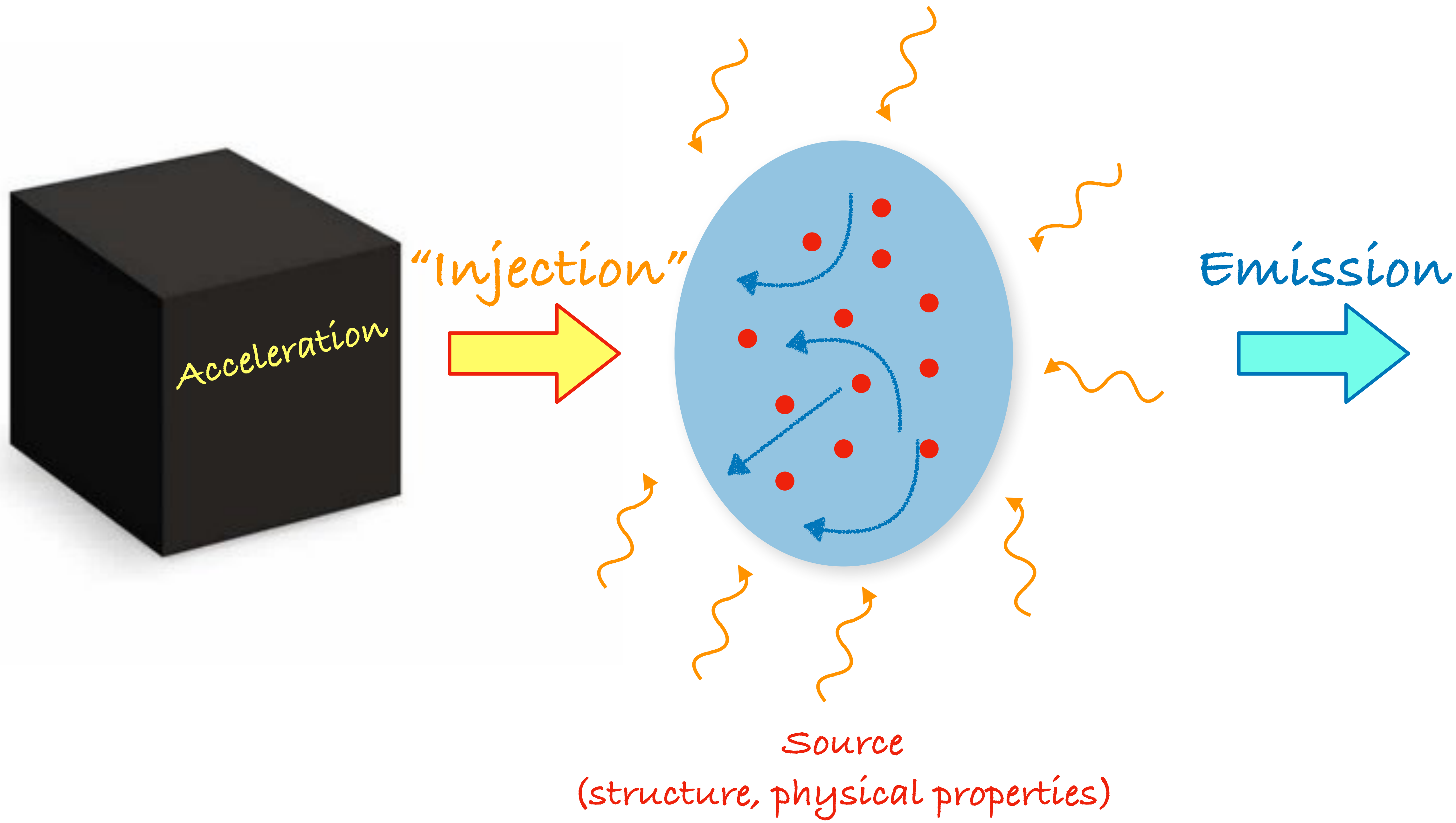
Spectral energy distribution (of blazars): modeling

F. Tavecchio
INAF-OABrera

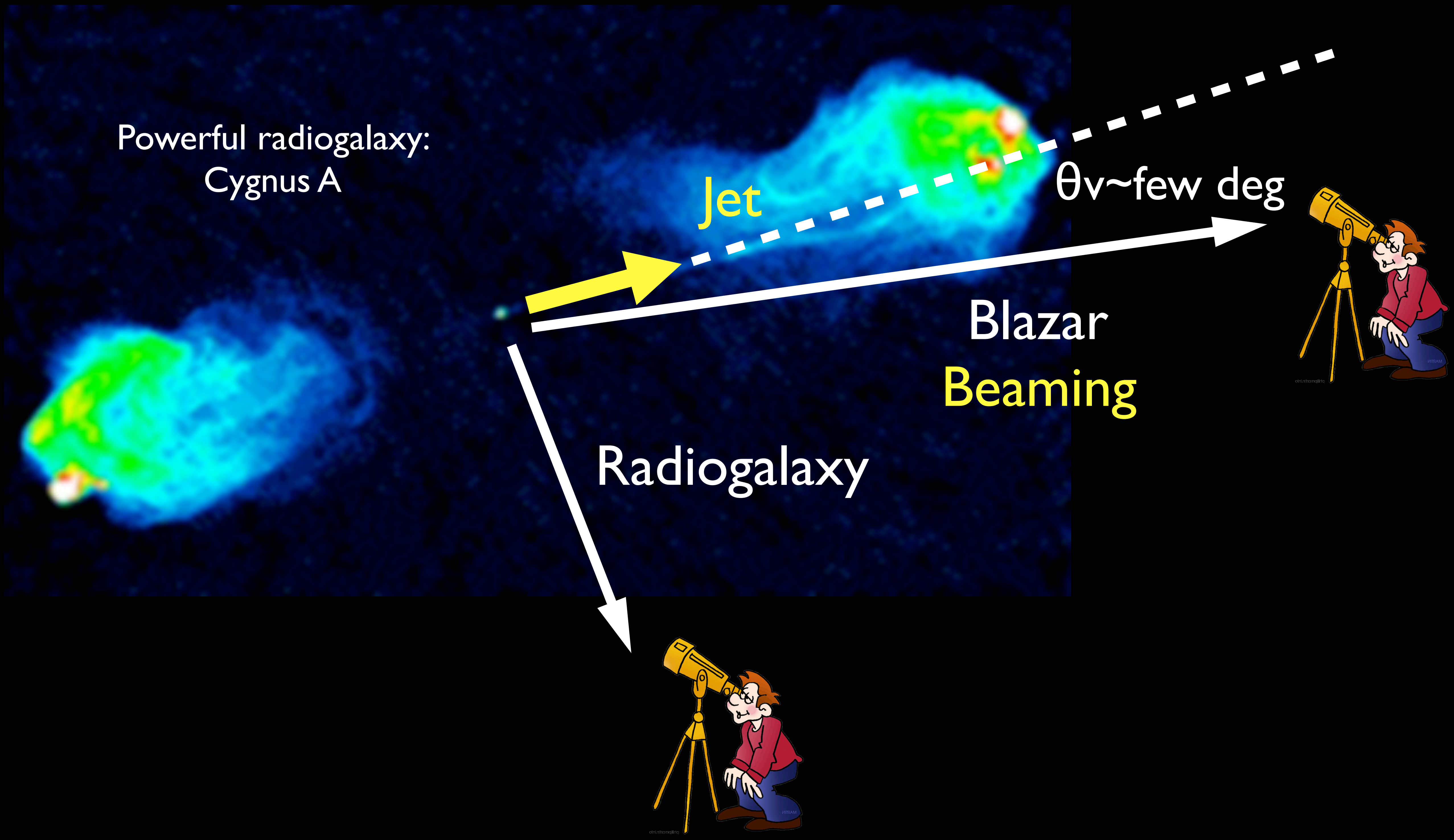
Multimessenger Data analysis in the era of CTA

Sexten - 28/6/2019

Our approach

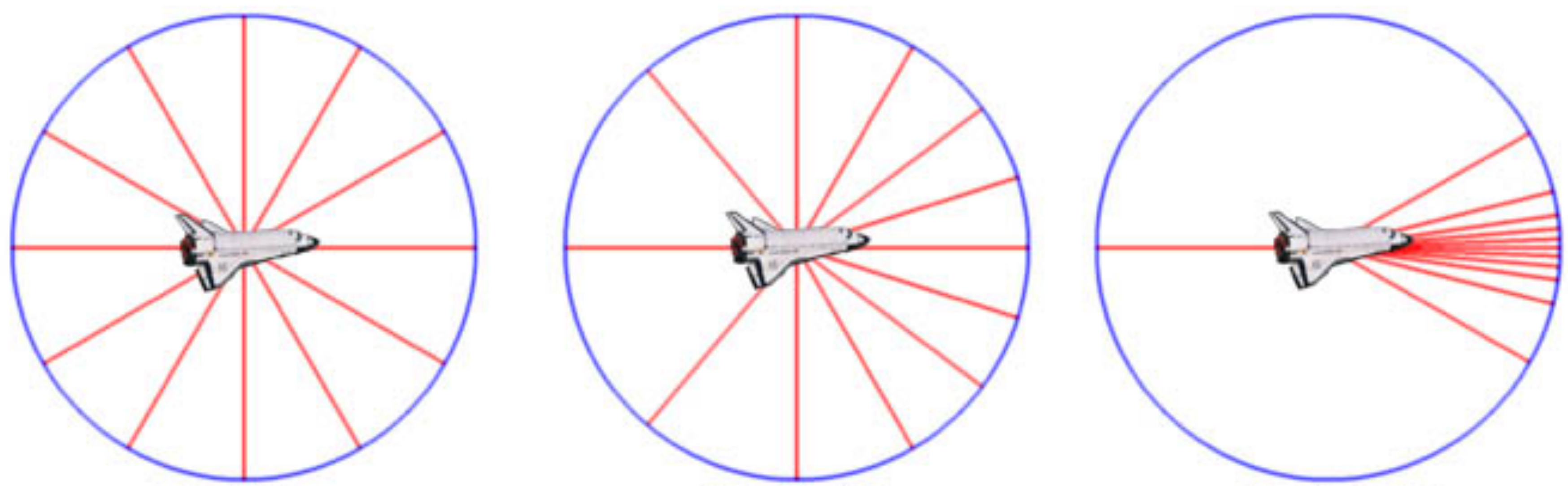


Blazars: relativistic jets pointing at us



(Special) relativity at work

Doppler beaming

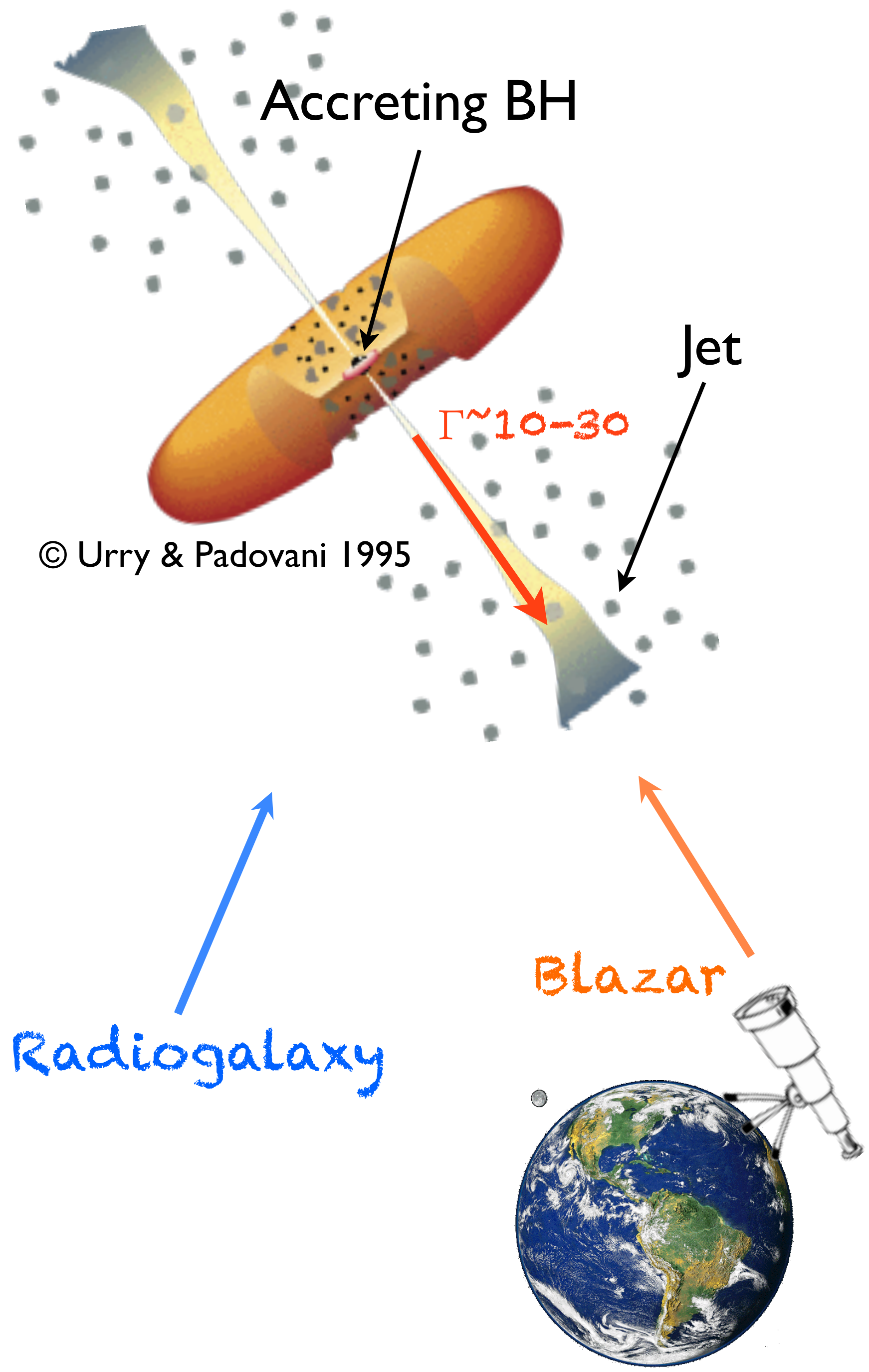


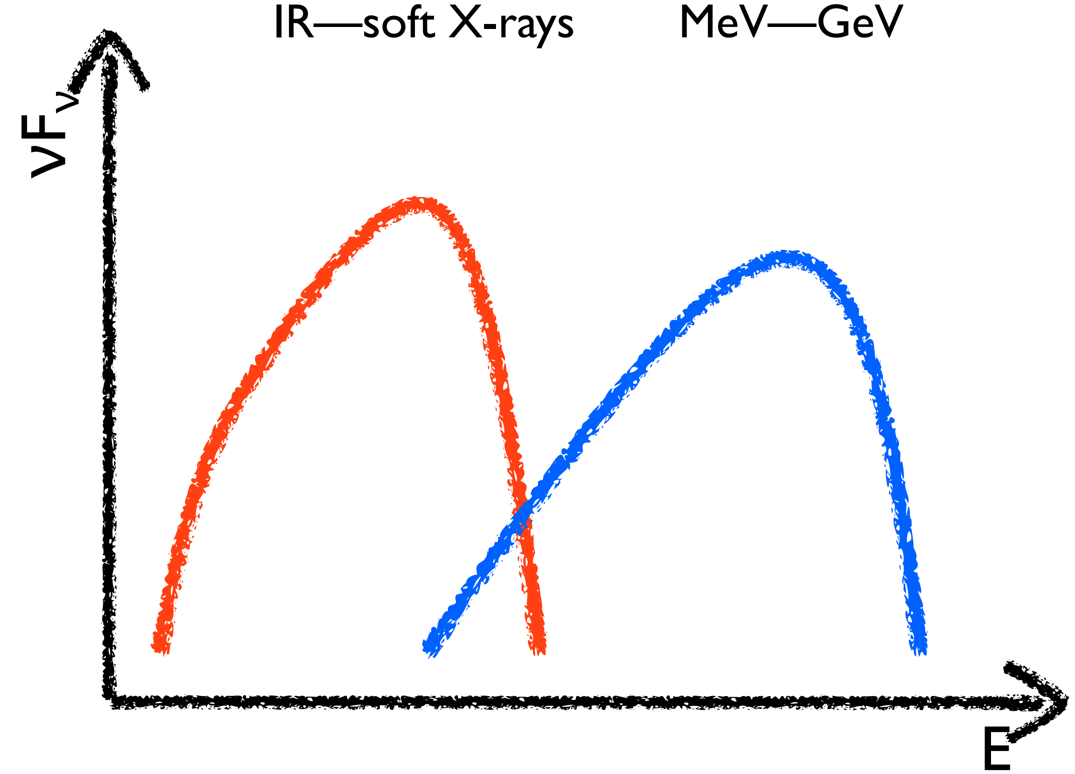
$$\delta = \frac{1}{\Gamma(1-\beta\cos\theta_{\rm v})}$$

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

$\delta \approx 10 - 20$

Blazars in a nutshell

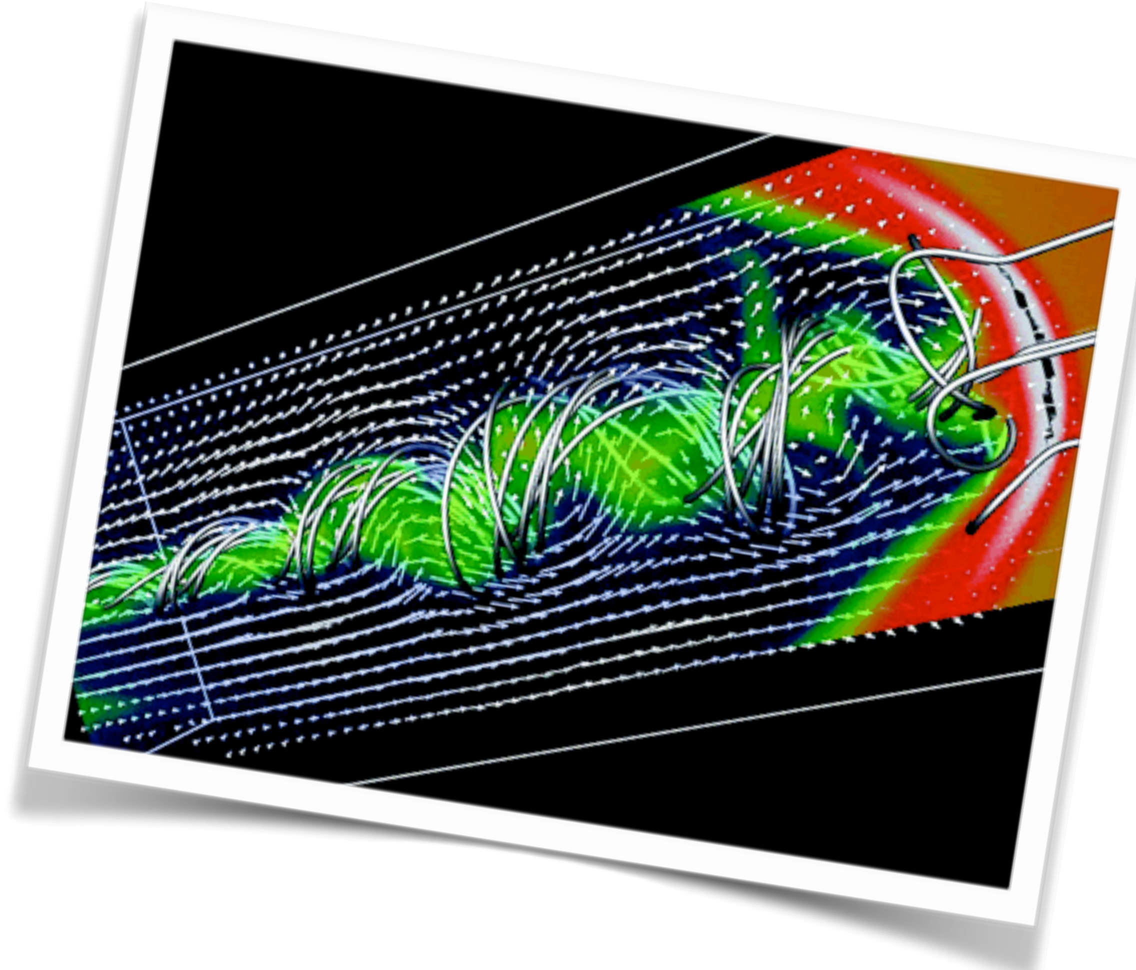




SED dominated by the relativistically boosted non-thermal continuum emission of the jet.

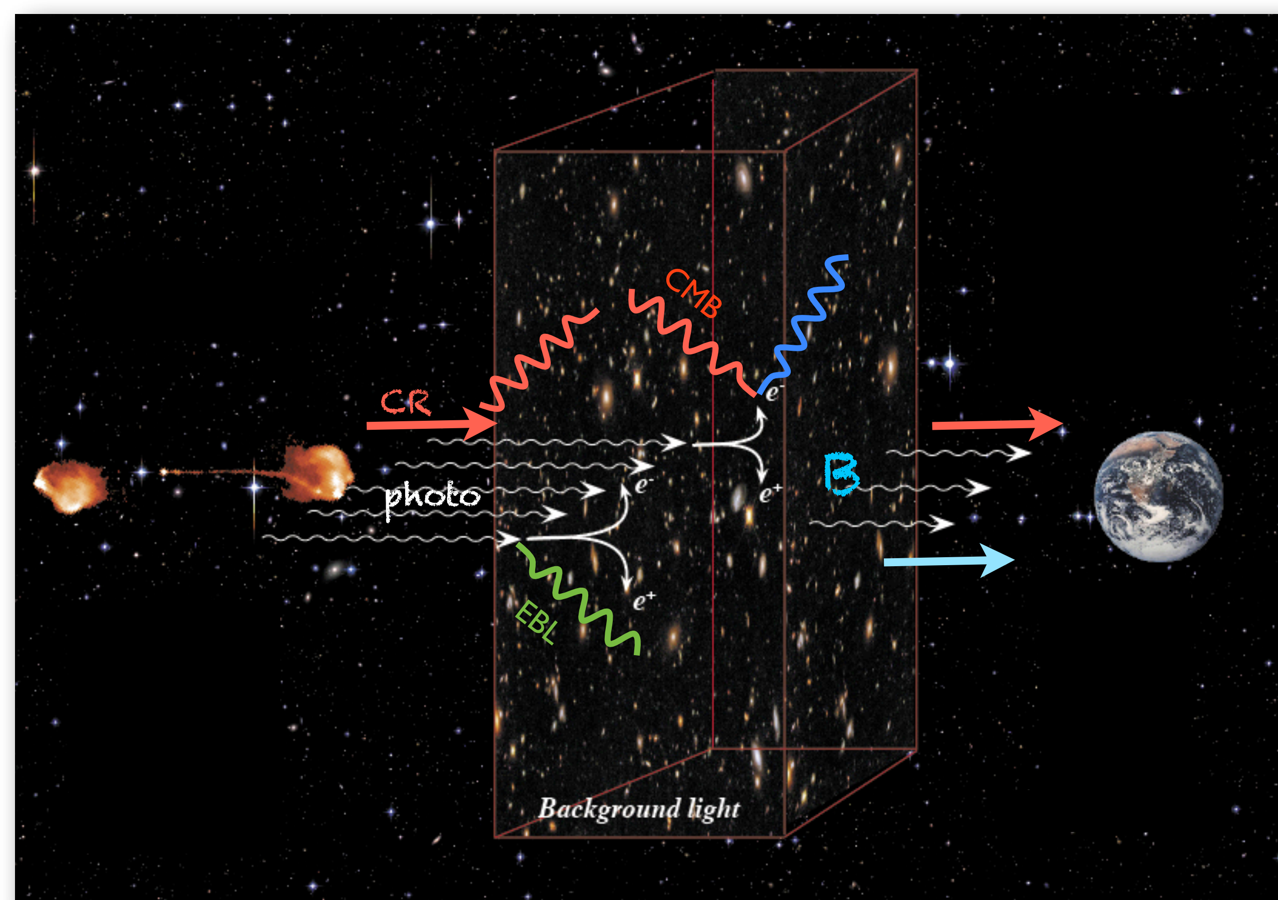
Jet physics

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



Propagation effects

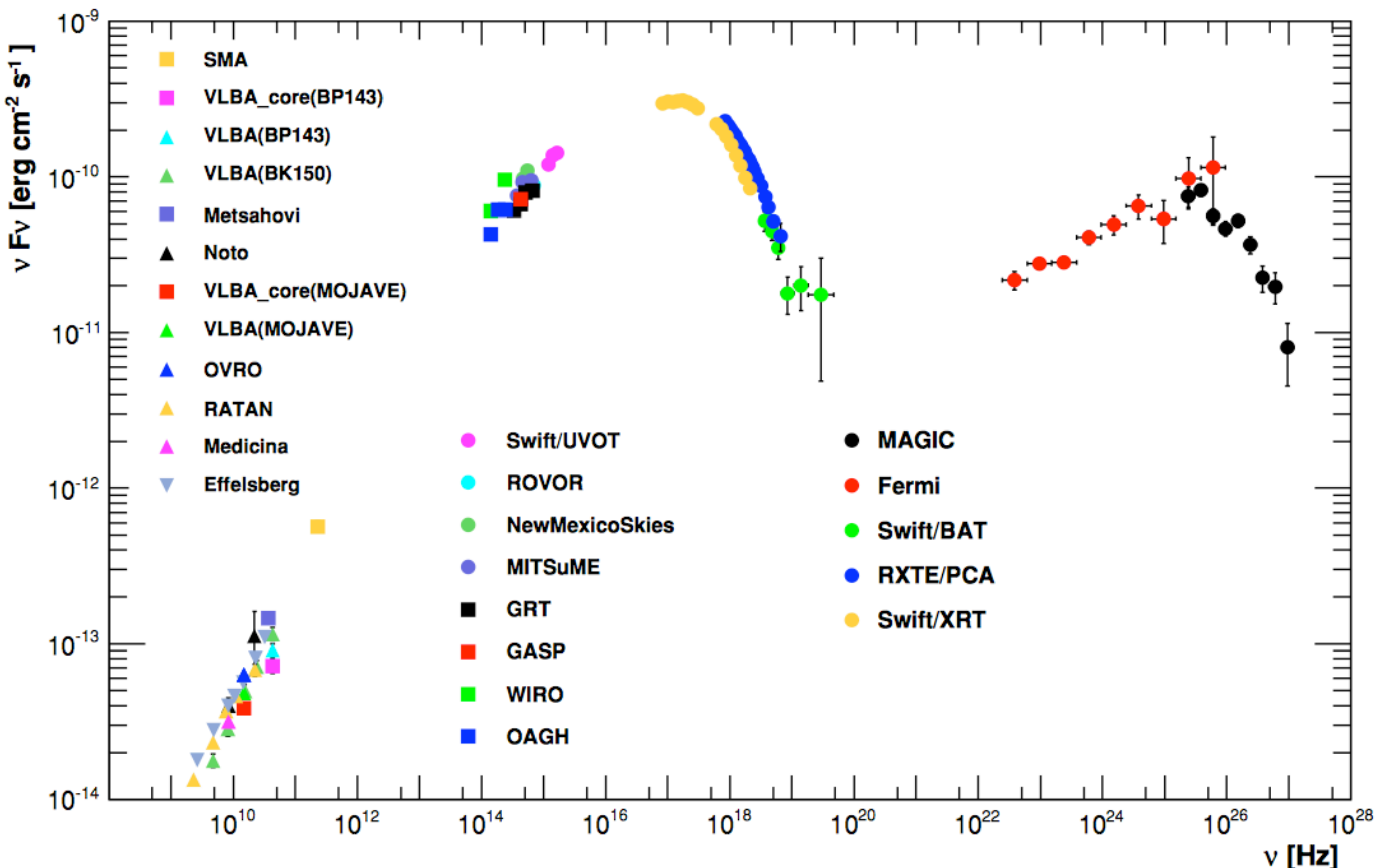
Extragalactic background light
Intergalactic magnetic field
Hadronic beams
LIV and ALPs-induced effects and other anomalies



The spectral energy distribution

Extended over the whole EM spectrum
Extremely variable

Important observational effort



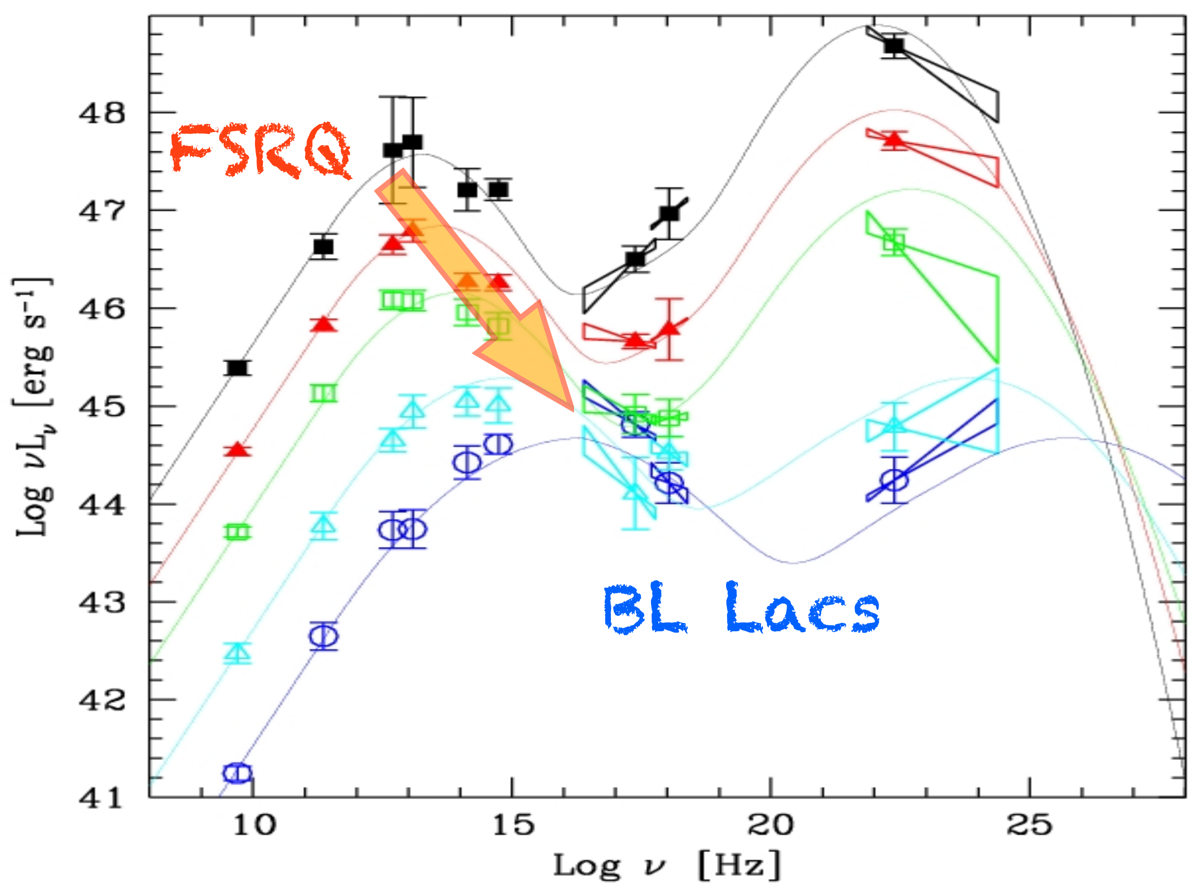
Abdo et al. 2011

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



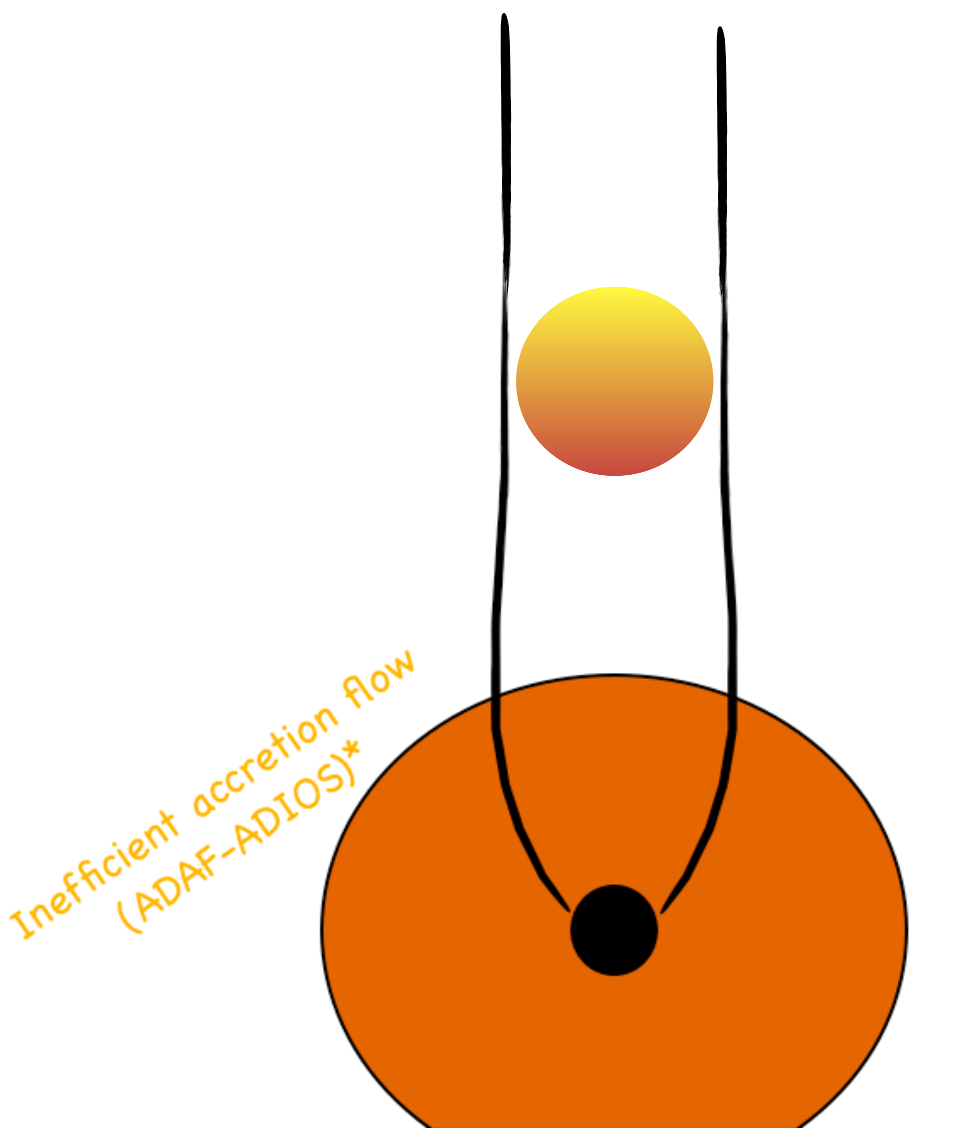
The "blazar sequence"

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

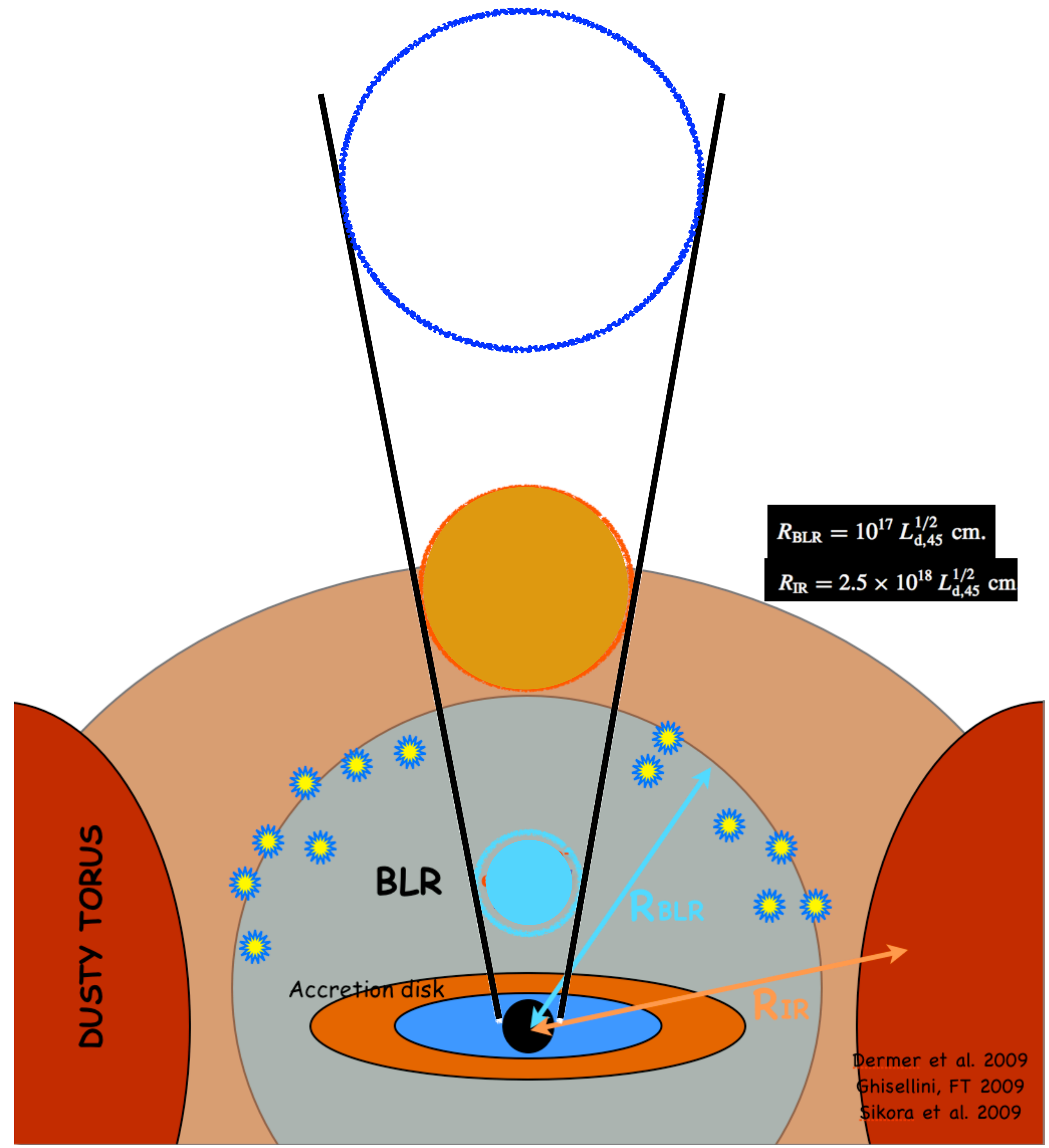
But see several papers by Giommi & Padovani

Blazars in a nutshell

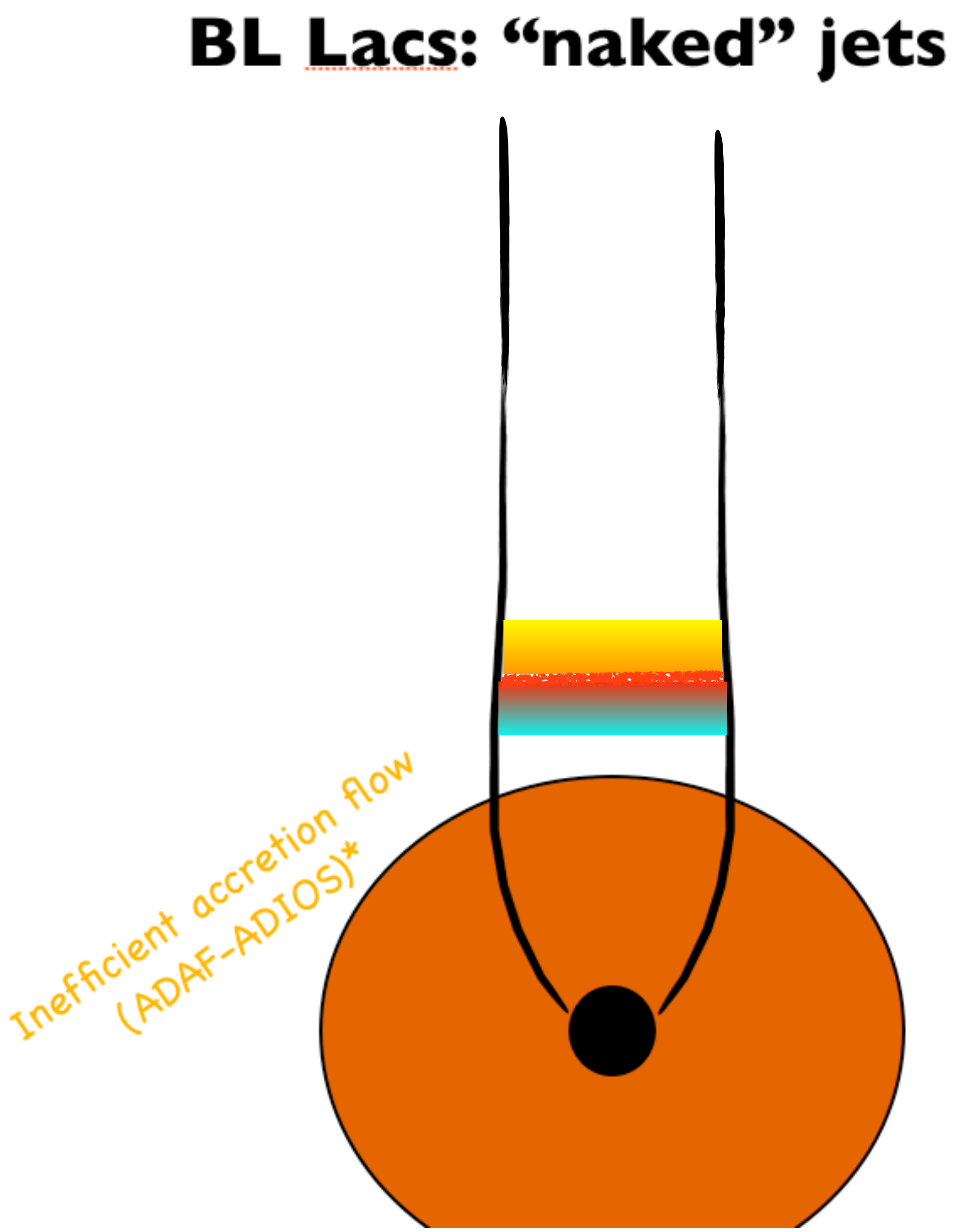
BL Lacs: "naked" jets

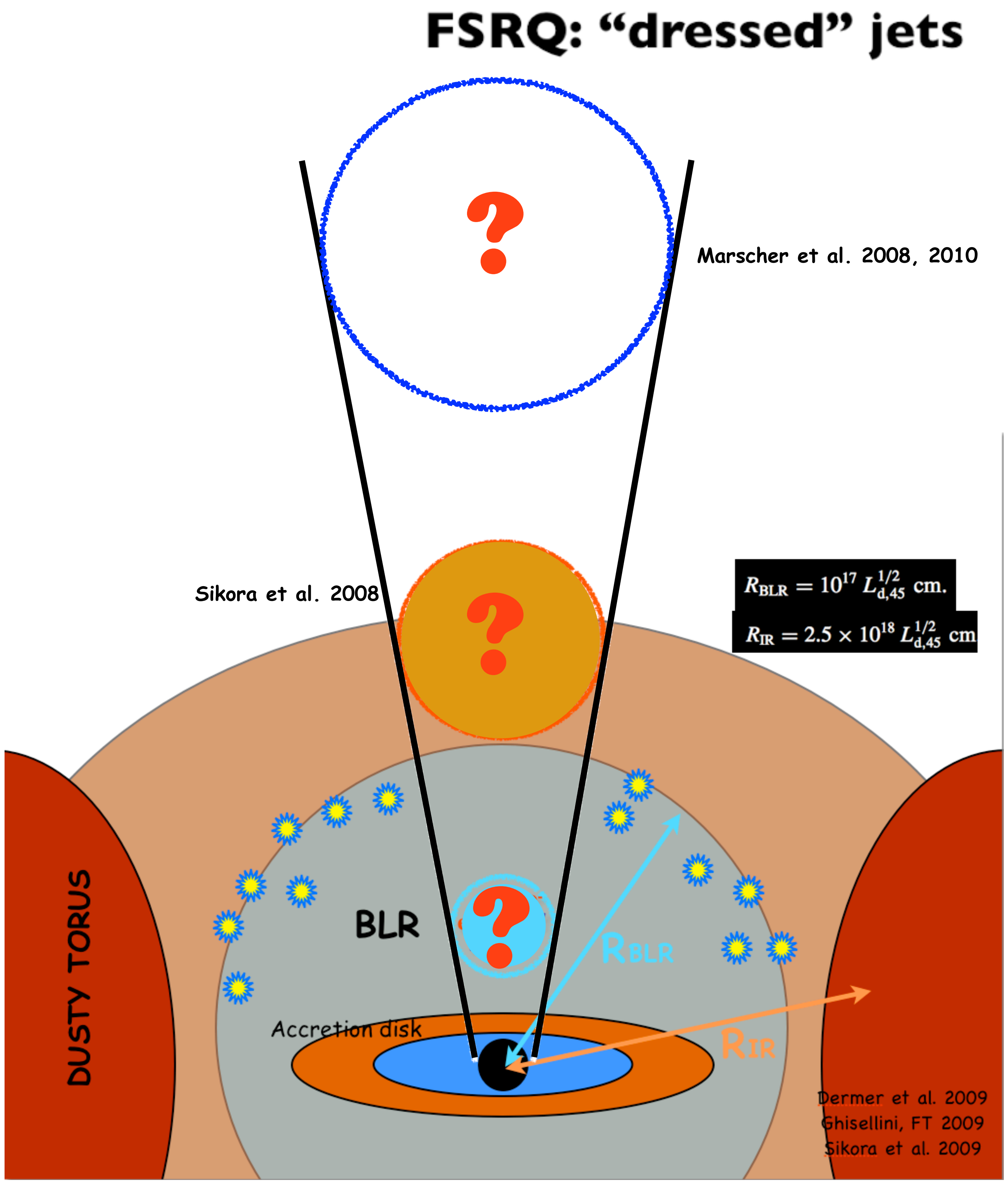


FSRQ: "dressed" jets

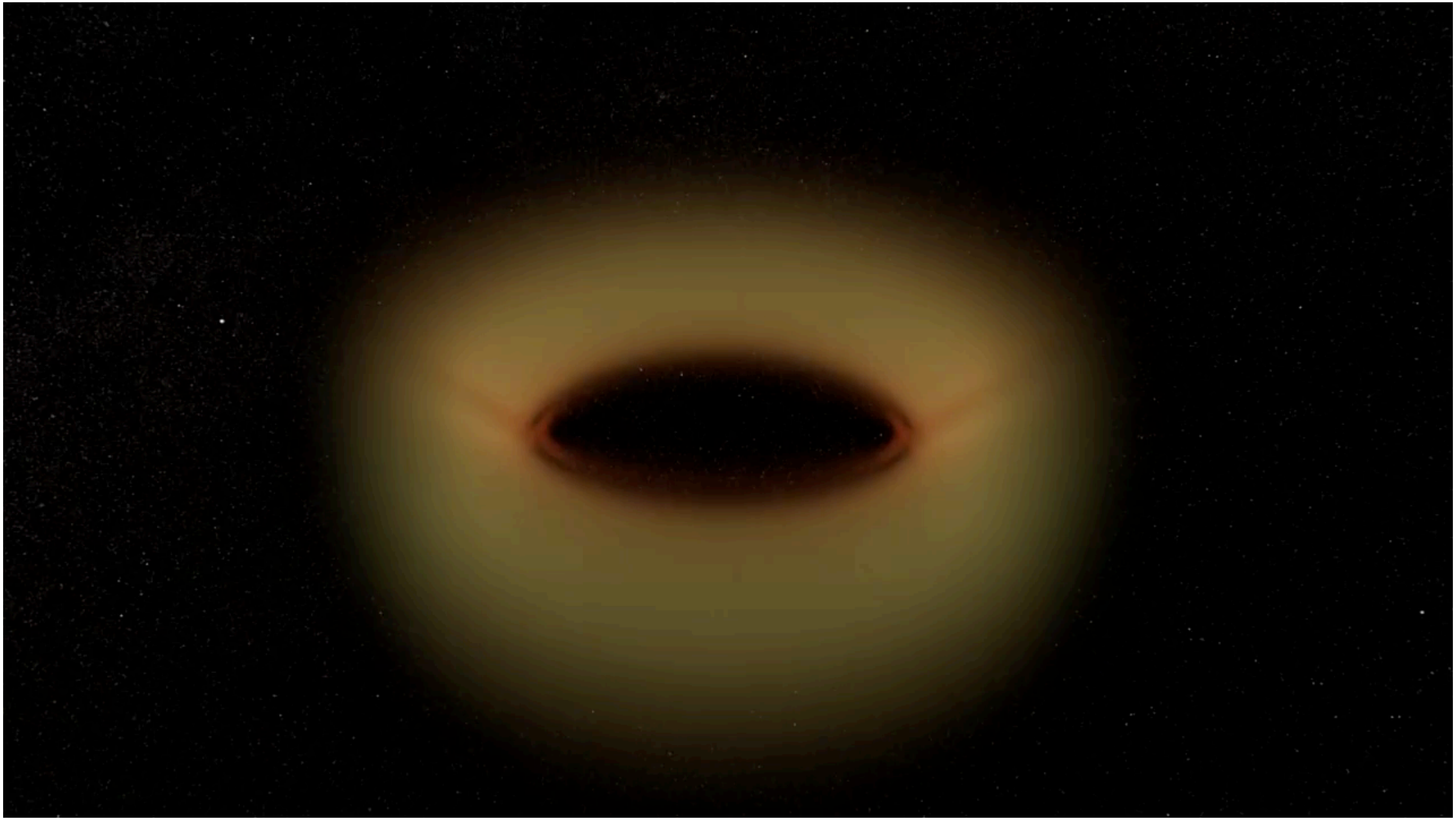


Blazars in a nutshell



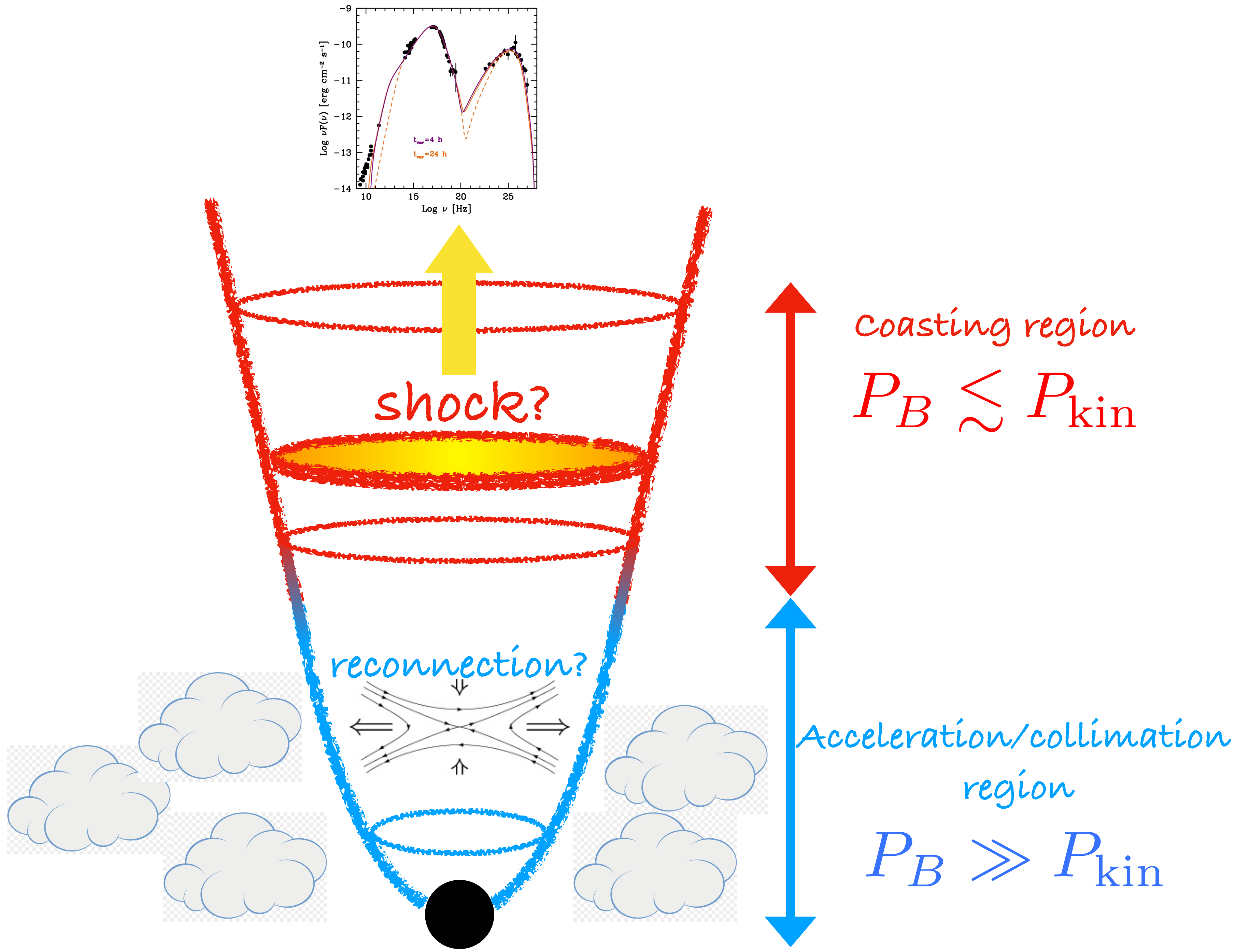


Producing the jet

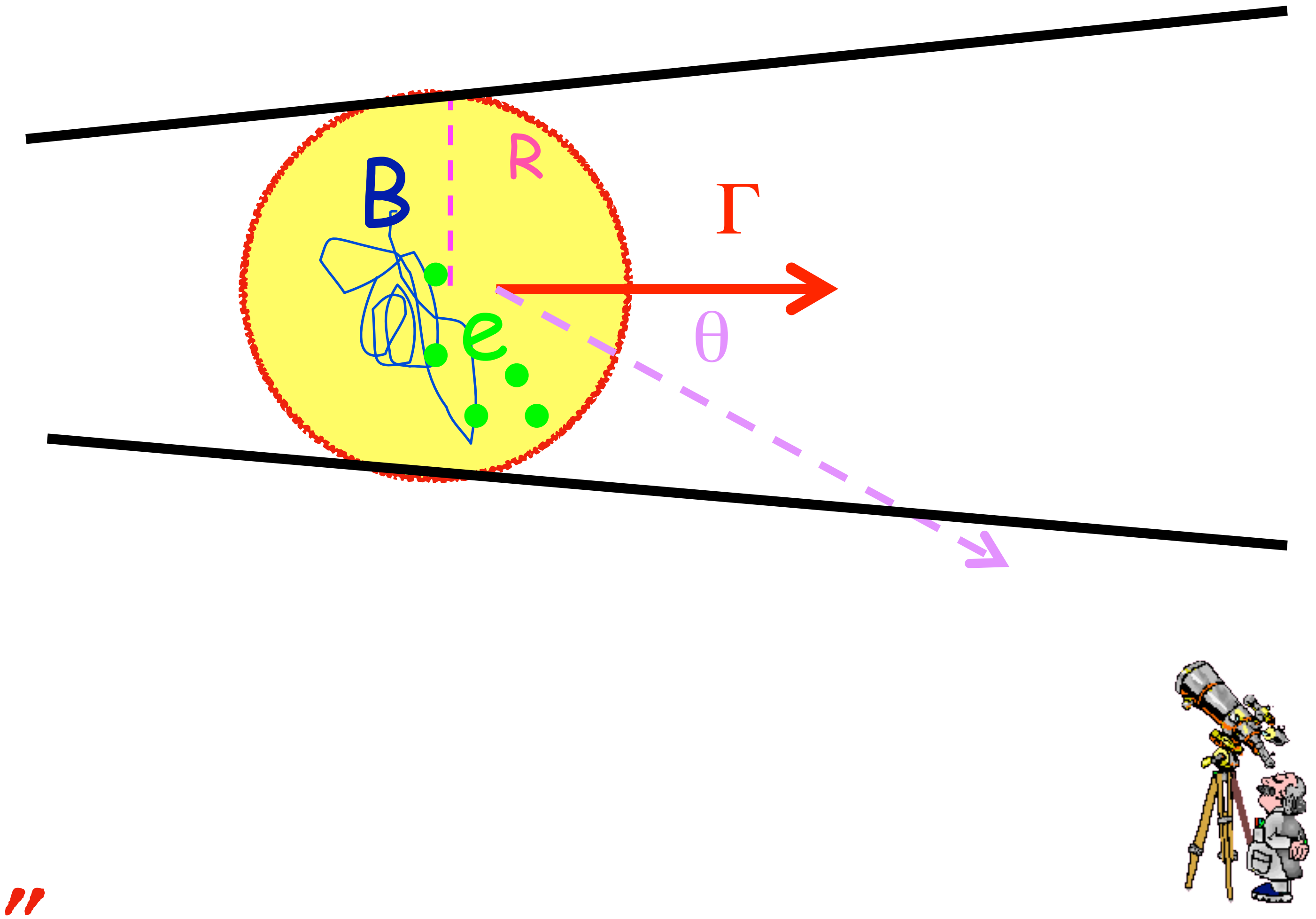


McKinney, Tchekhovskoy, and Blandford 2012

The full problem

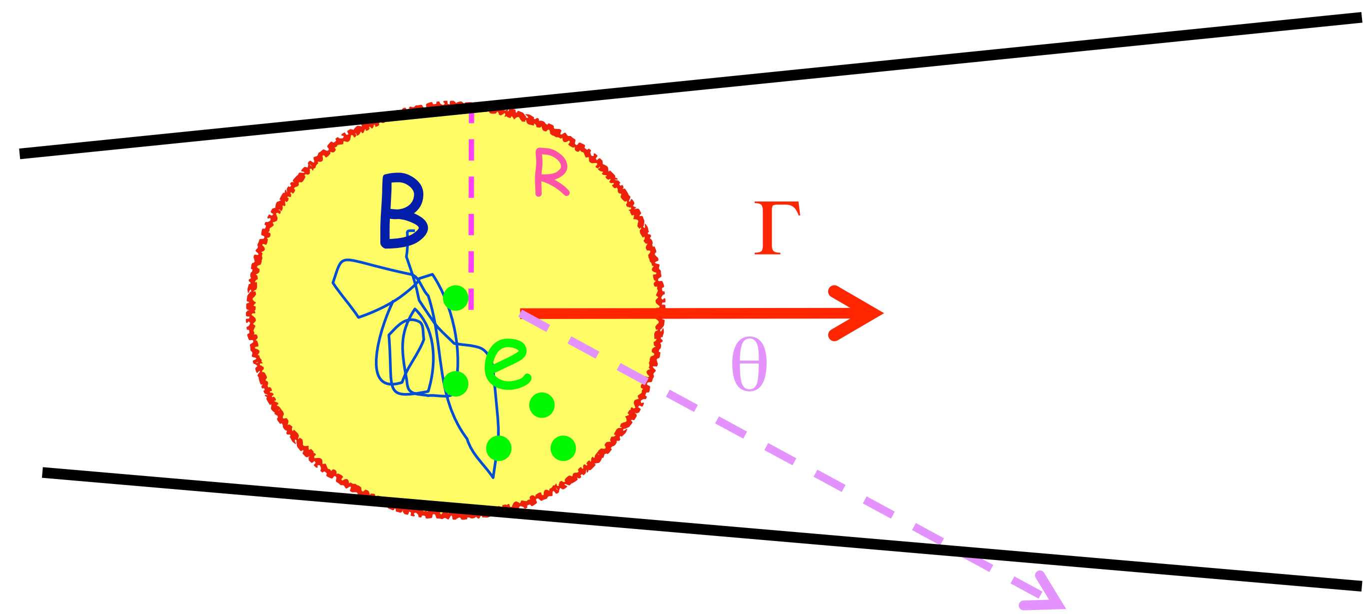


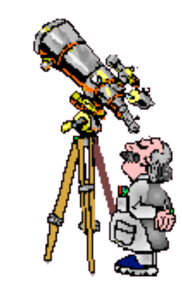
A more modest model - 1

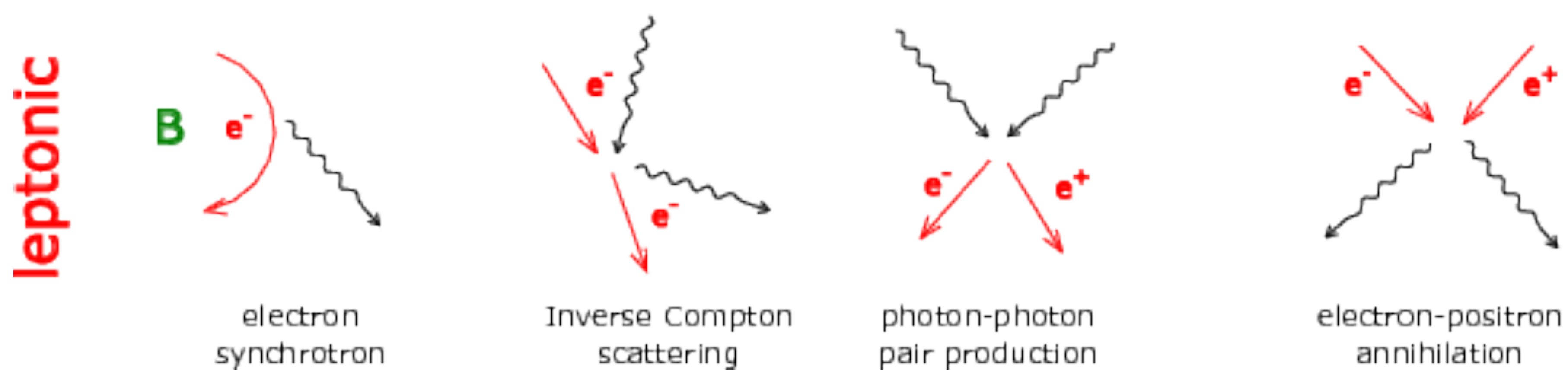


"One zone"

A more modest model - 1

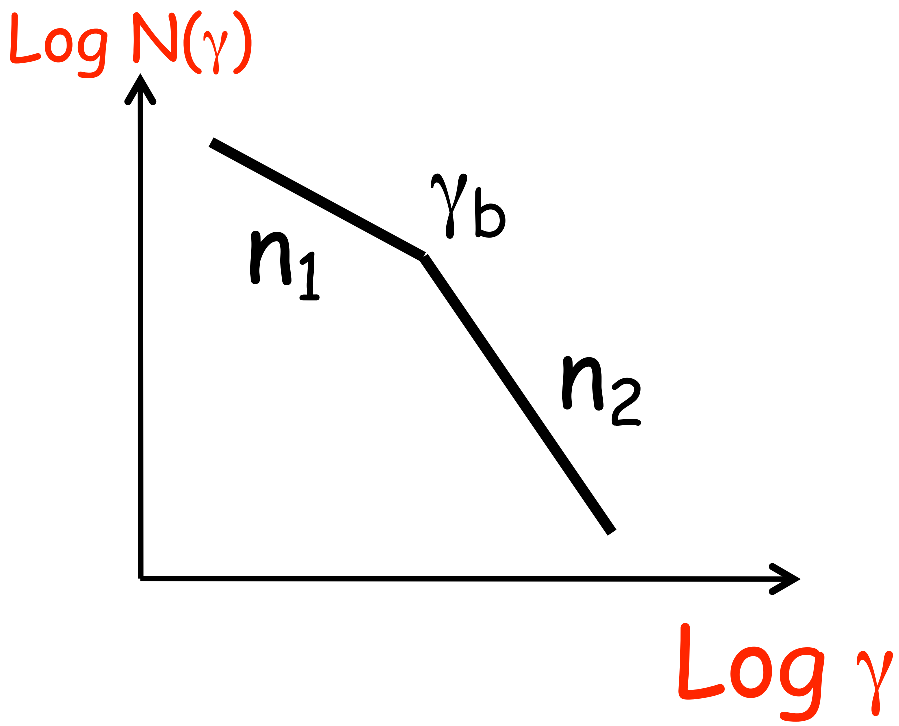


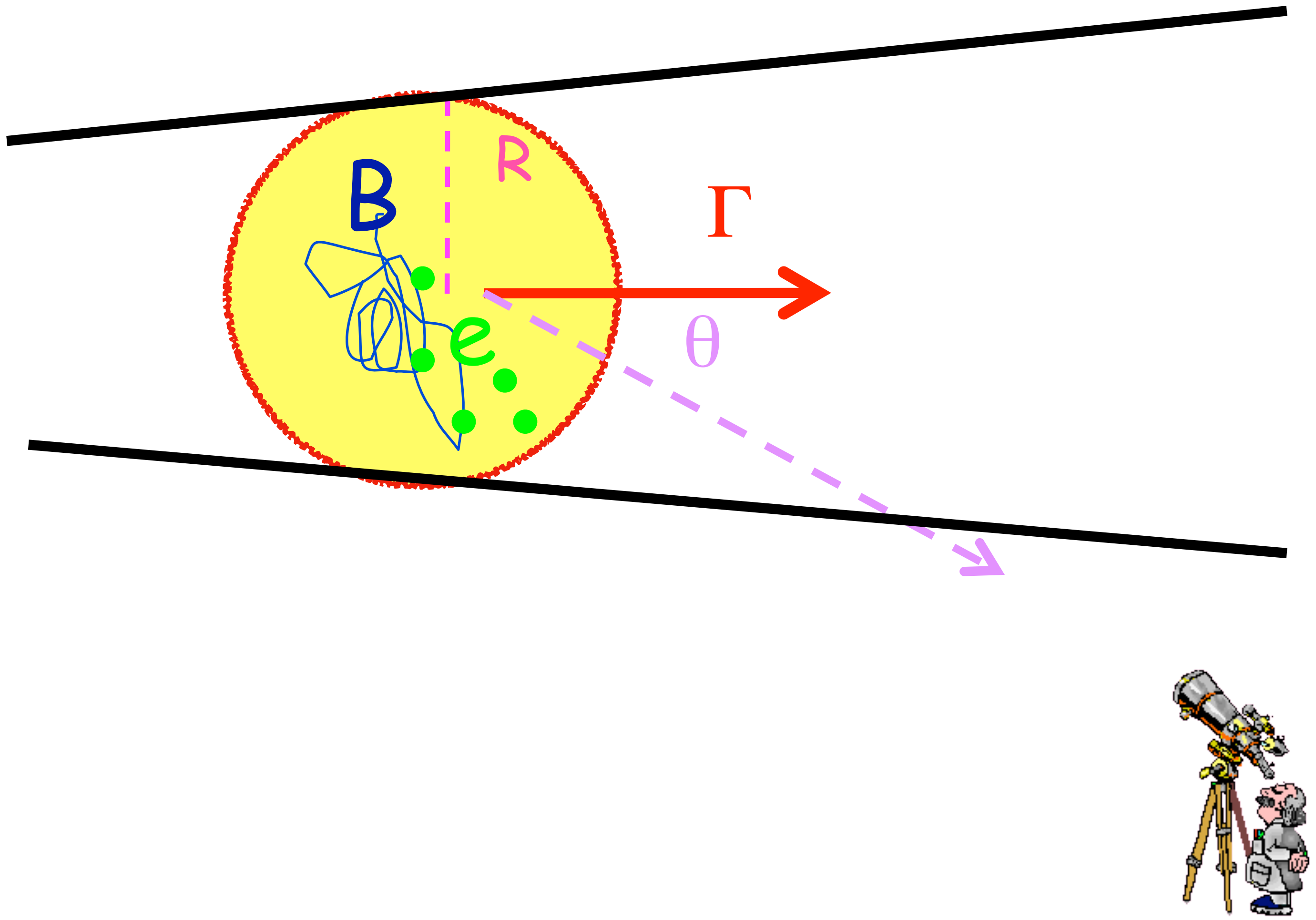




Hadron not important for the emission (but not for energetics!)

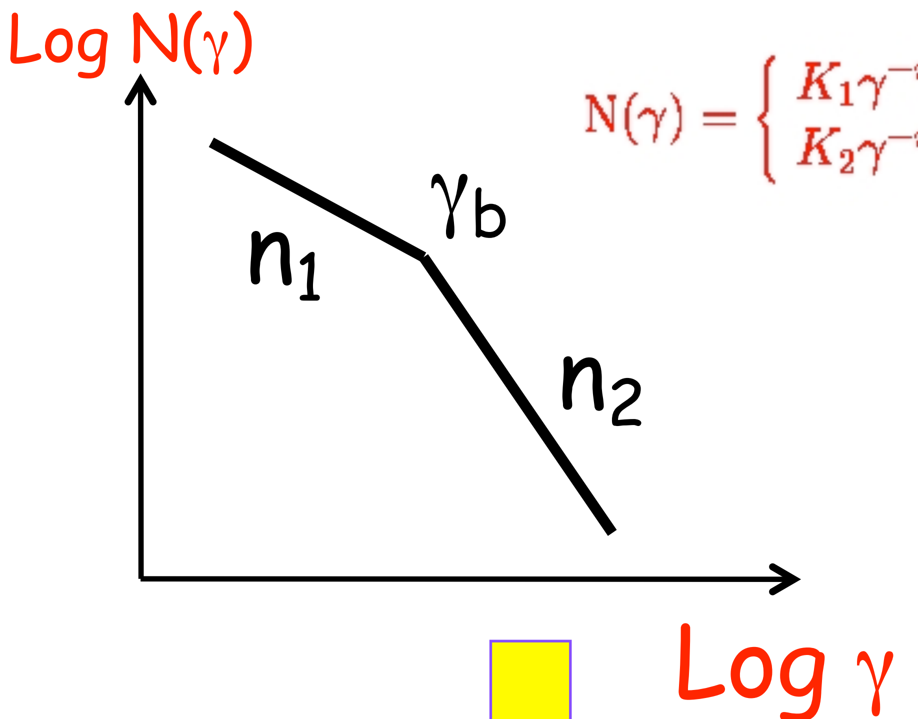
A more modest model - 1





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

A more modest model - 1



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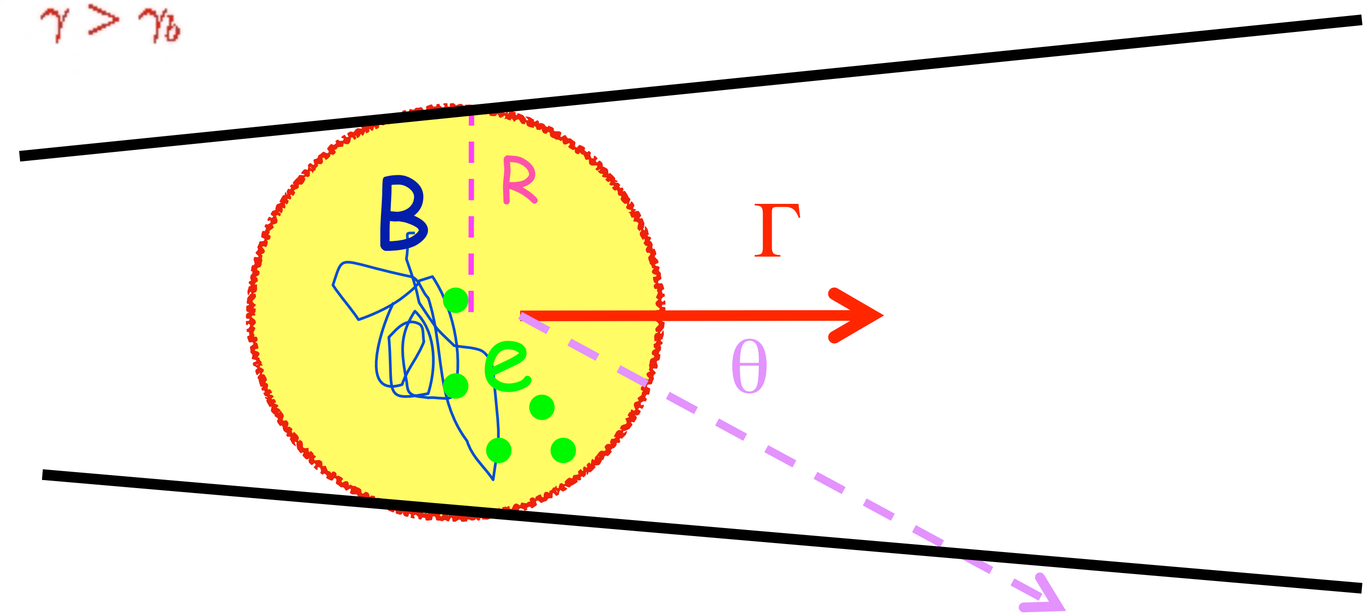
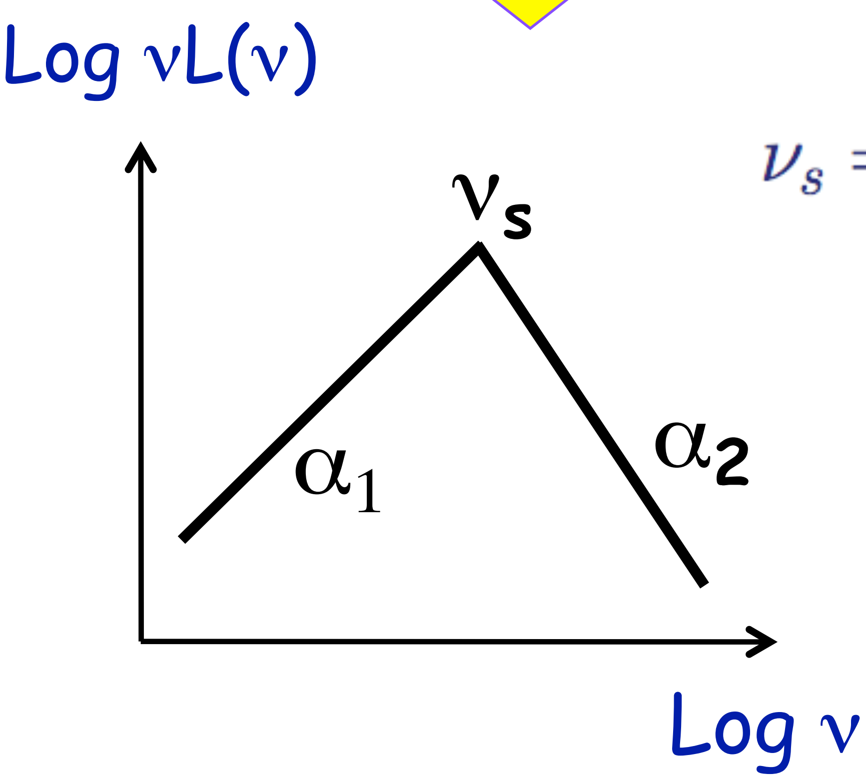
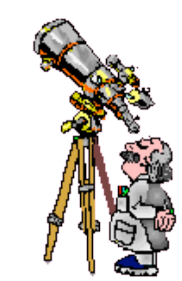


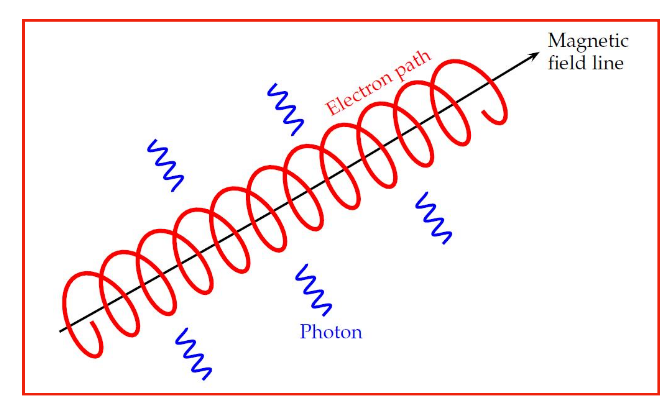


$$\nu_s = 3 \times 10^6 B \gamma_b^2 \delta$$

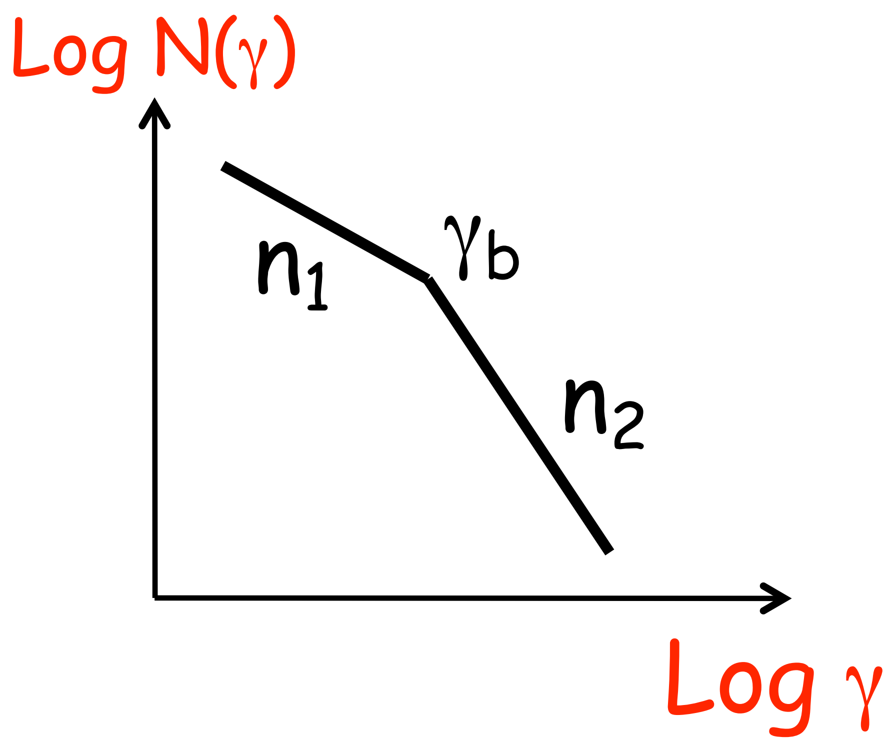
$$\alpha_i = \frac{n_i - 1}{2}$$



Synchrotron emission



A more modest model - 1



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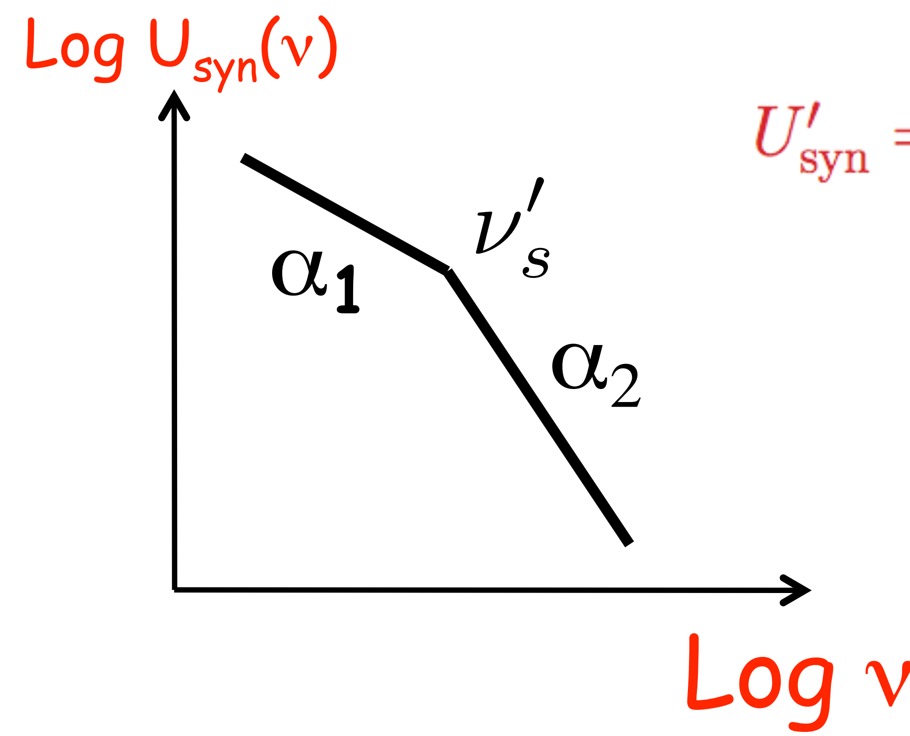
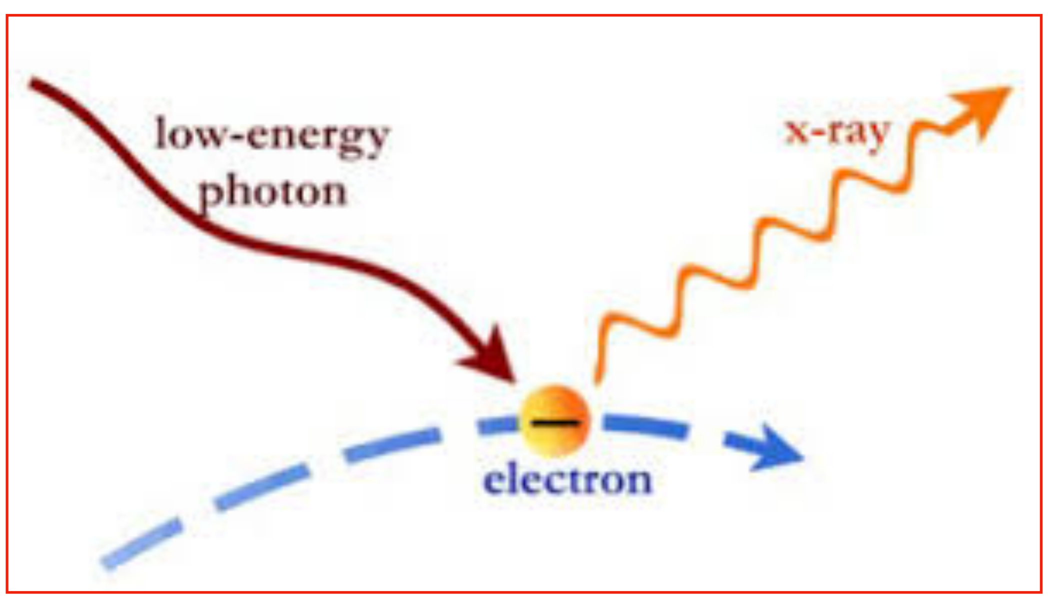
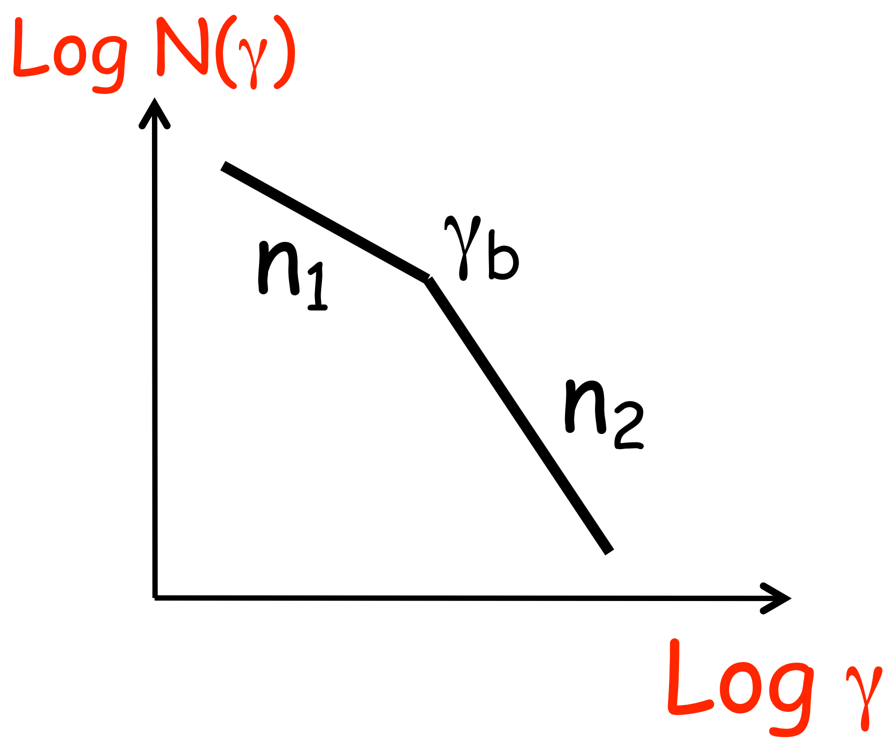


$$U'_{\rm syn} = \frac{\nu_s L(\nu_s)}{4\pi R^2 c \delta^4}$$

Inverse Compton



A more modest model - 1



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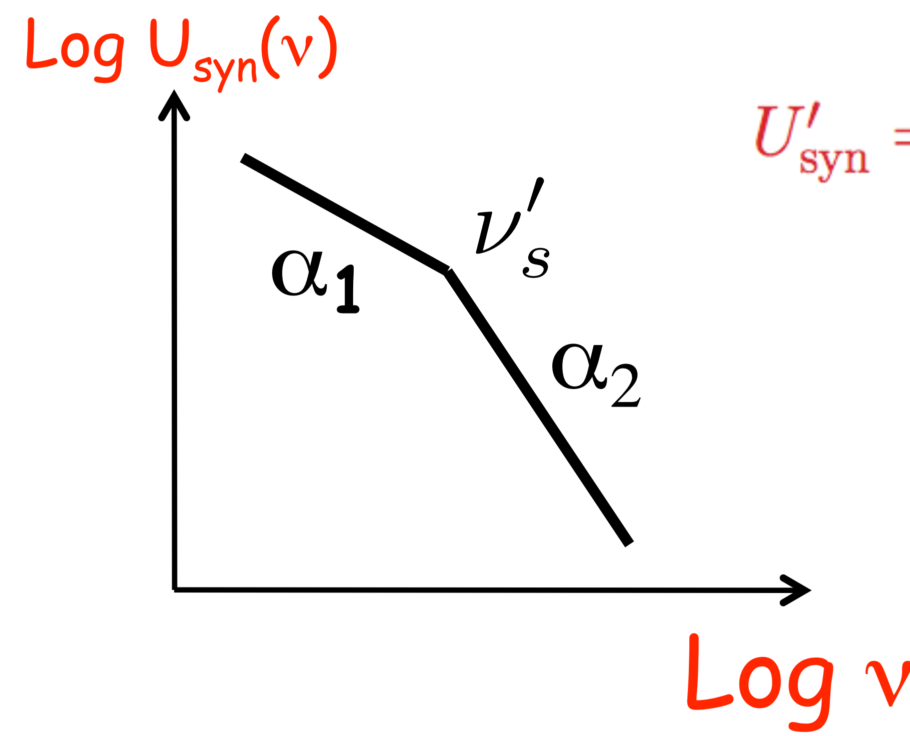
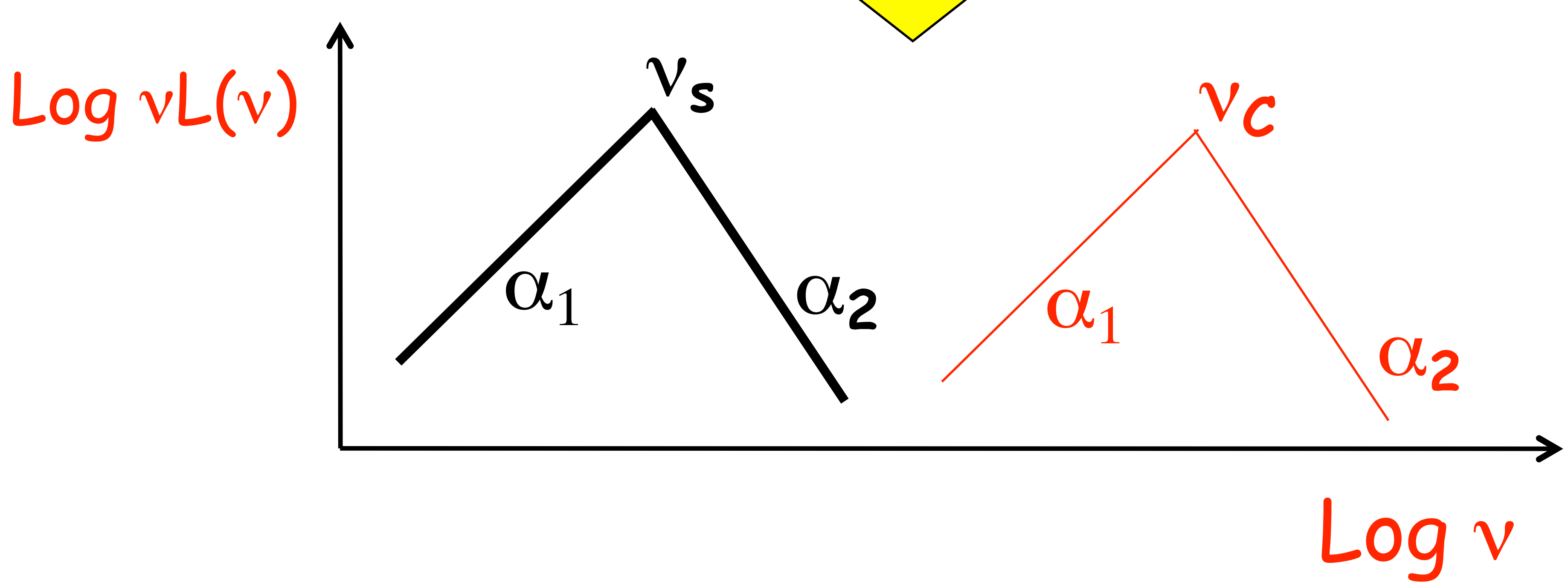


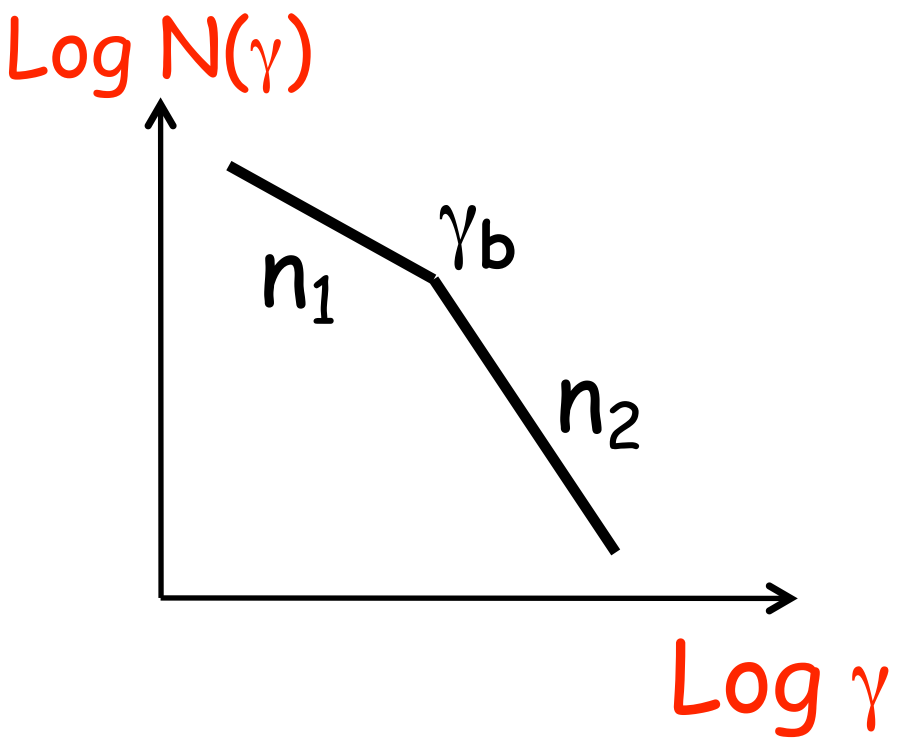
$$U'_{\rm syn} = \frac{\nu_s L(\nu_s)}{4\pi R^2 c \delta^4}$$

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



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

A more modest model - 1



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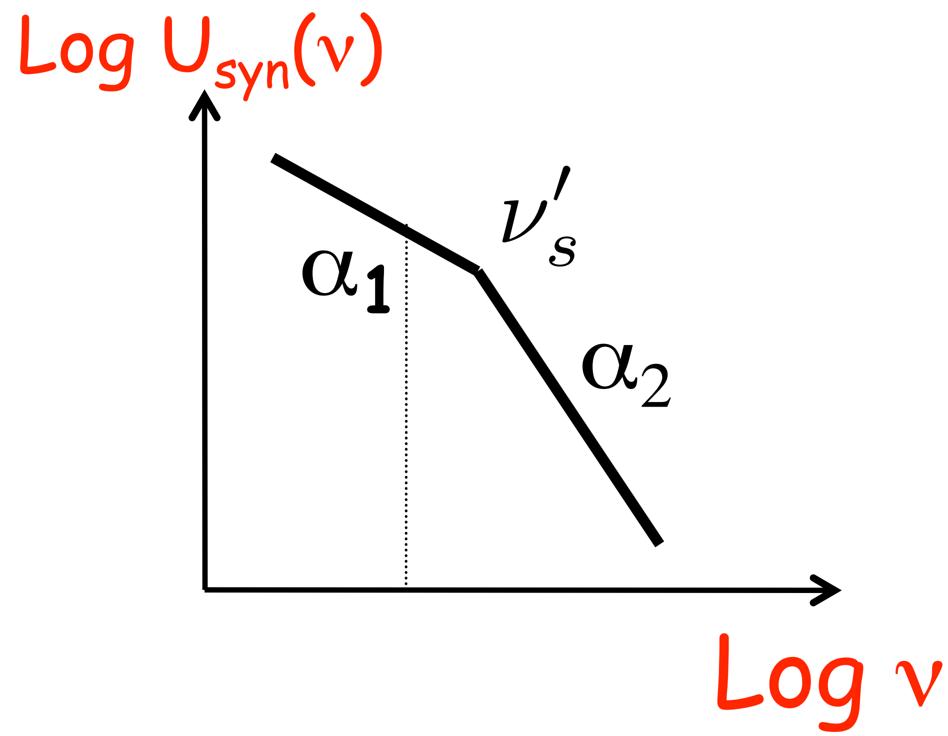
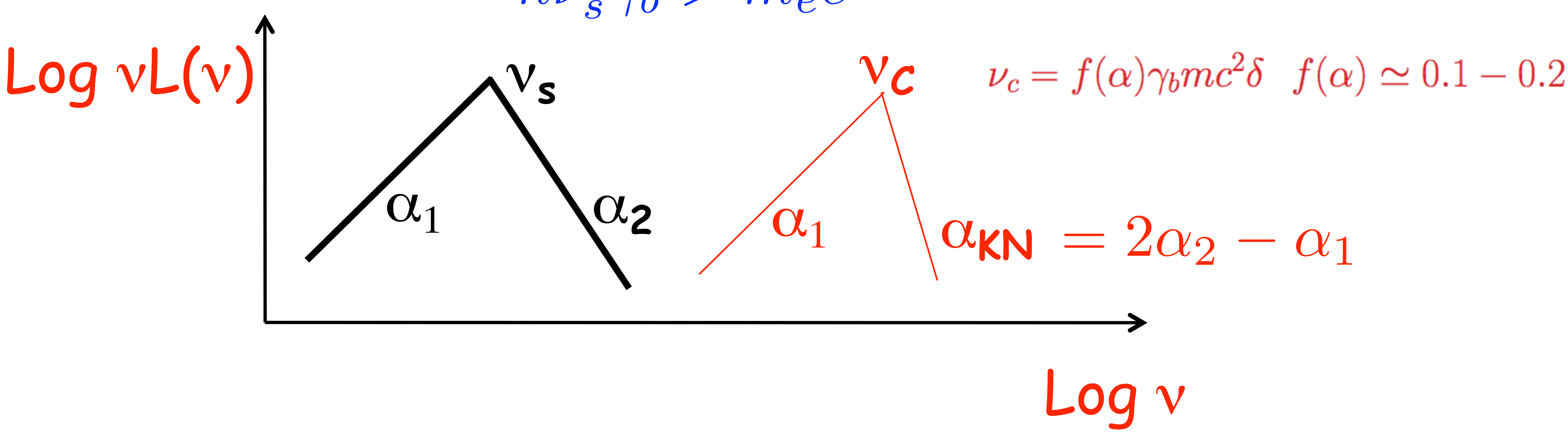


"Klein-Nishina regime"

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



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

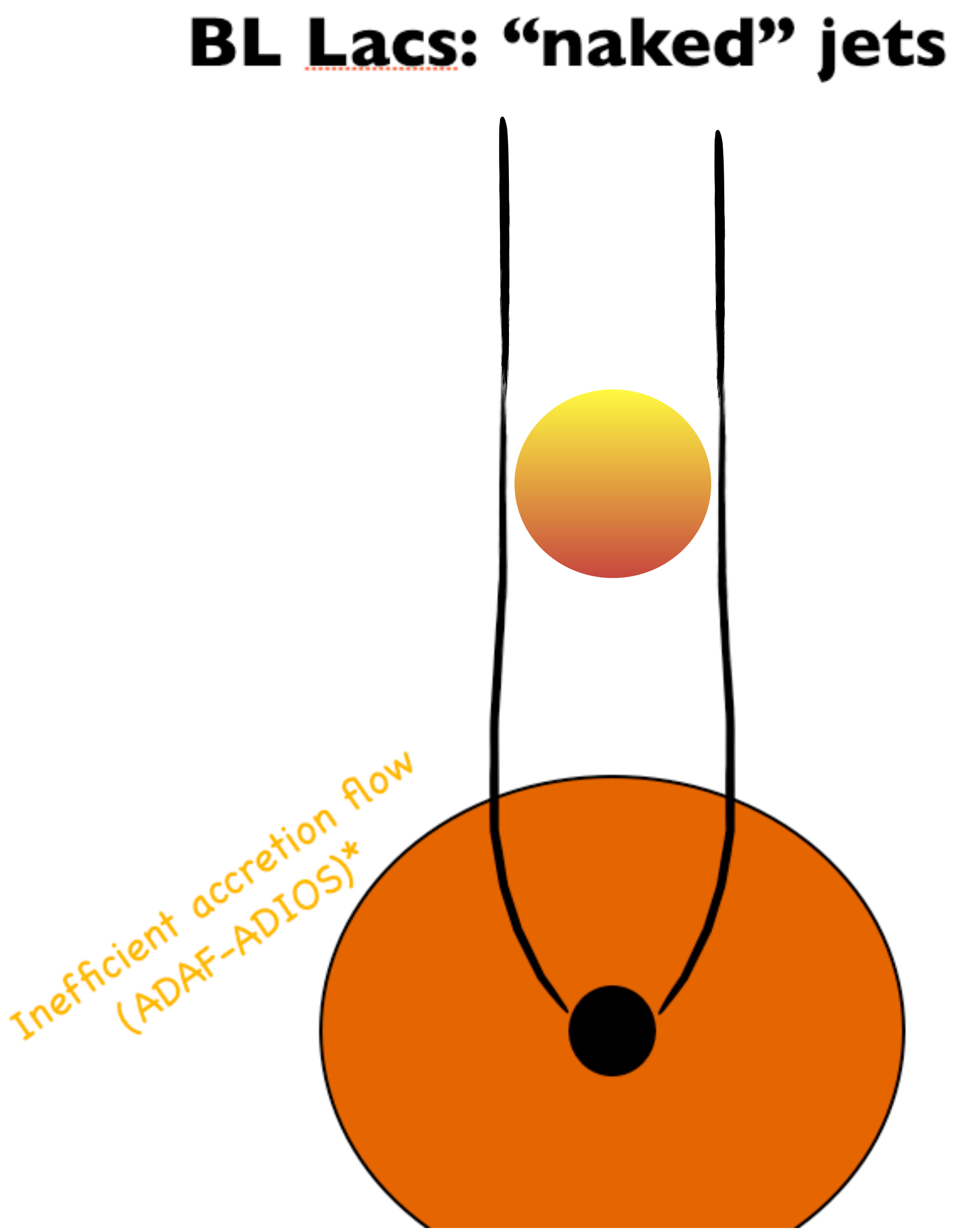
R B N_o γ_b n_1 n_2 δ

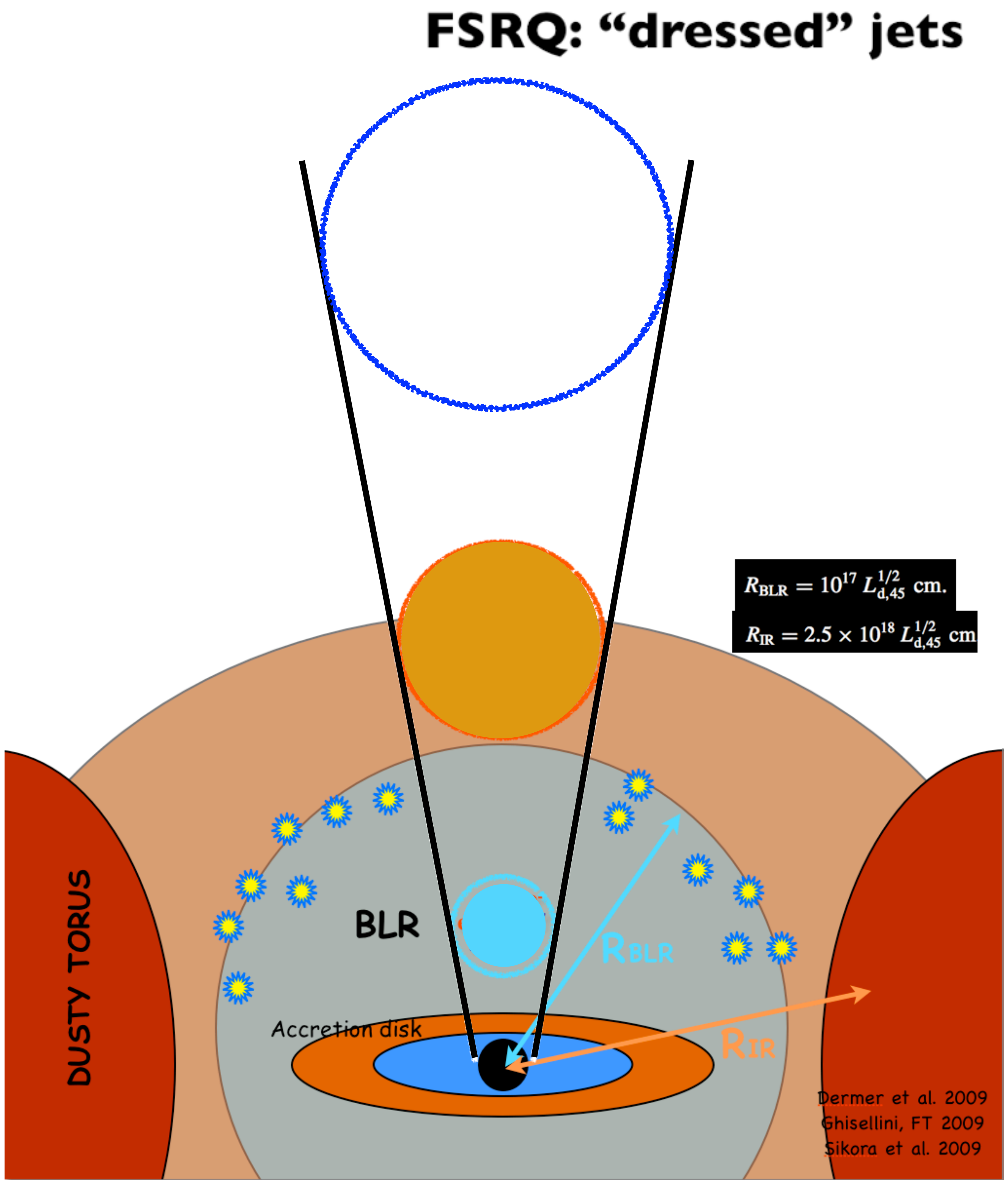
7 observational quantities

ν_s L_s ν_C L_C t_{var} α_1 α_2

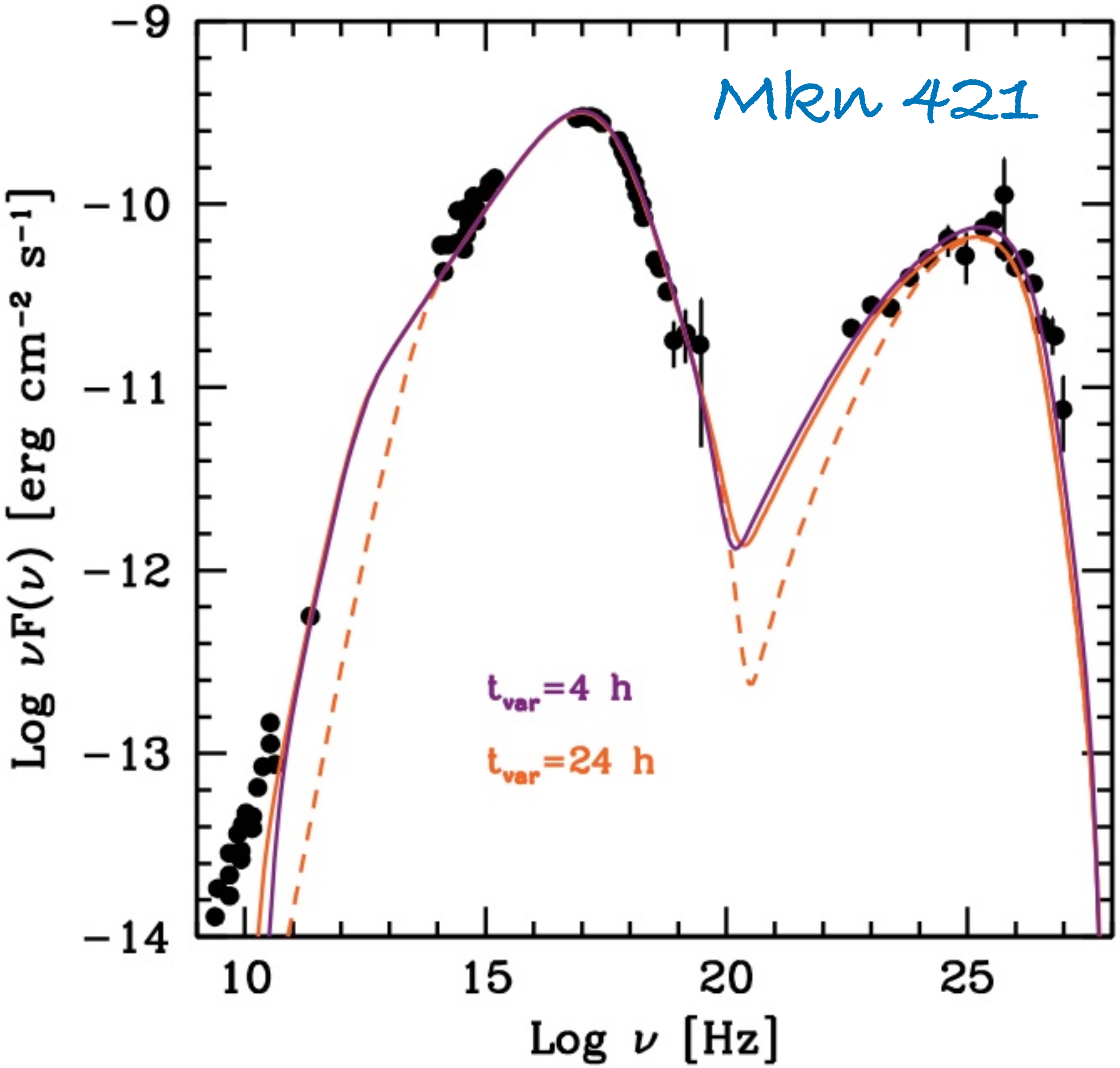
Tavecchio, Maraschi & Ghisellini 1998

Blazars in a nutshell





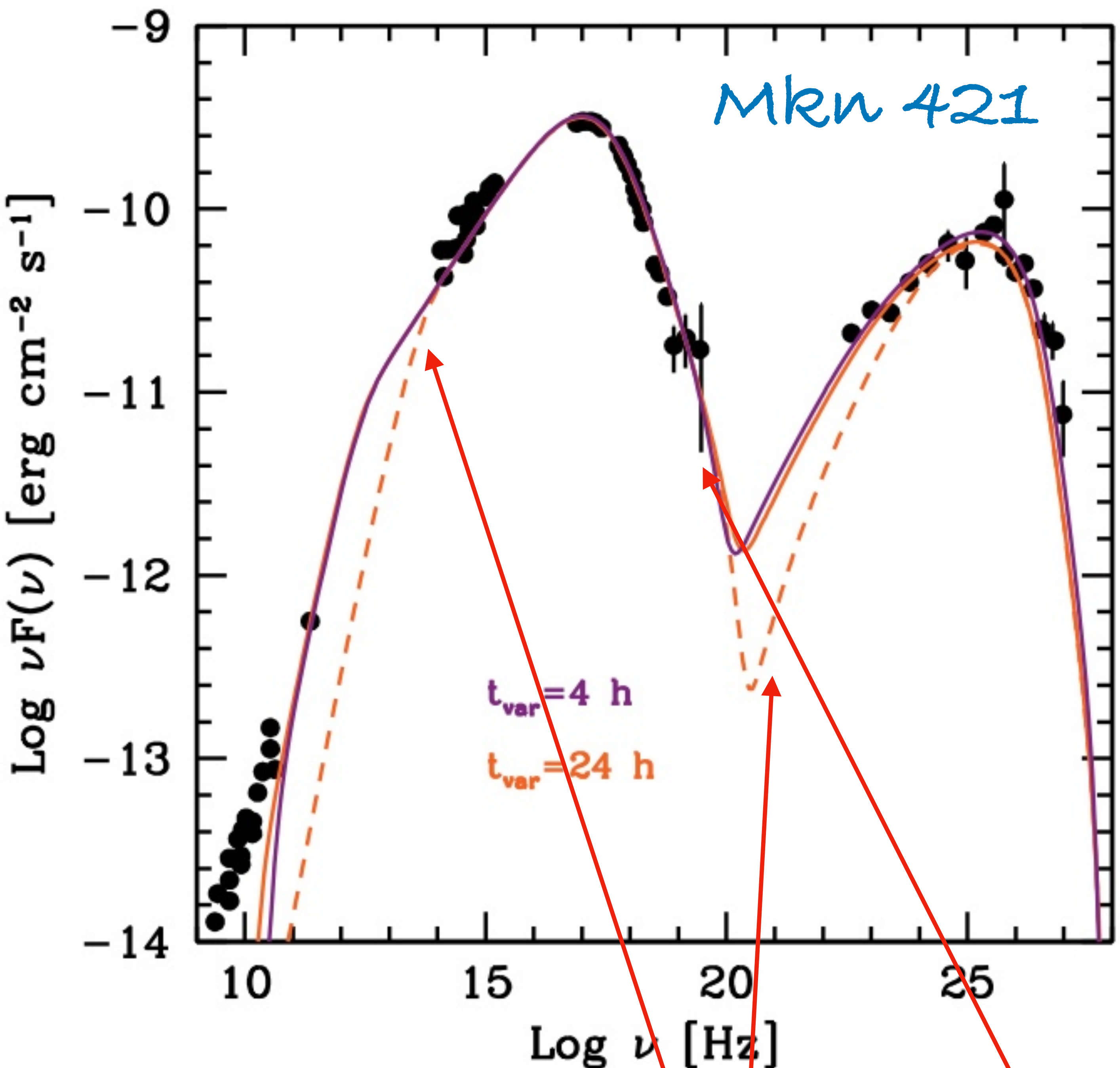
Application: BL Lacs



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 and Ghisellini 2016

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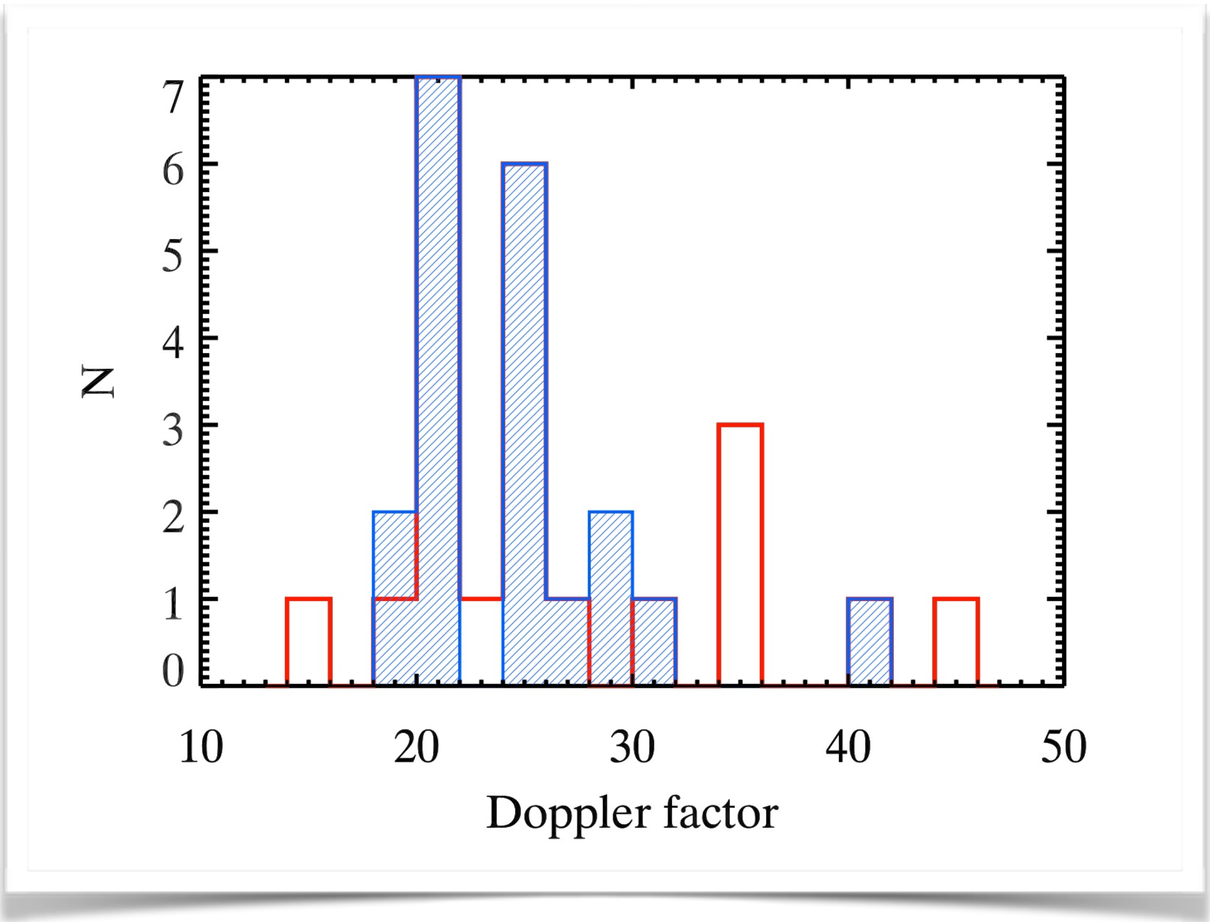
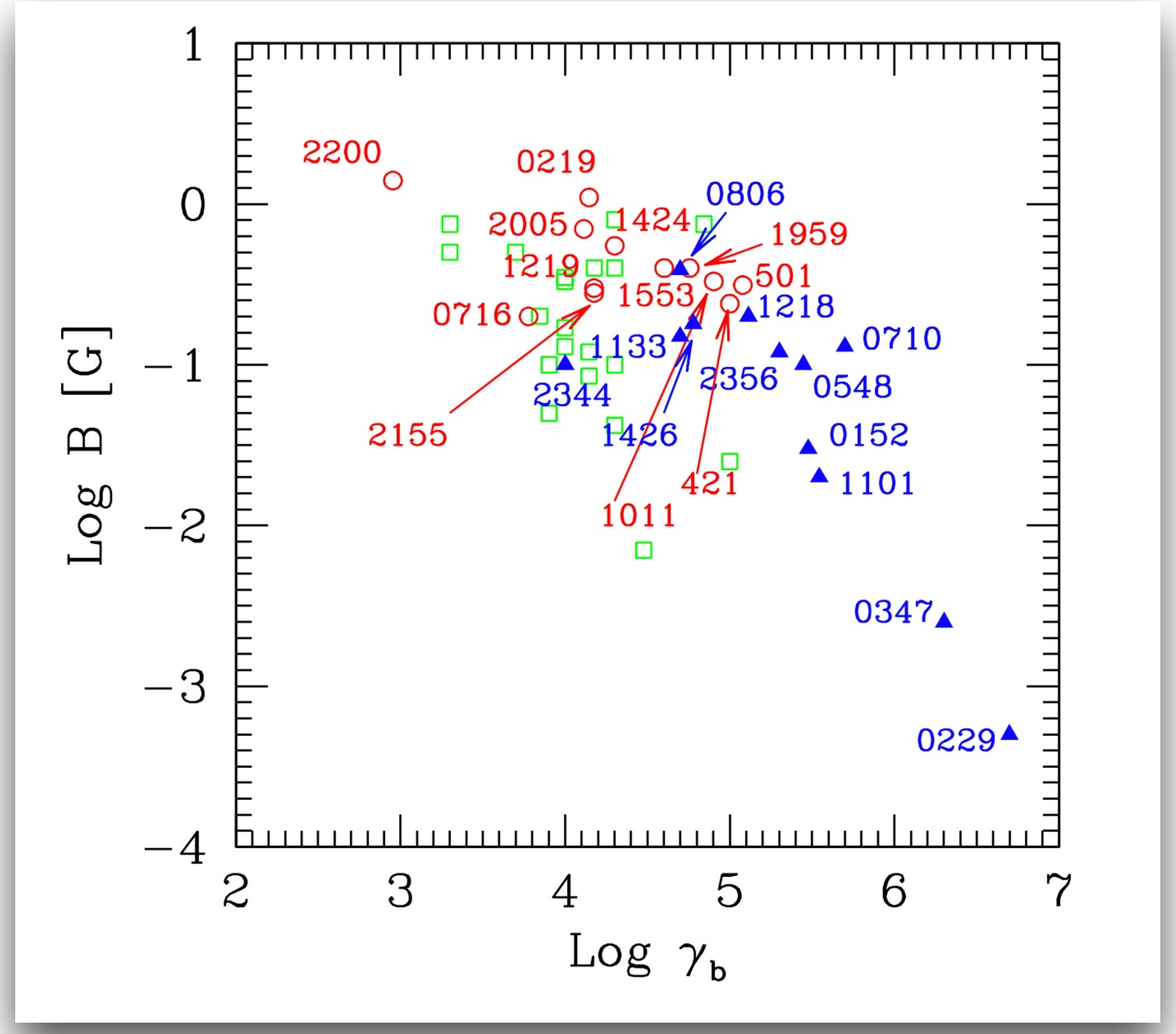
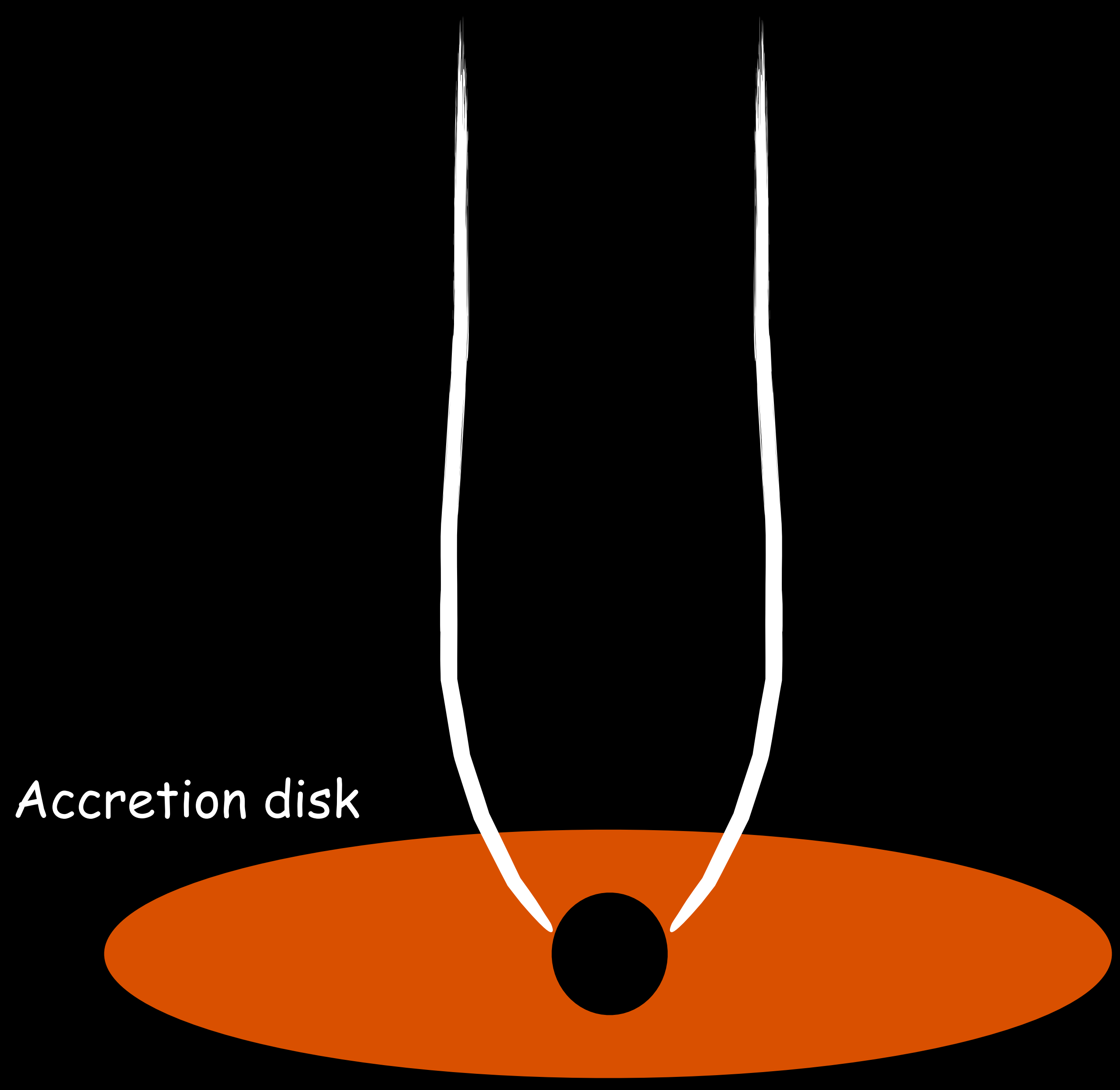
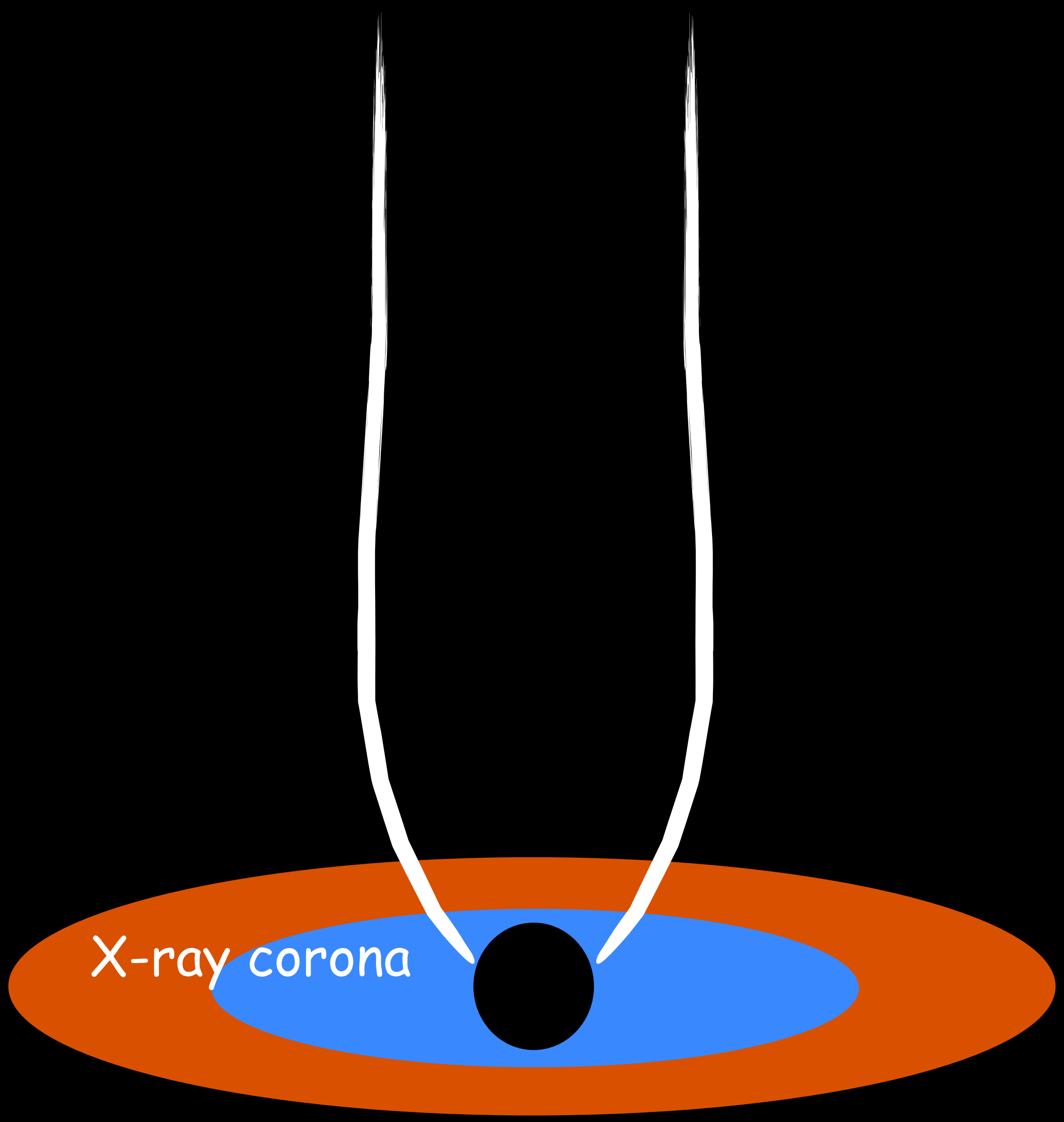




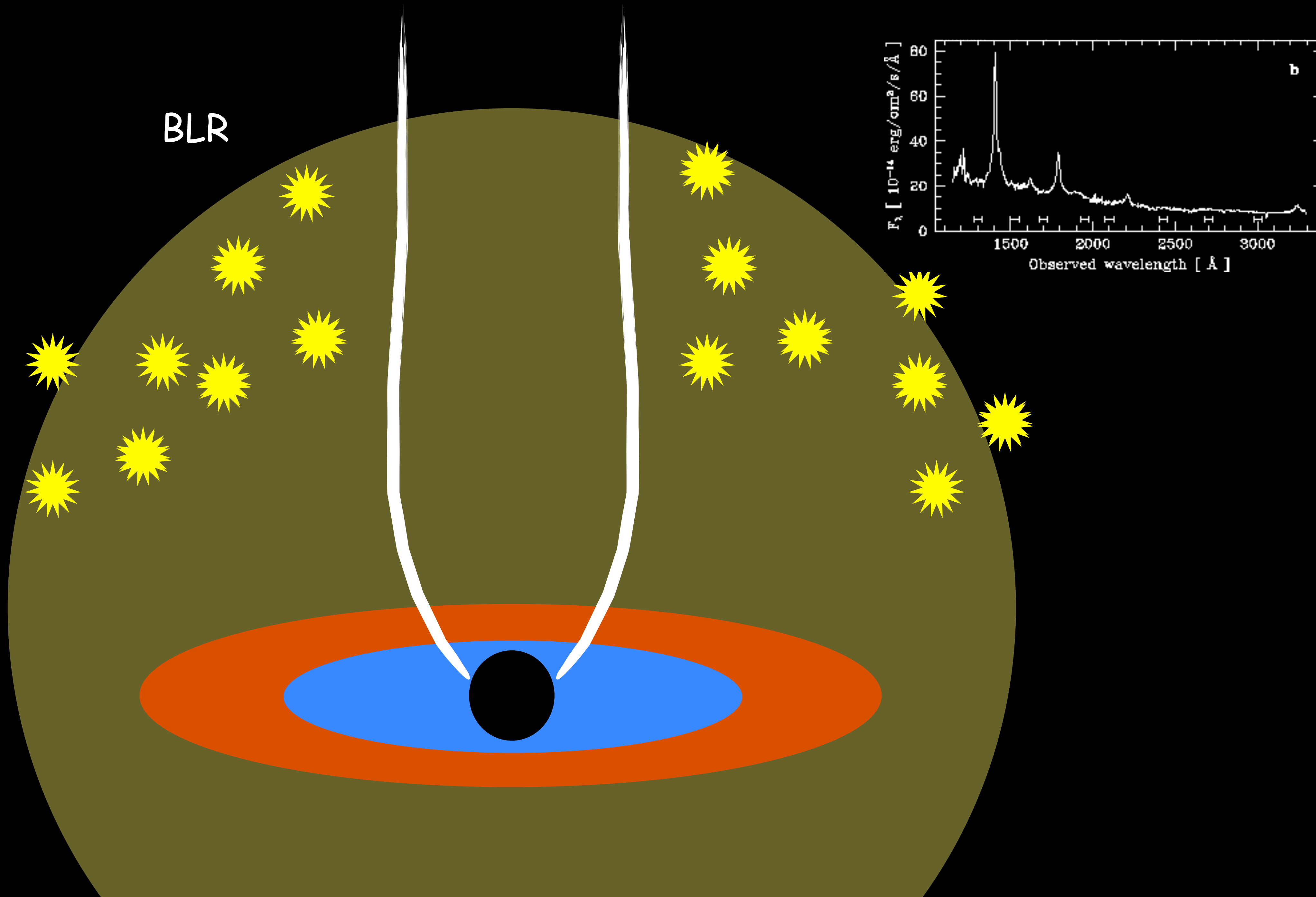
FSRQs: the general scenario



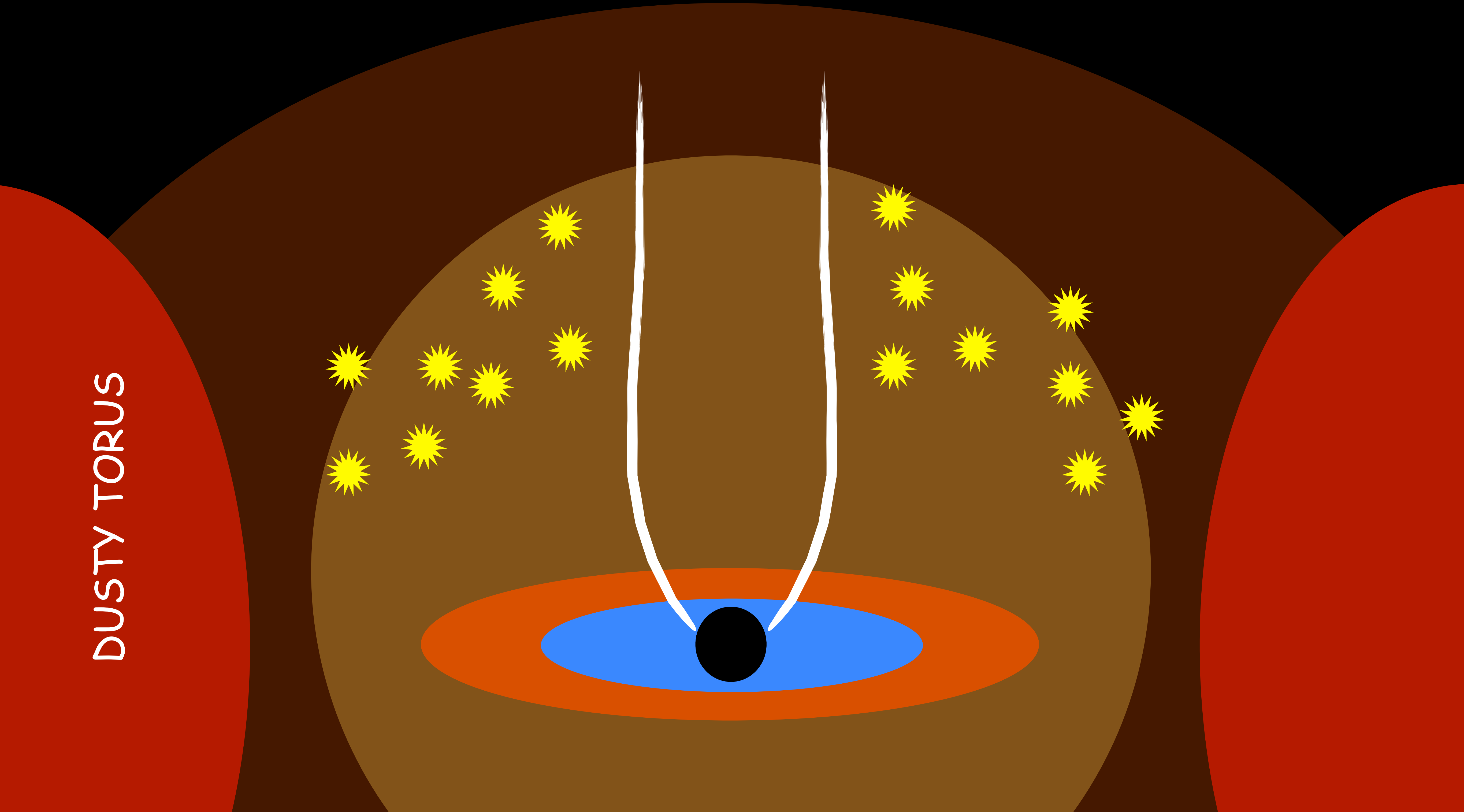
FSRQs: the general scenario



FSRQs: the general scenario

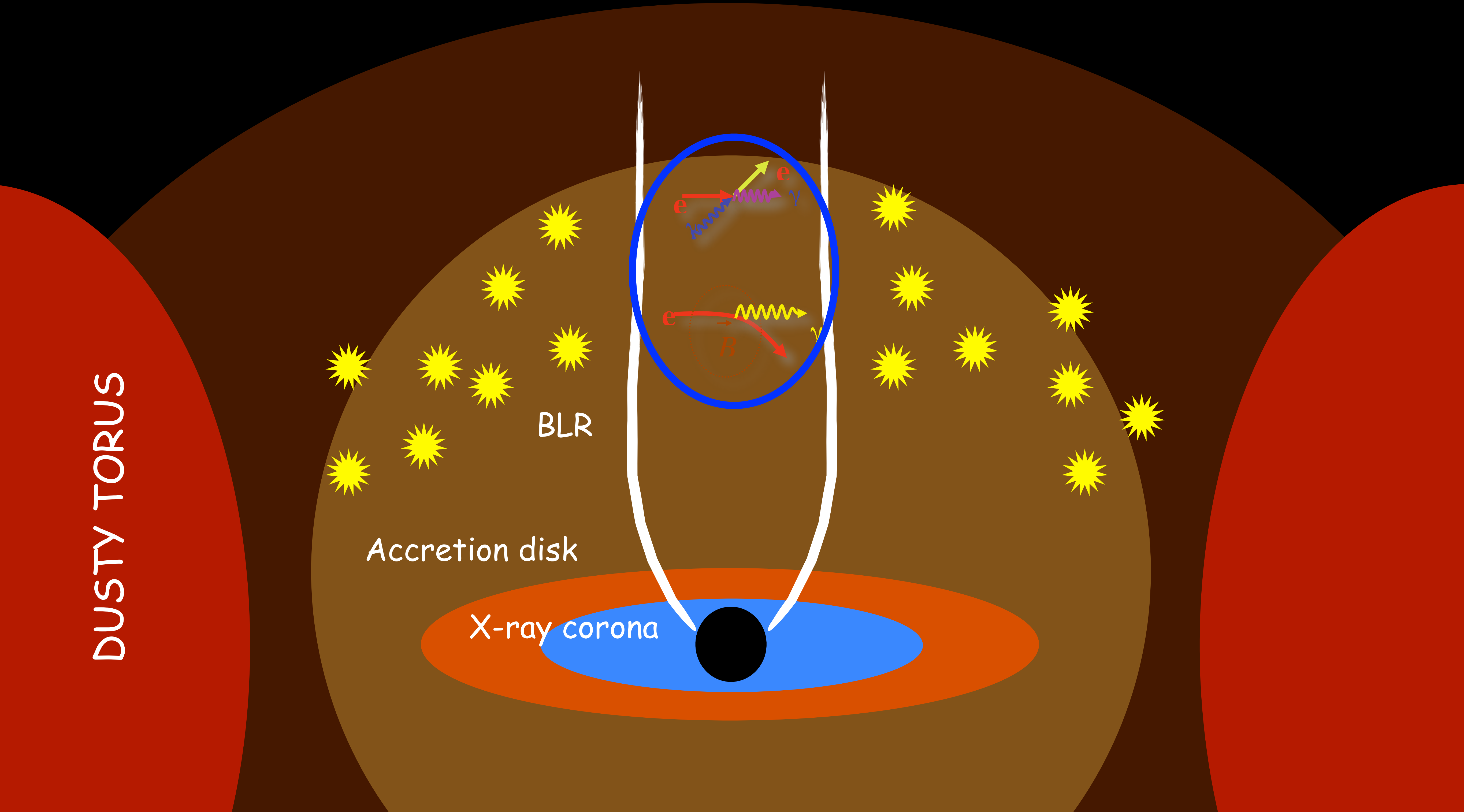


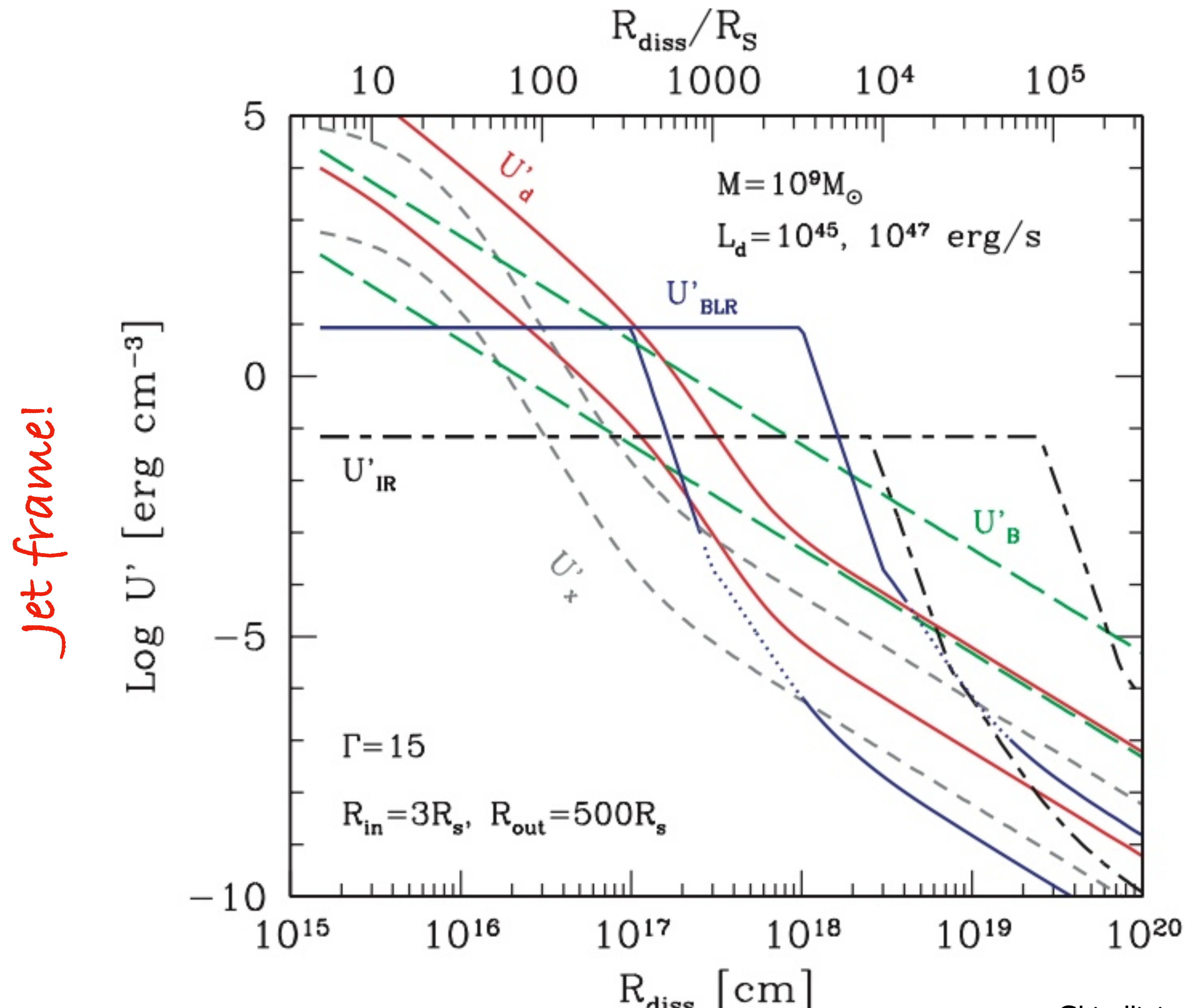
FSRQs: the general scenario



FSRQs: the "canonical" scenario

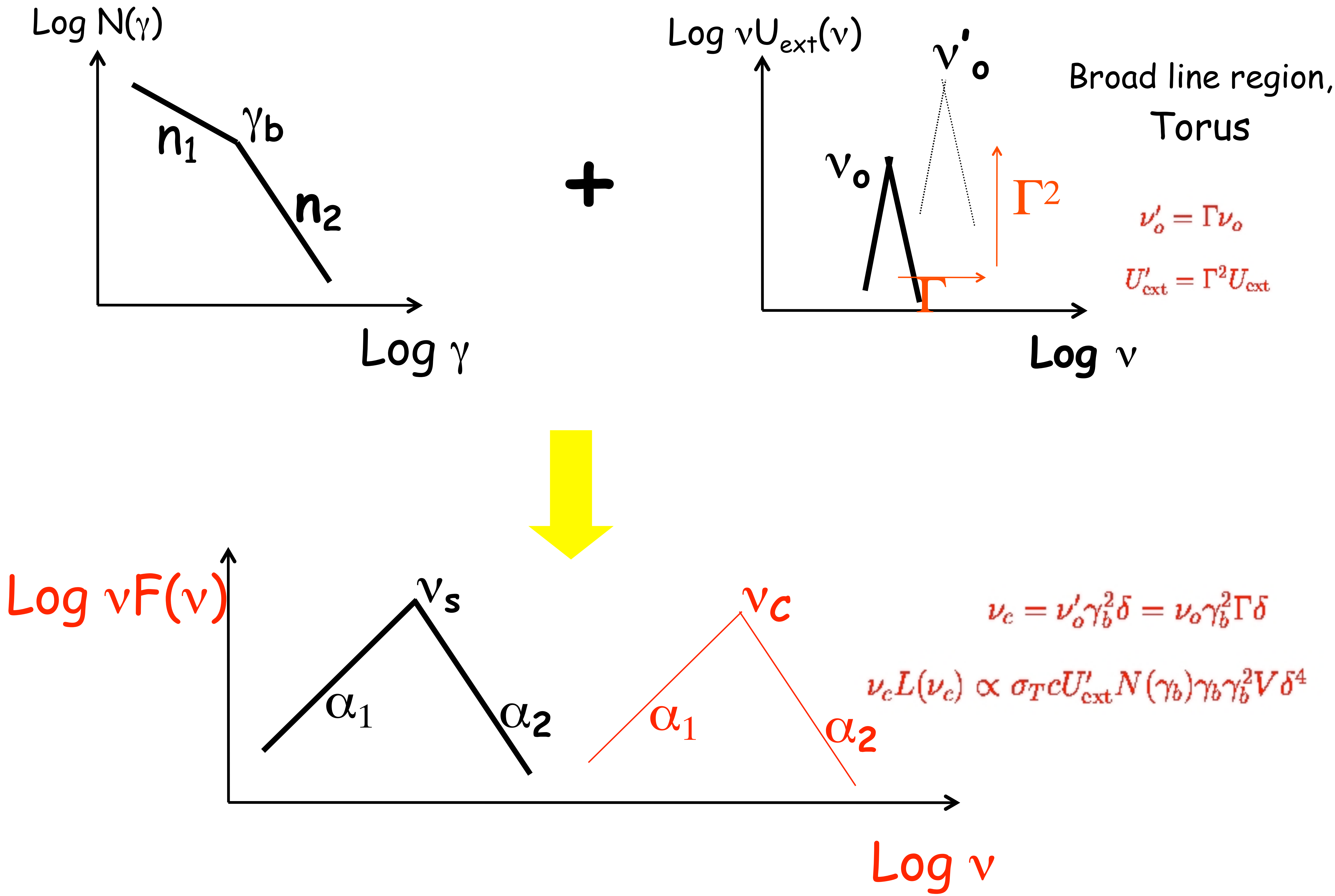
Dermer et al. 2009
Ghisellini, FT 2009
Sikora et al. 2009





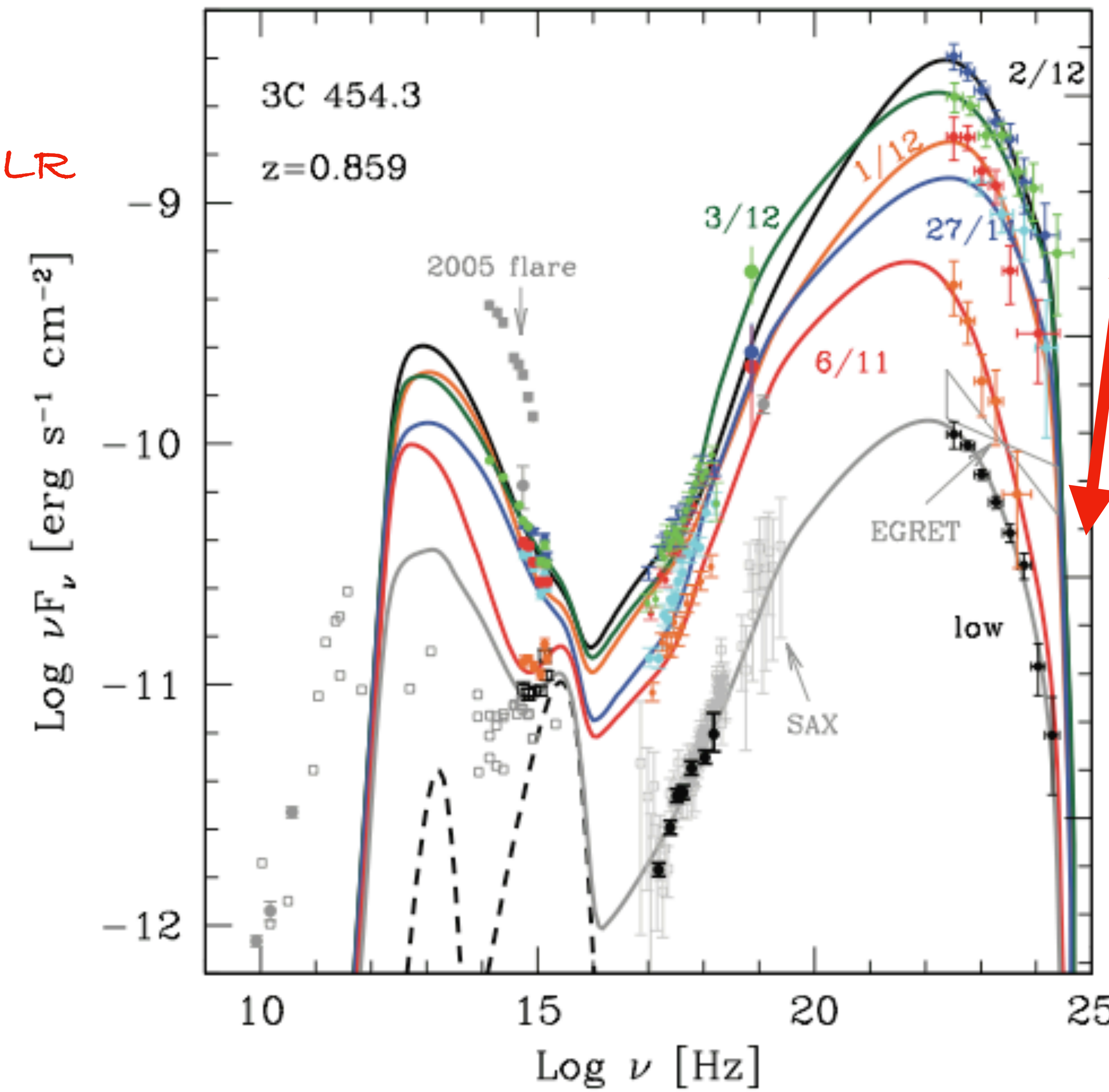
Ghisellini and Tavecchio 2009

A more modest model - 2



4C454.3

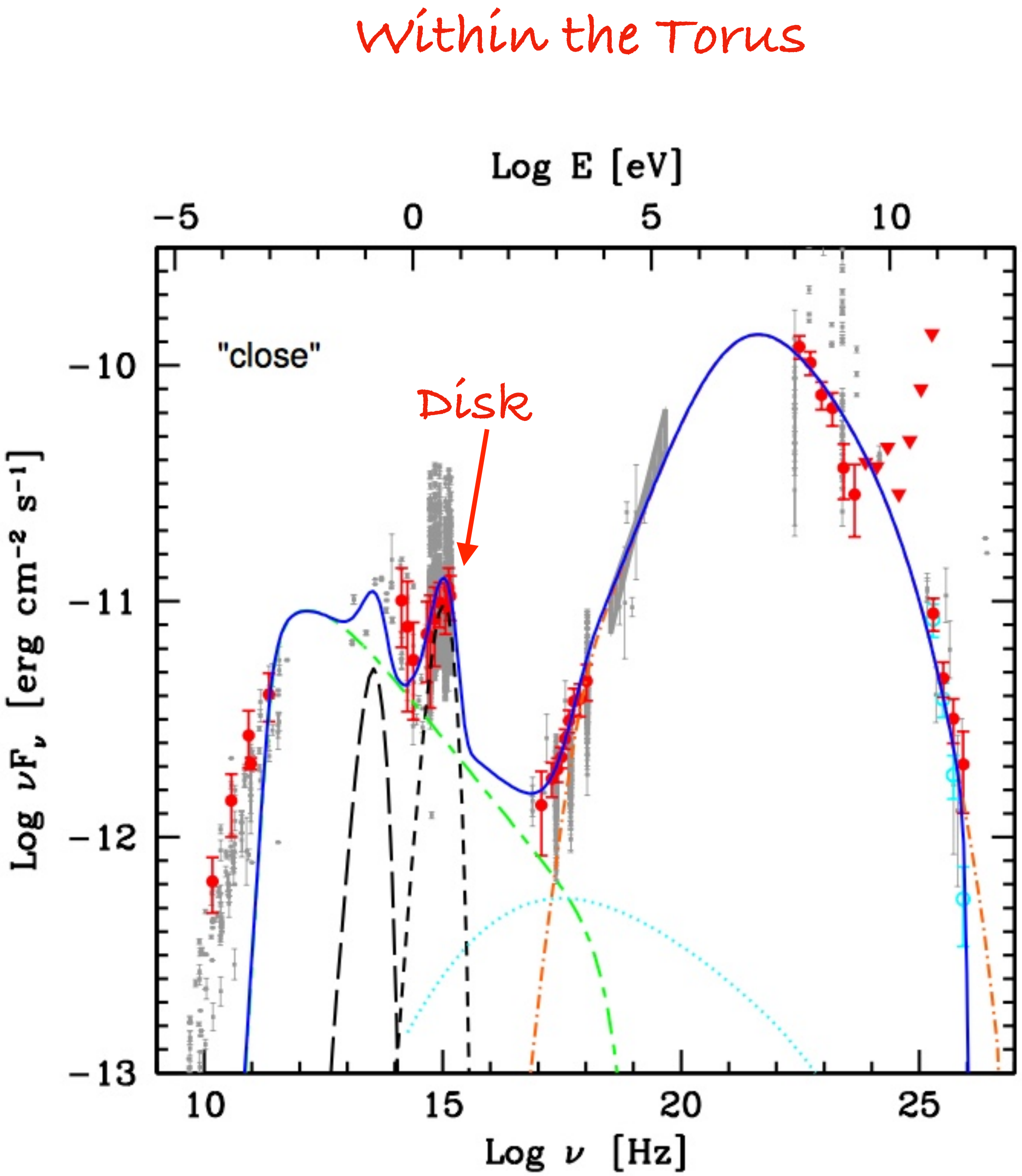
Within the BLR

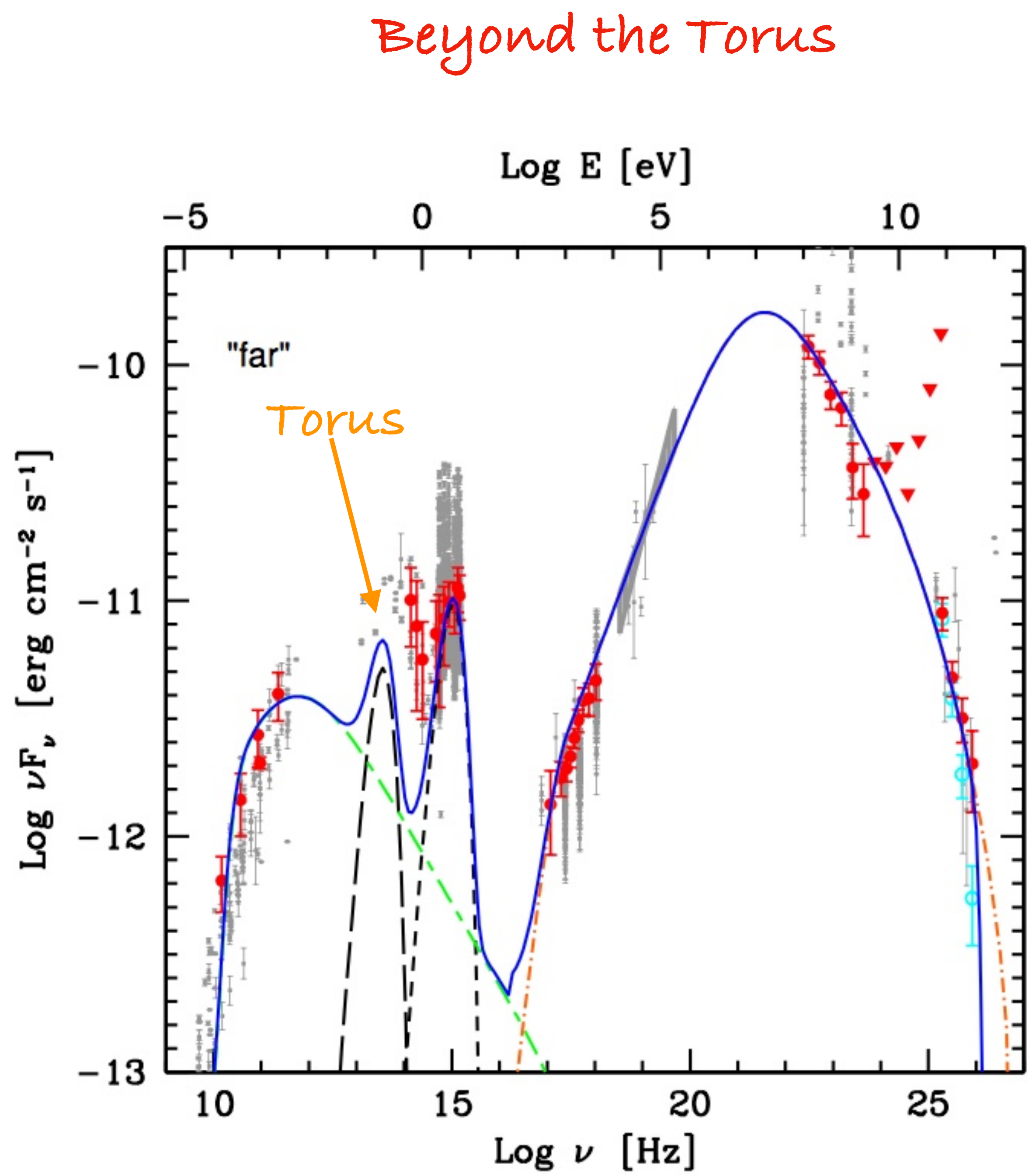


Absorption (20 GeV)

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

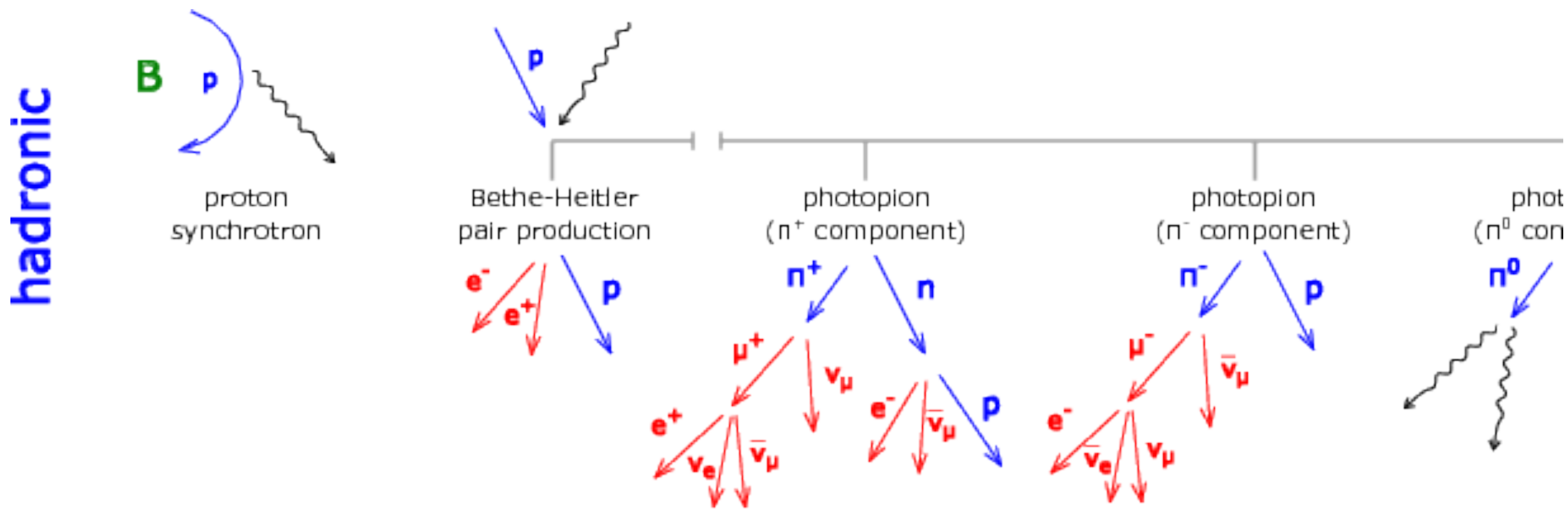
Leptons or hadrons?

UHECR
IceCube Neutrinos

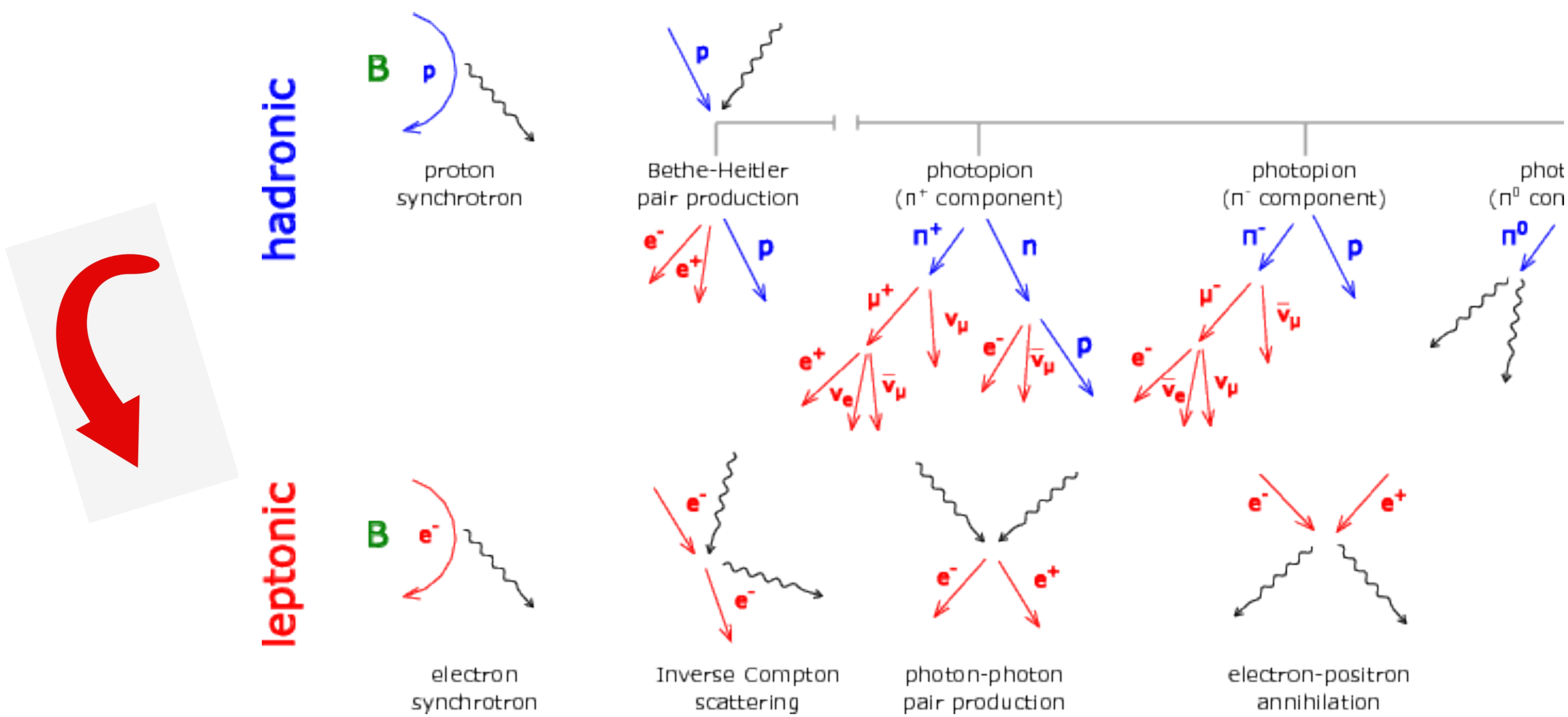
Hadrons are accelerated to very-high and ultra-high energy somewhere in the extragalactic space

Jets offer ideal conditions (B, radius,power)

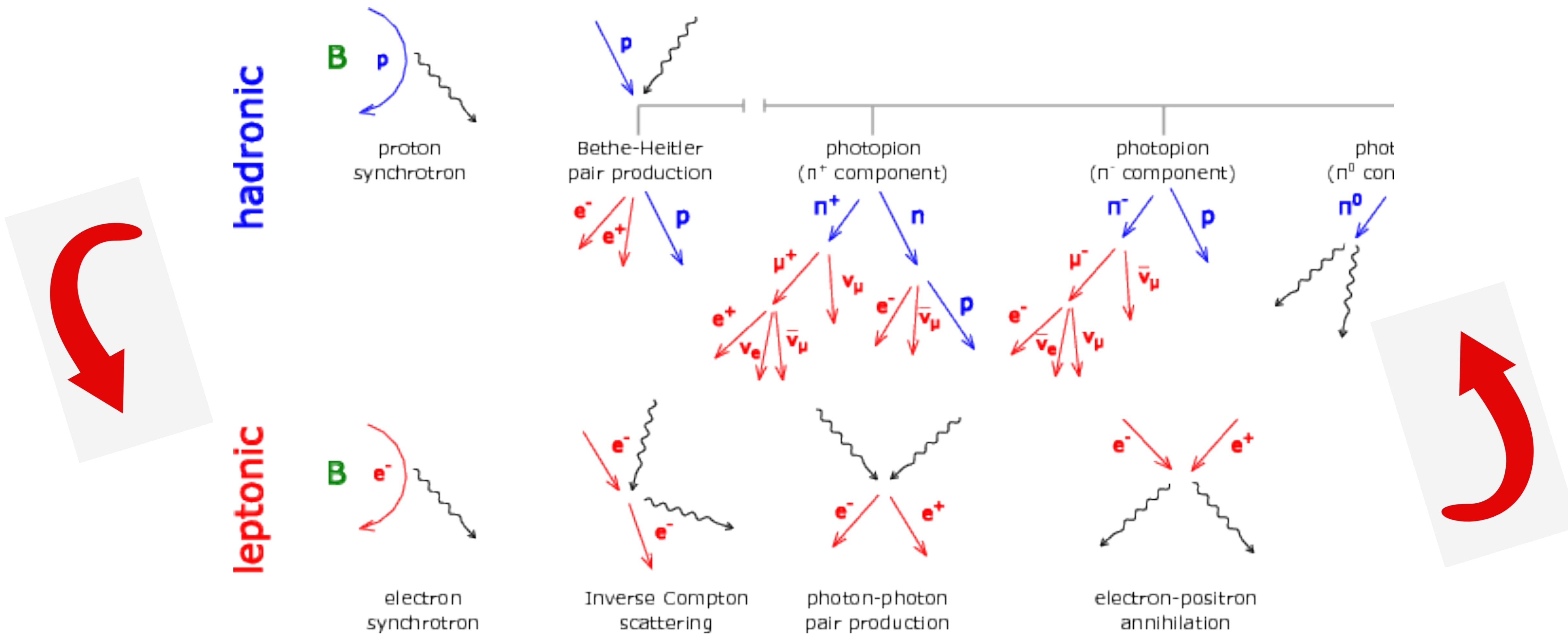
Leptons or hadrons?



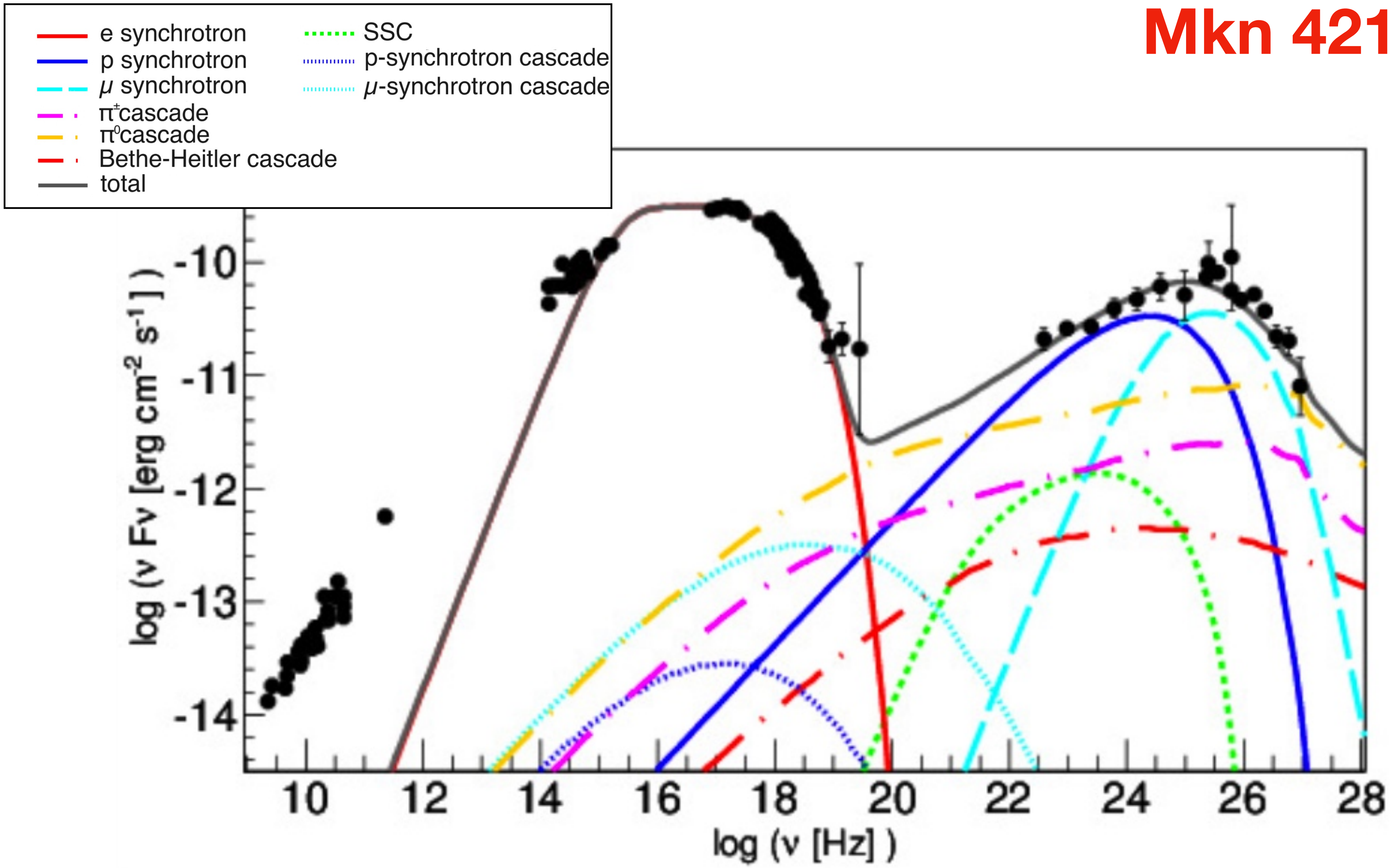
Leptons or hadrons?



Leptons or hadrons?



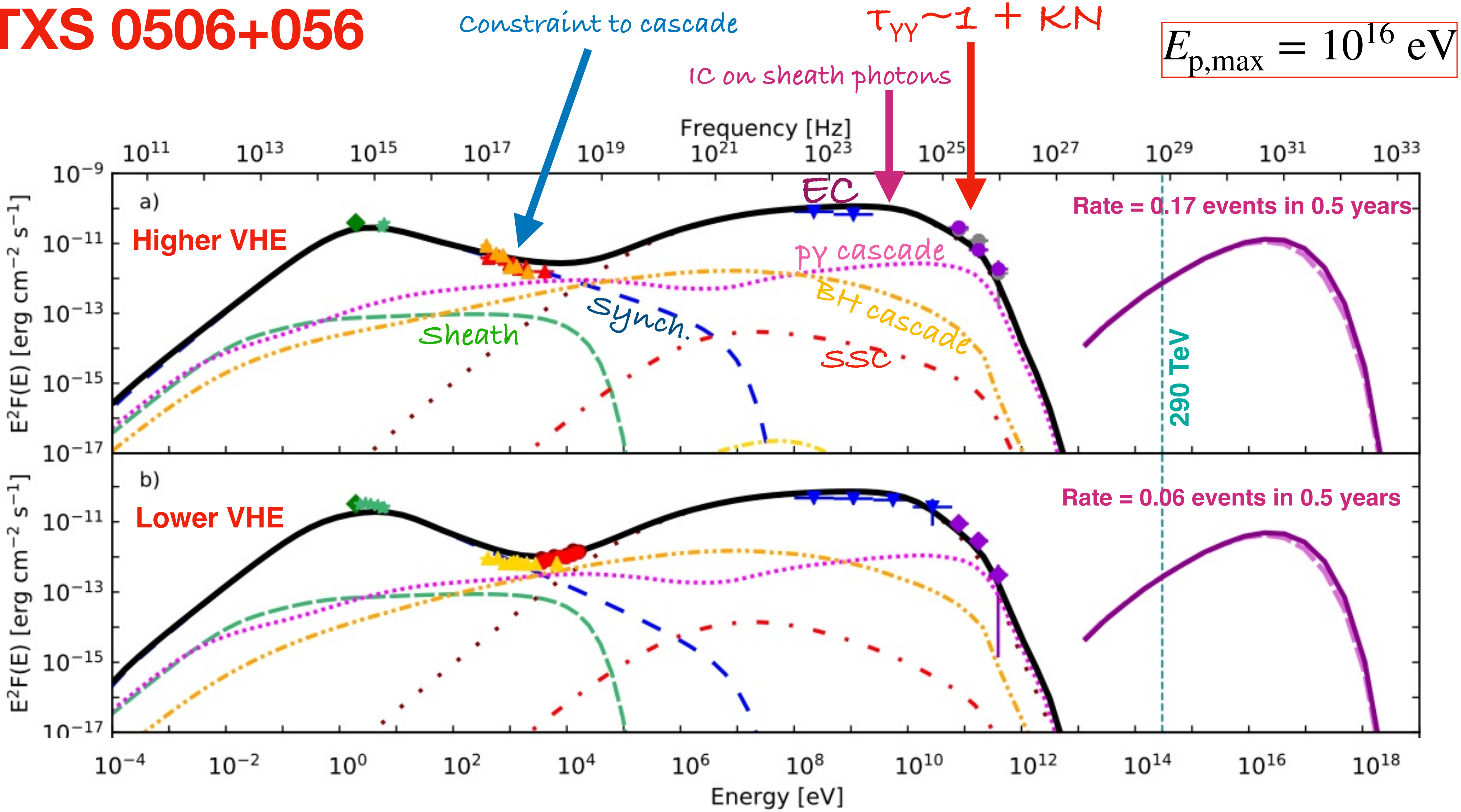
Lepto-hadronic models



Cerruti et al. 2015

Lepto-hadronic models

TXS 0506+056

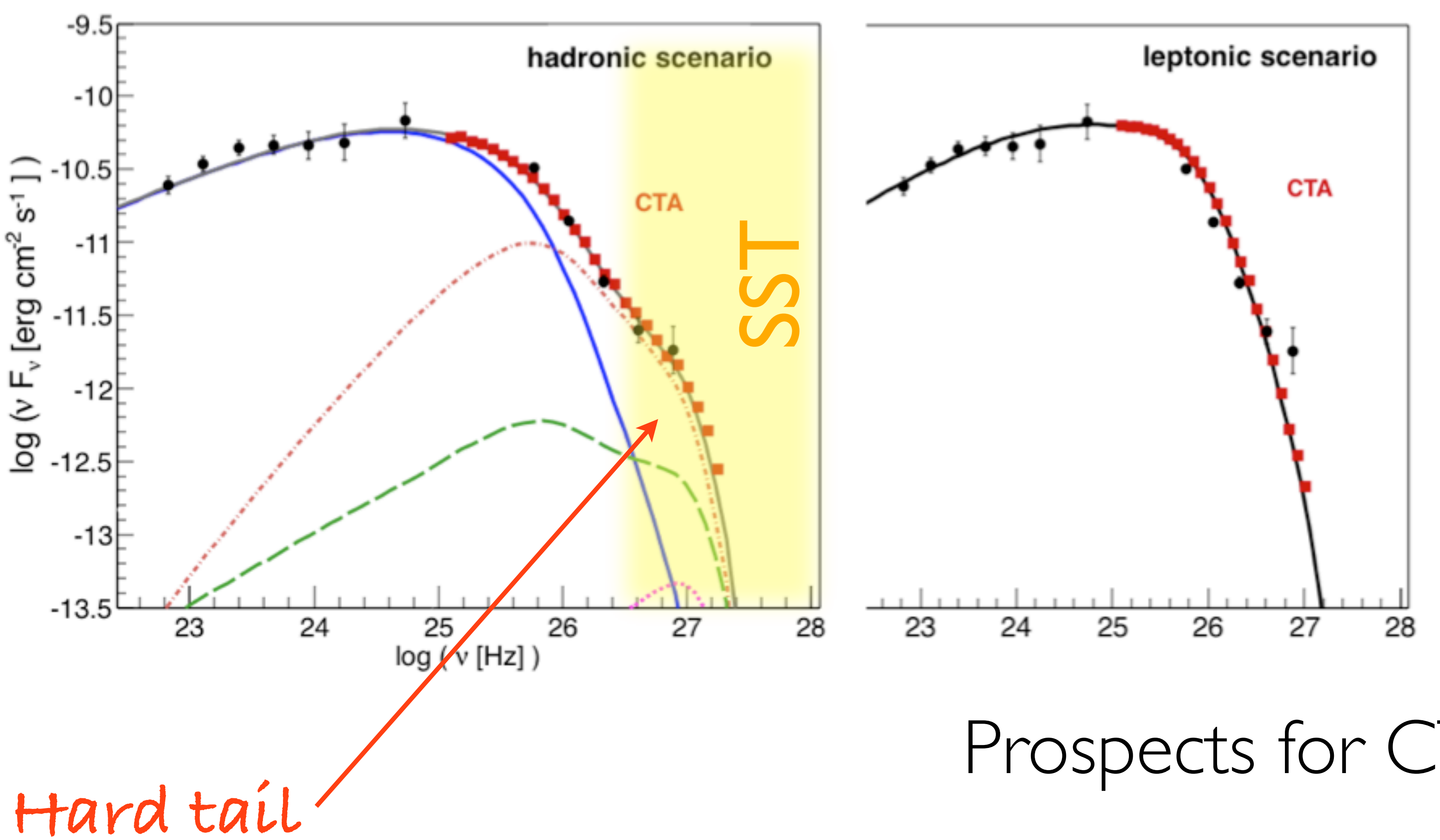


MAGIC Coll. 2018

Lepto-hadronic models

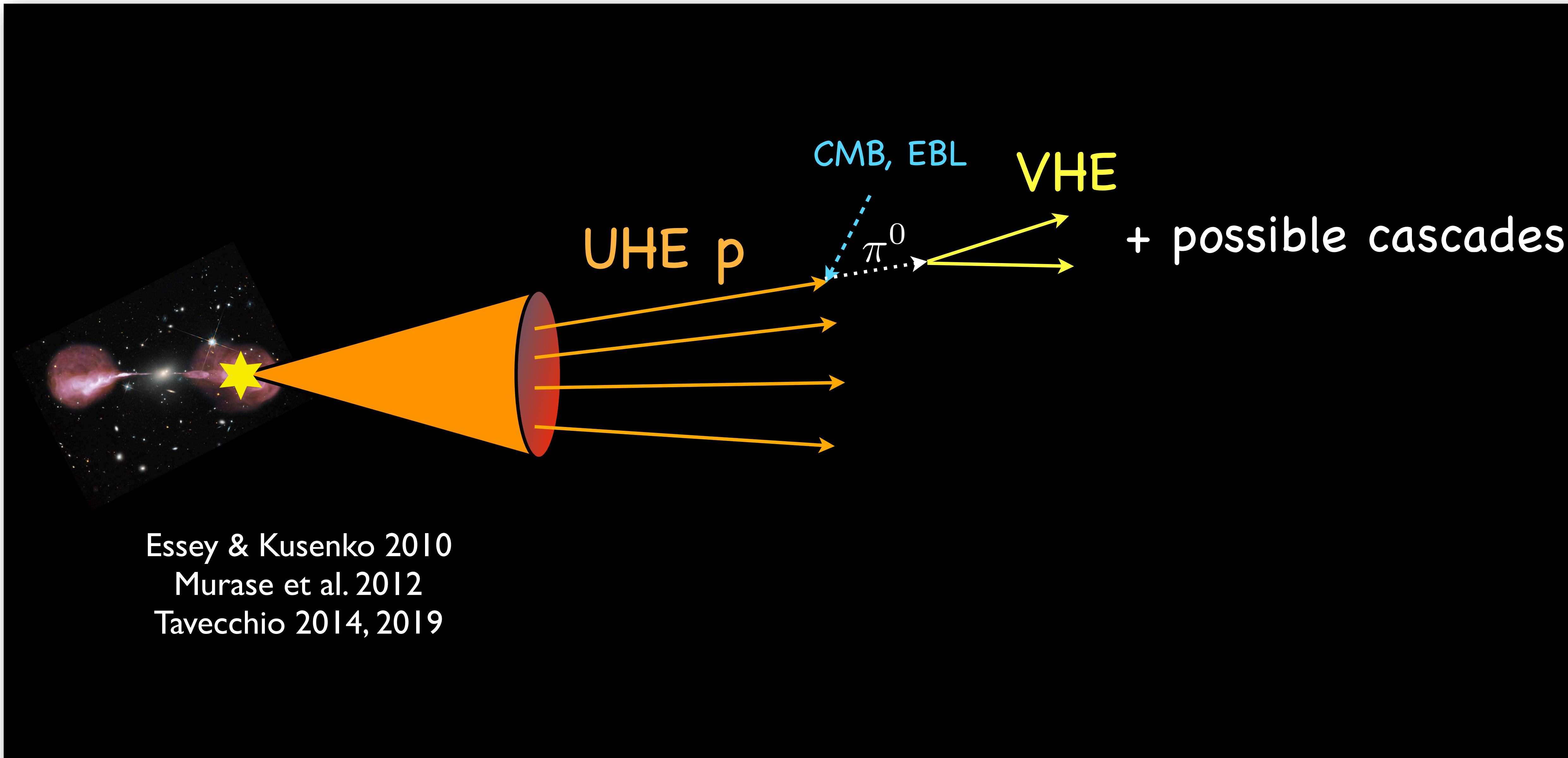
Zech et al. 2017

PKS 2155-304



Prospects for CTA

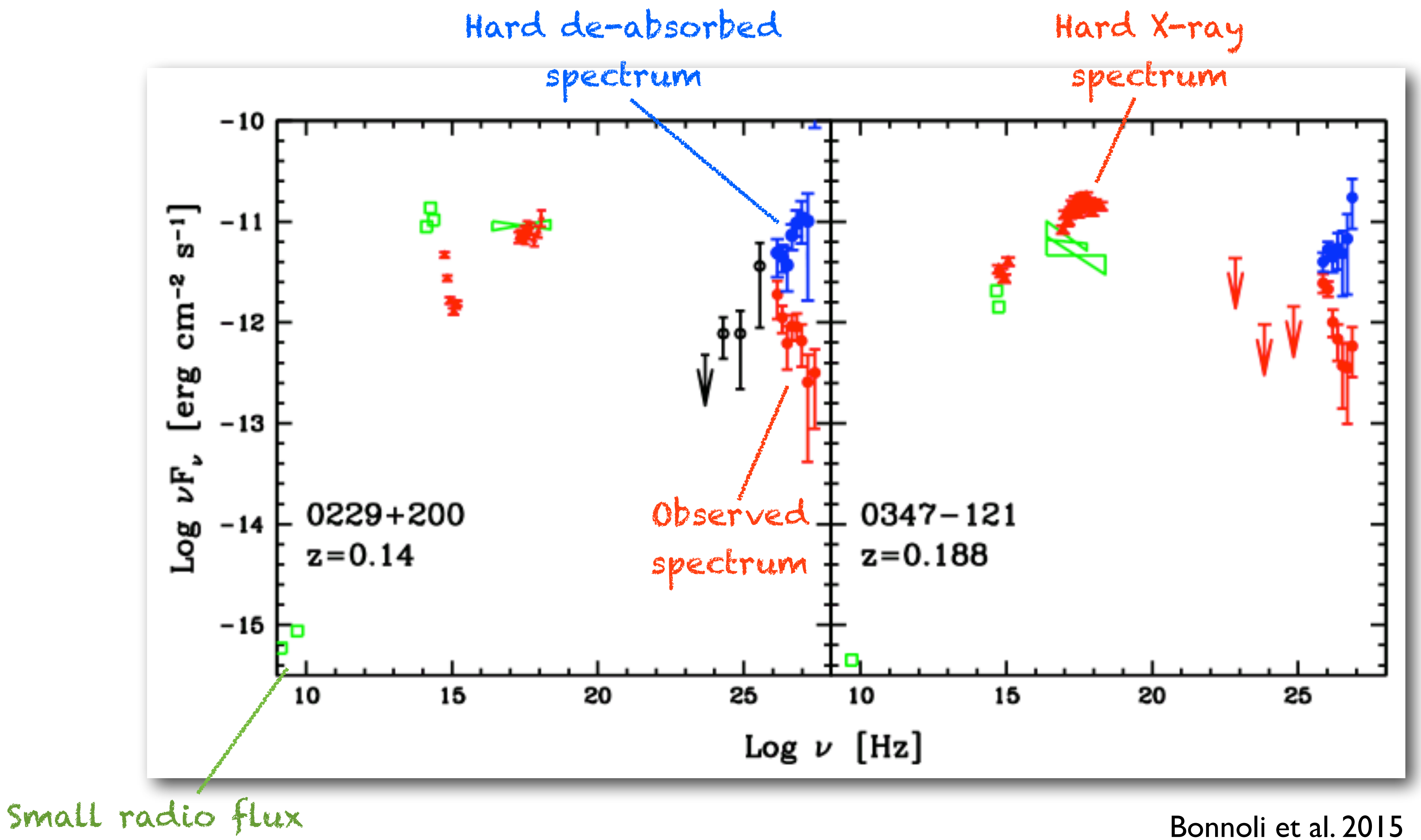
Hadron beams?



Scenario for "extreme Bl Lacs"

Extreme BL Lacs

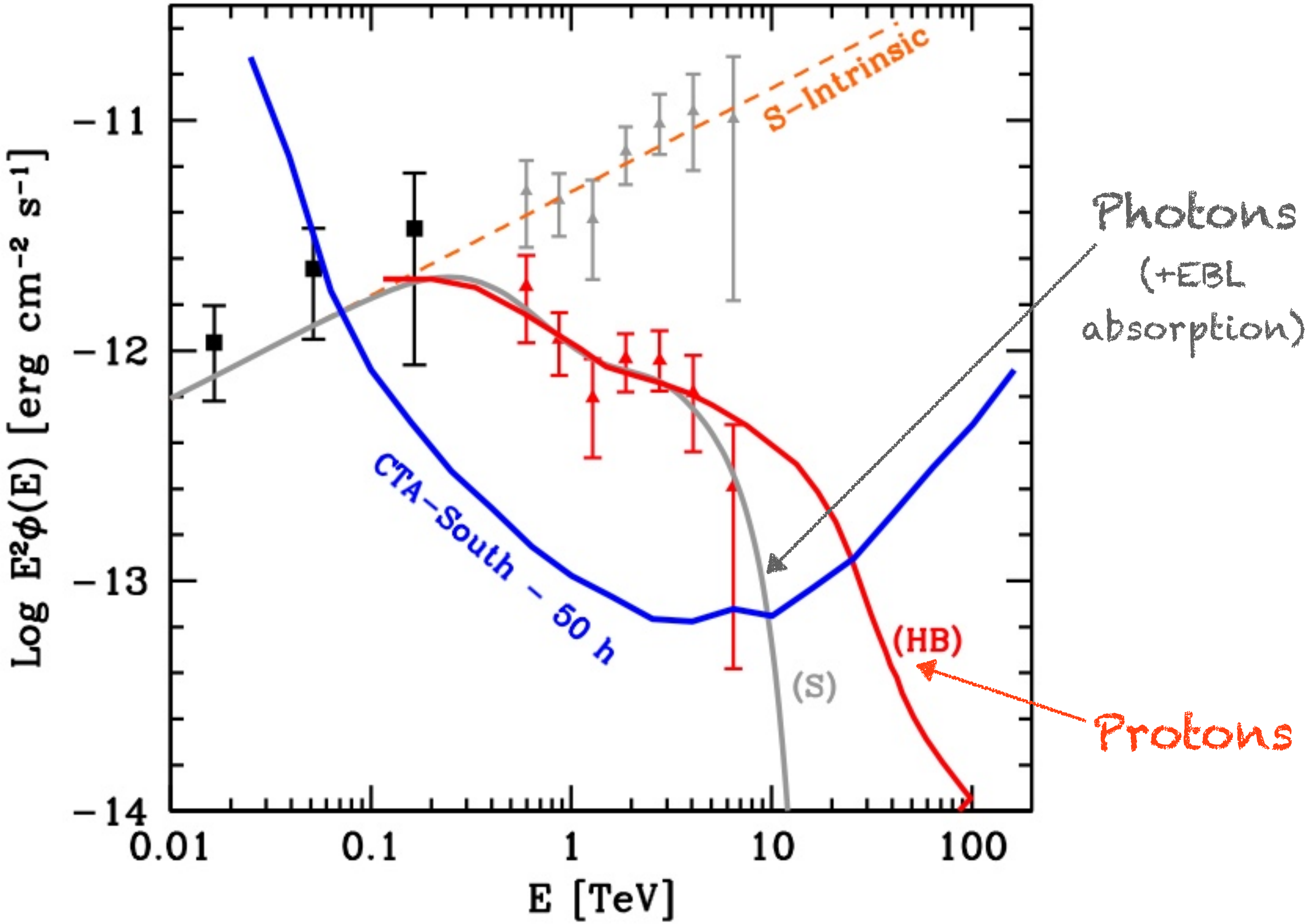
after Costamante et al. 2001



Bonnoli et al. 2015

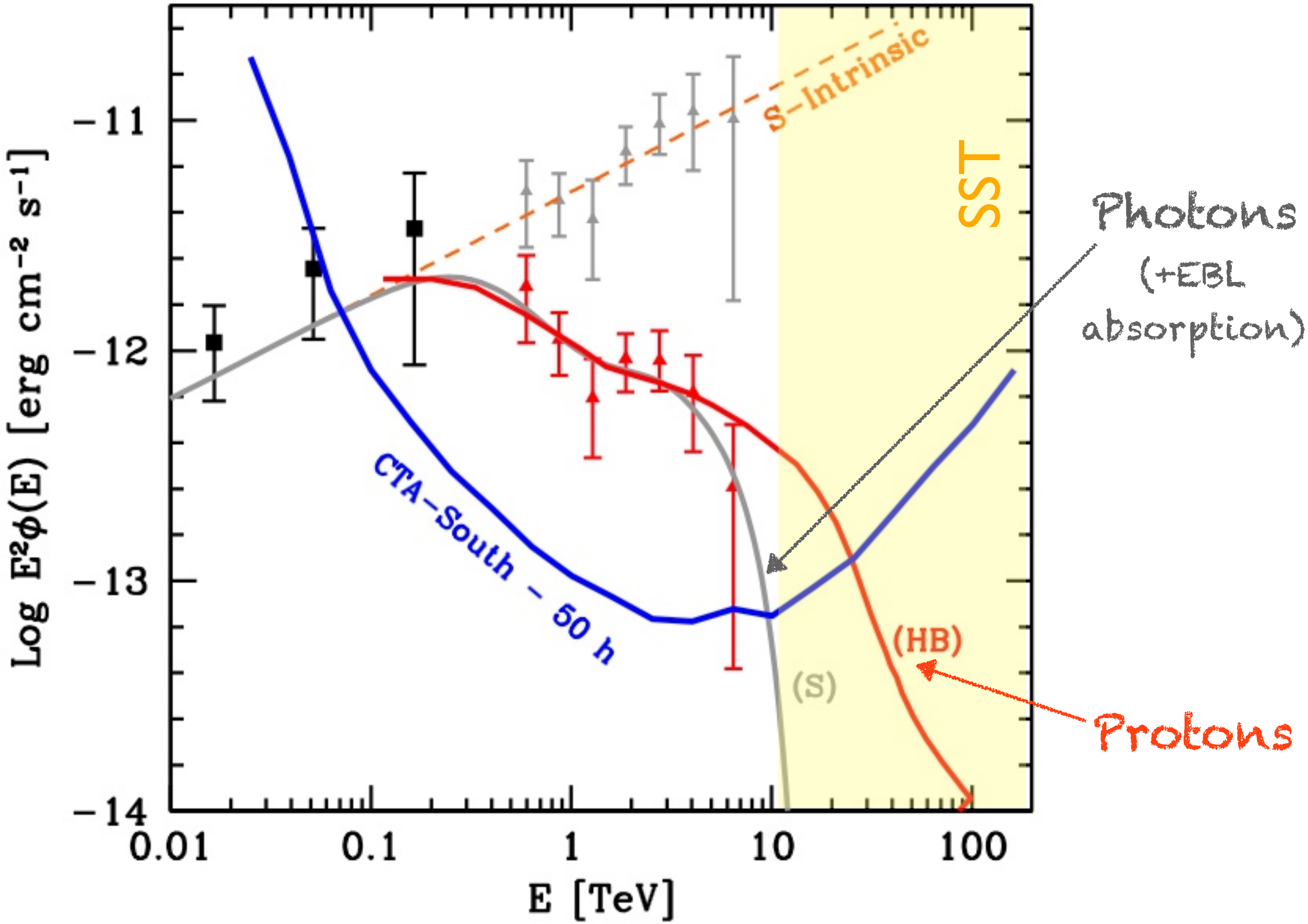
Hadron beams?

Tavecchio et al. 2019



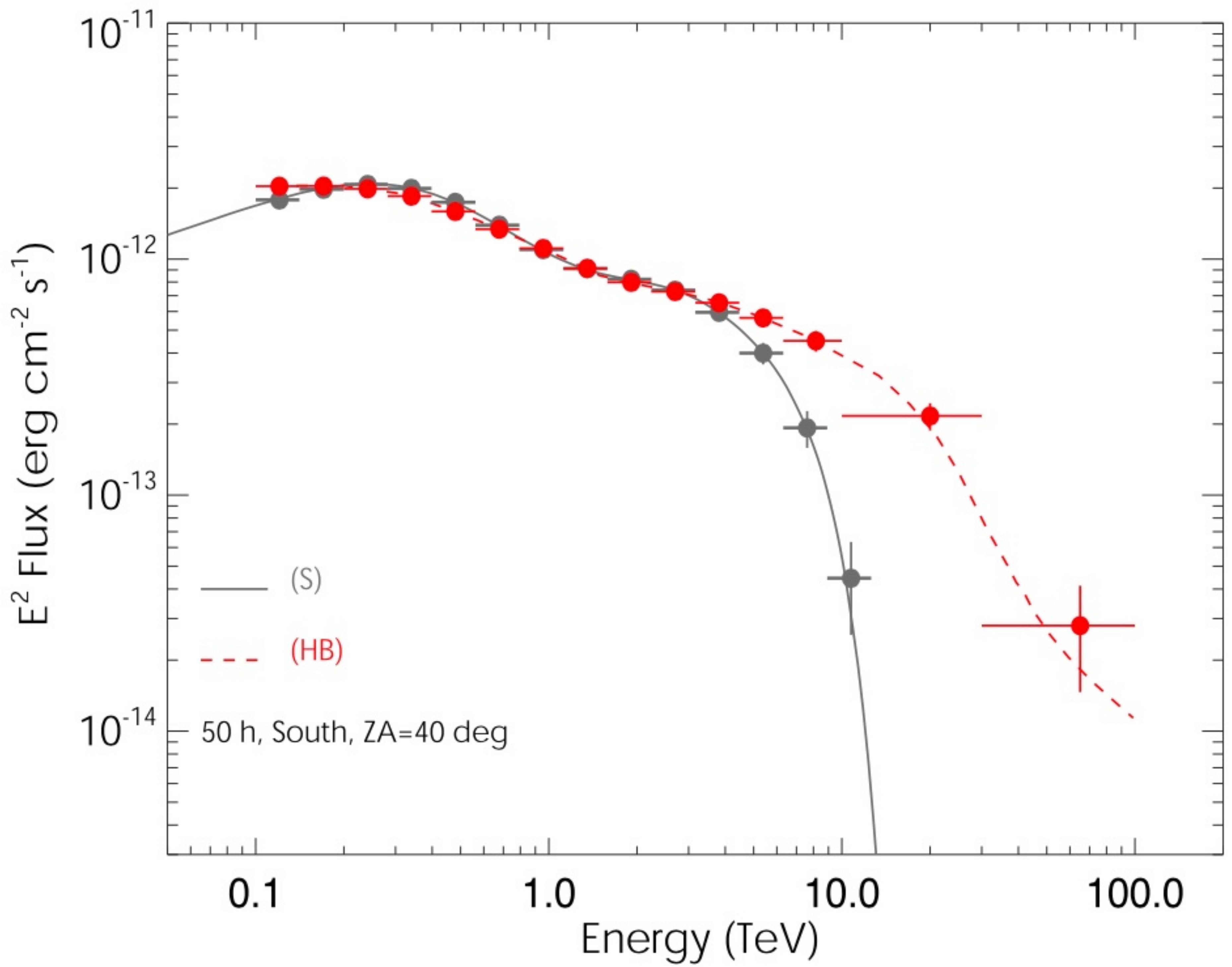
Hadron beams?

Tavecchio et al. 2019



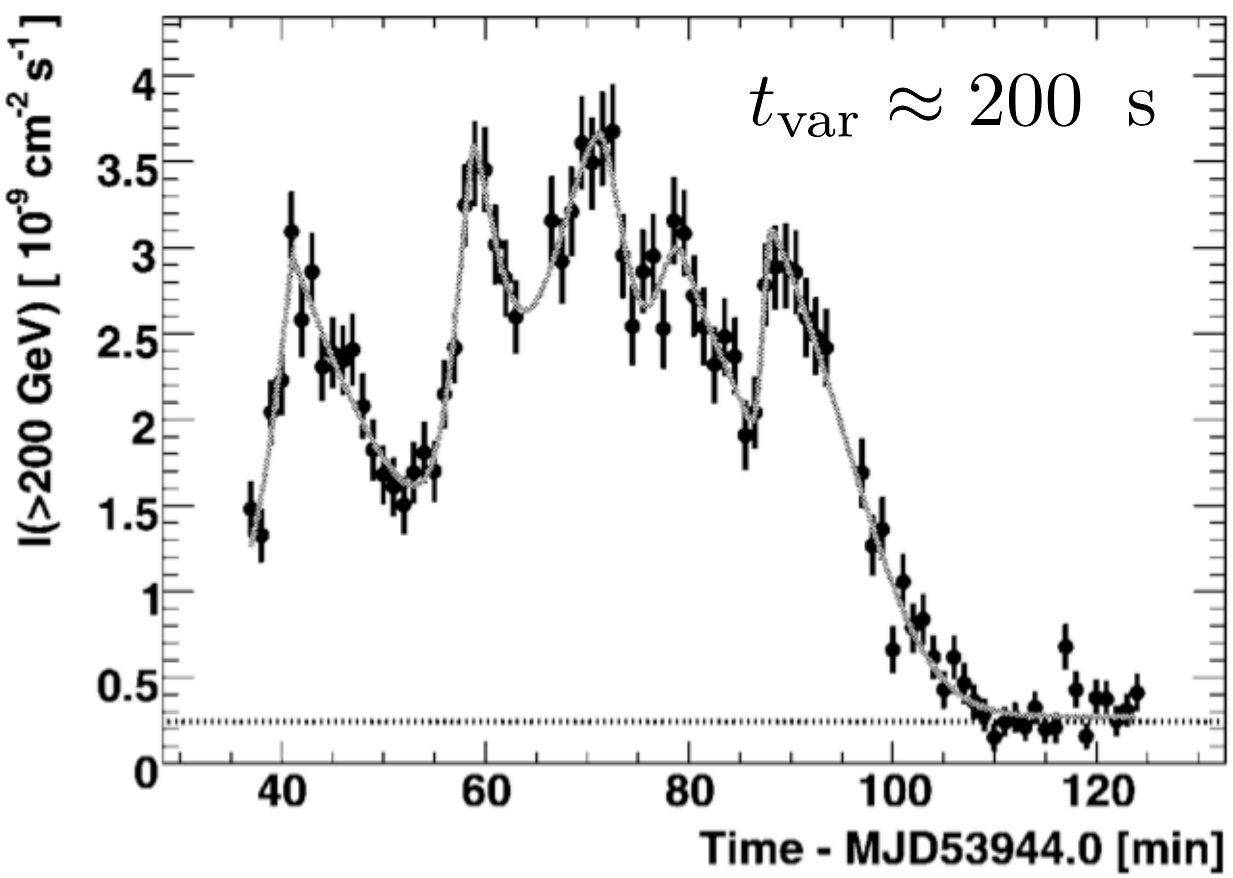
Hadron beams?

Tavecchio et al. 2019



Variability

PKS 2155-304@TeV



Aharonian et al. 2007

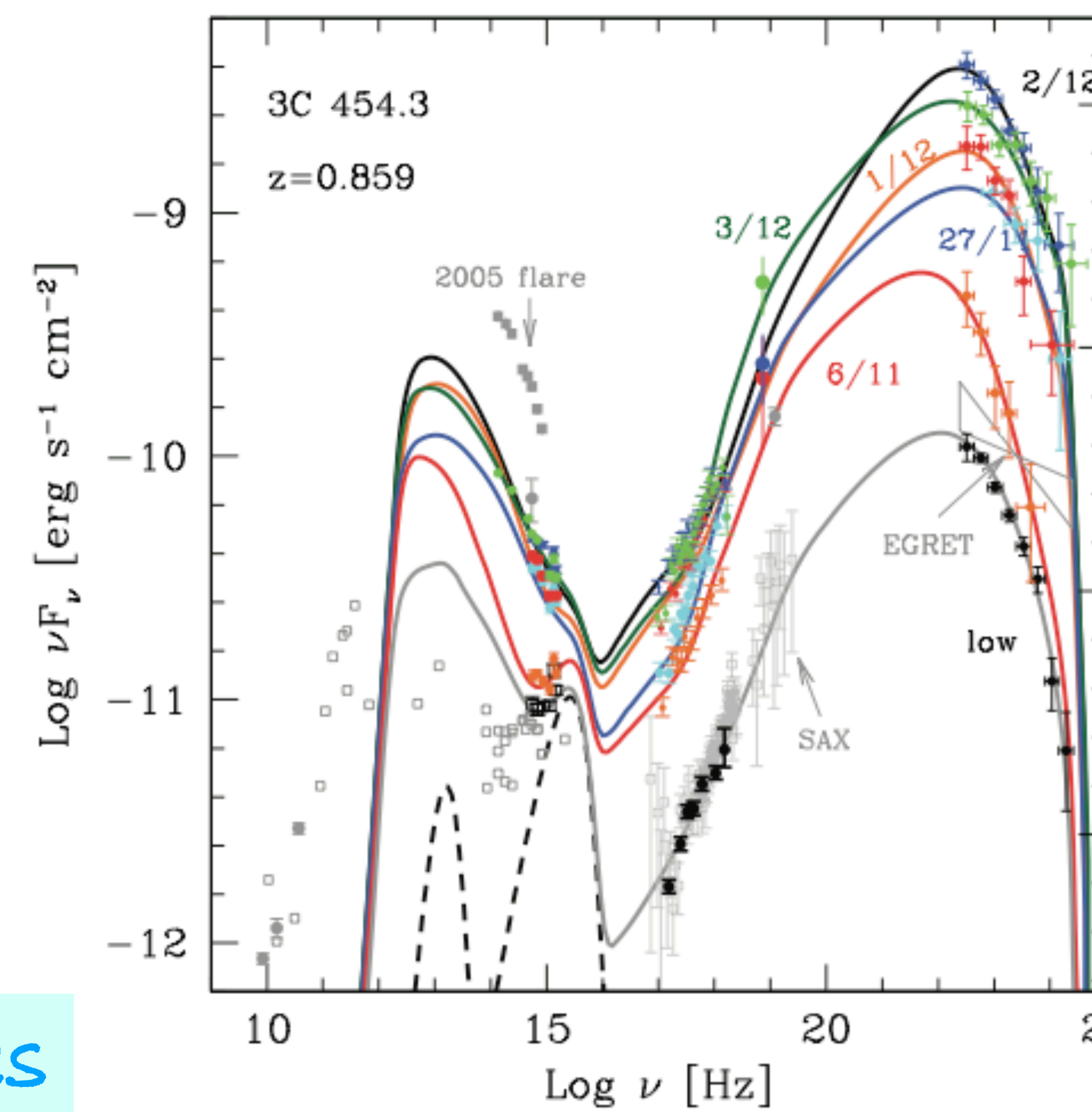
Short time-scales

Small spatial scales

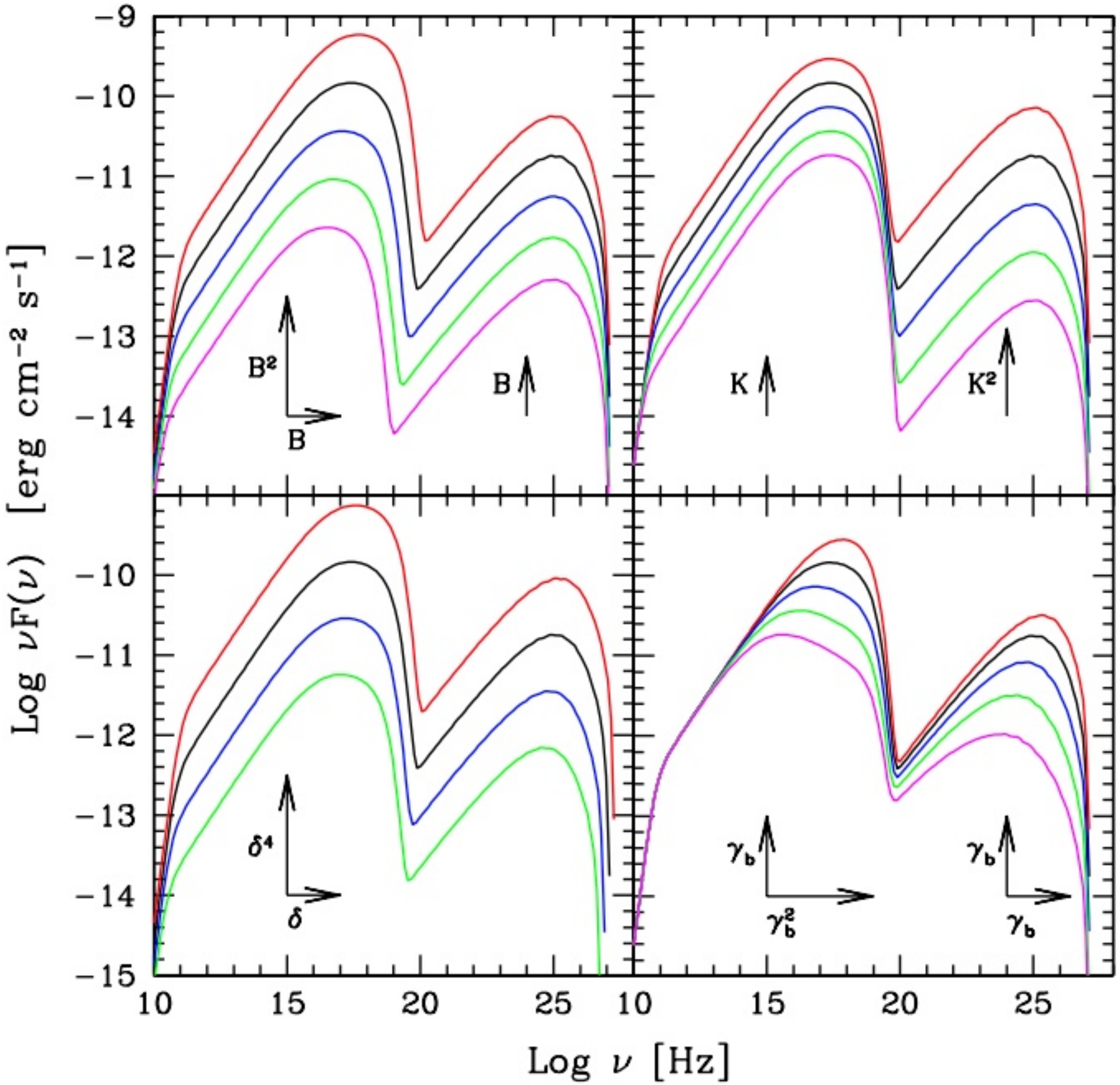
Close to the BH

Large amplitudes

Bonnoli et al. 2011



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

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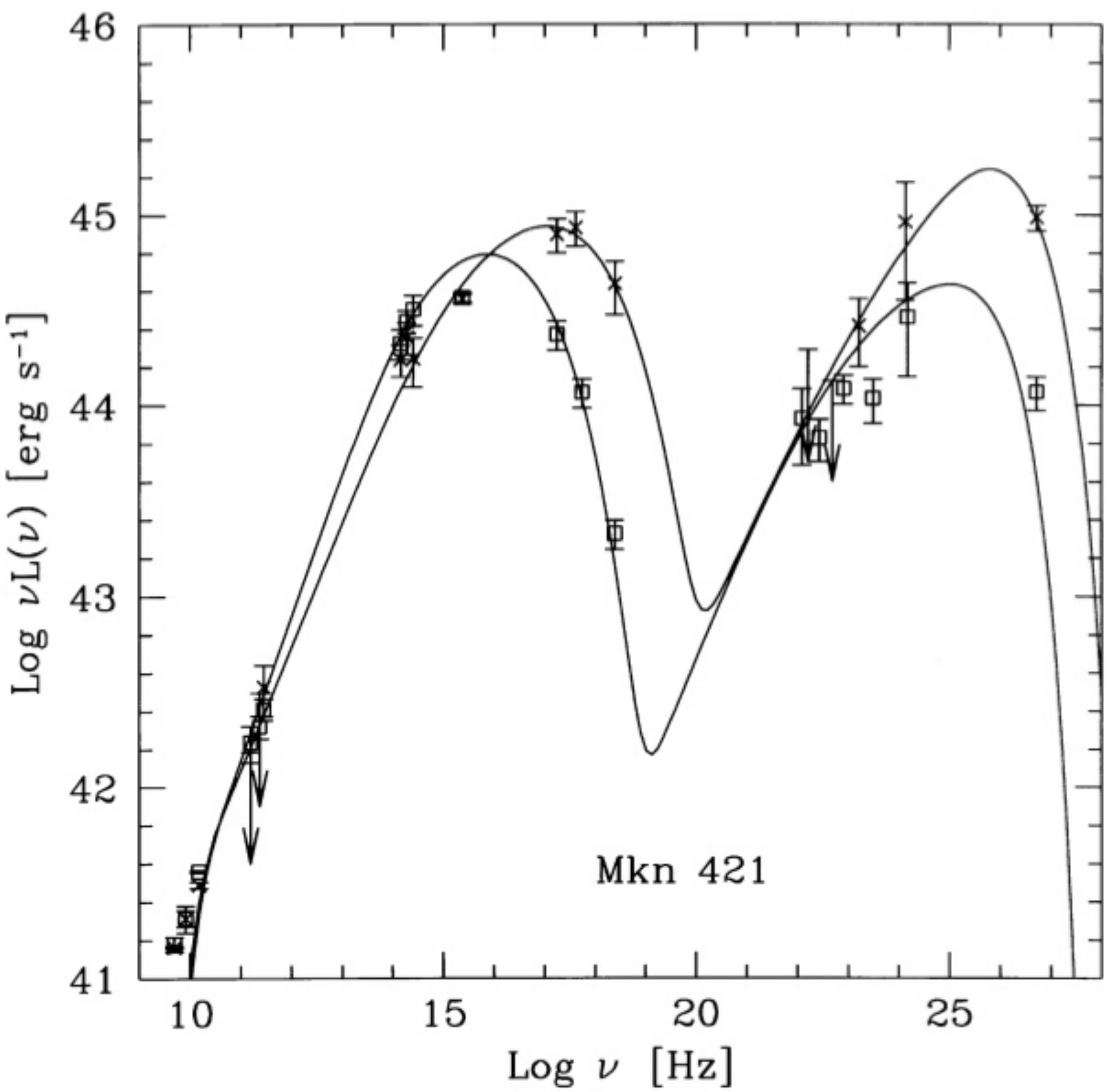
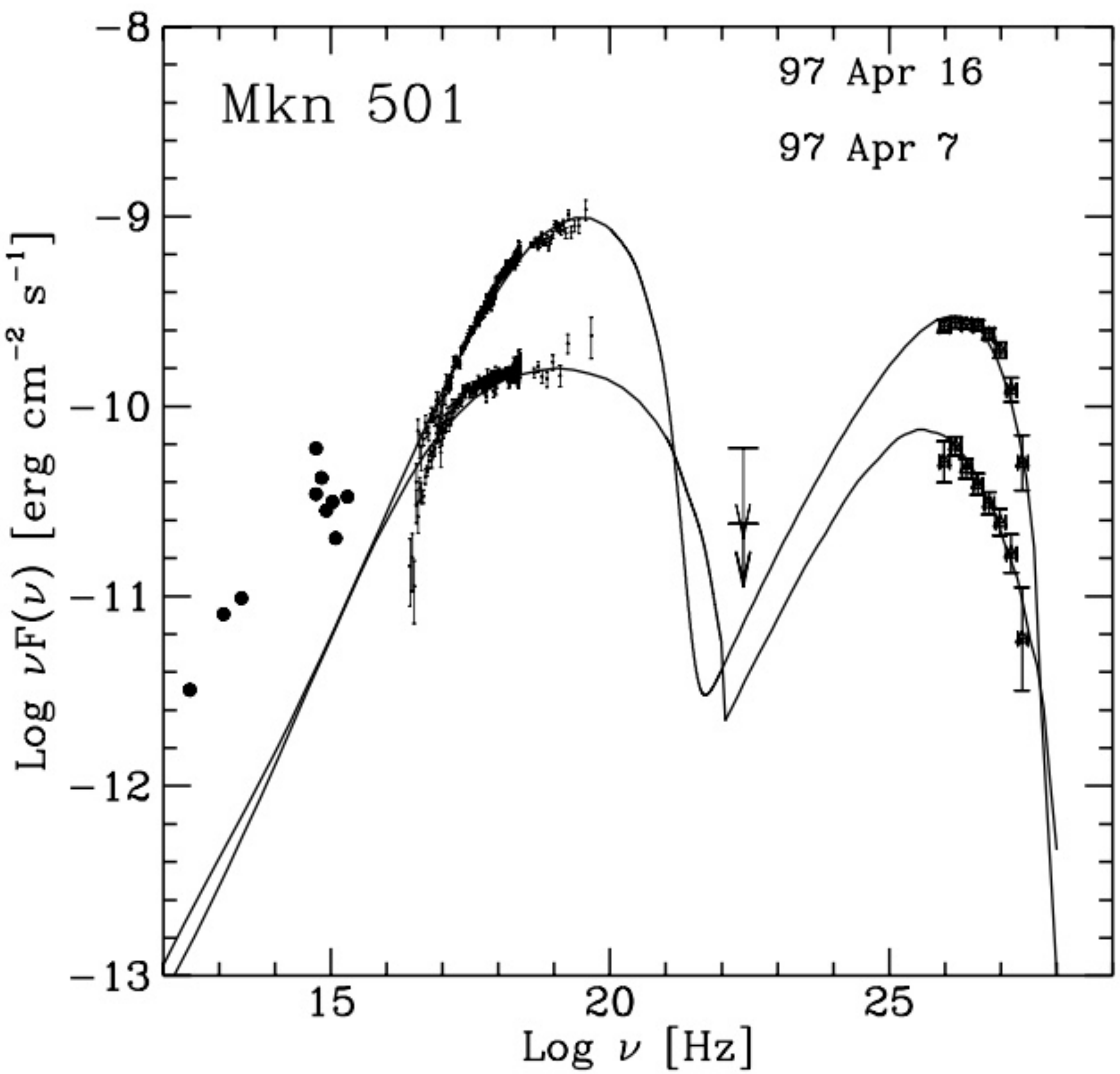
Chiaberge and Ghisellini 1999



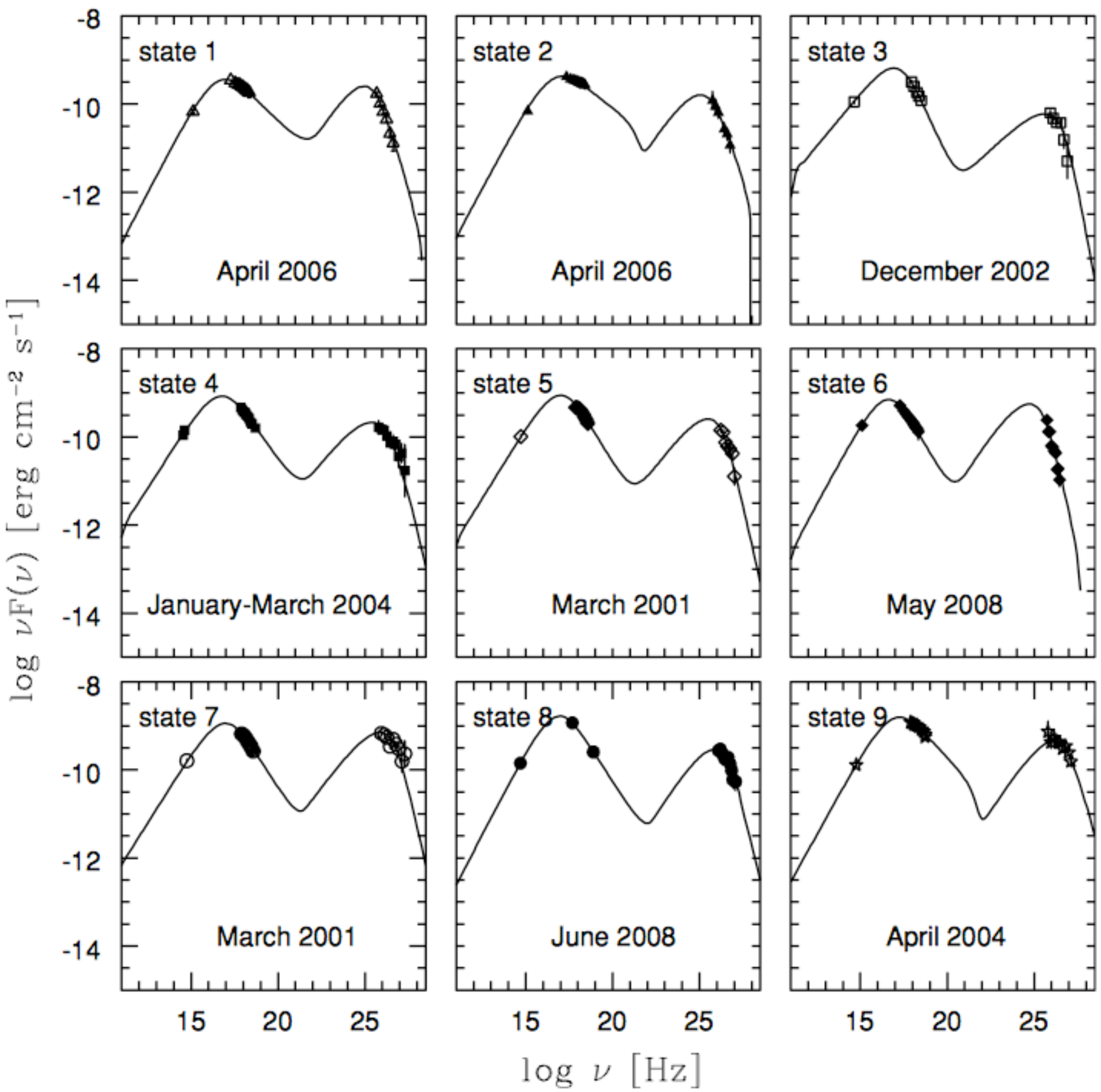
Quasi-stationary SED

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

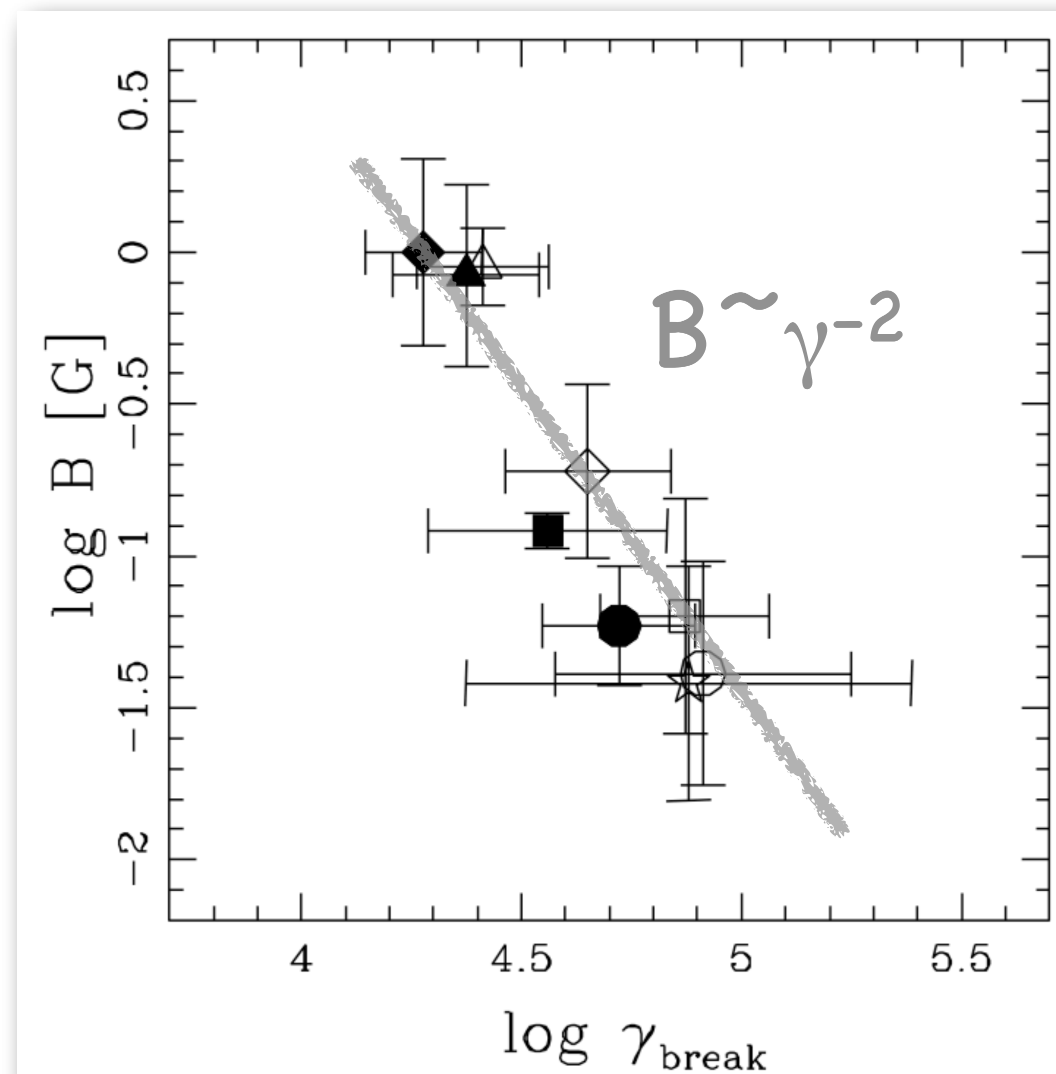


Tavecchio et al. 2001

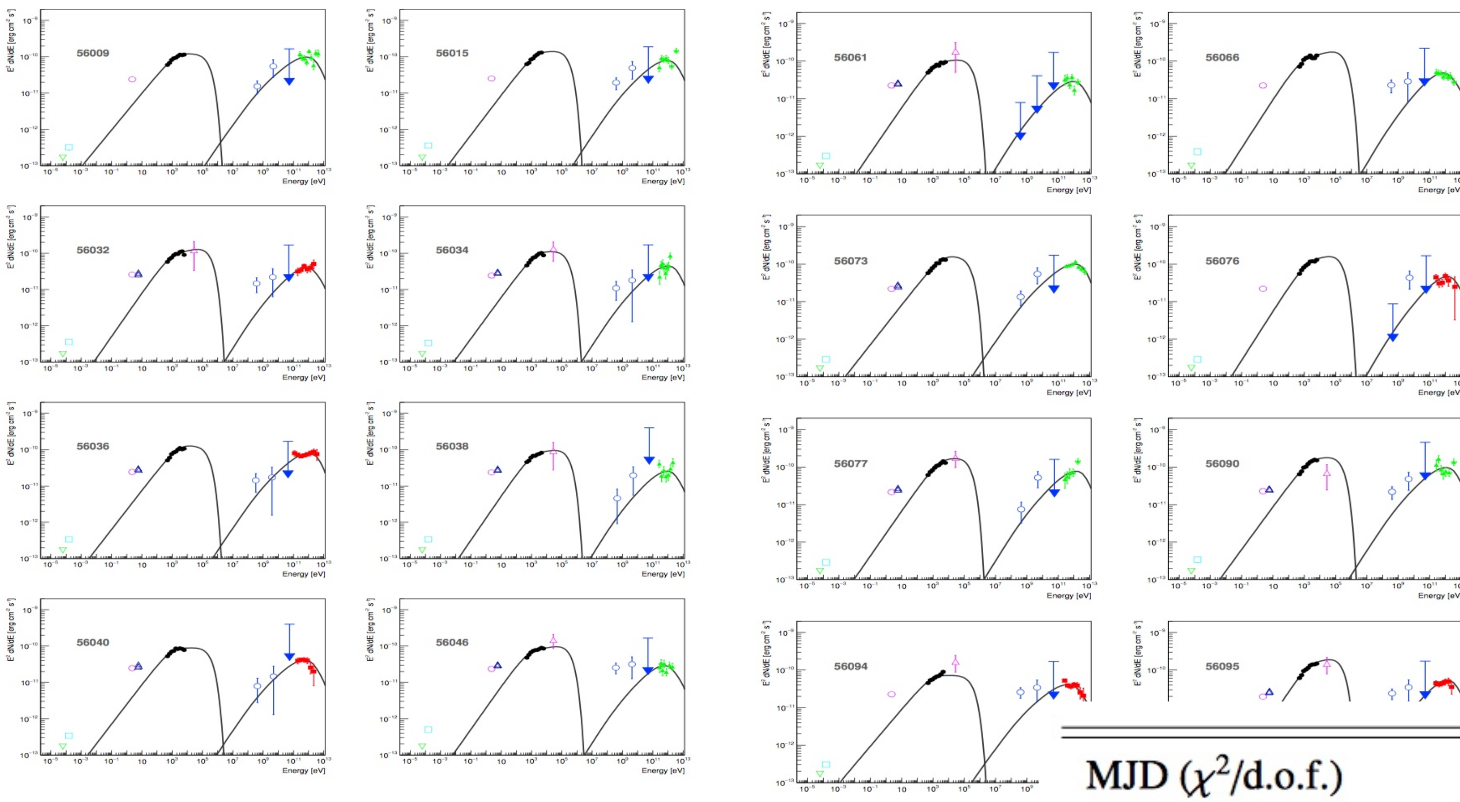
Quasi-stationary SED



Mankuzhiyil et al. 2011



Quasi-stationary SED



MJD (χ^2/d.o.f.)	B (10^{-2} G)	γ_{brk} (10^6)	p_1	p_2	U_e (10^{-3} erg cm^{-3})	η [U_e/U_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

Final thoughts

Jets are very complex systems but …

(Leptonic)One zone models are surprisingly successful!

We can obtain rather interesting clues one particle acceleration, evolution etc…

Lepto-Hadronic models suggested by neutrino data but still need improvements