

RUHR-UNIVERSITÄT BOCHUM

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**LOCAL SOURCE PHYSICS WITH CRPROPA - EXTENDING TEST PARTICLE
SIMULATIONS FOR MODELLING LEPTOHADRONIC AGN JETS**

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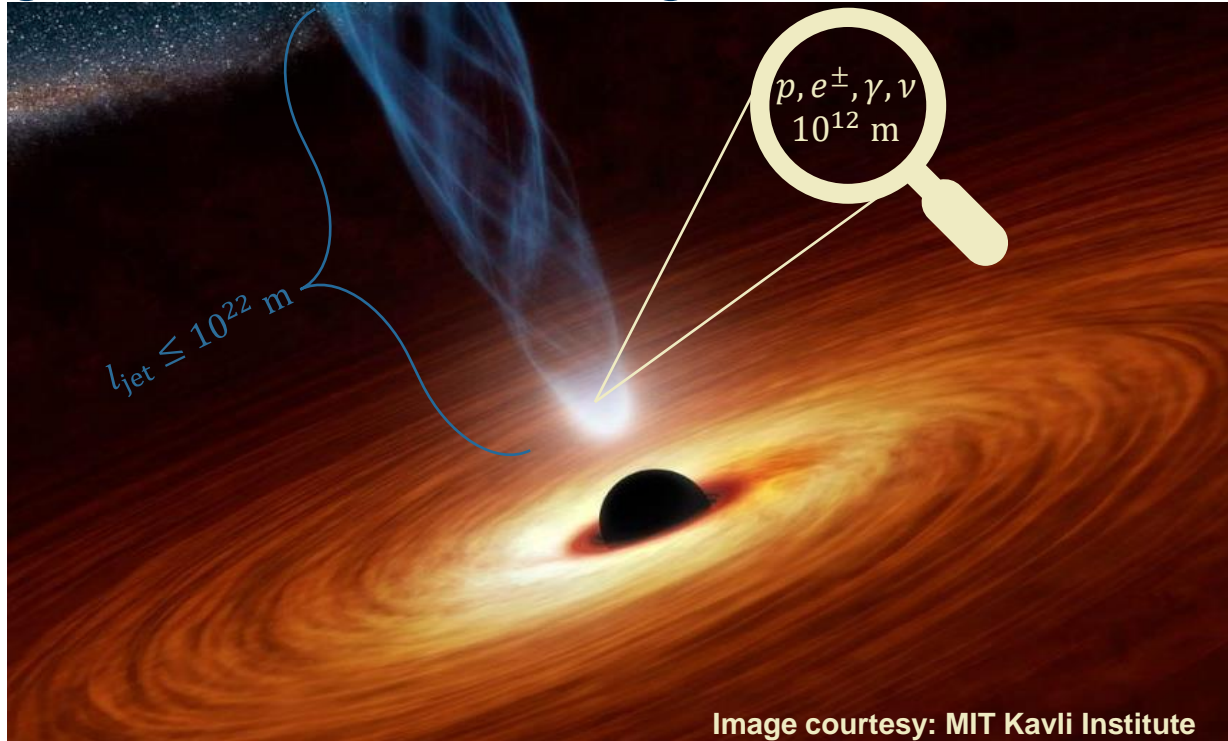
CRPropa Workshop 2023



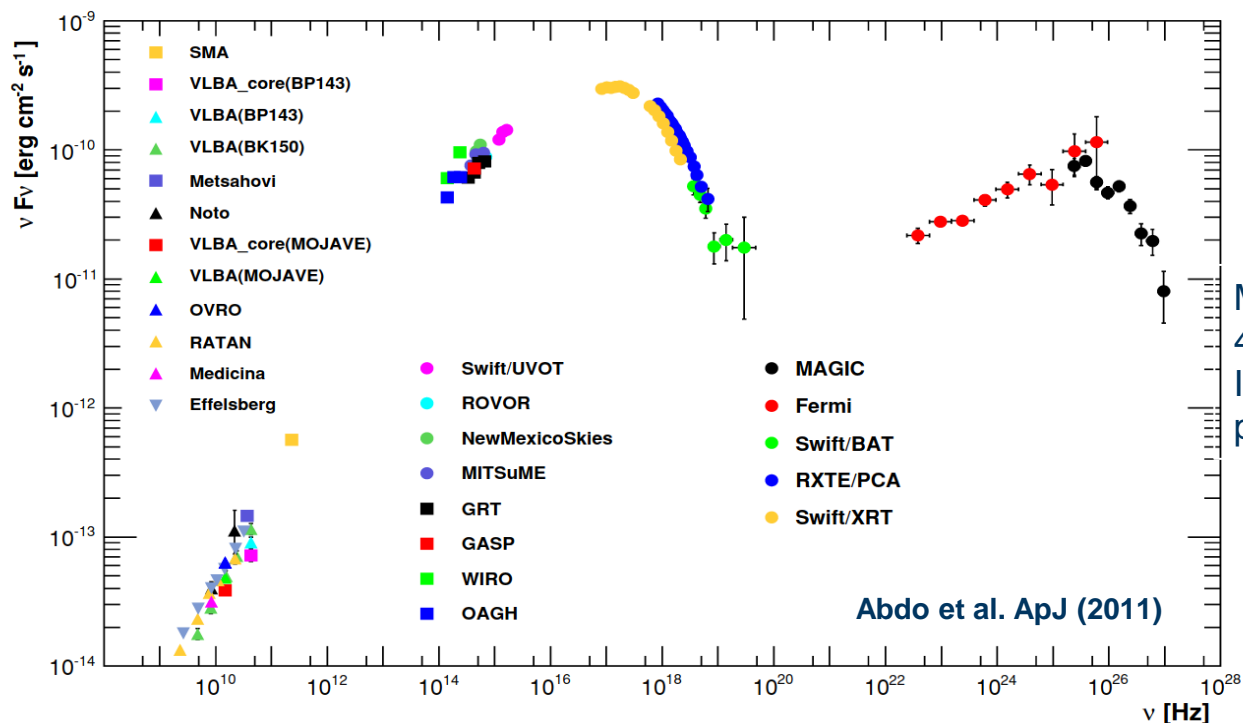


Image courtesy: IceCube Collaboration

Challenges I – AGN Jet Length Scales

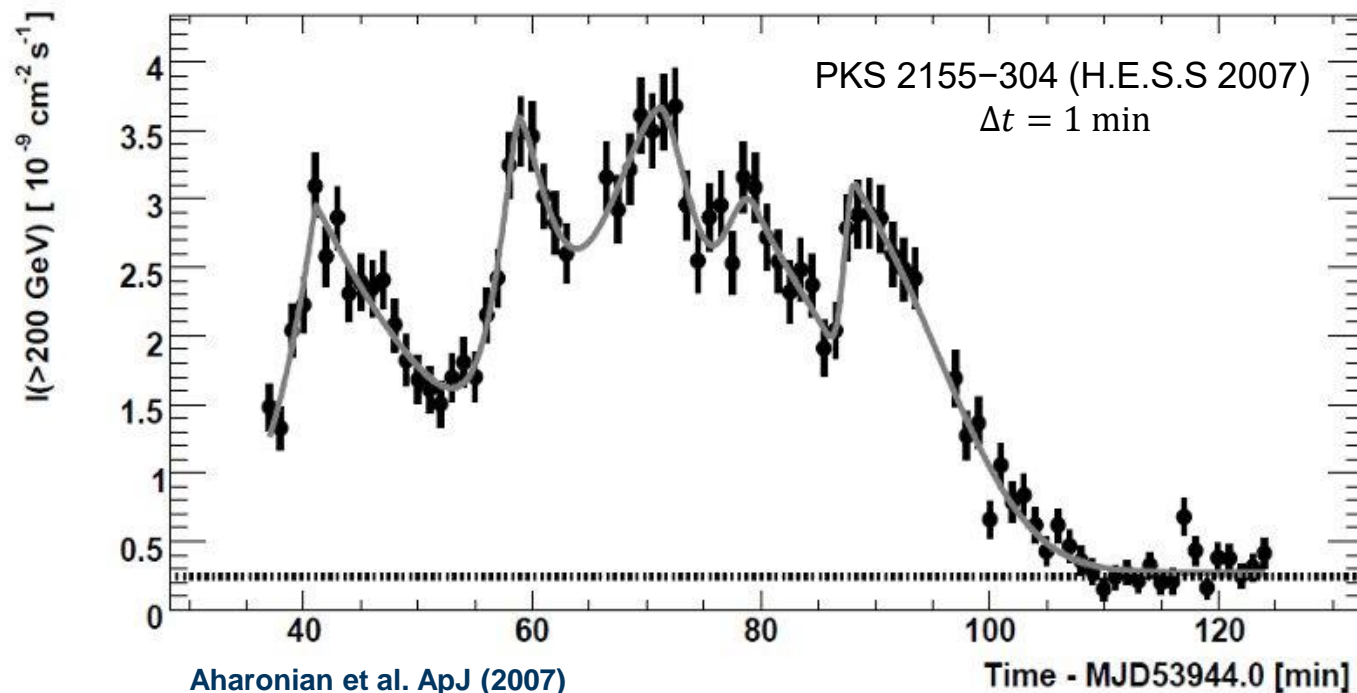


Challenges II – Energy Ranges (Multiwavelength)

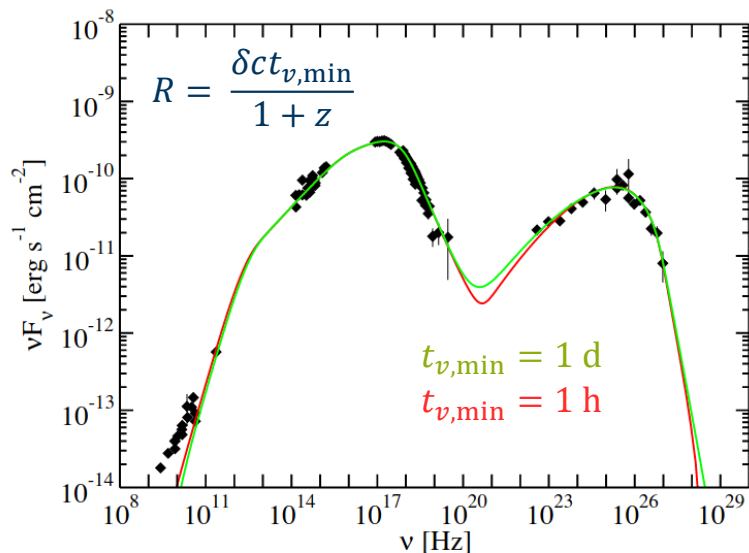


Markarian 421:
4.5-month-MWL-survey.
Integrated timescale
problematic!

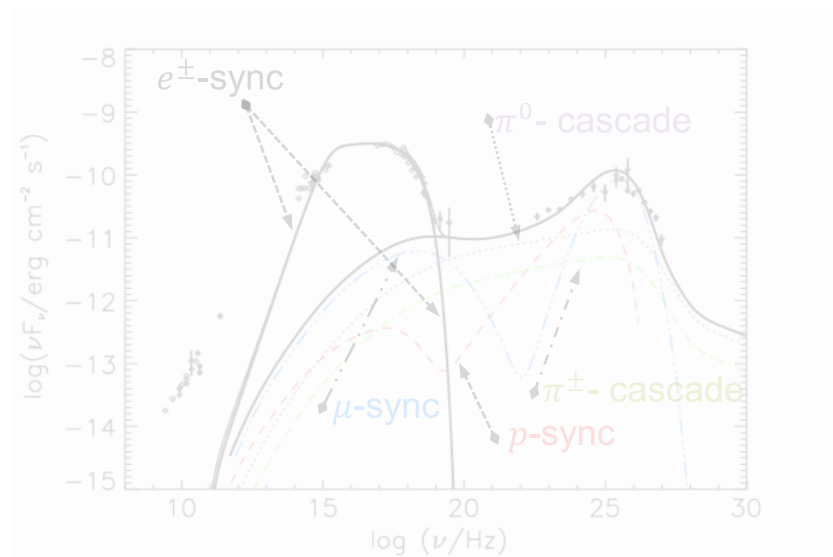
Challenges III – Time Variability



Challenges IV: Ambiguity of Signals



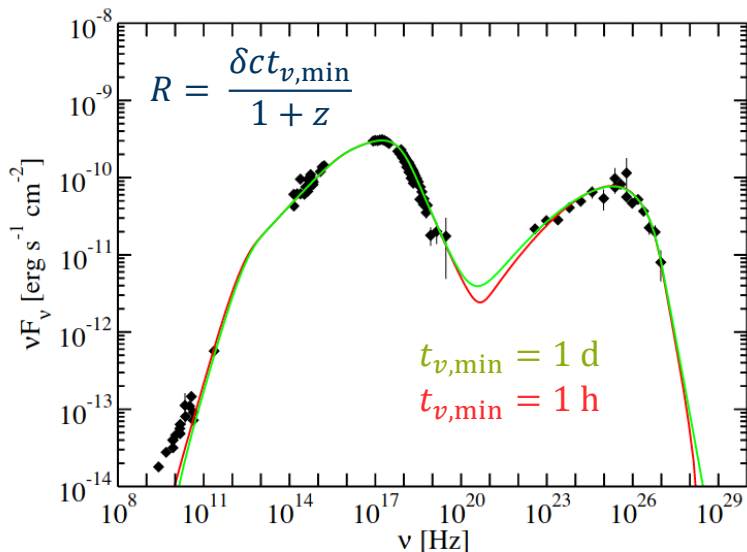
Leptonic SSC model for SED of Mrk 421



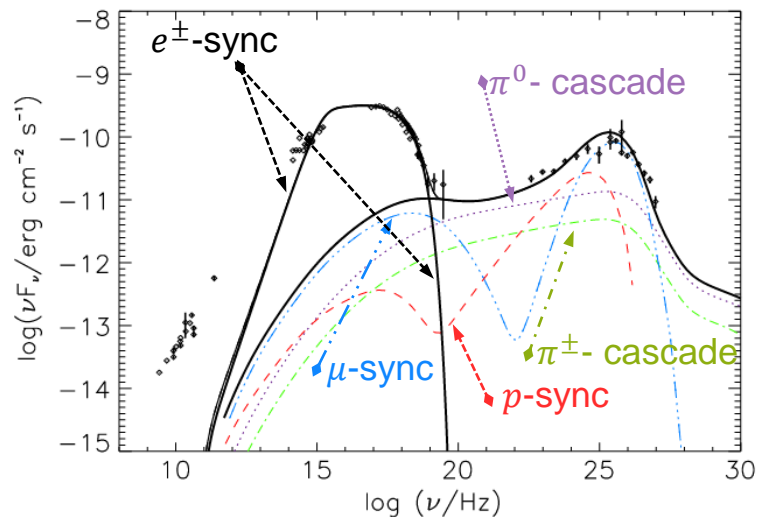
... same SED with hadronic model (for high-E bump)

Abdo et al. ApJ (2011)

Challenges IV: Ambiguity of Signals



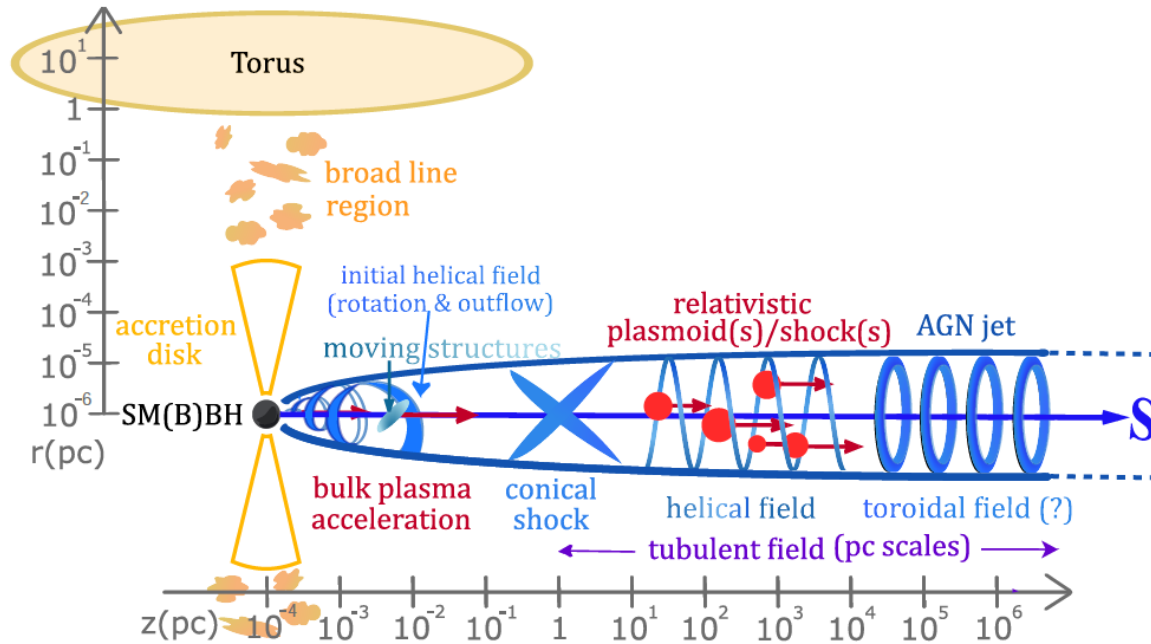
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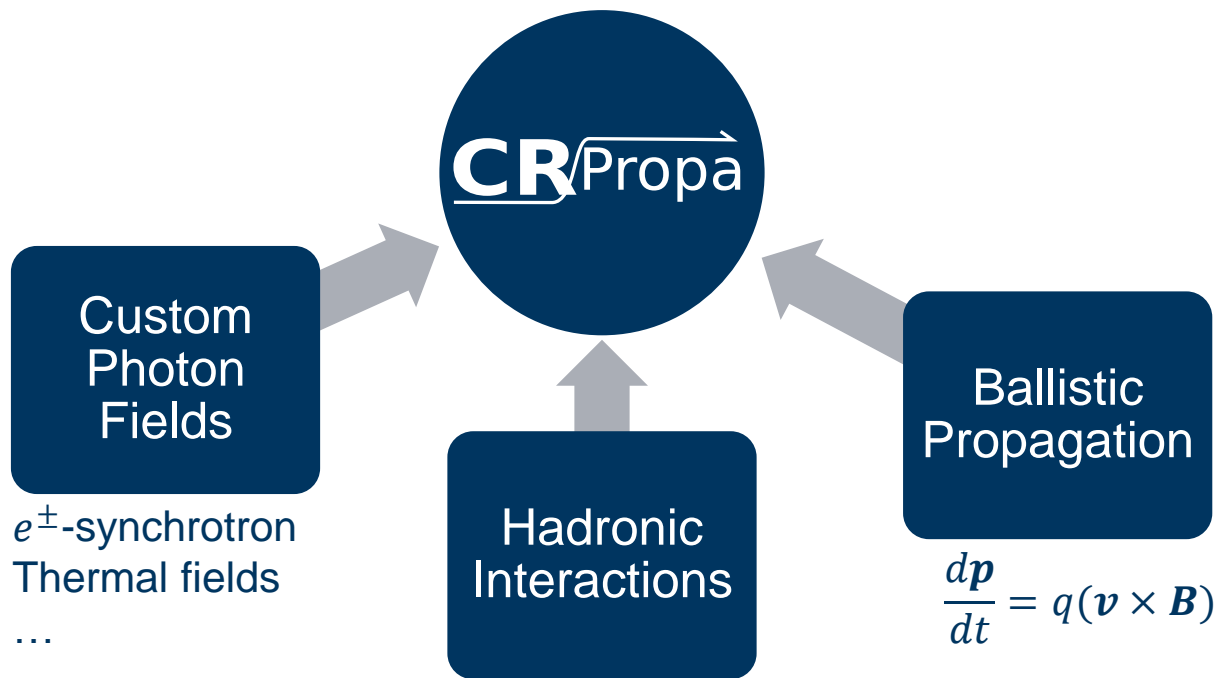
... same SED with hadronic model (for high-E bump)

Abdo et al. ApJ (2011)

Propagation in AGN Jets: Basic Structure

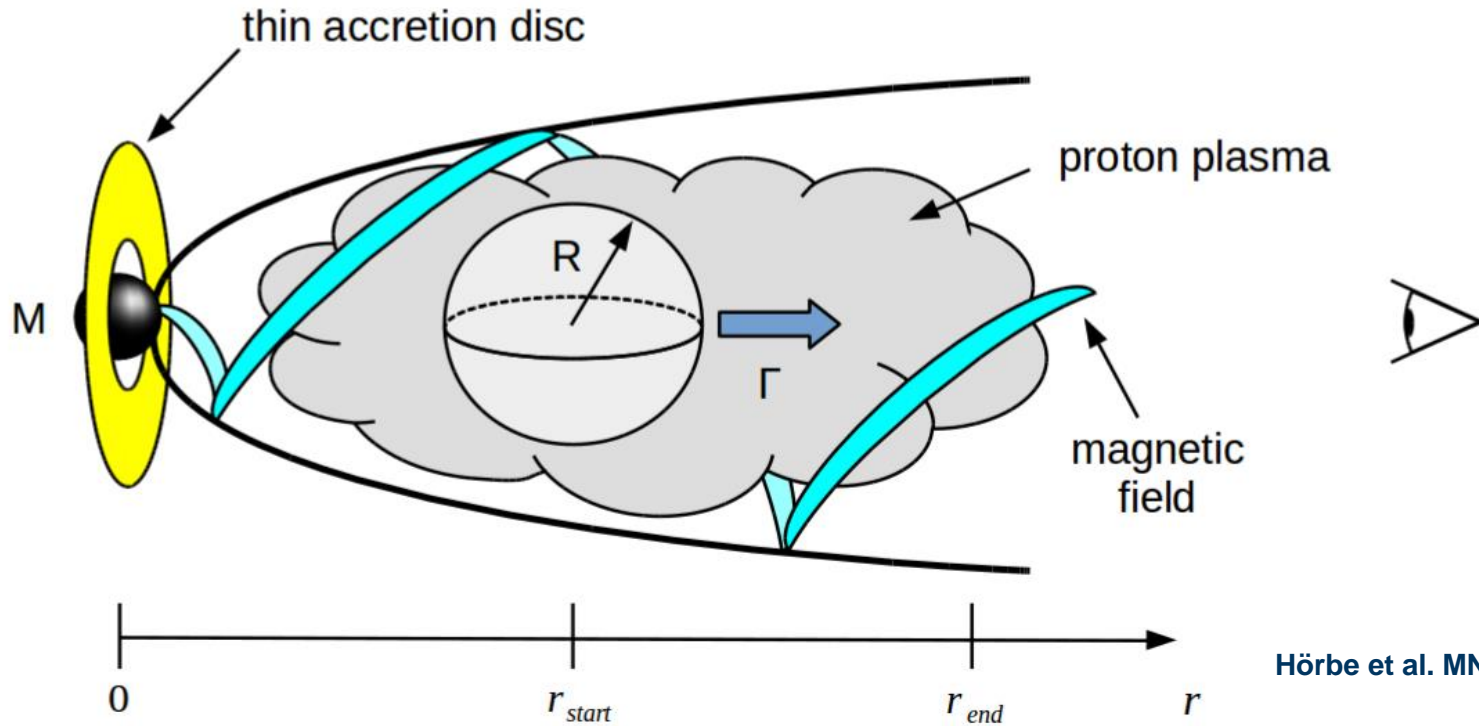


Simulation Setup for AGN-Jet-Model



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

Setup: Scheme



Hörbe et al. MNRAS (2020)

Setup: Parameter (excerpt)

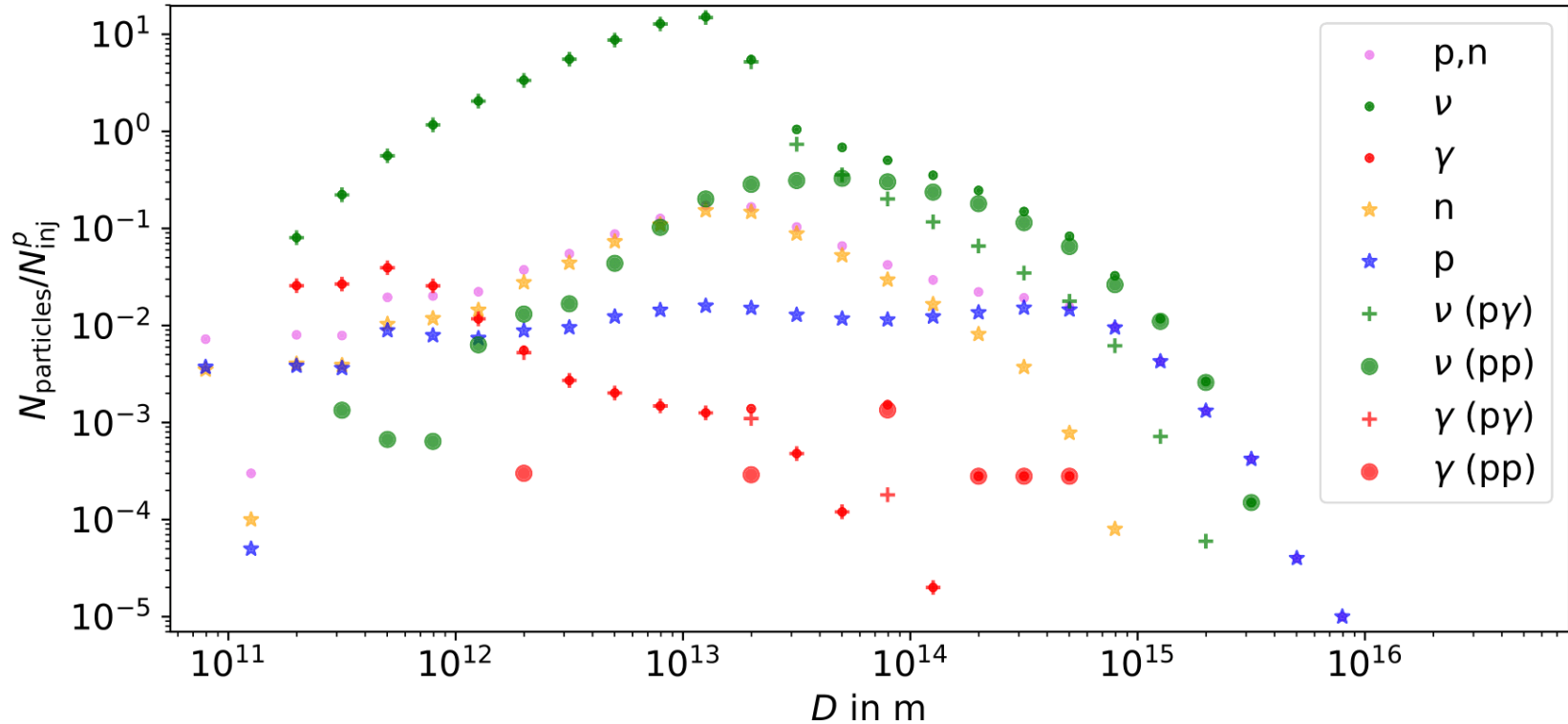
Parameter	Symbol	Value
Plasmoid Radius	R	10^{13} m
Plasmoid Propagation Start	r_{start}	10^{14} m
Plasmoid Propagation End	r_{end}	$r_{\text{start}} + 10$ pc
Plasmoid Lorentz Factor	Γ	10
Magnetic Field Initial RMS Value	B_0	1 G
Proton (primary) Initial Energy	$E_{p,\text{inj}}$	10^8 GeV
Proton Target 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

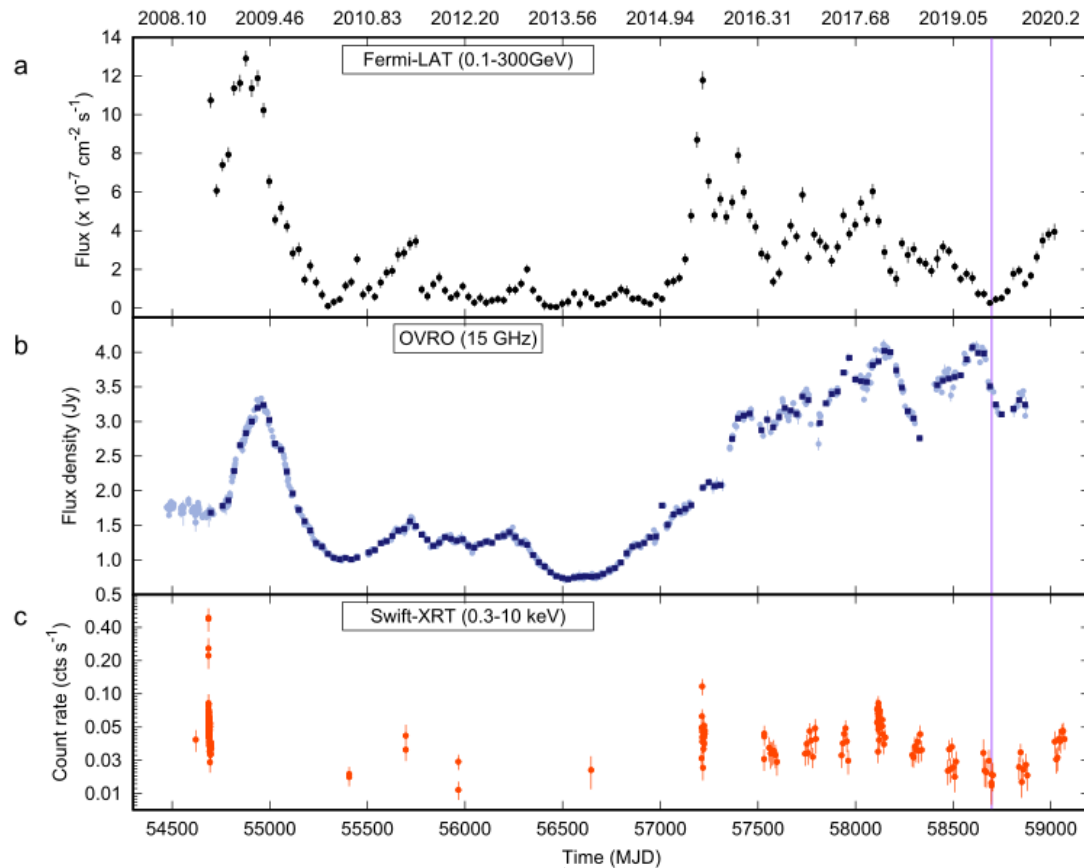
Hörbe et al. MNRAS (2020)

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 $\alpha_p = 2$;
 $E_{\text{min}} = 10^8$ GeV
 $E_{\text{max}} = 10^{11}$ GeV
- Instantaneous injection
- Black body field of accretion disk Doppler de-boosted inside plasmoid
- Synchrotron radiation of ambient electrons

Results: Combined Messengers (Pure Hadronic)





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

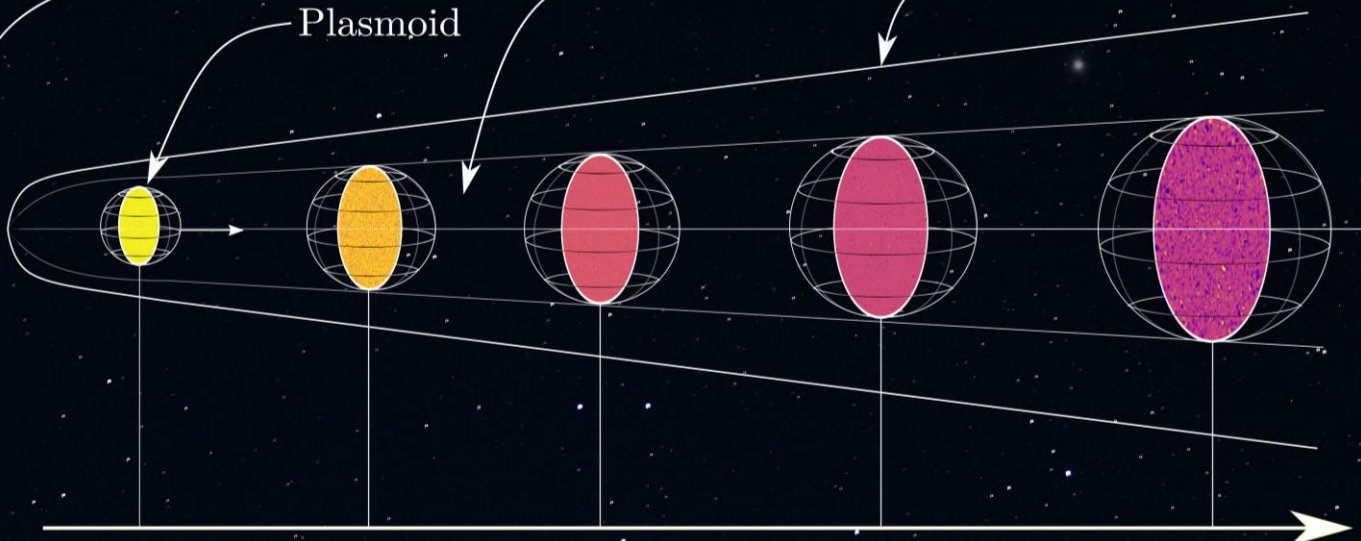
Accretion Disk

Black Hole

Plasmoid

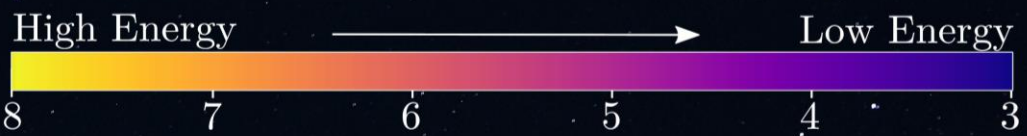
Ambient Gas

Jet



Time t

10 s
— " —
100 s
~ 2 min
1 000 s
~ 20 min
10 000 s
~ 3 h
100 000 s
~ 1 d



$\log_{10}(E/\text{GeV})$

Image courtesy: V. Kiselev & MS

Time & Density Dependence: Current Projects

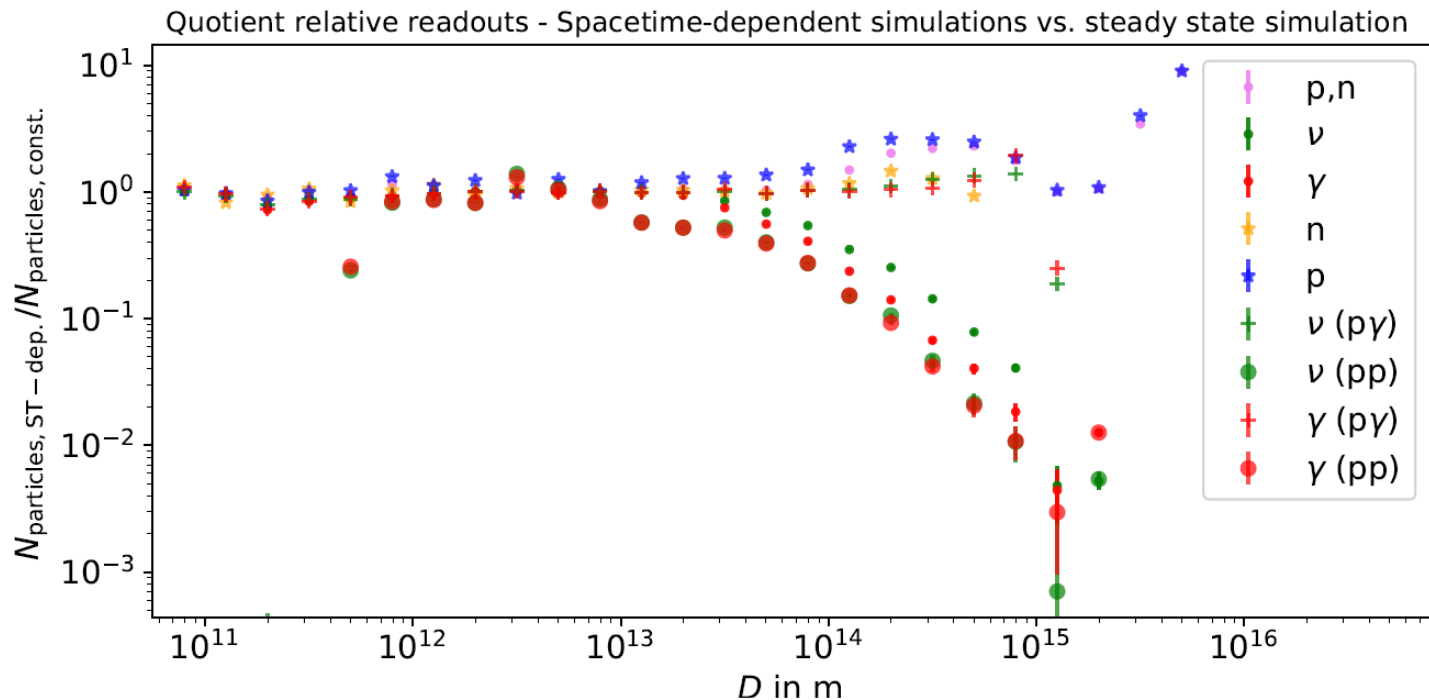
Different, each promising approaches to MM modelling of AGN jets exist

General approach:

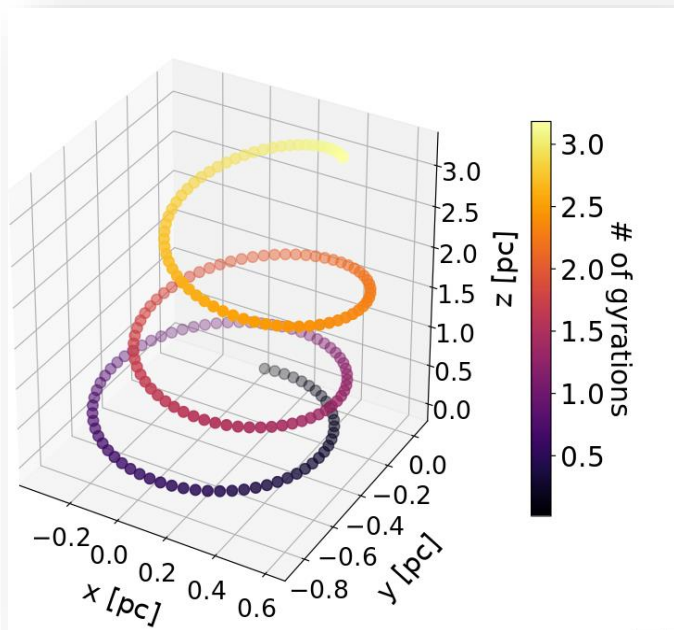
- Solve transport problem via FP-equation
- Impose energy losses and secondary particle production, find steady-state solution wrt. injection & escape
- Goal: Fit model parameters to SED and lightcurves - Simultaneously (!)

Code Reference	AM ³	PARIS	ATHErA	Böttcher	CRPropa	AGNPropa
	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)

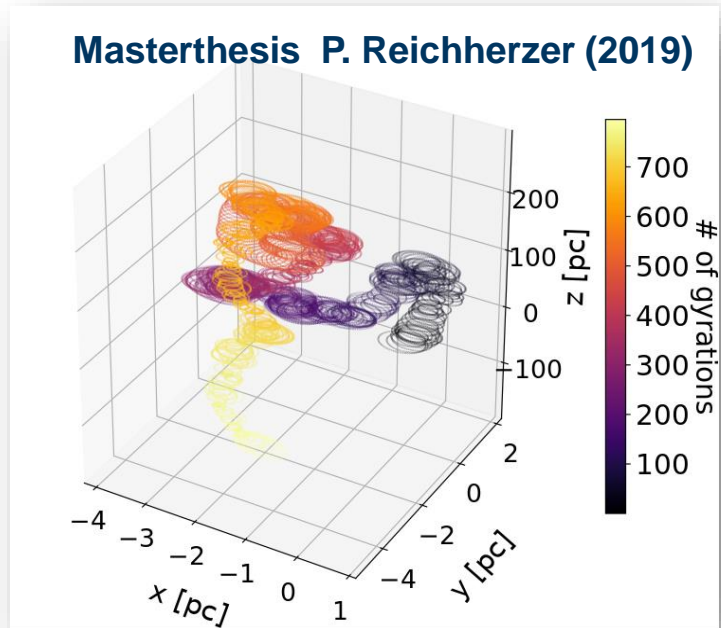
Time & Density Dependence: A Comparison



Transport in Turbulent Fields: Ballistic vs. Diffusive



$$\frac{dp}{dt} = q(\mathbf{v} \times \mathbf{B})$$



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

Transport: Running Diffusion Coefficient

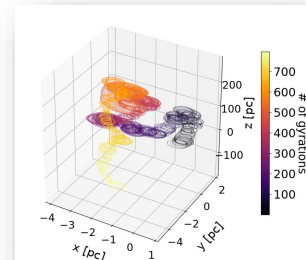
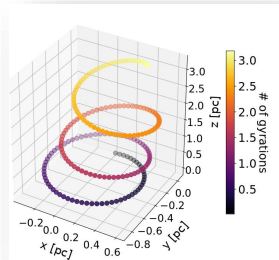
Particle Trajectory Data



Ensemble Averaging at t_i



Running Diffusion Coefficient $\kappa(t_i)$



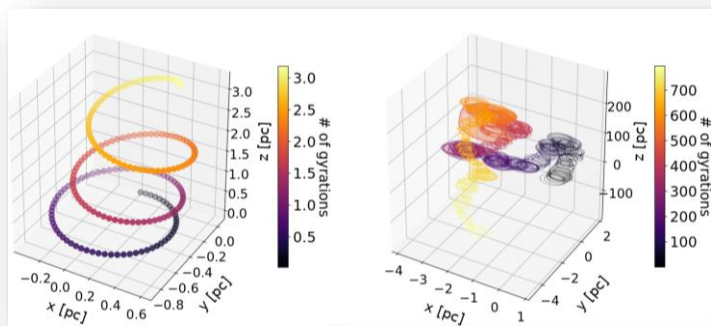
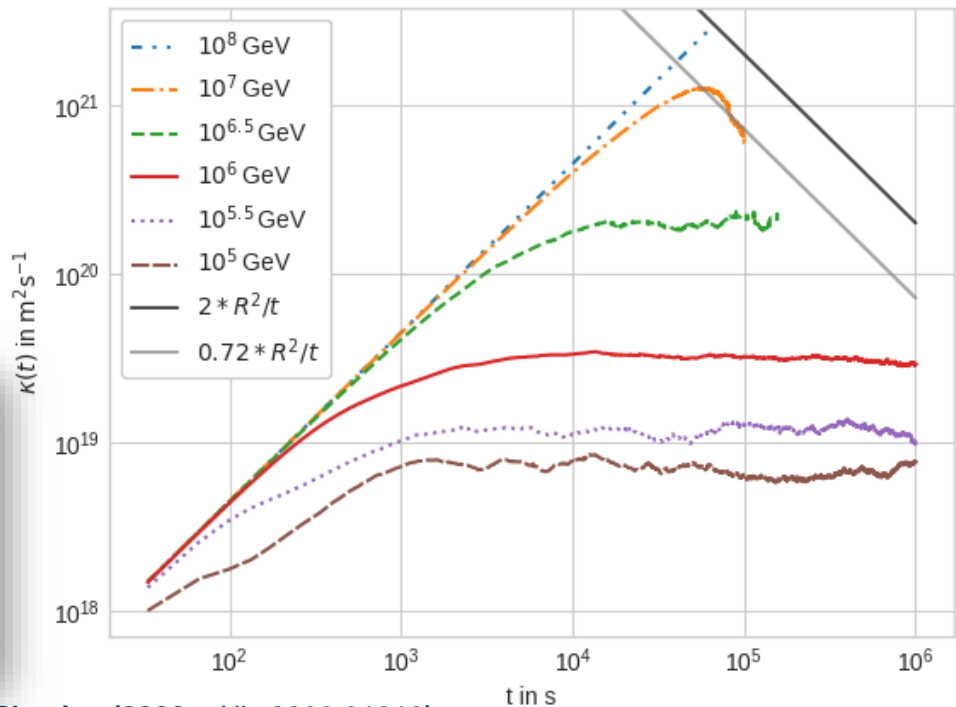
$$\kappa(t_i) = \frac{\langle r(t_i) - r(t_0) \rangle_{\text{particles}}^2}{2t_i}$$

Transport: Diffusion Coefficients

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

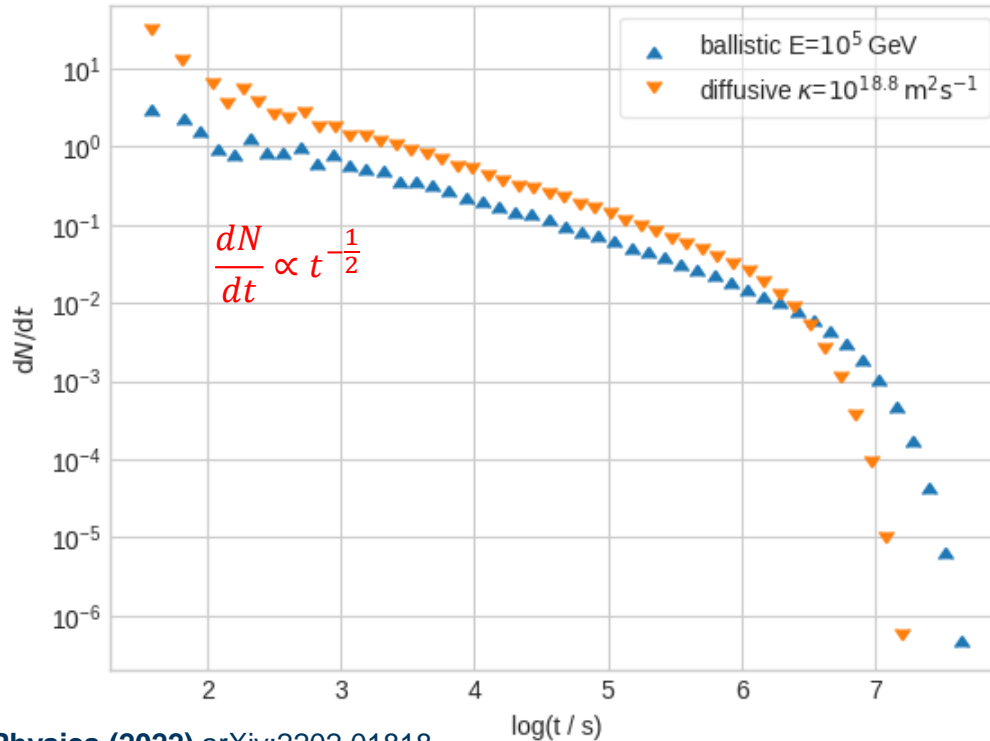
$$\kappa = \lim_{t \rightarrow \infty} \kappa(t) \approx \langle \kappa(t) \rangle_{t \gg t_0}$$

- Input for diffusive simulations (if applicable)



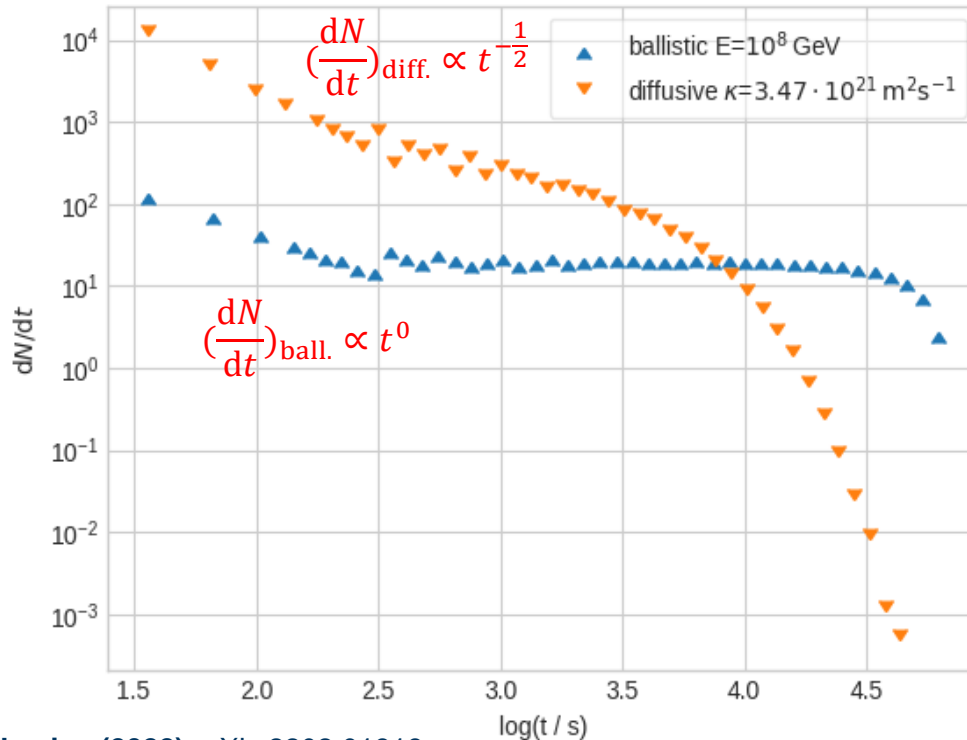
Becker Tjus et al. MDPI Physics (2022 arXiv:2202.01818)

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:

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



Article

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

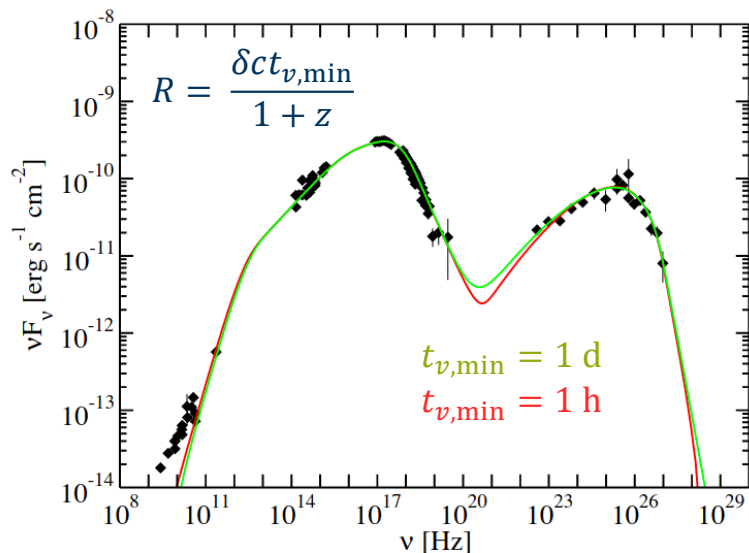
Julia Becker Tjus ^{1,2,*}, Mario Hörbe ^{1,2}, Ilja Jaroschewski ^{1,2}, Patrick Reichherzer ^{1,2,3}, Wolfgang Rhode ⁴, Marcel Schroller ^{1,2} and Fabian Schüssler ³

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

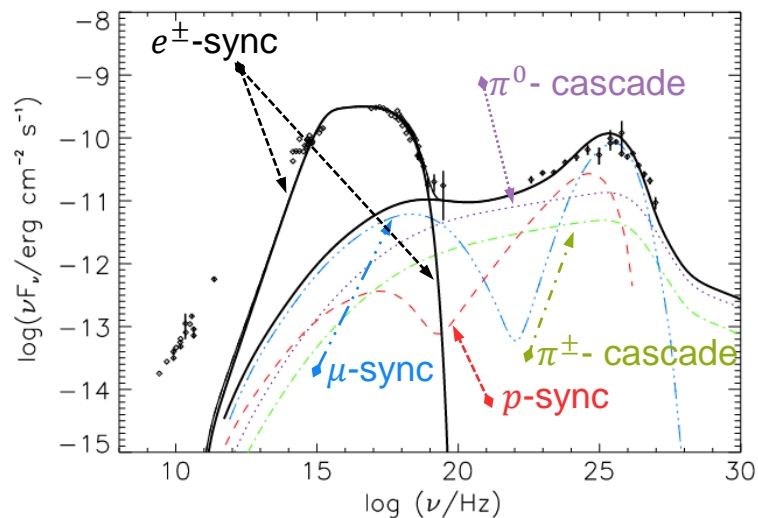


Prediction of spectral breaks from spatial and magnetic field configurations for AP neutrinos and gamma-rays from AGN jets!

Callback: Ambiguity of Signals



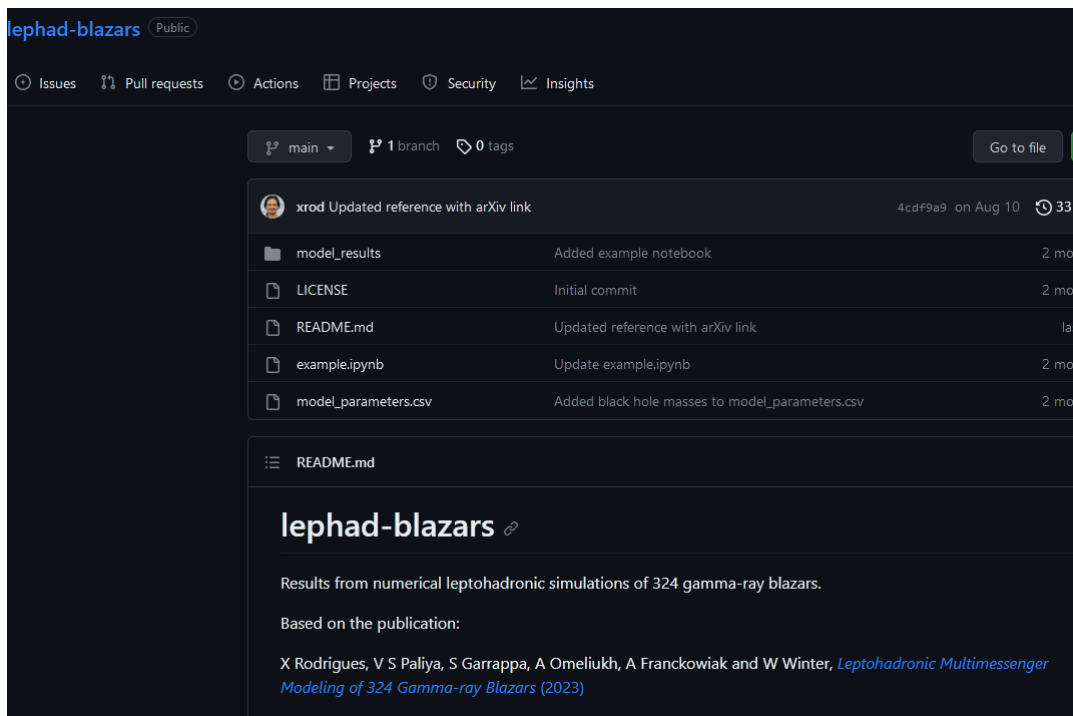
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... same SED with hadronic model (for high-E bump)

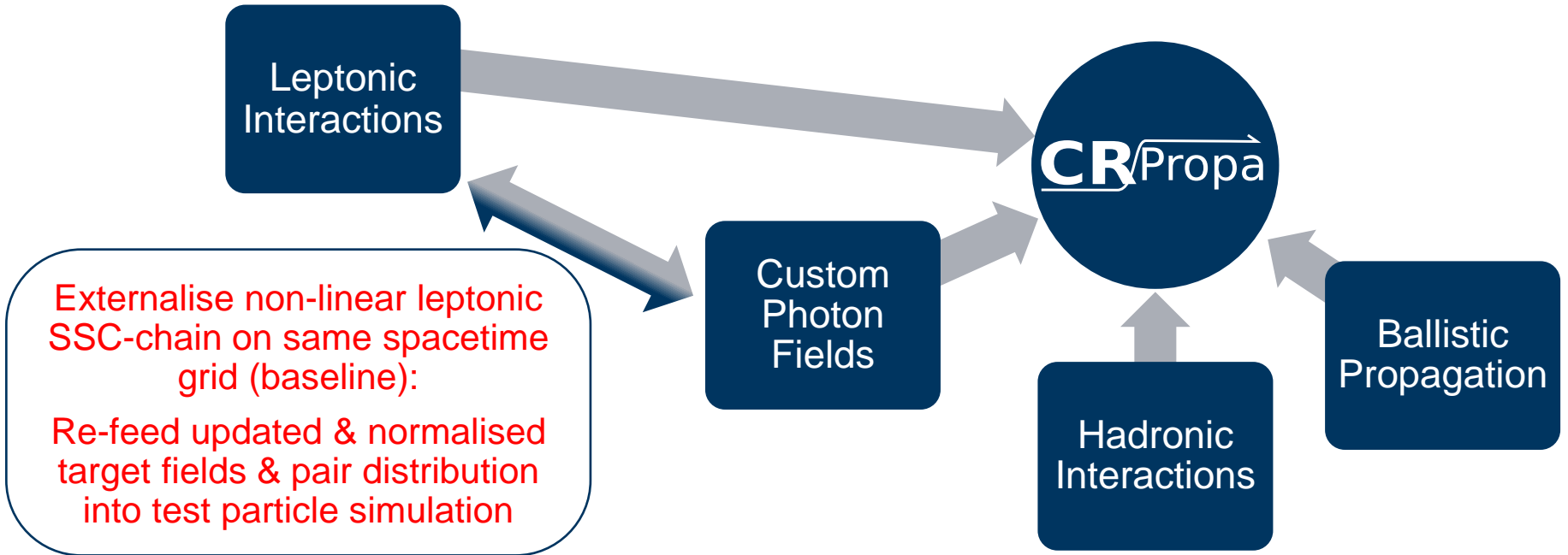
Abdo et al. ApJ (2011)

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

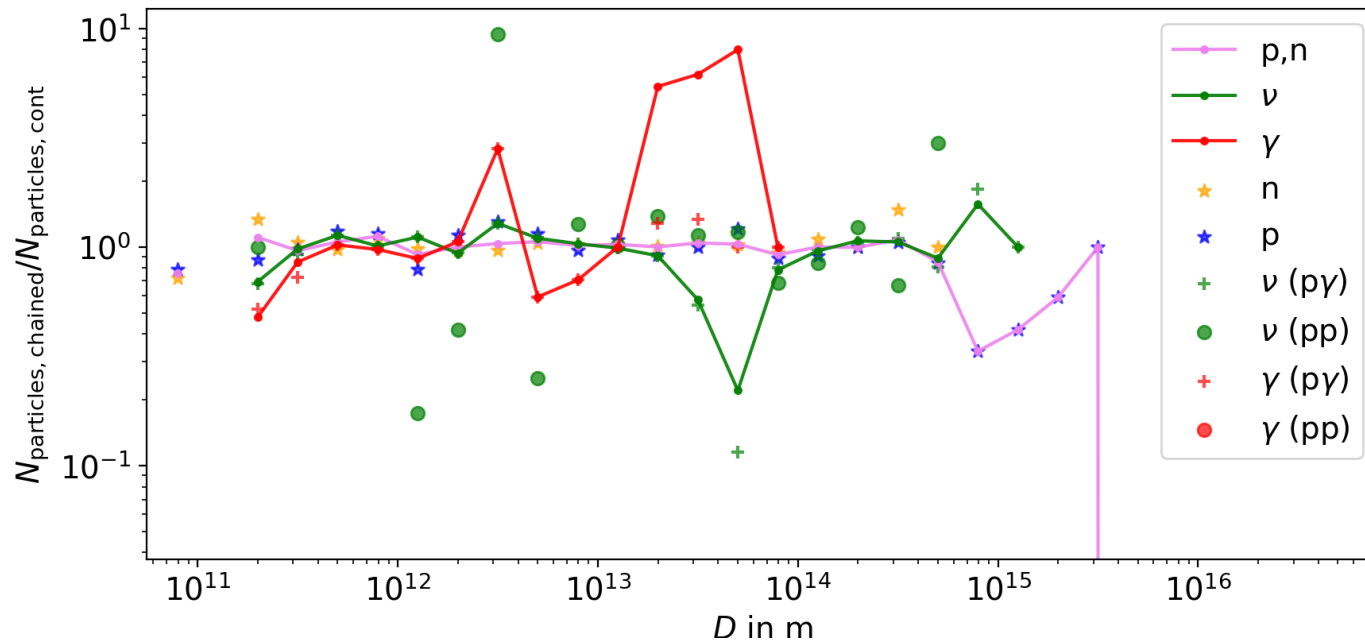


- 324 gamma-ray Fermi blazar SEDs modeled by **X. Rodrigues et al. (arXiv 2307.13024)**
- Approach for finding parameters:
 - Simulate purely leptonic one-zone model (IR, optical, UV, GeV range)
 - Superimpose hadronic signatures for $f \leq 300$ GHz
 - Combined fit for all wavelengths
- Suitable for detailed comparisons!

Extension to Lepto-Hadronic Simulations



Quotient relative readouts - Chained simulations vs. cont. sim



Extension to Lepto-Hadronic Simulations

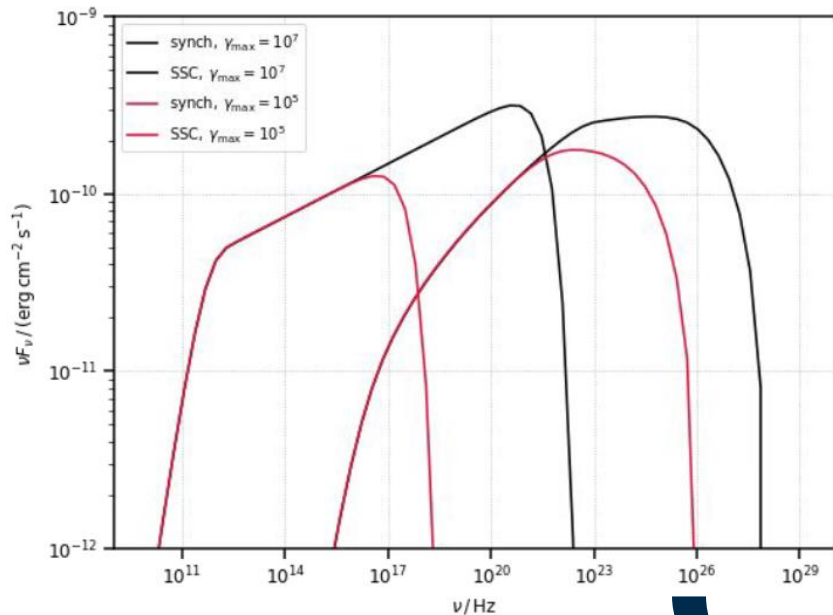
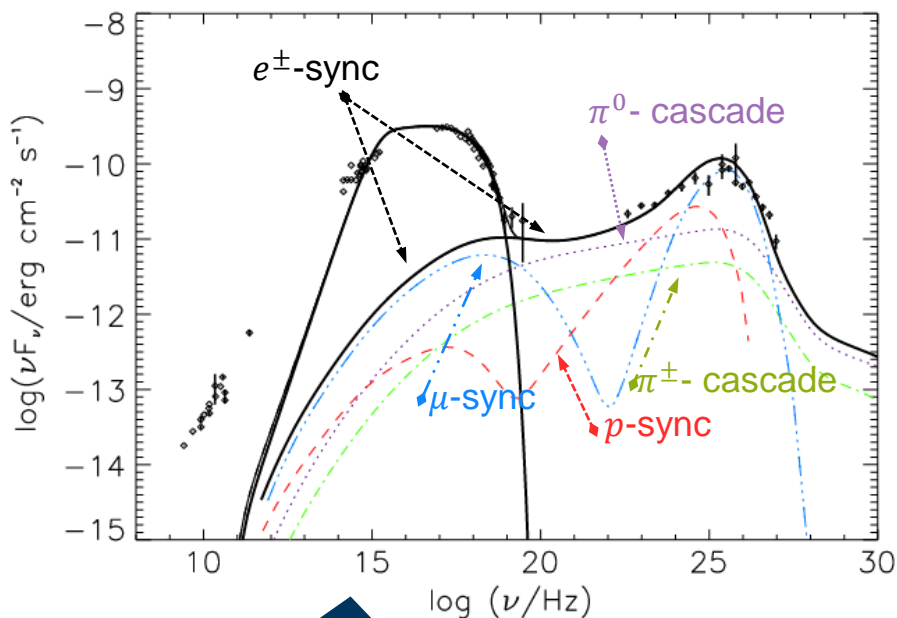


Figure courtesy: C. Nigro
(OSS AGNPy following Dermer & Menon)



Abdo et al. ApJ (2011)

Summary

- **Extension of established test-particle simulation framework for hadrons in AGN jet plasmoids to second-order leptonic processes is in progress**
- **Propagational effects on signatures are investigated, with first promising results**
- **A lot of testing with existing numerical and semi-analytical models for one-zone problems is inbound, so stay tuned!**
-



Glad to take questions!

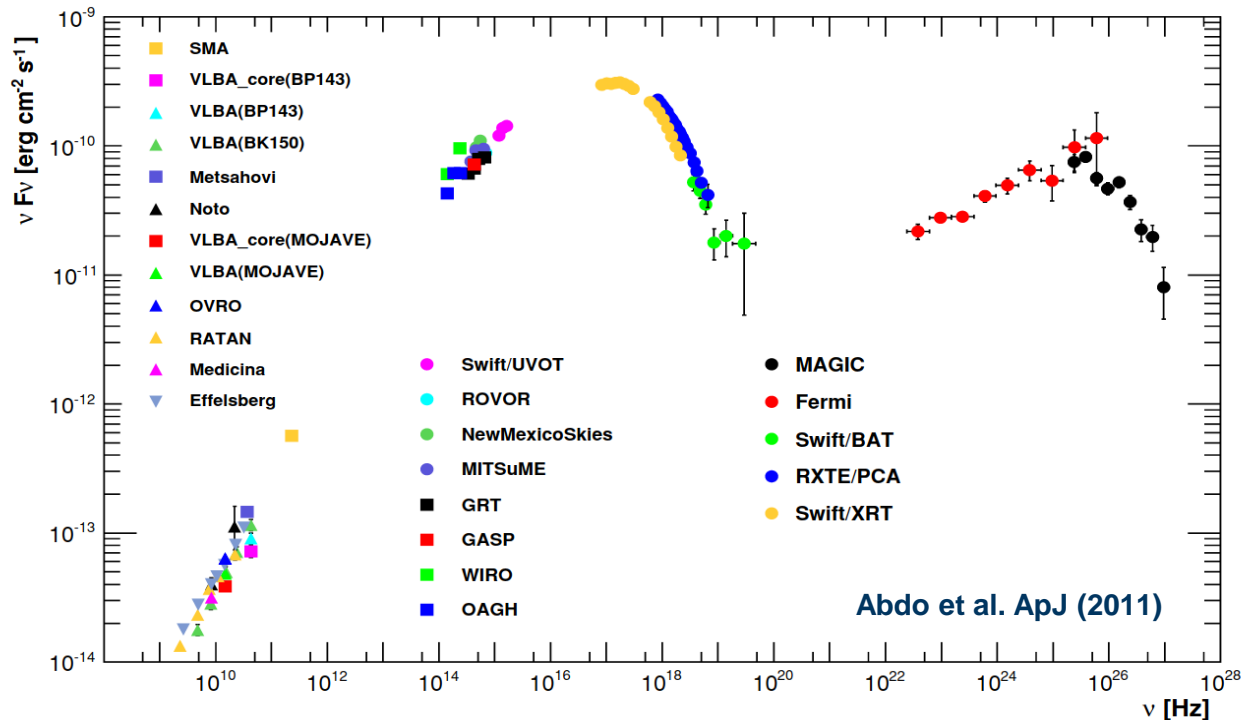
Image courtesy: IceCube Collaboration

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

BACKUP

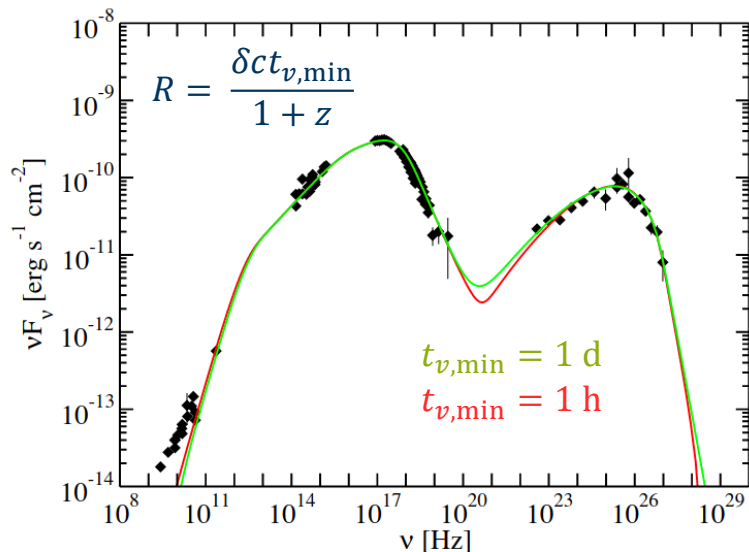
AGN-Jet Modelling Challenges

Example: Multiwavelength-SED (Mrk 421)

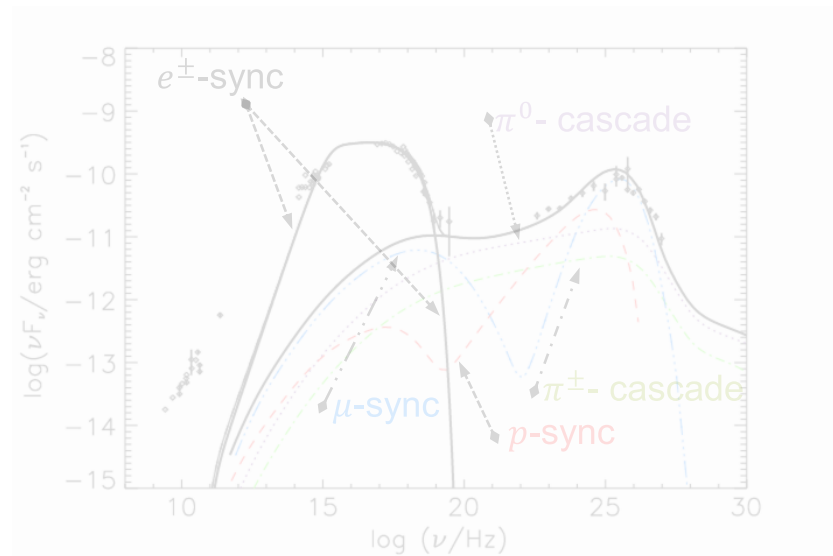


Markarian 421:
4.5-month-survey.
Integrated timescale
problematic!

Challenge: Ambiguity of Signals



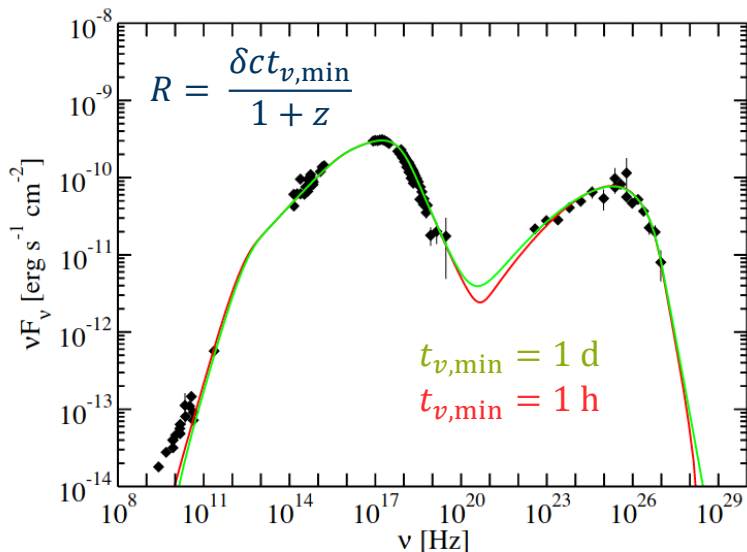
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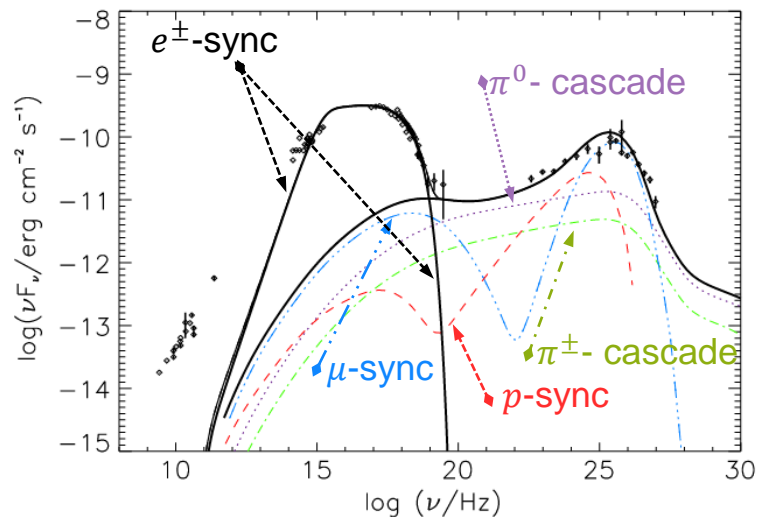
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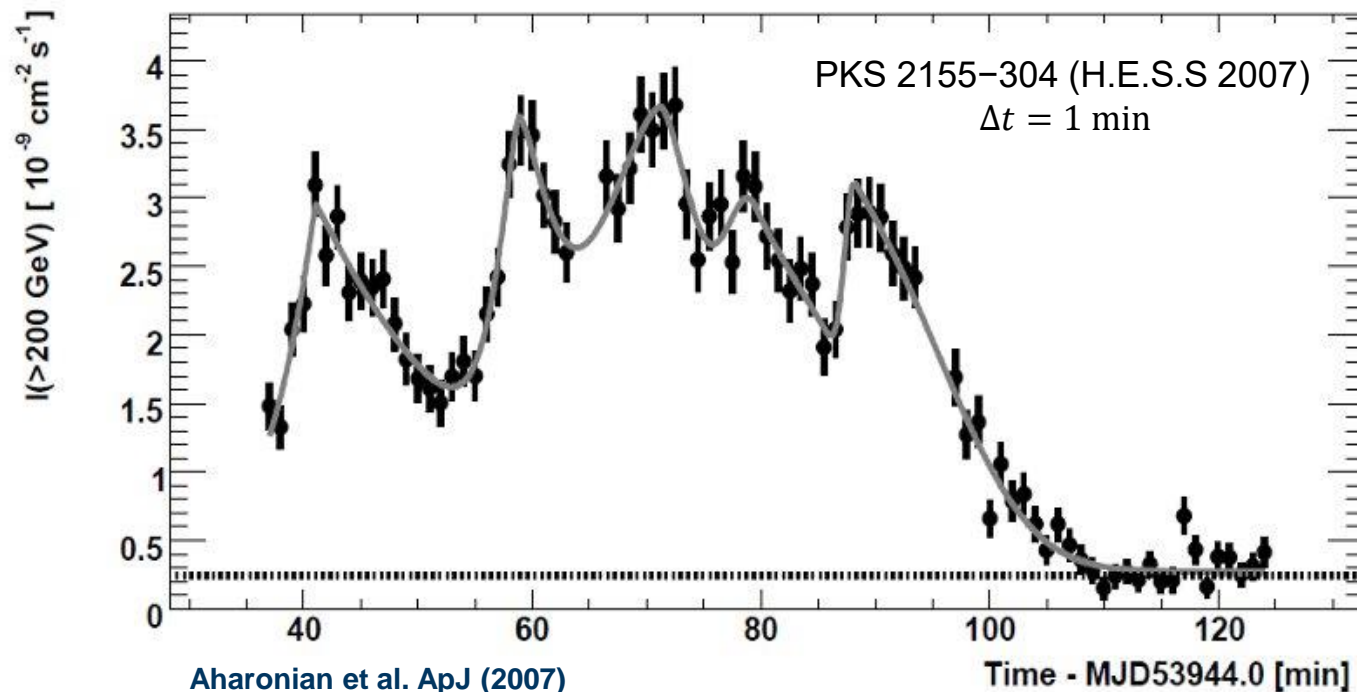
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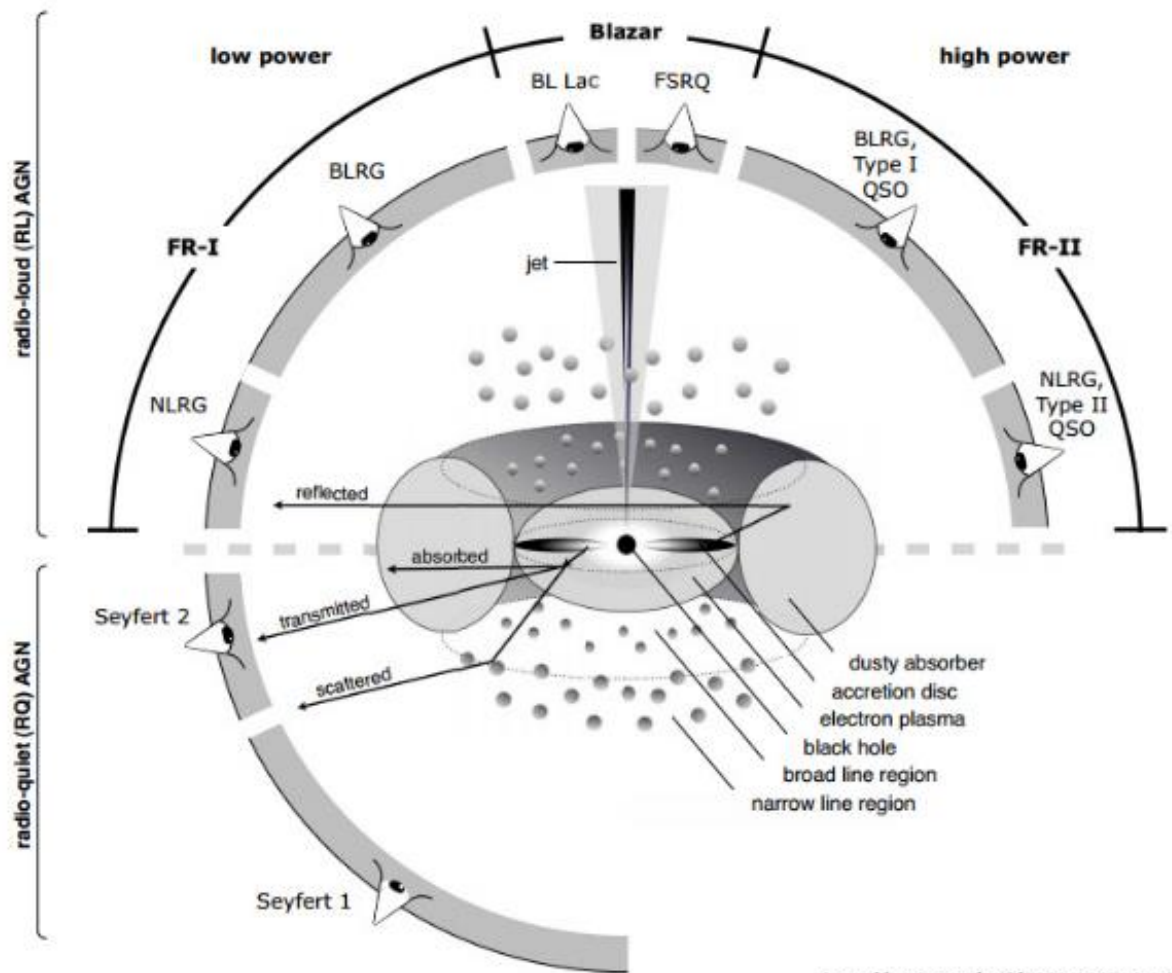


... same SED with hadronic model
(for high-E bump)

Abdo et al. ApJ (2011)

Challenge: Time Variability





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 $E_p = 10^8$ GeV or power-law-like distributed with $\alpha_p = 2$
- 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

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

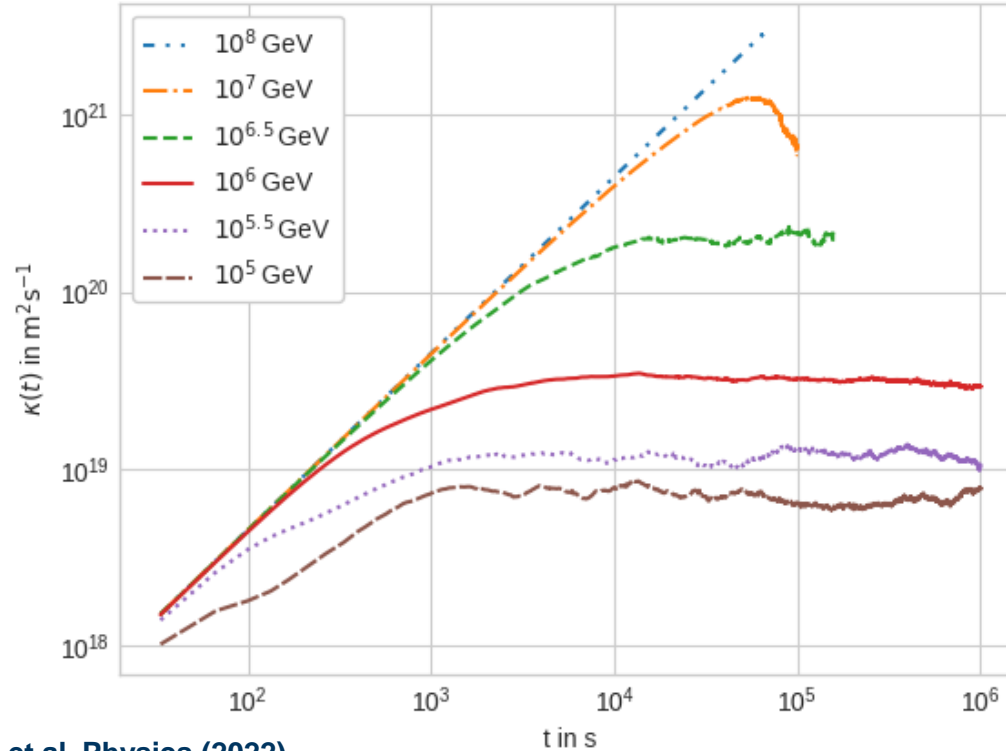
i	P_i	V_i	W_i
6	# of gridpoints N_{Gr}	256	512
7	Spacing Δs_B	R / (128)	R / (256 * 64)
8	Root Mean Value B_0	1 G	1 G
9	Correlation length l_c	$10^{(-2)}$ R	$10^{(-2)}$ R
10	Lmin l_{min}	R / (64)	R / (256 * 32)
11	Lmax l_{max}	R / (32)	R / (32)
12	# of spatial scalings $N_{x,y,z}^B$	2	4
13	# of temporal 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

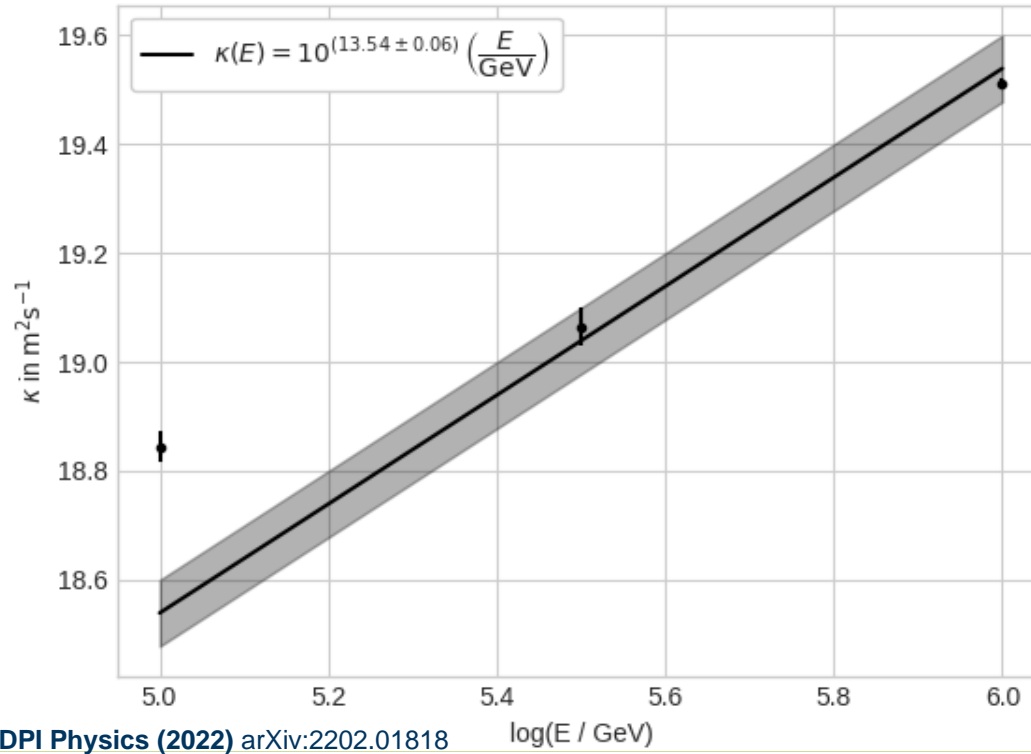
Propagation Effects

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

DEAD END