Multi-Zone Hadronic Blazar Model & Observable

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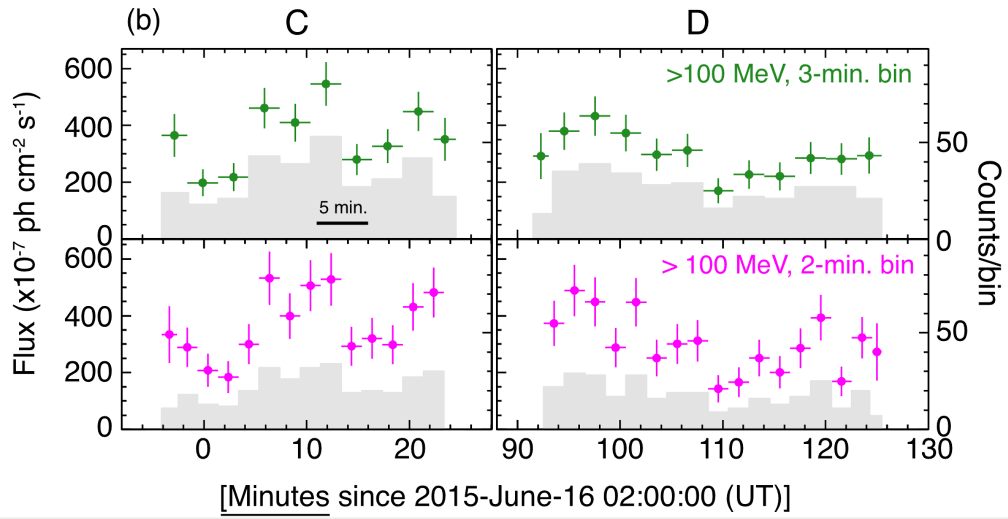
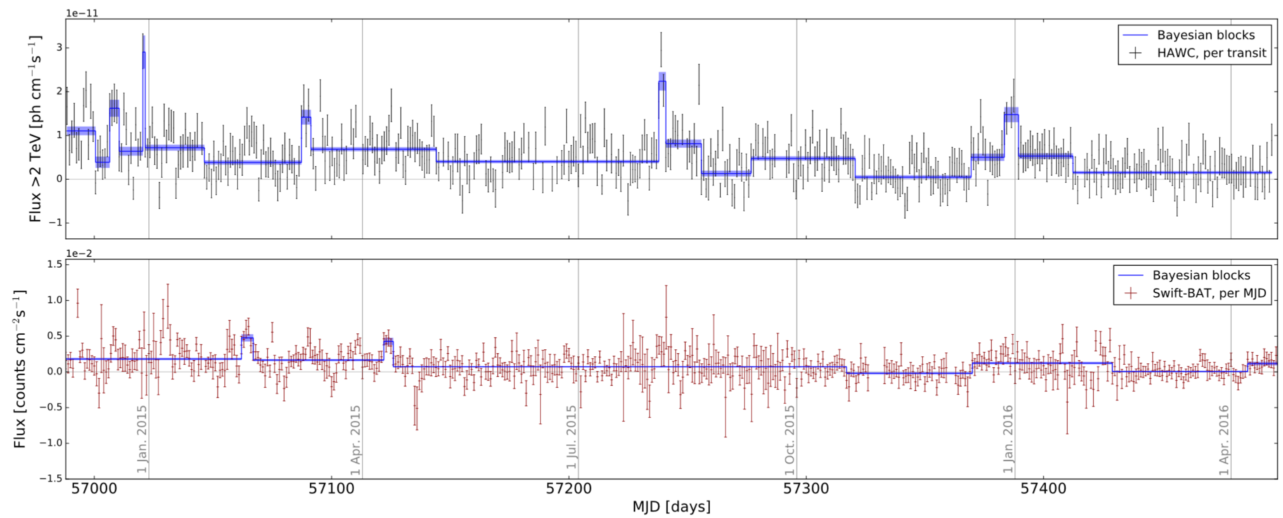
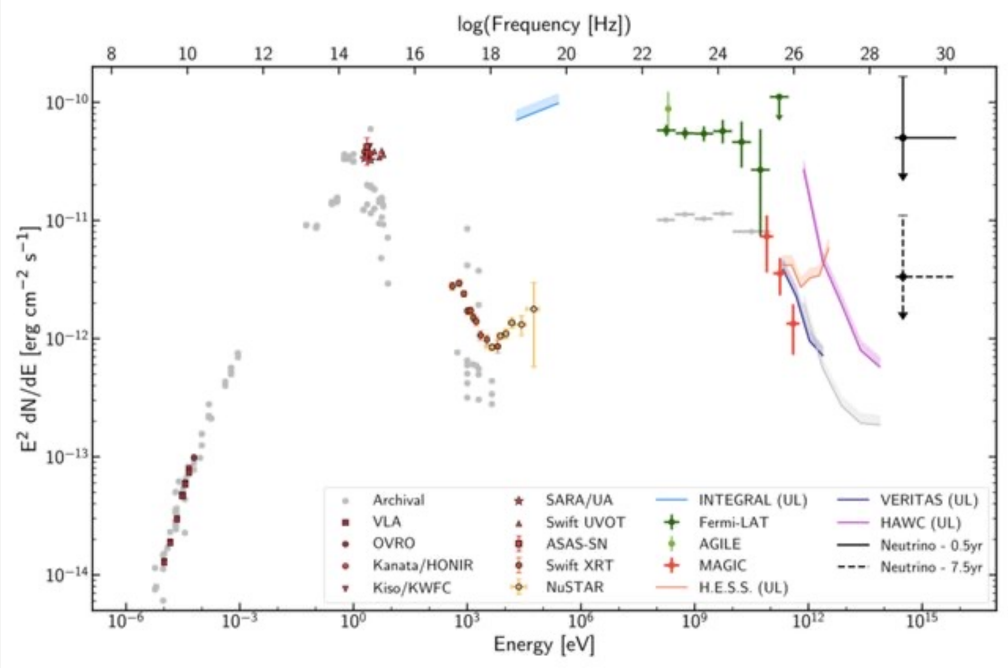
Why Multi-Zone?



Ackermann+ 2016 ApJL 824, L20



Abeysekara+ 2017, ApJ 841, 100



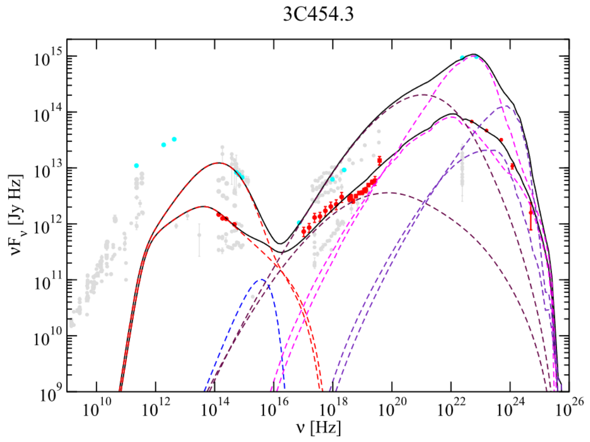
IceCube 2018 Science 361, 1387

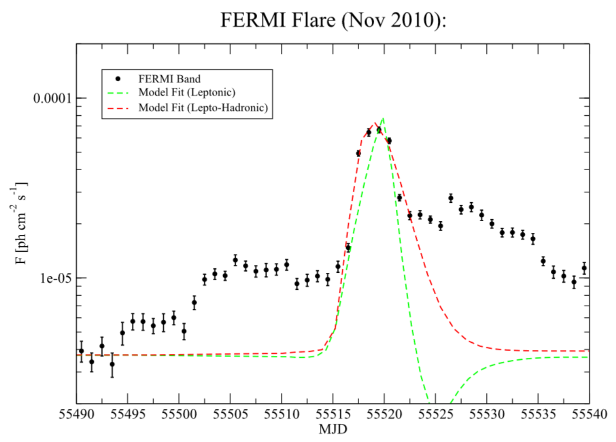
One-zone model faces serious challenges in explaining many time-domain and multi-messenger events:

1. Fast gamma-ray flares
2. Orphan flares
3. Neutrinos

Issues with Multi-Zone Models

Multi-zone models usually have too many free parameters, diminishing their predictive power.

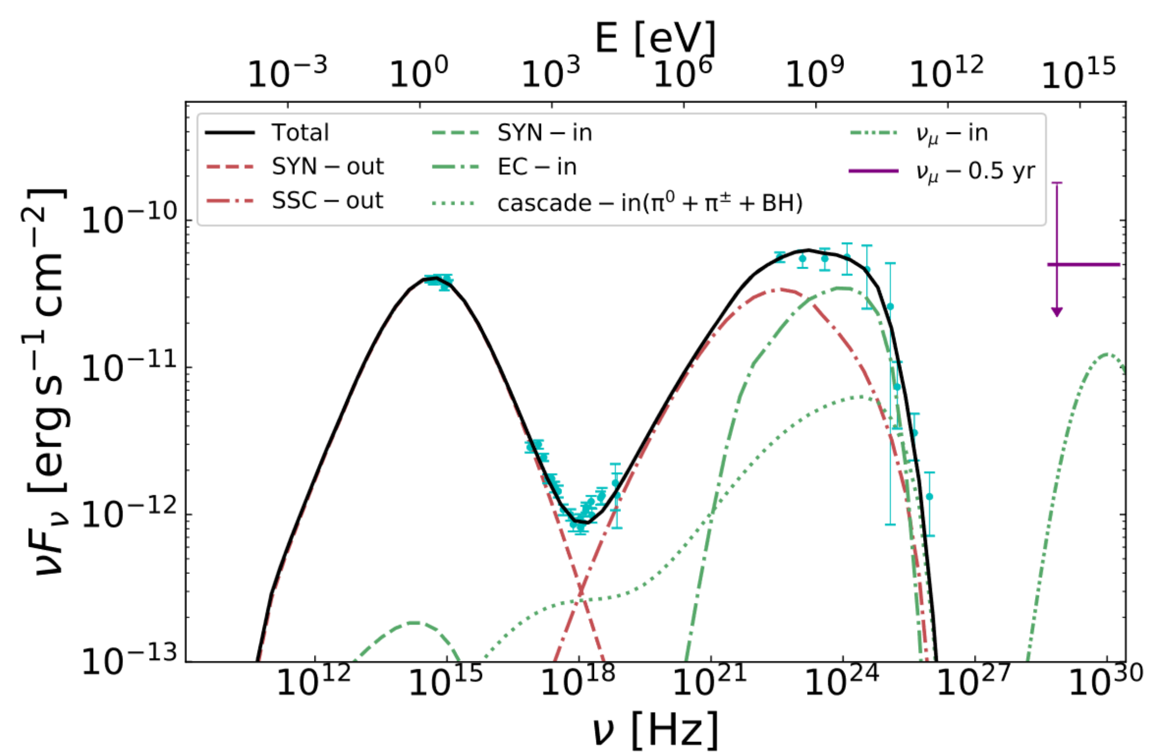




Parameter	Symbol	Leptonic Value	Hadronic Value
Magnetic field	B	1.5 G	125 G
Radius of emission region	R	2.51×10^{16} cm	2.51×10^{16} cm
Multiple for escape timescale	η	15	15
Bulk Lorentz factor	Γ	15	15
Observing angle	$\theta_{\rm obs}$	6.66×10^{-2} rad	6.66×10^{-2} rad
Proton injection minimum energy	$\gamma_{\rm p,min}$	...	1.0
Proton injection maximum energy	$\gamma_{\rm p,max}$	...	4.85×10^{8}
Proton injection spectral index	q_p	...	2.25
Proton injection luminosity	$L_{\rm p,inj}$	...	3.75×10^{46} erg s^{-1}
Electron injection minimum energy	$\gamma_{\rm e,\ min}$	9.0×10^{2}	5.0×10^{1}
Electron injection maximum energy	$\gamma_{\rm e,max}$	6.0×10^{4}	2.5×10^{3}
Electron injection spectral index	q_e	2.9	2.9
Electron injection luminosity	$L_{\rm e,\ inj}$	2.45×10^{43} erg s^{-1}	3.64×10^{42} erg s^{-1}
Supermassive black hole mass	$M_{\rm BH}$	$2.0 \times 10^{9}\ M_\odot$	$2.0 \times 10^{9}\ M_\odot$
Eddington ratio	$l_{\rm Edd}$	4.0×10^{-1}	4.0×10^{-1}
Accretion disk luminosity	$L_{\rm disk}$	1.0×10^{46} erg s^{-1}	1.0×10^{46} erg s^{-1}
Blob location along the jet axis	$R_{\rm axis}$	0.12 pc	0.12 pc
Radius of broad-line region	$R_{\rm BLR}$	0.25 pc	0.25 pc
Luminosity of broad-line region	$L_{\rm BLR}$	2.0×10^{45} erg s^{-1}	2.0×10^{45} erg s^{-1}
Ratio of ACC and ESC timescales	$t_{\rm acc}/t_{\rm esc}$	0.1	4.0
Luminosity of magnetic field	L_B	1.18×10^{45} erg s^{-1}	7.5×10^{48} erg s^{-1}
Luminosity of electrons	L_e	6.11×10^{45} erg s^{-1}	4.49×10^{42} erg s^{-1}
Ratio of magnetic and electron luminosity	ϵ_{Be}	0.19	1.67×10^{6}

Scenario	K_L (erg s^{-1})	K_q	K_B (G)	$K_{t_{\rm acc}}$
Electron (Leptonic)	8.0×10^{44}	...	−0.9	34.0
Proton (Lepto-hadronic)	...	−0.3	−50.0	3.0
Electron (Lepto-hadronic)	4.5×10^{43}	...	−50.0	3.0

Diltz+ 2016, ApJ 826, 54



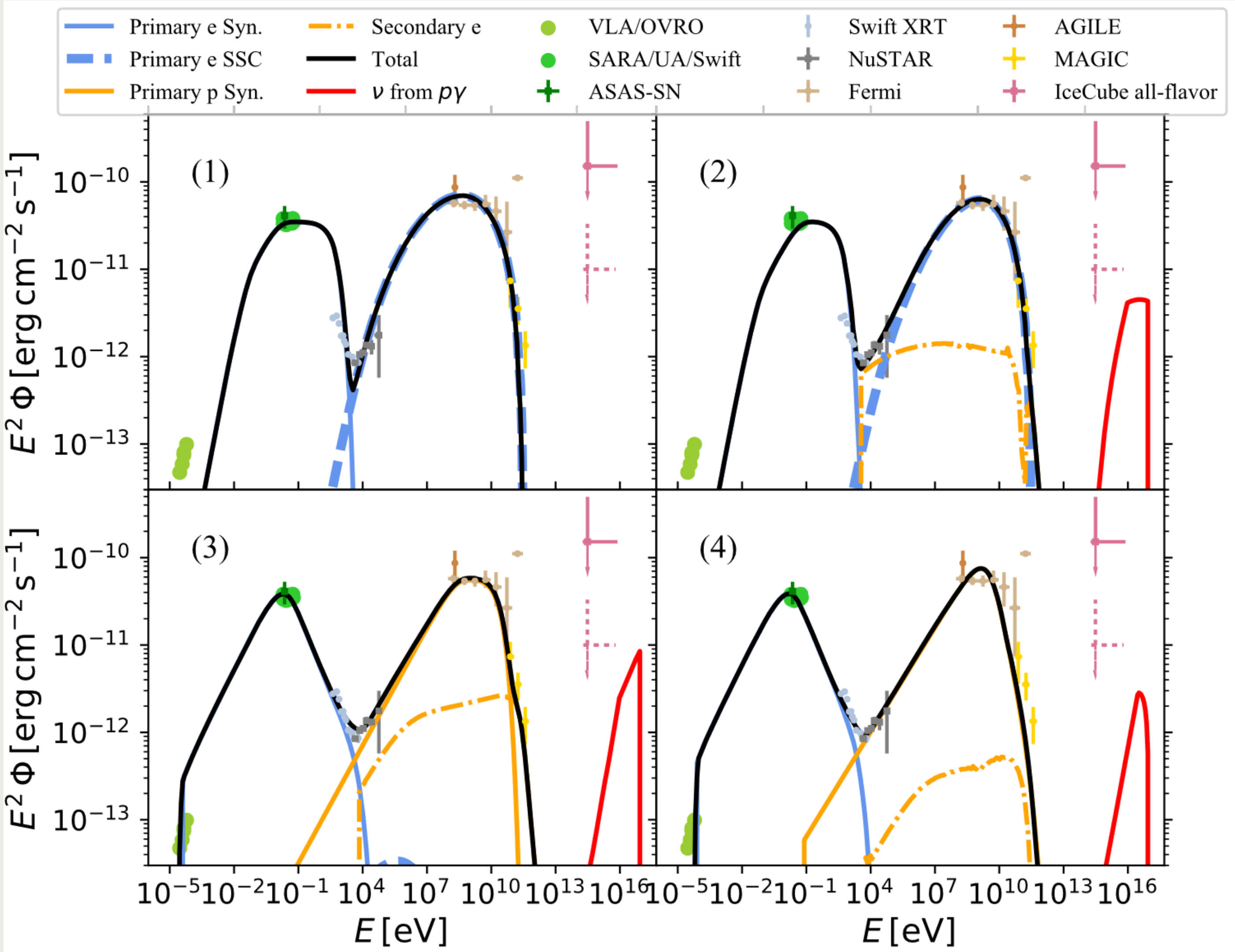
Parameters for SED Fitting with the Two-zone $p\gamma$ Model

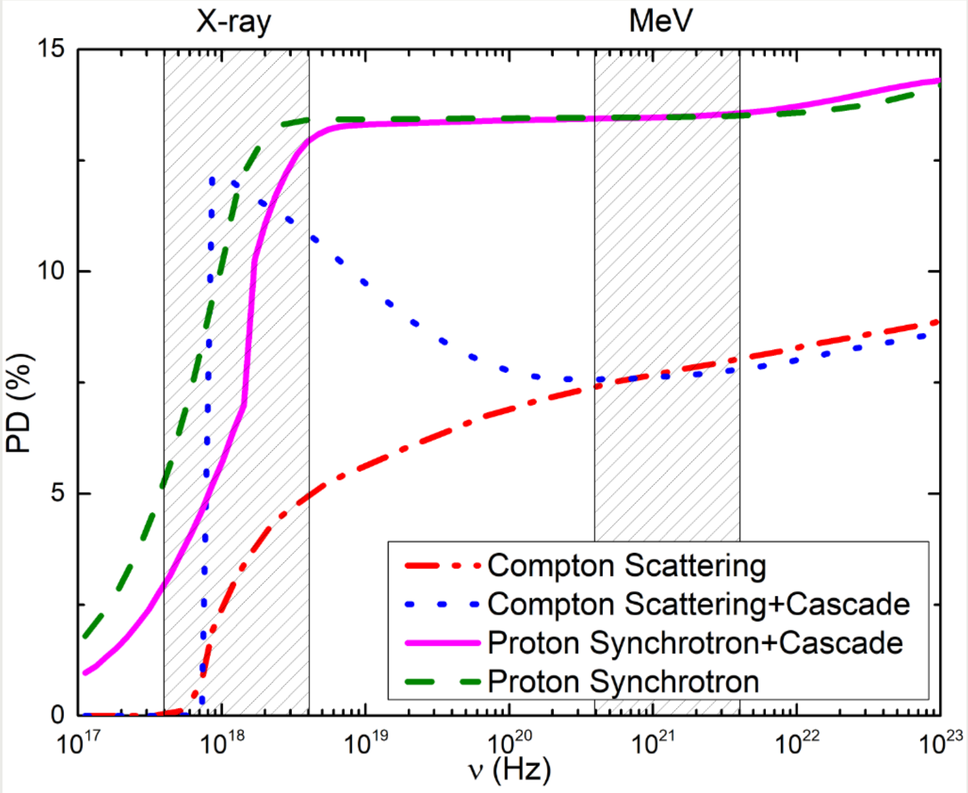
Free Parameters	$\delta_{\rm D}$	B (G)	$R_{\rm out}$ (cm)	$R_{\rm in}$ (cm)	$L_{\rm e,inj}$ (erg s^{-1})	$r_{\rm in}^{\rm AGN}$ (pc)	$n_{\rm e,1}$	$n_{\rm e,2}$	$\gamma_{\rm e,b}$
Values	26.5	0.11	4×10^{16}	1×10^{16}	2×10^{42}	0.05	1.4	4	8.1×10^{3}
Fixed/Derived Parameters	$L_{\rm BLR}^{\rm AGN}$ (erg s^{-1})	$L_{\rm p,inj}$ (erg s^{-1})	$\gamma_{\rm e,min}$	$\gamma_{\rm e,max}$	$n_{\rm p}$	$\gamma_{\rm p,min}$	$\gamma_{\rm p,max}$	$L_{\rm e,\ in}^{\rm k}$ (erg s^{-1})	$L_{\rm p,in}^{\rm k}$ (erg s^{-1})
Values	5×10^{43}	2.0×10^{44}	50	10^{7}	2	1	7.0×10^{6}	3.8×10^{43}	1.3×10^{47}

Xue+ 2019, ApJ 886, 23

Solution: 1. Reduce free parameters; 2. Derive more observable patterns

A One-Zone Example



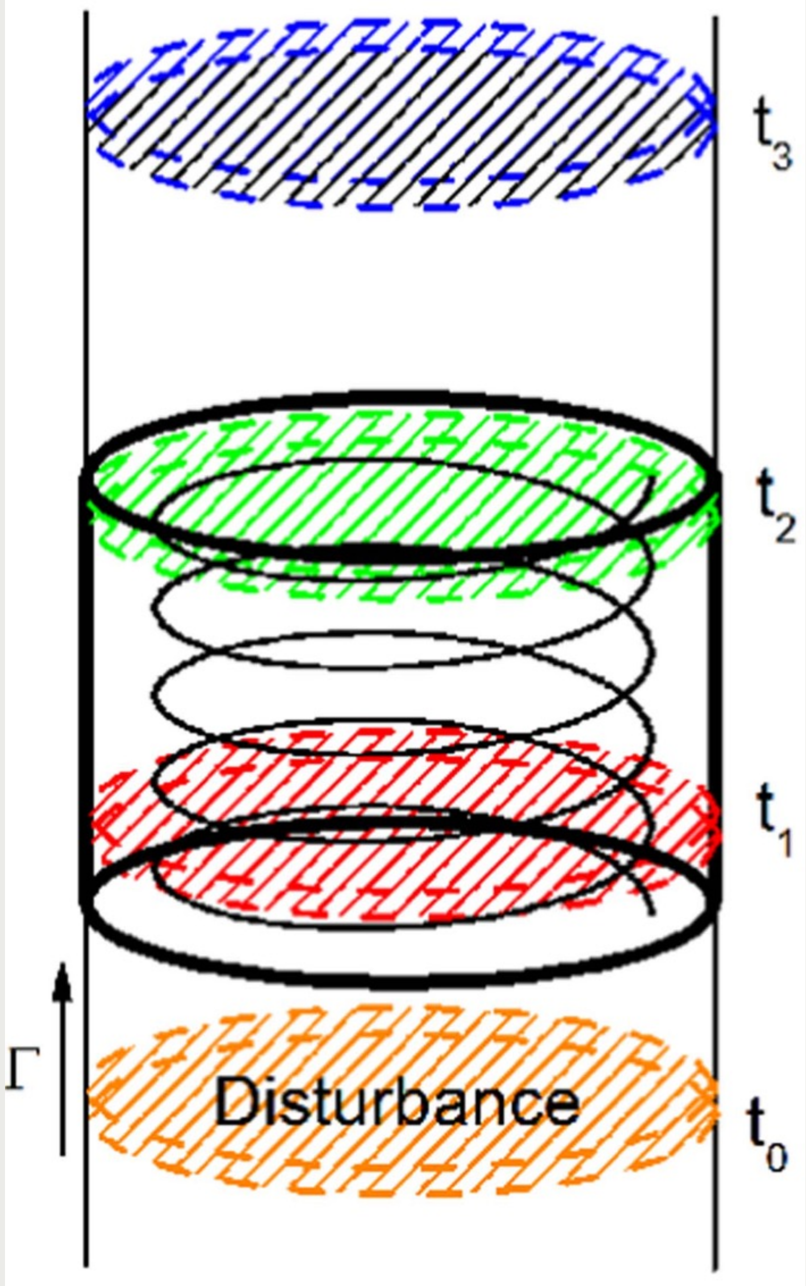


Zhang et al. 2019 ApJ 876, 109

Leptonic and hadronic models cannot be distinguished by spectral fitting only

1. Hadronic models predict higher polarization in X-ray and MeV gamma-ray bands.
2. MeV polarization can identify proton synchrotron.

Multi-Zone with Fokker-Planck Particle Evolution



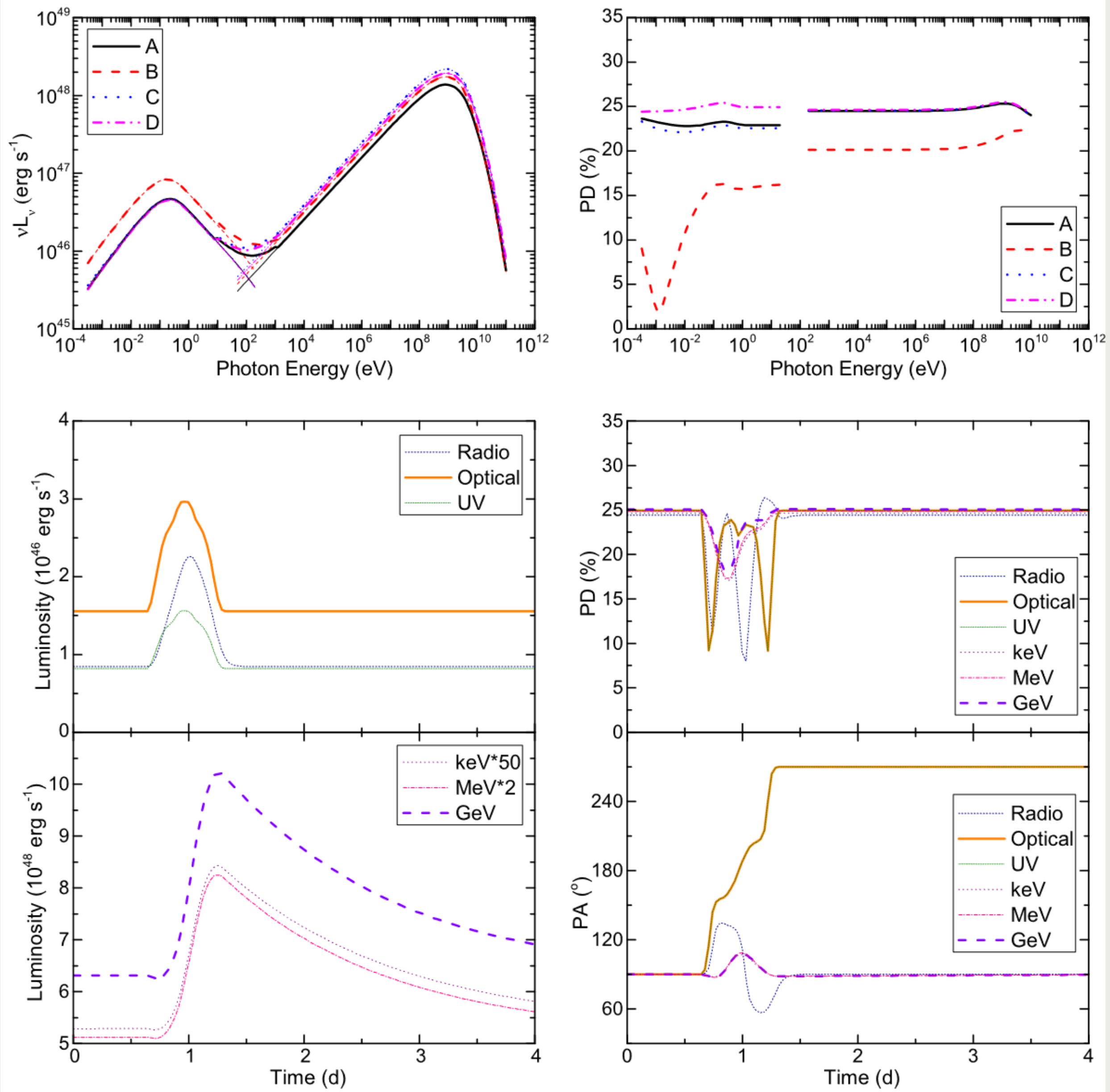
Parameters	Set 1
Bulk Lorentz factor Γ	20.0
Orientation of LOS θ_{obs} (°)	90
Radius of the emission region R (10^{16} cm)	1.0
Height of the emission region Z (10^{16} cm)	1.33
Acceleration timescale t_{acc} (10^6 s)	8.2
Escaping timescale t_{esc} (10^6 s)	2.0
Background injection electron density rate $\dot{u}_{e,inj}$ (erg s^{-1} cm^{-3})	2.8×10^{-7}
Background injection electron minimum energy $\gamma_{e,min}$	100
Background injection electron maximum energy $\gamma_{e,max}$	10000
Background injection electron spectral index p_e	2.8
Background injection proton density rate $\dot{u}_{p,inj}$ (erg s^{-1} cm^{-3})	3×10^{-3}
Background injection proton minimum energy $\gamma_{p,min}$	1
Background injection proton maximum energy $\gamma_{p,max}$	5×10^8
Background injection proton spectral index p_p	2.2
Helical magnetic field B (G)	50.0
Magnetic pitch angle θ_B (deg)	45

Parameters	Case 1a	Case 2a	Case 1b	Case 1c	Case 2c	Case 1d
$t_{acc,d}$ (10^6 s)	...	...	...	...	...	0.51
$\dot{u}_{e,inj,d}$ (erg s^{-1} cm^{-3})	3.0×10^{-6}	4.1×10^{-9}	...	1.6×10^{-6}	2.2×10^{-9}	...
$\dot{u}_{p,inj,d}$ (erg s^{-1} cm^{-3})	5.5×10^{-2}	9.8×10^{-6}	...	5.5×10^{-2}	9.6×10^{-6}	...
B_d (G)	36.6	58.6	136.6	...	...	...
θ_{B_d} (deg)	75	75	75	...	...	...

Zhang+ 2016, ApJ 829, 69

Similar number of free parameters as the one-zone time-dependent model.

Multi-Wavelength Signatures

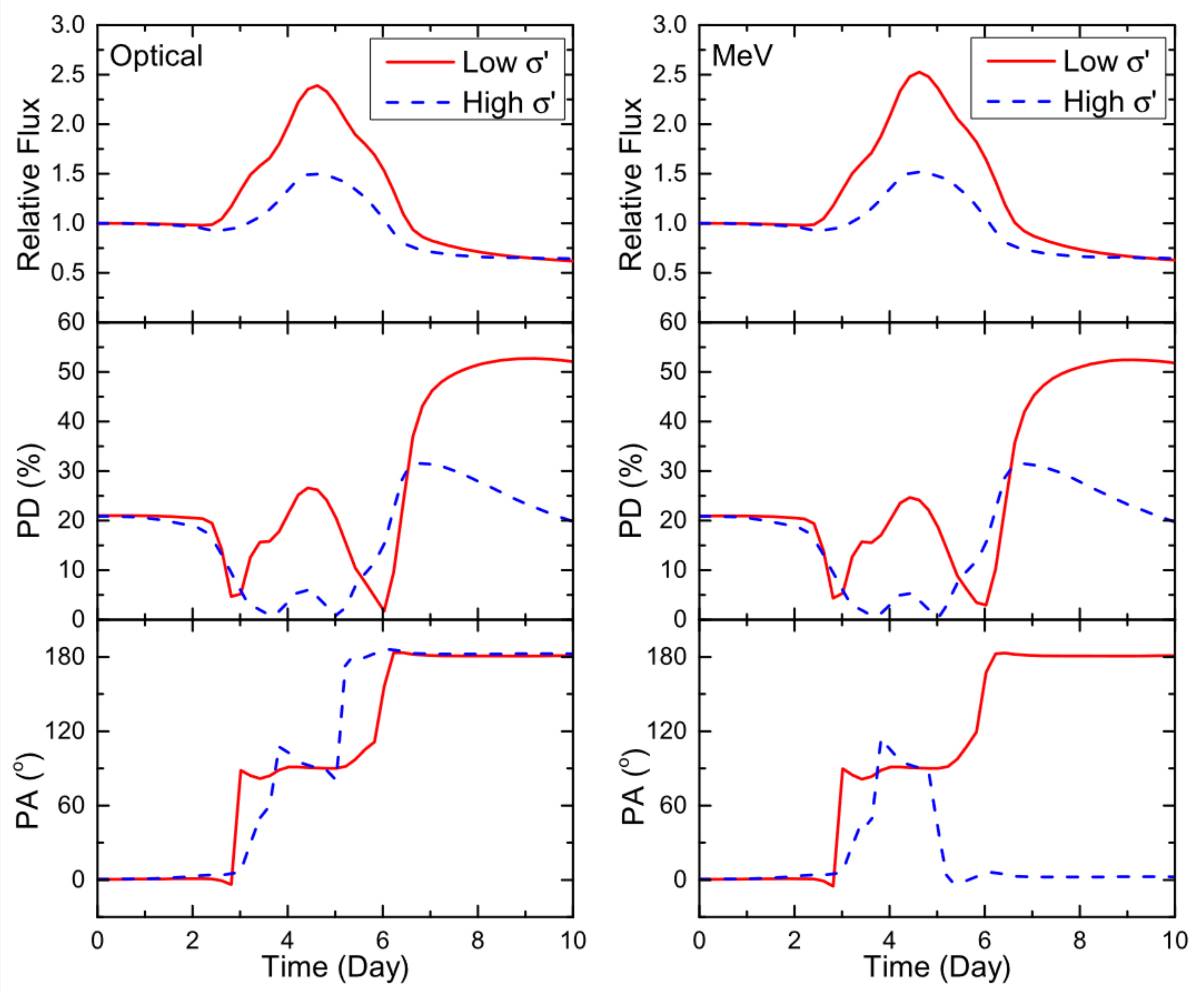


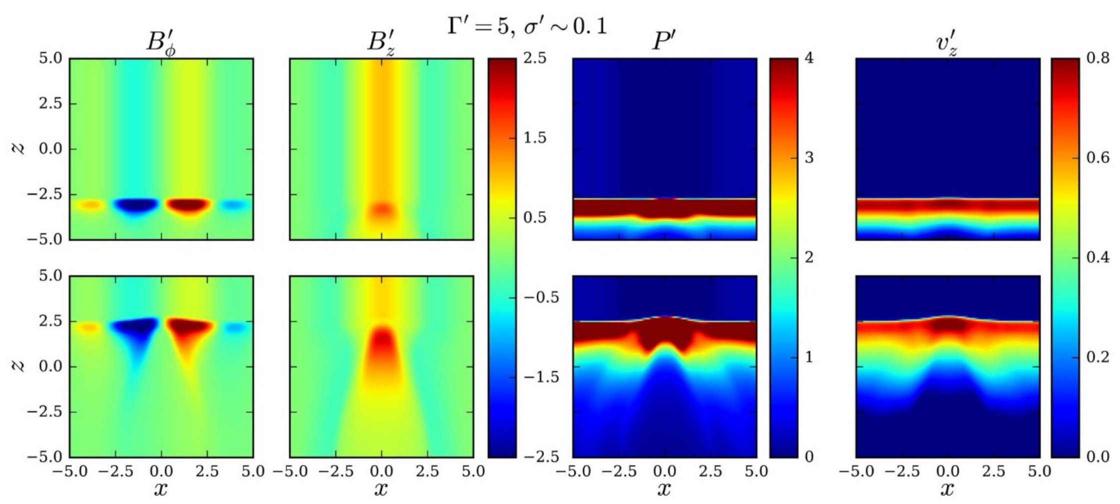
[Zhang et al. 2016 ApJ 829, 69]

1. We can derive all observable signatures, including time-dependent spectra, polarization spectra, multi-wavelength light curves, and polarization curves.
2. Unique signatures that are usually unavailable in one-zone models include:
   - ❑ Time-symmetric light curves in low-energy bands
   - ❑ Clear time delay between low- and high-energy bands
   - ❑ Spectral and temporal polarization signatures

Hadronic X-ray and MeV polarization do not vary much in time, ideal for future detections.

Multi-Zone with MHD

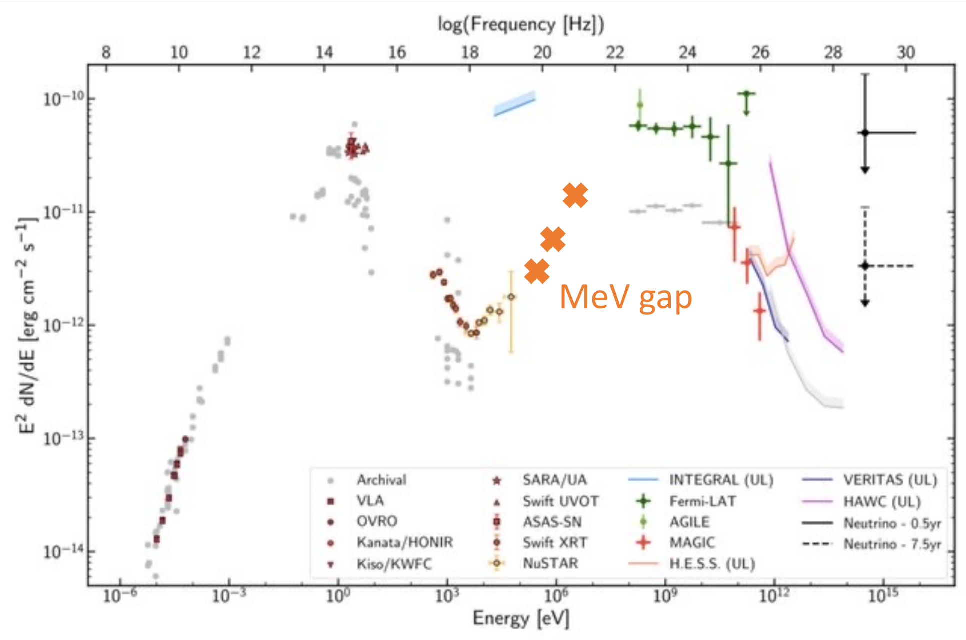


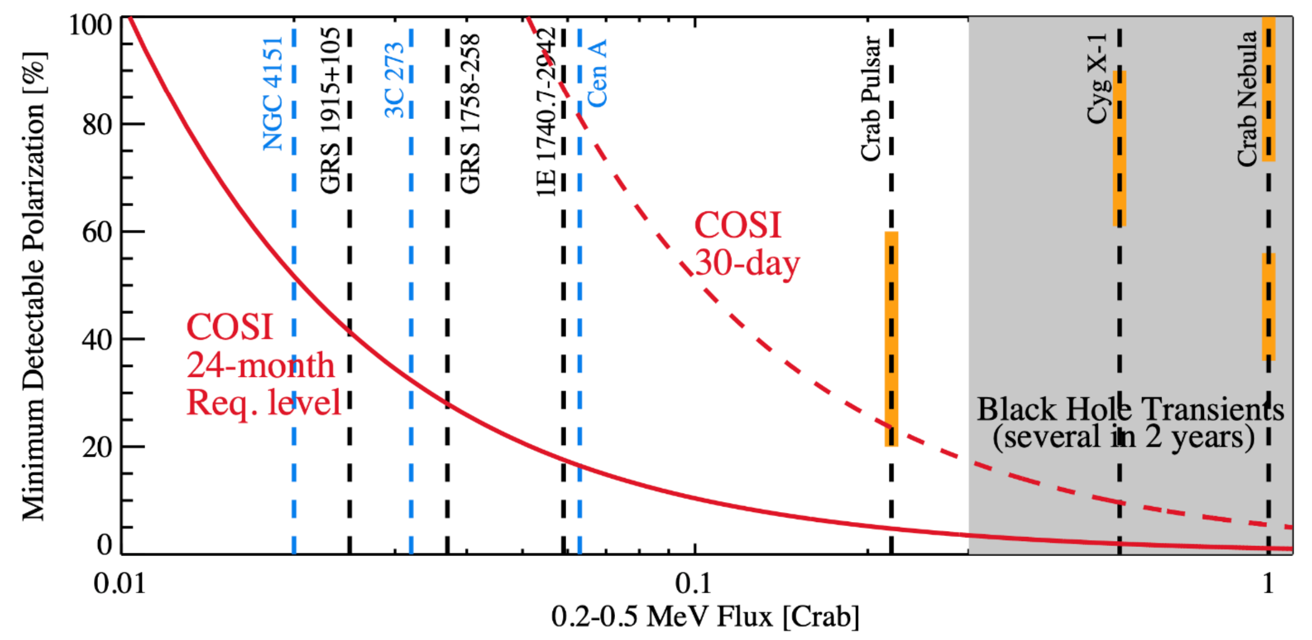


1. Fluid parameters such as the magnetic field evolution are calculated under first principles.
2. However, particle evolution is not included in this study, as we assume that the light crossing time scale is longer than the proton cooling time scale.

Zhang et al. 2019 ApJ 876, 109

Future Prospect

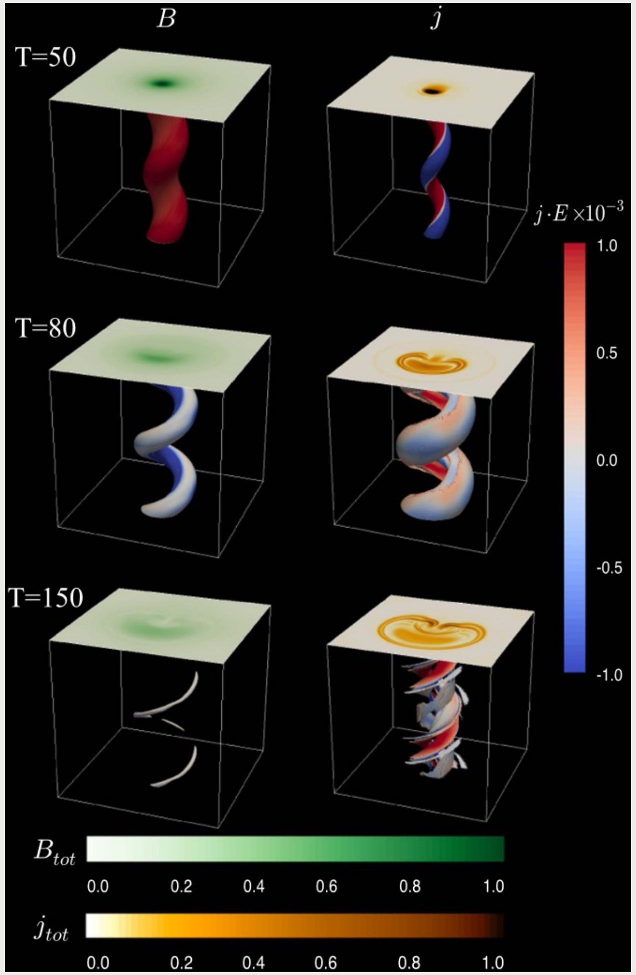




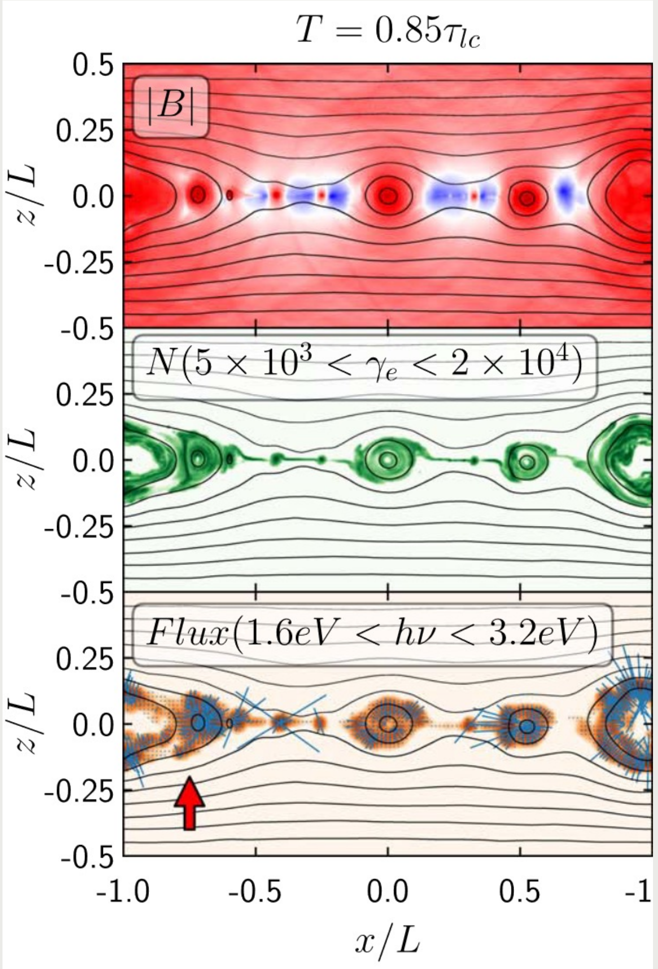
keV	MeV	ν	Conclusion
Y	Y	Y	Proton synchrotron, ν, UHECR (?)
N	Y	Y	Proton synchrotron, ν, UHECR (?)
Y	N	Y	Leptonic+hadronic cascades, ν, CR
Y/N	Y/N	N	Unknown mechanism (unlikely) or we need a better IceCube
N	N	Y	ν is not from the blazar zone
N	N	N	Pure leptonic

Flux: HEX-P, COSI, AMEGO-X, Astrogam
Polarization: IXPE, eXTP, COSI, AMEGO-X, Astrogam
Neutrino: IceCube-Gen2

Future Prospect

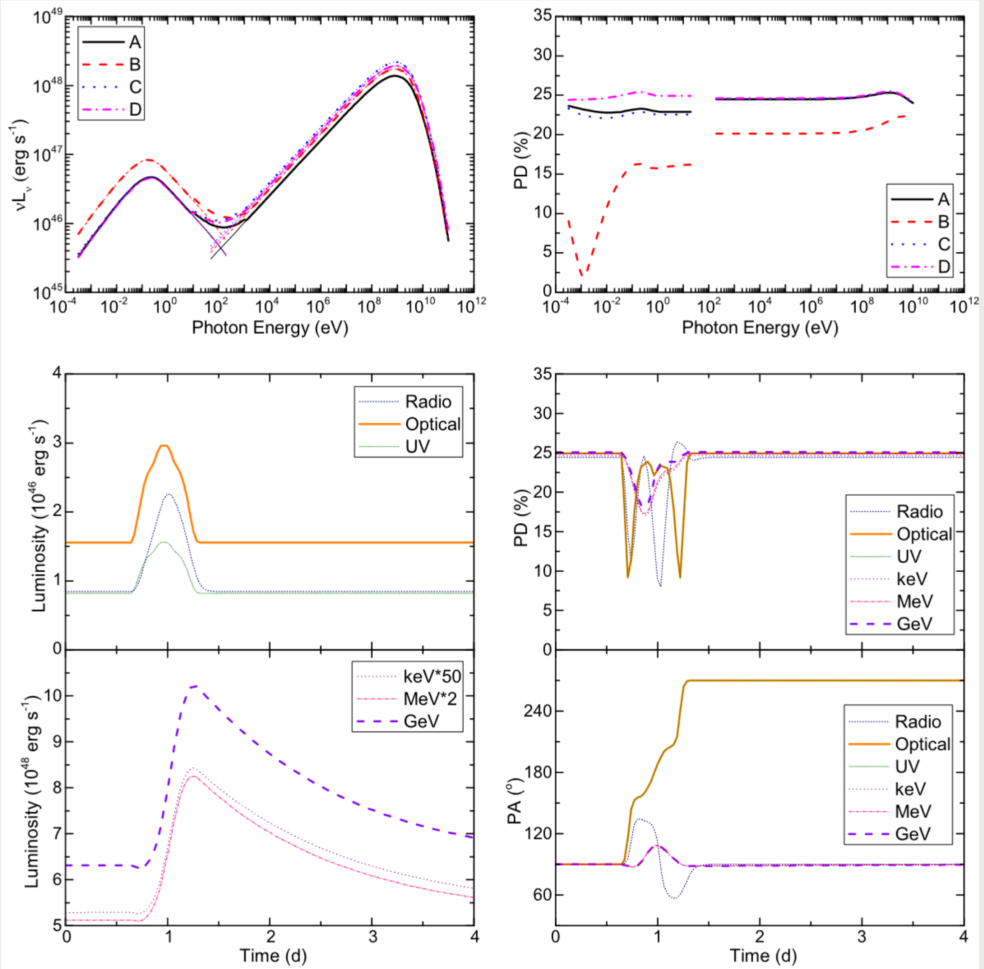


MHD



PIC

Parker Transport



Radiation Transfer

Time-domain and multi-messenger study of blazar jet requires a multi-scale, multi-physics model