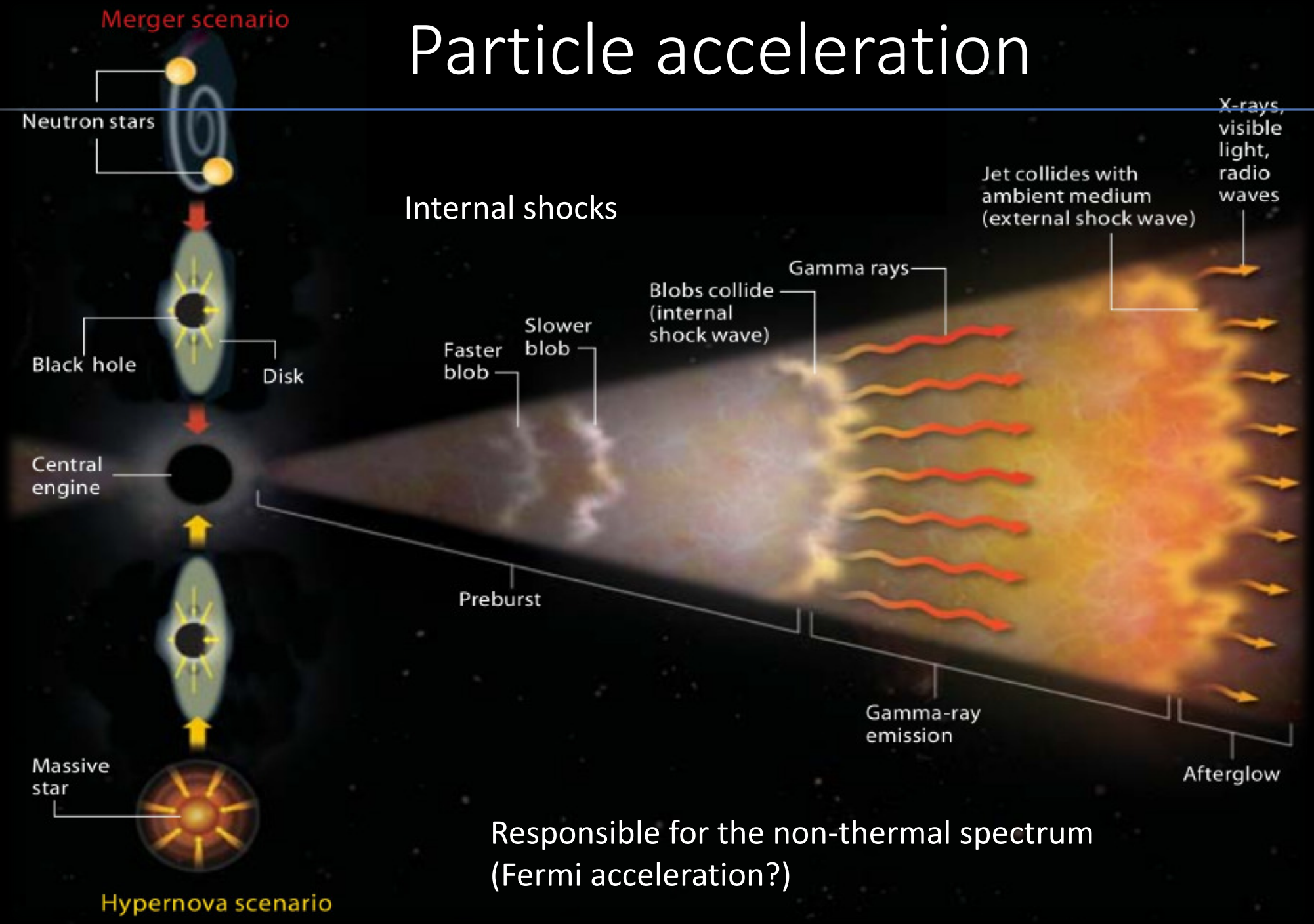
PHY 4905 | Modern Astrophysics

Lecture XX.

Gamma-ray Bursts

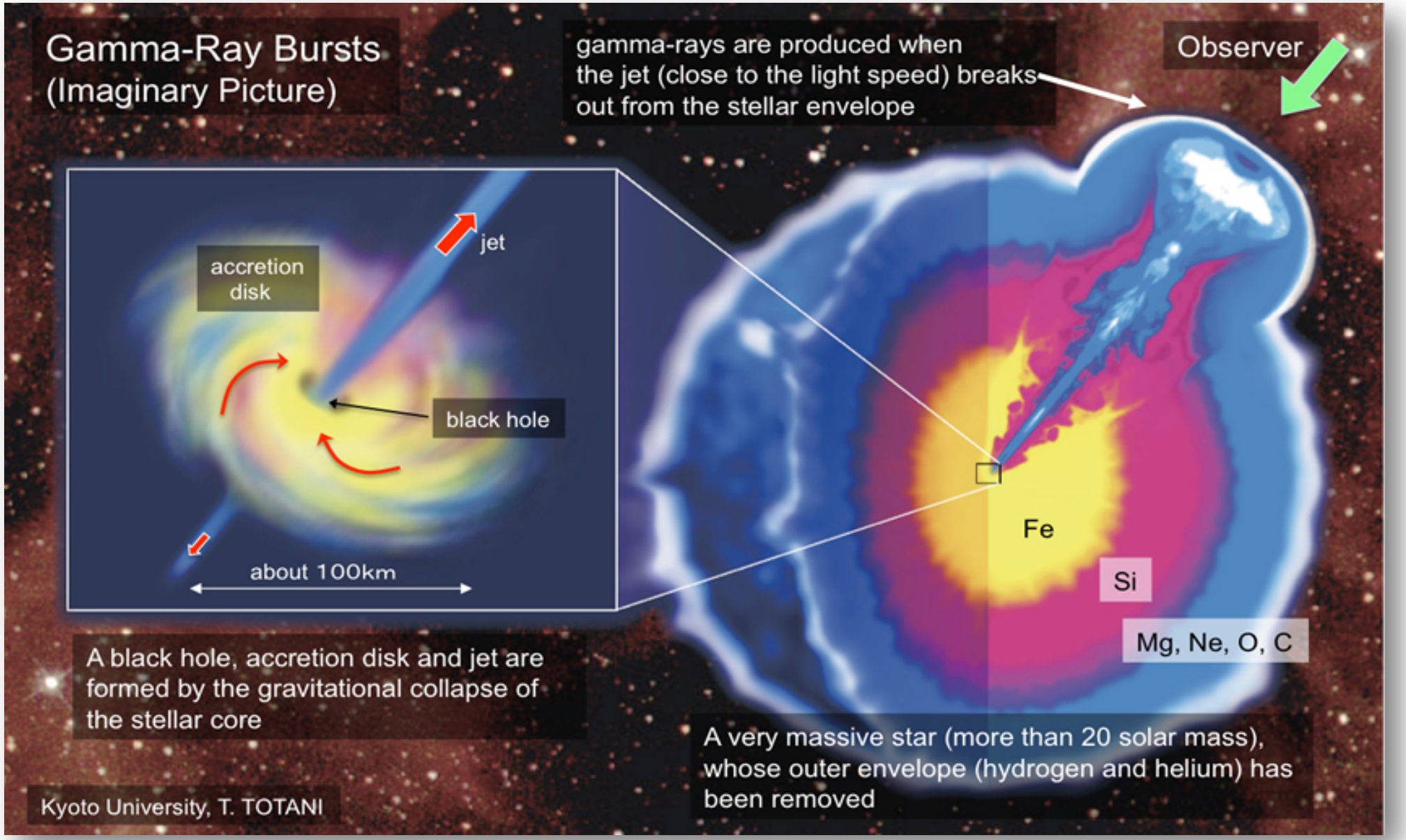
Imre Bartos | Fall 2019

Particle acceleration

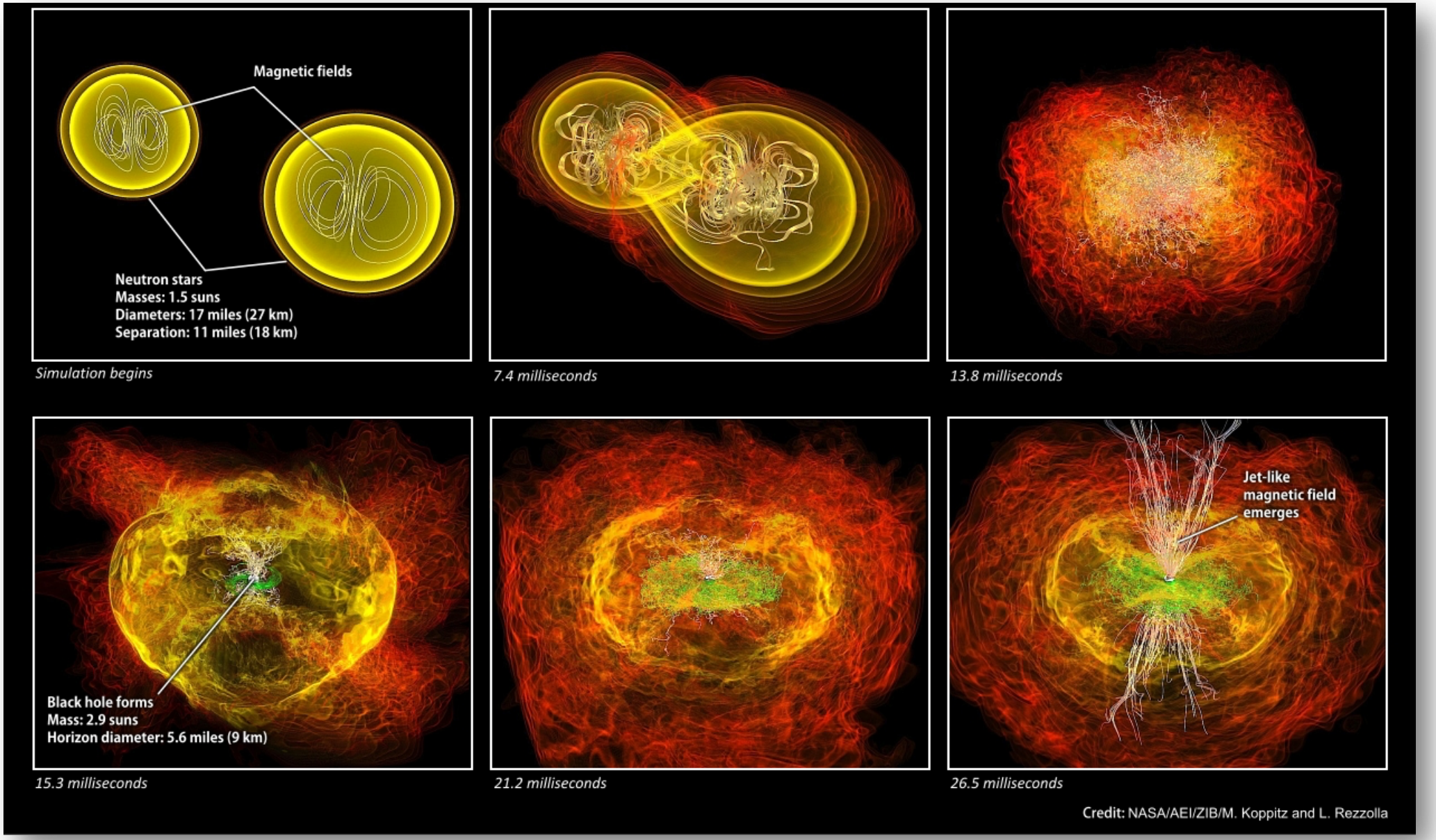


Responsible for the non-thermal spectrum
(Fermi acceleration?)

Long GRBs – stellar core collapse



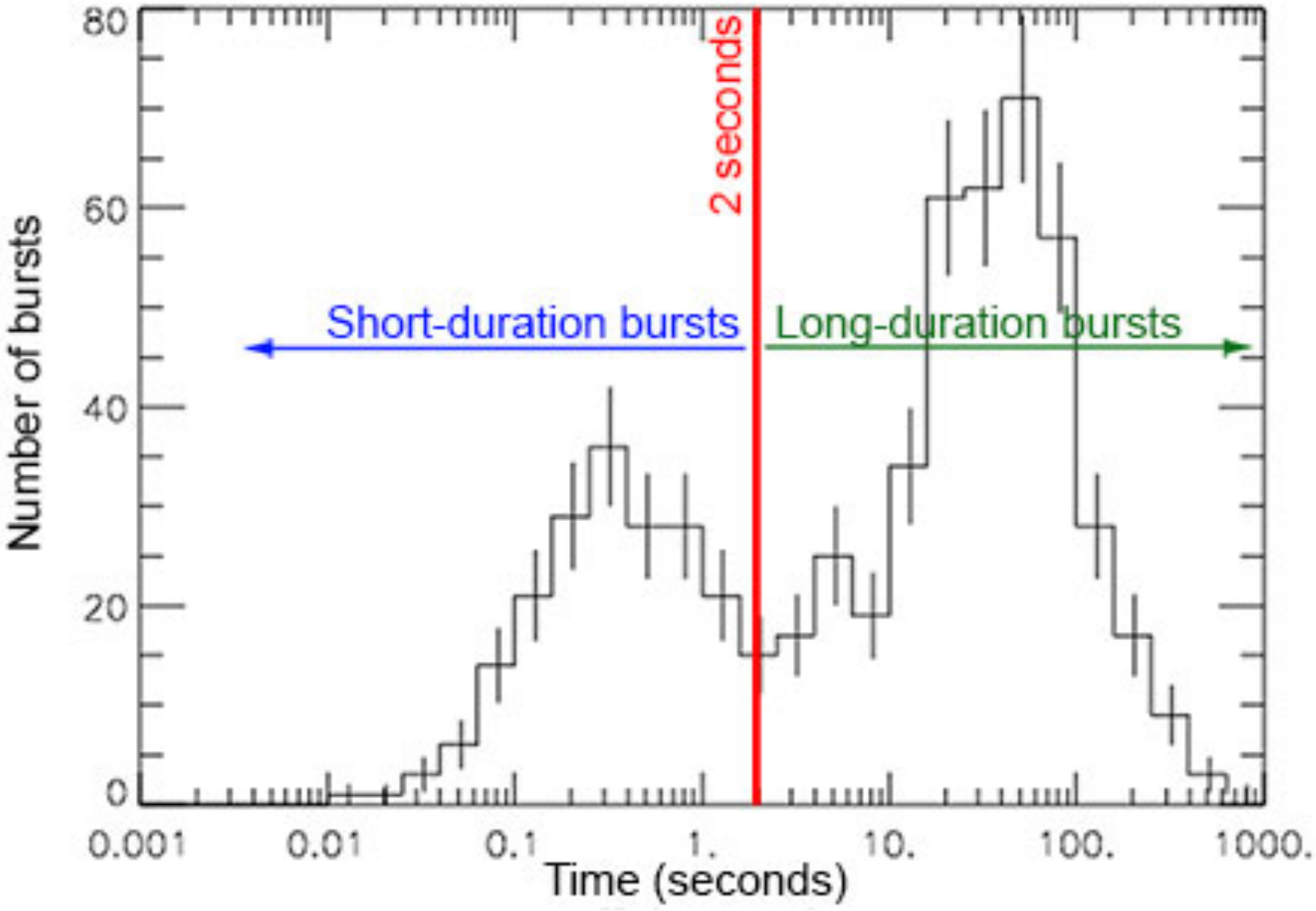
Short GRBs – binary mergers



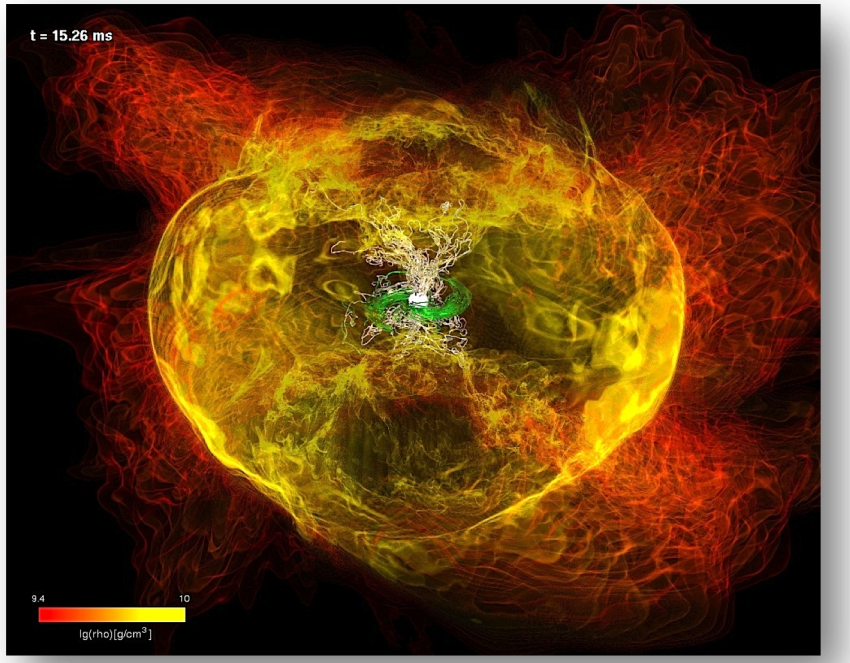
Duration ~ fallback time?

$$T = \pi \sqrt{\frac{R^3}{GM}} = T_{kepler}/2$$

Long vs short GRBs



How much energy is available?



Binary neutron star mergers or binary black hole mergers:

Typical value is ~0.01-0.1 Msun

Depends on:

- NS Equation of State
- Mass ratio

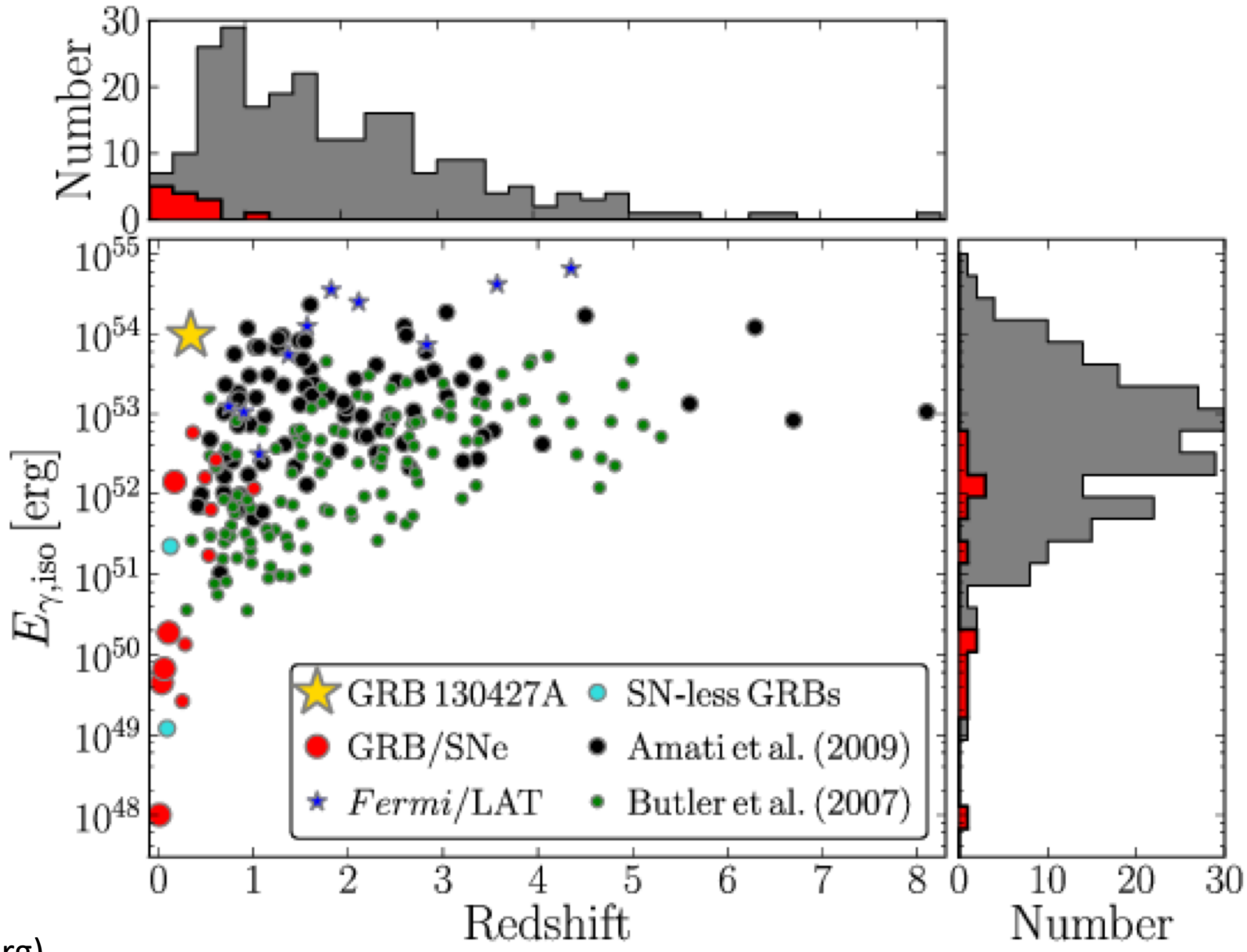
Stellar core collapse

Could be several Msun

Depends on:

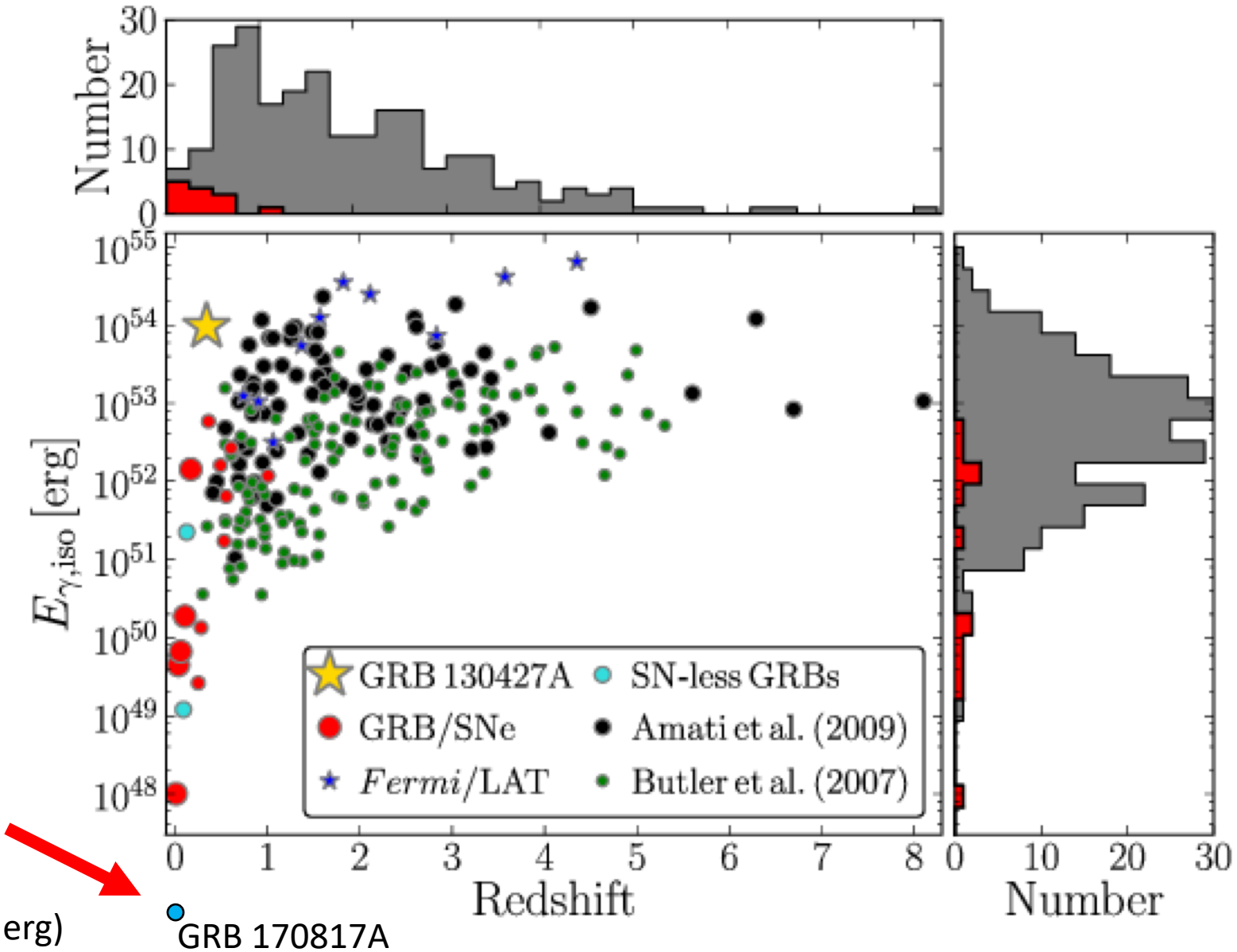
- How much energy is injected in the stellar envelope (?)

Energetics

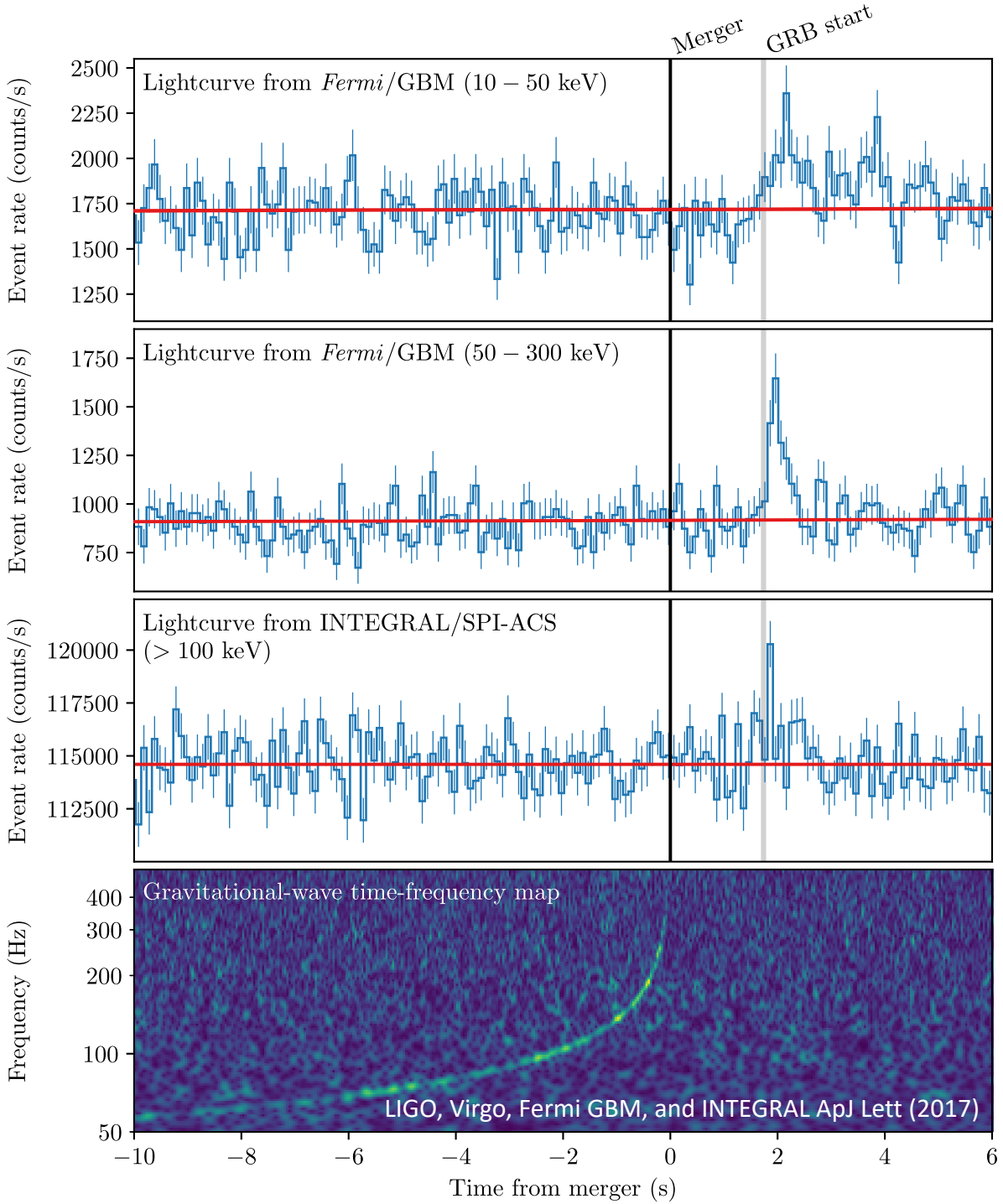


(solar mass = 1.8 x 10^{54} erg)

Energetics

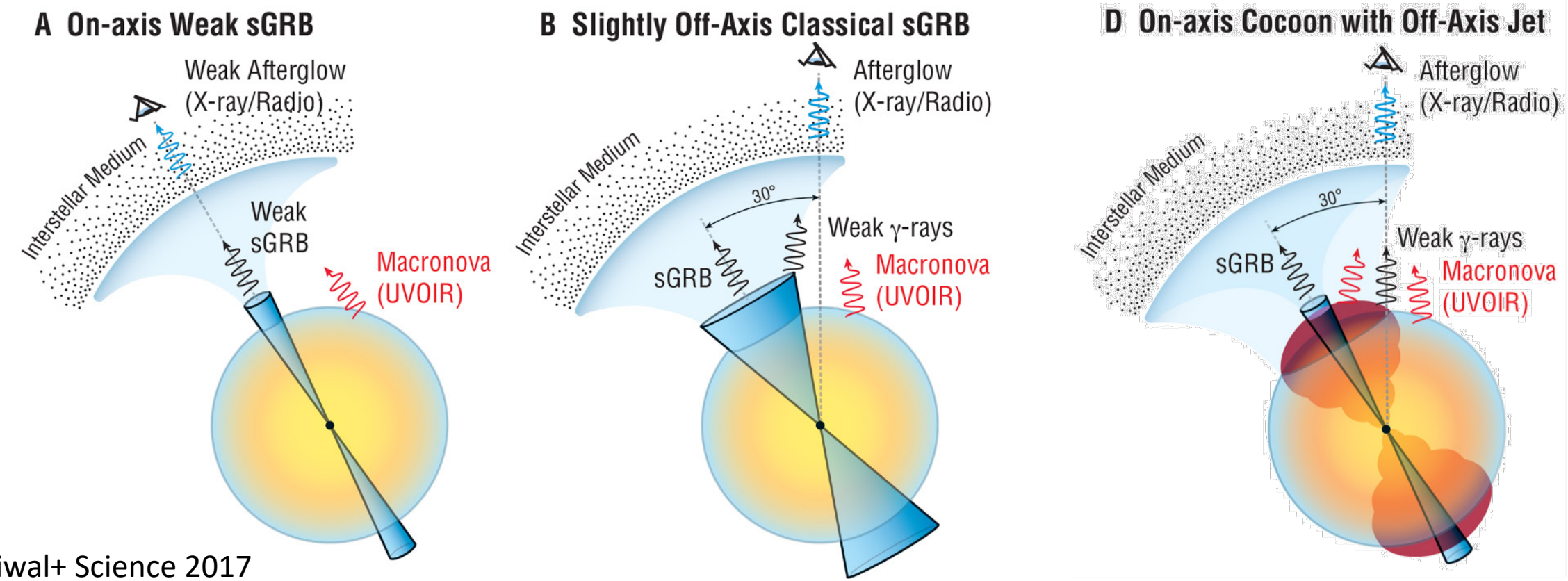


(solar mass = 1.8 x 10^{54} erg)


Merger
GRB start
Lightcurve from Fermi/GBM (10 – 50 keV)
Event rate (counts/s)
2500
2250
2000
1750
1500
1250
Lightcurve from Fermi/GBM (50 – 300 keV)
Event rate (counts/s)
1750
1500
1250
1000
750
Lightcurve from INTEGRAL/SPI-ACS
(> 100 keV)
Event rate (counts/s)
120000
117500
115000
112500
Gravitational-wave time-frequency map
Frequency (Hz)
400
300
200
100
50
LIGO, Virgo, Fermi GBM, and INTEGRAL ApJ Lett (2017)
−10
−8
−6
−4
−2
0
2
4
6
Time from merger (s)

Gamma-ray burst

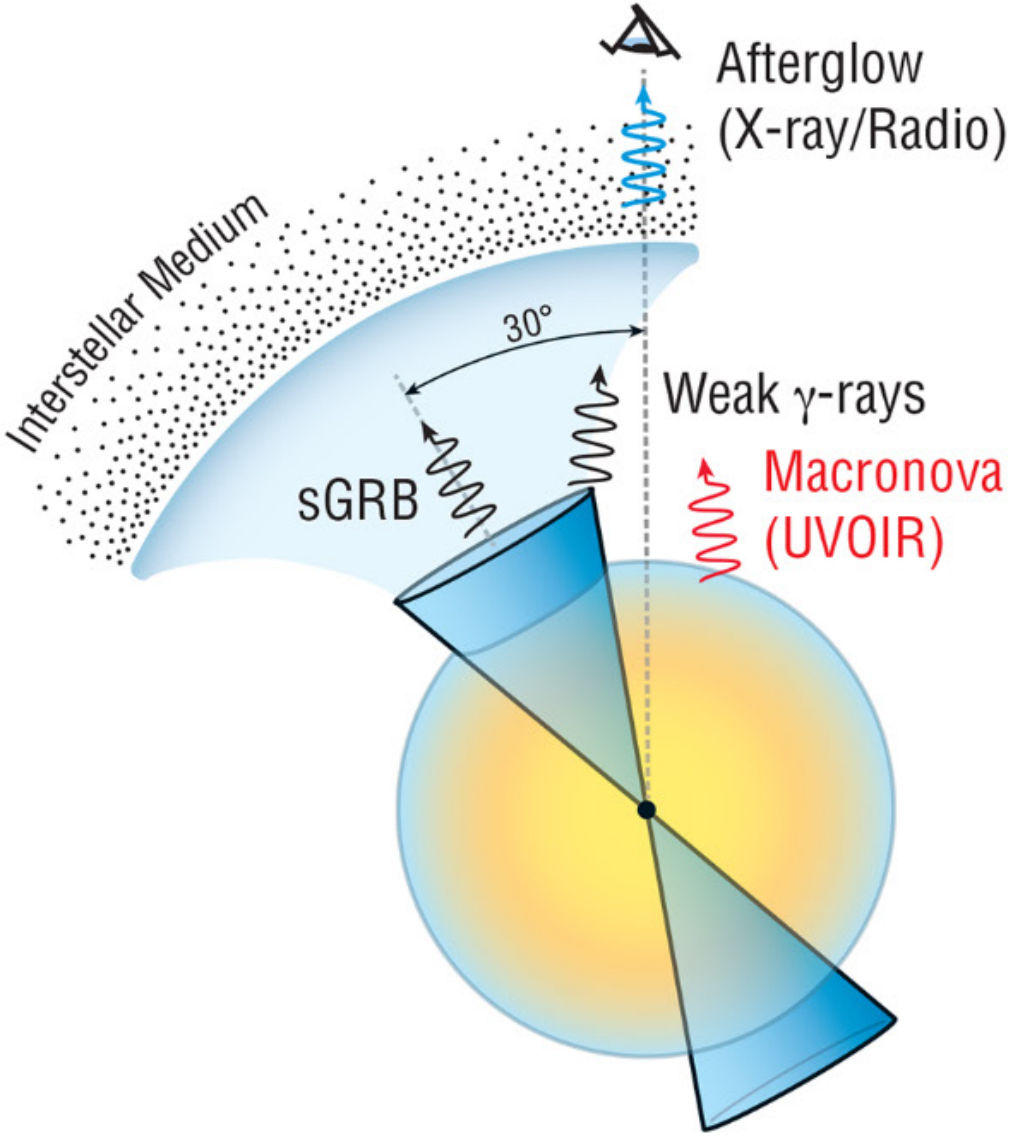
- Very weak --- energy orders of magnitude below weakest GRB detected
- Short-hard --- consistent with binary neutron star picture
- Host galaxy --- low star formation, probably very old NSs (Blanchard+ 2017)
- X-ray/Radio delay (9 and 15 days) --- unusual, consistent with off-axis scenario
- There was a GRB → merger remnant collapsed to a black hole
- 1.7 s delay --- e.g. jet propagation before shock
- Fundamental limits: Constraint on speed of gravity: ~10^{-15}c | rules out DM emulators | etc.



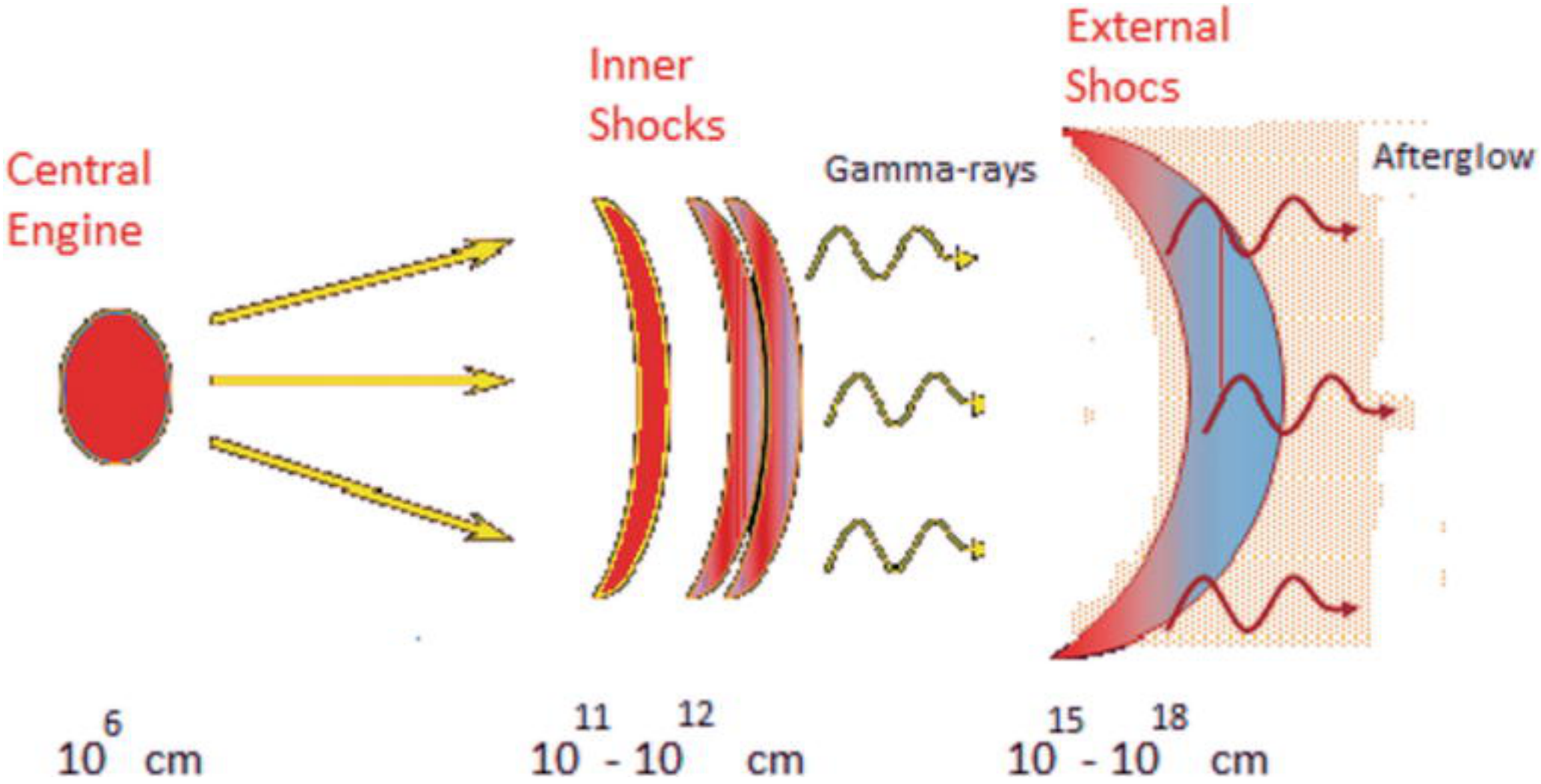
Kasliwal+ Science 2017

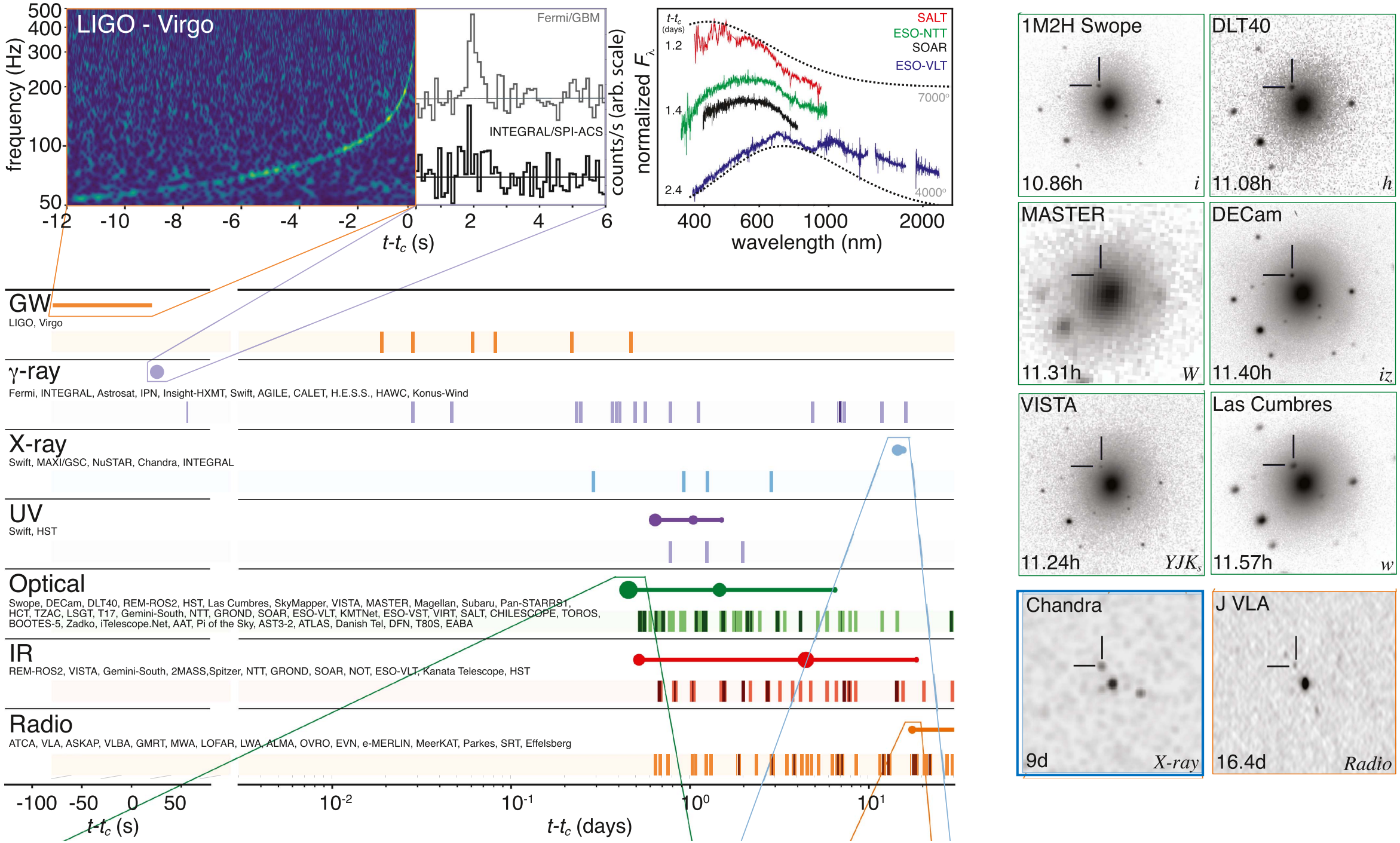
Off-axis?

We approximated the observed off-axis spectral fluence, $F_{\rm off}(E)$, for these models using $F_{\rm off}(E) = \eta F_{\rm on}(E/\eta)$, where the scaling factor $\eta = \delta(\theta_{\rm obs})/\delta(0)$ accounts for different Doppler factors $\delta(\theta_{\rm obs}) = [\Gamma(1 - \beta\cos(\theta_{\rm obs} - \theta_j))]^{-1}$ (Granot et al. 2002).

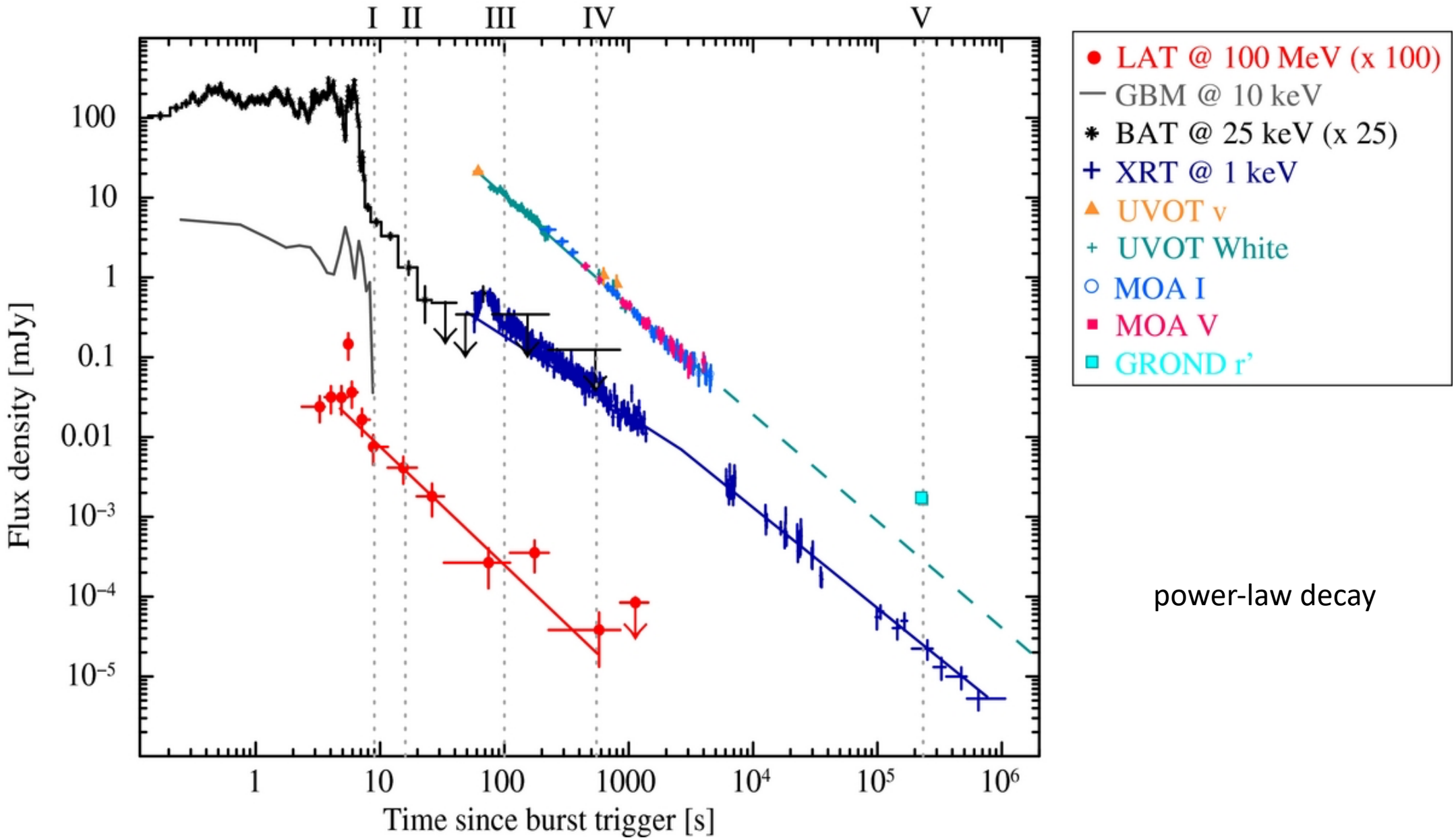


Afterglow


Central Engine
Inner Shocks
Gamma-rays
External Shocs
Afterglow
10^{6} cm
10^{11} - 10^{12} cm
10^{15} - 10^{18} cm

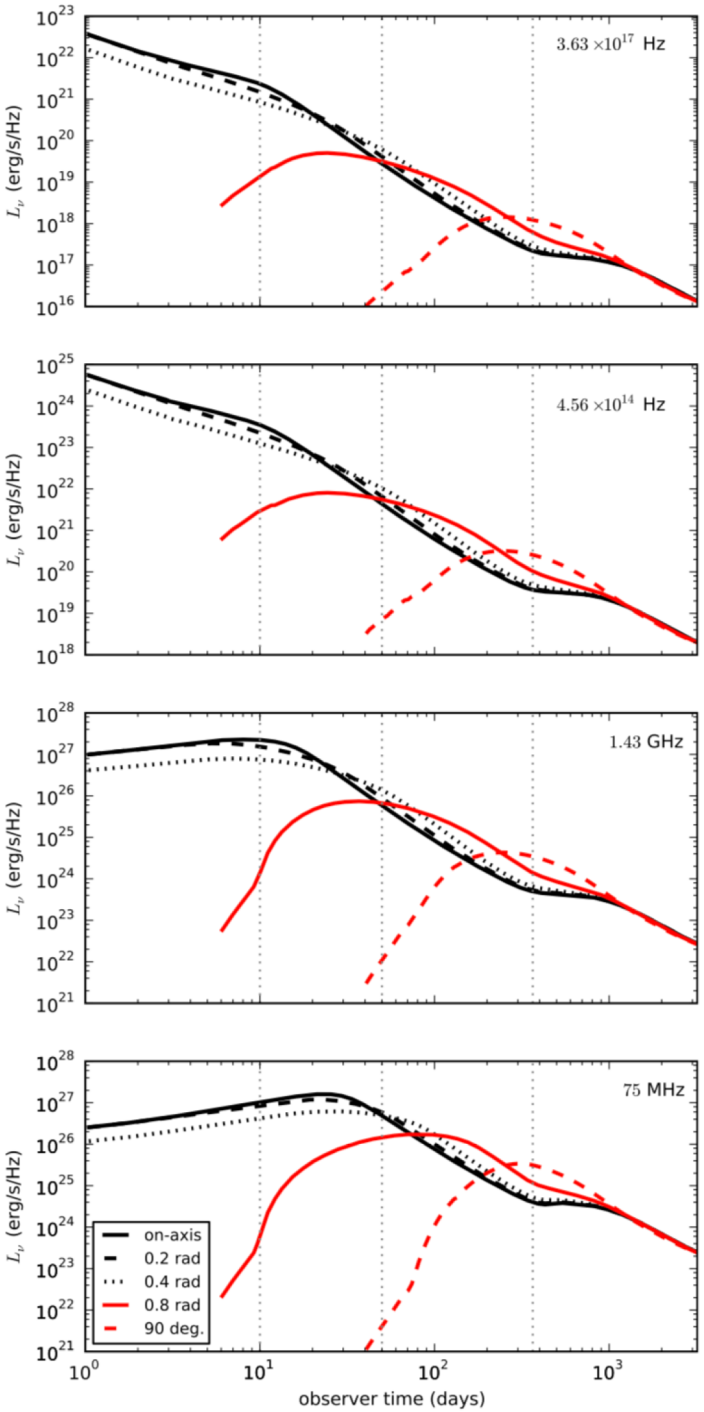

LIGO - Virgo
frequency (Hz)
500
400
300
200
100
50
-12
-10
-8
-6
-4
-2
0
2
4
6
t-tc (s)
Fermi/GBM
INTEGRAL/SPI-ACS
counts/s (arb. scale)
t-tc (days)
1.2
1.4
2.4
normalized Fλ
SALT
ESO-NTT
SOAR
ESO-VLT
7000°
4000°
400
600
1000
2000
wavelength (nm)
GW
LIGO, Virgo
γ-ray
Fermi, INTEGRAL, Astrosat, IPN, Insight-HXMT, Swift, AGILE, CALET, H.E.S.S., HAWC, Konus-Wind
X-ray
Swift, MAXI/GSC, NuSTAR, Chandra, INTEGRAL
UV
Swift, HST
Optical
Swope, DECam, DLT40, REM-ROS2, HST, Las Cumbres, SkyMapper, VISTA, MASTER, Magellan, Subaru, Pan-STARRS1, HCT, TZAC, LSGT, T17, Gemini-South, NTT, GROND, SOAR, ESO-VLT, KMTNet, ESO-VST, VIRT, SALT, CHILESCOPE, TOROS, BOOTES-5, Zadko, iTelescope.Net, AAT, Pi of the Sky, AST3-2, ATLAS, Danish Tel, DFN, T80S, EABA
IR
REM-ROS2, VISTA, Gemini-South, 2MASS,Spitzer, NTT, GROND, SOAR, NOT, ESO-VLT, Kanata Telescope, HST
Radio
ATCA, VLA, ASKAP, VLBA, GMRT, MWA, LOFAR, LWA, ALMA, OVRO, EVN, e-MERLIN, MeerKAT, Parkes, SRT, Effelsberg
-100
-50
0
50
t-tc (s)
10-2
10-1
100
101
t-tc (days)
1M2H Swope
10.86h
i
DLT40
11.08h
h
MASTER
11.31h
W
DECam
11.40h
iz
VISTA
11.24h
YJKs
Las Cumbres
11.57h
w
Chandra
9d
X-ray
J VLA
16.4d
Radio

Tipical multi-wavelength lightcurve



power-law decay

Time and viewing angle dependence



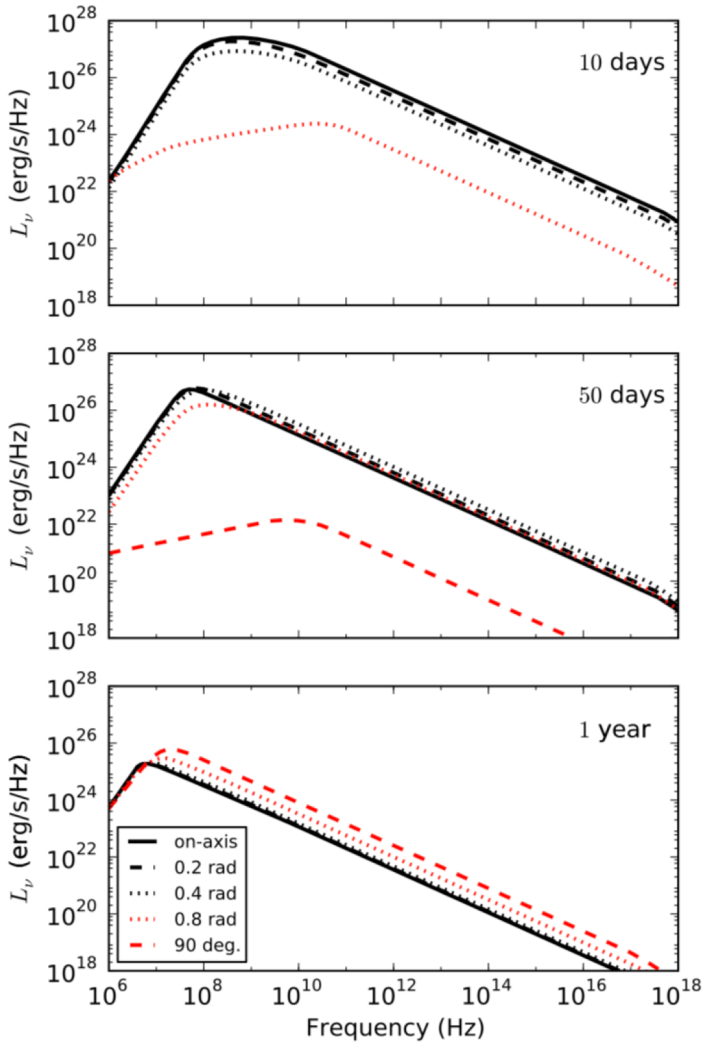


Figure 2. Spectra for $E_j = 10^{48}$ erg, $\theta_j = 0.2$ rad, and $n = 10^{-3}$ cm^{-3} at $t_{\rm obs} = 10$ days, 50 days, and 1 yr (top to bottom plot), for various observer angles. The legend applies to all plots.

Figure 1. Observed luminosity light curves for $E_j = 10^{48}$ erg, $\theta_j = 0.4$ rad, and $n = 10^{-3}$ cm^{-3} (case B). Observer frequencies from top to bottom: 3.63×10^{17} Hz, 4.56×10^{14} Hz, 1.43 GHz, and 75 MHz. The legend applies to all plots. 10 days, 50 days, and 1 yr have been marked with vertical dotted gray lines. Spectra for these times are provided in Figure 2.

Peak flux:

- Higher for lower angles
- Delayed for greater angles

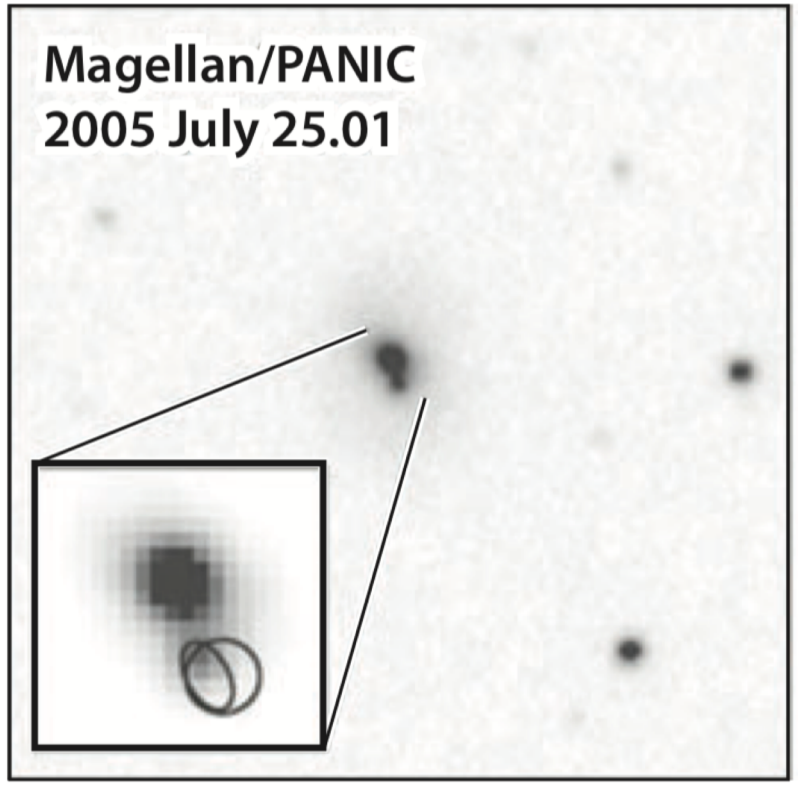
➢ After peak there is ~power law decay

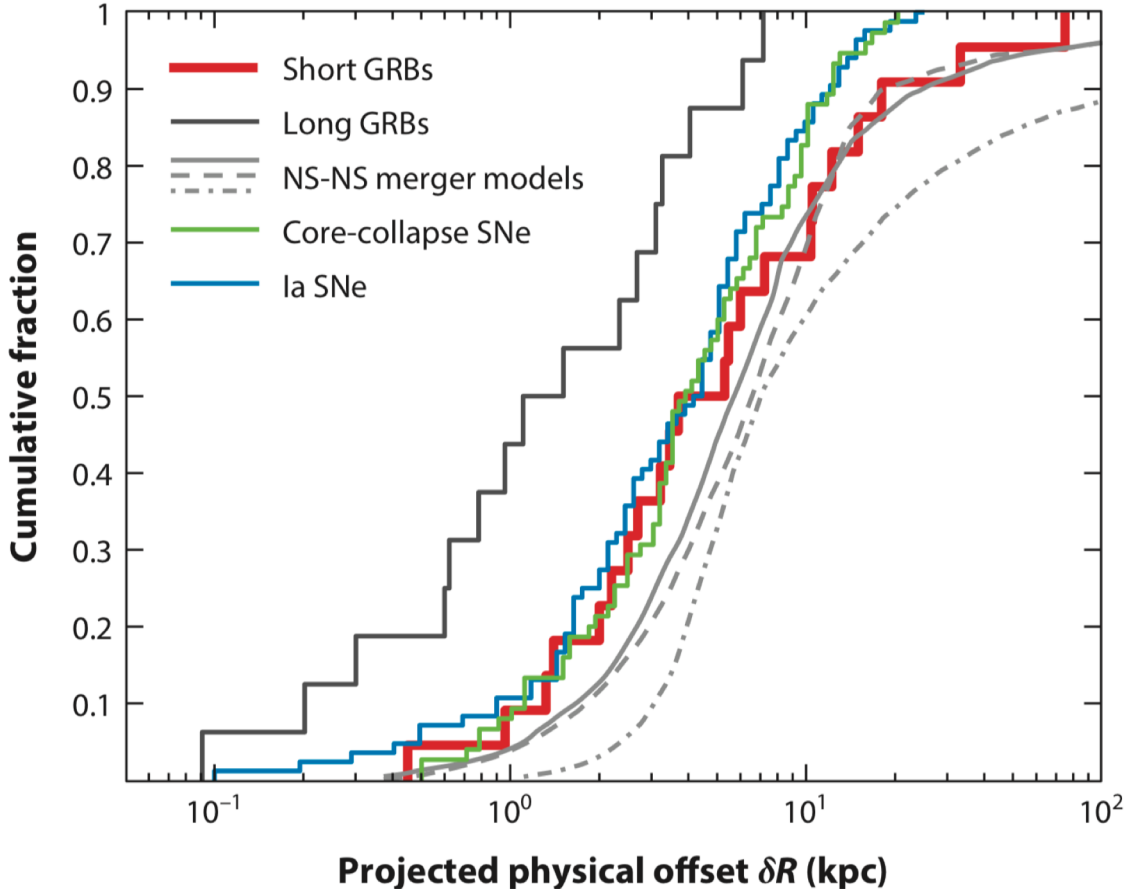
➢ Spectrum is also ~power law above some peak frequency

➢ Spectrum softens with time

Van Eerten+ ApJL 2011

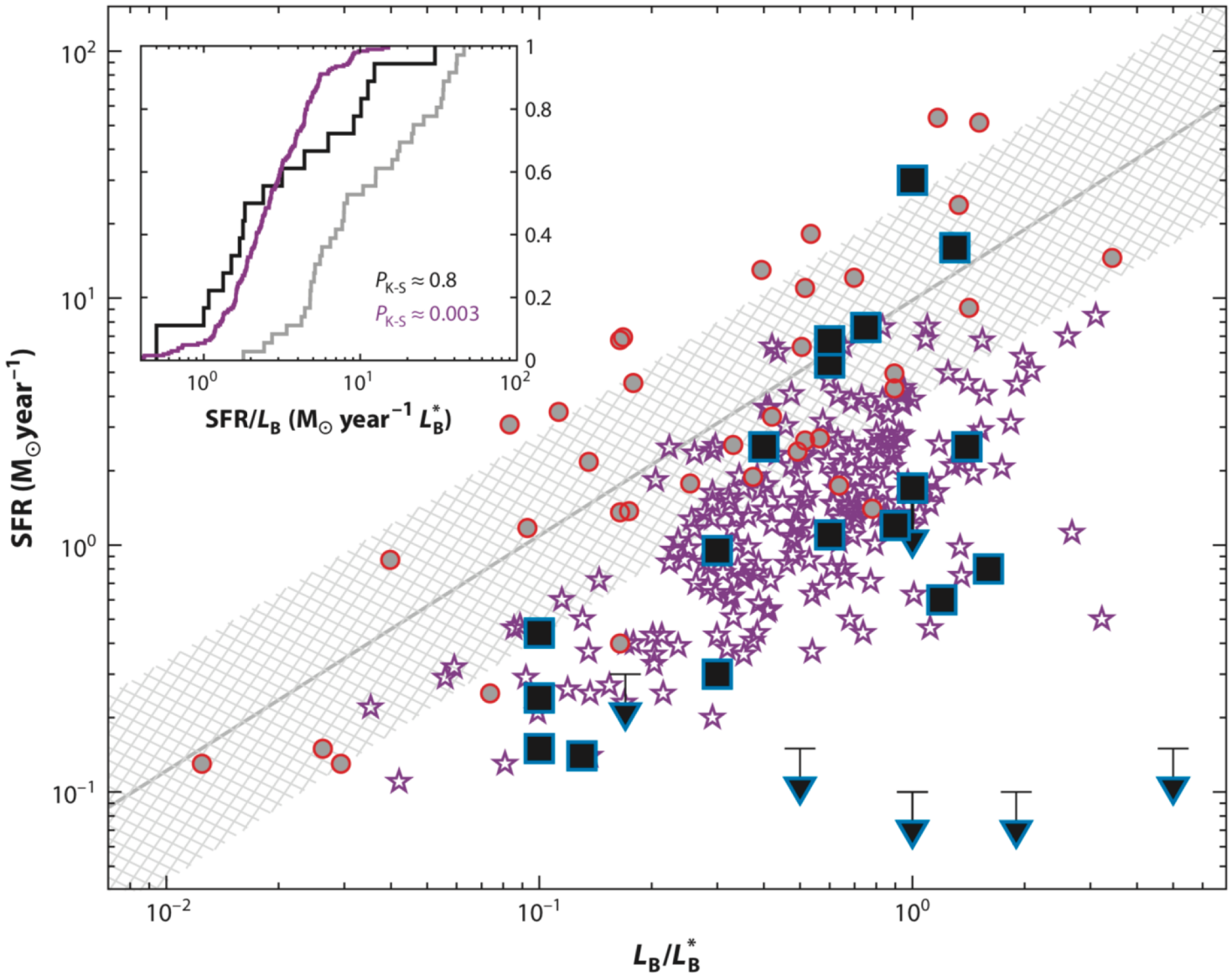
Kicks – short GRBs are often outside the host galaxy





Berger 2014

Star formation in host galaxies

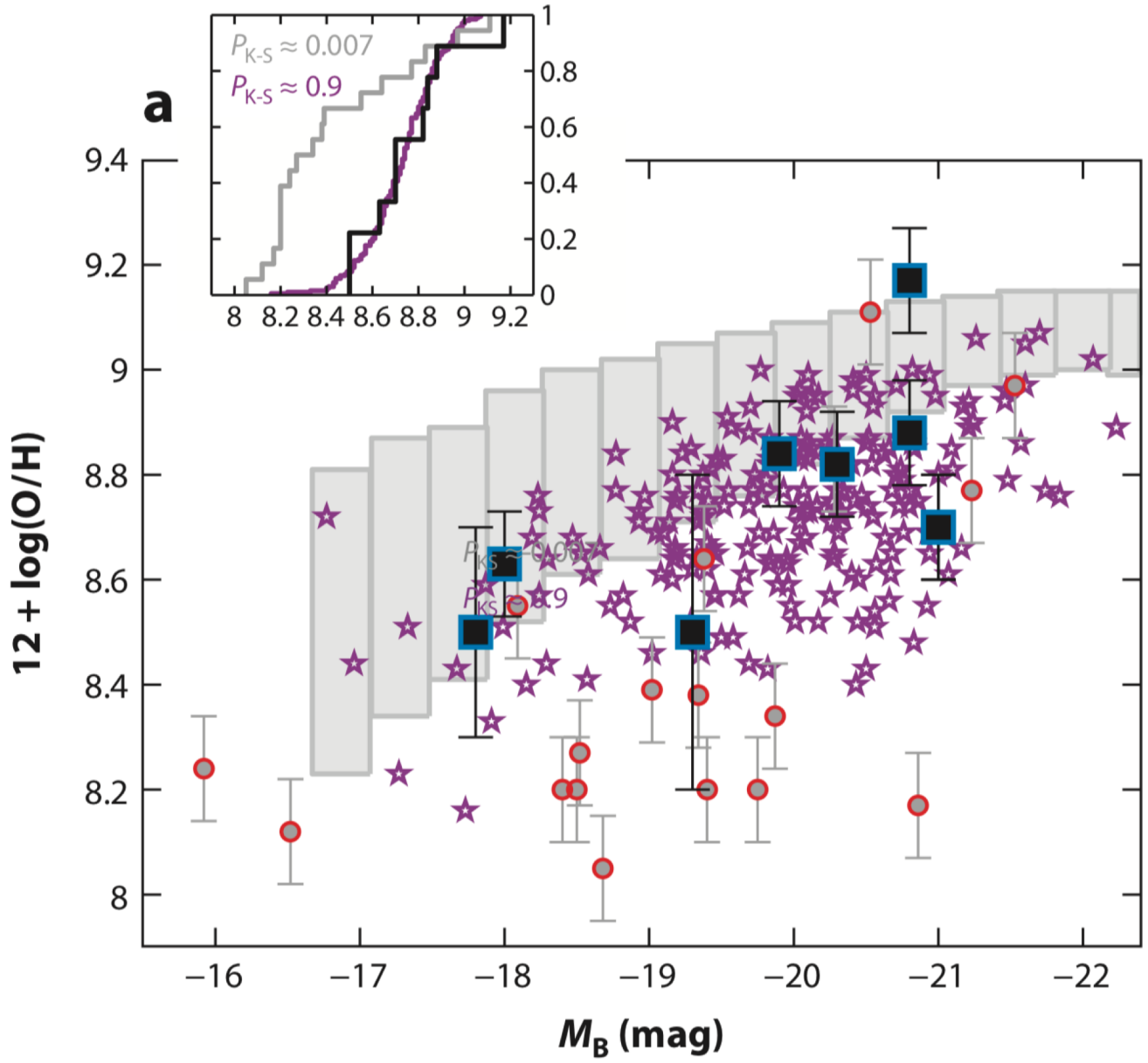


Star-formation rate (SFR) as a function of rest-frame B-band luminosity for the host galaxies of short GRBs (*squares*), long GRBs (*circles*), and field star-forming galaxies at similar redshifts to short GRB hosts (*stars*; Kobulnicky & Kewley 2004).

Low star formation indicates that the binary formed a long time ago.

Berger 2014

Metallicity of host galaxy

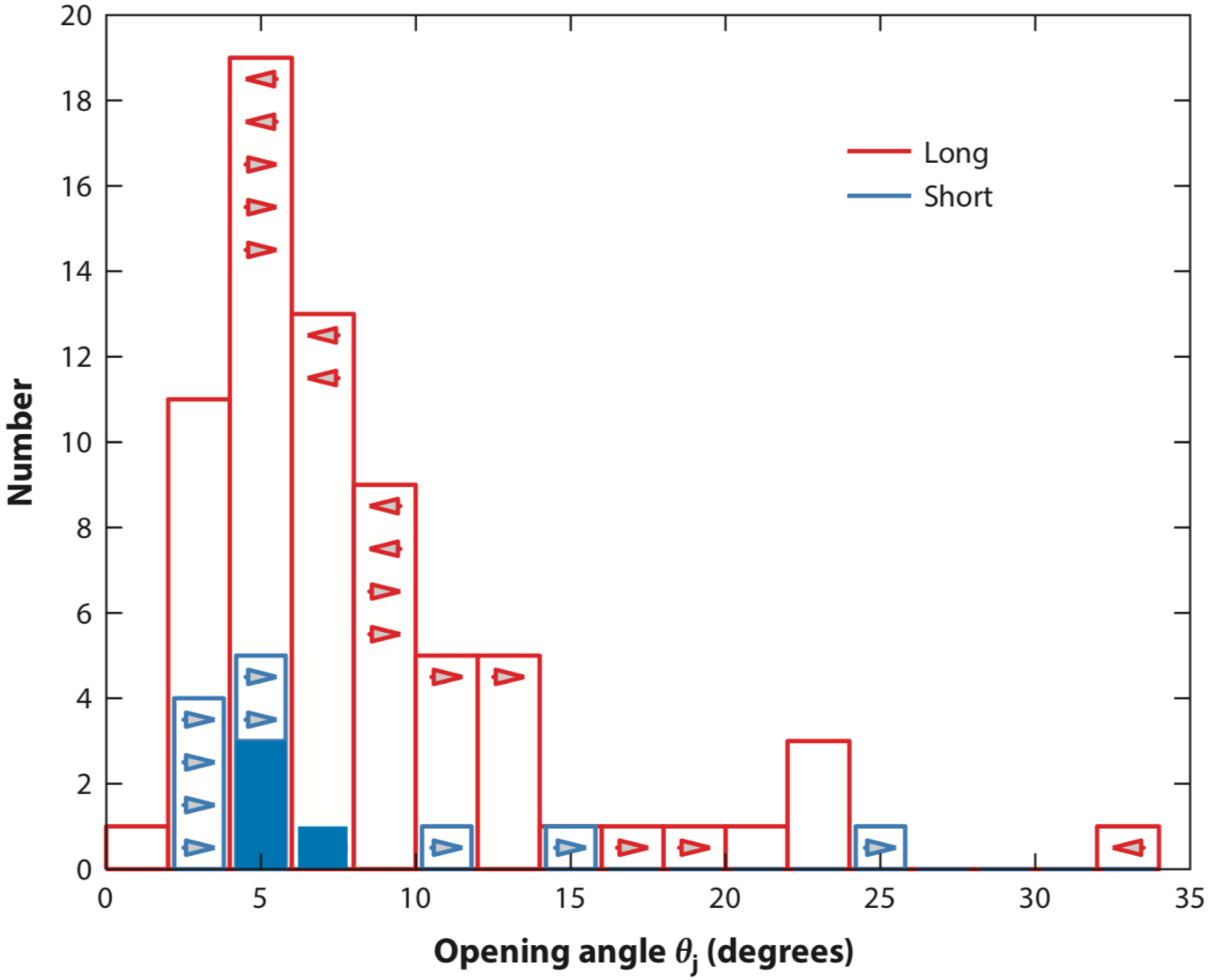


Metallicity as a function of host-galaxy rest-frame B-band luminosity for short GRBs (*squares*), long GRBs (*circles*), field galaxies at similar redshifts to short GRB hosts (*stars*; Kobulnicky & Kewley 2004), and the Sloan Digital Sky Survey luminosity-metallicity relation (Tremonti et al. 2004). Short GRB host galaxies have higher metallicities than long GRB hosts, but they closely track the luminosity-metallicity relation for the field galaxy population (*inset*).

Long GRBs prefer low-metallicity environments --- favorable for massive stellar explosions

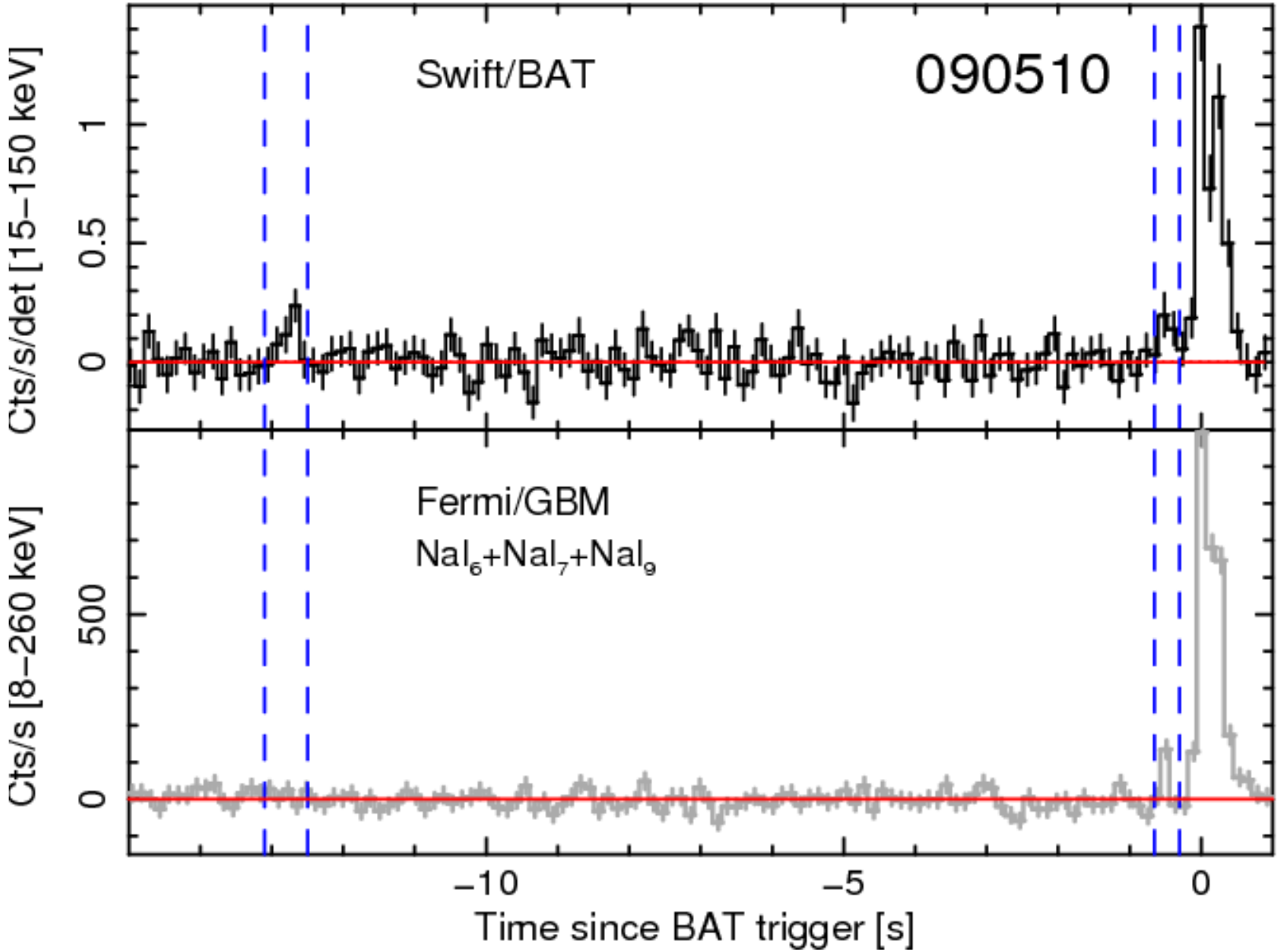
Berger 2014

Opening angles

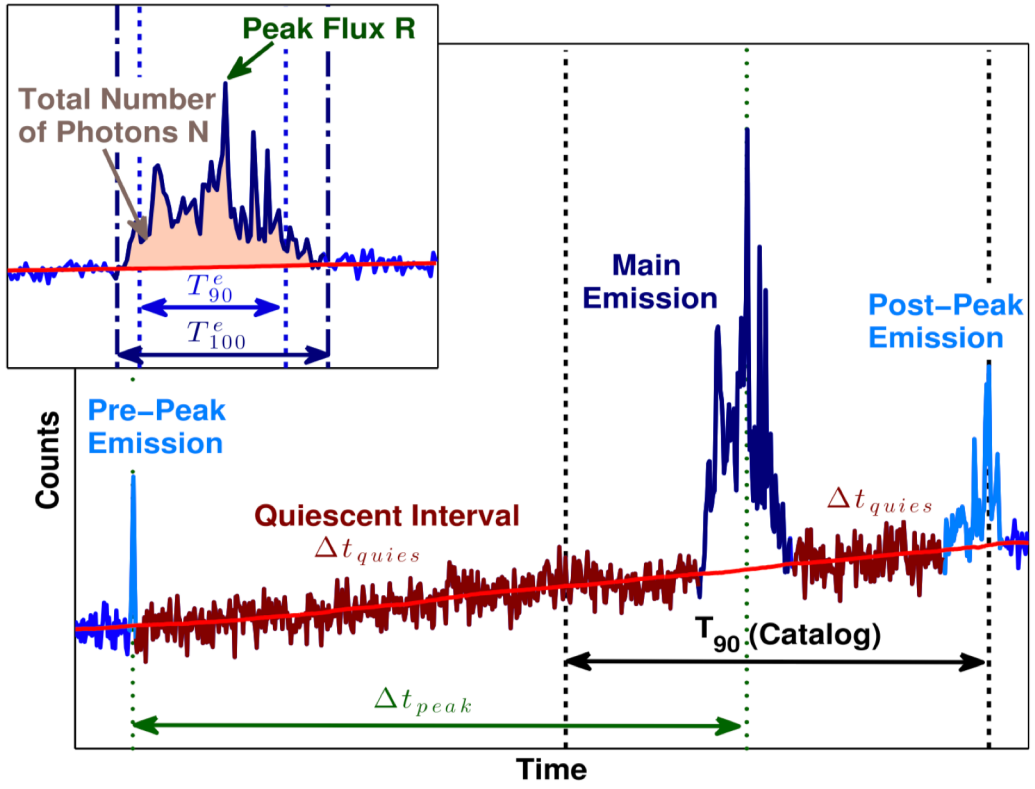


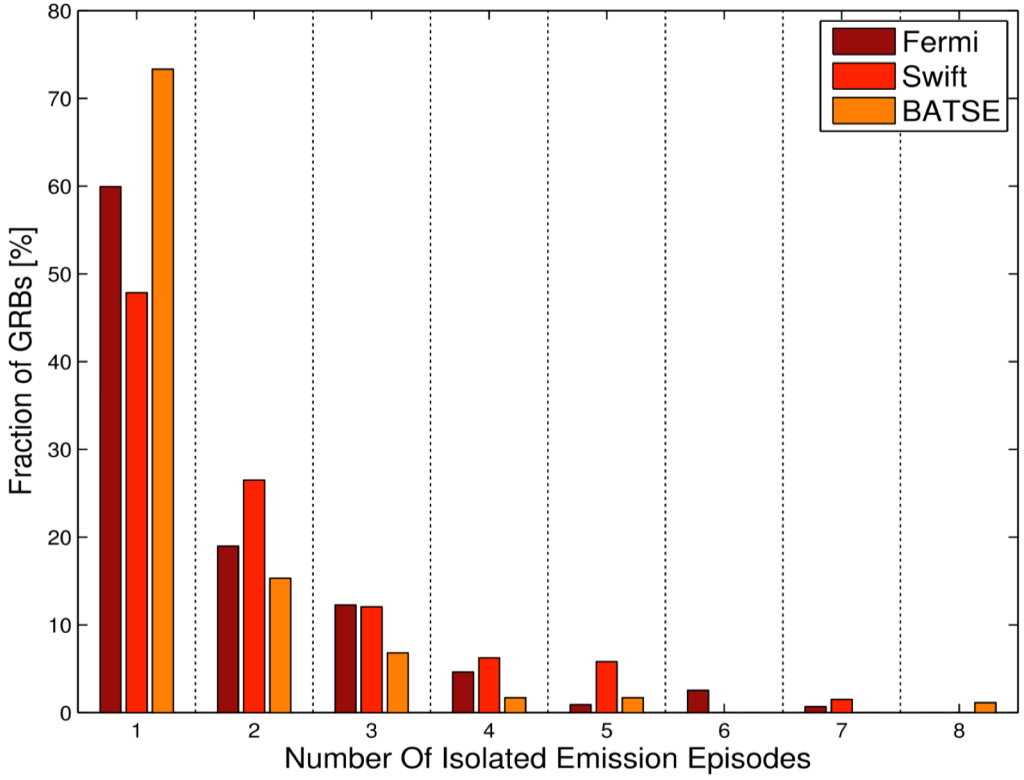
Berger 2014

Precursors


Swift/BAT
090510
Cts/s/det [15–150 keV]
1
0.5
0
Fermi/GBM
NaI6+NaI7+NaI9
Cts/s [8–260 keV]
500
0
–10
–5
0
Time since BAT trigger [s]

Precursors


Peak Flux R
Total Number of Photons N
T^e_{90}
T^e_{100}
Main Emission
Post–Peak Emission
Pre–Peak Emission
Counts
Quiescent Interval
Δt_{quies}
Δt_{quies}
T_{90} (Catalog)
Δt_{peak}
Time


Fermi
Swift
BATSE
Fraction of GRBs [%]
Number Of Isolated Emission Episodes
0
10
20
30
40
50
60
70
80
1
2
3
4
5
6
7
8