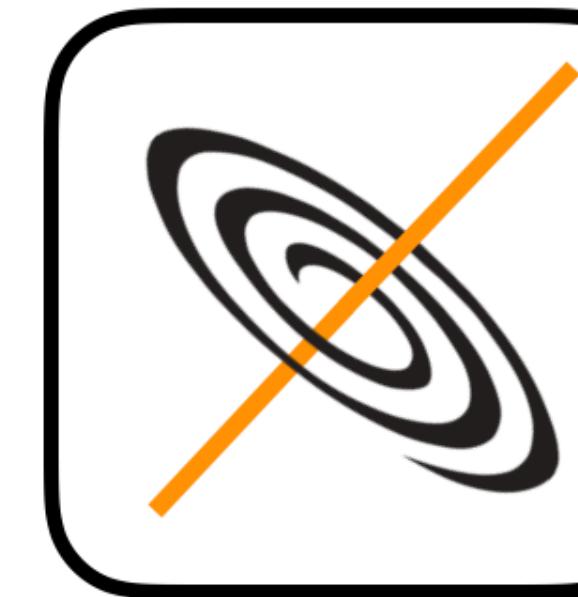


# Numerical modelling of radiative and accelerative processes with the JetSeT code



## JetSeT

Jets SED modeler and fitting Tool

Andrea Tramacere

<https://jetset.readthedocs.io/en/latest/>  
<https://github.com/andreatramacere/jetset>  
<https://www.facebook.com/jetsetastro/>

Linnaeus University  
12/06/2020 zoom lecture

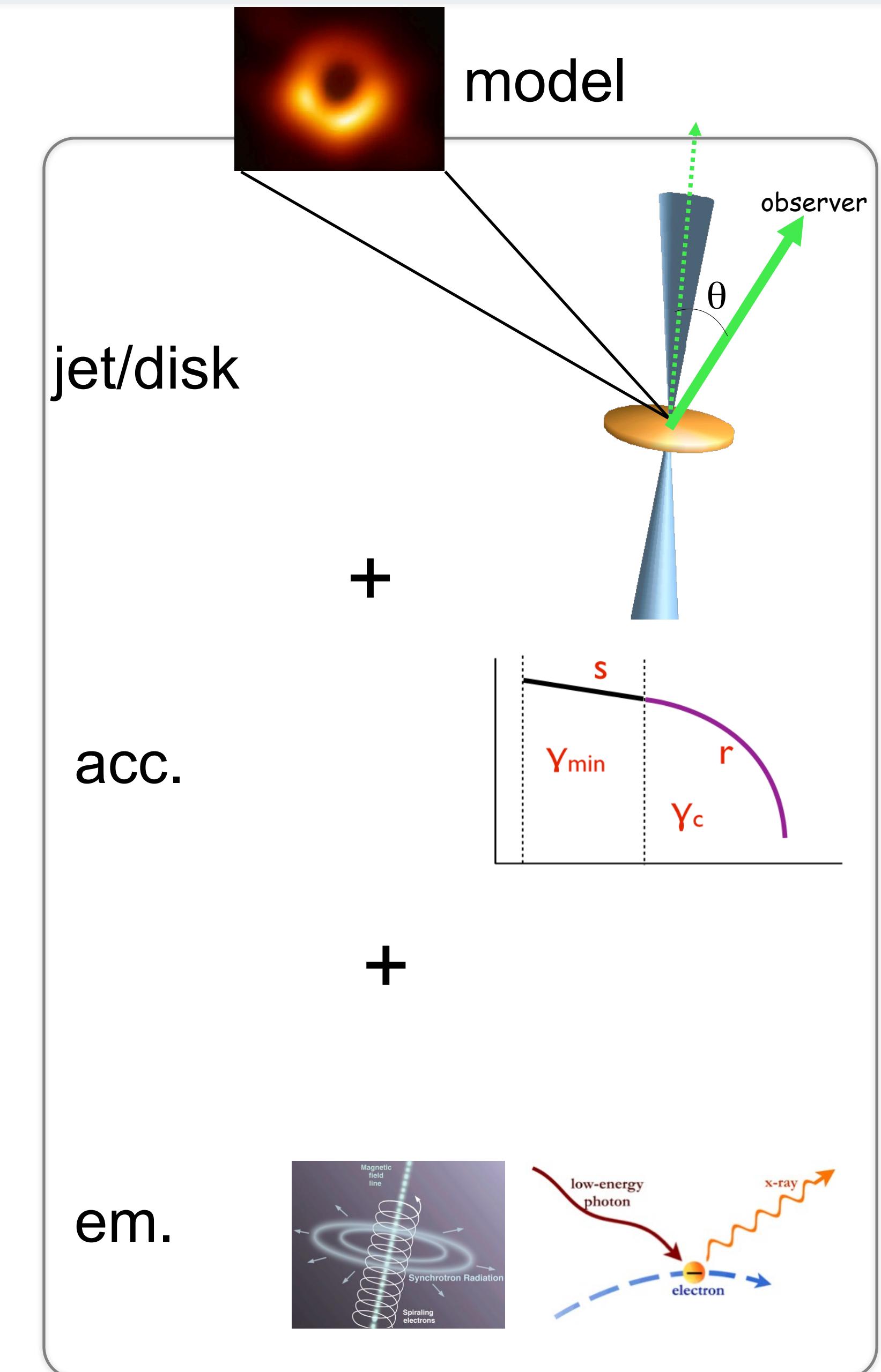
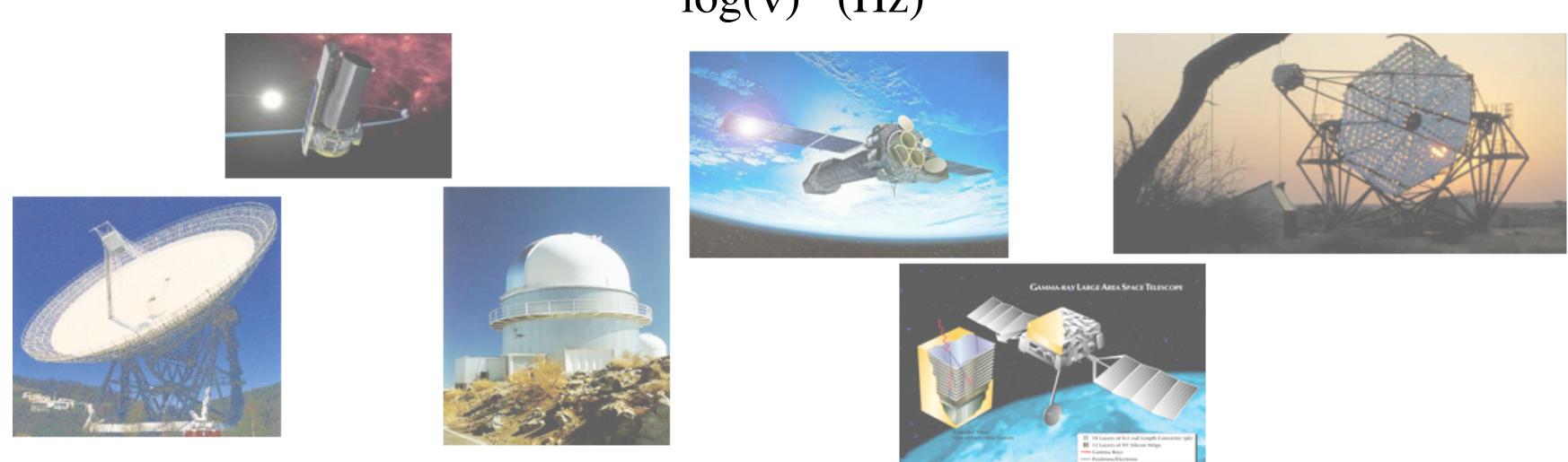
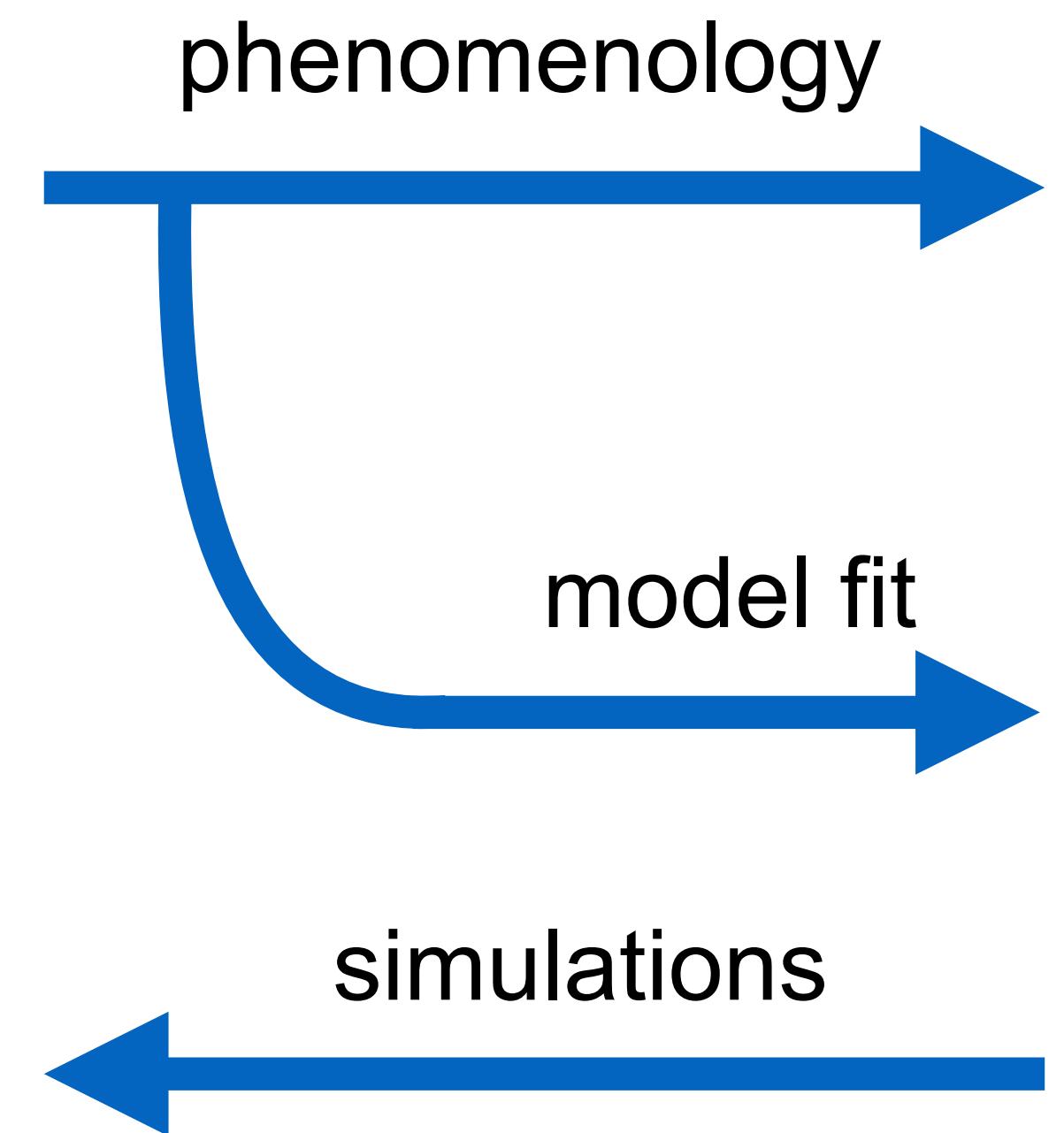
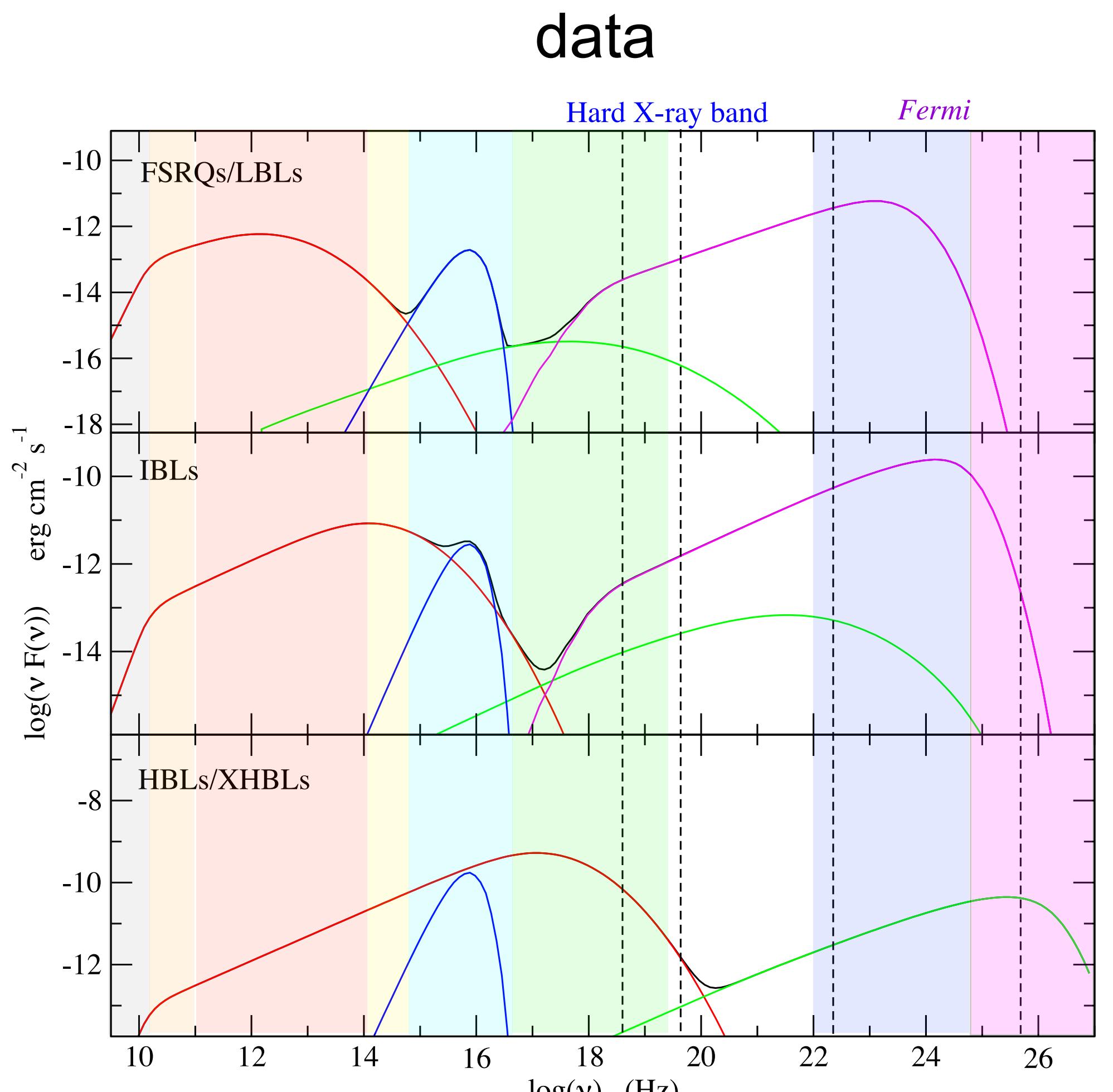
# Outline

- Theoretical background
- definition of complex radiative **models** SSC/EC IC against CMB/BLR/DT, plus analytical and template models
- handling observed **data** (grouping, definition of data sets, etc...)
- **constraining** of the model in the pre-fitting stage, based on accurate and already published **phenomenological trends**
- **fitting of multiwavelength SEDs** using both **frequentist** approach (iminuit/scipy) and Bayesian **MCMC** sampling (emcee)
- Textbooks
  - Radiative Processes in Astrophysics, Ribicky & Lightman, John Wiley & Sons, 1991
  - High Energy Radiation from Black Holes: Gamma Rays, Cosmic Rays, and Neutrinos, Dermer & Menon, Princeton University Press 2009

[https://github.com/andreatramacere/Linnaeus\\_JetSeT\\_Lesson](https://github.com/andreatramacere/Linnaeus_JetSeT_Lesson)

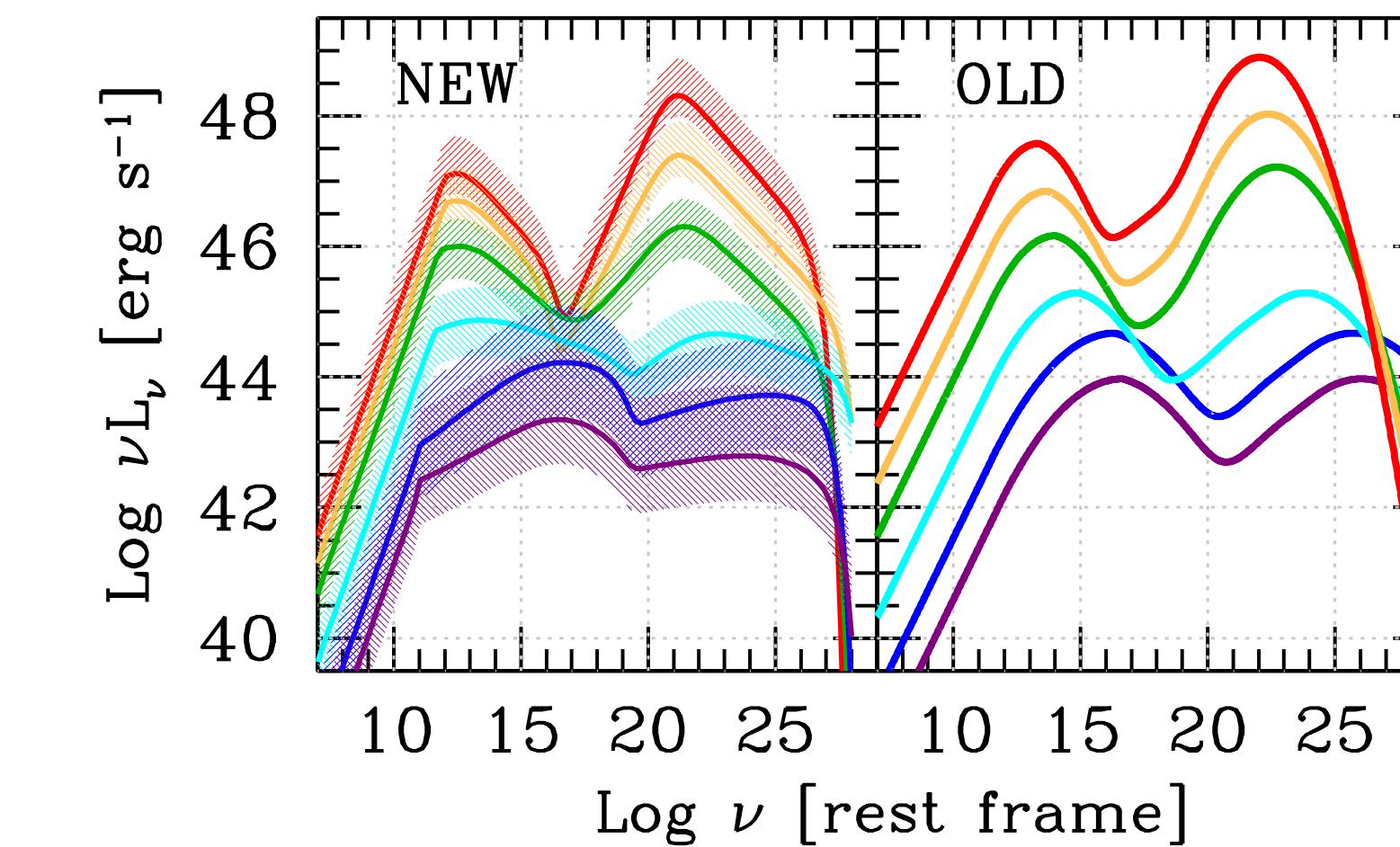
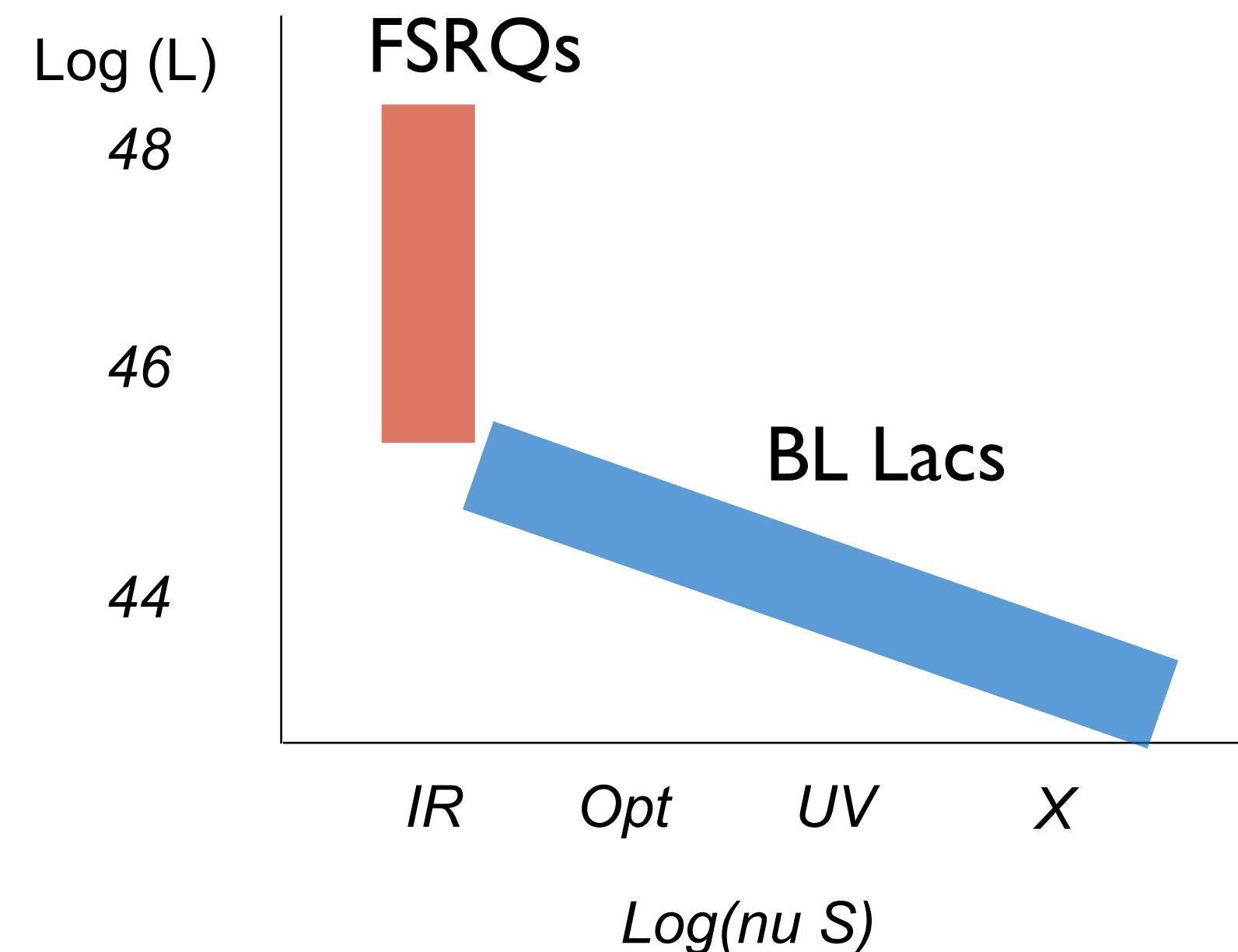
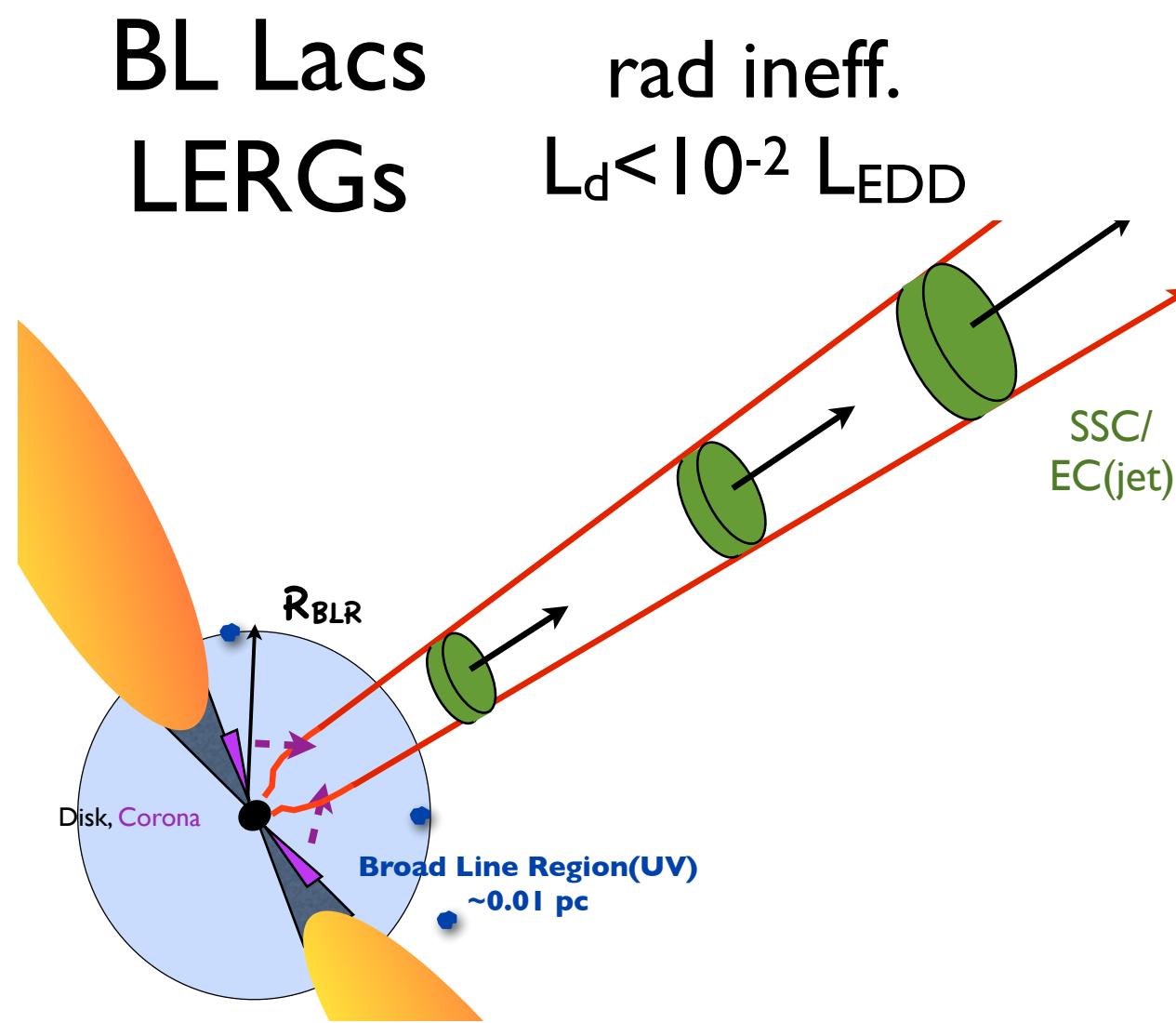
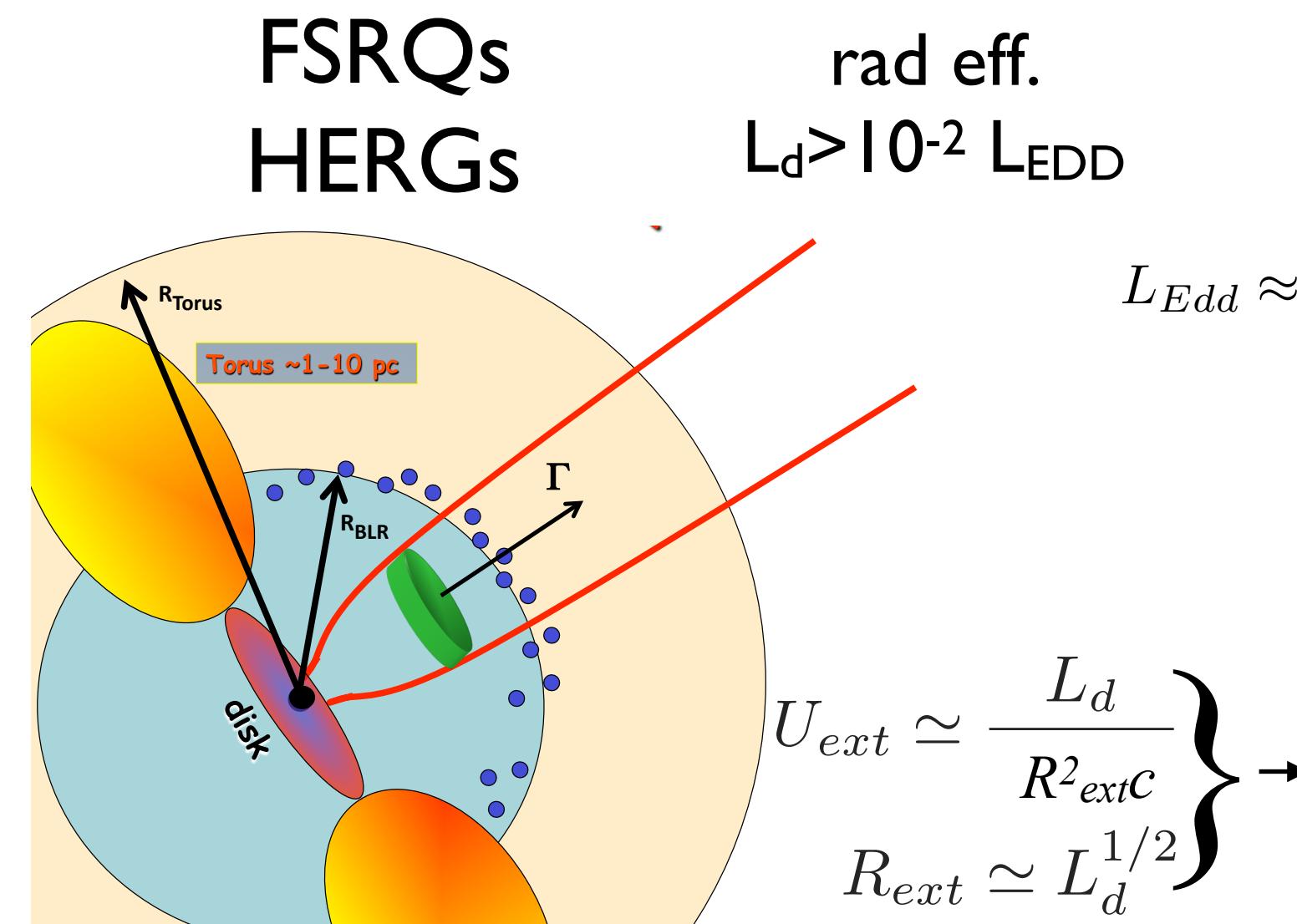
- Tutorial 1: basic operation with jet models
- Tutorial 2: phenomenological trends for synchrotron and SSC emission
- Tutorial 3: phenomenological trends for EC emission
- Tutorial 4: composite models and application to EBL (not covered in these slides)
- Tutorial 5: constraining of the model in the pre-fitting stage, based on accurate and already published phenomenological trends and fitting of multiwavelength SEDs using both frequentist approach ([iminuit/scipy](#)) and Bayesian MCMC sampling ([emcee](#))

# Blazars in a nutshell

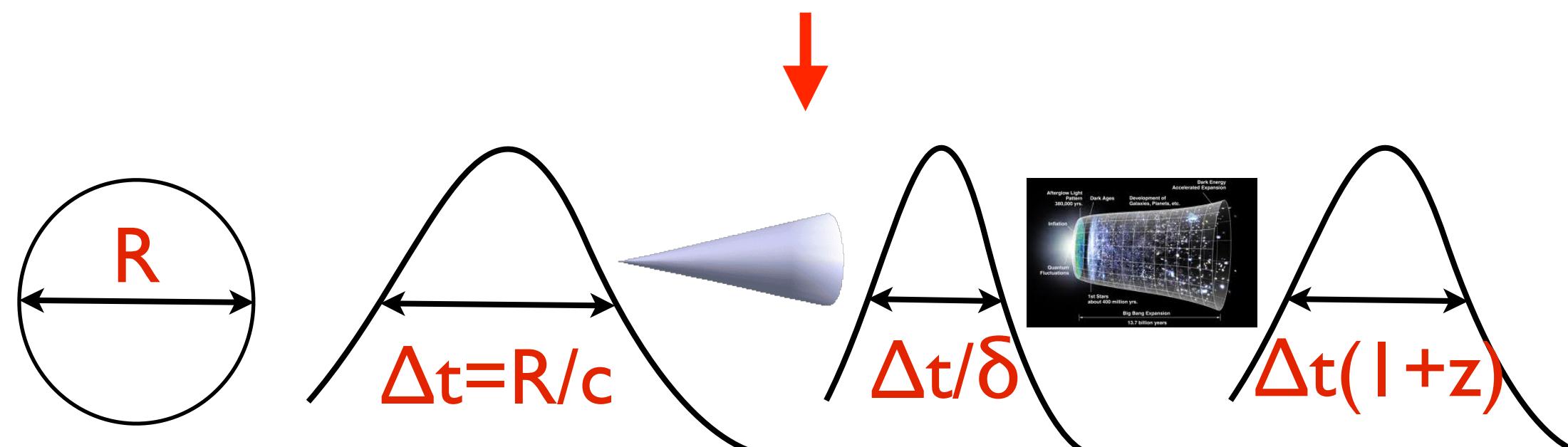
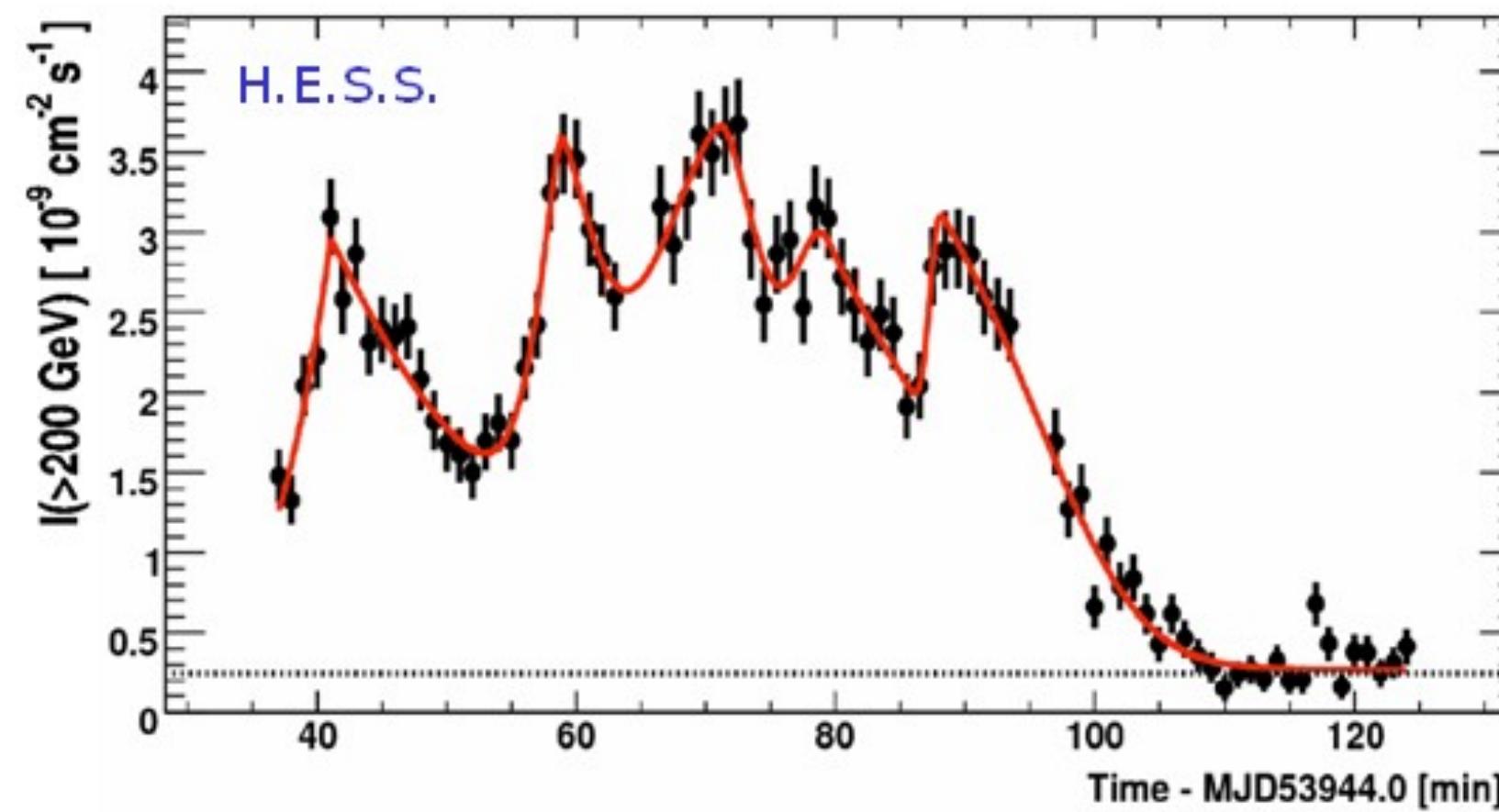


# standard picture: acceleration/cooling balance

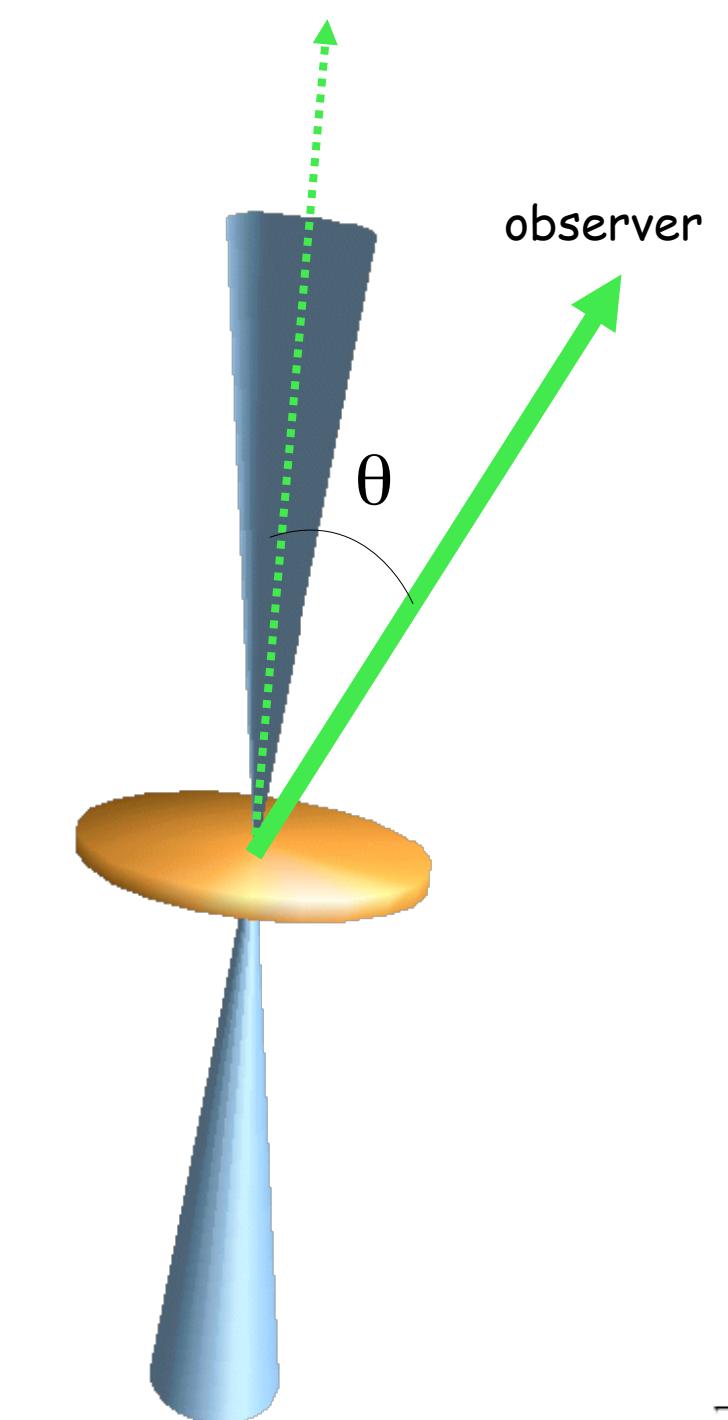
(Ghisellini,Fossati,Celotti 99-16)



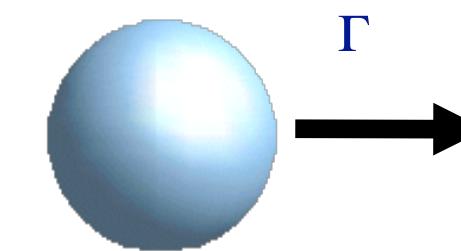
# Beamed Emission



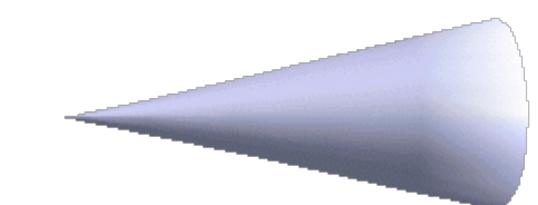
$$R \leq c \Delta t \delta / (1+z)$$



rest frame :  
isotropic emission

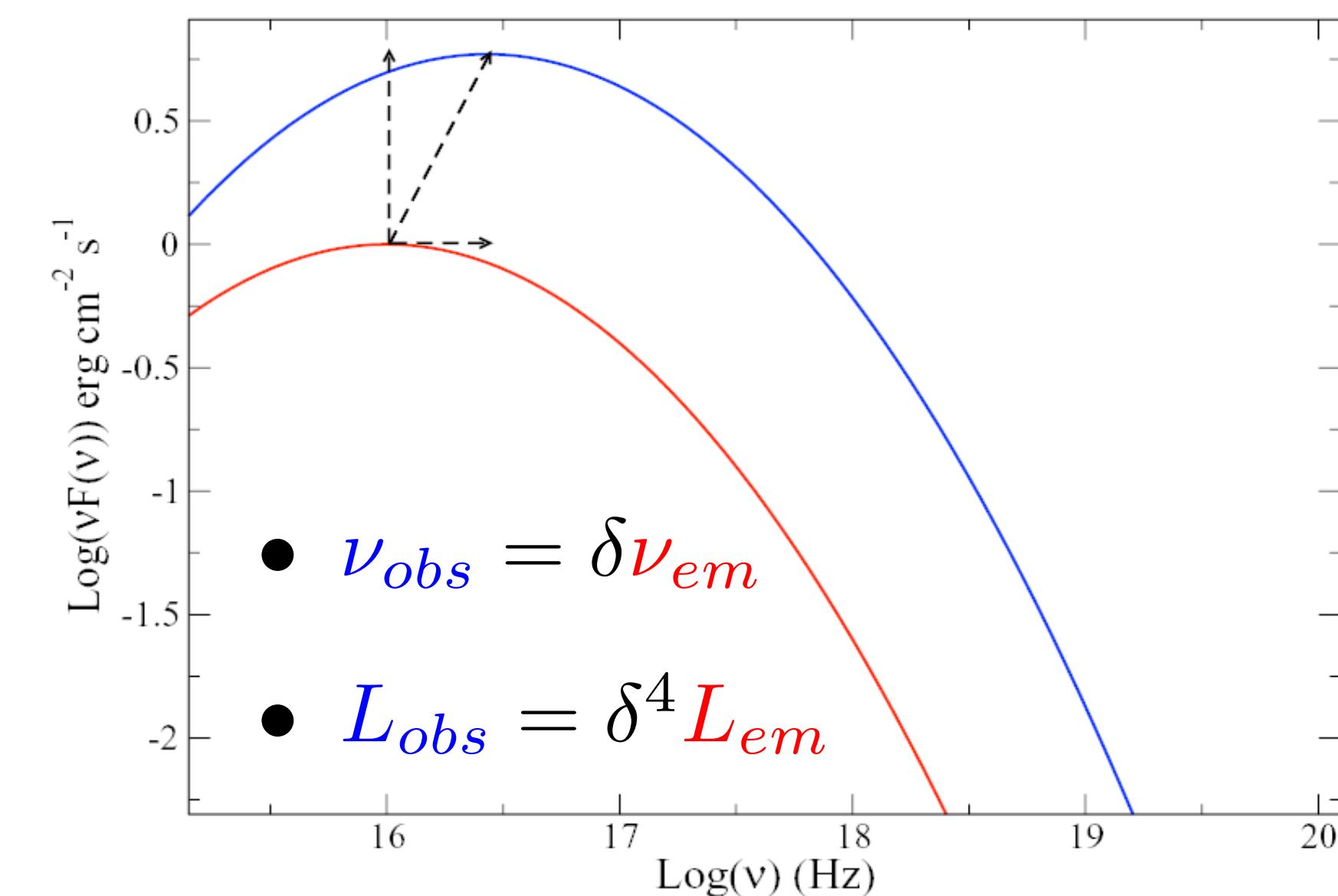


Observer frame: beamed

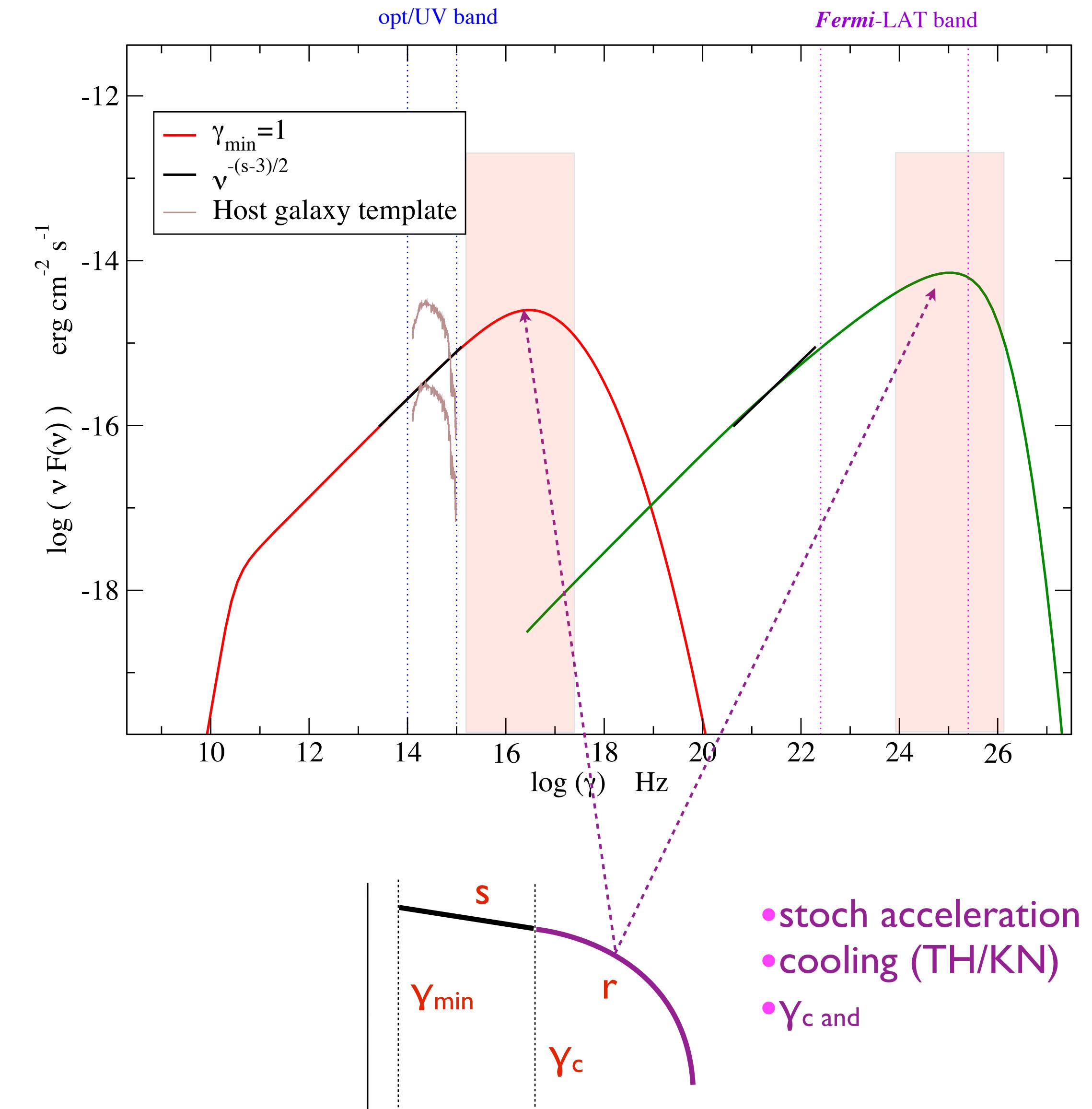
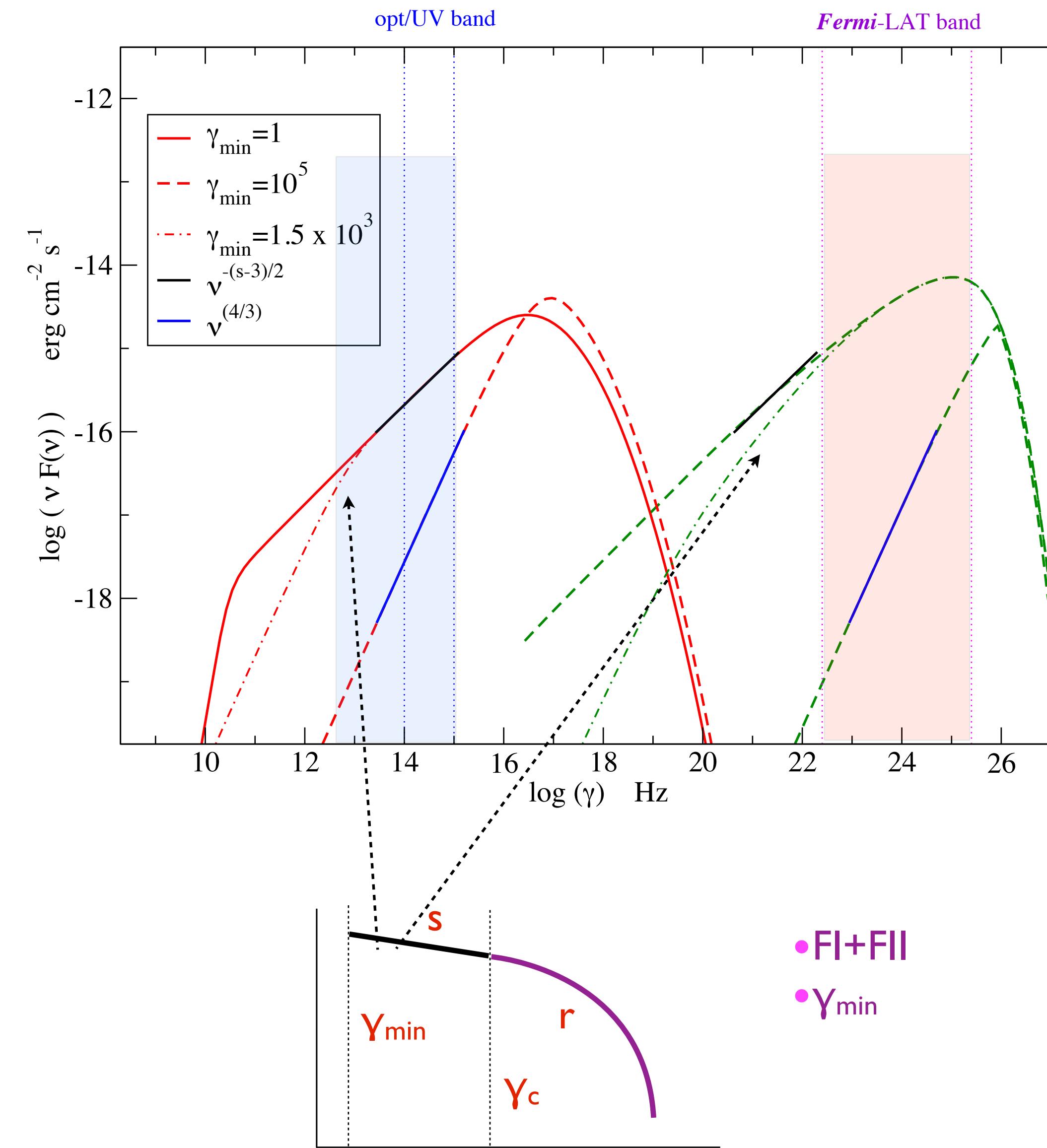


Beaming factor:

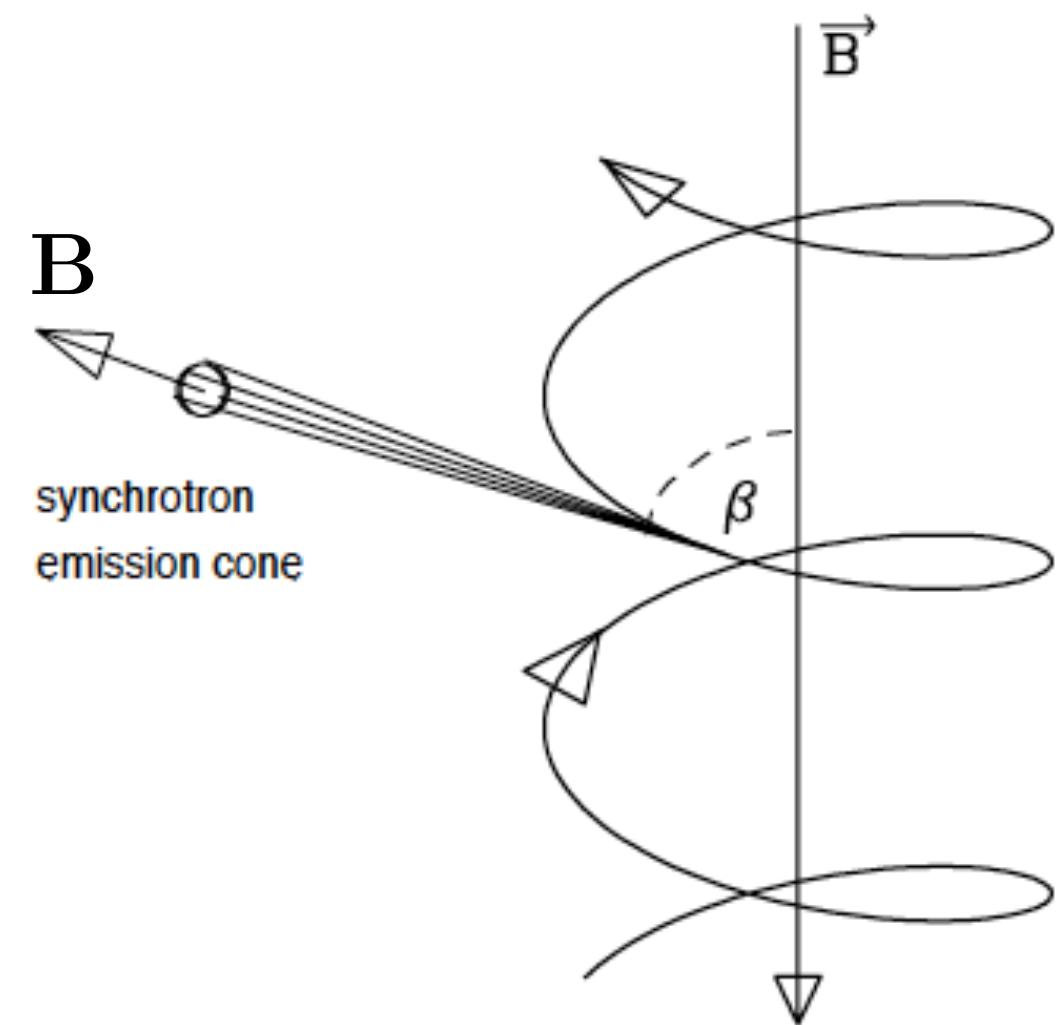
- $\delta = \frac{1}{\Gamma(1-\beta \cos(\theta))}$
- $\theta = 1/\Gamma$



# SED shaping and constraining the electron distribution



$$m\gamma \frac{d(\mathbf{v})}{dt} = \frac{q}{c} \mathbf{v} \times \mathbf{B}$$



$$a_{\parallel} = 0$$

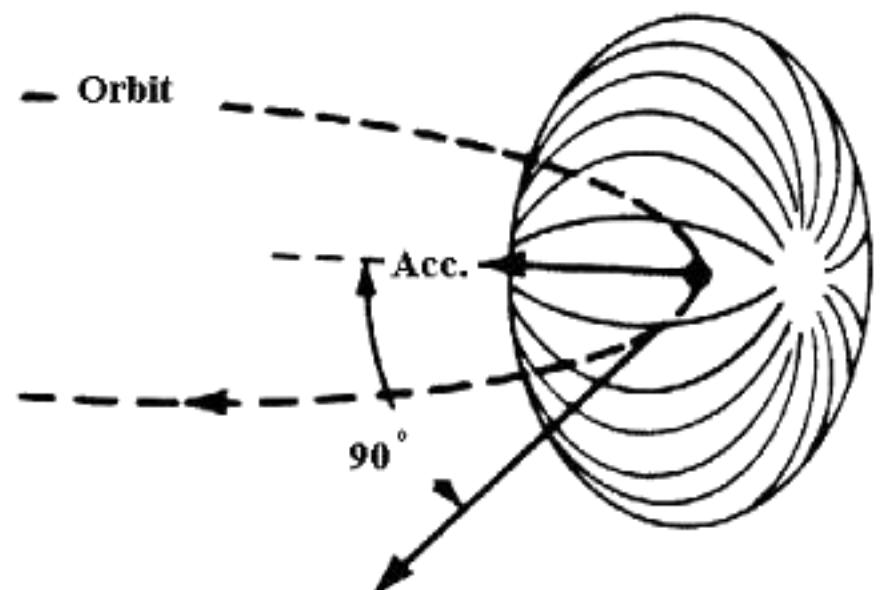
$$a_{\perp} = \frac{evB\sin\alpha}{\gamma m_e c}$$

$$\nu_B = \frac{eB}{2\pi\gamma mc} = \frac{\nu_L}{\gamma}$$

**total emitted power**

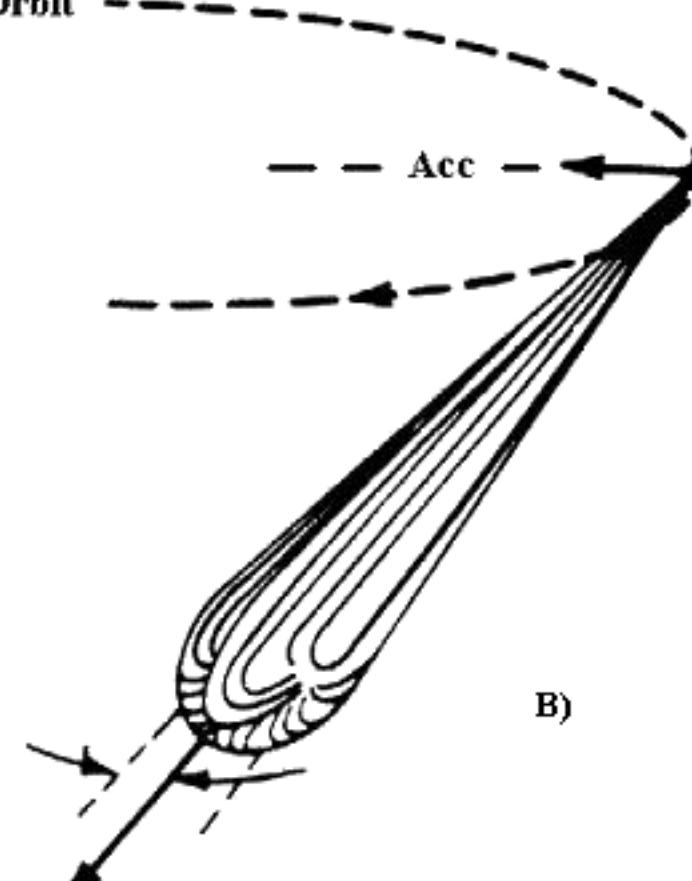
$$P_e = P'_e = \frac{2e^2}{3c^3} a'^2 = \frac{2e^2}{3c^3} [a'^2_{\parallel} + a'^2_{\perp}]$$

$$P_S = \frac{2e^4}{3m_e c^3} B^2 \gamma^2 \beta^2 \sin^2 \alpha$$



A)

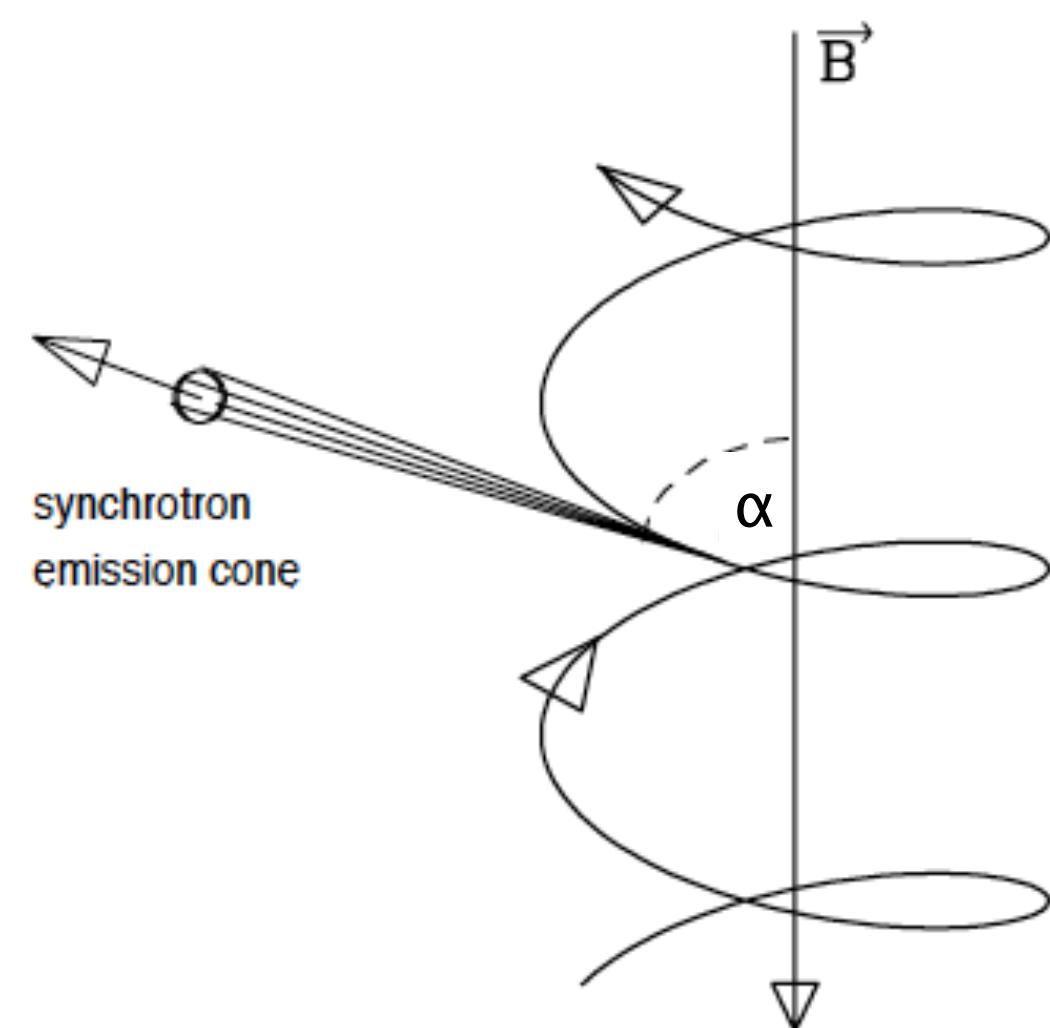
$$\Delta \phi = \frac{1}{\gamma}$$



B)

# synchrotron basics

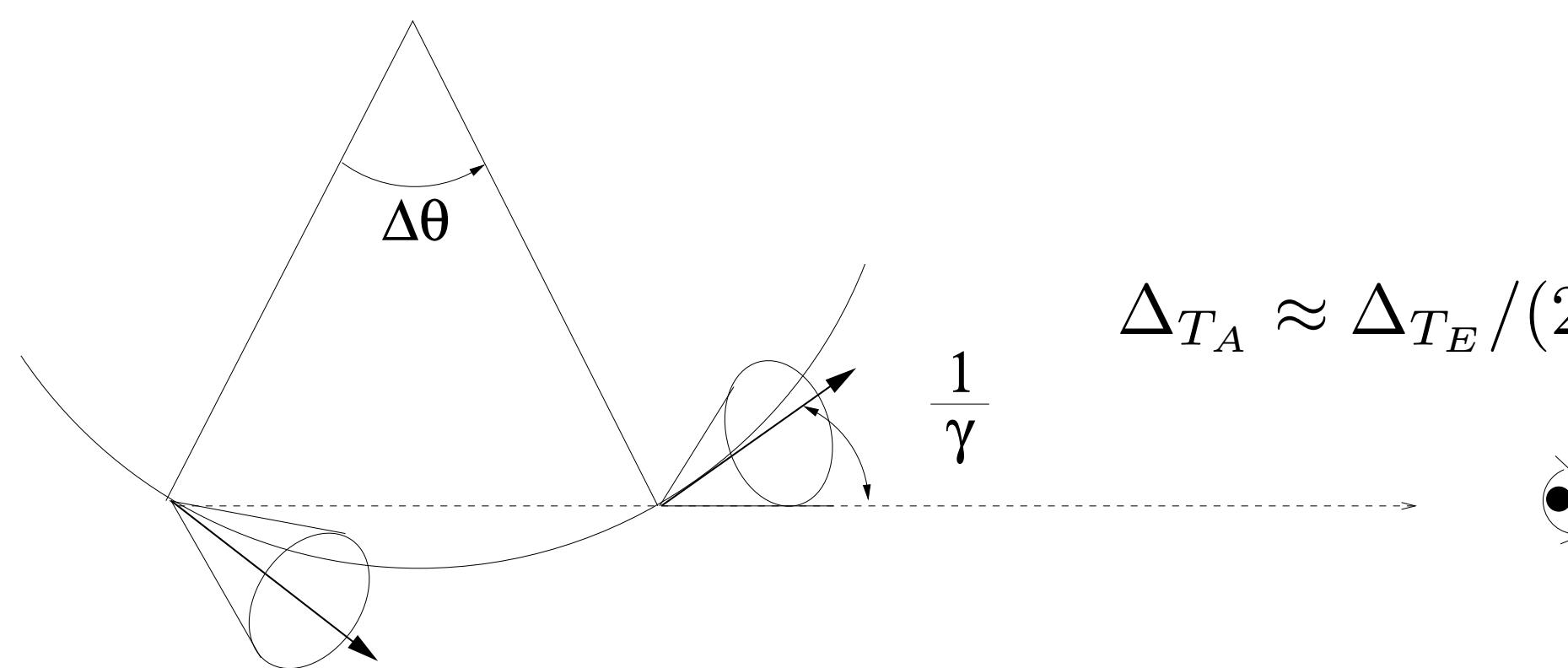
single particle



emitted spectrum

$$P_e(\nu, \gamma) = \frac{\sqrt{3}e^3 B \sin \alpha}{2m_e c^2} F(x)$$

$$\nu_c = \frac{3}{2} \nu_B \gamma^3 \sin \alpha = \frac{3\gamma^2 e B \sin \alpha}{4\pi m_e c}$$

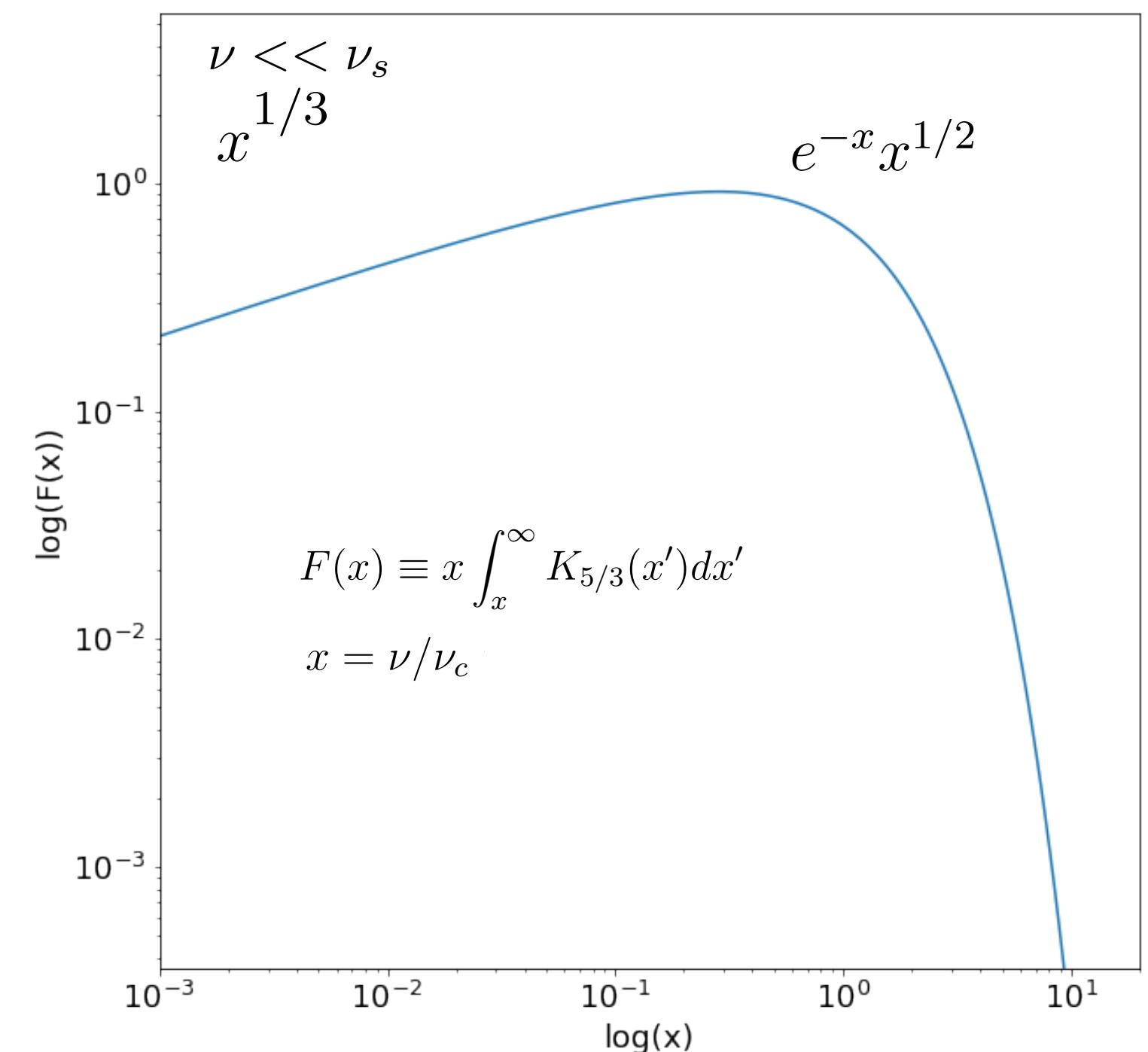
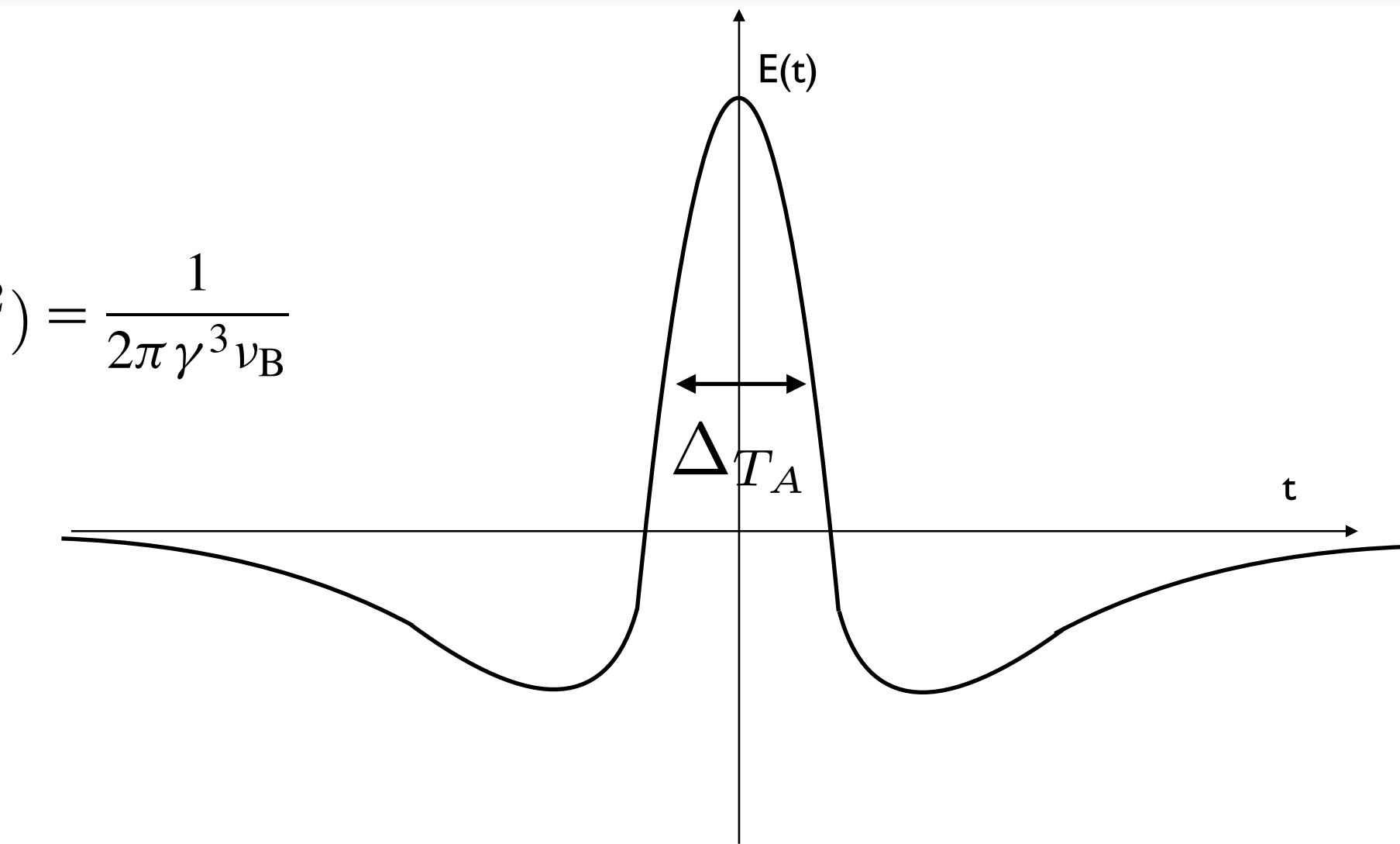


power spectrum

$$\Delta_{T_A} \nu_T = \frac{1}{2\pi} \rightarrow \nu_T = \gamma^3 \nu_B$$

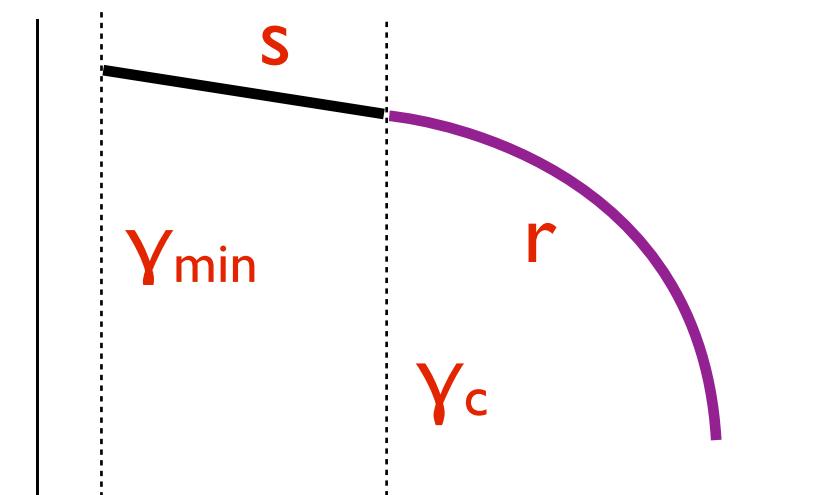
$$\nu_s \propto 10^6 B \gamma^2 \sin(\alpha) \text{ Hz}$$

$$\Delta_{T_A} \approx \Delta_{T_E} / (2\gamma^2) = \frac{1}{2\pi\gamma^3\nu_B}$$



## Tutorial 2

$$N(\gamma) \propto \gamma^{-s}$$

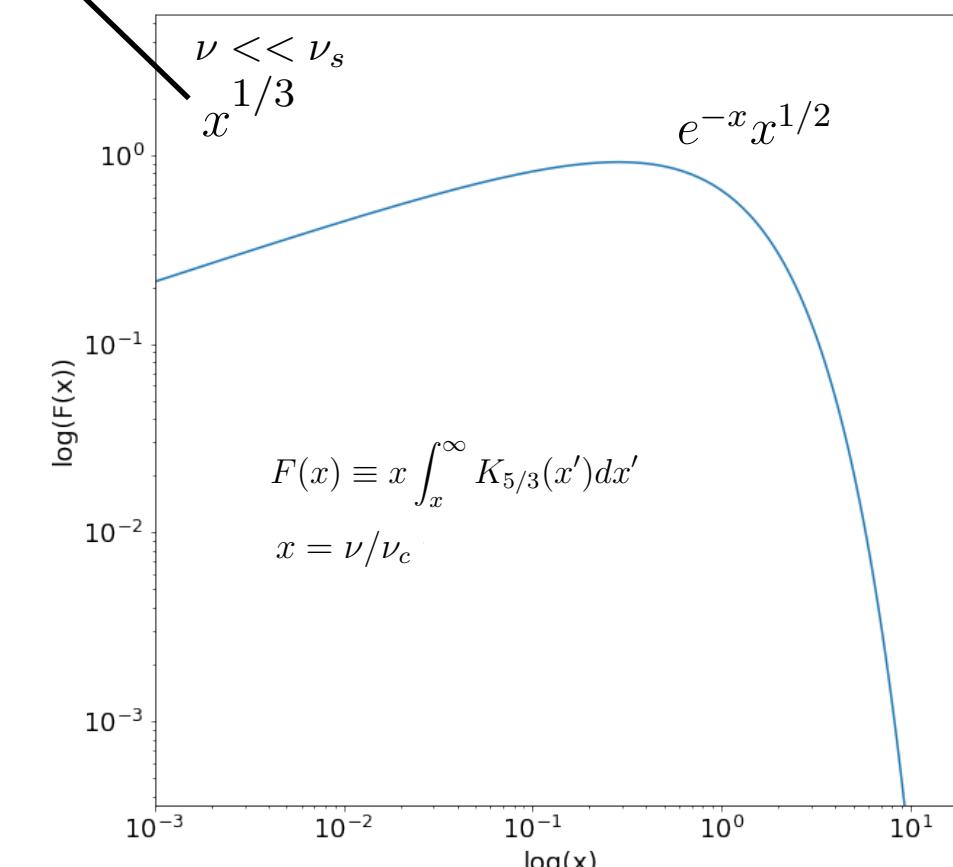
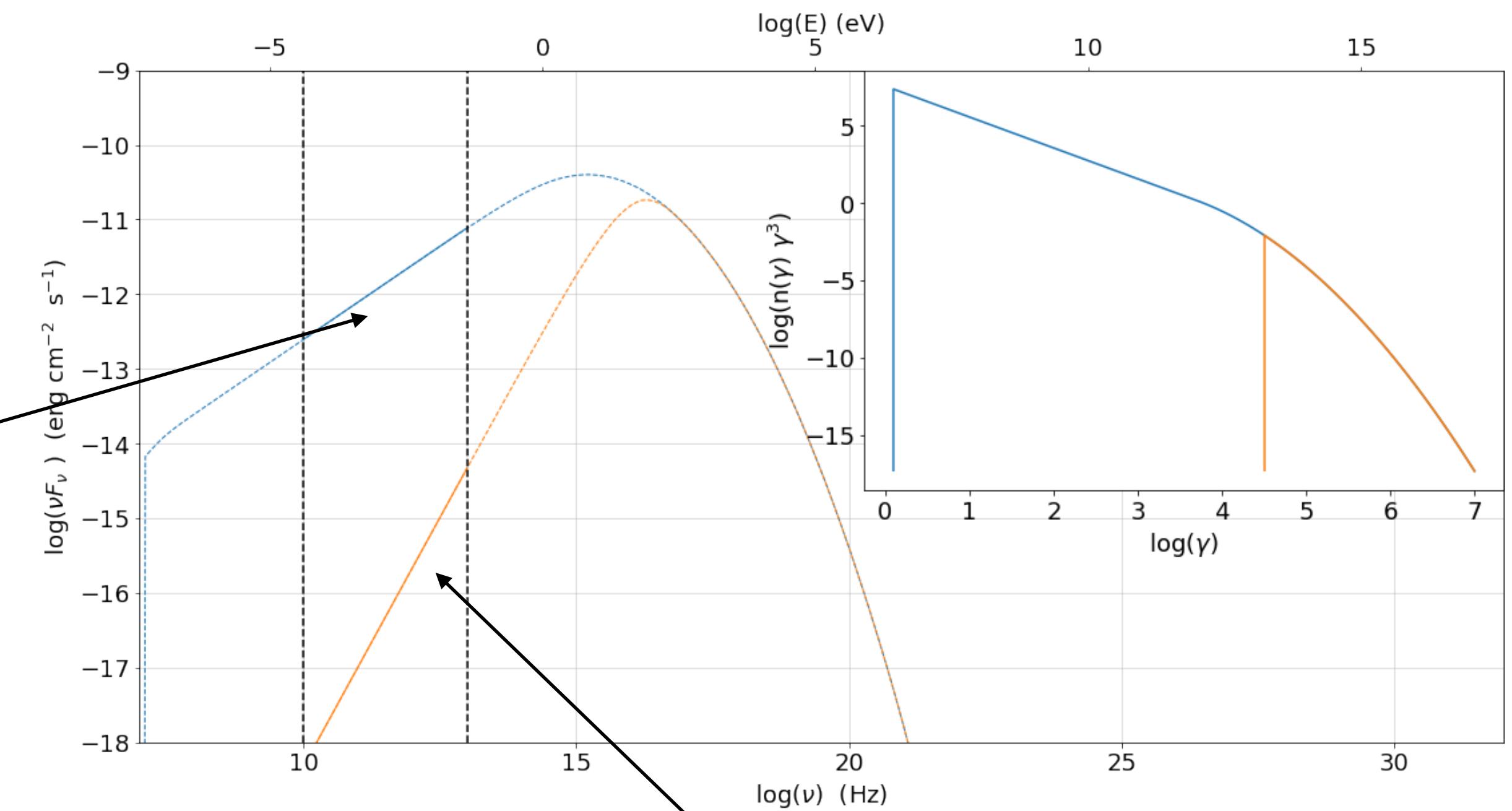


$$j_\nu^S(\nu) = \frac{1}{4\pi} \int_{\gamma_{min}}^{\gamma_{max}} P(\nu, \gamma) N(\gamma) d\gamma \propto \nu^{-\frac{s-1}{2}}$$

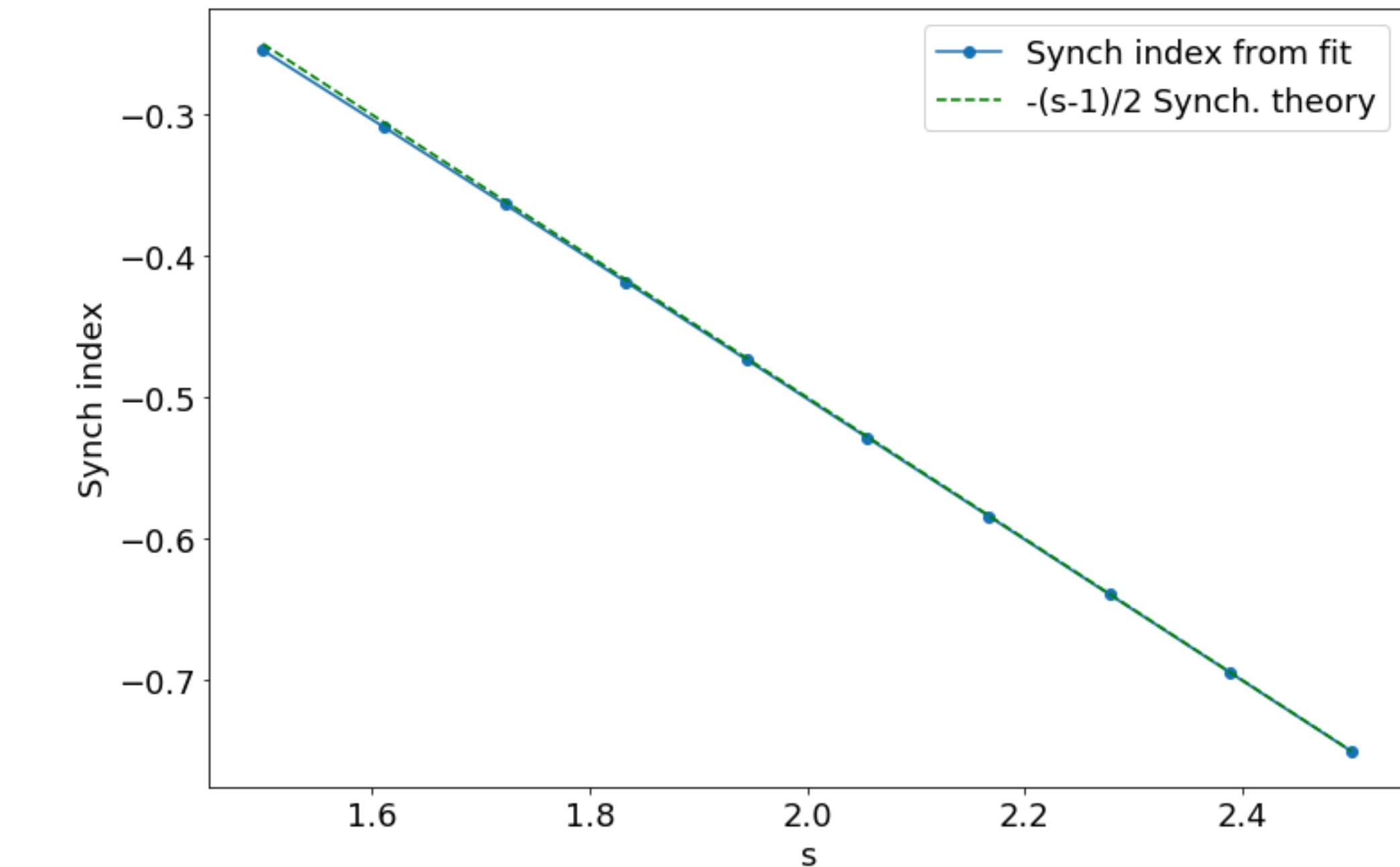
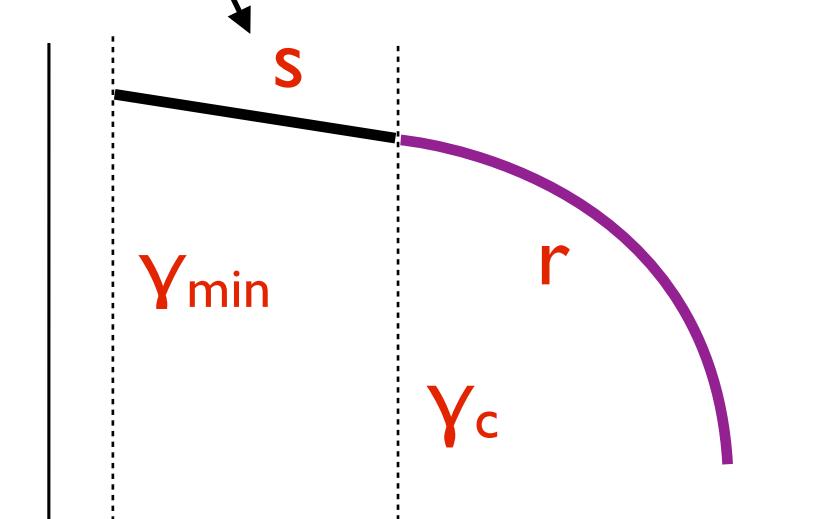
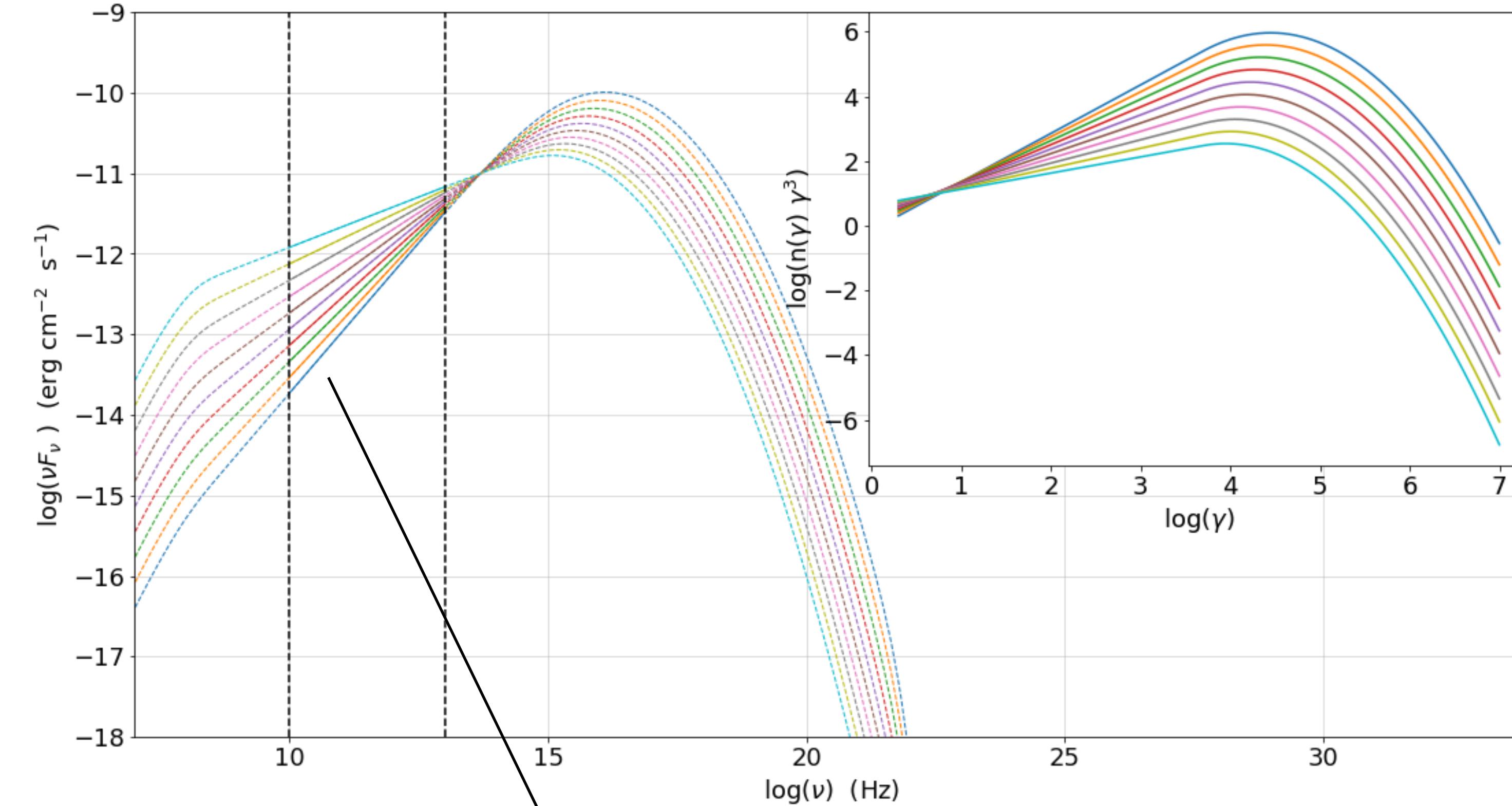
**δ-approx relations**

$$\text{SED} \propto N(\gamma) \gamma^3$$

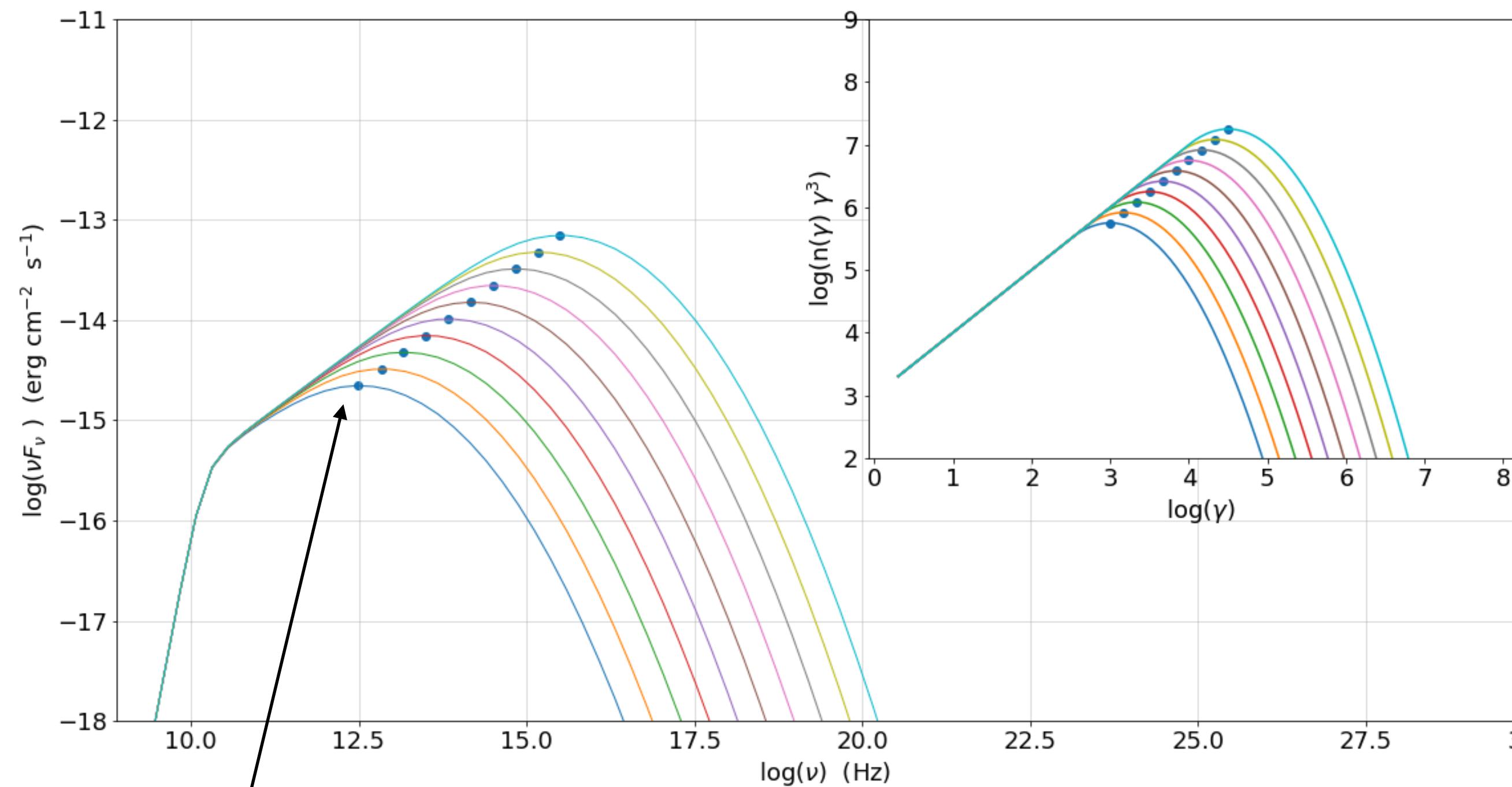
$$S_p^{Sync} \sim \frac{dN(\gamma)}{d\gamma} \gamma_{3p}^3 B^2 \delta^4 \quad \nu_p^{Sync} \sim 3.2 \times 10^6 (\gamma_{3p})^2 B \delta$$



## Tutorial 2

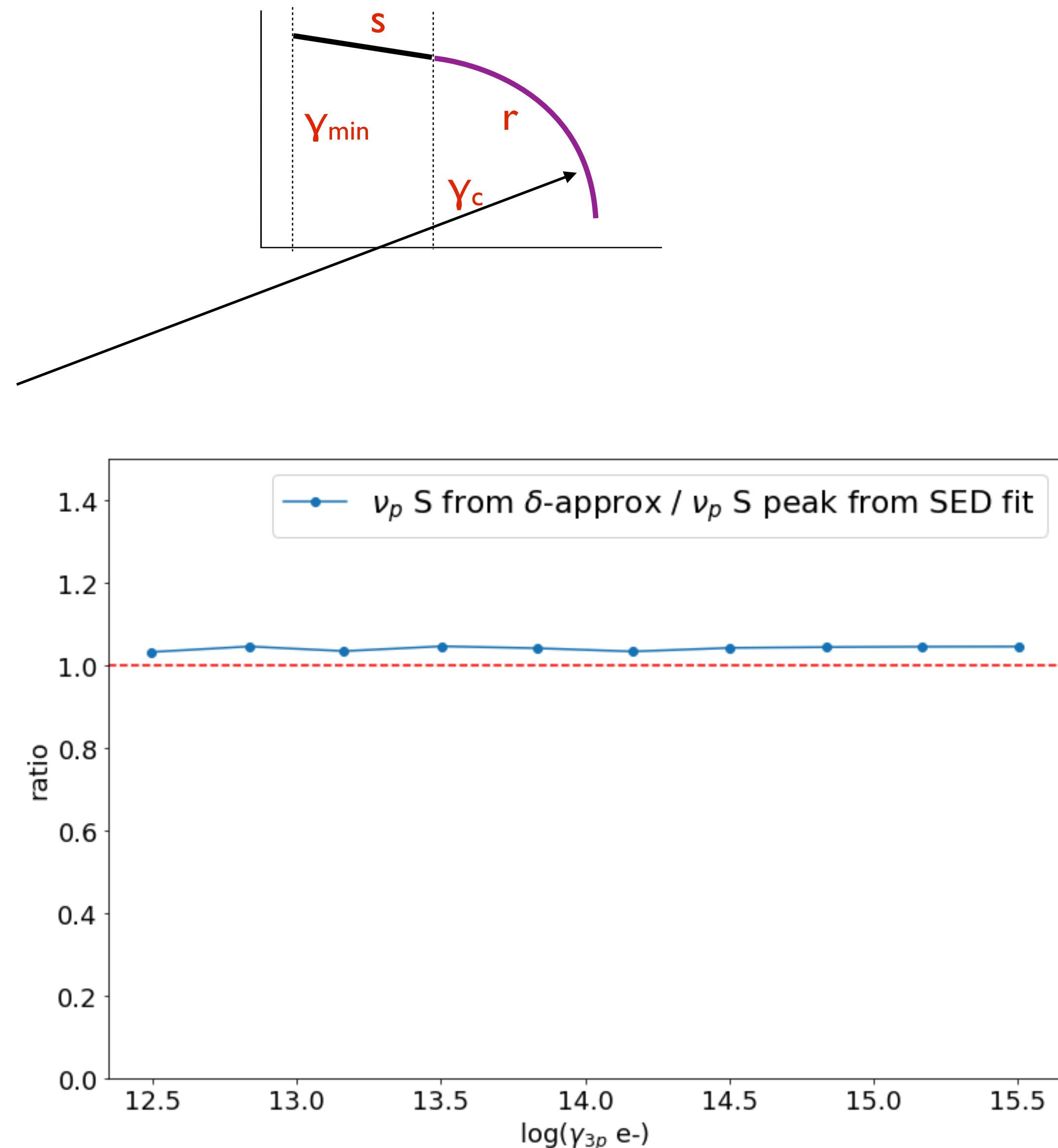


$$j_\nu^S(\nu) = \frac{1}{4\pi} \int_{\gamma_{\min}}^{\gamma_{\max}} P(\nu, \gamma) N(\gamma) d\gamma \propto \nu^{-\frac{s-1}{2}}$$

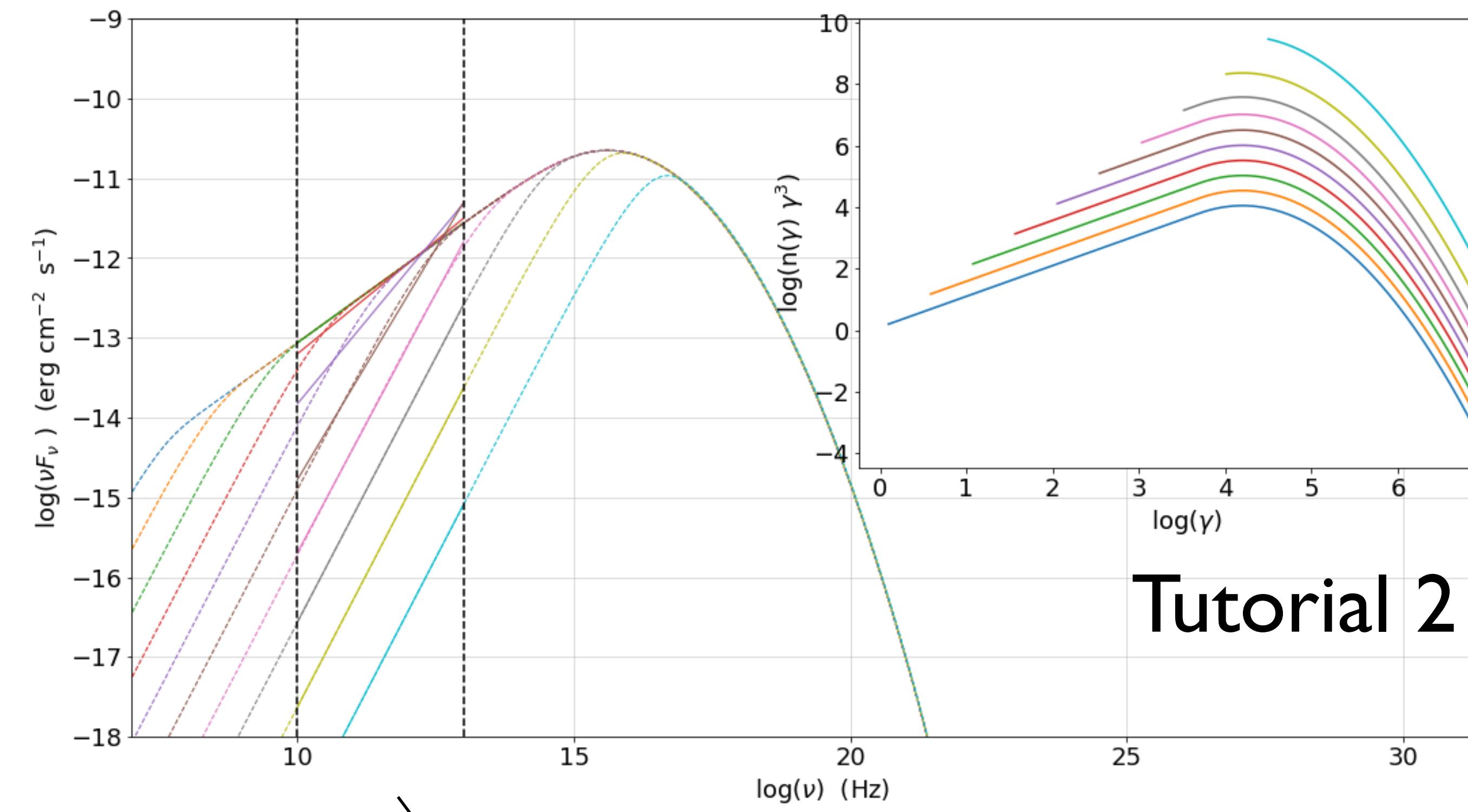


$$\nu_p^{Sync} \sim 3.2 \times 10^6 (\gamma_{3p})^2 B \delta$$

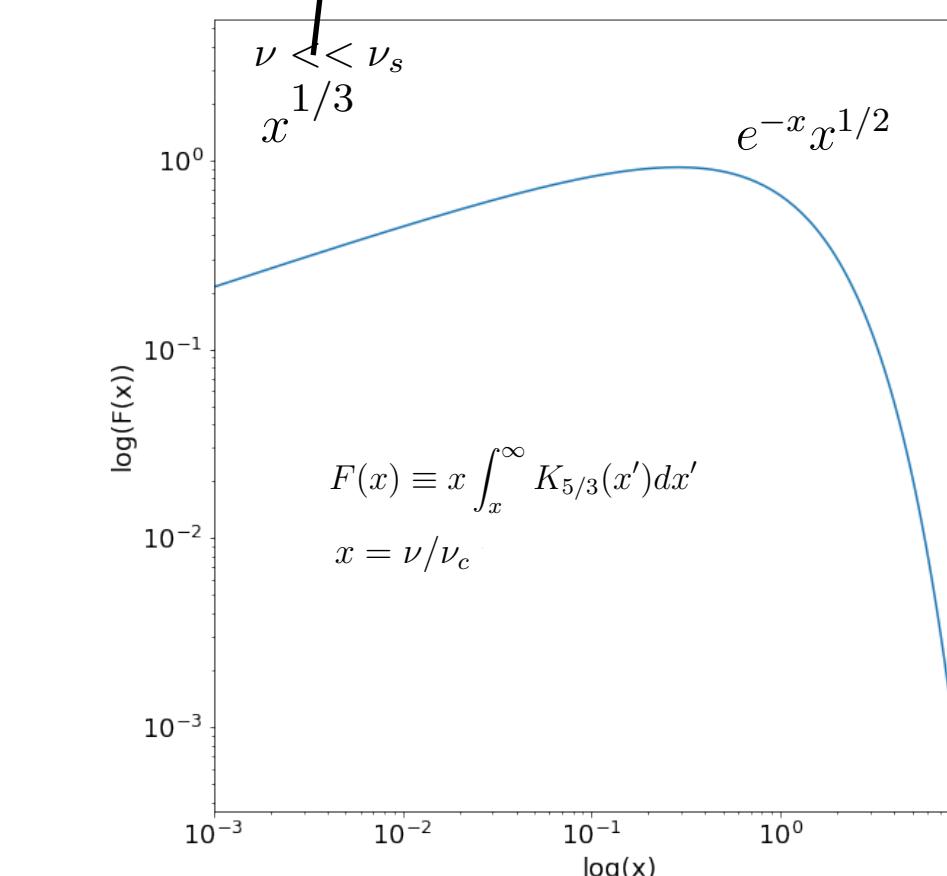
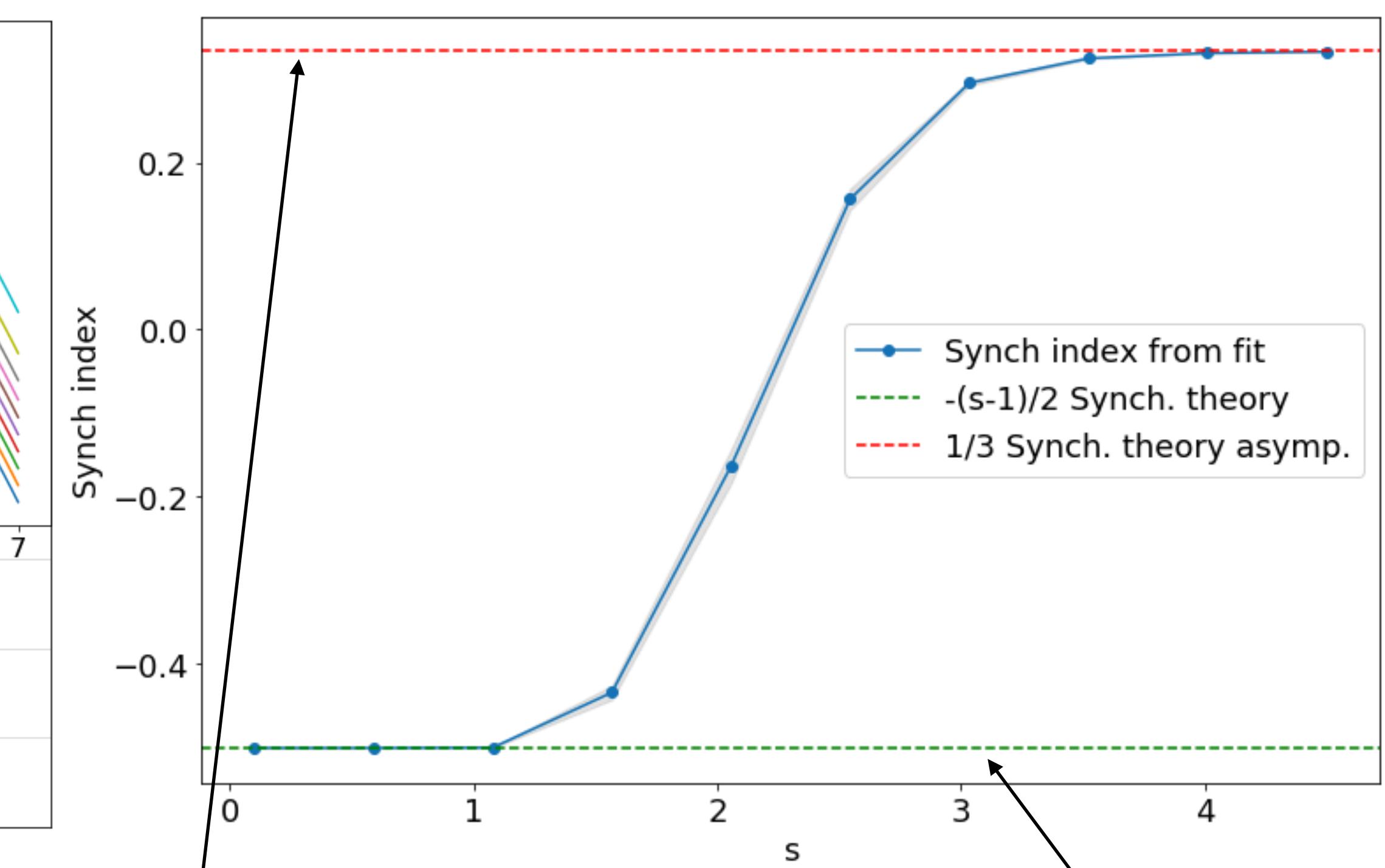
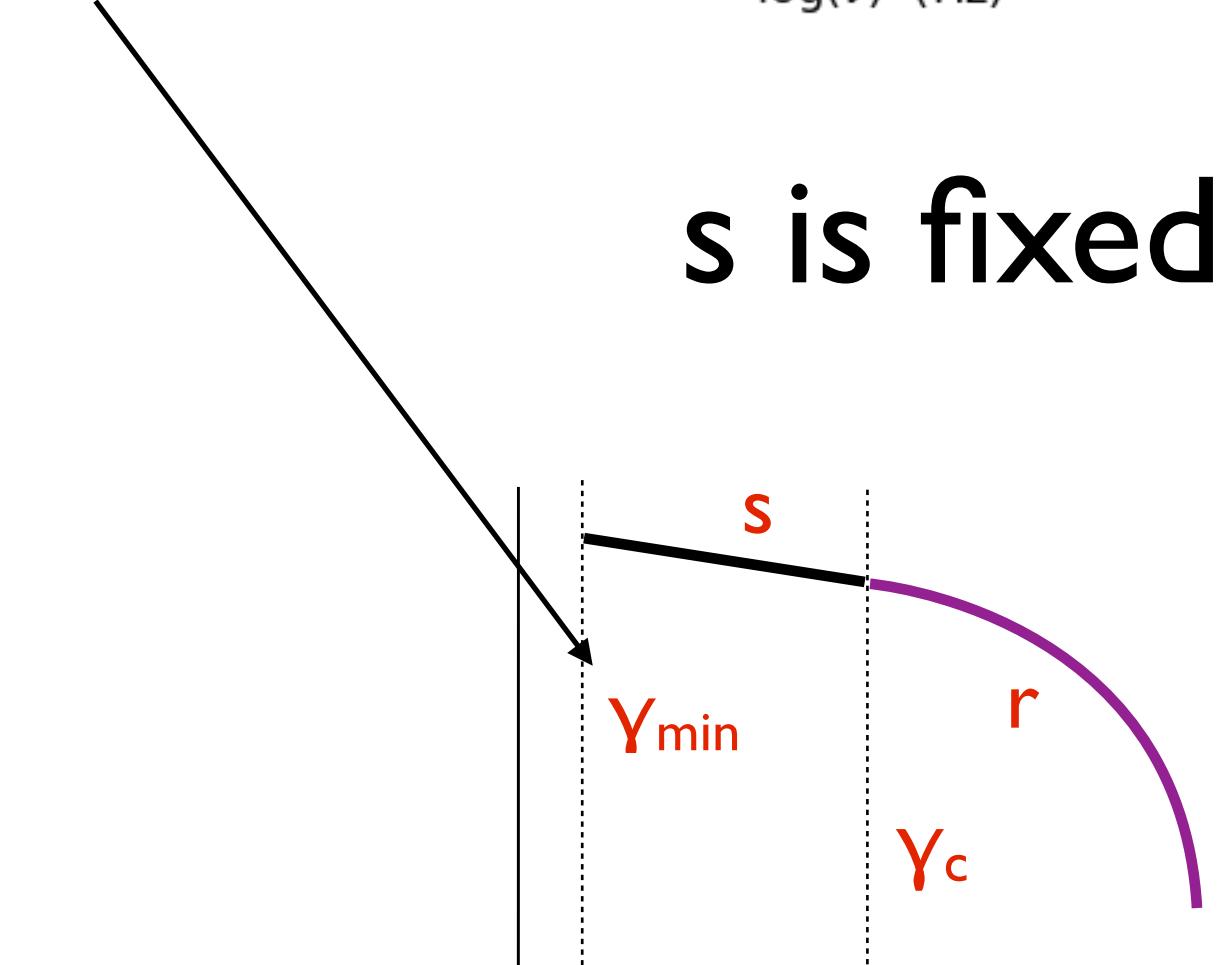
$$S_p^{Sync} \sim \frac{dN(\gamma)}{d\gamma} \gamma_{3p}^3 B^2 \delta^4$$



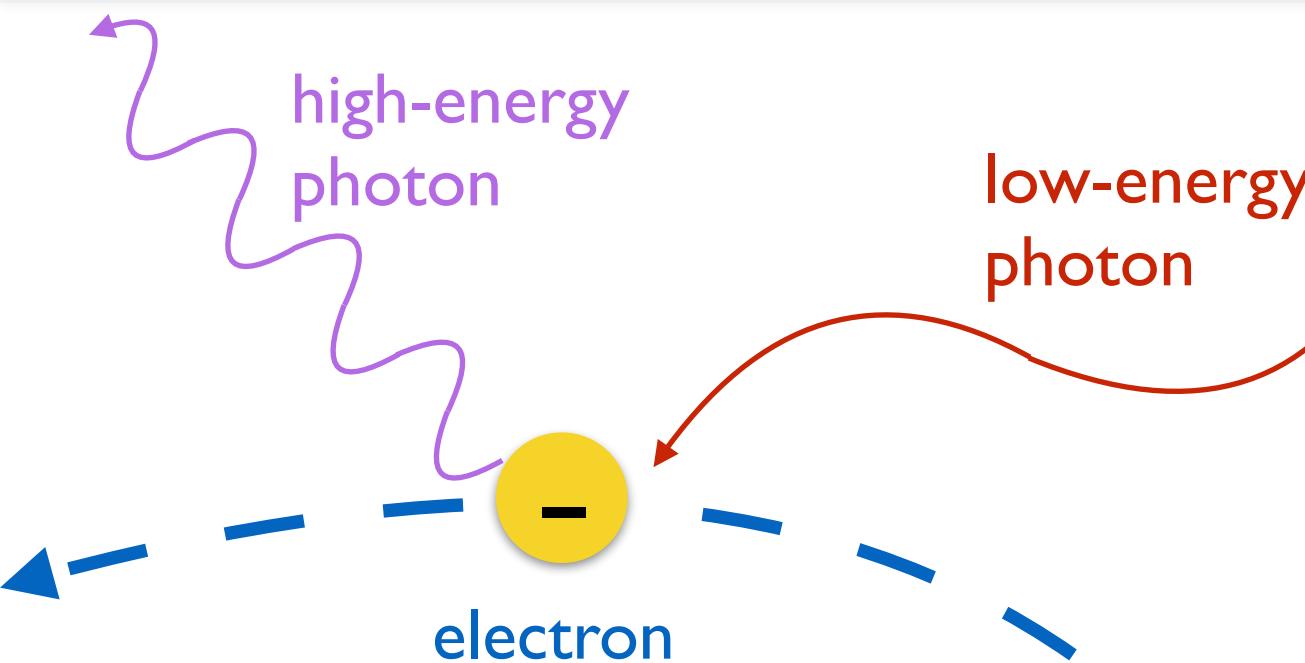
# Synchrotron emission Estimate of $\gamma_{min}$ from spectral index



**Tutorial 2**

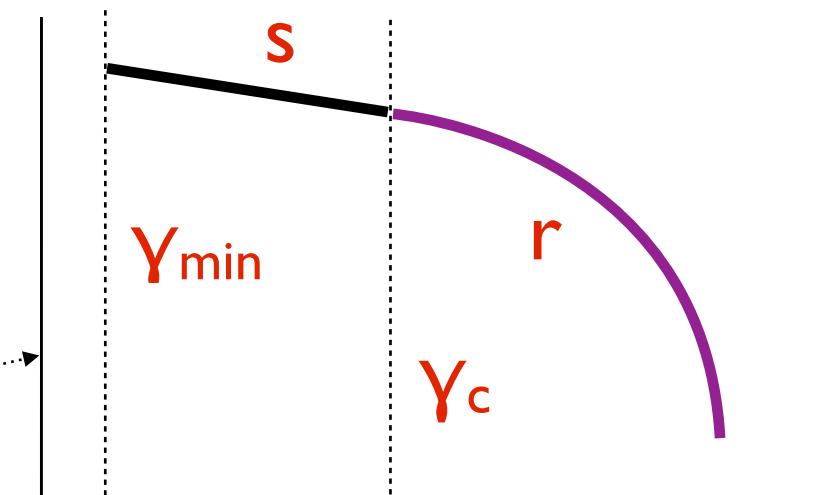
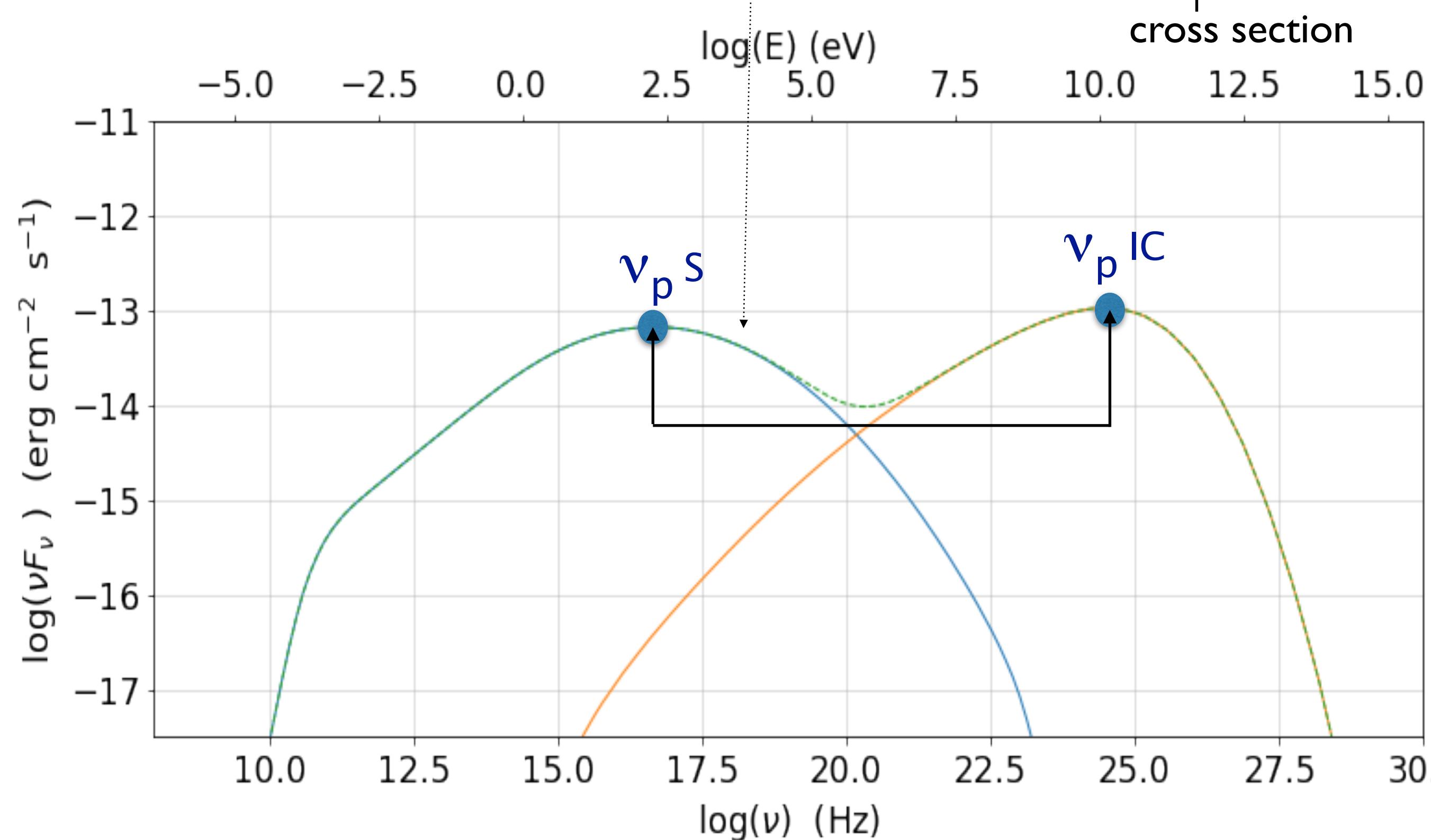


$$j_\nu^S(\nu) = \frac{1}{4\pi} \int_{\gamma_{min}}^{\gamma_{max}} P(\nu, \gamma) N(\gamma) d\gamma \propto \nu^{-\frac{s-1}{2}}$$



$$j_{\nu}^{SSC} = \frac{3}{4} \frac{h\nu\sigma_T c}{4\pi} \int_0^{\infty} n(\nu_0) d\nu_0 \int_{\gamma_{min}}^{\gamma_{max}} \frac{N(\gamma)}{\gamma^2} F_c(\gamma, \nu, \nu_0) d\gamma$$

cross section



soft photon energy  
in the e- rest frame

$$\epsilon' = \frac{h\nu'}{m_e c^2}$$

$$\epsilon' \ll m_e c^2$$

**TH regime**

$$\nu_p \text{ IC} / \nu_p \text{ S} \sim (4/3) \gamma_p^2$$

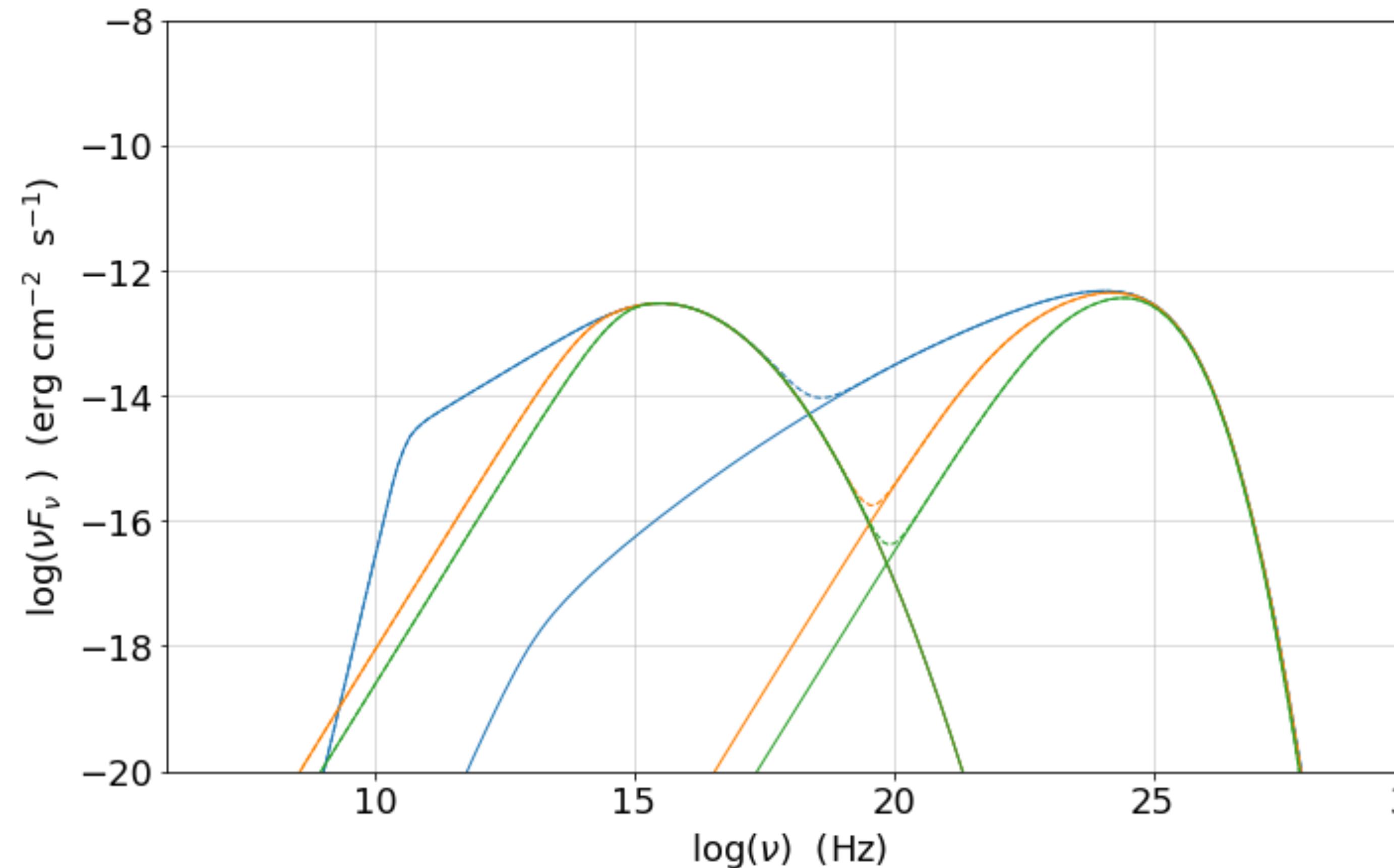
$$\epsilon' \geq m_e c^2$$

**KN regime**

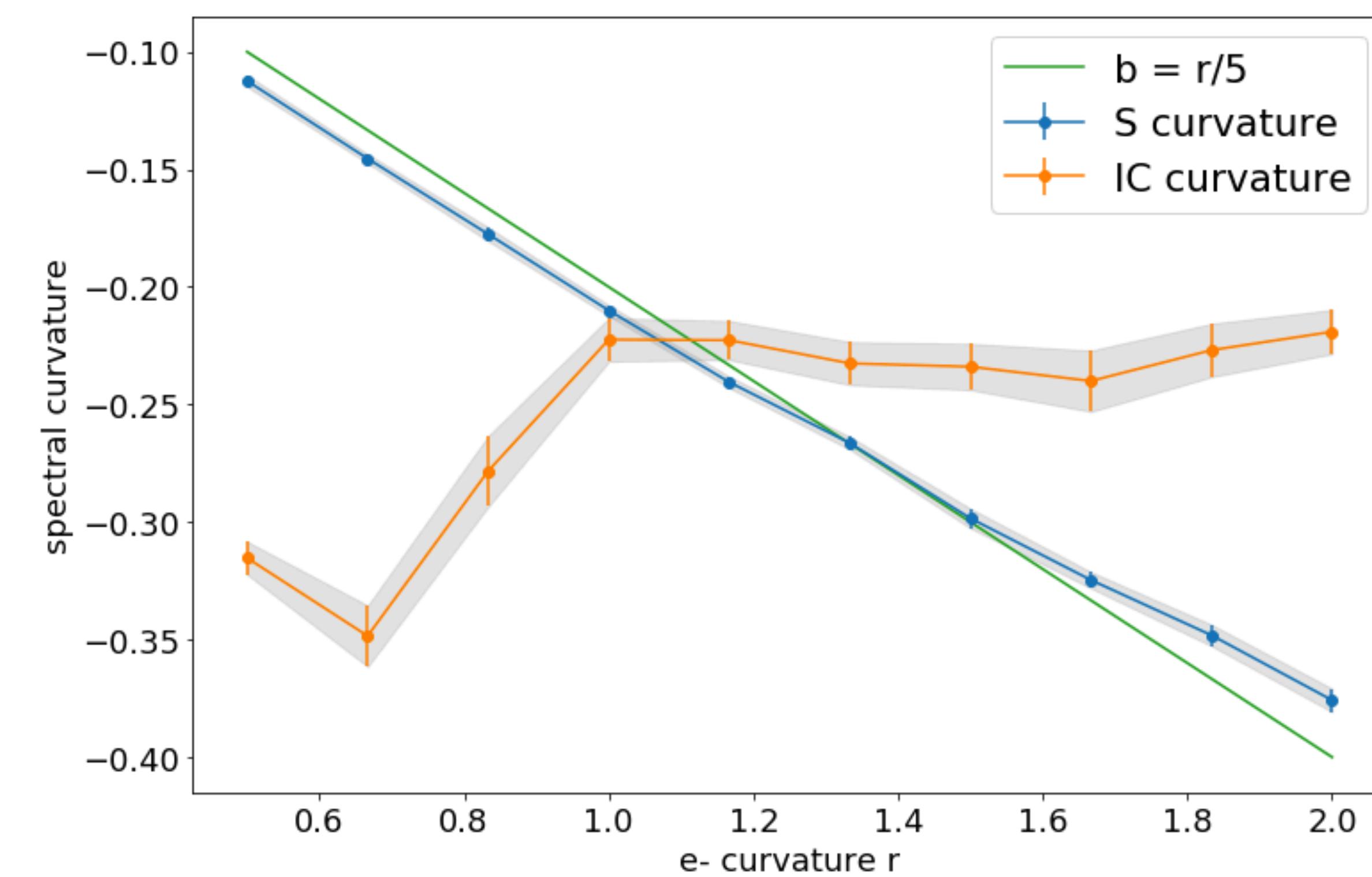
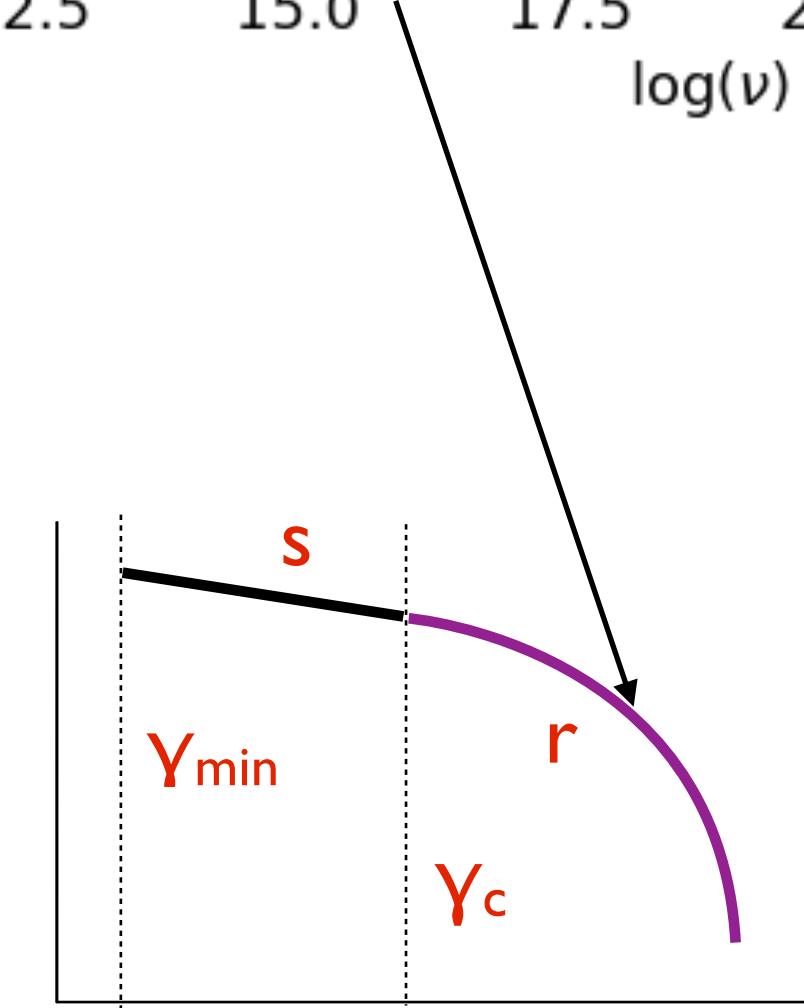
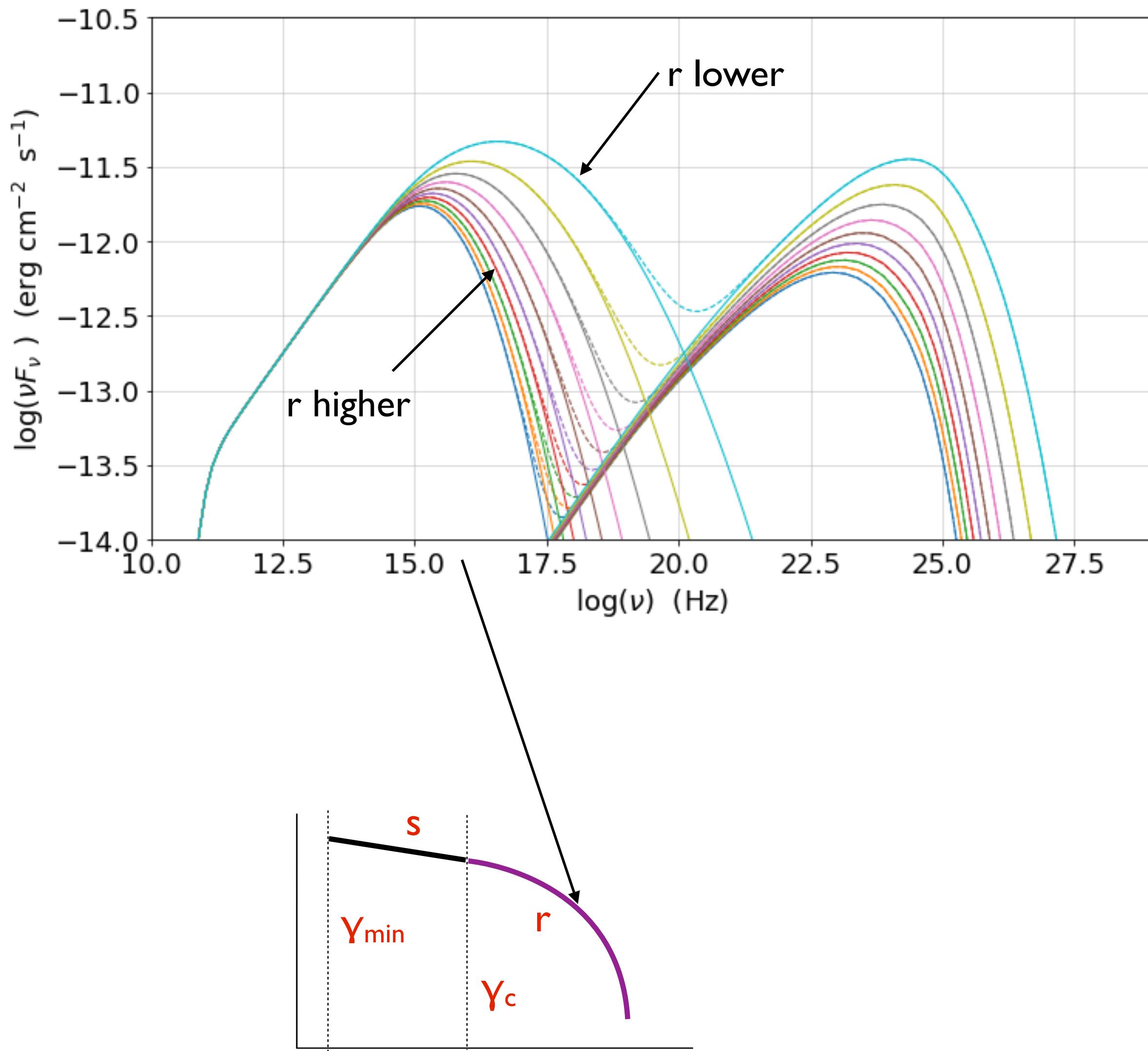
$$\nu_p \text{ IC} / \nu_p \text{ S} \sim \gamma_p$$

$$h\nu_p \text{ IC} \sim m_e c^2 \gamma_p$$

## Adding the IC emission SSC case



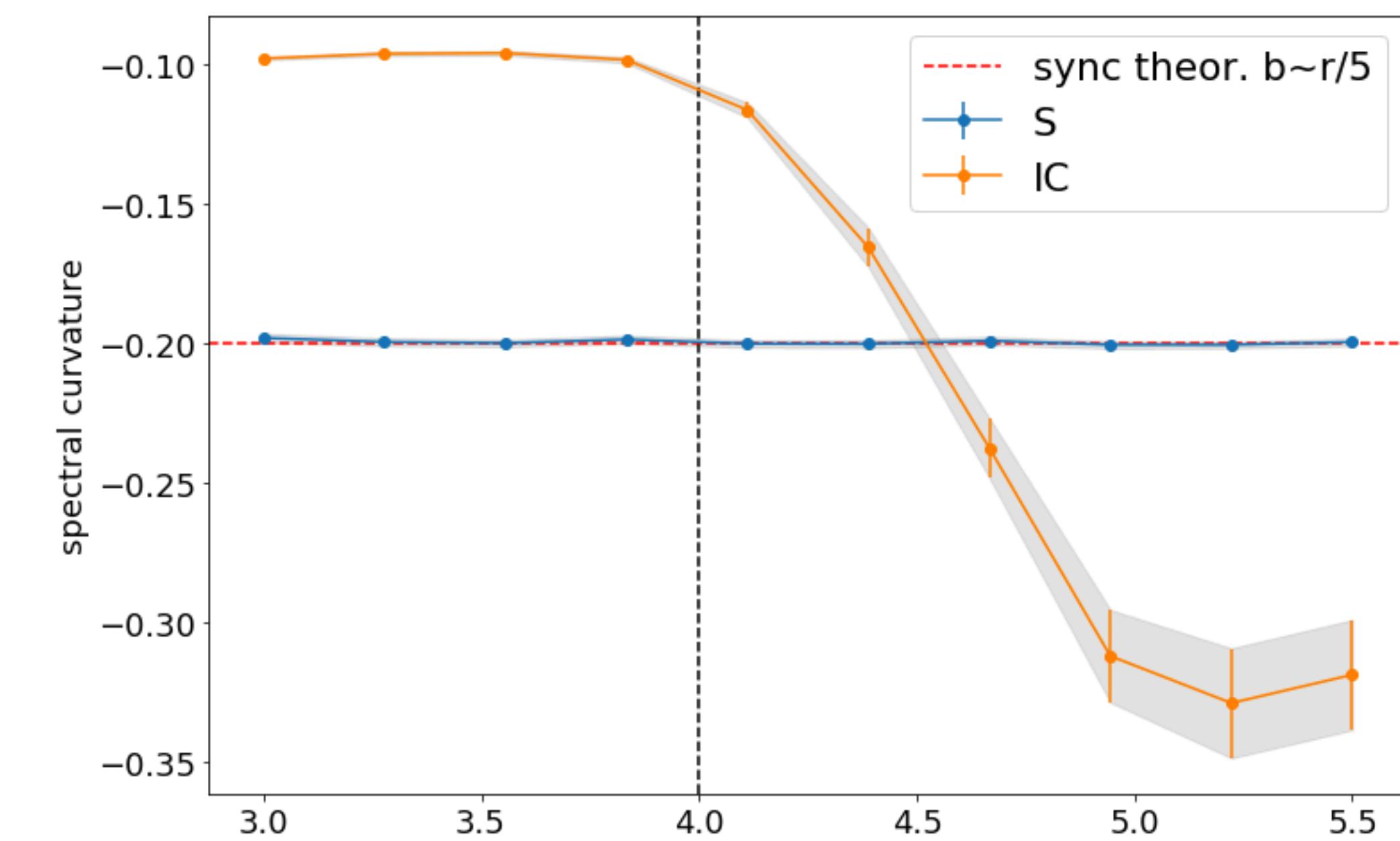
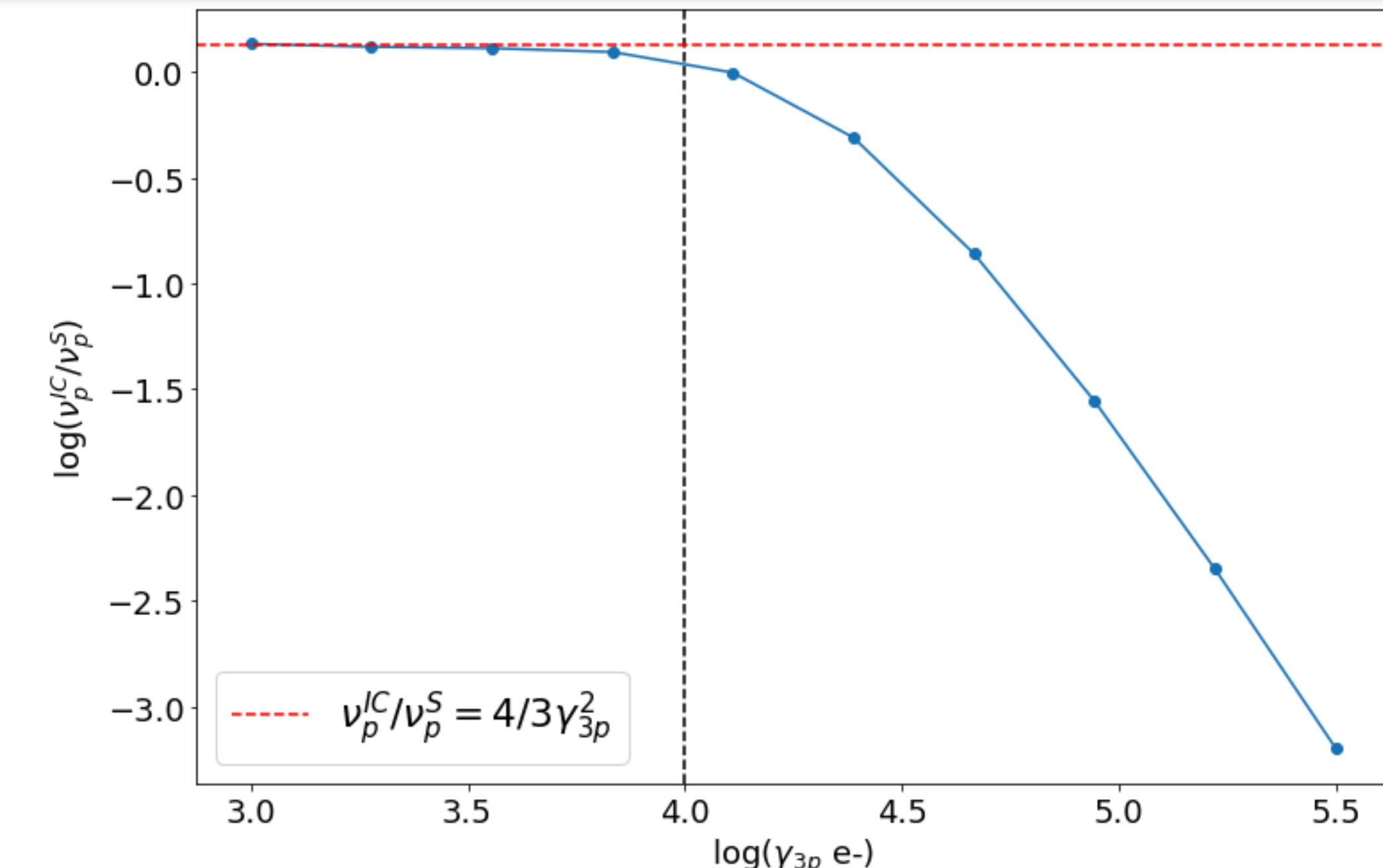
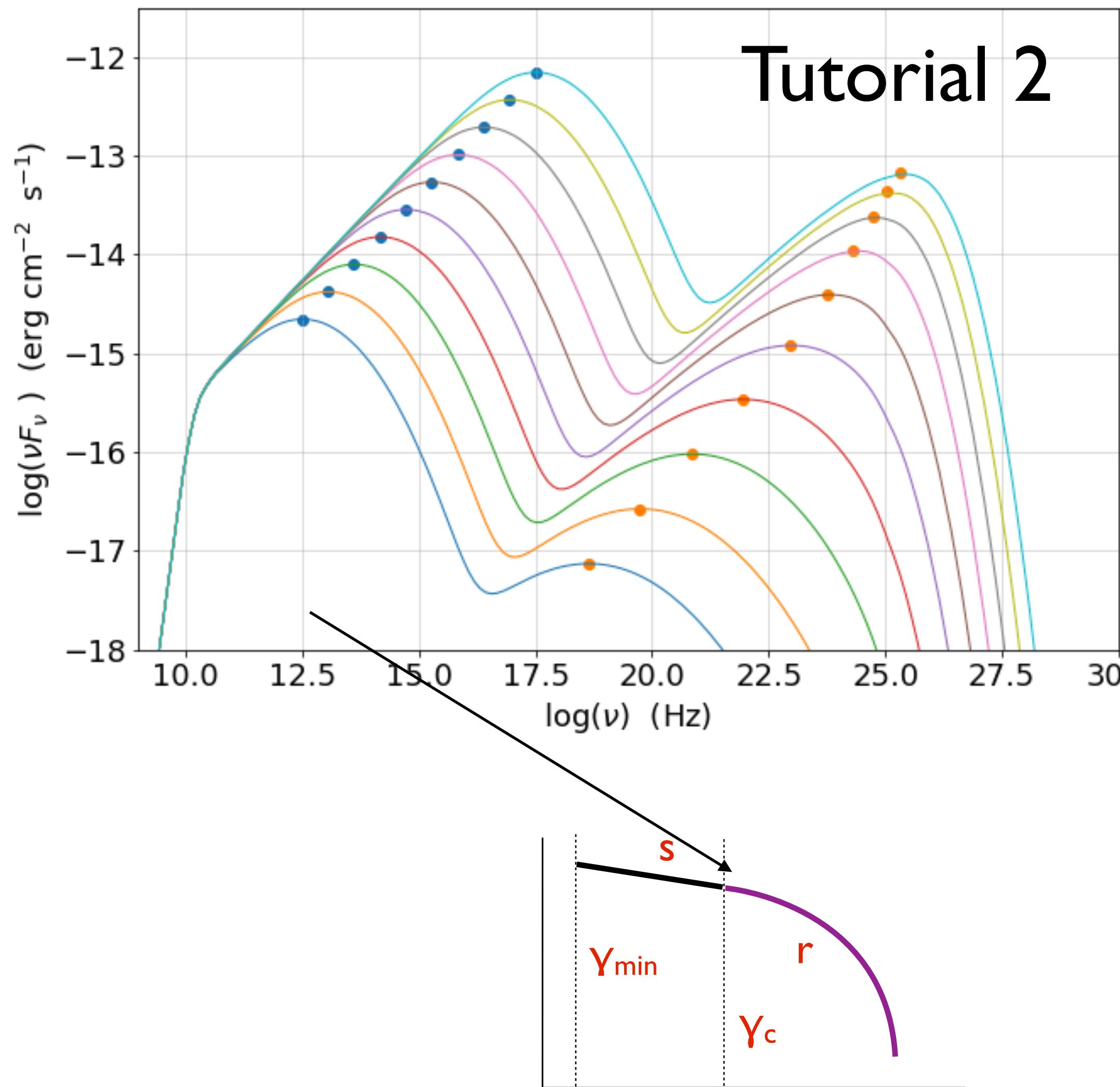
## IC emission TH/KN regime and peak curvature

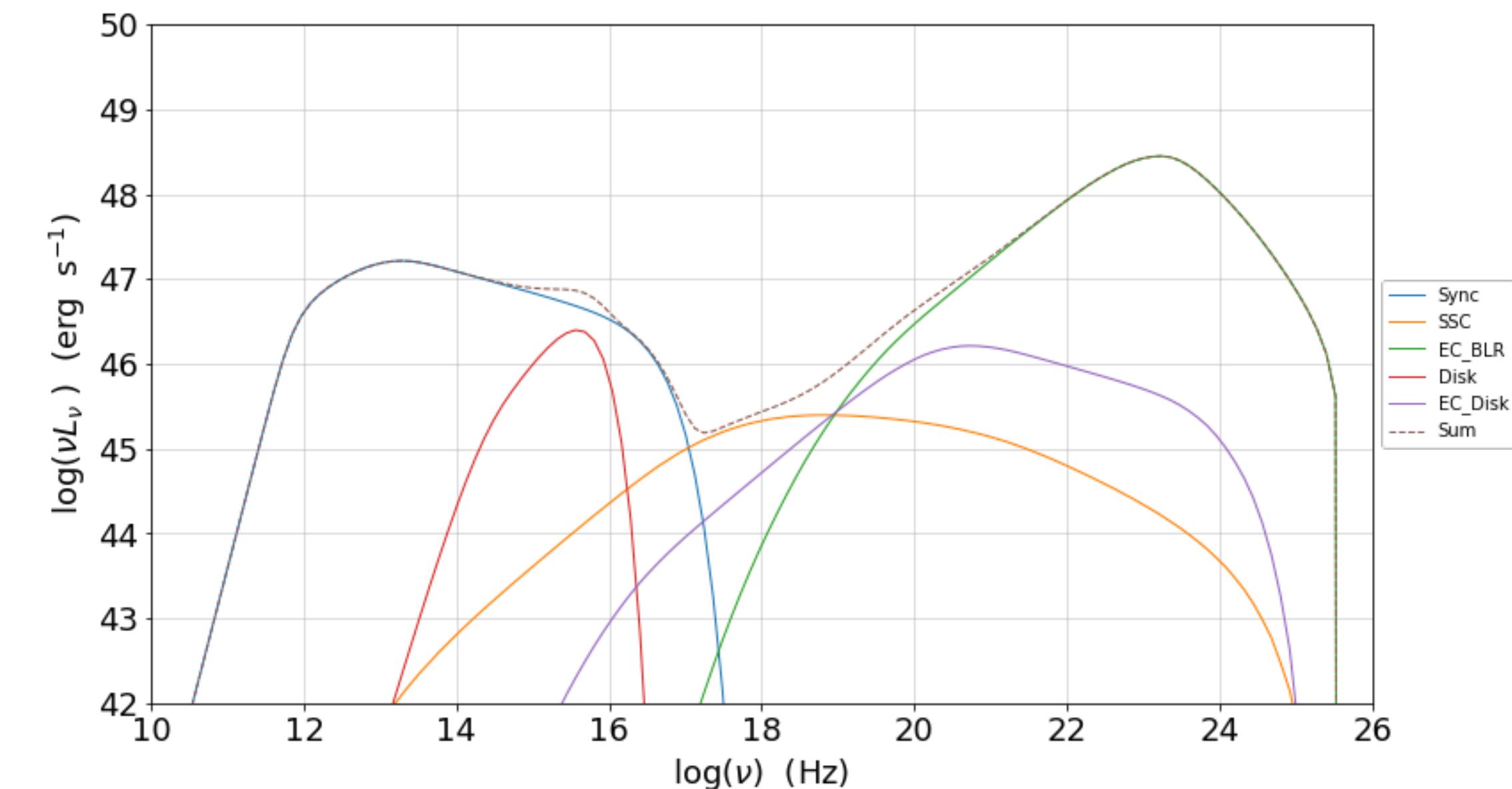
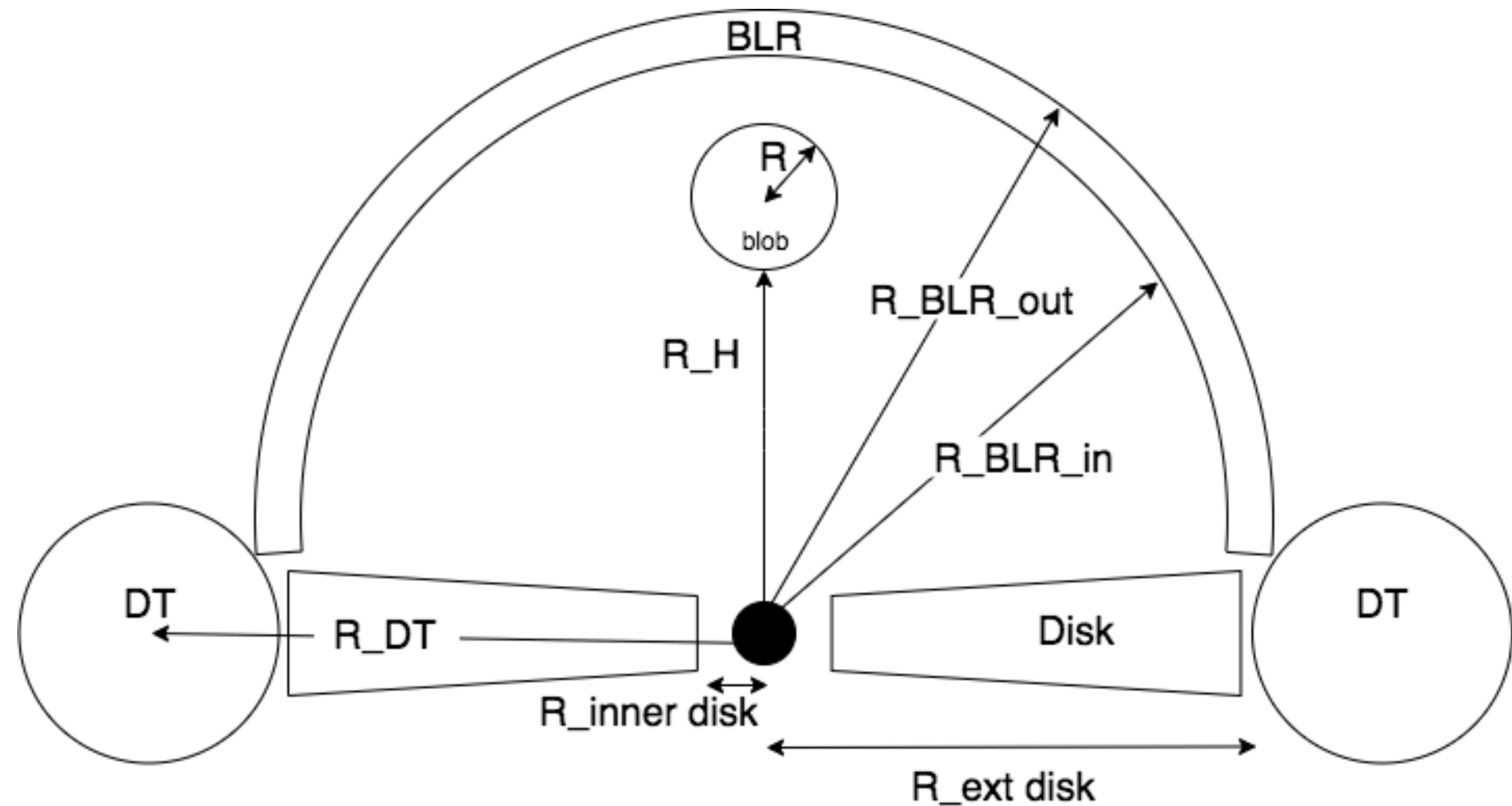


Tutorial 2

# IC emission TH/KN regime and peak freq.

- $v_p^{IC} / v_p^S \sim (4/3) \gamma_p^2 \equiv \gamma_{3p}^2$  is true only in TH regime





Transformation of the radiative fields

$$I_{v'} = \frac{1}{4\pi} \int d\Omega' \delta^3 I_{v=(v'/\Gamma)} \\ = \Gamma \tau \frac{L_{\text{nuc}}}{4\pi R^2} f_{v=(v'/\Gamma)}(T_{\text{ext}})$$

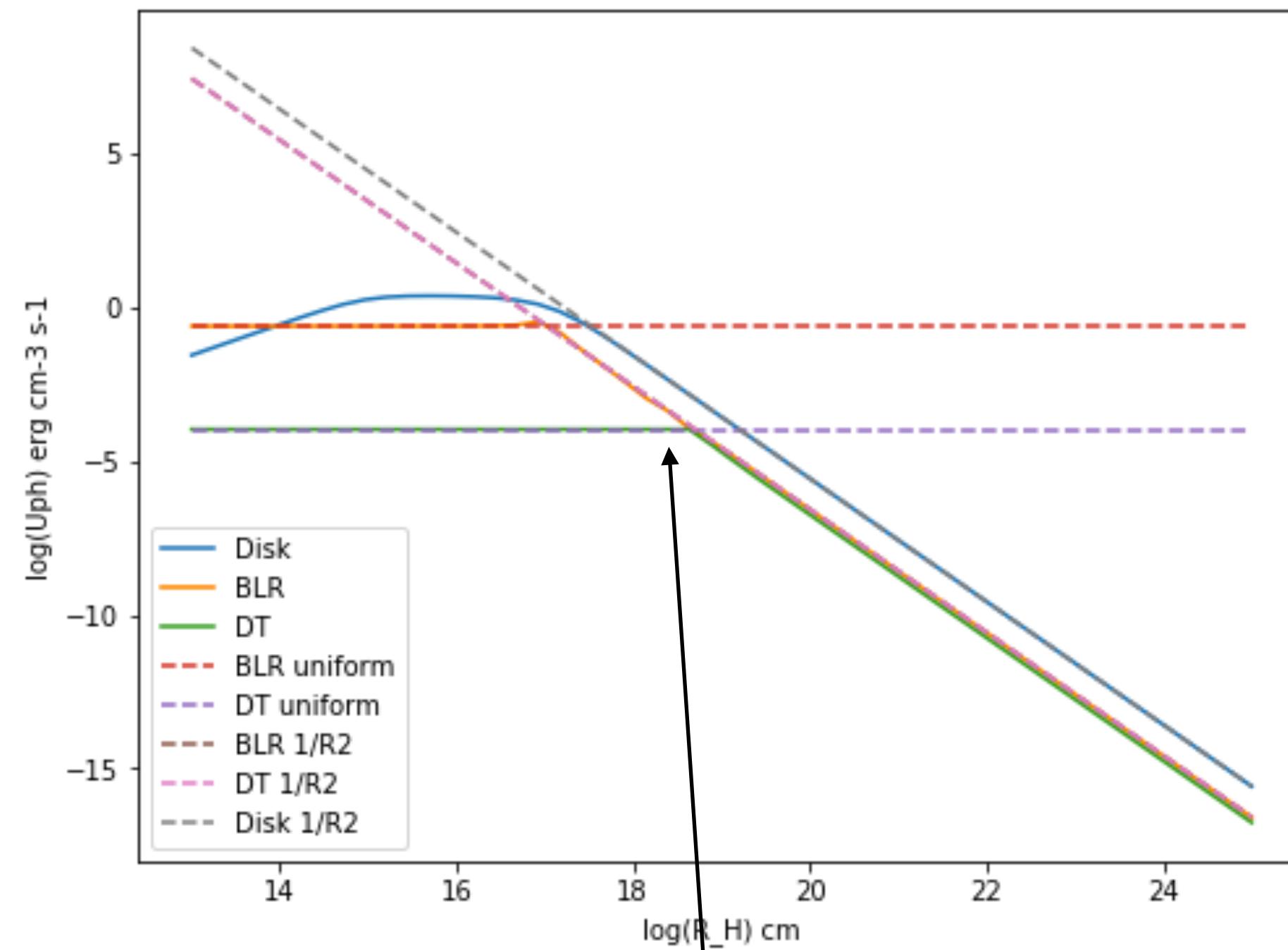
$$u'_{ext} \simeq \Gamma^2 u_{ext} \\ L_{ERC} \simeq \Gamma^6 U_{ext}$$

$$\eta = \frac{\dot{\gamma}_{IC}}{\dot{\gamma}_{sync}} = \frac{U_{ph}}{U_B}$$

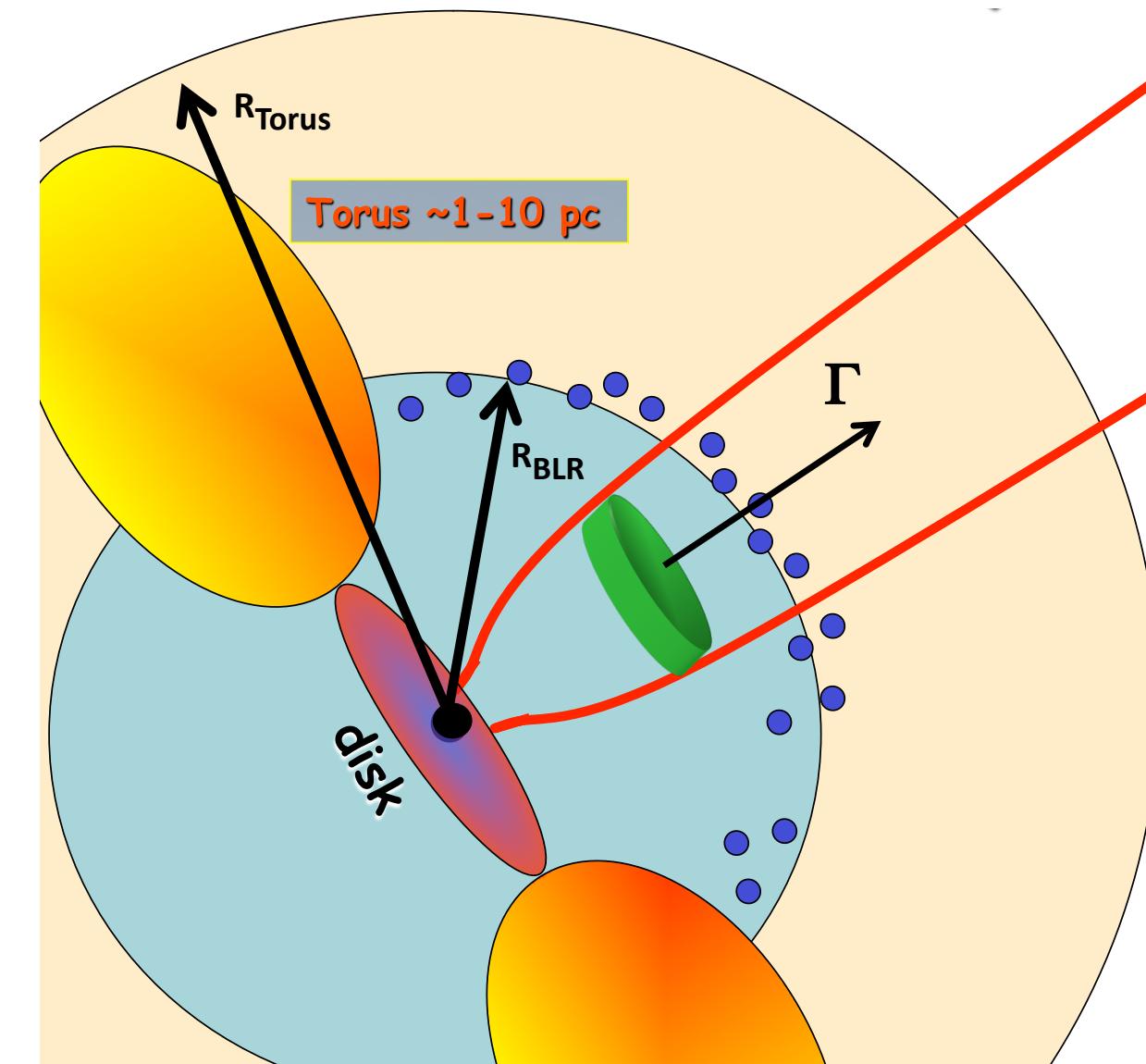
$$\epsilon^{-3} I_\epsilon \text{ and } \epsilon^{-2} j(\epsilon, \Omega) \\ \frac{u(\epsilon, \Omega)}{\epsilon^3} = \frac{u'(\epsilon', \Omega')}{\epsilon'^3} = inv.$$

# External Compton Scenario

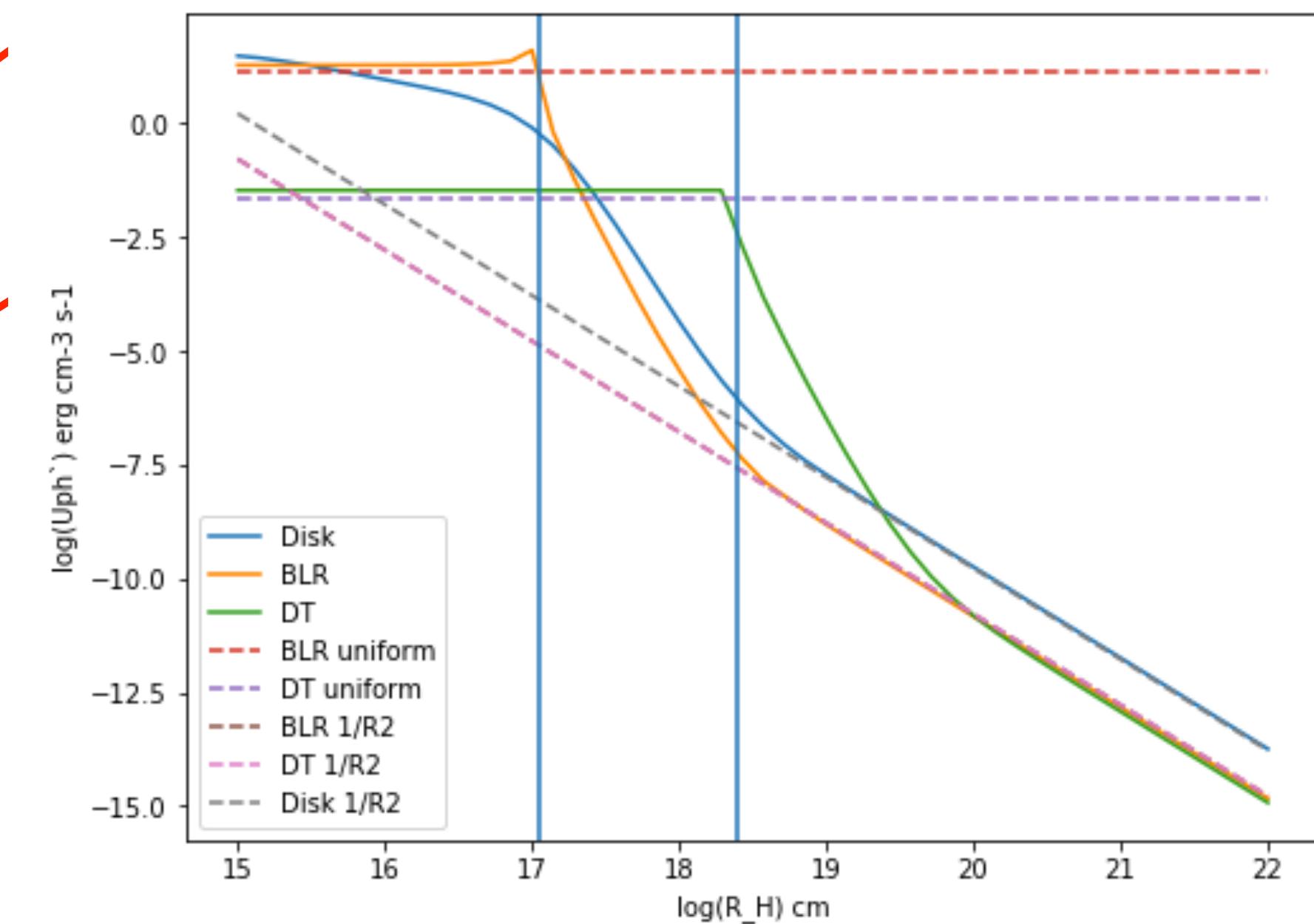
external photon fields in the disk  
rest frame



constant within  
the sphere



external photon fields in the blob  
rest frame

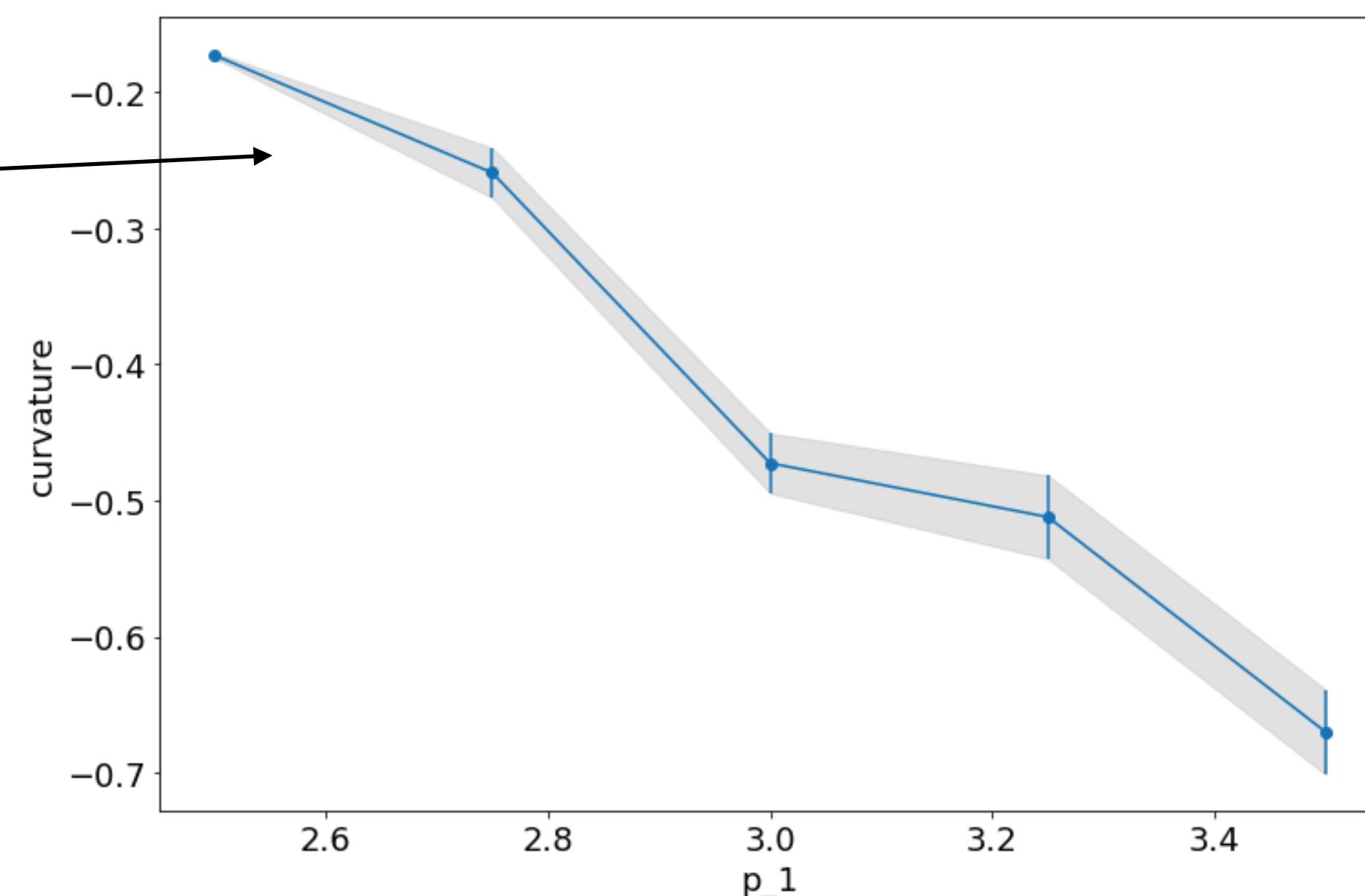
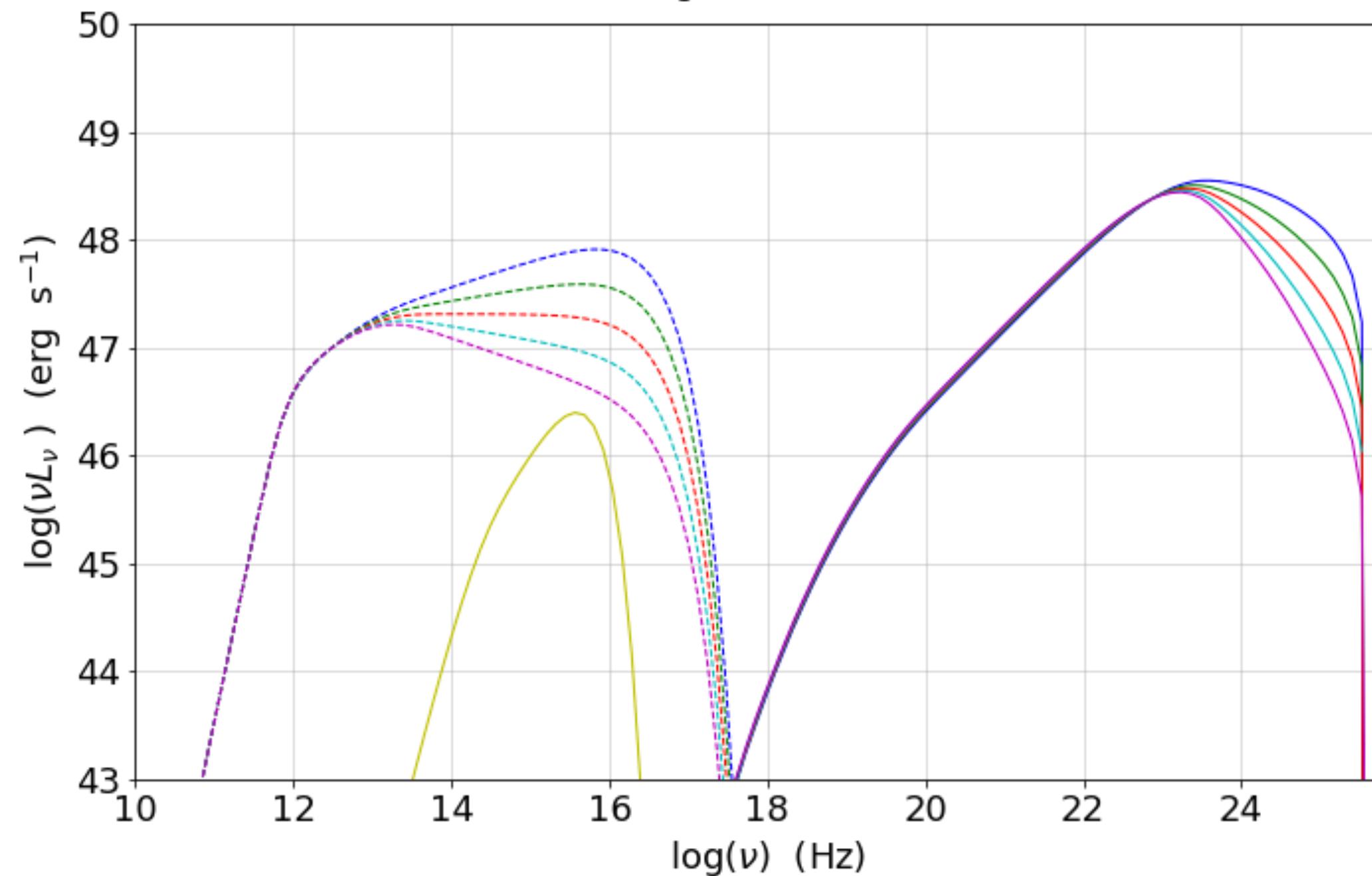
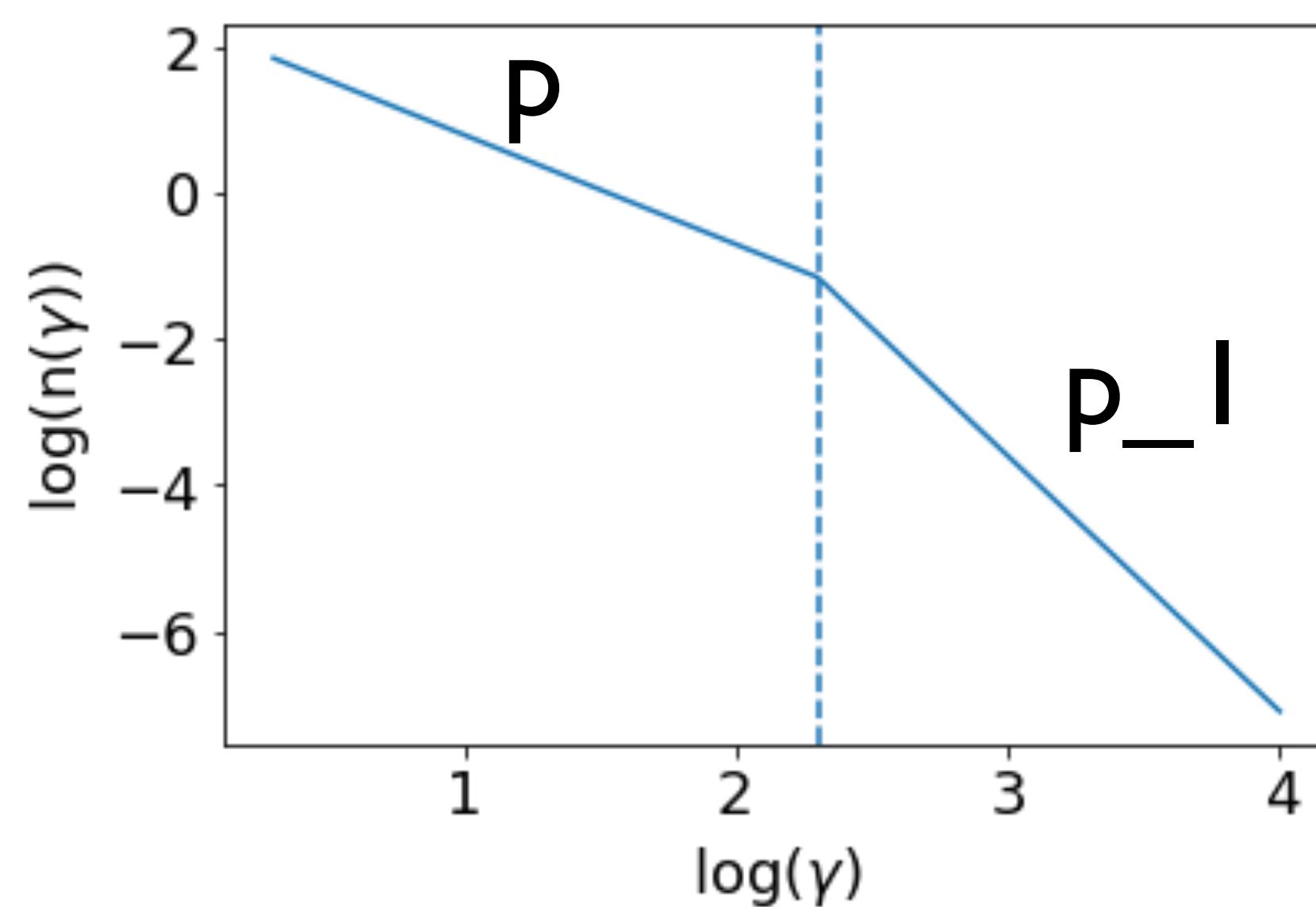
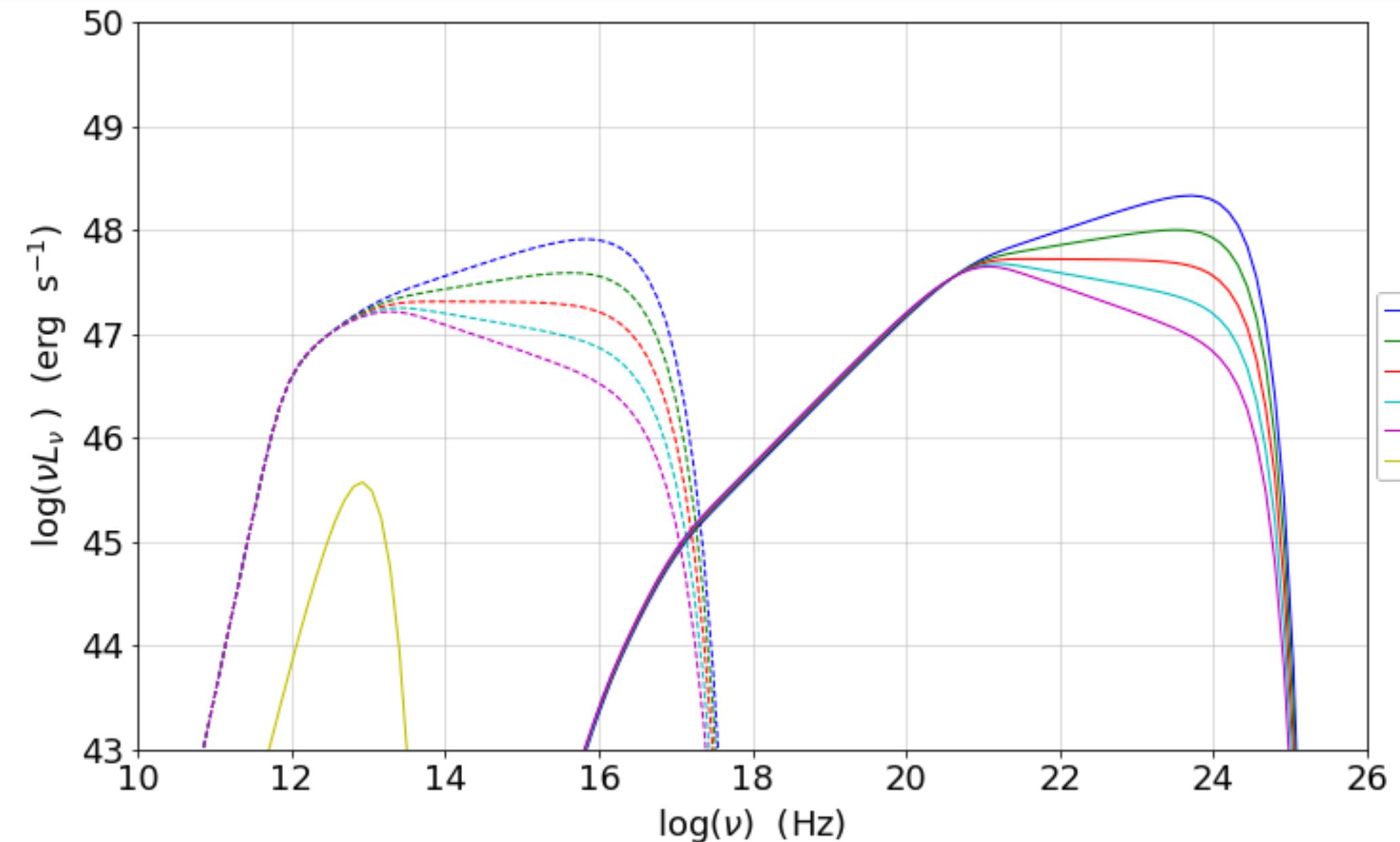


$$u'_{\text{ext}} \simeq \Gamma^2 u_{\text{ext}}$$

Tutorial 3

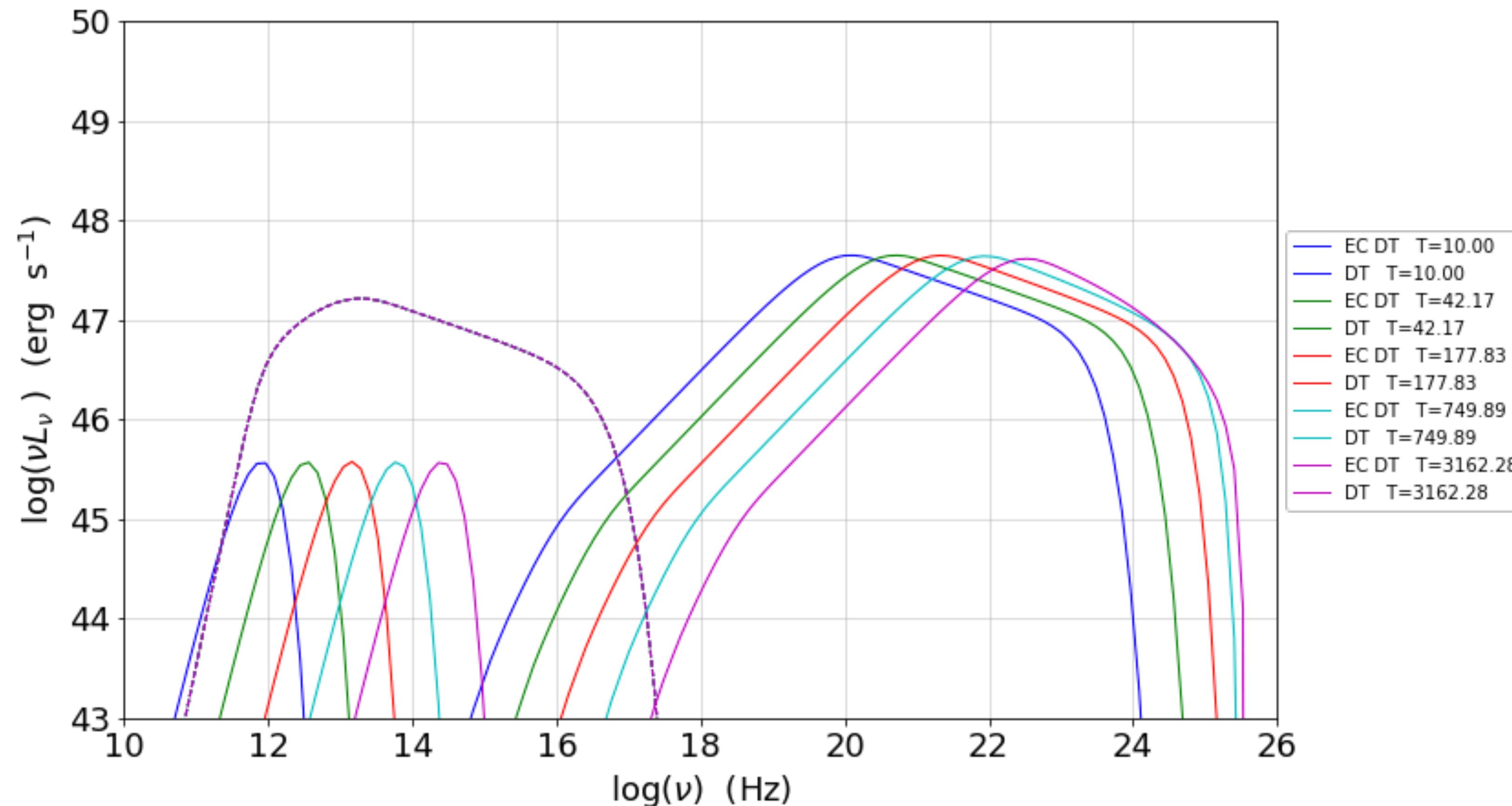
# External Compton Scenario and TH/KN

## Tutorial 3



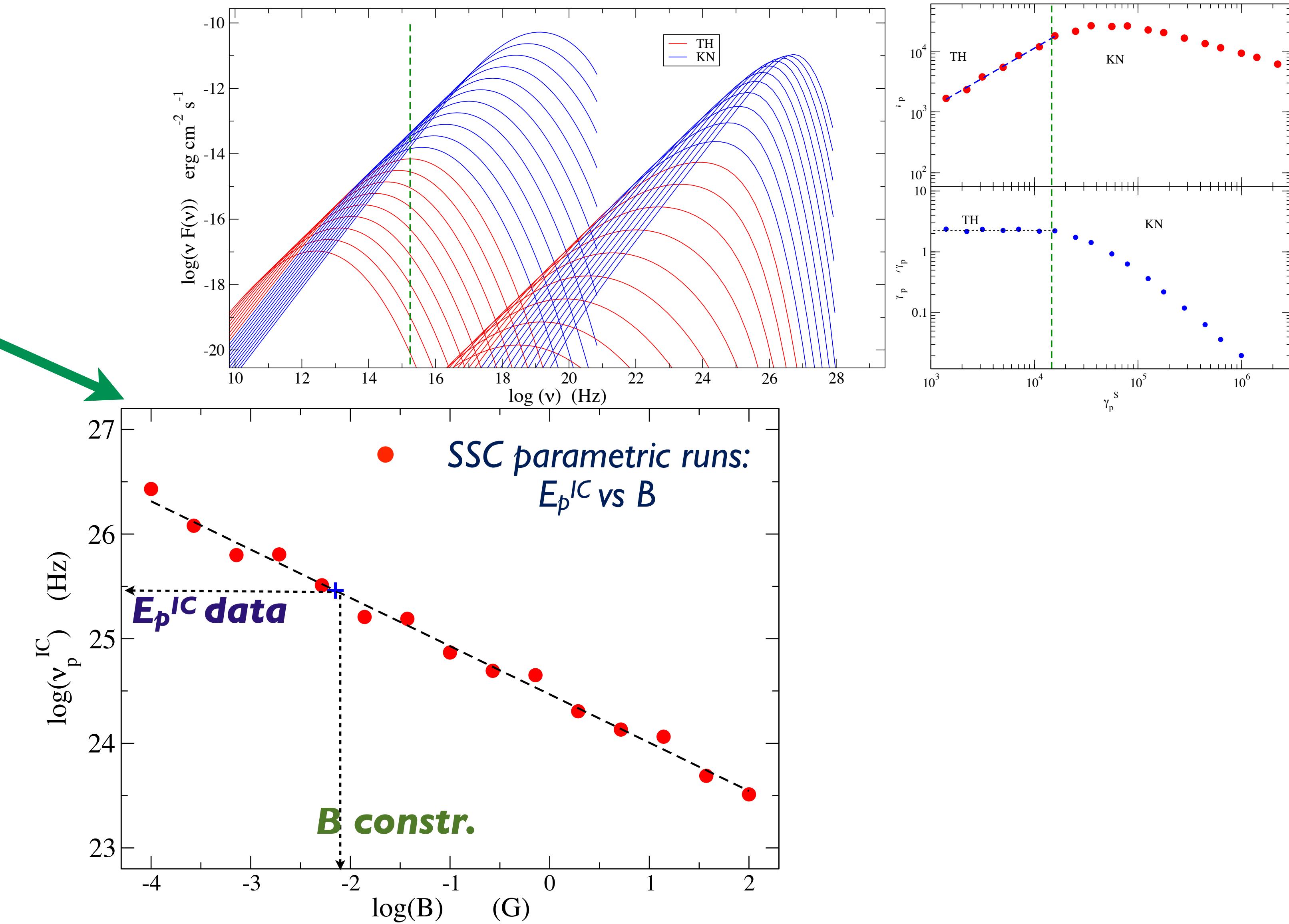
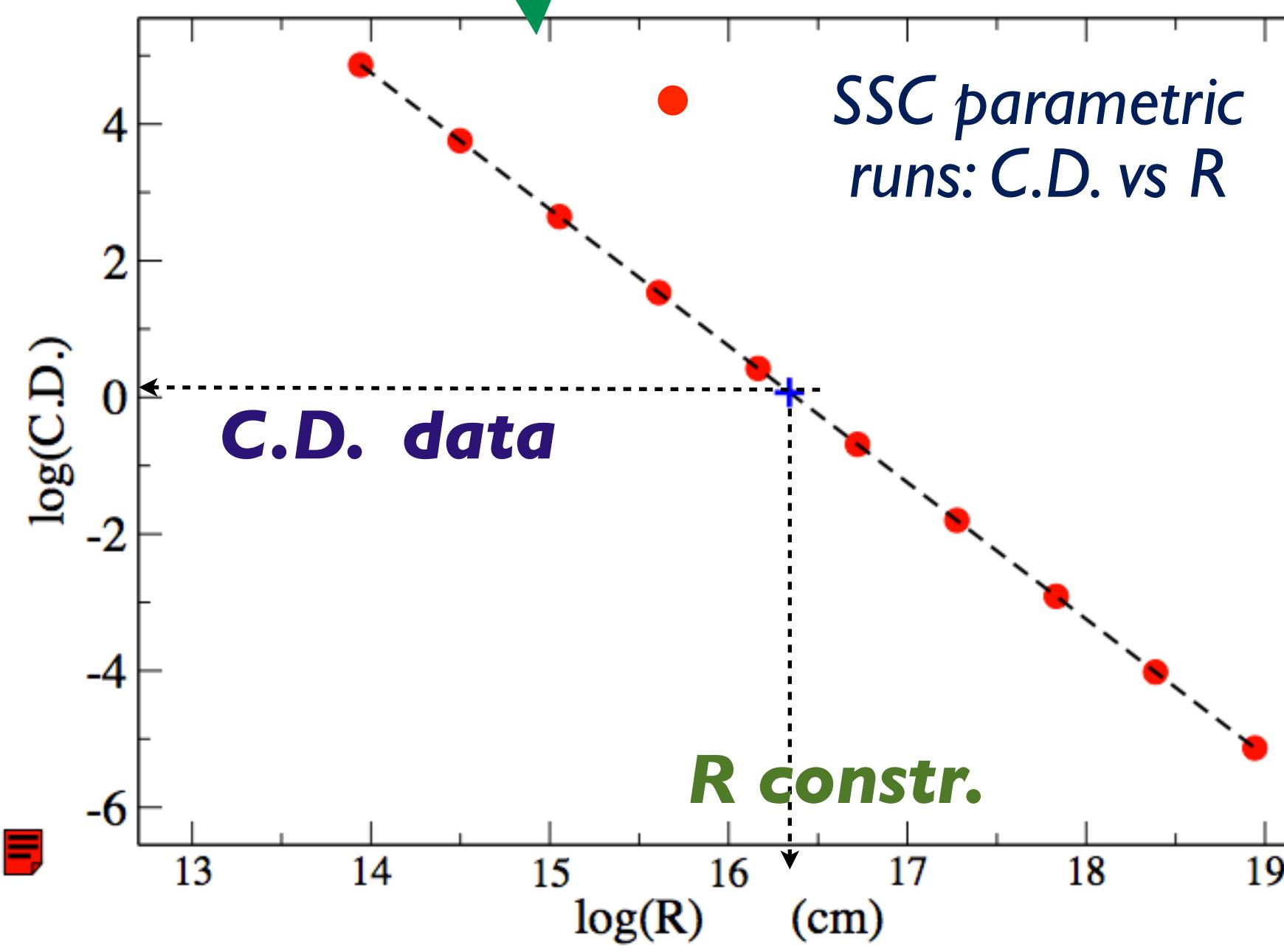
$$\nu_{p\text{ EC}} \sim (4/3) \gamma^2 \nu''_{p\text{ ext}} \delta\Gamma / (1+z) \quad \nu'_{\text{seed-IC}} = \nu''_{p\text{ ext}} \Gamma$$

Tutorial 3

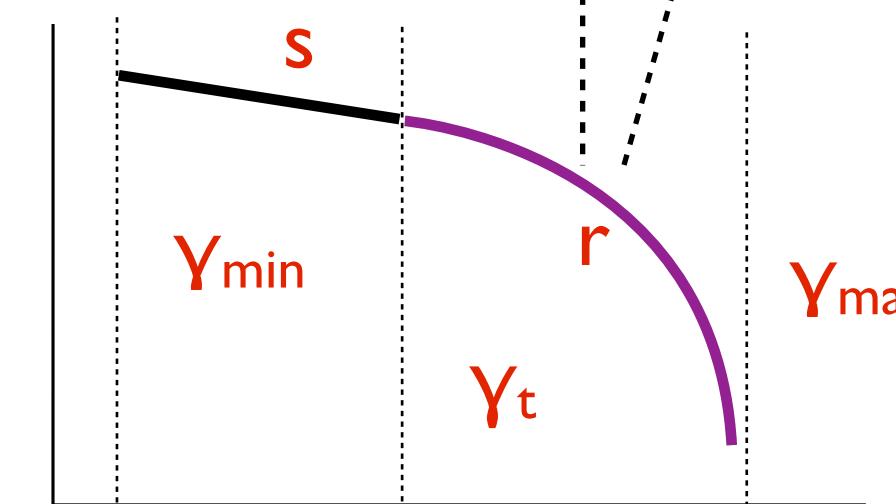
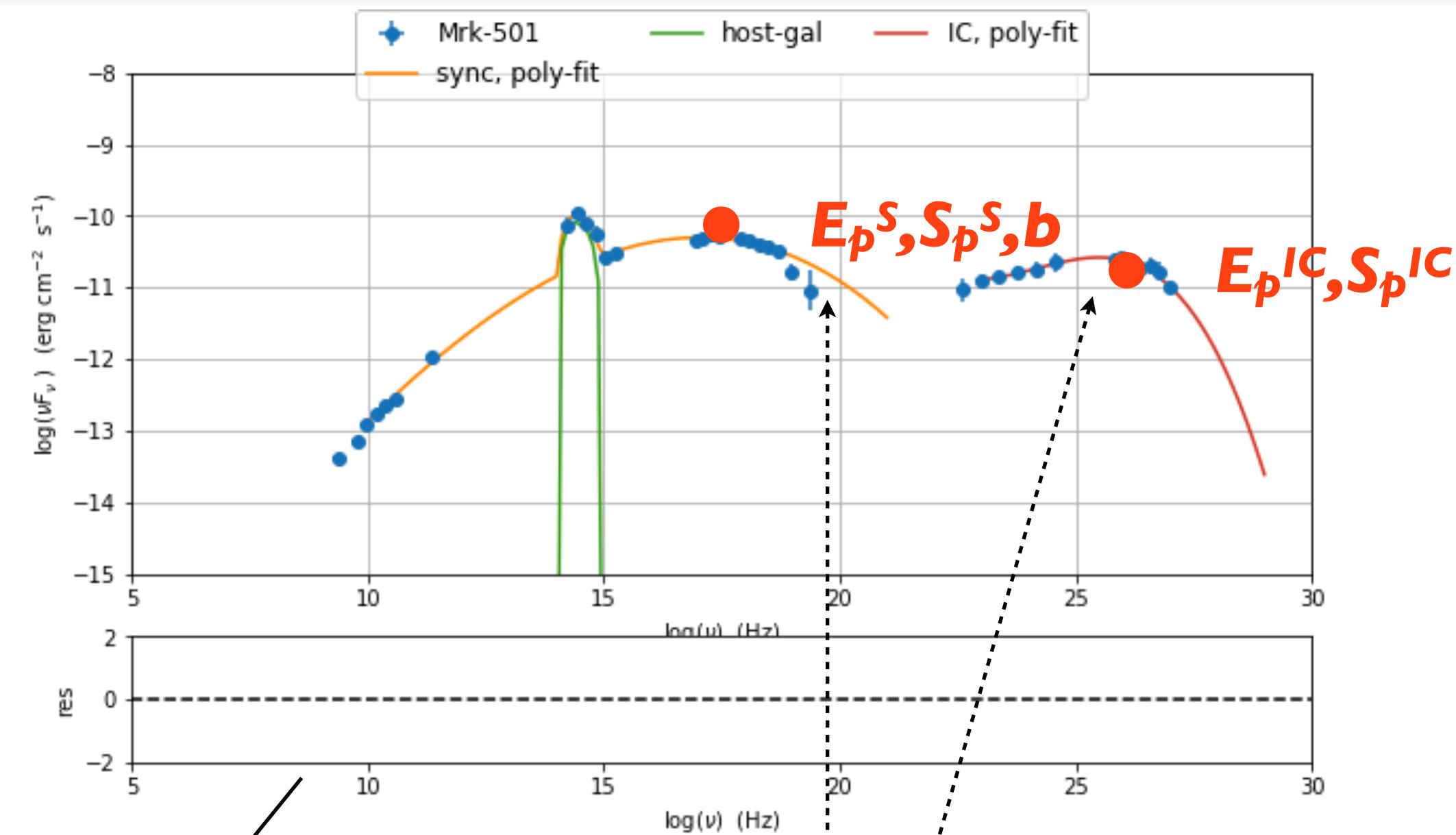
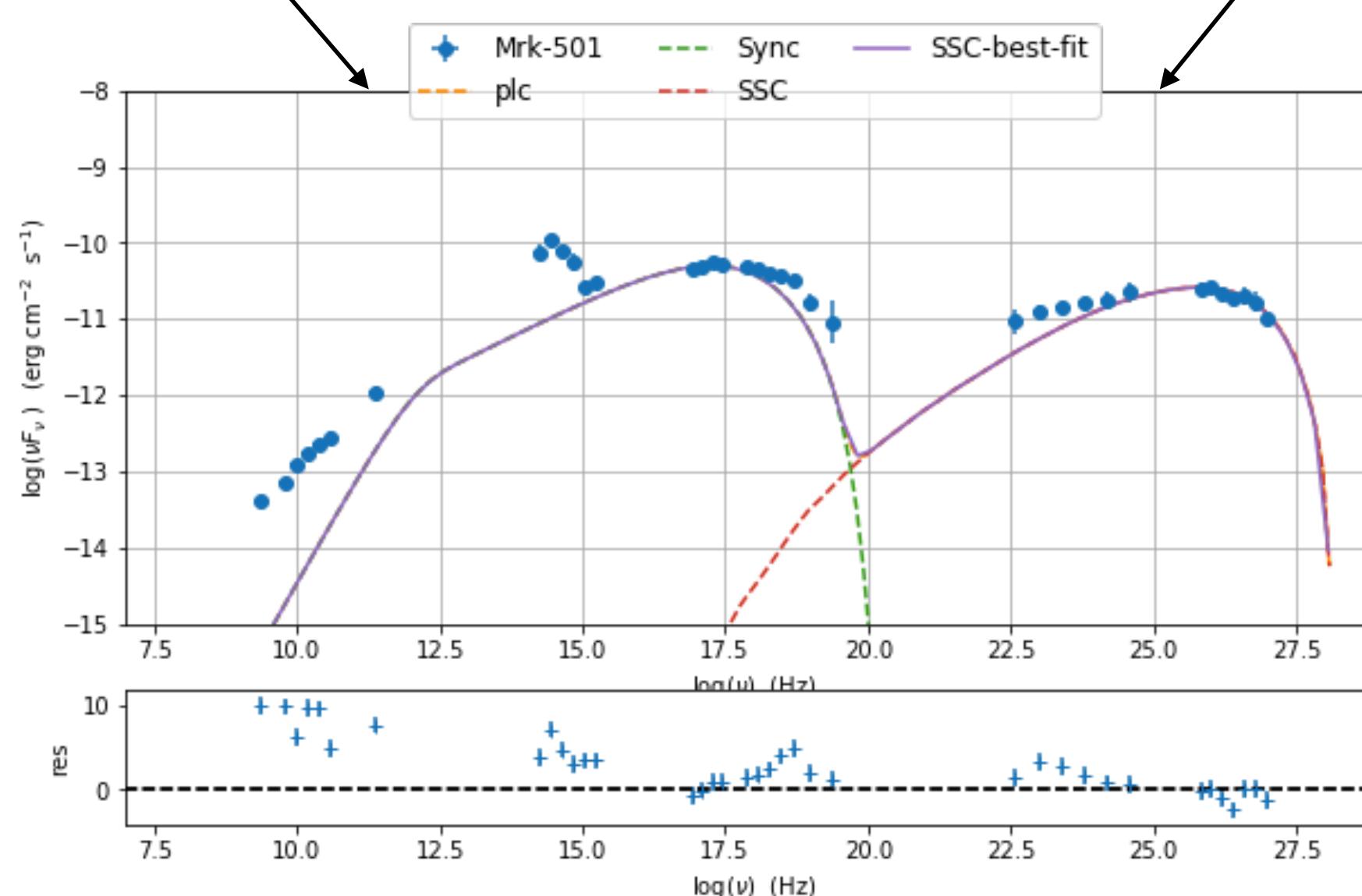
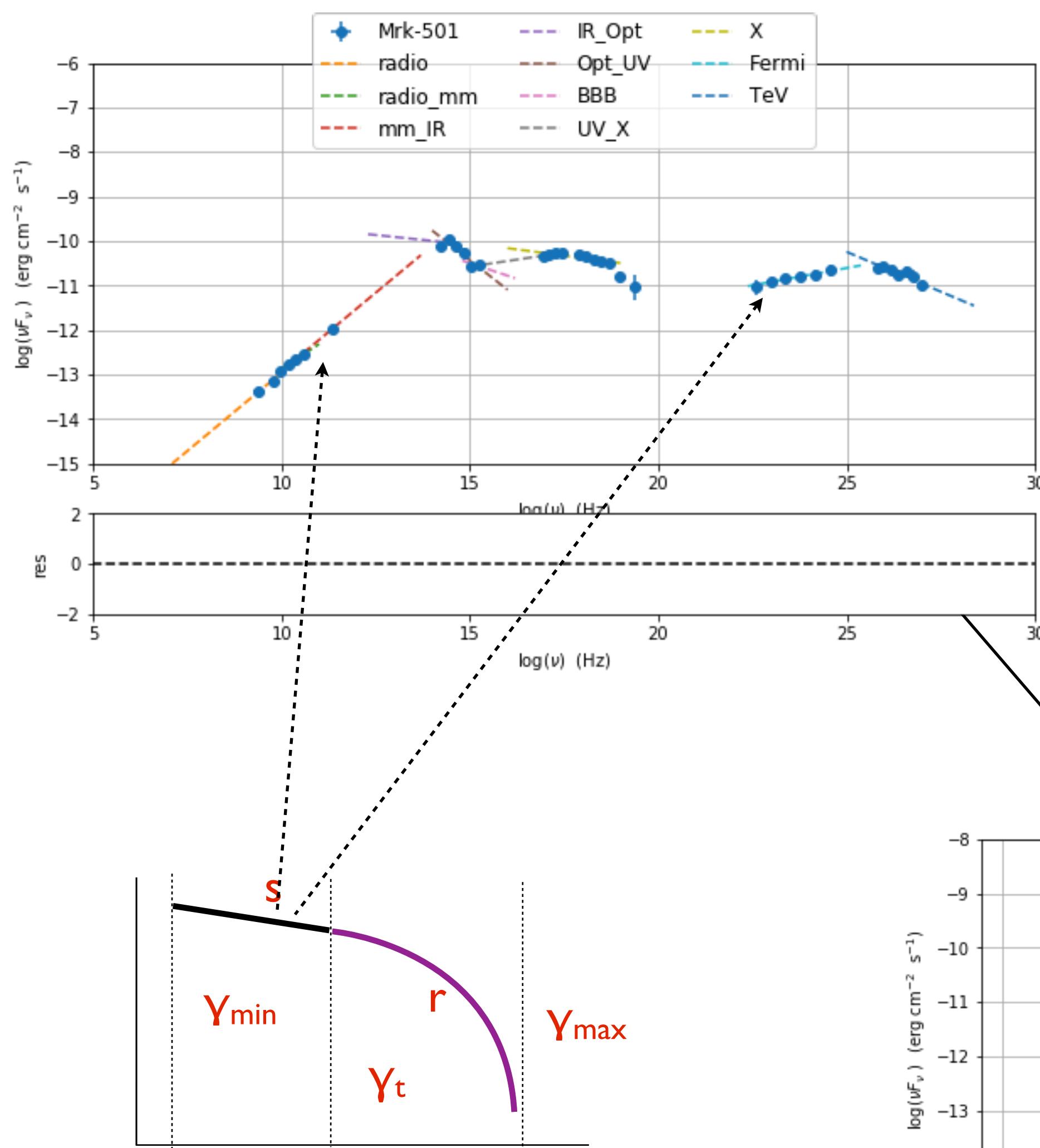


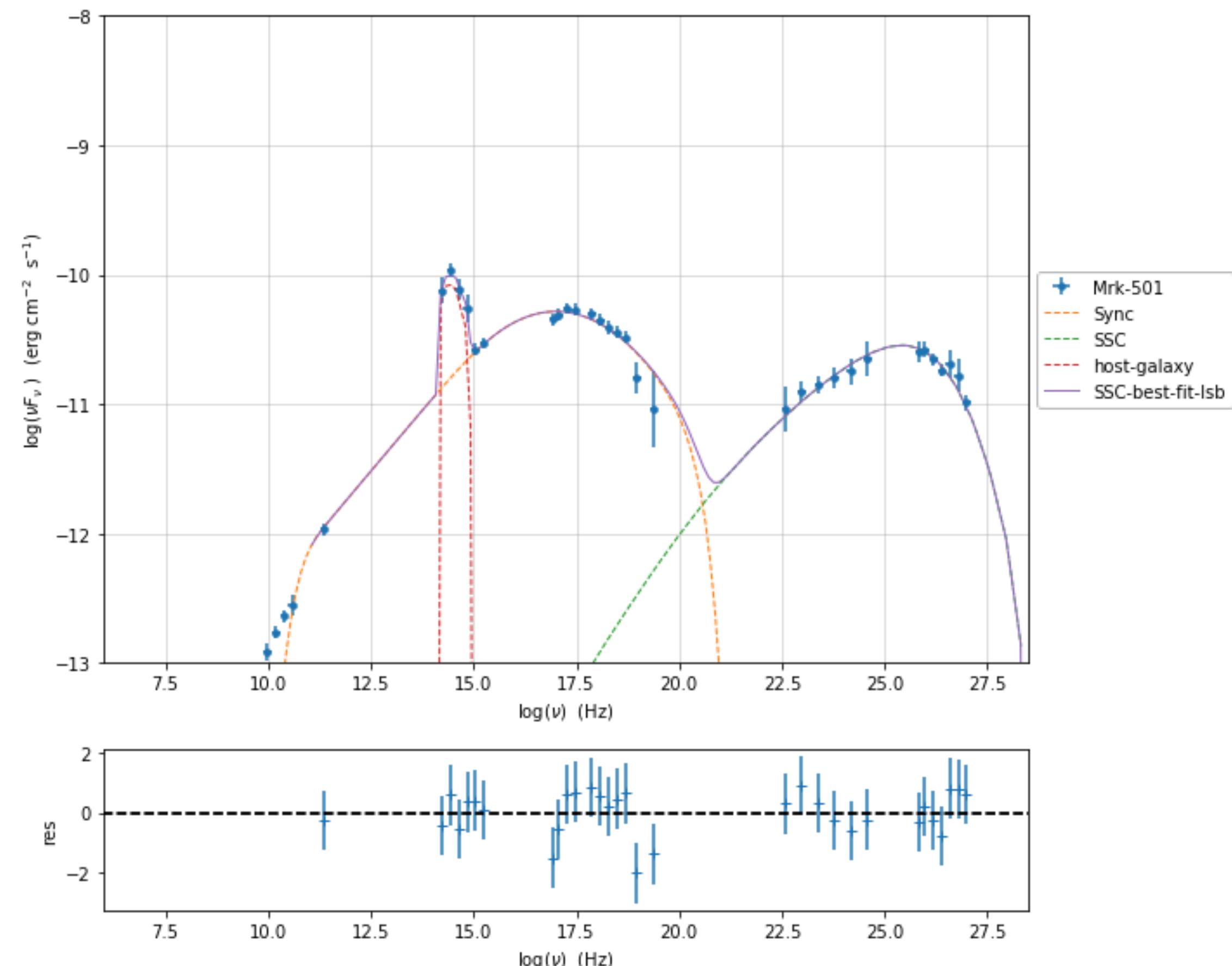
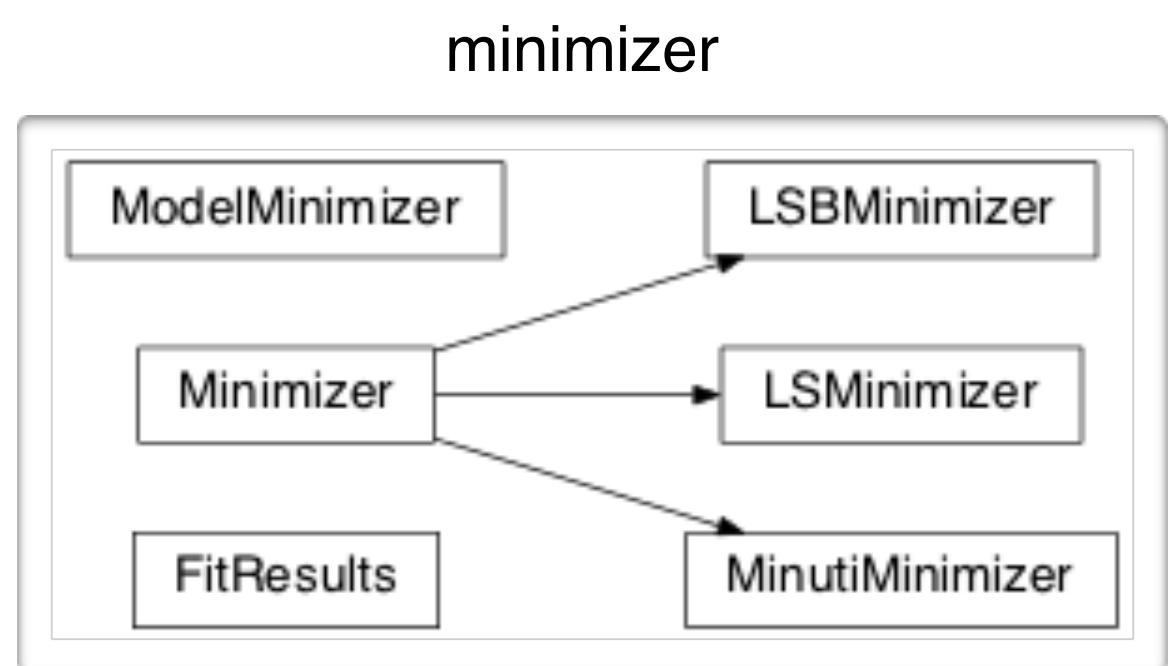
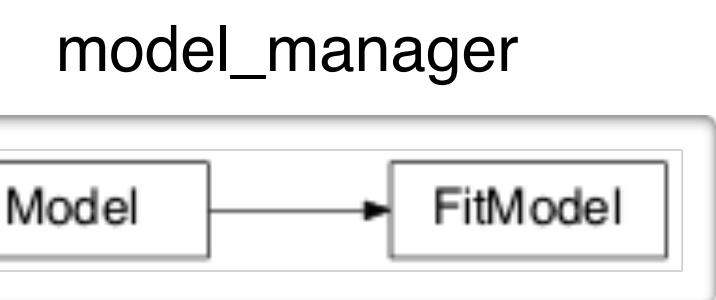
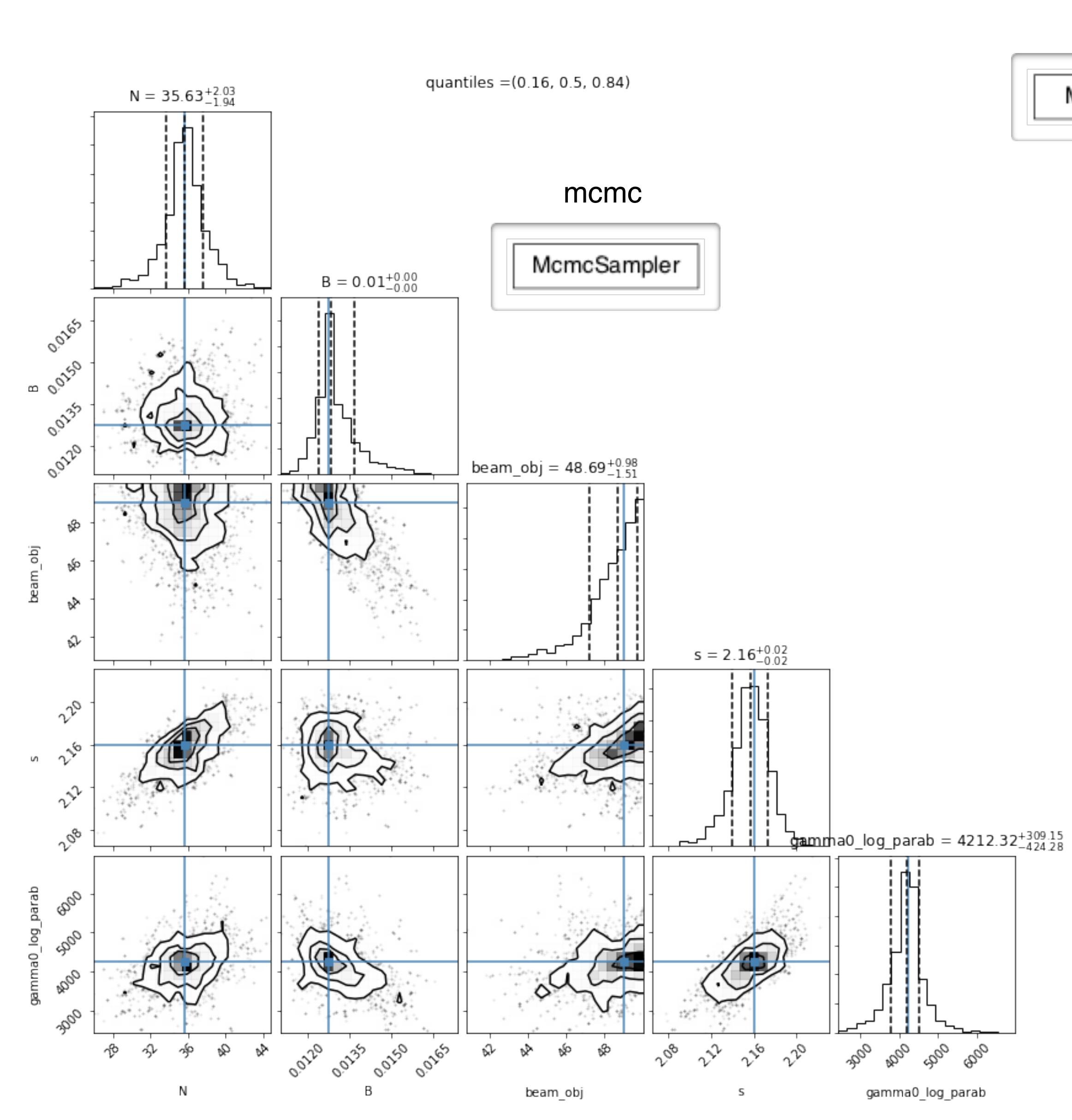
# SED shaping and model constraining

- ✓  $\Gamma \Rightarrow s$
- ✓  $b \Rightarrow r$
- ✓  $E_p^s, r, s \Rightarrow \gamma_0$
- ✓  $t_{var}, \delta \Rightarrow R$  u.l.
- N  $\Rightarrow$  best  $S_p^s$  match
- B  $\Rightarrow$  best  $E_p^{IC}, S_p^{IC}$  match
- R  $\Rightarrow$  CD

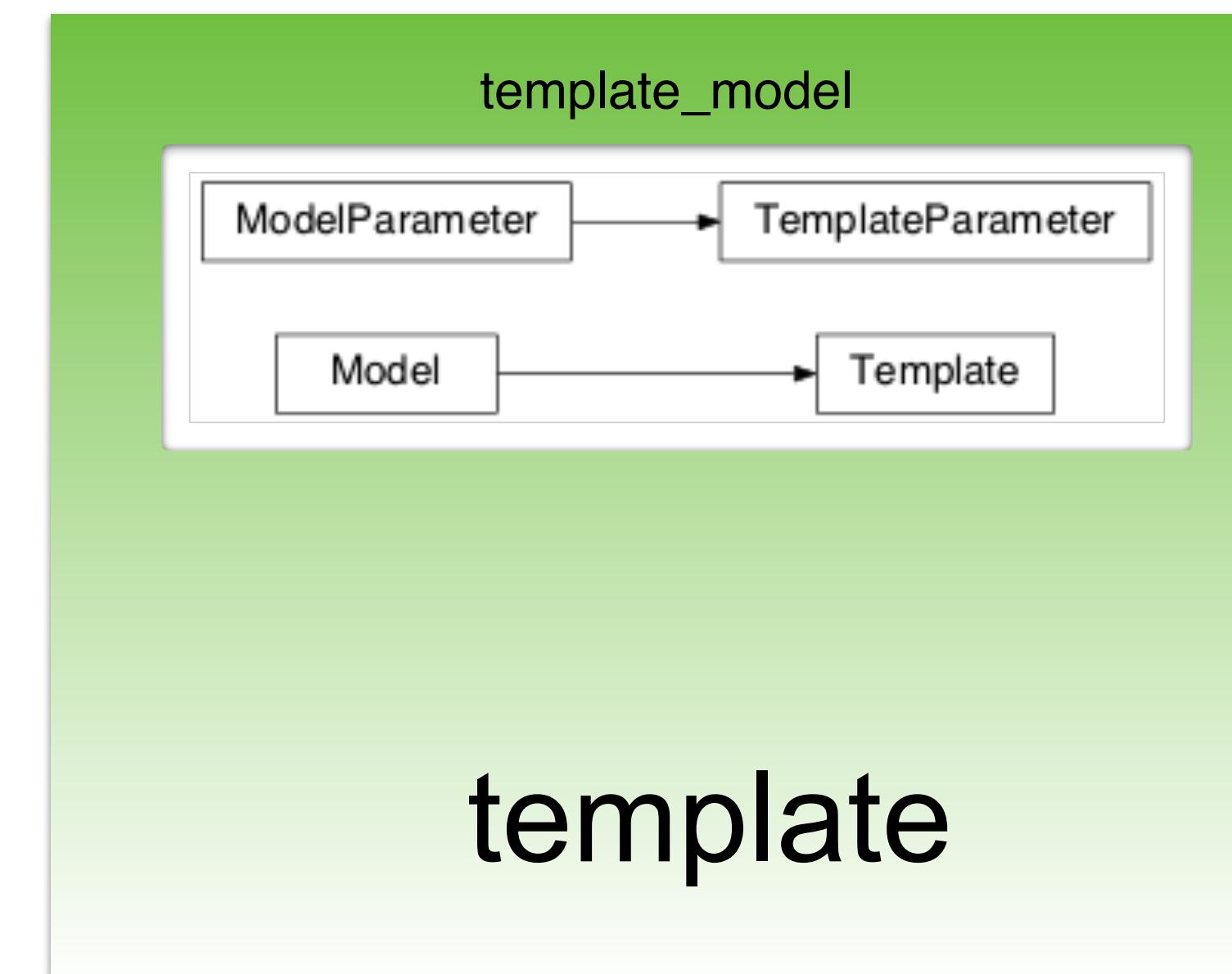
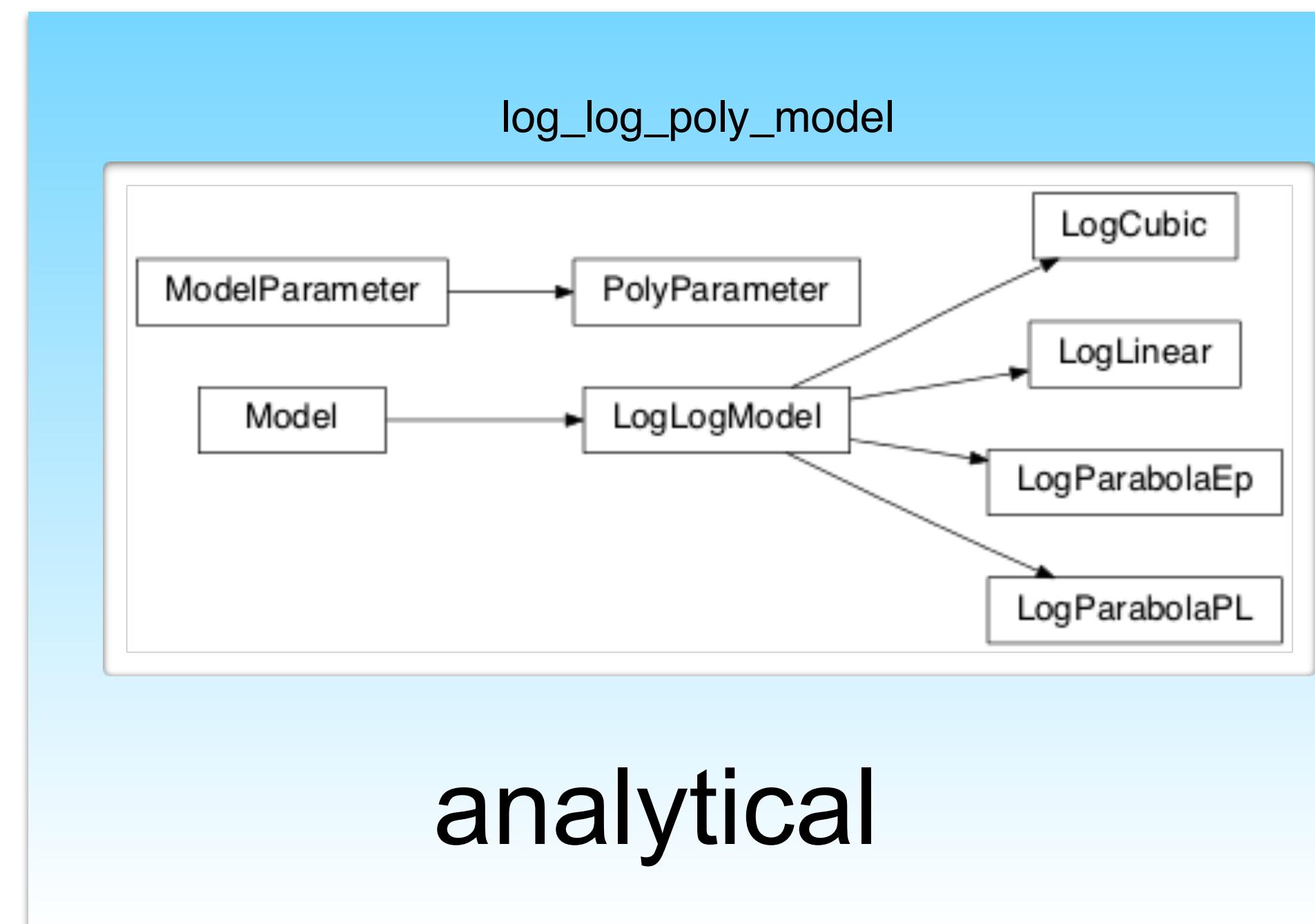
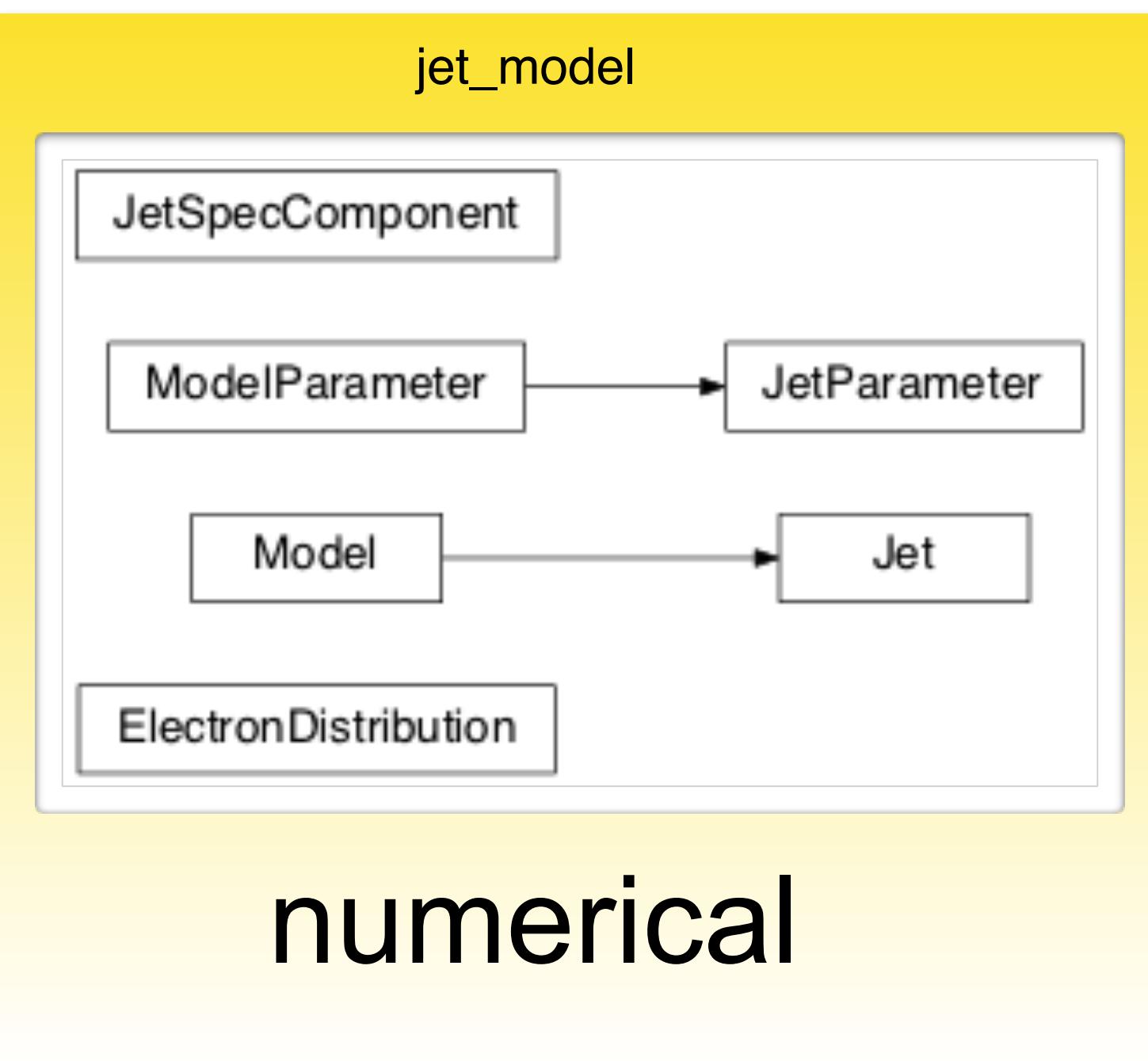
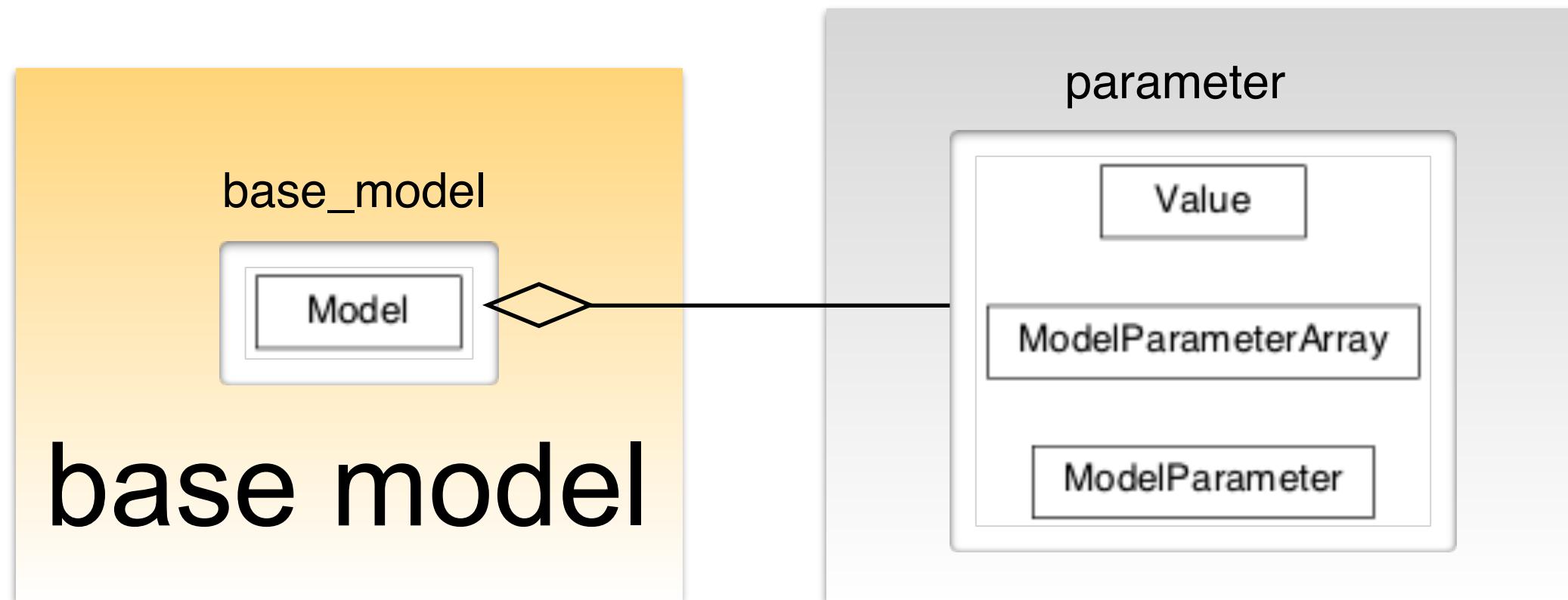


## Tutorial 5



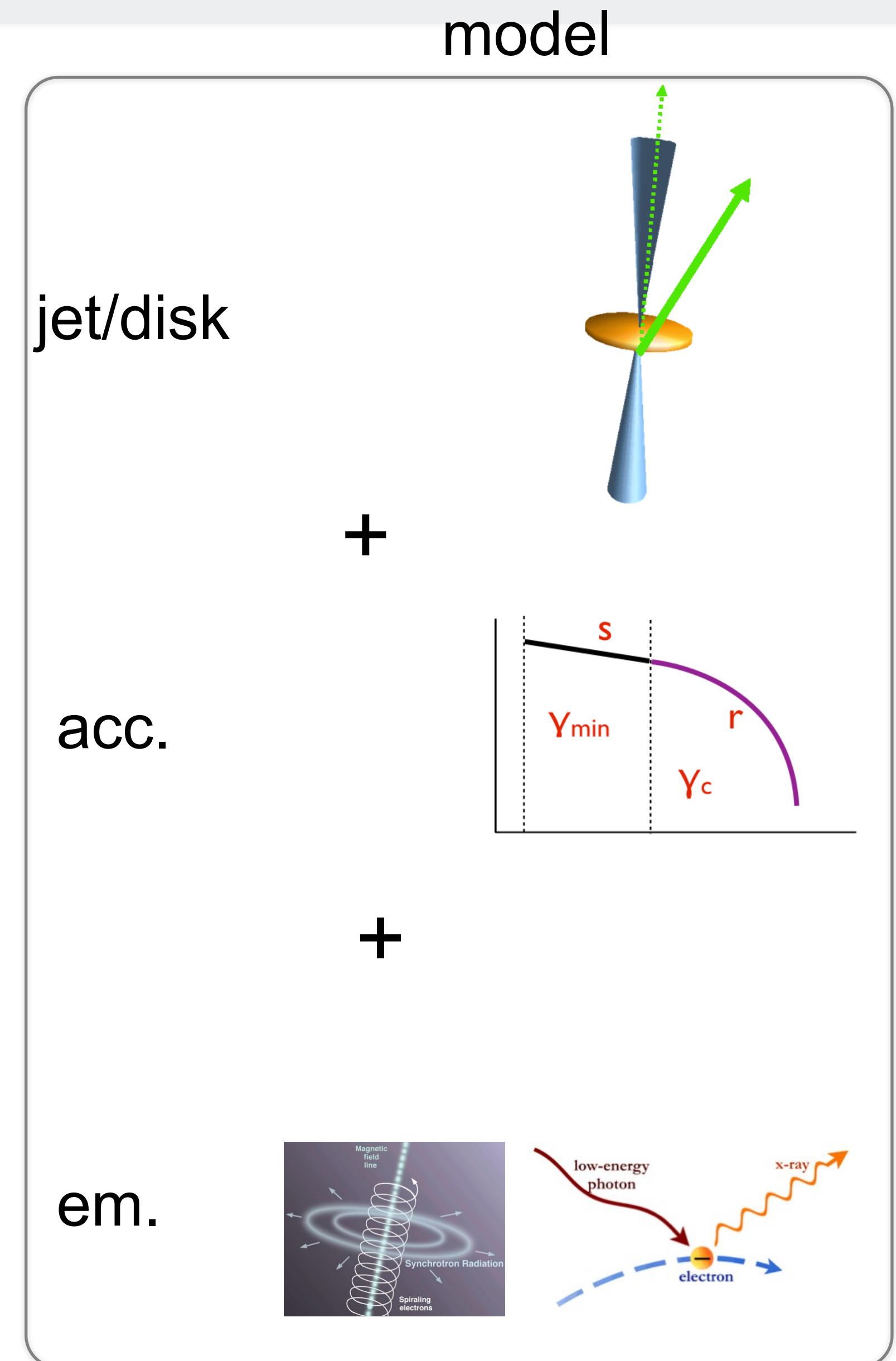
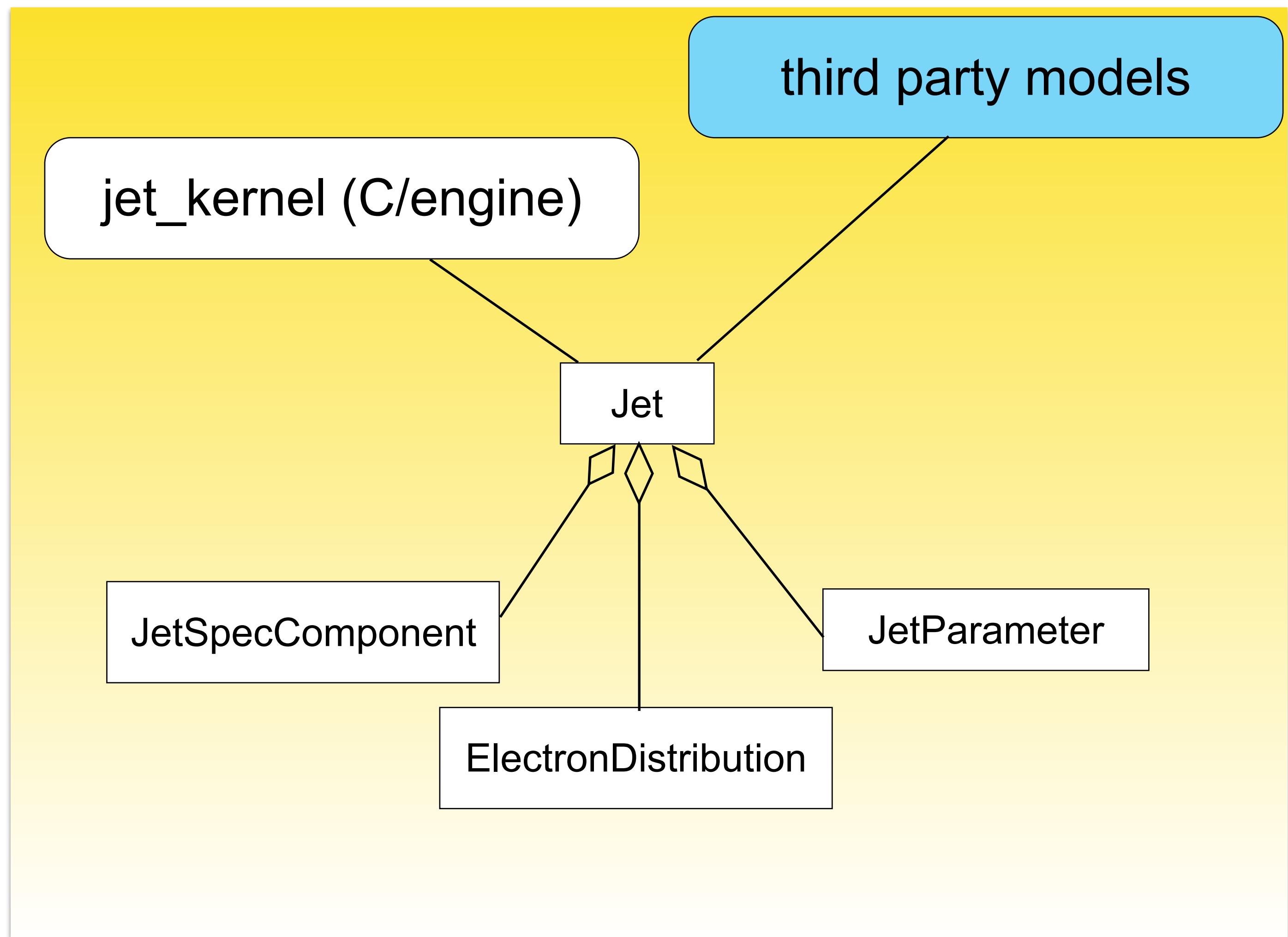


# backup slides

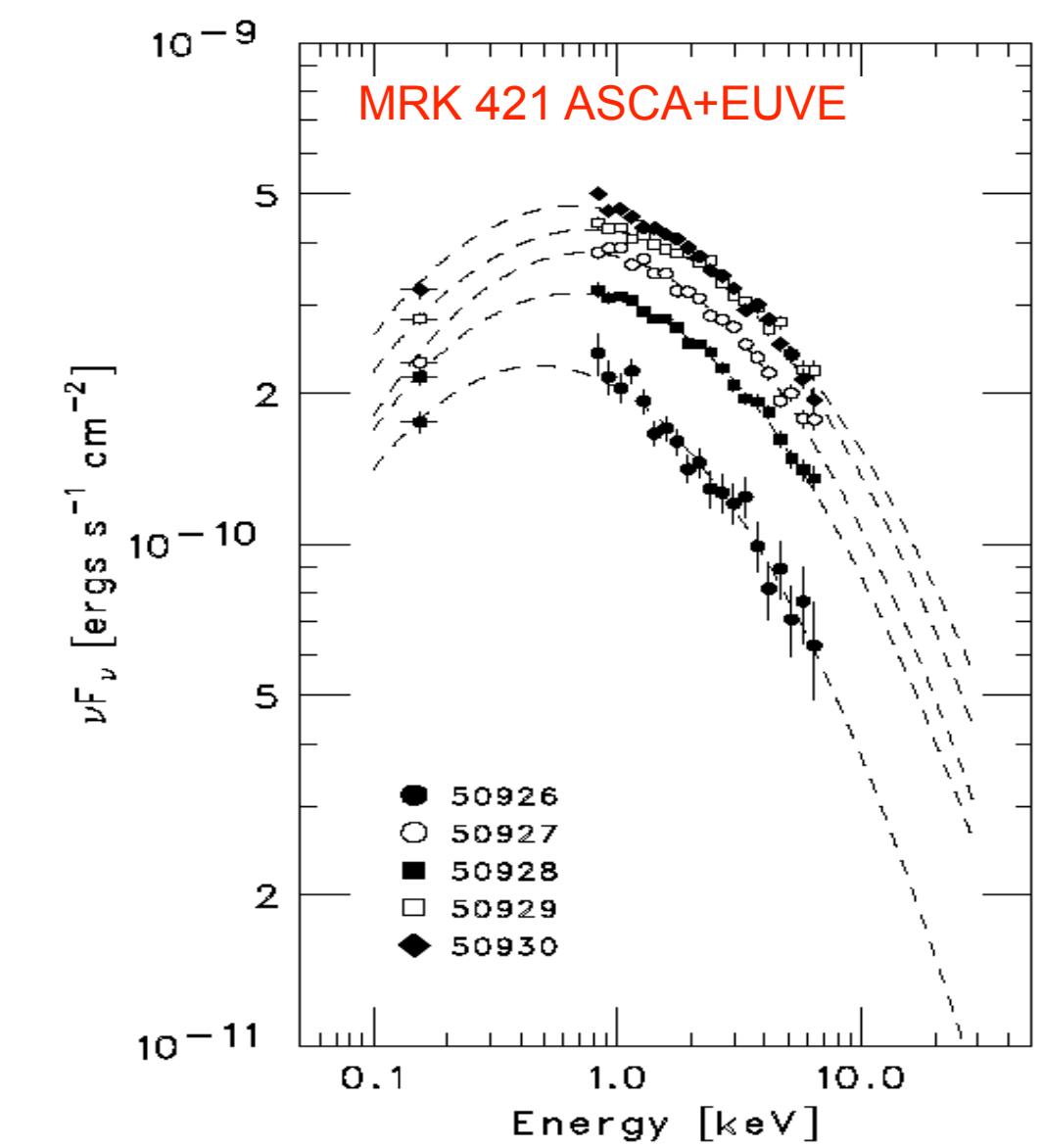
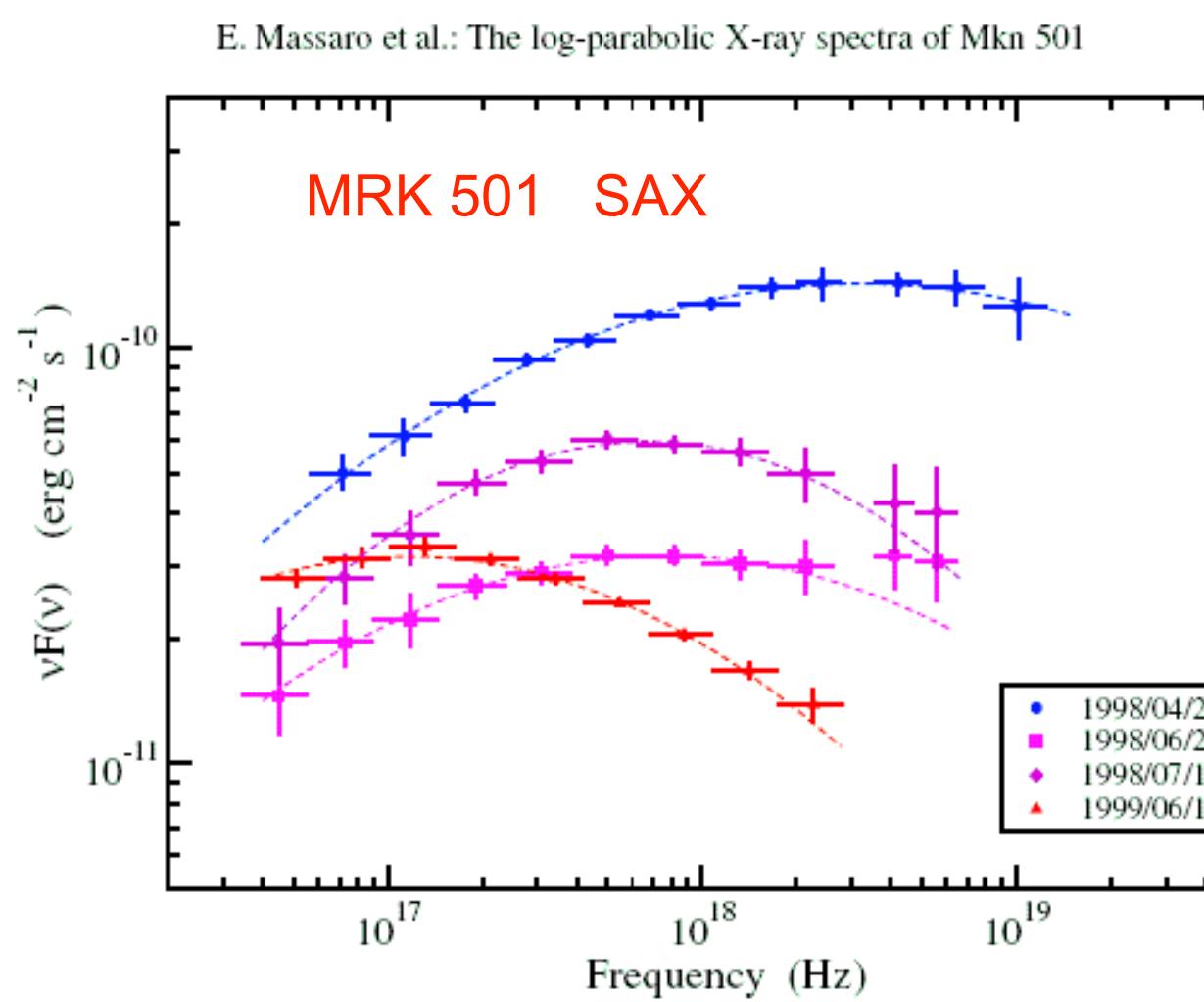
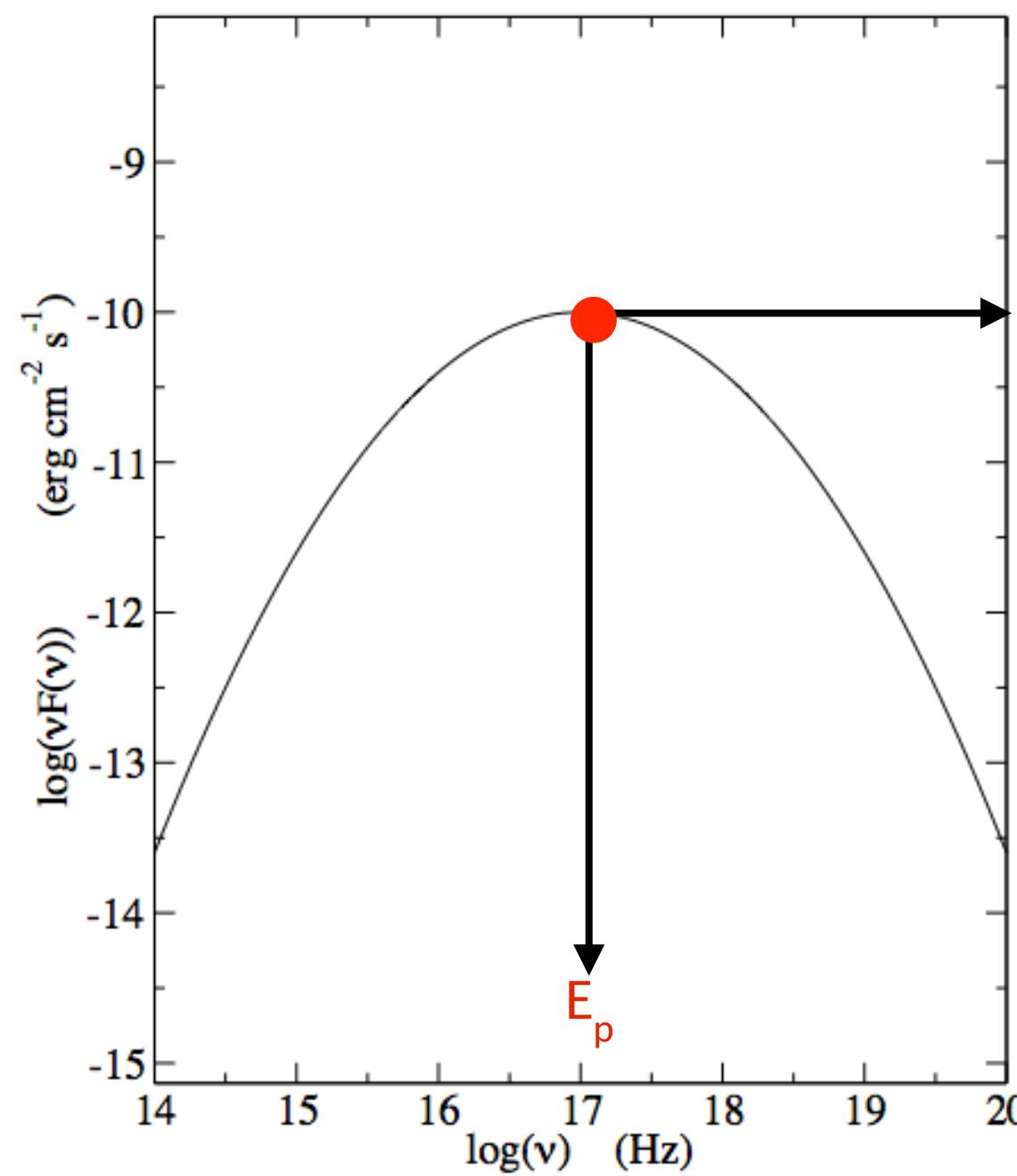
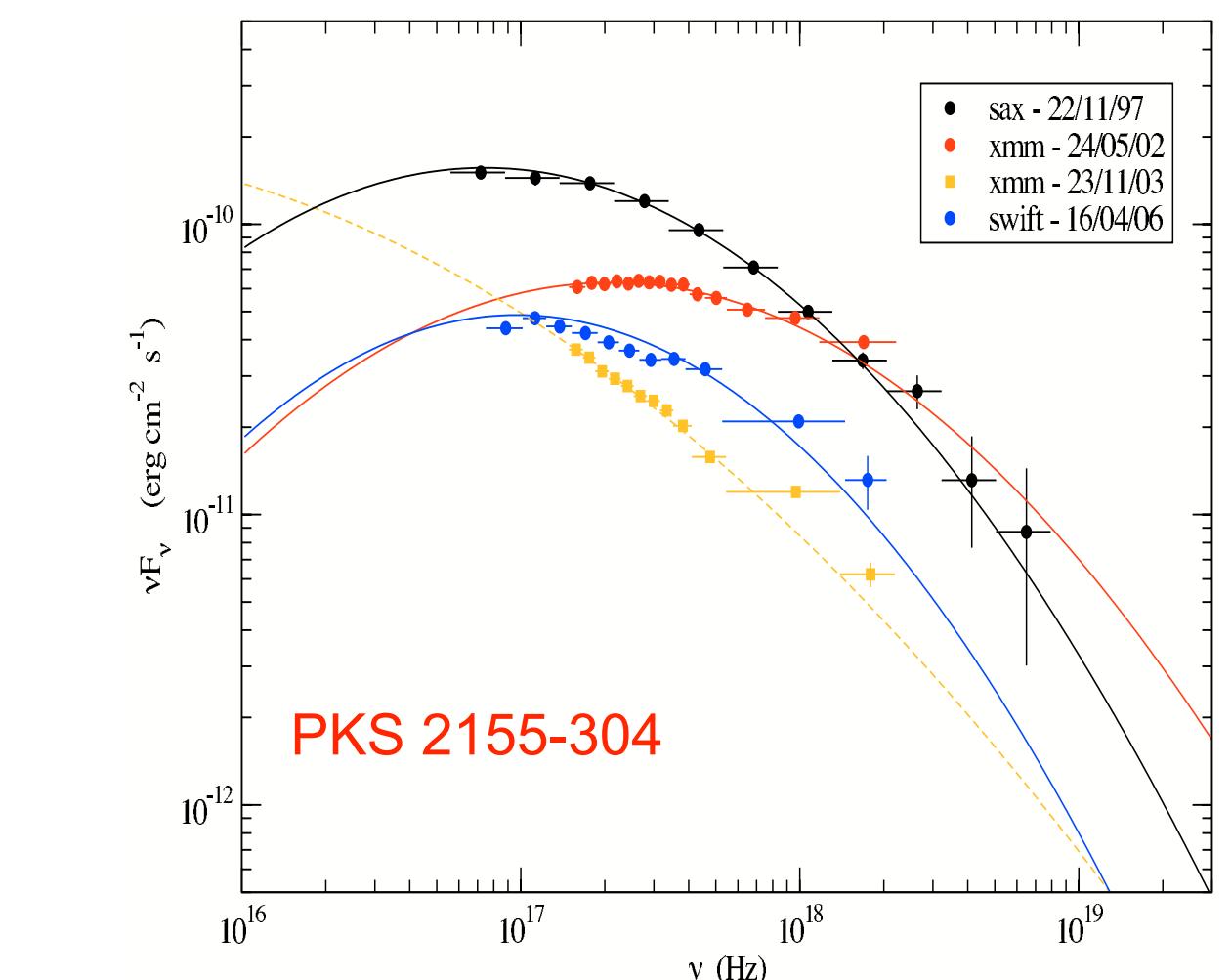
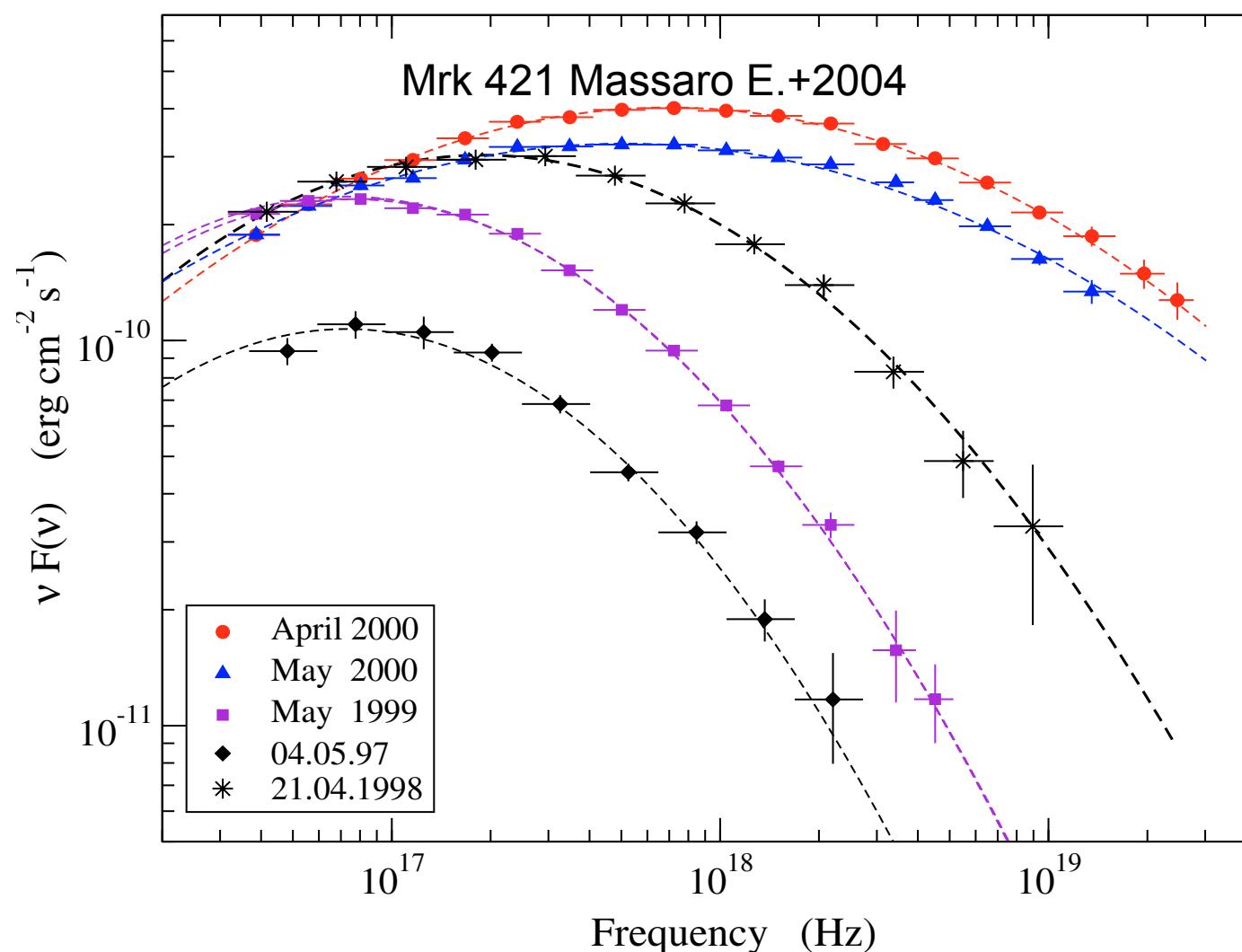
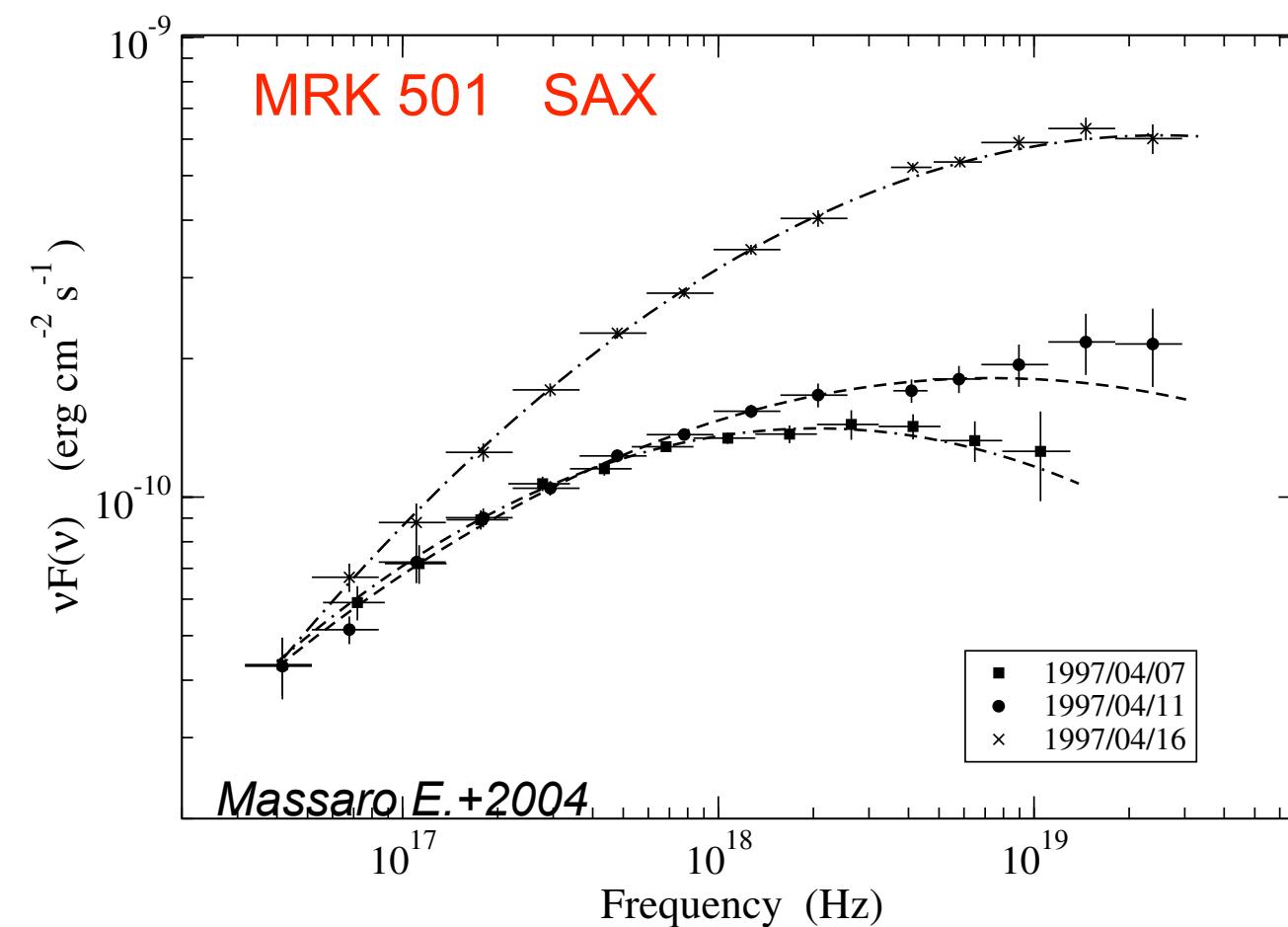


template

# jet model definition

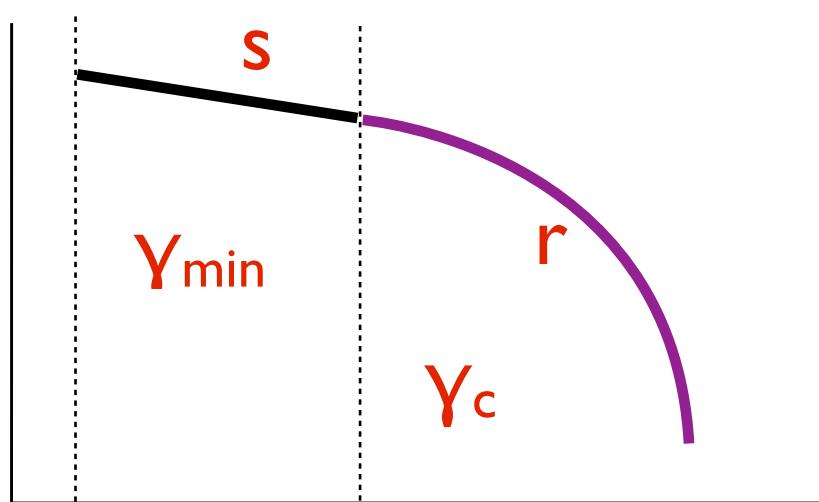


# X-ray SPECTRAL DISTRIBUTION OF HBLs (stochastic acceleration)

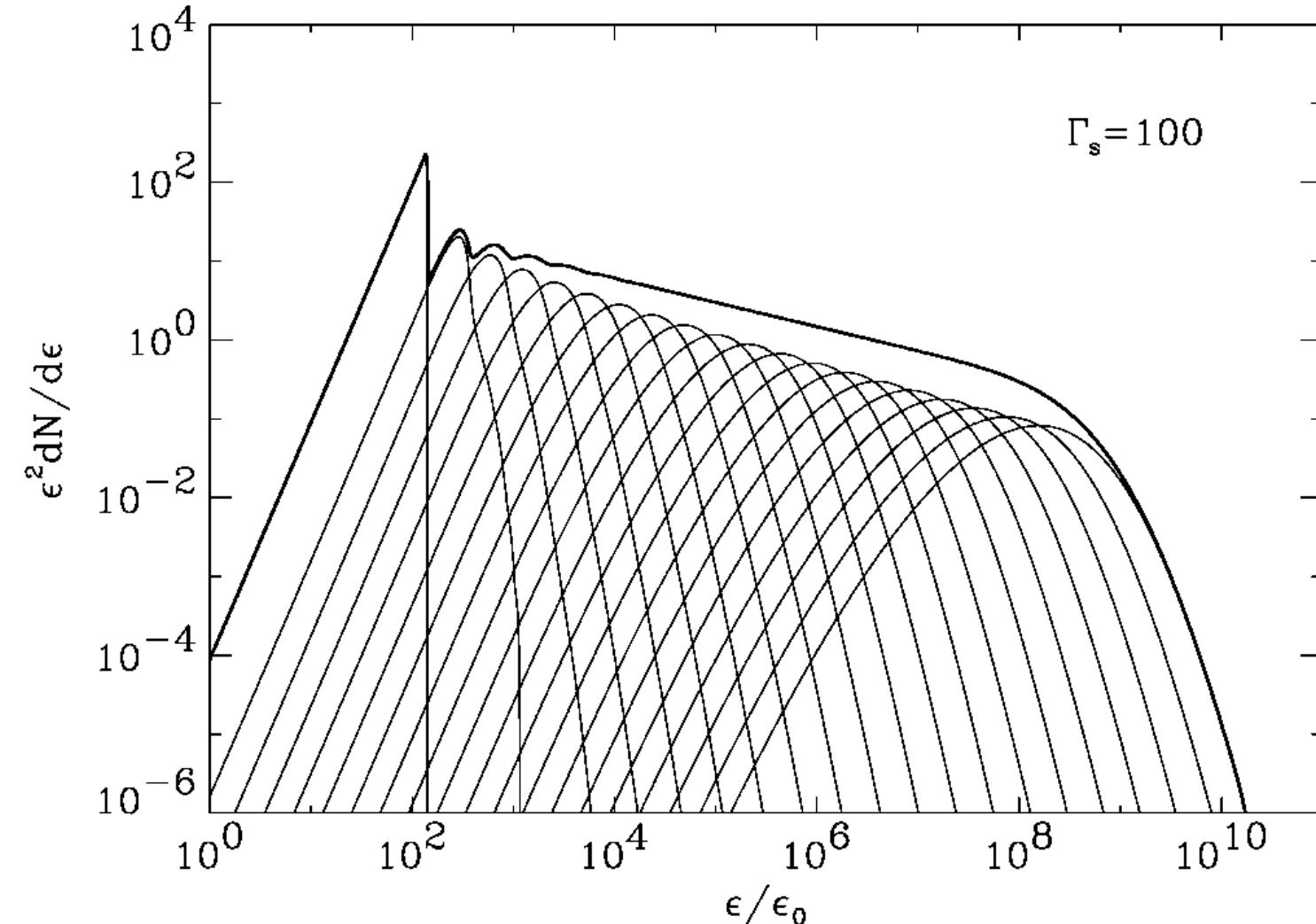


LP+PL spectra

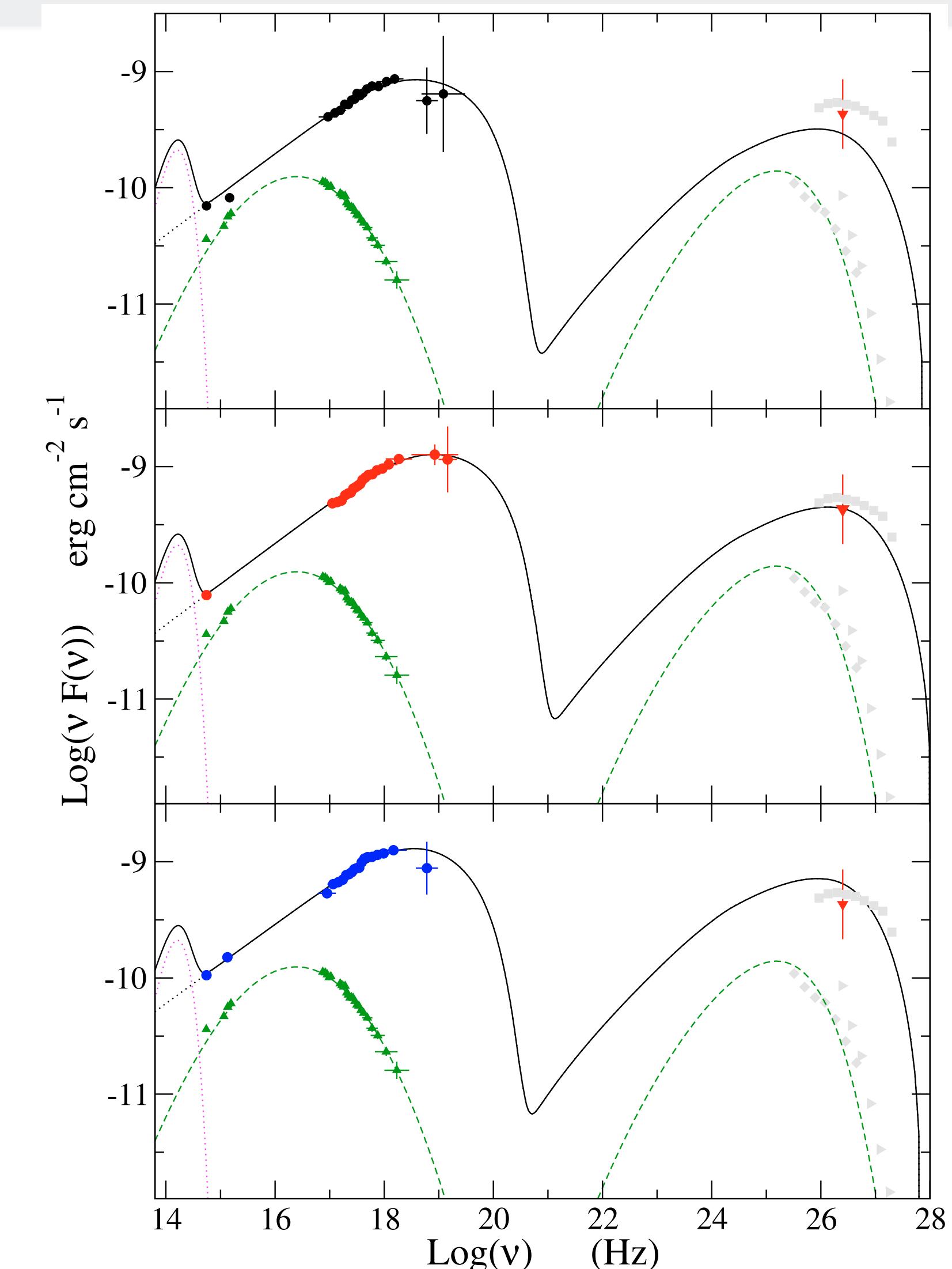
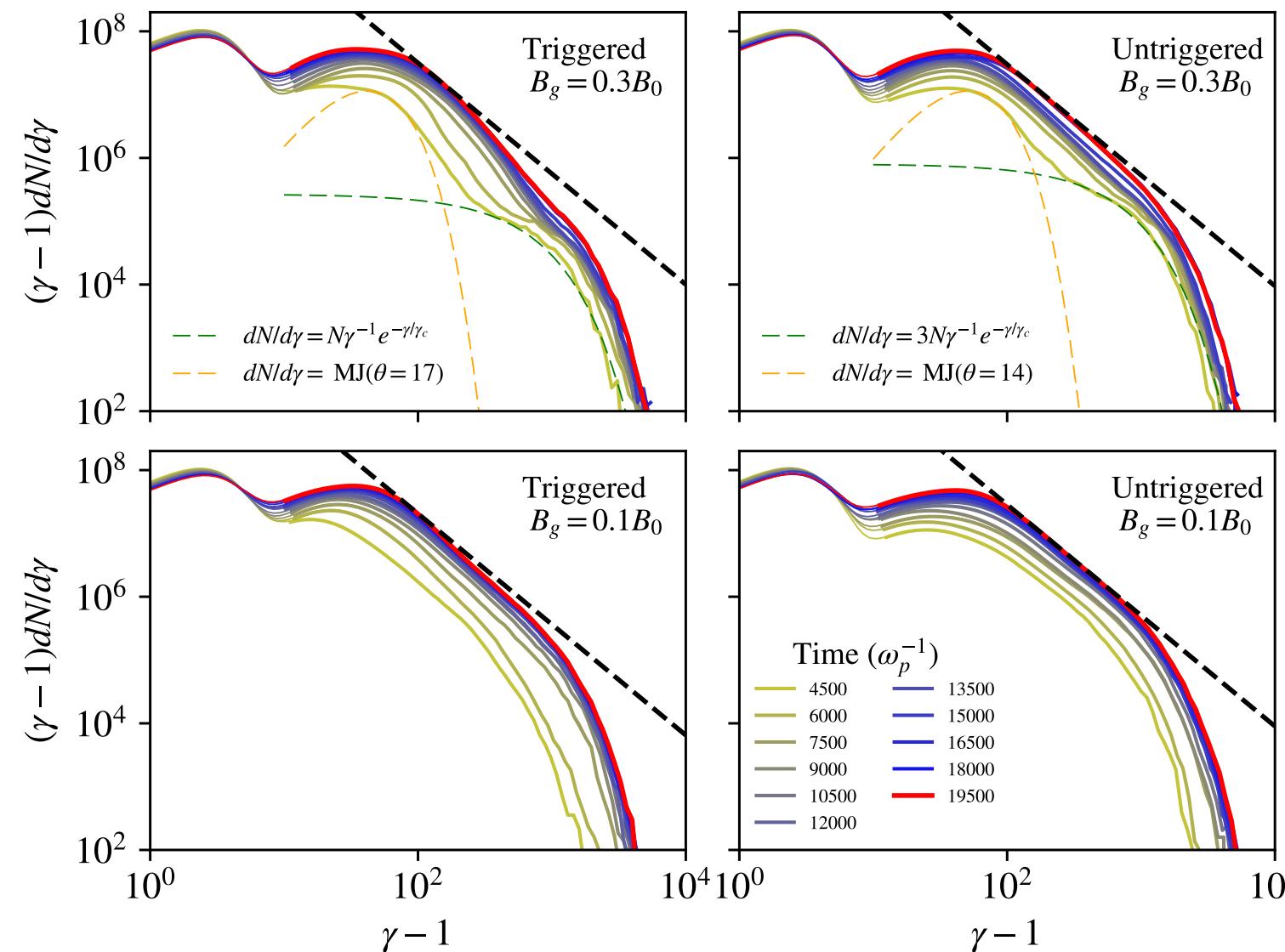
Synch index~[1.6-1.7]=> $s\sim[2.2-2.4]$



Lemoine,Pelletier 2003 FI multip.

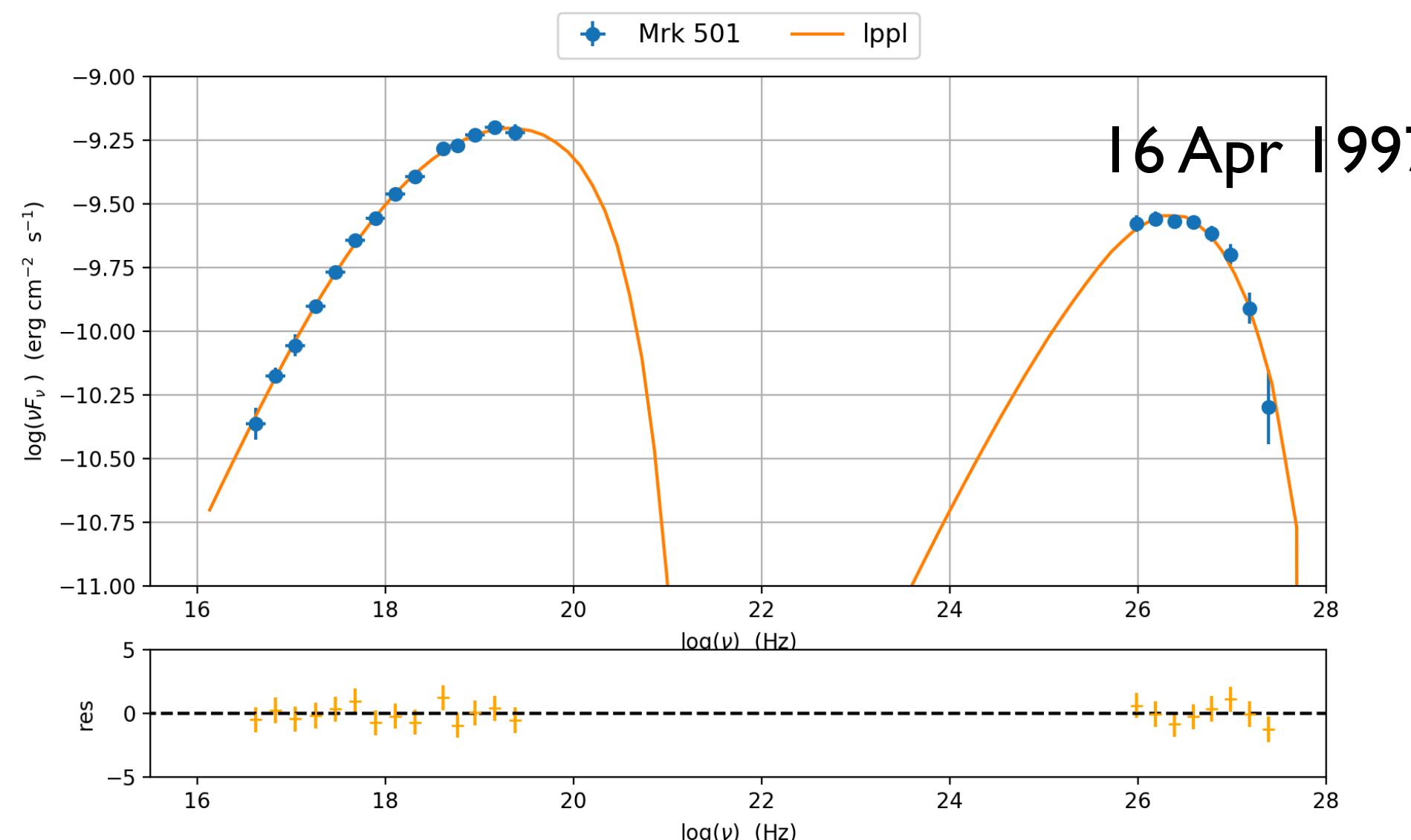
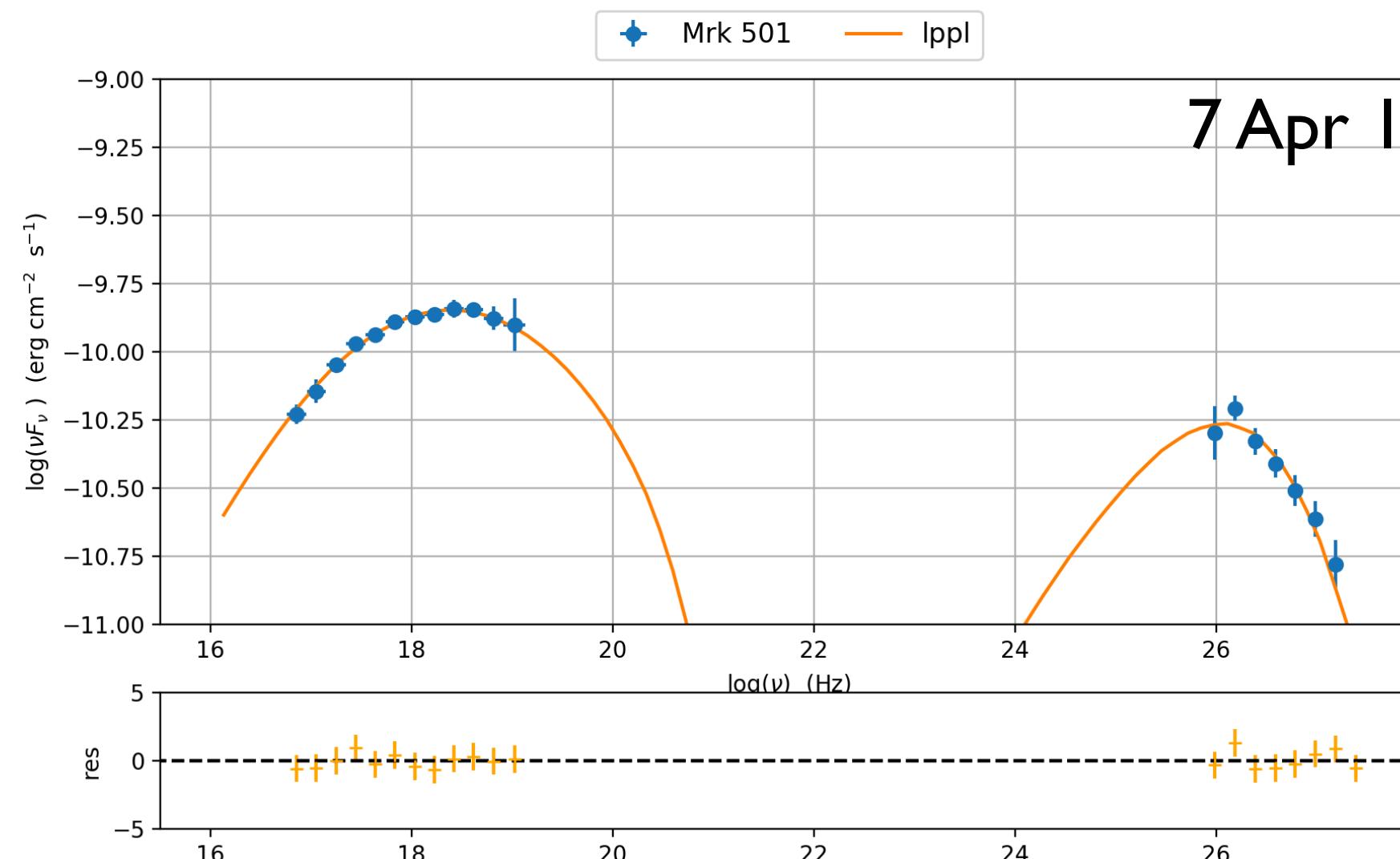


Ball+ 2019 magnetic reconnection (PIC)



## Mrk 501 1997 Flare

Massaro &amp; Tramacere +2006



$$s = 1 + \frac{t_{acc}}{2t_{esc}}$$

**s**      **r**  
 **$\gamma_c$**

## best fit pars

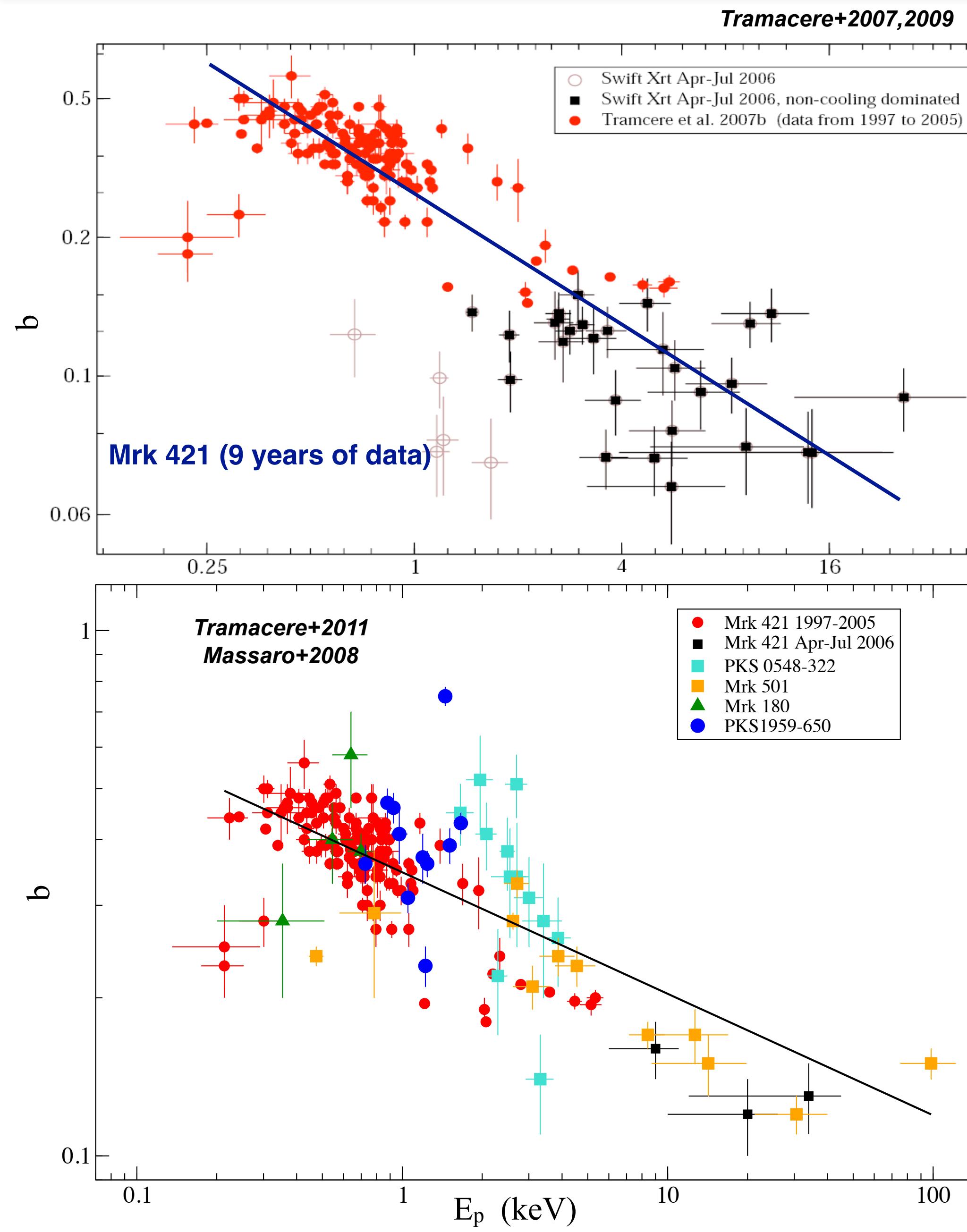
## best-fit parameters:

Name	best-fit value	best-fit err +
B	+1.072178e-01	+5.436622e-03
N	+4.585348e+00	+4.756569e-01
R	Frozen	Frozen
beam_obj	+2.450884e+01	+7.642113e-01
gamma0_log_parab	+6.609649e+04	+7.427709e+03
gmax	+1.860044e+14	+5.881595e+14
gmin	+1.404527e+03	+2.198648e+02
r	+7.513452e-01	+5.059815e-02
<b>s</b>	<b>+1.638026e+00</b>	<b>+3.170384e-02</b>
z_cosm	Frozen	Frozen

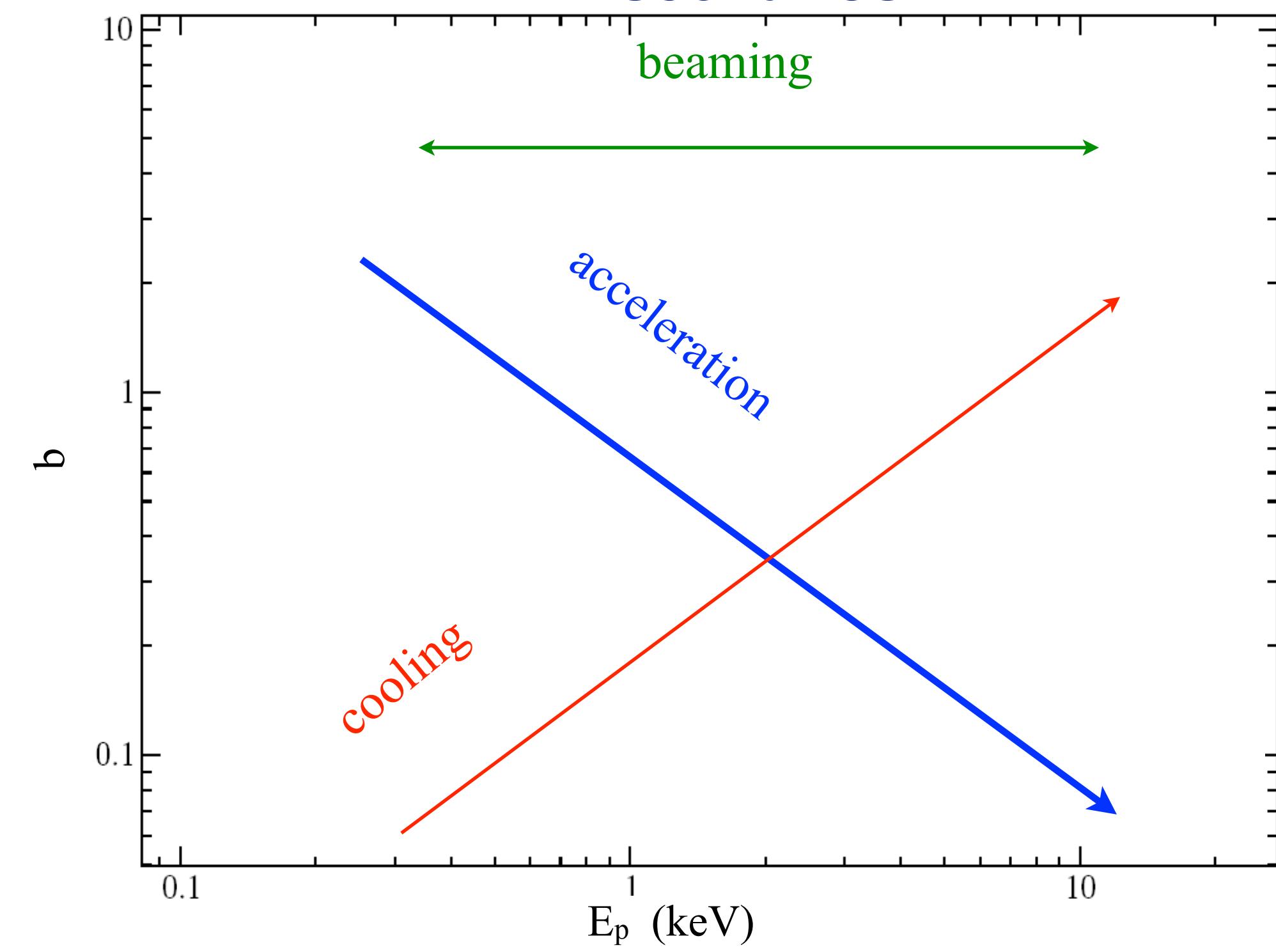
\*\*\*\*\*

## best-fit parameters:

Name	best-fit value	best-fit err +
B	+3.065207e-01	+1.159567e-02
N	+1.079944e+02	+7.375385e+00
R	Frozen	Frozen
beam_obj	+2.722013e+01	+5.889626e-01
gamma0_log_parab	+6.493888e+04	+5.410315e+03
gmax	+1.902146e+06	+2.216666e+02
gmin	+3.003970e+02	+5.686711e+01
r	+6.778727e-01	+3.526656e-02
<b>s</b>	<b>+1.321307e+00</b>	<b>+1.844825e-02</b>
z_cosm	Frozen	Frozen



Ep-vs-b, different scenarios

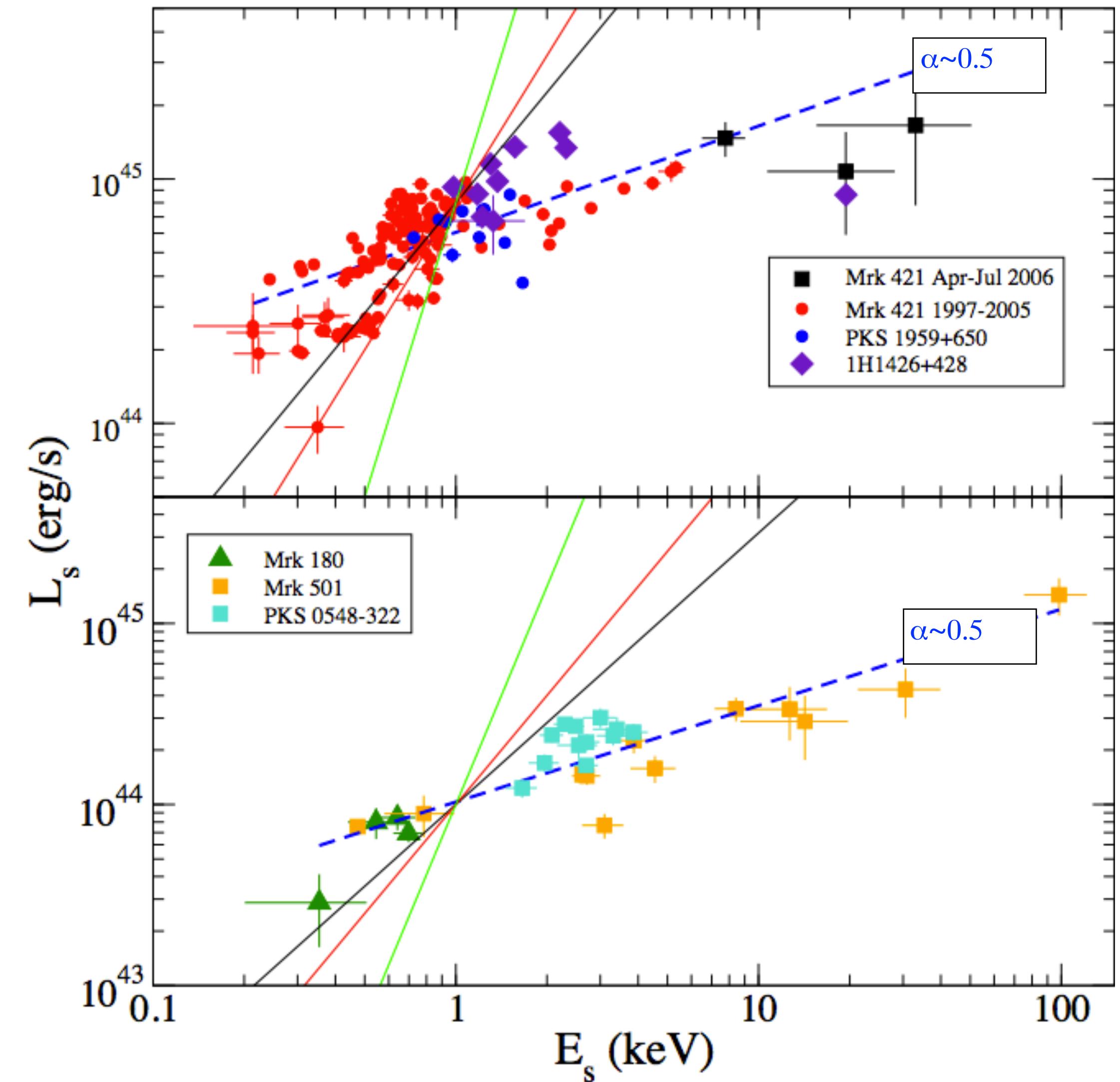


11 years of data:

PKS 0548-322, 1H1426+418,  
Mrk 501, 1ES1959+650, PKS2155-34

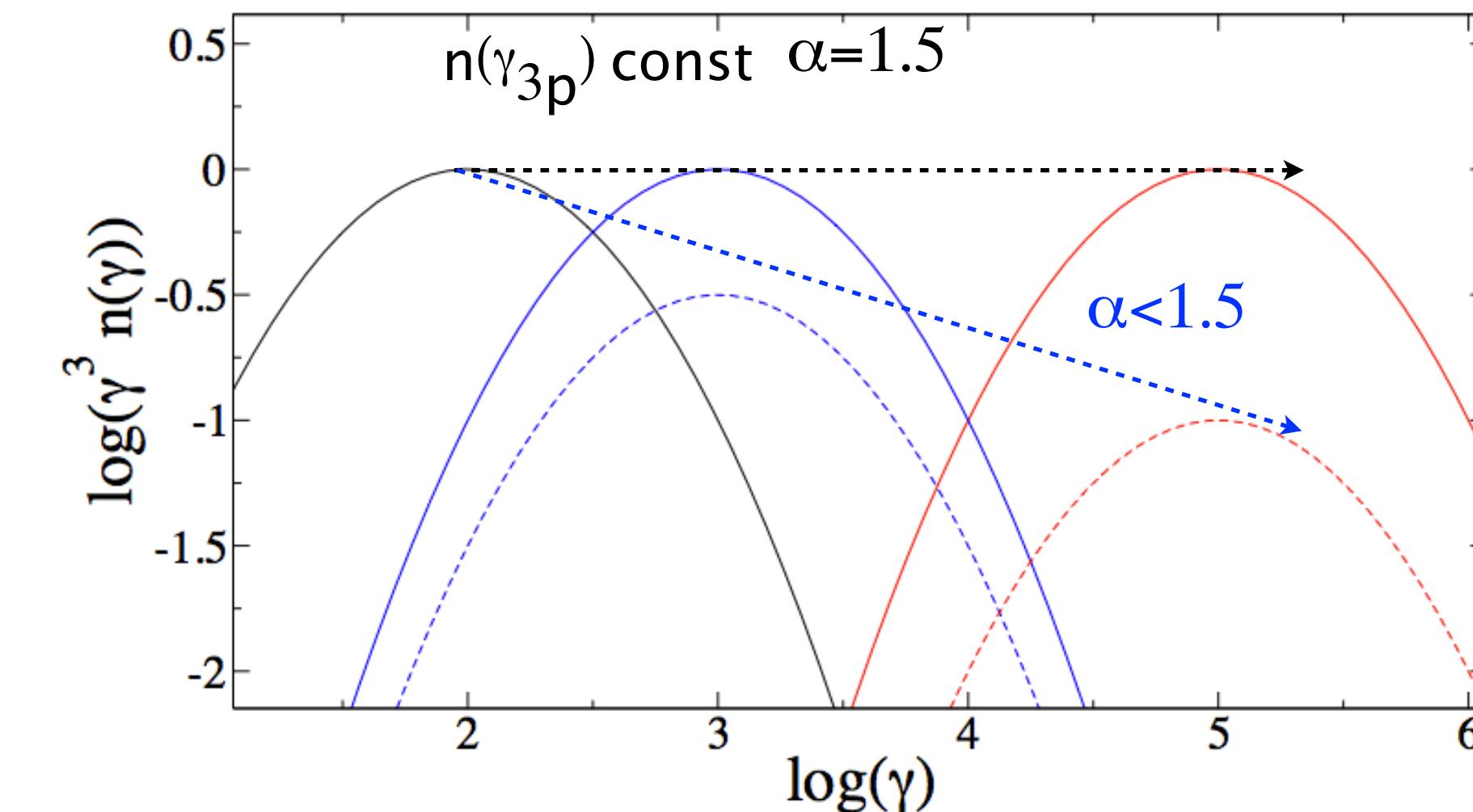
Long term (overall 13 years of data) Ep-vs-b  
trends hint for an acceleration dominated  
scenario

## long-trend main drivers



•  $\gamma_{3p} \uparrow$  and  $n(\gamma_{3p}) \downarrow \Rightarrow \alpha < 1.5$   
**acceleration+energy conservation**

•  $B \rightarrow \alpha = 2.0$ , incompatible as long-trend main driver  
•  $\delta \rightarrow \alpha = 4$

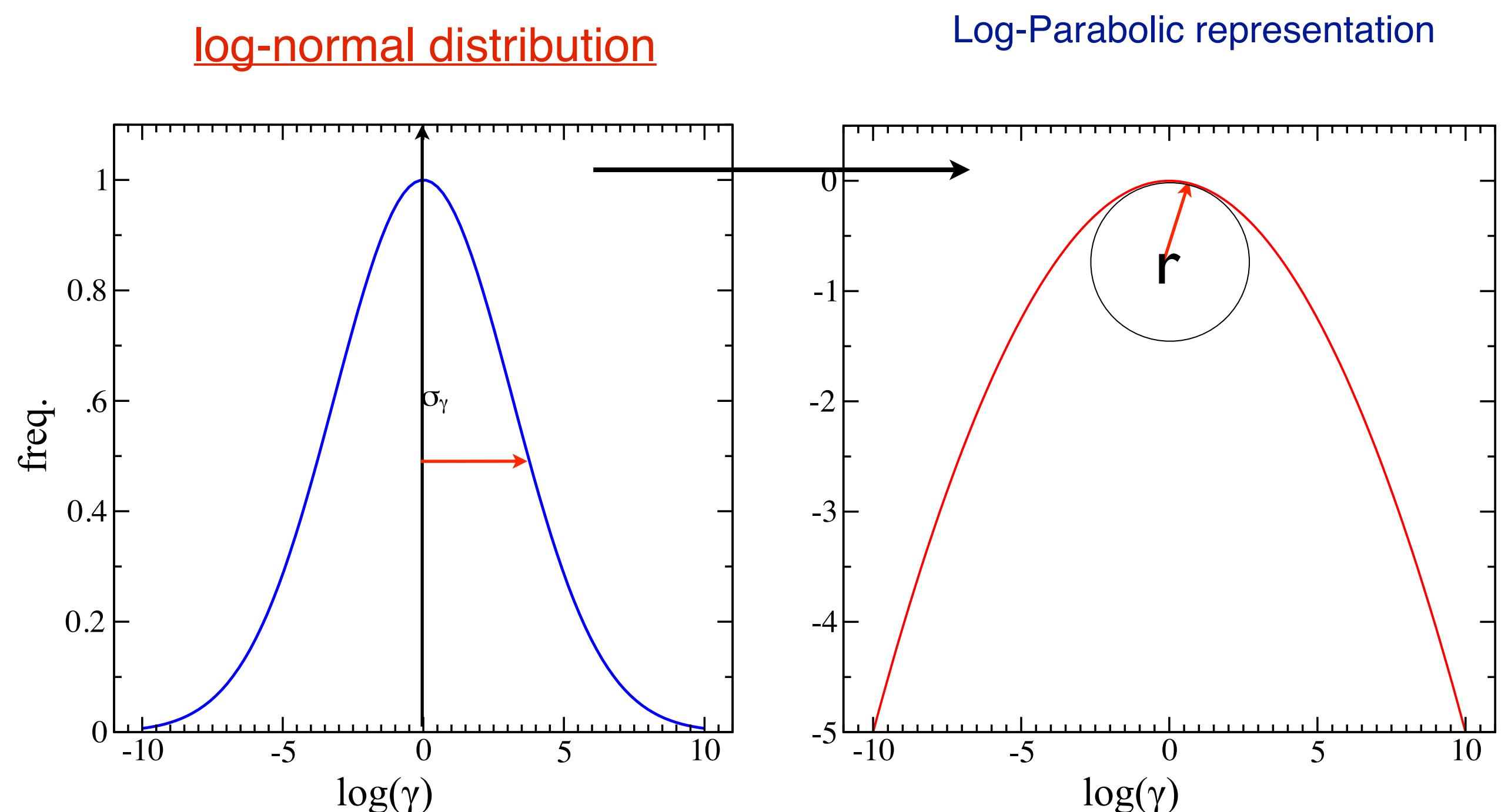


# The origin of the log-parabolic shape: statistical derivation



$$\gamma_{n_s} = \gamma_0 \prod_{i=1}^{n_s} \varepsilon_i$$

C.L. Theorem  
multipl. case



$$\log(n(\gamma)) \propto \frac{(\log \gamma - \mu)^2}{2\sigma_\gamma^2} \propto r [\log(\gamma) - \mu]^2$$

$$\sigma_y^2 = \sigma^2(\log(\gamma)) \approx n_s \left( \frac{\sigma_\varepsilon}{\bar{\varepsilon}} \right)$$

curvature =  $\frac{1}{\sigma_\gamma} = 2r$

$$r = \frac{c_e}{2n_s \left( \frac{\sigma_\varepsilon}{\bar{\varepsilon}} \right)^2}$$

# The origin of the log-parabolic shape: diffusion equation approach

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

**CL theorem**

analytical solution for:

$D_p \sim \gamma^q$ ,  $q=2$   
“hard-sphere” case

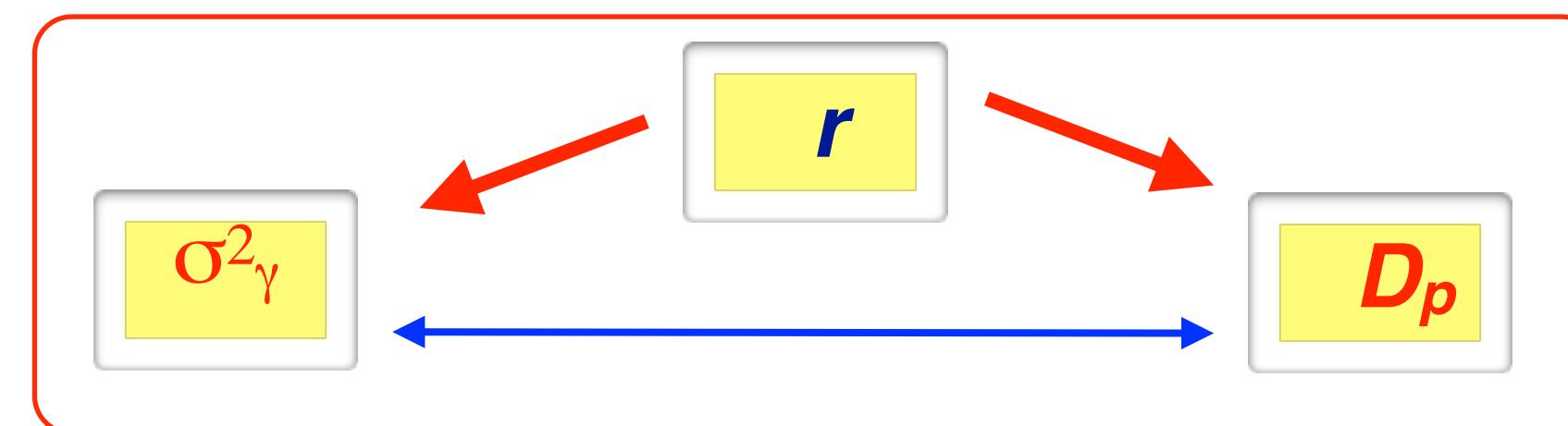
Melrose 1968, Kardashedv 1962

$$n(\gamma, t) = \frac{N_0}{\gamma \sqrt{4\pi D_{p0} t}} \exp \left\{ -\frac{[\ln(\gamma/\gamma_0) - (A_{p0} - D_{p0})t]^2}{4D_{p0}t} \right\}$$

$$\log(n(\gamma)) \propto \frac{(\log \gamma - \mu)^2}{2\sigma_\gamma^2} \propto r [\log(\gamma) - \mu]^2$$

$$\propto \frac{1}{D_{p0}t} \rightarrow D_{p0} \propto \left( \frac{\sigma_\varepsilon}{\bar{\varepsilon}} \right)^2$$

The curvature  $r$  is inversely proportional to  $t \Rightarrow n_s$  and  $D_p \Rightarrow \sigma_\varepsilon$



# Temporal evolution

Tramacere +2011

## injection term

$$L_{inj} = \frac{4}{3}\pi R^3 \int \gamma_{inj} m_e c^2 Q(\gamma_{inj}, t) d\gamma_{inj} \quad (\text{erg/s})$$

## systematic term

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

### cooling term

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

### syst. acc. term

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

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

## Turbulent magnetic field

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

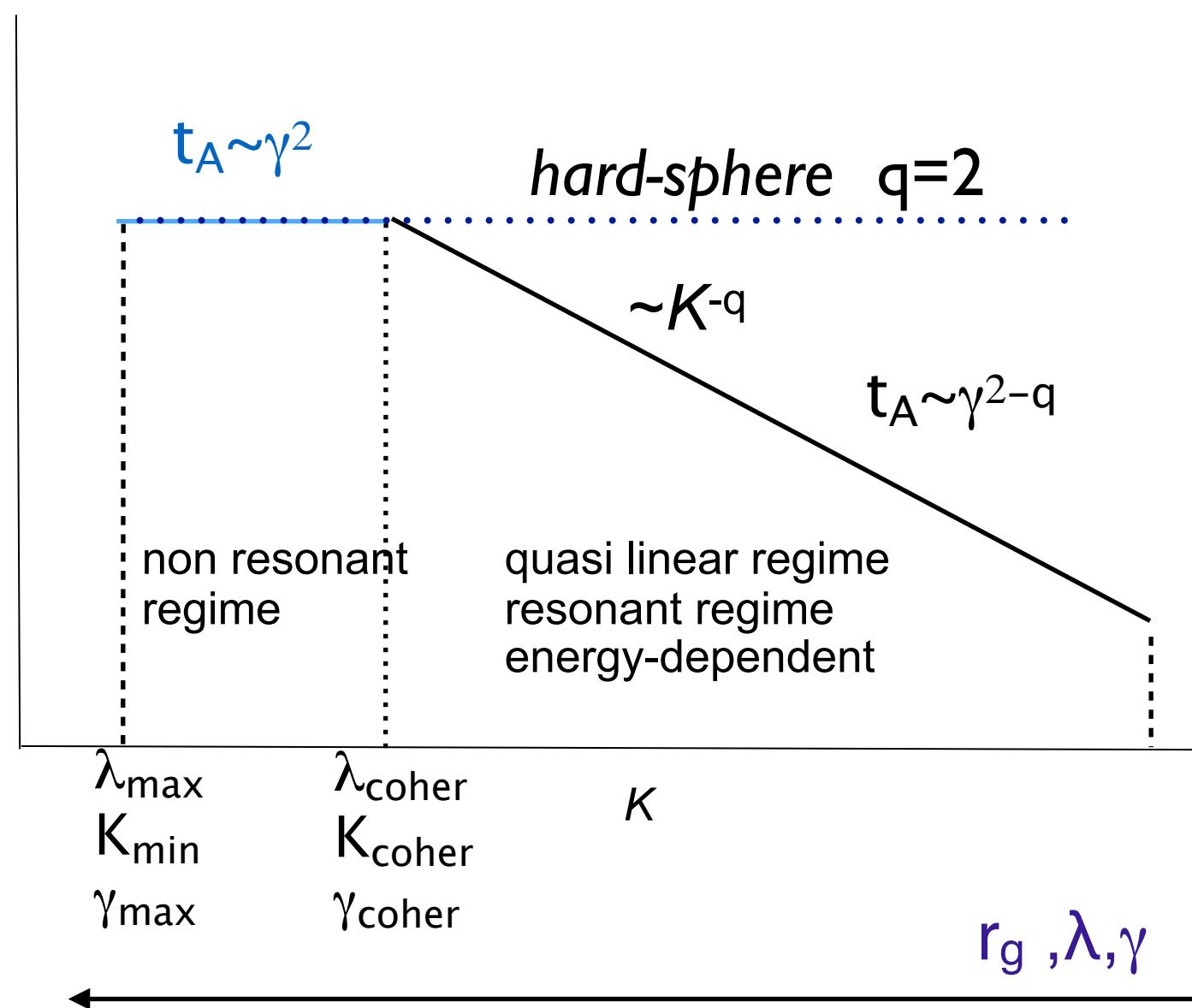
## momentum diffusion term

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

# set-up of the accelerator

$$t_D = \frac{1}{D_{p0}} \left( \frac{\gamma}{\gamma_0} \right)^{2-q}$$

$$t_{DA} = \frac{1}{2D_{p0}} \left( \frac{\gamma}{\gamma_0} \right)^{2-q}$$

 $W(k)$ 

e-folding time

observed values

$$E_{p1}/E_{p2} \sim 5$$

$$\Delta t \sim \text{few ks}$$

values compatible with  
Tammi & Duffy 2009

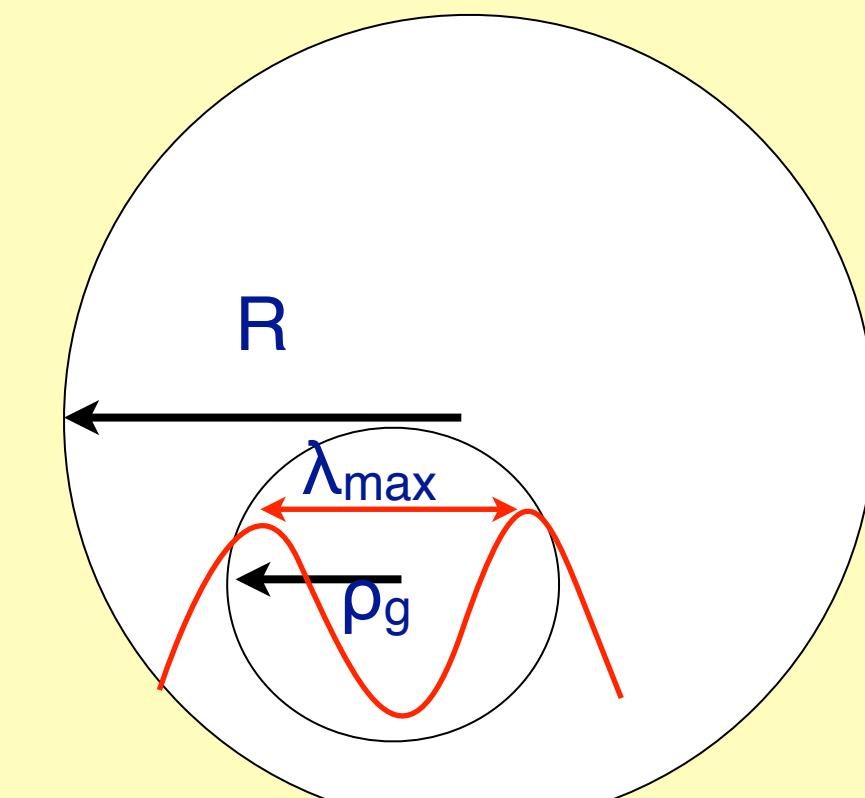
$$t_{DA} \sim < 5 \text{ ks}$$

$$t_D \sim < 10 \text{ ks}$$

## set-up of the accelerator

- $R \sim 10^{13}-10^{15} \text{ cm}$
- $\delta B/B \ll 1, B \sim [0.01-1.0] \text{ G}$
- $\beta_A \sim 0.1-0.5$
- $\lambda_{\max} < R \Rightarrow \sim 10^{[9-15]} \text{ cm}$
- $\rho_g < \lambda_{\max} \Rightarrow \gamma_{\max} \sim 10^{7.5}$

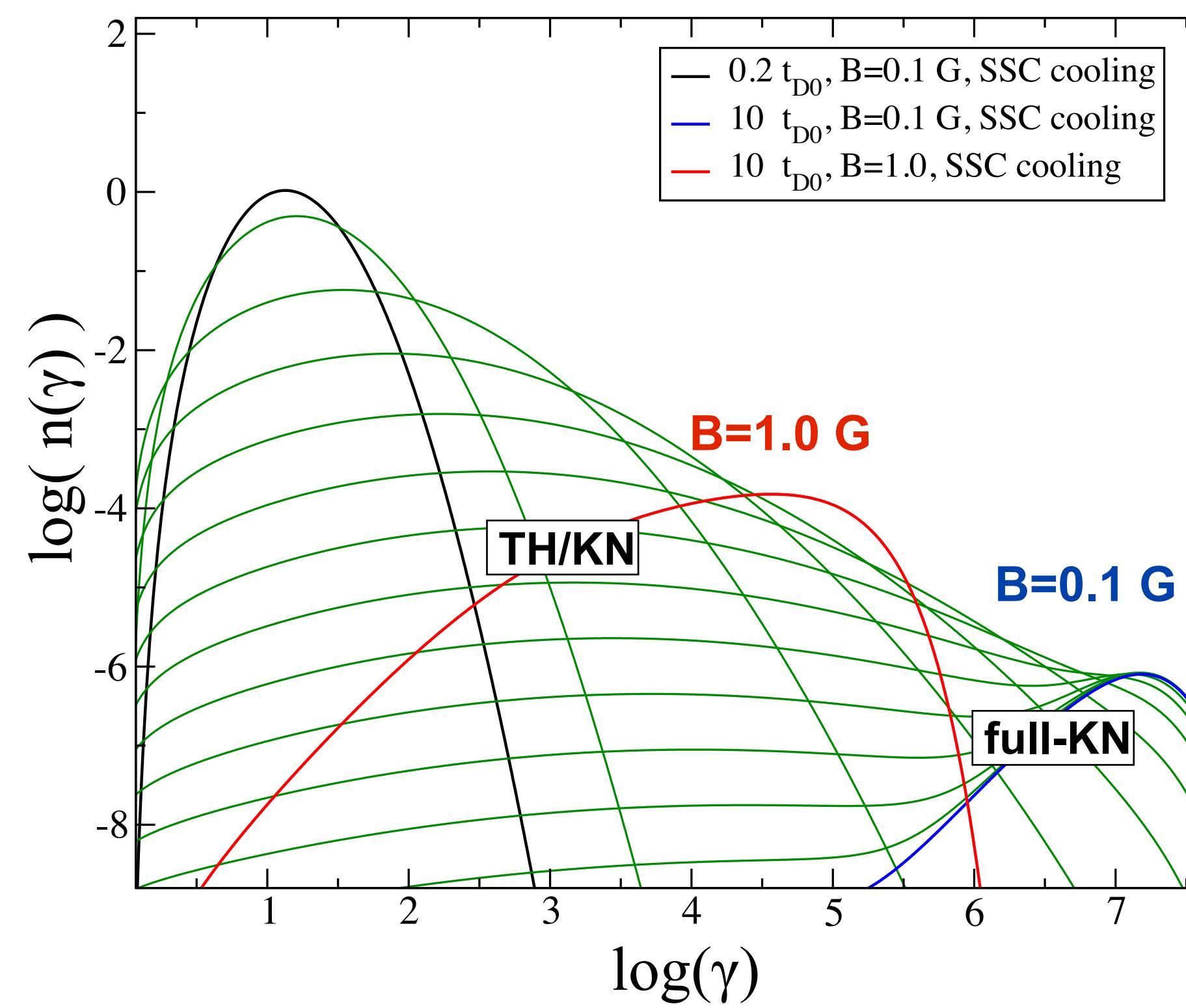
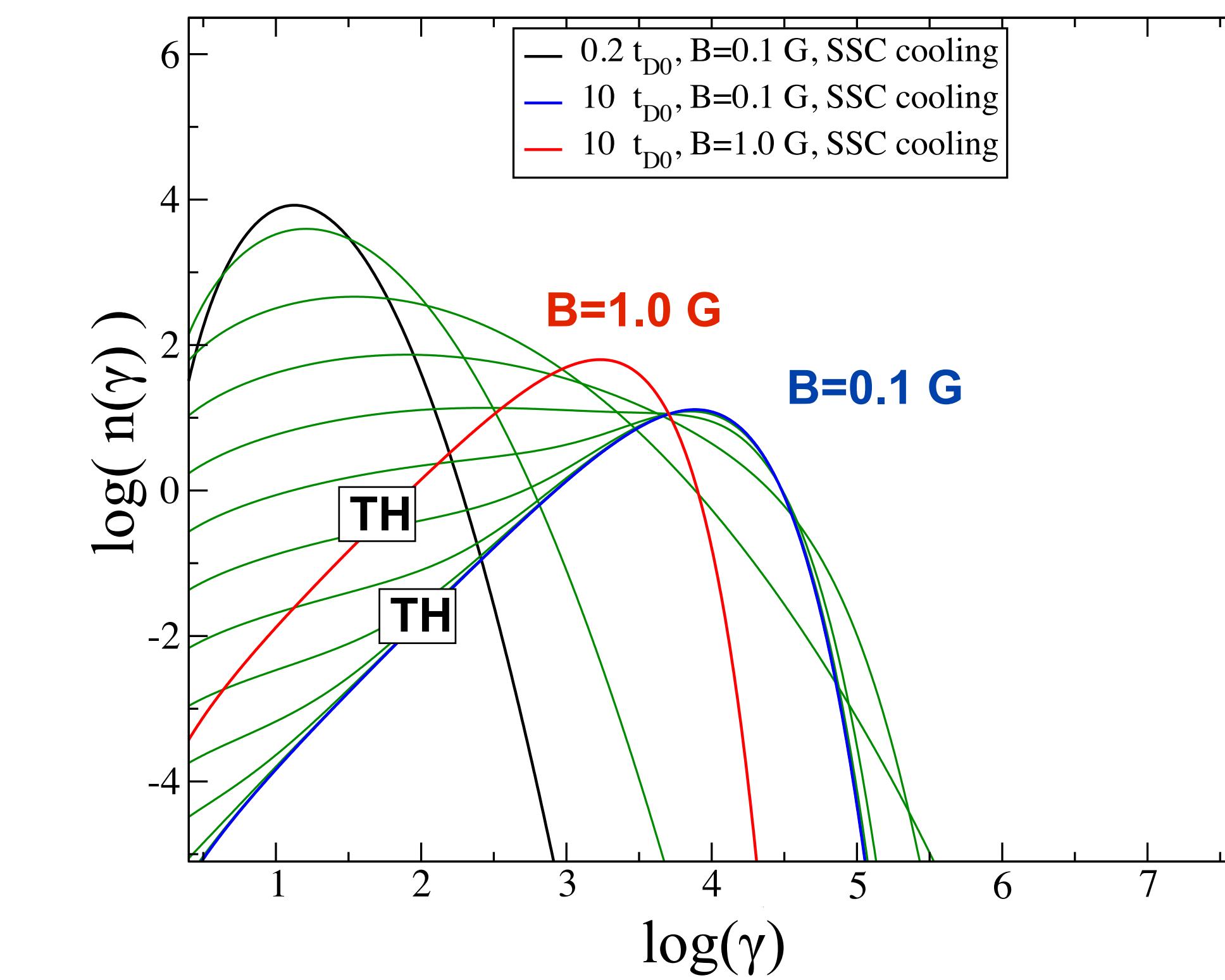
$\rightarrow t_D \sim < 10^4 \text{ ks}$



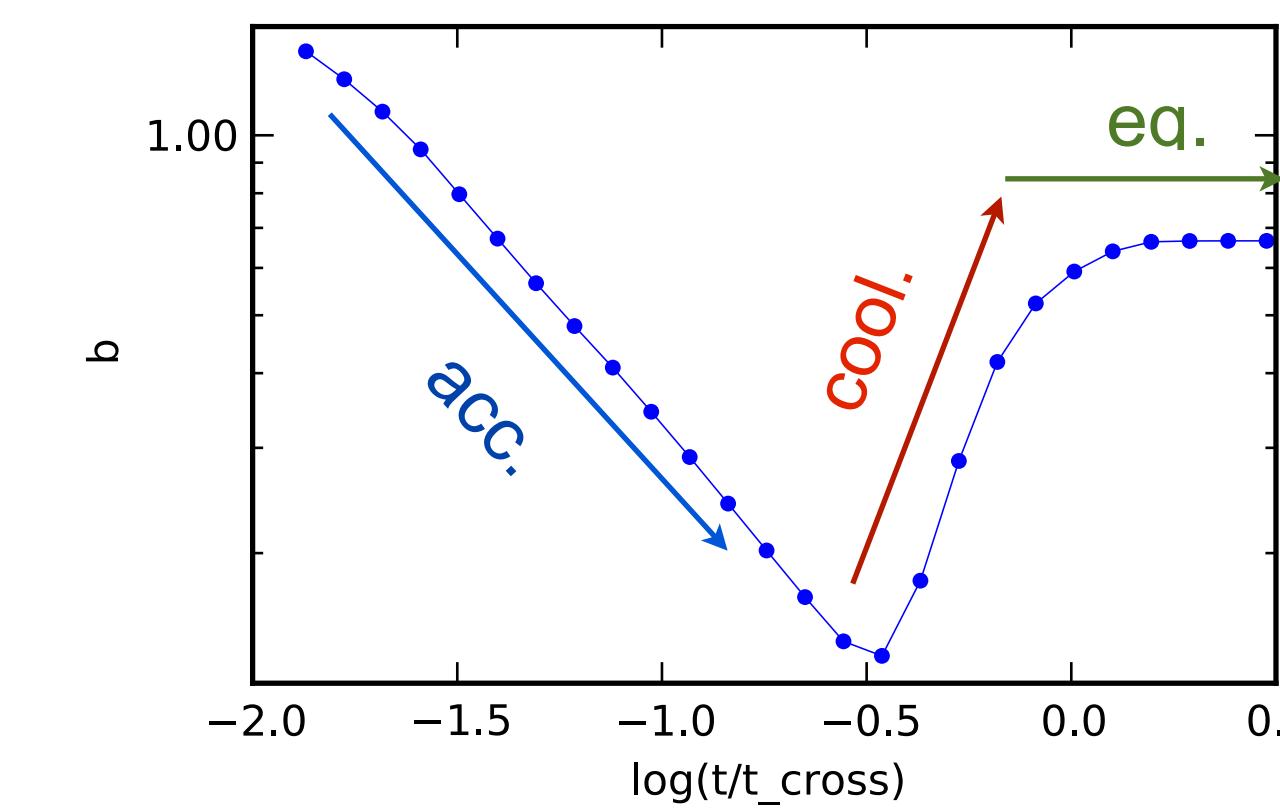
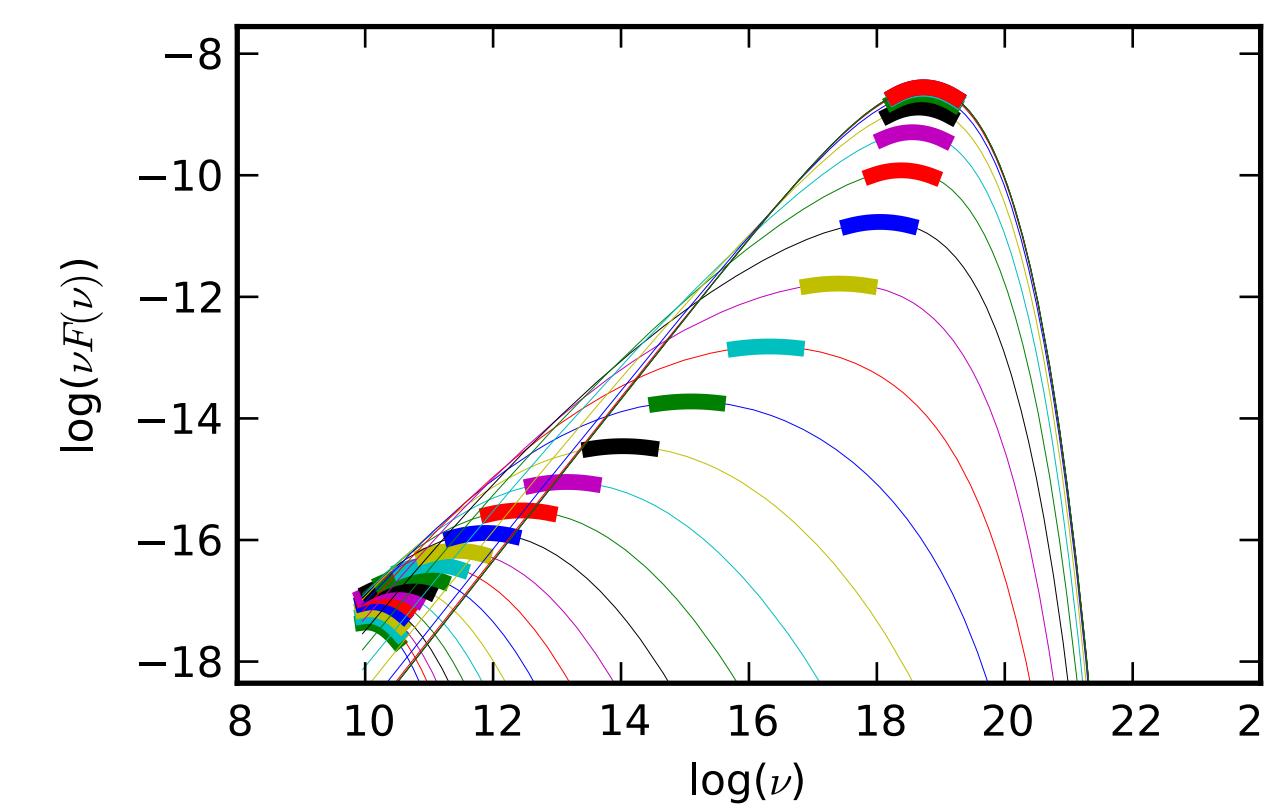
$$D_p \approx \beta_A^2 \left( \frac{\delta B}{B_0} \right)^2 \left( \frac{\rho_g}{\lambda_{\max}} \right)^{q-1} \frac{p^2 c^2}{\rho_g c}$$

$$\rho_g = pc/qB$$

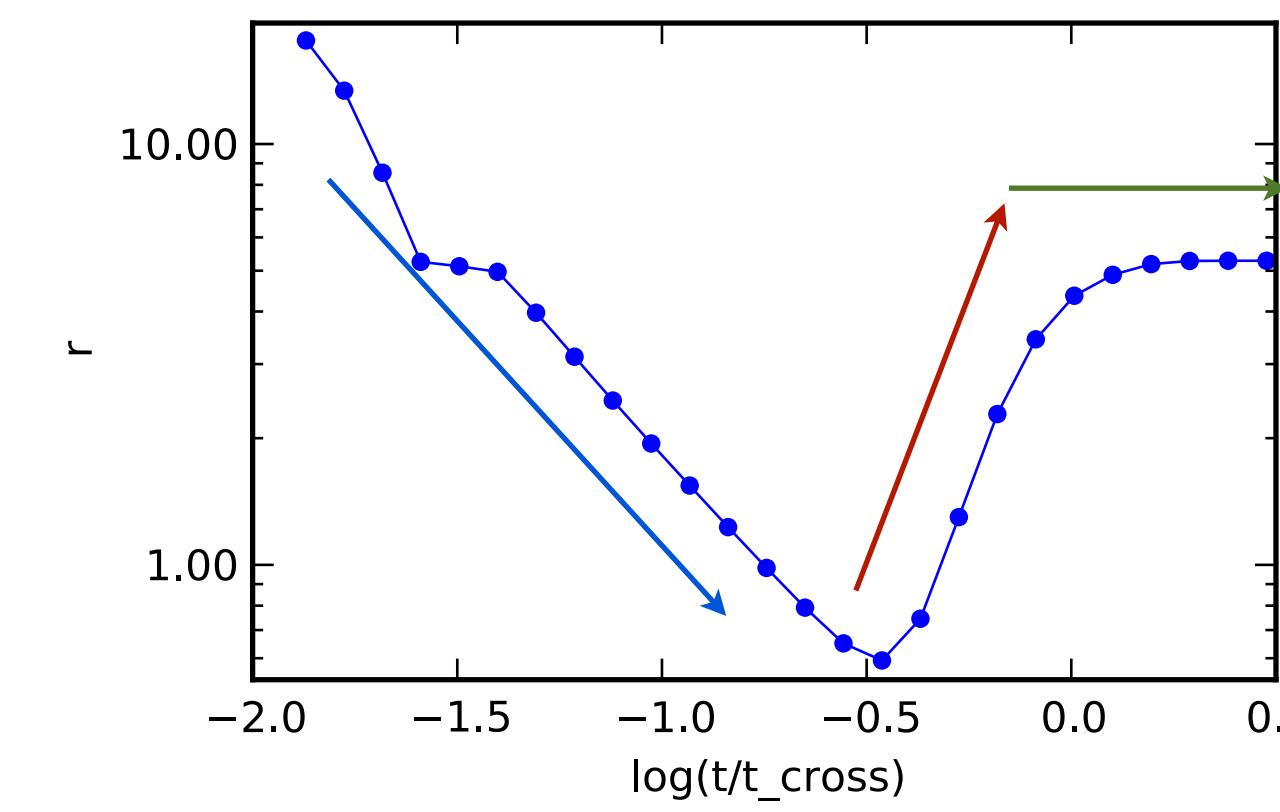
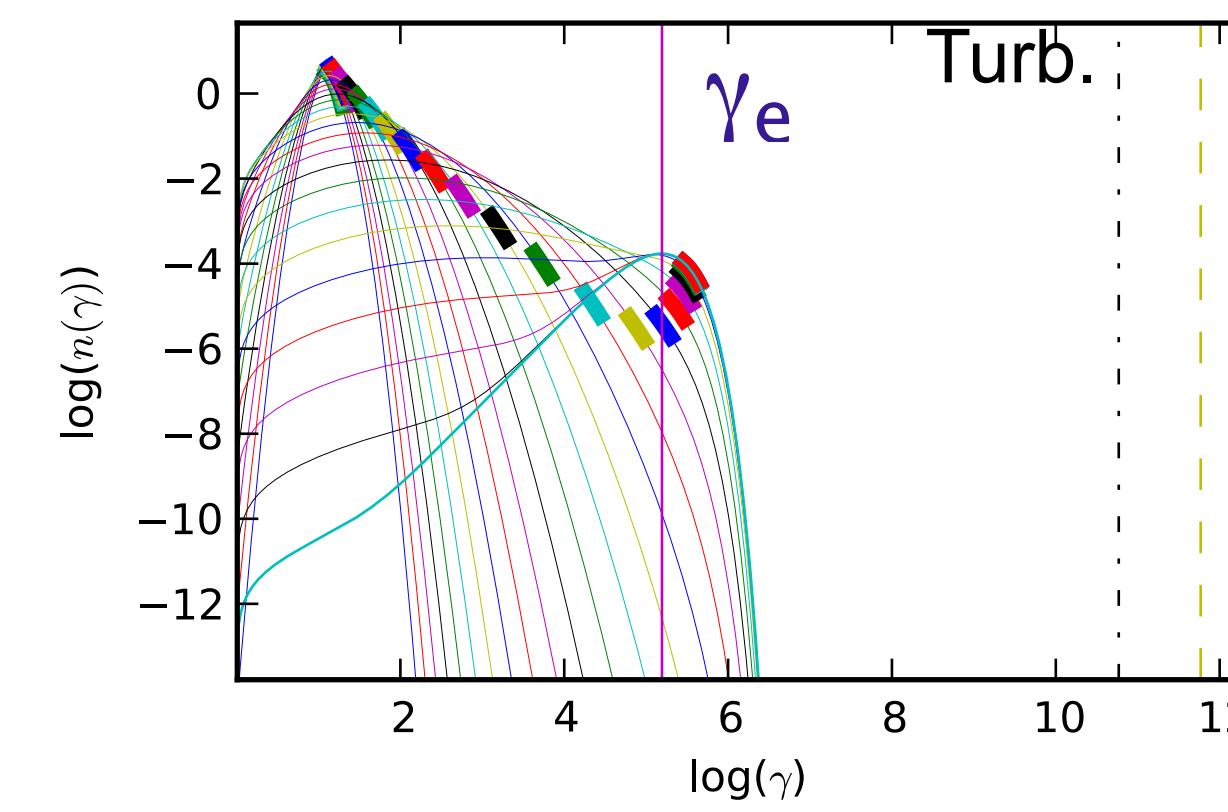
## IC cooling and equilibrium

 $R = 1 \times 10^{15} \text{ cm}$  $R = 5 \times 10^{13} \text{ cm}$ 

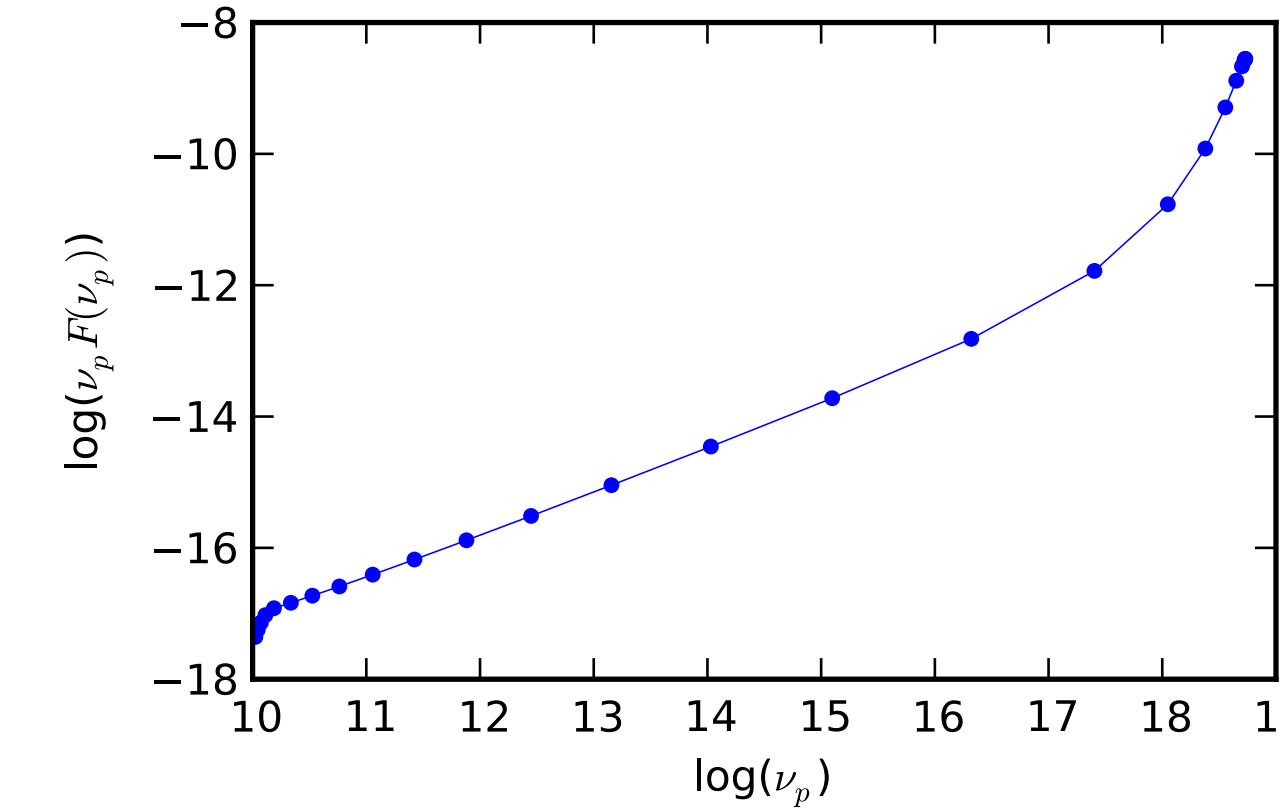
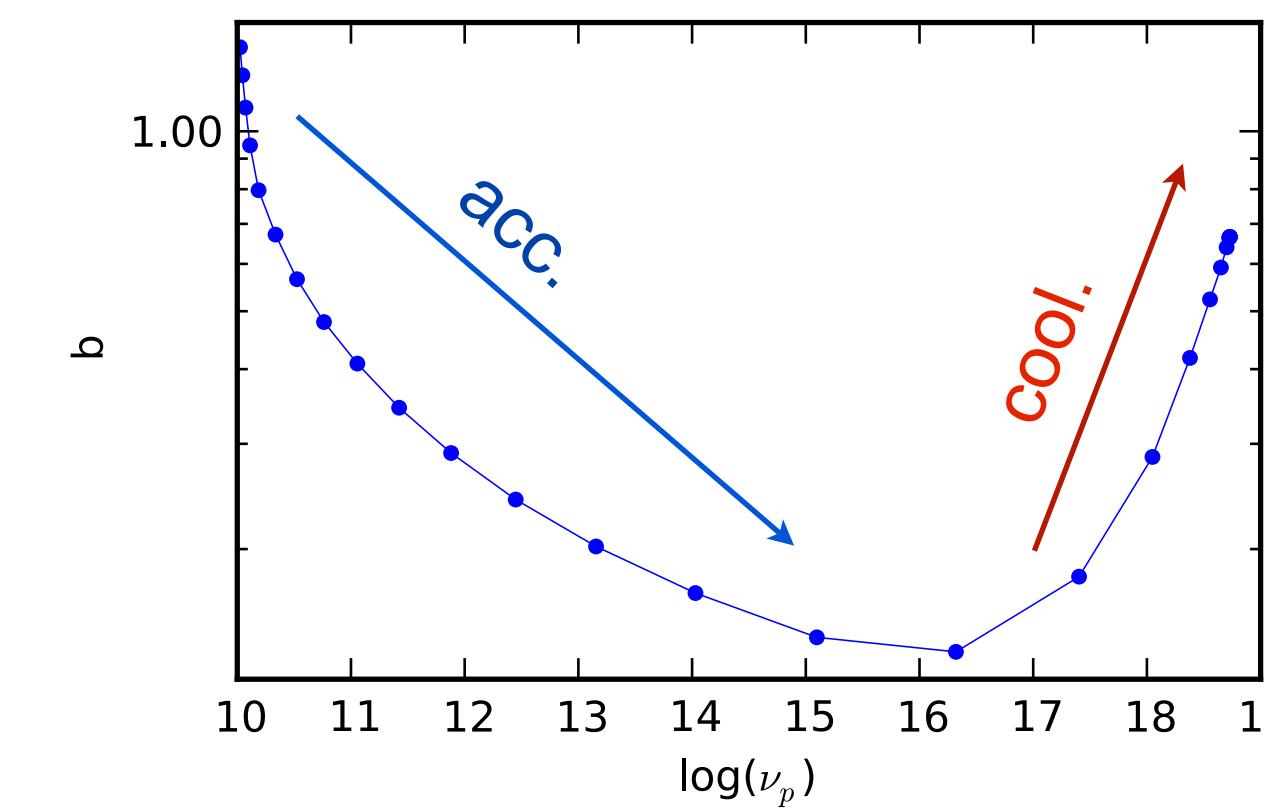
## acceleration-vs-equil.



Synchrotron

**Tramacere +2011**

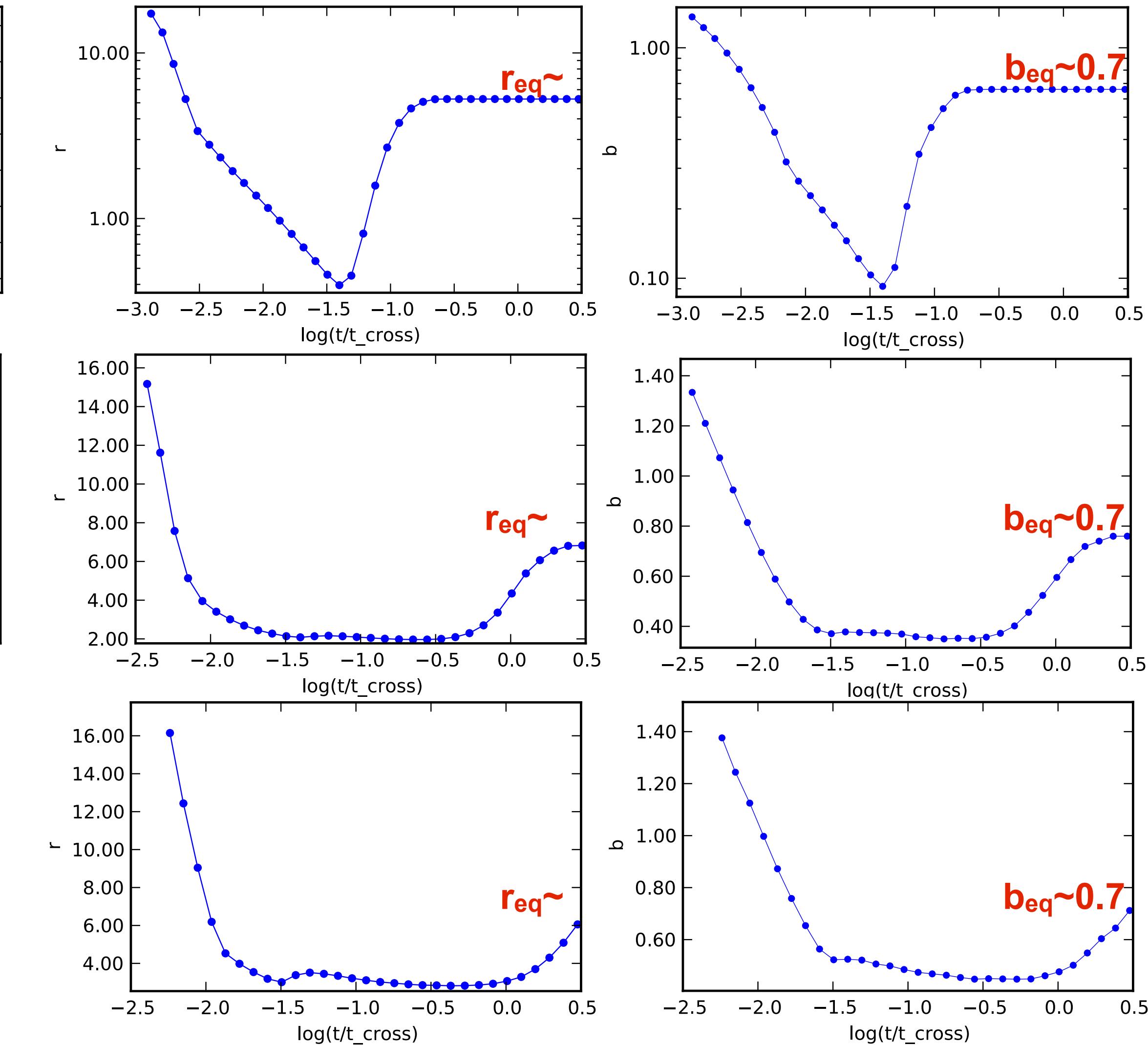
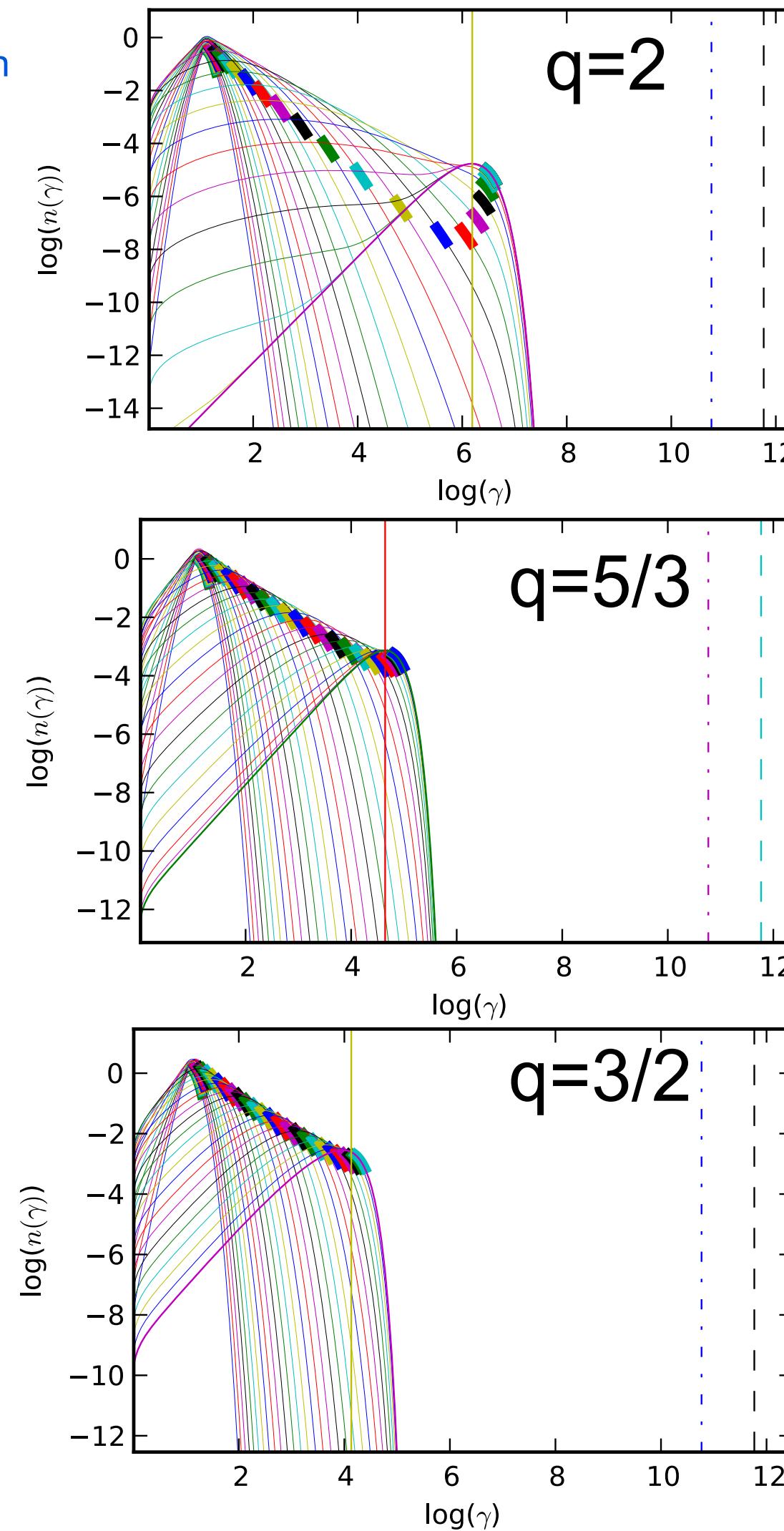
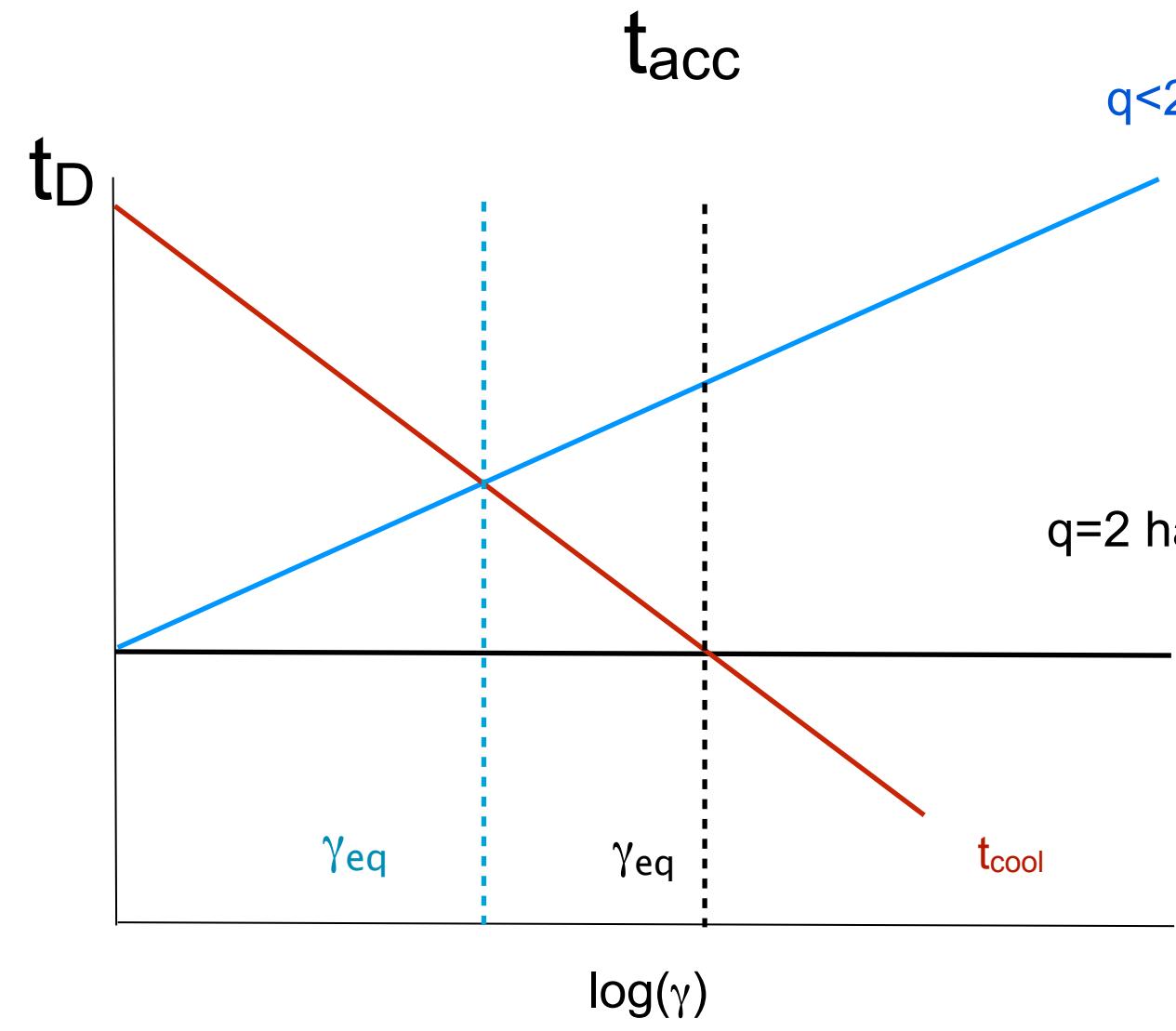
electrons



Synchrotron

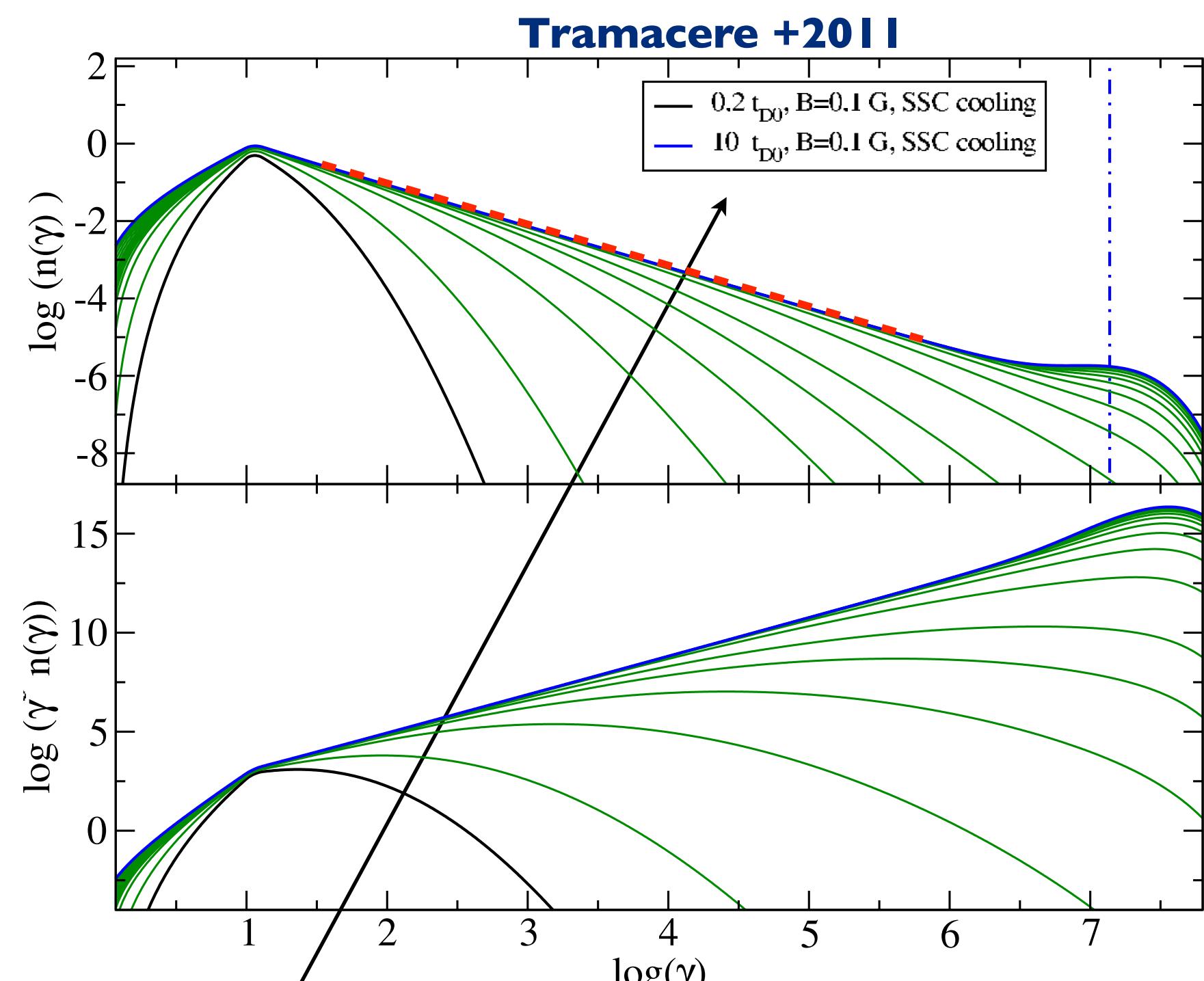
# effect of the turbulence index q and cooling

$B=1.0 \text{ G}$ ,  $t_{D0}=10^3$ ,  $R=5\times 10^{15} \text{ cm}$



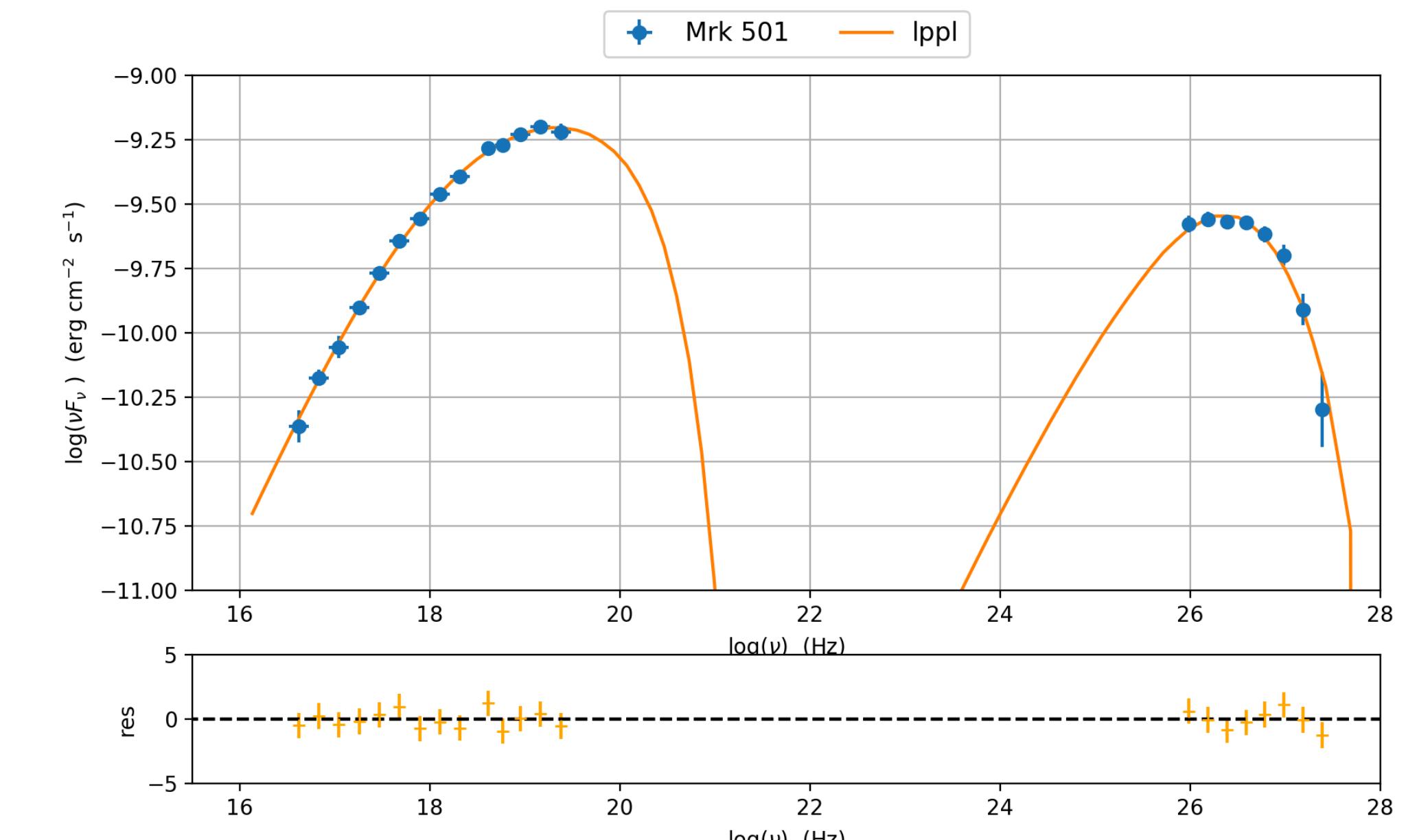
# Pile-up and hard spectra

$q=2$ ,  $R=10^{15}$  cm,  $B=0.1$  G,  $t_{\text{inj}}=t_D=10^4$  s



$s$  in agreement with  $s = 1 + \frac{t_{acc}}{2t_{esc}}$

Mrk 501 1997



Massaro & Tramacere +2006

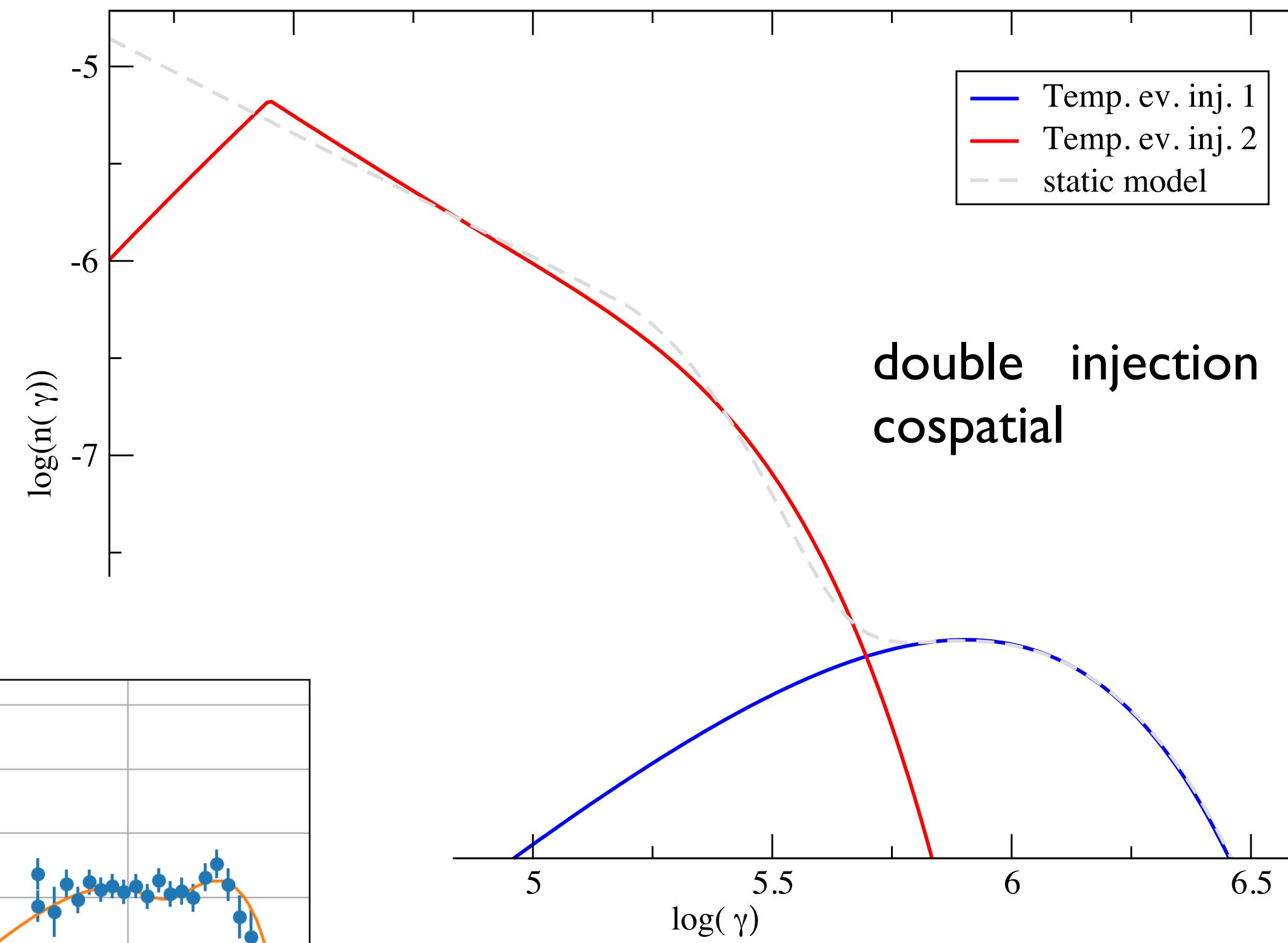
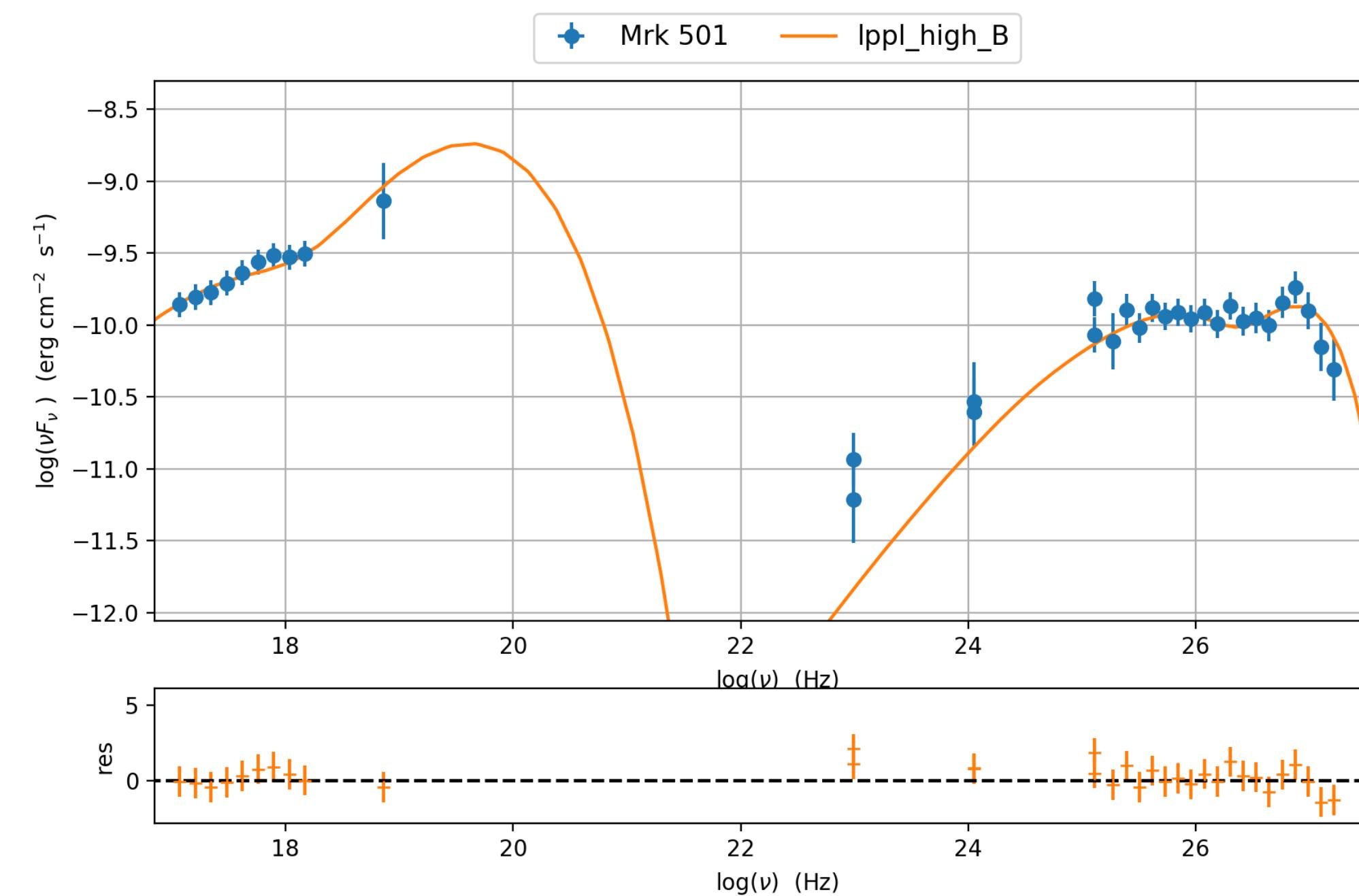
$s \sim 1.6$

$r \sim 0.7-0.8 \ll r_{eq} \sim 6$

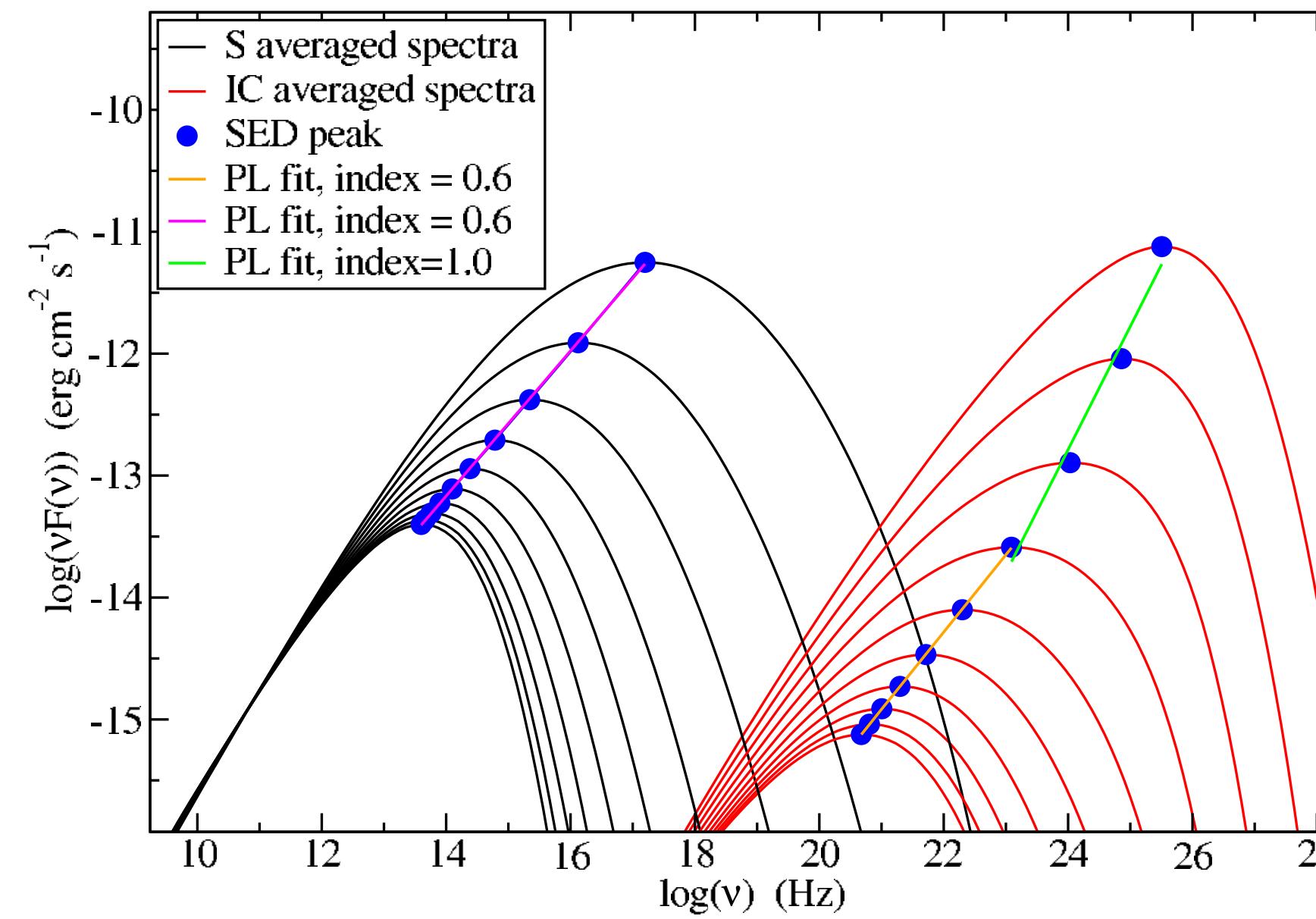
$s \ll s_{FI} \sim 2.3$

# Pile-up and hard spectra

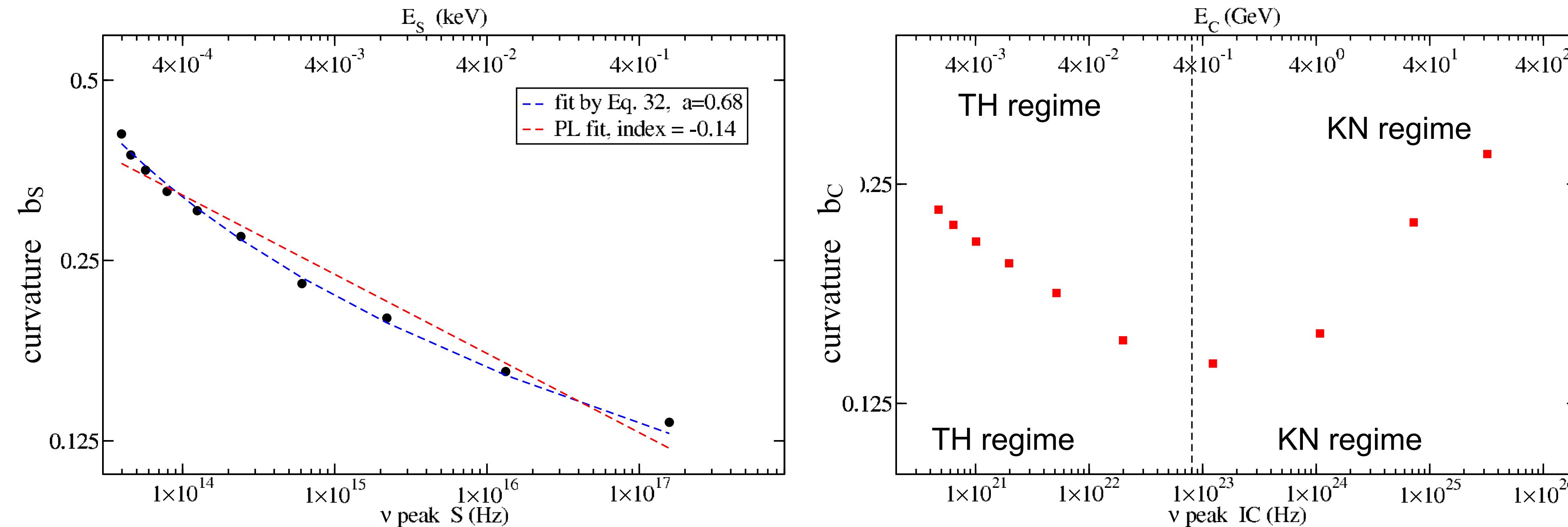
Mrk 501 2014 Flare  
MAGIC paper  
A&A 637, A86 (2020)



## S vs IC

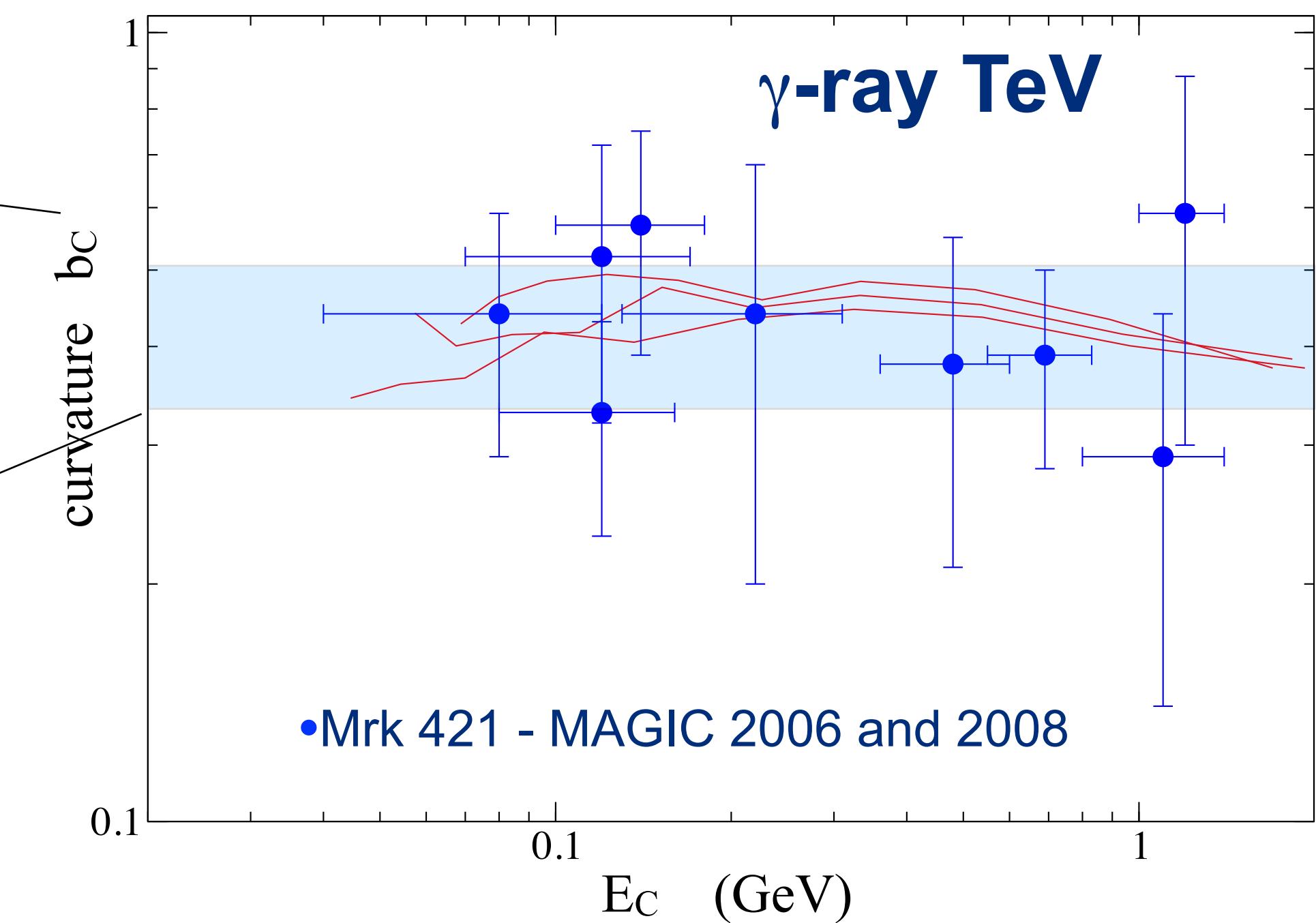
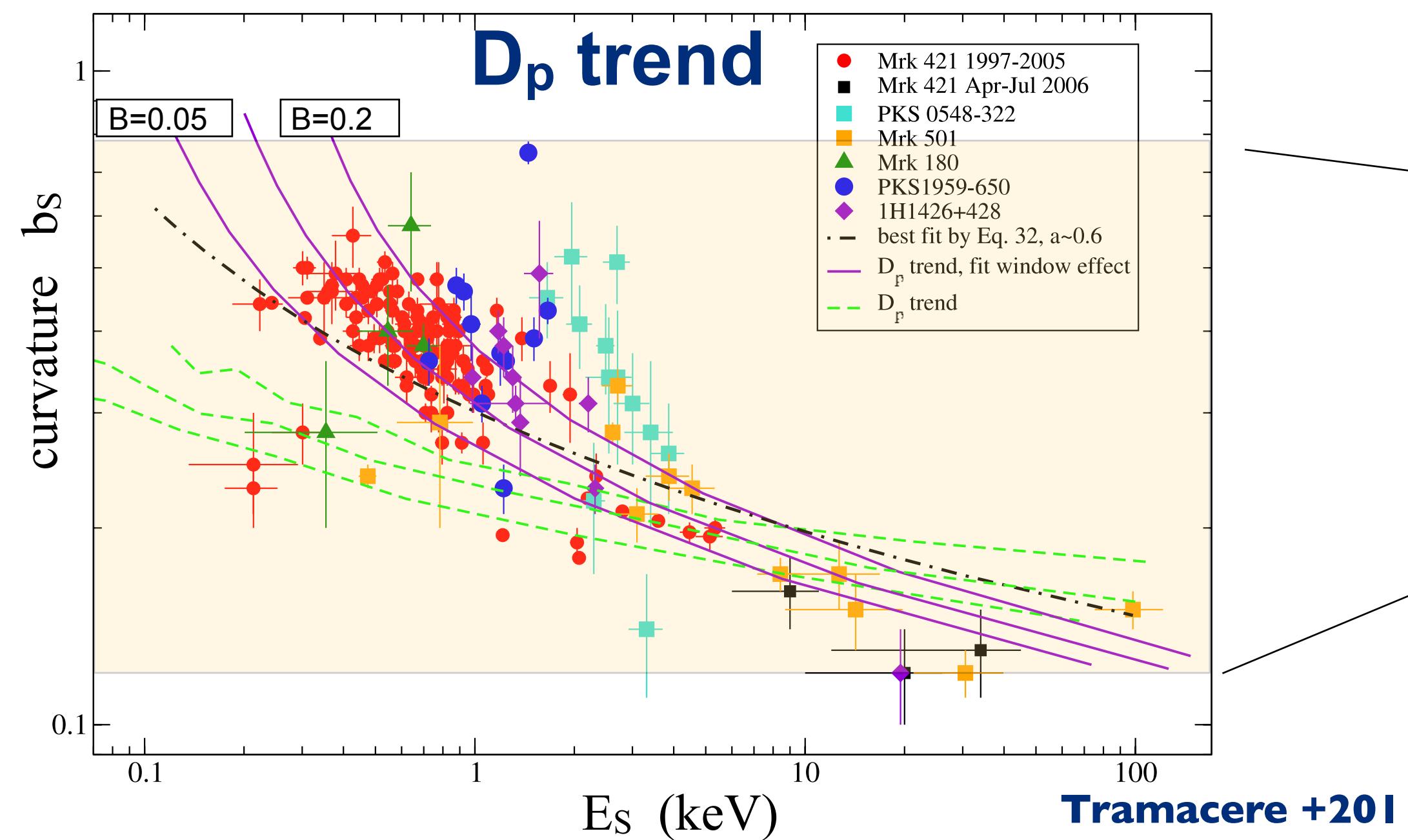


Tramacere +2011



	<b>Acceleration dominated</b>	<b>Equilibrium</b>
<b>curvature trend</b>	<b>curvature decreasing trend <math>b-E_p</math></b>	<b>curvature stable or increasing (<math>r \sim 7, b \sim 1.3</math>)</b>
<b>spectral shape</b>	<b>LPPL or LP</b>	<b>PL+exp-cutoff or Maxwellian</b>

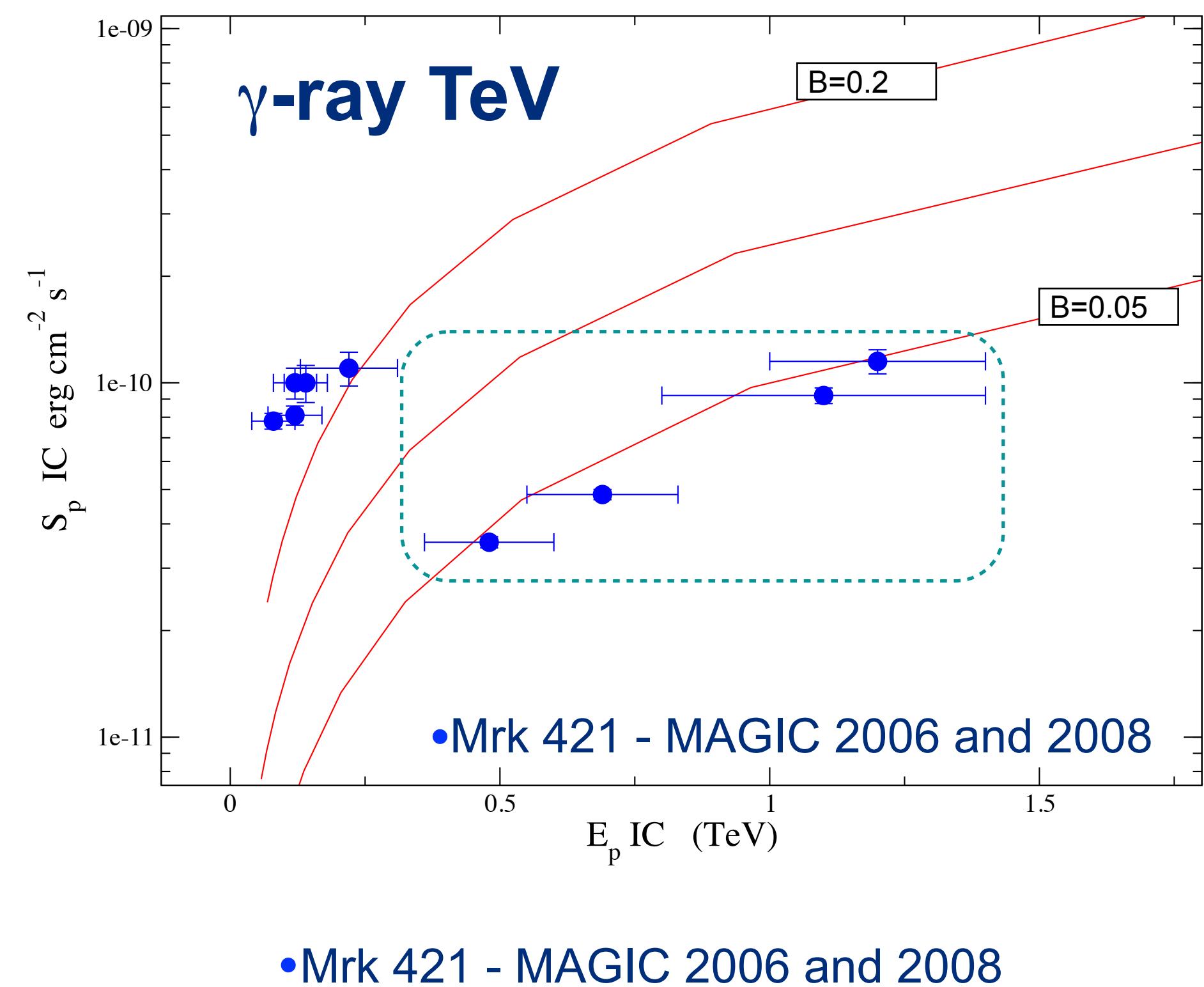
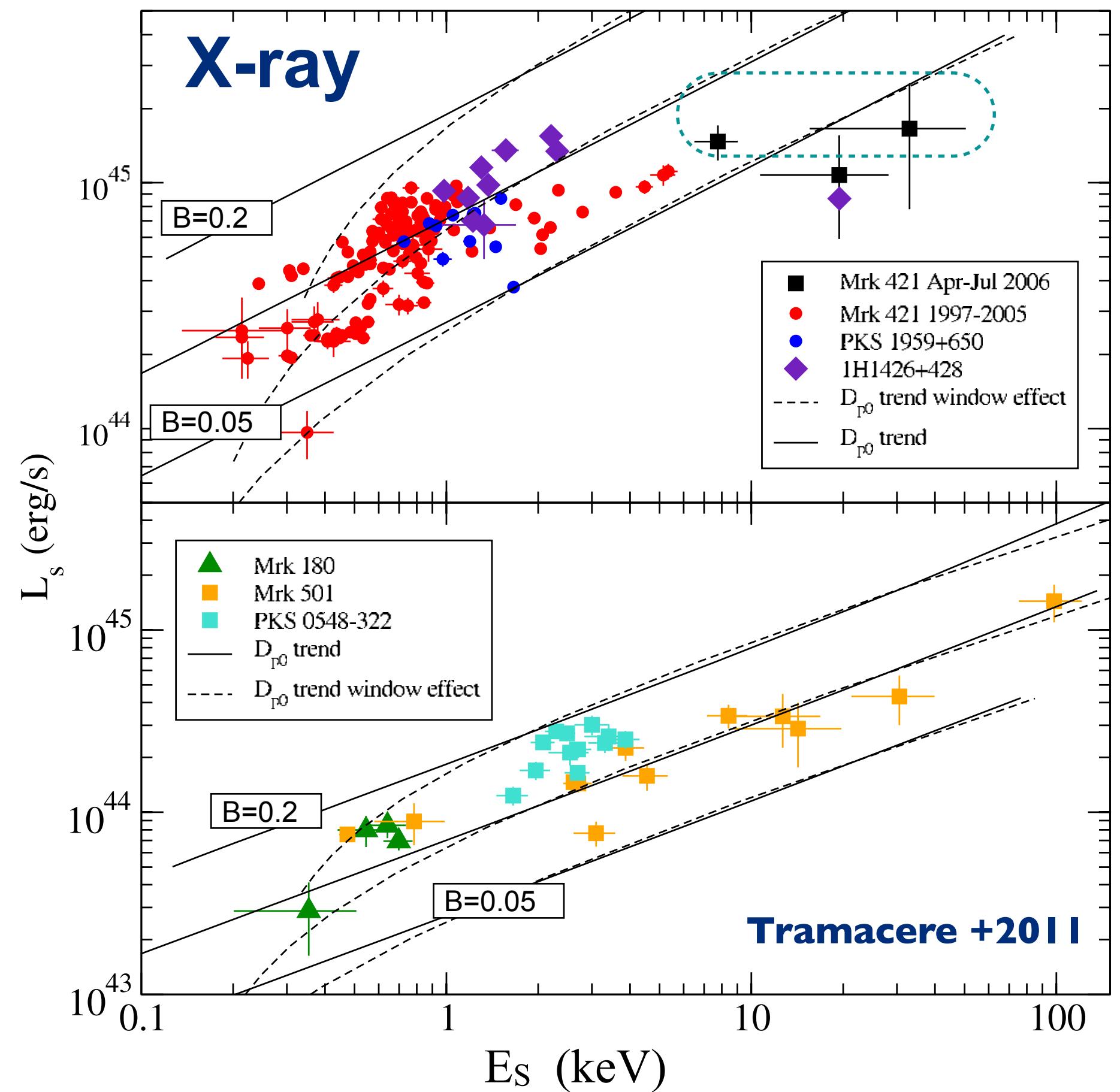
# $E_s$ - $b_s$ X-ray trend and $\gamma$ -ray predictions



- data span **13 years**, both flaring and quiescent states
- We are able to reproduce these long-term behaviours, by changing the value of only one parameter ( $D_p$ )
- for  $q=2$ , curvature values imply distribution far from the equilibrium ( $b \sim [1.0-0.7]$ )
- More data needed at GeV/TeV, curvature seems to be cooling-dominated
- Similar trend observed in GRBs (Massaro & Grindlay 2001)

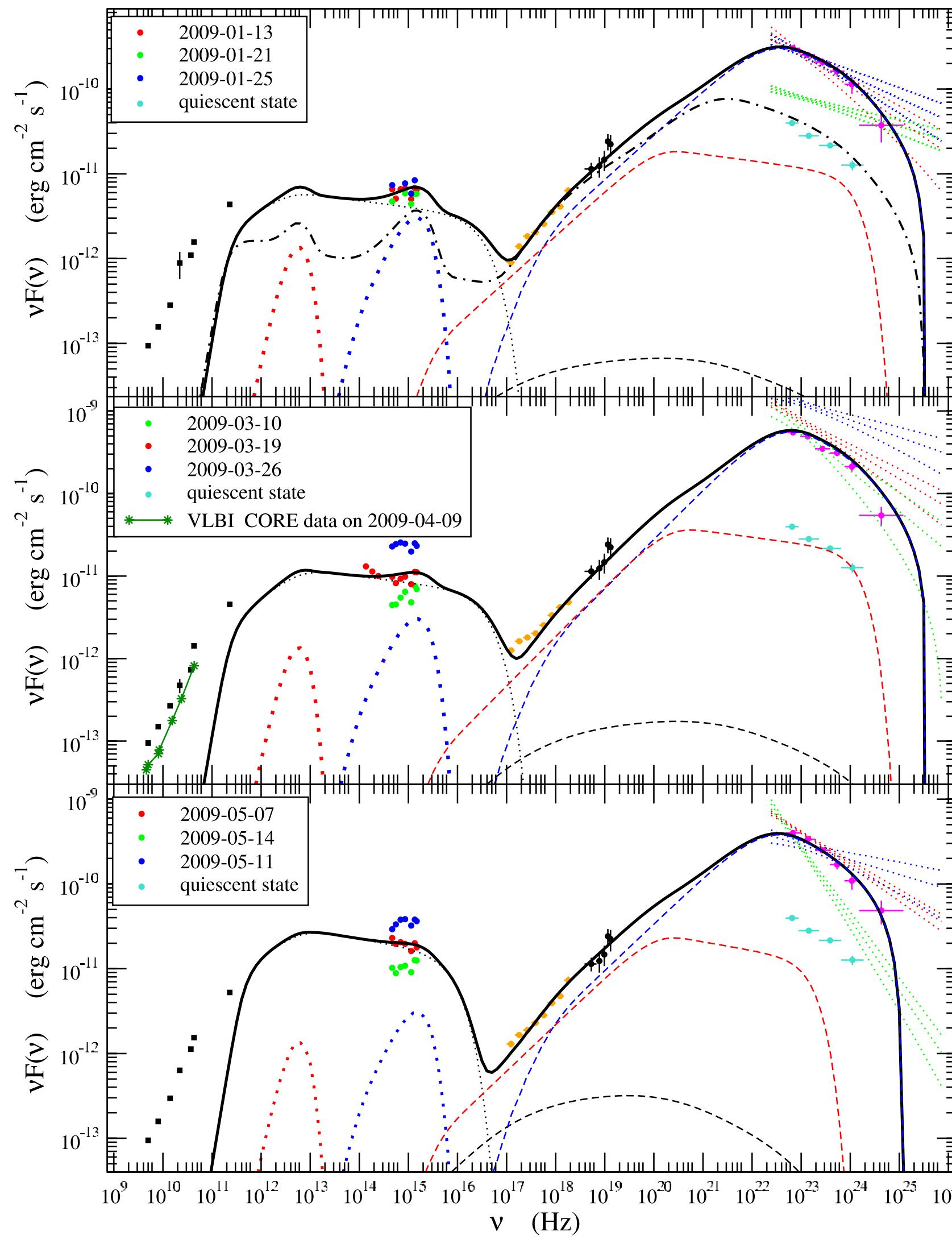
$L_{\text{inj}} (E_s - b_s \text{ trend})$ (erg s $^{-1}$ )	$5 \times 10^{39}$
$L_{\text{inj}} (E_s - L_s \text{ trend})$ (erg s $^{-1}$ )	$5 \times 10^{38}, 5 \times 10^{39}$
$q$	2
$t_A$ (s)	$1.2 \times 10^3$
$t_{D_0} = 1/D_{P0}$ (s)	$[1.5 \times 10^4, 1.5 \times 10^5]$
$T_{\text{inj}}$ (s)	$10^4$
$T_{\text{esc}}$ ( $R/c$ )	2.0

# $E_s$ - $L_s$ X-ray trend and $\gamma$ -ray predictions



- the  $E_s$ - $S_s$  ( $E_s$ - $L_s$ ) relation follows naturally from that between  $E_s$  and  $b_s$
- the low  $L_{\text{inj}}$  objects (Mrk 501 vs Mrk 421) reach a larger  $E_s$ , compatibly with larger  $\gamma_{\text{eq}}$
- Mrk 421 MAGIC data on 2006 match very well the Synchrotron prediction with simultaneous X-ray data
- the average index of the trend  $L_s \propto E_s^\alpha$  with  $\alpha \sim 0.6$ , is compatible with the data, and with a scenario in which a typical constant energy ( $L_{\text{inj}} \times t_{\text{inj}}$ ) is injected for any flare (jet-feeding problem), whilst the peak dynamic is ruled by the turbulence in the magnetic field.



**PSK 1510-089 Abdo+ 2010****Dammando+ 2012**