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Broad band modelling of Blazars: a tool to understand the physics of relativistic jets.

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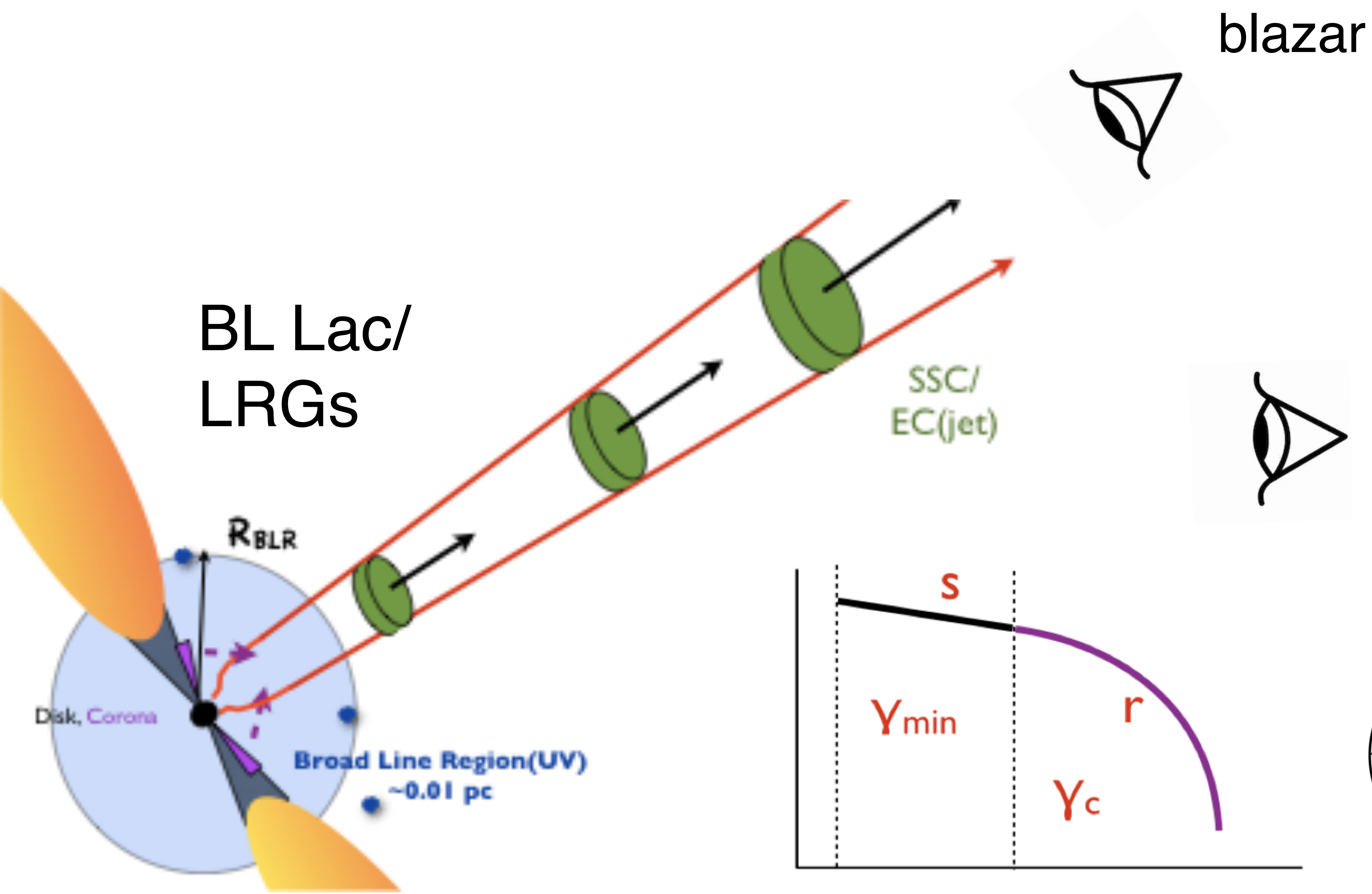
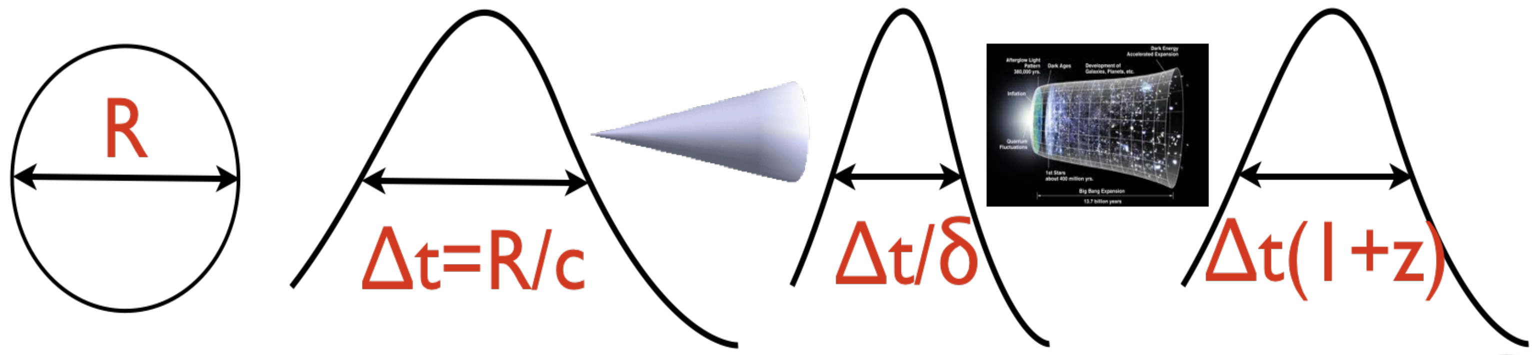
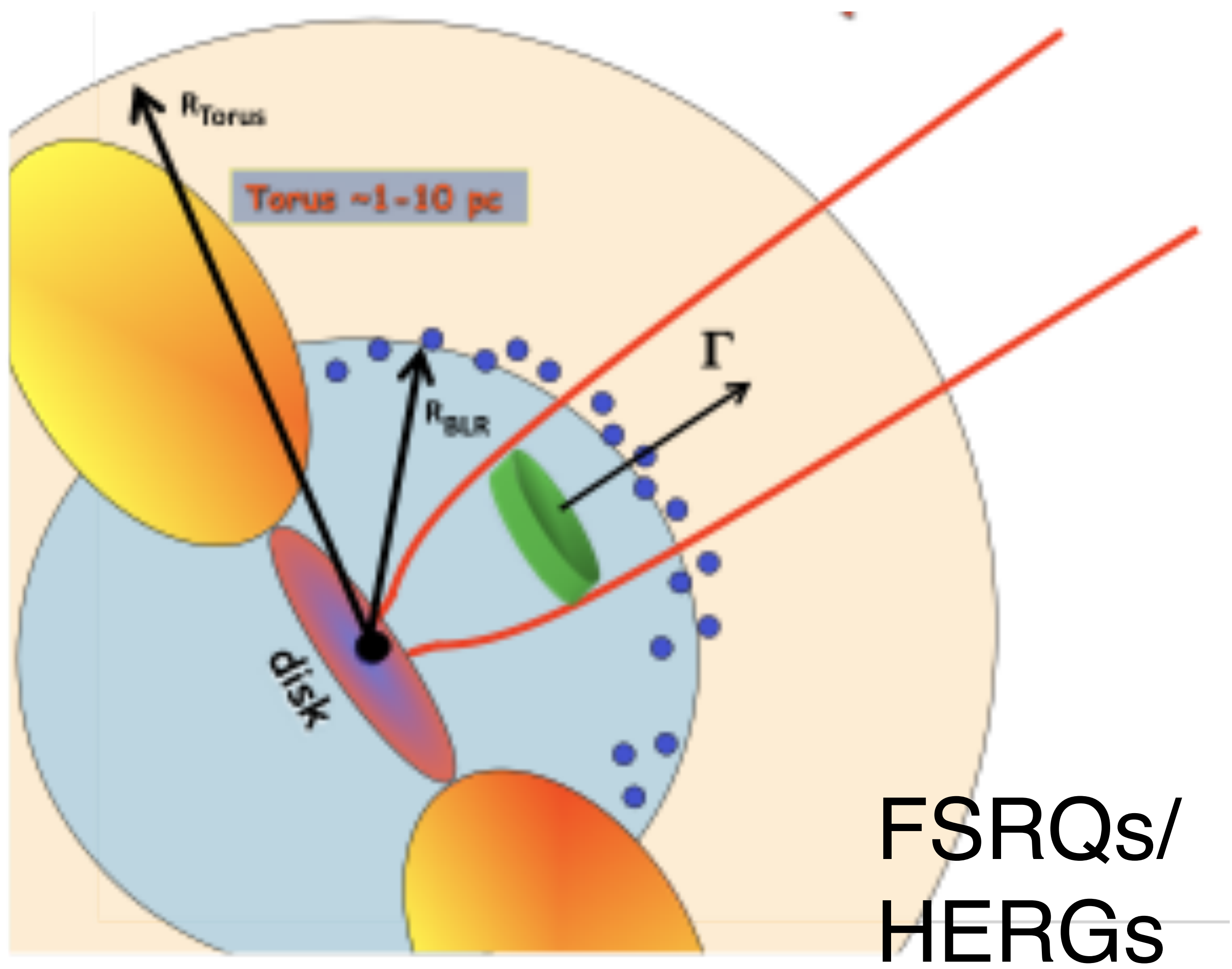
introduction

- current status of the modeling
- phenomenological signatures hinting for complex scenarios
- self-consistent modeling and degeneracy
- connection of micro to macro physics

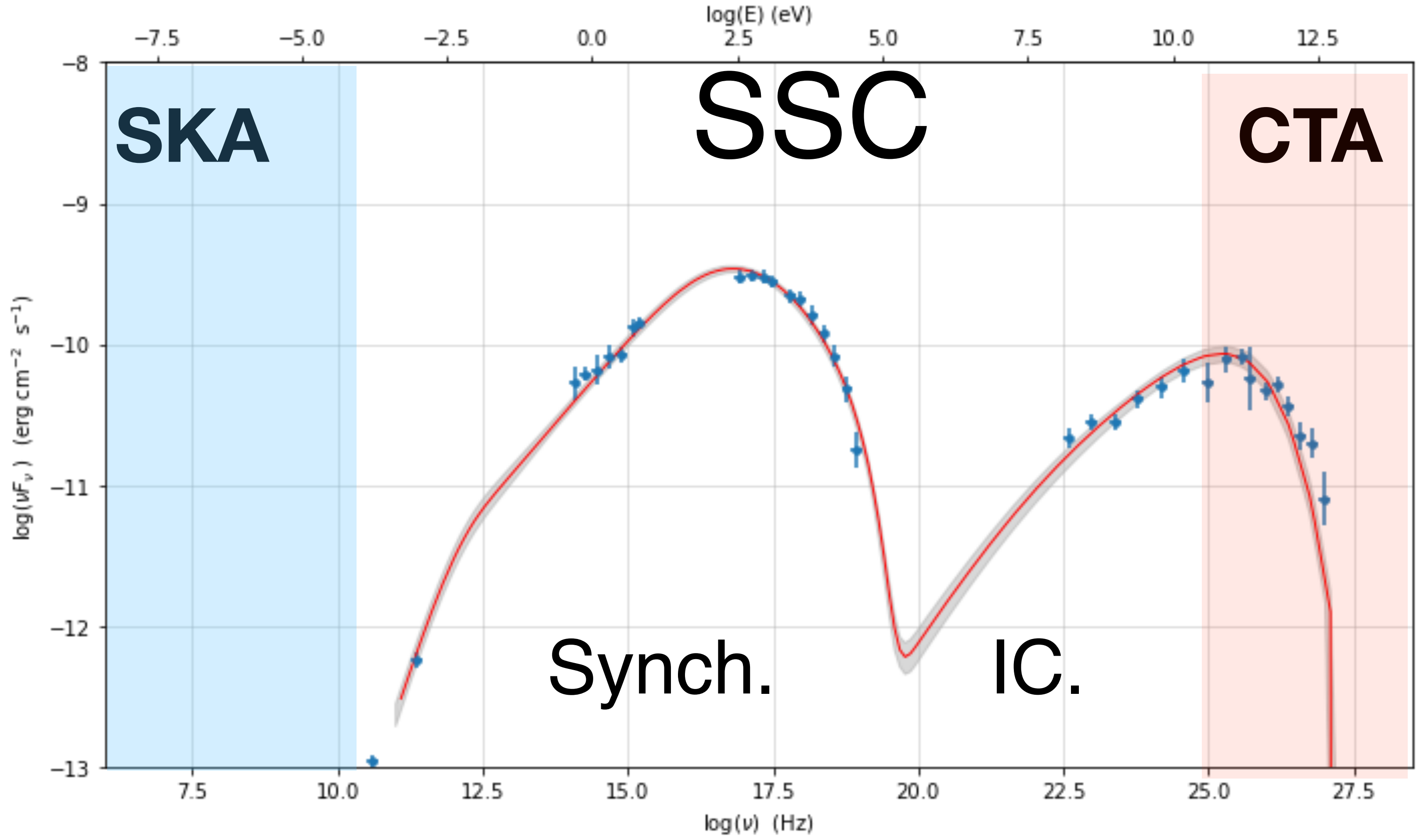
Blazars in a nutshell

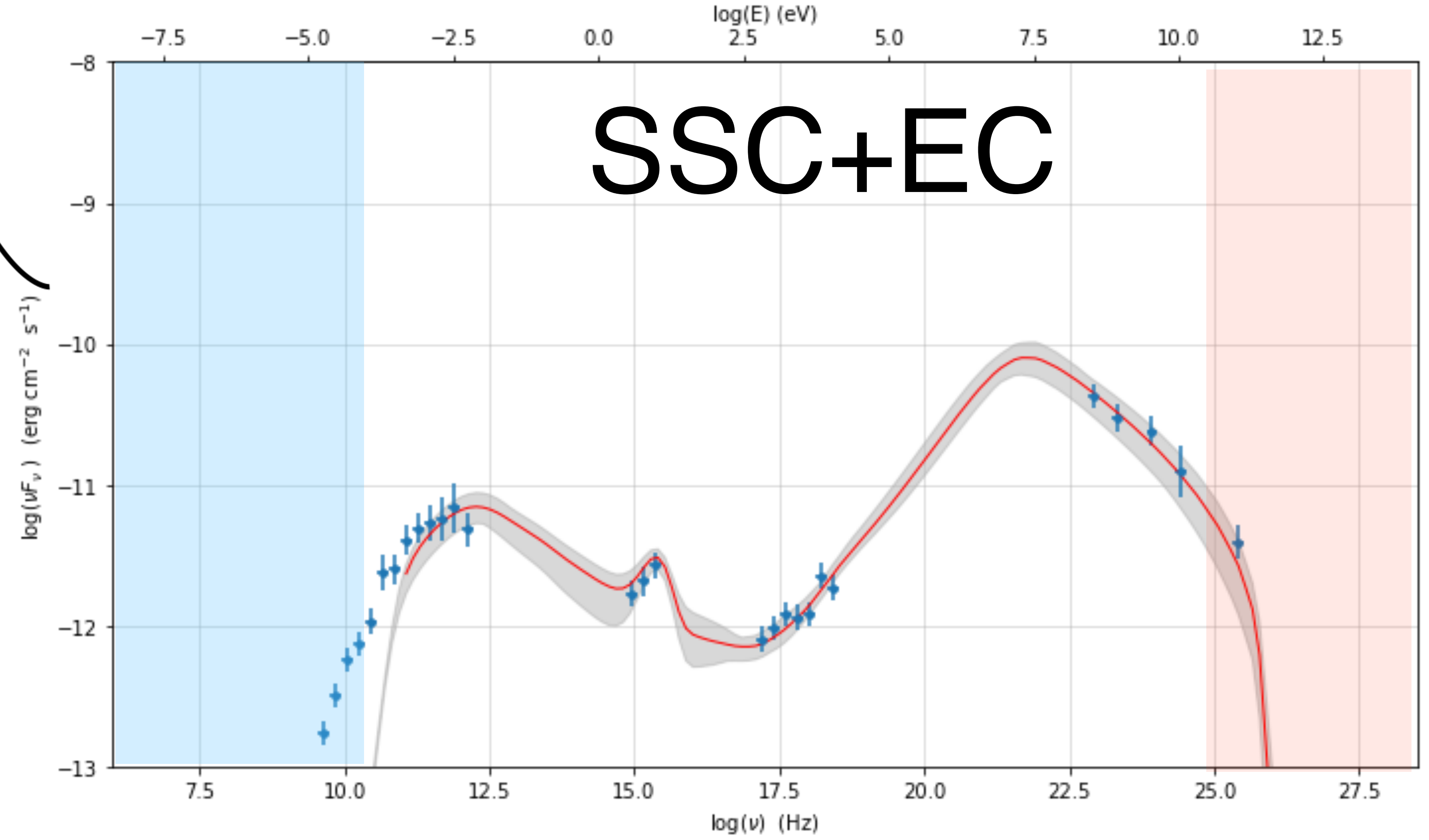




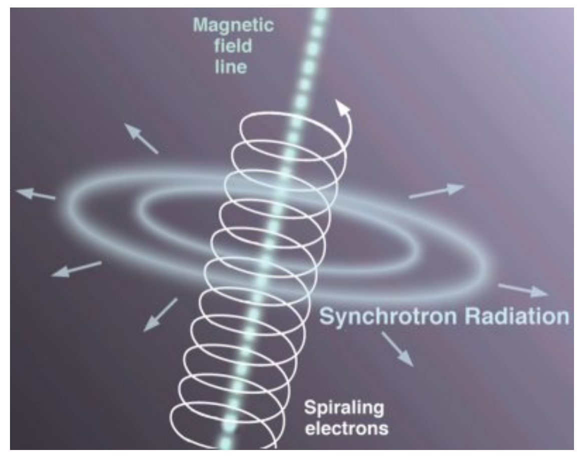


- rel. jest are powered by accr. on BH($10^{6-9}M_{sun}$)
- rel. plasma (Γ>10) acc. by non-thermal processes
- jet axis vs l.o.s. -> beaming (blazar/RG)
- variable emission over the entire EM spectrum
- Low energy bump S, high energy bump IC

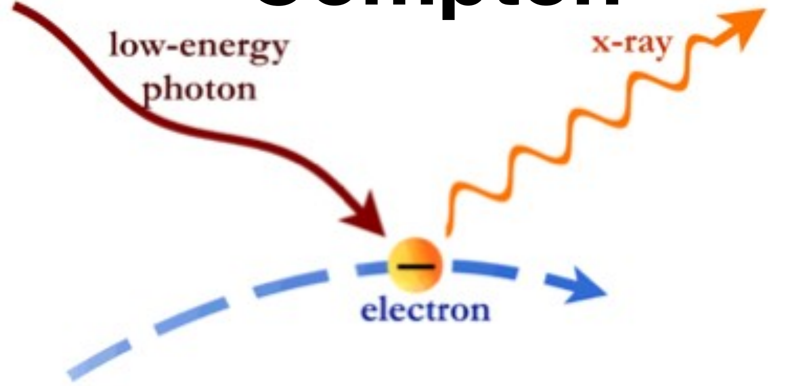




Synchrotron



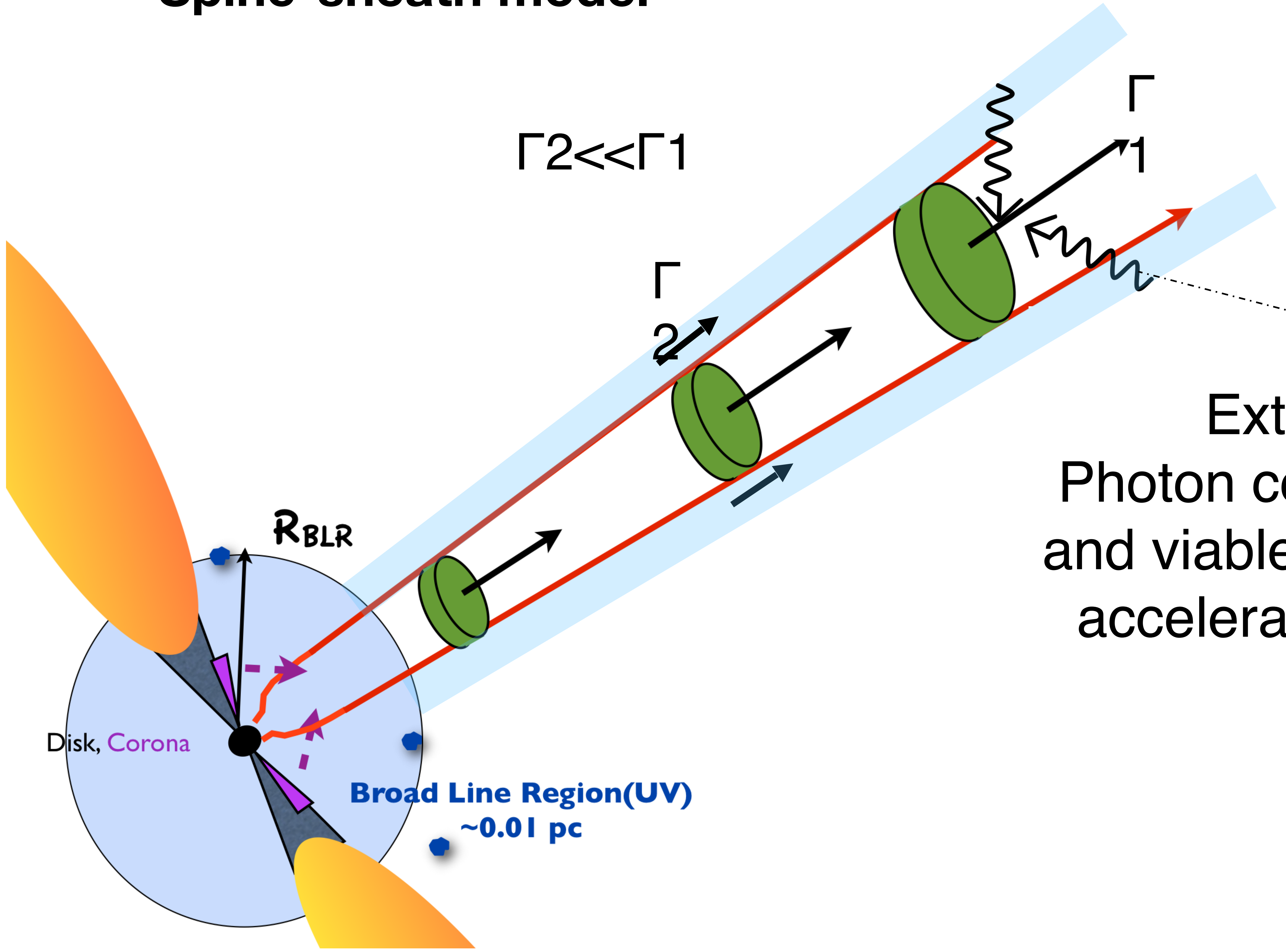
Inverse Compton



more complex scenarios

Hadronic models

Structured jets
Spine-sheath model



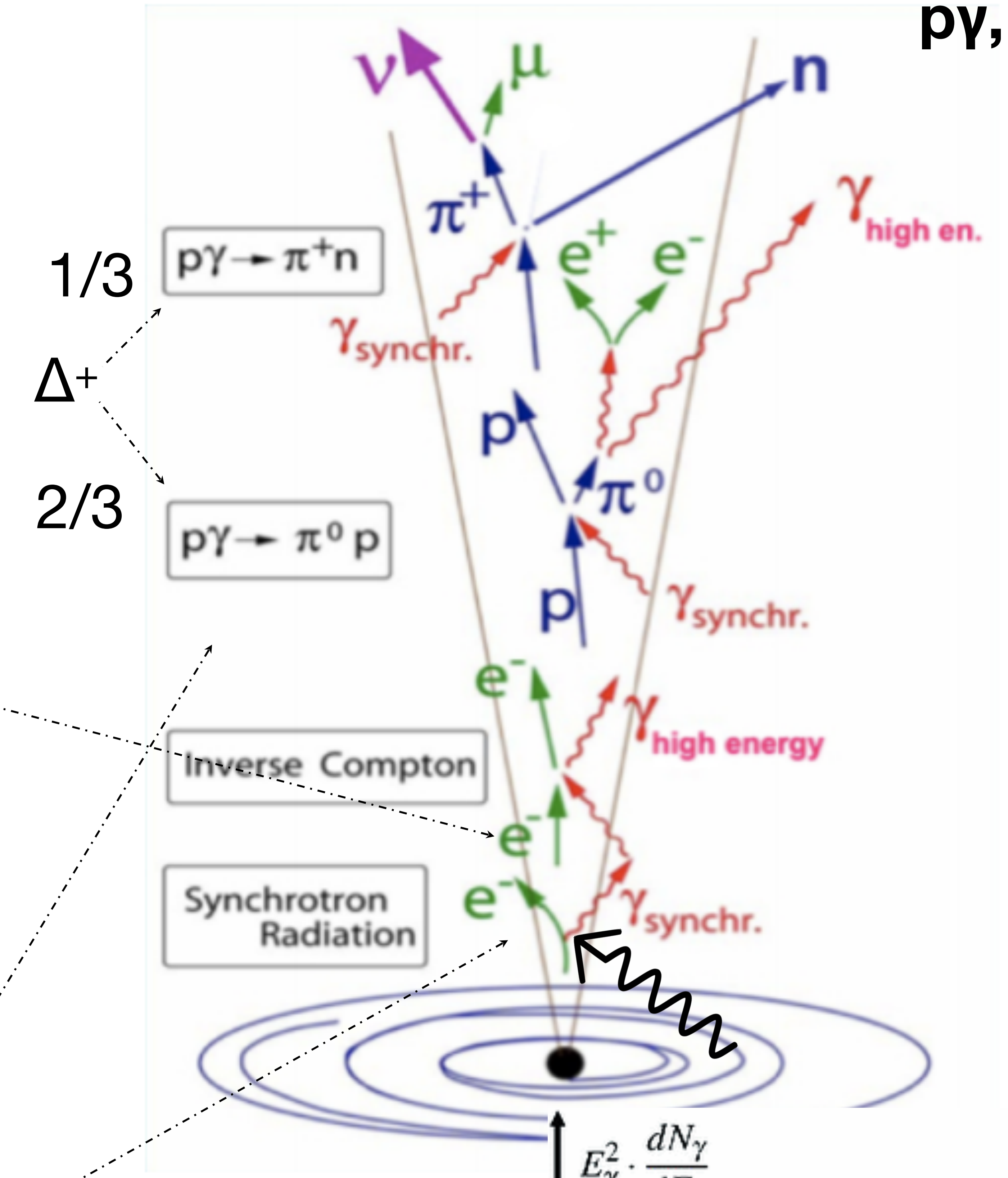
External
Photon contribution,
and viable process to
accelerate protons

pγ, p-synch

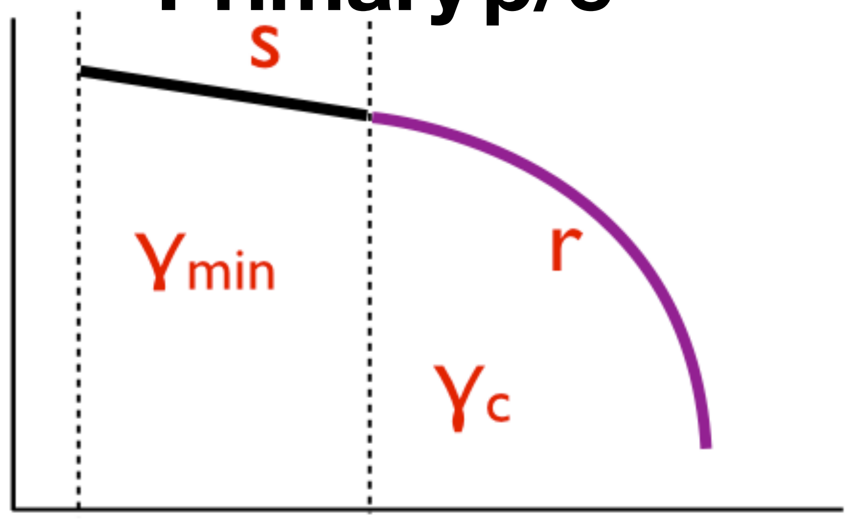
$E_pE_\gamma \sim E^2_{\Delta+}$

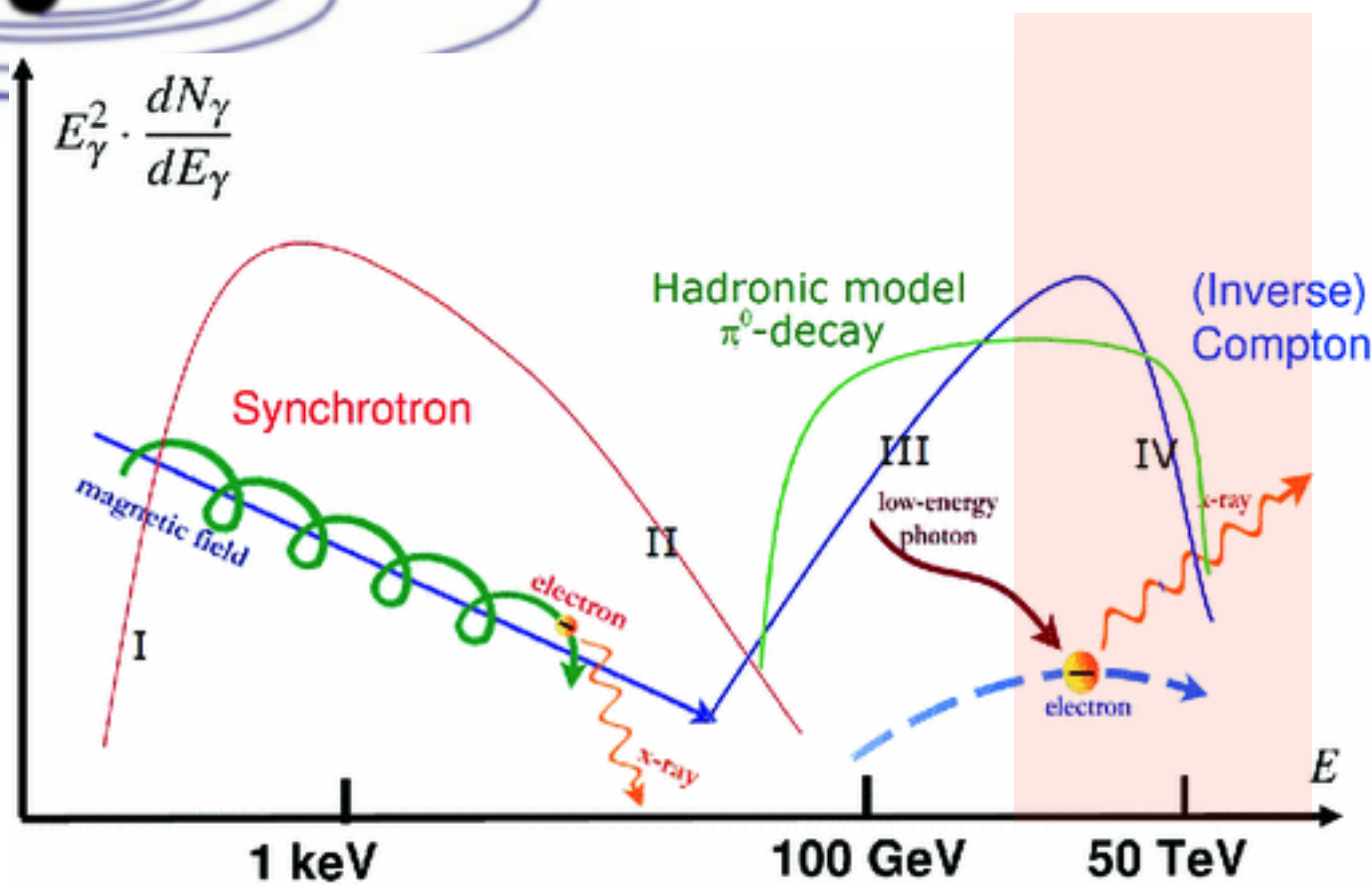
$E_\nu \sim E_p/20$

$E_p \sim 10^{17}\ (eV/E_\gamma)$



Primary p/e-





CTA/SKA/IceCube strong synergy

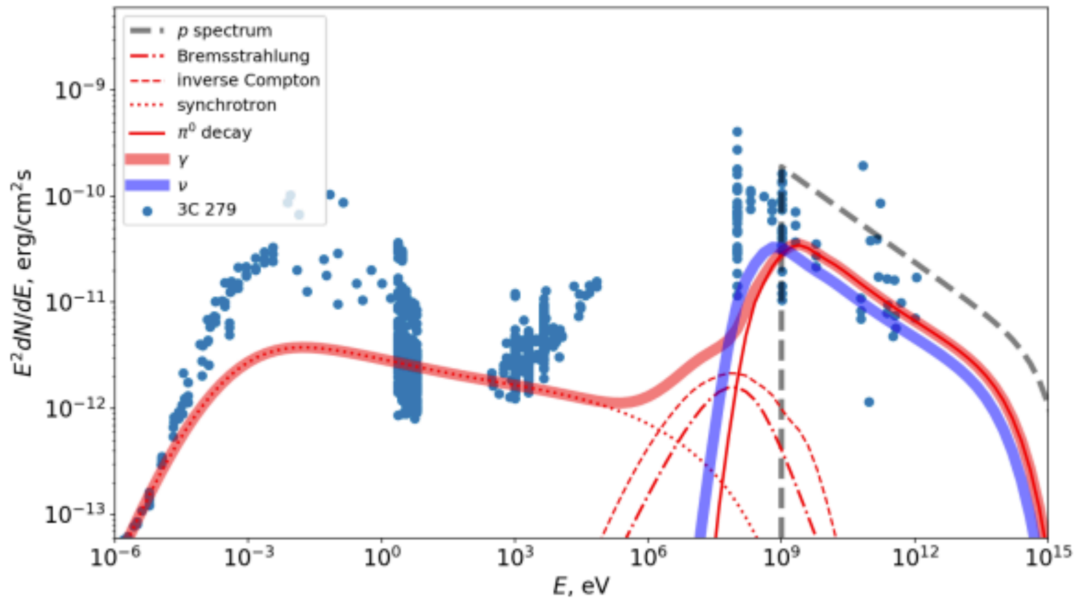
more complex scenarios

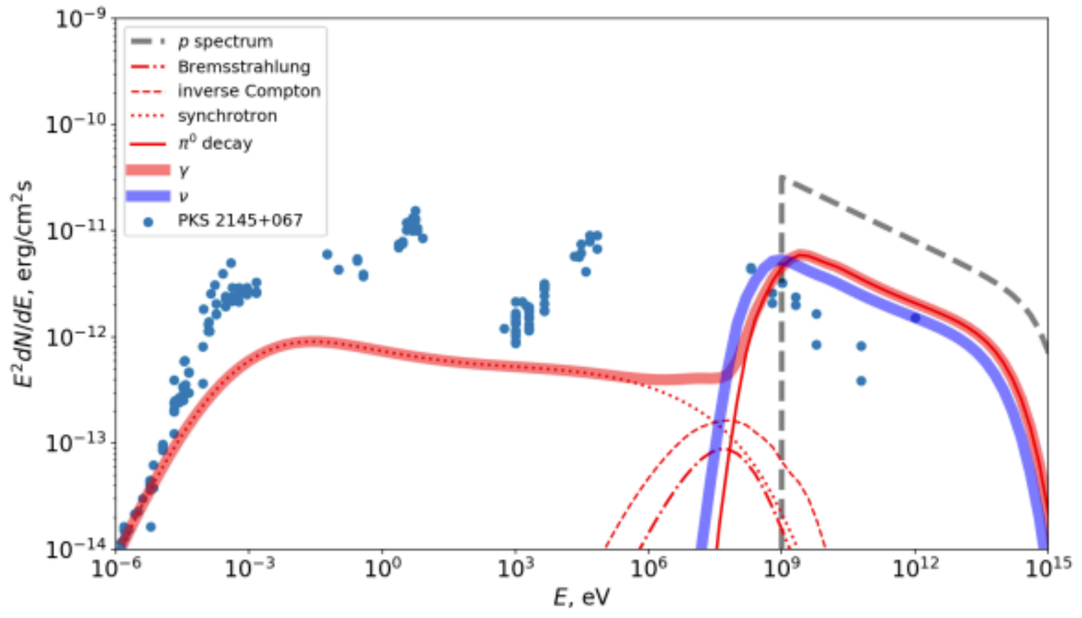
**more complex mode with
pp corona/outflows**

can explain IceCube results for Sy2 NGC 1068

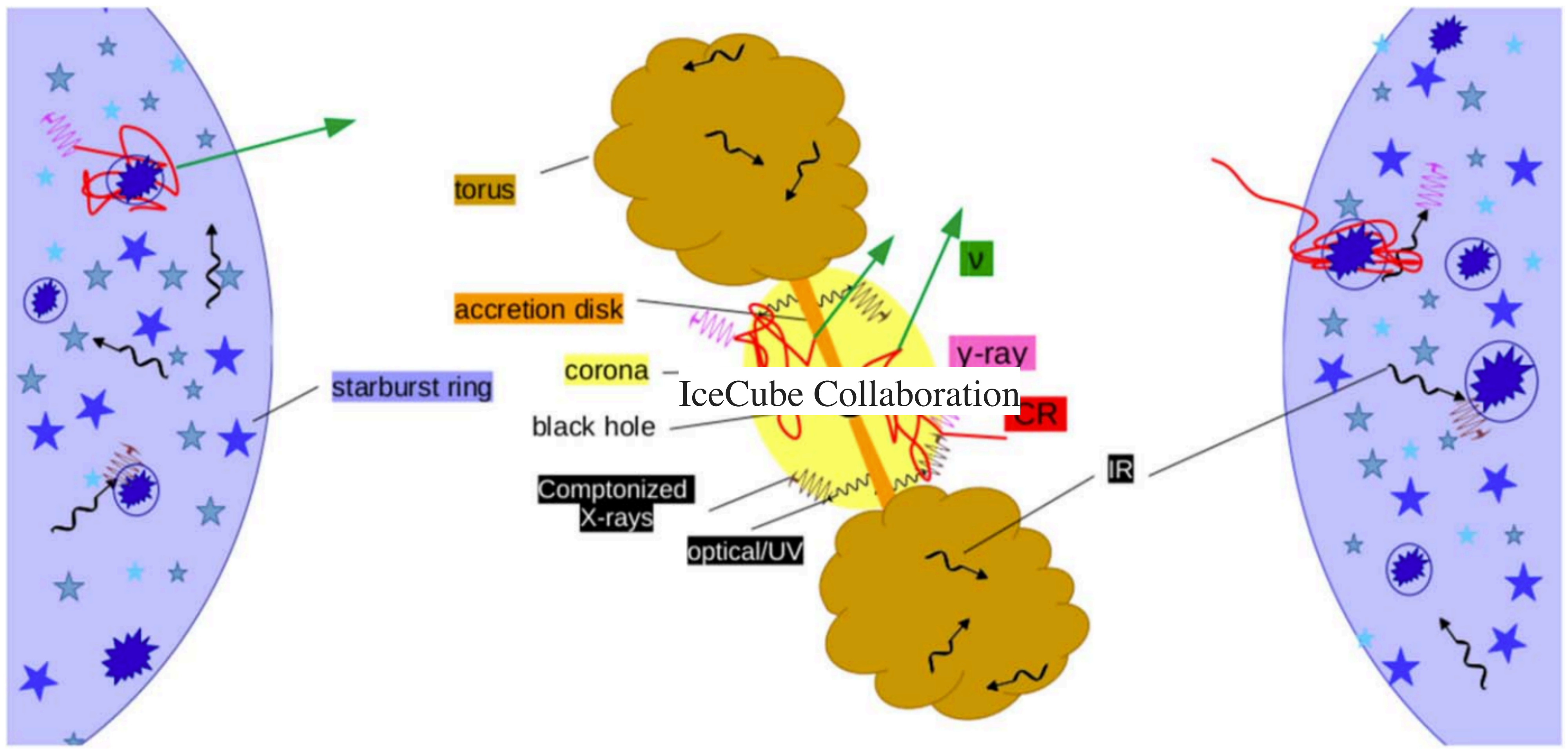
**but also γ-NLS1/CSS have a corona
and possible signatures of winds/outflows, hence
such a model might produce neutrinos in the gamma-ray
opaque regions of jetted AGNs**

Neronov&Semikoz 2020
for pp applied to pc scale of relativistic jets
propagating through circumnuclear medium of the AGN

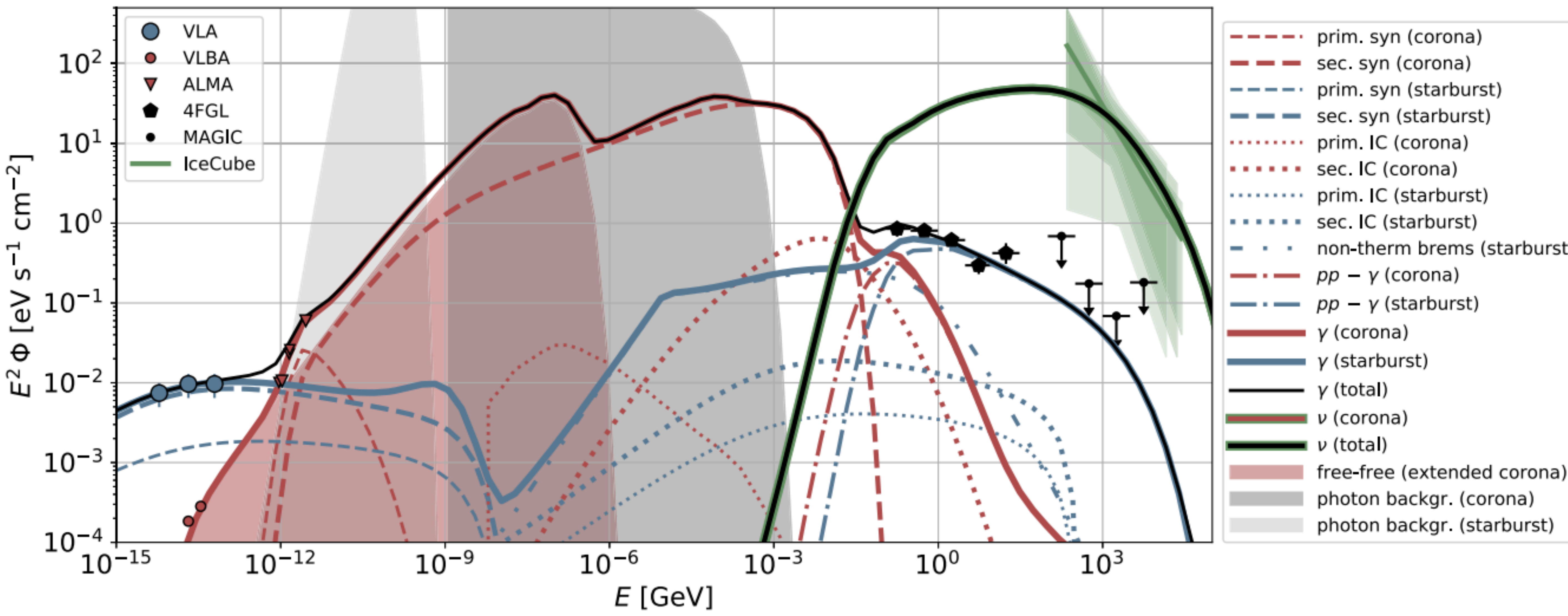




see Teresa Talk/ IceCube results 2022

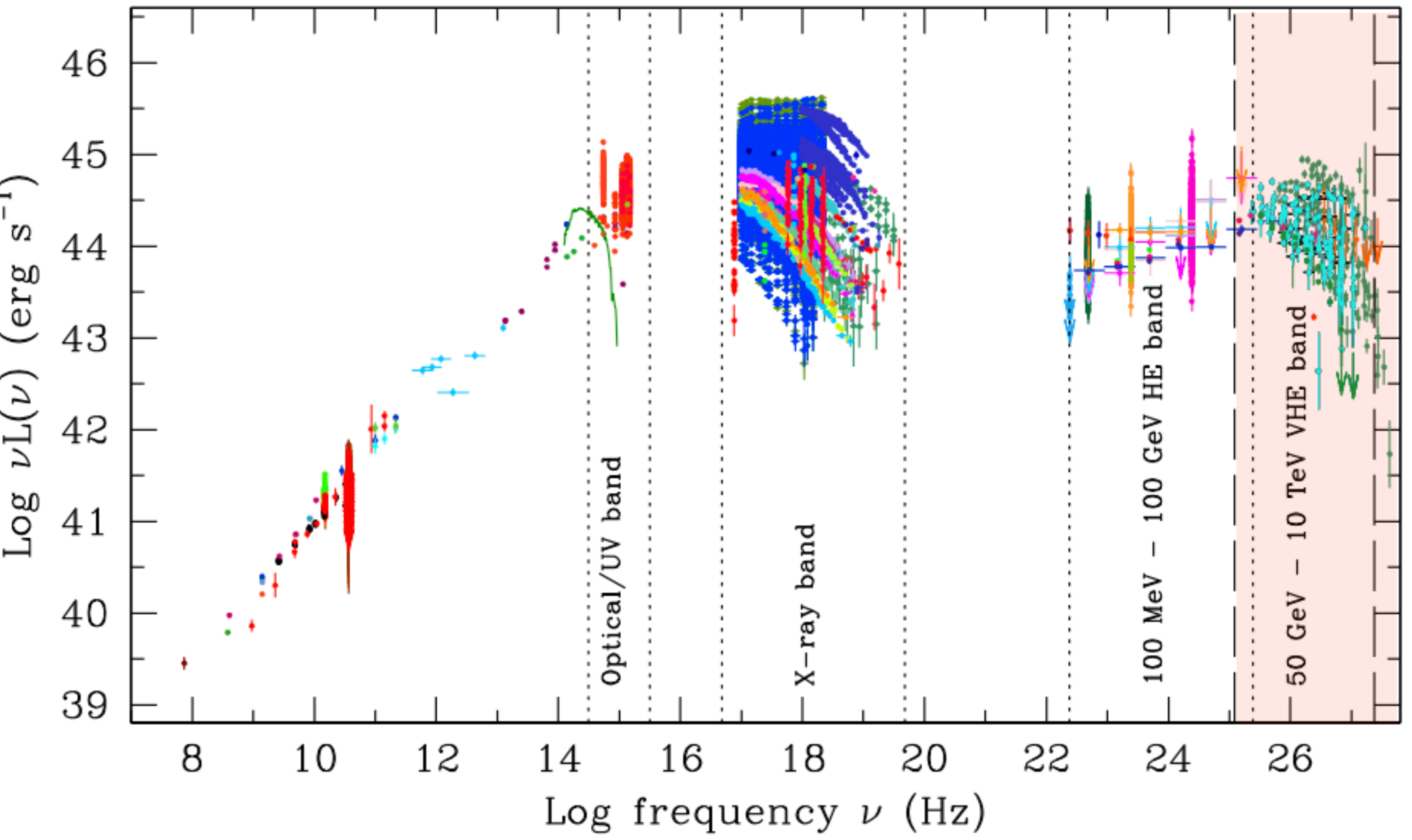


Eichmann+ 2022, see also Murase papers

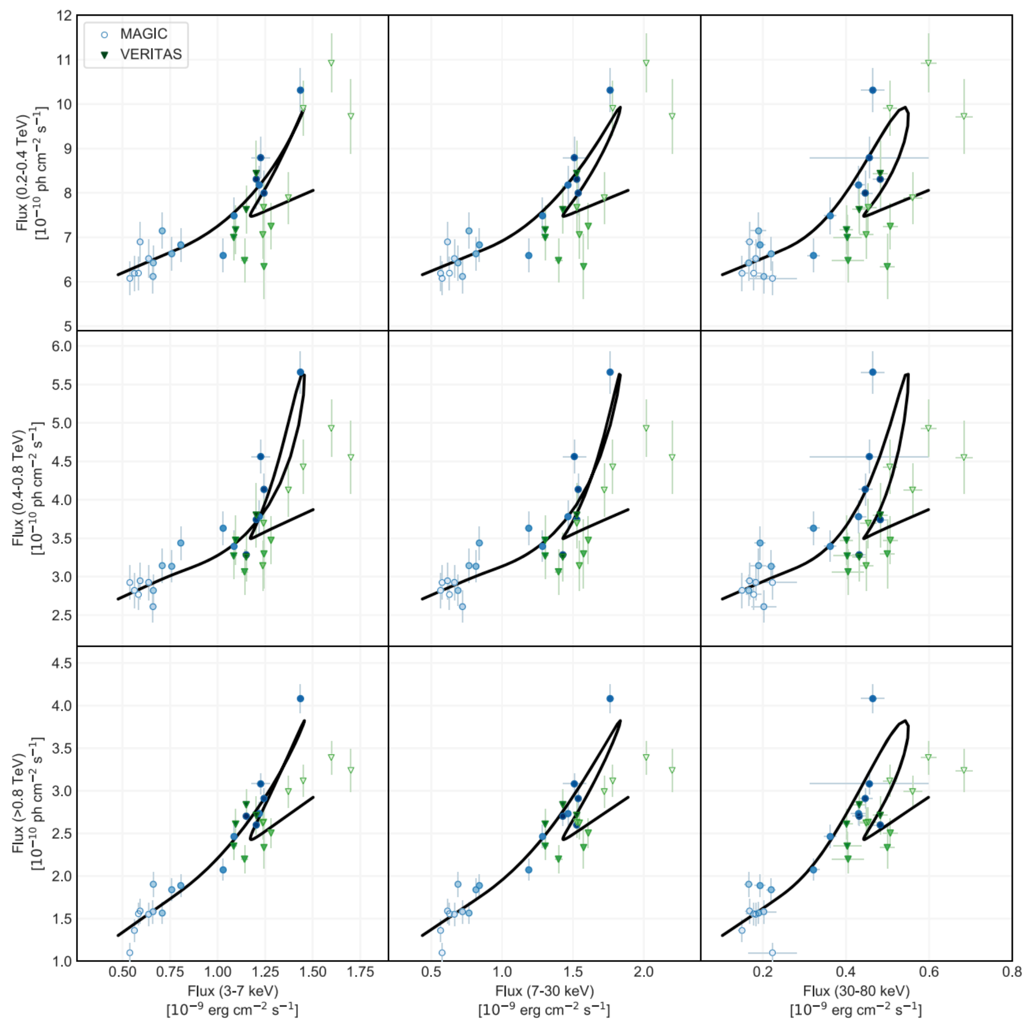


variability on short time scales: acc. and cooling (lags, hyst. cycle etc...)

Padovani+ 2017 **Mrk 421**



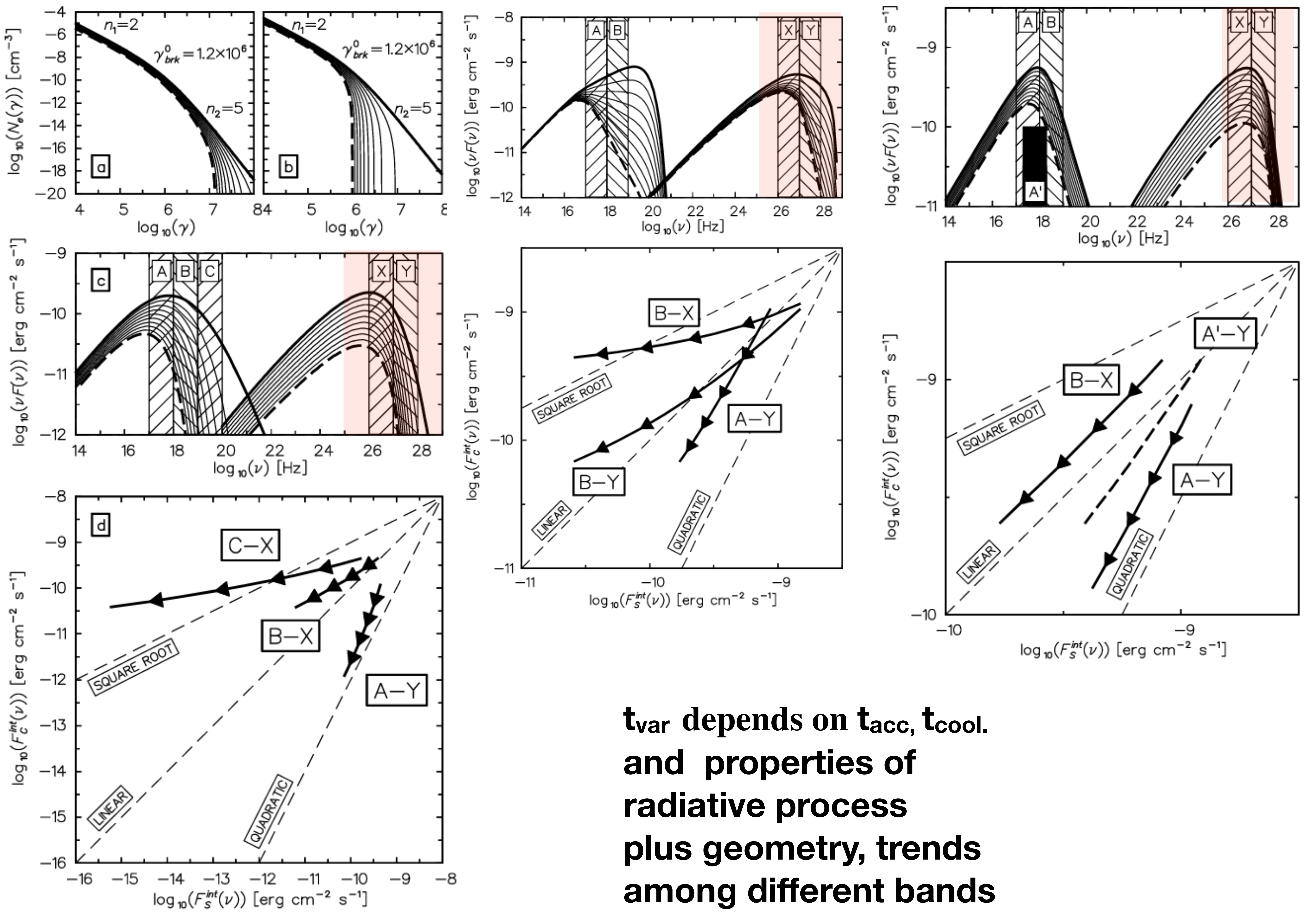
Mrk 421 2013 Acciari+ 2020



CW:soft lag, when the flare is observed at frequencies where the higher energy variability occurs more rapidly than at lower energy

CCW:In contrast, when observed at frequencies for which the acceleration and cooling timescale are almost equal, the loops are expected to be counter-clockwise with a possible hard lag

single episode, single process Katarzyński+ 2005

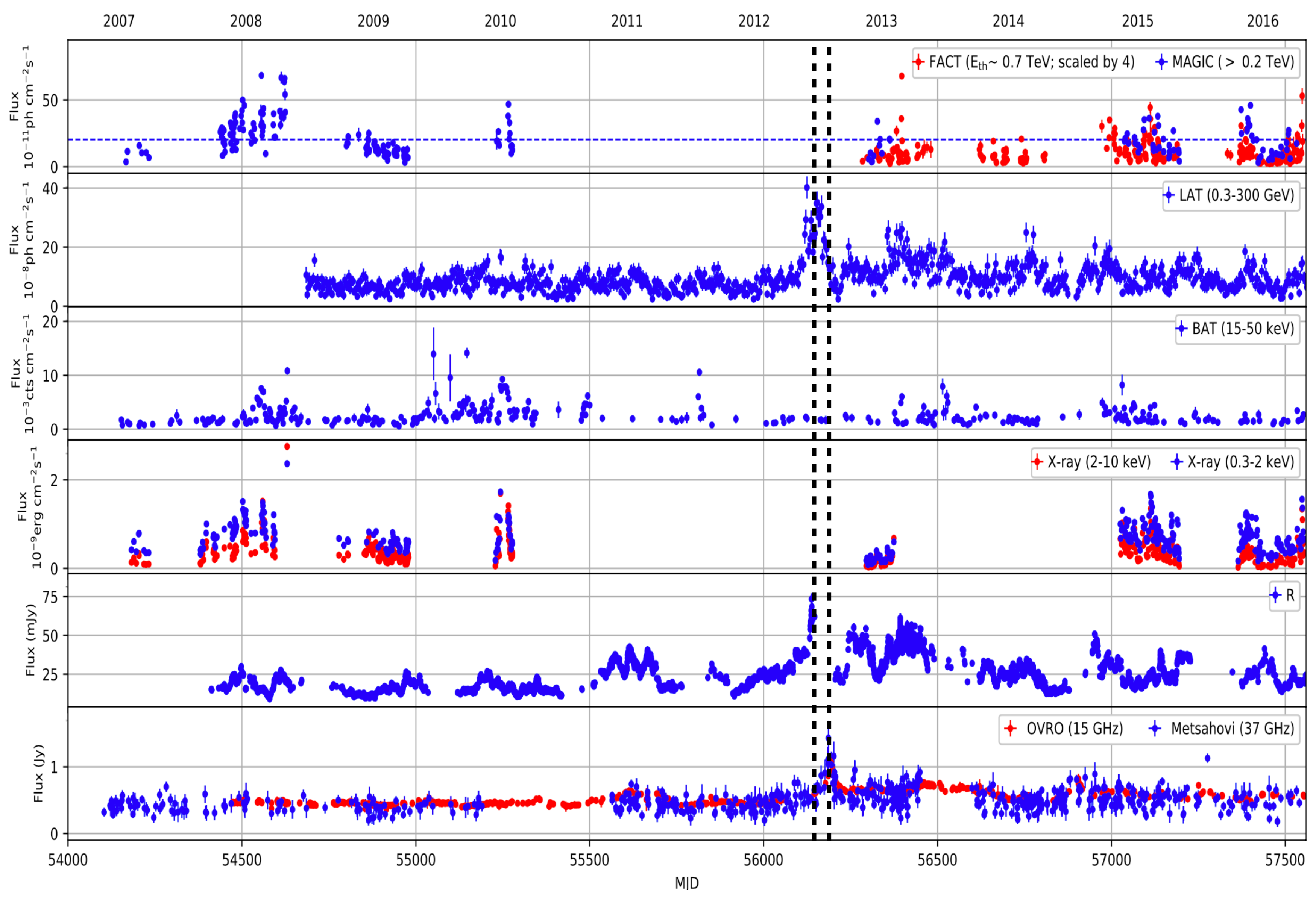


t_{var} depends on t_{acc}, $t_{cool.}$ and properties of radiative process plus geometry, trends among different bands bring signatures of different processe.

long term and delays on weeks to years timescales

MW variability and correlation studies of Mrk 421 during historically low X-ray and γ-ray activity in 2015-2016

Magic coll. 2020

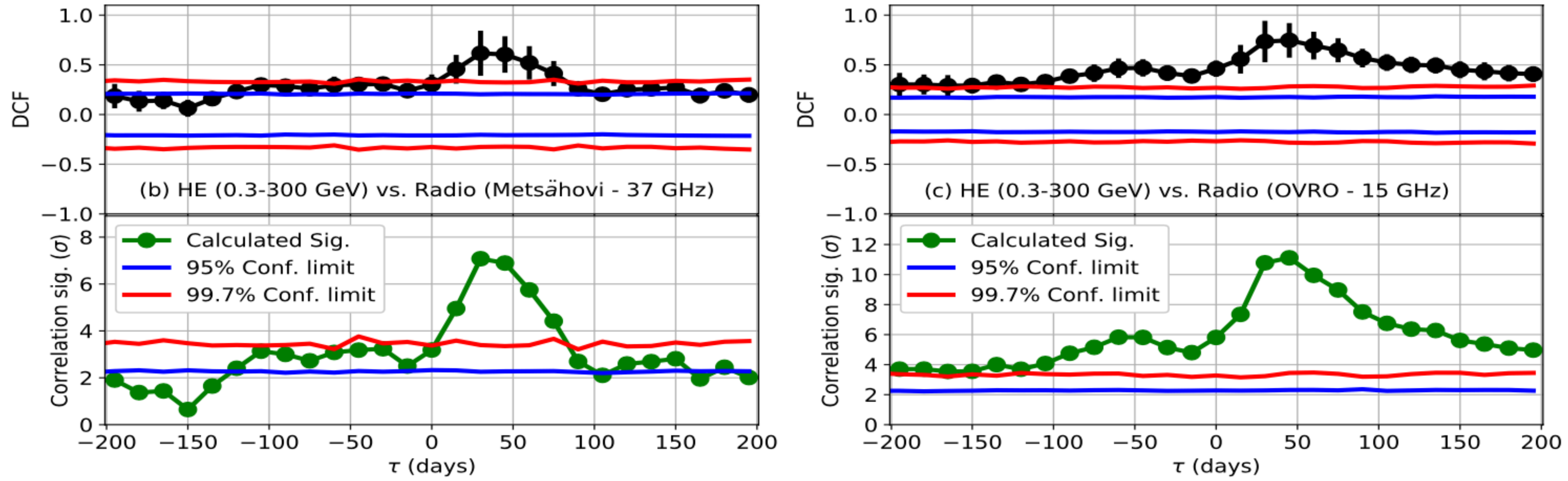


long terms depends on jet

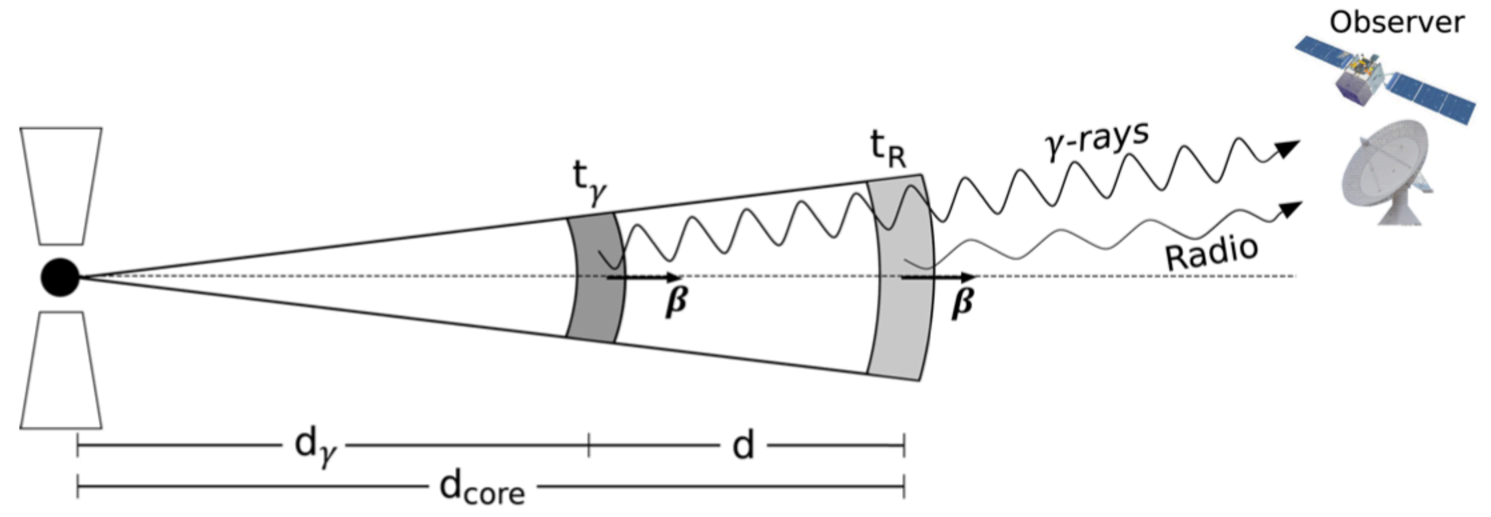
feeding processes and jet structure:

AD instabilities ,BH spin, jet geometry

Radio-γ delay in Mrk 421 (months)



Radio-γ delay ~ 1/ν



W. Max-Moerbeck+ 2014
B. Pushkarev+ 2010
Ghisellini+1985
McCray,R. 1968

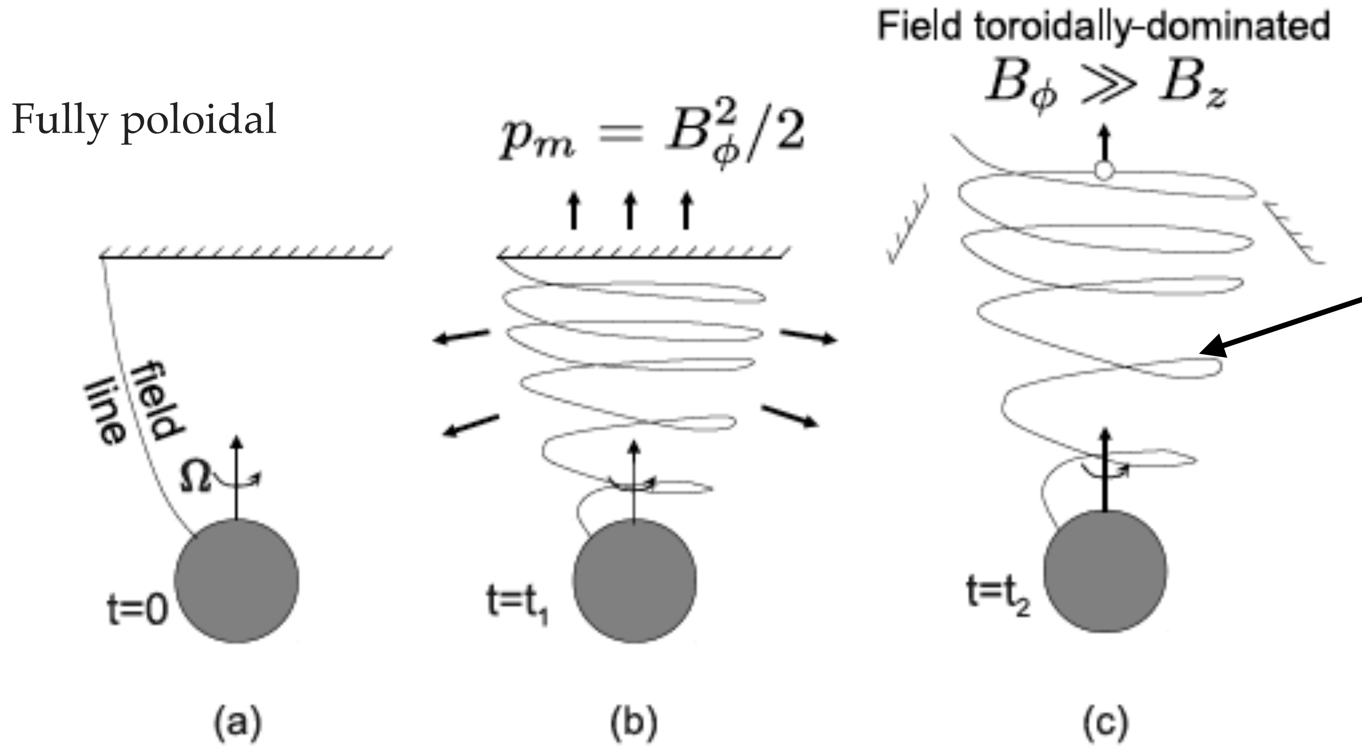
see Vitalii Talk

long/short term variability: jet feeding/powering

BZ process
mechanism to work, the system requires two ingredients:
- a central spinning black hole and
- a surrounding disk of plasma with a strong poloidal magnetic field. Once accretion onto the black hole has begun, the magnetic field lines embedded in the disk, due to the frame dragging, twists the field lines into following the rotation of the black hole.

provides the B gradient to accelerate the jet

credit picture Sera Markov

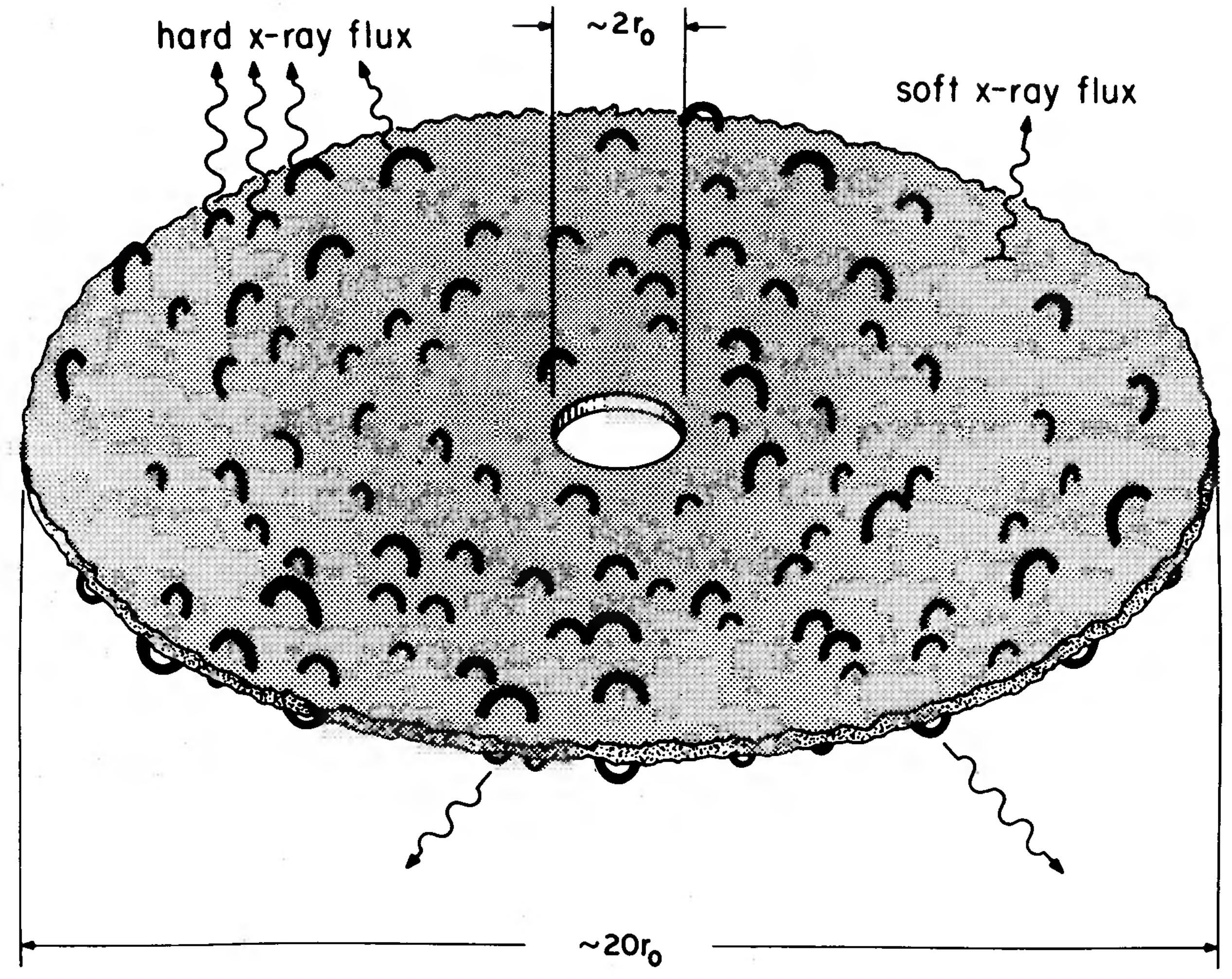


Frame dragging and differential rotation → **jet powering**

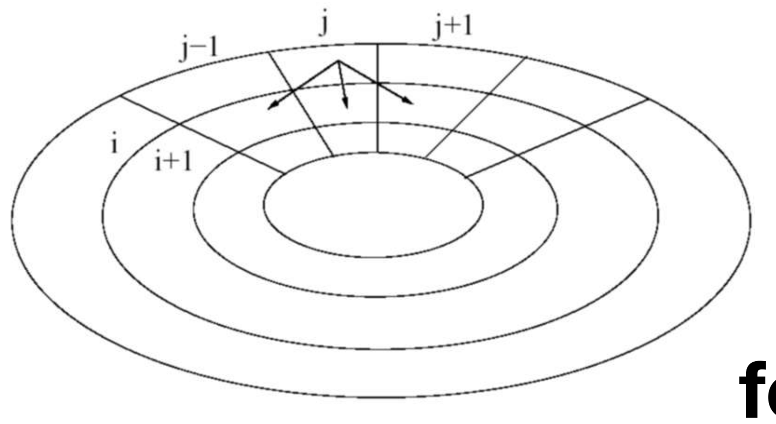
disk variability → **jet variability**

provides content of pairs during magneti reconnection plus pre-acceleration of particles

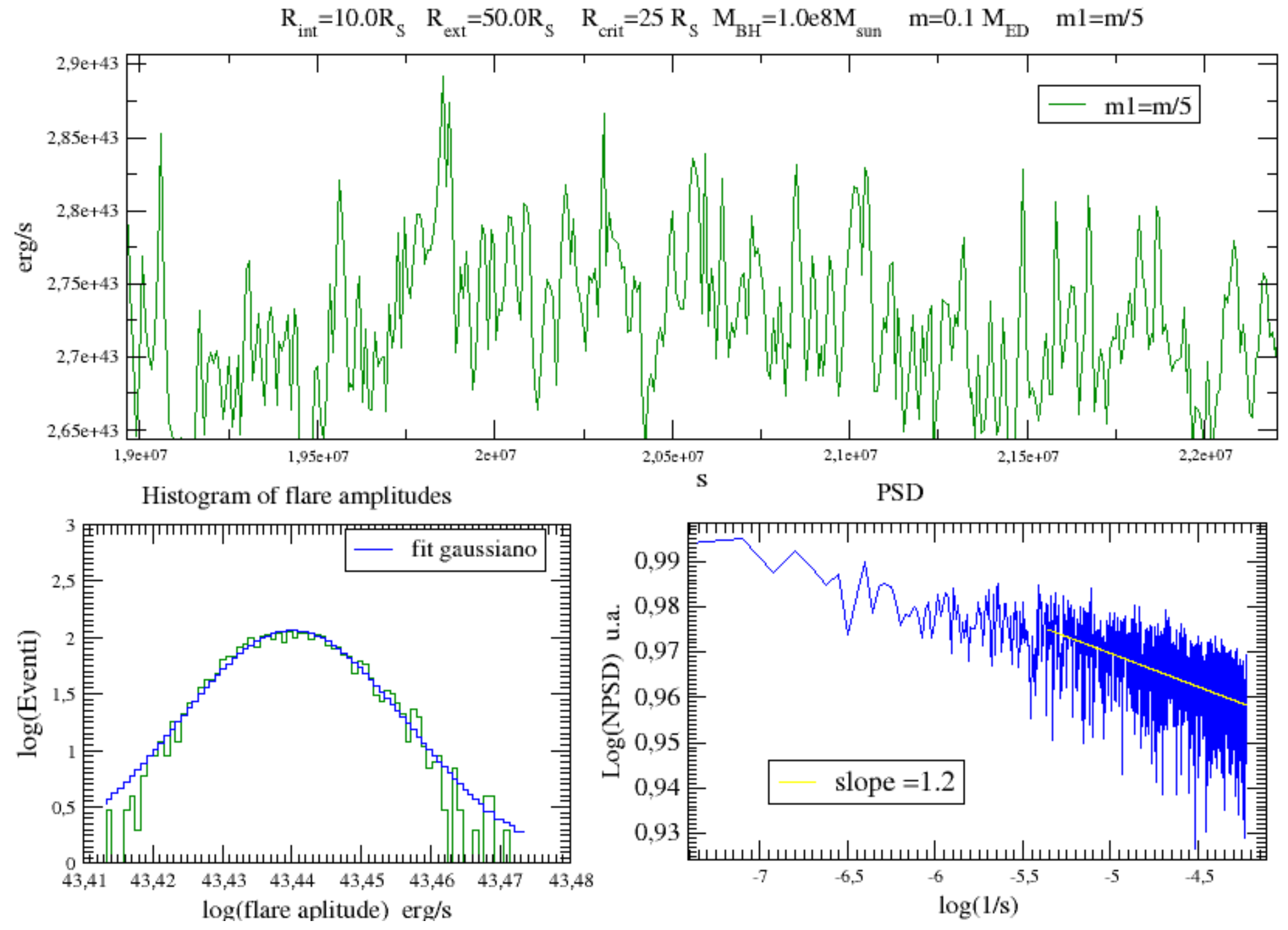
Disk, differential rotation, B&P wind plus plasmoids



Galev&Rosen 1979



feeding



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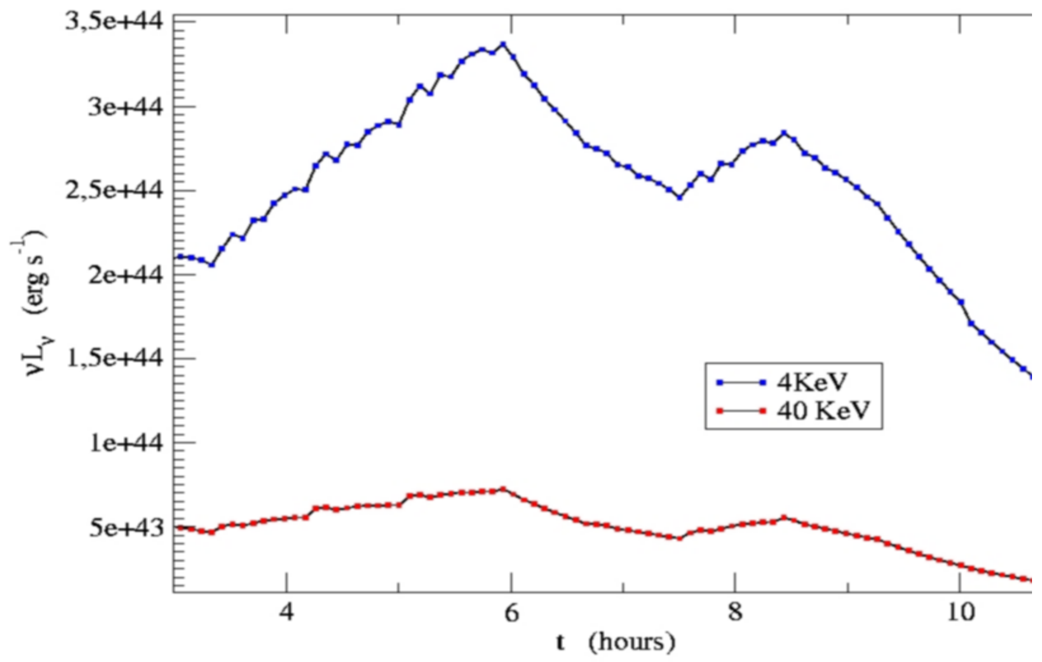
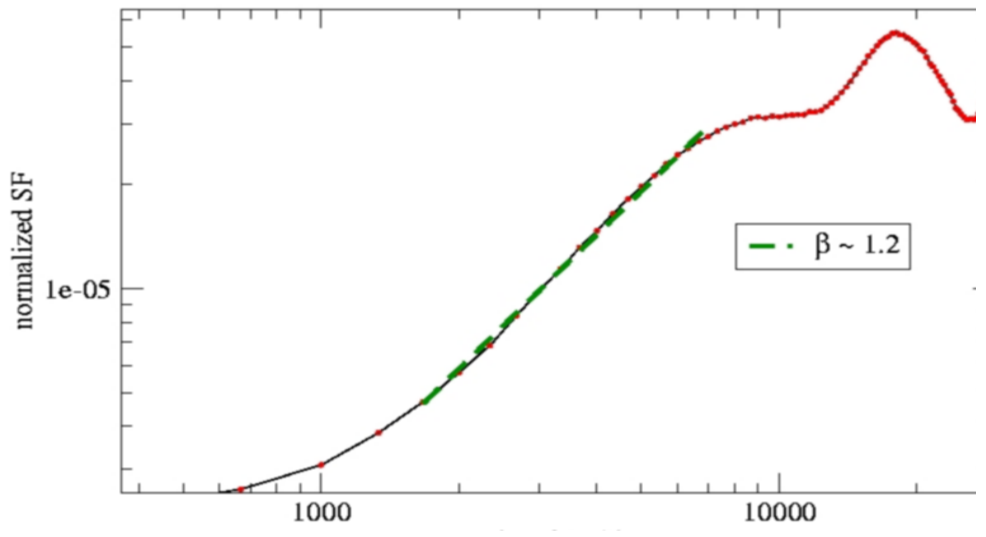
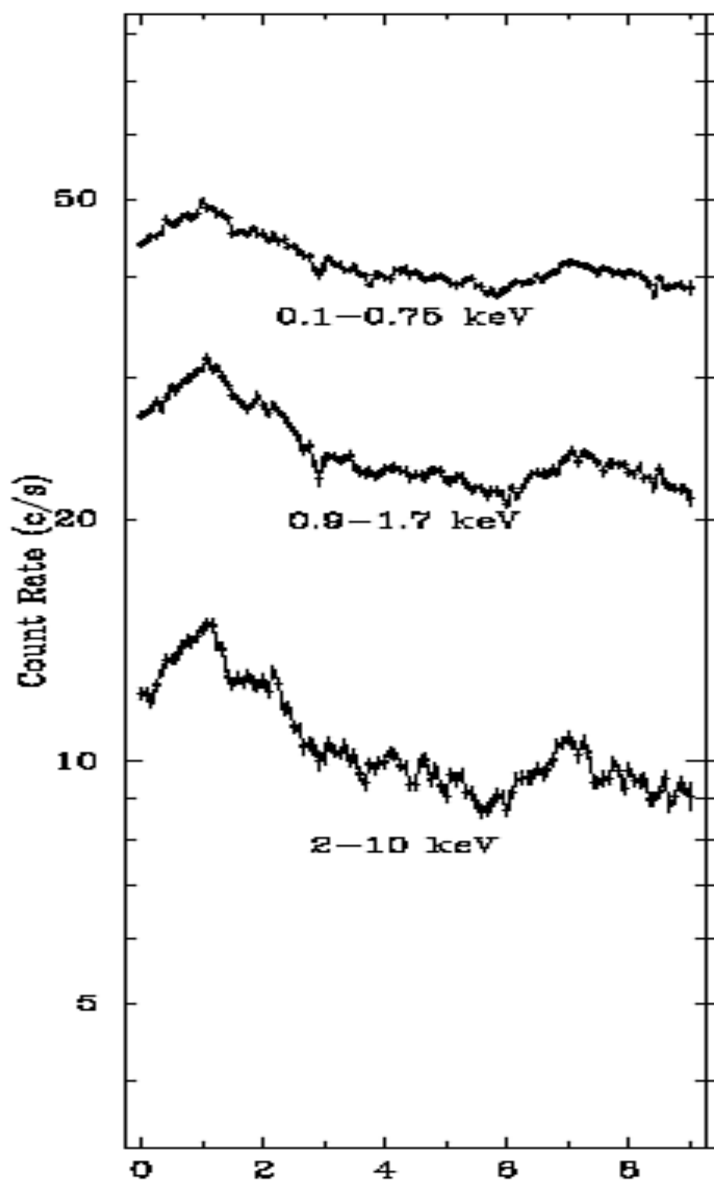




tramacere



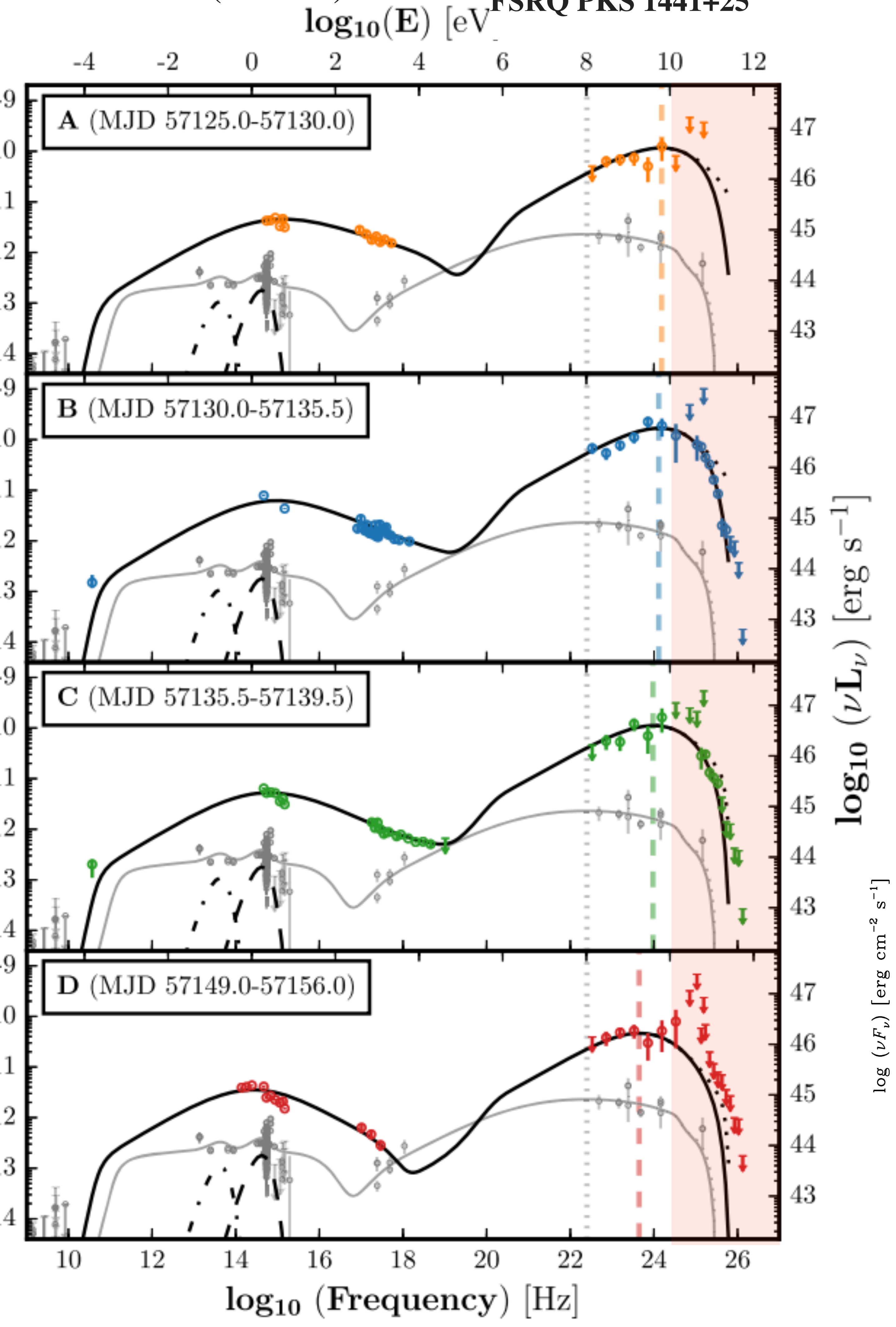
MRK 421 XMM-NEWTON SEMBAY et a

standard picture: cooling break scenario

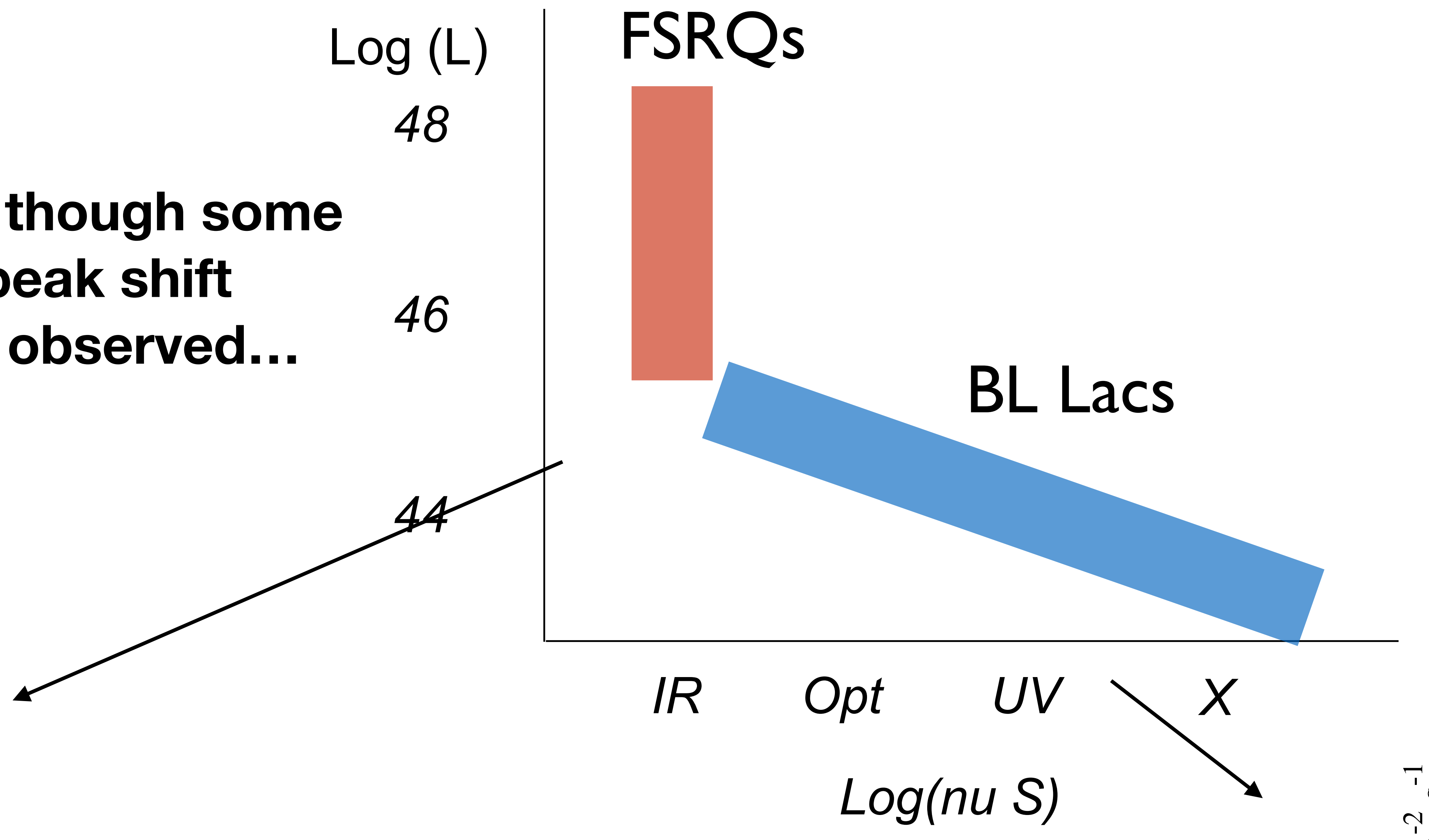
The peak frequency dynamic range, for LSP, is low, this might hide the emitters evolution

Ahnen+ 2015 (MAGIC)

FSRQ PKS 1441+25

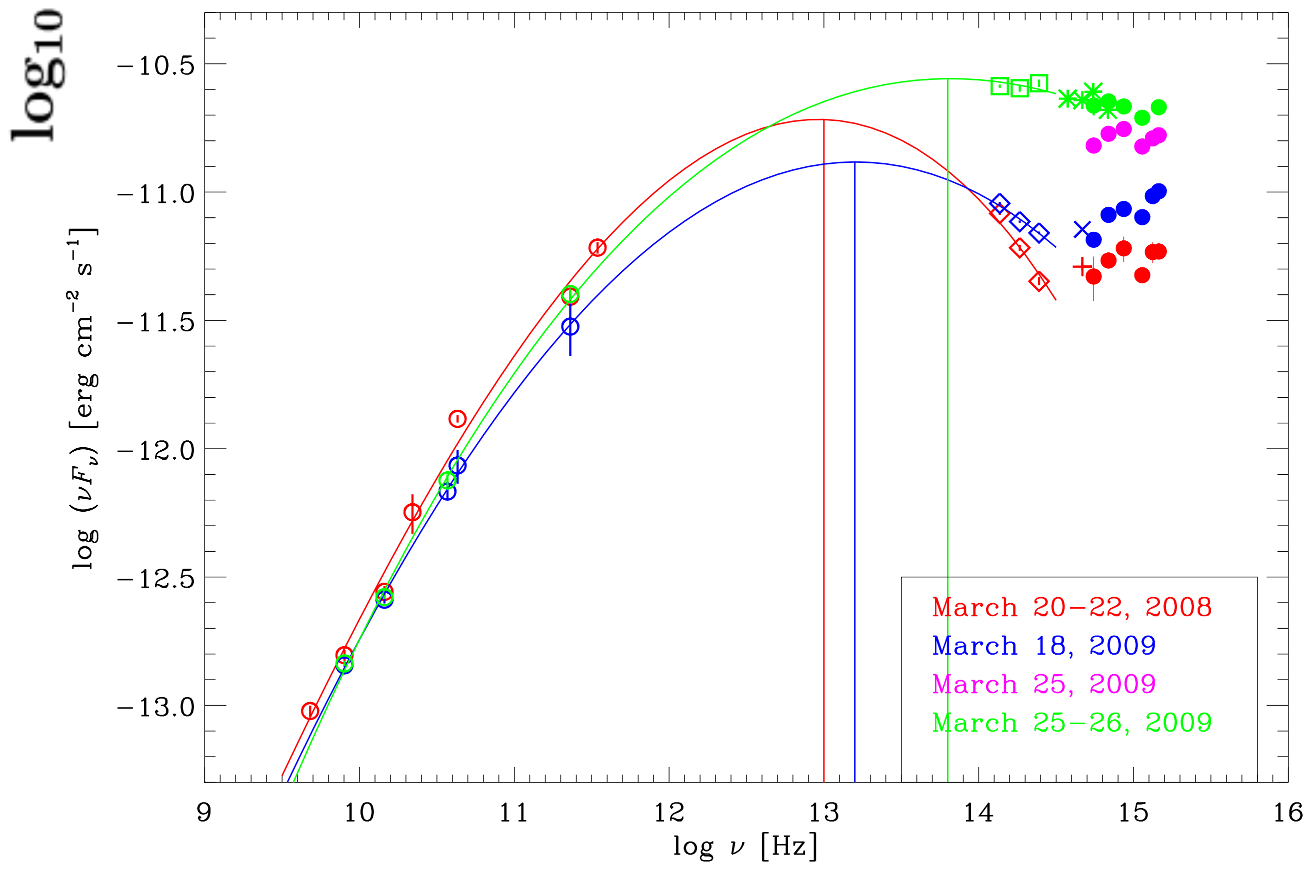


even though some peak shift are observed...

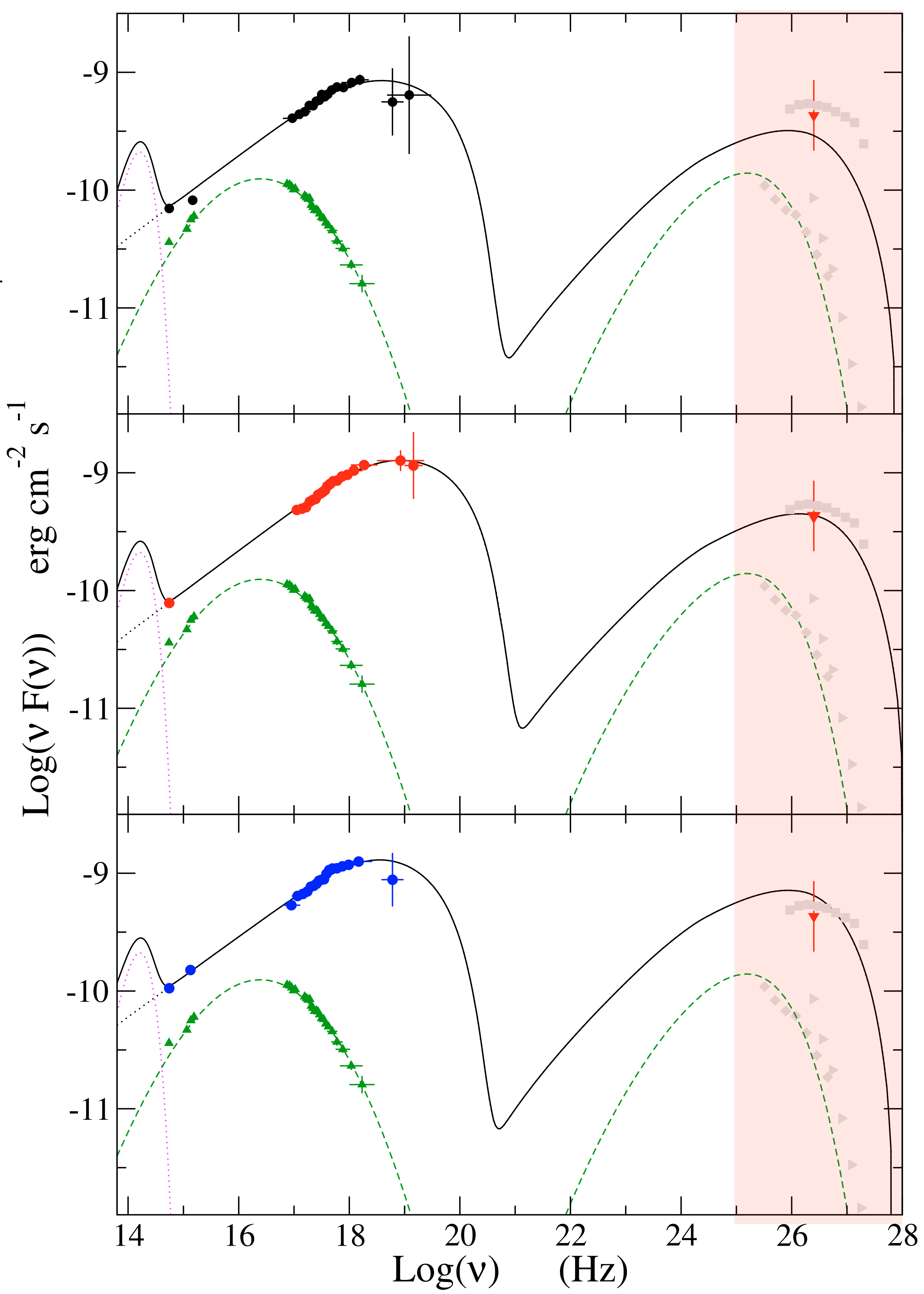


Dammando+ 2012

FSRQ PKS 1510-089



Tramacere +2009



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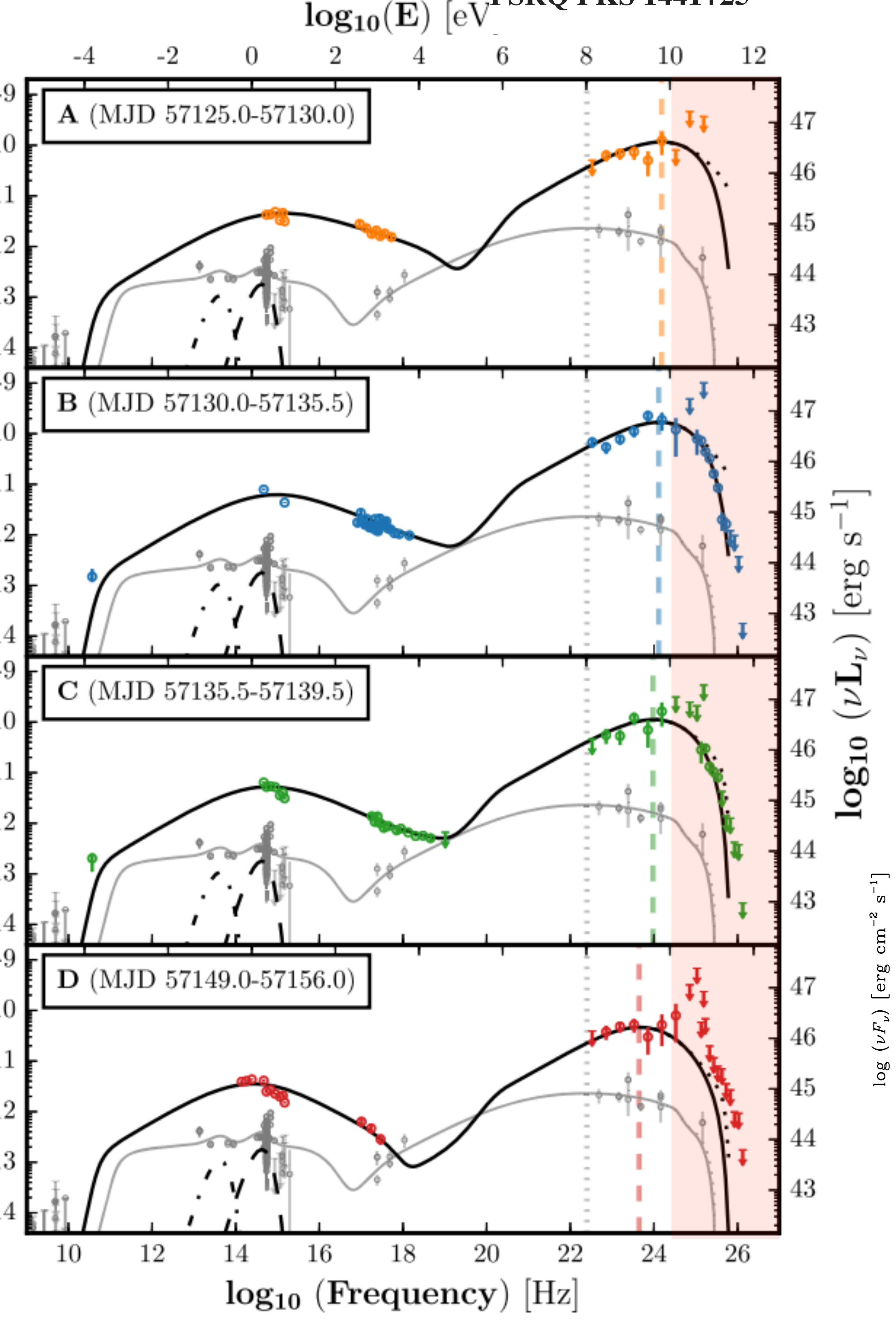

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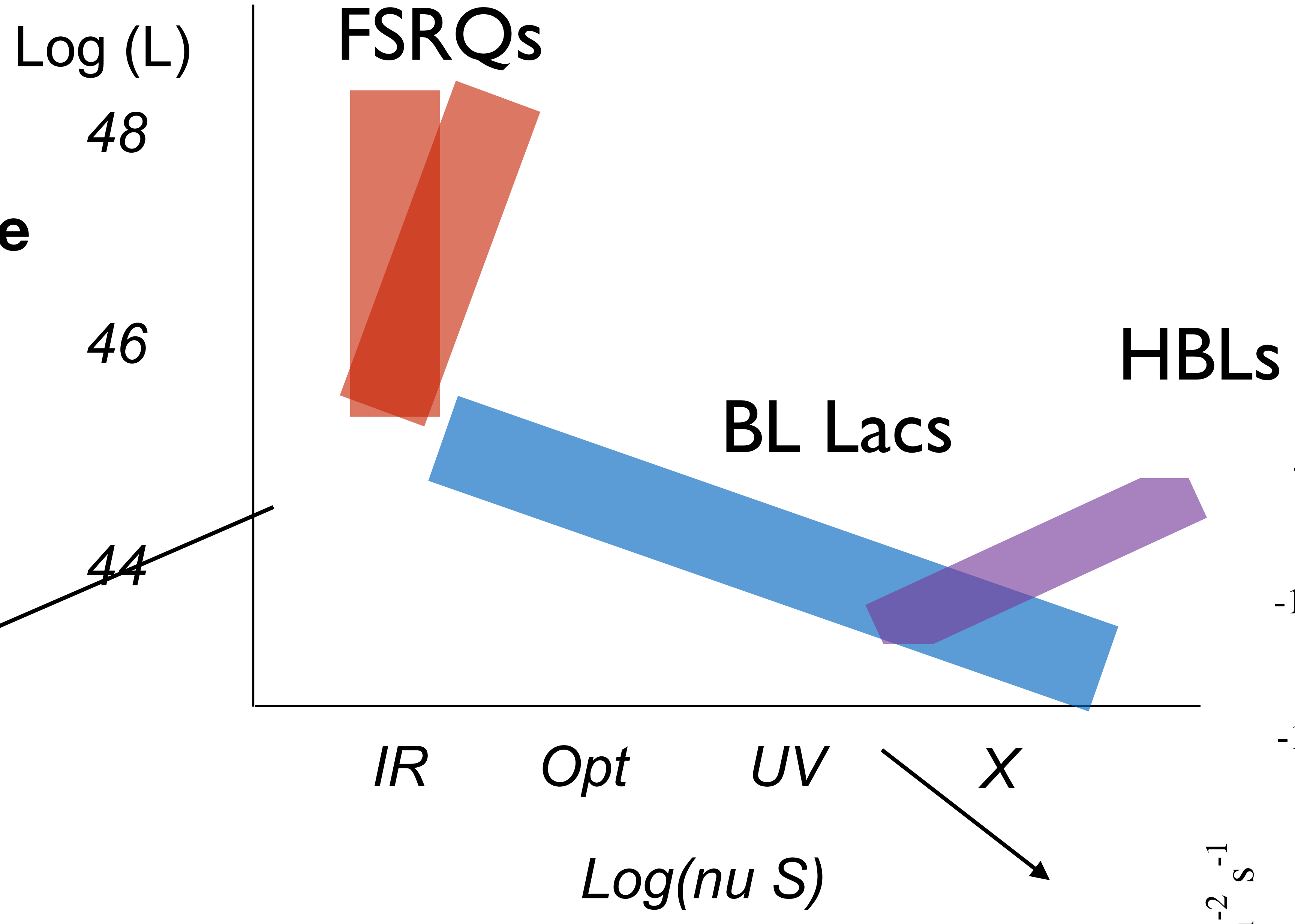
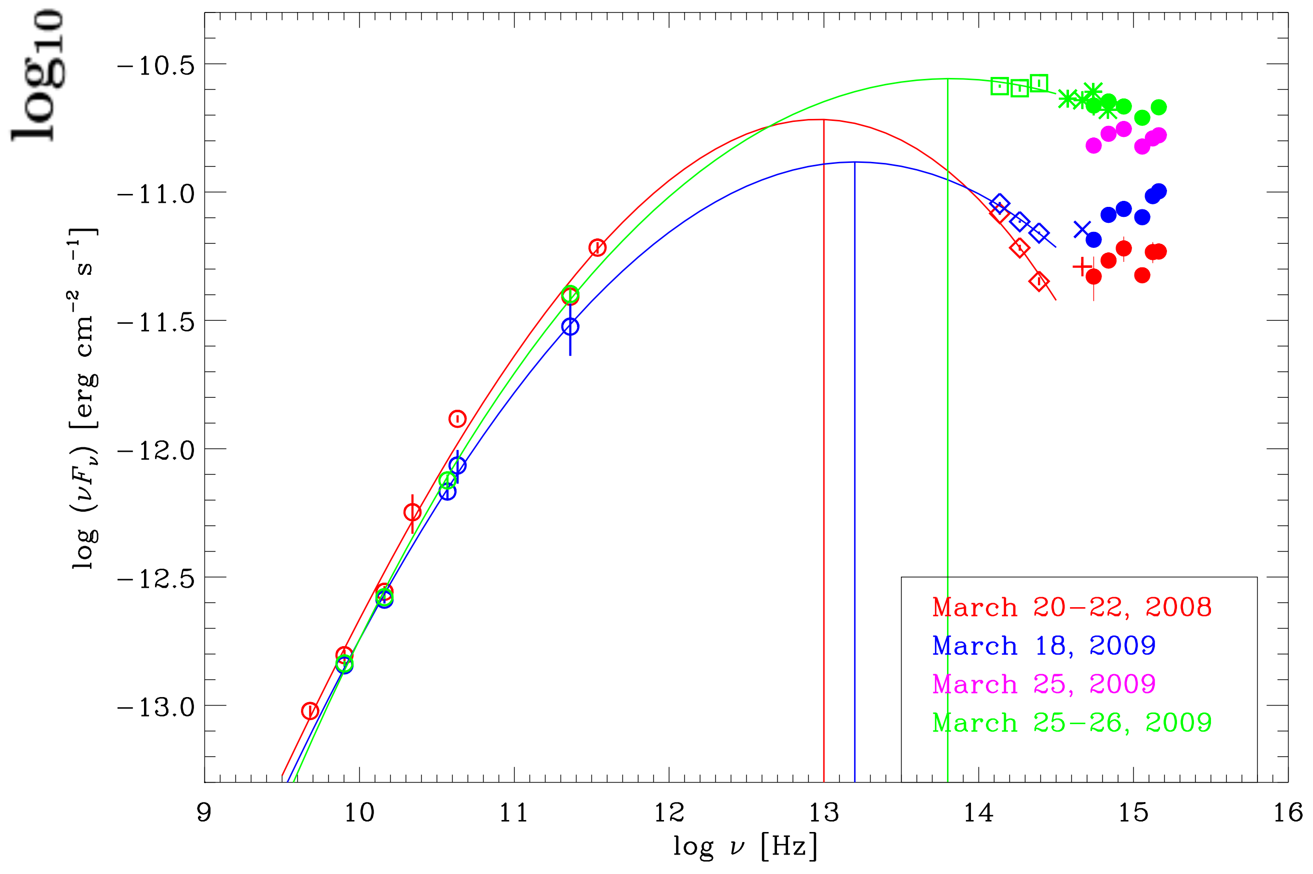
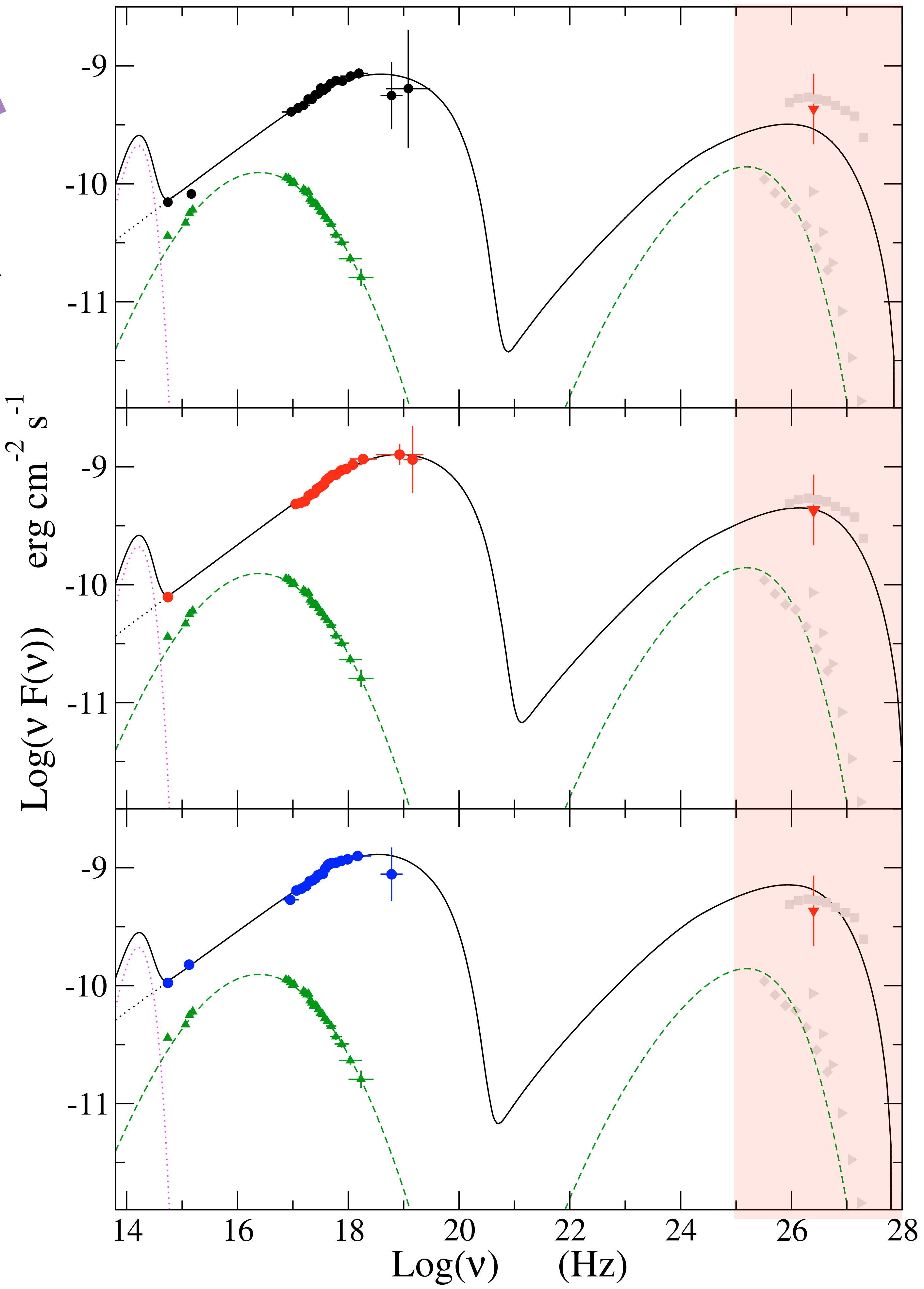


Dammando+ 2012 FSRQ PKS 1510-089

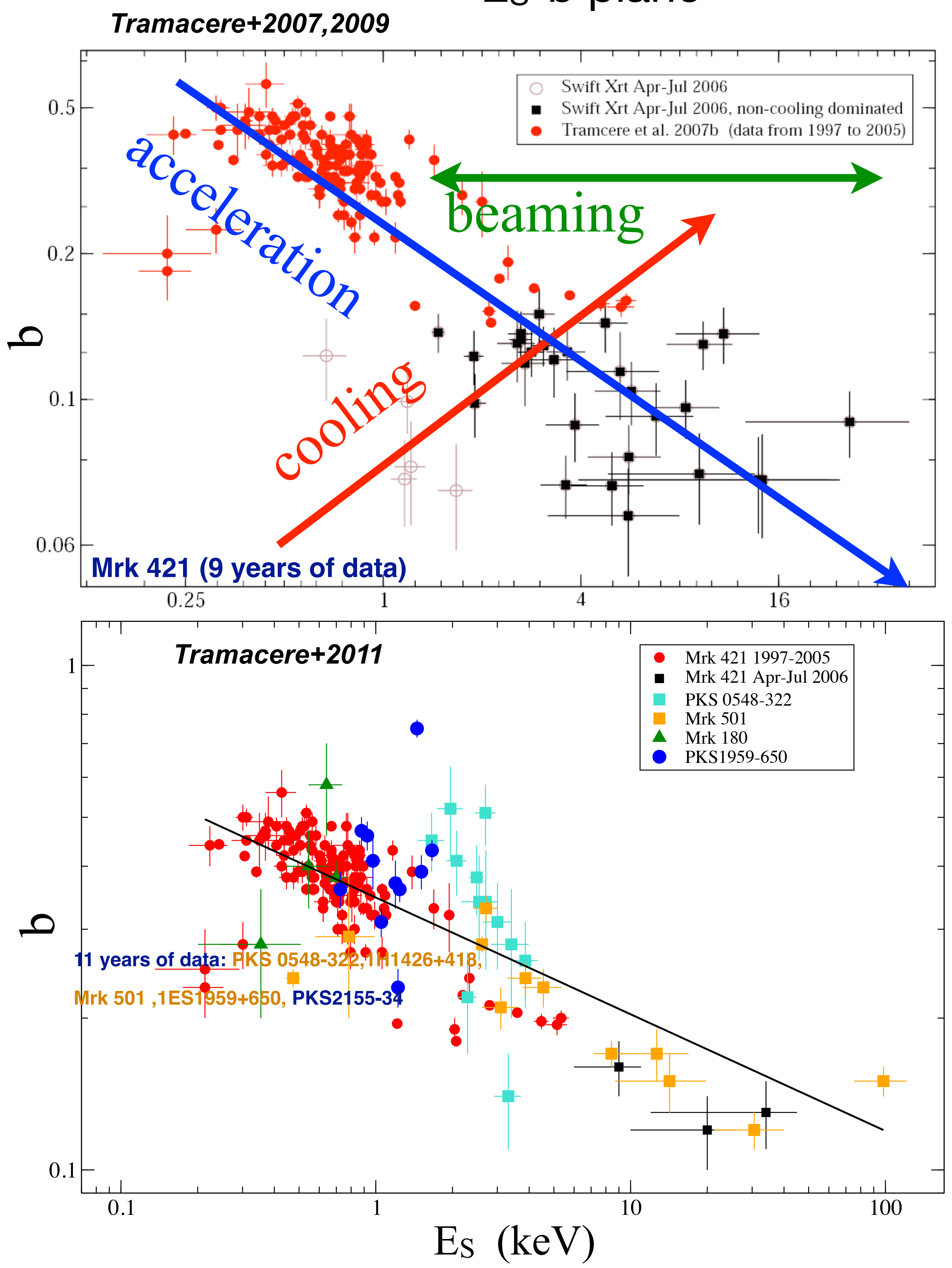


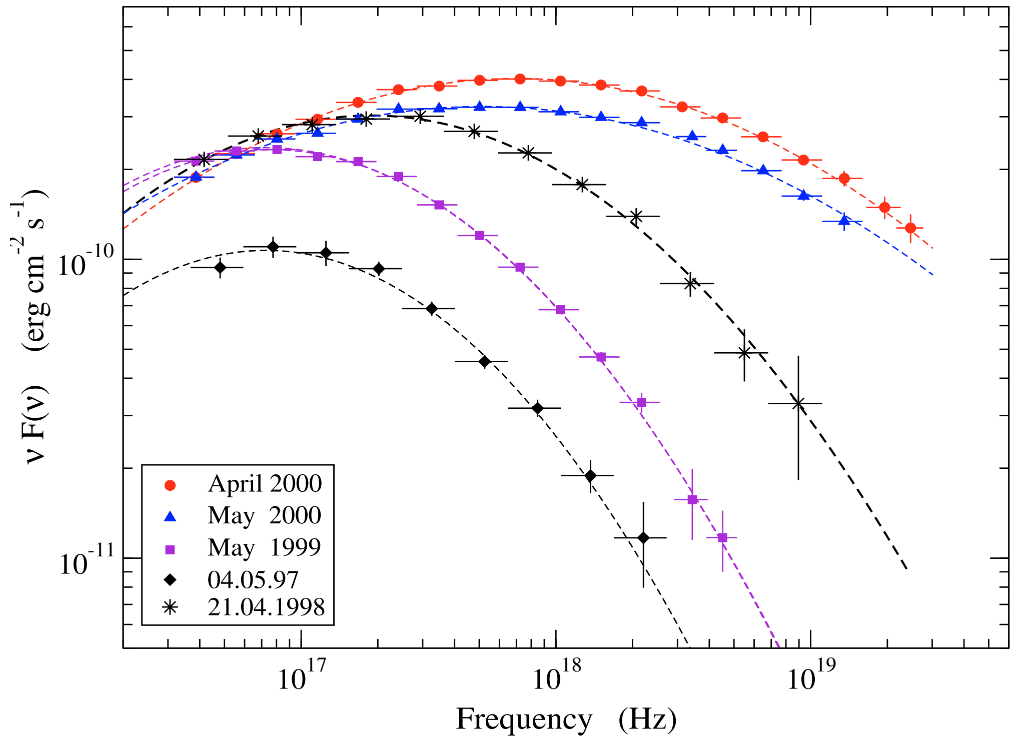
Tramacere +2009

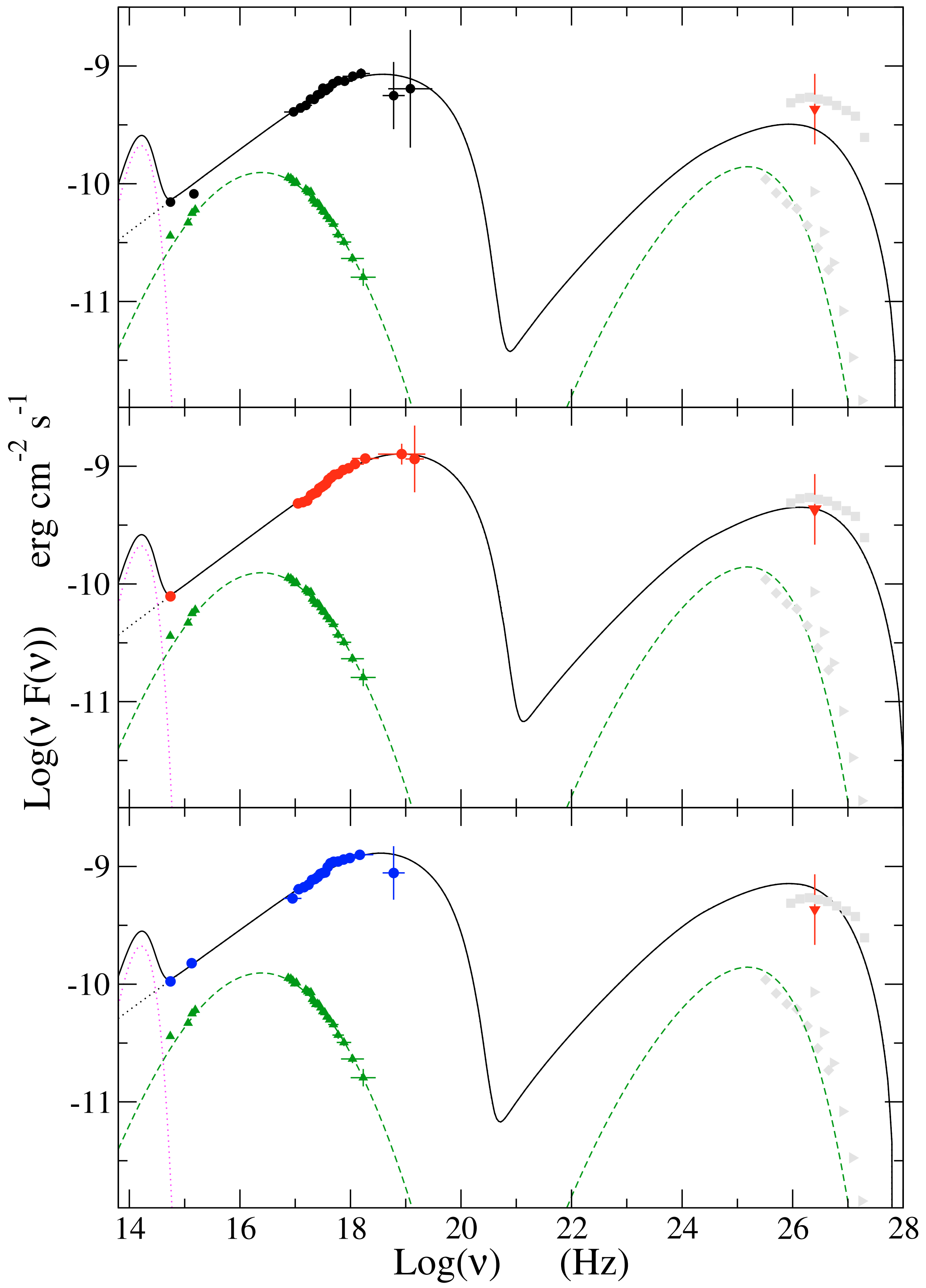


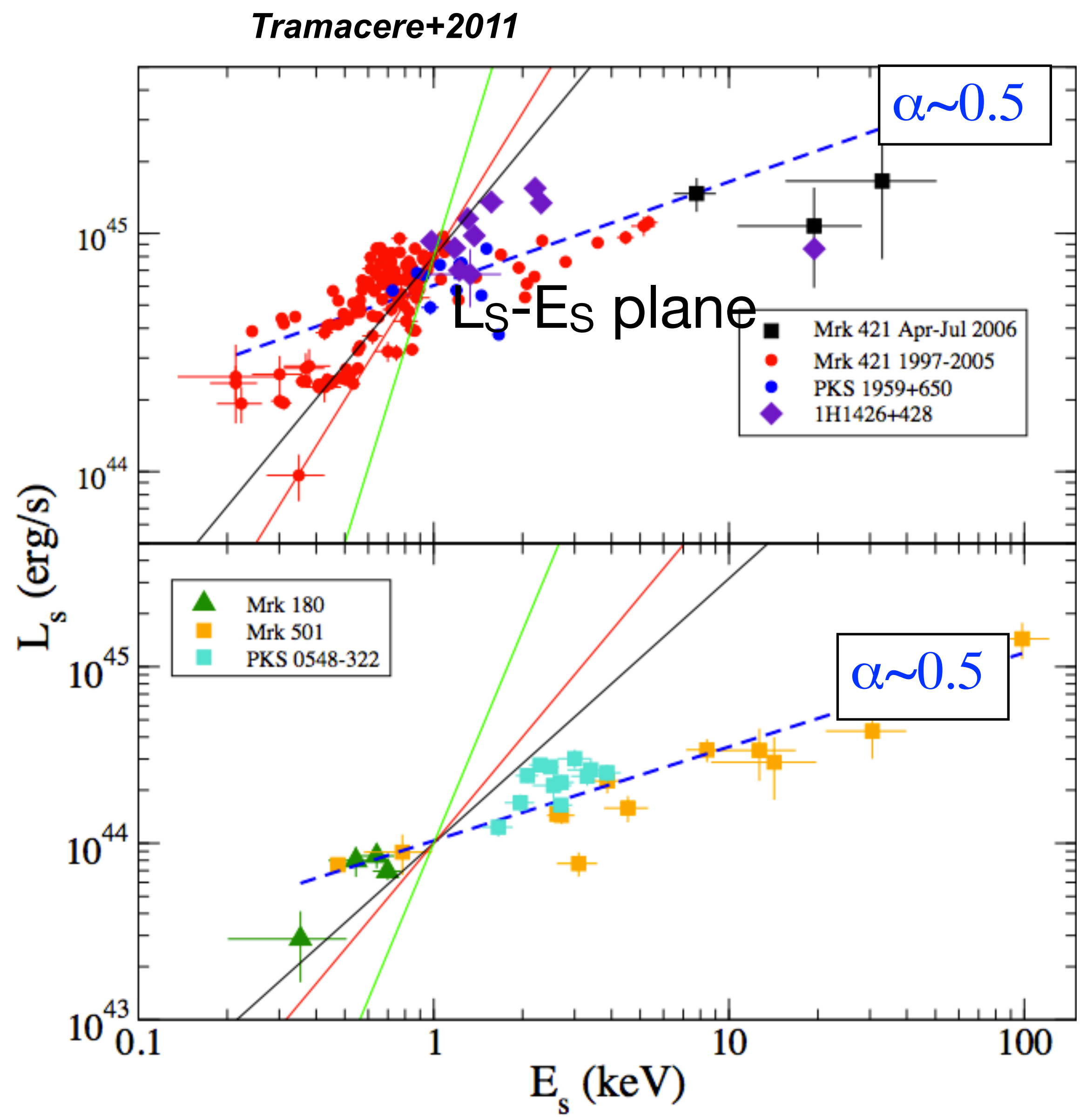
X-ray phenomenology and stochastic acceleration

Es-b plane







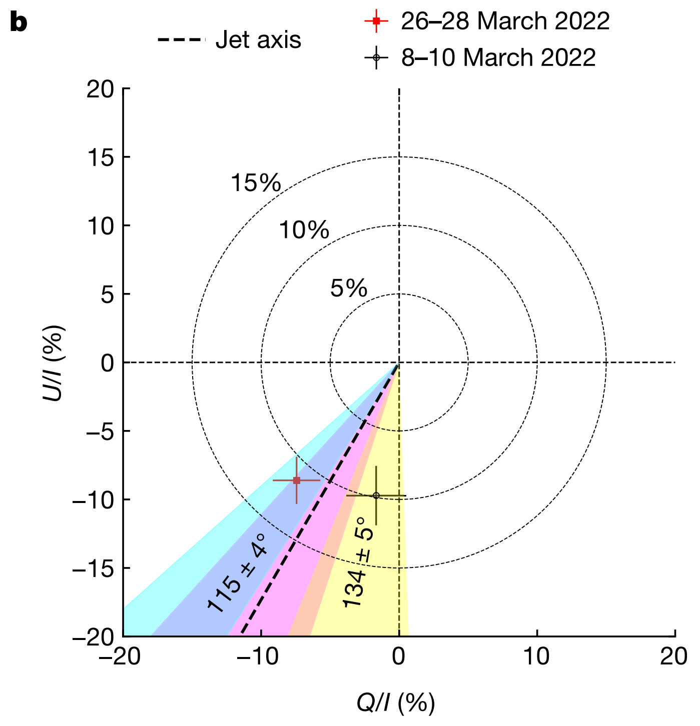


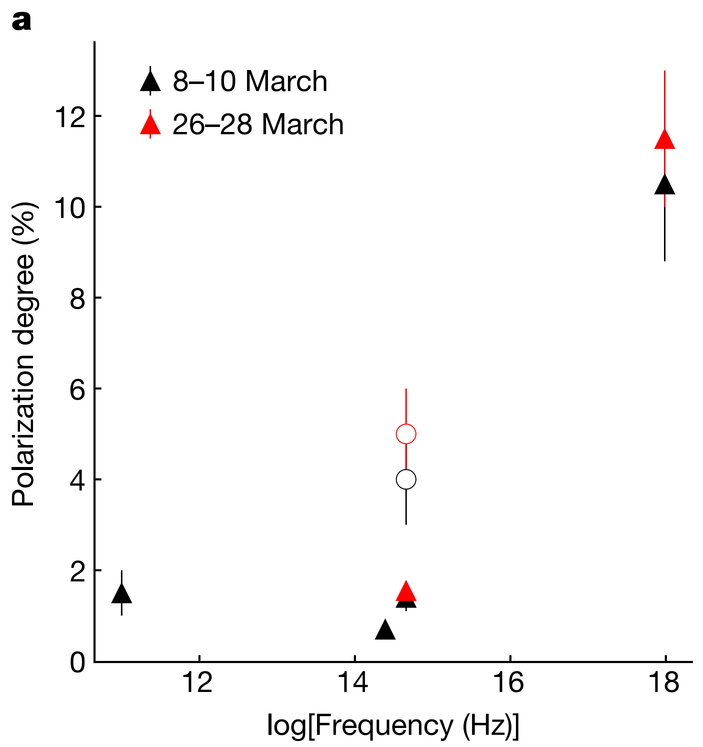
Does HBLs provide the most efficient class to study the acceleration?
Is it the blazar sequence: the larger the peak luminosity the lower the luminosity a signature of the physics, or is there a bias from considering only the cooling?

Polarization

see Hancheng Talk

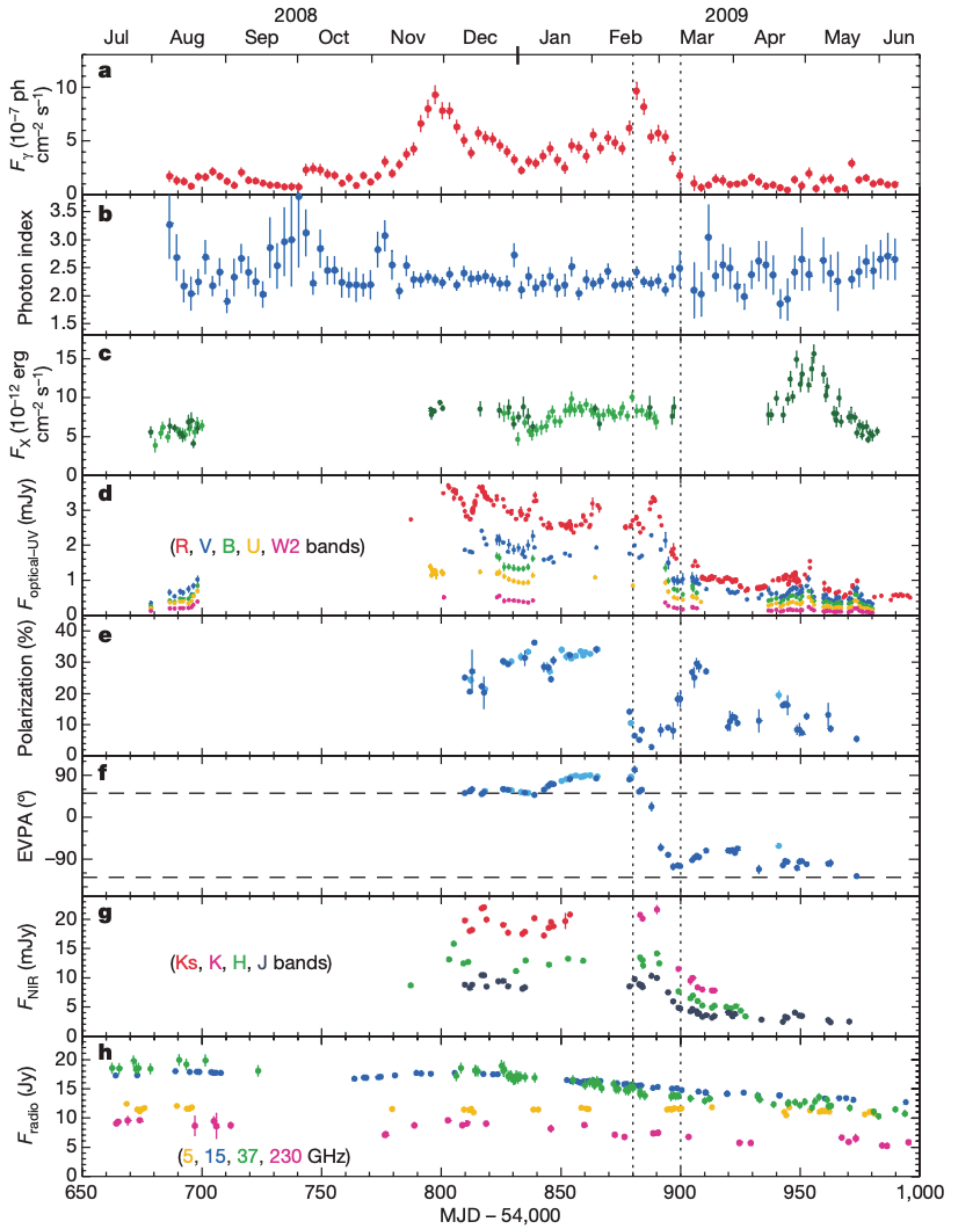
mrk 501, quiescent sate iXPE recent results (nature 2022)



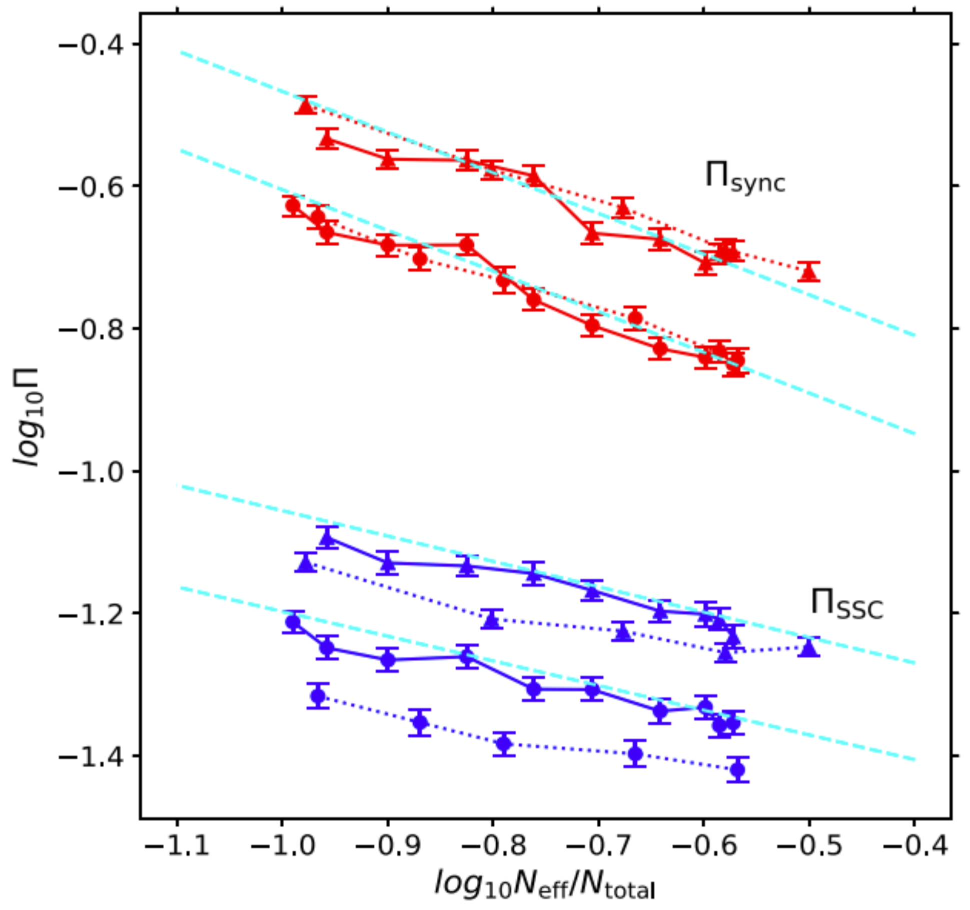


- polarization ~ 10%<< ~70% from ordered fields
- hints for turbulence impacting on B structure
- multi-zone vs single zone
- B orthogonal to the jet axis
- hadronic-leptonic discrimination (but VHE spectral signatures are mandatory to break degeneracy)
- intrinsic difference between classes

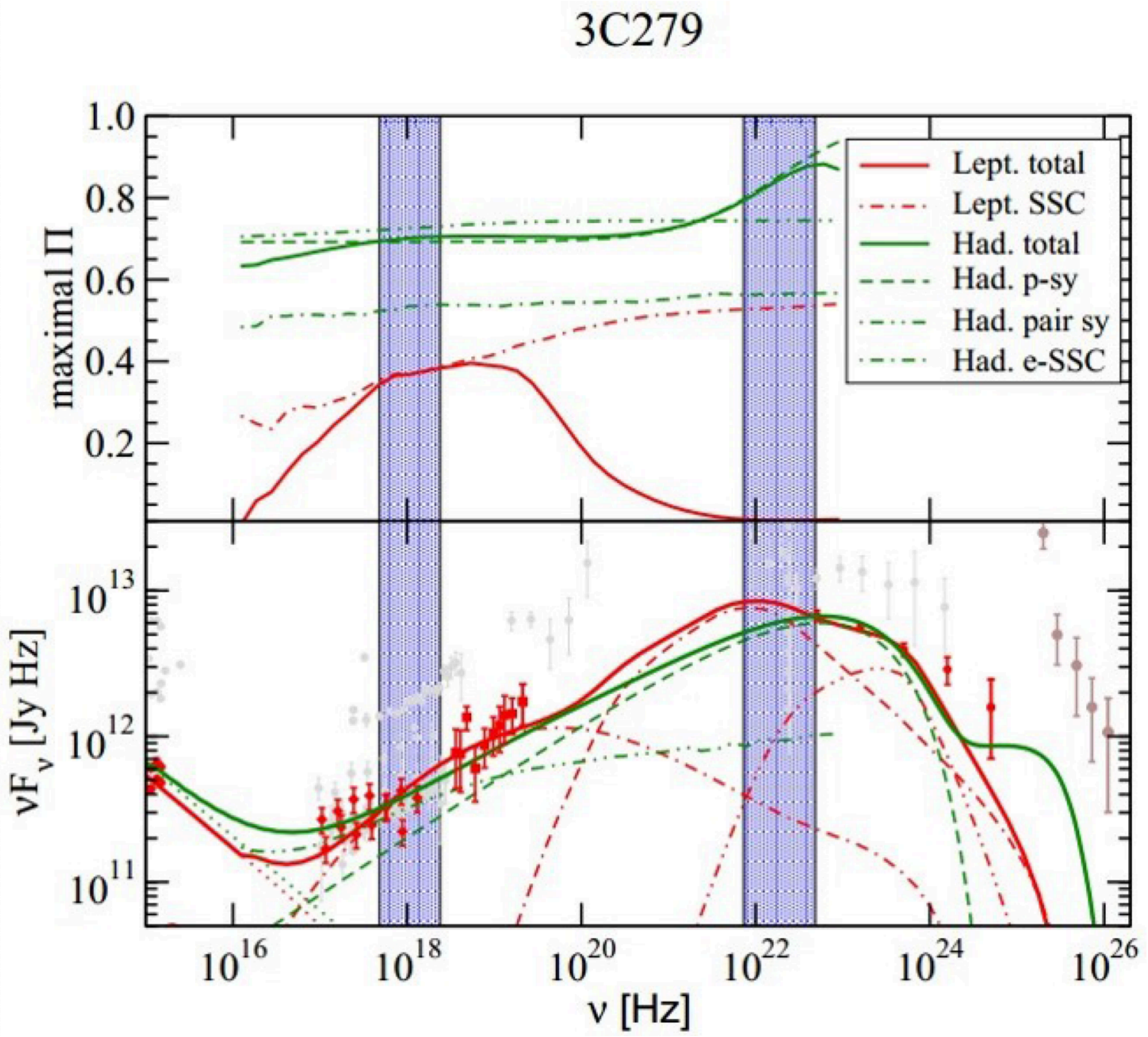
3C279 (nature Fermi-LAT 2010)



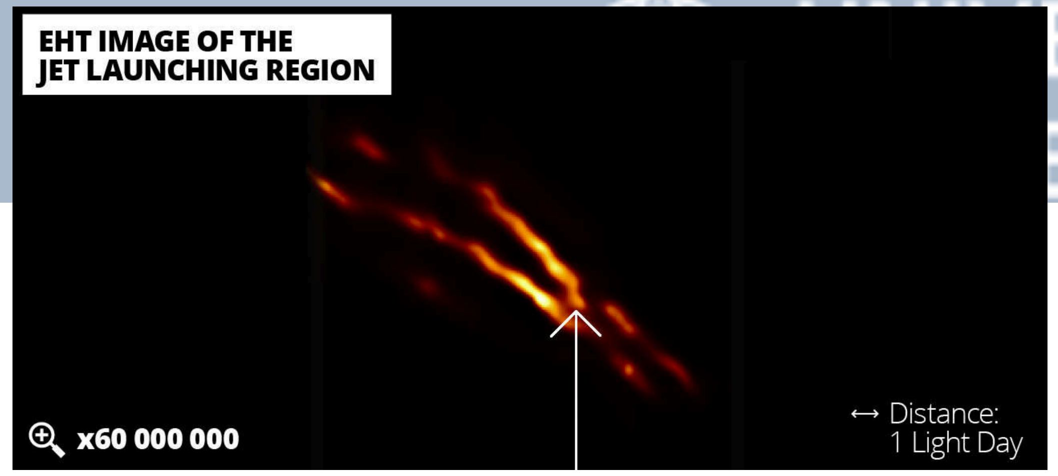
IC pol<<S pol
(Bonometto+ 70, Pairson&Romani 2019)



3C279 (Zhang 2017)



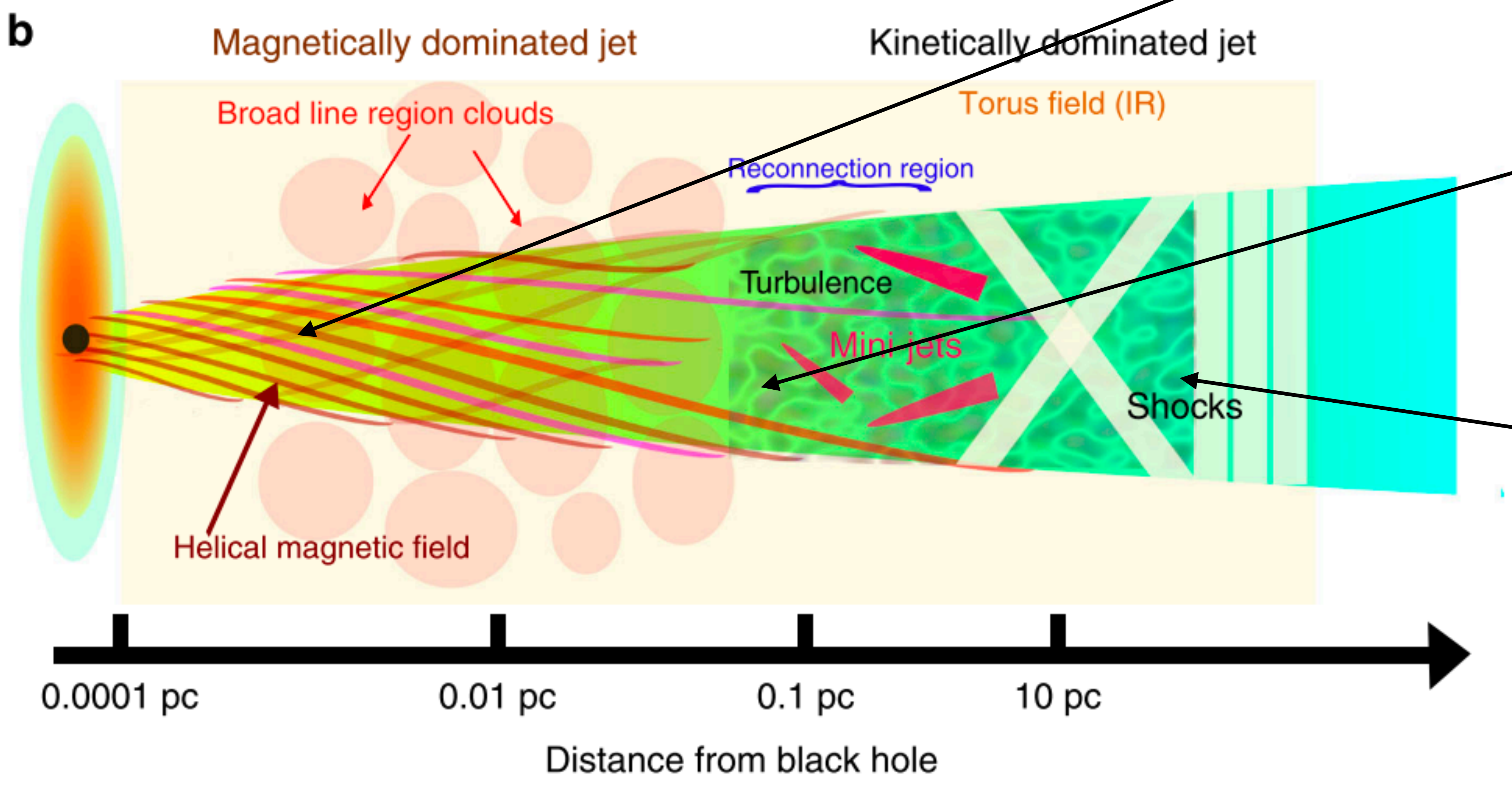
hint from phenomenology



EHT Nature 2021

interaction region between an accretion-powered outflow and the fast jet spine, which is potentially powered by the black hole spin

Shukla and Mannheim, Nature Communications 2020



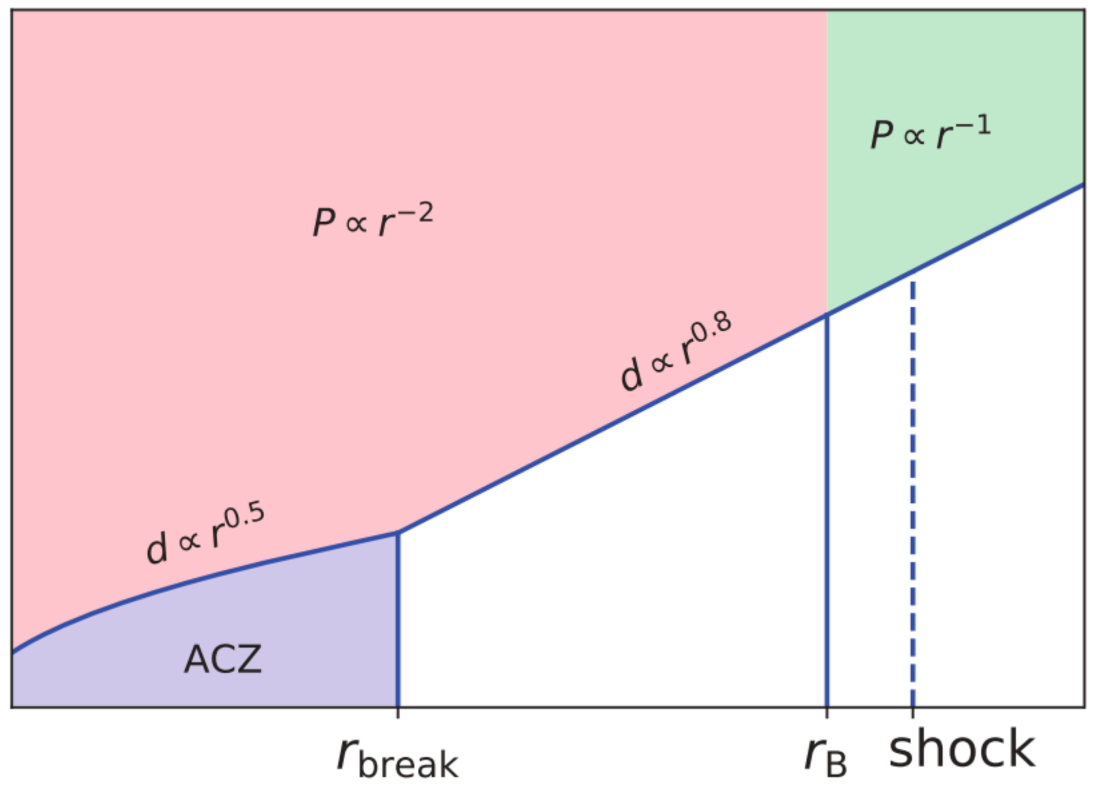
blazar zone (x/γ) flares turb. stochastic acceleration

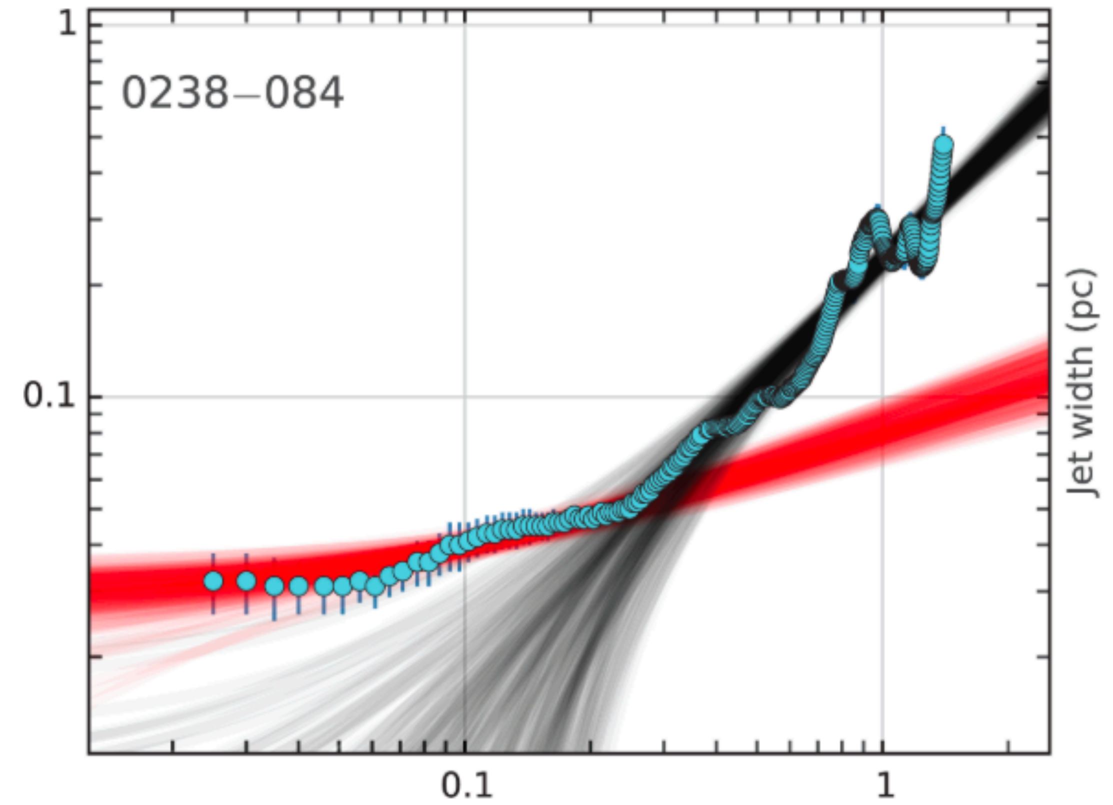
expansion radio delay

Radio morphology and radio-gamma delays

Kovalev+ 2020

break occurs at MD~KD, Γ saturates





self-consistent approach

here we add adiabatic cooling
(t=time elapsed from the expansion)

$$|\dot{\gamma}_{ad}| = \frac{1}{3}\frac{\dot{V}}{V}\gamma = \frac{\dot{R}(t)}{R(t)}\gamma = \frac{\beta_{\exp} c}{R(t)}\gamma$$

Parker 2006, Stawartz&Petrosian 2008 Tramacere+2011

JetSeT

injection term

$$L_{inj} = V_{\rm acc} \int \gamma m_e c^2 Q(\gamma, t) d\gamma \quad (erg/s)$$

systematic term

$$S(\gamma, t) = -C(\gamma, t) + A(\gamma, t)$$

cooling term

$$C(\gamma) = |\dot{\gamma}_{synch}| + |\dot{\gamma}_{IC}| + |\dot{\gamma}_{ad}|$$

syst. acc. term

$$A(\gamma) = A_{p0}\gamma, t_A = \frac{1}{A_0}$$

$$\frac{\partial n(\gamma, t)}{\partial t} = \frac{\partial}{\partial \gamma}\left\{ -[S(\gamma, t) + D_A(\gamma, t)]n(\gamma, t)\right\} + \frac{\partial}{\partial \gamma}\left\{D_p(\gamma, t)\frac{\partial n(\gamma, t)}{\partial \gamma}\right\} - \frac{n(\gamma, t)}{T_{esc}(\gamma)} - \frac{n(\gamma, t)}{T_{ad}} + Q(\gamma, t)$$

$$T_{ad} = \frac{1}{3}\frac{R(t)}{\beta_{\exp} c} \text{ (Gould 1975)}$$

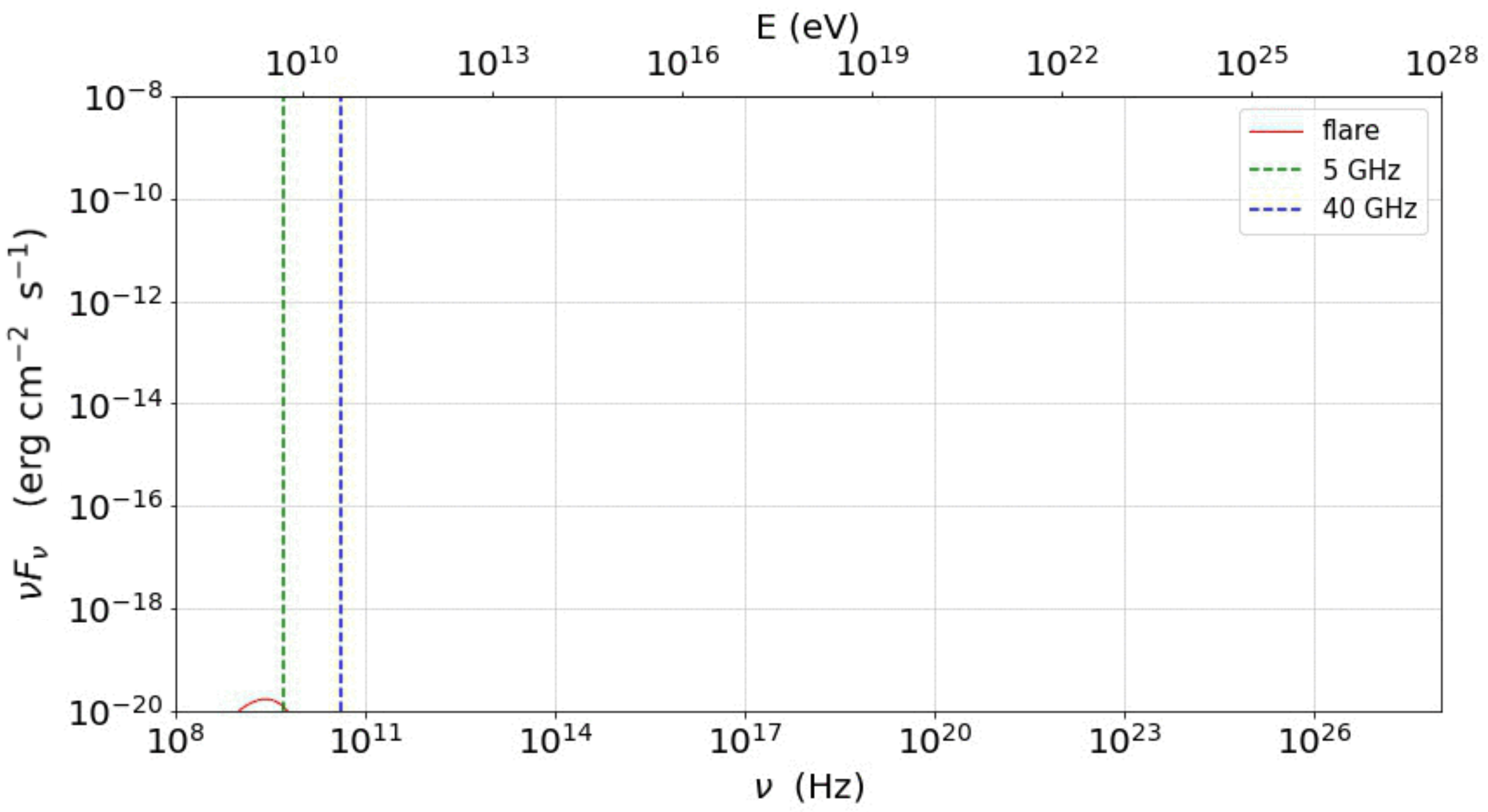
Turbulent magnetic field → momentum diffusion term

$$W(k) = \frac{\delta B(k_0^2)}{8\pi}\left(\frac{k}{k_0}\right)^{-q}$$

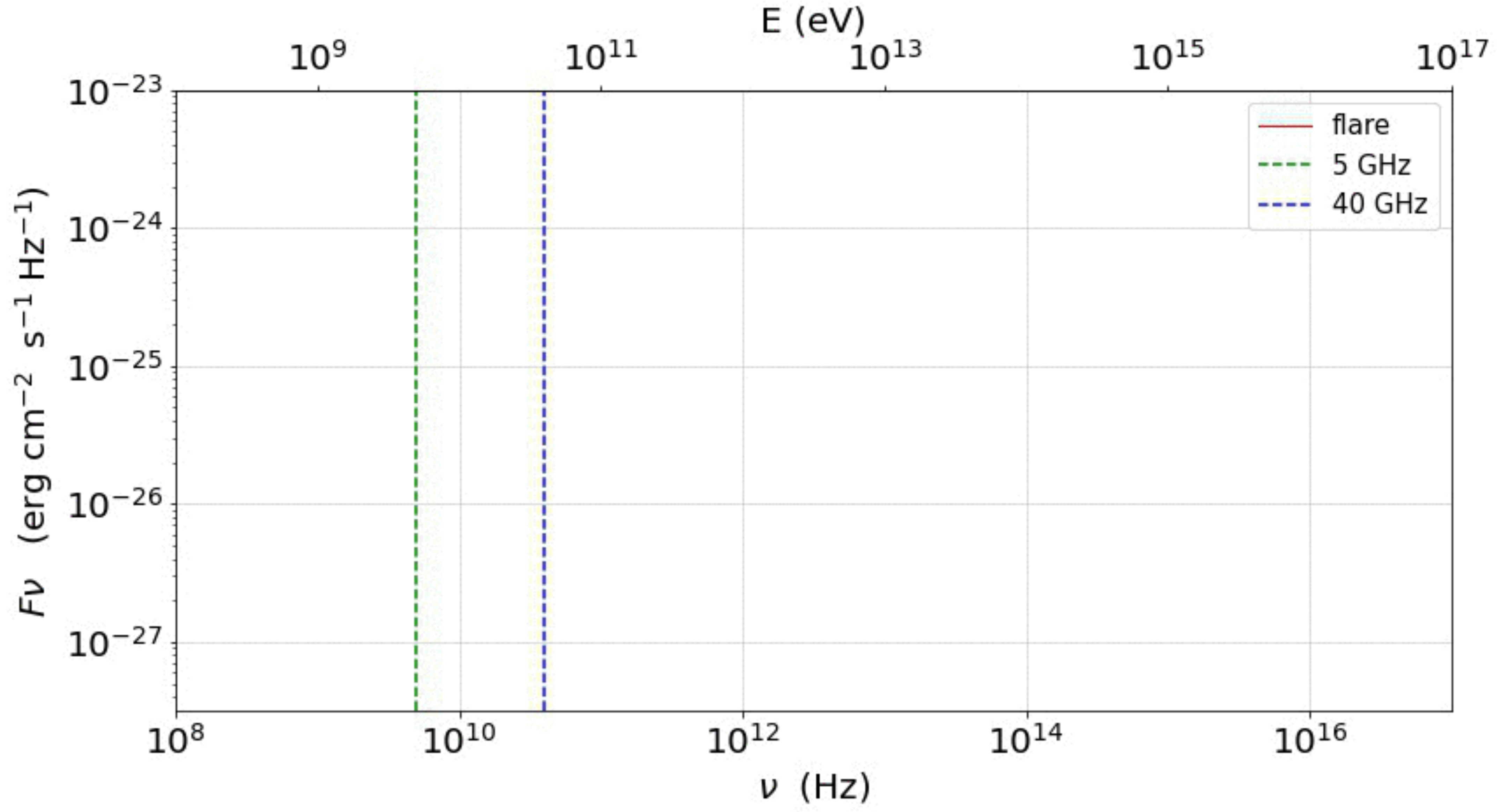
$$D_p \approx \beta_A^2 \left(\frac{\delta B}{B_0}\right)^2 \left(\frac{\rho_g}{\lambda_{\max}}\right)^{q-1} \frac{p^2 c^2}{\rho_g c}$$

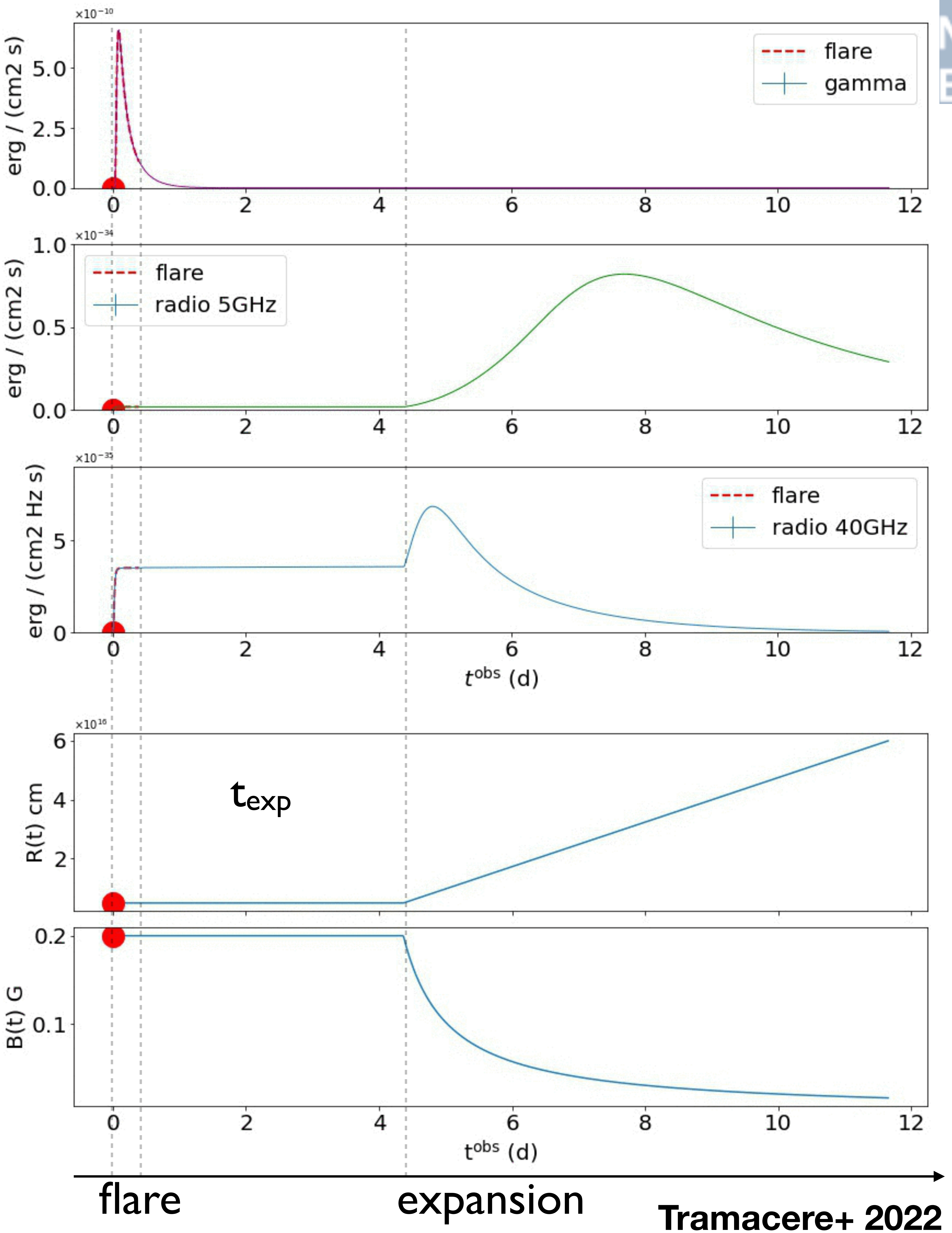
self-consistent approach

Tramacere+ 2022 (see also Boula 2022)



- **duration~3x10⁷ s (blob frame)~ 11 d obs**
- **t_{exp}=1x10⁷ s**
- **β_{exp}=0.1c**



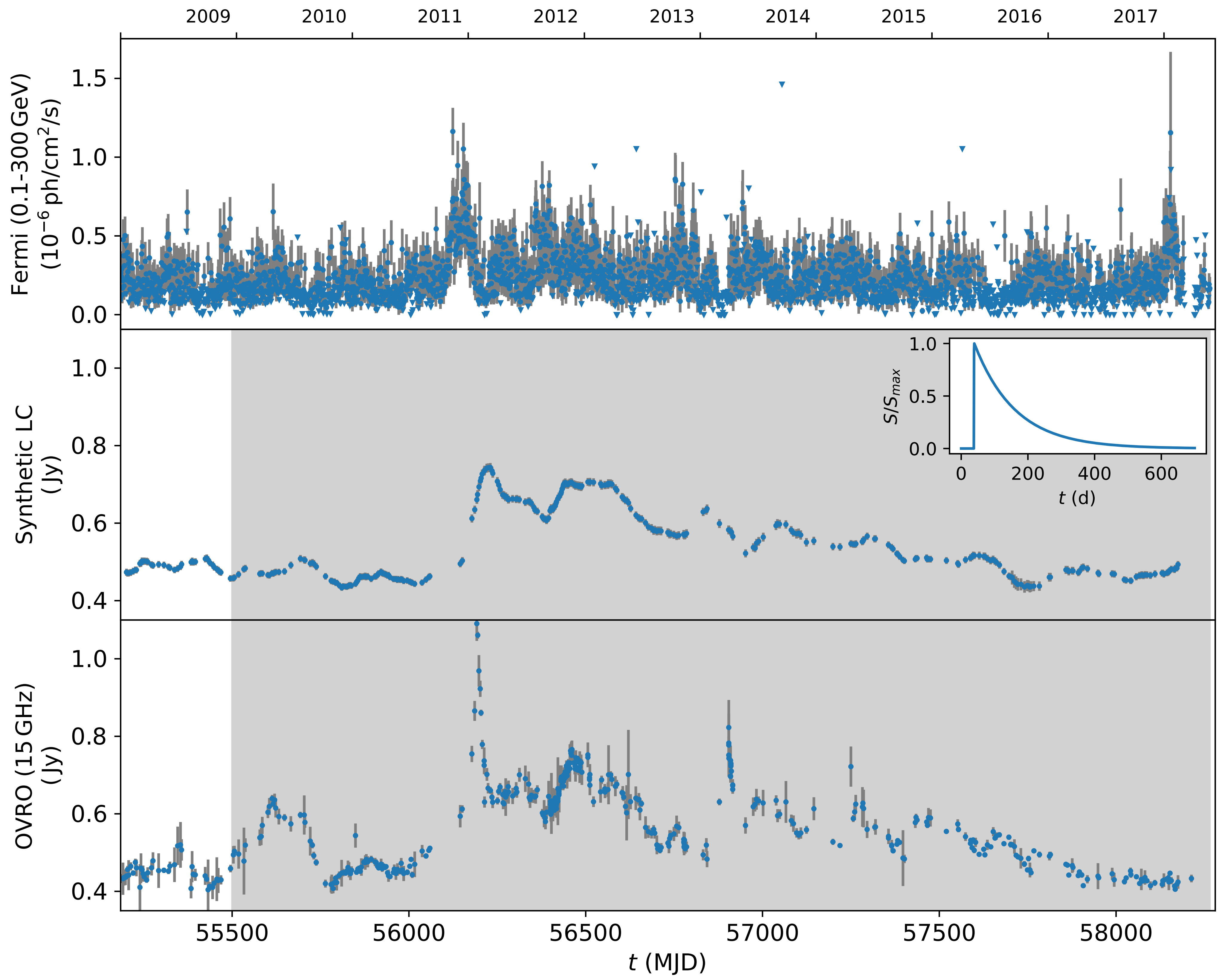


Tramacere+ 2022

JetSeT

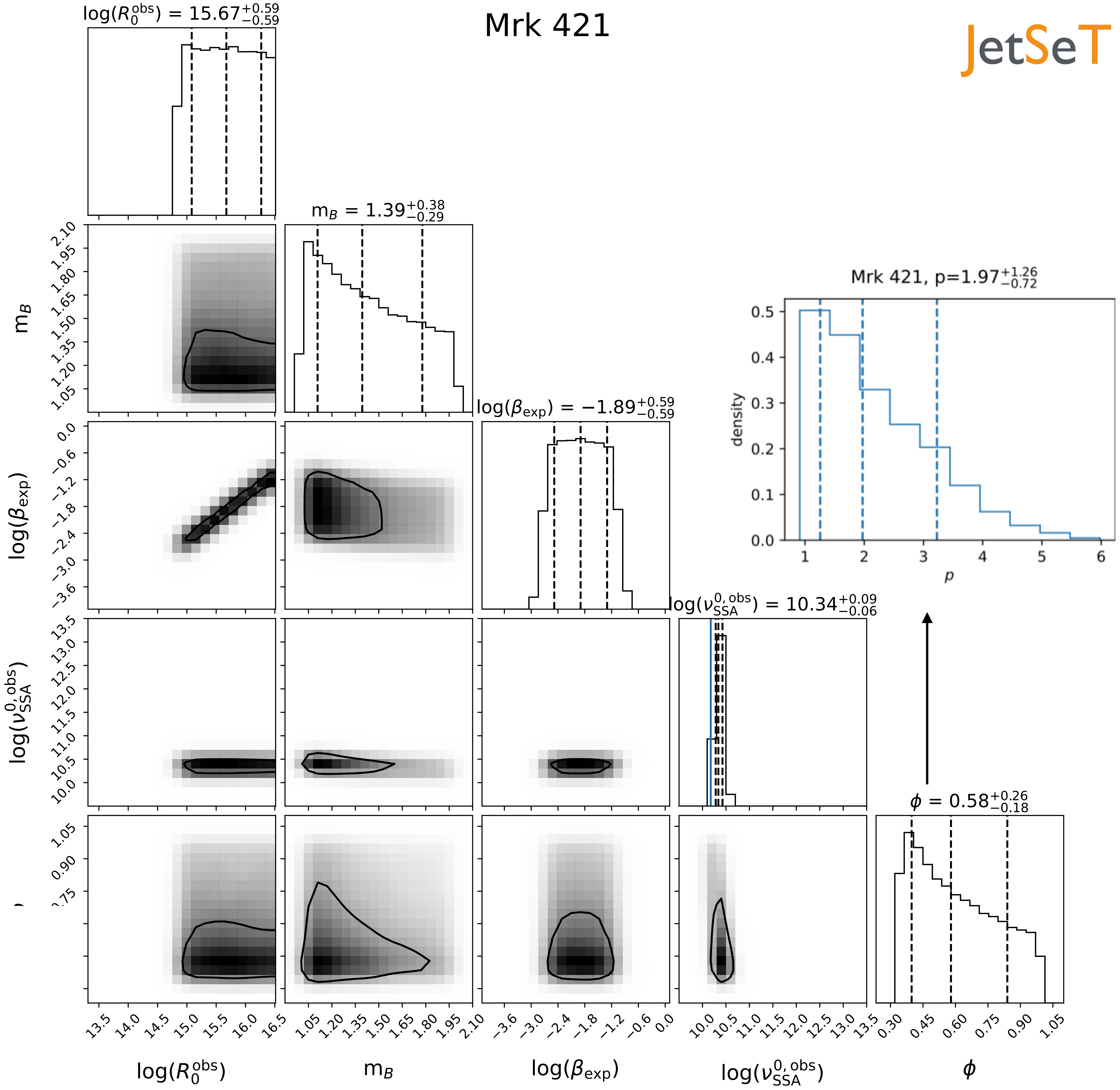
self-consistent approach

Tramacere+ 2022



Parameter	Value
A	$12.5^{+0.5}_{-0.013} \times 10^3$ Jy cm^2 s/ph
t_{rise}	$\lesssim 1$ day
t_{decay}	$126.5^{+1.3}_{-1.3}$ days
Δt	$37.58^{+0.13}_{-0.13}$ days
$F_{background}$	$0.18^{+0.008}_{-0.0004}$ Jy

$$S(t) = A \frac{\exp^{-(t-\Delta_t)/t^*_{\rm decay}}}{1 + \exp^{-(t-\Delta_t)/t_{\rm rise}}}$$



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Connection with MQ

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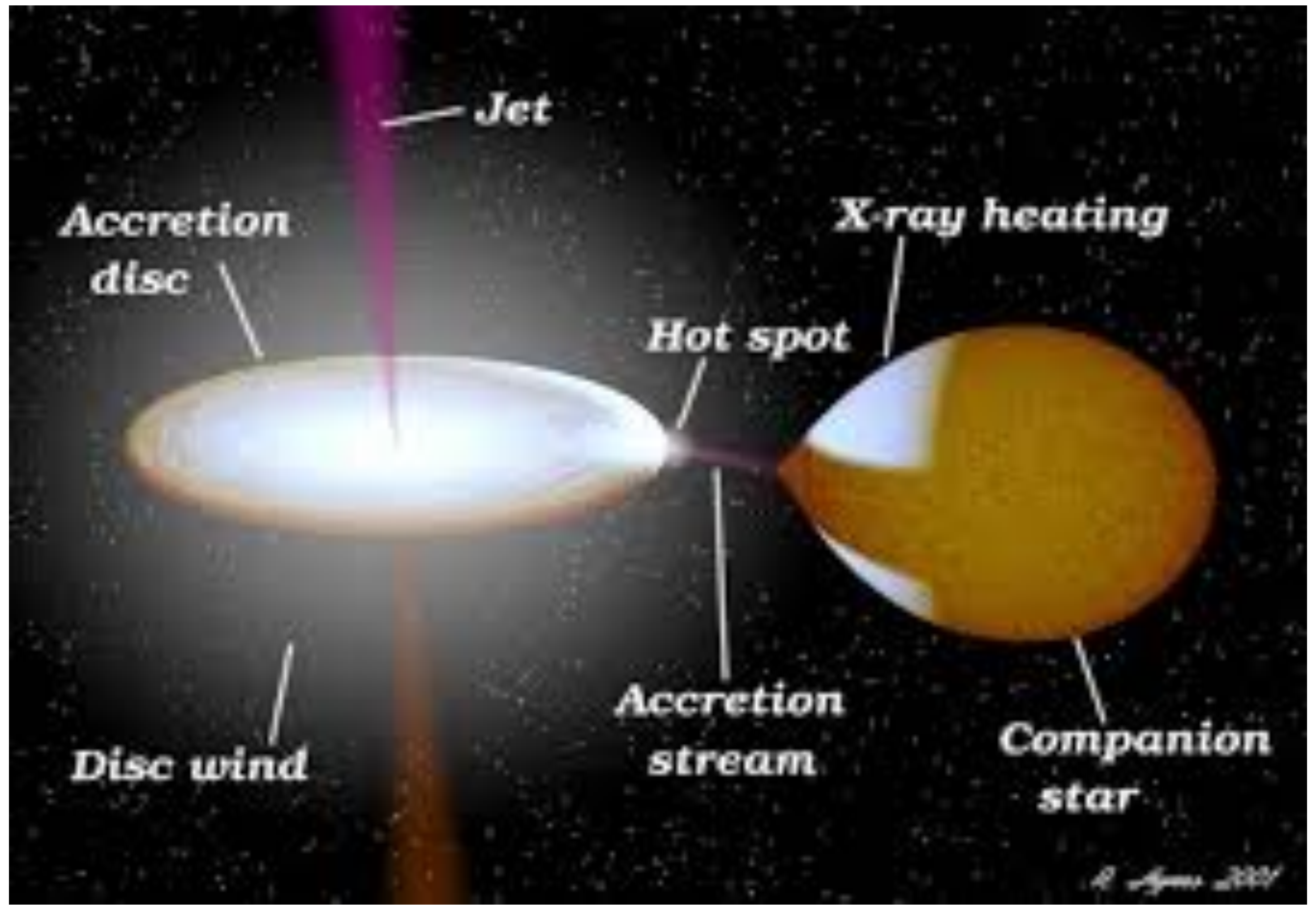
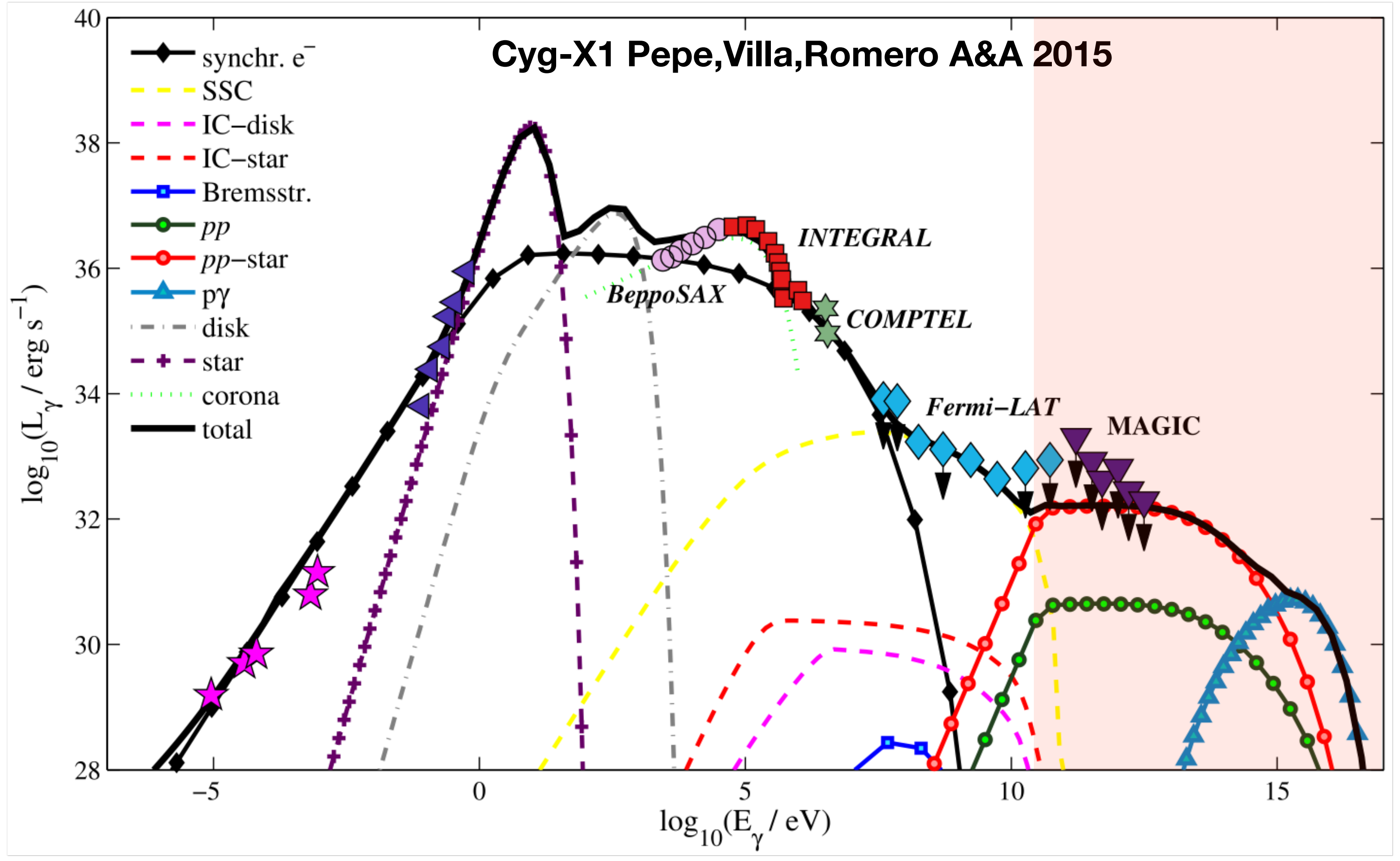
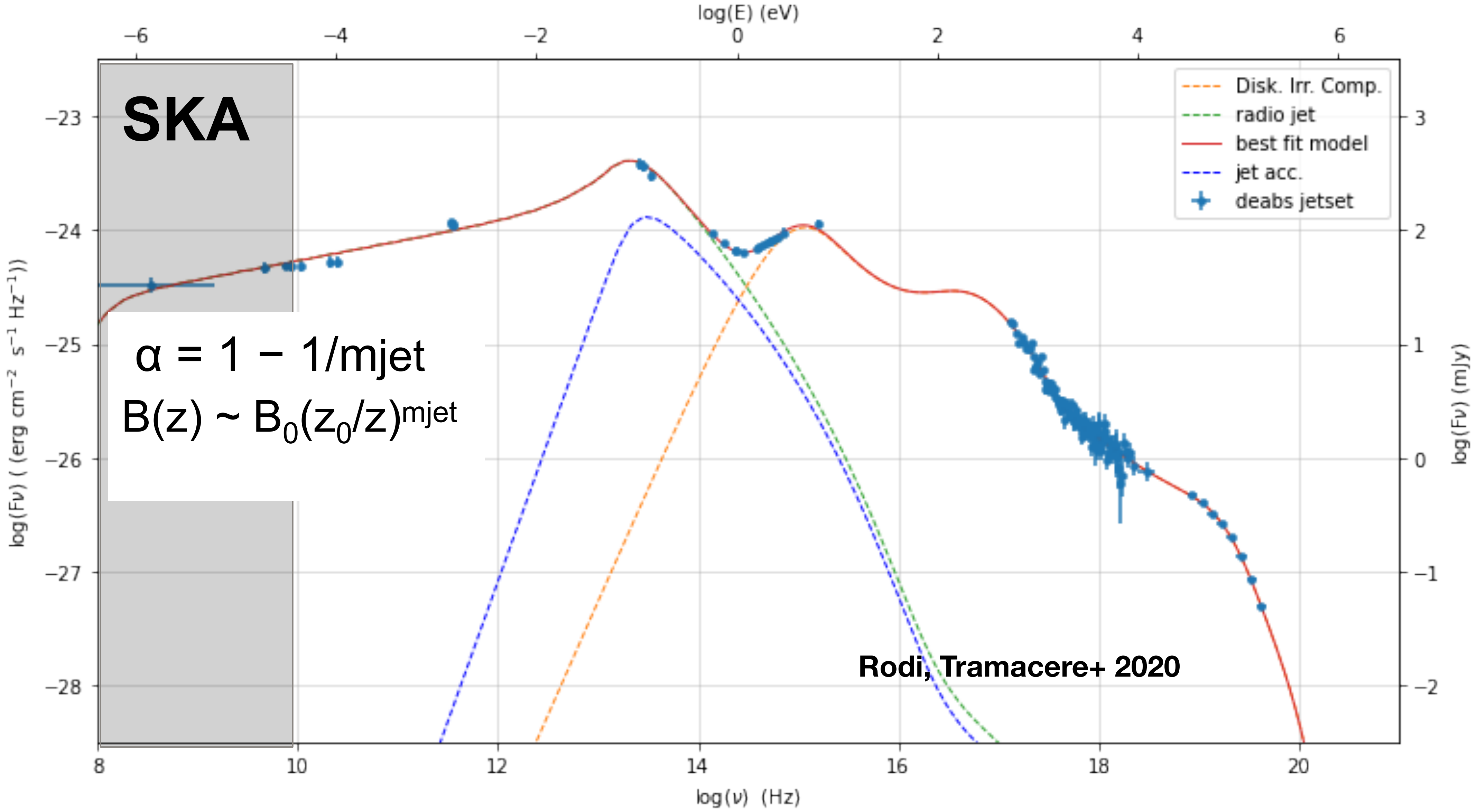
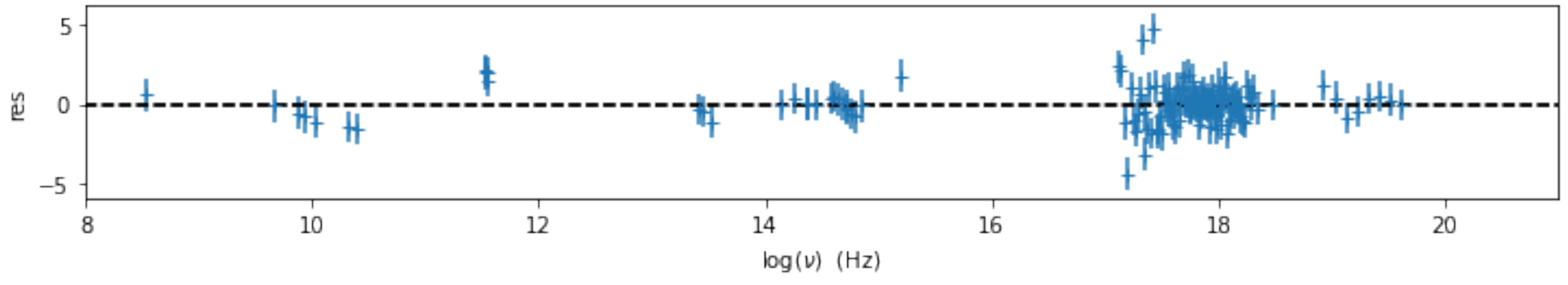
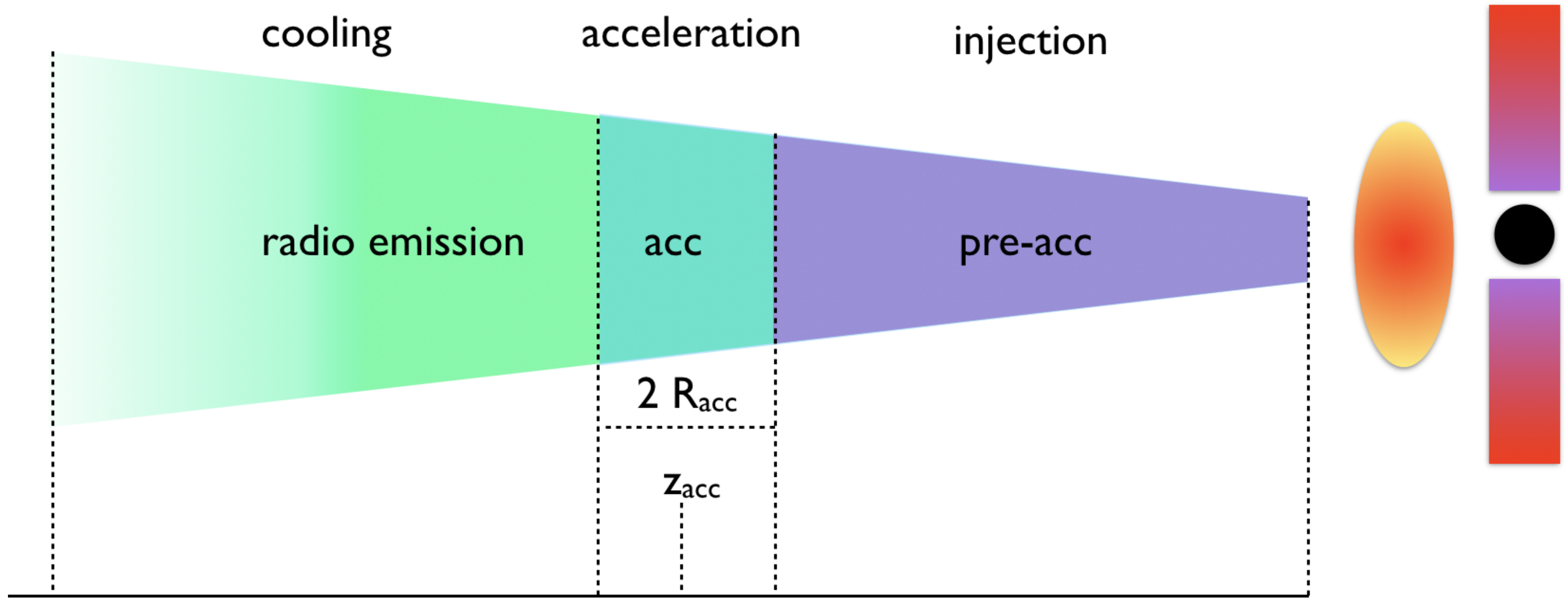




- Transient jets with BH ~ M_{Sun}, and complex interaction between accretion and **jet formation**. Crucial to understand processes of jets at AGN scales, and for understanding mechanisms such as BZ
- **CTA sensitivity will allow discriminate better between leptonic and lepto-hadronic models**
- **Synergy with SKA will have strong implication on jets energetic and Magnetic field topology**
- **CTA+SKA Jet feeding** (BZ,etc)
- Recent iXPE measurements confirm pol. angle parallel to the jet axis as in the case of blazars!

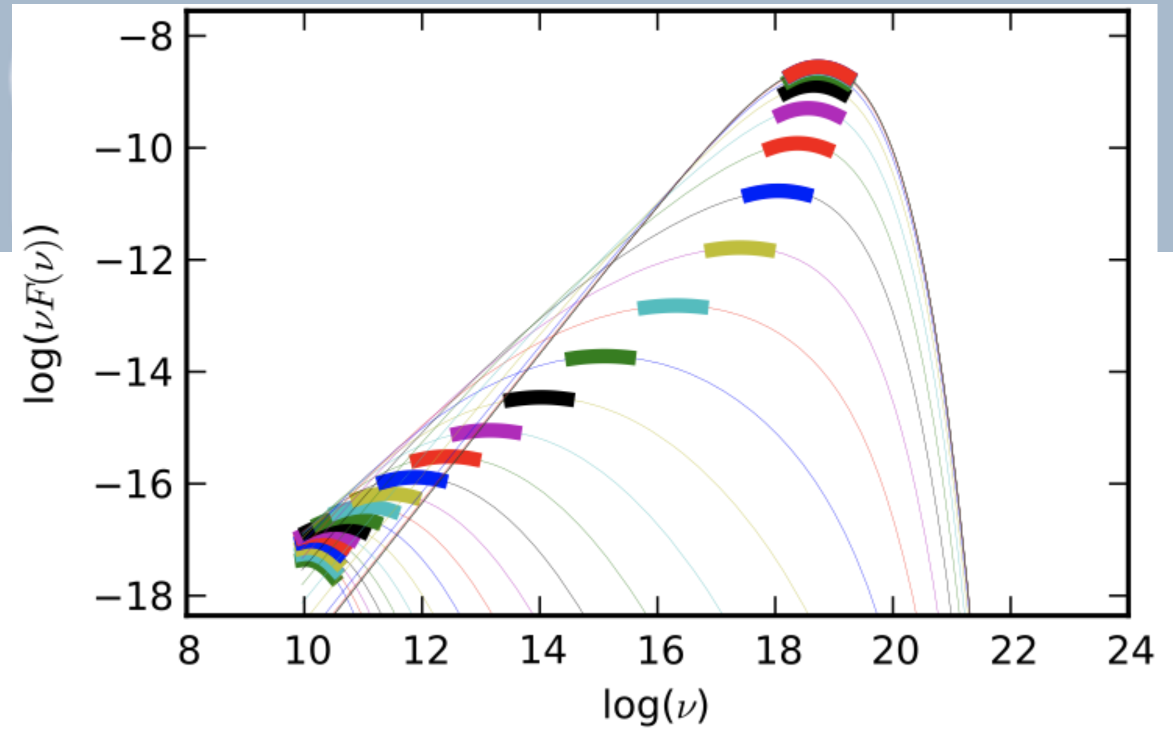


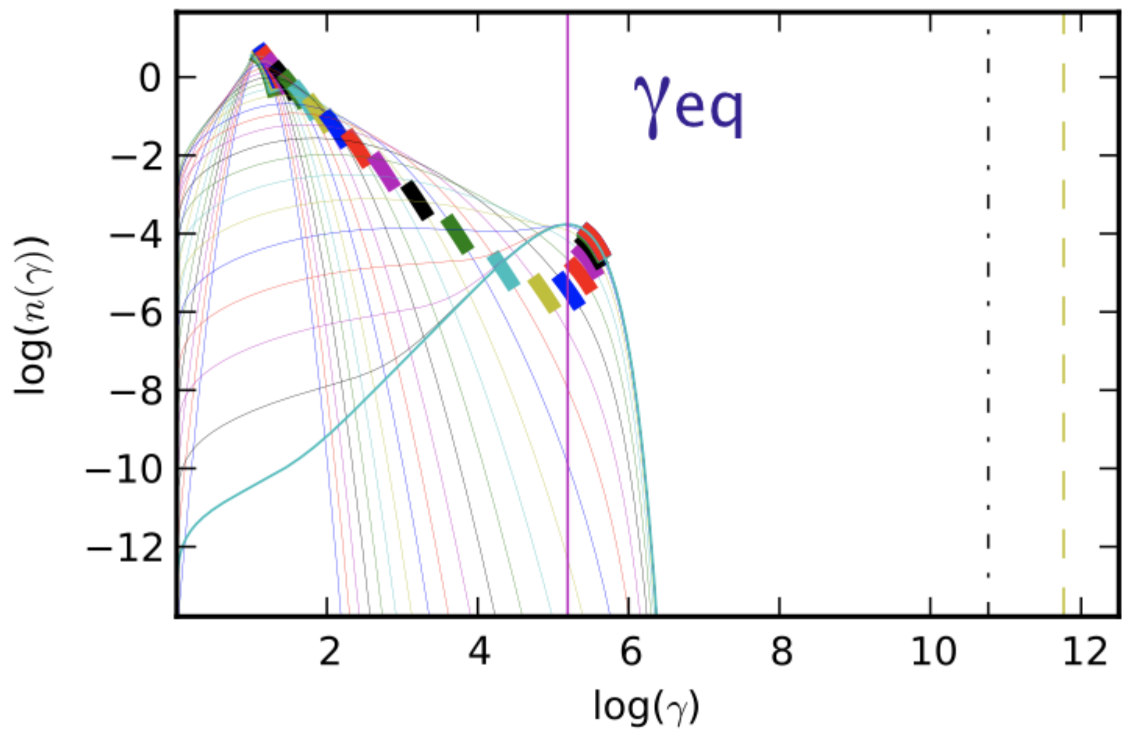




Spectral trends and acceleration

self-consistent approach



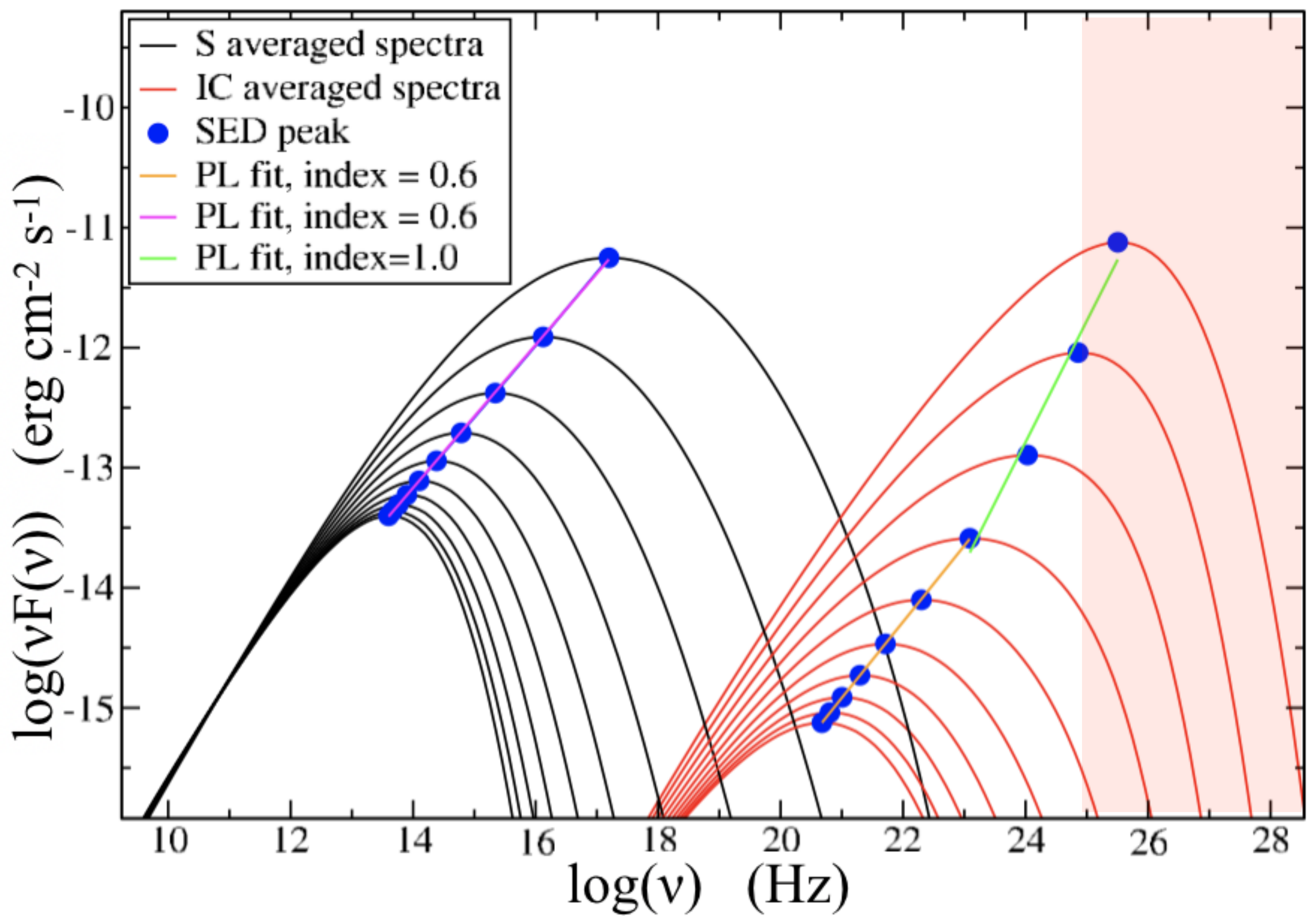


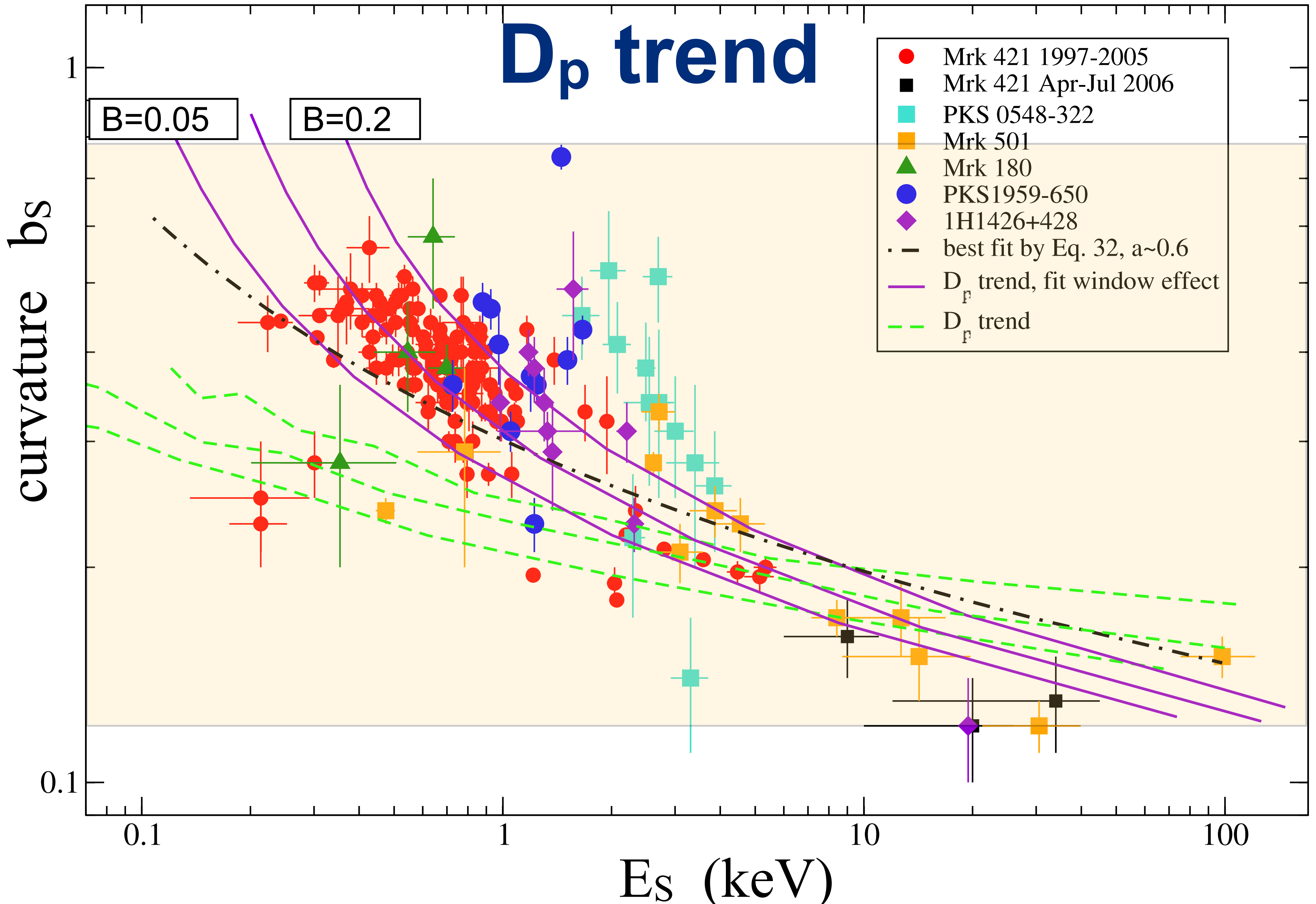
Ep-vs-curvature

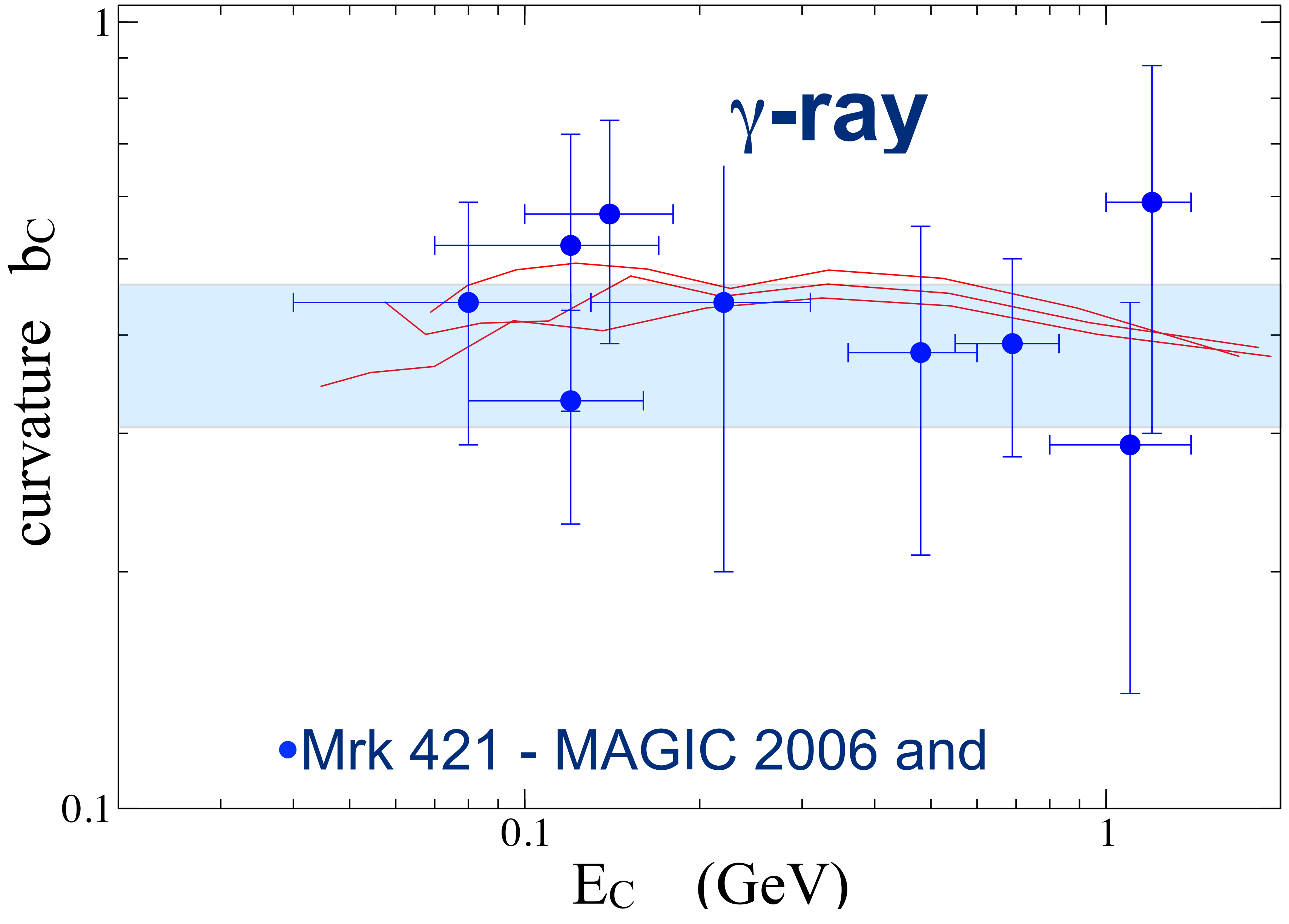
Tramacere+2011

JetSeT

Curvature is at acceleration dominated regime!





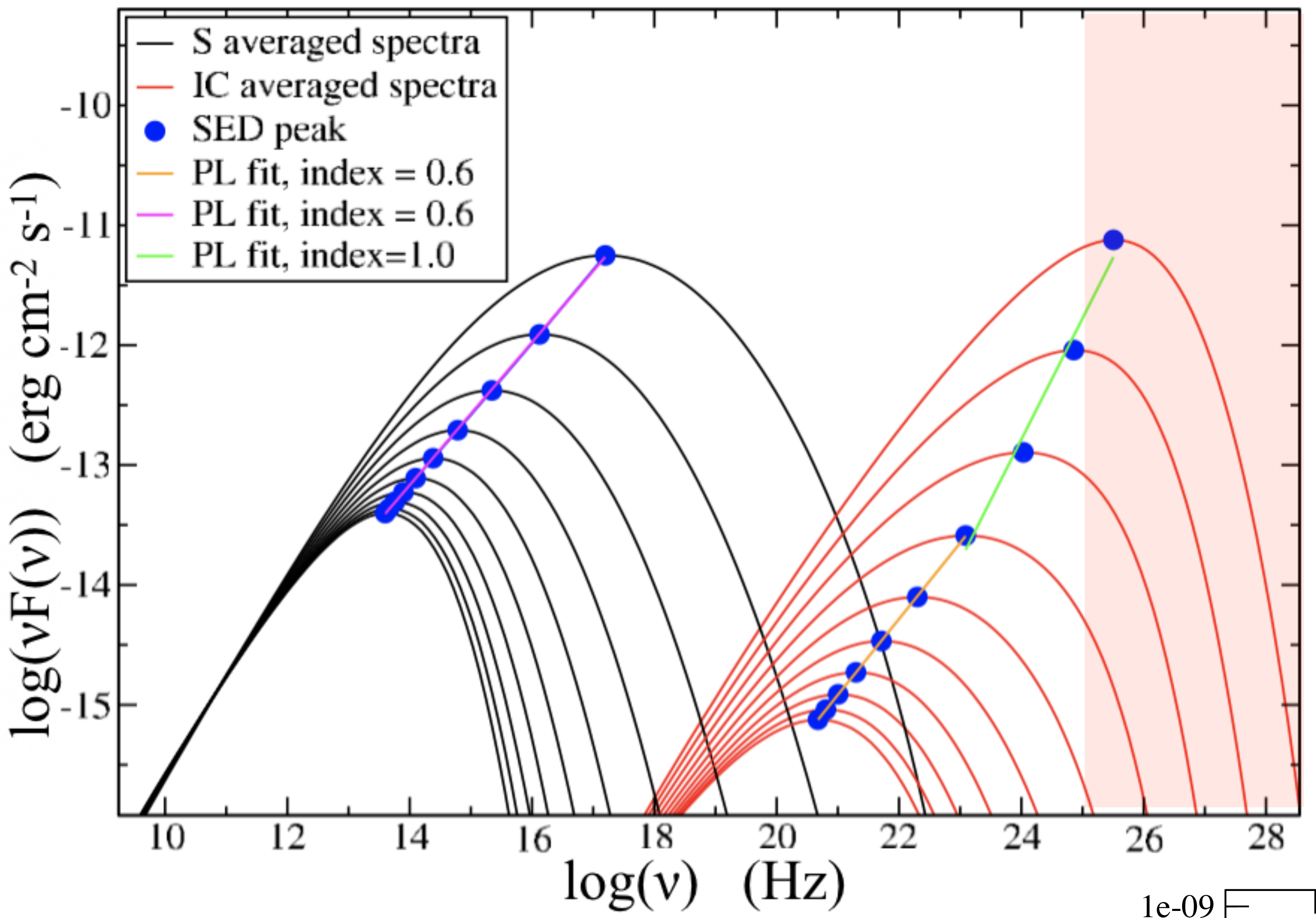


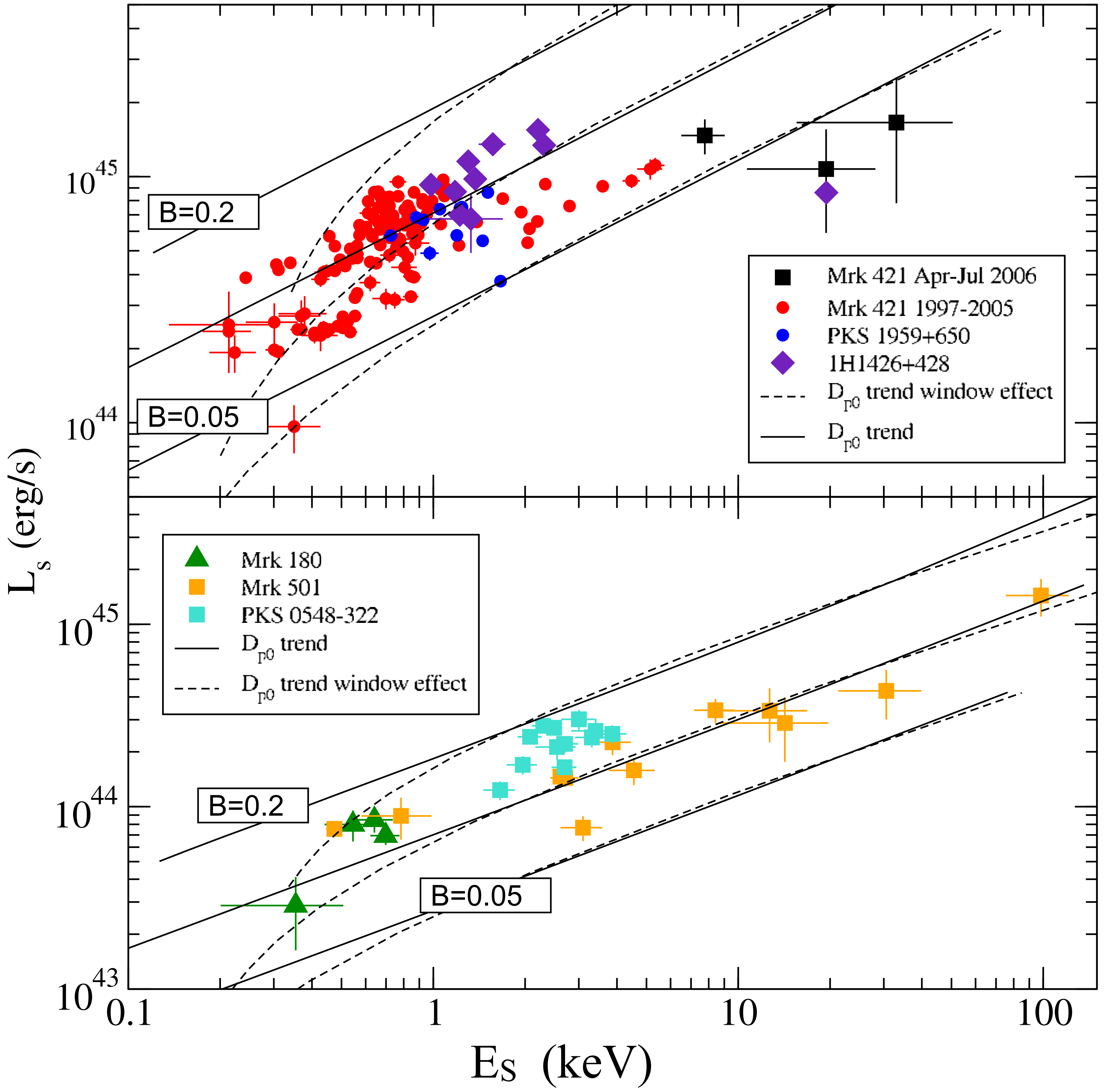
self-consistent approach

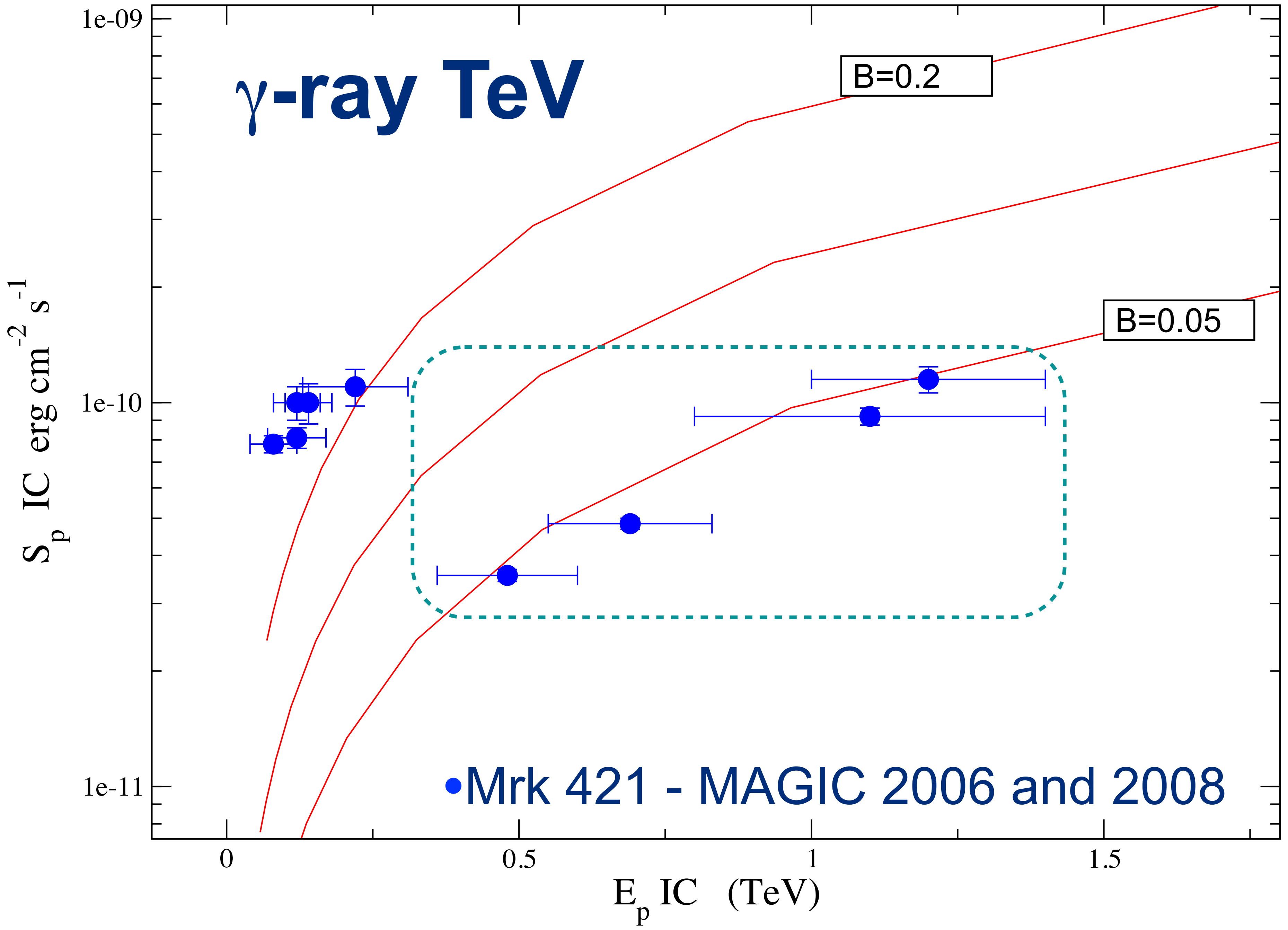
Lp-vs-curvature

Tramacere+2011

JetSeT



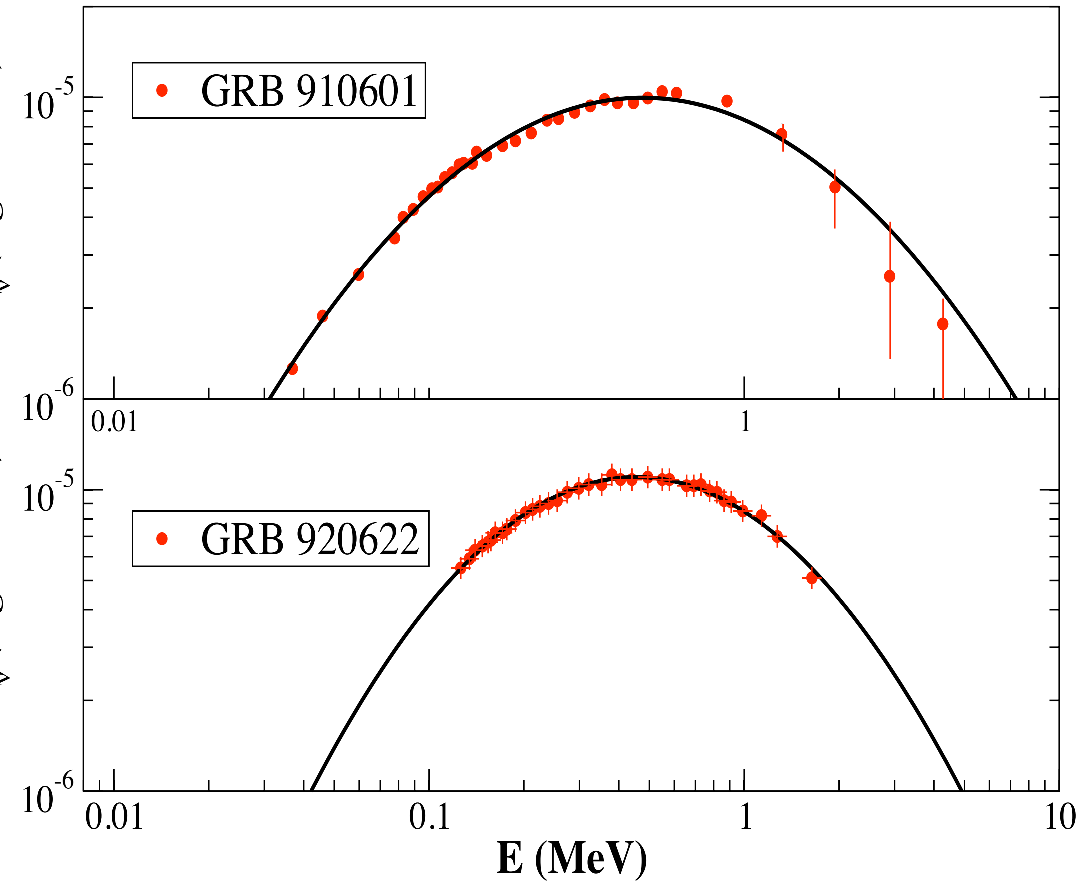




connection with GRBs

see satoshi

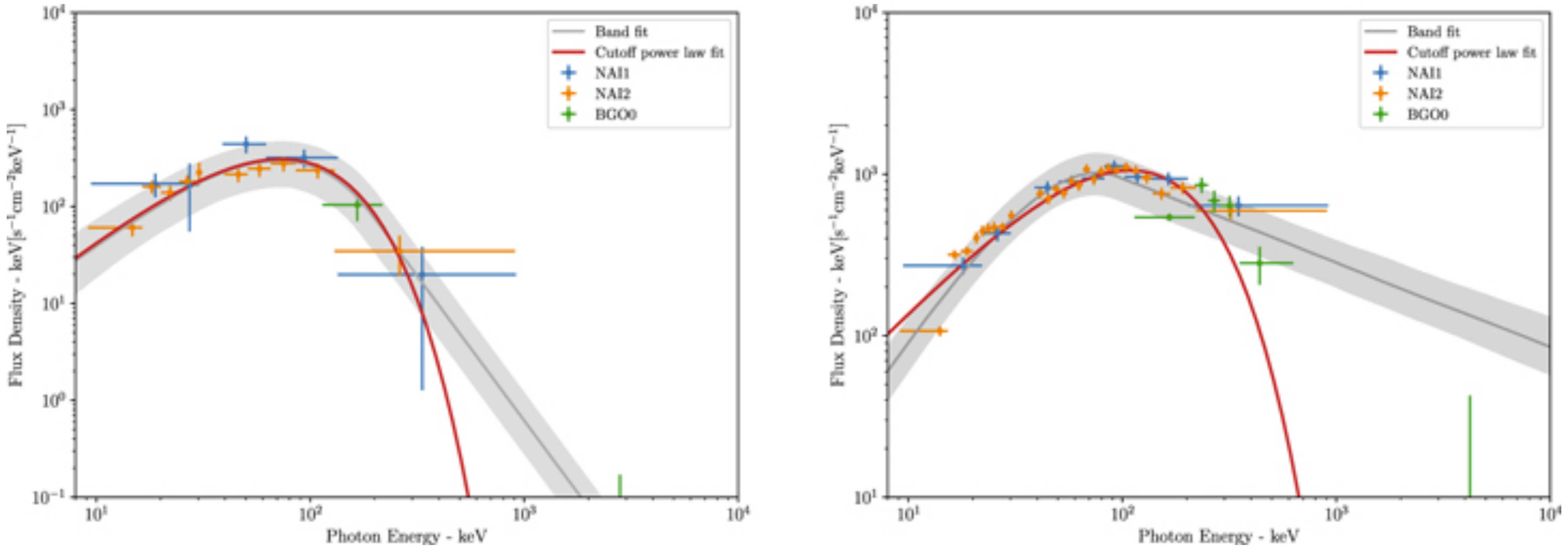
Massaro, Grindlay, Paggi 2010



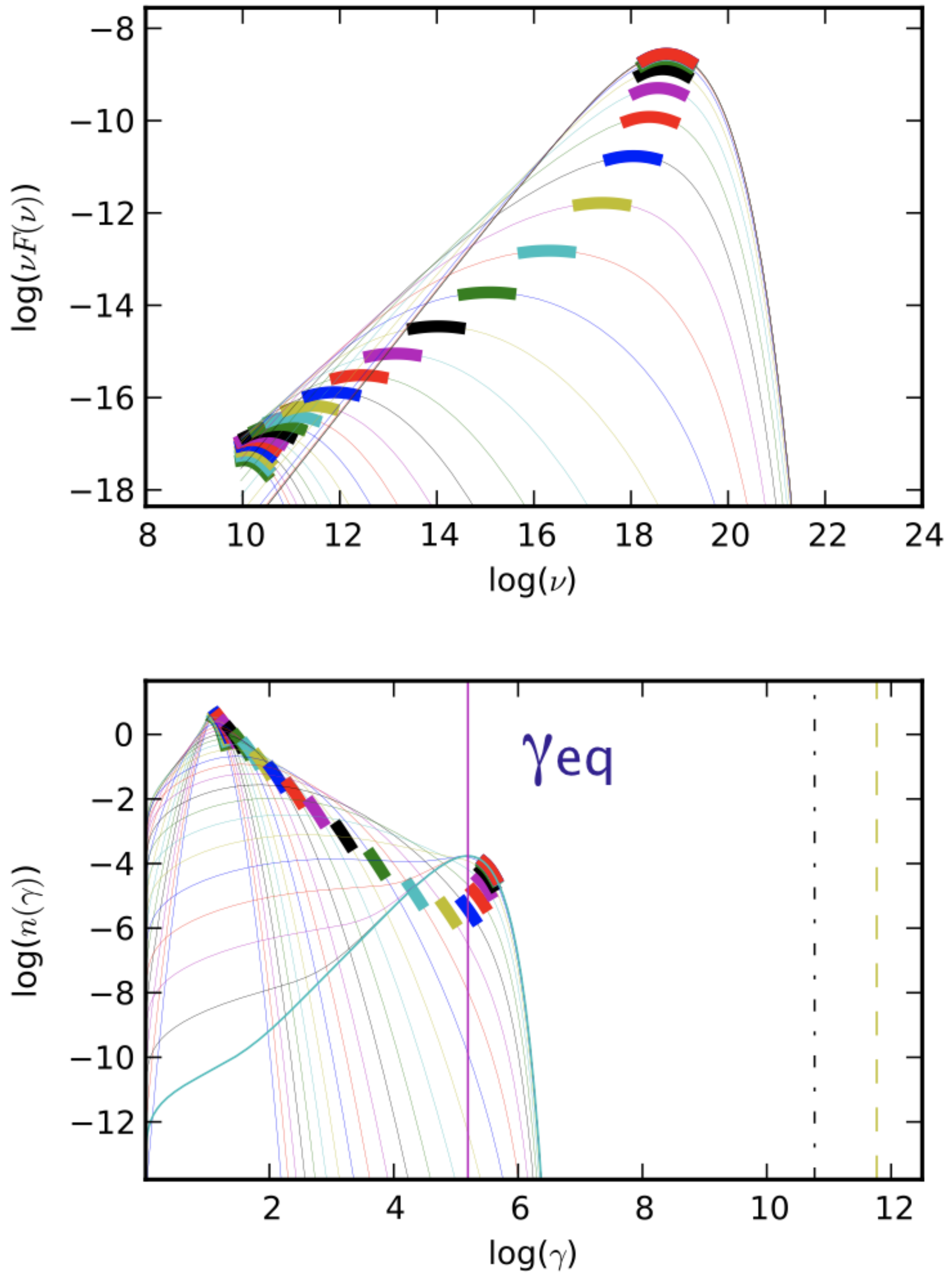
prompt spectral features

- b~[0.6-0.8] compatible with equilibrium, hinting for larger magnetic fields and shorter t_acc compared to blazars

Li 2022



Tramacere 2011



recent iXPE polarization measurements with PD~10% similar to Mrk 501 (see Hancheng)

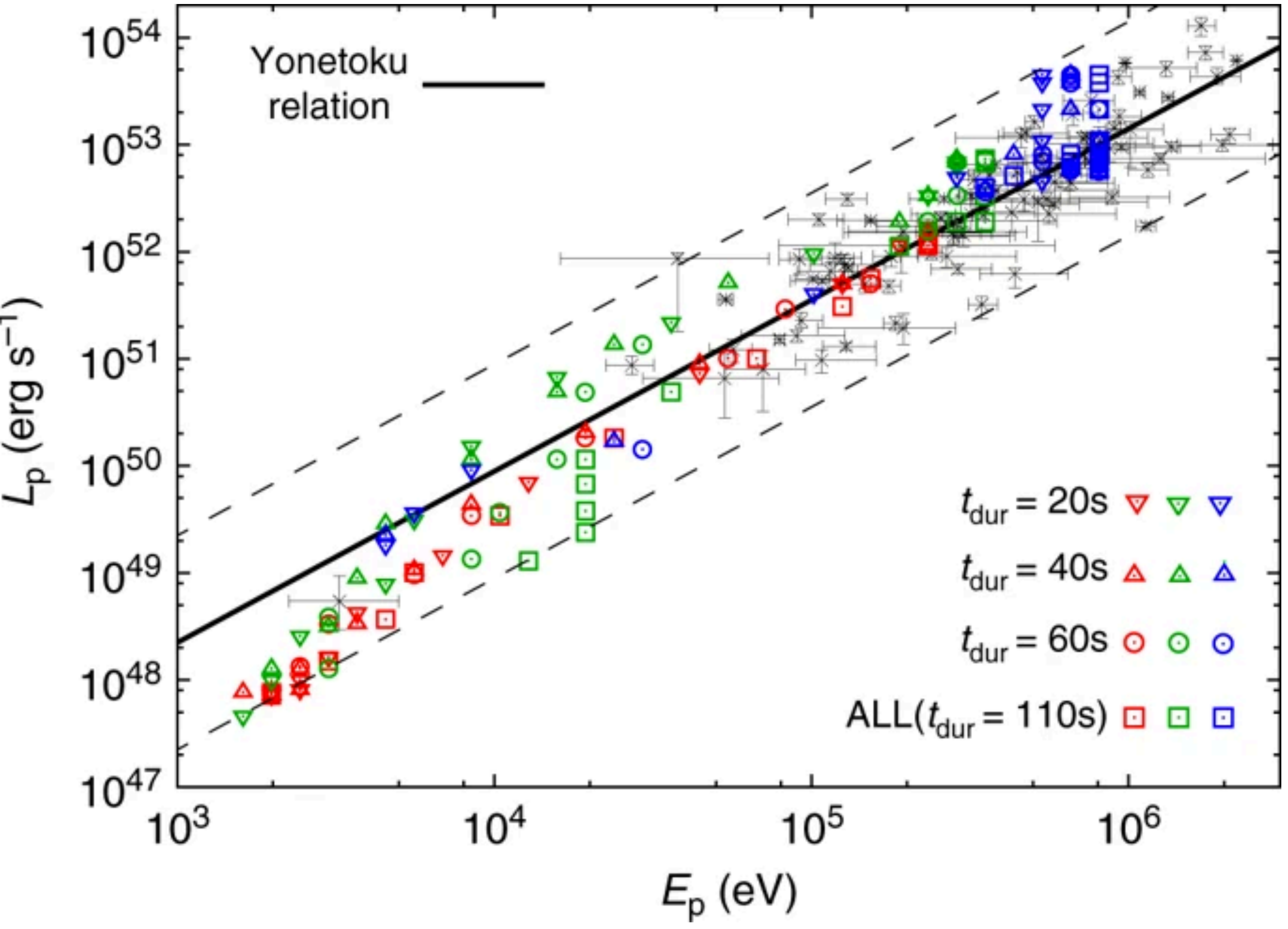
connection with GRBs

see satoshi

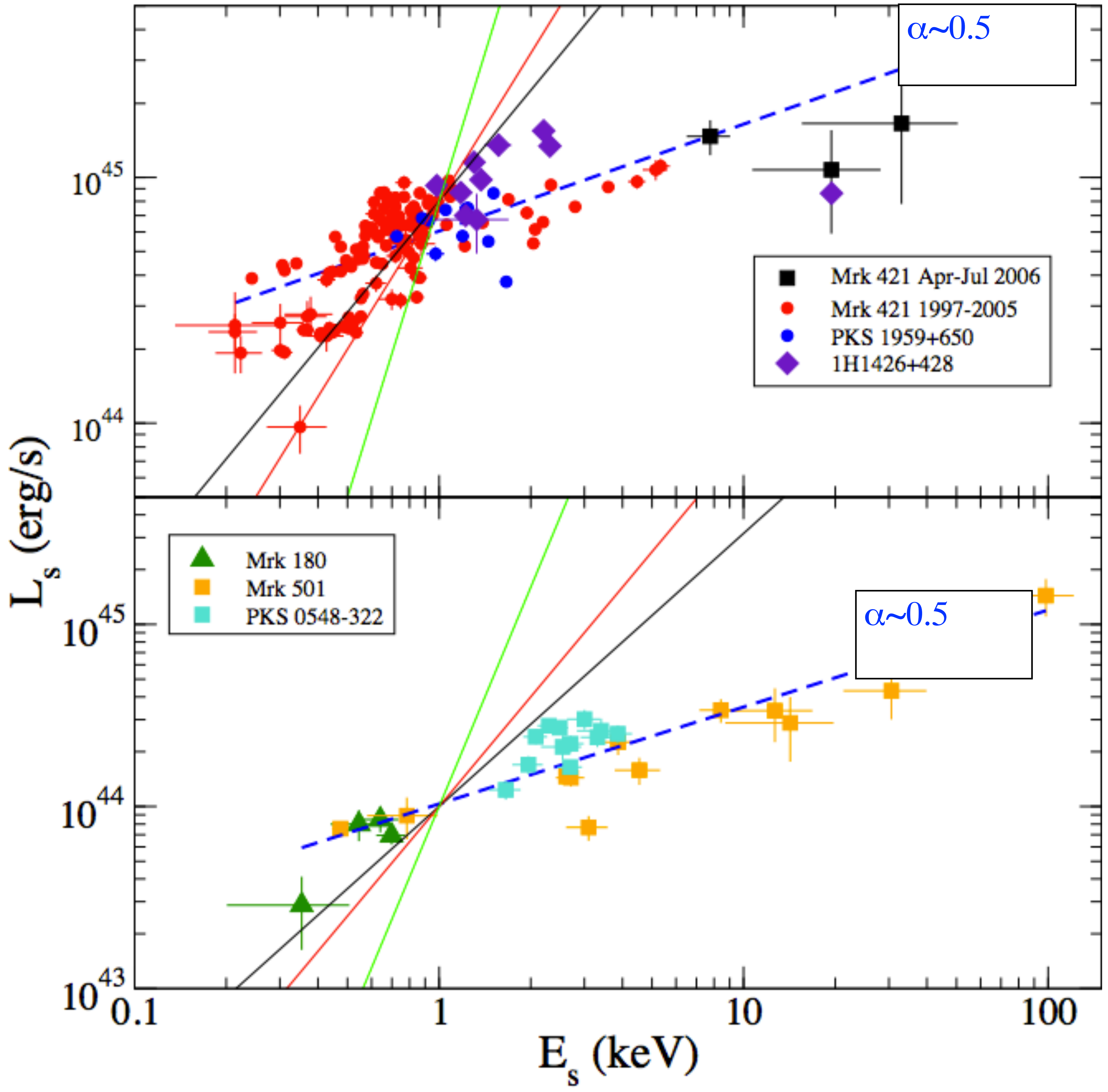
prompt $L_{p,iso} \sim E_p^{\alpha}$

- index of $\alpha \sim 2$ is compatible with B as main driver
- index of $\alpha \sim 1.5$ is compatible with γ_{3p} increasing keeping $N(\gamma_{3p})$ constant

Ito+ 2019 $\alpha \sim [1.5\text{-}2.0]$



Tramacere 2011



connection with GRBs

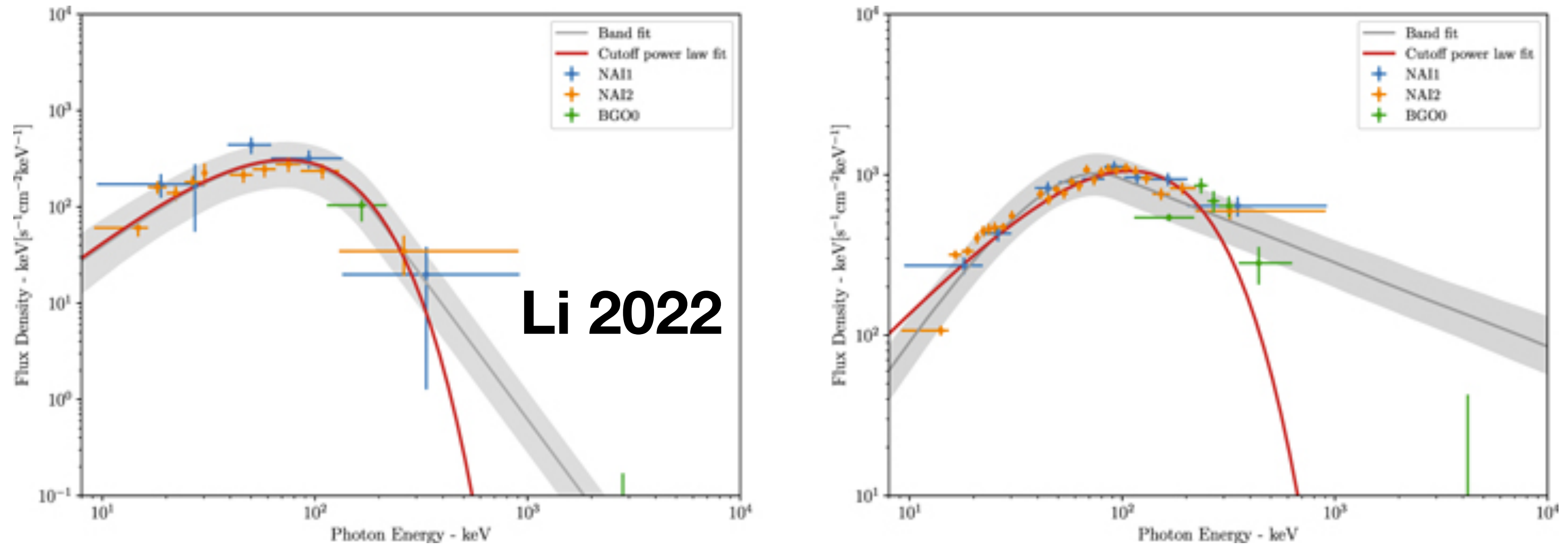
see satoshi

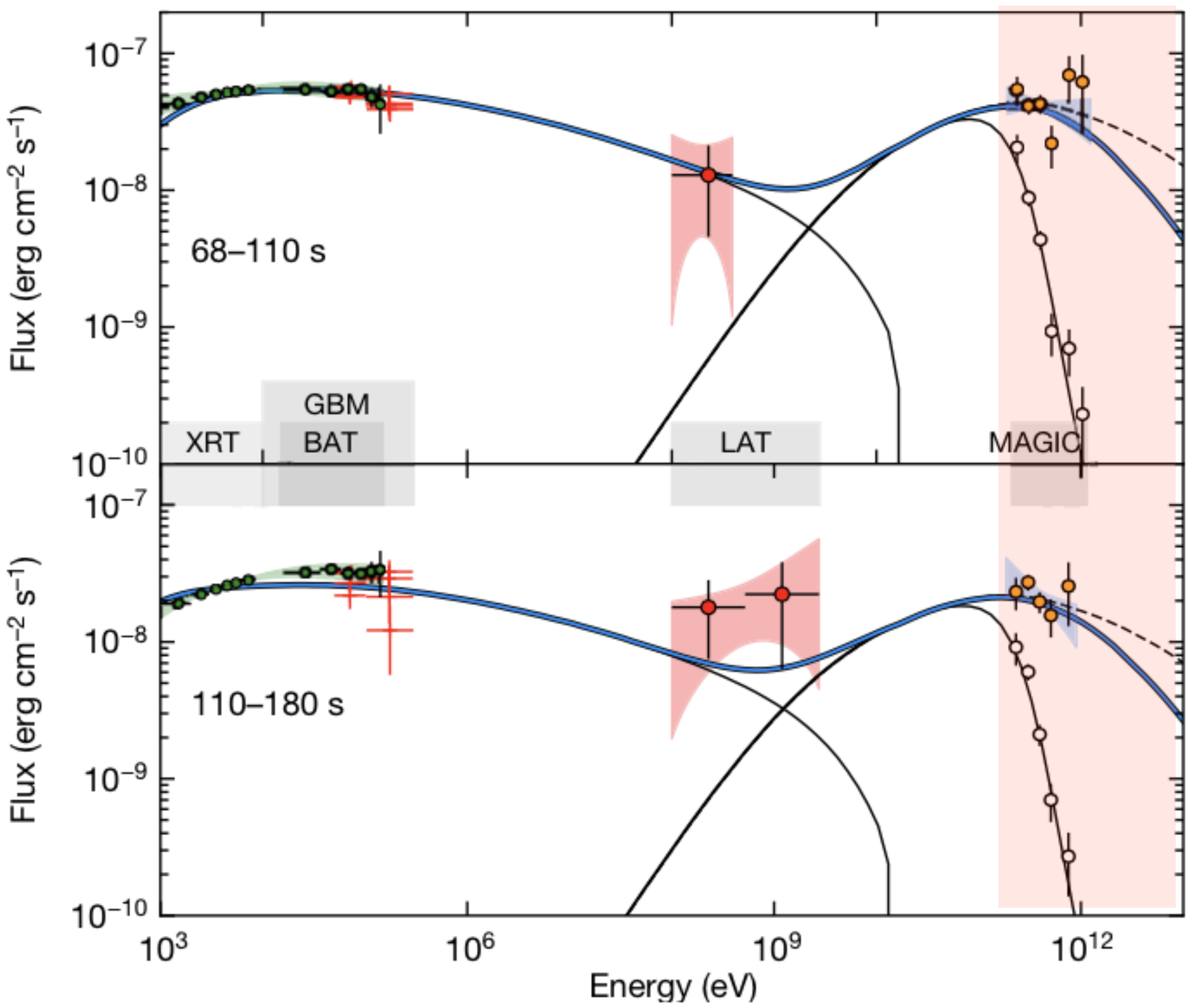
Magic Nature 2019 GRB 190114C

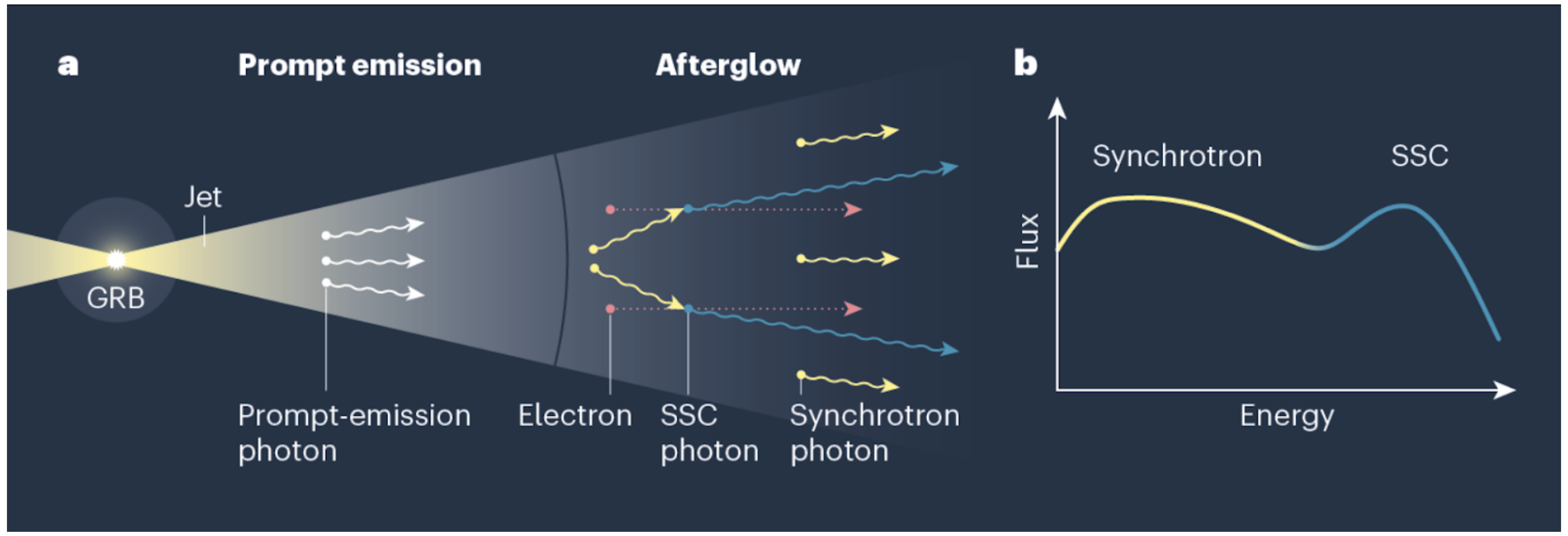
afterglow

prompt $L_{p,iso} \sim E_p^{\alpha}$

- b~[0.6-0.8] compatible with equilibrium, hinting for larger magnetic fields and shorter t_acc compared to blazars
- index of α~2 is compatible with B as main driver
- index of α~1.5 is compatible with γ_{3p} increasing keeping N(γ_{3p}) constant







Conclusions

CTA can help in filling the gap between macro and micro physics
But, we need to have MW/MM simultaneous observations in particular X-ray (possibly with polarimetry)
we need to look at jets in different environments