Gamma-Ray Bursts & Relativistic Jets

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Explore 2022
Summer School
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Goals of the course

- **To learn background knowledge about gamma-ray bursts (GRBs)**
- **To study an example of how a branch of astrophysics develops from observations**
- **To gain proficiency with (special-)relativistic calculation**

Gamma-Ray Bursts & Relativistic Jets

Lecture 1: Relativistic motion in the sources of gamma-ray bursts

- Historical remarks on GRBs
- Observational facts: prompt emission
- Observational facts: afterglow phase
- The compactness puzzle: relativistic motion in GRB sources
- The GRB phenomenon: global picture

Lecture 2: Basics of gamma-ray burst theory

- Questions
- Jets in GRBs: Acceleration — Energy dissipation — Deceleration
- Summary of GRB physics
- Contemporary GRB studies

Tutorial: Emission mechanisms for prompt and afterglow phases

- Internal shocks as a prompt emission mechanism
- The external forward shock synchrotron afterglow model

Historical remarks on GRBs

Gamma-ray bursts: discovery

- The US military VELA program

Treaty Banning Nuclear Weapon Tests in the Atmosphere, in Outer Space and under Water Signed by the Original Parties, the Union of Soviet Socialist Republics, the United Kingdom of Great Britain and Northern Ireland and the United States of America at Moscow : 5 August 1963

The Governments of the United States of America, the United Kingdom of Great Britain and Northern Ireland, and the Union of Soviet Socialist Republics, hereinafter referred to as the « Original Parties, »

Proclaiming as their principal aim the speediest possible achievement of an agreement on general and complete disarmament under strict international control in accordance with the objectives of the United Nations which would put an end to the armaments race and eliminate the incentive to the production and testing of all kinds of weapons, including nuclear weapons,

Seeking to achieve the discontinuance of all test explosions of nuclear weapons for all time, determined to continue negotiations to this end, and desiring to put an end to the contamination of man's environment by radioactive substances,

Have agreed as follows :

Article I

1. Each of the Parties to this Treaty undertakes to prohibit, to prevent, and not to carry out any nuclear weapon test explosion, or any other nuclear explosion, at any place under its jurisdiction or control :

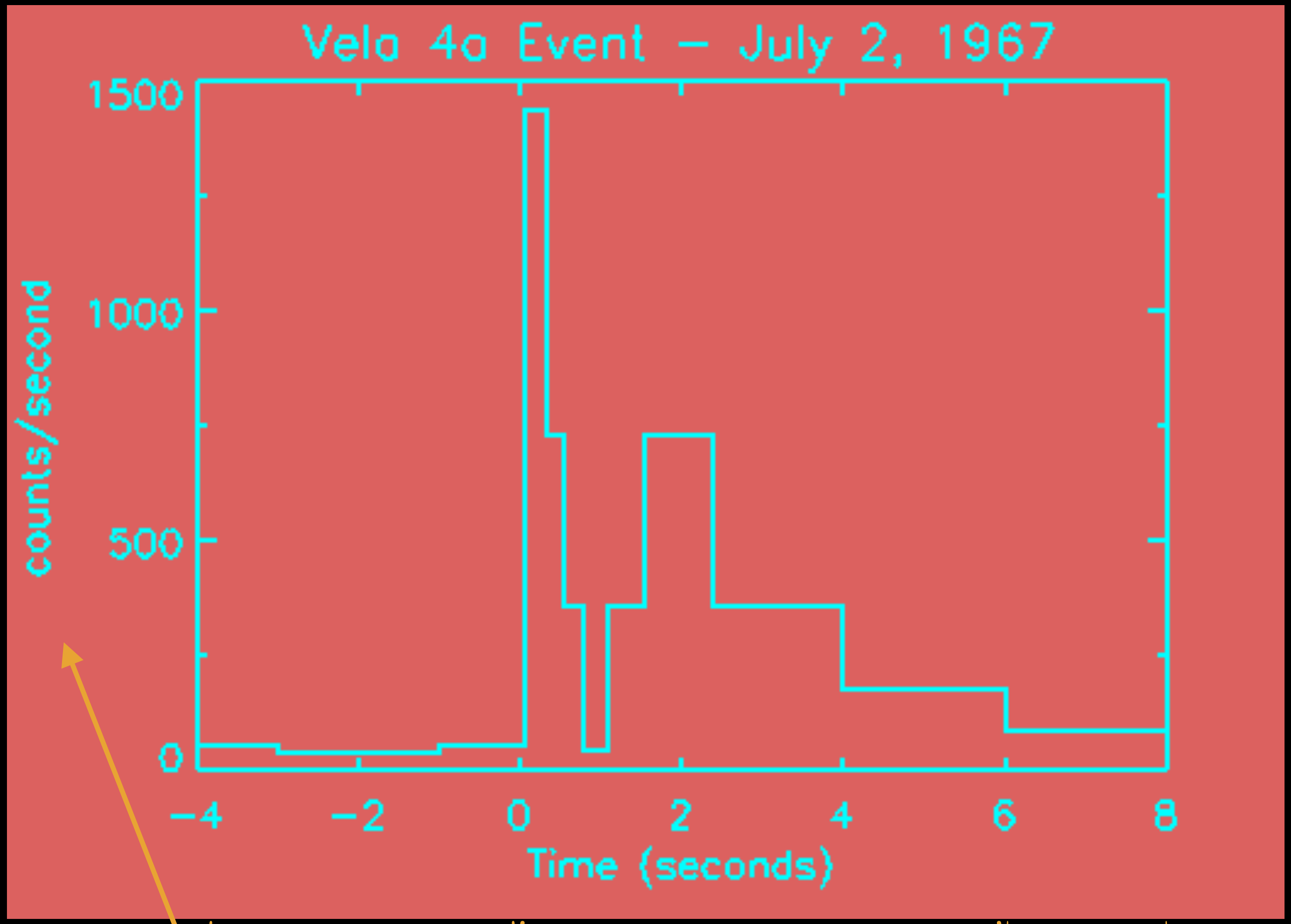
   (a) in the atmosphere ; beyond its limits, including outer space ; or under water, including territorial waters or high seas ; or

   (b) in any other environment if such explosion causes radioactive debris to be present outside the territorial limits of the State under whose jurisdiction or control such explosion is conducted. It is understood in this connection that the provisions of this subparagraph are without prejudice to the conclusion of a Treaty resulting in the permanent banning of all nuclear test explosions, including all such explosions underground, the conclusion of which, as the Parties have stated in the Preamble to this Treaty, they seek to achieve.

2. Each of the Parties to this Treaty undertakes furthermore to refrain from causing, encouraging, or in any way participating in, the carrying out of any nuclear weapon test explosion, or any other nuclear explosion, anywhere which would take place in any of the environments described, or have the effect referred to, in paragraph 1 of this Article.

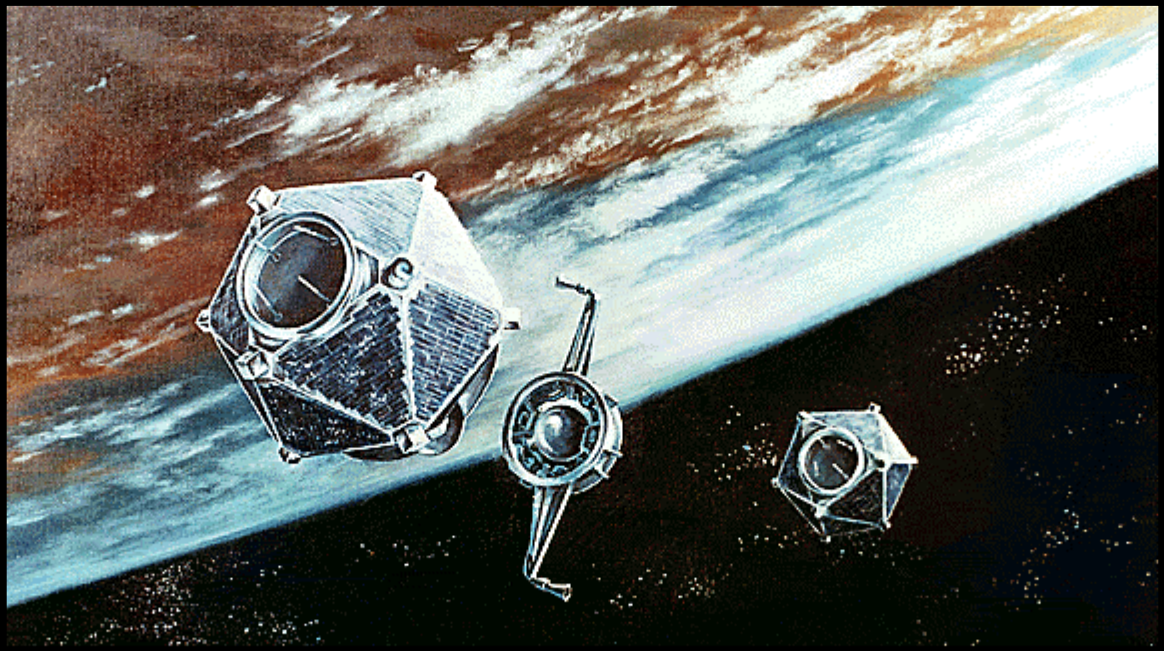
Gamma-ray bursts: discovery

- The US military VELA program
(3 pairs of satellites: 1963, 64 and 65)
- 1973: discovery paper (Klebesadel et al.)
- As of1980s: more studies with scientific satellites



Background ⟶ Transient ⟶ Background

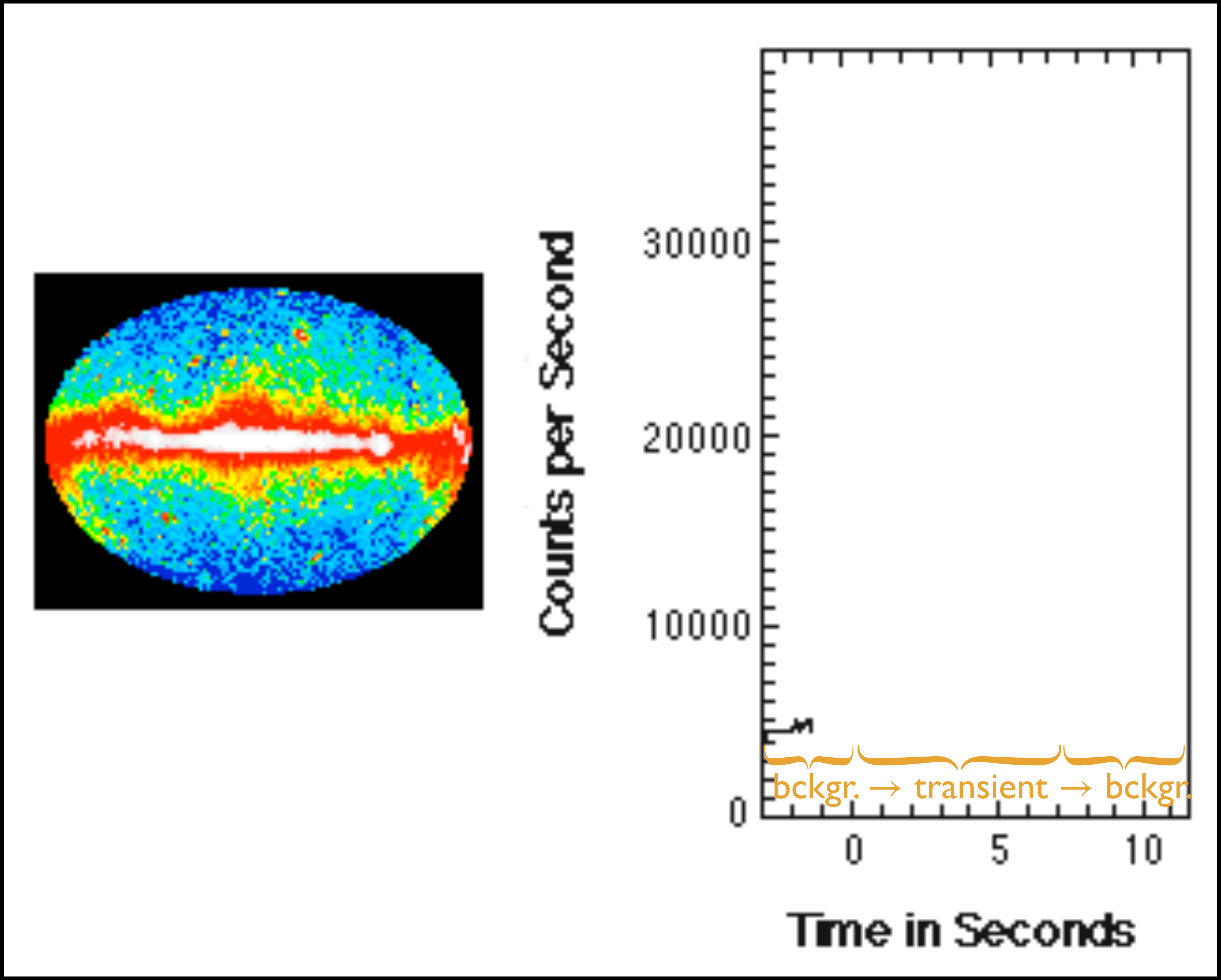
Photon counts in γ-ray band
($E_{\rm ph} \gtrsim 100\,{\rm keV}$)



Observational facts: prompt emission

What is a gamma-ray burst?

A non-repeating localized transient electromagnetic signal with energy output mostly in hard X-ray or gamma-ray photons of extra-galactic origin



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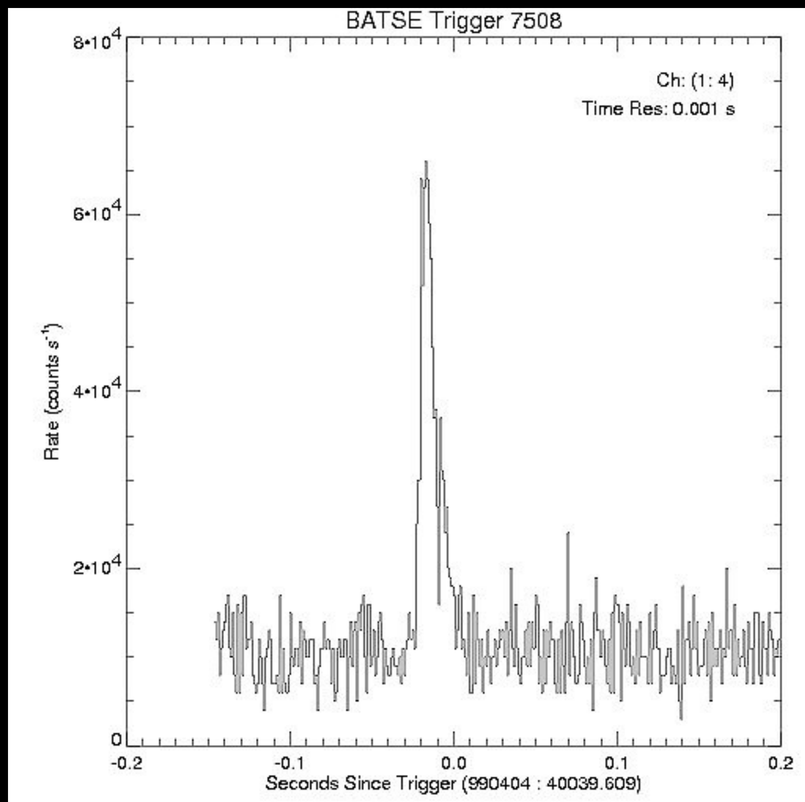
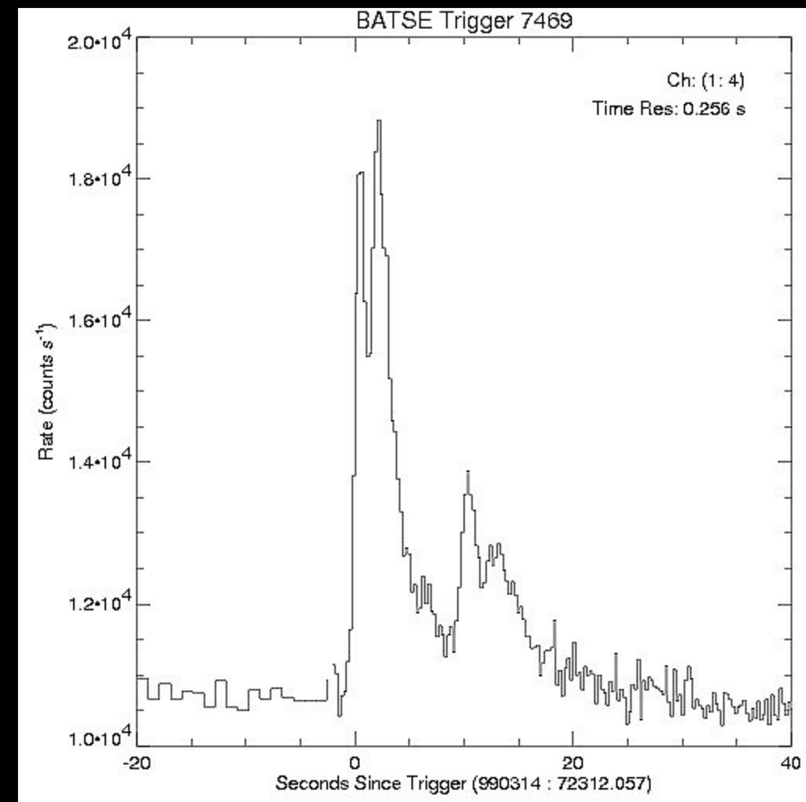
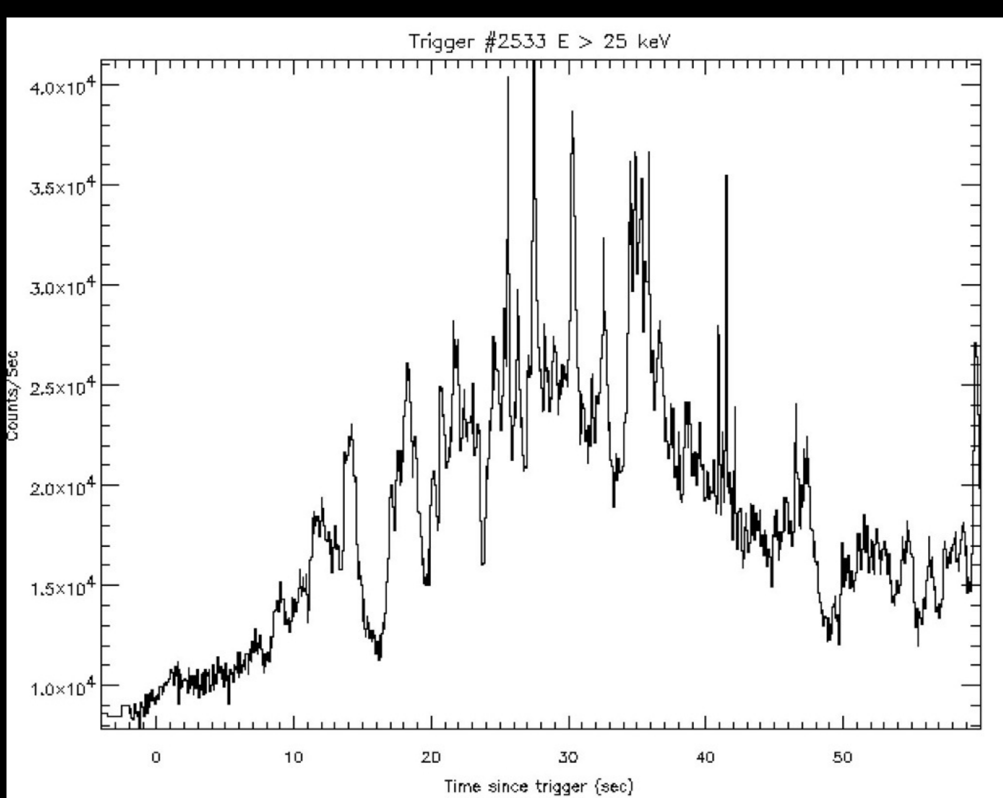
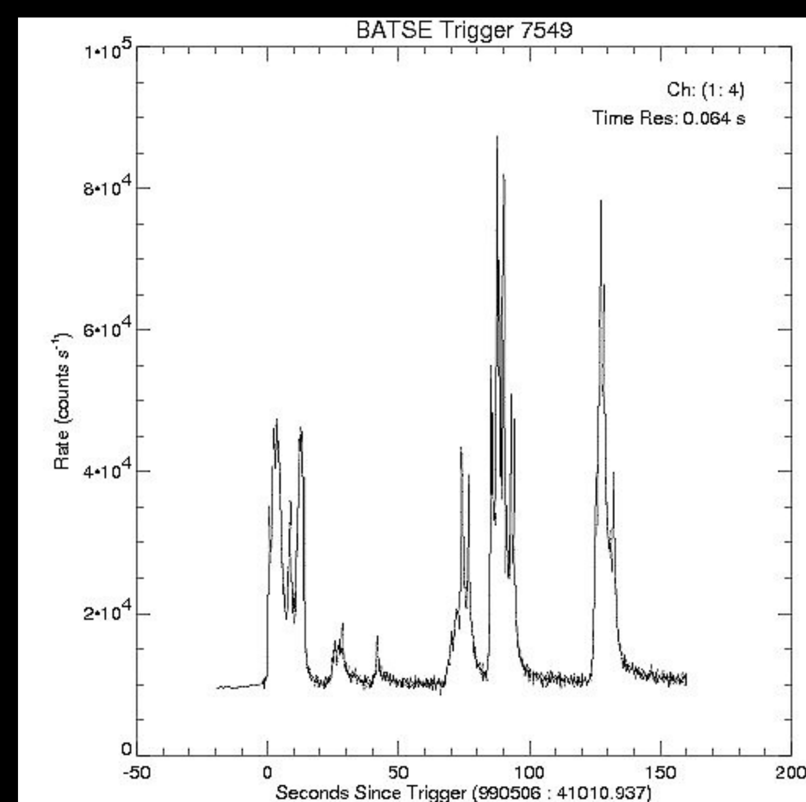
Light curves: diversity and variability









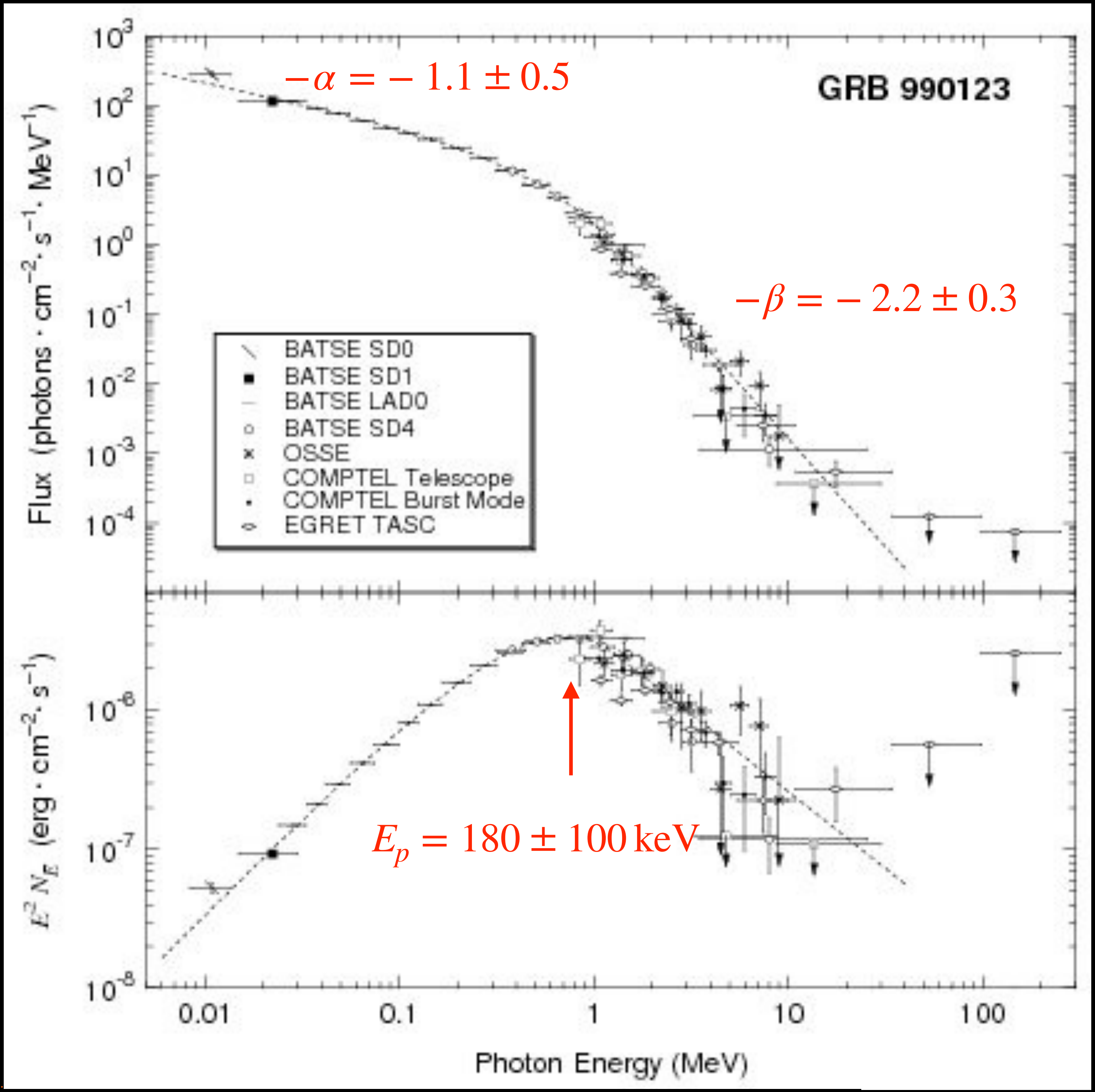
- Duration:
  $T_{90} = 0.1 \rightarrow 100\,\mathrm{s}$
- Single- or multi-pulsed
- Variability timescale:
  $\delta t_{\rm var} < 0.1\,\mathrm{s}$
- Gamma-ray fluence:

$$\mathcal{F}_\gamma = 10^{-7} \rightarrow 10^{-4}\,\mathrm{erg/cm^2}$$

Total detected energy in transient per unit detector surface

(BATSE catalog, Paciesas et al. 1999)

Non-thermal spectrum



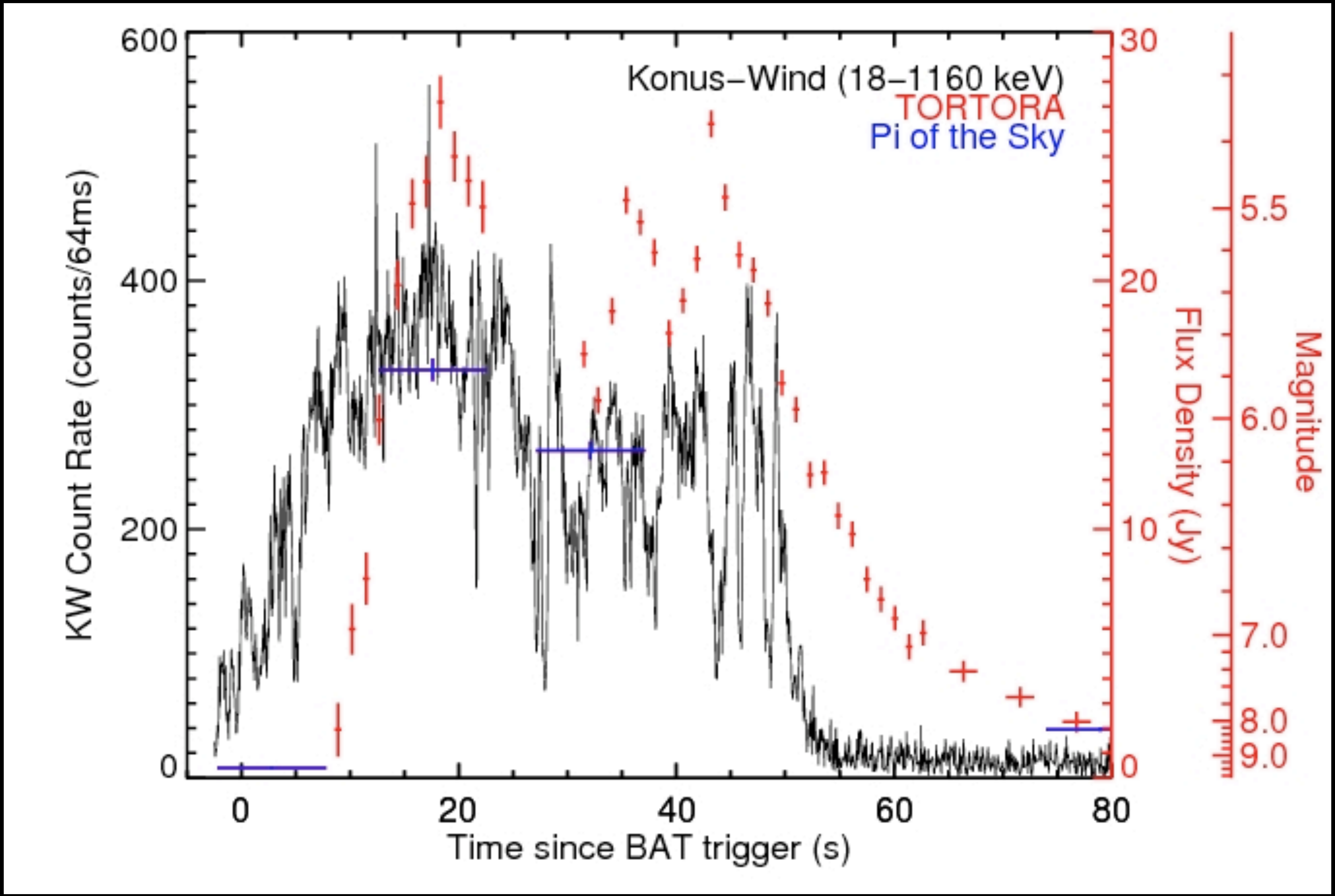
(BATSE catalog, Paciesas et al. 1999)

- Non-thermal spectra, made up of power-law segments
- Define slopes α, β in photon spectrum:

$$S_{\rm ph}(E_{\rm ph}) = \frac{{\rm d}N_{\rm ph}}{{\rm d}t\,{\rm d}S\,{\rm d}E_{\rm ph}} \quad [{\rm ph/cm^2/s/MeV}]$$

- Peak energy nearly always present

The optical prompt emission

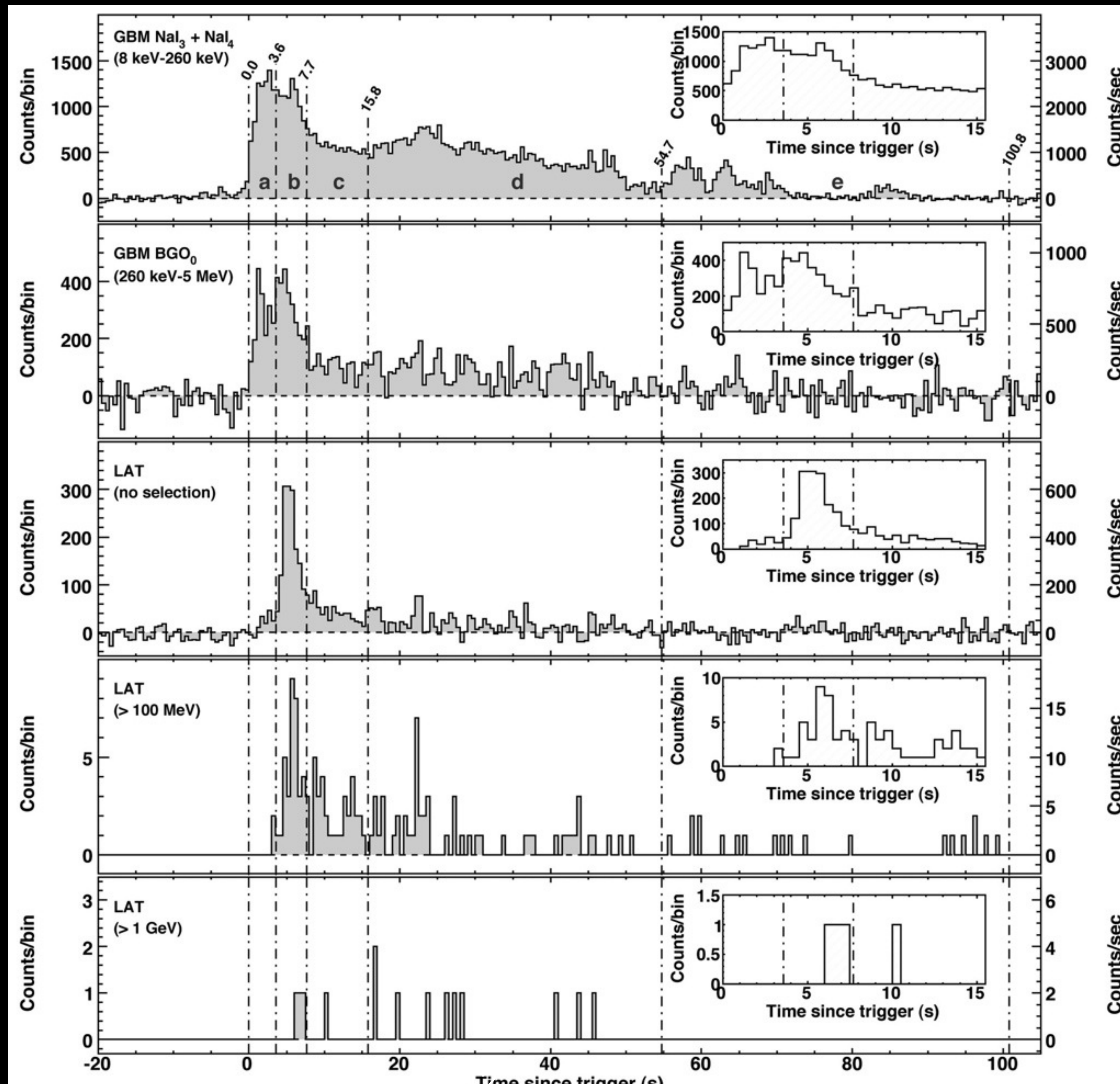


Naked eye burst (Racusin et al. 2008): an extreme case

The GeV prompt emission

Detection at high energy by *Fermi*

GRB 080916C (Abdo et al. 2009)



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What is the energy scale of GRBs? The great question of the 1970s to 1997!

⇒ Depends on the distance scale…

- The US military VELA program (3 pairs of satellites: 1963, 64 and 65)
- 1973: discovery paper (Klebesadel et al.)
- 1970-1980: more studies with scientific satellites
- 1973-1997: distance scale ?

Assuming isotropically emitting source, total energy output is:

$$E_{\mathrm{iso},\gamma} = 4\pi D_L^2 \mathscr{F}_\gamma$$

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Black-board calculation: E_{iso} for different D_L's

What is the energy scale of GRBs?
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Assuming isotropically emitting source, total energy output is:

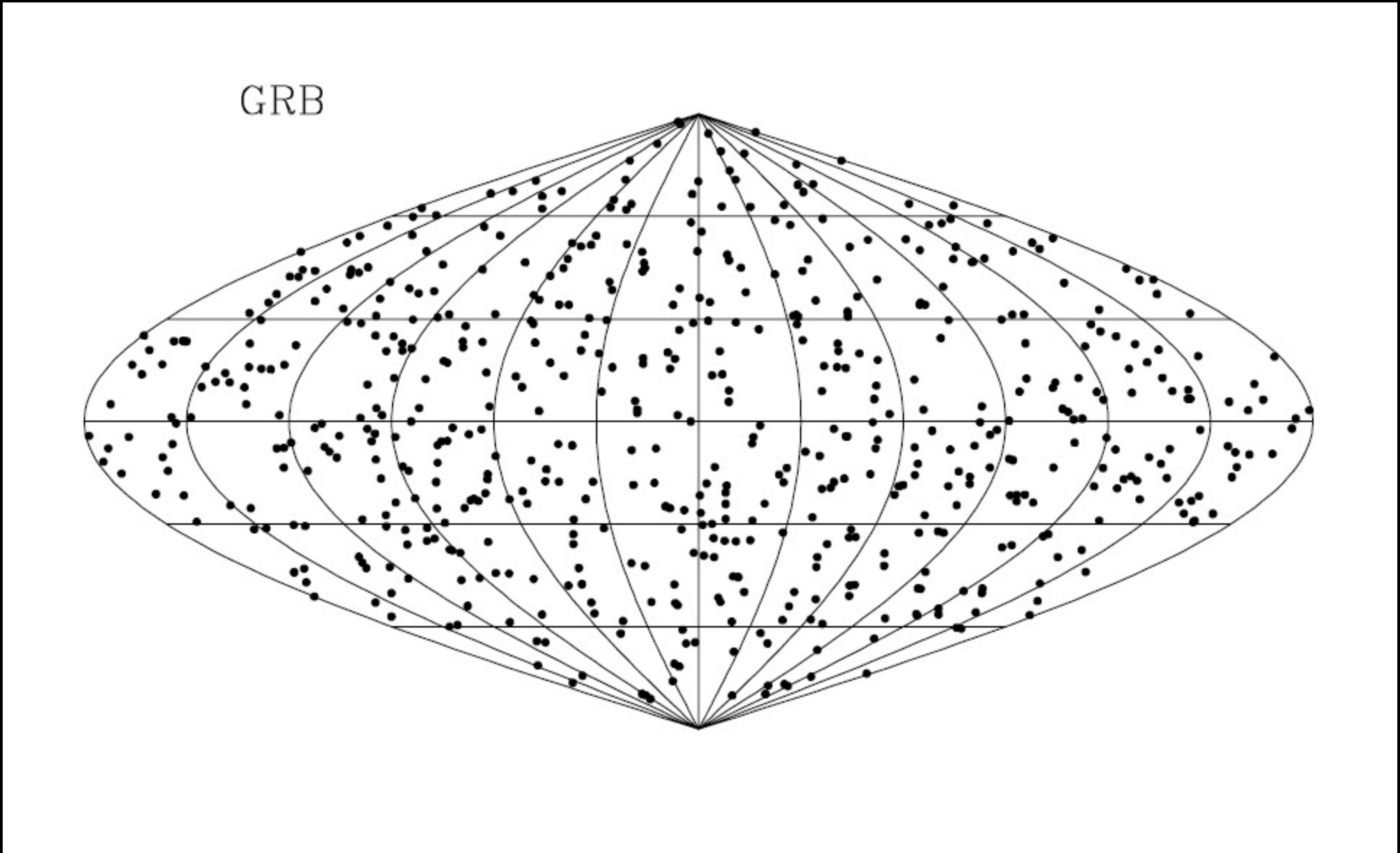
$$E_{\mathrm{iso},\gamma} = 4\pi D_L^2 \mathscr{F}_\gamma$$

Main problem = poor localisation
BATSE: ~ 10 degrees
IPN: ~arcmin, but with a delay of several days

Great Debate between Lamb and Paczynski about distance scale to GRBs (cf. Shapley & Curtis debate on the scale of the Universe in 1920)

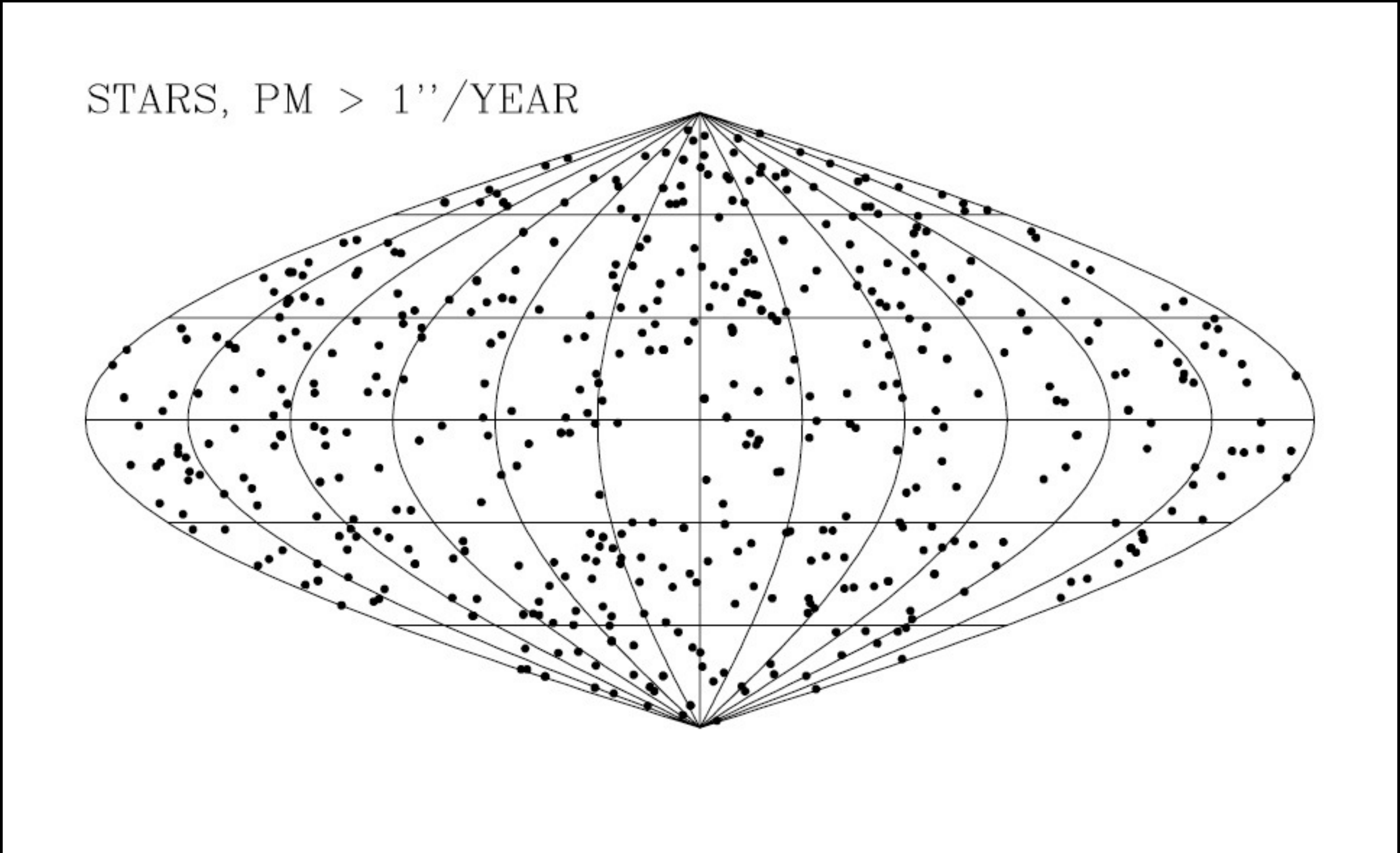
GRB distance scale?

GRB sky map (CGRO/BATSE, 1994)



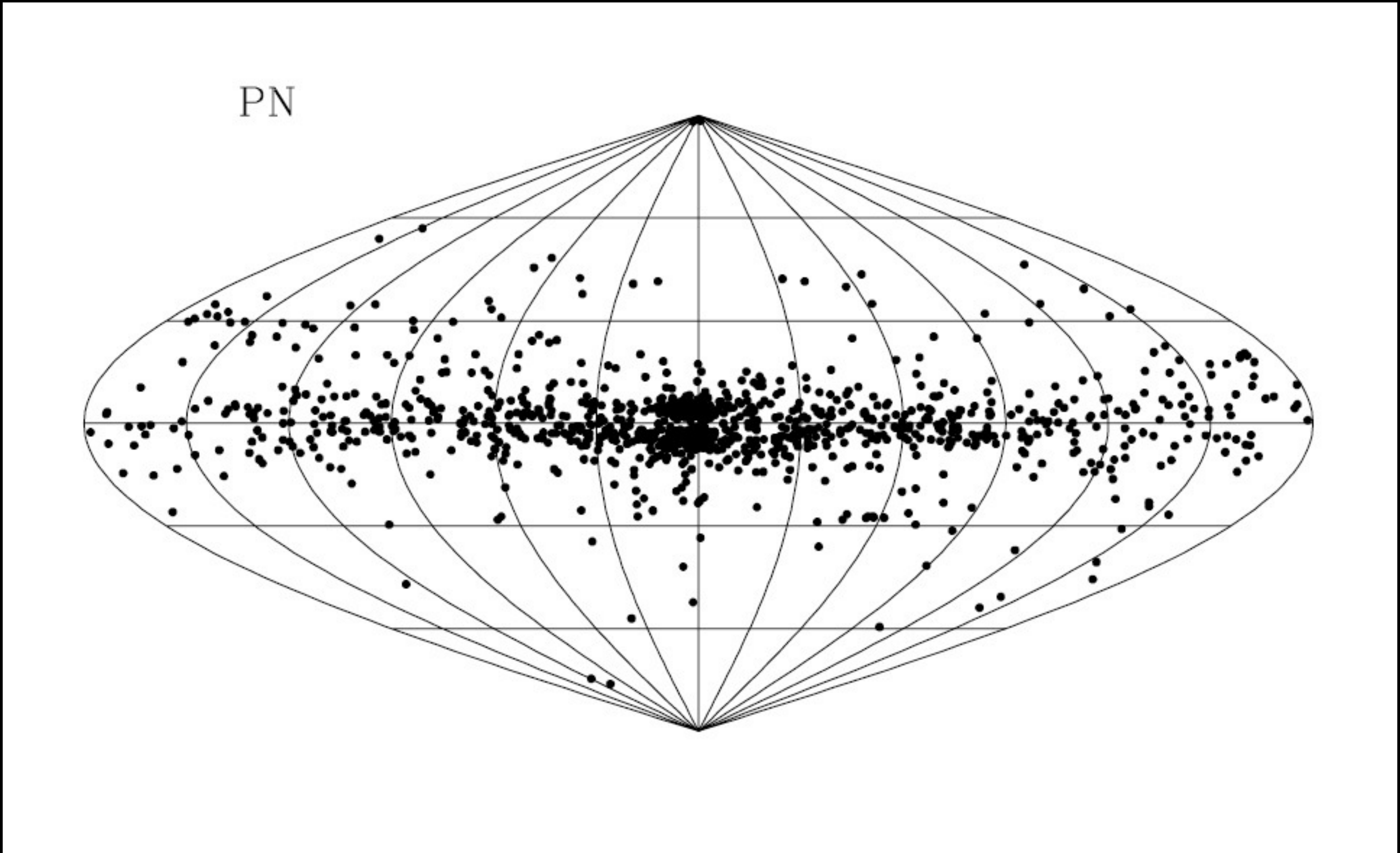
GRB distance scale?

Nearby stars (isotropy)



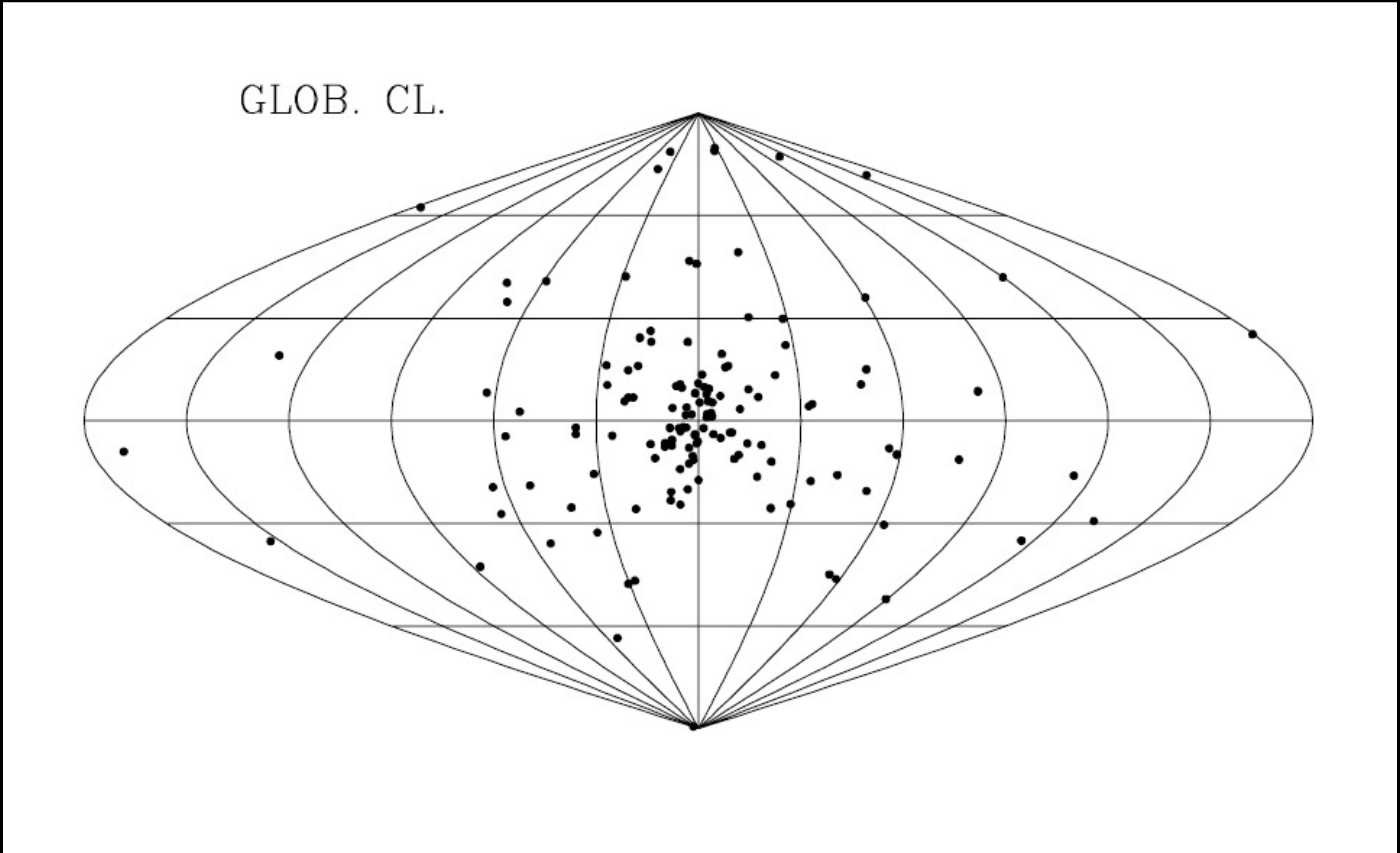
GRB distance scale?

Planetary nebulae (Galactic disk)



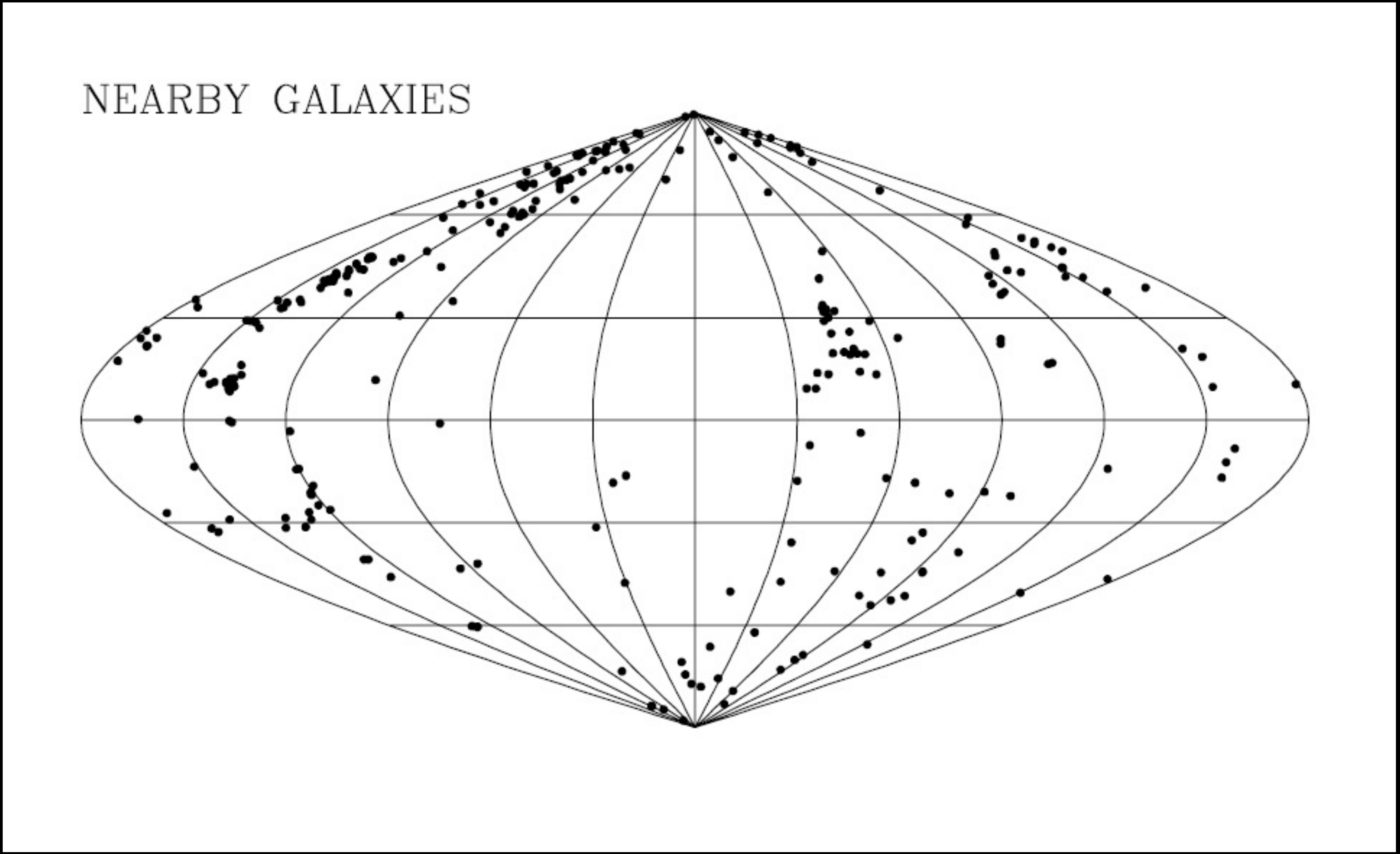
GRB distance scale?

Globular clusters (~spherical halo, Sun is not at the center)



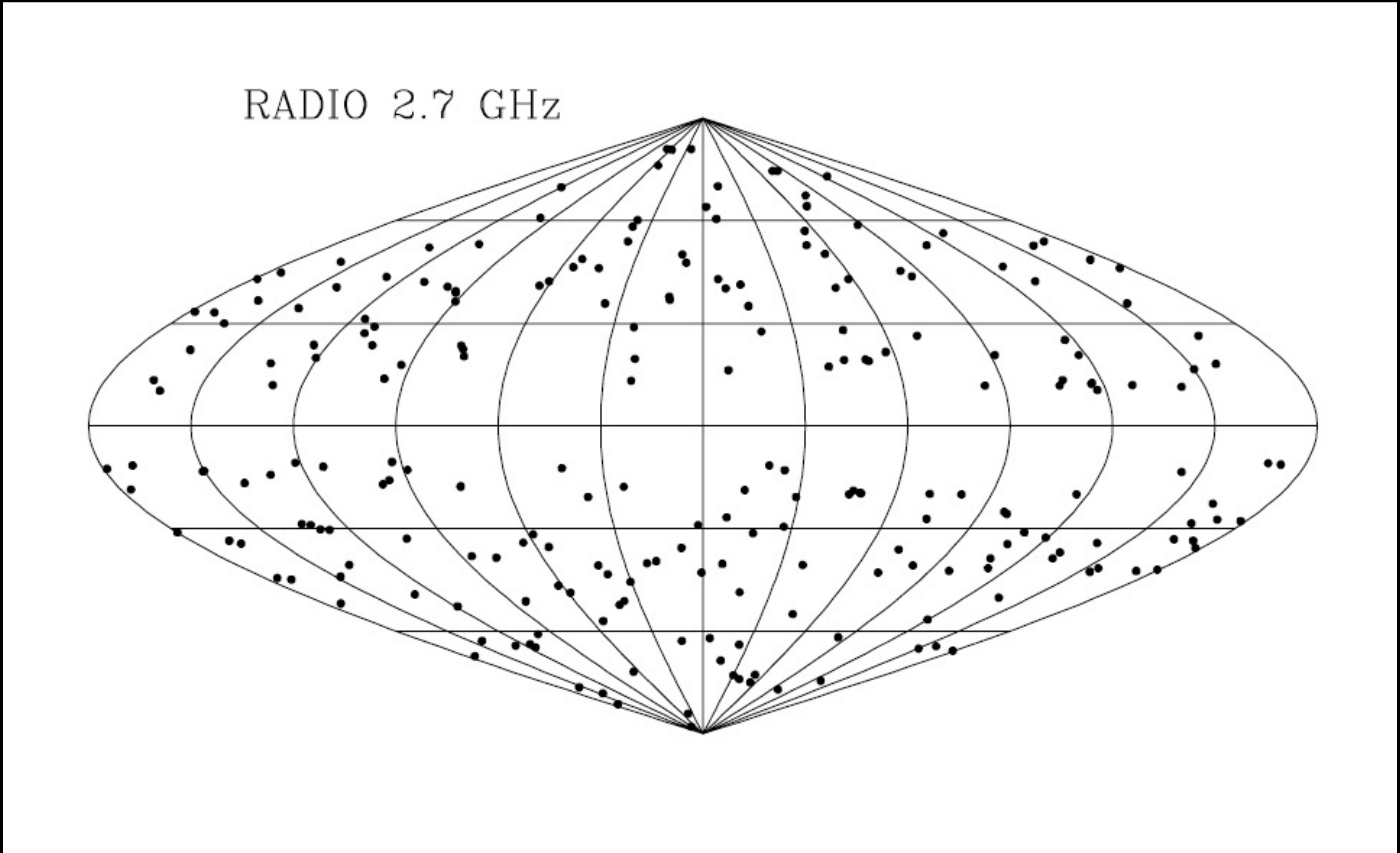
GRB distance scale?

Nearby galaxies (large-scale structure of the Universe)



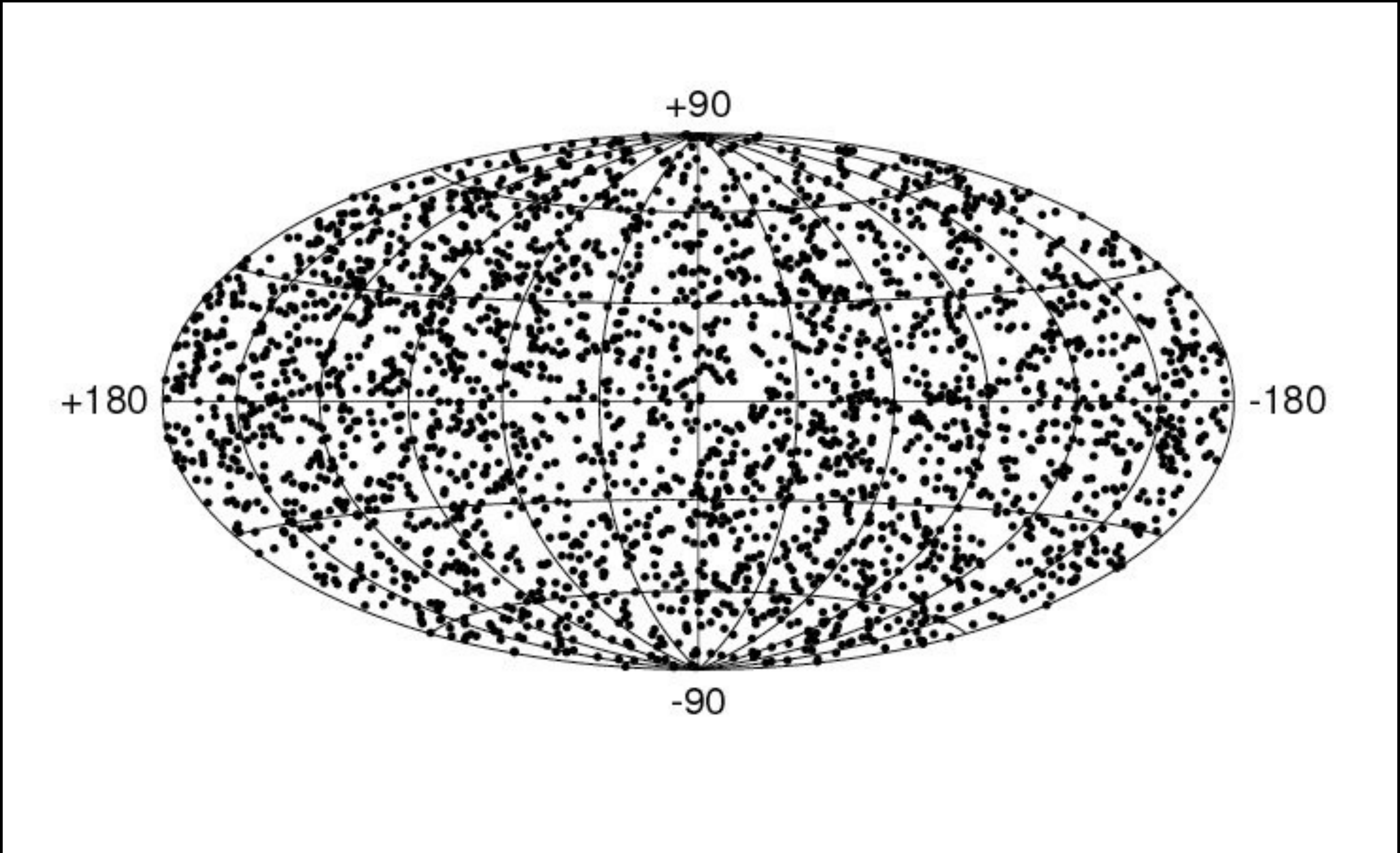
GRB distance scale?

Radio-galaxies (isotropy)



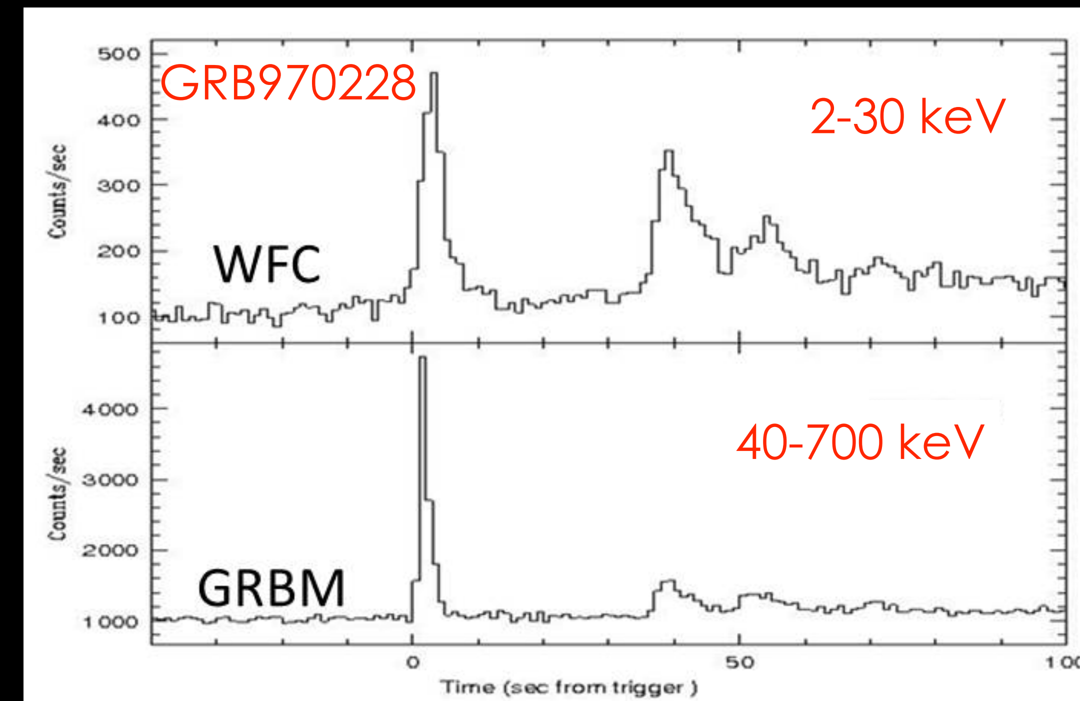
GRB distance scale?

Gamma-ray bursts (final BATSE catalog is isotropic)



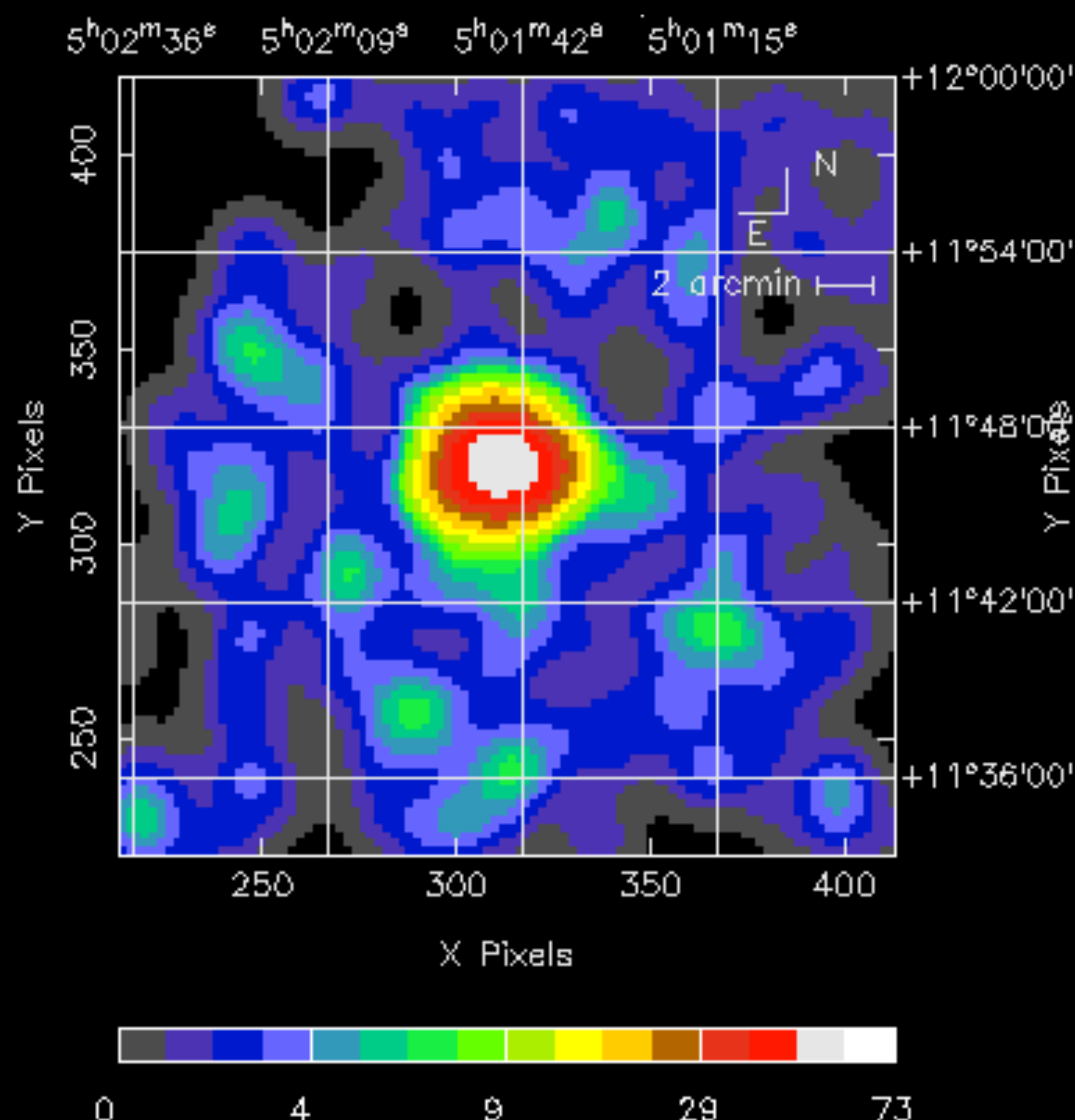
The discovery of afterglows:
Gamma-ray bursts occur at cosmological distance!

Discovery of afterglow phase

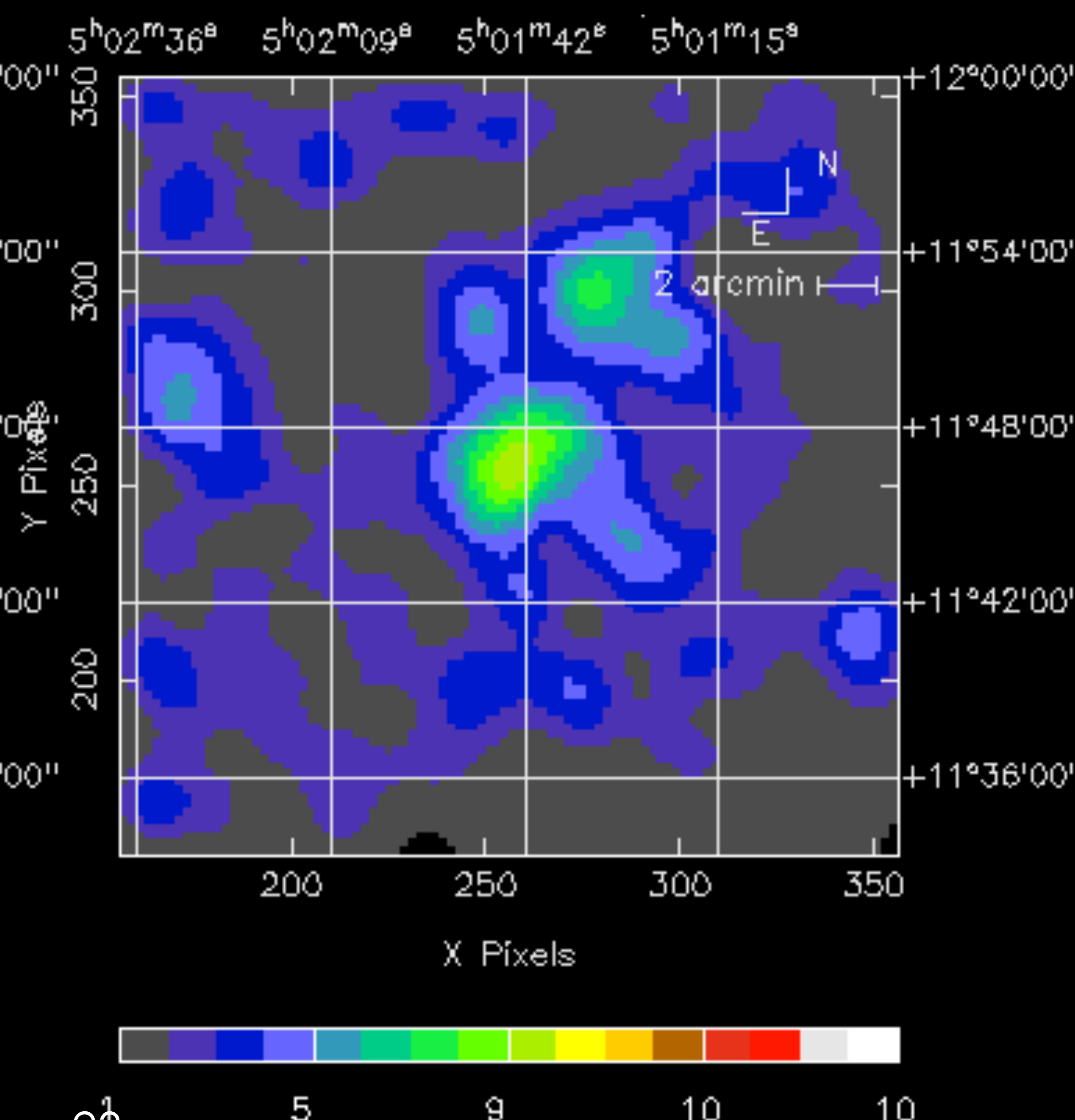


The first X-ray afterglow (GRB 970228):
Beppo-SAX can better localise GRBs thanks to its coded mask (WFC)

1997 Feb 28

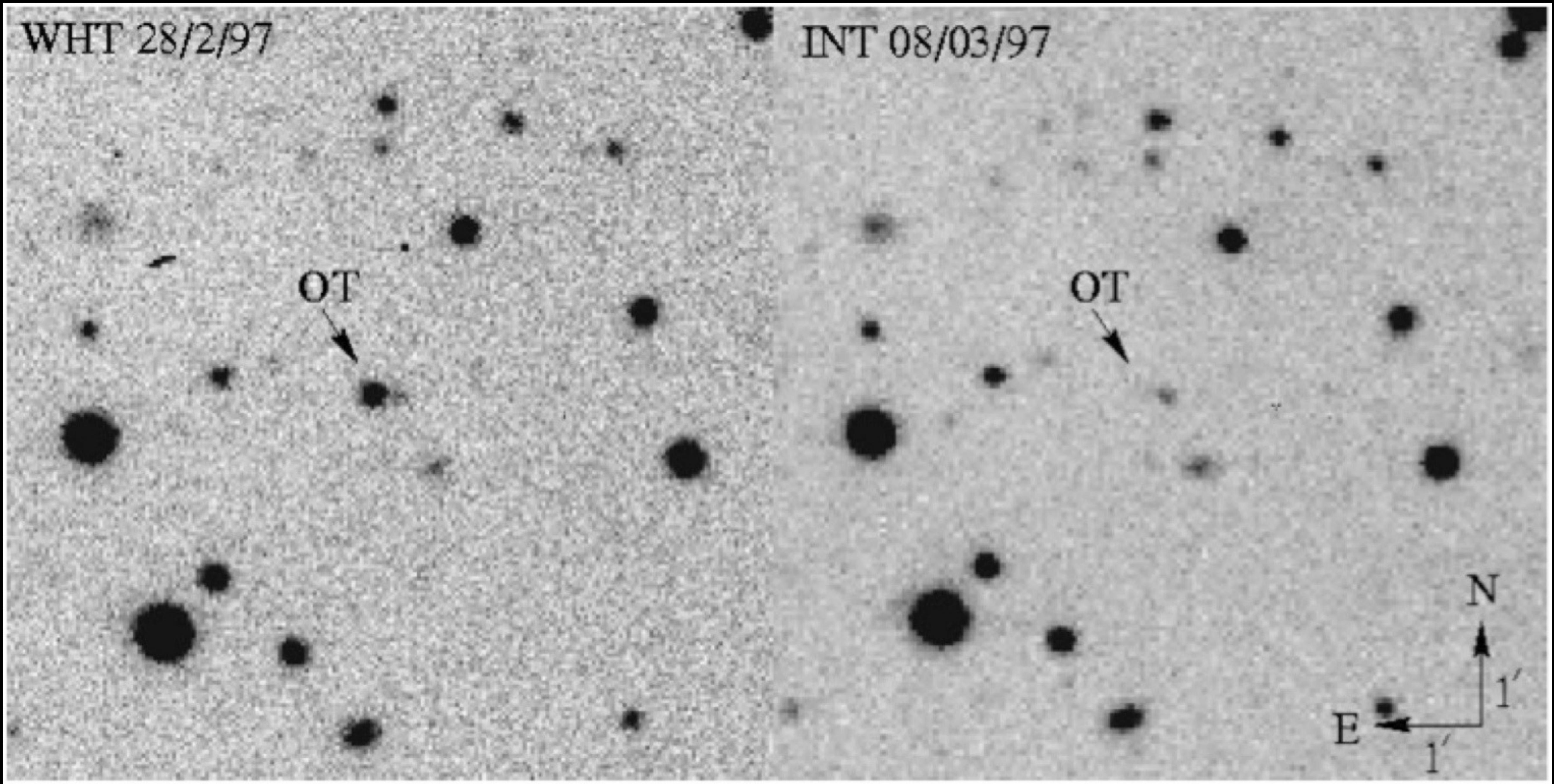


1997 Mar 3



Discovery of afterglow phase

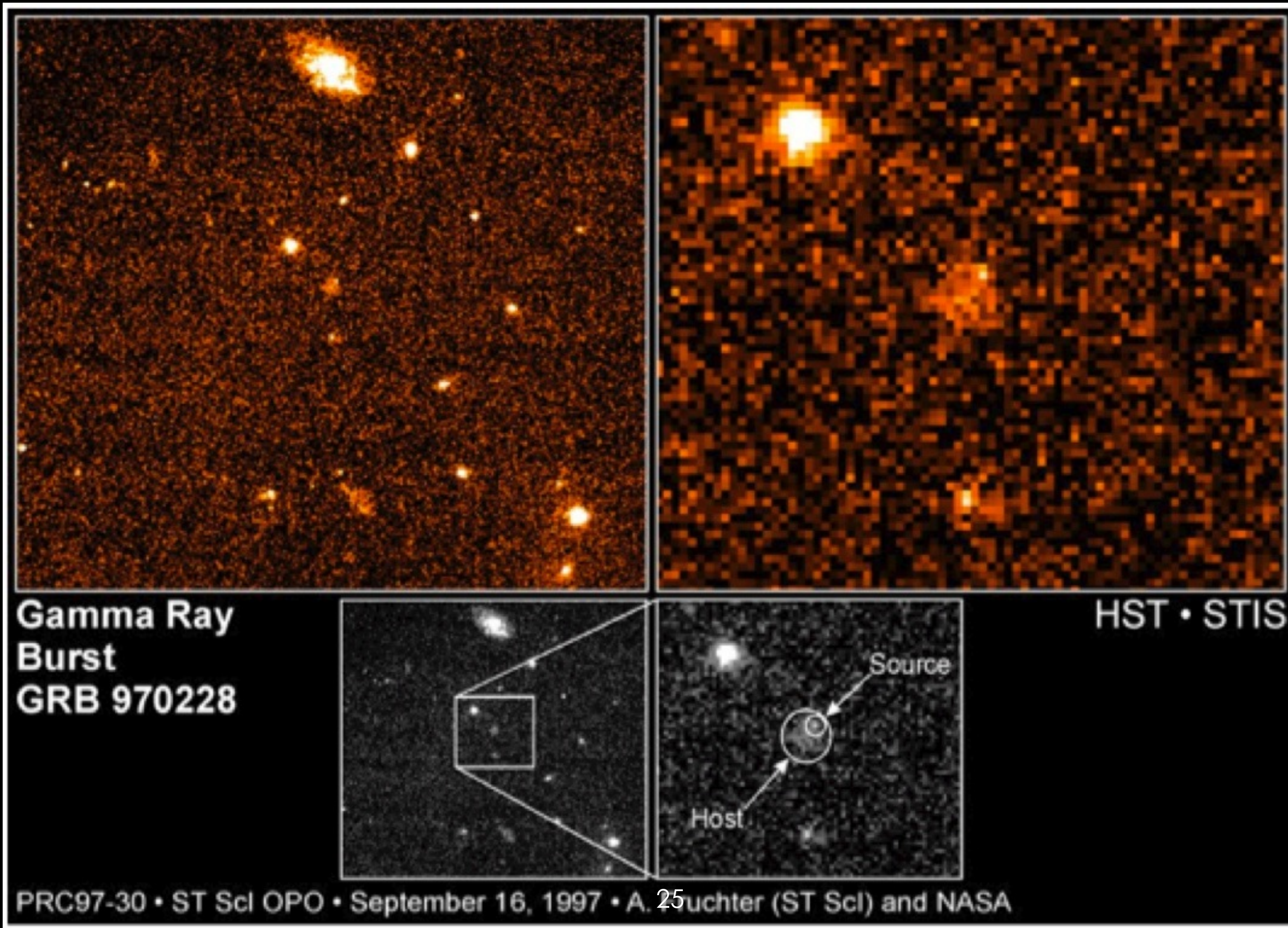
The first optical afterglow (GRB 970228)



van Paradijs et al. 1997

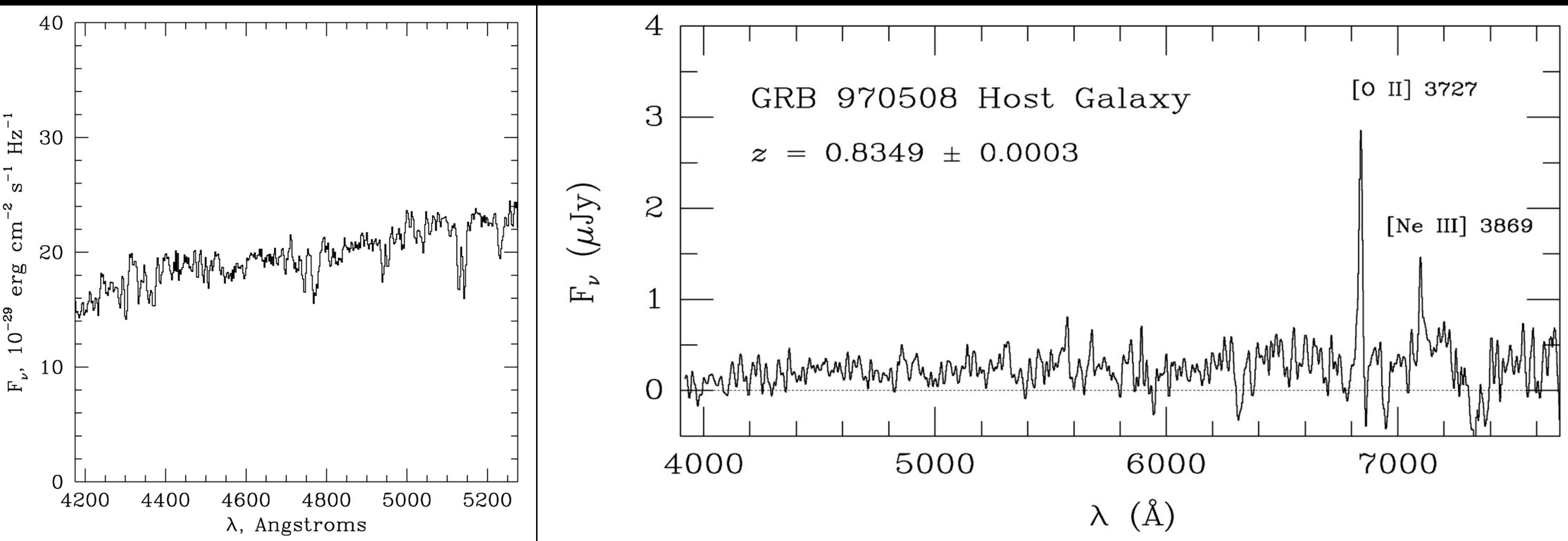
Discovery of afterglow phase

The first optical afterglow (GRB 970228): host galaxy



Discovery of afterglow phase

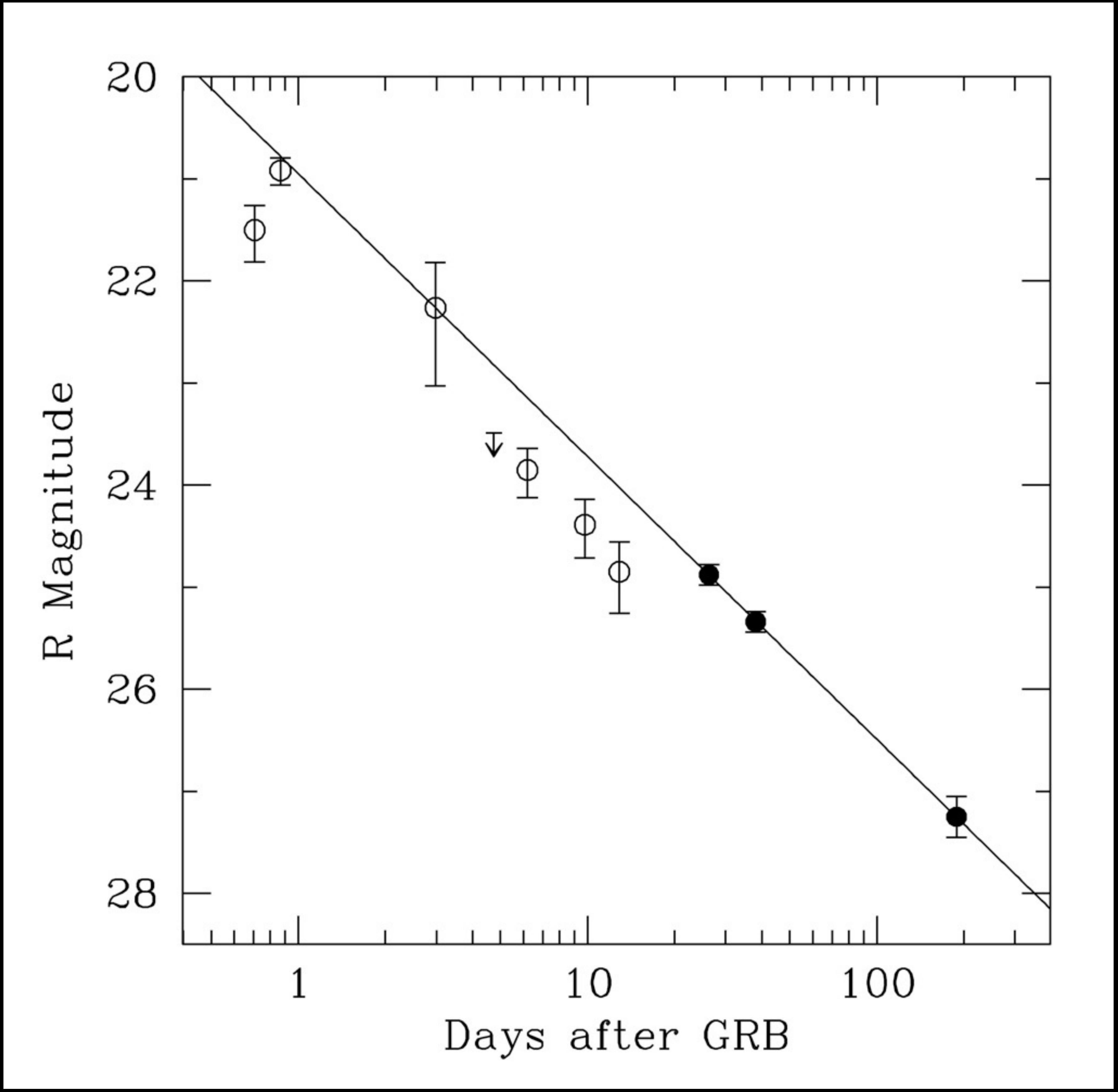
Optical spectrum of the afterglow of GRB 970508 and its host galaxy:
$z = 0.835$ and $D_L \sim 5\,\mathrm{Gpc}$!



Metzger et al. 1997

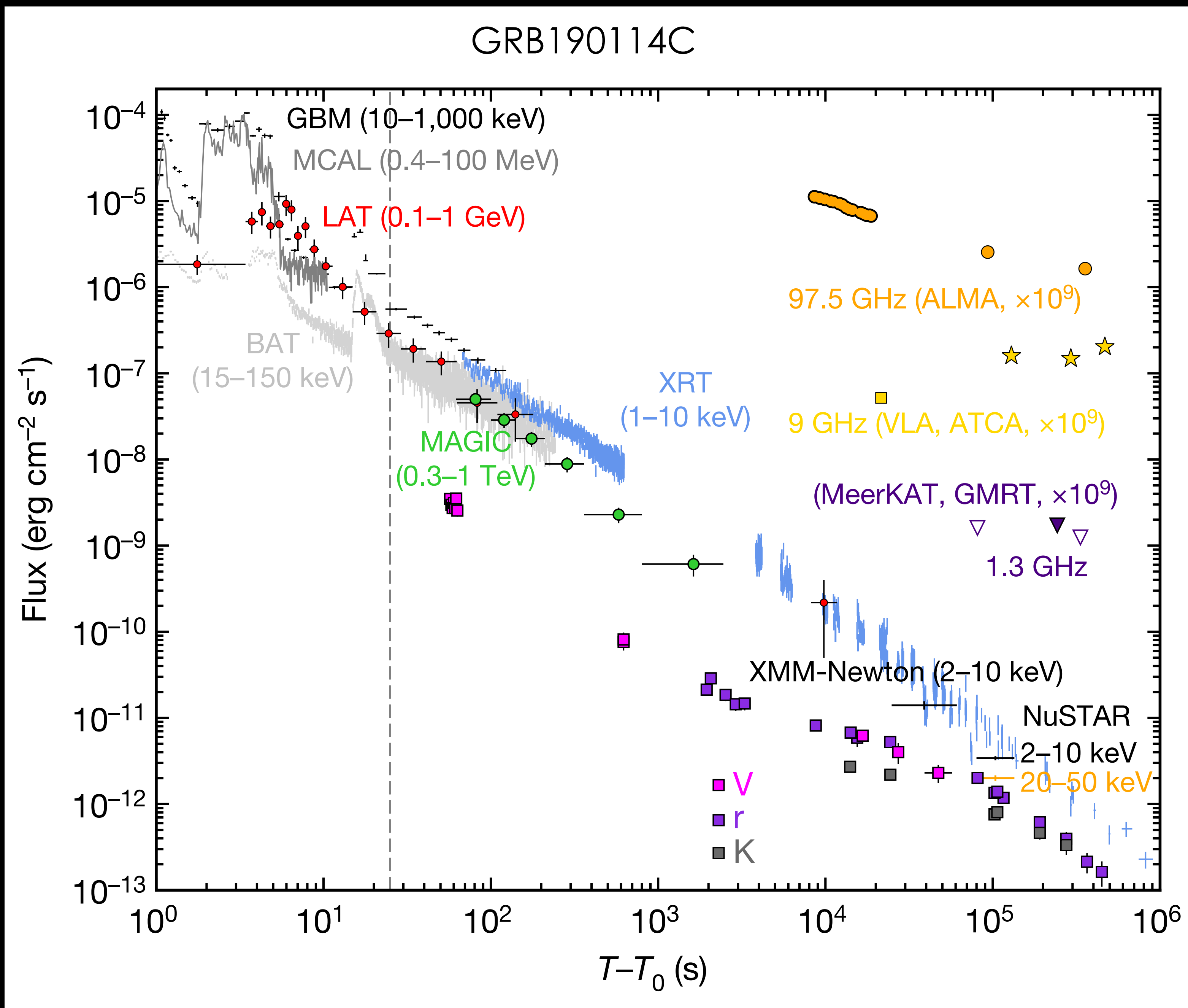
Afterglows: lightcurves

First optical afterglow (GRB 970228)



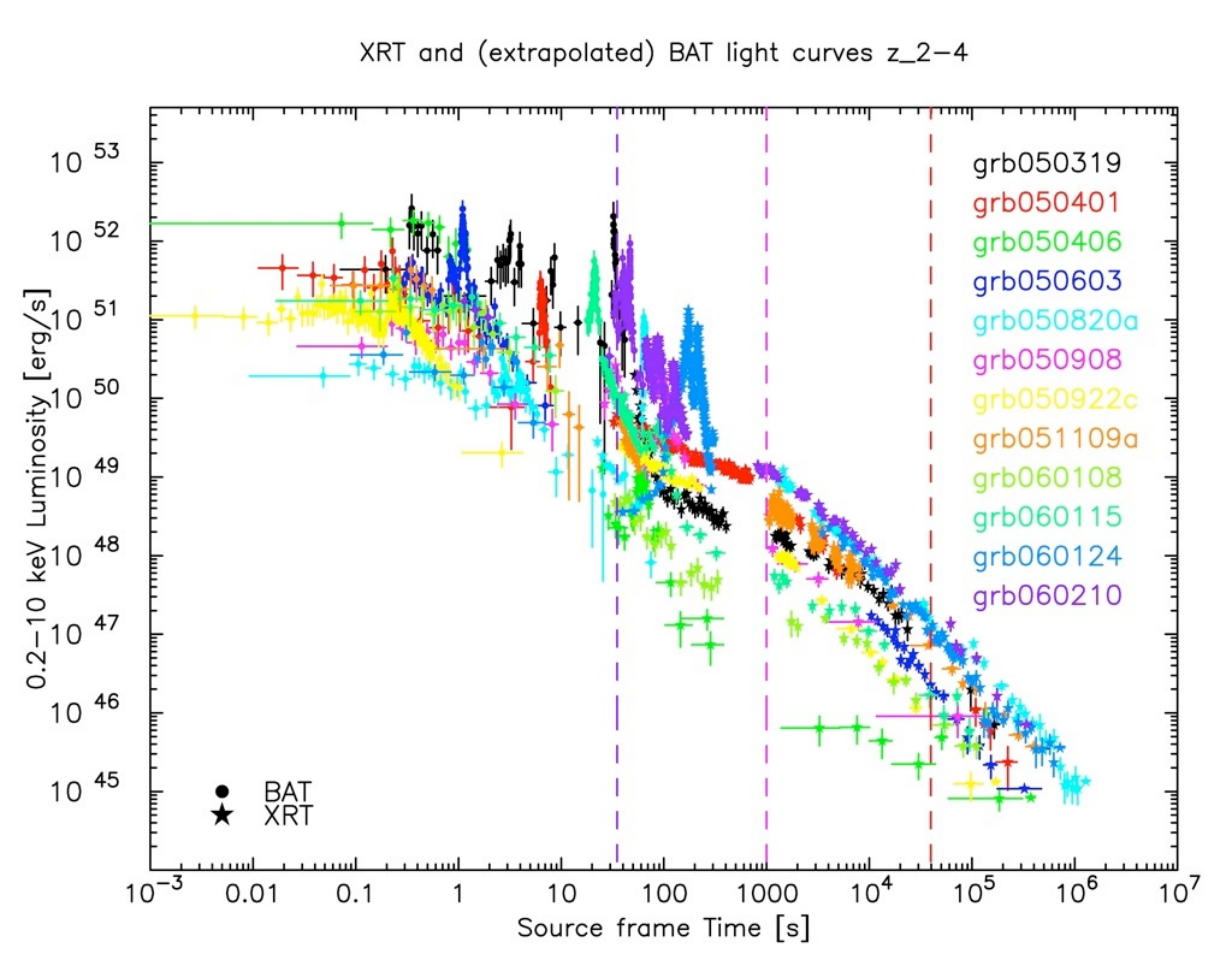
Observational facts: afterglow phase

Afterglows: light curves



- Detected in many wavelengths
- Very long-lived transient
- Little variability, light curves composed of power-law segments
- Non-thermal power-law spectrum

Afterglows: light curves

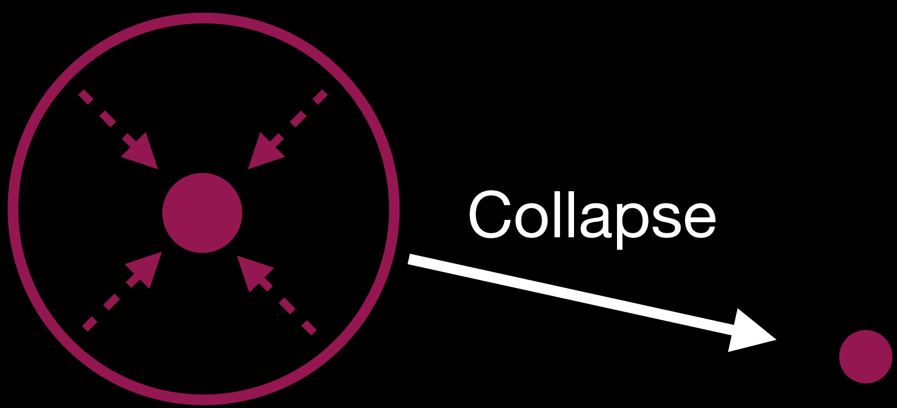


- Detected in many wavelengths
- Very long-lived transient
- Little variability, light curves composed of power-law segments
- Non-thermal power-law spectrum
- Complexity in light curves revealed by *Swift:* plateaus, flares

The compactness puzzle: relativistic motion in GRB sources

GRB sources: basic constraints on progenitor

— **Energy output**: $E_{\mathrm{iso},\gamma} = 10^{50\to54}\,\mathrm{erg} \Rightarrow$ Gravitational collapse to compact object (NS or BH)



$$\Delta E_{\mathrm{collapse}} \sim 2\times10^{53}\,\mathrm{erg}\left(\frac{\chi_{CO}}{0.1}\right)\left(\frac{M}{M_\odot}\right)$$

Compactness of object formed

— **Variability timescale**: $\delta t_{\mathrm{var}} < 0.1\,\mathrm{s} \Rightarrow$ Compact object of size $R \lesssim 3000\,\mathrm{km}\left(\frac{t_{\mathrm{var}}}{10\,\mathrm{ms}}\right)$

— **Non-thermal spectrum**: $E_p \sim 200\,\mathrm{keV} \Rightarrow$ What constraint?

Black-board calculation:
$\Delta E_{\mathrm{collapse}}$ and χ
Causality argument on R

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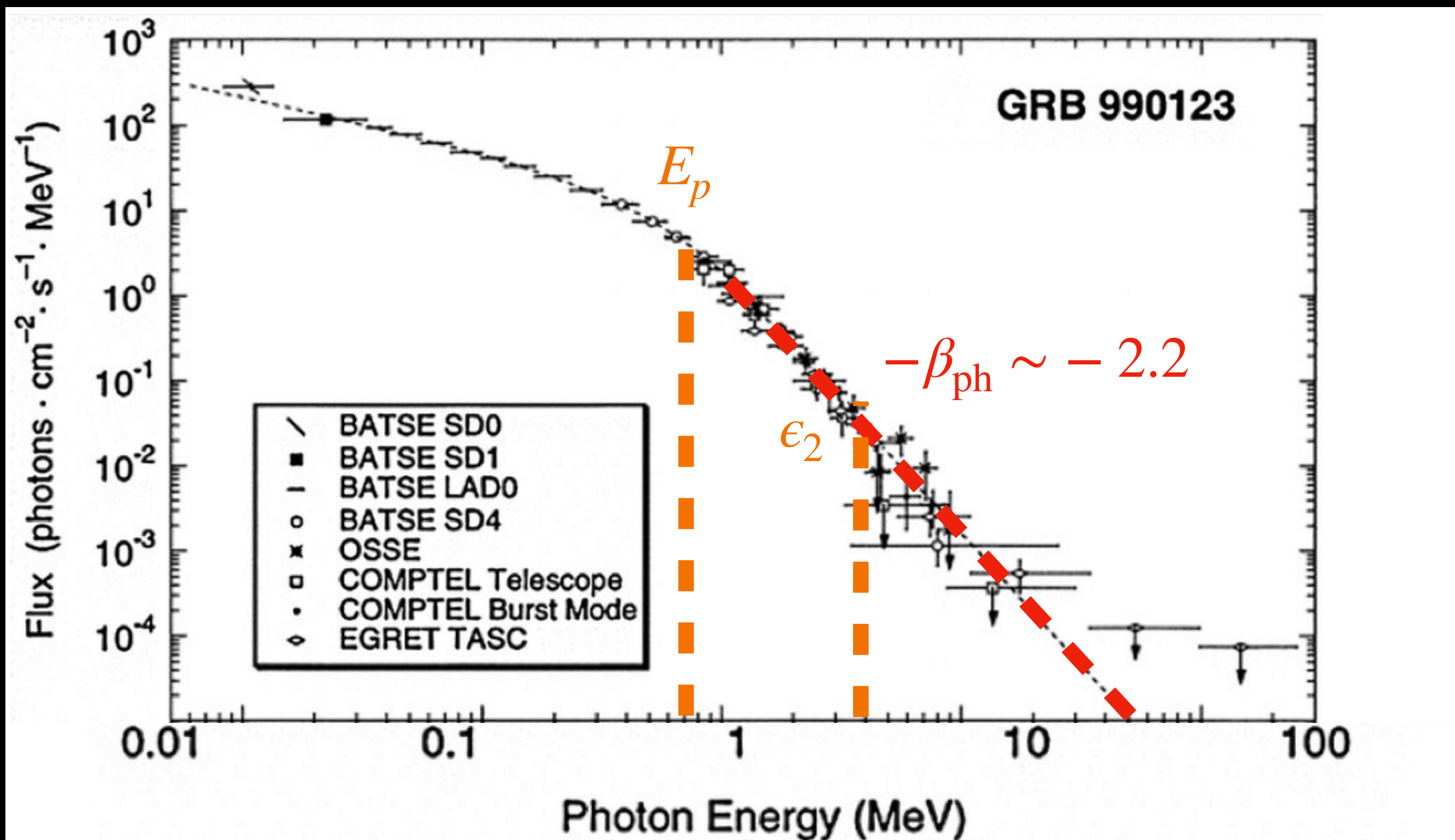
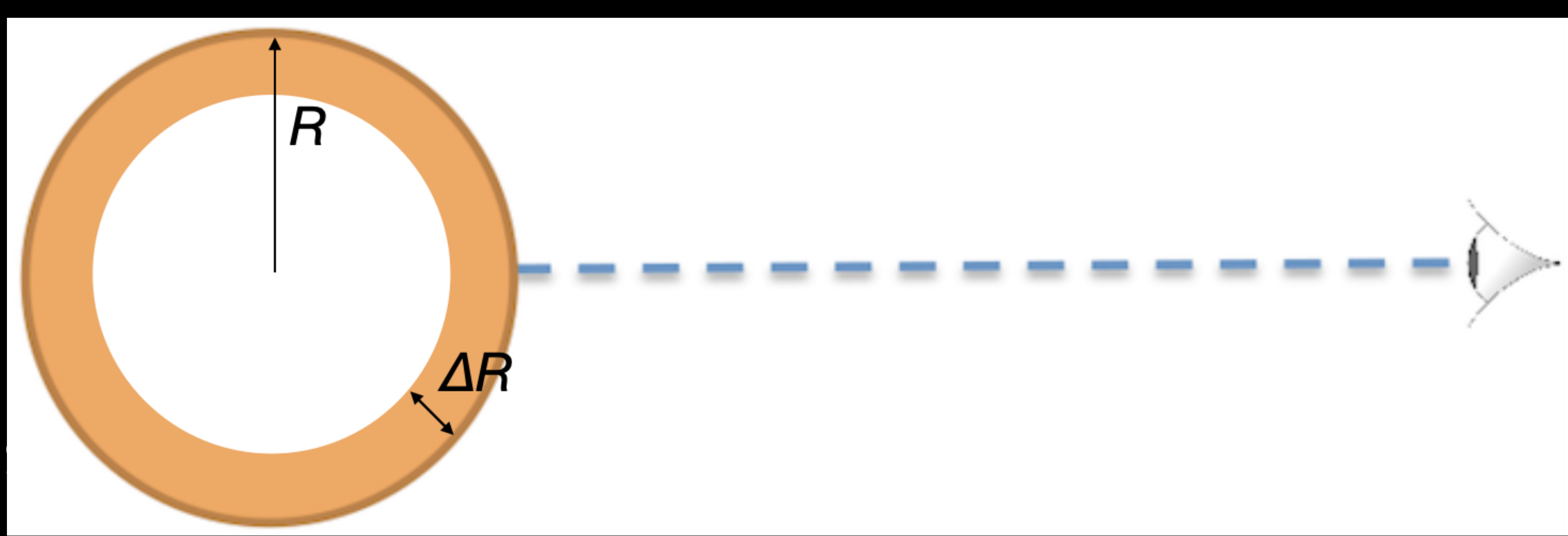
The compactness puzzle in GRB sources

- High-energy photons are prone to $\gamma\gamma \rightarrow e^+e^-$ pair creation, and there are a lot of photons in the source!





Black-board calculation: Optical depth to pair-production, static source

The compactness puzzle in GRB sources

- High-energy photons are prone to $\gamma\gamma \rightarrow e^+e^-$ pair creation, and there are a lot of photons in the source!

$$\tau_{\gamma\gamma} \sim 10^{12} \left(\frac{E_{\mathrm{iso},\gamma}}{10^{52}\,\mathrm{erg}} \right) \left(\frac{t_{\mathrm{var}}}{10\,\mathrm{ms}} \right)^{-2} \left(\frac{E_p}{200\,\mathrm{keV}} \right)^{1.2} \left(\frac{\epsilon_2}{1\,\mathrm{MeV}} \right)^{2.2}$$

$\Rightarrow$ γ-ray photons cannot escape from the source!

The compactness puzzle in GRB sources

- High-energy photons are prone to $\gamma\gamma \rightarrow e^+e^-$ pair creation, and there are a lot of photons in the source!

$$\tau_{\gamma\gamma} \sim 10^{12} \left(\frac{E_{\mathrm{iso},\gamma}}{10^{52}\,\mathrm{erg}}\right)\left(\frac{t_{\mathrm{var}}}{10\,\mathrm{ms}}\right)^{-2}\left(\frac{E_p}{200\,\mathrm{keV}}\right)^{1.2}\left(\frac{\epsilon_2}{1\,\mathrm{MeV}}\right)^{2.2}$$

⇒ γ-ray photons cannot escape from the source!

- Solution: relativistic motion in source

$$\tau_{\gamma\gamma,\mathrm{rel.}} \sim \Gamma^{-2-2\beta}\tau_{\gamma\gamma} \lesssim 1 \text{ for } \Gamma > 100$$

⇒ γ-ray photons can escape if they are produced in a relativistic ejecta!

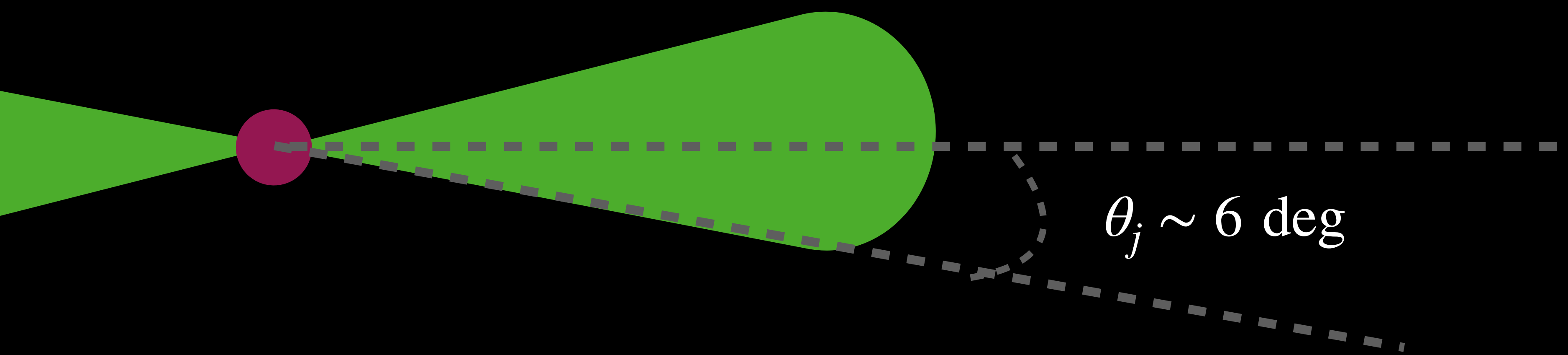
Black-board calculation: Optical depth to pair-production, relativistic source

Relativistic jet: reduced energy budget

- **Compactness puzzle proves relativistic motion:** Detailed calculation shows that $\Gamma \gtrsim 100$ for most GRBs

- **Material outside of $1/\Gamma$ angle is not detected:** Possibility of reducing the energy budget to:

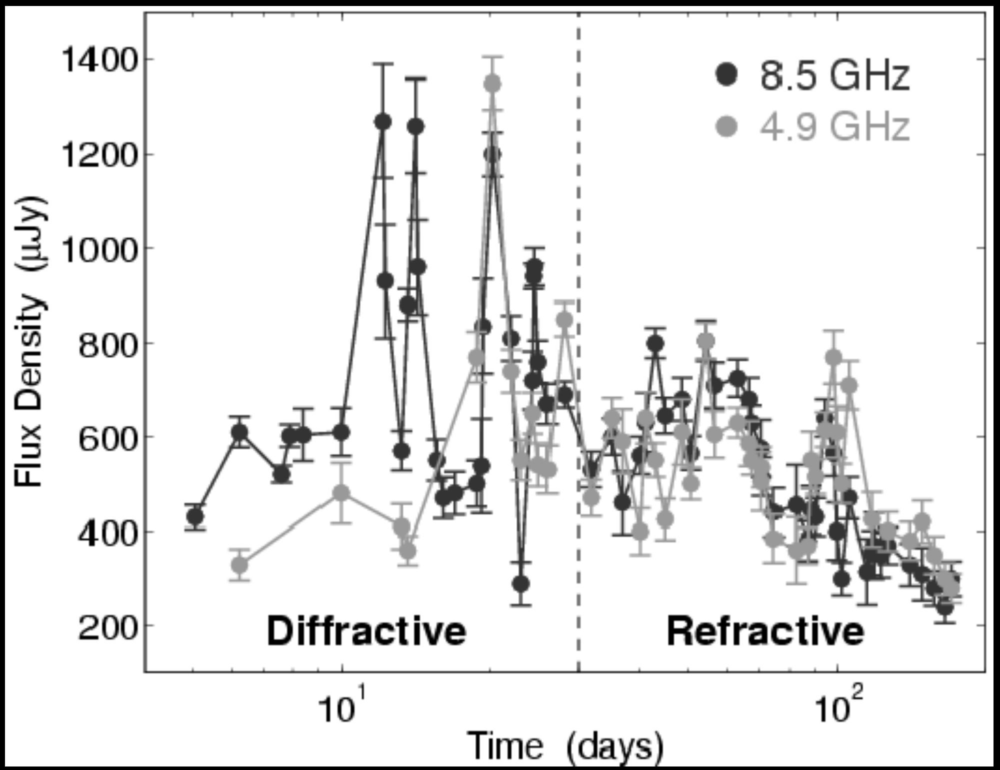
$$E_{\mathrm{real},\gamma} = 5 \times 10^{49}\,\mathrm{erg} \left(\frac{E_{\mathrm{iso},\gamma}}{10^{52}\,\mathrm{erg}} \right) \left(\frac{\theta_j}{6\,\mathrm{deg}} \right)^2$$



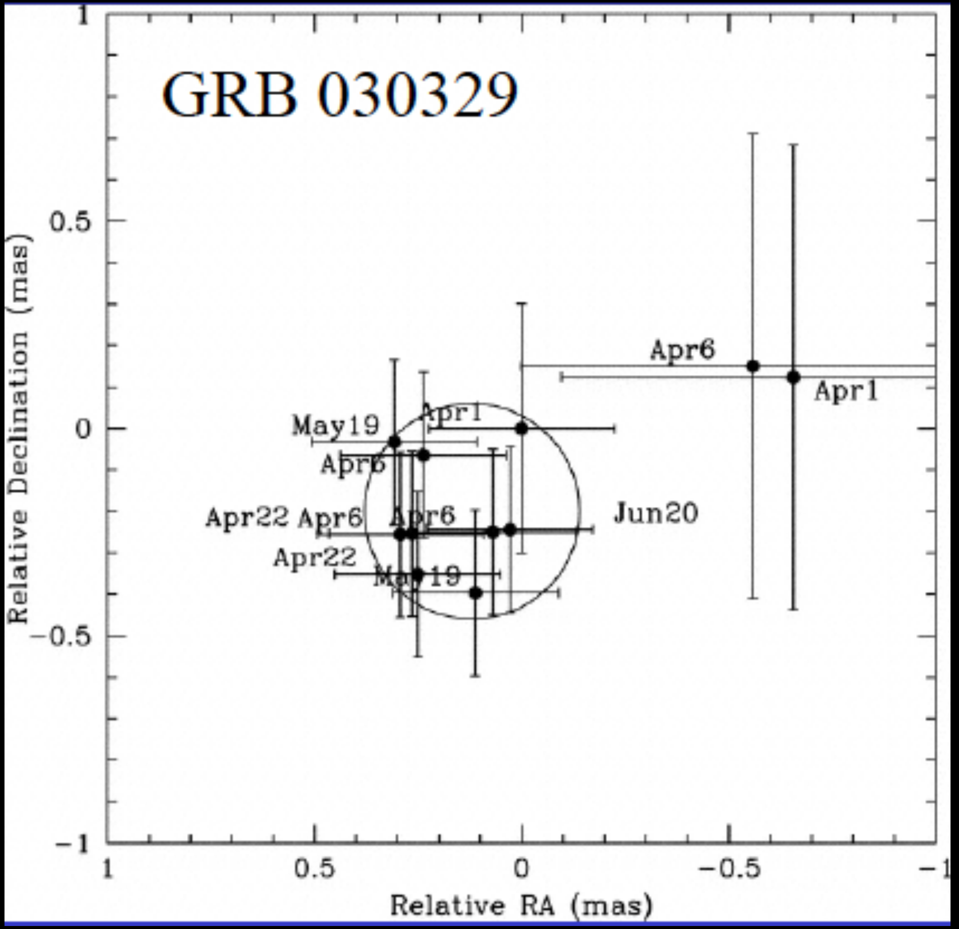
Black-board calculation: E_{real} function of $E_{\mathrm{iso}}, \theta_j$

Relativistic jet: direct evidence

Method 1: Radio scintillation quenches as the source increases
Transition diffractive / refractive
⇒ Estimate of the source size
⇒ Estimate of expansion velocity
⇒ Super-luminal motion as proof of relativistic motion



Method 2: VLBI imagery catch catch motion of jet head
⇒ Estimate of expansion velocity
⇒ Super-luminal motion as proof of relativistic motion

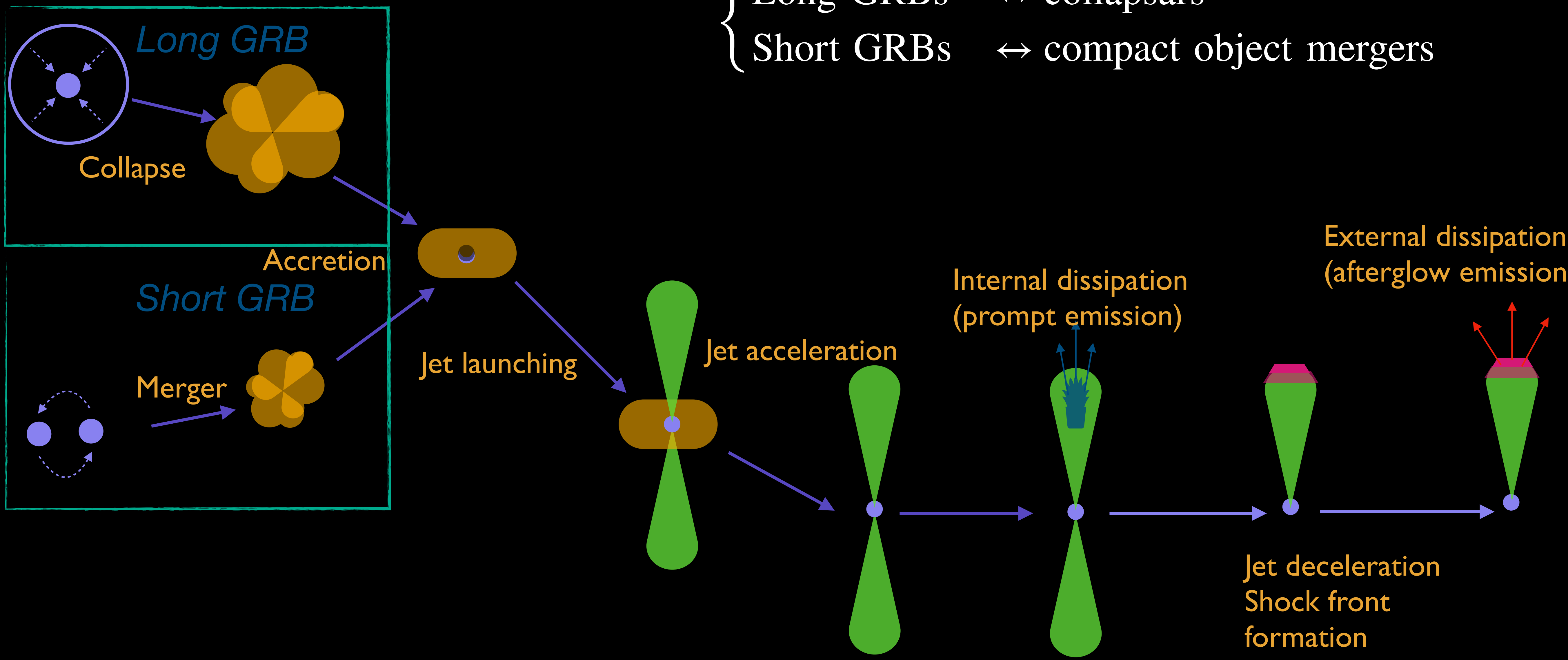


Taylor et al. 2004

The GRB phenomenon: global picture

Study of host galaxies:

$$\begin{cases} \text{Long GRBs} & \leftrightarrow \text{collapsars} \\ \text{Short GRBs} & \leftrightarrow \text{compact object mergers} \end{cases}$$



The GRB phenomenon: global picture

- Supernovae
- Star formation history
- High-redshift Universe

Study of host galaxies:

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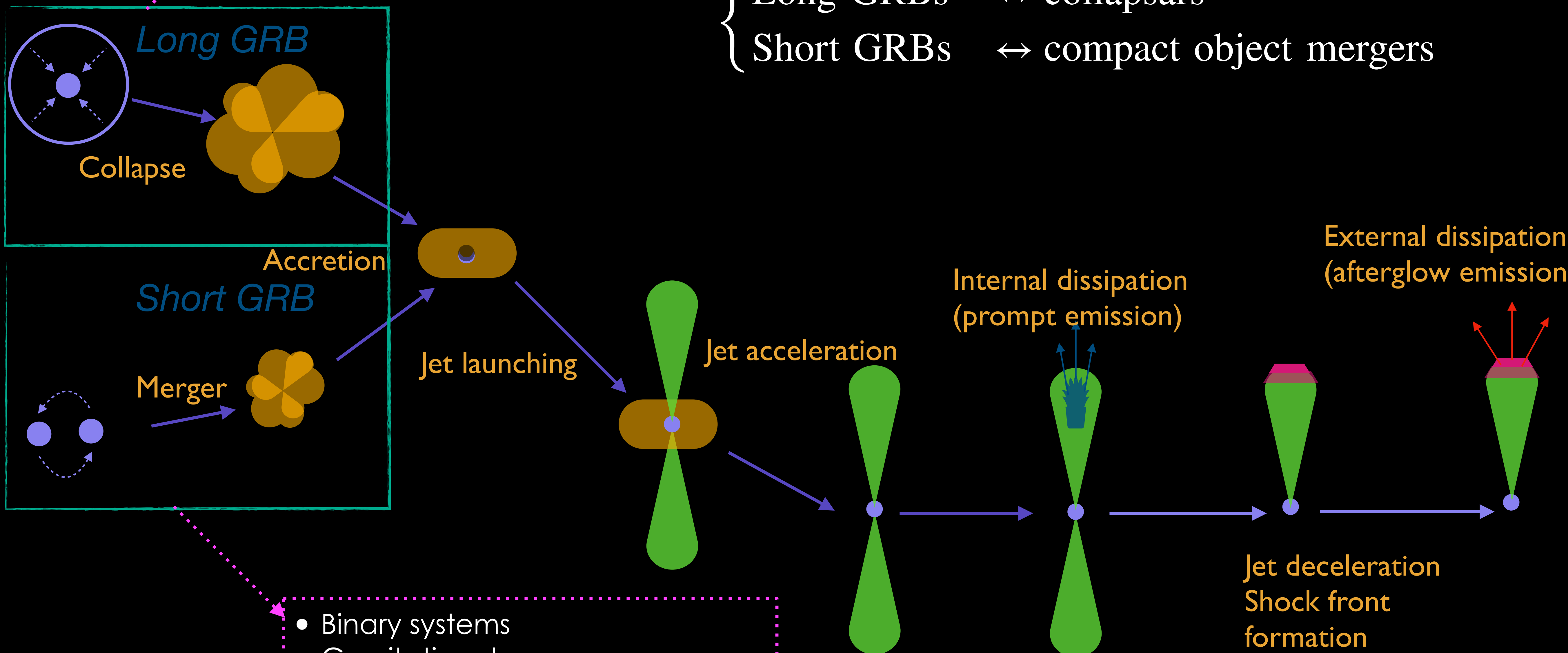

- Binary systems
- Gravitational waves
- Heavy-element nucleosynthesis
- Chemical enrichment of galaxies
- Cosmology

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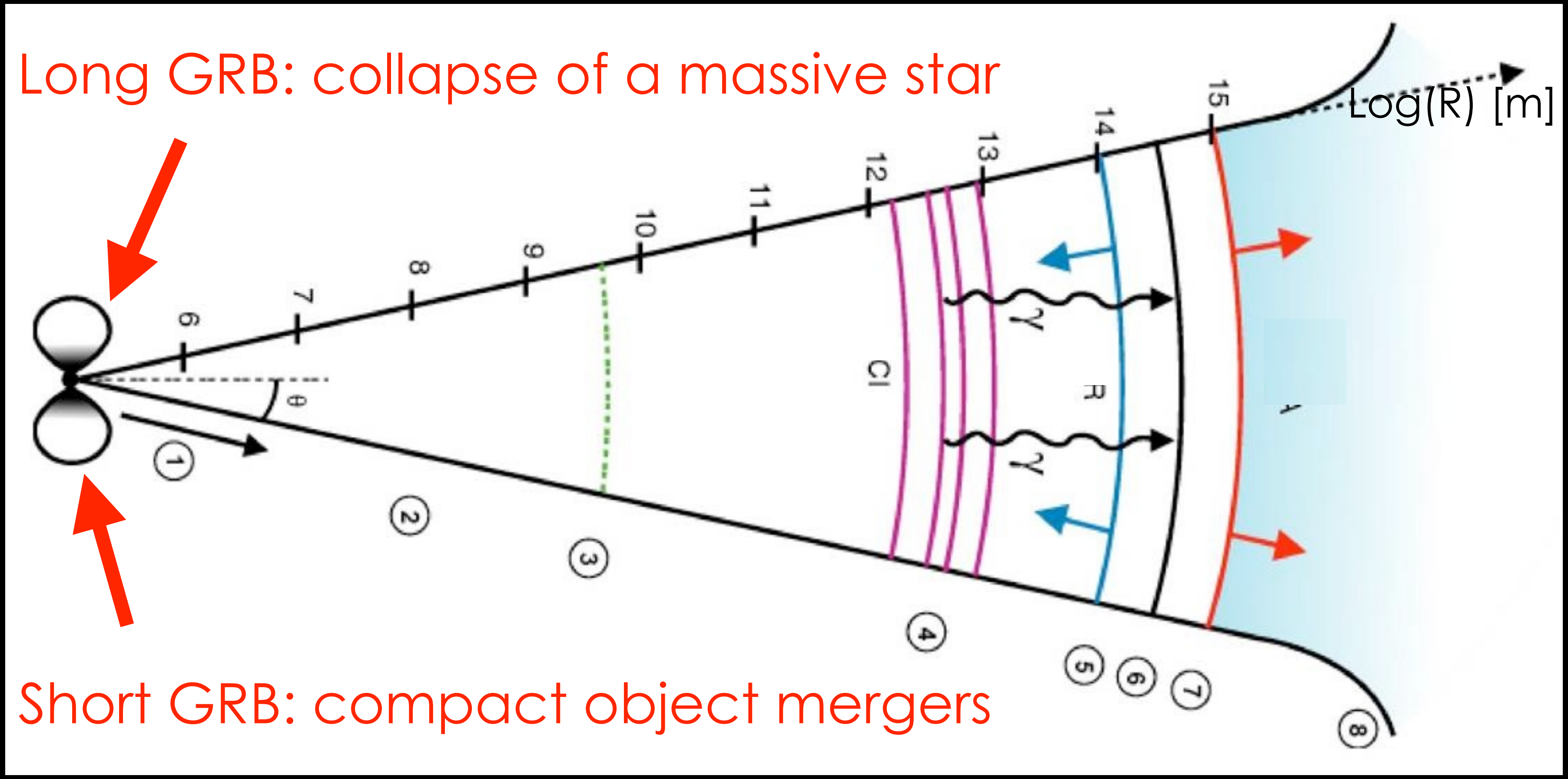
GRB Physics: initial event & central engine

- Large radiated energy ($E_{\mathrm{iso},\gamma} = 10^{50\to 53}$ erg) with short time scale variability ($t_{\mathrm{var}} < 100\,\mathrm{ms}$): cataclysmic event leading to the formation of a stellar-mass compact object and relativistic matter ejection



Questions:

- How to accelerate a jet to $\Gamma > 100$?
- How is kinetic energy dissipated into γ-rays?

End of Lecture #1

Gamma-Ray Bursts & Relativistic Jets

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Gamma-Ray Bursts & Relativistic Jets

Lecture 1: Relativistic motion in the sources of gamma-ray bursts

Historical remarks on GRBs
Observational facts: prompt emission
Observational facts: afterglow phase
The compactness puzzle: relativistic motion in GRB sources
The GRB phenomenon: global picture

Lecture 2: Basics of gamma-ray burst theory

Questions
Jets in GRBs: Acceleration — Energy dissipation — Deceleration
Summary of GRB physics
Contemporary GRB studies

Tutorial: Emission mechanisms for prompt and afterglow phases

Internal shocks as a prompt emission mechanism
The external forward shock synchrotron afterglow model

GRB Physics: initial event & central engine

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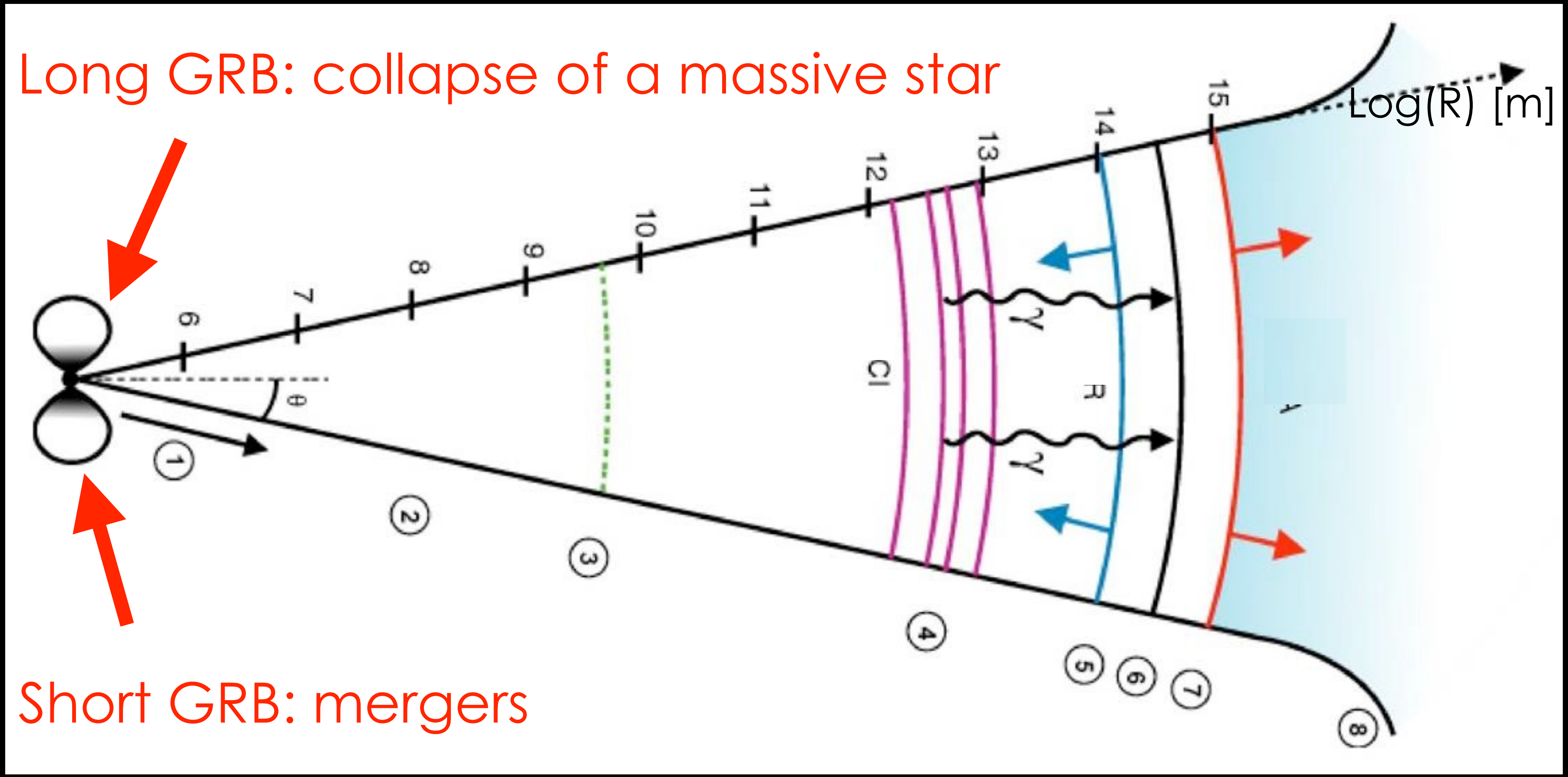

Questions:

- How to accelerate a jet to $\Gamma > 100$?
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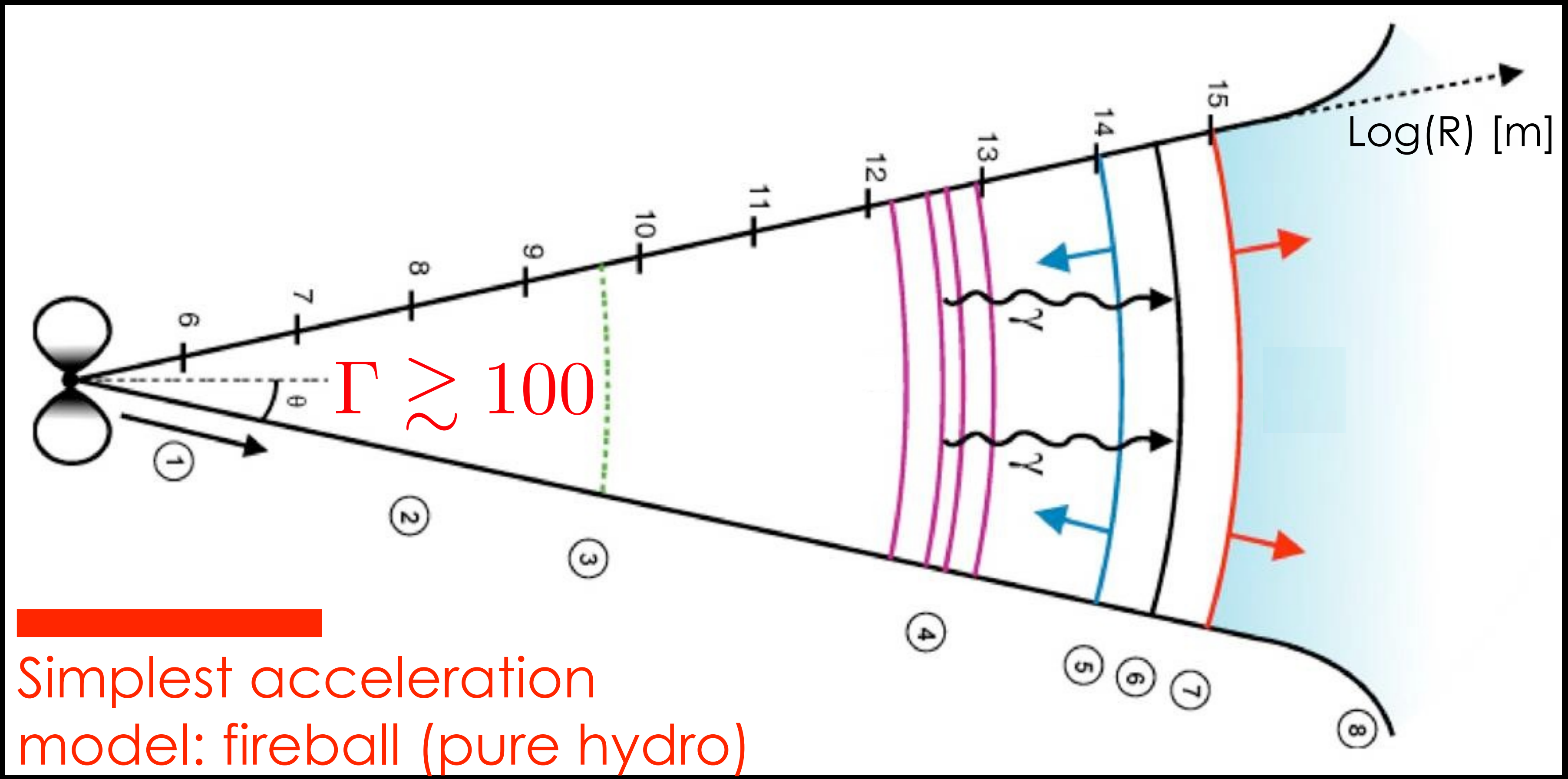
Relativistic jet ejection and acceleration

- Non-thermal gamma-ray spectrum: the gamma-ray burst is emitted by a relativistic outflow



Simplest acceleration model: fireball (pure hydro)

Fireball model:

Stationary, radial expansion of relativistic (very hot) material

⇒ Conversion of internal to kinetic energy

$$\begin{cases} 4\pi r^2 \rho \Gamma c \simeq \dot{M} = \mathrm{cst} \\ 4\pi r^2 \rho h \Gamma^2 c \simeq \dot{E} = \mathrm{cst} \\ \dfrac{P}{\rho^\gamma} = \mathrm{cst} \end{cases}$$

Black-board calculation: Expansion in fireball model

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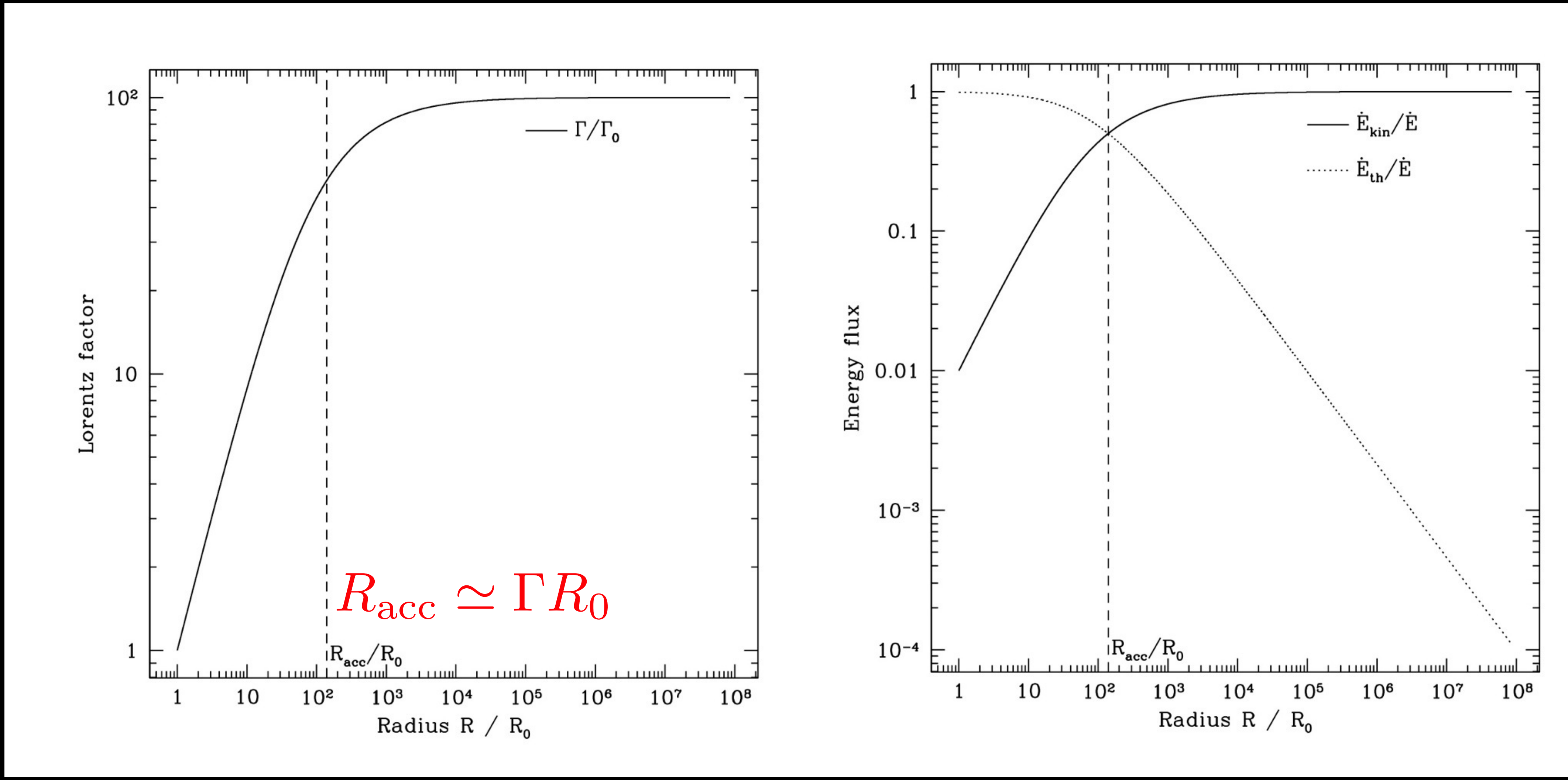
Fireball model for jet acceleration

Internal → kinetic energy conversion



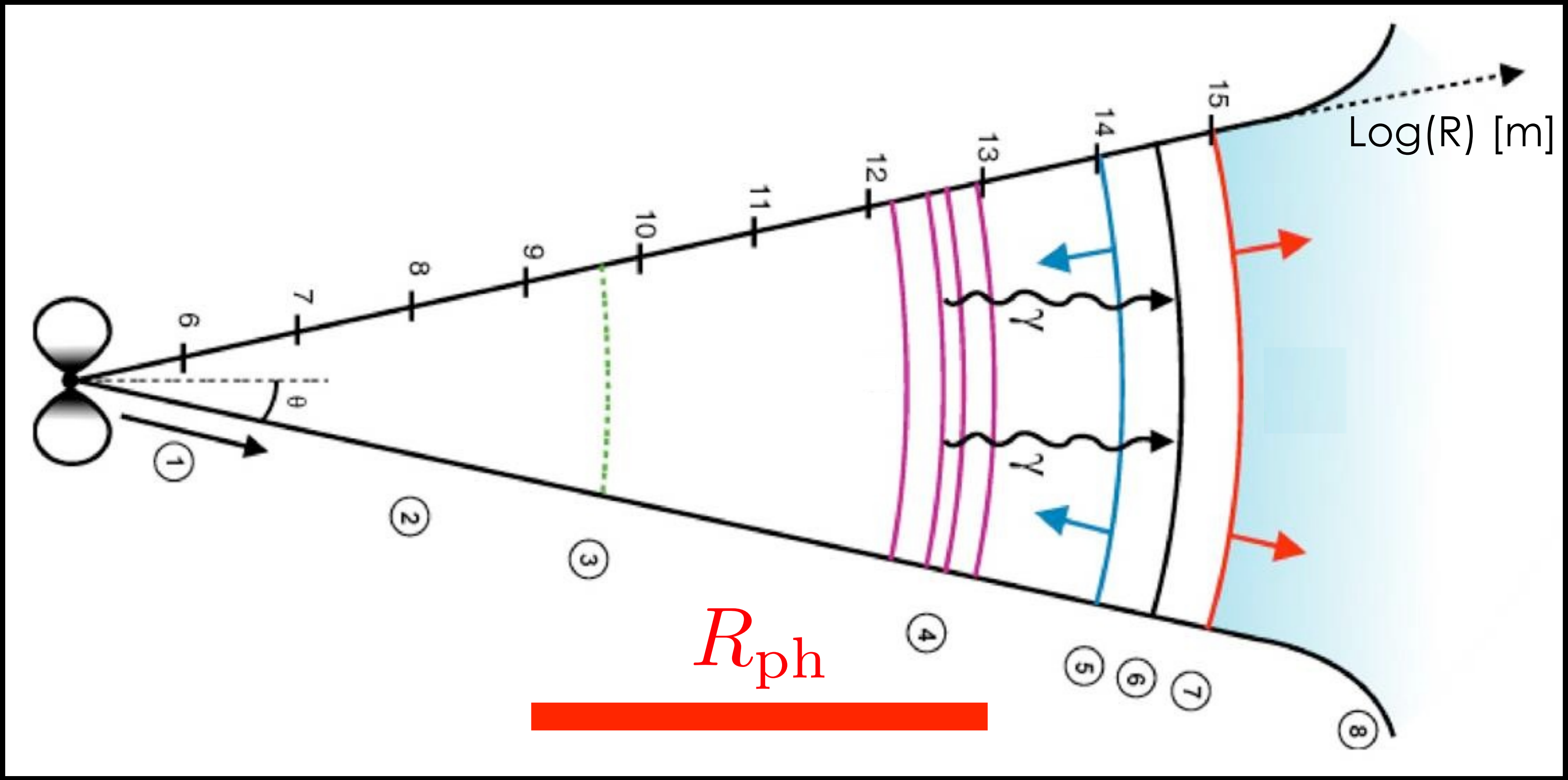
Valid as long as spreading is negligible:

$$R \ll R_{\rm spread} \sim \Gamma^2 c \Delta t_{\rm ej}$$

Note: Fireball-type expansion can be a primary launching-acceleration mechanism or a complement to another launching mechanism (e.g., accretion-ejection)

GRB physics: prompt emission locus in the jet

- Short time-scale non-evolving variability: the prompt emission has an internal origin

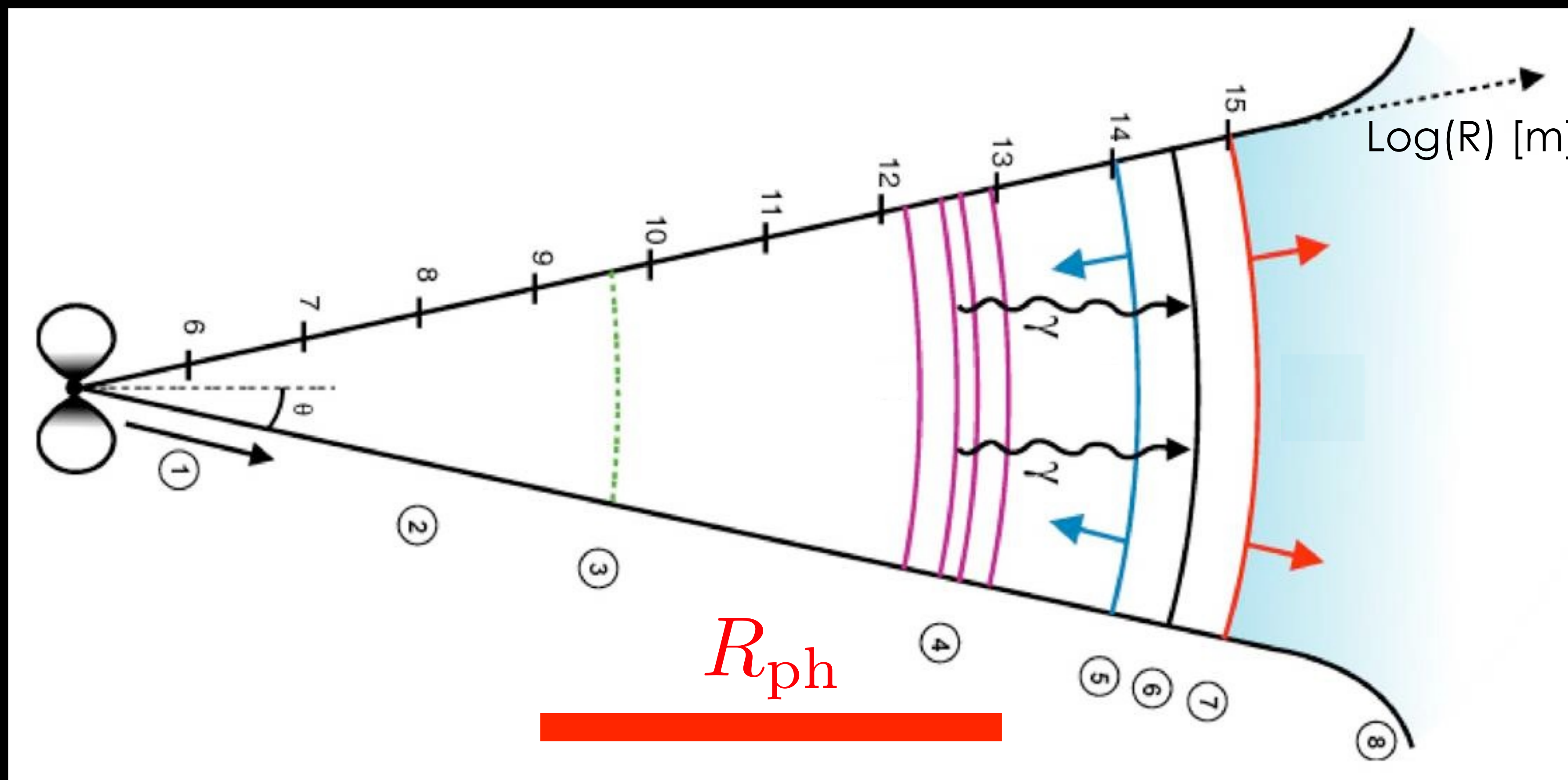


- **Main possibilities of internal dissipation:** above or below the photosphere
  (1) "dissipative photosphere": emission is below $R_{\rm ph}$, thermal → non-thermal evolution
  (2) "optically-thin emission": radiation is directly non-thermal (shocks/reconnection)

Black-board calculation:
Photospheric radius

GRB physics: prompt emission locus in the jet

- Short time-scale non-evolving variability: the prompt emission has an internal origin



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$$R_{\rm ph} \simeq \frac{\dot{E}\kappa_{\rm T}}{8\pi\Gamma^3 c^3} \simeq 6\,10^{12}\,{\rm cm}\left(\frac{\dot{E}}{10^{52}\,{\rm erg/s}}\right)\left(\frac{\Gamma}{100}\right)^{-3}$$

GRB physics: prompt emission locus in the jet

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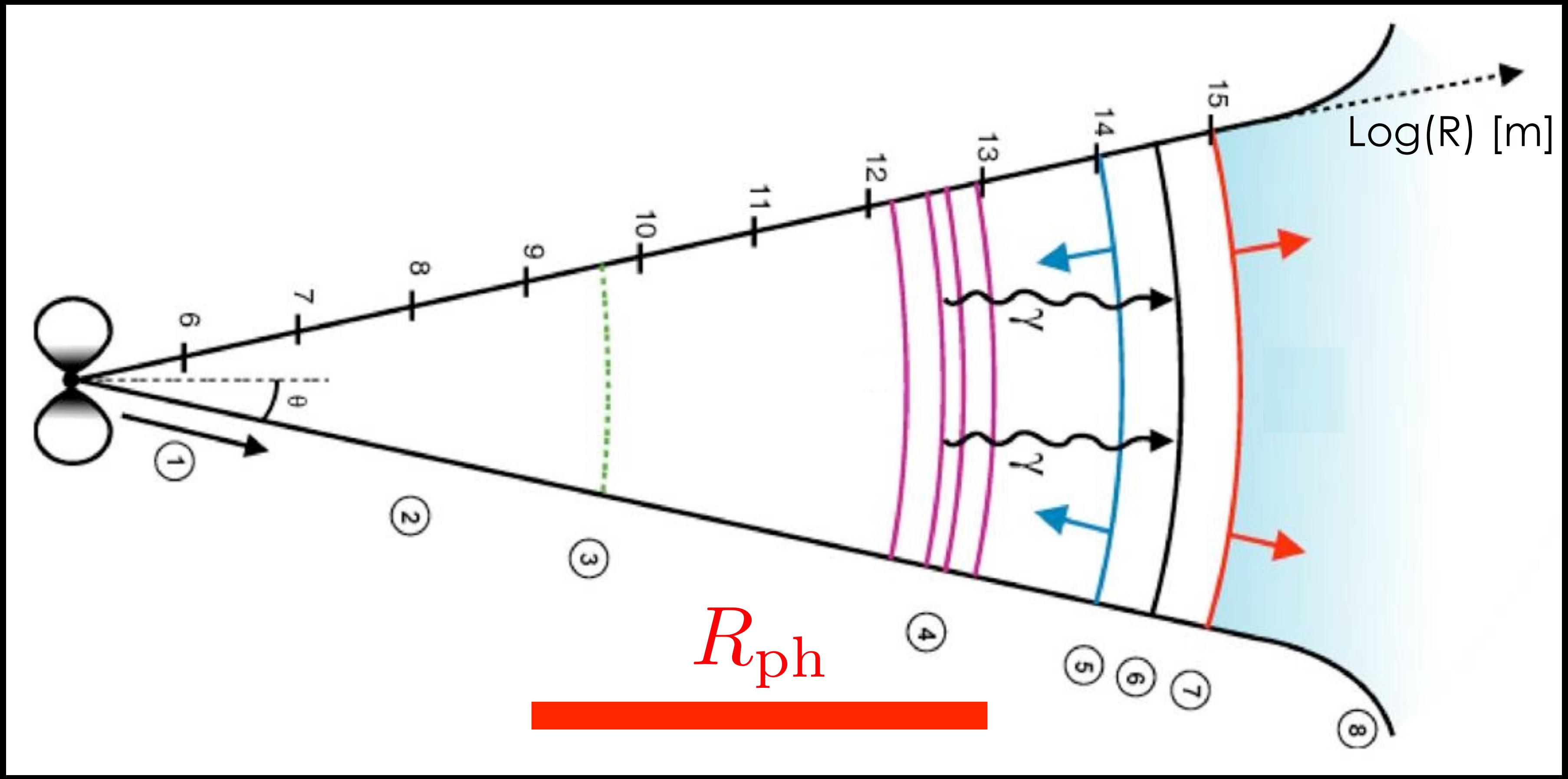

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One example in tutorial I

$$R_{\rm ph} \simeq \frac{\dot{E}\kappa_{\rm T}}{8\pi\Gamma^3 c^3} \simeq 6\,10^{12}\,{\rm cm}\left(\frac{\dot{E}}{10^{52}\,{\rm erg/s}}\right)\left(\frac{\Gamma}{100}\right)^{-3}$$

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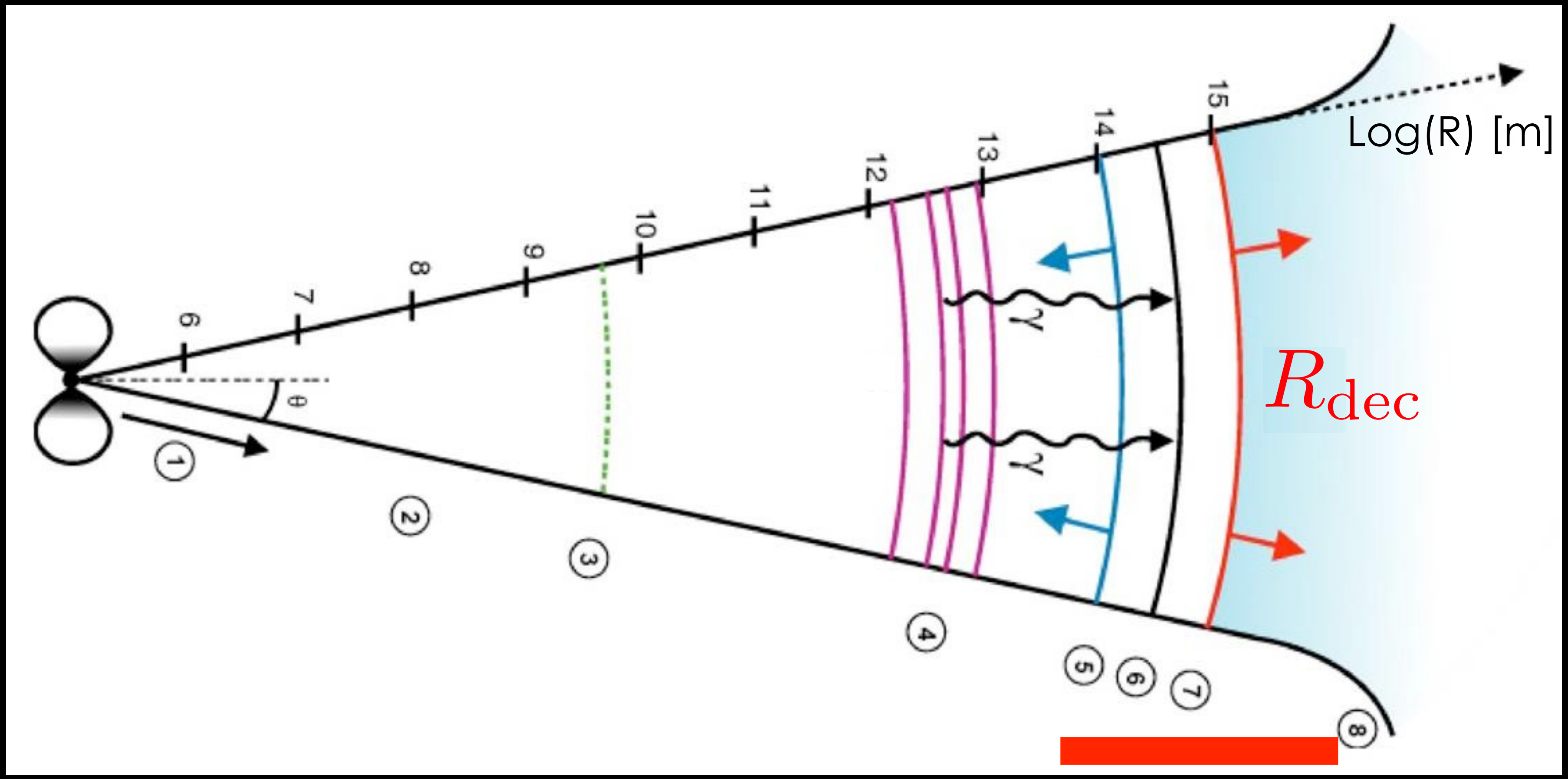
GRB physics: relativistic jet deceleration

- Long timescales (hours/days/weeks/years): the afterglow has an external origin
- Interaction of the relativistic ejecta with the circus-burst medium: deceleration
- Forward shock: strong ultra-relativistic shock in the external medium = afterglow



- Reverse shock (if the ejecta has a low magnetization): additional contribution?

$$R_{\rm dec} \simeq \left(\frac{3}{4\pi}\frac{\mathcal{E}_{\rm kin,0}}{\Gamma_0^2 n_{\rm ext} m_{\rm p} c^2}\right)^{1/3} \simeq 1.5\,10^{17}\,{\rm cm}\left(\frac{\Gamma_0}{100}\right)^{-2/3}\left(\frac{\mathcal{E}_{\rm kin,0}}{10^{53}\,{\rm erg}}\right)^{1/3}\left(\frac{n_{\rm ext}}{1\,{\rm cm}^{-3}}\right)^{-1/3}$$

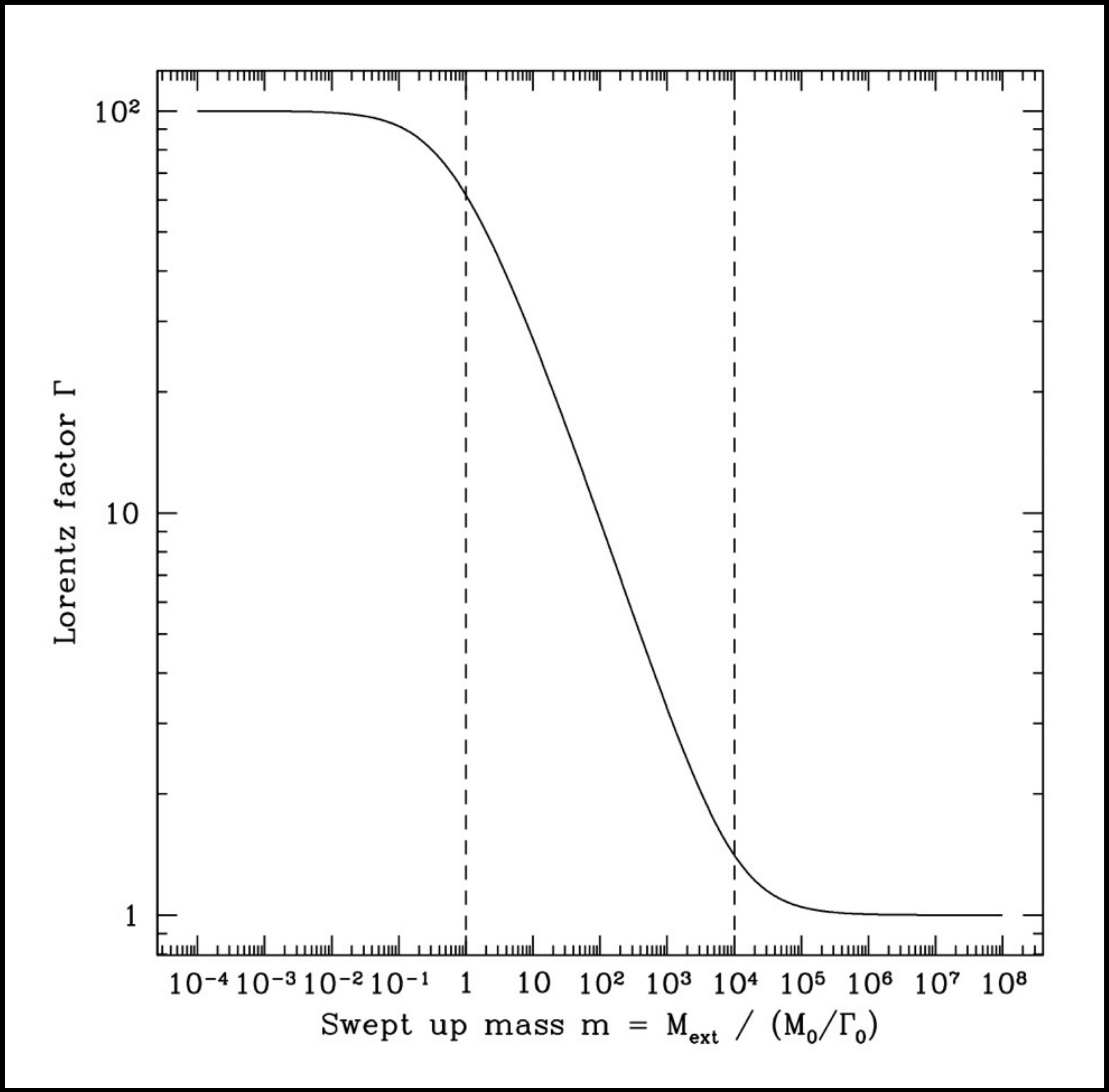
$$R_{\rm Newton} \simeq \left(\frac{3}{4\pi}\frac{\mathcal{E}_{\rm kin,0}}{n_{\rm ext} m_{\rm p} c^2}\right)^{1/3} \simeq 3.2\,10^{18}\,{\rm cm}\left(\frac{\mathcal{E}_{\rm kin,0}}{10^{53}\,{\rm erg}}\right)^{1/3}\left(\frac{n_{\rm ext}}{1\,{\rm cm}^{-3}}\right)^{-1/3}$$

Blackboard calculation:
Jet deceleration dynamics

Deceleration

Ejecta is decelerated
by the external medium

$$R_{\rm dec} \longleftrightarrow M_{\rm ext} \simeq \frac{M_0}{\Gamma_0}$$



$\Gamma \simeq \Gamma_0 \quad \text{if} \quad R \ll R_{\rm dec}$

$\Gamma \simeq \Gamma_0 \left(\frac{R}{R_{\rm dec}}\right)^{-3/2} \quad \text{if} \quad R_{\rm dec} \ll R \ll R_{\rm Newton}$

$\Gamma \simeq 1 \quad \text{if} \quad R \gg R_{\rm Newton}$ (Sedov: $\beta \propto R^{-3/2}$)

$$R_{\rm dec} \simeq \left(\frac{3}{4\pi}\frac{\mathcal{E}_{\rm kin,0}}{\Gamma_0^2 n_{\rm ext} m_{\rm p} c^2}\right)^{1/3} \simeq 1.5\,10^{17}\,{\rm cm}\left(\frac{\Gamma_0}{100}\right)^{-2/3}\left(\frac{\mathcal{E}_{\rm kin,0}}{10^{53}\,{\rm erg}}\right)^{1/3}\left(\frac{n_{\rm ext}}{1\,{\rm cm}^{-3}}\right)^{-1/3}$$

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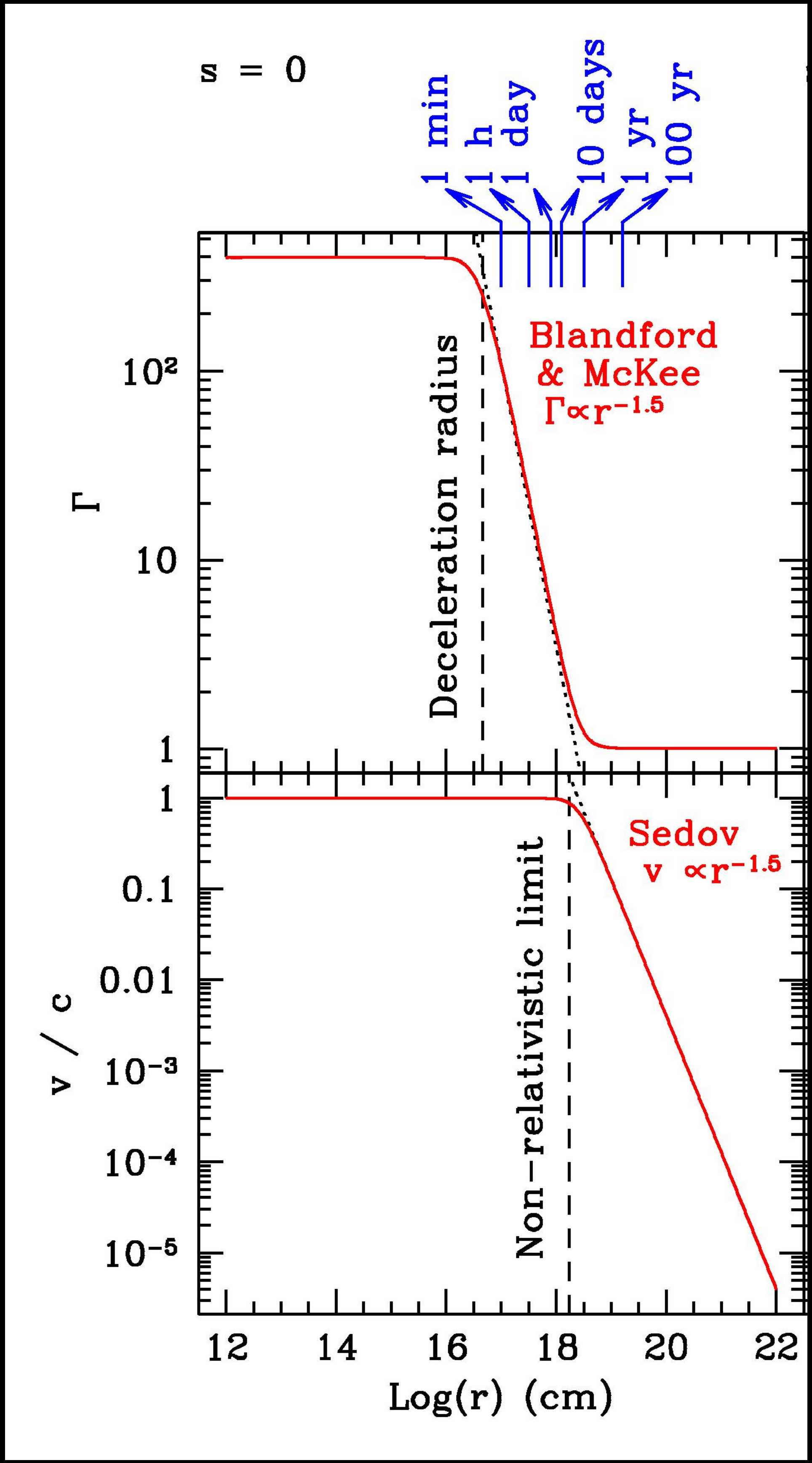
Deceleration

Ejecta is decelerated
by the external medium

Evolution of photon arrival time from forward shock:

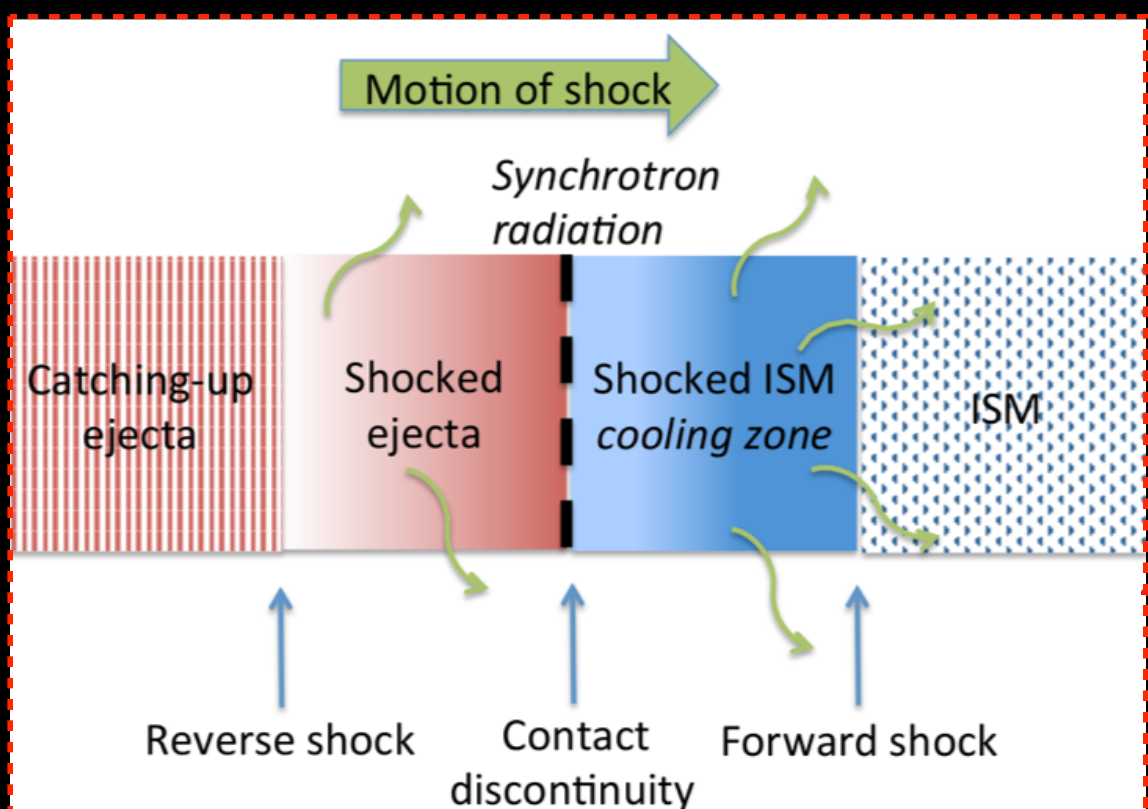
$$t_{\rm obs} = \left(\frac{D}{c}\right) + \int_0^R \frac{\mathrm{d}R}{2\Gamma^2 c}$$



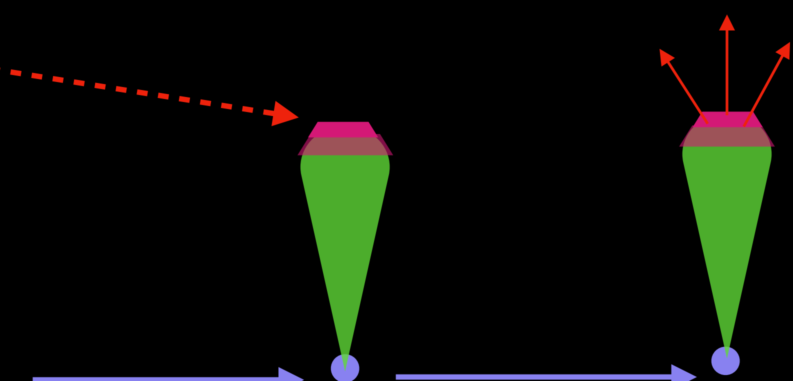
Afterglow emission mechanism in forward shock

emission mechanism will be studied in tutorial II

- Relativistic jet penetrates circum-burst medium
  $\Rightarrow$ Strong shock structure
- Microphysical conditions in forward shock downstream:
  1. internal energy $\epsilon*$,
  2. non-thermal electron population p, ϵ_e,
  3. turbulent magnetic field ϵ_B
- Radiative processes: synchrotron radiation, inverse-Compton scattering, self-absorption
- Mildly relativistic shock regime? Lateral expansion?



External dissipation (afterglow emission)



Jet deceleration
Shock front formation

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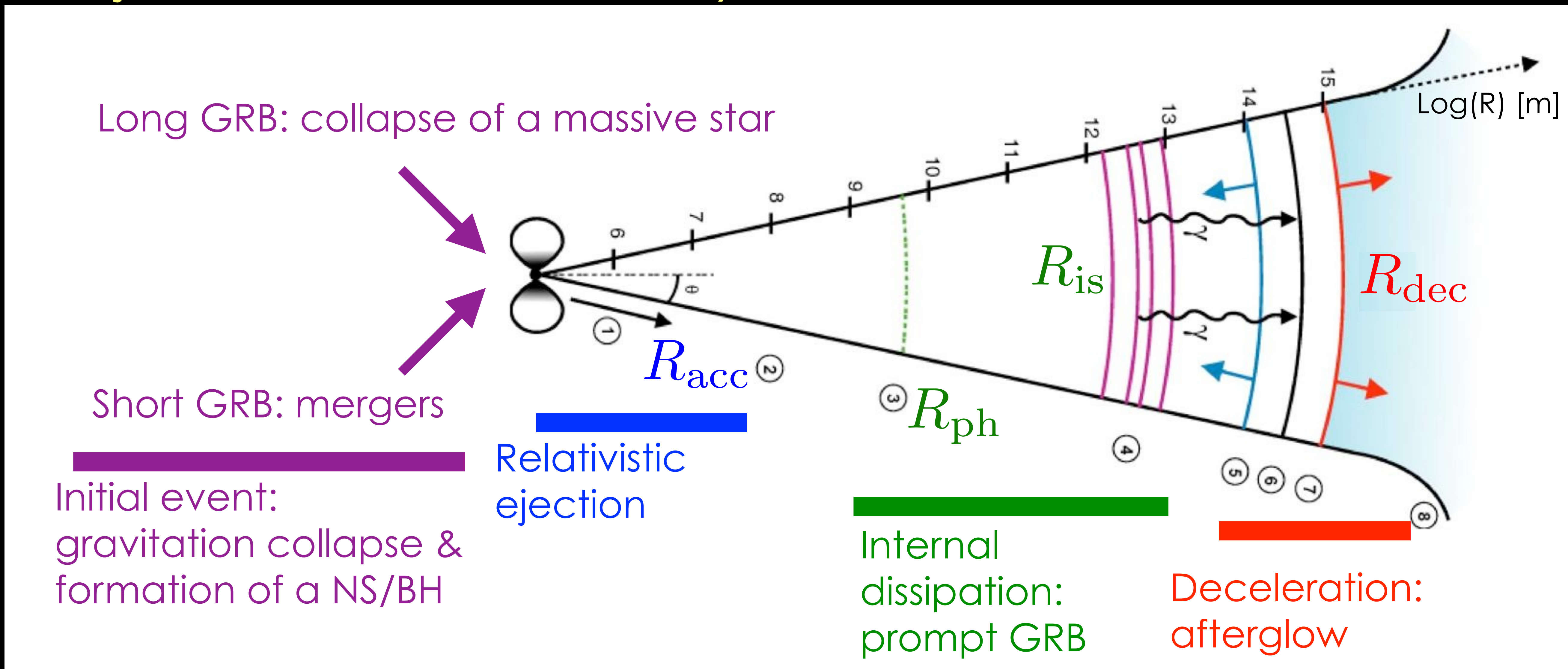
GRB jet evolution: summary



Acceleration

$$R_{\rm acc} \simeq \Gamma R_0 \simeq 10^9\,{\rm cm}\left(\frac{\Gamma}{100}\right)\left(\frac{R_0}{100\,{\rm km}}\right)$$

Internal dissipation

$$R_{\rm ph} \simeq \frac{\dot{E}\kappa_{\rm T}}{8\pi\Gamma^3 c^3} \simeq 6\,10^{12}\,{\rm cm}\left(\frac{\dot{E}}{10^{52}\,{\rm erg/s}}\right)\left(\frac{\Gamma}{100}\right)^{-3}$$

$$R_{\rm is} \simeq 2\Gamma^2\Delta \simeq 6\,10^{14}\,{\rm cm}\left(\frac{\Gamma}{100}\right)^2\left(\frac{\Delta/c}{1\,{\rm s}}\right)$$

see tutorial I

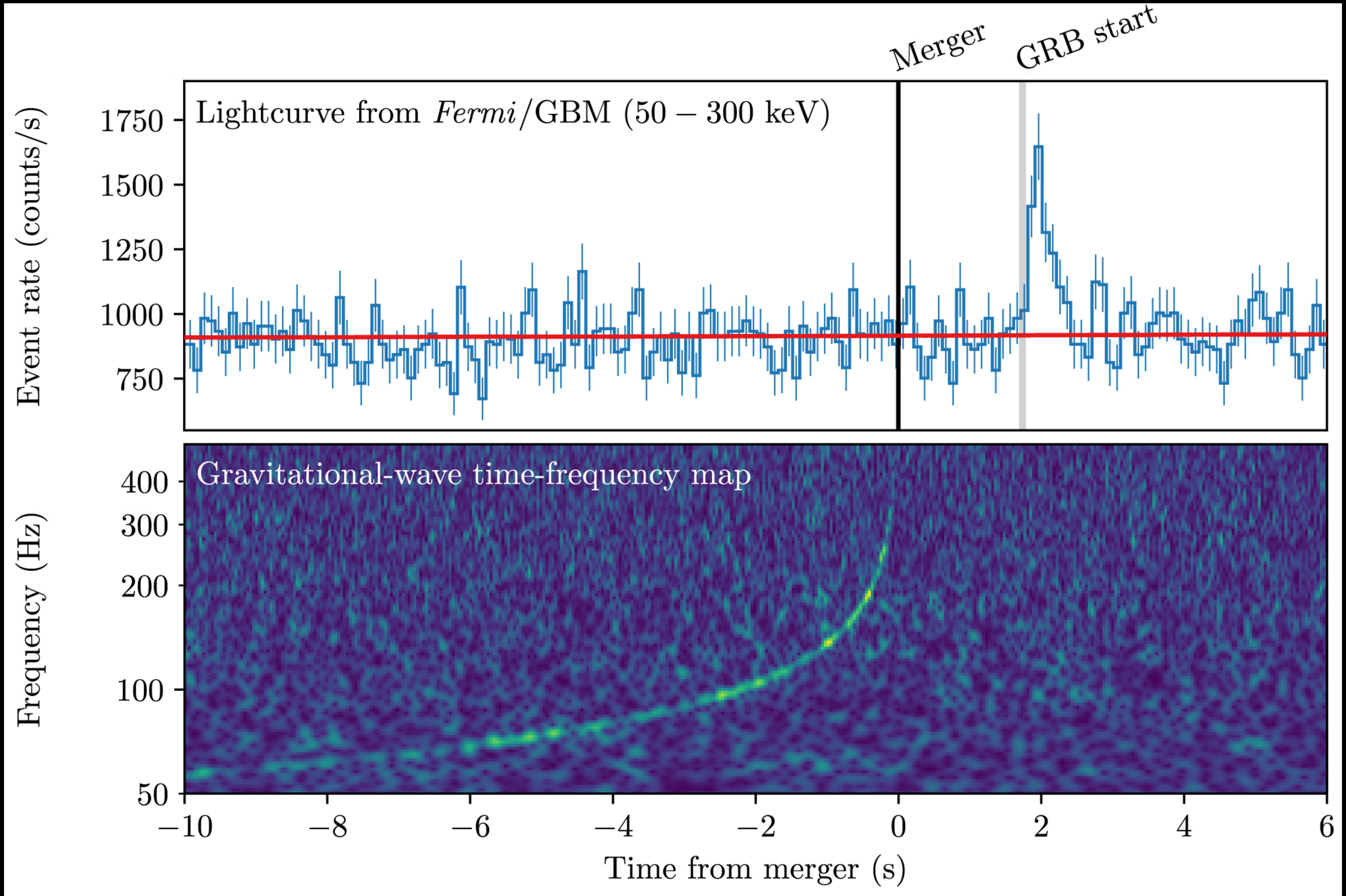
see tutorial II

Deceleration External diss.

$$R_{\rm dec} \simeq \left(\frac{3}{4\pi}\frac{\mathcal{E}_{\rm kin,0}}{\Gamma_0^2 n_{\rm ext} m_{\rm p} c^2}\right)^{1/3} \simeq 1.5\,10^{17}\,{\rm cm}\left(\frac{\Gamma_0}{100}\right)^{-2/3}\left(\frac{\mathcal{E}_{\rm kin,0}}{10^{53}\,{\rm erg}}\right)^{1/3}\left(\frac{n_{\rm ext}}{1\,{\rm cm}^{-3}}\right)^{-1/3}$$

Contemporary studies in GRB science

GRB170817A and the multi-messenger era



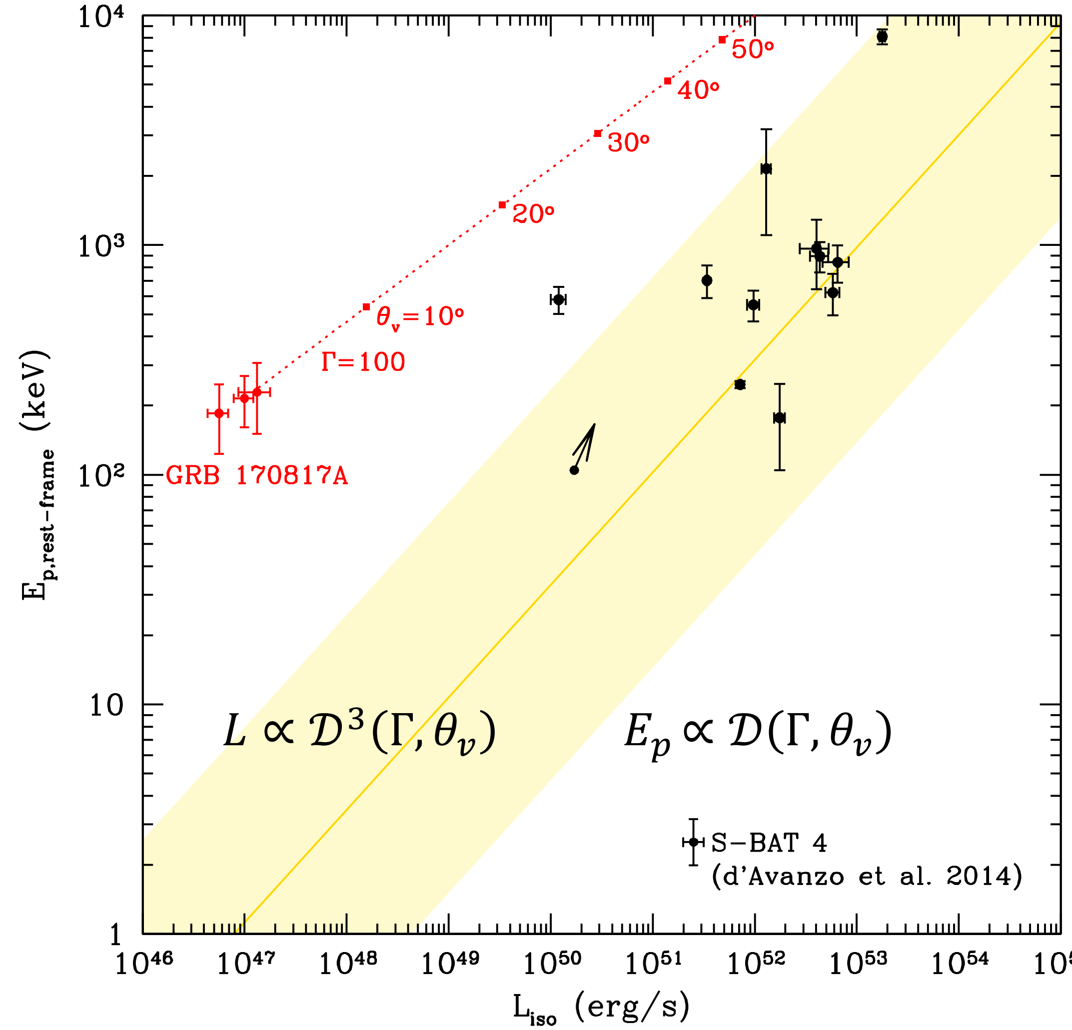
- GW170817: inspiral signal from a BNS merger ($D_L \sim 40$ Mpc)
- GRB170817A: weak, hard, short GRB
- First multi-messenger signal with gravitational waves

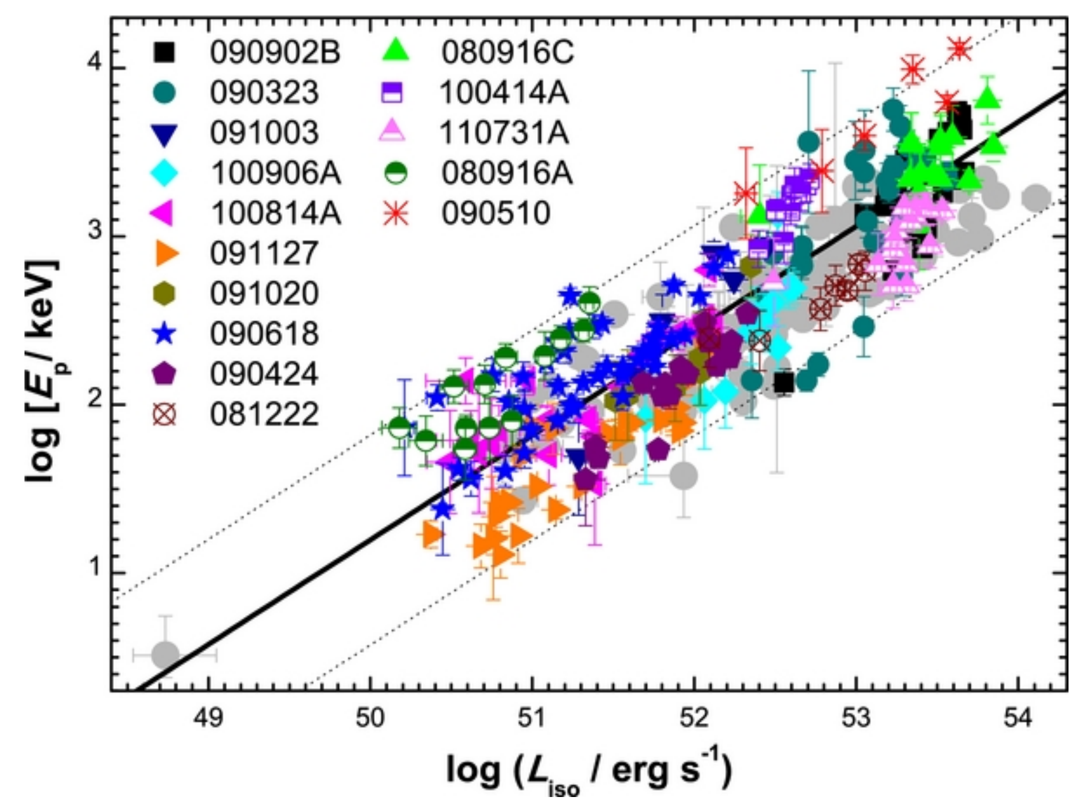
Abbott et al. 2017

GRB170817A is puzzling

- Very under-luminous
  $L_{iso,\gamma} \sim 10^{47}$ erg/s
- Still emits well above 200 keV
- Low $E_{iso,\gamma} \sim 10^{47}$ erg

- Standard GRB seen **off-axis**?
  unlikely (E_p would be very high if seen on-axis)





Lu et al. 2012

Structured relativistic jets: Concept

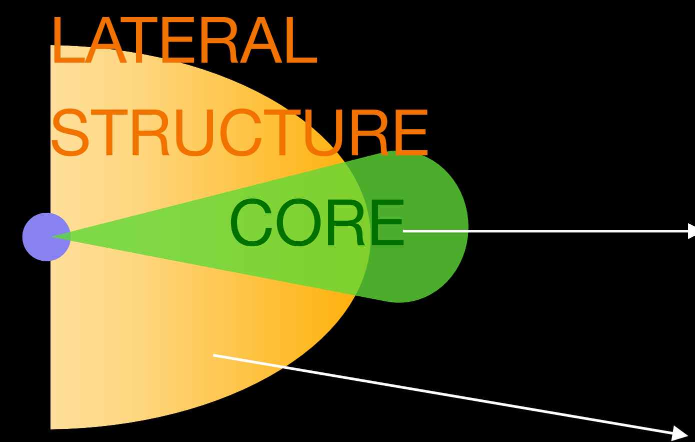
- Jet launched from central engine is likely to **interact** with merger ejecta or collapsar envelope

⇒ **Interaction-induced** structure in outflow

- Jet is subject to lateral expansion, instabilities, etc.

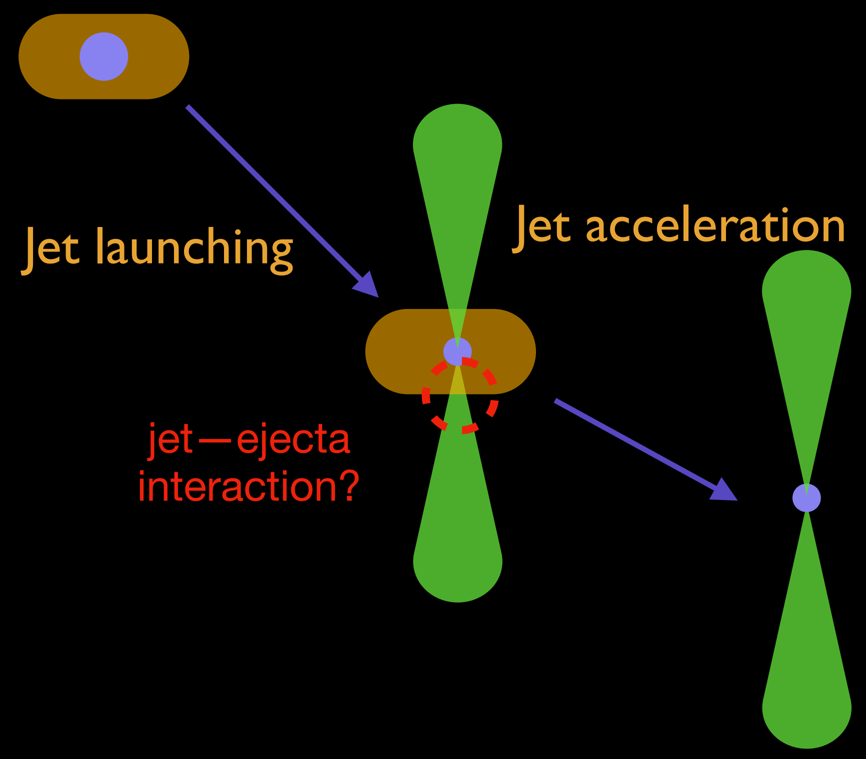
⇒ **Self-induced** structure

- This structure will influence the GRB afterglow



$$\begin{cases} E_{\mathrm{kin,iso}}(0) = E_c & \sim 10^{53}\ \mathrm{erg} \\ \Gamma(0) = \Gamma_j & \sim 250 \end{cases}$$

$$\begin{cases} E_{\mathrm{kin,iso}}(\theta) \\ \Gamma(\theta) \end{cases}$$



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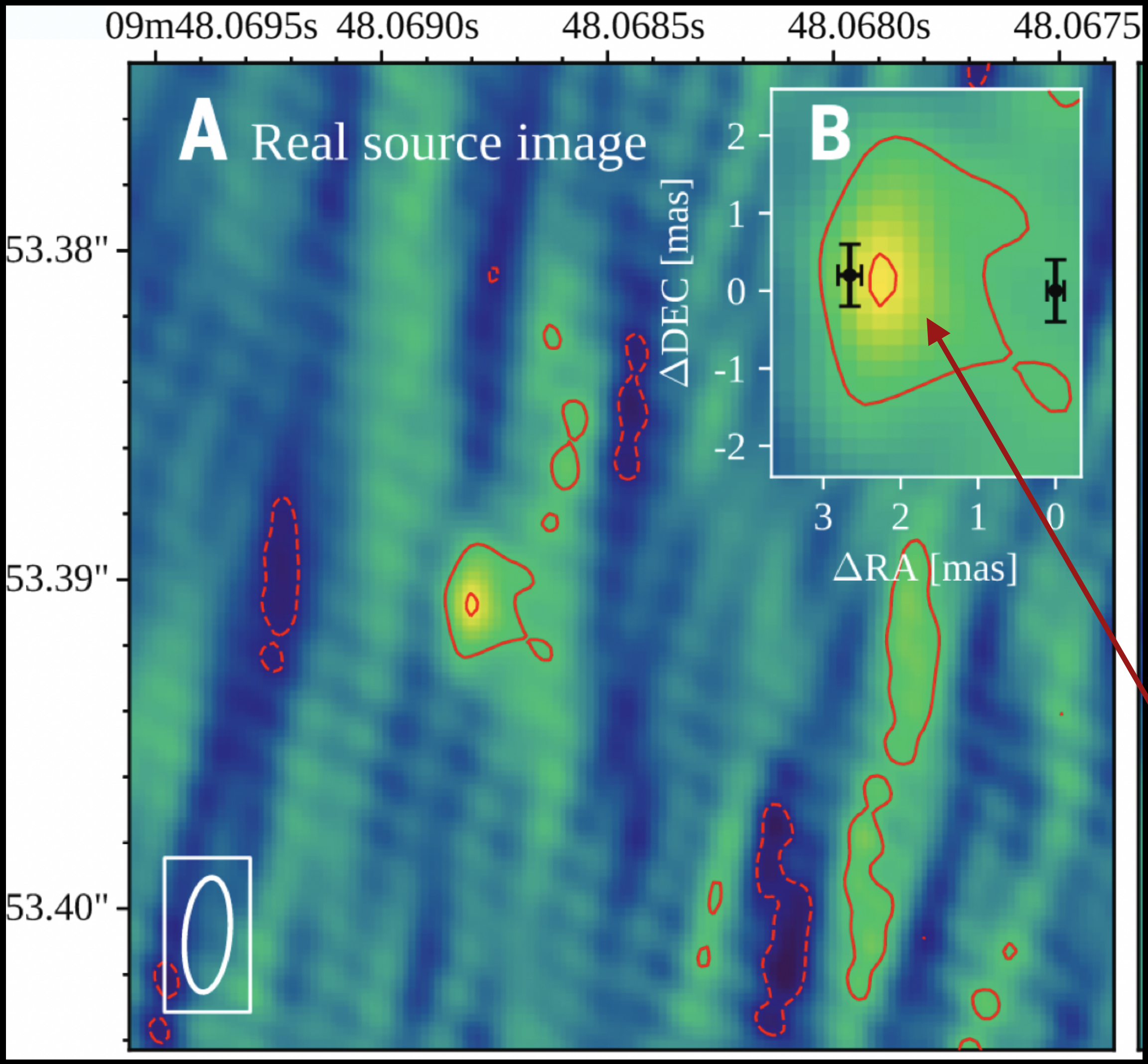
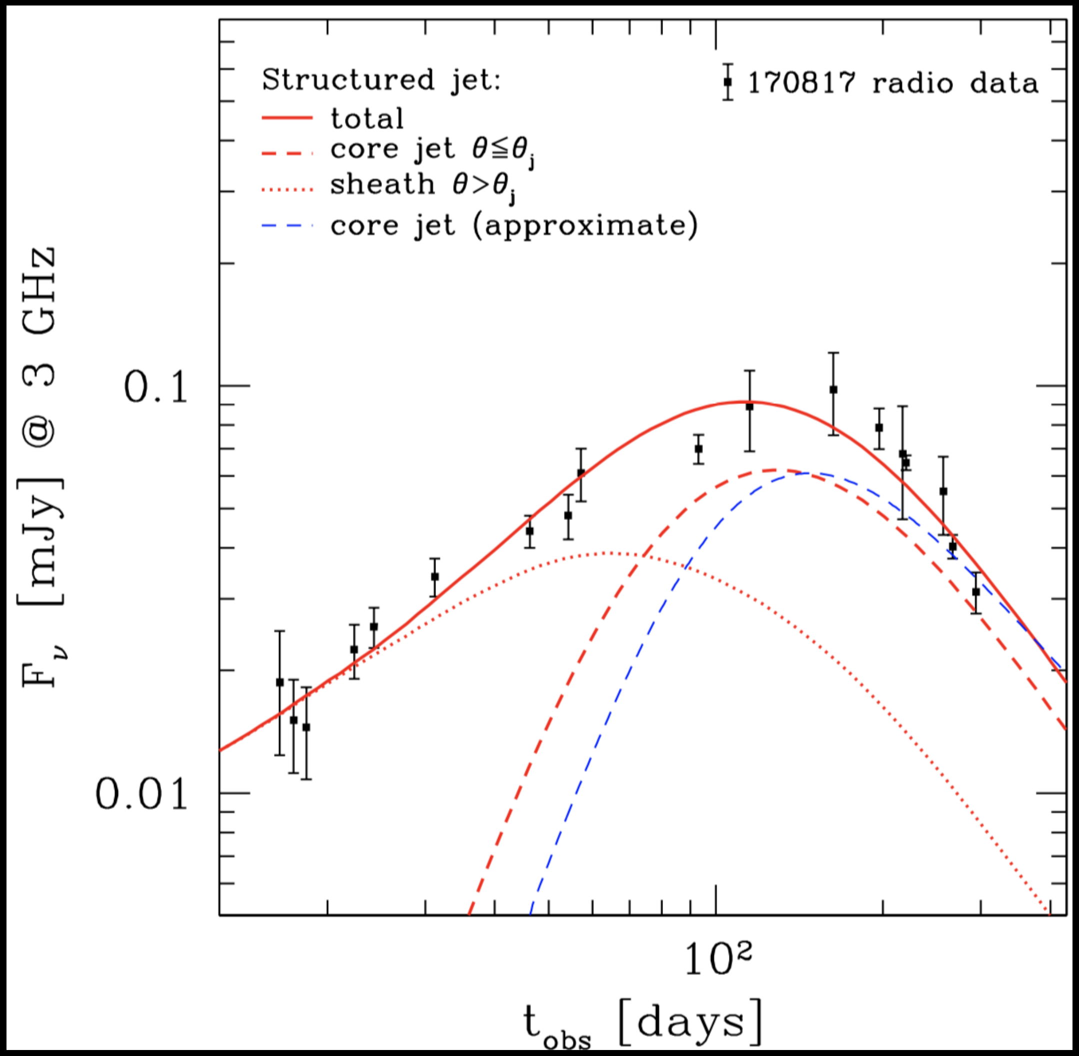
Structured relativistic jets: Observations in GRB170817A



Displacement: ~3 milliarcsec in 155 days
$\Rightarrow \beta_{app} \sim 4$

Ghirlanda et al. 2019



Duque et al. 2019

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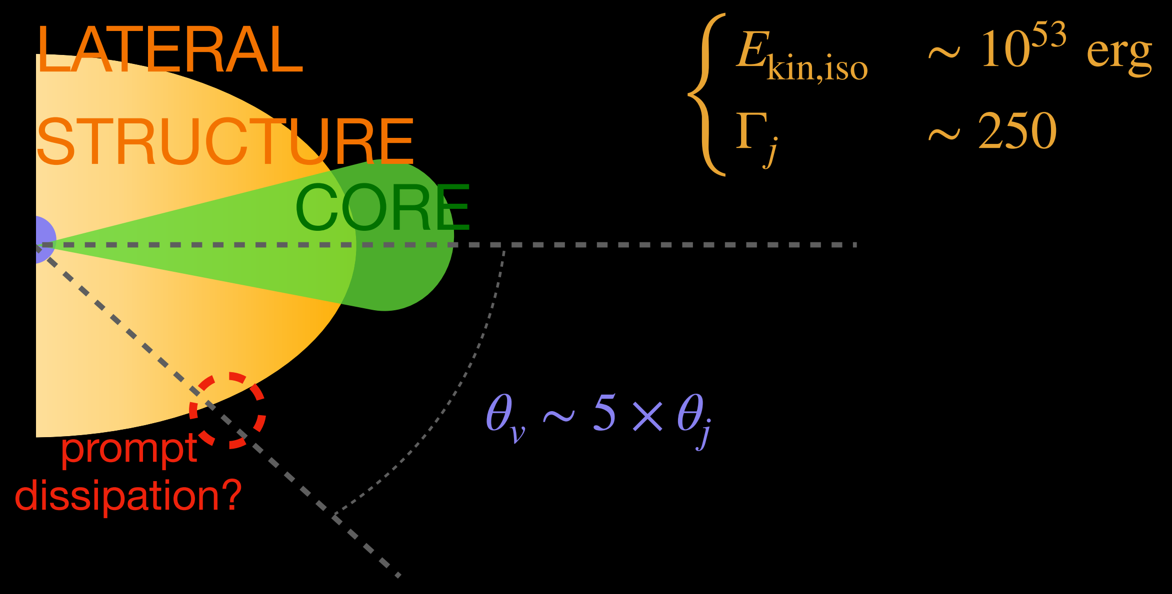
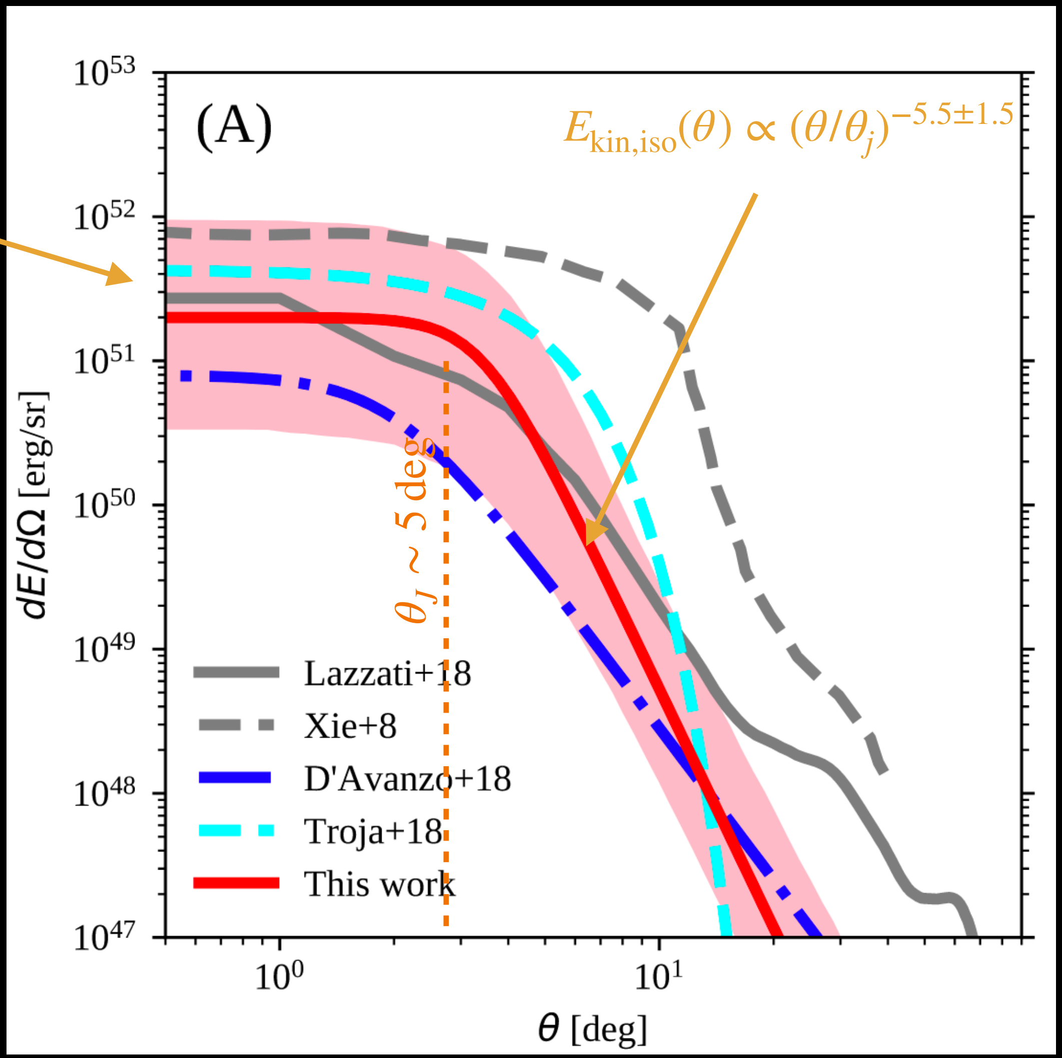
Structured relativistic jets: Observations in GRB170817A



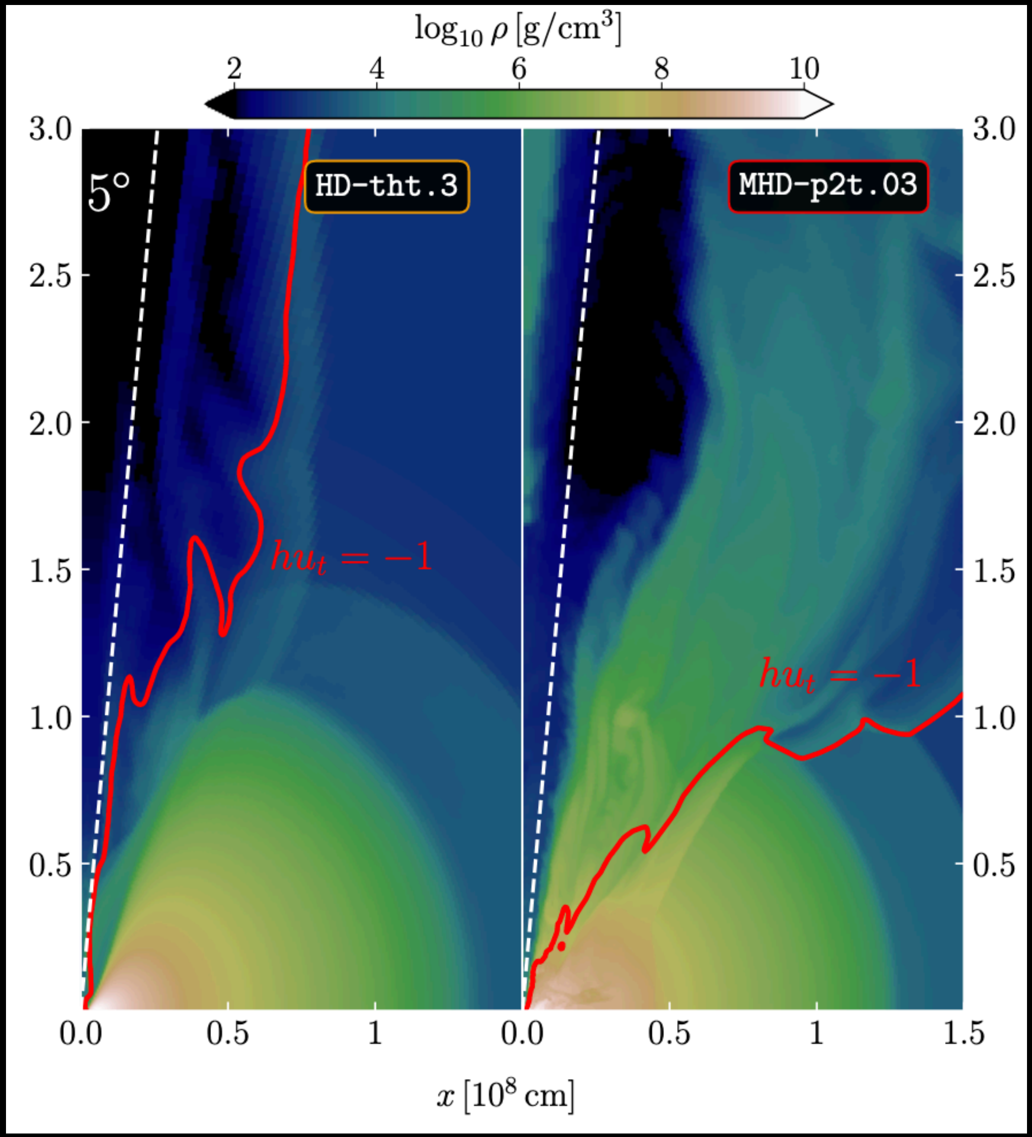


Ghirlanda et al. 2019

Historic firsts

- Detailed study of GRB jet
- Relativistic structured jet
- *Significantly* misaligned line of sight
- Prompt emission not from the core jet

Structured relativistic jets: Theory and simulations



- **Features**:
  - Hollow-core structure (Nathanail et al. 2020)
  - Jet asymmetry (Pavan et al. 2021)
  - Jet oscillations (Lazzatti et al. 2021)
  - Jet mixing and instabilities (Gottlieb et al. 2020)
- **Limitations**:
  - Inconsistent physics from one simulation to another
  - Either jet or ejecta a priori prescription
  - 2D axisymmetry
  - No gravity

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Conclusion

- Gamma-ray bursts are the brightest electromagnetic phenomena in the Universe
- They have strong ties to many other astrophysics topics

- A complex physics is at work: a stellar-mass compact source, a relativistic ejection, particle acceleration, non-thermal radiation, …

  ⇒Very difficult to model

- A standard scenario is well established
  but there are many open questions at each step

- GRBs are multi messenger events (GW, probably neutrinos): new constraints are coming and will lead to a more realistic physical scenario
  (e.g. evidence for a structured jet in 170817)

- GRB observational prospects in 2020+:
  - new space missions following Swift & Fermi (e.g. SVOM)
  - GW: improved sensitivity and localization
  - CTA and other very high energy telescopes,
  - new generation of radio-telescopes
  - Large surveys: orphan afterglows?

End of Lecture #2

Gamma-Ray Bursts & Relativistic Jets

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Explore 2022
Summer School
21—26 August, 2022

Tutorial I: Internal shocks model of GRB prompt emission

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The Yonetoku $E_p - L_{\mathrm{iso},\gamma}$ relation

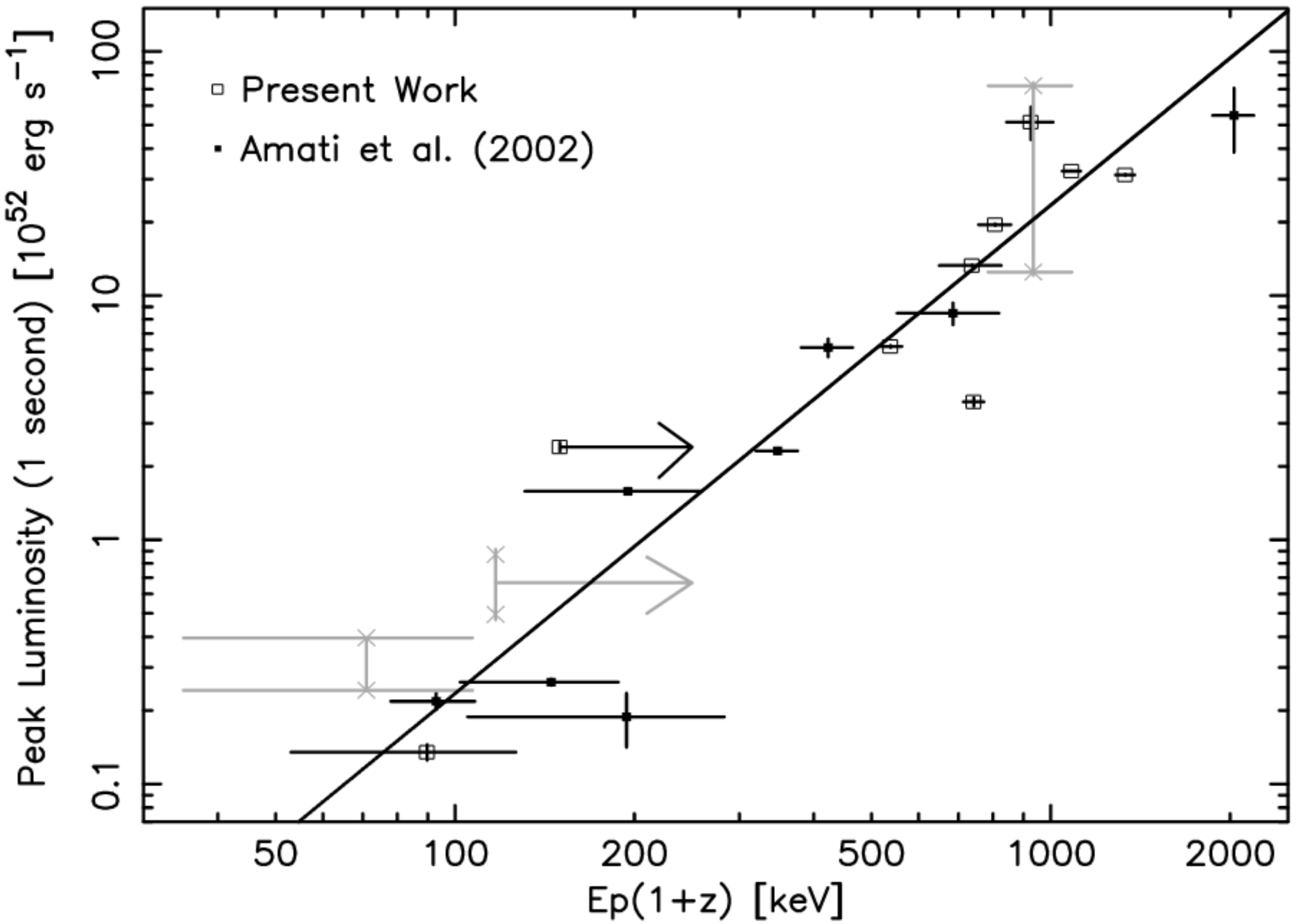

FIG. 1.—E_p-luminosity relation. The open squares are our present results with BATSE. The results of *BeppoSAX* (Amati et al. 2002) are also shown as the filled squares. Both results are plotted as $E_p(1+z)$ at the rest frame of the GRBs and the peak luminosity between 30 and 10,000 keV derived by the 1 s peak flux. The points shown with two crosses indicate the results of GRBs with ambiguous redshifts (GRB 980326, GRB 980329 and GRB 000214). The solid line is the best-fit power-law model for the data.

Yonetoku et al. 2004

Tutorial II: Synchrotron emission from the forward shock

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Multi-wavelength afterglow sample

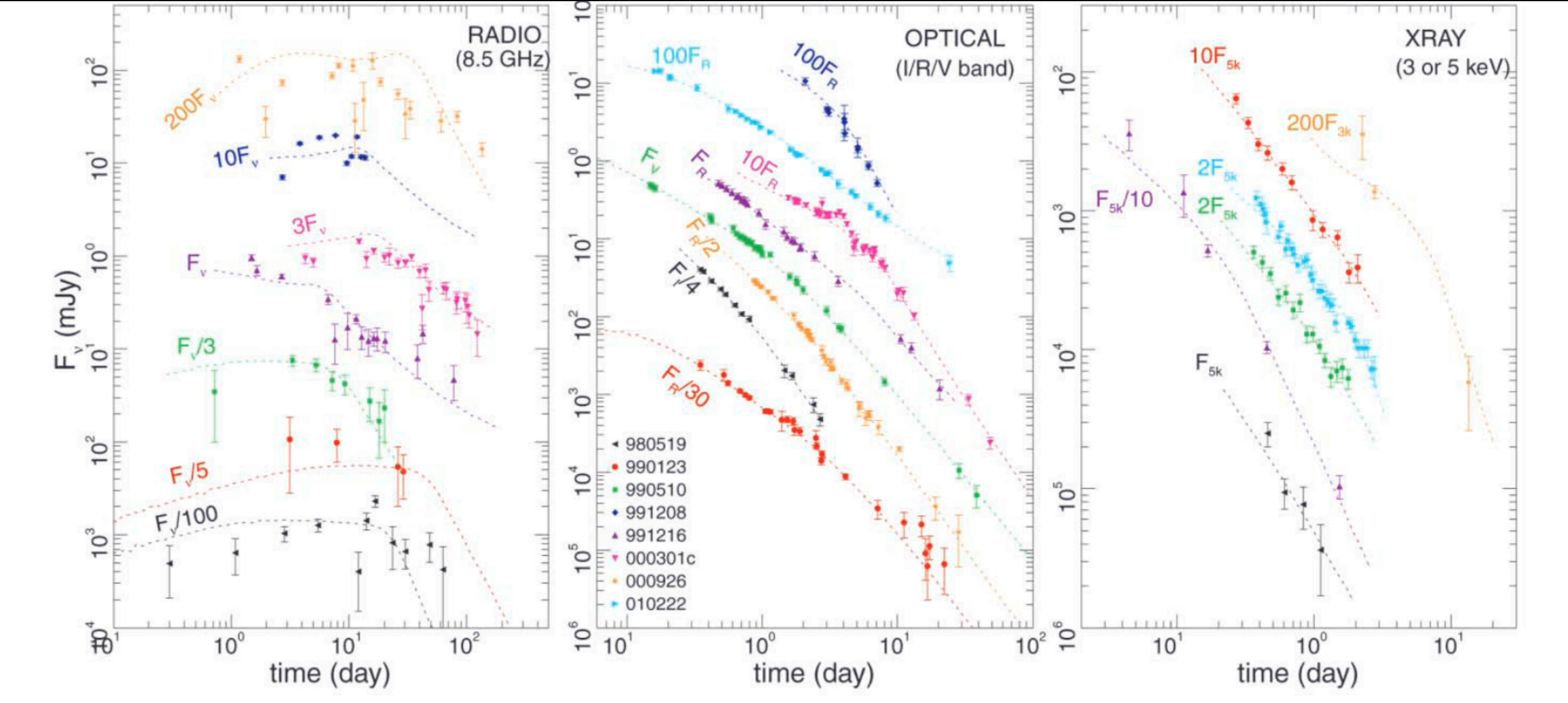

FIG. 1.—Radio, optical, and X-ray emission and model light curves for the GRB afterglows 980519, 990123, 990510, 991208, 991216, 000301c, 000926, and 010222 (the definition of the symbols in the lower left-hand corner of the middle graph applies to all panels). The numerical light curves have been obtained by the minimization of χ^2 between the model emission and the radio, millimeter, submillimeter, near-infrared, optical, and X-ray data (only a part of the used data is shown in this figure). The parameters of each model are given in Fig. 2. Optical data have been corrected for Galactic dust extinction. The spread around the model curves exhibited by the radio emission of 980519, 991208, 991216, 000301c, and 000926 can be explained by fluctuations due to scatterings by the inhomogeneities in the Galactic interstellar medium (Goodman 1997). Fluxes have been multiplied by the indicated factors, for clarity.

Panaitescu & Kumar 2001