PHZ 7097 | Modern Astrophysics

Lecture XXIV.

Gamma-ray bursts

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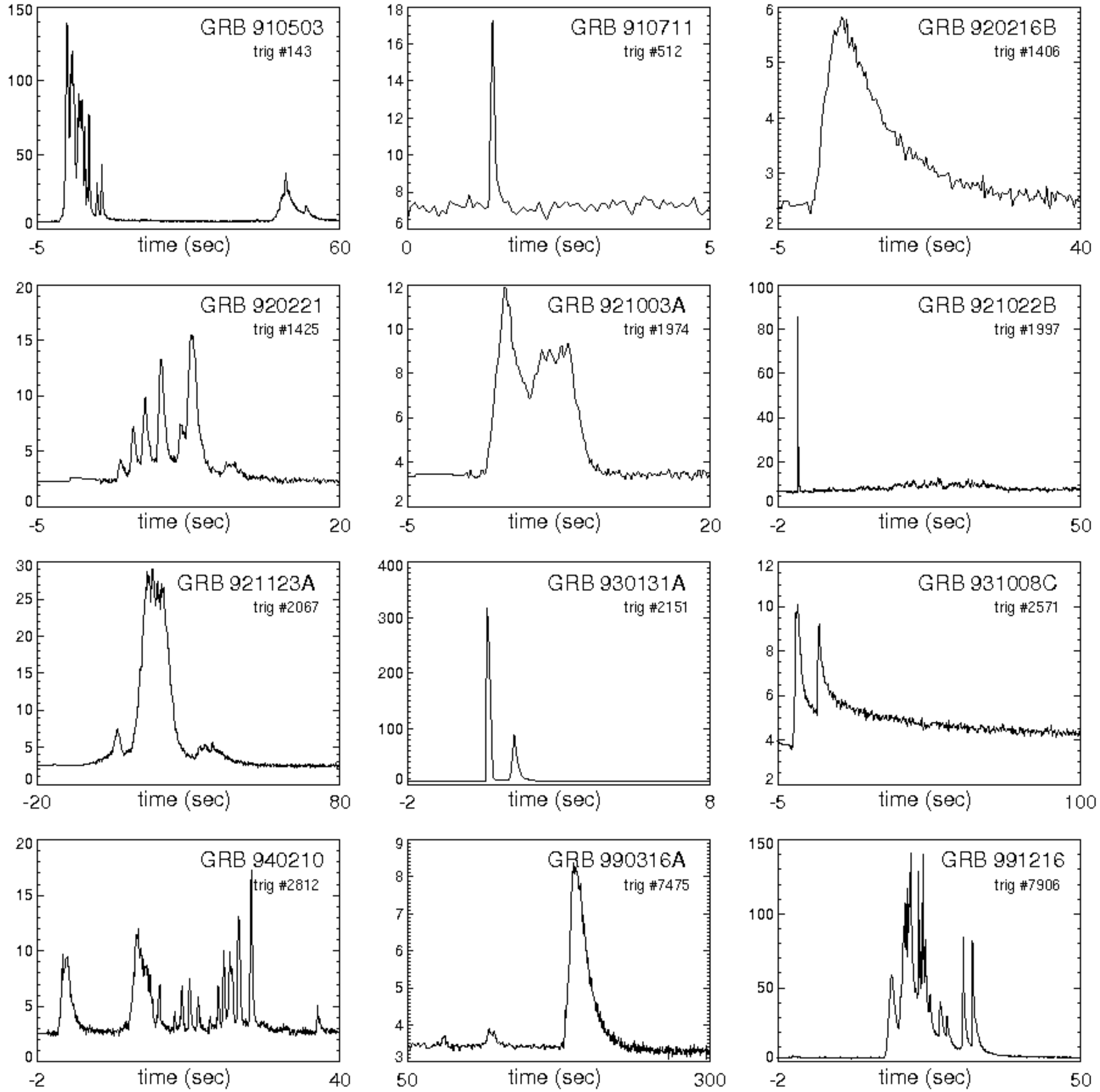
Light curves

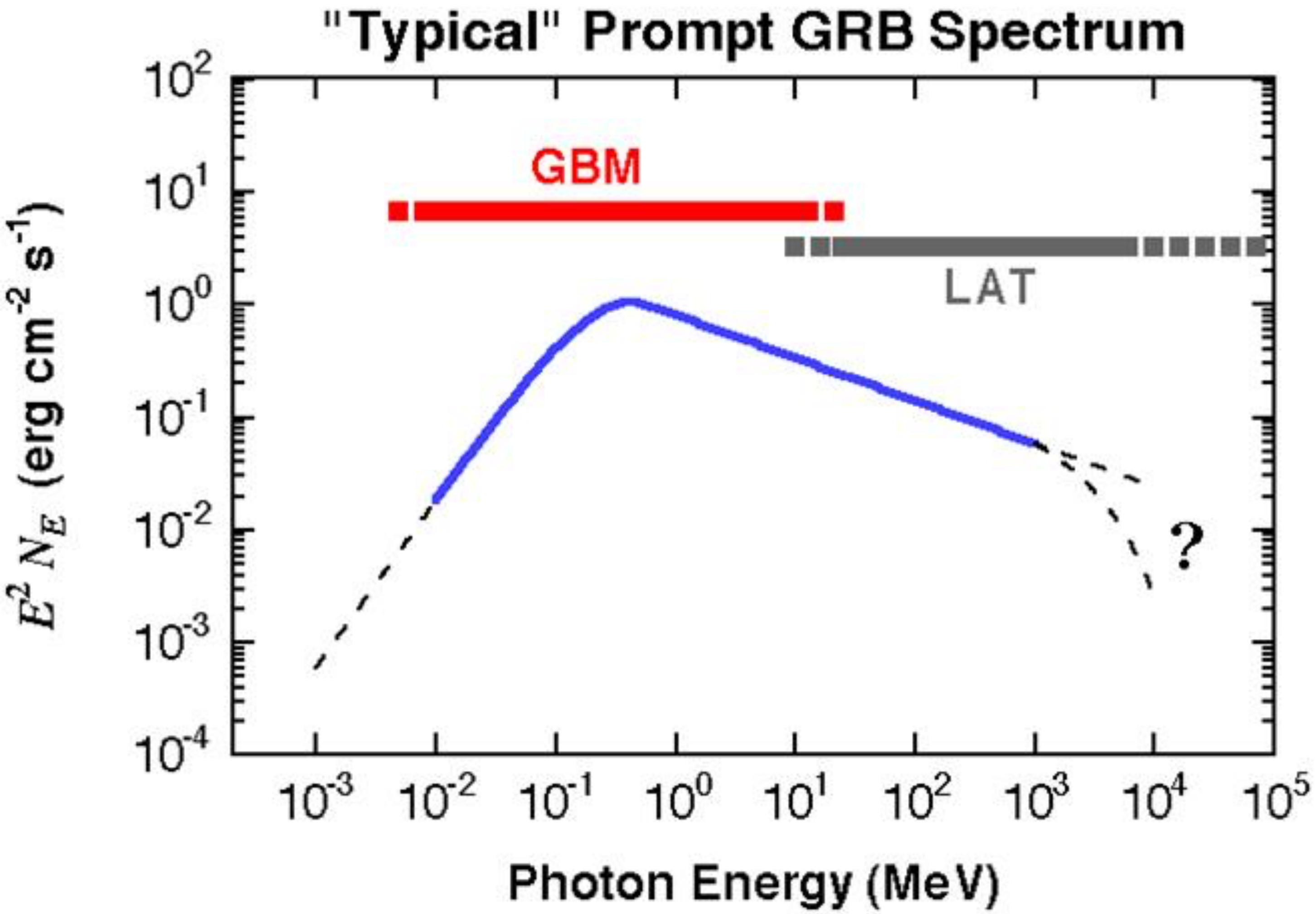
No two GRB light curves are identical.

Duration: milliseconds - minutes

Some are not continuous (precursors).



GRB spectrum

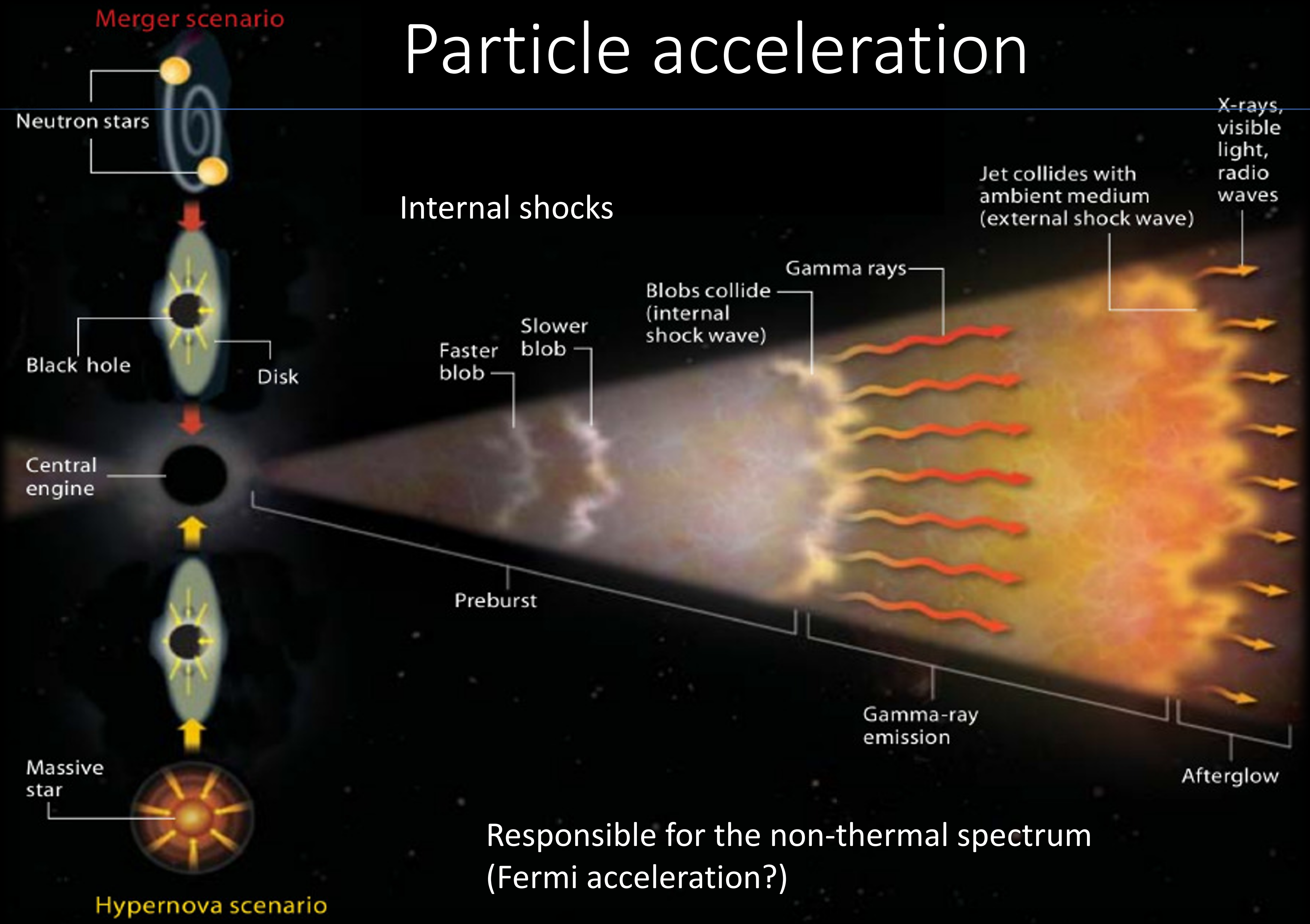


Band spectrum
(broken power-law)

$$N(E) = \begin{cases} N_0 \left(\frac{E}{100\ \mathrm{keV}}\right)^{\alpha} \exp\left[-\frac{E}{E_0}\right], & E \le E_b \\ N_0 \left(\frac{E_b}{100\ \mathrm{keV}}\right)^{\alpha-\beta} \exp[\beta-\alpha] \left(\frac{E}{100\ \mathrm{keV}}\right)^{\beta}, & E > E_b \end{cases} \quad (1)$$

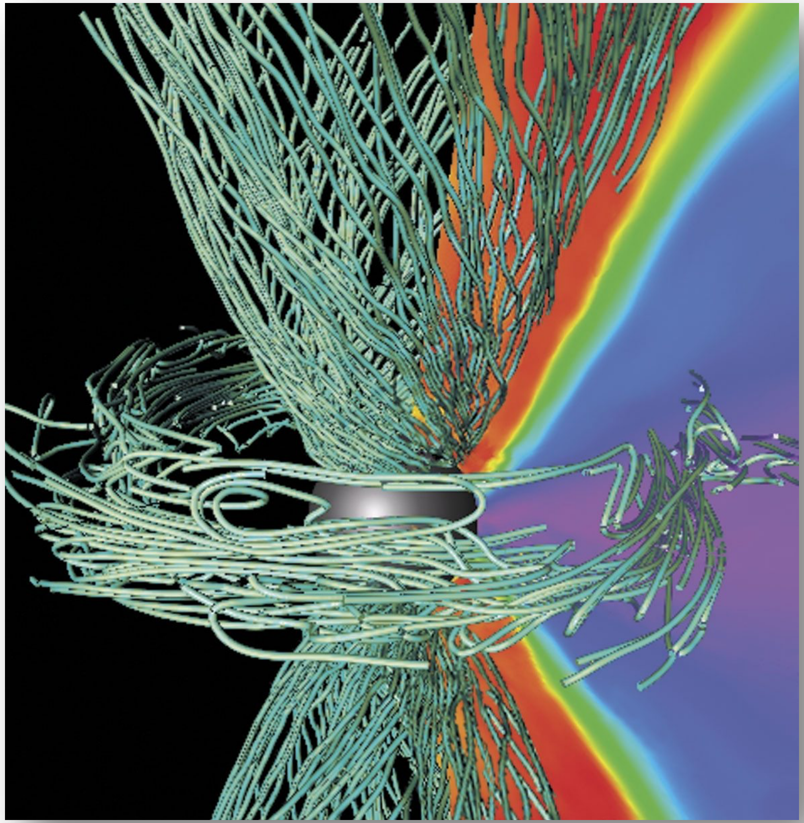
Particle acceleration

Internal shocks



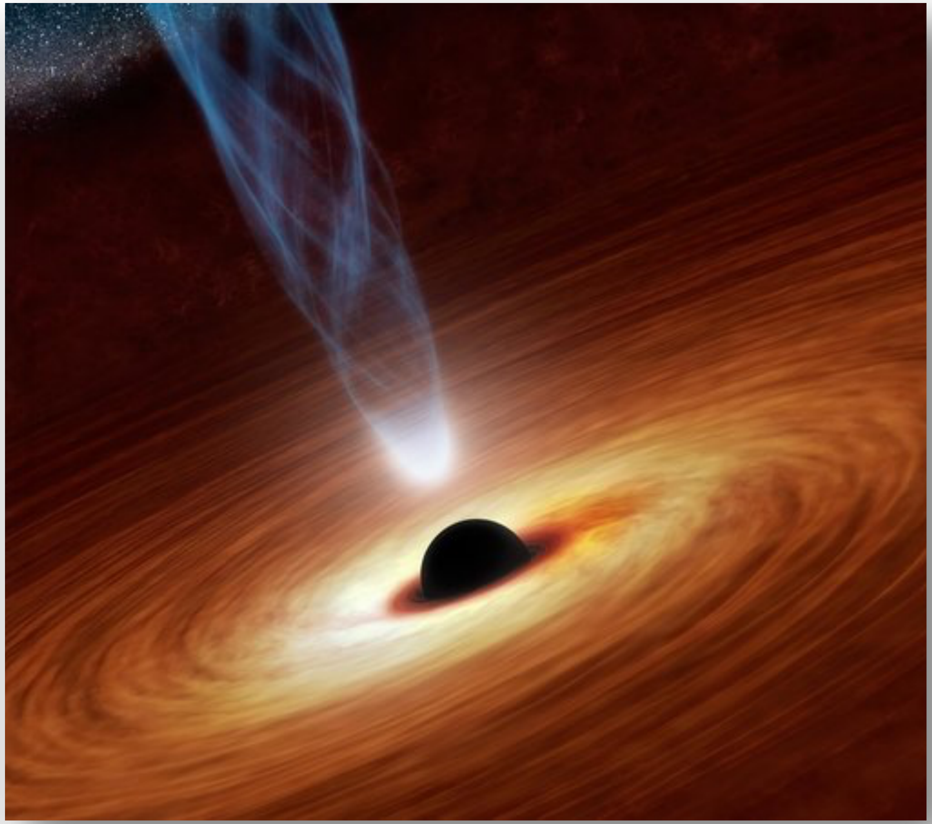
Responsible for the non-thermal spectrum
(Fermi acceleration?)

Relativistic outflow

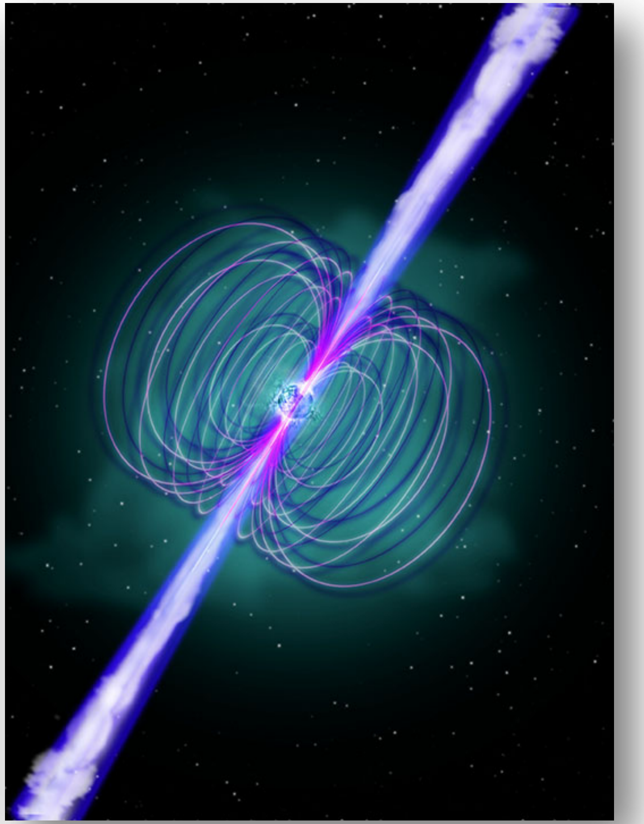


Magnetic field lines should be important (but we don't really know)

http://sites.krieger.jhu.edu/astronomy/numerical-simulations/



Accreting black hole



Magnetar
(neutron star with strong magnetic fields)

Fireball model

Luminosity is many orders of magnitude beyond the Eddington luminosity:

$$L_{\mathrm{E}} = 4\pi G M m_{\mathrm{p}} c/\sigma_{\mathrm{T}} = 1.25 \times 10^{38}\,(M/M_{\odot})\,\mathrm{erg\,s^{-1}}$$

So the high-temperature plasma expands → <u>outflow</u>.

For very high luminosities, the large density of gamma photons could make the fireball opaque to photons for energies above 0.5 MeV.

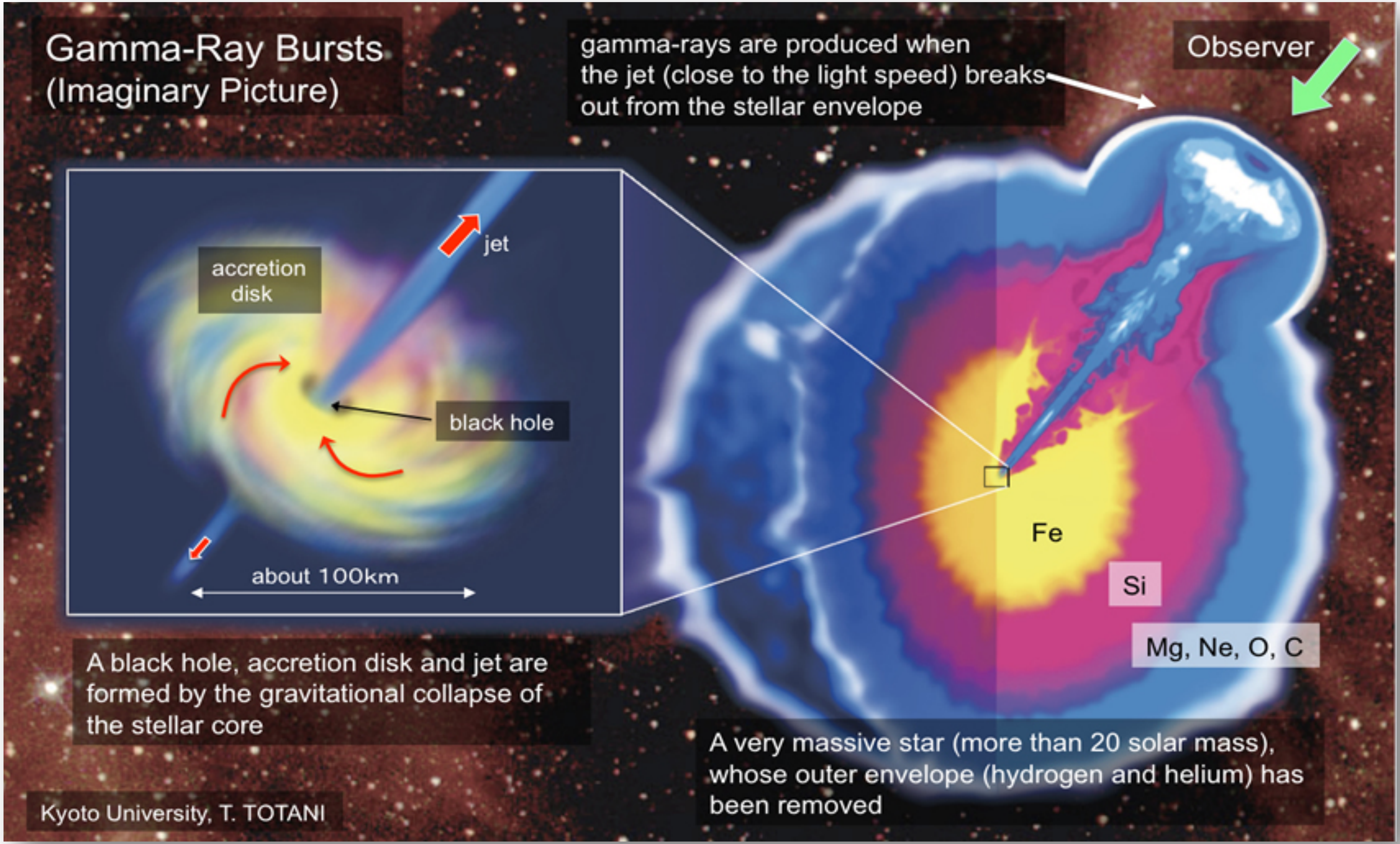
$$\gamma\gamma \rightarrow e^{\pm} \qquad\qquad m_{\mathrm{e}}c^2 = 0.511\,\mathrm{MeV}$$

But many GRB photons are >> 0.5 MeV → outflow needs to be <u>relativistic</u> (so it is less dense)

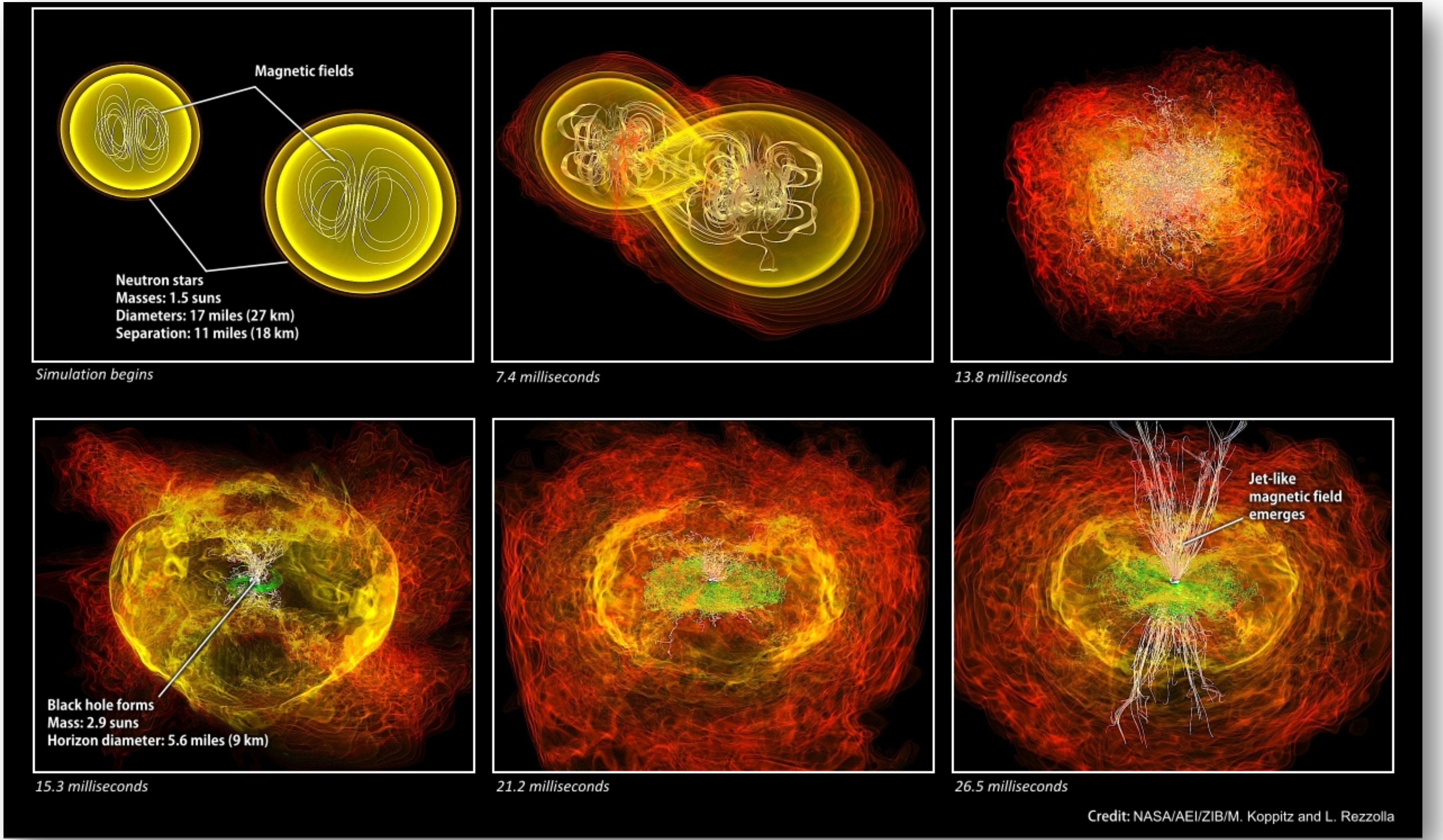
Total energy, as seen, is much more than what stellar core collapse and other events are thought to be able to produce → <u>beaming</u> (all the radiation is focused into some jet, so the total luminosity is not that high.)

Meszaros RPP 2006

Long GRBs – stellar core collapse



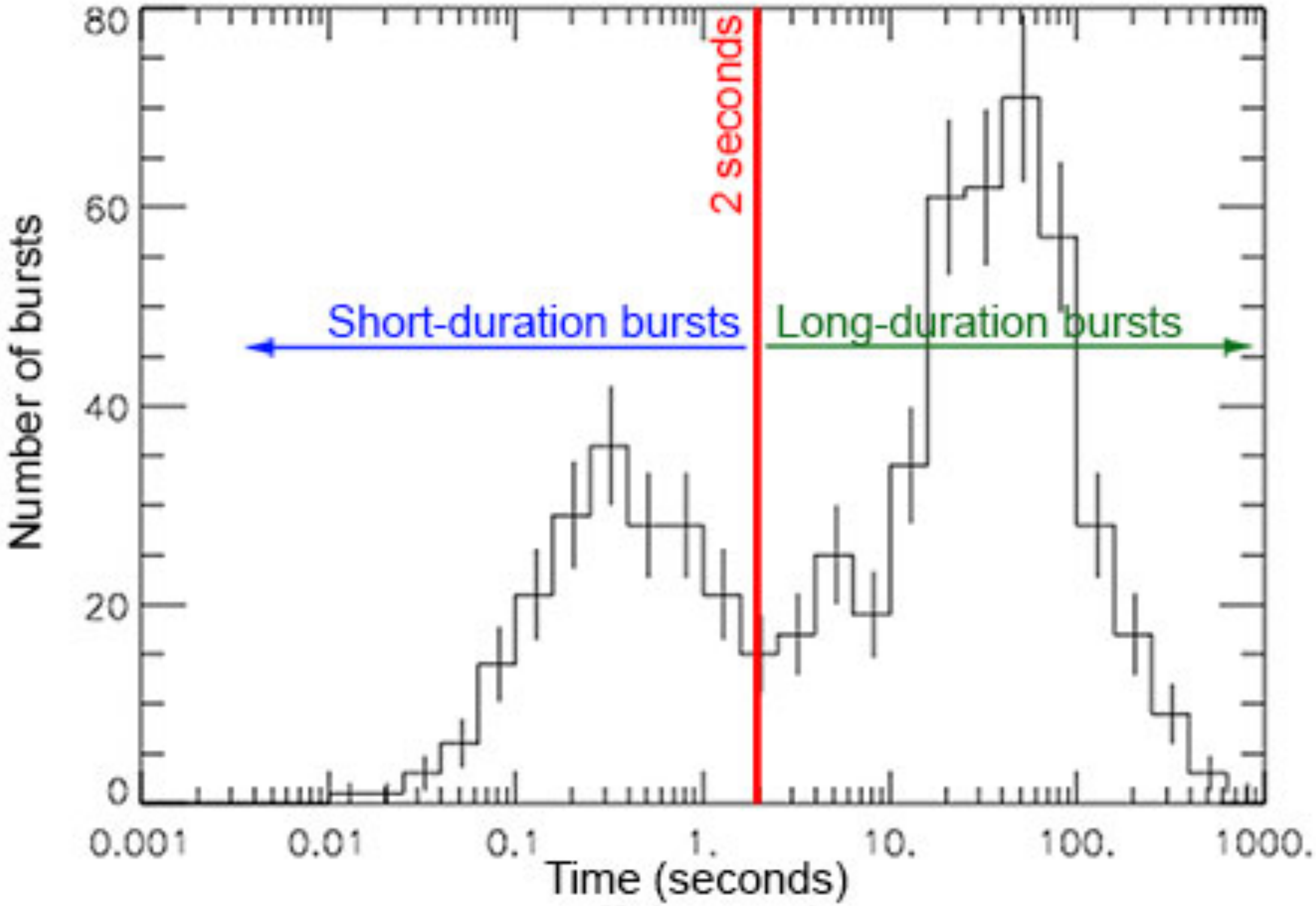
Short GRBs – binary mergers



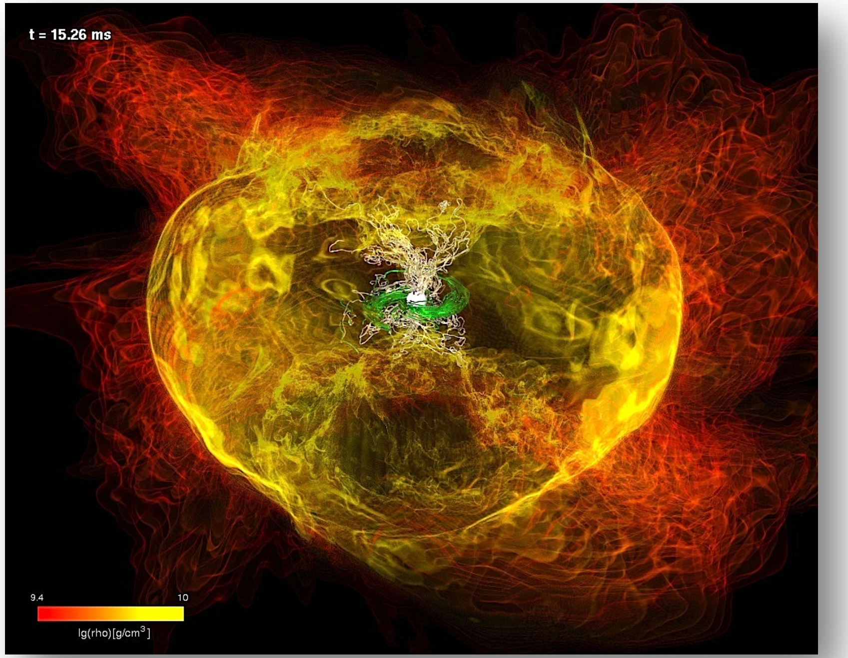
Duration ~ fallback time?

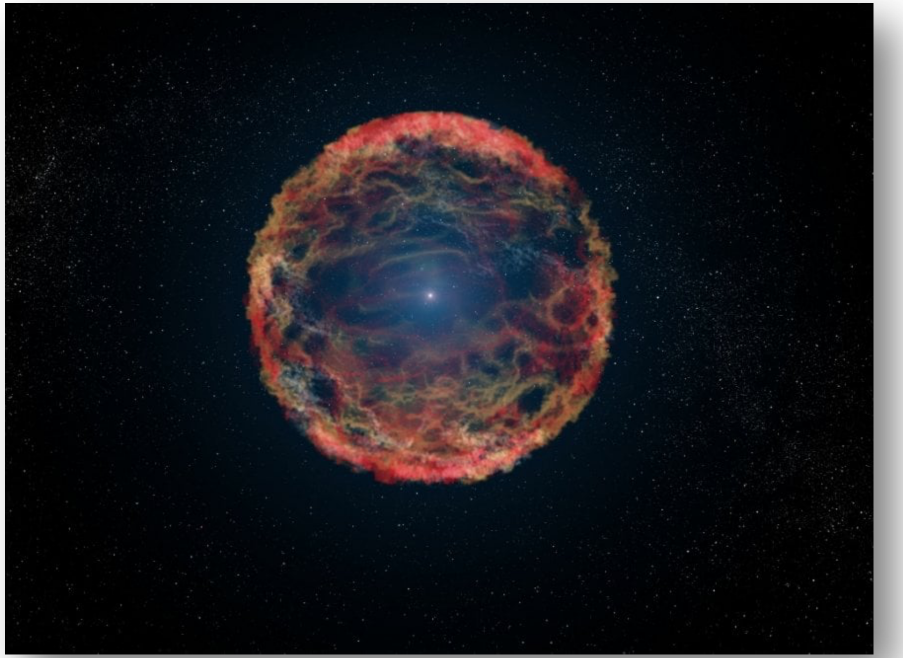
$$T = \pi\sqrt{\frac{R^3}{GM}} = T_{kepler}/2$$

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

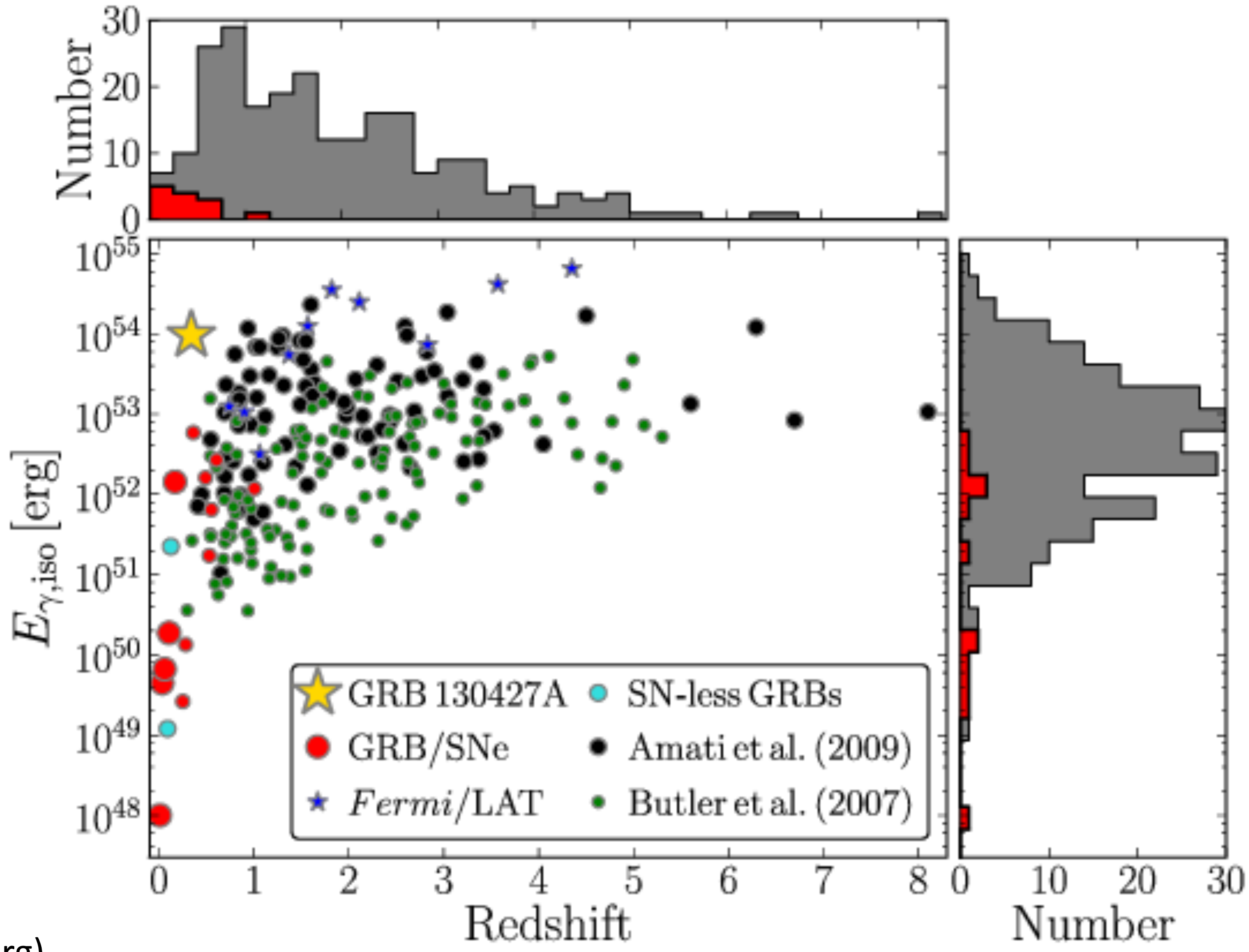
Depends on:
- NS Equation of State
- Mass ratio

Stellar core collapse

Could be several Msun

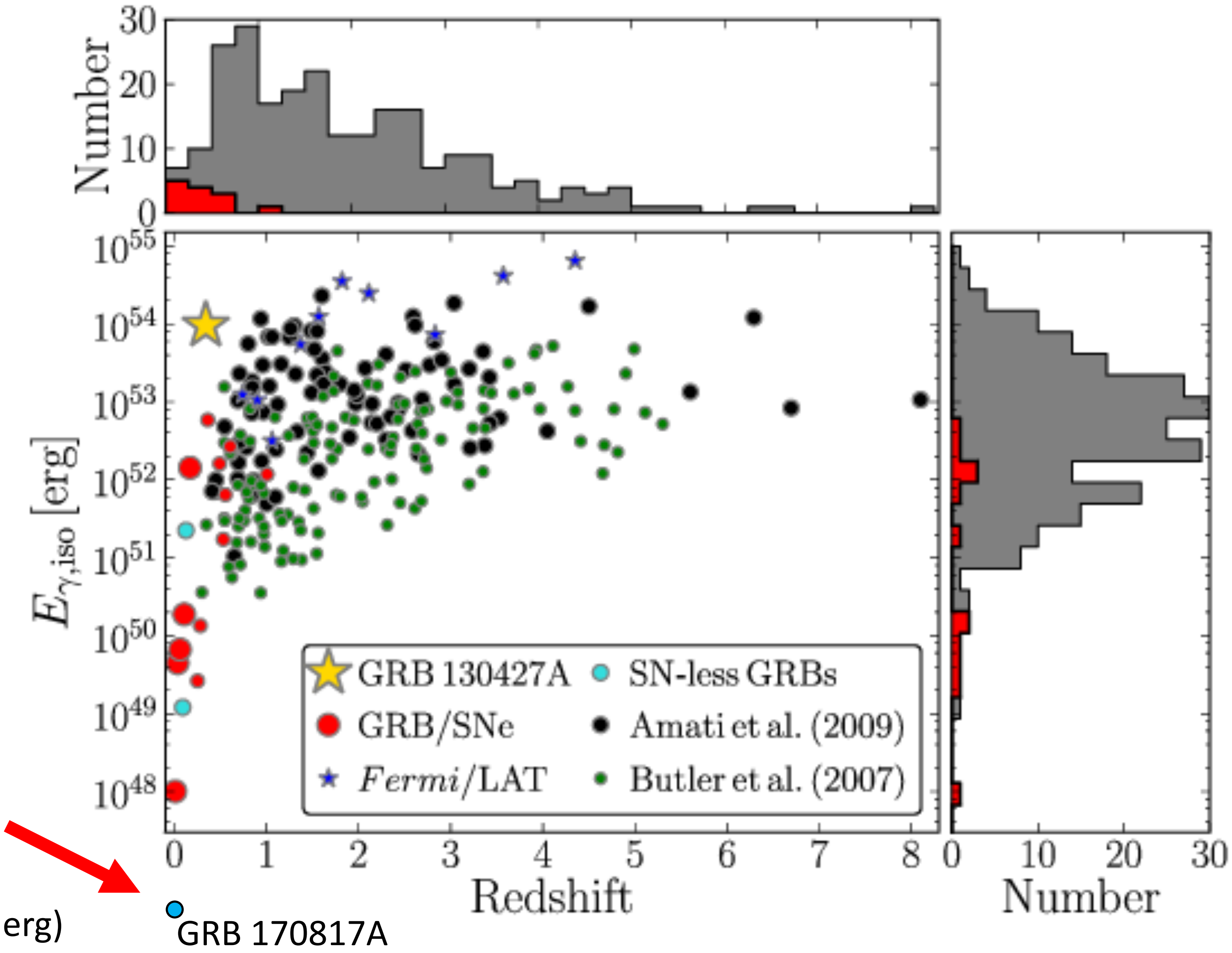
Depends on:
- How much energy is injected in the stellar envelope (?)

Energetics



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

Energetics



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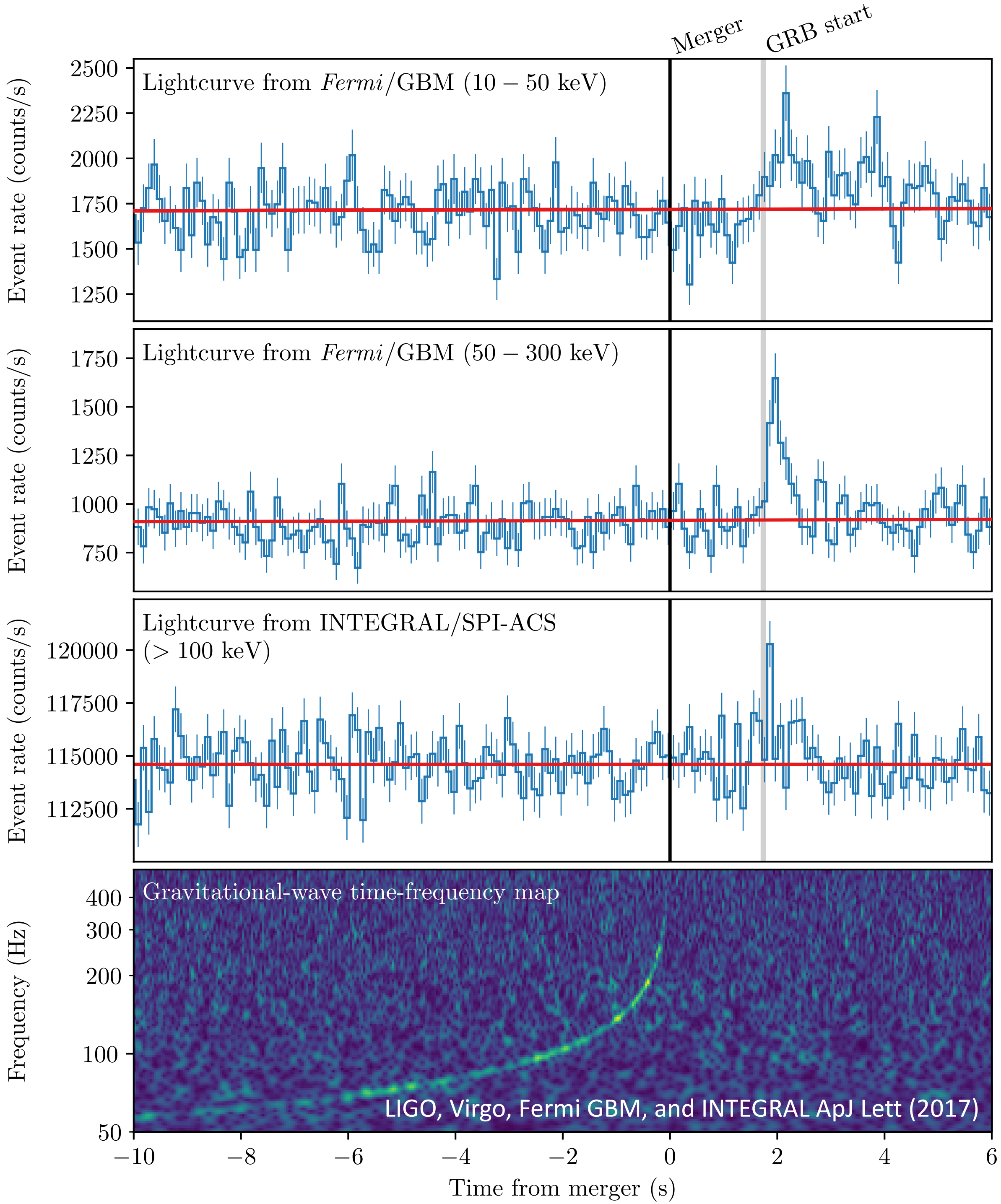
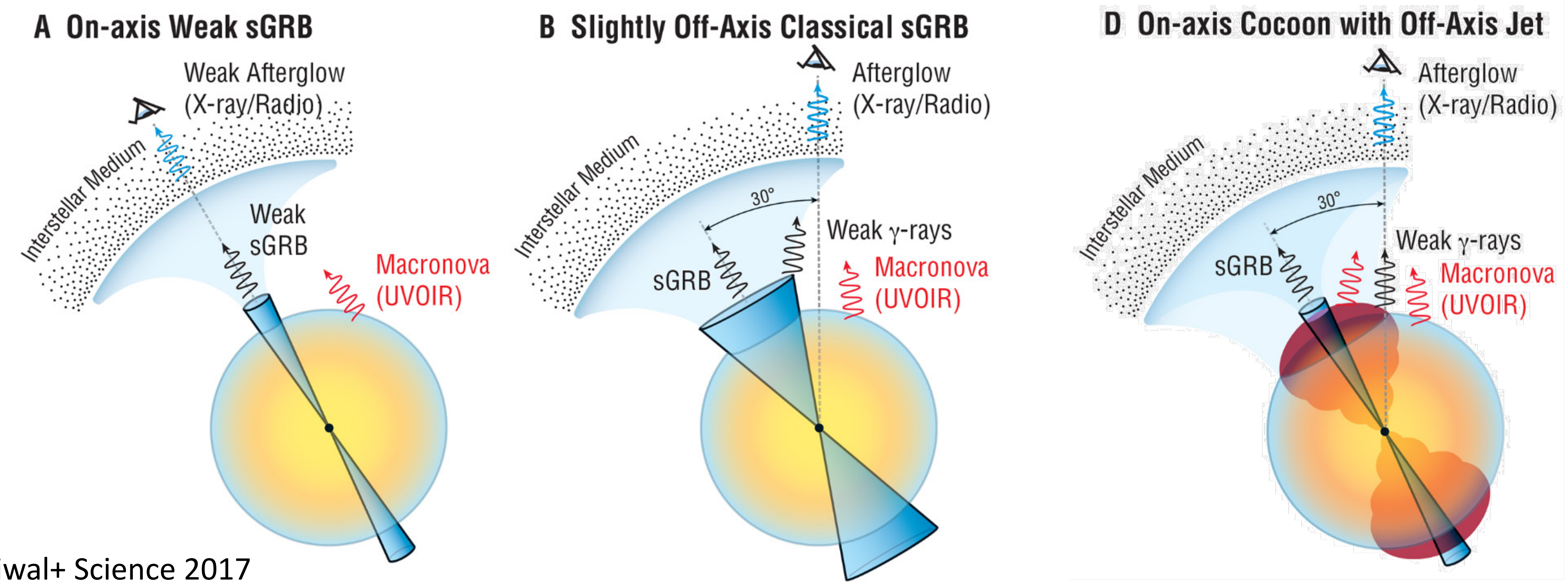


Merger
GRB start
Lightcurve from Fermi/GBM (10 – 50 keV)
Lightcurve from Fermi/GBM (50 – 300 keV)
Lightcurve from INTEGRAL/SPI-ACS
(> 100 keV)
Gravitational-wave time-frequency map
LIGO, Virgo, Fermi GBM, and INTEGRAL ApJ Lett (2017)
Event rate (counts/s)
Frequency (Hz)
Time from merger (s)

Gamma-ray burst

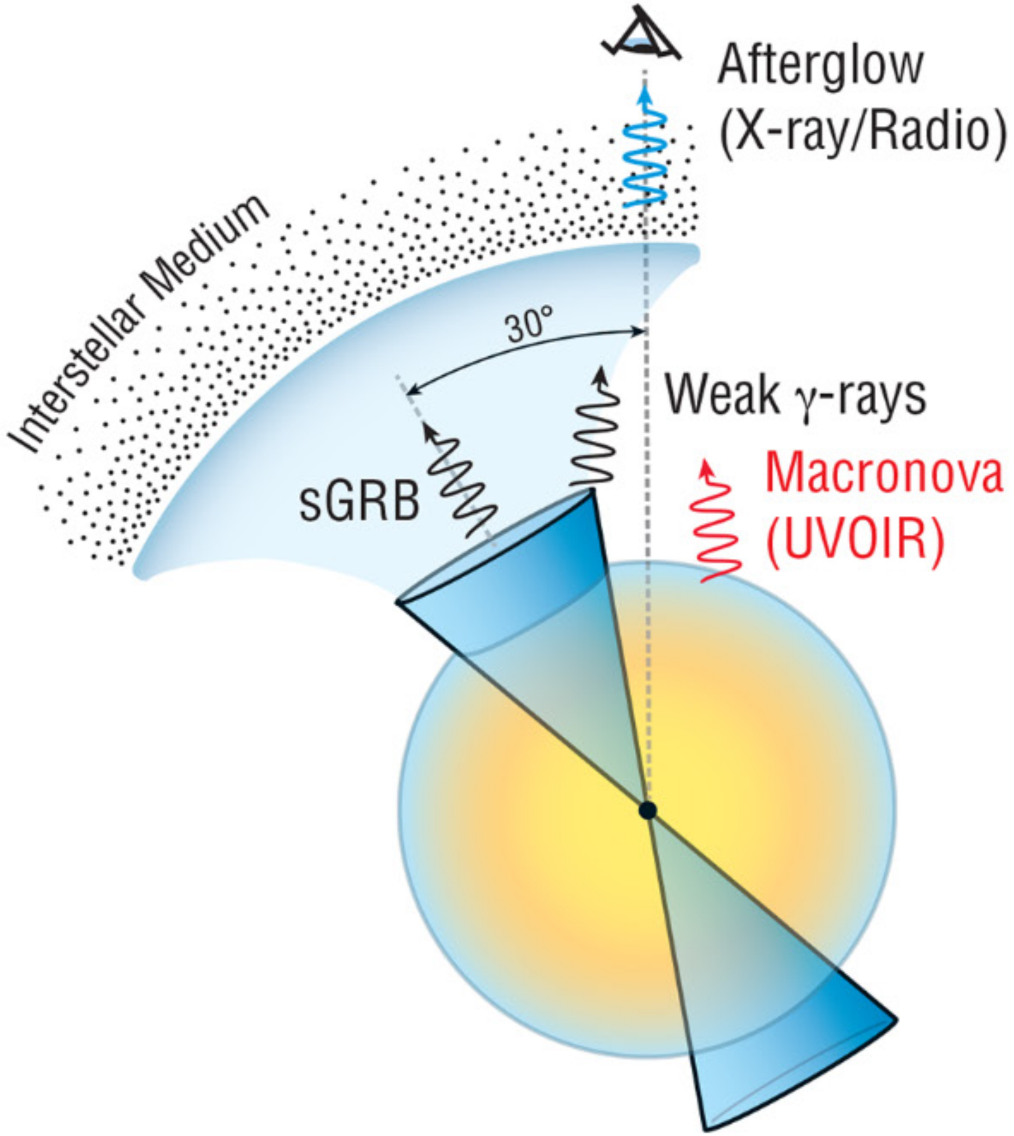
- Very weak --- energy orders of magnitude below weakest GRB detected
- Short-hard --- consistent with binary neutron star picture
- Host galaxy --- low star formation, probably very old NSs (Blanchard+ 2017)
- X-ray/Radio delay (9 and 15 days) --- unusual, consistent with off-axis scenario
- There was 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.



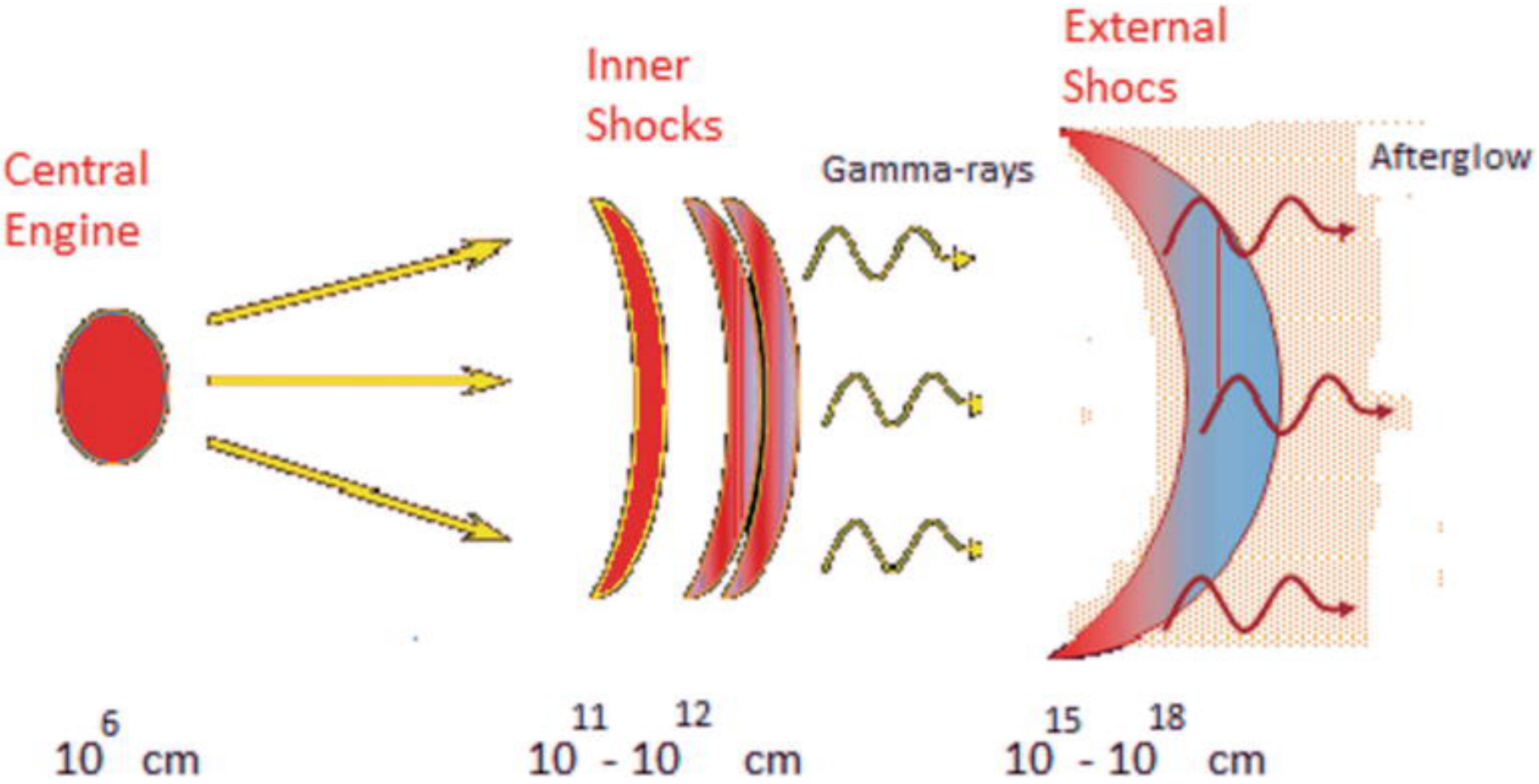
Kasliwal+ Science 2017

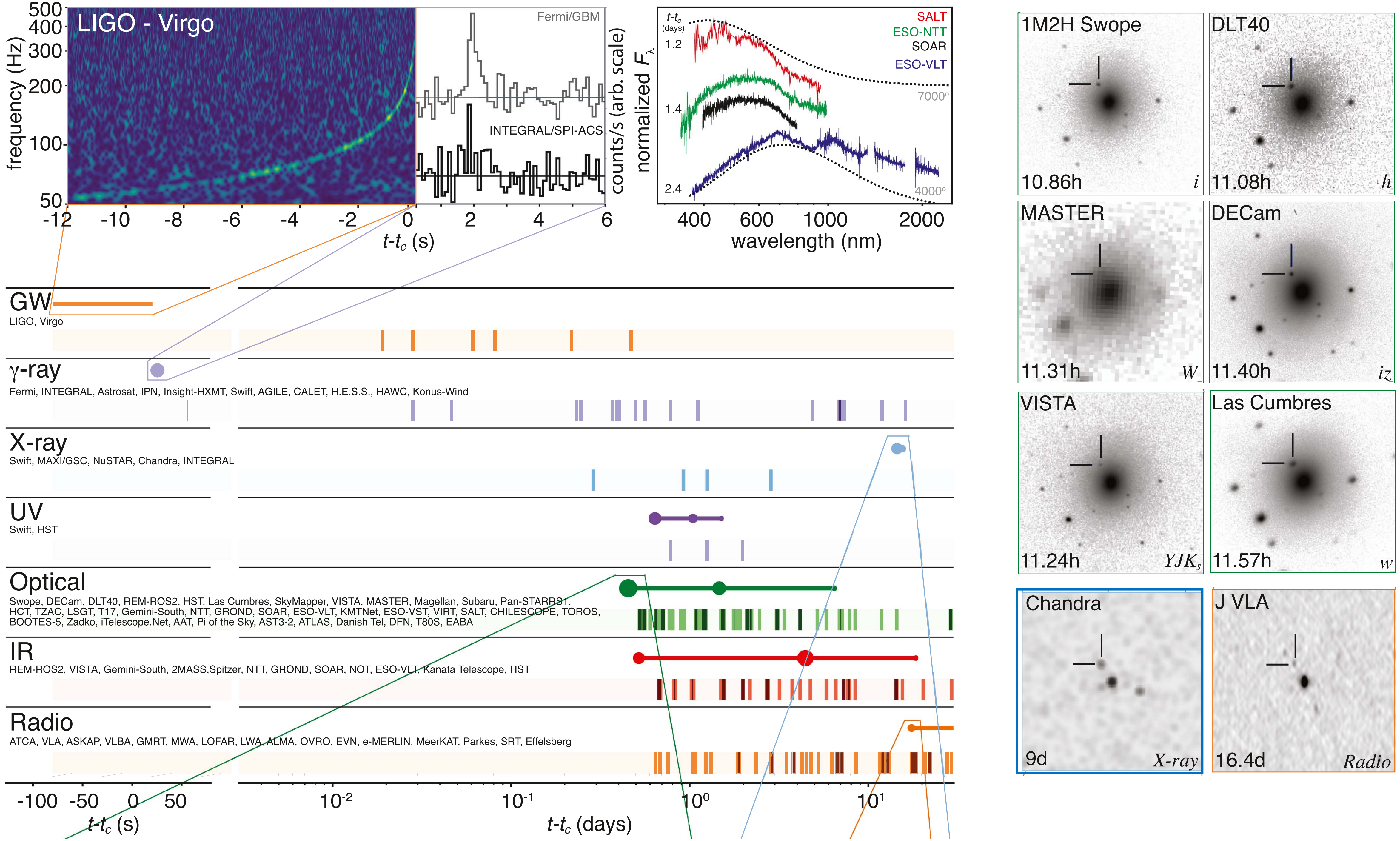
Off-axis?

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).



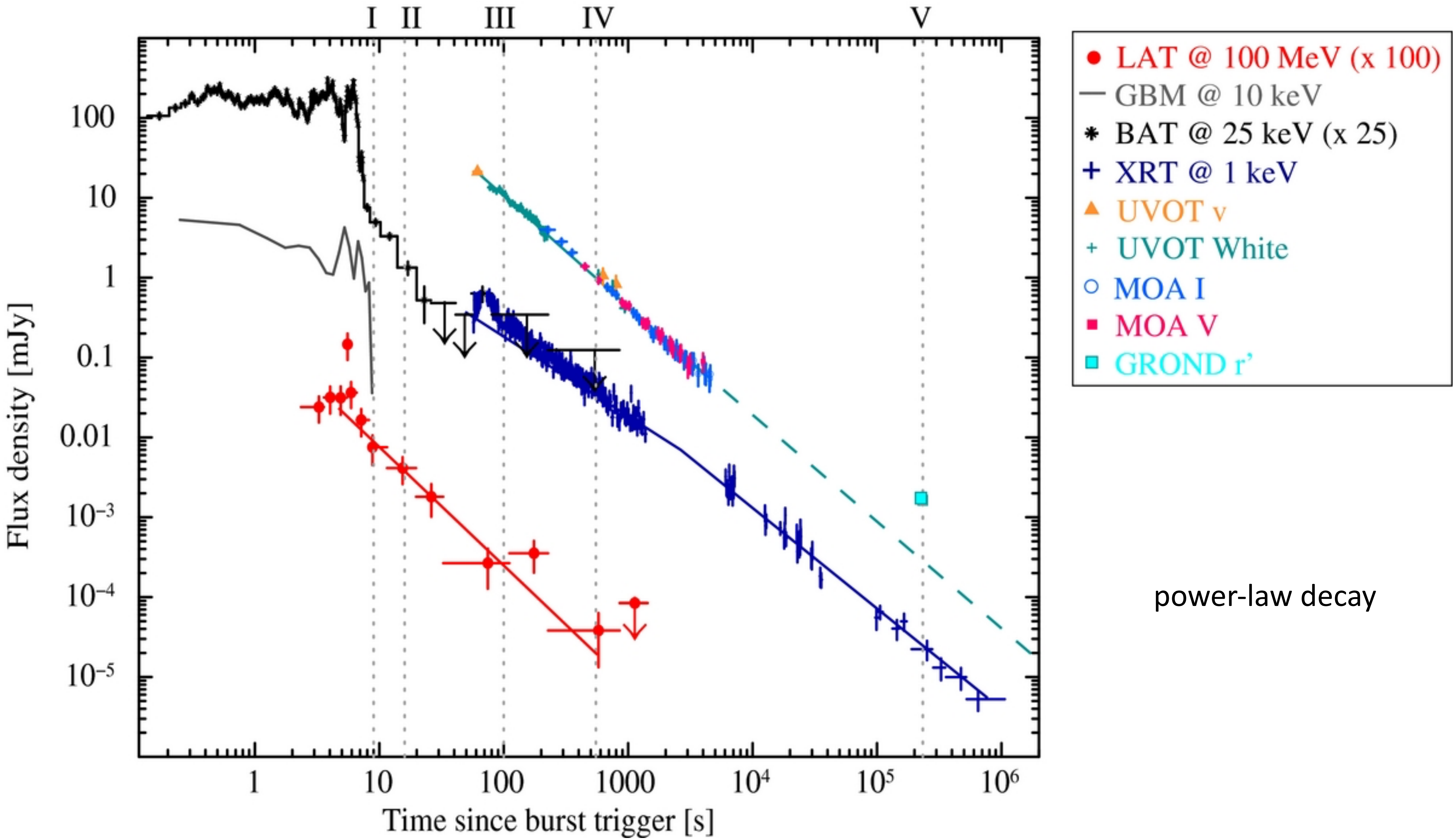
Afterglow


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



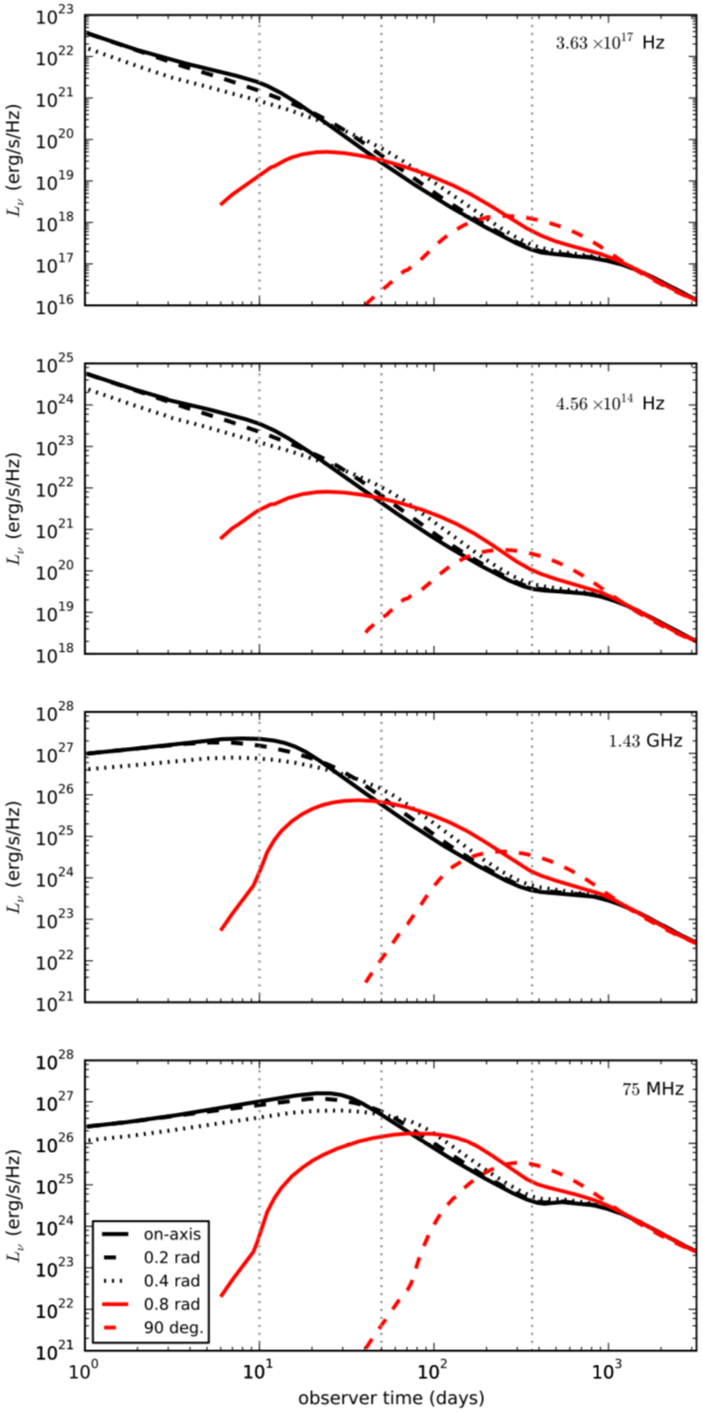
LIGO - Virgo
Fermi/GBM
INTEGRAL/SPI-ACS
frequency (Hz)
counts/s (arb. scale)
t-t_c (s)
normalized F_λ
wavelength (nm)
SALT
ESO-NTT
SOAR
ESO-VLT
7000°
4000°
GW
LIGO, Virgo
γ-ray
Fermi, INTEGRAL, Astrosat, IPN, Insight-HXMT, Swift, AGILE, CALET, H.E.S.S., HAWC, Konus-Wind
X-ray
Swift, MAXI/GSC, NuSTAR, 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
t-t_c (days)
1M2H Swope 10.86h i
DLT40 11.08h h
MASTER 11.31h W
DECam 11.40h iz
VISTA 11.24h YJK_s
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



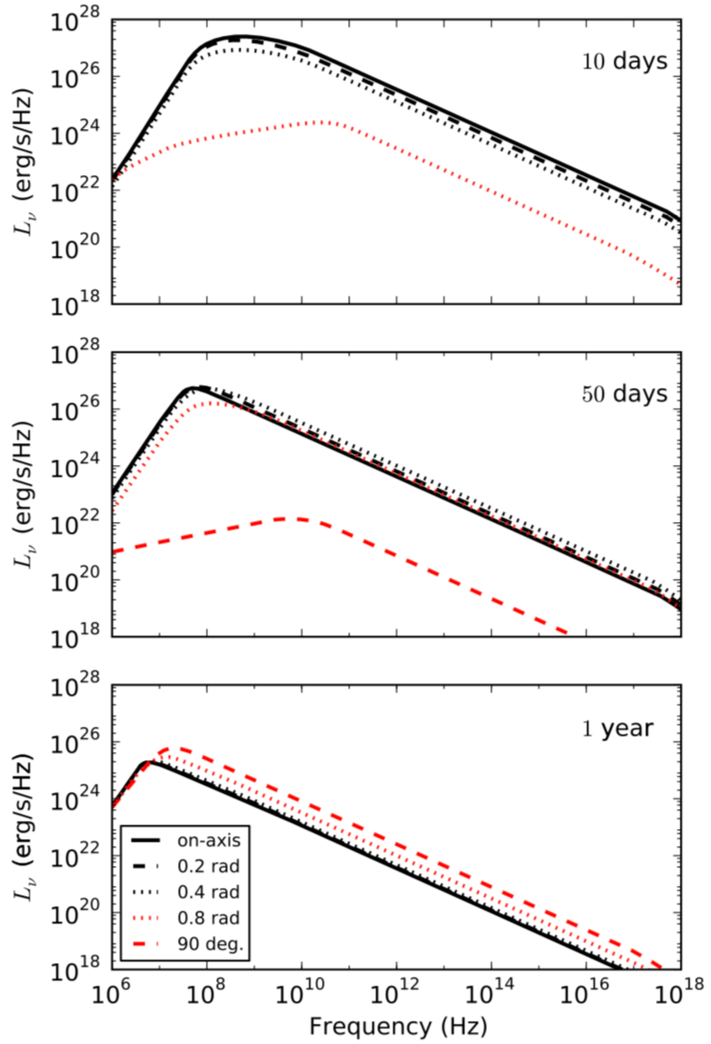


Figure 2. Spectra for $E_j = 10^{48}$ erg, $\theta_j = 0.2$ rad, and $n = 10^{-3}$ cm^{-3} at $t_{obs} = 10$ days, 50 days, and 1 yr (top to bottom plot), for various observer angles. The legend applies to all plots.

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