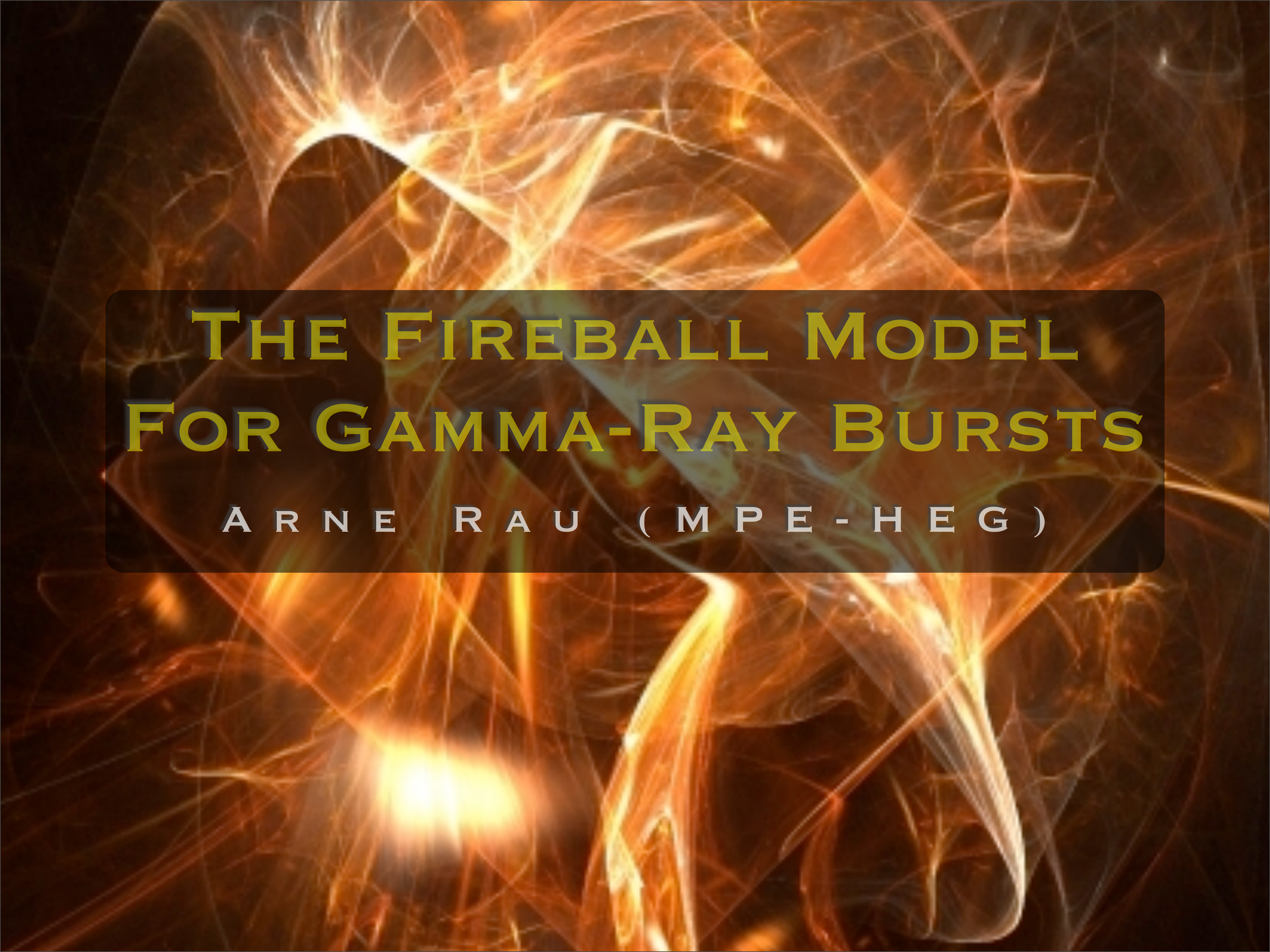


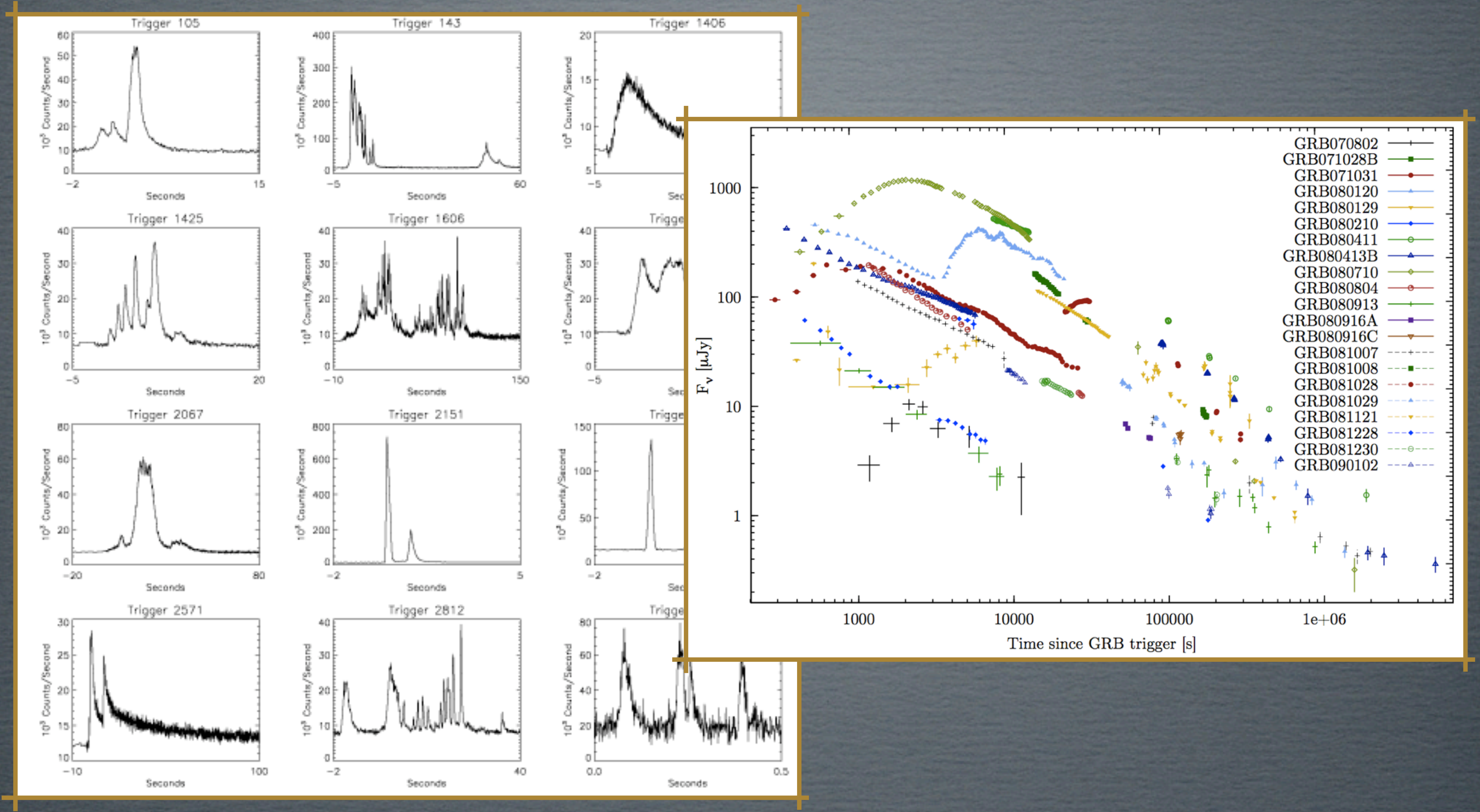
The Fireball Model For Gamma-Ray Bursts

Arne Rau (MPE-HEG)

OVERVIEW

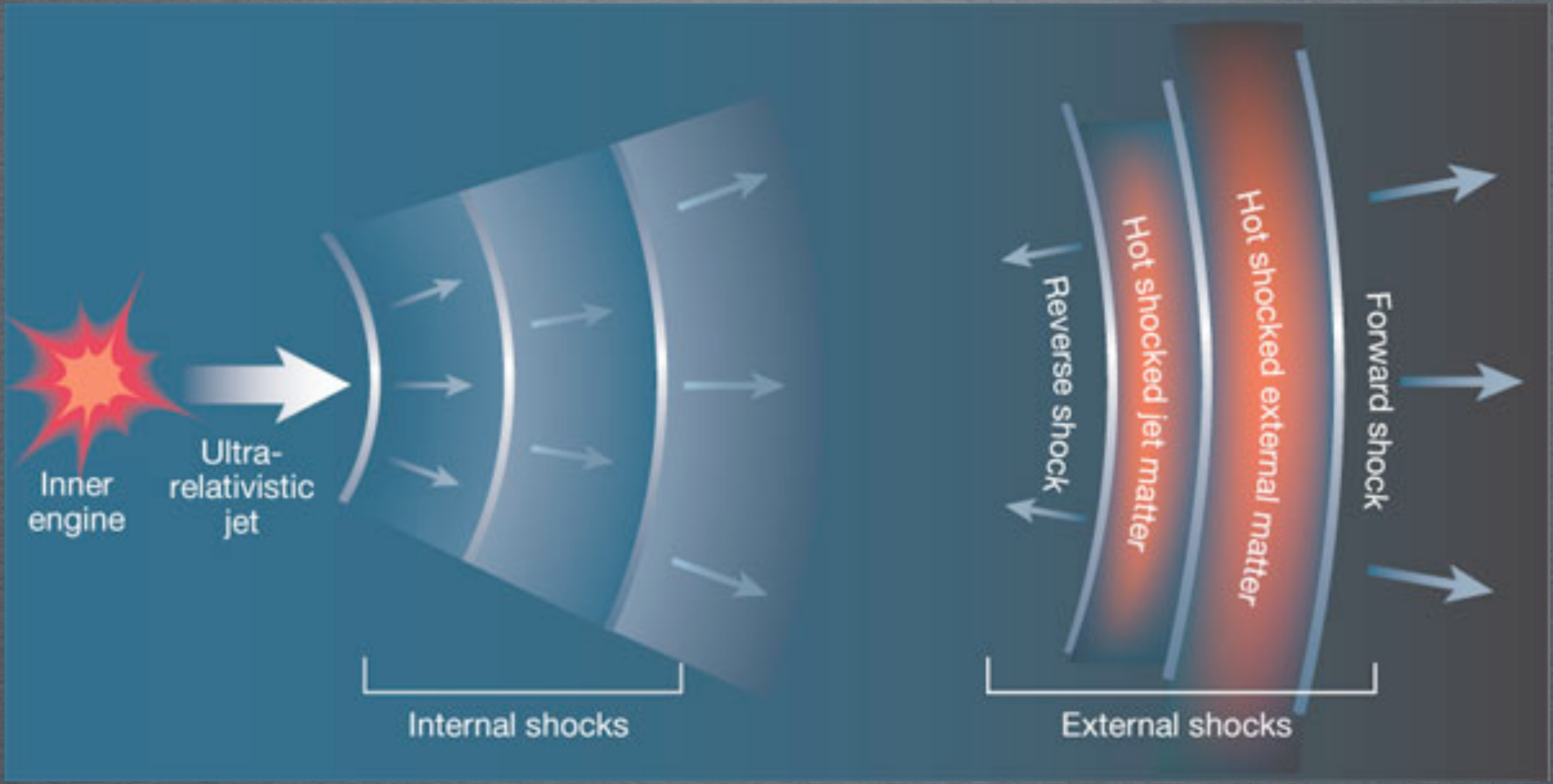
- Why should you care about the fireball model?
- Lorentz factor vs radius
- Afterglow spectrum
- Afterglow light curve
- Closure relations
- Consequences of jet geometry

MOTIVATION



- “If you have seen one burst, you have seen one burst!” – burst properties vary dramatically

STANDARD-MODEL SKETCH



(Piran 2006)

- Fireballs are dynamic objects whose properties evolve quickly with time (similar to evolution of first minutes of the Universe)

FIREBALL EVOLUTION

THE CAST - 1

Γ: Lorentz factor of the narrow shell

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$\eta = E_0/(M_0 c^2)$: energy-to-mass ratio of initial fireball

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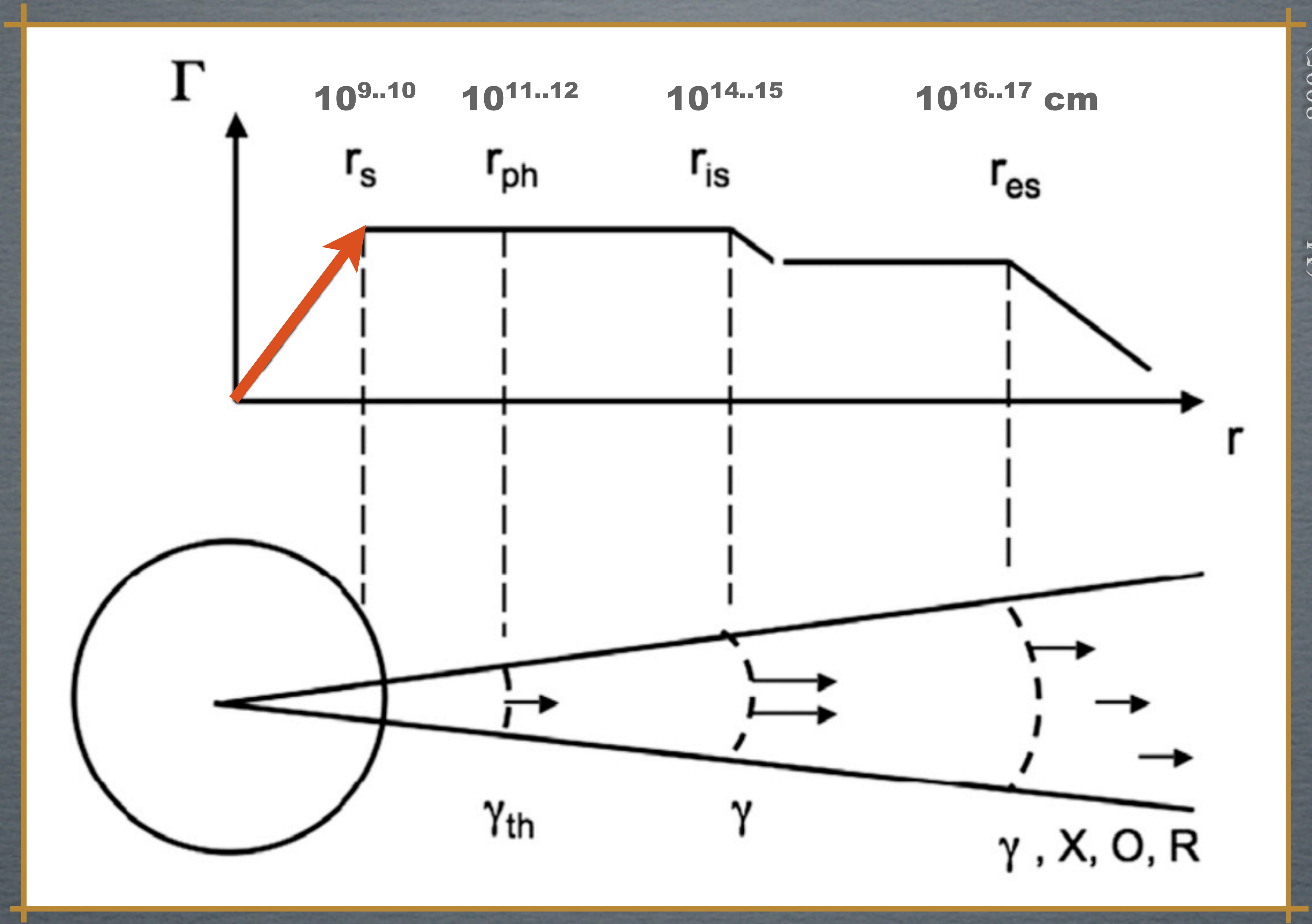
R_{in}, R_s, R_{ph}, R_{is}, R_{es}: various radii

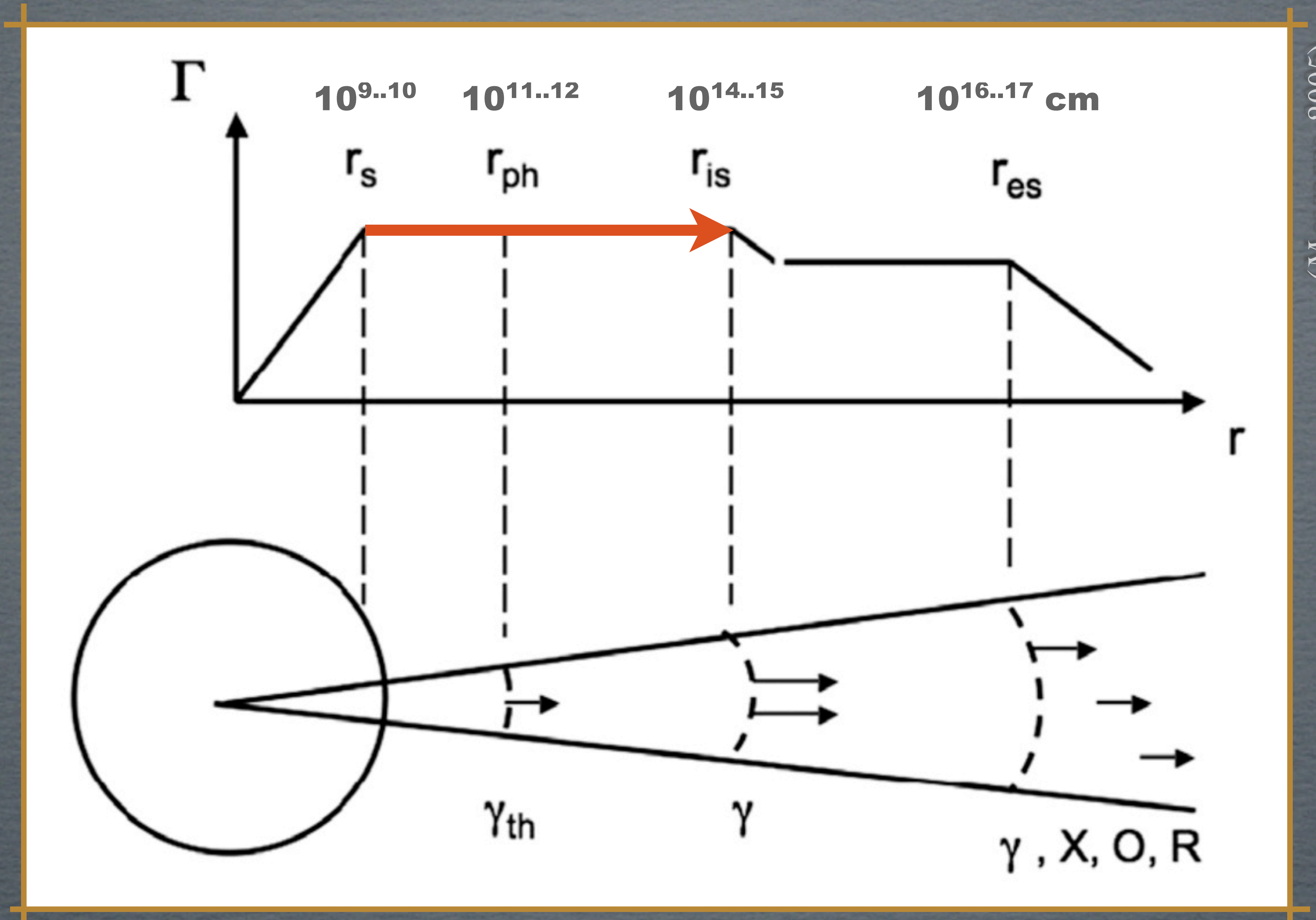
$R_{INITIAL}$ -> $R_{SATURATION}$



(Meszaros 2005)

- $\Gamma_0 \sim 1$
- $E_{internal}$ converted into $E_{kinetic}$
- $\Gamma \propto R$
- $R_s = \eta R_{in} = (E_0/(M_0c^2))R_{in}$

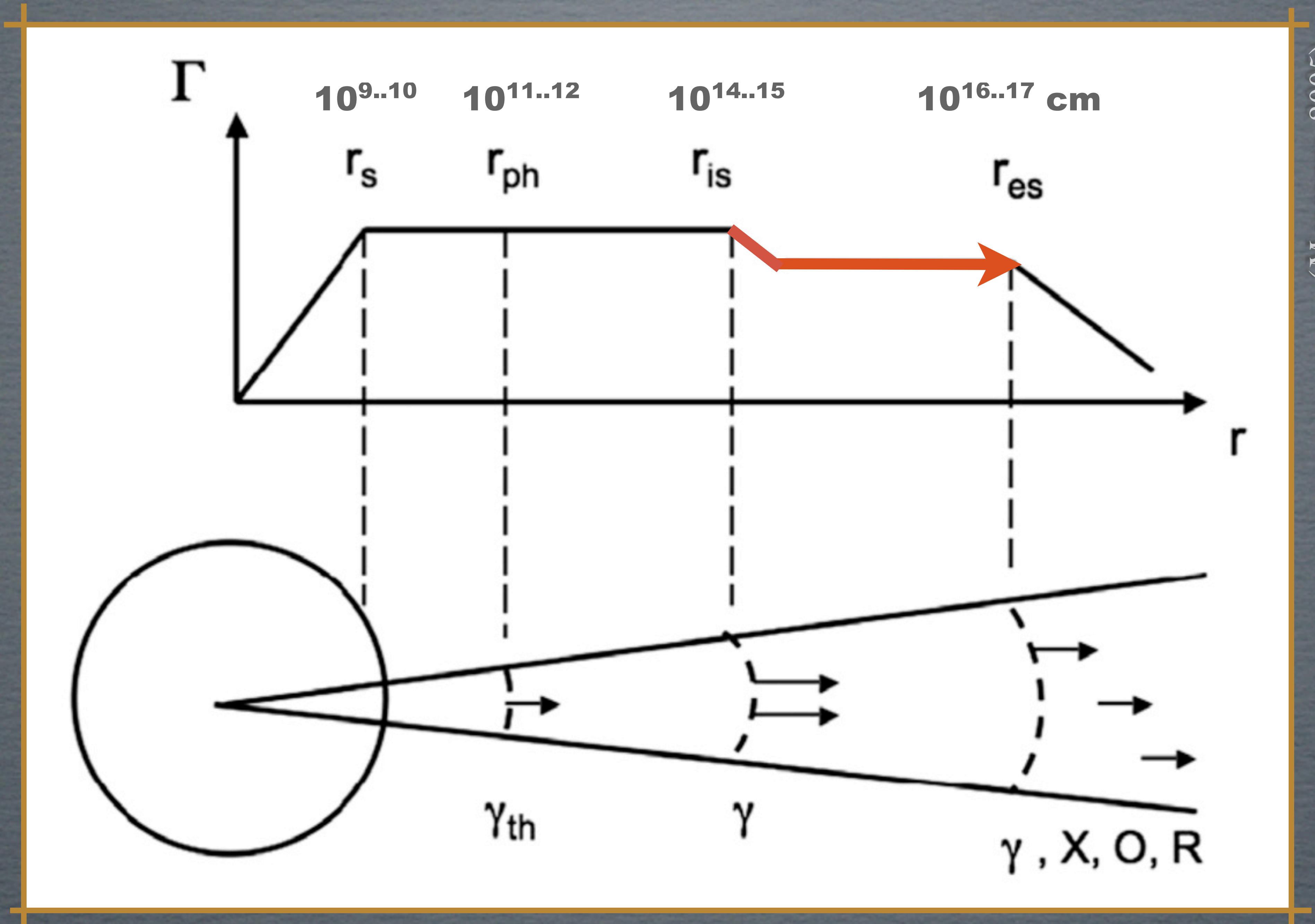
$R_{SATURATION}$ -> $R_{PHOTOSPH}$ -> $R_{INTERNAL\ SHOCK}$



(Meszaros 2005)

- Γ = cst
- $E_{internal} << E_{rest\ mass}$
- R_{ph}: $\tau_{pair\ creation} = 1$
- $R_{is} = \eta^2 R_{in}$

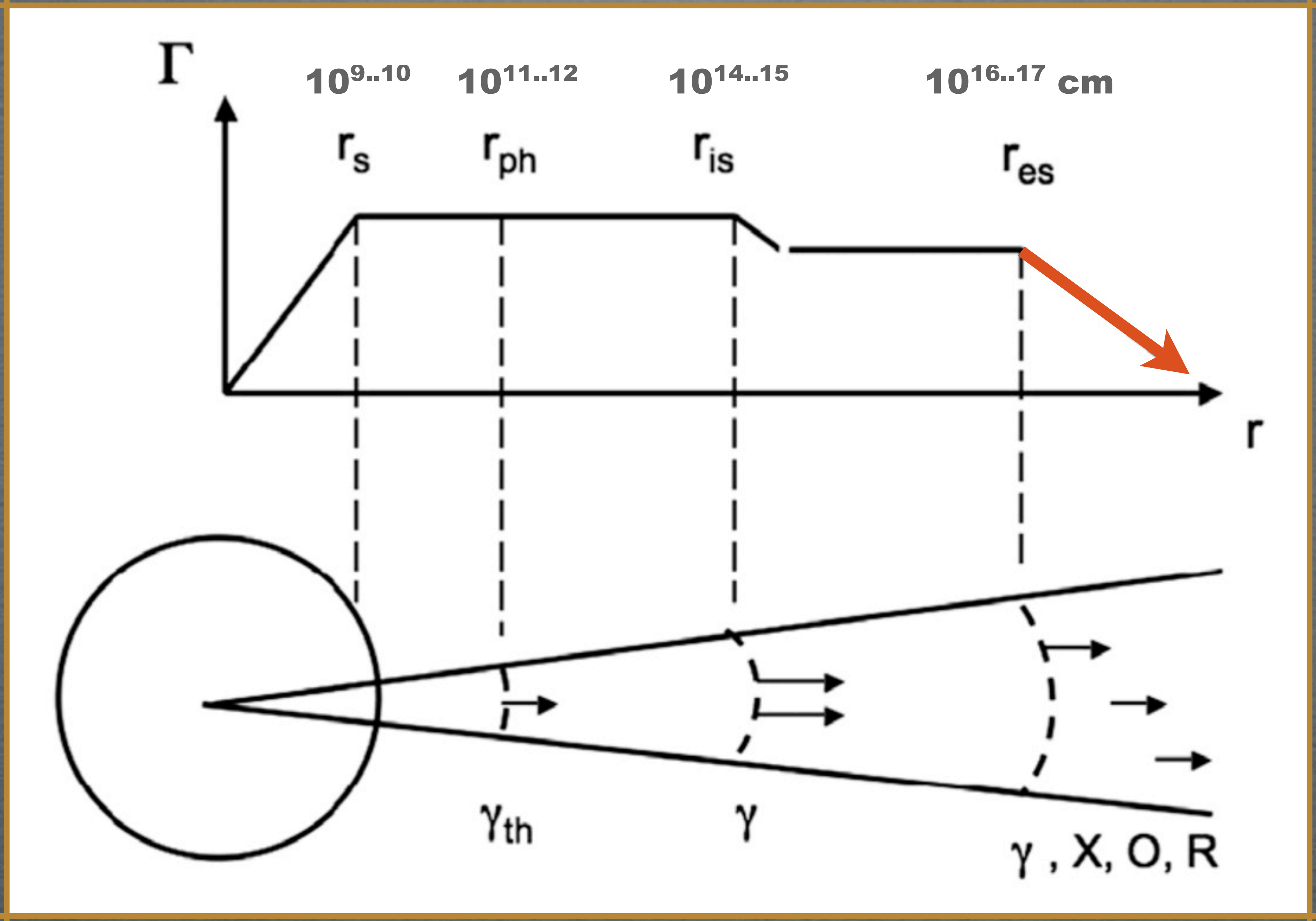
RINTERNAL SHOCK-> REXTERNAL SHOCK



(Meszaros 2005)

- R_{is} -> R_{es} : Γ = cst
- shock propagates into ISM with $\Gamma_{shock} = 2^{1/2}\Gamma$
- R_{es} = most of $E_{kinetic}$ transferred to ISM

$R_{\text{external shock}}$-> INFINITY



(Meszaros 2005)

- adiabatic: $E \propto \Gamma^2 m = cst \rightarrow \Gamma \propto m^{-1/2} \rightarrow \Gamma \propto R^{-3/2}$ ($\rho_{ext}=cst$)
- radiative: $\Gamma \propto R^{-3}$

AFTERGLOW SPECTRUM

THE CAST - 2

$N(\gamma)\, d\gamma \propto \gamma^{-p}\, d\gamma$: electron distribution with $p>2$

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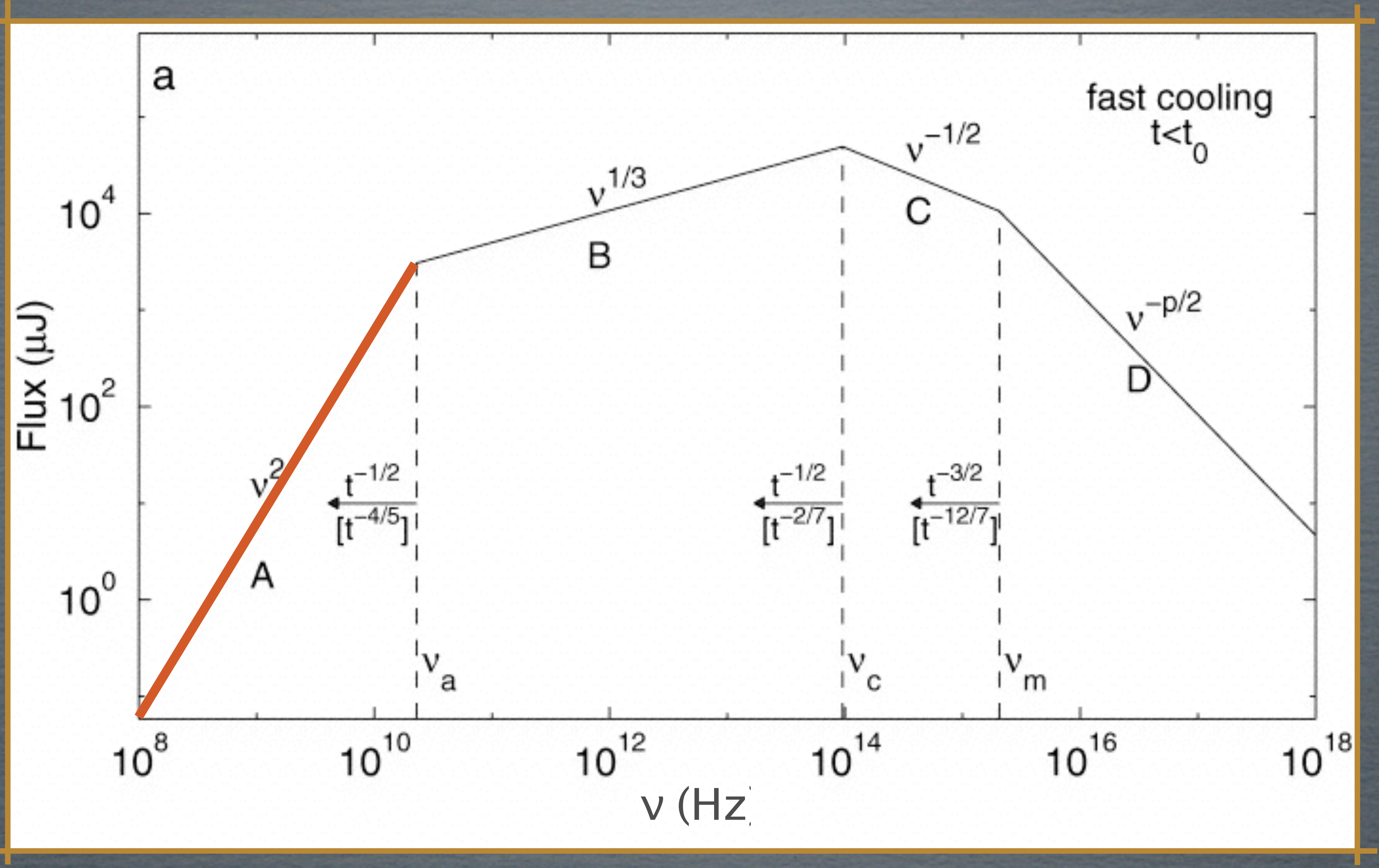
ν_m, ν_a, ν_c: various characteristic frequencies

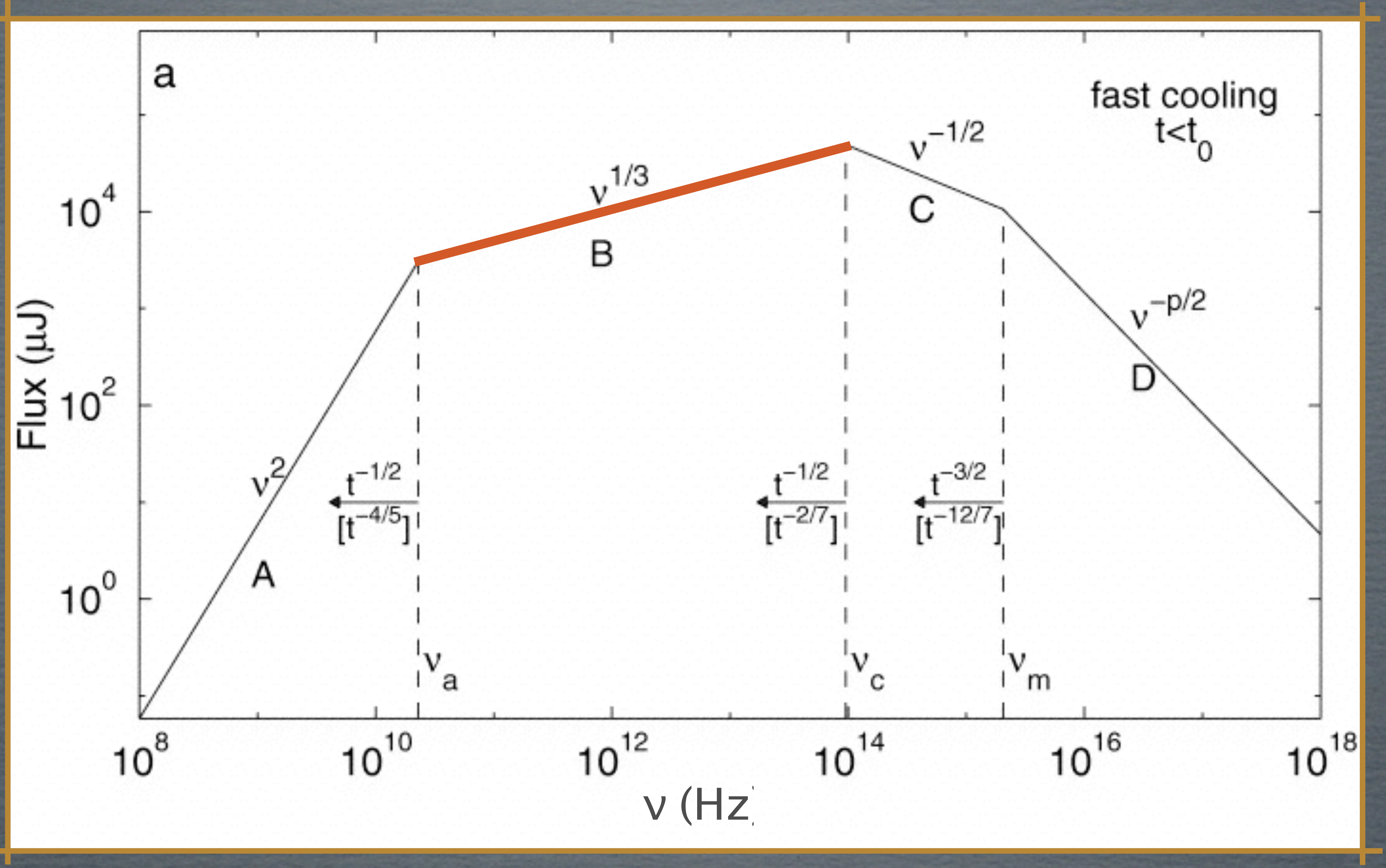
SYNCHROTRON SPECTRUM: A



(Sari et al. 1998)

- optically thick to synchrotron self-absorption
- $F_\nu \propto kT_{eff}\nu^2$, $kT_{eff} \propto \gamma_e m_e c^2 = cst$
  $\rightarrow F_\nu \propto \nu^2$

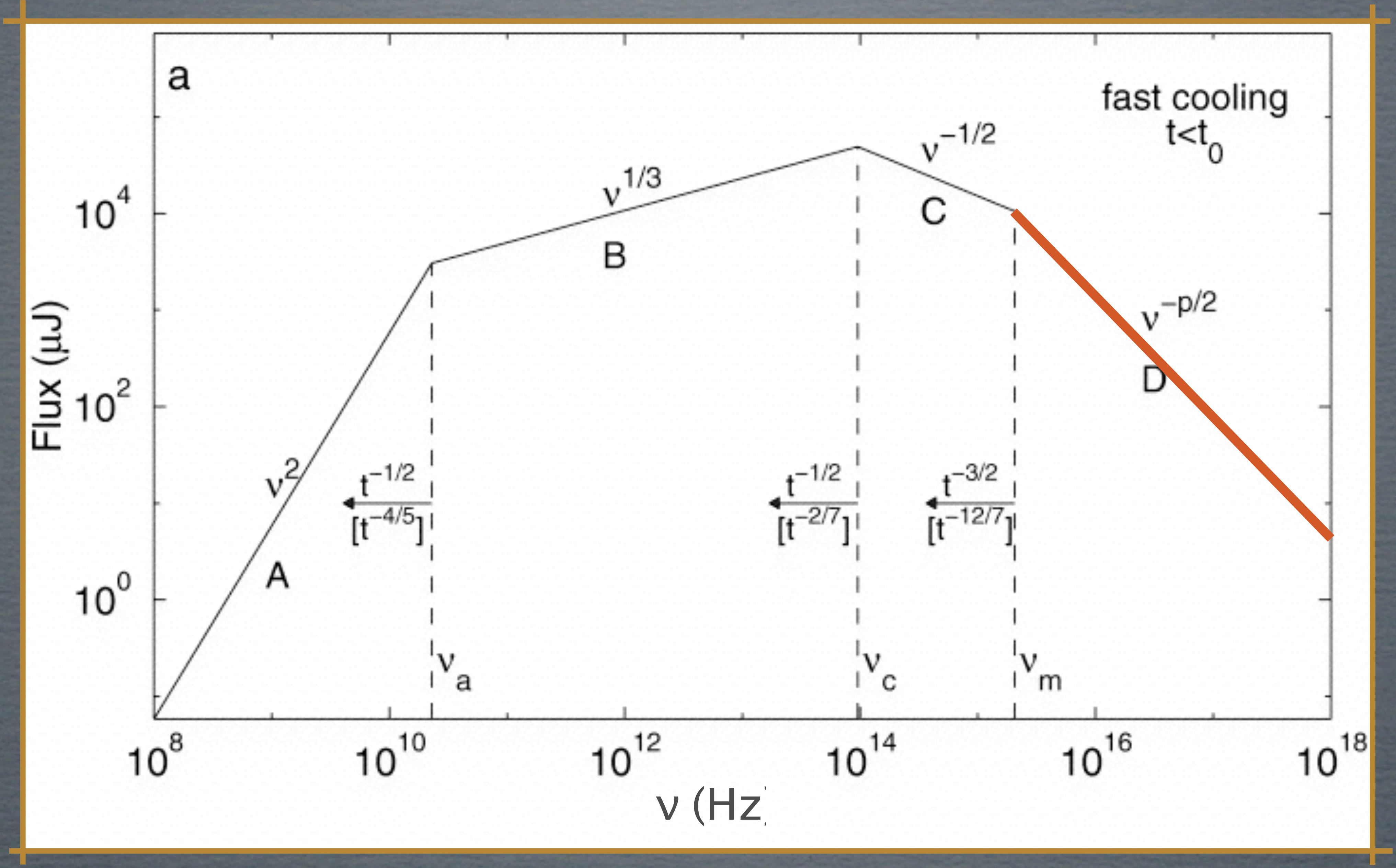
SYNCHROTRON SPECTRUM: B



(Sari et al. 1998)

- contributions of tails of the emission of all electrons
- $F_\nu \propto \nu^{1/3}$

SYNCHROTRON SPECTRUM: D

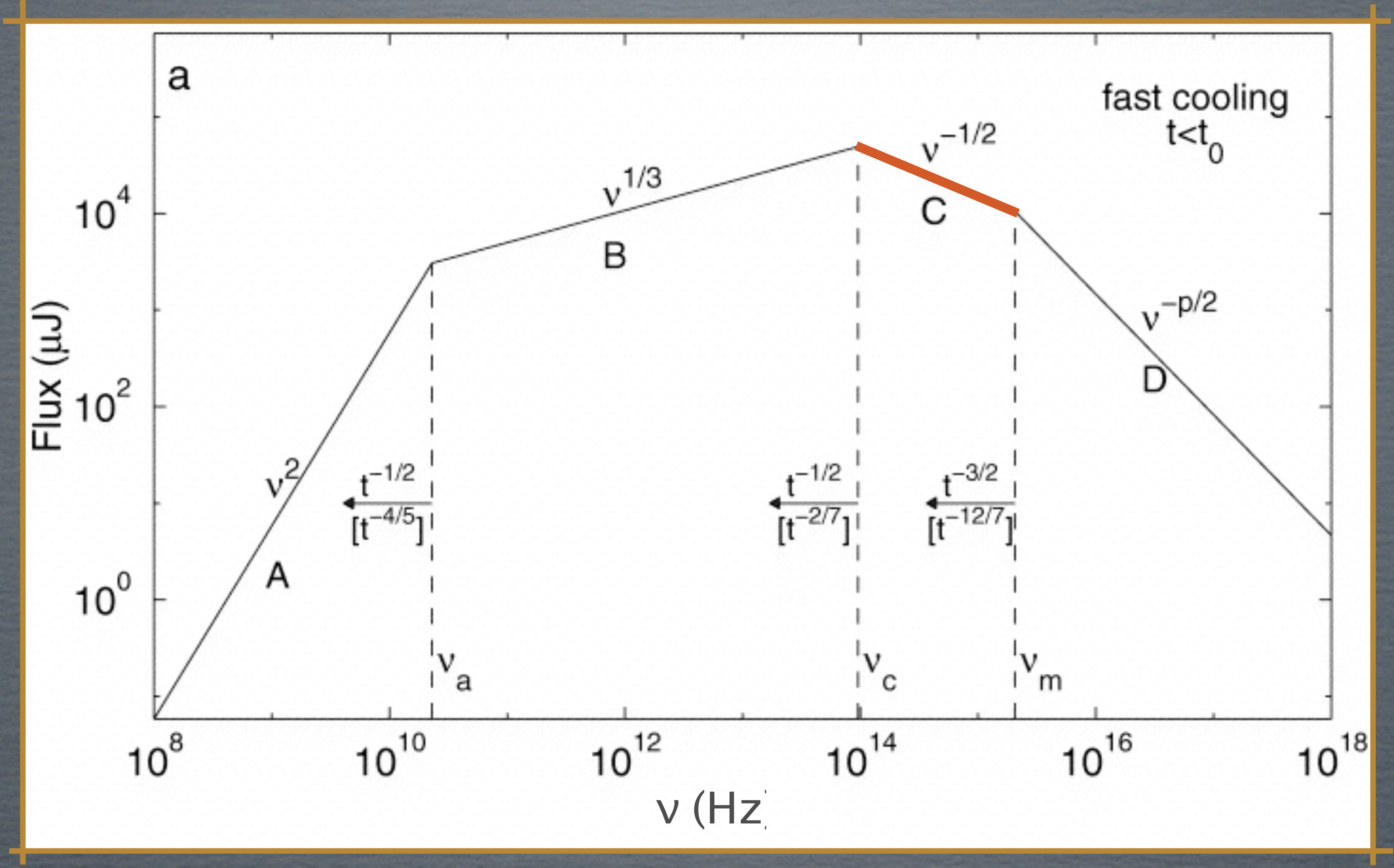


(Sari et al. 1998)

- rapid cooling of most energetic electrons at ν_{sync}
- $N(\gamma)d\gamma \propto \gamma^{-p}\, d\gamma \rightarrow N_\gamma \propto \gamma^{1-p}, E \propto \gamma^{2-p}$
- energy is deposited at $\nu_{sync}(\gamma) \propto \gamma^2$
- $F_\nu \propto (E/\nu) \propto (\gamma^{2-p} / \gamma^2) \rightarrow F_\nu \propto \nu^{-p/2}$

]

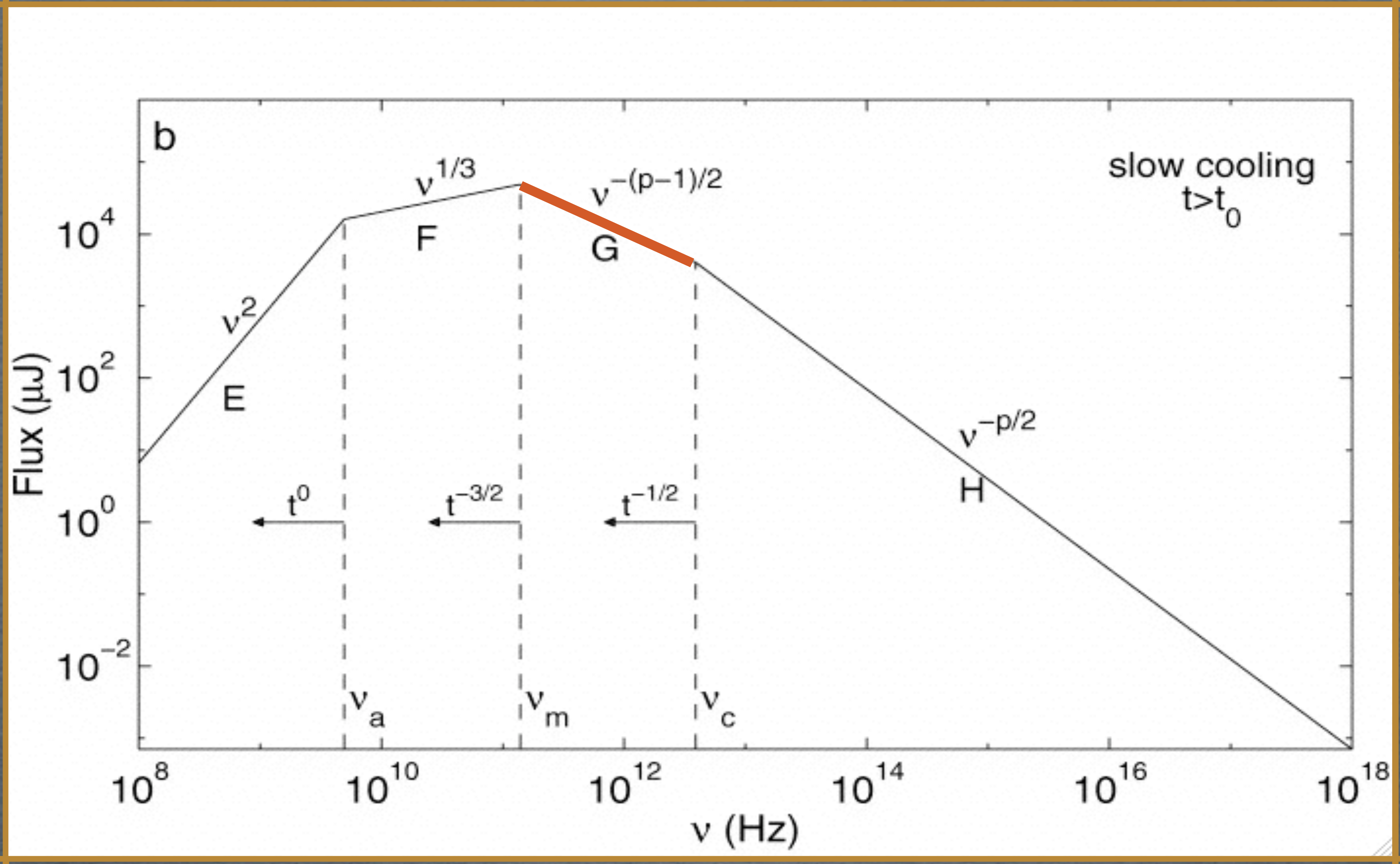
SYNCHROTRON SPECTRUM: C



(Sari et al. 1998)

- $\nu_m = \nu_{sync}(\gamma_{min})$, $\nu_c = \nu_{sync}(\gamma_c)$
- fast cooling: $\nu_m > \nu_c$ & $F_\nu \propto \nu^{-1/2}$
- slow cooling: $\nu_m < \nu_c$ & $F_\nu \propto \nu^{(1-p)/2}$

SYNCHROTRON SPECTRUM: C



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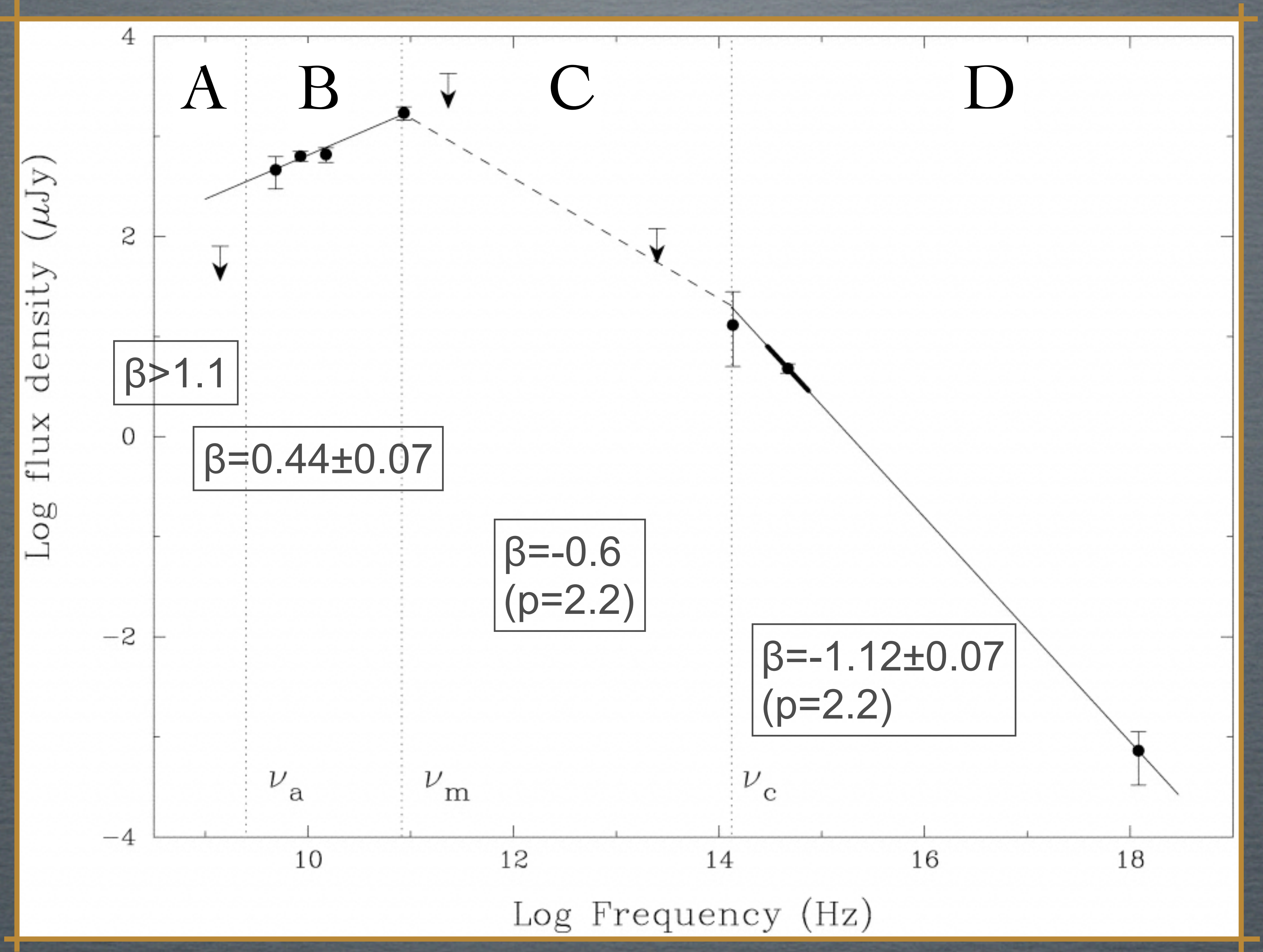
GRB 970508 - THE (BEST) EXAMPLE



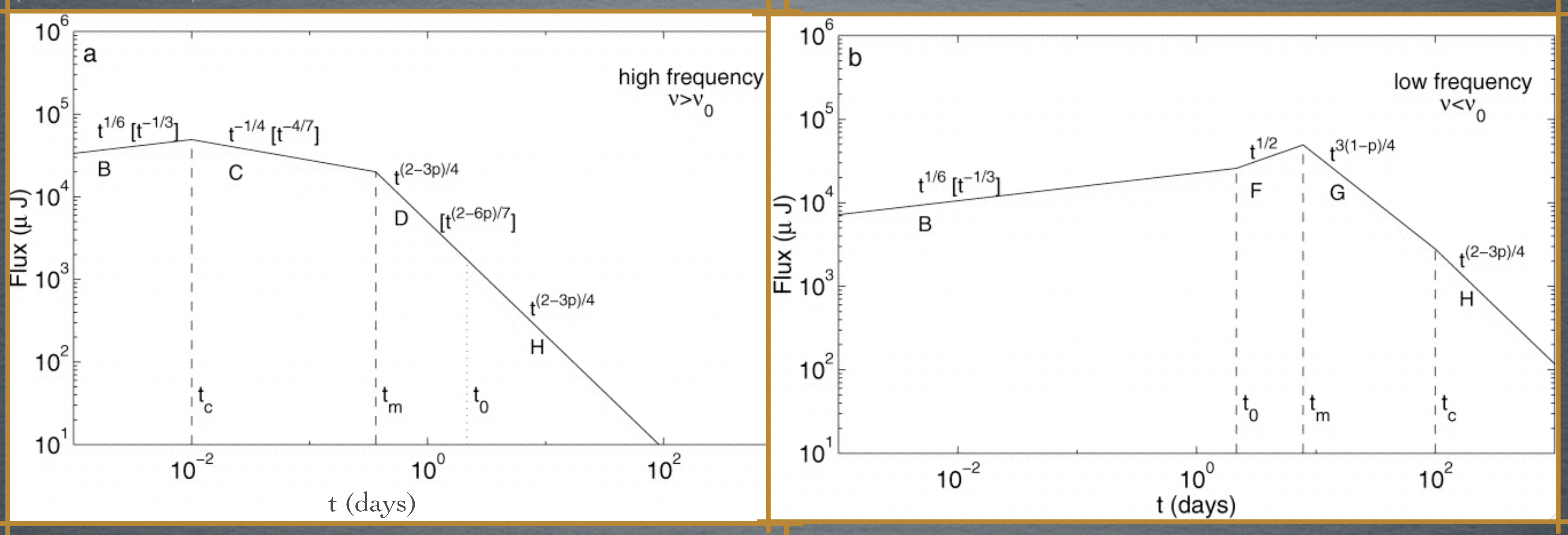
(Galama et al. 1998)

- T_0+12.1 days
- z=0.83

AFTERGLOW LIGHTCURVE & CLOSURE RELATIONS

AFTERGLOW LIGHT CURVES

(Sari et al. 1998)

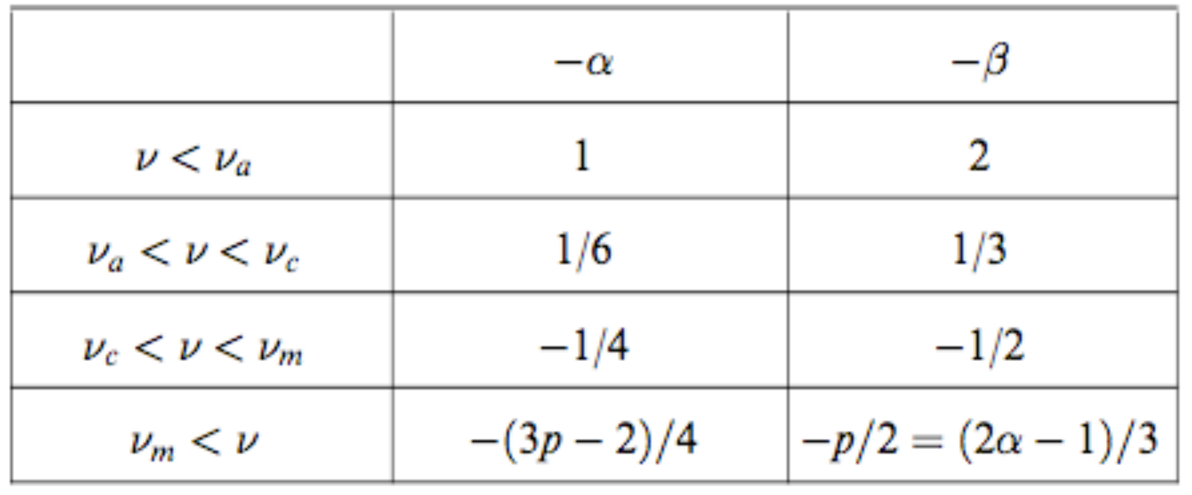


- if initially $\nu_m > \nu_c$ then: $\nu_o = \nu_c(t_0) = \nu_m(t_0)$ as ν_c decreases slower than ν_m
- transition from fast to slow cooling at t_0

CLOSURE RELATIONS

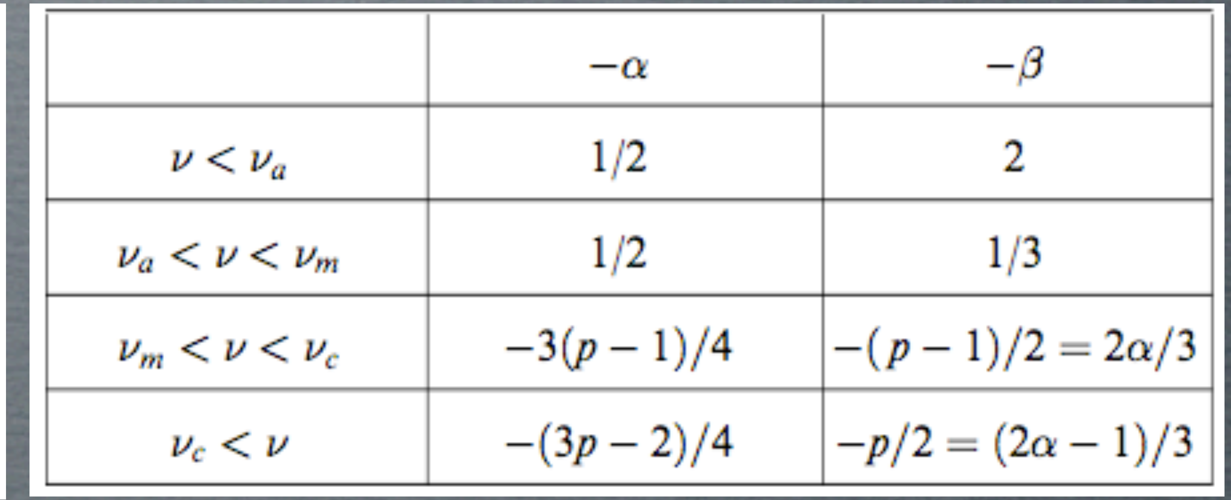
- combining spectral and temporal dependencies → $F_\nu \propto t^{-\alpha} \nu^{-\beta}$
- separated by ν_a, ν_c, ν_m

FAST COOLING ($\nu_A < \nu_C < \nu_M$)



	$-\alpha$	$-\beta$
$\nu < \nu_a$	1	2
$\nu_a < \nu < \nu_c$	1/6	1/3
$\nu_c < \nu < \nu_m$	−1/4	−1/2
$\nu_m < \nu$	$-(3p-2)/4$	$-p/2 = (2\alpha - 1)/3$

SLOW COOLING ($\nu_A < \nu_M < \nu_C$)



	$-\alpha$	$-\beta$
$\nu < \nu_a$	1/2	2
$\nu_a < \nu < \nu_m$	1/2	1/3
$\nu_m < \nu < \nu_c$	$-3(p-1)/4$	$-(p-1)/2 = 2\alpha/3$
$\nu_c < \nu$	$-(3p-2)/4$	$-p/2 = (2\alpha - 1)/3$

(Piran 2005)

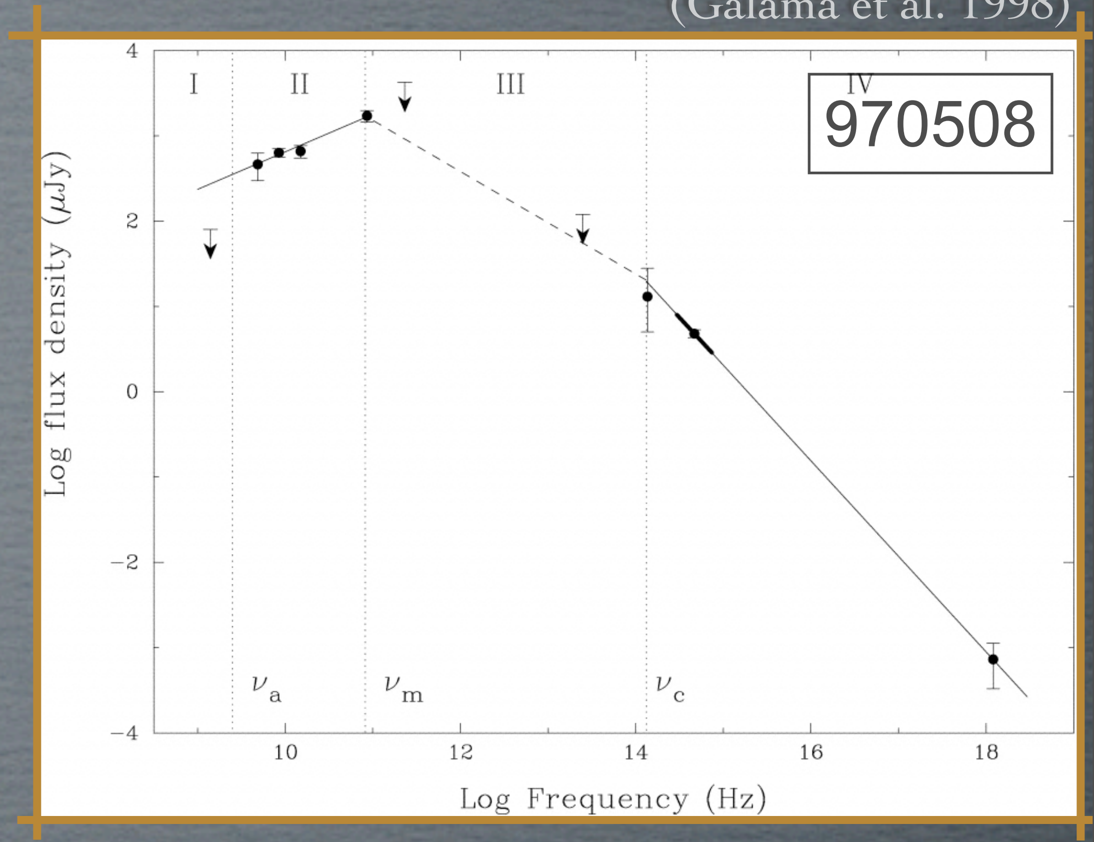
- α & β for many afterglows can confirm shock
- best made at various wavelengths to measure instantaneous positions of critical frequencies

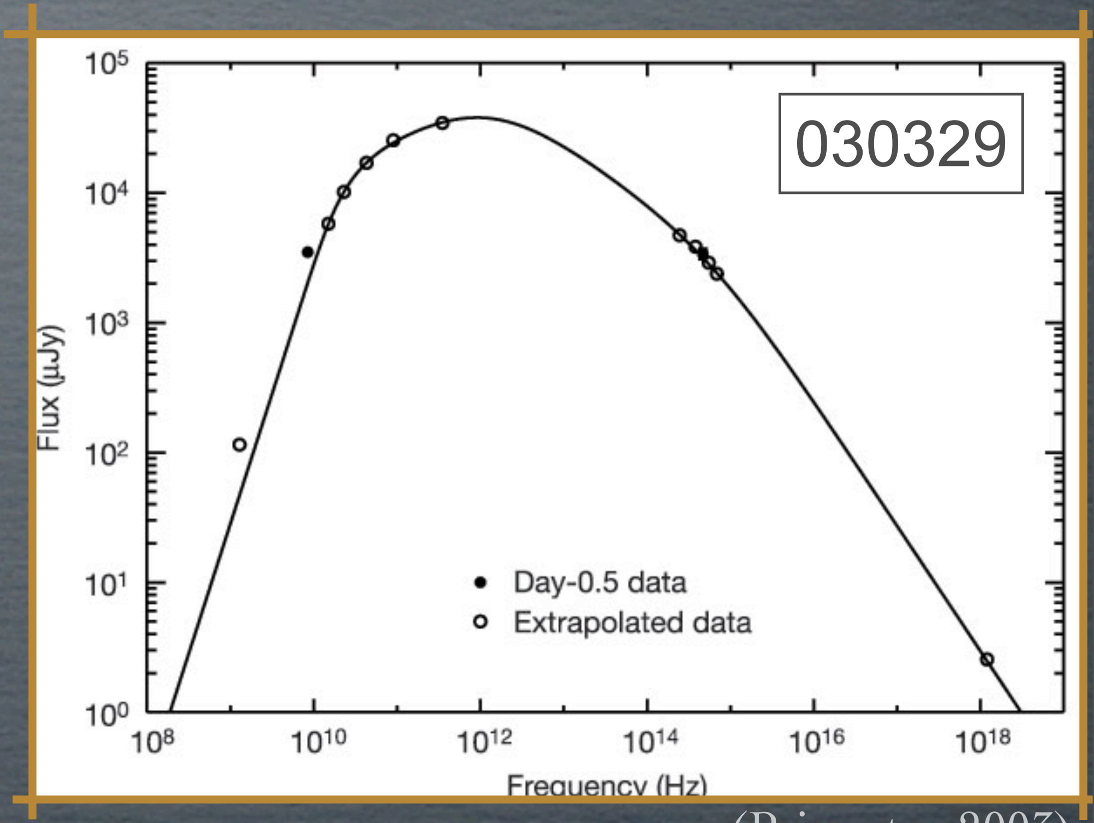
STANDARD MODEL MODIFICATIONS

ASSUMPTIONS SO FAR

- spherical outflow
- line-of-sight scaling relations valid for entire visible hemisphere
- impulsive energy input E_0 and single $\Gamma_0=\eta=E_0/M_0c^2$
- highly relativistic expansion in the adiabatic regime
- homogeneous external medium
- time-independent shock parameters $(p,\varepsilon_e,\varepsilon_B)$

(Galama et al. 1998)





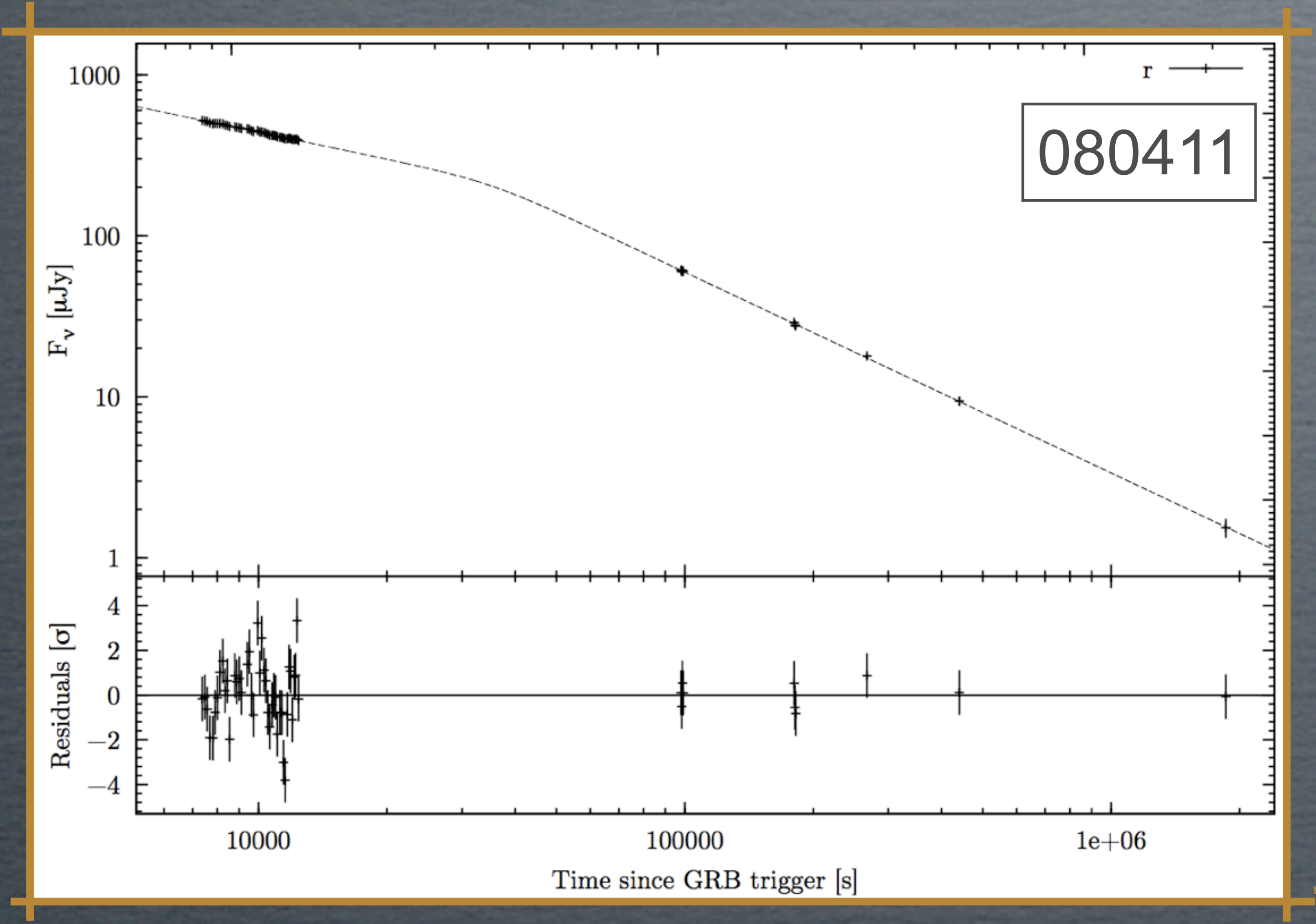
(Price et a. 2003)

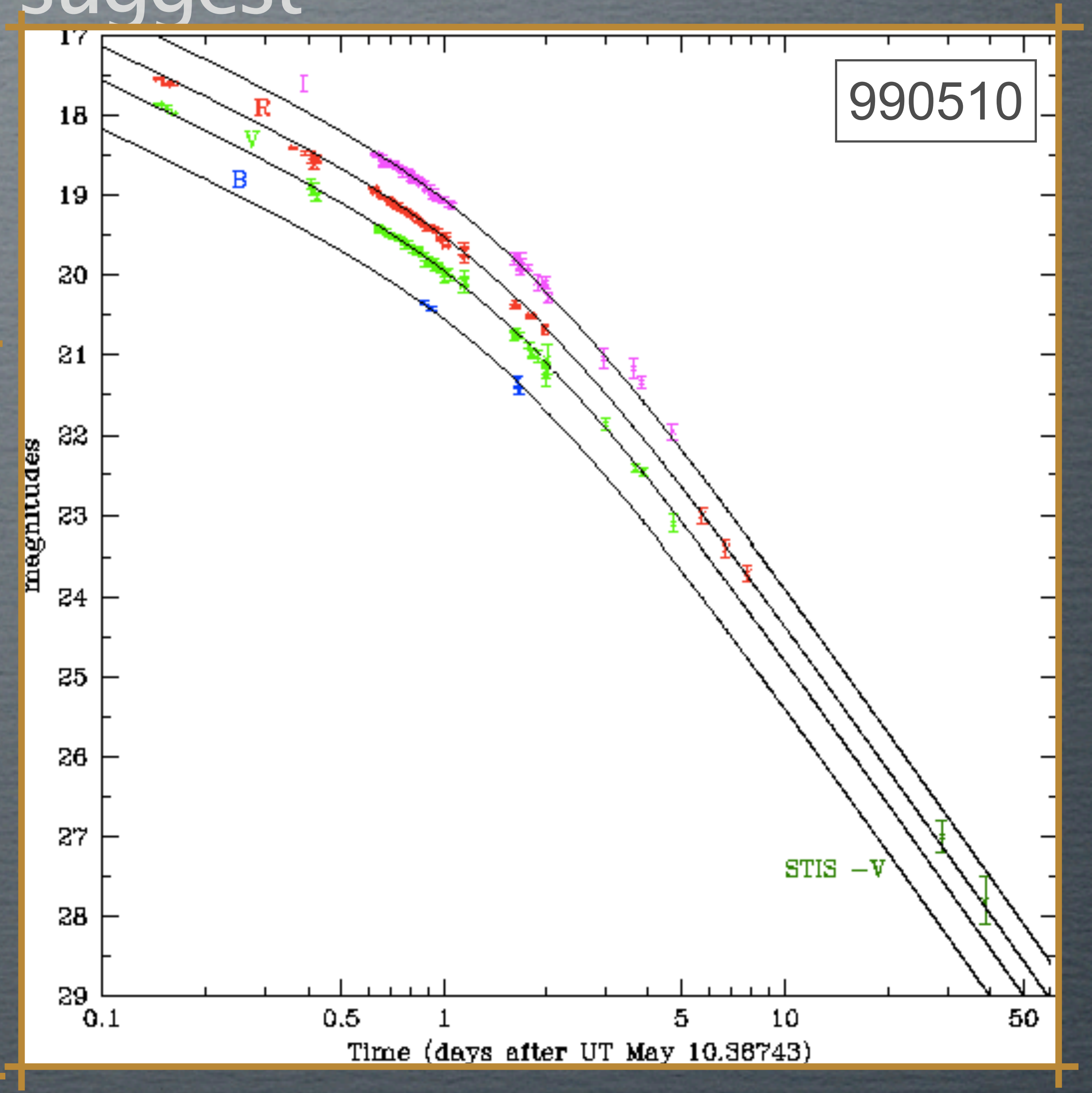
STANDARD MODEL MODIFICATIONS

- beaming of outflow within jet of solid angle $\Omega_j<4\Pi$
- refreshed shocks (e.g., lower Γ injection at la times)
- inhomogeneous external medium (wind case)
- impact of reverse shock

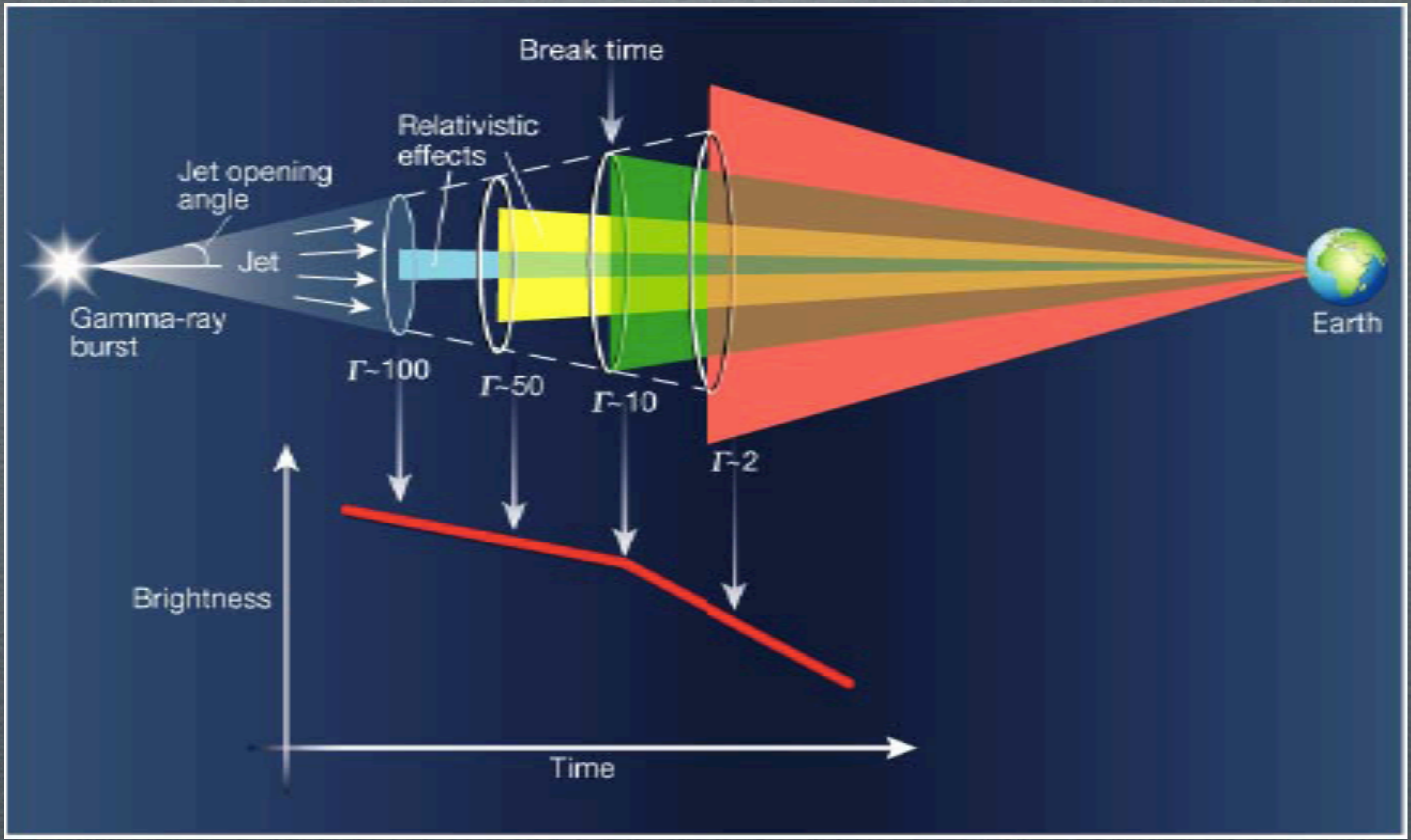
NON-SPHERICAL RELATIVISTIC EJECTA

- Three Lines of Evidence:
- 1) isotropic energy output exceeds $M_\odot c^2$
- 2) late radio observations suggest $E_{kinetic} \sim 10^{51}$ erg
- 3) (achromatic) jet breaks



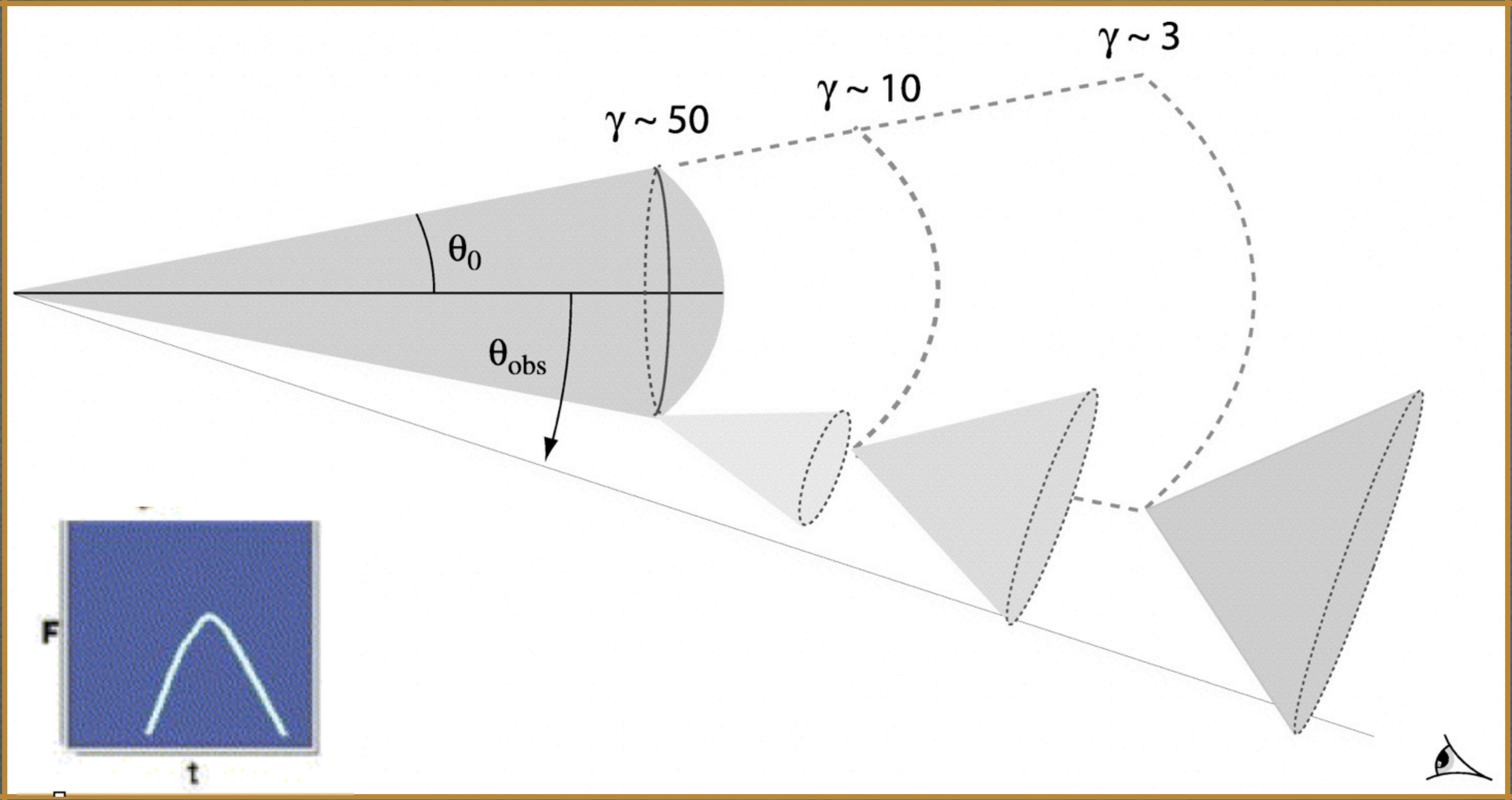


JET GEOMETRY



- observer sees emission from $\Theta = 1/\Gamma$
- geometrical light curve break when $\Theta_{jet} \sim 1/\Gamma$
- hydrodynamical break from lateral expansion

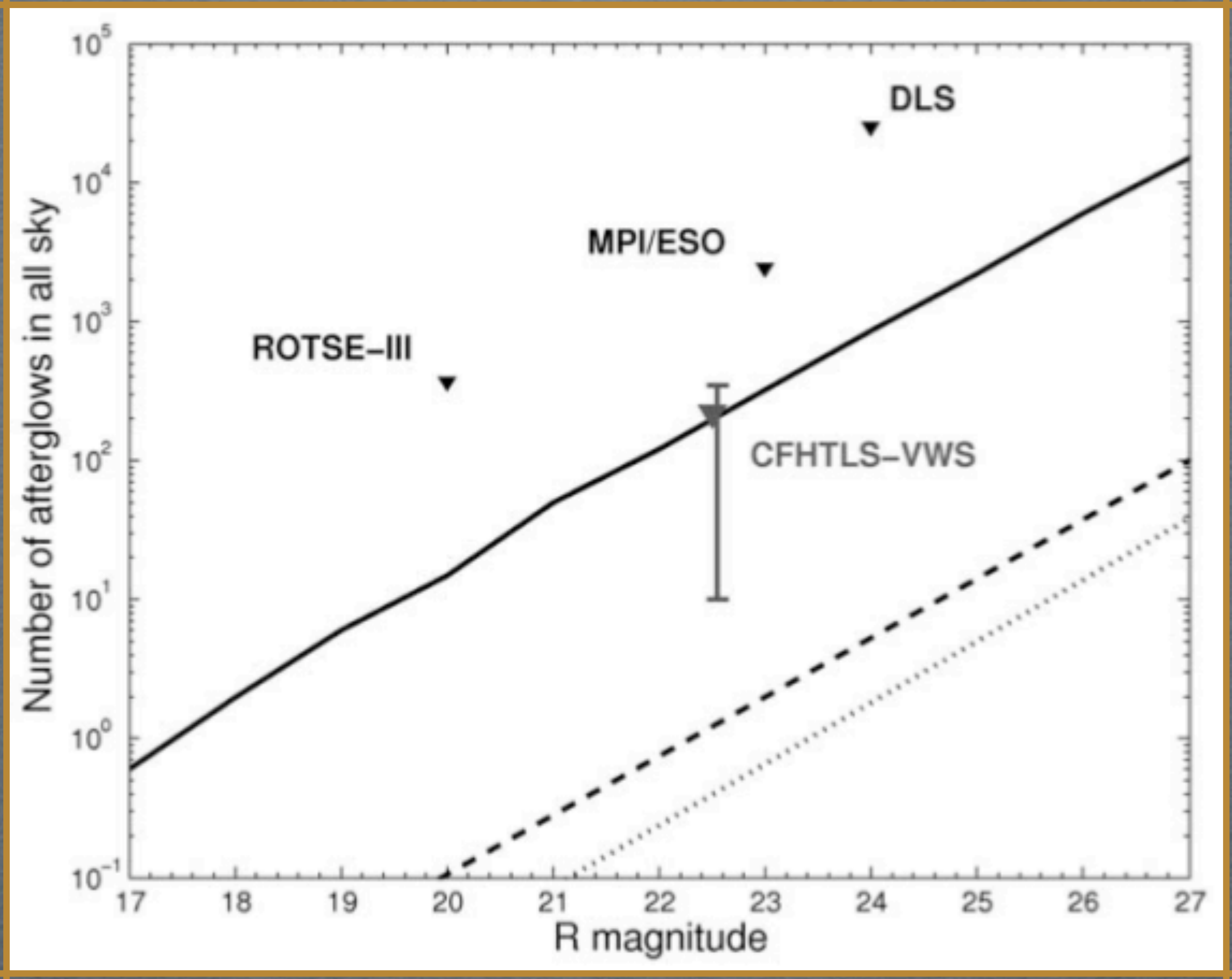
ORPHAN AFTERGLOWS -THEORY



(Granot et al. 2005)

- observer at $\Theta_{obs} > \Theta_0$
- light curve rises and peaks at $\Gamma \sim (\Theta_{obs} - \Theta_0)^{-1}$
- ratio of on- vs off-axis afterglows constrains Θ_0

ORPHAN AFTERGLOWS - OBSERVATIONS



(Malacrino et al. 2007)

- X-rays beamed similar to Gamma-rays (Greiner et al. 2000)
- radio $f_b^{-1}>60$ (Gal-yam et al. 2006)
- optical too shallow yet (e.g., Rau et al. 2006)

!! eROSITA + PanSTARRS (+LSST) !!

SUMMARY

- $F_\nu \propto t^{-\alpha} \nu^{-\beta}$
- closure relations
- Why homogenous medium fits best? Wind stratified medium expected from massive progenitors.
- Are breaks due to jets?
- What is the beaming fraction?

END