High Lorentz Factor Fireballs for High-Energy GRB Emission

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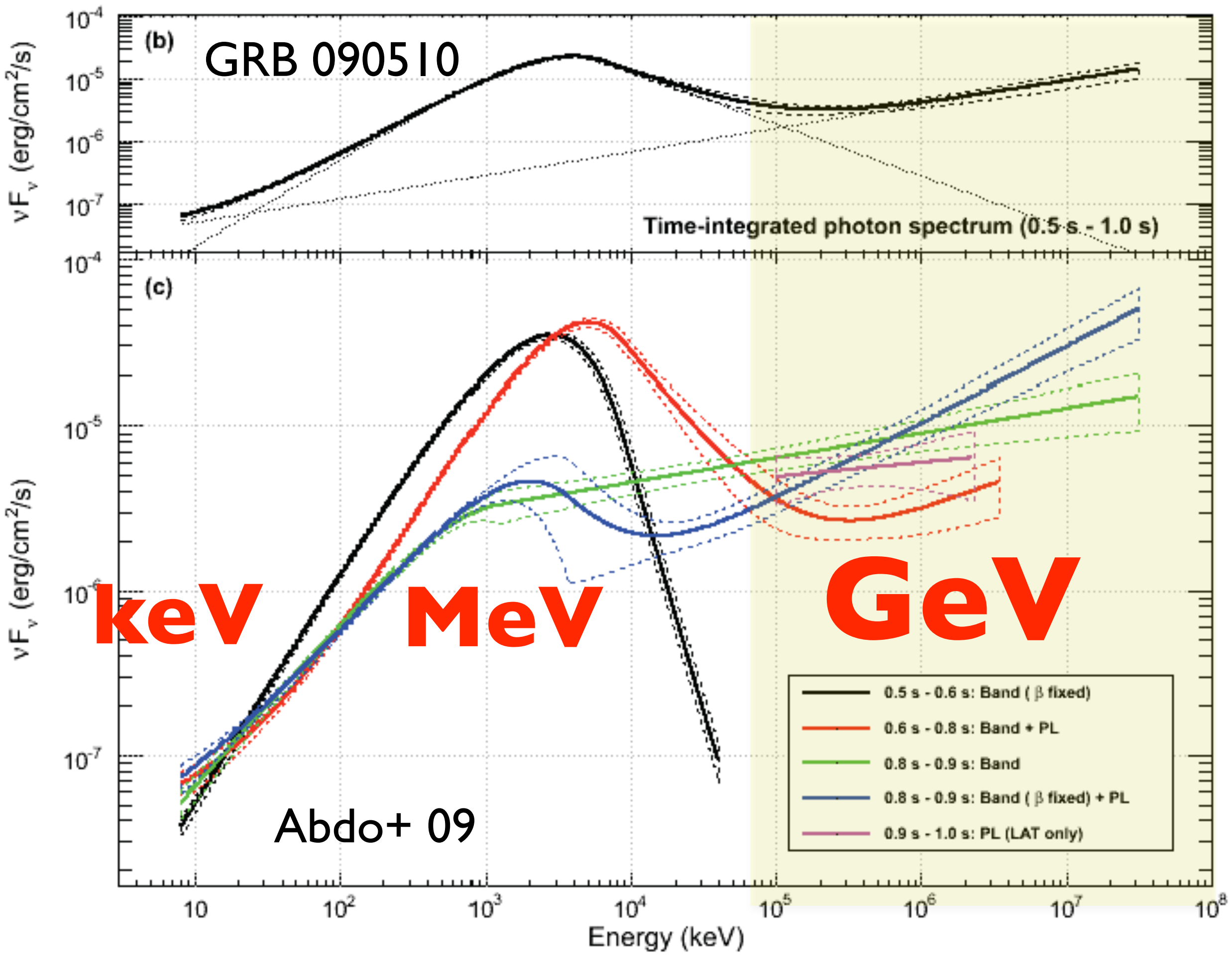
accepted in Prog. Theo. Phys.

1. $\Gamma > 10^3$ is possible
2. Internal shock synchro. ⇒ keV-GeV-TeV γ
3. 3-D relativistic MHD simulation (Movie only)

T. Inoue, Asano & KI, in preparation

Fermi Revolution

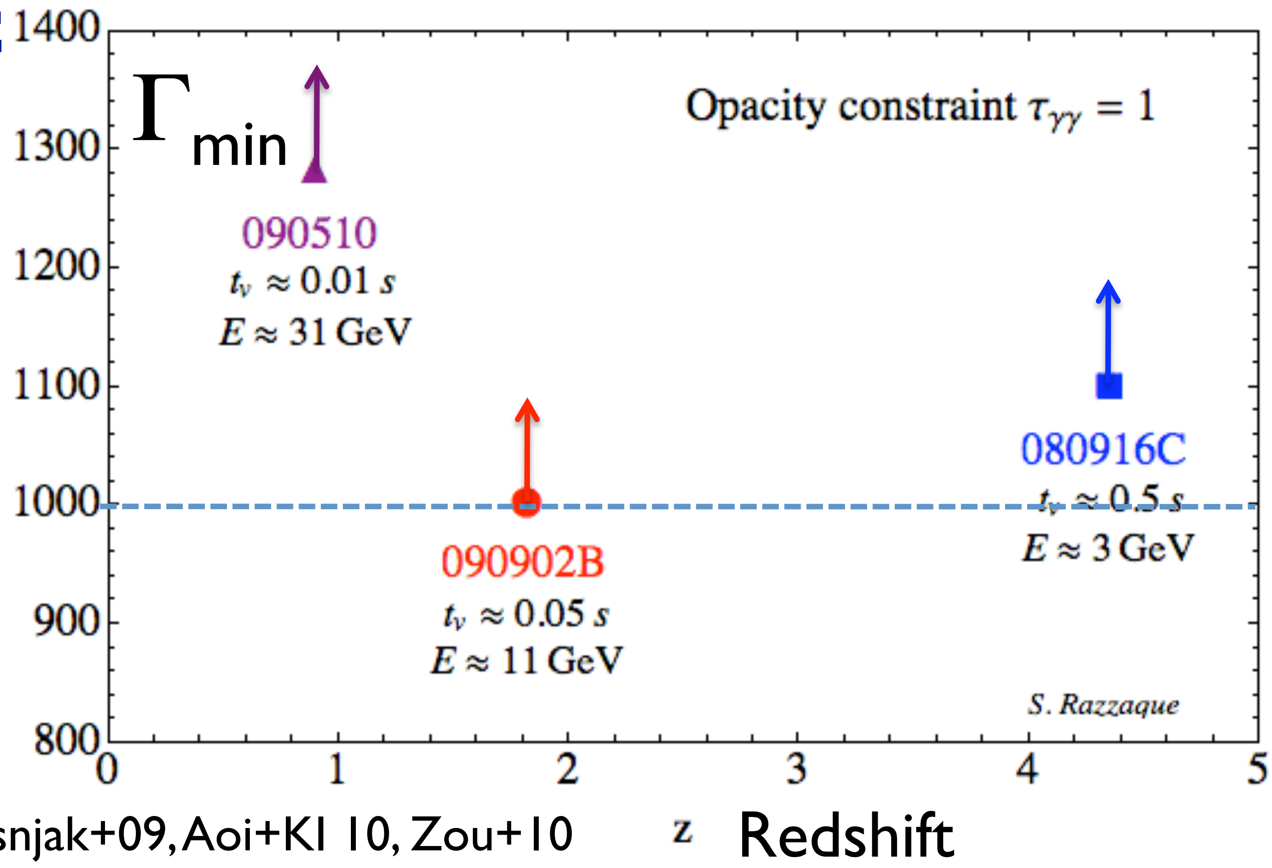
GeV γ from GRBs



High Lorentz Factor?

- $\gamma\gamma \to e^+e^-$ (ε_{th}~MeV)
  - $R \sim c\Delta t \Rightarrow \tau \sim \sigma_T N_\gamma / 4\pi R^2 \gg 1$ (γ-ray cannot escape)
- **Relativistic**
  - $R \sim \Gamma^2 c\Delta t$
  - Blueshift
  - $\tau \sim \Gamma^{2\beta-2} \sim \Gamma^{-6}$
- $\Gamma > 10^3$!

$v > 0.999999 \times c$



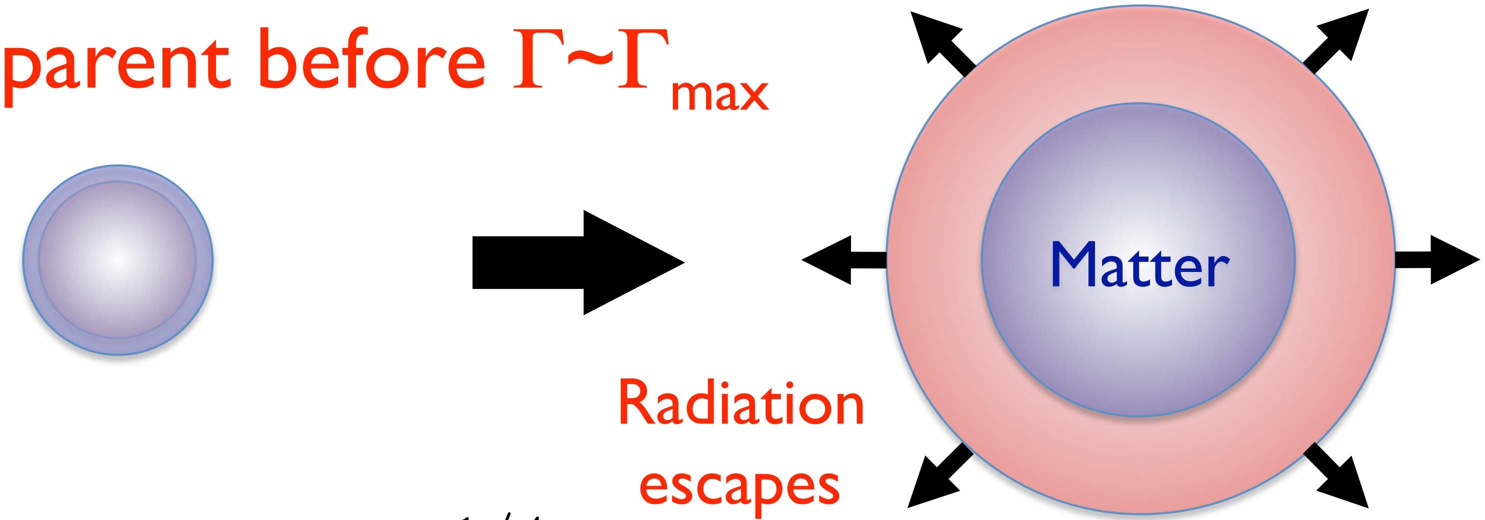
But see also Li 08, Granot+08, Bosnjak+09, Aoi+KI 10, Zou+10

Conventional Γ_{max}

- Fireball expands by radiation pressure
- In principle, Γ_{max} ~ Energy / Mass
- Mass ↓ Γ_{max} ↑ … However,

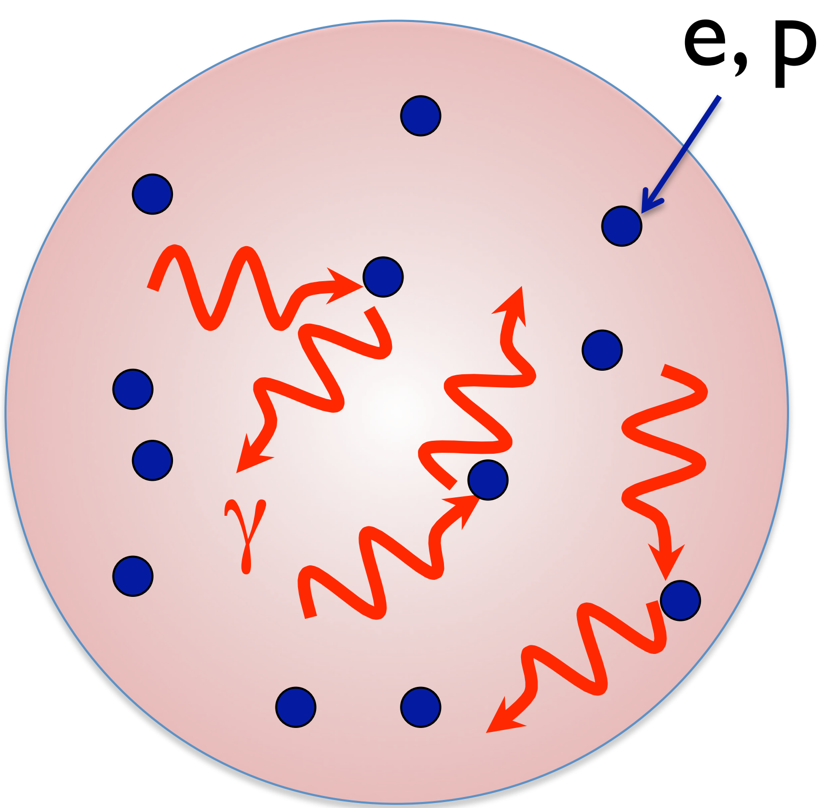
⇒ Transparent before $\Gamma \sim \Gamma_{max}$

Paczynski 86
Goodman 86
Shemi & Piran 90
Meszaros & Rees



$$\Gamma_{\rm max} = \left(\frac{L \sigma_T}{4\pi m_p c^3 r_0} \right)^{1/4} \sim 10^3 L_{53}^{1/4} r_{0,7}^{-1/4}$$

Nonradiative Pressure



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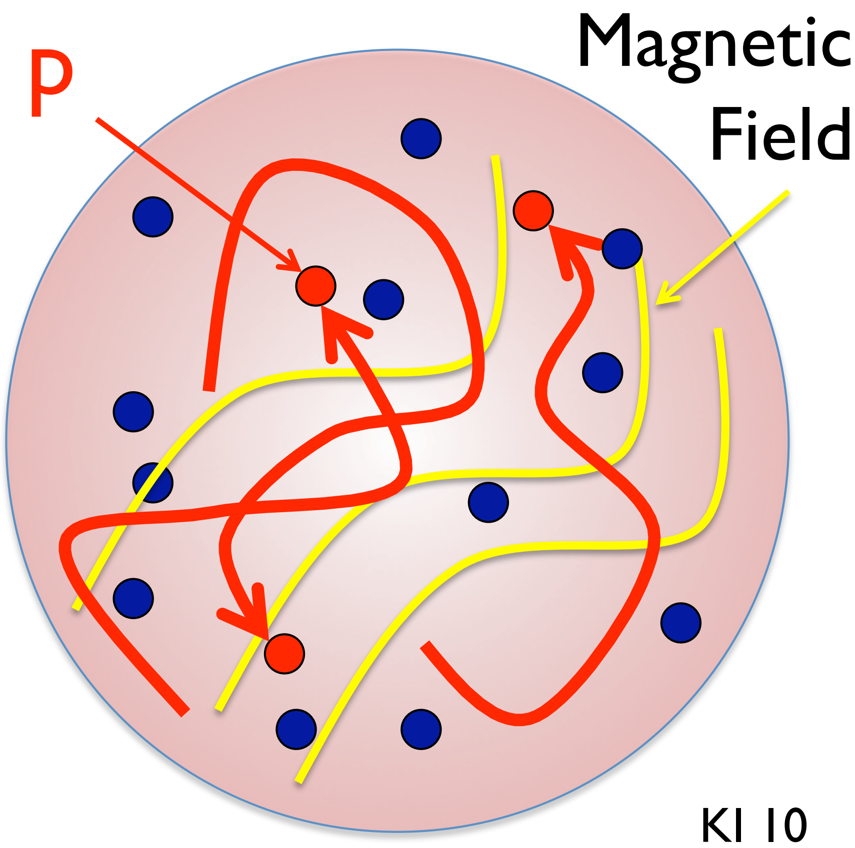
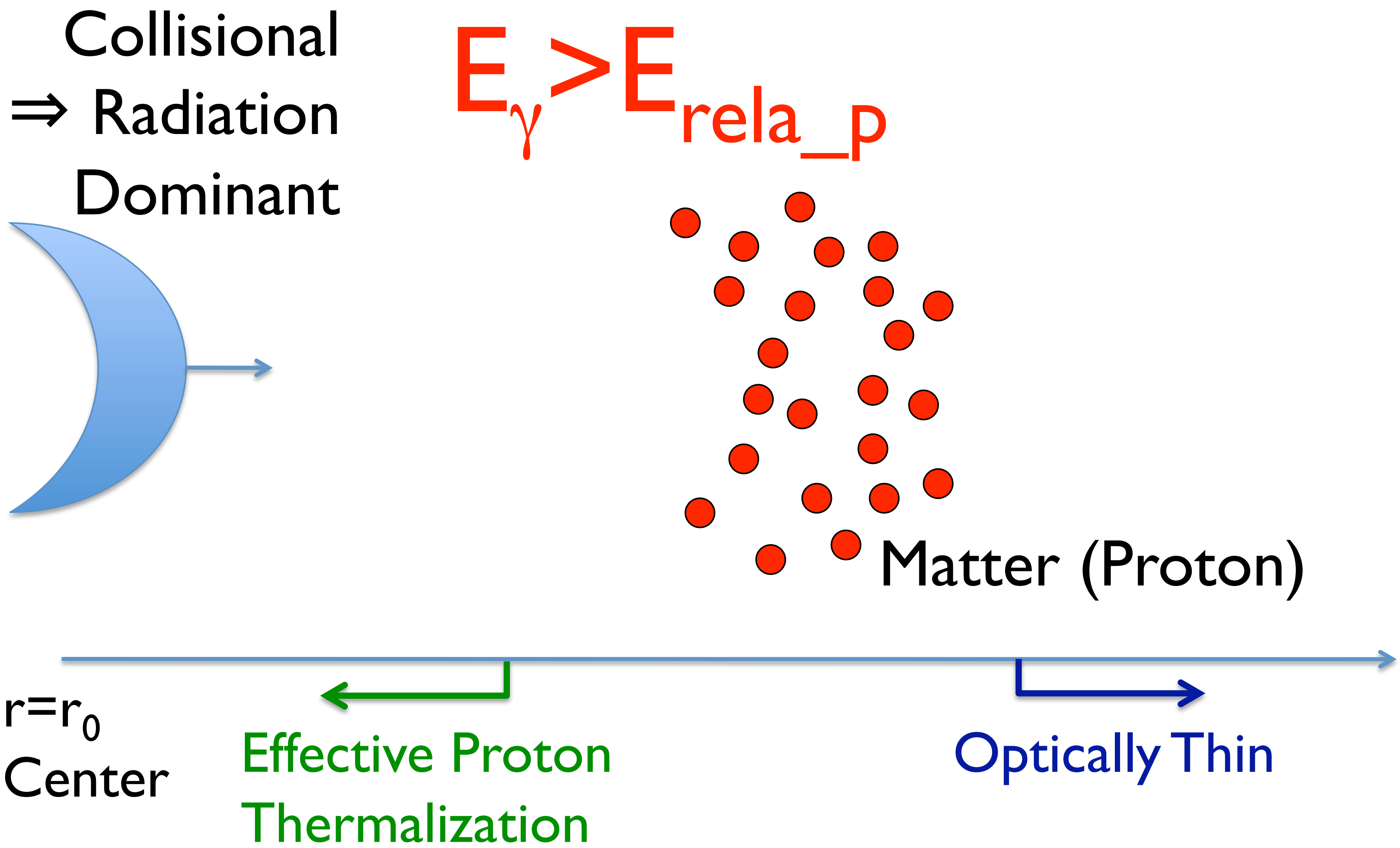


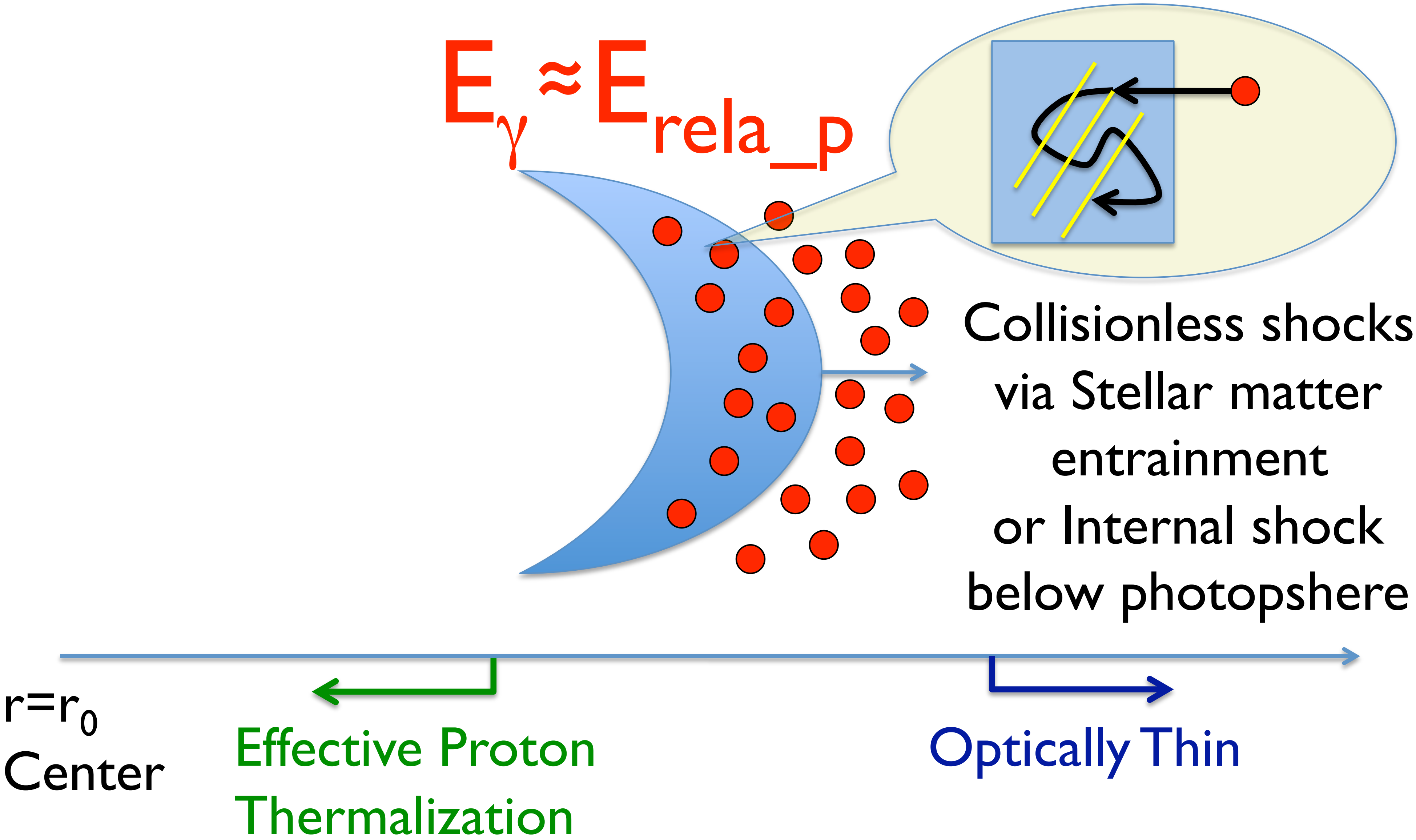
Radiation Pressure ~ Collisionless Pressure of Relativistic Particles

Not escape ⇒ Γ_{max}=**Energy/Mass** can be attained

Radiation to Collisionless

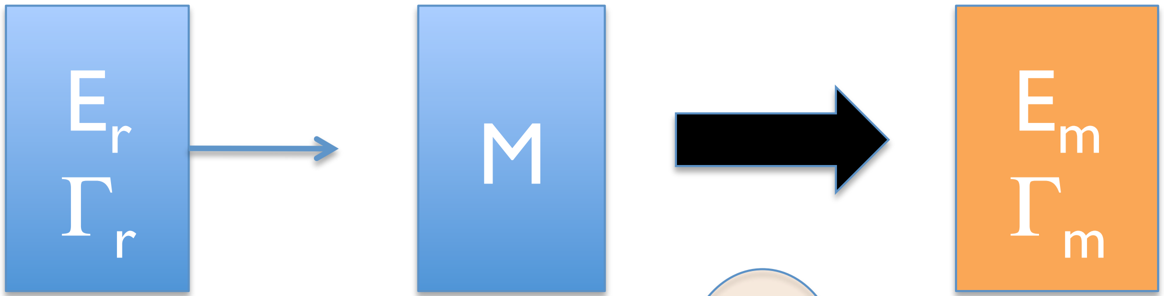


Radiation to Collisionless



Two Body Model

Radiation Dominated Fireball



Dissipated Fireball

Energy
$$\underbrace{E_r\Gamma_r}_{\text{Fireball}} + Mc^2 = \left(\underbrace{\Gamma_m Mc^2}_{\text{Collisionless}} + \underbrace{E_m}_{\text{Radiation}}\right)\Gamma_m$$

Momentum
$$E_r\sqrt{\Gamma_r^2 - 1} = \left(\Gamma_m Mc^2 + E_m\right)\sqrt{\Gamma_m^2 - 1}$$

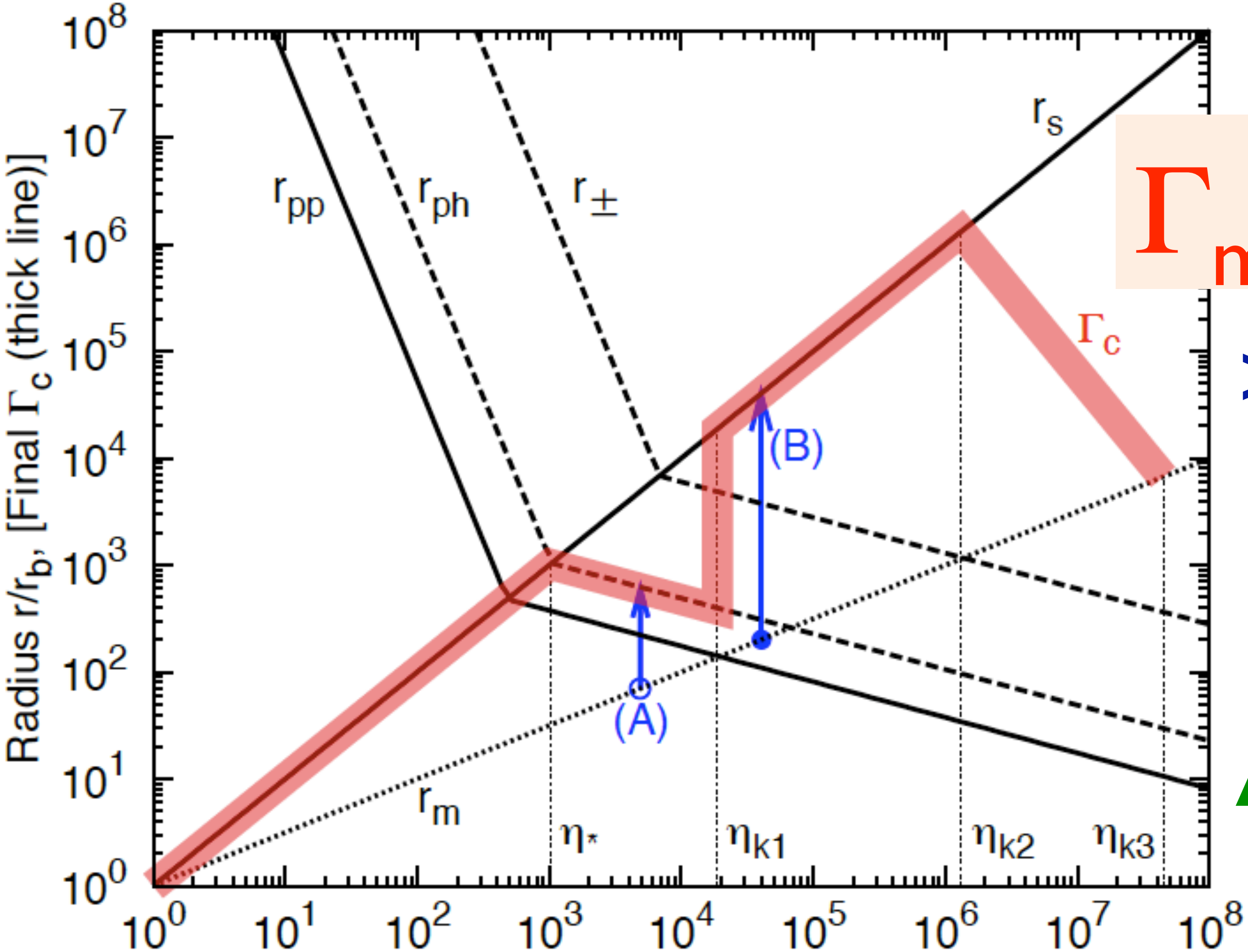
$$\Rightarrow \Gamma_m \sim \sqrt{\frac{E_r\Gamma_r}{2Mc^2}} \propto L^{1/2}$$

2 eqs. for 2 unknowns $\left(\frac{E_r}{\Gamma_r} < Mc^2 < E_r\Gamma_r\right)$

$E_m \sim \Gamma_m Mc^2$: **Radiation ~ Collisionless motion**

$\propto r^{-4}$ $\propto r^{-4}$

Γ_{max} of Dissipated Fireball



(To be opaque)

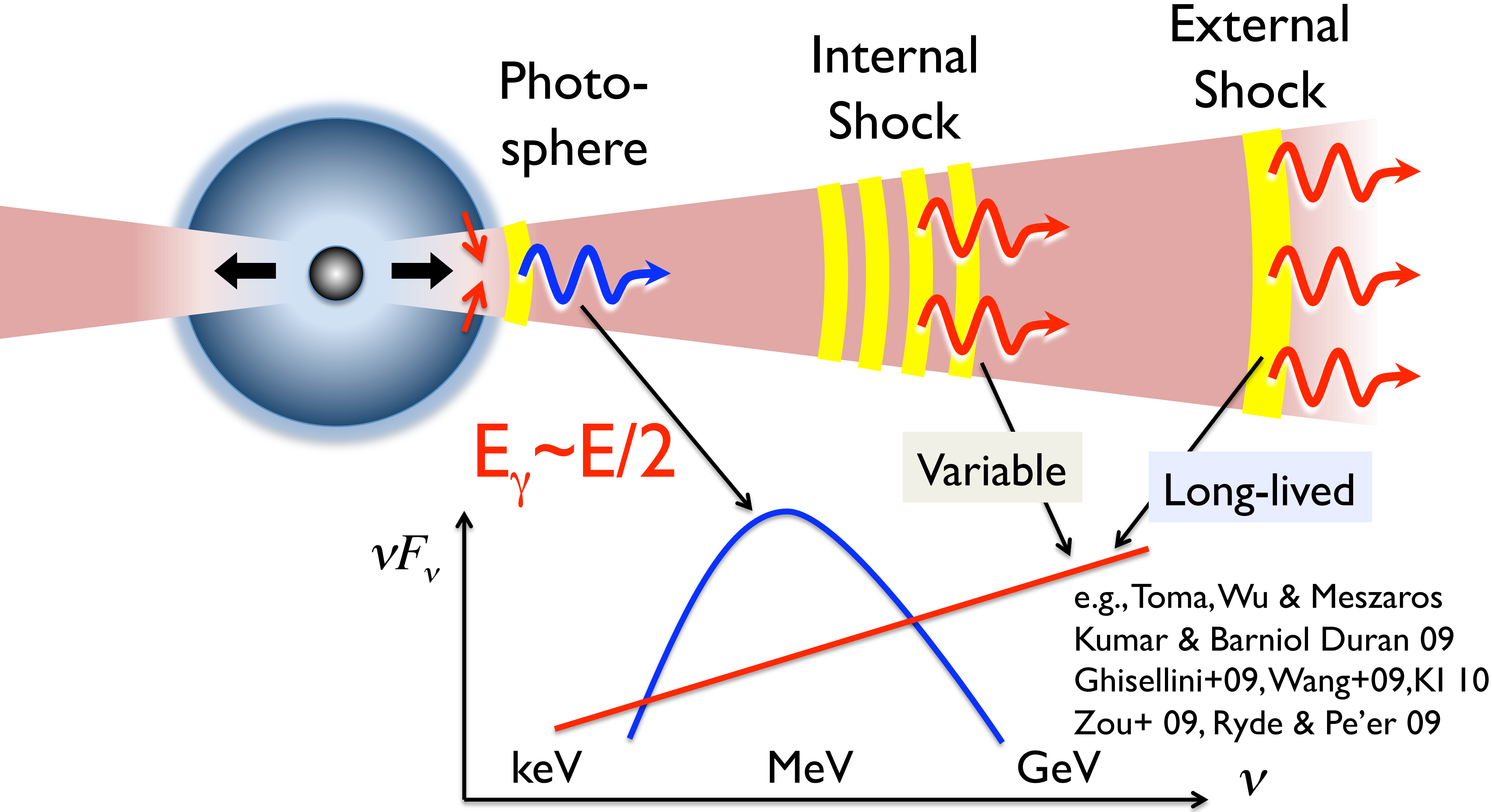
Γ_{max}~10^6!

$>\Gamma_{conv}$~10^3

Collsionless Bulk-Acceleration

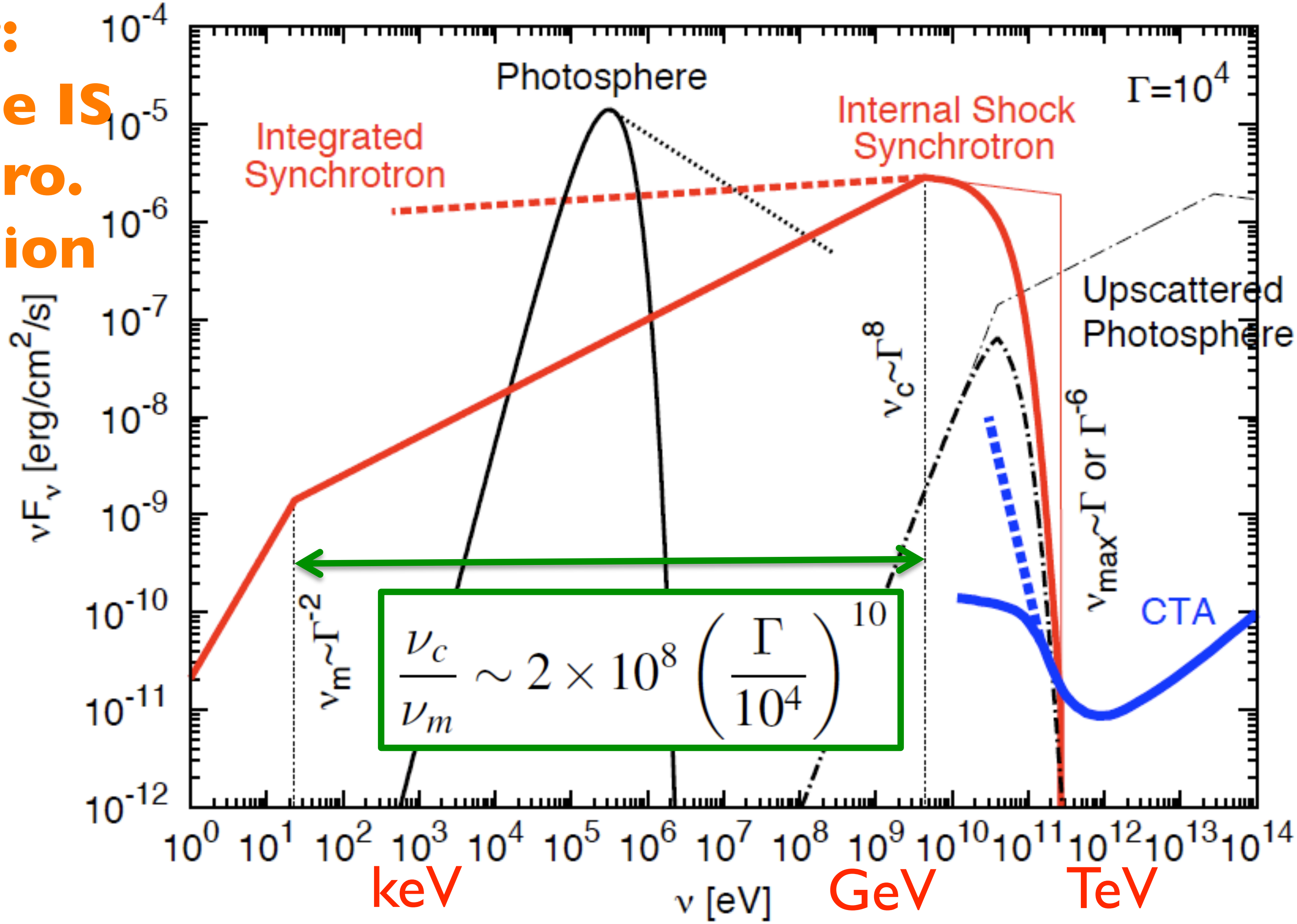
Baryon-Rich | Dimensionless Entropy $\eta = L/\dot{M}c^2$ | Baryon-Less

Photosphere-Internal-External Shock Model



High Γ Internal Shock

GeV γ: Simple IS synchro. emission

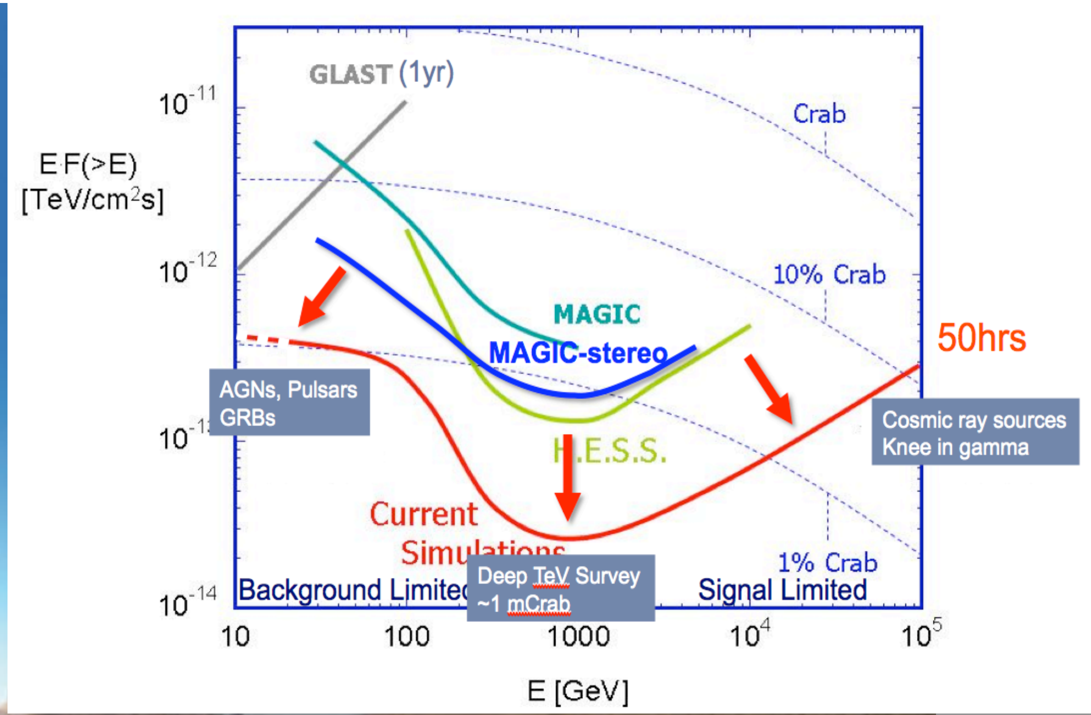


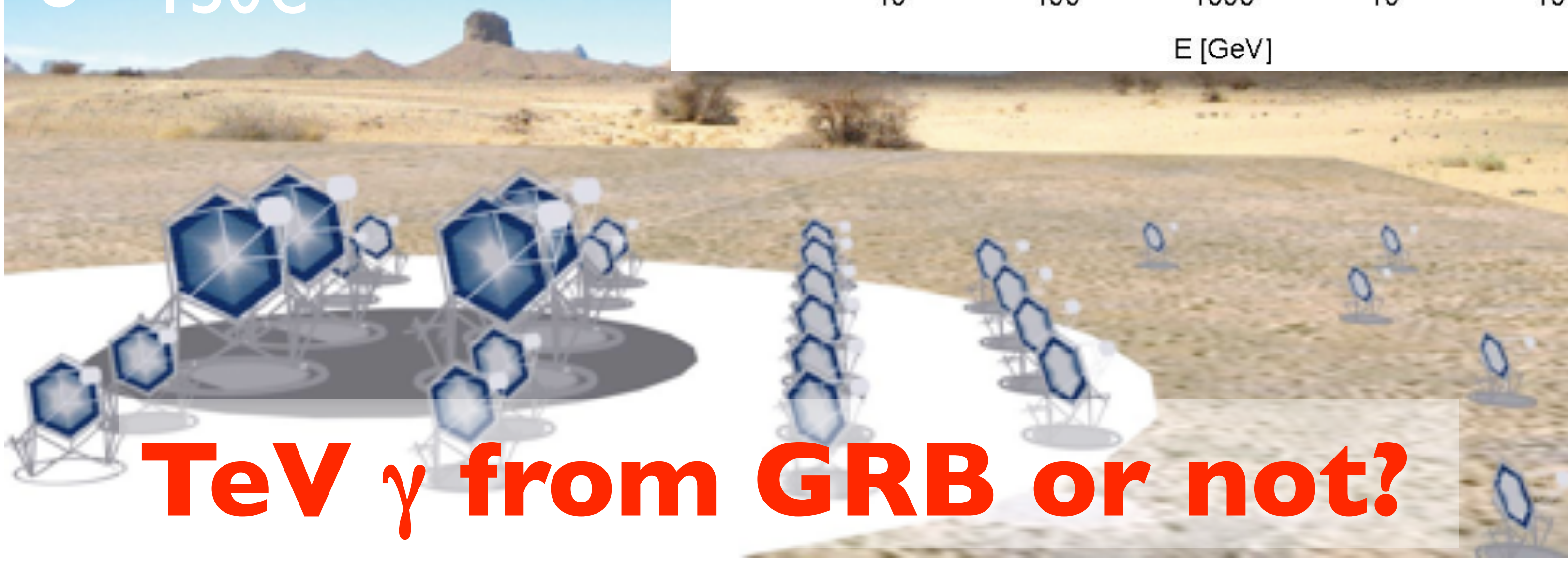
KI 10

CTA

Poster 13.05
Jun Kakuwa

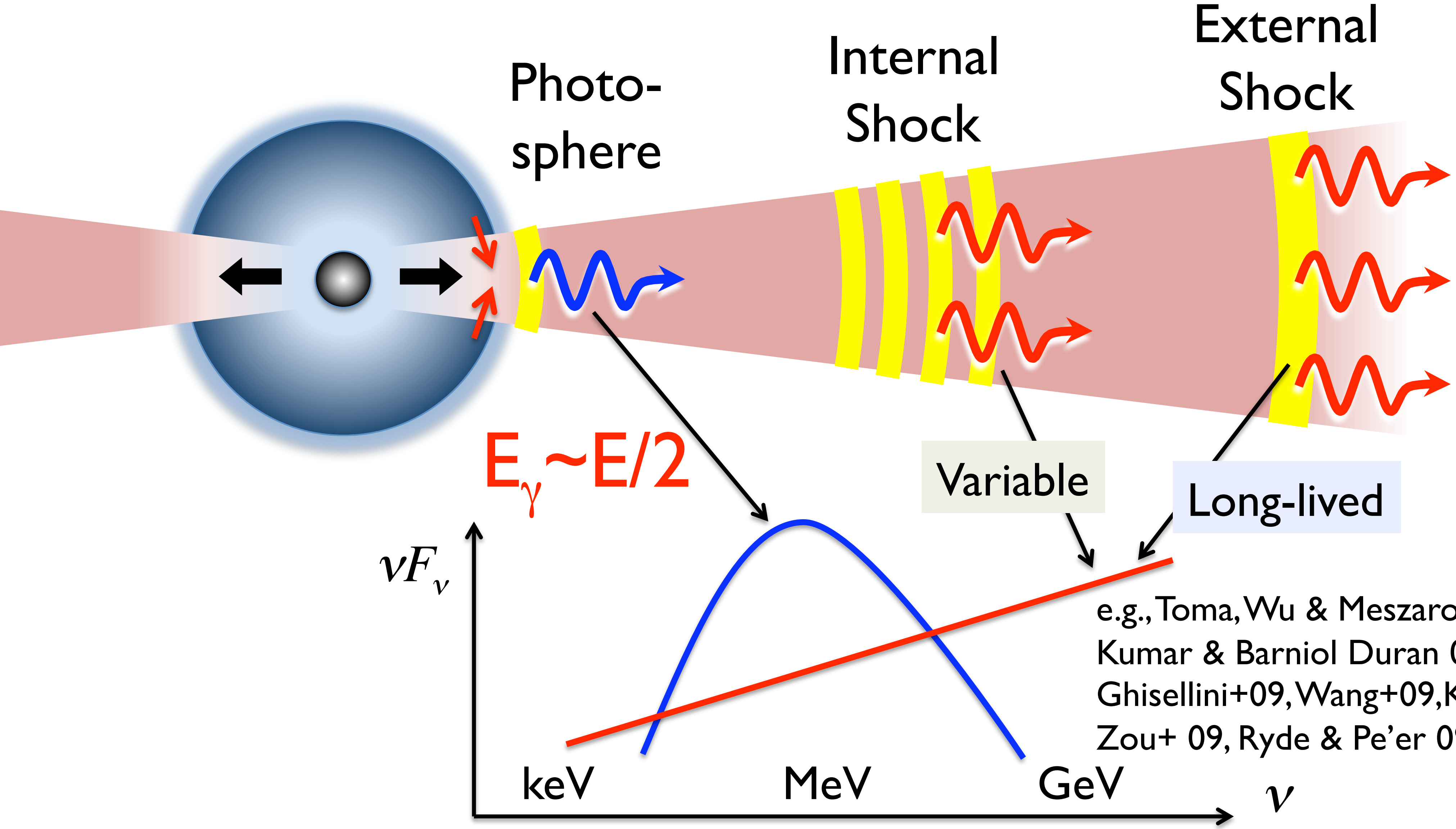
- ~20GeV-100TeV
- x10 Sensitivity
- Δθ~1-2 min
- FOV~5-10 deg
- ~20 s slew (LST)
- ~2015 (?)
- ~150€





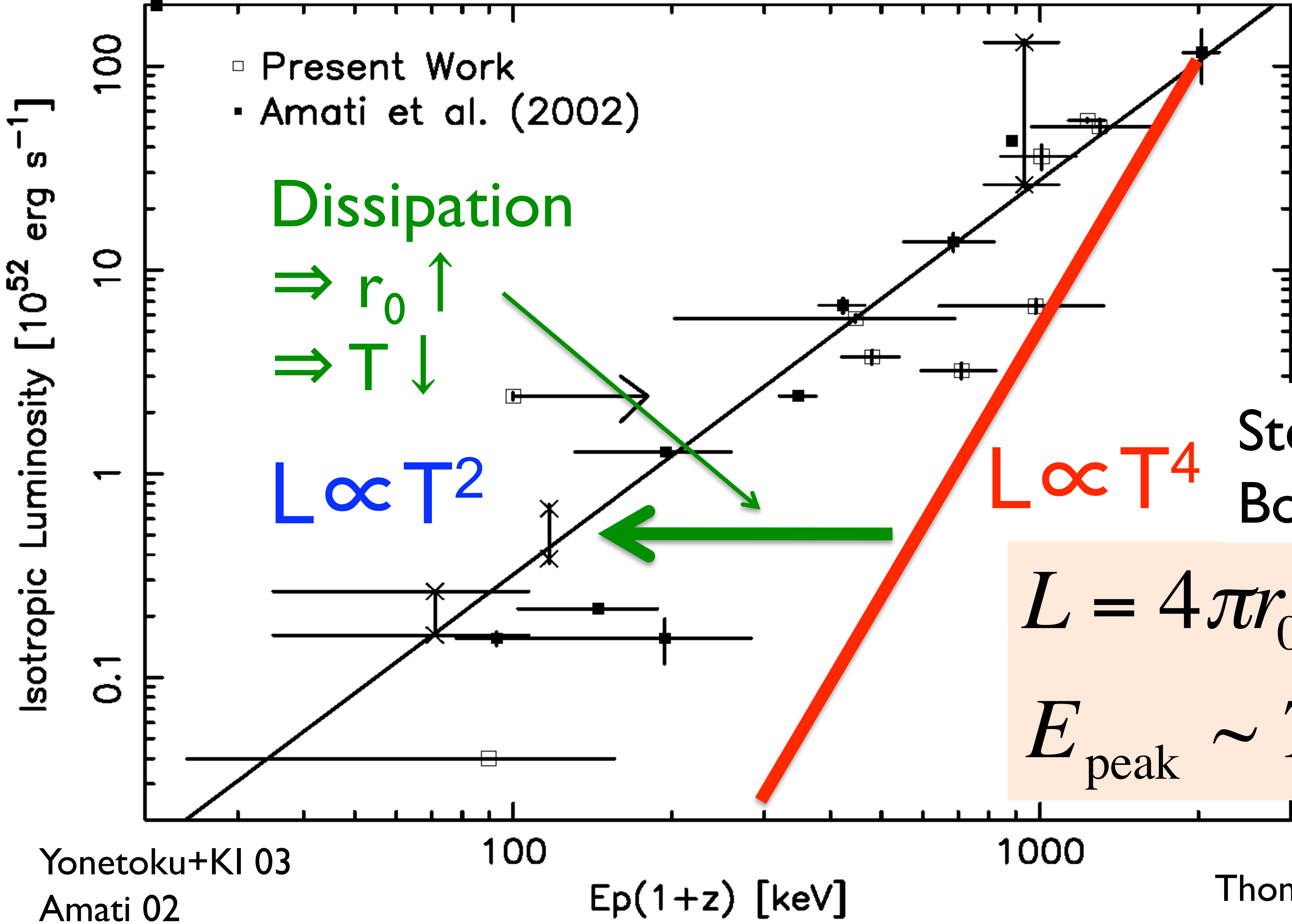
TeV γ from GRB or not?

Photosphere-Internal-External Shock Model



e.g., Toma, Wu & Meszaros
Kumar & Barniol Duran 09
Ghisellini+09, Wang+09, KI 10
Zou+ 09, Ryde & Pe'er 09

E_{peak}-Luminosity Relation



Stefan-Boltzmann

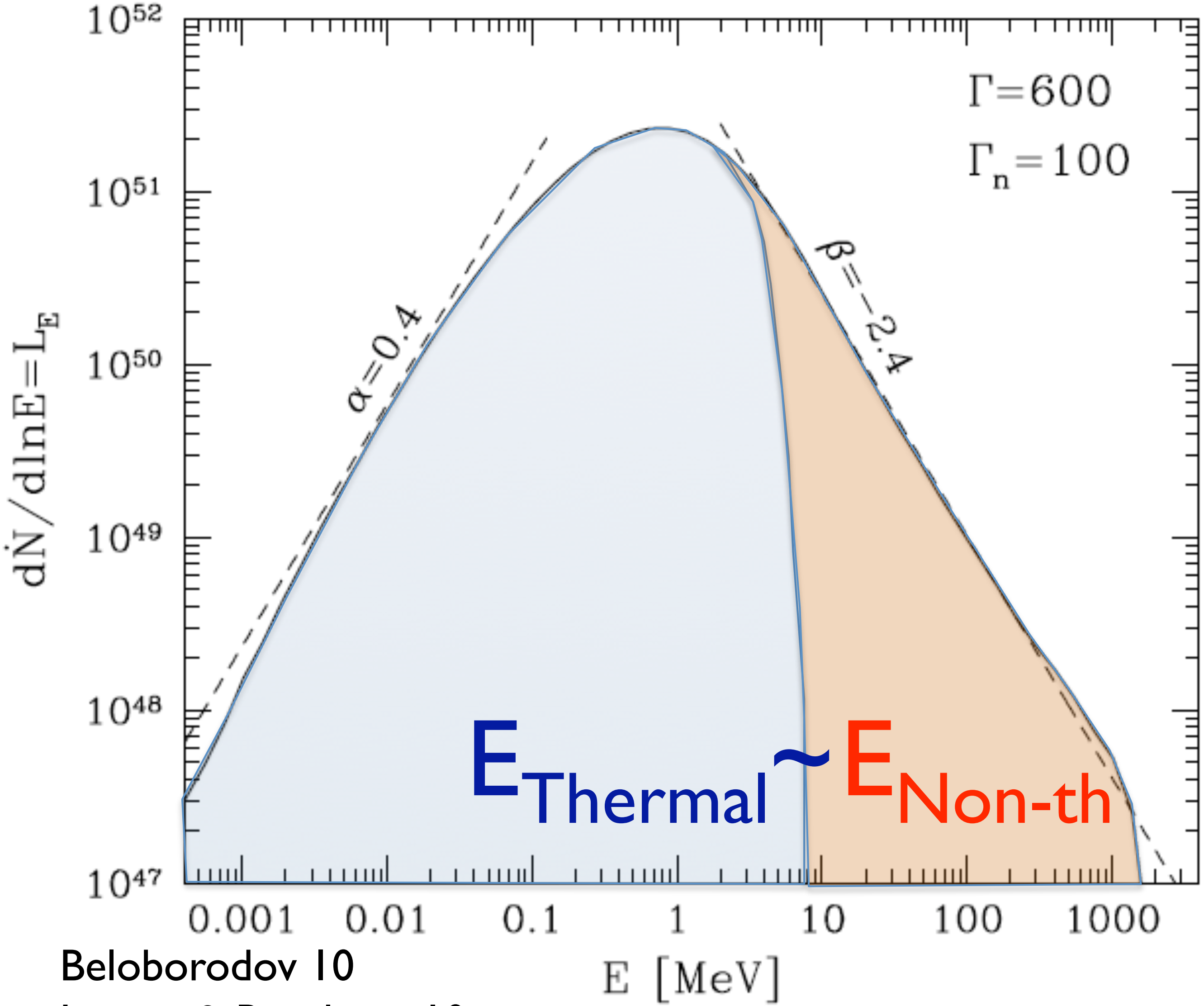
$$L = 4\pi r_0^2 c a T_0^4$$

$$E_{peak} \sim T_0$$

Yonetoku+KI 03
Amati 02

Thompson+ 07

Non-thermalization



Beloborodov 10
Lazzati & Begelman 10

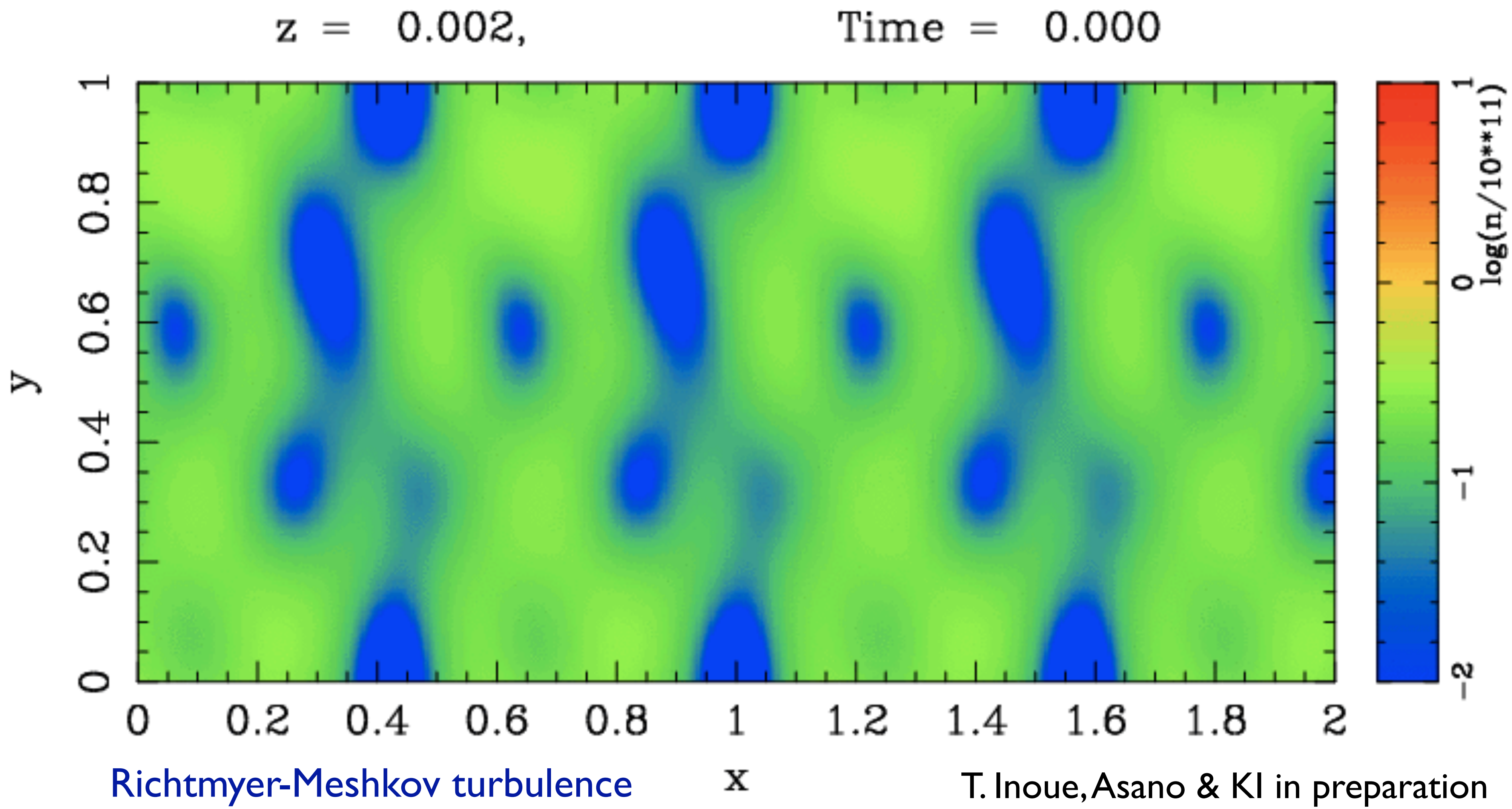
- Photospheric dissipation can reproduce Band
- $E_{Th} \sim E_{Non\text{-}th}$ without fine-tune in our rela. model
- Relativistic p, n may be important via pγ, nγ

KI 10

Summary

- $\Gamma > 10^3$ is possible
- Internal shock synchrotron
  $\Rightarrow$ keV-GeV-TeV γ
- Hot photosphere: $E_{Th} \sim E_{Non\text{-}th}$
- Photo.-Int.-Ext. shock model
  - $t_{delay} \sim [r_{th}/c \sim L^{-1/5}] \sim R_*/c \sim 0.3$sec
  - Neutrino – GeV γ Anti-Correlation
  - Max synchrotron energy $\Rightarrow$ CTA

3-D Rela. MHD Simulation

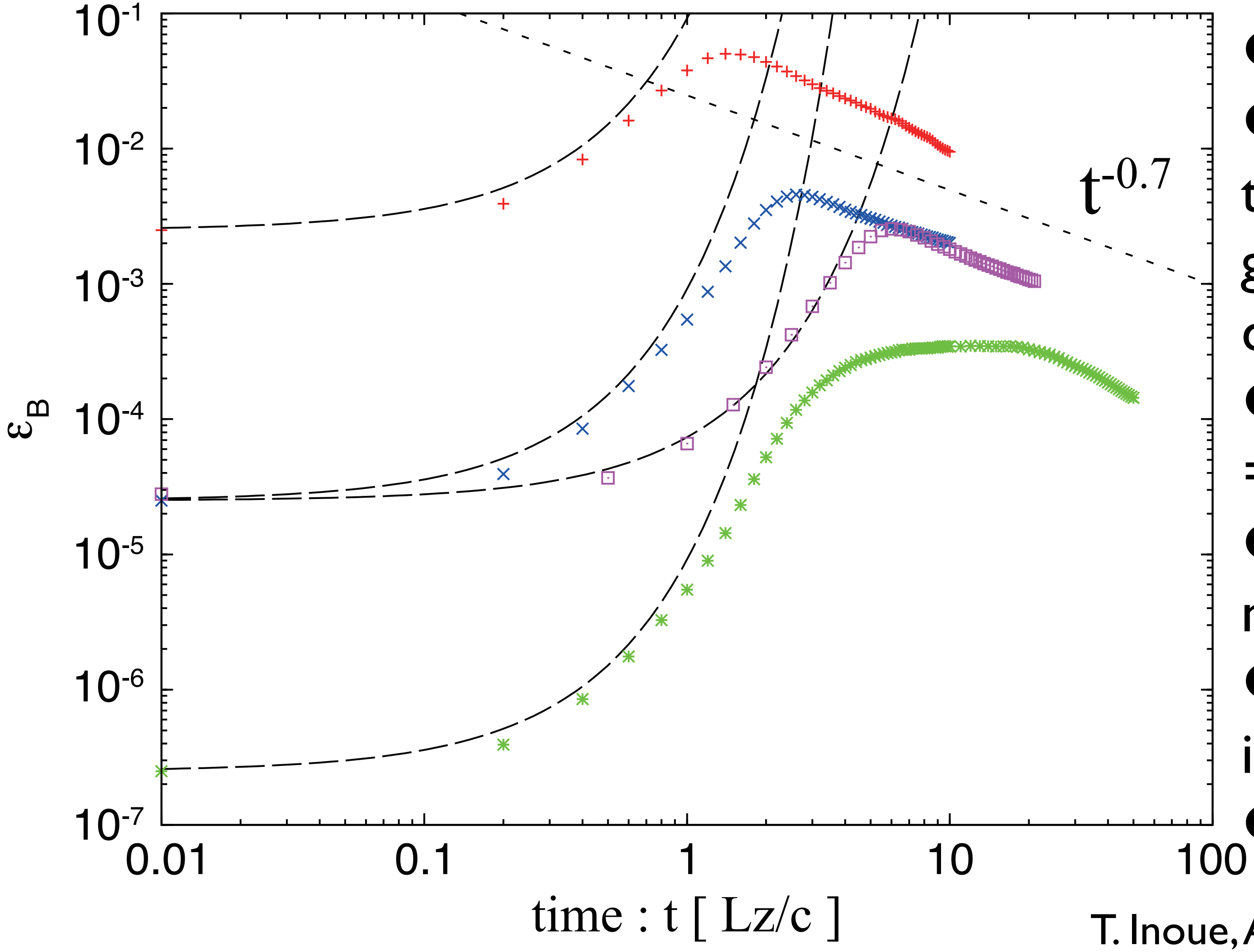


Richtmyer-Meshkov turbulence

T. Inoue, Asano & KI in preparation

Contact me for preprints (~10 copies)!

Magnetic Field Amplification



- ε_B~0.1 is possible
- In Eddy turnover time, exponential grow + power-law decay
- Depends on $\varepsilon_{B,ini}$ ⇒ Bring diversity
- Amplification does not depend on Δn
- Rela. Turbulence is not possible
- Π_L < 2%

T. Inoue, Asano & KI in preparation

GeV Onset Delay

η	L_{ph} [$\sim$Band]	L_k [$\sim$PL]	Spectrum	L_ν
$1 < \eta < \eta_* \sim 10^3$	$\ll L$	$\sim L$	PL	$\sim L$
$\eta_* < \eta < \eta_{k1} \sim 10^4$	$\sim L$	$\ll L$	Band	$\sim L$
$\eta_{k1} < \eta < \eta_{k2} \sim 10^6$	$\sim L$	$\sim L_p \sim L$	Band+PL	$\ll L$
$\eta_{k2} < \eta < \eta_{k3} \sim 10^7$	$\sim L$	$\sim L_\pm \sim L$	Band+PL	$\ll L$

Proton Thermalization Thick ⇒ Thin

[Baryon-rich ⇒ Barion-less]

$$t_{\text{delay}} \sim \frac{r_m(\eta_{k1})}{c} \sim \frac{r_{pp}(\eta_{k1})}{c} \sim 0.5\ s\ L_{53}^{-1/5},$$

$$t_{\text{delay}} \sim \frac{R_{\text{star}}}{c} \sim 0.3\ s\ \left(\frac{R_{\text{star}}}{10^{10}\ \text{cm}}\right)$$

Max Synchrotron Energy

Very High Lorentz Factor (VHLF) case

$$t'_{acc} = t'_{cool}$$

A target for CTA

$$\nu_{\max}^{cool} = \frac{m_e c^2}{\alpha} \Gamma \sim 500\ \mathrm{GeV} \left(\frac{\Gamma}{10^4} \right)$$

Wang+ 09
Piran & Nakar 10
Barniol Duran & Kumar 10

$$t'_{acc} = t'_{dyn}$$

$$\nu_{\max}^{dyn} \sim 1\ \mathrm{GeV} \left(\frac{\Gamma}{6 \times 10^4} \right)^{-6}$$

GRB 090926 Break??

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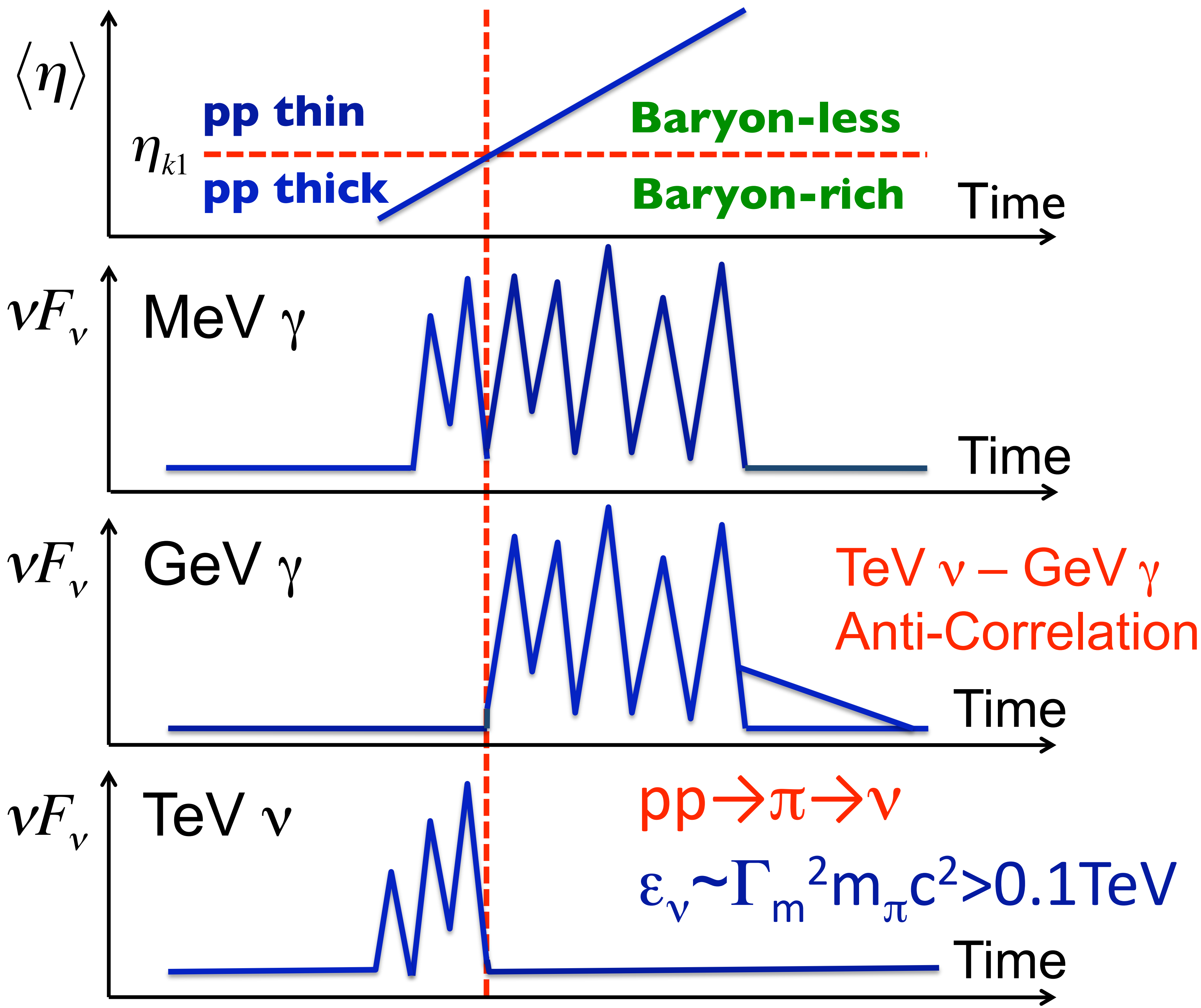

⟨η⟩
pp thin
η_k1
pp thick
Baryon-less
Baryon-rich
Time
νF_ν
MeV γ
Time
νF_ν
GeV γ
TeV ν – GeV γ
Anti-Correlation
Time
νF_ν
TeV ν
pp→π→ν
ε_ν~Γ_m^2m_πc^2>0.1TeV
Time

Necessary Mass Loading

- $E_p \sim (\Gamma_m / r_m)^{1/2} L^{1/4} \sim L^{1/2}$ (S-B law + Yonetoku)
- $\Gamma_m \sim \left(\frac{L}{\dot{M} c^2} \right)^{1/2}$ (Two mass collision)

$$\Rightarrow \dot{M} \sim 10^{-5} \ M_{\odot} \ \mathrm{s}^{-1} \ r_{m,10}^{-2}$$

(Isotropic Rate)

Only depends on the environments
Therefore, if progenitors are similar,
the E_{peak}-L relations are reproduced