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spectral curvature in TeV blazars: physical insight on stochastic acceleration

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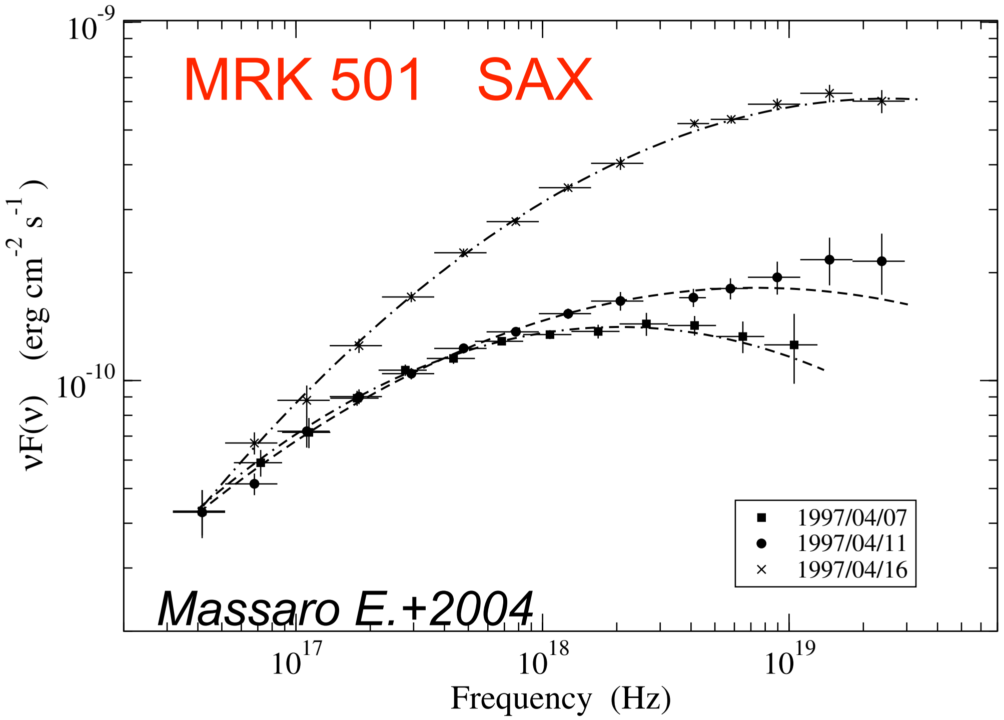
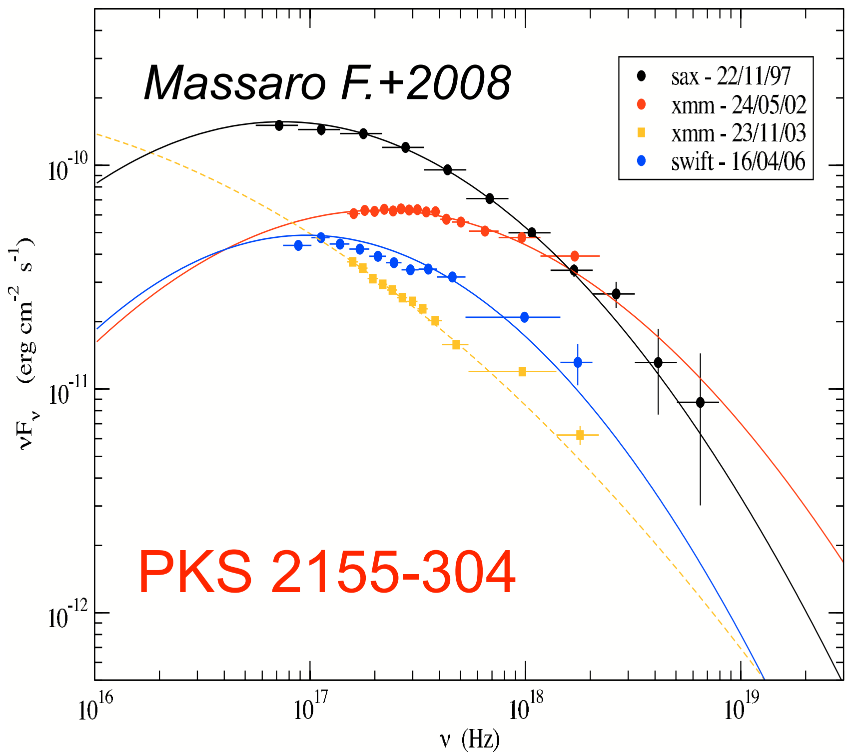
Half a Century of Blazars and Beyond

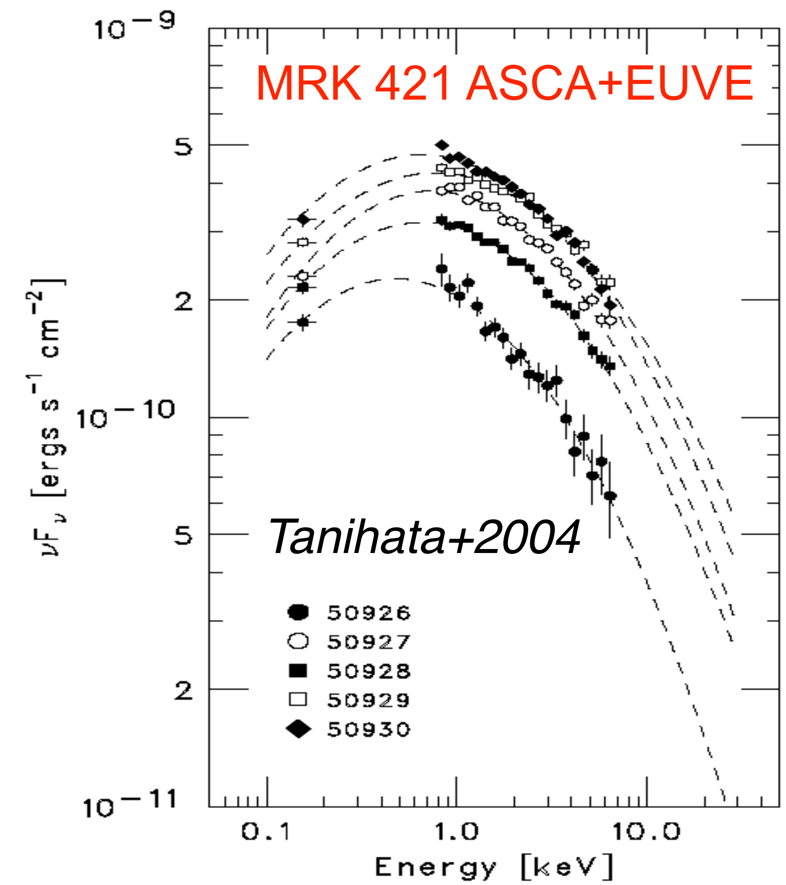
Turin

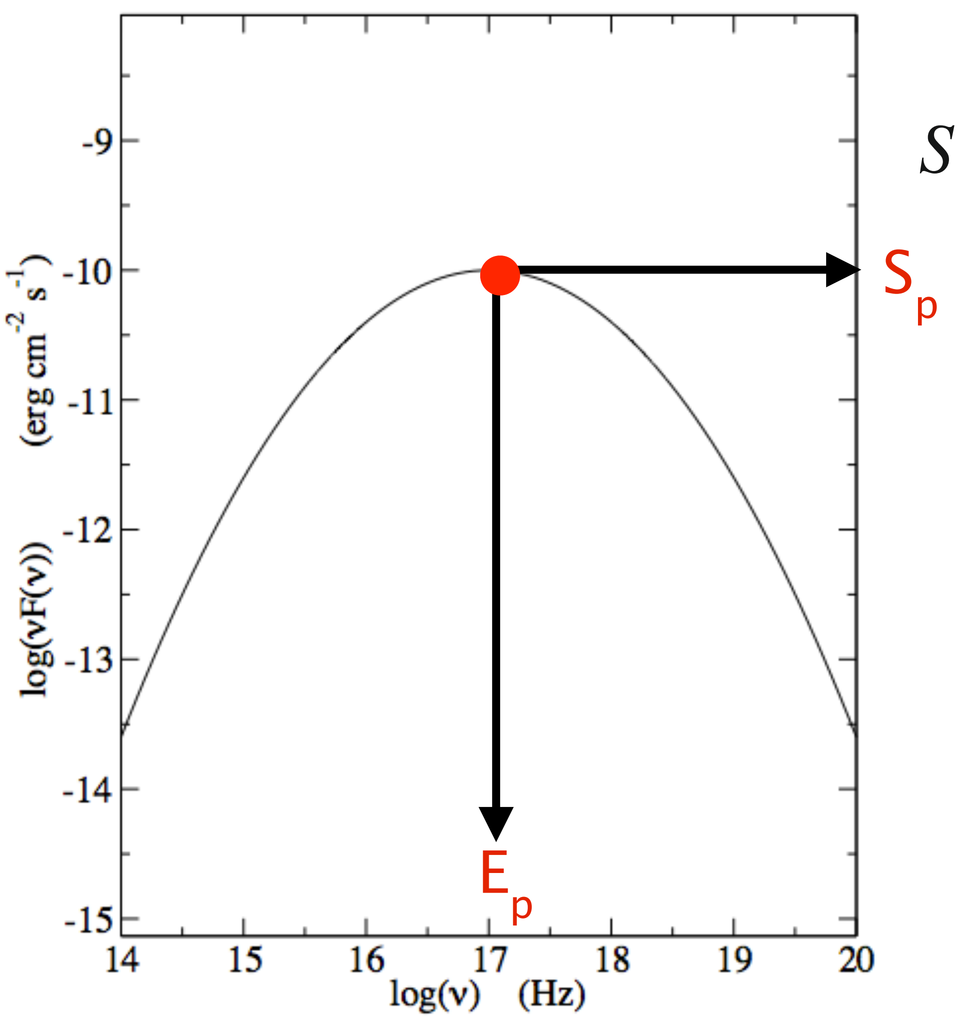
11-15 June 2018

LP SPECTRAL DISTRIBUTION OF HBLs



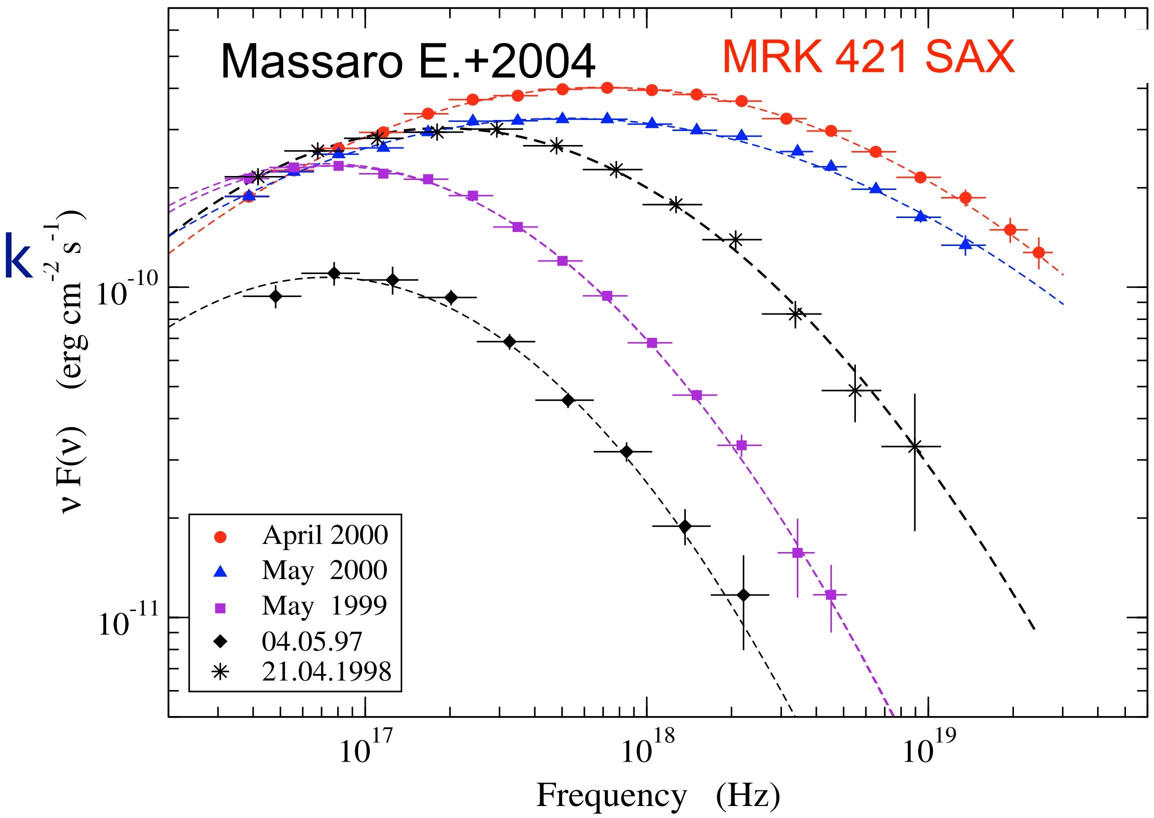






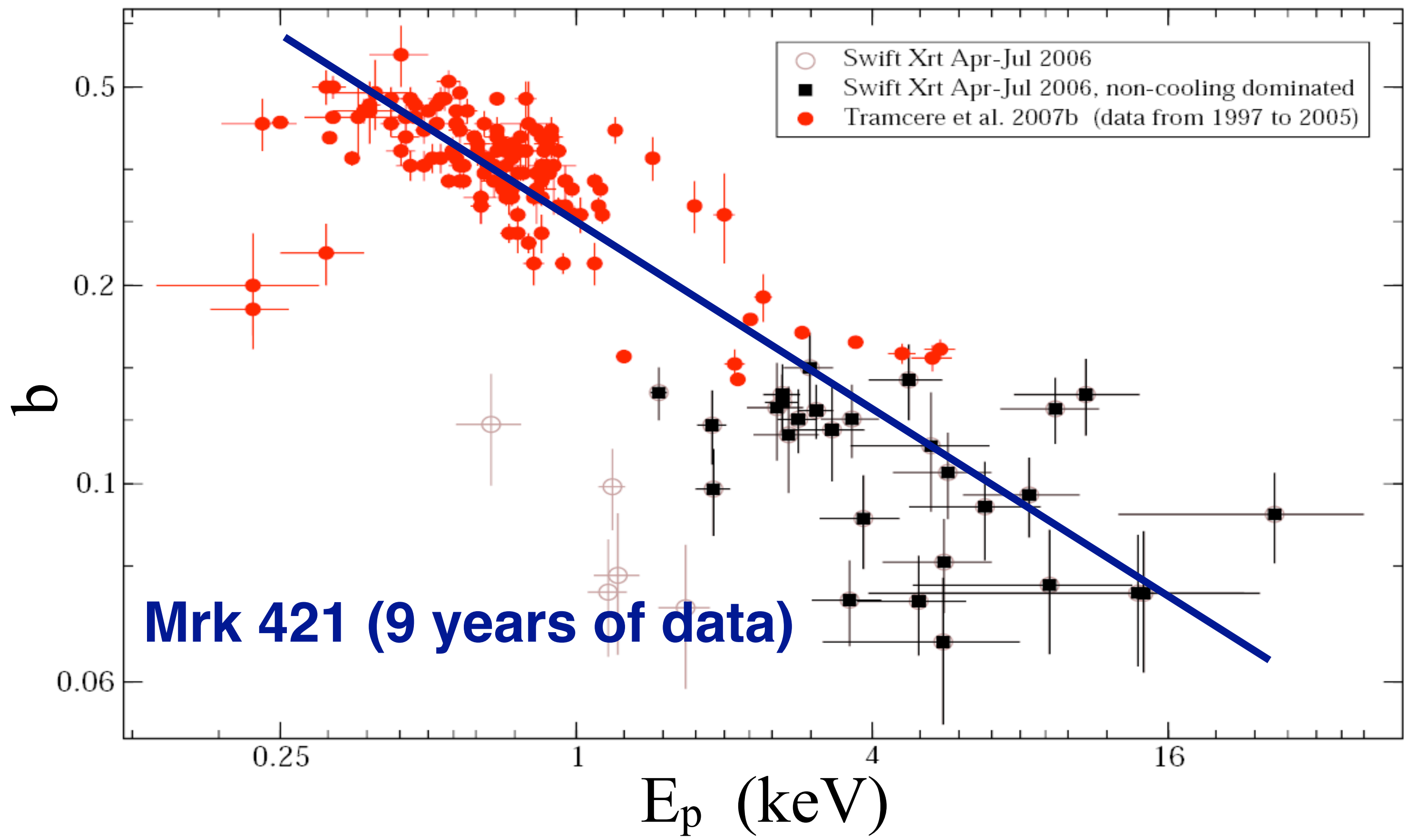
$$S(E) = S_{\mathrm{p}}\, 10^{-b\,(\log(E/E_{\mathrm{p}}))^2}$$

- b: curvature at peak
- E_p: peak energy
- S_p: SED height @ E_p

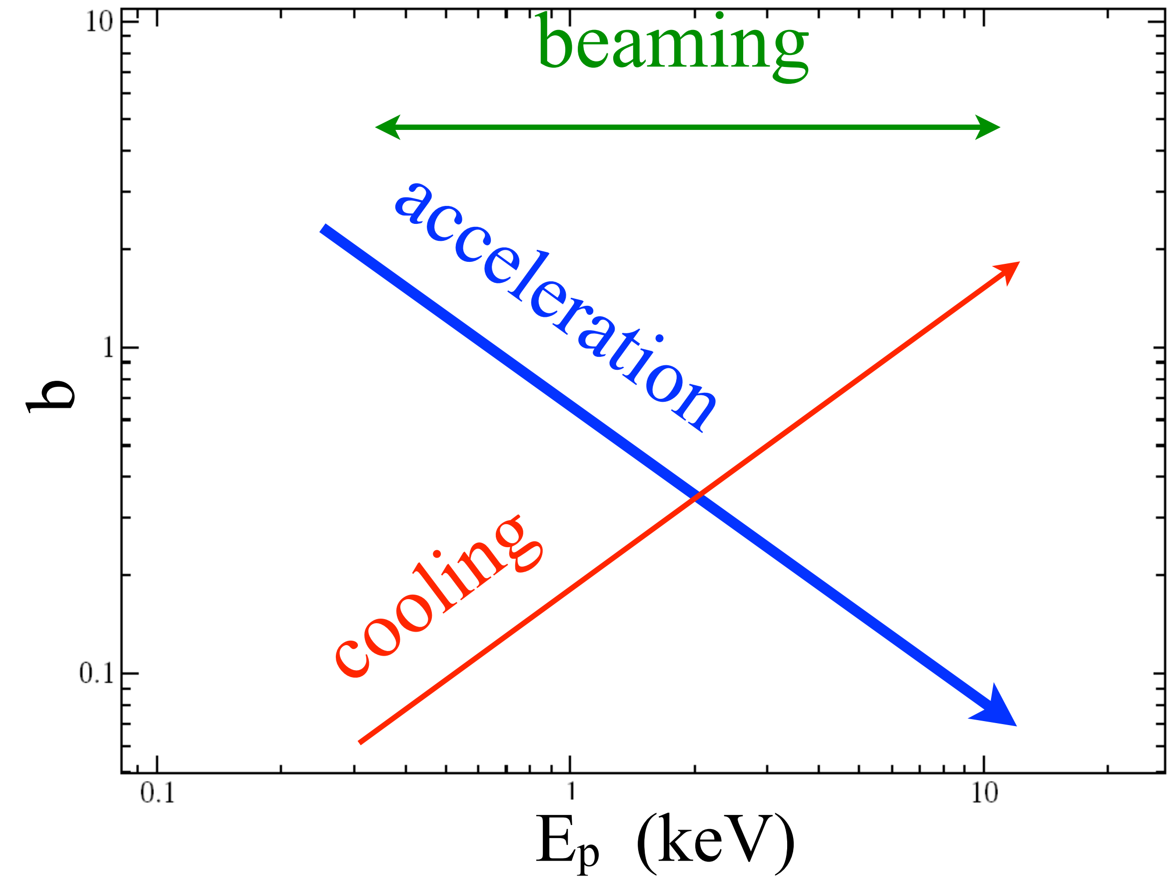


acceleration signature in the E_S-vs-b trend

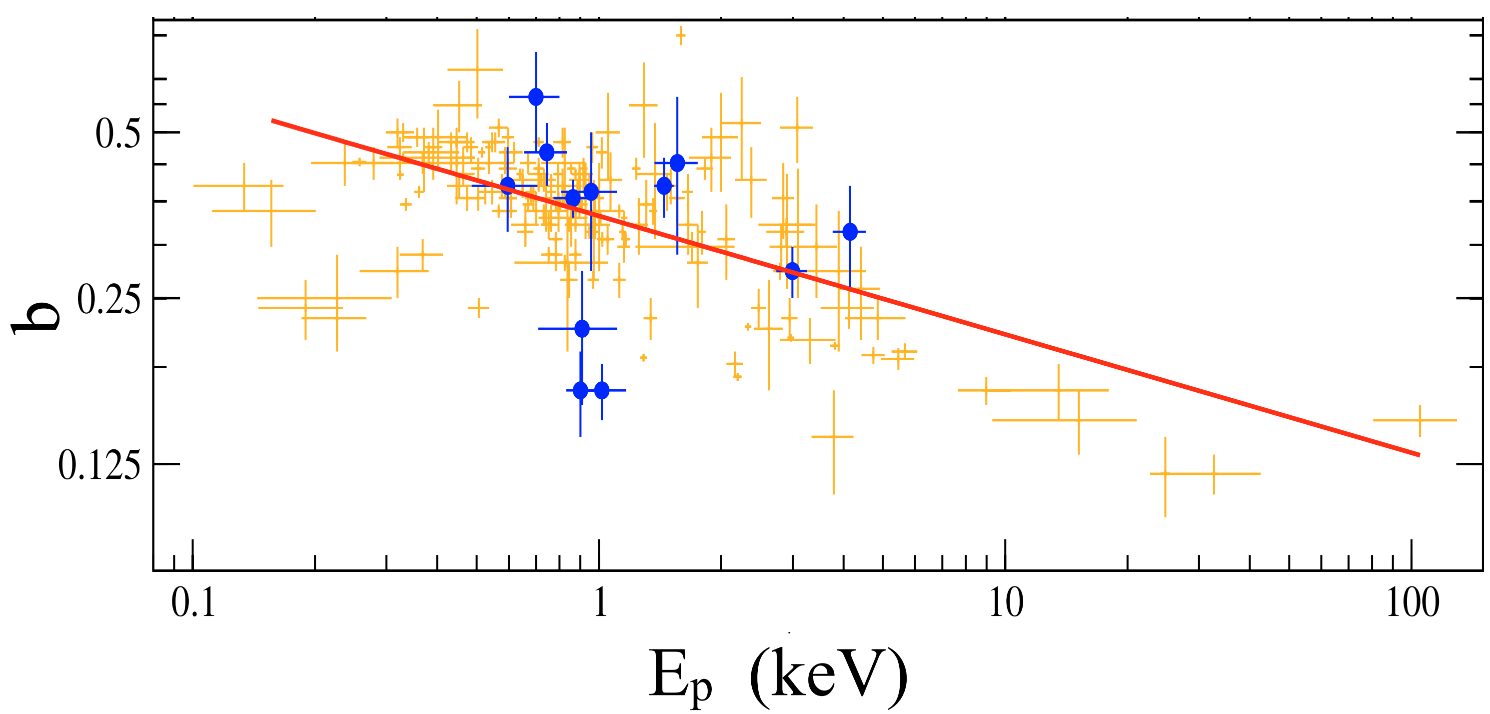
Tramacere+2007,2009



Ep-vs-b, different scenarios



Massaro F.+2008

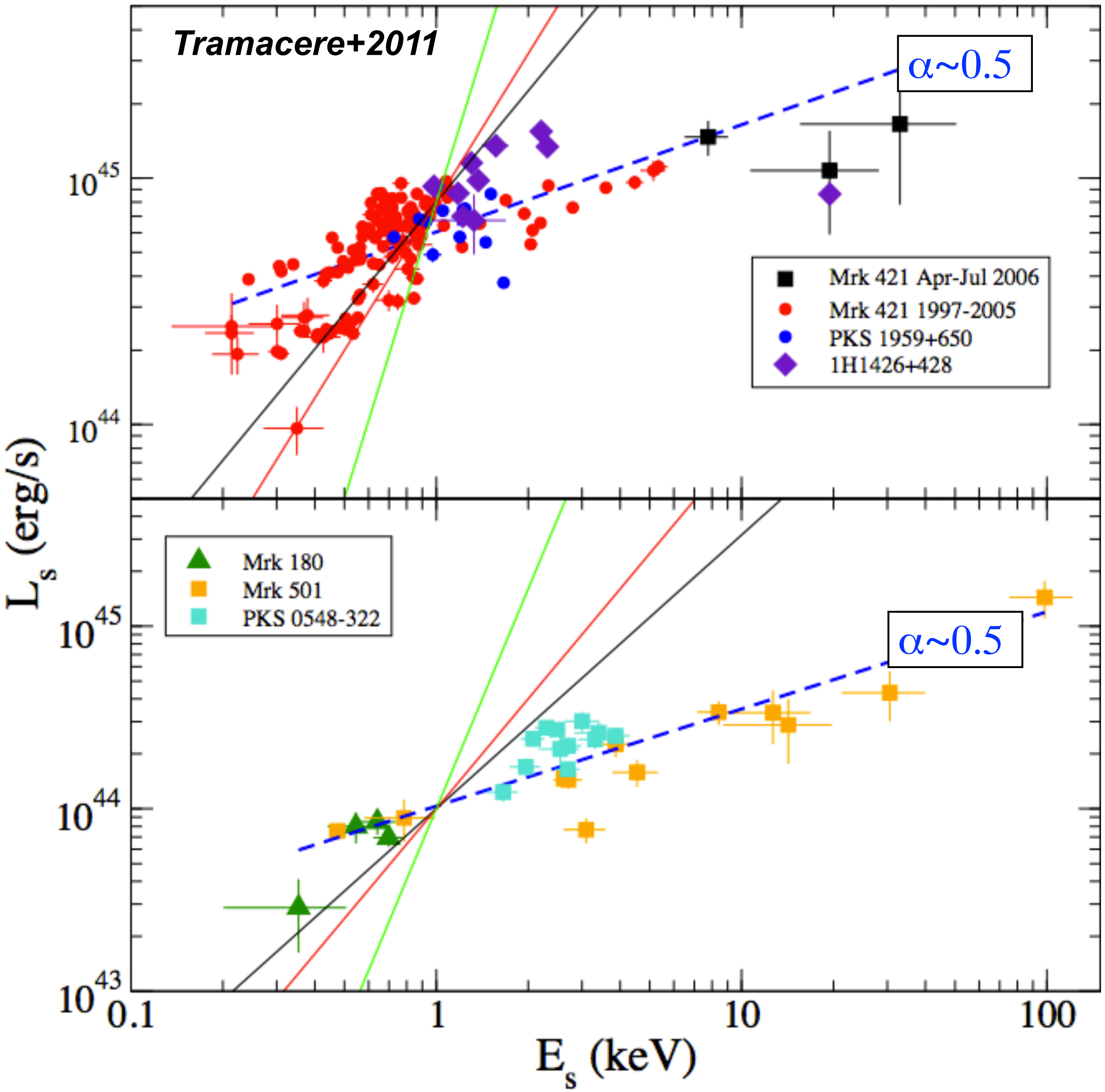


11 years of data:
PKS 0548-322,1H1426+418,
Mrk 501 ,1ES1959+650,
PKS2155-34

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

acceleration signature in the E_S-vs-L_s trend

long-trend main drivers



•γ_{3p}↑ **and n(γ3p)**↓ **=>** $\alpha<1.5$
acceleration+energy conservation

•B–>α=2.0, incompatible as
•δ–>α=4 long-trend main driver

The log-parabola origin:
physical insight

log-parabola is not a “new" model...

KARDASHEV 1962

At first, for simplicity, we consider the effect of each process viewed separately on the energy spectrum, and then the simultaneous effect of two or more processes.

Spectra of Isolated Processes

1. Random and Systematic Acceleration.

The kinetic equation is

$$\frac{\partial N}{\partial t} = \alpha_1(t)\frac{\partial}{\partial E}\left(E^2\frac{\partial N}{\partial E}\right) - \alpha_2(t)\frac{\partial}{\partial E}(EN).$$

Let the energy distribution be specified, at each instant of time t_0, by the δ-function in the neighborhood of energy E_0:

$$N(E, 0) = N_0\delta(E - E_0)$$

and

$$\int_0^\infty N(E, 0)\,dE = N_0.$$

Then, utilizing the techniques developed, e.g.,in [13], we may find that

$$N(E, t) = \frac{N_0}{\sqrt{\pi}E2\sqrt{a_1}}e^{-\left(\ln\frac{E_0}{E}+a_1+a_2\right)^2 / 4a_1}, \quad (1)$$

where

$$a_1 = \int_{t_0}^t \alpha_1(t)\,dt, \qquad a_2 = \int_{t_0}^t \alpha_2(t)\,dt.$$

increases c
The quanti
to expansi
the quanti
sistently p
creasing E
and conve
correspond
For th
= $KE_0^{-\gamma}$ is
$E_{min} \leq E_0$
initial con

$$\int_{E_{min}}^{E_{max}} K$$

=

where

x

At E_{max}

log-parabola is not a “new" model...

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

analytical solution for:

$D_p \sim \gamma^q$, $q=2$

“hard-sphere” case

Melrose 1968,

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

The origin of the log-parabolic shape: statistical derivation

fluctuation

$$\varepsilon = \bar{\varepsilon} + \chi$$

systematic

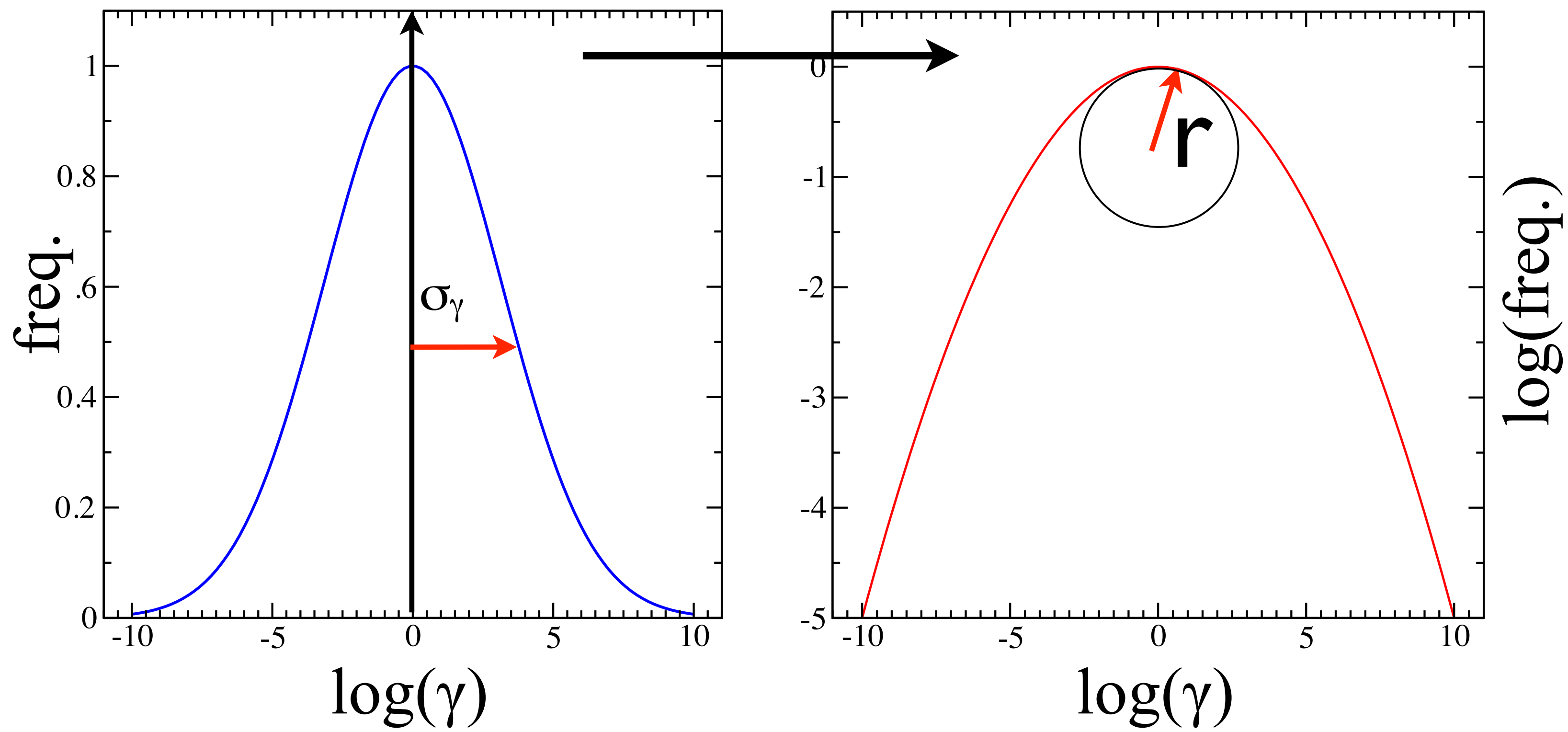
ε_i **is a R.V.**

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

C.L. Theorem
multipl. case

log-normal distribution

Log-Parabolic representation



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

Tramacere+2011

statistical approach

$$n(\gamma) = \frac{N_0}{\gamma \sigma_\gamma \sqrt{(2\pi)}} \exp\left[\frac{-\left(\ln(\gamma/\gamma_0) - n_s\left[\ln\bar{\varepsilon} - \frac{1}{2}(\sigma_\varepsilon/\bar{\varepsilon})^2\right]\right)^2}{2n_s(\sigma_\varepsilon/\bar{\varepsilon})^2}\right]$$

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

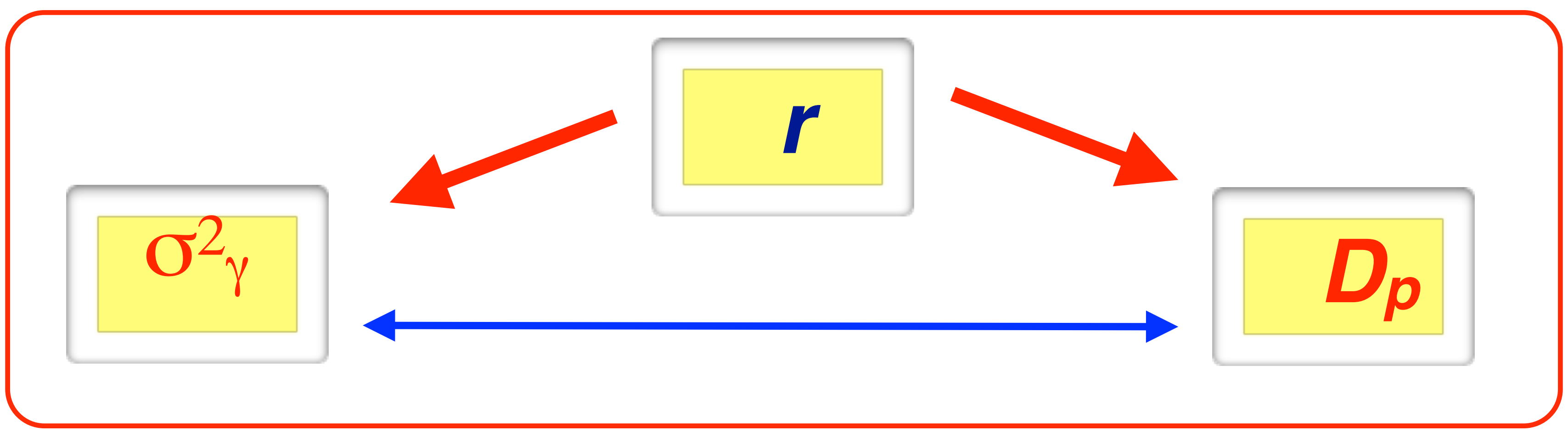
diffusion equation approach

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

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

The curvature *r* is inversely proportional to ***t=>n_s*** and ***D_p=>*** σ_ε

log-parabolic shape natural consequence of dispersion



Physical insight of the curvature:

A self-consistent approach

acc+cooling

injection term

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

systematic term

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

cooling term

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

syst. acc. term

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

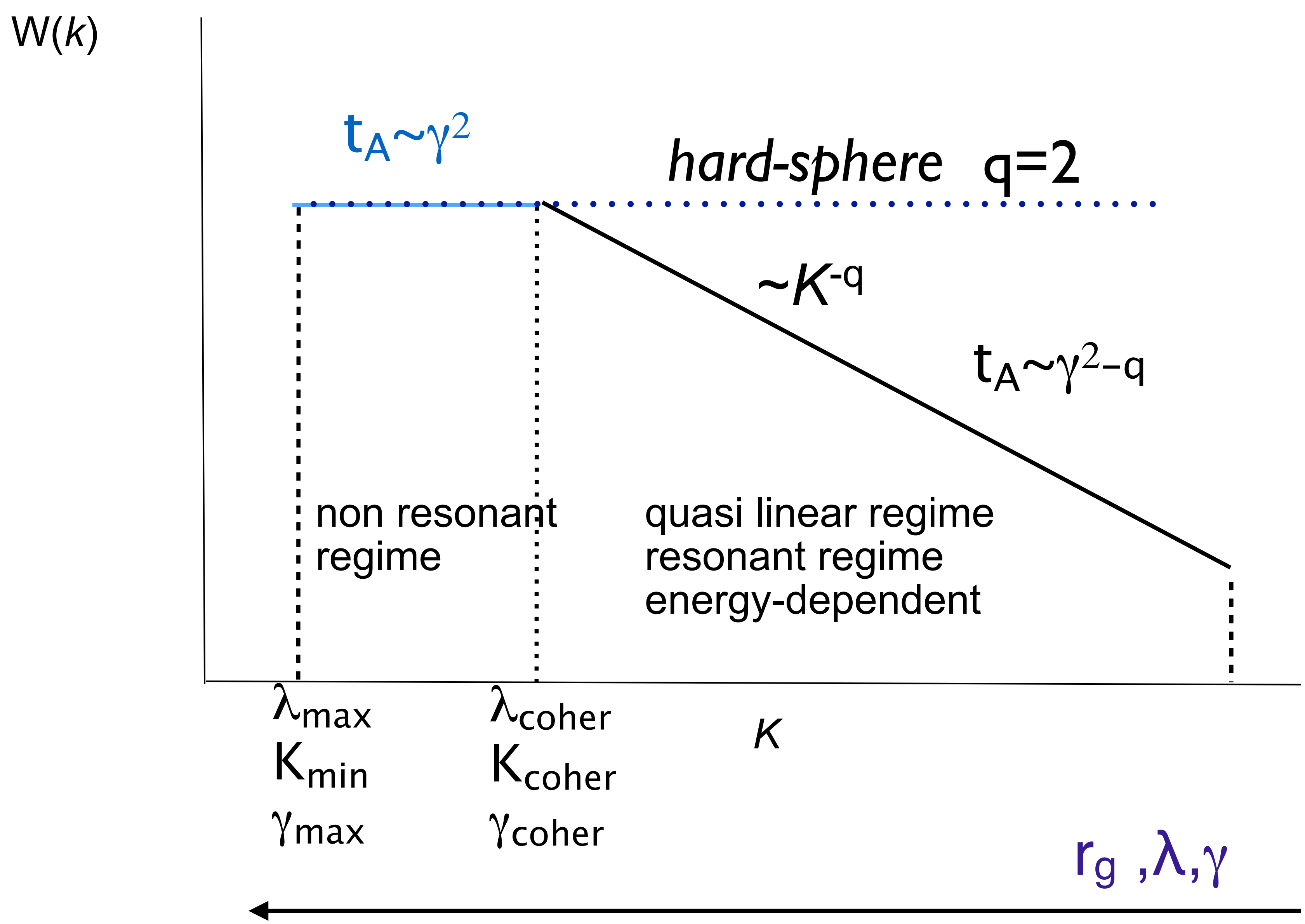
$$\frac{\partial n(\gamma, t)}{\partial t} = \frac{\partial}{\partial \gamma}\left\{ -[S(\gamma, t) + D_A(\gamma, t)]n(\gamma, t) + D_p(\gamma, t)\frac{\partial n(\gamma, t)}{\partial \gamma} \right\} - \frac{n(\gamma, t)}{T_{\rm esc}(\gamma)} + Q(\gamma, t)$$

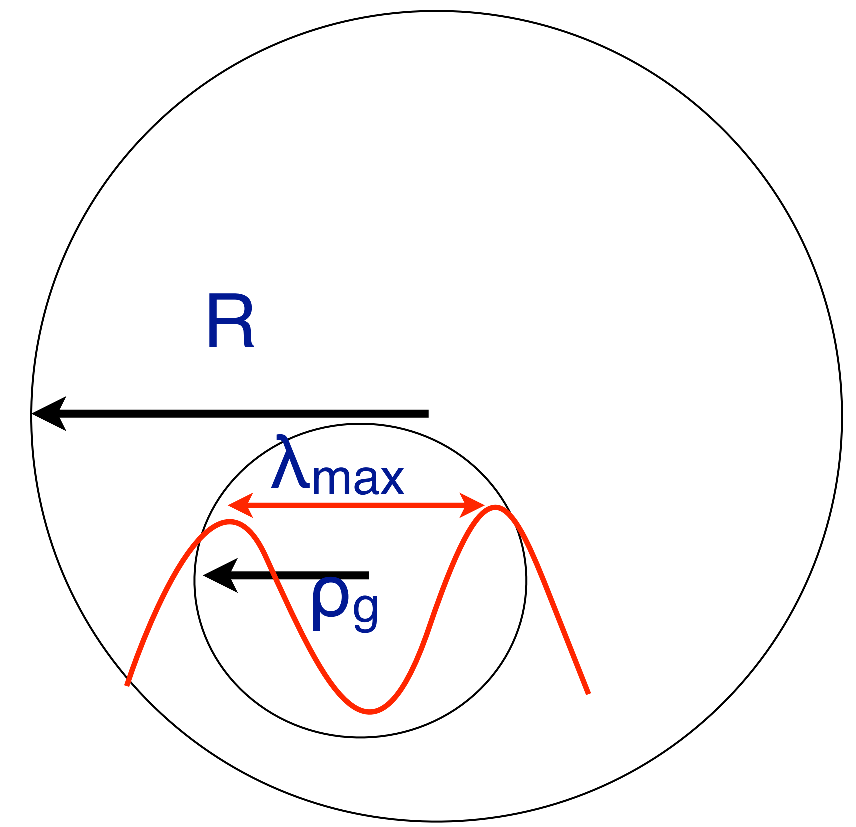
Turbulent magnetic field $\longrightarrow$ momentum diffusion term

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

$$t_D = \frac{p^2}{D_p} \approx \frac{< L > \beta_A^{-2}}{c}$$

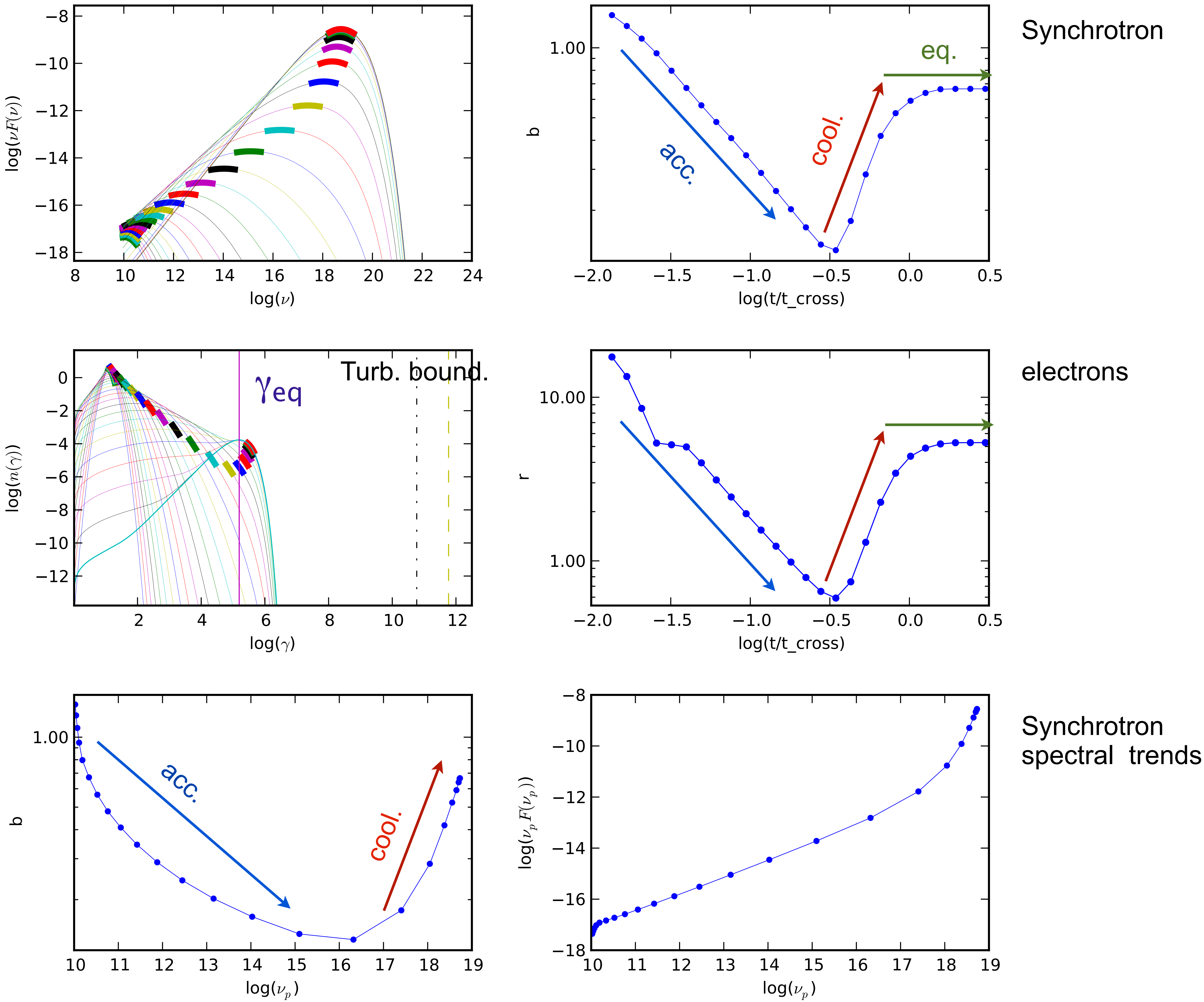
set-up of the accelerator



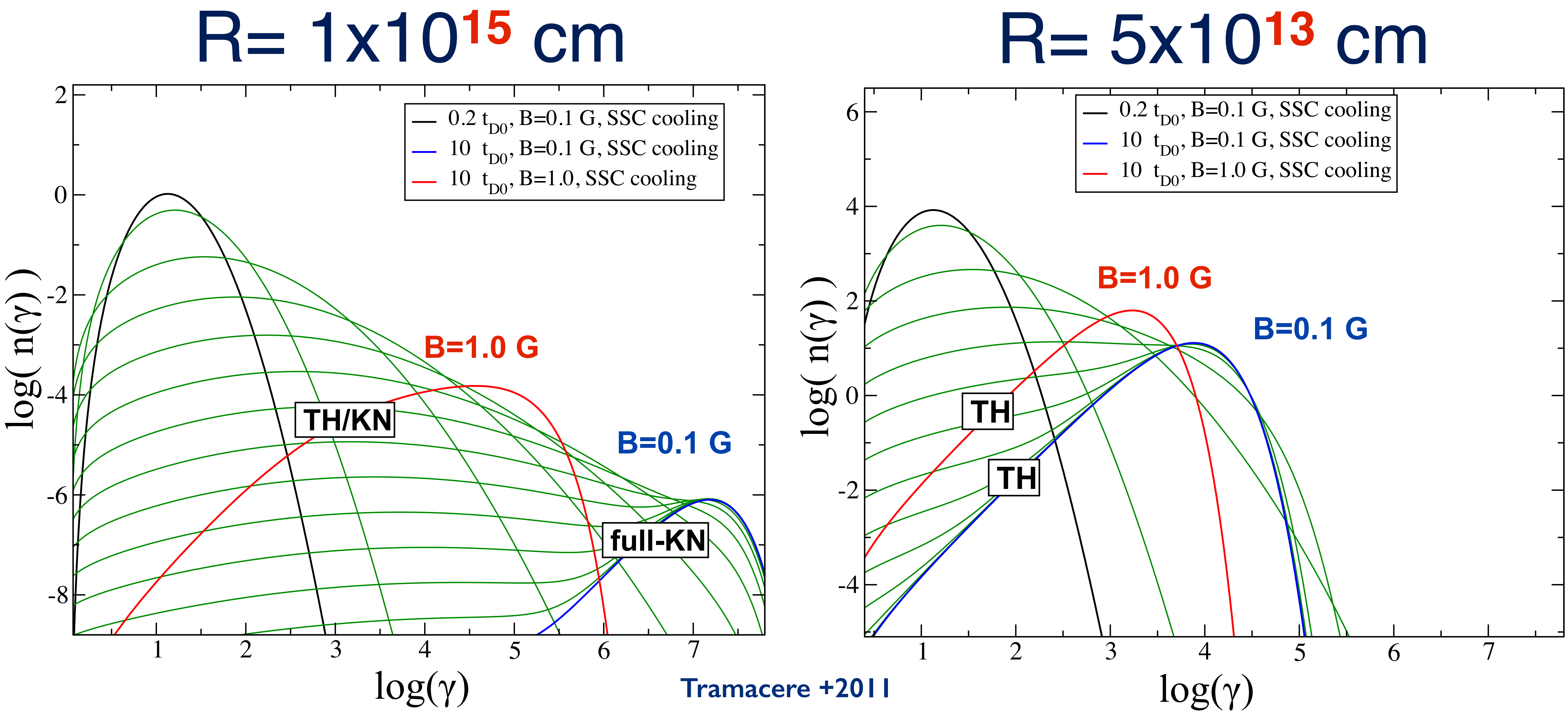


spectral trends

single flare


Synchrotron
electrons
Synchrotron
spectral trends
log(νF(ν))
log(ν)
b
log(t/t_cross)
acc.
cool.
eq.
log(n(γ))
log(γ)
γeq
Turb. bound.
r
log(ν_p)
log(ν_p F(ν_p))

IC cooling and equilibrium



U_{ph} (R= 1x10^{13} cm**) >> U_{ph} (**R= 1x10^{15} cm**)**

IC prevents higher energies in more compact accelerators (if all the parameters are the same) **Impact on rapid TeV variability!**

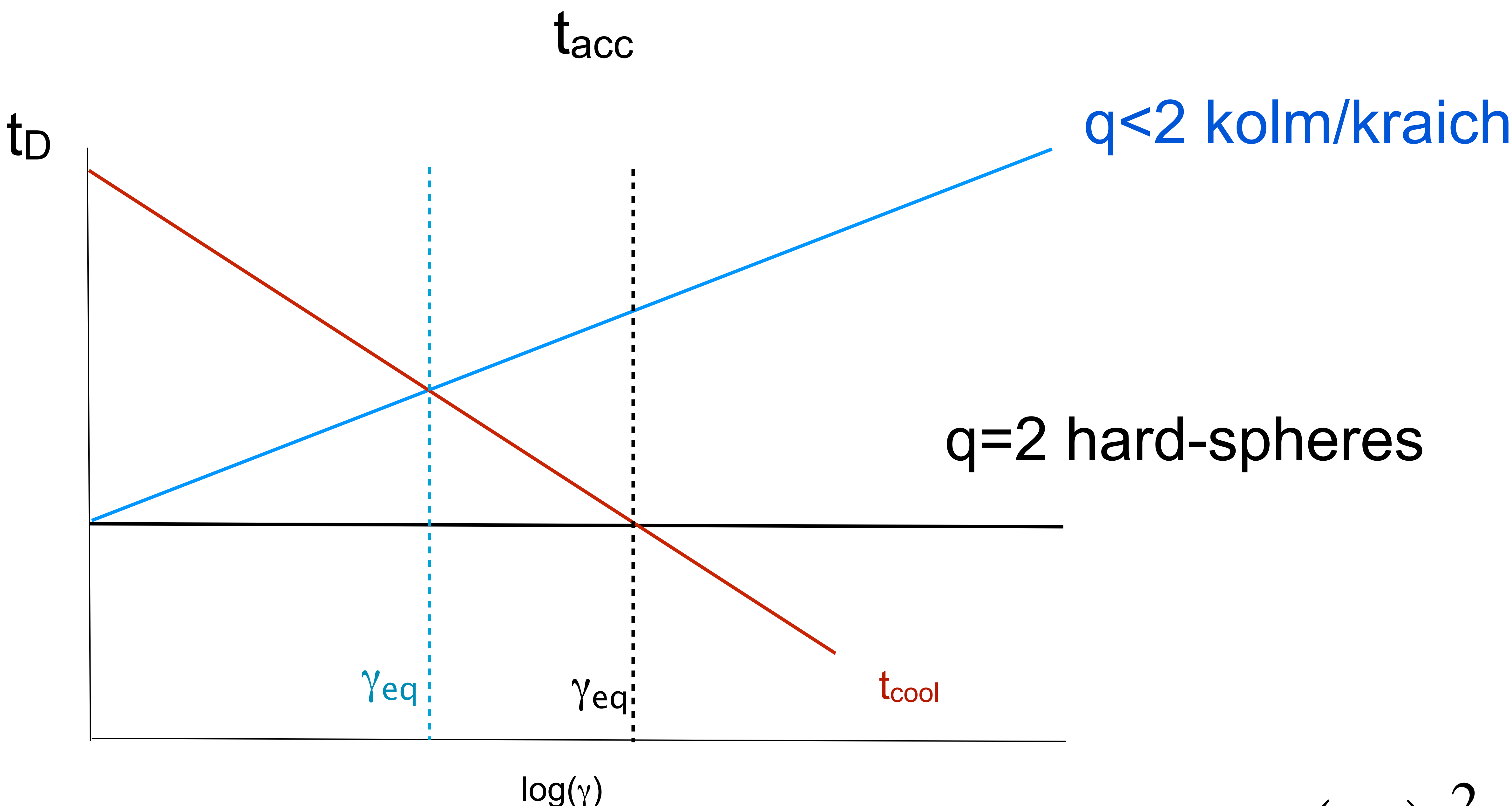
•curvature decreasing trend-> acceleration is dominating
•pure log-parabolic shape -> acceleration is dominating

system far from equilibrium

•exp cut-off shape-> system ~@equilibrium

•the equilibrium energy can change if B and t_acc are unchanged, depending on R, a smaller value of R implies a larger IC cooling, hence less energetic particles

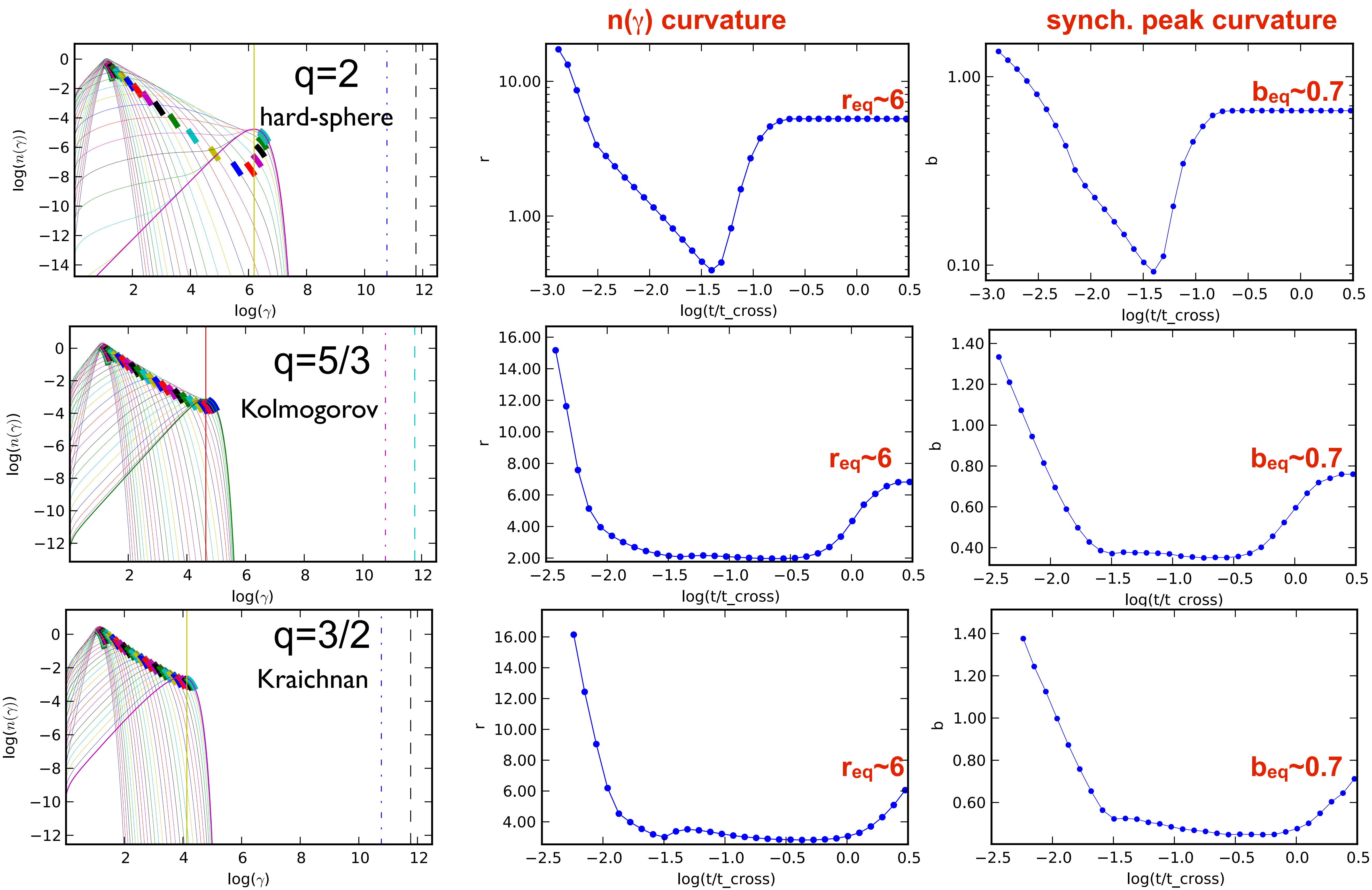
effect of the turbulence index q



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

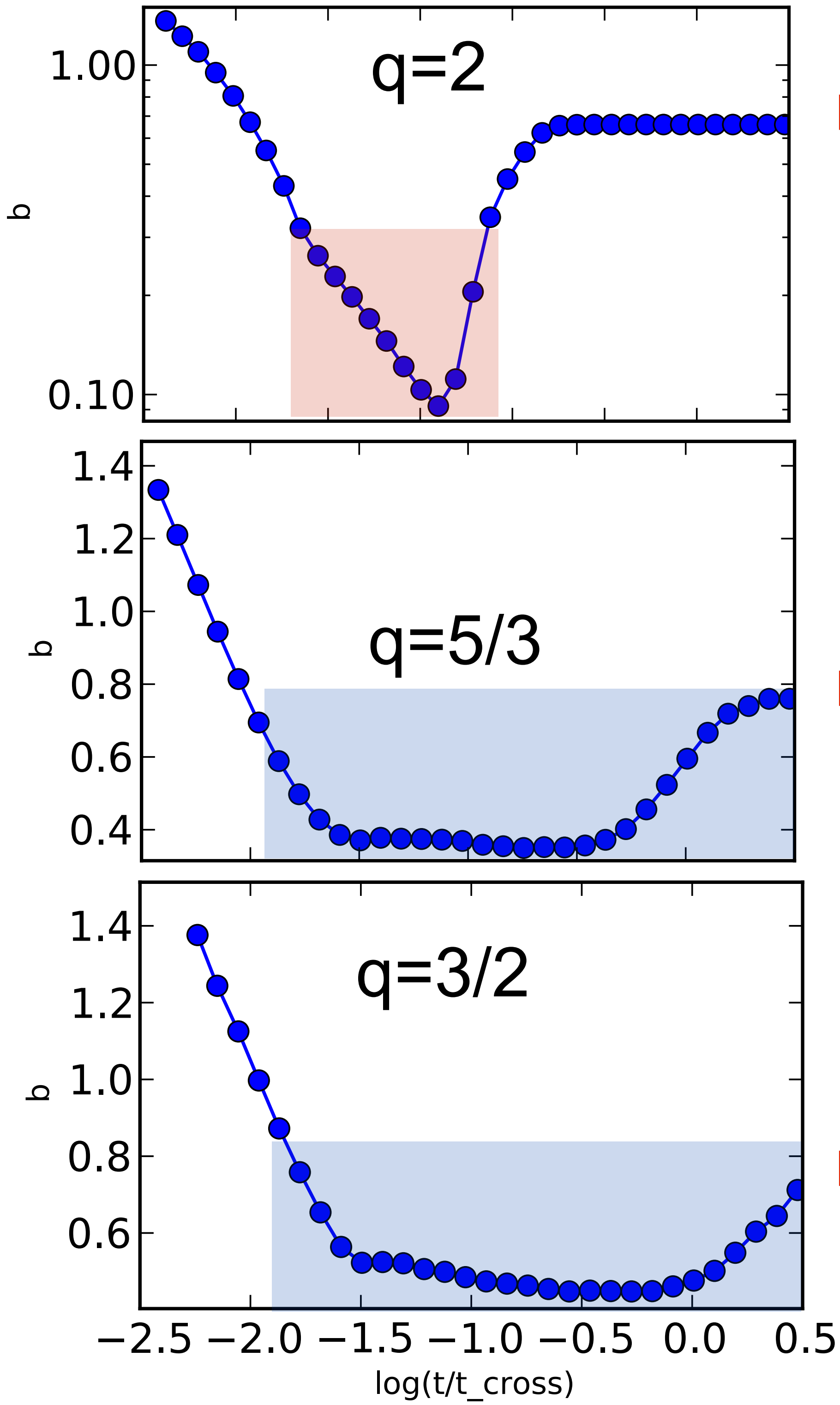
effect of the turbulence index q

B=1.0 G, $t_{D0}=10^3$, R=5x10^{15} cm



b distributions and q

synch. peak curvature

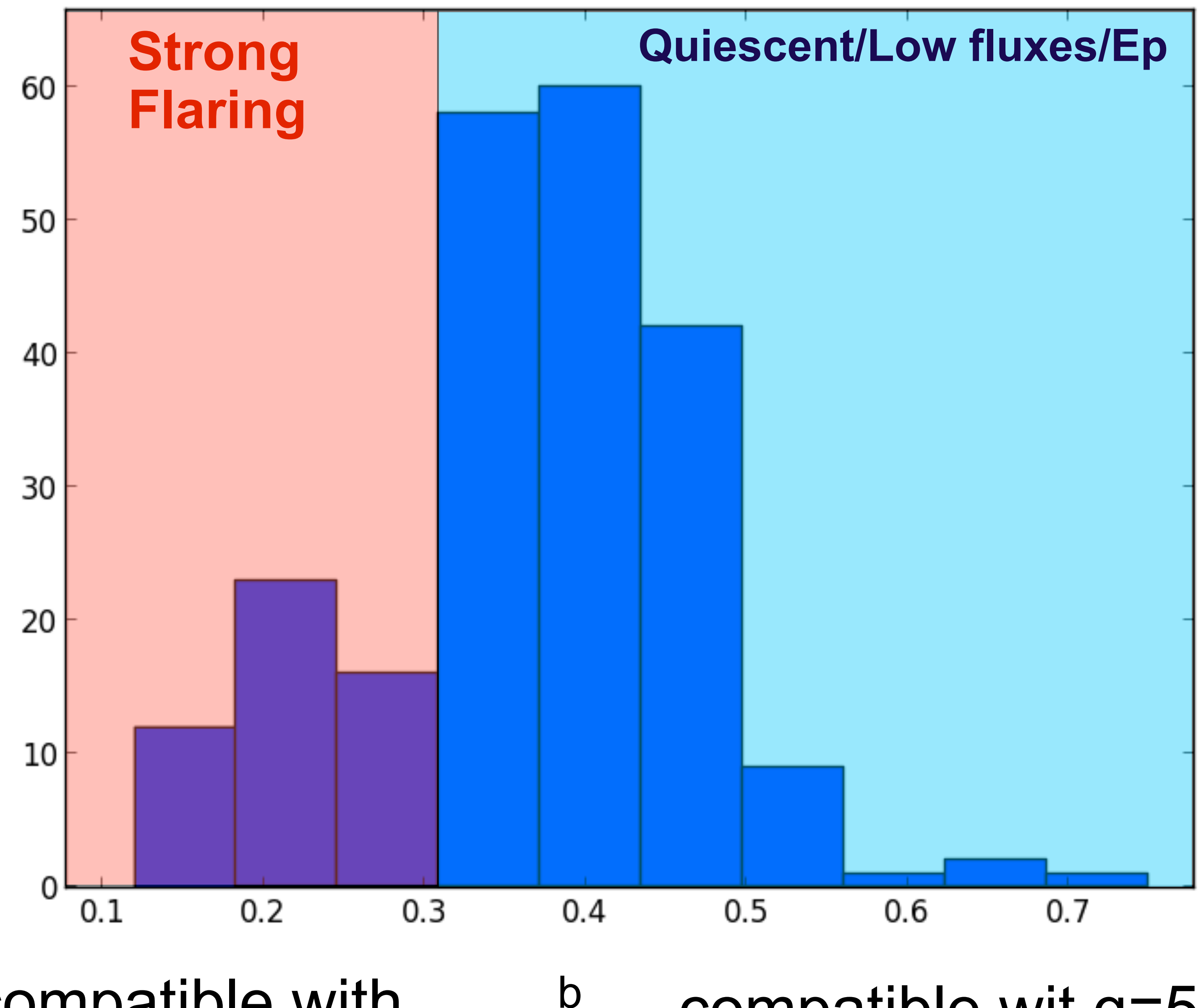


b_{eq}~0.7

b_{eq}~0.7

b_{eq}~0.7

both flaring and quiescent seem to be far from equilibrium b eq.~[0.7-1.0] (if full KN or S)



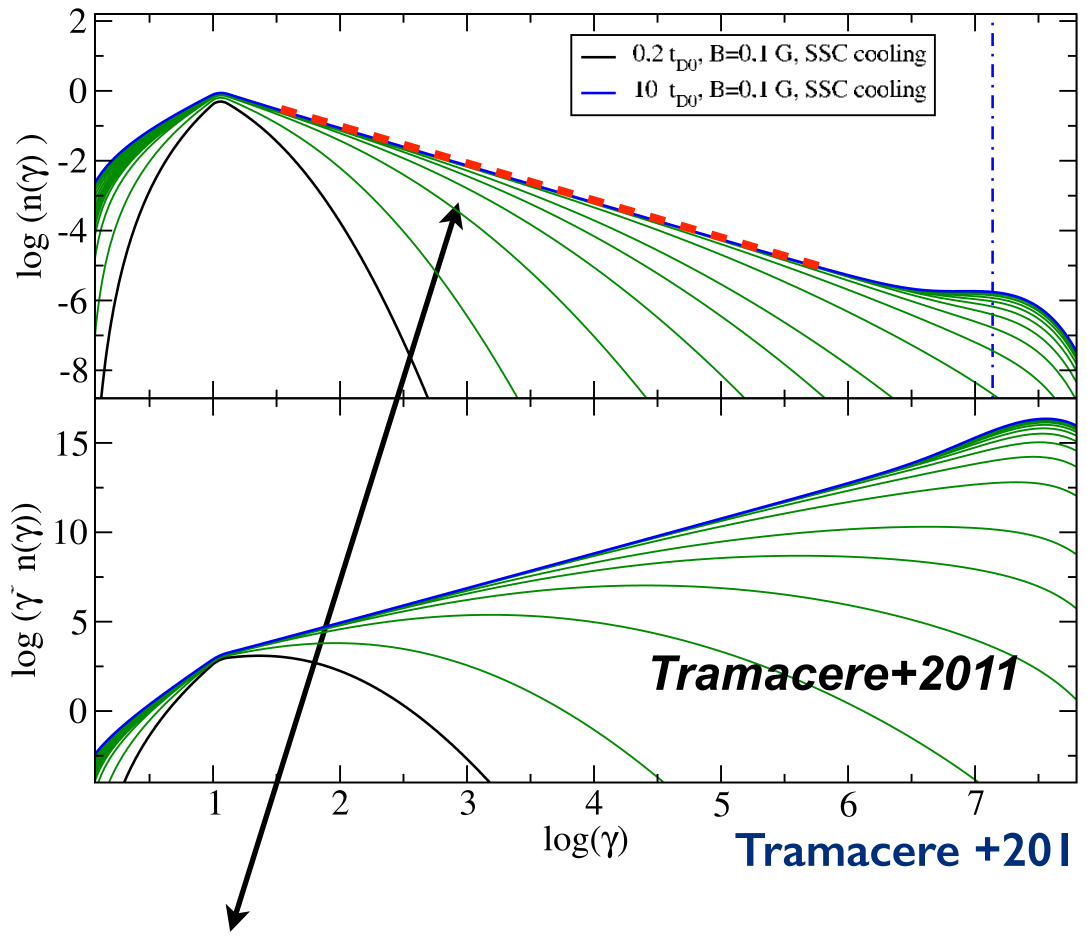
compatible with q=2 far from equilibrium constraint on B

compatible wit q=5/3 constraint on B, and duration, or TH/KN

q=2 require more fine tuning,especially on duration

Continuous injection

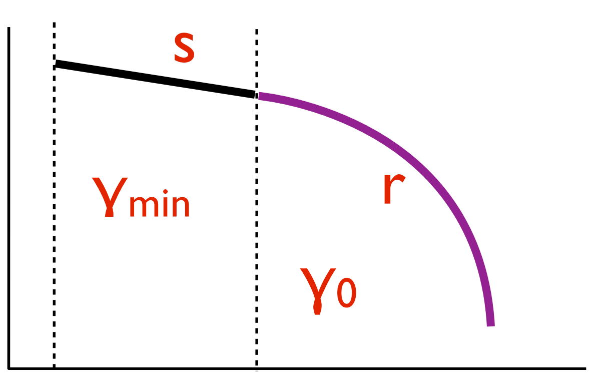
q=2, $R=10^{15}$ cm, B=0.1 G, $t_{inj}=t_D=10^4$ s



Tramacere +2011

s~1.06, in agreement with $1+t_{min\text{-}acc}/2t_{esc}$

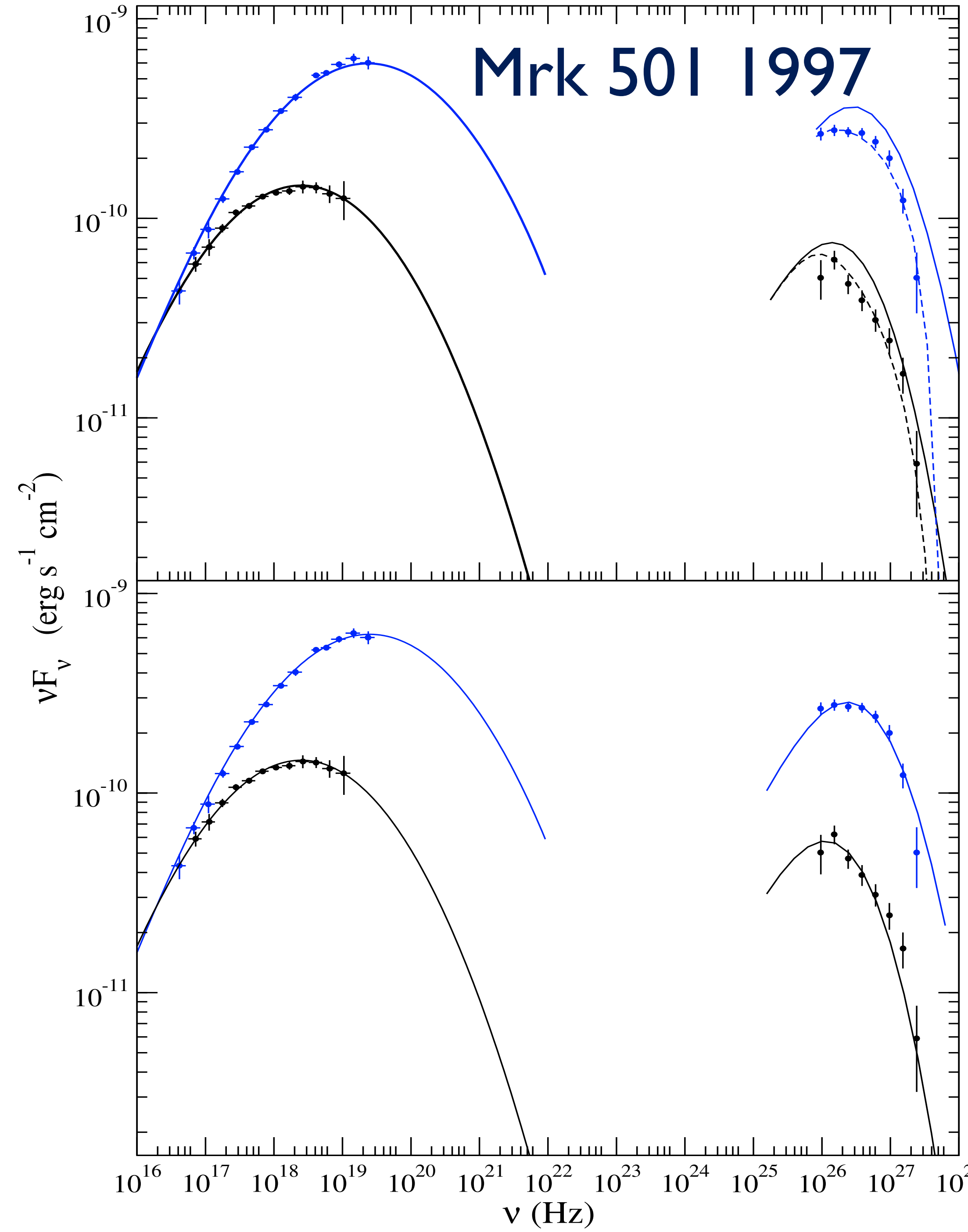
$$N(\gamma) = N_0\,(\gamma/\gamma_0)^{-s_0} \quad \gamma \le \gamma_0$$
$$N(\gamma) = N_0\,(\gamma/\gamma_0)^{-(s_0+r\ \mathrm{Log}(\gamma/\gamma_0))} \quad \gamma > \gamma_0,$$



r~0.7-0.8<<r_{eq}~6

s<<s_{FI}~2.3

Massaro &Tramacere +2006



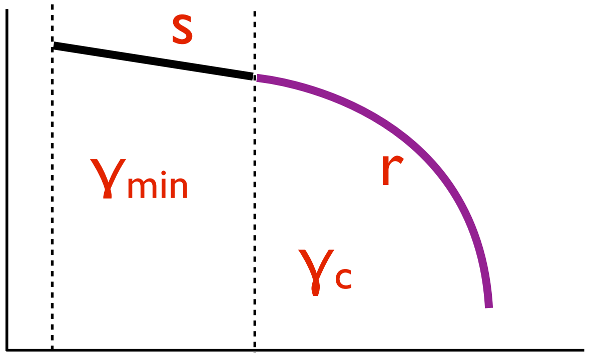
Date	s	r	N cm^{-3}	γ_0 10^4	γ_p 10^5
SSC - 1 zone					
Apr. 07	1.12	0.81	4.25	4.80	1.67
Apr. 16	1.18	0.70	30.0	8.70	3.36

Fermi I+Fermi II   Mrk 421 2006

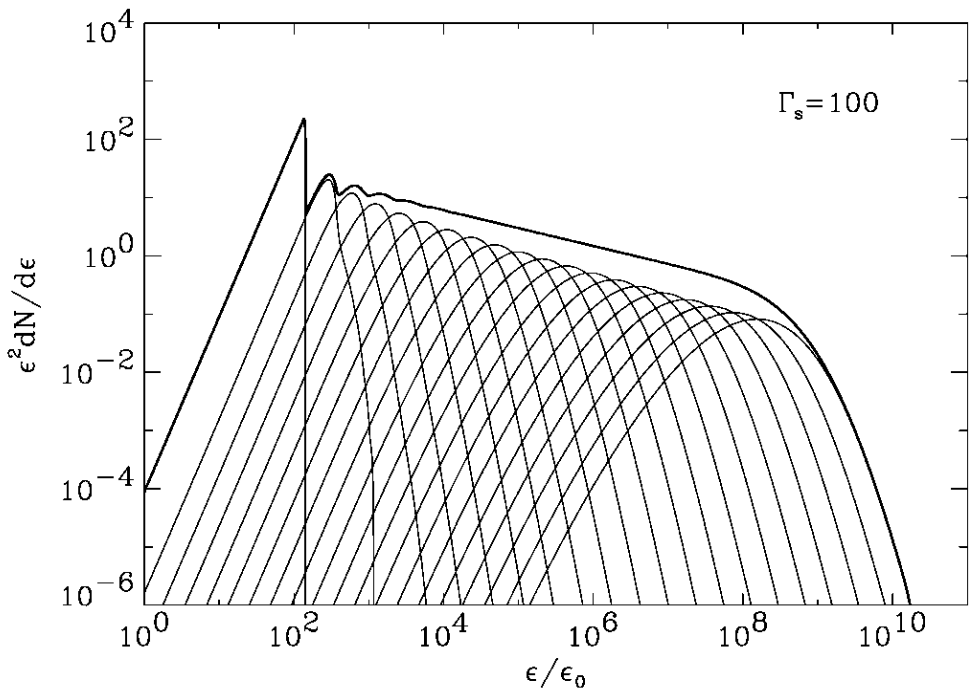
LP+PL spectra

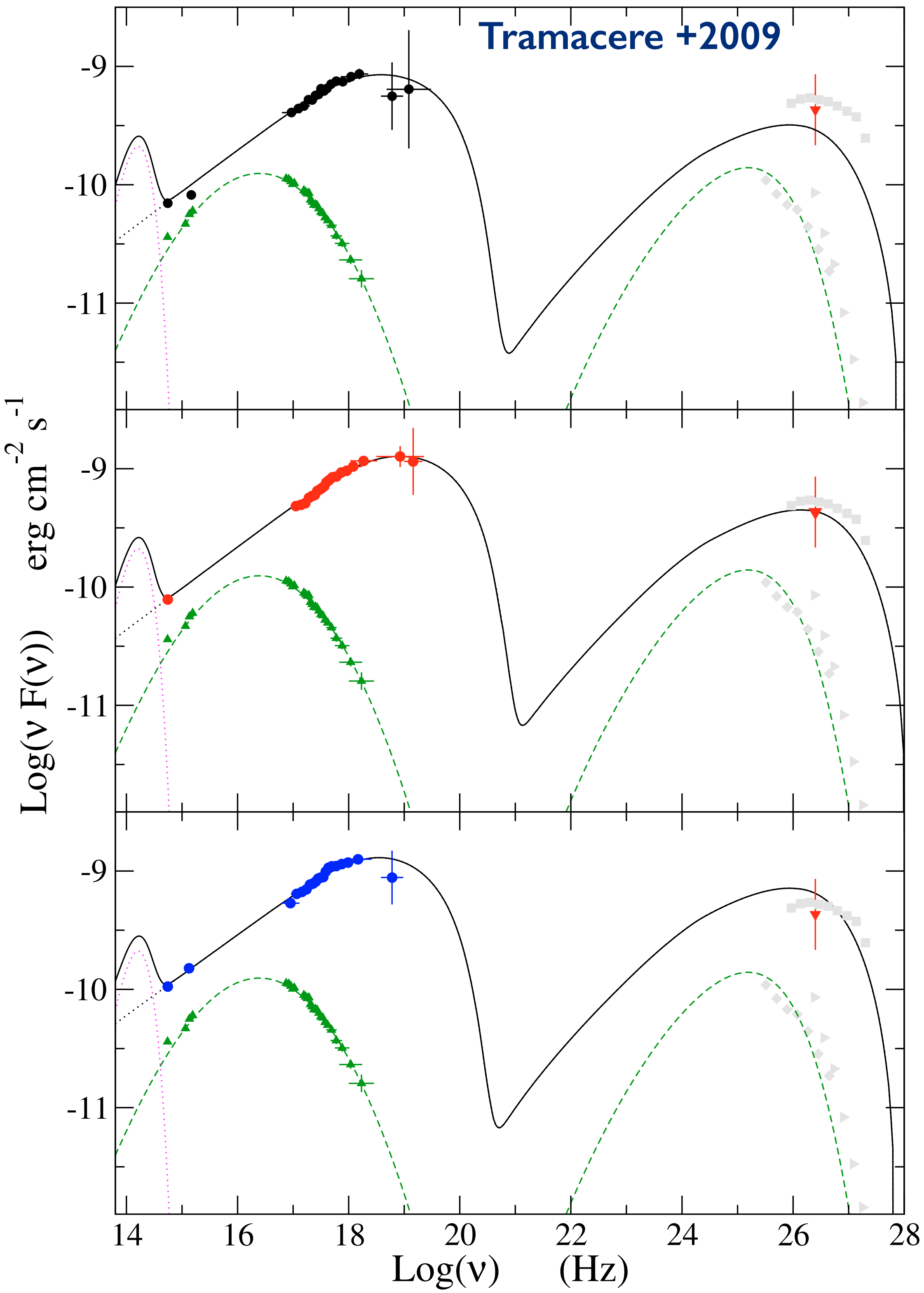
Synch index~[1.6-1.7]=>s~[2.2-2.4]

r~0.7-0.8<<r_{eq}~6



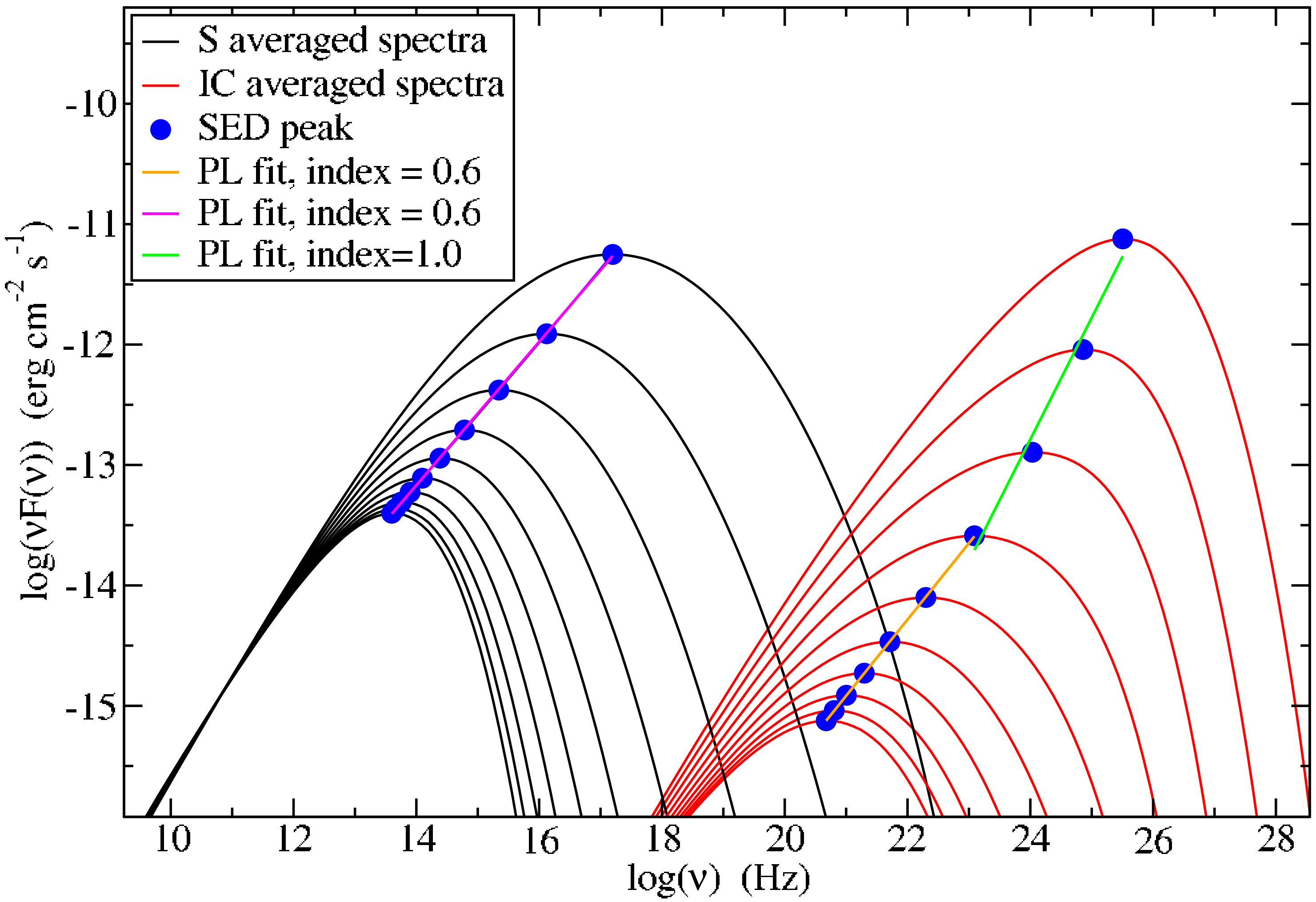
Lemoine,Pelletier 2003



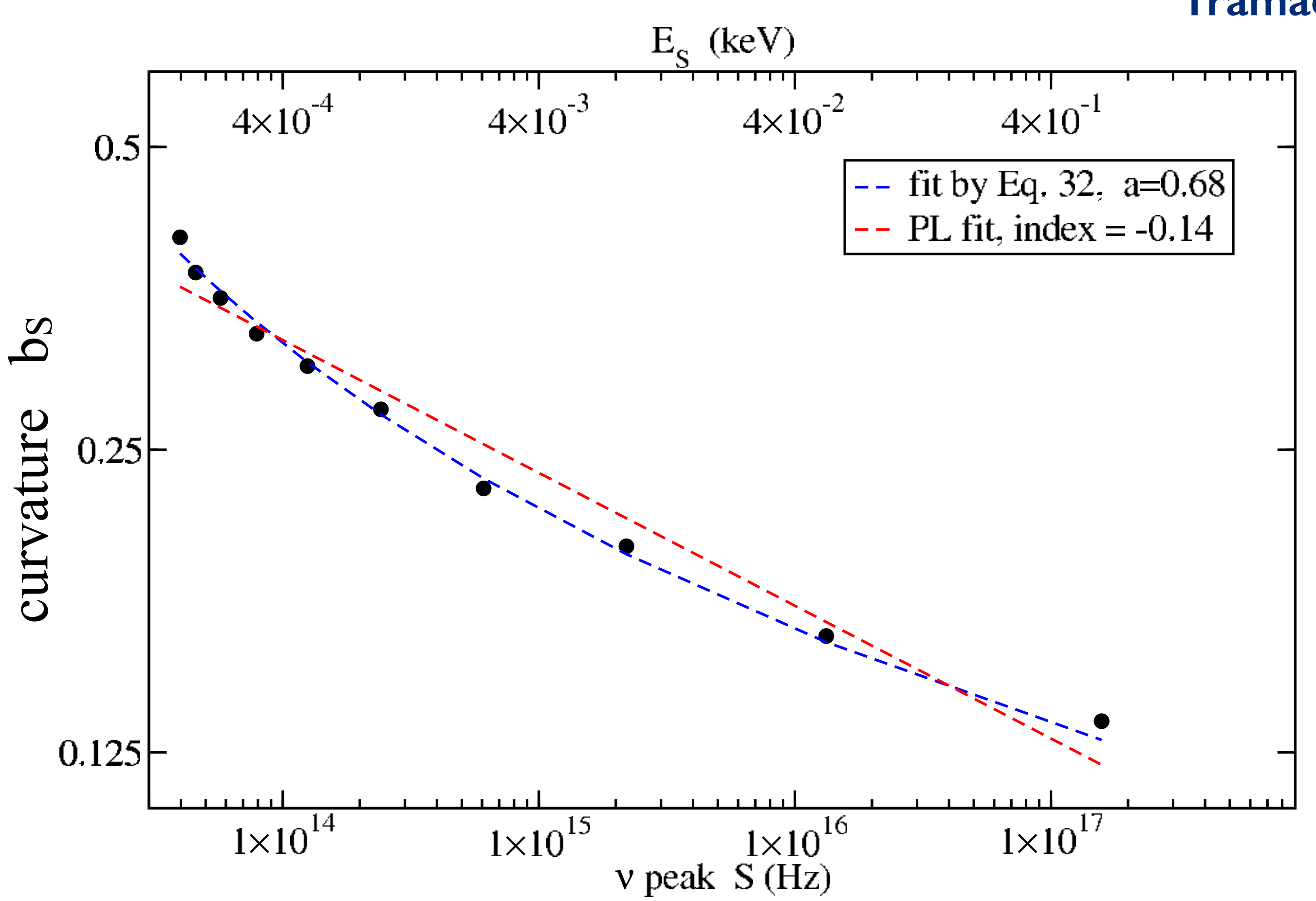


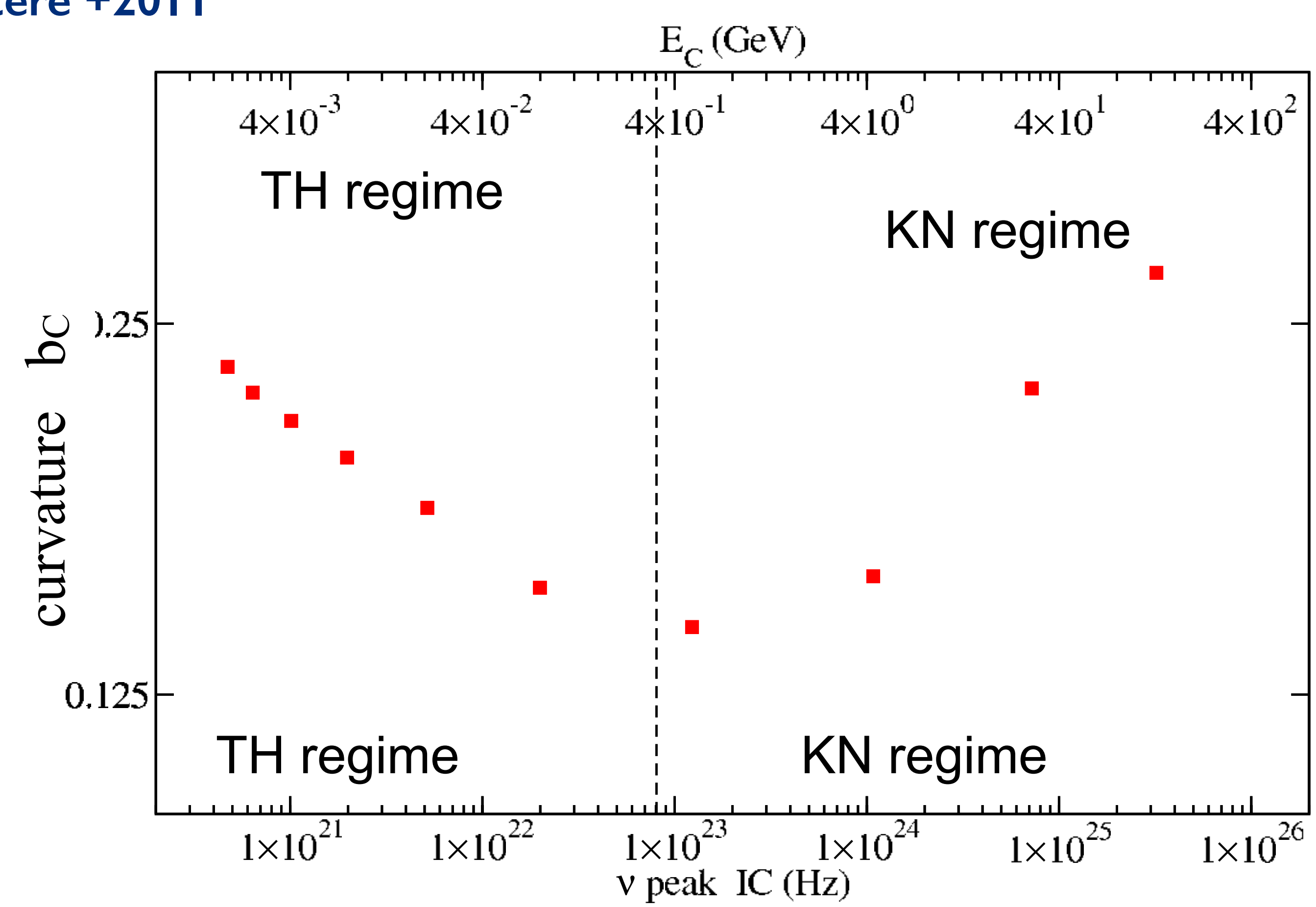
S vs IC

Tramacere+2011



Tramacere +2011

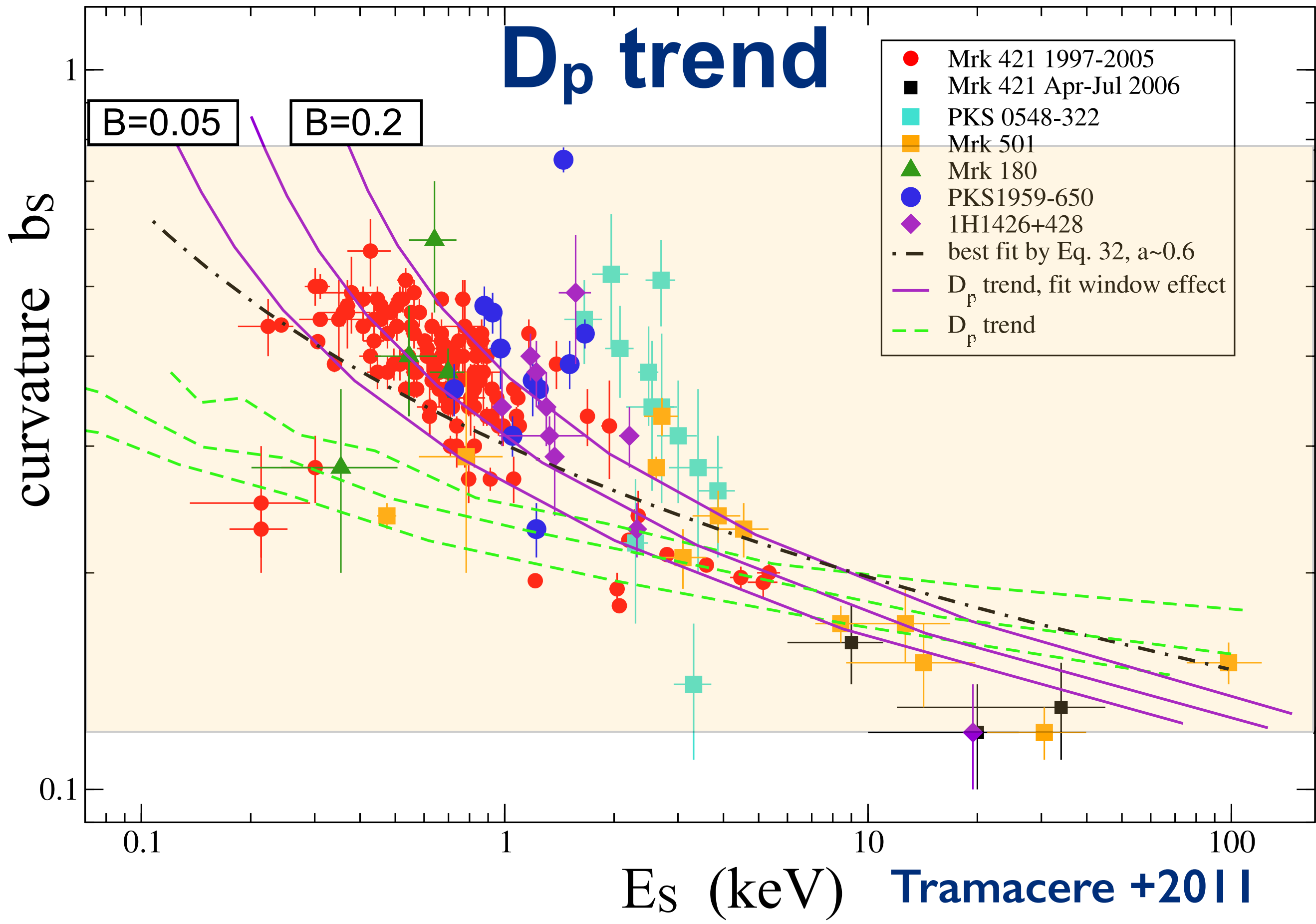


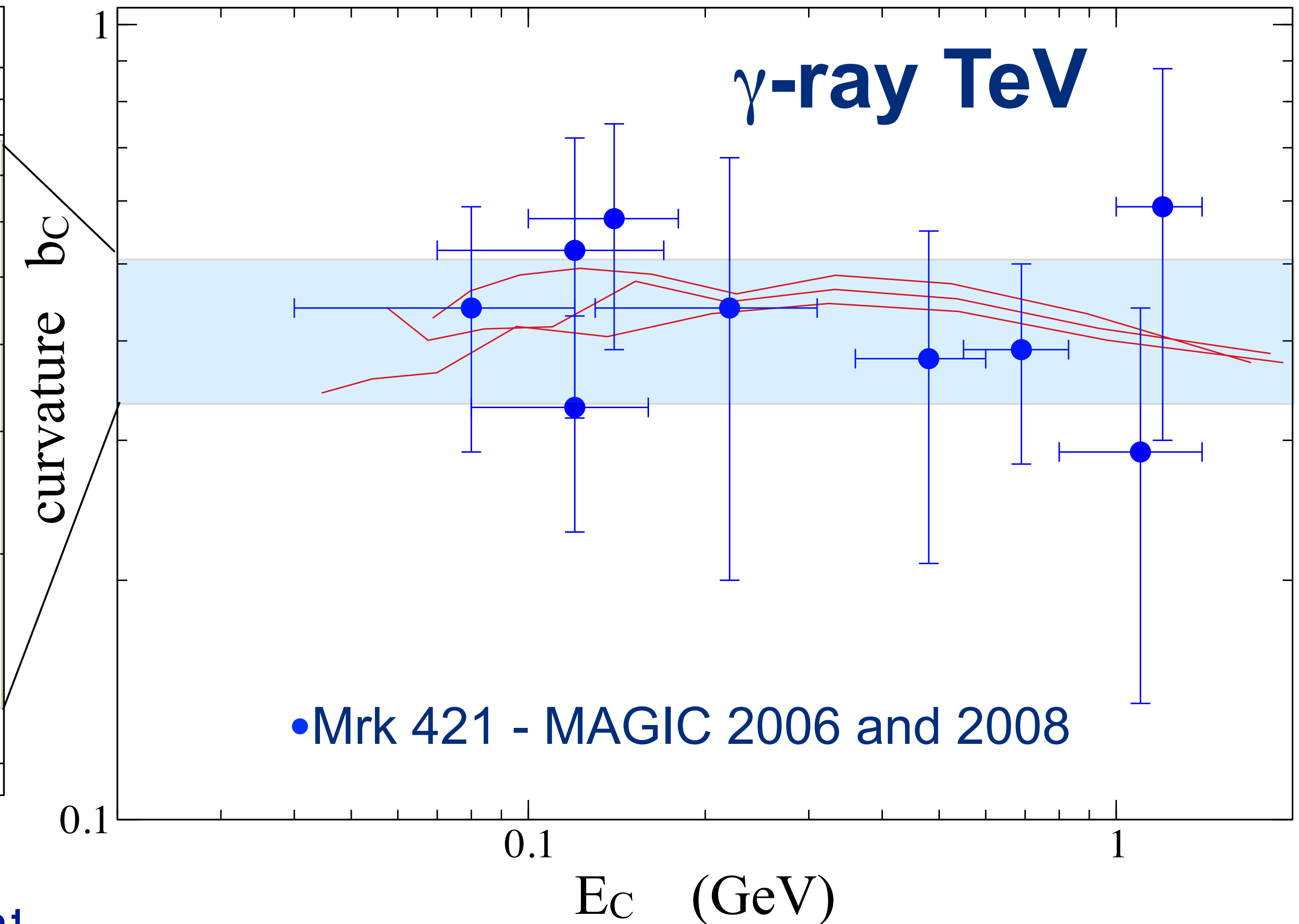


spectral trends

multiple flares and population trends

E_s-b_s X-ray trend and γ-ray predictions

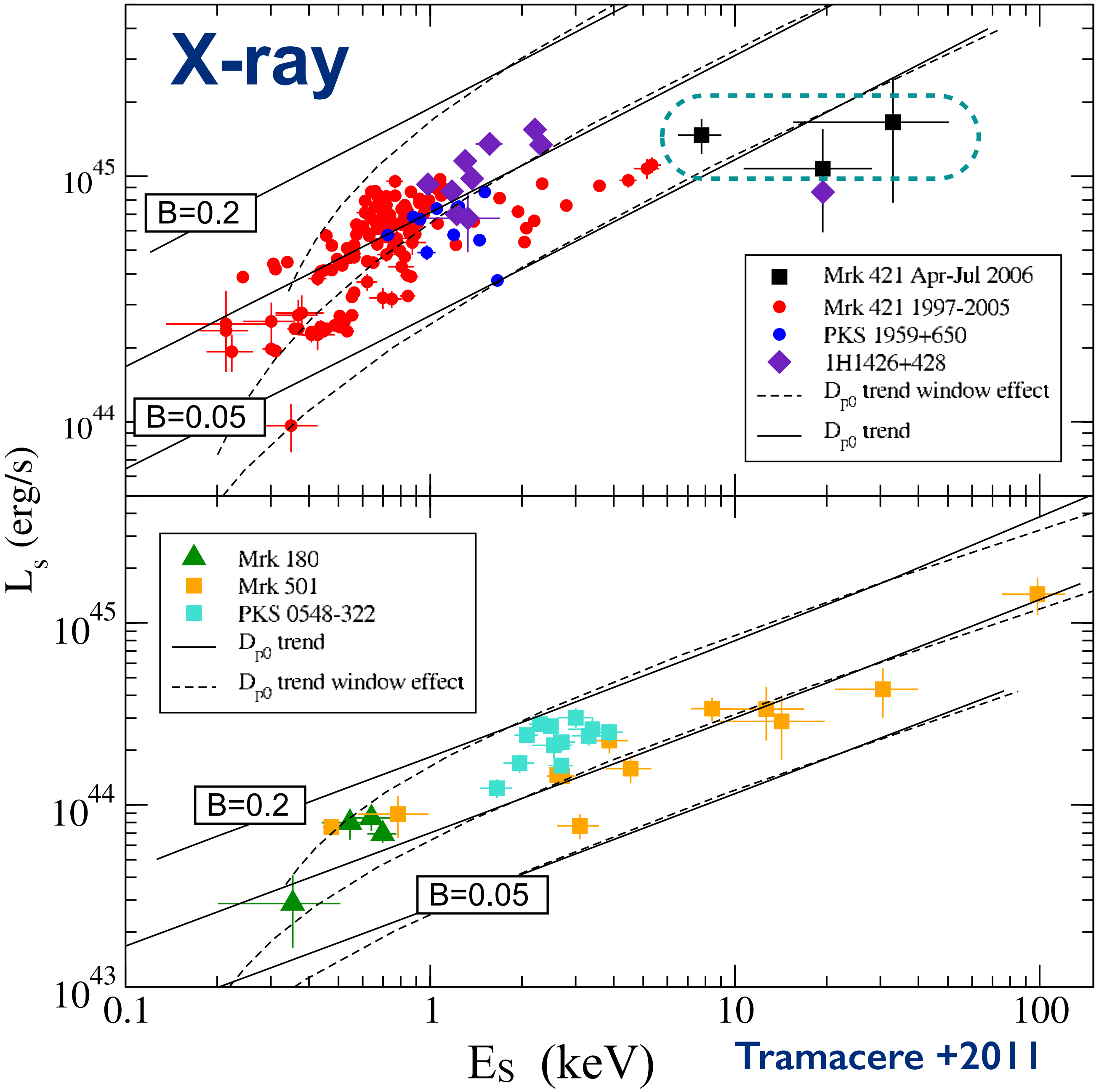


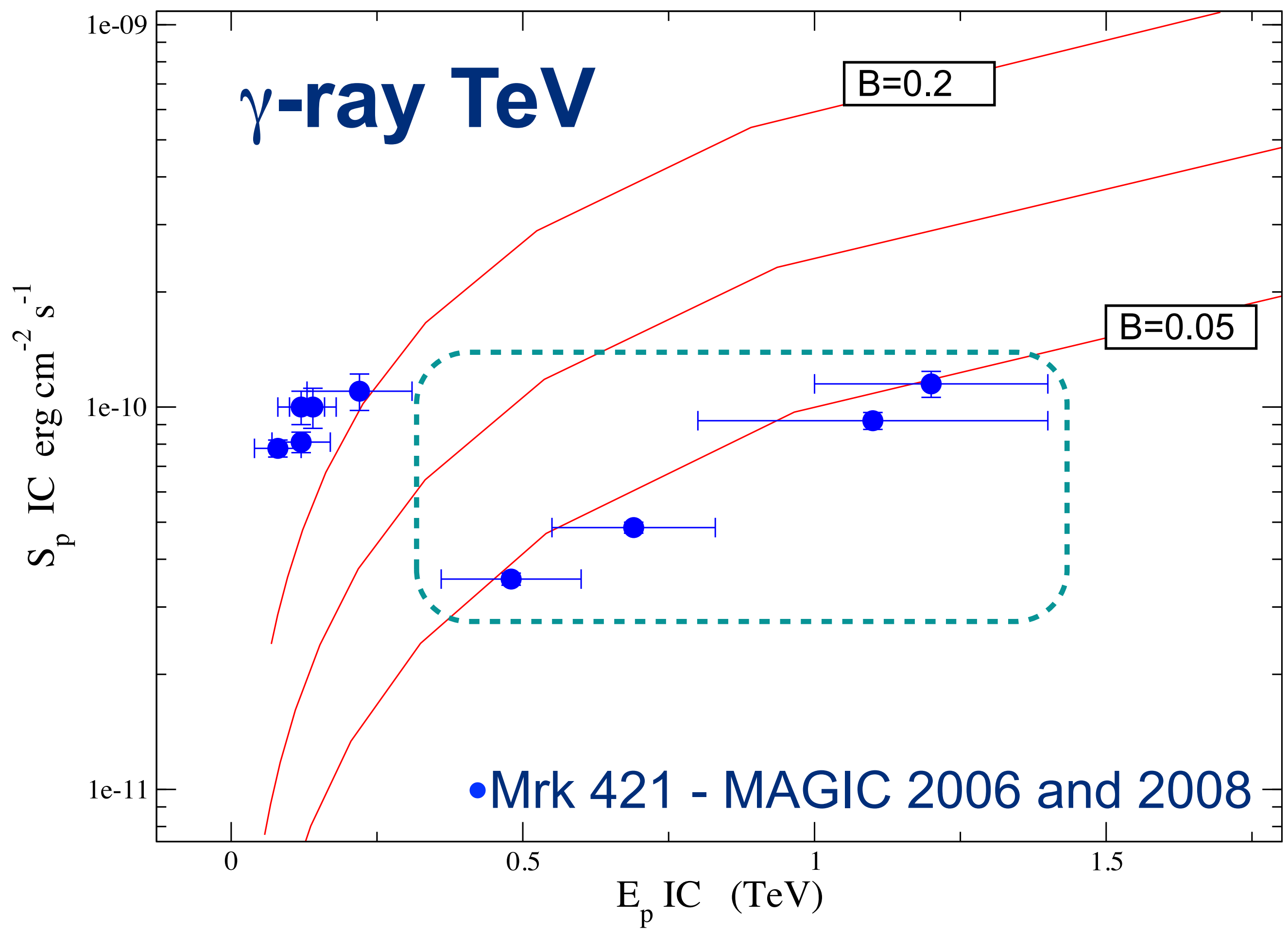


- data span **13 years**, both flaring and quiescent states
- We are able to reproduce these long-term behaviours, by changing the value of only one parameter (D_p)
- for q=2, curvature values imply distribution far from the equilibrium (b~[1.0–0.7])
- More data needed at GeV/TeV, curvature seems to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

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

E_S-L_S X-ray trend and γ-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_{inj} objets (Mrk 501 vs Mrk 421) reach a larger E_S, compatibly with larger γ_{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_{inj} xt_{inj}) is injected for any flare (jet-feeding problem), whilst the peak dynamic is ruled by the turbulence in the magnetic field.

backup slides

self-consistent approach: acc+cooling

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

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

observed values

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

$\Delta t \sim$ few ks

→

values compatible with Tammi & Duffy 2009

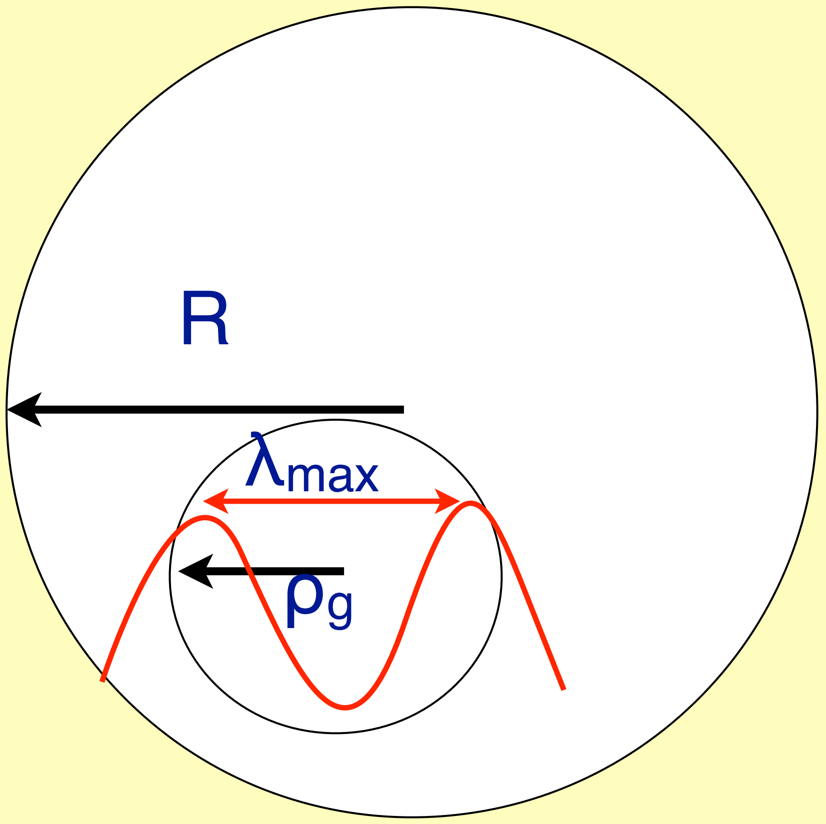
$t_{DA} \sim< 5$ ks

$t_D \sim< 10$ ks

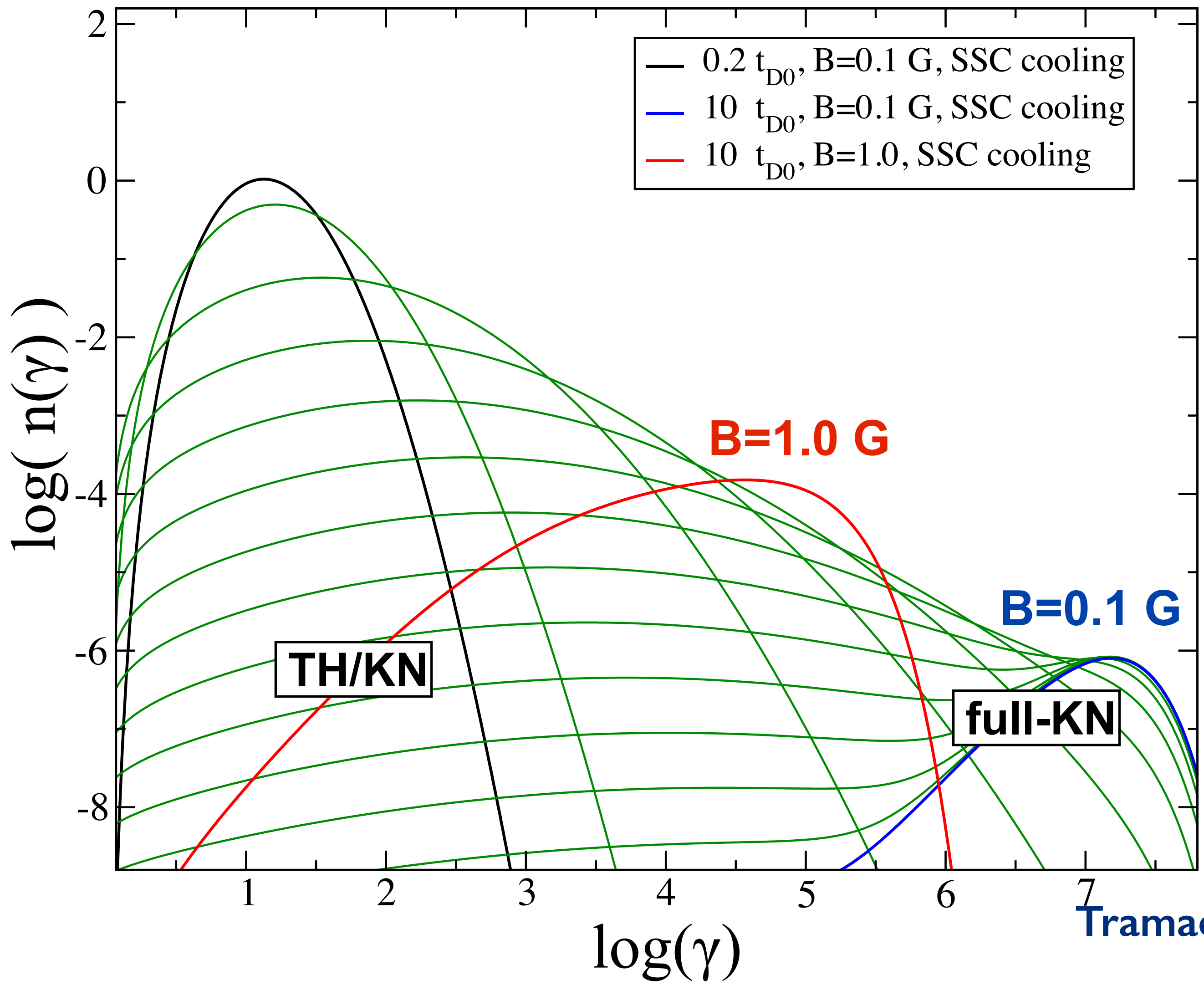
set-up of the accelerator

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

→ **$t_D \sim< 10^4$ ks**



Flare: acc.-dominated-vs-equil.,R= 10^{15} cm, q=2



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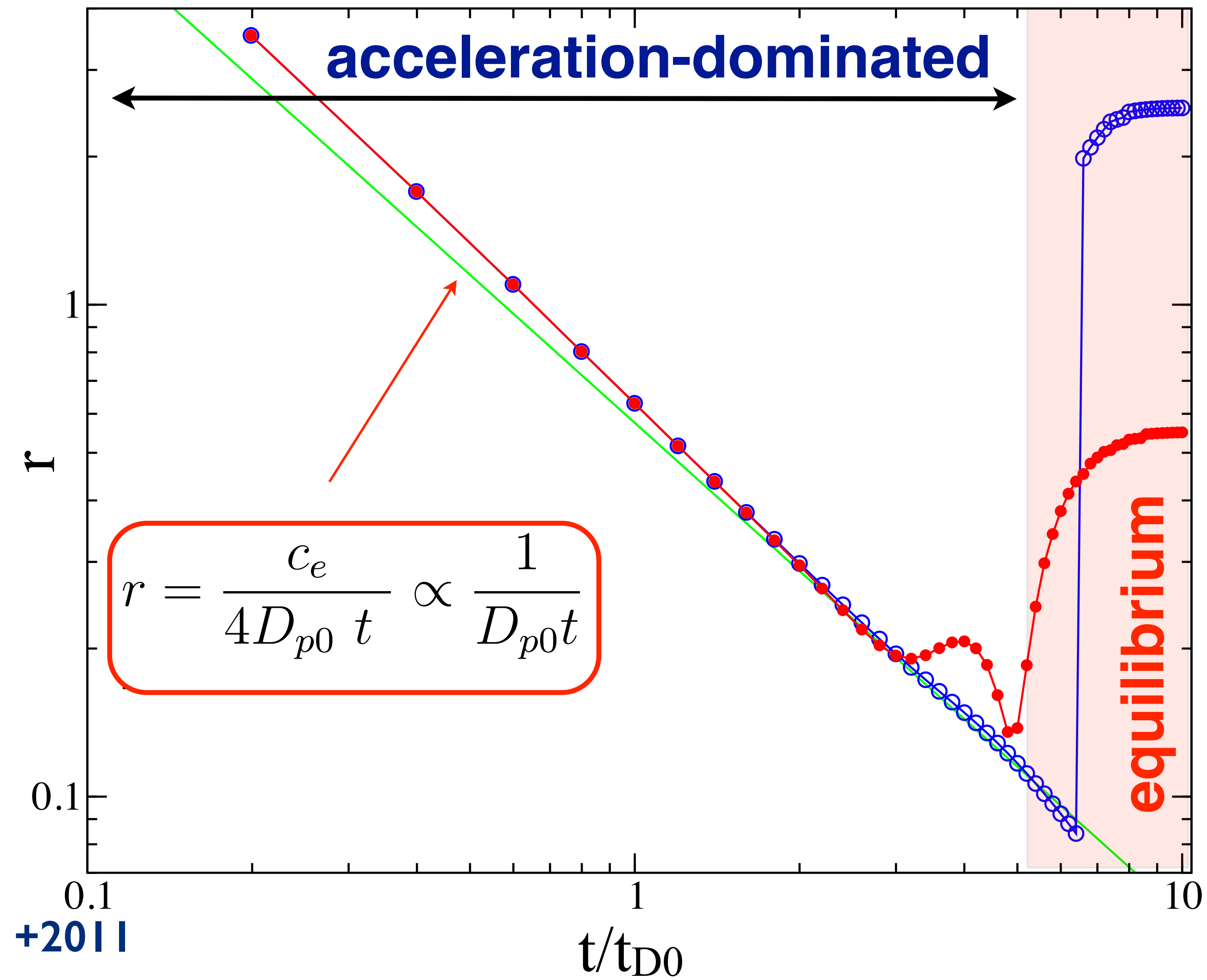
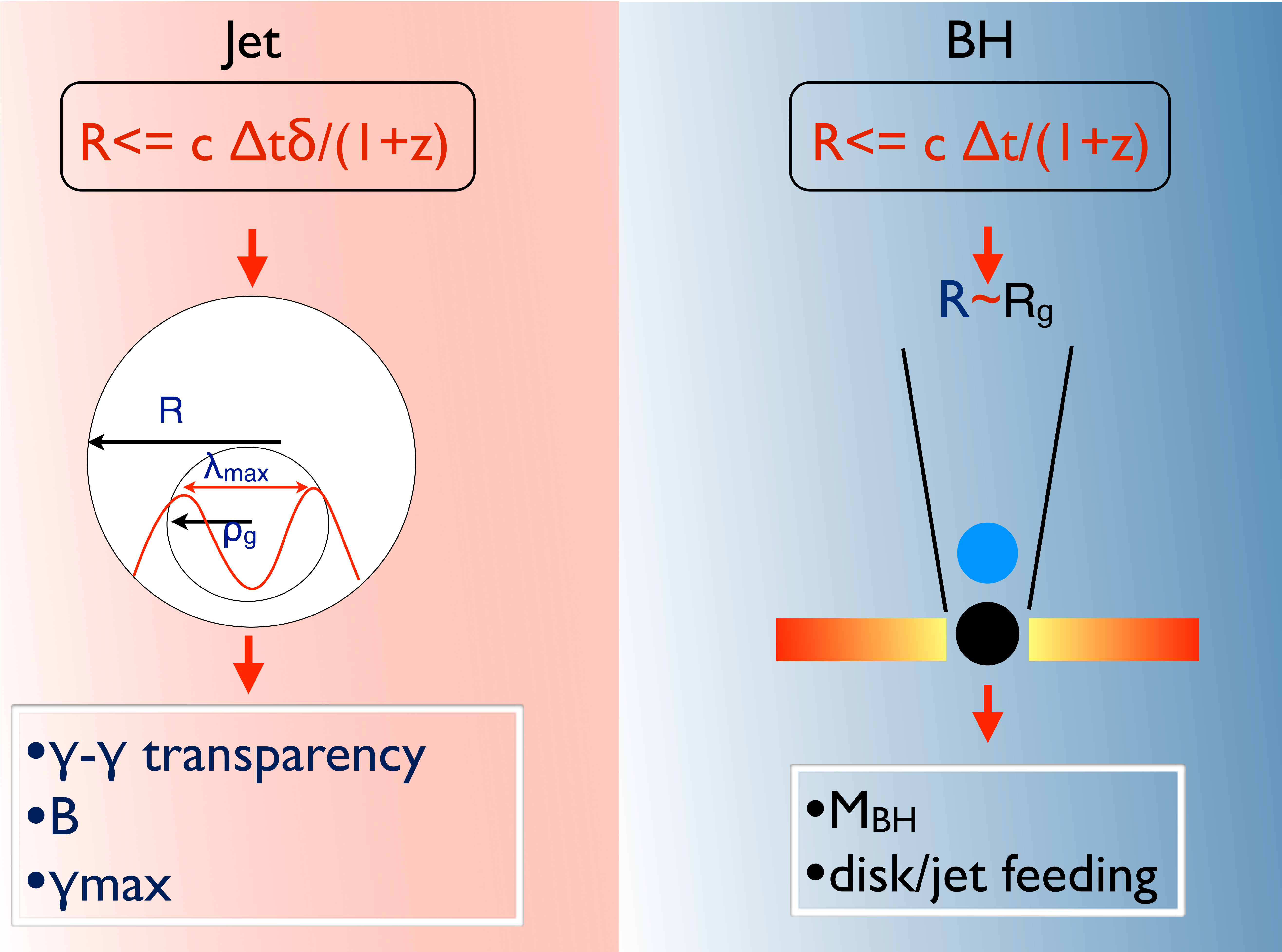
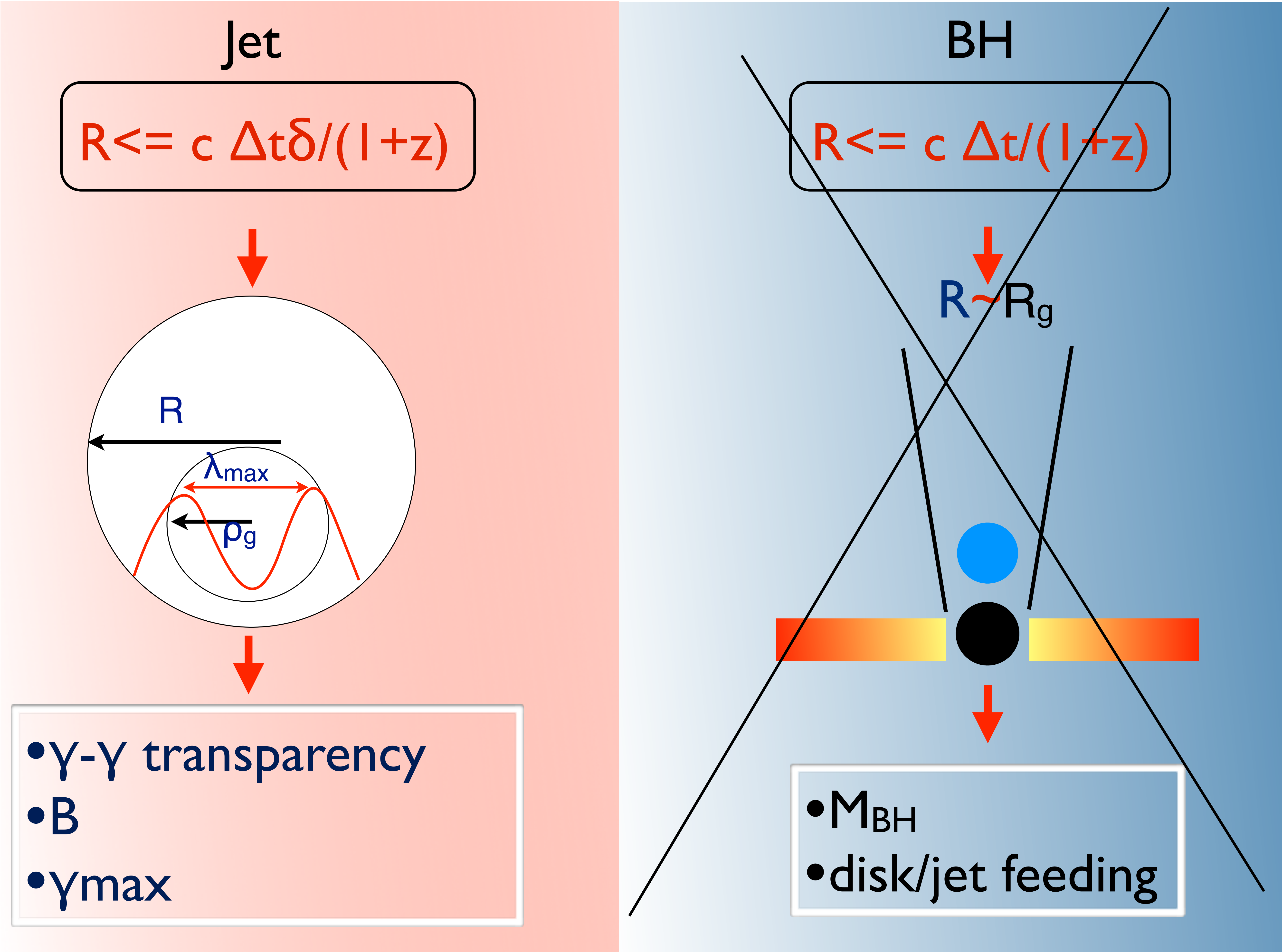


- mono energetic inj., $t_{inj} << t_{acc}$, $t_{inj} << t_{sim}$
- we measure r@peak as a function of the time
- two phase: **acceleration-dominated**, **equilibrium**
- equil. distribution:
  - **f=1 for q=2 and S, full TH, or full KN**
- **equil. curv.: r~2.5, (r_{3p}~6.0) for TH or full KN**
- **equil. curv.: r~0.6, (r_{3p}~4.0) for TH-KN**

$$n(\gamma) \propto \gamma^2 \exp\left[\frac{-1}{f(q,\dot\gamma)}\left(\frac{\gamma}{\gamma_{eq}}\right)^{f(q,\dot\gamma)}\right]$$



Jet
R<= c Δtδ/(1+z)
R
λmax
ρg
•γ-γ transparency
•B
•γmax
BH
R<= c Δt/(1+z)
R~Rg
•MBH
•disk/jet feeding



Jet
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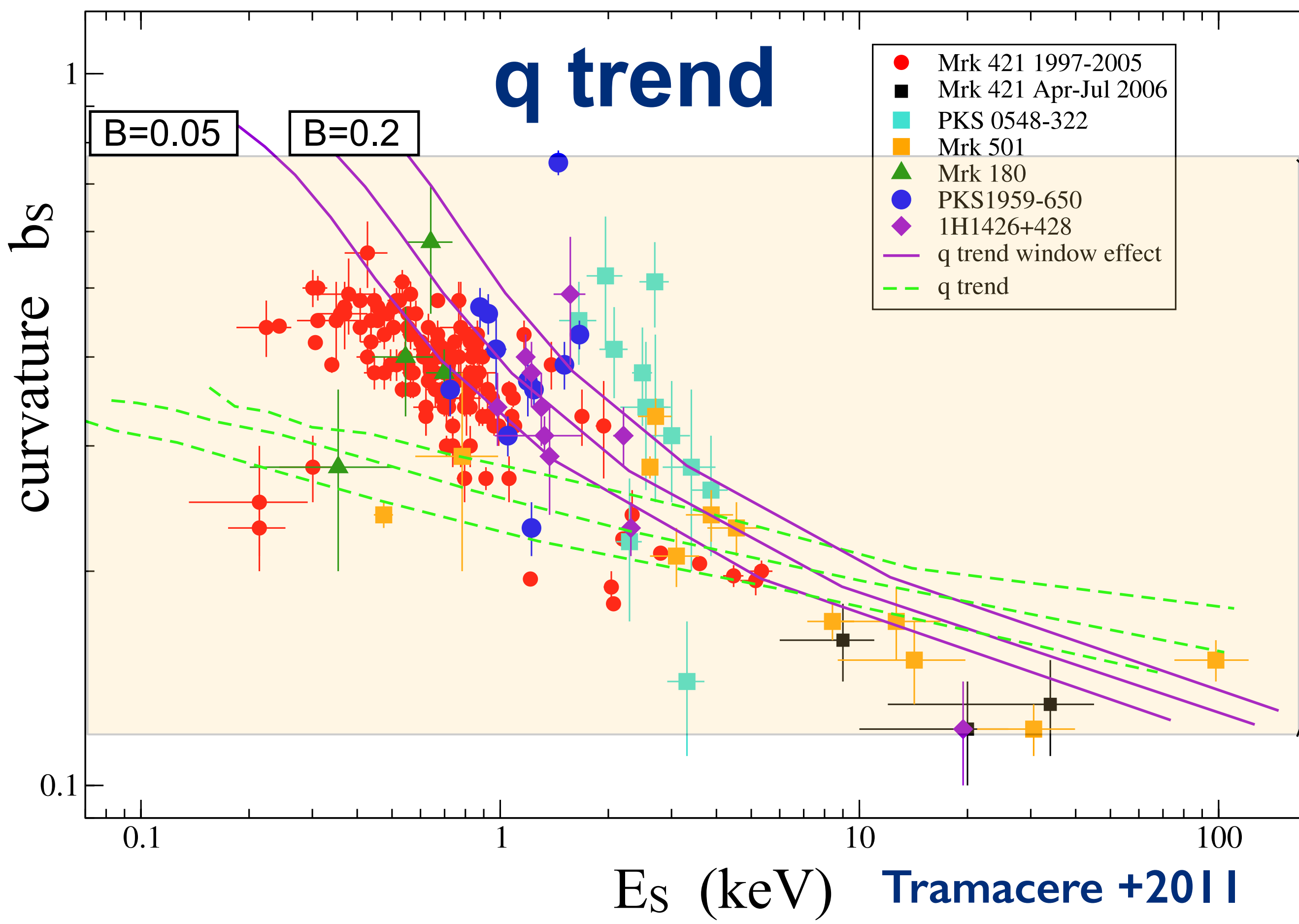
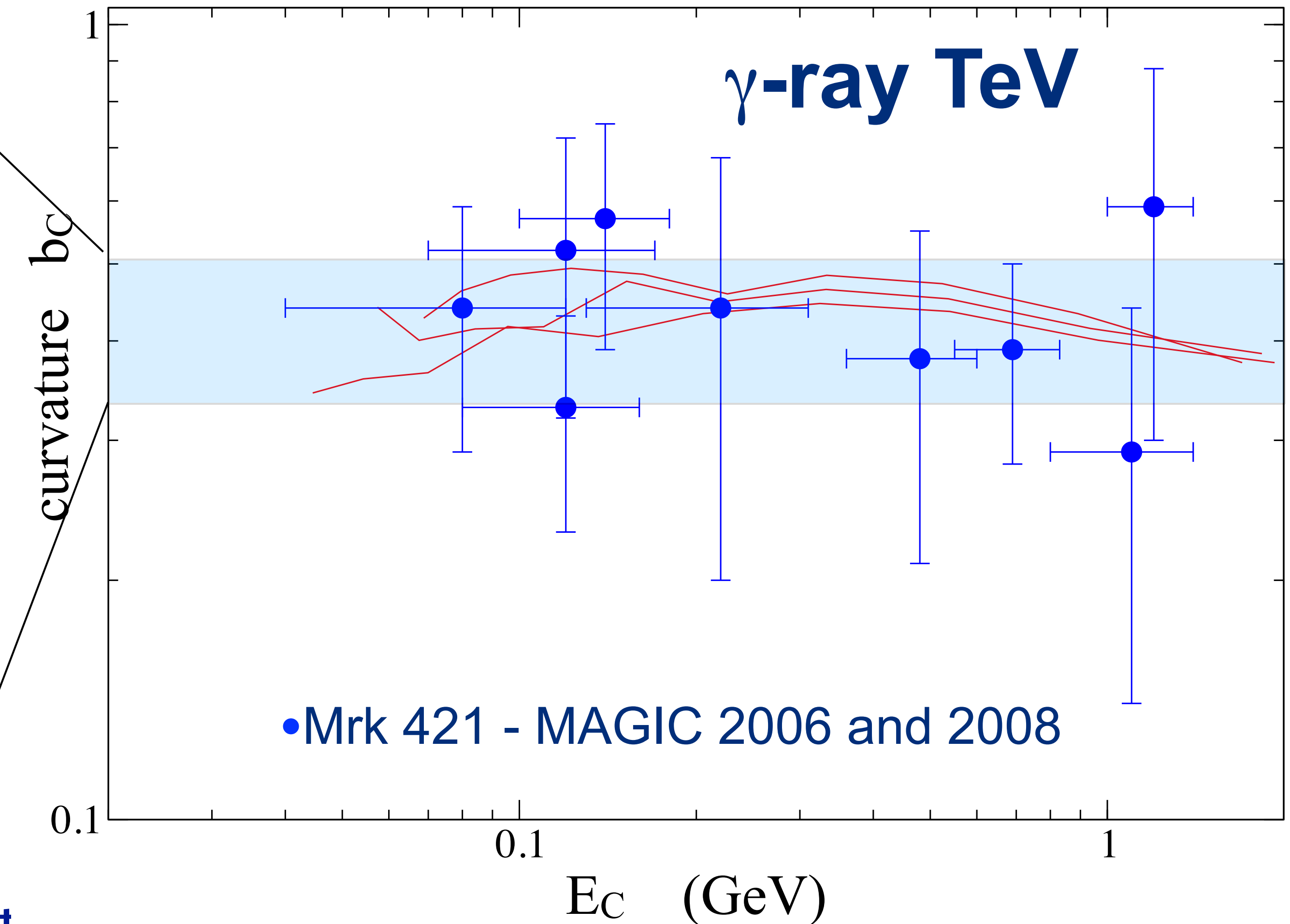


Tramacere +2011



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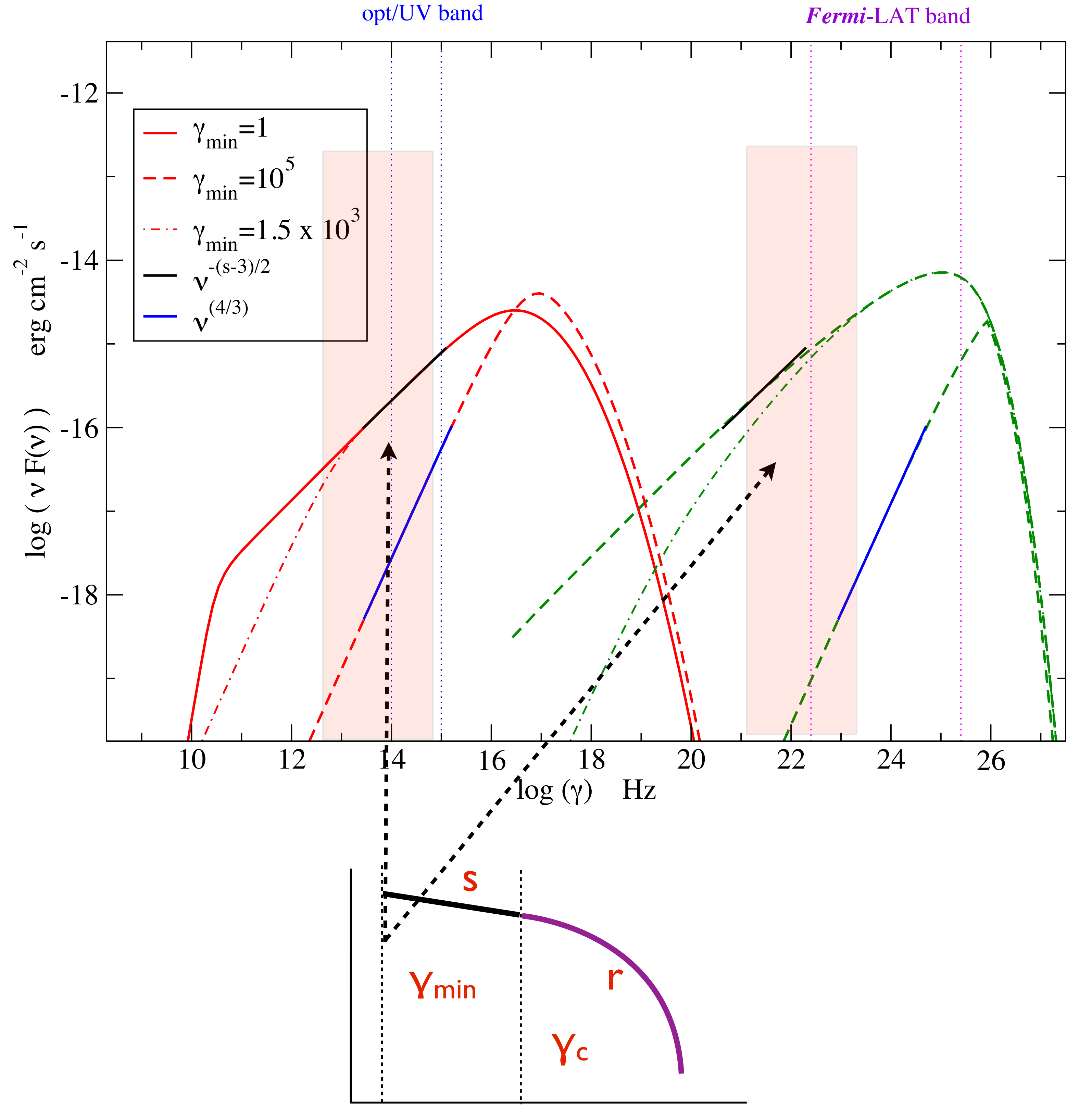
q		[3/2, 2]
t_A	(s)	1.2×10^3
$t_{D_0} = 1/D_{P0}$	(s)	[1.5×10^4, 1.5×10^5]
$T_{\rm inj}$	(s)	10^4
$T_{\rm esc}$	(R/c)	2.0

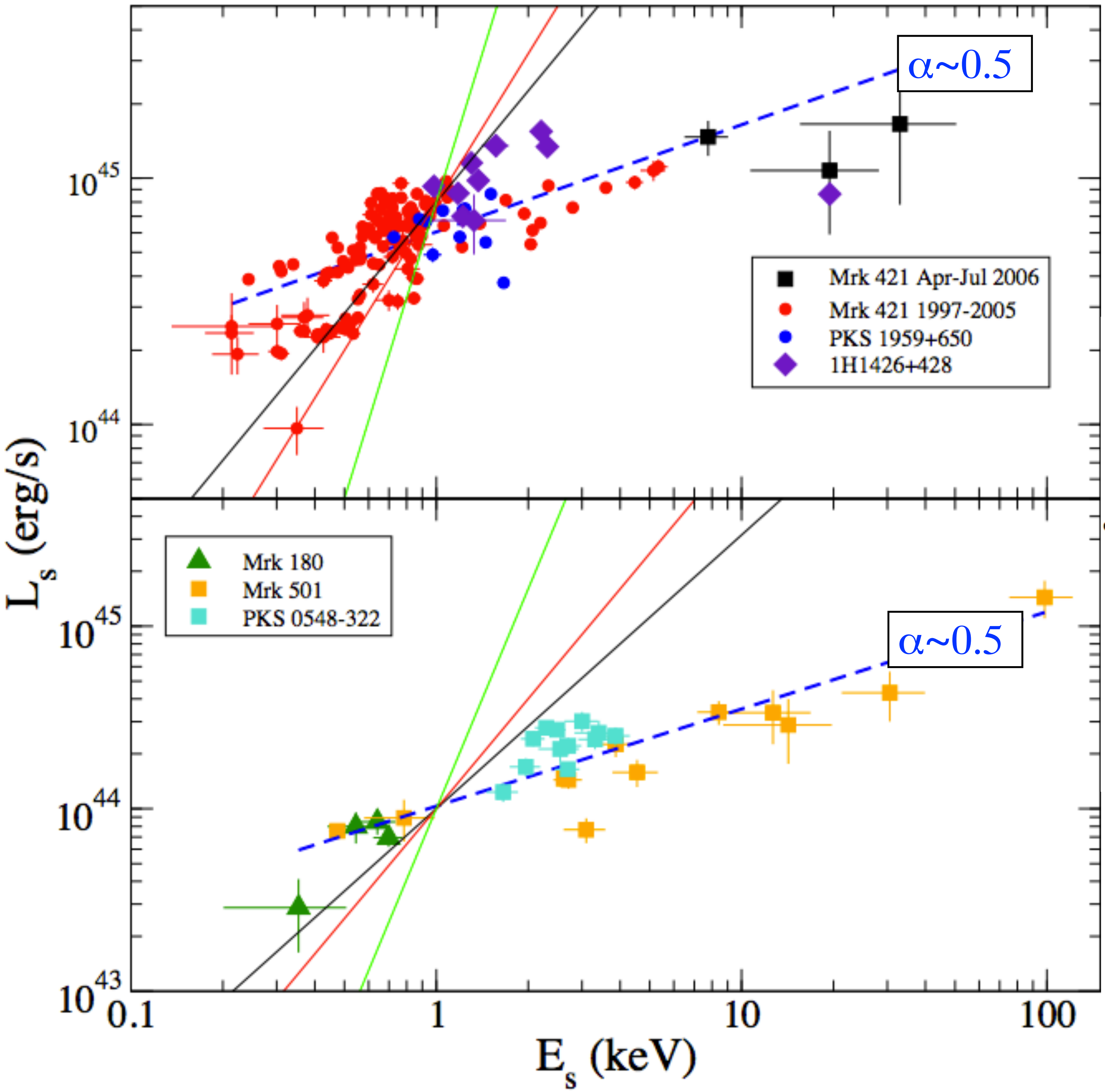
HBLs case



opt/UV band
Fermi-LAT band
γ_{min}=1
$\gamma_{min}=10^5$
$\gamma_{min}=1.5 \times 10^3$
$\nu^{-(s-3)/2}$
$\nu^{(4/3)}$
log (ν F(ν)) erg cm^{-2} s^{-1}
-12
-14
-16
-18
10
12
14
16
18
20
22
24
26
log (γ) Hz
s
γ_{min}
r
γ_c

acceleration signature in the E_S-vs-L_s trend

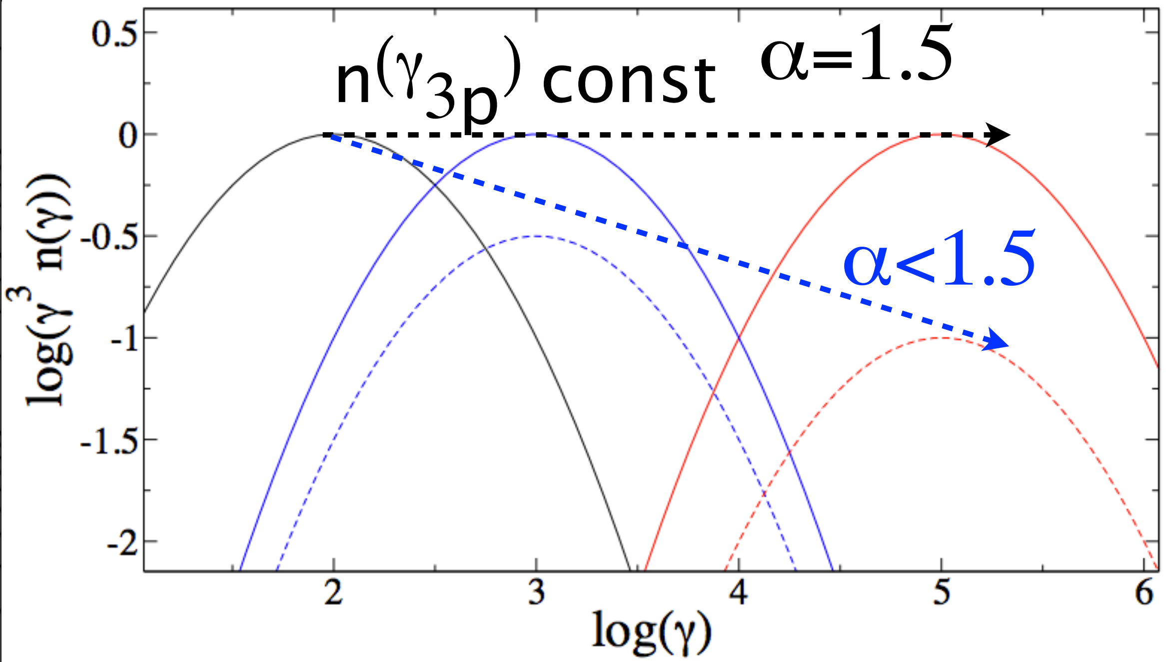
long-trend main drivers



Tramacere+2009

$$S_s(E_s) \propto n(\gamma_{3p})\gamma_{3p}^3 B^2 \delta^4$$
$$E_s \propto \gamma_{3p}^2 B\delta.$$

$$S_s \propto (E_s)^\alpha$$



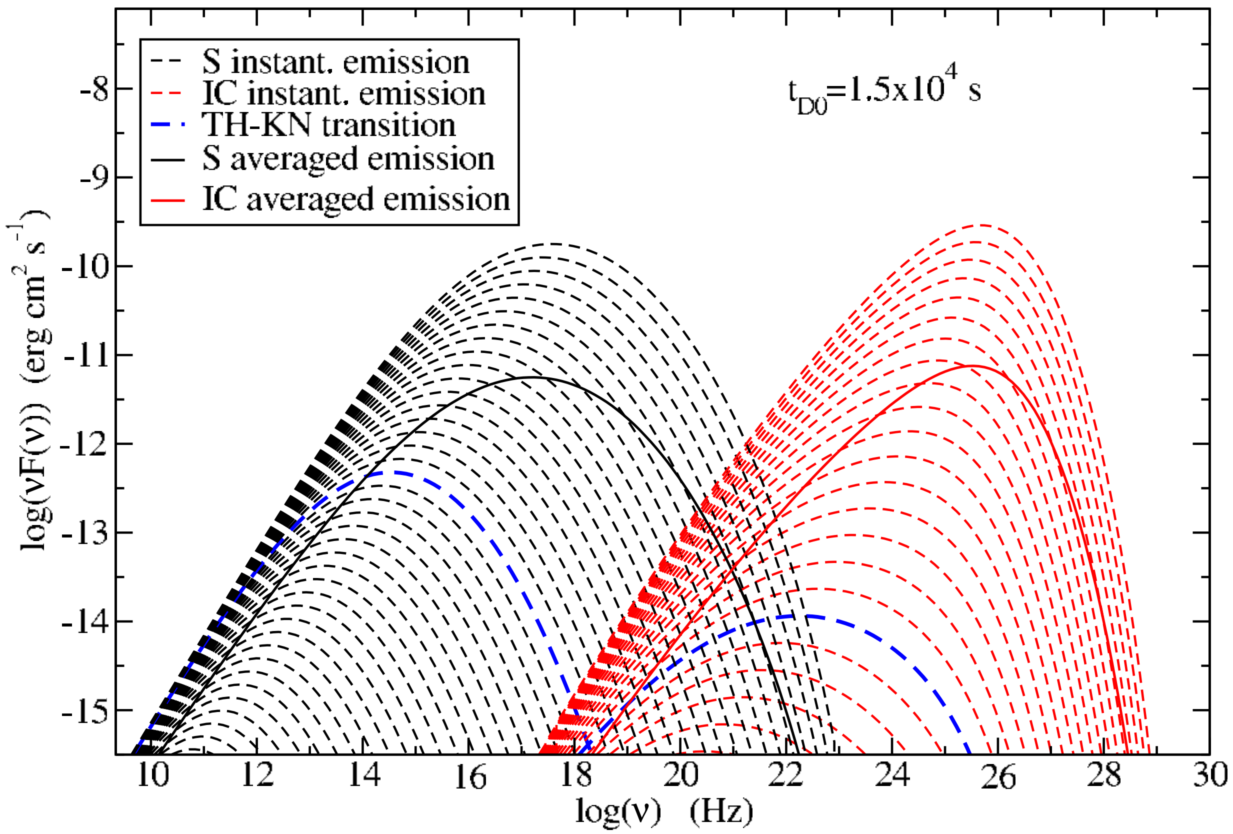
- $\gamma_{3p}\uparrow$ **and** $n(\gamma 3p)\downarrow$ **=>** α<1.5

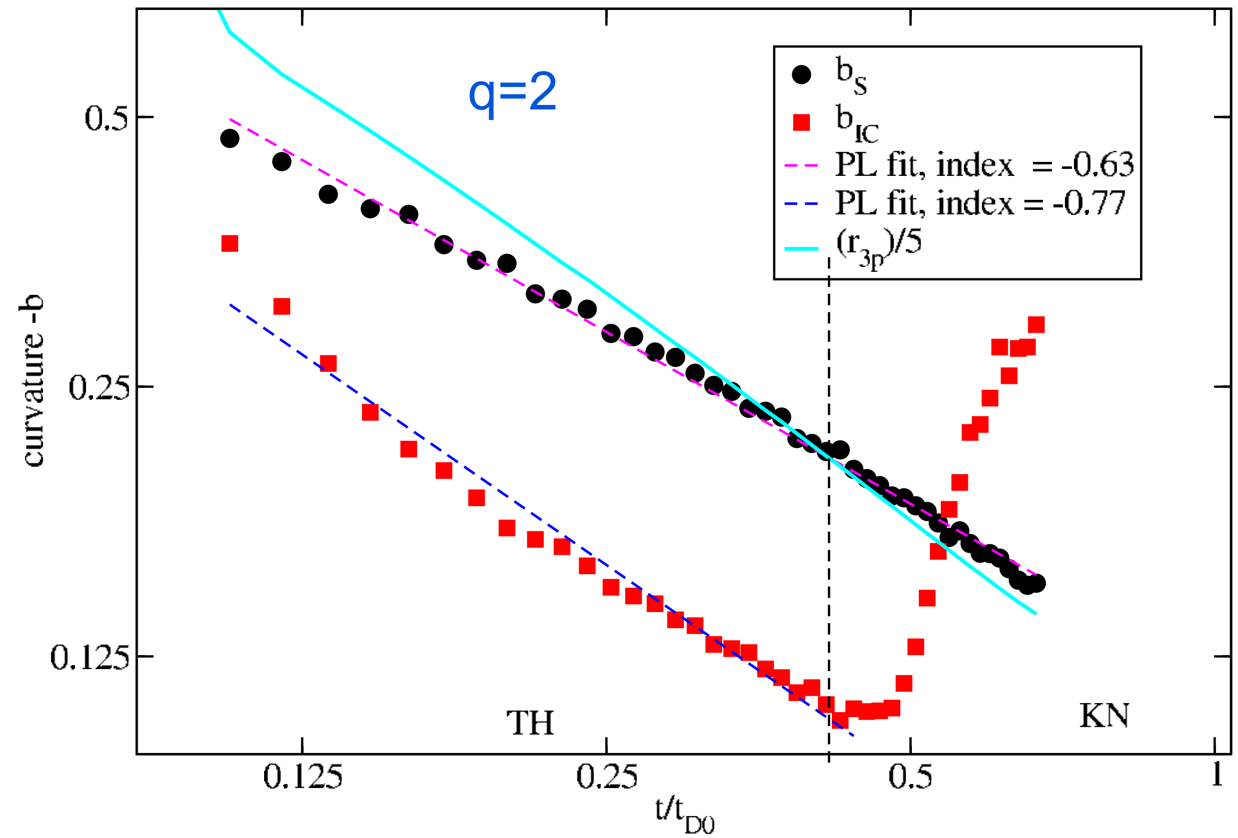
acceleration+energy conservation

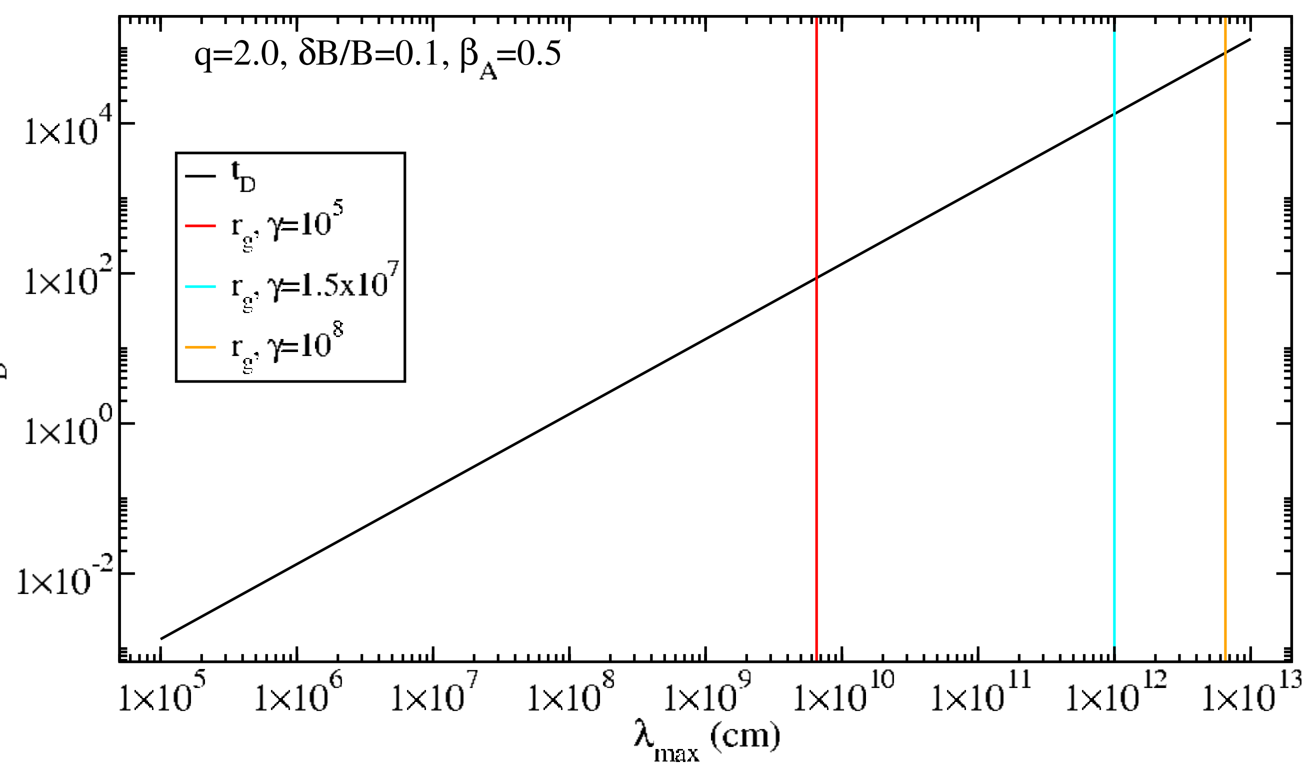
- B–>α=2.0,
- δ–>α=4

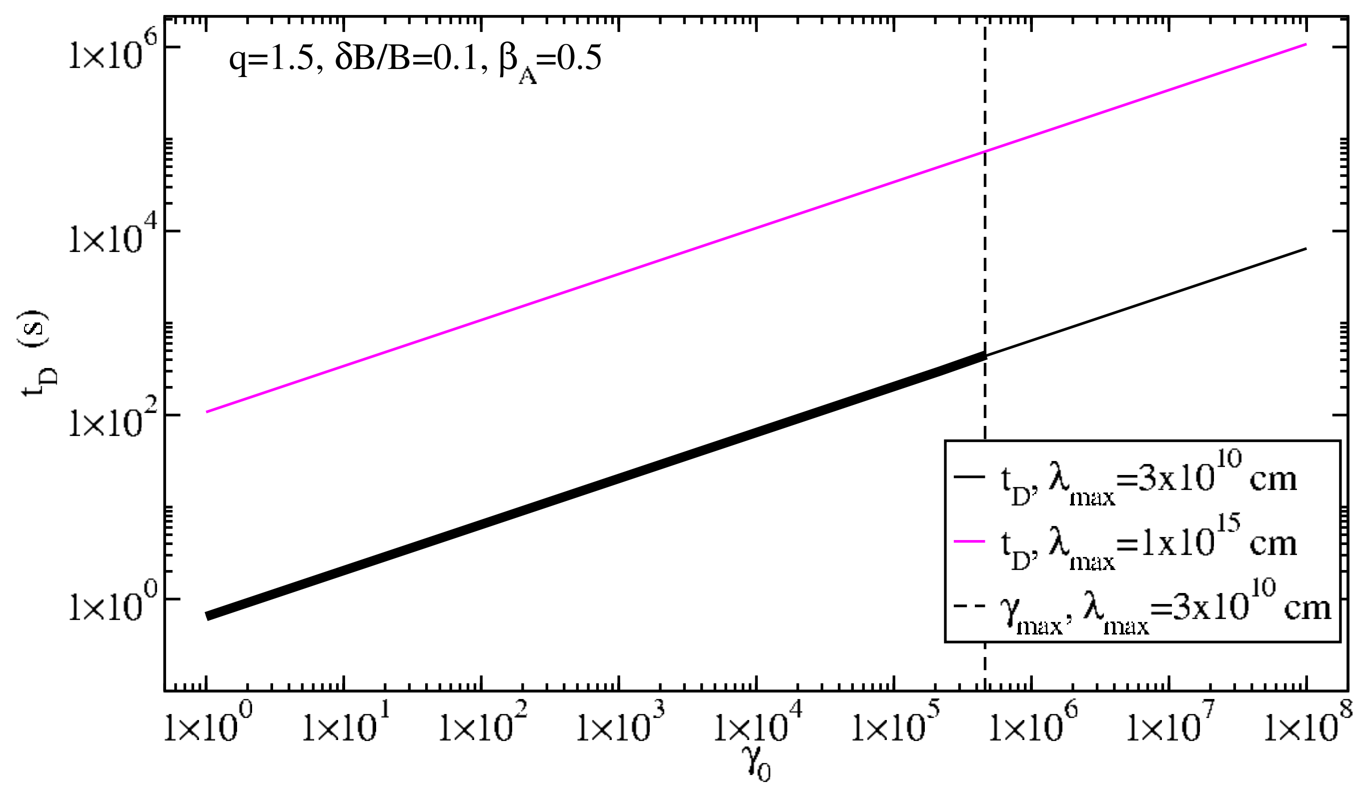
incompatible as long-trend main driver

SEDs evolution

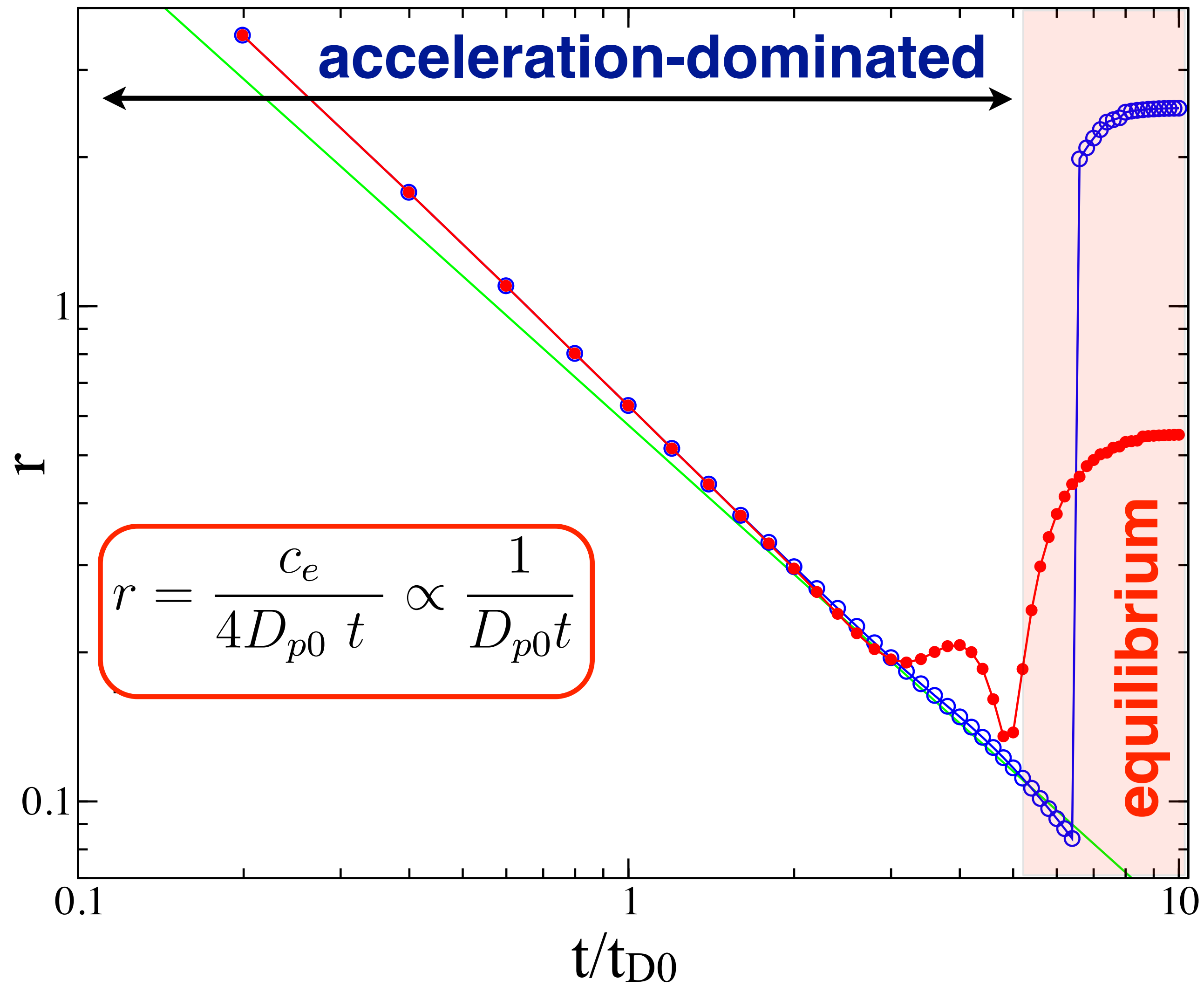


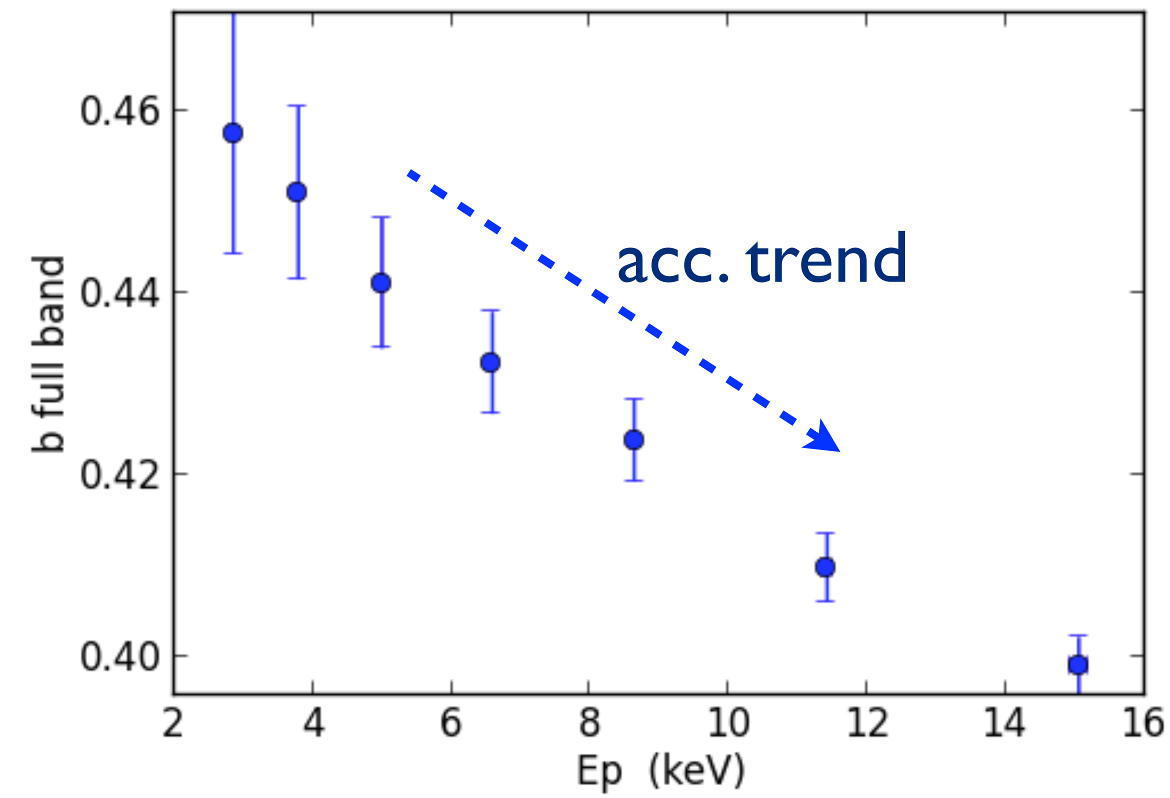


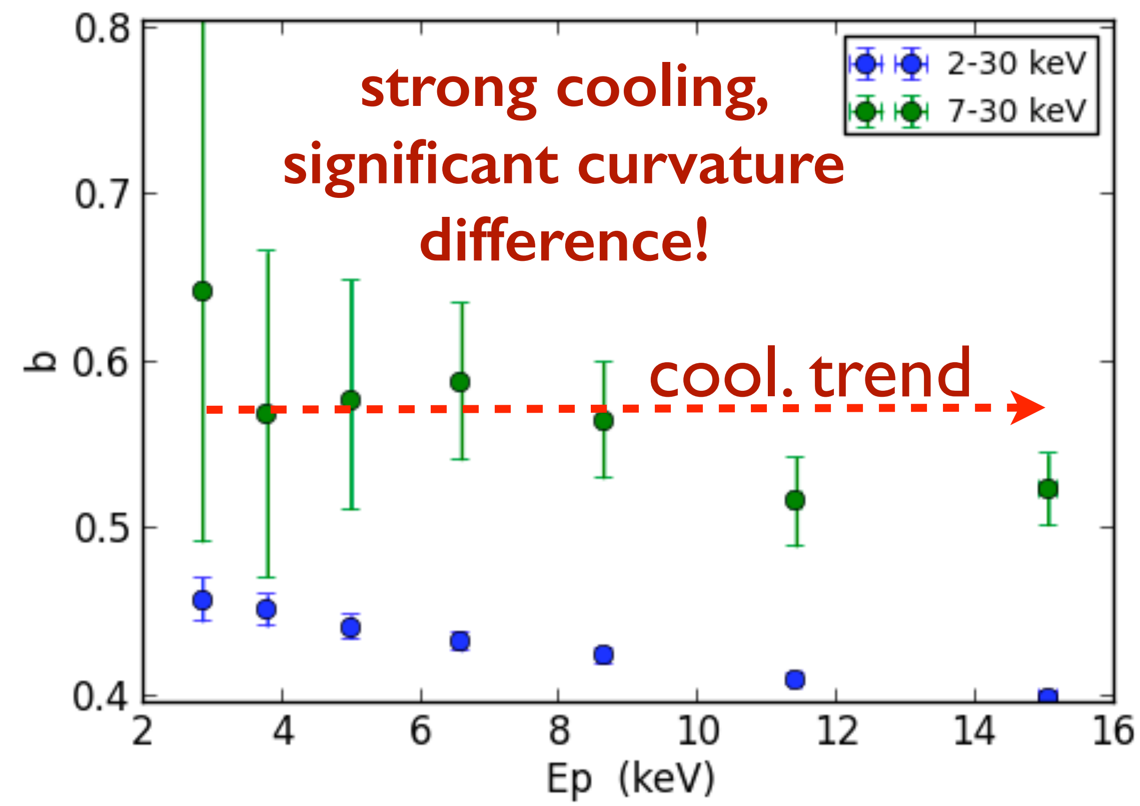




Strong cooling



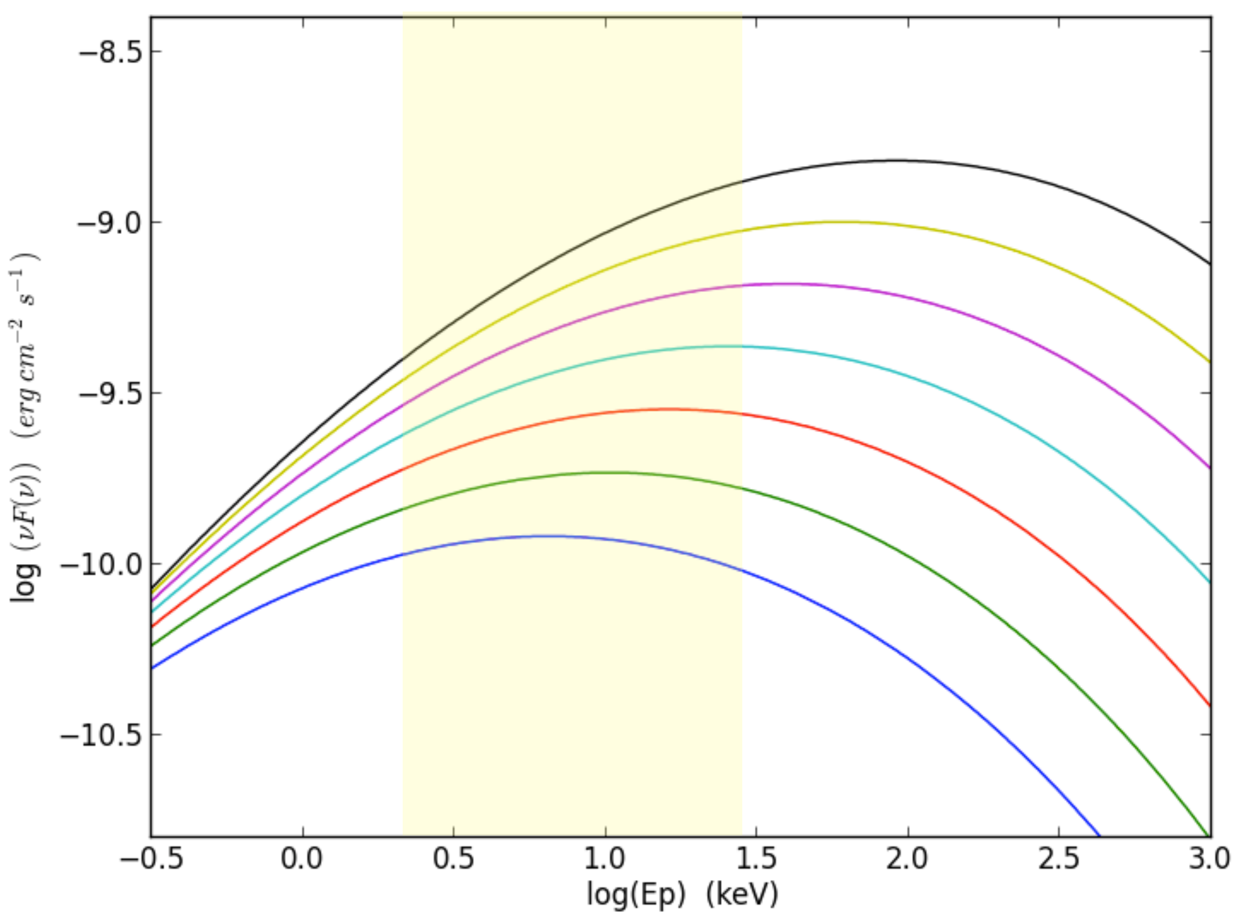




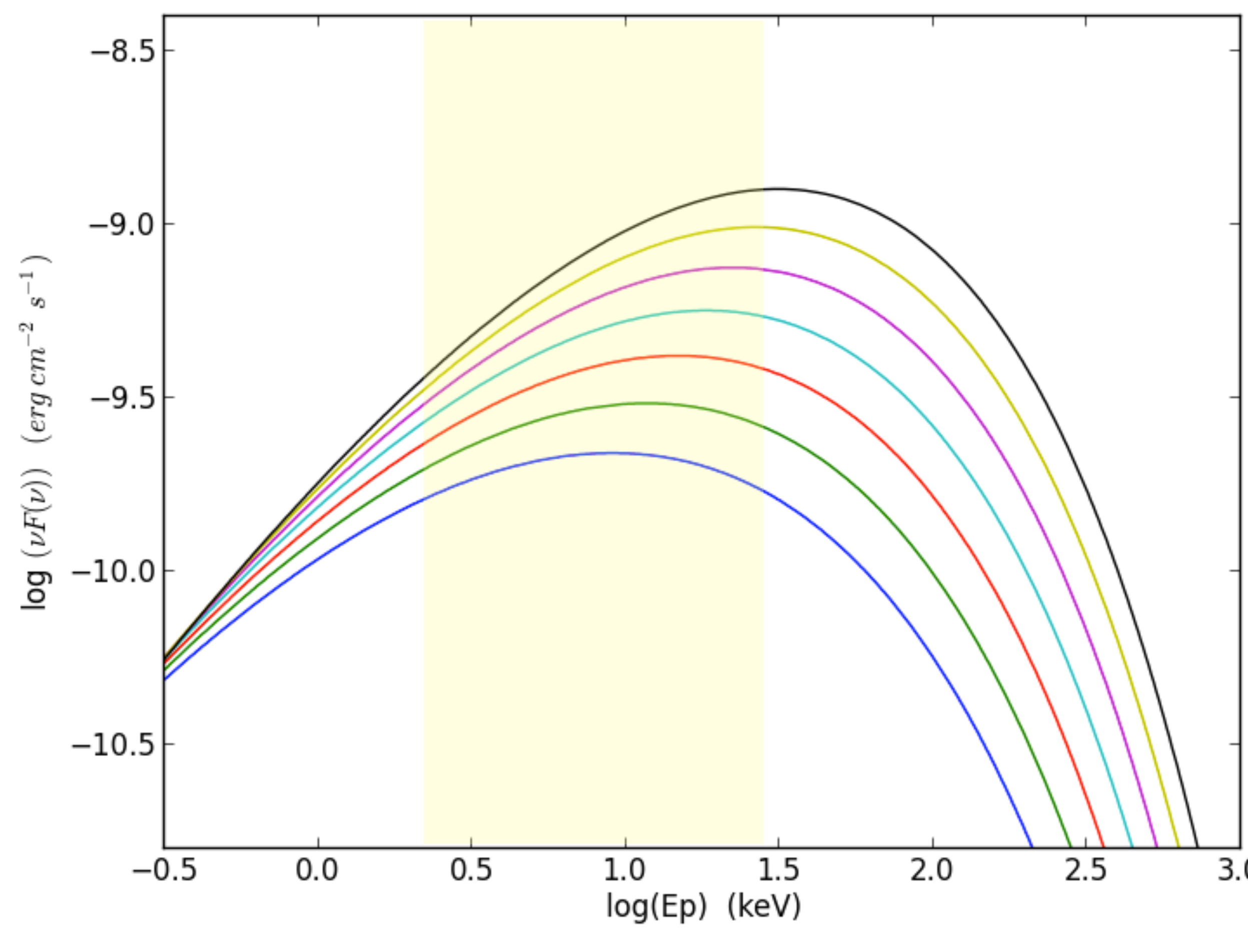
- Full bands curvature related to EED broadness, acceleration signature
- High energy band, dominated by cooling, moving towards the equilibrium

Moving Ep above 30 keV

Low cooling



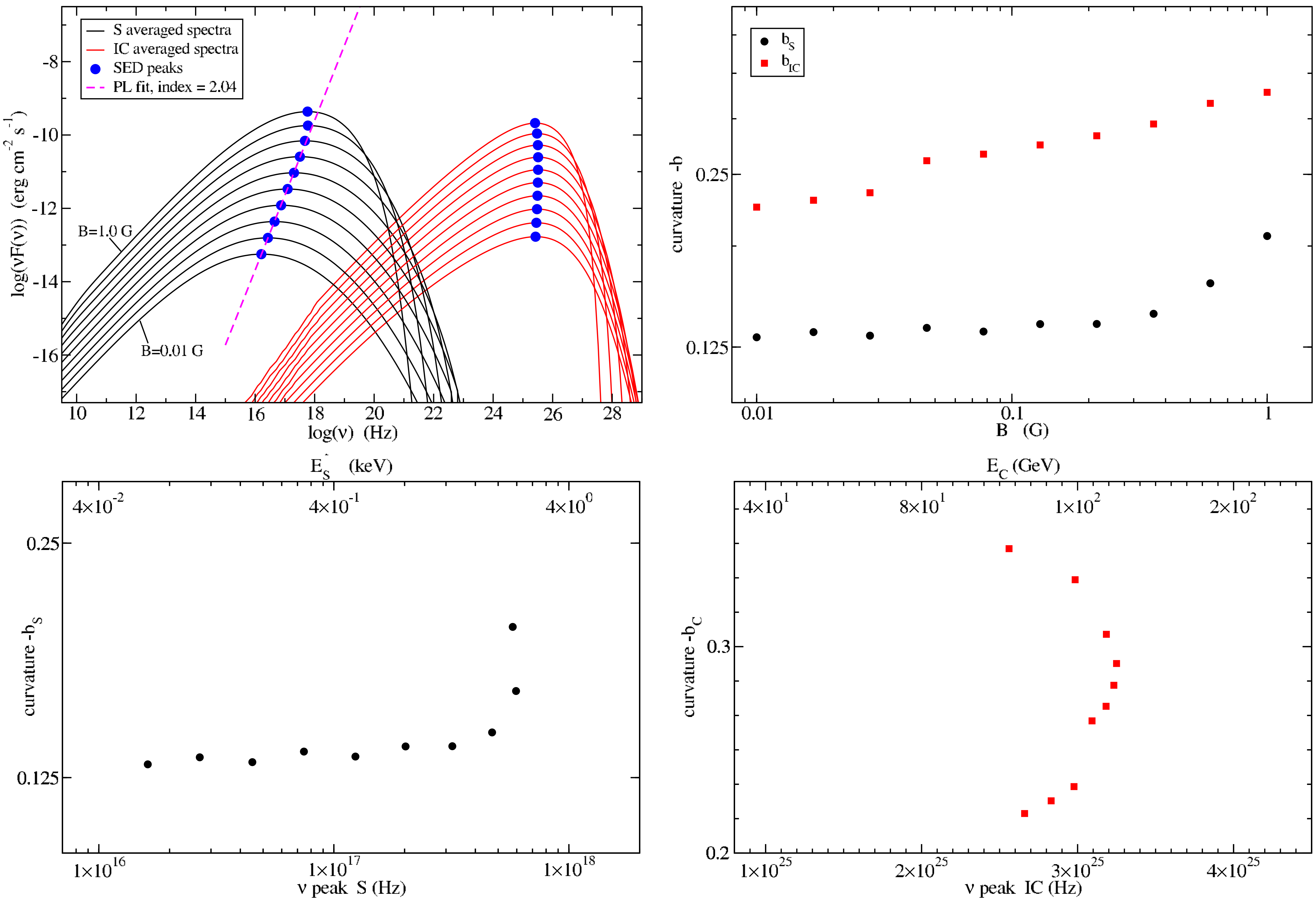
Strong cooling



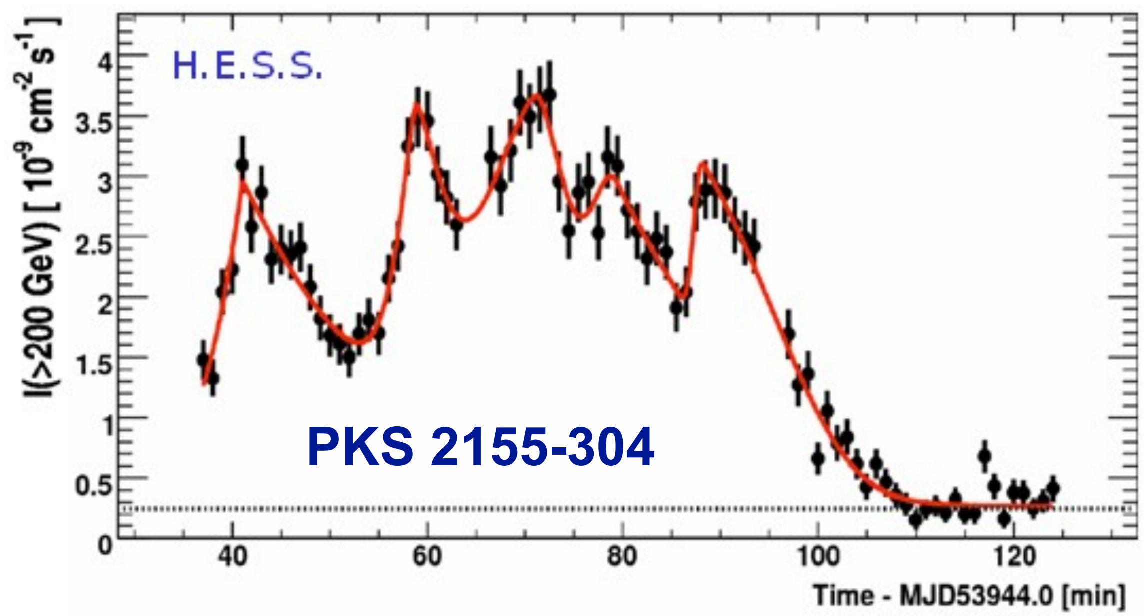
B	0.2/1.0	*G*
R	3×10^{15}	*cm*
$\mathbf{L_{inj}}$	5×10^{39}	*erg/s*
q	2	
$\mathbf{t_A}$	1.2×10^{3}	*s*
$\mathbf{t_D}$	$2.2\text{-}\times10^{4}$	*s*

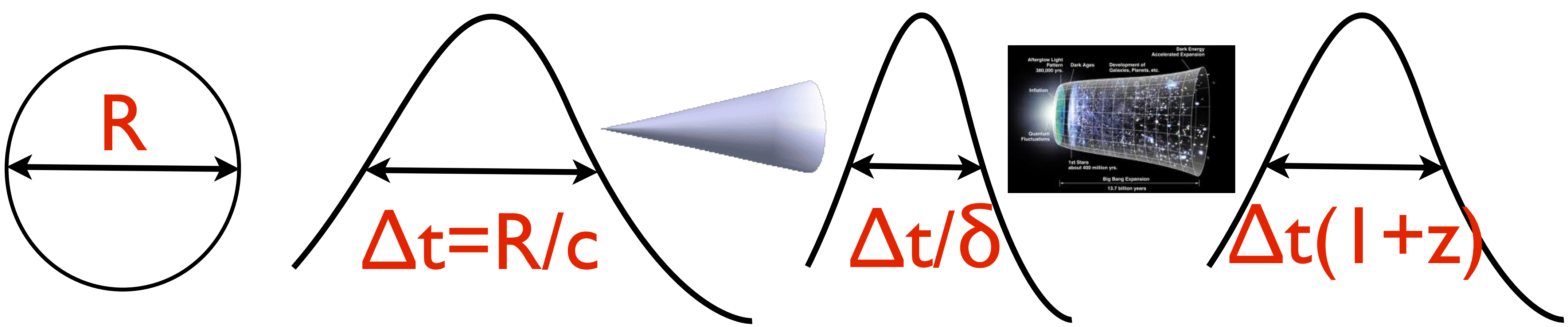
- SEDs are rescaled in order that the **brightest** state matches the flux of 10^{-09} erg cm^{-2} s^{-1} [2-10] keV
- during the flares, the fluxes range in ~ 1×10^{-10}-10^{-9} erg cm^{-2} s^{-1}
- **1 ks integration time**

Effect o B on SEDs



Rapid Variability

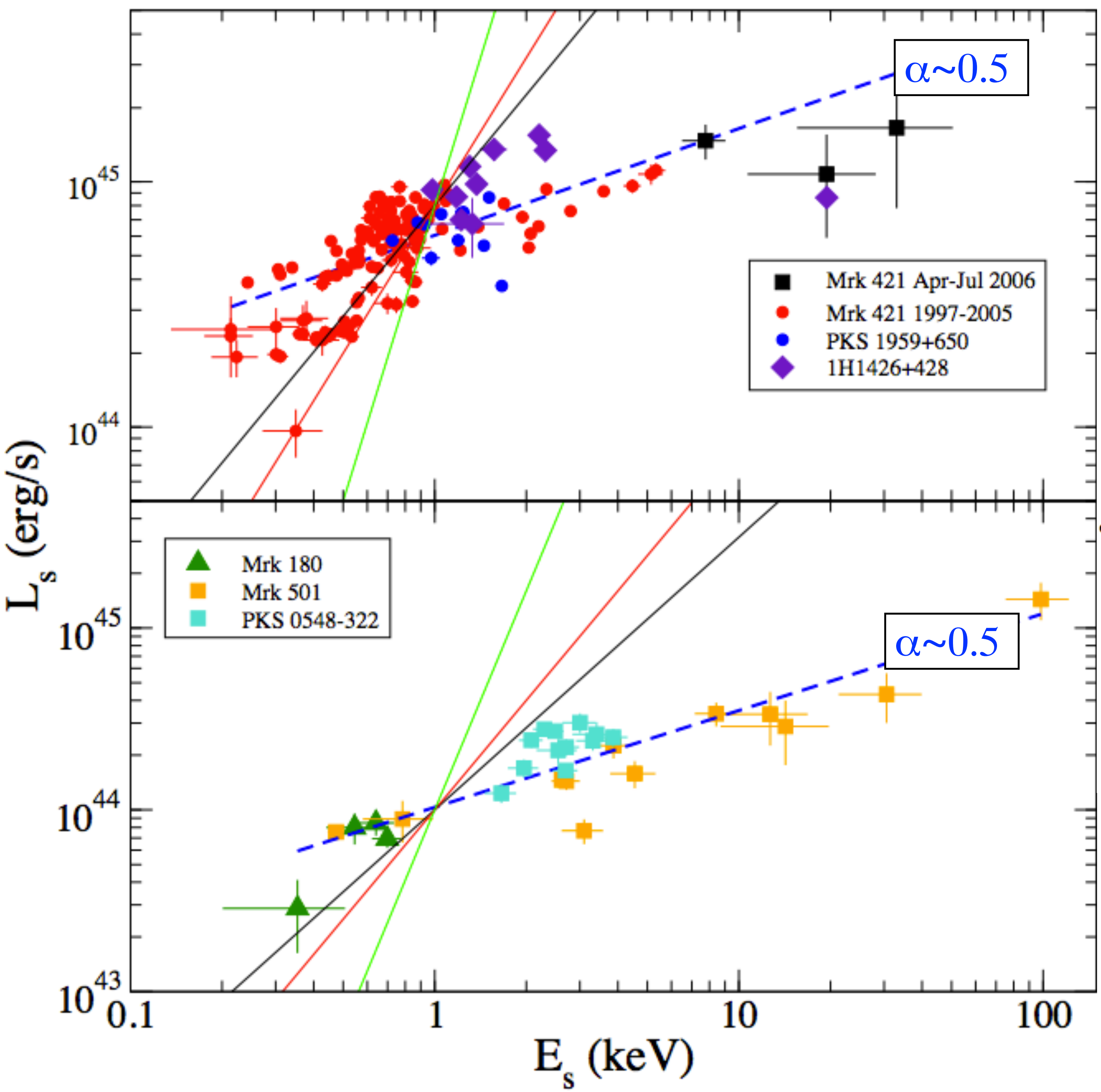




R<= c Δtδ/(1+z)

acceleration signature in the E_S-vs-L_s trend

long-trend main drivers



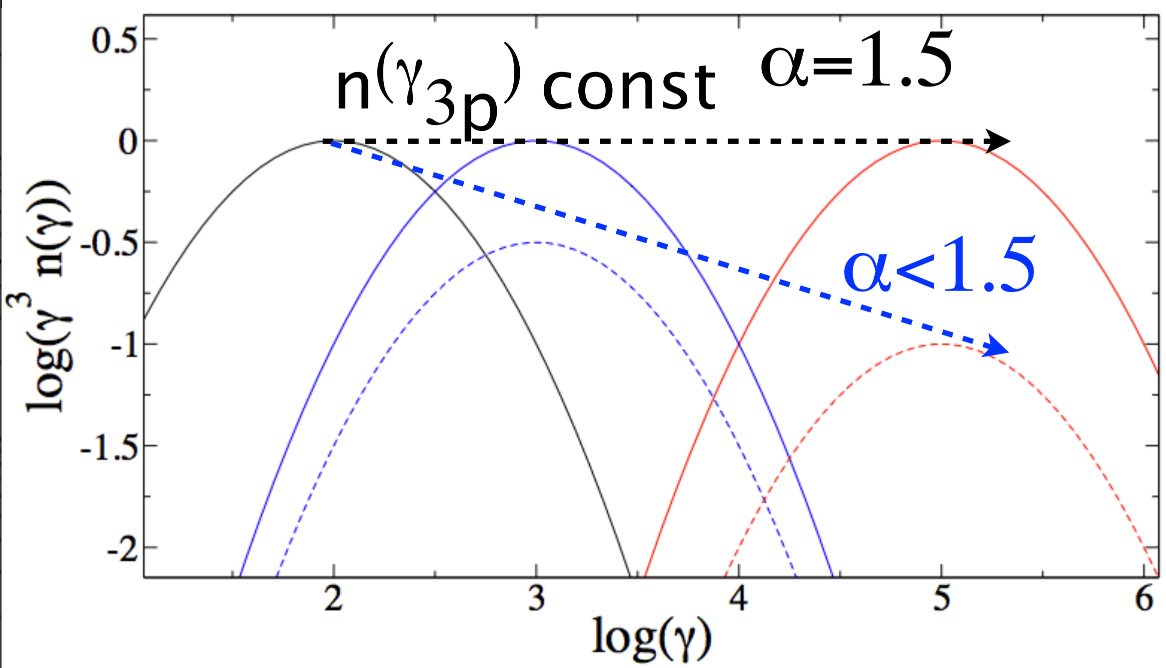
Tramacere A., et al.2009A&A...501

$$S_s(E_s) \propto n(\gamma_{3p})\gamma_{3p}^3 B^2 \delta^4$$

$$E_s \propto \gamma_{3p}^2 B \delta.$$

↓

$$S_s \propto (E_s)^\alpha$$

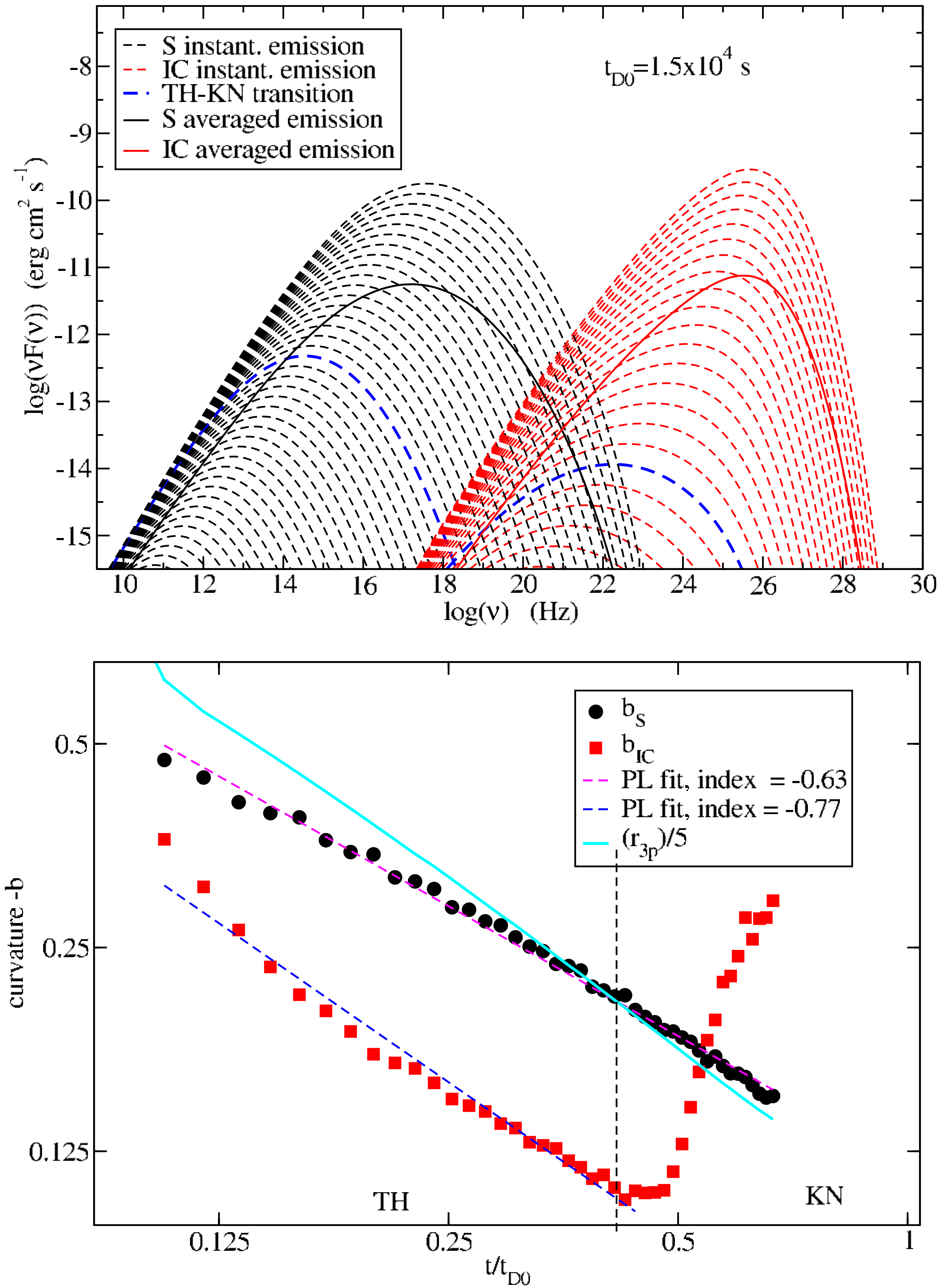


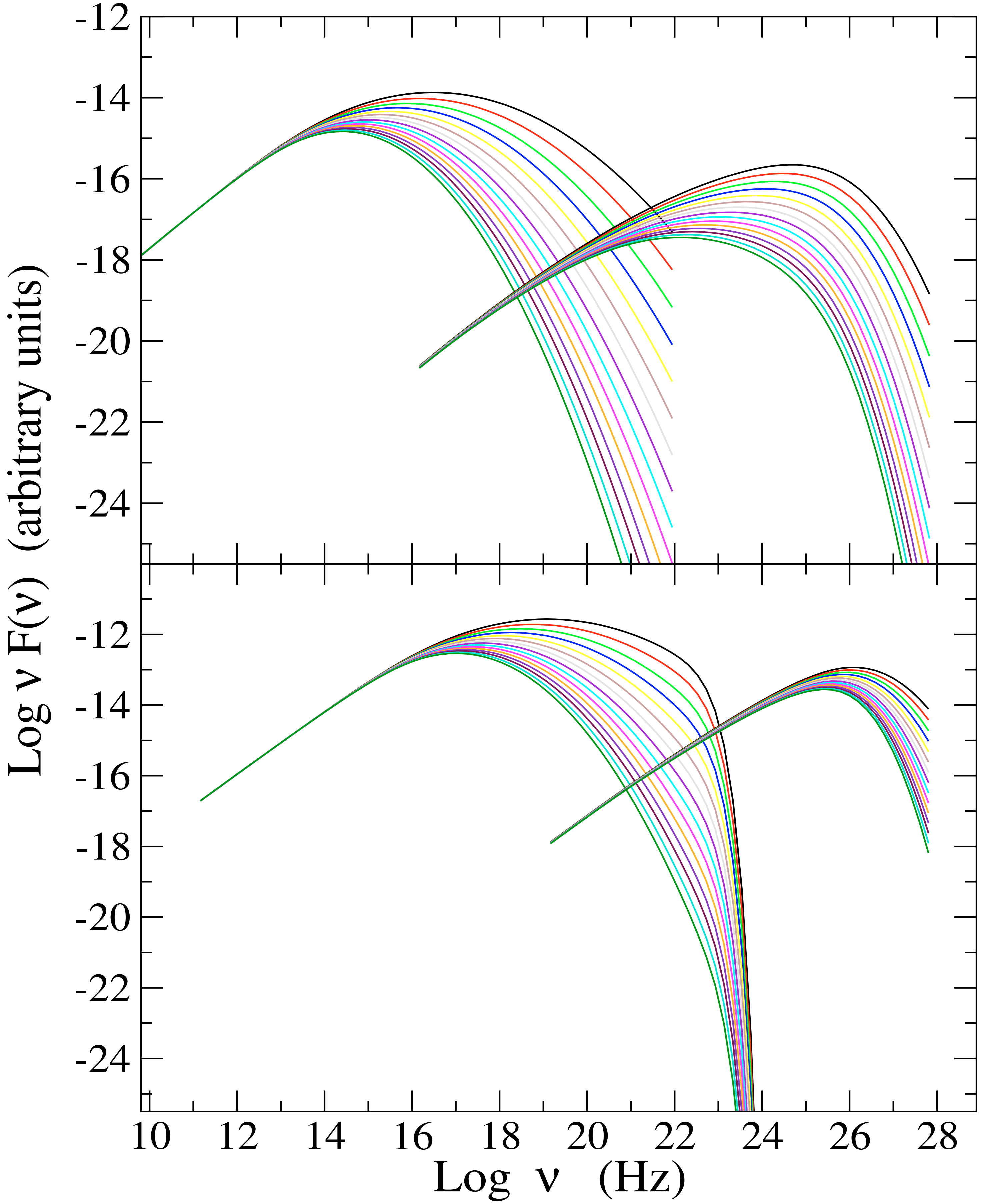
•γ_{3p}↑ **and n(γ3p)↓ =>** α<1.5

acceleration+energy conservation

•B−>α=2.0,
•δ−>α=4

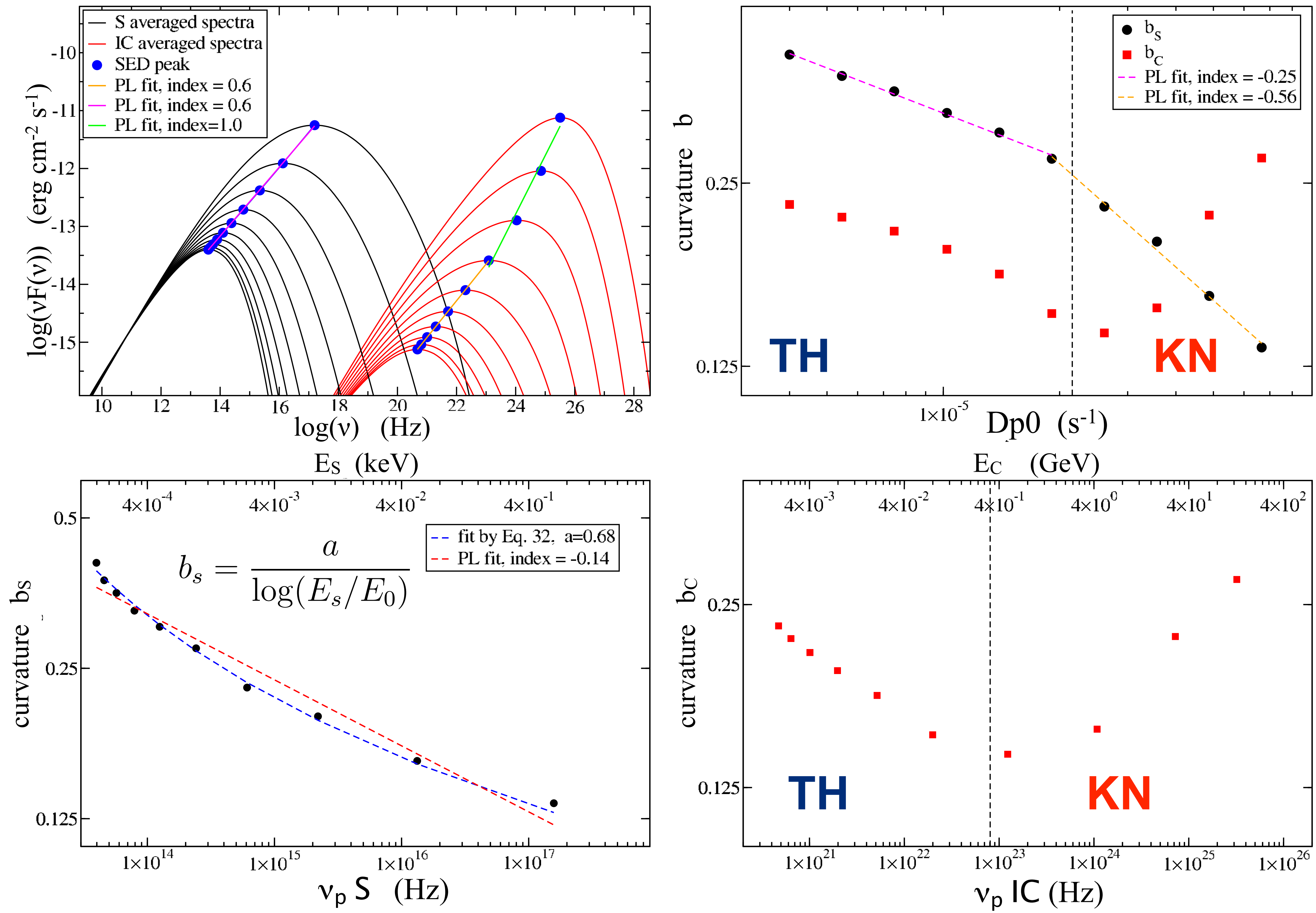
incompatible as long-trend main driver

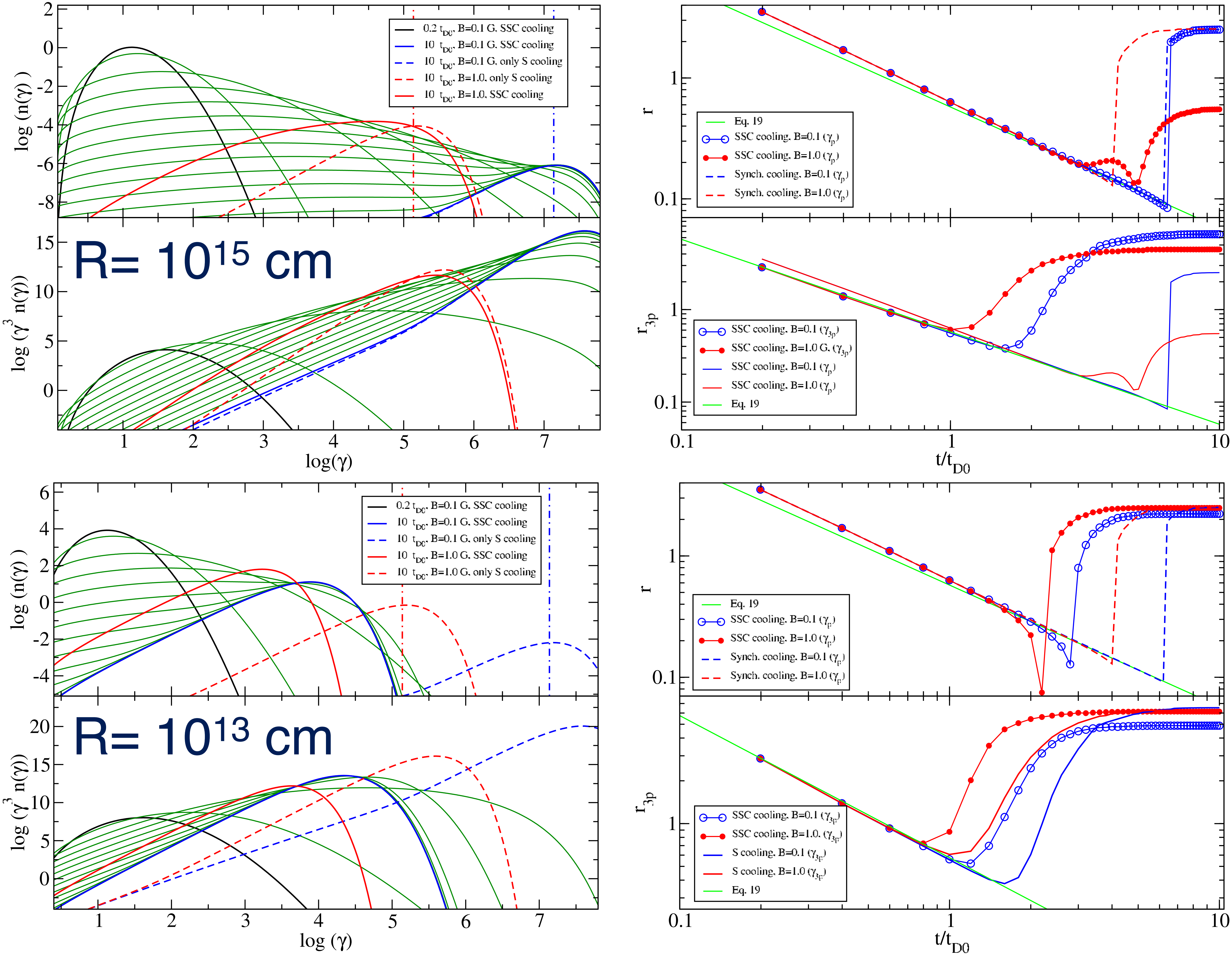

S instant. emission
IC instant. emission
TH-KN transition
S averaged emission
IC averaged emission
$t_{D0}=1.5x10^4$ s
log(νF(ν)) (erg cm^2 s^{-1})
log(ν) (Hz)
b_S
b_{IC}
PL fit, index = -0.63
PL fit, index = -0.77
$(r_{3p})/5$
curvature -b
TH
KN
t/t_{D0}



-12
-14
-16
-18
-20
-22
-24
-12
-14
-16
-18
-20
-22
-24
Log ν F(ν) (arbitrary units)
10
12
14
16
18
20
22
24
26
28
Log ν (Hz)

D_p-driven trends $t_{D=}[1.5x10^4-1.5x10^5]$, L_{inj}=const.

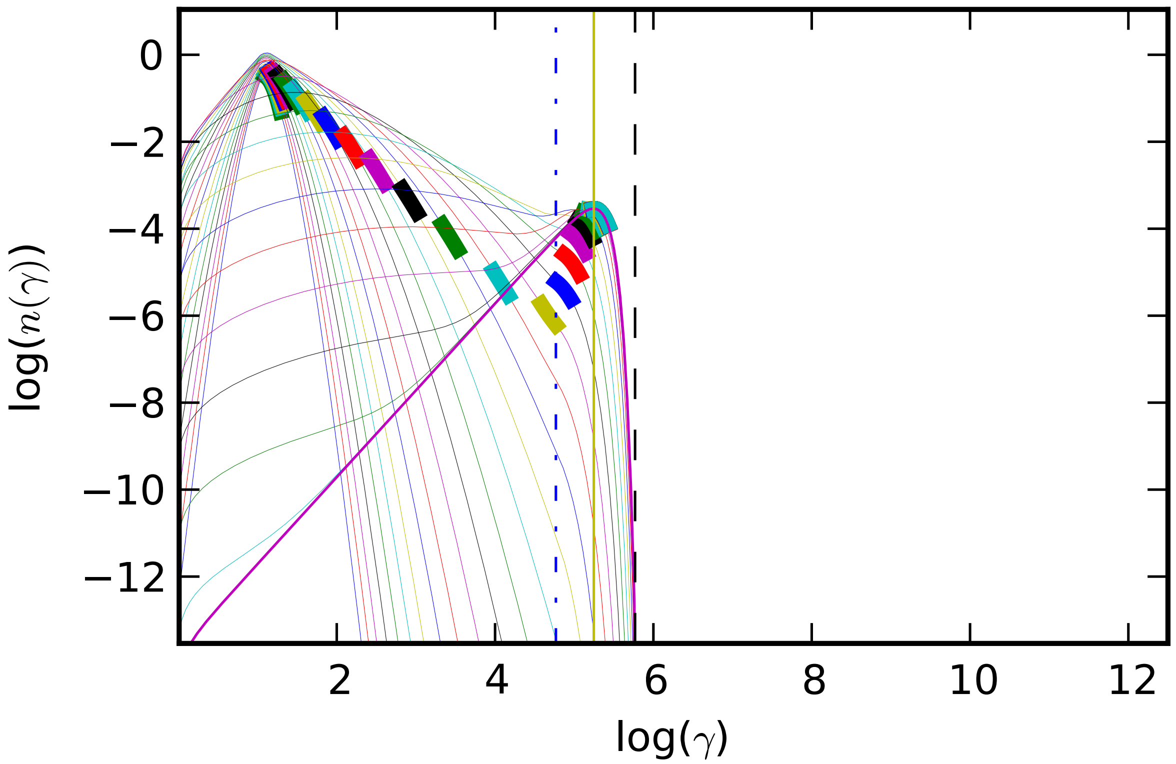




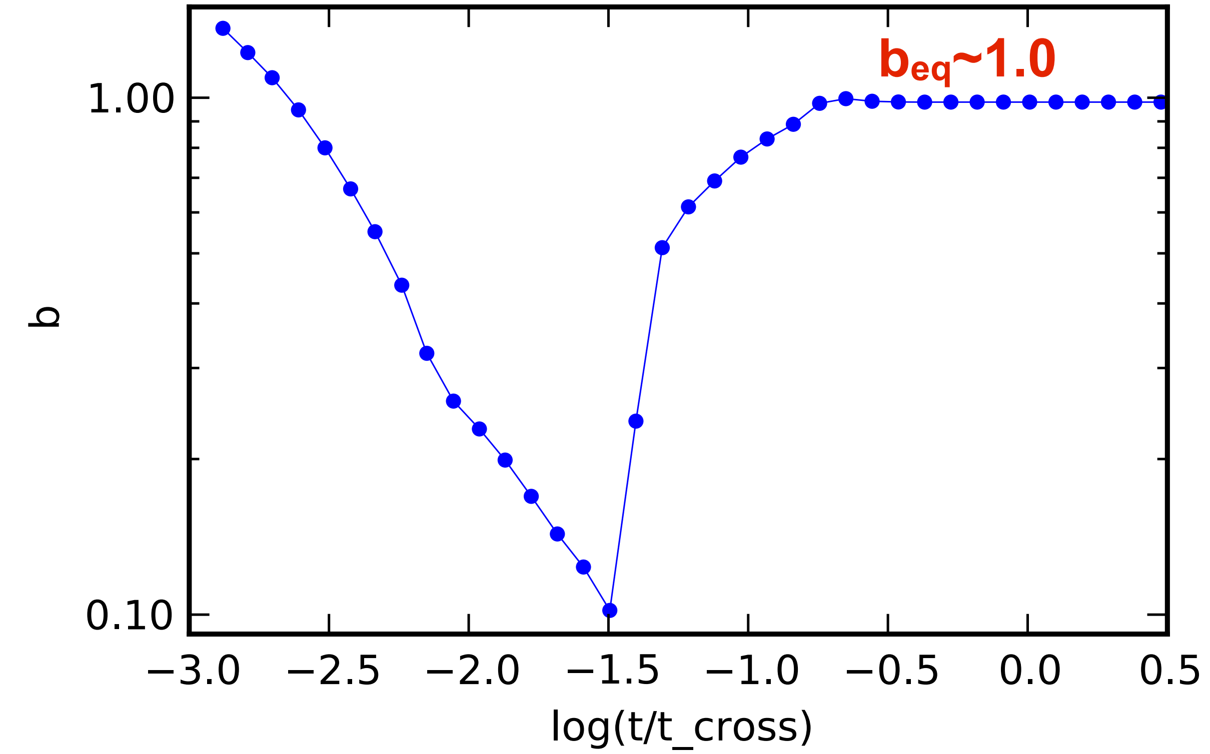
0.2 t_D0, B=0.1 G, SSC cooling
10 t_D0, B=0.1 G, SSC cooling
10 t_D0, B=0.1 G, only S cooling
10 t_D0, B=1.0, only S cooling
10 t_D0, B=1.0, SSC cooling
log (n(γ))
log (γ^3 n(γ))
R= 10^15 cm
log(γ)
r
Eq. 19
SSC cooling, B=0.1 (γ_p)
SSC cooling, B=1.0 (γ_p)
Synch. cooling, B=0.1 (γ_p)
Synch. cooling, B=1.0 (γ_p)
r_3p
SSC cooling, B=0.1 (γ_3p)
SSC cooling, B=1.0 G, (γ_3p)
SSC cooling, B=0.1 (γ_p)
SSC cooling, B=1.0 (γ_p)
t/t_D0
0.2 t_D0, B=0.1 G, SSC cooling
10 t_D0, B=0.1 G, SSC cooling
10 t_D0, B=0.1 G, only S cooling
10 t_D0, B=1.0 G, SSC cooling
10 t_D0, B=1.0 G, only S cooling
R= 10^13 cm
log (γ)
SSC cooling, B=1.0, (γ_3p)
S cooling, B=0.1 (γ_3p)
S cooling, B=1.0 (γ_3p)

effect of λ_{max}, λ_{coher}

B=1.0 G, t_{D0}=1E3 s,q=2.0, **$\lambda_{max}=10^9$ cm**



synch. peak curvature



B=1.0 G, t_{D0}=1E3 s,q=2.0, **$\lambda_{max}=10^{15}$ cm**