UNIVERSITÉ DE GENÈVE

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extreme19

Stochastic acceleration in blazars: HBLs and EHBLs

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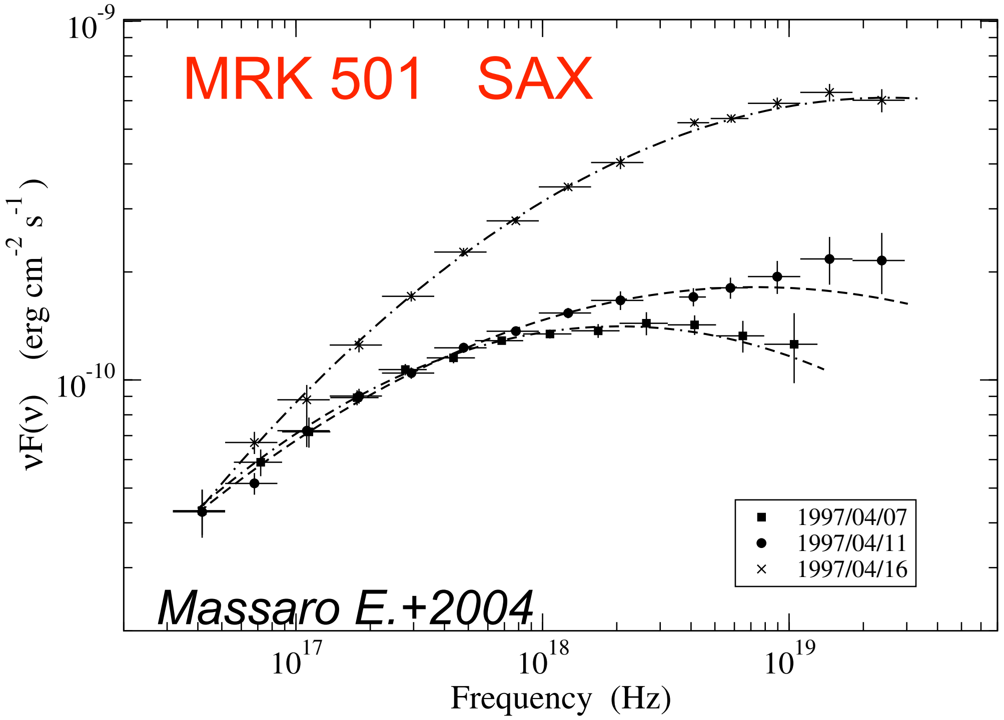
Padova

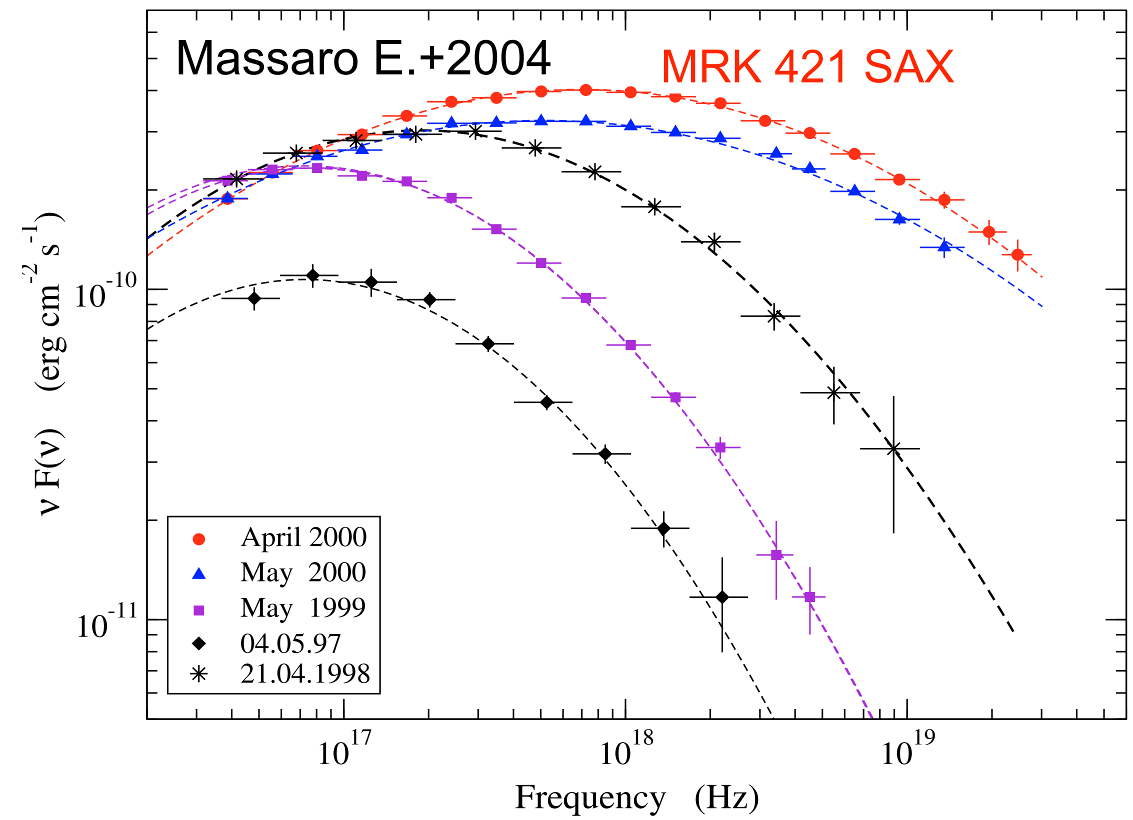
22-25 January 2019

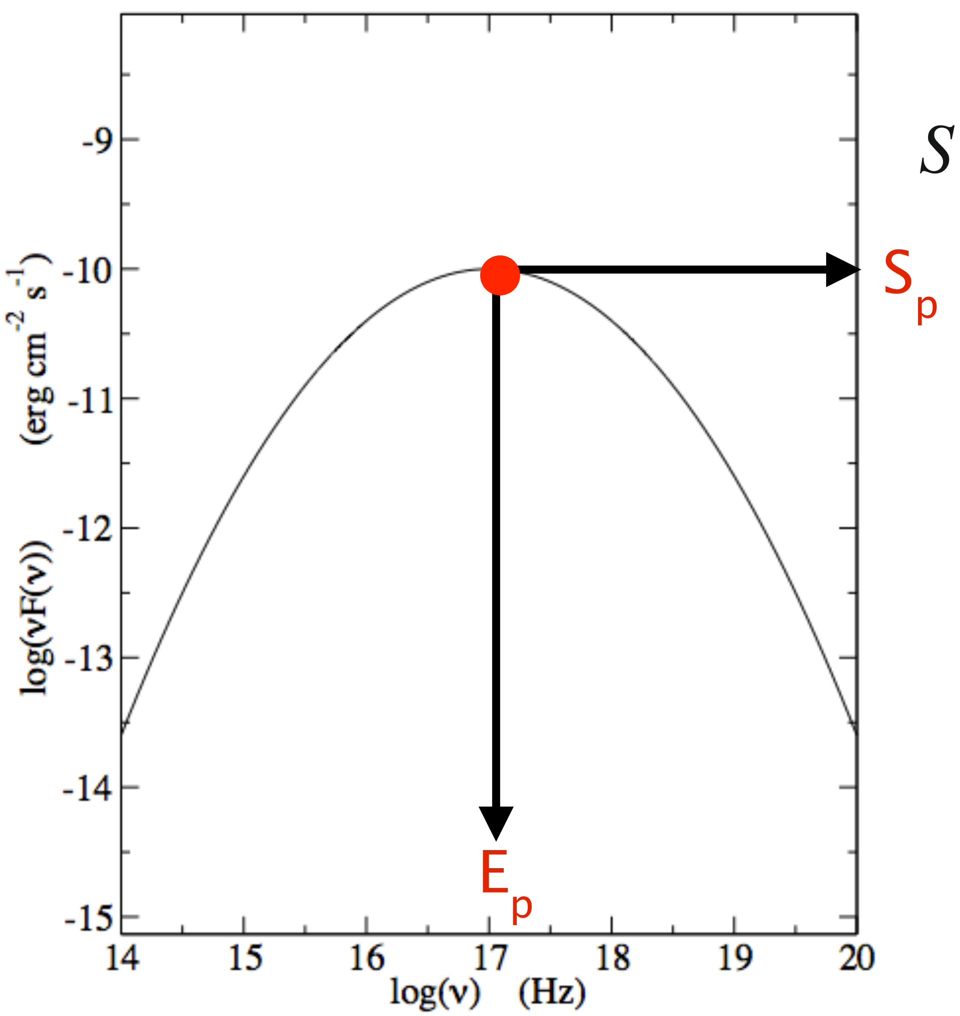
Outline

- Phenomenological signatures
- setup of Theory/Numerical framework for stochastic acceleration
- Self-consistent reproduction of Long Term Trends
- numerical modeling, numerical fit (no eyeball fit) no analytical approximations

SPECTRAL DISTRIBUTION OF HBLs





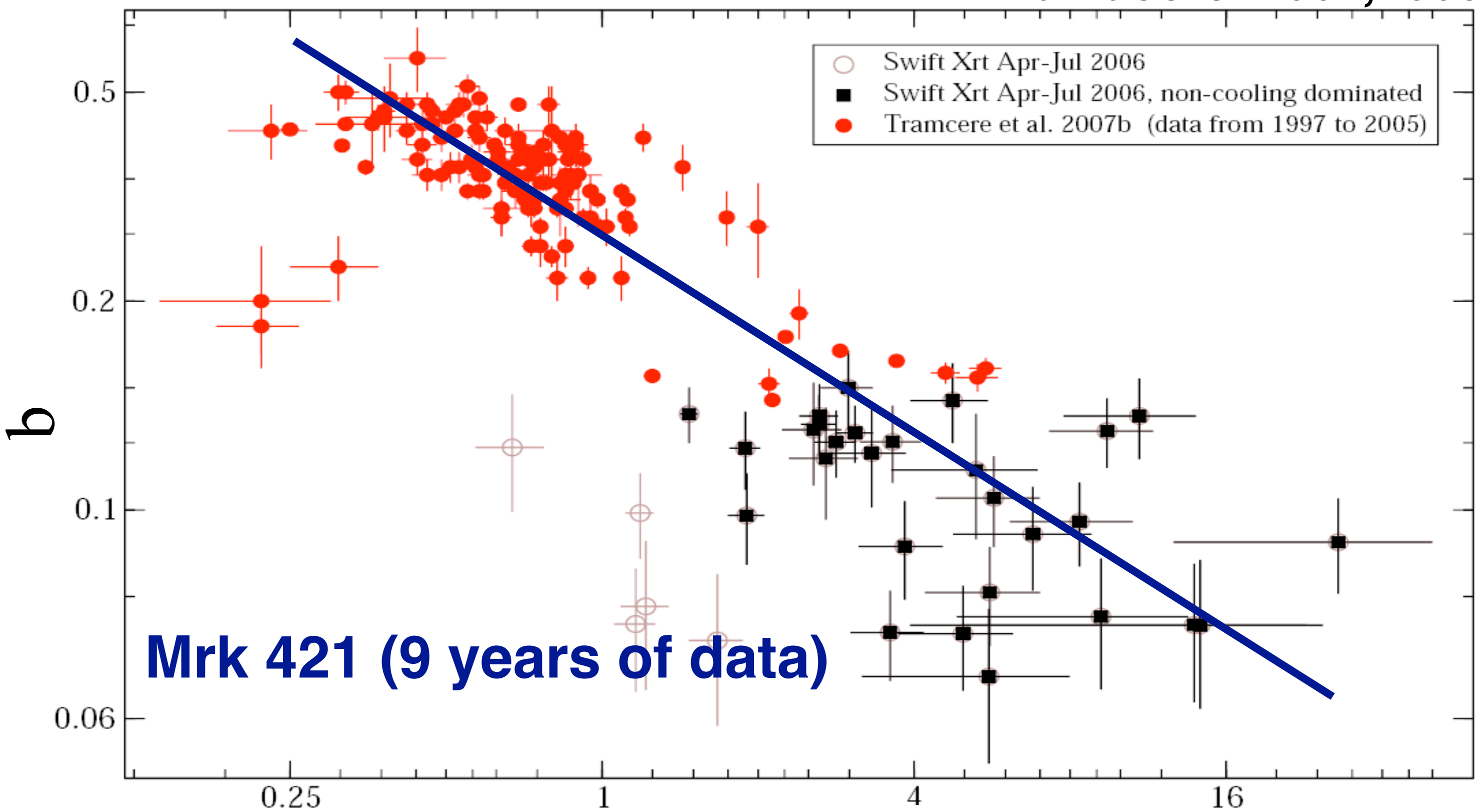


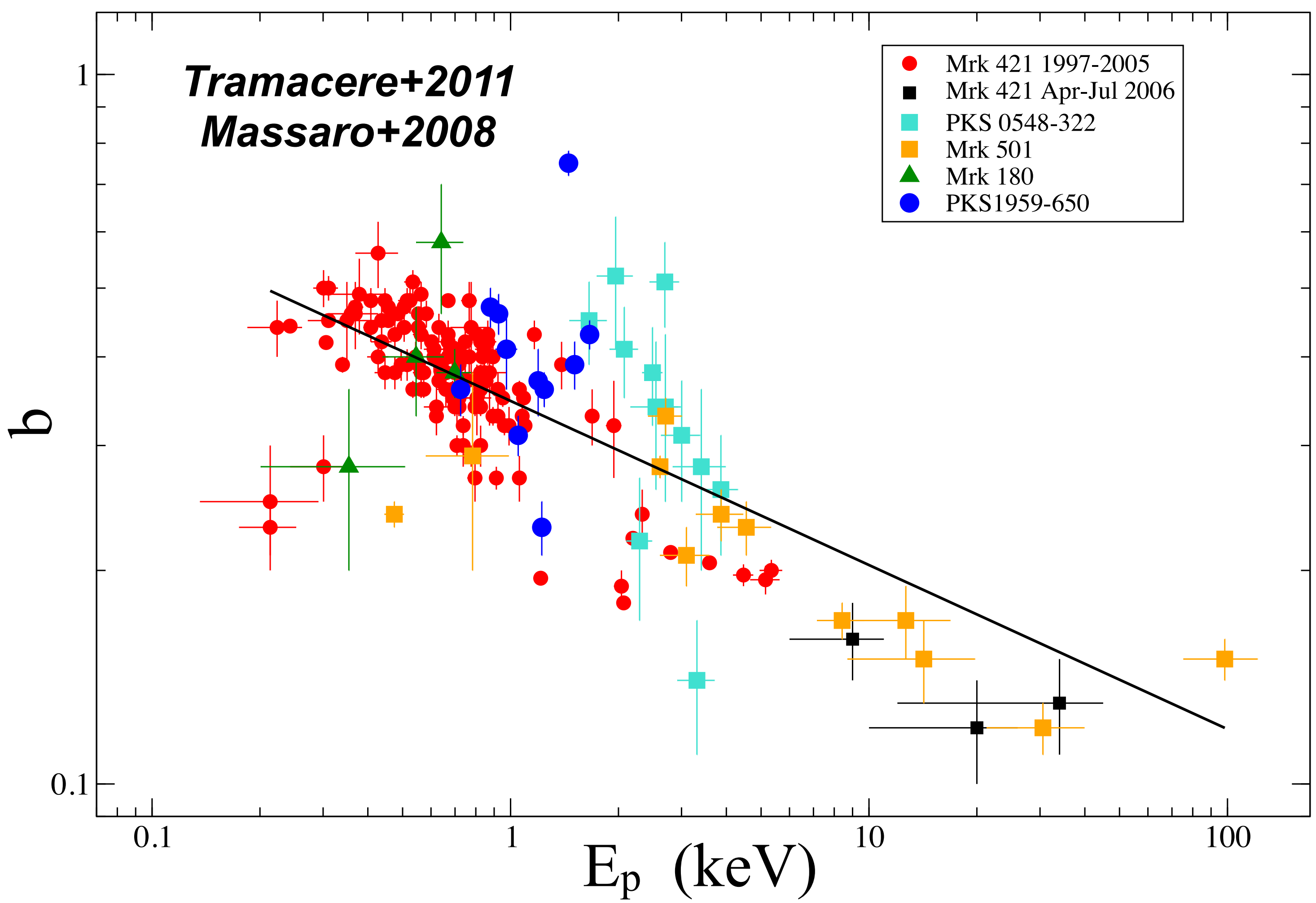
$$S(E) = S_{\rm p}\, 10^{-b\, (\log(E/E_{\rm p}))^2}$$

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

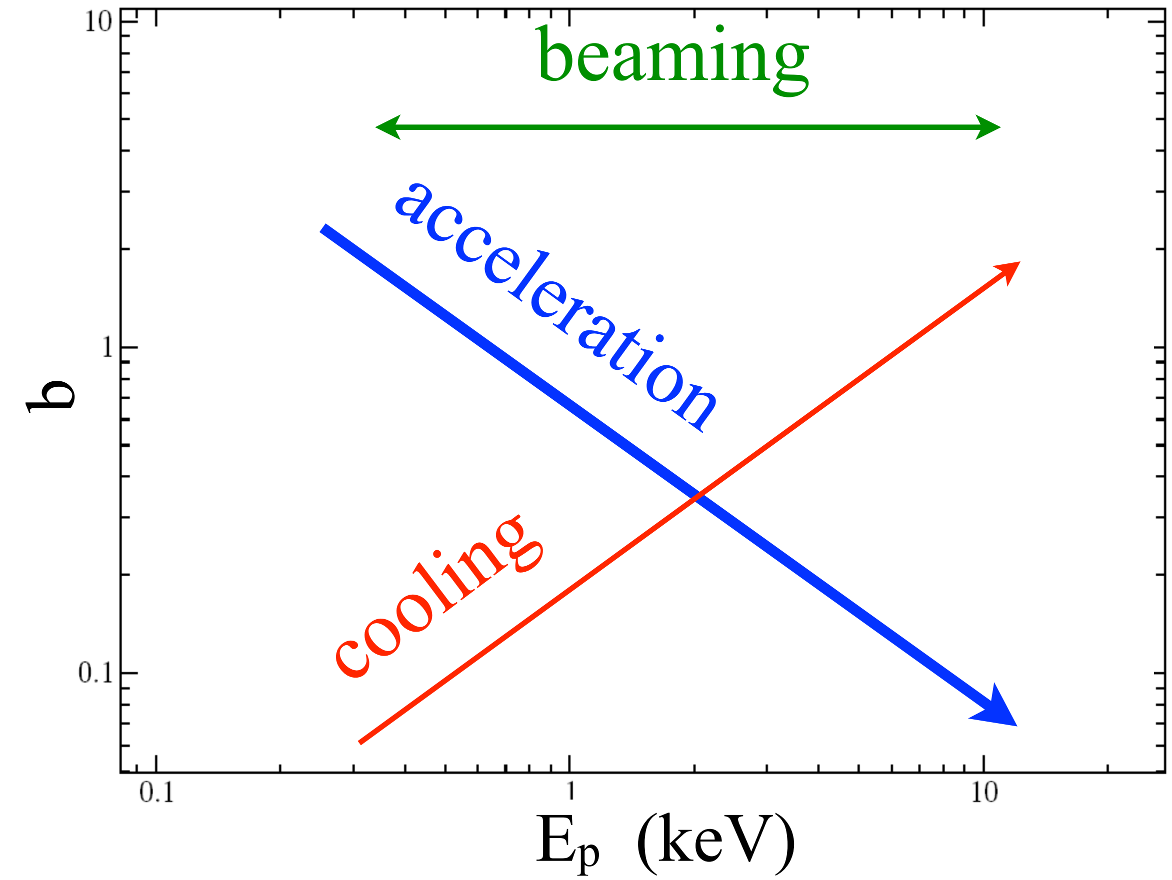
acceleration signature in the E_S-vs-b trend

Tramacere+2007,2009





Ep-vs-b, different scenarios

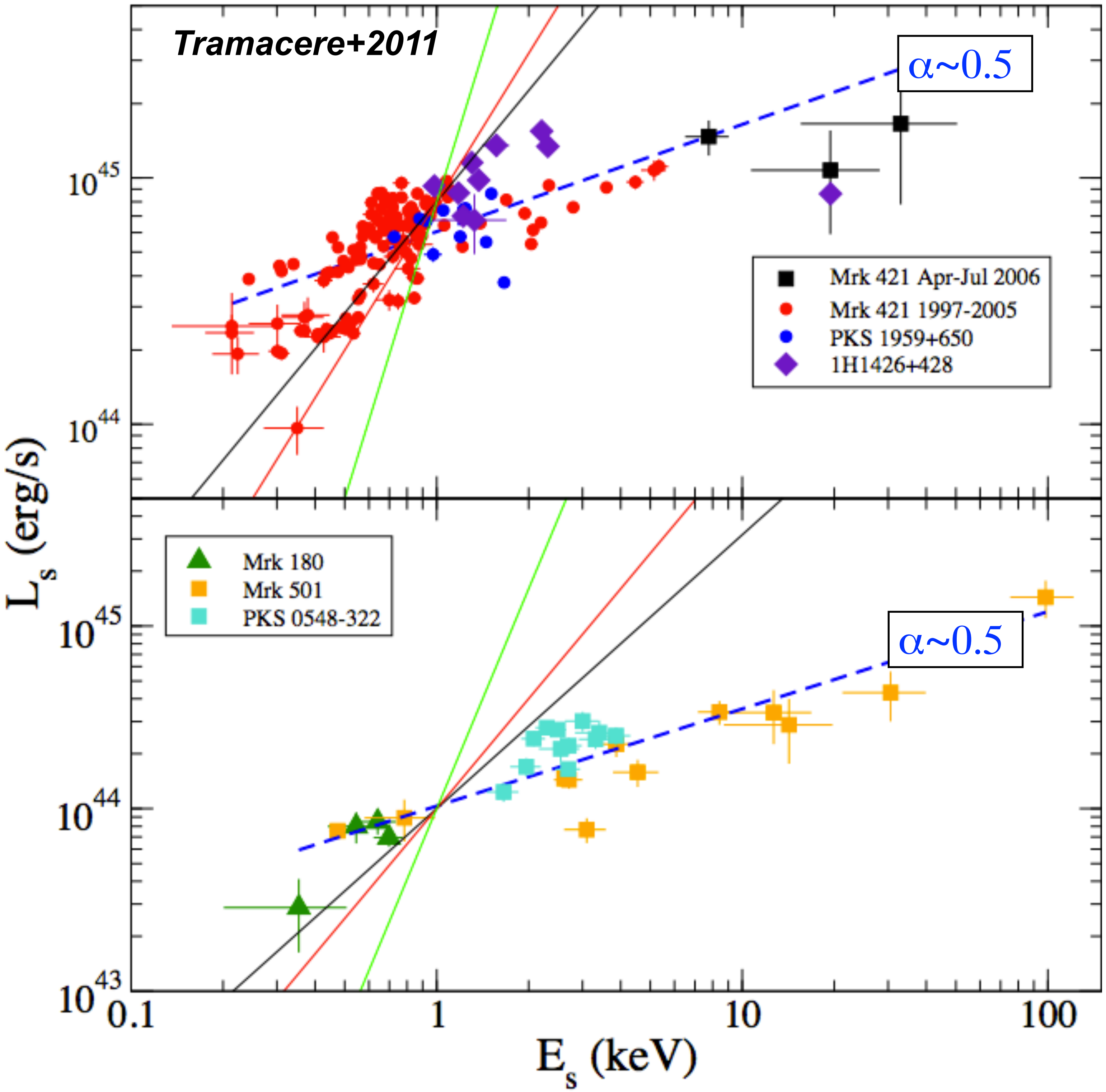


11 years of data:
PKS 0548-322,1H1426+418,
Mrk 501 ,1ES1959+650,
PKS2155-34

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

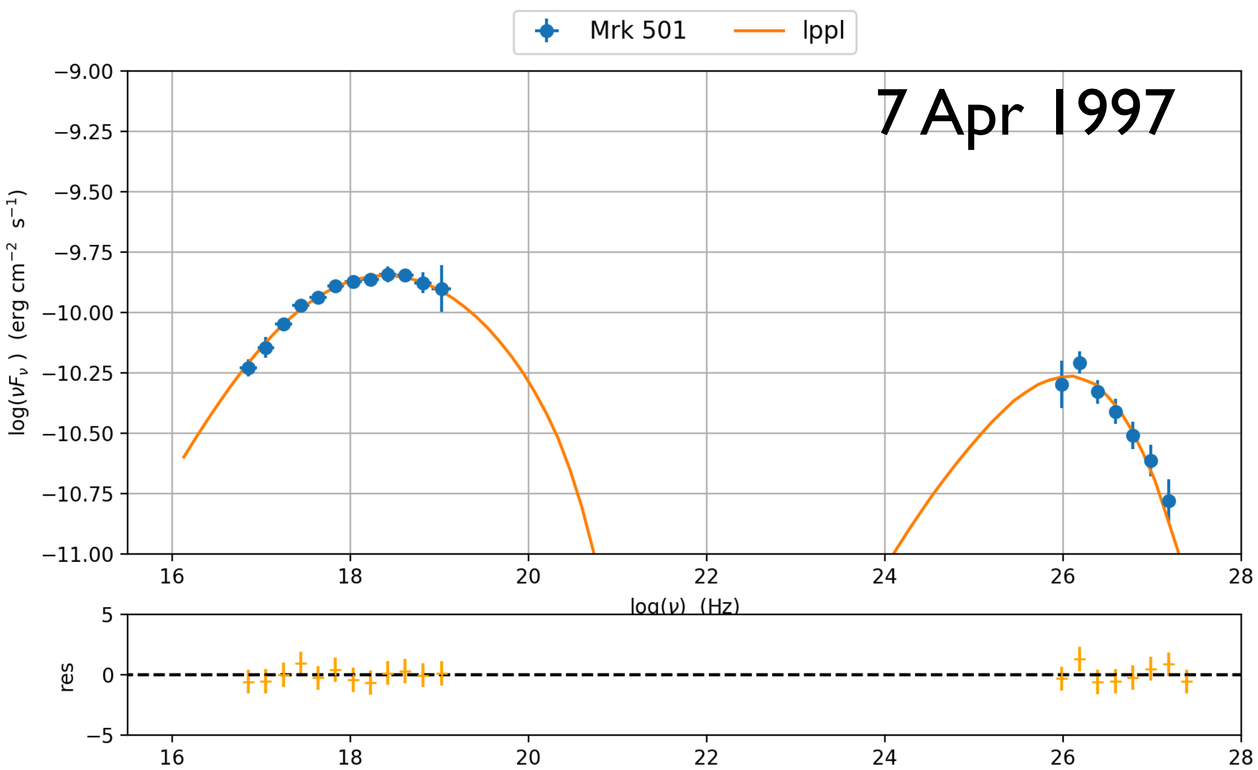
- B->α=2.0,
- δ->α=4

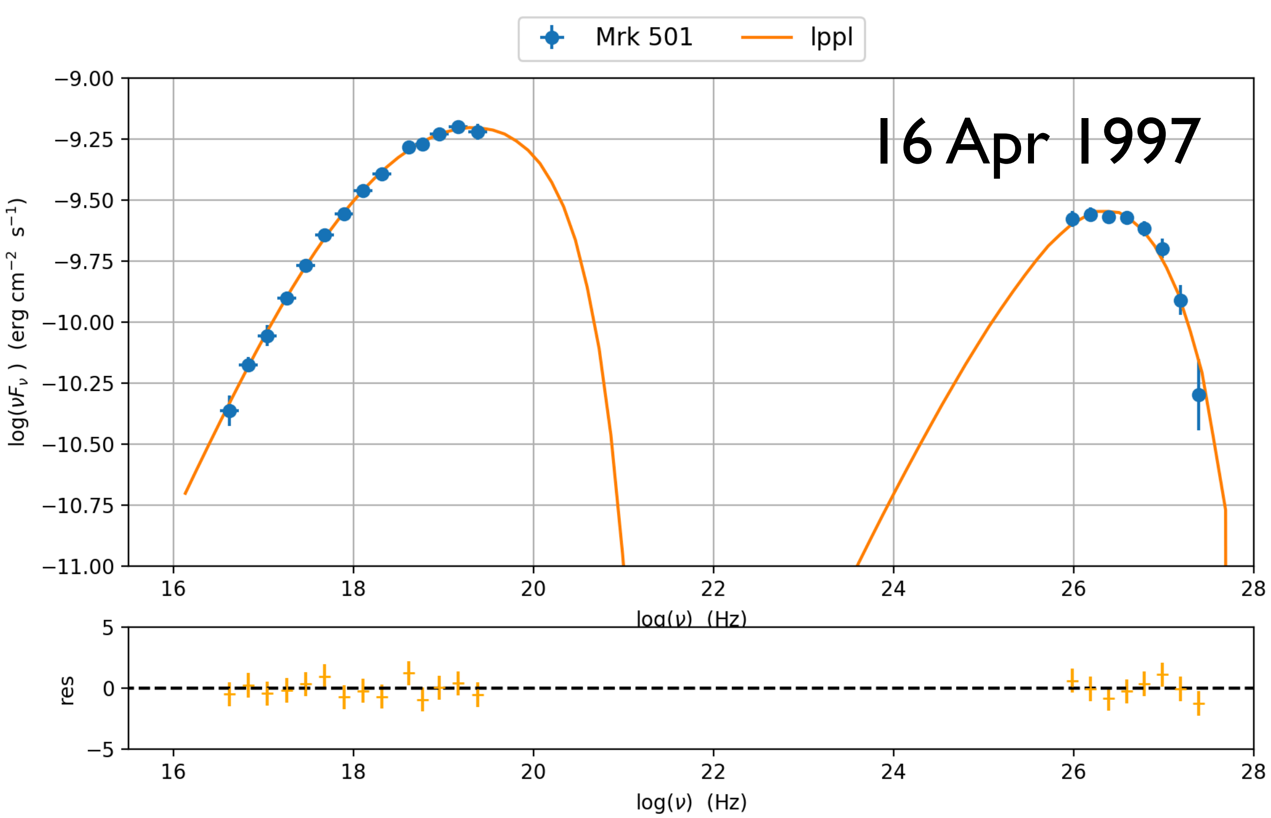
incompatible as long-trend main driver

Hard spectra $s << 2.00$

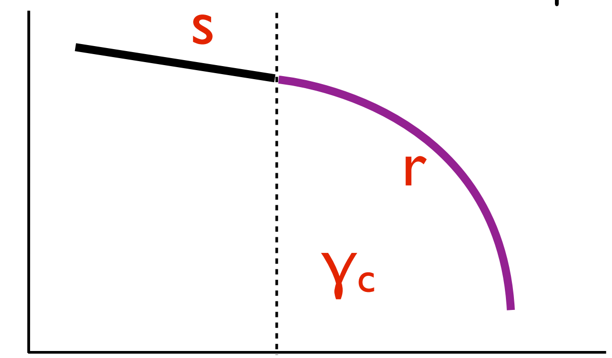
Mrk 501 1997 Flare

Massaro & Tramacere +2006





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



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
s	+1.638026e+00	+3.170384e-02
z_cosm	Frozen	Frozen

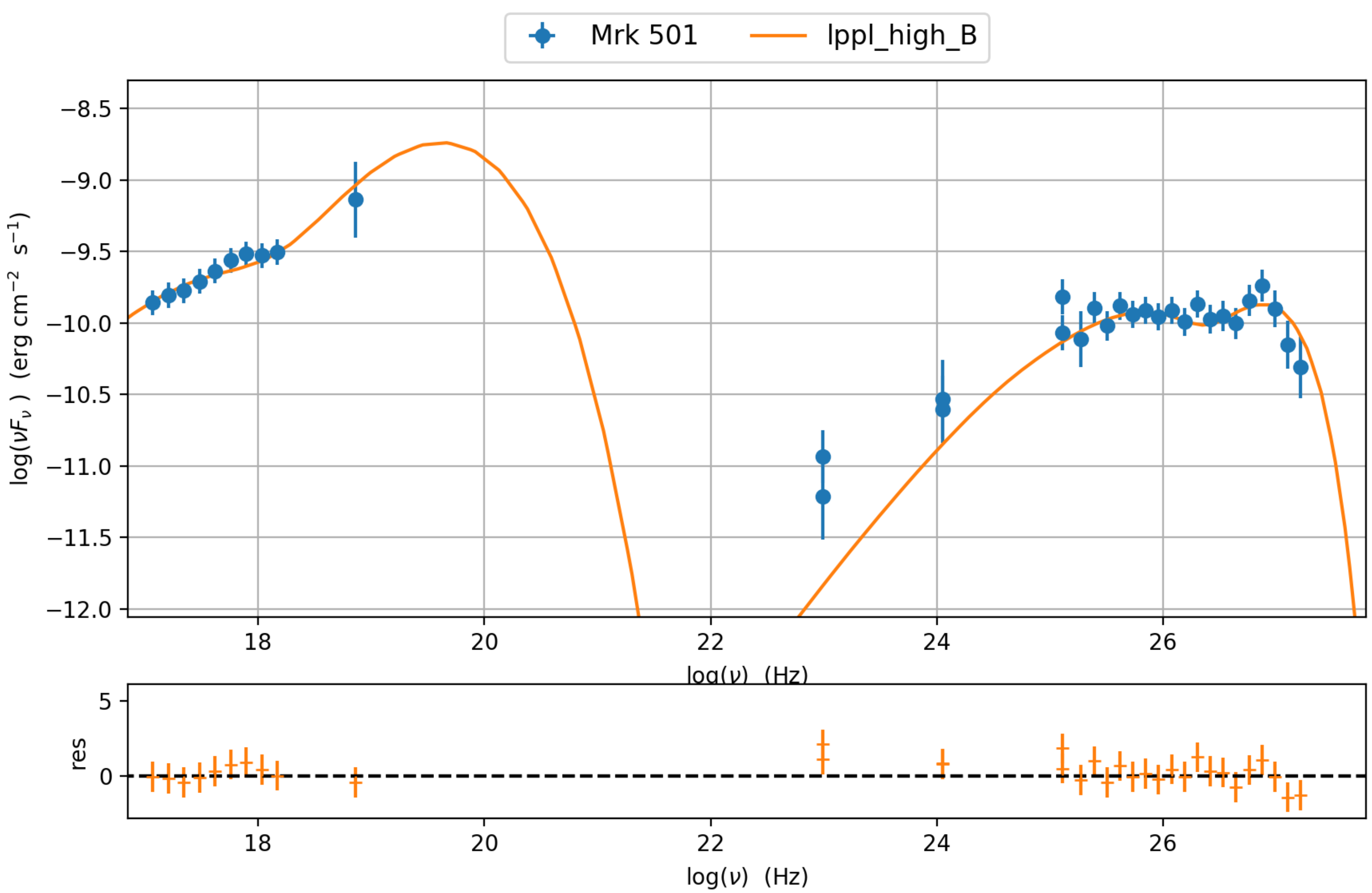
best-fit parameters:

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
s	+1.321307e+00	+1.844825e-02
z_cosm	Frozen	Frozen

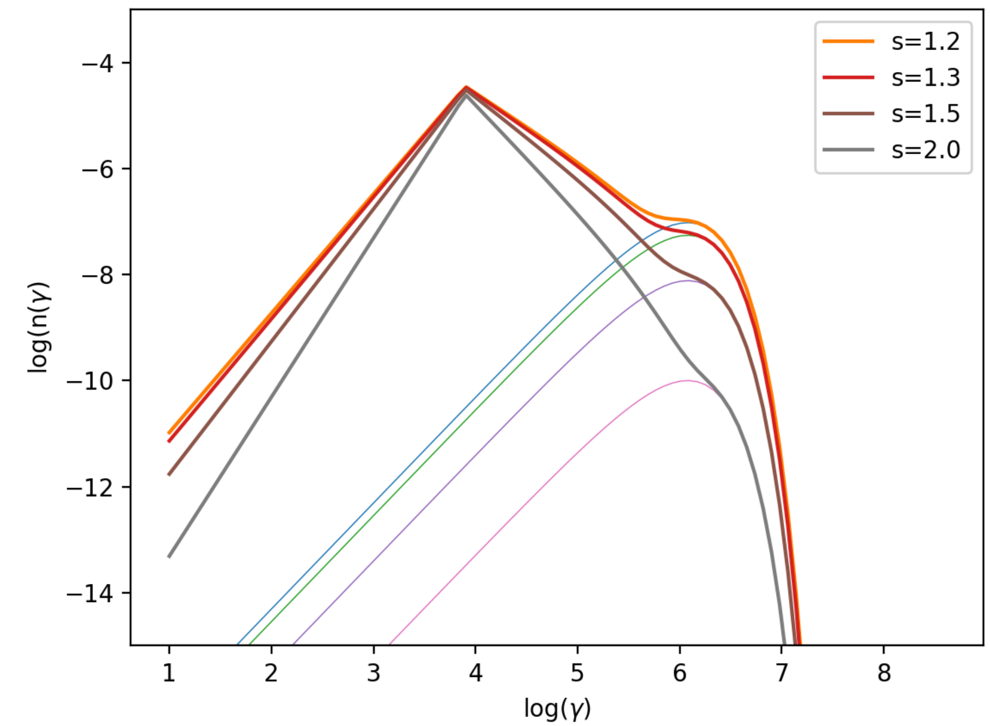
Mrk 501 2014 Flare
Paneque's talk MAGIC paper

model parameters:

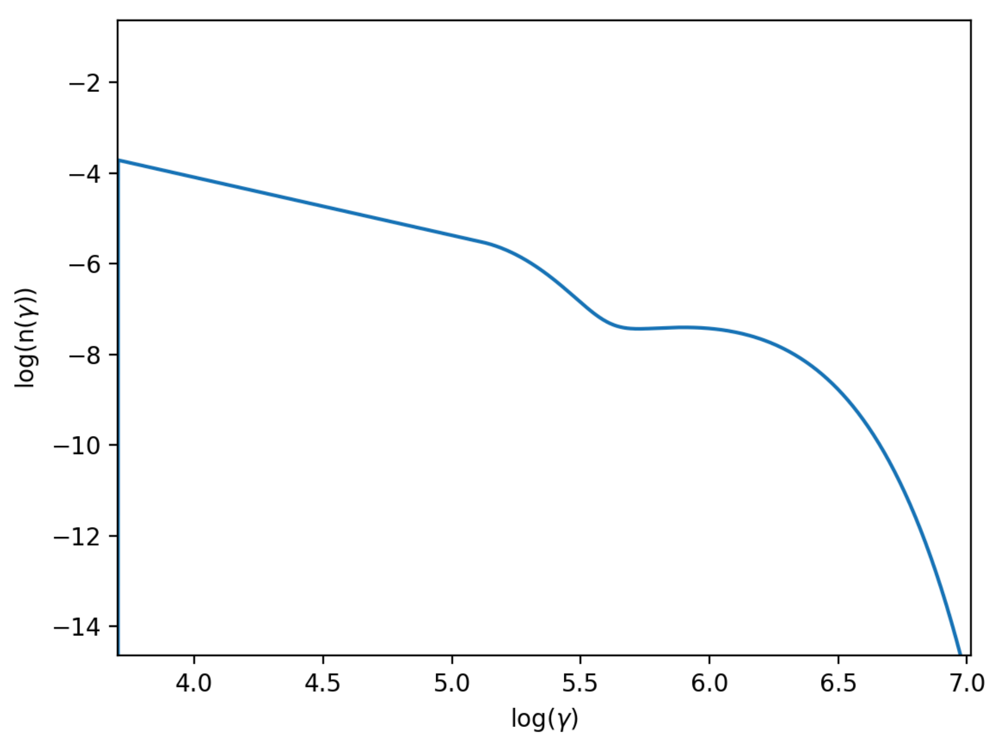
Name	Type	Units	value
B	magnetic_field	G	+3.000000e-01
N	electron_density	cm^-3	+2.360060e+00
R	region_size	cm	+1.551851e+01
alpha_pile_up	turn-over-energy		+1.000000e+00
beam_obj	beaming		+1.000000e+01
gamma0_log_parab	turn-over-energy	Lorentz-factor	+1.300000e+05
gamma_inj	turn-over-energy	Lorentz-factor	+5.000000e+03
gamma_pile_up	turn-over-energy	Lorentz-factor	+4.000000e+05
gmax	high-energy-cut-off	Lorentz-factor	+1.000000e+07
gmin	low-energy-cut-off	Lorentz-factor	+5.000000e+03
r	spectral_curvature		+6.100000e+00
ratio_pile_up	turn-over-energy		+7.000000e-18
s	LE_spectral_slope		+1.280000e+00
z_cosm	redshift		+3.364200e-02



cont. single injection (Stawarz&Petrosian 2009)
not compatible with MW data



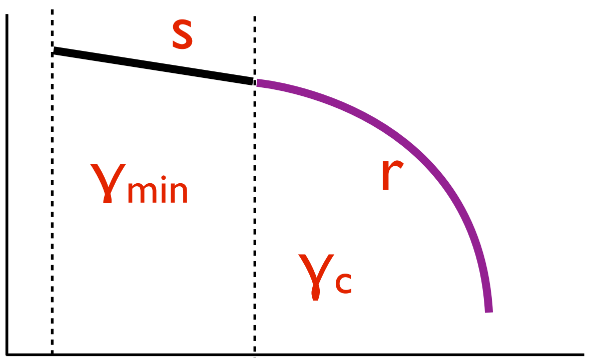
double cospatial injection
compatible with data



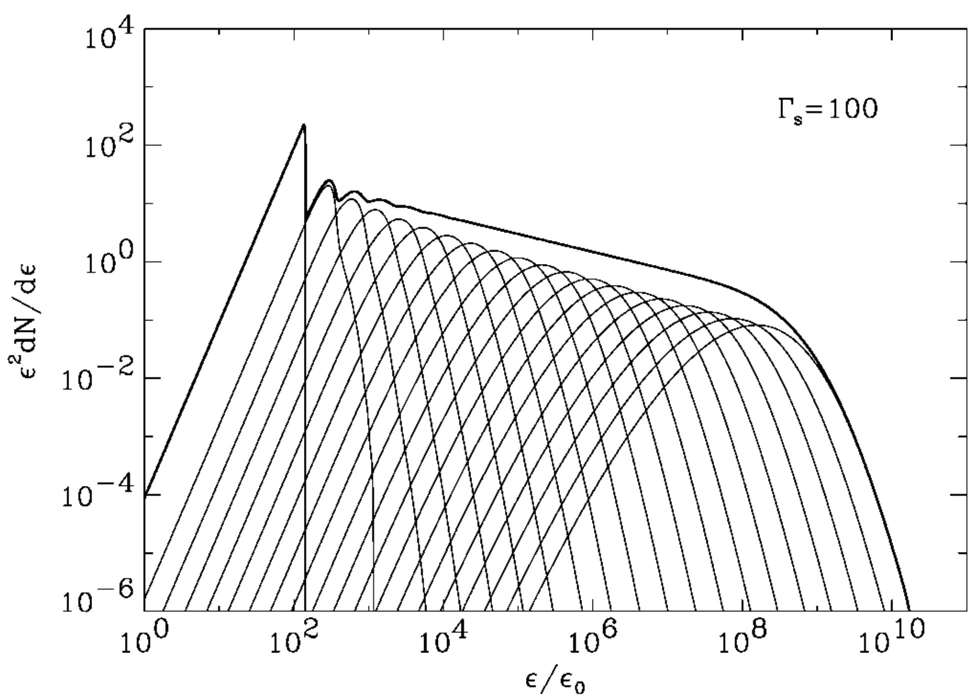
Fermi I+Fermi II   Mrk 421 2006

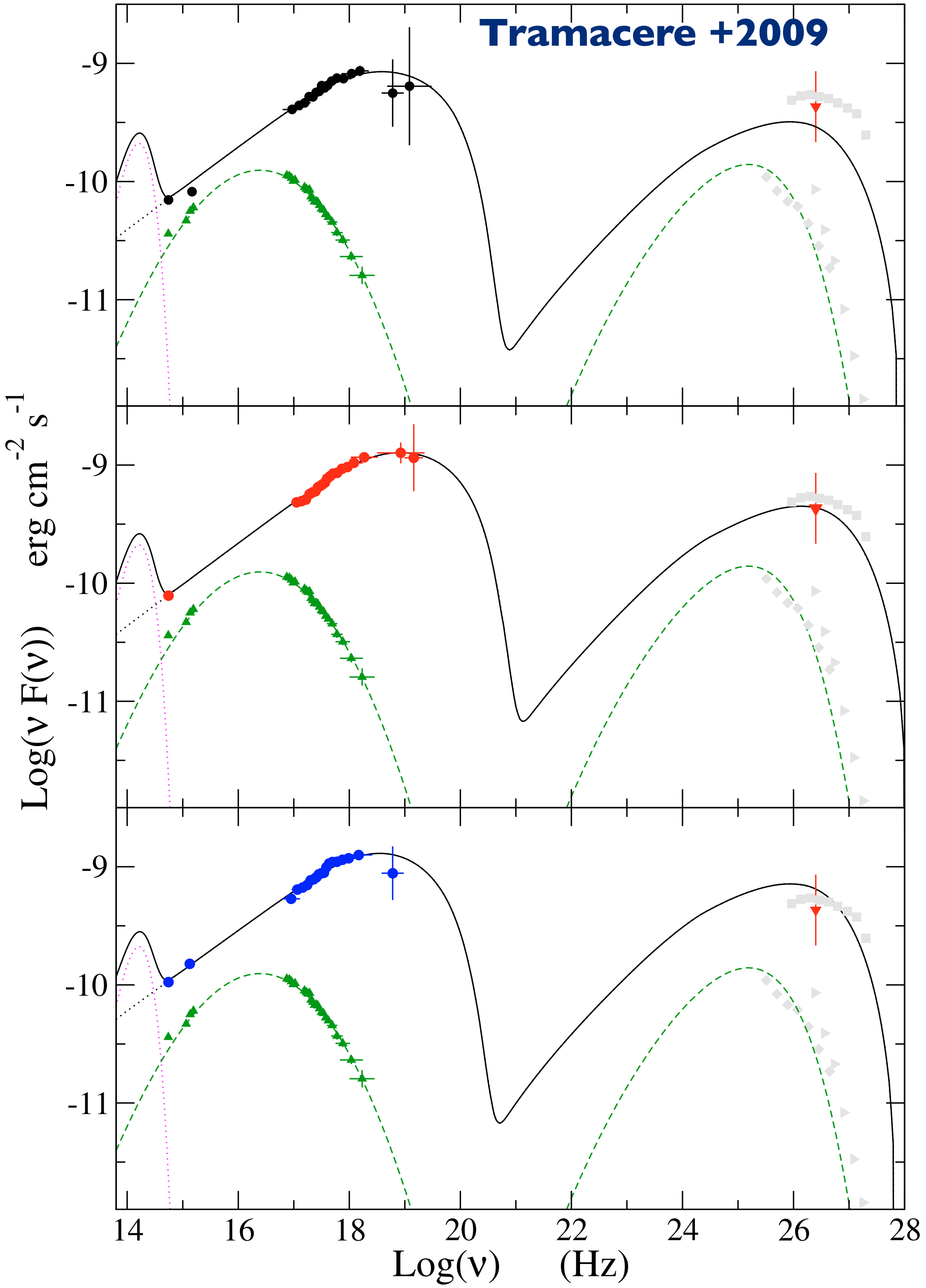
LP+PL spectra

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



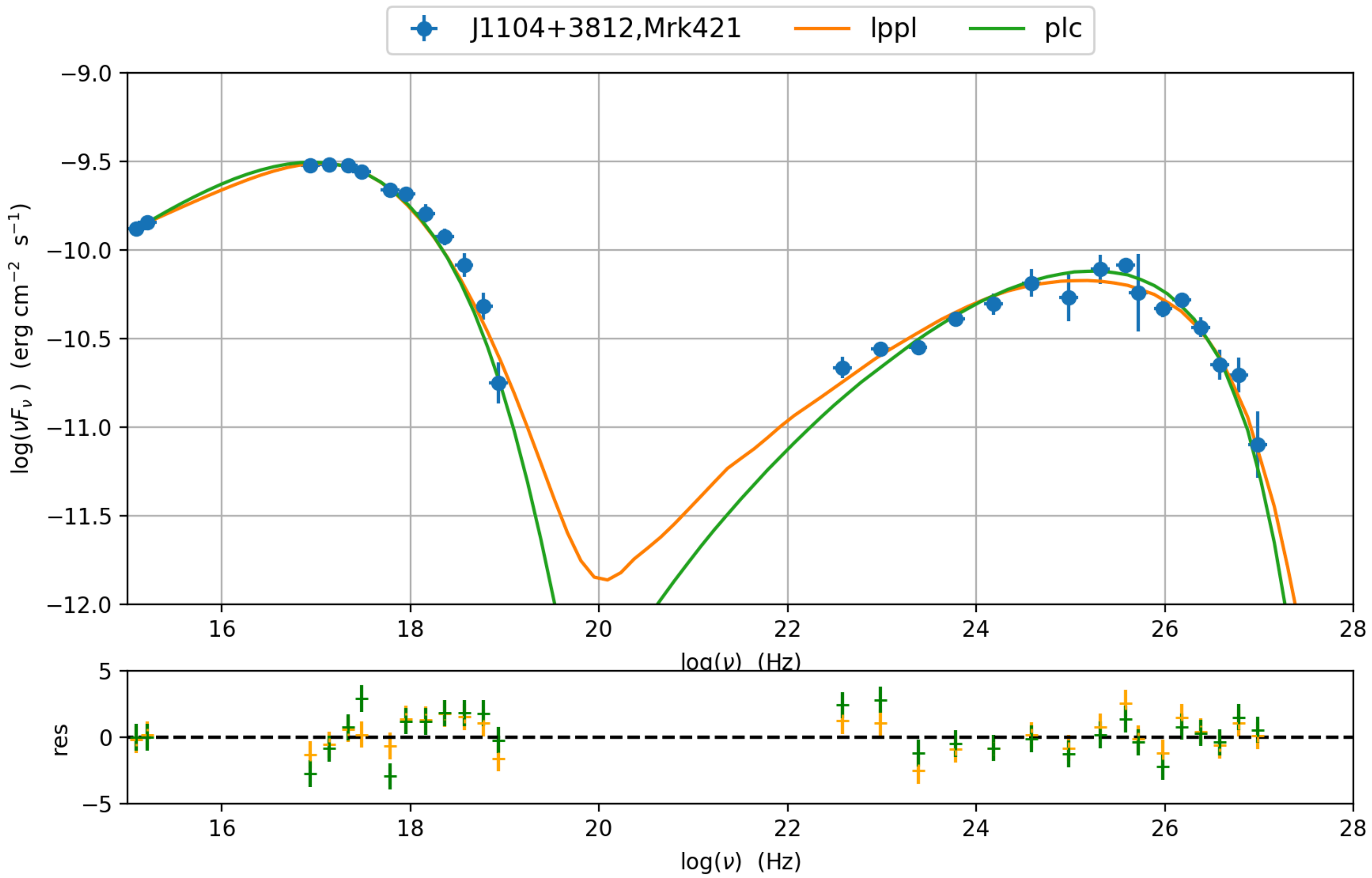
Lemoine,Pelletier 2003





Mrk 421 2009 data

data from Abdo et al 2011
Fermi-LAT+Magic coll.




```
dof=21
chisq=39.696427, chisq/red=1.890306 null hypothesis

best fit pars
---------------------------------------------------
best-fit parameters:
  Name             | best-fit value| best-fit err +|
---------------------------------------------------
 B                 | +2.096016e-02 | +5.744998e-05 |
 N                 | +1.152143e-01 | +1.545857e-03 |
 R                 | Frozen        | Frozen        |
 beam_obj          | +2.619674e+01 | +8.501912e-02 |
 gamma0_log_parab  | +1.884210e+05 | +1.891713e+03 |
 gmax              | +3.492780e+08 | +6.130842e+08 |
 gmin              | +1.929302e+03 | +2.109472e+01 |
 r                 | +1.681768e+00 | +3.032664e-02 |
 s                 | +2.509224e+00 | +2.902511e-03 |
 z_cosm            | Frozen        | Frozen        |
---------------------------------------------------
***************************************************

===================================================
```

lppl/plc p-value= 6.8E-6

The log-parabola origin:
physical insight

The origin of the log-parabolic shape: statistical derivation

fluctuation

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

systematic

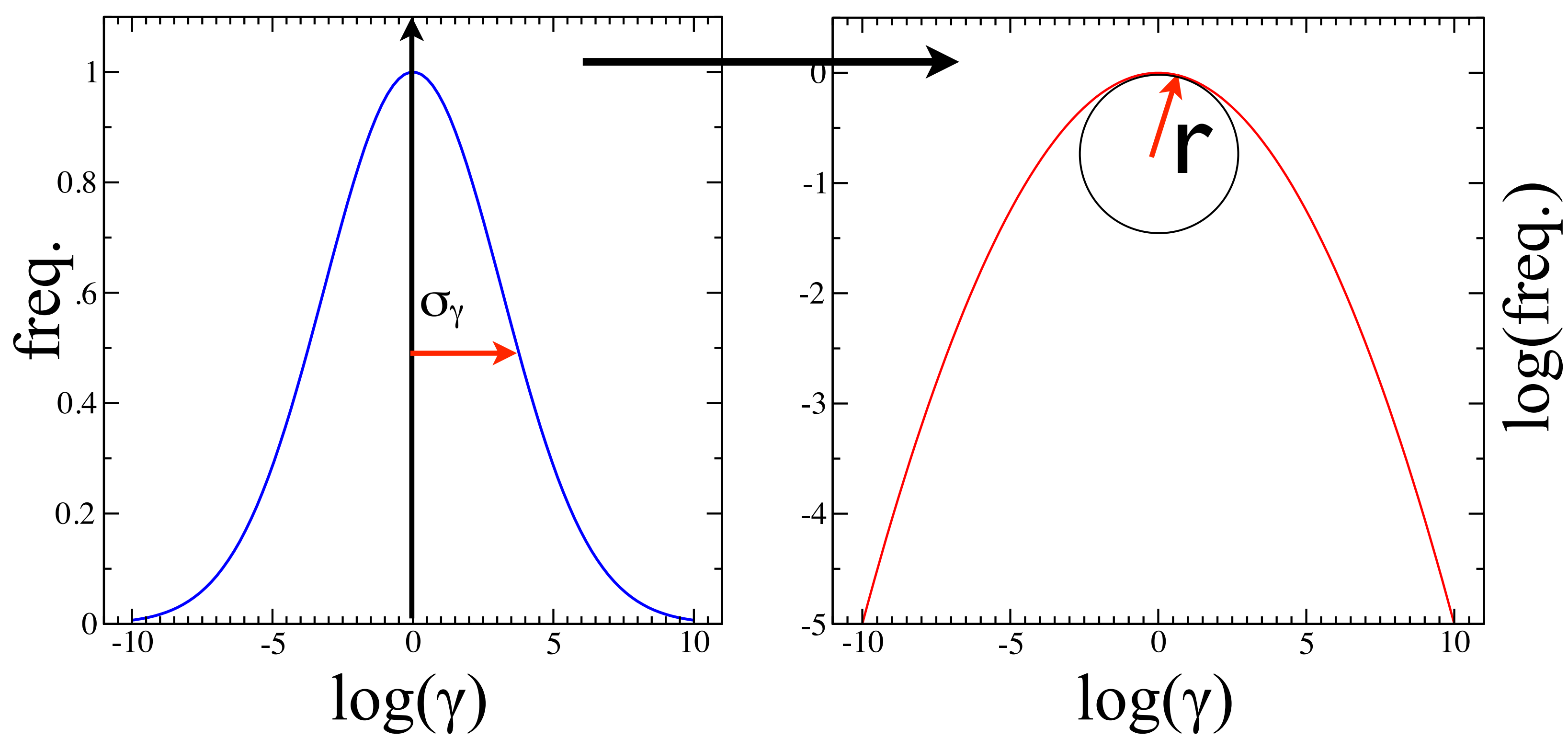
***ε_i* is a R.V.**

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

C.L. Theorem
multipl. case

log-normal distribution

Log-Parabolic representation



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

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

analytical solution for:

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

"hard-sphere" case no cooling

Melrose 1968,

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

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

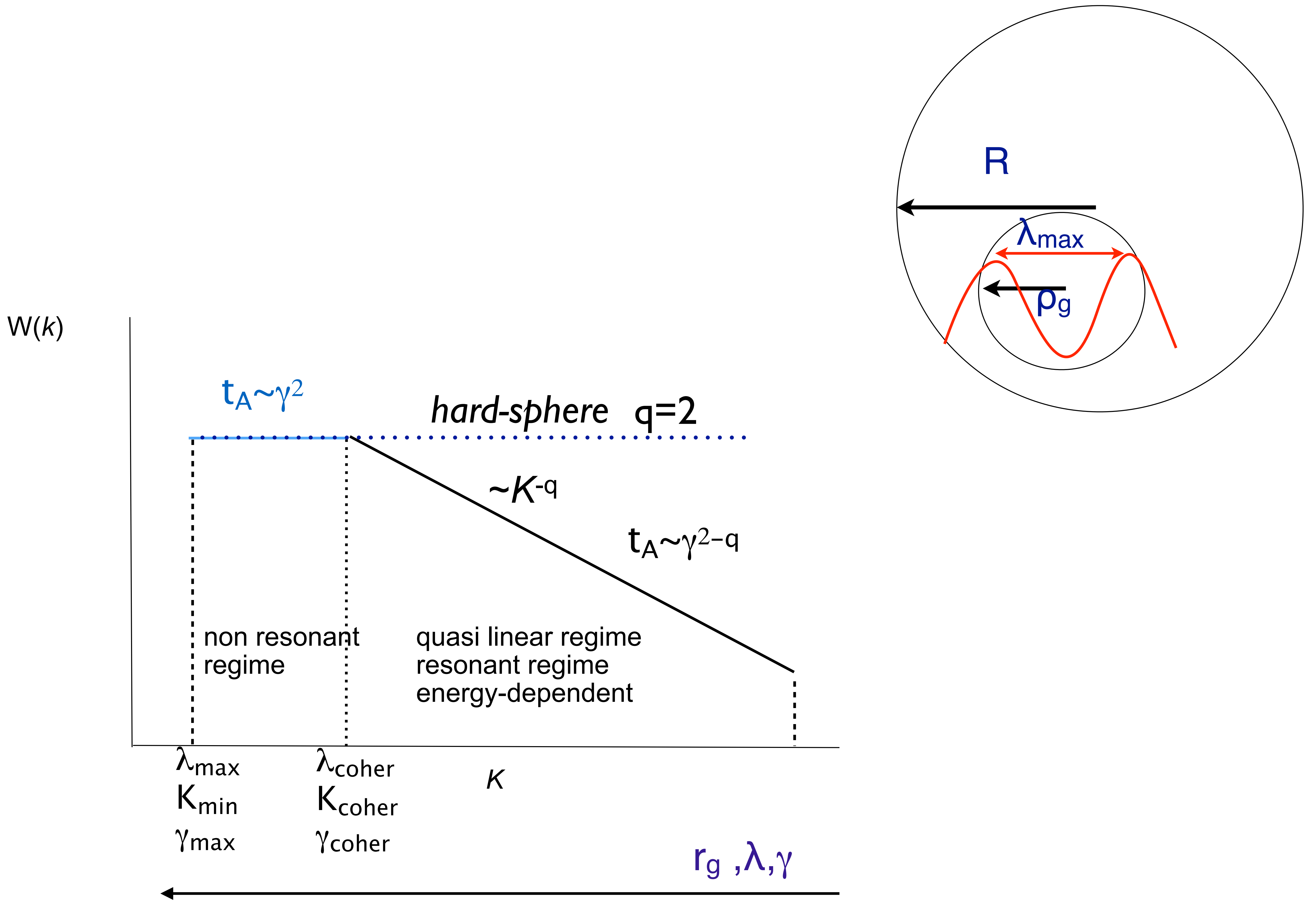
$$A(\gamma) = A_{p0}\gamma,\ t_A = \frac{1}{A_0}$$

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

Turbulent magnetic field → momentum diffusion term

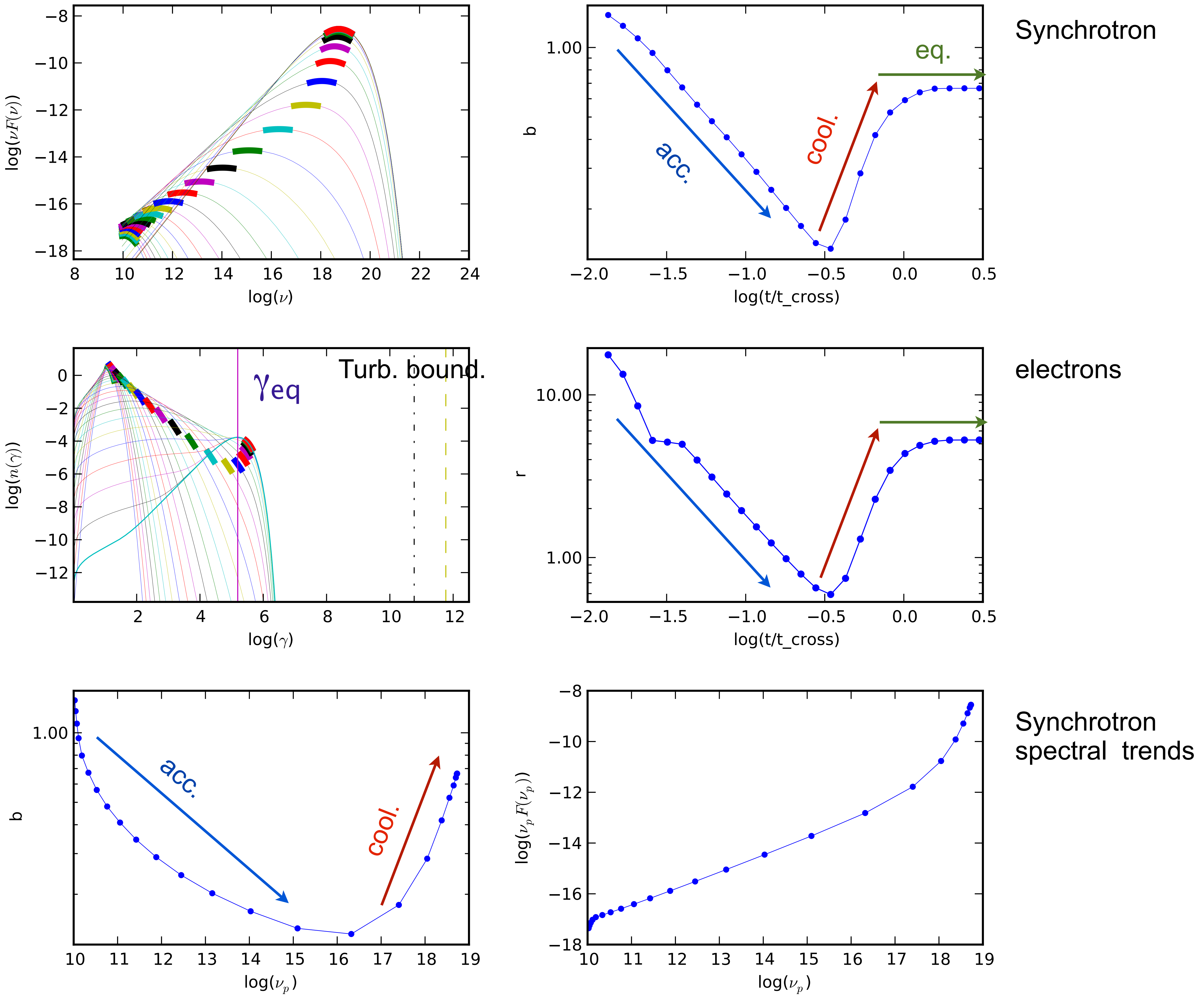
$$W(k) = \frac{\delta B(k_0^2)}{8\pi}\left(\frac{k}{k_0}\right)^{-q}$$

set-up of the accelerator



spectral trends

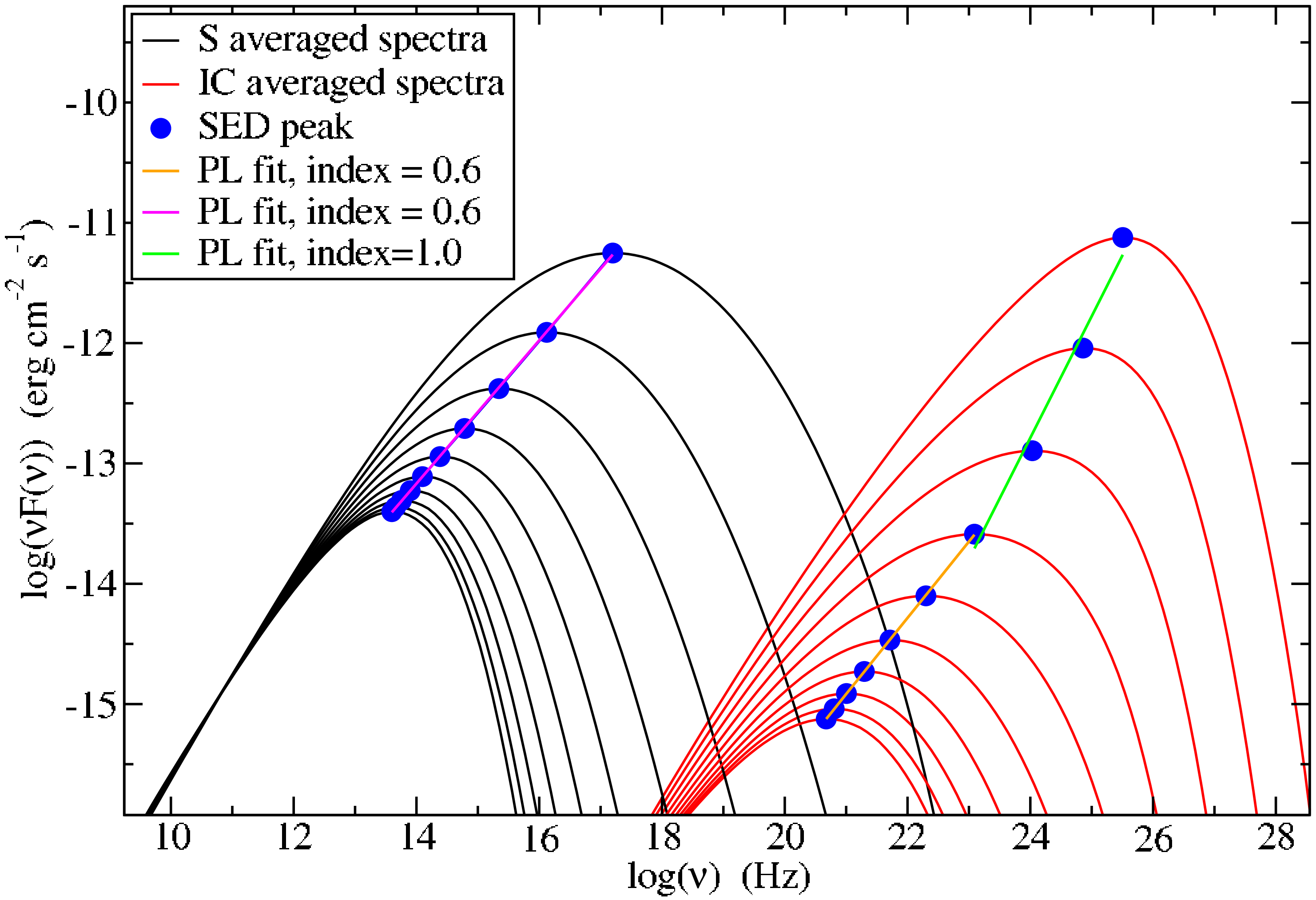
single flare



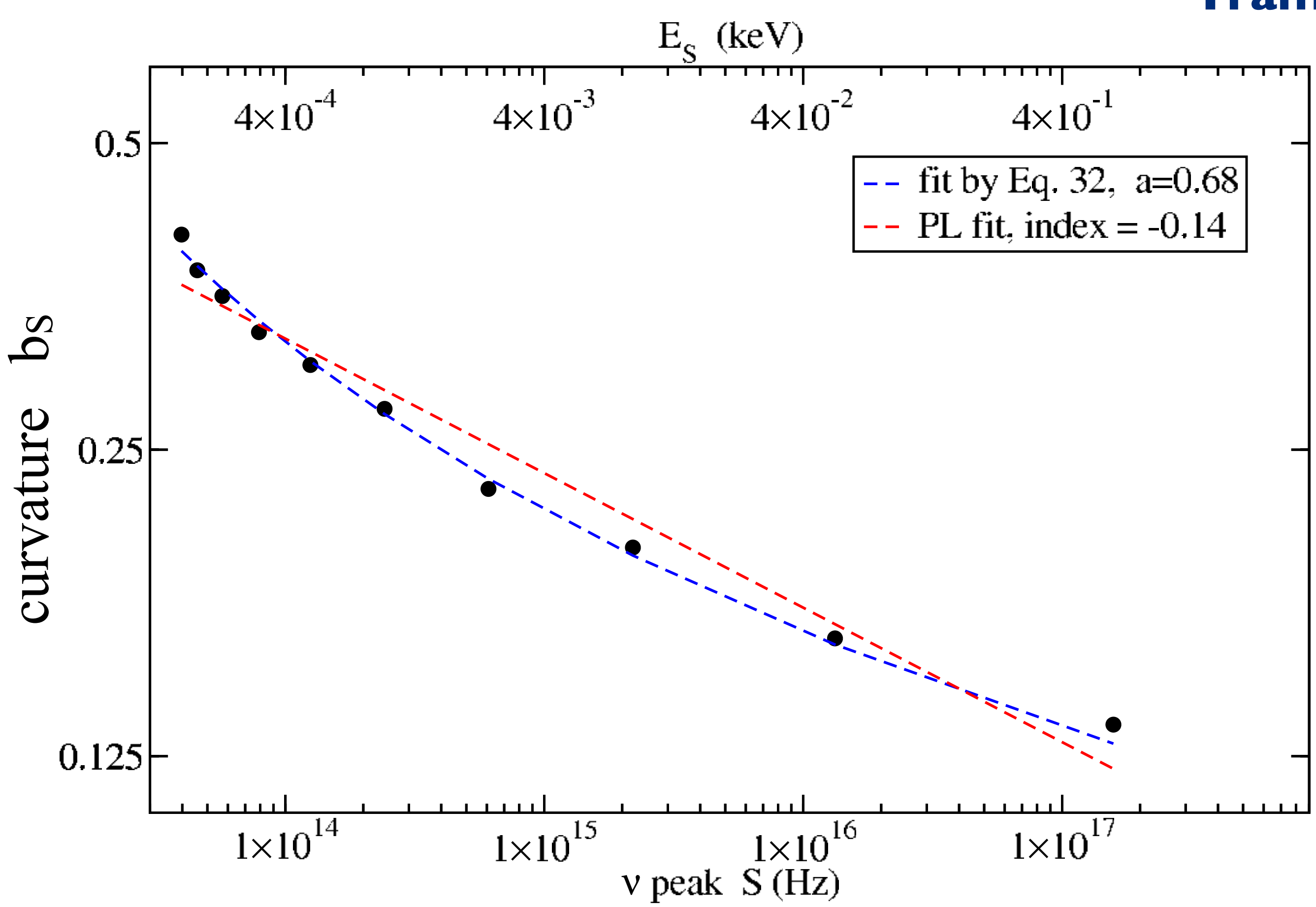
Synchrotron
electrons
Synchrotron spectral trends
log(νF(ν))
log(ν)
b
log(t/t_cross)
eq.
acc.
cool.
log(n(γ))
log(γ)
γeq
Turb. bound.
r
log(ν_p)
log(ν_p F(ν_p))

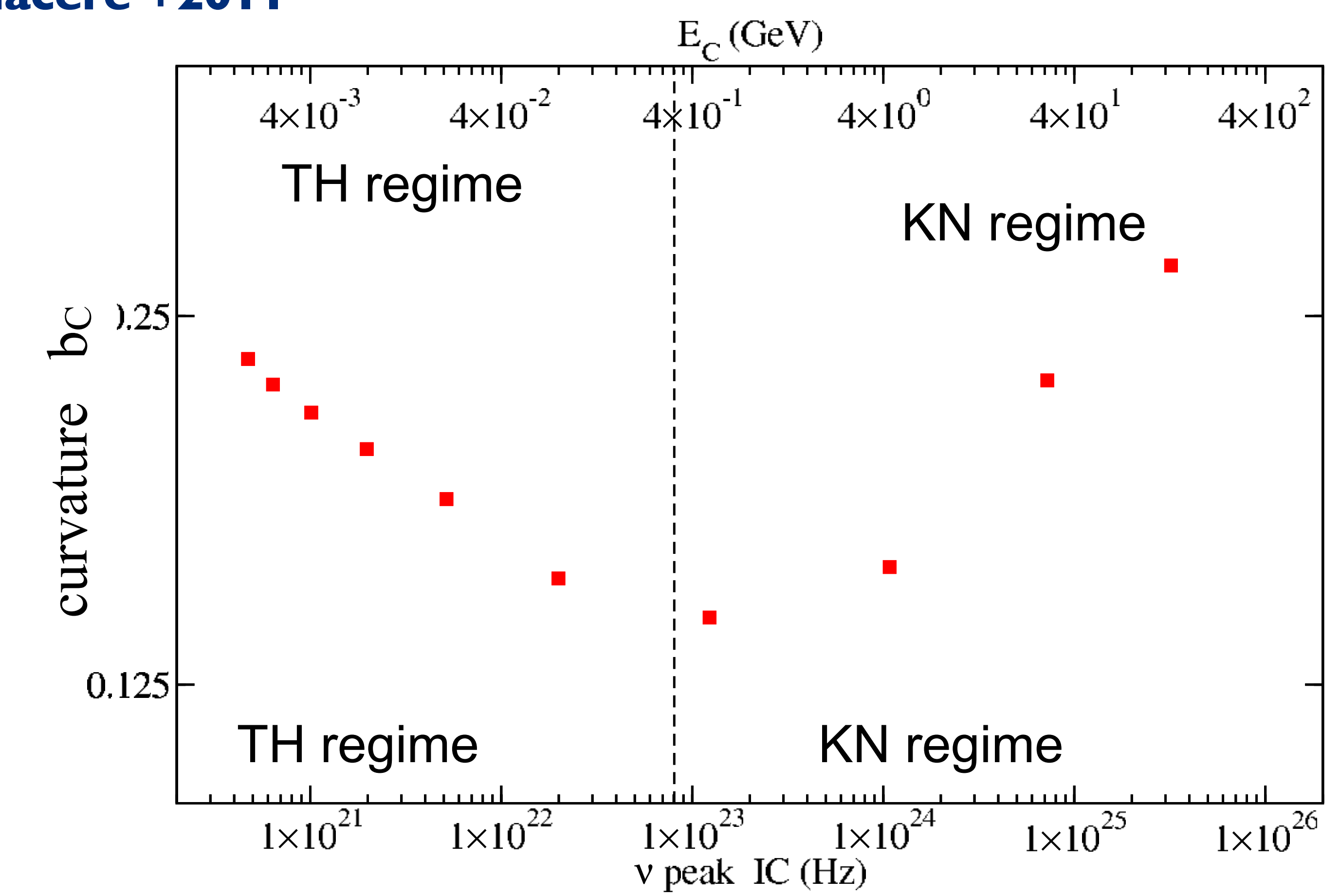
S vs IC

Tramacere+2011



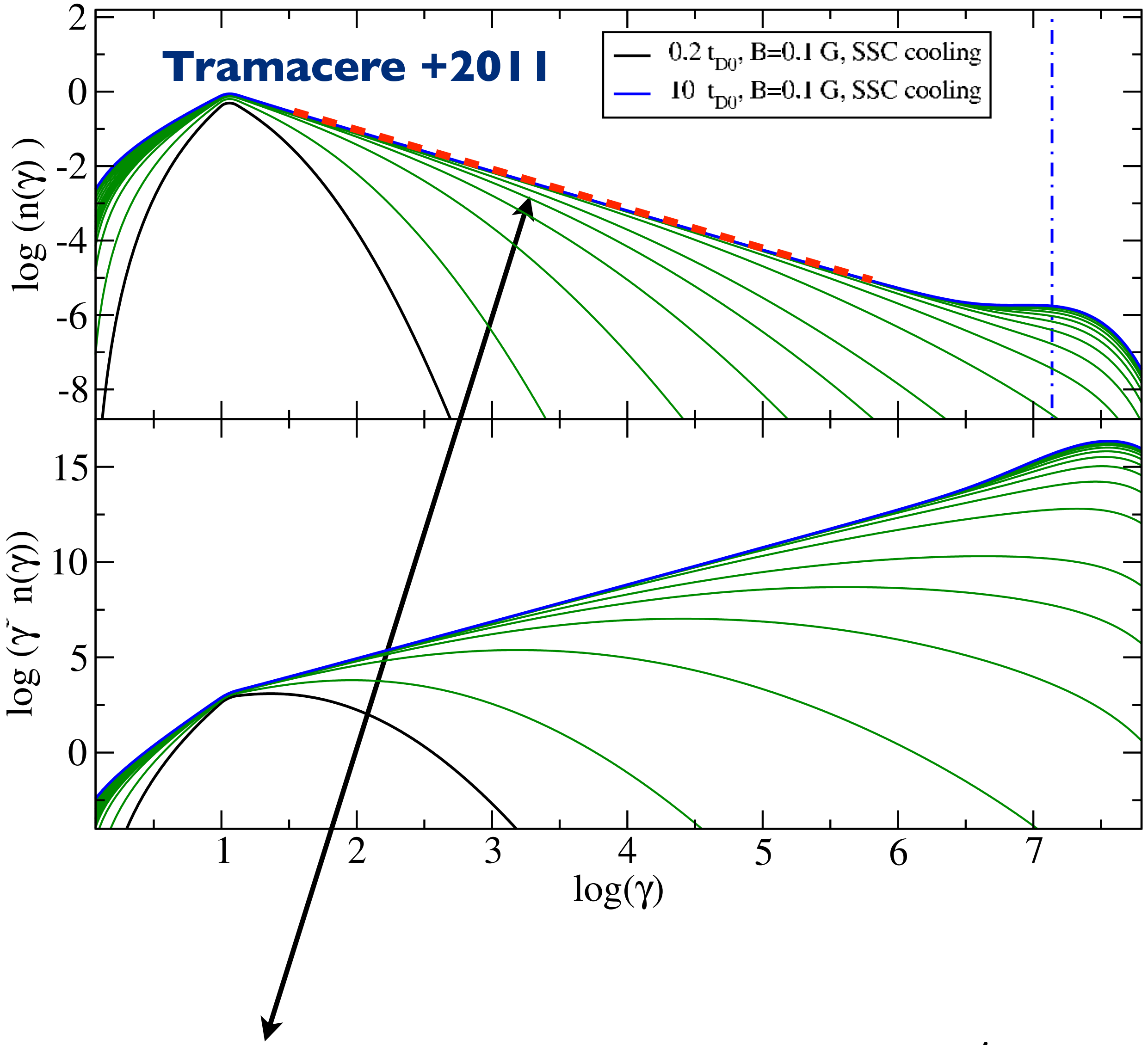
Tramacere +2011





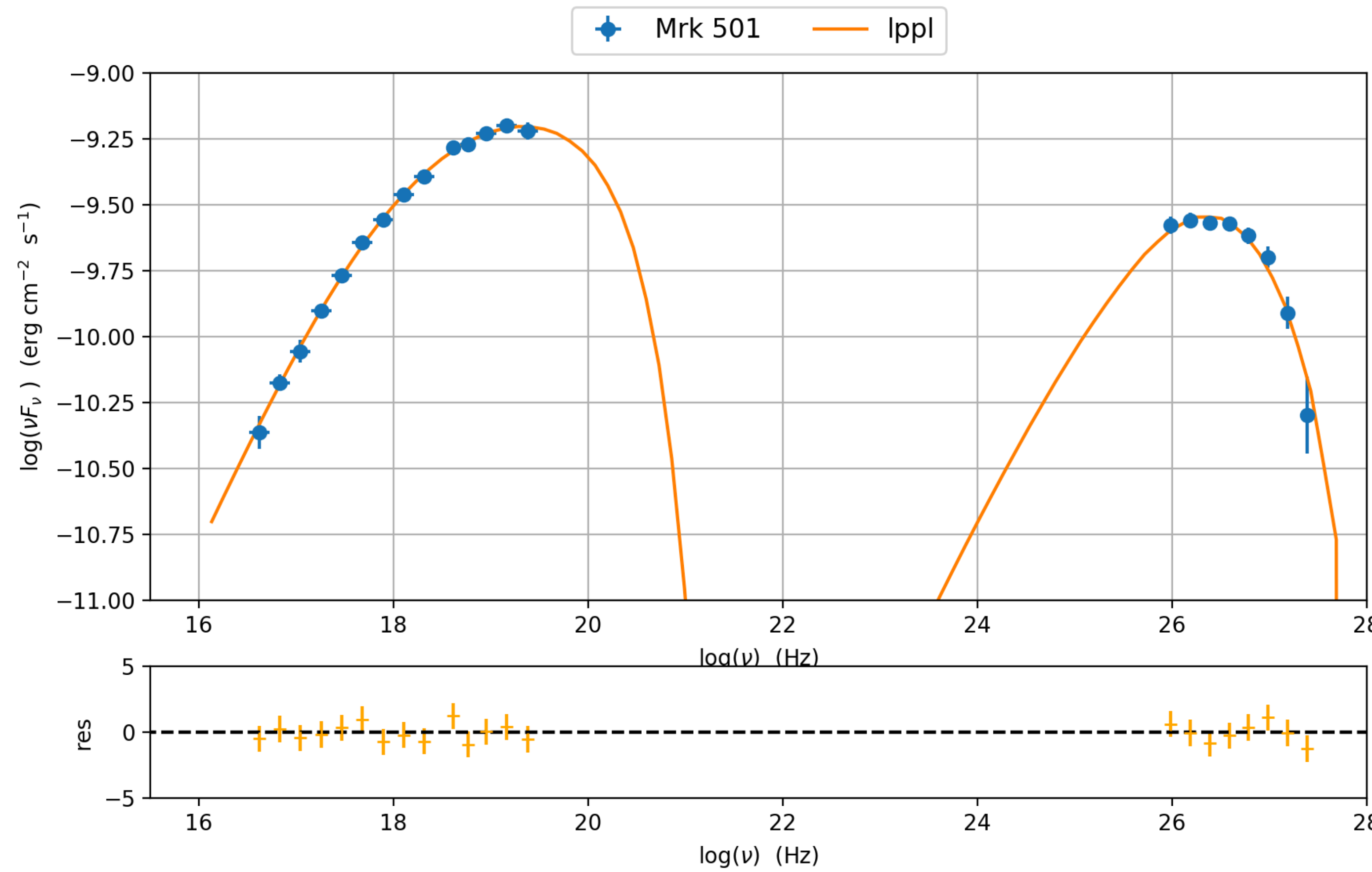
Pile-up and hard spectra

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



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

Mrk 501 1997



Massaro & Tramacere +2006

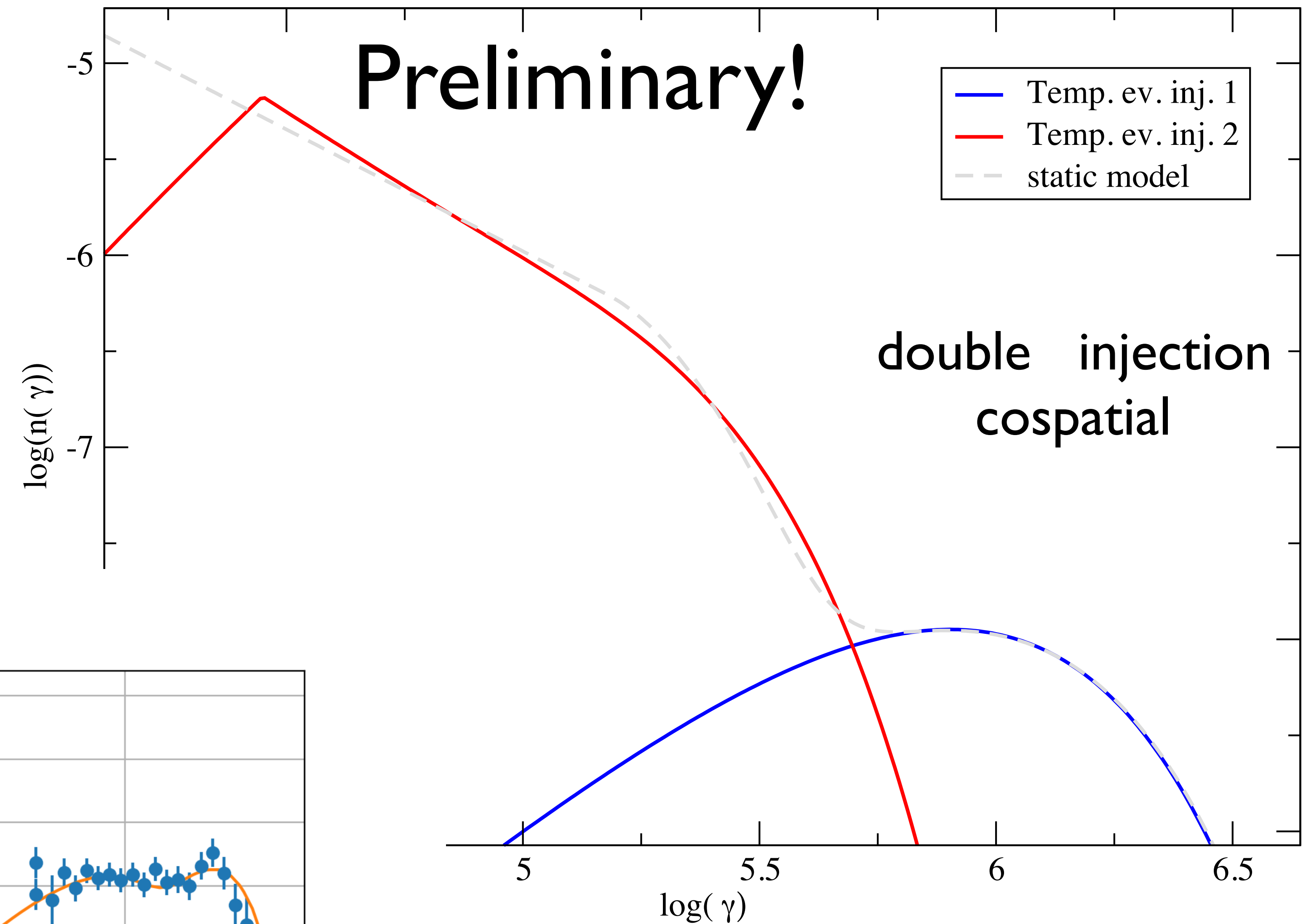
s~1.6

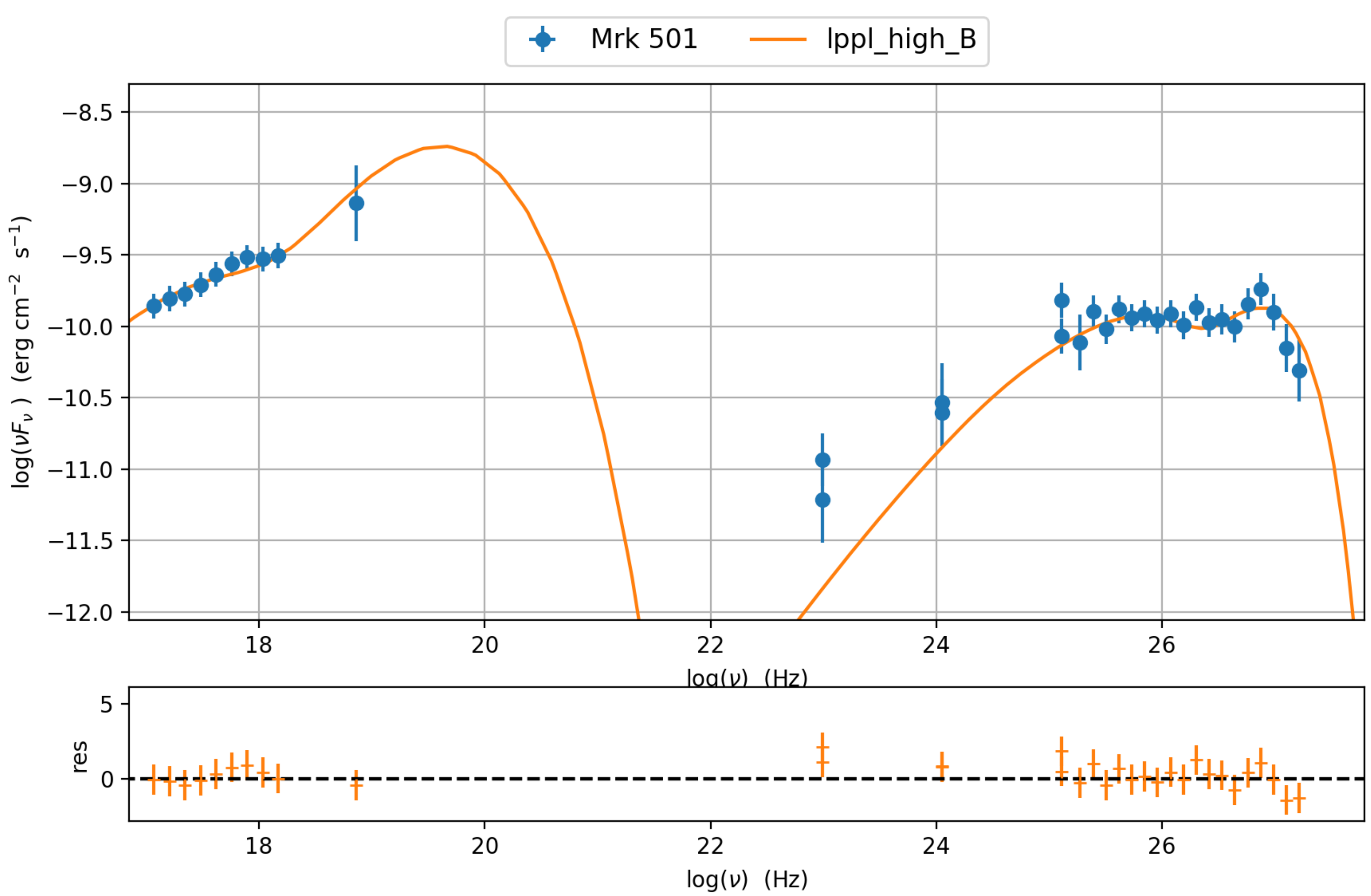
$r \sim 0.7\text{-}0.8 << r_{eq} \sim 6$

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

Pile-up and hard spectra

Mrk 501 2014 Flare
Paneque's talk
MAGIC paper





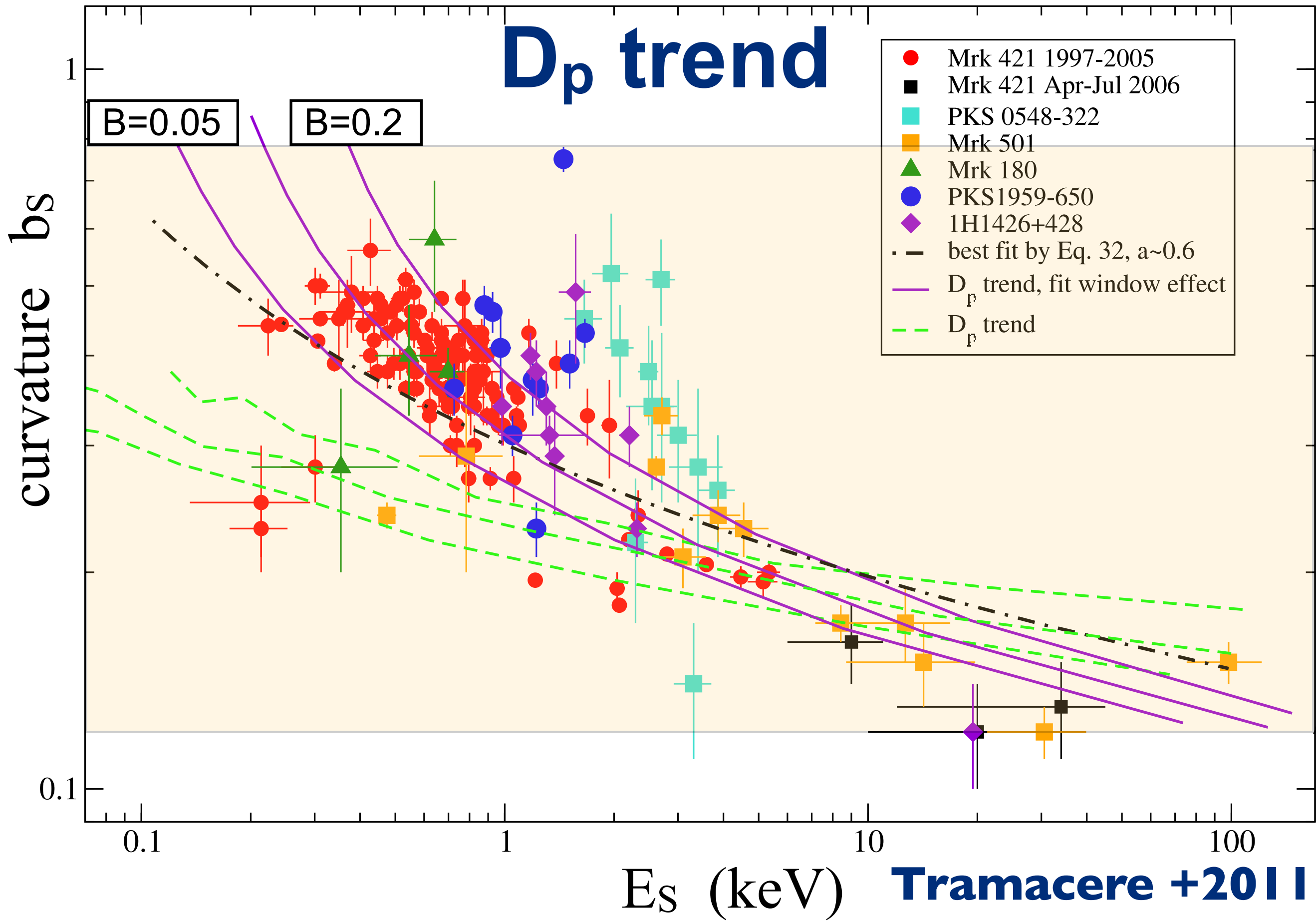
Summary of Stochastic signatures from self-consistent modeling

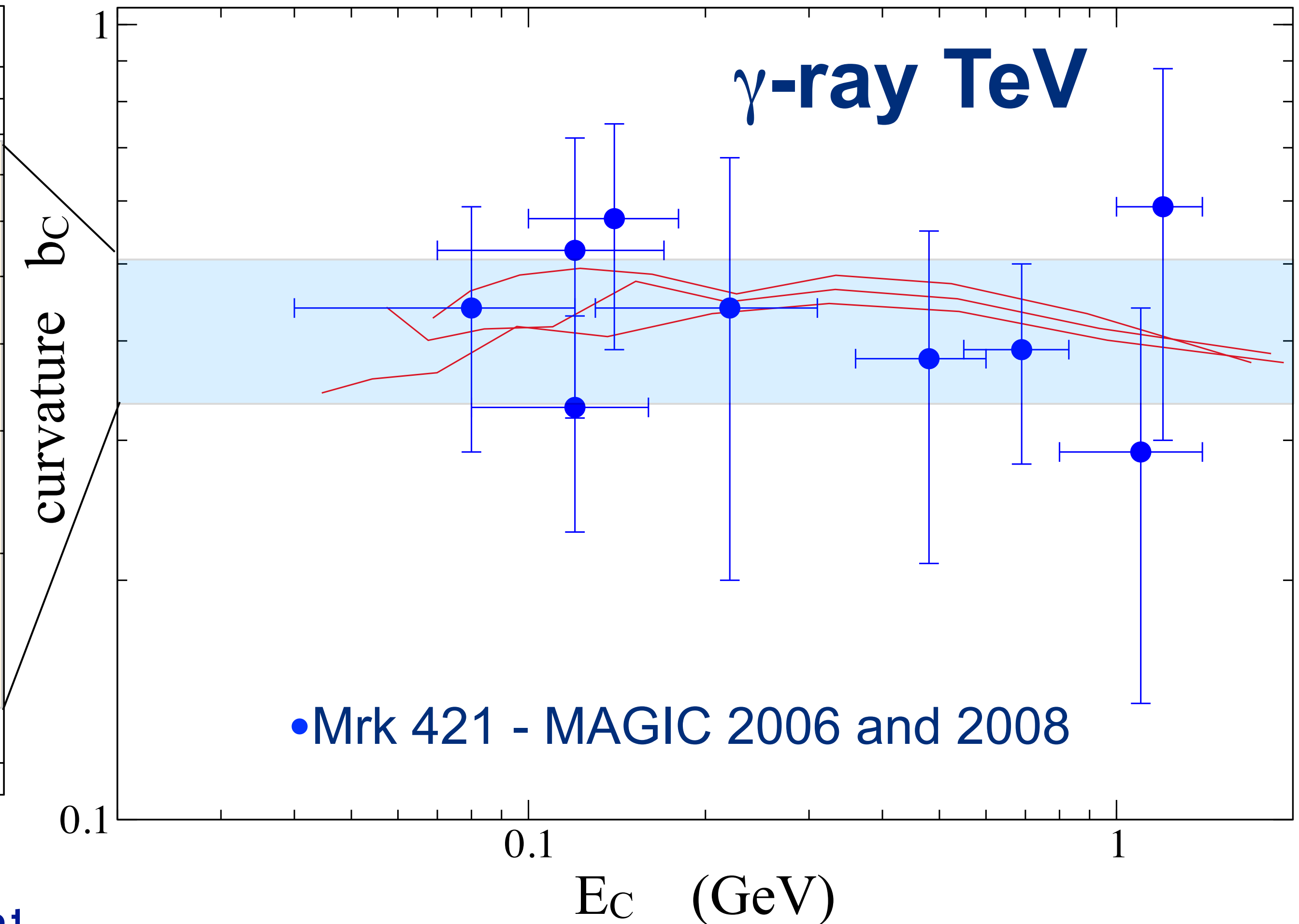
	Acceleration dominated	Equilibrium
curvature trend	curvature decreasing trend *b-Ep*	curvature stable or increasing (r~7,b~1.3)
spectral shape	LPPL or LP	PL+exp-cutoff or Maxwellian

spectral trends

multiple flares and population trends

E_S-b_S X-ray trend and γ-ray predictions

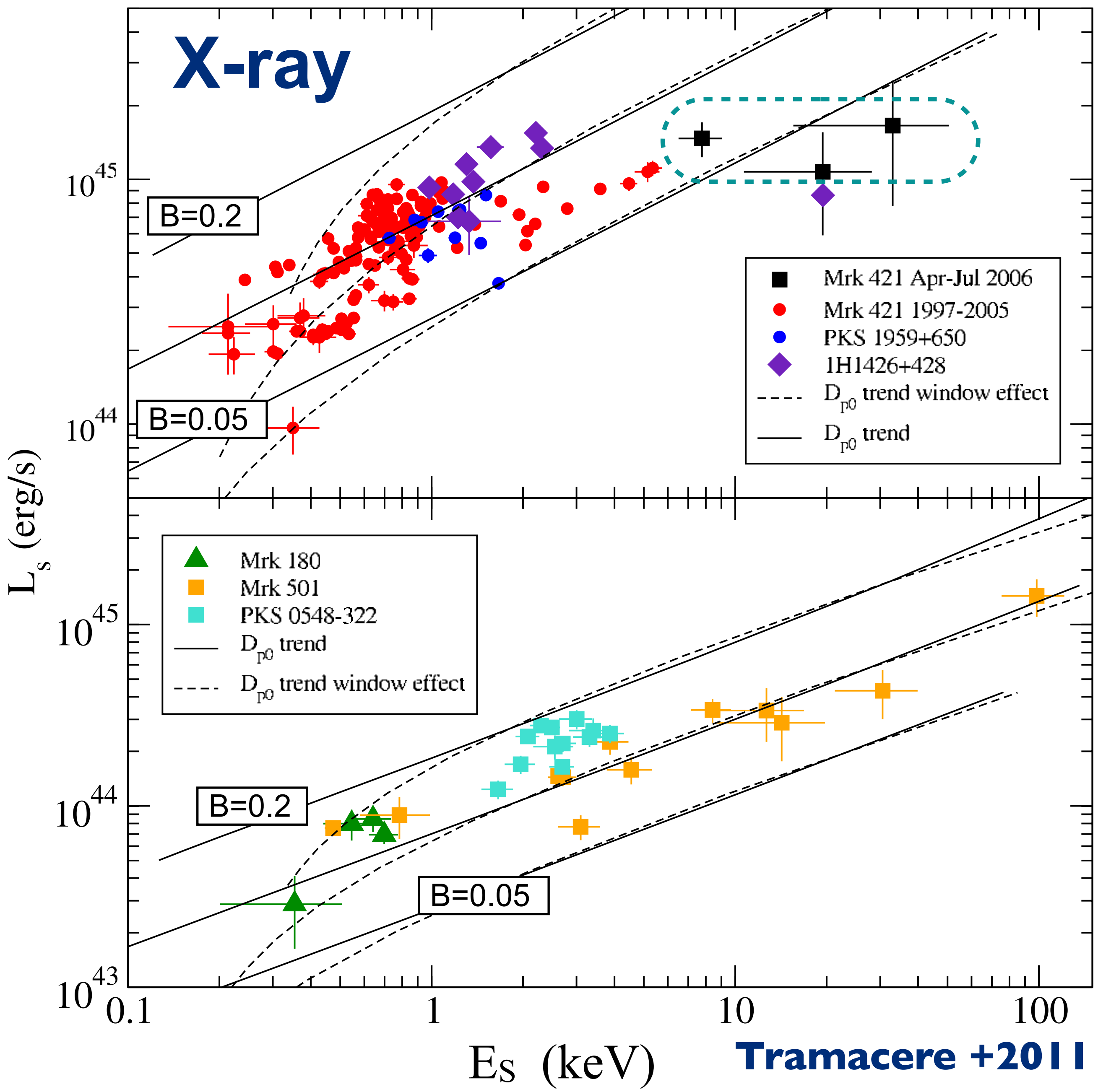




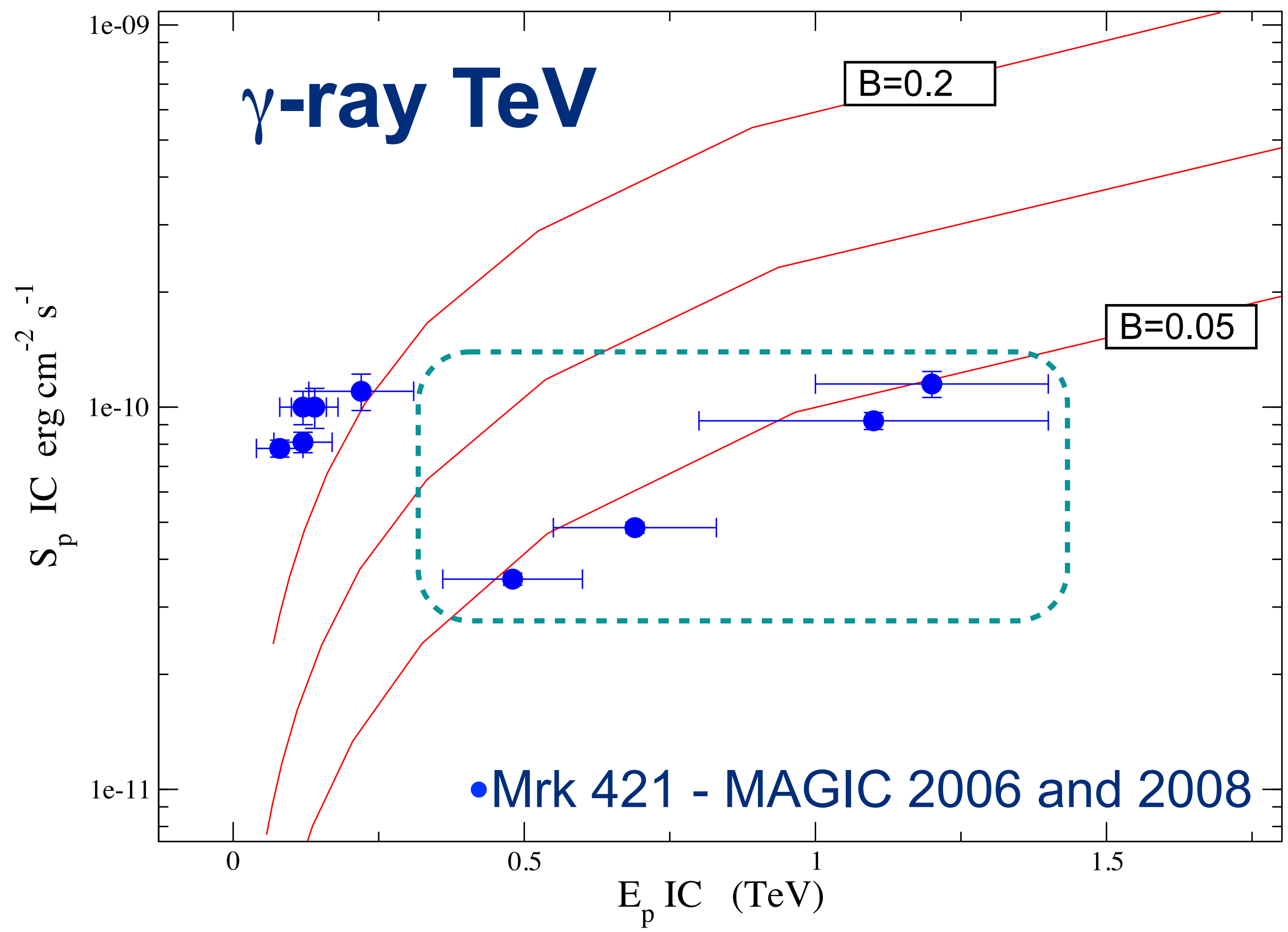
- data span **13 years**, both flaring and quiescent states
- We are able to reproduce these long-term behaviours, by changing the value of only one parameter (D_p)
- for q=2, curvature values imply distribution far from the equilibrium (b~[1.0–0.7])
- More data needed at GeV/TeV, curvature seems to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



Tramacere +2011



- 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.

https://andreatramacere.github.io/jetsetdoc/

to get the beta release write to

- andrea.tramacere@gmail.com
- andrea.tramacere@unige.ch

JetSeT 1.0 JetSeT Page JetSeT User Guide » Source Search

User Documentation

Index

Search

JetSeT

Jets SED modeler and fitting Tool

Author: Andrea Tramacere

This page provides the documentation for the `JetSeT` package, a framework providing tools for:

- reproducing radiative and accelerative process acting in relativistic jets
- modeling and fitting multiwavelength SEDs
- handling observed data

If you use this code in any kind of scientific publication please cite the following papers:

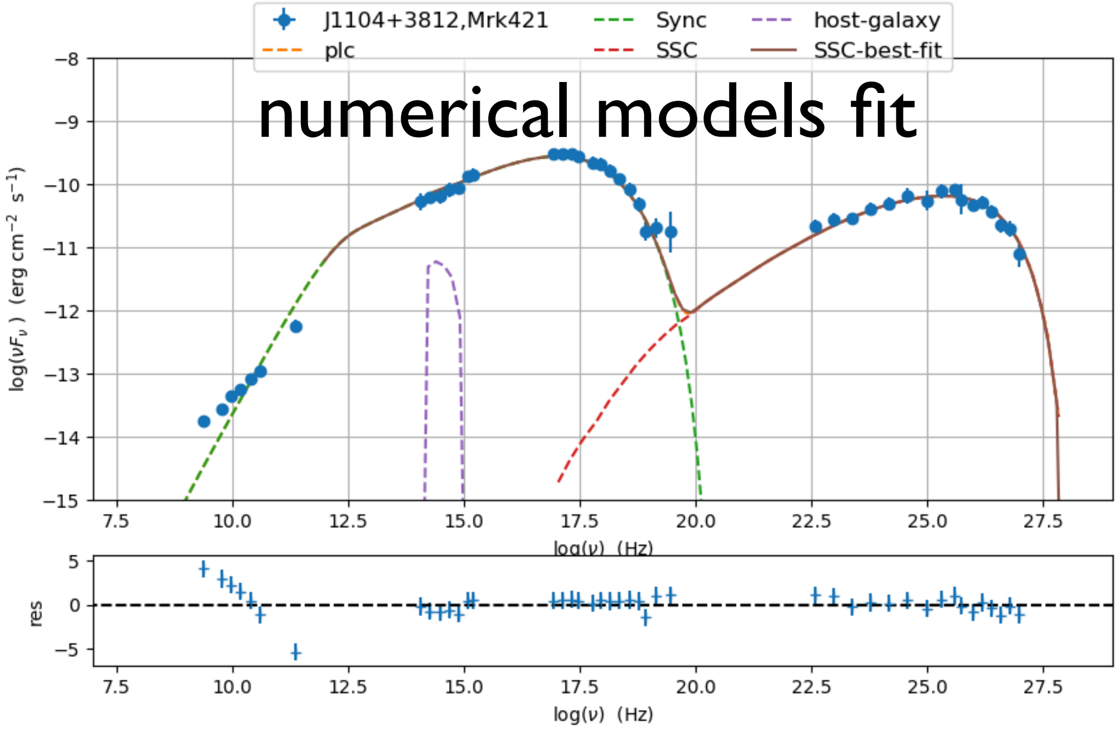
- Tramacere A. et al. 2011
- Tramacere A. et al. 2009
- Massaro E. et. al 2006

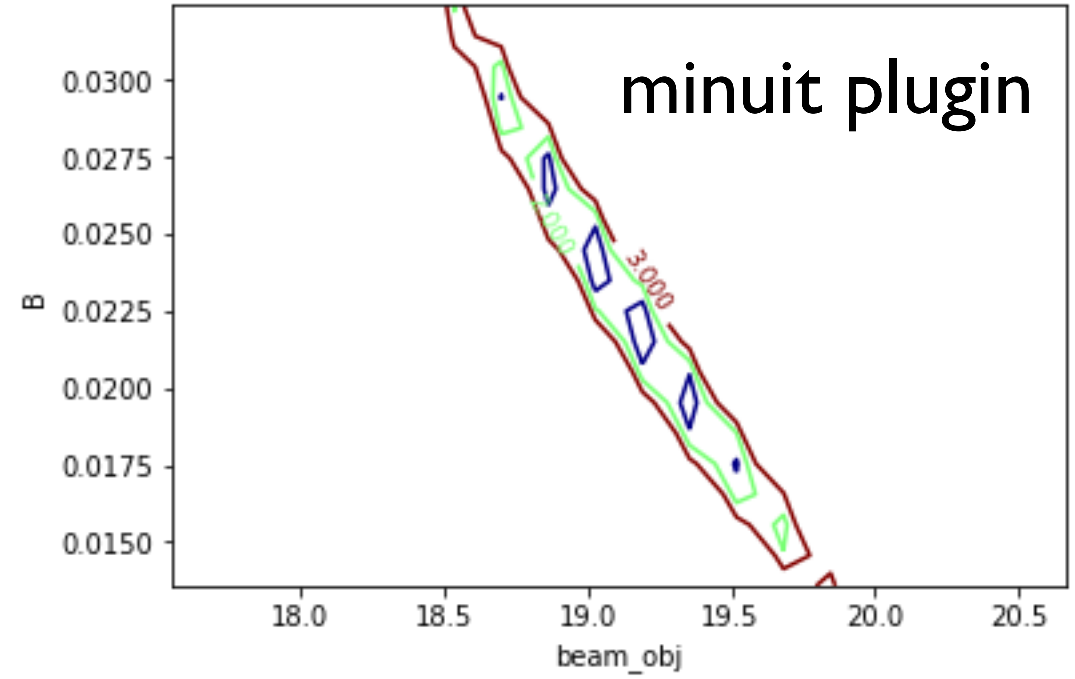
User Documentation

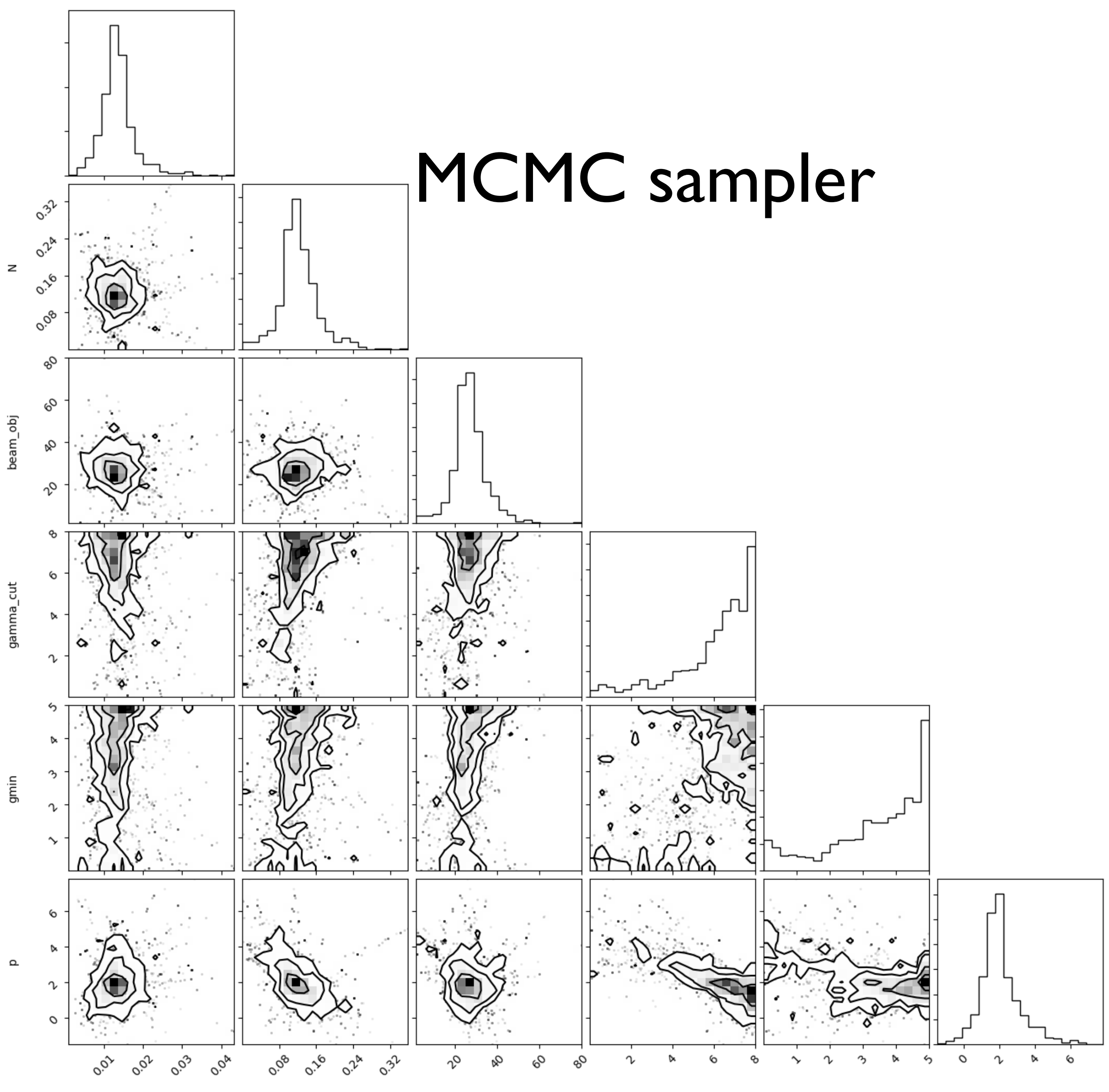
- user guide

Index

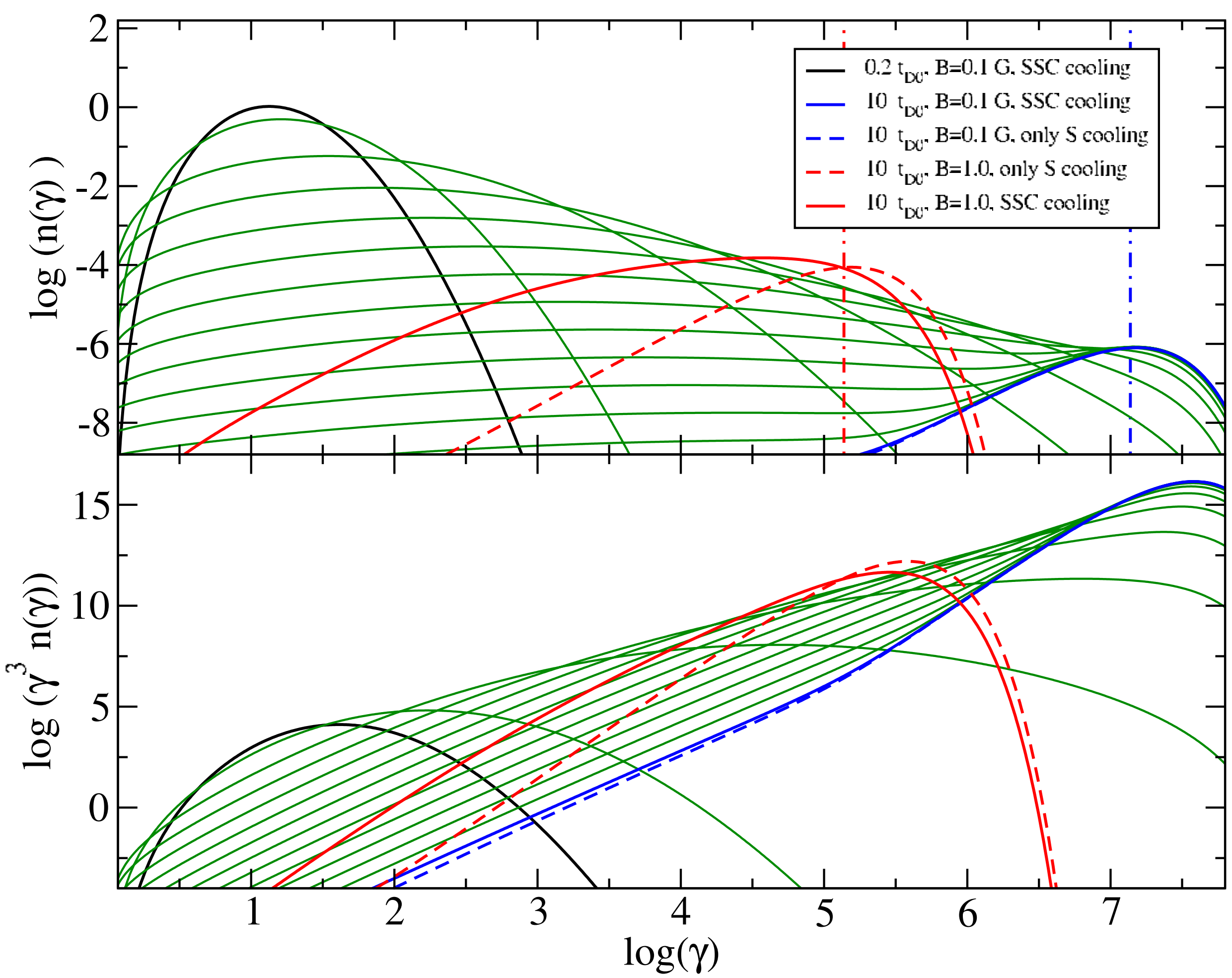
- Index
- Module Index
- Search Page







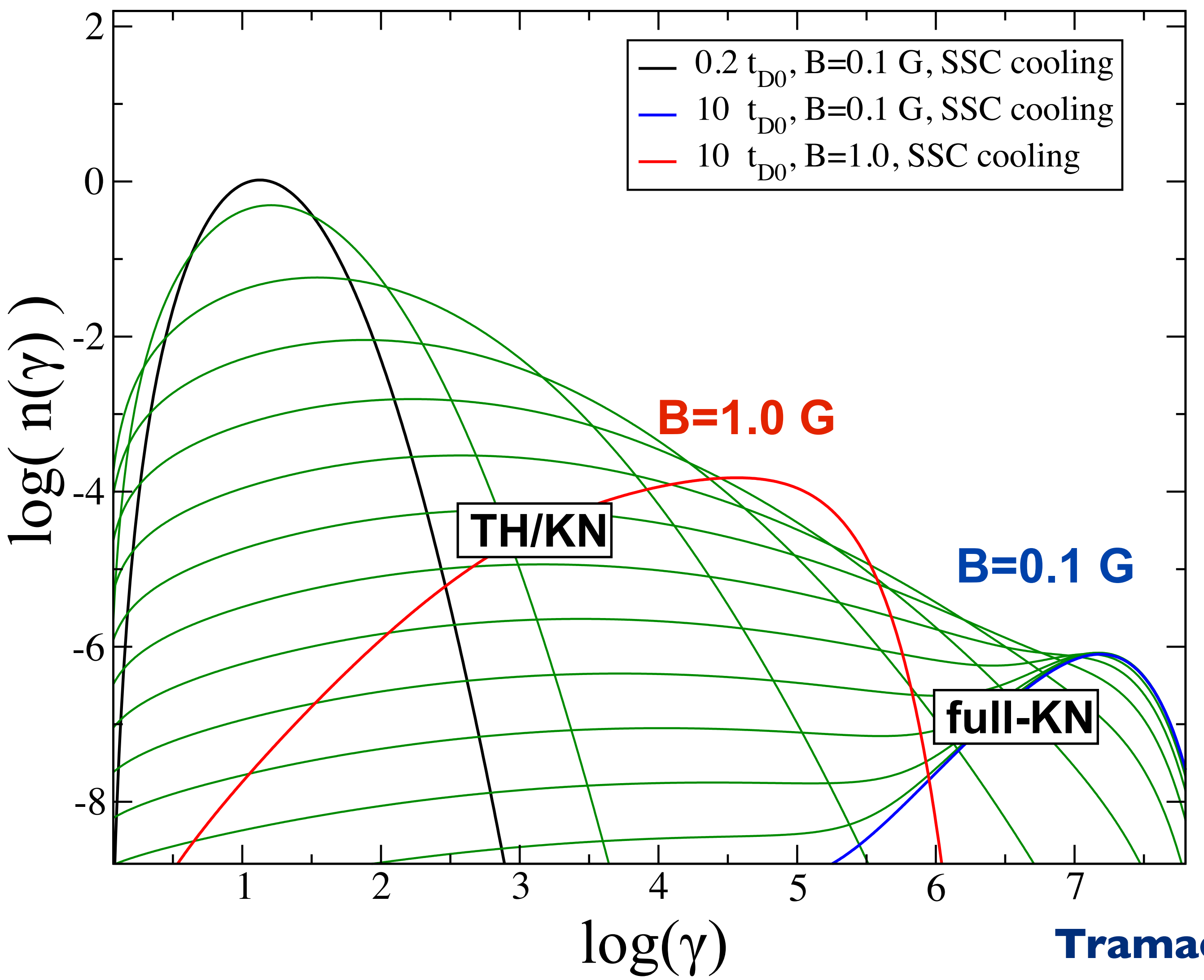
Temp. ev. of the plasma



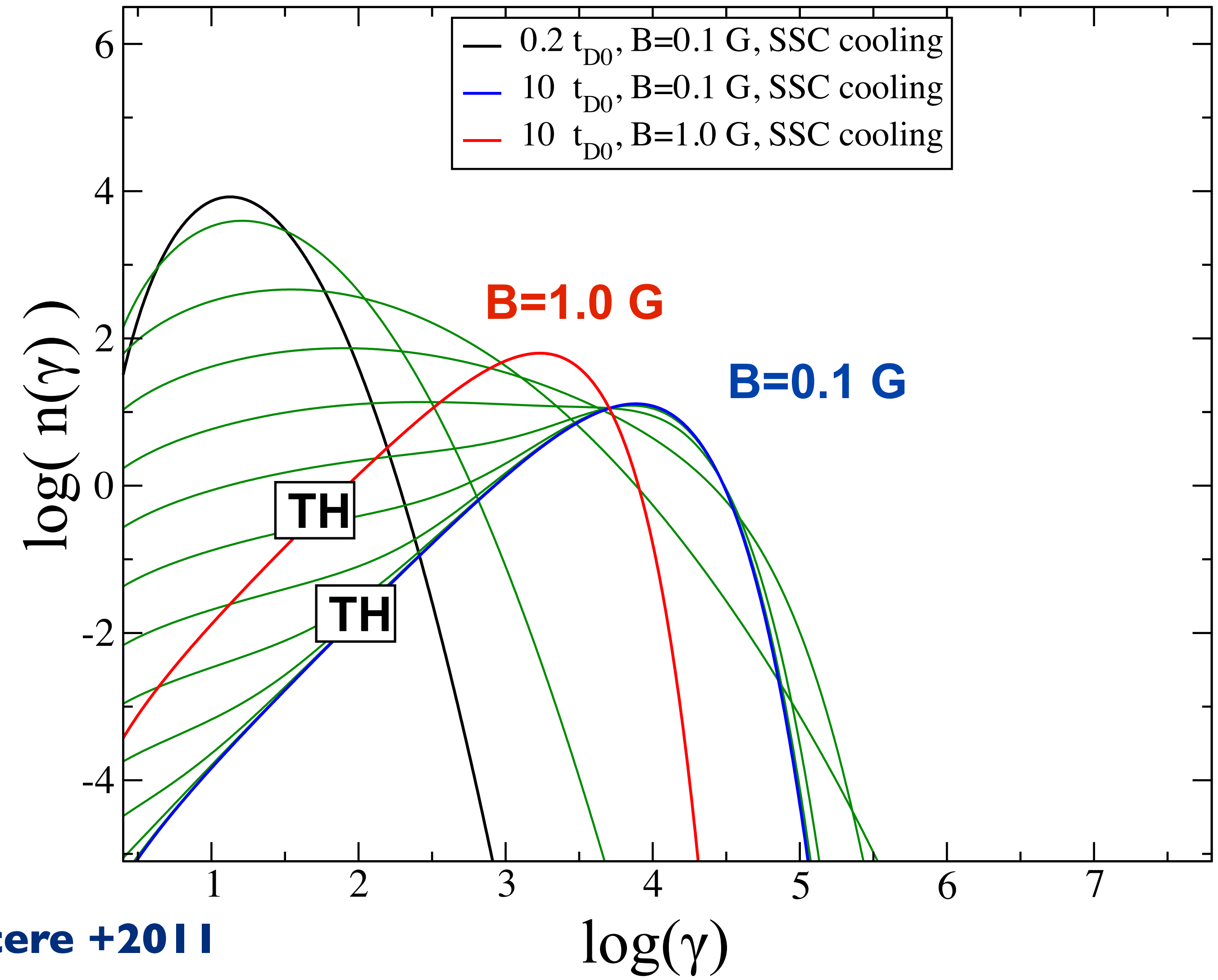
backup slides

IC cooling and equilibrium

R= 1×10^{15} cm



R= 5×10^{13} cm



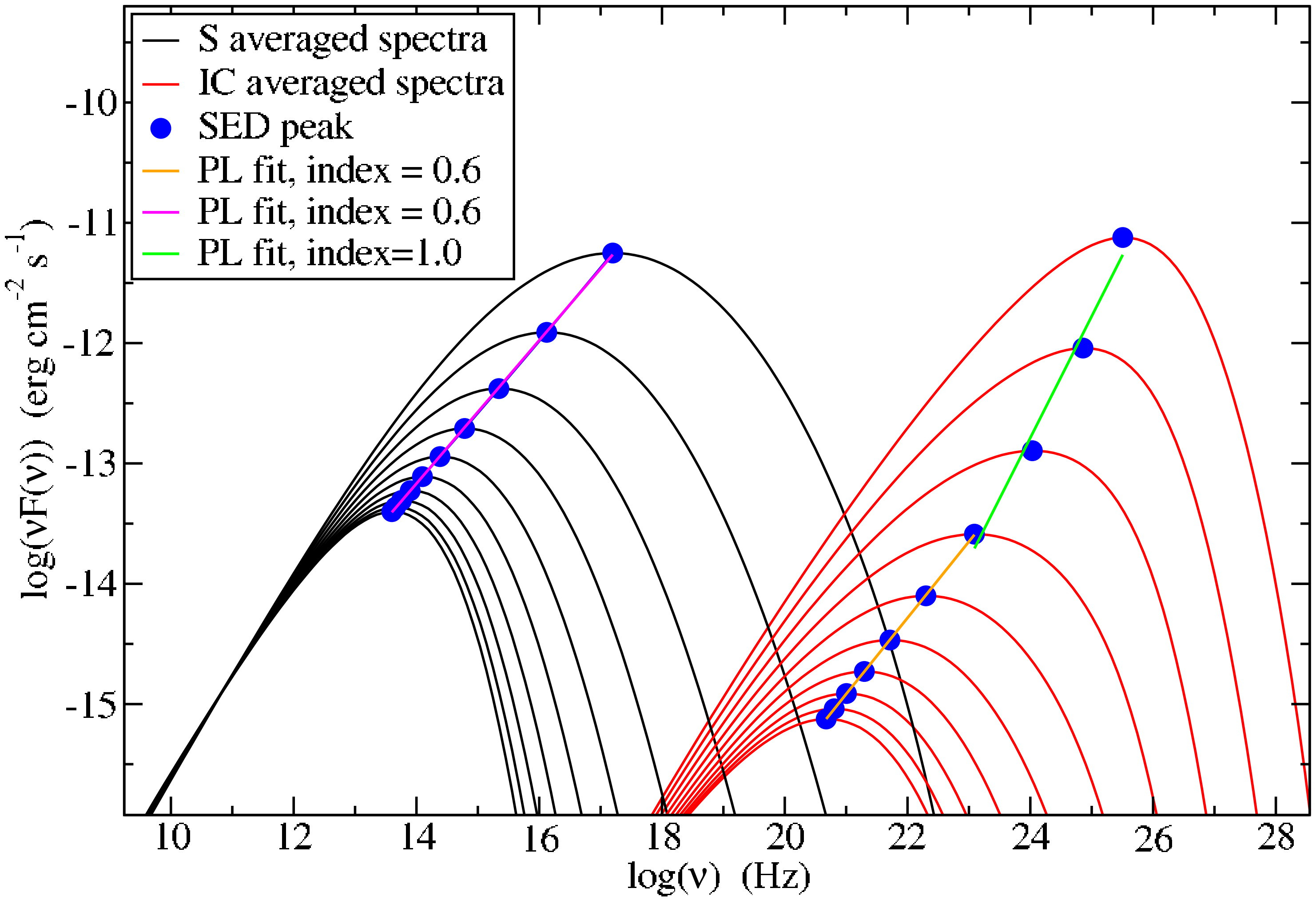
Tramacere +2011

U_{ph} (R= 1×10^{13} cm**) >> U_{ph} (**R= 1×10^{15} cm**)**

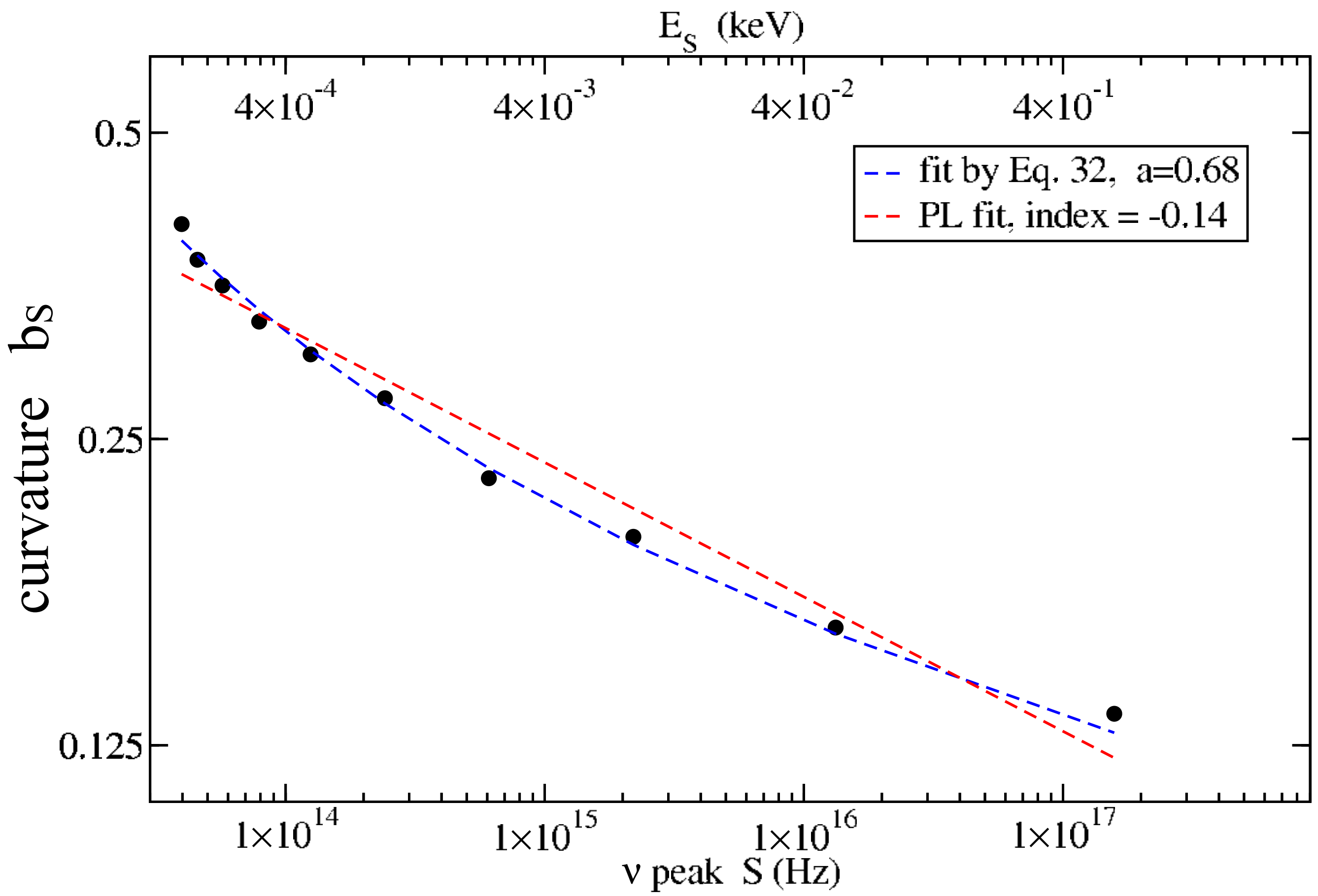
IC prevents higher energies in more compact accelerators (if all the parameters are the same) **Impact on rapid TeV variability!**

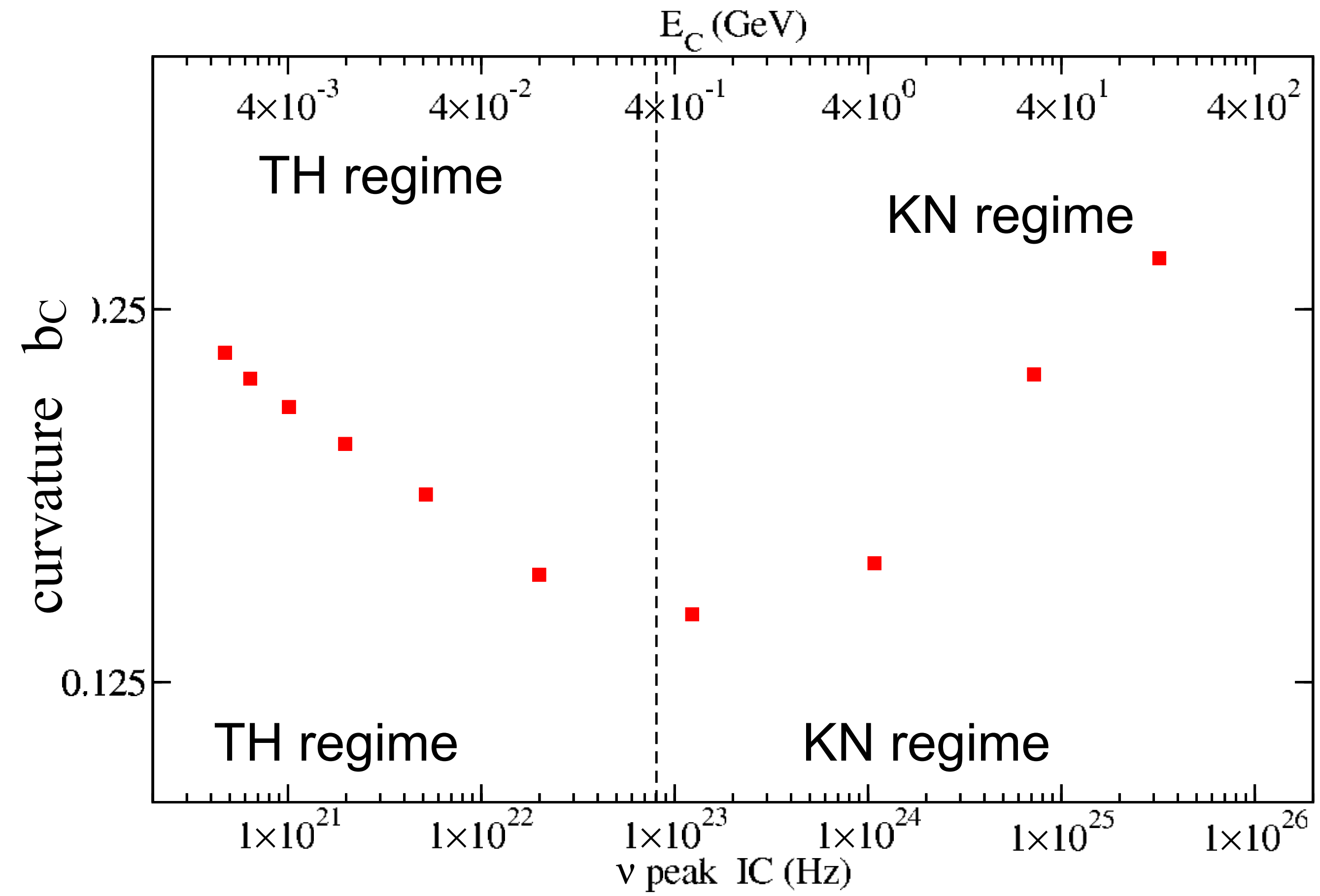
S vs IC

Tramacere+2011

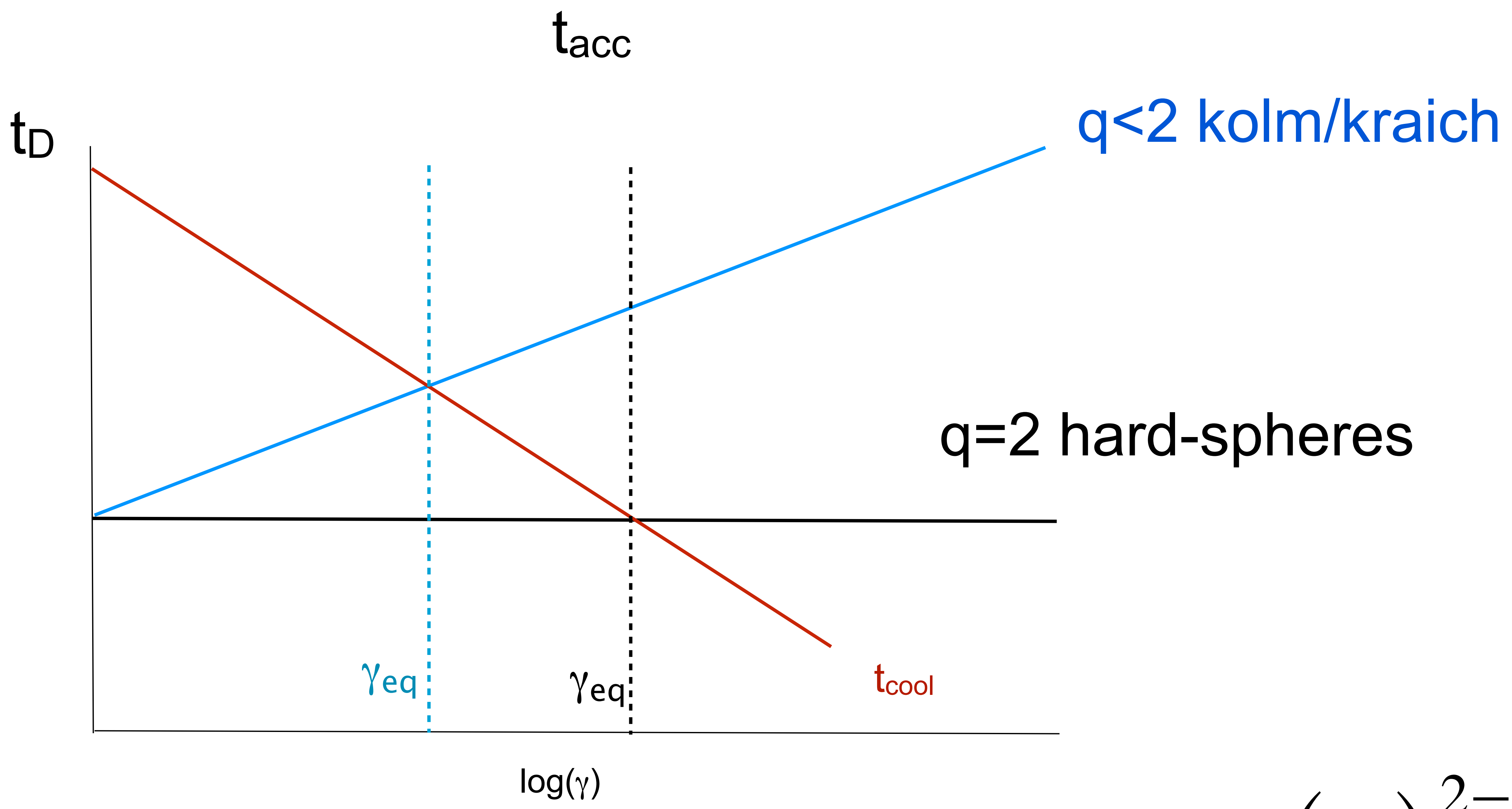


Tramacere +2011





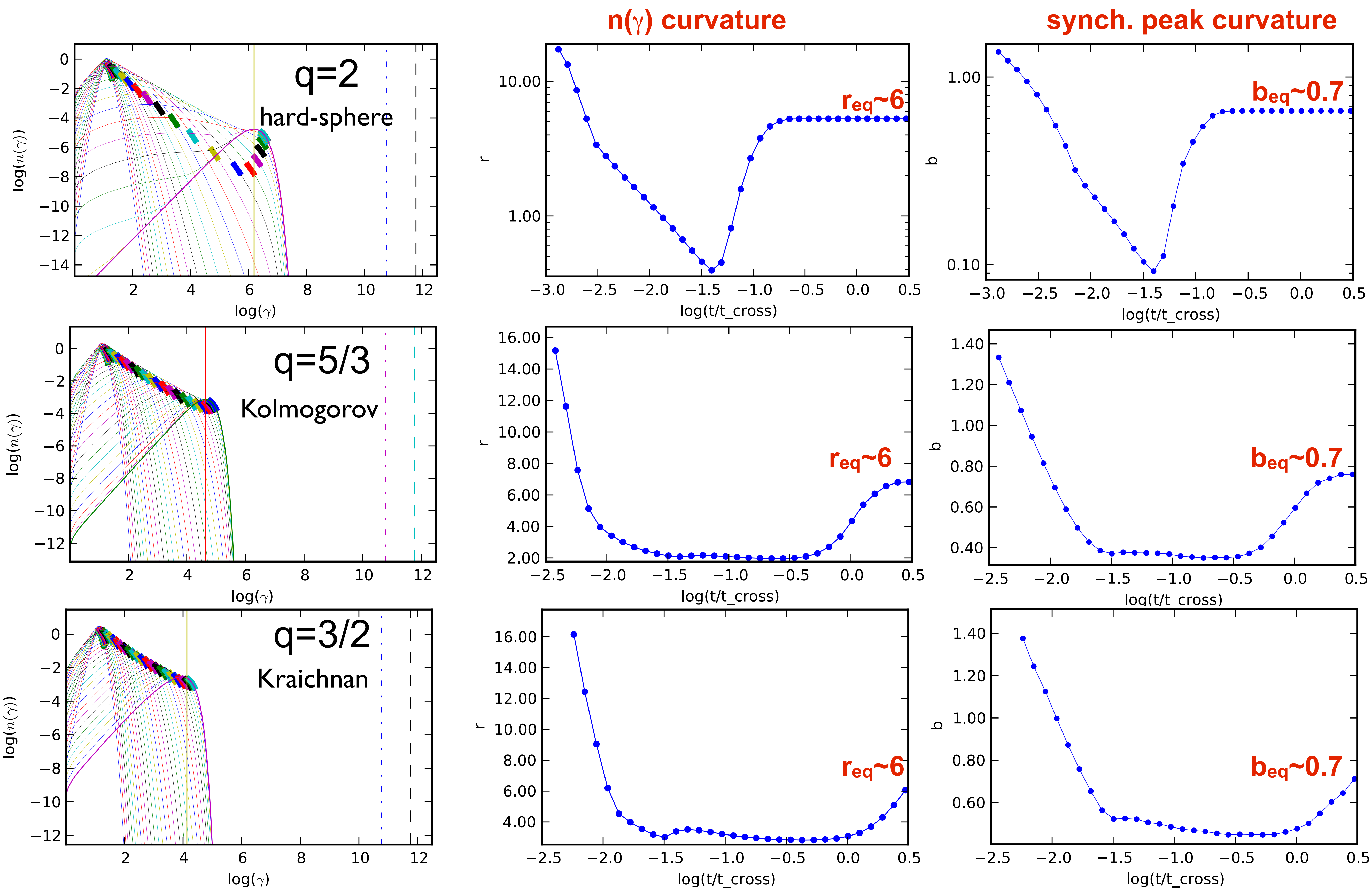
effect of the turbulence index q



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

effect of the turbulence index q

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



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}

Tramacere+2011

statistical approach

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

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

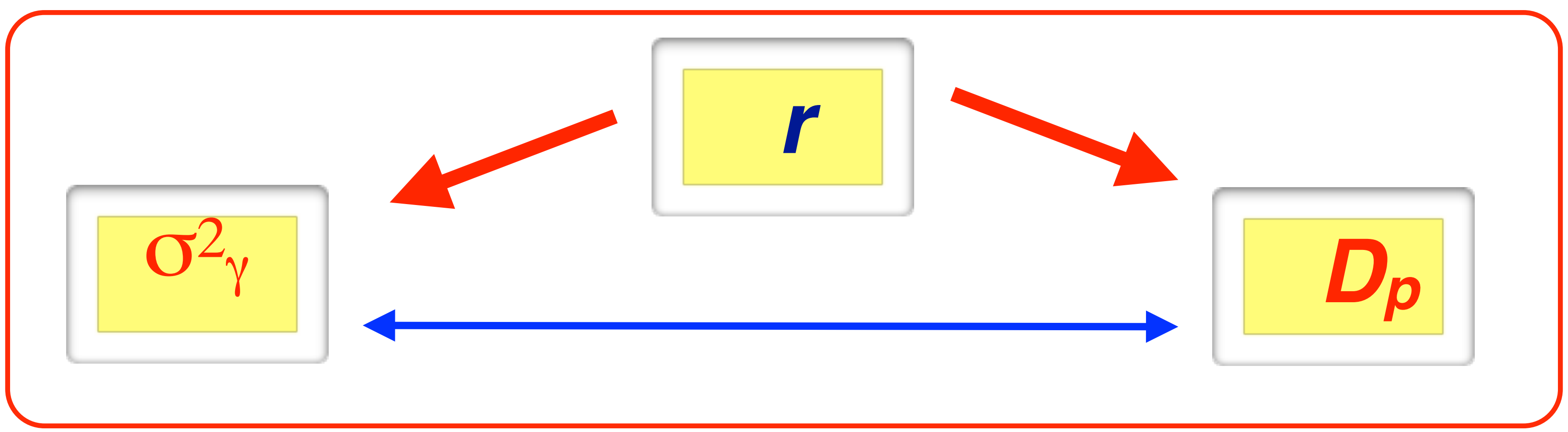
diffusion equation approach

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

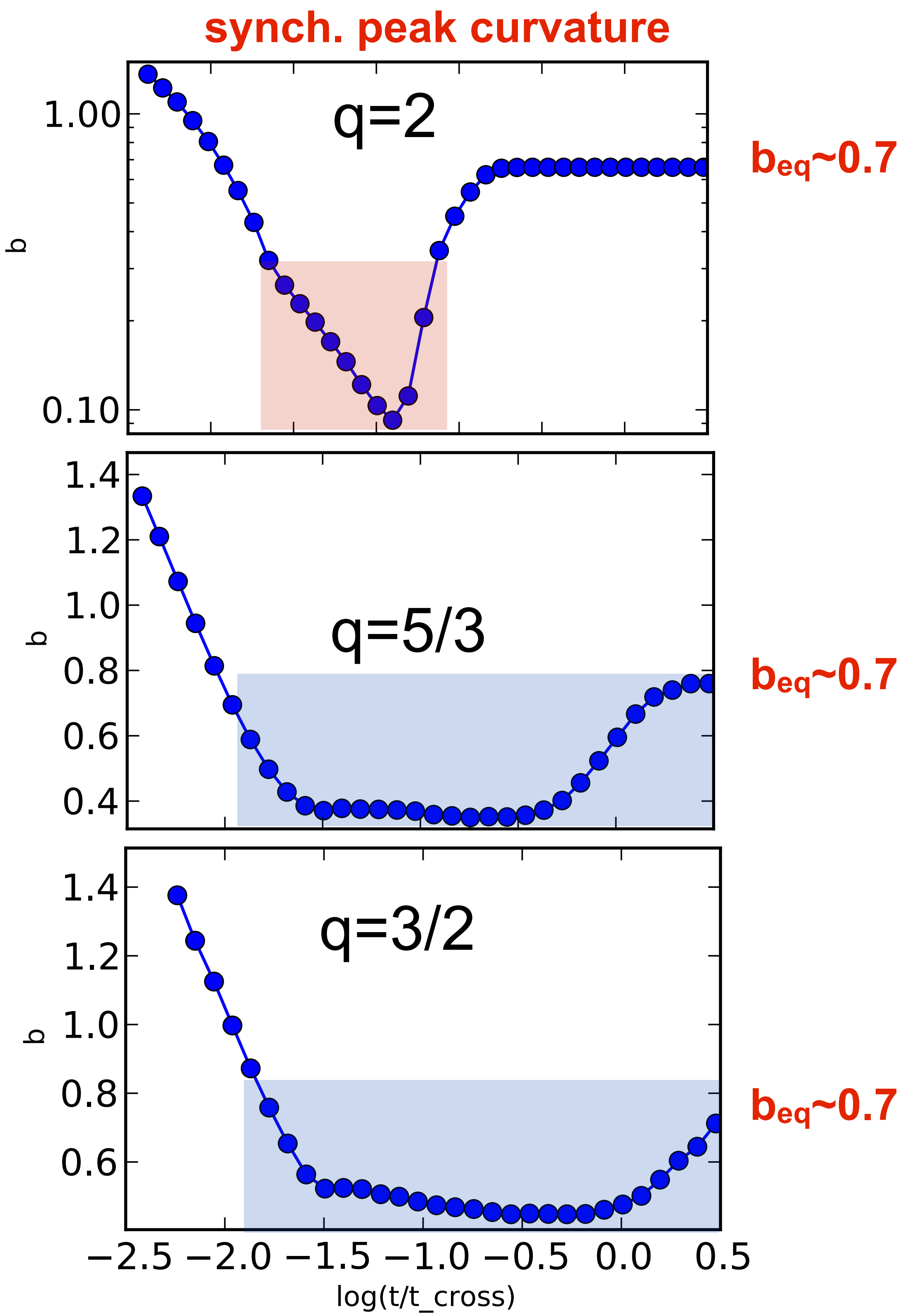
$$r \propto \frac{1}{D_{p0}t} \rightarrow D_{p0} \propto \left(\frac{\sigma_\varepsilon}{\bar{\varepsilon}}\right)^2$$

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

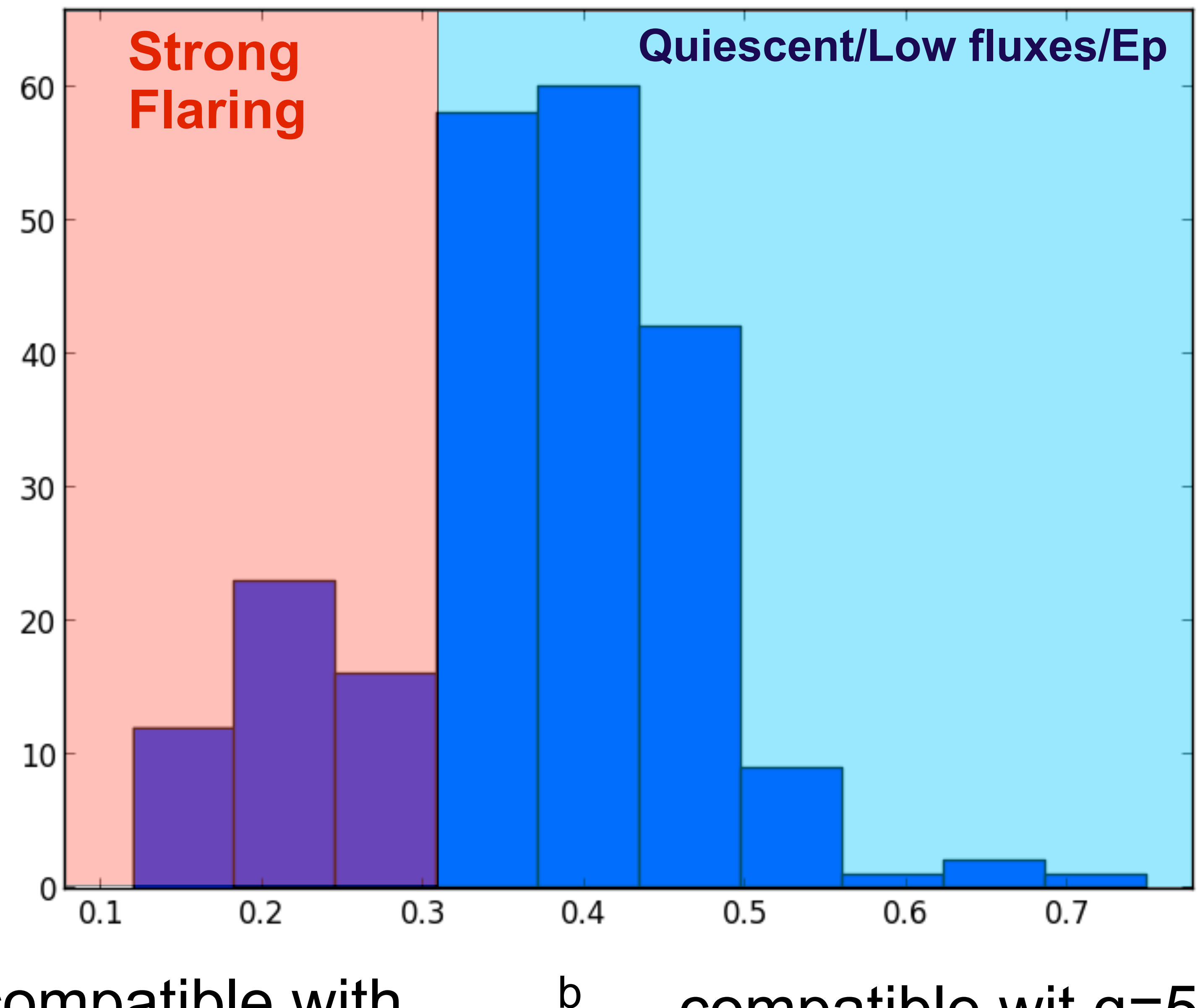
log-parabolic shape natural consequence of dispersion



b distributions and q



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

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

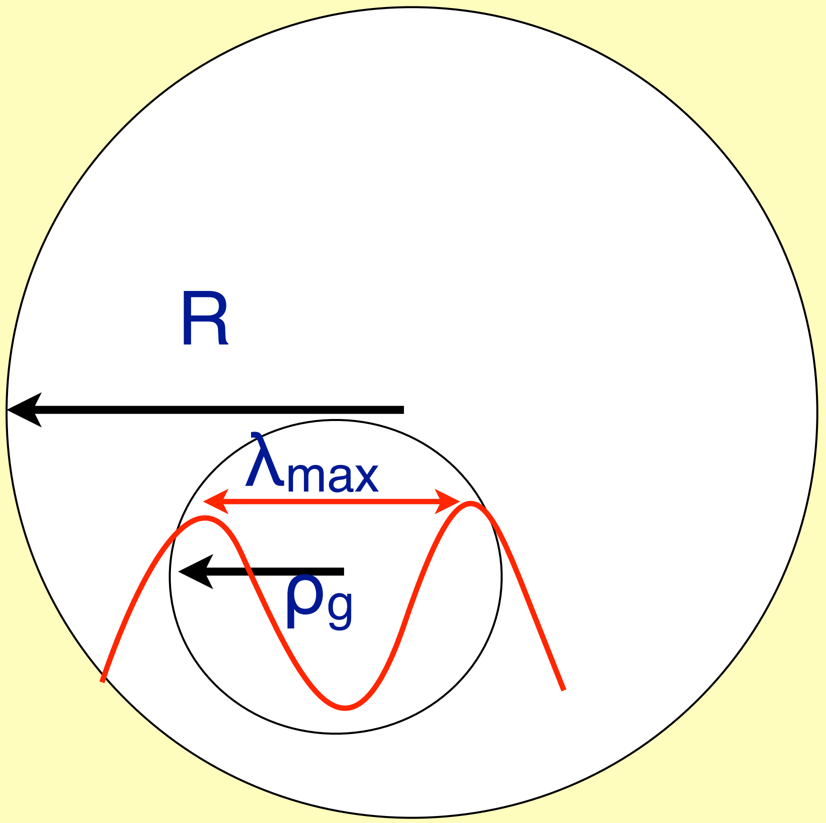
t_{DA} ~< 5 ks

t_D ~< 10 ks

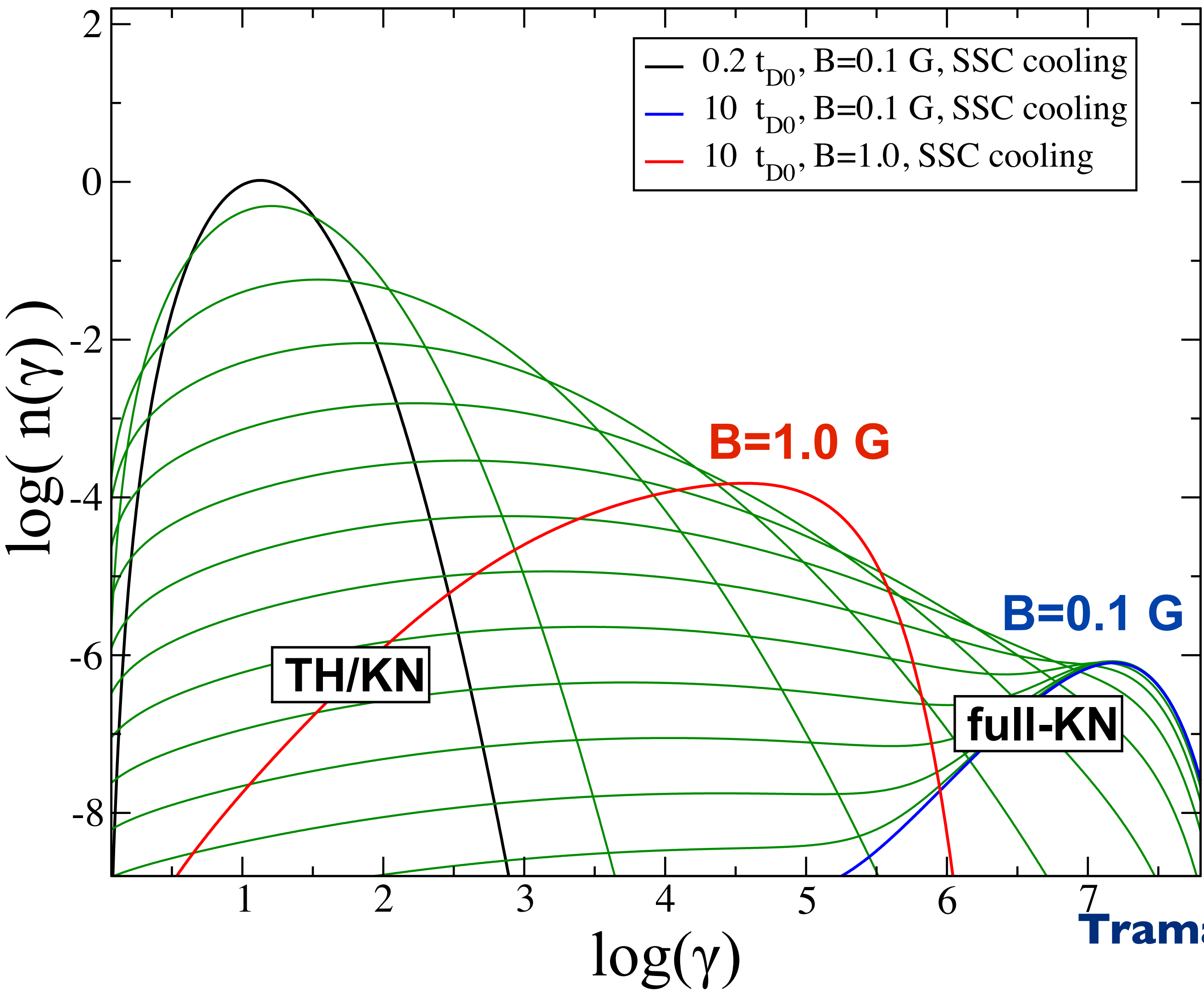
set-up of the accelerator

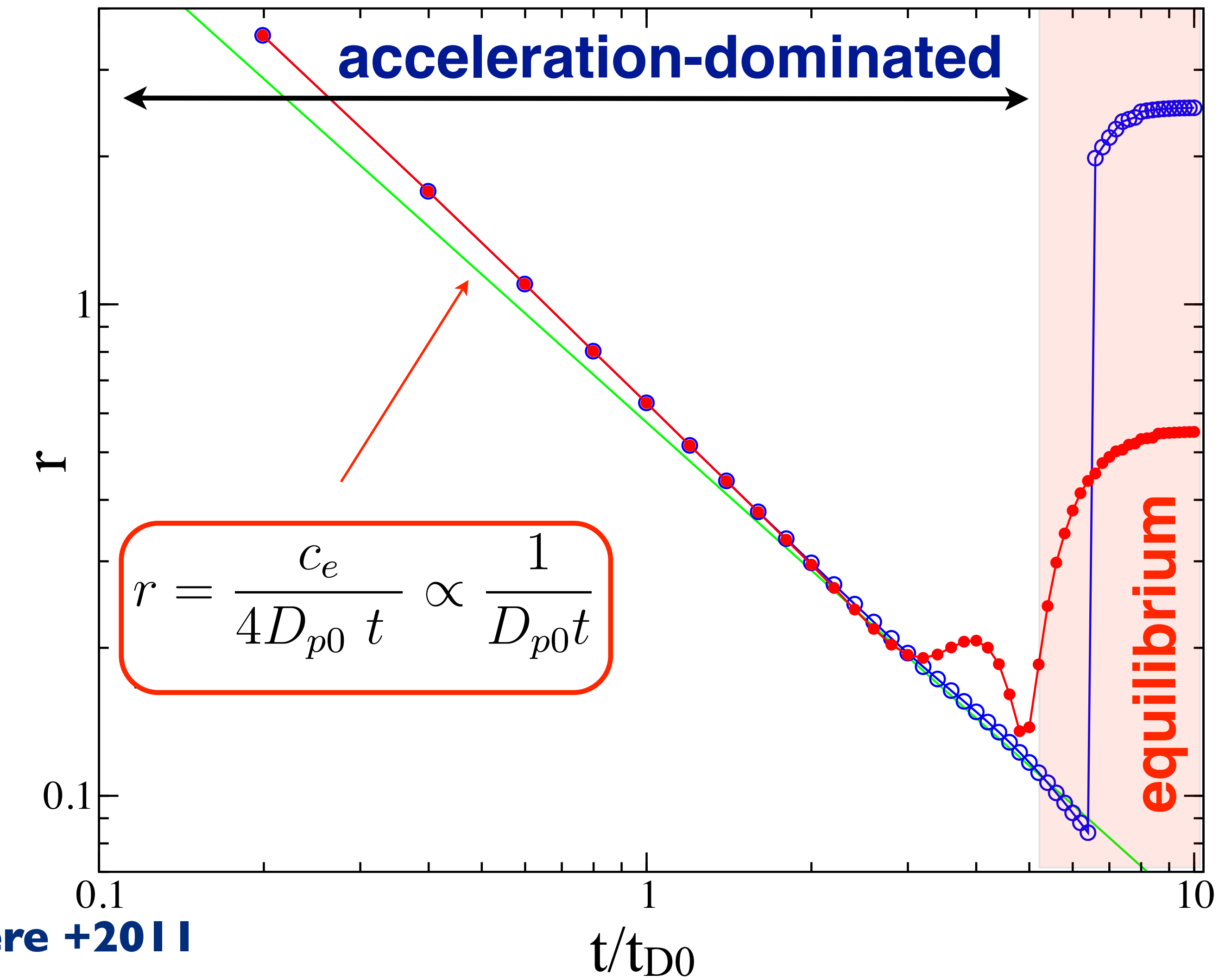
- R~ 10^{13}-10^{15} cm
- $\delta B/B<<1$, B~[0.01-1.0] G
- $\beta_A \sim 0.1$-0.5
- $\lambda_{max}<R$ => ~ $10^{[9-15]}$ cm
- $\rho_g<\lambda_{max}$ => $\gamma_{max} \sim 10^{7.5}$

→ **t_D~<10^4 ks**



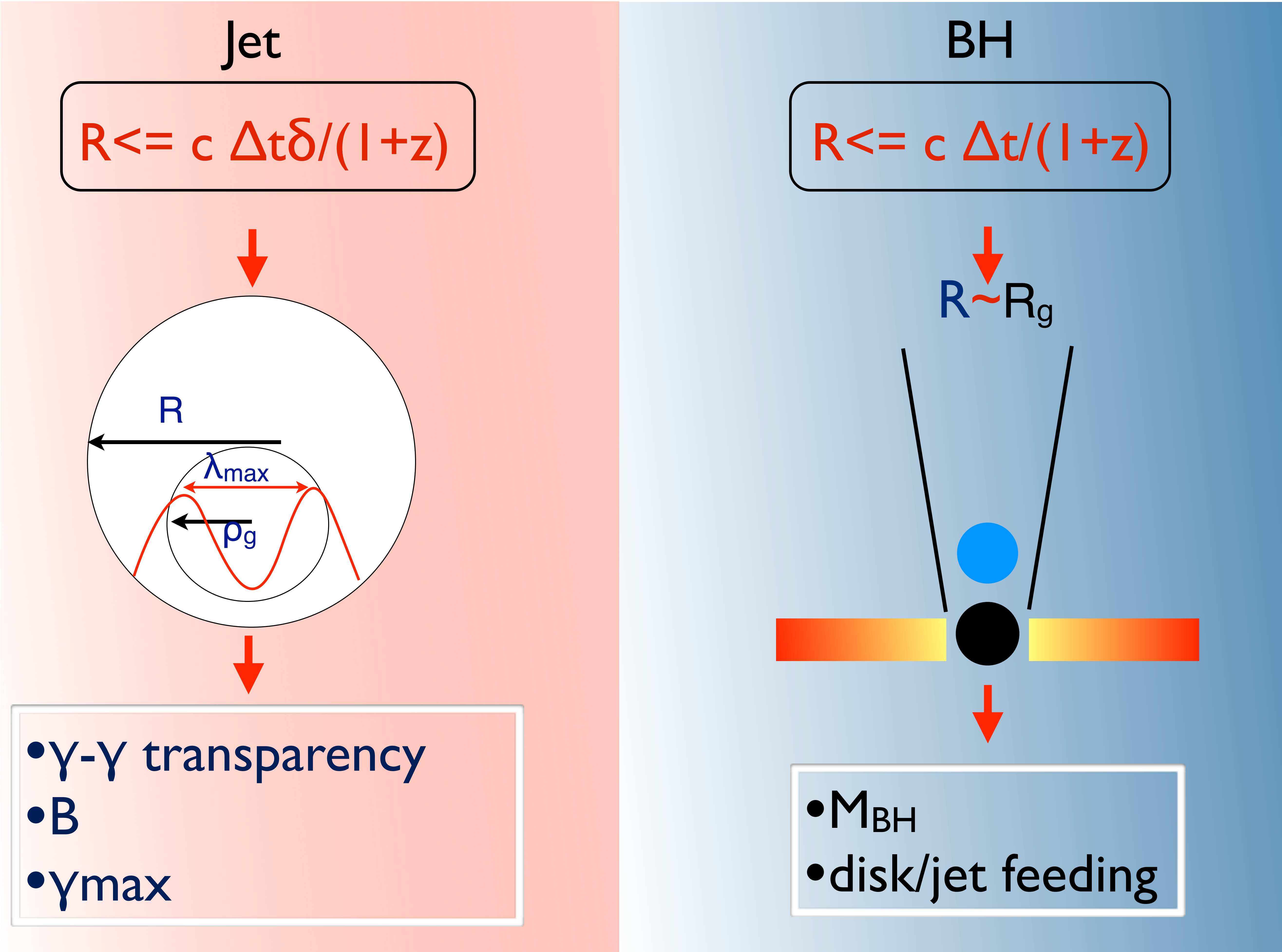
Flare: acc.-dominated-vs-equil.,R= 10^{15} cm, q=2



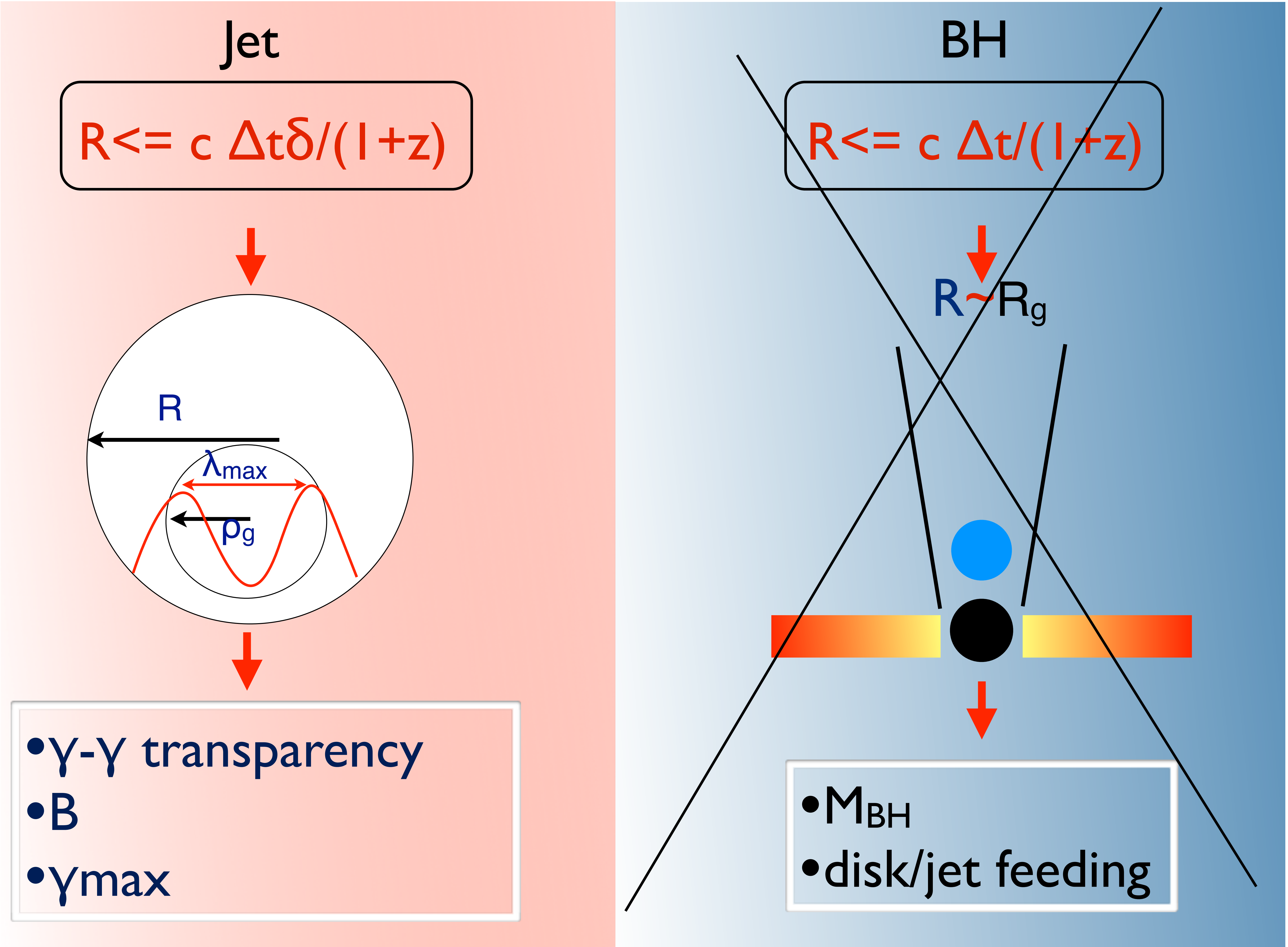


- mono energetic inj., $t_{inj} << t_{acc}$, $t_{inj} << t_{sim}$
- we measure r@peak as a function of the time
- two phase: **acceleration-dominated**, **equilibrium**
- equil. distribution:
  - **f=1 for q=2 and S, full TH, or full KN**
- **equil. curv.: r~2.5, (r_{3p}~6.0) for TH or full KN**
- **equil.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

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

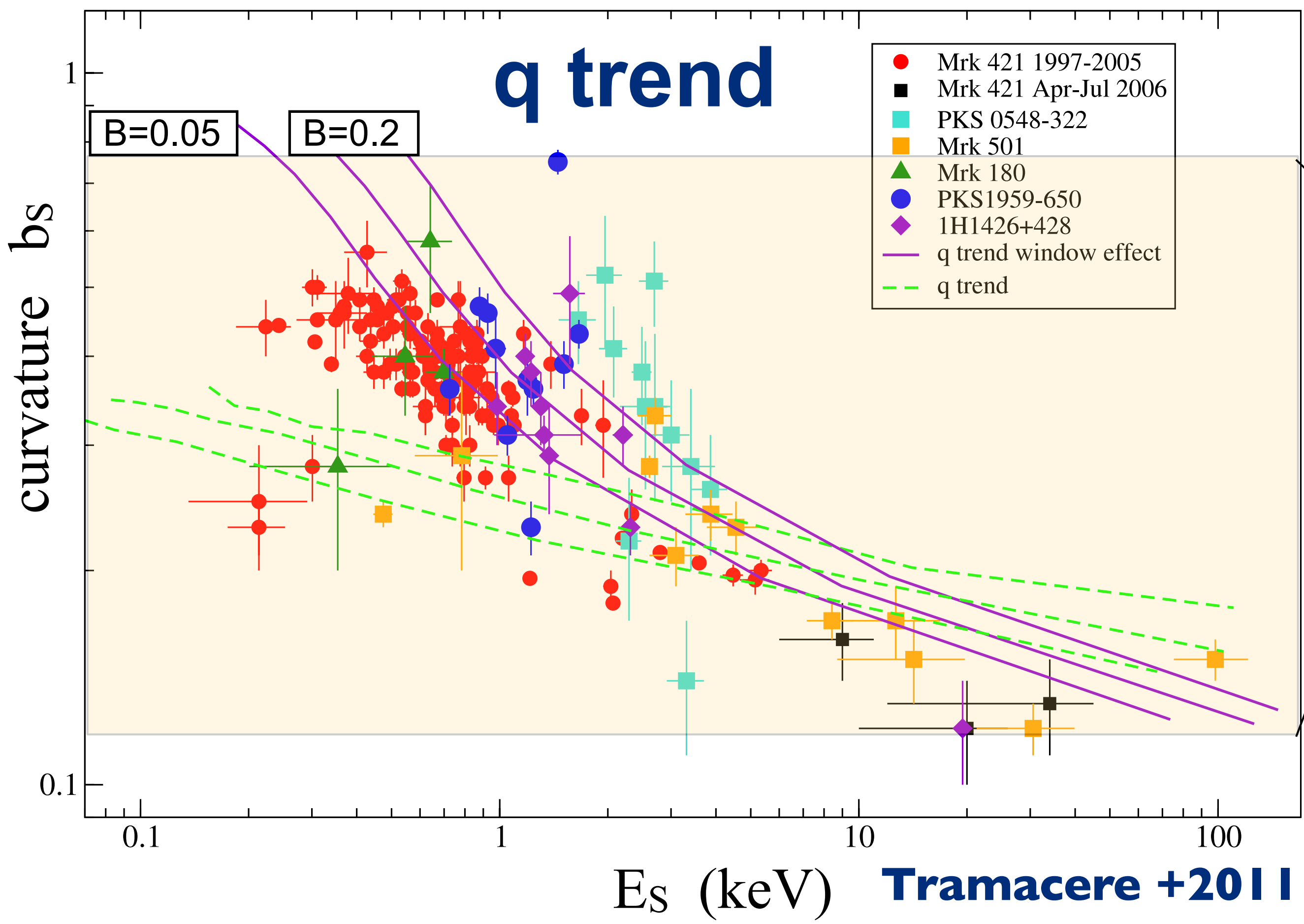


Jet
R<= c ΔtΔ/(1+z)
R
λmax
ρg
•γ-γ transparency
•B
•γmax
BH
R<= c Δt/(1+z)
R~Rg
•MBH
•disk/jet feeding

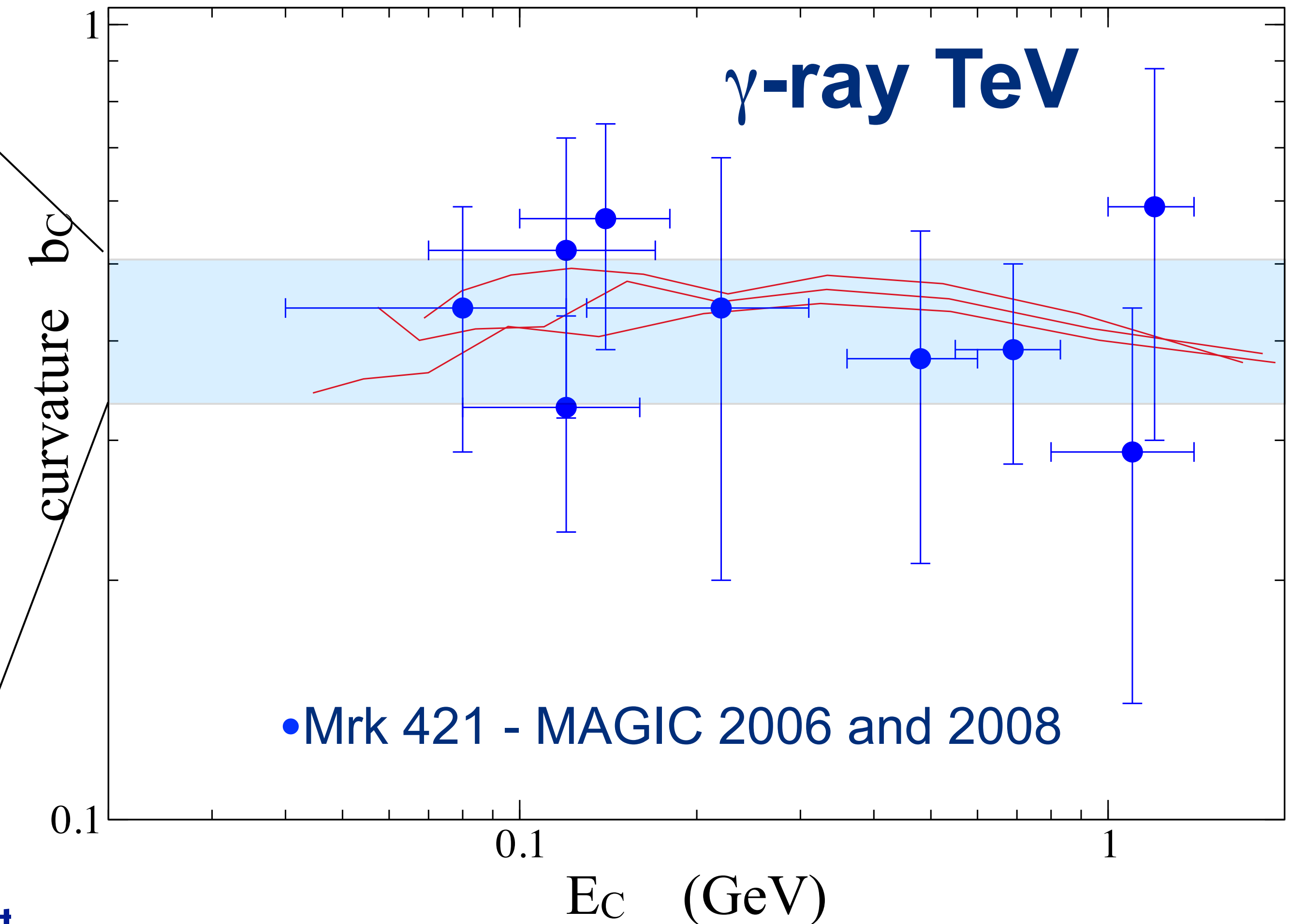


Jet
R<= c Δtδ/(1+z)
R
λmax
ρg
•γ-γ transparency
•B
•γmax
BH
R<= c Δt/(1+z)
R~Rg
•MBH
•disk/jet feeding

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



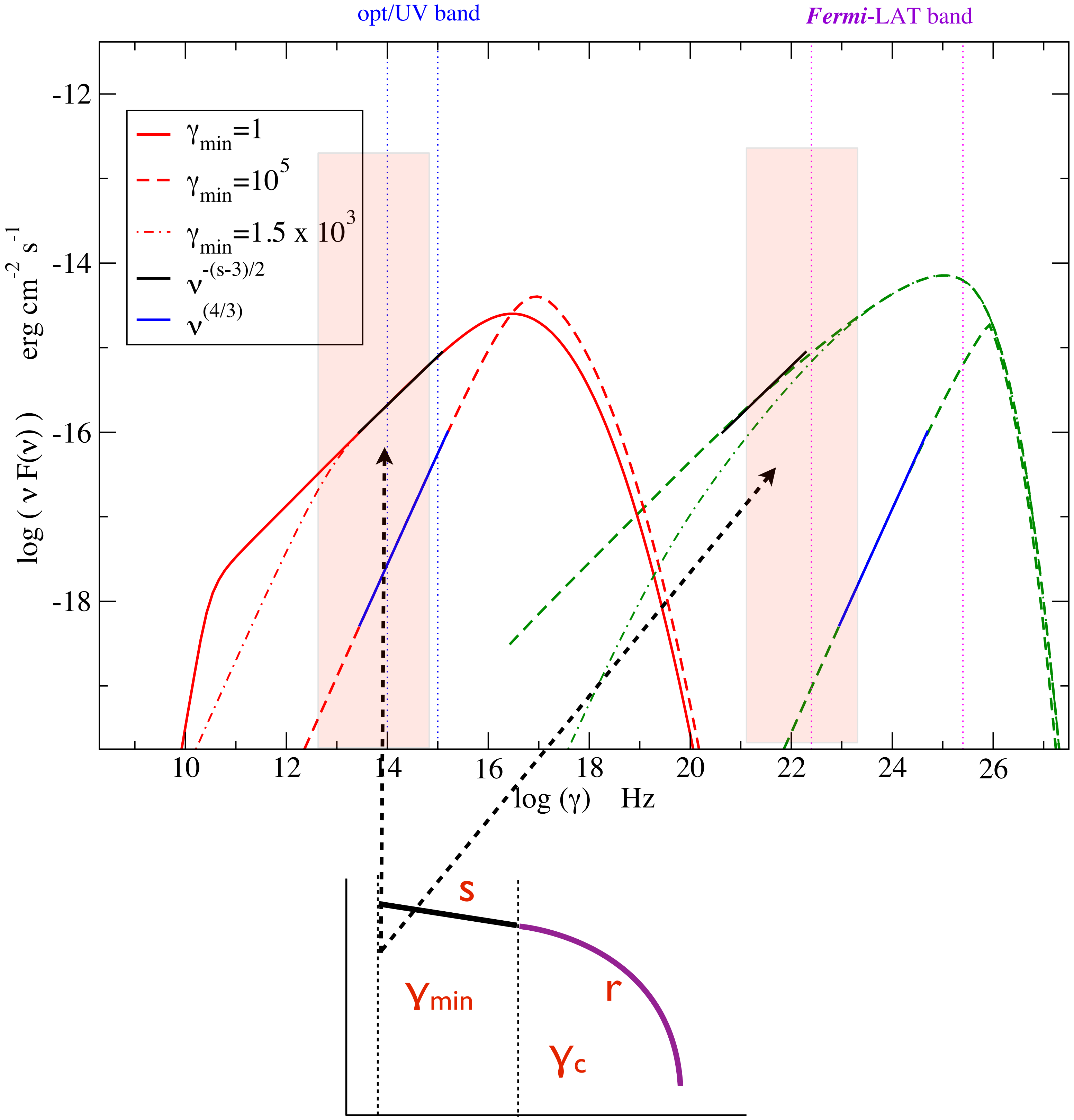
Tramacere +2011



- 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 (*q*)
- curvature values imply distribution far from the equilibrium (b~[0.7–1.0])
- More data needed at GeV/TeV, curvature seems to be cooling-dominated

$L_{\rm inj}$ (E_s–b_s trend)	(erg s^{-1})	5×10^{39}
$L_{\rm inj}$ (E_s–L_s trend)	(erg s^{-1})	5×10^{38}, 5×10^{39}
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

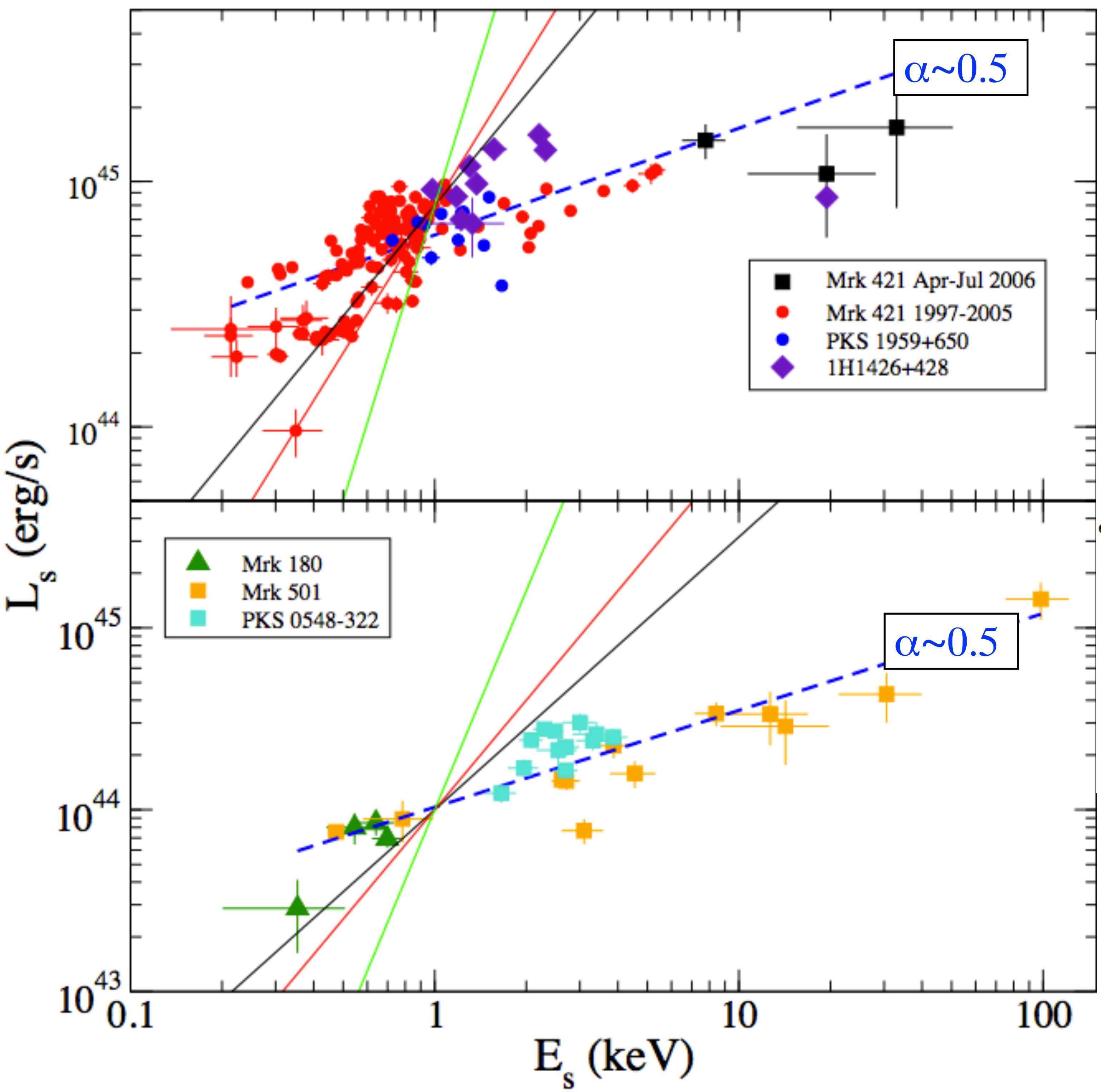
HBLs case



opt/UV band
Fermi-LAT band
-12
-14
-16
-18
log (ν F(ν)) erg cm^-2 s^-1
γmin=1
γmin=10^5
γmin=1.5 x 10^3
ν^-(s-3)/2
ν^(4/3)
10
12
14
16
18
20
22
24
26
log (γ) Hz
s
γmin
r
γc

acceleration signature in the E_S-vs-L_s trend

long-trend main drivers



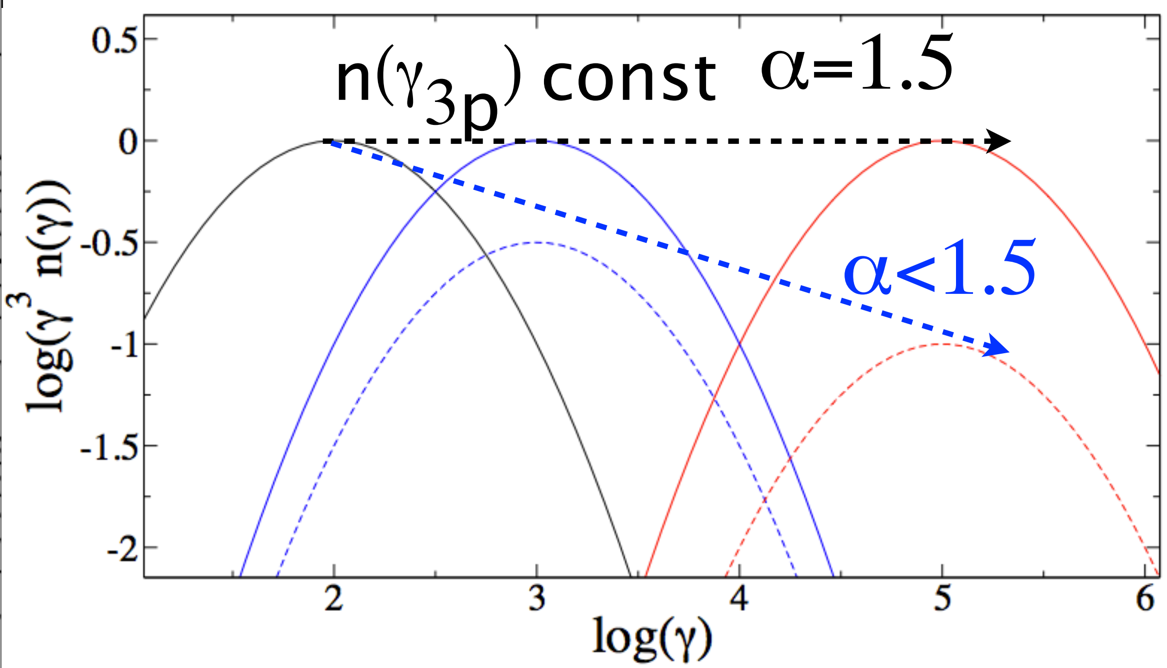
Tramacere+2009

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

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

↓

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



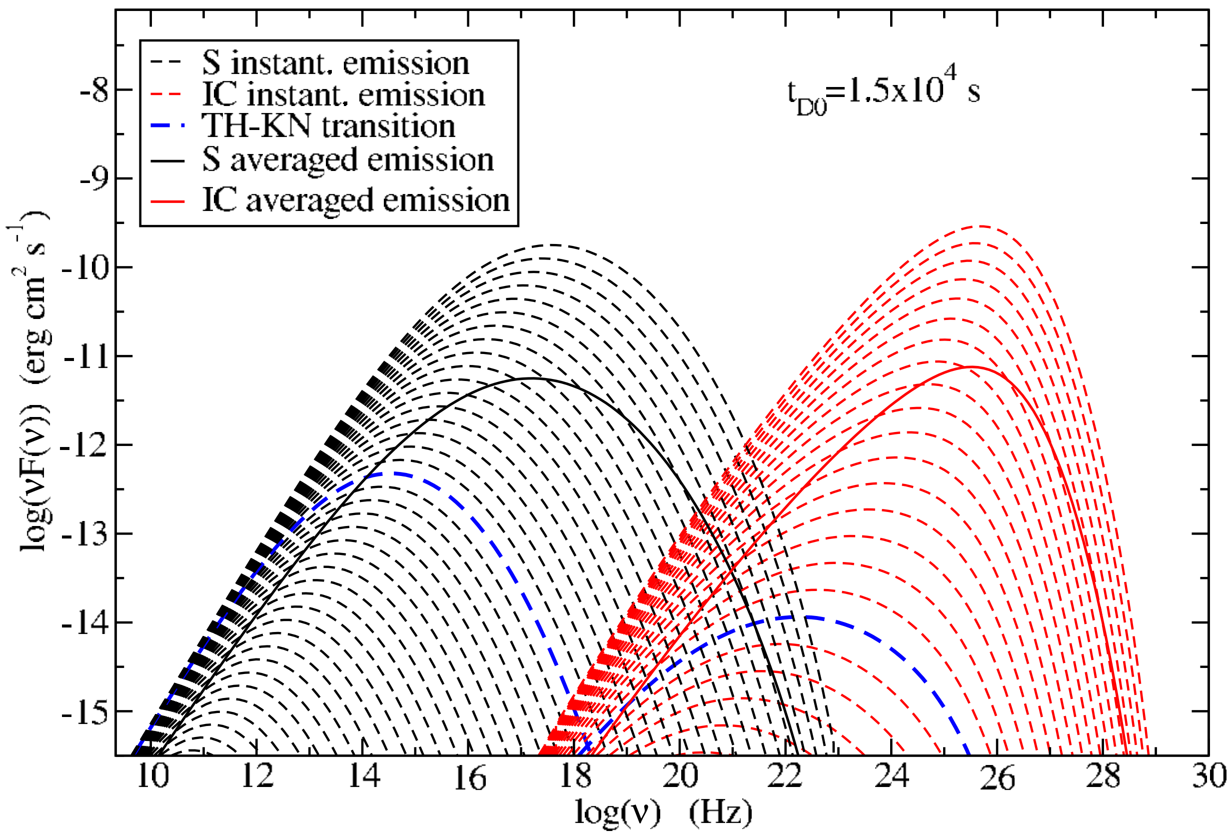
• γ_{3p}↑ **and n(γ3p)**↓ **=>** α<1.5

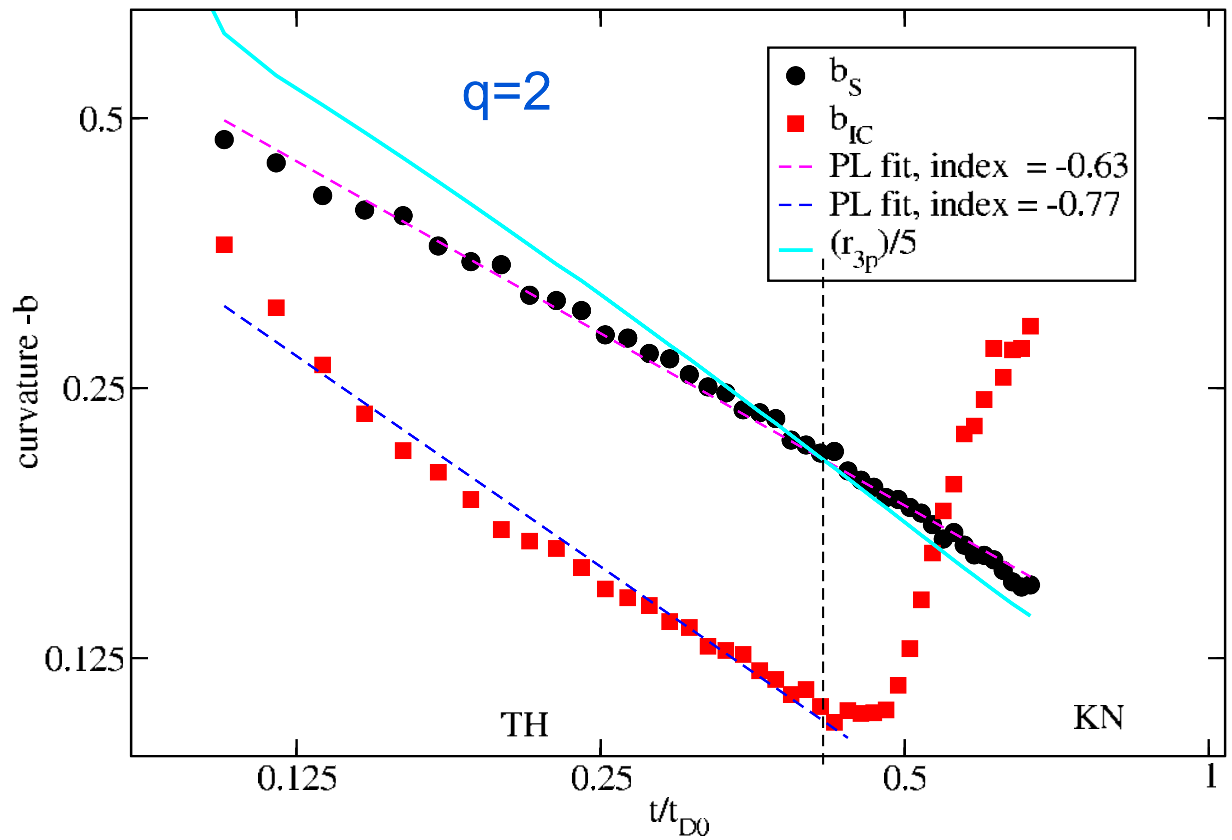
acceleration+energy conservation

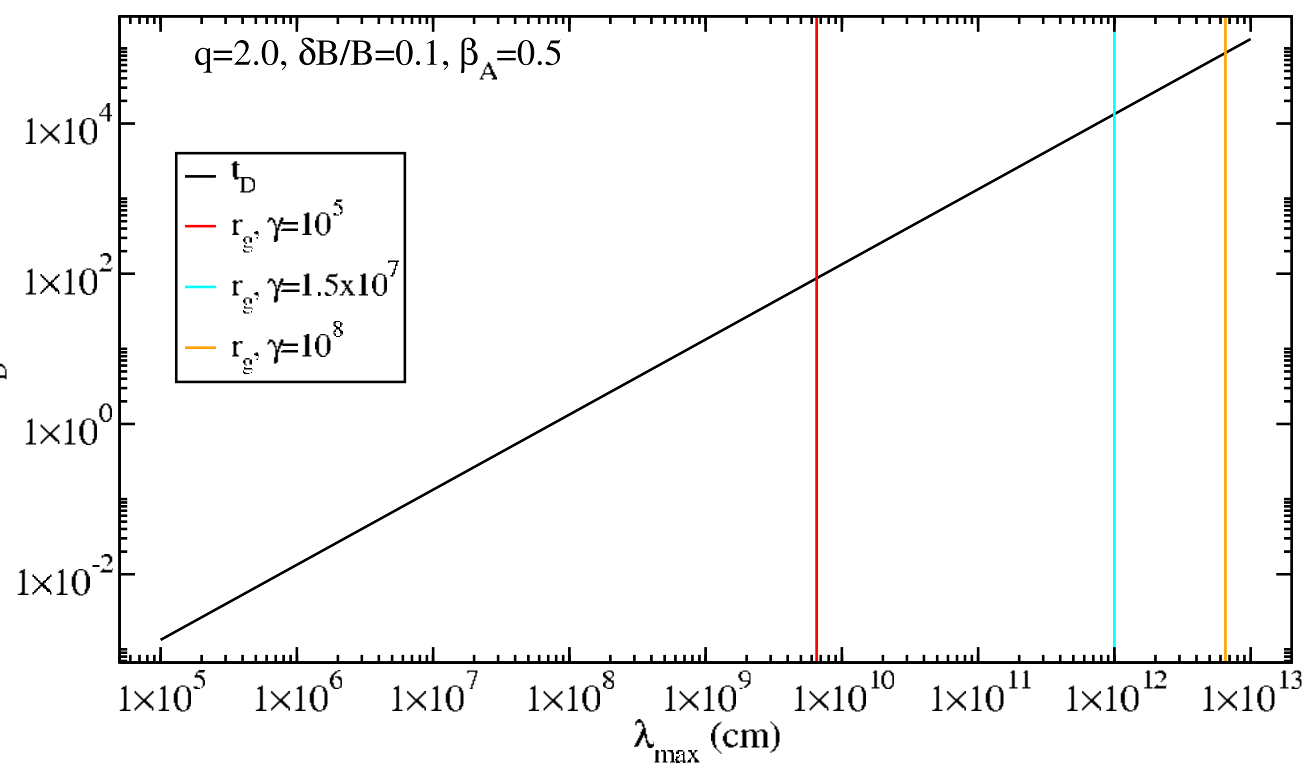
• B−>α=2.0,
• δ−>α=4

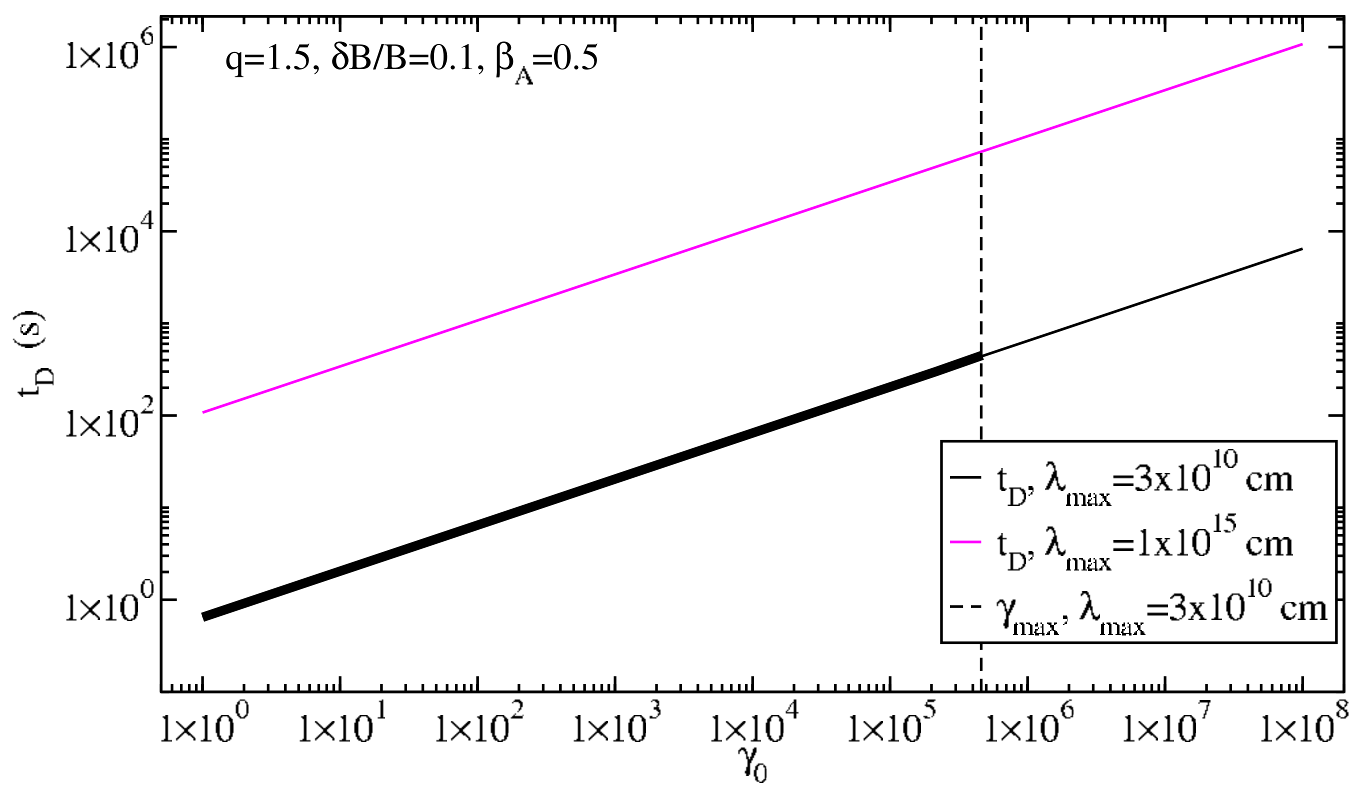
incompatible as long-trend main driver

SEDs evolution

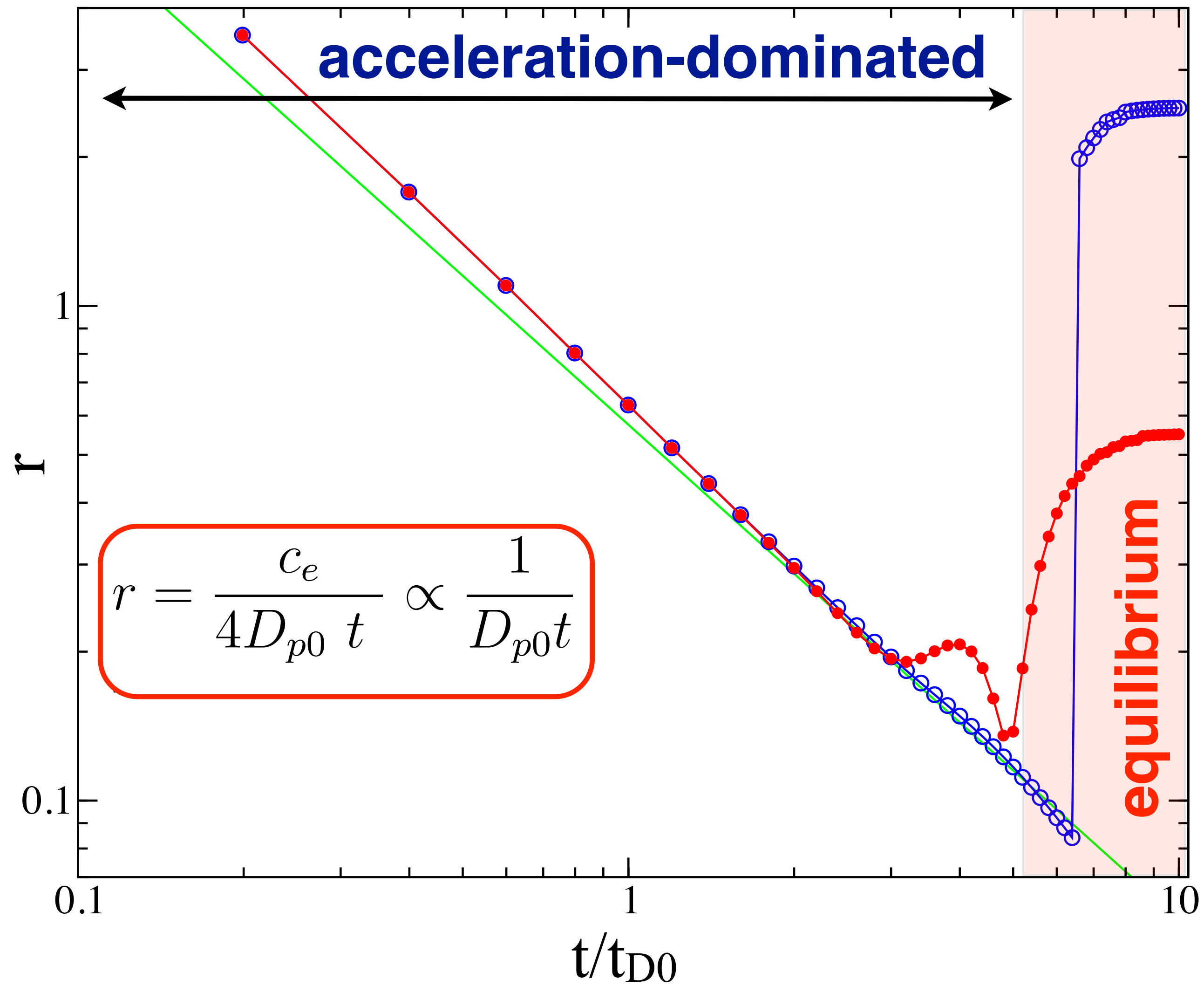


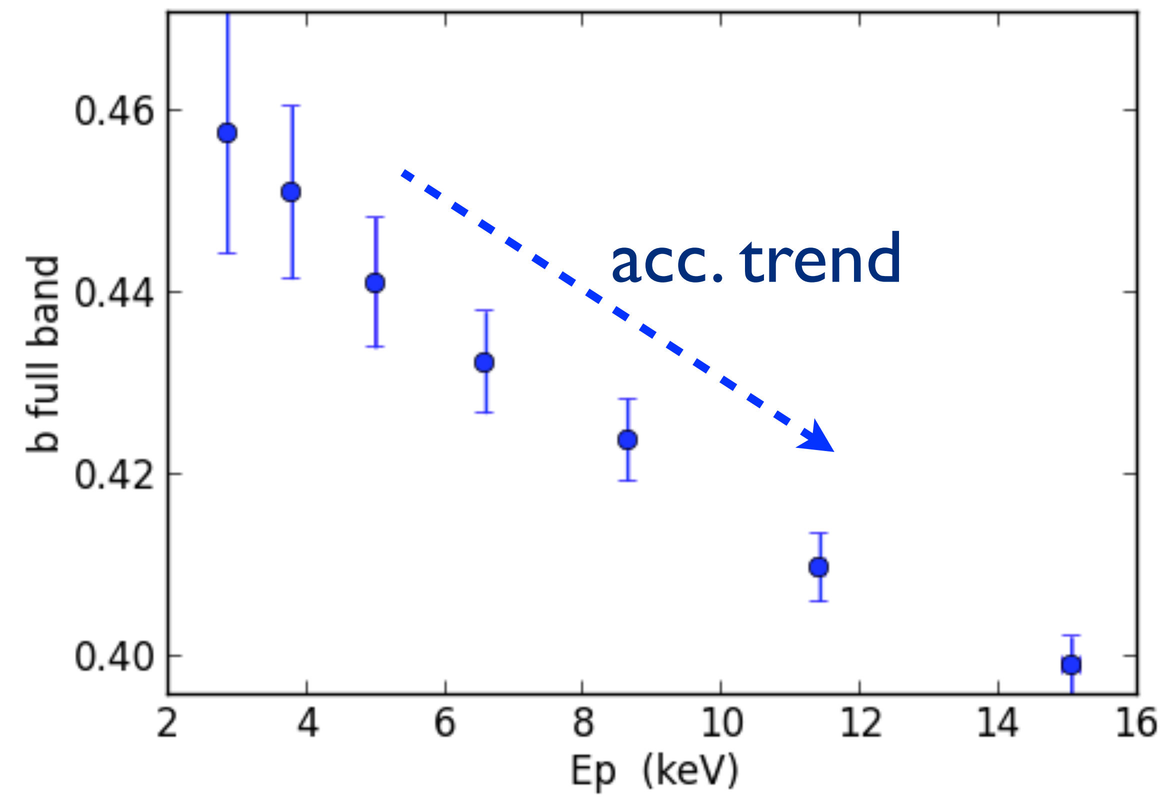


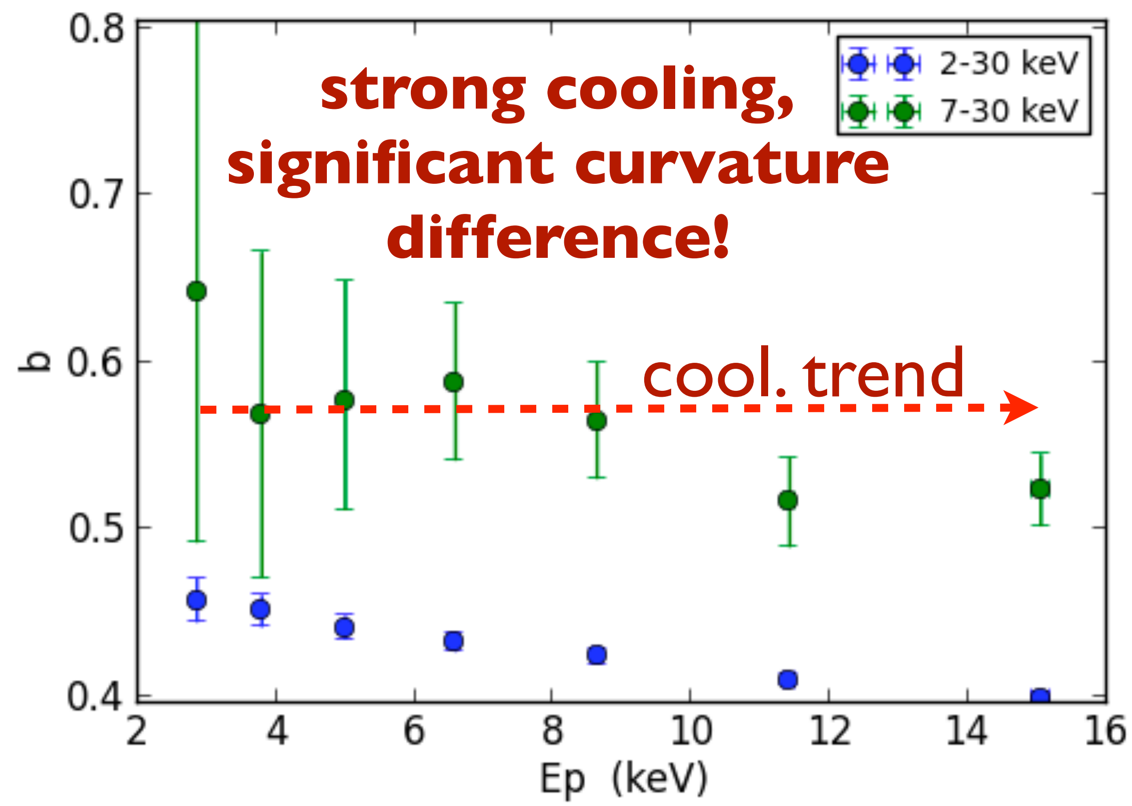




Strong cooling





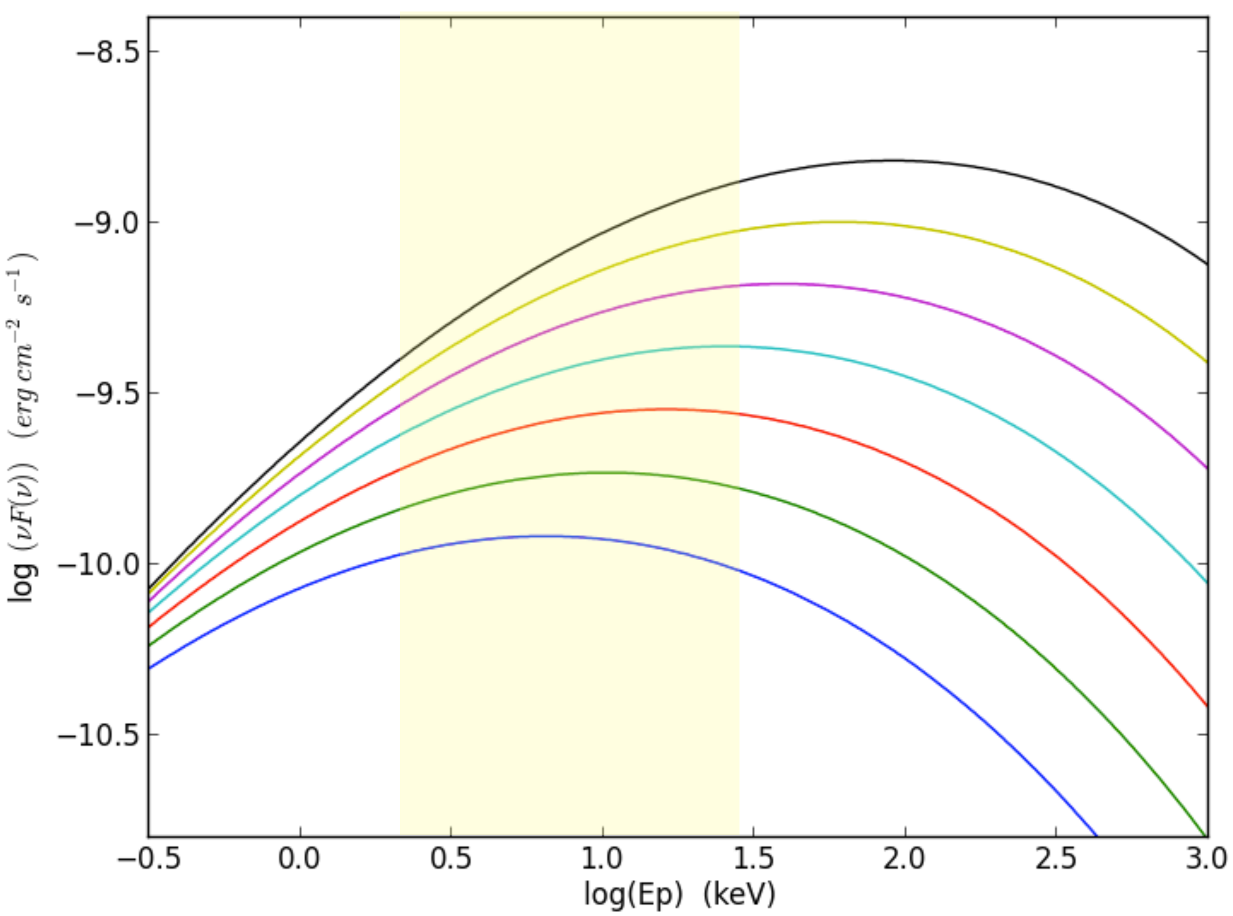


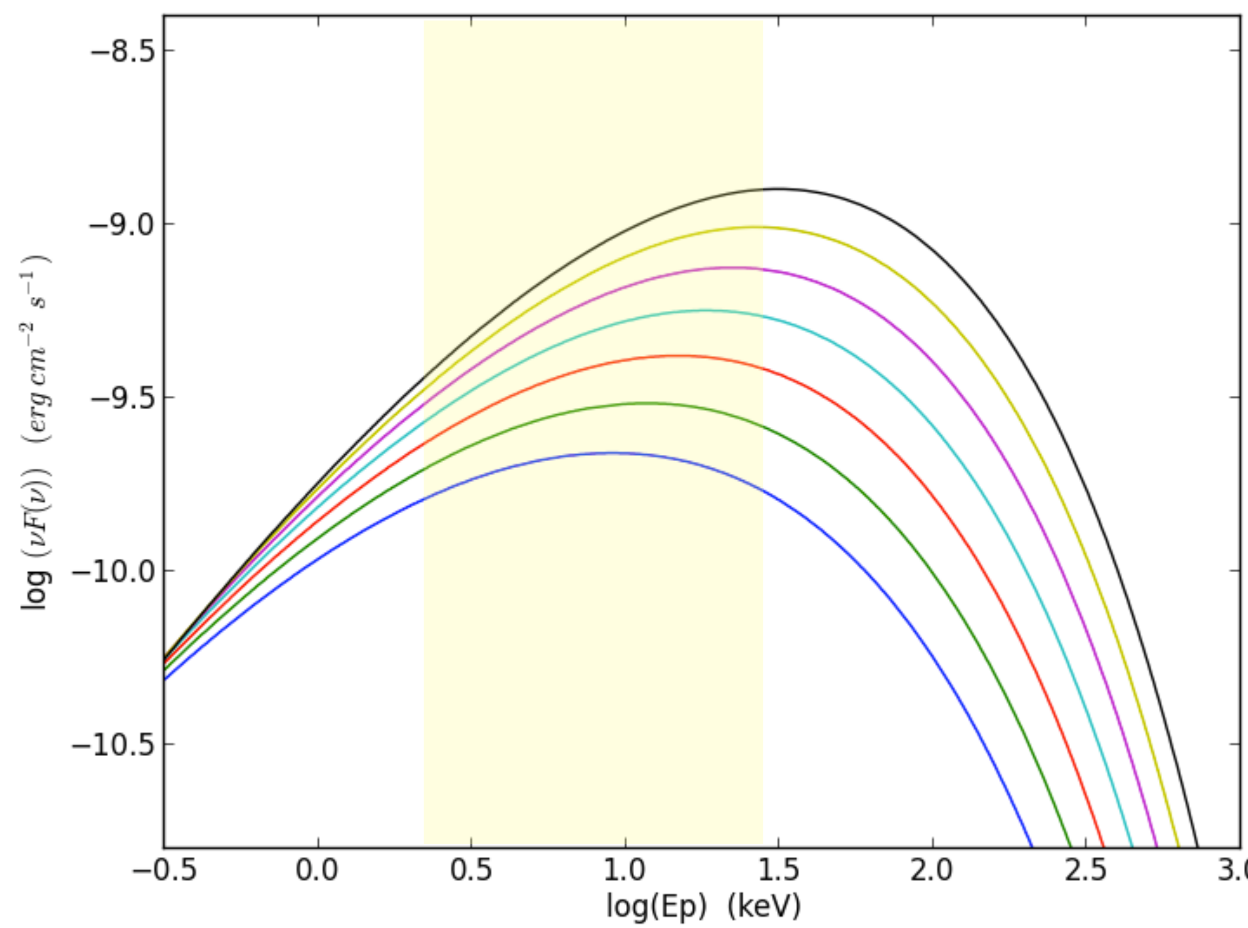
- Full bands curvature related to EED broadness, acceleration signature
- High energy band, dominated by cooling, moving towards the equilibrium

Moving Ep above 30 keV

Low cooling

Strong cooling

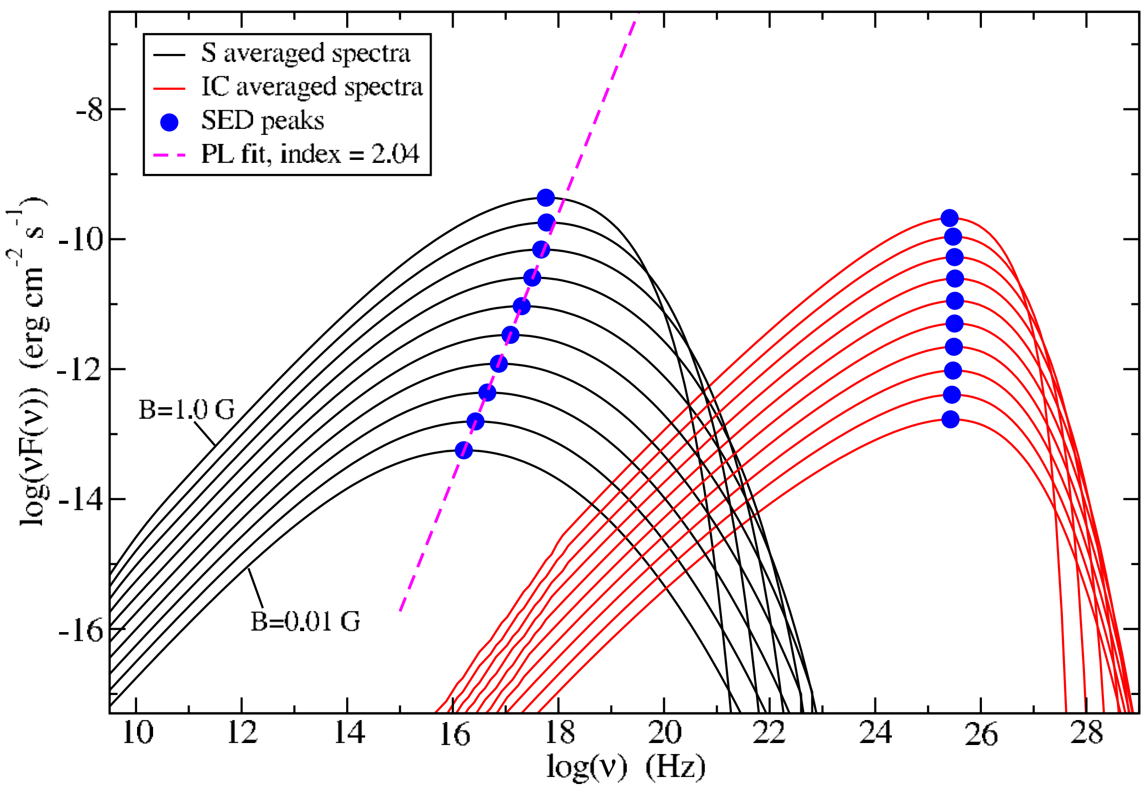


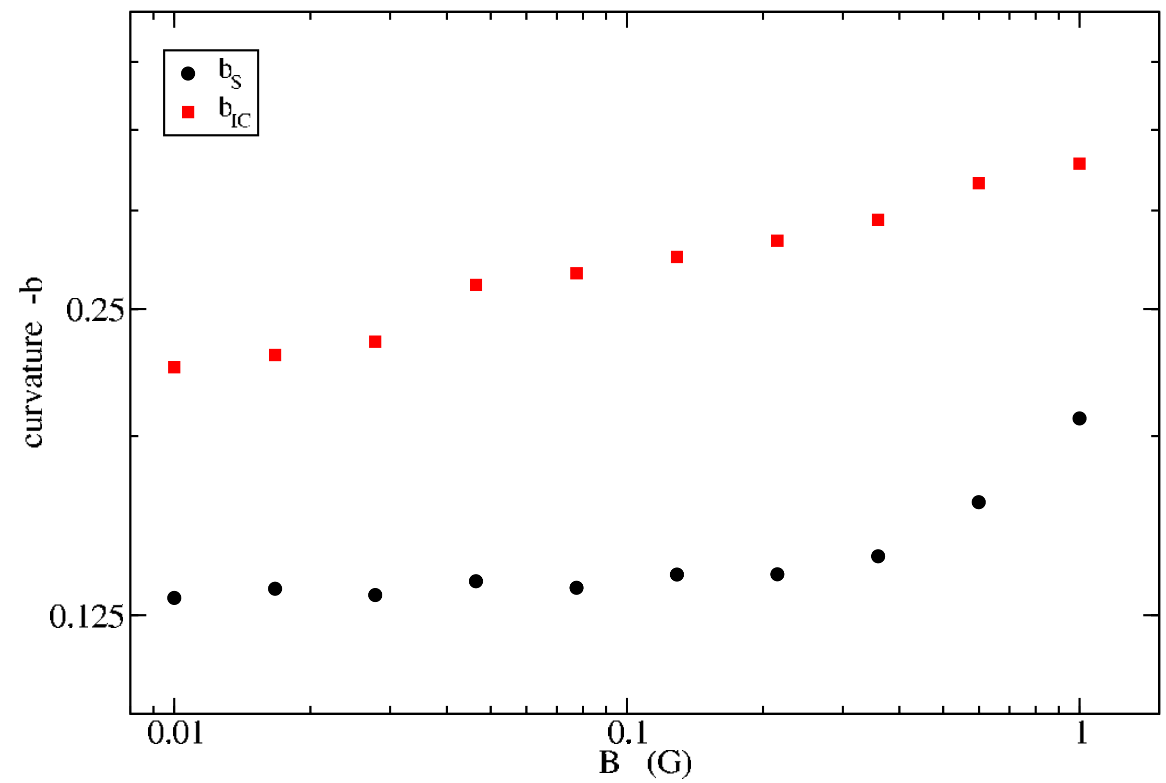


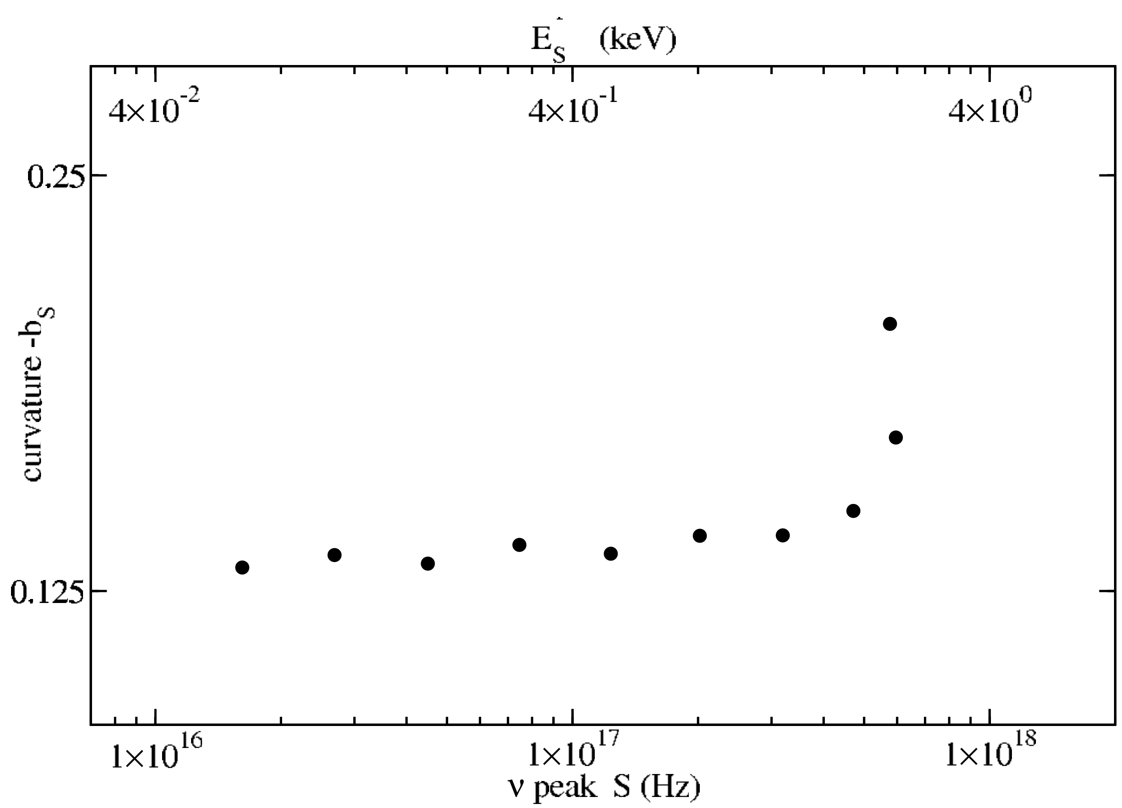
B	0.2/1.0	*G*
R	3×10^{15}	*cm*
L_{inj}	5×10^{39}	*erg/s*
q	2	
t_A	1.2×10^{3}	*s*
t_D	$2.2\text{-}\times10^{4}$	*s*

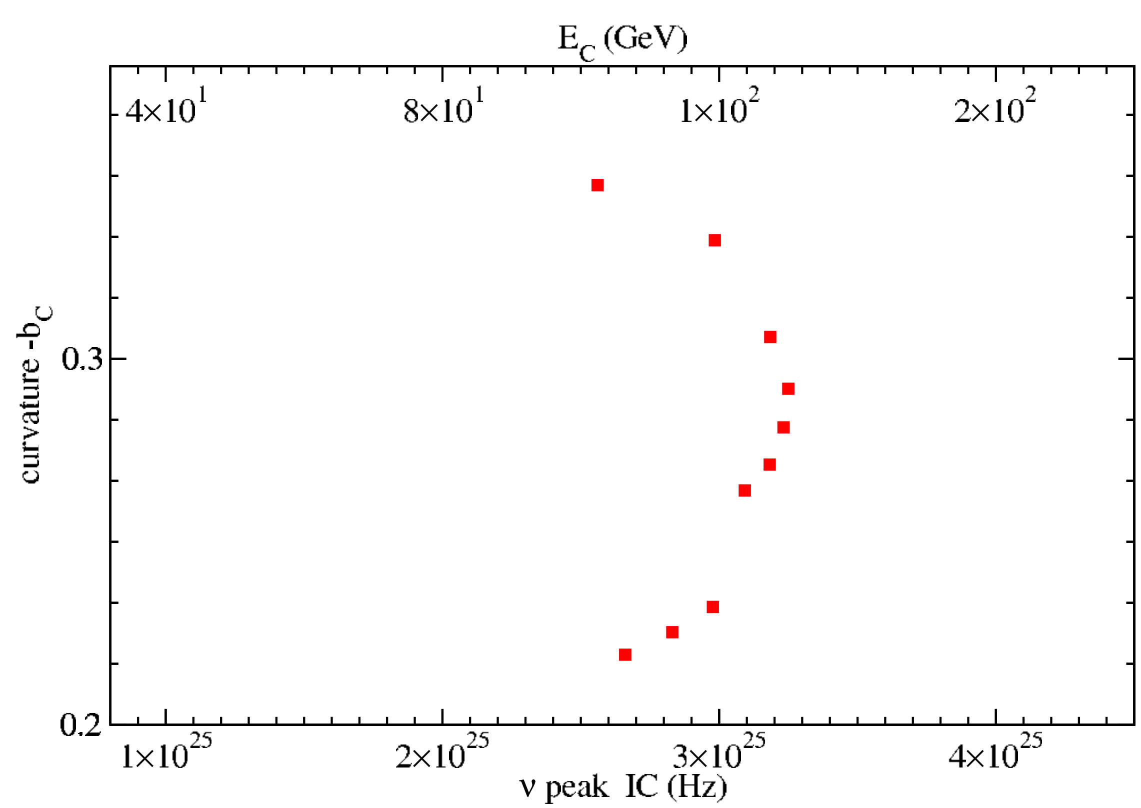
- SEDs are rescaled in order that the **brightest** state matches the flux of 10^{-09} erg cm^{-2} s^{-1} [2-10] keV
- during the flares, the fluxes range in ~ 1×10^{-10}-10^{-9} erg cm^{-2} s^{-1}
- **1 ks integration time**

Effect o B on SEDs

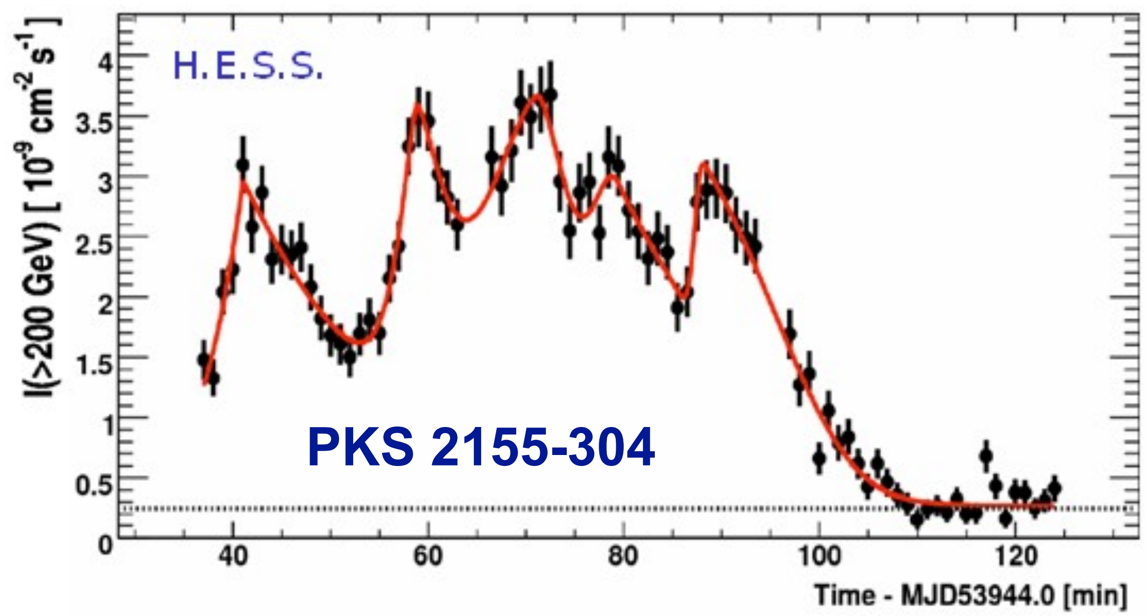


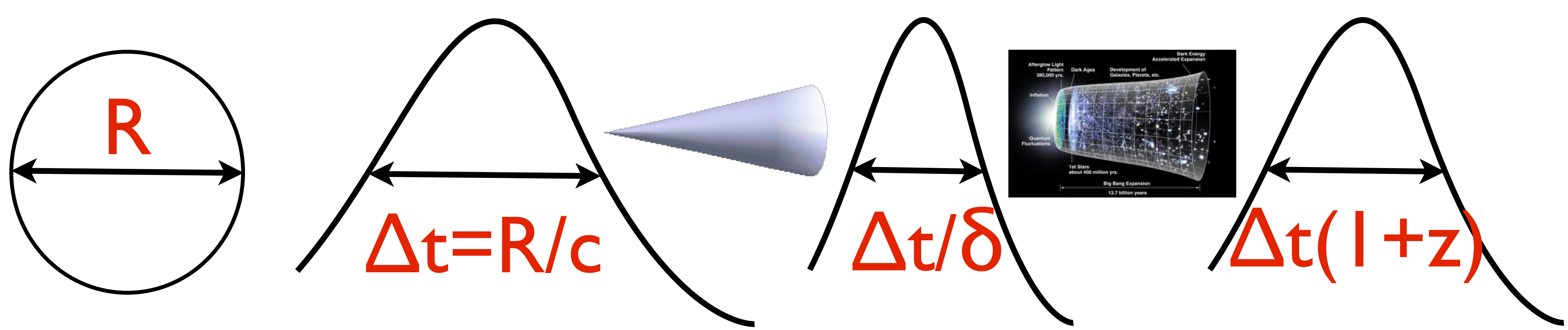






Rapid Variability



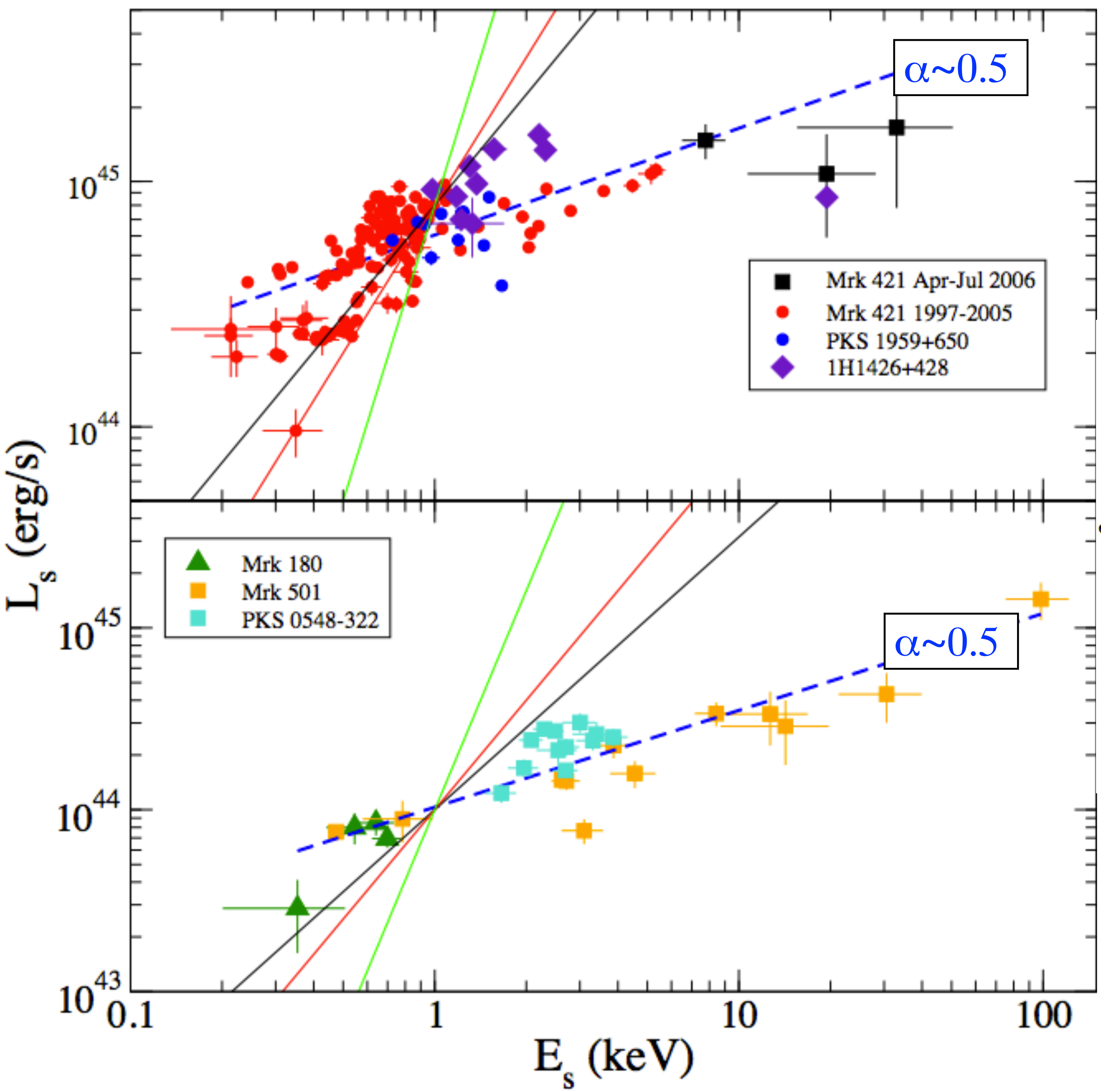


$$R <= c\, \Delta t \delta / (1+z)$$

acceleration signature in the E_S-vs-L_s trend

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

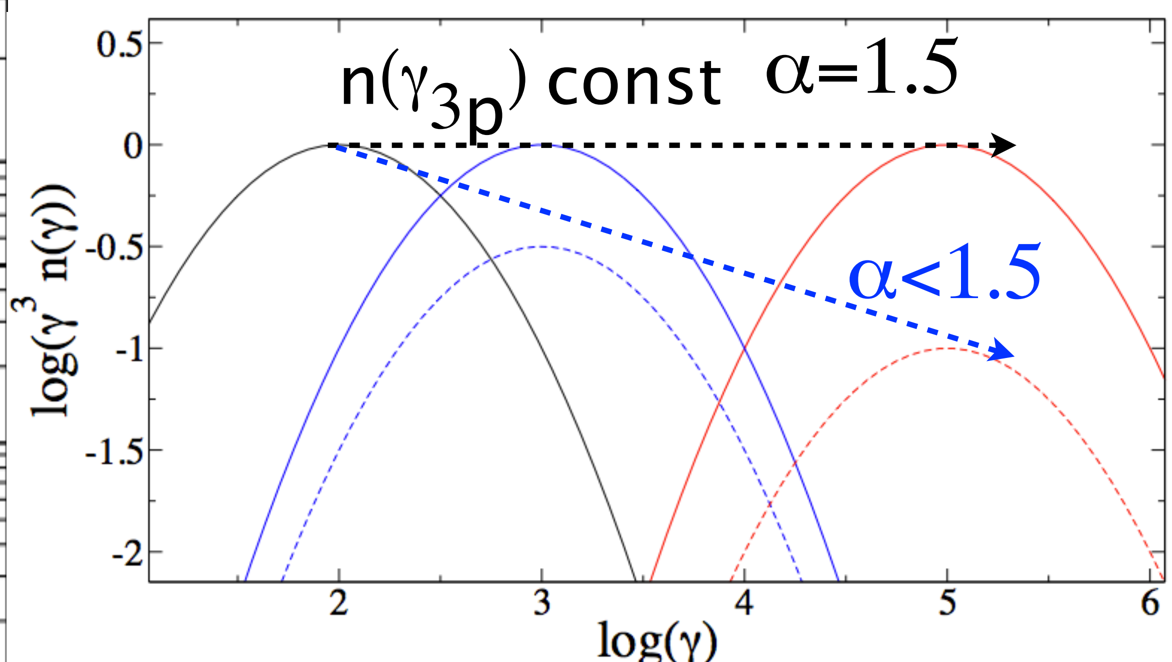
long-trend main drivers



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

↓

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



- γ_{3p}↑ **and $n(\gamma 3p)$↓ =>** α<1.5

acceleration+energy conservation

- B−>α=2.0,
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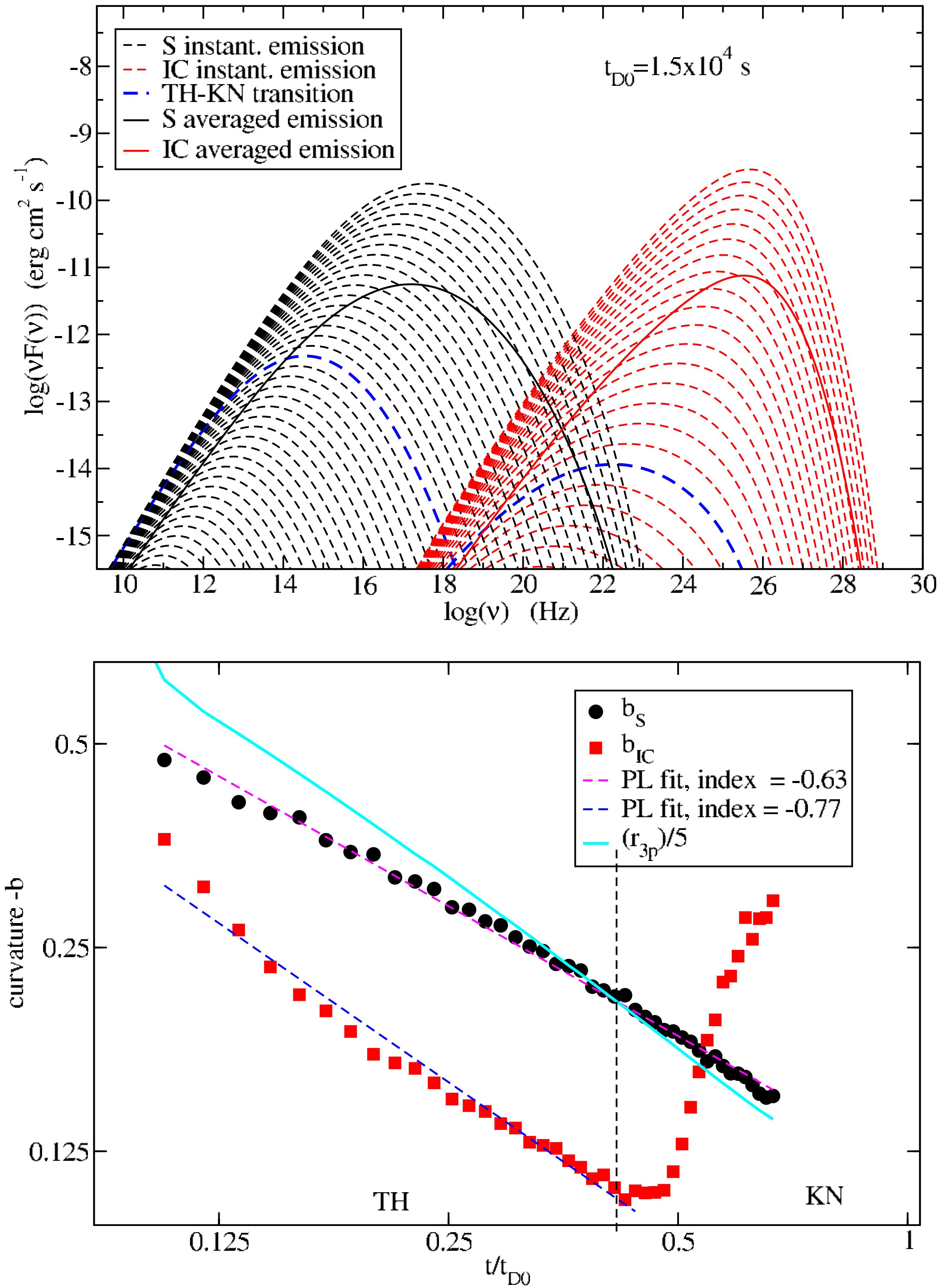
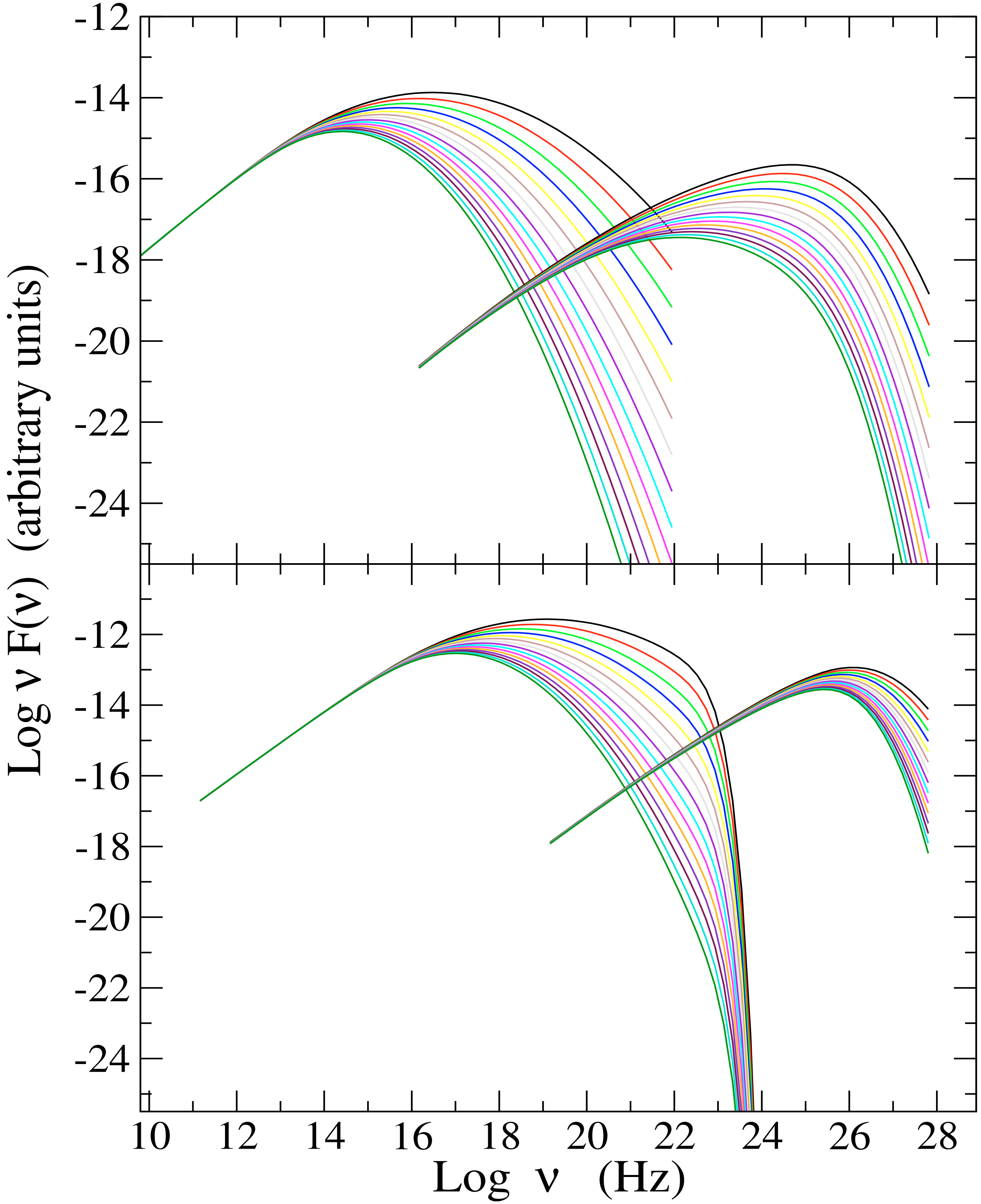
incompatible as long-trend main driver

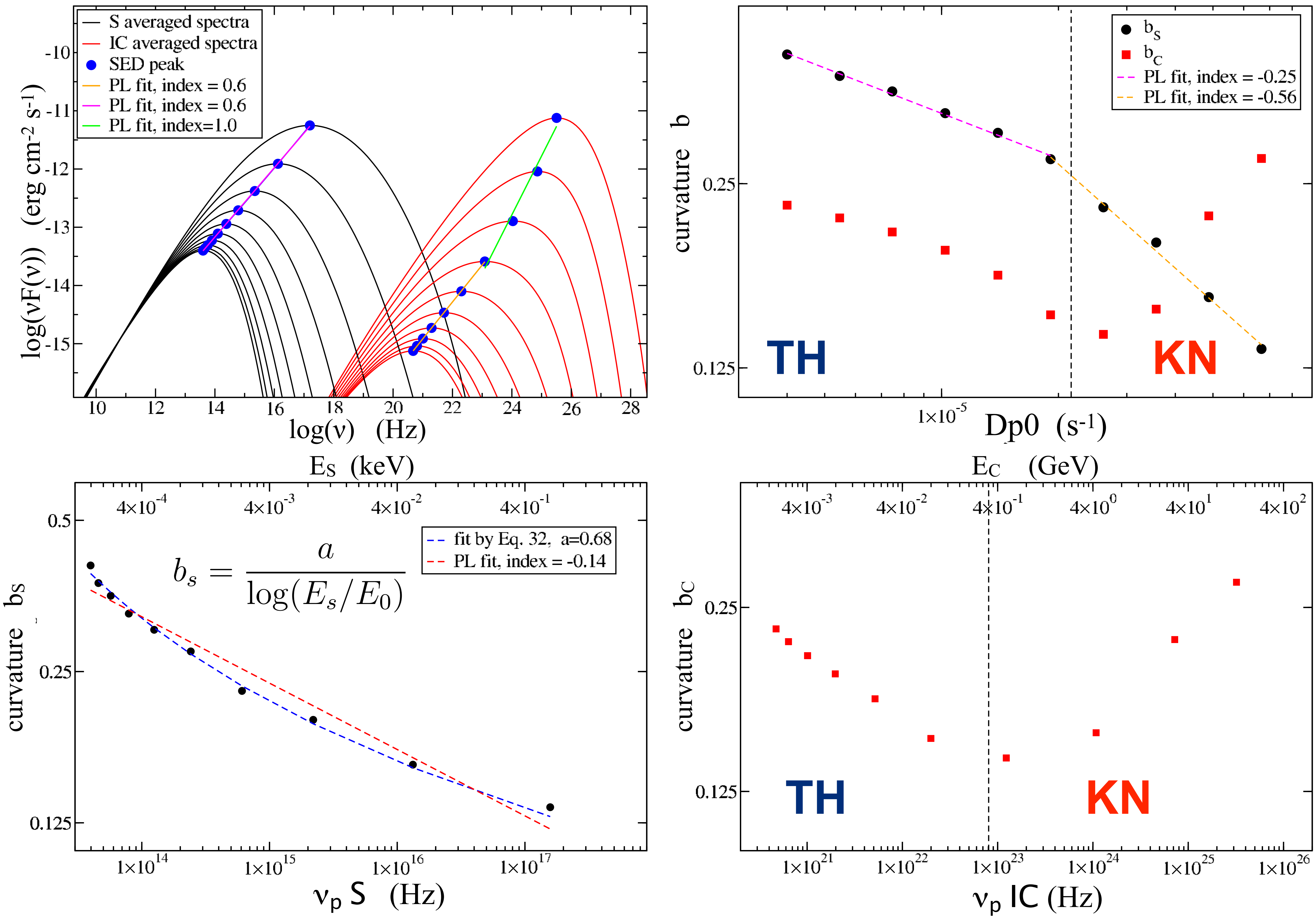


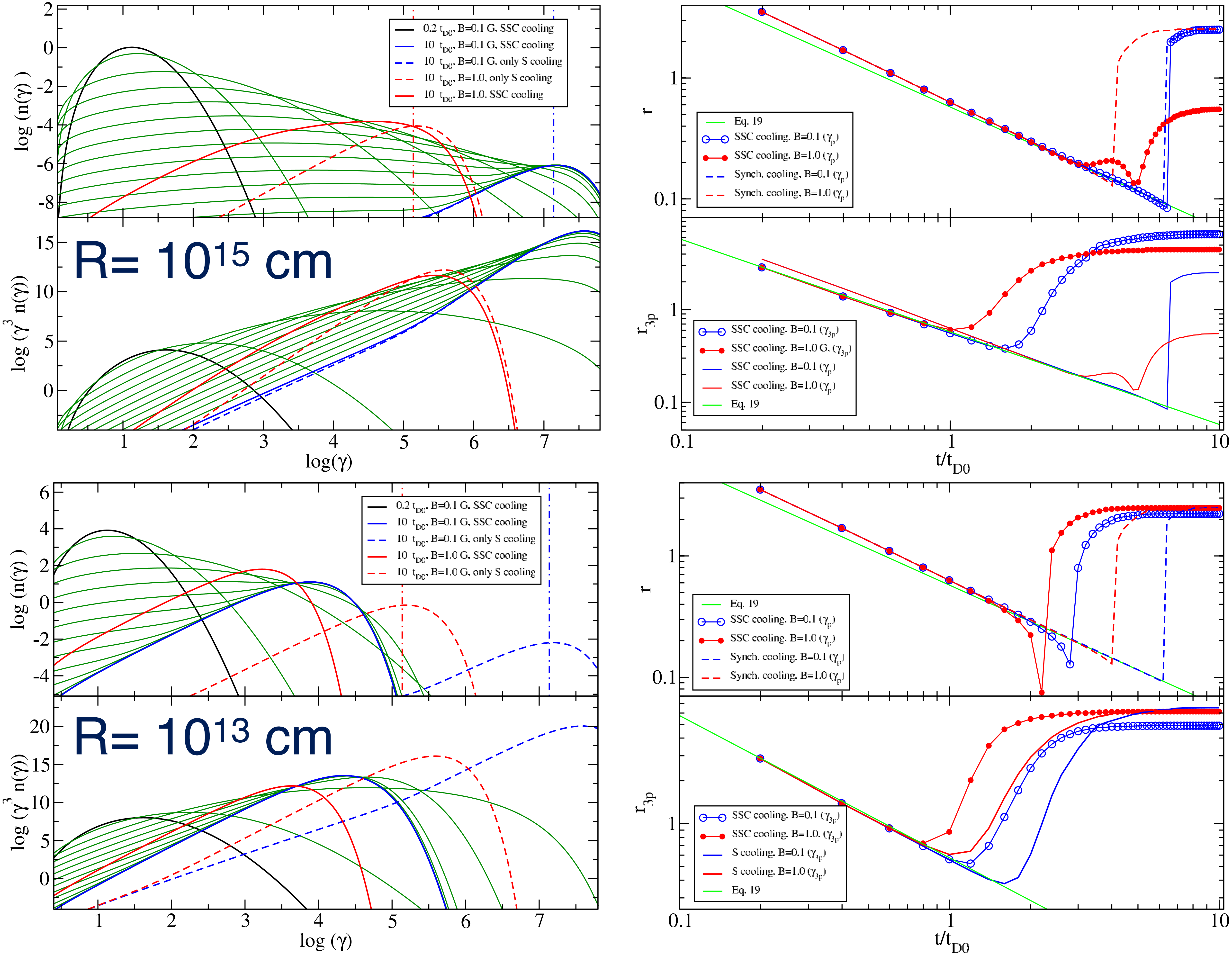
S instant. emission
IC instant. emission
TH-KN transition
S averaged emission
IC averaged emission
$t_{D0}=1.5x10^4$ s
$\log(\nu F(\nu))$ (erg cm^2 s^{-1})
$\log(\nu)$ (Hz)
b_S
b_{IC}
PL fit, index = -0.63
PL fit, index = -0.77
$(r_{3p})/5$
curvature -b
TH
KN
t/t_{D0}



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

D_p-driven trends $t_{D}=[1.5\times10^4-1.5\times10^5]$, L_{inj}=const.

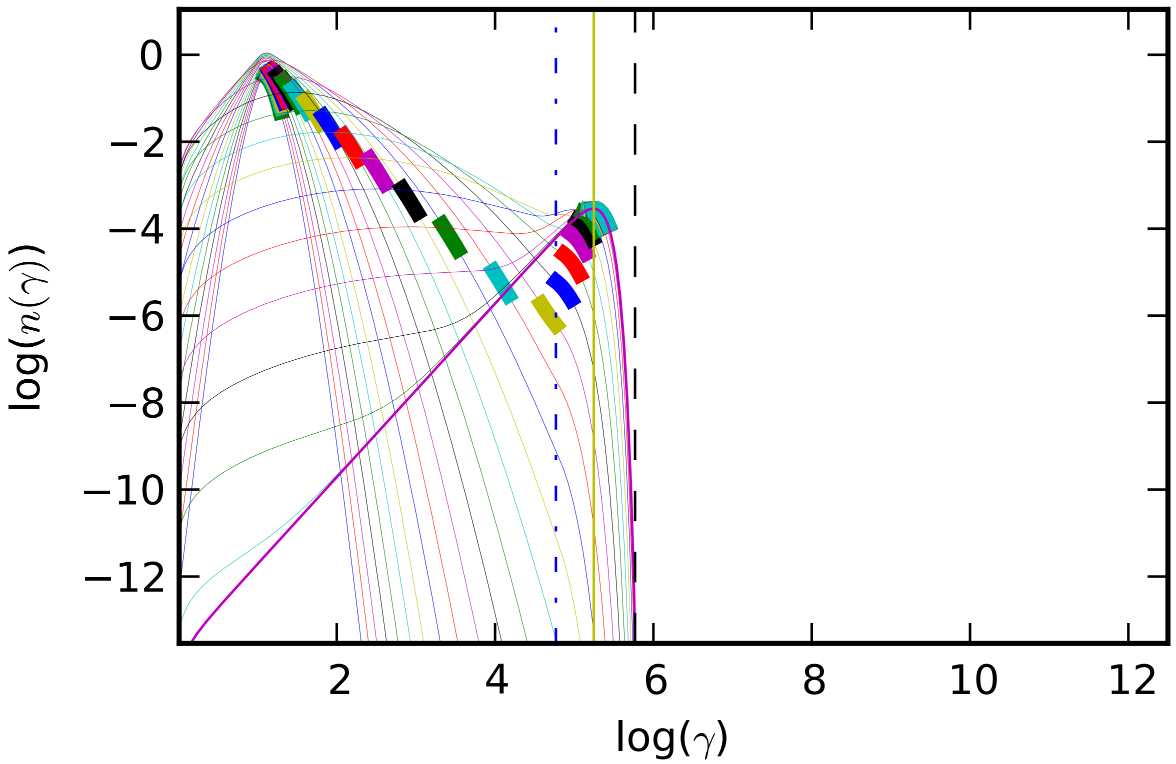




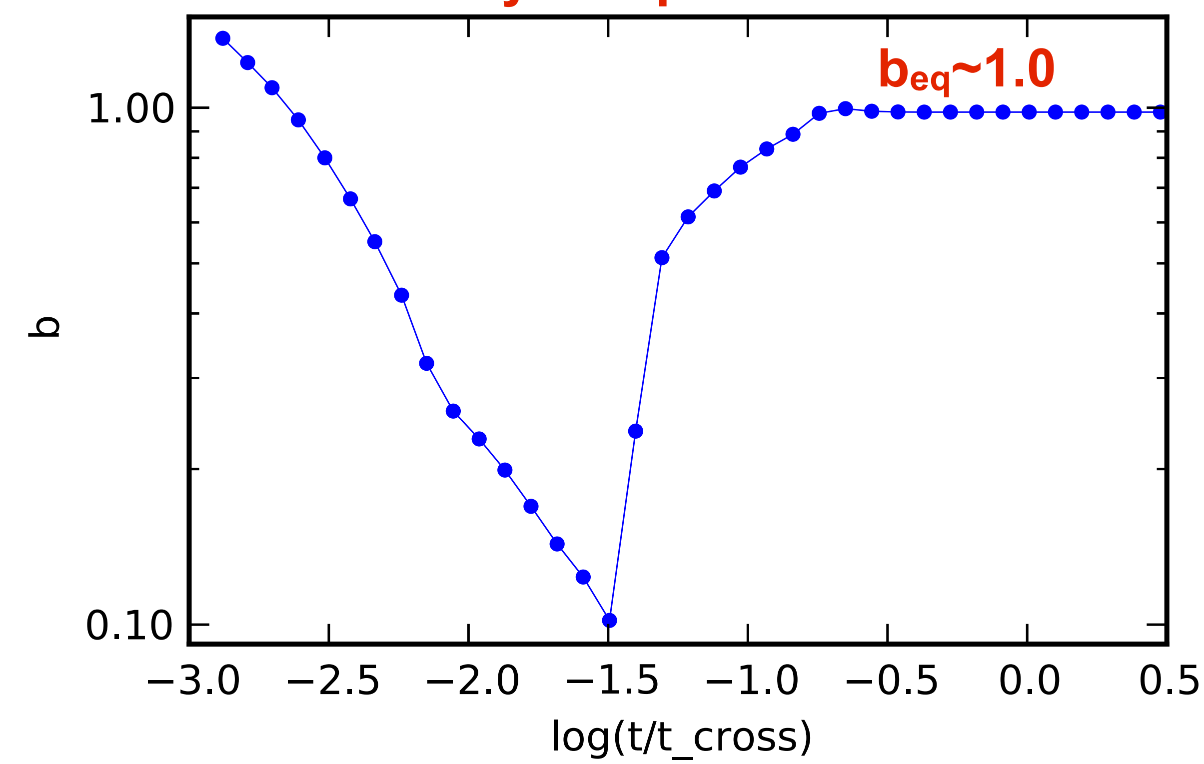
R= 10^15 cm
R= 10^13 cm
log (n(γ))
log (γ^3 n(γ))
log(γ)
0.2 t_D0, B=0.1 G, SSC cooling
10 t_D0, B=0.1 G, SSC cooling
10 t_D0, B=0.1 G, only S cooling
10 t_D0, B=1.0, only S cooling
10 t_D0, B=1.0, SSC cooling
10 t_D0, B=1.0 G, SSC cooling
10 t_D0, B=1.0 G, only S cooling
r
r_3p
t/t_D0
Eq. 19
SSC cooling,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