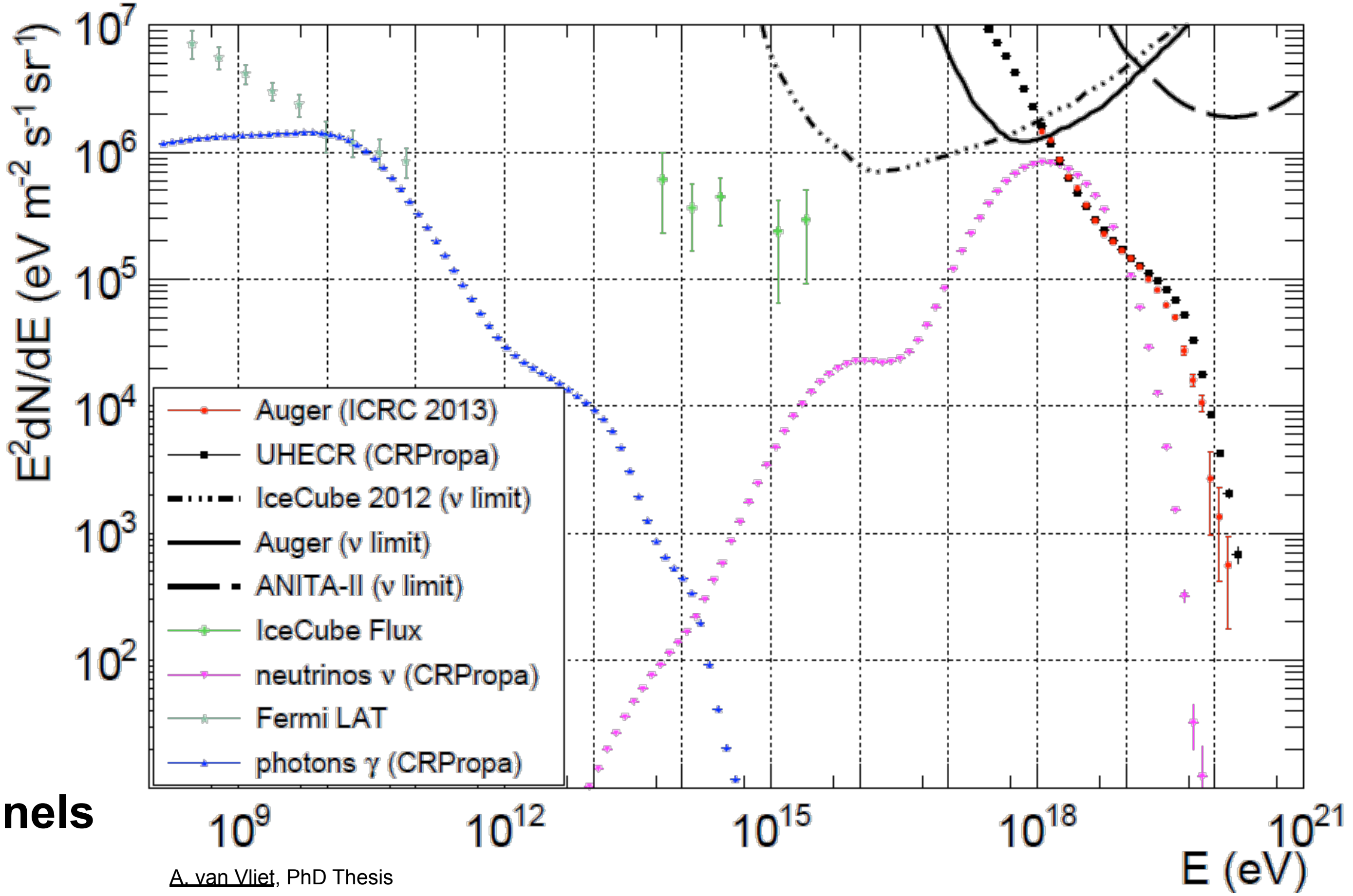
- **DINT**
- EleCa
- Propagation using CRPropa (new in 3.2)
  - Full modular 3D treatment of EM cascades

## 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

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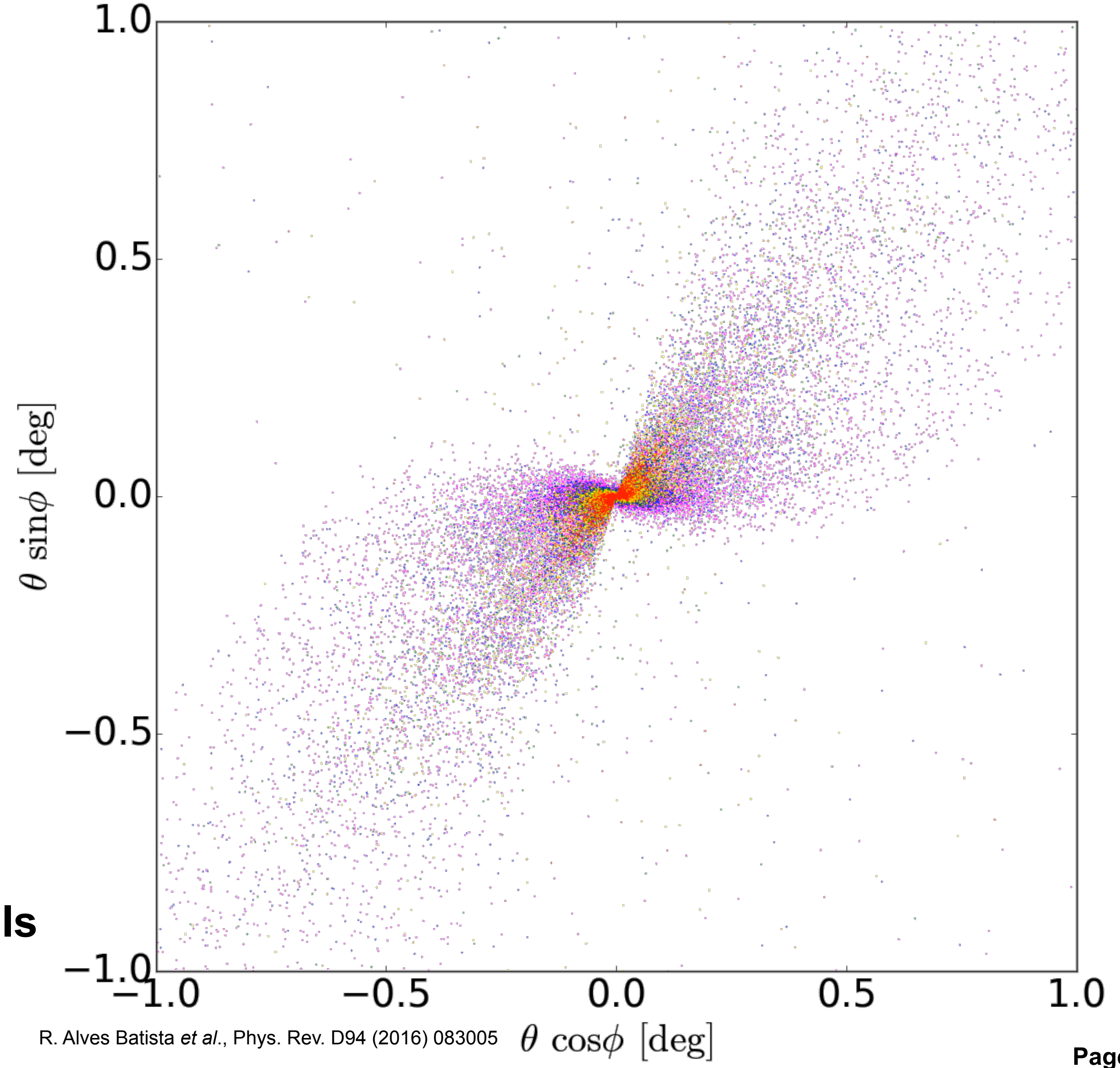
**New in 3.2: additional photon production channels**

**Morphology of blazar pair haloes**



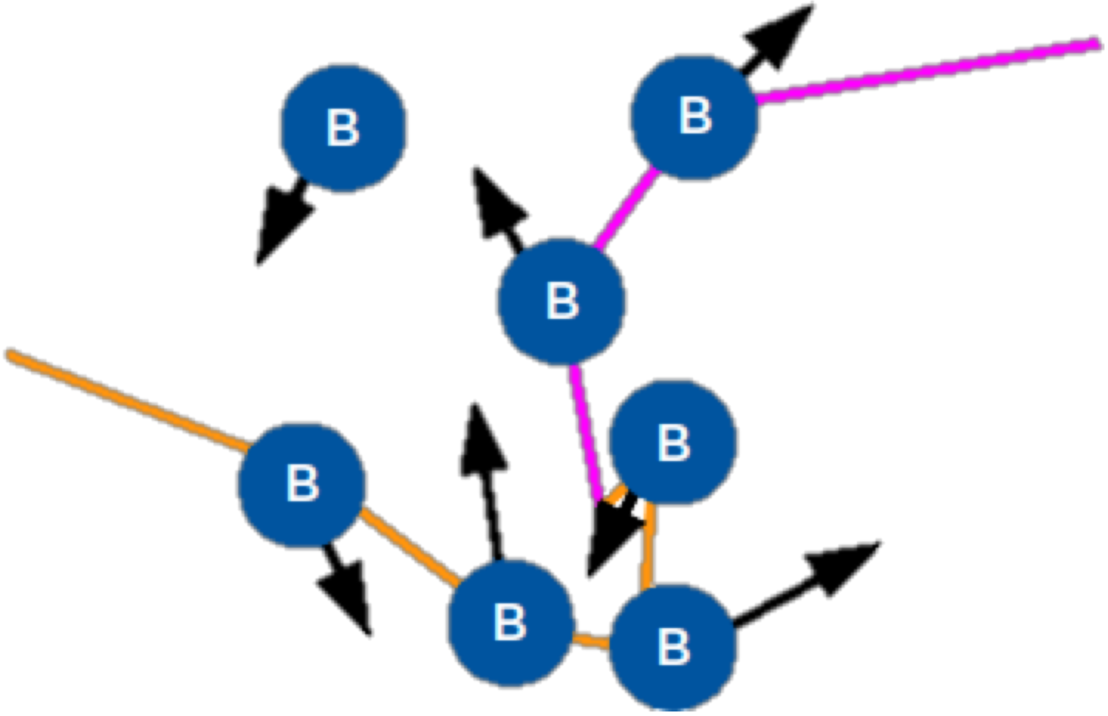

R. Alves Batista *et al.*, Phys. Rev. D94 (2016) 083005

# Diffusive shock acceleration (new in 3.2)

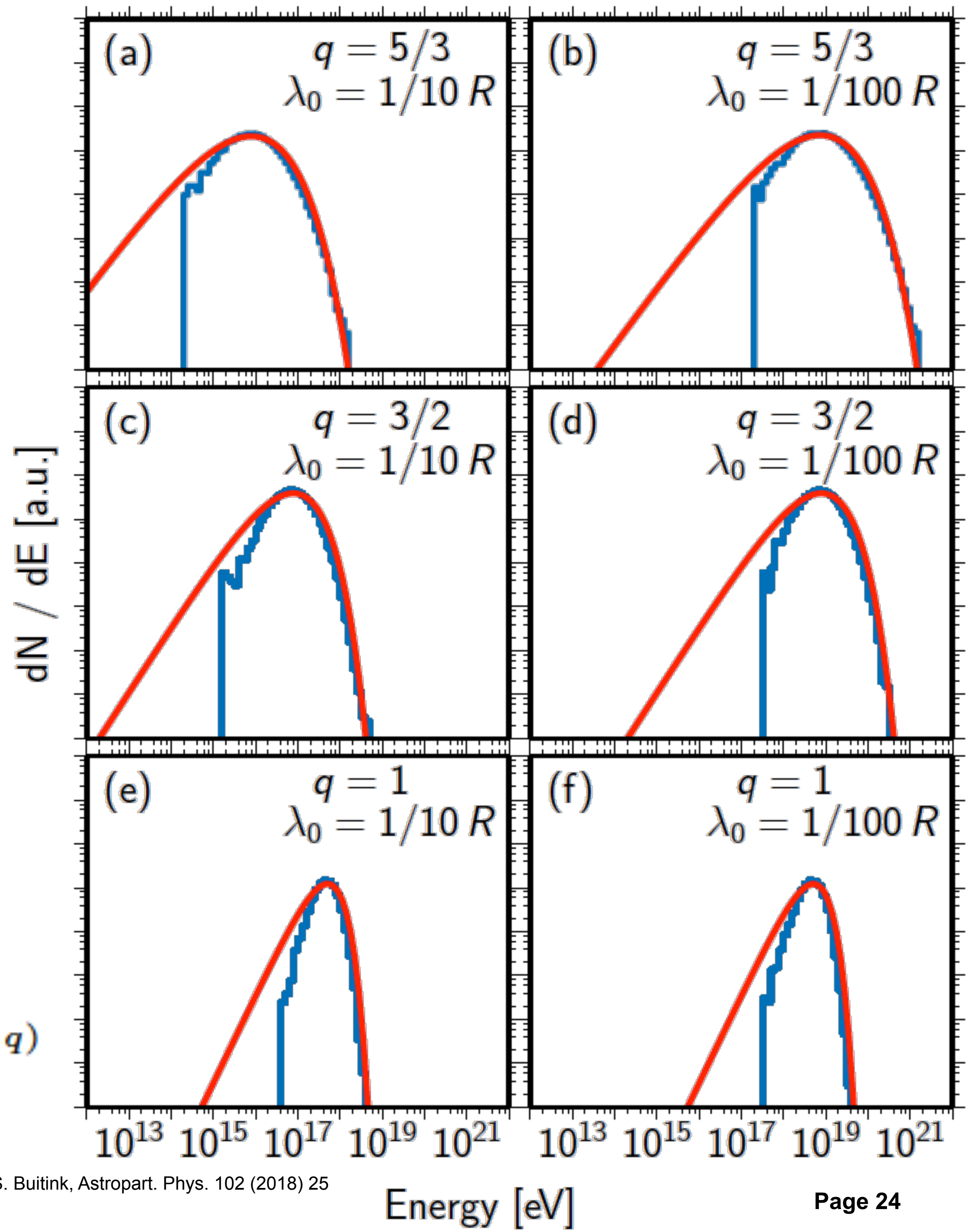
# Diffusive shock acceleration

**Second order**

- Acceleration at random scattering centres




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

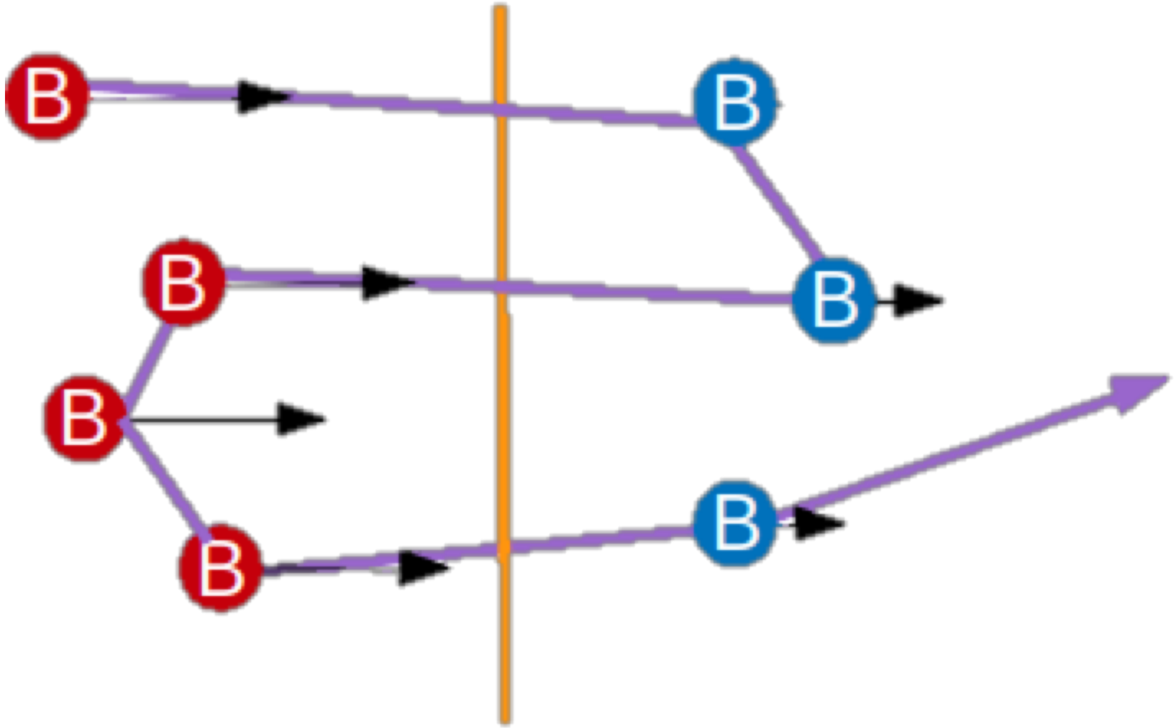


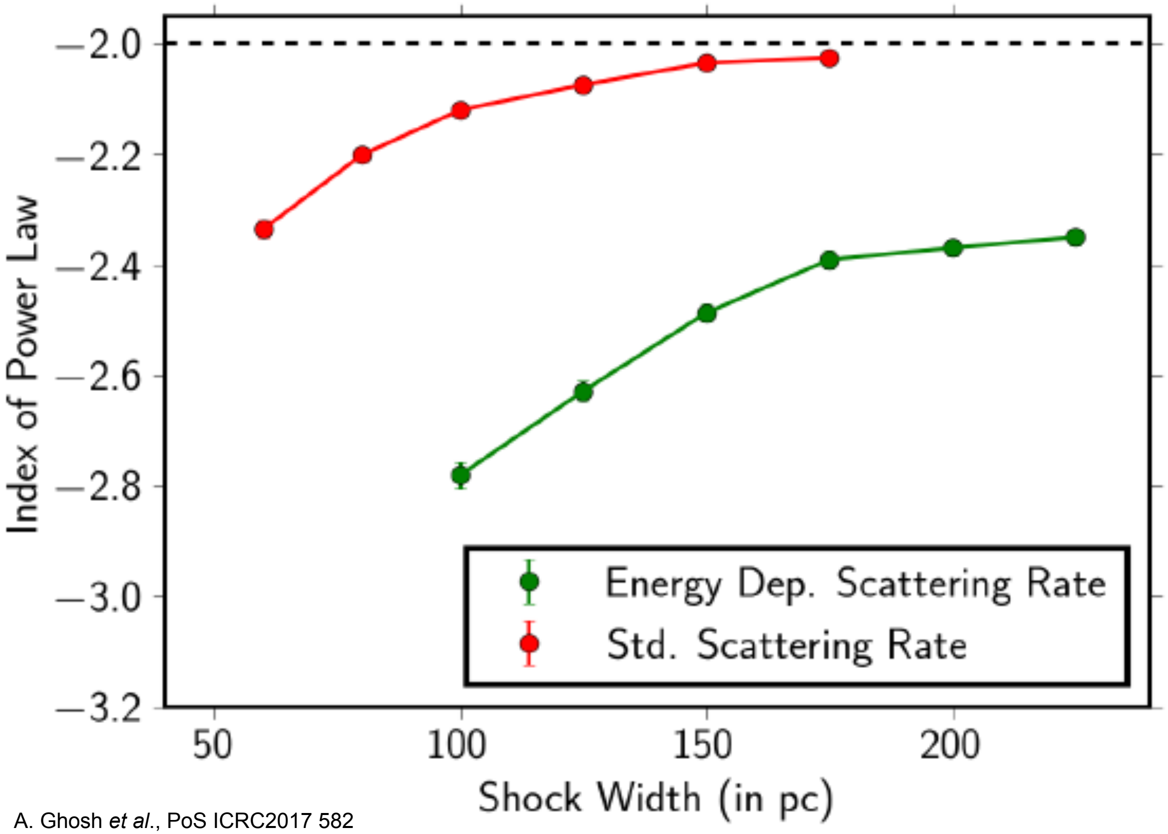

T. Winchen and S. Buitink, Astropart. Phys. 102 (2018) 25

# Diffusive shock acceleration

**First order**

- Acceleration at directed scattering centres




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

# Extragalactic CRs example: Cosmogenic neutrinos

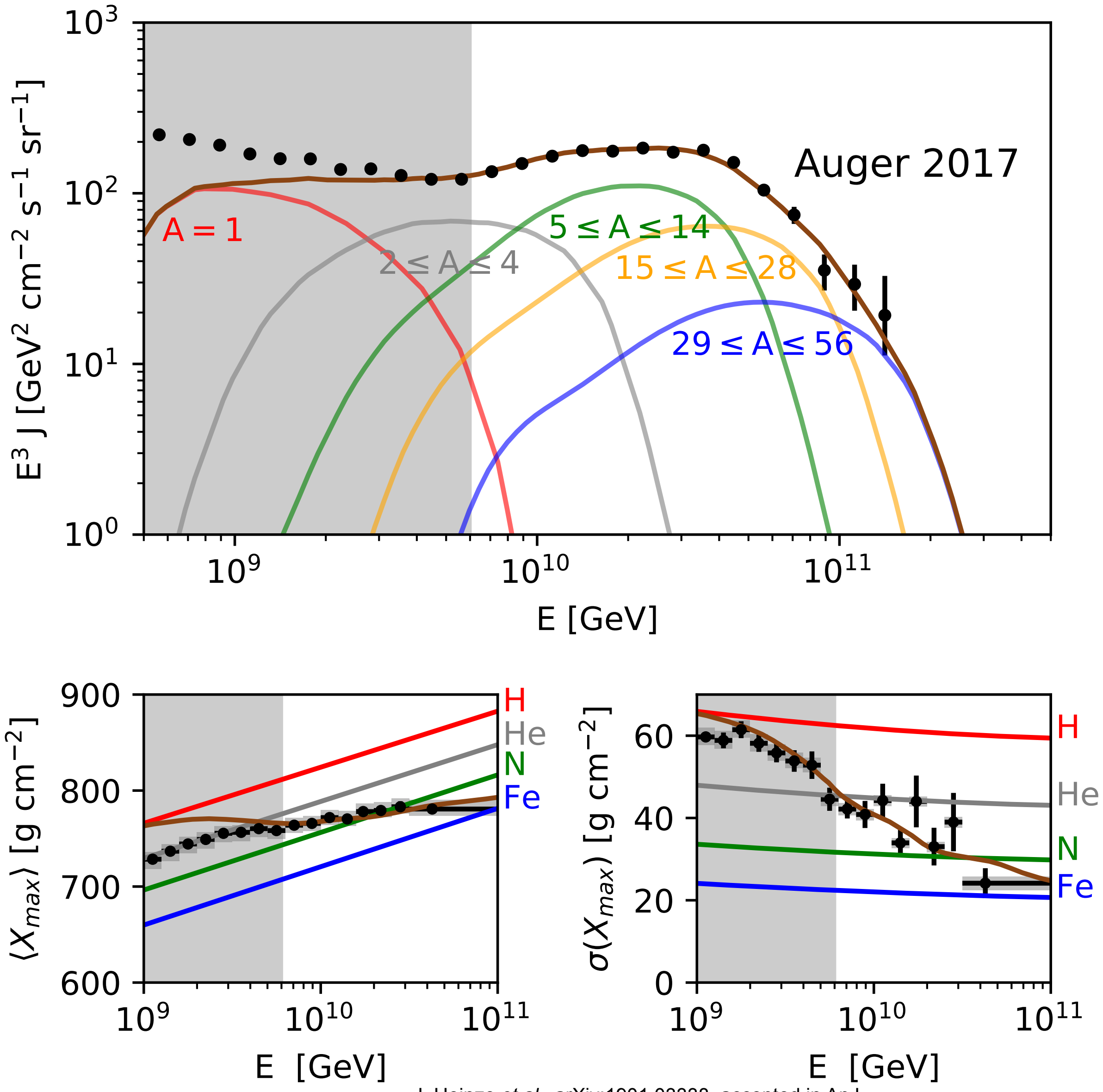
# Combined fit

- Continuous source distribution of identical sources
- Composition at the sources:

  Intermediate to heavy,

  no protons at highest *E*
- Spectrum at the sources:

  Power law with rigidity-dependent cut-off
- $\gamma < 0.5$, hard spectral index
- $R_{max} < 4$ EV, low max. rigidity




J. Heinze *et al.*, arXiv:1901.03338, accepted in ApJ

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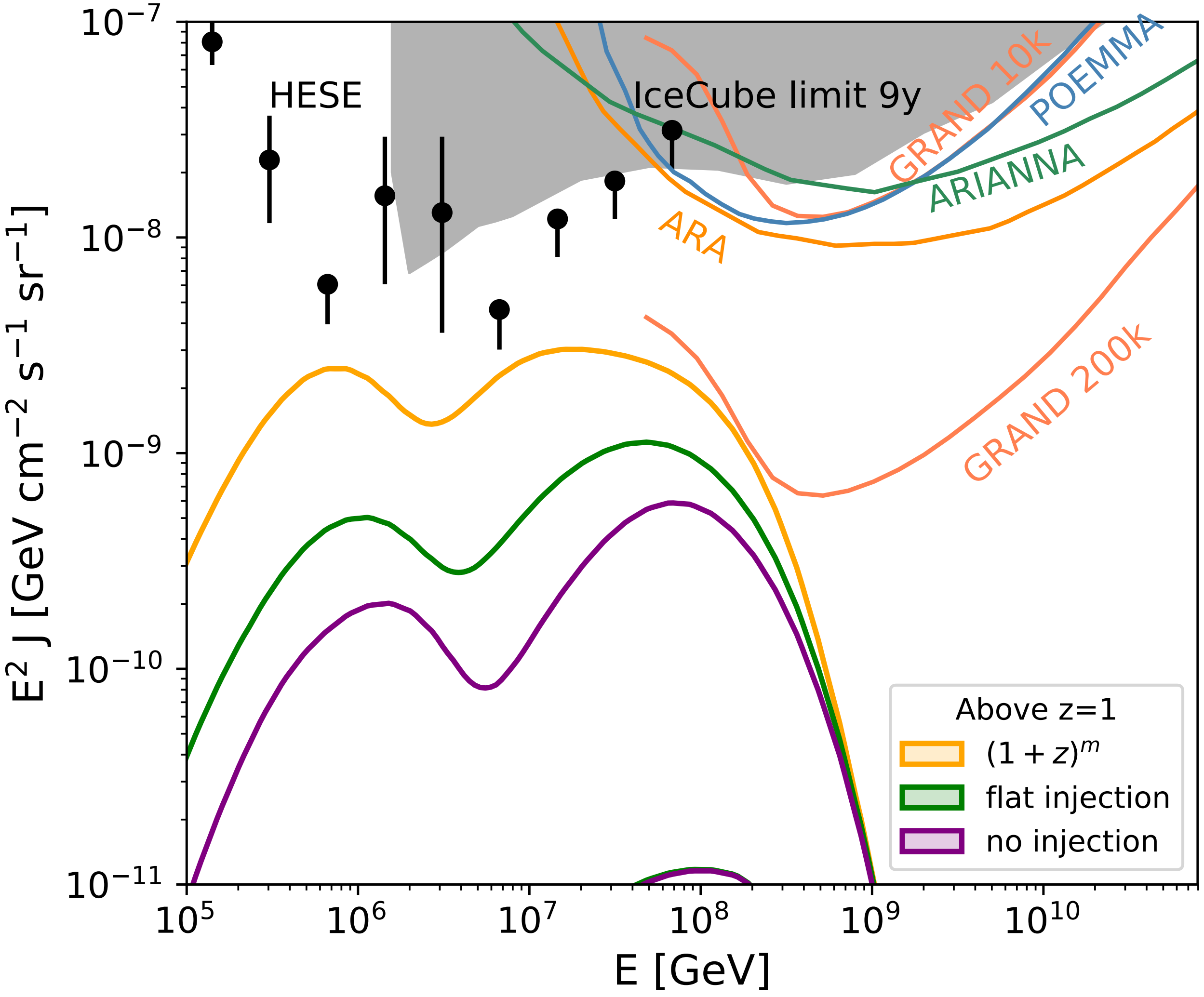


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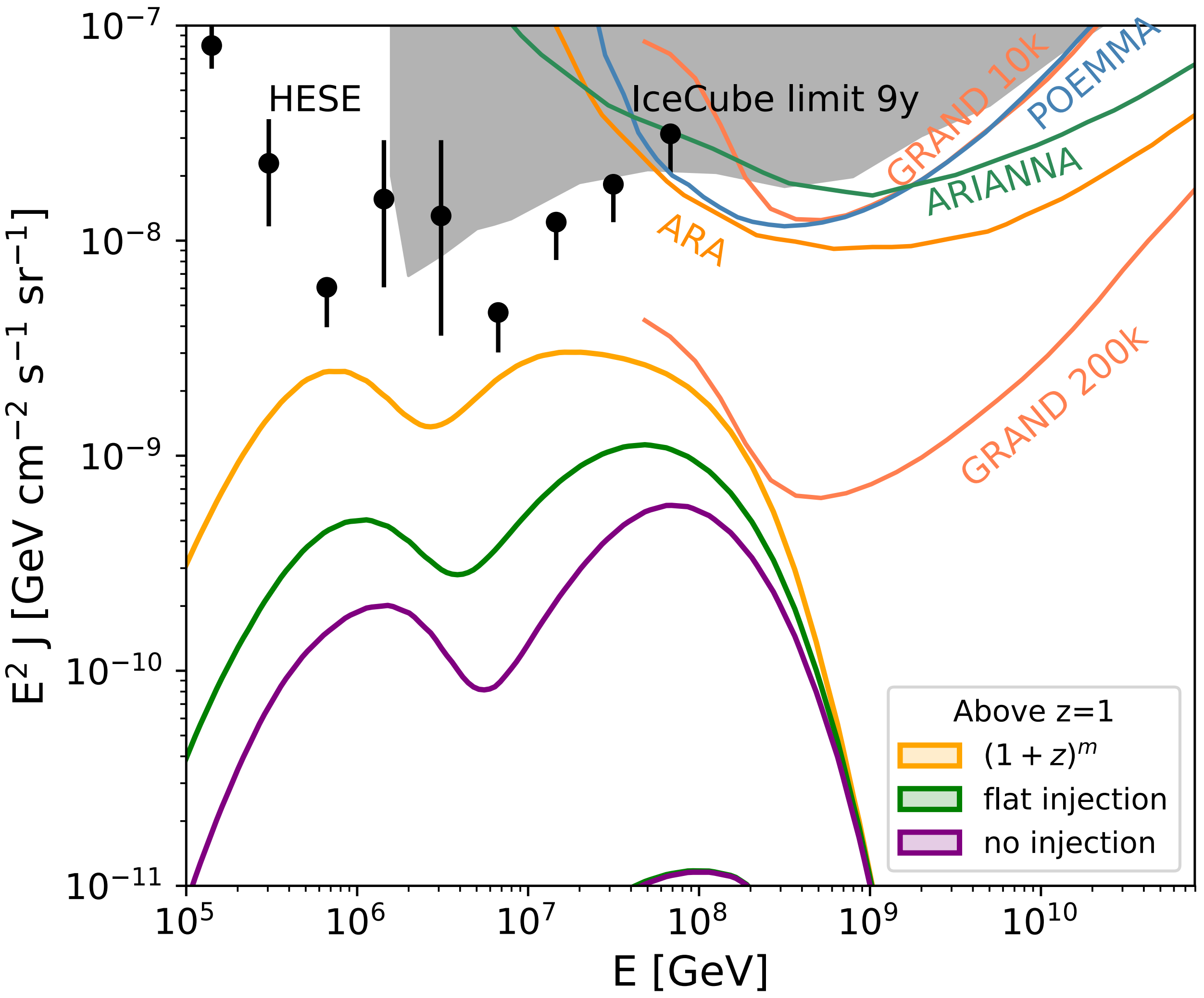


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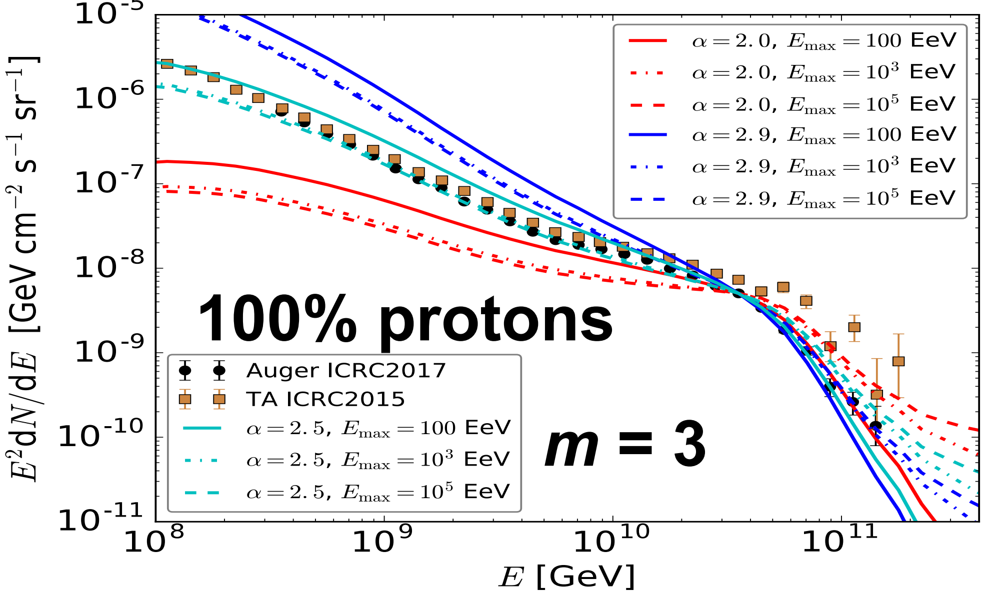
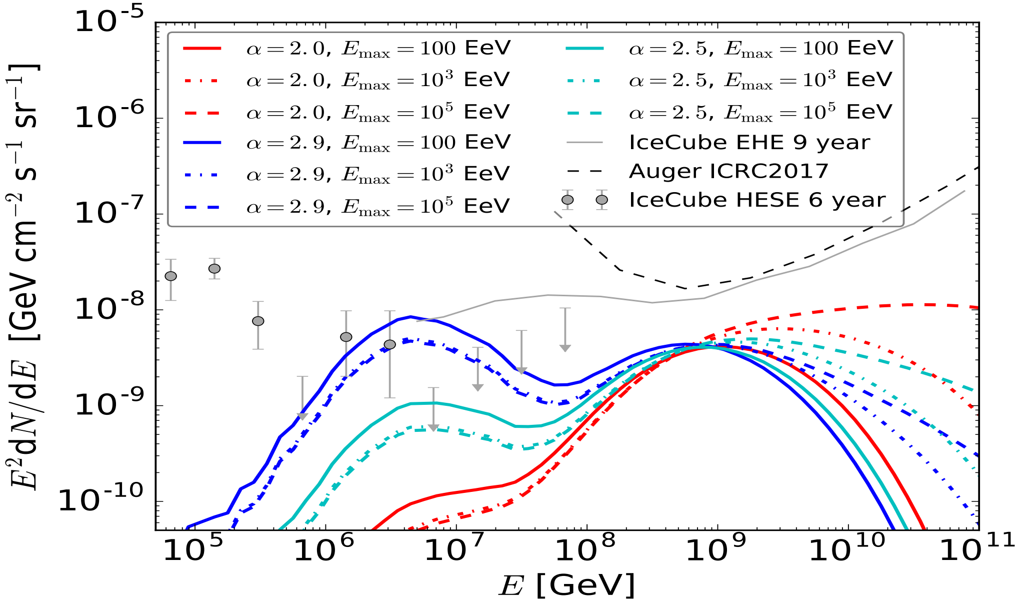
# Neutrinos at ~1 EeV

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

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

A. van Vliet, J. R. Hörandel and R. Alves Batista, arXiv:1901.01899, subm. to PRL



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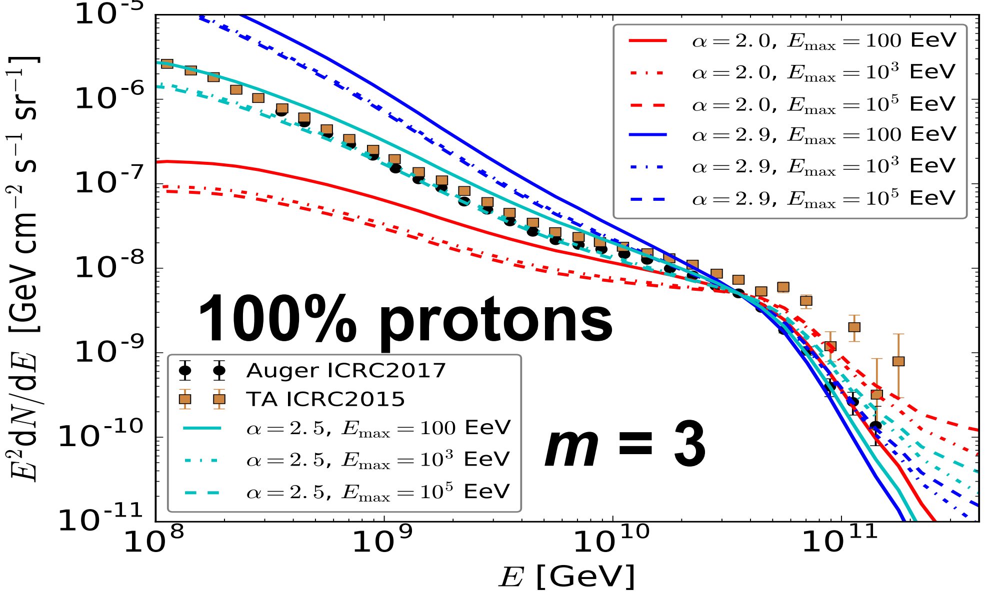
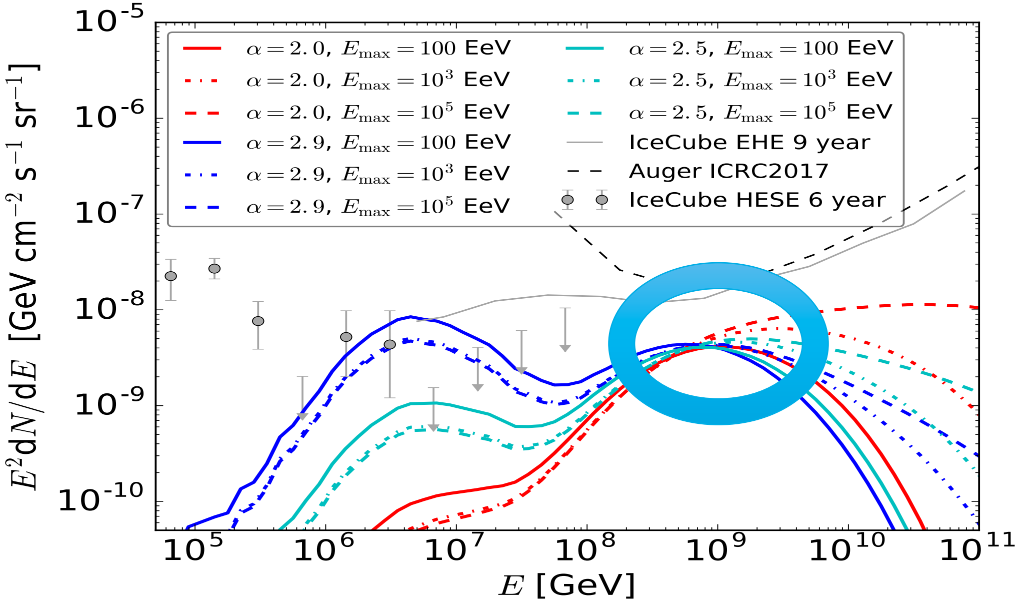
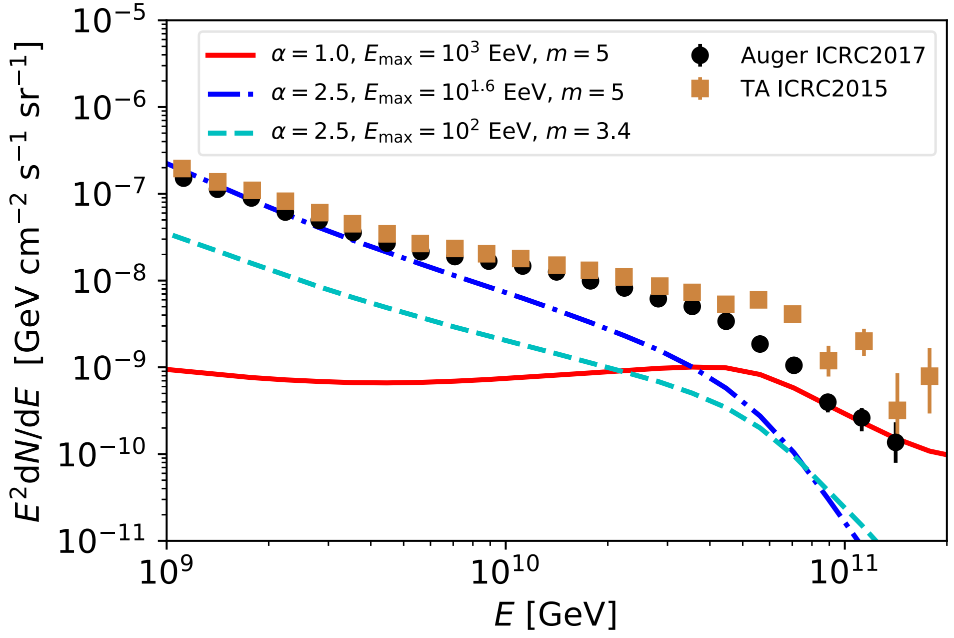
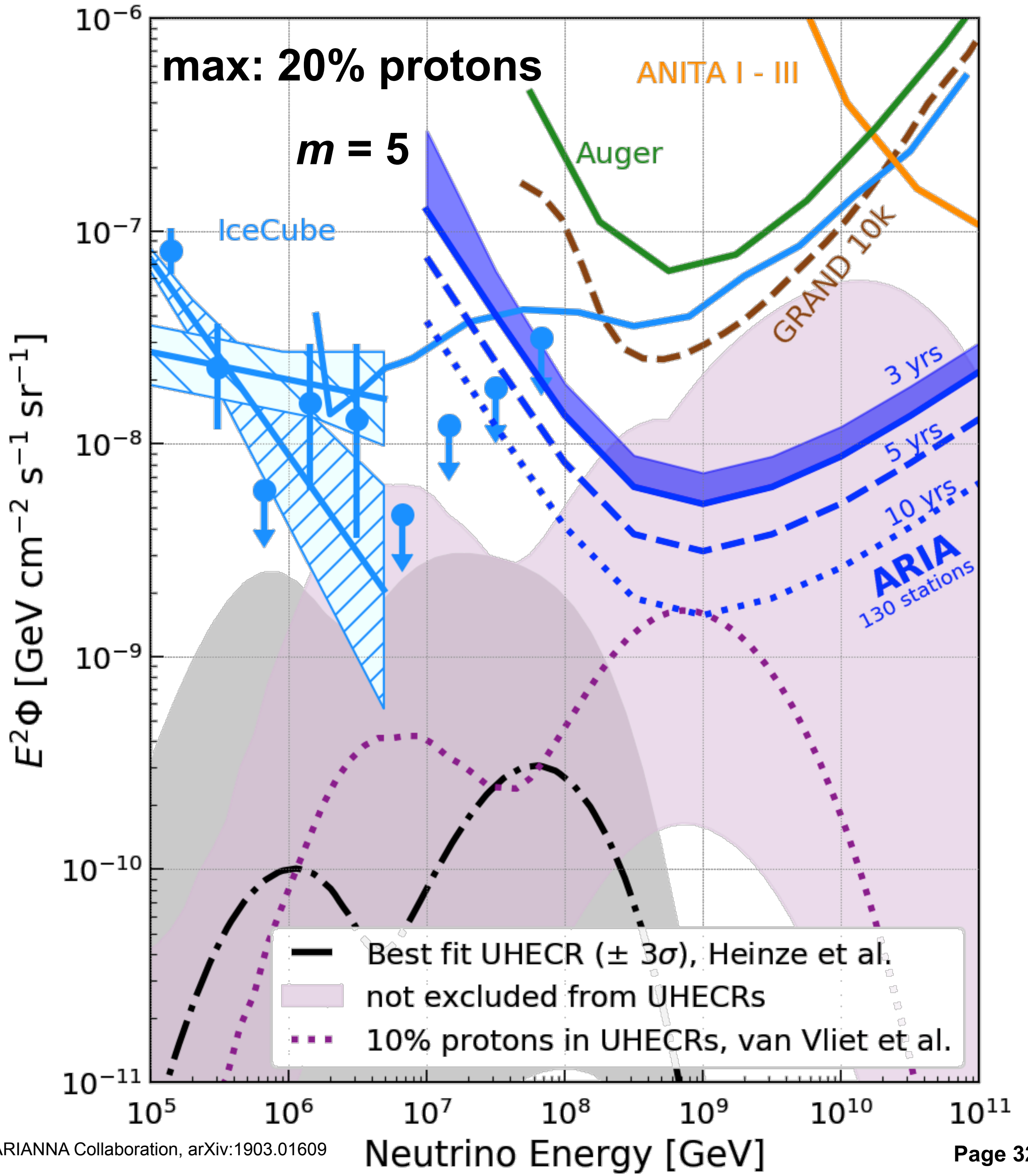


# Neutrinos from subdominant proton component

- 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
  - $m < 5$



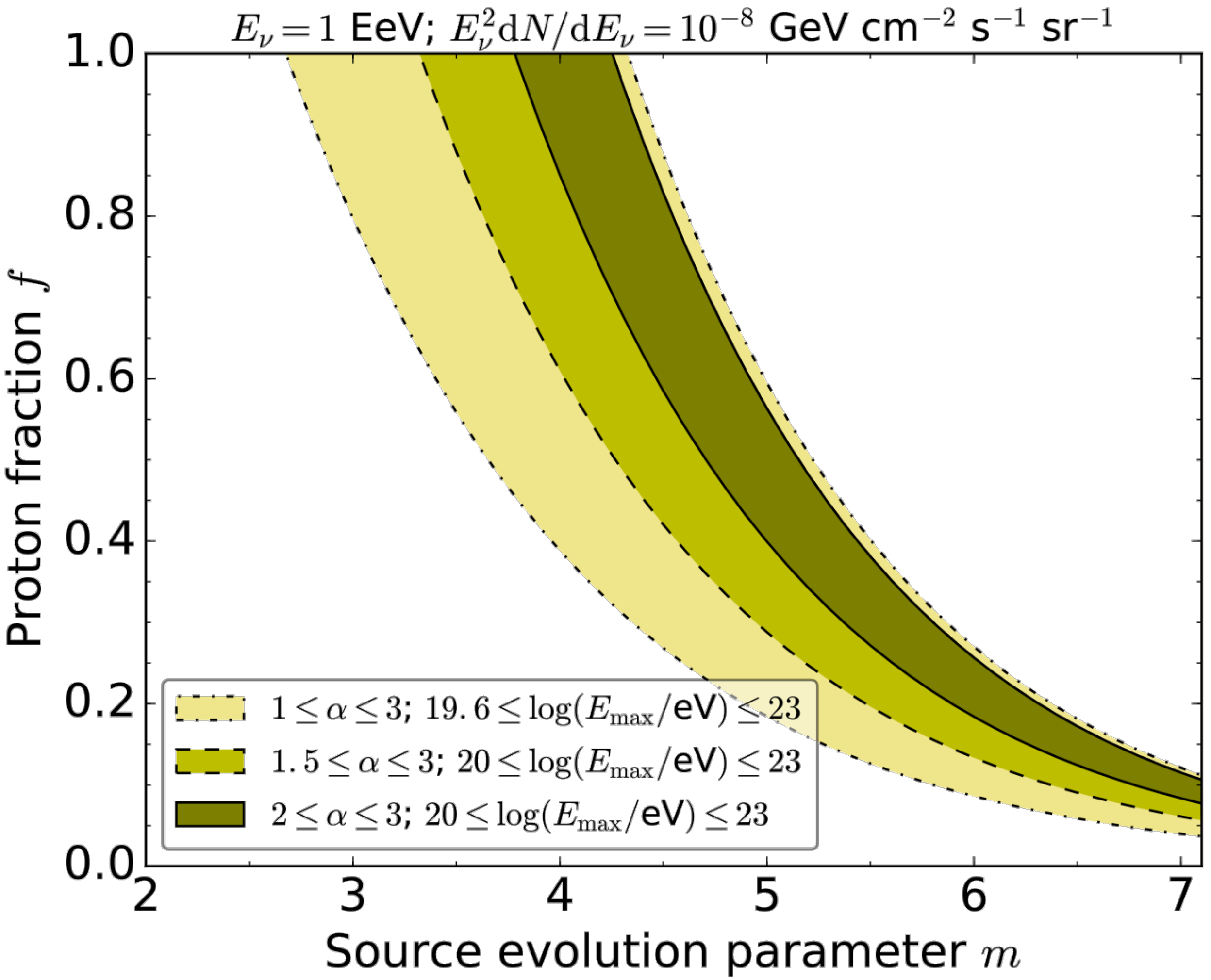




ARIANNA Collaboration, arXiv:1903.01609

# Current sensitivity

- 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

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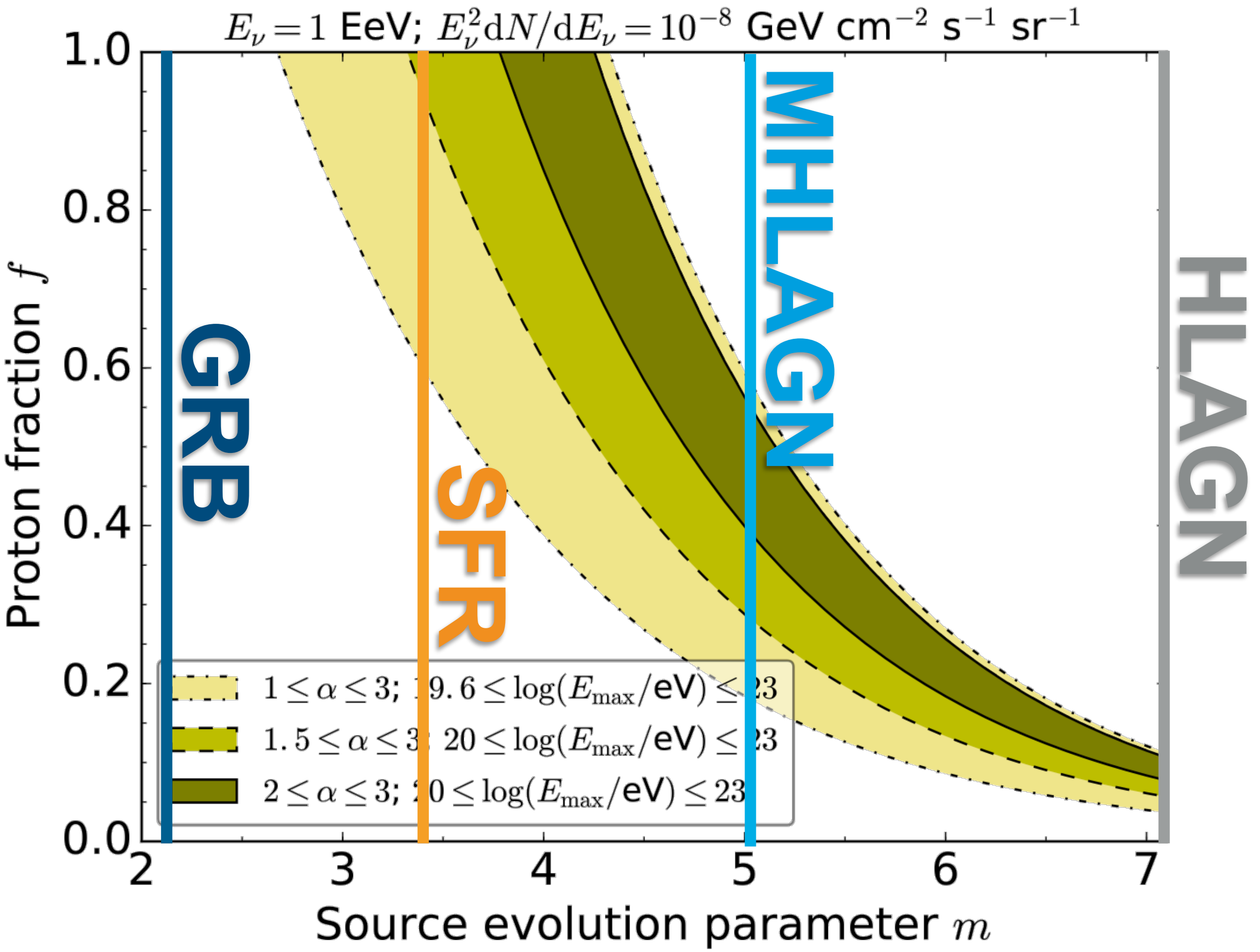
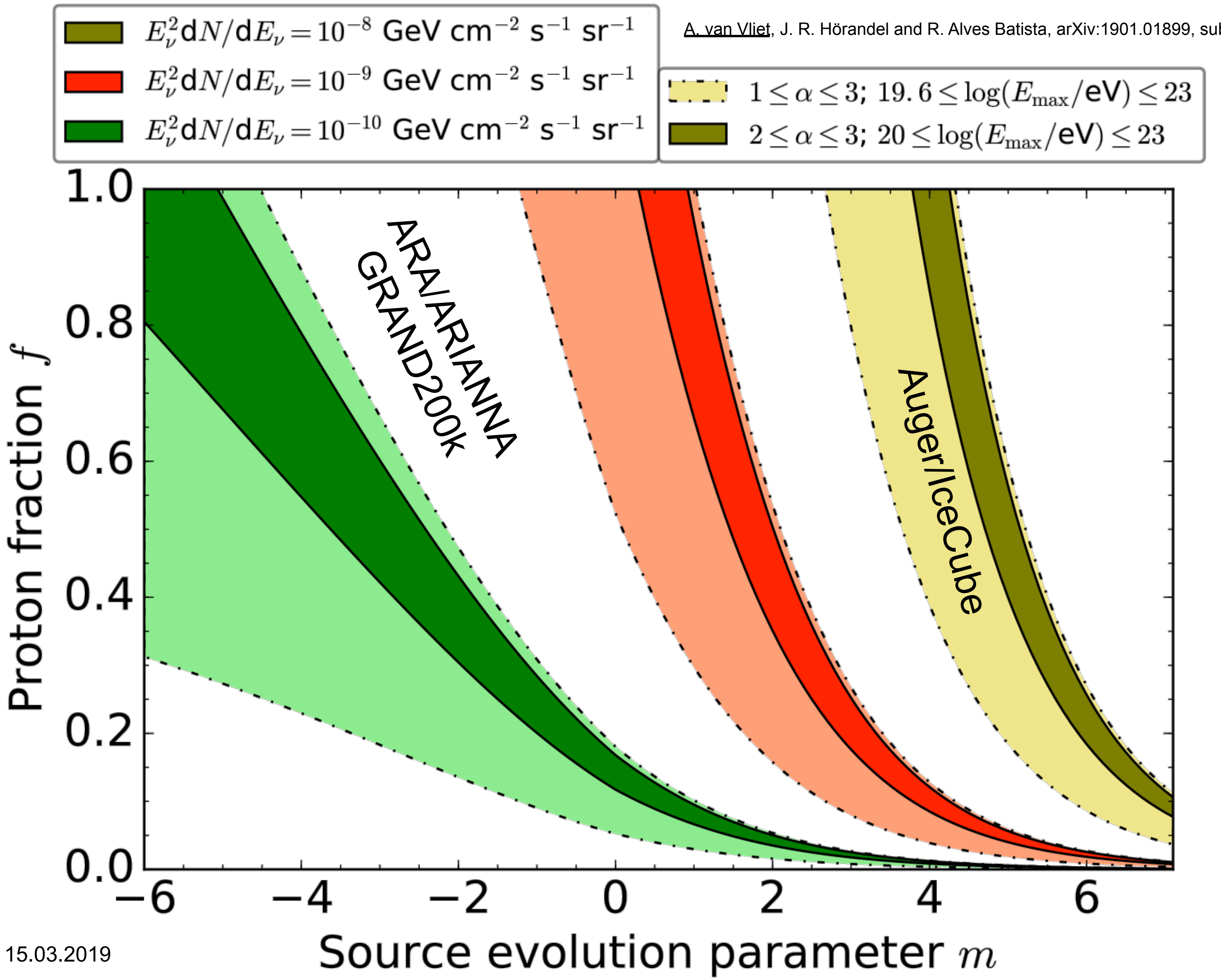



A. van Vliet, J. R. Hörandel and R. Alves Batista, arXiv:1901.01899, subm. to PRL

# Upcoming experiments

A. van Vliet, J. R. Hörandel and R. Alves Batista, arXiv:1901.01899, subm. to PRL



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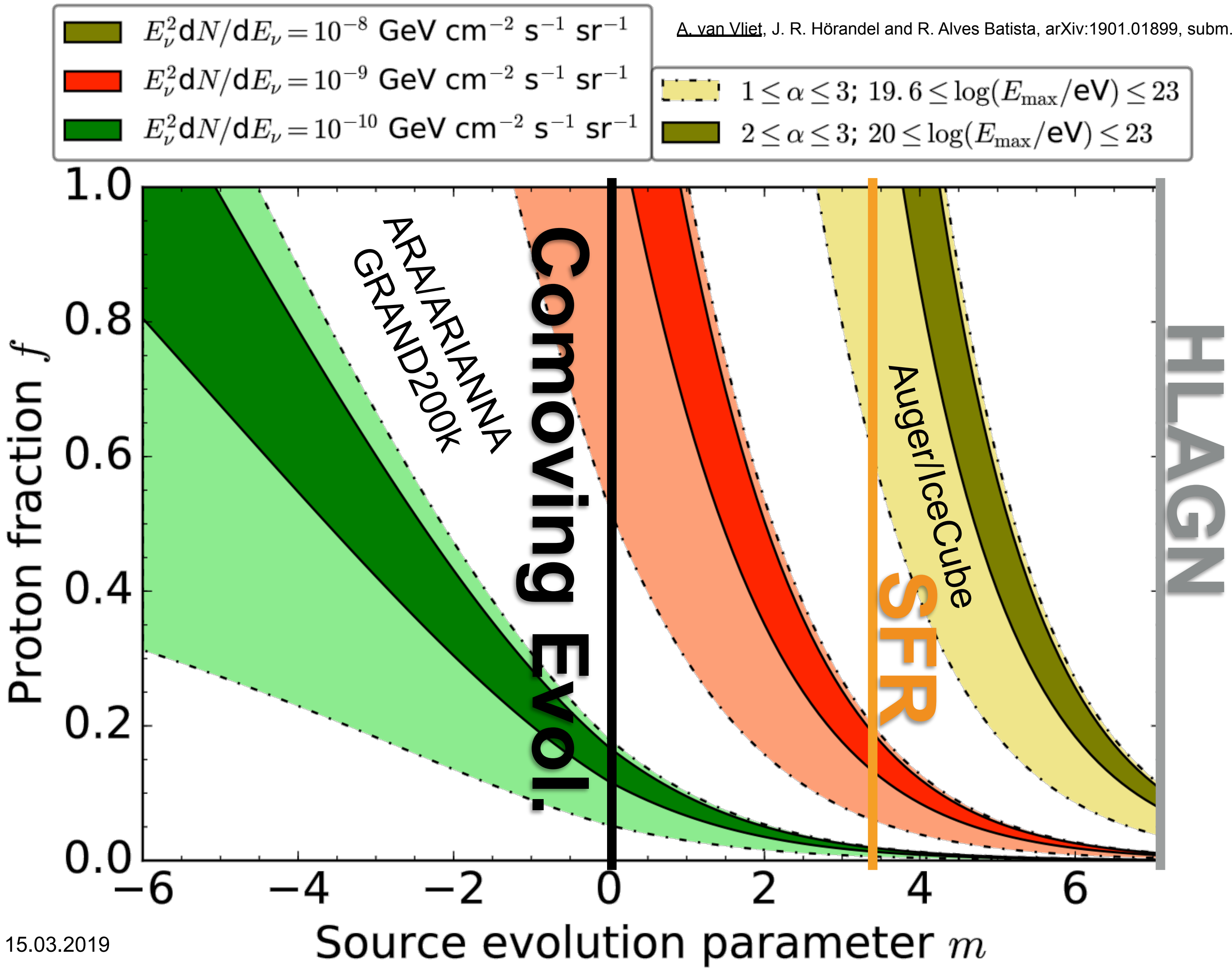
A. van Vliet, J. R. Hörandel and R. Alves Batista, arXiv:1901.01899, subm. to PRL



# 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

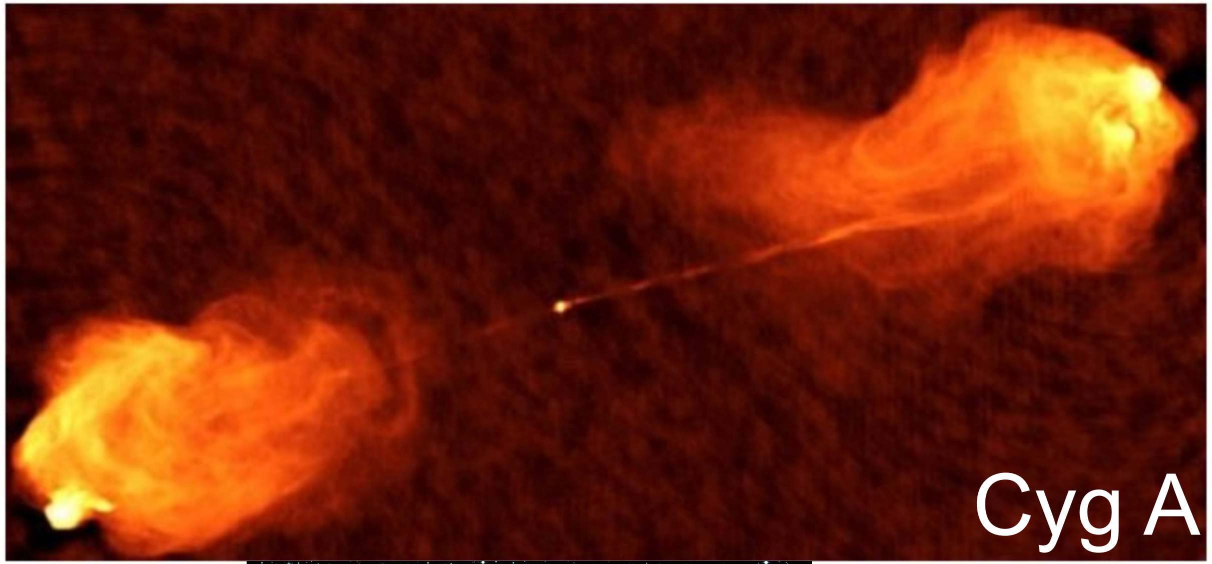
# Extragalactic CRs example: UHECRs from radio galaxies

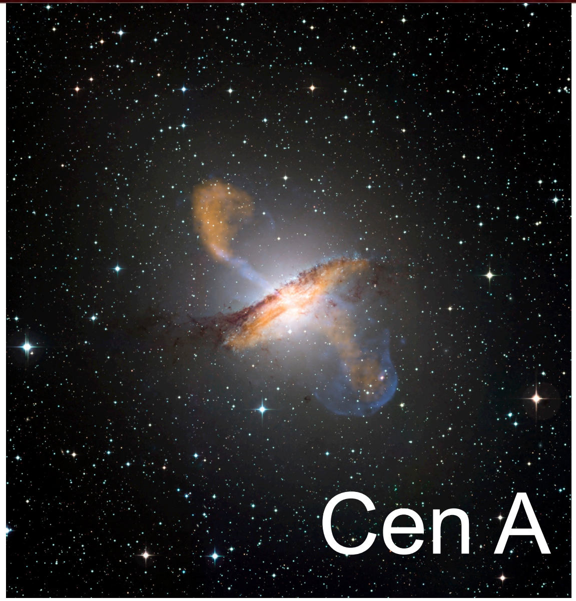
B. Eichmann, J. Rachen, L. Merten, A. van Vliet and J. Becker Tjus, JCAP 1802 (2018) 036

# Radio galaxies (radio-loud AGN)

**Potential sources of UHECRs**

- FR-II: very powerful but very rare
  distance > 100 Mpc
  brightest: Cygnus A (~250 Mpc)
- FR-I: less powerful but more common
  closest: Centaurus A at ~3 Mpc
- Catalogue: Van Velzen *et al.* 2012
  3D position + radio luminosity



# Environment

- Interactions with CMB and EBL
- EGMF: Dolag *et al.* 2005,
  constrained LSS simulations
  up to ~120 Mpc from Earth
- GMF: Jansson & Farrar 2012
- Source distribution:
  - Local RGs, $D < 120$ Mpc, 3D
  - Non-local RGs, $D > 120$ Mpc, 1D

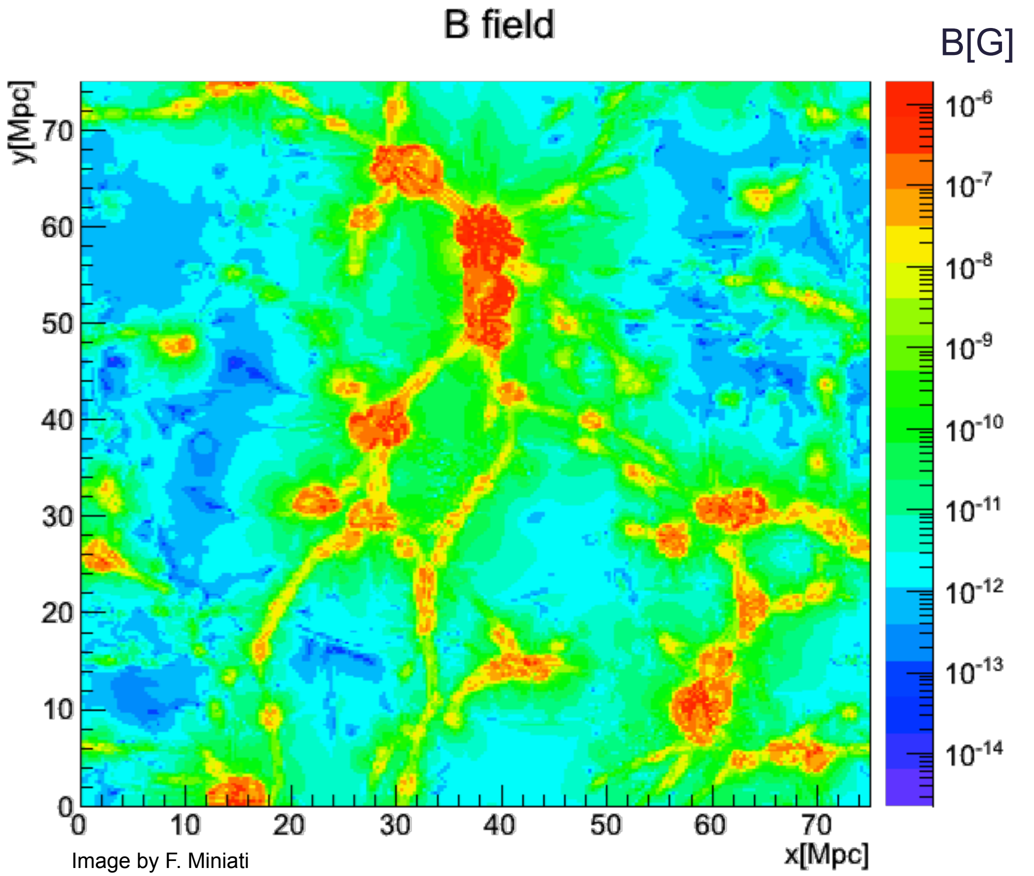
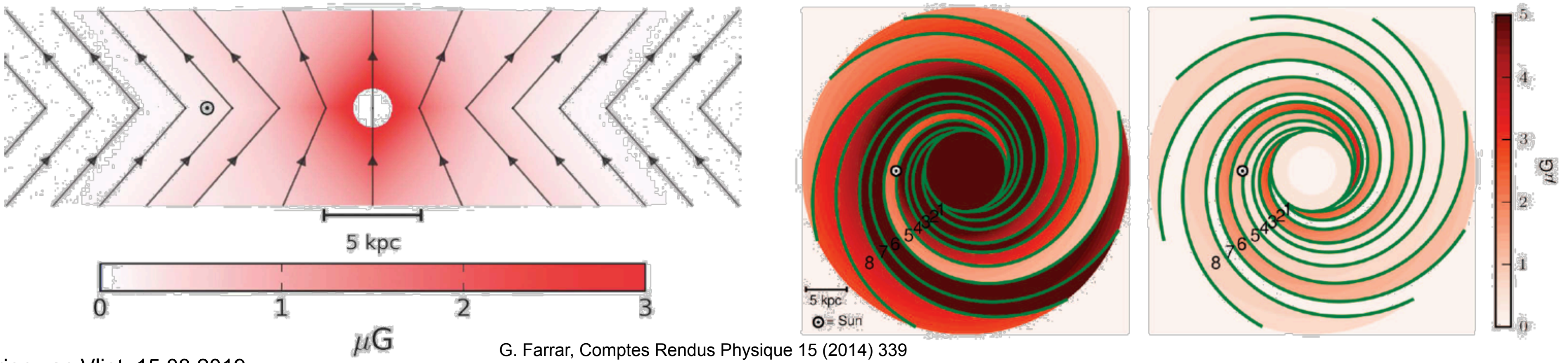



Image by F. Miniati




G. Farrar, Comptes Rendus Physique 15 (2014) 339

# Source setup

- Cosmic-ray power: $Q_{cr}$
- Max. rigidity: $R_{max} = E_{max}/Ze$
- Luminosity $L$ ➔ jet power $Q_{jet}$

  ➔ $Q_{cr}$ and $R_{max}$ for each source

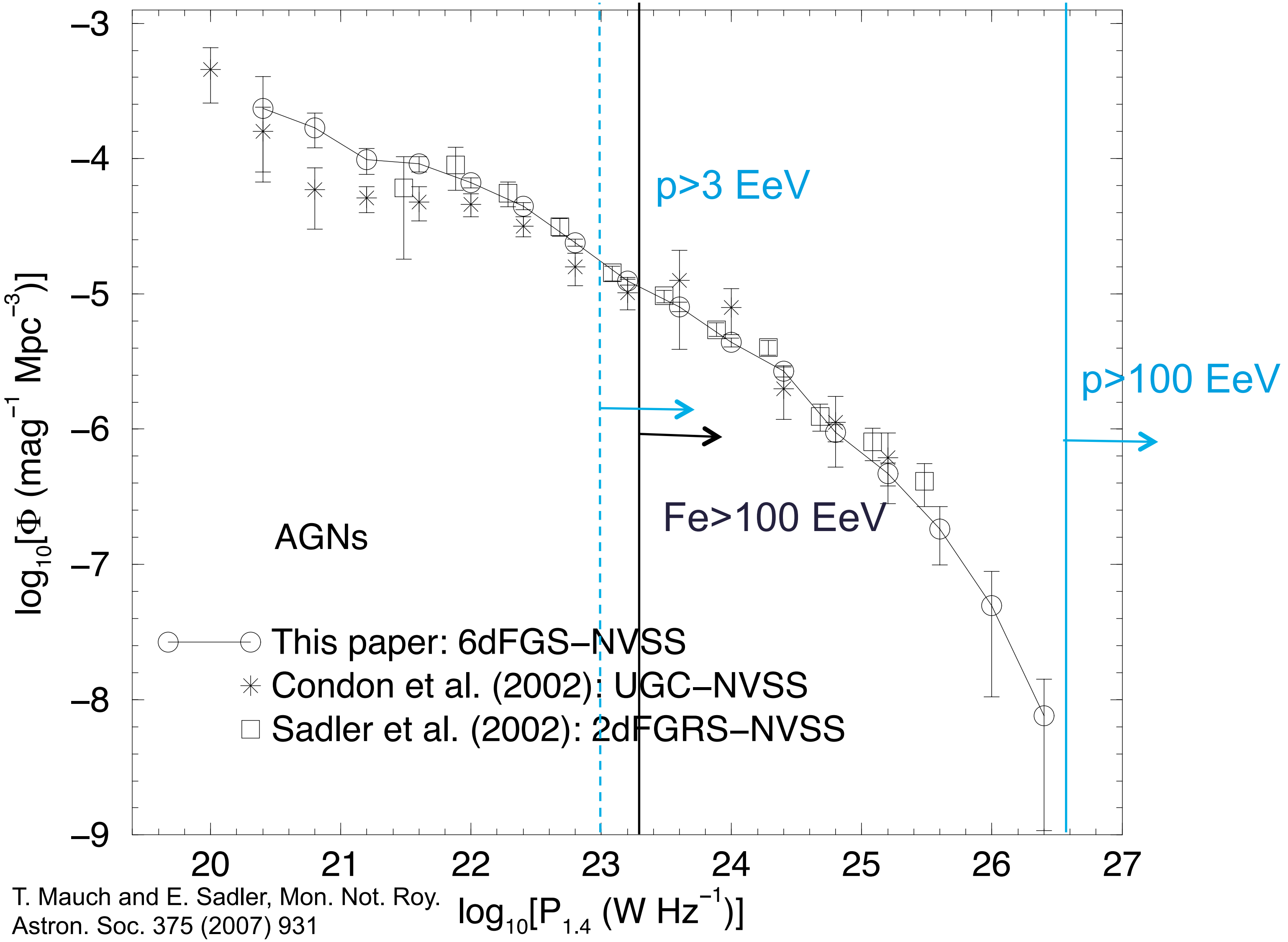
  $$Q_{cr} \propto g_{cr} L_{1.1}^{6/7}$$

  $$R_{max} \propto g_{acc} \sqrt{Q_{cr}}$$

- Initial composition:

  solar abundance × $Z^q$

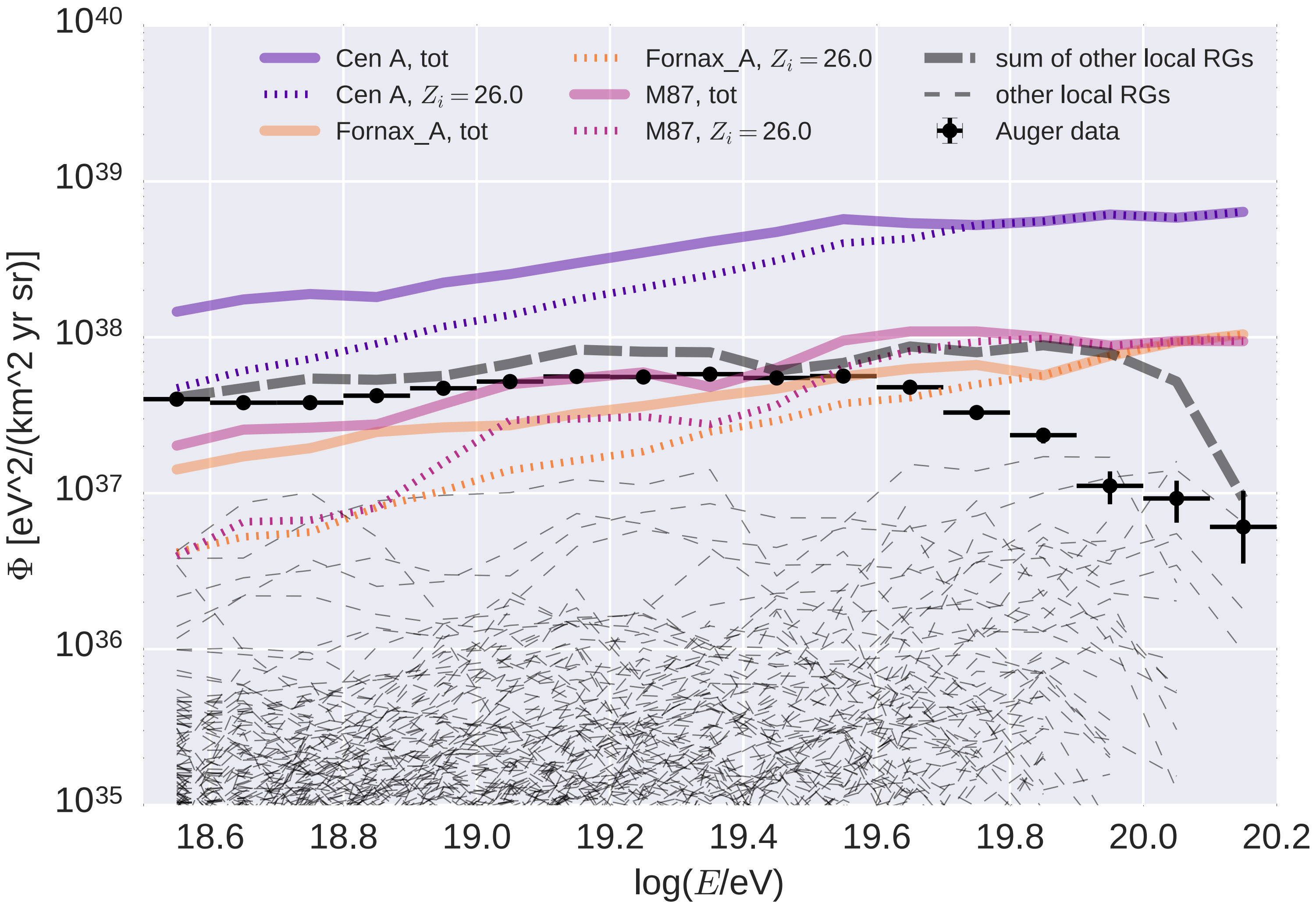
- Spectral index: $a$




T. Mauch and E. Sadler, Mon. Not. Roy. Astron. Soc. 375 (2007) 931

# Local sources

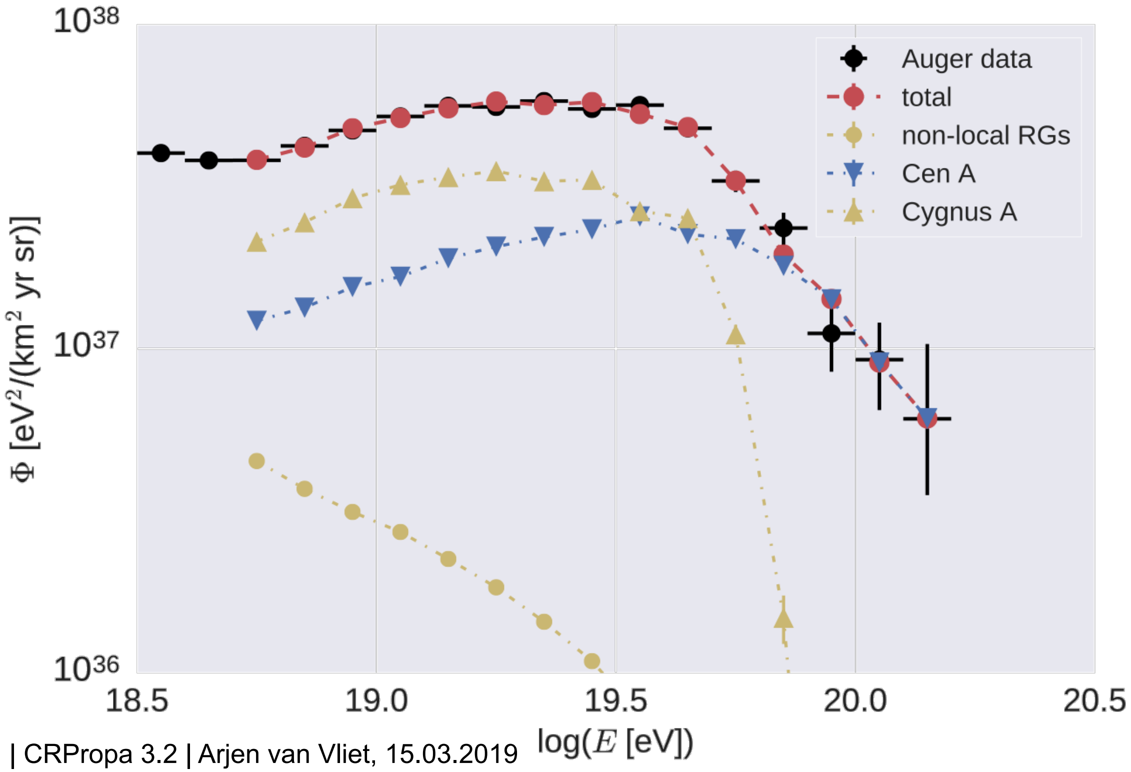
- Single-source spectra after propagation
- All parameters at maximum (no fit)
- Important local sources:
  - Cen A
  - Fornax A
  - M87

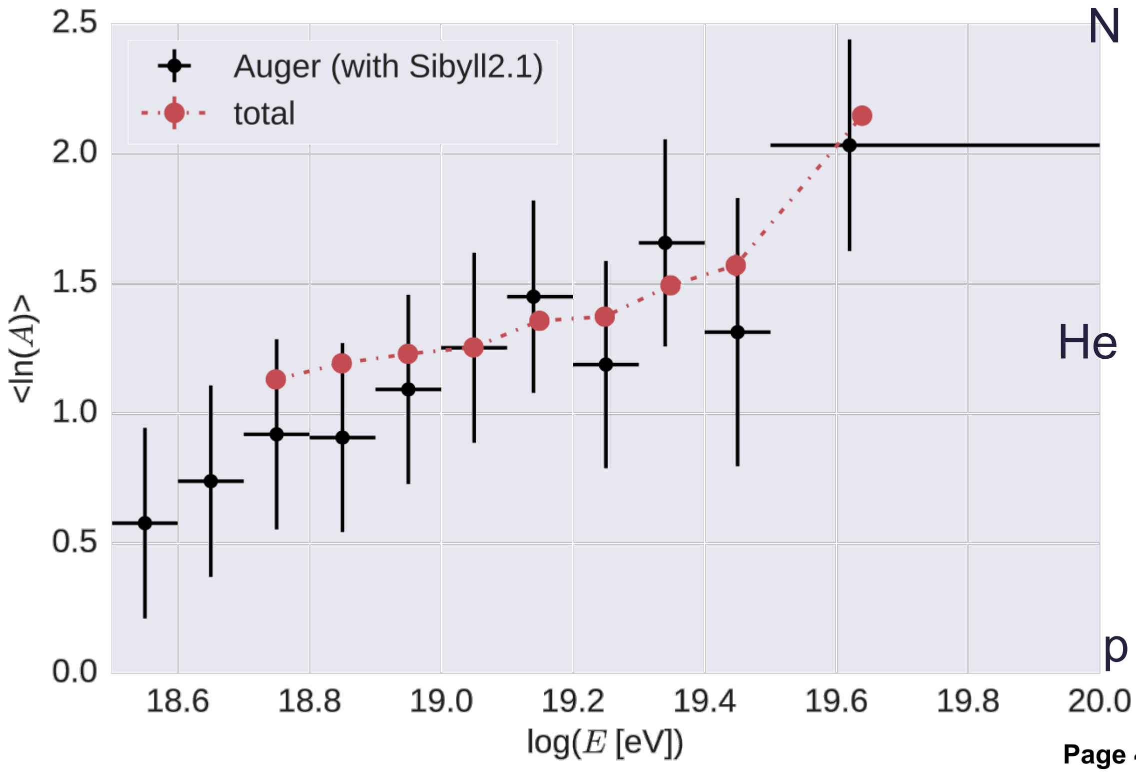


# Powerful Cen A + Cyg A

- Fit to spectrum and composition (3 hadronic interaction models)
- Spectral index >1.8
- Composition close to solar abundance
  - Only Cen A slightly heavier

| | $a$ | $\bar{g}_{\rm cr}$ | $g_{\rm cr}^{\rm CenA}$ | $g_{\rm cr}^{\rm CygA}$ | $g_{\rm acc}$ | $g_{\rm acc}^{\rm CygA}$ | $q$ | $\chi^2$ |
|---|---|---|---|---|---|---|---|---|
| **EPOS-LHC** | 1.85 | 7.73 | 41.54 | 43.94 | 0.127 | 0.059 | 2 | 1.1 |
| **QGSJetII-04** | 1.82 | 6.31 | 21.20 | 48.84 | 0.220 | 0.056 | 2 | 1.4 |
| **Sibyll2.1** | 1.83 | 6.67 | 24.77 | 47.90 | 0.19 | 0.056 | 2 | 1.3 |



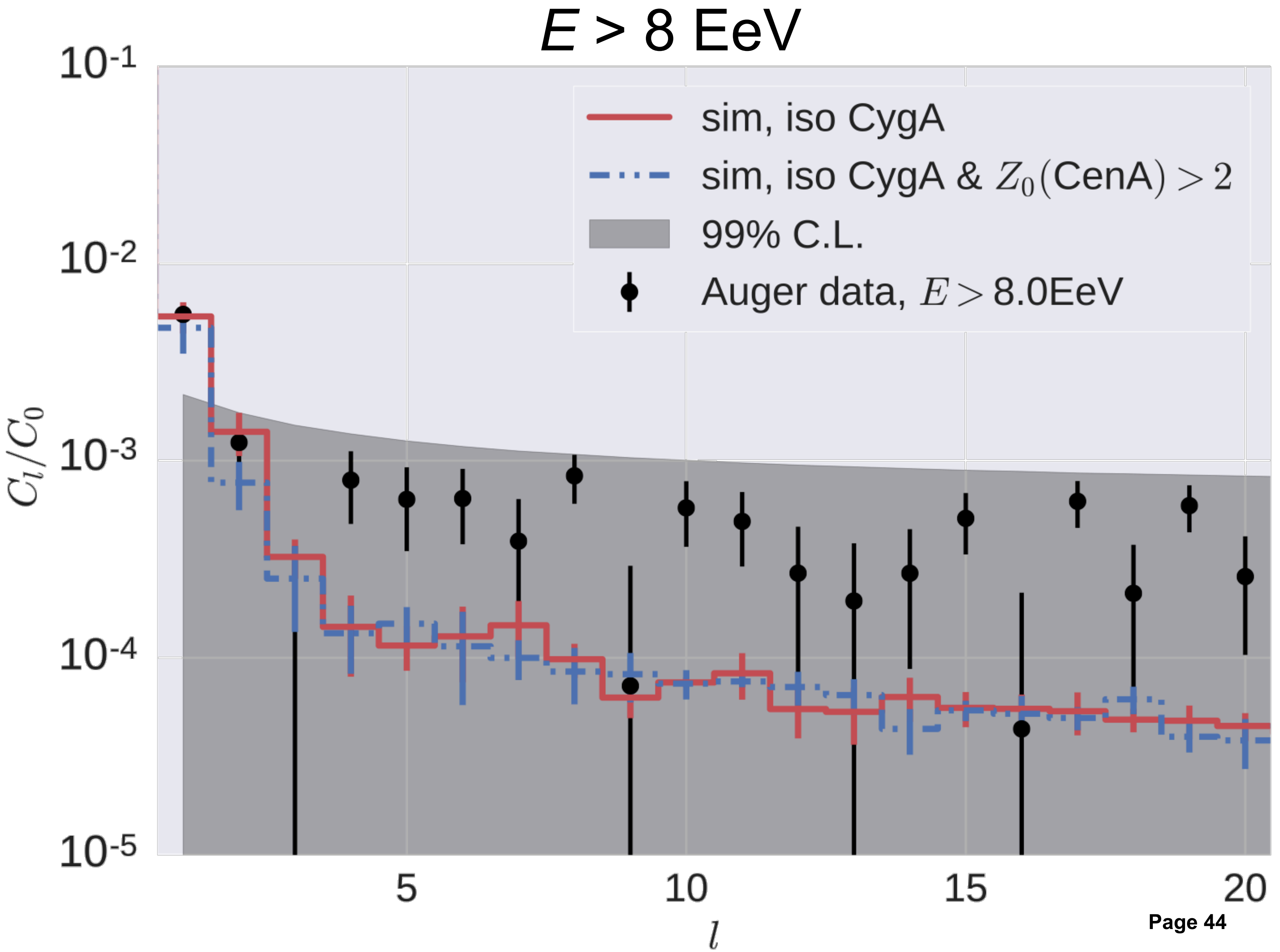



# Arrival directions

- Angular power spectrum

$$C_l = \frac{1}{2l+1}\sum_{m=-l}^{l}|a_{lm}|^2$$

- Auger dipole reproduced
- Not fitted!



# Conclusions

- Spectrum, composition and angular power spectrum can be explained by powerful Cyg A and Cen A
  - Cyg A: light composition, dominant for $E<60$ EeV
  - Cen A: heavy composition, dominant for $E>60$ EeV
- If best-fit scenario is correct:
  - Spectral index ~1.8: much softer than what many other papers find as best fit
  - Local UHECR flux ~10x higher than average in universe: predicted cosmogenic neutrino and photon fluxes overestimated

# 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
- Example applications:
  - Strong potential for cosmogenic neutrino measurements at ~1 EeV
  - Radio galaxies viable as sources of UHECRs

**Contact**

DESY. Deutsches
Elektronen-Synchrotron

www.desy.de

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+49 33762 7-7381

# Backup slides

# Software design

# Simulation Framework CRPropa

*Rafael Alves Batista[a,b], Julia Becker Tjus[c], Andrej Dundovic[a], Martin Erdmann[d], Christopher Heiter[d], Karl-Heinz Kampert[e], Daniel Kuempel[d], Lukas Merten[c], Gero Müller[d], Günter Sigl[a], Arjen van Vliet[a,f], David Walz[d], Tobias Winchen[d,e,g], Marcus Wirtz[d]*
RWTH Aachen University[d], Ruhr Universität Bochum[c], Vrije Universiteit Brussels[g], University Hamburg[a], Radboud University Nijmegen[f], University of Sao Paolo[b], Bergische Universität Wuppertal[e]

## Toolbox for Simulations of UHECR Propagation

**Deflection**
- SimplePropagation
- PropagationCK
- DiffusionSDE

**Nucleon-Interacion**
- ElectronPairProduction
- PhotoPionProduction
- PhotoDisintegration
- NuclearDecay

**EM-Interactions**
- EM(Double/Triple)-PairProduction
- EMInverseCompton-Scattering

**General Interactions**
- Redshift
- SynchrotronRadiation
- AdiabaticCooling

**Boundaries/ Thresholds**
- MaximumTrajectory-Length
- MinimumEnergy
- CubicBoundary
- SphericalBoundary
- ...

**Observer**
- ObserverSmallSphere
- ObserverTracking
- ObserverPoint
- ObserverDetectAll
- ObserverTimeEvolution
- ...

**Output**
- ShellOutput
- TextOutput
- HDF5Output
- ParticleCollector

**Others**
- PerformanceModule

Sketch by Lukas Merten

**Download**:
http://crpropa.desy.de

**Online demo in your Browser:**
http://vispa.physik.rwth-aachen.de

# Example: Steering / Simulation Setup Code

Example in Python, but C++ would also be possible

**1. Import + define empty simulation**

```
from crpropa import *
sim = ModuleList()
```

**2. Add modules**

```
sim.add( SimplePropagation(1*kpc, 10*Mpc) )

sim.add( Redshift() )
sim.add( PhotoPionProduction(CMB) )
sim.add( PhotoPionProduction(IRB) )
sim.add( PhotoDisintegration(CMB) )
  … more interactions ...
obs = Observer()
obs.add( ObserverPoint() )
output = TextOutput('events.txt', Output.Event1D)
obs.onDetection( output )
sim.add( obs )
```

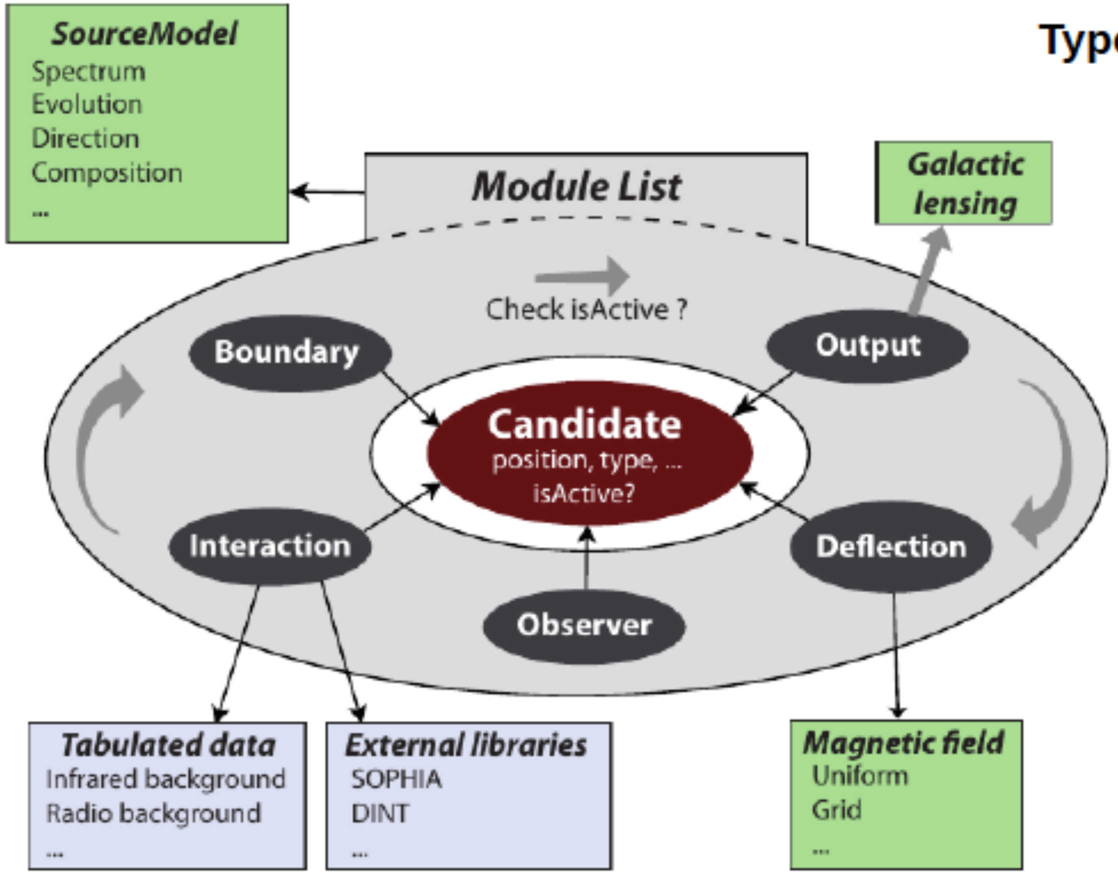
**3. Define sources**

```
source = Source()
source.add( SourceUniform1D(1 * Mpc, 1000 * Mpc) )
source.add( SourceRedshift1D() )

composition = SourceComposition(1 * EeV, 100 * EeV, -1)
composition.add(1,  1,  1)  # H
composition.add(4,  2,  1)  # He-4
composition.add(14, 7,  1)  # N-14
composition.add(56, 26, 1)  # Fe-56
source.add( composition )
```

**4. Execute modules on output of sources**

```
sim.setShowProgress(True)
sim.run(source, 200, True)
```

# Overview Object Oriented Design




**Types of Objects:**

**Candidate:**

Data storage for state of single cosmic ray particle state (Energy, position, id, ..)

**Sources:**

Creates new candidates

**Modules:**

Change state of candidate (Move, interact, output, …)

**Auxiliary:**

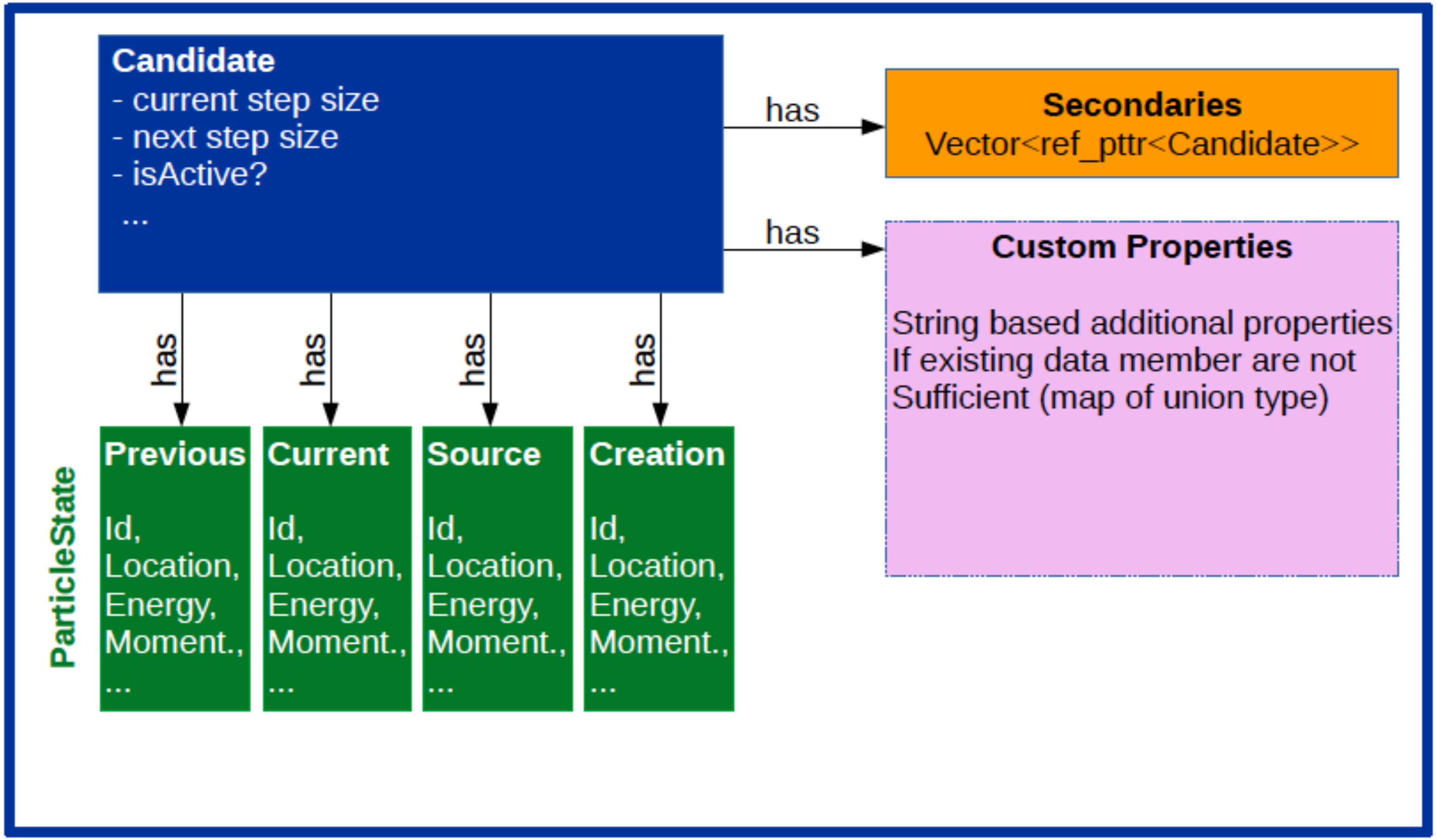
Magnetic field, photon field, ...

**Sources, Modules and Auxiliary class are independent and stateless to enable parallel processing**



New objects can be coded in C++ or Python (Interface generated using SWIG) by the user Without recompiling CRPropa core.

# Candidate: Stores Data on Particle



# Modules: Modify Candidate

**Prototype Propagator**

```
1. Save current state:
PreviousState = CurrentState

2. Make step
    - CurrentStep=NextStep
    - Update position
      according to CurrentStep

3.  Set NextStep to maximum

    exit module
```

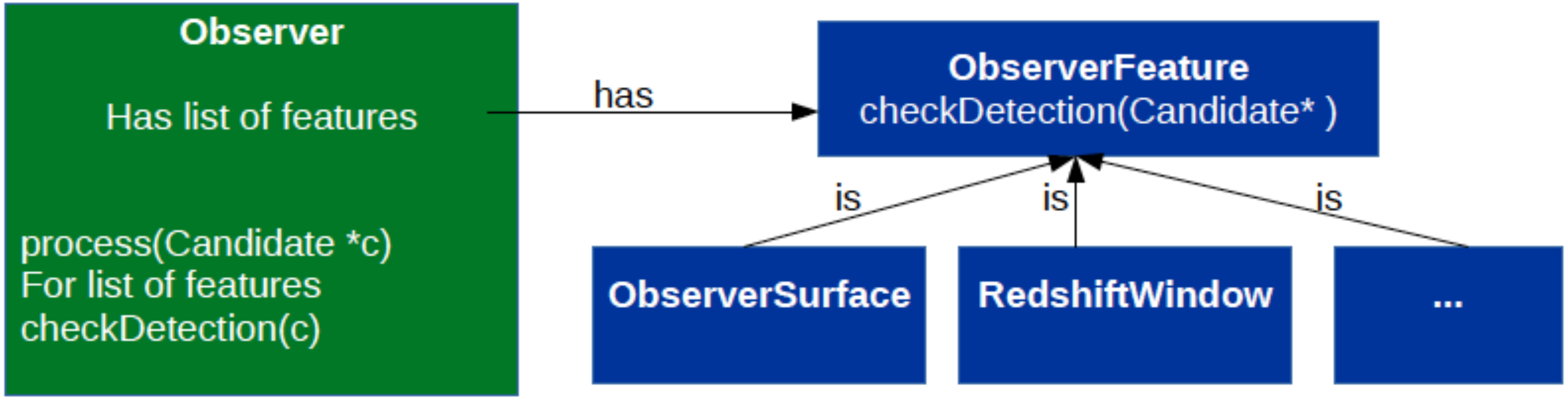
**Prototype Interaction**

```
1.If not applicable:
   Do nothing

2.Calculate  probability
  to interact in current
  step according to
  current candidate state

3.If no interaction:
    - Limit next step to small
      fraction of m. free path
    - exit module

  If interaction:
    - Modify current particle
    - add secondaries
    - Repeat from 2
```

- Candidate has individual step size
- Every module limits the stepsize to a **small** fraction of its mean free path
  - Order does not matter
  - Modules are independent, no communication required
- Modularity in interactions is paid for by random numbers as need to be generated in every cycle by every module (CRPropa not limited by RNG)

# Module Features are Separate Objects

E.g. Observer



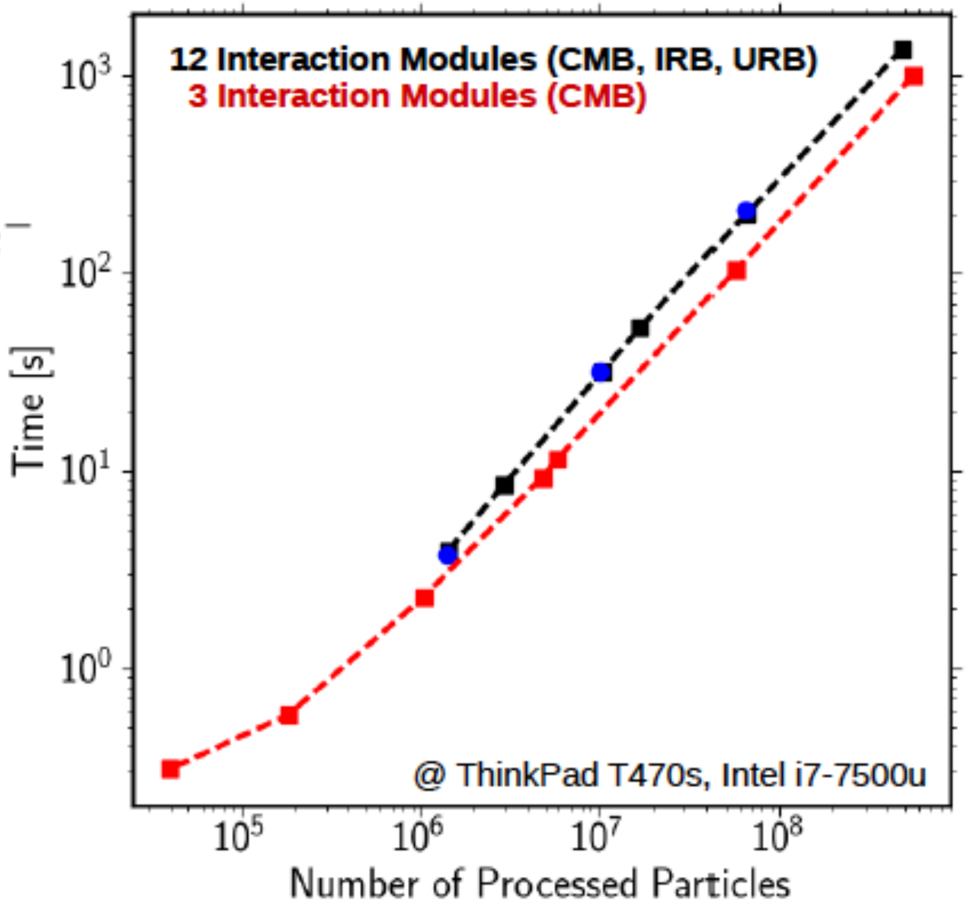

Example: Output particles crossing different planes

```
obs = Observer()
obs.add( ObserverSurface( Plane( Vector3d(0, 0, 0), Vector3(0,0,1) )))
obs.add( ObserverSurface( Plane( Vector3d(0, 0, 100 * meter), Vector3(0,0,1) )))
obs.add( ObserverSurface( Plane( Vector3d(0, 0, 200 * meter), Vector3(0,0,1) )))
obs.onDetection( TextOutput('output1.txt') )
```

# Does this Scale for Many Particles?

- EM Cascades of secondary photon and electrons (Heiter et al. 2018)
  - → Pair production
    $\gamma + \gamma_{\mathrm{bg}} \longrightarrow e^+ + e^-$
  - → Double pair production
    $\gamma + \gamma_{\mathrm{bg}} \longrightarrow e^+ + e^- + e^+ + e^-$
  - → Triplet pair production
    $e + \gamma_{\mathrm{bg}} \longrightarrow e + e^+ + e^-$
  - → Inverse Compton scattering
    $e + \gamma_{\mathrm{bg}} \longrightarrow e + \gamma$

  3 background (CMB, IRB, URB) → 12 stochastic interaction modules
- Continuous energy loss due to redshift
- Injected 1000 EeV photons in 4 Mpc distance
- Cascaded to z=0 or variable minimum energy




**Implementation scales linearly with number of processed particles**

# How did we get There?

- Several versions of CRPropa
- Previous modular codes
  - →PAX, PXL, RDAS

**Software development philosophy:**

- KISS: Keep it simple, not stupid
- YAGNI: You ain't gonna need it
- Refactor often and early
- Dev. Substeps:
  - →Make it work
  - →Make it right
  - →Make it nice
  - →*Make it fast (if needed)*

- Code review (of substantial changes)
  git + pull requests (github)
- Unit Tests + Continuous Integration
  gtest + travis
- Minimize dependencies:
  - →User should not need to compile dependencies
  - →Dependencies should be standard / trivial available on supported platforms (Linux + Mac)
    - » Cmake
    - » Python
    - » Swig
    - » hdf5

    or shipped in static version.
    - » Healpix subset, eigen, kiss, (tinyxml, thread), hepid
  - →Boost (and ROOT) are known to cause problems

# Conclusion

VRIJE UNIVERSITEIT BRUSSEL

- CRPropa3 highly modular code design
  - →User friendly (all dependencies except python + swig) shipped + compiles using standardized tool chain (cmake)
  - →Highly modular
  - →Easily extendable (C++/python modules and features without recompiling)
  - →Scales linearly to high particle numbers
  - →Webpage / Code / Issue-tracker / Examples / Documentation / ...

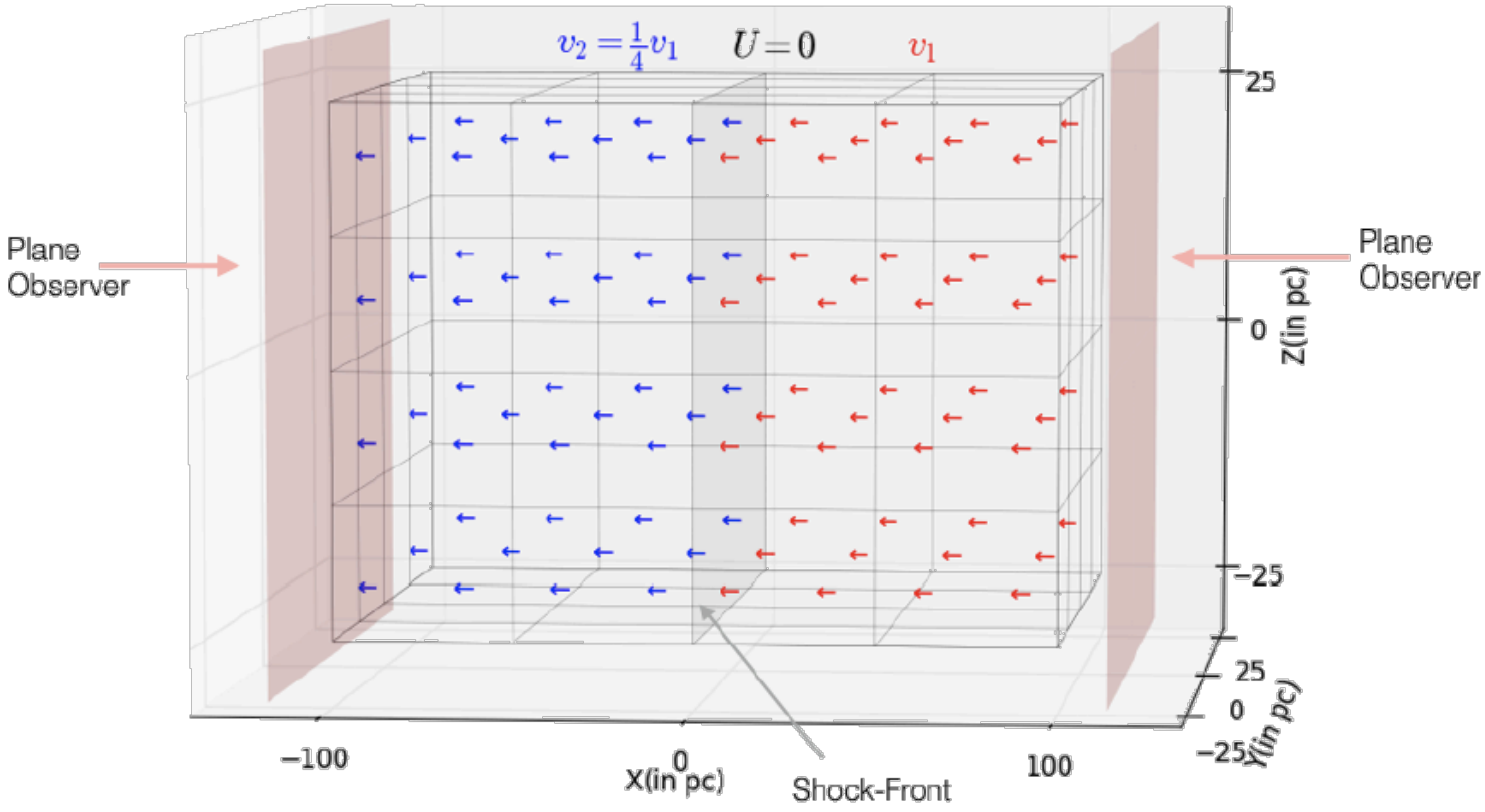
    https://crpropa.desy.de/
    https://github.com/CRPropa/CRPropa3
- Several approaches probably transferable to Next Generation CORSIKA



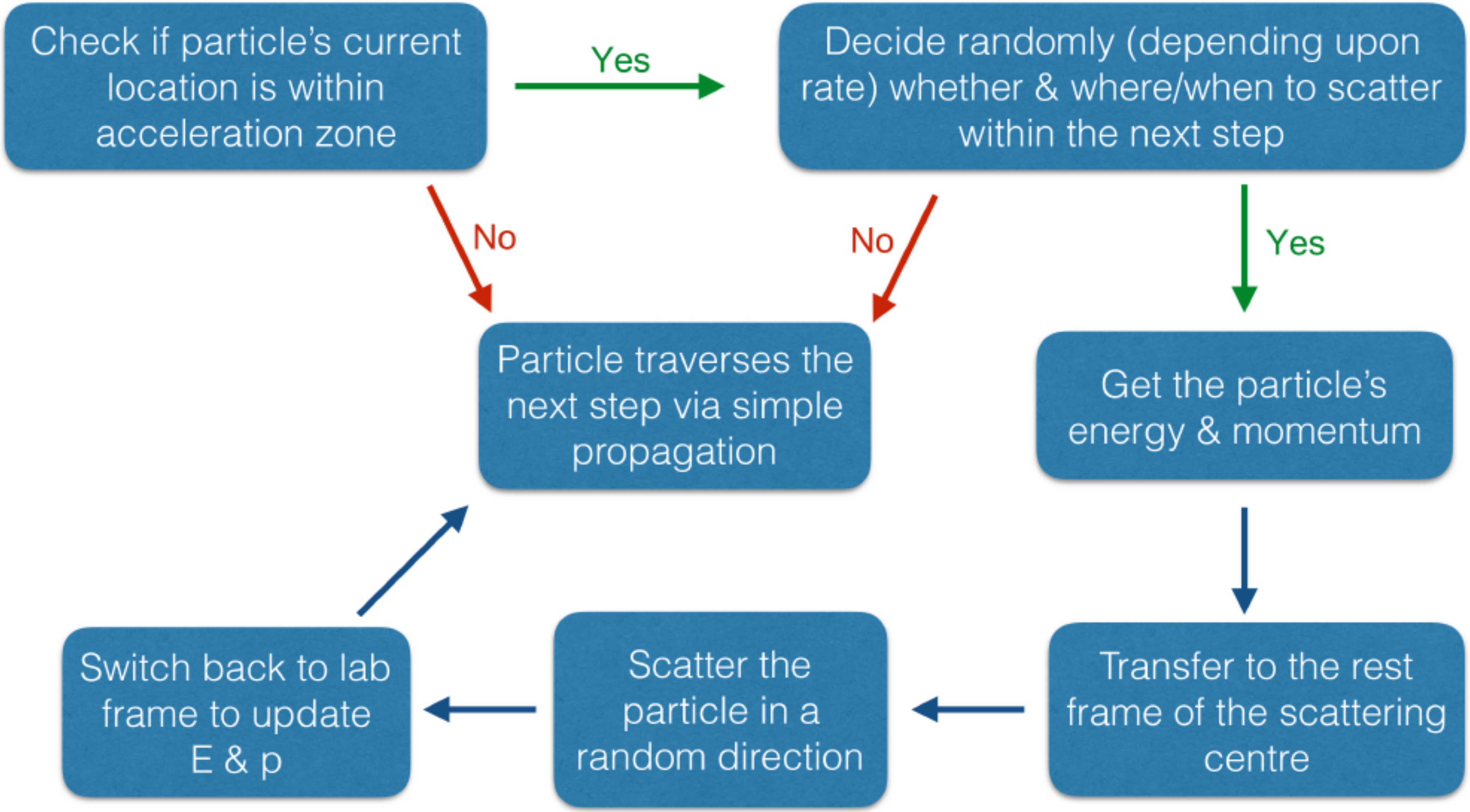
Contact: tobias.winchen@rwth-aachen.de

# Diffusive shock acceleration (new in 3.2)

# Simulation setup



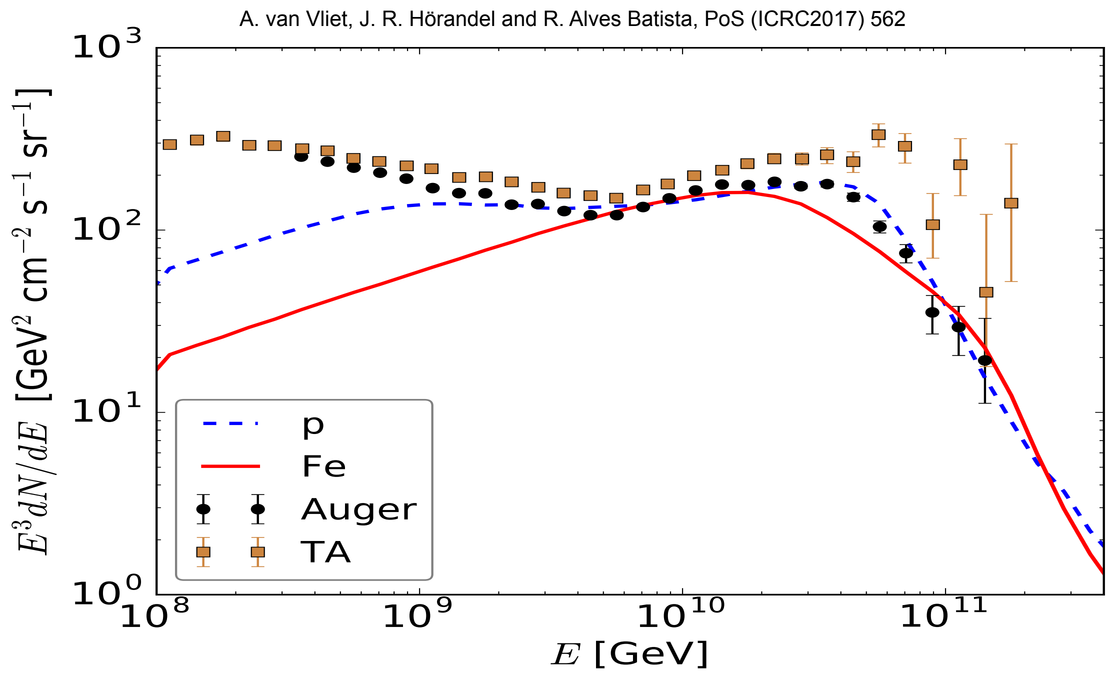
# Simulation scheme

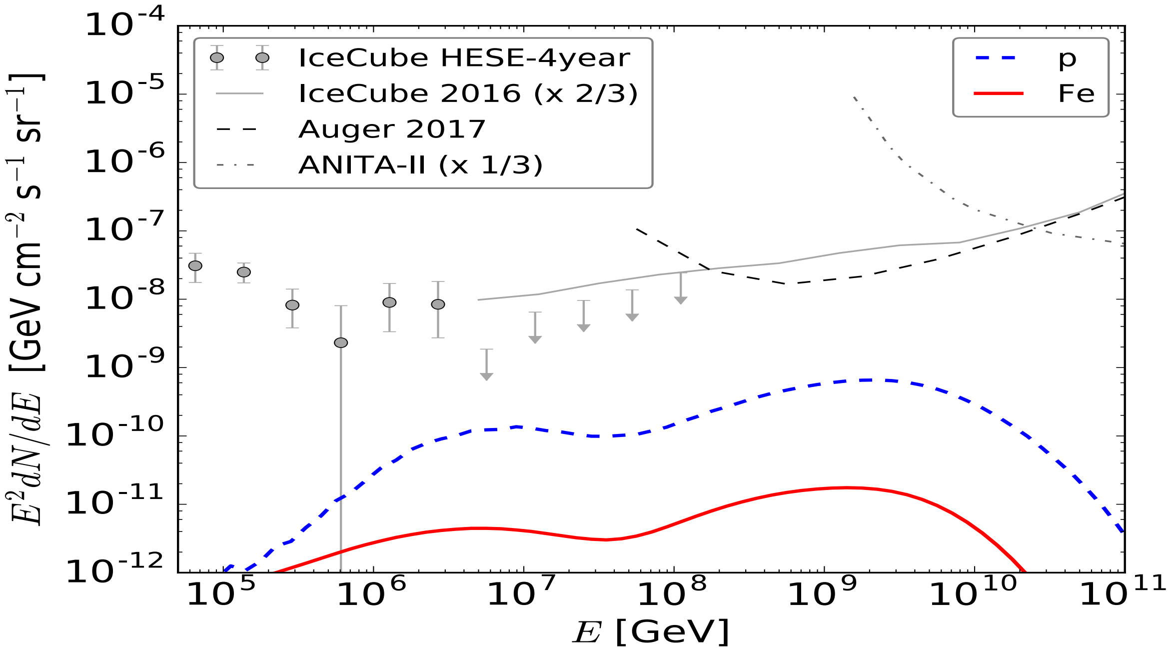


# Extragalactic CRs example: Cosmogenic neutrinos

# Proton vs. Iron

- $R_{cut}$ = 200 EV
- $\alpha$ = 2.5
- Comoving source evolution
- Neutrino flux strongly reduced in the case of iron primarie

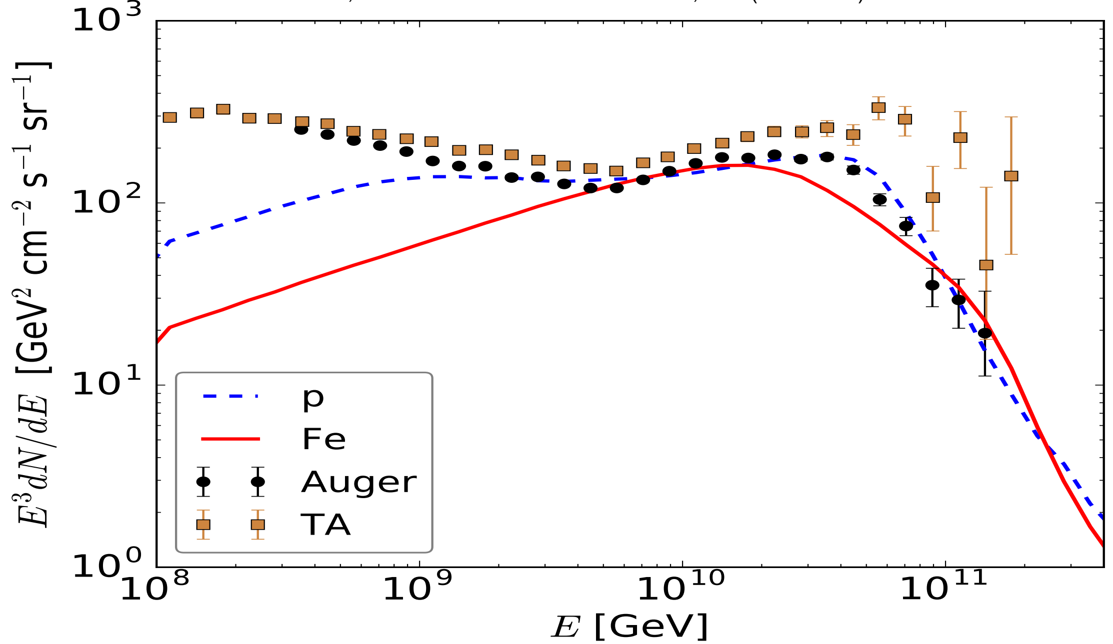


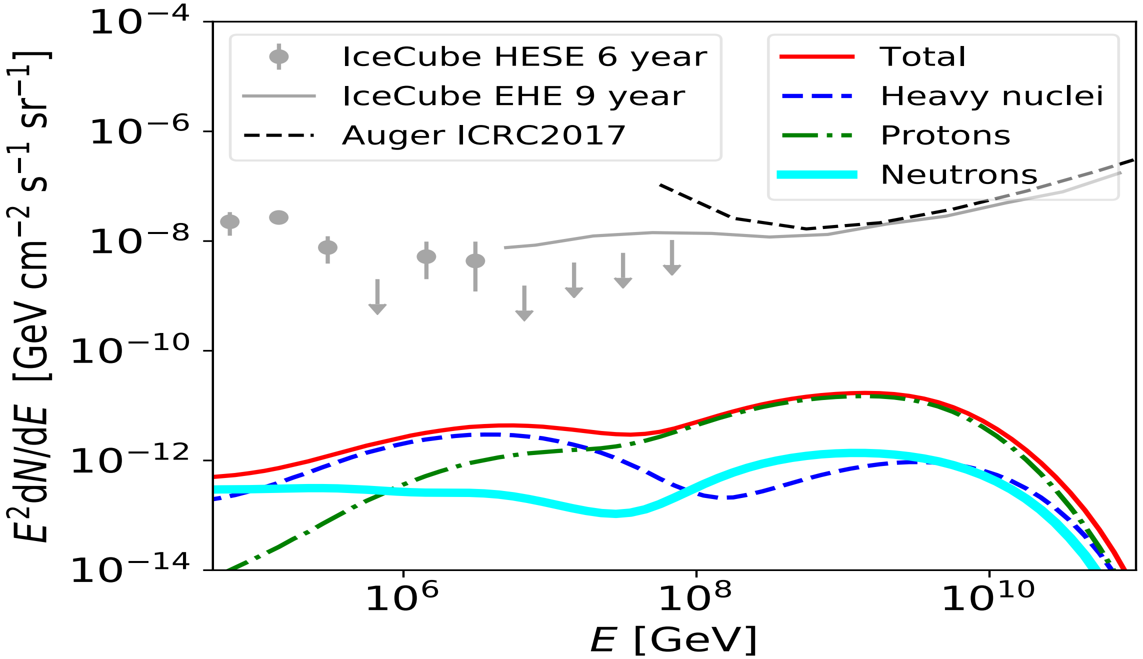



# Iron specifics

- $R_{\mathrm{cut}}$ = 200 EV
- $\alpha$ = 2.5
- Comoving source evolution
- Most ν's from secondary protons for $E$ > $10^8$ GeV

A. van Vliet, J. R. Hörandel and R. Alves Batista, PoS (ICRC2017) 562



# Reference scenario

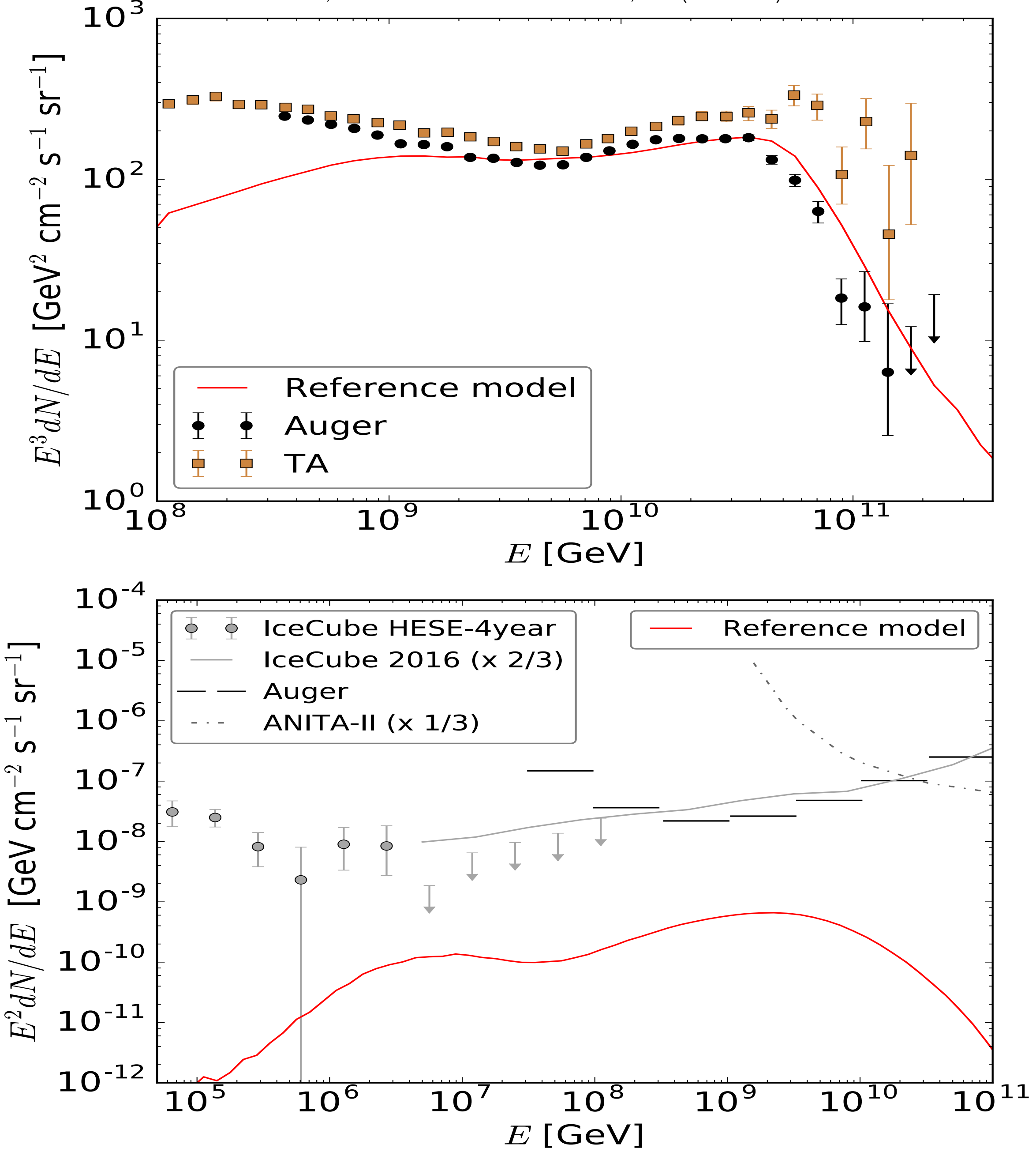
A. van Vliet, J. R. Hörandel and R. Alves Batista, *Cosmogenic gamma-rays and neutrinos constrain UHECR source models*, PoS (ICRC2017) 562
A. van Vliet, *Cosmogenic photons strongly constrain UHECR source models*, EPJ Web Conf. 135 (2017) 03001

- 1D simulation including neutrinos
- Homogeneous distribution of identical sources
- Initial CR type: protons
- Injection spectrum: $\frac{\mathrm{d}N}{\mathrm{d}E} \propto E^{-\alpha} \exp(-E / ZR_{\mathrm{cut}})$
- Cut-off rigidity: $R_{\mathrm{cut}}$ = 200 EV
- Injection index: $\alpha$ = 2.5
- Source evolution: comoving (no evolution)
- EBL: Gilmore *et al.* 2012

# Reference model

- Protons
- $R_{cut}$ = 200 EV
- $\alpha = 2.5$
- comoving

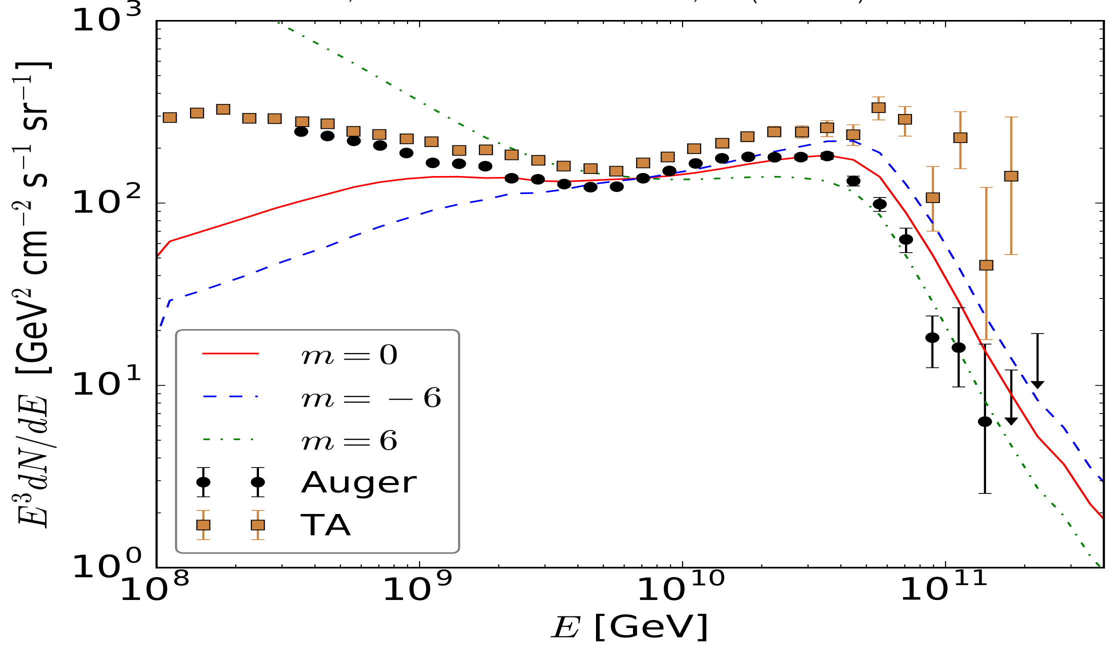
A. van Vliet, J. R. Hörandel and R. Alves Batista, PoS (ICRC2017) 562

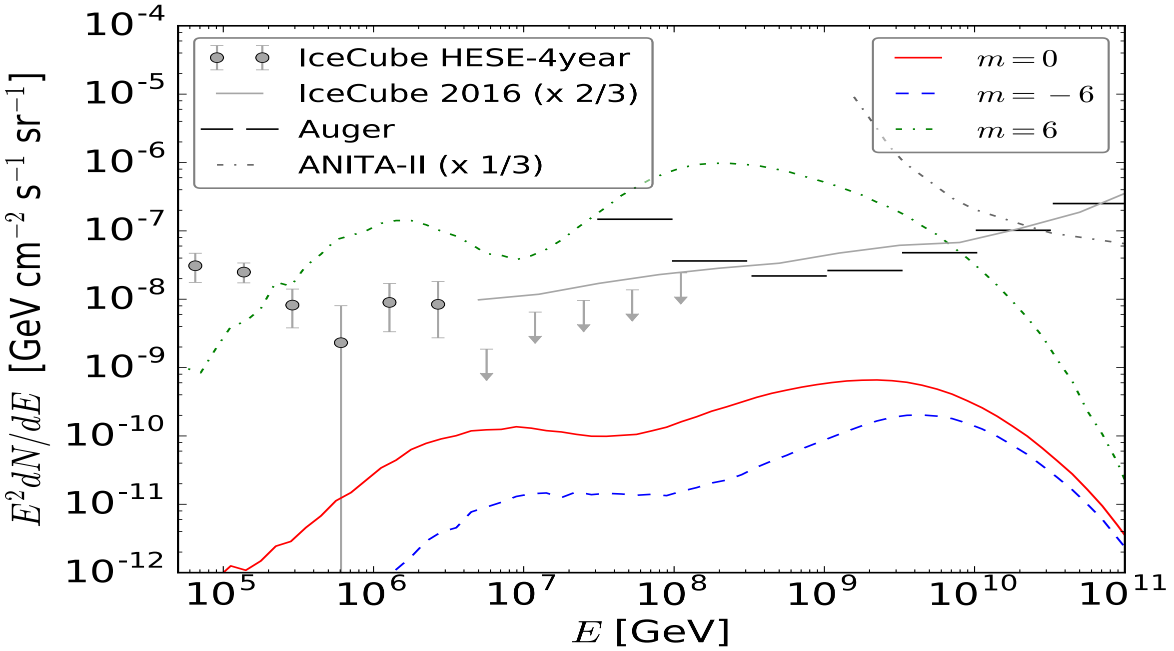


# Source evolution

- Protons
- $R_{cut}$ = 200 EV
- $\alpha = 2.5$
- evolution multiplied by $(1+z)^m$, for $-6 \le m \le 6$
- $m = 0$: BL Lacs, $m = -6$: HSP BL Lacs
- ν's strongly affected

A. van Vliet, J. R. Hörandel and R. Alves Batista, PoS (ICRC2017) 562

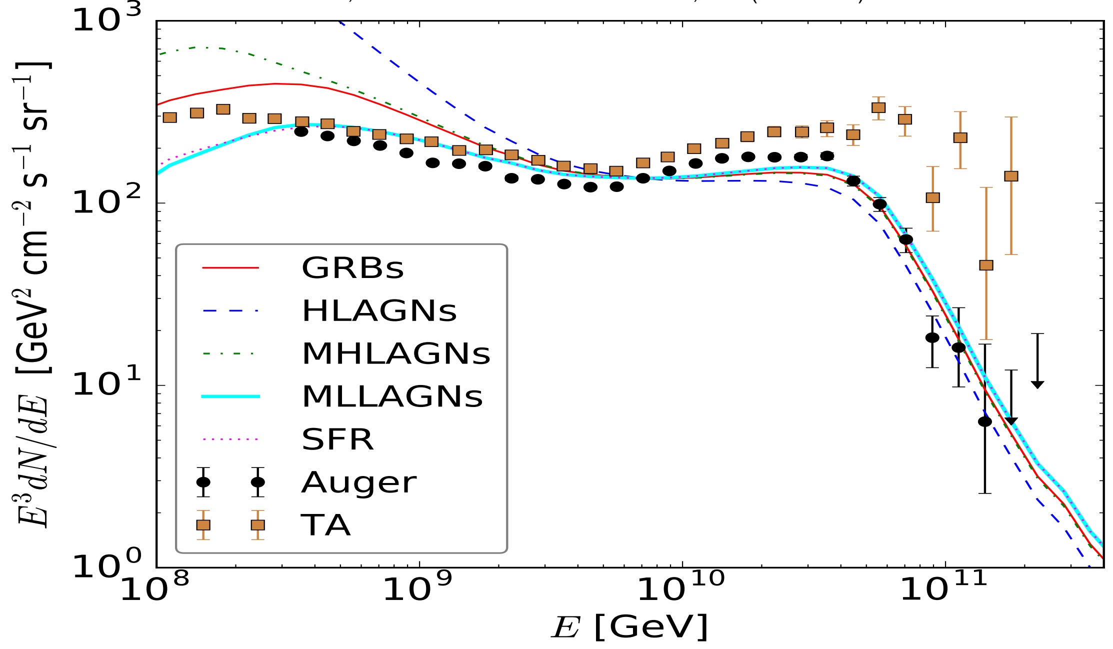


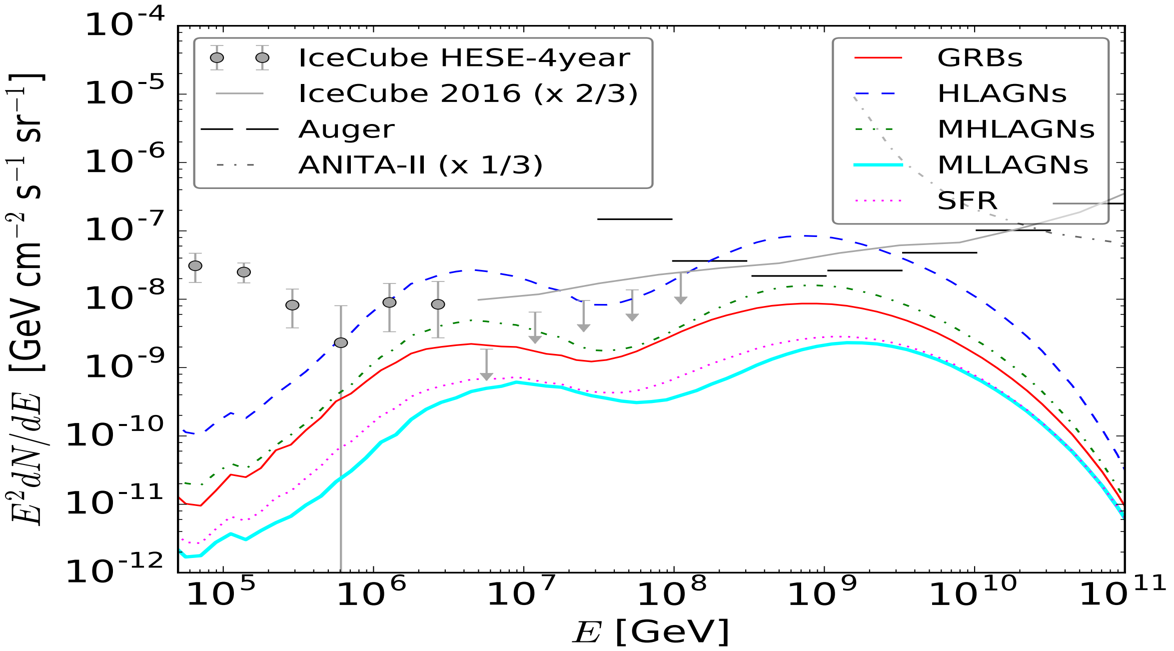



# Source ev. models

- Protons
- $R_{cut}$ = 200 EV
- $\alpha = 2.5$
- GRBs, AGNs, SFR
- ν's strongly affected
- Constrained by neutrino limits

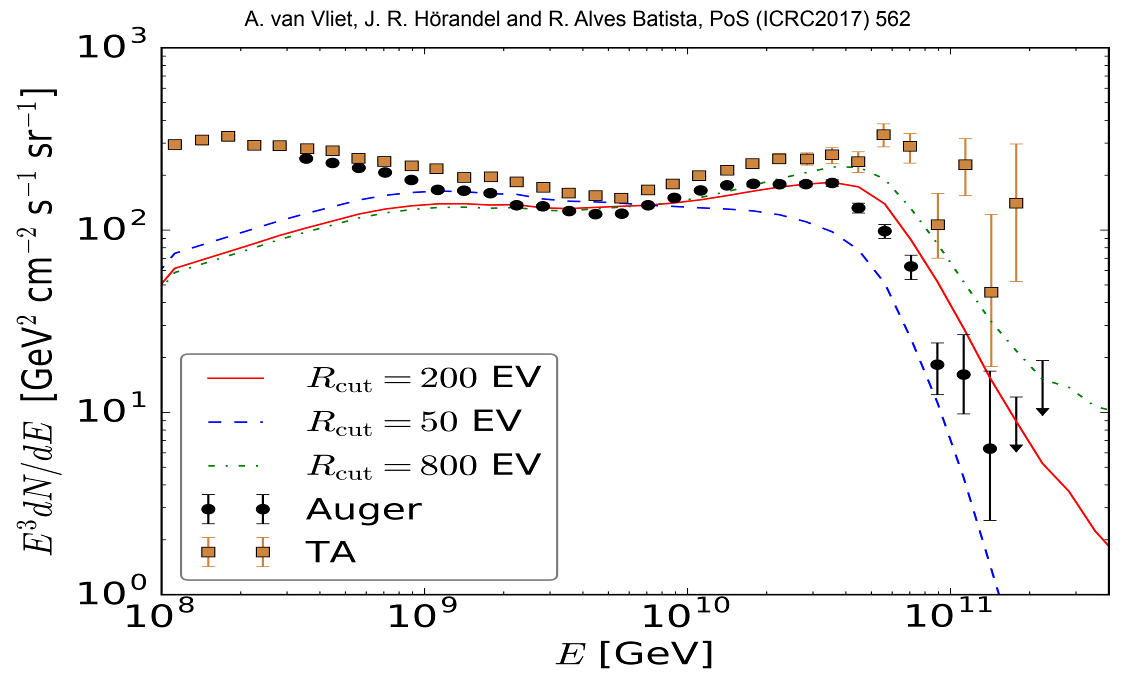
A. van Vliet, J. R. Hörandel and R. Alves Batista, PoS (ICRC2017) 562

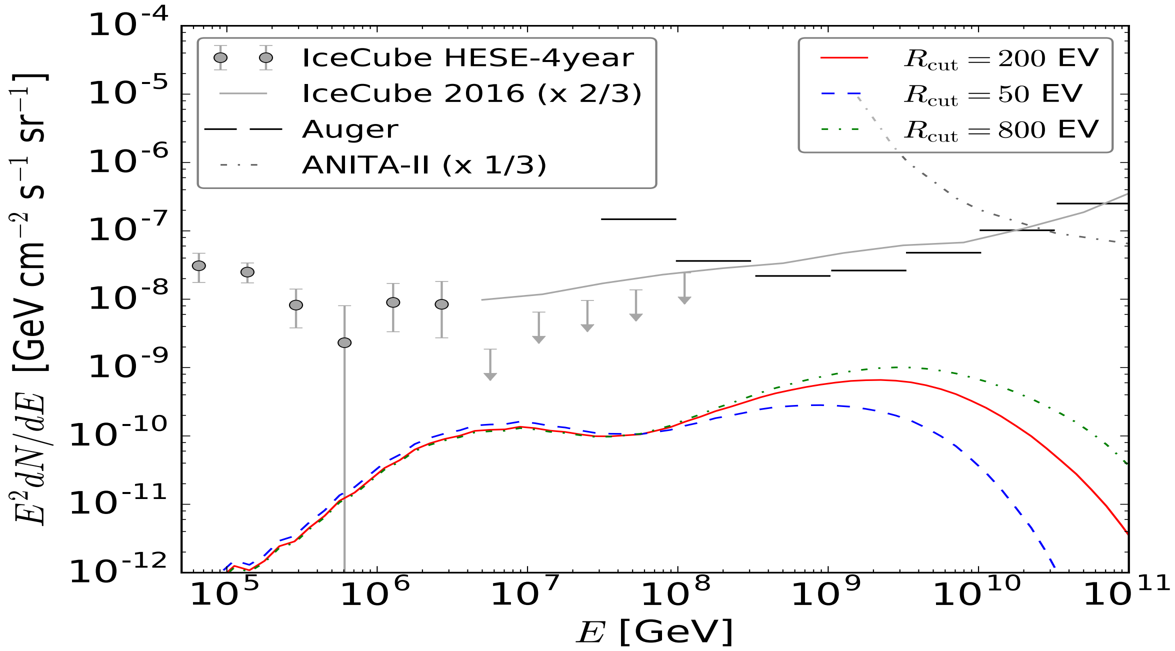


# Max. rigidity

- Protons
- $50 \leq R_{\mathrm{cut}} \leq 800$ EV
- $\alpha = 2.5$
- Comoving
- ν's only affected for $E > 10^8$ GeV

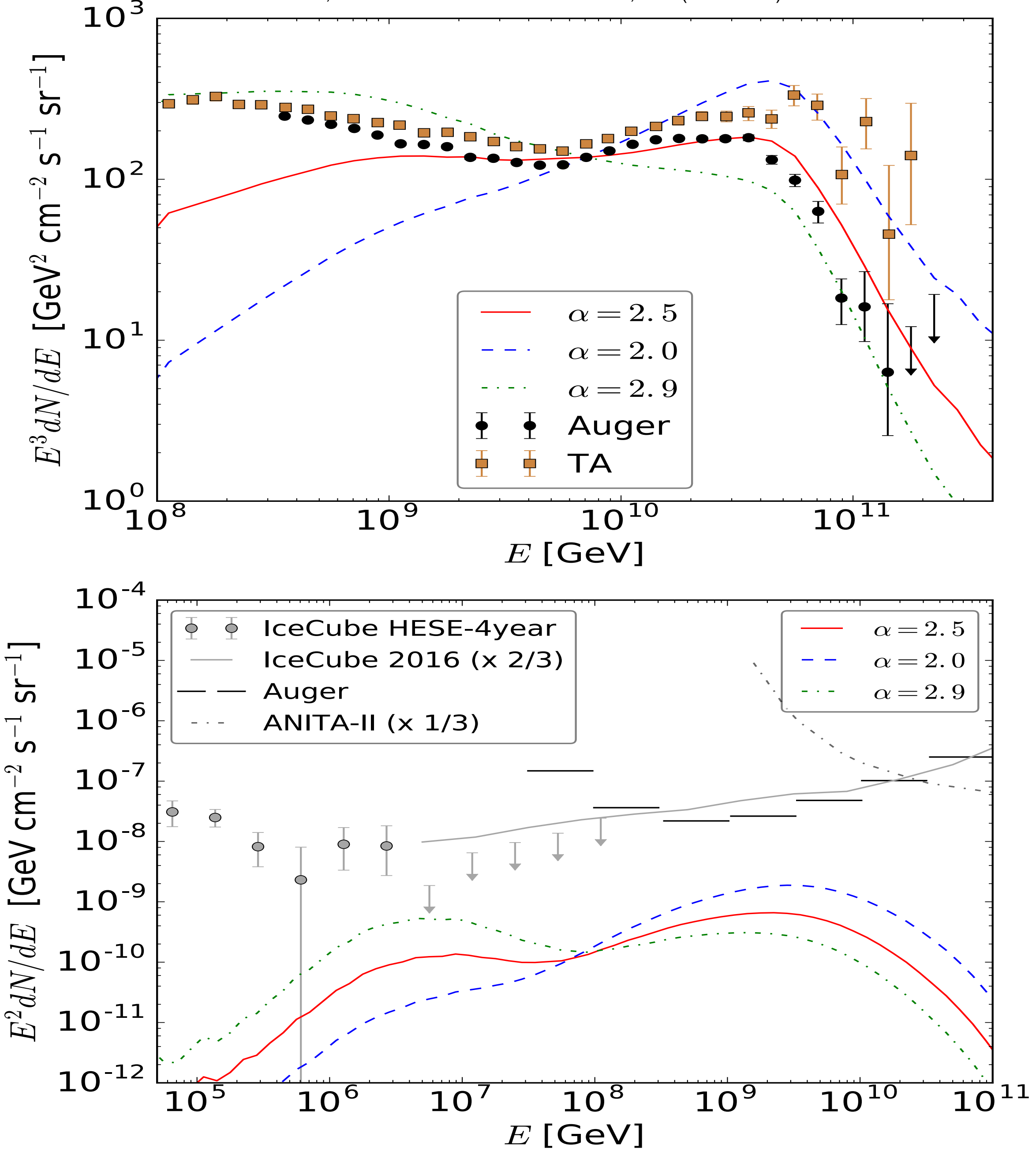


# Spectral index

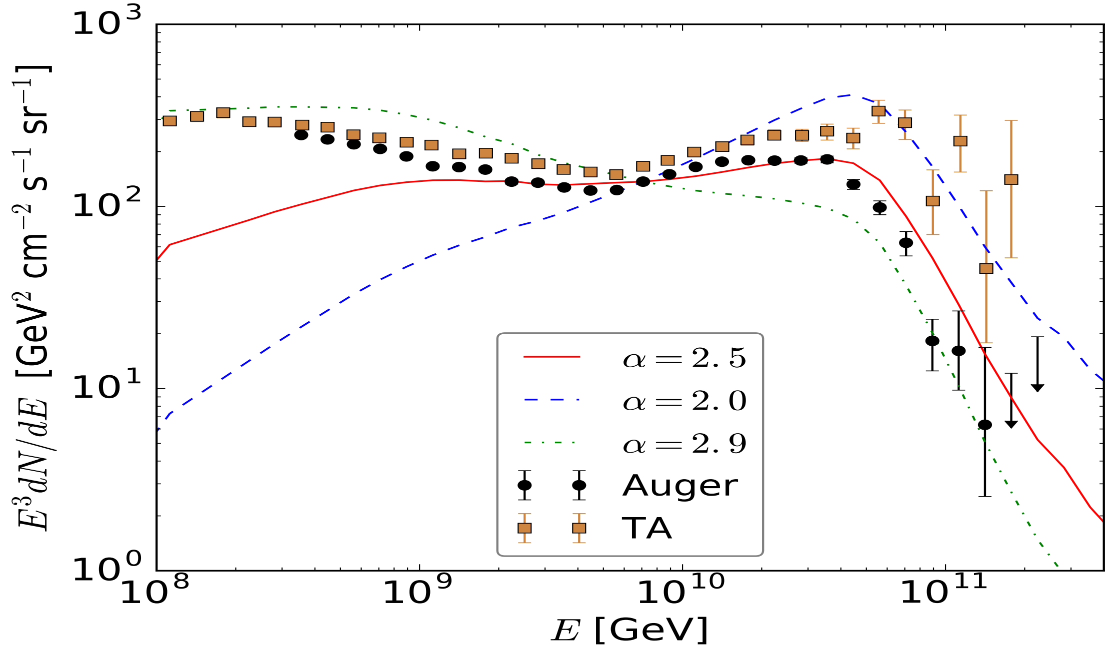
- Protons
- $R_{cut}$ = 200 EV
- $\alpha = 2.5$
- Comoving
- ν's affected similarly as CRs

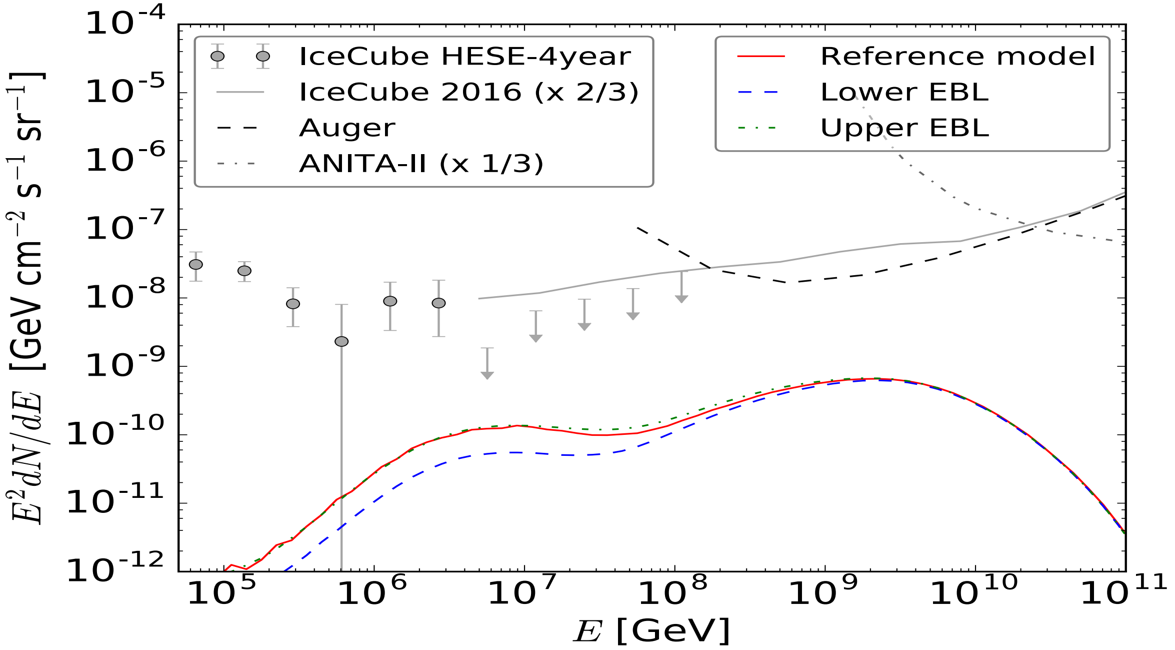
A. van Vliet, J. R. Hörandel and R. Alves Batista, PoS (ICRC2017) 562



# EBL

- Protons
- $R_{\text{cut}}$ = 200 EV
- 2.0 ≤ $\alpha$ ≤ 2.9
- Comoving
- EBL: Gilmore 2012, Stecker 2016 upper and lower
- ν's significantly affected only for $E < 10^8$ GeV



# Extragalactic CRs example: UHECRs from radio galaxies

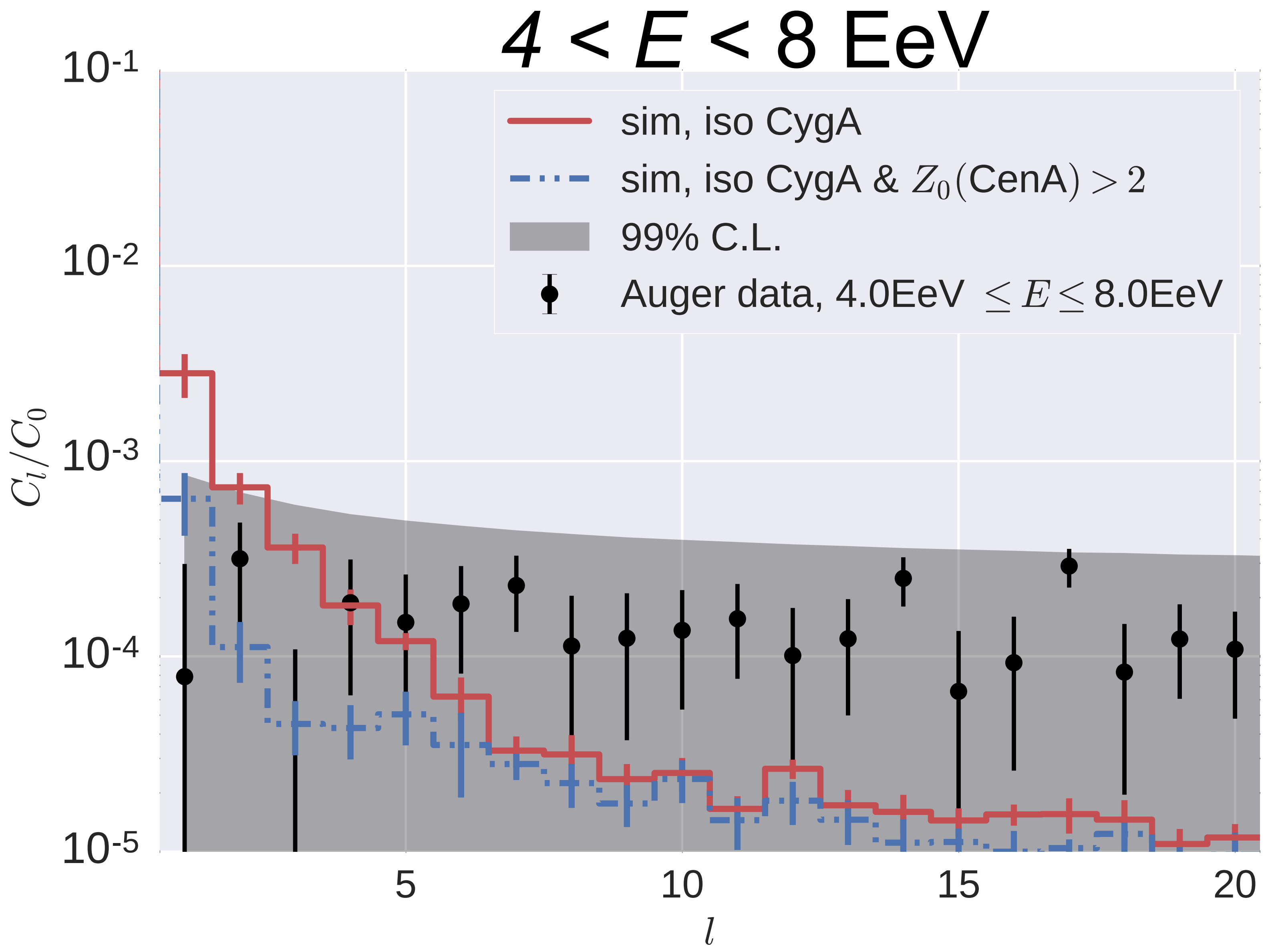
B. Eichmann, J. Rachen, L. Merten, A. van Vliet and J. Becker Tjus, JCAP 1802 (2018) 036

# Arrival Directions

- Angular power spectrum

$$C_l = \frac{1}{2l+1}\sum_{m=-l}^{l} |a_{lm}|^2$$

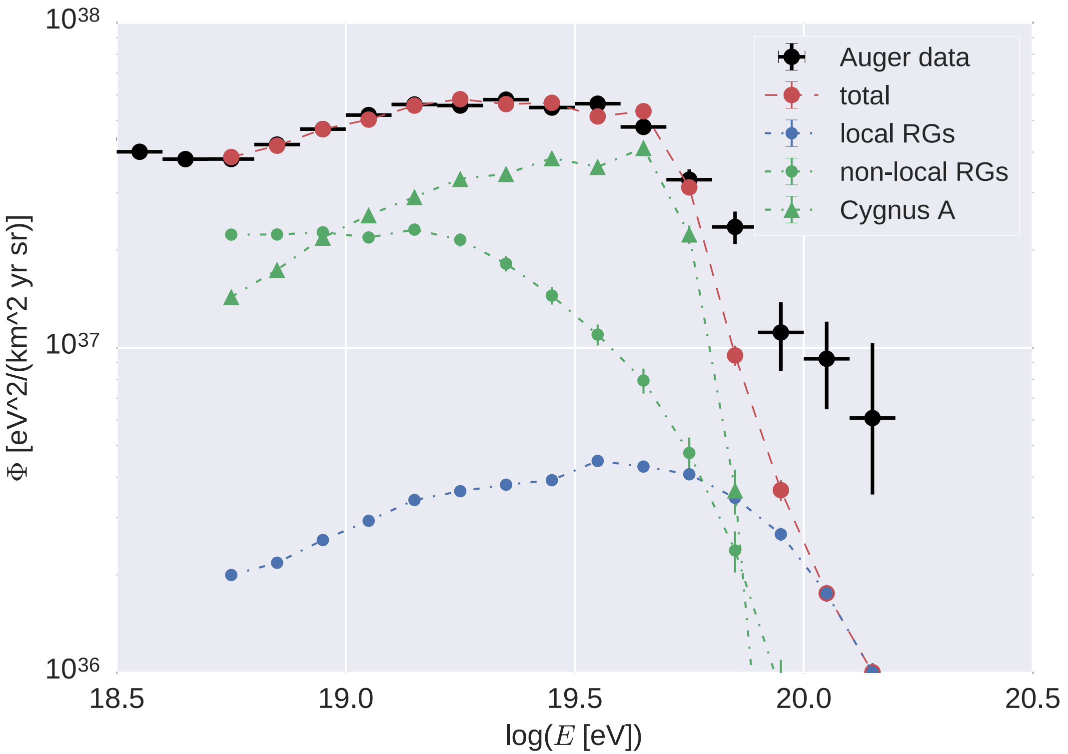
- Dipole too large
- Fit only for *E* > 5 EeV
- Low *E* contribution could reduce difference

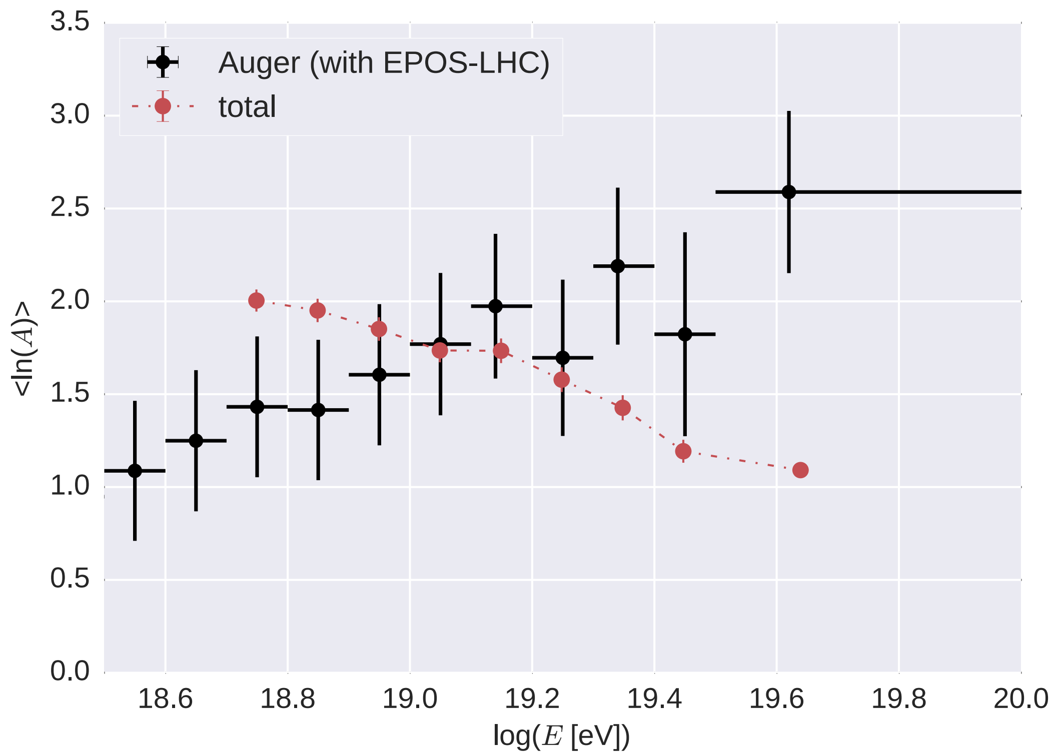


# Only Cyg A Special

- Not possible to get a good fit

| | $a$ | $\bar{g}_{\rm cr}$ | $g_{\rm cr}^{\rm CygA}$ | $\bar{g}_{\rm acc}$ | $g_{\rm acc}^{\rm CygA}$ | $q$ | $\chi^2$ |
|---|---|---|---|---|---|---|---|
| **EPOS-LHC** | 1.7 | 1.94 | 22.17 | 0.6 | 0.11 | 2 | 5.4 |
| **QGSJetII-04** | 1.76 | 2.23 | 32.60 | 0.6 | 0.090 | 1.84 | 5.6 |
| **Sibyll2.1** | 1.83 | 2.29 | 42.51 | 0.6 | 0.085 | 1.97 | 5.7 |

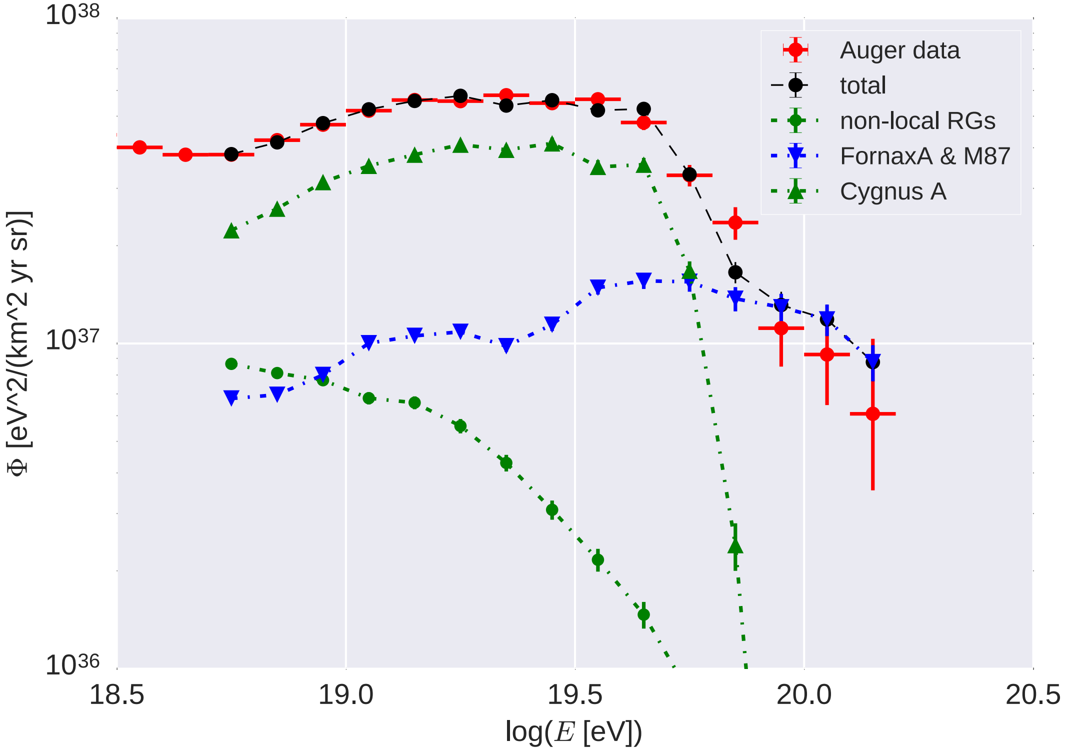


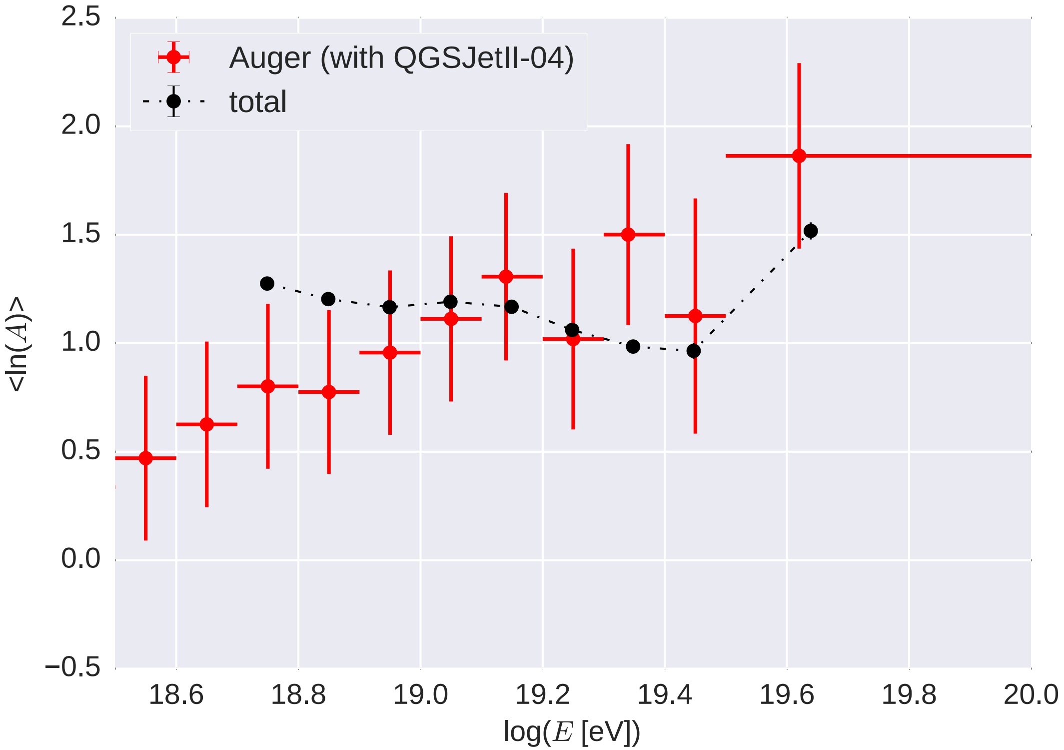



# Powerful M87, Fornax A and Cyg A

- Only composition M87 & Fornax A enhanced

| | $a$ | $\bar{g}_{\rm cr}$ | $g_{\rm cr}^{\rm M/F}$ | $g_{\rm cr}^{\rm CygA}$ | $g_{\rm acc}$ | $g_{\rm acc}^{\rm CygA}$ | $q$ | $\chi^2$ |
|---|---|---|---|---|---|---|---|---|
| **EPOS-LHC** | 1.71 | 12.83 | 50 | 32.04 | 0.100 | 0.065 | 2 | 4.8 |
| **QGSJetII-04** | 1.76 | 9.83 | 50 | 41.61 | 0.133 | 0.061 | 1.87 | 2.8 |
| **Sibyll2.1** | 1.71 | 10.02 | 48.91 | 34.05 | 0.121 | 0.064 | 1.87 | 3.1 |

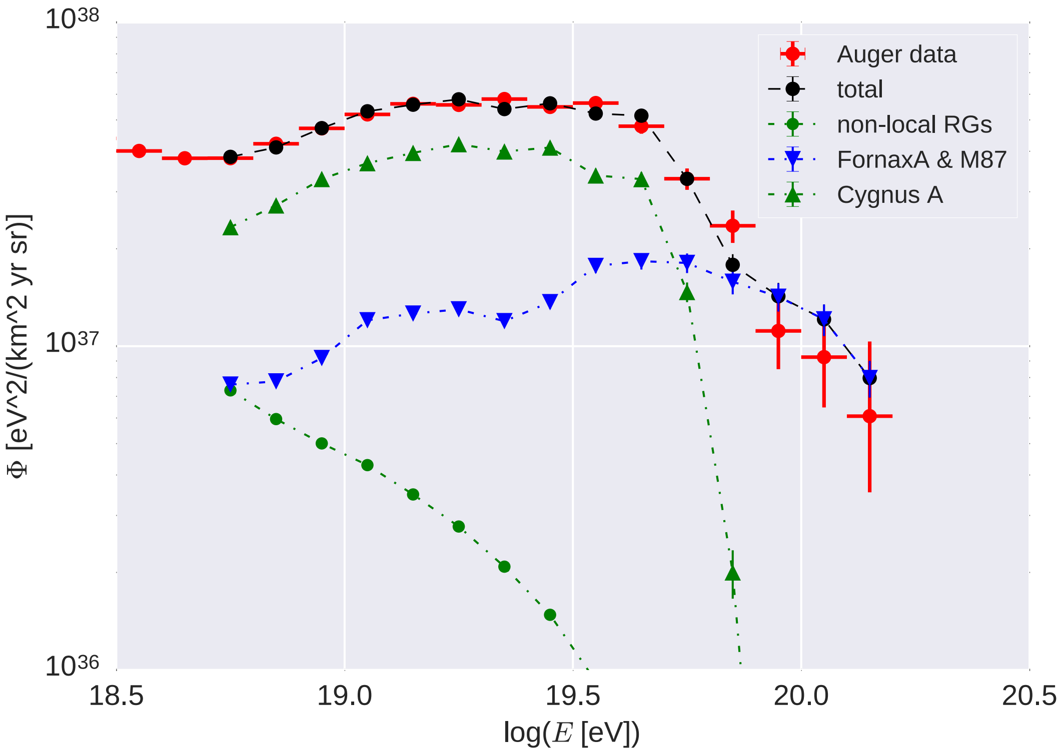


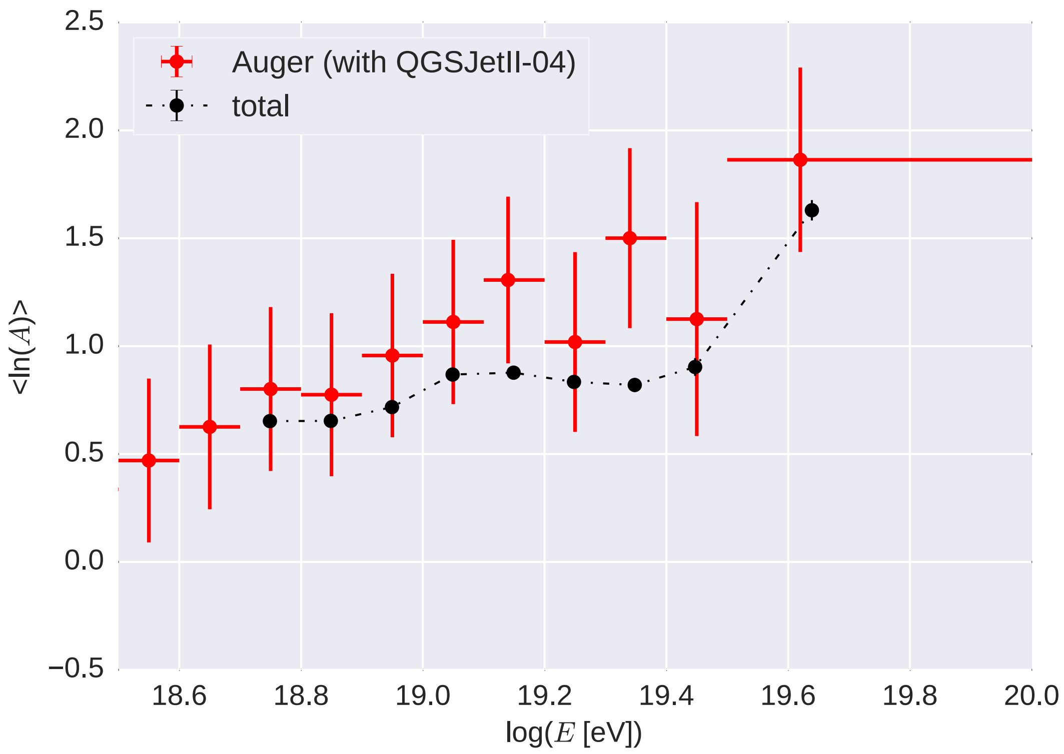



# Powerful M87, Fornax A and Cyg A

- Composition enhanced for all sources except Cygnus A

| | $a$ | $\bar{g}_{\rm cr}$ | $g_{\rm cr}^{\rm M/F}$ | $g_{\rm cr}^{\rm CygA}$ | $g_{\rm acc}$ | $g_{\rm acc}^{\rm CygA}$ | $q$ | $\chi^2$ |
|---|---|---|---|---|---|---|---|---|
| **EPOS-LHC** | 1.71 | 2.17 | 39.94 | 27.70 | 0.123 | 0.078 | 1.99 | 2.7 |
| **QGSJetII-04** | 1.80 | 2.11 | 45.48 | 44.20 | 0.170 | 0.065 | 1.84 | 2.4 |
| **Sibyll2.1** | 1.71 | 2.14 | 44.96 | 31.50 | 0.147 | 0.072 | 1.78 | 2.4 |

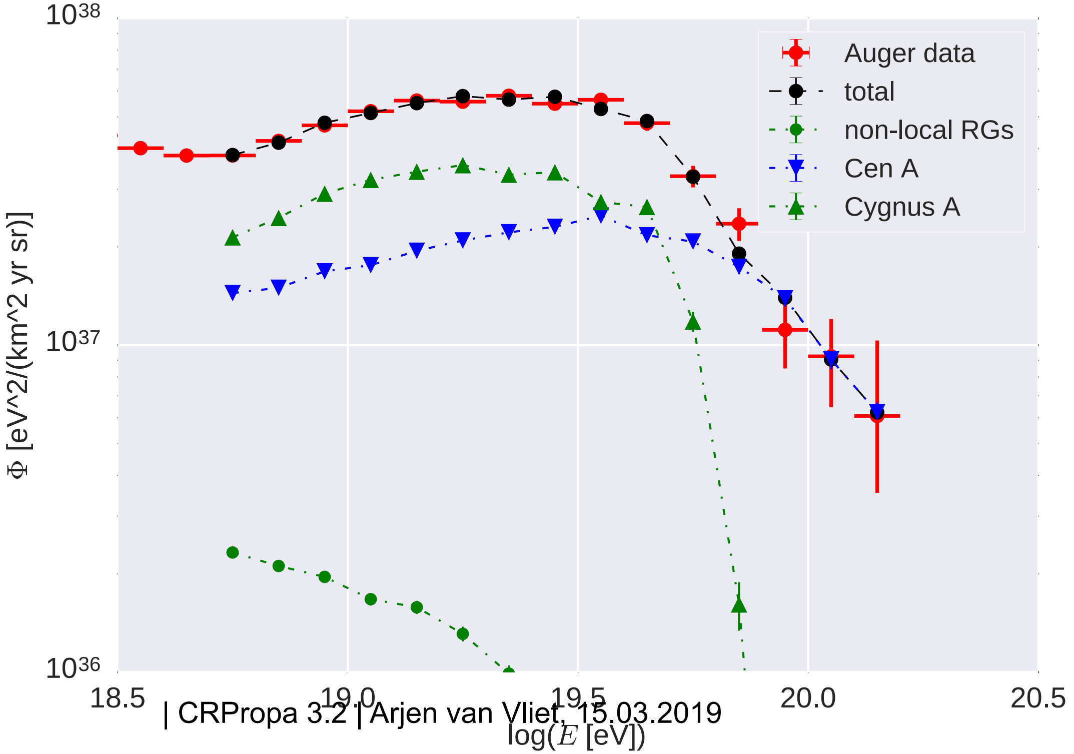


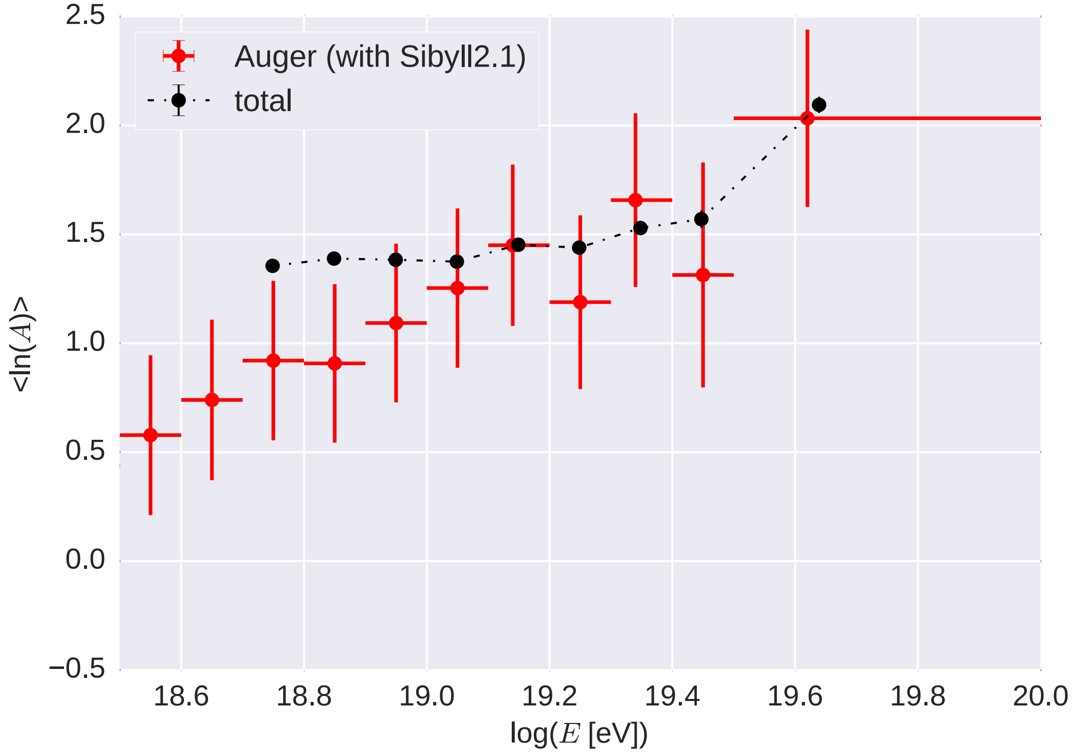



# Powerful Cen A + Cyg A

- Composition enhanced for all sources except Cygnus A

| | $a$ | $\bar{g}_{cr}$ | $g_{cr}^{CenA}$ | $g_{cr}^{CygA}$ | $g_{acc}$ | $g_{acc}^{CygA}$ | $q$ | $\chi^2$ |
|---|---|---|---|---|---|---|---|---|
| **EPOS-LHC** | 1.77 | 1.02 | 46.73 | 30.48 | 0.117 | 0.068 | 1.77 | 1.3 |
| **QGSJetII-04** | 1.82 | 1.06 | 27.42 | 49.34 | 0.211 | 0.057 | 1.81 | 1.8 |
| **Sibyll2.1** | 1.83 | 1 | 38.77 | 50 | 0.159 | 0.057 | 1.8 | 1.6 |

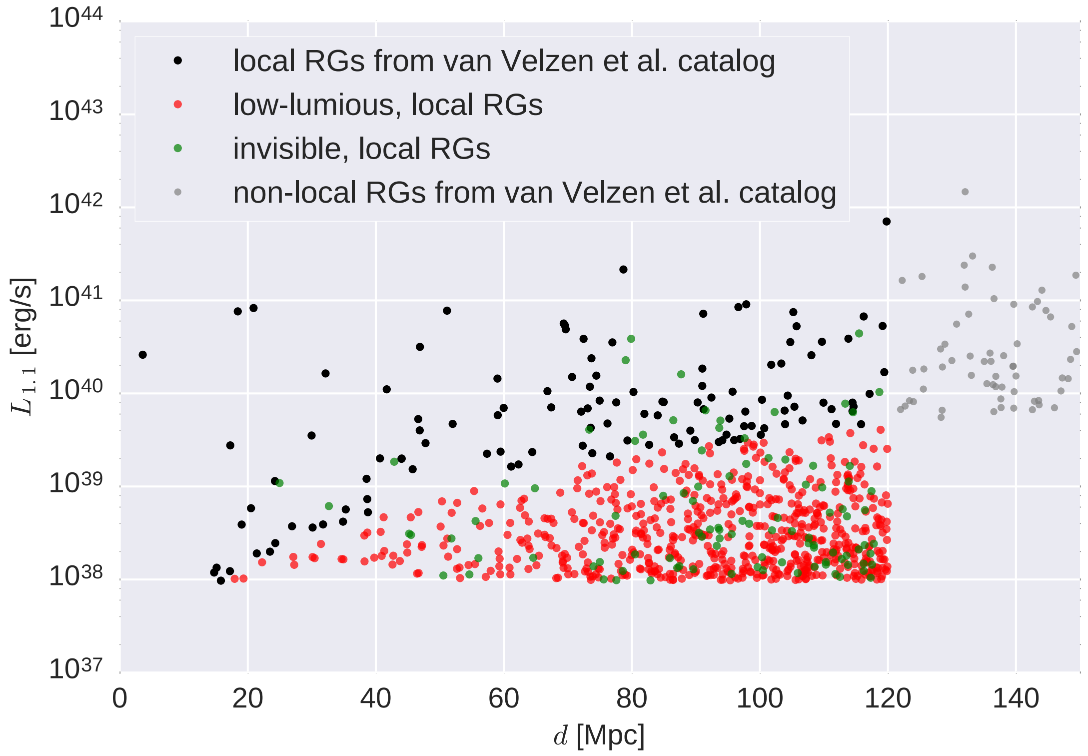


# Local Sources

- Catalogue: Van Velzen *et al.* for *D* < 120 Mpc
- Covers 88% of the sky
- Complete for bright sources
- Missing low-luminous distant RGs due to flux limit
- Compensated for by adding sources following the LSS
- Luminous nearby sources treated separately:

  Cen A, M87, Fornax A



# Non-local Sources

- 1D simulations following continuous source function for radio galaxies
- Including cosmological evolution
- Arrival directions assumed isotropic
- Special case: Cygnus A at 255 Mpc, treated separately

# Fit parameters

- Spectral index: $1.7 \leq a \leq 2.2$
- Cosmic-ray load: $1 \leq g_{CR} \leq 50$
- Acceleration efficiency: $0.01 \leq g_{\mathrm{acc}} \leq 0.5$
- Composition parameter: $0 \leq q \leq 2$ (solar abundance $\times Z_i^q$)
- For Cen A, M87, Fornax A and Cygnus A can get separate values for $g_{CR}$ and $g_{\mathrm{acc}}$
- 6/7 free parameters in the fit for each scenario
- Fit spectrum and composition