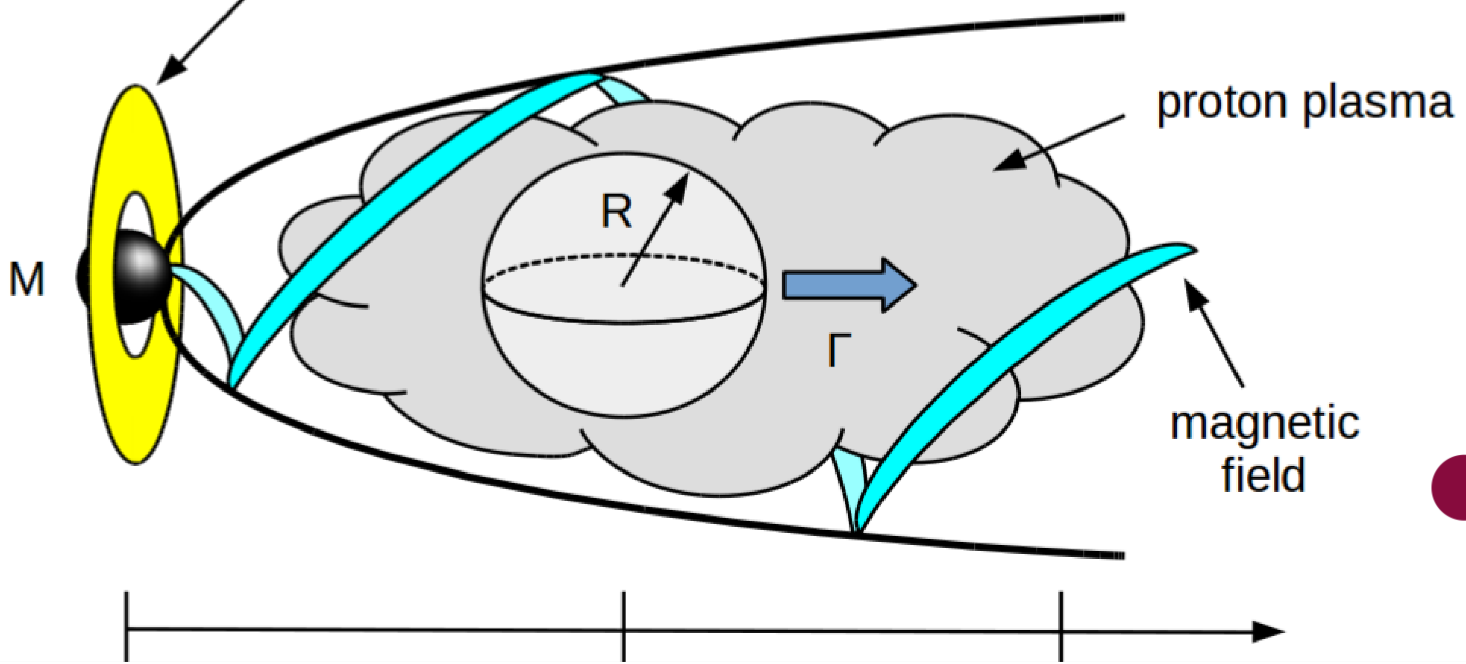

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Funded by DFG Deutsche Forschungsgemeinschaft German Research Foundation

PROJECT A7: DENSITY DEPENDENT MULTIMESSENGER MODELLING OF BLAZAR JETS – STATUS UPDATE

Marcel Schroller, Julia Becker Tjus and Lukas Merten | marcel.schroller@ruhr-uni-bochum.de

CRC 1491 General Assembly 2023

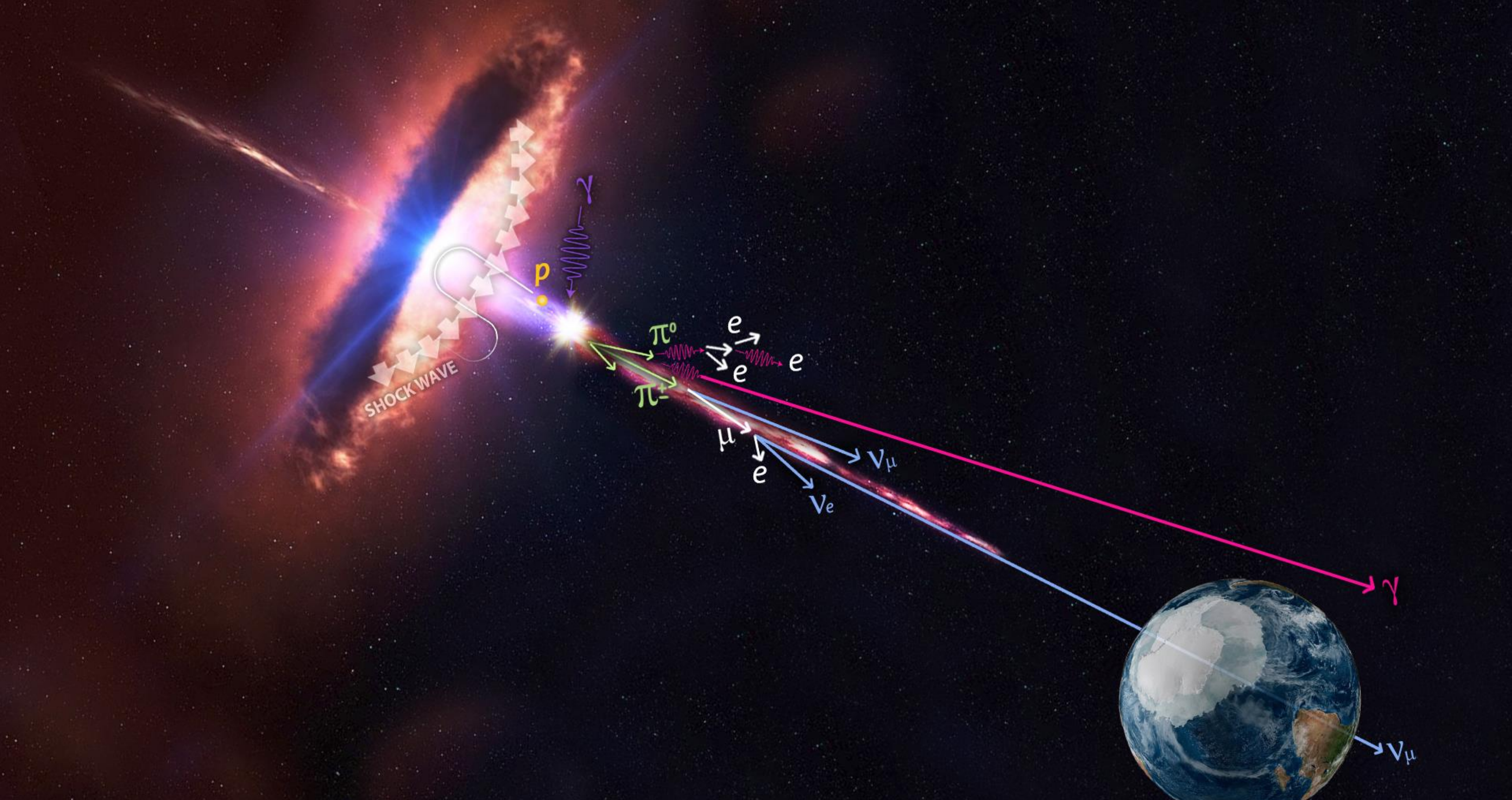
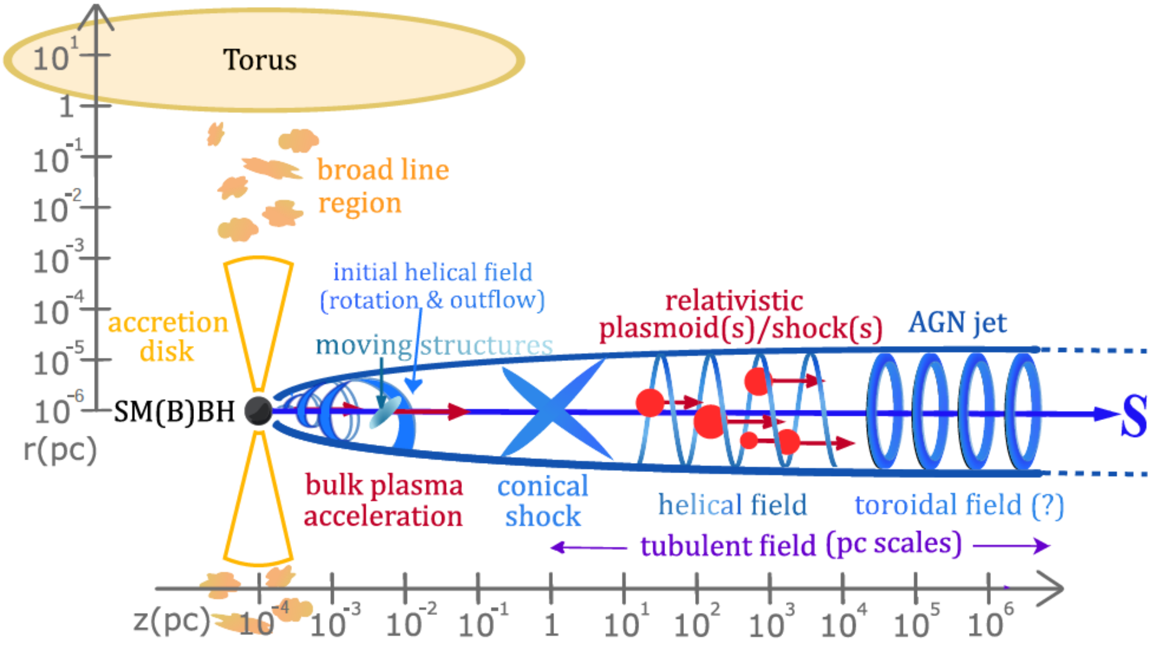
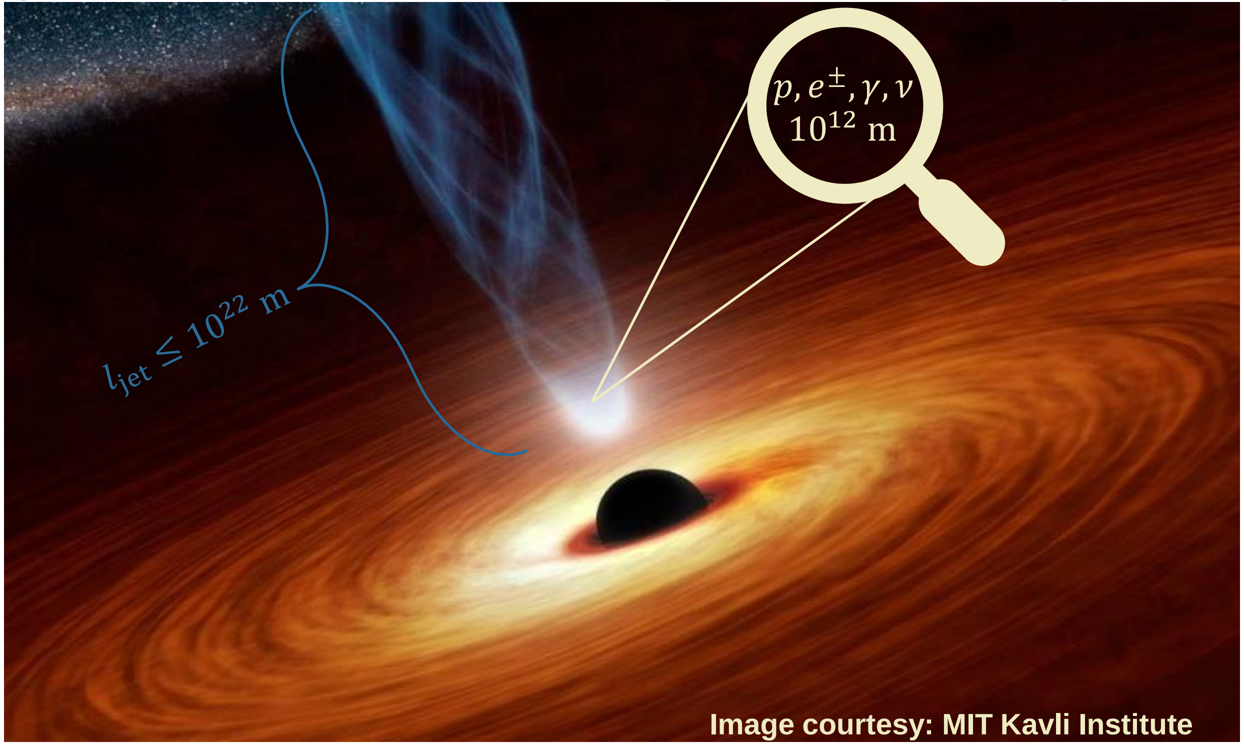


Image courtesy: IceCube Collaboration

Propagation in AGN Jets: Basic Structure



Challenges I – AGN Jet Length Scale Separation



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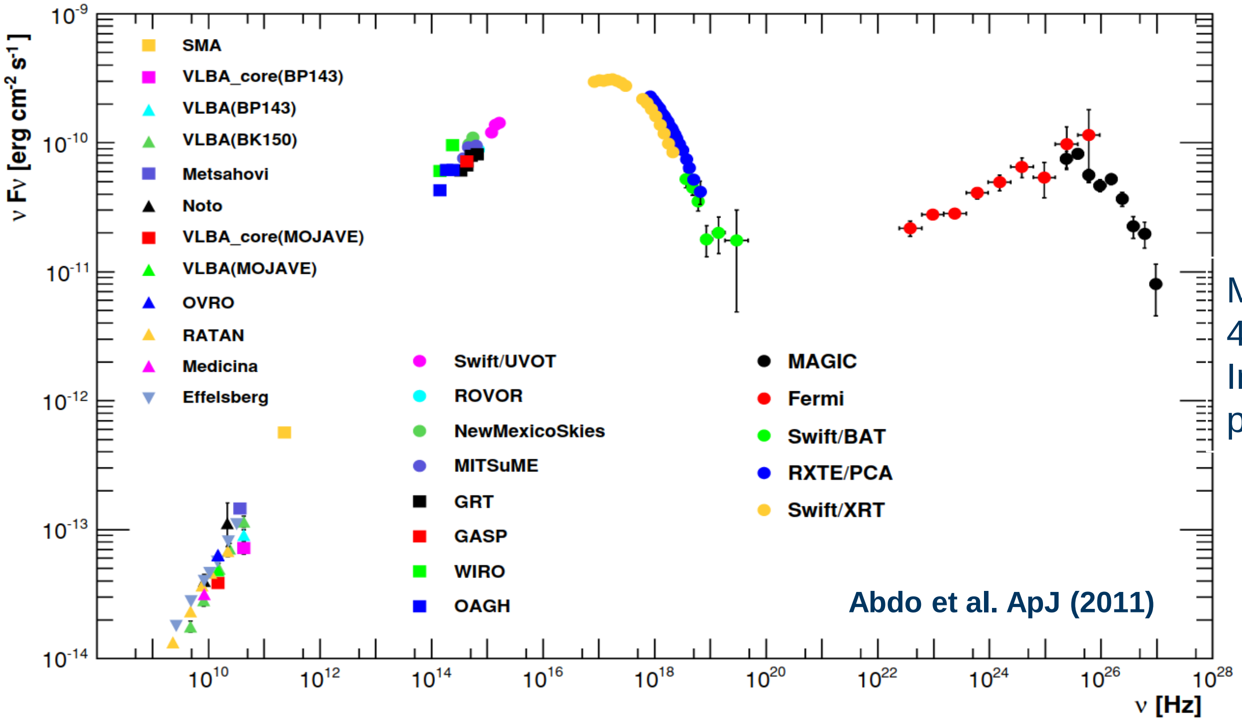
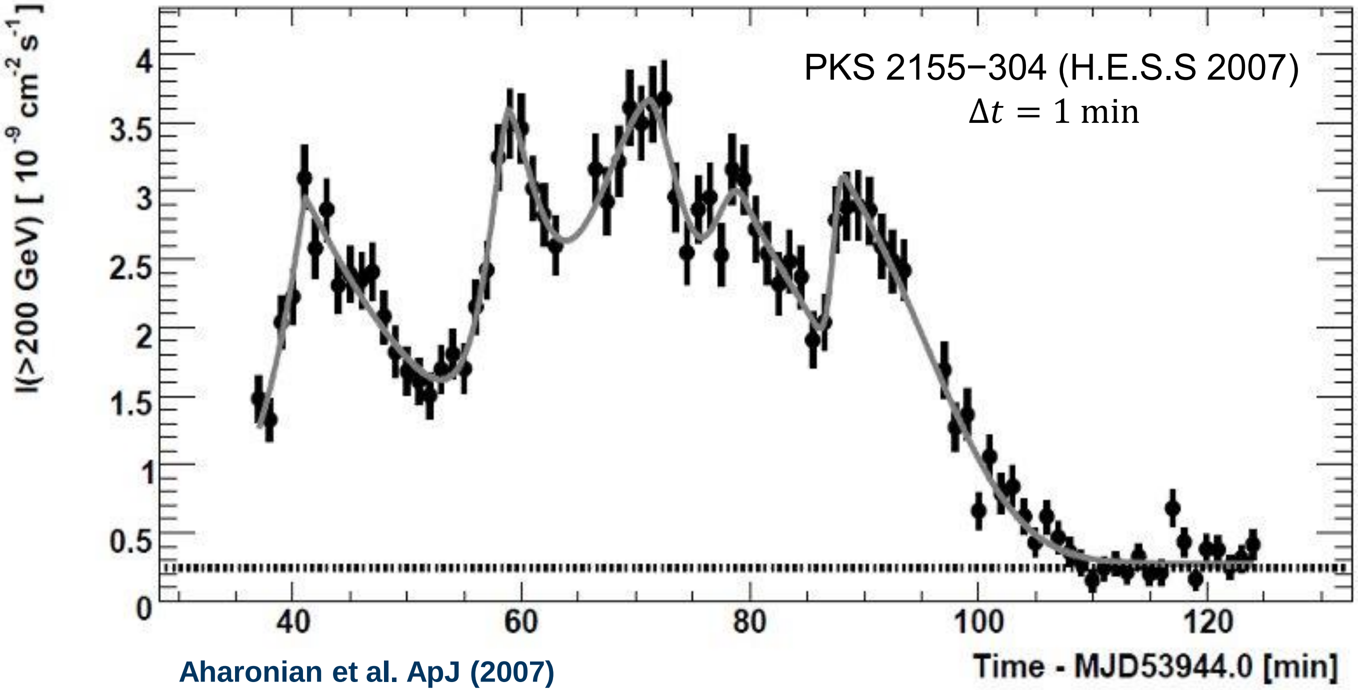
Challenges II – Energy Ranges (Multiwavelength)



Markarian 421:
4.5-month-MWL-survey.
Integrated timescale problematic!

Challenges III – Time Variability



Aharonian et al. ApJ (2007)

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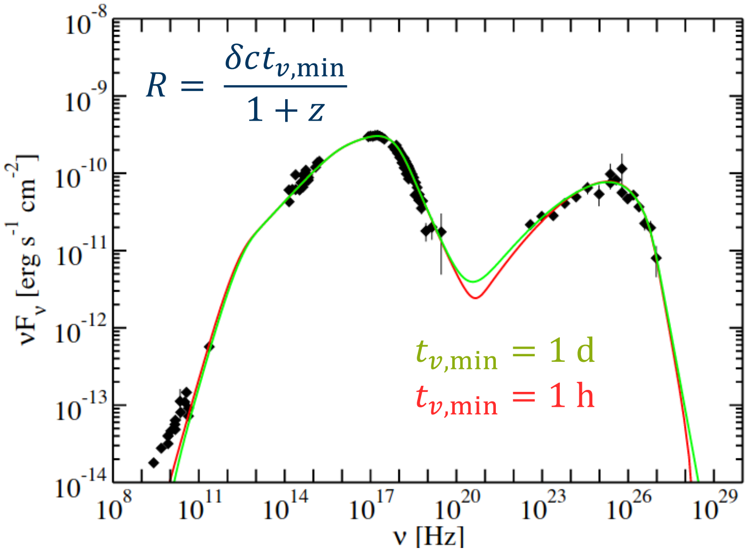
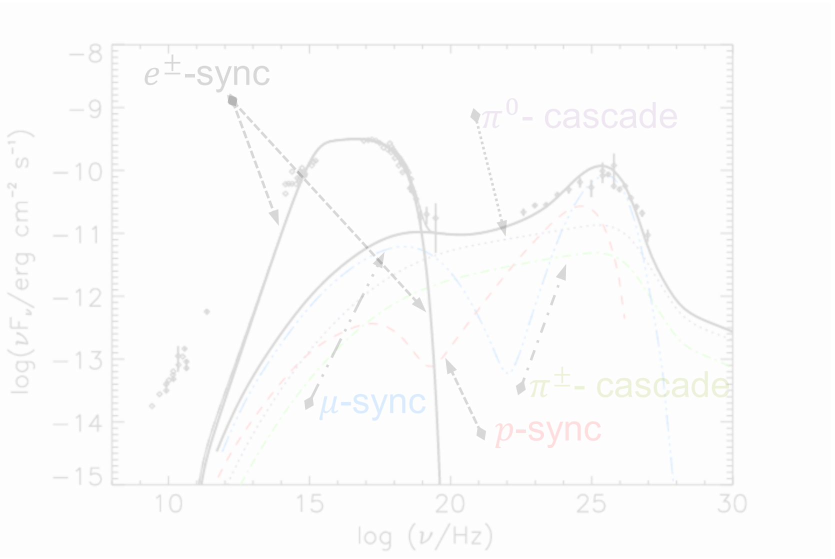
Challenges IV: Ambiguity of Signals



Leptonic SSC model for SED of Mrk 421



… same SED with hadronic model (for high-E bump)

Abdo et al. ApJ (2011)

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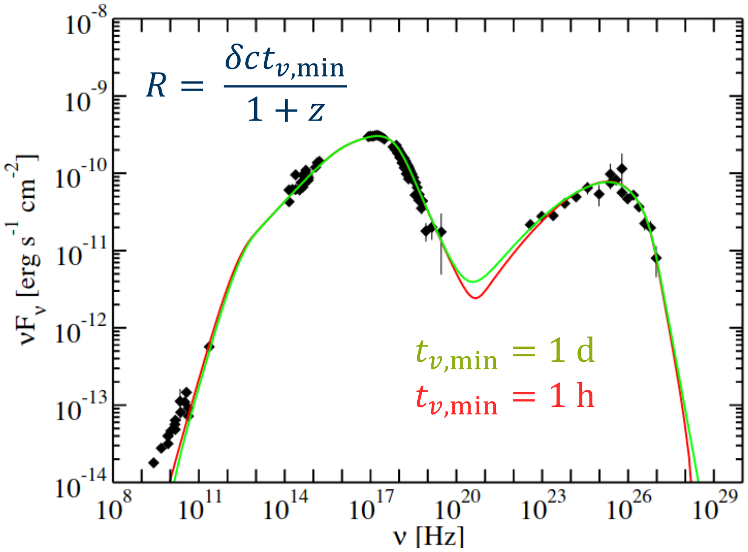
Challenges IV: Ambiguity of Signals



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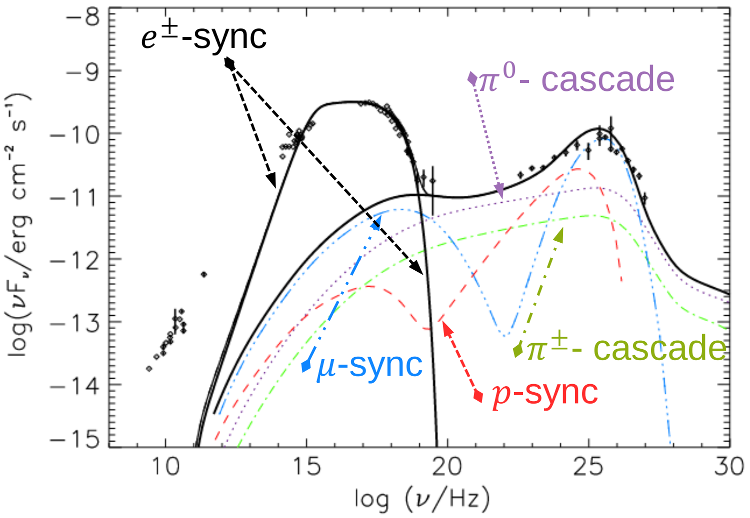
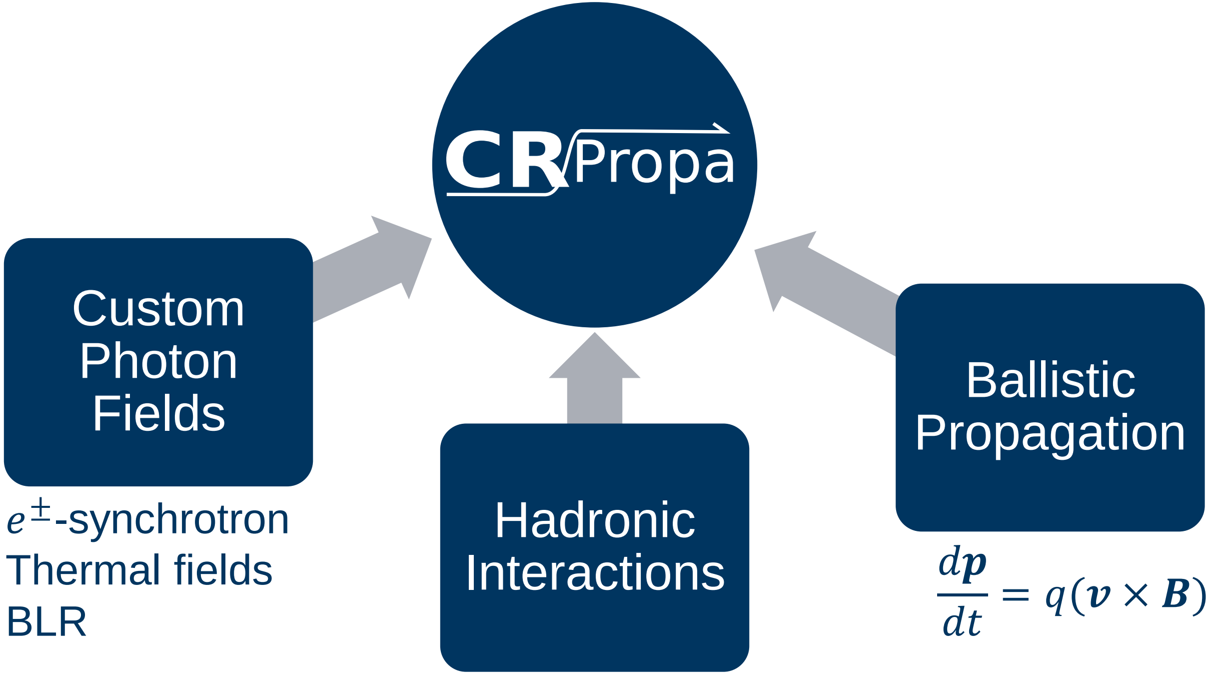


… same SED with hadronic model (for high-E bump)

Abdo et al. ApJ (2011)

Simulation Setup for AGN-Jet-Model



$e^{\pm}$-synchrotron
Thermal fields
BLR
…

$$pp \rightarrow X + \Sigma(\pi^{+} + \pi^{0})$$

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

Ref. CRPropa 3.2: Alves Batista et al. JCAP (2022)

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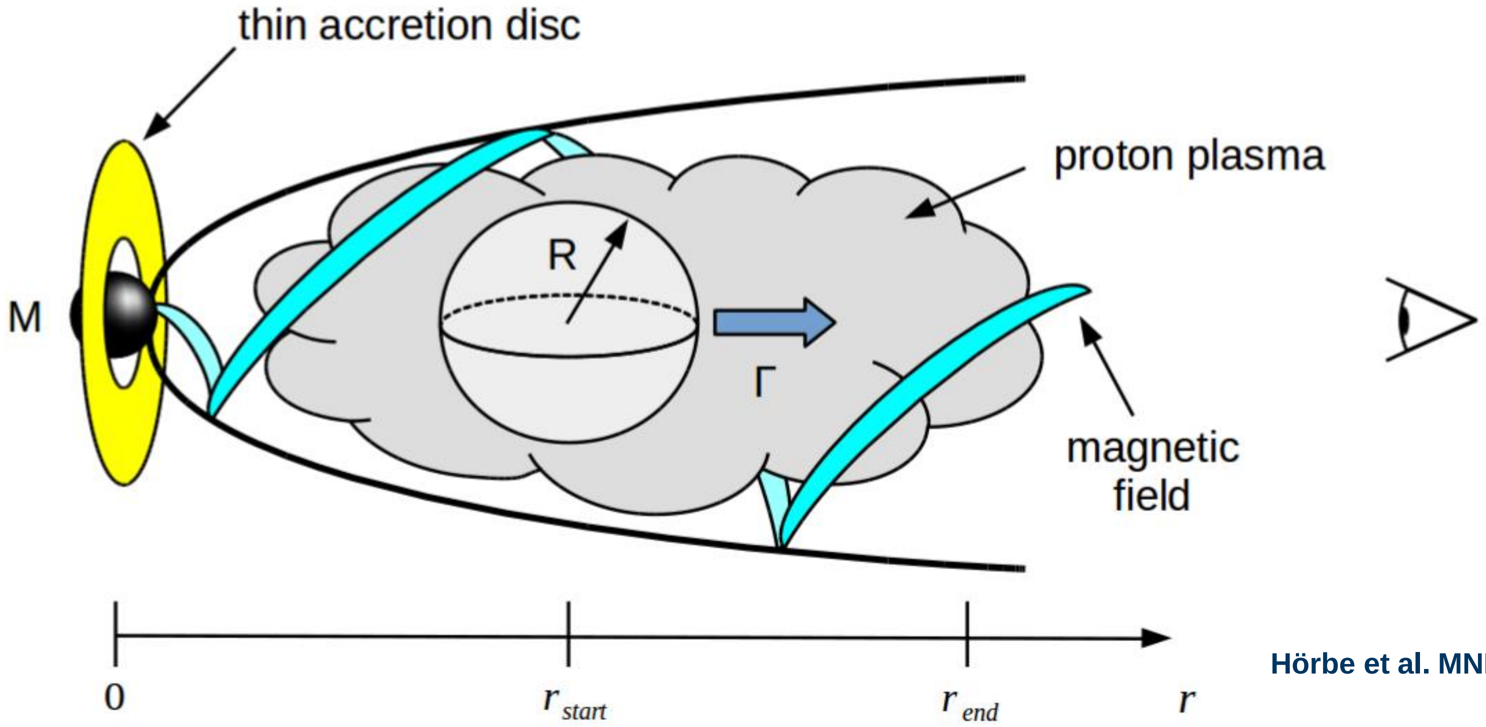
Setup: Scheme



Hörbe et al. MNRAS (2020)

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}	$r_{\text{start}} + 10$ pc
Plasmoid Lorentz Factor	Γ	10
Magnetic Field Initial RMS Value	B_0	1 G
Proton (primary) Initial Energy	$E_{p,\text{inj}}$	10^8 GeV
Proton Target Density (up-scaled)	$n_{0,\text{plasma}}$	10^{15} m^{-3}
Electron Minimal Lorentz Factor	$\gamma_{e,\text{min}}$	10
Electron Maximal Lorentz Factor	$\gamma_{e,\text{max}}$	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)

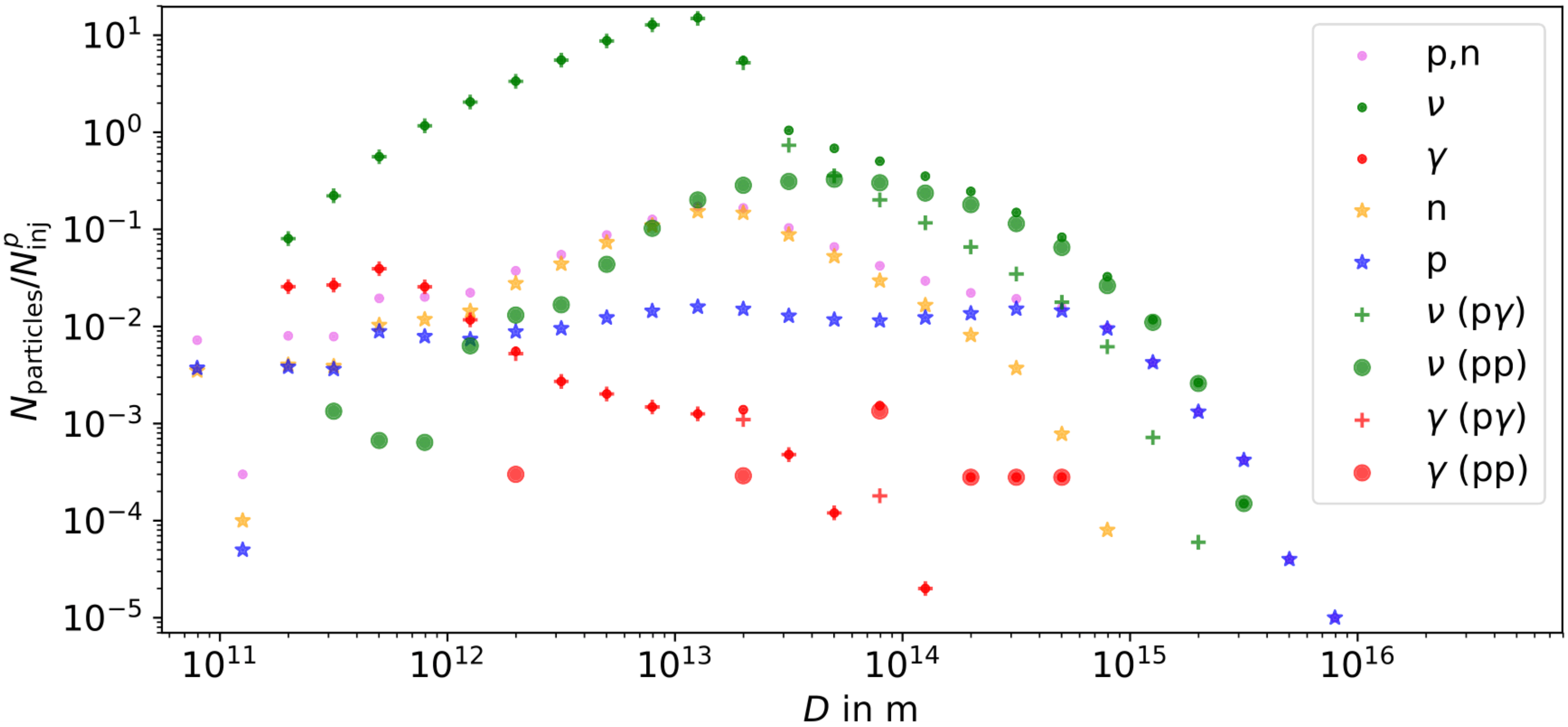
Assumptions:

- 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

Results: Combined Messengers (Pure Hadronic)



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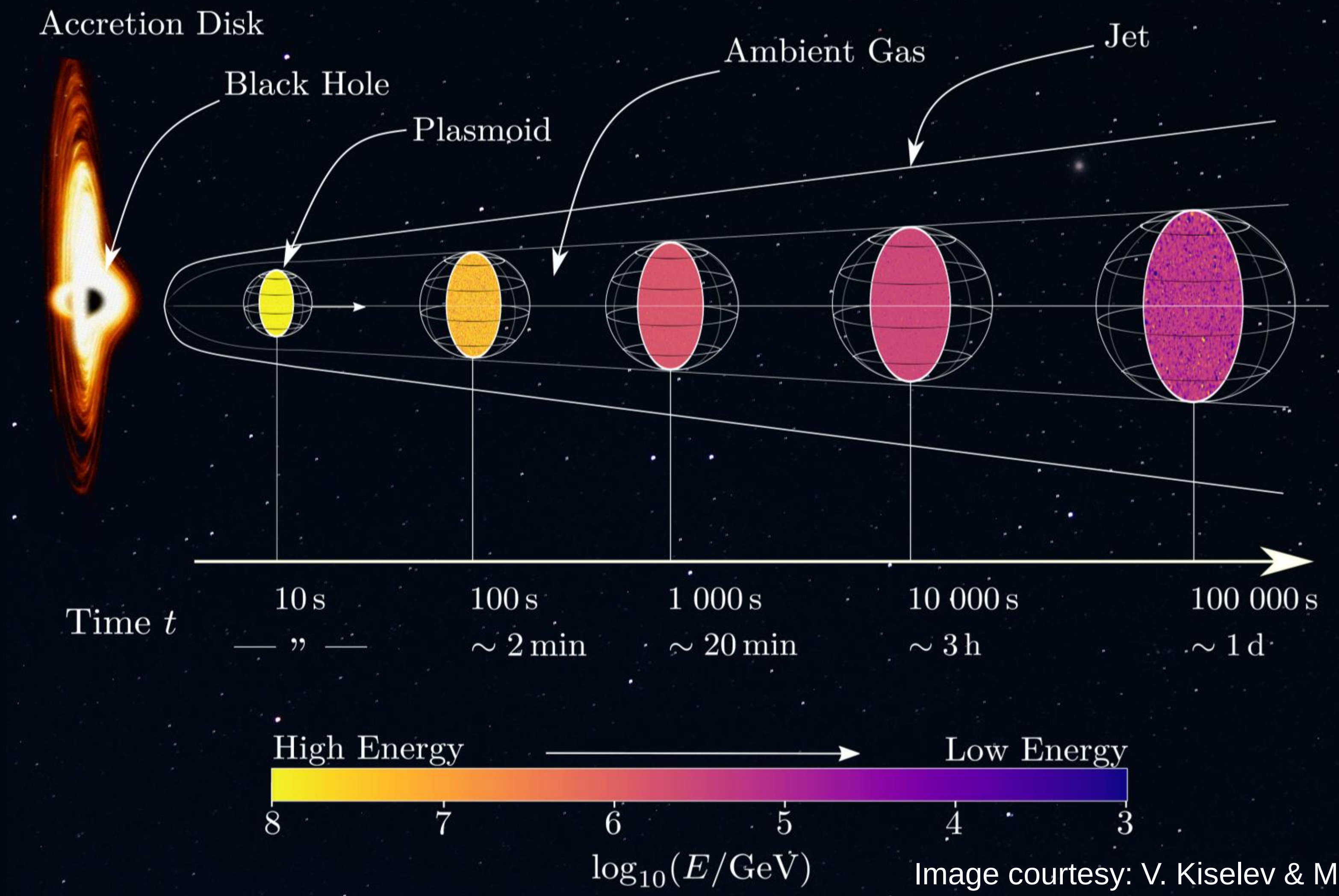

Image courtesy: V. Kiselev & MS

Time & Density Dependence: Current Projects

Different, each promising approaches to MM modelling of AGN jets exist

General approach:

- **Solve transport problem via FP-equation**
- **Impose energy losses and secondary particle production, find steady-state solution wrt. injection & escape**
- **Goal: Fit model parameters to SED and lightcurves - Simultaneously (!)**

Code	AM^3	PARIS	ATHEνA	Böttcher	CRPropa	**AGNPropa**
Reference	Gao et al. (2017)	Cerruti et al. (2015)	Dimitrakoudis et al. (2012)	Böttcher et al. (2013)	[3]	**CIM-Development**
Transport equation	yes	yes	yes	yes	yes	yes
Ballistic	no	no	no	no	yes	yes
steady state	yes	yes	yes	yes	yes	yes
time dependent	yes	no	yes	no	yes	yes
B-field	turbulent (isotropic)	turbulent (isotropic)	turbulent (isotropic)	turbulent (isotropic)	turbulent (isotropic), regular (helical)	turbulent (isotropic, **anisotropic, intermittent**); regular (helical)
Diffusion	1-dim	1-dim	1-dim	1-dim	1-dim	**3-dim**
Photohadron	yes	yes	yes	yes	yes	yes
Hadron-hadron	no	no	no	no	yes	**yes (F4)**
Prompt component	no	no	no	no	no	**yes (F3)**

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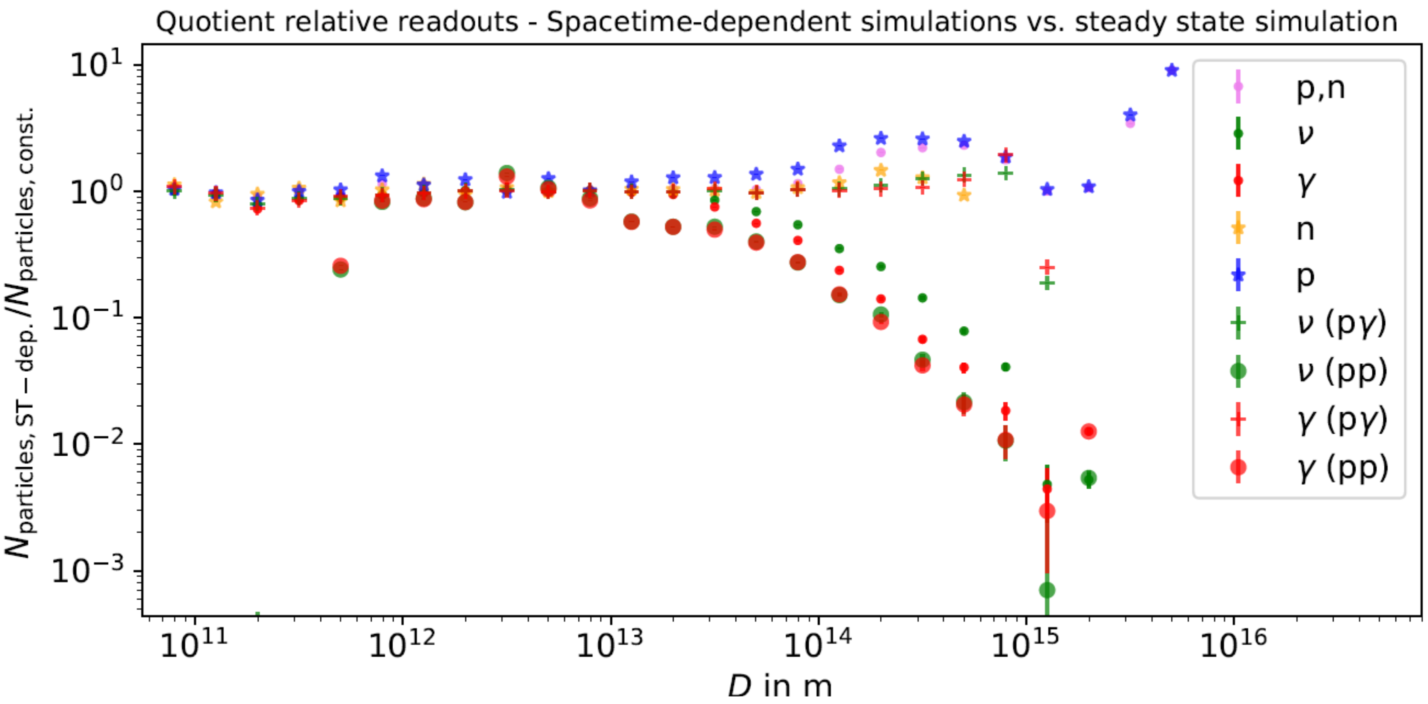
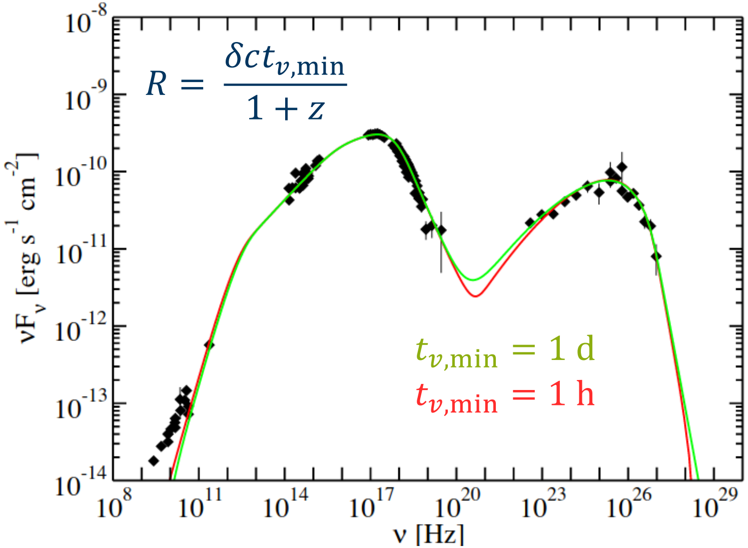
Time & Density Dependence: A Comparison



Callback: Ambiguity of Signals



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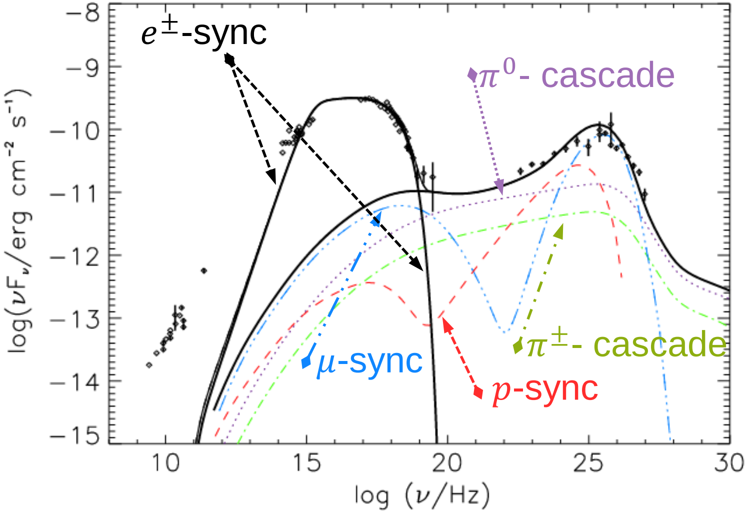

… same SED with hadronic model (for high-E bump)

Abdo et al. ApJ (2011)

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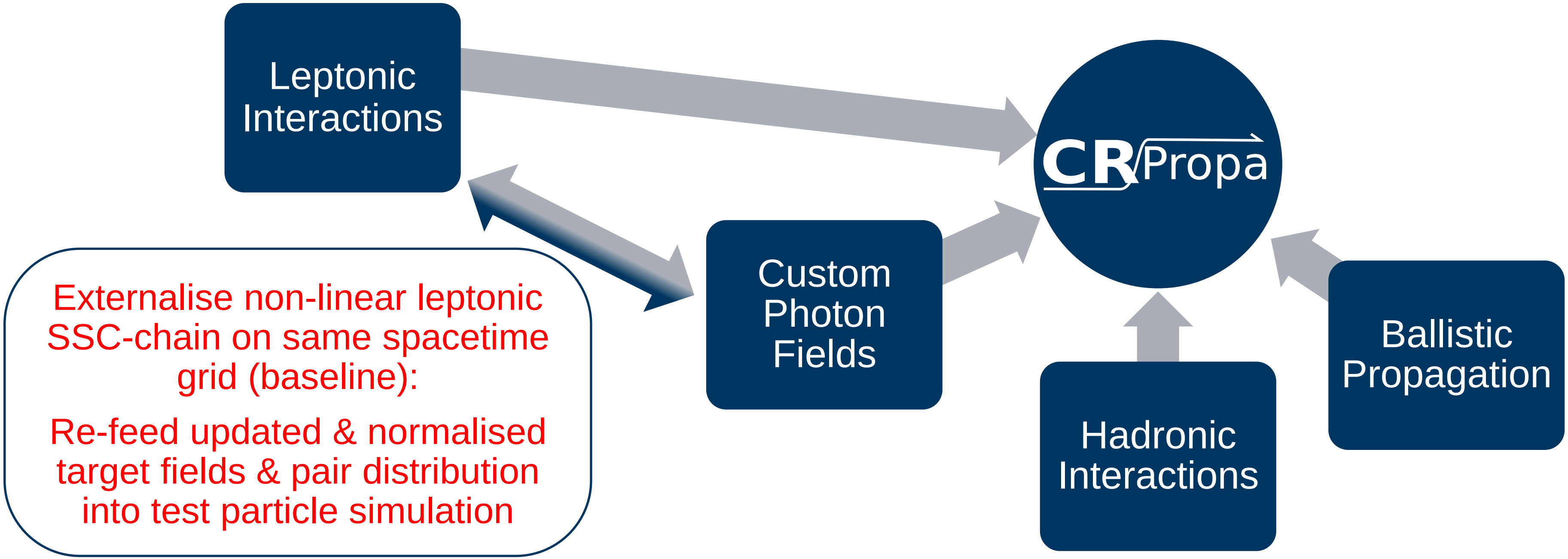
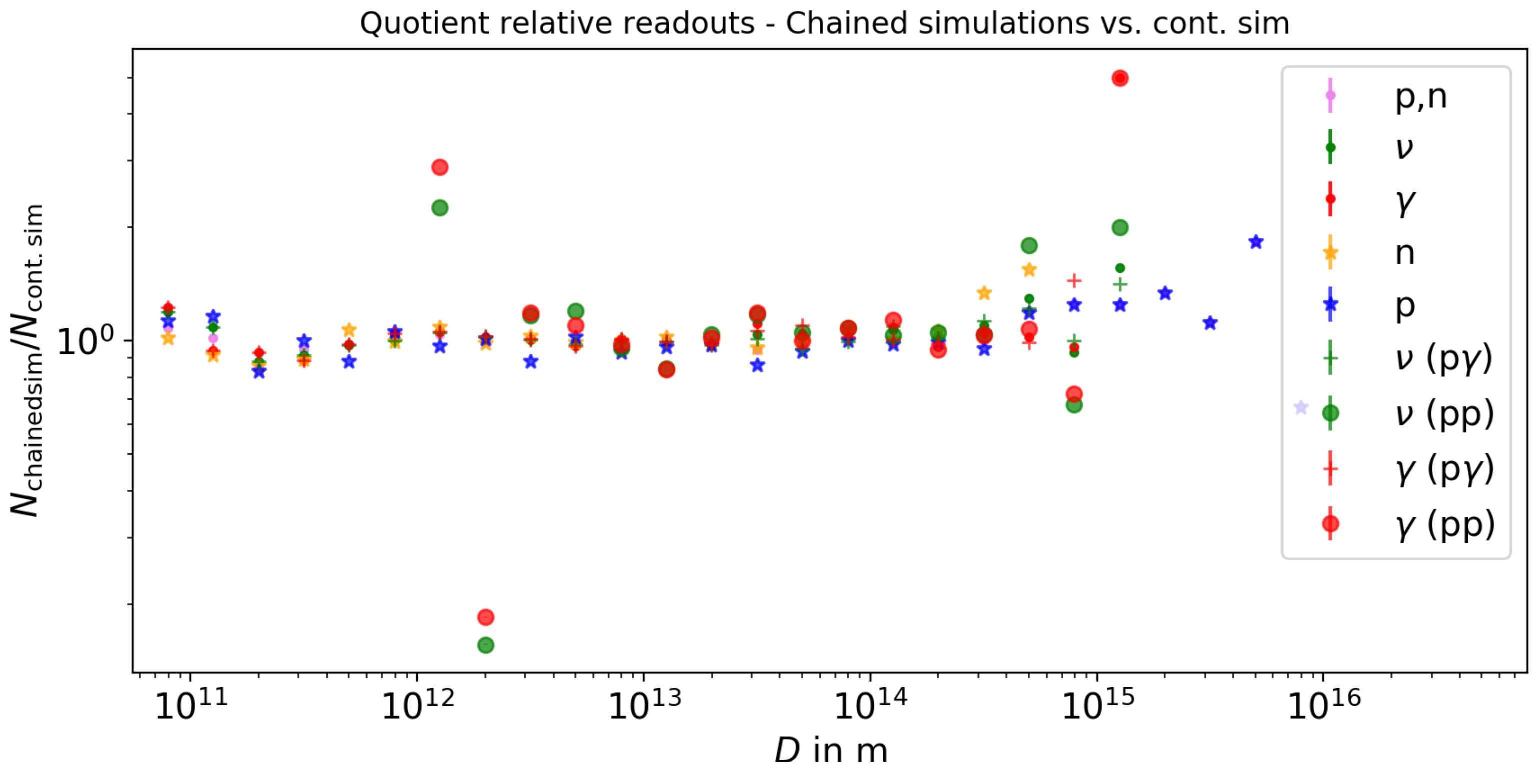
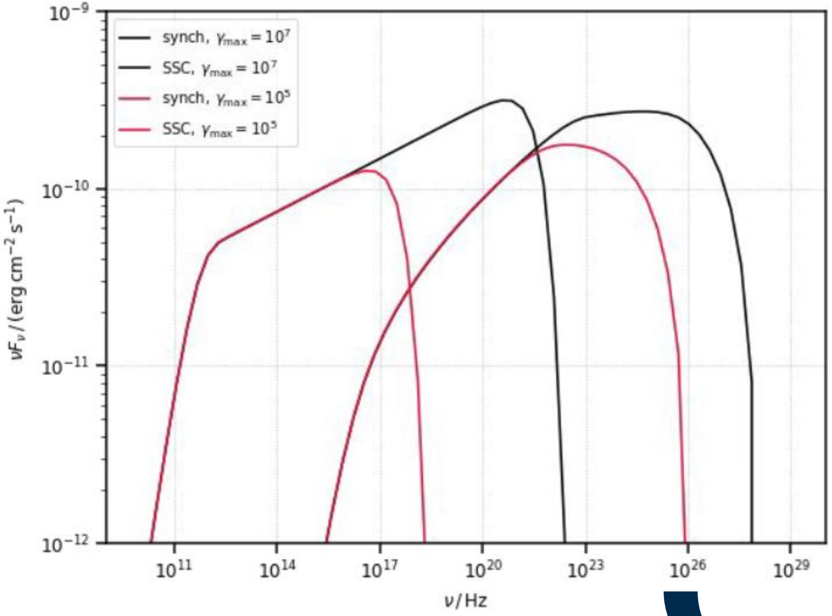
Extension to Lepto-Hadronic Simulations





Quotient relative readouts - Chained simulations vs. cont. sim
$N_{\text{chainedsim}}/N_{\text{cont. sim}}$
10^0
10^{11}
10^{12}
10^{13}
10^{14}
10^{15}
10^{16}
D in m
p,n
ν
γ
n
p
ν (pγ)
ν (pp)
γ (pγ)
γ (pp)

Extension to Lepto-Hadronic Simulations



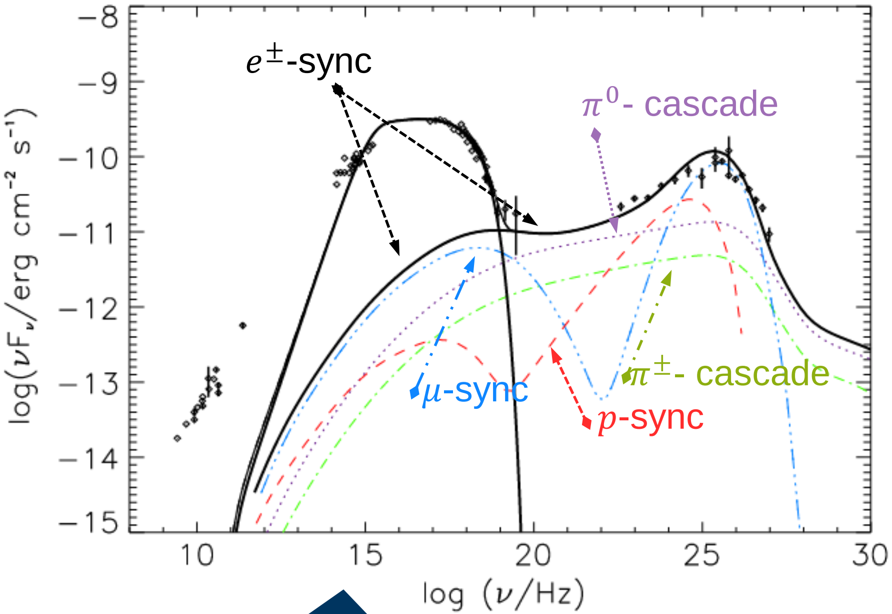


Figure courtesy: C. Nigro (OSS AGNPy following Dermer & Menon)

Abdo et al. ApJ (2011)

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]

Becker Tjus, …, MS et al. MDPI Physics (2022) arXiv:2202.01818

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

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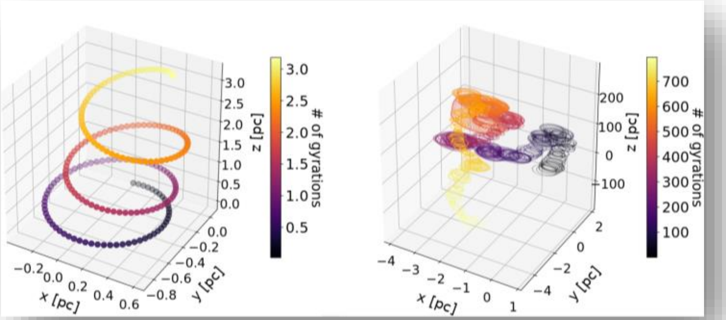
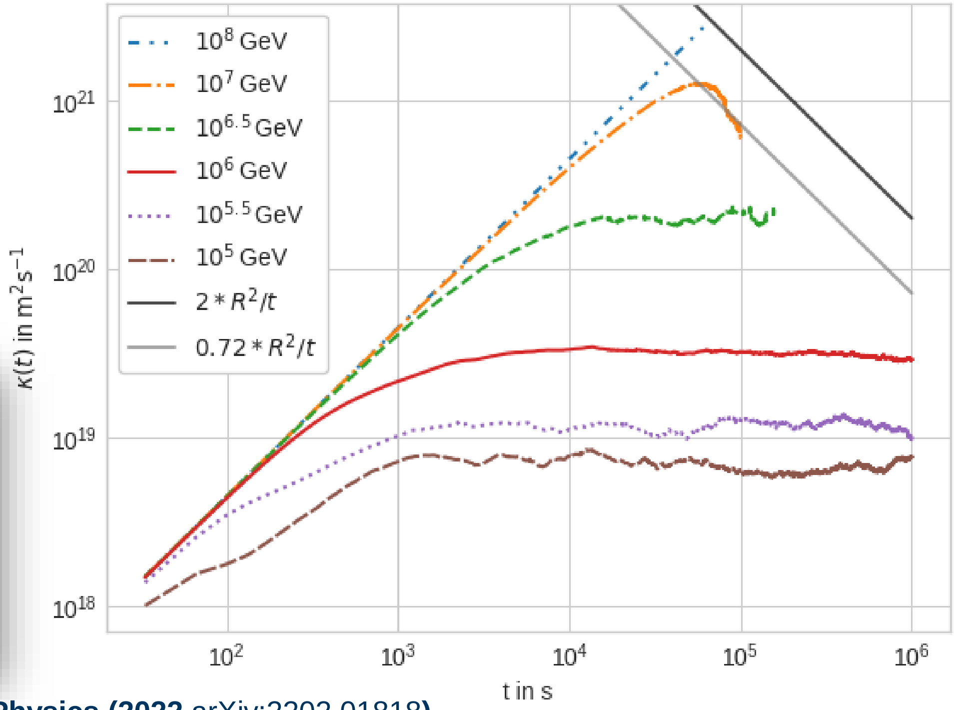
Transport: Diffusion Coefficients

- 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: B.Thesis **V. Kiselev**)





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

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Summary

- **Additional modifications in terms of additional/improved photon fields and density structures are implemented.**
- **Extension of established test-particle simulation framework for hadrons in AGN jet plasmoids to second-order leptonic processes is in progress.**
- **Validation via a lot of testing with existing numerical and semi-analytical models for one-zone problems is inbound, so stay tuned!**
- **Propagational effects on signatures are investigated, with first promising results.**

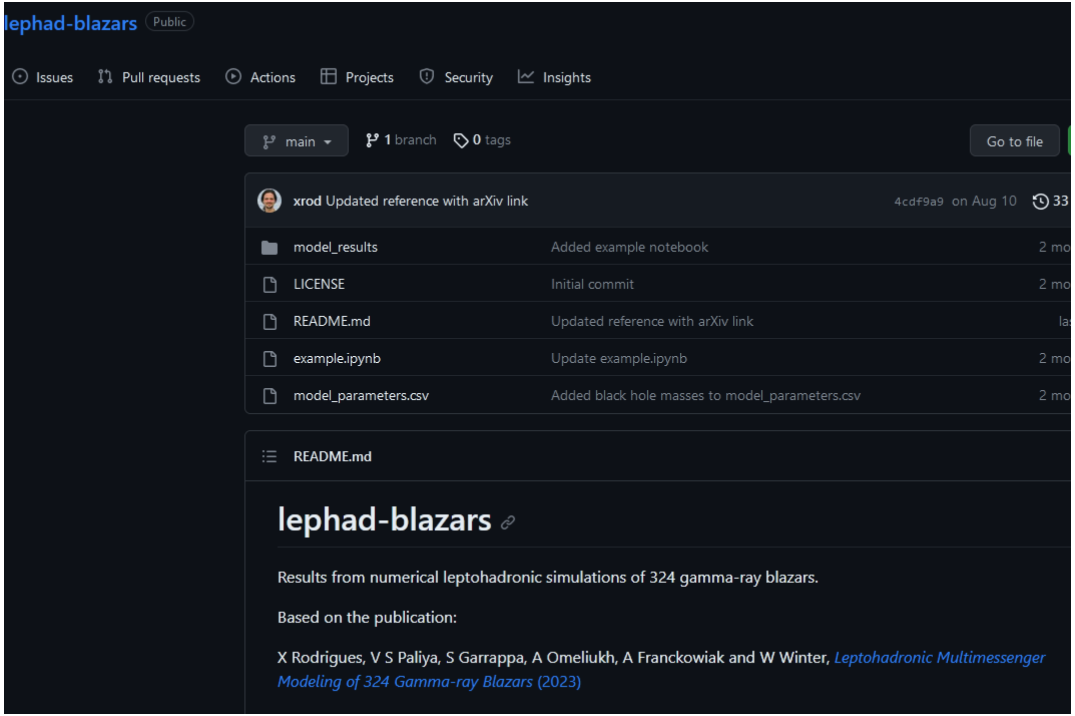
Glad to take questions!

Image courtesy: IceCube Collaboration

Contact: marcel.schroller@ruhr-uni-bochum.de

BACKUP

State-of-the-Art catalogue: LepHad-Blazars



- 324 gamma-ray Fermi blazar SEDs modeled by **X. Rodrigues et al. (arXiv 2307.13024)**
- Approach for finding parameters:
  - Simulate purely leptonic one-zone model in e.g. IR, optical, UV, GeV range, find parameter
  - Superimpose hadronic signatures for $f \geq 300$ GHz
  - Then: Combined fit of parameters for all wavelengths

- Suitable for detailed comparisons!

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Parameter Space

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	$10\ \mathrm{eV/k}_b$

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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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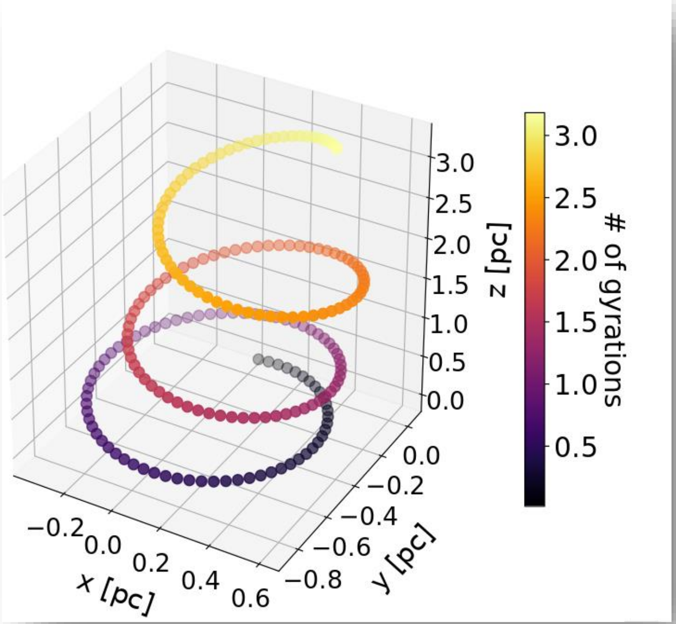
Propagation and energy: comparison parameter

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

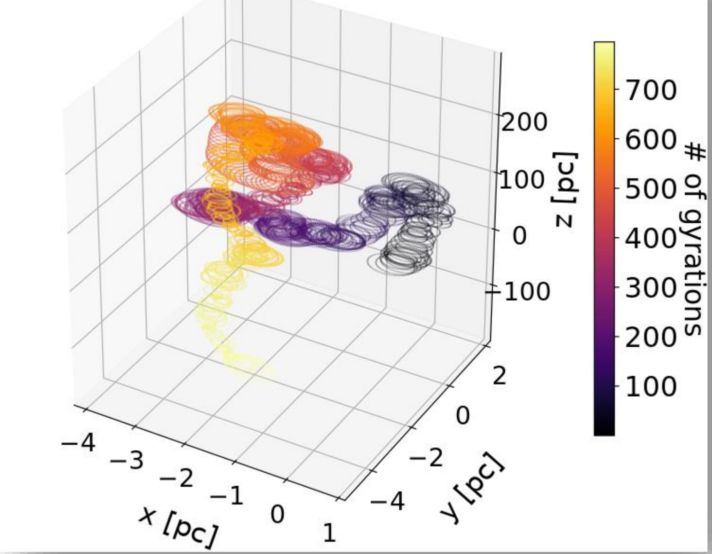
Propagation Effects

Transport in Turbulent Fields: Ballistic vs. Diffusive



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

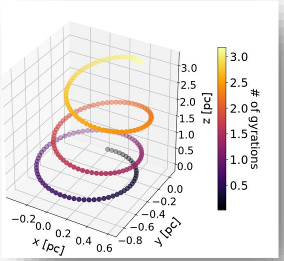
Masterthesis P. Reichherzer (2019)

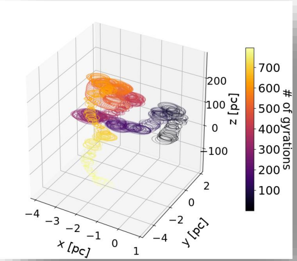


$$\frac{\delta n}{\delta t} = \nabla \cdot \left(\hat{D} \cdot \nabla n\right) - \vec{u} \cdot \nabla n + Q$$

Transport: Running Diffusion Coefficient

Particle Trajectory Data



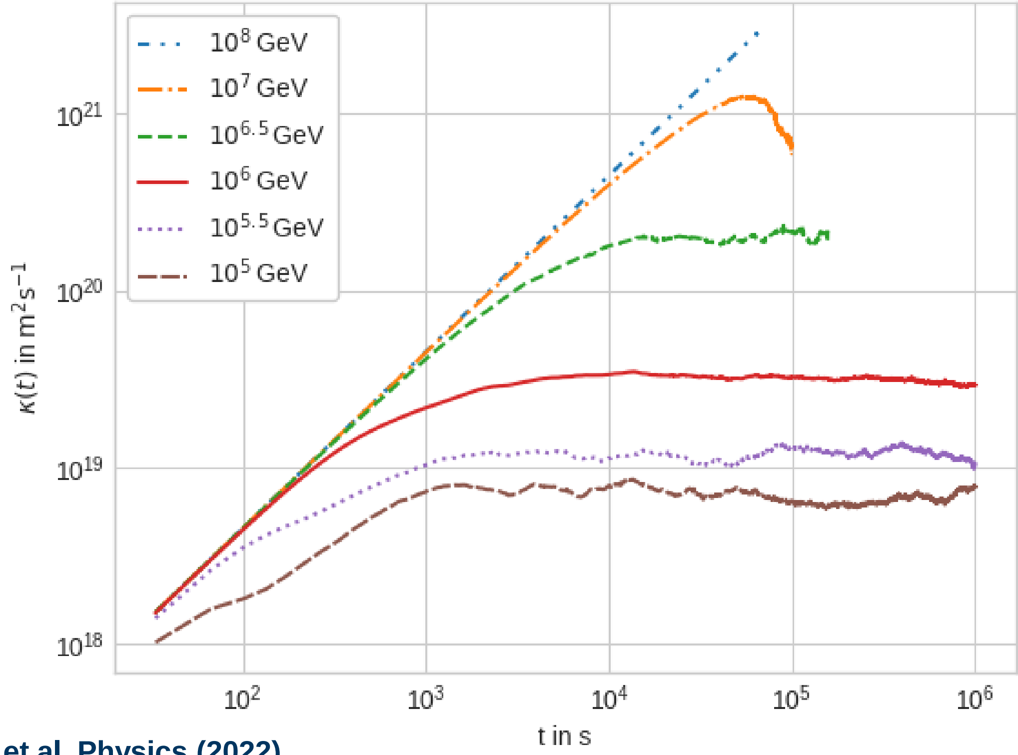


→ Ensemble Averaging at t_i

→ Running Diffusion Coefficient $\kappa(t_i)$

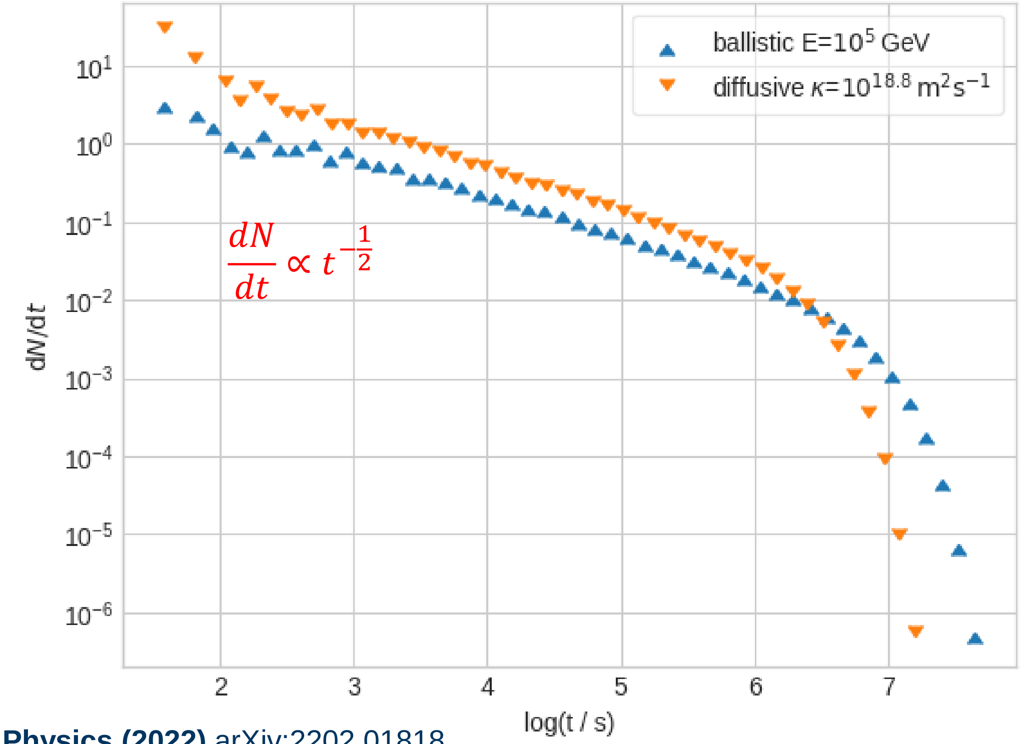
$$\kappa(t_i) = \frac{< r(t_i) - r(t_0) >^2_{\text{particles}}}{2t_i}$$

Setup: Results (Running Diffusion Coefficient)



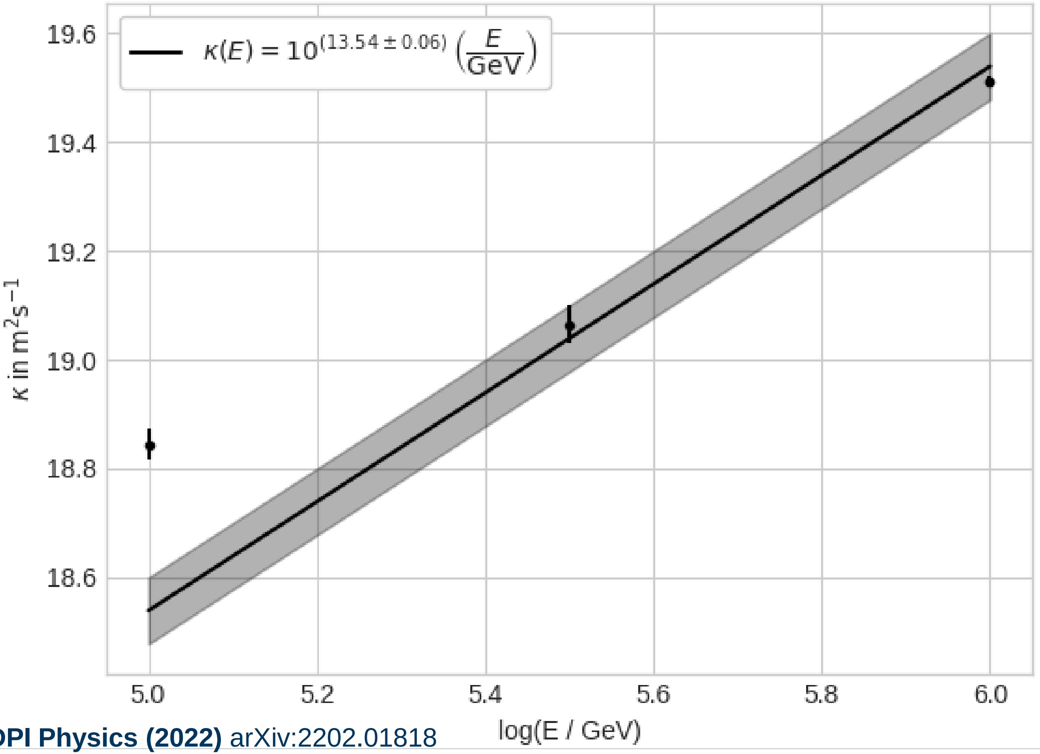
Becker-Tjus et al. Physics (2022)

Propagation Effects: Comparison @ 10^5 GeV



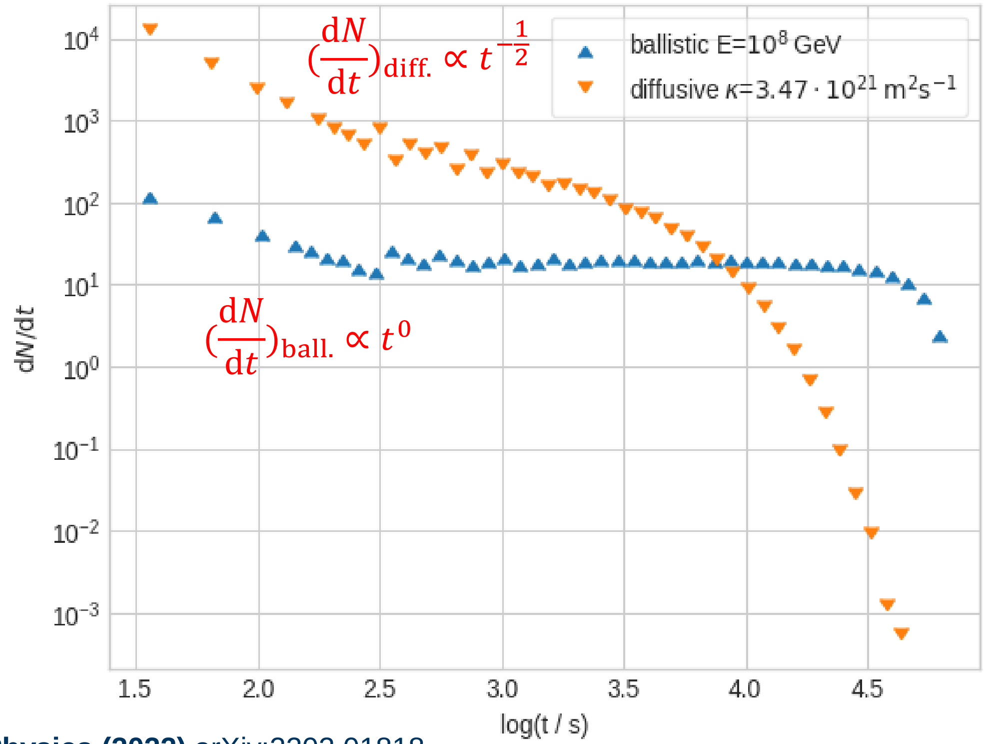
Becker-Tjus et al. MDPI Physics (2022) arXiv:2202.01818

Setup: Results (Diffusion Coefficients)



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

Propagation Effects: Comparison @ 10^8 GeV



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

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