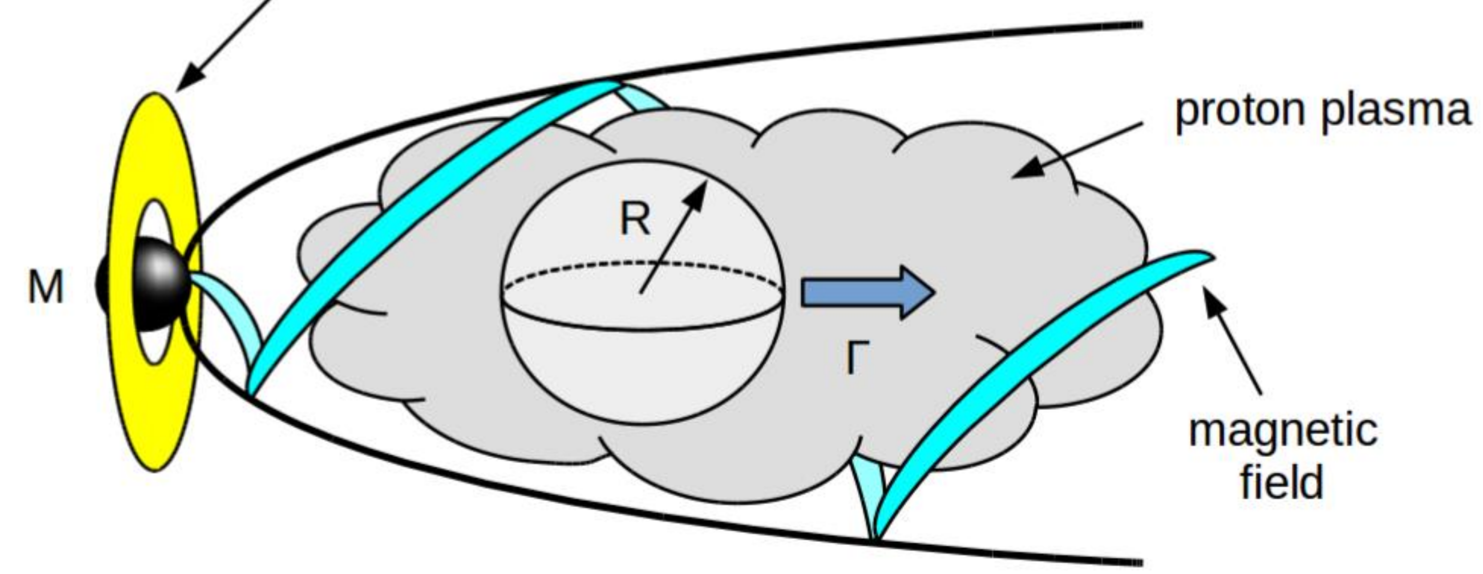

Propagation of Cosmic Rays in Plasmoids of AGN Jets: Implications for Multimessenger Predictions

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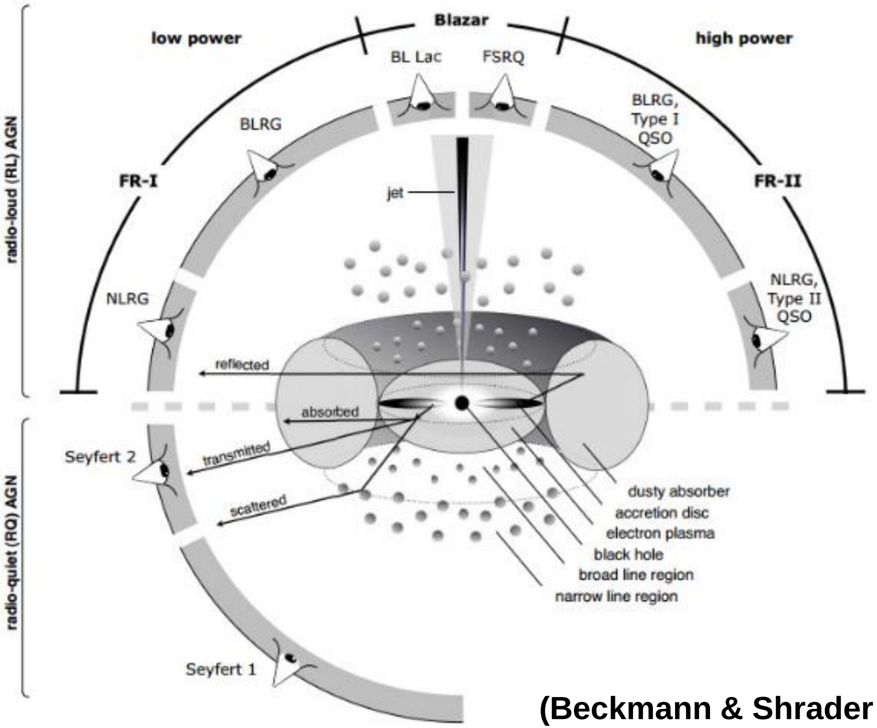
RUHR-UNIVERSITÄT BOCHUM
Department of Physics and Astronomy
Chair for Theoretical Physics IV

arXiv:2202.01818

RAPP Center

Motivation

- **A**ctive **G**alactic **N**uclei (**AGN**): one of most luminous objects in Universe
- Assumed accelerator of **C**osmic **R**ays (**CR**s) with highest energies up to $E_{\text{CR}} = 10^{21}\ \text{eV}$
- **Blazars:** leptonic/hadronic components, both possibly → secondary neutrinos
- Modelling is **challenging!**



(Beckmann & Shrader 2012)

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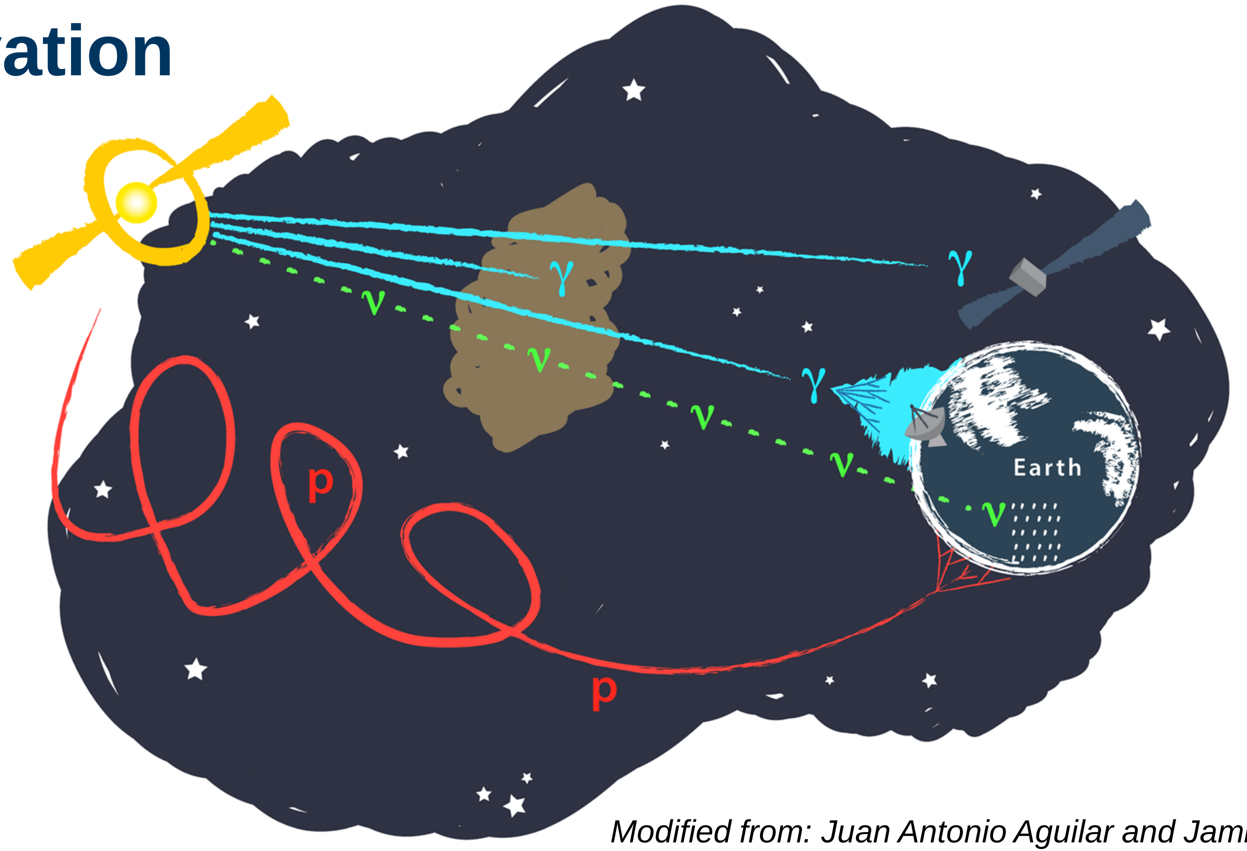
Motivation



Modified from: Juan Antonio Aguilar and Jamie Yang. IceCube/WIPAC

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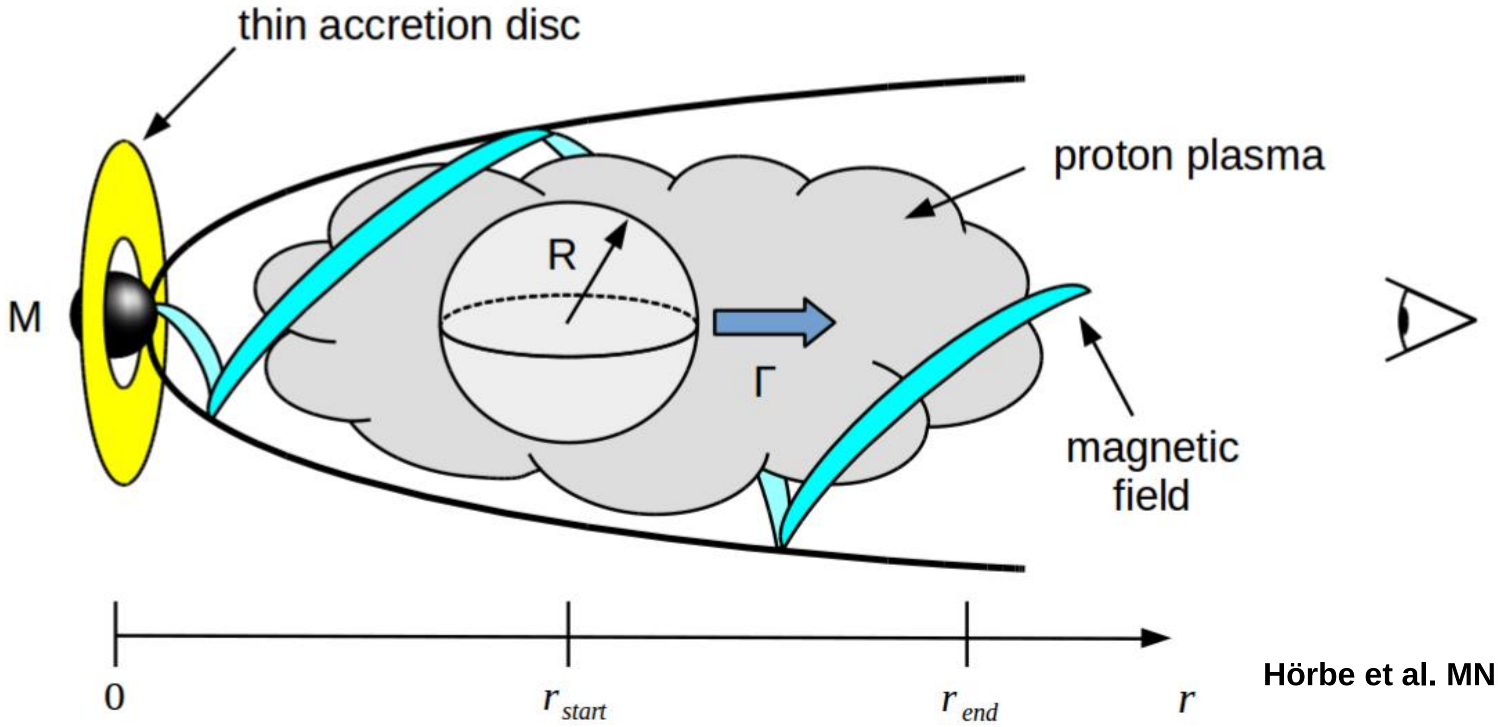
AGN structure with a Jet



Hörbe et al. MNRAS (2020)

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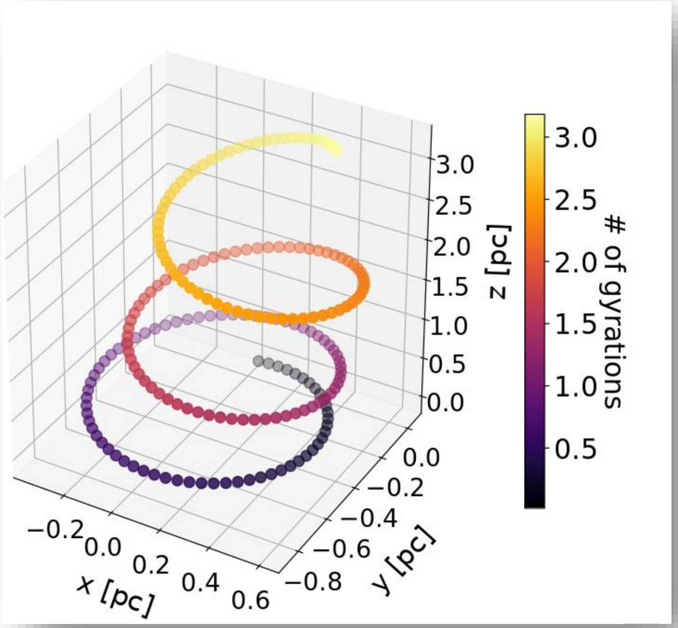
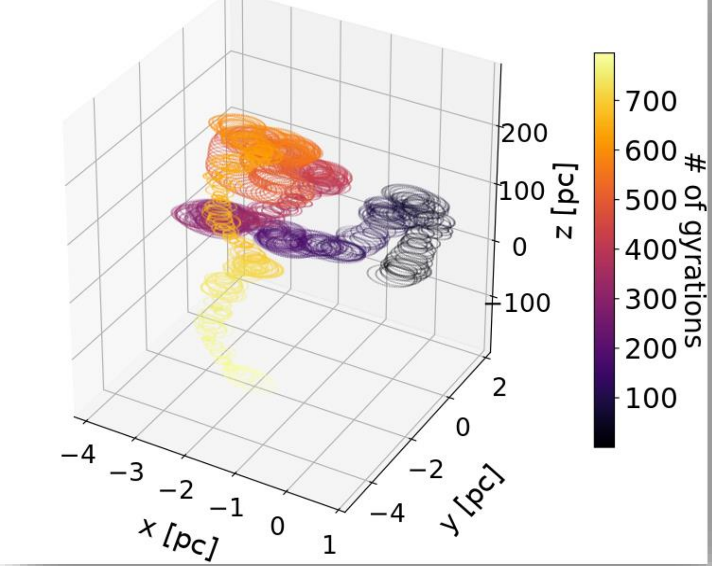
The Space domain

Transport in turbulent fields: Ballistic vs. Diffusive



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

Masterthesis P. Reichherzer (2019)



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

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Transport in turbulent fields: Criteria

Following [Reichherzer et al. MNRAS (2020)]:

Reduced rigidity:

$$\rho = \frac{r_g}{l_c} = \frac{E}{q\,c\,B\,l_c} \rightarrow E \geq \frac{5}{2\pi} \cdot l_c \cdot c \cdot q \cdot B$$

- Reduced rigidity ρ can be used as criterion to distinguish between the necessity to either propagate ballistically (**QB**) or diffusively (**RSR**):
  - Ballistic motion for $\rho \geq \frac{5}{2\pi}$
  - Diffusive propagation for $\frac{l_{\min}}{l_{\max}} \leq \rho < \frac{5}{2\pi}$
  - $l_{max} = \frac{2\pi}{k_{min}}$ → maximum scale of magnetic turbulence spectrum
  - k_{min}: lowest wave number – defined by turbulence injection scale

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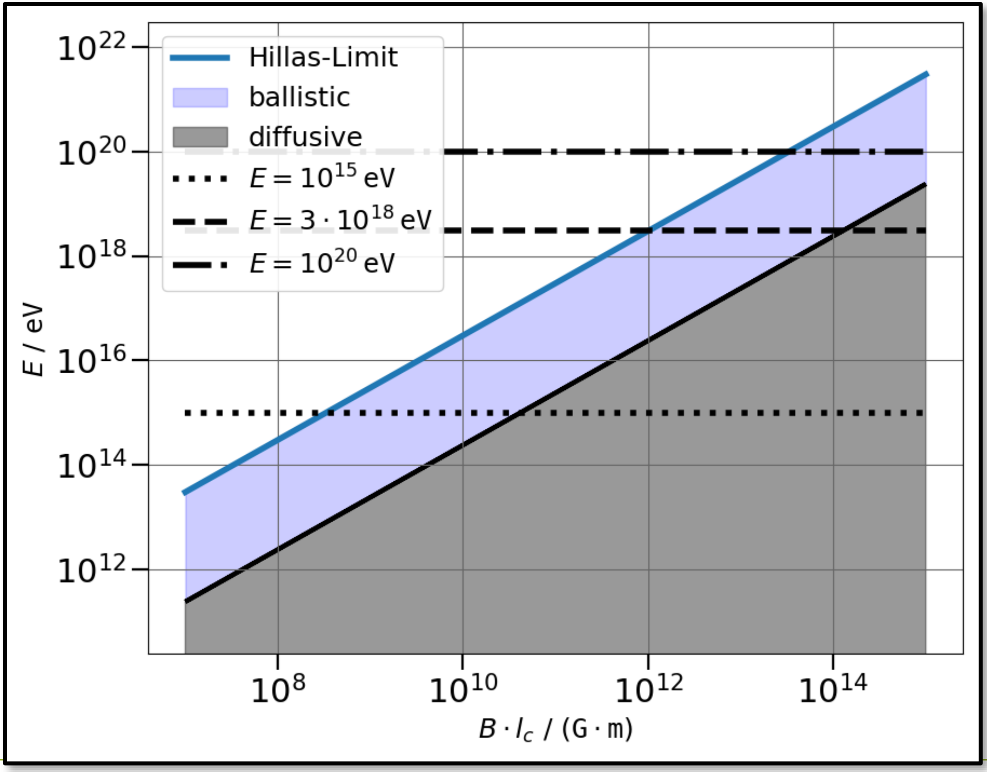
Transition between QB and RSR

$$E \geq Z \cdot \left(\frac{l_c}{10^{11}\ \mathrm{m}}\right) \cdot \left(\frac{B}{0.42\ \mathrm{G}}\right) \cdot 10^{15}\mathrm{eV}$$



Plasmoid:

- $10^{12}\ \mathrm{m} < R < 10^{16}\ \mathrm{m}$
  - $l_c = 1\%\ R$

    → $10^{10}\ \mathrm{m} < l_c < 10^{14}\ \mathrm{m}$
- $10^{-3}\ \mathrm{G} < B < 10\ \mathrm{G}$

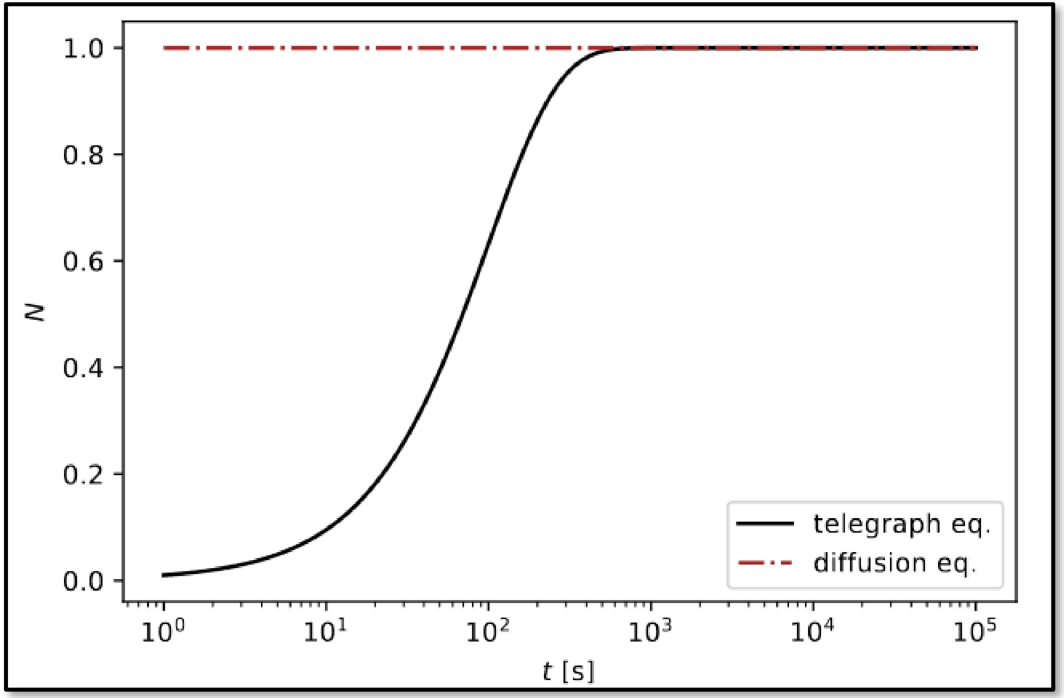
The Time domain

Telegraph vs. Diffusion equation

$$\frac{\partial f}{\partial t} + \tau \frac{\partial^2 f}{\partial t^2} = \kappa \left(\frac{\partial^2 f}{\partial x^2} + \frac{\partial^2 f}{\partial y^2} + \frac{\partial^2 f}{\partial z^2} \right)$$

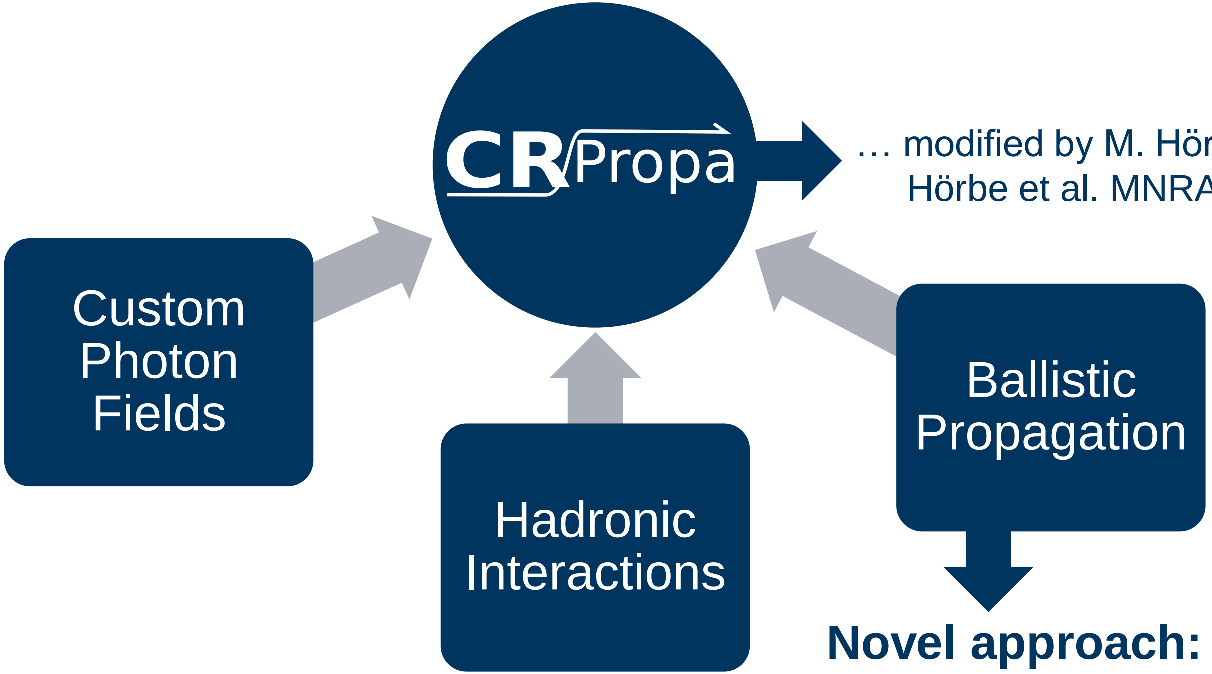
τ: Transition time between ballistic and diffusive propagation

$$t_{\mathrm{diff,N}} = -\ln(1-N) \cdot \tau$$



Simulations

Simulation Setup for AGN-Jet-Model



… modified by M. Hörbe and M. Schroller
Hörbe et al. MNRAS (2020)

Novel approach: Commonly simulated purely diffusive!

Ref. CRPropa 3: Batista et al. JCAP (2016)

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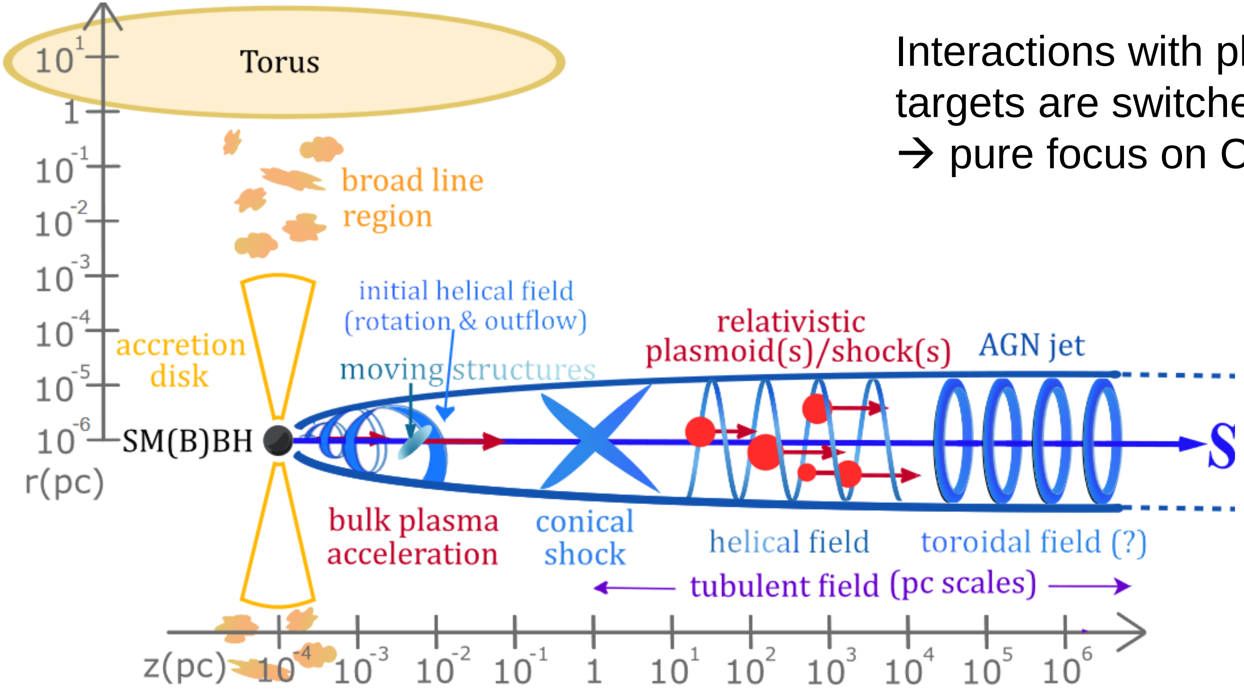
Simulation: AGN structure with a Jet



Interactions with photon + gas targets are switched off
→ pure focus on CR propagation

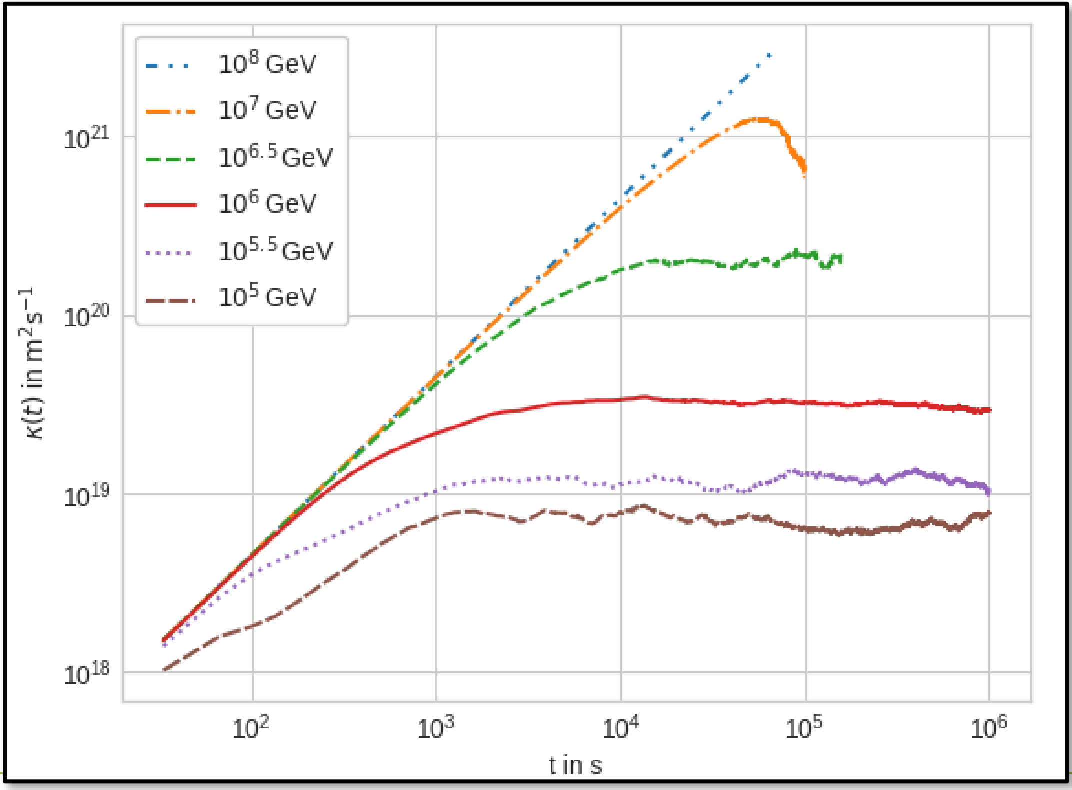
Running Diffusion Coefficients

- Simulation parameters (incomplete):
  - $B = 1\ \mathrm{G}$
  - $l_c = 10^{11}\ \mathrm{m}$
  - Homogeneous particle distribution
- Averaging $\kappa(t)$ for late times (plateaus) to approximate the **diffusion coefficient**:

$$\kappa = \lim_{t\to\infty} \kappa(t) \approx \langle\kappa(t)\rangle_{t\gg t_0}$$

- Fit of three most distinct low-energy plateaus for simple power-law yields:

$$\kappa(E) = 10^{13.54\pm0.06}\left(\frac{E}{\mathrm{GeV}}\right)$$



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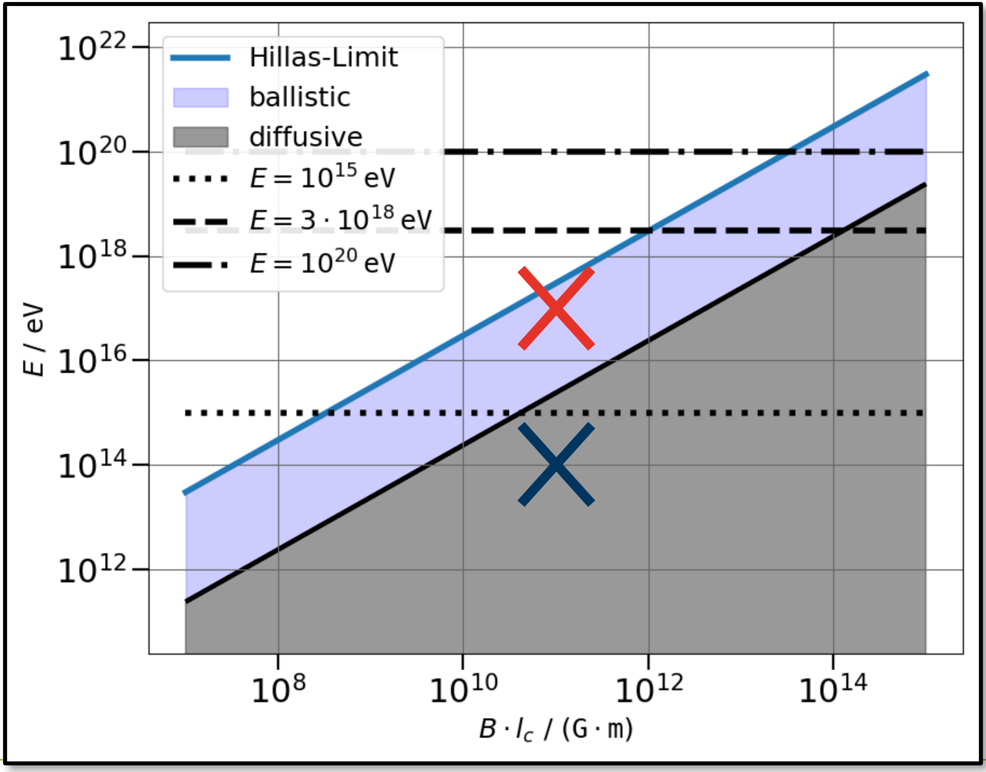
10^5GeV vs. 10^8GeV (10^{14}eV vs. 10^{17}eV)

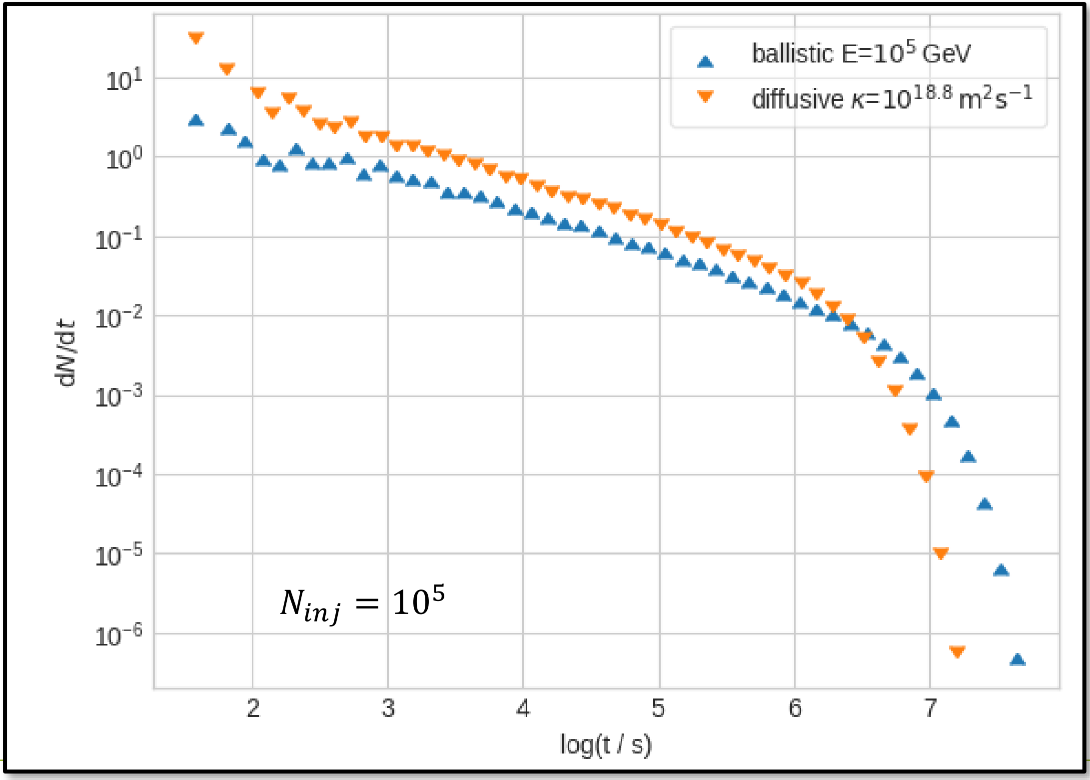
$$B = 1\,\mathrm{G}$$
$$l_c = 10^{11}\,\mathrm{m}$$



Propagation Effects: Comparison @ 10^5 GeV

- **Horizontal shift:** uncertainty in numerical determination of diffusion coefficient
- **Cut-off** at large times
- **Diffusive transport** (constant diffusion coefficient):

$$\frac{dN}{dt} \propto t^{-1/2}$$



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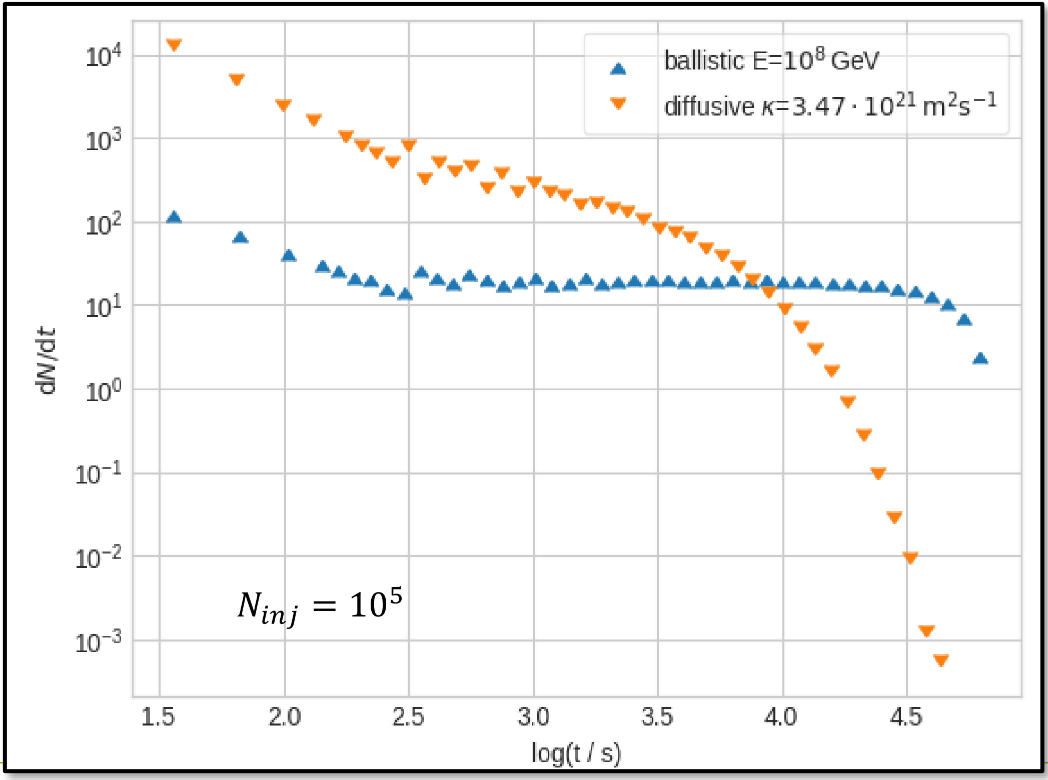
Propagation Effects: Comparison @ 10^8 GeV

- **ballistic transport:**

$$\frac{dN}{dt} \propto t$$

- **Initial slight drop:** statistical deviations from homogeneous particle distribution in plasmoid
→ more particles on outer spheres at $t = 0$



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Summary & Conclusions

- A simulation scheme is established for the **ballistic propagation** of hadronic plasmoids traveling along the AGN jet axis.
- For the proper implementation of hadronic or leptonic interactions in AGN-jets, **propagation regimes** must be considered accordingly!
  - Estimates for **secondary particle fluxes (e.g., neutrinos)** in highly variable and violent environments depend on the primary particle spectrum!

Shape of simulated flares can be misinterpreted if propagation regimes and time-scales are not considered!

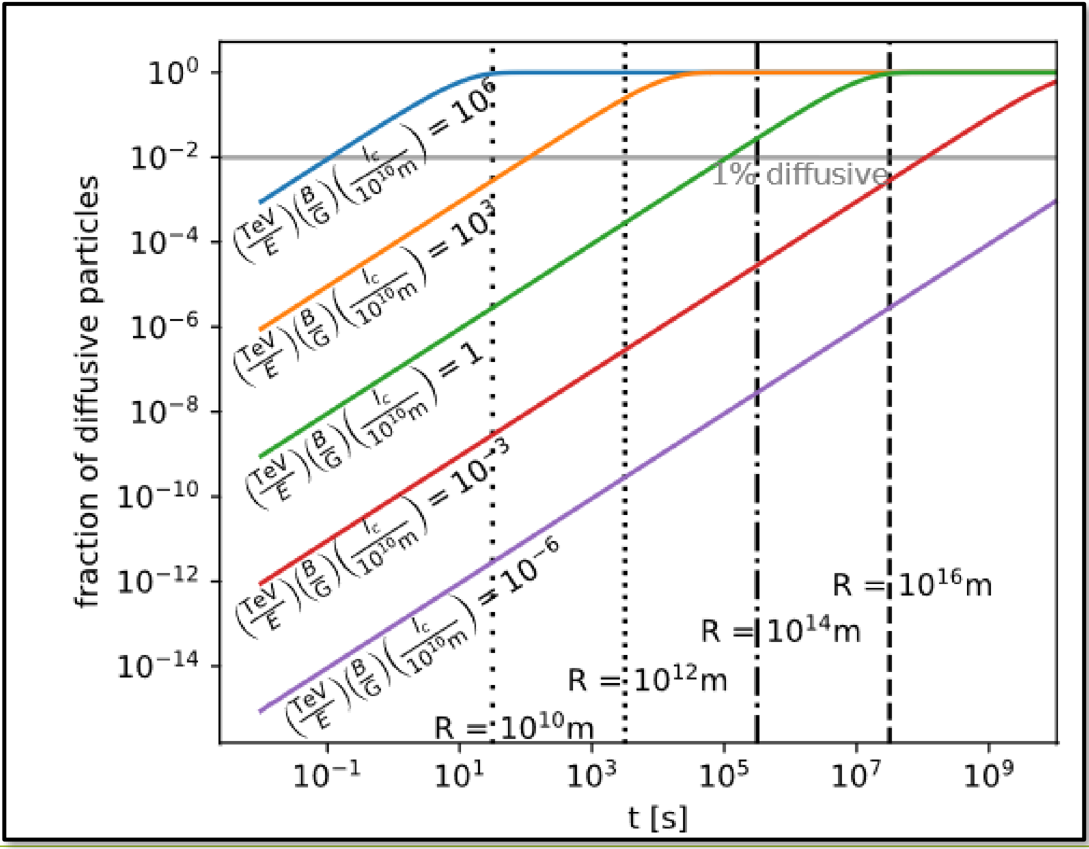
Thank you!

Appendix

Diffusion timescales

$$t_{\mathrm{diff},N} = -\ln(1-N)\frac{3\kappa_0}{v^2}\left(\frac{2\pi E}{5qcBl_c}\right)^{\delta}$$

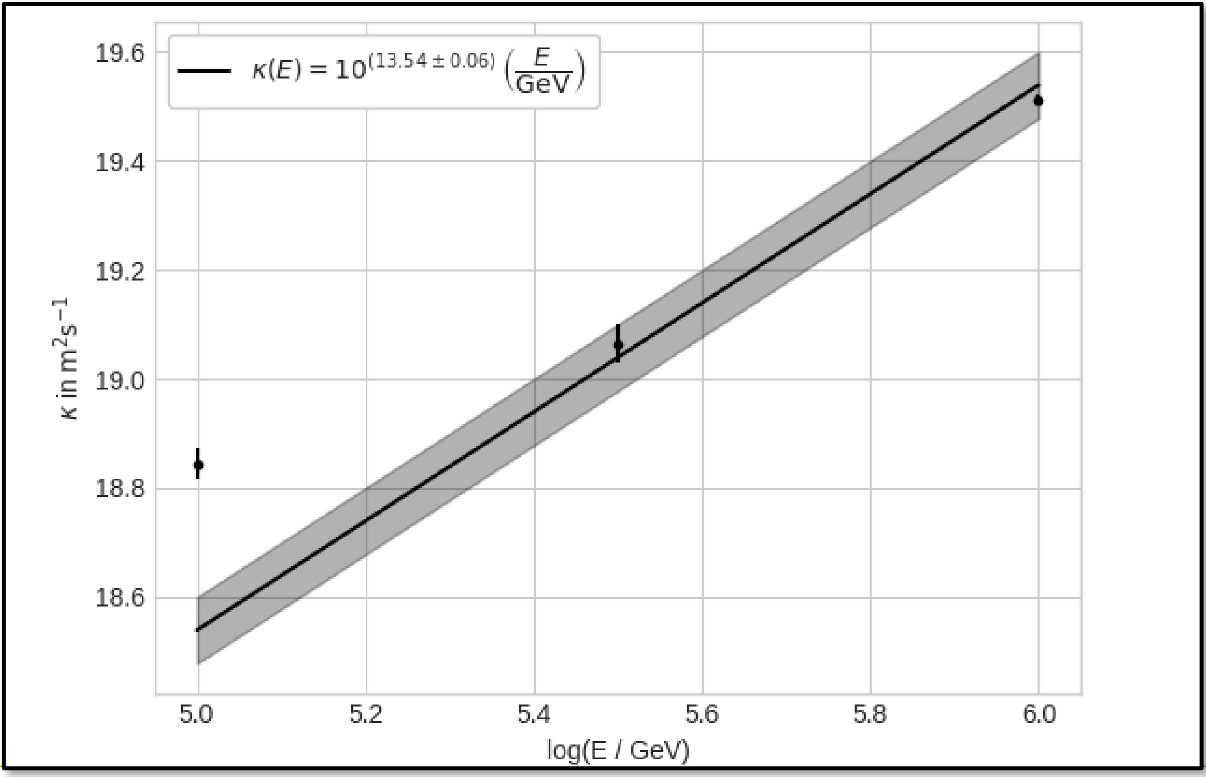
$$\text{with}\begin{cases}\delta = 1 & \text{for } \rho \lesssim 1\\ \delta = 2 & \text{for } \rho \gg 1\end{cases}$$



Full list of simulation parameters

Parameter	Value
Proton energy E_p	10^5 GeV $-$ 10^8 GeV
Plasmoid radius R	10^{13} m
Plasmoid Lorentz factor Γ	10
Magnetic field: Initial RMS value B_0	1 G
Magnetic field: Turbulence & spectral index α	Kolmogorov-type, $\alpha = -5/3$
Magnetic field: Correlation length l_c	10^{11} m
Magnetic field: Grid points	$(512)^3$
Magnetic field: Spacing	$R/256$
Propagation module (CRPropa intern): Ballistic	PropagationBP
Propagation module (CRPropa intern): Diffusive	DiffusionSDE
Propagation step size	$10^{-3} R$

Steady-state diffusion coefficient



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System: parameter comparison

i	P_i	Hoerbe et al. (V_i)	Schroller et al. (W_i)
1	Radius of plasmoid R	1e13 m	1e13 m
2	Spacing Δs	2*R	2*R
3	timestep Δt	33358 s	33358 s
4	# timesteps N_t	308557	308557
5	# spatial steps $N_{x,y,z}$	2	2

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Magnetic field: former parameter

i	P_i		V_i	W_i
6	# of gridpoints	N_{Gr}	256	512
7	Spacing	Δs_B	R / (128)	R /(256 * 64)
8	Root Mean Value	B_0	1 G	1 G
9	Correlation length	l_c	10^(-2) R	10^(-2) R
10	Lmin	l_{min}	R / (64)	R / (256 * 32)
11	Lmax	l_{max}	R / (32)	R / (32)
12	# of spatial scalings	$N^B_{x,y,z}$	2	4
13	# of temporal scalings	N^B_t	308557	617114
14	Scaling: spacing	Δs^B	2 * R	R
15	Scaling: timesteps	Δt^B	33358 s	16679

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Propagation and energy: comparison parameter

i	P_i		V_i	W_i
16	Propagation method	P	CK	BP
17	Min. step size	Δx_{min}	10^(-2) R	10^(-5) R
18	Max step size	Δx_{max}	10^(-2) R	10^(-3) R
19	Precision	ε	10^(-3)	10^(-3)
20	Injection energy	E	10^(8) GeV	10^(8) GeV
21	Max. trajectory length	d	10 pc	10 pc
22	Minimum energy	E_{min}	10^(2) GeV	10^(2) GeV
23	# of particles	N	10000	10000

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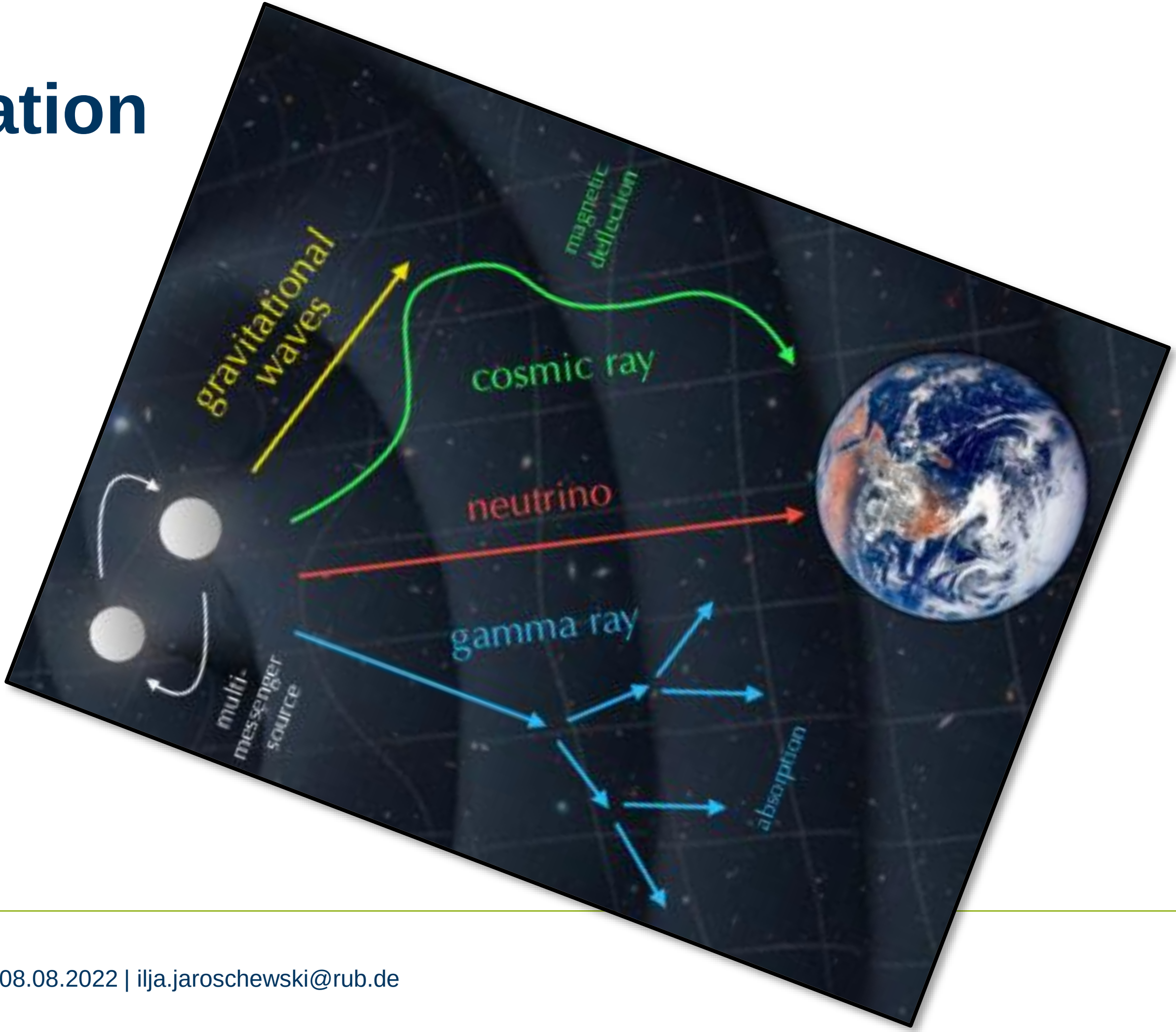
Motivation



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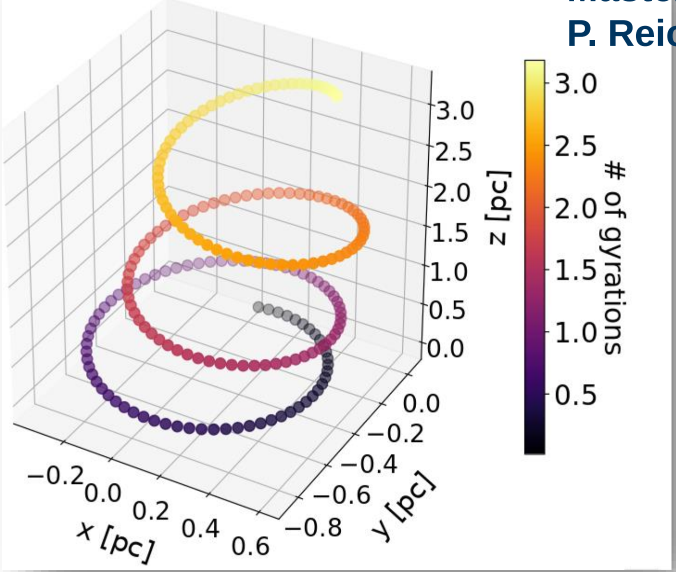
Transport in Turbulent Fields: Ballistic vs. Diffusive

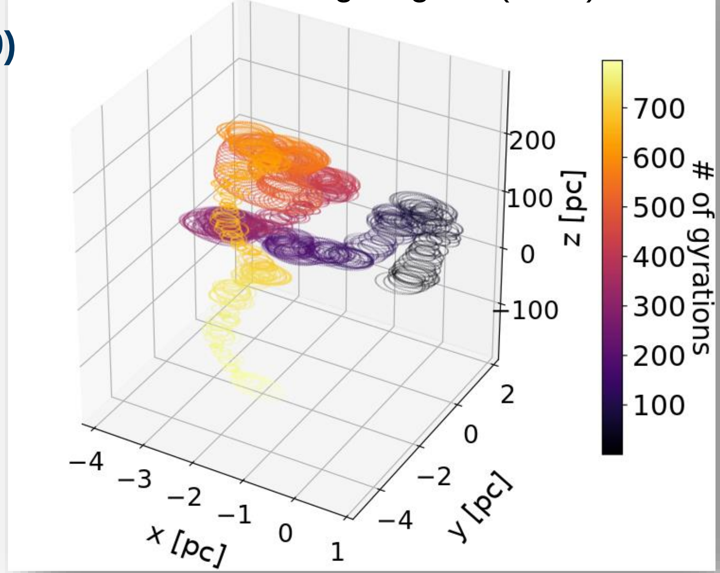
Quasi-**B**allistic (**QB**)



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

Masterthesis
P. Reichherzer (2019)

Resonant **S**cattering **R**egime (**RSR**)



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

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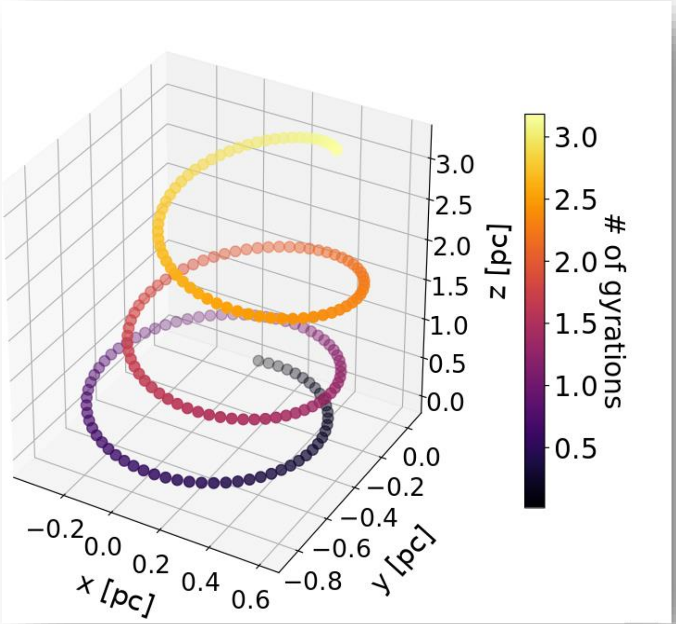
Transport in turbulent fields: Ballistic vs. Diffusive



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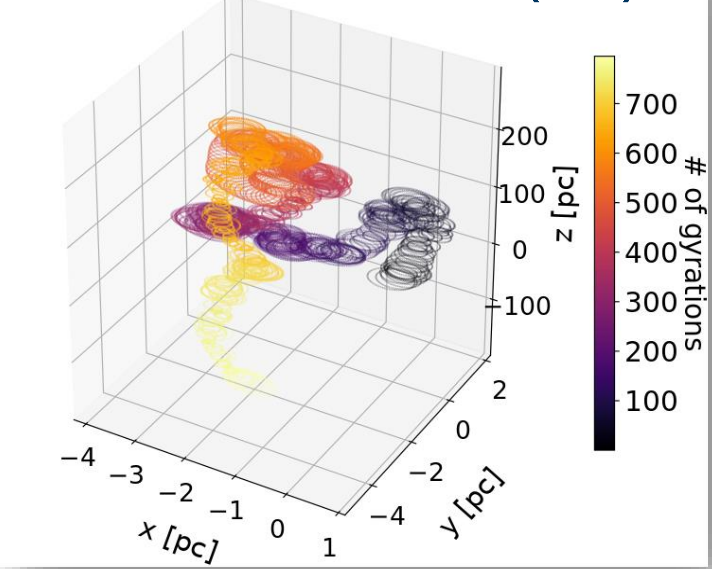

Quasi-Ballistic (QB)

Resonant Scattering Regime (RSR)

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Simulations – expectation:

diffusive + ballistic approach

deviate

at small timescales and

converge

at larger times

→ steady state diffusion coefficient reached