Gamma-ray bursts

Fermi Summer school 2023

Peter Veres
(University of Alabama in Huntsville)

New & exciting developments

- GW counterparts (2017)
- Magnetar Giant Flares
- BOAT - GRB 221009A
- Long GRBs from compact mergers
- LIGO-Virgo-KAGRA (LVK) GW observing run 4 (O4) start, LEAP & MoonBEAM instruments

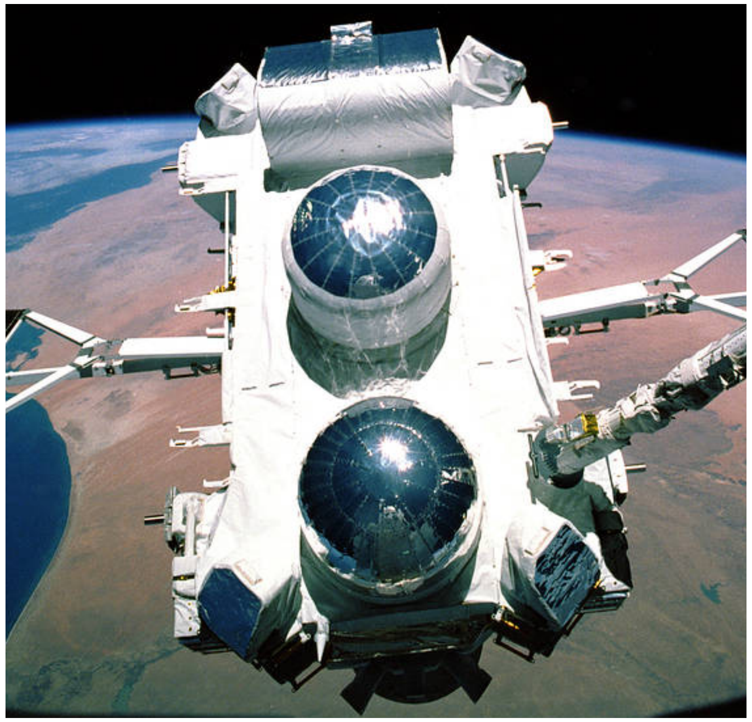
Gamma-ray bursts

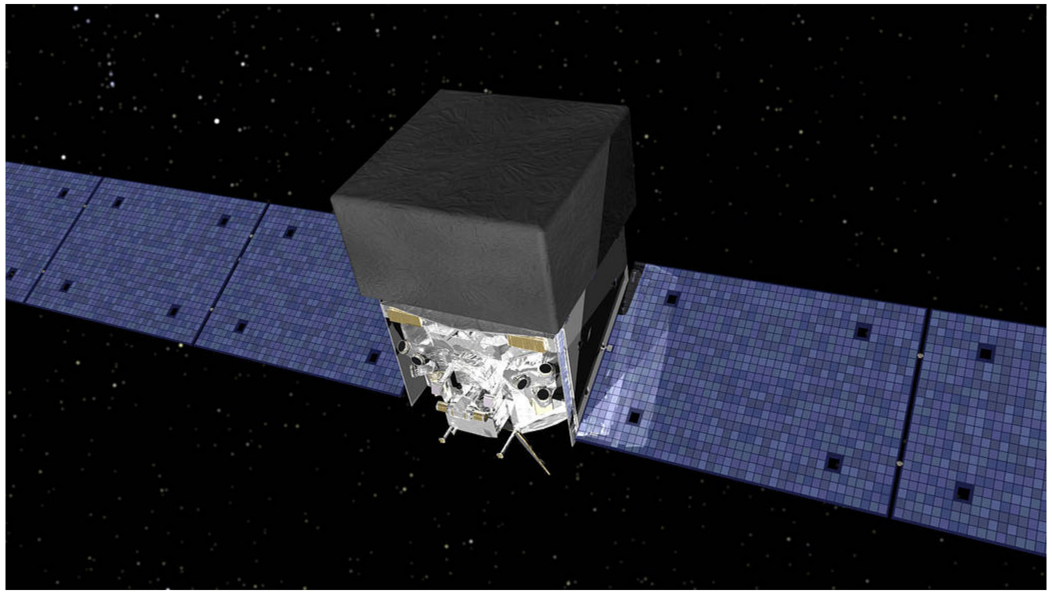
- History: from 1967, published in 1973 (https://www.nasa.gov/feature/goddard/2023/nasa-looks-back-at-50-years-of-gamma-ray-burst-science)

- Naming convention GRB YYMMDDA, e.g. GRB 190114C, GRB170817A

- Spacecraft: Swift (BAT), Fermi (GBM), Konus-WIND, Glowbug, GRBalpha, GECAM, etc.

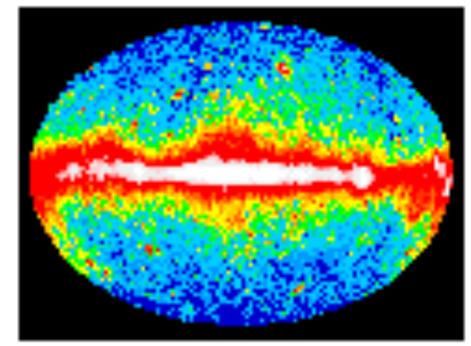
- Sign up to receive GCNs

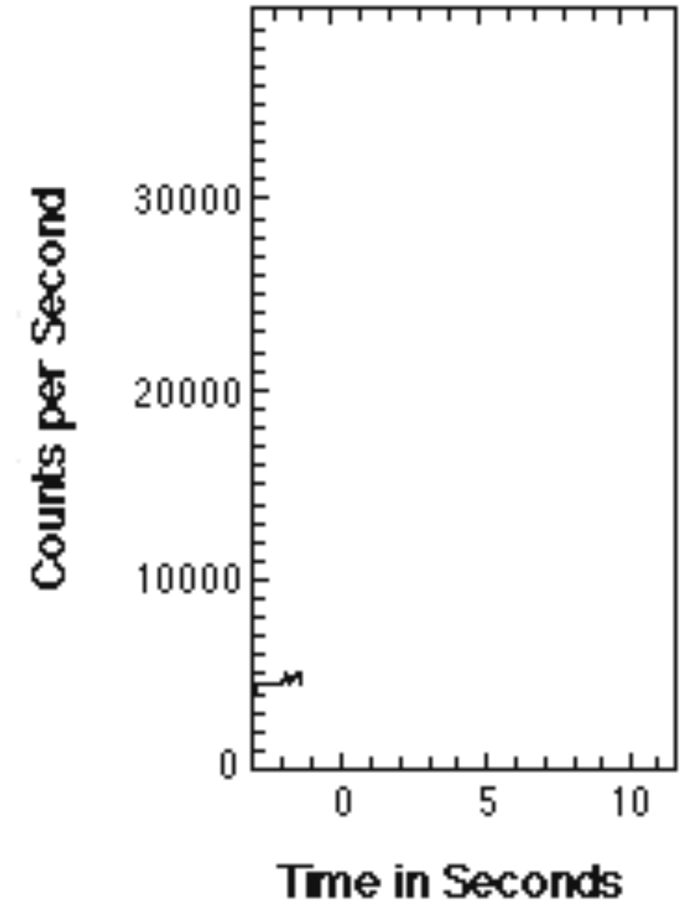




GRB observations (1.)

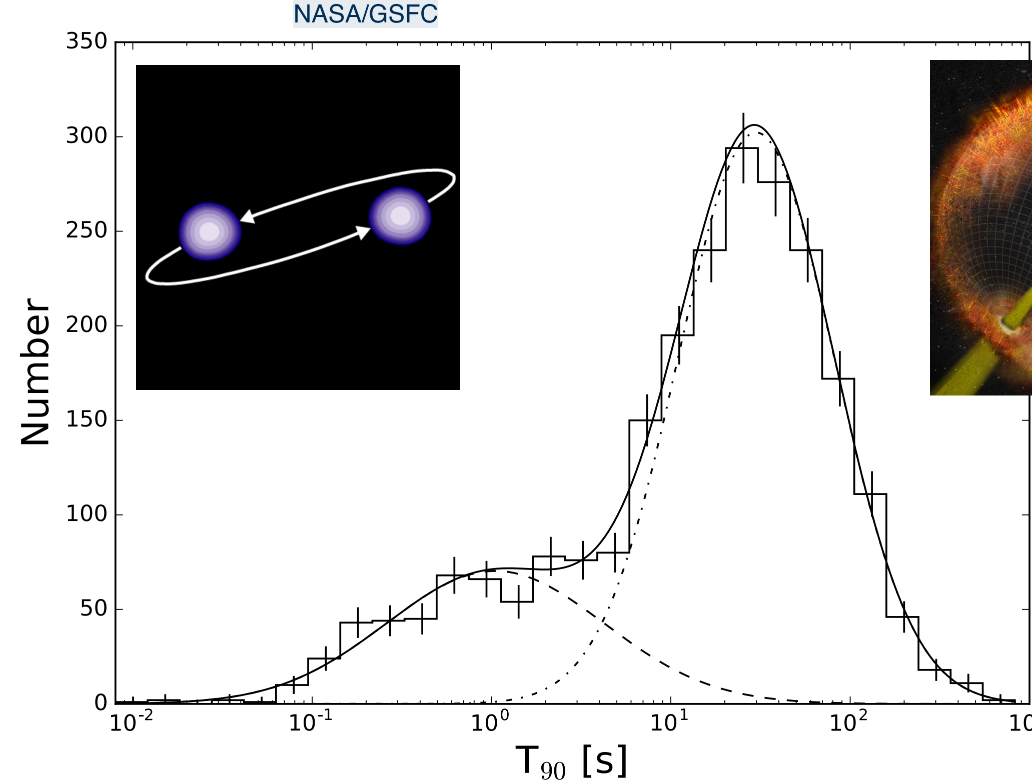
- Lightcurves
  - Highly variable, unique
- Two classes:
  - short ($\lesssim 2$ s)
  - long ($\gtrsim 2$ s)
  - (division closer to 4-5 s in GBM; 2 s historical)

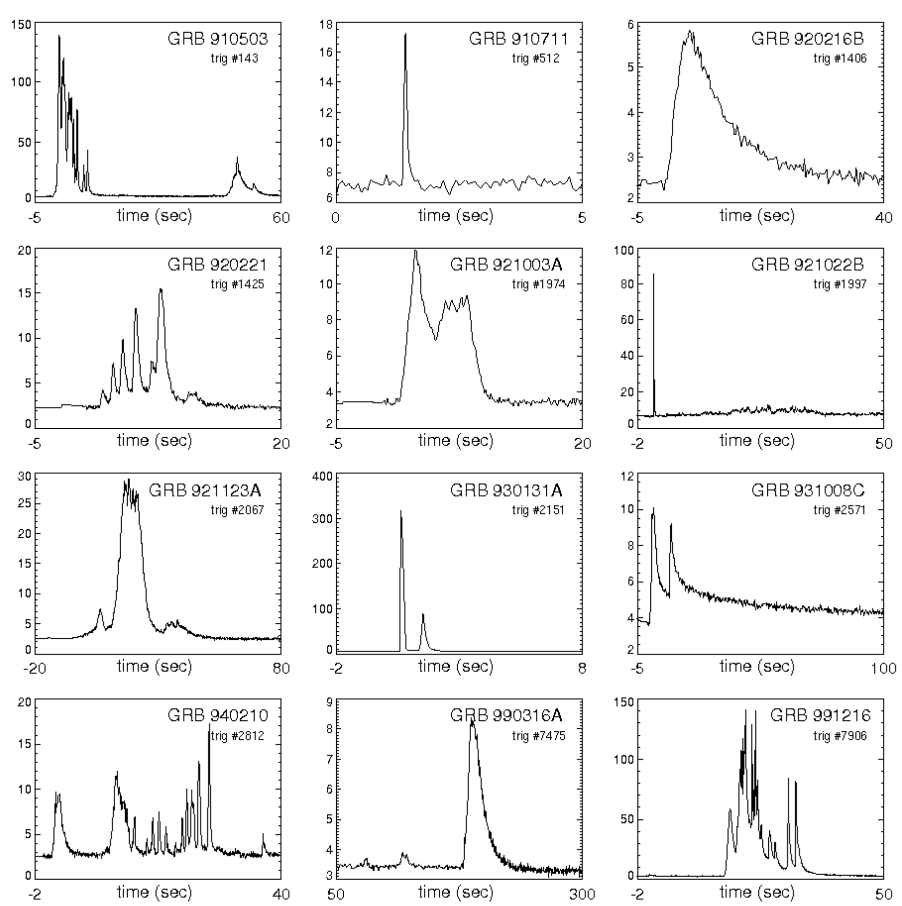




Credit: PJT Leonard NASA/GSFC

Credit: Bill Saxton, NRAO/AUI/NSF

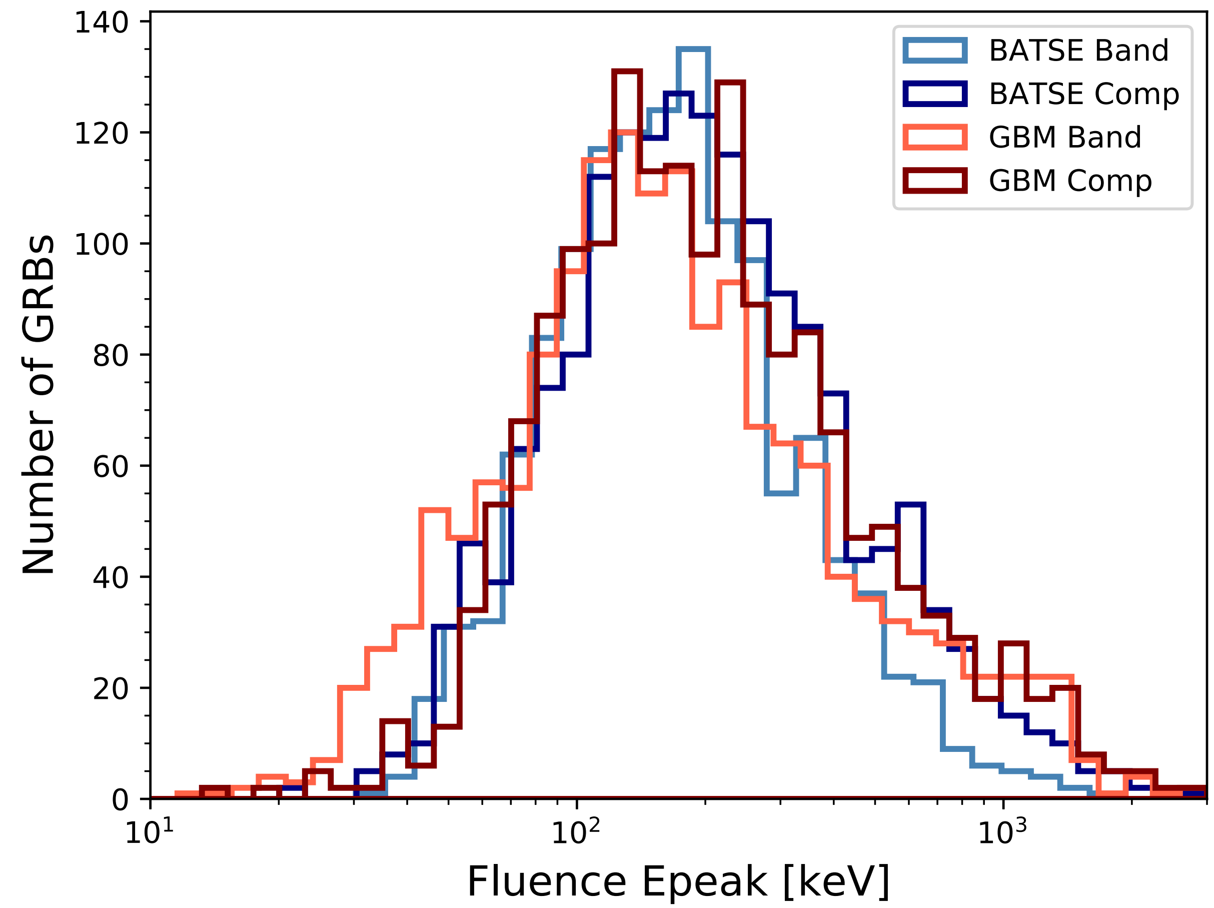




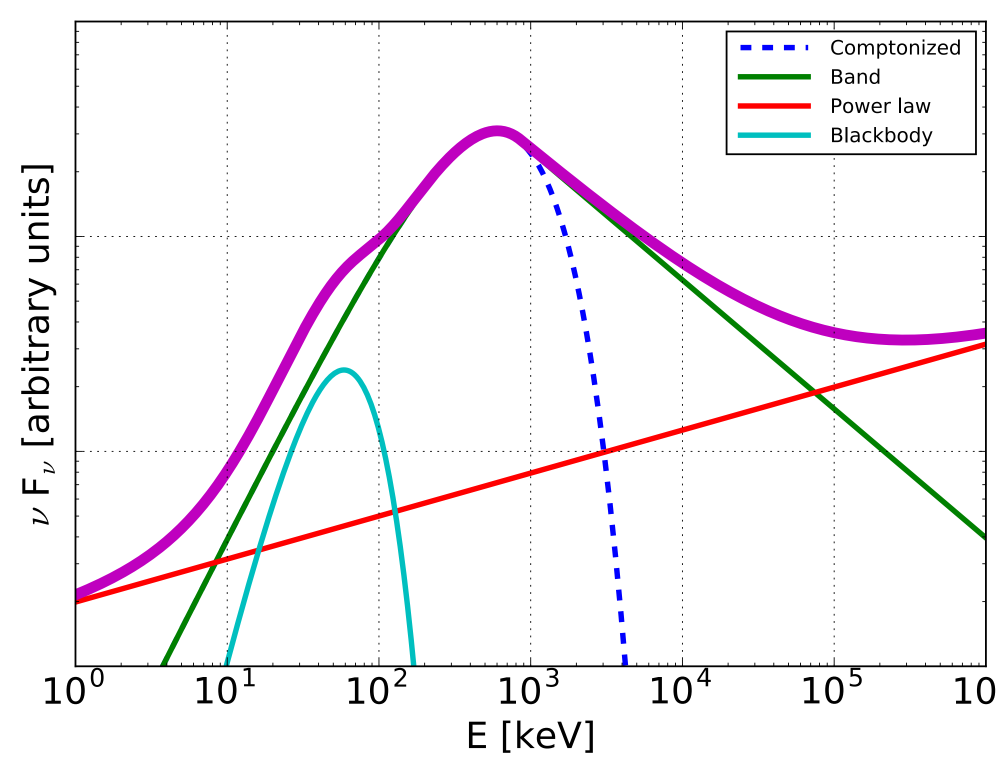
von Kienlin, …, **Veres** et al. ApJ 2020

GRB observations (2.)

- Spectrum
  - Smoothly connected power laws ; Band function- **non-thermal**
  - Peak energy E_{peak} clusters around 200 keV
  - Less variation than the lightcurve
  - Sometimes: blackbody
  - Additional power law component

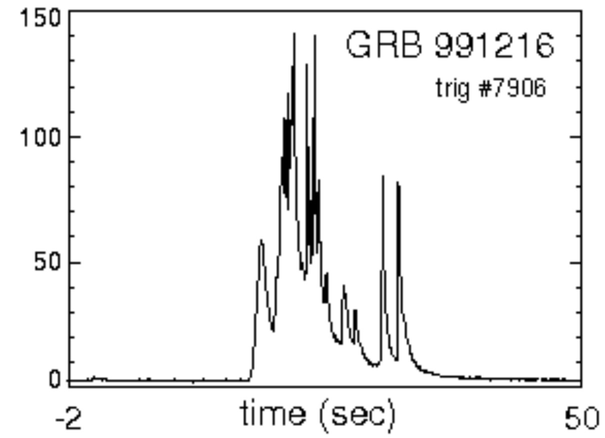


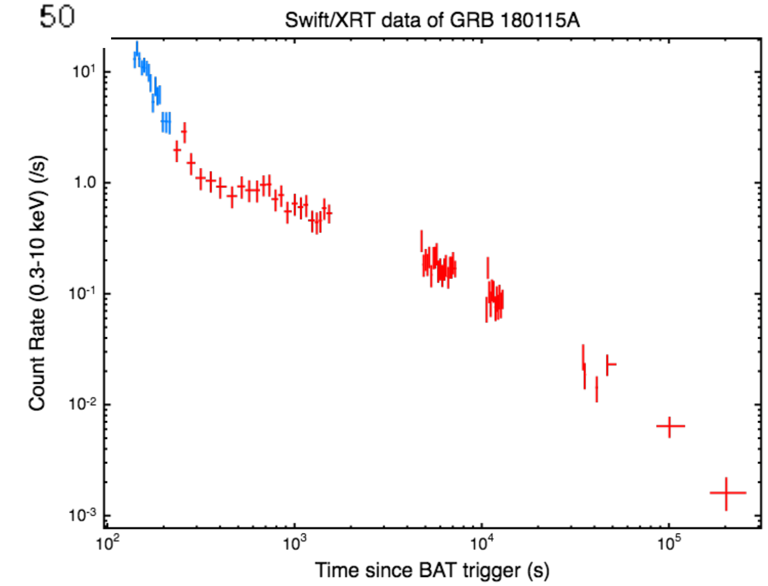
Poolakkil et al., ApJ 2021

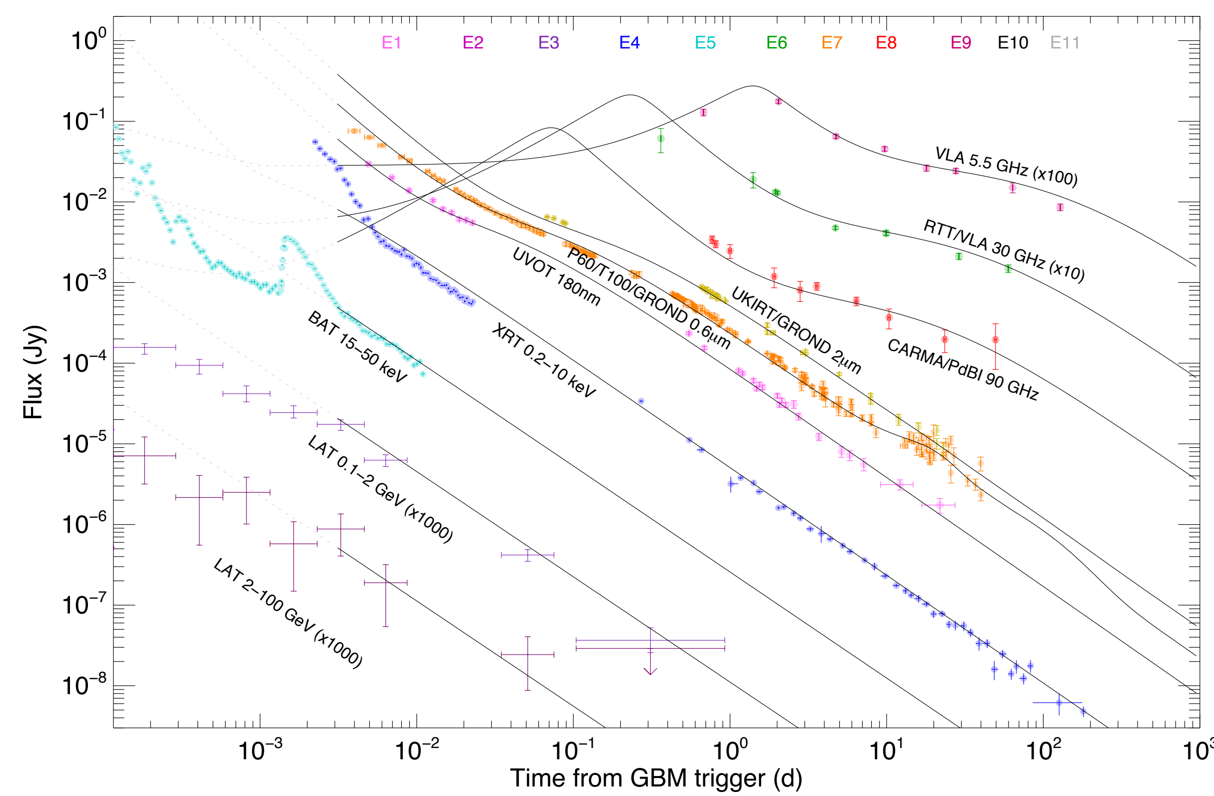


Observations (3.)

- Two phases:
  - Prompt (most of the energy), gamma-rays
  - Afterglow (~10% of energy), radio (GHz) to TeV gamma-rays.
- Distance:
  - z~0.01 to z~9
- Gamma-ray energy comparable to $M_{\odot}c^2$ or $\approx 2 \times 10^{54}$ erg
- Jetted outflow
  - $\sim 10°$ pointing towards us
  - reduce reqs. by $\Omega/4\pi \approx 1/100$



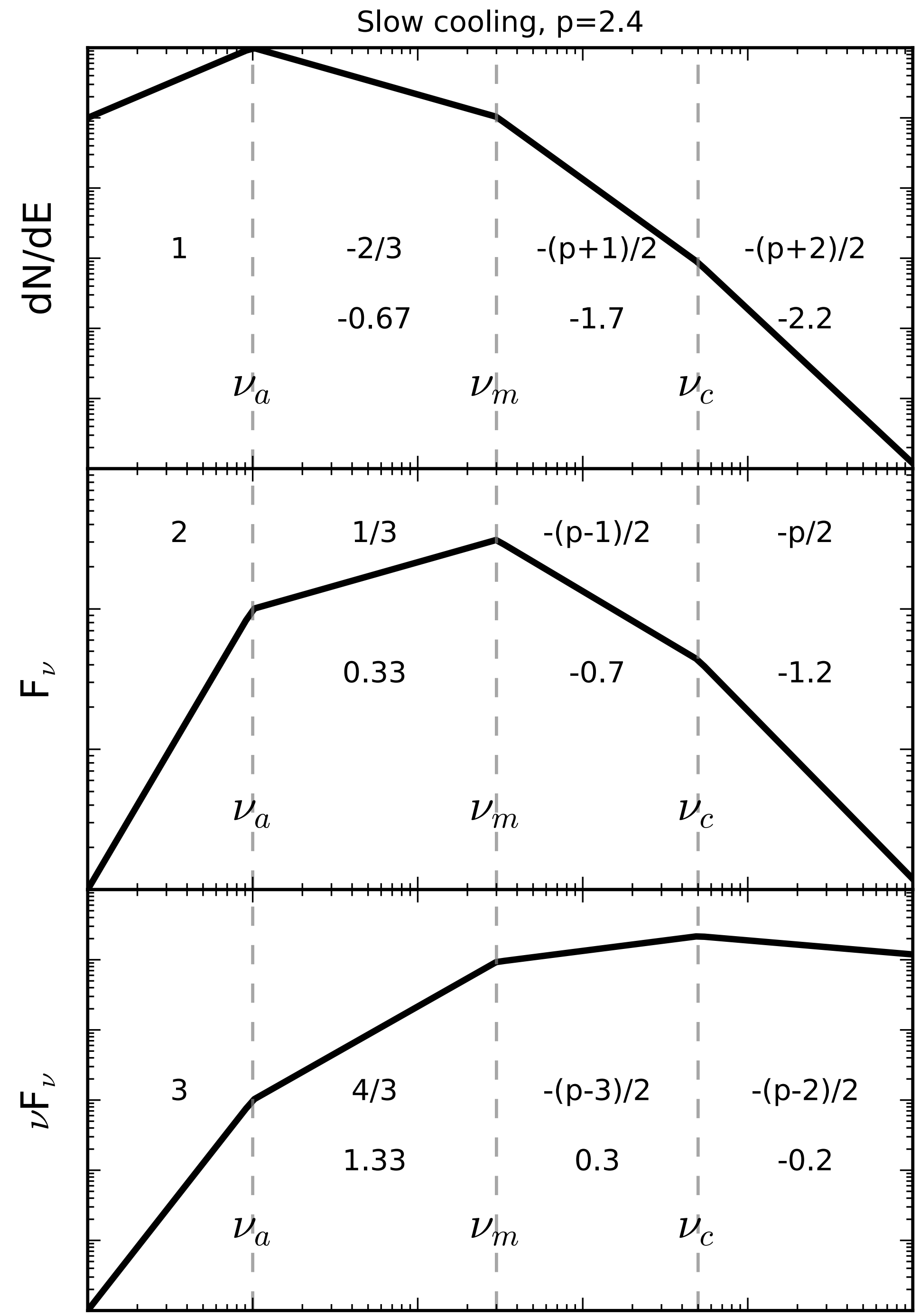




Perley et al 2014 ApJ

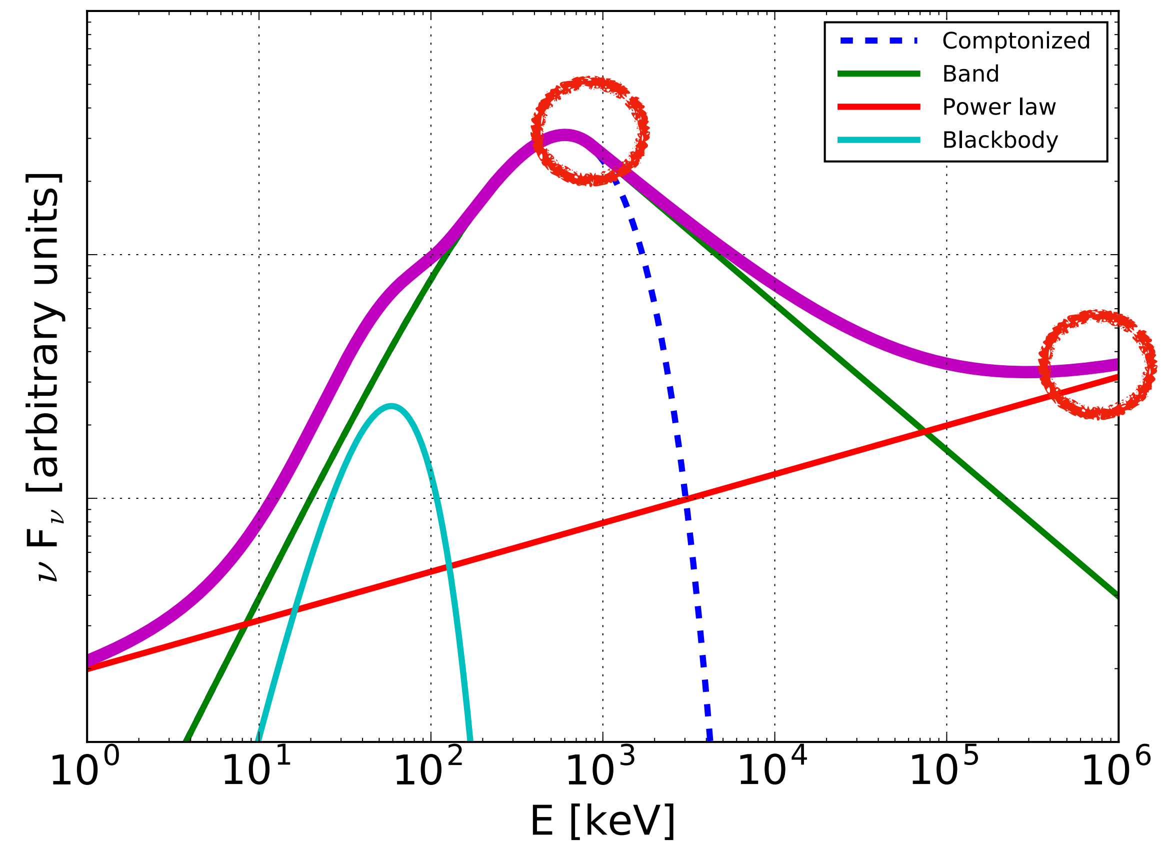
Convention

- power laws (x^{α}) are everywhere. Sometimes they are confusing, especially when it comes to spectra
- photon spectrum: some notations $N_E(E)$, $\frac{dN}{dE}$ etc.
    - units: $\mathrm{photons\ cm^{-2}\ s^{-1}\ keV^{-1}}$
    - gamma-ray indices are reported in this representation.
    - Band function, typical $\alpha = -1.2$, $\beta = -2.2$, $N_E = A(E/E_{\mathrm{pivot}})^{\alpha}$
- flux density: F_ν
    - units $\mathrm{erg\ cm^{-2}\ s^{-1}\ Hz^{-1}}$, Jansky
    - Common in most of astro, afterglow measurements reported using this notation: $F_\nu \propto t^{\alpha}\nu^{\beta}$
    - all indices negative, sometimes the convention is $F_\nu \propto t^{-\alpha}\nu^{-\beta}$
- energy spectrum: νF_ν
    - $\mathrm{erg\ cm^{-2}\ s^{-1}}$
    - energy-per-decade: its peak tells you at what frequency is most of the energy emitted



GRB basics: Relativistic speeds

- Scaling notation easy to see how parameters change with different choice of input: $Q_x = Q/10^x$
- Flux=10^{-7} erg cm^{-2} s^{-1} (typically: 10-1000 keV range, brightest in 50-300 keV); Duration $< T_{90} > = 20$ s
- Total energy emitted:
$$E_{\rm iso} = 4\pi D_L^2 \times {\rm Flux} \times {\rm duration}/(1+z) \approx 10^{51} \frac{D_{L,28}^2}{(1+z)/2} F_{-7}\ (T_{90}/20\ {\rm s})\ {\rm erg}$$
- Eddington luminosity $L_E = 4\pi G M m_p c/\sigma_T = 1.3 \times 10^{38}\ (M/M_\odot)\ {\rm erg\ s^{-1}} \ll L_{GRB}$ outflow.
- Observe E>1 GeV photons: in a non-relativistic scenario GeV photons quickly produce pairs and lose their energy. We shouldn't observe them. *Unless: relativistic motion.*
- Lorentz factor suppresses pair prod. threshold: $E_1' E_2'(1-\cos\theta') \approx 2E_1E_2/\Gamma^2 \lesssim 4m_ec^2$ (comoving frame): $\Gamma \gtrsim 100(E_1/{\rm MeV})(E_2/{\rm GeV})$
- Also possible using optical depth to pair production

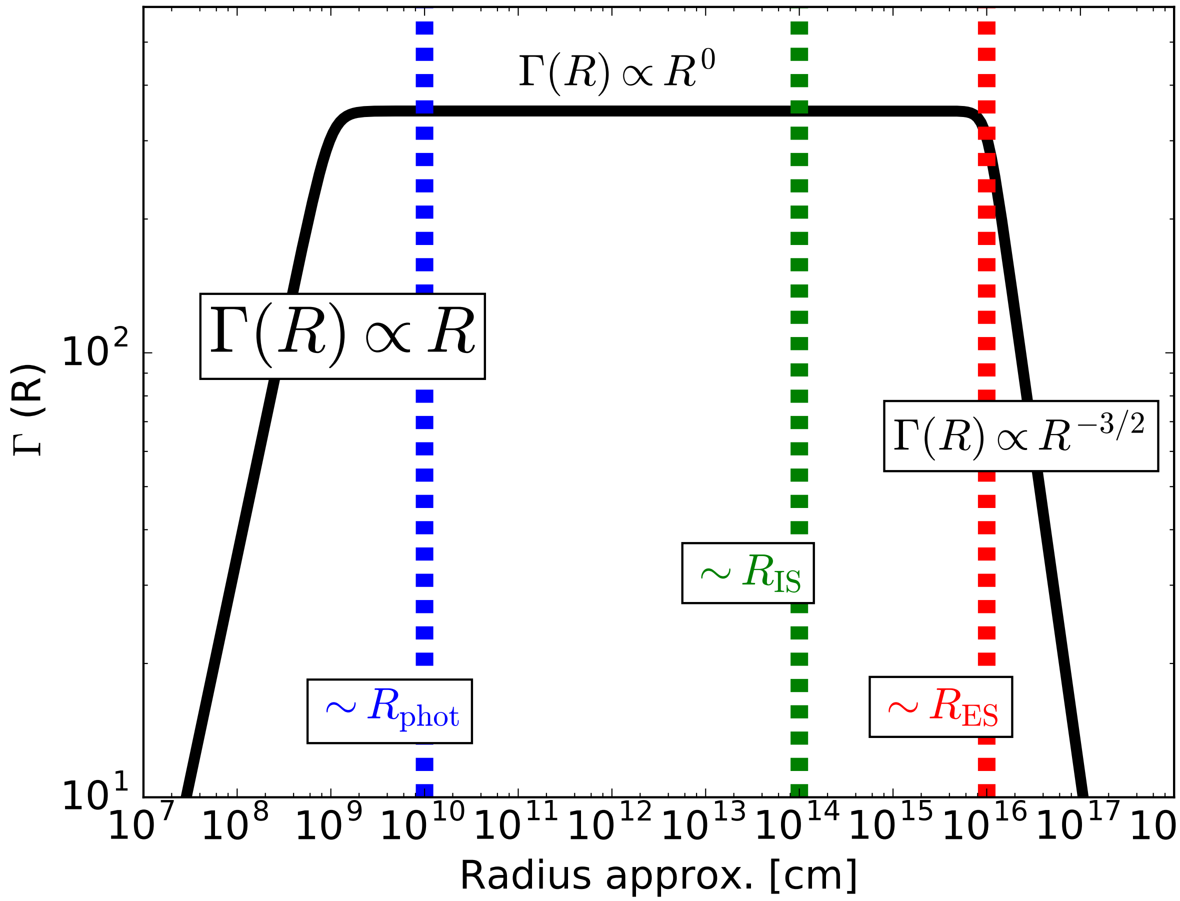


Lithwick & Sari 2001 (ApJ)

Lorentz factor evolution

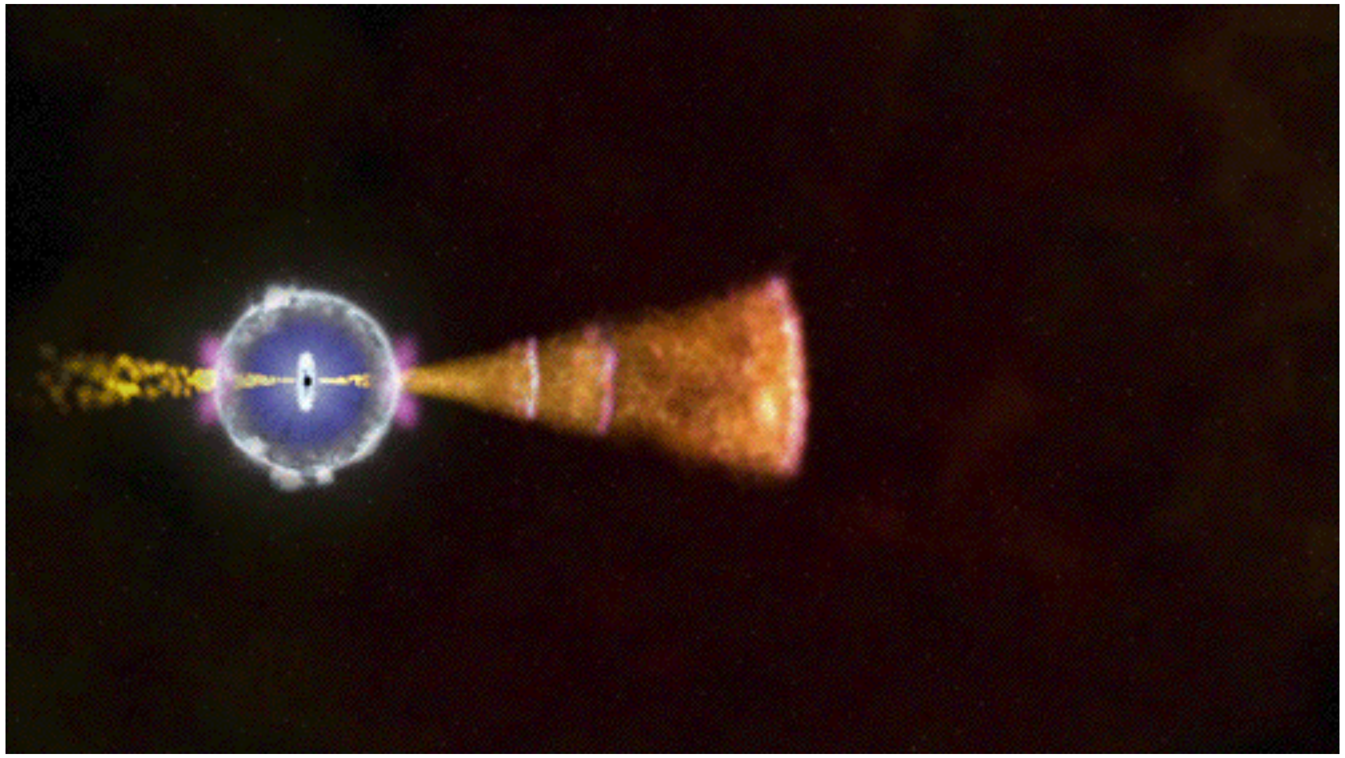
- Explosion/energy injection: $E_0 \approx 10^{52}$ erg imparted to: $M \approx 10^{-5} M_\odot \ll E_0/c^2$
- Define: $\eta = E/Mc^2$ or $\eta = L/\dot{M}c^2$
- Optical depth is large, radiation dominant, $\gamma_{ad} = 4/3$, adiabatic expansion
- Comoving temperature or random Lorentz factor per particle (γ'): $T' \propto V'^{1-\gamma_{ad}}$ but $V' \propto R^3$ it follows: $T' \propto \gamma' \propto R^{-1}$
- During expansion energy is conserved: $\gamma' \Gamma = \mathrm{const}$. Γ is bulk or jet Lorentz factor $\Gamma \propto R$;
- Starting size: R_0 smallest: ~ISCO of BH: $R_0 \approx 3R_S = 6\frac{GM}{c^2}$; $\Gamma = \frac{R}{R_0}$
- Interesting: $T_{obs} = T'\Gamma = T_0$ initial temperature at jet launch
- Acceleration at the expense of internal energy
- Saturation radius $R_s = \eta R_0$
- Above saturation radius: $\Gamma =$ constant
- Interaction with external medium:

$$R_{\rm ES} = \left(\frac{3E}{4\pi n_{\rm ext} m_p c^2 \Gamma^2}\right)^{1/3} \approx 3 \times 10^{16} \left(\frac{E_{52}}{n_{\rm ext,0}}\right)^{1/3} \Gamma_2^{-2/3}\ \mathrm{cm}$$



- Possible dissipation radii:
  - *dissipation*: energy is released, typically from kinetic/magnetic to gamma-rays
- Photosphere: $R_{\rm phot} \sim 10^{11}$ cm
- Internal shocks: $R_{\rm IS} \sim 10^{14}$ cm

Internal shocks



- Lot of variations in the lightcurve
- Idea: assume many 'shells', different Lorentz factors
- Slower one catch up
- $\Gamma_2 - \Gamma_1 = \Delta\Gamma \approx \Gamma$
- Ejection time difference: $\Delta t \approx t_{\rm var}$ (variability time)
- Radius: $R_{\rm IS} = 2\Gamma^2 c\Delta t \approx 2\Gamma^2 c t_{\rm var} = 10^{14}\ \Gamma_2^2\ t_{\rm var,-1}\ \rm cm$
- shock acceleration of electrons in compressed magnetic fields: *synchrotron* rad
- Peak energy at: $E_p(\propto \Gamma\gamma_e^2 B) = 1\ \epsilon_e^2 R_{IS,12}^{-1}\epsilon_B^{1/2}L_{52}^{1/2}\ \rm MeV$ strong dep. on variables

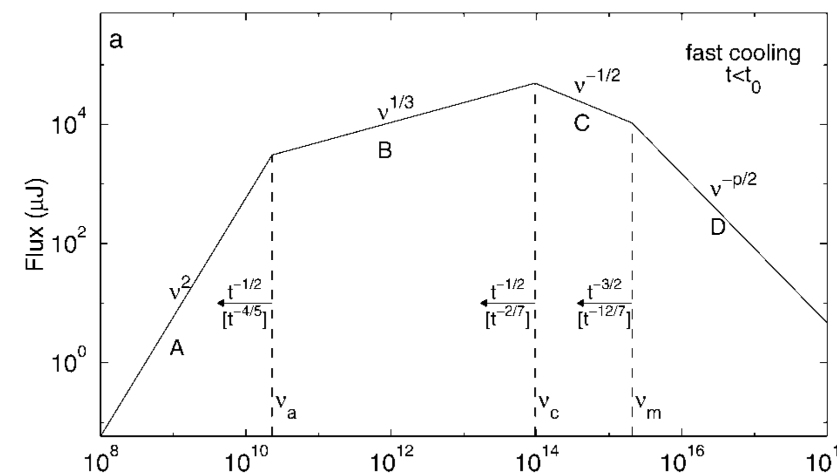
Photospheric models

- Outflow $\dot{M}$, proton number comoving (primed) density:
  $n'_p = \frac{\dot{M}}{4\pi R^2 m_p \Gamma c} = \frac{L}{4\pi R^2 m_p \Gamma \eta c^3}$, because
  $\dot{M} = L/\eta c^2 \approx 5.6 \times 10^{-5}\ L_{52}\ \eta_2^{-1}\ M_\odot s^{-1}$
- optical depth $\tau = n'_p \sigma_T \Delta R' = n'_p \sigma_T R/\Gamma$
- photosphere: $R_{phot.} = \frac{\dot{M}\sigma_T}{8\pi m_p c \Gamma^2} = \frac{L\sigma_T}{8\pi m_p c^3 \eta \Gamma^2} \approx 6 \times 10^{12}\ L_{52}\Gamma_2^{-3}\ \mathrm{cm}$
- Peak energy: temperature, from $\epsilon L = 4\pi R_0^2 a T^4$,
- $E_p \approx 10\ \epsilon_0^{1/4} L_{52}^{1/4} R_{0,6}^{1/2}\ \mathrm{MeV}$ -weak dependence on parameters

Beloborodov & Mészáros
arxiv.org/abs/1701.04523

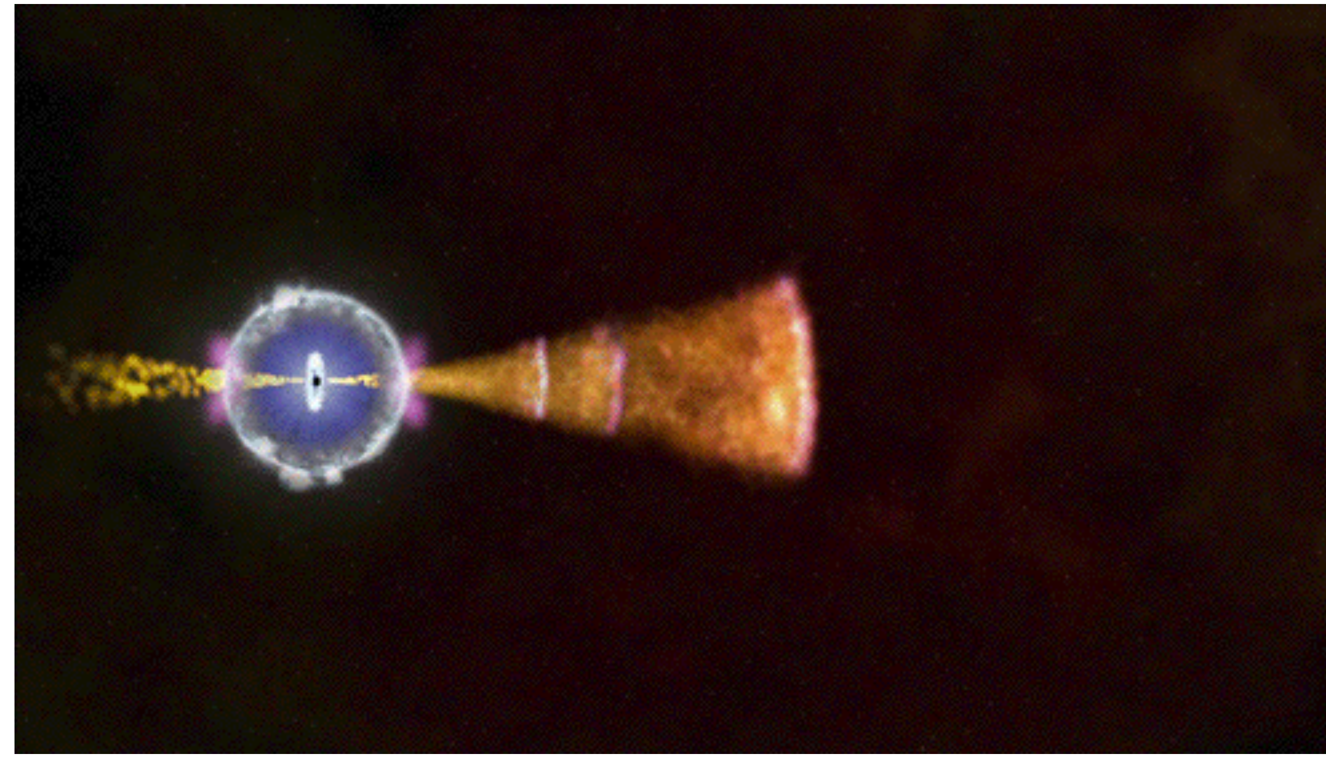
External shocks

- Most natural counterpart of an explosion - interacting with external medium - Many variants. Basic picture (Sari, Piran & Narayan 98 ApJ)
- Shocked ISM: $N(\gamma_e) = N_0(\gamma_e/\gamma_{e,m})^{-p}$; random/thermal Lorentz factor γ_e; electron distribution, power law, $p \approx 2.4$
- radiates synchrotron, 1 electron: $\nu_{\rm syn,peak}(\gamma_e) = \Gamma\gamma_e^2 \frac{q_e B}{2\pi m_e c}$. Slope:1/3 then exp. cutoff.
- superpose many electrons: $F_\nu \propto \nu^{1/3}$ then $\propto \nu^{-p/2}$, $F_{\nu,\max} = \frac{N_e P_{\nu,\max}}{4\pi D_L^2}$
- cooling, energy of electron (γ_c) that cools/looses energy on dyn. timescale ($R/\Gamma c$): insert $F_\nu \propto \nu^{-1/2}$ (fast cooling) or $\propto \nu^{-(p-1)/2}$ (slow cooling)
- Recipe for mag. field: fraction ϵ_B of total energy density ($4\pi n_{\rm ext} c^2 \Gamma^2$) in magnetic fields ($B^2/8\pi$):
  - $B = (32\pi m_p c^2 n_{\rm ext})^{1/2}\Gamma$
- Bottom line: determine $\nu_c, \nu_m, F_{\nu,\max}$; connect with power laws. Dynamics introduces time evolution



- Self-absorption freq. (radio)
- Circumstellar material can be: constant density or $\rho \propto R^{-2}$ (wind)
- Synchrotron self-Compton-shift to $\nu_{SSC} \approx \gamma_e^2 \nu_{syn}$: relevant for E~TeV energy (Sari & Esin 01 ApJ)

Rival models for prompt emission



Credit: NASA/GSFC

- **Photospheric models**
  - Gamma-rays from $\tau \approx 1$
  - PRO: explains $E_{\rm peak}$ clustering
  - CON: obs. spectrum too broad, must have dissipation below photosphere
- **Internal shocks**
  - Unsteady outflow, $\Gamma \approx 100$ collisions, $\tau \ll 1$ accelerated particles, magnetic field, synchrotron
  - PRO: explains variability, nonthermal spectrum
  - CON: low efficiency, spectral index, $E_{\rm peak}$ clustering

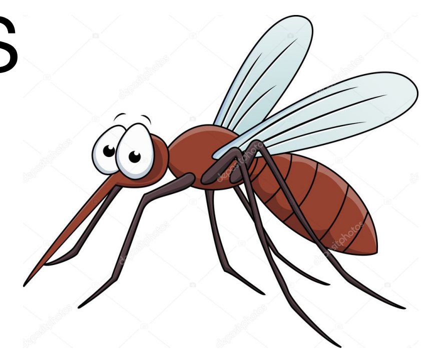
One model for the afterglow

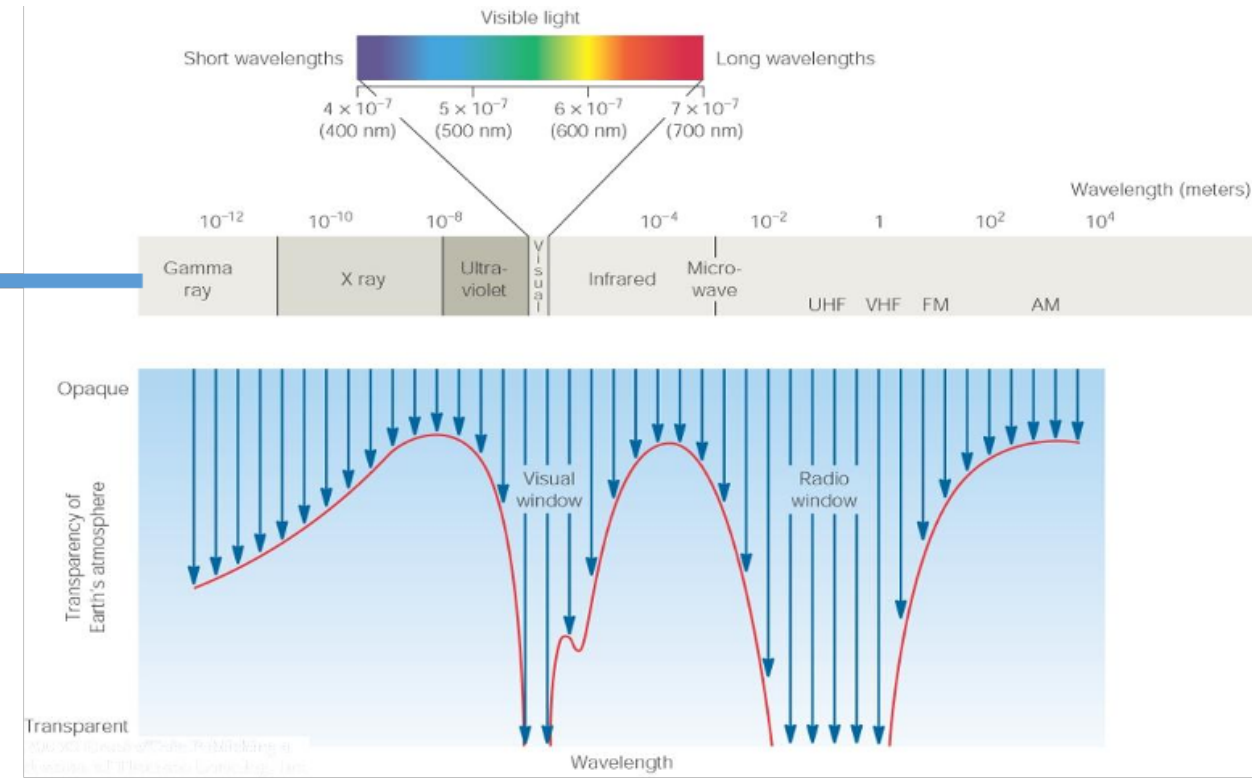
- **External shocks**
  - Jet interacts with the external medium
  - Shock accelerated electrons radiate synchrotron emission
  - Works well

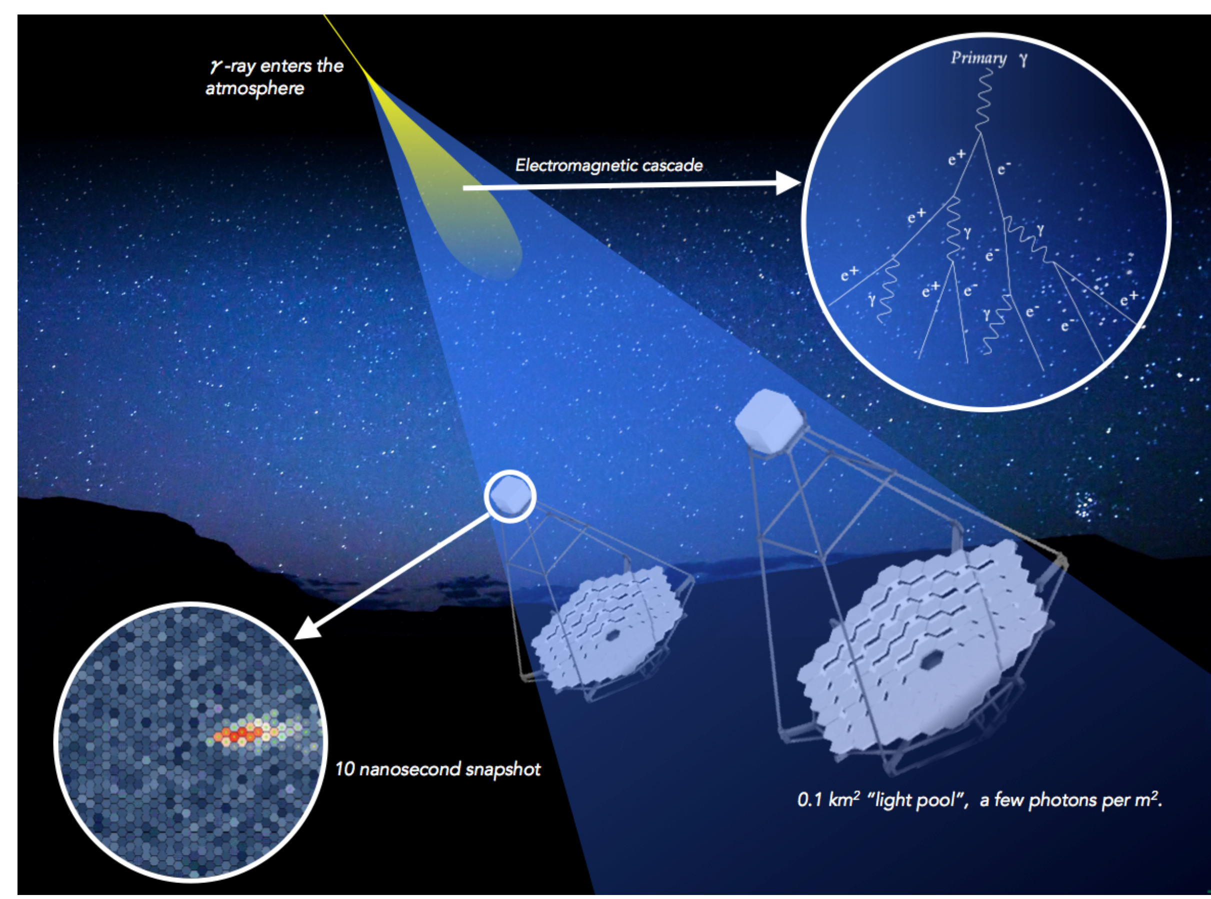
Very high energy radiation

Very high energy radiation

- E>100 GeV=0.1 TeV
- Cherenkov telescopes MAGIC, VERITAS, H.E.S.S HAWC, Cherenkov Telescope Array (CTA, future)
- The atmosphere as a detector
- Active galactic nuclei (AGN) and galactic objects
- GRB observations recently

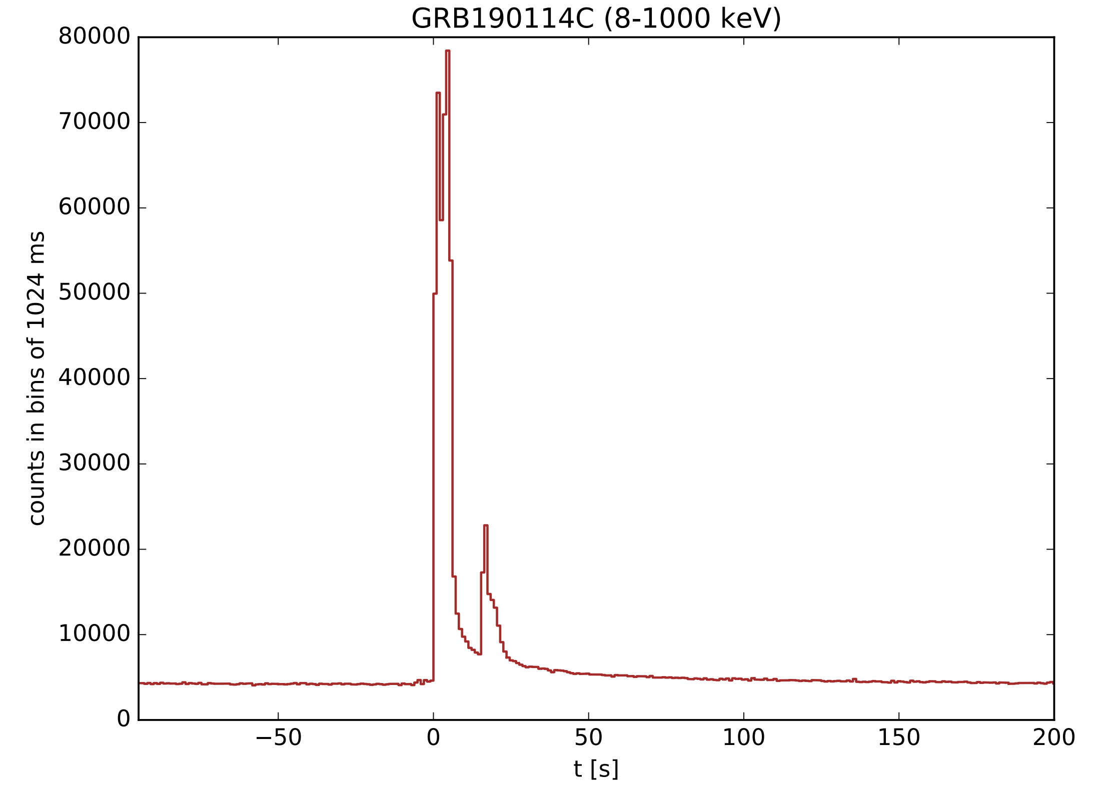


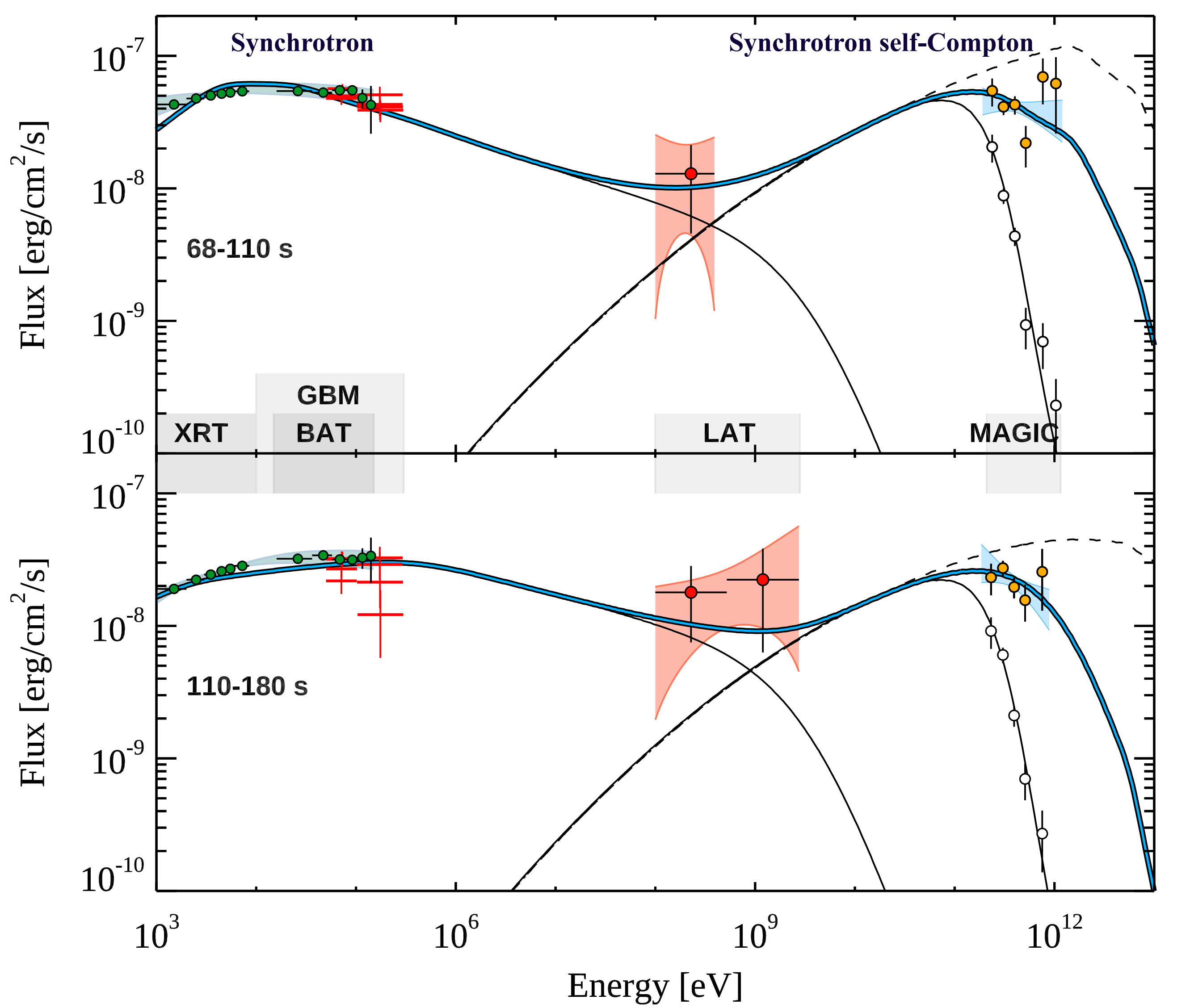




First detection

- GRB 190114C
- Monster GRB
- GBM observes the afterglow too
- Synchrotron self-Compton emission

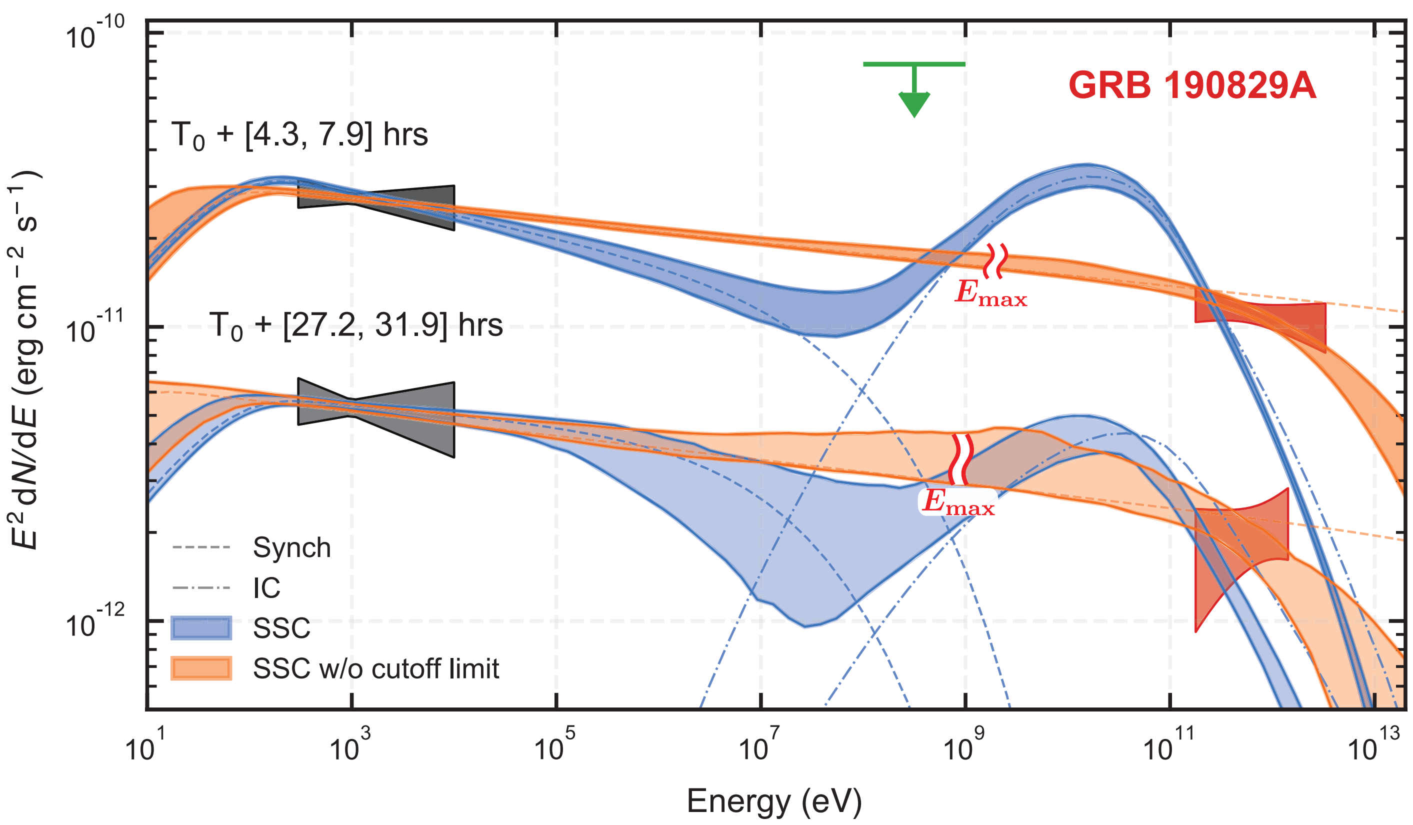




MAGIC coll., **Veres** et al., Nature 2019

Challenges for GRB models

- 3rd VHE detection was a nearby, weak GRBs: surprising
- Time evolution consistent with synchrotron
- Max. synchrotron energy requirement violated
    - $E < 50\ \Gamma$ MeV
- New ideas needed



H.E.S.S. Collab., Science, 2021

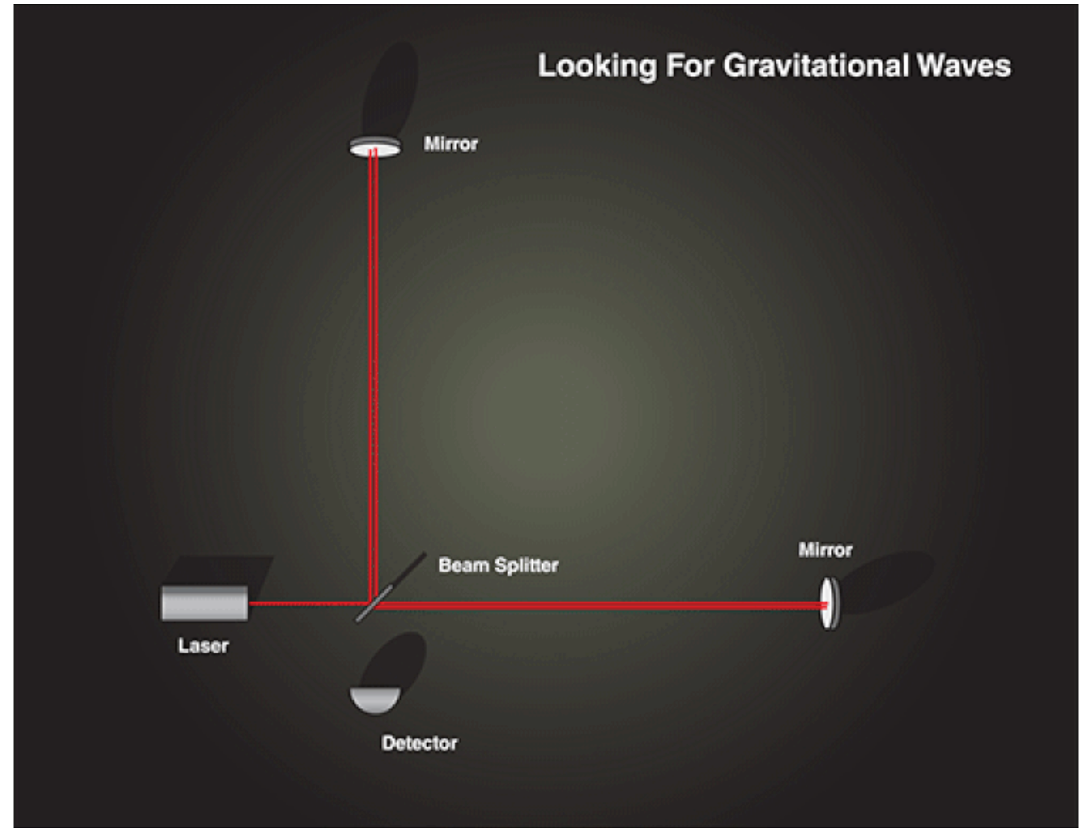
GRB 221009A

BOAT

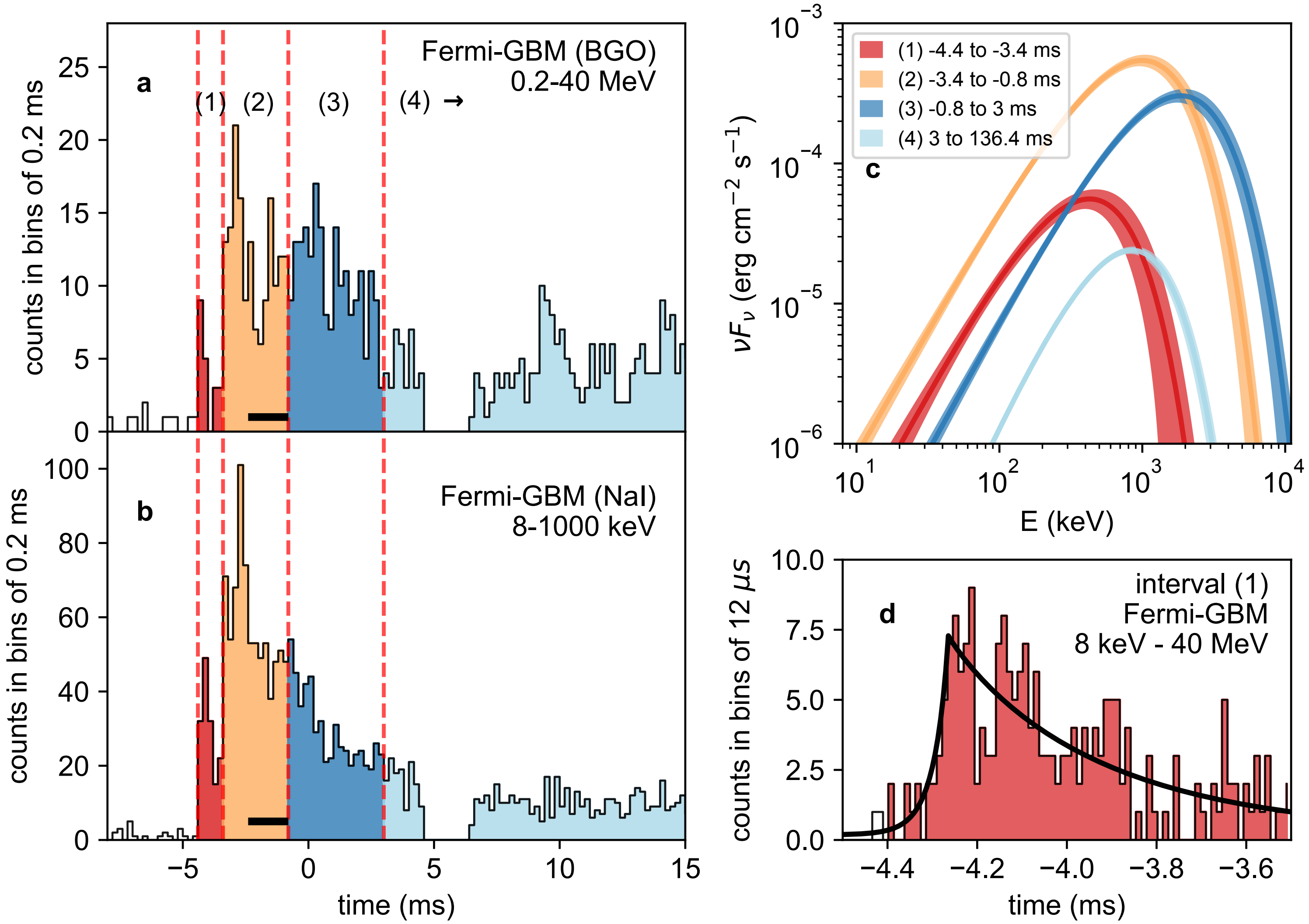
- switch to PPT.

Gravitational waves

- Ripples in space-time
- Laser Interferometers with a few km long arms
- Sensitive to changes 1 part in approx. 10^{22}
- GW direct detection: 2015 merger of two black holes
- In 2017 merger of two neutron stars **GW170817**
- **Switch to GW pres.**



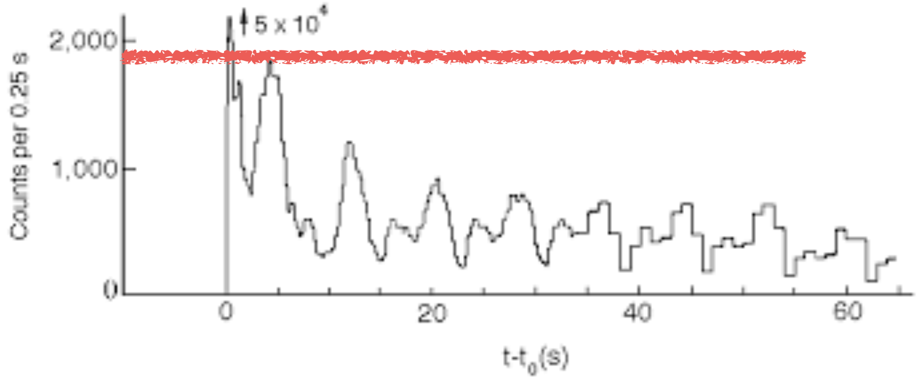
GRB 200415A - a highly magnetized neutron star masquarading as a short GRB

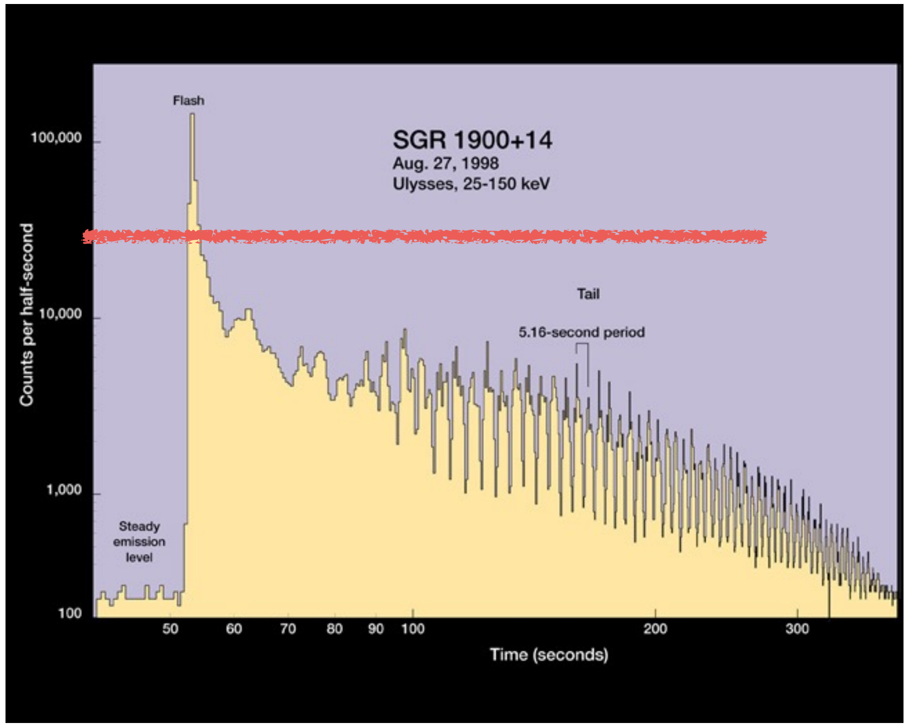


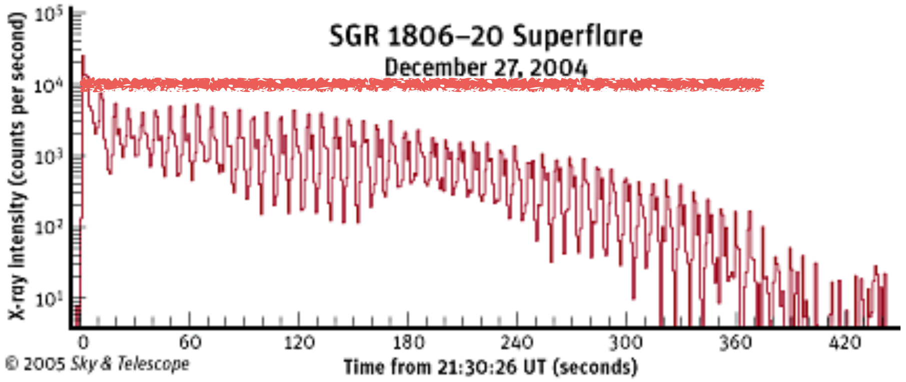
Roberts, **Veres** et al., Nature, 2021

Background

- Magnetar giant flares (MGFs)
- Hard spike + soft, modulated tail
- 3 gold plated giant flares ('79, '98, '04)
    - 2 in MW, 1 in LMC
- Long suspected: some MGFs observed as short GRBs
- If far away, $\gtrsim$1 Mpc only short spike detected
- Few sGRB-like candidates
    - locations consistent with nearby galaxies

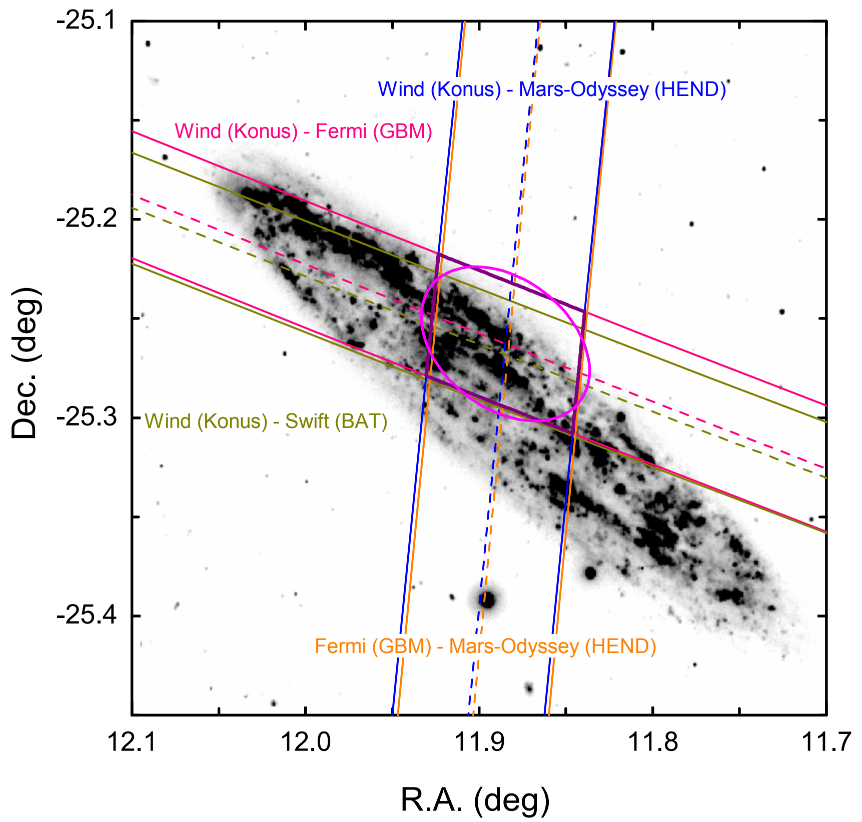




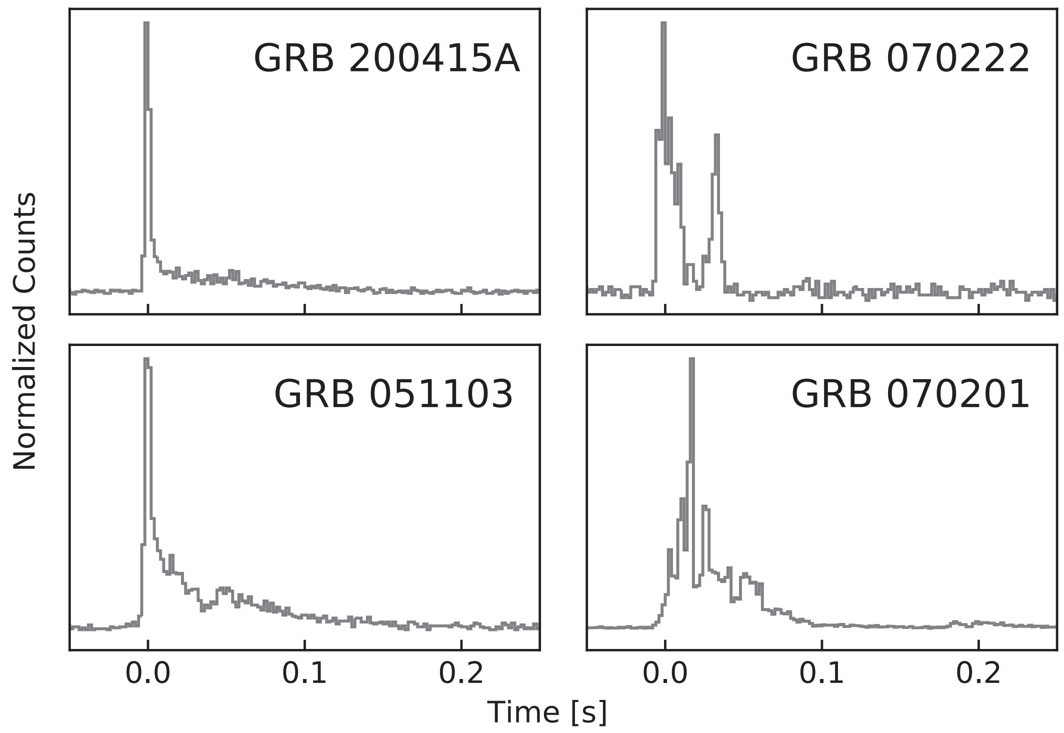


Other work on GRB 200415A

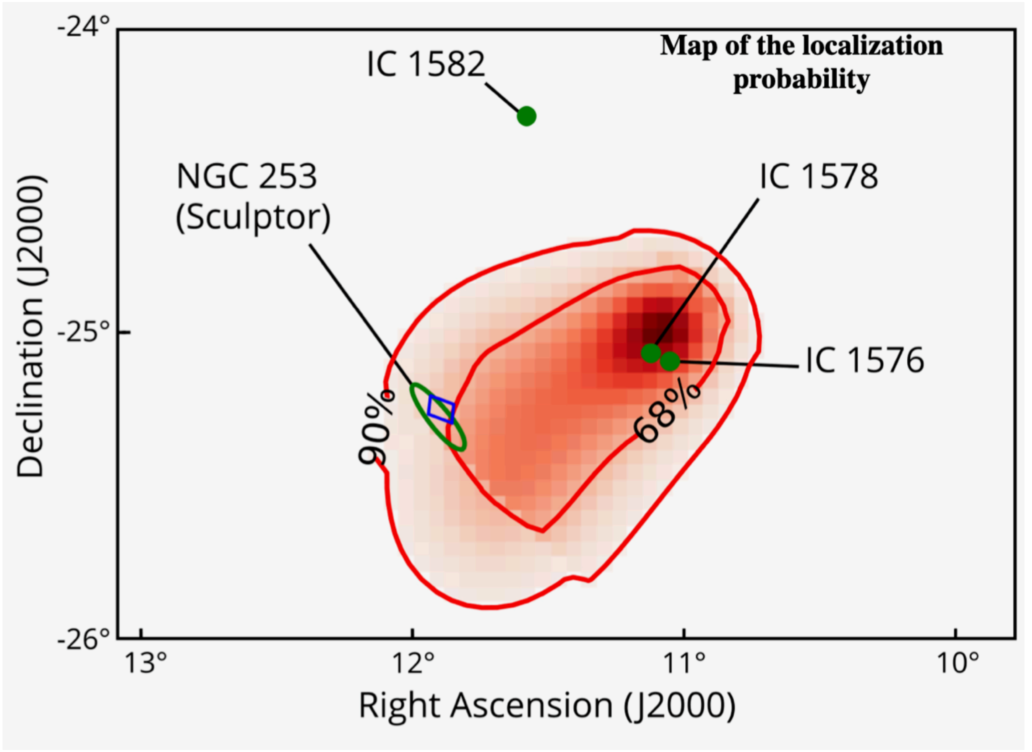
- Konus-WIND - localization - Sculptor galaxy at 3.5 Mpc
- Fermi-LAT - first detection in GeV
- Statistical characterization + new MGF candidates
- Conclusion: **GRB 200415A is an MGF**



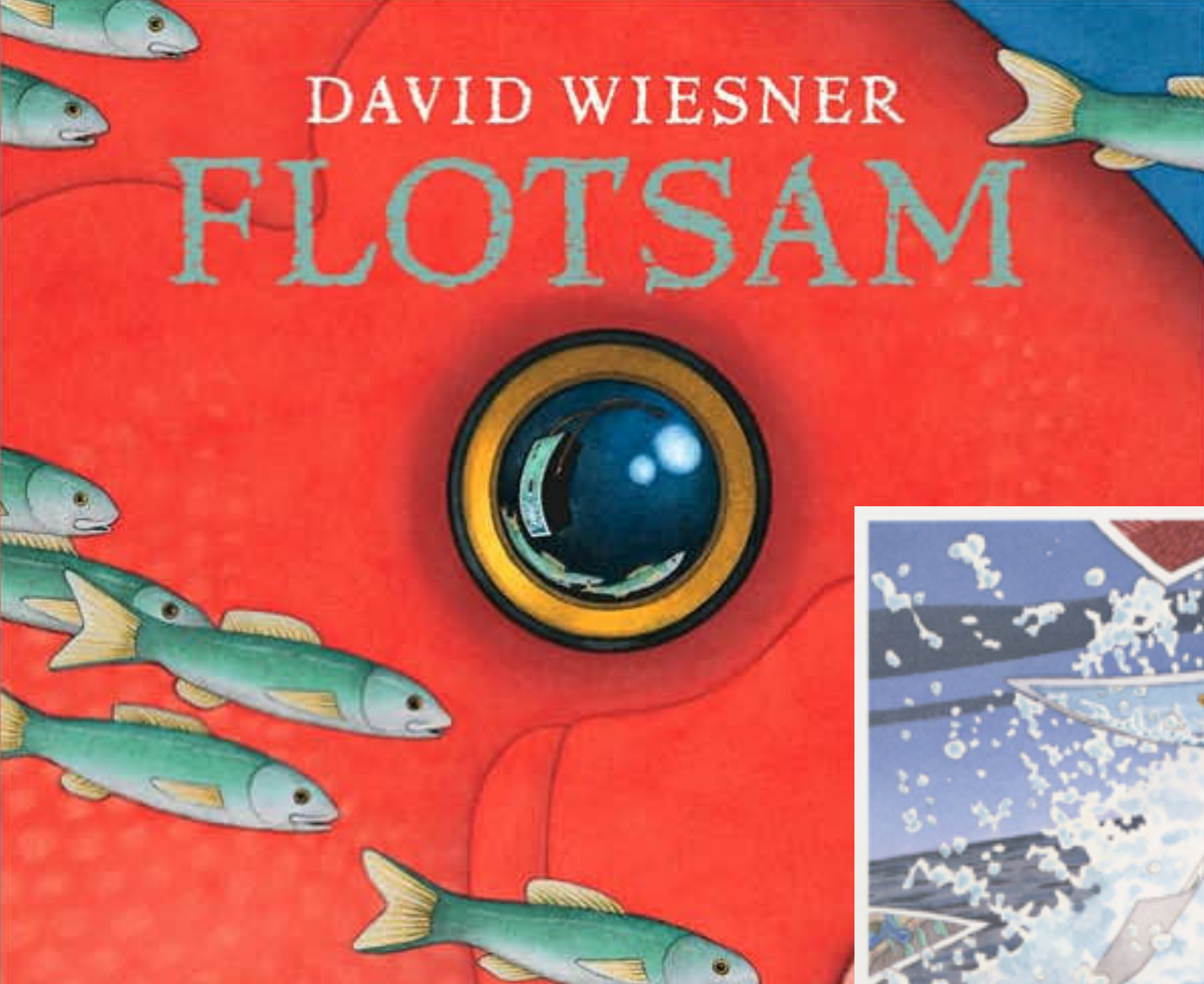
IPN triangulation, Svinkin+21



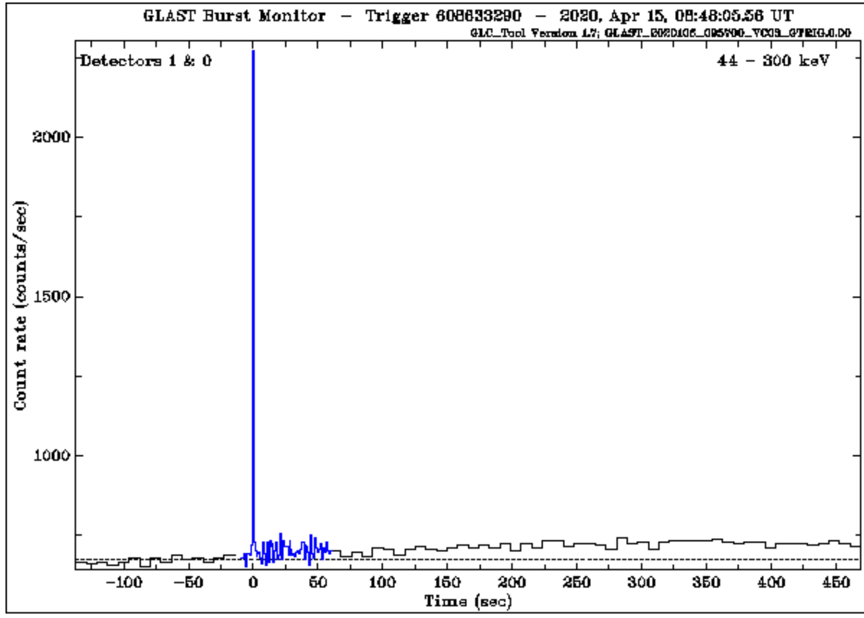
new archival MGF/GRB events, Burns+21



LAT photons from 200415A, Ajello+21

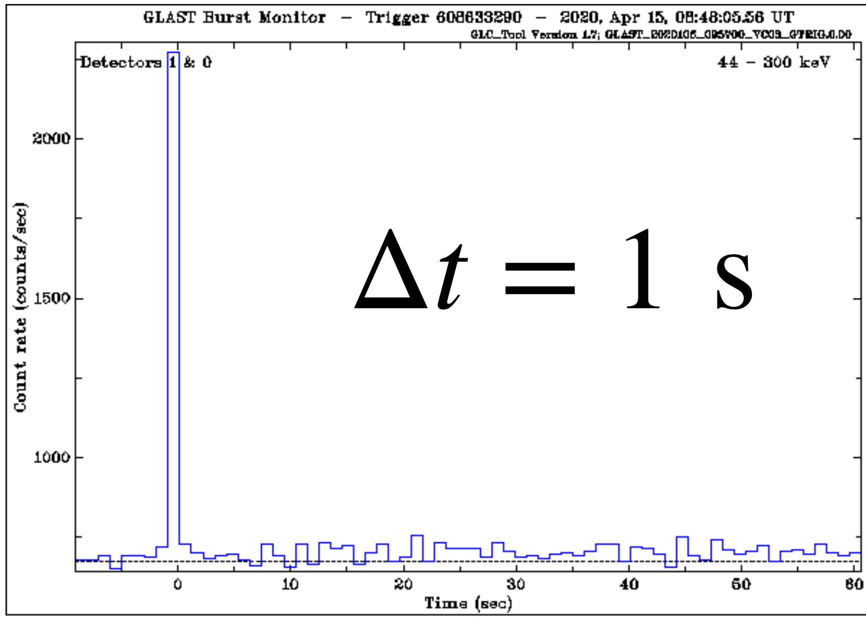

DAVID WIESNER
FLOTSAM

GRB 200415A

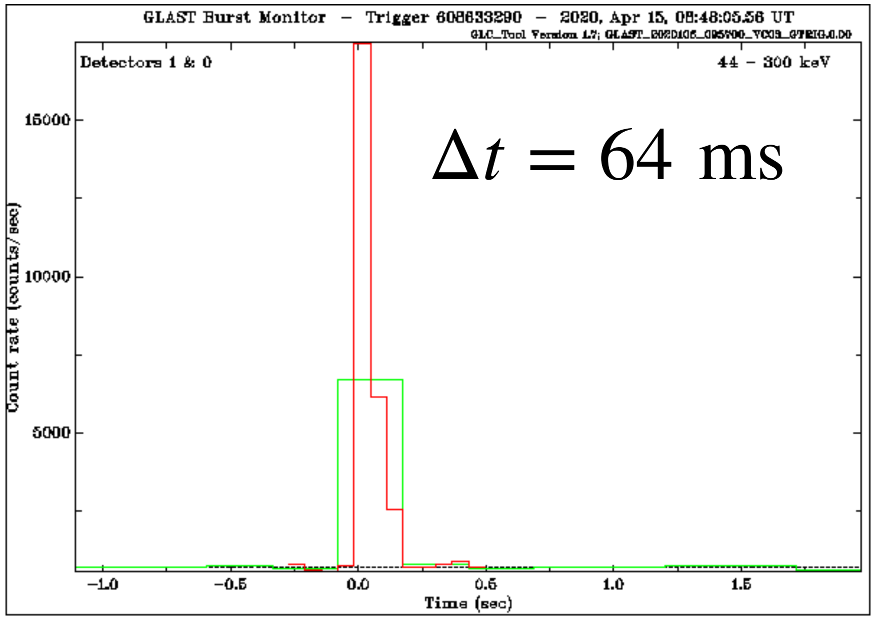


- Triggered Fermi-GBM at 08:48:05 UTC

- First impression: very short, very bright



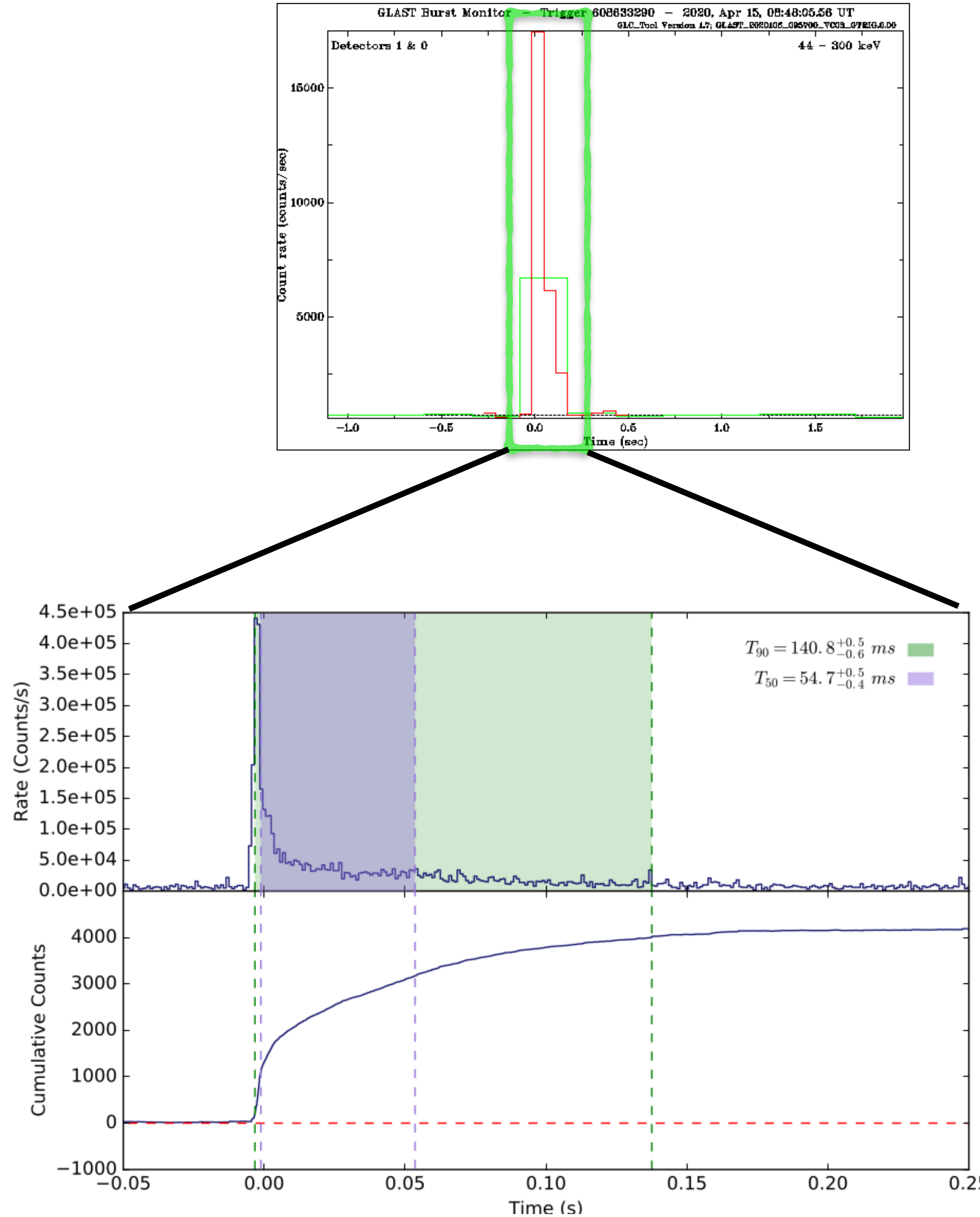
- Analyzed in context of short GRBs:
  - Peak flux: 74 photons cm^{-2} s^{-1} **[98th percentile]**
  - Photon index, α: 0.4 **[89th percentile]**
  - Peak energy, $E_{peak} \approx$1 MeV **[79th percentile]**
    $dN/dE \propto E^{\alpha} \exp(-E(\alpha+2)/E_{\rm peak})$



- Hints at non-GRB origin

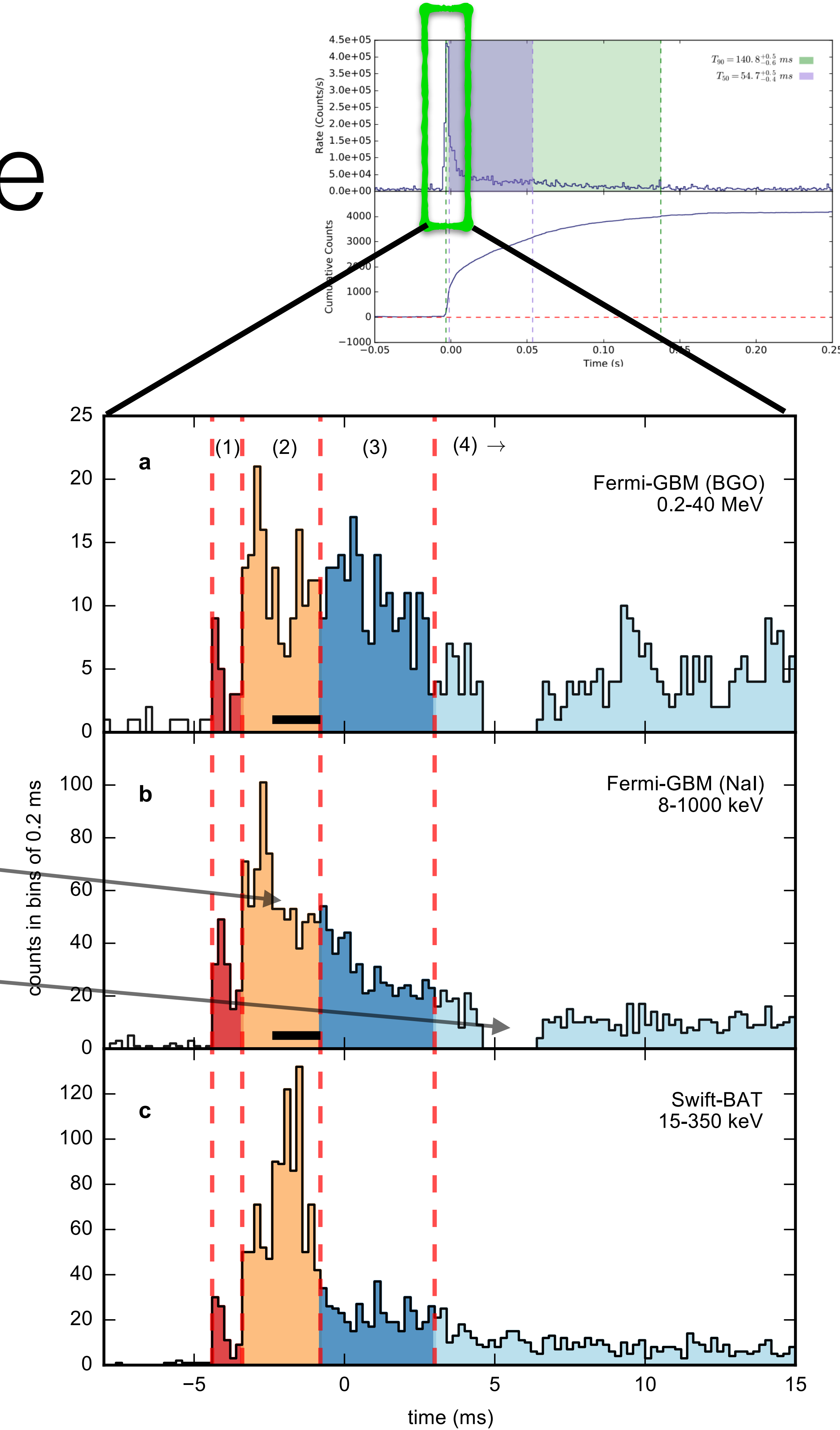
GRB 200415A

- T_{90} =140.8 ms (Swift)
- Swift-BAT-GUANO - no saturation
- No pulsations - but 10^{44} erg @3.5 Mpc (Sculptor) is below GBM sensitivity
- No radio detections



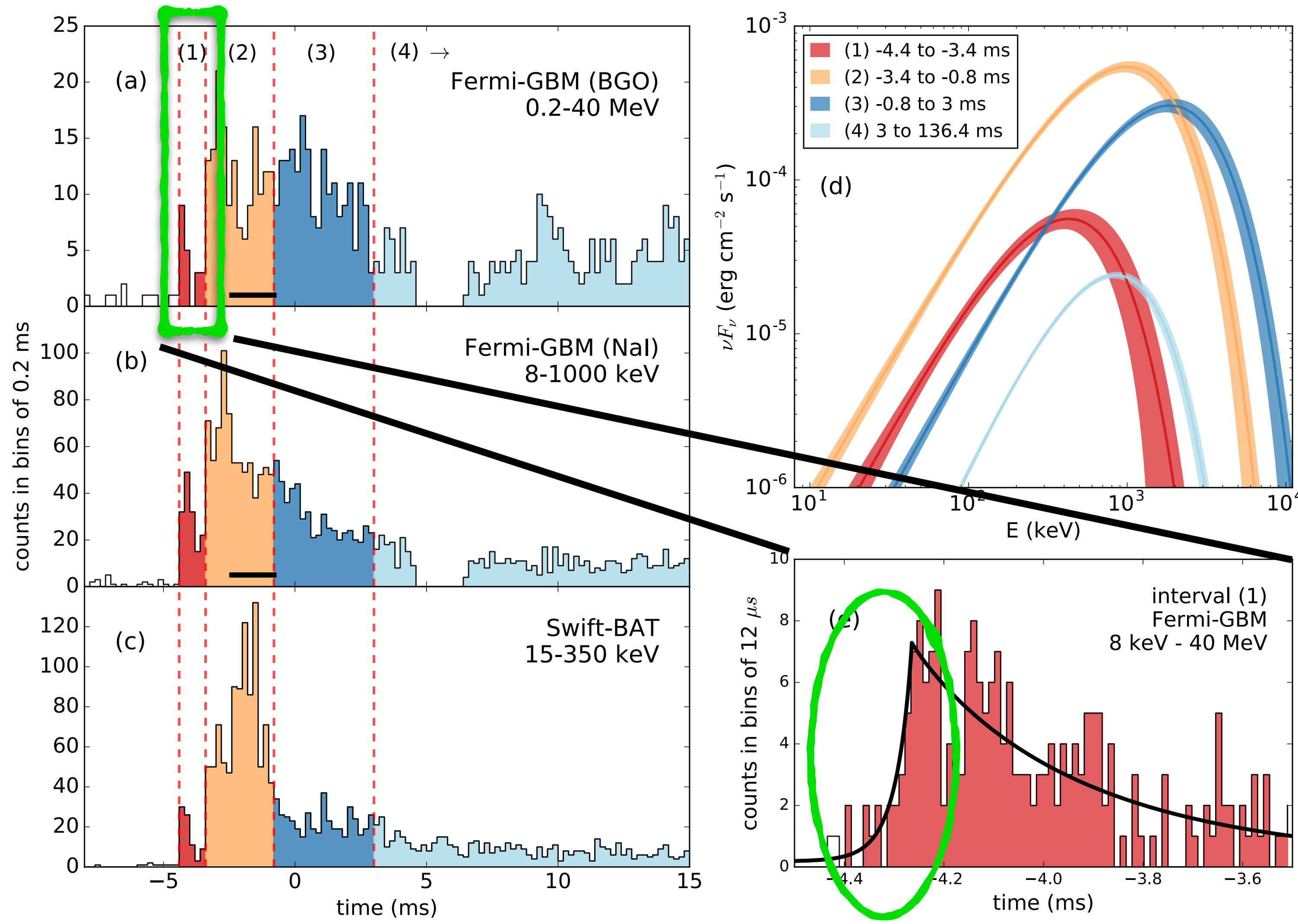
Short peak structure

- zoom in
- 4 intervals
- saturation
- missing data



Detailed properties

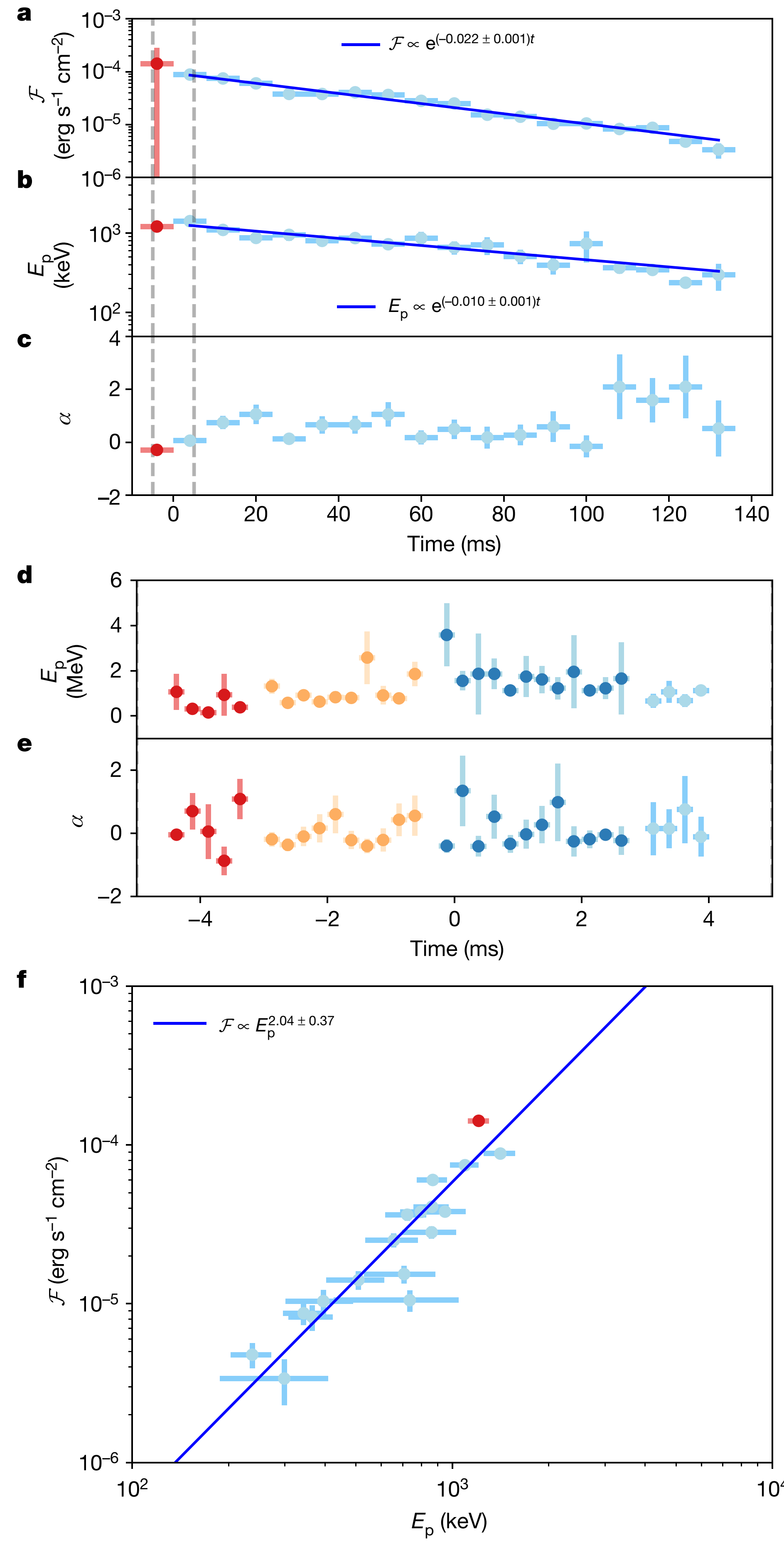
- 4 intervals:
  - (1) fastest, $t_{\rm rise} = 77\ \mu s$
  - (2) brightest, $L_{\gamma,iso} = 1.5 \times 10^{48}$ erg s^{-1}
  - (3) hardest, $E_{\rm peak} = 1.9$ MeV
  - (4) longest
- $E_{\gamma,iso,tot} = 1.5 \times 10^{46}$ erg
- $L_{\gamma,iso,tot} = 1.1 \times 10^{47}$ erg s^{-1}



Time (ms)	$E_{\rm peak}$ (keV)	photon index	Flux (10^{-5} erg cm^{-2} s^{-1})	Corr.	$L_{\gamma,iso}$ (10^{47} erg s^{-1})	$E_{\gamma,iso}$ (10^{45} erg)	C-Stat/dof
(1) -4.4 to -3.4	428 ± 71	-0.08 ± 0.23	9.9 ± 1.2	1.0	1.51 ± 0.18	0.15 ± 0.02	431.0/633
(2) -3.4 to -0.8	997 ± 77	-0.21 ± 0.08	33.7 ± 1.5	1.896	15.3 ± 1.3	3.97 ± 0.33	634.5/659
(3) -0.8 to 3.0	1856 ± 155	-0.11 ± 0.08	17.5 ± 0.81	1.0	8.29 ± 0.38	3.15 ± 0.15	705.5/685
(4) 3.0 to 136.4	846 ± 39	0.34 ± 0.08	2.69 ± 0.06	1.036	0.58 ± 0.032	7.79 ± 0.43	736.9/698
T_{90} Duration (140.8)					1.07 ± 0.17	$\mathbf{15.1 \pm 2.46}$	

Spectral evolution and search for quasi-periodic oscillations

- All spectra: power law with exponential cutoff
  $dN/dE \propto E^{\alpha} \exp(-E(\alpha+2)/E_{\rm peak})$
- $E_{peak}(t)$ and Flux(t) - exponential decay, typical time: 100 and 45 ms
- $F \propto E^2_{\rm peak}$
- QPO: nothing significant found.
  - 180 Hz -> p-value ~ 1-3 %
    $(\approx 2.5\sigma)$

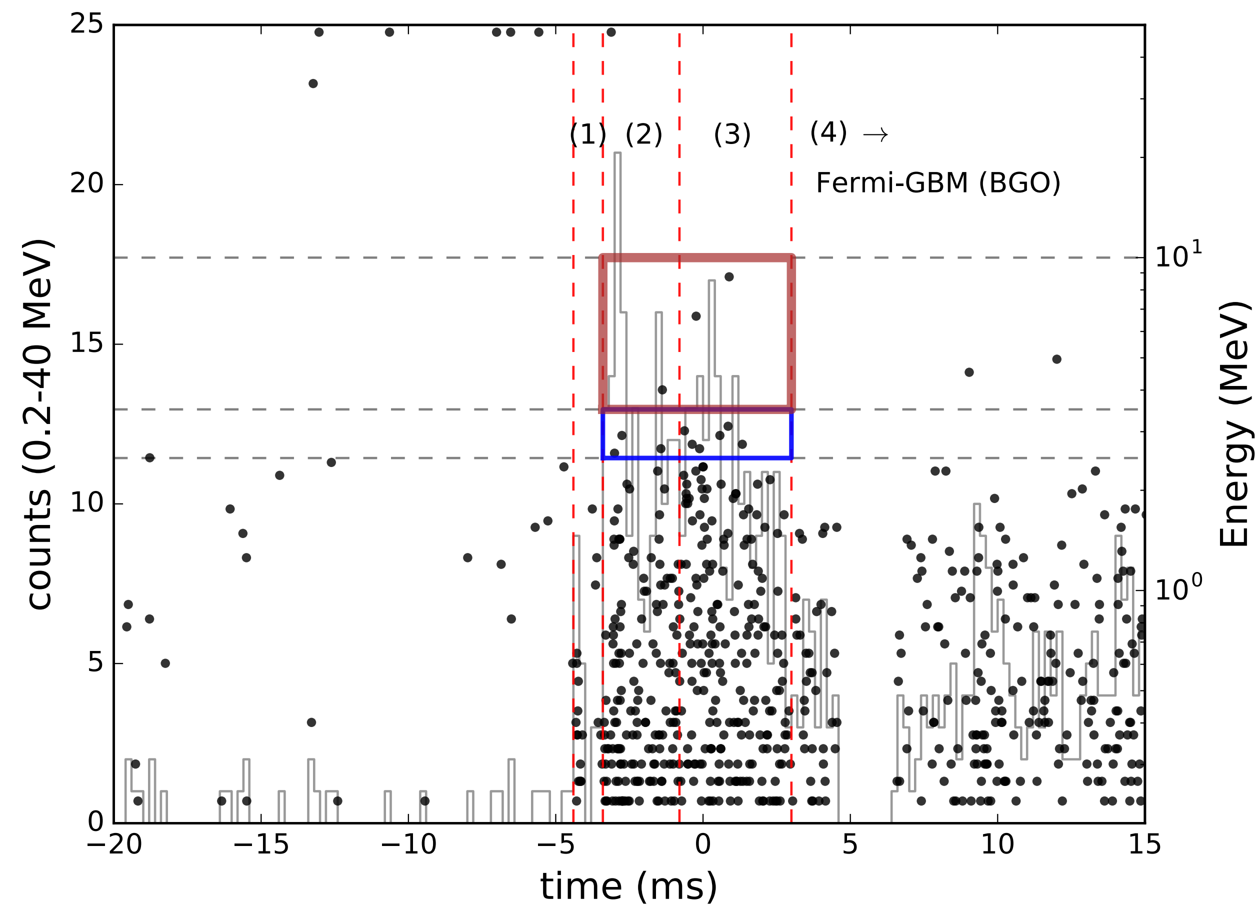


Highest energy photon - Lorentz factor constraint

- Highest energy photon in BGO
    - ~3 MeV - secure association
    - E<1 MeV for other MGFs during initial peak
    - Hints of ~9 MeV
- Conservatively the Lorentz factor:

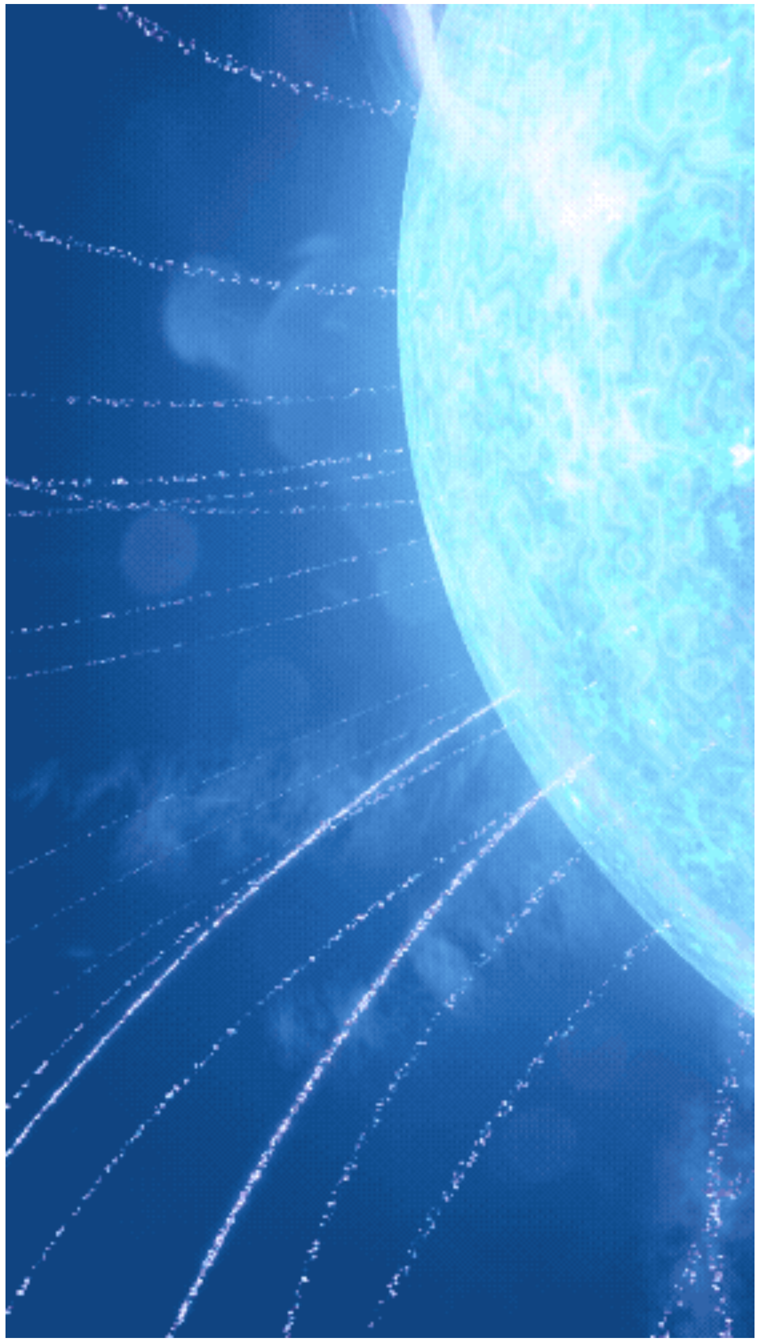
$$\Gamma \gtrsim \frac{3\ \mathrm{MeV}}{0.511\ \mathrm{MeV}} \approx 6$$

- Relativistic outflow



Interpretation

- Relativistic outflow $\Gamma \gtrsim 6$, but likely $\Gamma = \mathcal{O}(100)$ (model dependent)
- Narrow but non-thermal spectrum
  - $\alpha \sim 0$ disfavors synchrotron
  - Comptonization shapes the obs. spectrum
- Flux / Luminosity decay timescale $L \propto e^{-t/45\mathrm{ms}}$ may be rotating beam: $45\ \mathrm{ms} = P/(2\pi\Gamma)$ e.g. P=8 s, $\Gamma = 30$
- Flux: $F \propto E_{\mathrm{peak}}^2$ - from simple transformation
  - $F \propto L \propto \Gamma^2$ and $E_{\mathrm{peak}} \propto \Gamma$



animation credit: NASA/GSFC/Smith

Conclusions
for GRB 200415A

- Bright, short γ-ray signal GRB 200415A is in fact a Magnetar Giant Flare
- Detailed properties of Magnetar Giant Flares can be analyzed for the first time
- Record breaking properties:
  - shortest timescale
  - highest photon energy
  - relativistic motion

details here:

Roberts, PV et al., Nature, **589**, 207 (2021)

<u>(link to paper)</u>

image credits: NASA/GSFC/Wiessinger & D. Wiesner