Hadronic cascades in GRBs and AGNs

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Collaboration with
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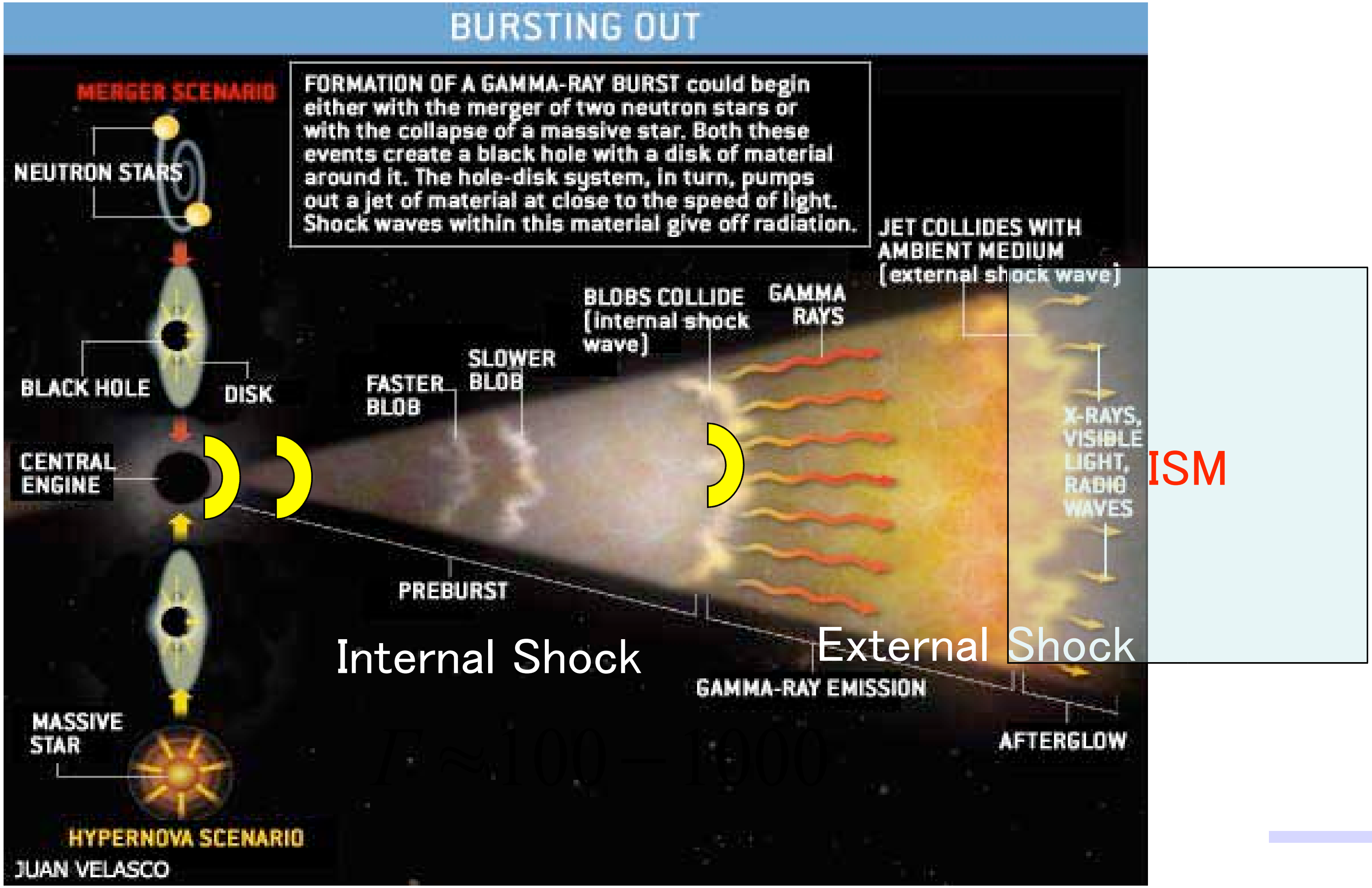
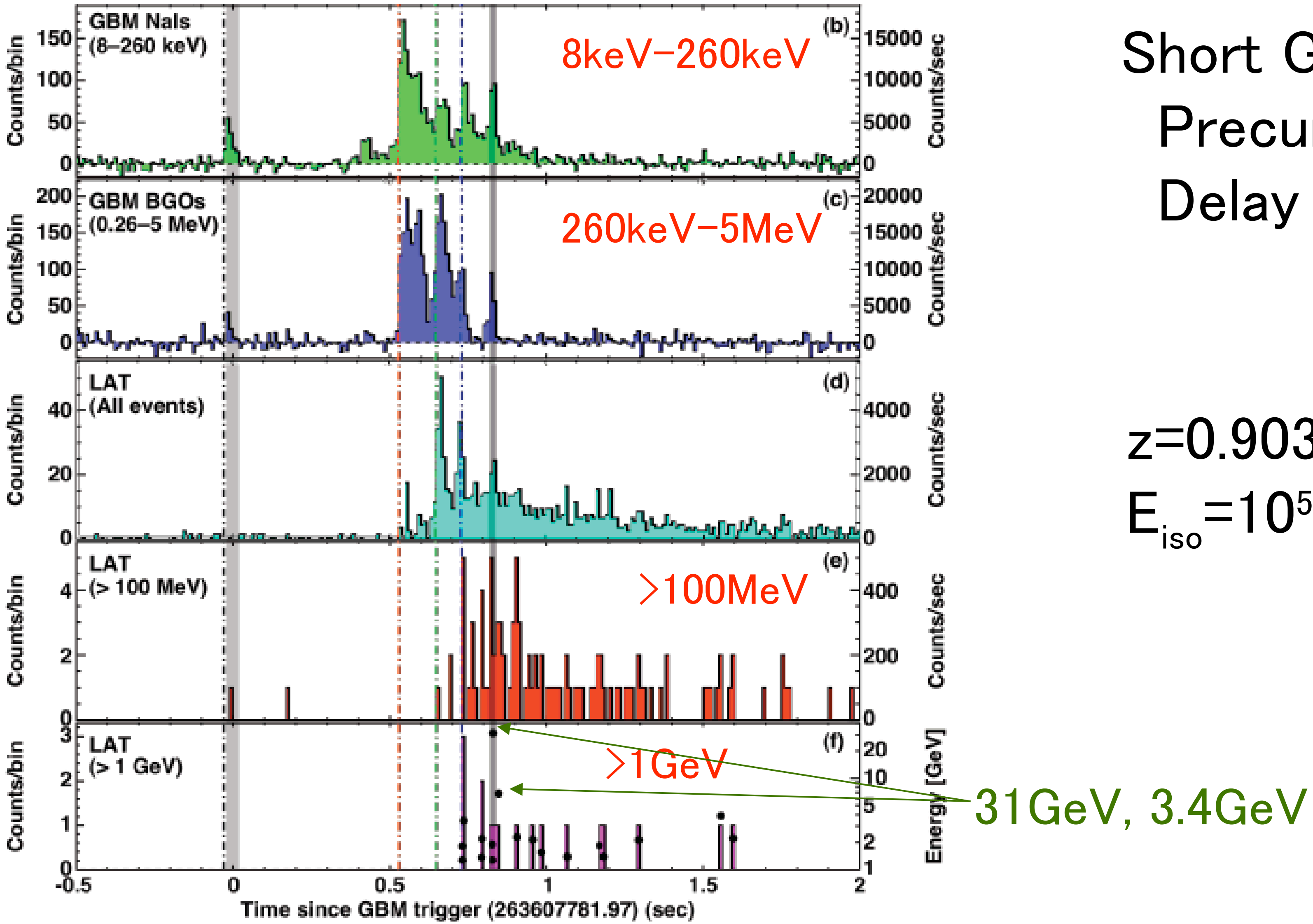
M.Kino

GRB Standard Picture



GRB 090510

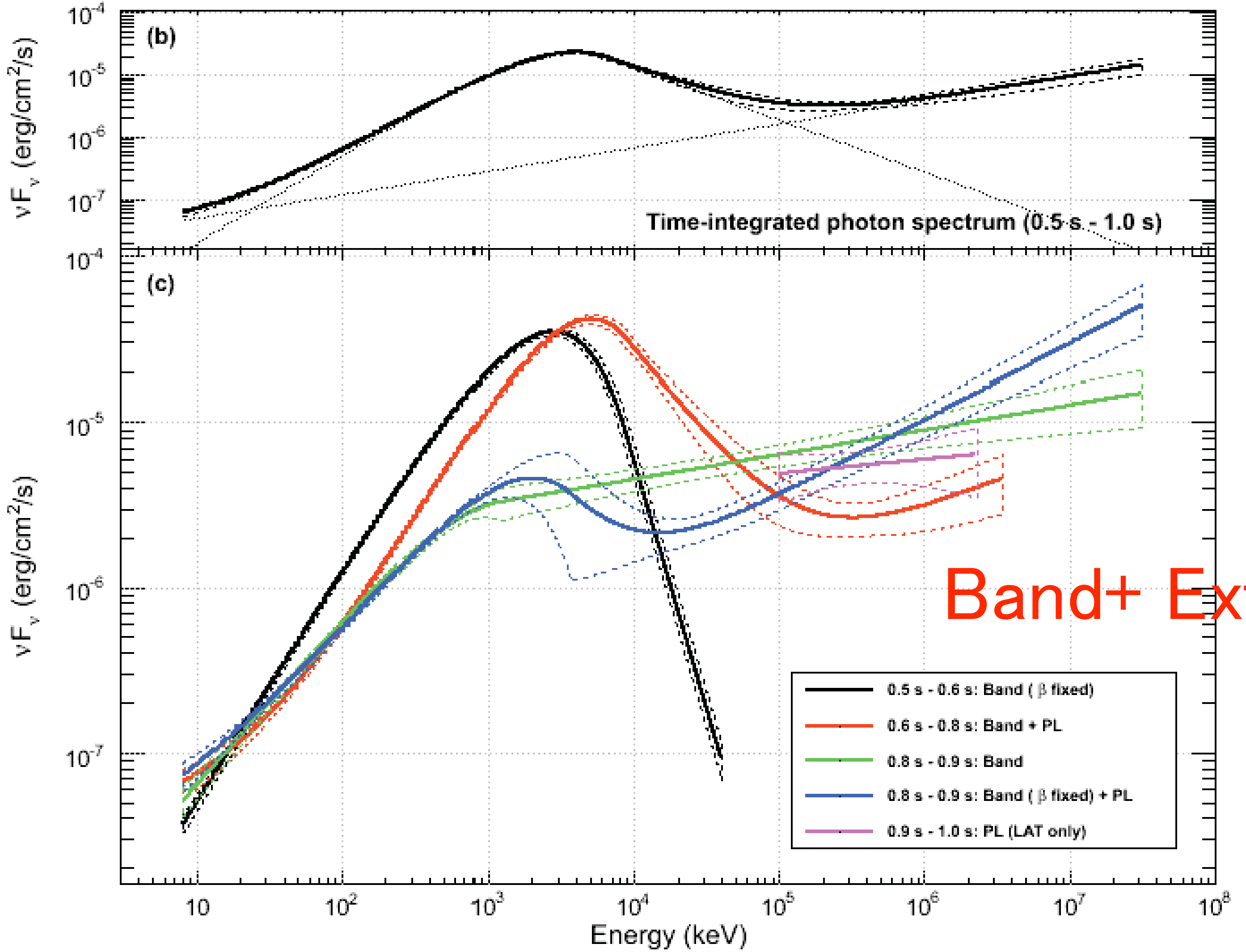


Short GRB
Precursor
Delay

z=0.903

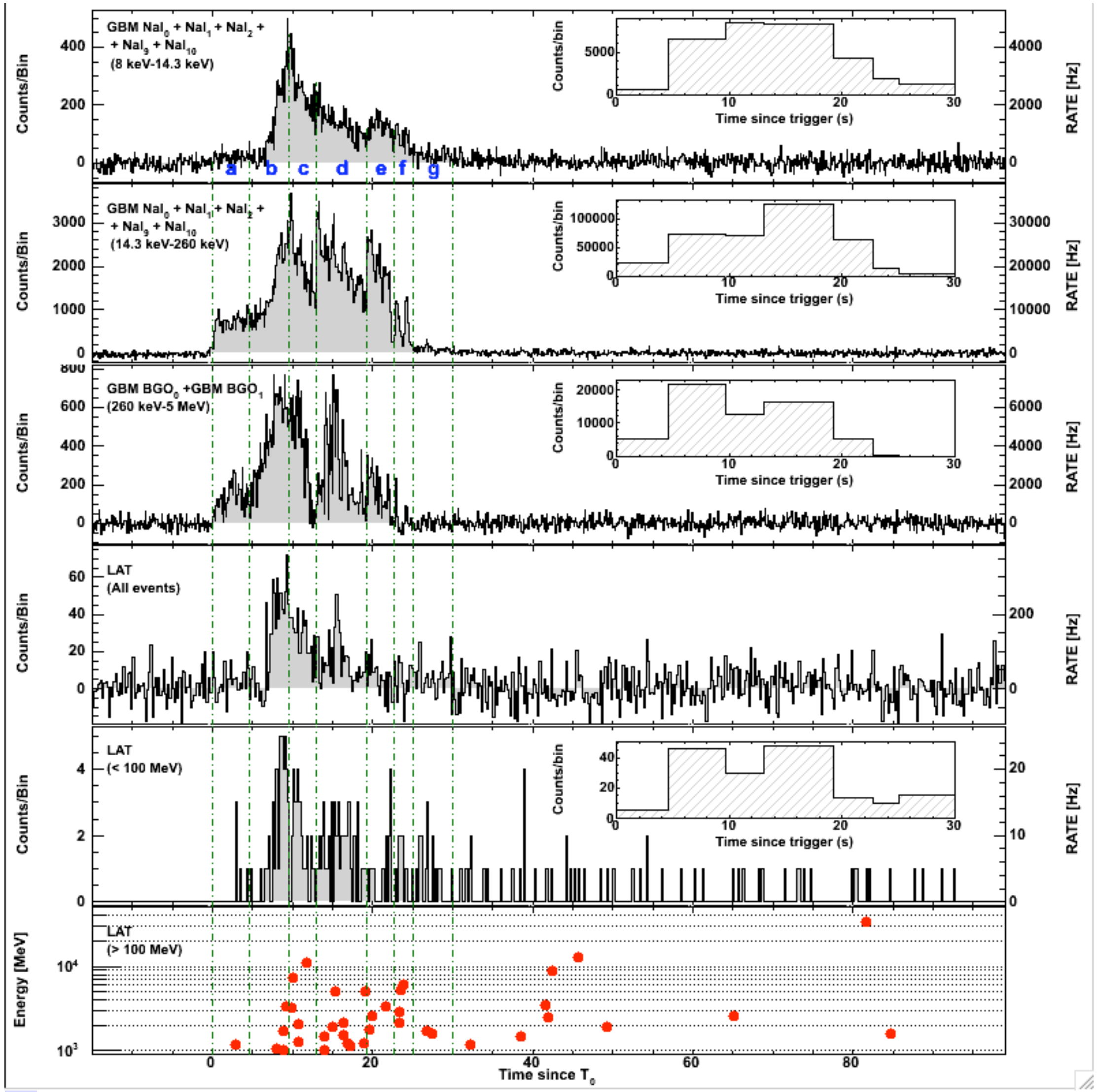
$E_{iso}=10^{53}$erg

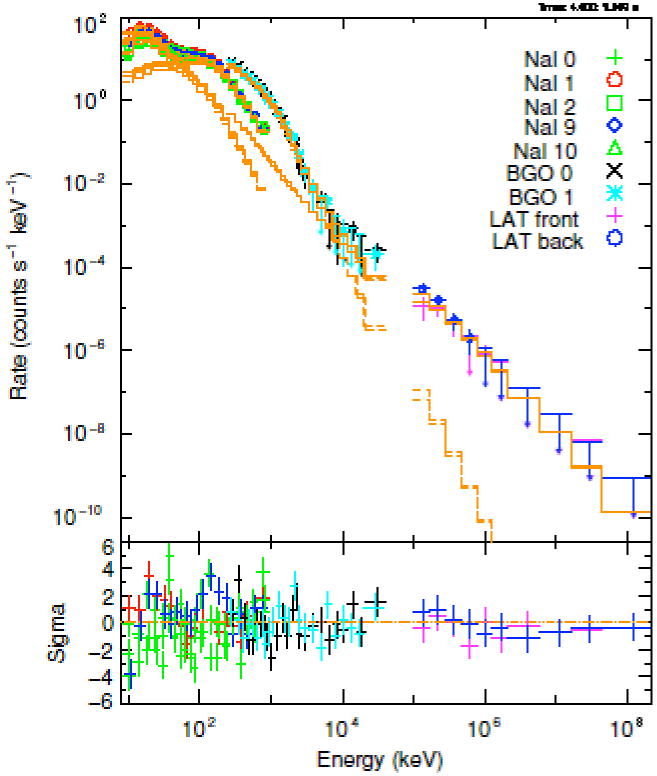
GRB 090510; Spectra



Band+ Extra PL

GRB 090902B



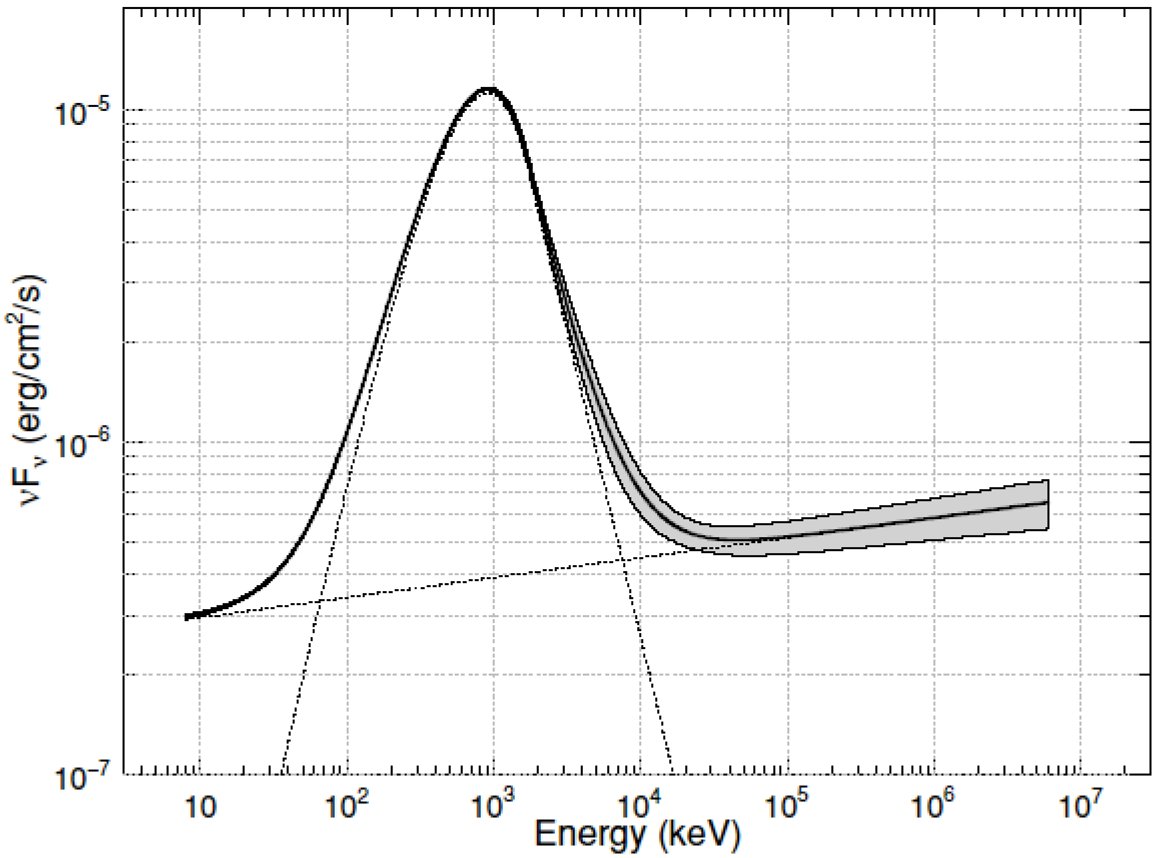


E_{iso}=4x10^{54} erg

@ z=1.822

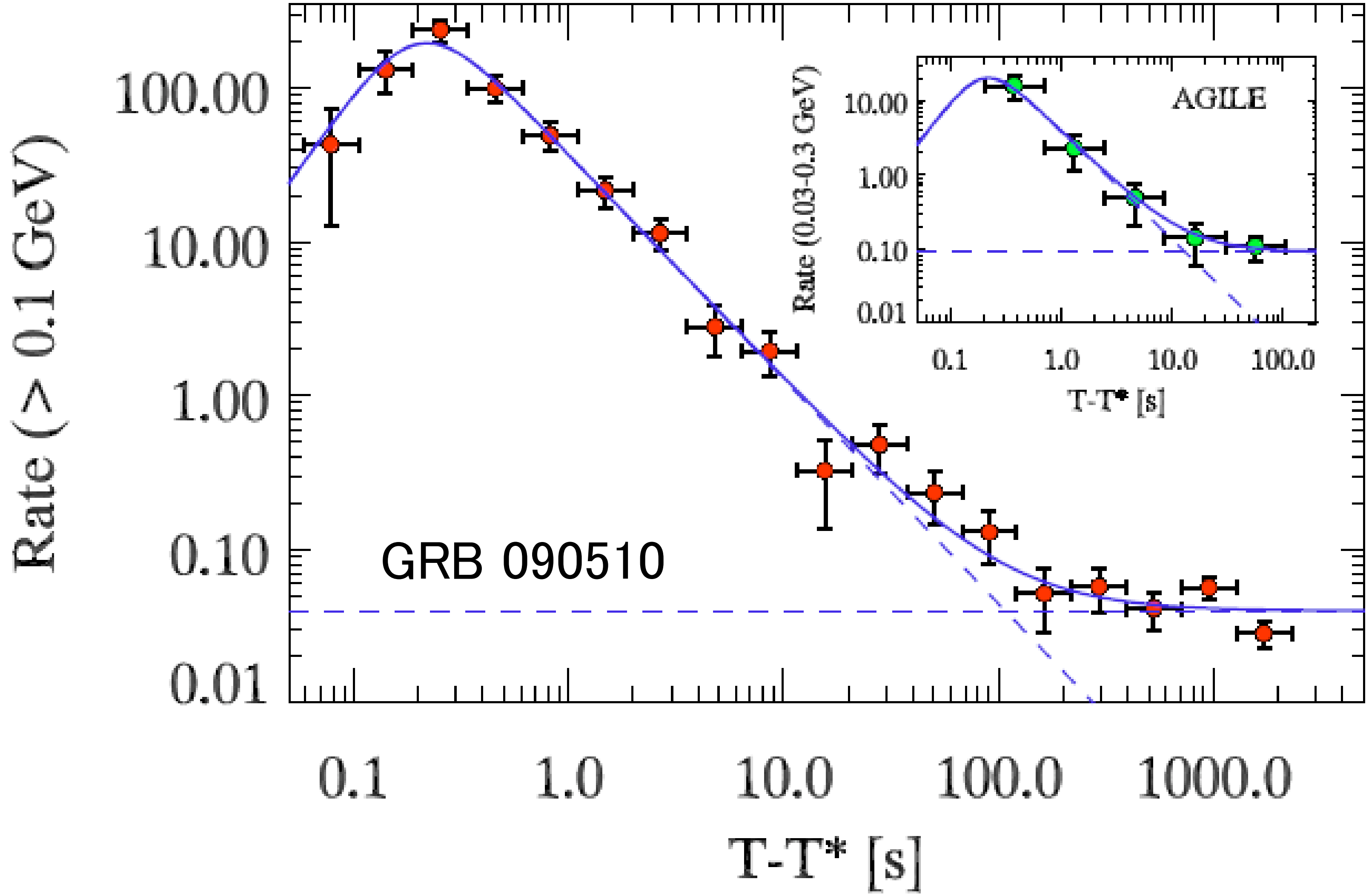
Abdo et al. ApJ 706, L138

Extra Component in 090902B

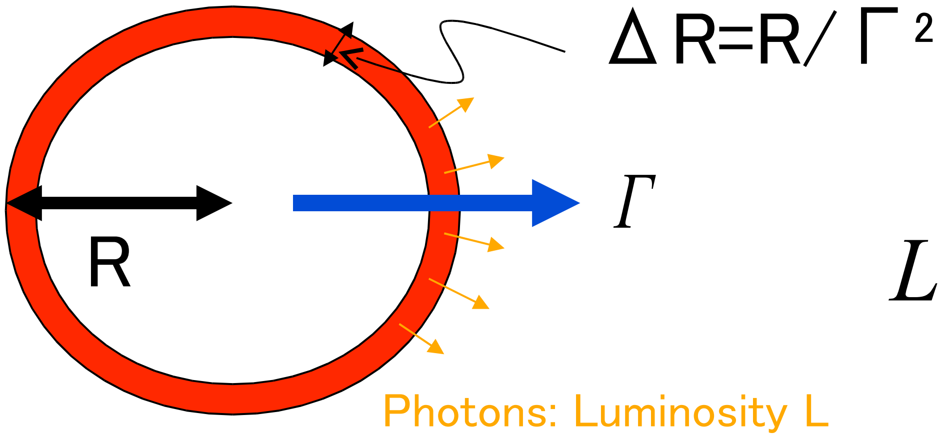


Extra Component=Afterglow?

G. Ghirlanda[1], G. Ghisellini[1] and L. Nava[1,2] 2009



Monte-Carlo Method



$$L \approx E_{sh} / \Delta t\ , \quad \Delta t = R/(c\Gamma^2)$$

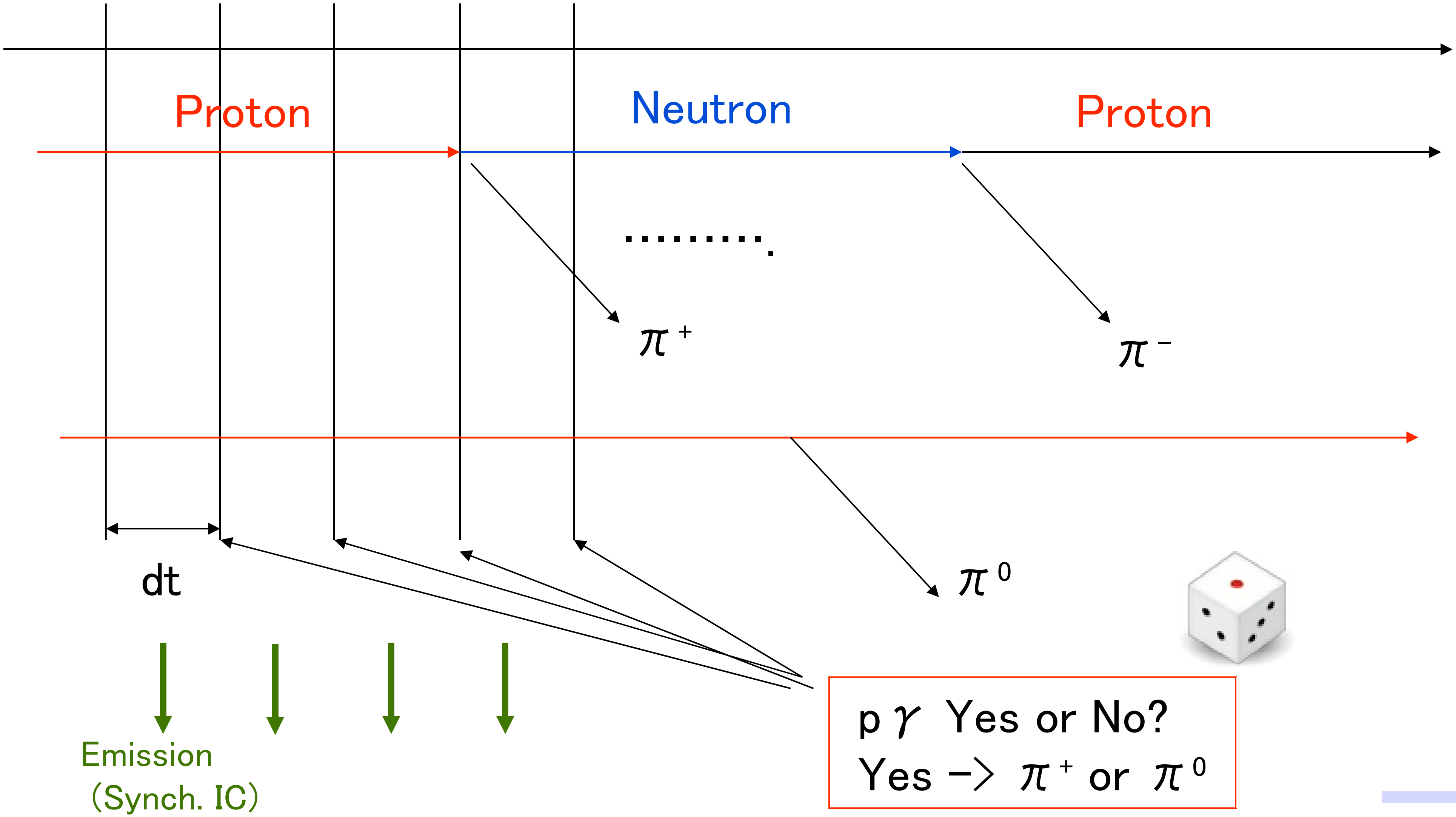
Power-law injection of protons

Energy density of photons U_γ

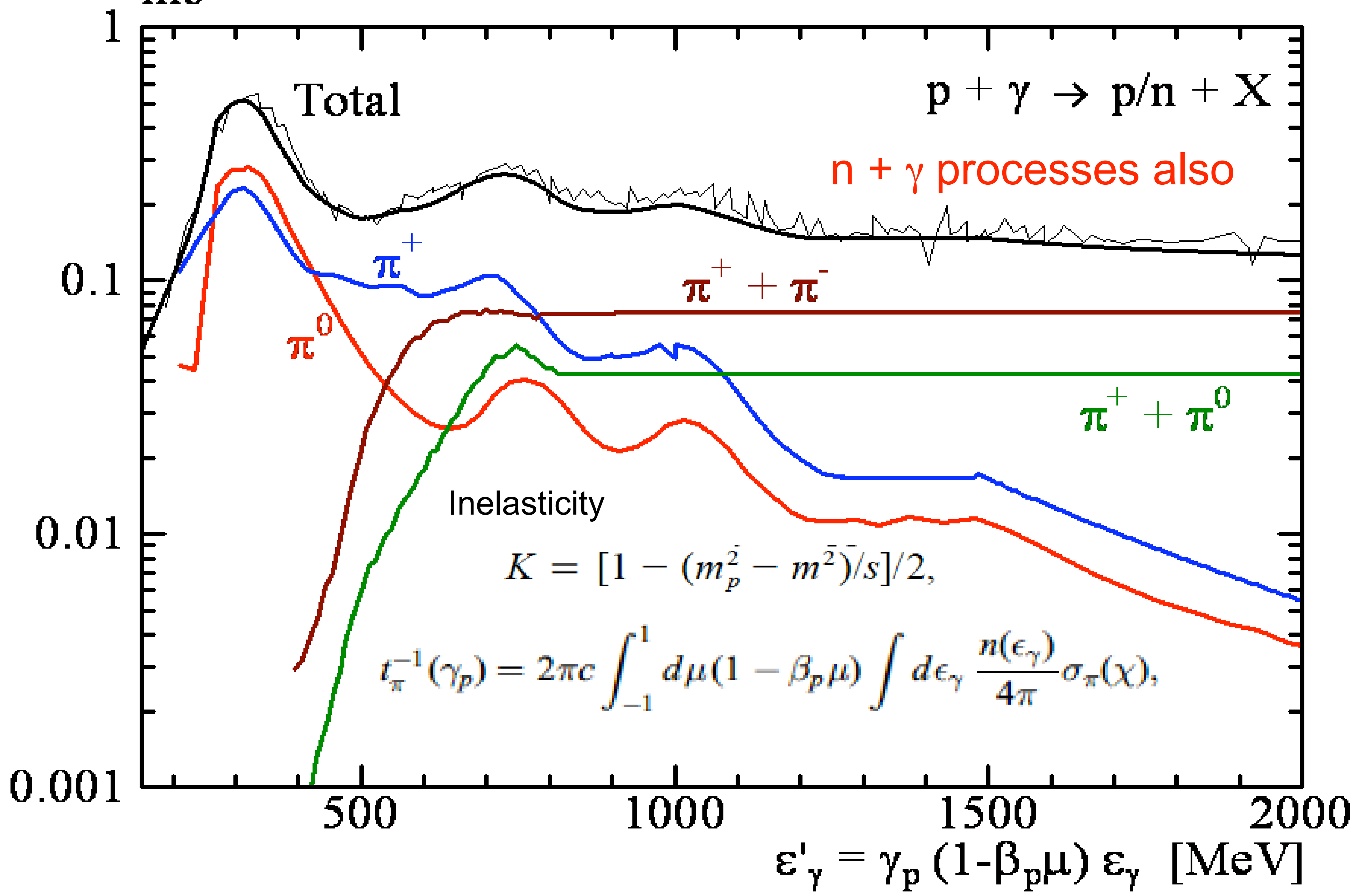
Energy density of magnetic field $U_B = f_B U_\gamma$

Energy density of Accelerated protons $U_p = f_p U_\gamma$

Method

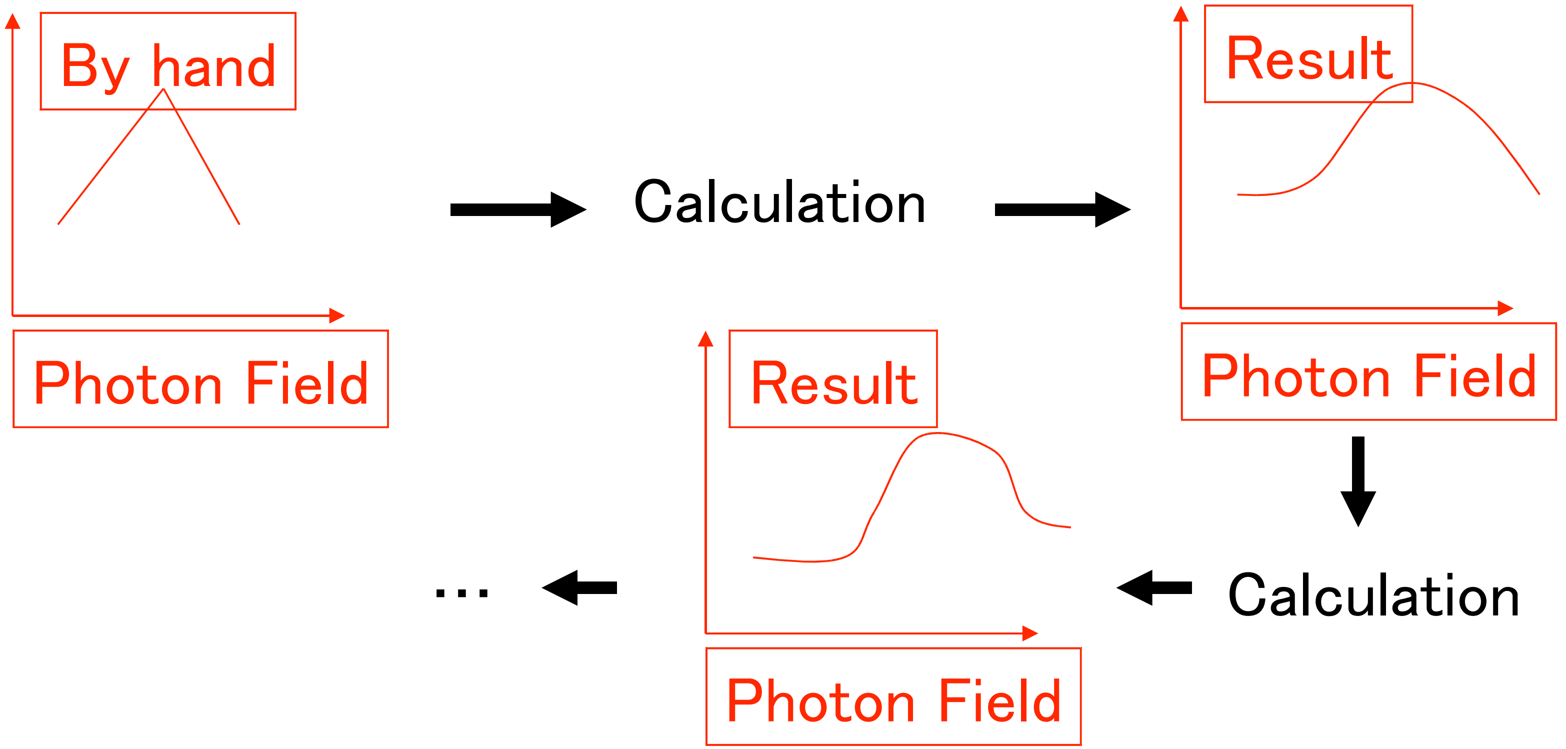

t
Proton
Neutron
Proton
π+
π−
π0
dt
Emission
(Synch. IC)
pγ Yes or No?
Yes -> π+ or π0

Cross Sections



Iterative Method

To estimate pγ, Inv.Comp., $\gamma\gamma$ processes, we need a photon field.



During the dynamical timescale, the photon field is assumed to be steady.

Cascade Processes

$p + \gamma \rightarrow n + \pi^+$

$\pi^+ \rightarrow \mu^+ + \nu_\mu$

$\mu^+ \rightarrow e^+ + \overline{\nu}_\mu + \nu_e$

$p + \gamma \rightarrow p + \pi^0$

$\pi^0 \rightarrow \gamma + \gamma$

$p + \gamma \rightarrow p + e^- + e^+$

$\gamma + \gamma \rightarrow e^- + e^+$

Synchrotron + Inv.Comp.: $p,\ \pi^\pm, \mu^\pm, e^\pm \rightarrow \gamma$

Synchrotron Self-absorption: $\gamma + e \rightarrow e$

Iterative Method -> Both photon field and cascade processes are solved consistently.

Highest Energy

The energy of particles is limited by two conditons.

- The Larmor radius R_L=e E_p/B < shell width Δ=R/Γ.
- The acceleration time ξR_L/c < cooling time.

Cooling Processes:

- Proton Synchrotron+IC
- Photoproduction of pions
- Bethe-Heitler

Proton acceleration efficiency

We need 6–8 10^{43} ergs/Mpc^3/yr to explain UHECRs

$$E_{\rm CR}^2 \frac{d\dot{N}_{\rm CR}}{dE_{\rm CR}} = 3.0 \times 10^{43}\,{\rm ergs\,Mpc^{-3}\,yr^{-1}} \left(\frac{\xi_{\rm acc}}{10}\right)\left(\frac{20}{R}\right) \times \left(\frac{E_\gamma^{\rm iso}}{3\times 10^{53}\,{\rm ergs}}\right)\left(\frac{\rho_{\rm HL}(0)}{0.2\,{\rm Gpc^{-3}\,yr^{-1}}}\right) \quad @10^{19}\,{\rm eV}$$

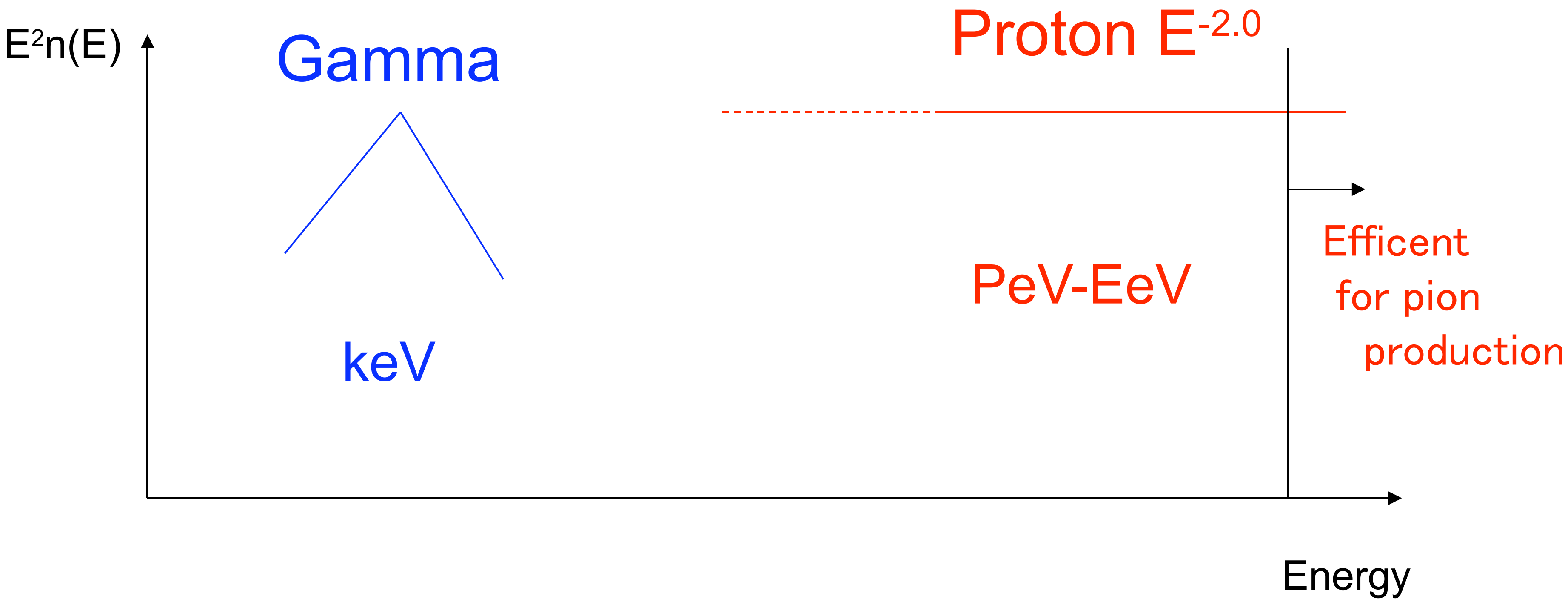
$$\xi_{acc} \equiv U_p / U_e \approx U_p / U_\gamma \qquad R \equiv \ln(E_{\rm CR}^{\rm max} / E_{\rm CR}^{\rm min})$$

See e.g. Murase, Ioka, Nagataki, Nakamura 2008

We may need Up/Uγ>20.

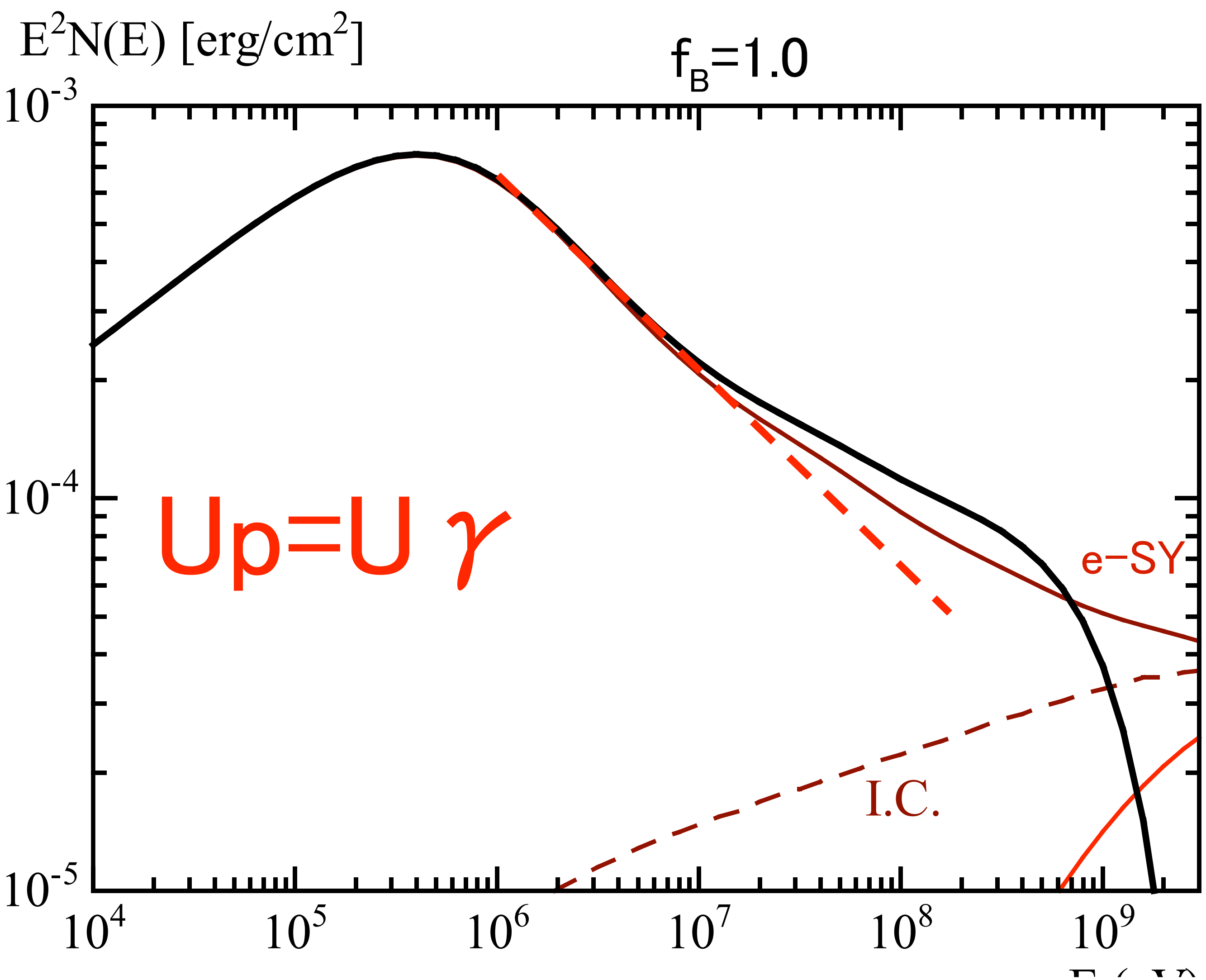
If GRB rate is 0.05 Gpc^{-3}/yr, Up/Uγ>100

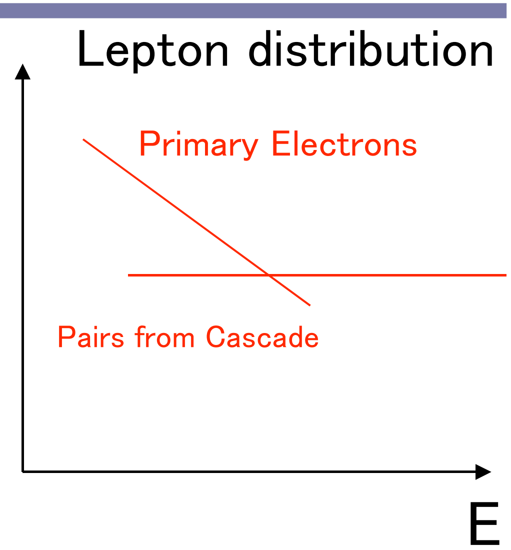
Proton Dominated?



To make gamma-rays from protons contribute enough,
the proton energy largely exceeds the gamma-ray energy??

Distortion due to proton cascade



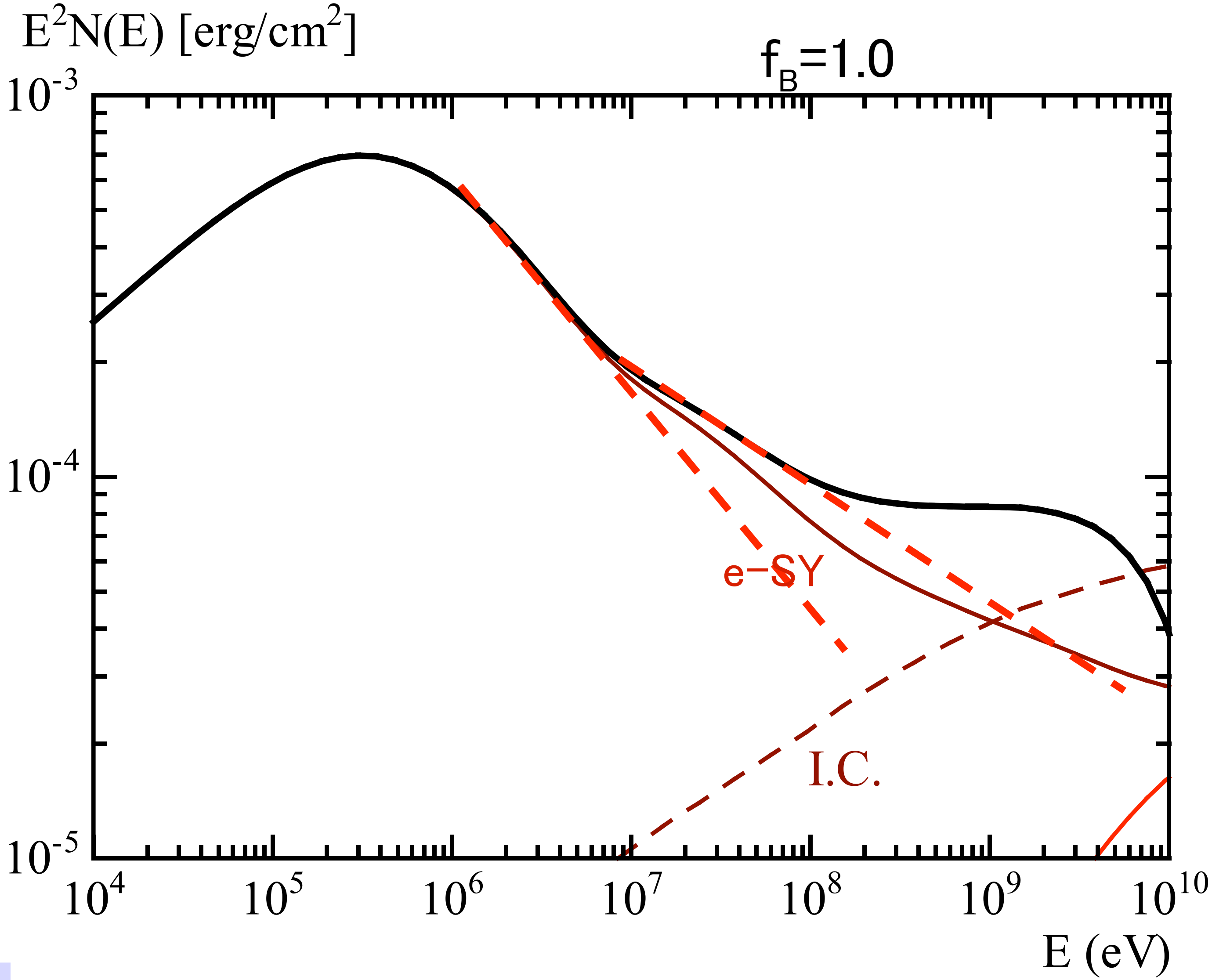


$E_{sh} = 10^{51}$ erg

$\Gamma = 100$

$\Delta t = 1.1$ s

Double break

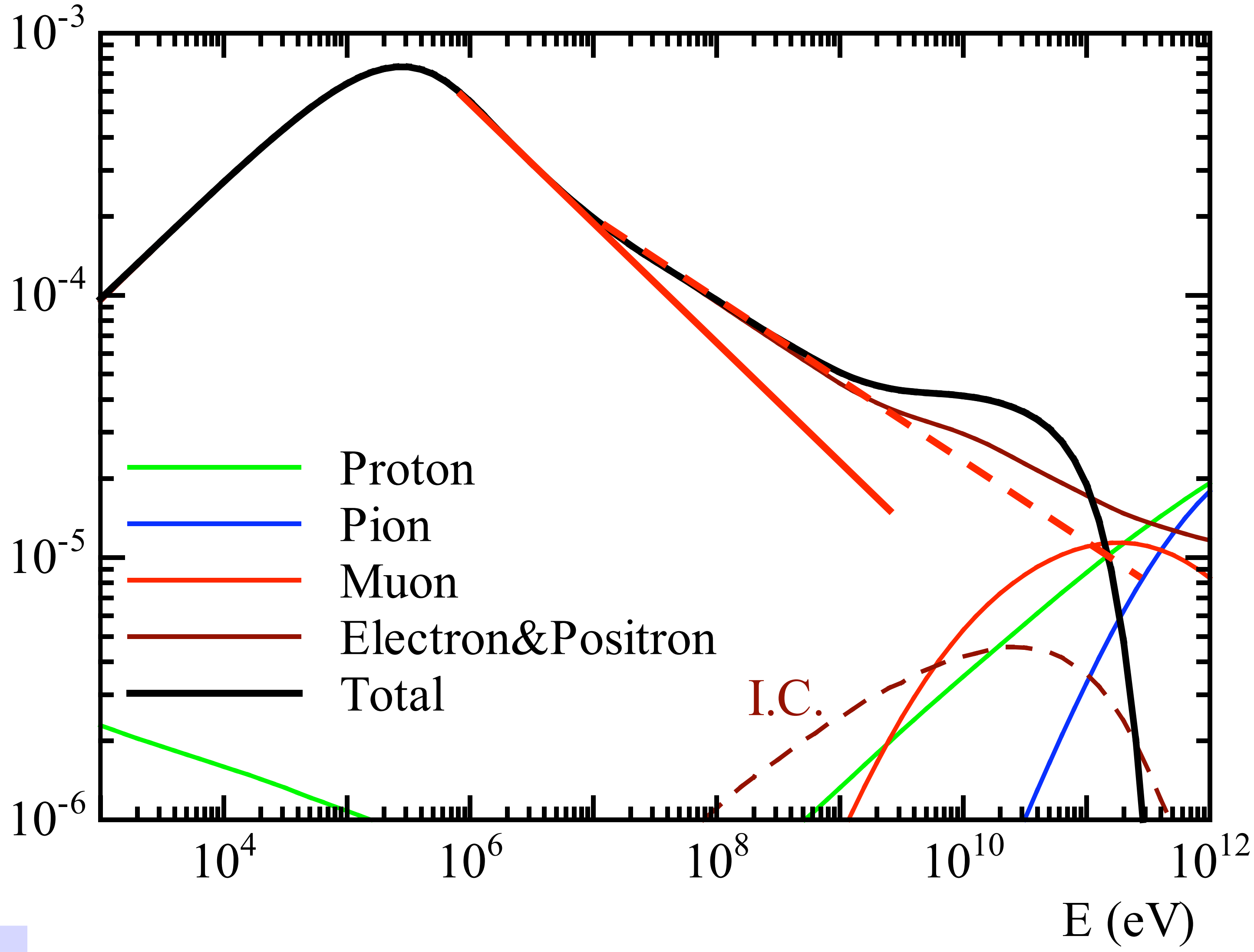


$E_{sh} = 10^{51}$ erg

$\Gamma = 300$

$\Delta t = 0.12$ s

Double break 2

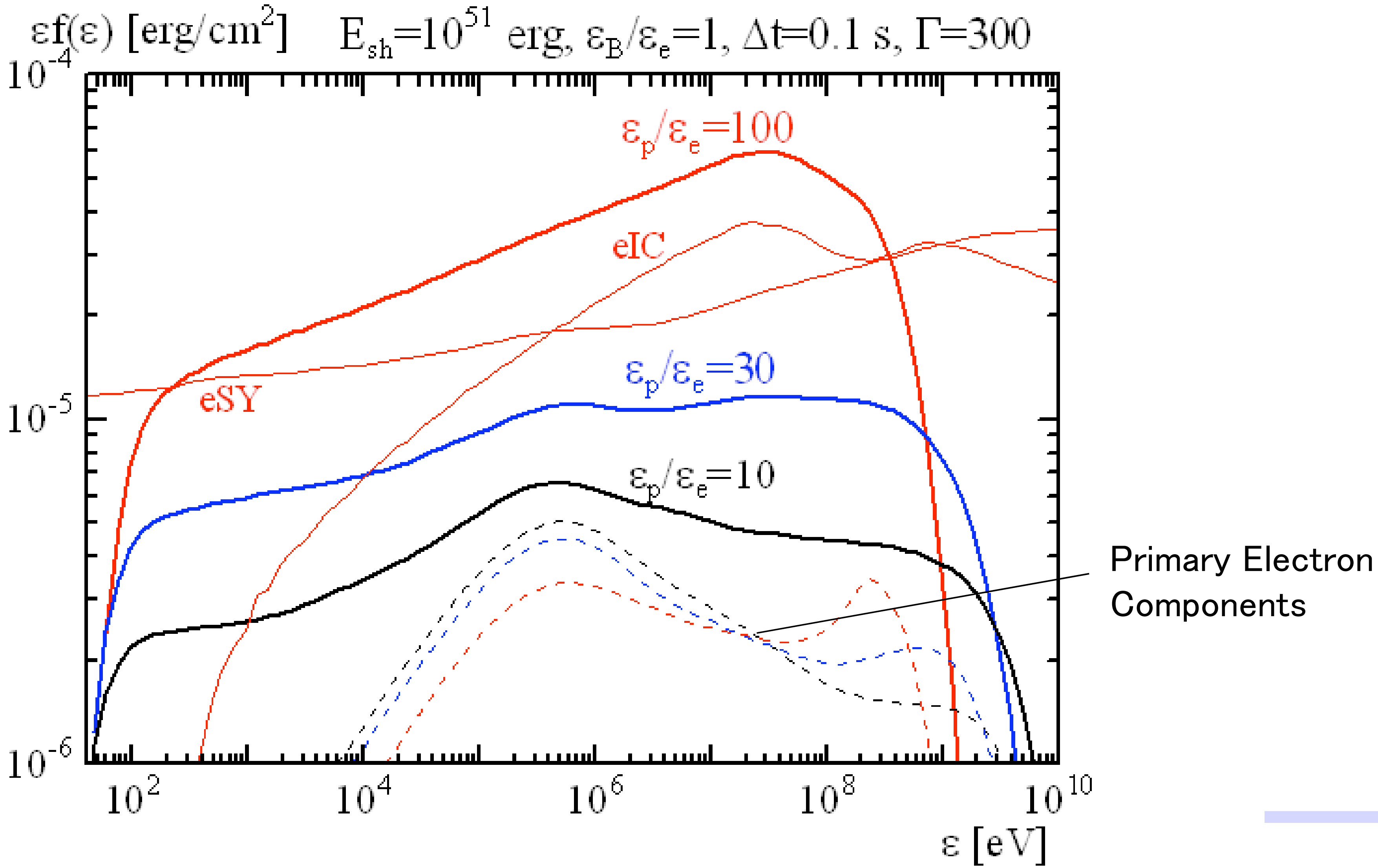


$E_{sh} = 10^{52}$ erg

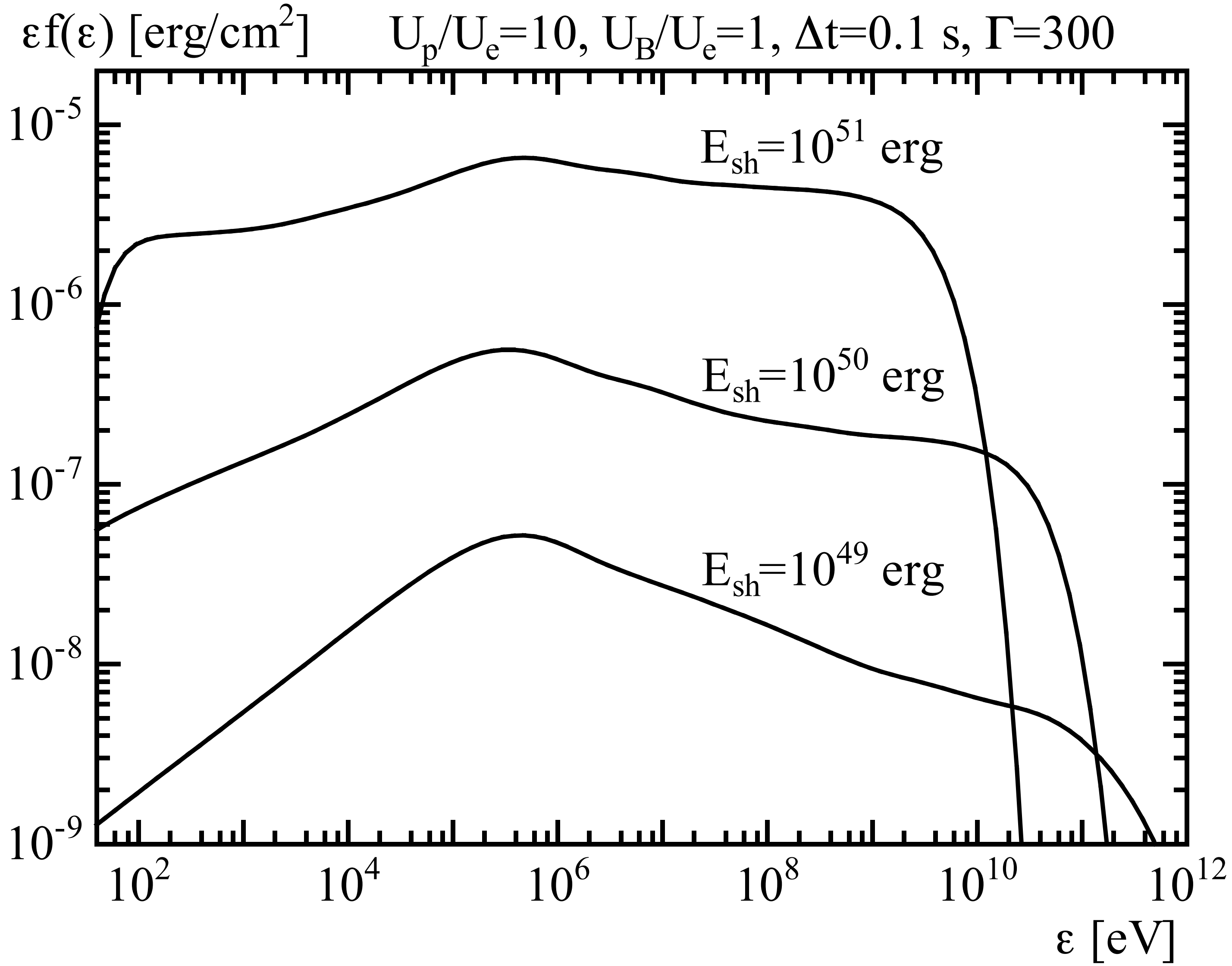
$\Gamma = 1000$

$\Delta t = 0.033$ s

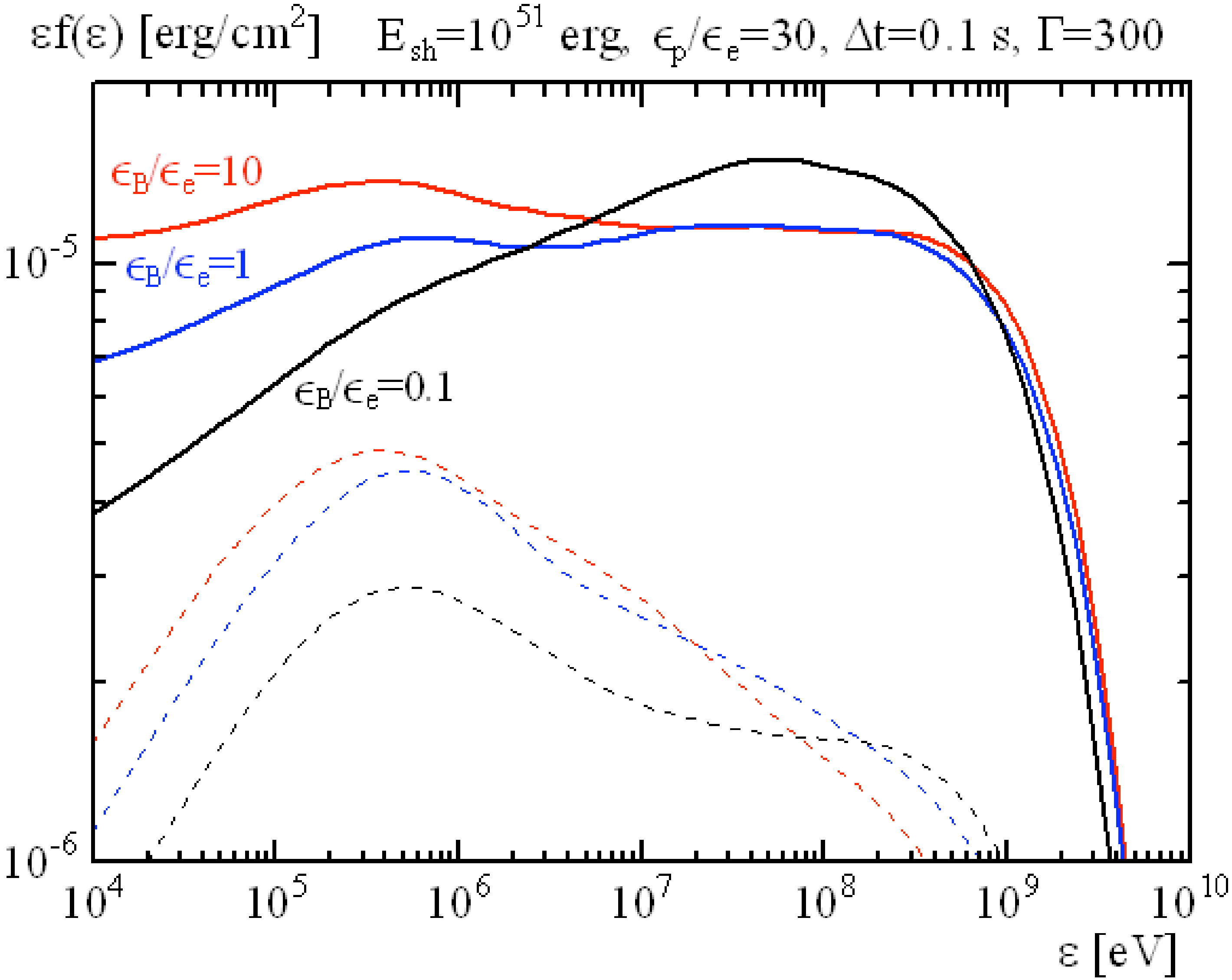
Much More Protons



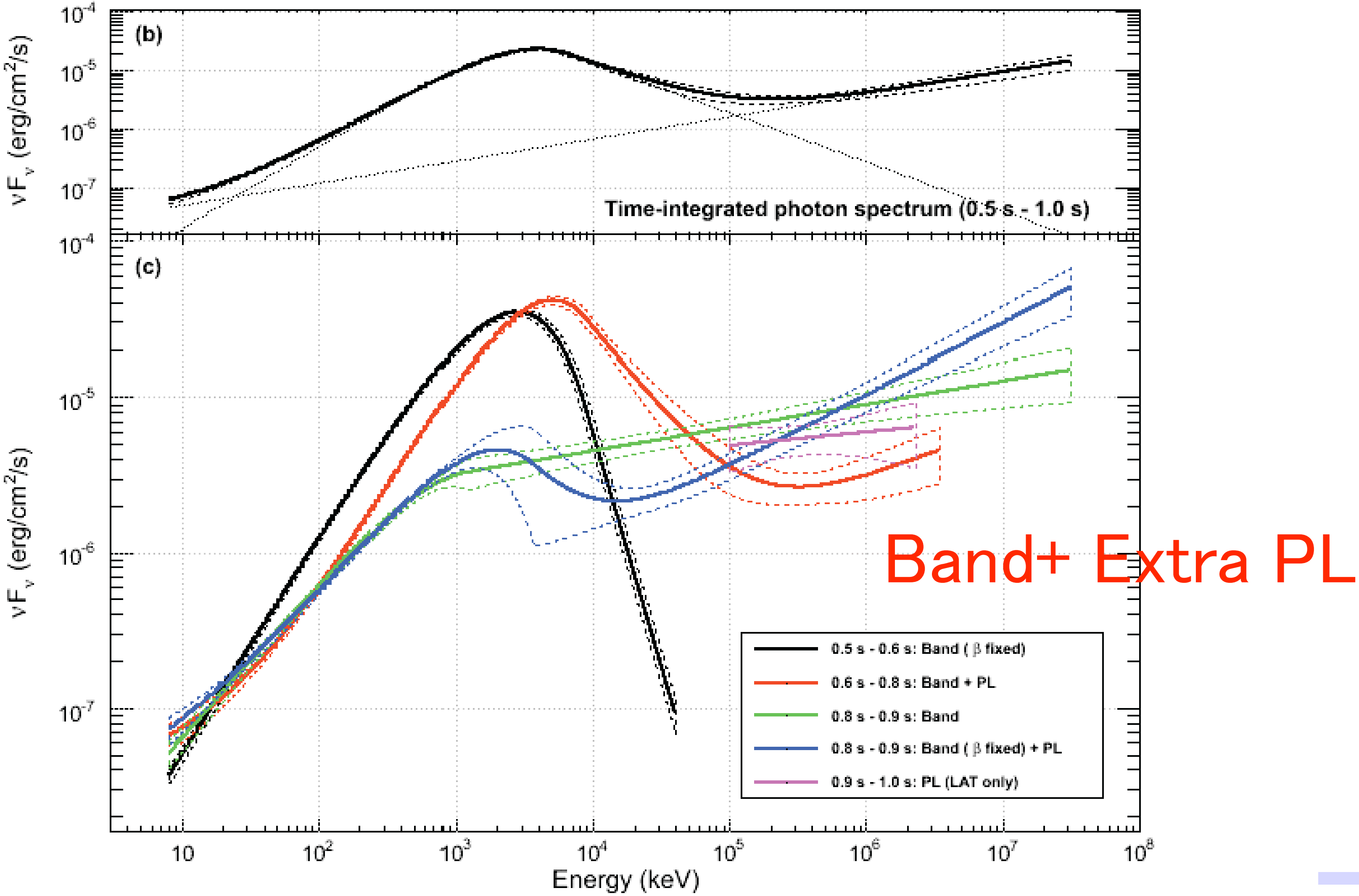
Energy-dependence



B-dependence

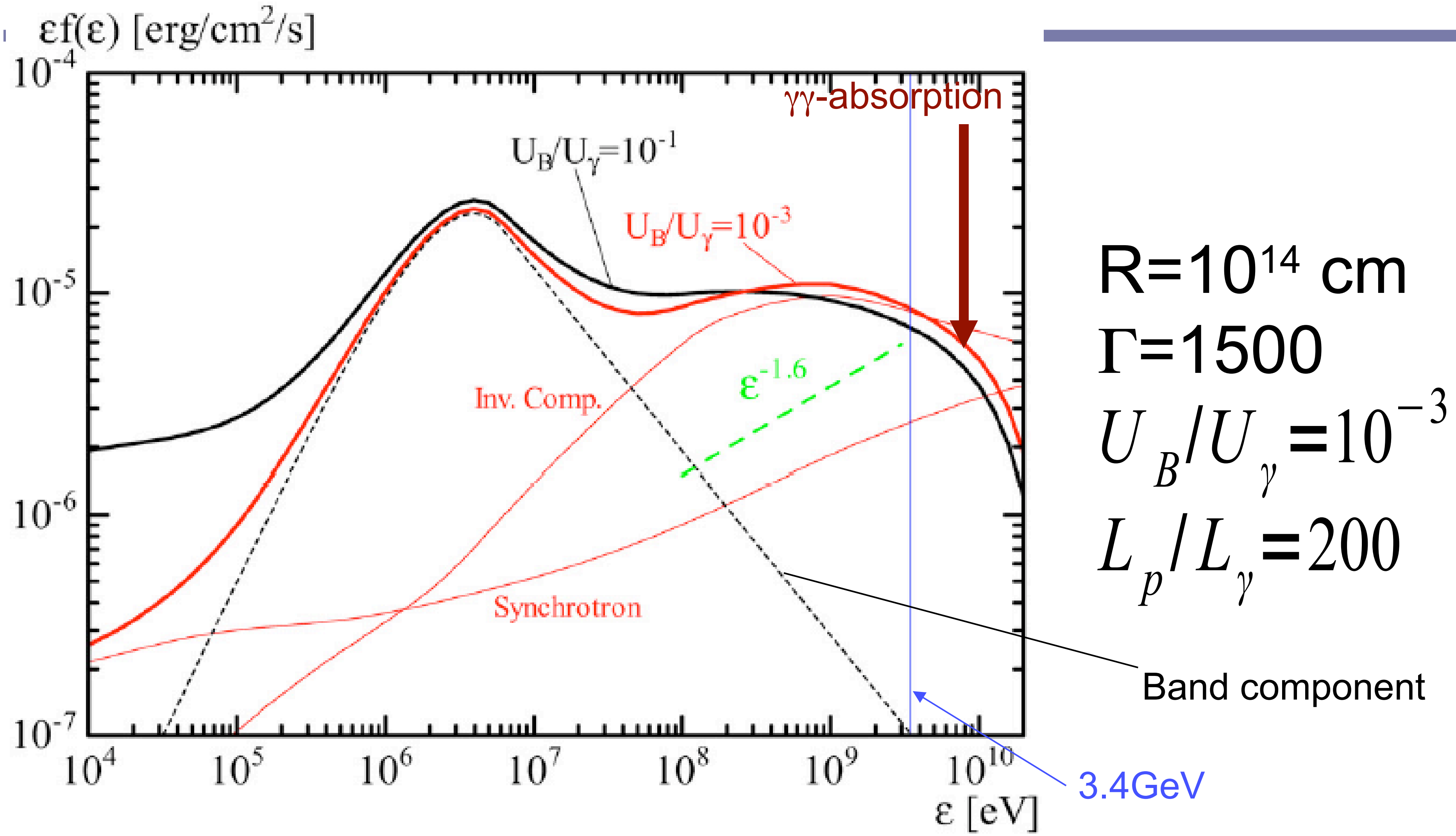


GRB 090510; Spectra



Asano, Guiriec & Meszaros 2009

Cascade due to photopion production



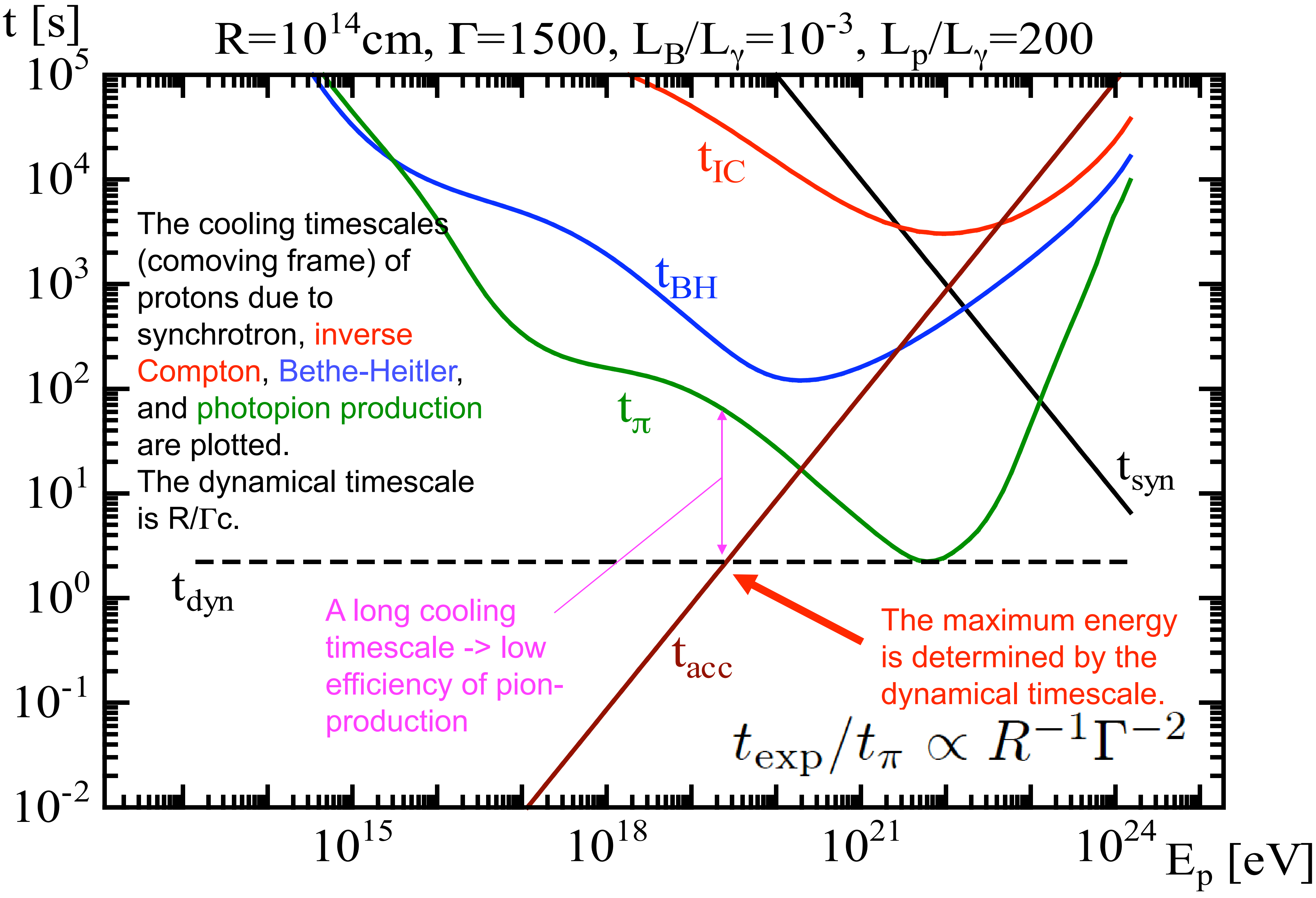
$R=10^{14}$ cm

$\Gamma=1500$

$U_B/U_\gamma=10^{-3}$

$L_p/L_\gamma=200$

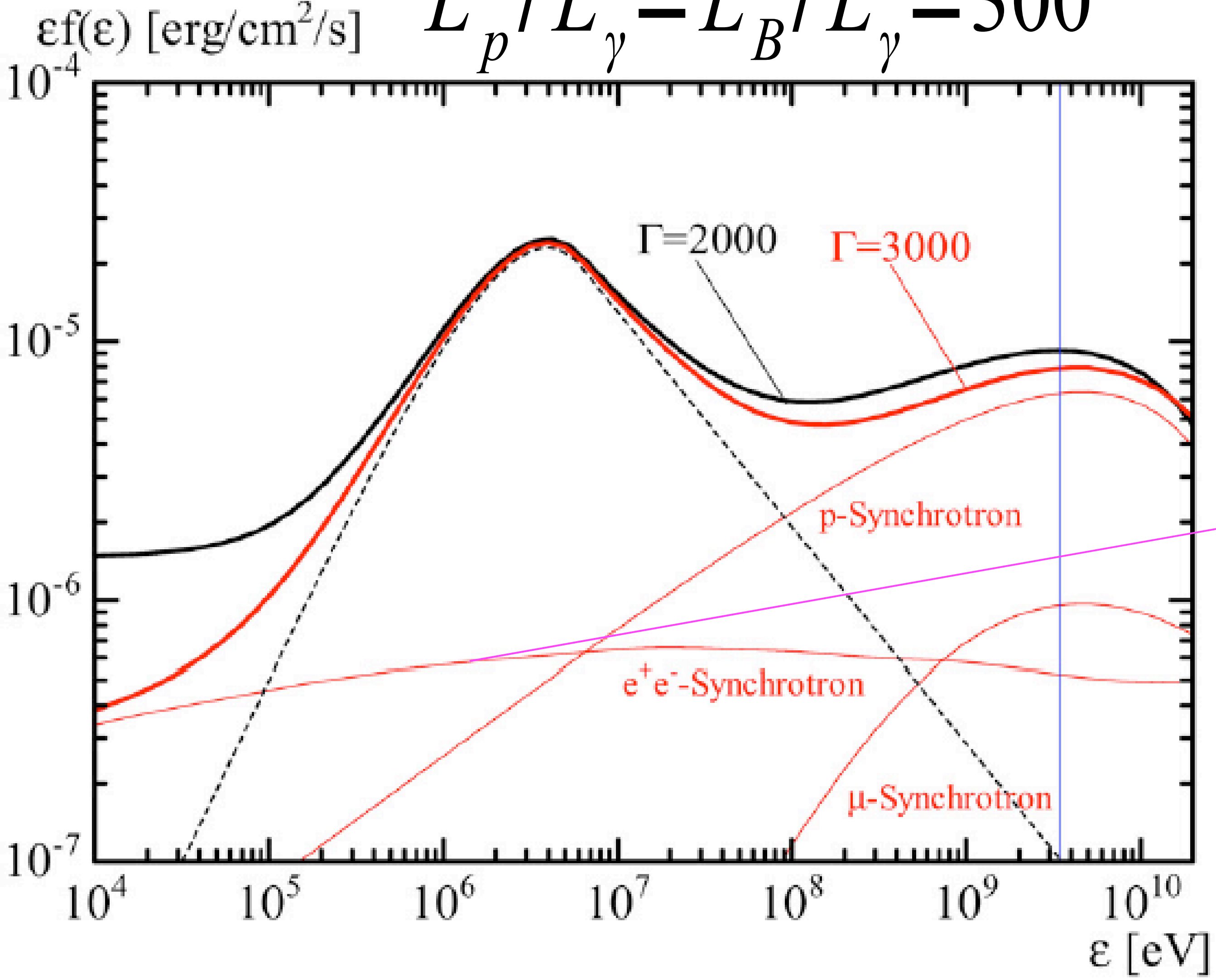
Synchrotron and Inverse Compton due to secondary electron-positron pairs



t [s]
R=10^14cm, Γ=1500, L_B/L_γ=10^-3, L_p/L_γ=200
The cooling timescales (comoving frame) of protons due to synchrotron, inverse Compton, Bethe-Heitler, and photopion production are plotted.
The dynamical timescale is R/Γc.
t_IC
t_BH
t_π
t_syn
t_dyn
t_acc
A long cooling timescale -> low efficiency of pion-production
The maximum energy is determined by the dynamical timescale.
$t_{\exp}/t_{\pi} \propto R^{-1}\Gamma^{-2}$
E_p [eV]

Proton Synchrotron

$L_p / L_\gamma = L_B / L_\gamma = 300$

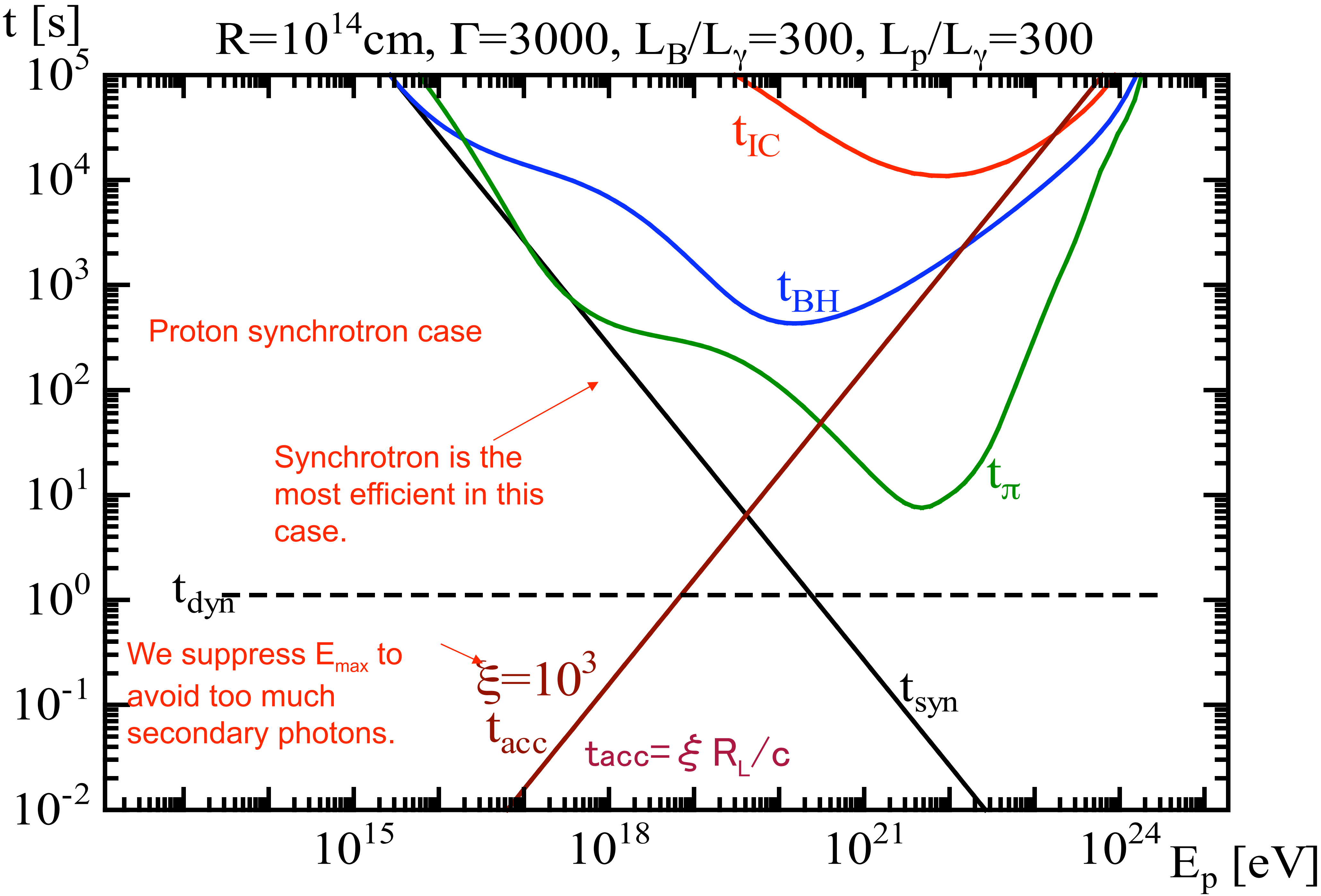


$\xi = 10^3$

R=10^14 cm

Even in this case,
secondary pairs contribute

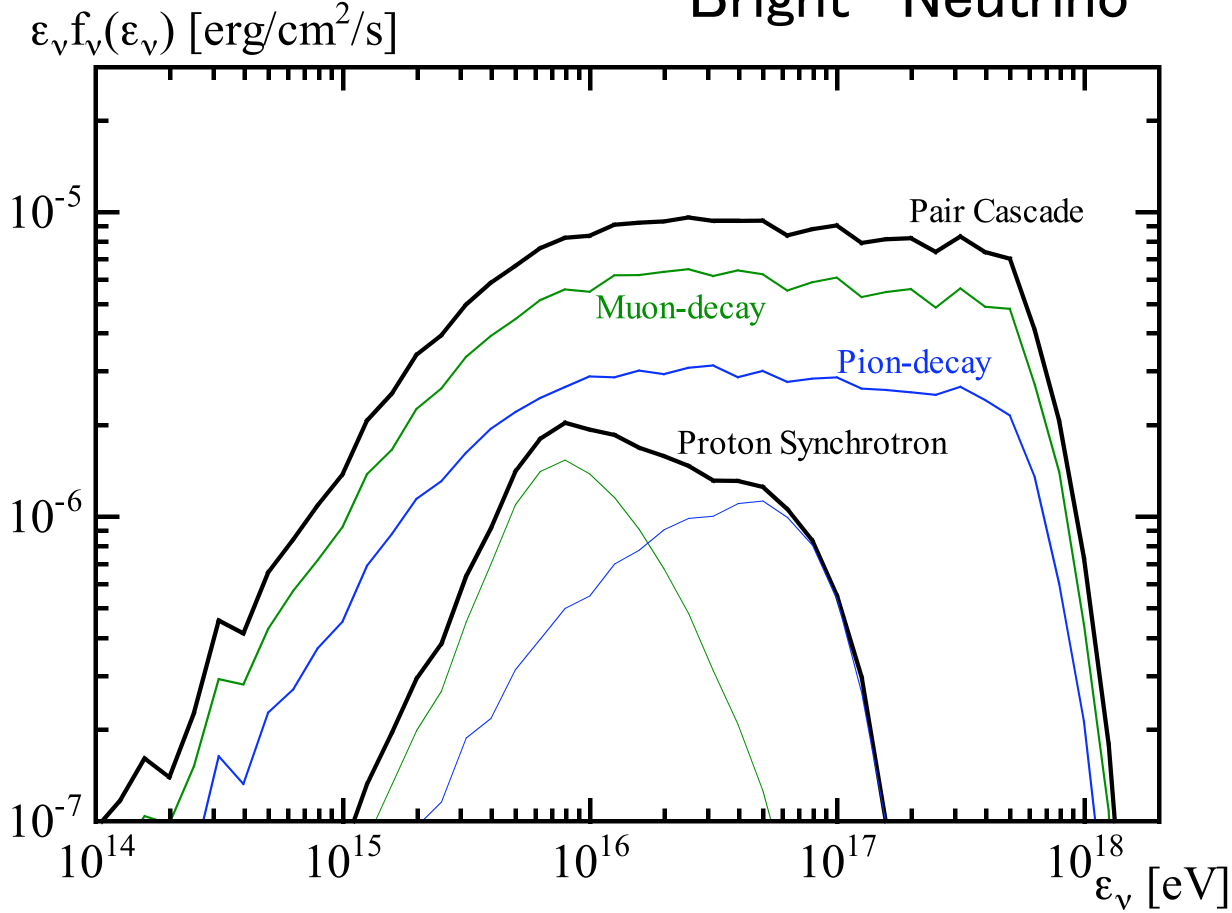
$t_{\rm exp}/t_{\rm syn} \propto \Gamma^{-3} R^{-1/2} (U_B/U_\gamma)^{3/4}$



t [s]
R=10^14cm, Γ=3000, L_B/L_γ=300, L_p/L_γ=300
t_IC
t_BH
t_π
t_syn
t_dyn
t_acc
ξ=10^3
tacc=ξ R_L/c
Proton synchrotron case
Synchrotron is the most efficient in this case.
We suppress E_max to avoid too much secondary photons.
E_p [eV]

Neutrinos from GRB 090510

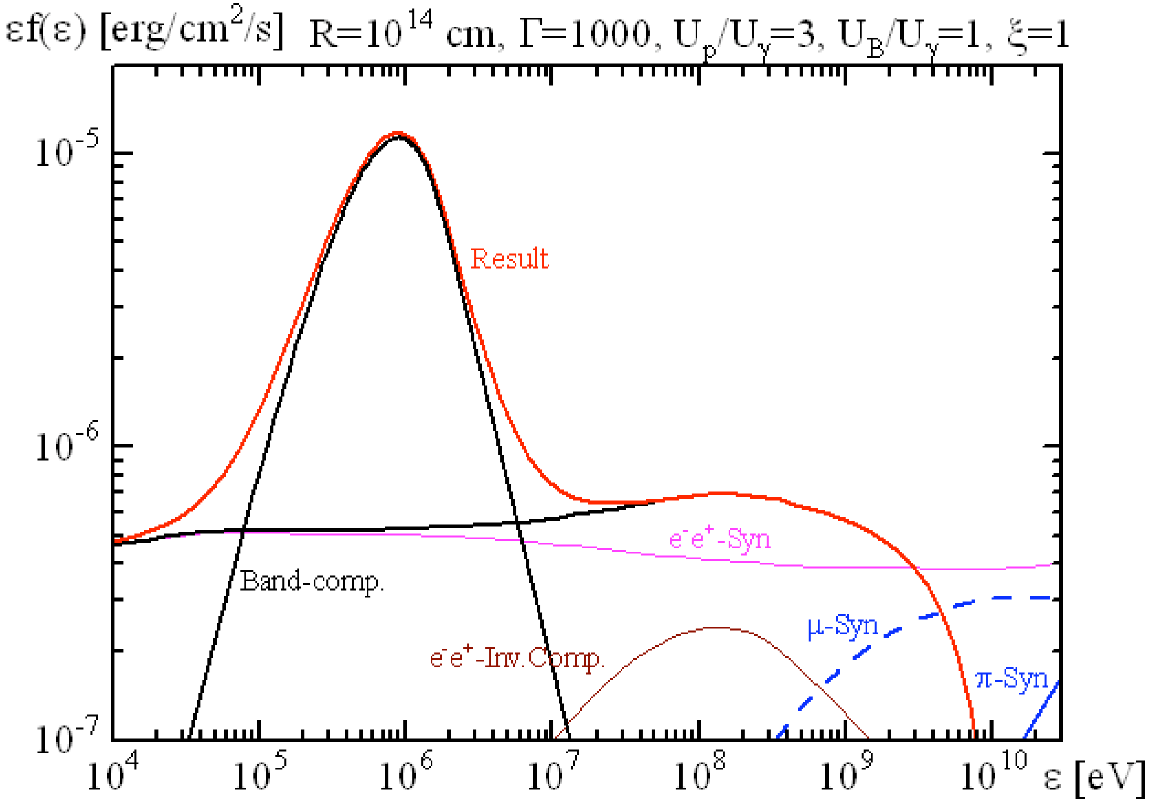
"Bright" Neutrino



We may need $>10^{-2}$ erg/cm² to detect with IceCube.

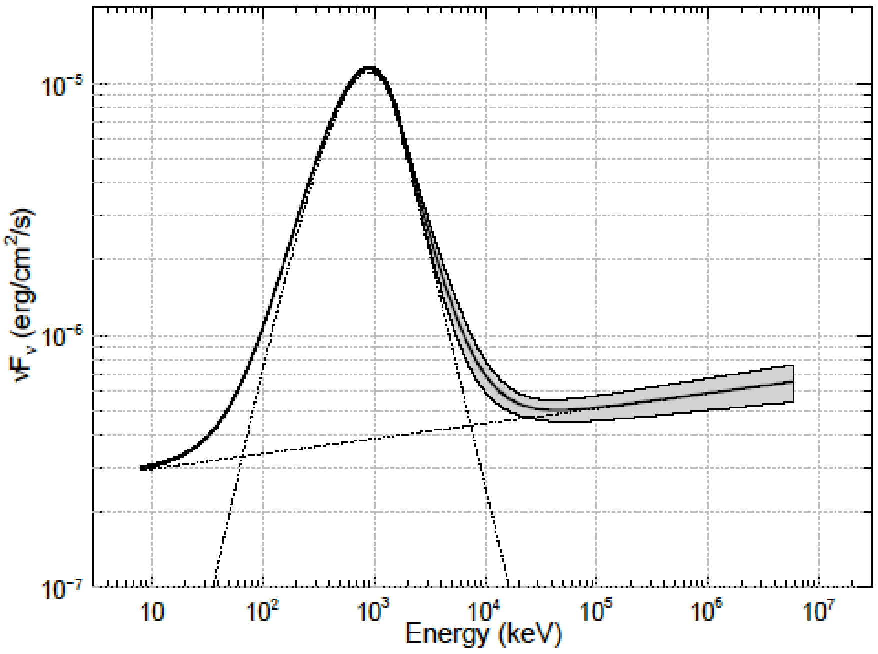
GRB 090902B

Photosperic?



Hadronic Model

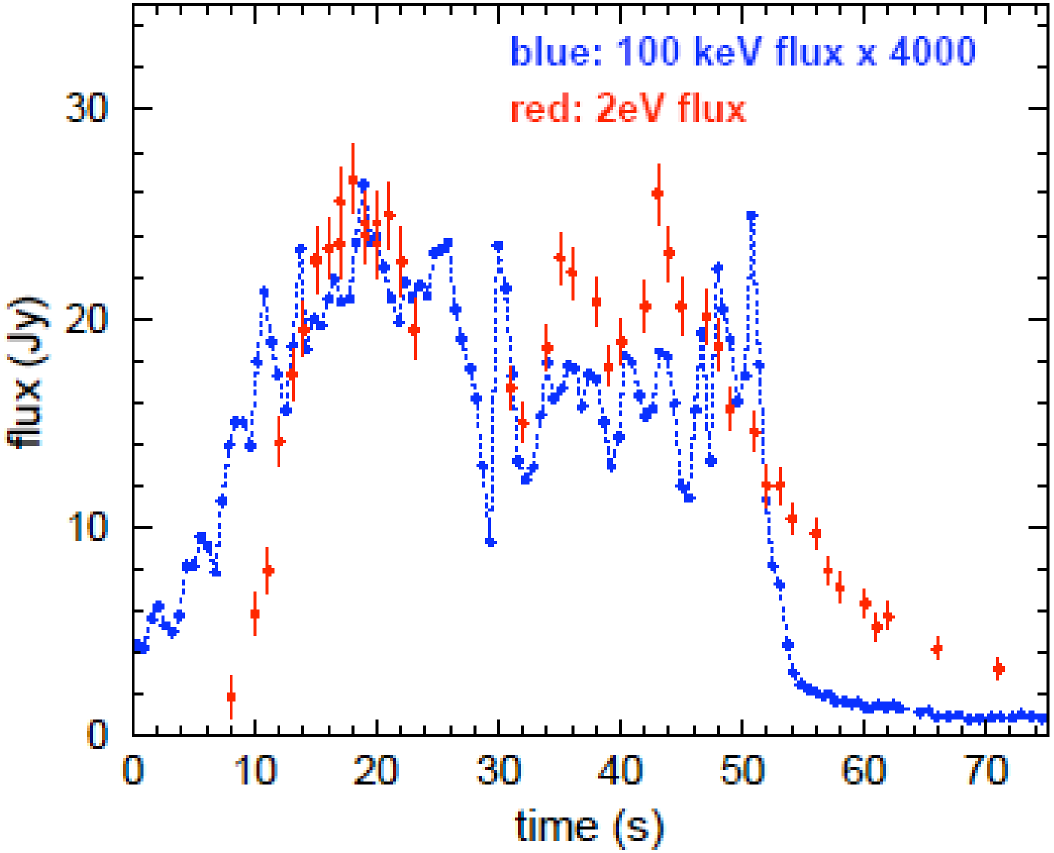
4.6−9.6s



α =−0.07, β =−3.9

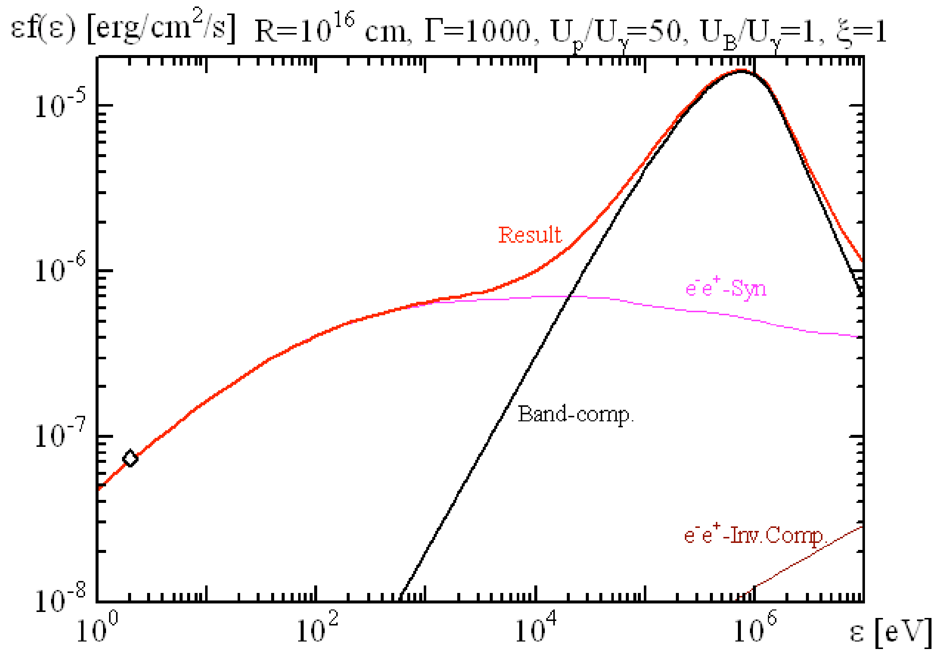
Naked Eye GRB

GRB080319B



$E_{iso} \sim 10^{54}$erg

In preparation



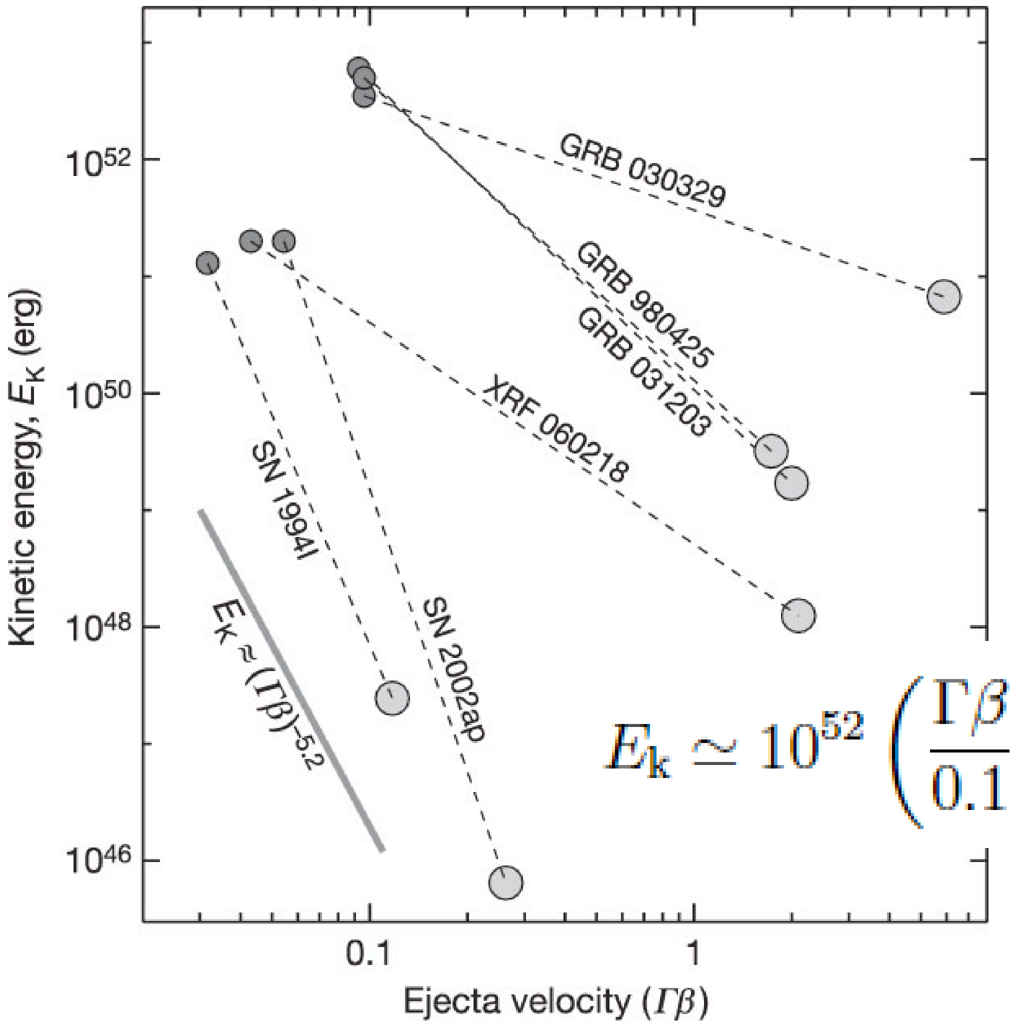
Hadronic

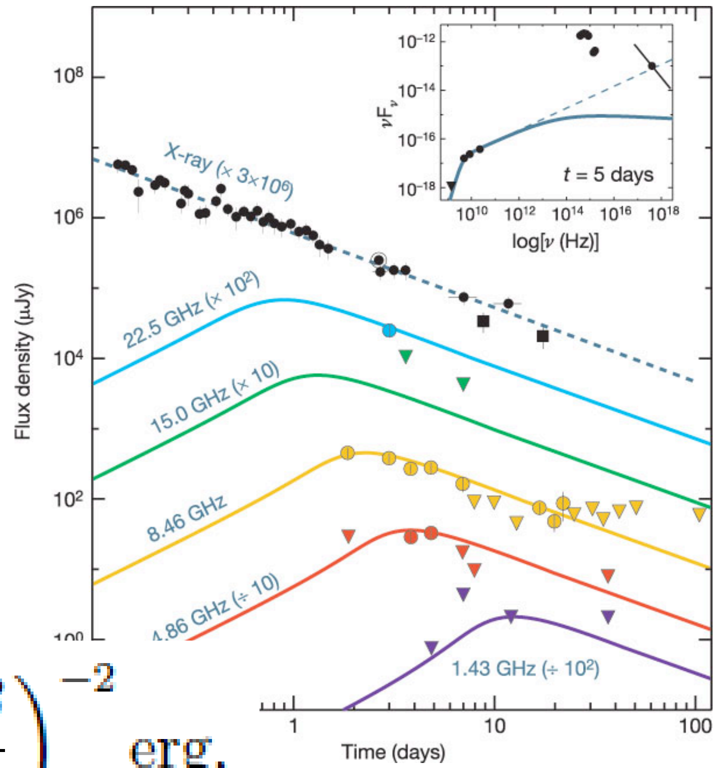
GRBs

- GeV Photon detection -> $\Gamma > 1000$
- Extra Component -> Afterglow? Hadronic?
- High Γ -> Lower Photon Density, Magnetic Field
- ->Lower Effciency for Photopion Production
- Hadronic Models require $>10^{55}$erg/s for GRB 090510

Ref. $E_{iso} \sim 10^{55}$erg in gamma-rays
for GRB080916C

Gamma-rays from hypernovae

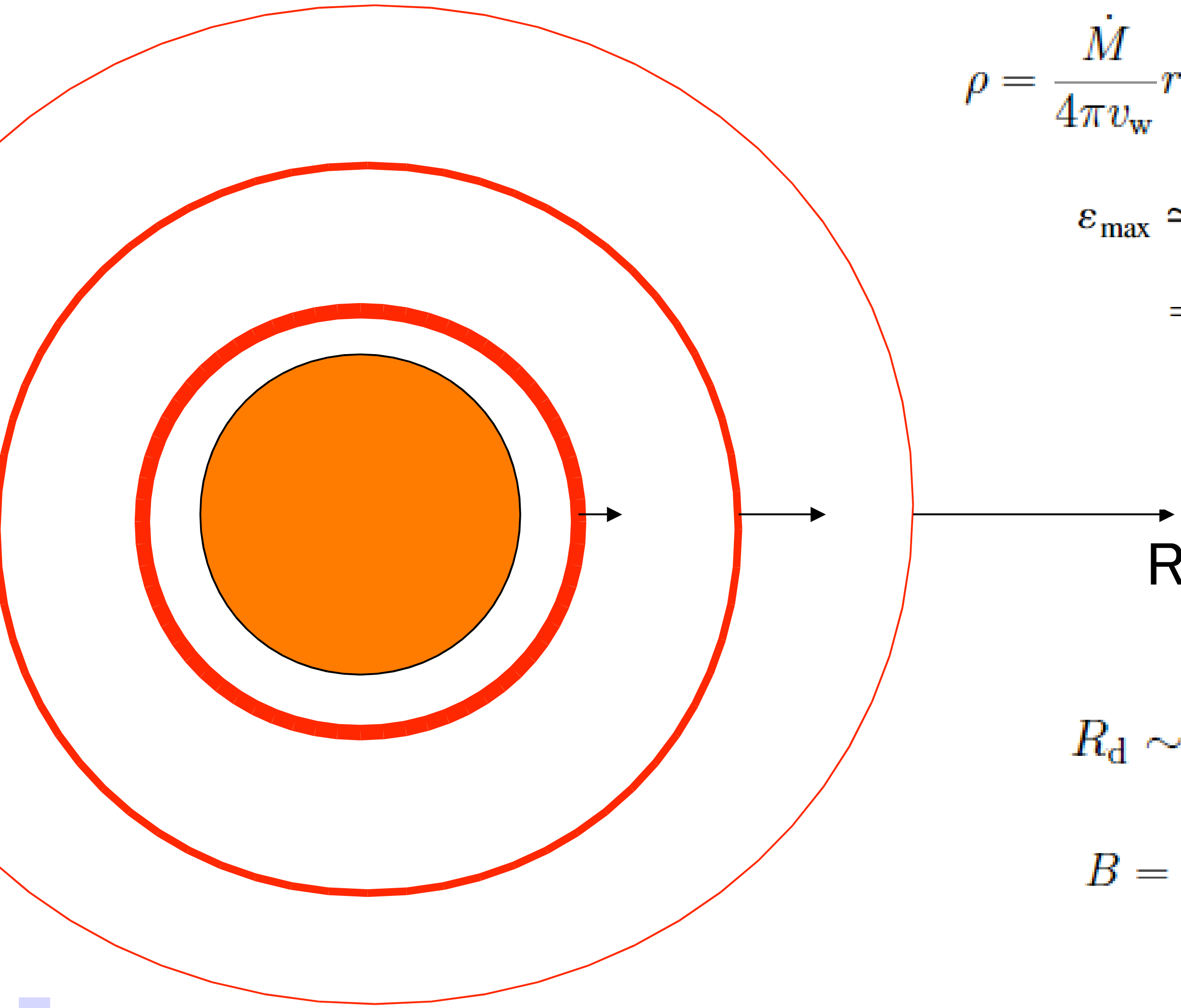




$$E_\mathrm{k} \simeq 10^{52} \left(\frac{\Gamma\beta}{0.1}\right)^{-2} \mathrm{erg},$$

Soderberg et al. 2006

Particle Acceleration in Winds



$$\rho = \frac{\dot{M}}{4\pi v_{\rm w}} r^{-2} = 5\times 10^{11} A_* r^{-2} \mathrm{g\ cm^{-1}},$$

$$\varepsilon_{\max} \simeq ZeBR\beta$$

$$= 4\times 10^{18} Z \epsilon_{B,-1}^{1/2} \left(\frac{v}{10^{10}\ \mathrm{cm\,s^{-1}}}\right)^2 \times \left(\frac{\dot{M}}{3\times 10^{-5} \mathrm{M_\odot\ yr^{-1}}}\right)^{1/2} v_{w,3}^{-1/2}\ \mathrm{eV}.$$

Relativistic component

$\Gamma\beta \sim 1$, $E \sim 10^{50}$ erg

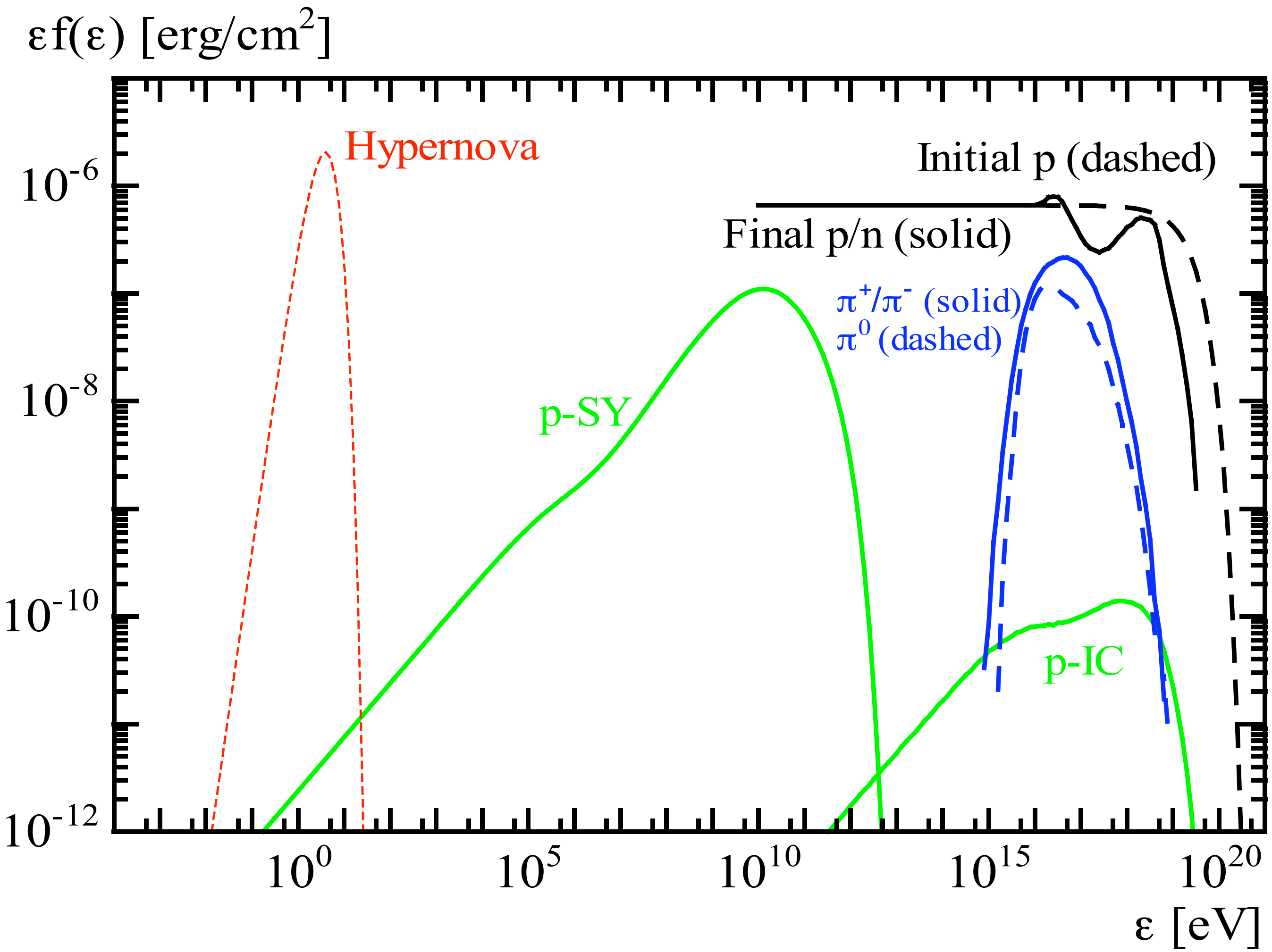
$$R_{\rm d} \sim 10^{16} \left(\frac{\Gamma\beta}{1.0}\right)^{-1} A_*^{-1} \mathrm{cm}.$$

$$B = 3.4 \epsilon_{B,-1}^{1/2} A_*^{3/2} \mathrm{G}.$$

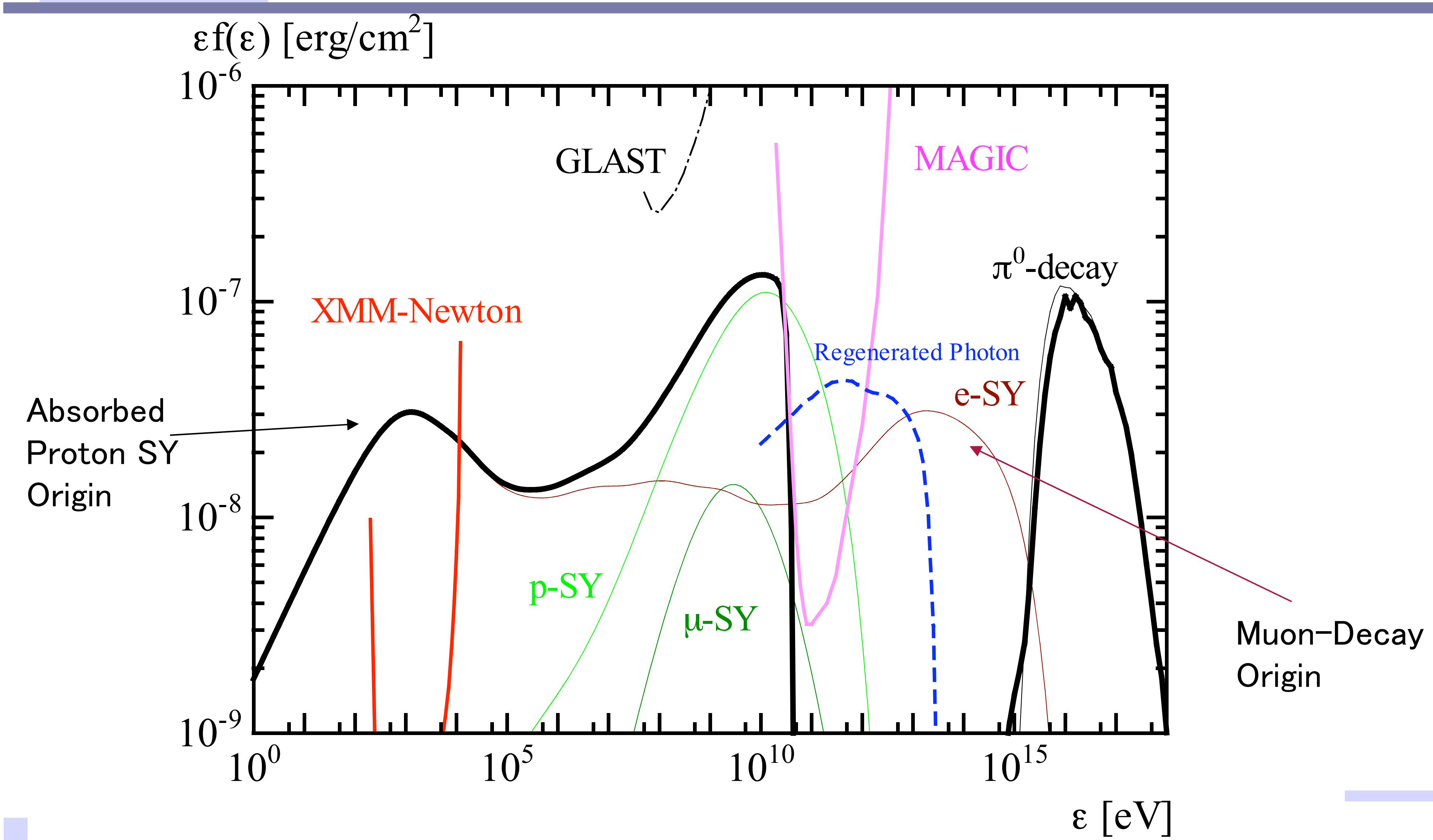
$$\varepsilon_{\max} = 10^{19} \epsilon_{B,-1}^{1/2} A_*^{1/2} \mathrm{eV},$$

Proton Cooling in Hypernova

A*=5



Secondary Photons

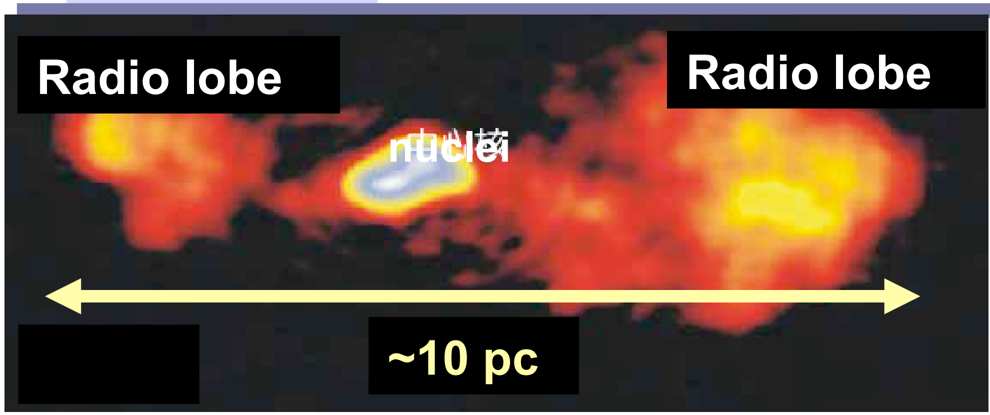


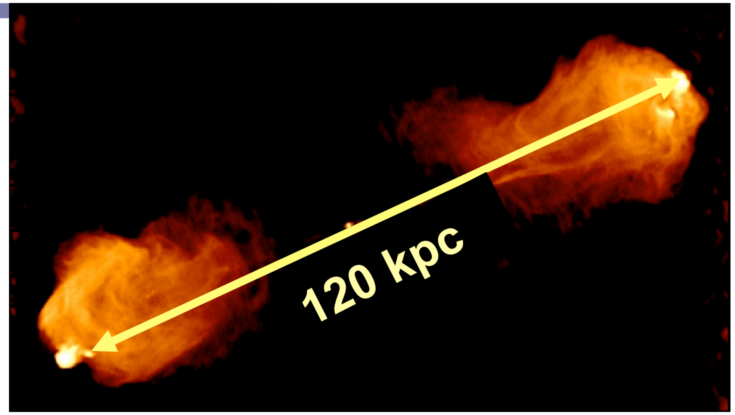
Hypernovae

- Secondary emission from hyeprnovae
  - X-ray due to cascade from muon decay
  - GeV emission from proton synchrotron
  - “Delayed” TeV emission

HN Rate ～ 500 $Gpc^{-3}yr^{-1}$

Compact Radio-Loud AGN





Evolution??

CSOs (Compact symmetric objects)

FRII radio galaxies

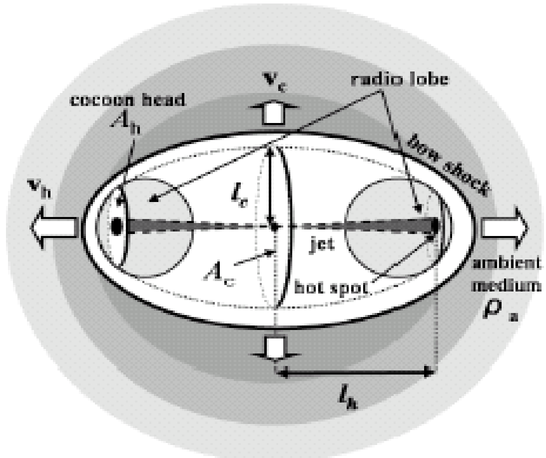
Size < 500 pc

e.g., Carvalho et al. 1985; Fanti et al. 1995; Begelman 1996; Readhead et al. 1996, …

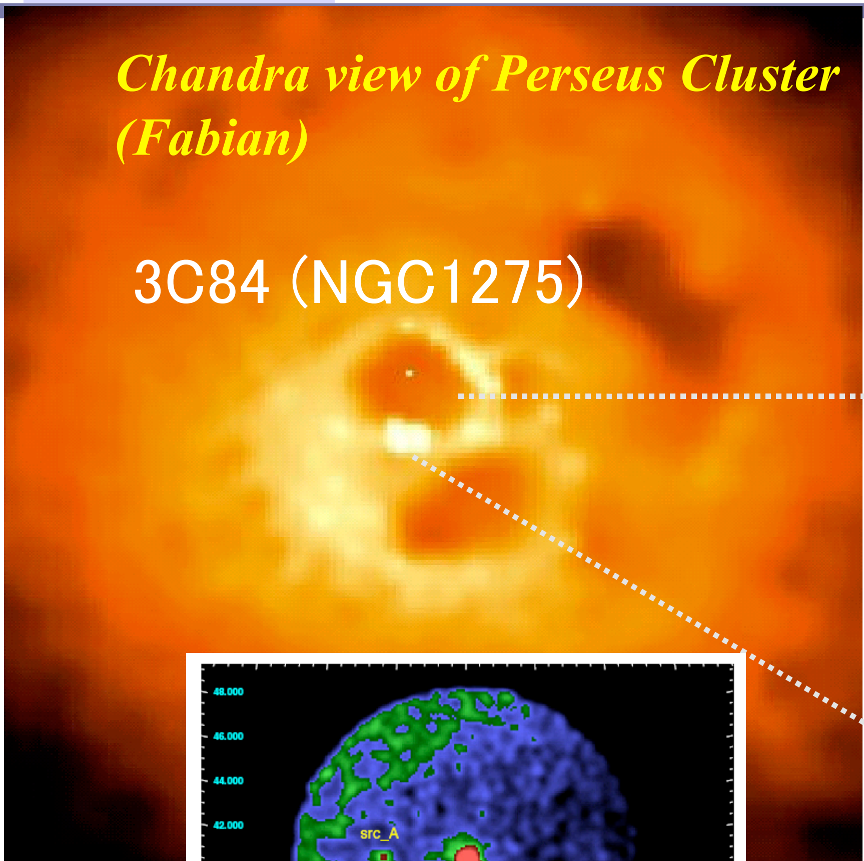
Velocity of Hot Spot: ～ 0.1 c for ～ 20 CSOs

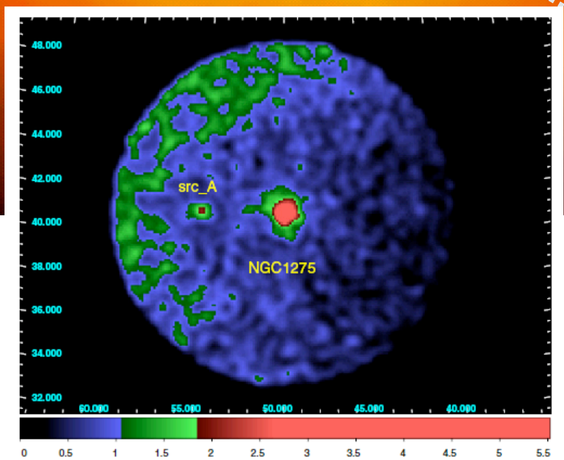
CORALZ(COmpact RA-dio sources at Low-Redshift): 10^{40}–10^{42} erg/s

HFPs(high frequency peakers): 10^{43}–10^{45} erg/s



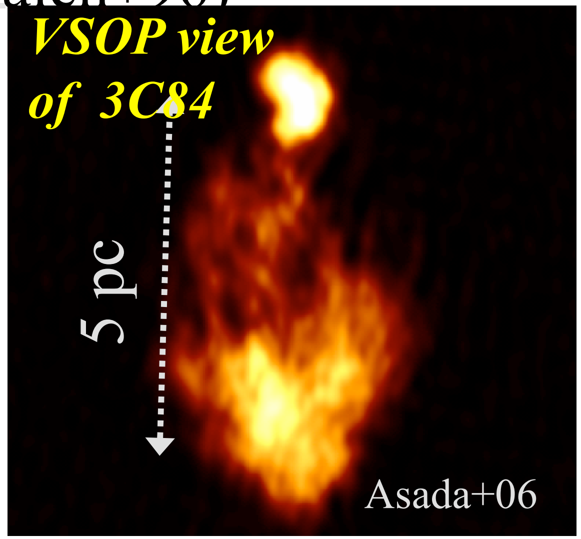
Gamma-Rays from Compact Radio AGNs



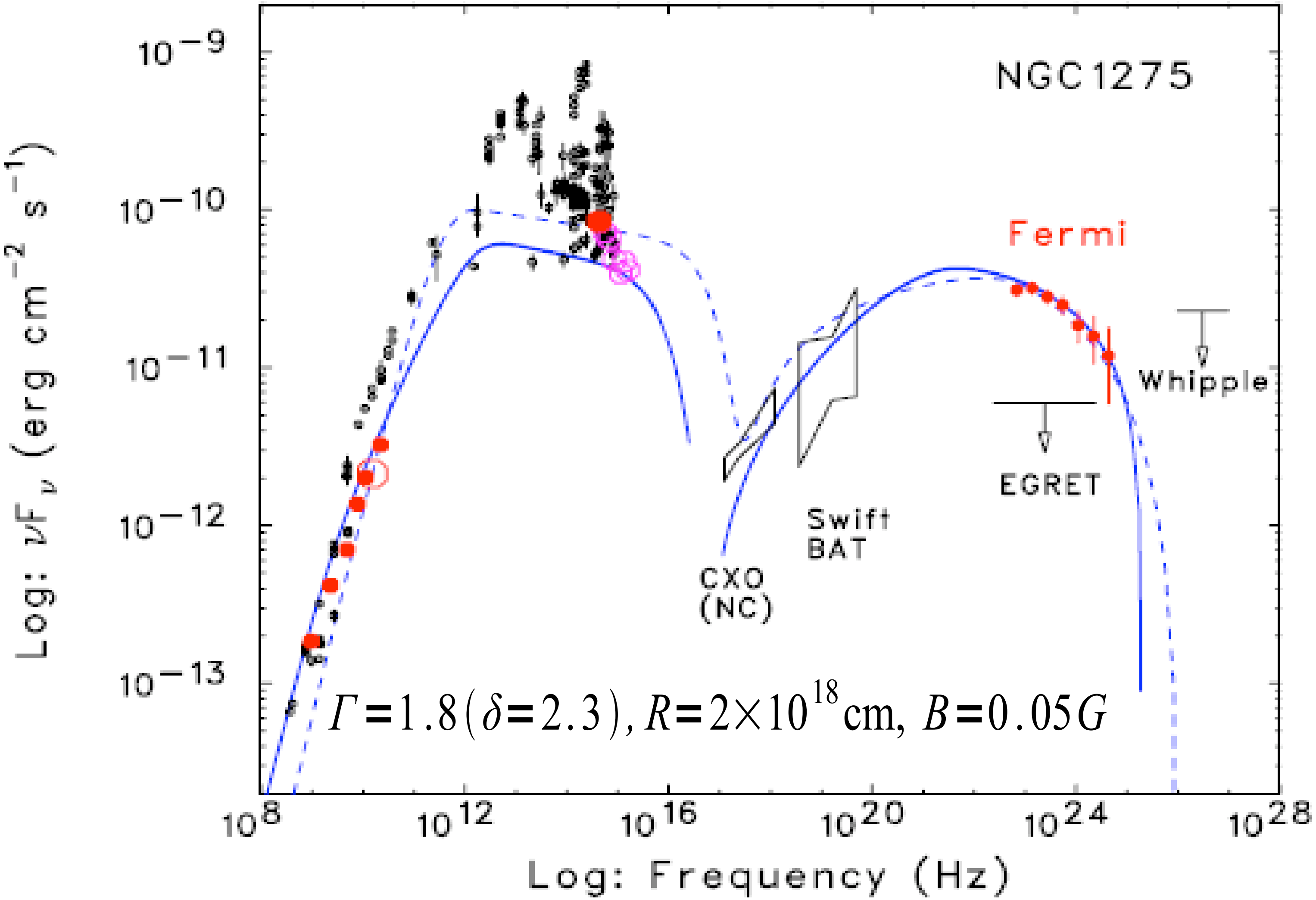


Fermi (>200MeV)

- Core of Seyfart 2 gal. NGC 1275 ($M_{BH}=3*10^8 M_{sun}$)
- z=0.0176
- Other radio bubbles (Pedler+91, Vermeulen+96)



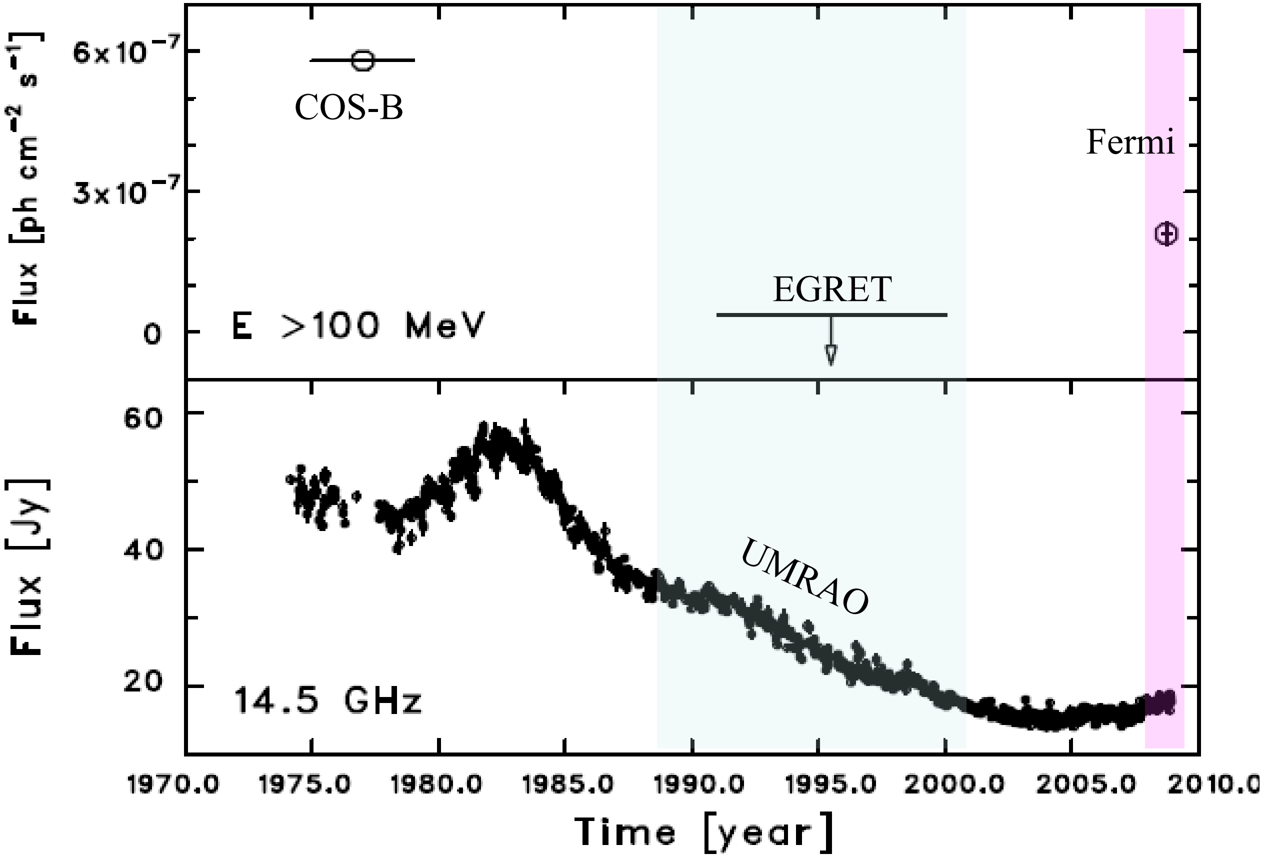
SSC Model



NGC1275
Fermi
Whipple
EGRET
Swift
BAT
CXO
(NC)
$\Gamma = 1.8(\delta = 2.3), R = 2\times10^{18}$cm, $B = 0.05G$
Log: νF_ν (erg cm^{-2} s^{-1})
Log: Frequency (Hz)

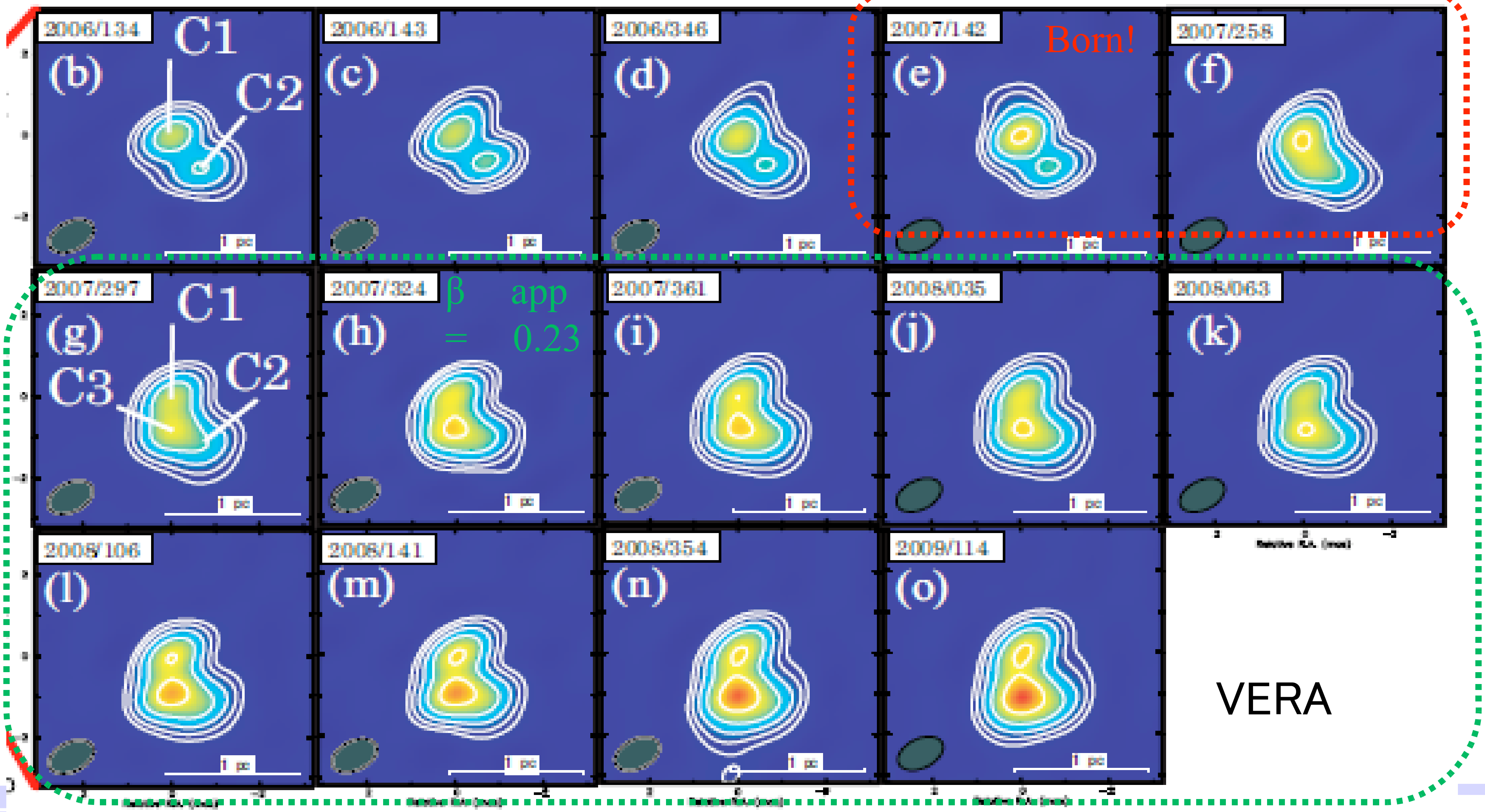
Long Term Evolution

Abdo+09



Lobe Generation

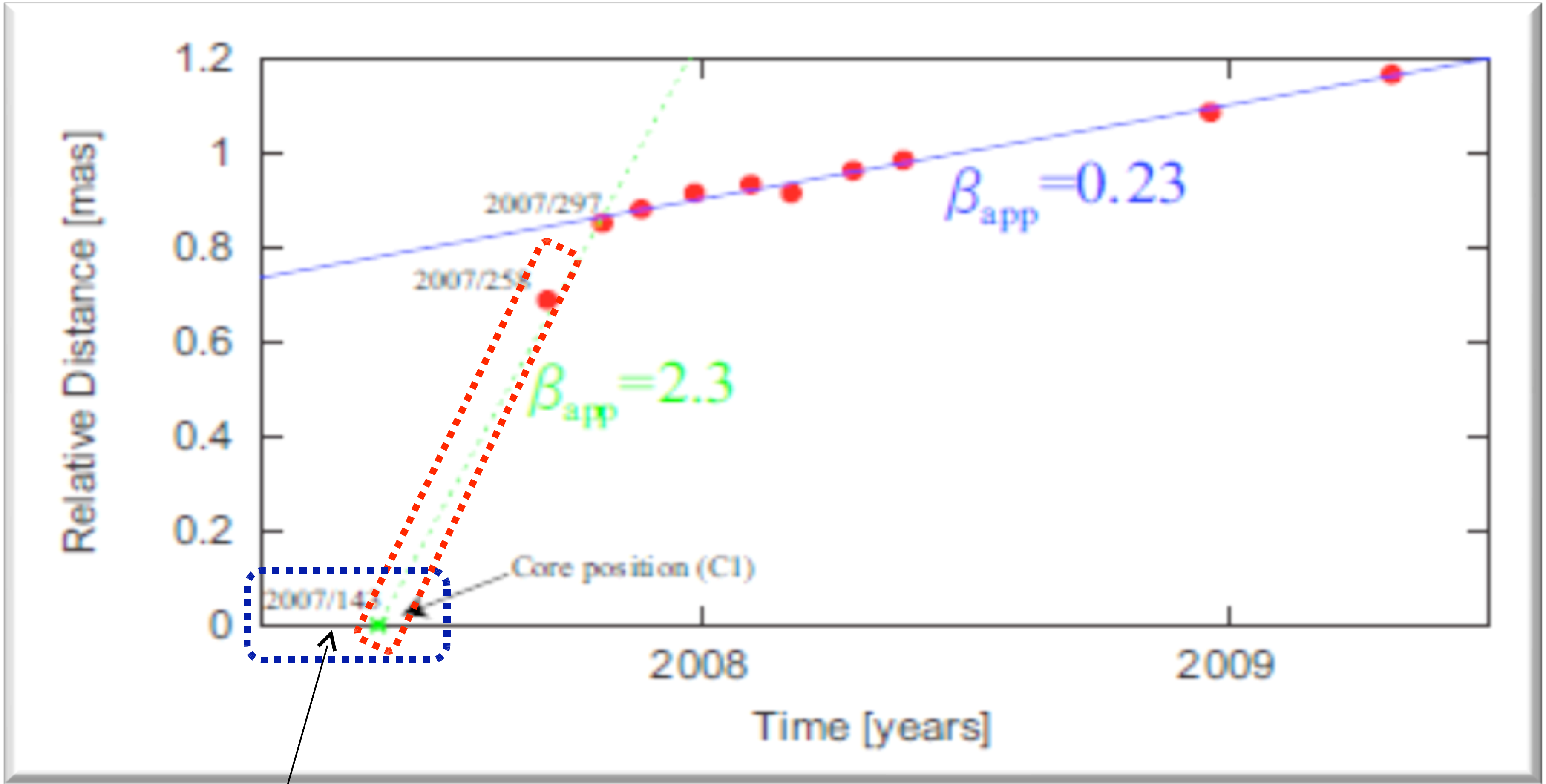
Nagai+09, submitted



VERA

Lobe Velocity

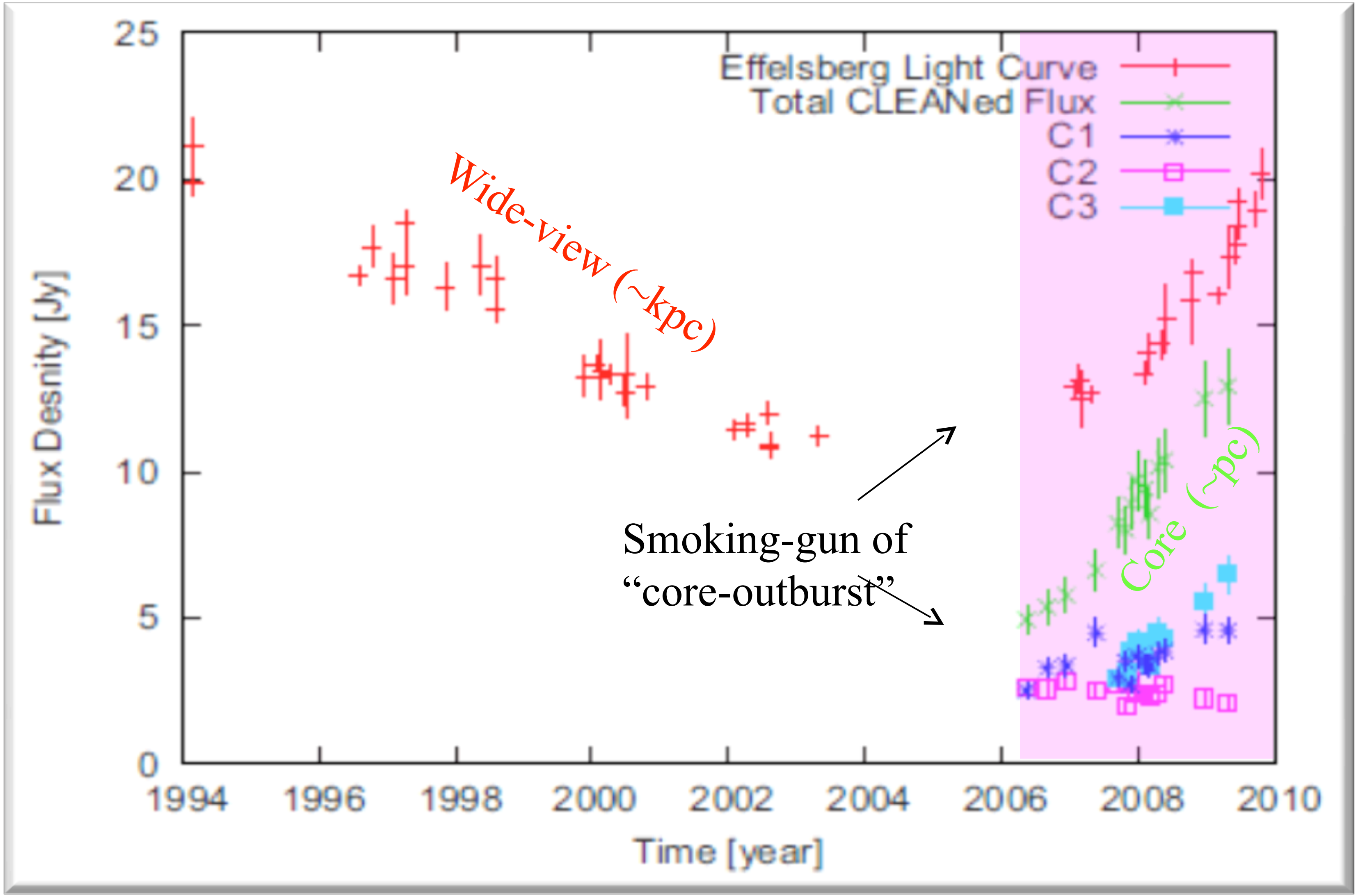
Nagai+09, submitted



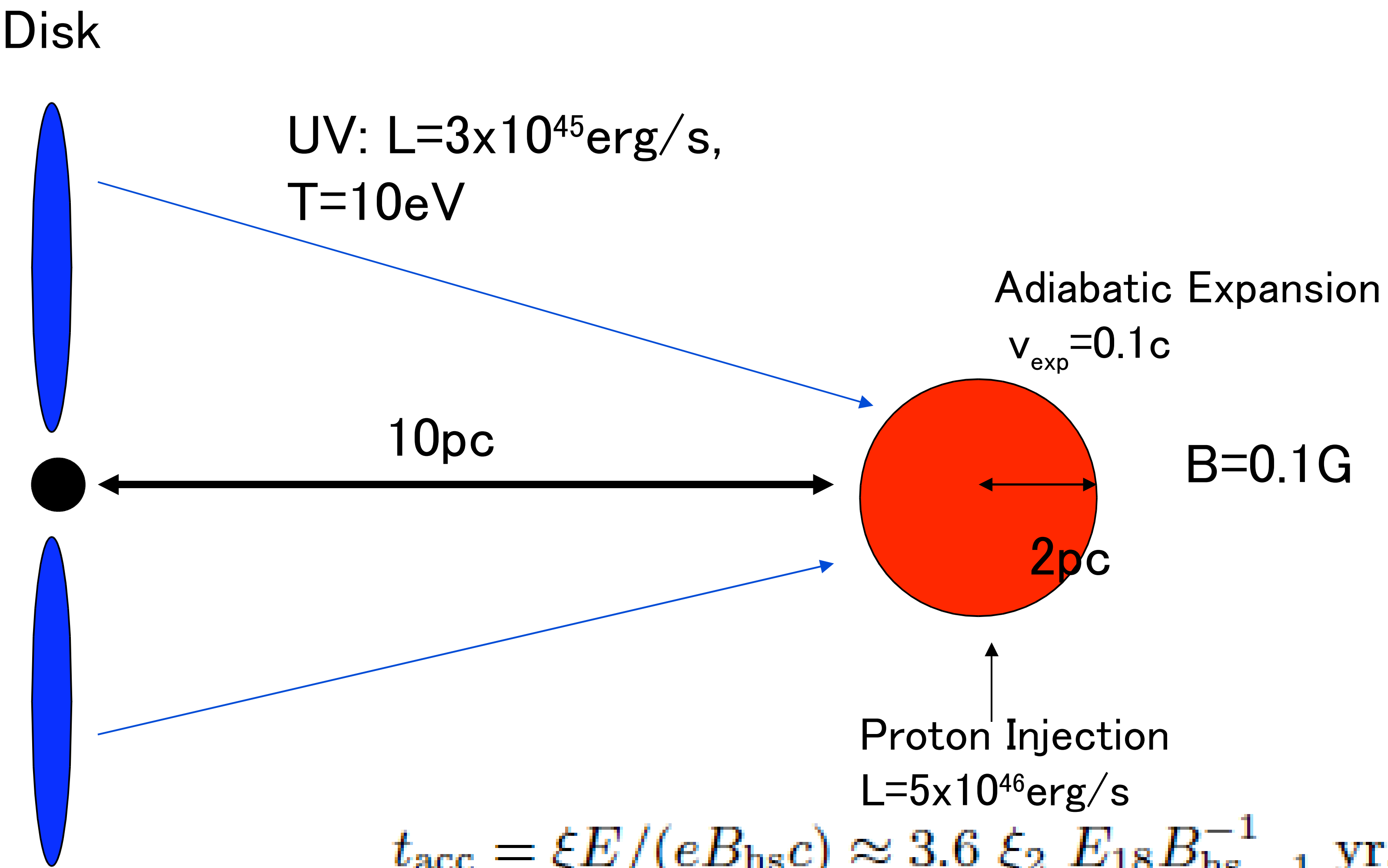
freq. dependent?
(need further studies)

Radio Light Curve

Nagai+09, submitted

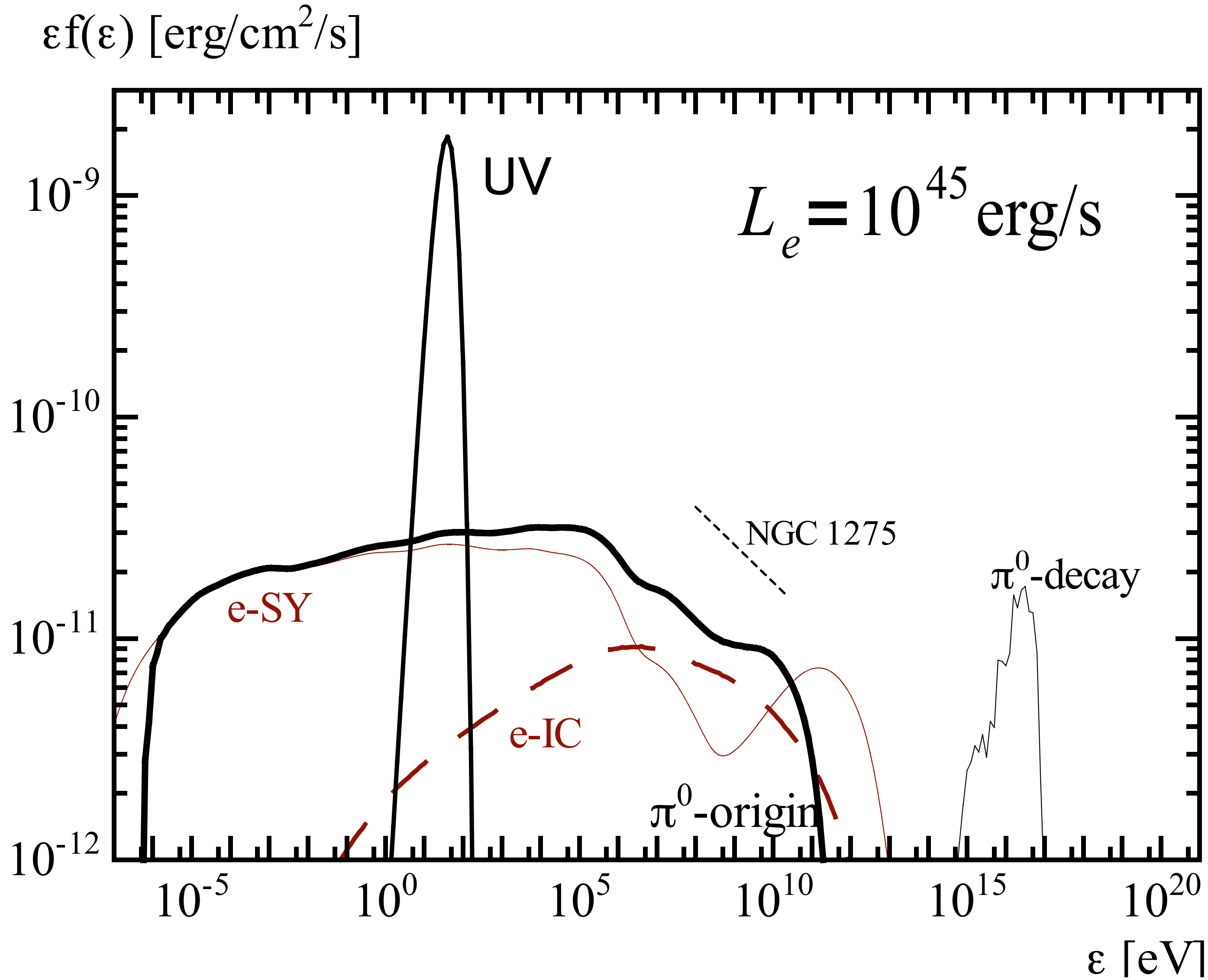


Hadronic Model for Compact Radio AGNs



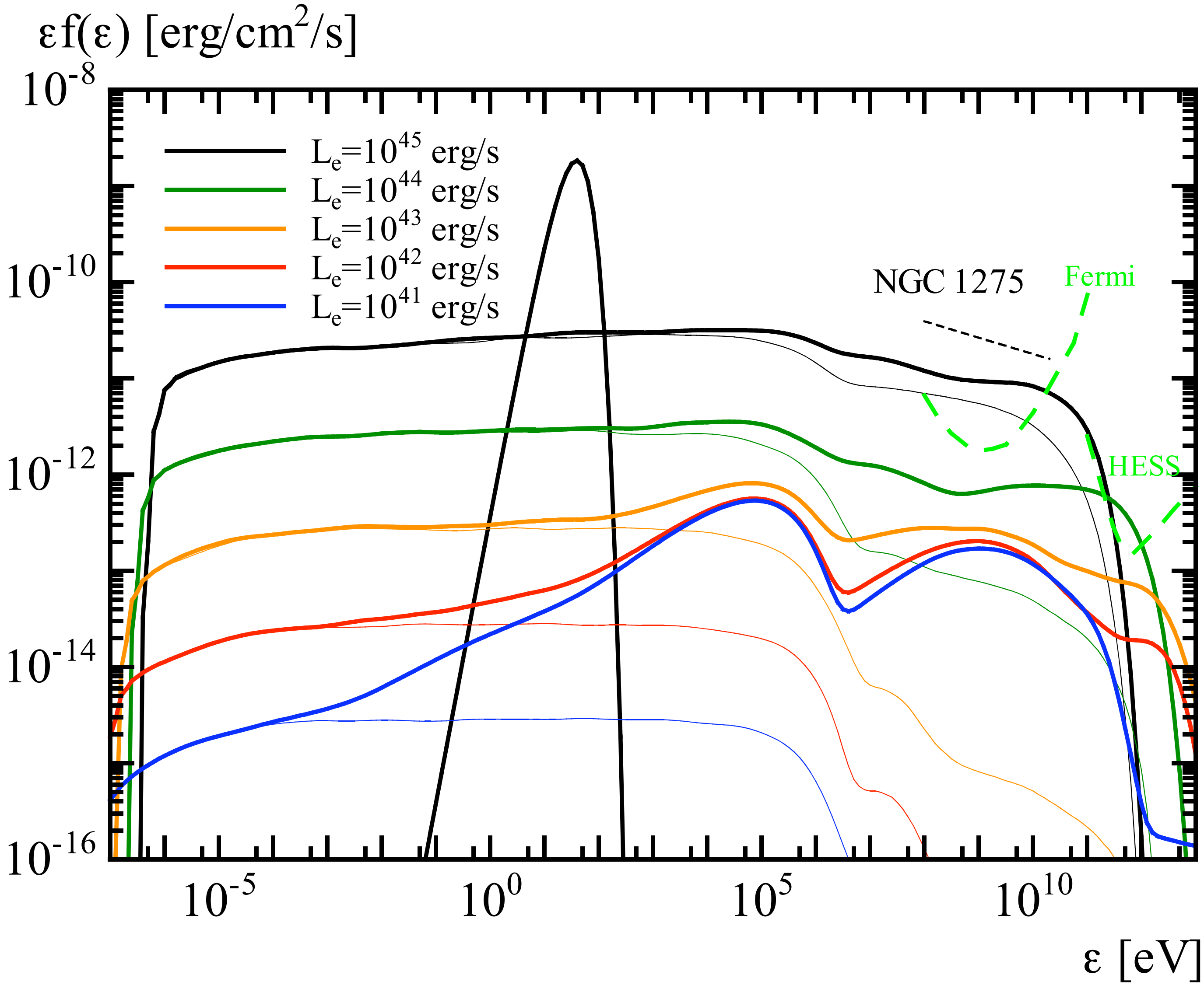
$$t_{\rm acc} = \xi E/(eB_{\rm hs}c) \approx 3.6\ \xi_2\ E_{18} B_{\rm hs,-1}^{-1}\ \rm{yr},$$

Spectrum



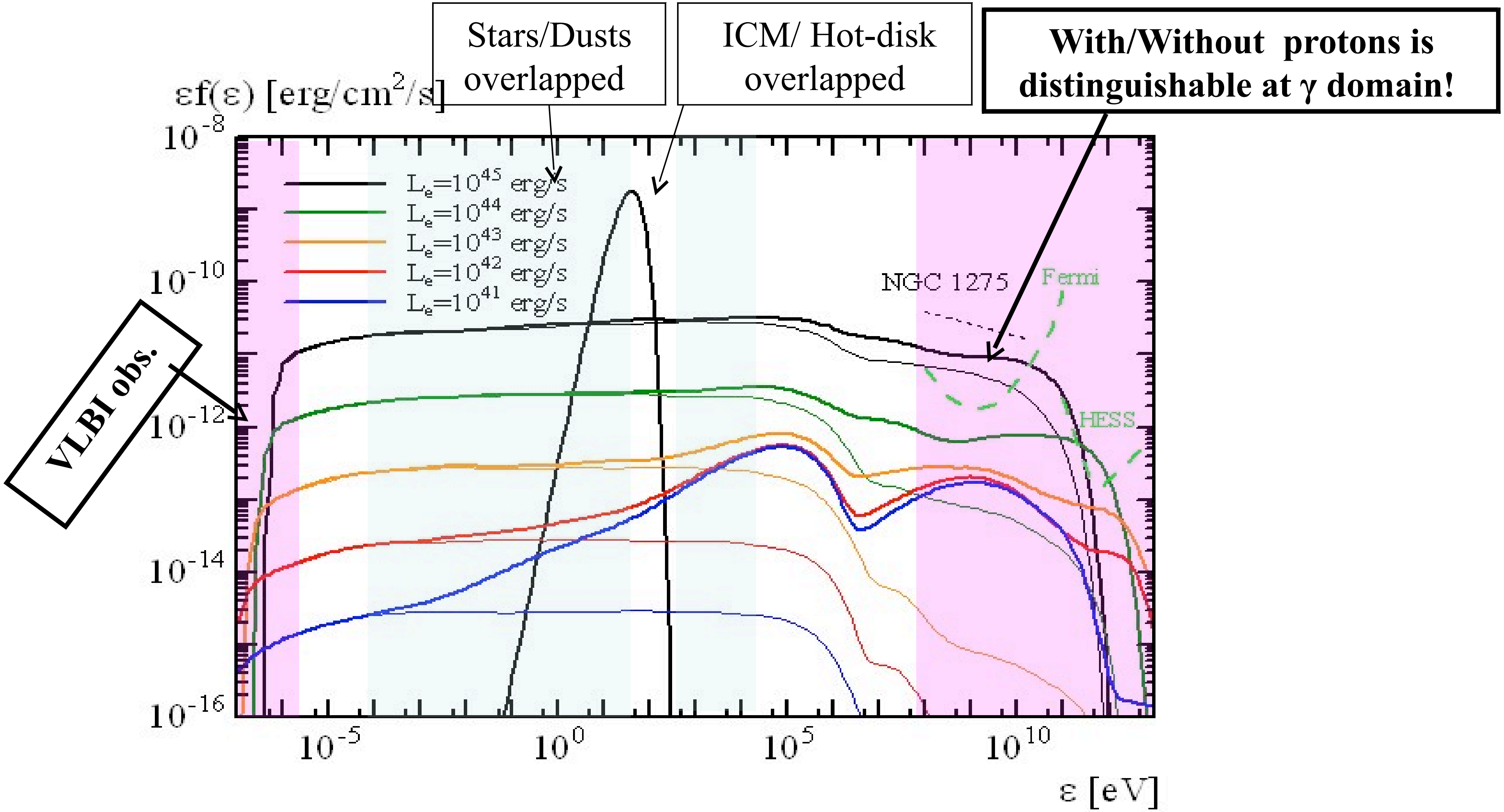
D=100Mpc

Hadronic Contributions



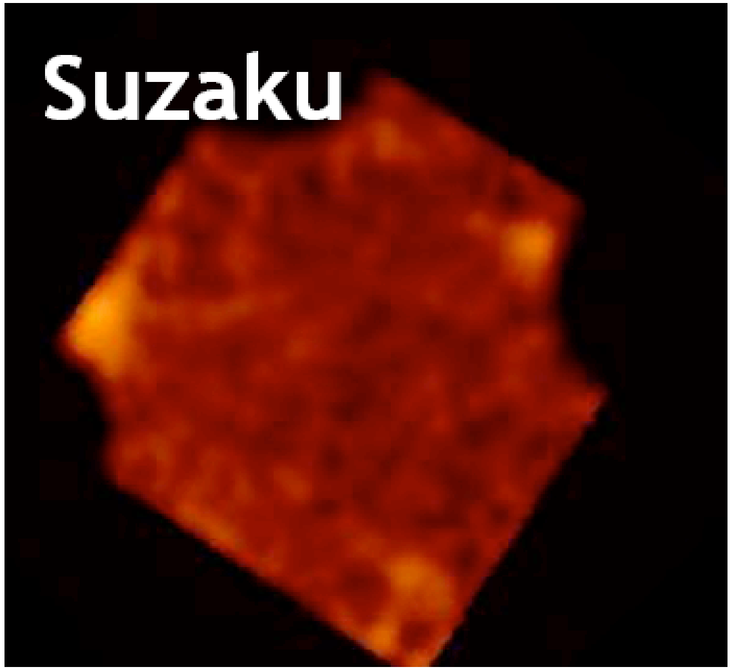
SED of mini radio-lobe (t_age=t_inj)

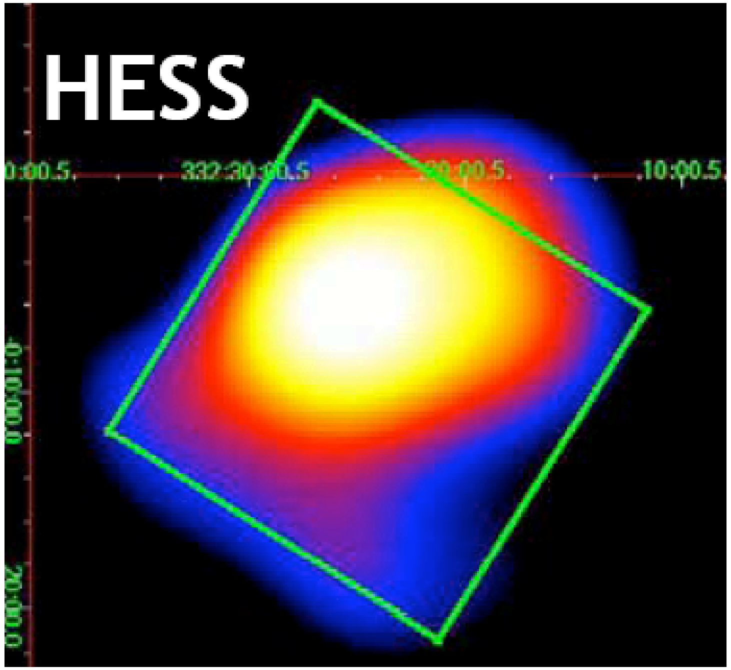
Kino & Asano in prep



SNR(?) Case

HESSJ 1616-508 (Matsumoto+07)



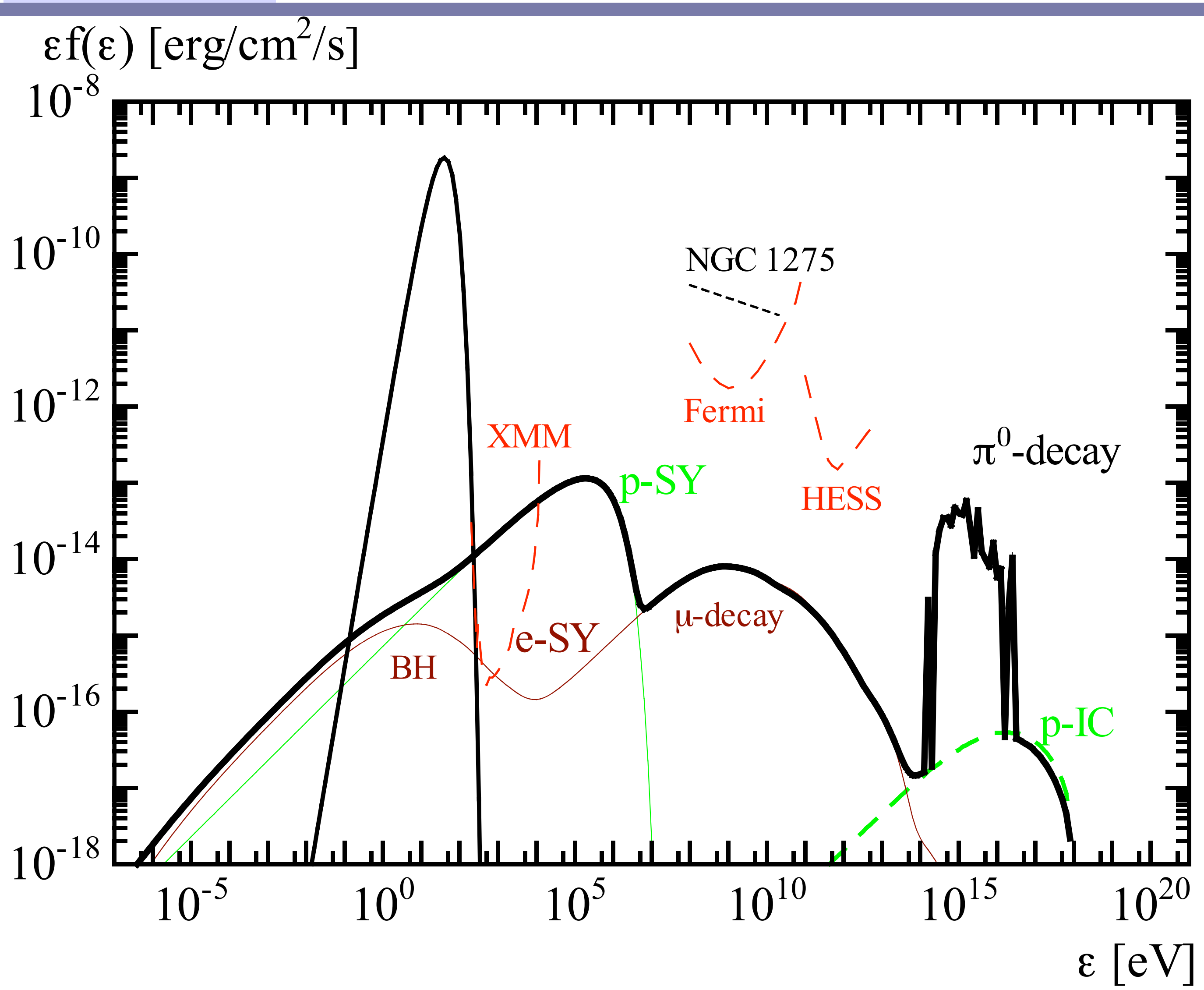


upper-limit !

$F_{TeV}/F_X > 55$

Electron Injection
has been already stopped?

Pure Hadronic Case



$t_{\rm dyn} = R/c \approx 6.5\,{\rm yr}$

$t_{\rm cool}@{\rm GHz} \approx 40\,{\rm yr}$

$$E_p = L_p t_{\rm dyn}$$