GRB afterglow observations

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Science with GRB afterglows

GRB physics
- Shocks
- Role of magnetic fields
- Jets
- Central engine

Progenitors
- Long GRBs: GRB-SN connection
- Short GRBs: compact objects merging (GW)

GRB redshifts
- From the local Universe to the re-ionization era

GRB environment
- Circumburst environment
- IGM
- Chemical history of the Universe

A bit of history

- discovered in the '60s by the Vela satellites (military program to monitor nuclear tests)
- announced in 1973

The Astrophysical Journal, **182**:L85–L88, 1973 June 1

OBSERVATIONS OF GAMMA-RAY BURSTS OF COSMIC ORIGIN

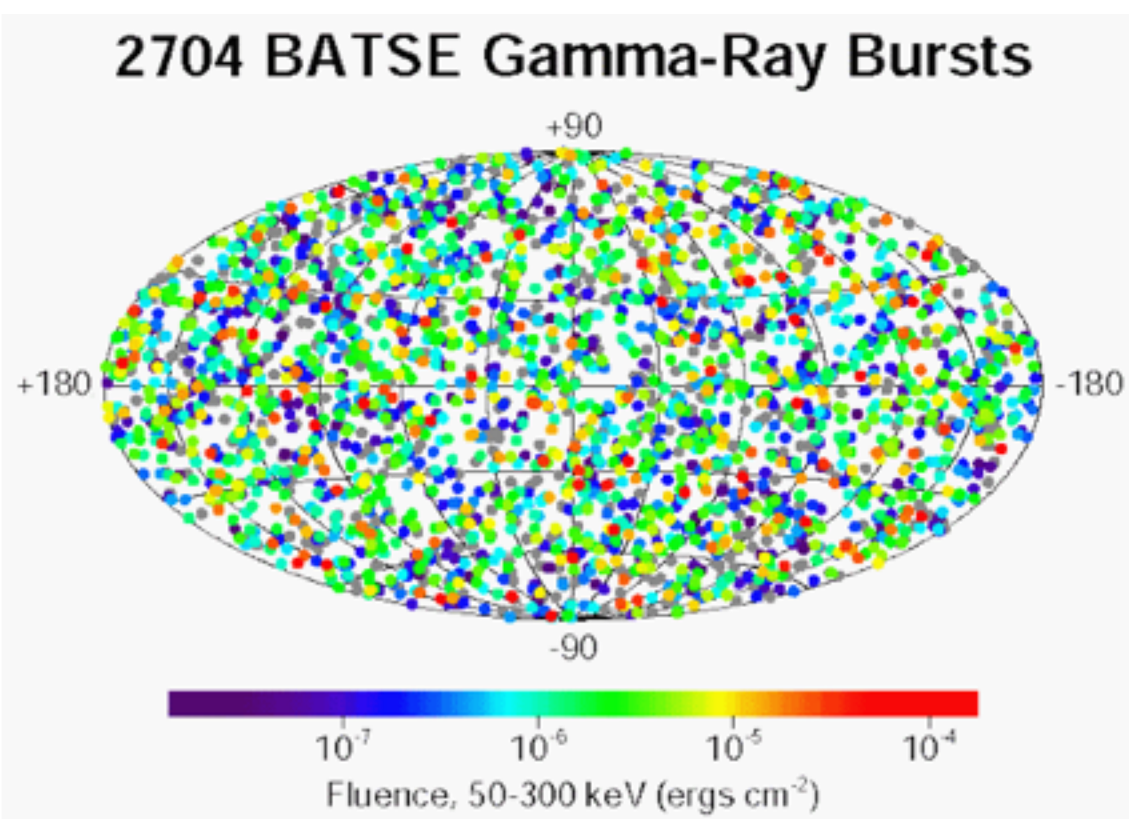
Ray W. Klebesadel, Ian B. Strong, and Roy A. Olson

University of California, Los Alamos Scientific Laboratory, Los Alamos, New Mexico
Received 1973 March 16; revised 1973 April 2

ABSTRACT

Sixteen short bursts of photons in the energy range 0.2–1.5 MeV have been observed between 1969 July and 1972 July using widely separated spacecraft. Burst durations ranged from less than 0.1 s to ∼30 s, and time-integrated flux densities from $\sim 10^{-5}$ ergs cm^{-2} to $\sim 2 \times 10^{-4}$ ergs cm^{-2} in the energy range given. Significant time structure within bursts was observed. Directional information eliminates the Earth and Sun as sources.

Subject headings: gamma rays — X-rays — variable stars

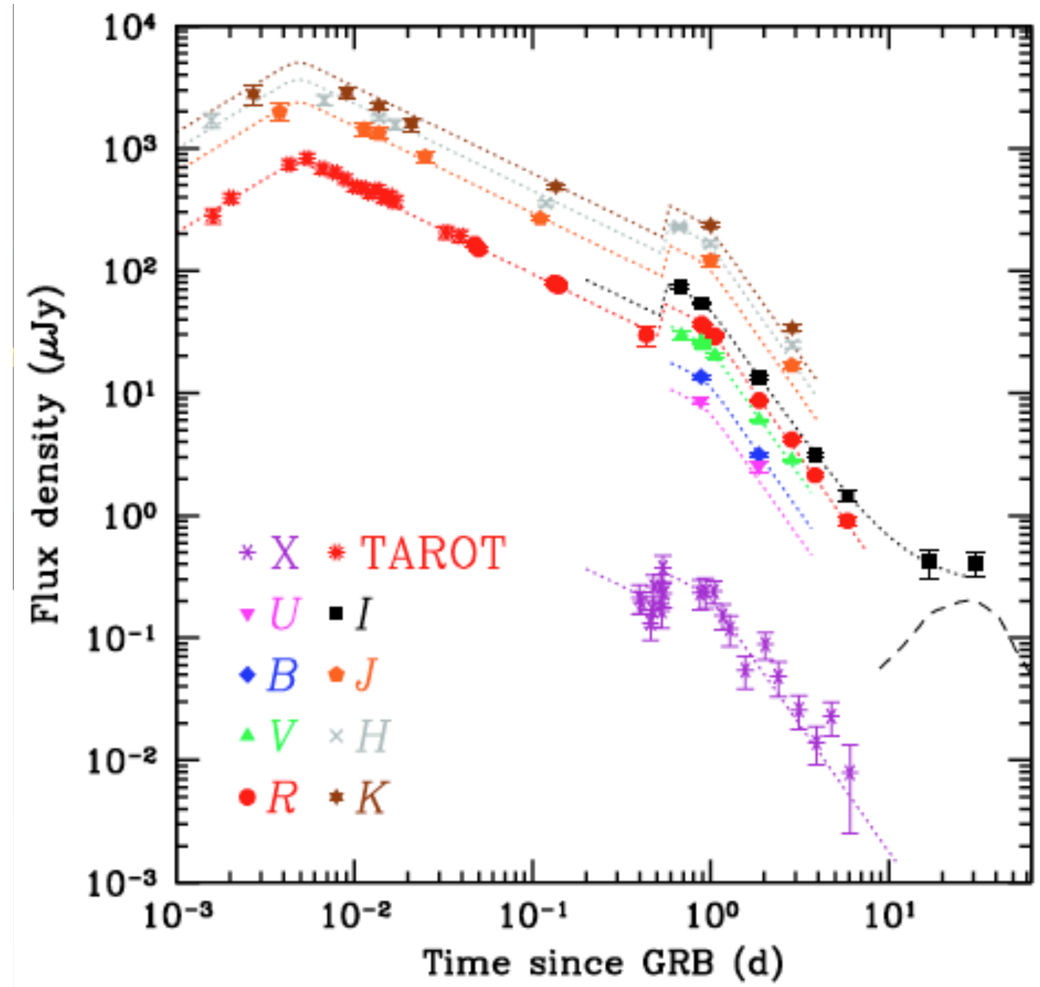


- **BATSE instrument (CGRO, 1991):** GRBs isotropically distributed over the sky

so they are "likely" extragalactic objects....

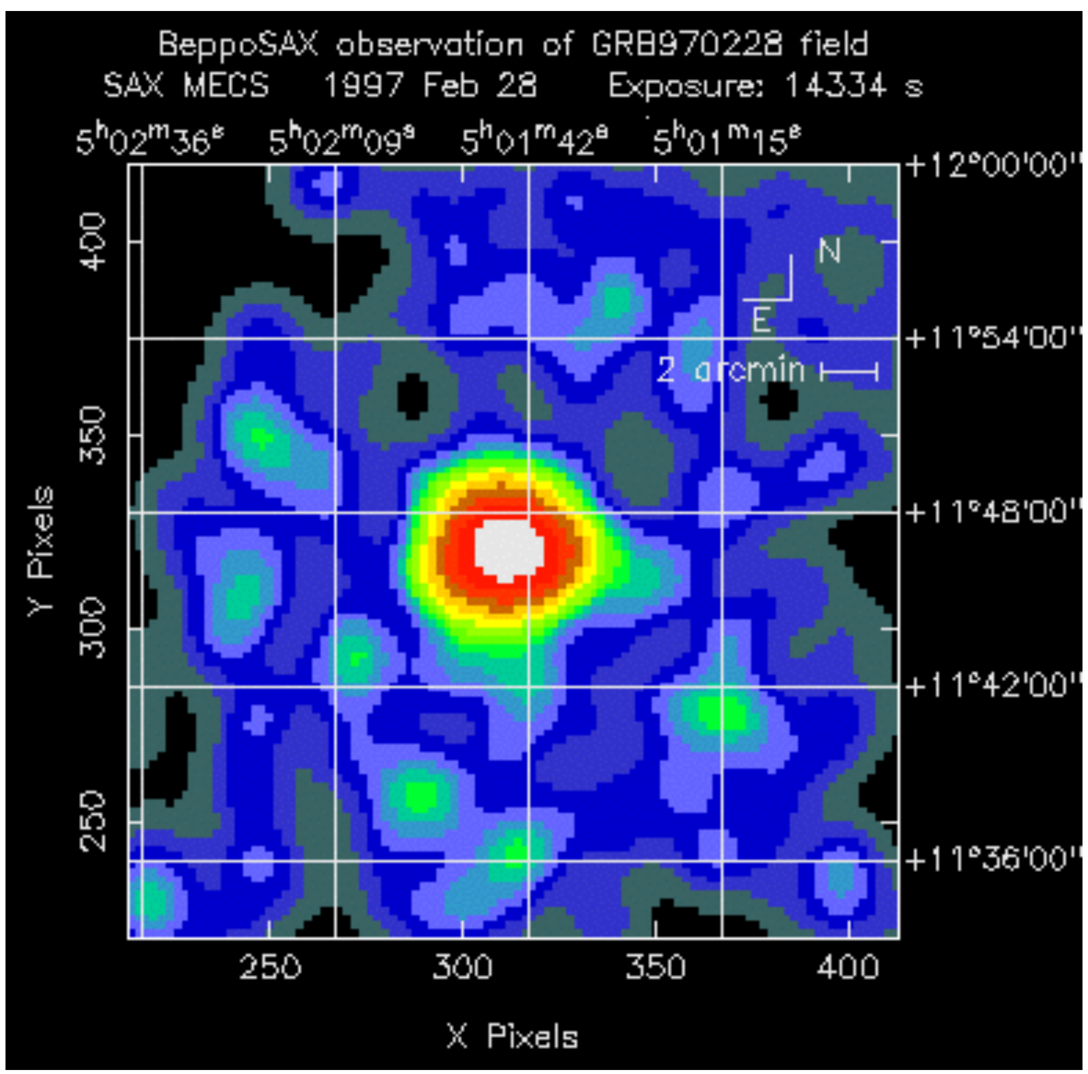
The discovery of the afterglow of long (L)GRBs

- **BeppoSAX (1996):** discovery of counterpart and localization of LGRBs



AFTERGLOW

- from GeV to radio
- power-law decay
- duration hours to days

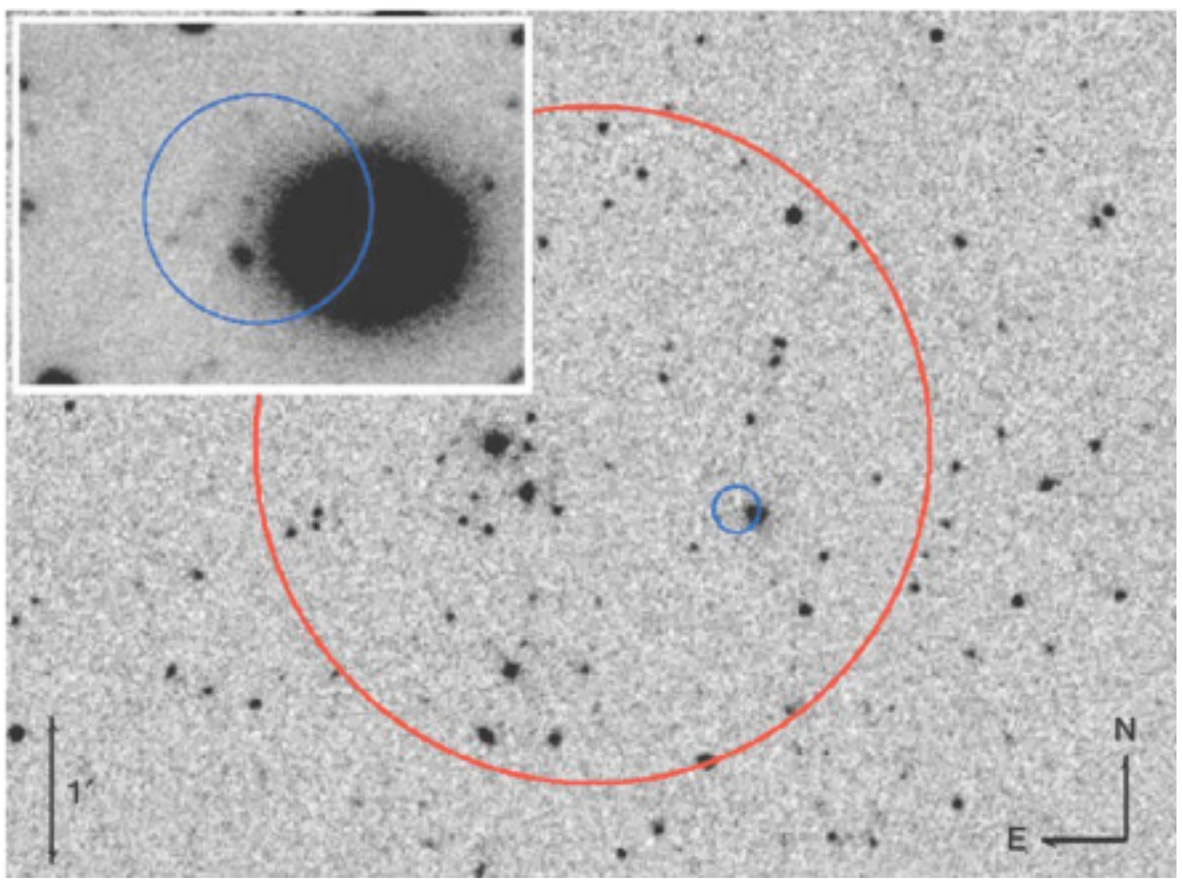


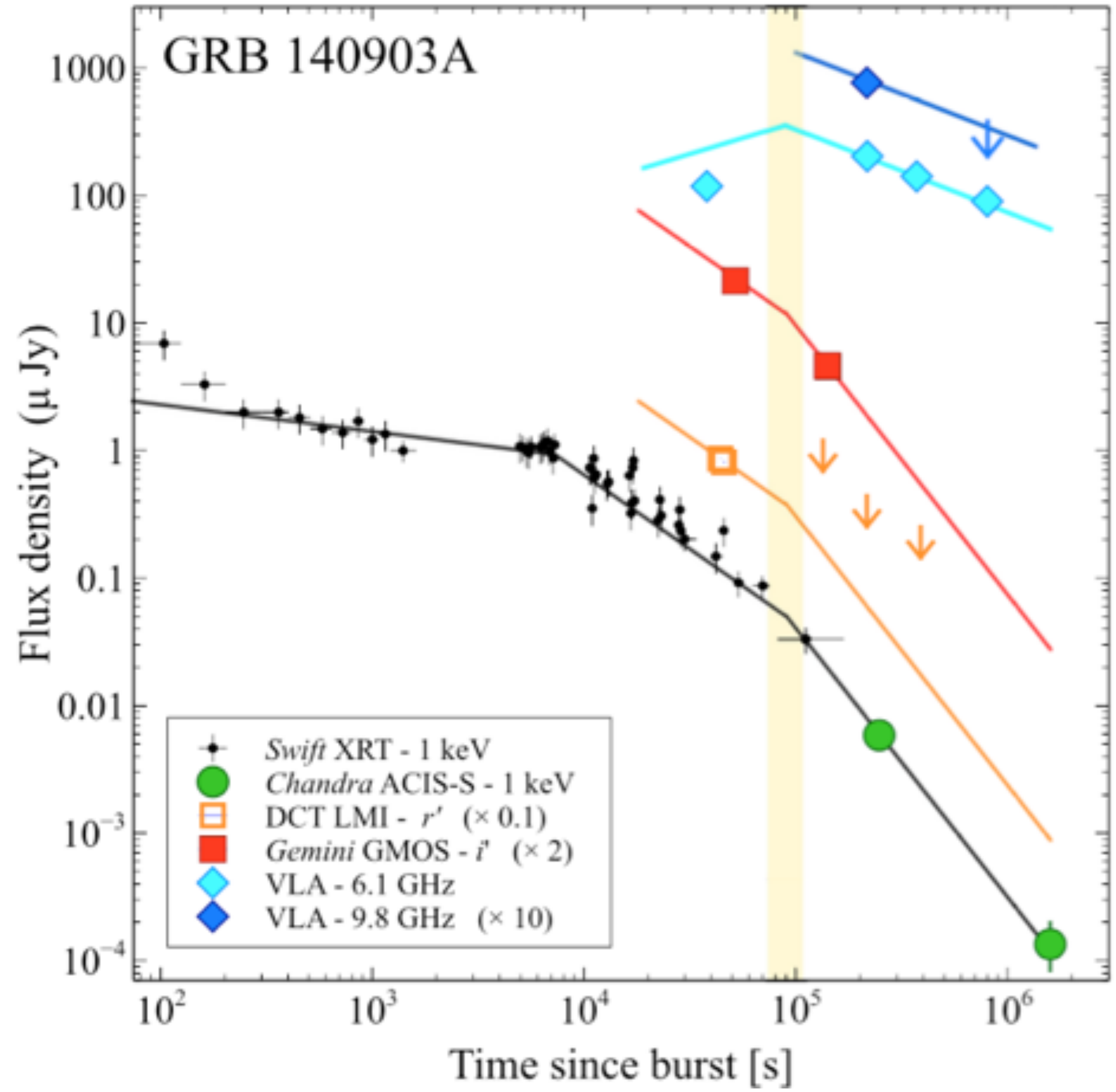
LGRBs are distant: <z>=2.1, z_{max}=8.2

This implies they are the most powerful objects in the Universe ($E_\gamma \sim 10^{52}$ erg)

The discovery of the afterglow of short (S)GRBs

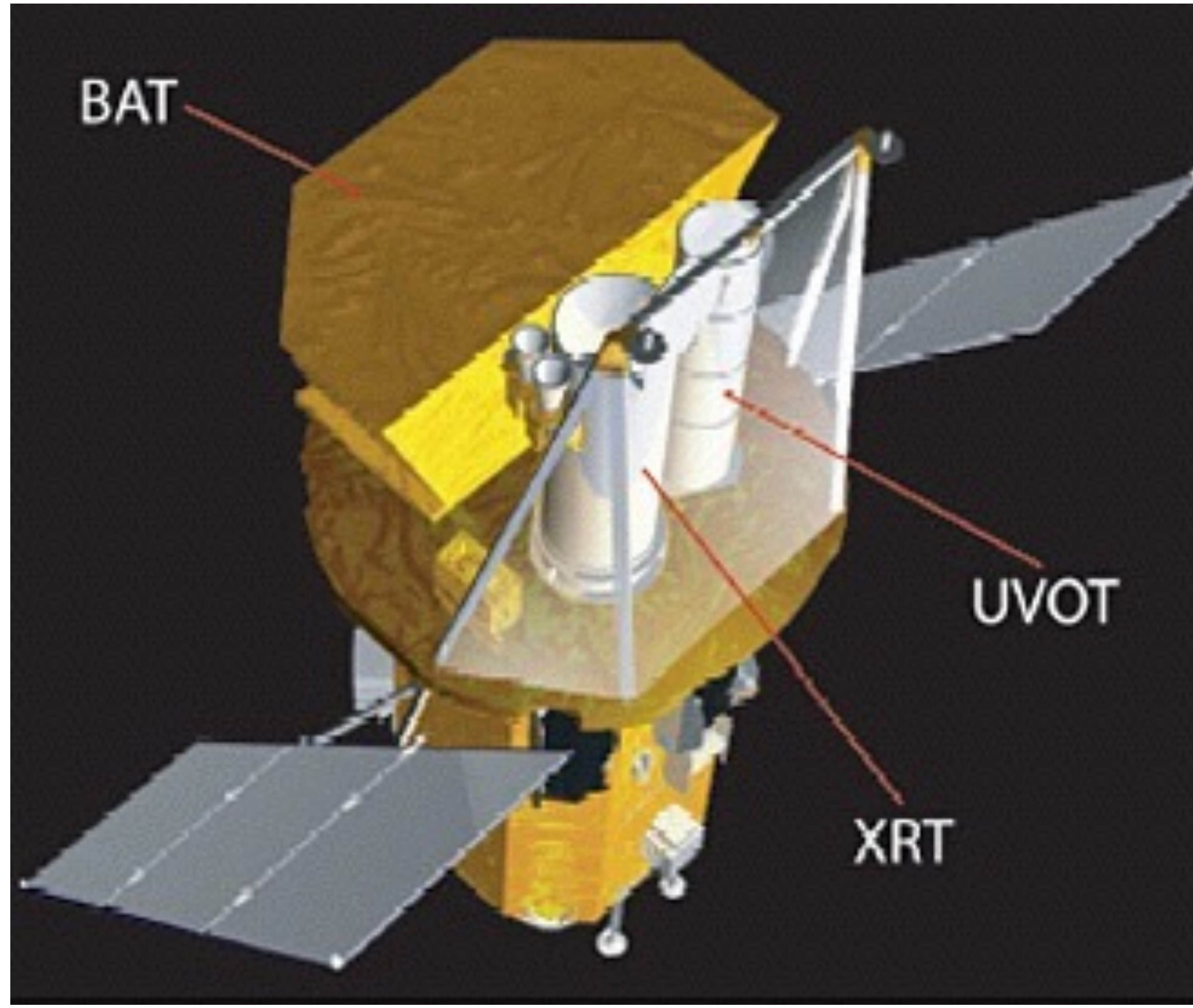
- **Swift (2005):** discovery of SGRB afterglow





The Neil Gehrels Swift observatory

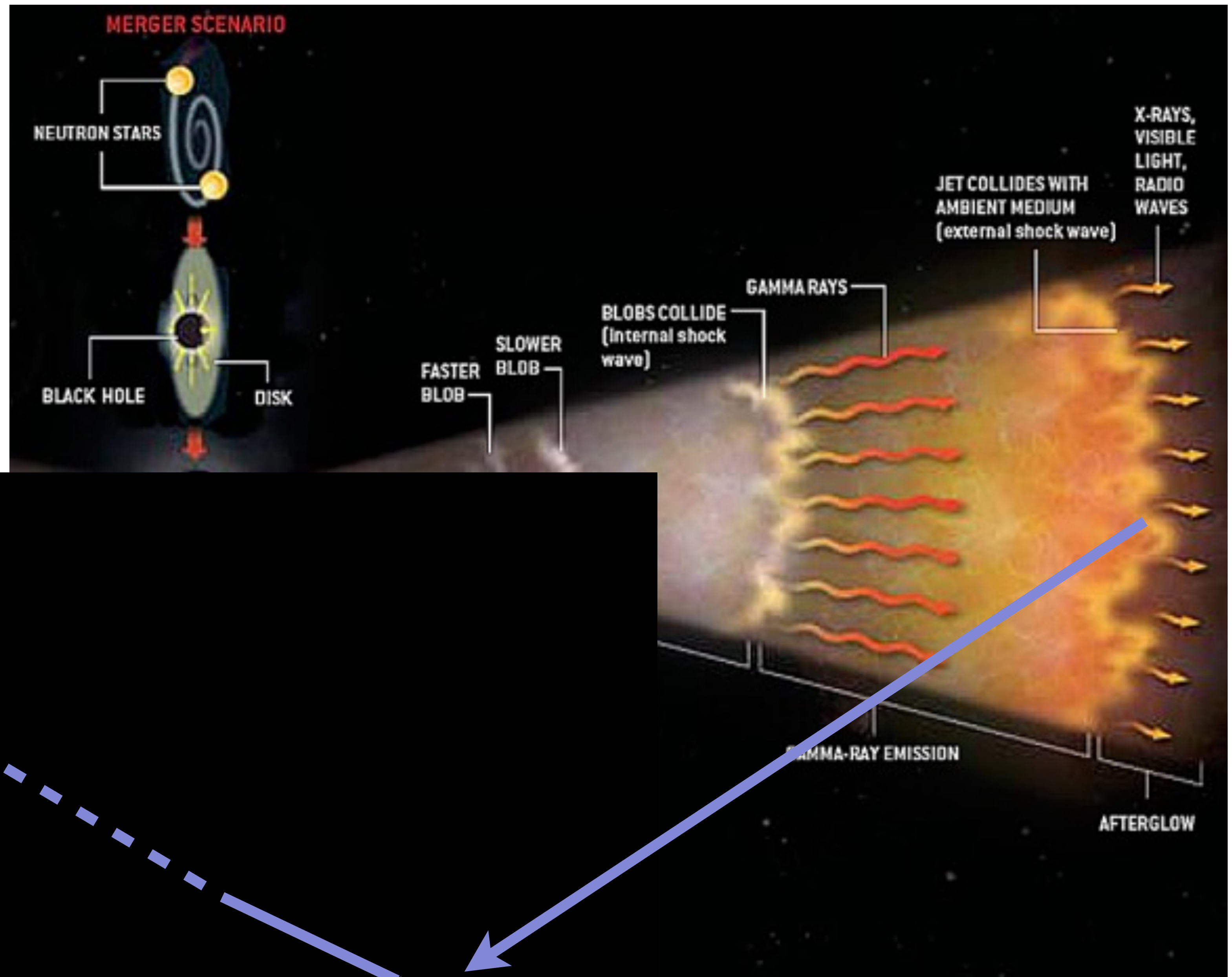
- **BAT**: coded mask, 15-150 keV, ~2 sr fov, transients detection and localisation
- **XRT**: 0.3-10 keV, rapid slew (~ 1 min) and accurate localisation (5”)
- **UVOT**: 6 filters (170-600 nm), 24th mag sensitivity (1000 s), centroid accuracy 0.5”

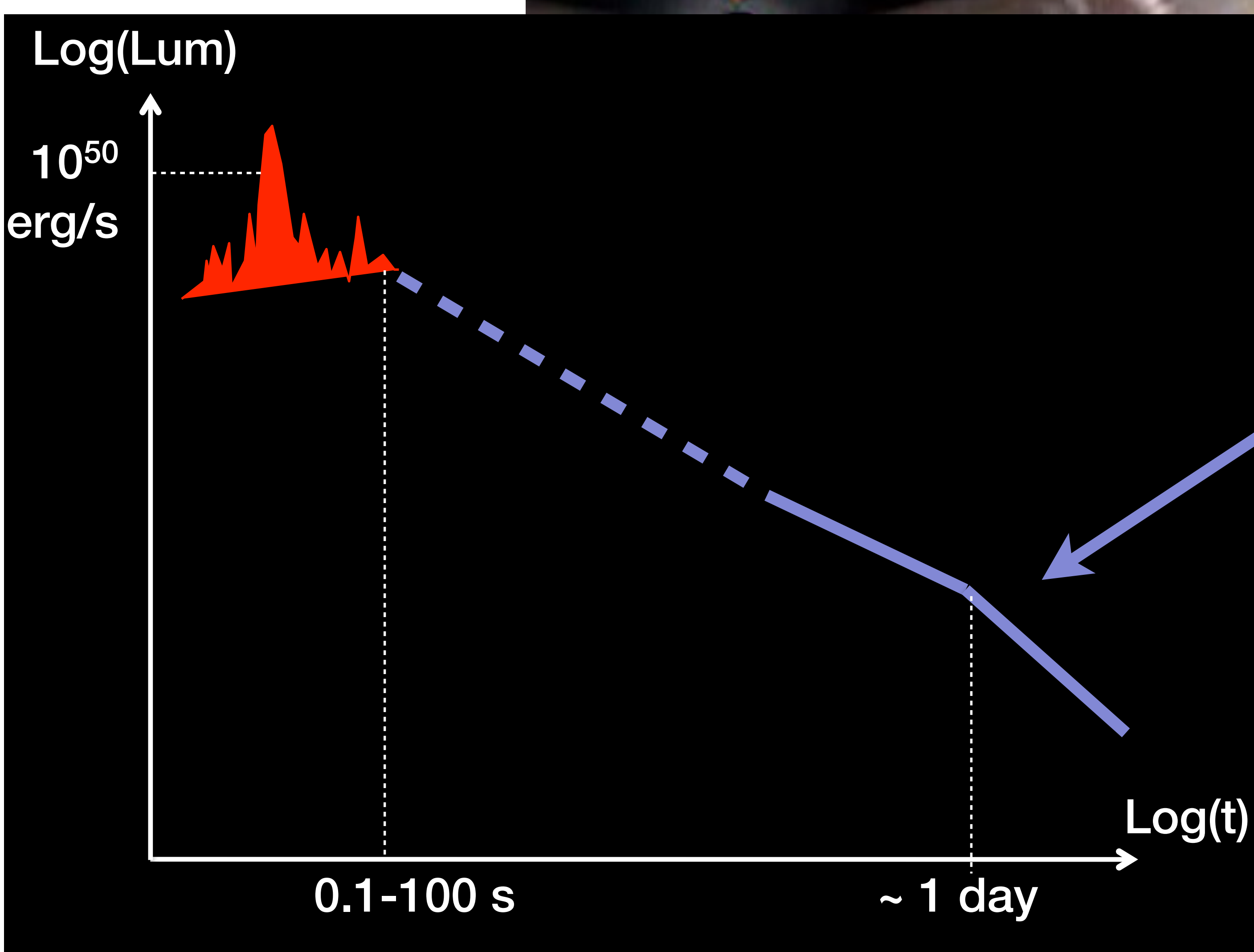


➡ **currently ~1000 GRB afterglows detected in X-rays, and ~1/3 detected also in optical-UV**

Gamma-ray bursts: the current paradigm

AFTERGLOW

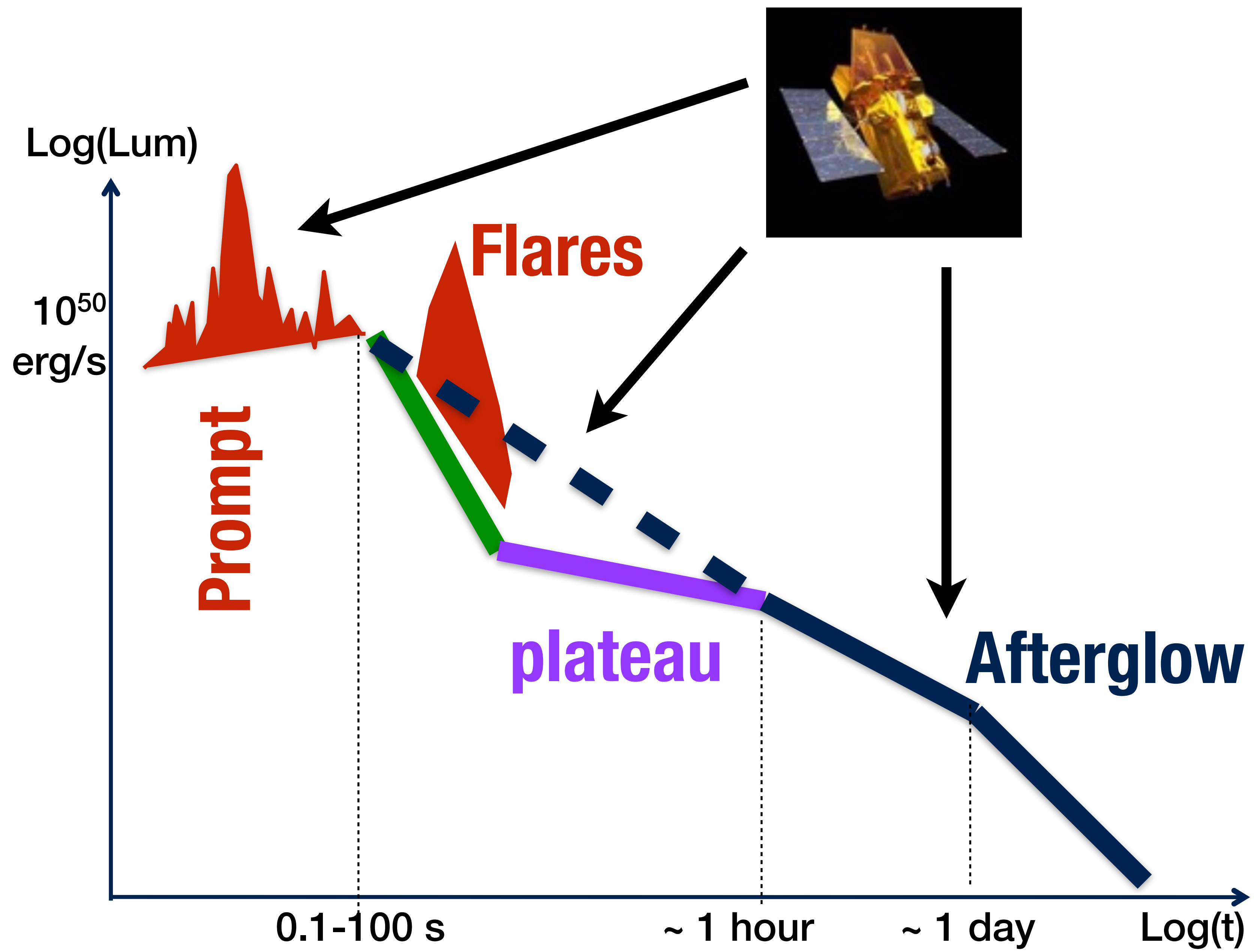




➡interaction with ambient medium (**external shocks**)

GRB X-ray afterglow

- **“canonical”** X-ray light curve (steep-**plateau**-normal) in ~ 1/2 GRBs
- **X-ray flares** in ~ 1/3 GRBs



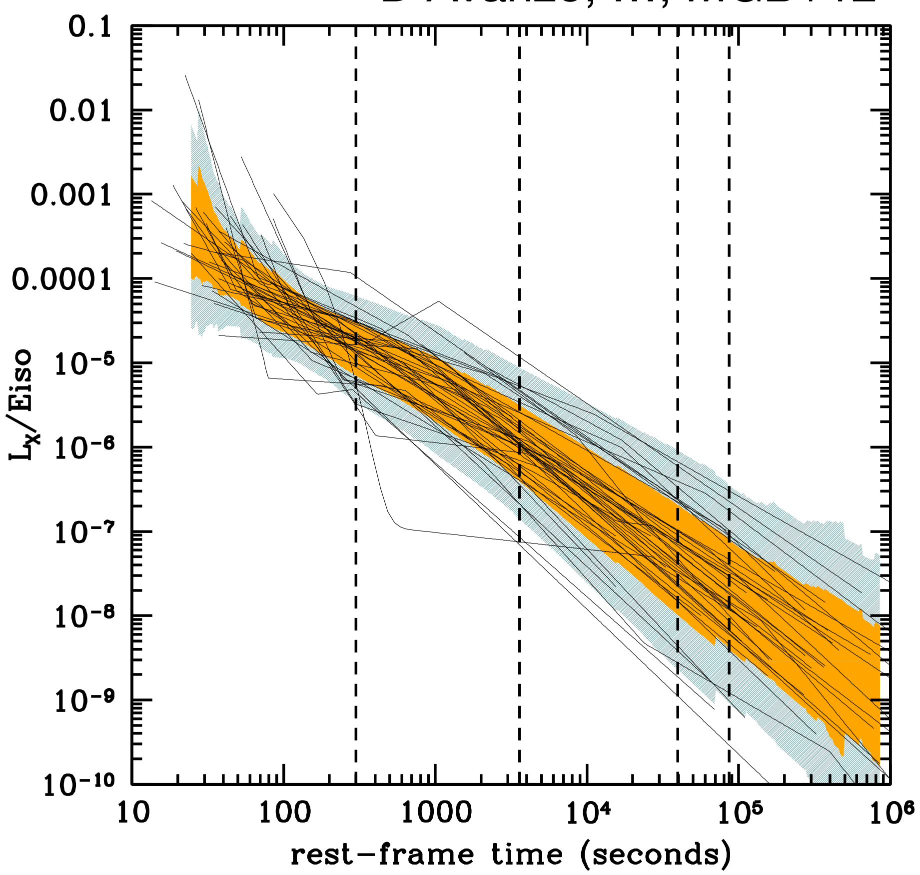
➡ **not expected by standard model**

➡**likely related to the central engine activity**

LGRB X-ray afterglow

- **Catalogues** of all the XRT observations (e.g. Evans+11; Margutti, Zaninoni, MGB+13)
- **BAT6 complete (flux-limited) sample** (Salvaterra+12): sample of bright LGRBs observed by BAT, with favourable observing conditions from ground
  - ➡high level of completeness in redshift (97%)
  - ➡ observational biases controlled

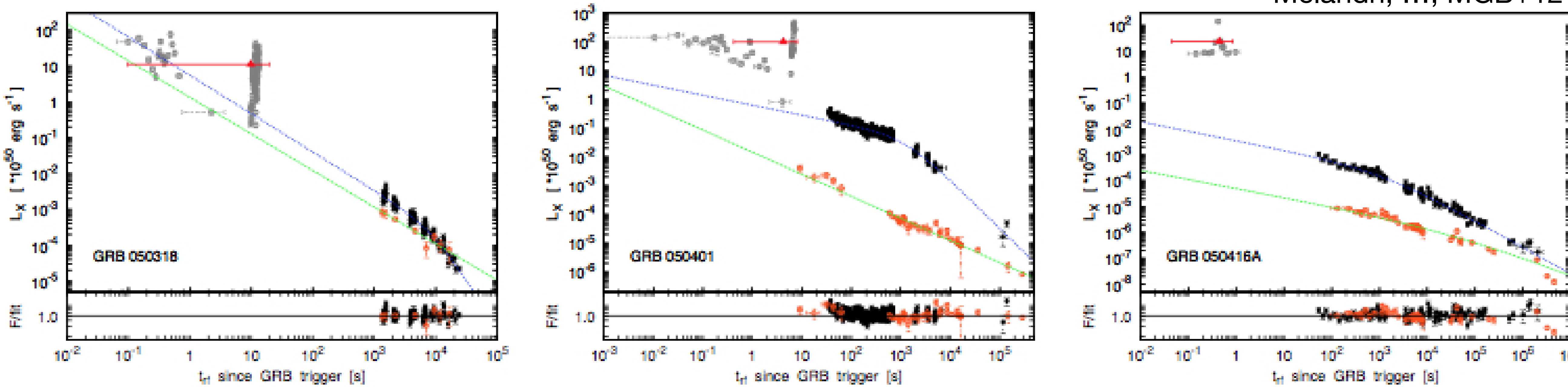
D'Avanzo, ..., MGB+12

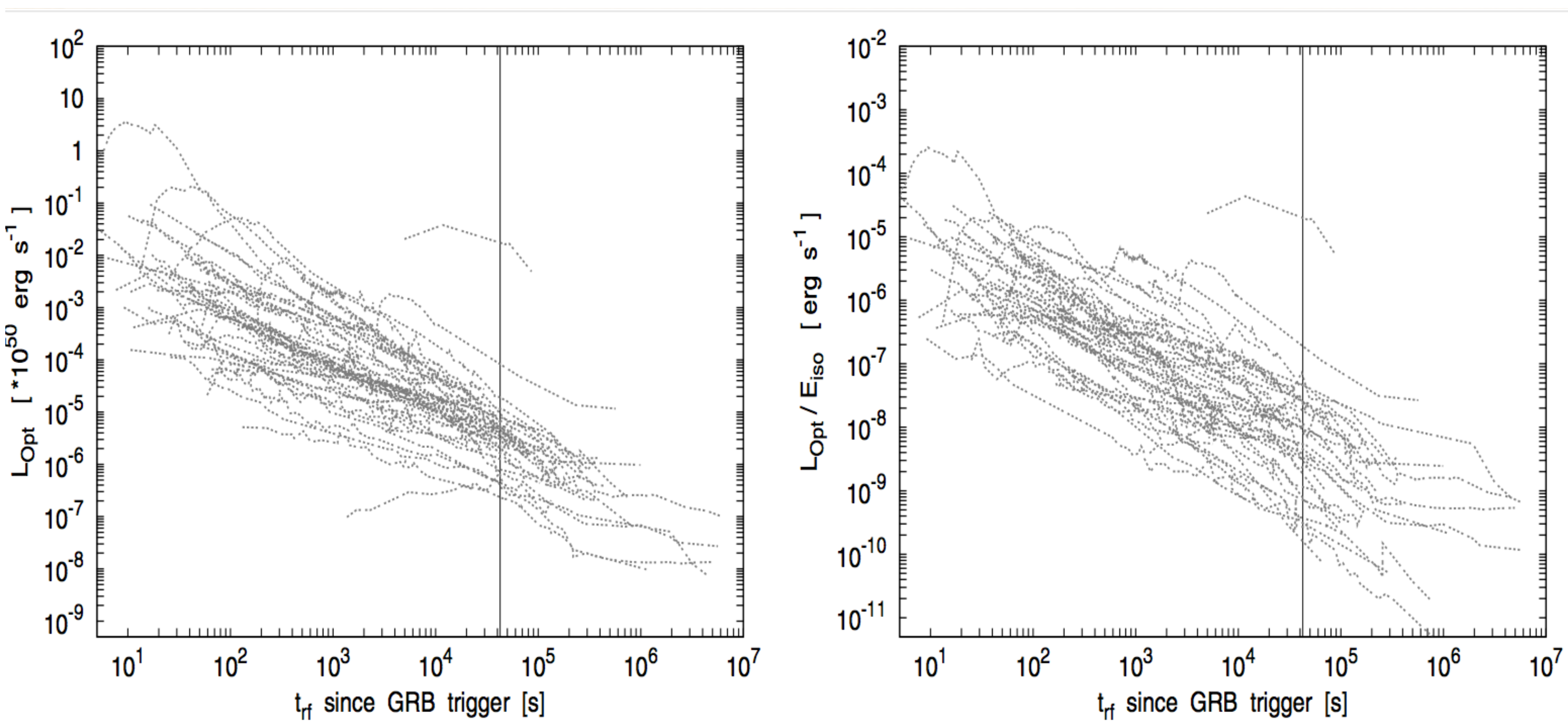


- ✦Strong **correlations of the prompt and X-ray afterglow** emission properties
- ✦Lx correlates with the prompt only at early times
  - ➡**contribution of the central engine at early (~ hours) times**

LGRB optical afterglow

Melandri, …, MGB+12





Credits: A.Melandri

- ✦ only **~30% of LCs have the same behaviour in optical and X-ray**
- ✦ no cluster of L_{ot}/E_{iso}

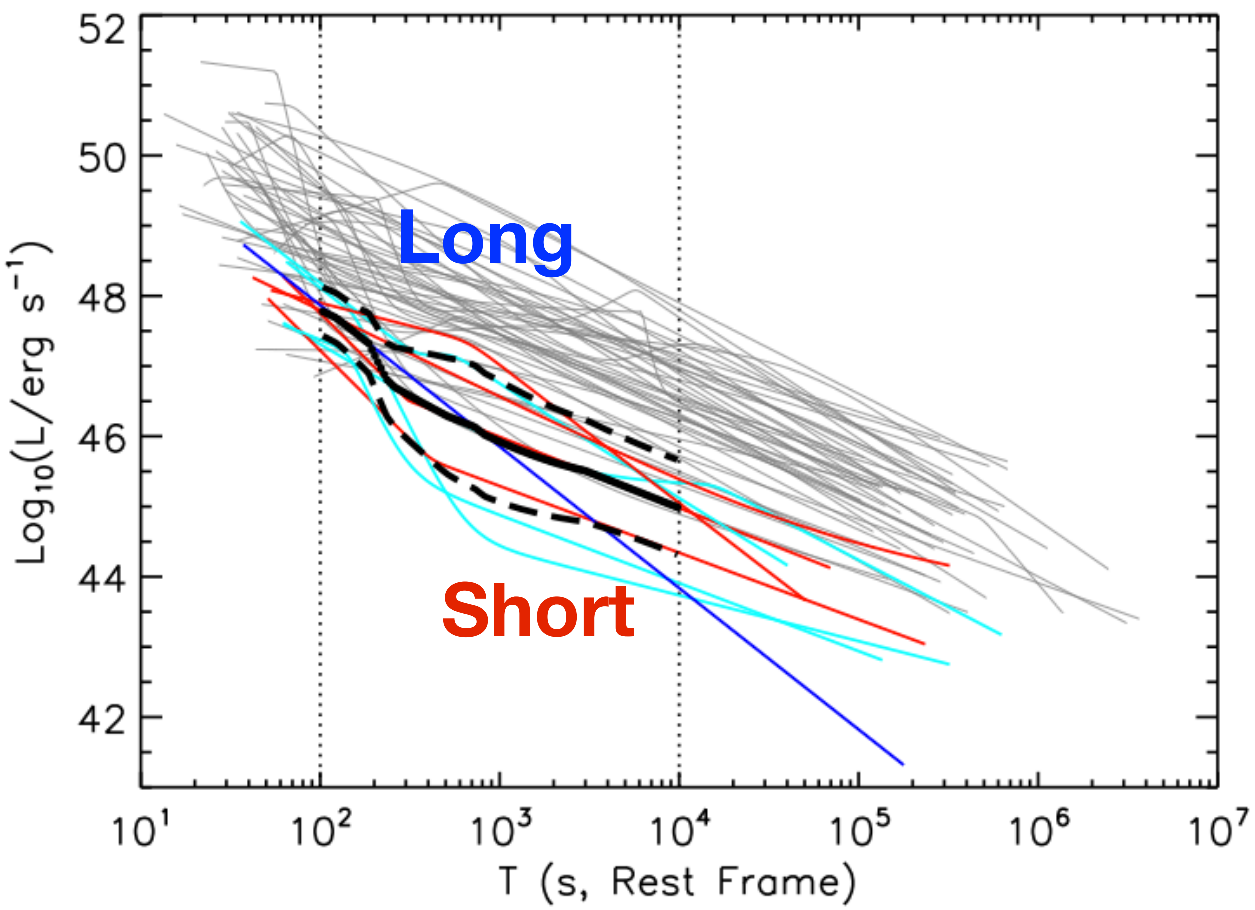
➡contribution of the central engine "chromatic"

+ GRB luminosity function and evolution, optical extinction, the origin of dark GRBs, GRB host galaxies, …

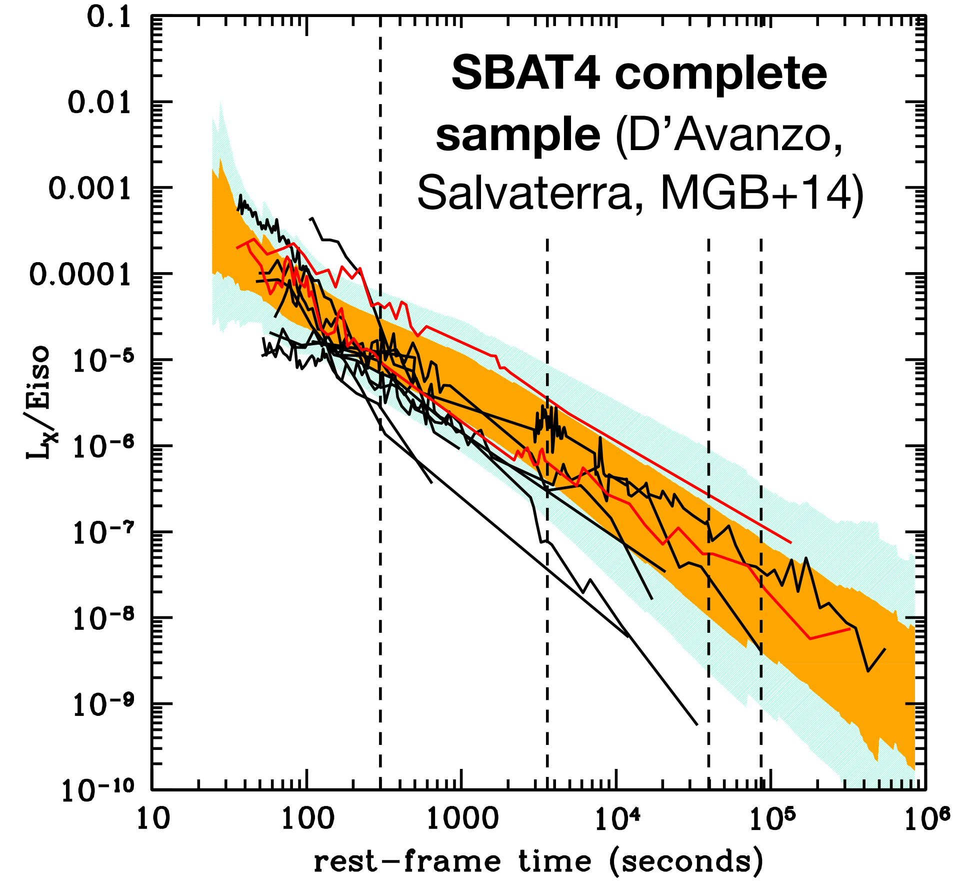
Melandri, …, MGB+12
Zaninoni, MGB+13

SGRB vs LGRB afterglow

X-ray afterglow light curve

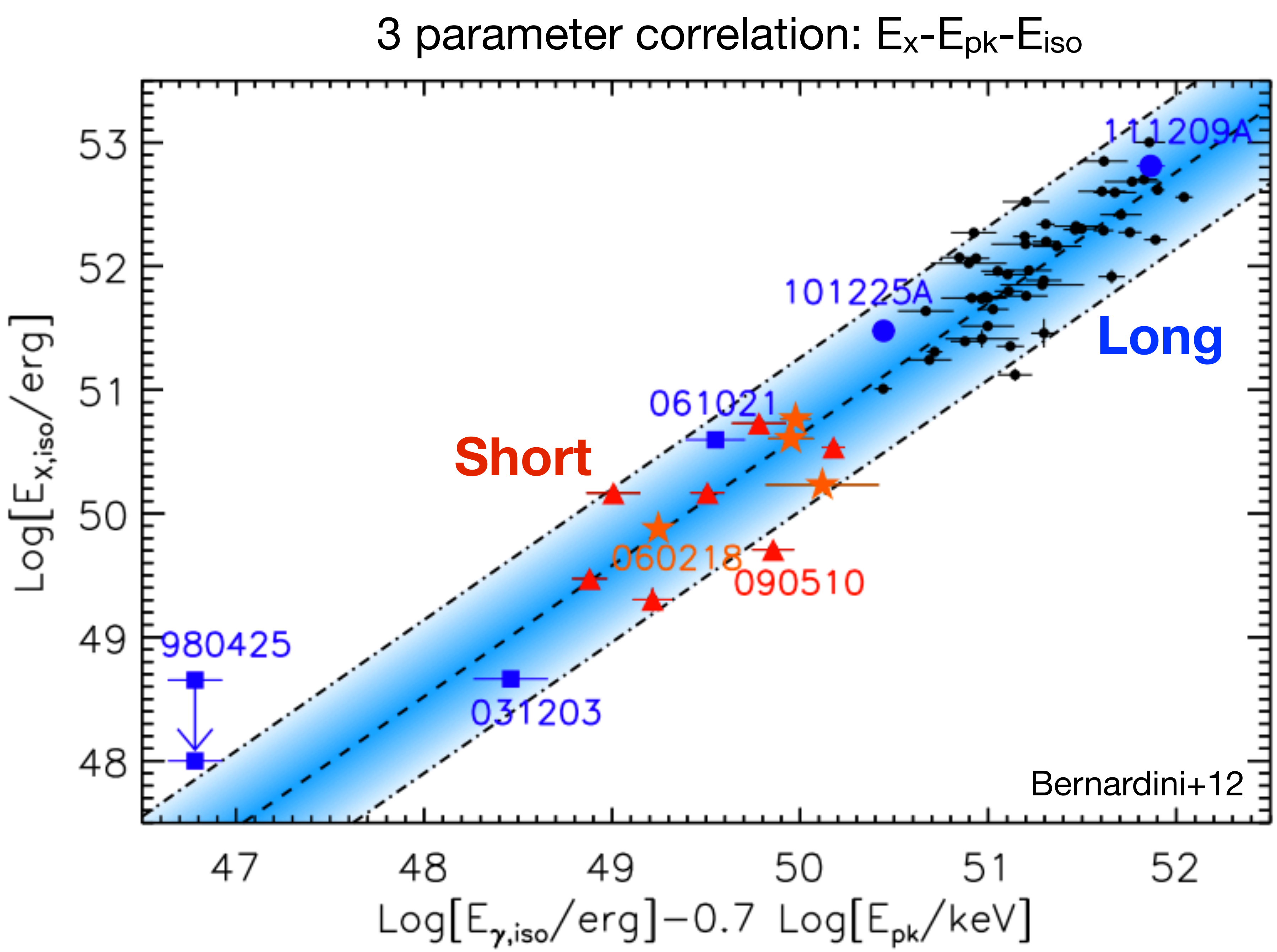


Margutti, Zaninoni, MGB+13



- SGRBs 100 times less energetic than LGRBs
- SGRBs and LGRBs have similar luminosities in the prompt emission
- SGRBs have fainter X-ray afterglow
- SGRBs and LGRBs are similar when we rescale for the total energy

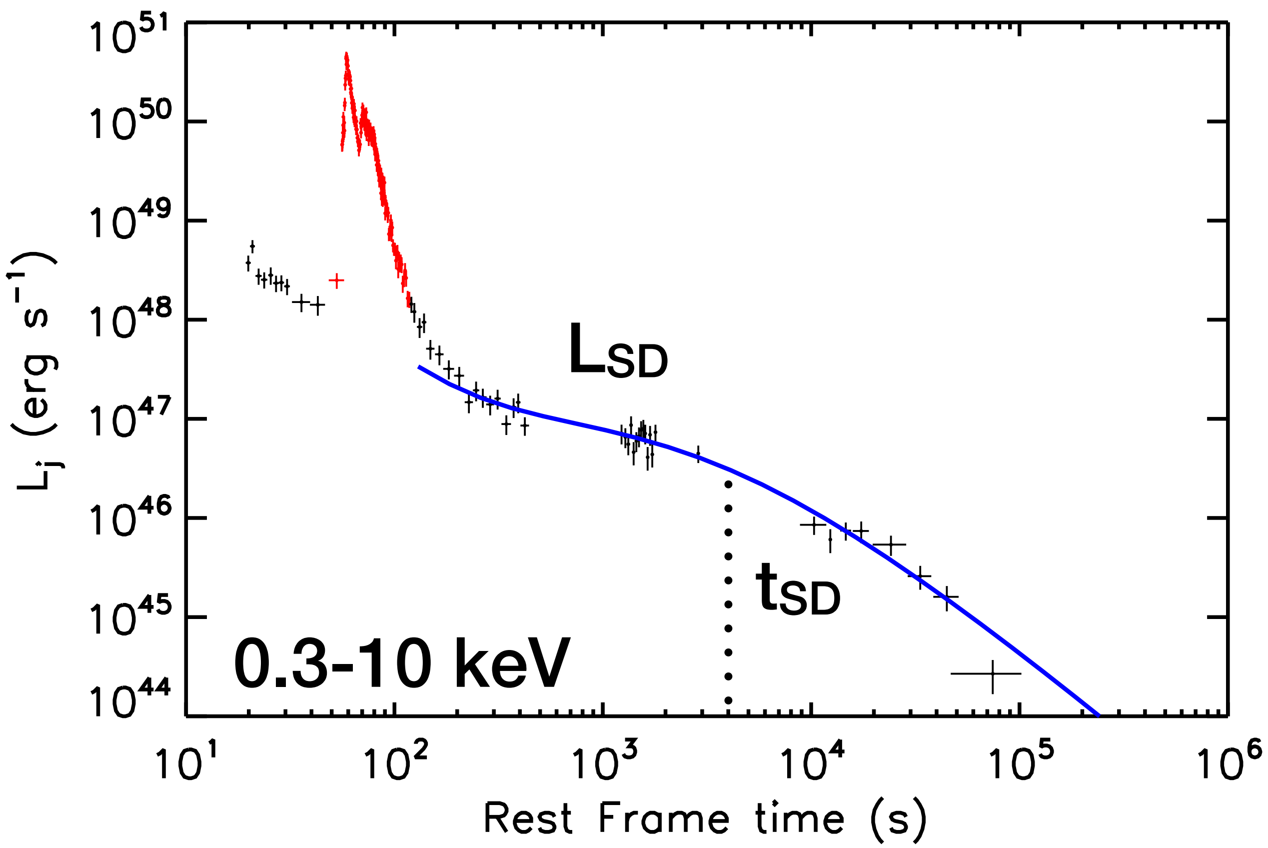
SGRBs vs LGRBs: general picture

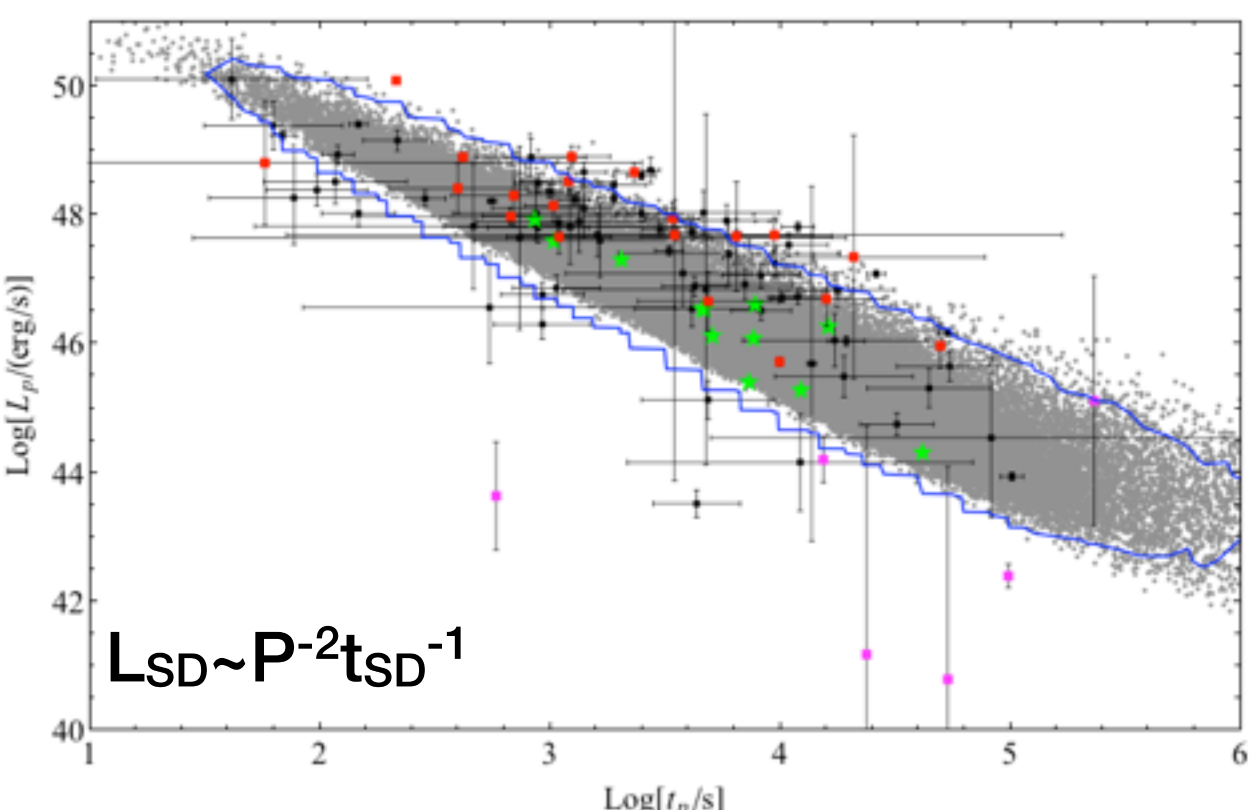


➡whatever powers SGRBs lasts on shorter timescale, with a lower overall energy supply

➡radiation/dissipation mechanisms are similar

The X-ray afterglow: clues to the central engine





Bernardini et al. 2012

- Magnetar **spin-down power** reproduces the **plateau** properties

$$L_{\rm sd} = 10^{49} B_{15}^2\, P_{-3}^{-4}\, {\rm erg\, s^{-1}}$$

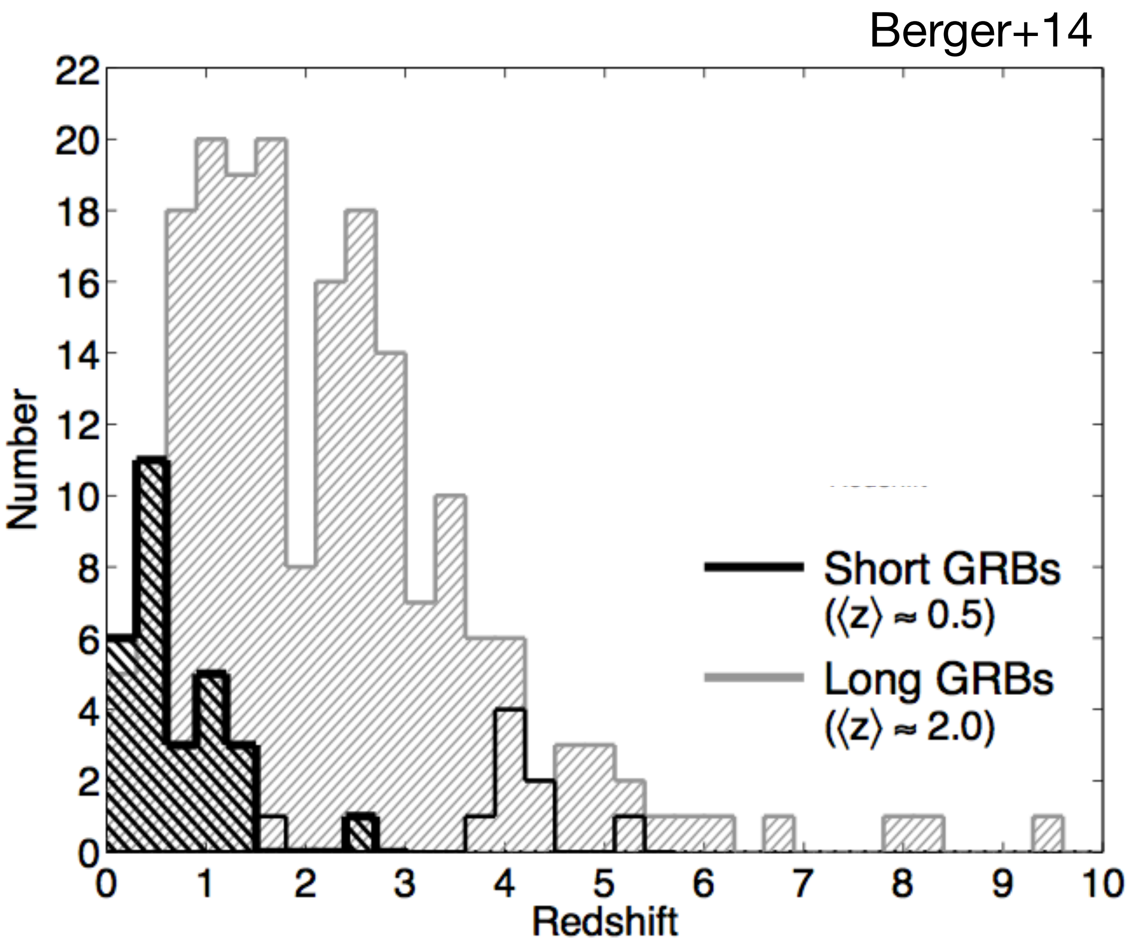
$$t_{\rm sd} = 3 \times 10^3 B_{15}^{-2}\, P_{-3}^2\, {\rm s}\,,$$

- Luminosity-duration correlation implied by the model Bernardini+12, Rowlinson+14

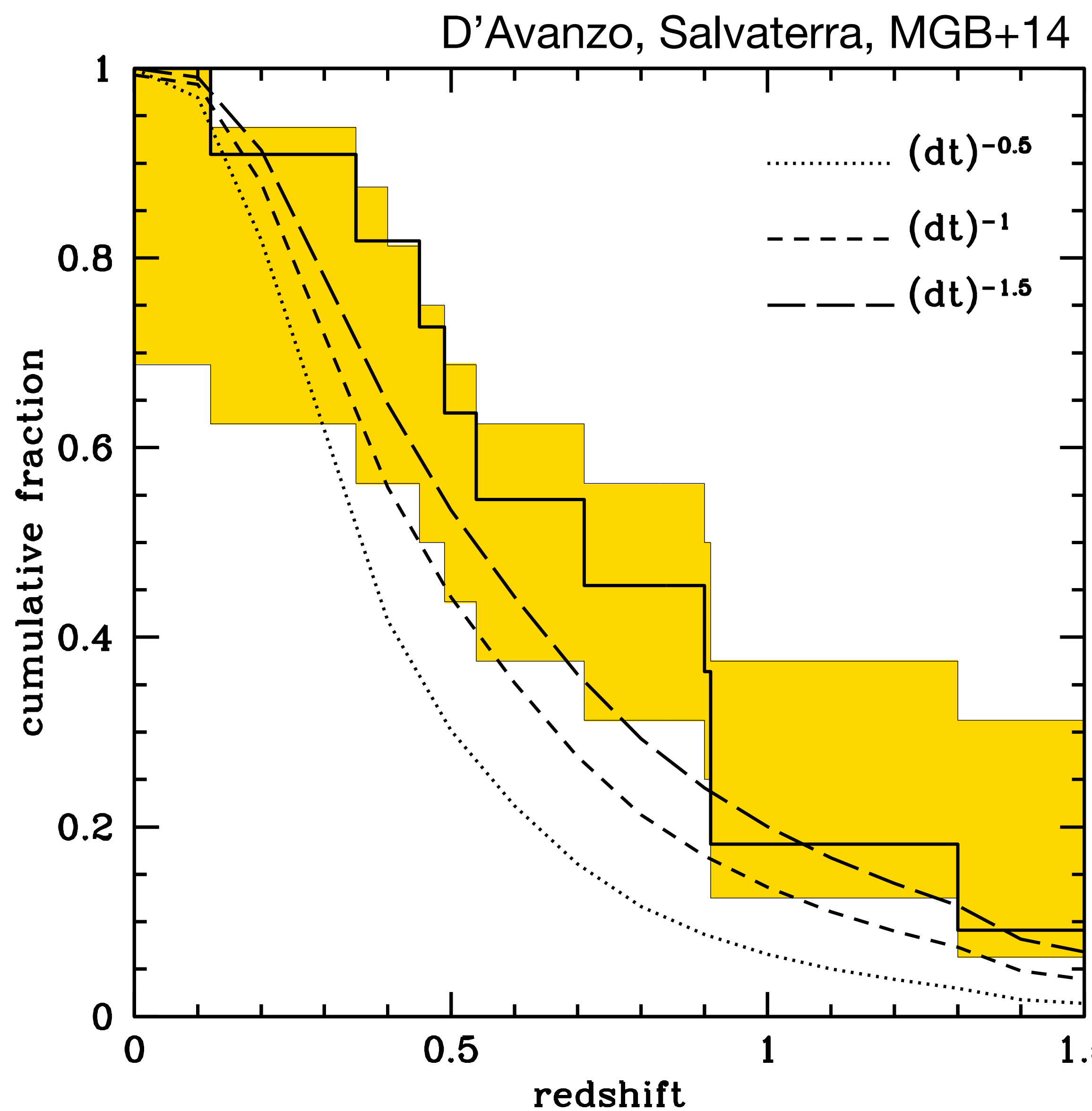
Dai & Lu 1998
Zhang & Meszaros 2001
Corsi & Meszaros 2009
Lyons et al. 2010
Dall'Osso et al. 2011

Metzger et al. 2011
Bernardini et al. 2012,2013
Rowlinson et al. 2013, 2014
Lu & Zhang 2014
Lu et al. 2015

Probing the GRB redshift distribution



- LGRBs: <z>~2
- SGRBs: <z>~0.5-0.8
- redshift distributions significantly different



- LGRBs follow the star-formation rate (SFR, with some caveats)
- SGRBs: delayed SFR

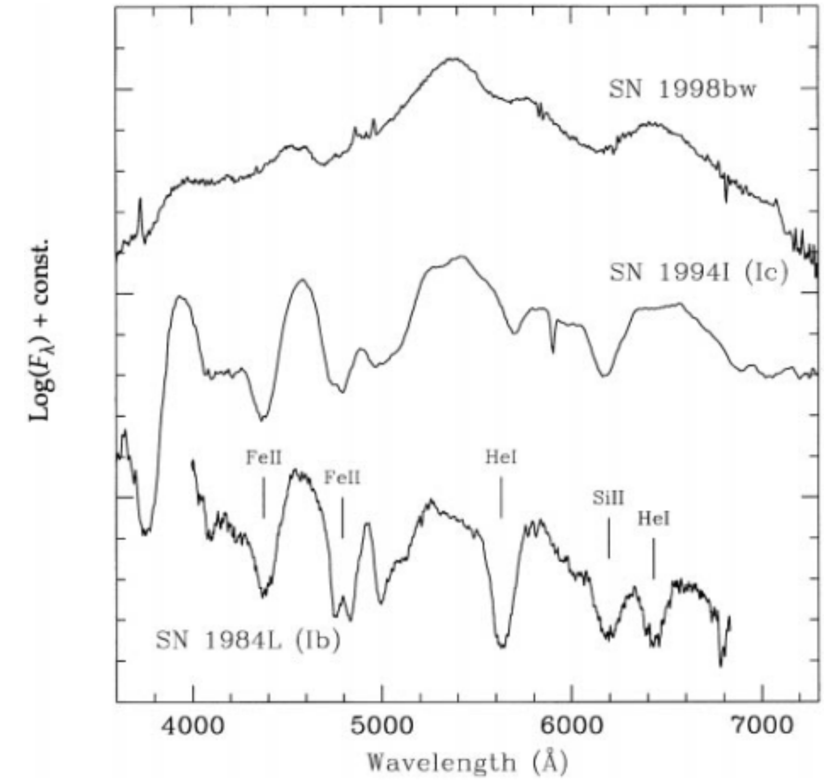
➡**LGRBs: death of massive stars**

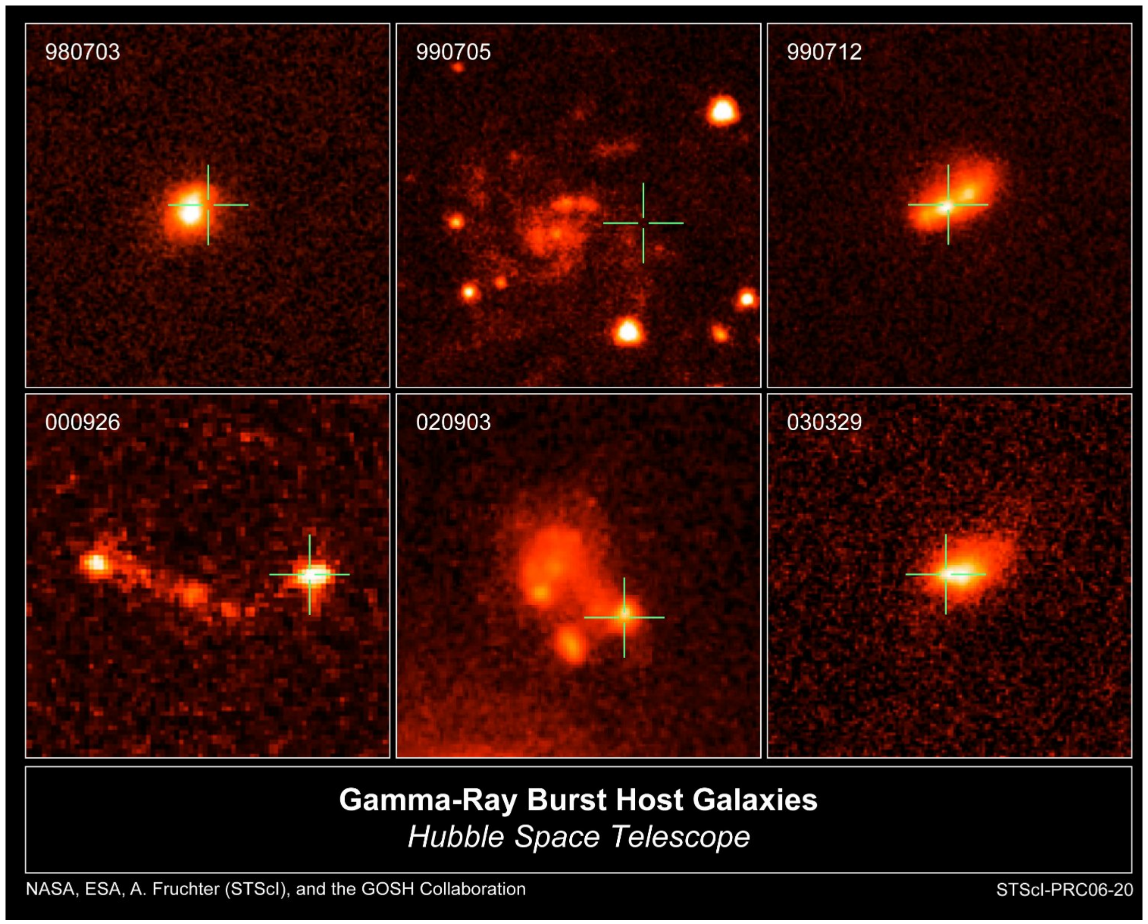
➡**SGRBs: merging of compact objects**

LGRB progenitors

- star-forming galaxies
- young stellar population
- SNe spectroscopically associated

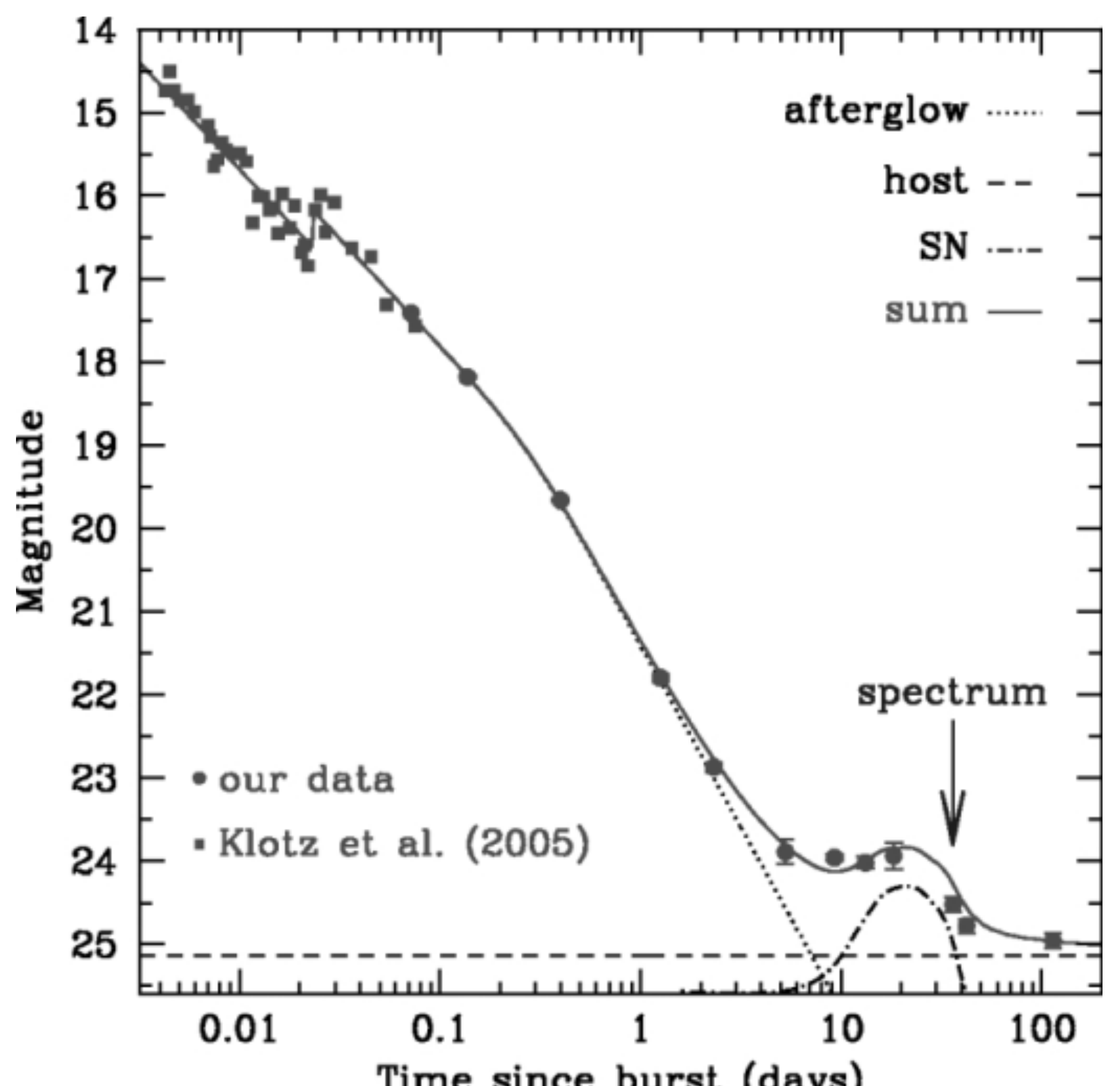
  ➡**core-collapse of Type Ic SNe**





Gamma-Ray Burst Host Galaxies
Hubble Space Telescope

NASA, ESA, A. Fruchter (STScI), and the GOSH Collaboration STScI-PRC06-20

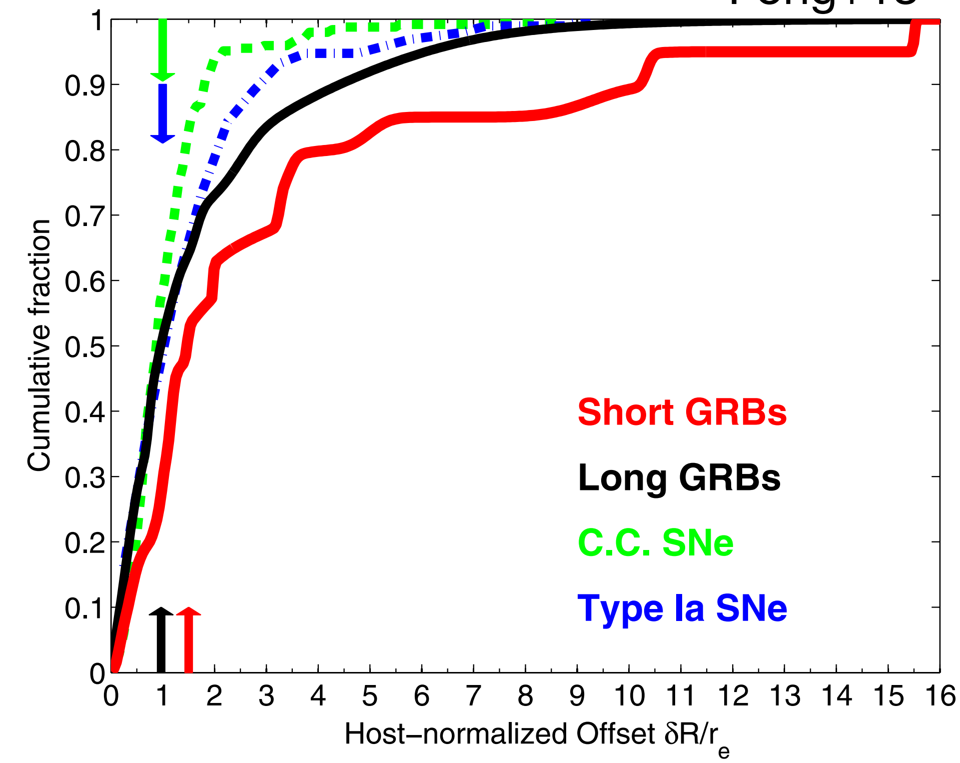


Galama+98; Stanek+03; Hjorth+03; Della Valle+03; Malesani+04; Soderberg+05; Pian+06; Campana+06; Della Valle+06; Bufano+12; Melandri+12,14; Schulze+14 ....

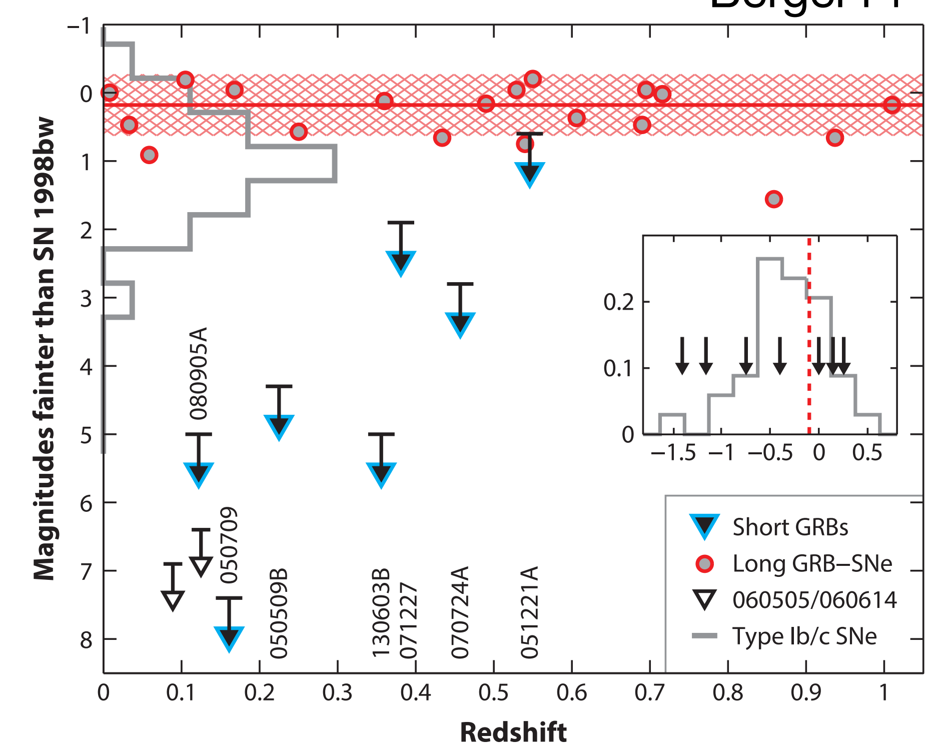
SGRB progenitors

- mix of early and late type galaxies
- kicks/migration from their birth sites:
  - ➡offset
  - ➡no correlation with UV light of their host galaxies
  - ➡diversity of their environment
- no supernova associated
- association with kilonova
  - ➡**merging of compact objects (NS-NS or NS-BH)**

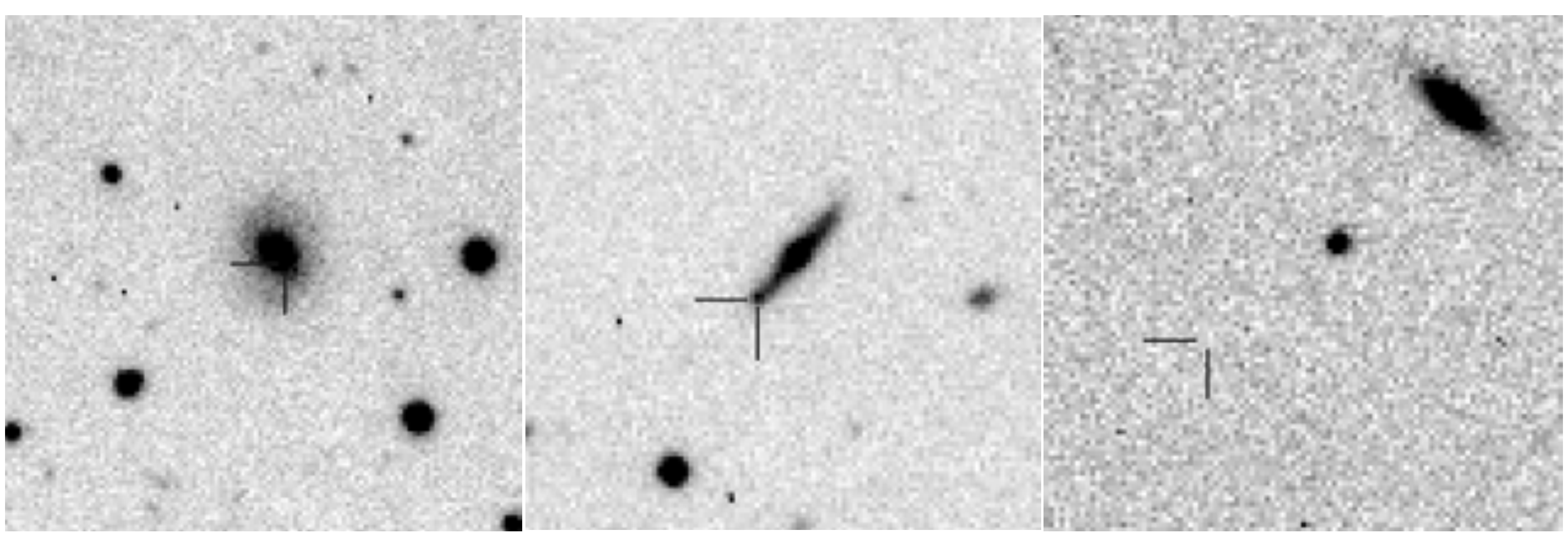
Fong+13



Berger14

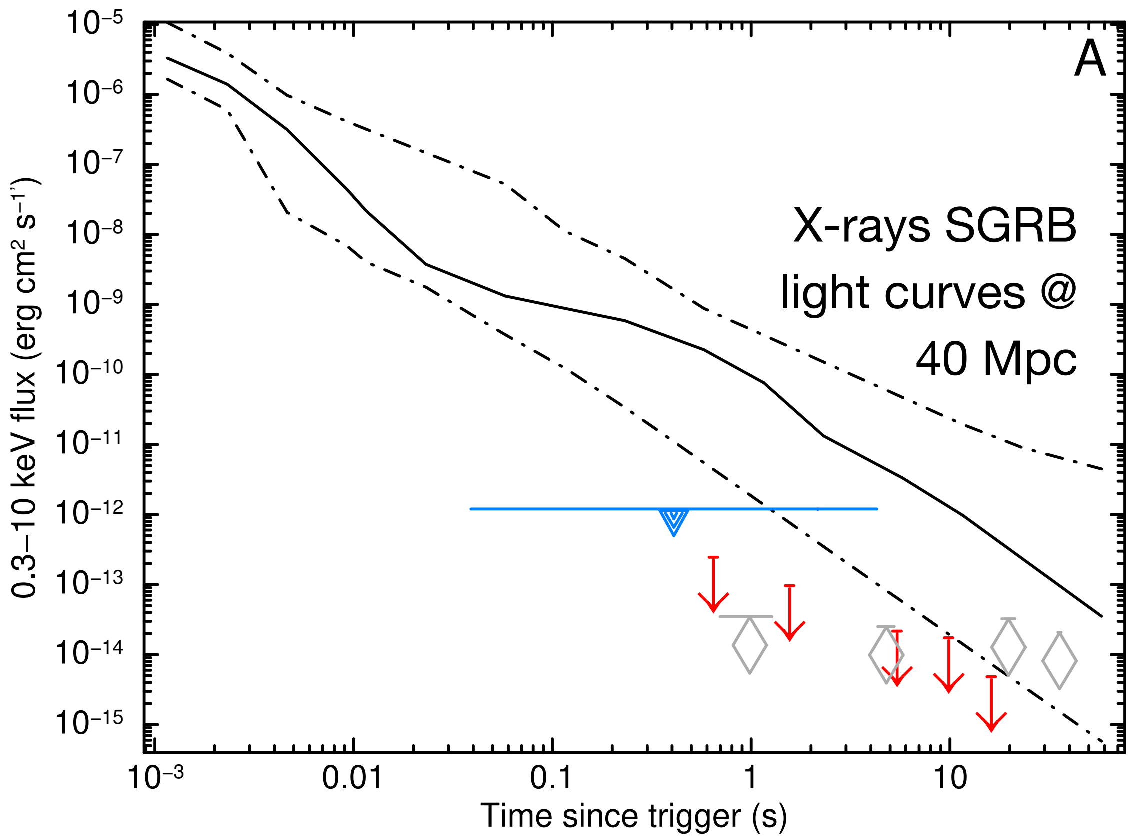


D'Avanzo15



The afterglow of GW 170817/GRB 170817A: constraints on the outflow geometry

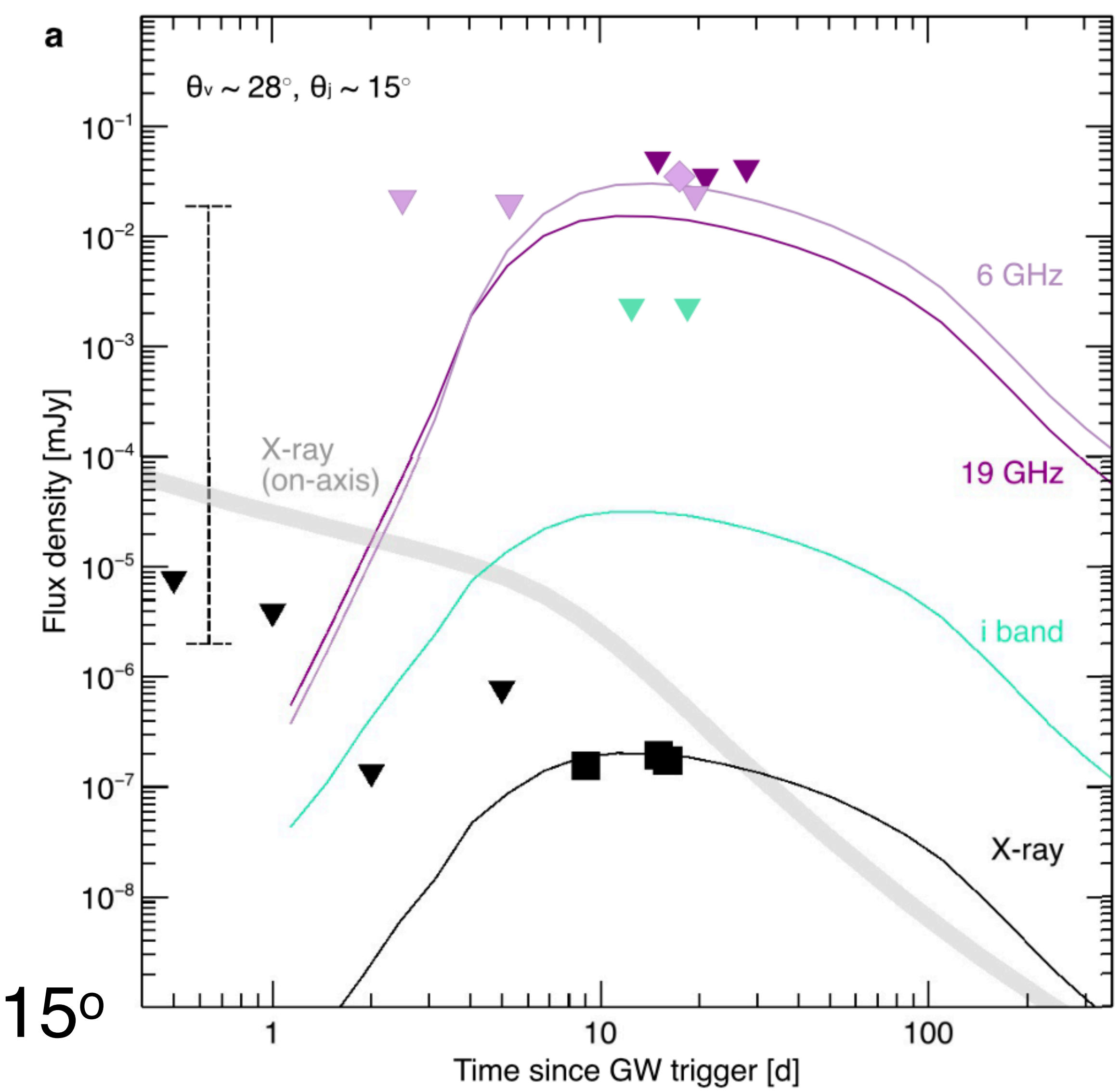
Evans+17



X-ray (and radio) emission not expected to be related to the kilonova but to the GRB itself

➡**information on the SGRB afterglow**

Troja+17

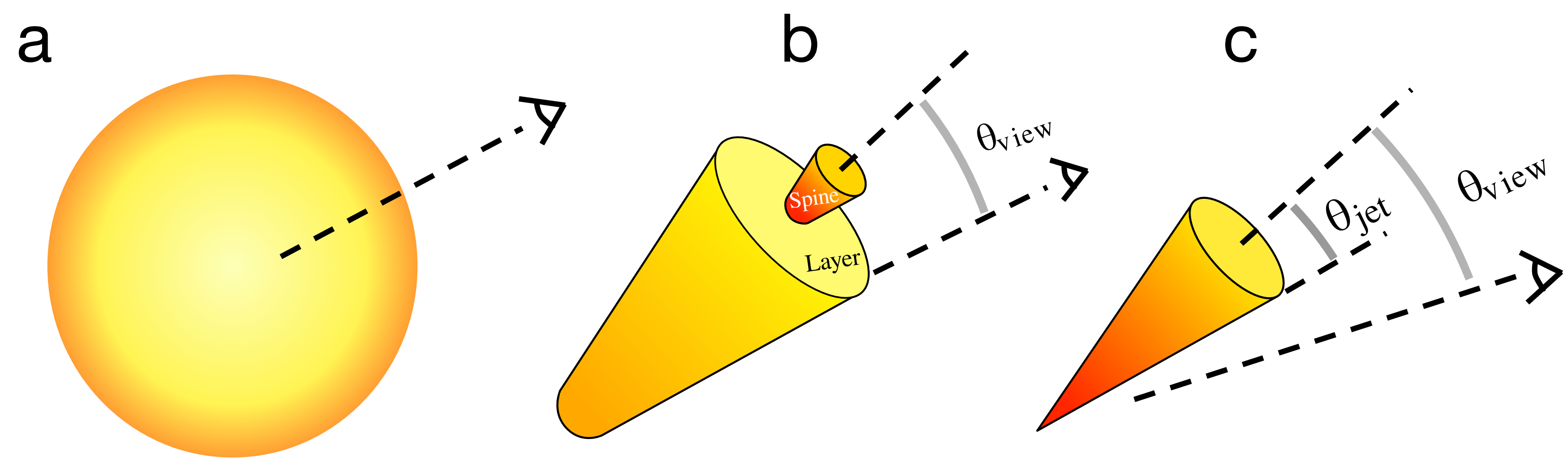


- non-detection with **Swift/XRT, NuSTAR** and **Chandra** before 2 days
- detection with **Chandra** after 9 days
- simultaneous radio detection with **VLA**

➡on-axis GRB afterglow is ruled out

➡**off-axis afterglow** with θ_v~20^o-40^o and θ_j~15^o

The afterglow of GW 170817/GRB 170817A: constraints on the outflow geometry



Salafia+17

Different scenarios are still consistent with early observations:

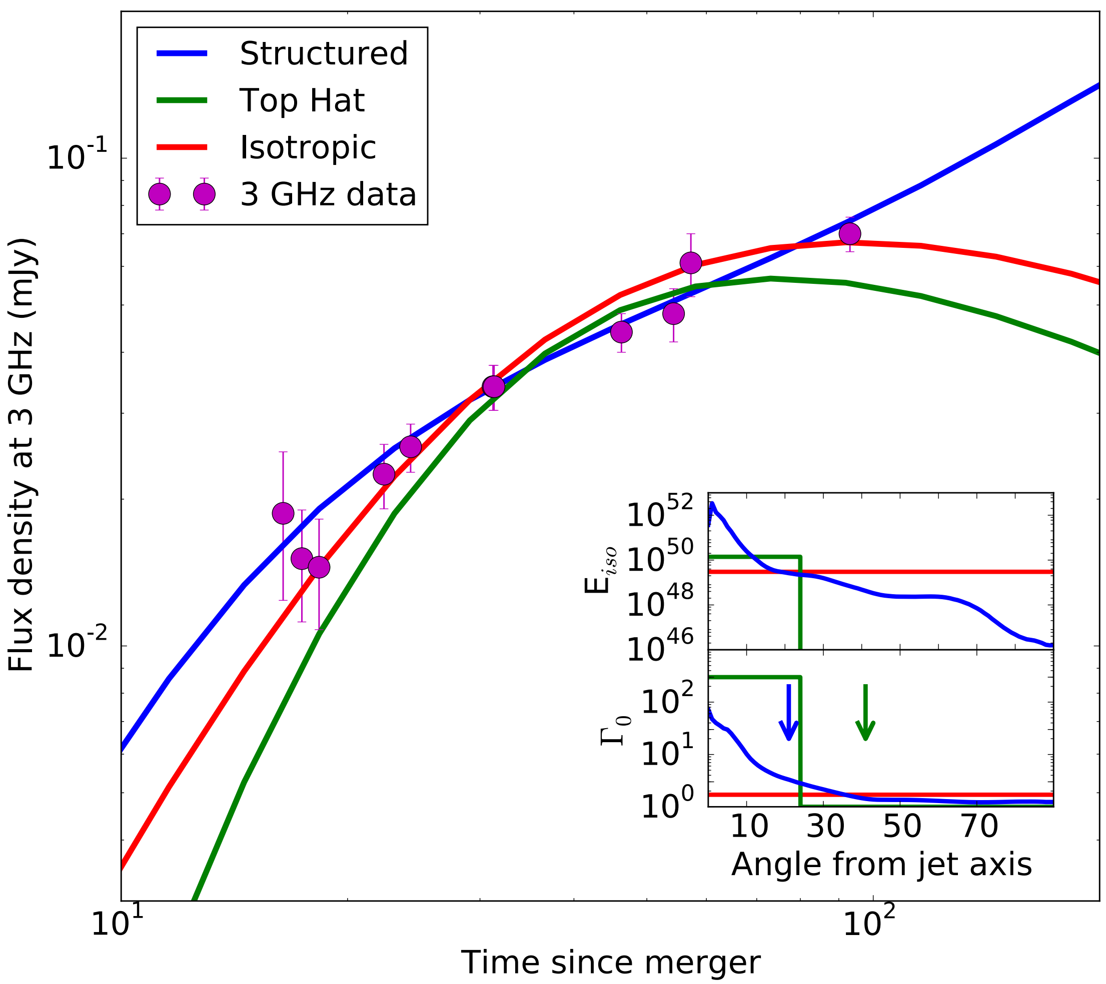
a. isotropic fireball Salafia+17 or hot cocoon from a failed jet Mooley+17

b. structured jet: standard jet+less energetic cocoon/layer Lazzati+17, Kathirgamaraju+17, Gottlieb+17, Lyman+18, Margutti+18, D'Avanzo+18, Nakar & Piran 18, …

c. uniform (top-hat) jet with unusually low Lorentz factor Pian+17

The afterglow of GW 170817/GRB 170817A: constraints on the outflow geometry

Lazzati+17



Radio observations up to 100 days with **VLA** Mooley+17

➡**the radio afterglow is rising**

Different scenarios are still consistent with early observations:

a. isotropic fireball Salafia+17 or hot cocoon from a failed jet Mooley+17

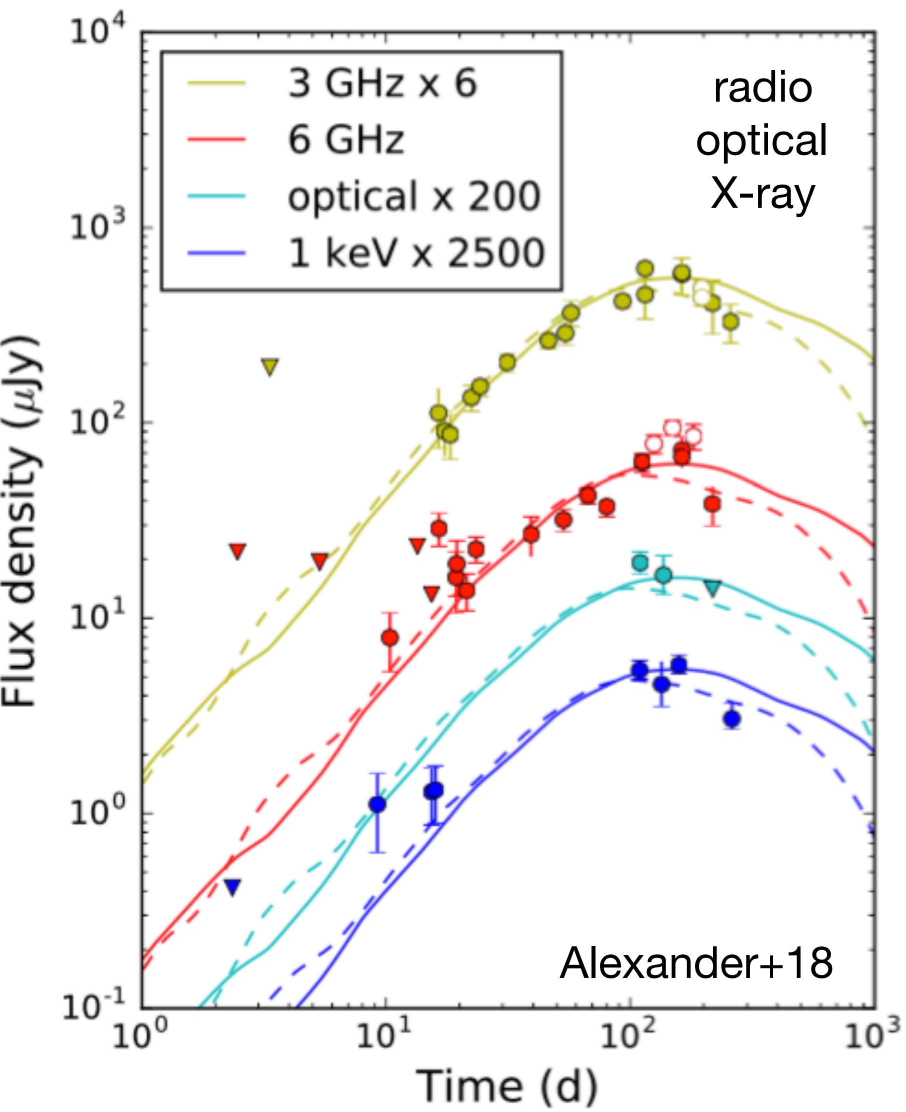
b. structured jet: standard jet+less energetic cocoon/layer Lazzati+17, Kathirgamaraju+17, Gottlieb+17, Lyman+18, Margutti+18, D'Avanzo+18, Nakar & Piran 18, …

c. ~~uniform (top-hat) jet with unusually low Lorentz factor Pian+17~~

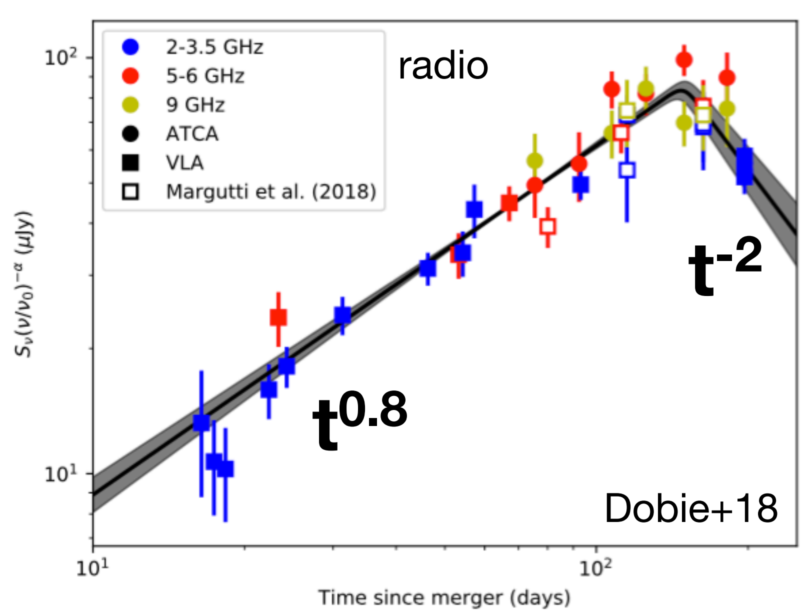
GW 170817/GRB 170817A: late afterglow observations

- Observations with **Chandra** and **XMM** once the source exit the Sun constraint (~100-160 days) D'Avanzo, ..,MGB+18; Margutti+18; Haggard+18; Troja+18
- Optical and radio observations (~200-264 days) Lyman+17; Margutti+18; Alexander+18, Dobie+18

➡**the afterglow lightcurve has risen, then flattened and started decaying**



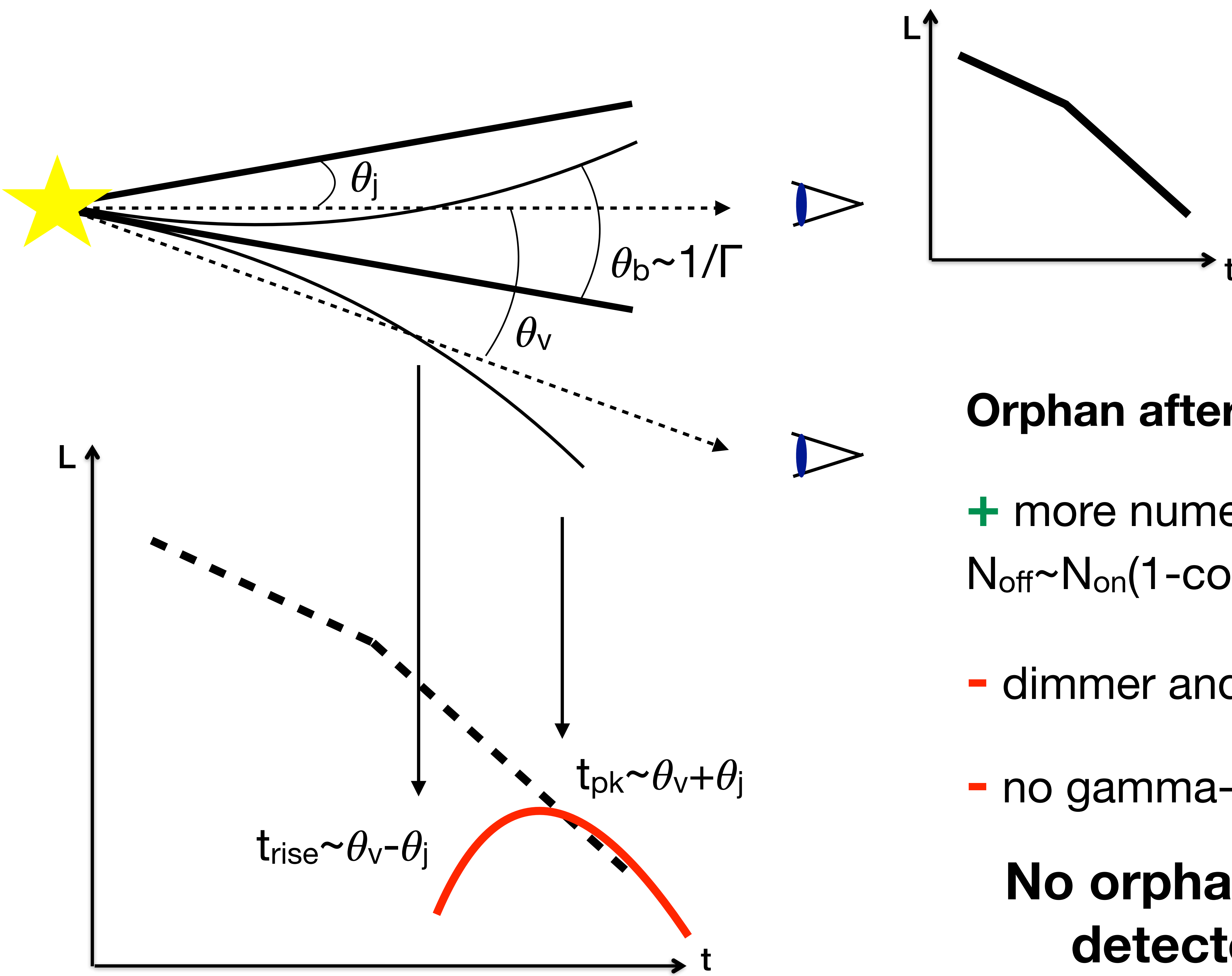
- **constraints on the nature of the emission process** (synchrotron emission)
- **no constraints on the nature of the relativistic ejecta** (both scenarios still valid)



- Measures of superluminal motion and source size with VLBI Mooley+18; Ghirlanda+18

- **the outflow is likely a structured jet**

Off-axis "orphan" afterglow



Orphan afterglows:

+ more numerous,
$N_{off} \sim N_{on}(1-\cos\theta_j)^{-1} \sim 200\ N_{on}$

- dimmer and delayed

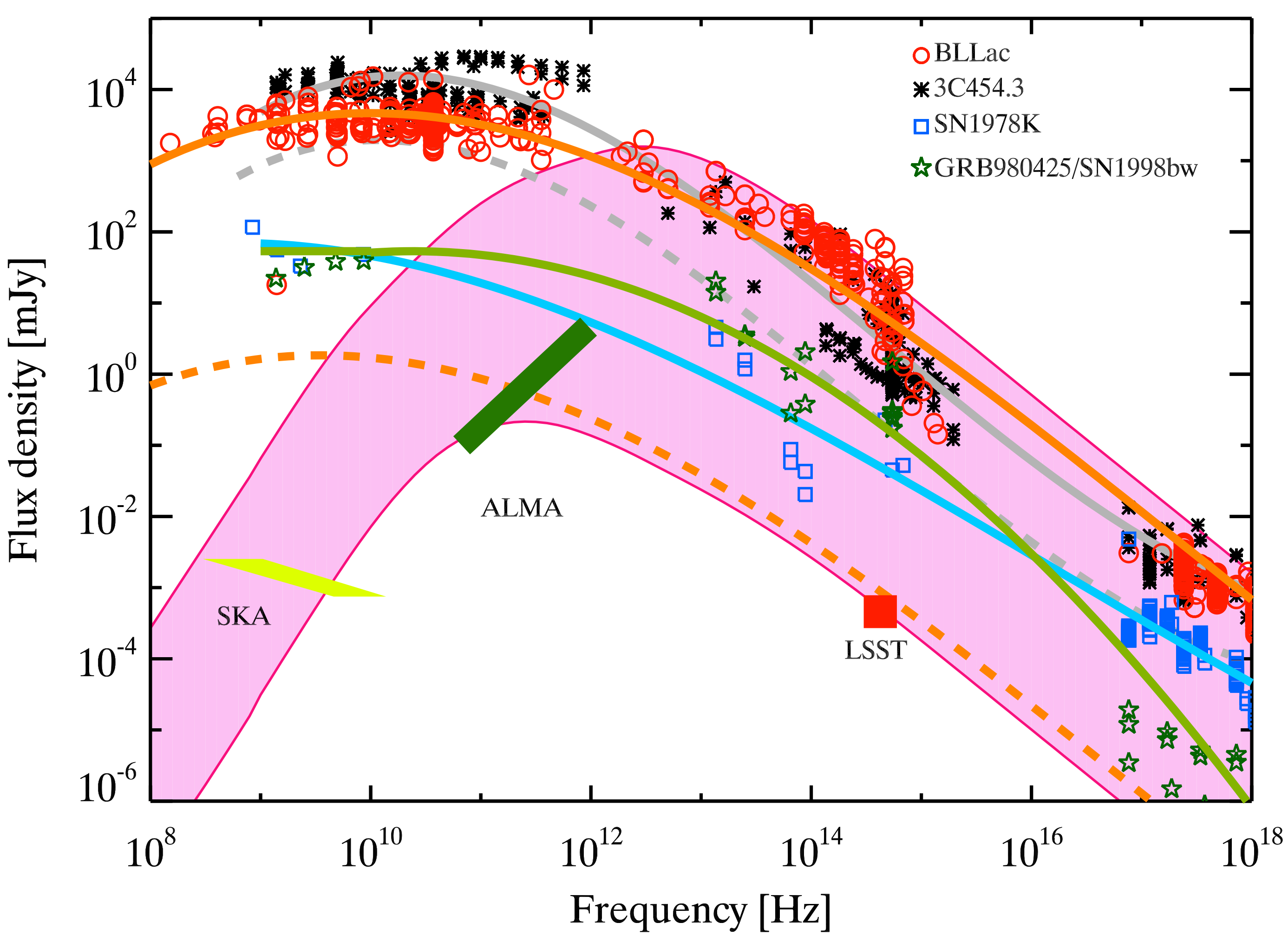
- no gamma-ray trigger

No orphan afterglow detected so far

Prospects for detection of orphan afterglows (OAs)

- Prospects for OA detection from LGRBs using a population synthesis code +standard afterglow model Ghirlanda, ..., MGB+15
  - **most of the past and on-going surveys have small chances to detect OAs (except for *Gaia* - ~ 2 OT/yr).** Better prospects for future surveys
  - **In optical: ~20 OA/yr with ZTF, ~50 OA/yr with LSST**
  - **In X-rays: ~30 OA/yr with eROSITA**

Ghirlanda+17



- Major problem: **how to distinguish an OA from another optical transient?**

➡**optical and X-ray photometrical** follow-up

➡**optical spectroscopy** (if bright enough)

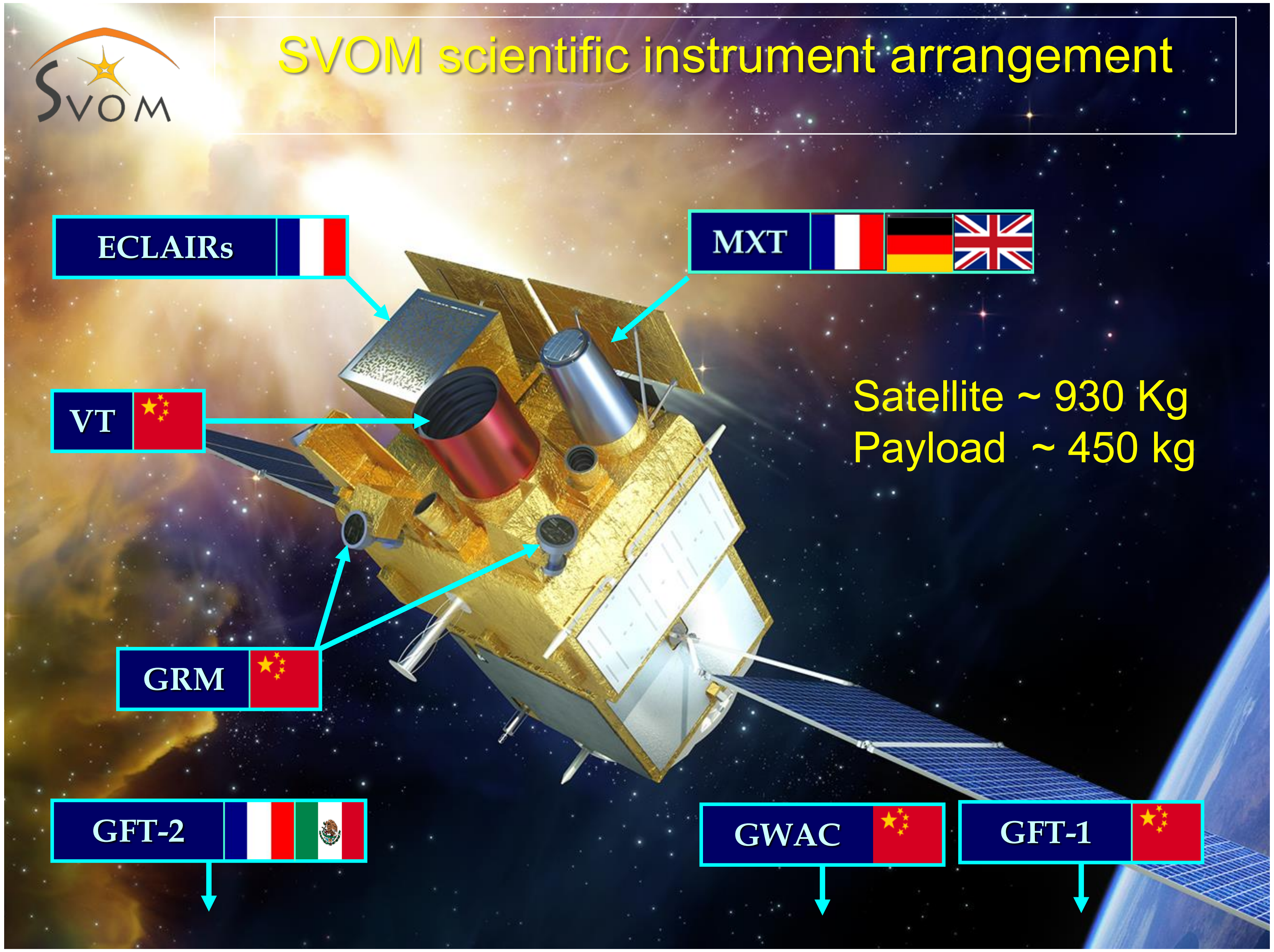
➡**GHz and mm follow-up** will characterise the SED and distinguish from other similar transients

Conclusions

- EM observations of GRBs at all wavelengths in the last 20 years revolutionised our understanding of this phenomenon
- Multi-wavelength observations of GRB afterglows are important to unveil the GRB phenomenon itself (progenitors, central engine, outflow properties and composition) and to use them as probes of the local environment up to high redshift
- Future developments:
  - GRB afterglows as counterparts of GWs
  - GRB orphan afterglows in large surveys (es. LSST), also as counterparts of GW emitters
  - ….

➡Necessary to continue monitoring GRBs at all wavelengths!

The SVOM mission



- French-chinese mission, launch ~2021
- **ECLAIRs**: coded mask, 4-150 keV, ~2 sr fov, transients detection and localisation
- **GRM**: 3 detectors, 15-5000 keV, ~2 sr fov
- **MXT** and **VT** onboard + **ground segment**

- **Dedicated to the study of gamma-ray bursts and hard X-ray transients**
- **Key role in the multi-messenger and multi-wavelength era**