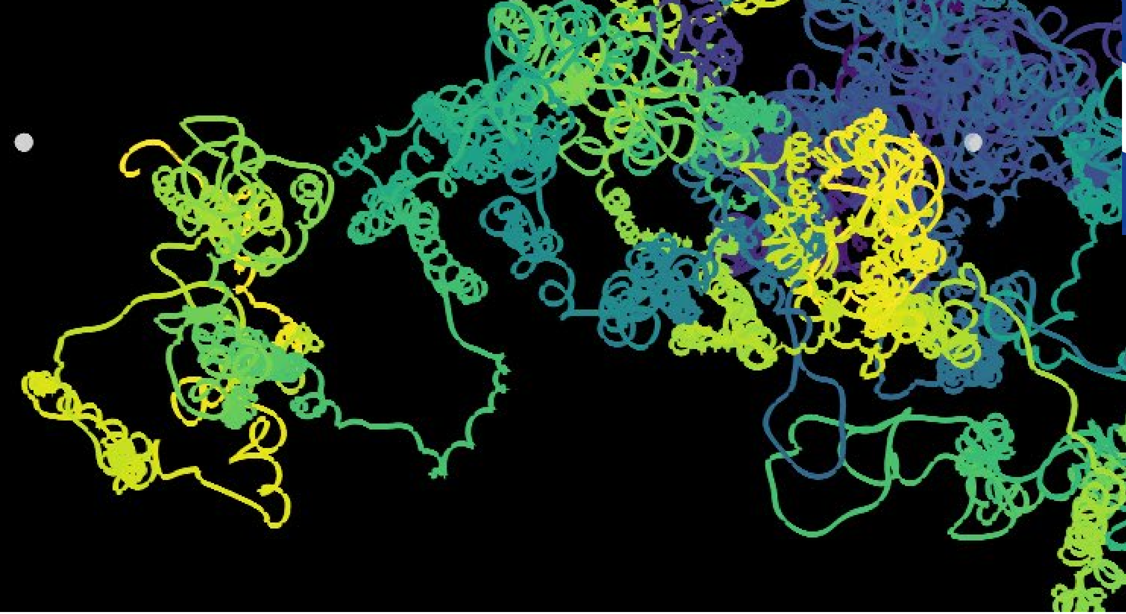


RAPP Center

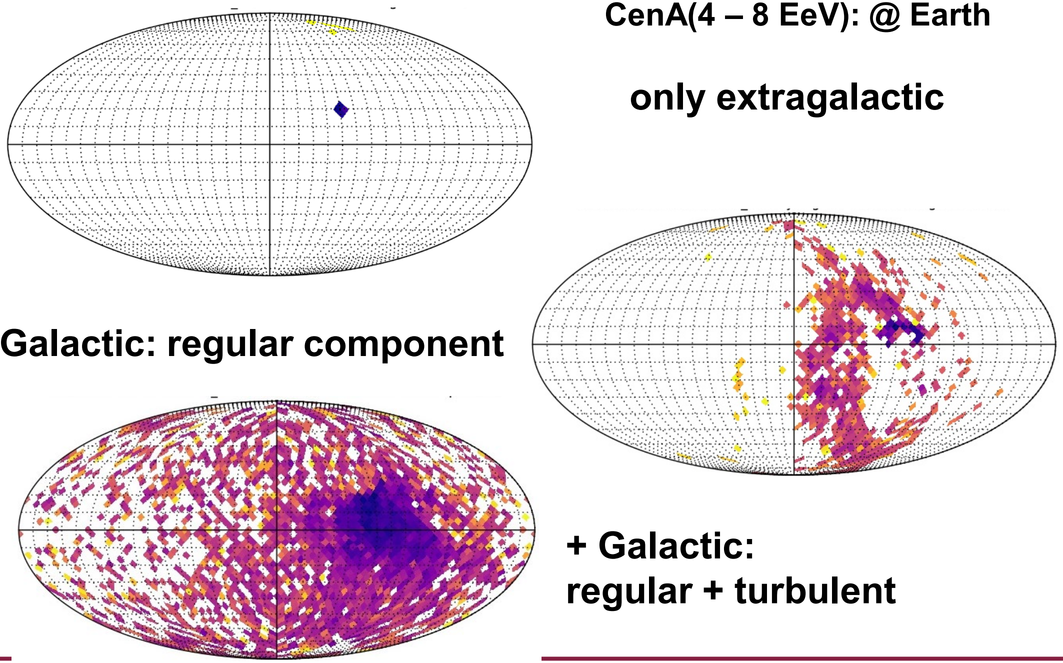
RUHR-UNIVERSITÄT BOCHUM

Constraining cosmic-ray propagation with gamma rays

Julia Tjus

Origin of cosmic rays unknown:

Example ultra high energy cosmic-ray transport in Galactic B-field

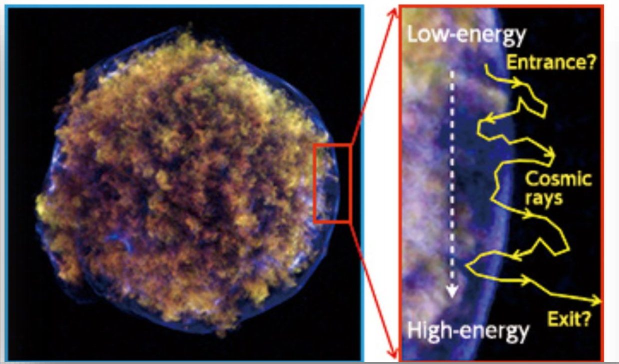


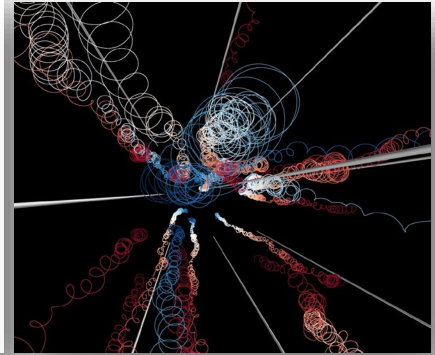
Gamma-rays to the rescue!

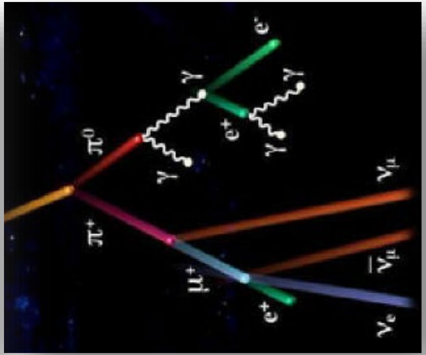
RAPP Center

Magnetic fields → cosmic rays → gamma-rays

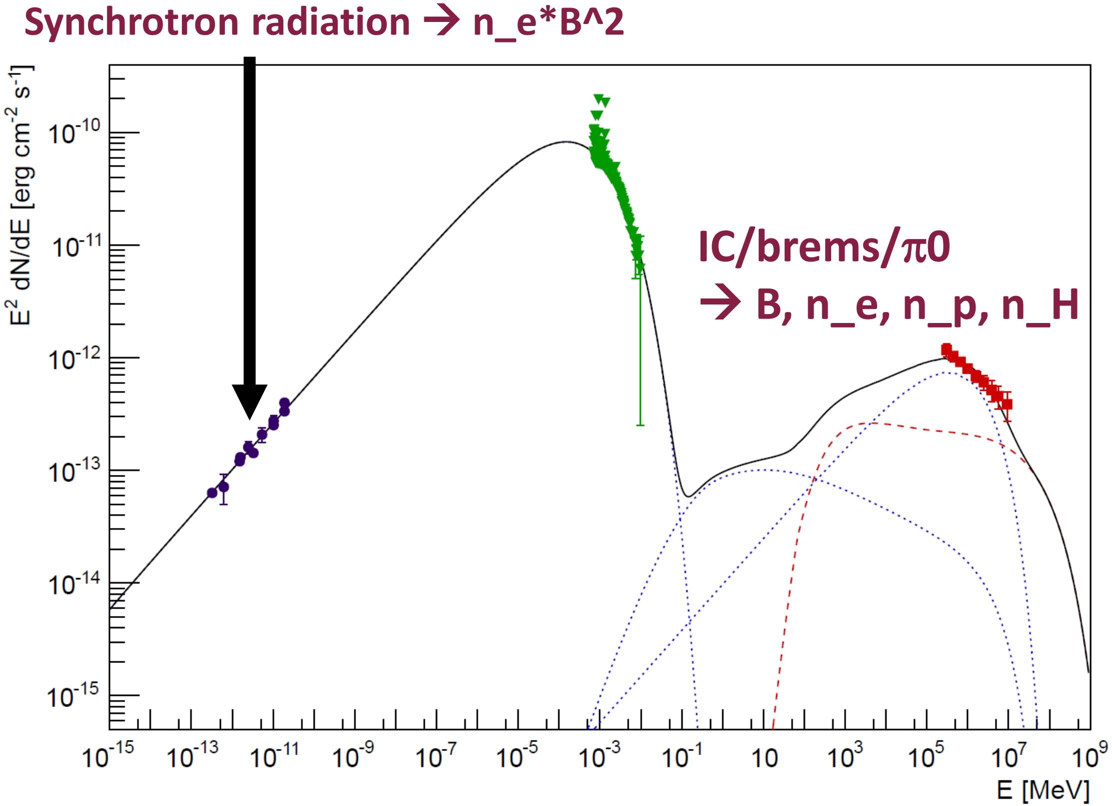
1. Magnetic fields → accelerate (= create) cosmic rays
2. Cosmic rays → transport in B-fields (diffusive/advective/…)
3. Cosmic rays → interaction with ambient medium (gas/B-fields/photons) → γ production







Spectral Energy Distribution: Imprinted environment & transport properties



- Simplified view:
- normalization governed by environmental properties
- Spectral properties can reveal transport properties
- But: both is coupled, need multimessenger modeling to understand things
- (radio-gamma-rays, neutrinos, cosmic rays)

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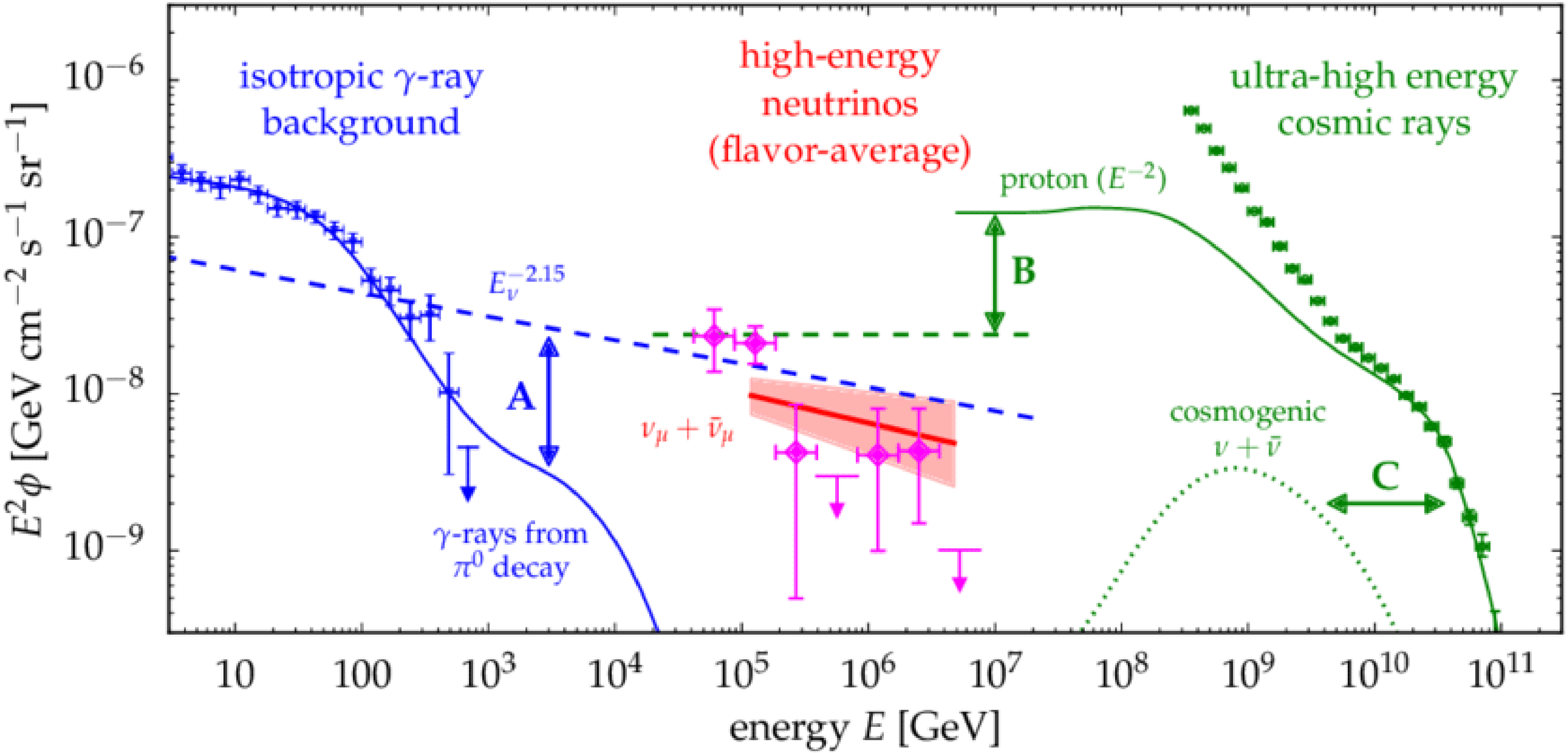
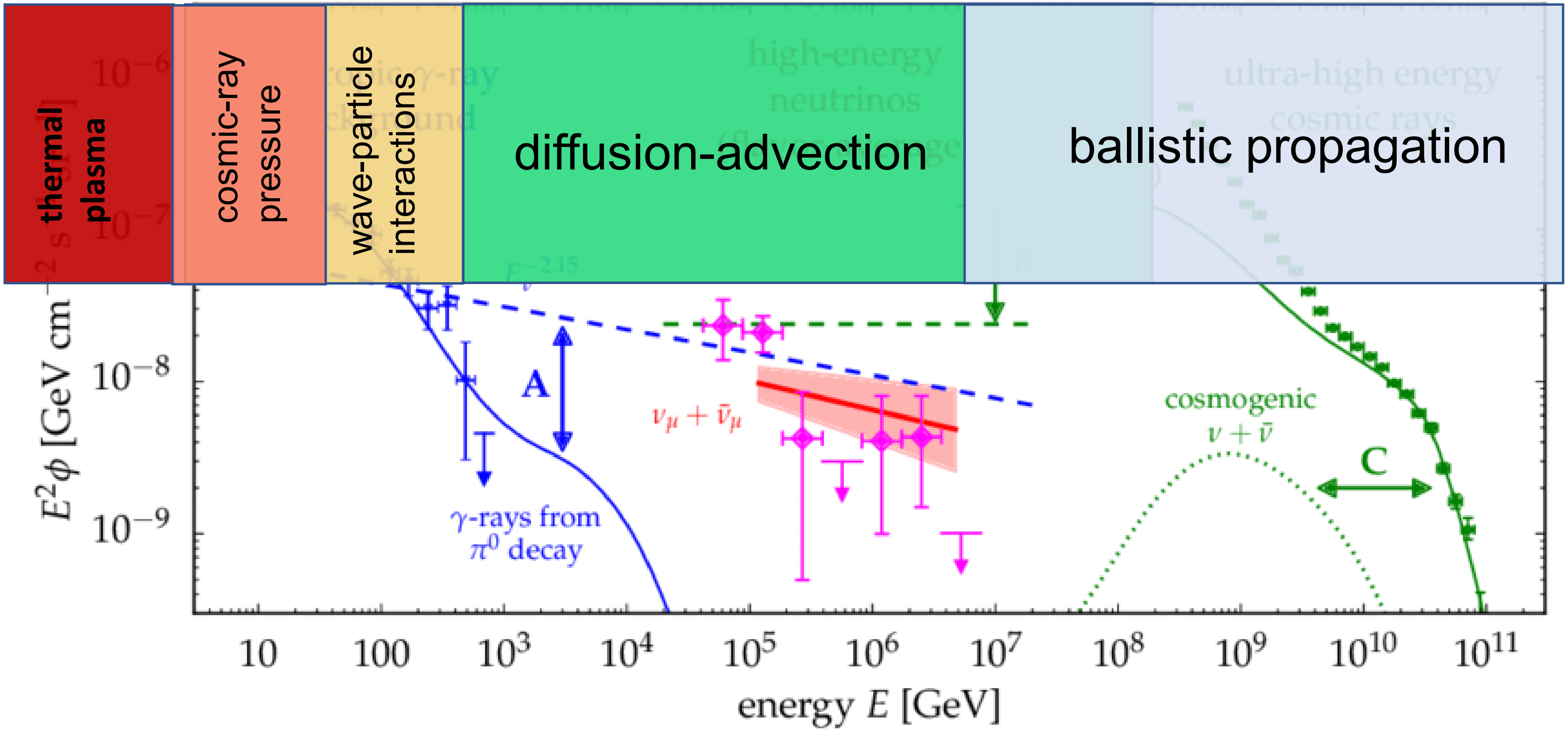
Cosmic-ray propagation regimes



(B = 3 μG)

Fig: IceCub-Gen2 Whitepaper

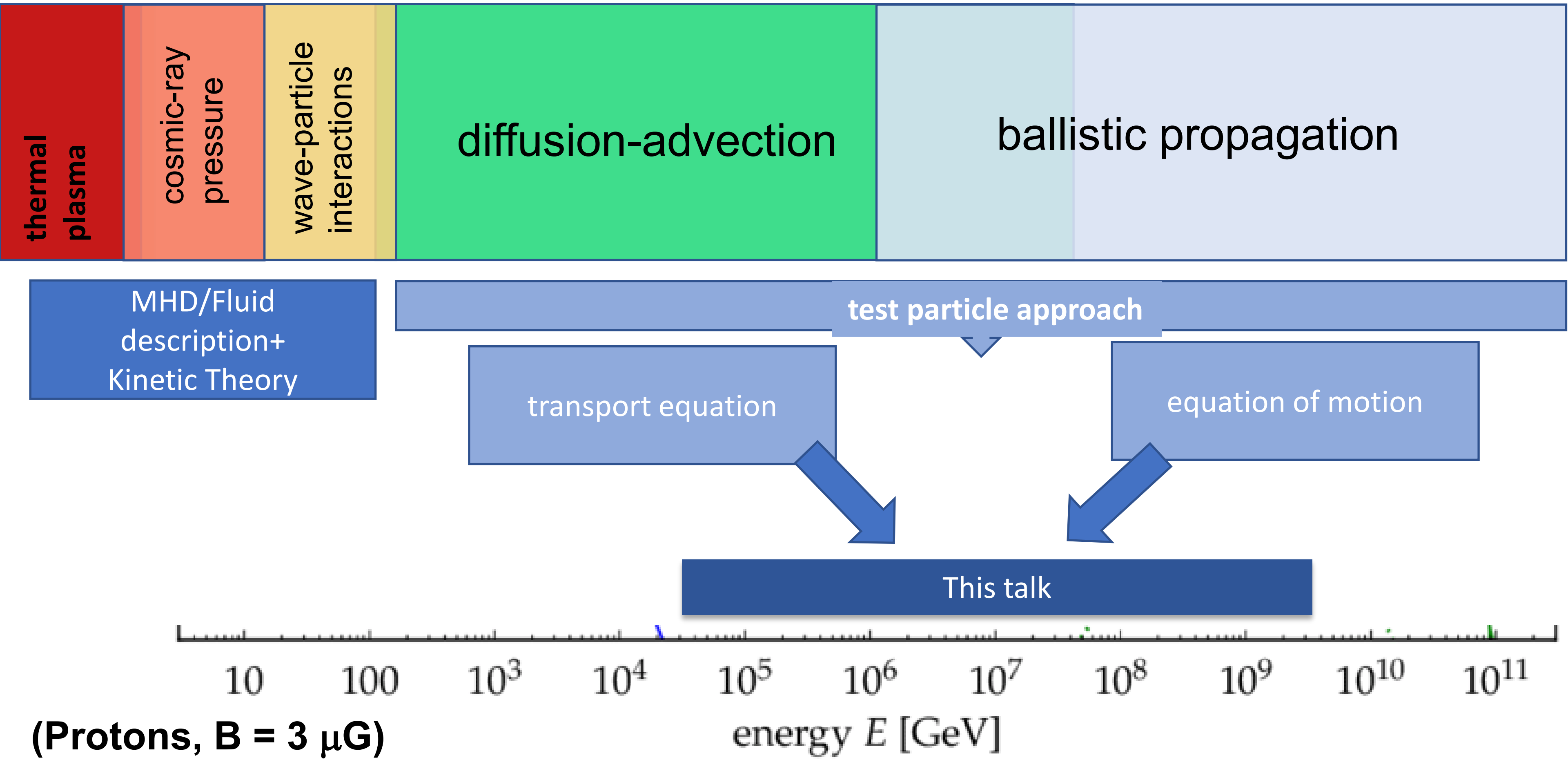
Cosmic-ray propagation regimes



(B = 3 μG)

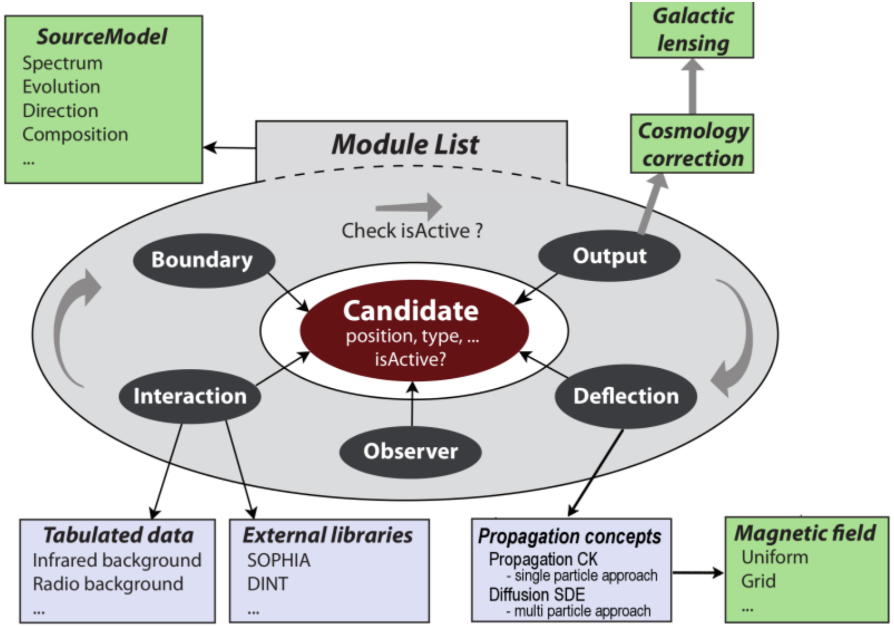
Fig: IceCub-Gen2 Whitepaper

Cosmic-ray propagation regimes: methods



(Protons, B = 3 μG)

CRPropa 3.2 Open Source Propagation Tool



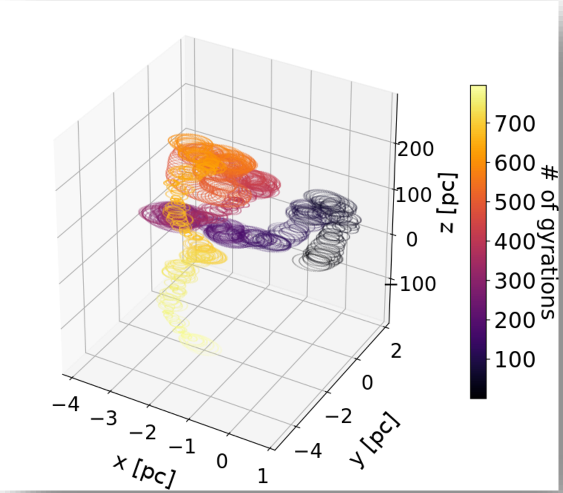
CRPropa 3.2 — an advanced framework for high-energy particle propagation in extragalactic and galactic spaces

Rafael Alves Batista,[a,b] Julia Becker Tjus,[c,d] Julien Dörner,[c,d] Andrej Dundovic,[e,f] Björn Eichmann,[c,d] Antonius Frie,[c,d] Christopher Heiter,[g,h] Mario R. Hoerbe,[c,i,d] Karl-Heinz Kampert,[j,d] Lukas Merten,[k,c,d] Gero Müller,[g] Patrick Reichherzer,[c,d,l] Andrey Saveliev,[m,n] Leander Schlegel,[c,d] Günter Sigl,[o] Arjen van Vliet[p] and Tobias Winchen[q,h]

Ruhr University Bochum

CRPropa 3.2: bridging diffusive and ballistic propagation

$$\frac{\delta n}{\delta t} = \nabla \cdot (\hat{D} \cdot \nabla n) - \vec{u} \cdot \nabla n + Q$$

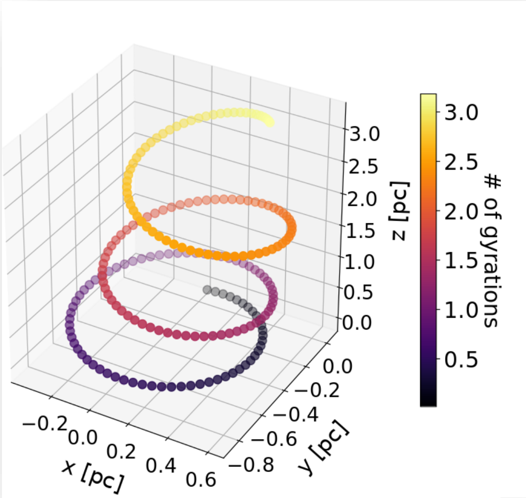


conversion into Stochastic Differential Equation (SDE):

$$dr_\nu = A_\nu dt + D_{\nu\mu} d\omega^\mu$$

➔ treatment as quasi-particles

$$\frac{d\boldsymbol{p}}{dt} = q(\boldsymbol{v} \times \boldsymbol{B})$$



Numerical solution via Cash-Karb or Boris-Push

Treatment in one framework
(CRPropa 3.1 - Merten, JBT, Fichtner, Sigl, JCAP 2017)

Merten, JBT, Fichtner, Sigl, JCAP (2017)

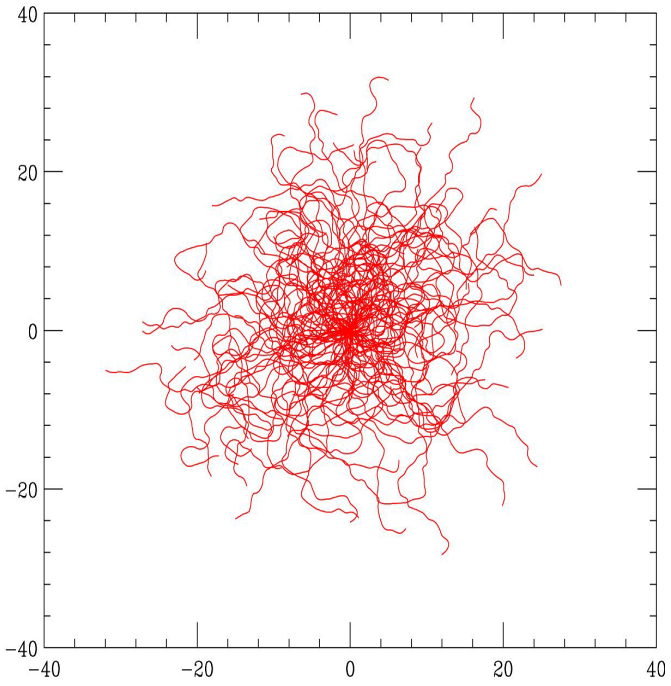
Simulations of the steady-state diffusion coefficient

Diffusion equation:

$$D(t)\Delta f(x,t) = \frac{\delta f(x,t)}{\delta t}$$

Solution is known:

$$f(x,t) = \frac{1}{2\sqrt{\pi D_{xx} t}} \exp\left(-\frac{x^2}{4D_{xx}t}\right)$$



Simulations of the steady-state diffusion coefficient

Taylor Green Kubo ansatz:
Calculate diffusion coefficient from numerical results:

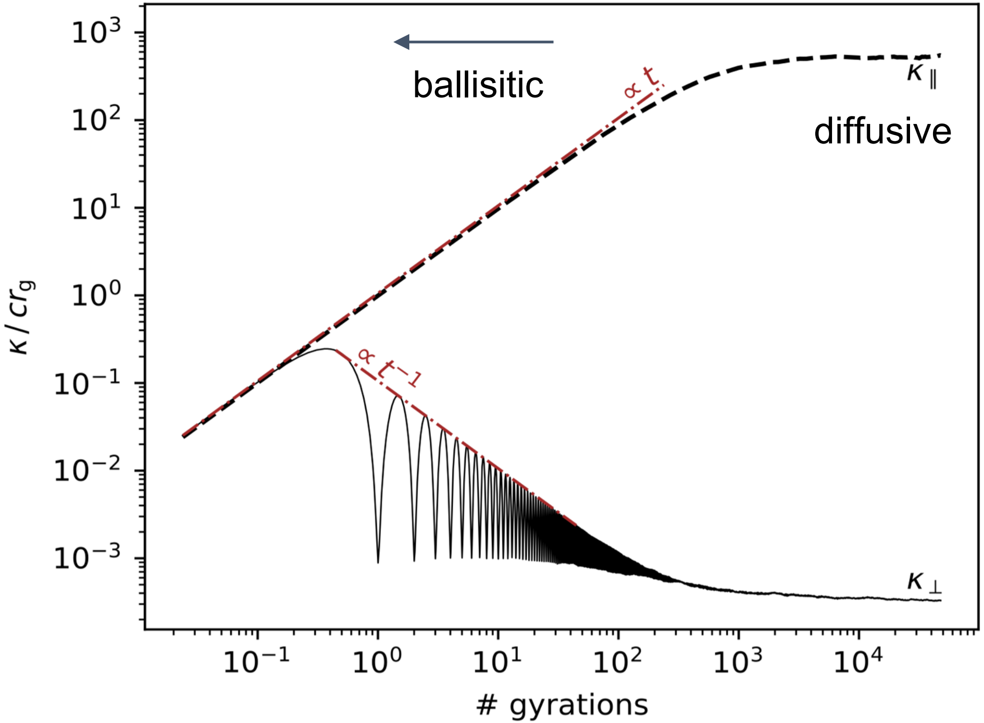
$$\langle(\Delta x)^2\rangle = \int_{-\infty}^{+\infty} dx\, x^2 f(x,t) = 2tD_{xx}(t)$$

$$D_{xx} = \lim_{t\to\infty} \frac{\langle(\Delta x)^2\rangle}{2t}$$ =const in diffusion limit

Expectation: energy dependence of $D_{\parallel} \sim E^{\alpha}$ (power law)

$\alpha = \frac{1}{3}$ (Kolmogorov & $\frac{\delta B}{B} \ll 1$)

$\alpha = 1$ (Bohm limit $\frac{\delta B}{B} \gg 1$)



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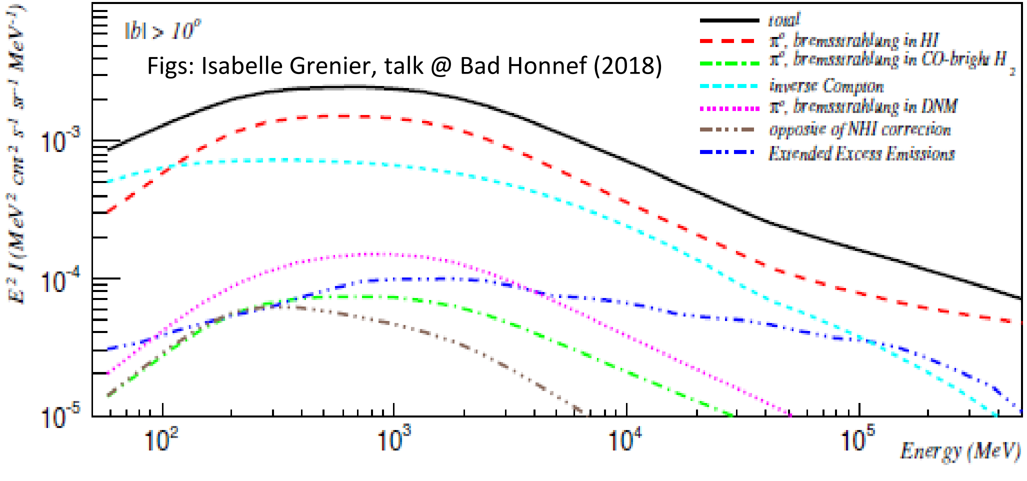
1. Cosmic-ray propagation at high energies
2. Gamma-ray observations and cosmic-ray propagation
    1. The Milky Way
    2. Active Galaxies

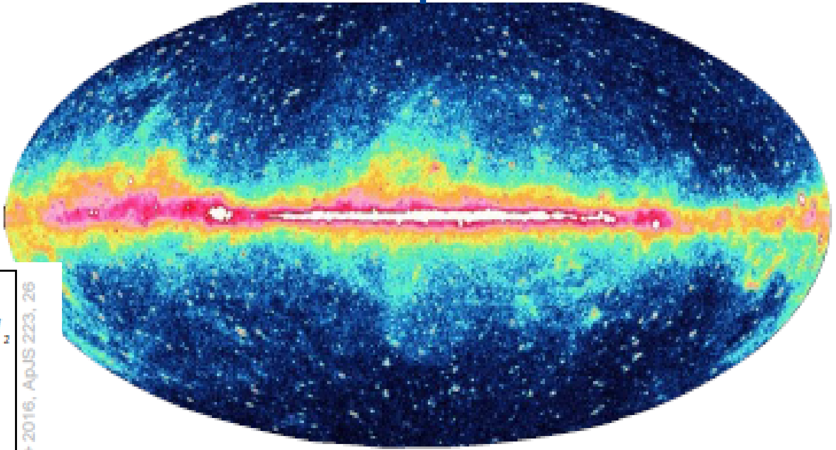
Astrophysical application: Gamma-ray measurements of the Galactic plane

- Signatures dominated by hadronic interactions
- ➔ proton spectrum can be deduced

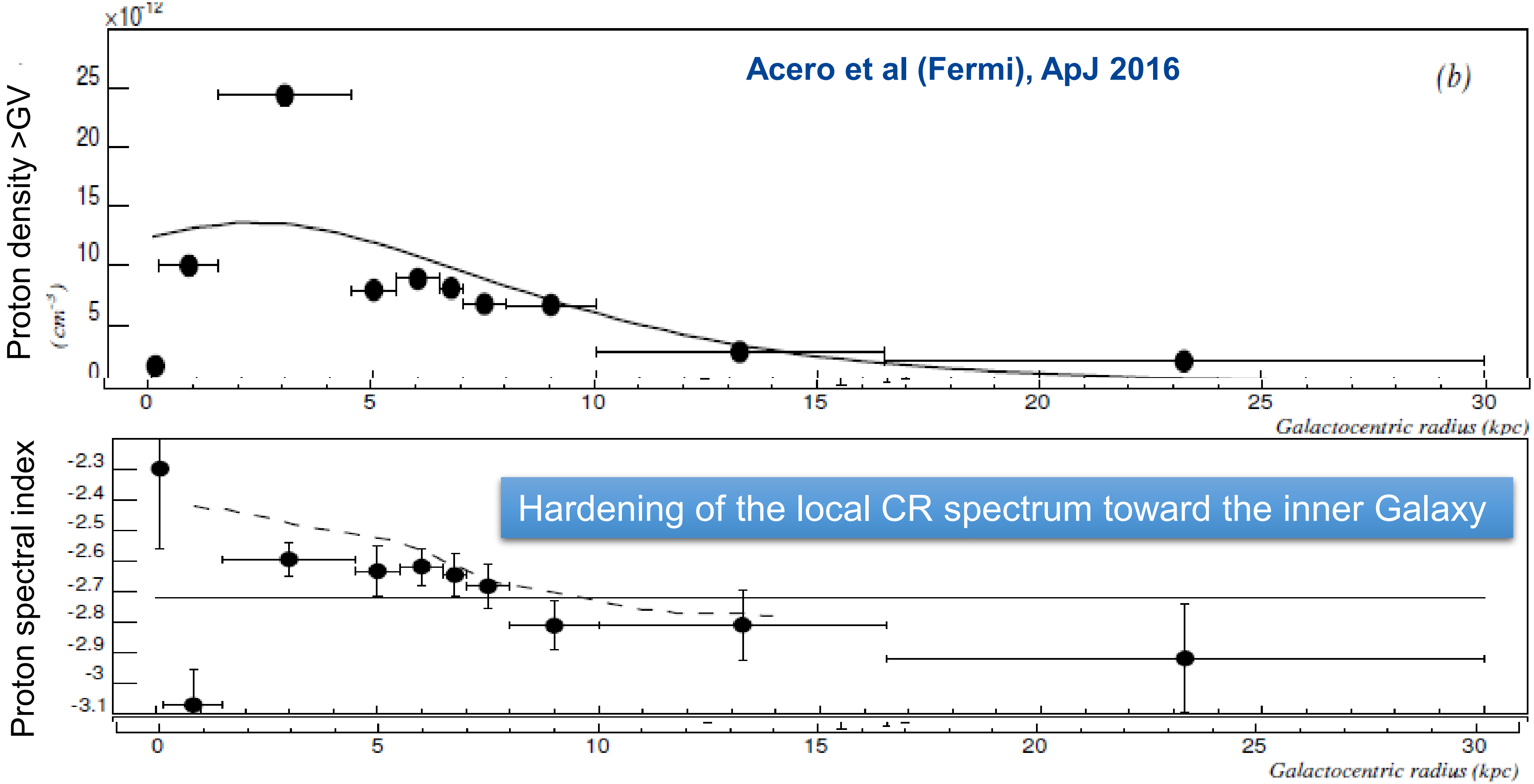


Figs: Isabelle Grenier, talk @ Bad Honnef (2018)

Acero+ 2016, ApJS 223, 26



Fermi: proton gradient along galactocentric radius



Energy spectra after transport in Leaky Box

- Phenomenological ansatz

(Evoli 2012, Gaggero et al, 2015):

- $D(E,r) \sim E^{\gamma(r)}$
- $\gamma(r) = A + C*r$

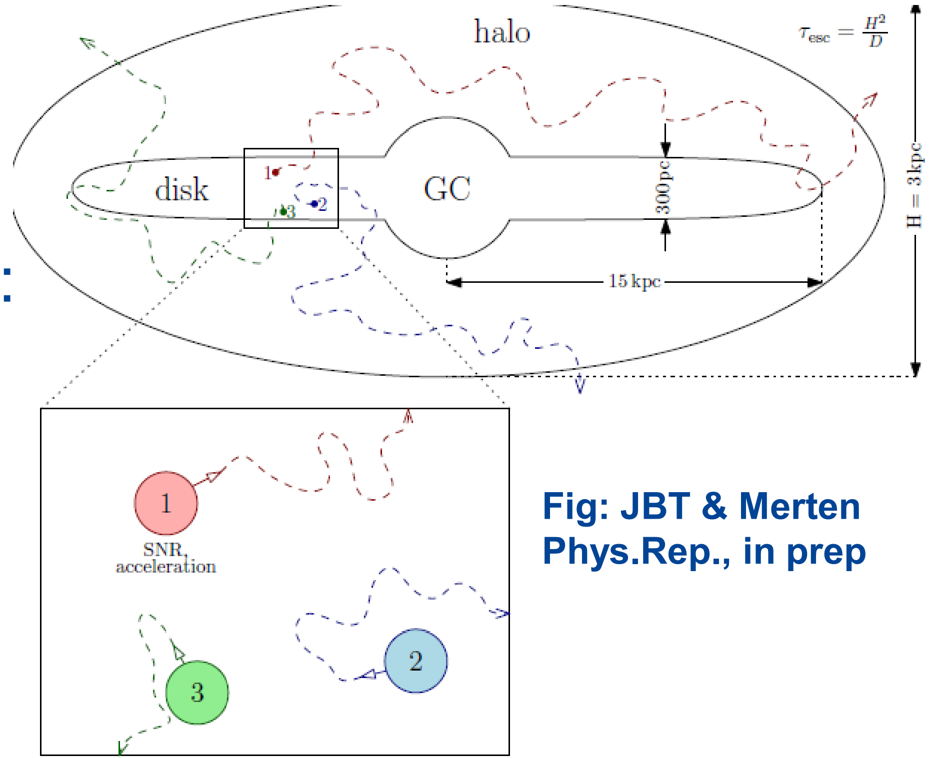
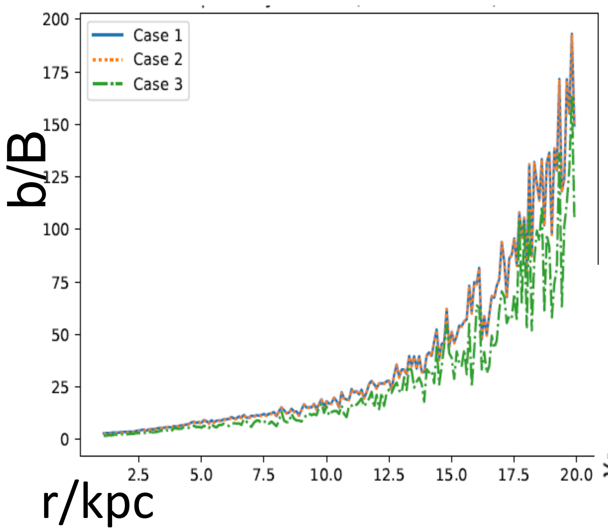
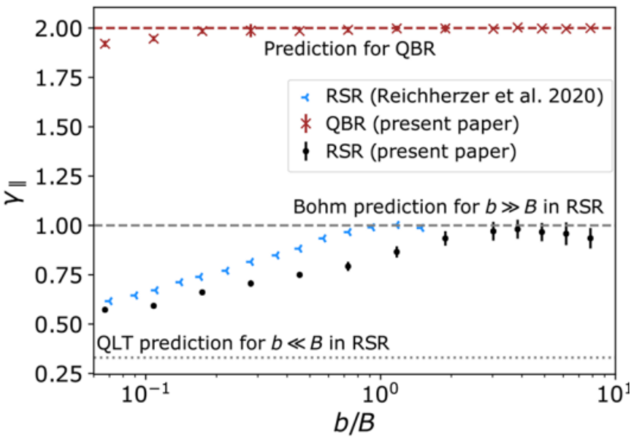


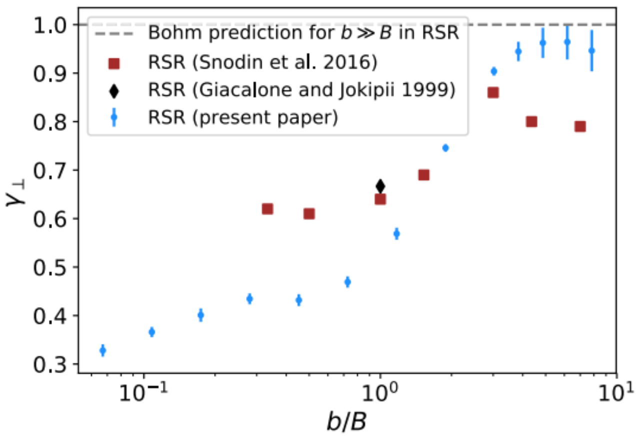
Fig: JBT & Merten Phys.Rep., in prep

Support of this argument from plasma physics



$$\gamma(b) = A + C^*(b/B)^{\beta}$$



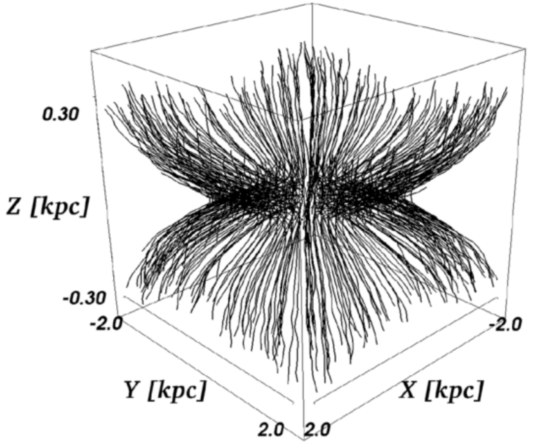


Reicherzer, Merten, Dörner, JBT, Zweibel, Püschel, SNAS (2022)

Turbulence level from modified JF12 GF model
(Janson & Farrar 2012, Kleimann, JBT et al 2019)

Energy spectra after transport in Leaky Box

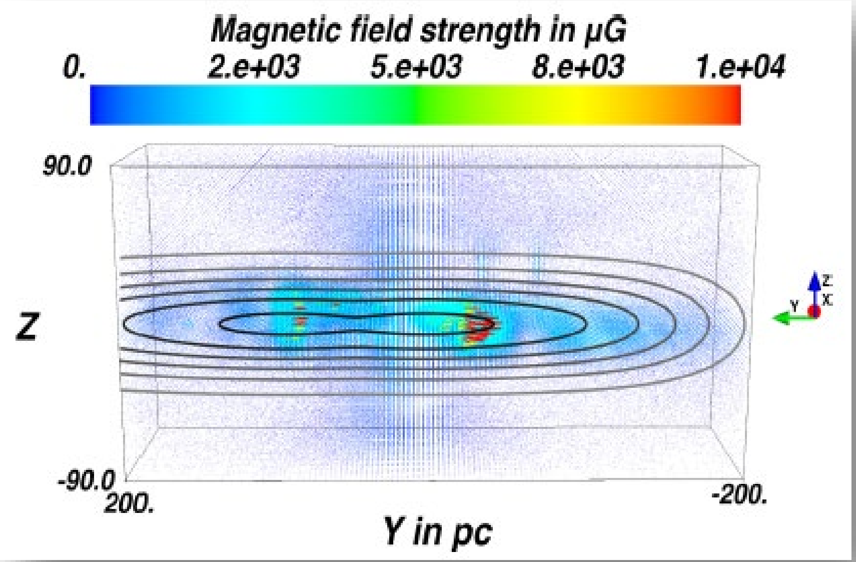
- $D(E, b/B) \sim E^{\gamma(b/B)}$
- $\gamma(b) = A + C^*(b/B)^{\beta}$
- $\delta B/B$ increases with r
- ➔ phenomenological model receives fundamental explanation!
- Details even depend on escape-direction of cosmic rays

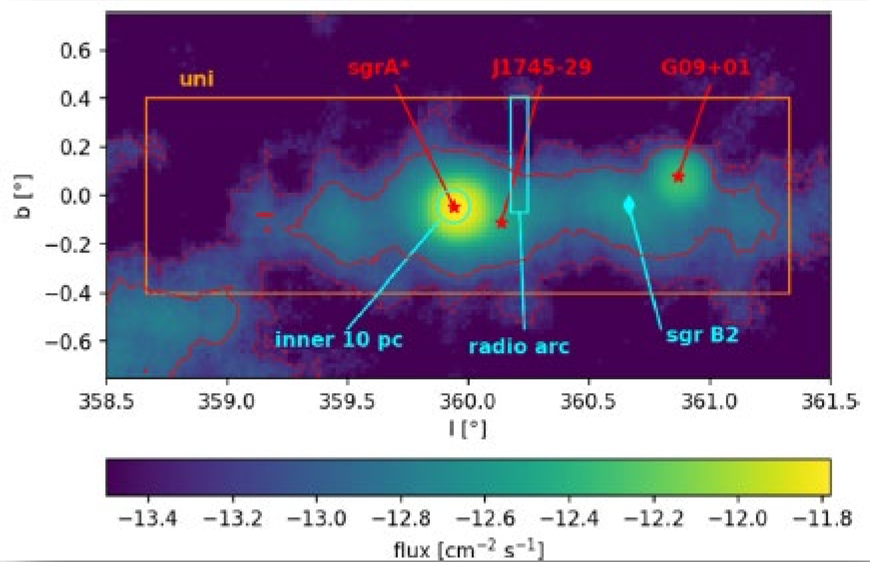


$$\tau_{\mathrm{diff}}(r_{\mathrm{gc}}) \approx \begin{cases} \tau_{\parallel} \propto \left(\frac{b}{B}\right)^{2}\left(\frac{E}{B_{\mathrm{tot}}}\right)^{-\gamma_{\parallel}}\left\langle\frac{d_{\parallel}^{2}}{H^{2}}\right\rangle & \text{for } r_{\mathrm{gc}} \lesssim 5\,\mathrm{kpc} \\ \tau_{\perp} \propto \left(\frac{b}{B}\right)^{-2}\left(\frac{E}{B_{\mathrm{tot}}}\right)^{-\gamma_{\perp}}\left\langle\frac{d_{\perp}^{2}}{H^{2}}\right\rangle & \text{elsewhere} \\ \tau_{\parallel} \propto \left(\frac{b}{B}\right)^{2}\left(\frac{E}{B_{\mathrm{tot}}}\right)^{-\gamma_{\parallel}}\left\langle\frac{d_{\parallel}^{2}}{H^{2}}\right\rangle & \text{for } r_{\mathrm{gc}} \gtrsim 19\,\mathrm{kpc} \end{cases}$$

Reichherzer, Merten, Dörner, JBT, Püschel, Zweibel, SNAS (2022)

3D Transport modeling of the PeVatron in the Galactic Center

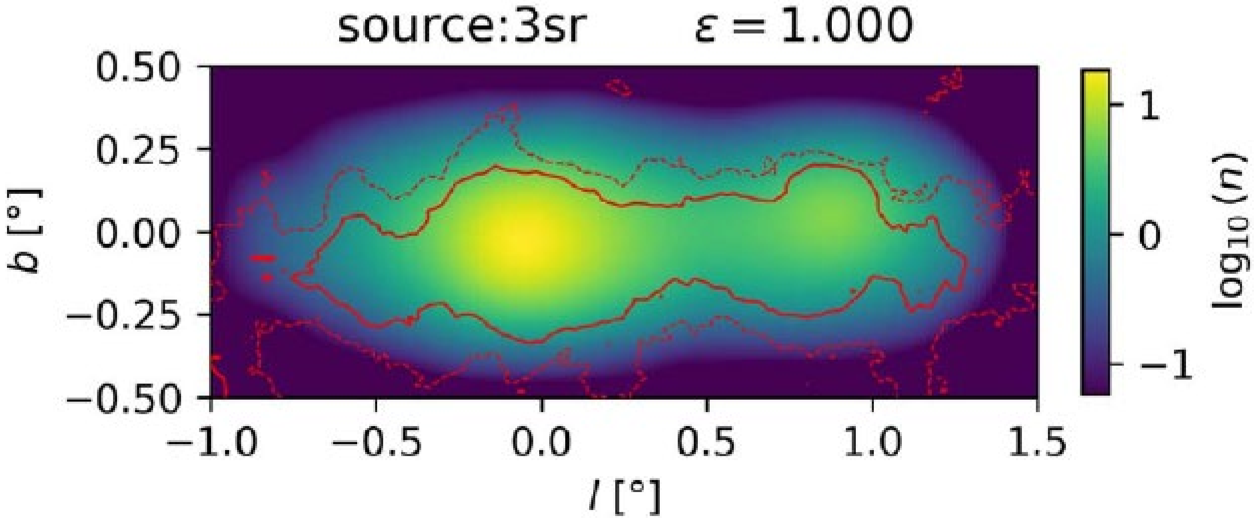


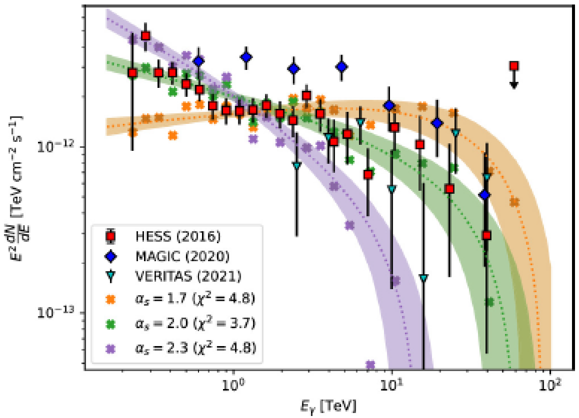


3D B-field representation (Gündüz, JBT, et al (2022)); 3 source model;
Anisotropic transport ($D_{\parallel}/D_{\perp} = \epsilon$)

Best fit for isotropic diffusion ($\epsilon = 1$)

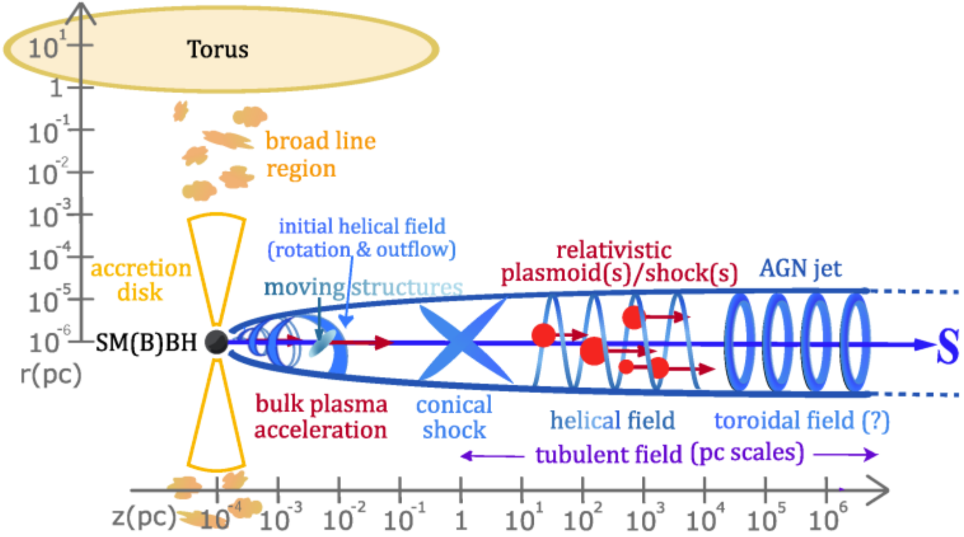
- 2D distribution can be fit reasonably well using isotropic diffusion





Dörner et al, A&A (2024)

Application to plasmoids of AGN



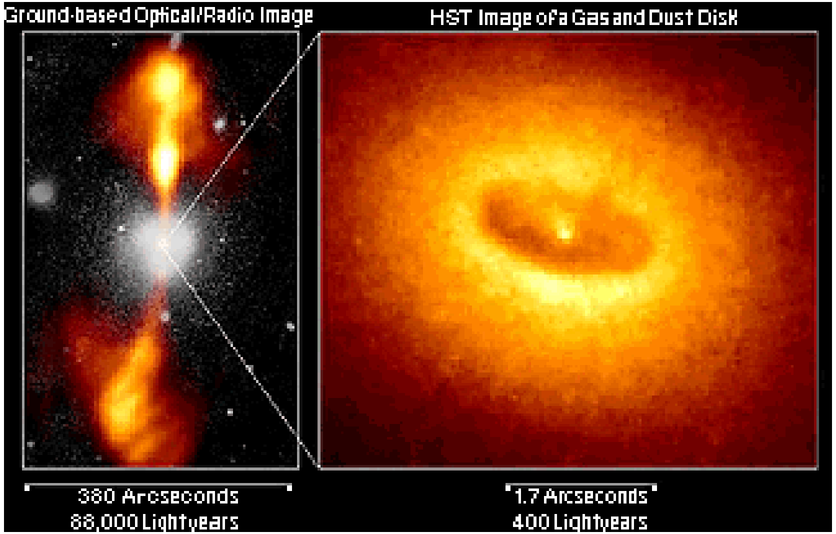
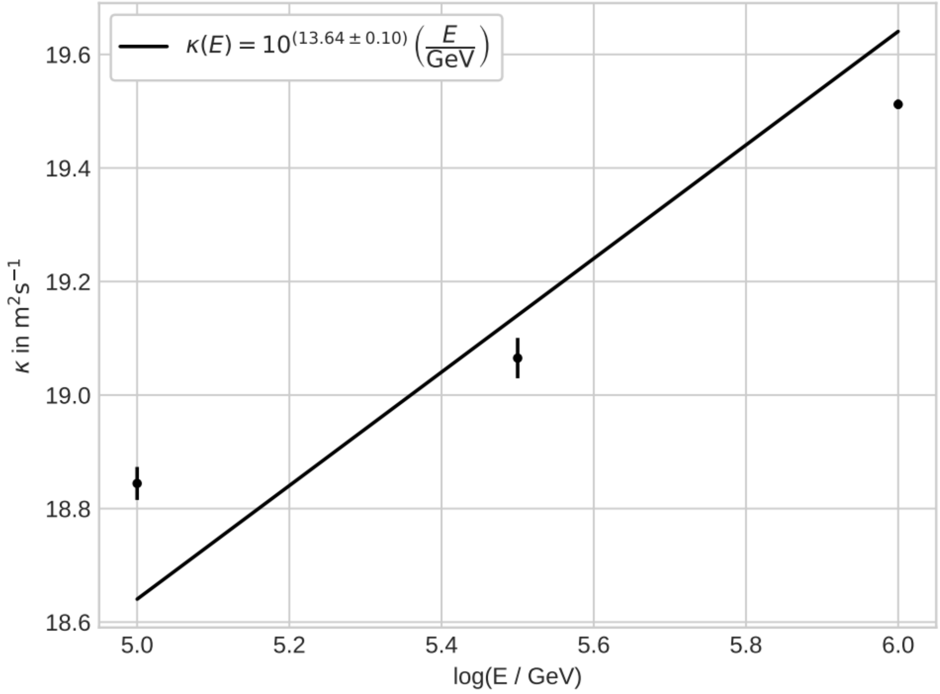


Fig: Becker Tjus et al, MPDI Physics (2022)

Application to plasmoids of AGN

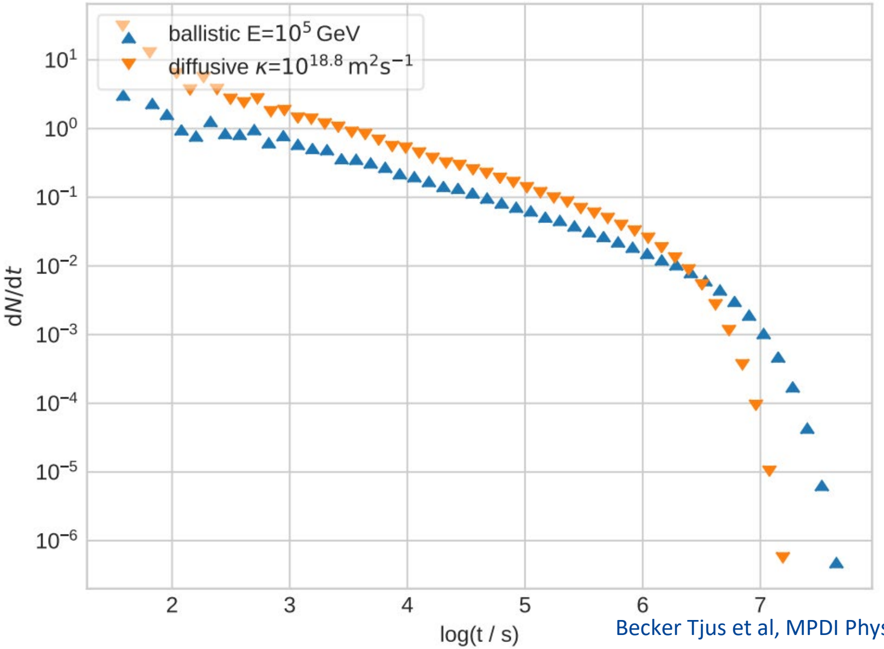
- Calculation of diffusion coefficient in equation of motion picture
- As a function of reduced rigidity (~energy)
- Purely turbulent field → assumption of Bohm diffusion



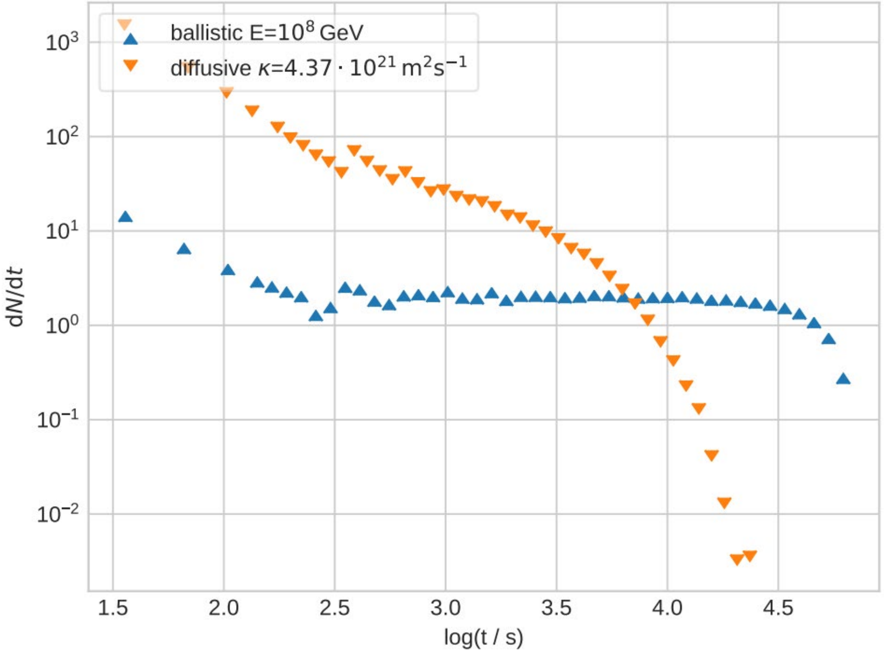
Becker Tjus et al, MPDI Physics (2022

Comparison of results

- Diffusive Regime (1e5 GeV)
- Ballistic Regime (1e8 GeV)



Becker Tjus et al, MPDI Physics

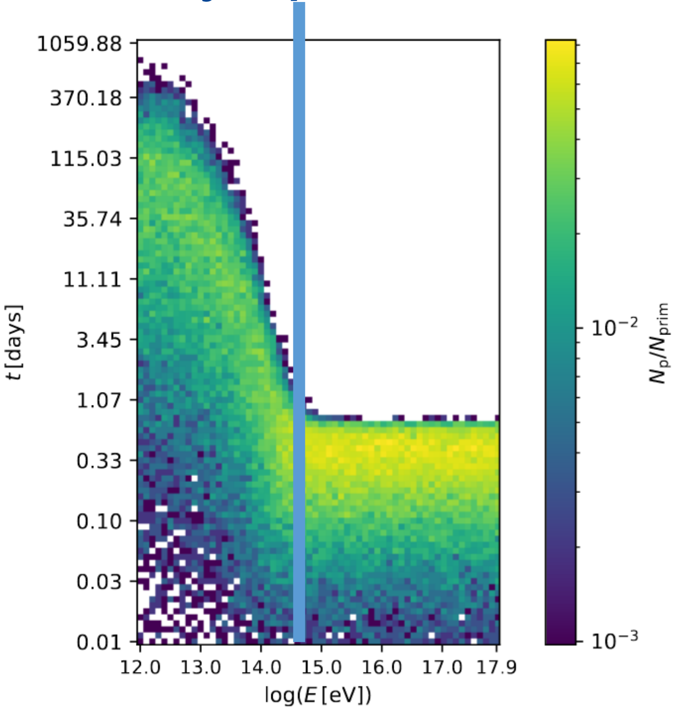


Vladimir Kiselev, Bachelor thesis (2022)

Marcel Schroller, PhD thesis (ongoing)

Transition of diffusive to ballistic propagation: predicted break in gamma-ray spectrum

- Example R = 1e13m
- B = 0.03G
- ➔ change from diffusive to ballistic at around 1e13eV-1e15eV CR energy ➔ TeV-100TeV gamma-ray energy
- ➔ expected break in the spectrum



3. Summary & Conclusions

- **CRPropa 3.2** first tool to handle transport equation and equation of motion at the same time
- Now able to **quantitatively bridge diffusive and ballistic** regimes
- **Galactic cosmic-ray gradient** can be explained with a varying spatial diffusion coefficient
- **Diffuse Galactic Center PeVatron** can be explained with isotropic diffusion and the three most prominent sources
- Depending on source parameters, **break** between diffusive and ballistic propagation to be expected in future CTA data. Important to include in modeling, and search for with IACTs
- Gamma rays are great, but even better in the Multimessenger Picture ☺