Leptonic modeling of blazars
A brief sketch and some new clues

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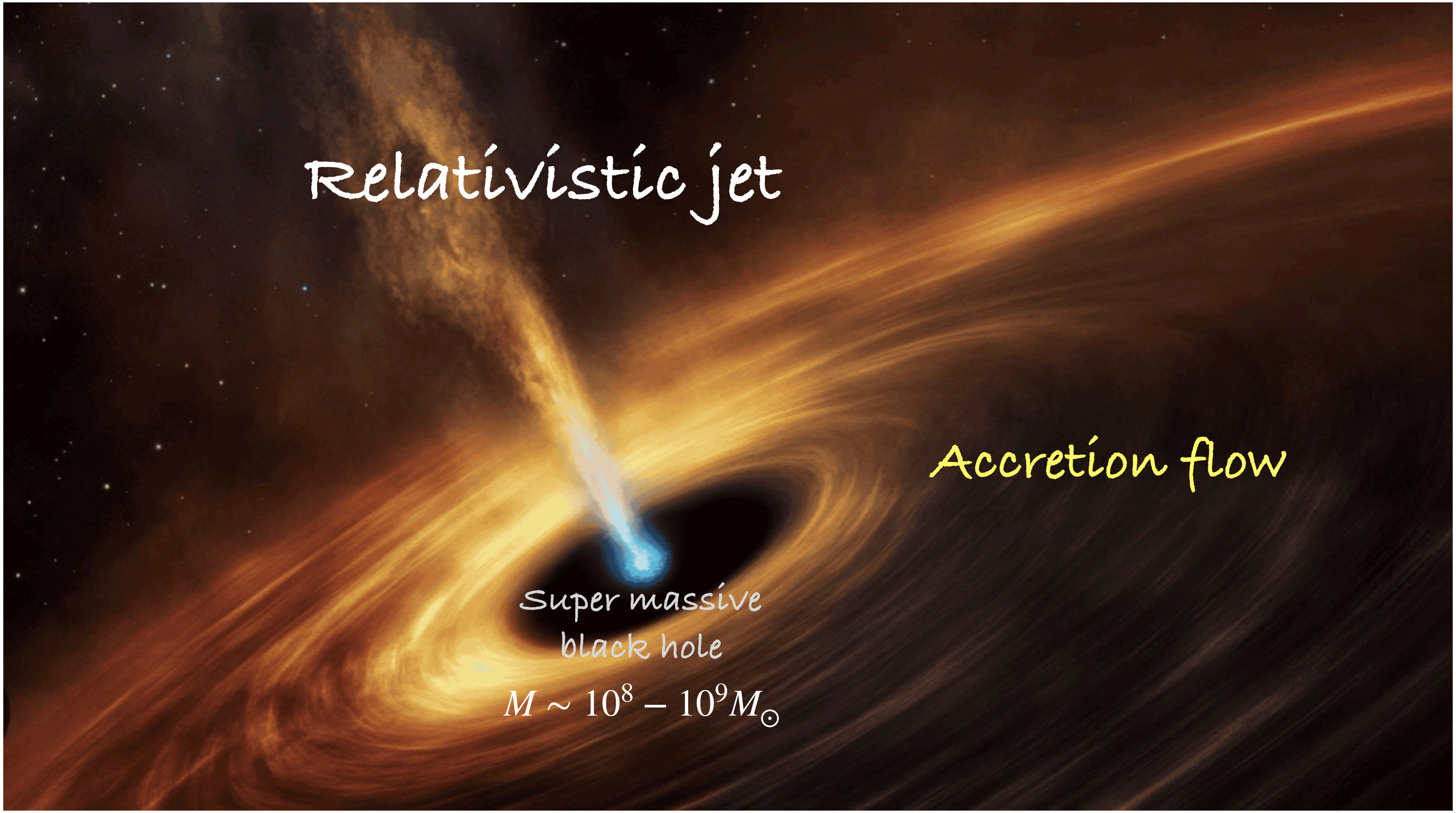
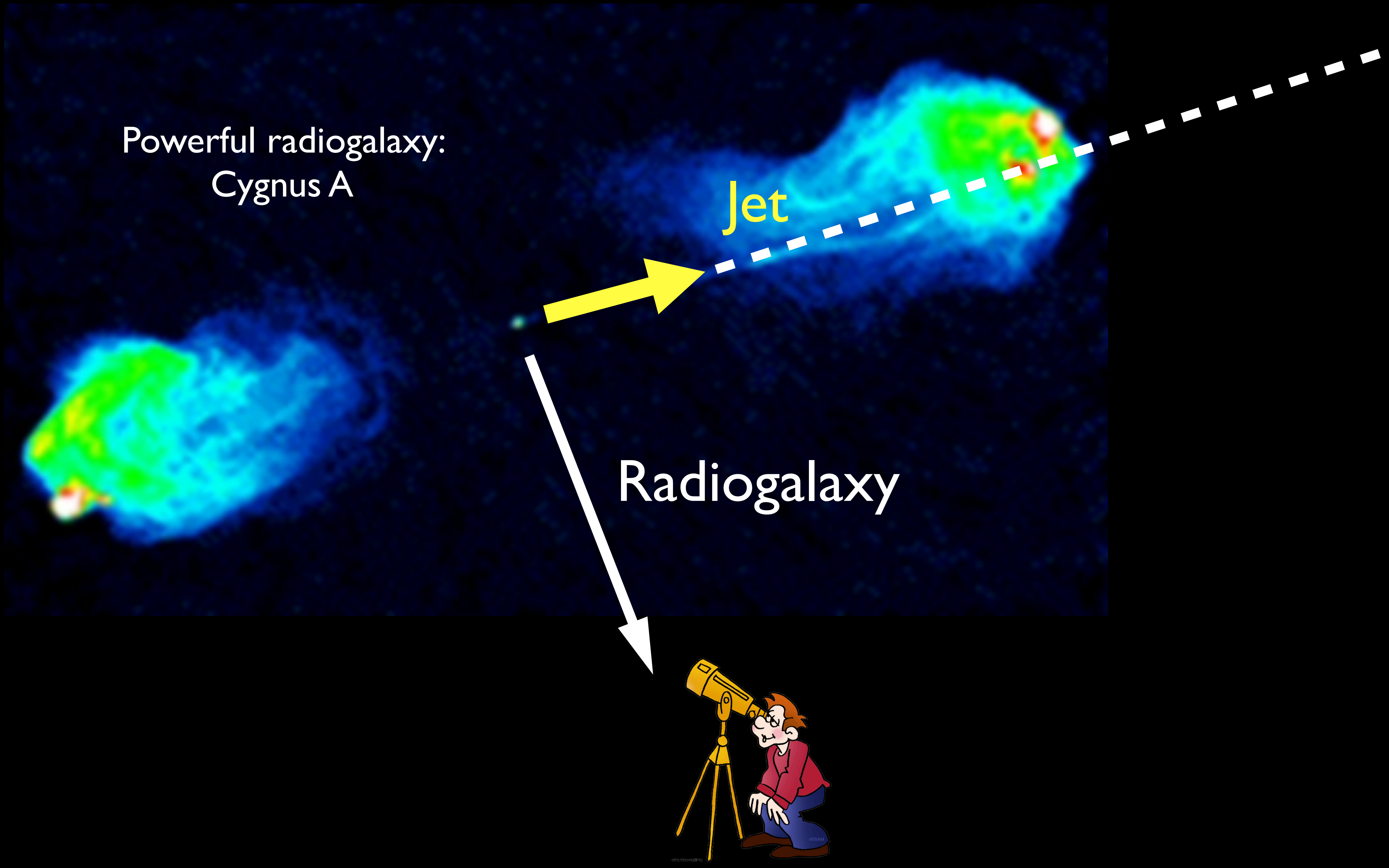
ADVANCES IN MODELING HIGH-ENERGY ASTROPHYSICAL SOURCES

Sexten - 1/7/2025

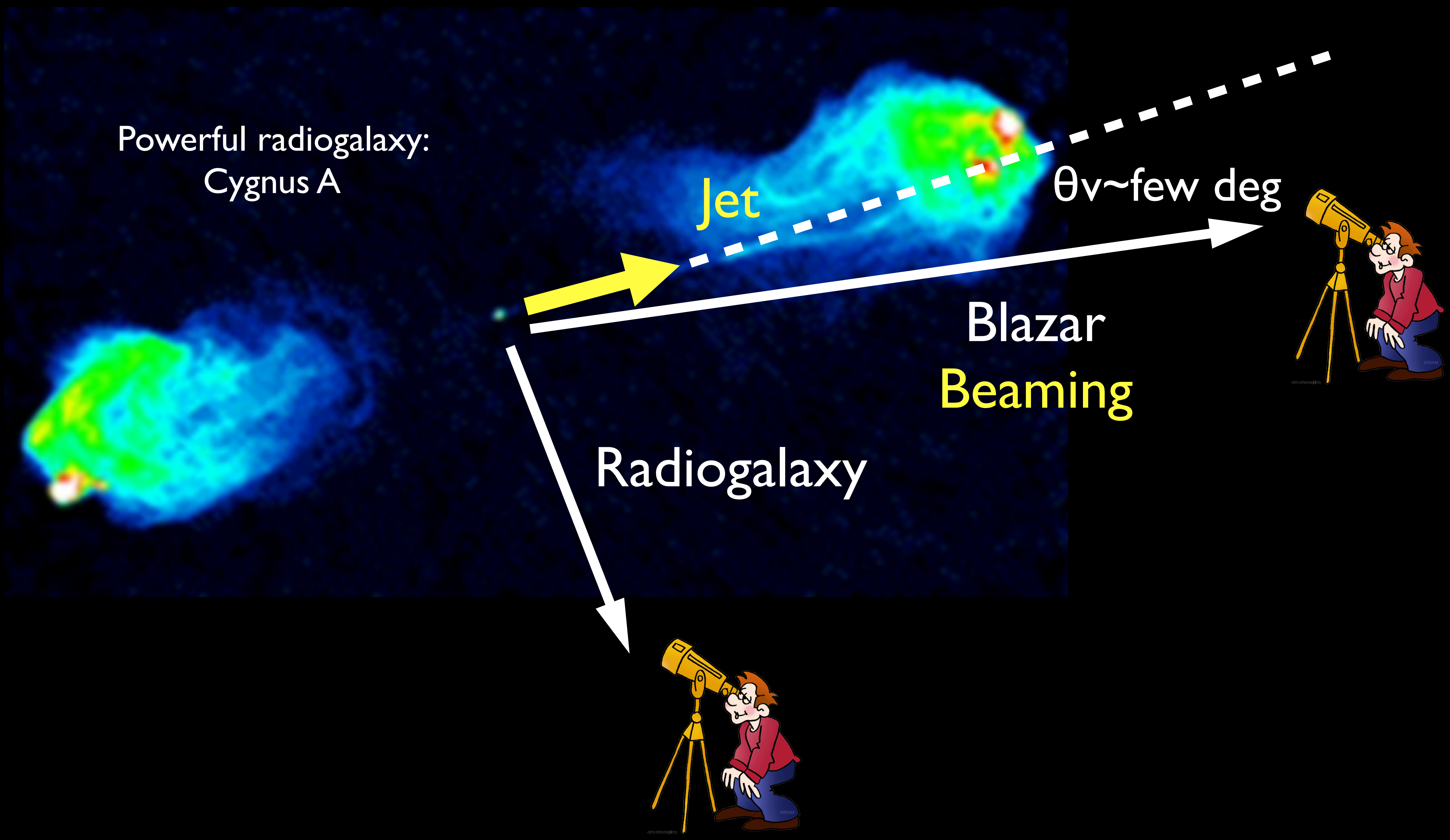
The heart of a jetted AGN



Blazars: relativistic jets pointing at us

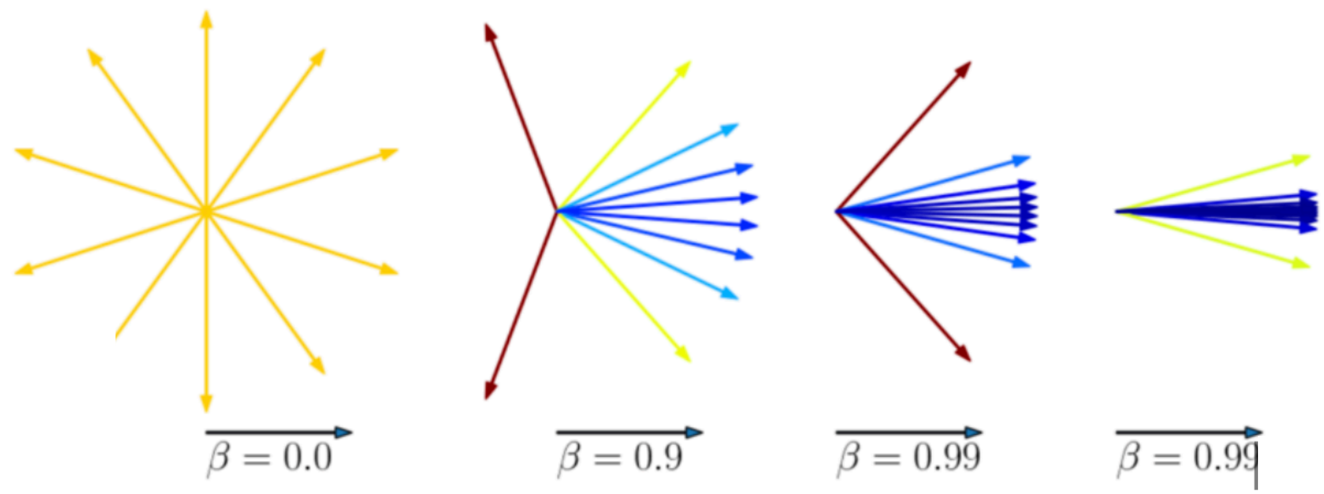


Blazars: relativistic jets pointing at us



(Special) relativity at work

Beaming = Aberration + Doppler effect



$$\omega' = -k_\mu u^\mu = \omega\gamma - \gamma \mathbf{k} \cdot \mathbf{v} = \omega\gamma(\mathbf{1} - \mathbf{n} \cdot \beta) = \omega/\delta$$

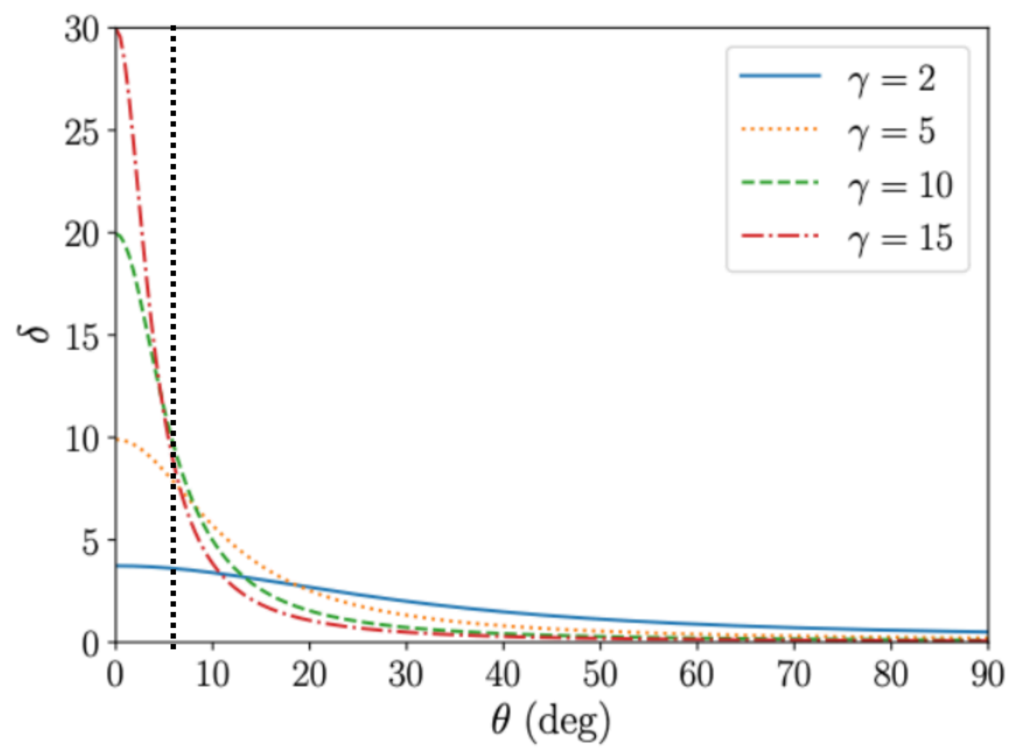
$$\mathbf{k} = \frac{\omega}{\mathbf{c}}\mathbf{n}$$

$$\delta = \frac{1}{\Gamma(1 - \beta \cos\theta_{\rm v})}$$

Relativistic Doppler factor

$\delta = \Gamma$ for $\theta_{\rm v} = 1/\Gamma$

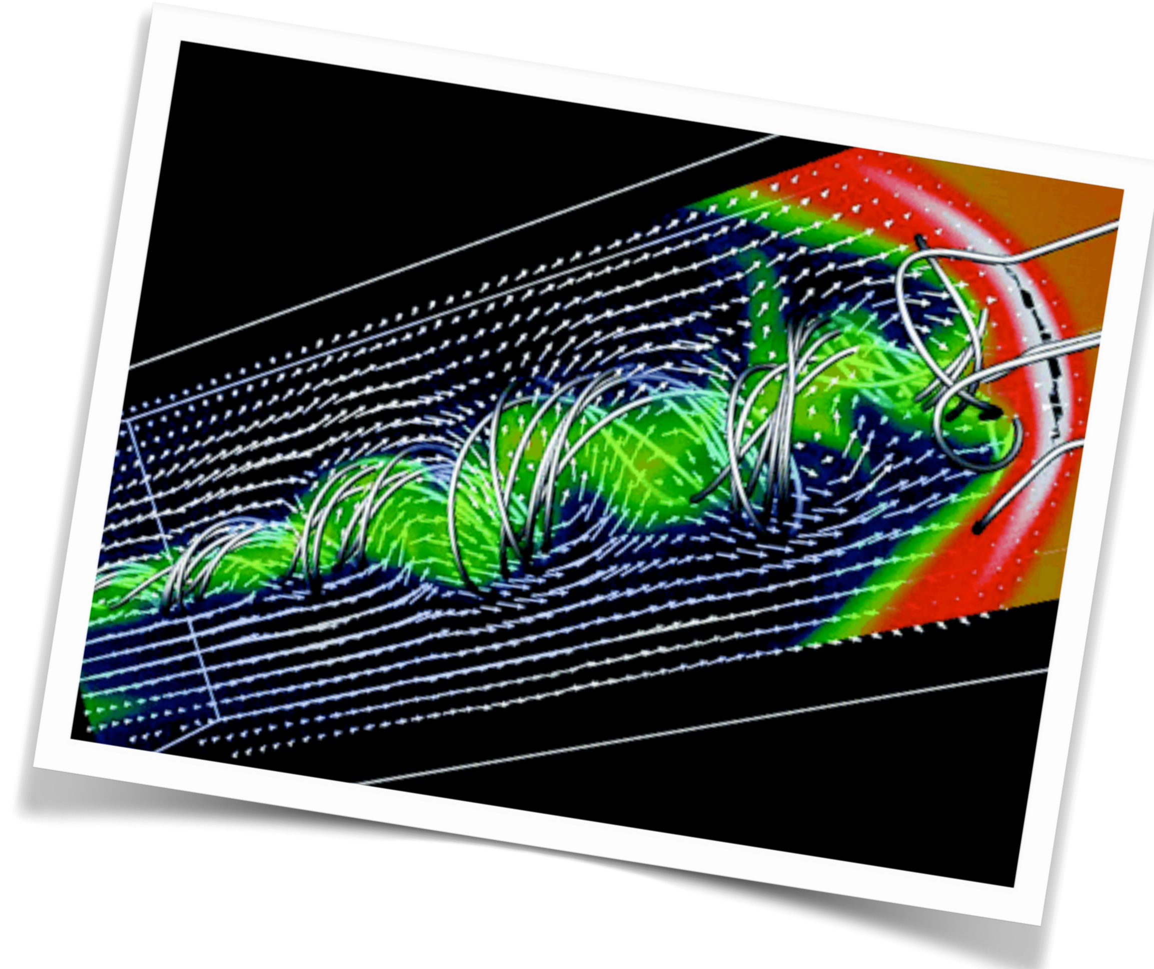
$\delta \approx 10 - 20$



$$L_{obs} = L'\delta^4$$
$$\nu_{obs} = \nu'\delta$$
$$\Delta t_{obs} = \Delta t'/\delta$$

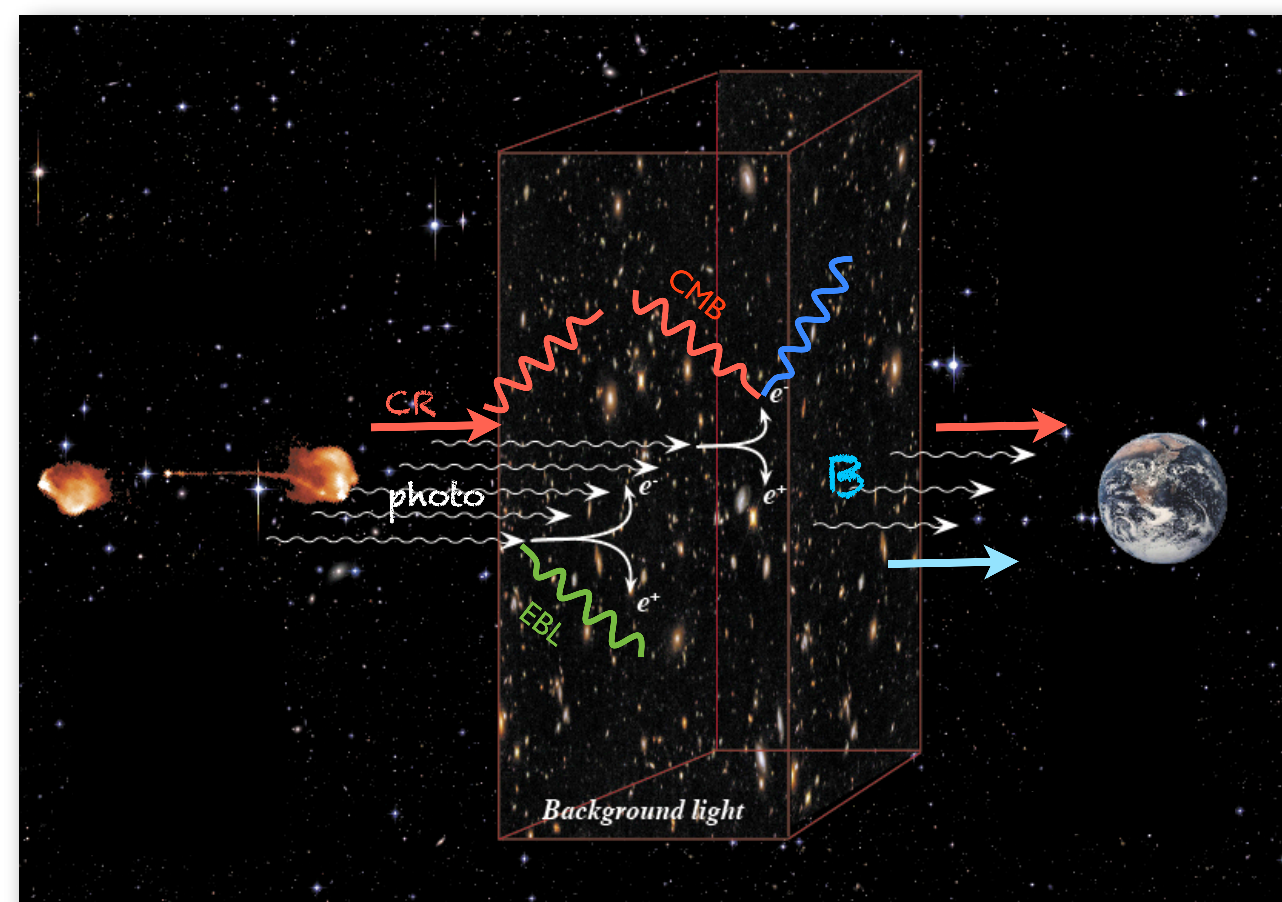
Jet physics

Particle acceleration
Plasma and B-field physics
Reconnection vs shock
Hadronic vs leptonic emission
Location of emission region
...



Propagation effects

Extragalactic background light
Intergalactic magnetic field
Hadronic beams
LIV and ALPs-induced effects and other anomalies



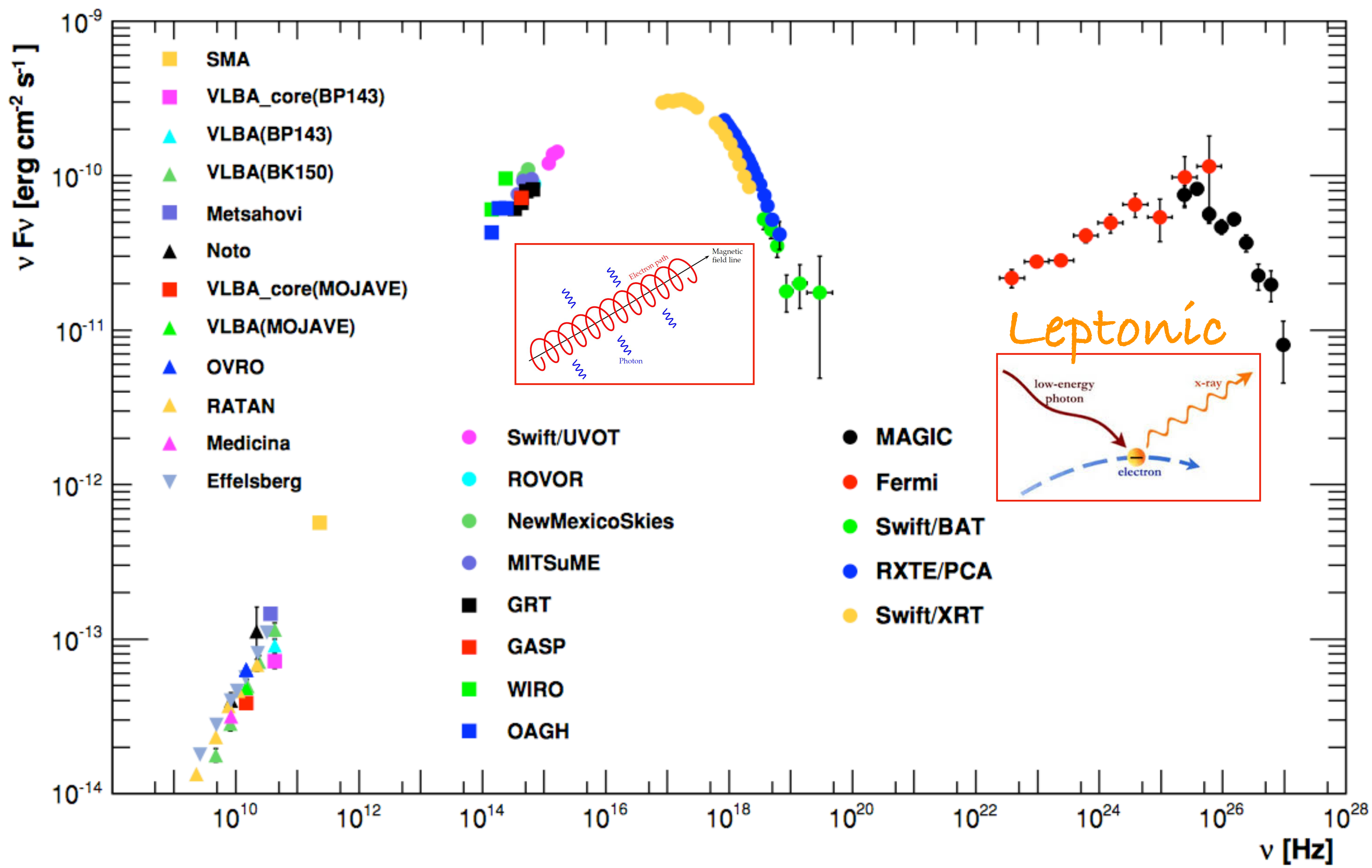
The spectral energy distribution

Extended over the whole EM spectrum
Extremely variable

Multiwavelength sources

Important observational effort

Abdo et al. 2011

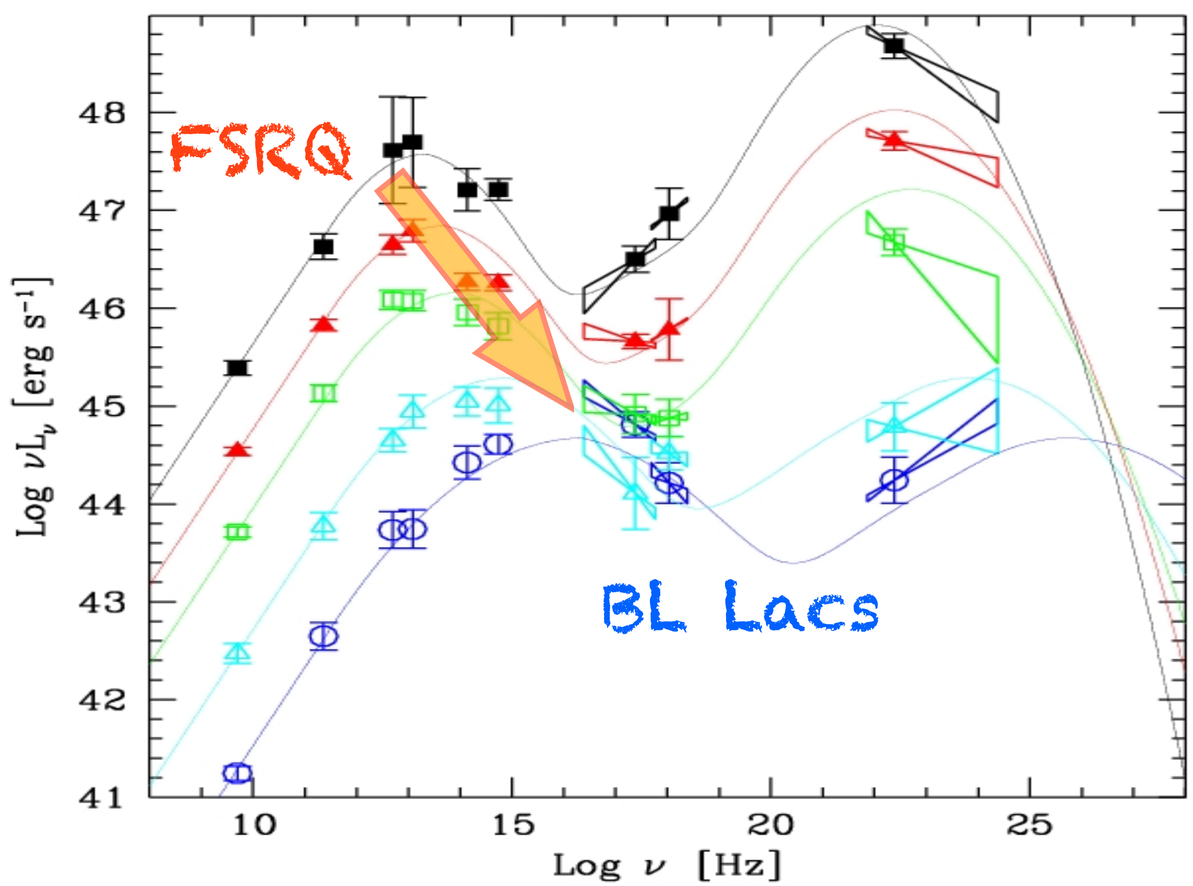


Blazars: basic phenomenology

Blazars occur in two flavors:

FSRQ: high power, thermal optical components (broad lines)

BL Lacs: low power, almost purely non-thermal components



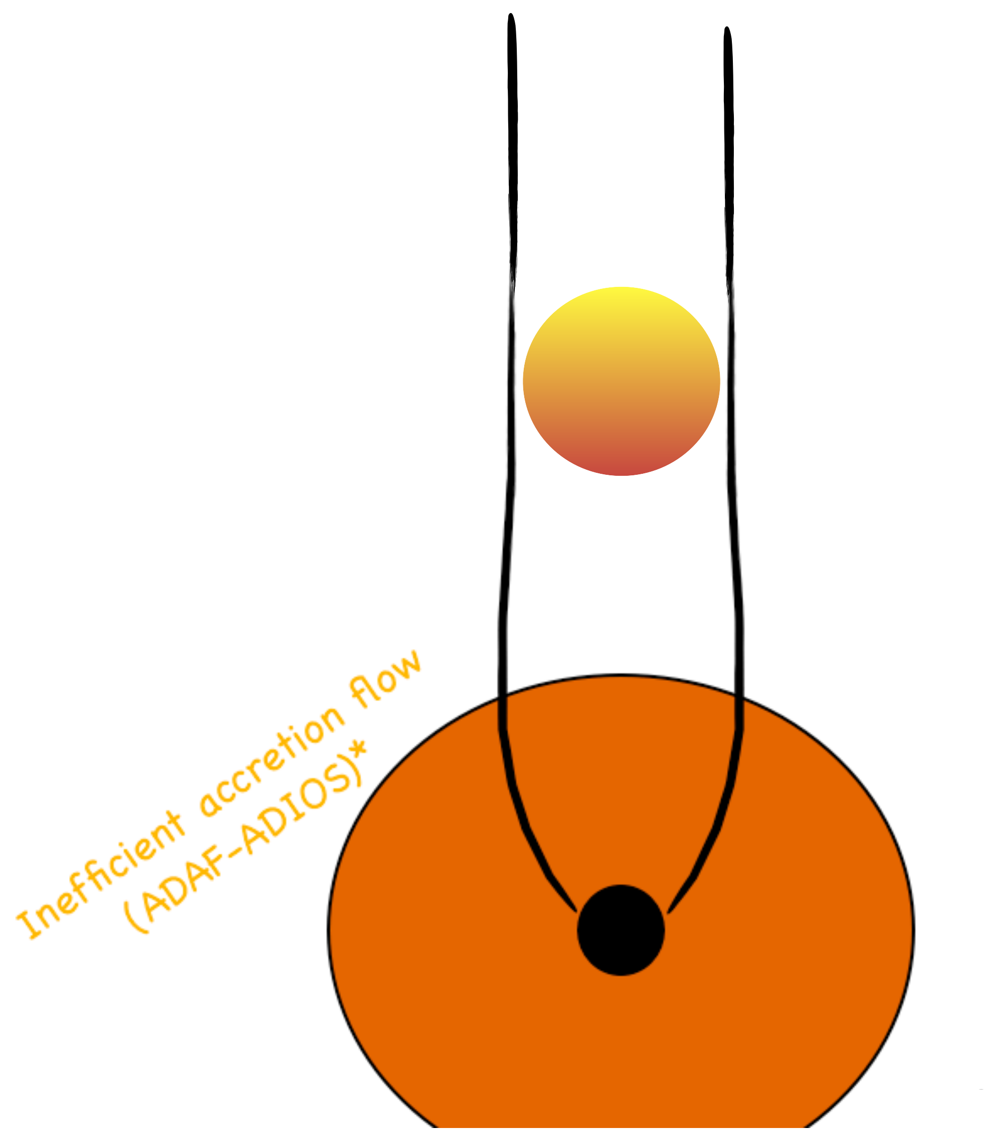
The "blazar sequence"

Fossati et al. 1998
Donato et al. 2002
Ghisellini et al. 2009

But see several papers by Giommi & Padovani

Blazars in a nutshell

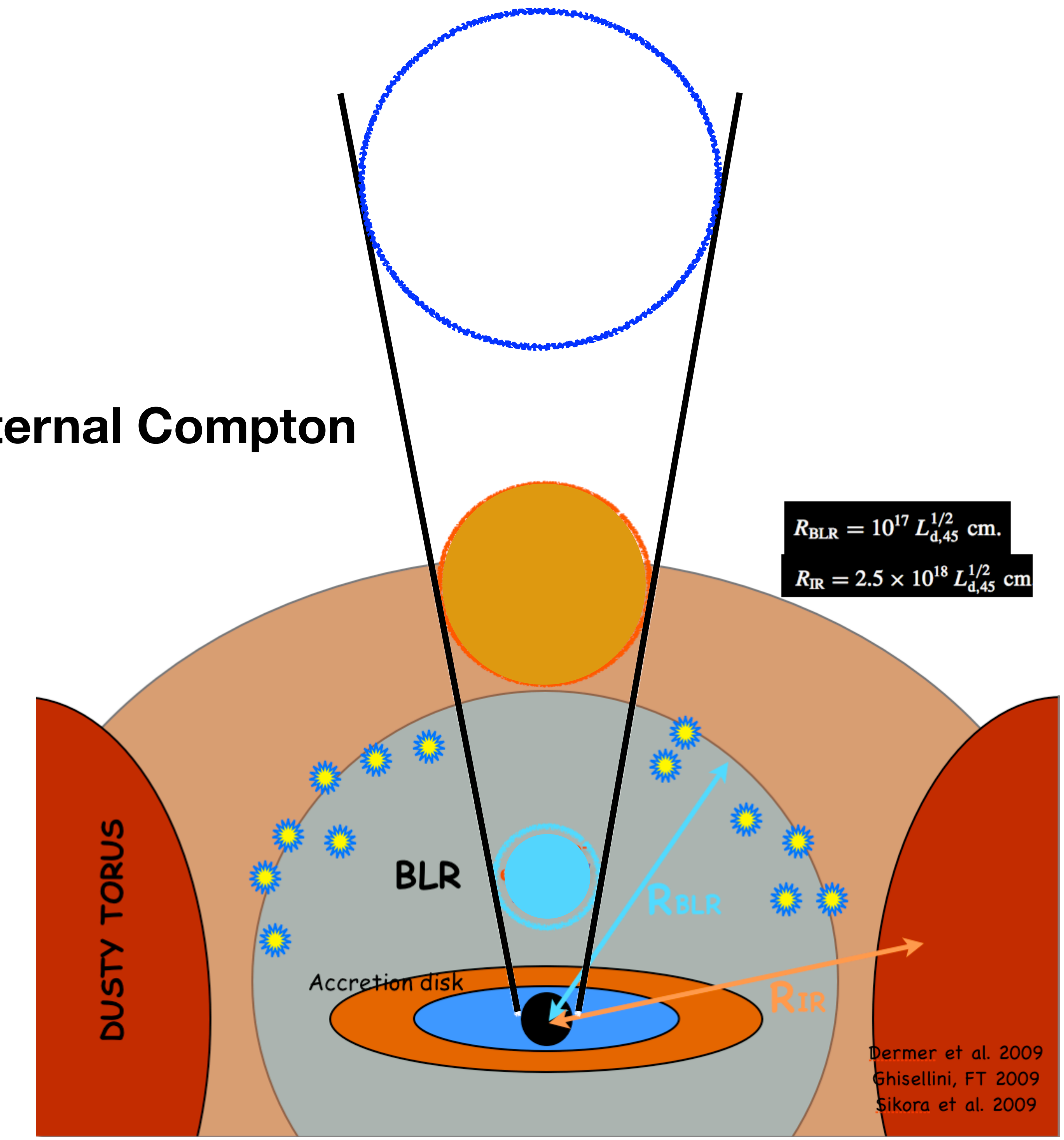
BL Lacs: “naked” jets



Synchrotron-self Compton

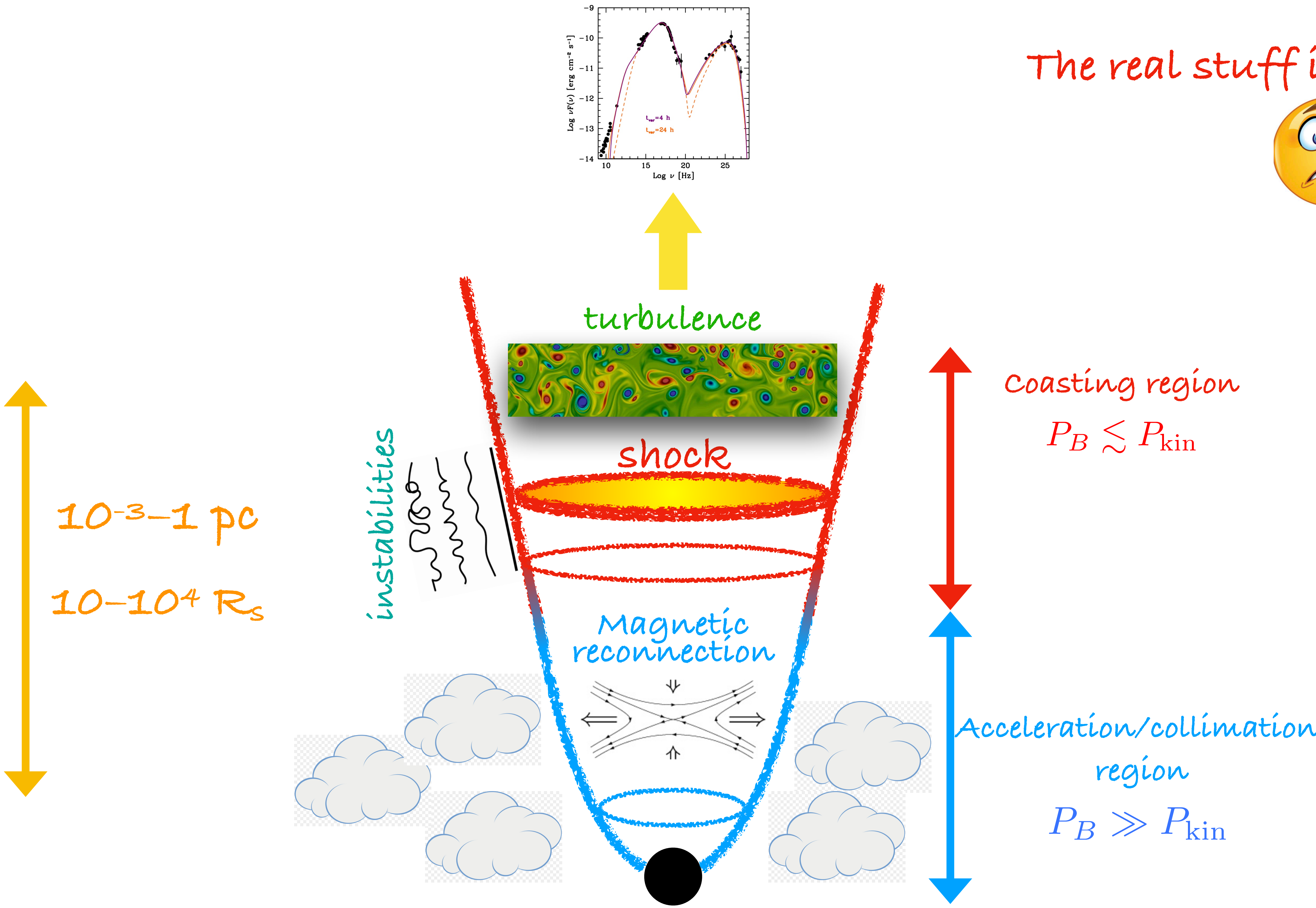
FSRQ: “dressed” jets

External Compton



The full problem

The real stuff is a mess!!

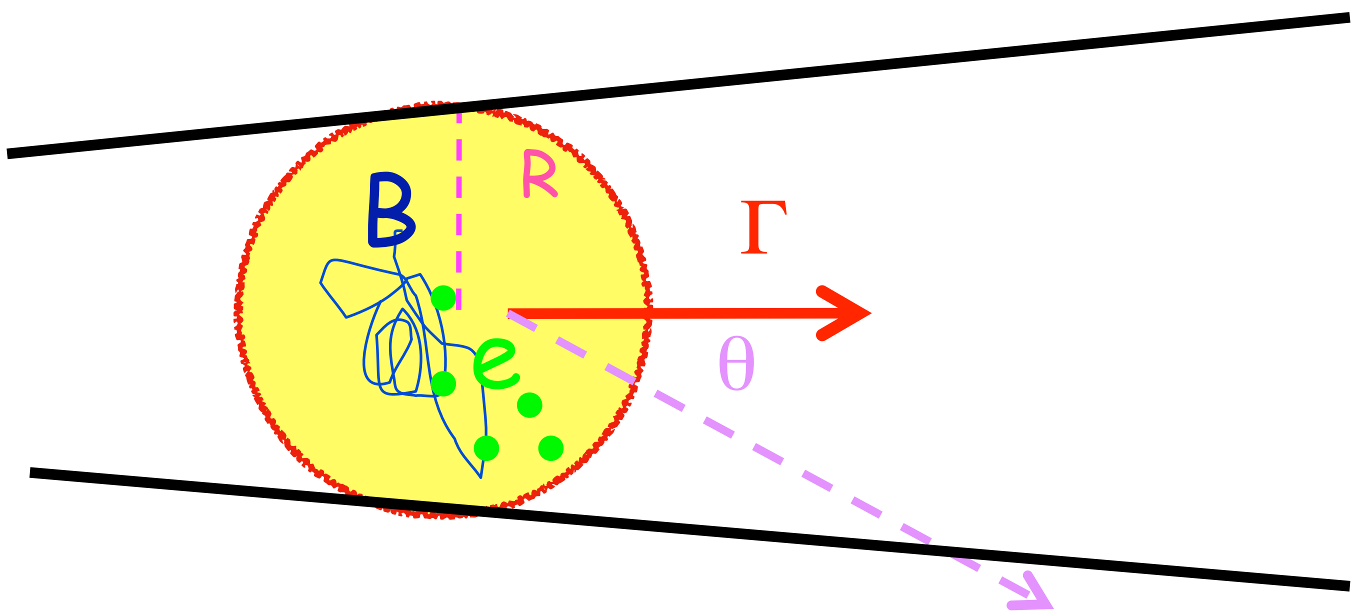


E.g. Blandford et al. 2019
Matthews et al. 2020

A modest model

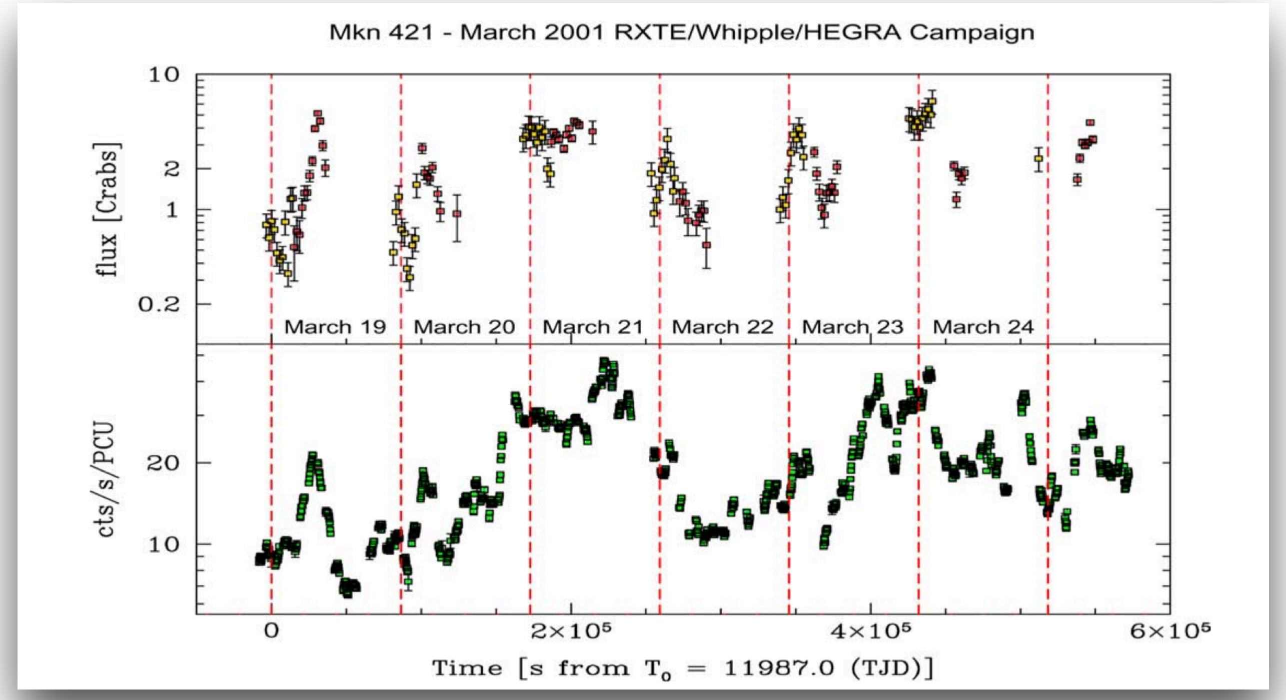
A drastic simplification!!

"One zone"



Historically supported by correlated variability

Fossati et al. 2004



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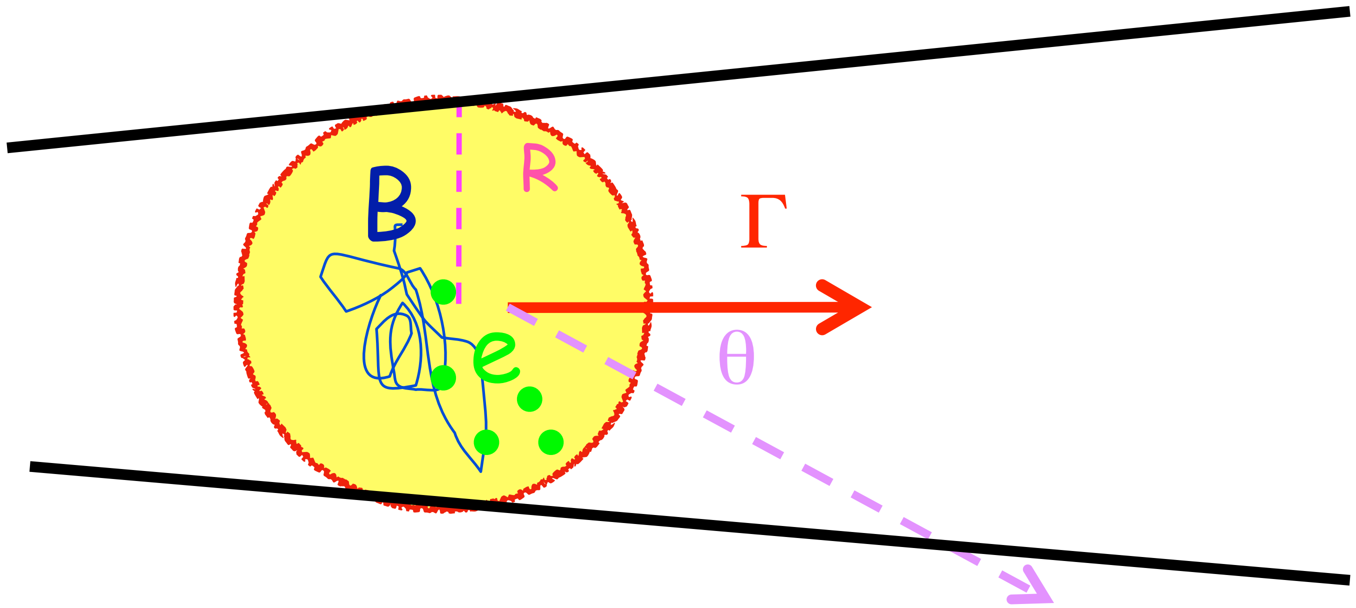


Additional standard assumptions:

-Magnetic field is tangled (turbulent)

-Leptons have an isotropic pitch angle distribution

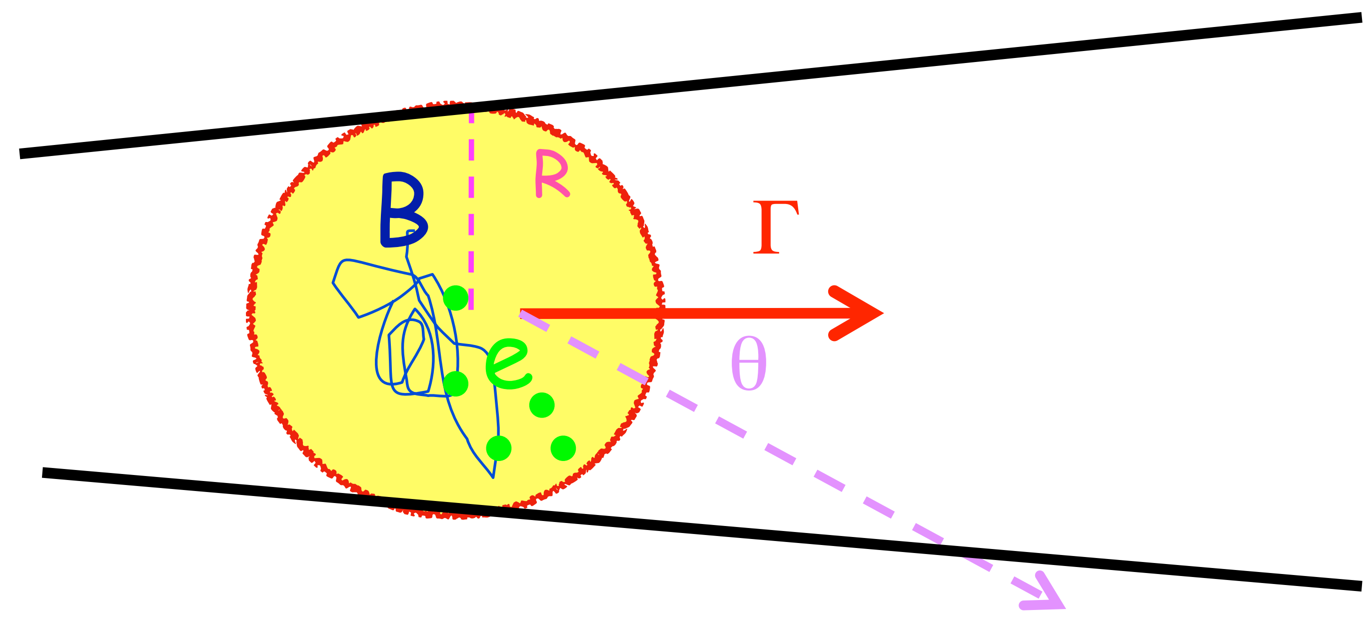
But see Sobacchi et al. 2020, 2021

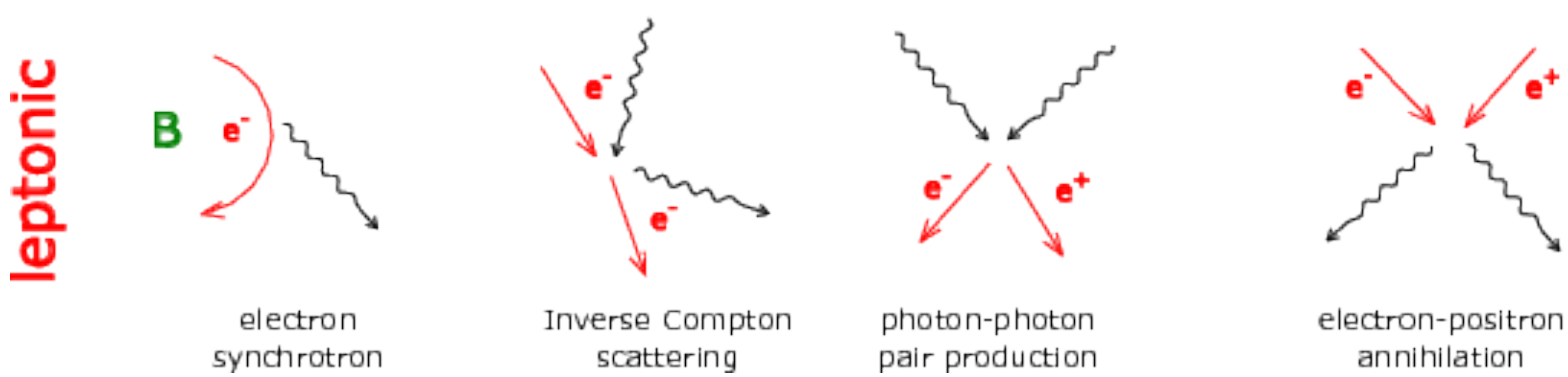
-For BL Lacs the only relevant photons for IC are the synchrotron ones

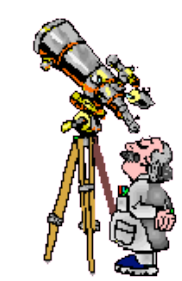
A modest model

A drastic simplification!!

"One zone"

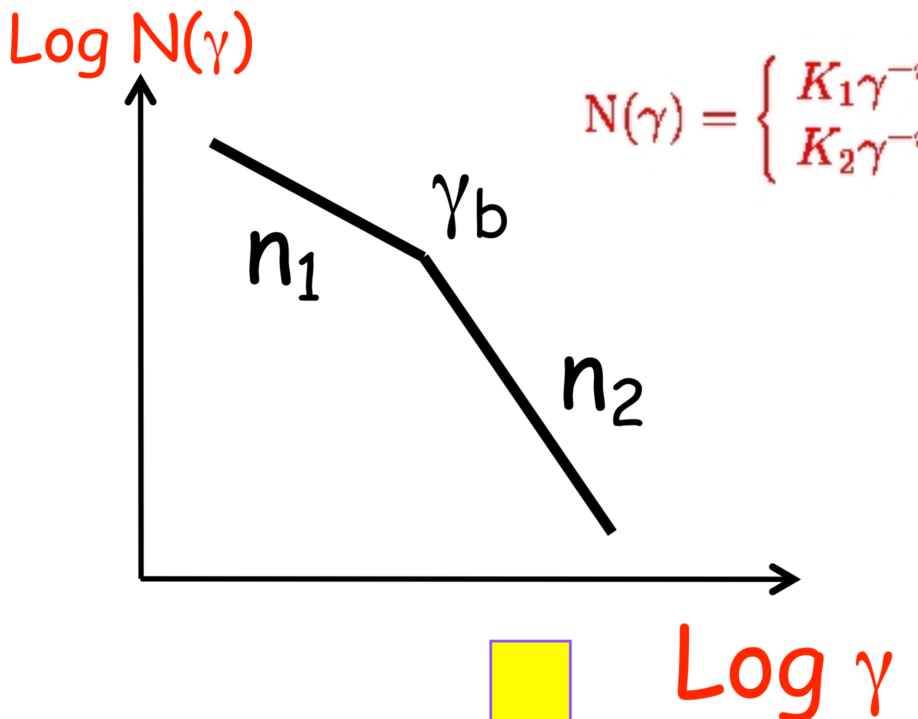




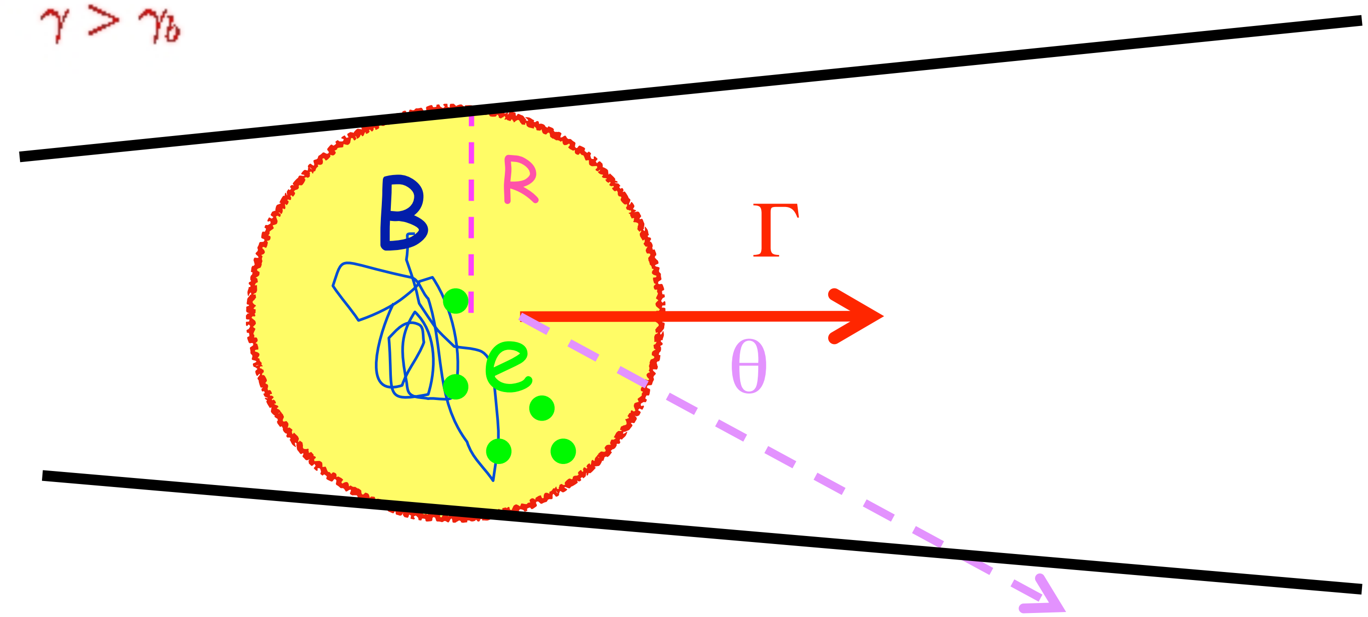


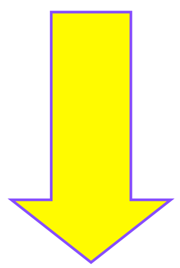
Hadrons not relevant for the emission (but not for energetics!)

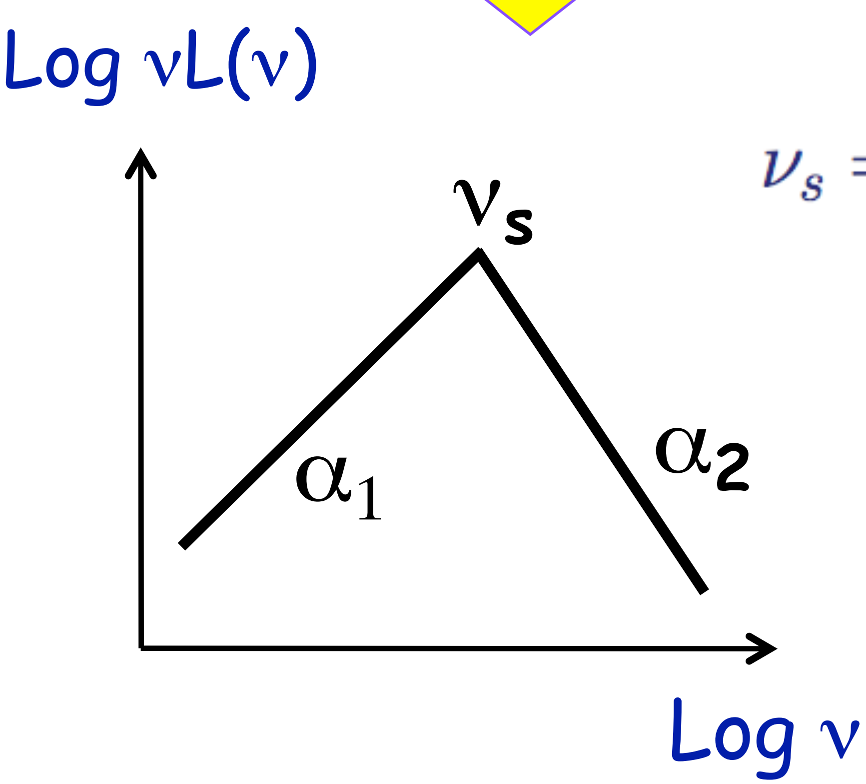
A modest model



$$N(\gamma) = \begin{cases} K_1 \gamma^{-n_1} & \gamma < \gamma_b \\ K_2 \gamma^{-n_2} & \gamma > \gamma_b \end{cases}$$

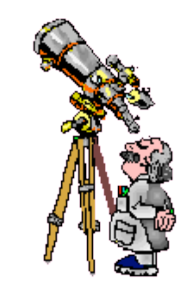




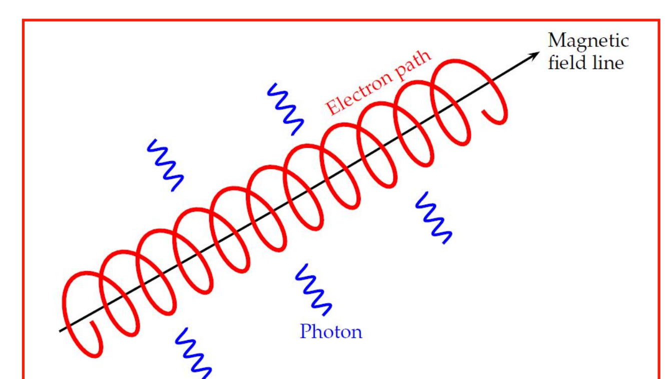


$$\nu_s = 3 \times 10^6 B \gamma_b^2 \delta$$

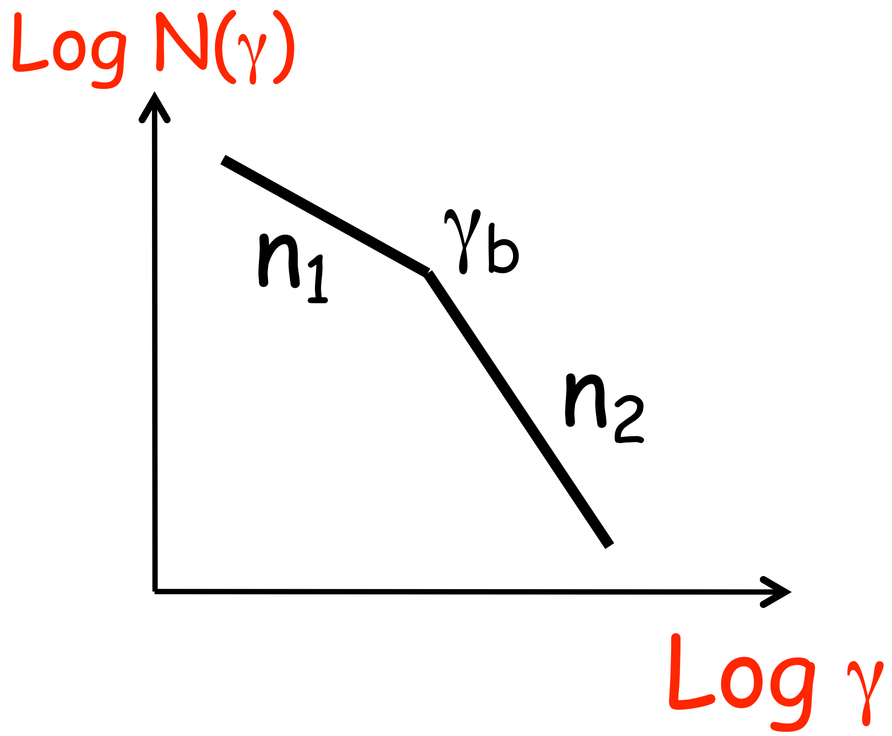
$$\alpha_i = \frac{n_i - 1}{2}$$



Synchrotron emission



A modest model



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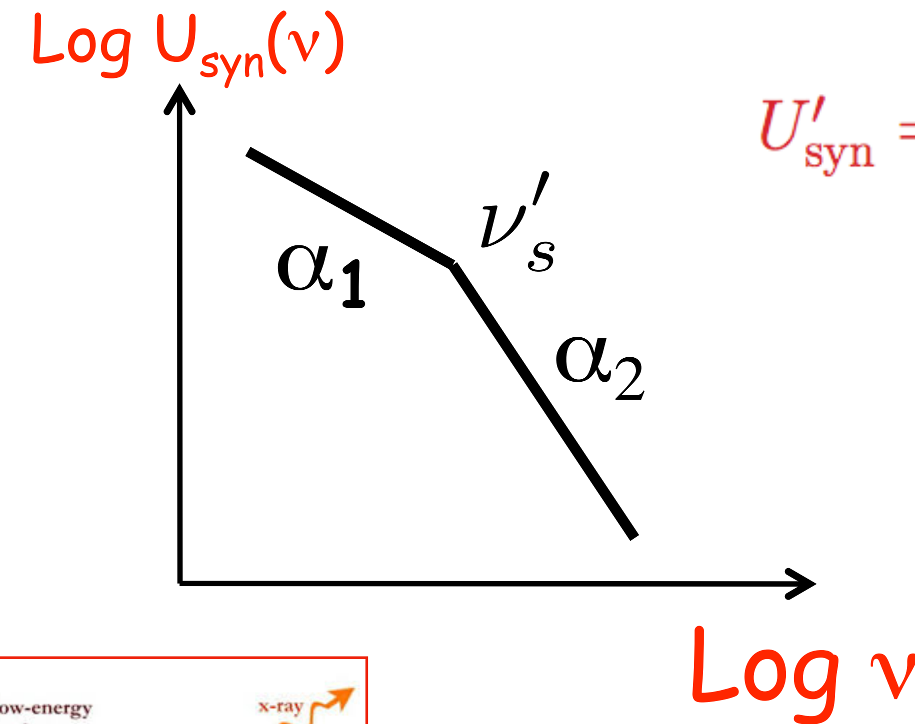
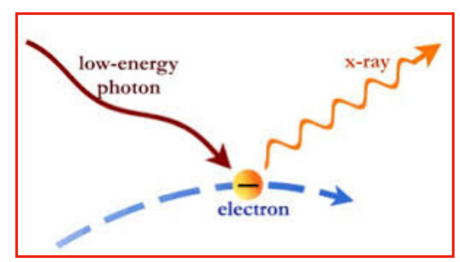
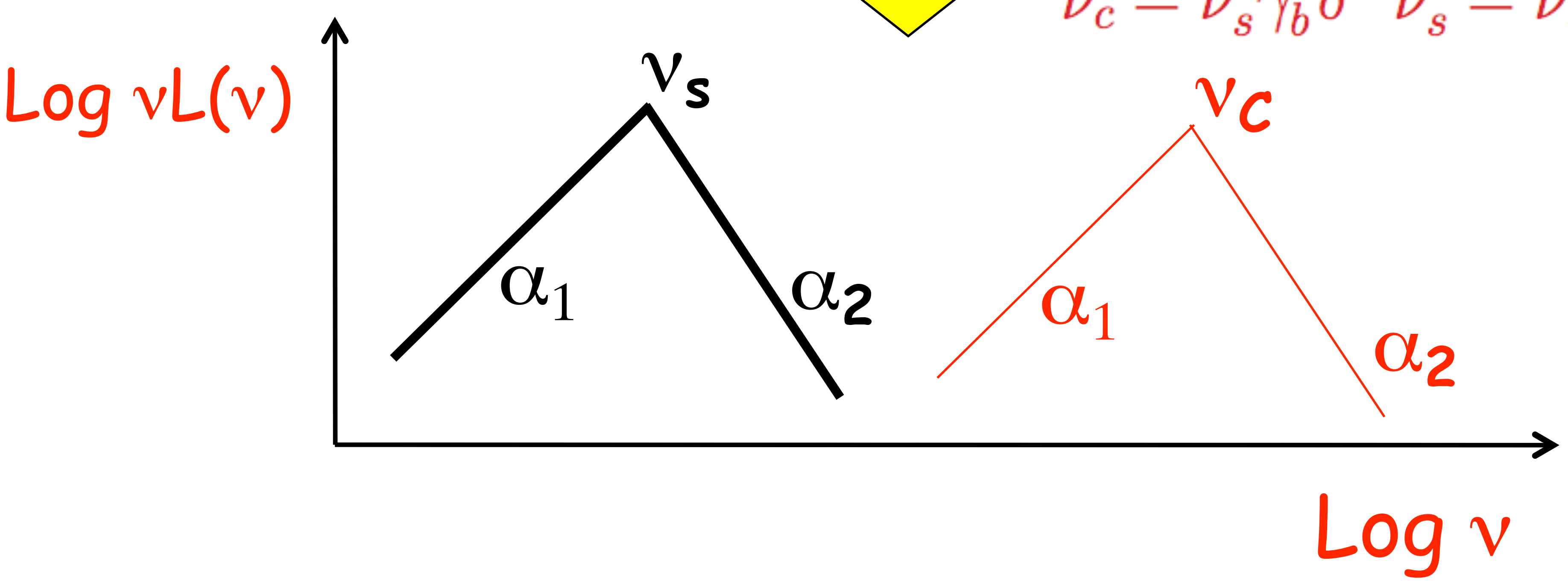


$$U'_{\rm syn} = \frac{\nu_s L(\nu_s)}{4\pi R^2 c \delta^4}$$

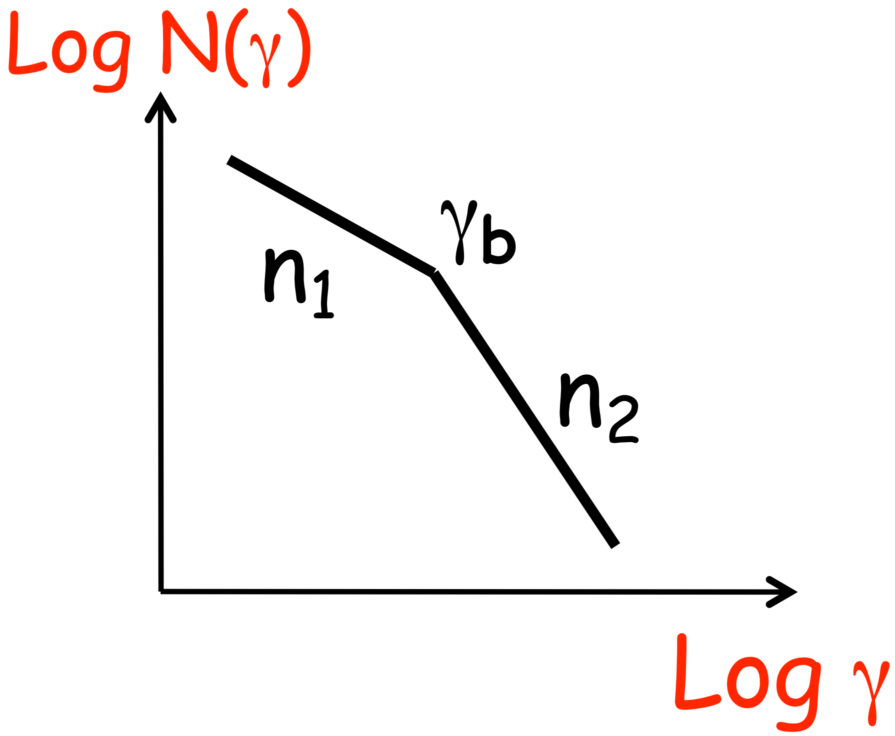


$$\nu_c = \nu'_s \gamma_b^2 \delta \quad \nu'_s = \nu_s/\delta$$



$$\frac{\nu_c L(\nu_c)}{\nu_s L(\nu_s)} = \frac{U'_{\rm syn}}{U_B}$$

A modest model



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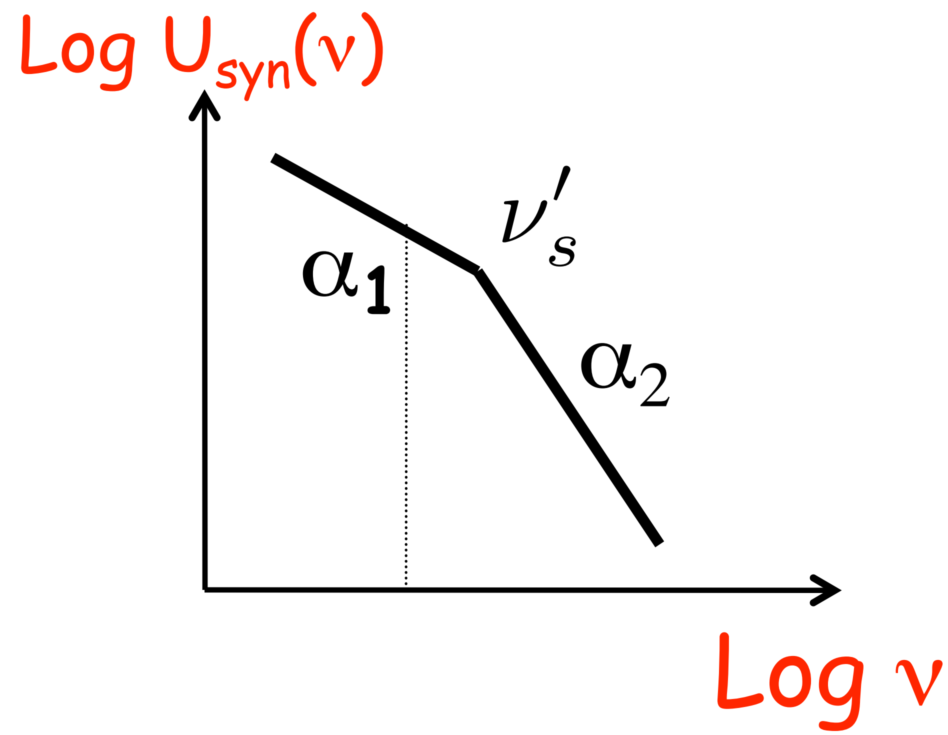
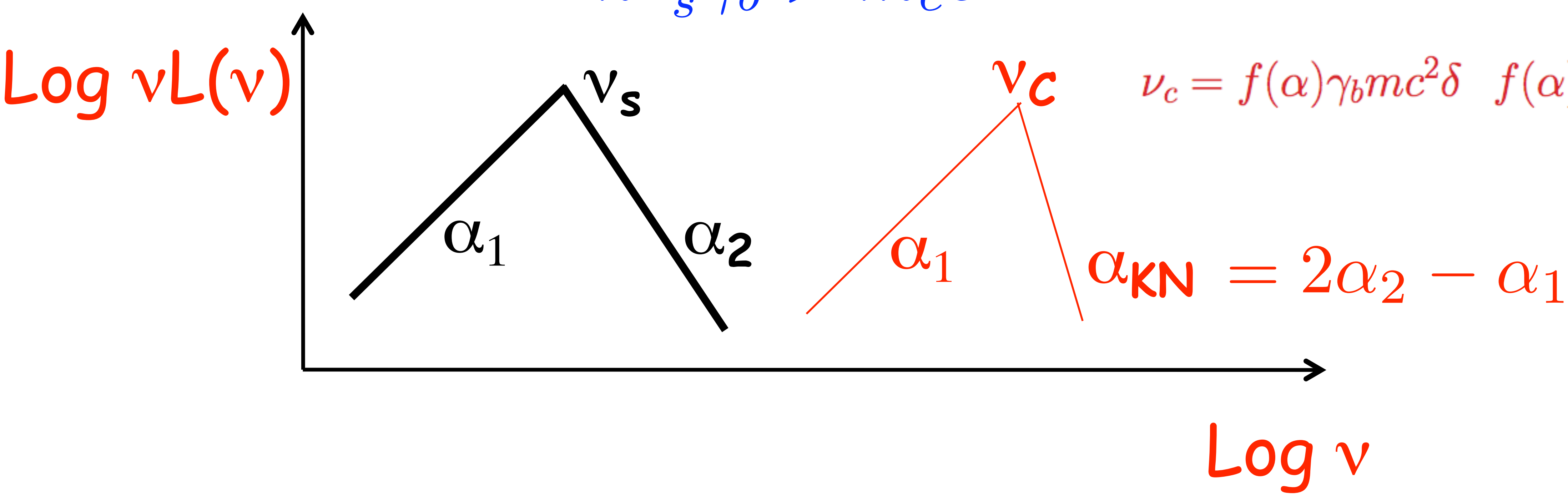


"Klein-Nishina regime"

$$h\nu'_s\gamma_b > m_e c^2$$

$$\nu_c = f(\alpha)\gamma_b mc^2\delta \quad f(\alpha) \simeq 0.1 - 0.2$$



In principle, in this simple version of the Synchrotron-Self Compton (SSC) model, all parameters can be constrained by quantities available from observations:

7 free parameters

R B N_o γ_b n_1 n_2 δ

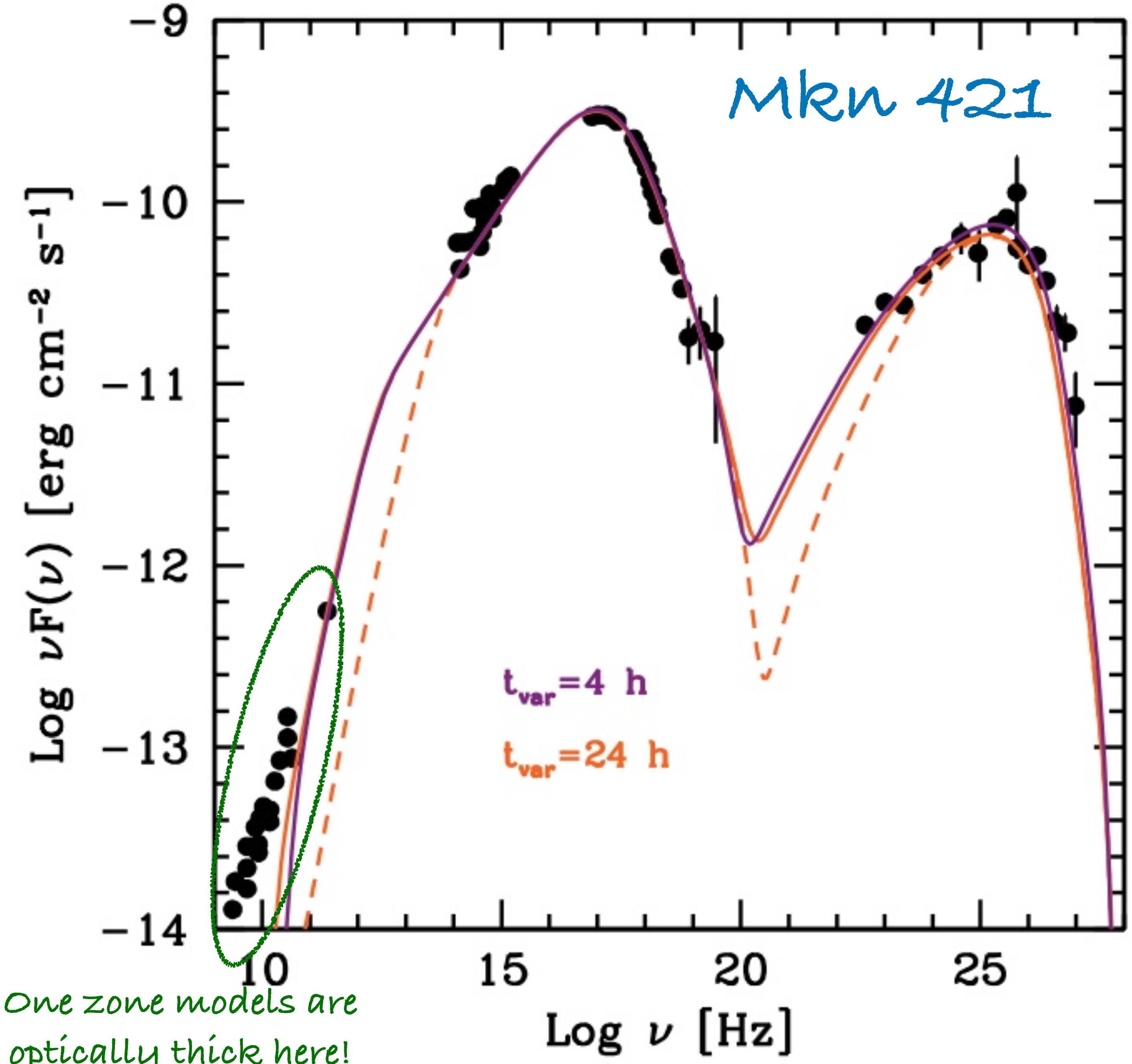
7 observational quantities

ν_s L_s ν_C L_C t_{var} α_1 α_2

Tavecchio, Maraschi & Ghisellini 1998

Application: BL Lacs

Modest but effective!

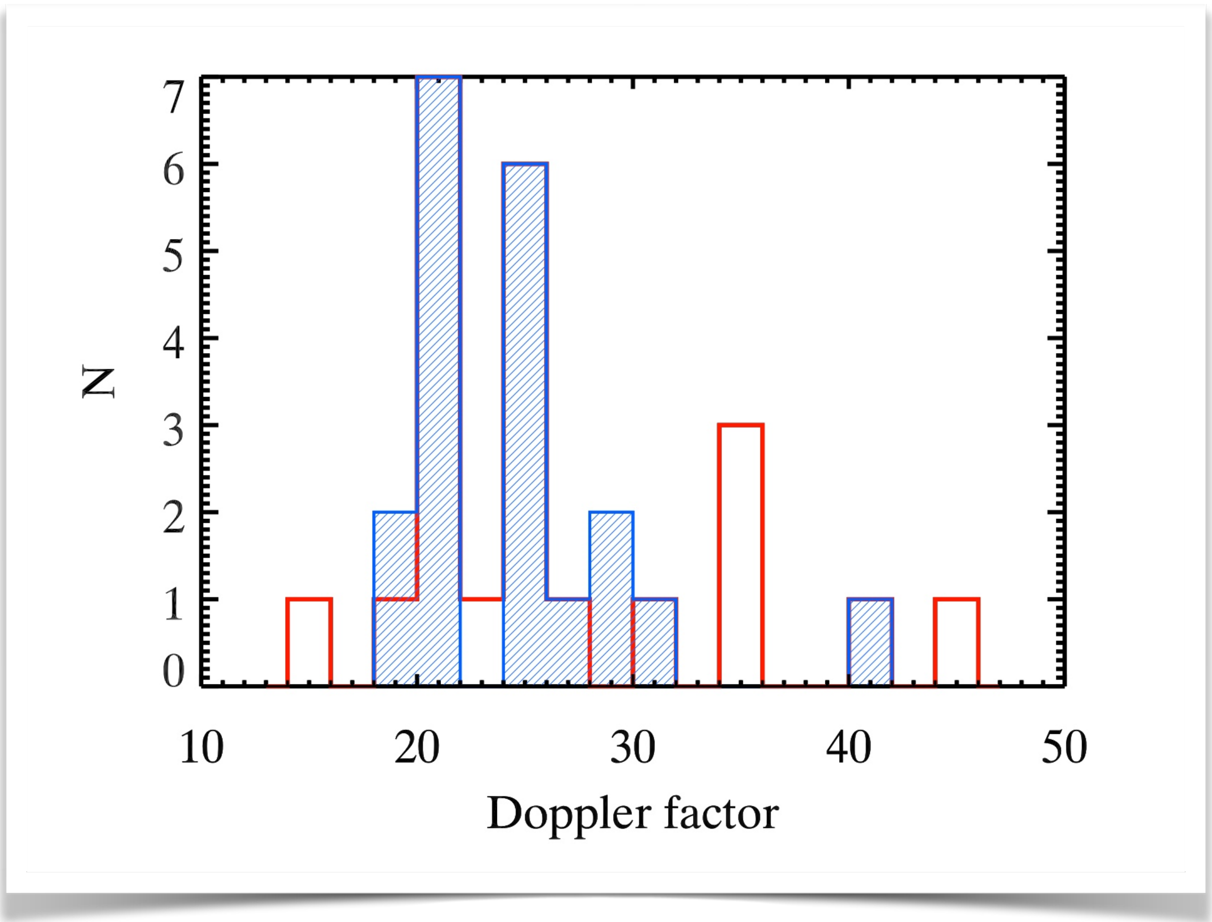


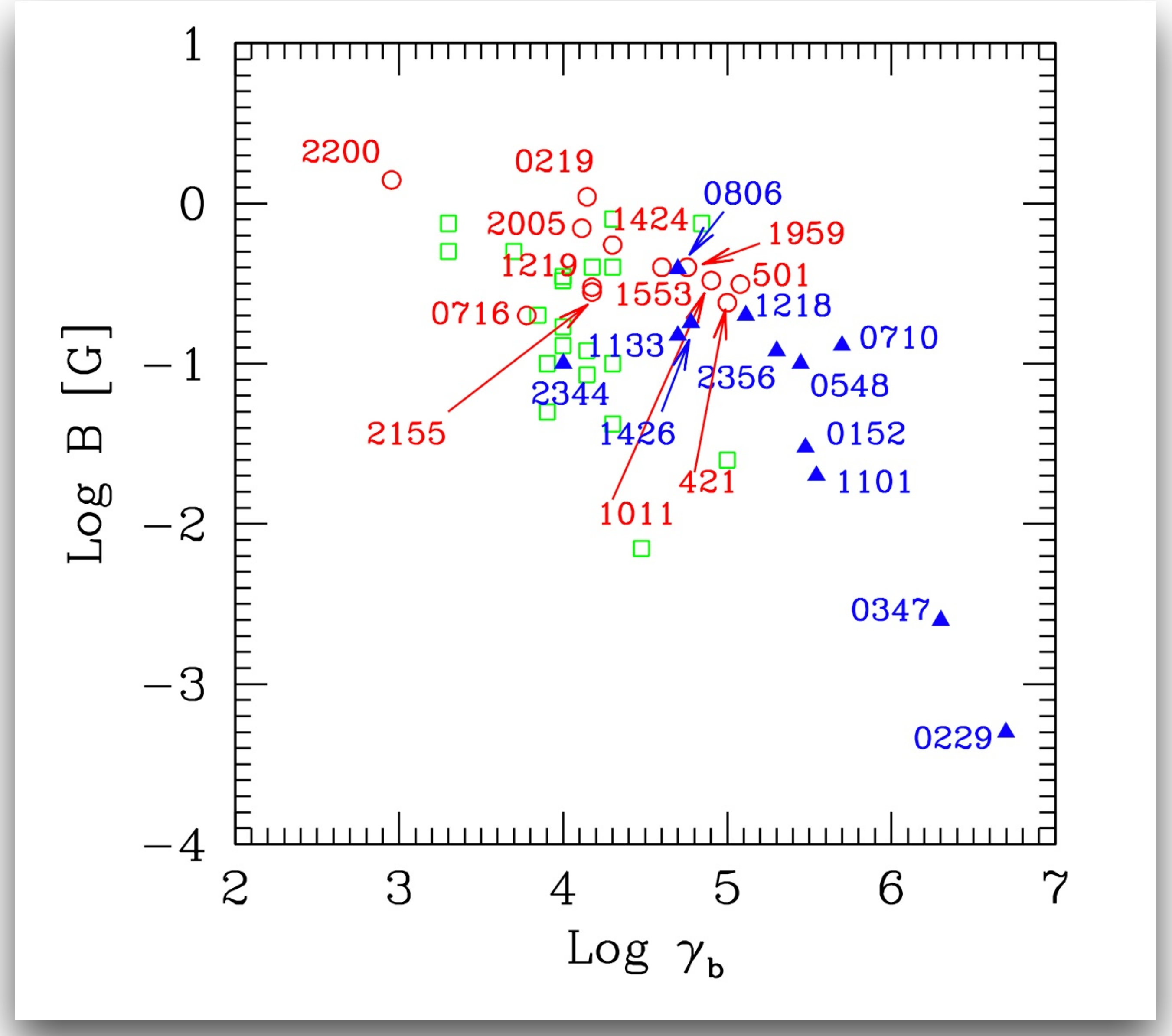
One zone models are optically thick here! Produced by larger, more extended jet regions

Tavecchio and Ghisellini 2016

Model (1)	γ_{min} (2)	γ_b (3)	γ_{max} (4)	n_1 (5)	n_2 (6)	B (7)	K (8)	R (9)	δ (10)
1	500	1.7×10^5	2×10^6	2.2	4.8	0.075	1.3×10^4	1	25
2	700	2.5×10^5	4×10^6	2.2	4.8	0.06	3.2×10^3	3.6	14

Application: BL Lacs



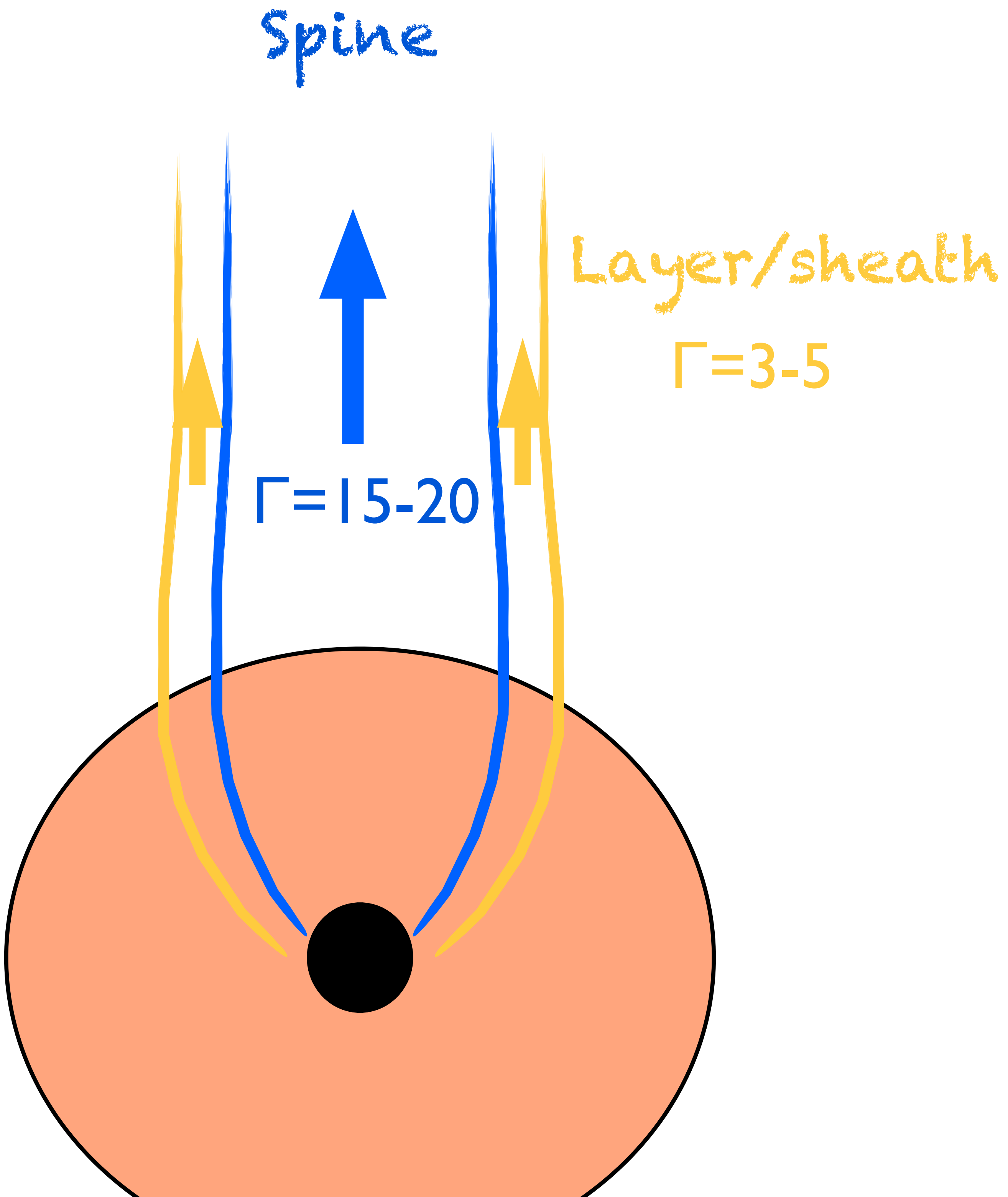


Tavecchio et al. 2010

An improved model

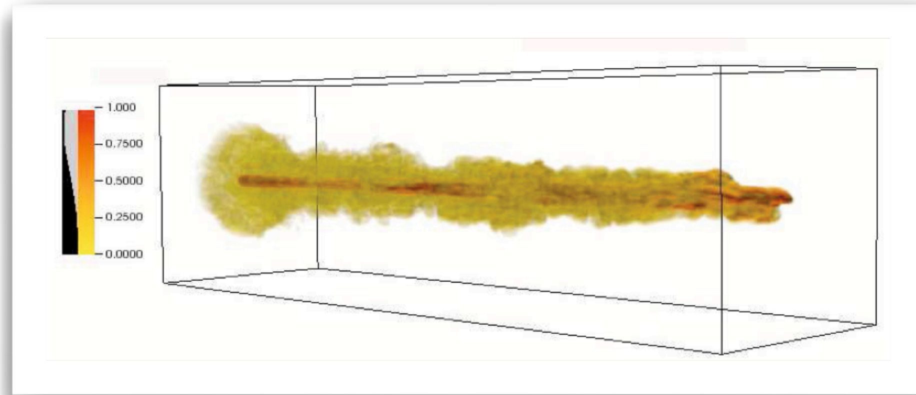
Structured jets

"Two zones"



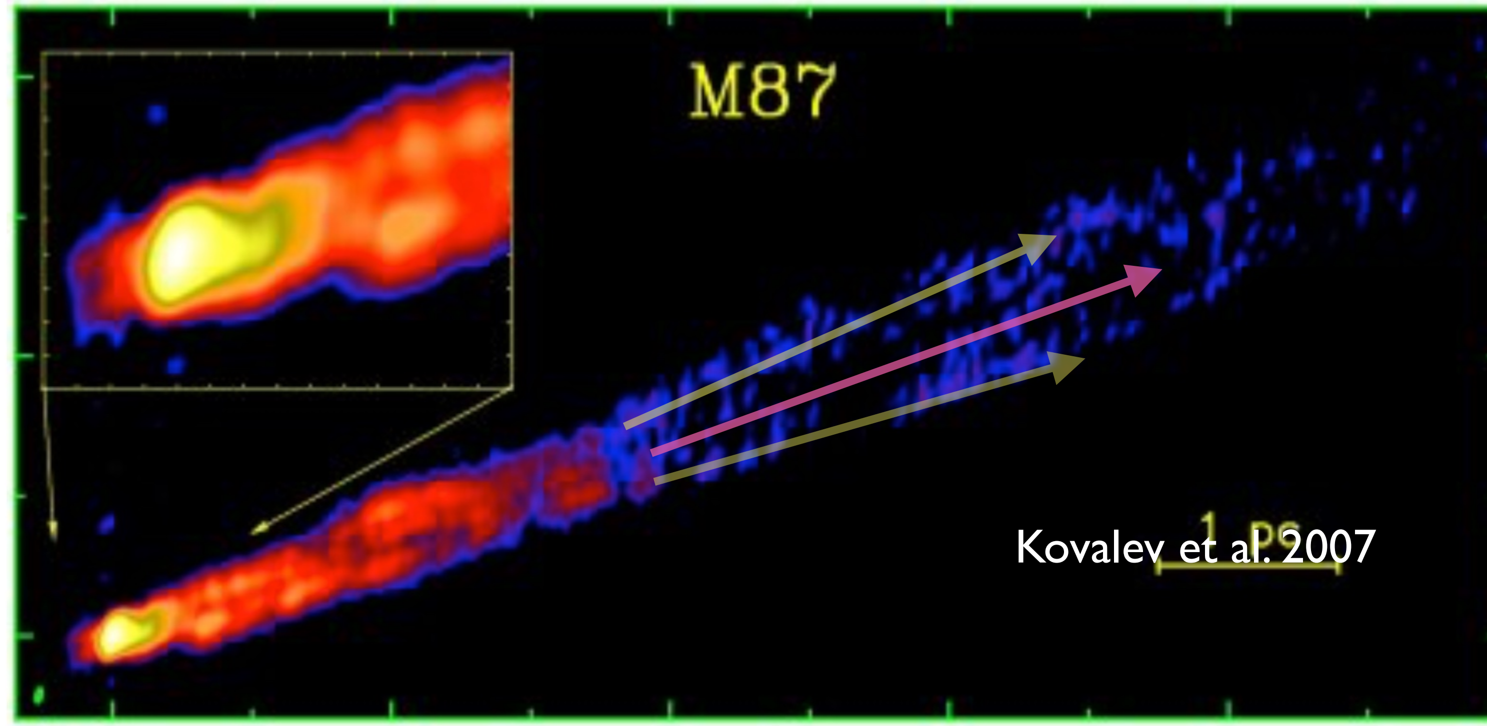
Ghisellini, FT and Chiaberge 2005
Tavecchio & Ghisellini 2008

Structured jets in BL Lacs



Simulations predict spine-layer structure

Entrainment/instability e.g. Rossi et al. 2008
Acceleration process e.g. McKinney 2006

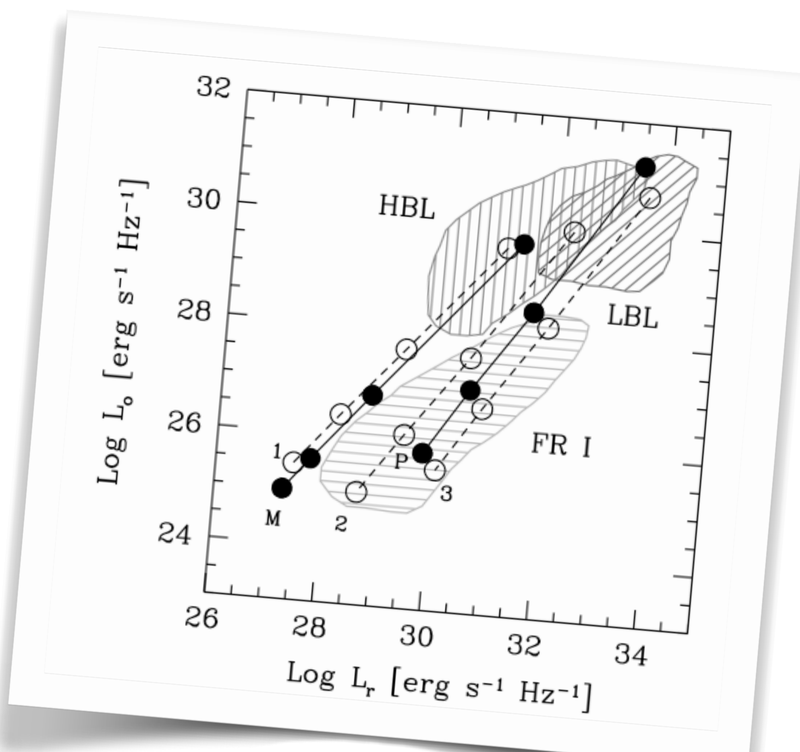


Limb brightening
Mkn 501, Mkn 421, M87, NGC 1275

Laing 1996
Giroletti et al. 2004
Piner & Edwards 2014
Pushkarev et al. 2005
Clausen-Brown 2011
Murphy et al. 2013

Unification requires velocity structures

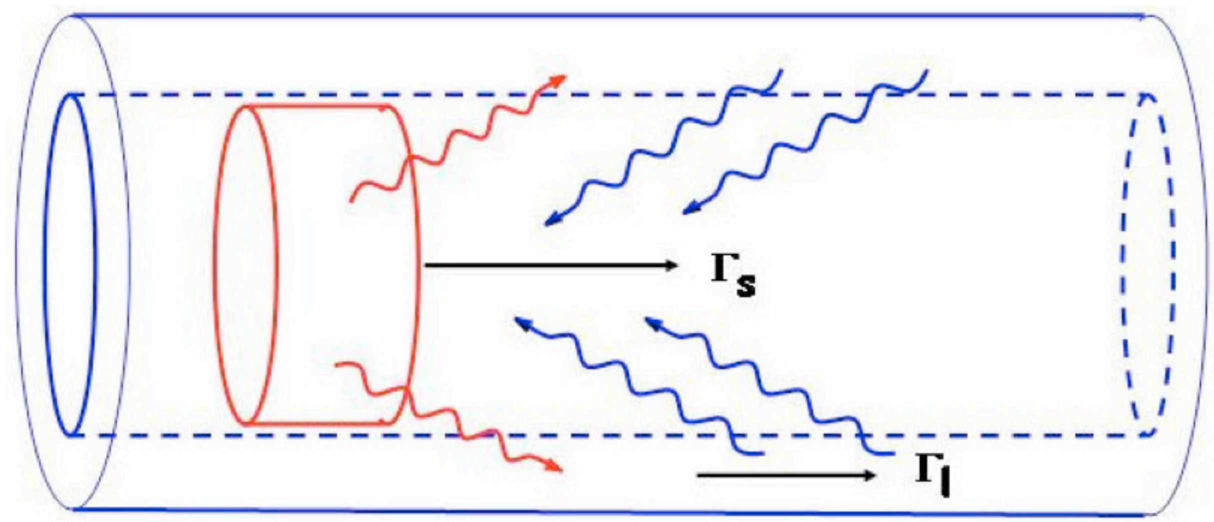
Chiaberge et al. 2000
Meyer et al.
Sbarrato et al. 2014



An improved model

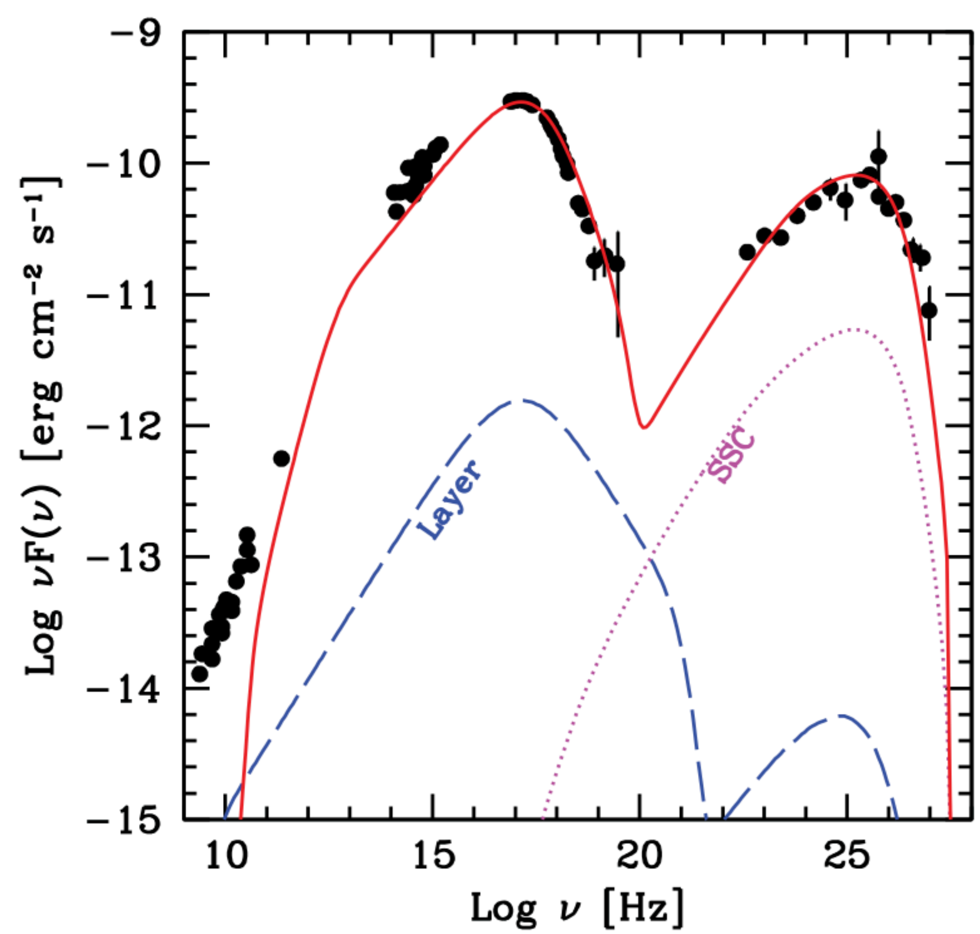
$$\Gamma_{\rm rel} = \Gamma_{\rm s}\Gamma_{\rm l}(1-\beta_{\rm s}\beta_{\rm l})$$

$$U' \simeq U\Gamma_{\rm rel}^2$$

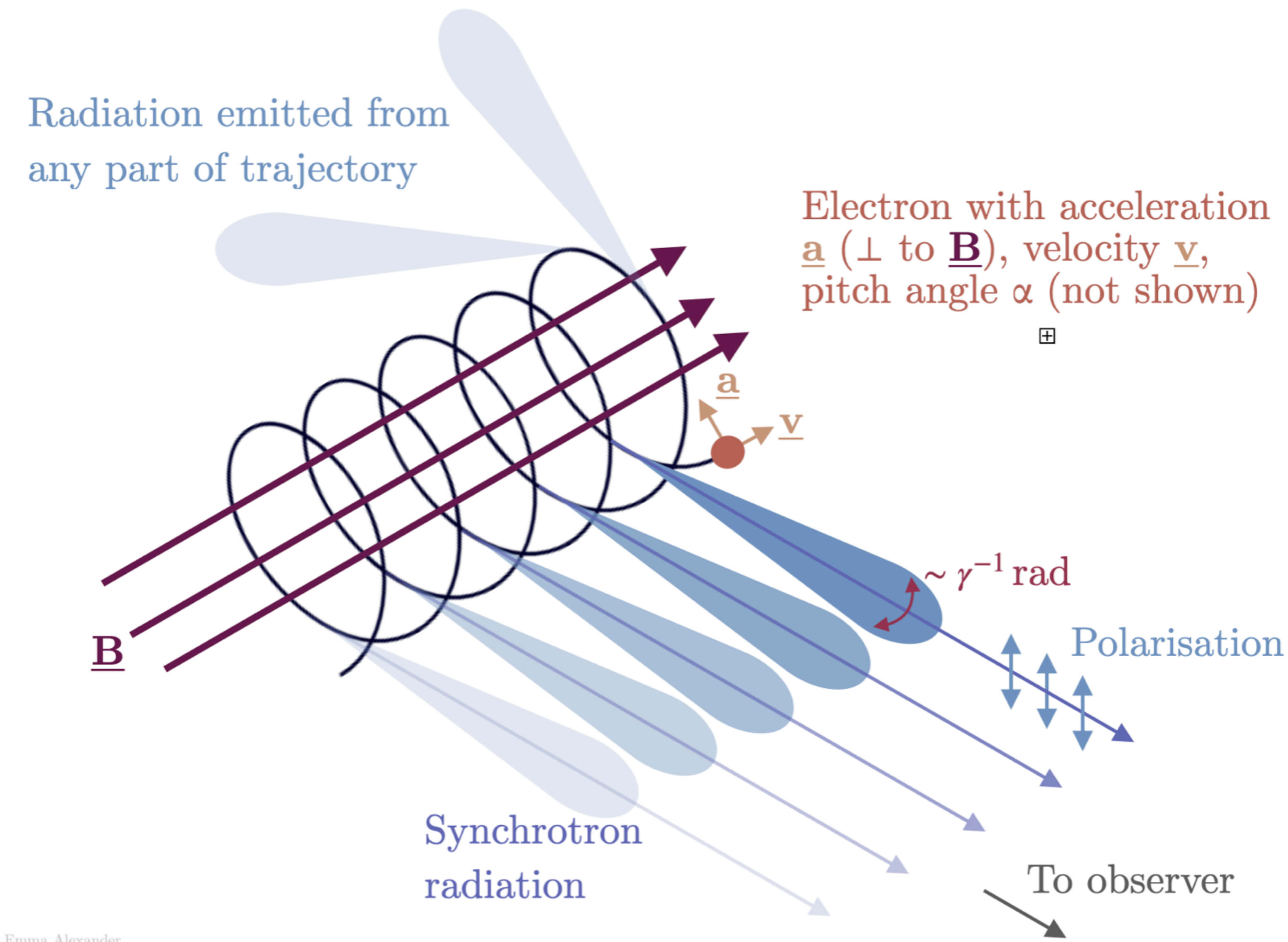


★ The spine "sees" an enhanced u_{rad} coming from the layer

➡ **Rates of processes involving soft photons are enhanced w.r.t. to the one-zone model**



Pause: synchrotron polarization

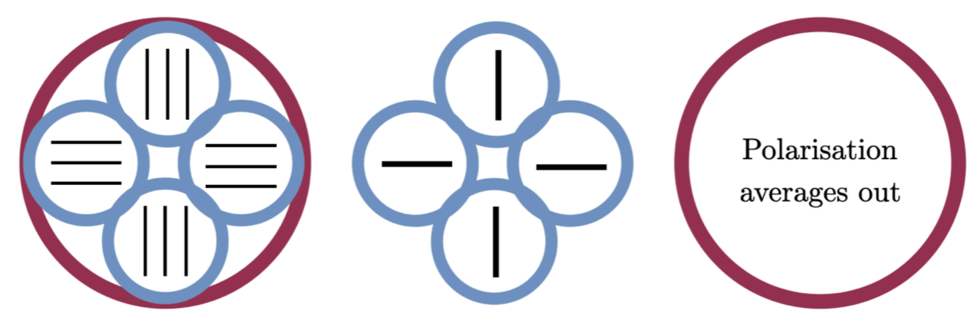


For uniform field:

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

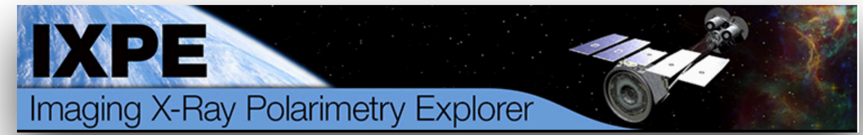
Electron slope

$$\Pi_{\rm uni} \simeq 70\,\% \text{ for } p = 2$$



Magnetic domains with different orientation (e.g. turbulence) determine a lower Π

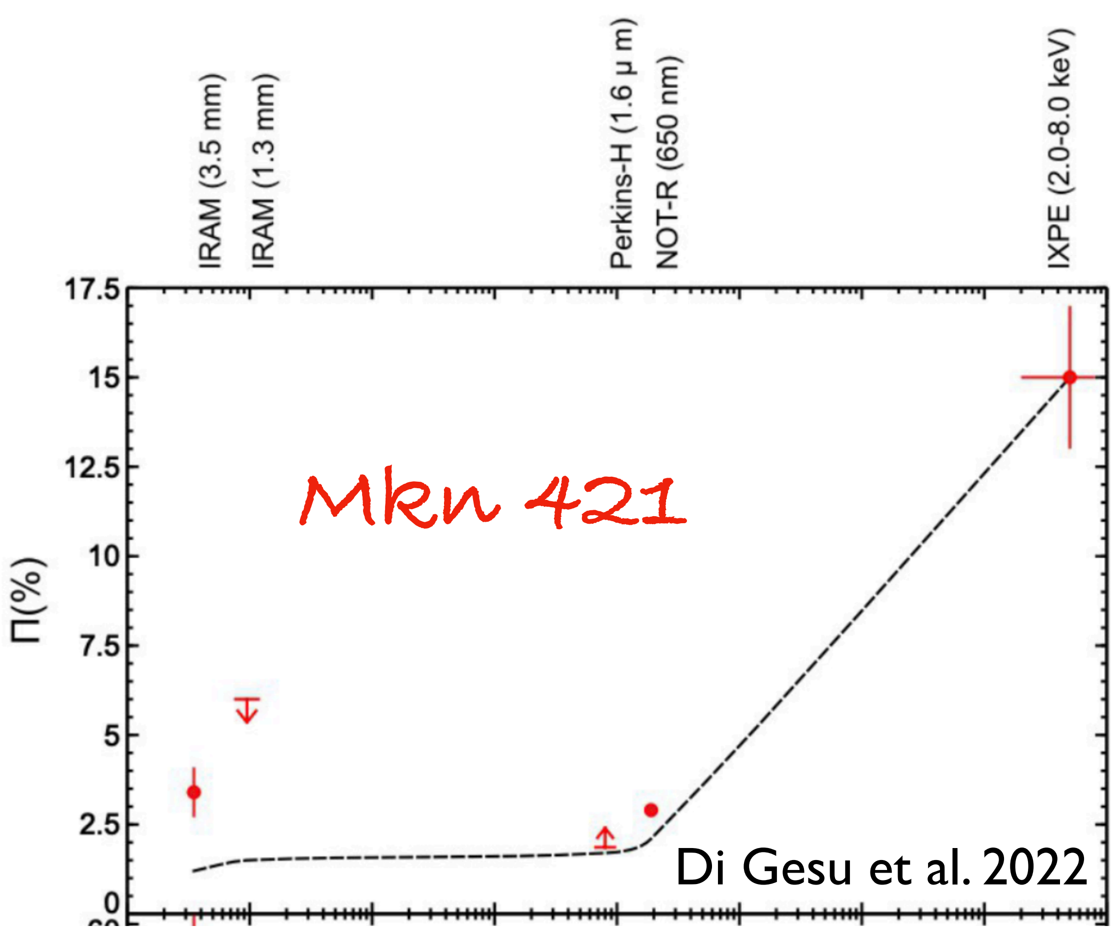
Some new clues from polarimetry

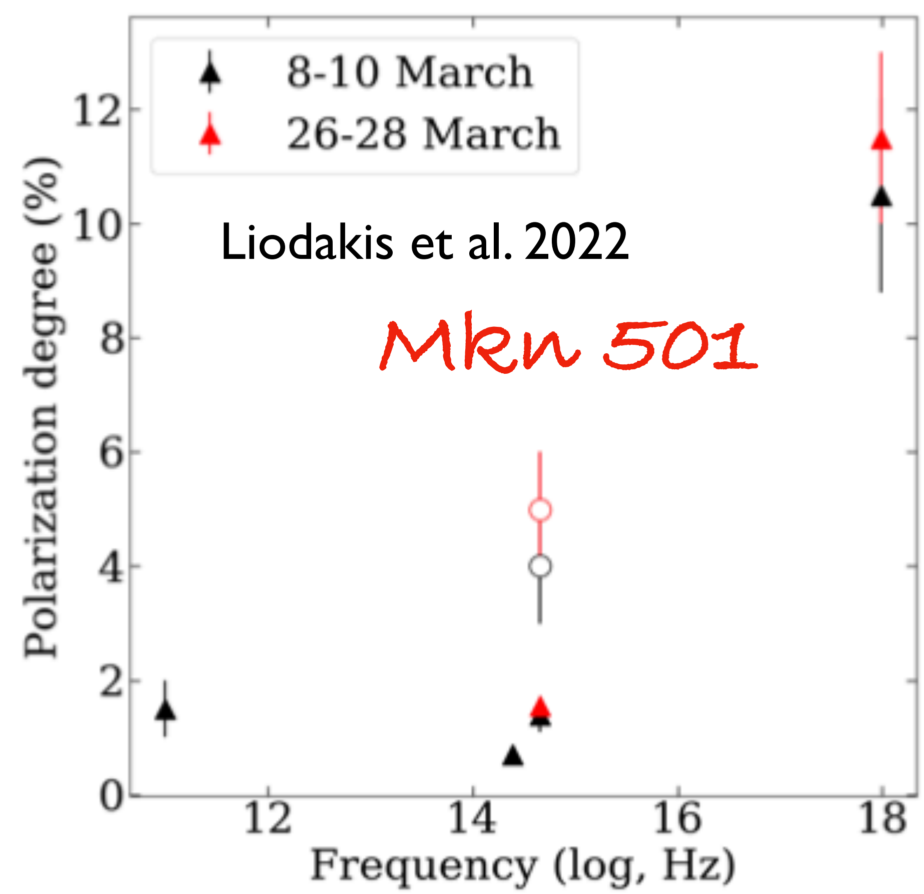


IXPE pointed several HBL during the first two years, usually in low/quiescent flux states, with consistent results.

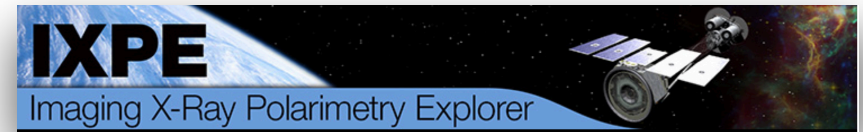
Strong "chromaticity" of Π

$$\Pi_X > \Pi_O$$



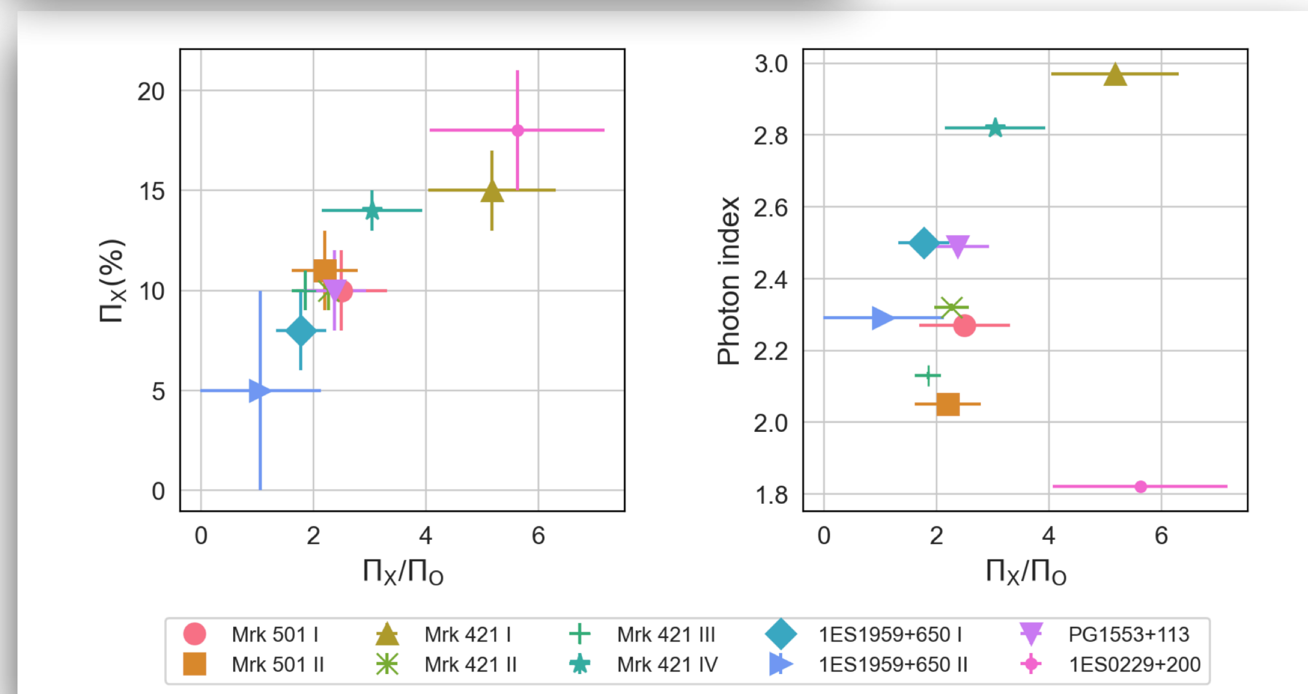


Hints from IXPE

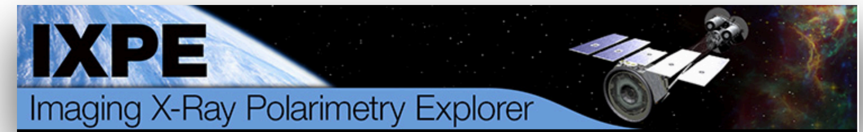


Kim et al. 2024

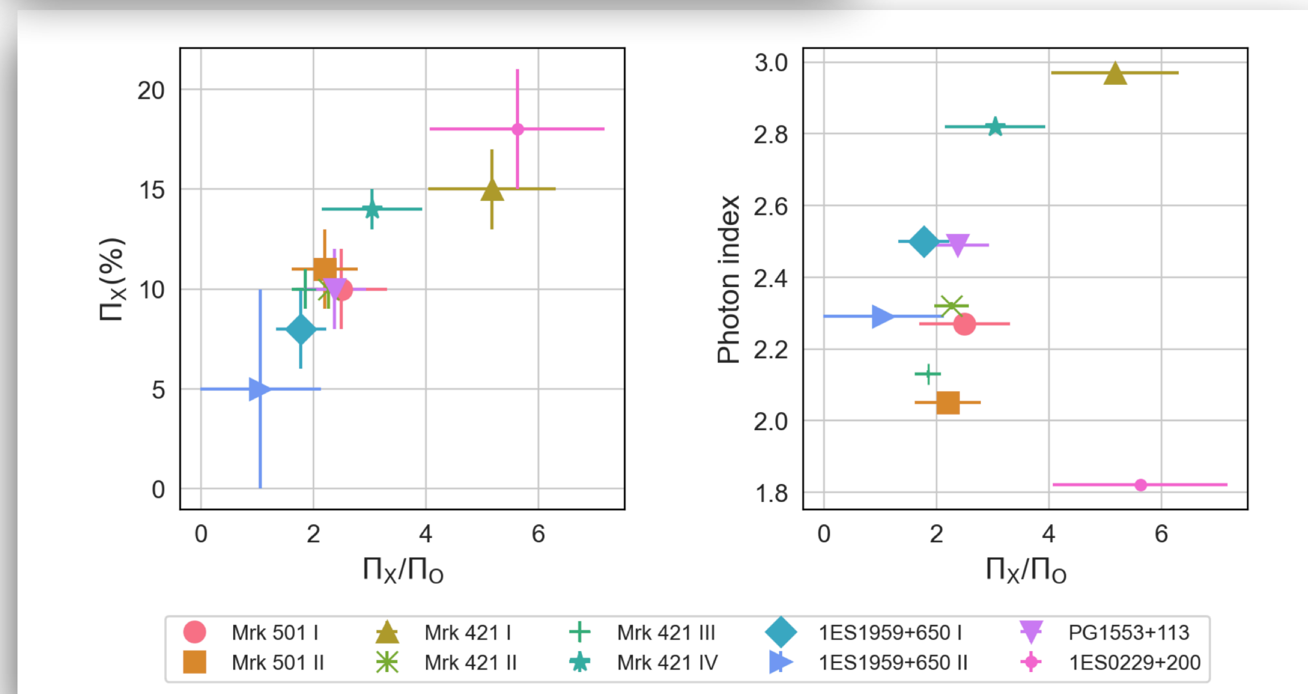
HSP in low/quiescent flux states



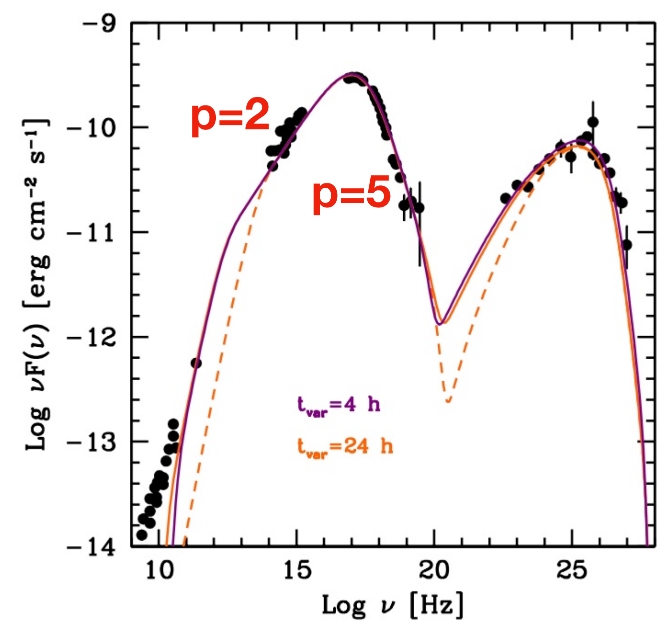
Hints from IXPE



Kim et al. 2024



HSP in low/quiescent flux states



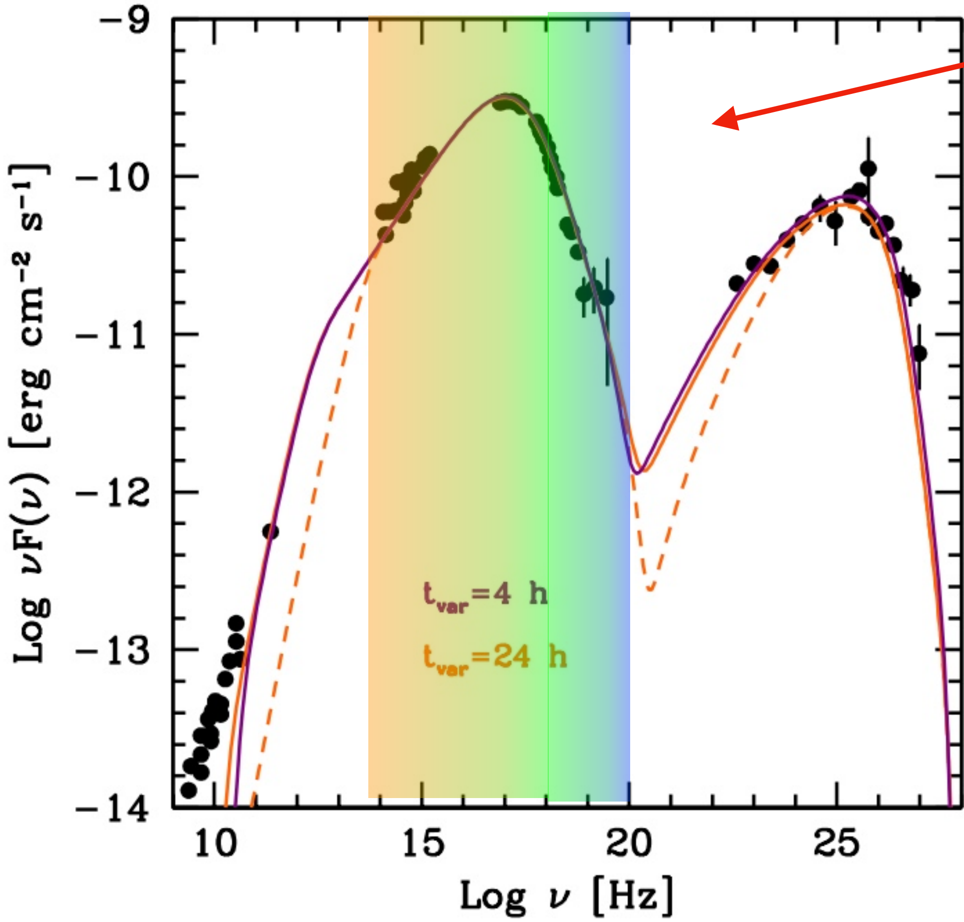
Π less than for uniform field → **Turbulent component** / Globally structured field

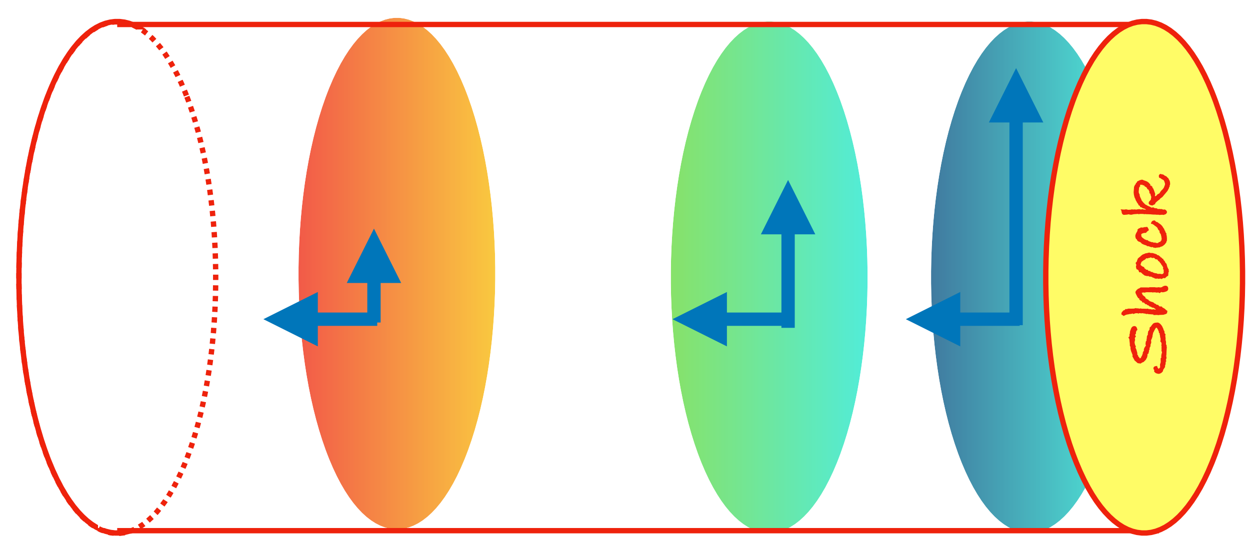
$\Pi_{\rm uni} \simeq 70\,\%$ for $p = 2$

Π_x/Π_o larger than for uniform field → **Non cospatial** / Globally structured field

Stratified shock: a toy model

$$\nu_s \propto \gamma^2 B$$



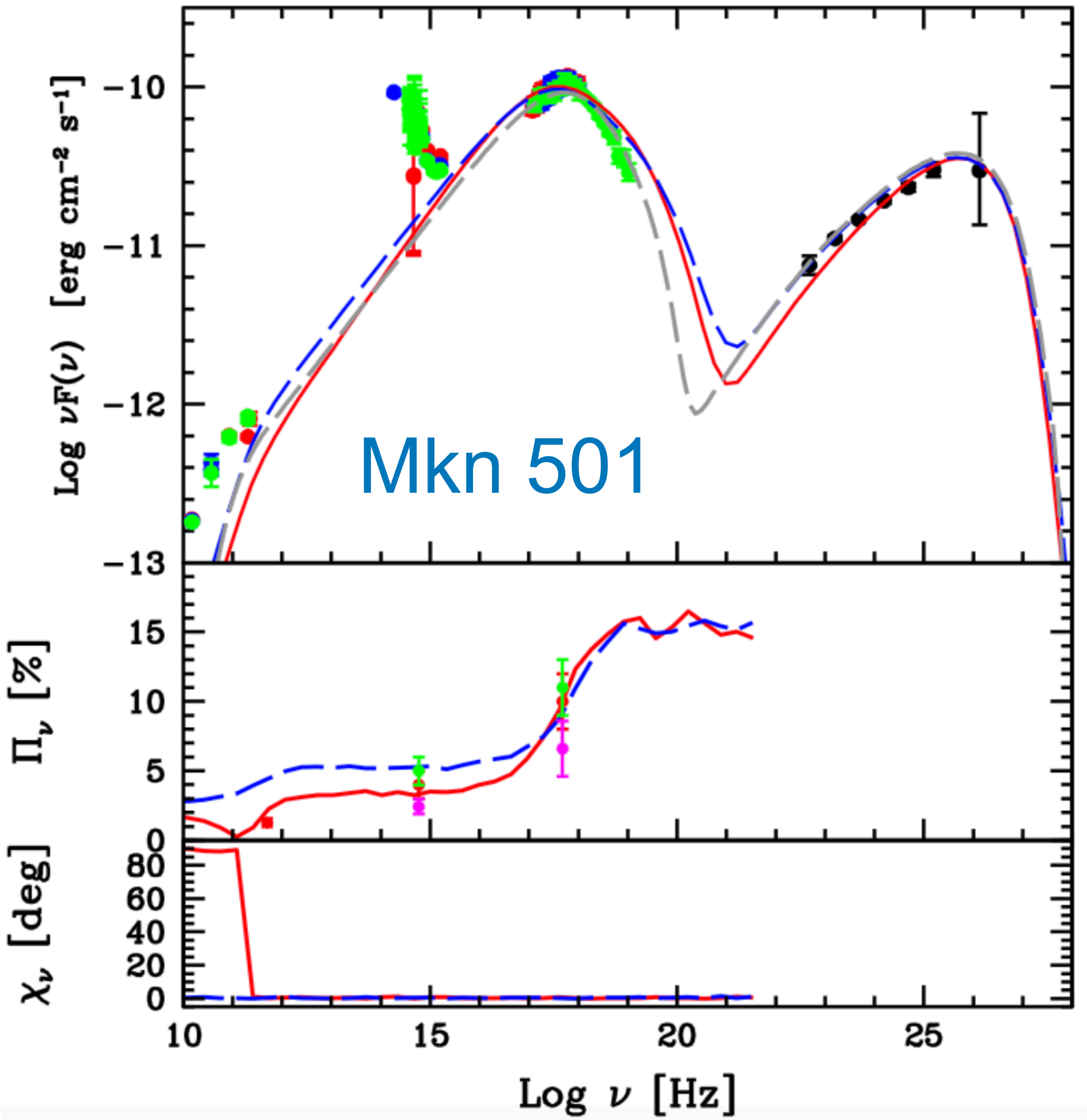


$$v_{\rm adv} t_{\rm cool} \propto \gamma^{-1}$$

Electrons do not occupy the same volume $\neq$ One-zone

Tavecchio et al. 2018, 2020

Stratified shock: a toy model



Lisalda et al., 2025

Just two possible realizations!
A full exploration of the parameter space is required (MCMC)

$$B_{\perp}(d) = B_{\perp,0}\left[1+\frac{d}{\lambda}\right]^{-m}$$

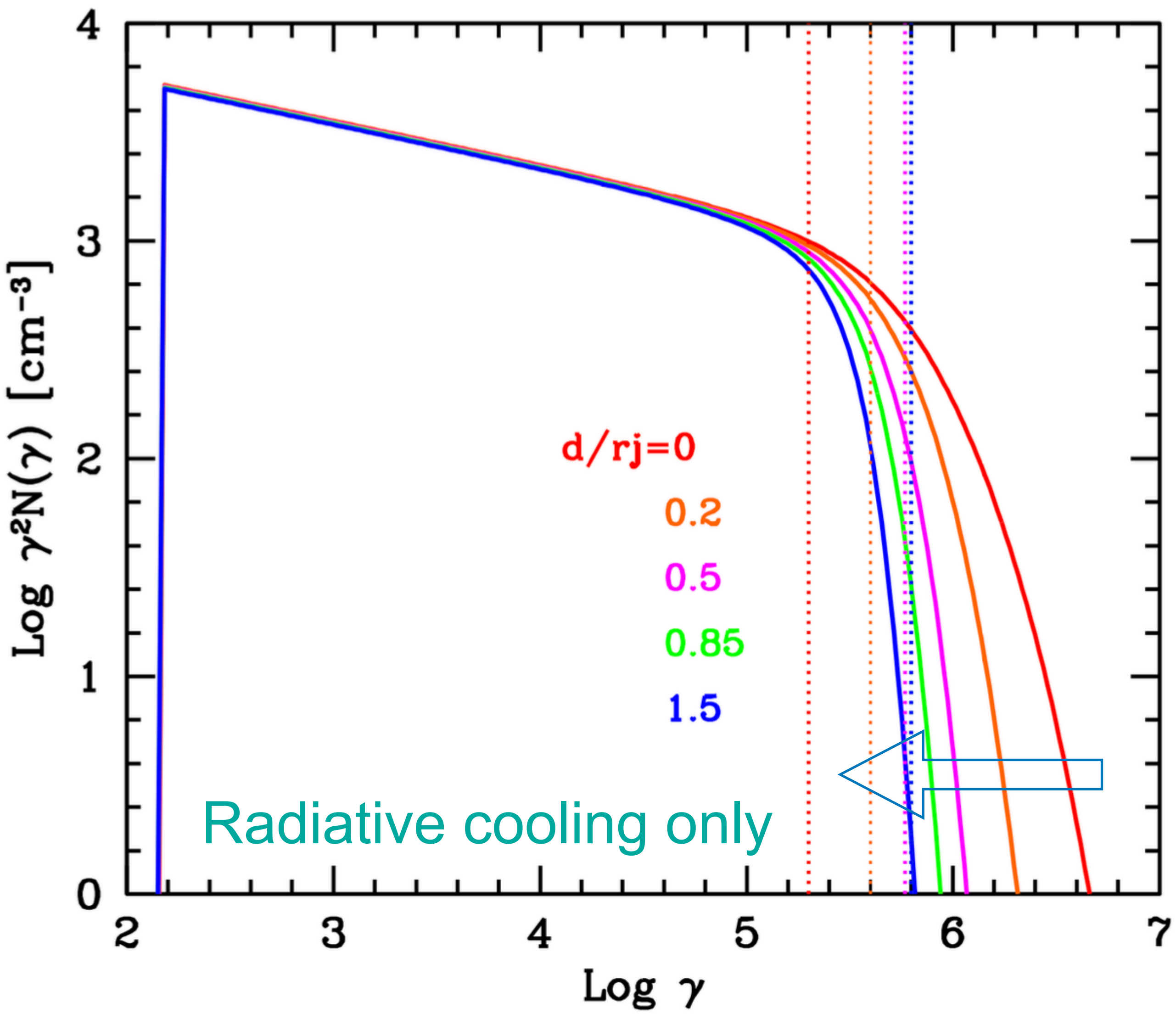
Phenomenological law for the field
e.g. Lemoine 2013

$\Gamma = 22,\ \theta_v = 1.3^{\circ}$

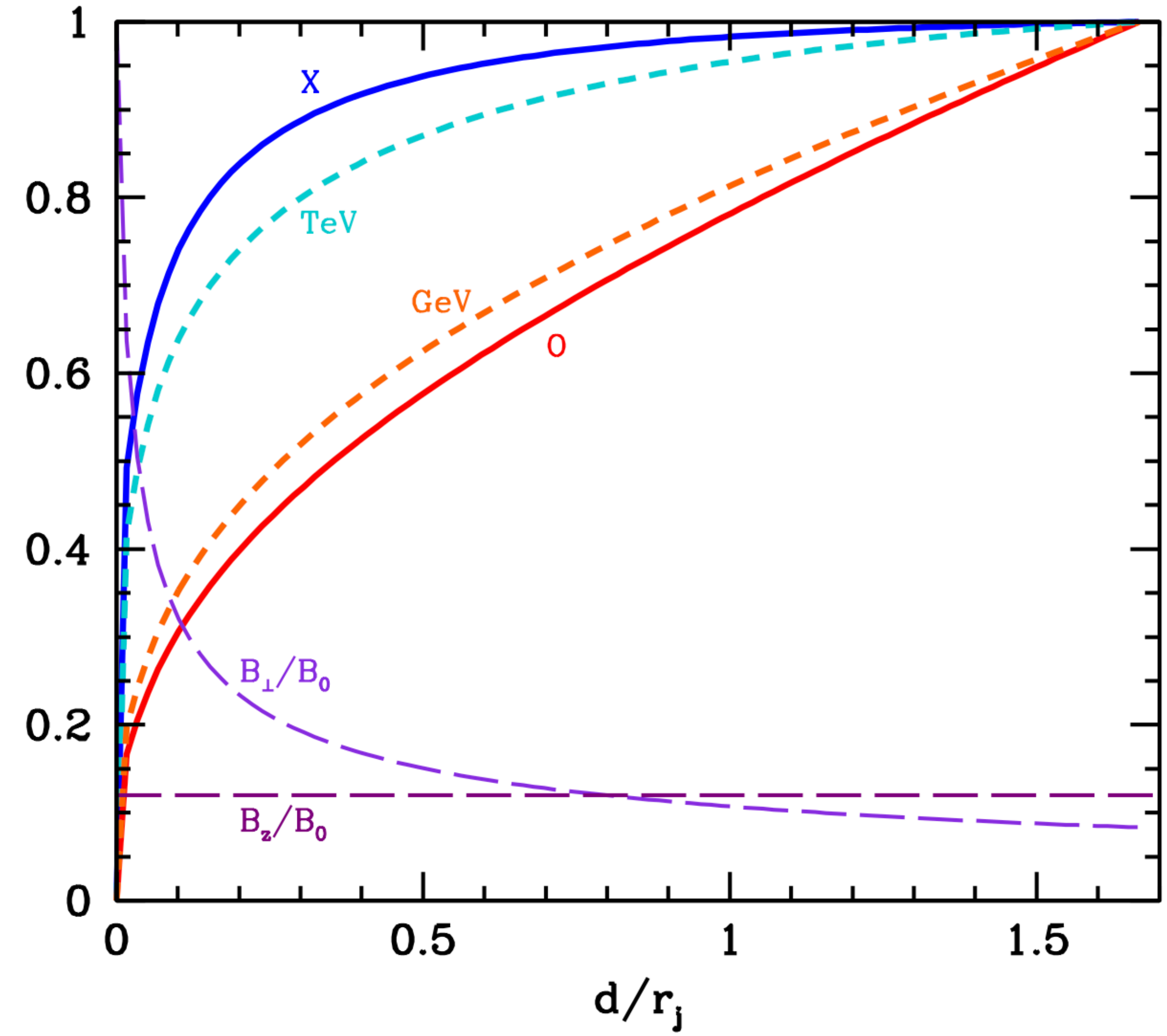
Model	$\gamma_{\rm cut}$ ($\times 10^5$) [1]	n [2]	$n_{e,0}$ [3]	$B_{\perp,0}$ [4]	B_z [5]	$r_{\rm j}$ ($\times 10^{15}$) [6]	λ [7]	m [8]
1	8.5	2.1	20	0.25	0.03	4.3	5×10^{13}	0.5
2	12.6	2.2	30	0.25	0.03	4.8	1.2×10^{12}	0.25

Stratified shock: a toy model

Electron distribution
at different distances

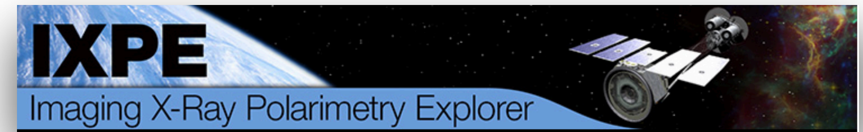


Emission profiles



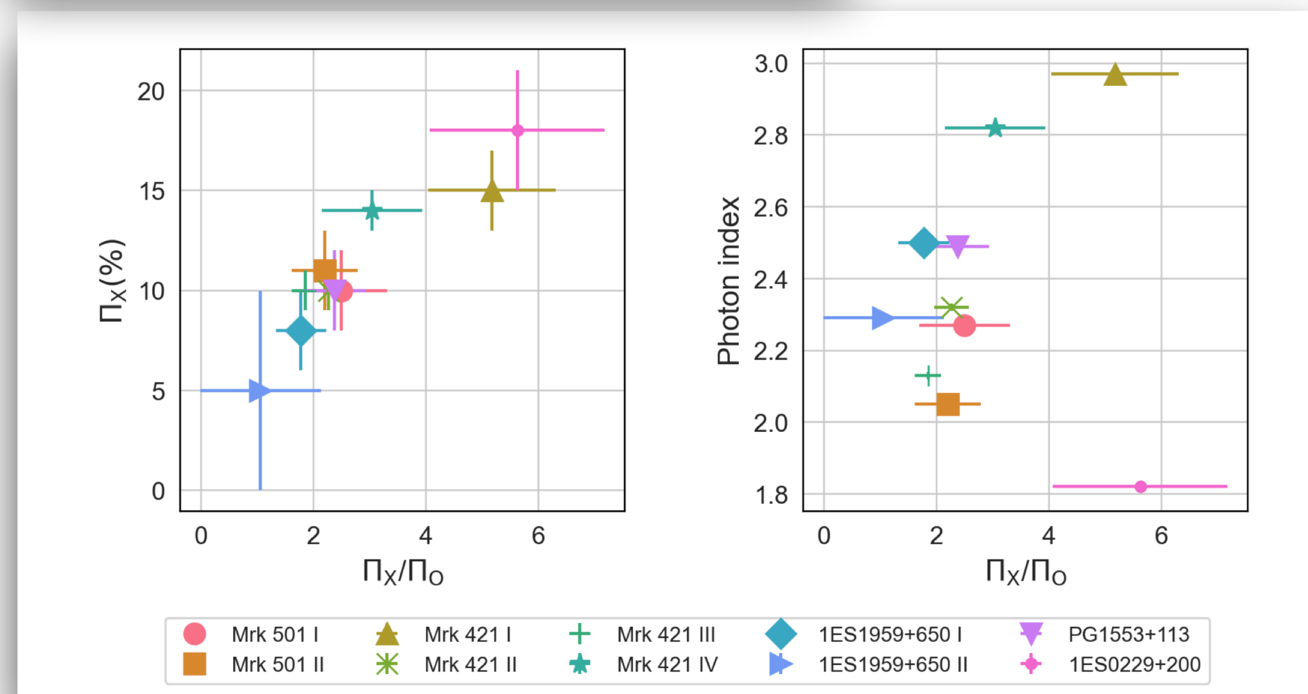
Effective "two zone" model

Hints from IXPE



Kim et al. 2024

HSP in low/quiescent flux states

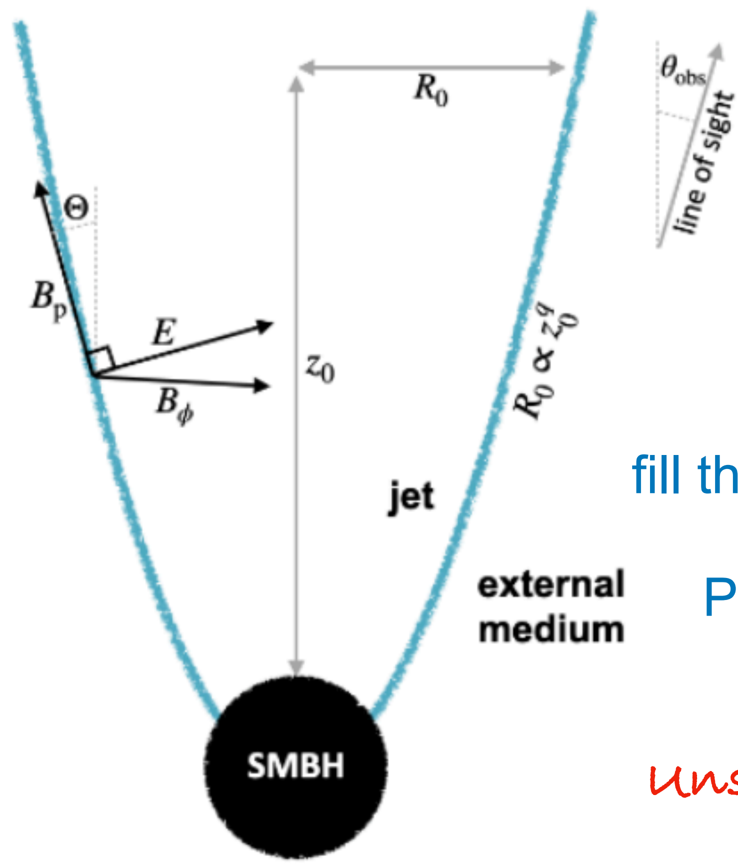


Π less than for uniform field → Turbulent component / Globally structured field

Π_x/Π_o larger than for uniform field → Non cospatial / Globally structured field

Shocks & energy stratification? Not necessarily!

Bolis et al., 2024



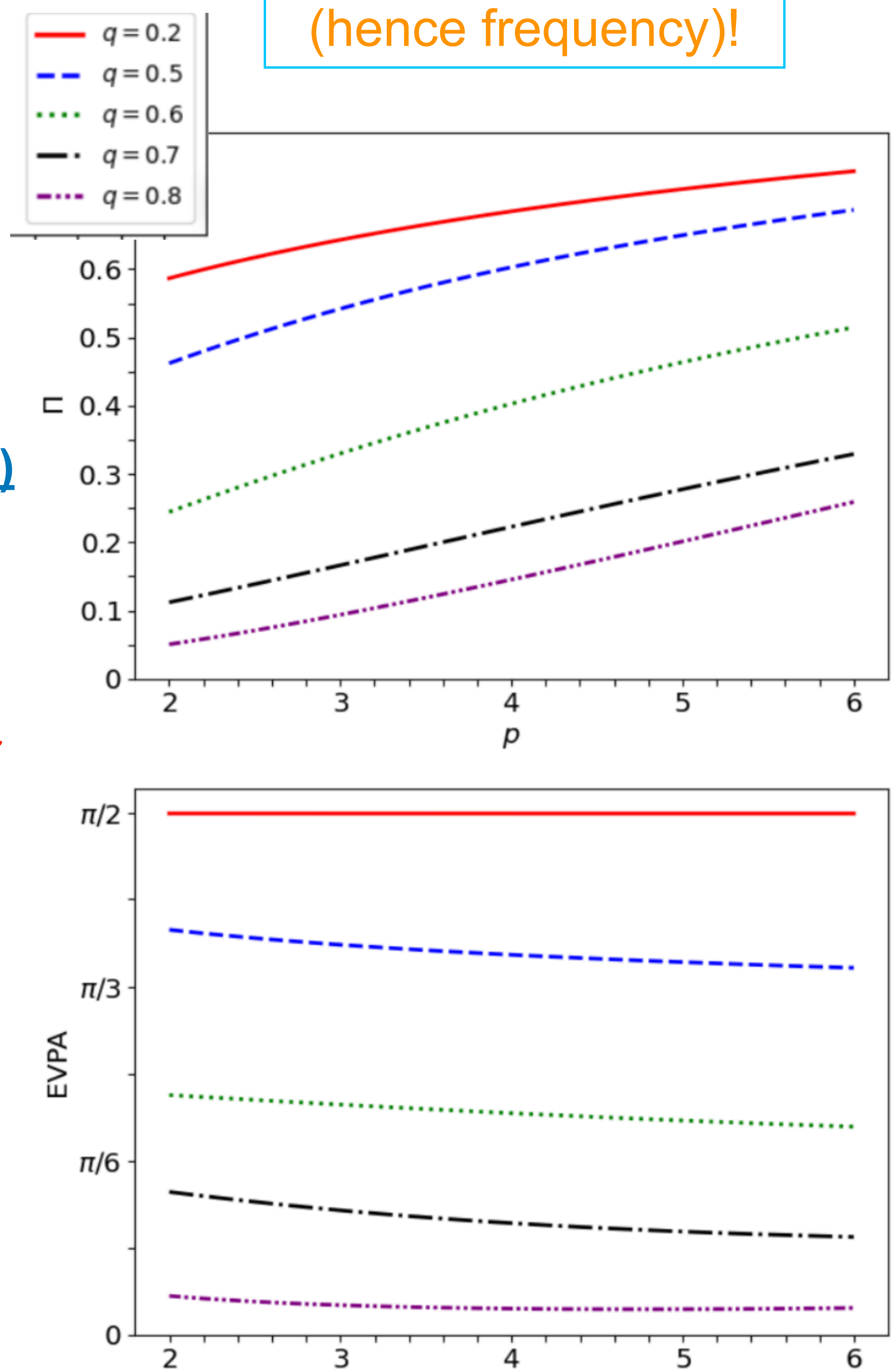
MHD solutions of confined, magnetically dominated jets (Lyubarsky 2009)

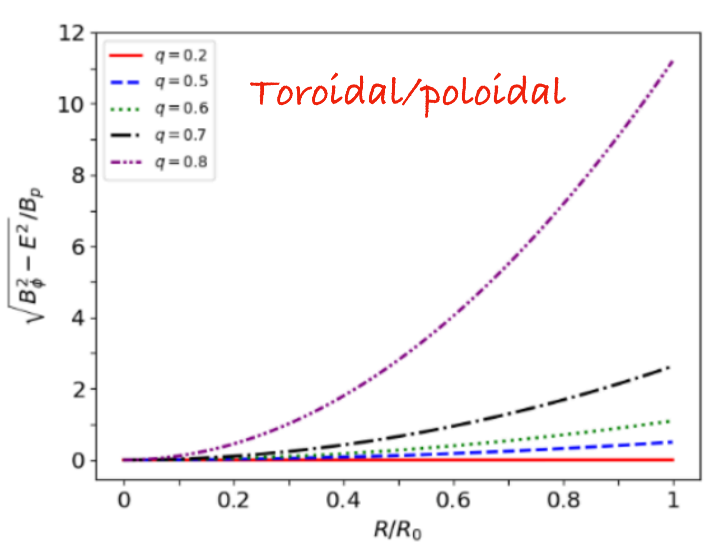
Electrons with different energy fill the **same volume (no stratification!)**

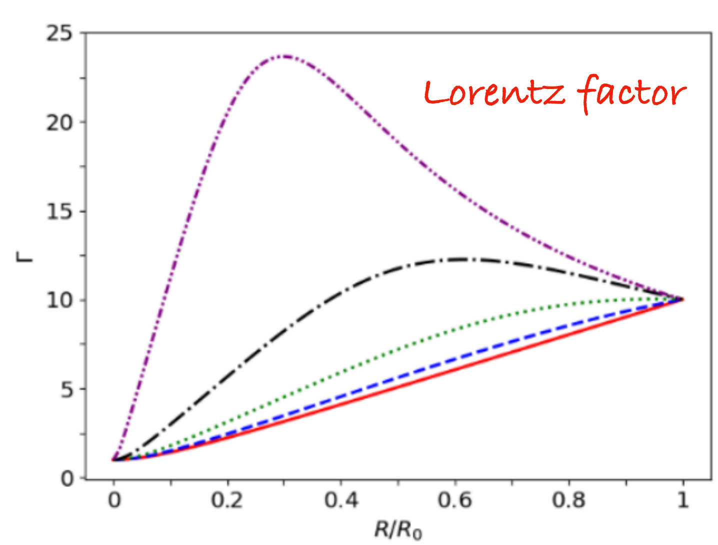
Polarization depends on the global (ordered) B-field structure

Unspecified acceleration mechanism

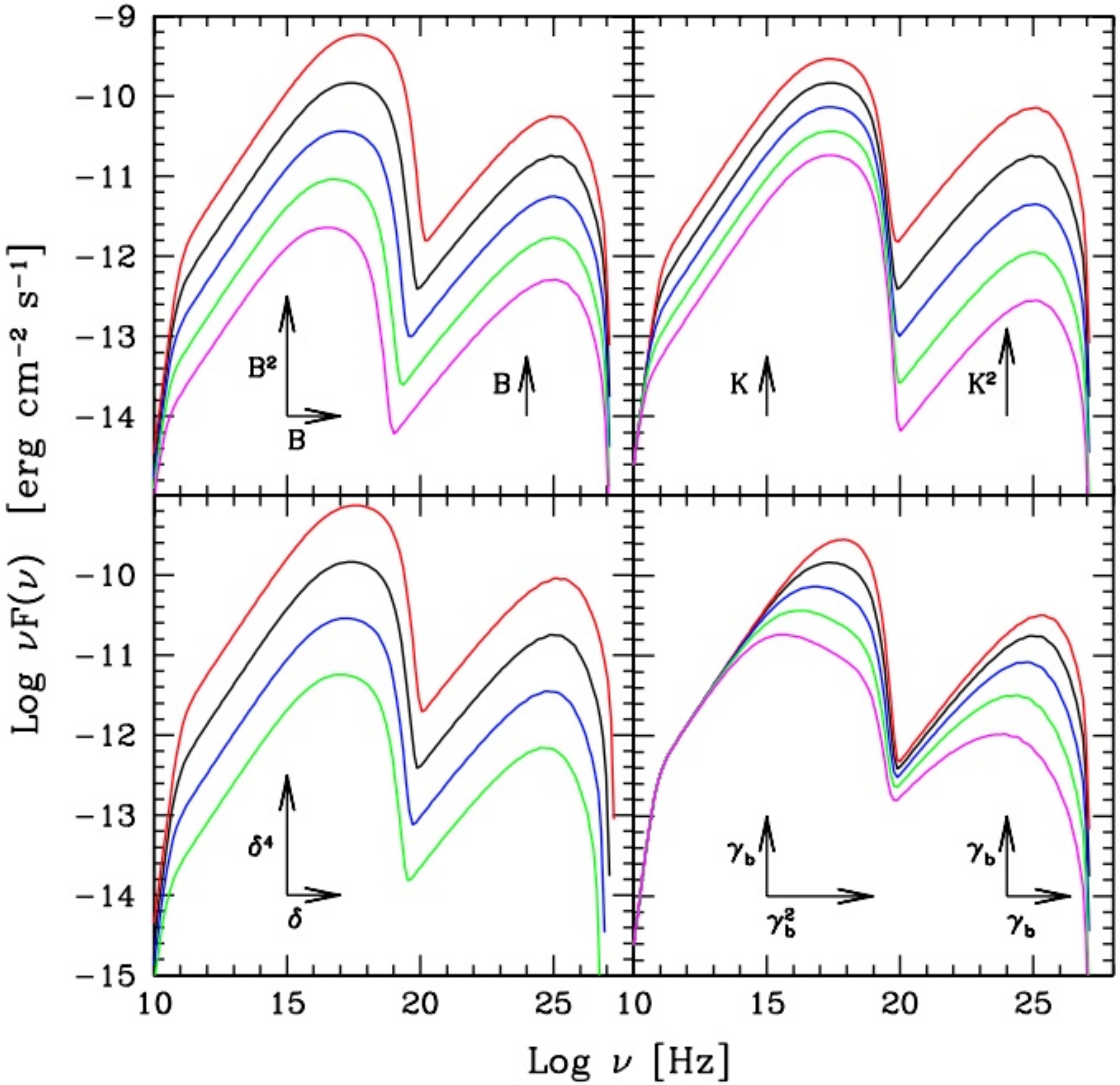
Strong dependence on the electron slope (hence frequency)!







Time dependent models



Time dependent models

Continuity equation

escape

$$\frac{\partial N(\gamma,t)}{\partial t} = \frac{\partial}{\partial \gamma}\left[\dot{\gamma}(\gamma,t)N(\gamma,t)\right] + Q(\gamma,t) - \frac{N(\gamma,t)}{t_{\rm esc}}$$

cooling

injection

$$\dot{\gamma} = \frac{4}{3}\frac{\sigma_{\rm T} c}{m_{\rm e} c^2}\left[U_B + U_{\rm rad}(\gamma,t)\right]\gamma^2$$

Time dependent models

Continuity equation

escape

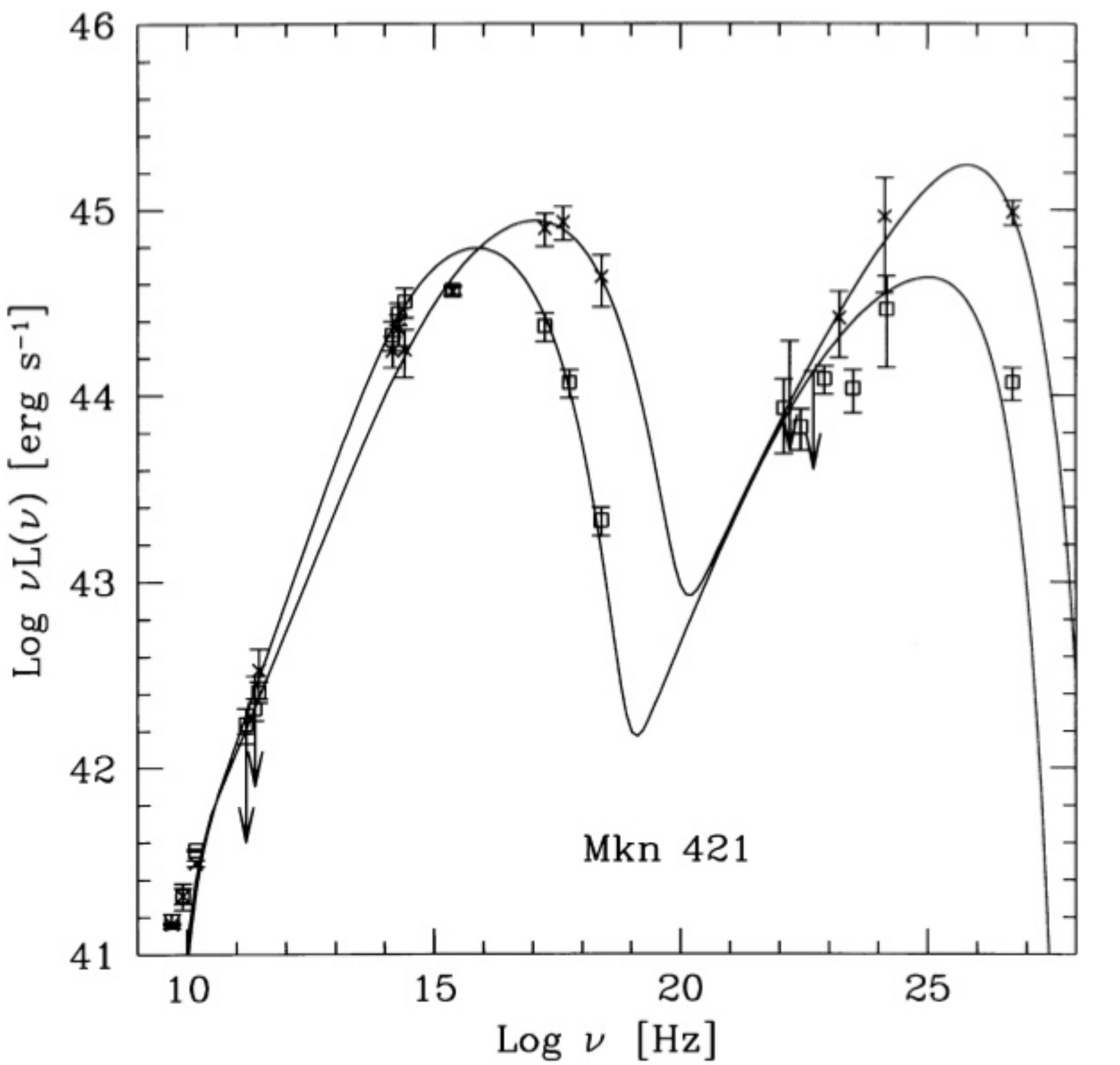
$$\frac{\partial N(\gamma,t)}{\partial t} = \frac{\partial}{\partial \gamma}\left[\dot{\gamma}(\gamma,t)N(\gamma,t)\right] + Q(\gamma,t) - \frac{N(\gamma,t)}{t_{\rm esc}}$$

cooling

injection

$$\dot{\gamma} = \frac{4}{3}\frac{\sigma_{\rm T}c}{m_{\rm e}c^2}[U_B + U_{\rm rad}(\gamma,t)]\gamma^2$$

Chiaberge and Ghisellini 1999



Final thoughts

Jets are very complex systems but …

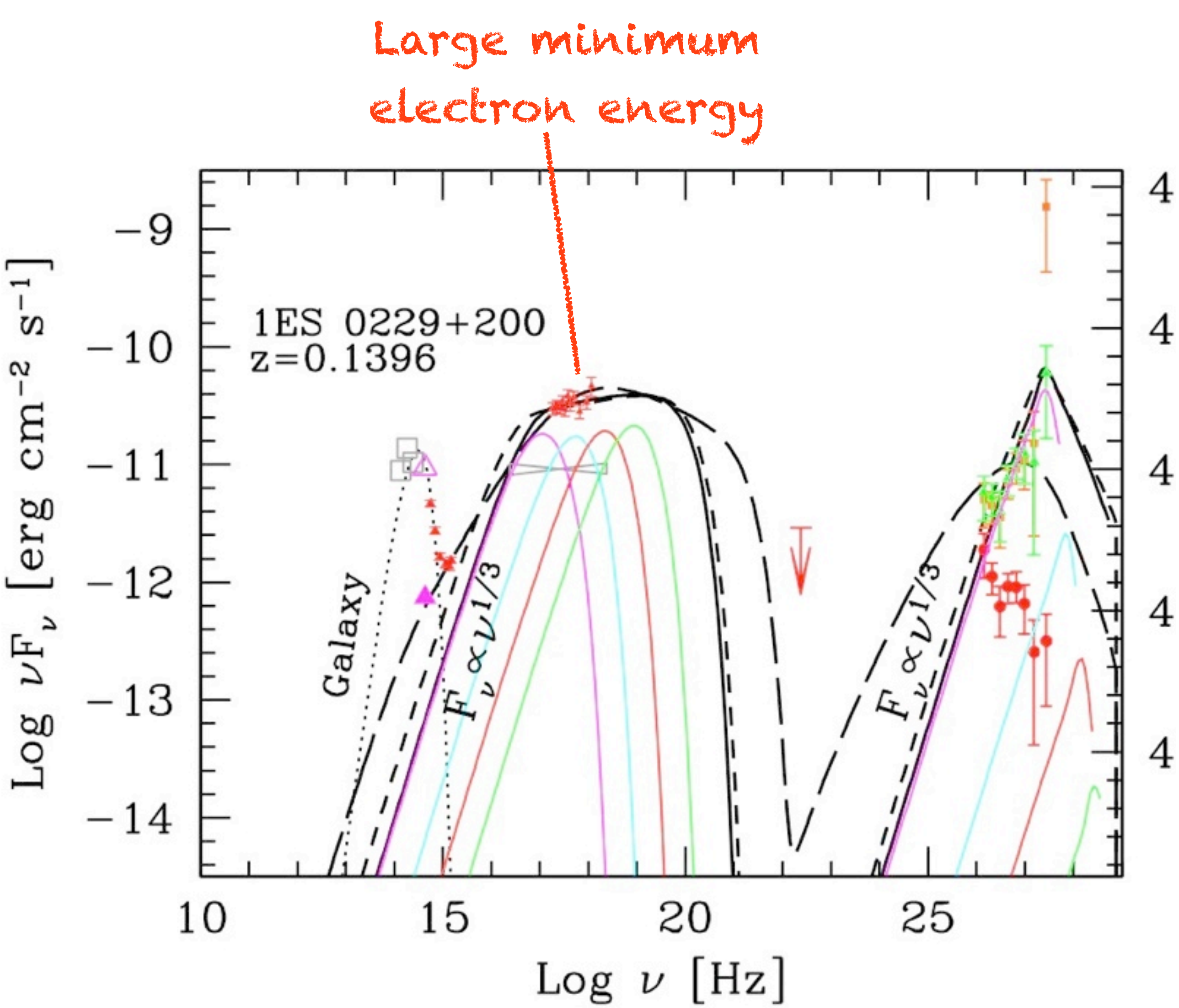
(Leptonic)One zone models are surprisingly successful!

We can infer clues one particle acceleration, evolution etc…

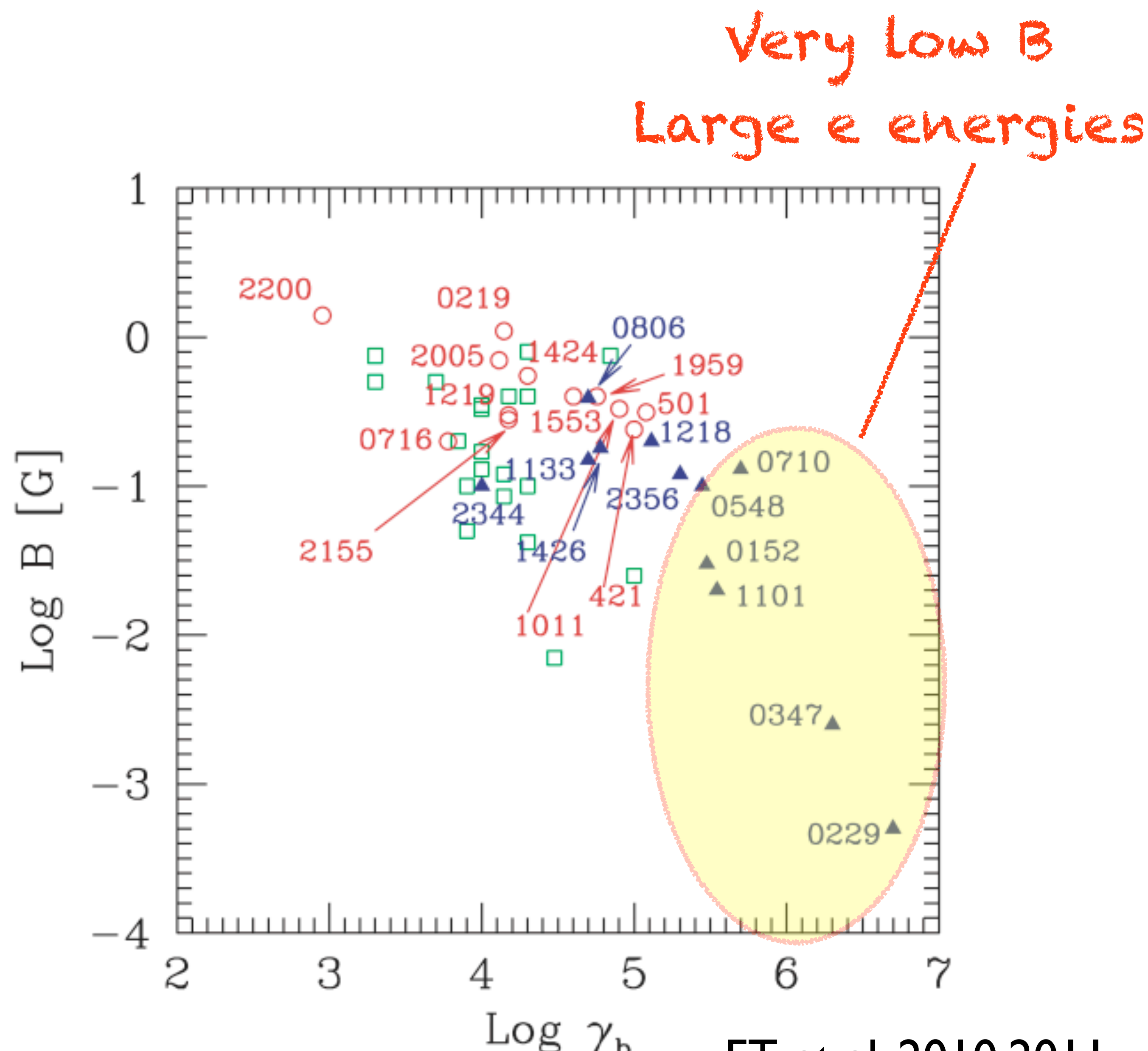
Polarimetric measurements suggest that more complexity must be added

Not clear which kind of scenario …

Extreme accelerators?



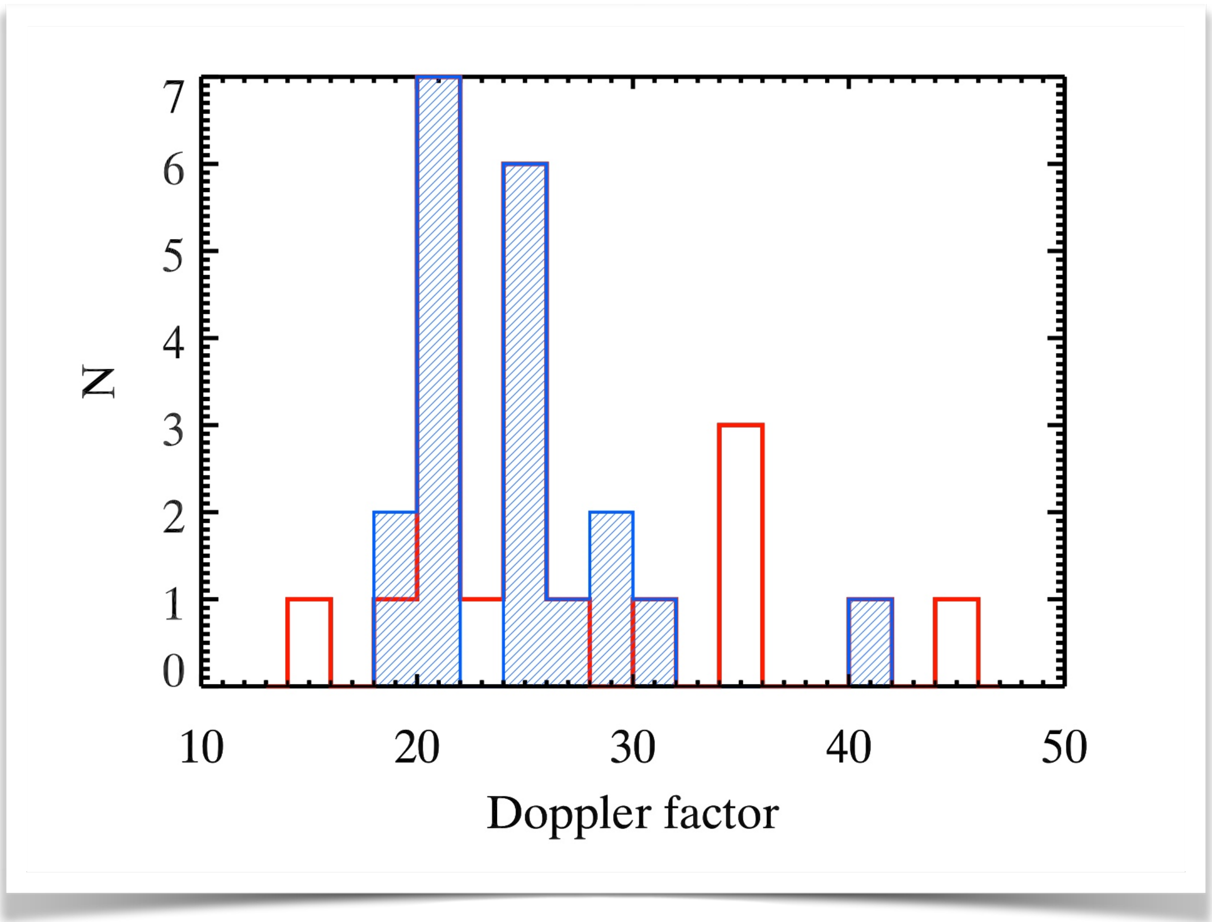
Katarzyński et al. 2005
FT et al. 2009

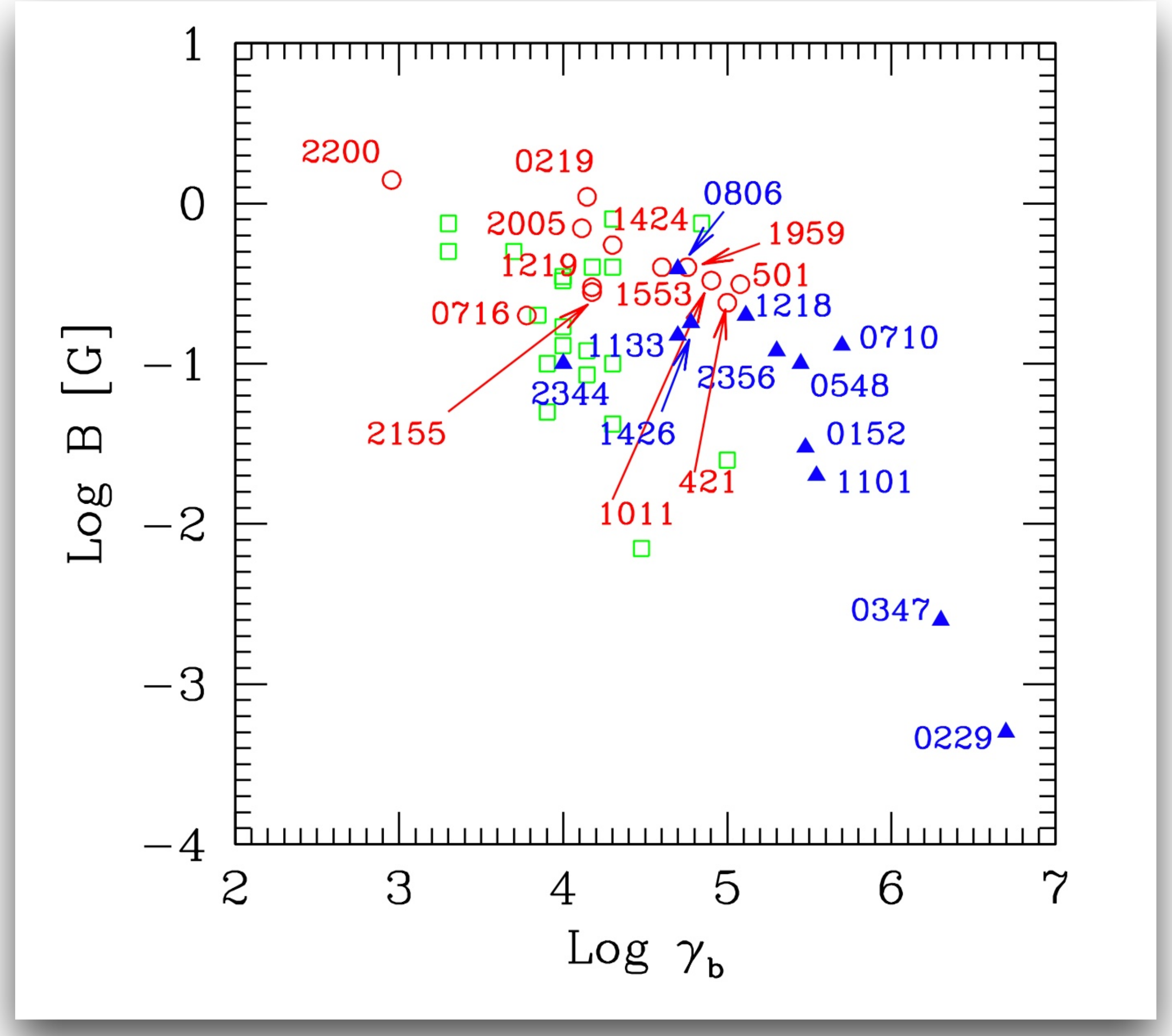


FT et al. 2010,2011

- Acceleration process?
- Why cooling so small?
- Why weakly/slowly variable?

Application: BL Lacs





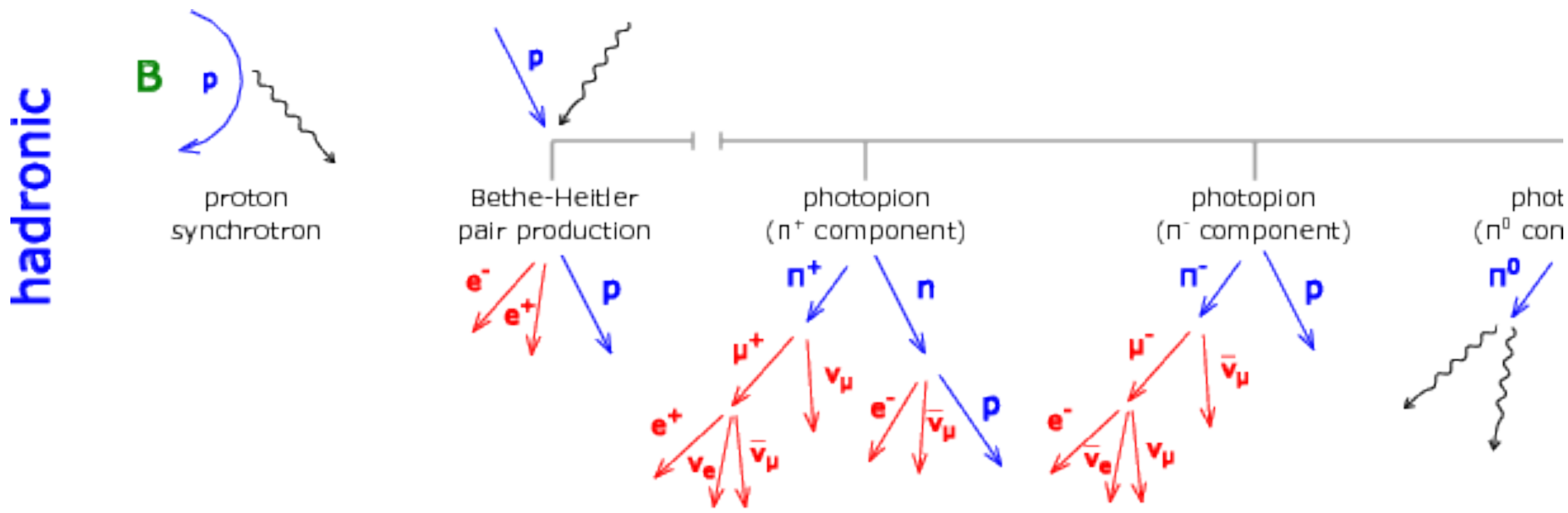
Leptons or hadrons?

UHECR
IceCube Neutrinos

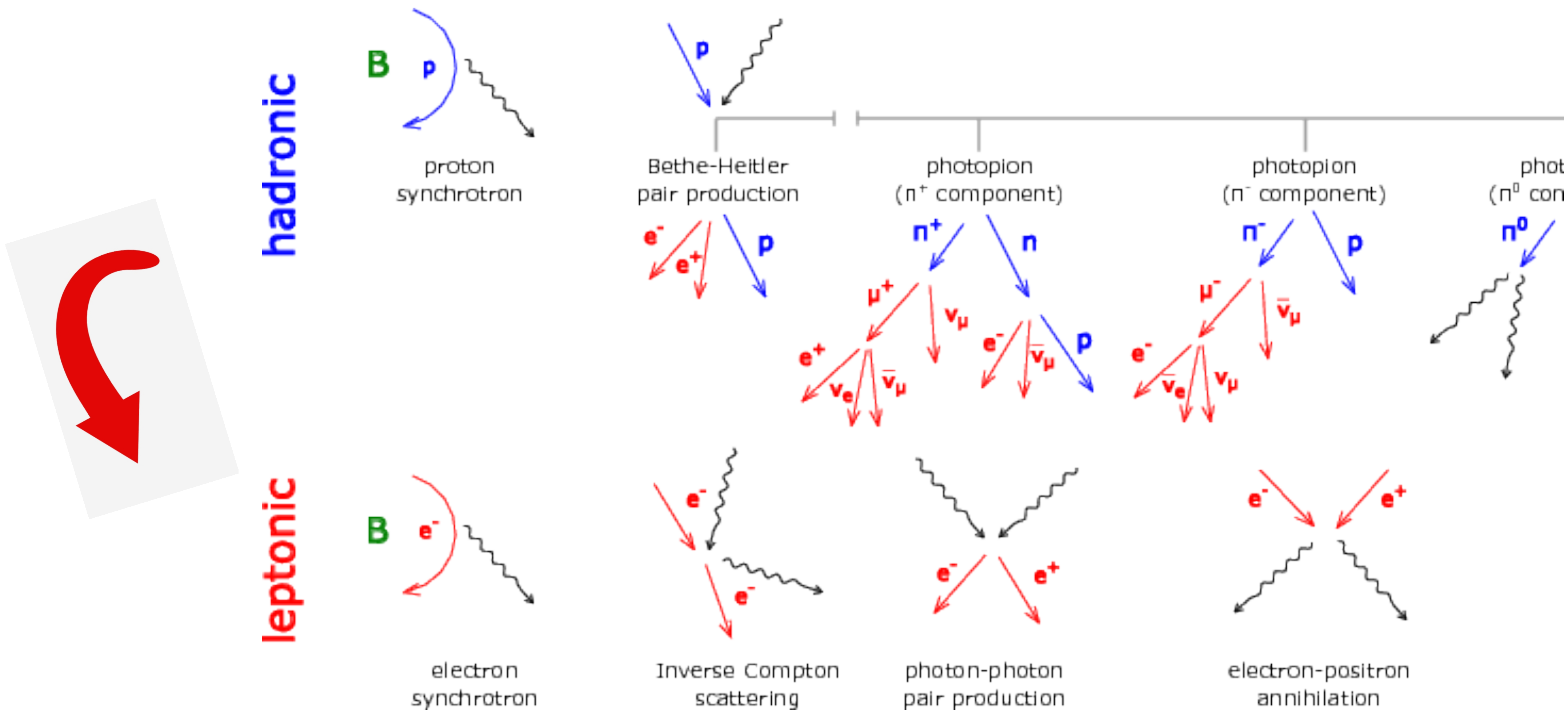
Hadrons are accelerated to very-high and ultra-high energy somewhere in the extragalactic space

Jets offer ideal conditions (B, radius,power)

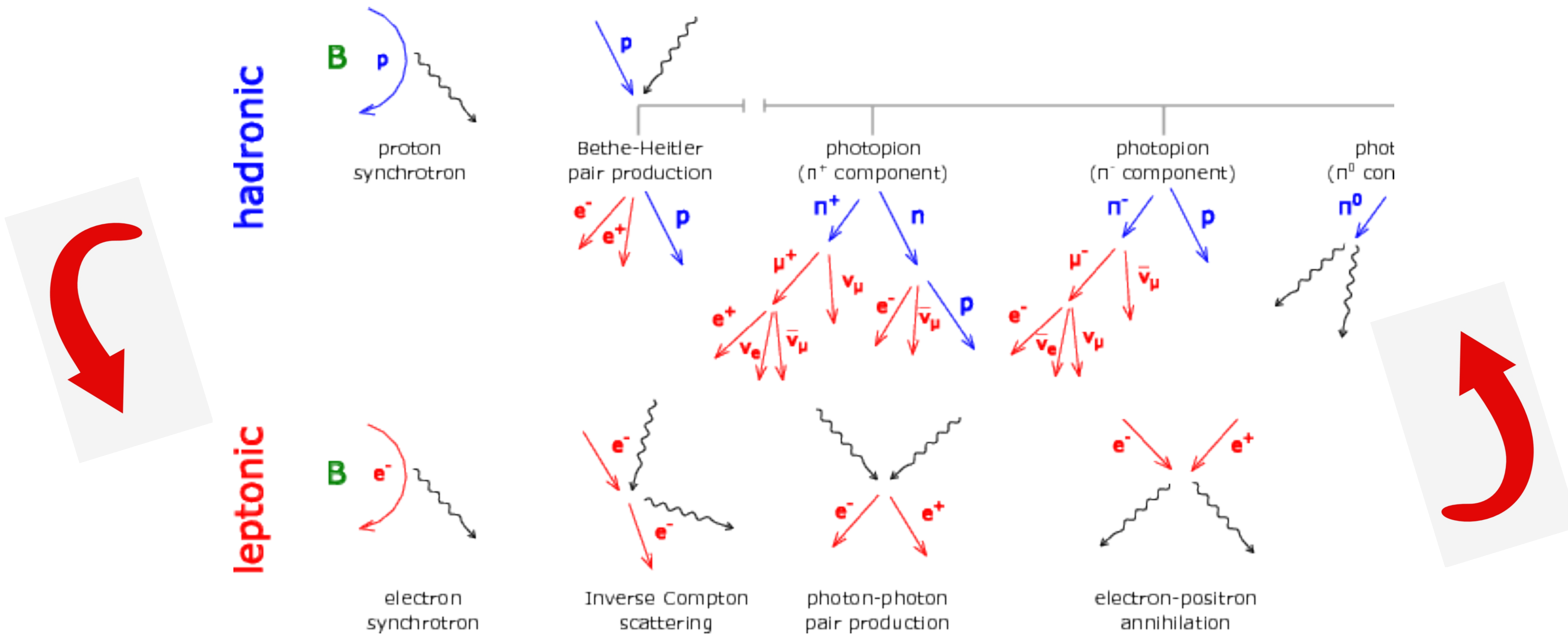
Leptons or hadrons?



Leptons or hadrons?

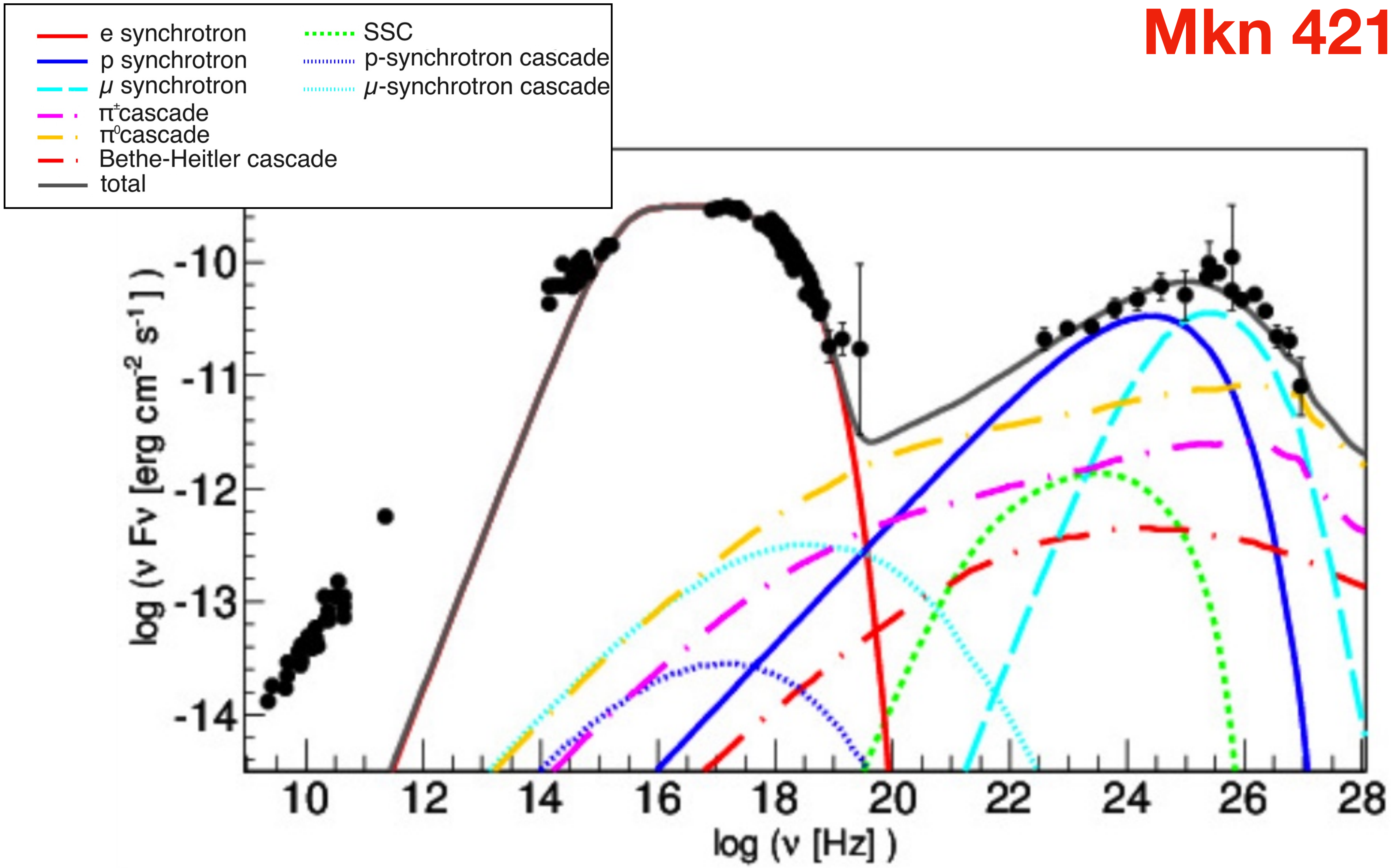


Leptons or hadrons?



Lepto-hadronic models

Mkn 421

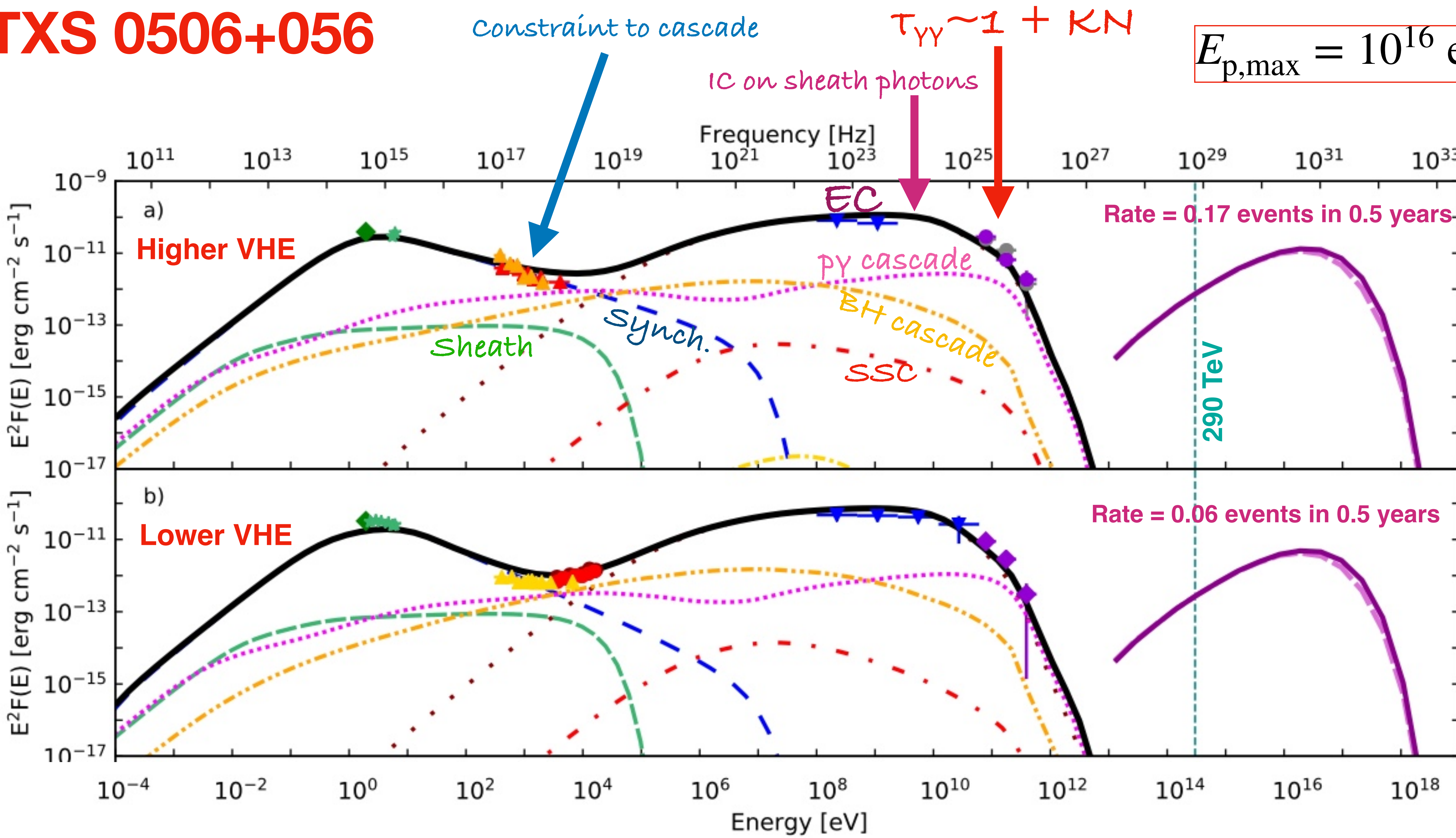


Cerruti et al. 2015

Lepto-hadronic models

TXS 0506+056

$E_{p,max} = 10^{16}$ eV

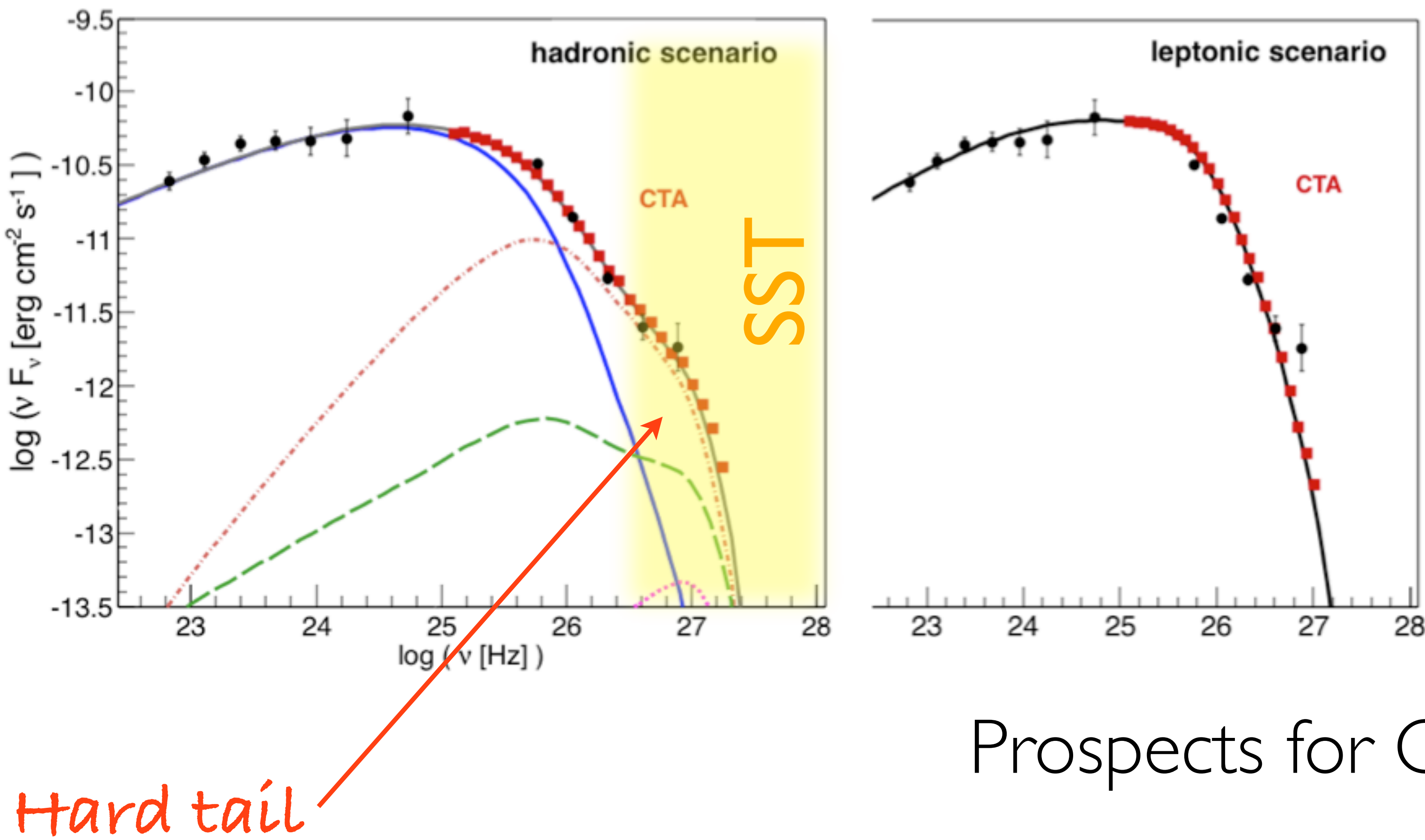


MAGIC Coll. 2018

Lepto-hadronic models

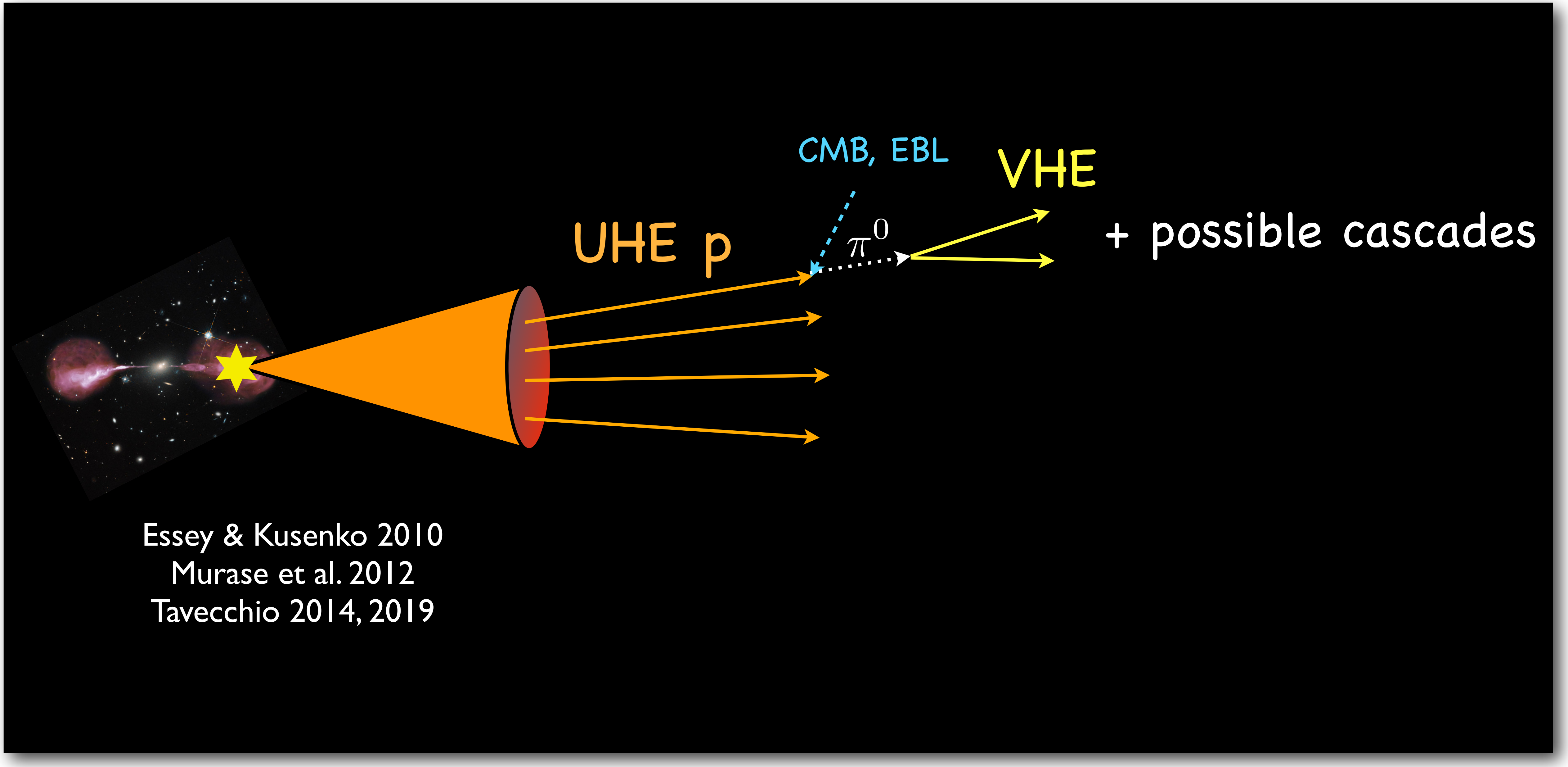
Zech et al. 2017

PKS 2155-304



Prospects for CTA

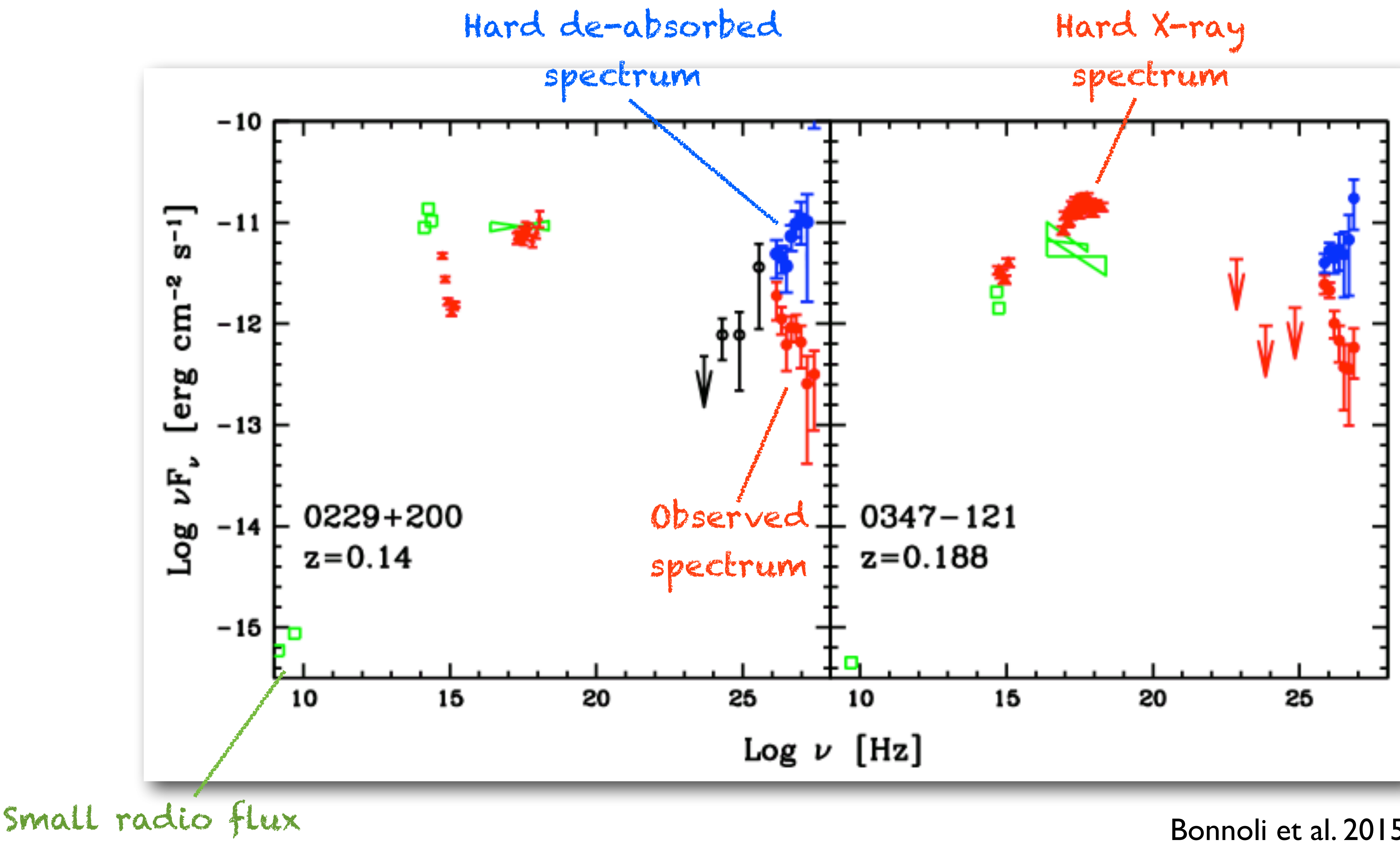
Hadron beams?



Scenario for "extreme Bl Lacs"

Extreme BL Lacs

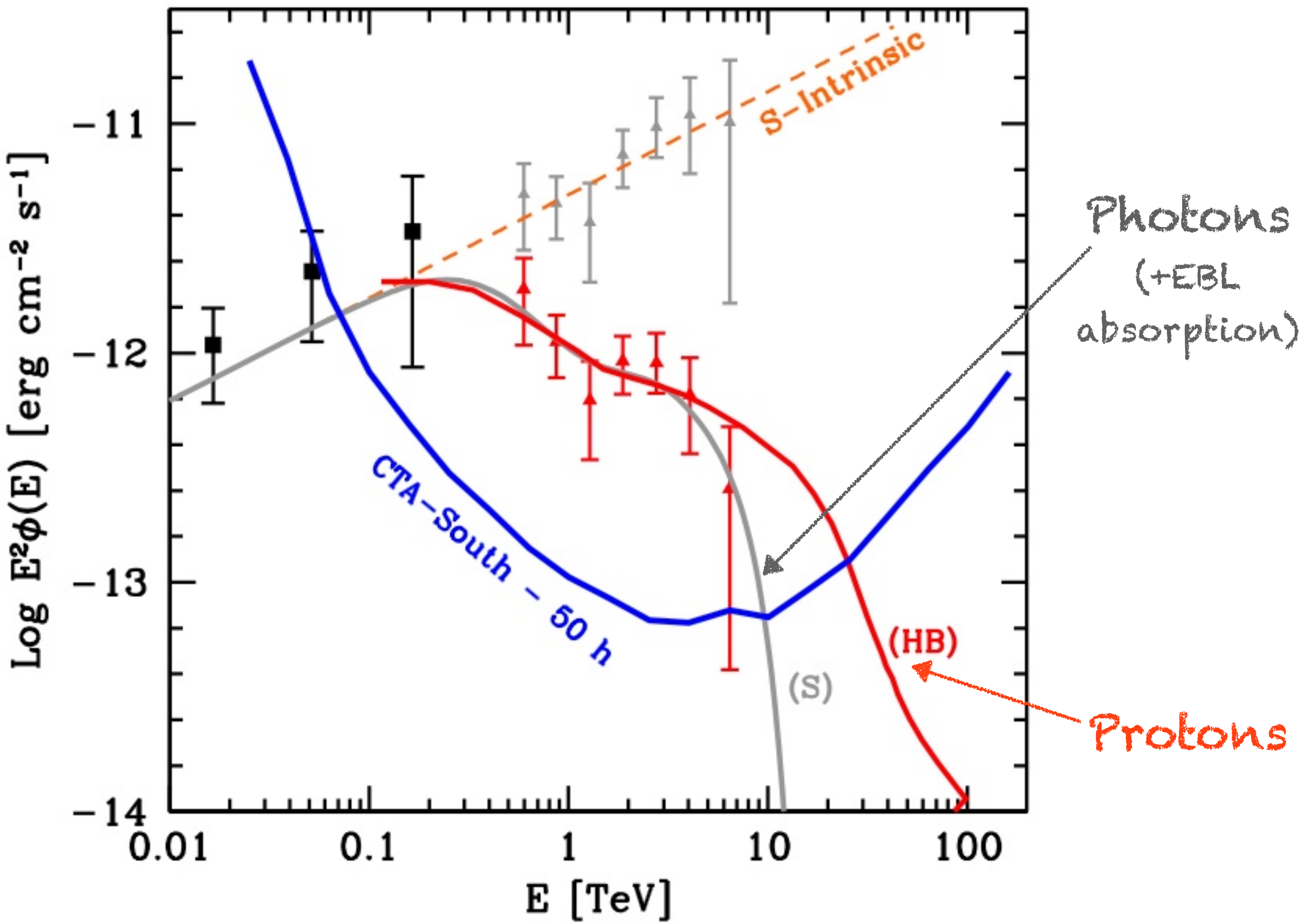
after Costamante et al. 2001



Bonnoli et al. 2015

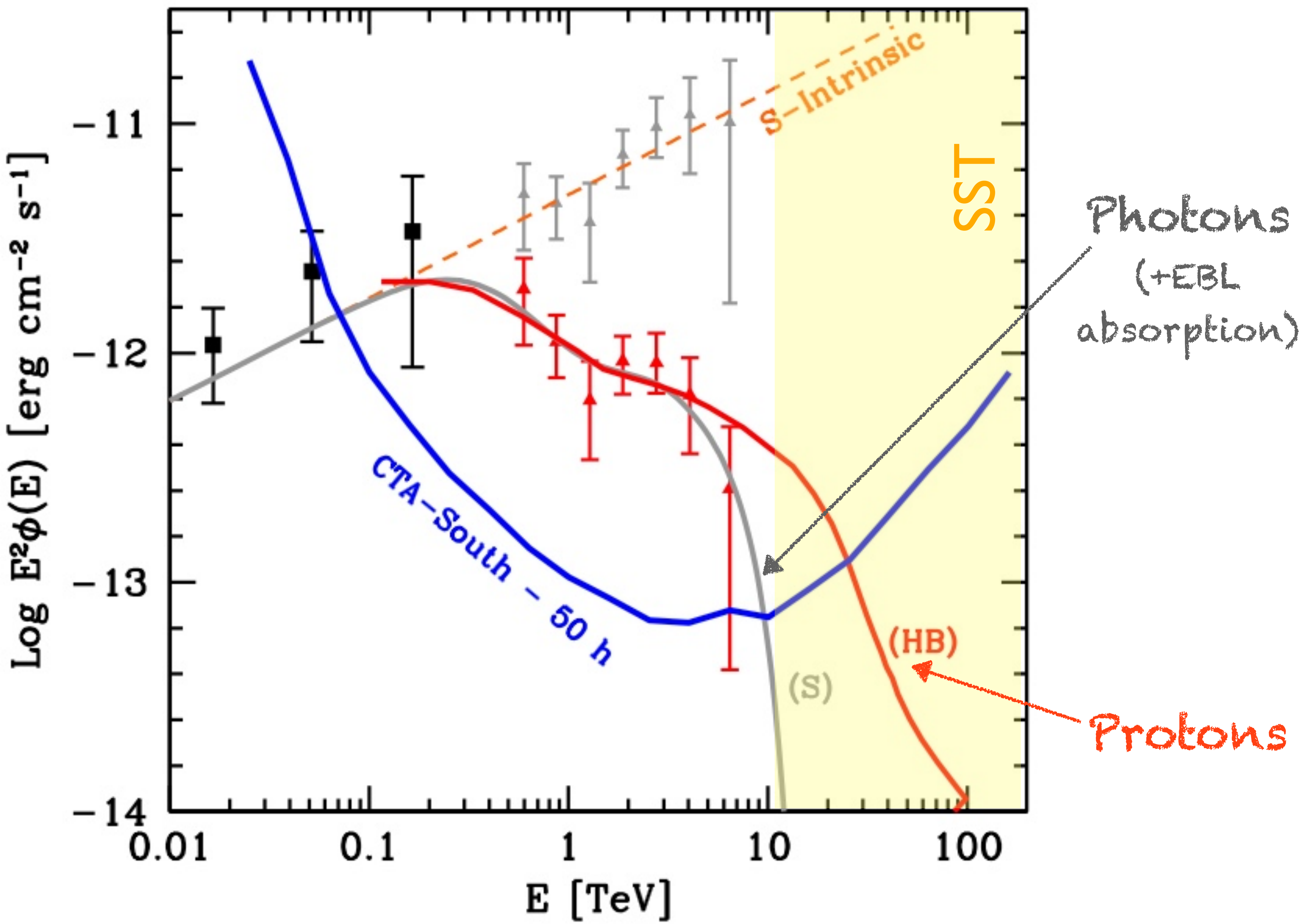
Hadron beams?

Tavecchio et al. 2019



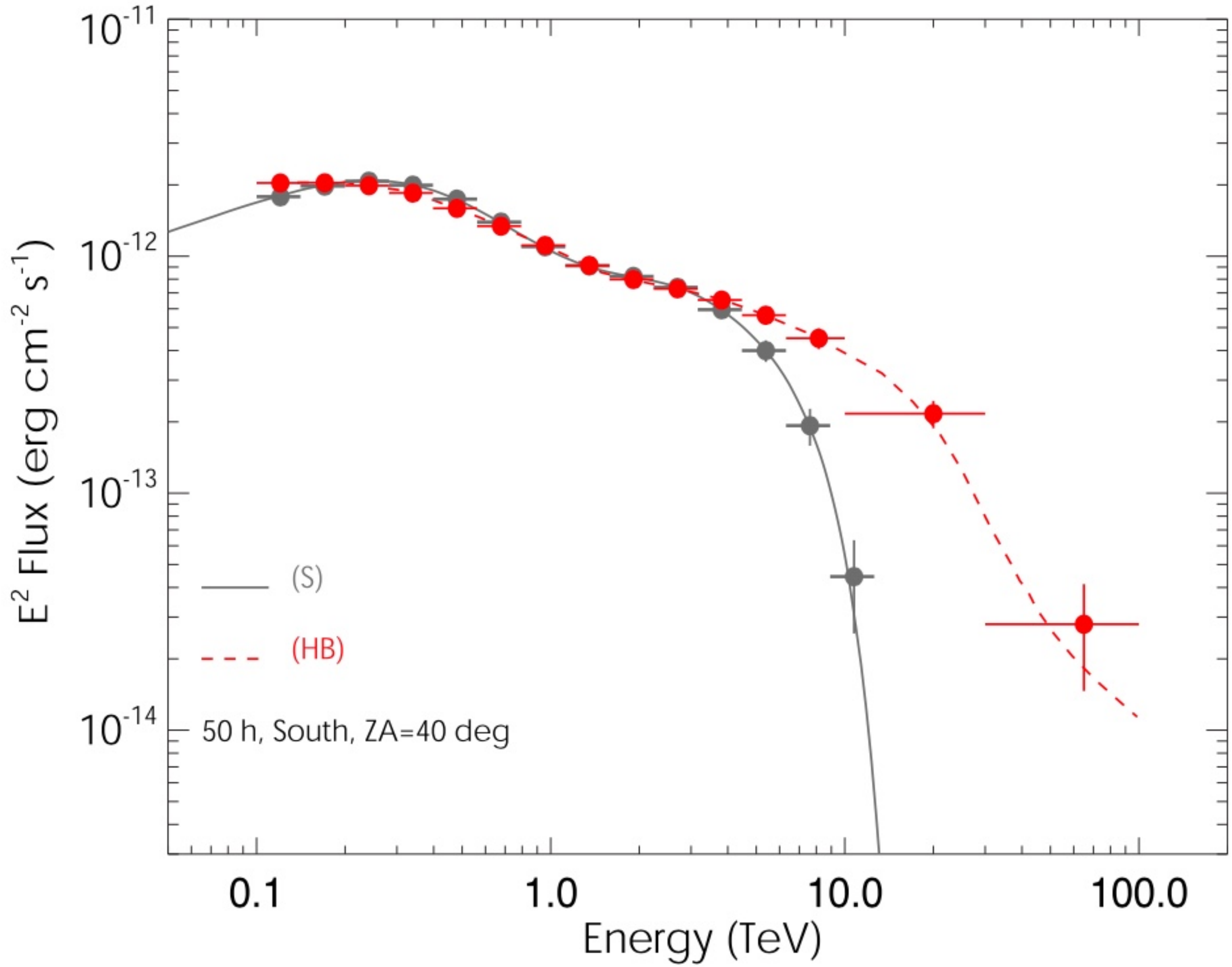
Hadron beams?

Tavecchio et al. 2019



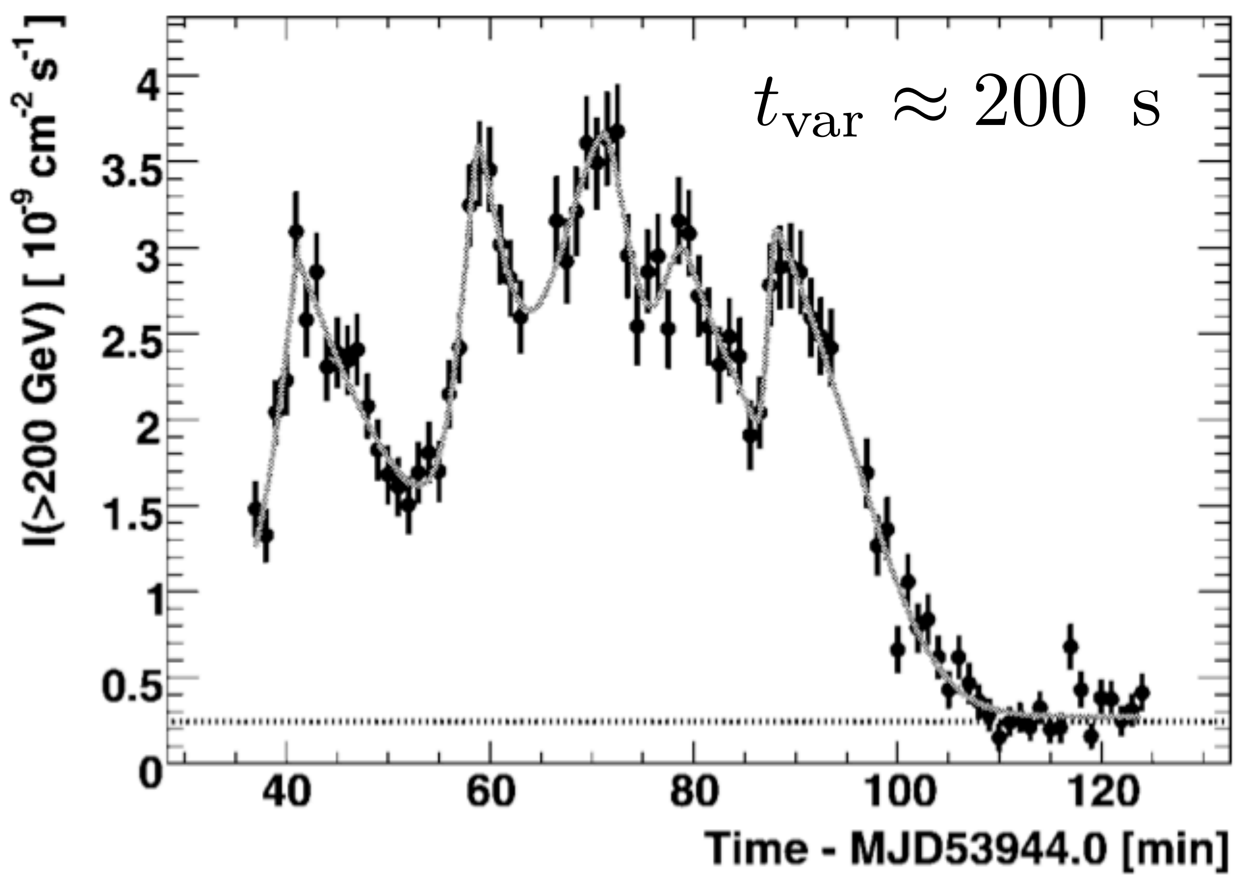
Hadron beams?

Tavecchio et al. 2019



Variability

PKS 2155-304@TeV



Aharonian et al. 2007

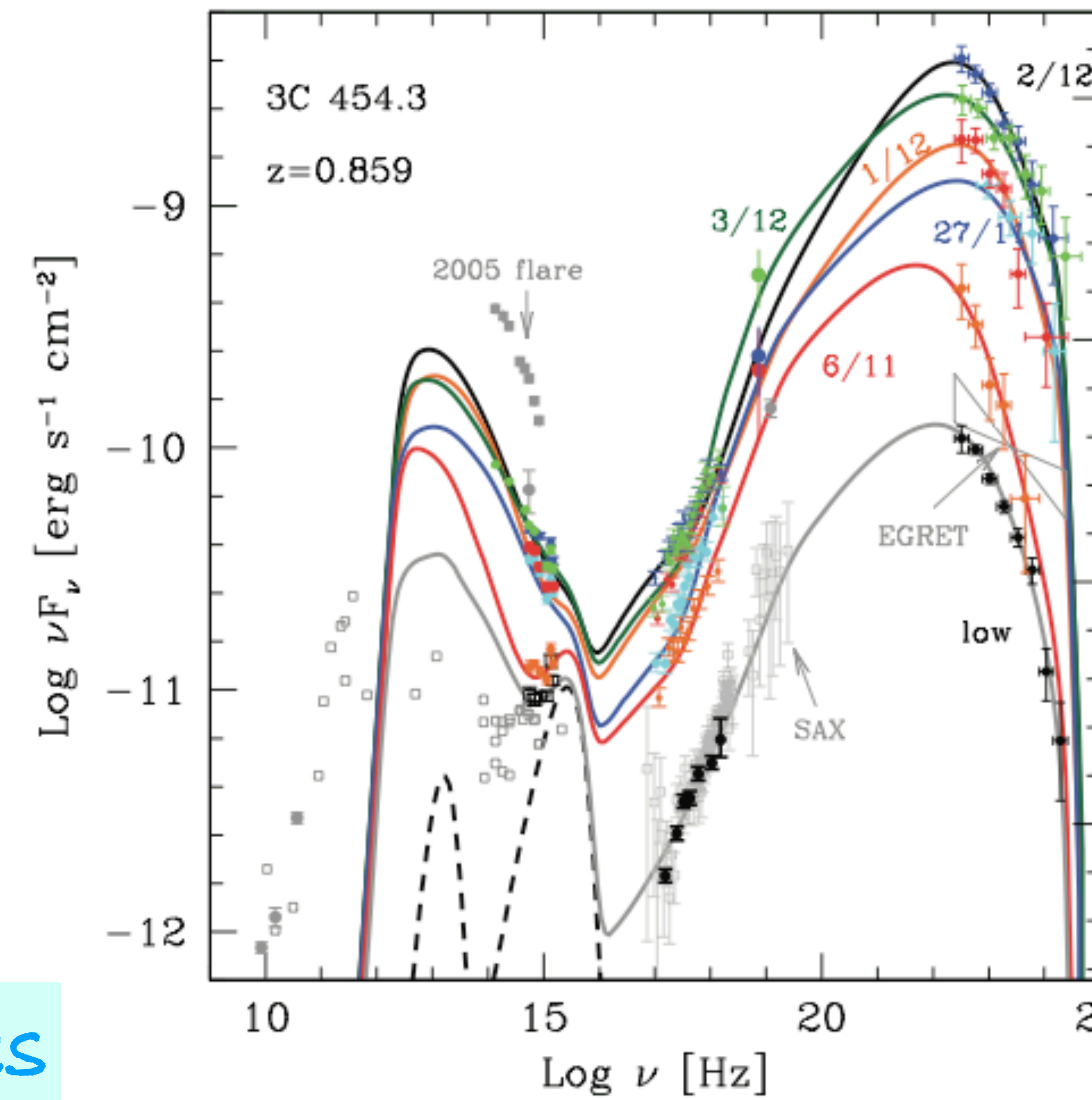
Short time-scales

Small spatial scales

Close to the BH

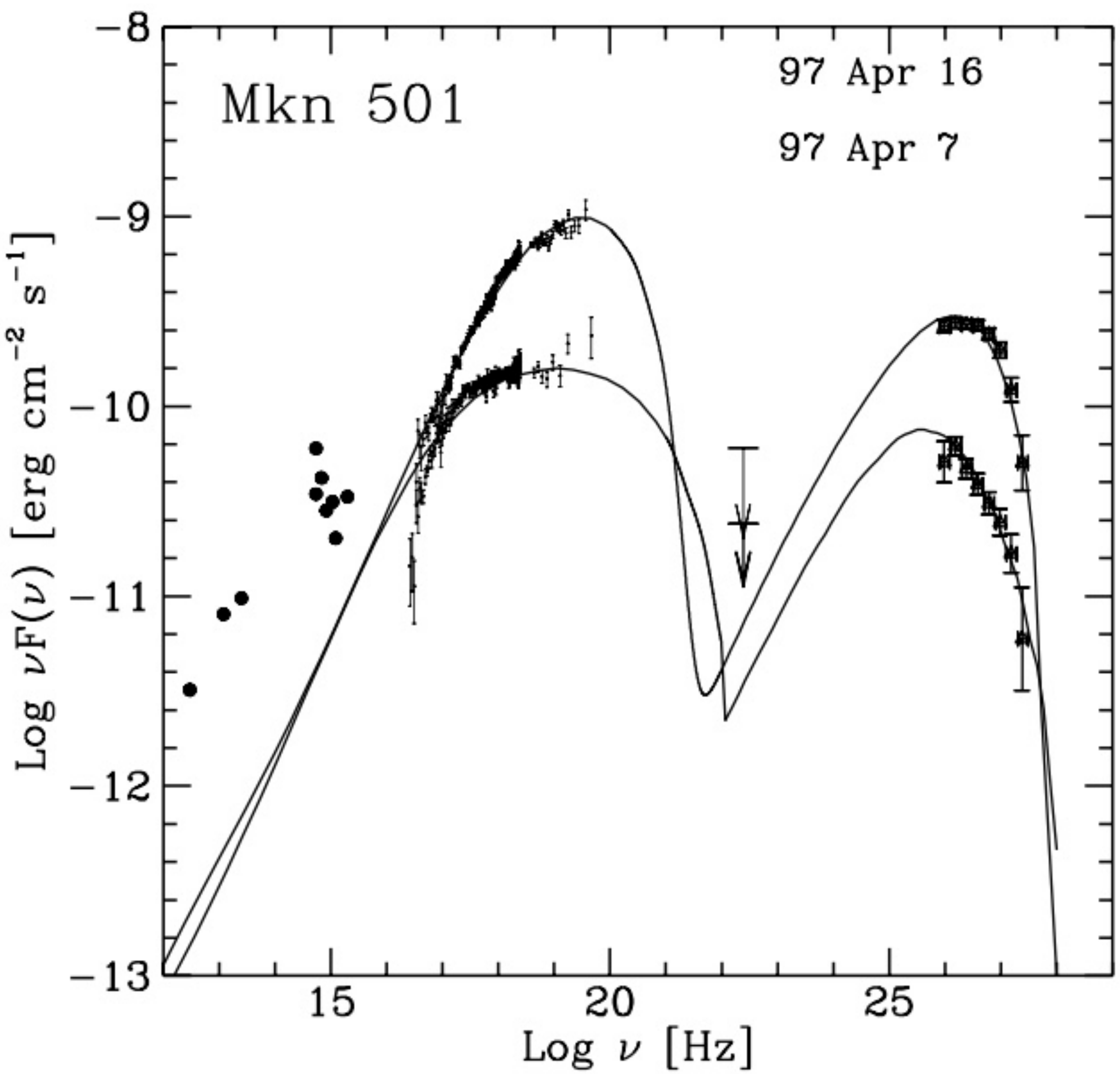
Large amplitudes

Bonnoli et al. 2011



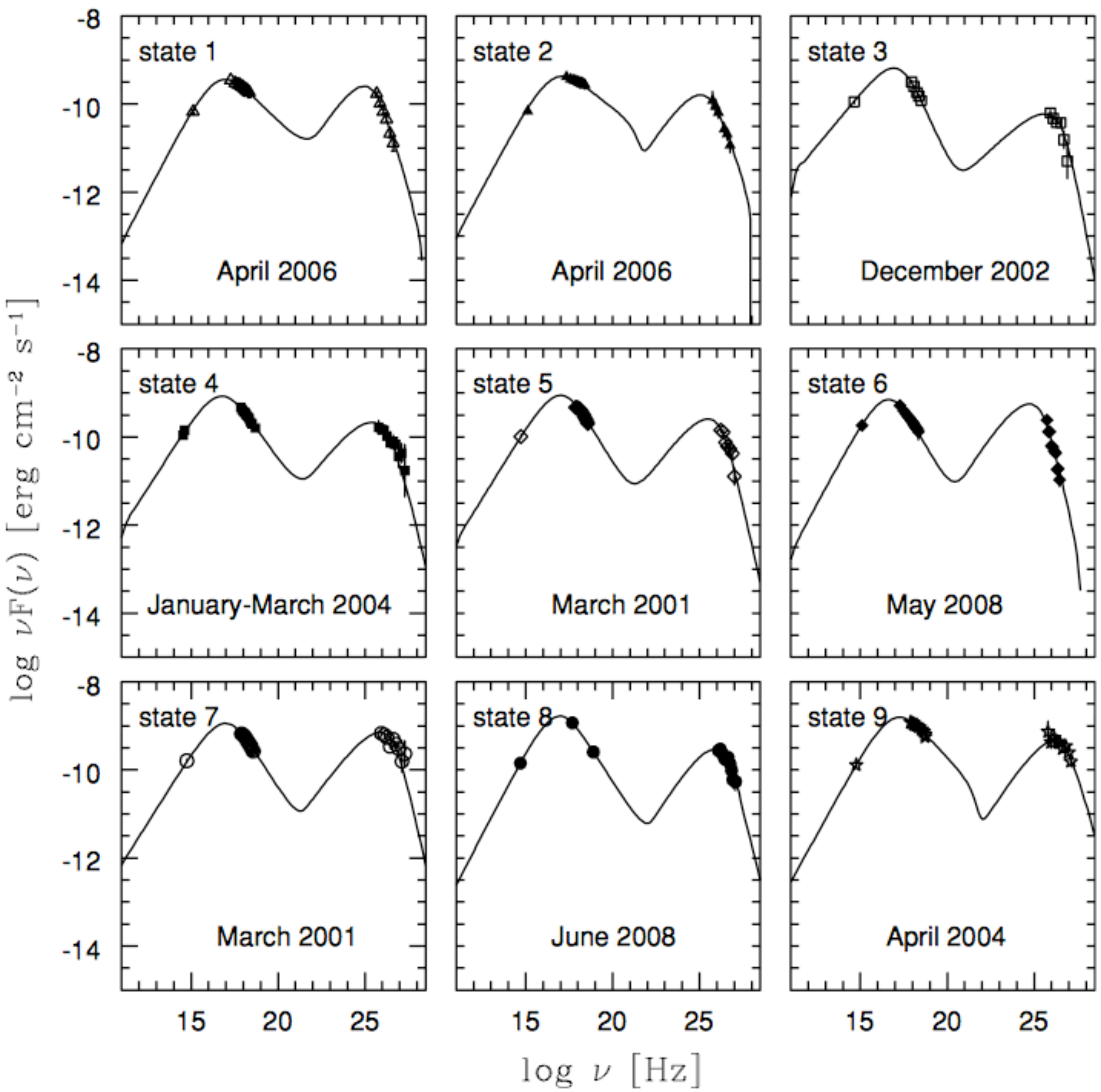
Quasi-stationary SED

Observation	R_{15} (cm)	B (G)	δ	γ_{break}	K (cm^{-3})	n_1	n_2
1997 April 7	1.9	0.32	10	1.1×10^5	750	1.5	3
1997 April 16	1.9	0.32	10	7×10^5	10^3	1.55	3

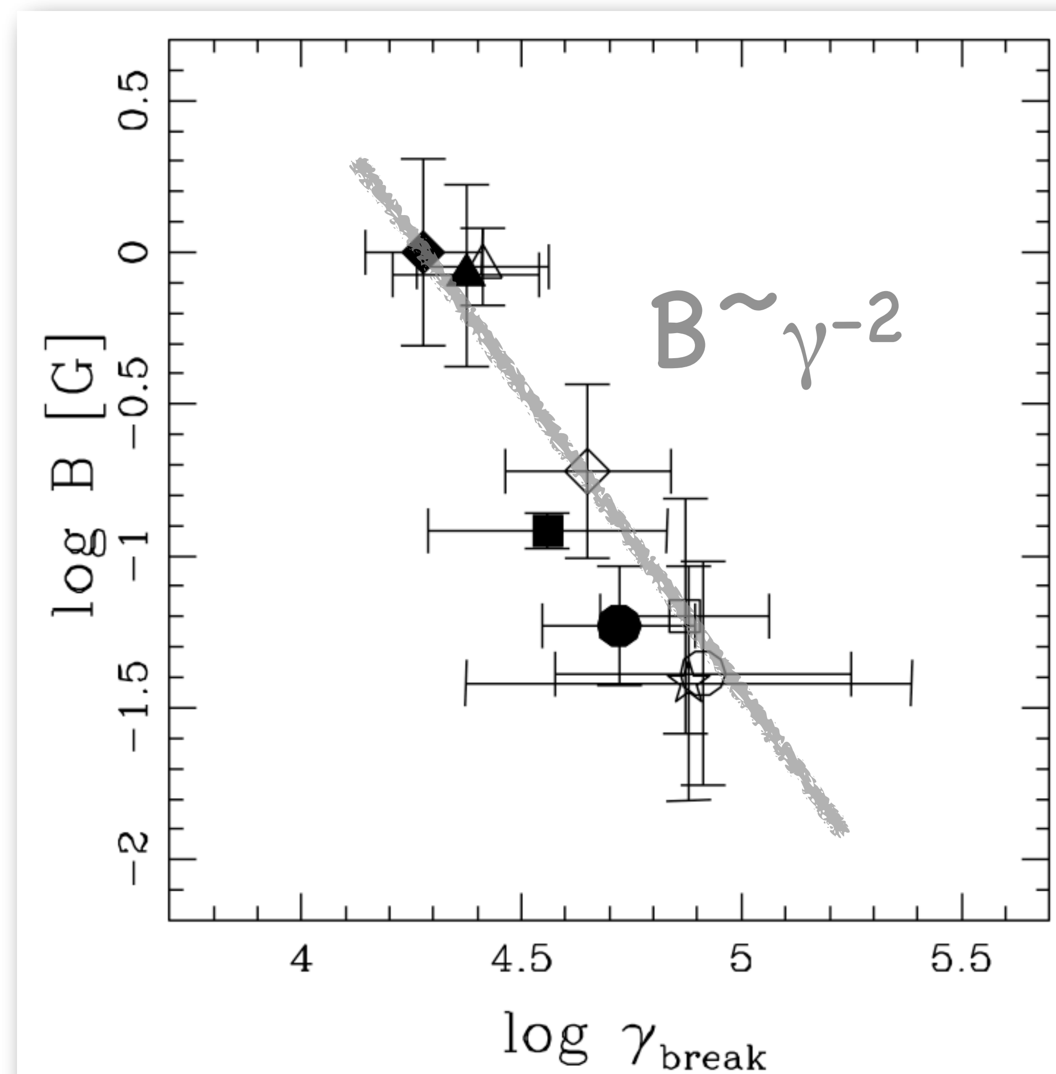


Tavecchio et al. 2001

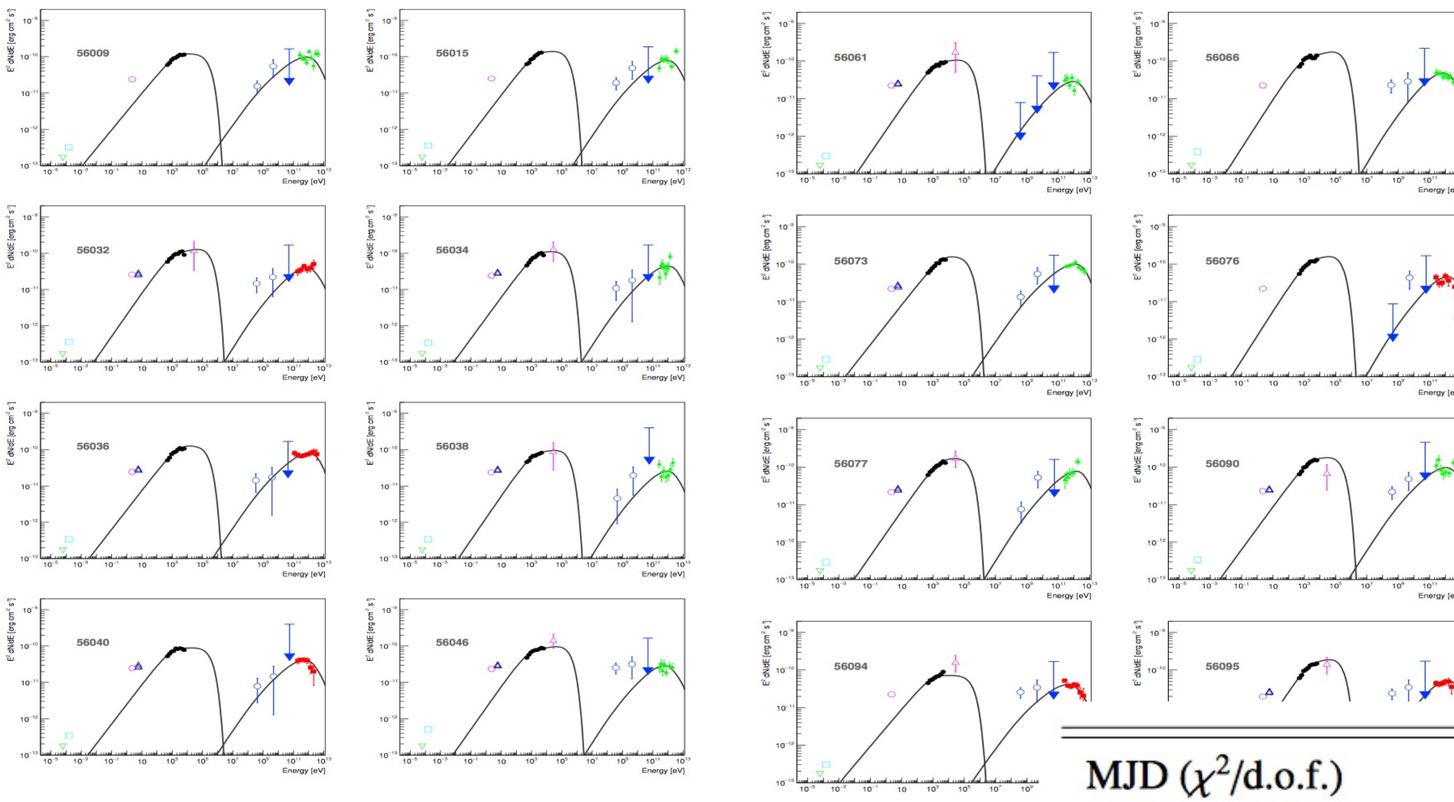
Quasi-stationary SED



Mankuzhiyil et al. 2011



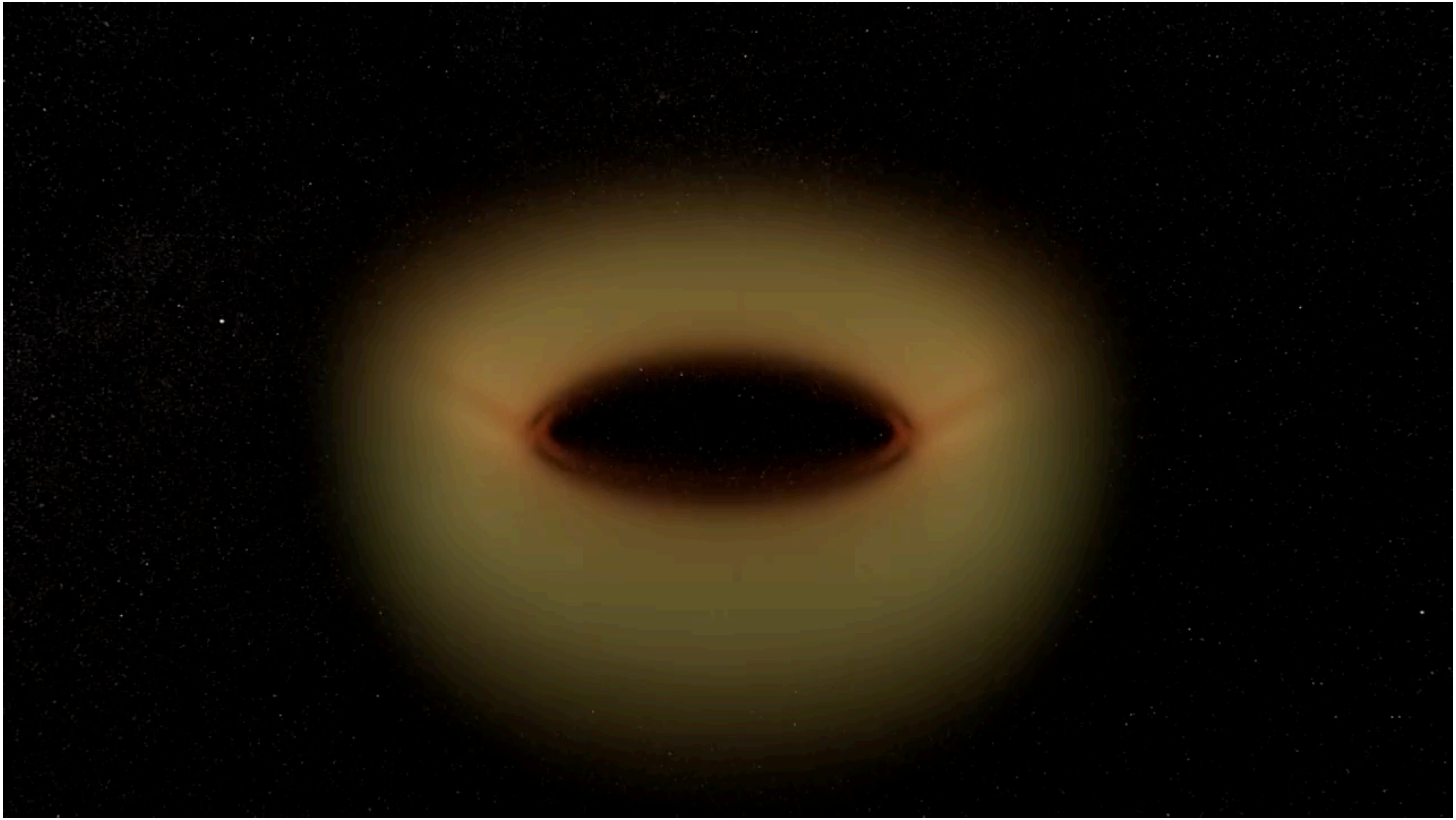
Quasi-stationary SED



MJD (χ^2/d.o.f.)	B (10^{-2} G)	$\gamma_{\rm brk}$ (10^6)	p_1	p_2	$U_{\rm e}$ (10^{-3} erg cm^{-3})	η [$U_{\rm e}/U_{\rm B}$]
56009 V (34.0/13)	2.26	0.85	1.90	2.87	11.96	589
56015 V (29.9/11)	2.34	0.81	1.90	2.87	9.27	425
56032 M (19.9/10)	2.99	0.49	1.88	2.77	5.20	146
56034 V (24.3/12)	2.22	0.90	1.86	2.90	6.88	350
56036 M (21.0/11)	2.00	1.07	1.93	2.96	10.50	659
56038 V (19.8/10)	2.55	0.63	1.78	2.82	4.50	173
56040 M (18.8/11)	3.00	0.51	1.91	2.93	5.98	166
56046 V (23.5/12)	3.26	0.41	1.81	2.82	4.30	102
56061 V (24.0/10)	2.65	0.65	1.78	2.82	4.66	166
56066 V (36.0/12)	3.39	0.42	1.70	2.73	5.11	112
56073 V (13.3/11)	2.00	1.28	1.93	2.96	11.70	736
56076 M (19.7/10)	2.13	0.81	1.69	2.70	6.57	361
56077 V (17.7/9)	1.96	1.07	1.80	2.82	9.29	607
56087 M (62.5/12)	1.64	1.70	1.89	2.91	21.30	1398
56090 V (32.7/10)	2.21	0.91	1.86	2.83	10.10	520
56094 M (18.0/10)	2.98	0.50	2.00	2.97	7.04	199
56095 M (16.8/10)	2.25	0.84	1.68	2.73	6.78	336

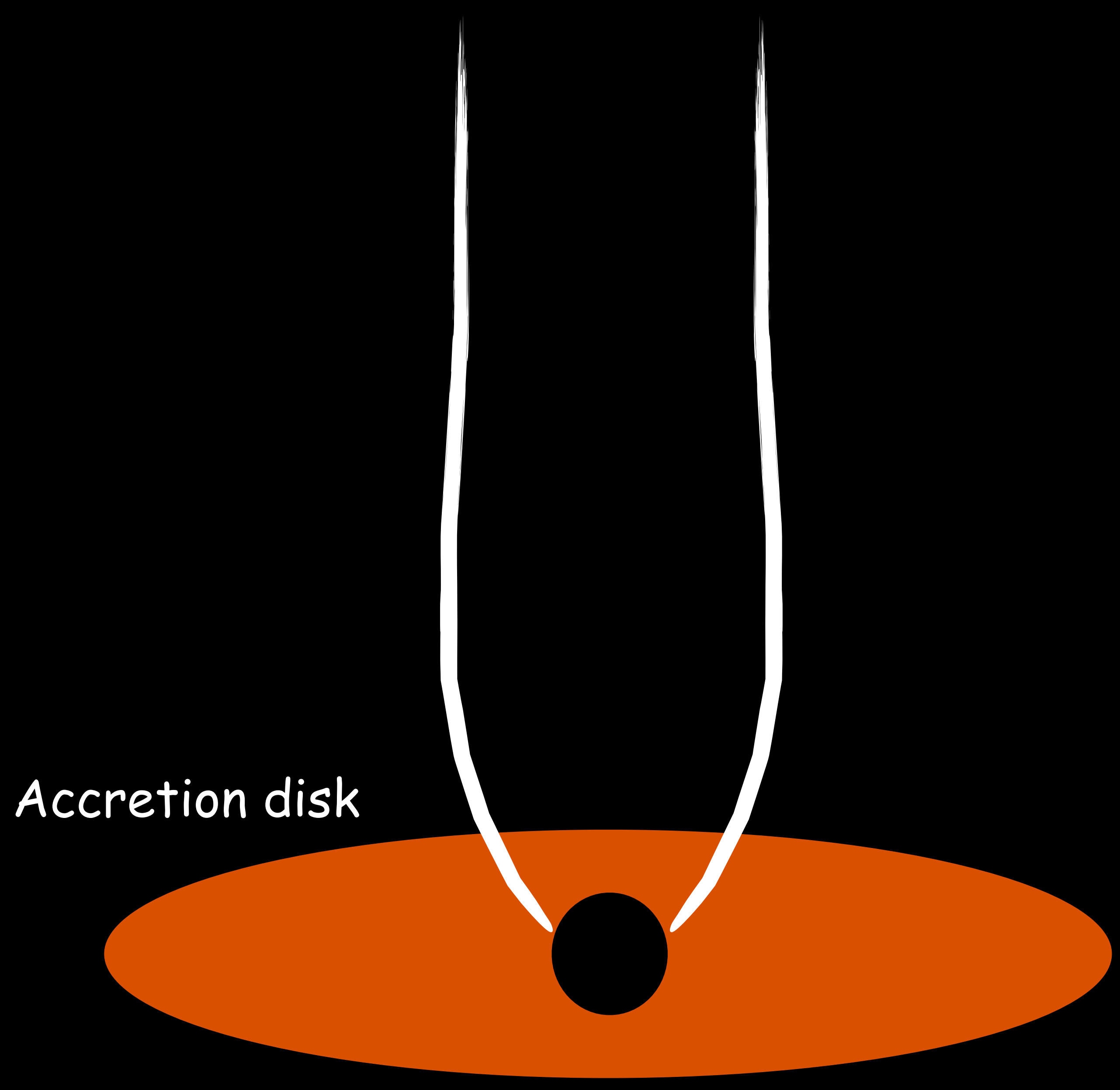
Ahnen et al. 2018

Producing the jet

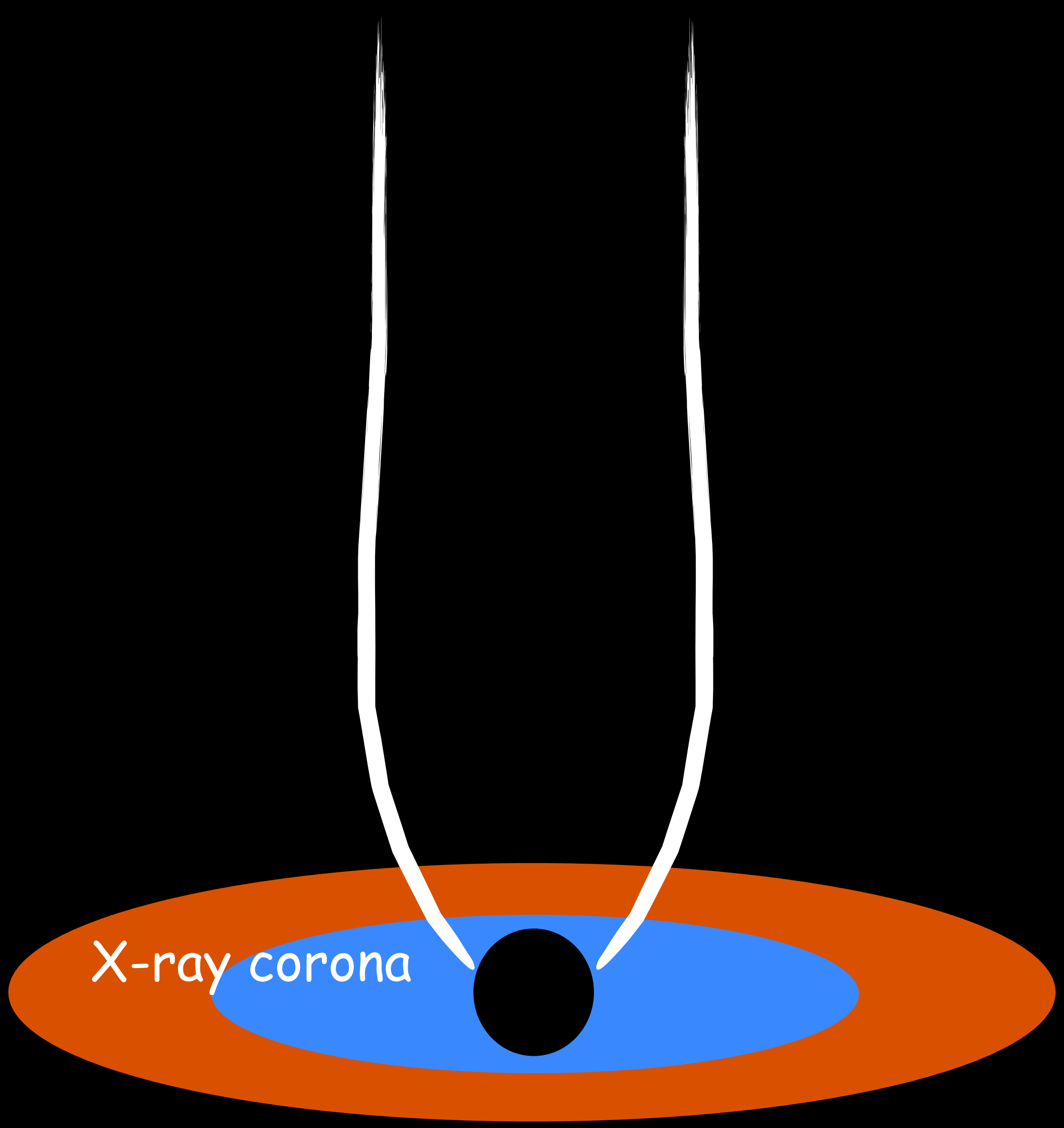


McKinney, Tchekhovskoy, and Blandford 2012

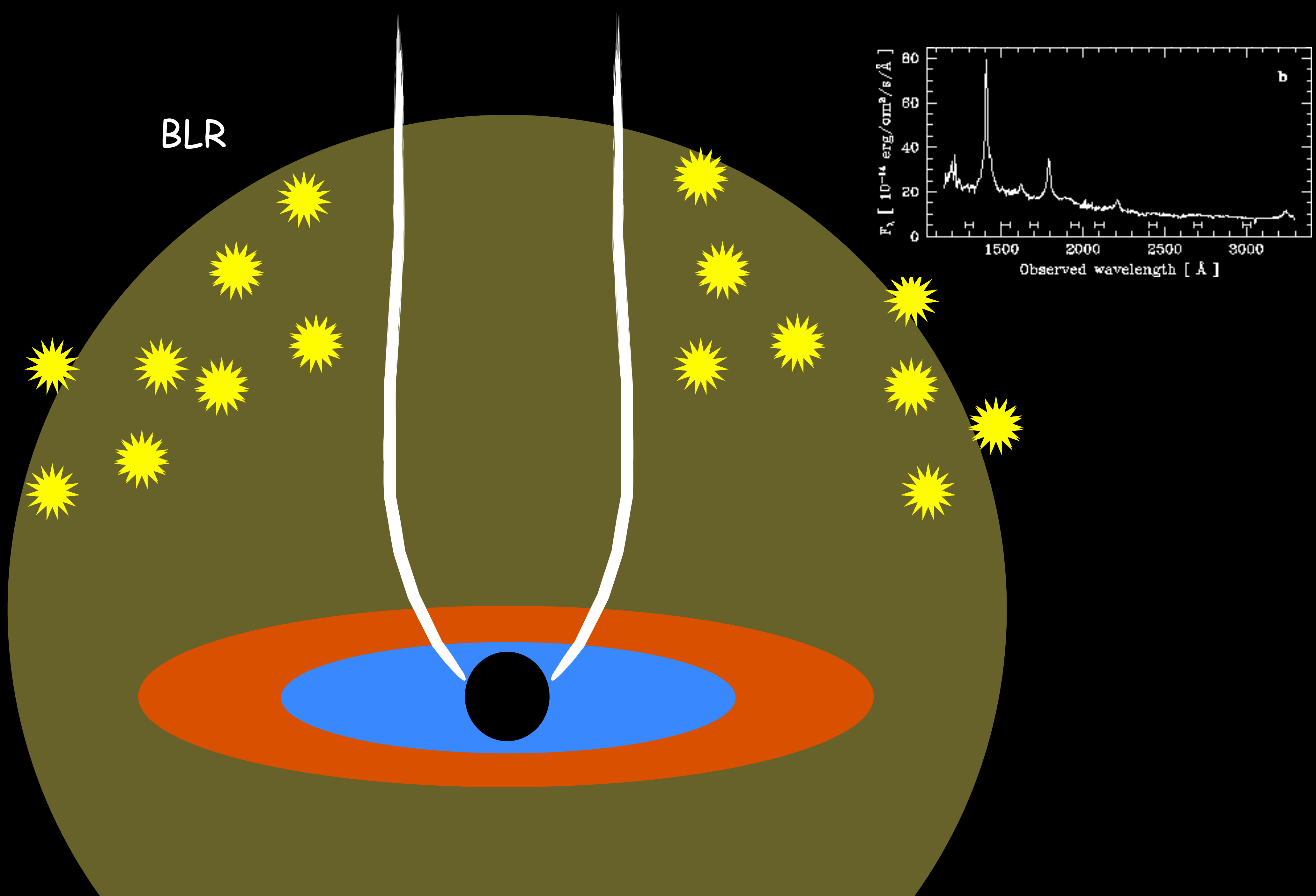
FSRQs: the general scenario



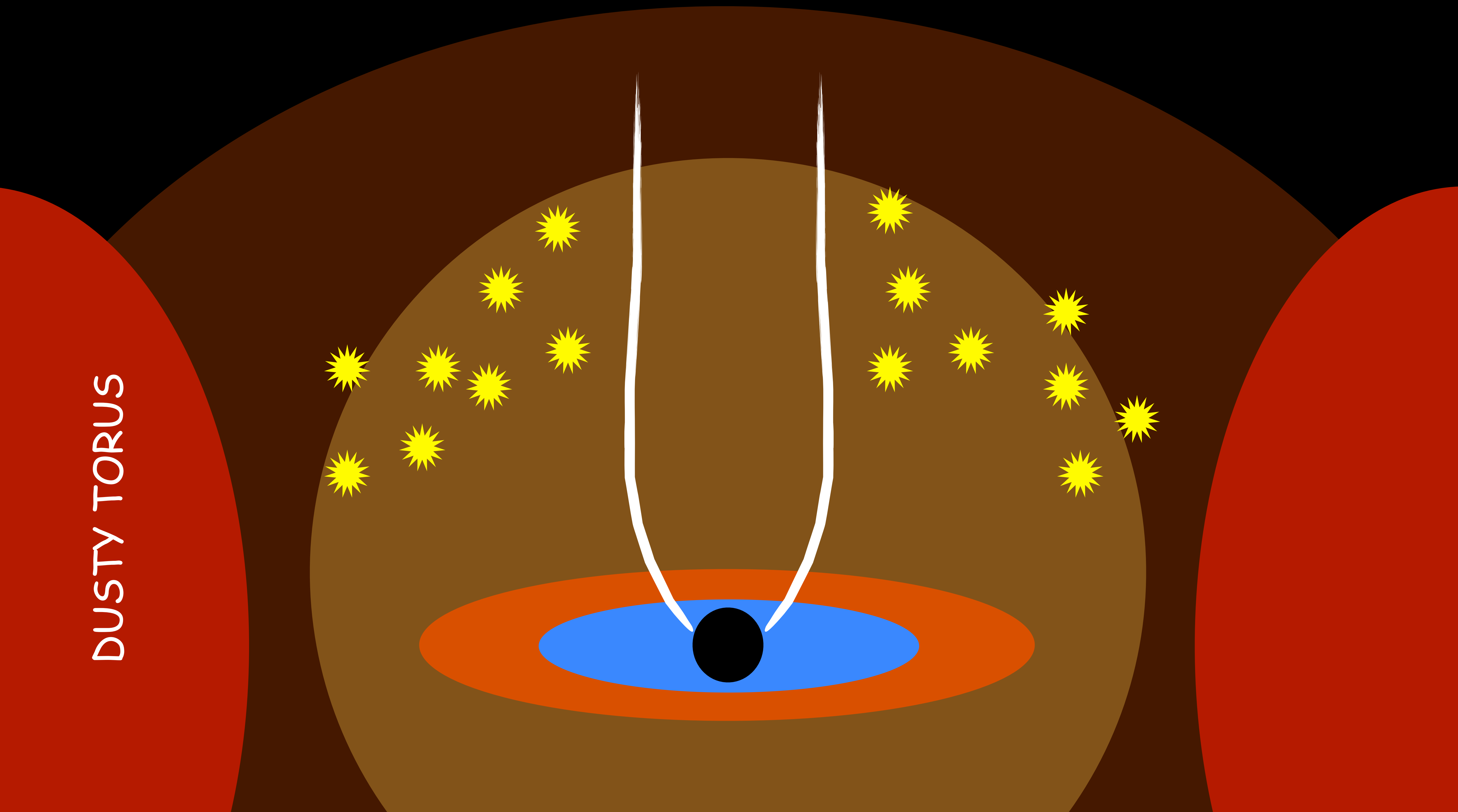
FSRQs: the general scenario



FSRQs: the general scenario

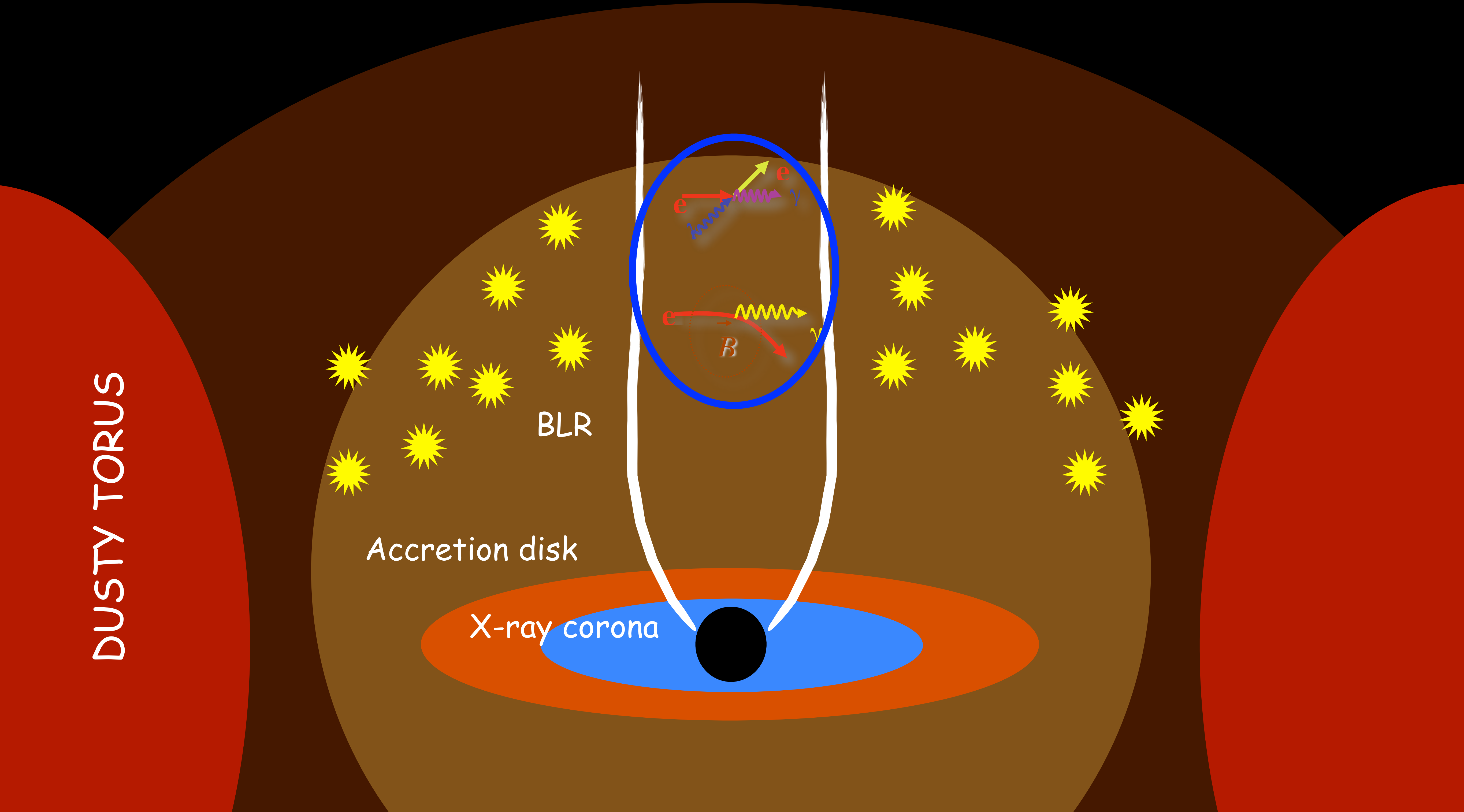


FSRQs: the general scenario

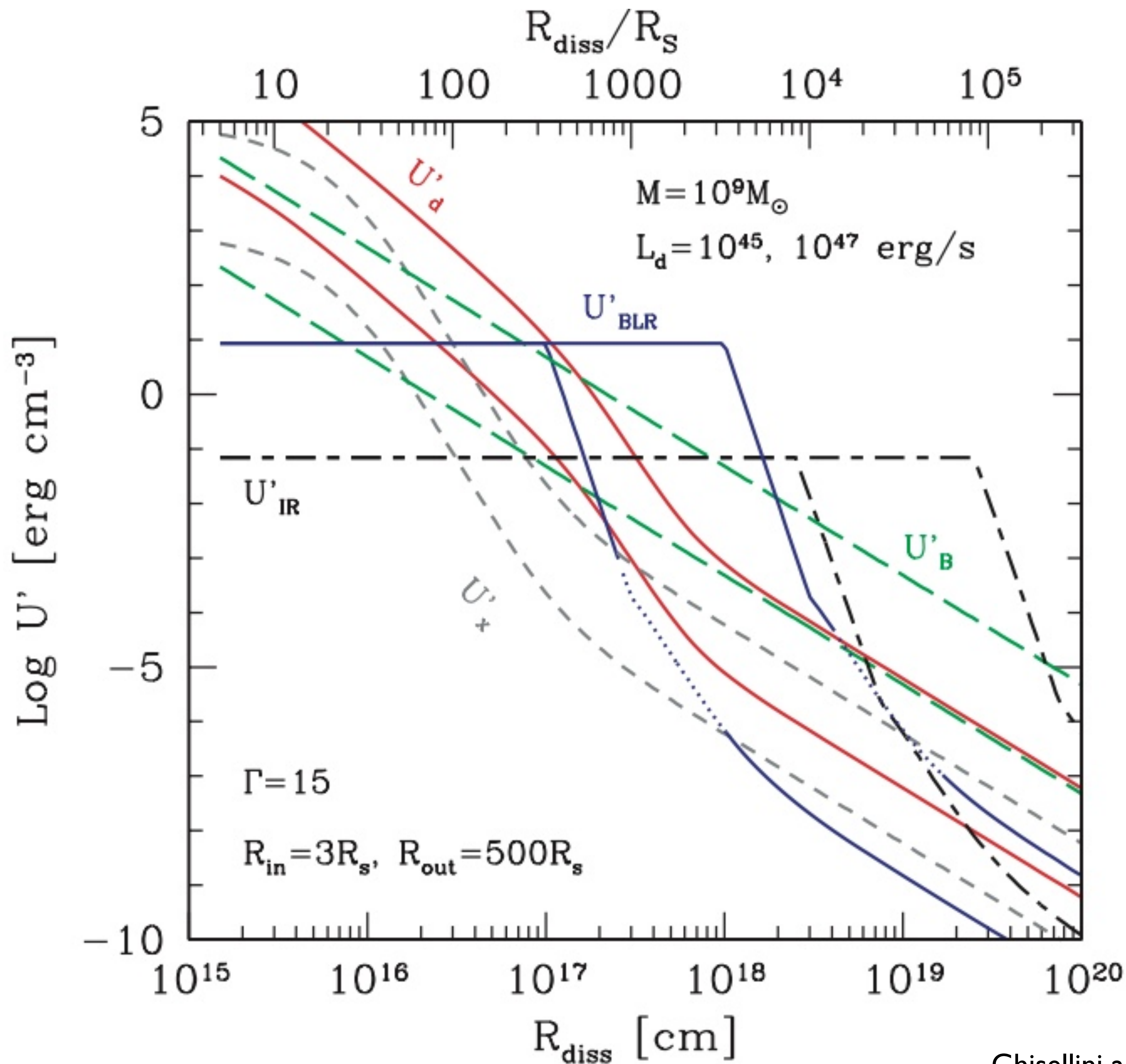


FSRQs: the "canonical" scenario

Dermer et al. 2009
Ghisellini, FT 2009
Sikora et al. 2009

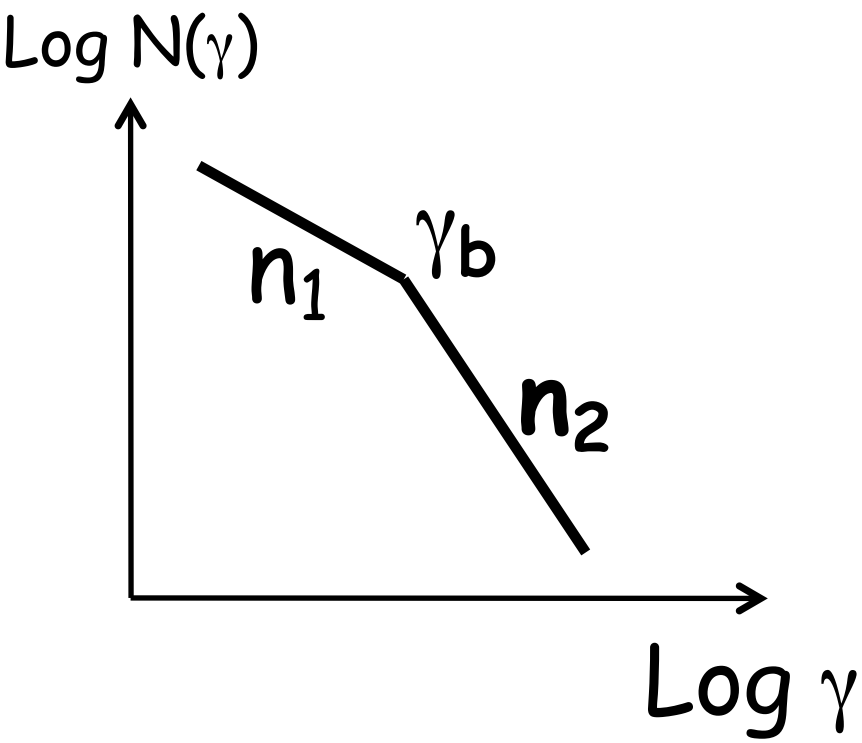


Jet frame!

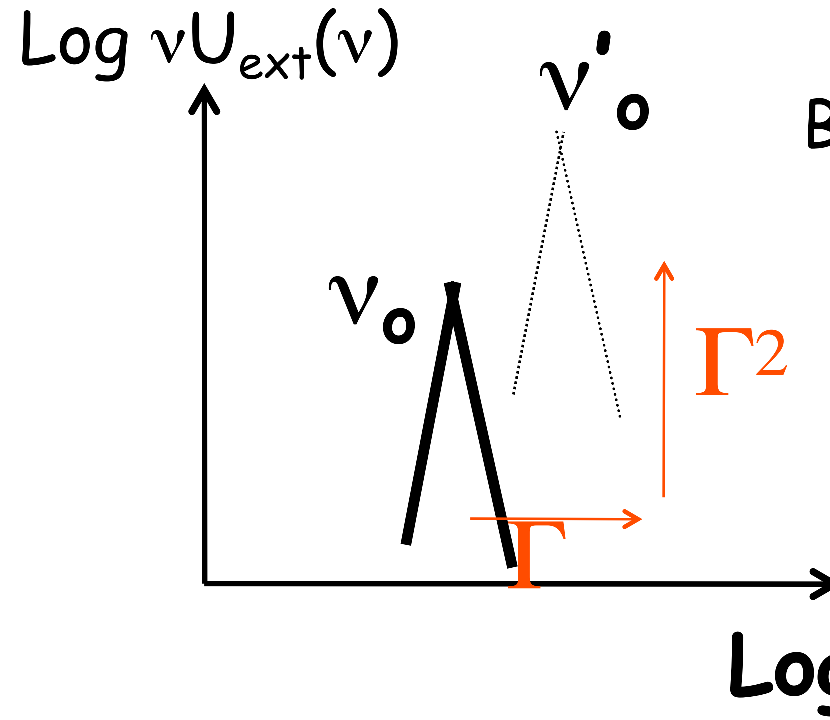


Ghisellini and Tavecchio 2009

A more modest model - 2



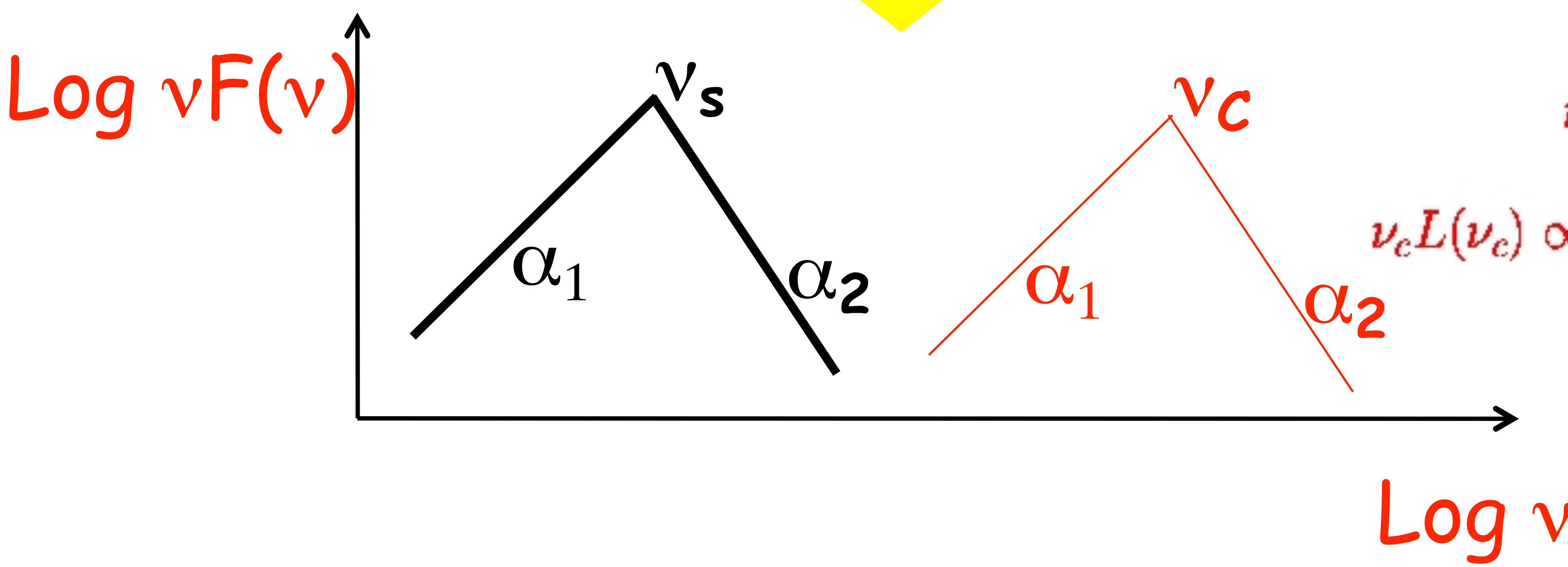
+



Broad line region,
Torus

$$\nu'_o = \Gamma \nu_o$$

$$U'_{\rm ext} = \Gamma^2 U_{\rm ext}$$

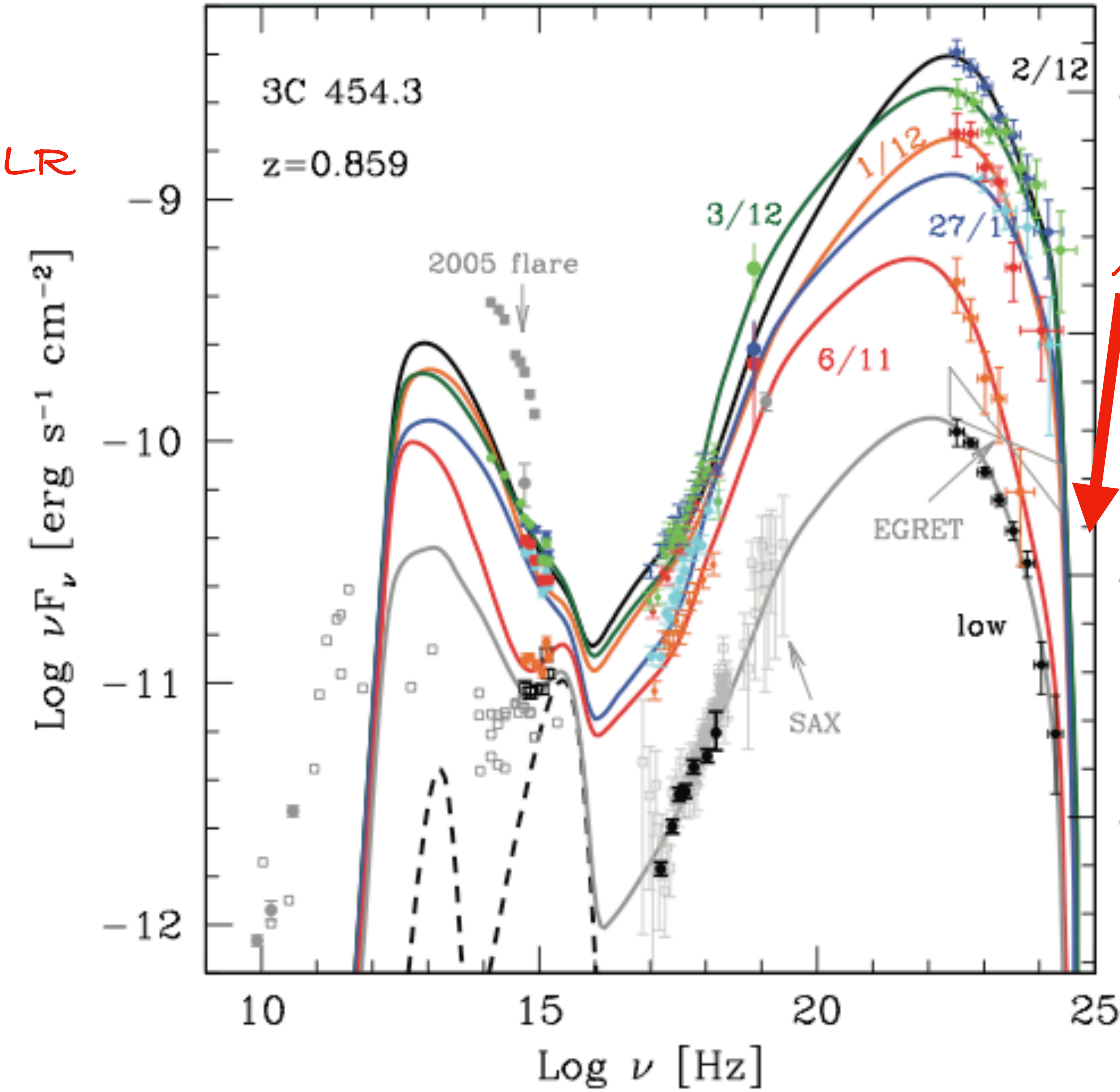


$$\nu_c = \nu'_o \gamma_b^2 \delta = \nu_o \gamma_b^2 \Gamma \delta$$

$$\nu_c L(\nu_c) \propto \sigma_T c U'_{\rm ext} N(\gamma_b) \gamma_b \gamma_b^2 V \delta^4$$

4C454.3

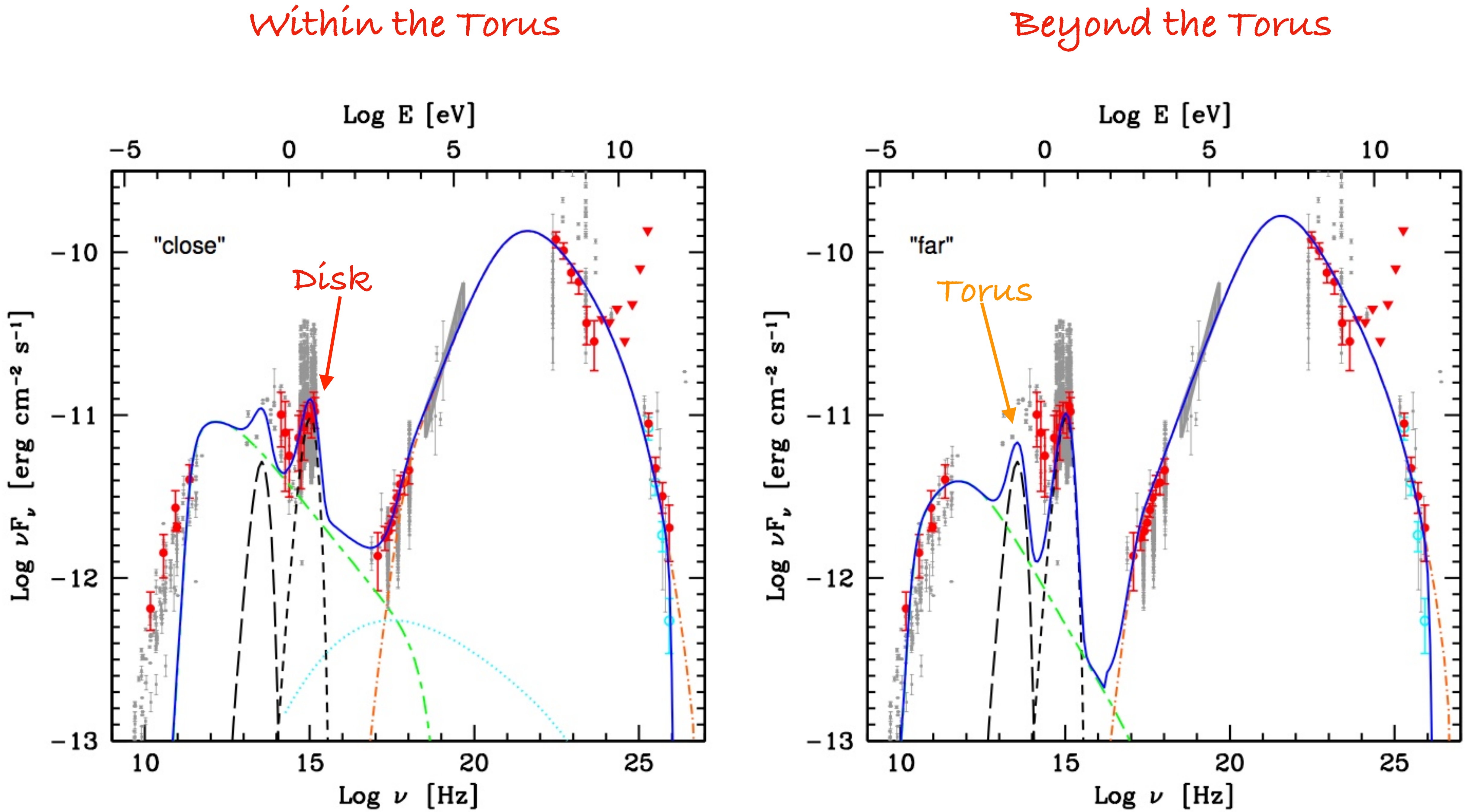
Within the BLR



Absorption (20 GeV)

Bonnoli et al. 2011

1ES 1510-089

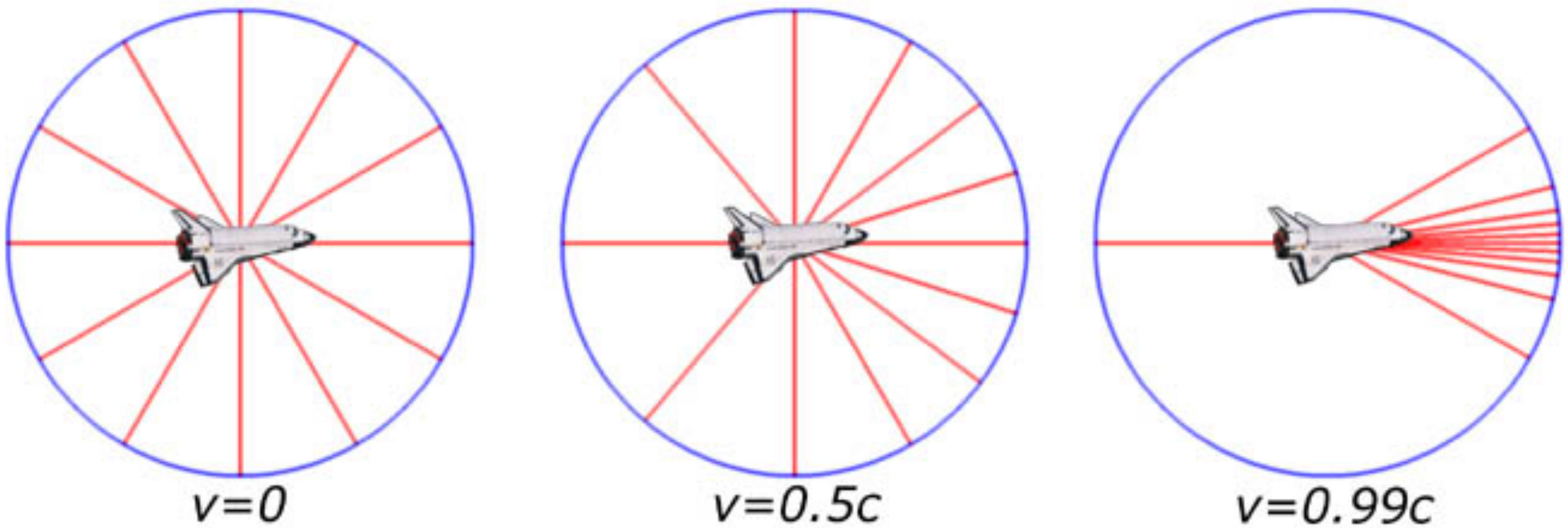


	γ_{min}	γ_b	γ_{max}	n_1	n_2	B	K	δ	Γ	r	R
Low state (close)	2.5	130	3×10^5	1.9	3.5	0.35	3×10^4	25	20	7.0×10^{17}	2.0×10^{16}
Low state (far)	2	300	3×10^5	1.9	3.7	0.05	80	25	20	3.0×10^{18}	3.0×10^{17}

Acciari et al. 2018

(Special) relativity at work

Doppler beaming

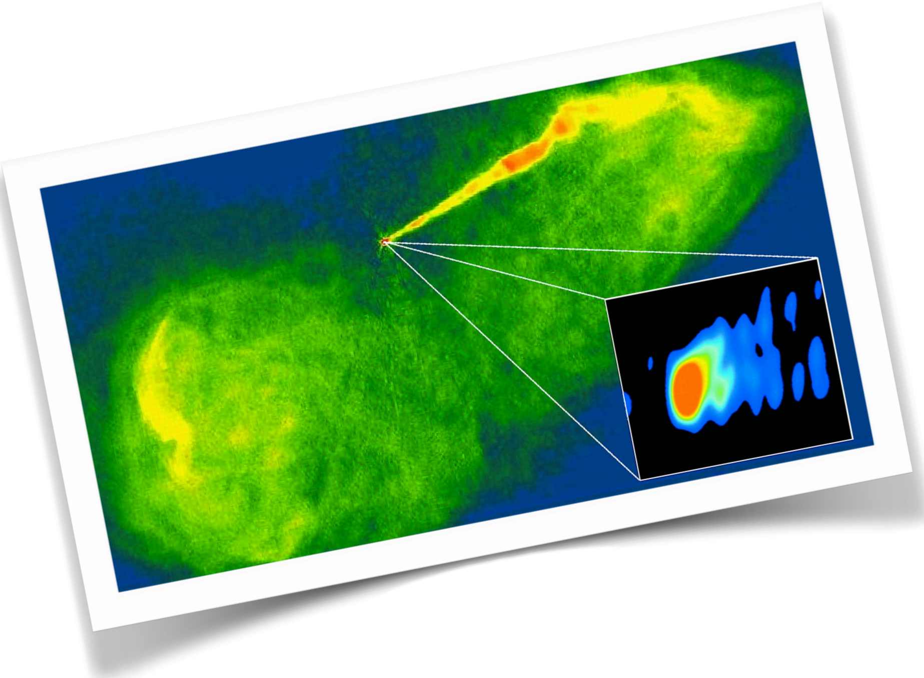


$$\delta = \frac{1}{\Gamma(1 - \beta \cos \theta_{\rm v})}$$

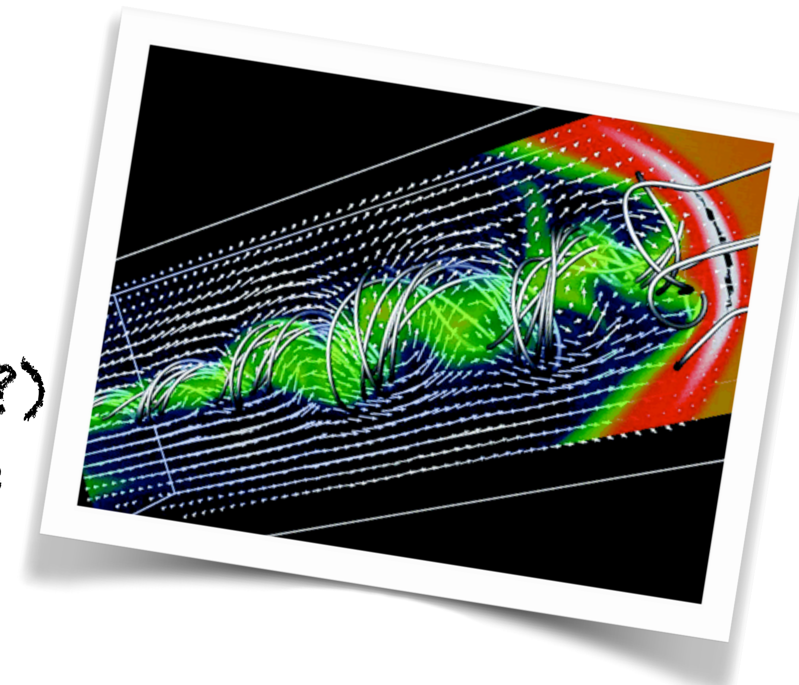
Amplification	$L_{\rm obs} = L' \delta^4$
Blueshift	$\nu_{obs} = \nu' \delta$
Shortening of timescales	$t_{\rm obs} = t'/\delta$

$$\delta \approx 10 - 20$$

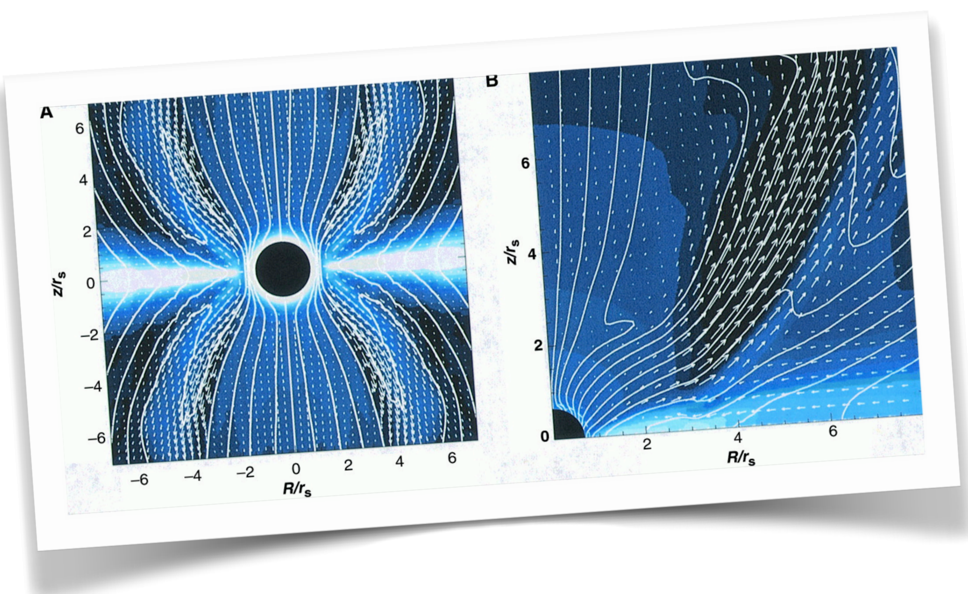
A wealth of astrophysical issues



Jet speed,
composition,
power, impact
on the environment



Magnetic fields,
particle acceleration (?)
emission mechanisms



Formation, collimation,
acceleration, stability

Huge range of spatial and temporale scales
(from electron gyroradius to Mpc!)

$10^5 - 10^{24}$ cm

e.g. Blandford et al. 2019
Blackman and Lebedev 2022