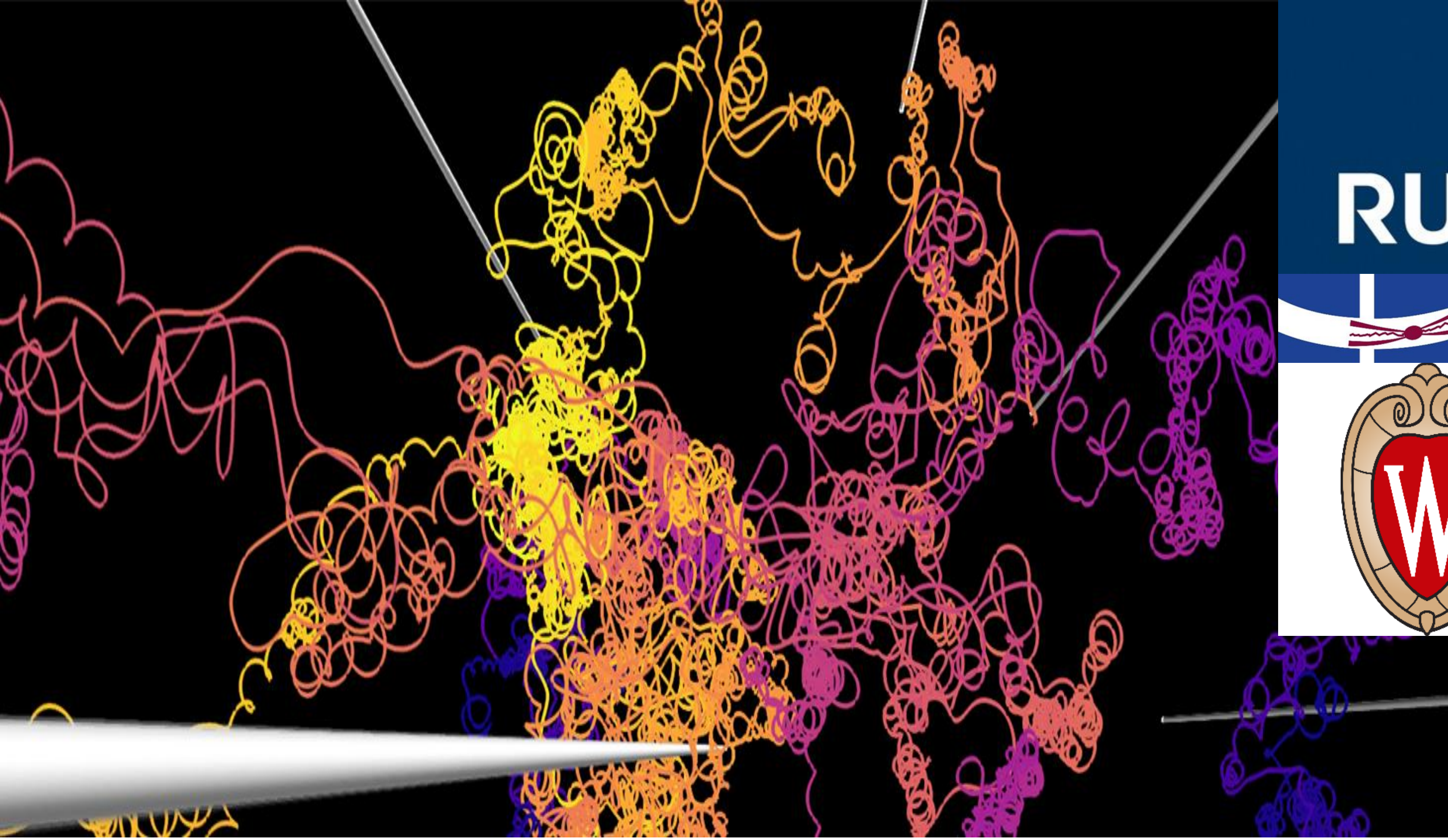

Cosmic-Ray Transport between the Knee and the Ankle with CRPropa

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Motivation

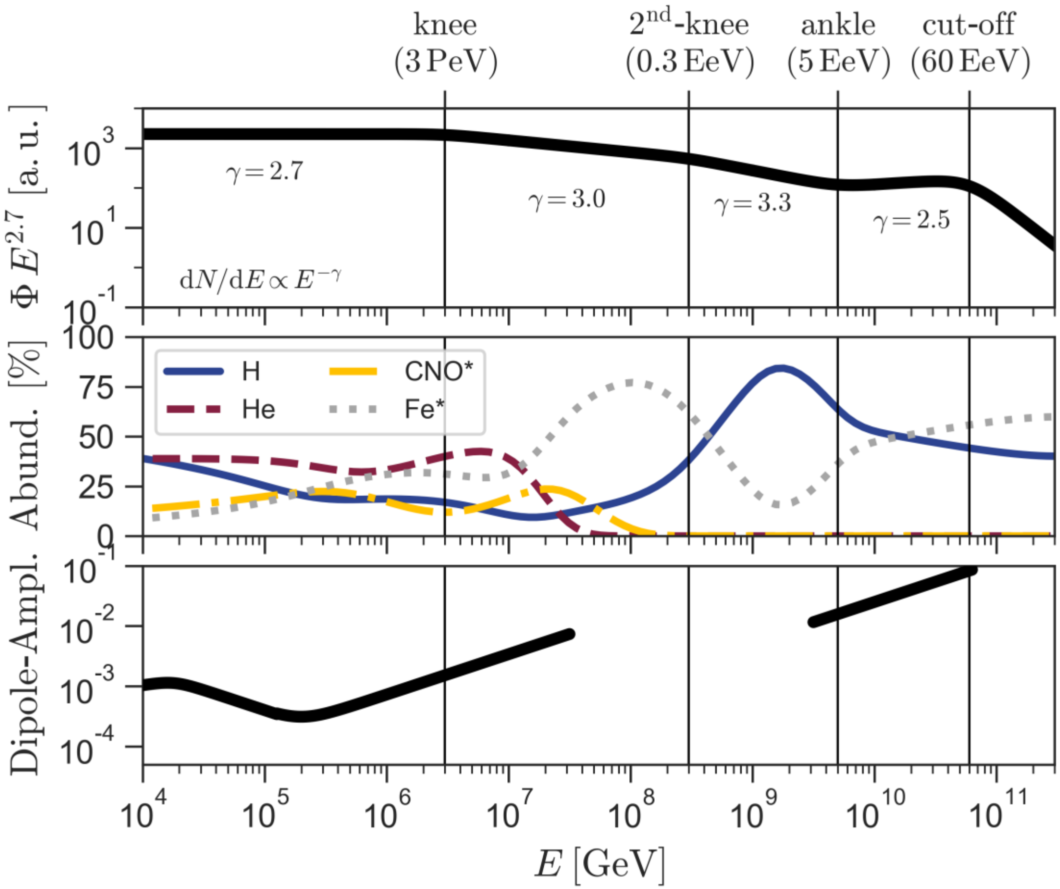
Direct observation of CRs at their sources is impossible

→**Indirect information based on:**

- **Neutral messengers (ν, γ)**
- **Transport modelling**

All observables (spectrum, composition, arrival direction) are influenced during the transport

→**Three-dimensional modeling including interactions**



Impossible to simulate all particle individually on long time scales

→ **Ensemble averaged description**

Modelling the Transport

$$\frac{\partial n(\vec{r},p,t)}{\partial t} + \vec{u}\cdot\nabla n = \nabla\cdot(\hat{\kappa}\nabla n) + \frac{1}{p^2}\frac{\partial}{\partial p}\left(p^2\kappa_{pp}\frac{\partial n}{\partial p}\right) + \frac{p}{3}(\nabla\cdot\vec{u})\frac{\partial n}{\partial p} + S$$

Advection: $\vec{u}\cdot\nabla n$

Spatial Diffusion: $\nabla\cdot(\hat{\kappa}\nabla n)$

Momentum-diffusion: $\frac{1}{p^2}\frac{\partial}{\partial p}\left(p^2\kappa_{pp}\frac{\partial n}{\partial p}\right)$

Adiabatic Effects: $\frac{p}{3}(\nabla\cdot\vec{u})\frac{\partial n}{\partial p}$

Sources: S

Partial (Fokker-Planck) Differential Equation (FPG) for particle density n

Equivalence

Stochastic Differential Equations (SDEs)

$$\mathrm{d}\vec{x} = \underline{\vec{u}dt} + \underline{\widehat{D}\mathrm{d}\vec{w}}$$

$$\mathrm{d}p = \underline{-{}^{p}/_{3}\,(\nabla\cdot\vec{u})\mathrm{d}t} + \underline{D_{pp}\mathrm{d}w_p}$$

Comparison

Grid

GalProp, DRAGON, PICARD, …

Advantages

- ✓ Shorter computation times
- ✓ Widely used and well tested
- ✓ Good interaction implementation
- ✓ PICARD: Explicit stationary solver

Disadvantages

- Huge memory requirements
- Not possible to reweight
- No information on single particles
- Shocks hard to simulate

SDE

CRPropa, Kopp+ (´12), Miyake+ (´14), …

Advantages

- ✓ Scales linearly with number of processors
- ✓ Reweighting is possible
- ✓ Not restricted to grid
- ✓ Backtracking is possible

Disadvantages

- Averaging of results necessary
  → Many pseudo particles
- Not all interactions implemented yet

Numerical Solution in CRPropa

Merten+ in JCAP **06**-046 (2017)
Merten+ in ApJ **859**-63 (2018)

CRPropa 3.0 (Alves Batista+, 2016):
Open source Software for CRs with ($E > 10^{17}$eV)
CRPropa 3.1 (Merten+, 2017):
Extension to lower energies ($E > 10^{13}$ eV)

Numerical Integration: Euler-Maruyama-Scheme

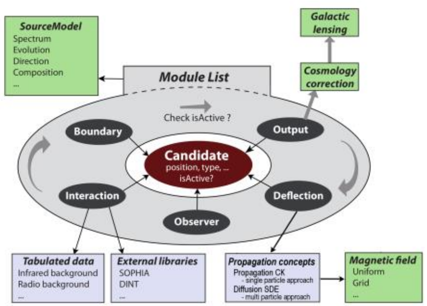
$$\vec{x}_{n+1} - \vec{x}_n = (u_x\vec{e}_x + u_y\vec{e}_y + u_z\vec{e}_z)\cdot h$$
$$+\left(\sqrt{2\kappa_\parallel}\eta_\parallel\vec{e}_\mathrm{t} + \sqrt{2\kappa_\perp}\eta_{\perp,1}\vec{e}_\mathrm{n} + \sqrt{2\kappa_\perp}\eta_{\perp,2}\vec{e}_\mathrm{b}\right)\cdot\sqrt{h}$$
$$p_{n+1} - p_n = -{}^{p_n}/_{3}\,(\nabla\cdot\vec{u})\cdot h$$

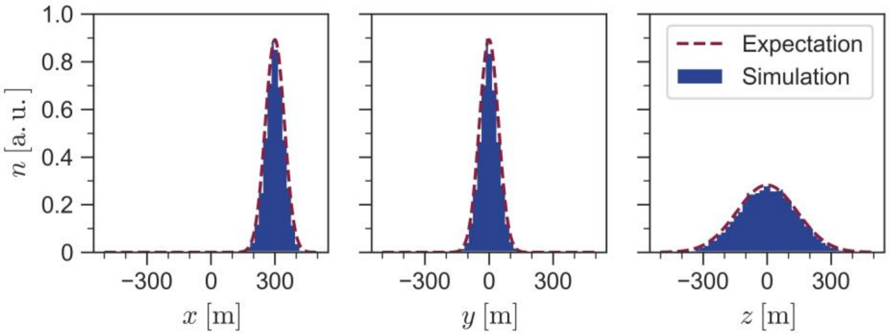
New modules

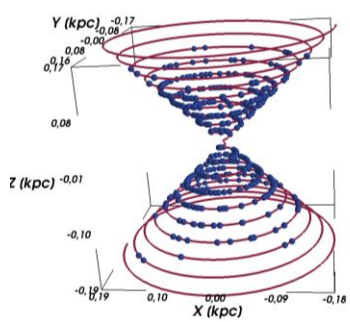
- DiffusionSDE
- AdiabaticCooling
- AdvectionField
  - Constant, Spherical, SphericalShock
- Source
  - UniformCylinder
  - SNR
  - Pulsar

Validation I: Mag. field $\vec{B} = B_0\vec{e}_z$, wind $\vec{u} = u_0\vec{e}_x$ and aniso. diffusion $\epsilon := \frac{\kappa_\perp}{\kappa_\parallel} = 0.1$

Validation II: Spiral magnetic field, no wind and pure parallel diffusion $\epsilon = 0$

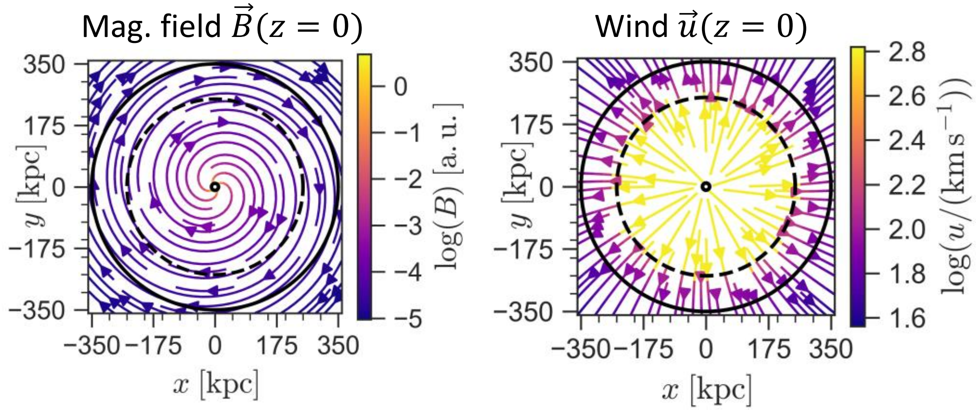




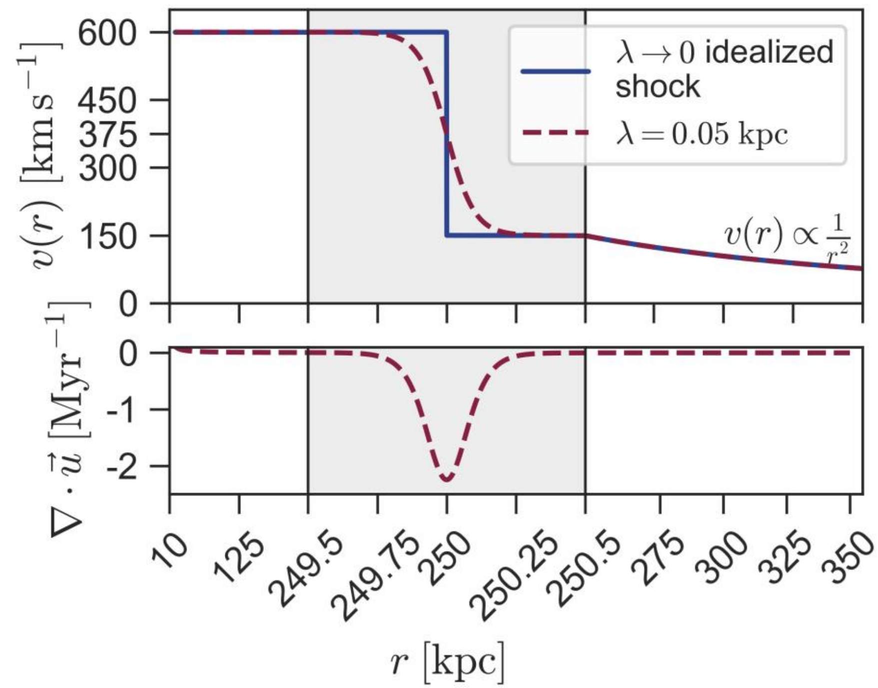


Cosmic rays from the GTS

- **Assumption**: The galactic termination shock (GTS) is able to accelerate CR, e.g., Bustard+ (2017).
- **Question**: Can they diffuse back into the Galaxy?



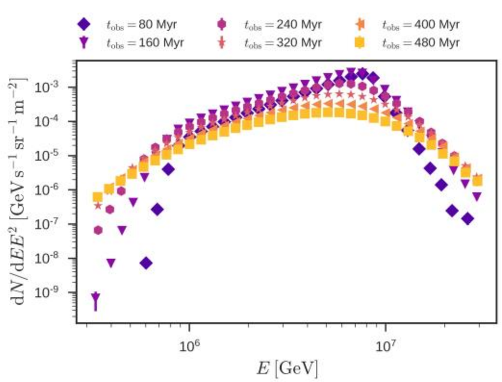
- **Diffusion:** $D = 5 \times 10^{28} C_\epsilon \cdot \left(\frac{R}{4\ \mathrm{GV}}\right)^\delta \cdot \mathrm{diag}(1, \epsilon, \epsilon)\ \mathrm{cm}^2/\mathrm{s}$
- **Magnetic field:** Spherical symmetric **(model S)** and an Archimedian spiral **(model A)**
- **Wind Modell:** Continuous differentiable also at shock
- **Schock:** $L_{\mathrm{CR}} = 10^{40}\ \mathrm{erg/s}$, $\Delta T = 100\ \mathrm{Myr}$, $\frac{\mathrm{d}n}{\mathrm{d}E} \propto E^{-2}$, $r_{\mathrm{shock}} = 250\ \mathrm{kpc}$
- **Simulationvolume:** Free-Escape-Boundaries at $r_{\mathrm{obs}} = 10\ \mathrm{kpc}$, $r_{\mathrm{b}} = 350\ \mathrm{kpc}$

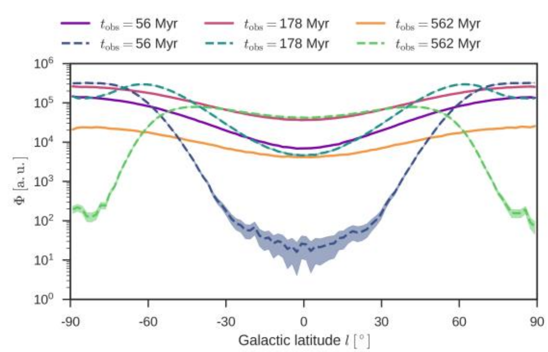


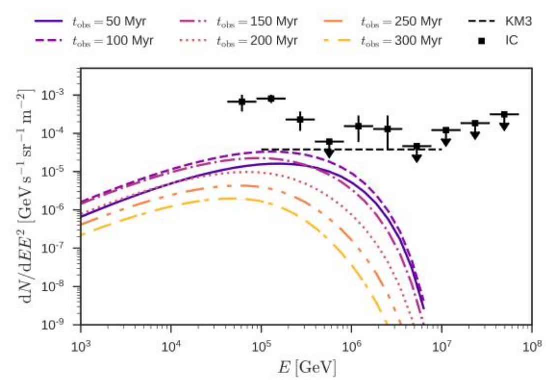
CRs from the GTS (results)

- Ensemble loses energy in most cases (adiabatic cooling)
- Time scale and maximum luminosity depend on the diffusion index δ
- Energy spectrum is time dependent
- Perpendicular diffusion mitigates the anisotropy problem
- Upper limit of the neutrino flux is below the oberserved IceCube flux

Model S	$\delta = 0.3$	$\delta = 0.4$	$\delta = 0.5$	$\delta = 0.6$
E/E_0	1.46	0.65	0.86	0.95
$L_{\max}$ [erg/s]	$7{,}8 \times 10^{34}$	$3{,}1 \times 10^{37}$	$2{,}5 \times 10^{38}$	$3{,}9 \times 10^{38}$
$T_{\max}\|\Delta T$ [Myr]	742|3370	160|3417	103|1427	93|429
Model A	$\delta = 0{,}5$ $\epsilon = 0$	$\delta = 0{,}5$ $\epsilon = 0{,}1$	$\delta = 0{,}6$ $\epsilon = 0$	$\delta = 0{,}6$ $\epsilon = 0{,}1$
E/E_0	1,35	0,86	1,00	0,92
$L_{\max}$ [erg/s]	$6{,}9 \cdot 10^{37}$	$6{,}9 \cdot 10^{37}$	$3{,}0 \cdot 10^{38}$	$3{,}5 \cdot 10^{38}$
$T_{\max}\|\Delta T$ [Myr]	115|5923	129|3427	104|1985	104|3826







The CR flux in the shin region can be partly explained by the GTS.

Summary & Outlook

- CRPropa allows for anisotropic Diffusion in arbitrary magnetic background fields
- Consistent description of advection and corresponding adiabatic effects
- SDE method: Advantages at high energies compared with grid-based methods, e.g., intrinsic parallelization, backtracking, and reweighting.

- The GTS is an interesting source candidate for the CR flux in the shin region
- Magnetic field morphology has an important influence on observables
- 3D-modelling is necessary: Time evolution differs between 1D and 3D and anisotropy is only available in 3D

- Implementation of Momentum diffusion → Acceleration of CRs
- $\left({}^{\delta b}/_{B}\right)$ → Space dependent eigenvalues of the diffusion tensor
- Analyses the additional propagation towards the Earth
- Analyses the *lost* CRs from starburst galaxies