

Tenth International Fermi Symposium

9th-15th October 2022

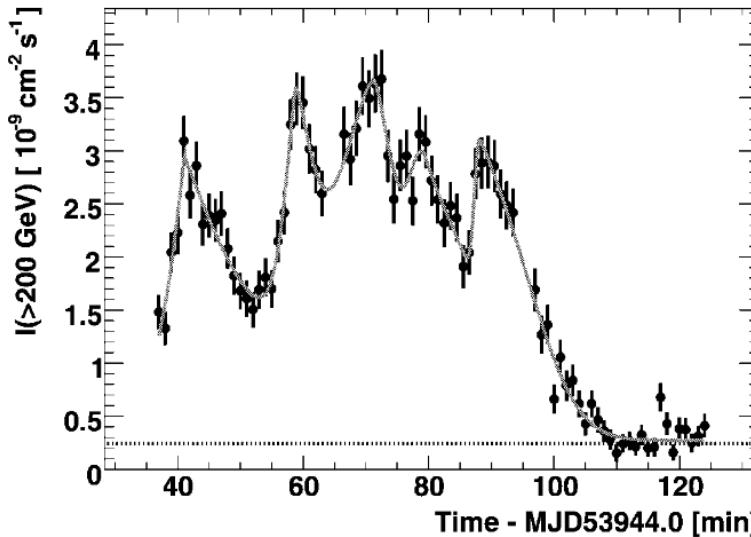
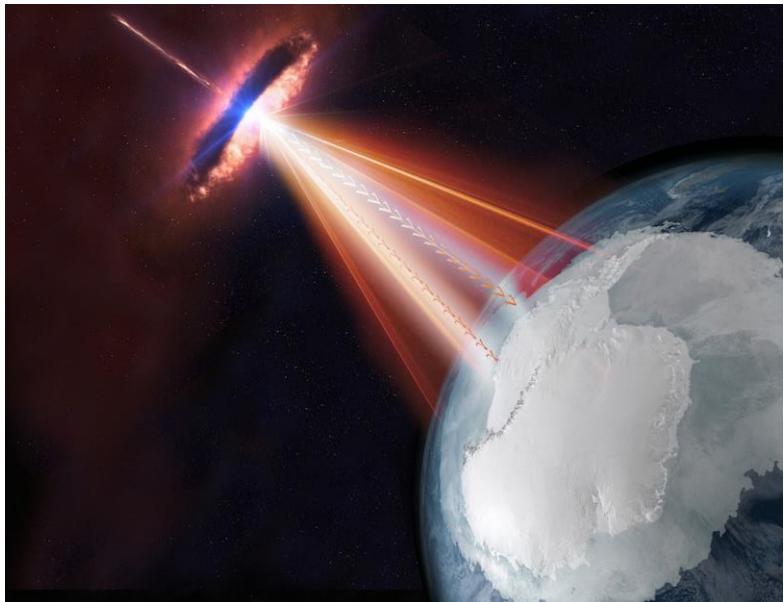
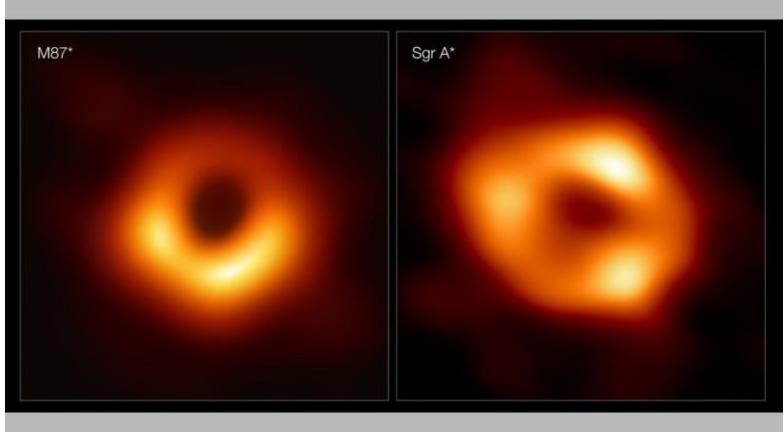


MULTI-WAVELENGTH EMISSION OF BLAZARS: CONNECTING THEORIES WITH OBSERVATIONS

HAOCHENG ZHANG (NPP FELLOW/NASA GSFC)

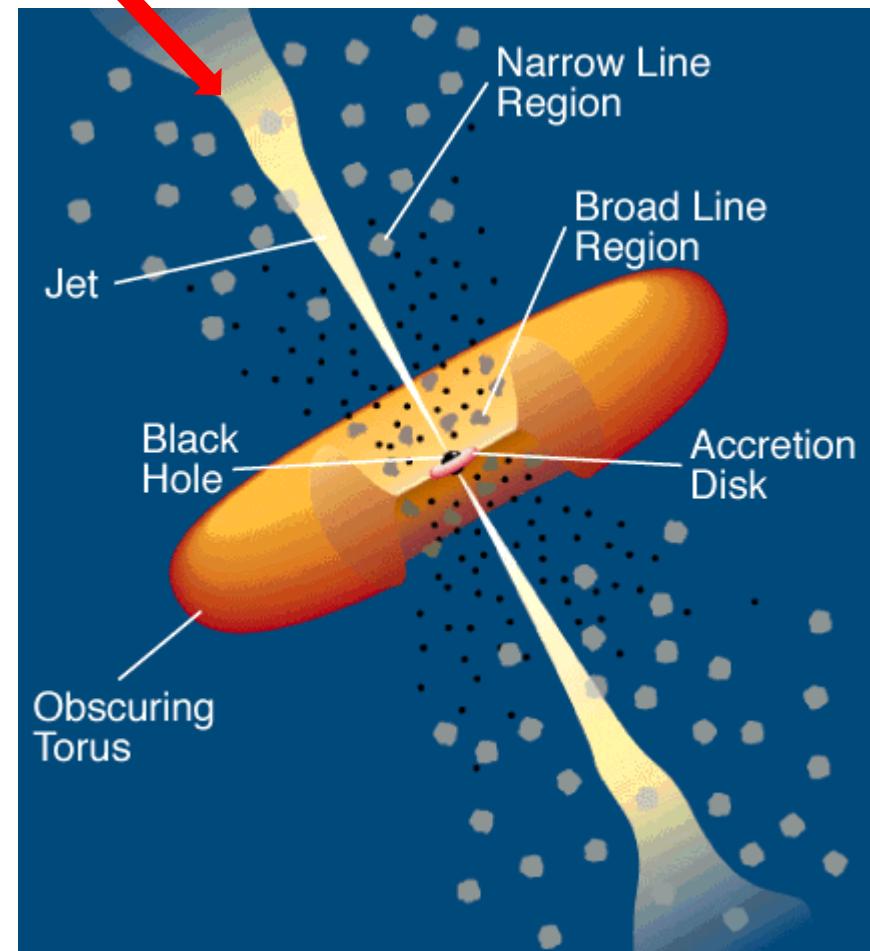
haocheng.zhang@nasa.gov

BLAZAR

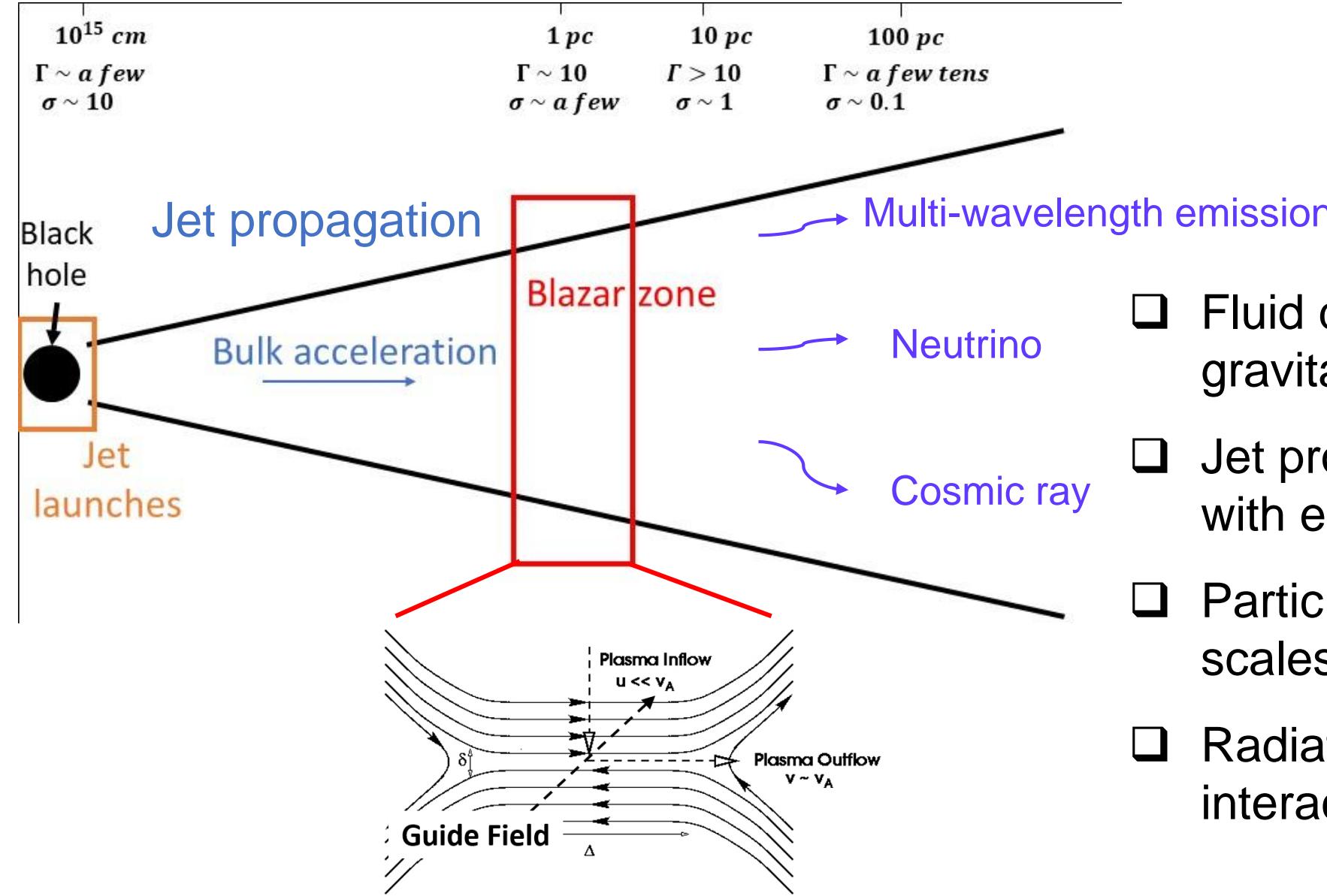


Flat spectrum radio quasar (FSRQ) has broad emission lines, BL Lac object (BL Lac) does not.

Blazar

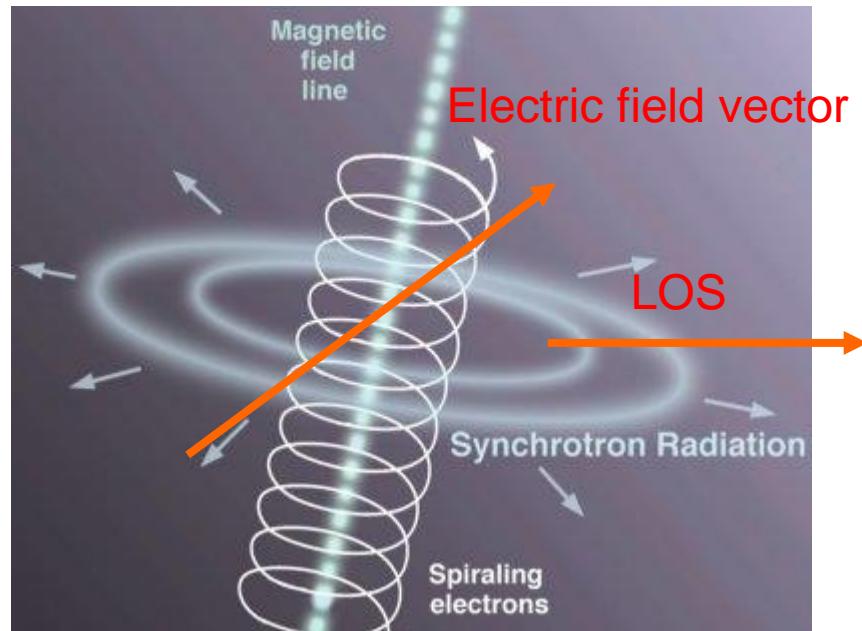


JET DYNAMICS

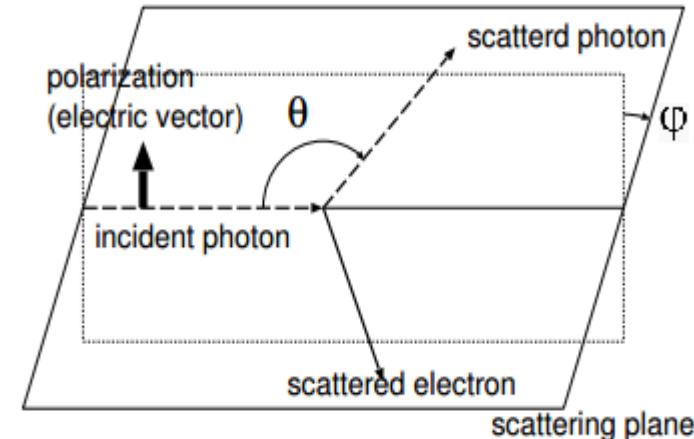


- Fluid dynamics in extreme gravitational field (GRMHD)
- Jet propagation and interaction with environment (SRMHD)
- Particle acceleration on kinetic scales (PIC/Particle transport)
- Radiation, photon and particle interactions (Radiation transfer)

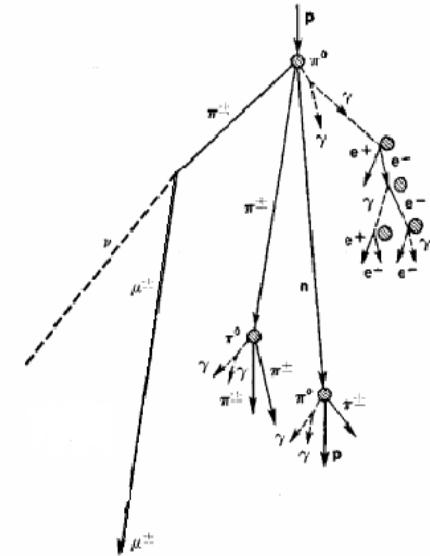
RADIATION MECHANISMS



Synchrotron is strongly polarized.

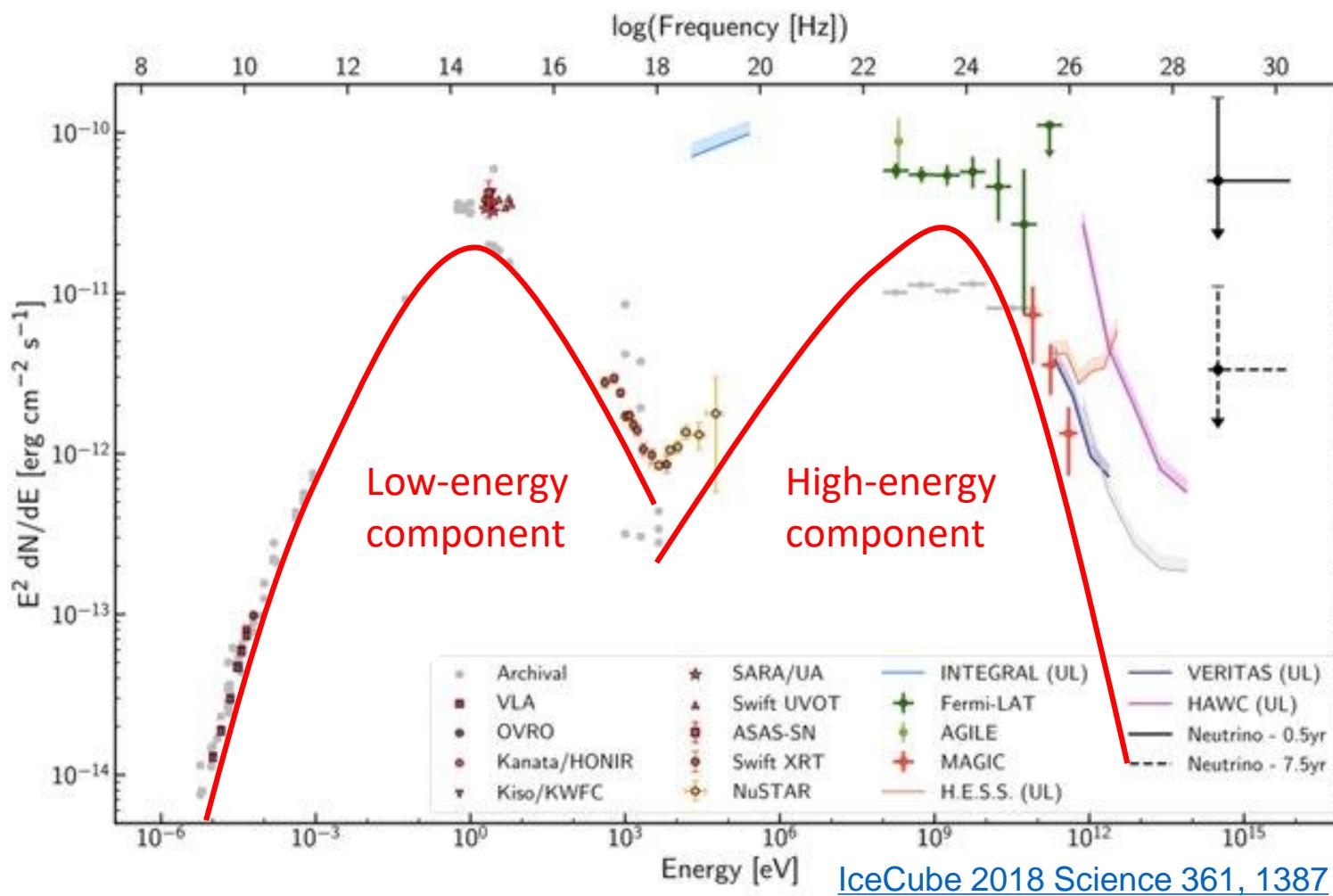


Compton scattering reduces polarization.



Protons and cascading charged particles can emit via synchrotron.

SPECTRUM AND NEUTRINO



Leptonic Model:

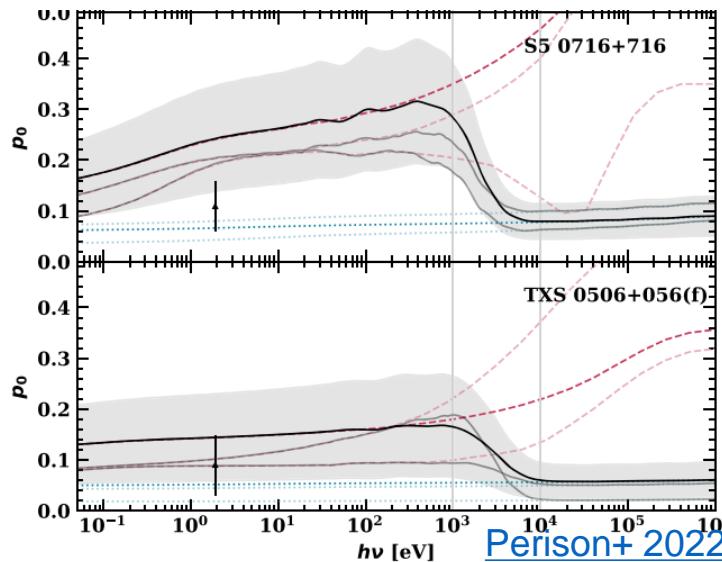
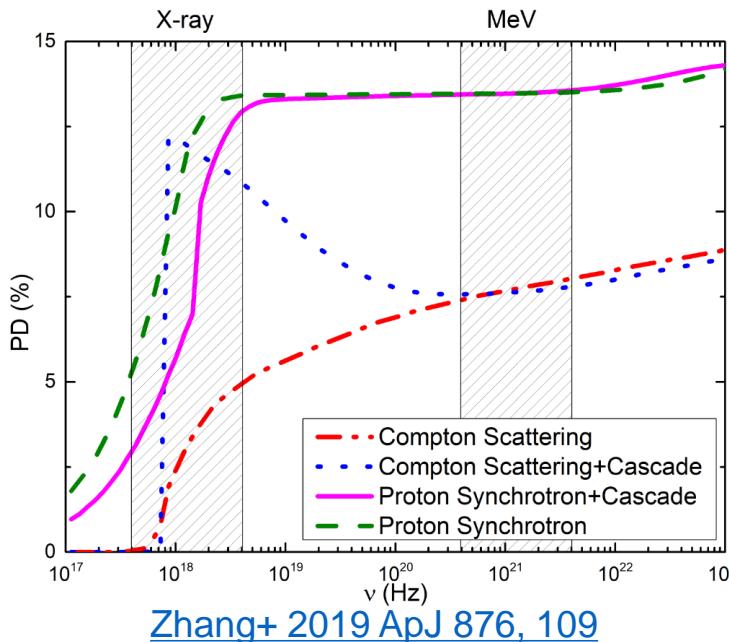
1. Inverse Compton scattering by electrons.
2. Seed photons may be synchrotron itself (SSC), or external thermal photons (EC).

Hadronic Model:

1. Proton synchrotron and/or hadronic cascades.
2. Inverse Compton scattering by electrons can contribute as well.
3. Acceleration of cosmic rays and production of neutrinos

Neutrinos are detected!

HIGH-ENERGY POLARIMETRY



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

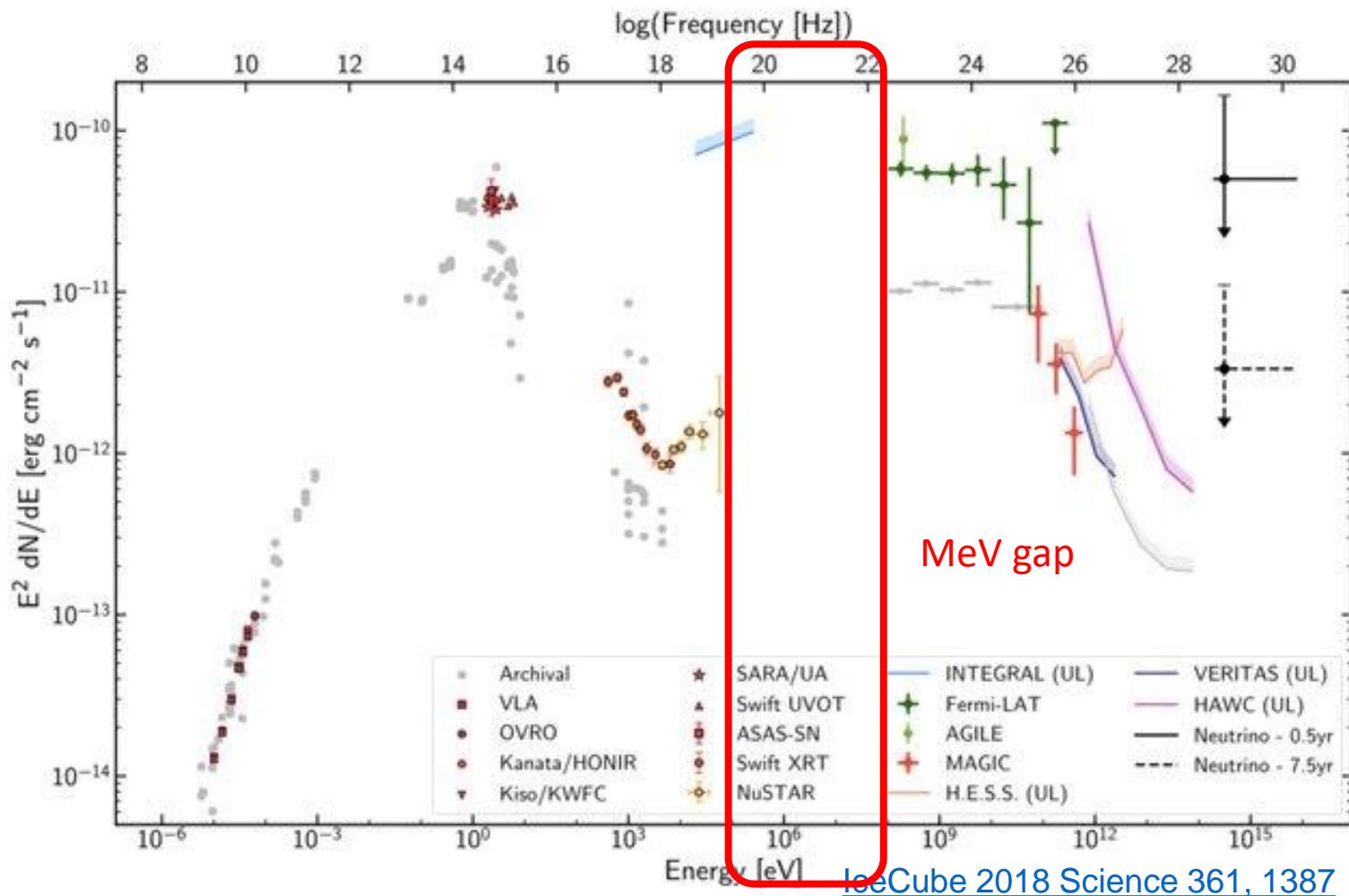
See my poster

X-ray polarimetry: IXPE, eXTP

MeV polarimetry: COSI, AMEGO-X, AMEGO, e-Astrogam

Multi-wavelength spectropolarimetric model (talk by Hester Schutte)

MEV GAP

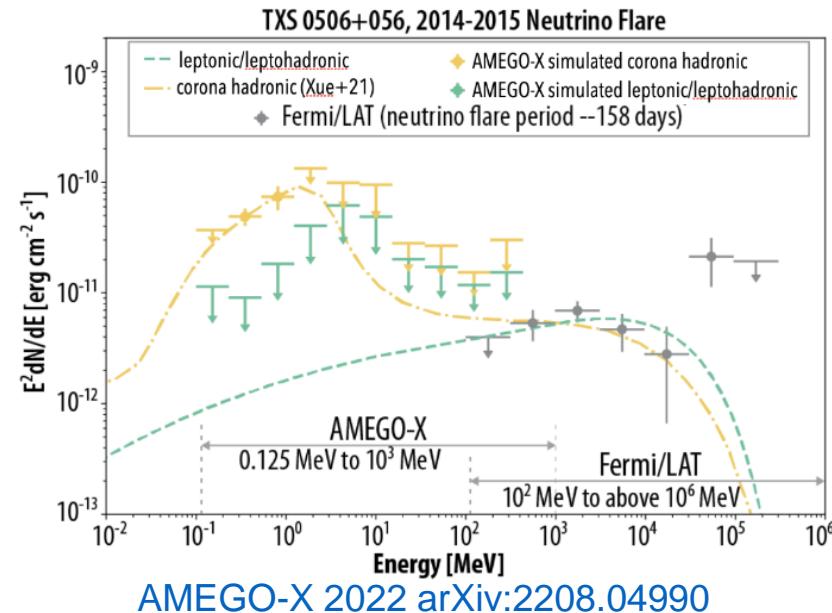
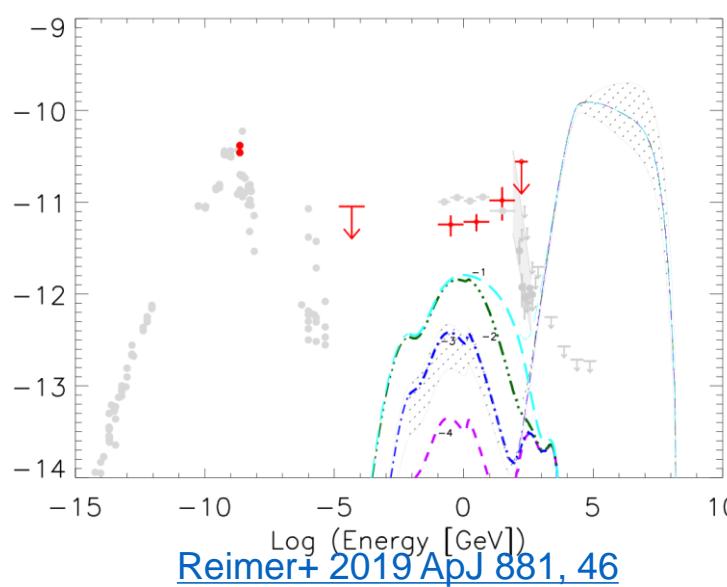
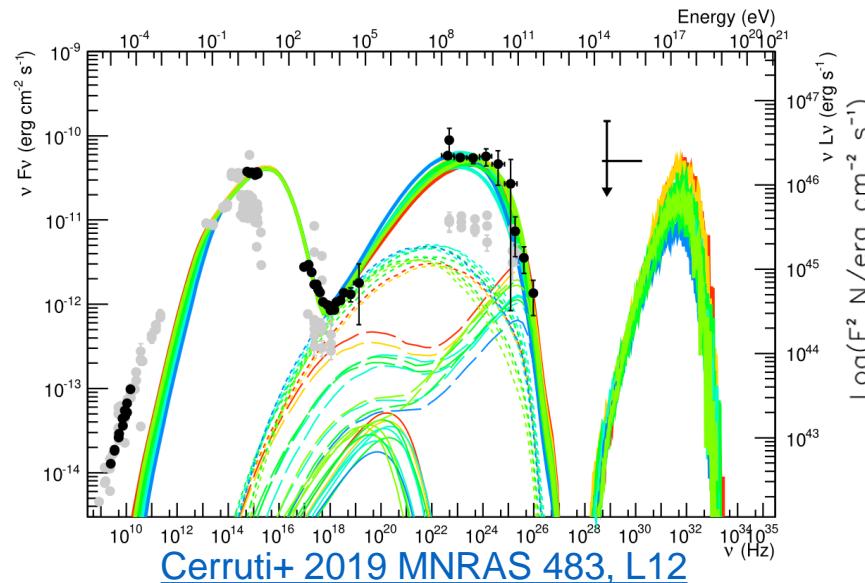


- ❑ What kind of blazars can emit neutrinos?
- ❑ Can they also accelerate ultra-high-energy cosmic rays?
- ❑ How to find more?

MeV band is crucial for constraining hadronic models!

COSI (talk by Michela Negro),
AMEGO-X (talk by Regina Caputo),
AMEGO, e-Astrogram

HADRONIC MODEL



Physical Processes	Codes			
	AM3	ATHEvA	B13	LeHa-Paris
electron synchrotron radiation	✓	✓	✓	✓
synchrotron self-absorption	✓	✓	✓	✓
electron inverse Compton scattering	✓	✓	✓	✓
electron-positron annihilation	✓	✓	✓	✗
photon-photon pair production	✓	✓	✓	✓
triplet pair production	✗	✓	✗	✗
proton synchrotron radiation	✓	✓	✓	✓
proton inverse Compton scattering	✓	✗	✗	✗
proton-photon pair production	✓	✓	✓	✓
neutron-photon pion production	✓	✓	✗	✗
kaon synchrotron radiation	✗	✓	✗	✗
pion synchrotron radiation	✓	✓	✗	✗
muon synchrotron radiation	✓	✓	✗	✓

Cerruti+ 2021 arXiv:2107.06377

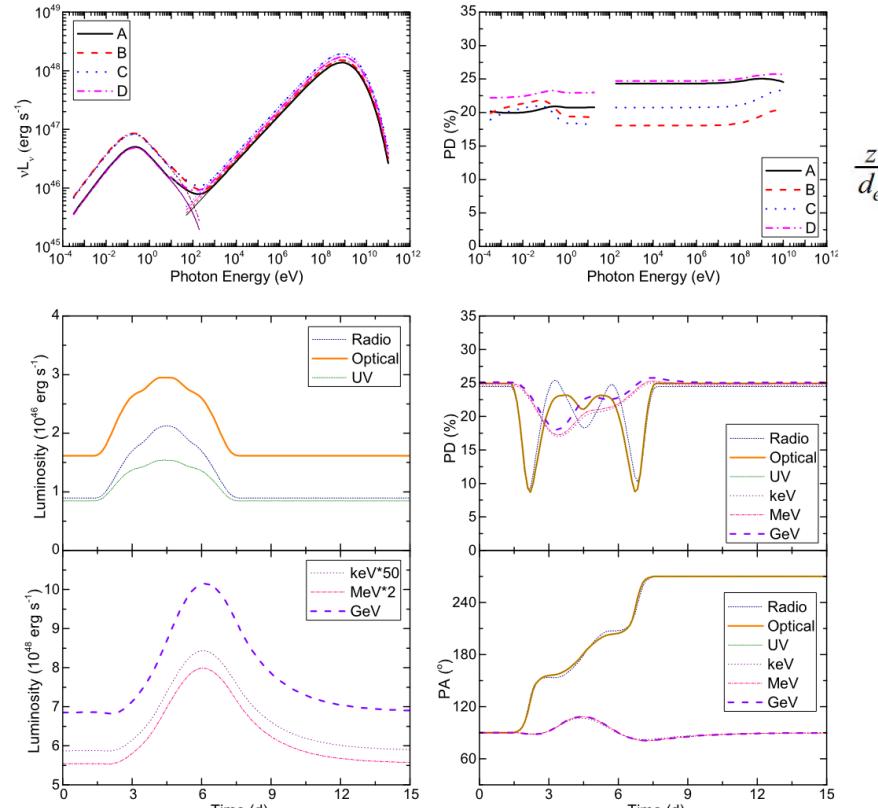
- One-zone model cannot well explain the 2017 event or the 2014-2015 period.
- Many free model parameters cannot be constrained.
- X-ray band cannot distinguish leptonic/hadronic models, but can put soft upper limits on the photomeson process.

MeV band is the key! (talk by Tiffany Lewis)

Hadronic codes yield similar results (talk by Natalia Żywucka)

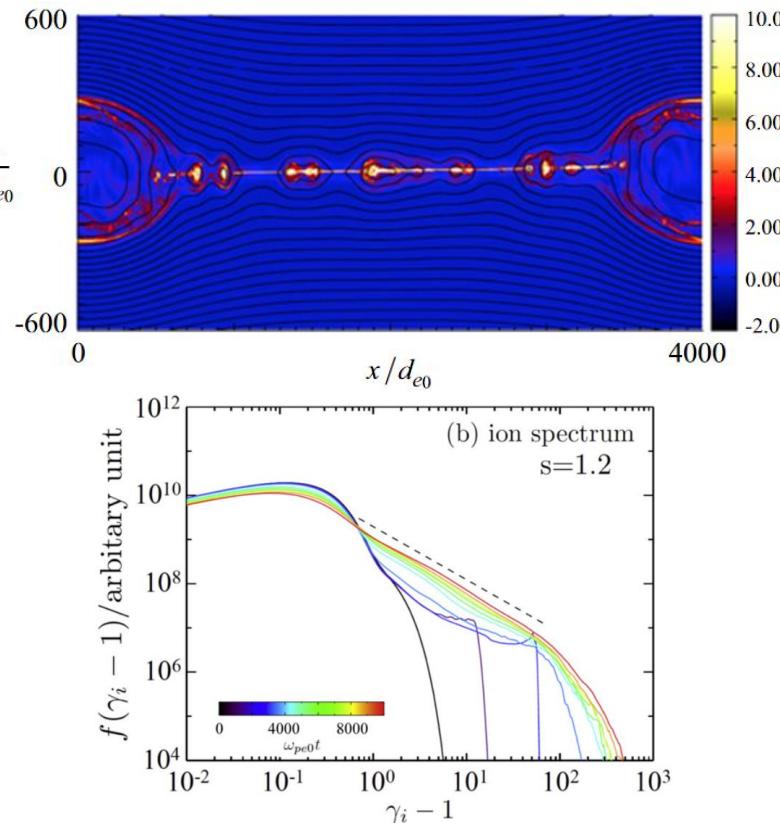
HADRONIC MODEL

Multi-zone time-dependent



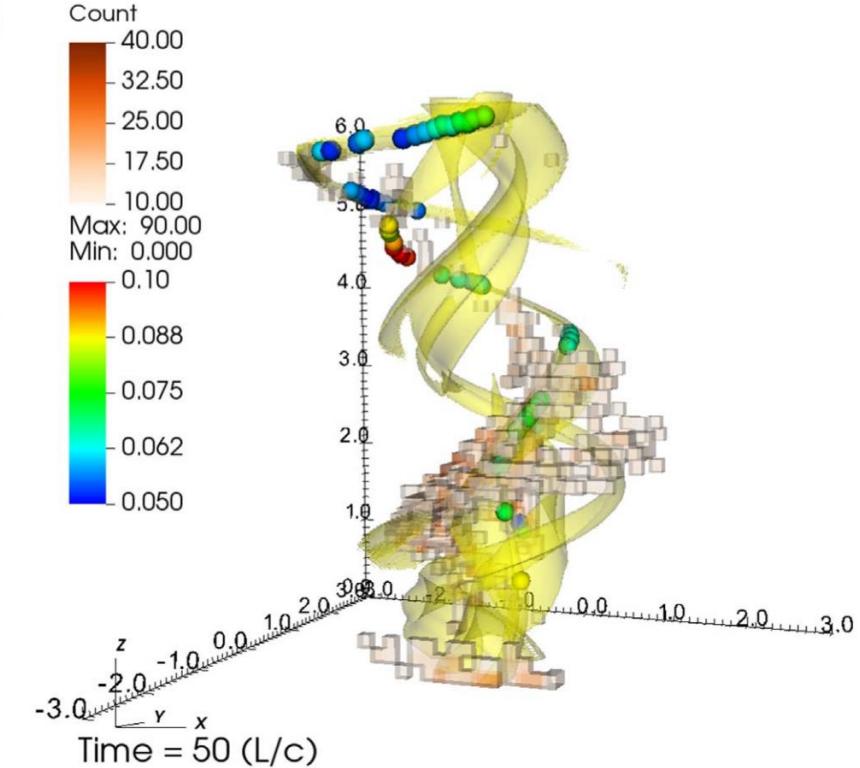
[Zhang+ 2016 ApJ 829, 69](#)

Particle-in-cell (PIC)



[Guo+ 2016 ApJL 818, L9](#)

Magnetohydrodynamics (MHD)



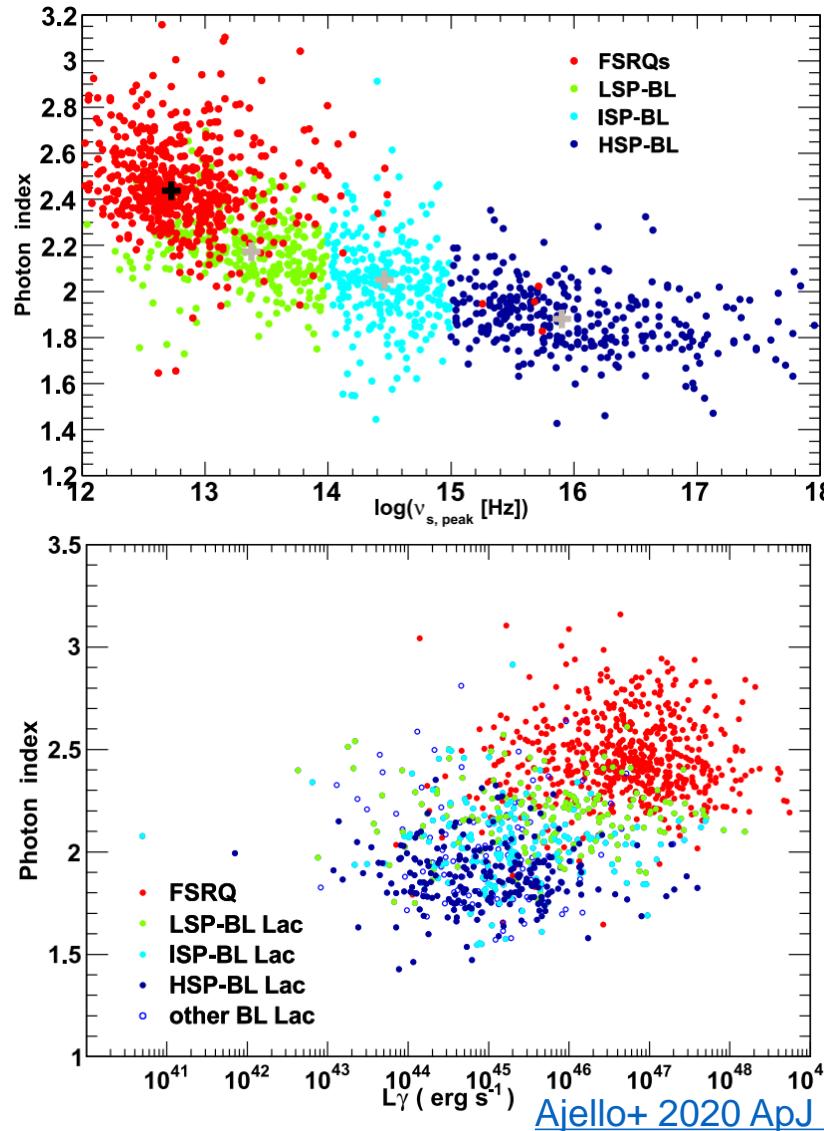
[Medina-Torrejon+ 2021 ApJ 908, 193](#)

Masquerading BL Lac? Spine-sheath structure? Multi-messenger temporal correlation?

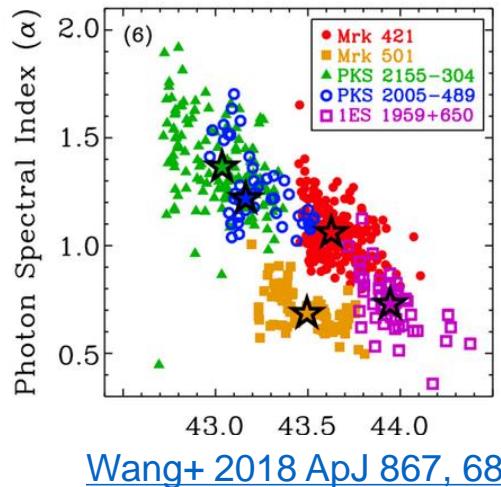
Time-dependent multi-zone hadronic codes integrated with MHD/PIC are under development.

SPECTRAL BEHAVIORS

More blazar sequences



Harder-when-brighter

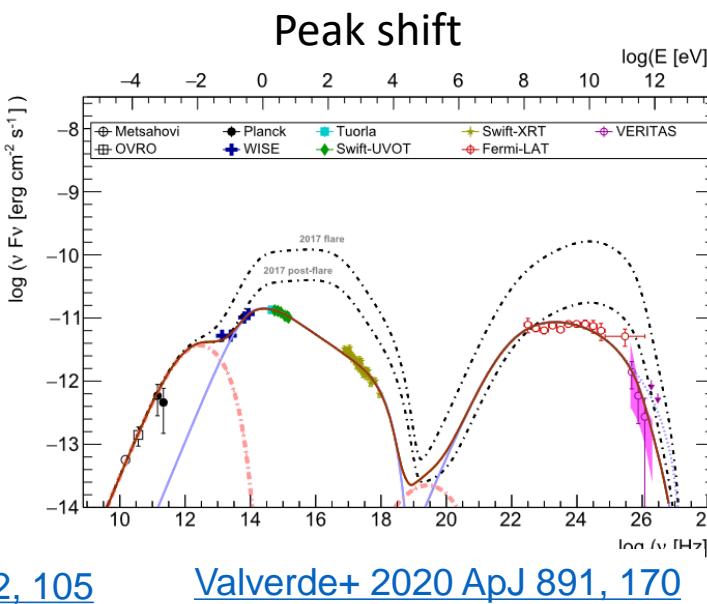


[Wang+ 2018 ApJ 867, 68](#)

Blazar sequence requires the reduction of fitting variables to a few key parameters

Harder-when-brighter hints on particle acceleration

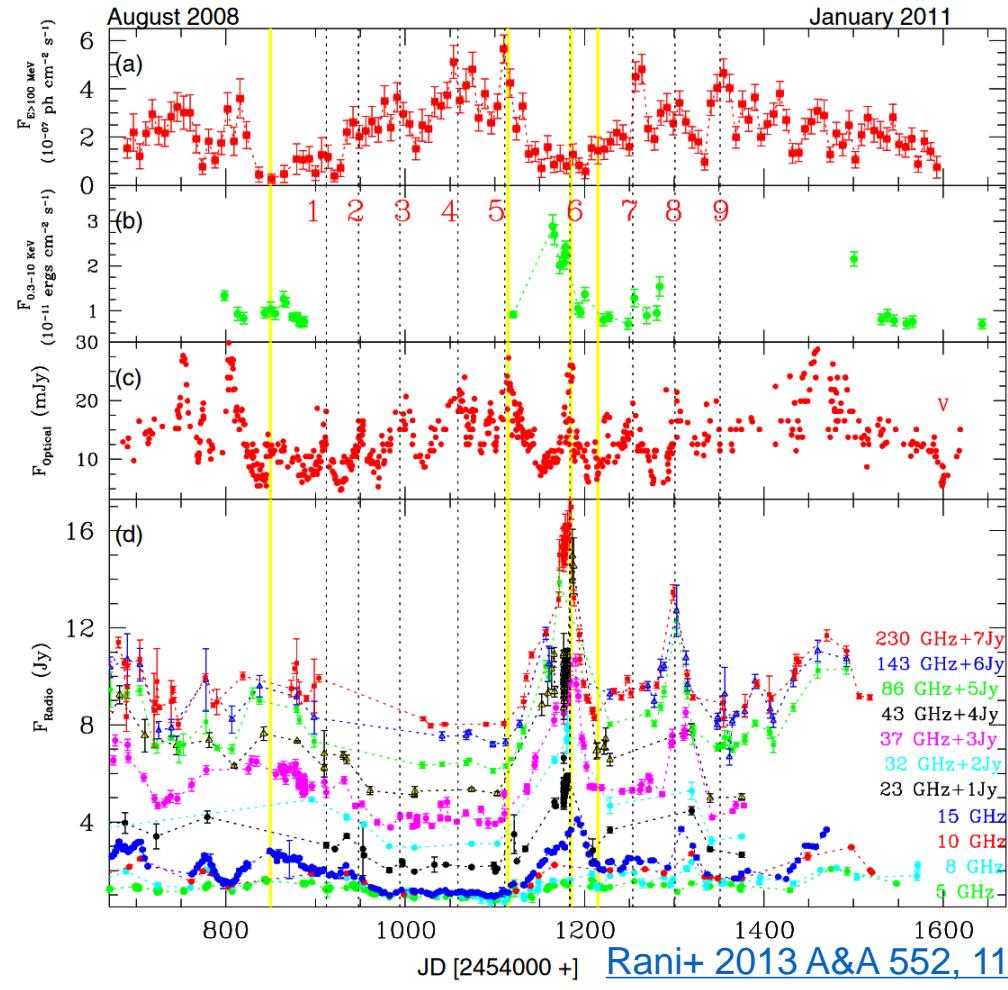
Peak shift results from new emission components or extreme particle acceleration?



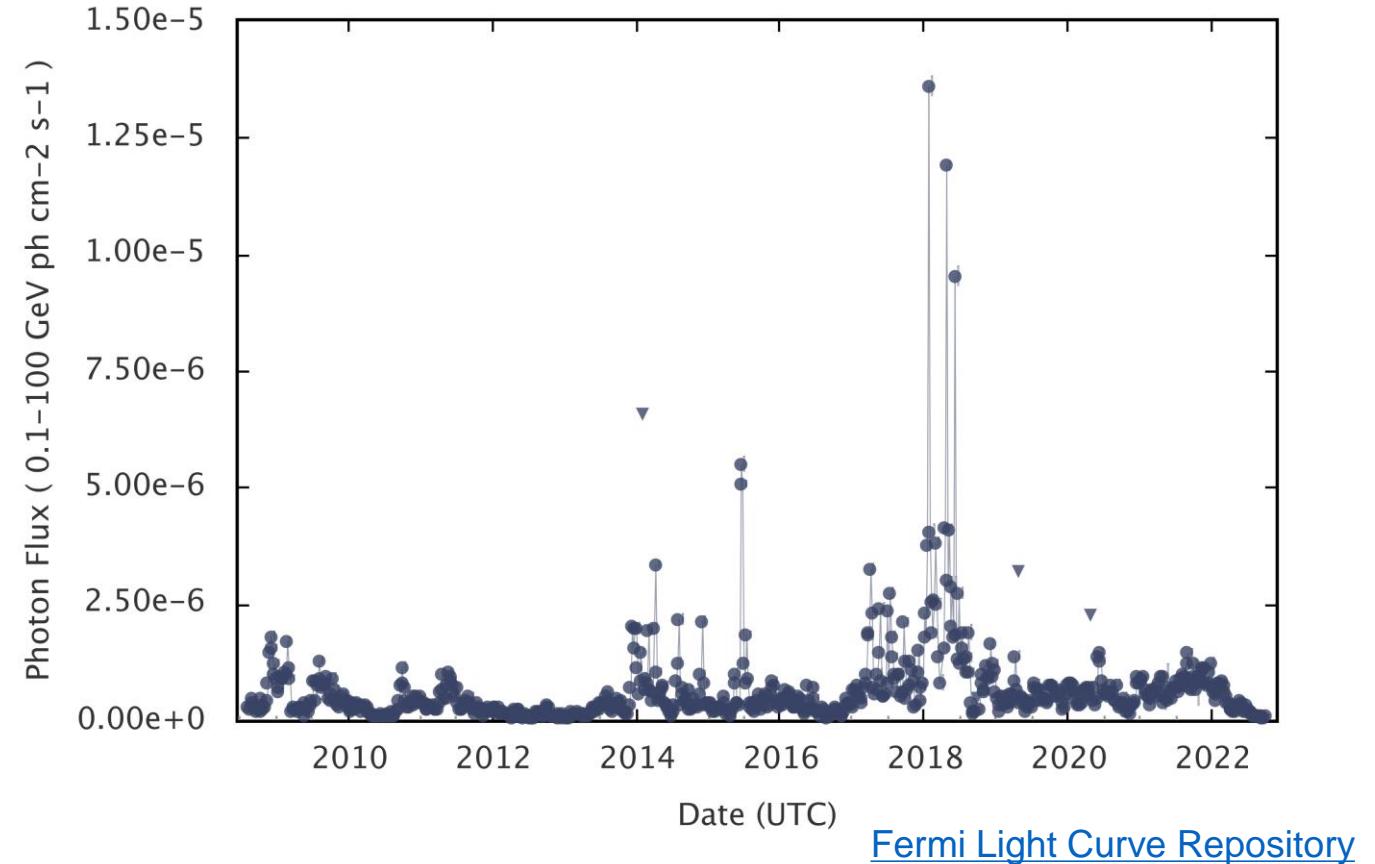
[Valverde+ 2020 ApJ 891, 170](#)

Semi-analytical model needed for the global jet + blazar zone dynamics

VARIABILITY



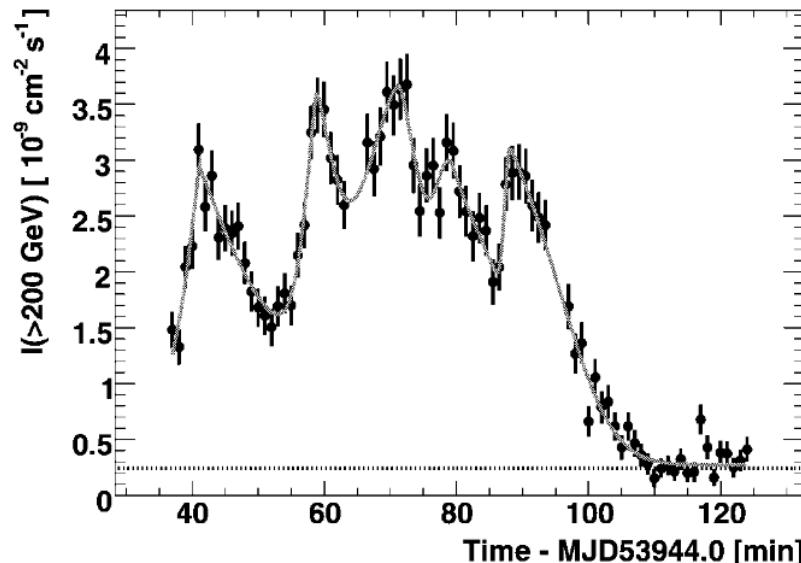
Multi-wavelength correlation sheds light on jet evolution, particle acceleration, radiation mechanisms



Simultaneous, high cadence, long-term monitoring is crucial for multi-messenger studies

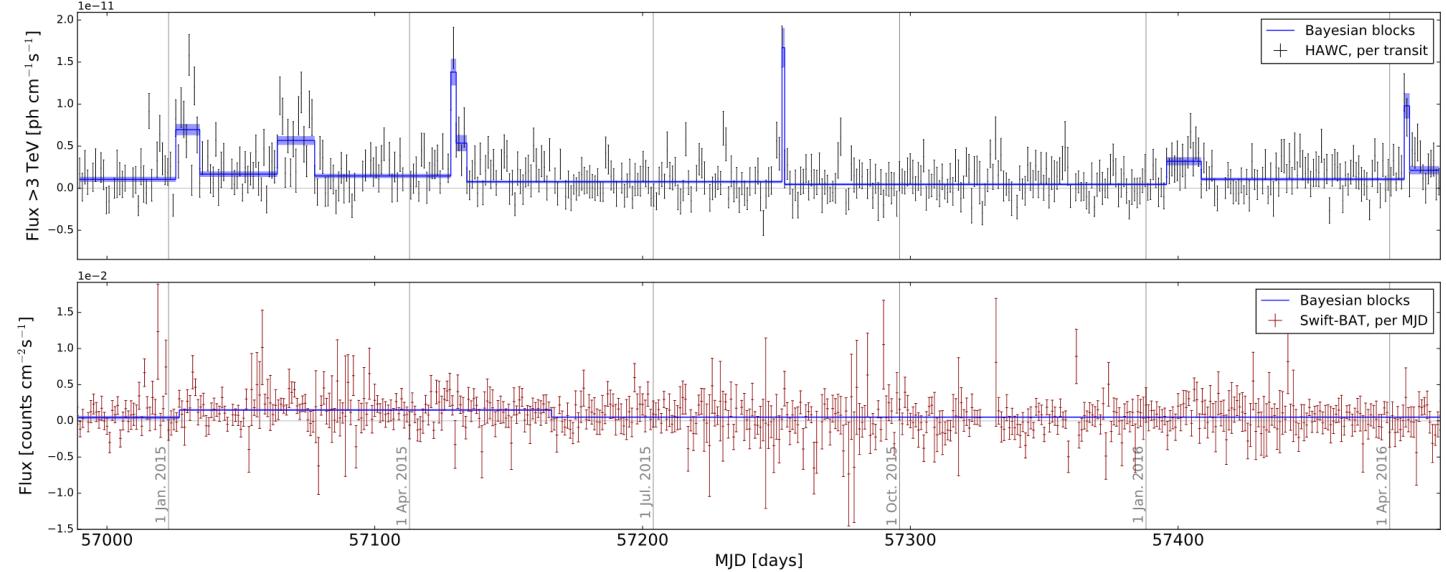
FAST FLARES ORPHAN FLARES

Minute-scale variability

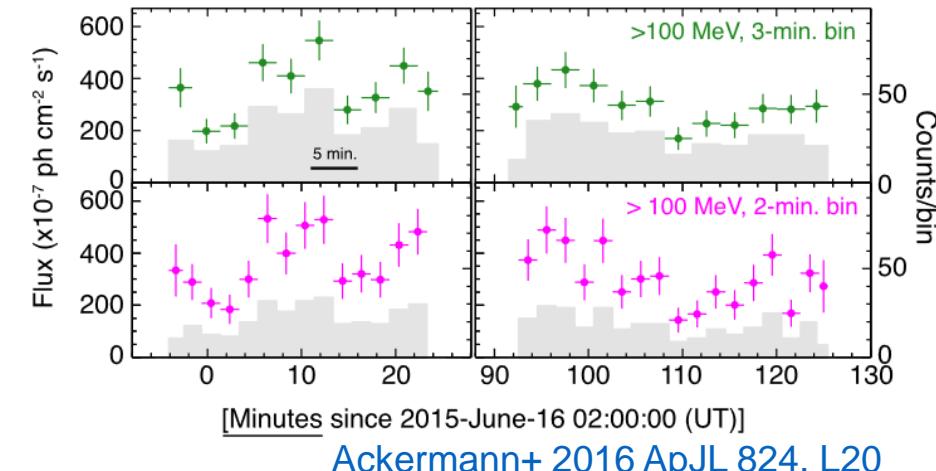


[Aharonian+ 2007 ApJL 664, L71](#)

Orphan TeV flare



[Abeysekara+ 2017 ApJ 841, 100](#)



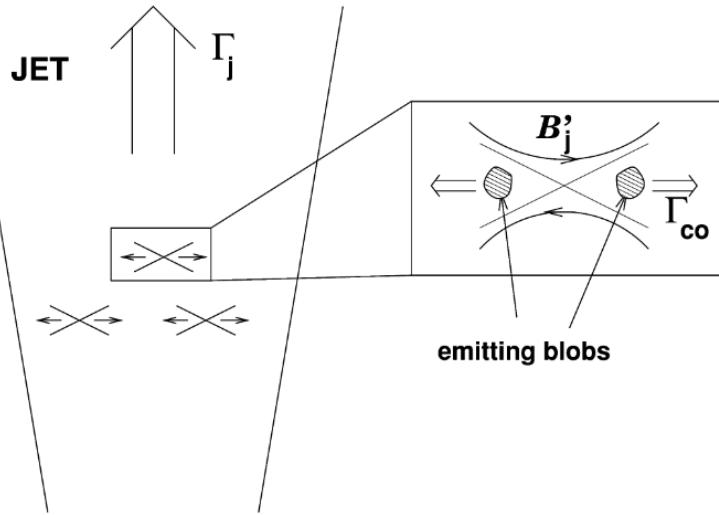
[Ackermann+ 2016 ApJL 824, L20](#)

Fast flares and orphan flares are only possible with high-cadence multi-wavelength monitoring.

- Extreme particle acceleration
- Hadronic signatures?

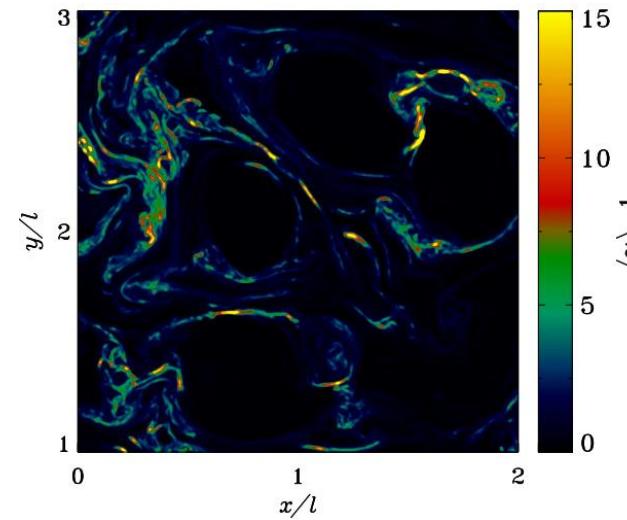
MINI-JET ANISOTROPY INHOMOGENEITY

Mini-jet



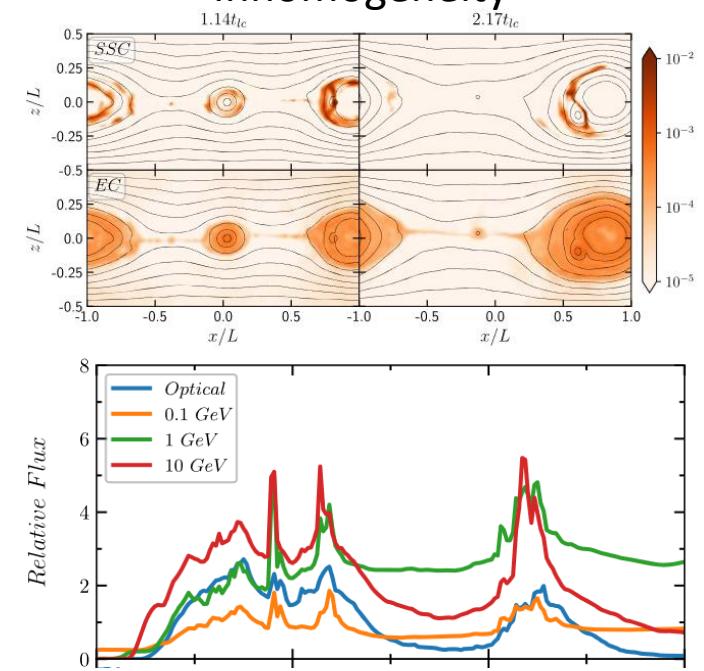
[Giannios+ 2009 MNRAS 395, L29](#)

Anisotropy



[Sobacchi+ 2021 MNRAS 503, 688](#)

Inhomogeneity



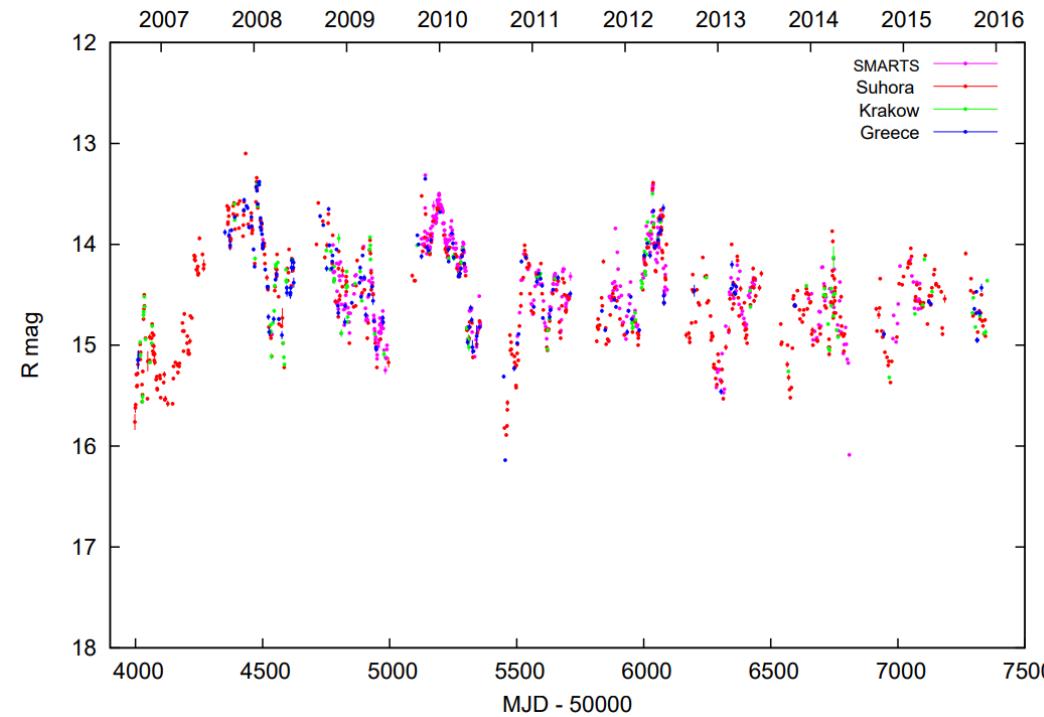
[Zhang+ 2022 ApJ 924, 90](#)
or see my poster

Magnetized blazar zone!

- ❑ Mini-jet allows extreme Doppler boosting in tiny regions, which may result from magnetic reconnection.
- ❑ Anisotropy may come from particle acceleration along magnetic field lines in turbulence, suppressing synchrotron emission.
- ❑ Plasmoid mergers in reconnection can lead to high concentration of particles in low magnetic field regions, strongly boosting SSC.

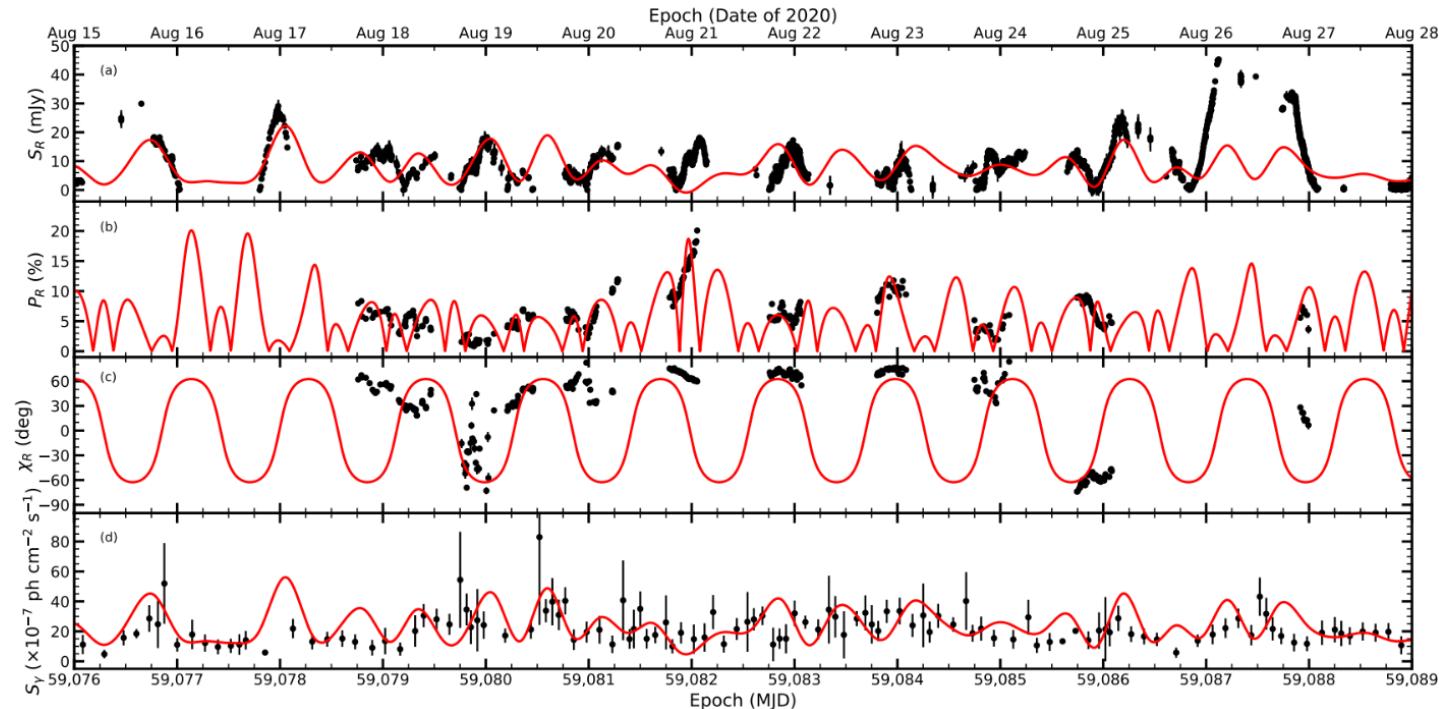
QUASI-PERIODIC OSCILLATION

Long-term QPO



[Bhatta+ 2016 ApJ 832, 47](#)

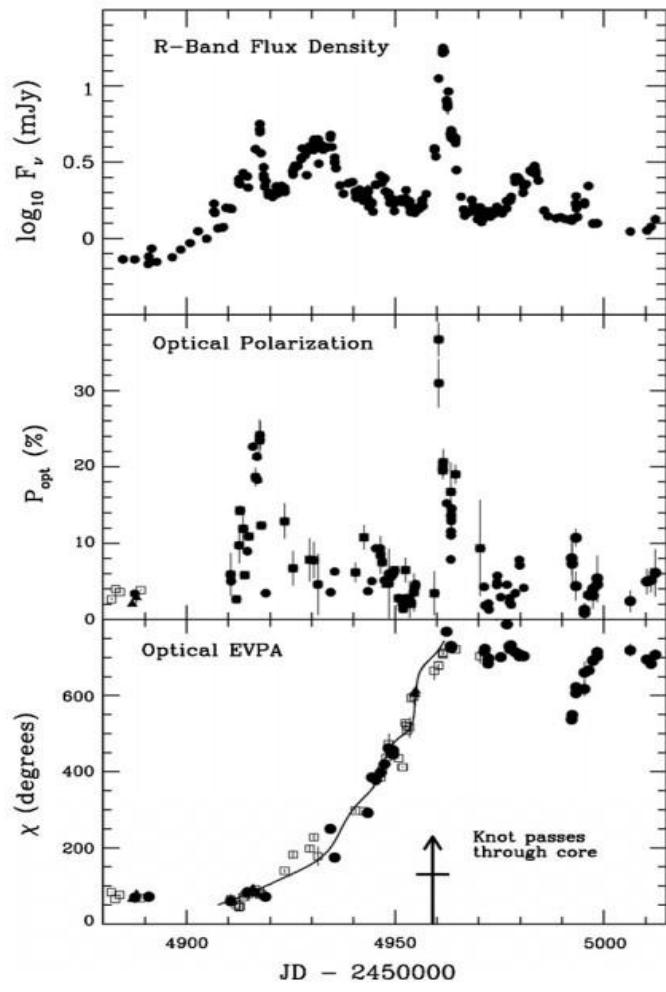
Rapid QPO



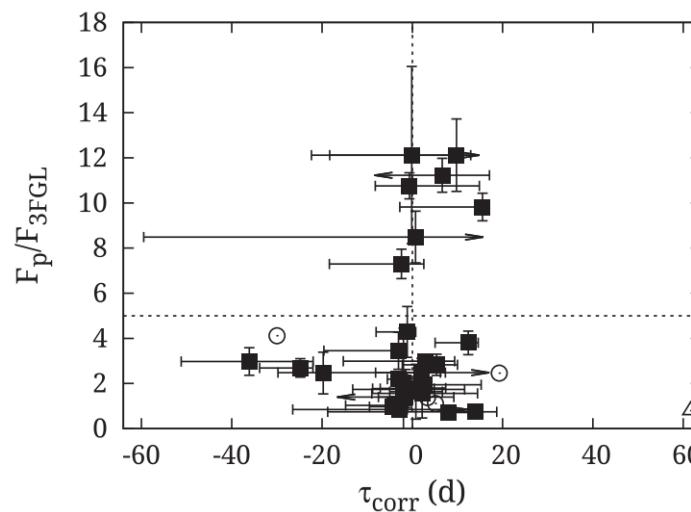
[Jorstad+ 2022 Nature 609, 265](#)

- Long-term QPO (period \sim year) may result from supermassive black hole binaries, jet precession, or helical morphology.
- Short-term QPO (period $<$ month) may come from kink instabilities.
- Long-term multi-wavelength monitoring (with polarization) is the key to QPO searches.¹³

POLARIZATION MONITORING



[Marscher+ 2010 ApJL 710, L126](#)



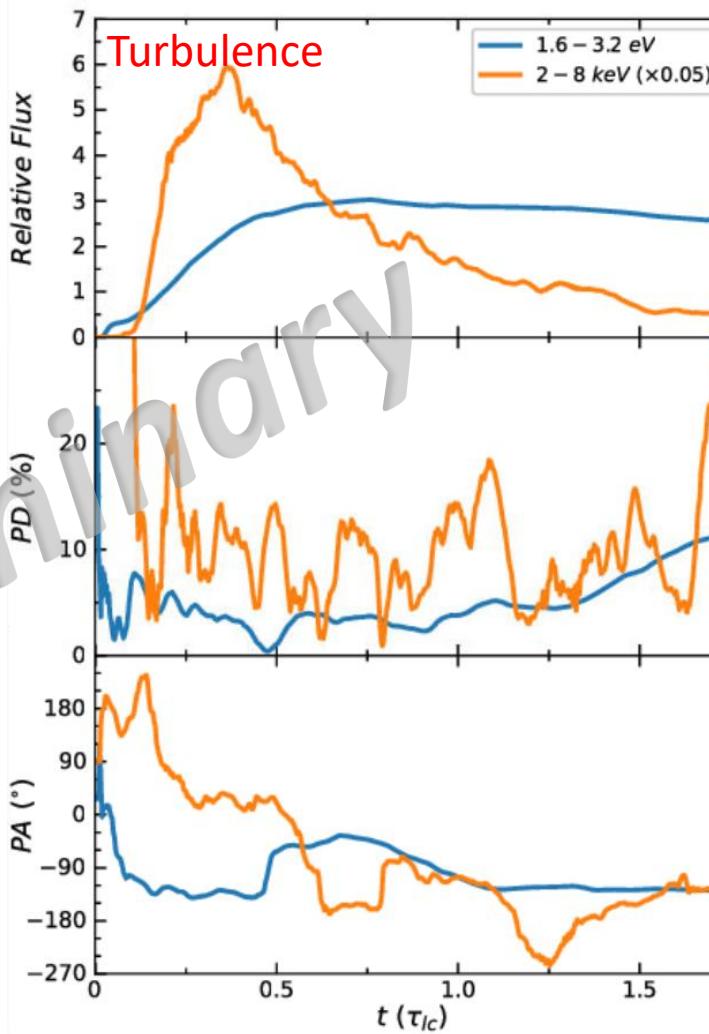
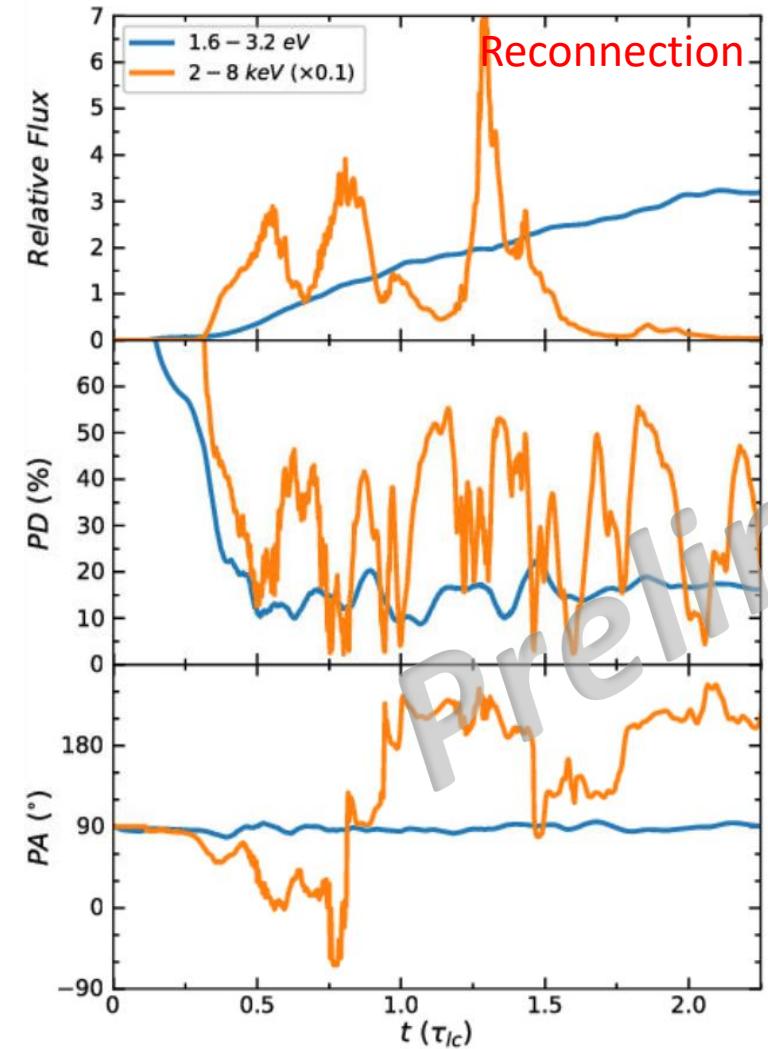
[Blinov+ 2018 MNRAS 474, 1296](#)

- Polarization angle swings are associated to flares
- Co-evolution of magnetic field and nonthermal particles
- Energy stratified particle distribution

Model	Multiwavelength polarization	X-ray polarization variability [†]	X-ray polarization angle
Single-zone	constant*	slow	any
Multi-zone	mildly chromatic	high	any
Energy stratified (shock)	strongly chromatic	slow	along the jet axis
Magnetic reconnection (kink instability)	constant	moderate	perpendicular to jet axis
Observed	strongly chromatic	slow	along the jet axis

[Lioudakis+ 2022 arXiv:2209.06227](#)

OPTICAL AND X-RAY POLARIMETRY



Energy stratified particles require treatment of particle evolution!

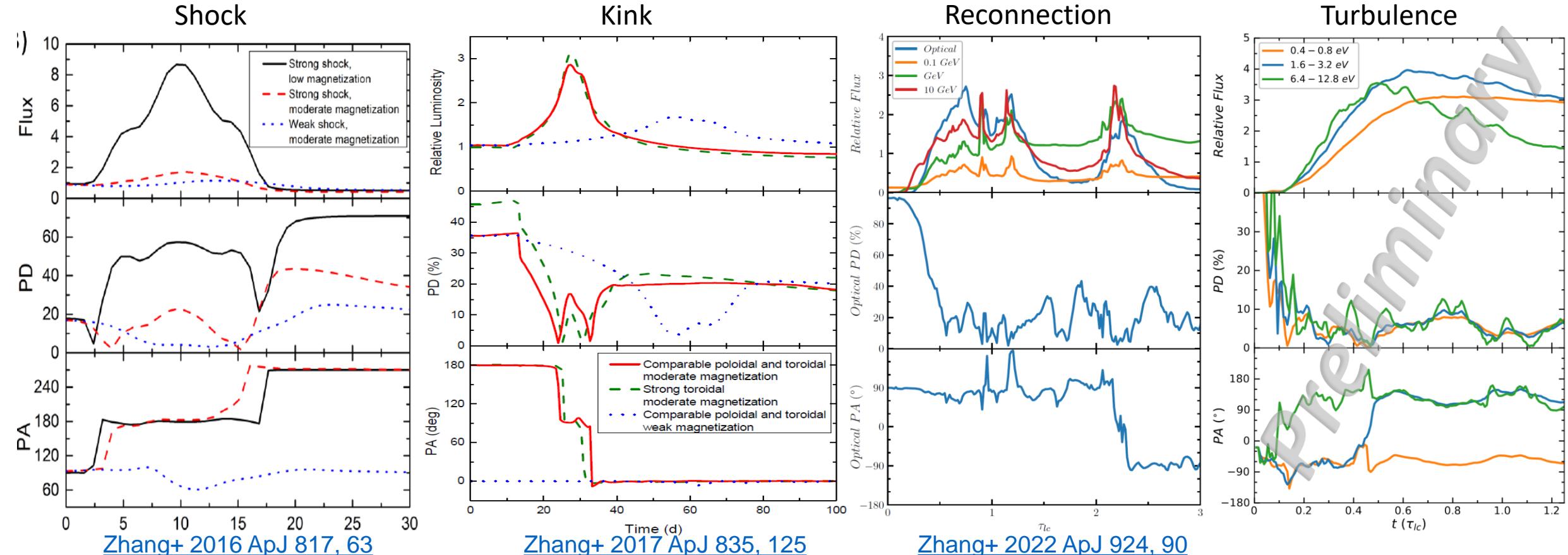
Reconnection

- ❑ Flashes of high X-ray polarization $\sim 40\text{-}50\%$
- ❑ Fast X-ray angle swings

Turbulence

- ❑ Relatively low X-ray polarization degree (10-20%)
- ❑ Slow X-ray angle swings not associated to flare/PD changes.

PHYSICS OF ANGLE SWING



- Step-like angle rotations
- Unrealistic high PD
- 180 degree max

- PD drops during swing
- 180 degree max

- PD drops during swing
- Can go beyond 180 degree

- Flare, PD, swings are uncorrelated
- Orphan swing

FUTURE PROSPECT

Neutrino and gravitational wave

Multi-wavelength (**MeV gap**)

Simultaneous high cadence

Long-term monitoring

Polarimetry

Multi-messenger
Statistical trend

Machine learning

Radiation transfer

Particle-in-cell

Magnetohydrodynamics

Particle transport

Semi-analytical model

Machine learning/AI can help to match the cadence of observations and simulations, enable apples-to-apples comparison and examine the validity of statistical trends.

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THANK YOU FOR YOUR ATTENTION!

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