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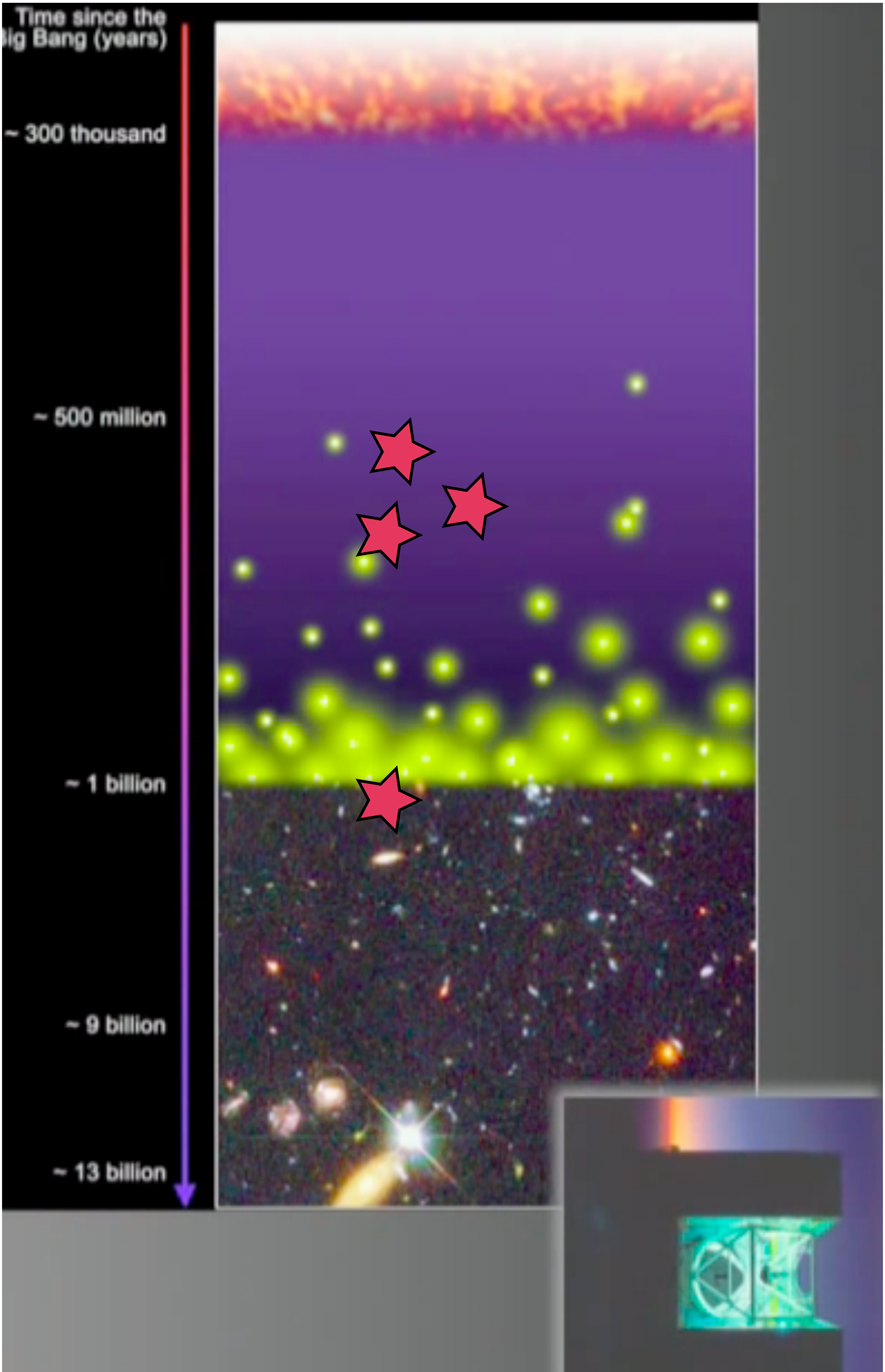
GAMMA RAY BURST THEORY

Fermi Summer School (2015)

GRBs are the death throws of super-massive stars or the mergers of compact objects in the distant Universe

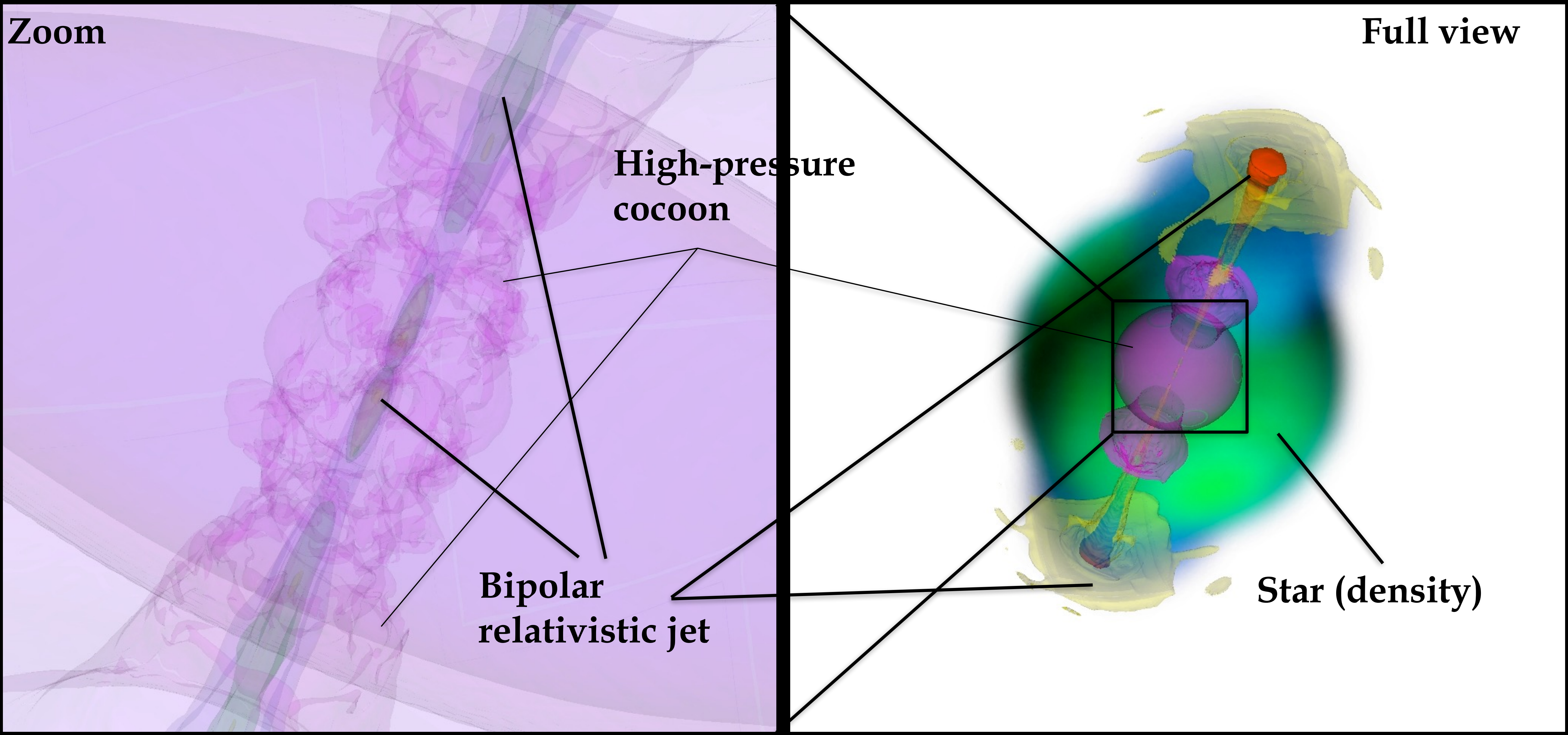
GRBs are the <superlative> (choose one) objects/ events in the Universe



Time since the
Big Bang (years)
~ 300 thousand
~ 500 million
~ 1 billion
~ 9 billion
~ 13 billion

FLASH SIMULATIONS

$16 M_{\odot}$, $\Theta_0 = 10^{\circ}$, $\Gamma_0 = 5$, $H = 400$, $L = 5 \times 10^{43}$ J/S



LOPEZ-CAMARA ET AL. 2013; MORSONY ET AL. IN PREP

FLASH SIMULATIONS

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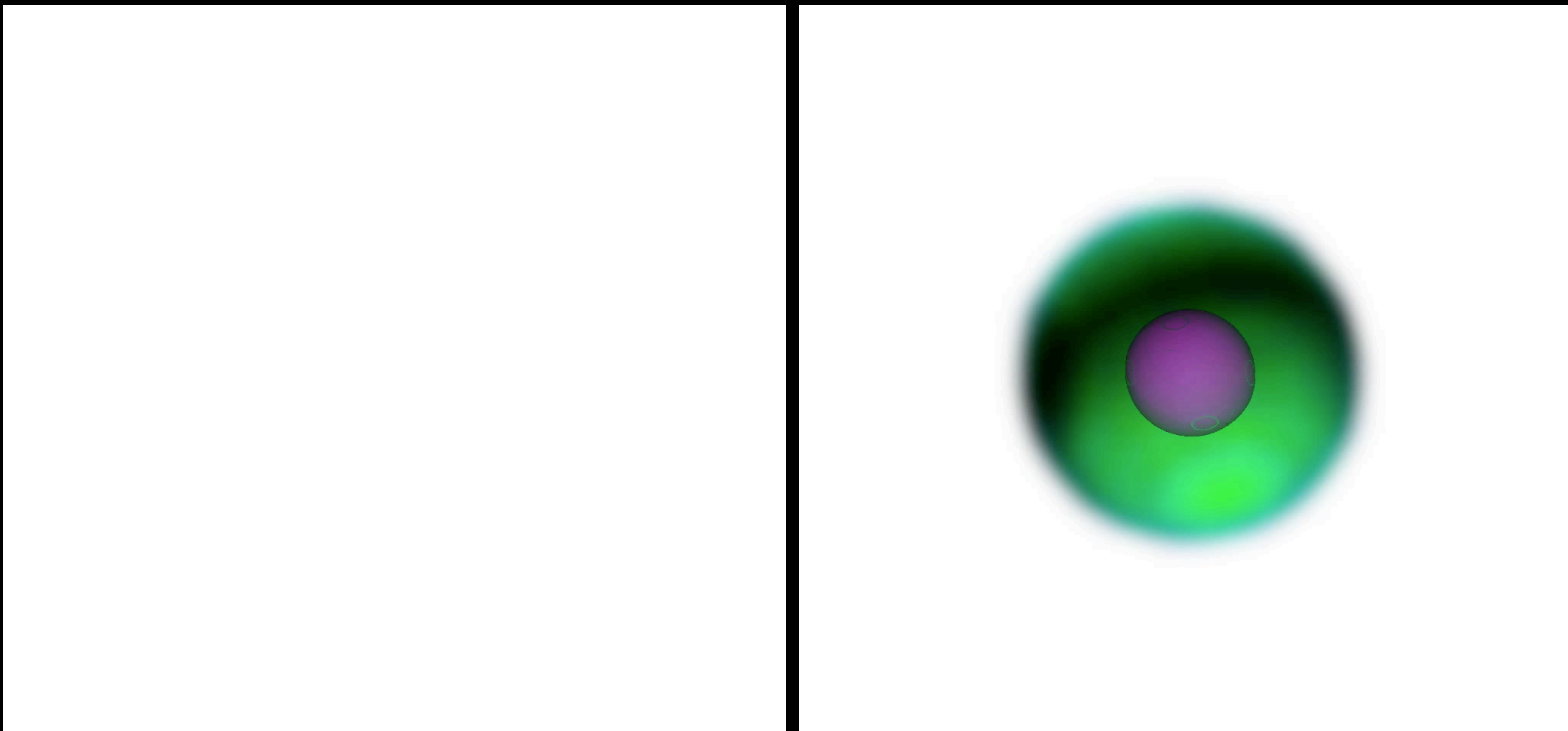
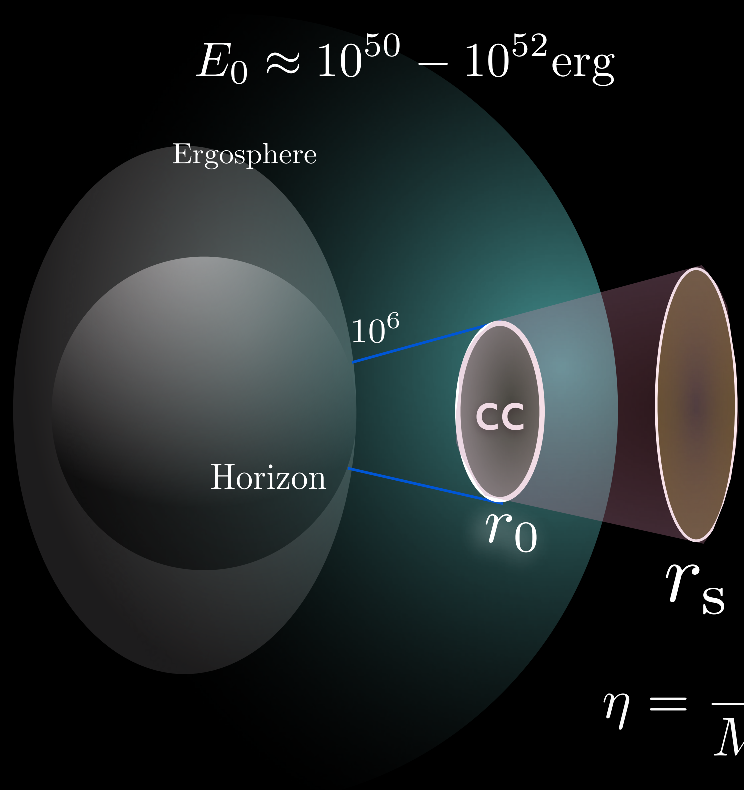


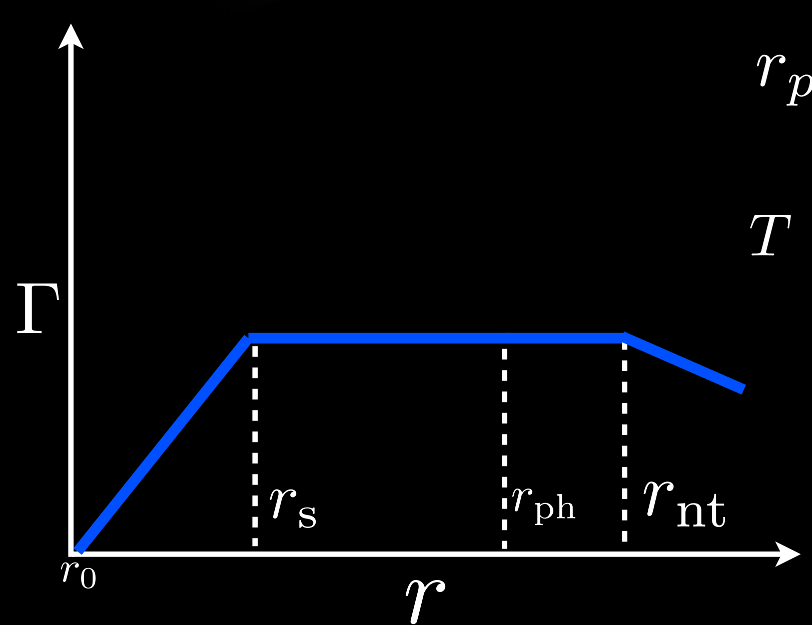
LOPEZ-CAMARA ET AL. 2013; MORSONY ET AL. IN PREP

Progenitor

$$E_0 \approx 10^{50} - 10^{52}\mathrm{erg}$$



$$\eta = \frac{E_0}{M_0 c^2}$$



$$r_{ph} \approx \frac{\dot{M}\sigma_T}{8\pi m_p c \Gamma^2}$$

$$T \propto T_0 \left(\frac{r}{r_{ph}}\right)^{-2/3}$$

$$L_0 \gg L_E = 4\pi G M m_p/\sigma_T$$

$$T' \propto V'^{1-\gamma_{\mathrm{a}}} \Rightarrow T' \propto \gamma \propto r^{-1}$$

$$\gamma\Gamma = constant \Rightarrow \Gamma \propto r$$

$$r_{dis} \sim c t_v \eta^2$$

$$r_{is,min} \sim 2\Gamma^2 r_s$$

THE LIGHT CURVES

- Wealth of temporal properties
- Single pulse GRBs “typically” exhibit fast-rise and exponential-decay in flux
- Variability ranging from milliseconds to days

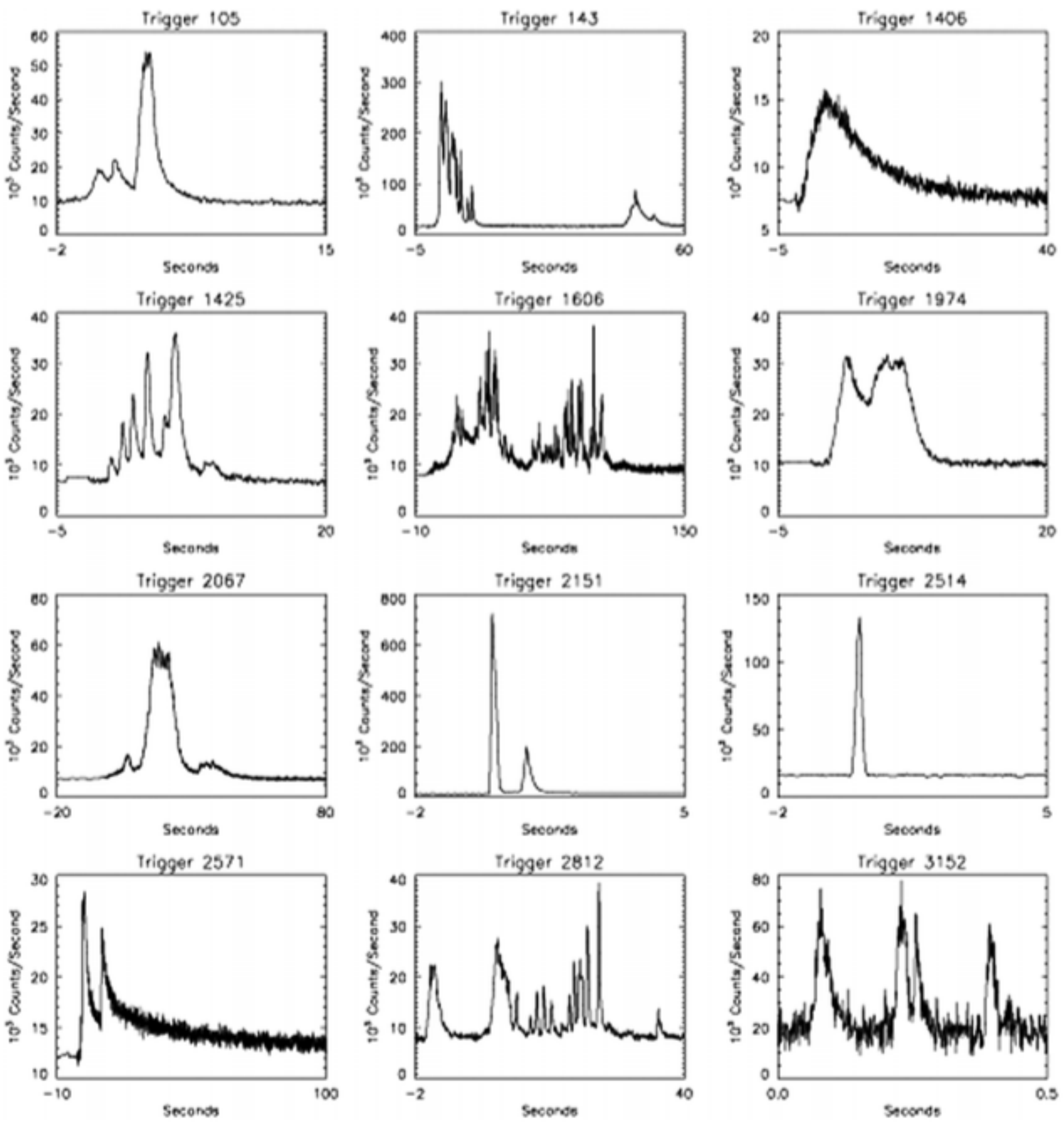
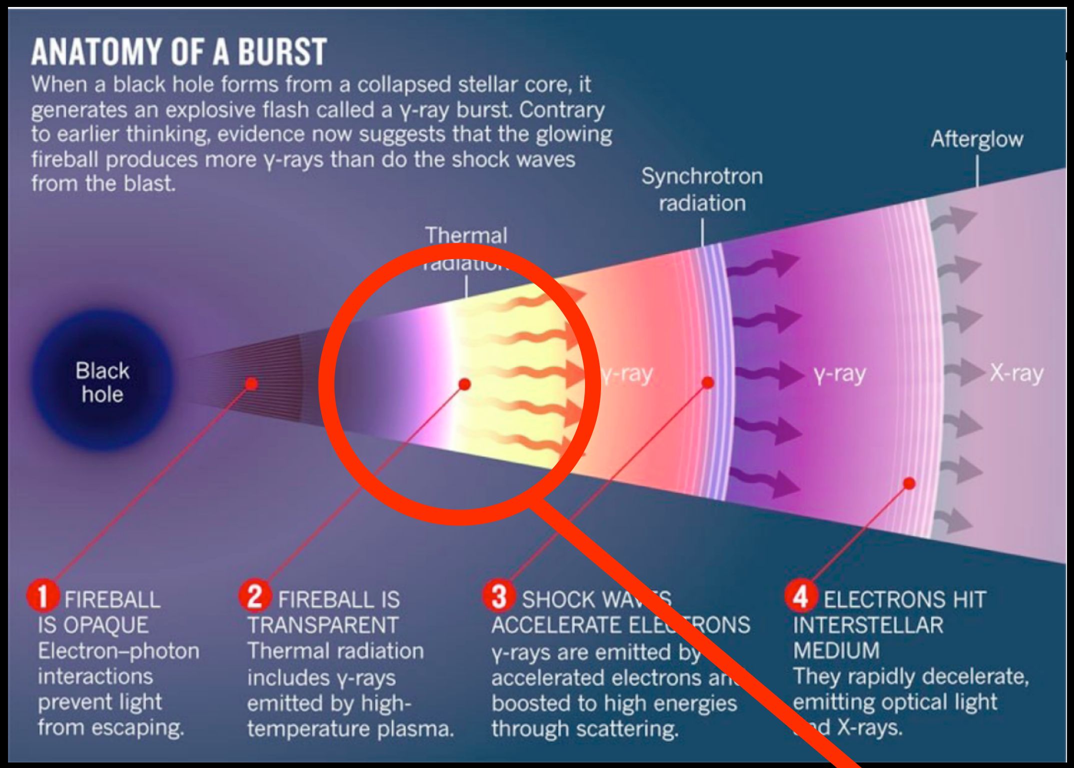


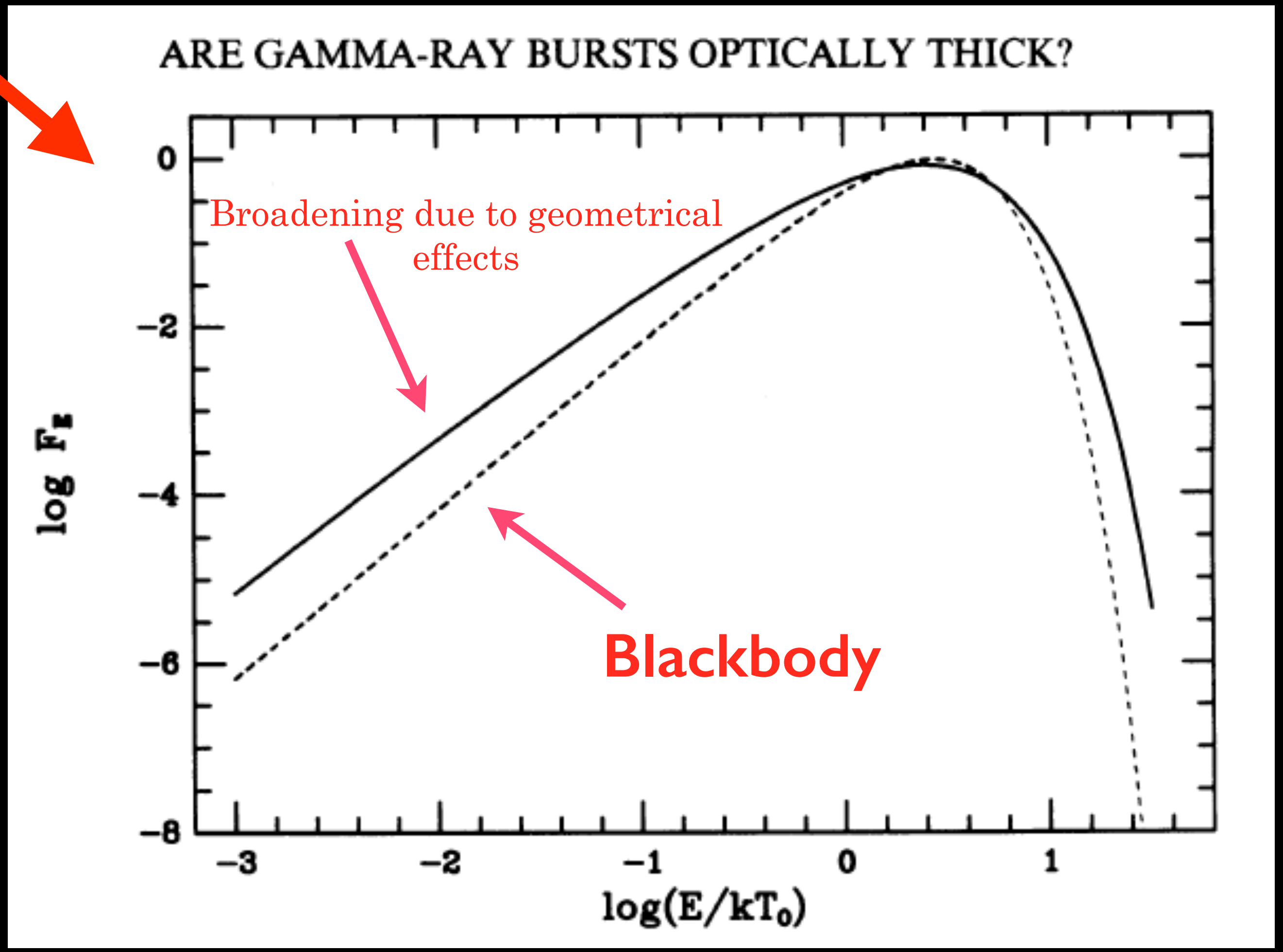
Figure 1. Diversity of gamma-ray light curves observed by BATSE [132].



The simplest explanation is photospheric emission when the jet becomes optically thin

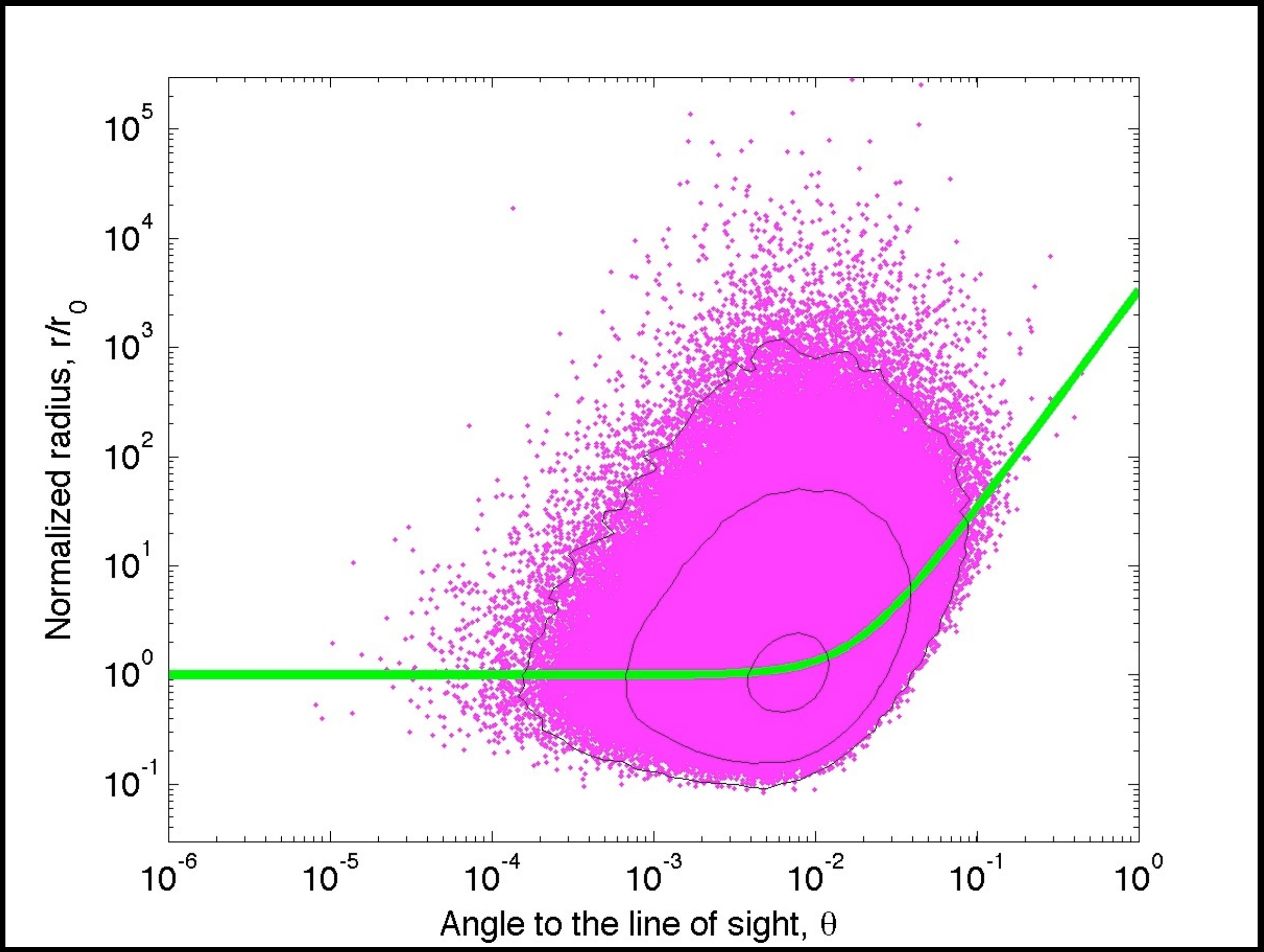
Geometric effects can alter the spectrum from a true blackbody

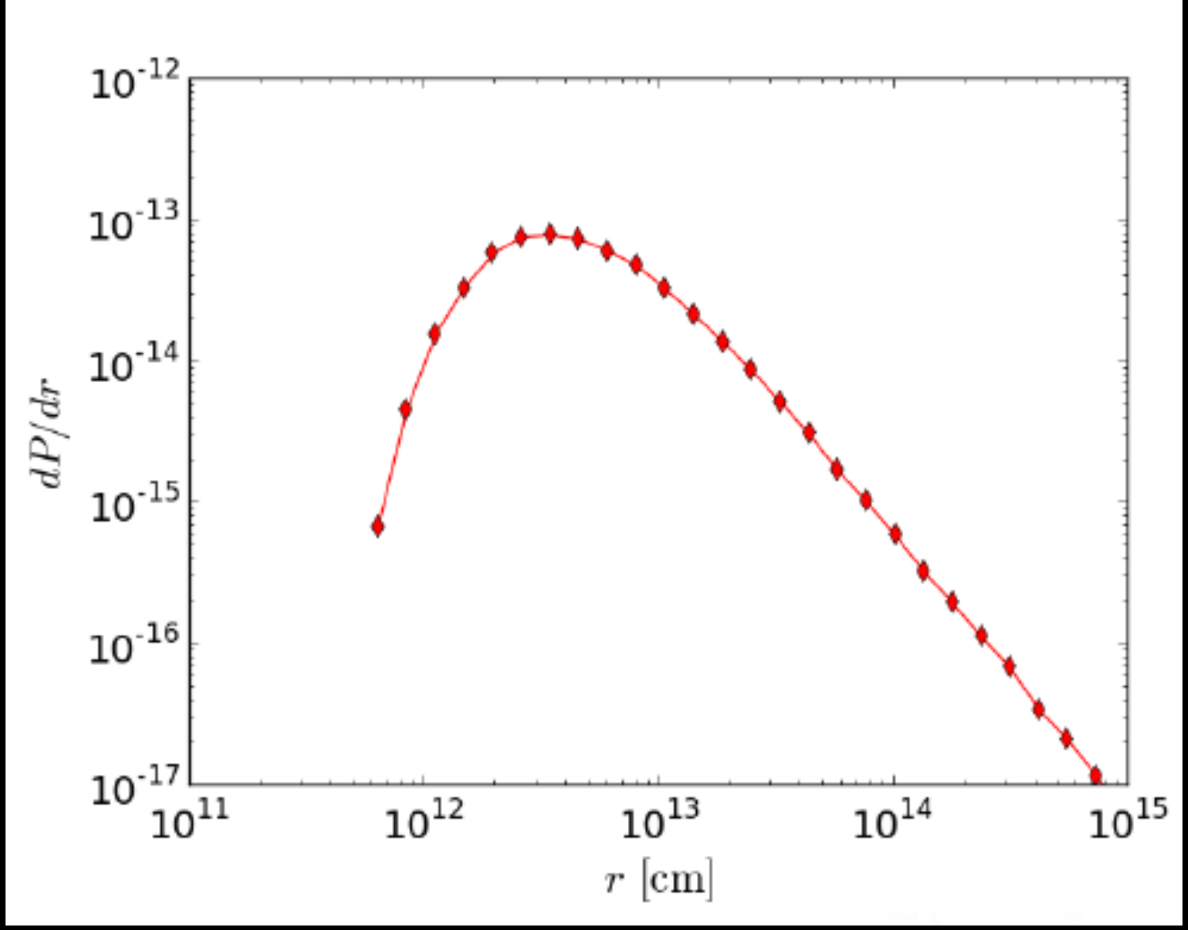
PACZYŃSKI 1986:



MODIFICATION OF PLANCK SPECTRUM

Geometrical broadening: ‘photosphere’ is NOT a single radius, but is 3-dimensional

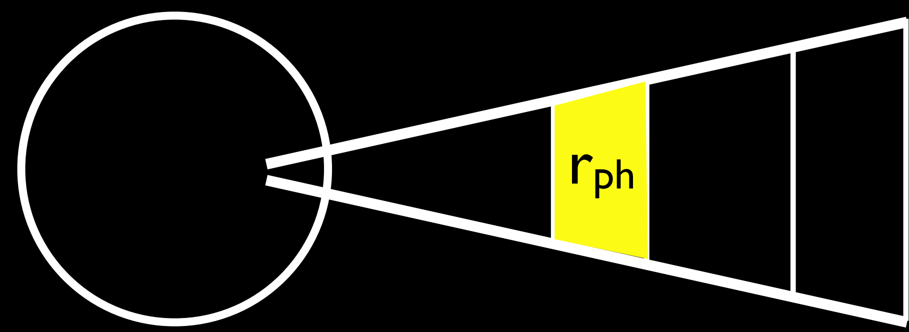




Pe’er 2008; Pe’er & Ryde 2011 Lundman, Peer, Ryde 2012

‘Limb darkening’ in relativistically expanding plasma;
Emission from the photosphere is NOT seen as Planck !

PHOTOSPHERIC RADIUS

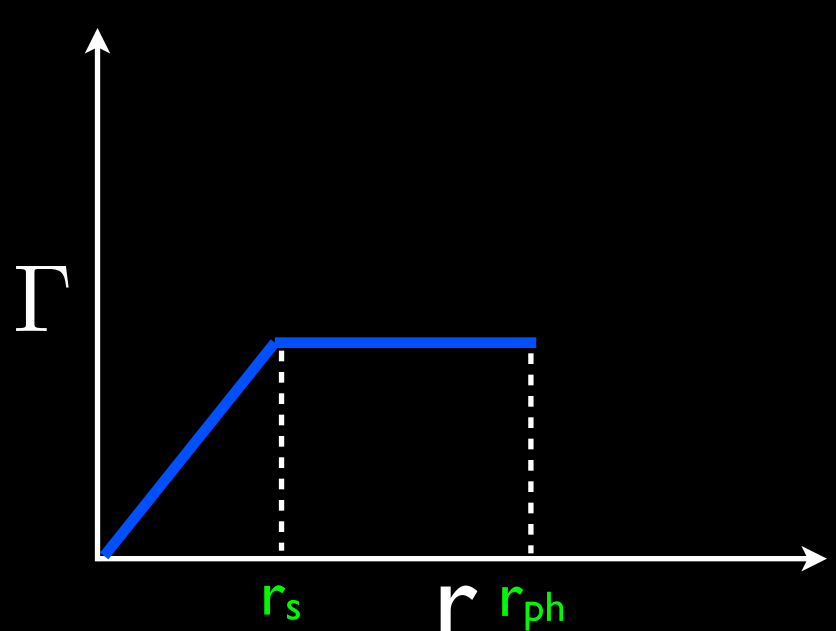


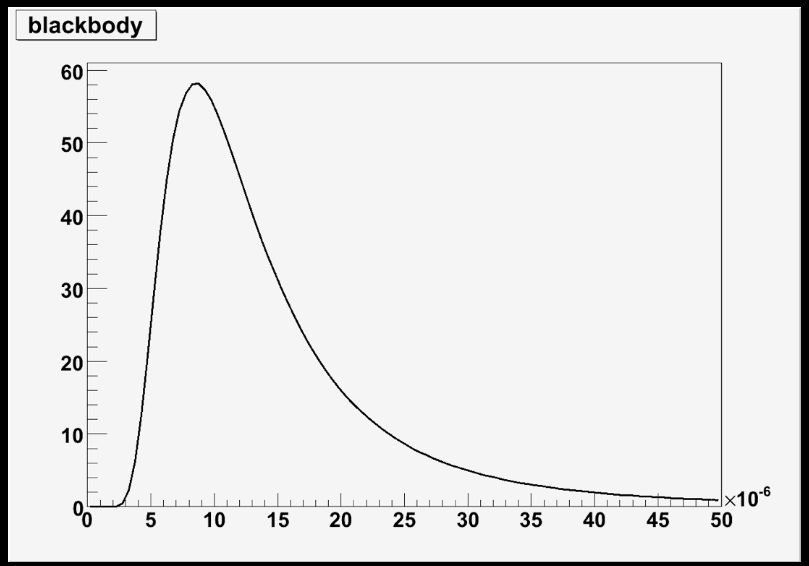
- Important parameters

$$T \propto T_0 \left(\frac{r}{r_{ph}} \right)^{-2/3}$$

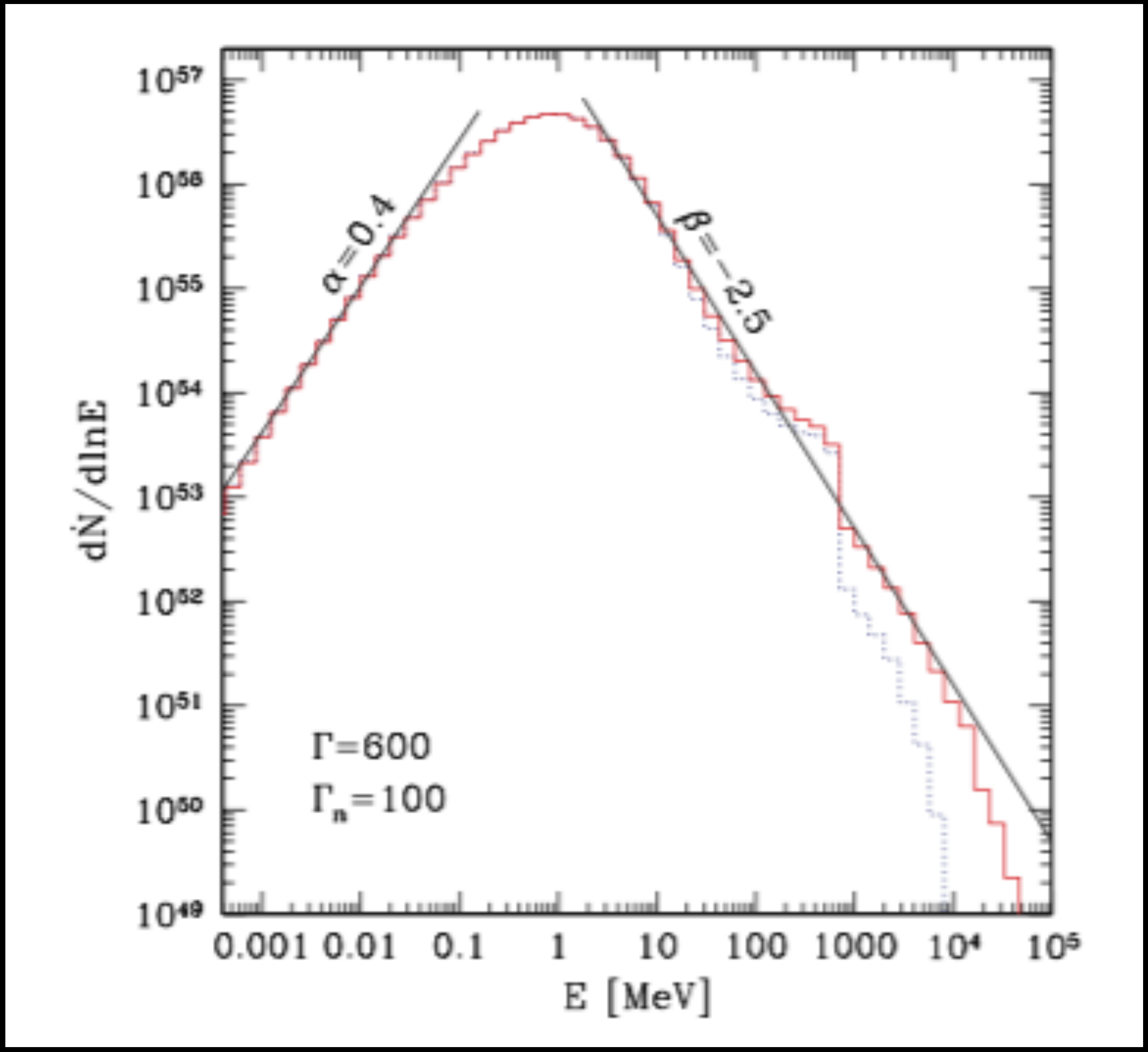
$$r_{ph} \approx \frac{\dot{M} \sigma_T}{8 \pi m_p c \Gamma^2}$$

- Radiation and particles come into TDE
- Blackbody radiation emitted
- Could have energy dissipated below the photosphere





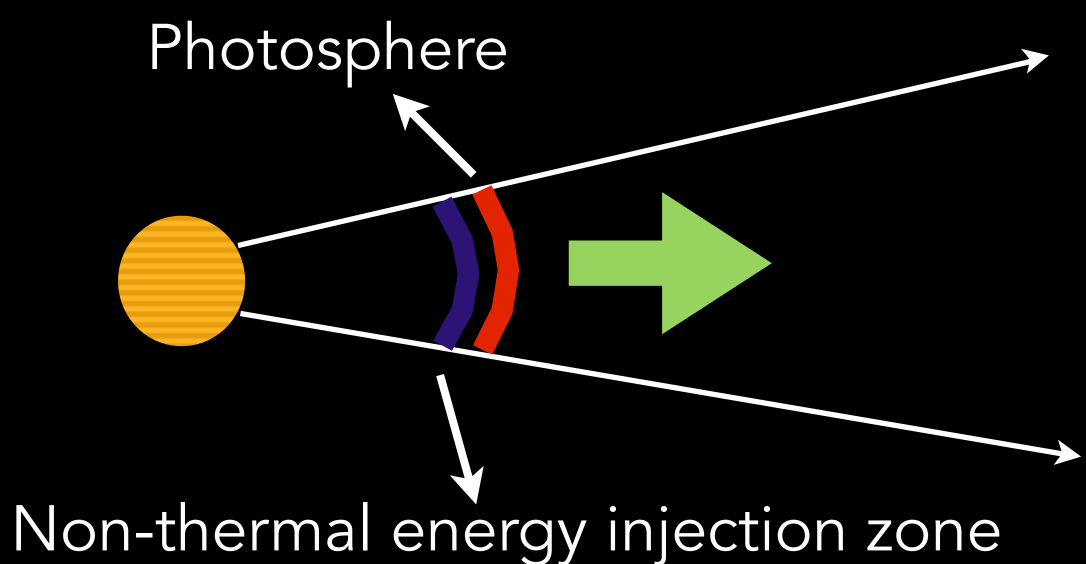
COLLISIONAL HEATING



Beloborodov (2010)

There are many ways to generate "photospheric" emission through various processes

SUBPHOTOSPHERIC DISSIPATION



Entire emission is from the photosphere

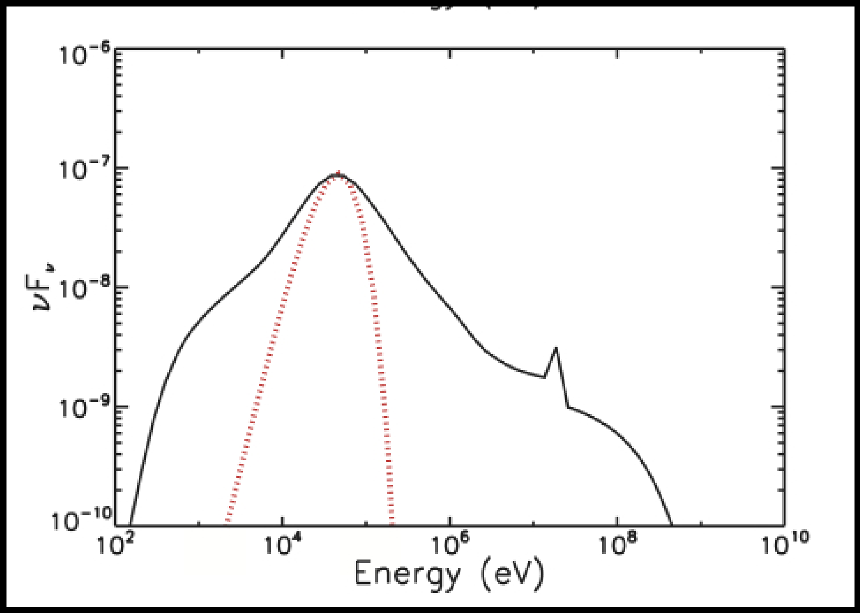
I. Photospheric emission is not thermal but non-thermal

↓

Sub-photospheric dissipation

Injection of kinetic energy at low optical depth -
Not enough time to thermalize

A broad spectra unlike Planck function



Ryde et al. 2011

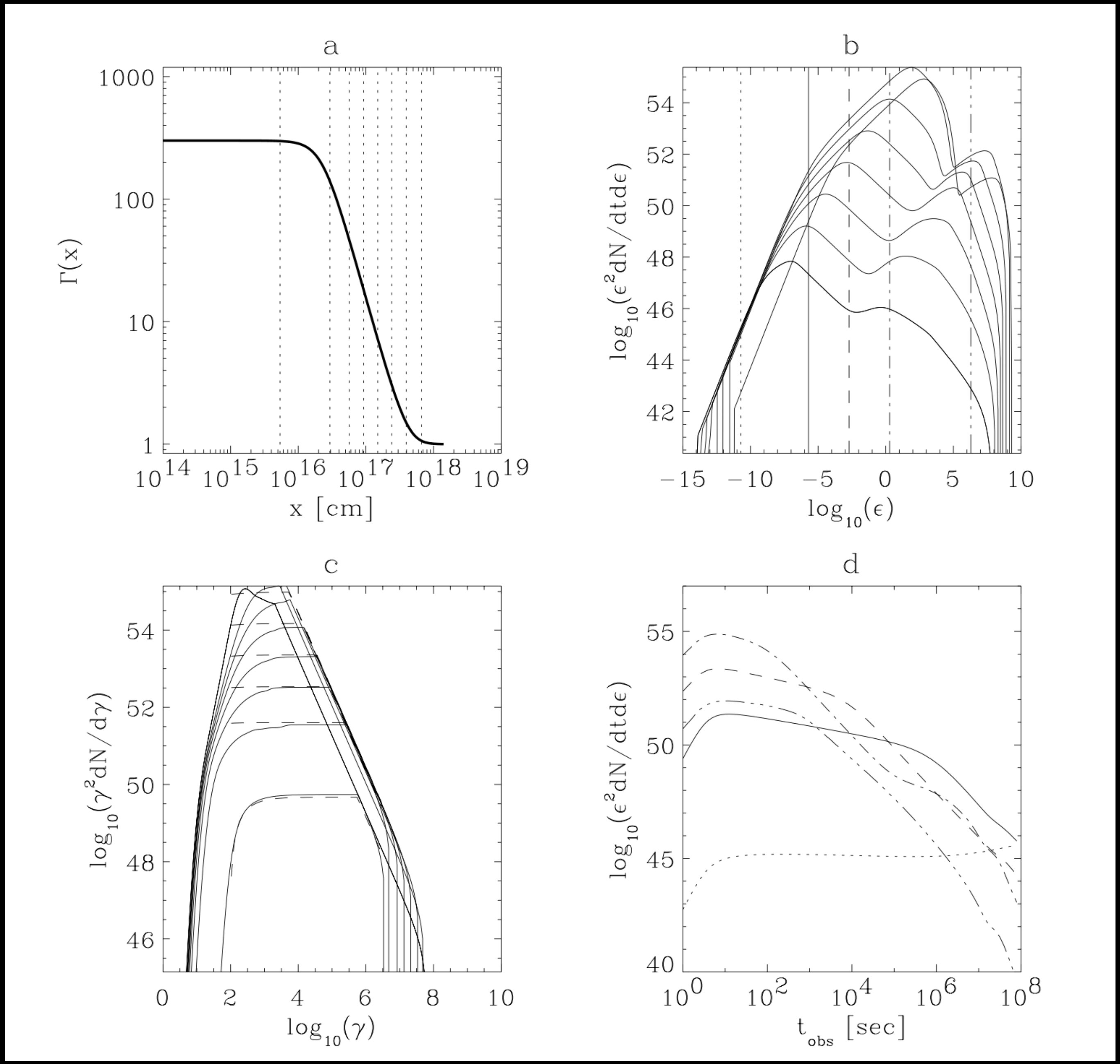
OPEN QUESTIONS

- Dynamics?
- Existence of non-thermal spectra
- Dearth of purely thermal spectra

Many variations of spectral shape can be obtained from simple (to complex) photospheric emission!

THE EXTERNAL SHOCK MODEL

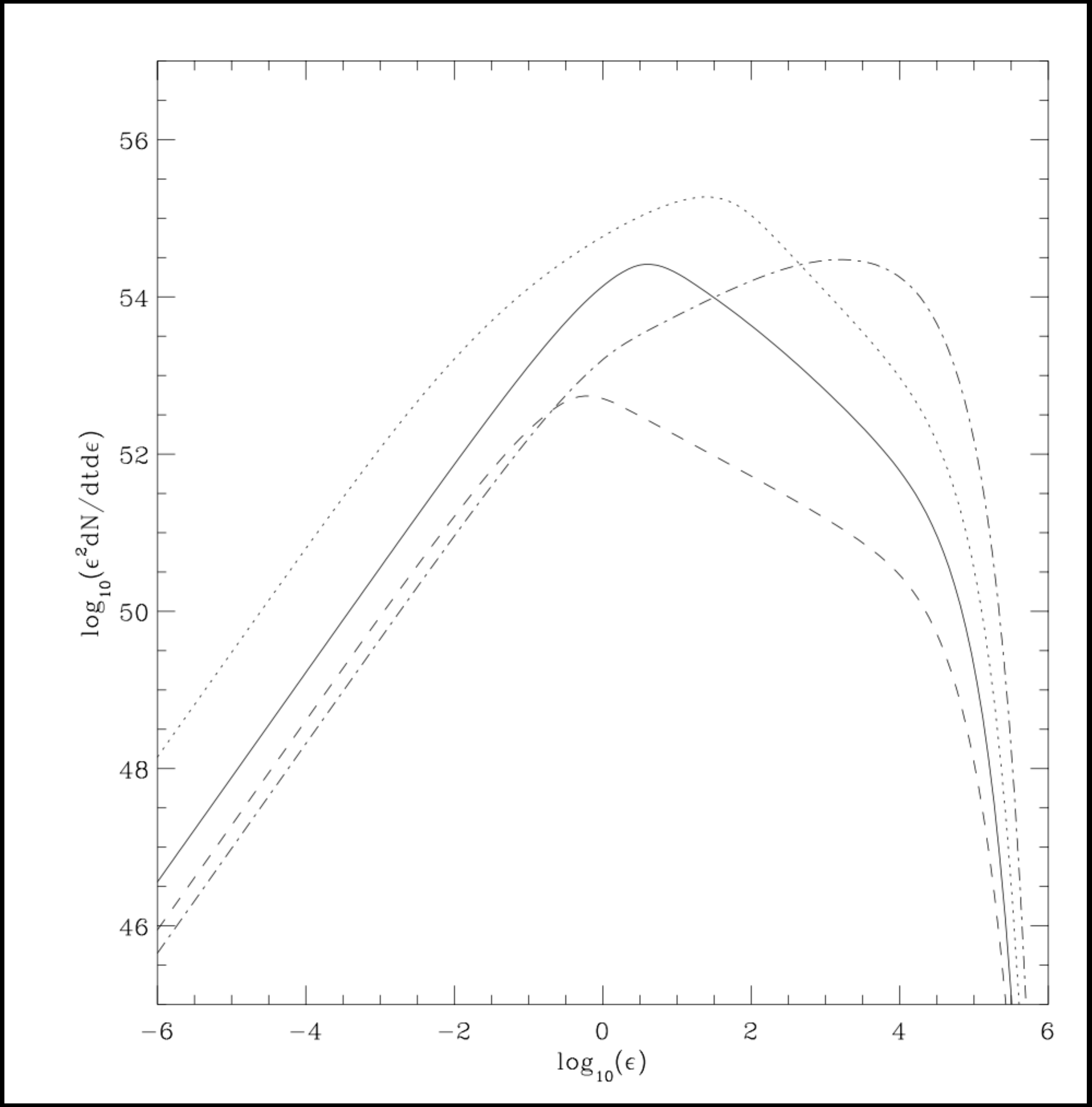
A single blast wave is formed via some mechanism which collides with an external medium. A shock is formed which subsequently decelerates the blast wave. The extracted energy can go into accelerating electrons which then radiate away this energy.

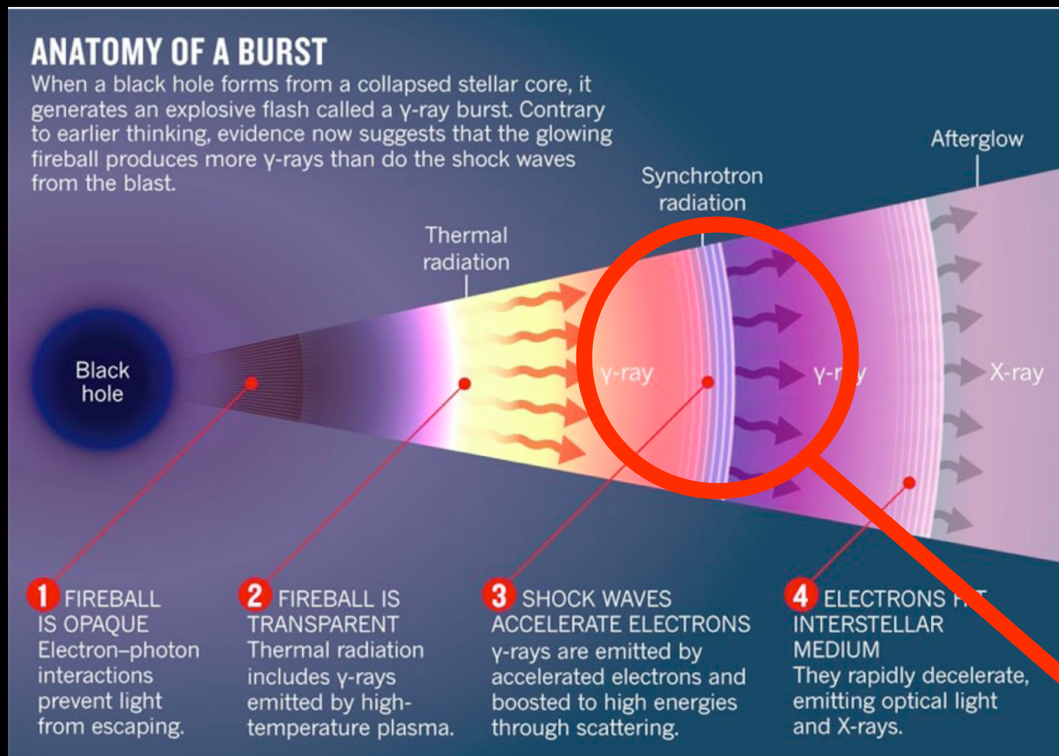


THE EXTERNAL SHOCK MODEL

The blast wave will emit non-thermal synchrotron radiation. Depending on the strength of the magnetic field, the shape of the emission will be different.

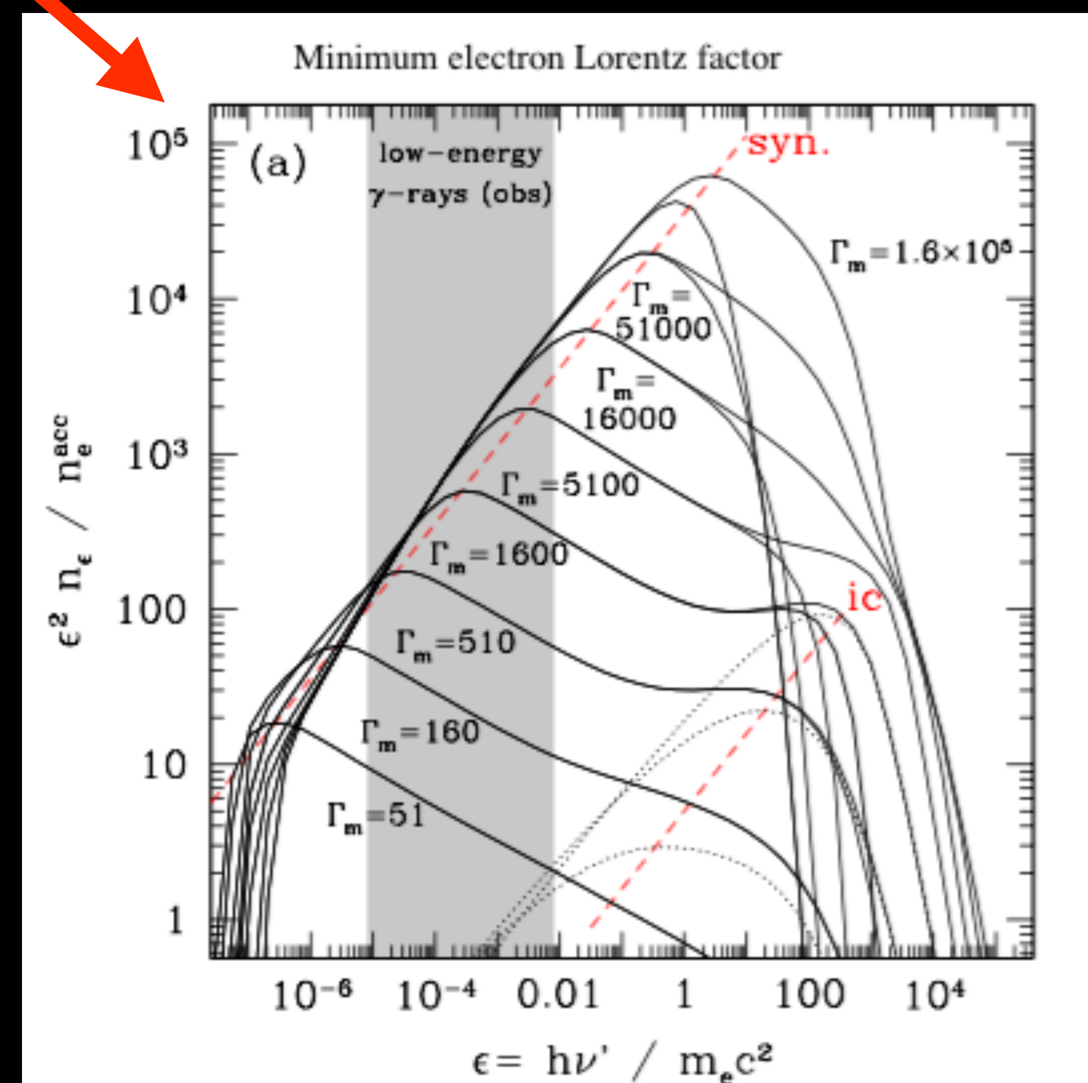
We will call this fast and also cooled synchrotron radiation. Mode on this later.





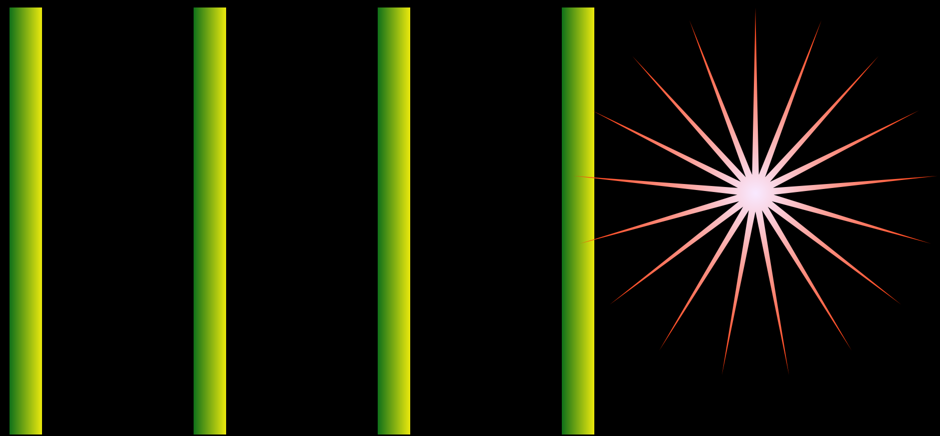
Optically-thin non-thermal emission via dissipation at internal shocks

BOSNJAK ET AL (2010)



Emission primarily comes from gyrating electrons in the entrained or generated magnetic field of the jet. This synchrotron radiation can seed inverse compton radiation.

THE INTERNAL SHOCK MODEL



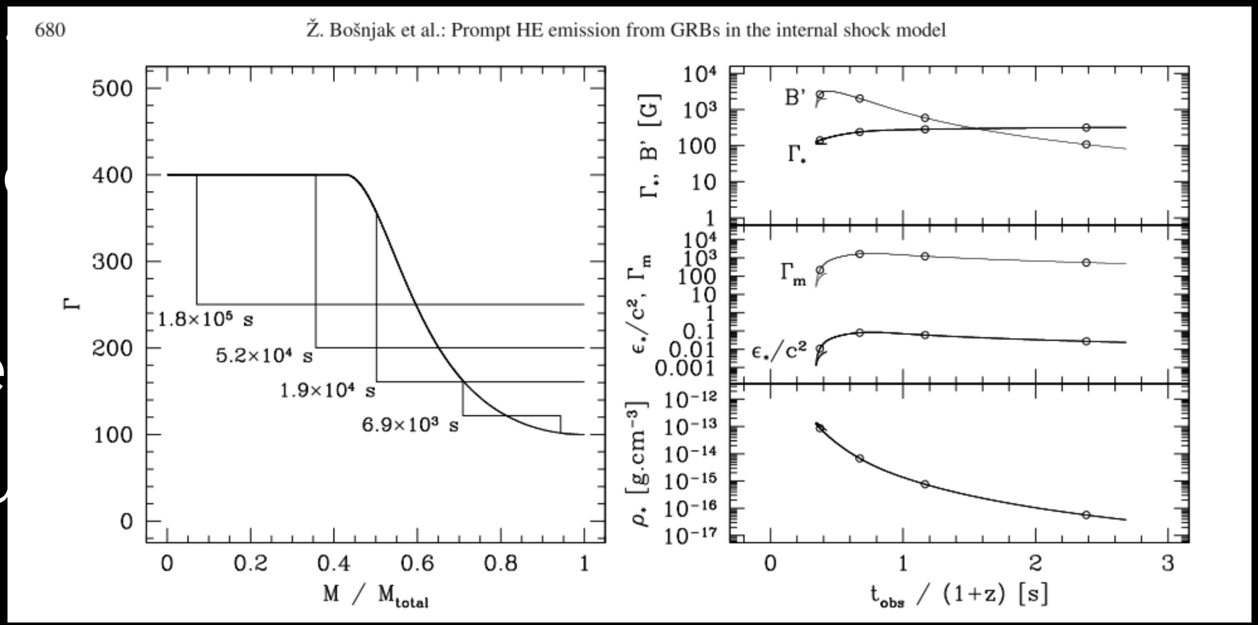
- Important parameters

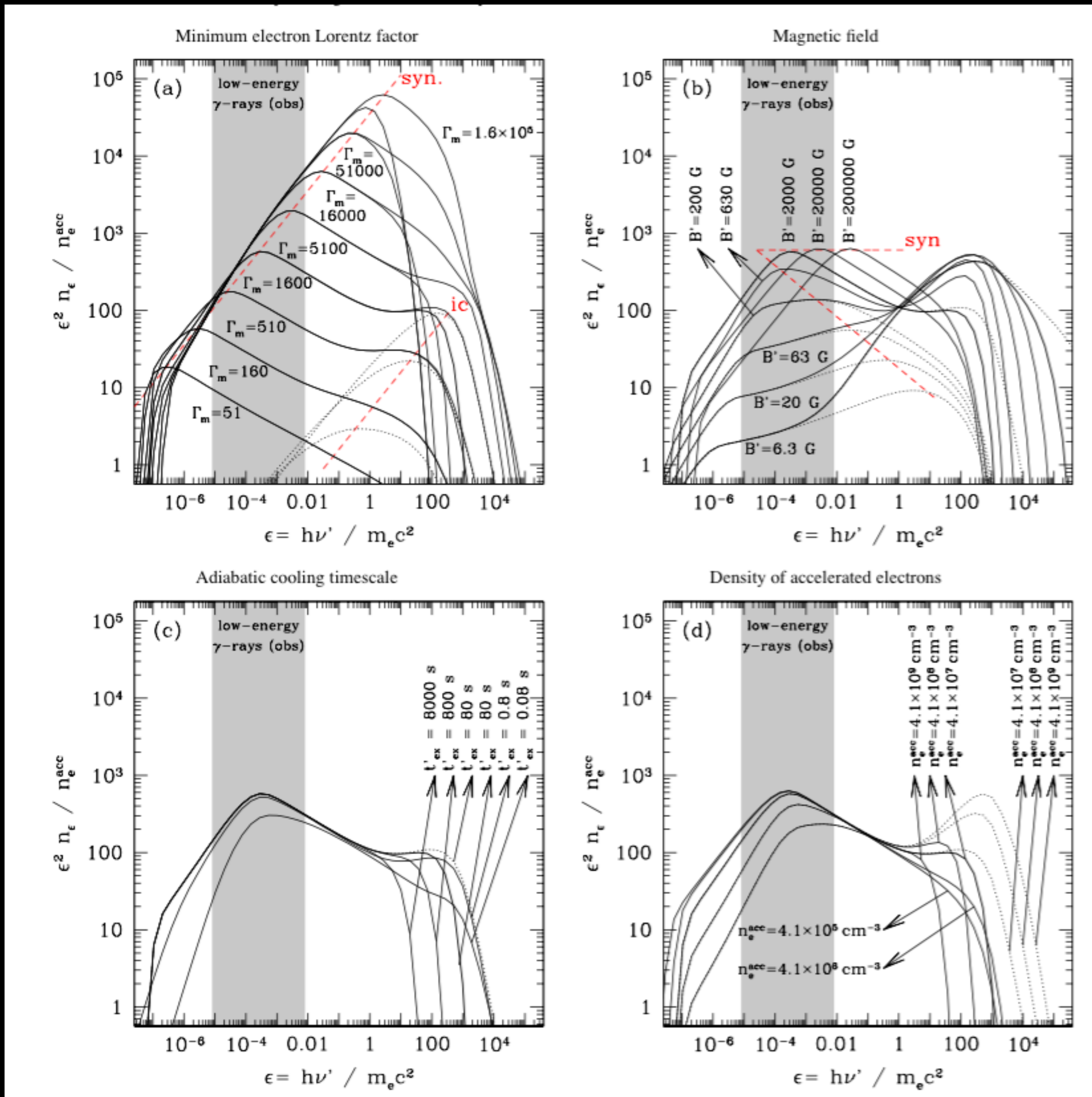
$$\Gamma_m = \left(\frac{\Gamma_1 m_1 + \Gamma_2 m_2}{m_1/\Gamma_1 + m_2/\Gamma_2}\right)$$

$$eff = 1 - \frac{m_1 + m_2}{\sqrt{m_1^2 + m_2^2 + m_1 m_2 (\frac{\Gamma_1}{\Gamma_2} + \frac{\Gamma_2}{\Gamma_1})}}$$

Very low radiative efficiency!

- Shocks transform internal kinetic energy into particle energy via Fermi acceleration
- Deta… unkn…
- Time… turbu…



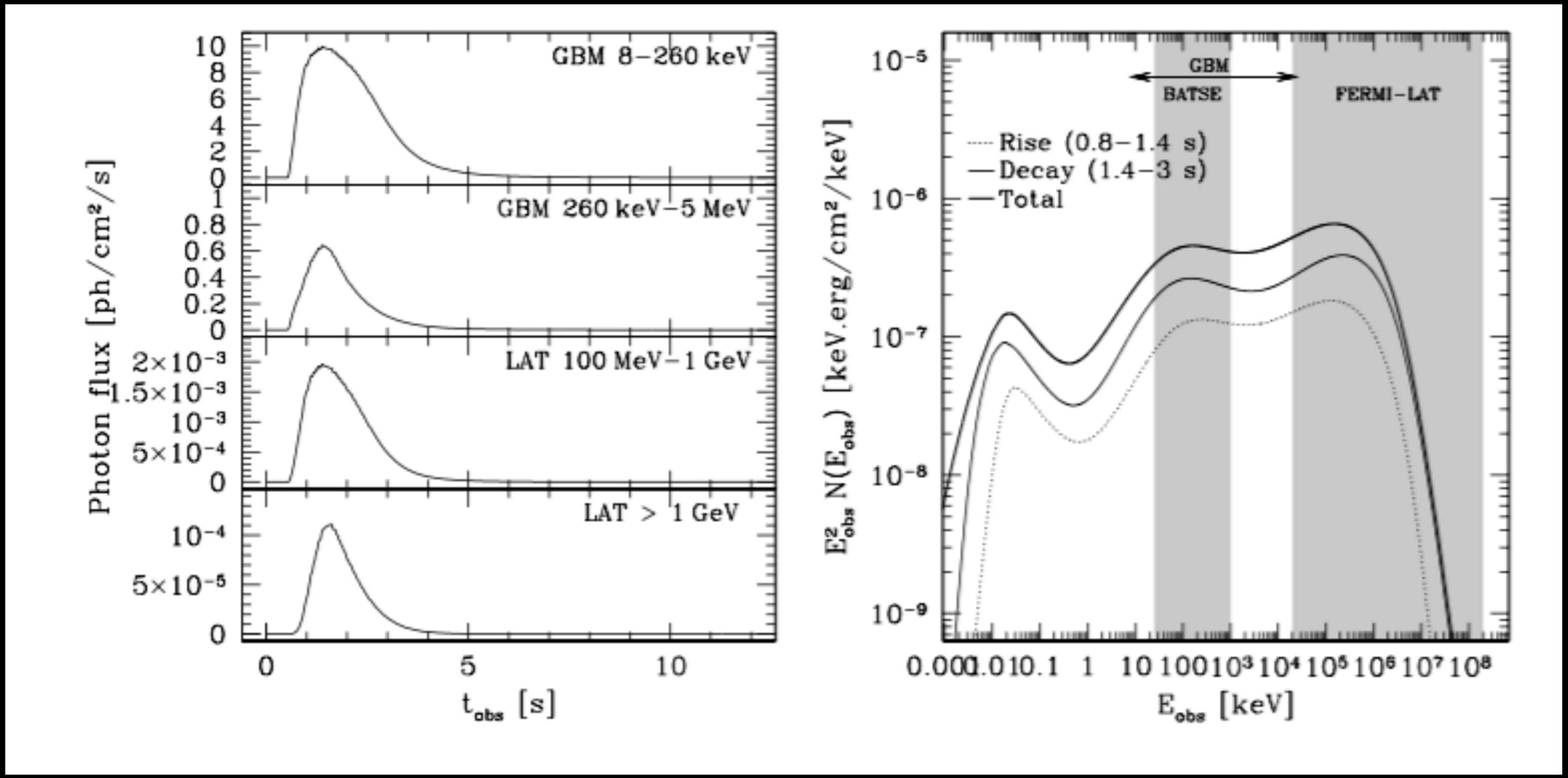


BOSNJAK ET AL (2010)

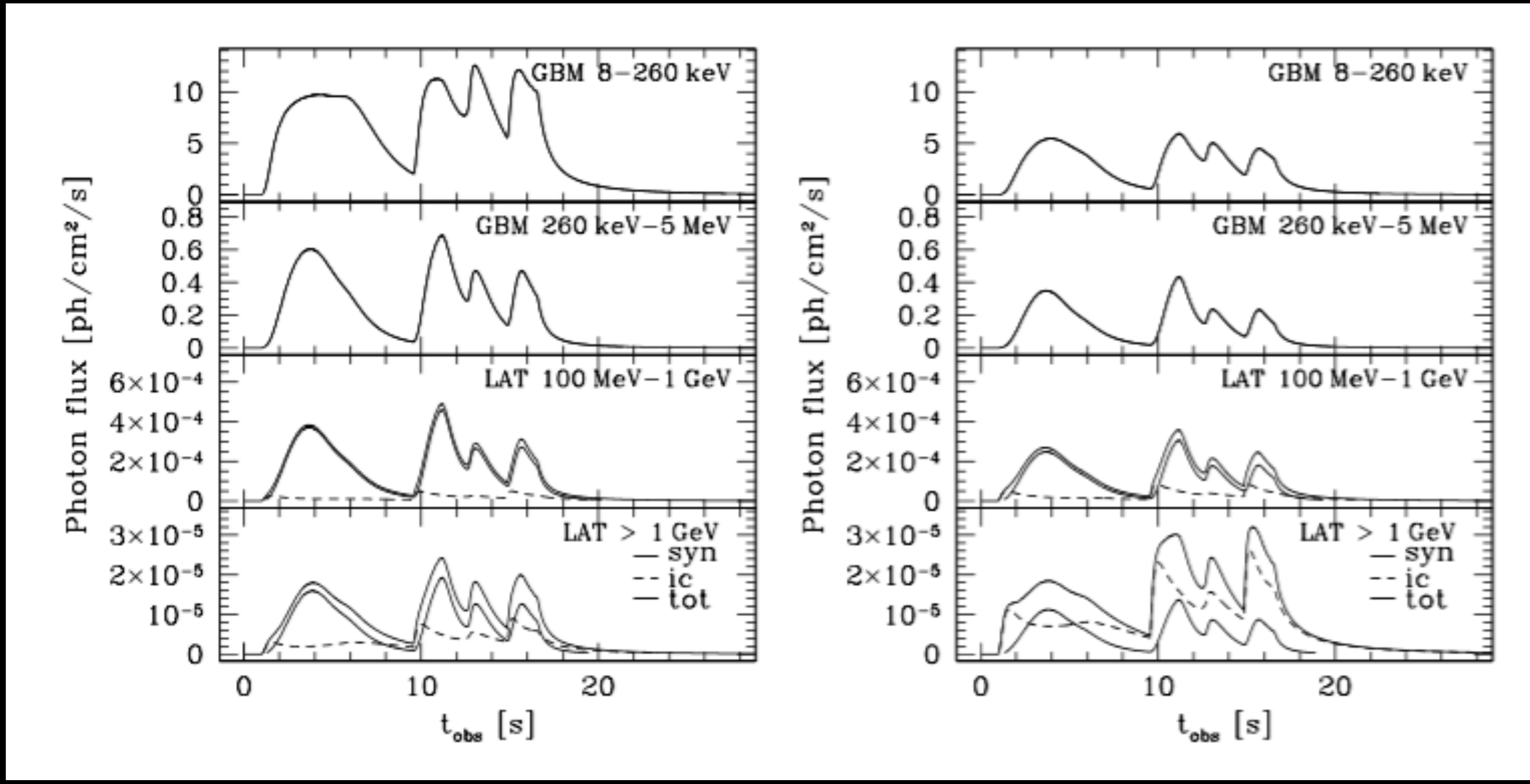
VARIATIONS OF PARAMETERS CAN LEAD TO A MYRIAD OF SPECTRAL SHAPES…

FINE TUNING OF PARAMETERS REQUIRED TO REPRODUCE CORRECT ENERGY SCALING

HOWEVER, SPECTRAL WILL NEVER LOOK “THERMAL”

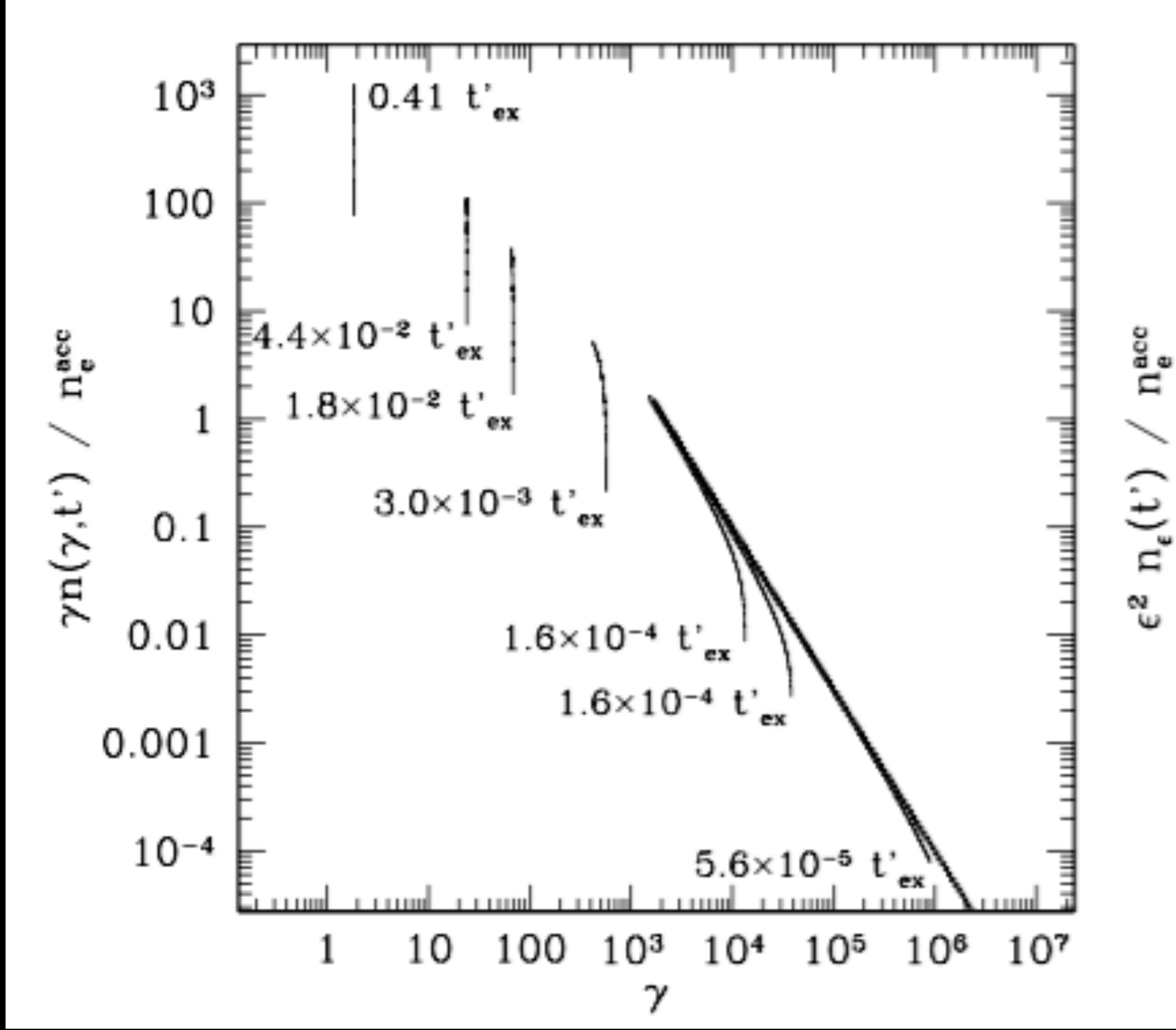


LIGHTCURVES AND VARIABILITY EASILY REPRODUCED



SOME ASSEMBLY REQUIRED

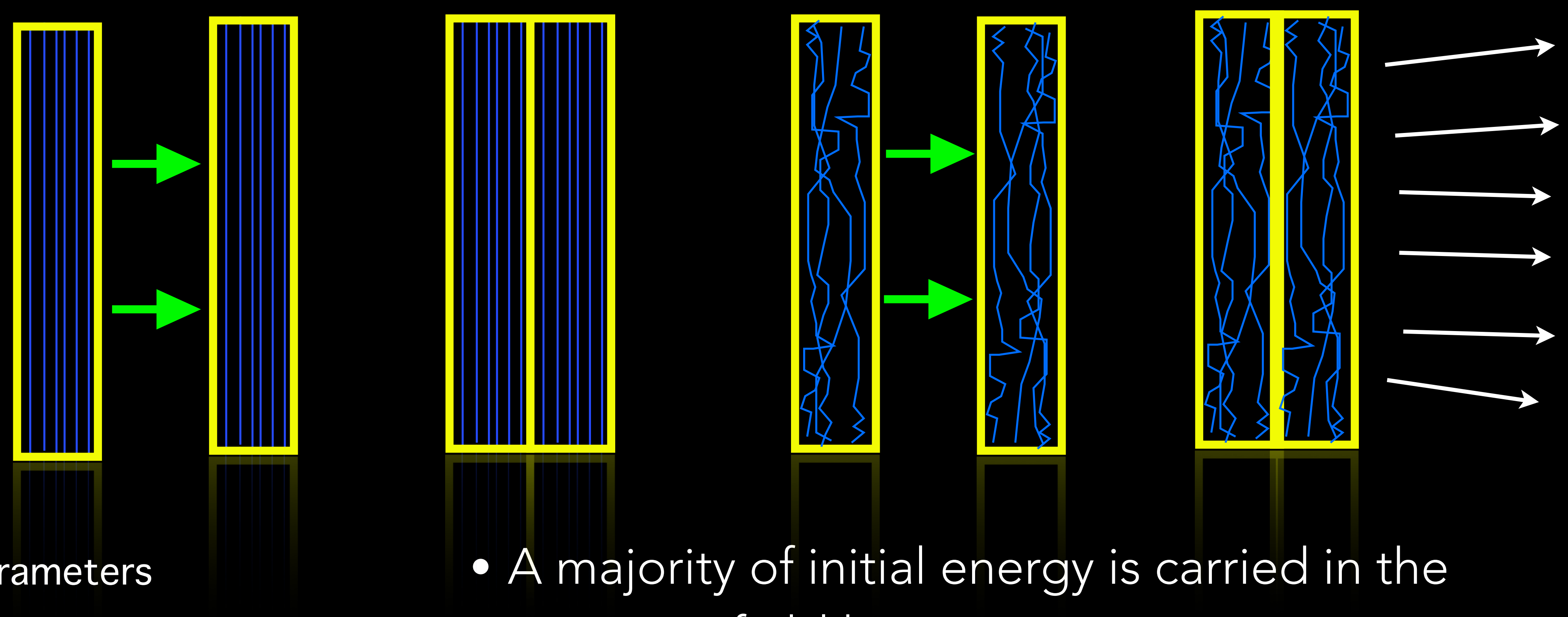
- The internal-shock model requires fine-tuning
- The free parameters Γ, B and γ_{el} must be carefully adjusted so that the energy scaling of the spectra matches observations
- Additionally, the radiative and dynamical timescales imply that the electrons are cooled very quickly by synchrotron radiation



BOSNJAK ET AL (2010)

$$\dot{\gamma}_{\rm sync} \ll \frac{\Delta r'}{c}$$

DISSIPATION: POYNTING



- Important parameters

$$\sigma = \frac{B^2}{4\pi\Gamma\rho c^2}$$

ICMART Model

- A majority of initial energy is carried in the magnetic field lines.
- Early internal shocks distort magnetic fields
- Regions of turbulent fields collide triggering reconnection avalanche.
- 2nd order Fermi acceleration slowly heats particles

MODEL COMPARISON

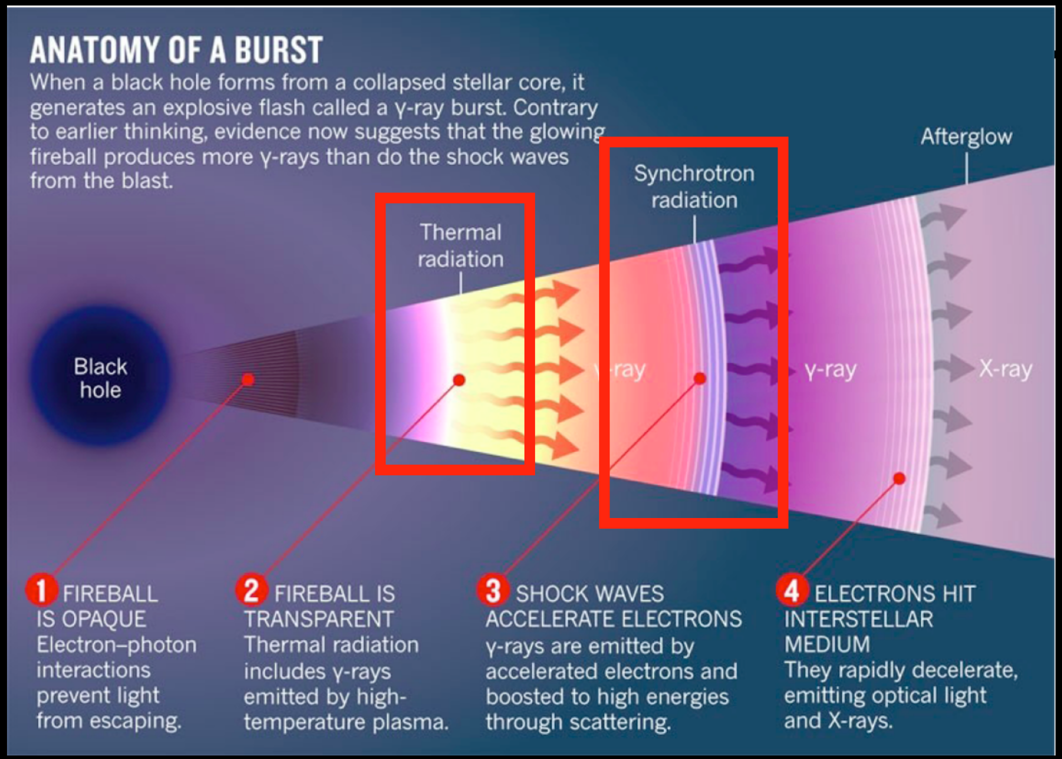
Photosphere

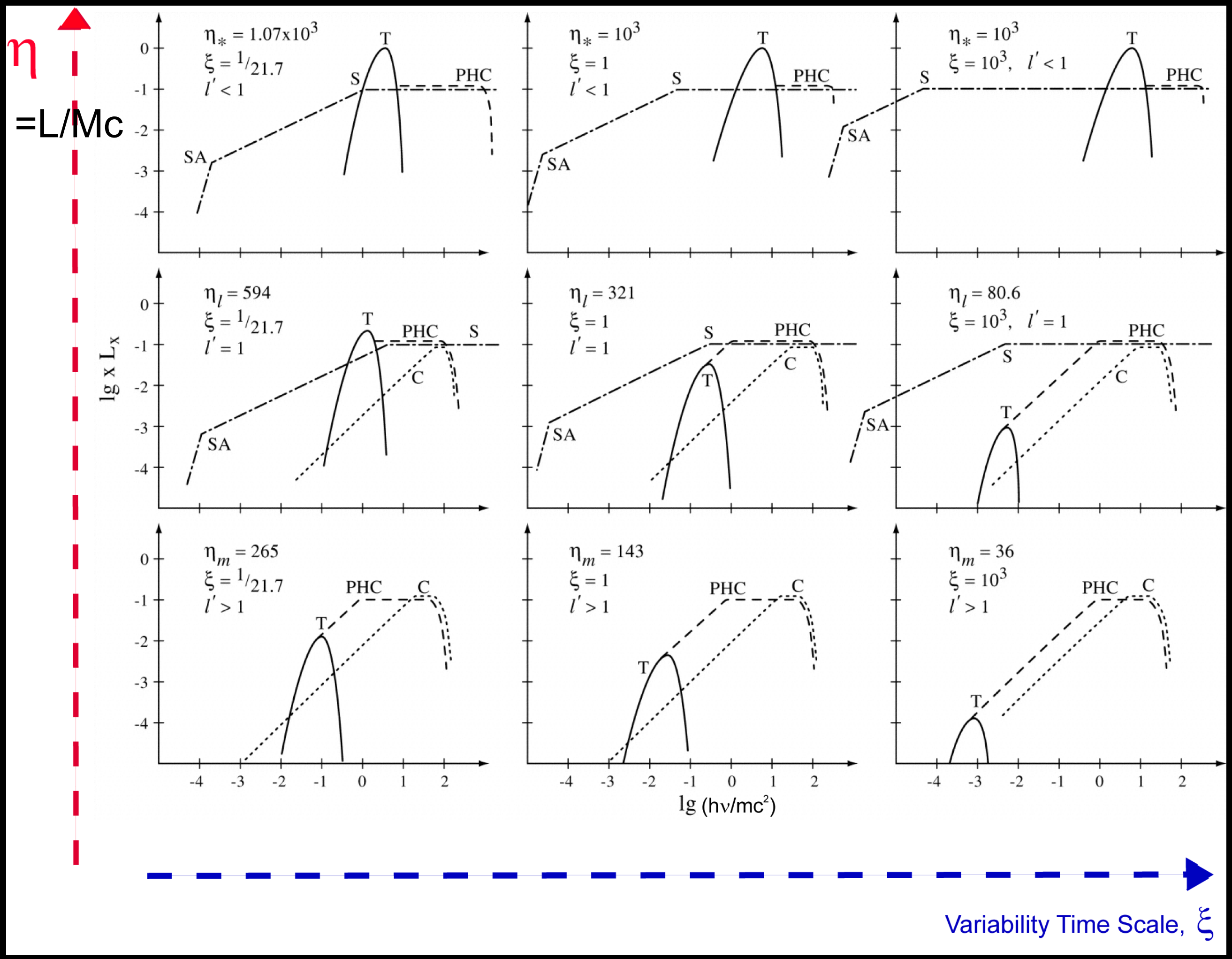
- Simple and natural spectra
- Variety of spectral shapes
- Dynamics rely on central engine
- Variability is adhoc

Non-thermal Dissipation

- Spectra require fine-tuning
- Variety of spectral shapes
- Dynamics rely on central engine
- Variability comes naturally

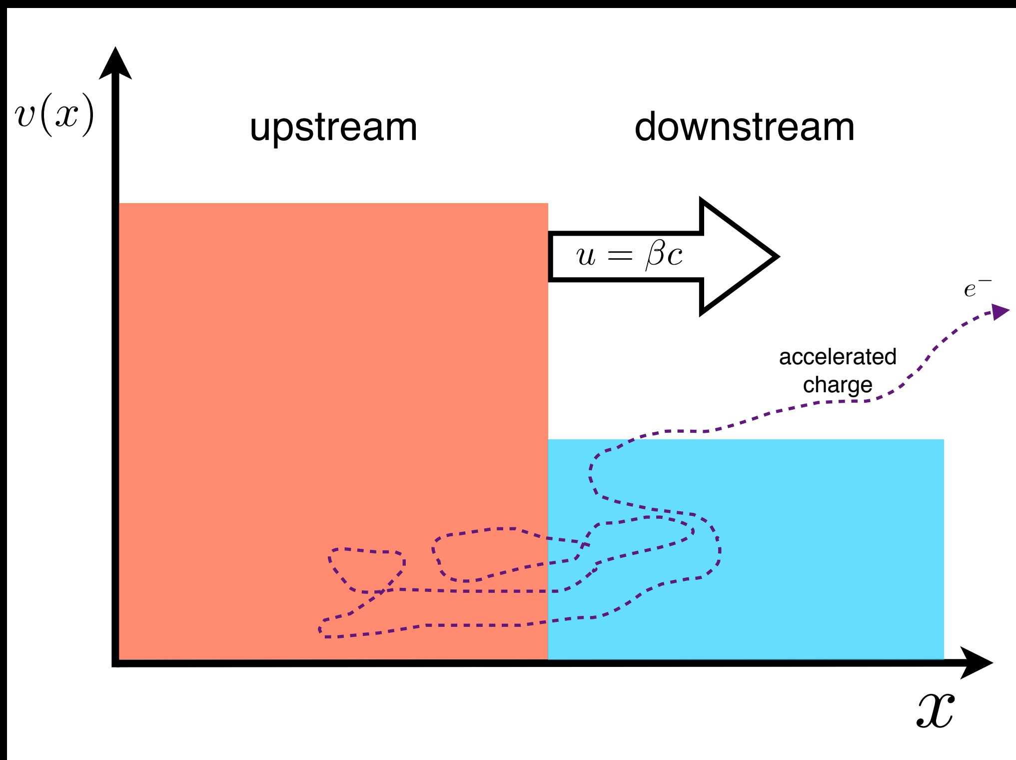
TWO-ZONE EMISSION

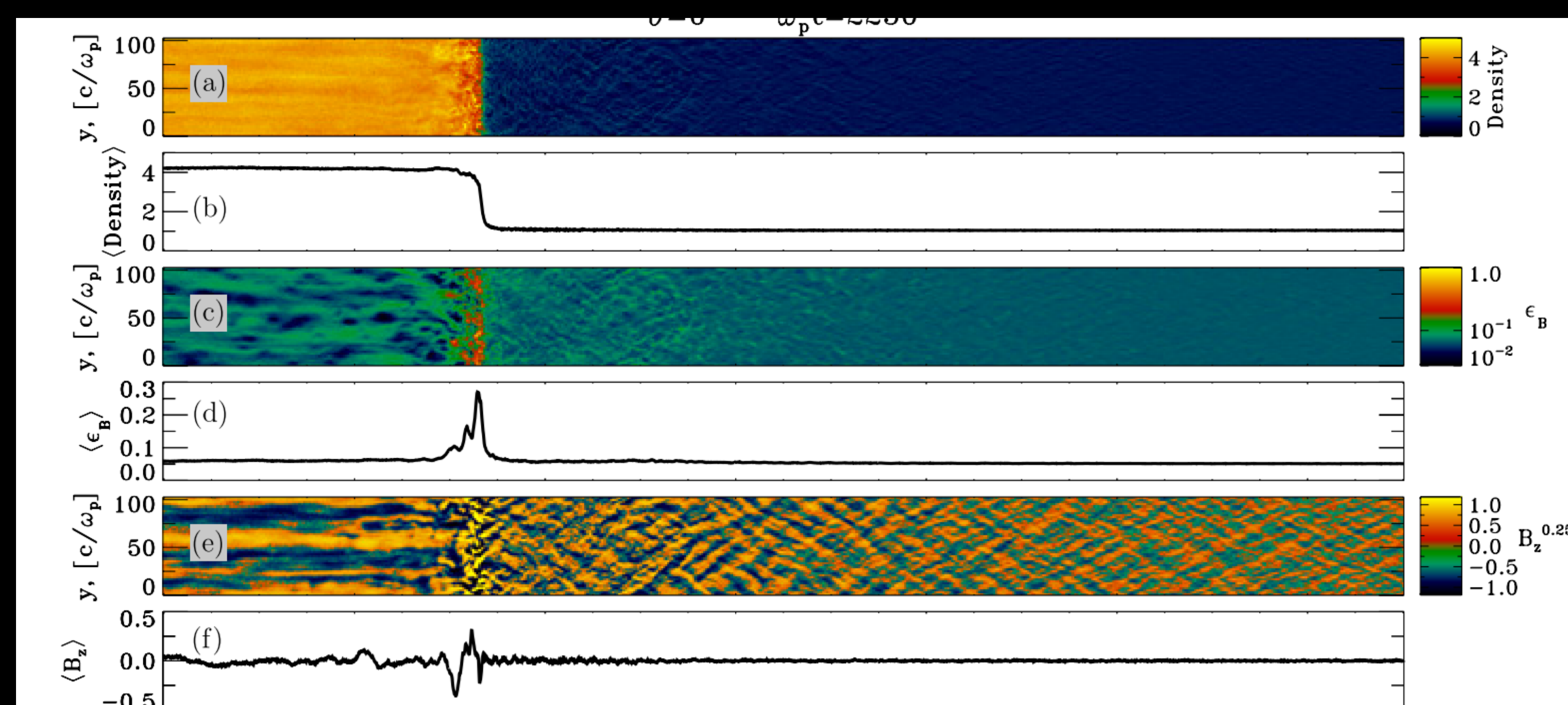




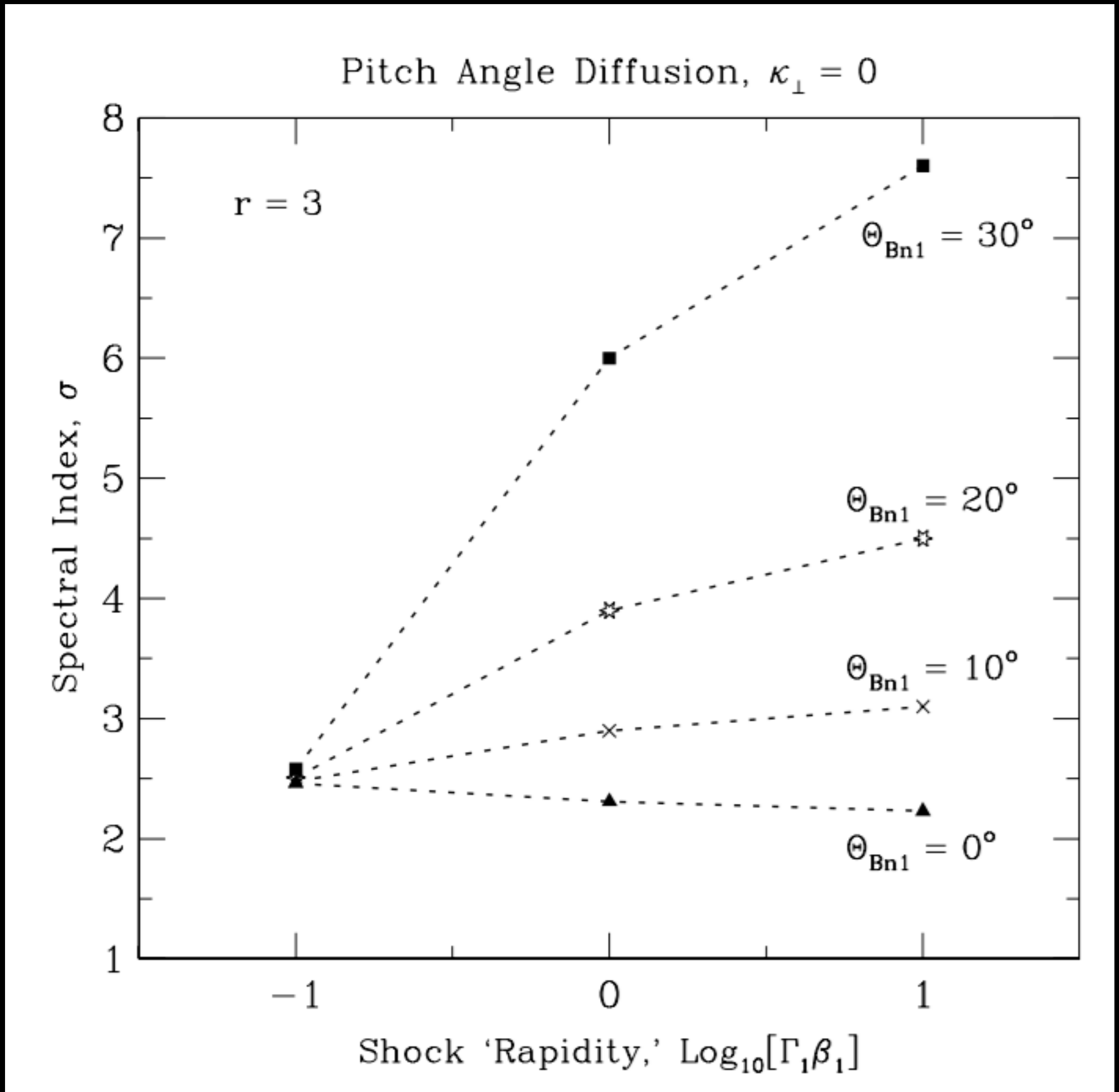
WHAT IF WE INCLUDE BOTH COMPONENTS?

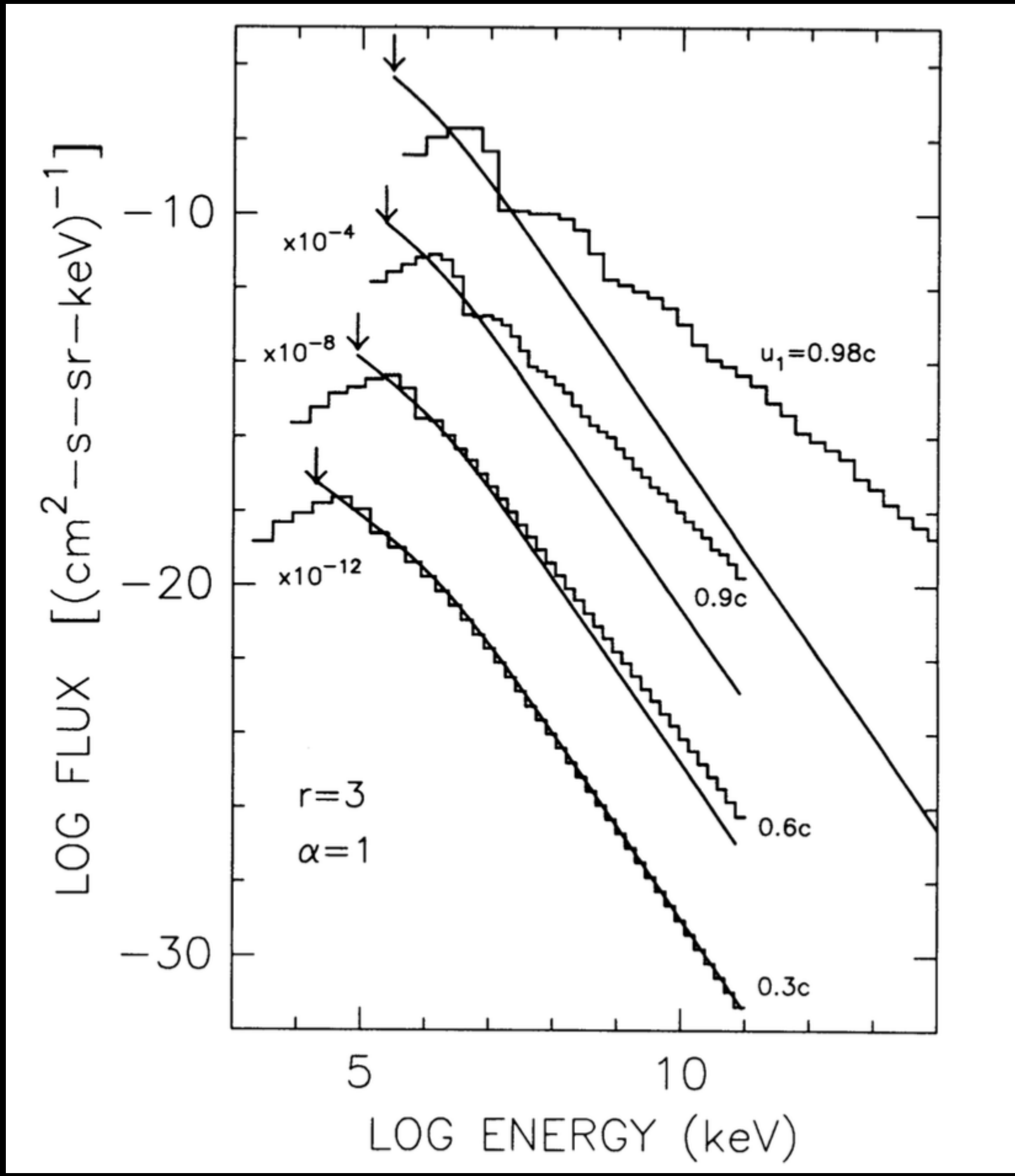
PARTICLE ACCELERATION



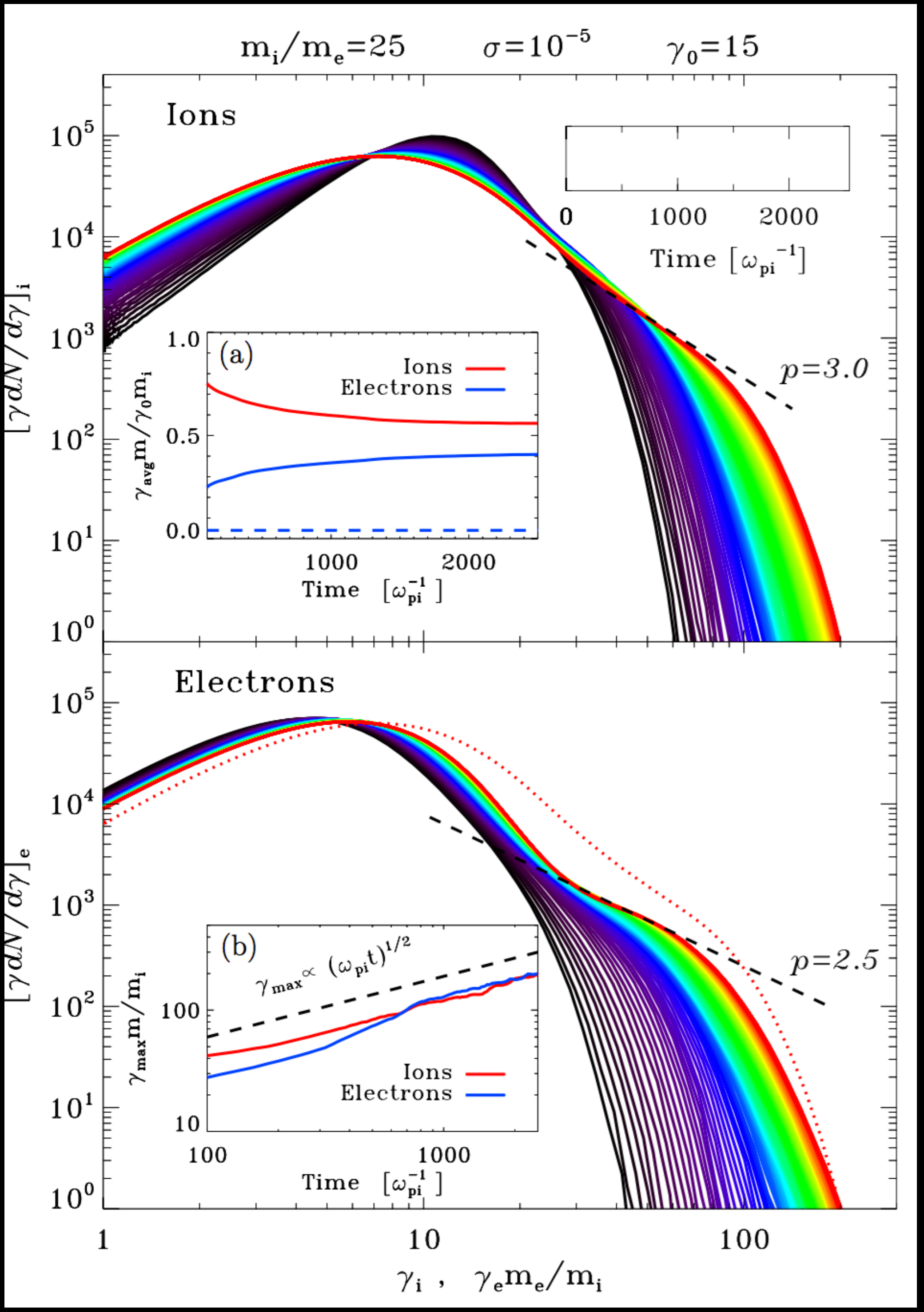


PARTICLE ACCELERATION

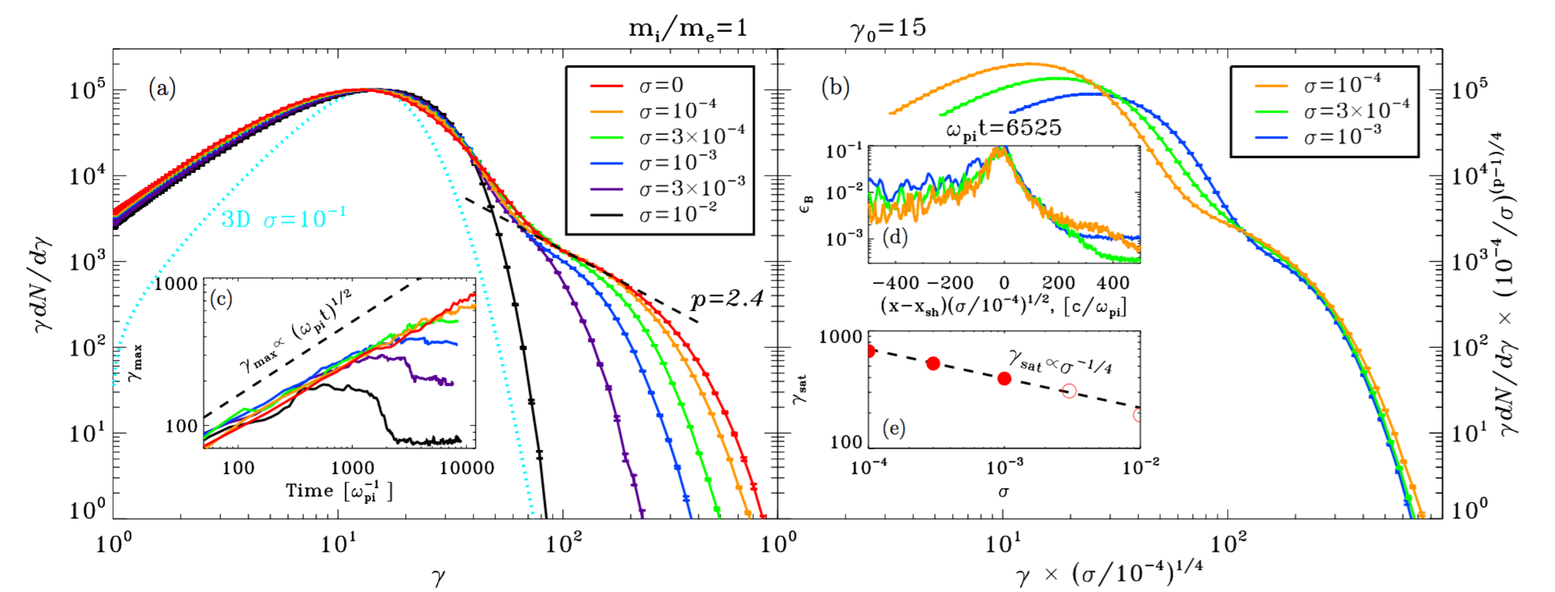




PARTICLE ACCELERATION



Spitkovsky (2013)



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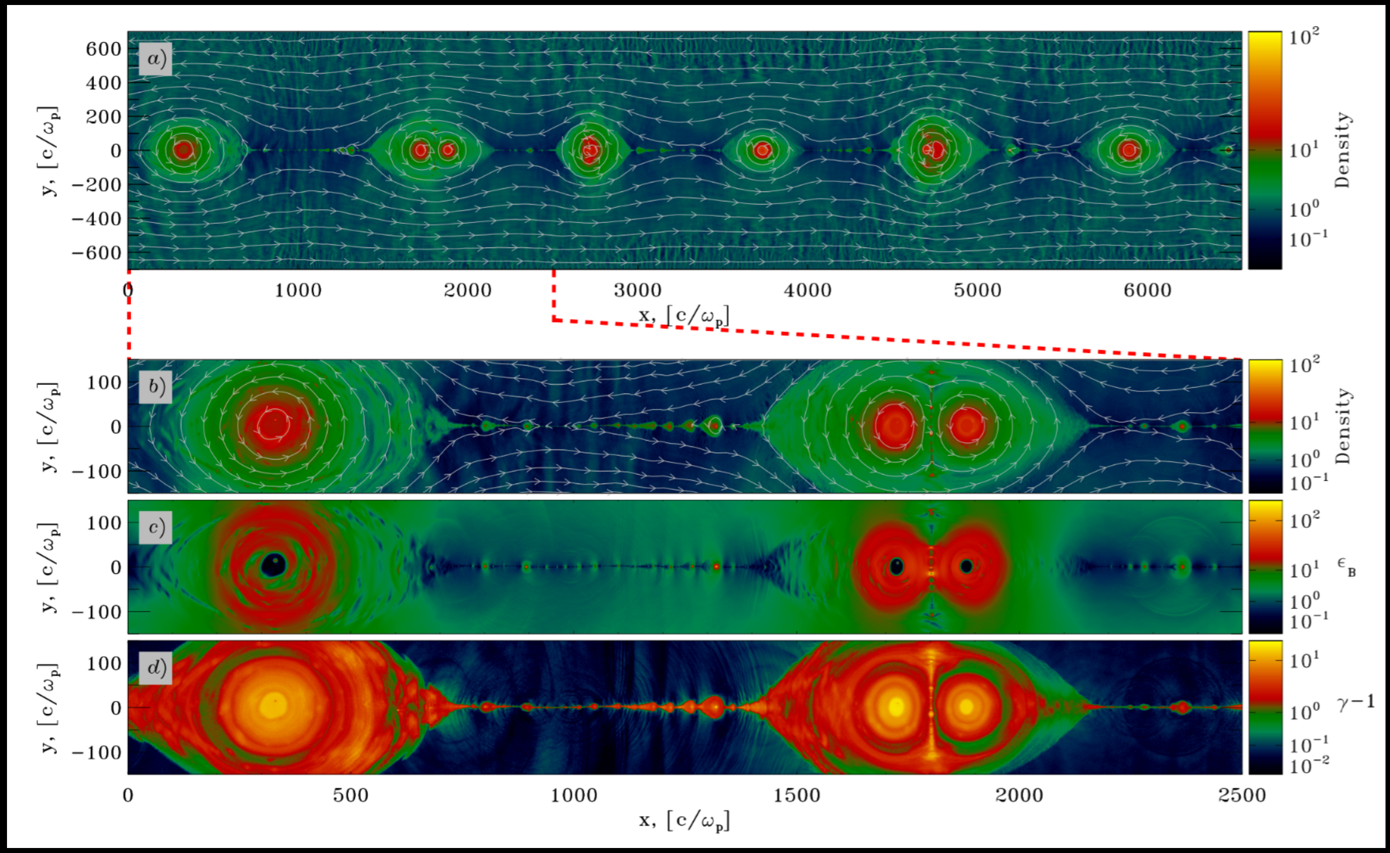
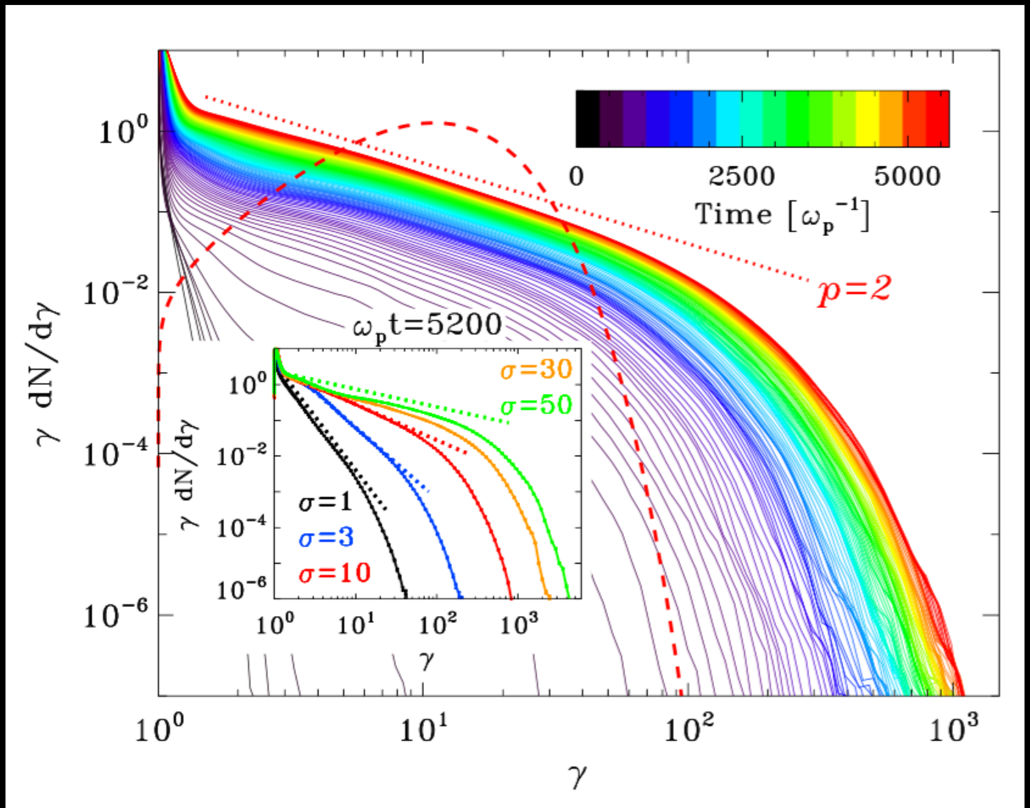


Spitkovsky (2014)



Magnetic Reconnection

SUMMARY

- Emission Mechanisms
  - Photospheric
    - Easiest scenario to imagine. Radiation is emitted when outflow becomes optically thin.
    - In the simplest form, emission would be in the form of a blackbody.
    - High-latitude emission can broaden the spectrum.
    - If energy is dissipated below or near the photosphere, the spectrum can be modified and appear non-thermal.

SUMMARY

- Emission Mechanisms
  - External Shocks
    - Blast wave shocks external medium
    - The dissipated energy can shock electrons to high energies which then radiate via synchrotron emission
    - Slow variability

SUMMARY

- Emission Mechanisms
  - Internal Shocks
    - Rapid shocks in the outflow
    - The dissipated energy can shock electrons to high energies which then radiate via synchrotron emission
    - Fast variability: inefficient

SUMMARY

- Particle Acceleration
  - Internal Shocks
    - Shocks -> We know how to do it
    - Magnetic Reconnection -> We almost know how to do it