Full Universe Monte Carlo for UHECRs

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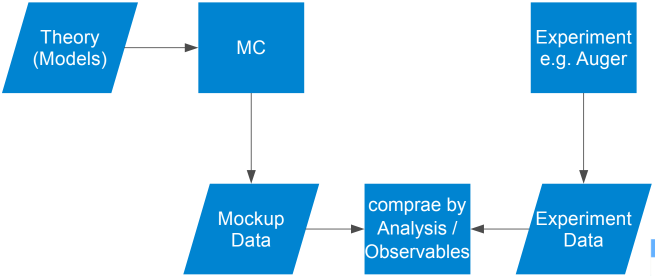
Motivation

CR Physics: Many open questions

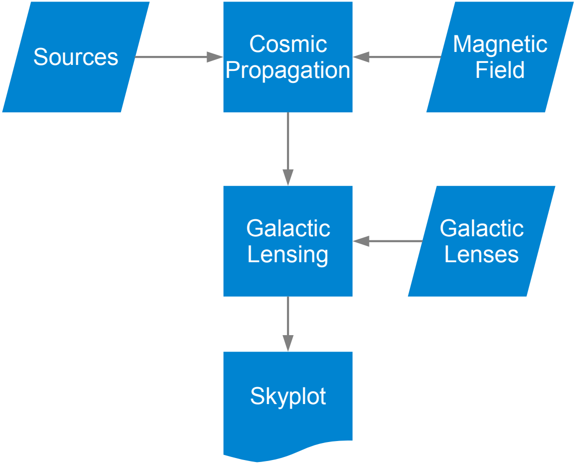
- source positions
- composition
- magnetic field strength
- ...

Use methods from High Energy Physics



Full Monte Carlo

Propagate each UHECR through the nearby ($\approx$ 120 Mpc) universe.



Propagation

We use a modified version of CRPropa[1] for the propagation of the cosmic rays (currently only protons)

Features

- numerical solution of propagation equations
- sources and observers
- custom magnetic field
- particle interactions (energy loss)

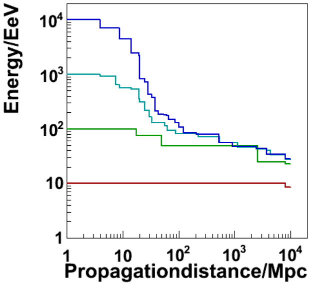


Figure: Energy loss of 4 protons with different starting energies. GZK-Effekt

[1] Günter Sigl et al., Astropart. Phys. 28, 463-471

Large Scale Structure I

Simulation of the universe using smooth particle hydrodynamics[2] (Millenium Run)

- (dark) matter distribution
- uses constraints to match real observations ($\pm \approx 5$ Mpc)
- prediction of magnetic field
- resolution ≈ 100 kpc

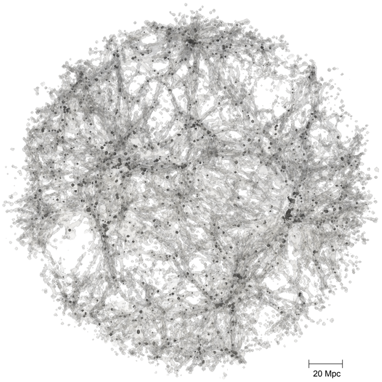


Figure: Mass distribution of simulated universe

[2]Klaus Dolag et. al., Journal of Cosmology and Astroparticle Physics, 2005

Large Scale Structure II

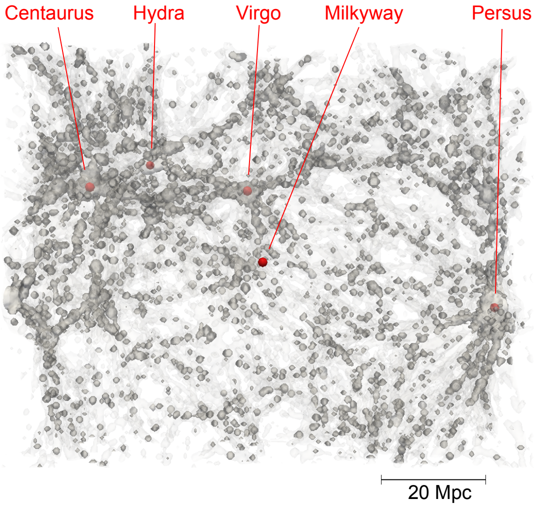


Figure: Positions of clusters in the simulation which correlate with real observations, as a result of the implemented constraints.

Integrate the LSS field into CRPropa I

First Approach: use smooth particles directly

- 55 billion particles ($\approx$ 1.5 GB)
- very slow near high density regions (calculate $\vec{B}$ on-the-fly from up to 1 billion particles)
- full resolution of LSS
- good for verification

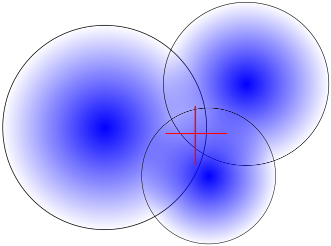


Figure: 3 smooth particles with different smoothing lengths (radius) contribute to the mass/b-field.

Integrate the LSS field into CRPropa II

Second Approach: paged regular grid

- trade memory for speed
- resolution: 100 kpc ($\approx$ LSS)
- 2400^3 samples $\rightarrow$ 150 GB
- linear interpolation
- divide into cubes (pages) with 10 samples length
- only load needed pages into memory

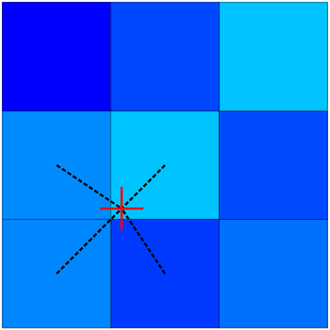


Figure: Interpolation example in two dimensions. The color represents the field strength.

First Trajectories

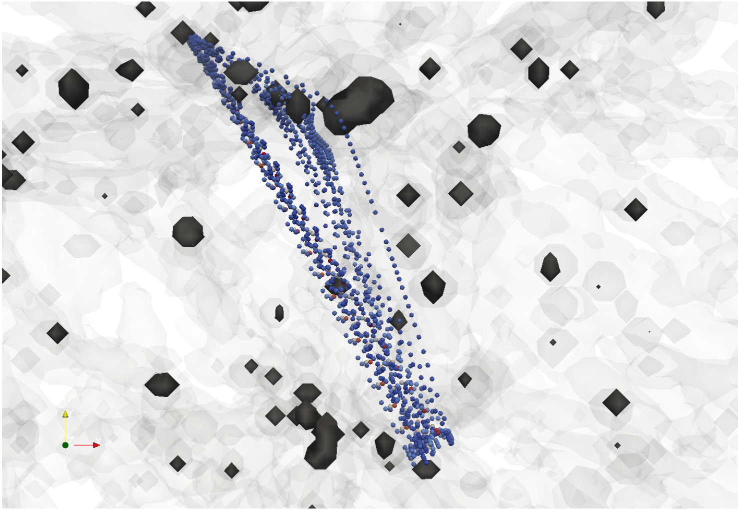


Figure: Trajectories of protons from a ≈ 14 Mpc distant source (top). The color of the spheres represents the current energy. Protons are isotropically radiated. Only those hitting the observer (1 Mpc) are shown.

Source Distributions I

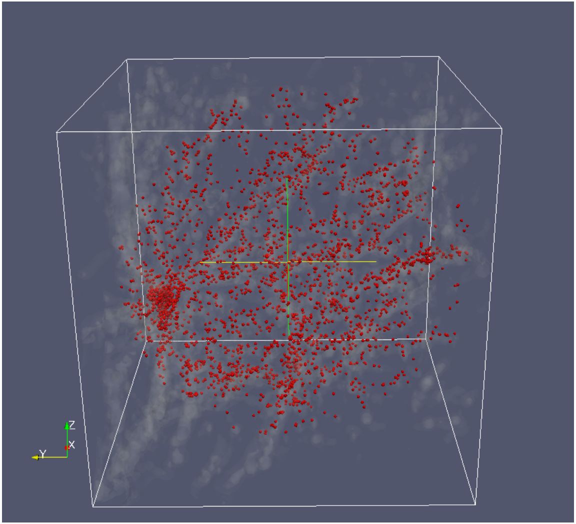


Figure: Place sources in high density regions.

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Source Distributions II

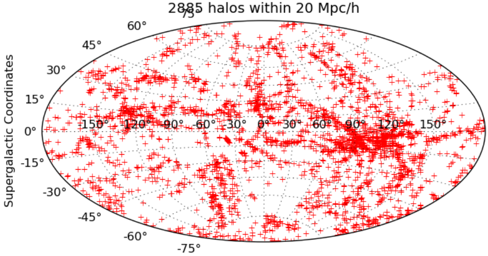

Figure: Skymap of sources as seen from the observer (aka Milkyway).

Different Magnetic Field Strength

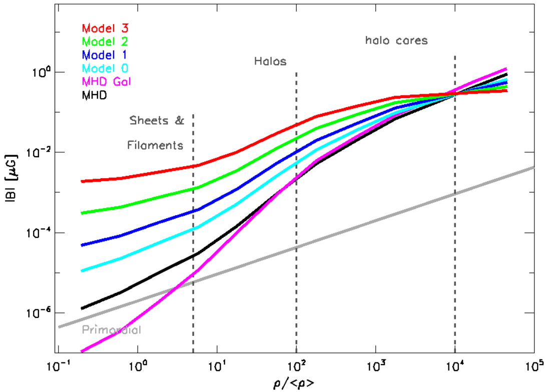

Figure: MHD und MHD Gal are the results of direct simulations (primordial seed vs. galactic outflow seed). Models 0..4 are scaled versions. Plotted is the mean field stregth over overdensity.

Magnetic Field Strength Low

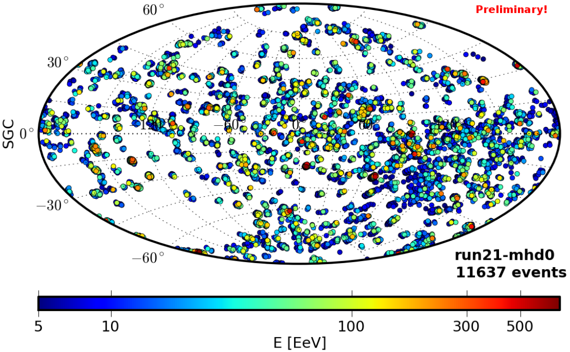

Figure: Skymap of 1063 random sources as seen from the observer in supergalactic coordinates. Low field strength.

Magnetic Field Strength High

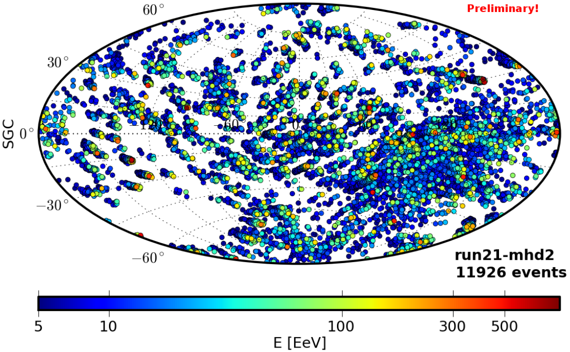

Figure: Skymap of 1063 random sources as seen from the observer in supergalactic coordinates. High field strength.

Skyplots Supergalactic

example skyplots as observed from the '"milkyway" . . .

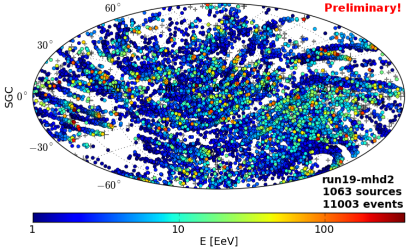

Figure: Supergalactic coordinates

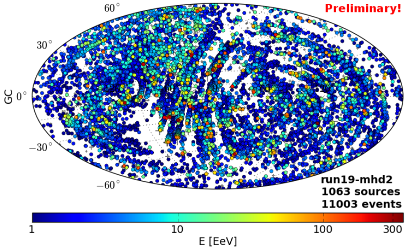

Figure: Galactic coordinates

Skyplots Galactic

. . . and finally propagated through our galaxy using galactic lensing.

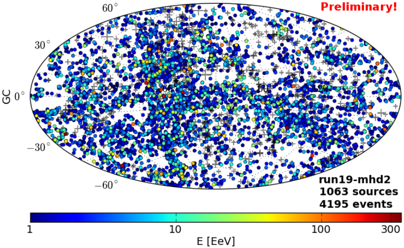

Figure: after galactic lensing

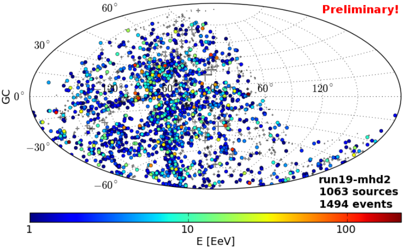

Figure: after galactic lensing and Auger coverage applied

Performance

Memory usage and cpu time needed highly depend on many parameters, e.g.:

- distance between source and observer (1 - 120 Mpc, currently < 20 Mpc)
- stepsize: numerical accuracy (currently 0.1 Mpc)
- size of the observer: angular accuracy ($1.2^{\circ} \rightarrow 200$ kpc for a 10 Mpc distant source)

With our current settings we get *roughly*
1000 Events per hour per cpu core.

For optimal performance more than 1 GB of memory is recommended.

Conclusion and Outlook

Conclusion

- technical stage finished, understand the system
- a Full Monte Carlo of UHECRs is possible
- results look very promising
- interesting insights about trajectories of UHECRs

Outlook

- create Monte Carlo production stack
- more studies about sources: distribution, luminosity, directional radiation
- compare results with Fast Monte Carlos
- compare results with isotropy
- further improve performance, e.g. use GPU, better data structures (e.g. AMR)