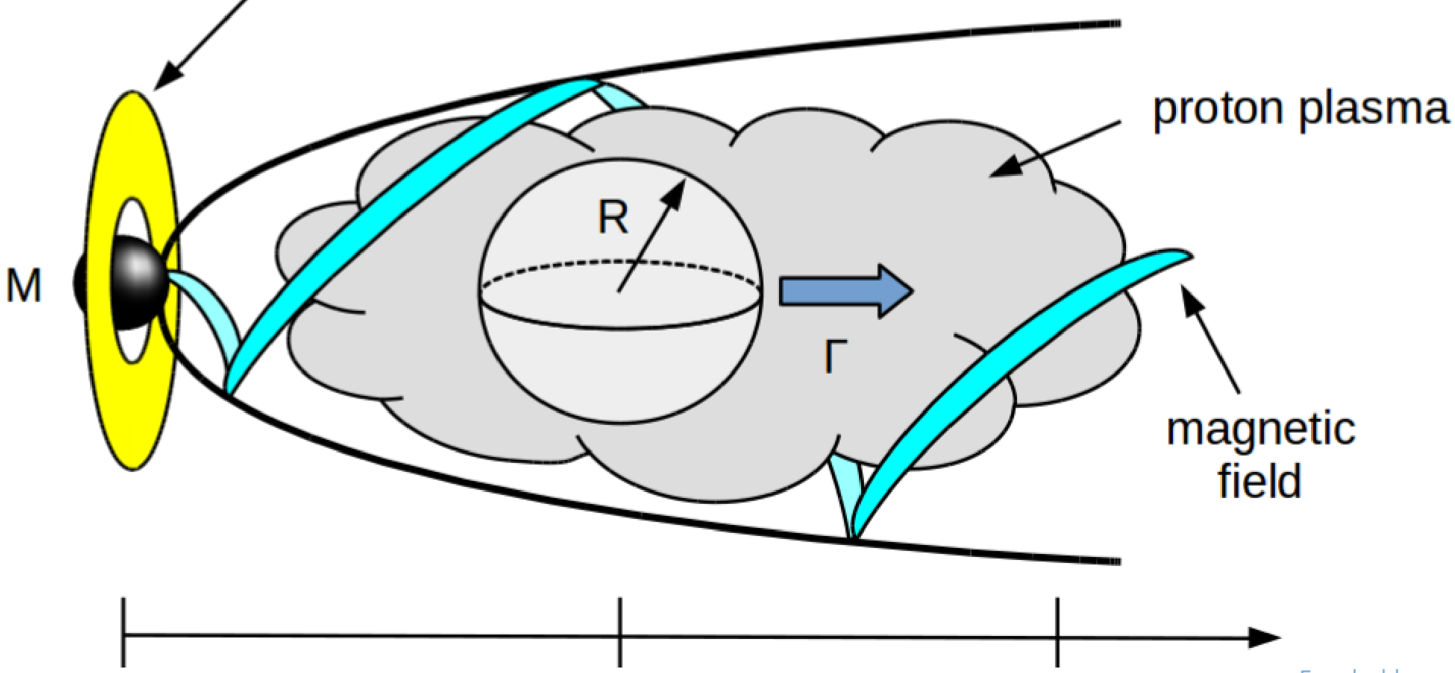

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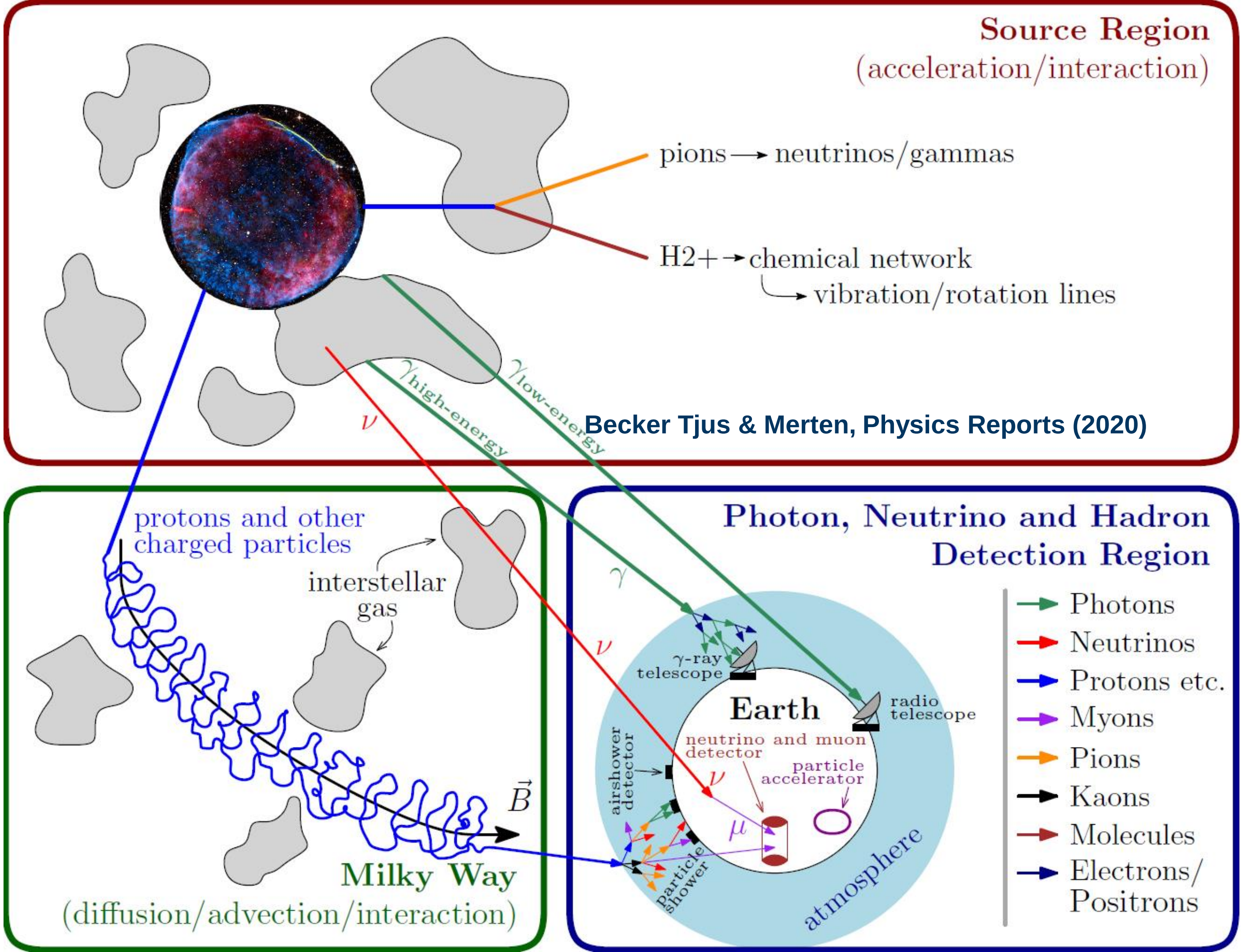
Funded by DFG Deutsche Forschungsgemeinschaft German Research Foundation

COMPARISON OF DIFFUSIVE AND BALLISTIC PROPAGATION OF COSMIC RAYS IN FLARES OF BLAZARS

Marcel Schroller, Julia Becker-Tjus, Mario Hörbe, Ilja Jaroschewski, Patrick Reichherzer,
Wolfgang Rhode, Fabian Schüssler | Erice 2022 | marcel.schroller@ruhr-uni-bochum.de



Becker Tjus & Merten, Physics Reports (2020)

Motivation – AGN as Multi-Messenger Sources

- **Active Galactic Nuclei (AGN) are one of the most luminous, observable sources**
  - Engine of the cosmic rays with highest energies up to $E_{CR} = 10^{21}$eV ?
- **Modelling is challenging; ambiguous signatures need to be understood via numerical simulation.**

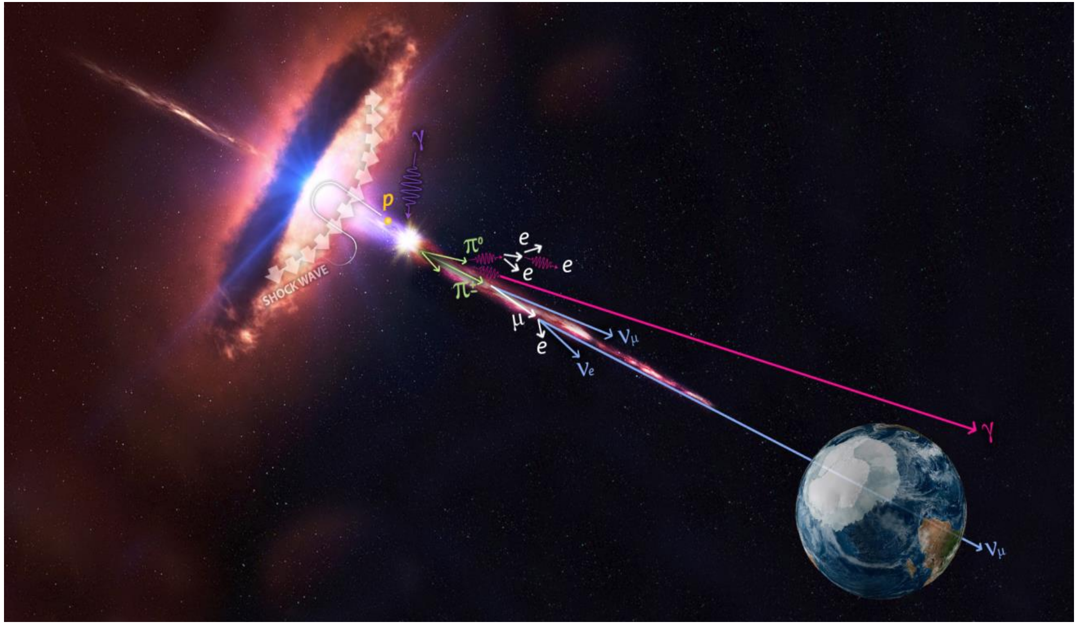
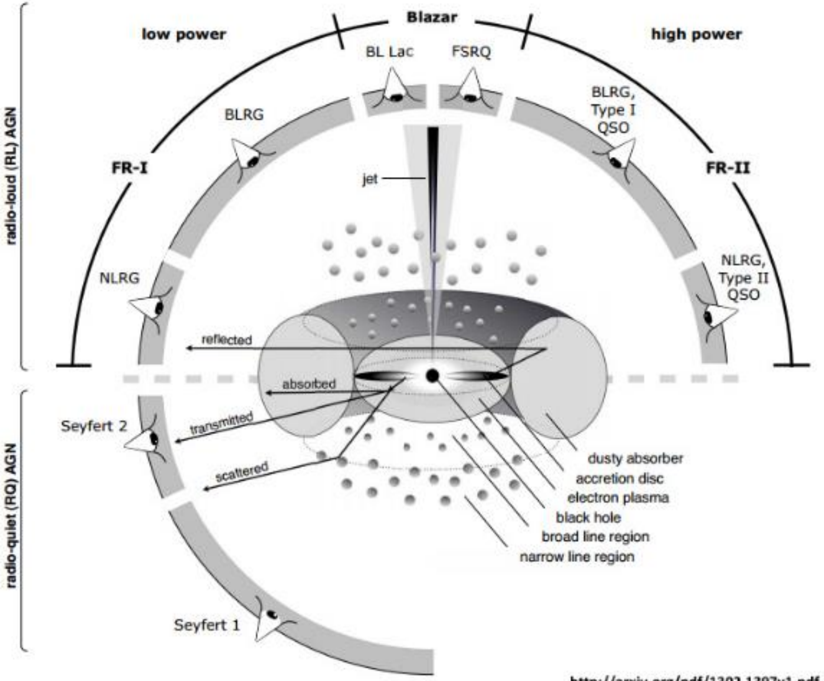


Image courtesy: IceCube Collaboration

Motivation – AGN Classification

- **Unification of AGN regarding**
  - Luminosity
  - Radio emissivity
  - Angle between LOS and axis perpendicular to accretion disk

  - Subclass of interest today: Blazars as MM – sources!



http://arxiv.org/pdf/1302.1397v1.pdf

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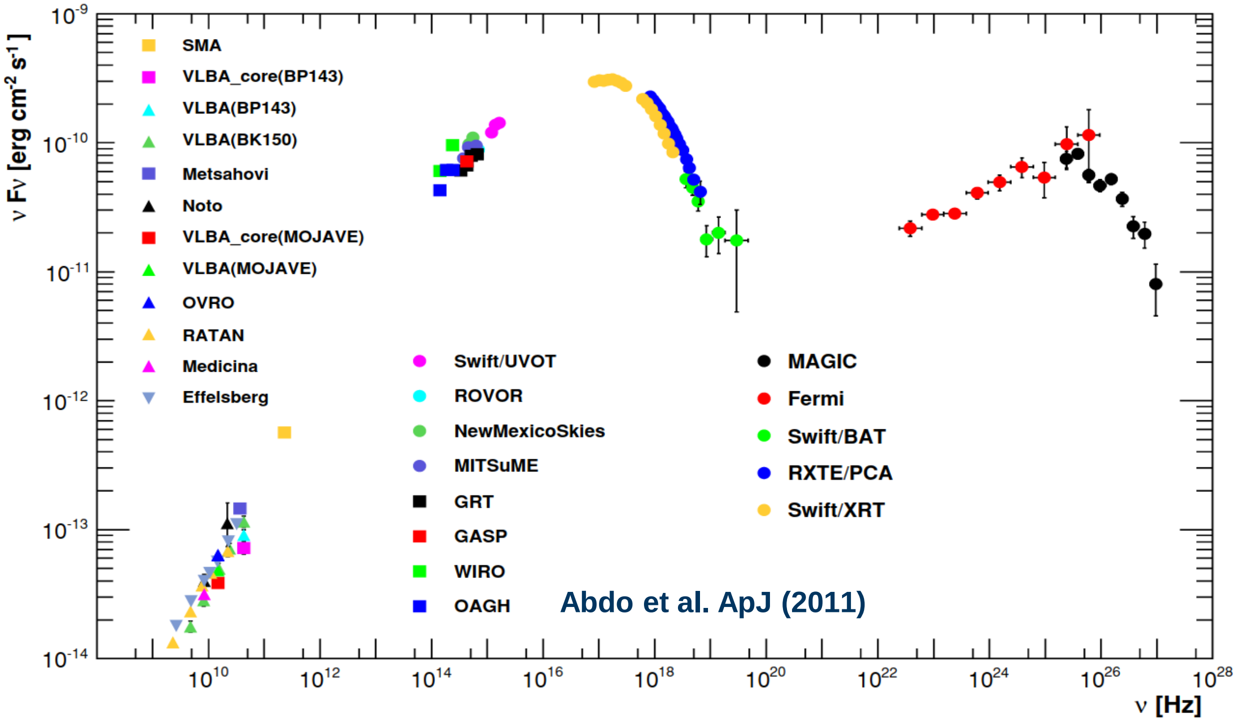
Challenges I – AGN Jet Length Scales

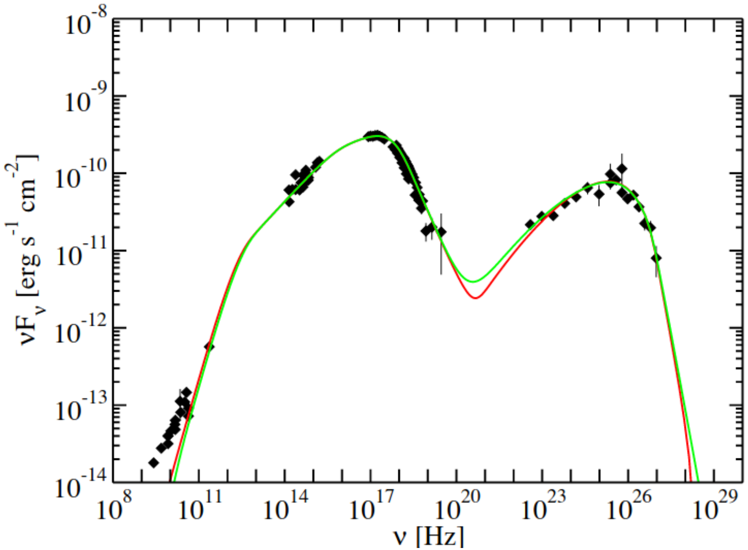
- **AGN jets are the largest coherent structures in the universe**
  - Extend up to Megaparsecs ($\approx 10^{22}$ m) from central engine
- **Contrast: MM-modelling needs to resolve small-scale ($\lesssim 10^{-4}$ pc $\approx 10^{12}$ m) environments!**

Image courtesy: MIT Kavli Institute

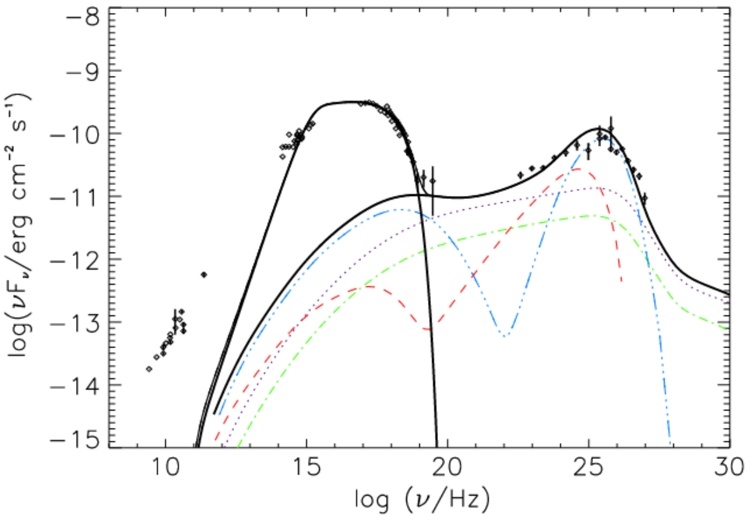
Challenges II – Energy Ranges (Multiwavelength)



Challenges III: Ambiguity of Signals



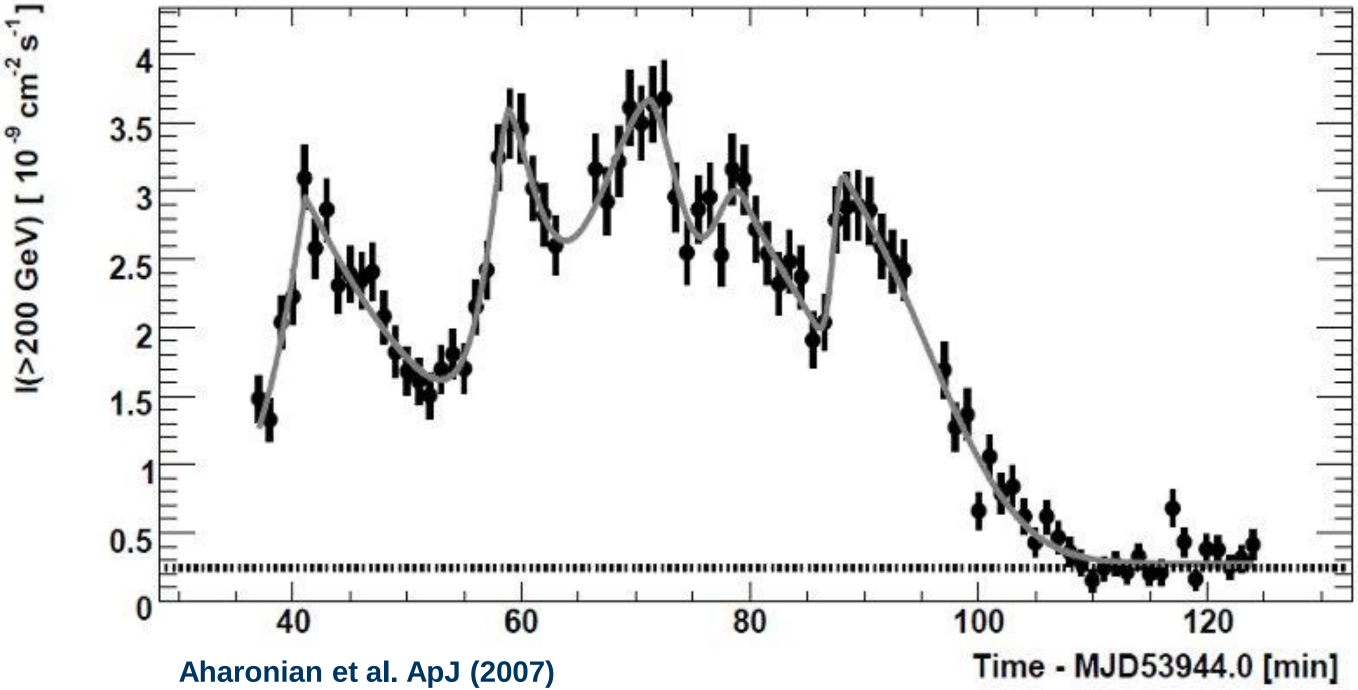
Leptonic model for SED of Mrk 421



… same SED with hadronic model

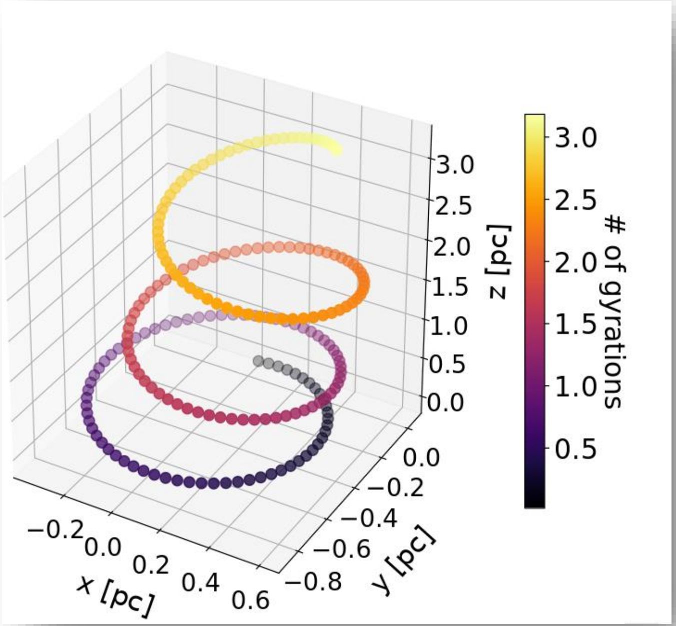
Abdo et al. ApJ (2011)

Challenges IV – Time Variability

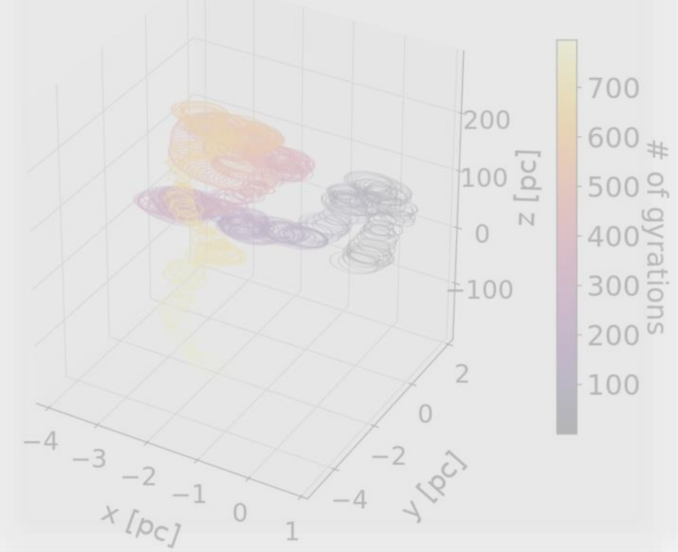


Aharonian et al. ApJ (2007)

Transport in Turbulent Fields: Ballistic vs. Diffusive



Masterthesis P. Reichherzer (2019)



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

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

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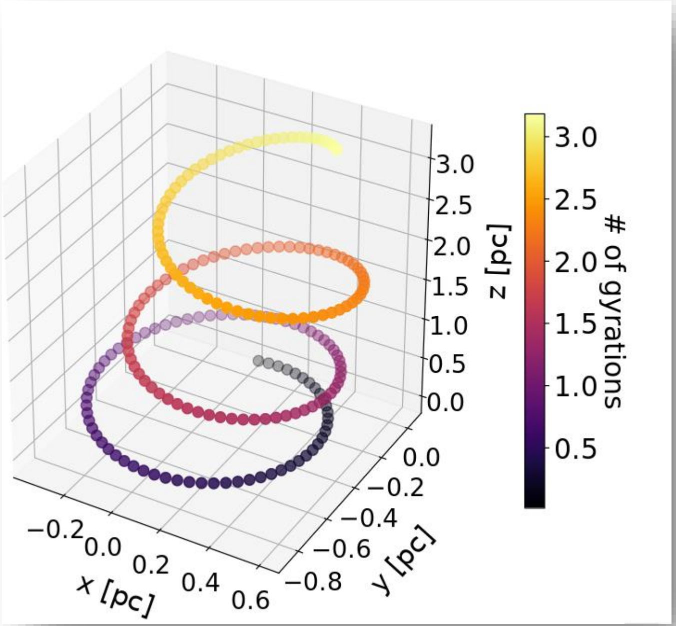
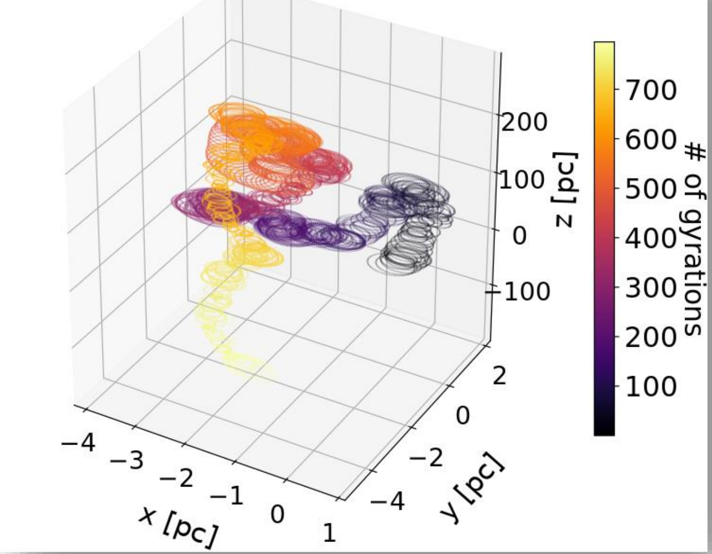
Transport in Turbulent Fields: Ballistic vs. Diffusive



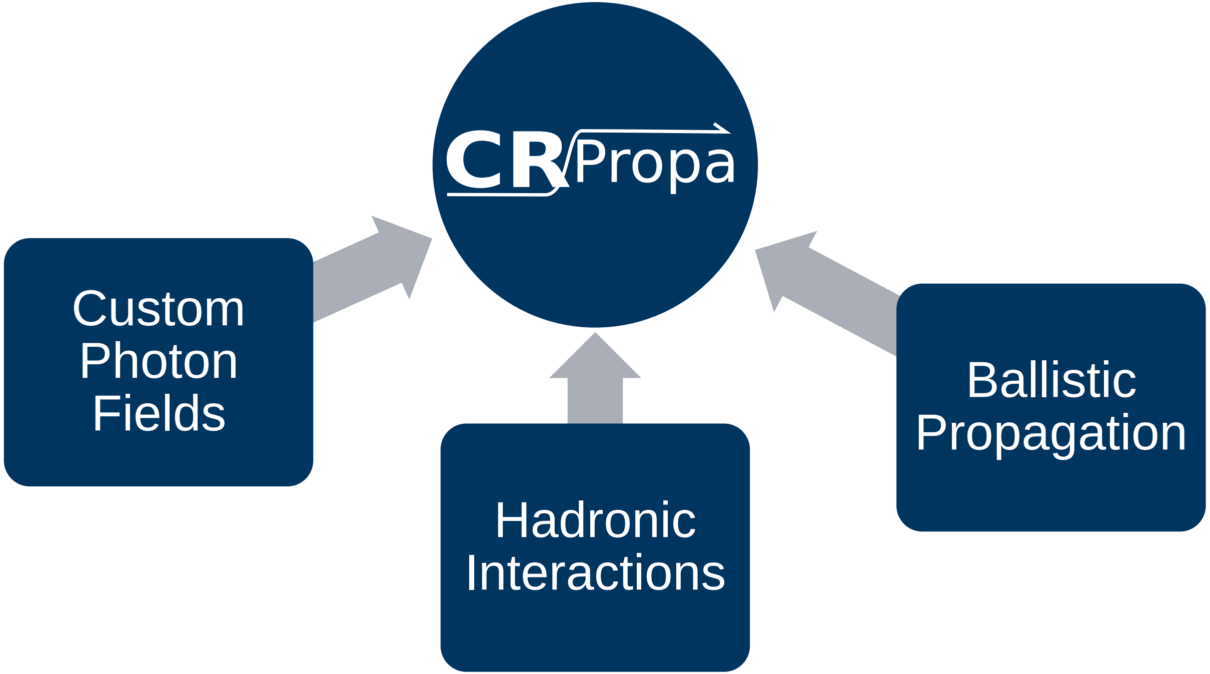
$$\frac{d\boldsymbol{p}}{dt} = q(\boldsymbol{v} \times \boldsymbol{B})$$

Masterthesis P. Reichherzer (2019)



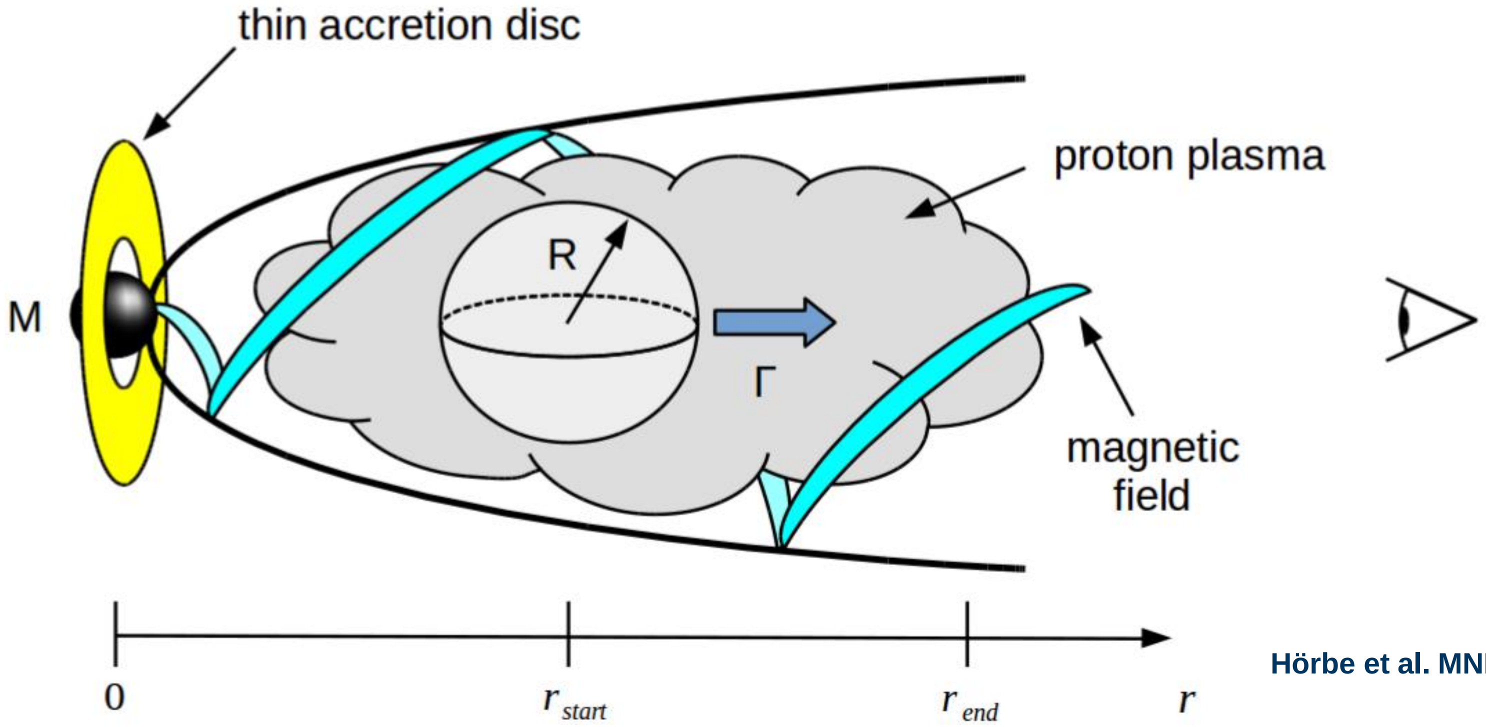
$$\frac{\delta n}{\delta t} = \nabla \cdot \left(\hat{D} \cdot \nabla n\right) - \vec{u} \cdot \nabla n + Q$$

Simulation Setup for AGN-Jet-Model



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

Setup: Scheme



Hörbe et al. MNRAS (2020)

Setup: Parameter (excerpt)

Assumptions:

- Equipartition: $U_B = U_p + U_e$
- Purely Kolmogorov-type turbulent magnetic field in 3d with $l_c = 10^{-2}R$
- Injection monochromatic or power law w. spectral index $\alpha_p = 2$;

  $E_{min} = 10^8$ GeV

  $E_{max} = 10^{11}$ GeV
- Instantaneous injection
- Black body field of accretion disk Doppler de-boosted inside plasmoid
- Synchrotron radiation of ambient electrons

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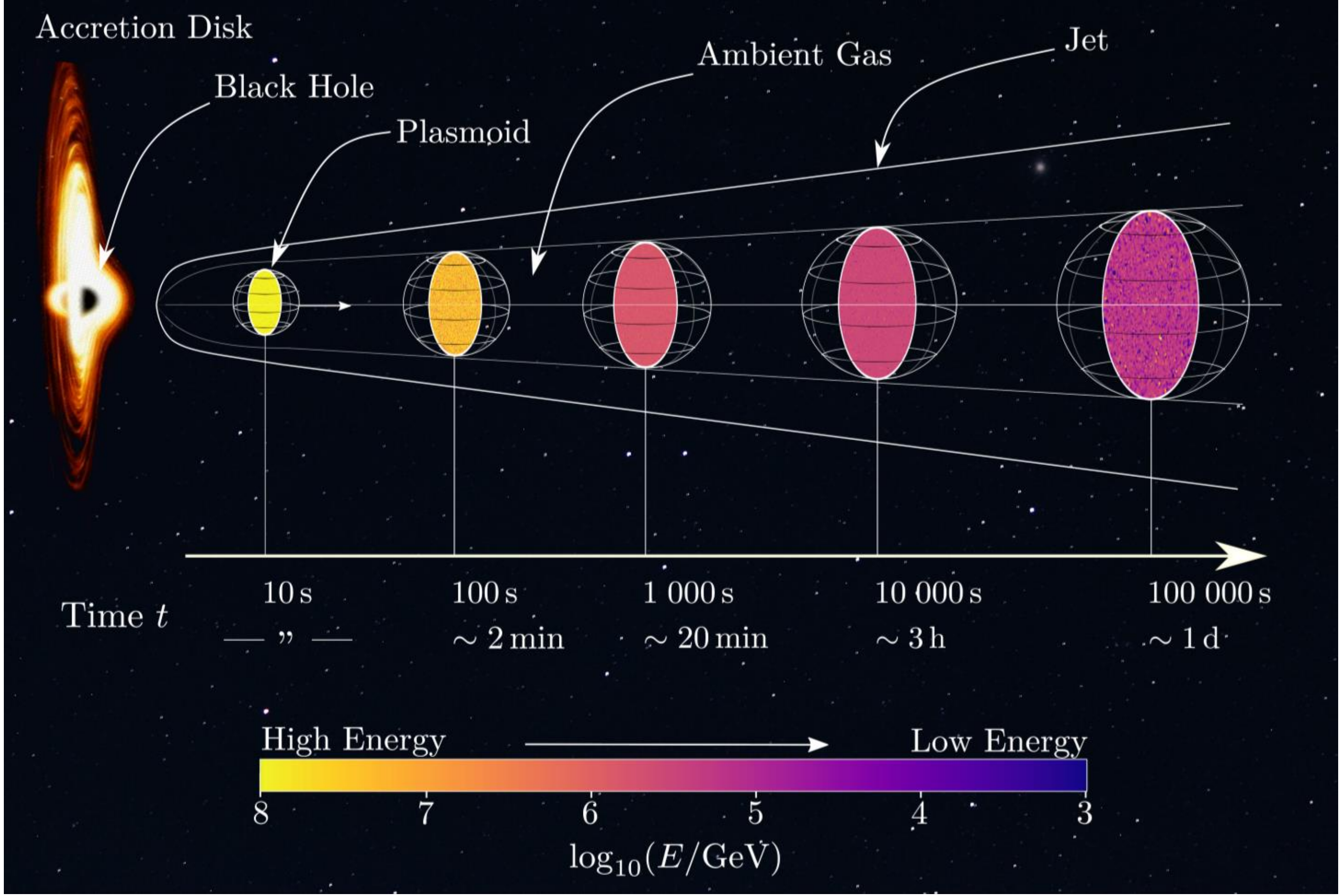
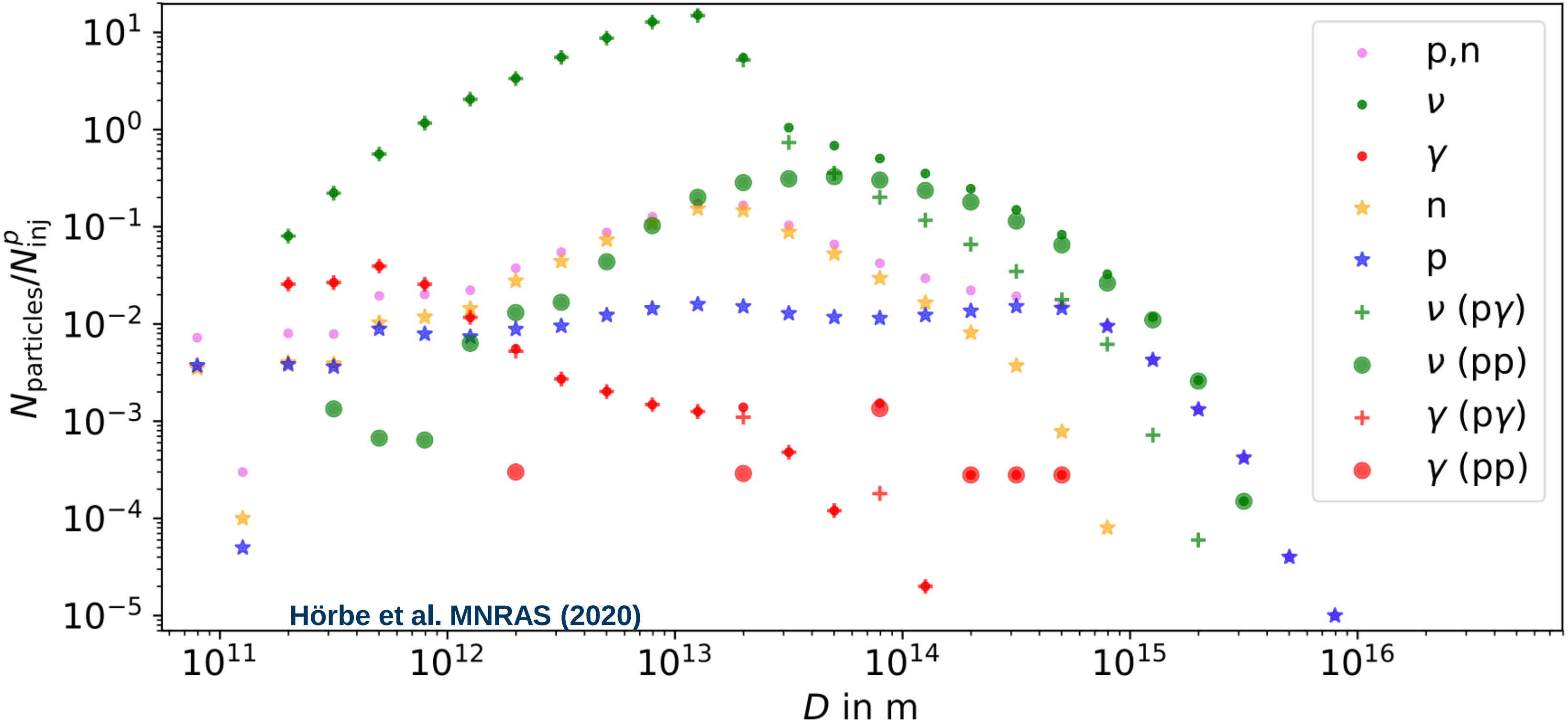


Image courtesy: Vladimir Kiselev & MS

Setup: Results (combined messengers)



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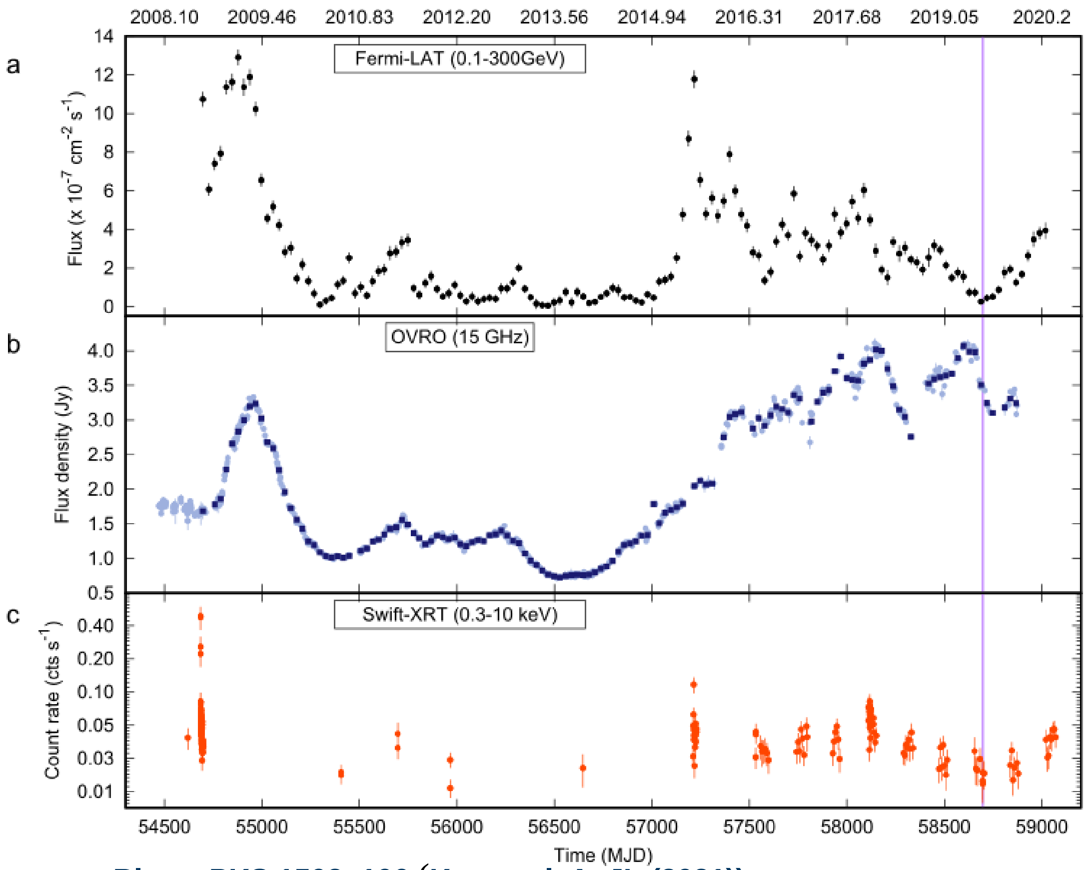


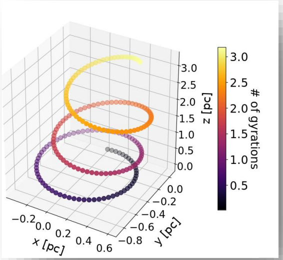
Blazar PKS 1502+106 (Kun et al. ApJL (2021))

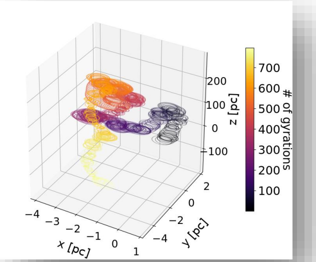
Transport: Running Diffusion Coefficient

Particle Trajectory Data

Ensemble Averaging at t_i

Running Diffusion Coefficient $\kappa(t_i)$





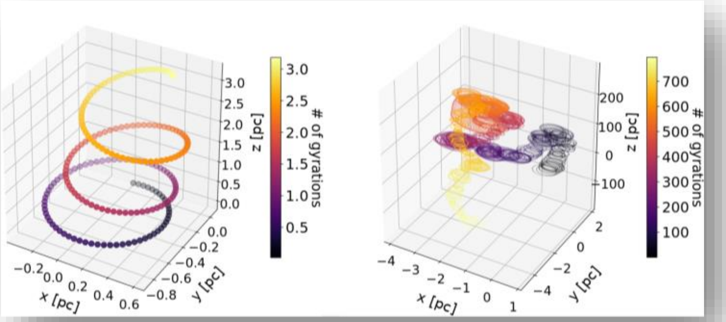
$$\kappa(t_i) = \frac{< r(t_i) - r(t_0) >^2_{\text{particles}}}{2t_i}$$

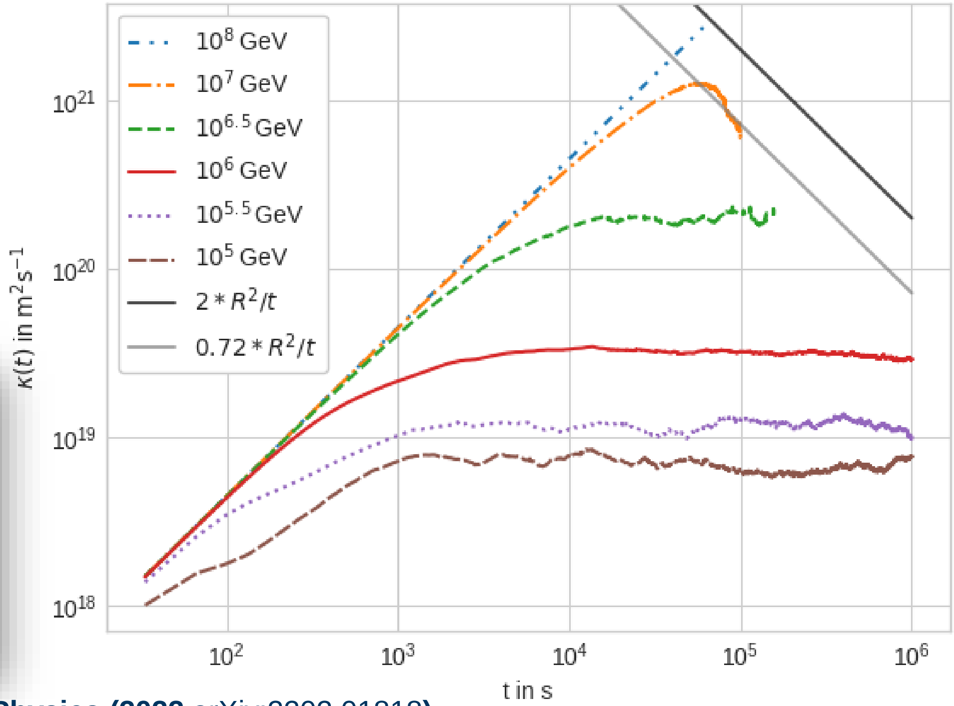
Transport: Diffusion Coefficients

- Averaging $\kappa(t)$ for late times (plateaus) to approximate the **diffusion coefficient**:

$$\kappa = \lim_{t\to\infty} \kappa(t) \approx <\kappa(t)>_{t\gg t_0}$$

  - Input for diffusive simulations (if applicable)





Becker-Tjus et al. MDPI Physics (2022 arXiv:2202.01818)

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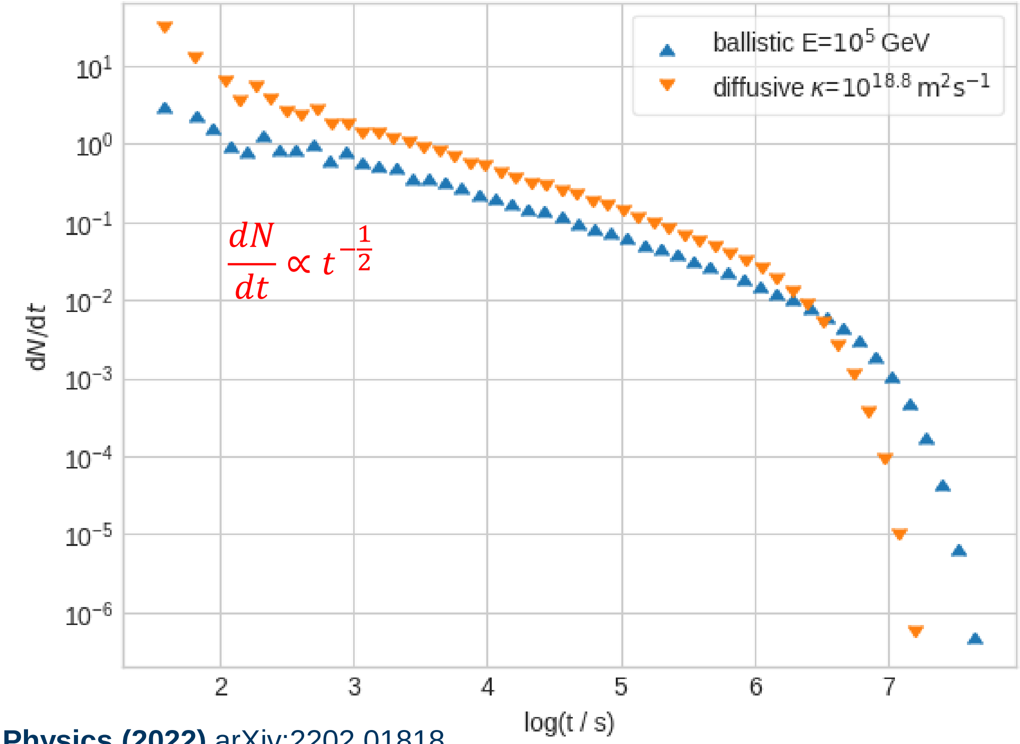
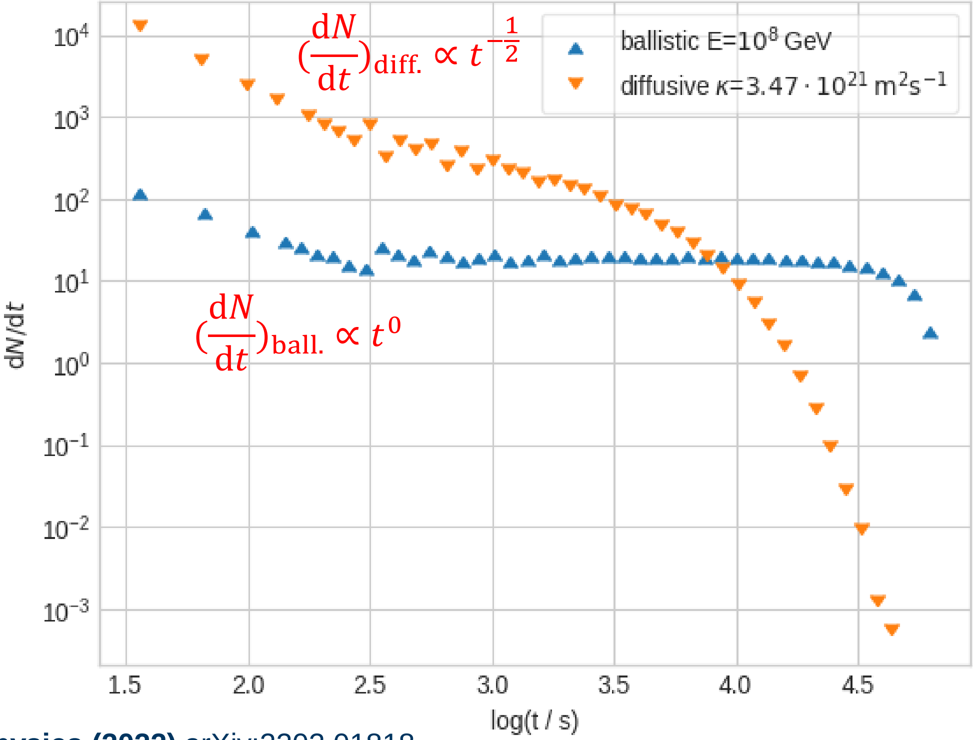
Propagation Effects: Comparison @ 10^5 GeV



Becker-Tjus et al. MDPI Physics (2022) arXiv:2202.01818

Propagation Effects: Comparison @ 10^8 GeV



Becker-Tjus et al. MDPI Physics (2022) arXiv:2202.01818

Further Implications (Teaser): Spectra

Telegrapher‘s equation for transitional time scales:

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

physics MDPI

Article

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

Julia Becker Tjus [1,2,*], Mario Hörbe [1,2], Ilja Jaroschewski [1,2], Patrick Reichherzer [1,2,3], Wolfgang Rhode [4], Marcel Schroller [1,2] and Fabian Schüssler [3]

Prediction of spectral breaks from spatial and magnetic field configurations for AP neutrinos and gamma-rays from AGN jets!

Becker-Tjus et al. MDPI Physics (2022) arXiv:2202.01818

Summary & Conclusion

- **MM-Modelling and simulation of AGN jet signatures is notoriously difficult: Need to cover several orders of magnitude in extend, energy, temporal resolution and environmental scalings**
- With the **extension** of **CRPropa,** the first step towards a consistent hadronic test particle simulation was achieved
    - This will shed light into mechanisms of the (possible) birthplace of UHE **cosmic rays, gamma-rays and neutrinos**.
    - First predictions of possible spectral breaks in UHE neutrino and gamma-ray spectra are deduced
    - Impact of transitions between streaming and diffusion on fluxes and secondary particle production is not neglible!
- Ultimately, the interconnection of **plasma-, astro- and particle physics** in AGN jets makes them perfect to study fundamental physics.

Thank you for your attention!

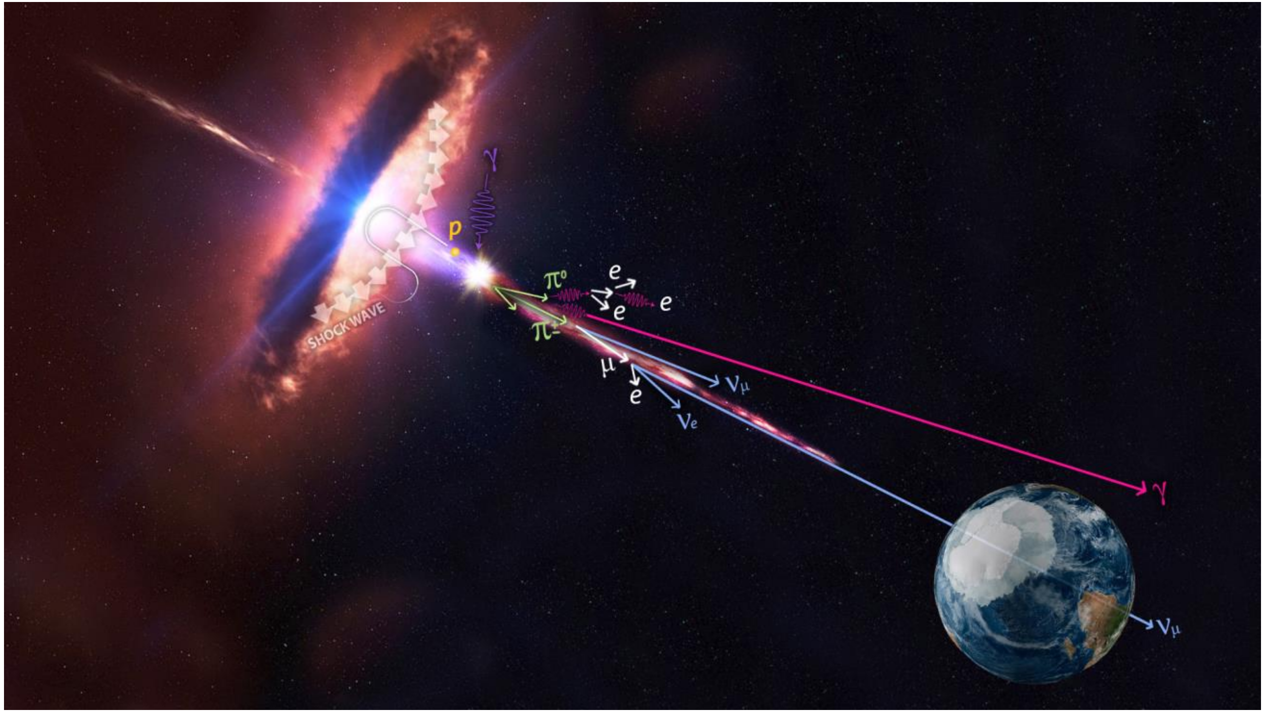


Image courtesy: IceCube Collaboration

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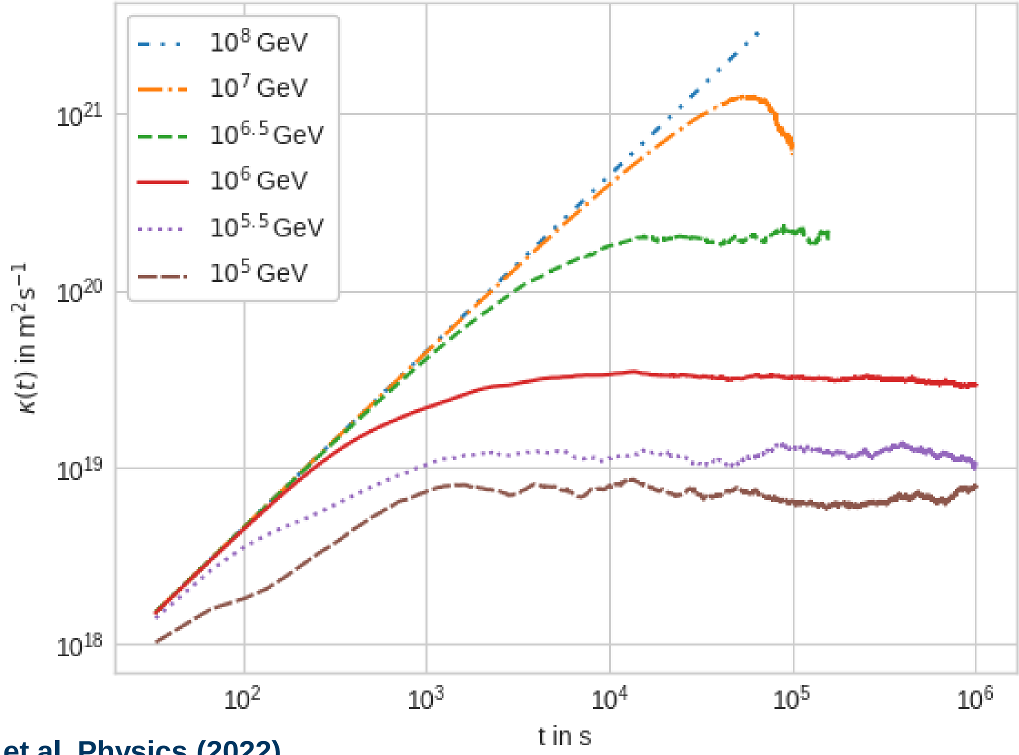
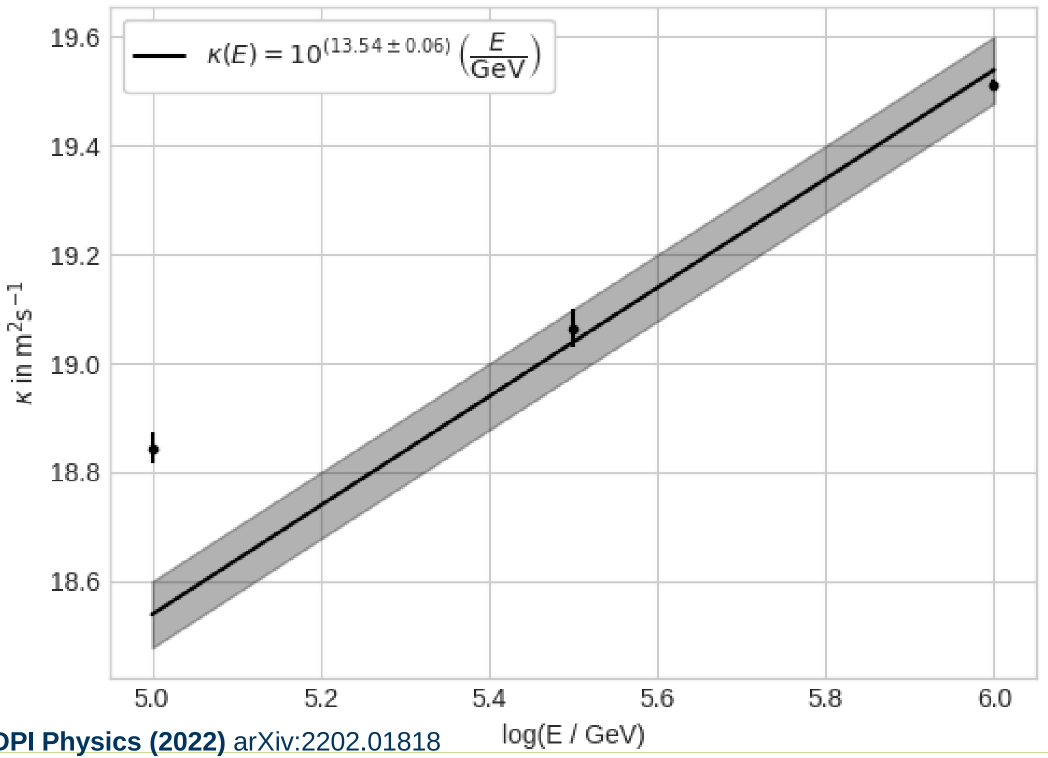
BACKUP

Setup: Results (Running Diffusion Coefficient)



Becker-Tjus et al. Physics (2022)

Setup: Results (Diffusion Coefficients)



Becker-Tjus et al. submitted MDPI Physics (2022) arXiv:2202.01818

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

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	$N_{x,y,z}^B$	2	4
13	# of temporal scalings	N_t^B	308557	617114
14	Scaling: spacing	Δs^B	2 * R	R
15	Scaling: timesteps	Δt^B	33358 s	16679

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

Transport in turbulent fields: Criteria

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

The reduced rigidity $\rho = \frac{r_\mathrm{g}}{l_\mathrm{c}} = \frac{E}{qcB\,l_\mathrm{c}}$

- Reduced rigidity ρ can be used as criterion to distinguish between the necessity to either propagate ballistically or diffusively:
  - Ballistic motion for $\rho > 1$
  - Diffusive propagation for ${}^{l_{min}}/_{l_{max}} \leq \rho \leq 1$

Motivation II – γ suppression vs. ν-emission

- **Example: Observations of blazar PKS 1502+106:**
  - Hint onto association of blazar to IceCube-event IC-190730A
- **Long-term survey of gamma-ray and radio fluxes show some correlation**
- **At event time IC-190730A: Deficient gamma-ray flux while de-correlated, strong radio activity**
- **Question: Can we implement models, which reproduce this behavior?**

Simulation: Visualization

Example: AGN of 3C 279:

- $z = 0.53620 \pm 0.00040$
- Distance SMBH – apparent base of jet:

  $d \approx 0.5\,\text{pc} \approx 1.8 \cdot 10^{16}\ \text{m}$
- Start of propagation/simulation:

  $r_0 = \ 10^{14}\ \text{m}$

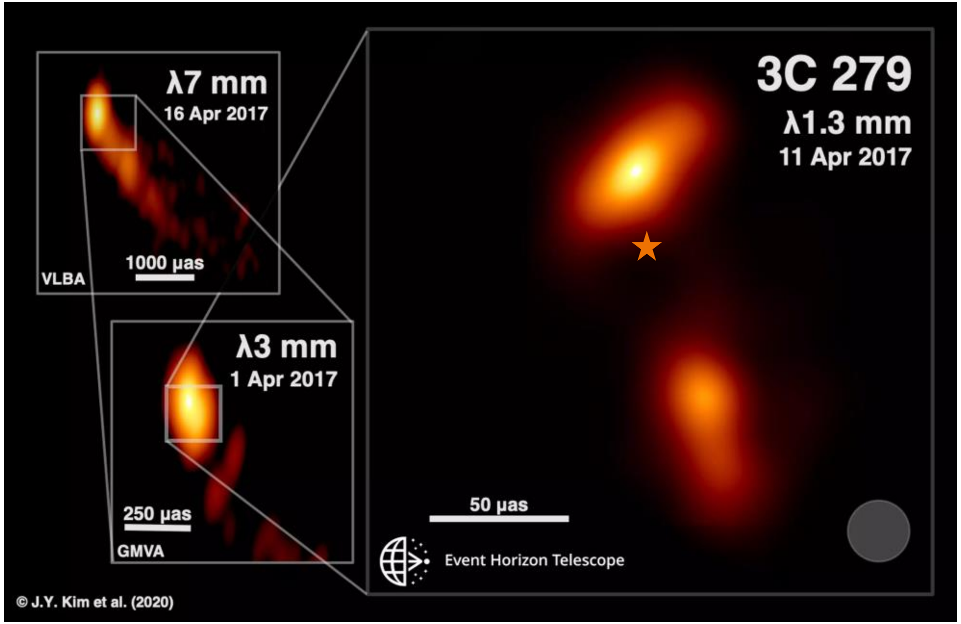


Fig. 4: Nucleus of 3C 279 with base of jet. The orange star approximates the starting point of the´simulation. [https://www.mpg.de/14651902/jet-des-quasars-3c279-mit-eht. Accessed at 28.09.2021]

Setup: Parameter (excerpt)

Parameter	Symbol	Value
Plasmoid Radius	R	10^{13} m
Plasmoid Propagation Start	r_{start}	10^{14} m
Plasmoid Propagation End	r_{end}	$r_{\mathrm{start}} + 10$ pc
Plasmoid Lorentz Factor	Γ	10
Magnetic Field Initial RMS Value	B_0	1 G
Proton (primary) Initial Energy	$E_{p,\mathrm{inj}}$	10^8 GeV
Proton Target Density (up-scaled)	$n_{0,\mathrm{plasma}}$	10^{15} m^{-3}
Electron Minimal Lorentz Factor	$\gamma_{e,\mathrm{min}}$	10
Electron Maximal Lorentz Factor	$\gamma_{e,\mathrm{max}}$	10^6
Electron Spectral Index	α_e	2.6
Energy Density Ratio U_p/U_e	χ	1/100
Accretion Disc Inner Radius	$3R_s$	$8.86 \cdot 10^{11}$ m
Accretion Disc Outer Radius	R_{acc}	10^{14} m
Accretion Disc Temperature	T_0	10 eV/k_b

Hörbe et al. MNRAS (2020)

Assumptions:

- Equipartition: $U_B = U_p + U_e$
- Purely turbulent field with $l_c = 10^{-2}R$
- Injection monochromatic (Tab. 1) or power law w. spectral index $\alpha_p = 2$;

  $E_{min} = 10^8$ GeV

  $E_{max} = 10^{11}$ GeV
- Instantaneous injection
- Black body field of accretion disk Doppler de-boosted inside plasmoid
- Synchrotron radiation of ambient electrons

Correlation between γ-rays and Neutrinos

- **Investigation of particle readouts of photons and neutrinos at equal points in time**
  - Can we observe a correlated emission of both messengers?

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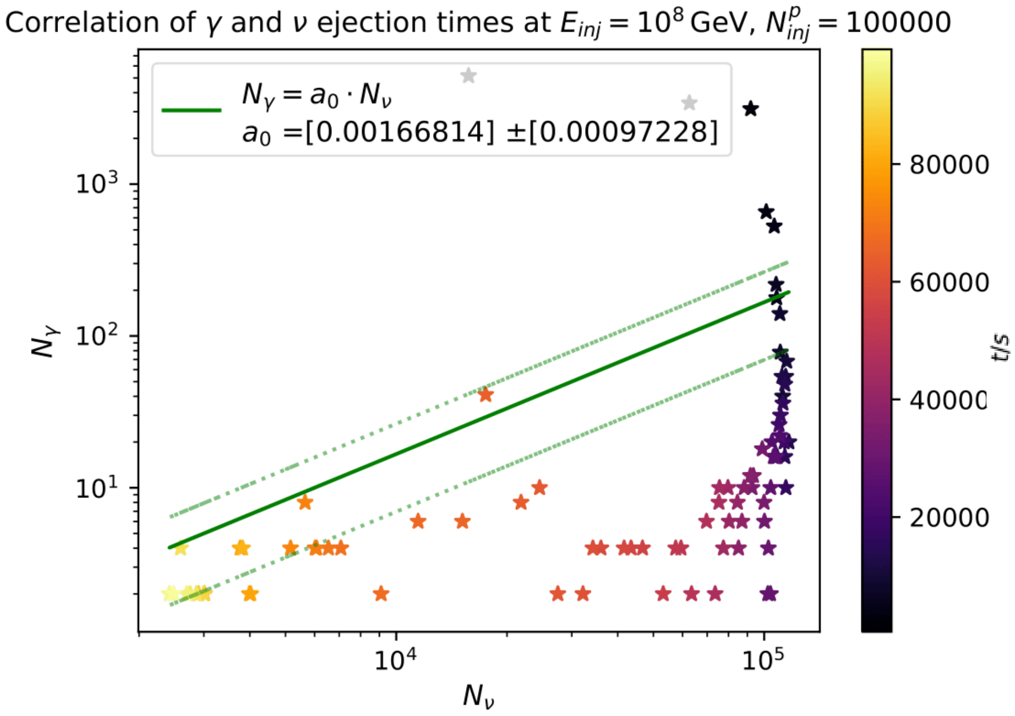

Fig 7.: The correlation between neutrino and gamma-ray emission at equal points in time, which are color-coded by the bar on the right-hand side. Gamma-rays are absorbed by the dense photon fields, while neutrinos escape.

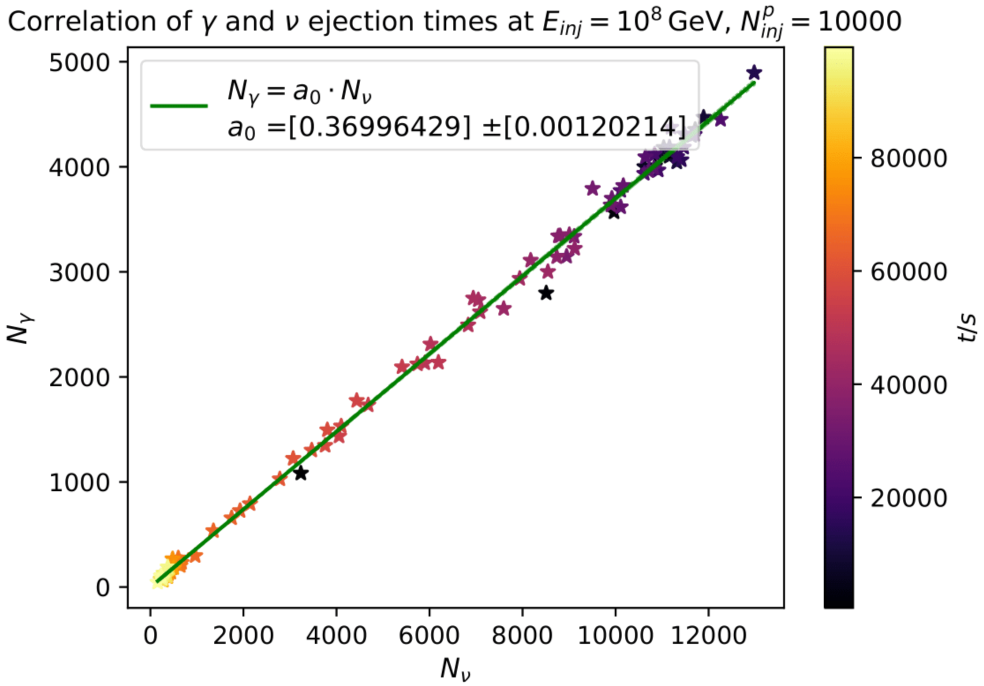

Fig 8.: The correlation between neutrino and gamma-ray emission at equal points in time, which are color-coded by the bar on the right-hand side. In this unphysical view-case, the Breit-Wheeler pair production of secondary γ**-**rays with background photons is disabled for visualization.

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Setup: Results (Running Diffusion Coefficient)

- Trajectory data can be used to calculate the **running diffusion coefficient** at instance t_i:

$$\kappa(t_i) = \frac{< r(t_i) - r(t_0) >^2_{particles}}{2t_i}$$

Erice 2022 | Marcel Schroller | marcel.schroller@ruhr-uni-bochum.de

01.09.21 Zusatz

A7: Density-dependence of the temporal structure in the multimessenger spectrum of blazars

- **Parameter setup for AGNPropa (working example):**
  - Environment, interactions and scalings are (conservatively) chosen from literature
  - Primary protons are either injected monochromatic with $E_{\mathrm{p}} = 10^{8}$ GeV or power-law-like distributed with $\alpha_{\mathrm{p}} = 2$
  - Detailed justification and in-depth explanation in Hoerbe et al. MNRAS (2020) and references therein
  - Table on the right-hand-side illustrates the model with a selection of parameters

Parameter	Symbol	Value
Plasmoid radius	R	10^{13} m
Propagation distance (Plasmoid's rest-frame)	D	10 pc
Plasmoid Lorentz factor	Γ	10
Magnetic field: Initial RMS value	B_0	1 G
Accretion disk: Inner radius	$3R_S$	$8.86 \cdot 10^{11}$ m
Accretion disk: Outer radius	R_{acc}	10^{14} m
Accretion disk: Temperature (Black body)	T_0	10 eV/k_b