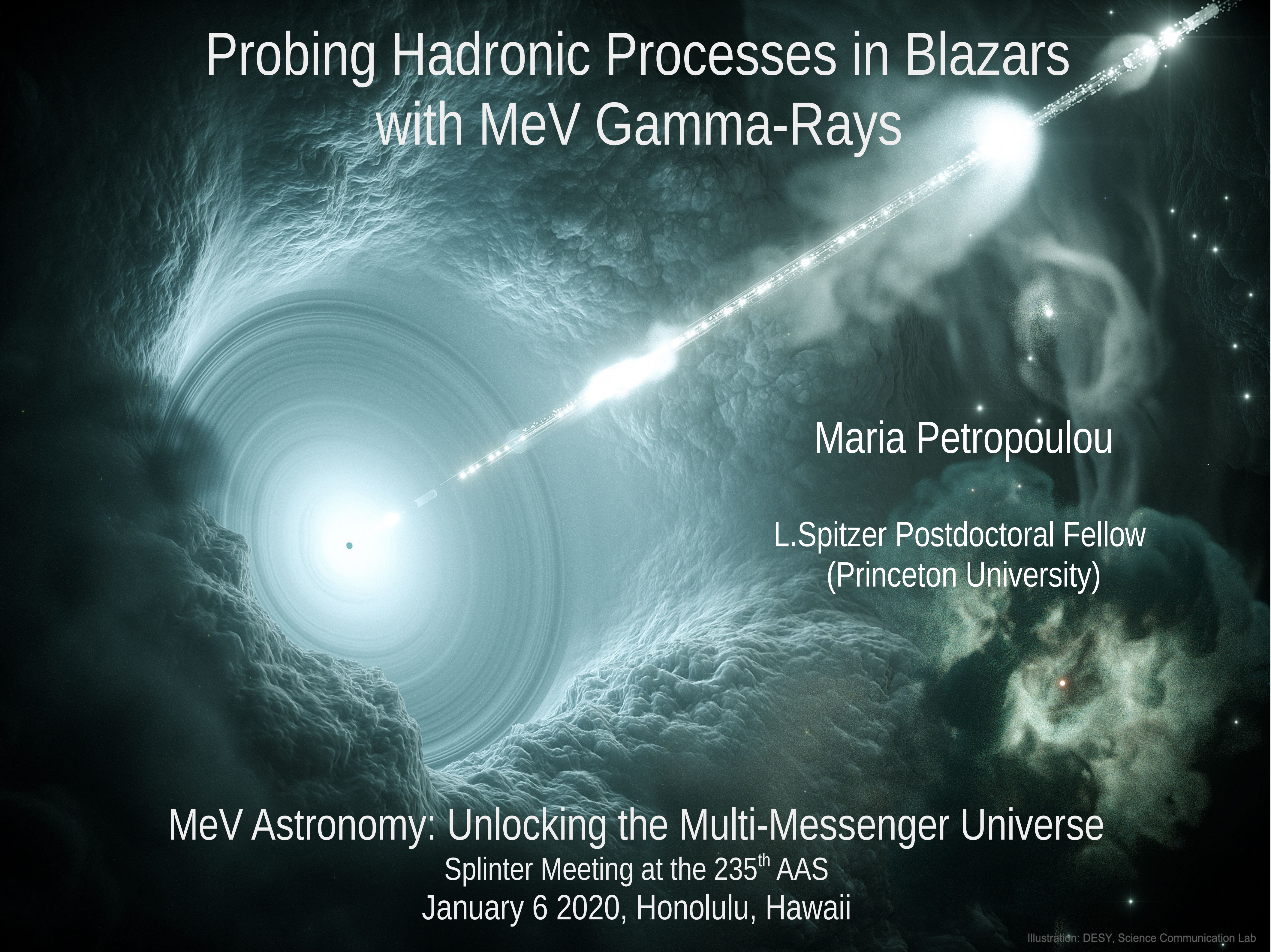


Probing Hadronic Processes in Blazars with MeV Gamma-Rays

Maria Petropoulou

L.Spitzer Postdoctoral Fellow
(Princeton University)

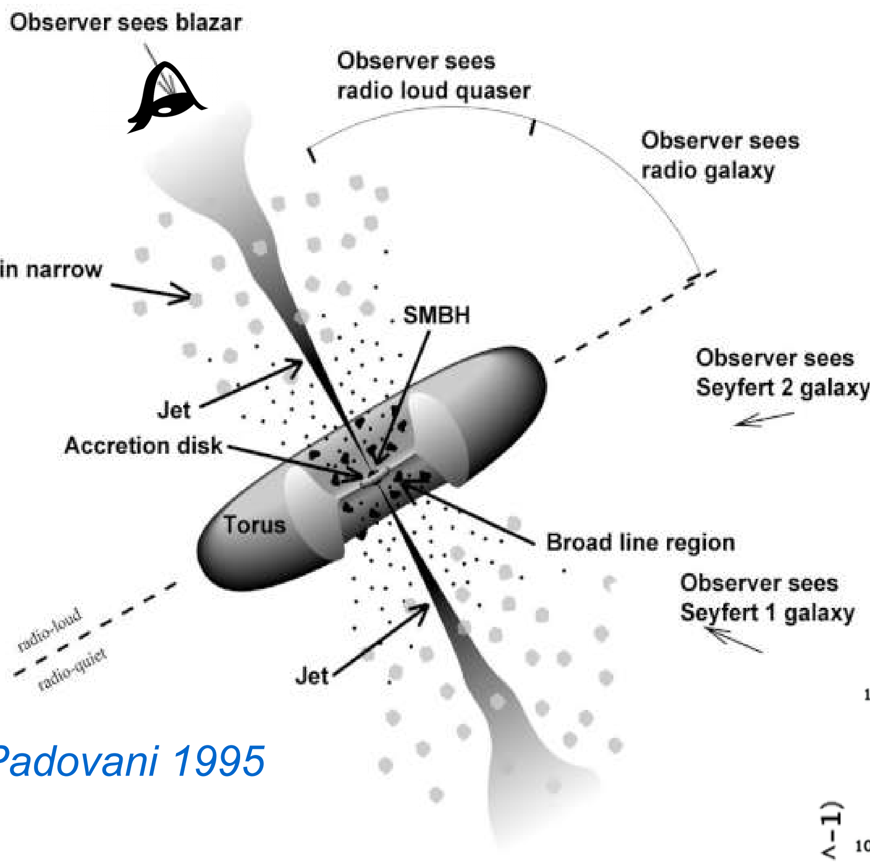
MeV Astronomy: Unlocking the Multi-Messenger Universe

Splinter Meeting at the 235th AAS

January 6 2020, Honolulu, Hawaii

Illustration: DESY, Science Communication Lab

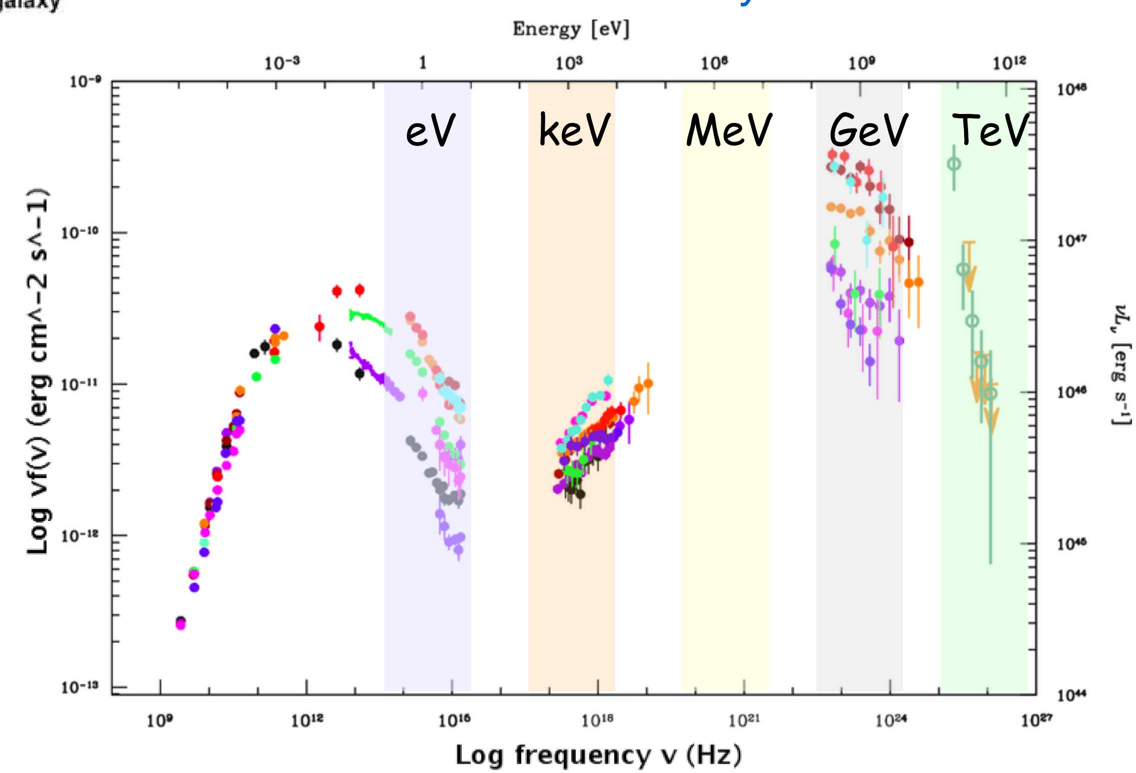
Blazars: AGN with jets viewed face-on



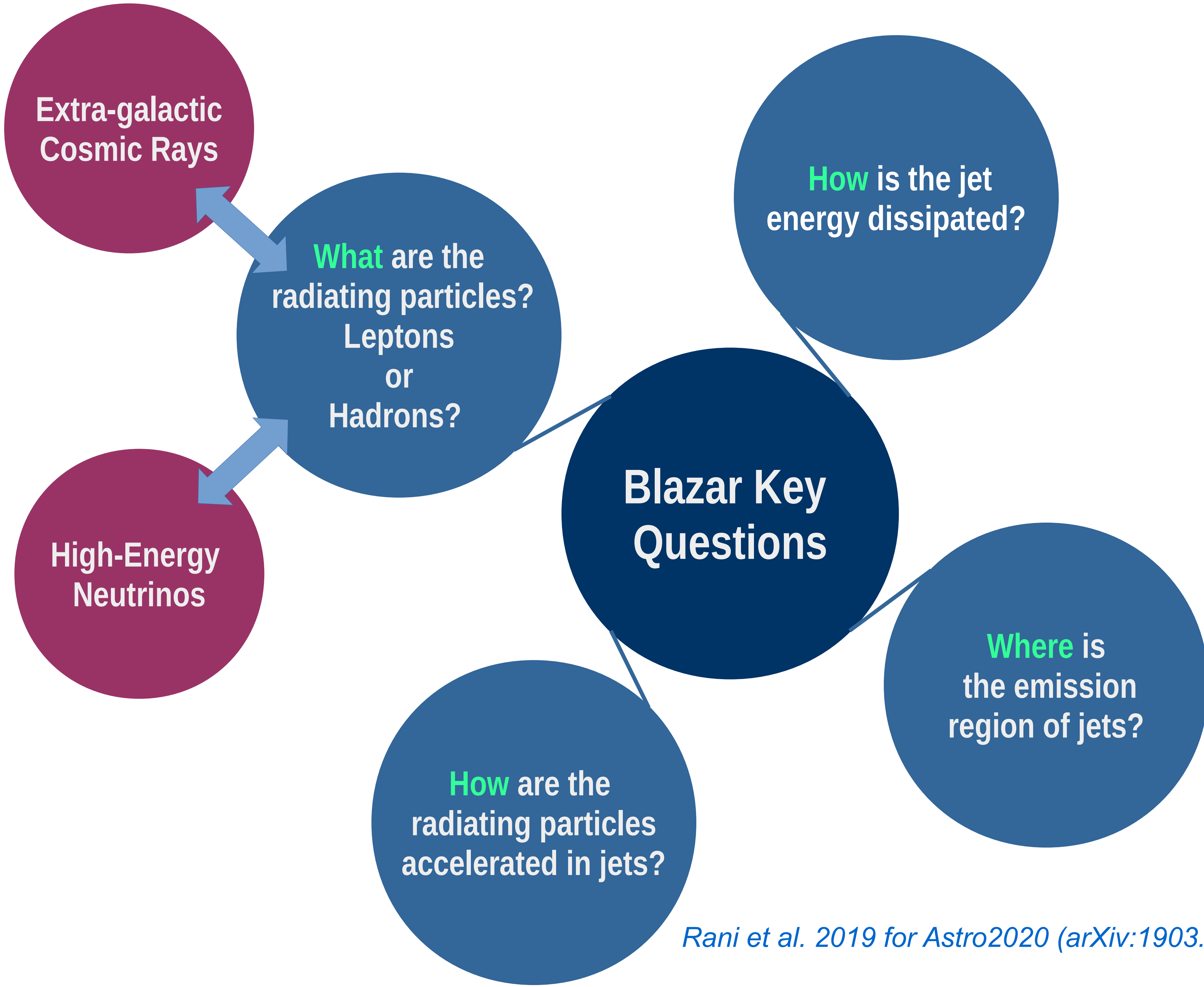
Urry & Padovani 1995

- Jetted AGN at small viewing angles.
- Emission dominated by the jet.

Hayashida et al. 2012



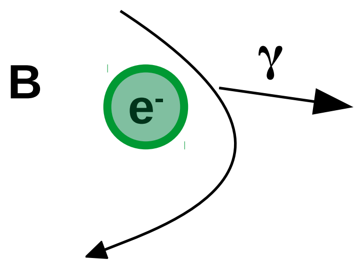
- Multi-wavelength emission.
- Double-humped photon spectra.
- Flux variability on multiple timescales (min to months).



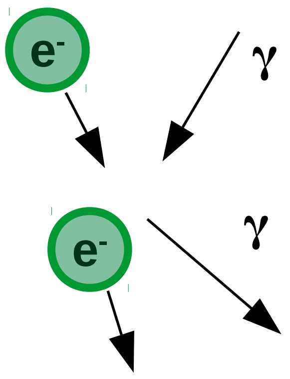
Rani et al. 2019 for Astro2020 (arXiv:1903.04504)

Non-thermal Radiative Processes – Leptons

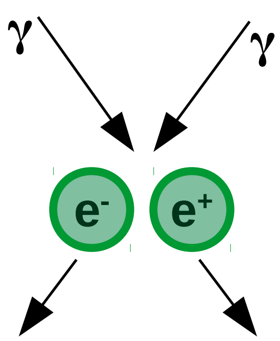
1) Synchrotron radiation



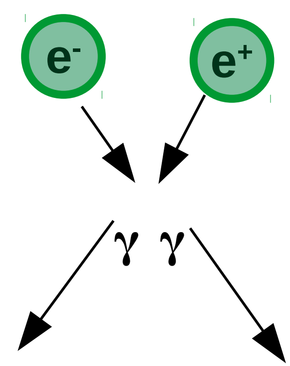
2) Inverse Compton scattering (ICS)



3) Photon-photon (γγ) pair production

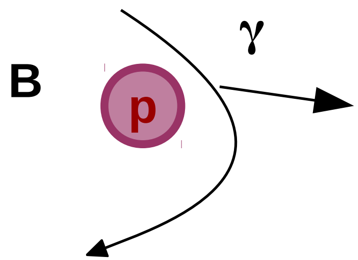


4) Electon-positron annihilation

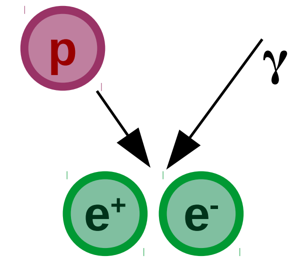


Non-thermal Radiative Processes – Hadrons

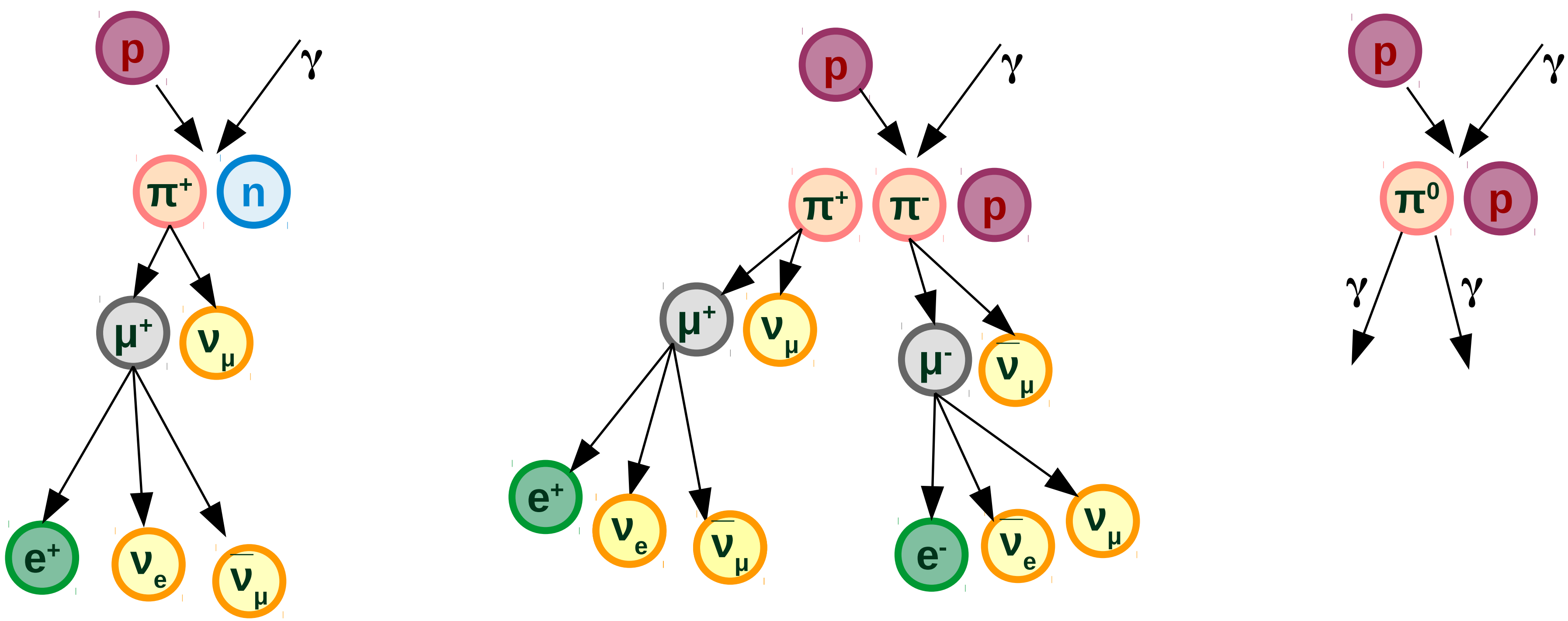
1) Synchrotron radiation



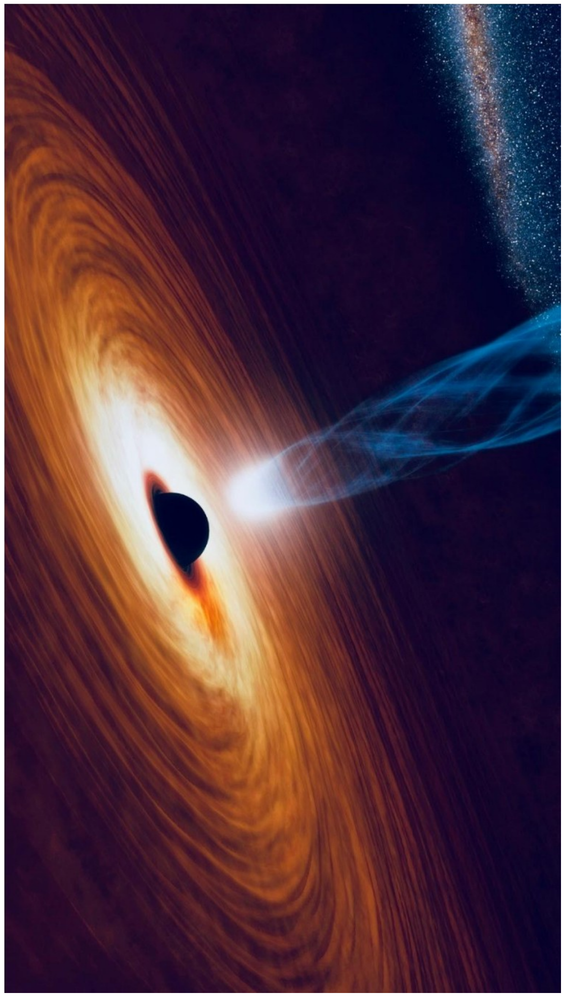
2) Photo-pair (Bethe-Heitler) production



3) Photo-meson (pπ) production

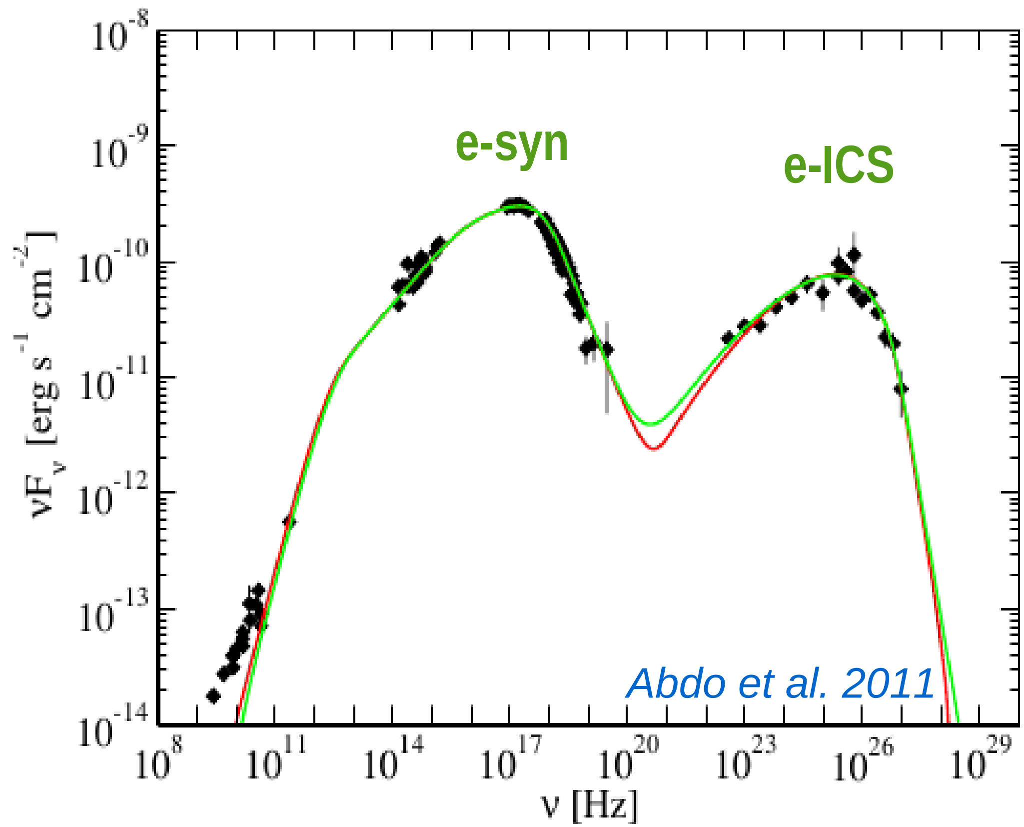


Blazar Emission Models



Leptonic Models

- **Jet plasma:** relativistic e^+e^- + cold e,p
- **HE emission:** ICS from rel. e^+e^-

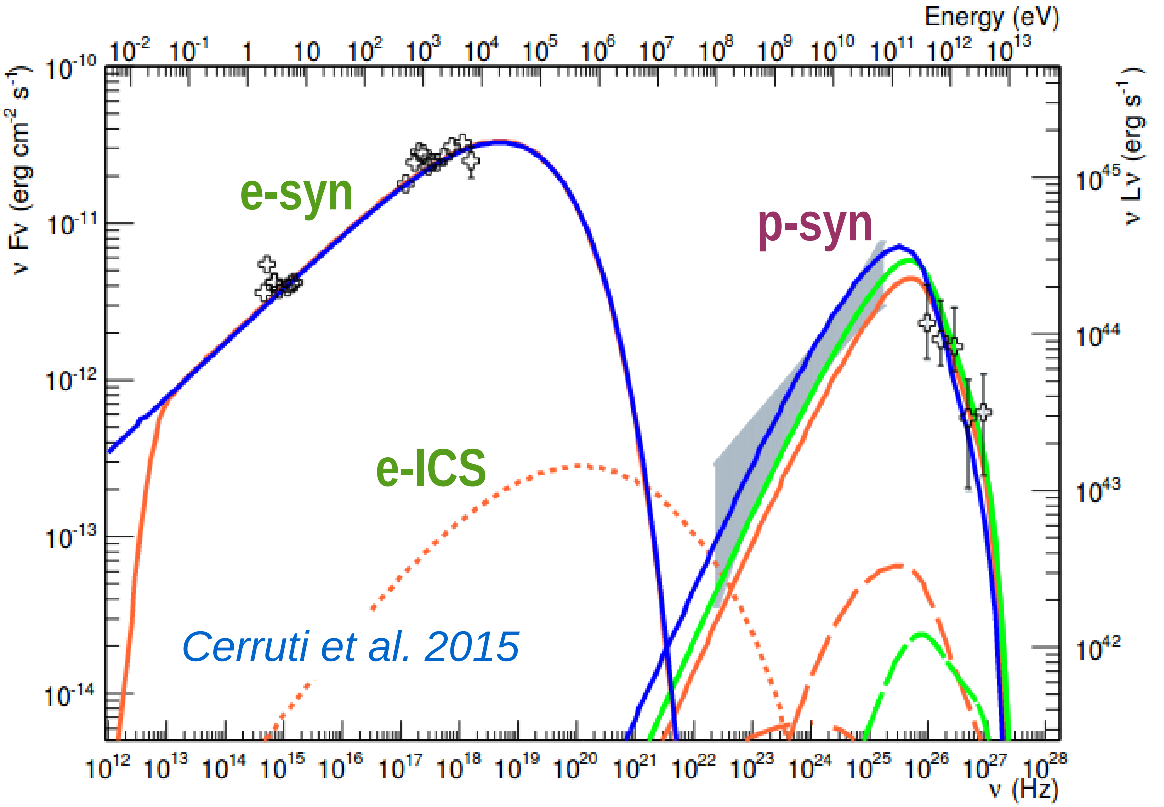


e.g., Maraschi et al. 1992; Dermer et al. 1992; Dermer & Schlickeiser 1993; Sikora et al. 1994; Mastichiadis & Kirk 1995; Bloom & Marscher 1996; Mastichiadis & Kirk 1997; Tavecchio et al. 1998; Boettcher & Dermer 1998; Cerruti et al. 2012 …

Blazar Emission Models

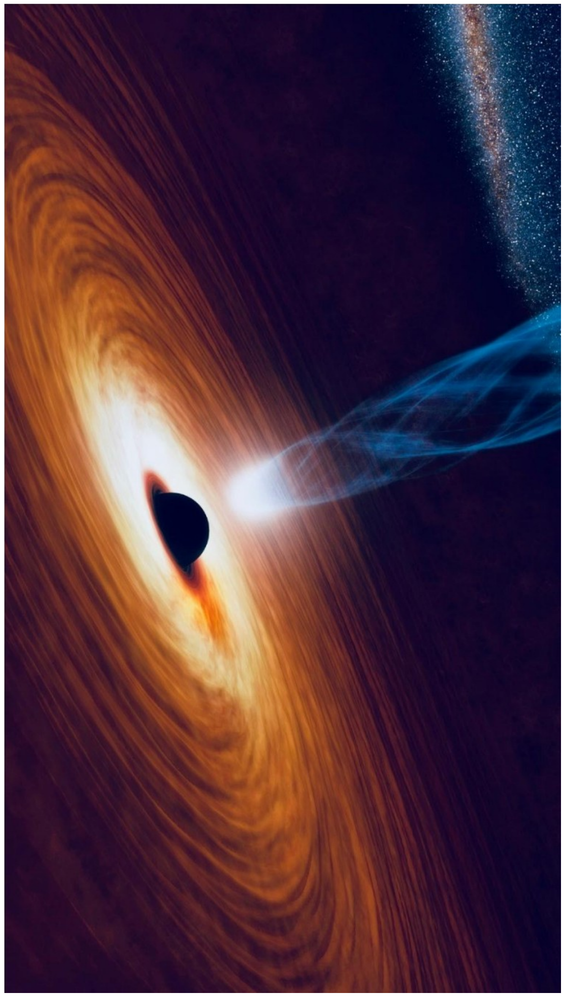
Hadronic Synchrotron Models

- **Jet plasma:** relativistic e^+e^- p + cold e,p
- **HE emission:** SYN from rel. p



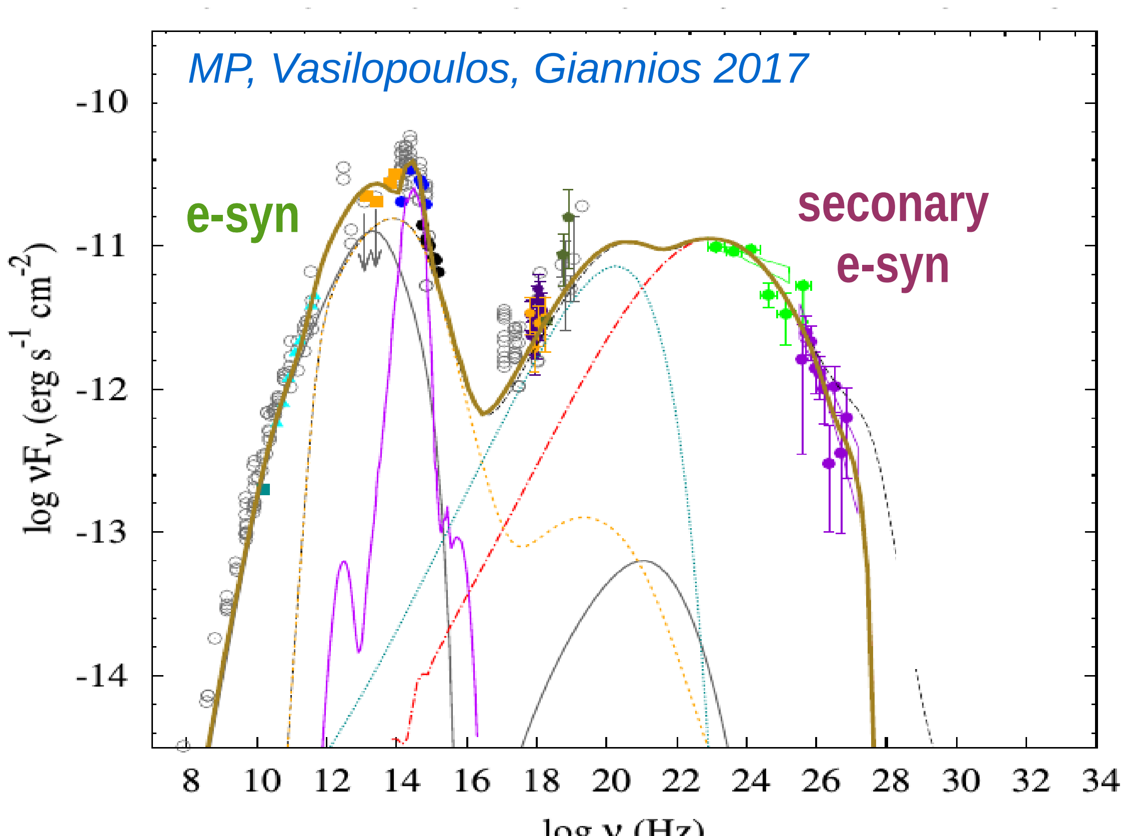
e.g., Mannheim & Biermann 1992; Aharonian 2000; Muecke & Protheroe 2001; Muecke et al. 2003, Boettcher et al. 2013; Cerruti et al. 2015, Petropoulou & Dimitrakoudis 2015; …

Blazar Emission Models



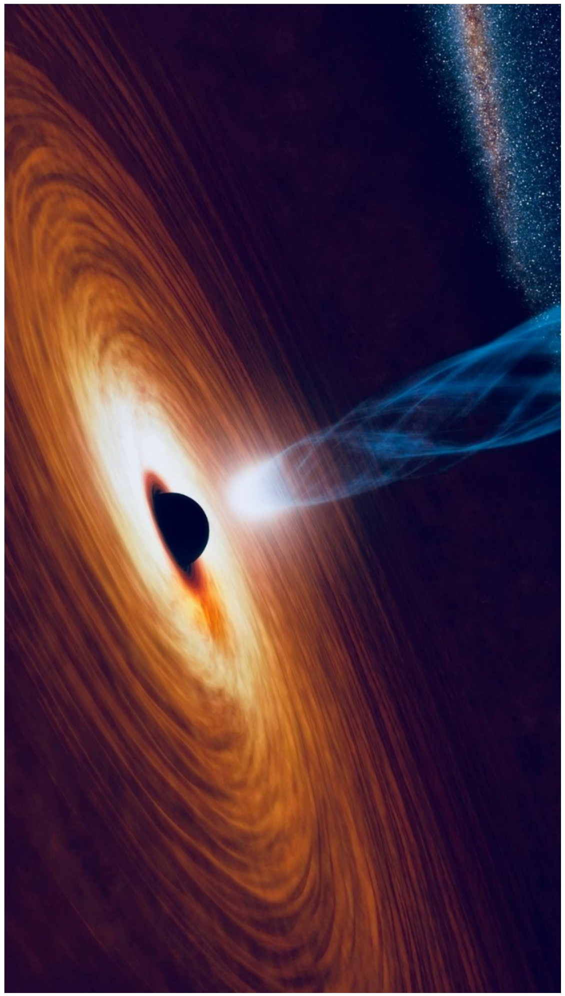
Hadronic Cascade Models

- **Jet plasma:** relativistic e^+e^- p + cold e,p
- **HE emission:** ICS/SYN from secondary e^+e^-



e.g., Mannheim et al. 1991; Mannheim 1993; Sahu et al. 2013; Petropoulou & Mastichiadis 2012; Petropoulou et al. 2015; Petropoulou et al. 2017; …

Blazar Emission: A Challenging Problem



All models describe equally well the photon spectra.

1) Many free parameters for each zone (13 – 20)

2) Non-contemporaneous multi-wavelength data besides exceptional periods (e.g. flares)

3) Not full coverage of the electromagnetic spectrum

How can we tell which scenario is true?

1) High-energy neutrinos (see talk by F. Halzen)

2) Multi-frequency temporal information

3) **MeV monitoring observations (flux & polarization)**

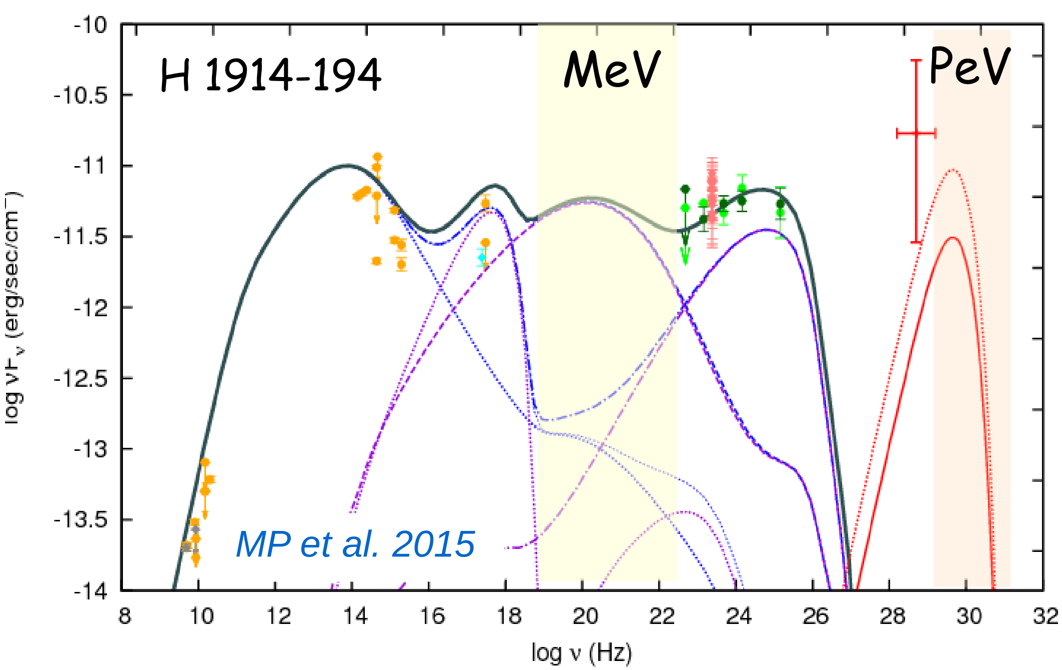
Filling the “MeV Gap” in TeV Blazars

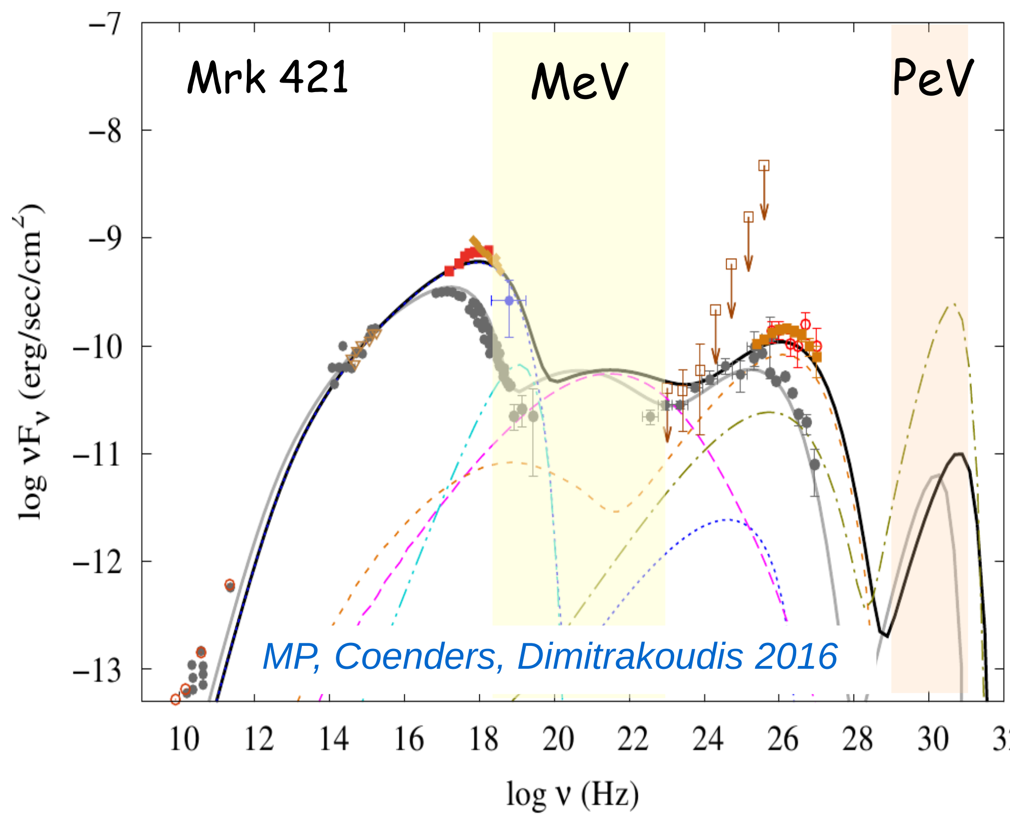
- Synchrotron from Bethe-Heitler pairs → Broad spectrum → MeV spectral bump *(MP & Mastichiadis 2015)*

$$\varepsilon_{\rm syn}^{\rm BH} \approx 6 \text{ keV} B_{0.5 \text{ G}} (\varepsilon_p / 6 \text{ PeV})^2 (20/\delta)$$

- PeV neutrino luminosity ~ MeV luminosity from Bethe-Heitler pairs *(MP & Mastichiadis 2015; Murase, Oikonomou, MP 2018)*

$$\varepsilon_\nu L_{\varepsilon_\nu}^{0.1-1 \text{ PeV}} \sim \varepsilon_\gamma L_{\varepsilon_\gamma}|_{\varepsilon_{\rm syn}^{\rm BH}} \sim \frac{1}{4} g[\beta] f_{p\gamma} \varepsilon_p L_p$$

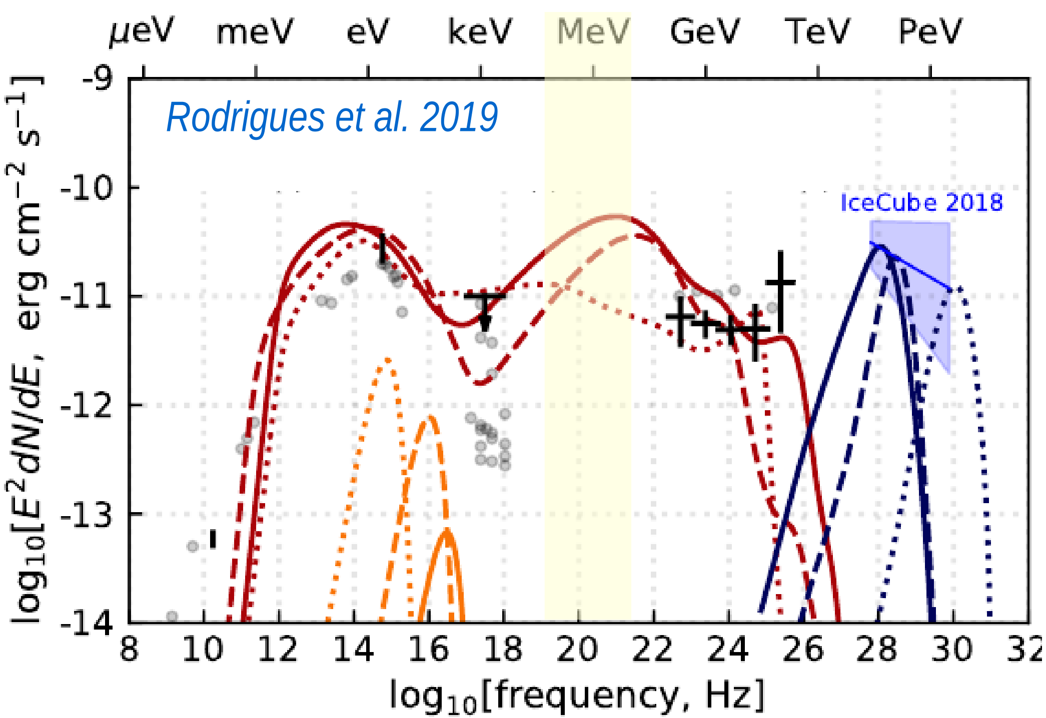


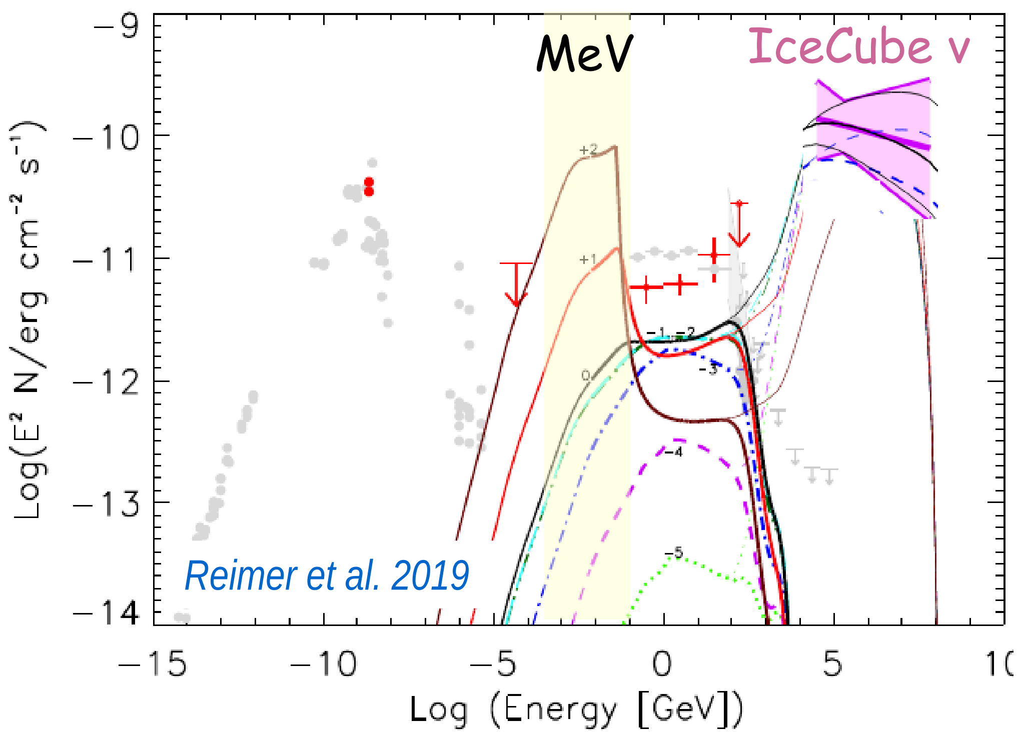


MeV observations are crucial for constraining hadronic cascade models & PeV neutrino signal

MeV Spectral Bumps in TXS 0506+056

- The most optimistic models for the 2014-15 neutrino excess predict bright MeV emission *(Rodrigues et al. 2019, Reimer et al. 2019, MP et al. 2019)*
- No strong constraints on models due to lack of deep X-ray limits + MeV observations

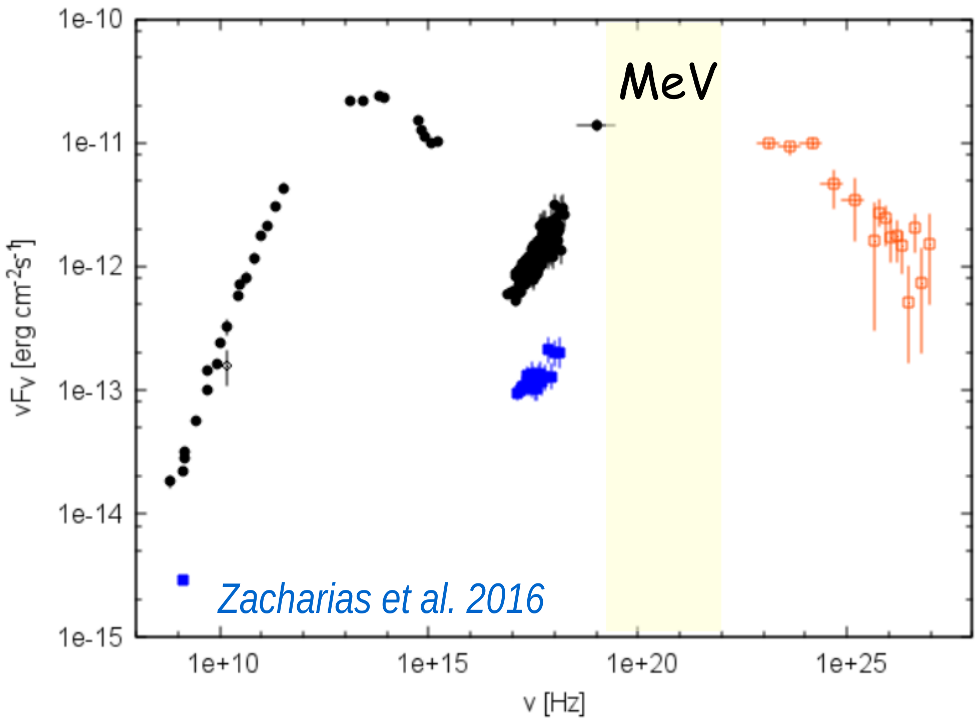


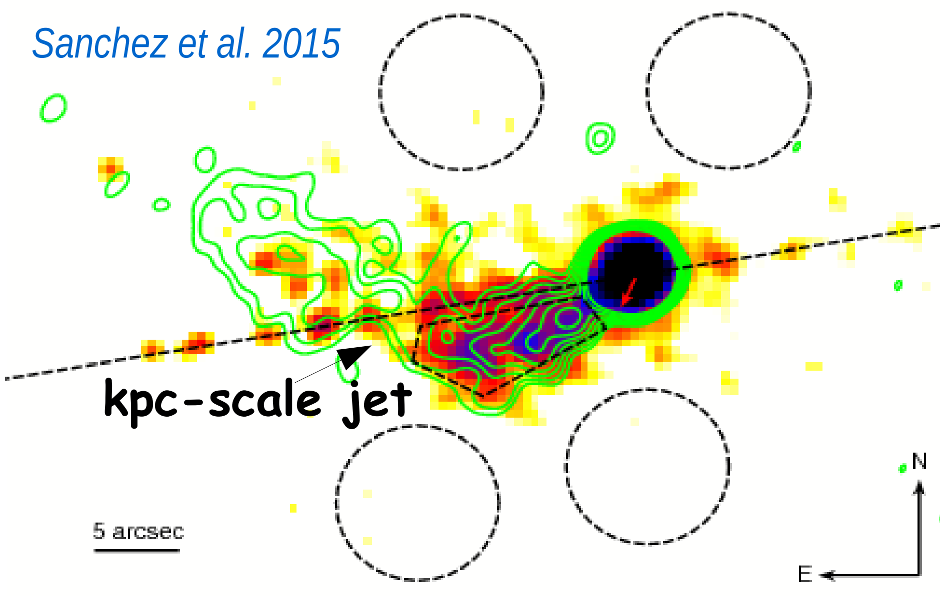


MeV monitoring observations are crucial for multi-messenger blazar studies

The Curious Case of Ap Librae

- Unusually broad HE component (~9-10 orders of magnitude in frequency) *(HESS Collaboration 2015)*
- The only TeV blazar with X-ray detected kpc scale jet *(Kaufmann et al. 2013)*

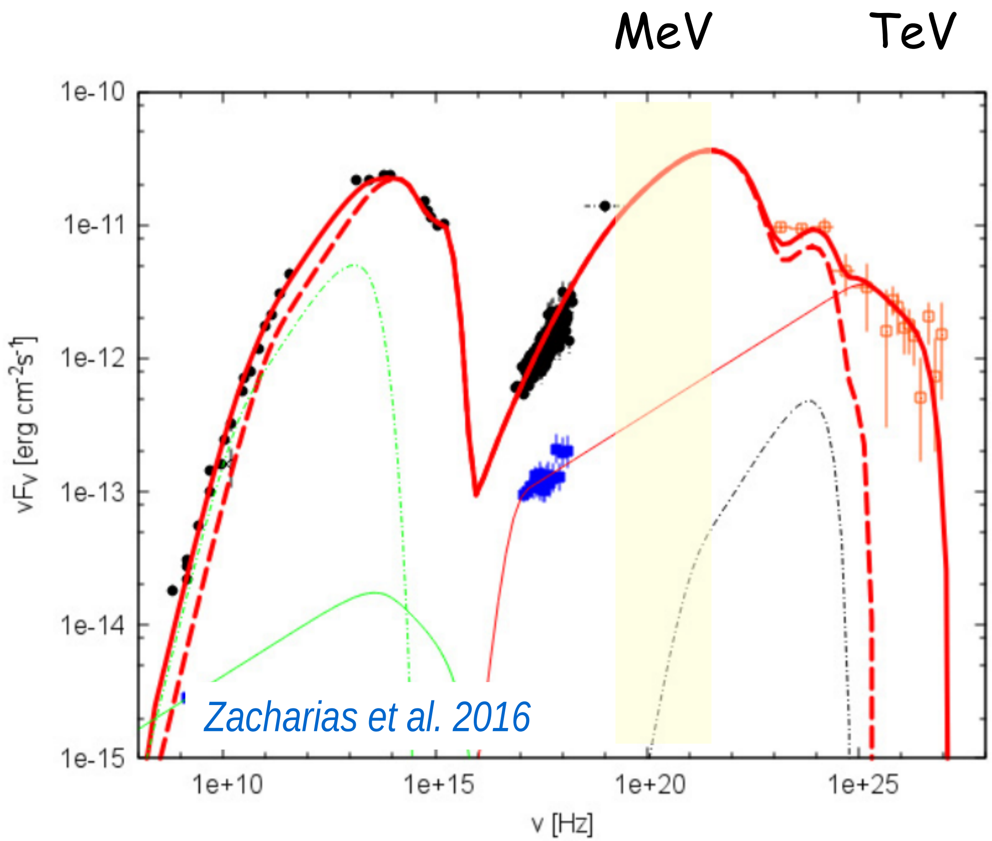


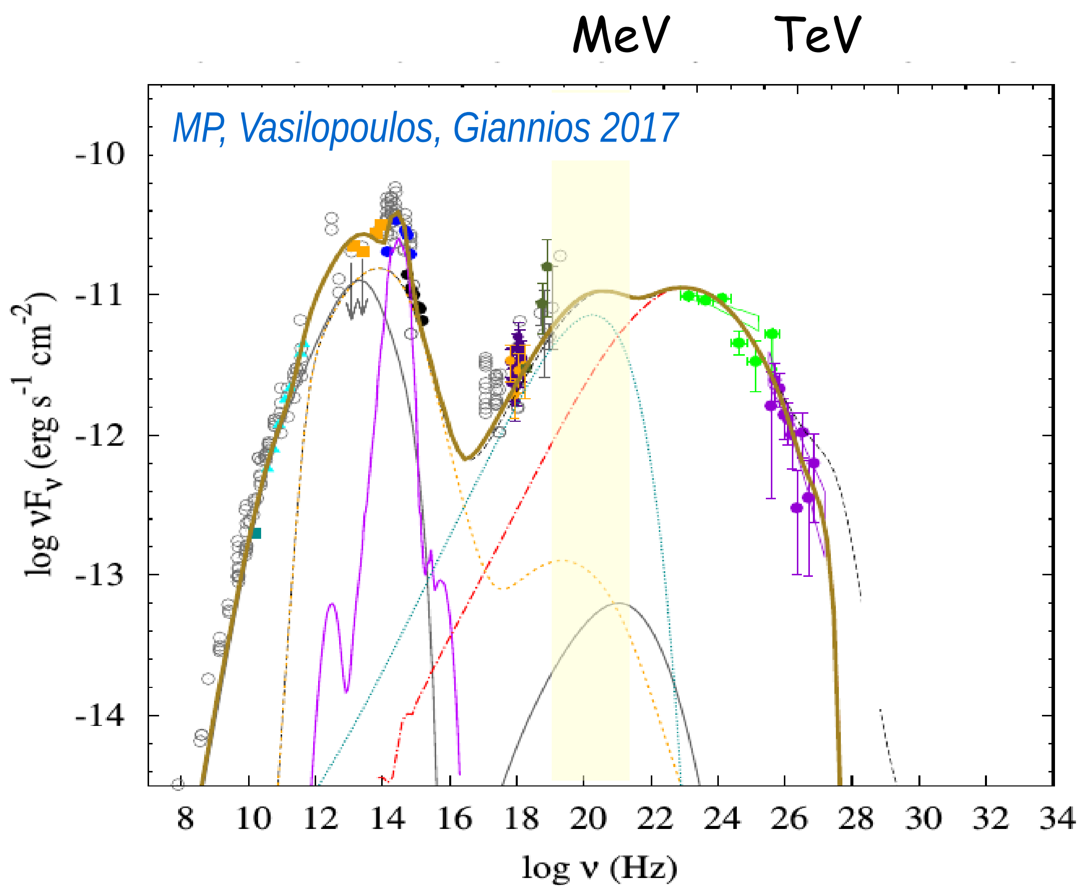


Open Questions

- Where is the HE emission produced? In the **sub-pc** or **kpc-scale** jet?
- Is the HE emission **leptonic** or **hadronic** ?

The “MeV Gap” of Ap Librae



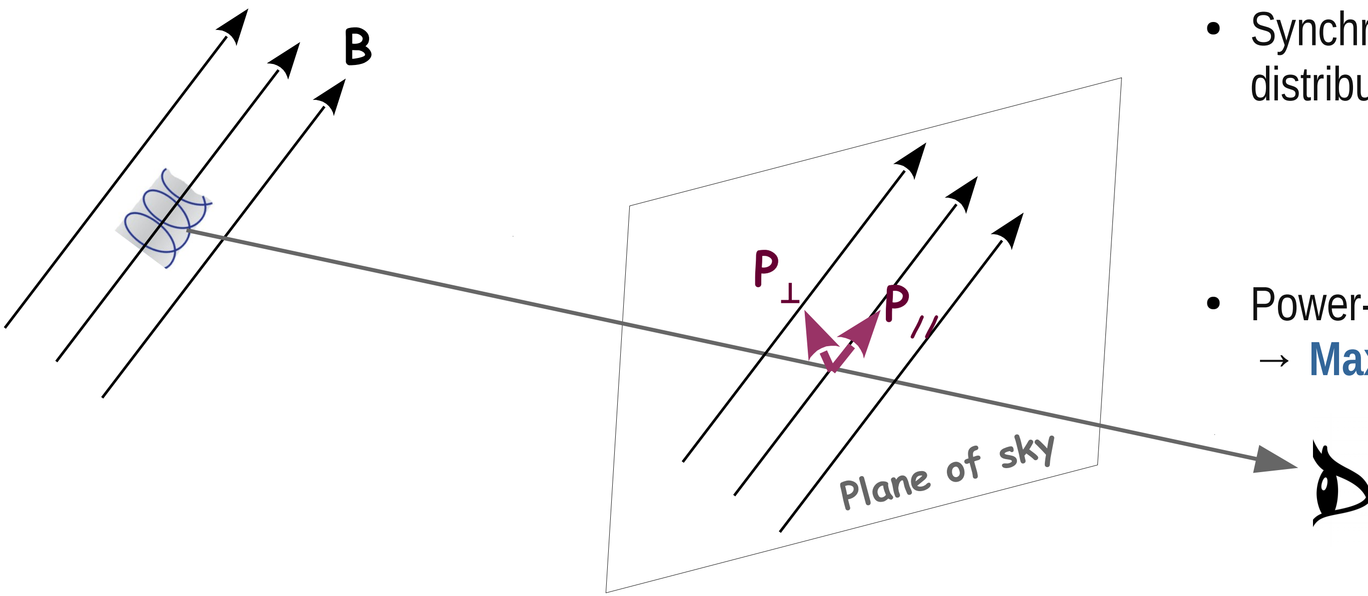


- **MeV** γ-rays: **e-ICS** from **sub-pc** jet
- **TeV** γ-rays: **e-ICS** from **kpc** jet

- **MeV** γ-rays: **p-syn** from **sub-pc** jet
- **TeV** γ-rays: **BH+pπ e-syn** from **sub-pc** jet

MeV observations are crucial for probing the location & origin of gamma-ray emission

Polarization of Synchrotron & Compton Processes

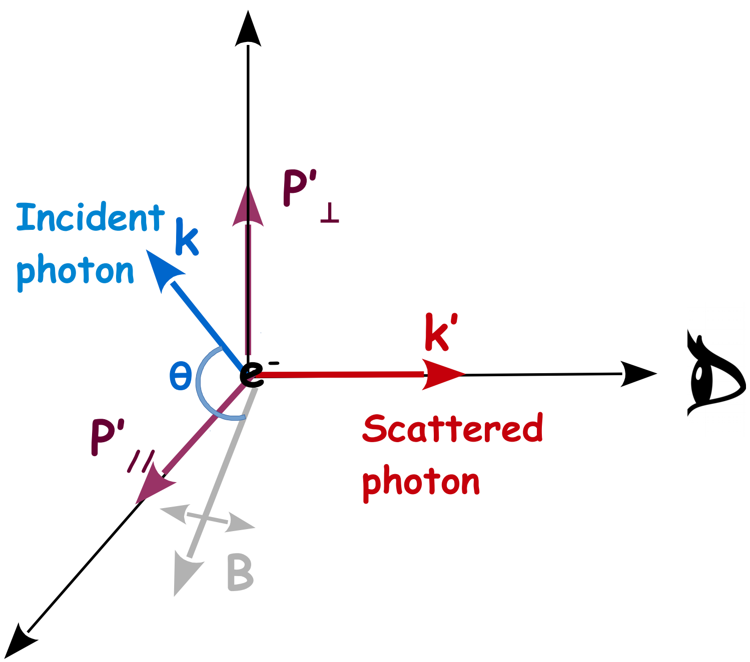


- Synchrotron emission from a pitch-angle distribution → partially **linearly pollarized**

$$\Pi(\omega) = \frac{P_\perp(\omega) - P_\parallel(\omega)}{P_\perp(\omega) + P_\parallel(\omega)}$$

- Power-law particle distribution in ordered B filed → **Maximal polarization degree**

$$\Pi_{\rm powerlaw} = \frac{p+1}{p+7/3}$$



$$P_\parallel^{\rm SSC}(\epsilon') = \pi \left(\frac{e^2}{4\pi}\right)^2 \frac{c}{m_e c^2}\epsilon' \int \frac{d\epsilon}{\epsilon} d\Omega_k \; E_{\rm min} n(\epsilon) q(\vartheta) \cdot (Z_\parallel(\Sigma_1 + \Sigma_2) + \Sigma_2)$$

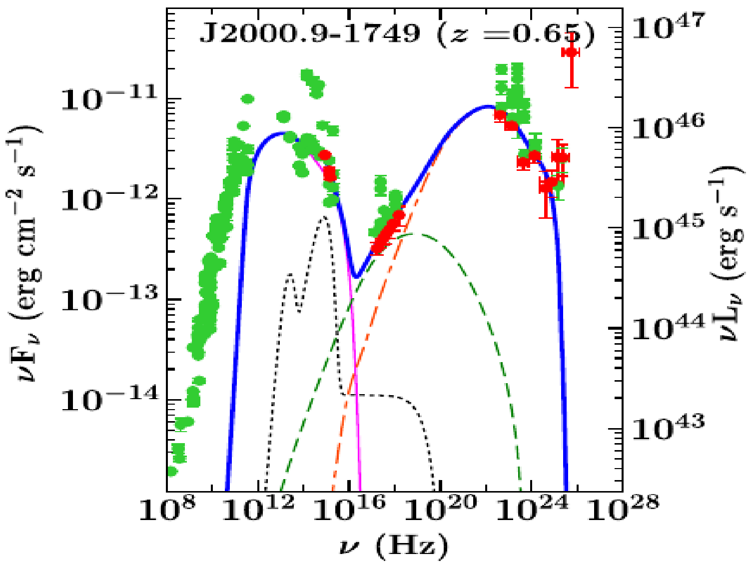
$$P_\perp^{\rm SSC}(\epsilon') = \pi \left(\frac{e^2}{4\pi}\right)^2 \frac{c}{m_e c^2}\epsilon' \int \frac{d\epsilon}{\epsilon} d\Omega_k \; E_{\rm min} n(\epsilon) q(\vartheta) \cdot (Z_\perp(\Sigma_1 + \Sigma_2) + \Sigma_2),$$

(Bonometto & Saggion 1973; Krawczynski 2012; Zhang & Boettcher 2013; Zhang 2019)

High-Energy Polarization: Leptonic or Hadronic ?

(Paliya et al. 2018)

Leptonic Model

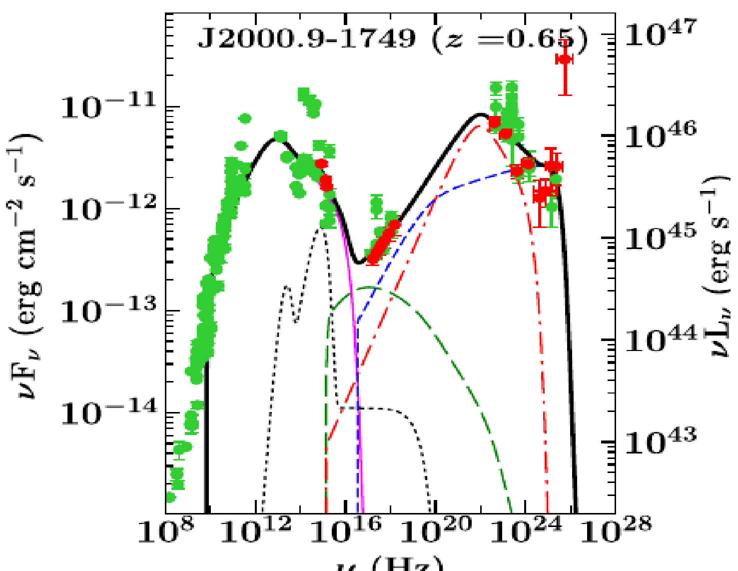


$$\Pi_{\mathrm{lep}}(\nu) = Z_{\mathrm{m}} \frac{P_{\mathrm{SSC,pol}}(\nu)}{P_{\mathrm{SSC,tot}}(\nu) + P_{\mathrm{EC,tot}}(\nu)}$$

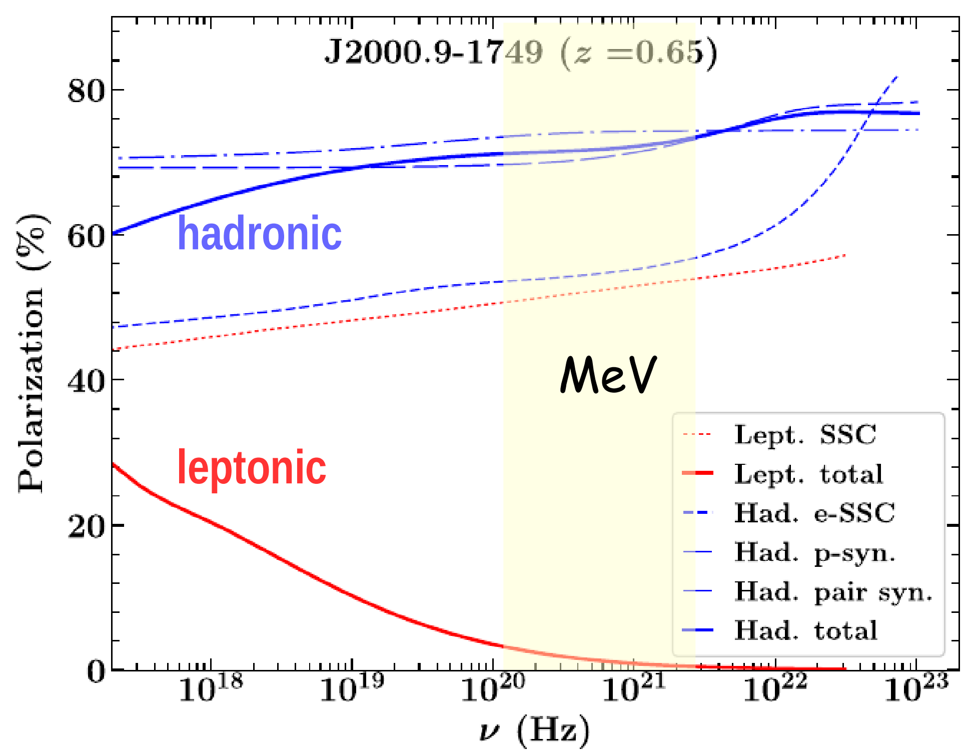
De-polarization factor

$$\Pi_{\mathrm{had}}(\nu) = Z_{\mathrm{m}} \frac{P_{\mathrm{p,pol}}(\nu) + P_{\mathrm{pair,pol}}(\nu) + P_{\mathrm{SSC,pol}}(\nu)}{P_{\mathrm{p,tot}}(\nu) + P_{\mathrm{pair,tot}}(\nu) + P_{\mathrm{SSC,tot}}(\nu)}$$

Hadronic Synchrotron Model

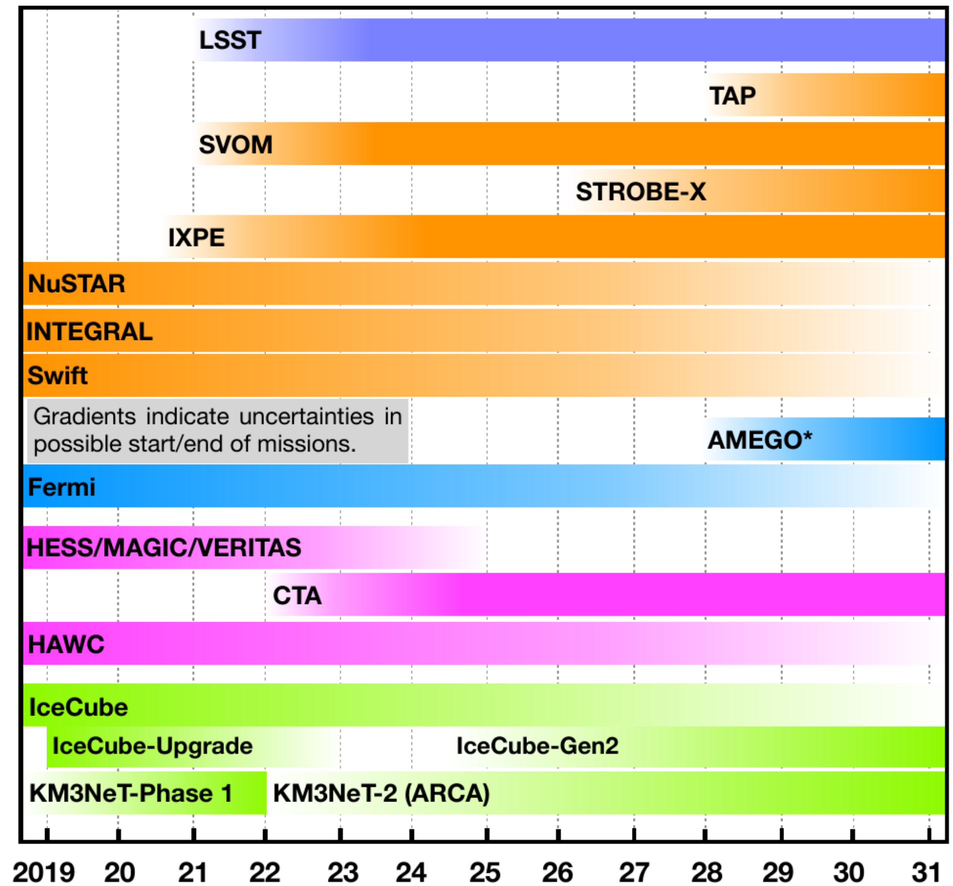


Maximal Polarization Degree



Conclusions

- Unveiling the origin of high-energy emission in blazars will have profound implications for **jet physics**, **particle acceleration physics**, & **neutrino astrophysics**.
- The poorly explored **MeV window** holds the key for future discoveries.
- A **sensitive MeV monitor** of the sky with **polarization capabilities** should be an integral part of **multi-messenger** astronomy in the next decade.

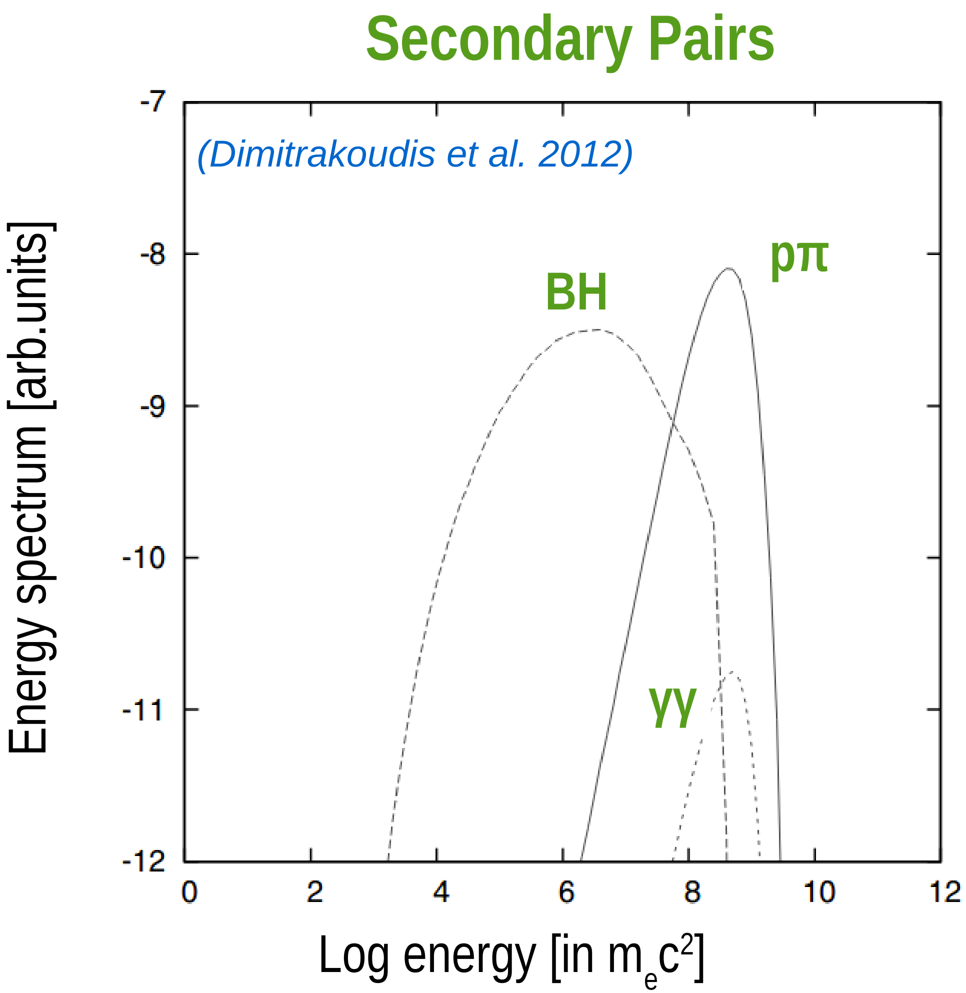


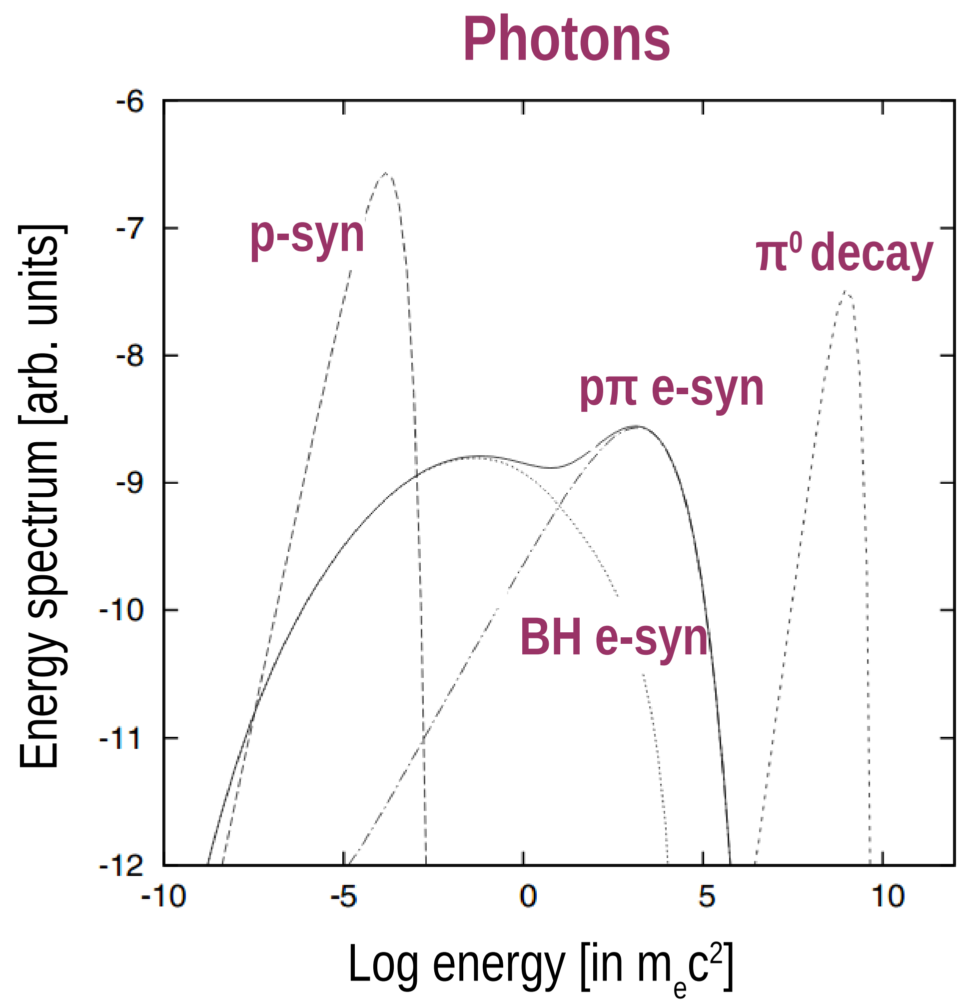
Buson et al. 2019 for Astro2020 (arXiv:1903.04447)

Thank you

Back-up Slides

Multi-Component Photon Spectra from Hadronic Processes



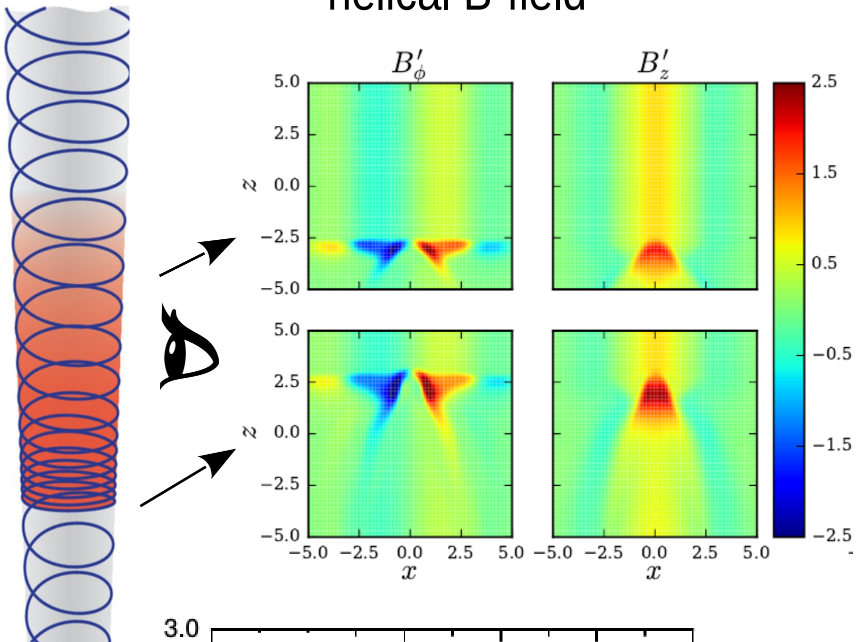


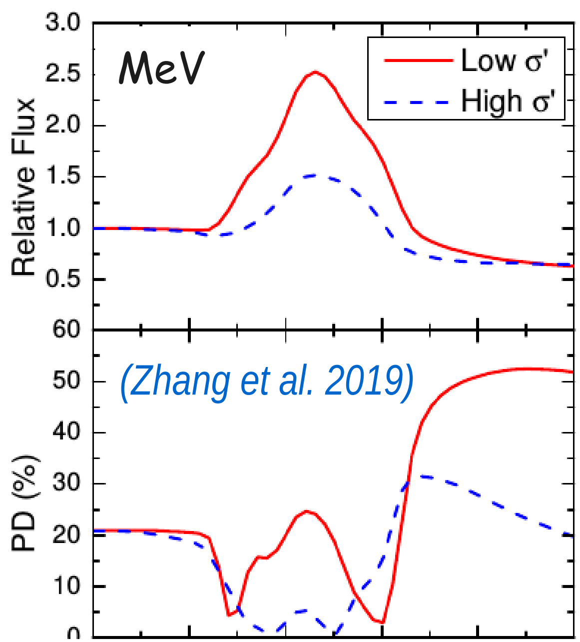
Many **variants** of hadronic photon emission due to:

- **Unknown** source conditions (e.g., magnetic field, size …)
- **Multi-componen**t spectra

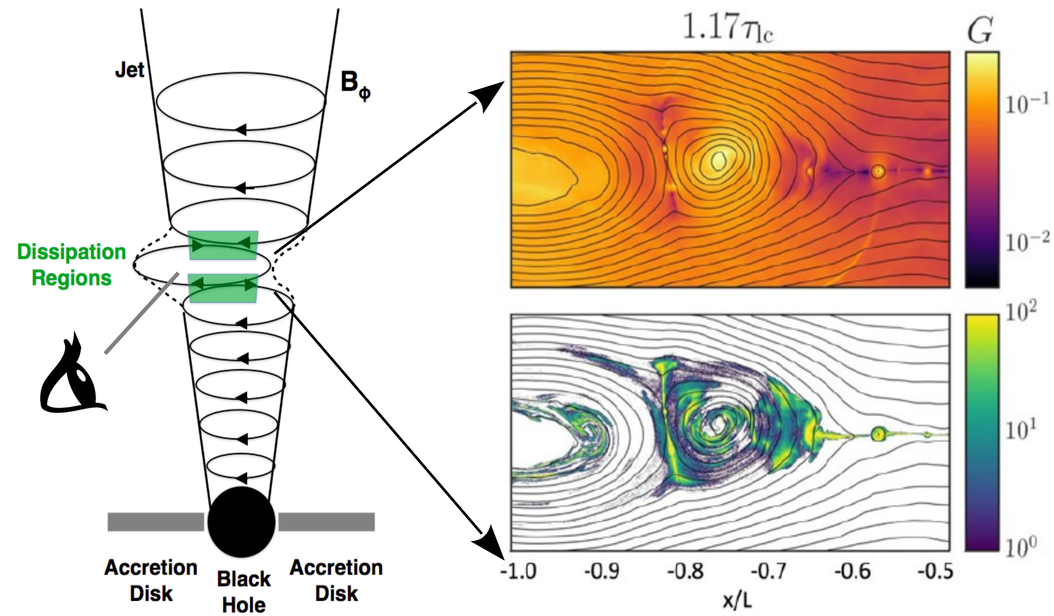
High-Energy Polarization: Shocks or Reconnection ?

Case A: Shock compression of force-free helical B-field

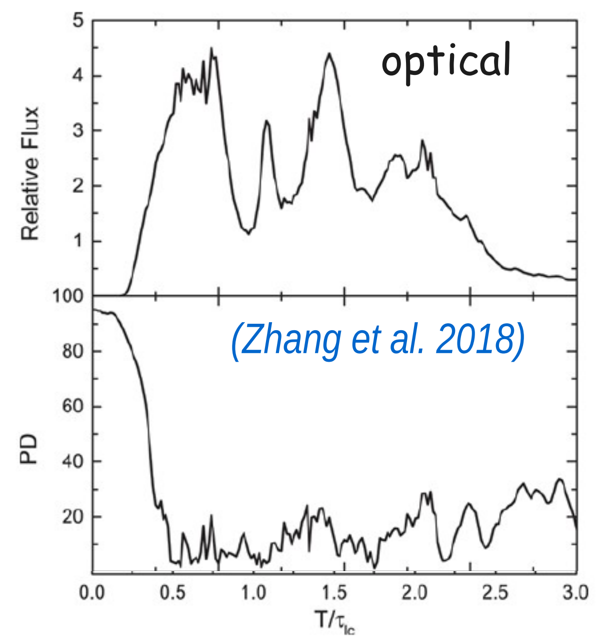




Case B: Reconnection of anti-parallel B-field



- Polarization Degree (PD) depends on plasma magnetization
- Temporal evolution of PD depends on dissipation mechanism
- Contemporeneous MeV/optical polarization measurements during flares are needed



Main Results of Blazar Modeling

- All models describe equally well the photon spectra.

- **Leptonic** models:

a) Work for both FSRQs and BL Lacs.
b) Jet power **$L_j \sim 10^{44} - 10^{46}$ erg/s** for BL Lacs, **$\sim 10^{46} - 10^{48}$ erg/s** for FSRQs
c) Particle-dominated emitting regions in BL Lacs.
d) No neutrinos.

- **Hadronic synchrotron** models:

a) Work for both FSRQs and BL Lacs
b) High jet power **$L_j \sim 10^{47} - 10^{48}$ erg/s** for FSRQs, but **lower for BL Lacs**
c) High proton energies, e.g. **$E_{pmax} \sim 10$ EeV** (for BL Lacs)
d) Strong magnetic fields, e.g. **B ~1-100 G**
e) **~ EeV** neutrinos

- **Hadronic cascade** models:

a) Work for BL Lacs, but unlikely for FSRQs
b) High jet power **$L_j \sim 10^{47} - 10^{48}$ erg/s**
c) Moderate proton energies e.g. **$E_{pmax} \sim 10$ PeV**
d) Moderate magnetic fields, e.g. **B ~ 0.1-1 G**
e) **~ PeV** neutrinos

How can we tell which scenario is true?

Spectral MeV Features

High-Energy Neutrinos

Multi-band Flux Variability

Polarization of MeV Emission