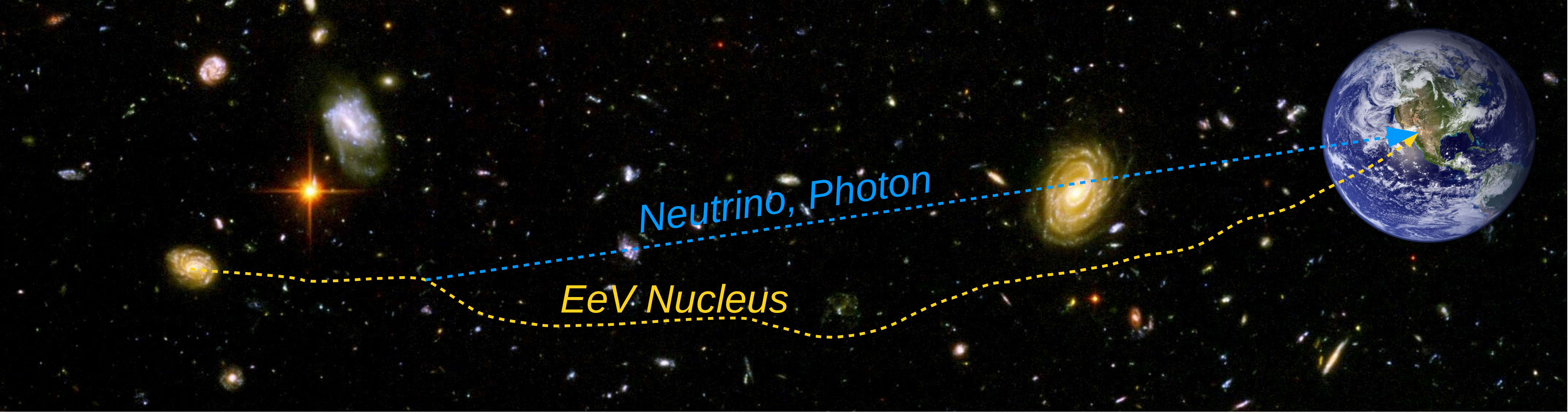


Cosmic Ray Propagation with CRPropa 3

D. Walz[1], R. Alves Batista[2], M. Erdmann[1], C. Evoli[2], D. Kuempel[1], K.-H. Kampert[3], G. Mueller[1], G. Sigl[2], A. Van Vliet[2], T. Winchen[3]

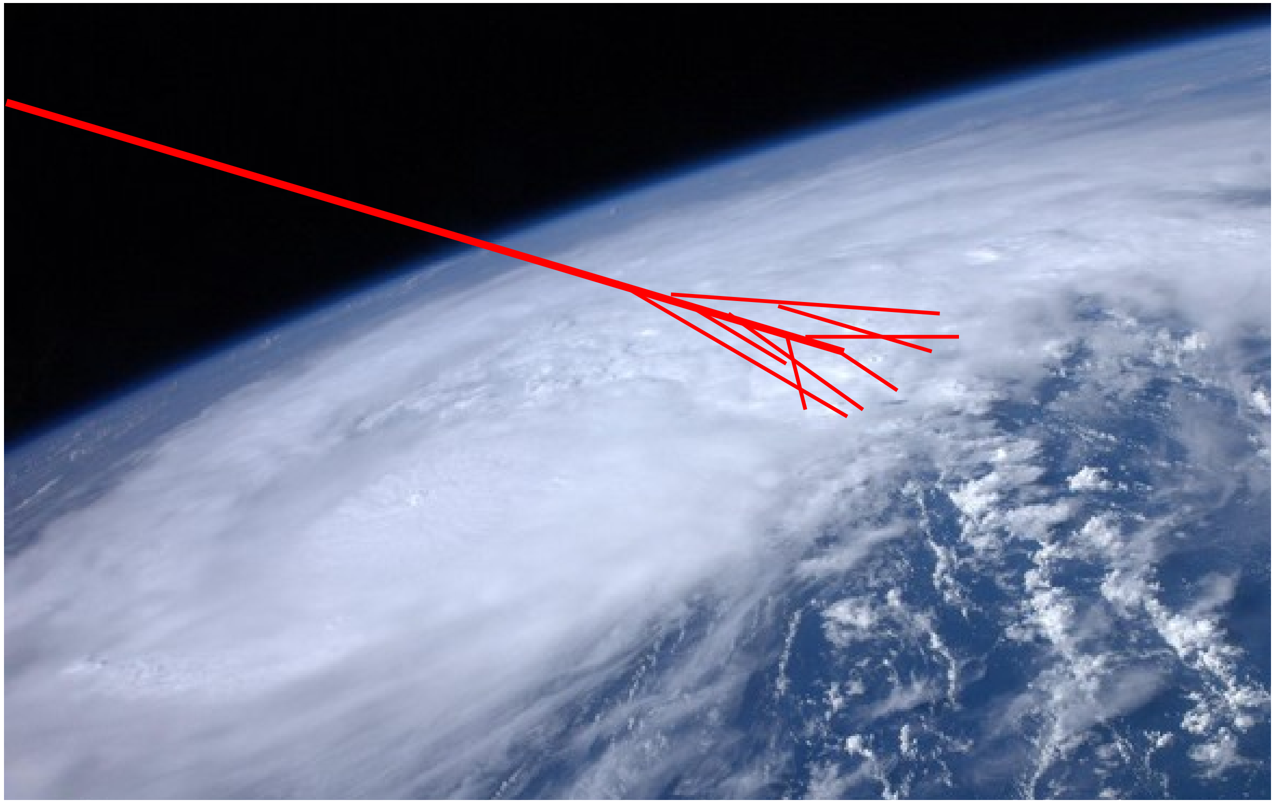
CASPAR 2014, Hamburg

bmb+f - Förderschwerpunkt
Astroteilchenphysik
Großgeräte der physikalischen Grundlagenforschung

Forschungs- und Wissenschaftsstiftung Hamburg

(1) RWTH AACHEN UNIVERSITY
(2) UHH Universität Hamburg
DER FORSCHUNG | DER LEHRE | DER BILDUNG
(3) BERGISCHE UNIVERSITÄT WUPPERTAL

The Highest Energy Cosmic Rays



Hadrons with energies up to ~ $10^{20.2}$ eV

- How are they accelerated?
- Where do they come from?
- What is their chemical composition?
- What can they tell us about the universe?

Need propagation simulations (from source to observer) to connect **<u>measurements</u>** and **<u>theory</u>**

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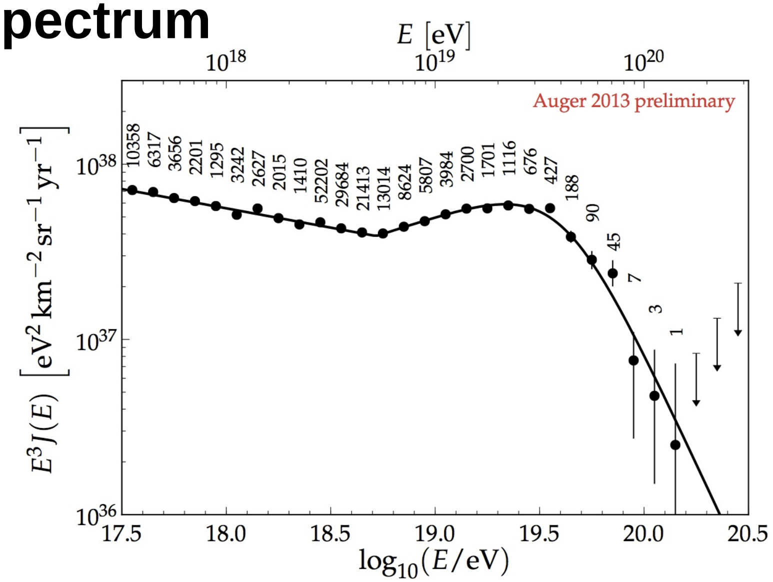
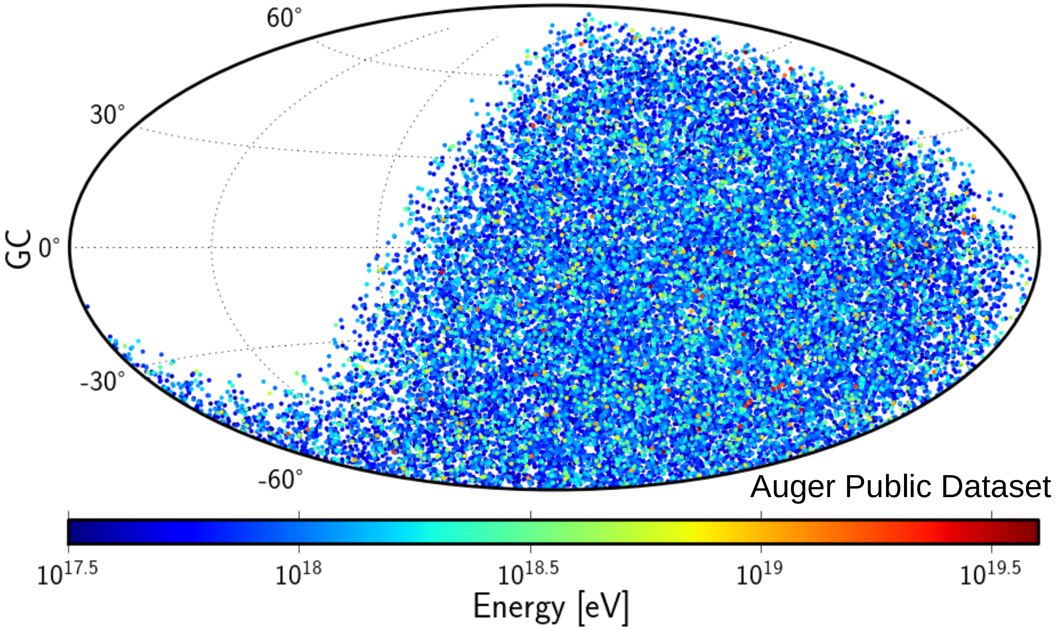
Currently largest experiments:
Telescope Array &
Pierre Auger Observatory

Measurements

Spectrum

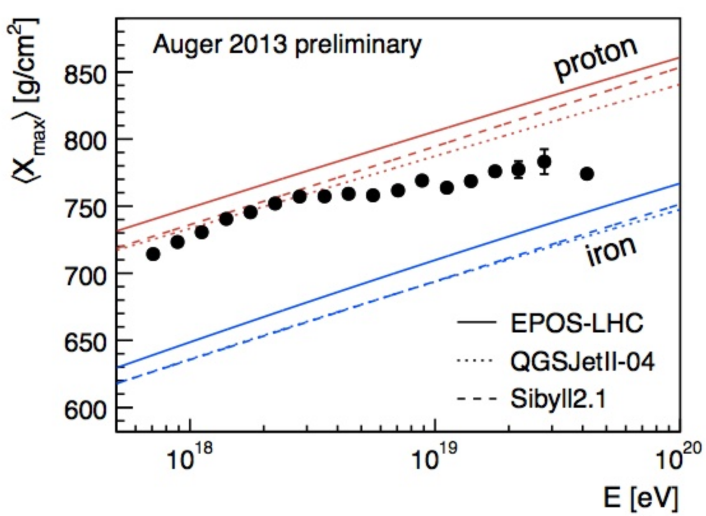


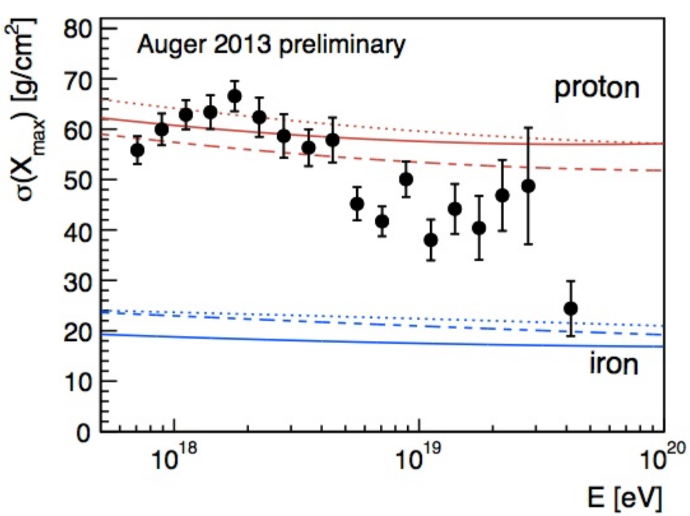
Arrival Directions



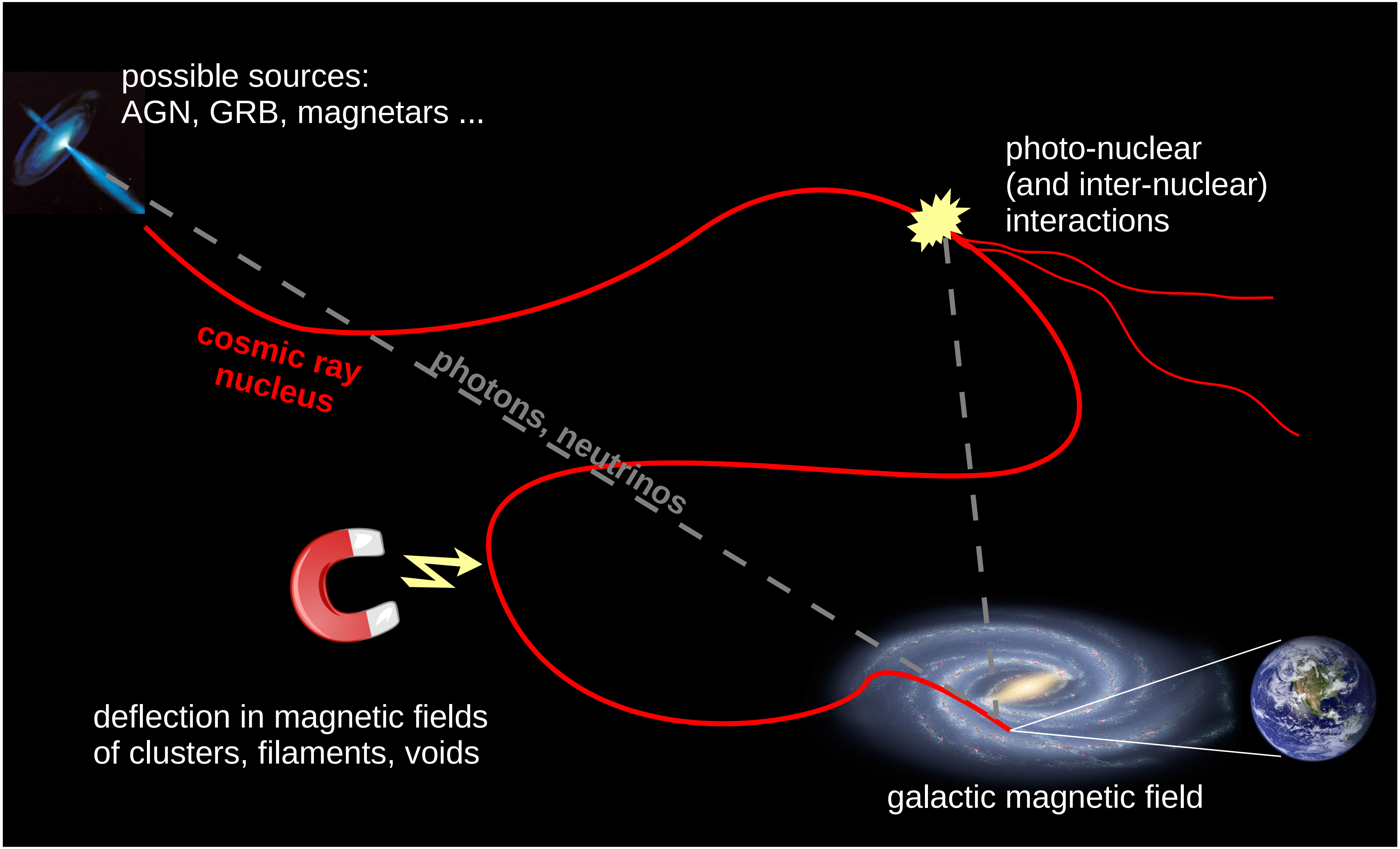
Composition

Mass-sensitive
air shower
observables





Simulation Challenge



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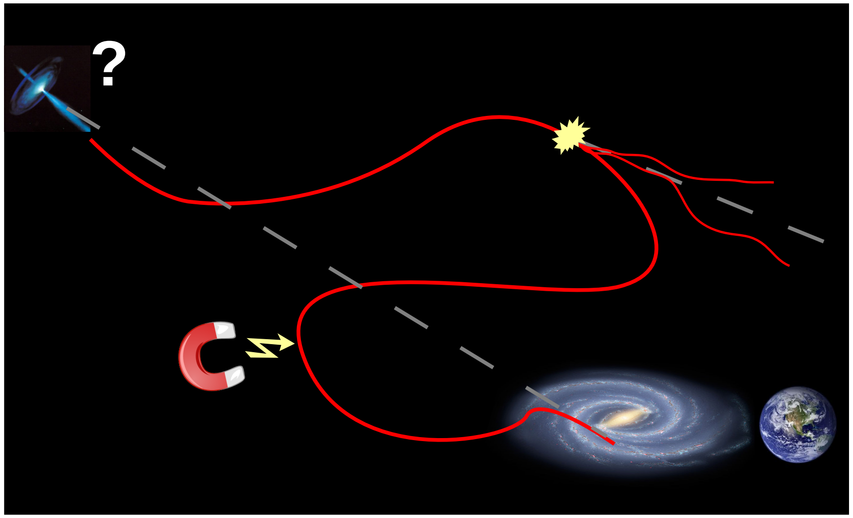
Simulation Challenge

Many unknowns
Large parameter space,
large statistics needed,
multiple use cases

4D simulations
3D simulations including
expansion of the universe



High resolution fields
Large volume, fast lookup

Galactic Propagation
Milky Way tiny (~ 30 kpc) compared to
extragalactic distances (~ Mpc)
Earth tiny compared to Galaxy

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CRPropa – Overview

- Public framework for simulation of ultra-high energy cosmic rays
  - → *https://crpropa.desy.de*
  - → *https://github.com/CRPropa*
- CRPropa, Armengaud *et al.*, Astropart.Phys. 28 (2007) 463-471
  - → Extragalactic propagation of cosmic ray protons, gamma-rays and neutrinos
- CRPropa 2.0, Kampert *et al.*, Astropart.Phys. 42 (2013) 41-51
  - → Extension to cosmic ray nuclei
- **Today: CRPropa 3**

Interactions and Energy Loss Processes

photopion production

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

- mean free path for nuclei written as a function of the mfp for protons and neutrons

photodisintegration

- tabulated cross sections from TALYS

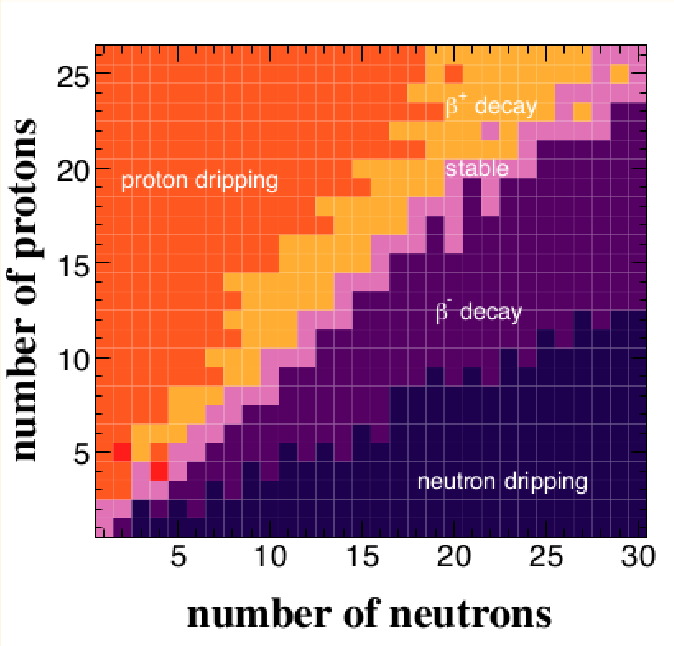
$$\frac{1}{\lambda(\Gamma)} = \int_{E_{min}}^{E_{max}} n(\epsilon, z)\bar{\sigma}(\epsilon'_{max} = 2\Gamma\epsilon)d\epsilon$$

expansion of the universe

$$\frac{dt}{dz} = \frac{1}{H_0}\frac{1}{1+z}\frac{1}{\sqrt{\Omega_m(1+z)^3 + \Omega_\Lambda}}$$

$$E = \frac{E_0}{1+z}$$

nuclear decay



pair production

$$-\frac{dE_{A,Z}}{dt} = 3\alpha\sigma_T h^{-3} Z^2 m_e c^2 k_B T f(\Gamma)$$

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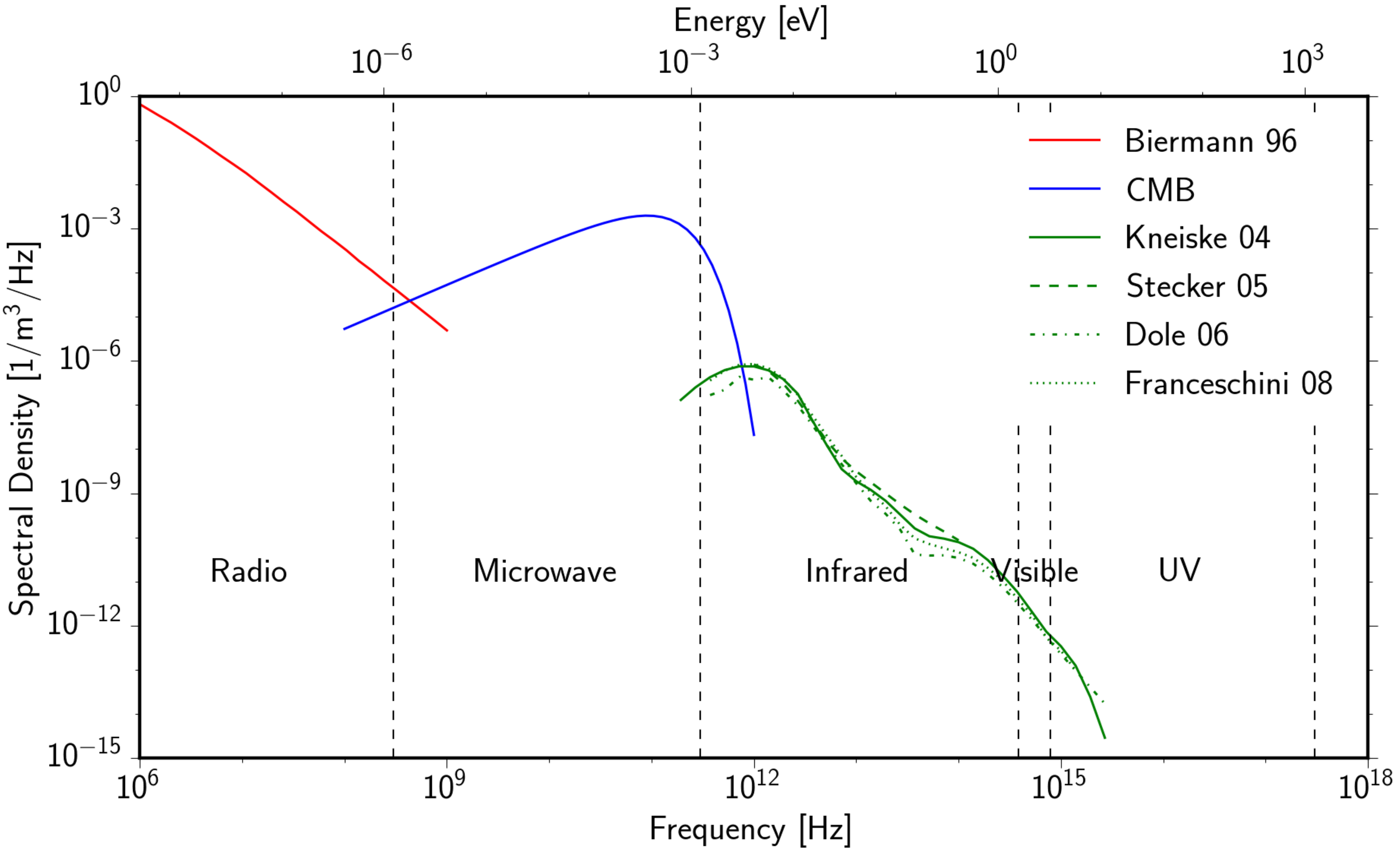
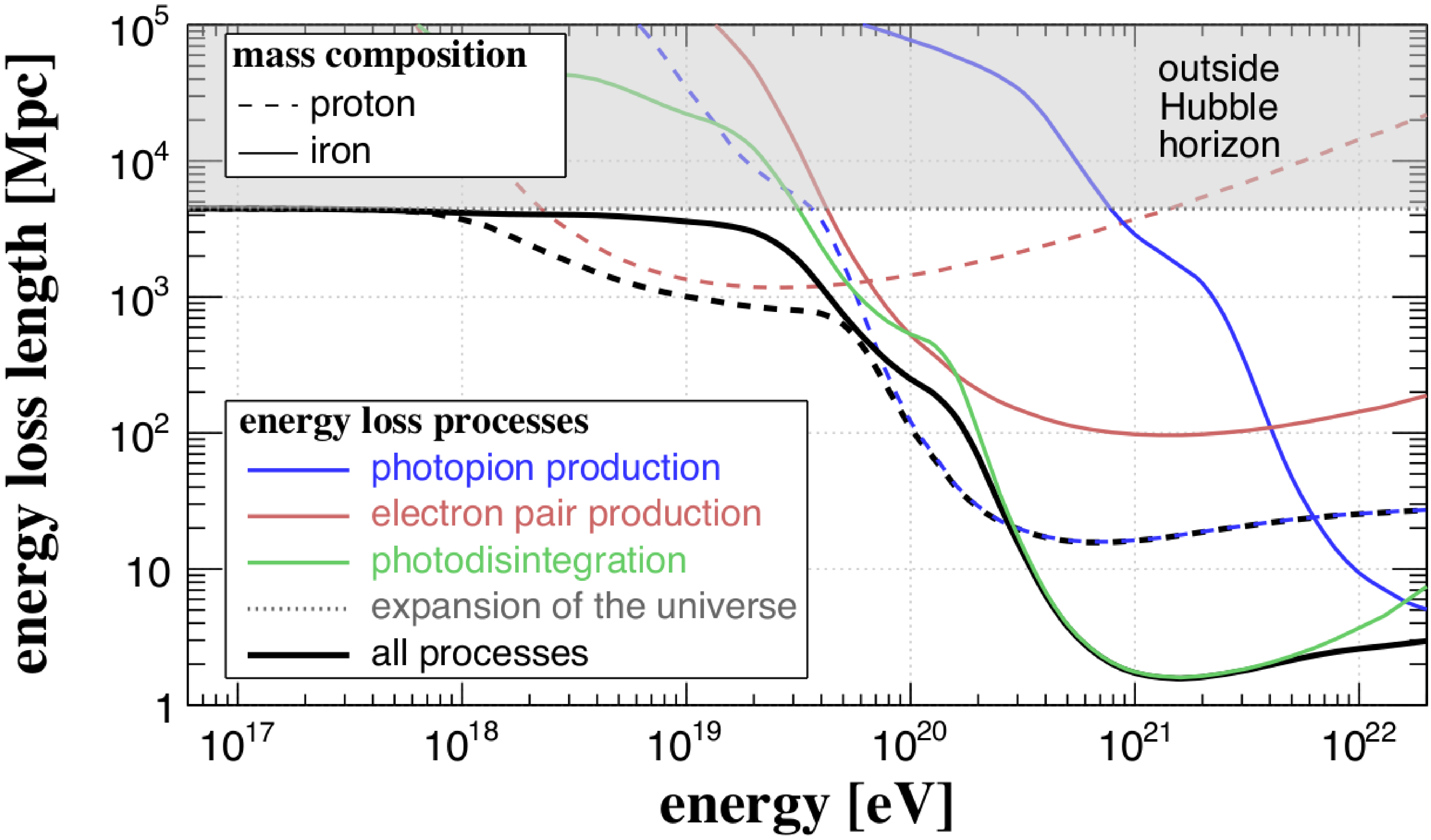
The Intergalactic Medium



Mean Free Pathes



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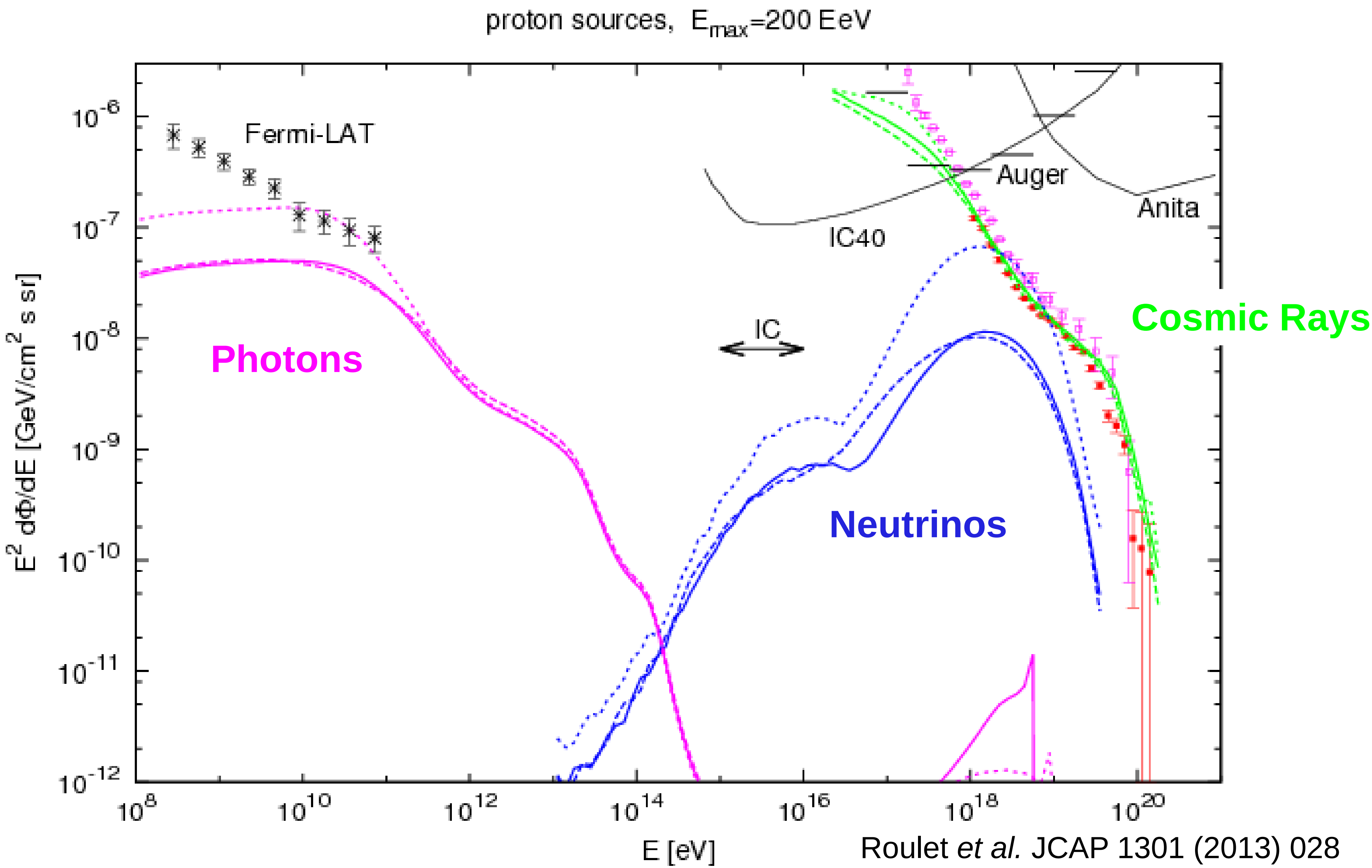
Secondary Particles

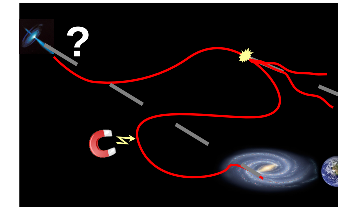


Roulet *et al.* JCAP 1301 (2013) 028

Multi-messenger studies

CRPropa 3 – Simulation Layout

Parameter space & Use cases



- Modular redesign of code
  - → Separation of simulation into independent parts
    - » Interactions, break conditions, output, …
  - → C++ classes with common simple interface
    - » process: update the cosmic ray and bid for next step size

```
Module
process( CosmicRay )
```

- Adaptive step control
  - → Step size needs to dynamically adjusted for efficient propagation
    - » numerical integration, stochastic interactions, …
  - → Bidding system

Module 1	Module 2	→ make largest allowed step
100 Mpc	0.02 Mpc	

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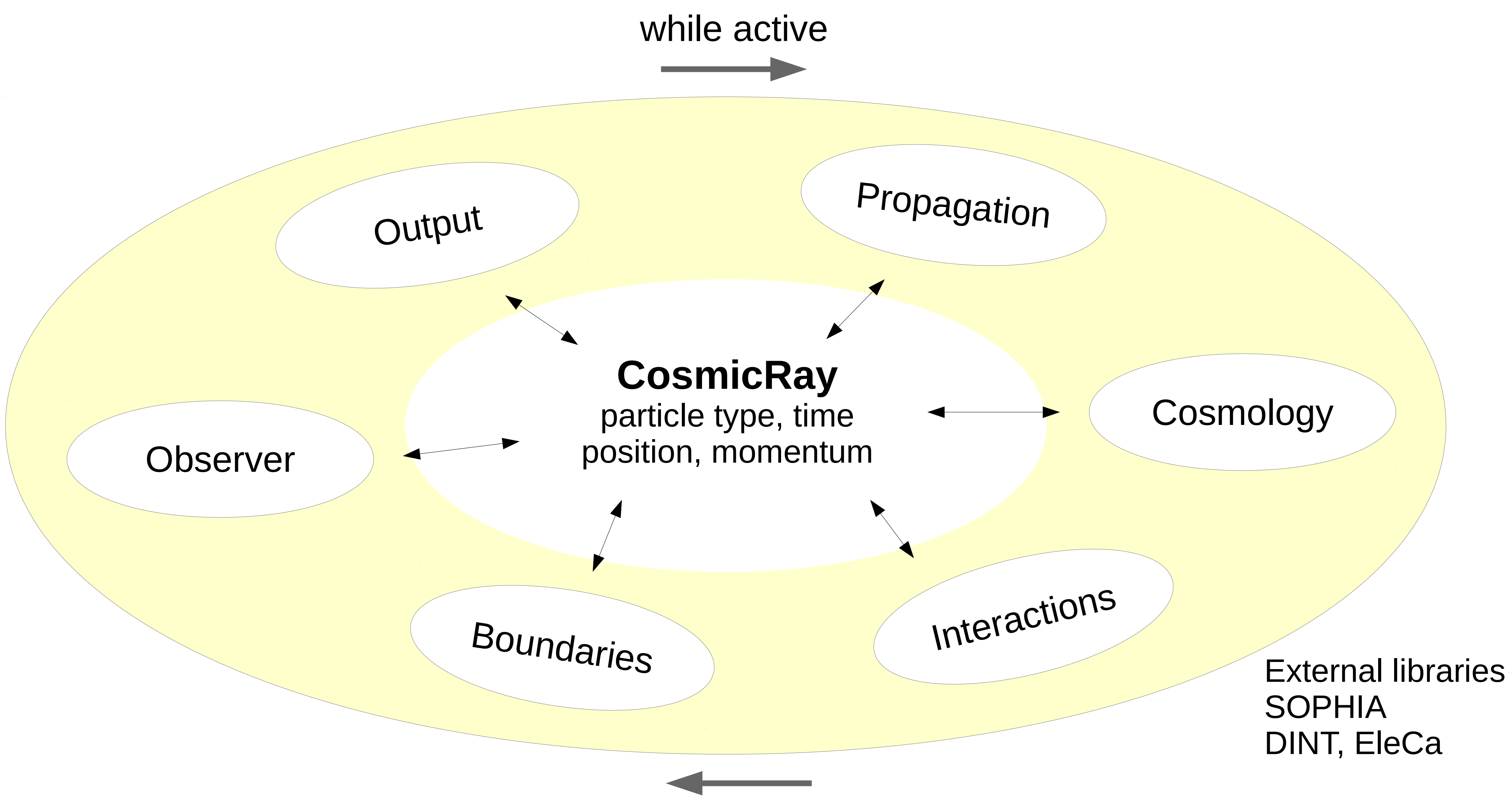
CRPropa 3 – Simulation Layout



- Independence: no communication between modules
- Stateless: straightforward parallelization

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Python Steering

```
from crpropa import *

sim = ModuleList()
sim.add( PropagationCK( myEGMF ) )
sim.add( PhotoPionProduction(CMB) )
sim.add( PhotoDisintegration(CMB) )
sim.add( ElectronPairProduction(CMB) )
sim.add( NuclearDecay() )
sim.add( TrajectoryOutput('trajectories.txt') )

sim.run( myCosmicRay, recursive=True )
```

*all functionality exposed to Python using **SWIG***

define simulation settings

propagate cosmic ray including secondary particles

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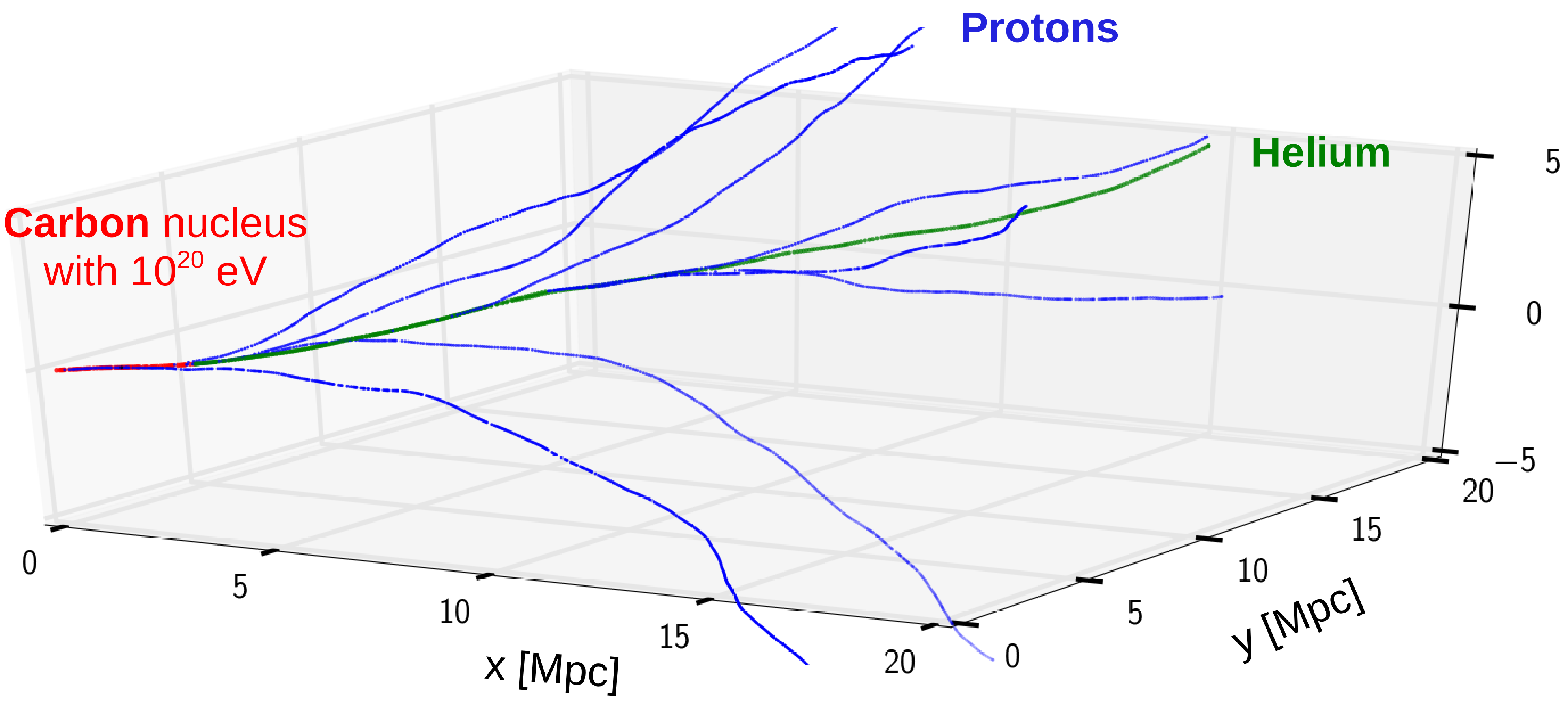
Example: Trajectories in a Turbulent B-Field



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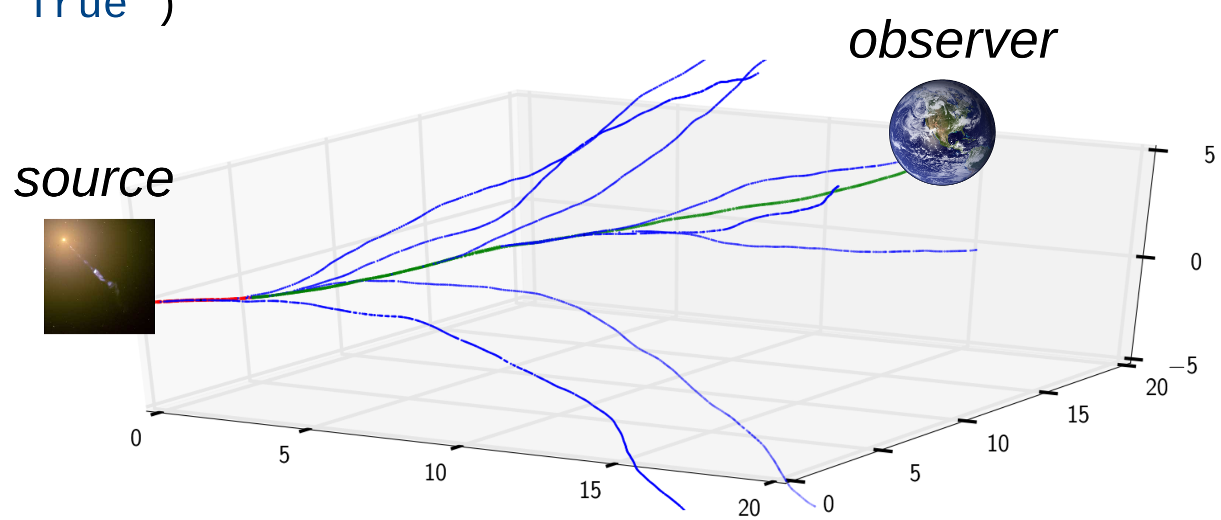
Example: Simulating Arrival Directions

```
sim = ModuleList()
sim.add( PropagationCK( myEGMF ) )
…

sim.add( SmallObserverSphere(position, 0.5*Mpc) )
sim.add( EventOutput('events.txt') )

sim.run( mySources, True )
```



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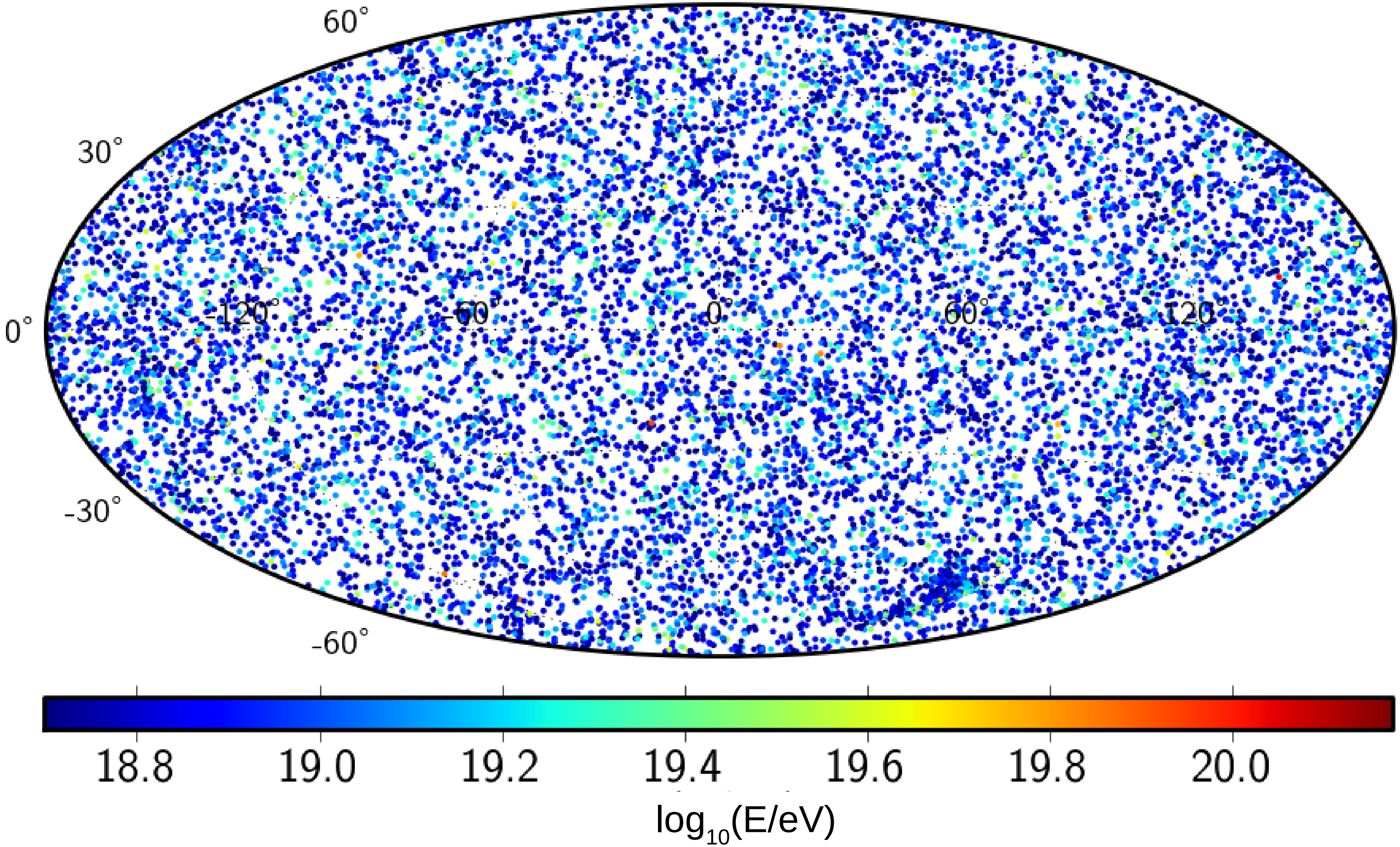
Example: Arrival Directions



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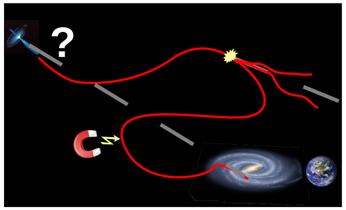
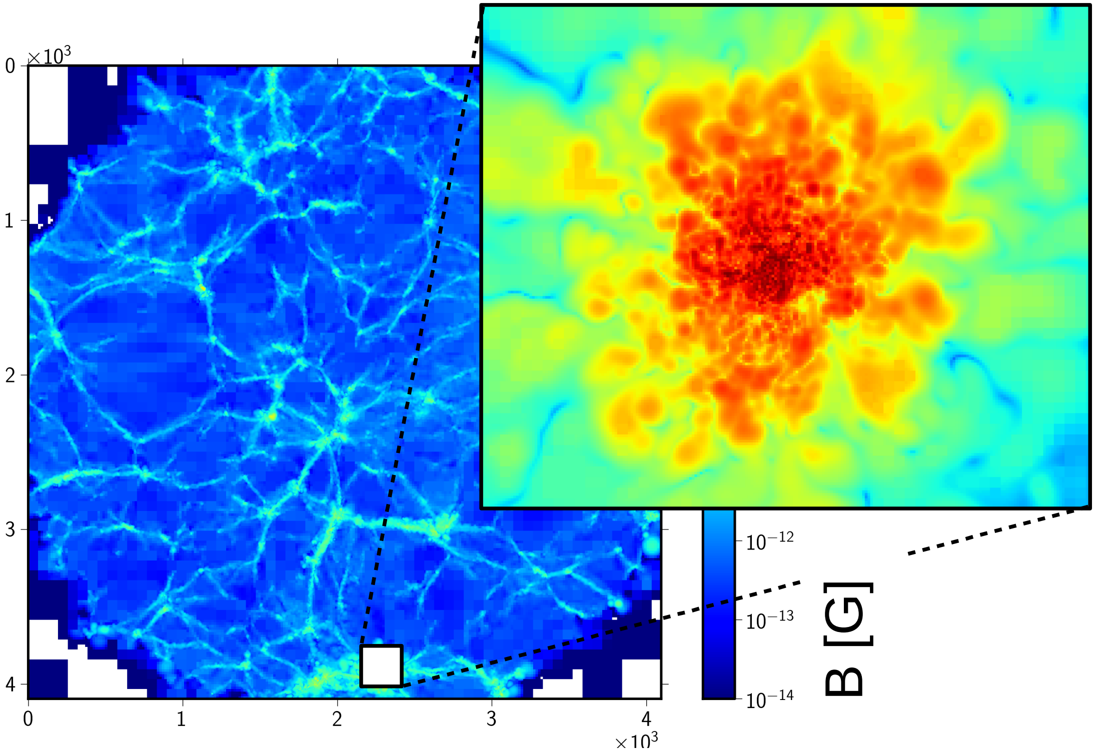


Magnetic Field Techniques

- Models from large scale structure simulations
  - → Large volume and high resolution
  - → Fast lookup required

- New techniques in CRPropa 3
  - → Modulated grid
  - → Multi-resolution grid
  - → Interfaces to
    - » Smooth particle
    - » Adaptive mesh refinement

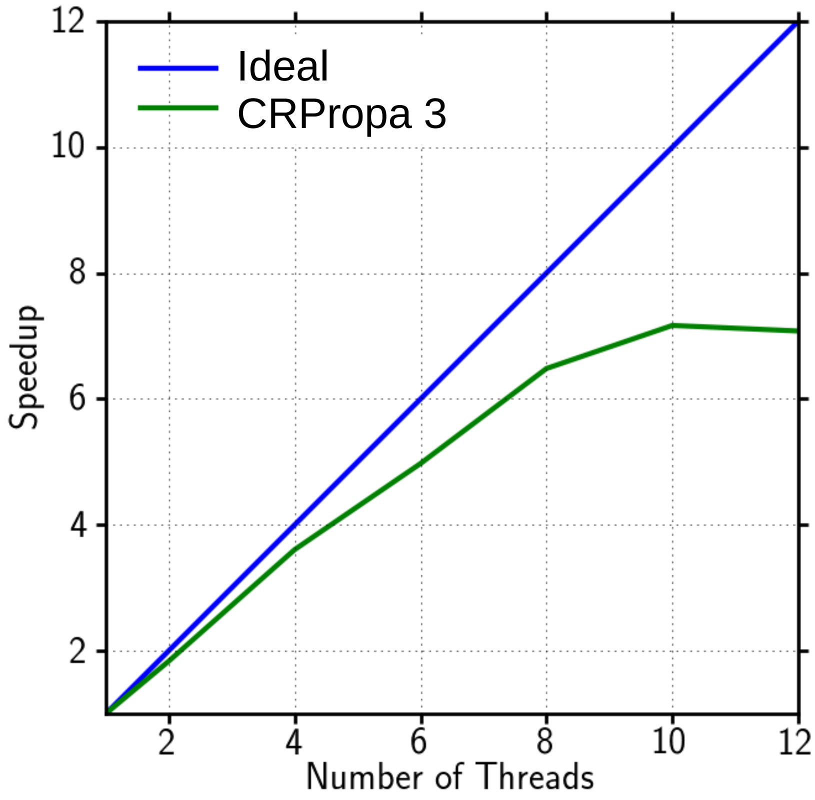


Dolag *et al.* 2004
with multi-resolution grid
220^3 Mpc, ~ 54 kpc resolution
20 GB of 825 GB

Magnetic Field Techniques

- **CRPropa 3 enables shared memory multi-threading**
  - → Better use of computing resources
    - » many-core systems, typically 2 GB per core
    - » select number of cores to match memory demand

- Speedup
  - → Determined by critical sections external libraries (e.g. SOPHIA)
  - → Scales well up to ~8 threads



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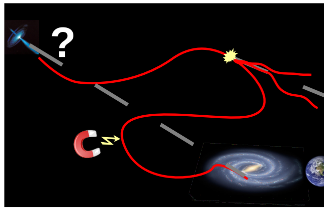
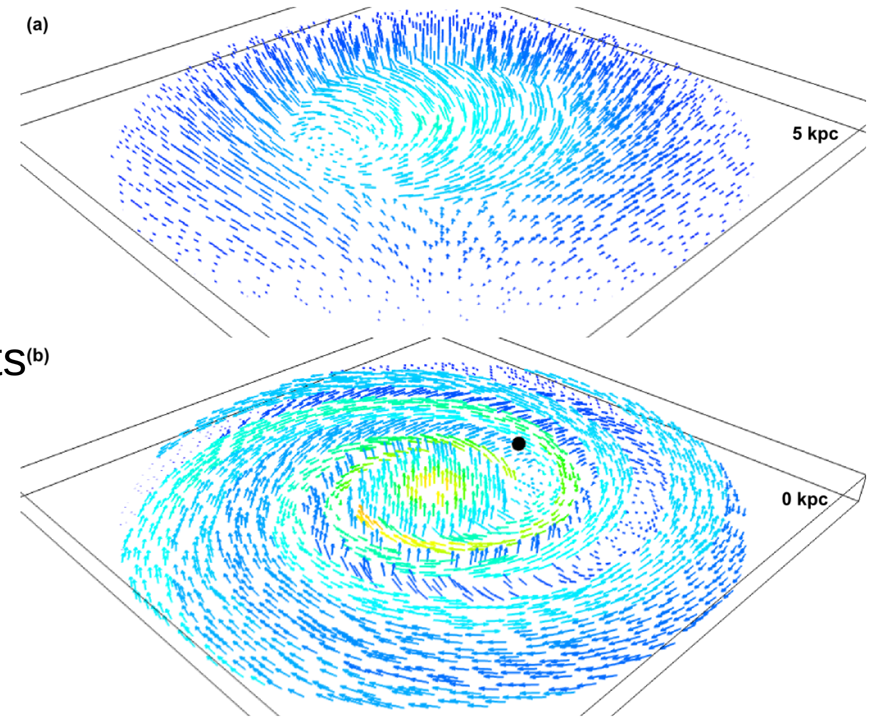


Galactic Propagation

- **CRPropa 3 enables galactic forward and backtracking**
  - → Asymmetric and bisymmetric spiral fields
  - → Toroidal halo fields



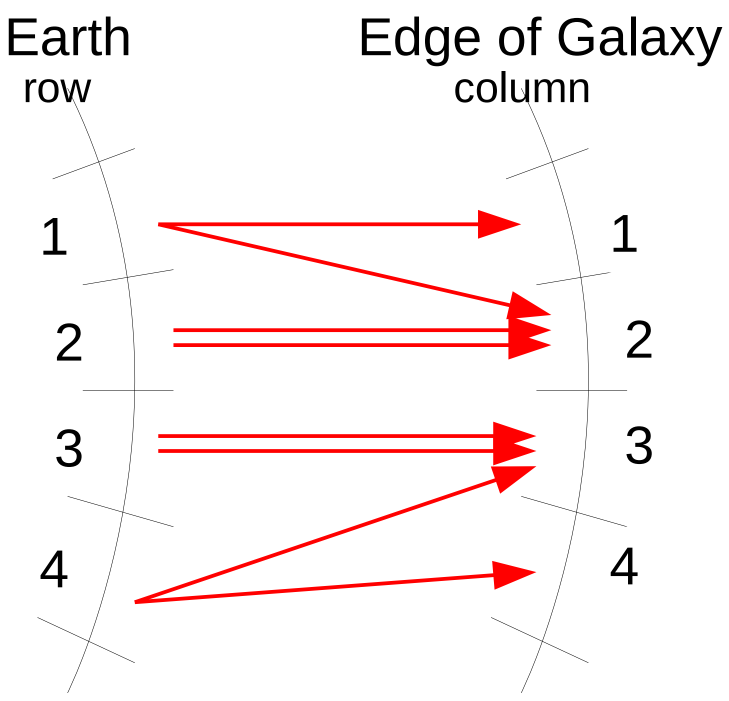
- **Full JF2012 GMF model implemented**
  - → Jansson *et al.* 2012,
  - → Regular, striated and turbulent components
  - → Persistent random fields

- Difference of scale
  - → Galaxy tiny (~ 30 kpc) compared to extragalactic distances (Mpc - Gpc)
  - → Earth tiny compared to Galaxy
  - → Negligible energy loss

} **Galactic lensing**

Galactic Lensing

- **Lensing technique**, cf. Bretz *et al.* Astrop. Phys. 54 (2014)
  - → Backtrack anti-protons from Earth to edge of Galaxy
  - → Construct transformation matrix M from initial and final directions
  - → Nuclei (energy E, charge Z) transform as protons of energy E/Z



$$L = \begin{pmatrix} 1 & 1 & 0 & 0 \\ 0 & 2 & 0 & 0 \\ 0 & 0 & 2 & 0 \\ 0 & 0 & 1 & 1 \end{pmatrix}$$

$$\mathbf{p}_{\mathbf{Earth}} = \mathbf{L} * \mathbf{p}_{\mathbf{Galaxy}}$$

observed arrival directions

arrival directions at edge of Galaxy

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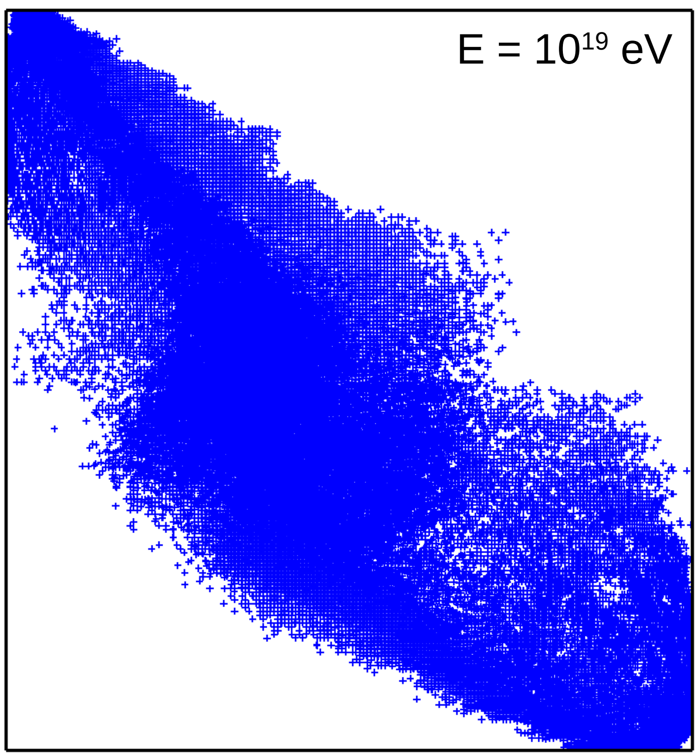
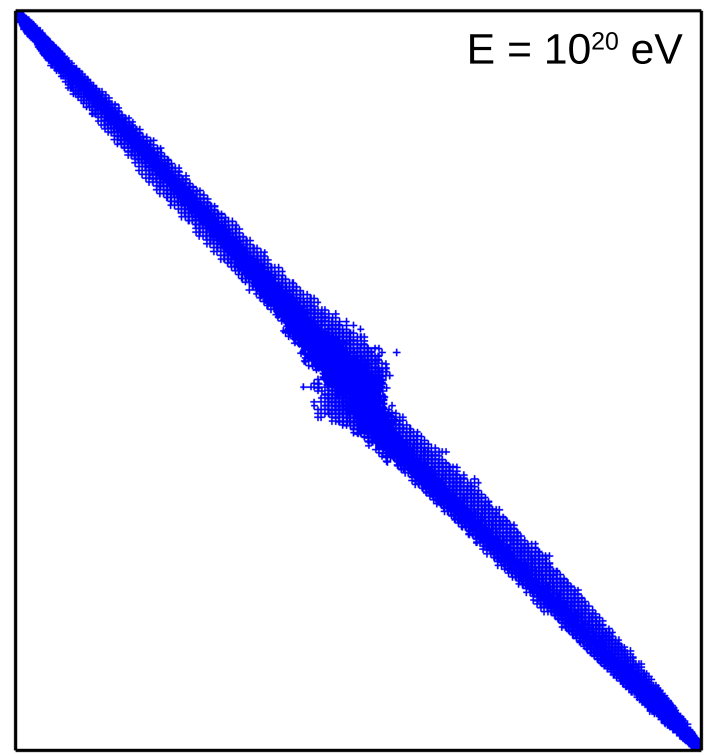
Galactic Lensing

- Directions binned using HEALpix scheme
  - → ~ 50,000 pixel → angular resolution < 1°
- Each transformation matrix has 2.5 x 10^9 entries
  - → Use sparse matrices

JF2012 model
incl. random field

L(E) =





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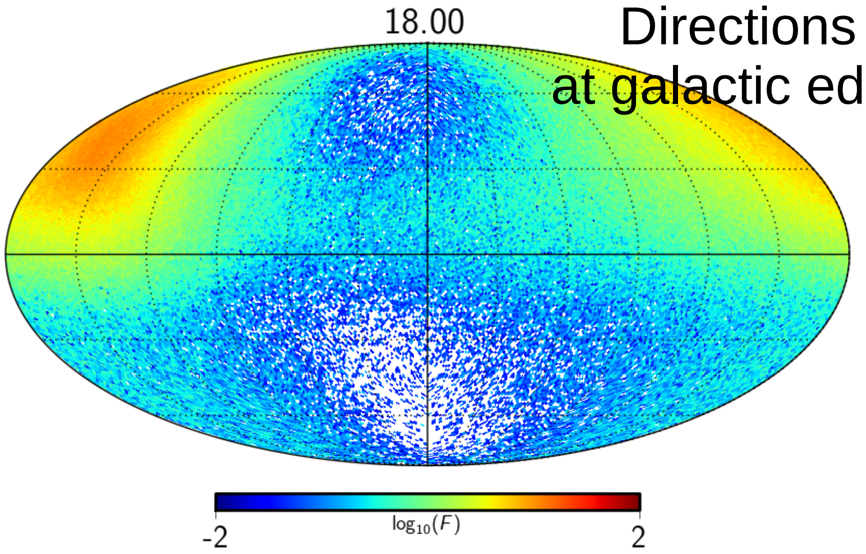
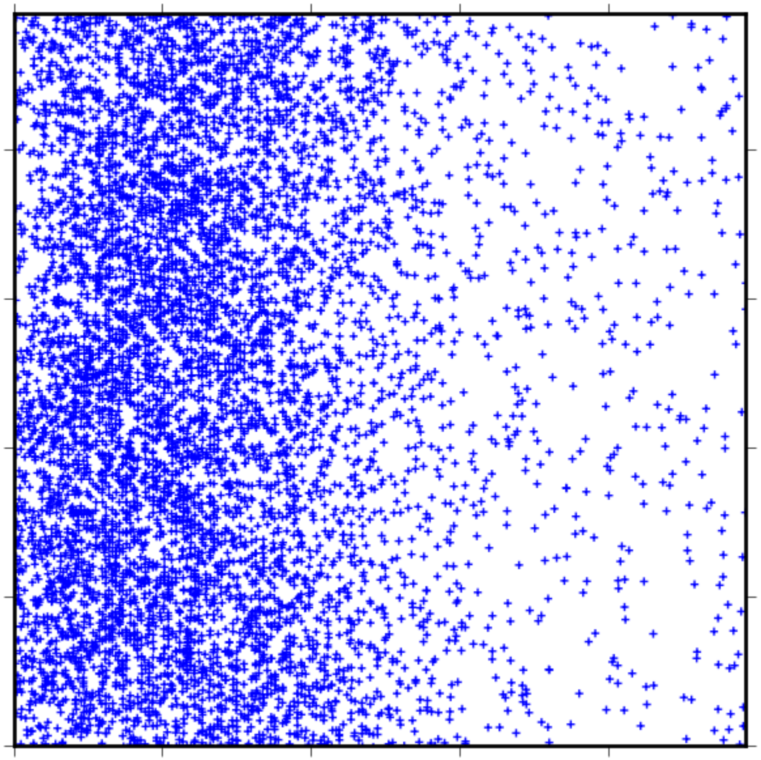
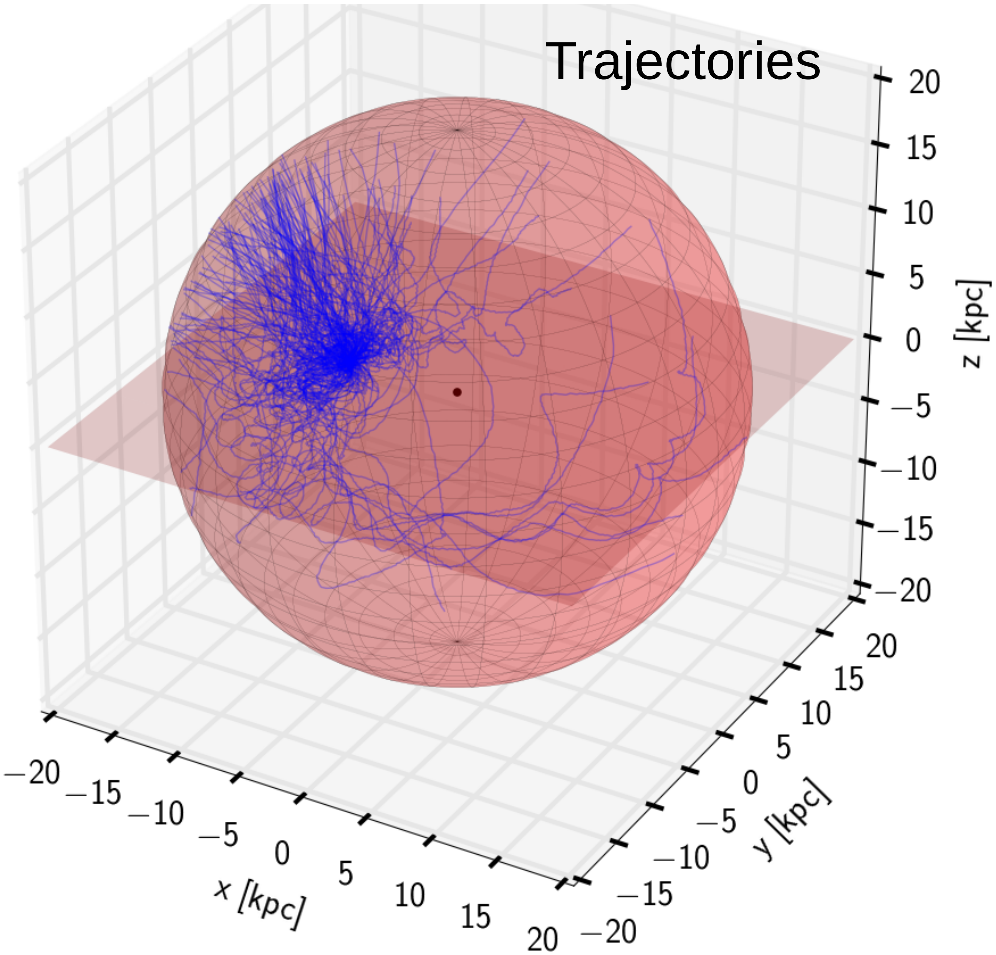
Galactic Lensing



E = 10^{18} eV

L(E) = 



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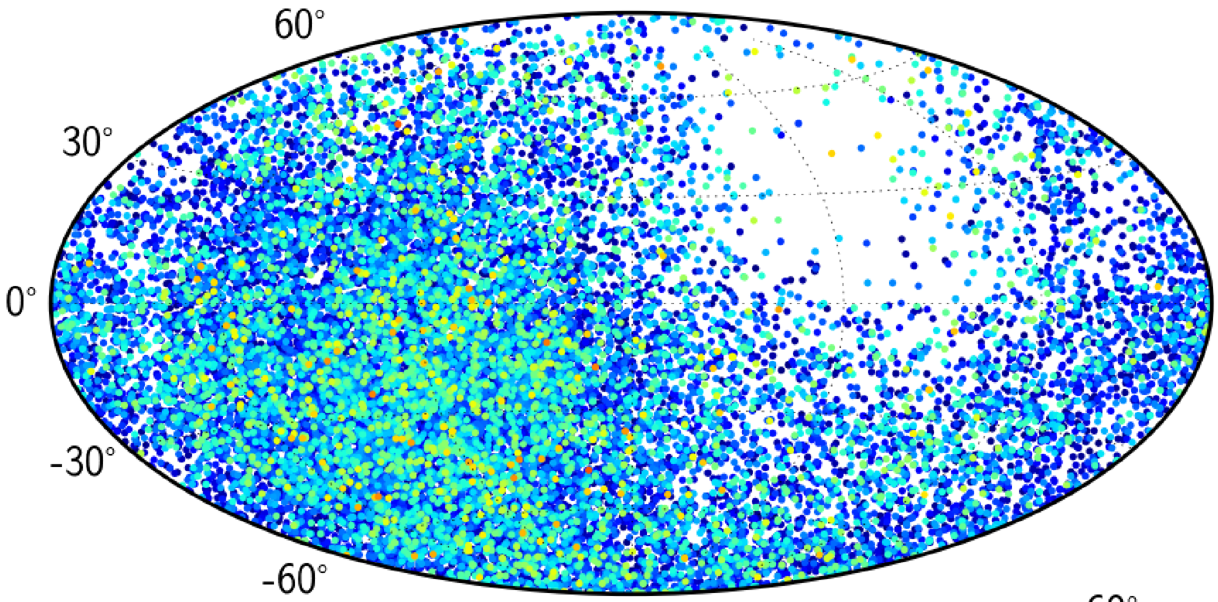
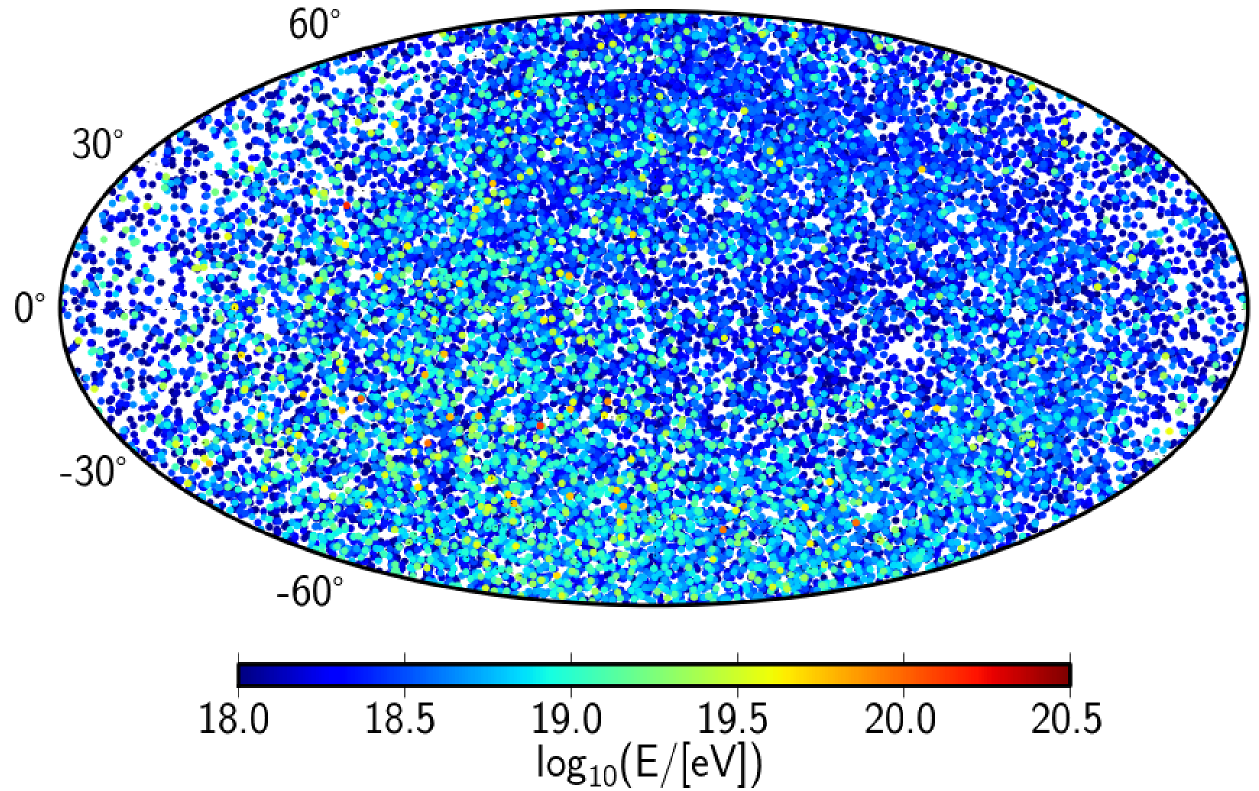
Example: Extragalactic and Galactic Propagation



Extragalactic arrival directions

Observed arrival directions



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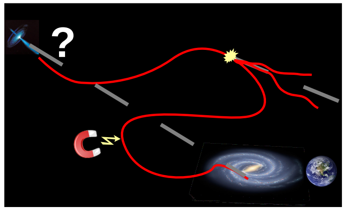
Cosmology in 3D Simulations

4D Propagation



- Effects of the expanding universe
  - → Adiabatic energy loss
  - → Evolution of photon fields
    - » large impact on photo-nuclear interaction rates
  - → Source evolution / intermittent sources

- Straightforward to consider in 1D simulations, however …
  - → No simulation of arrival directions
  - → Neglects magnetic suppression

- Need to simulate both spatially and in time

Example: 4D Propagation

```
sim = ModuleList()
sim.add( PropagationCK( myEGMF ) )
sim.add( Redshift() )
sim.add( PhotoPionProduction(CMB) )
sim.add( PhotoPionProduction(IRB_Kneiske04) )
…
sim.add( RedshiftWindow(0, 0.05) )
sim.add( SmallObserverSphere(postion, radius) )

sim.run( mySources )
```

calculate redshift and apply adiabatic energy loss

evolution of photon fields

detect events which arrive at z = 0 – 0.05

observer as 4D “hypersphere”

source model including evolution

→ Cosmic evolution in anisotropy studies

Magnetic suppression in spectrum & composition studies

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Extending CRPropa

Cross language polymorphy allows extensions in **C++** and **Python**

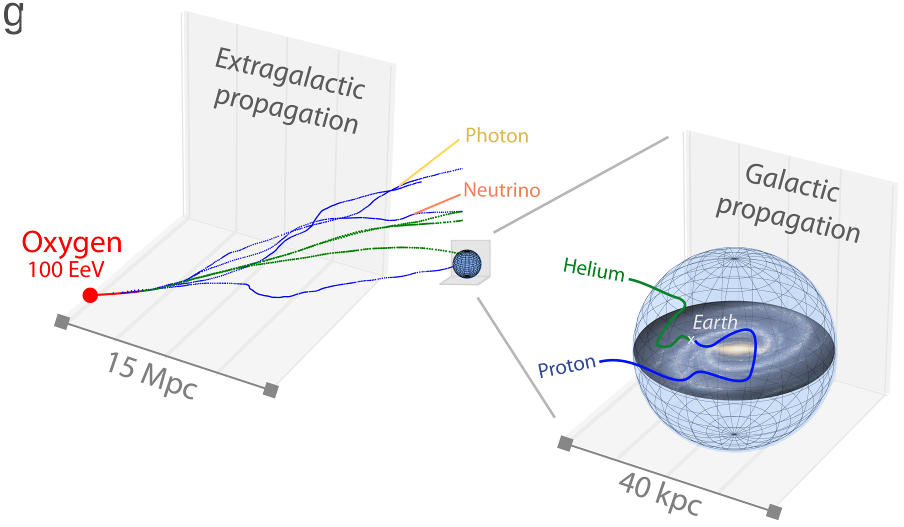
```
class MyTrajectoryOutput(Module):
    """Custom trajectory output: i, x, y, z"""
    def __init__(self, fname):
        Module.__init__(self)
        self.fout = open(fname, 'w')
        self.fout.write('#i\tX\tY\tZ\n')
        self.i = 0
    def process(self, c):
        v = c.current.getPosition() / kpc
        self.fout.write(
            '%i\t%.3f\t%.3f\t%.3f\n'%(self.i, v.x, v.y, v.z))
        if not(c.isActive()):
            self.i += 1

sim = ModuleList()
t = MyTrajectoryOutput('trajectories.txt')
sim.add(t)
```

Summary

- CRPropa framework: Propagation of UHE nuclei and secondaries
  - → *https://github.com/CRPropa*, open development

- New challenges addressed by CRPropa 3
  - → Flexibility in using the tool
    - » Modular simulation layout, Python steering
  - → Magnetic fields
    - » High resolution fields with fast lookup
    - » Shared memory parallelization
  - → Galactic propagation
    - » Direct propagation and GMF models
    - » Galactic lensing
  - → 4D mode
    - » 3D propagation including cosmic evolution



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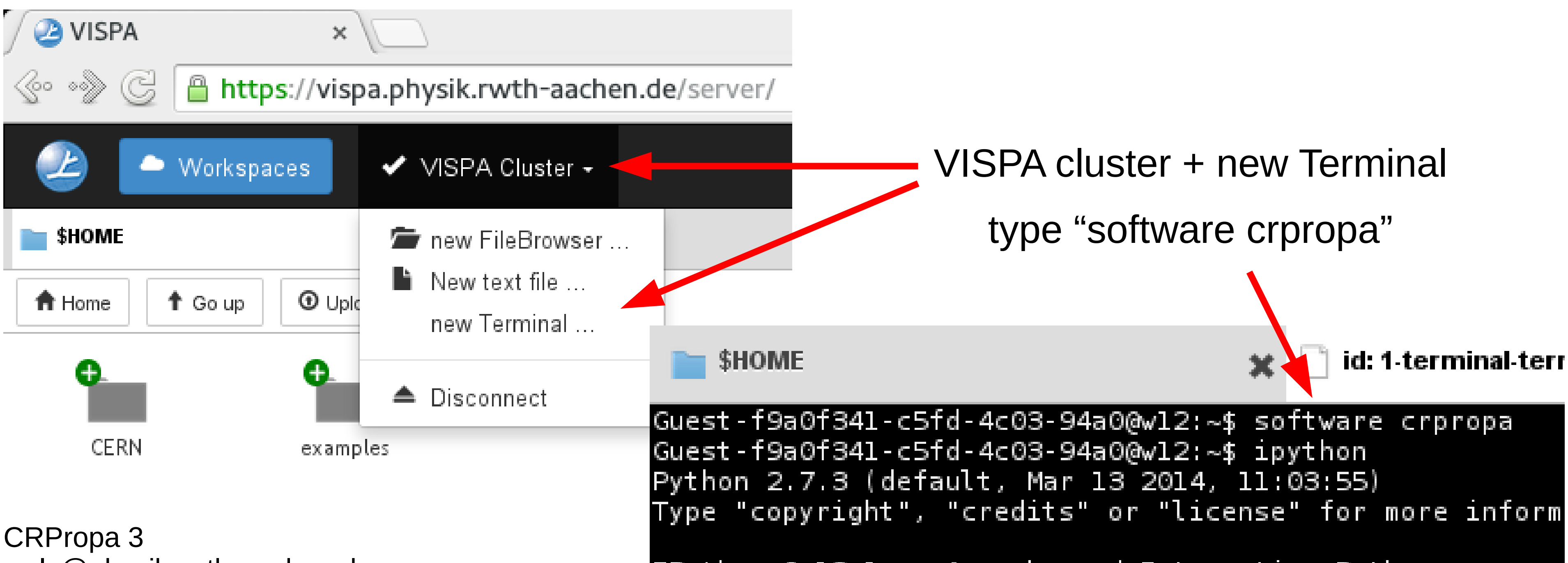
Get CRPropa 3 Running

- Follow the install instruction on the wiki
  https://github.com/CRPropa/CRPropa3/wiki

Cry for help, if needed!

- "Plan B": Use CRPropa via the VISPA platform
  a) https://vispa.physik.rwth-aachen.de/server/login
  b) https://vispa.physik.rwth-aachen.de/server/guest_login
  (temporary guest account, *data is lost on disconnect)*



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Getting Started

- Wiki: https://github.com/CRPropa/CRPropa3/wiki
  → Start with Basics and try out the commands in a python / ipython shell