High Energy Neutrinos from Gamma-Ray Bursts

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CARLSBERG FOUNDATION

Outline

- General GRB picture & current neutrino limits
- Prompt emission models
- Diffuse flux constraints: Fit to UHECR data
- Single event constraints: energetic events & GRB170817A
- Beyond typical candidates: Low-luminosity GRBs & multi-epoch emission

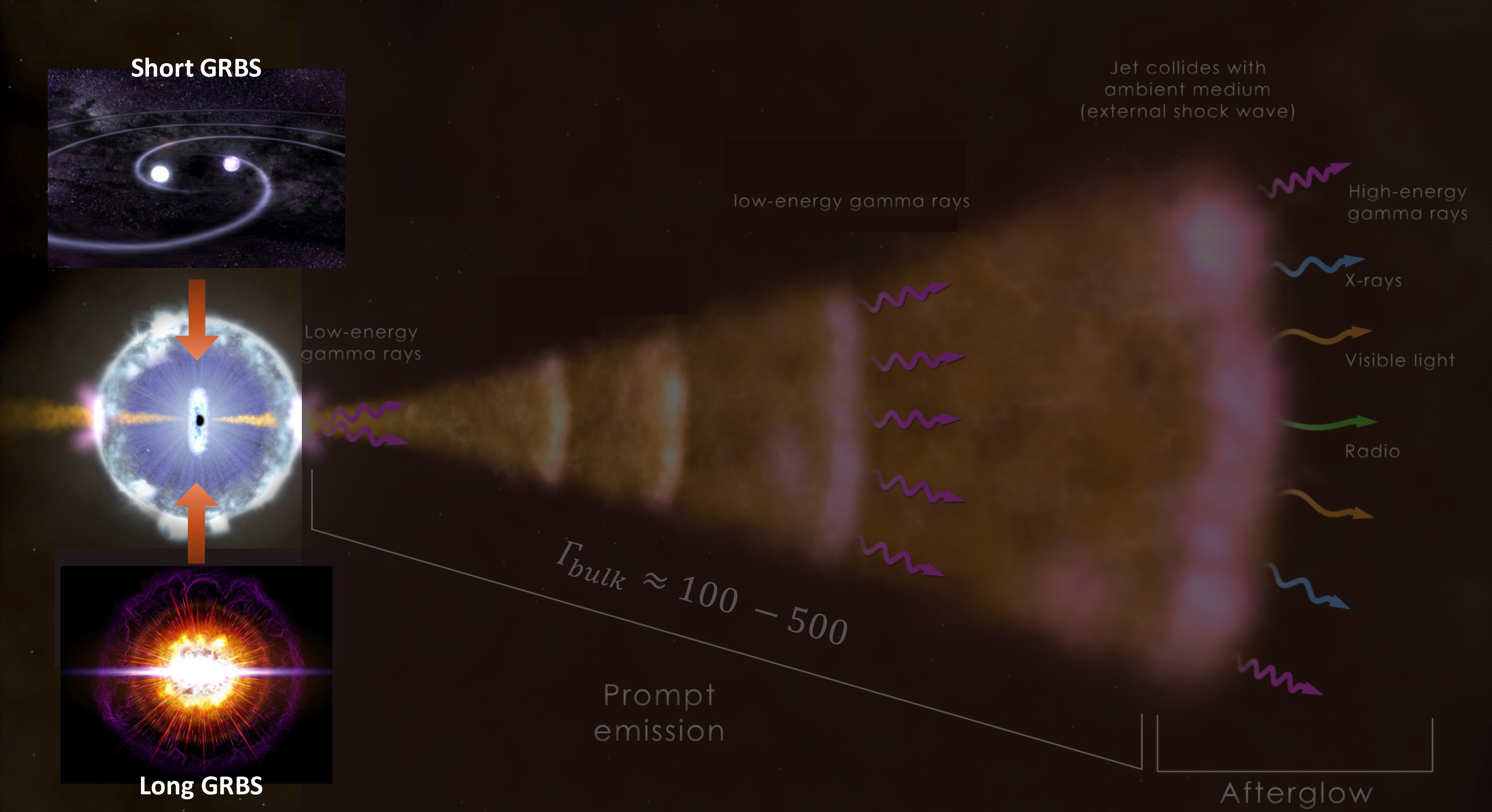


Image credit: NASA's Goddard Space Flight Center

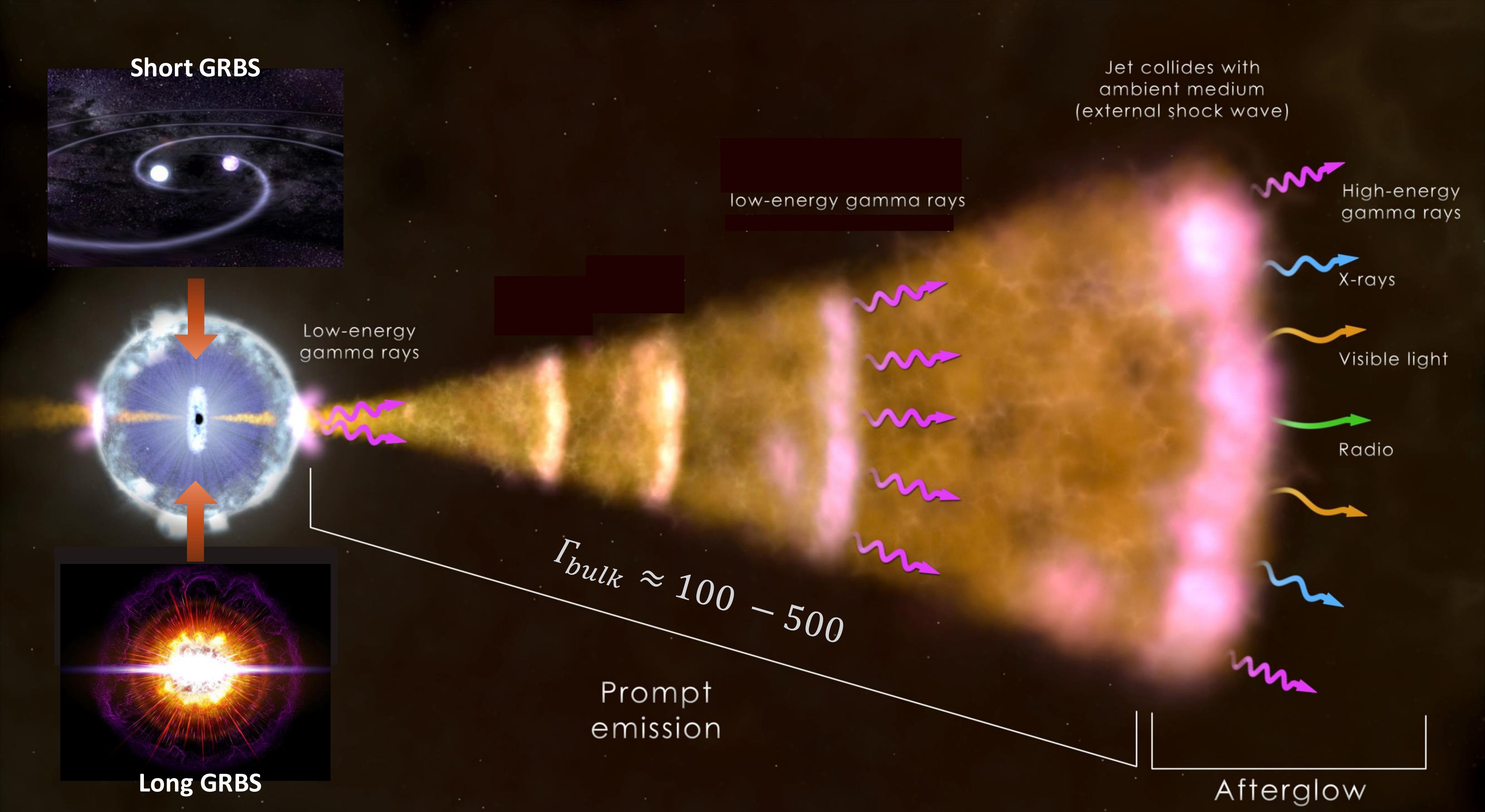


Image credit: NASA's Goddard Space Flight Center

Gamma-Ray Bursts

Observational properties of GRBs

- Energetic outbursts of gamma-rays

  $E_{iso} \sim 10^{49} – 10^{55}$ erg

- Jet with opening angle of few degrees
- Large variety of **light curves with fast time variability**
- **Similar spectra** (narrow broken power law)

Examples of observed light curves

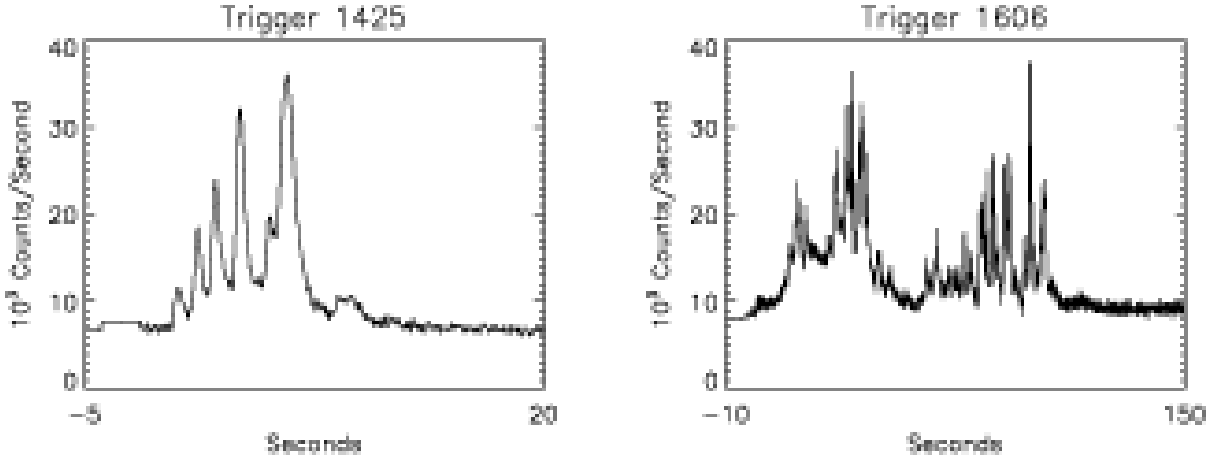
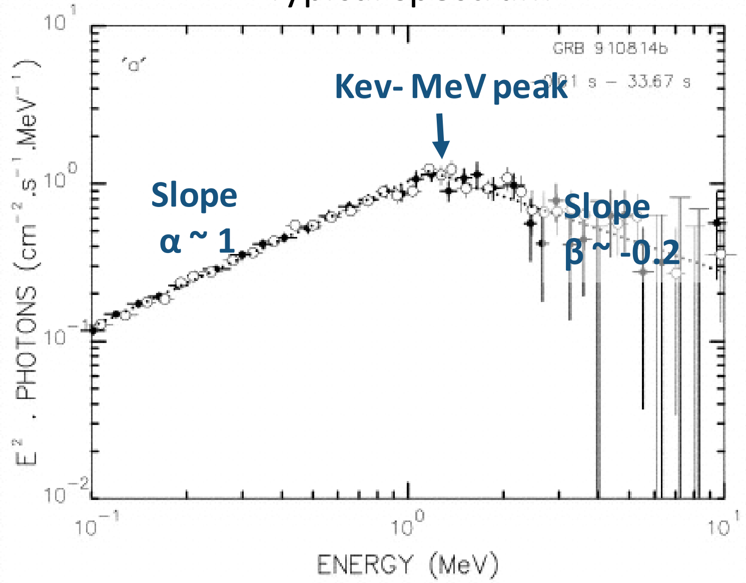


Image credit: J.T. Bonnell (NASA/GSFC)

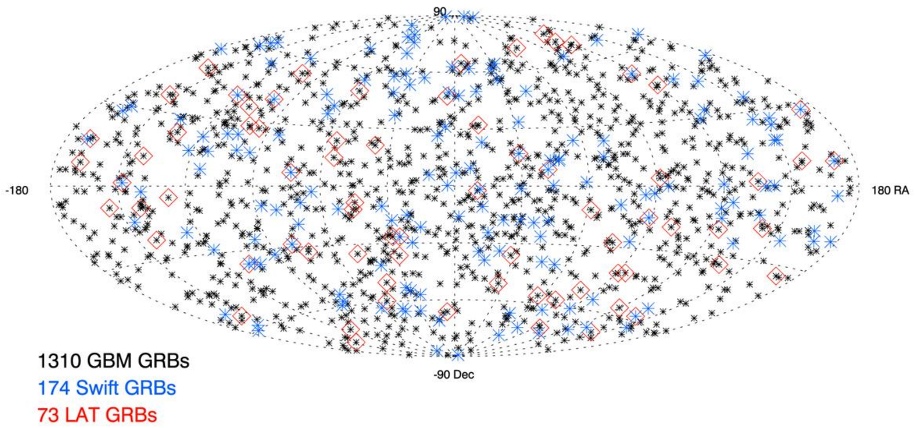
Typical spectrum



Barat et al 2000, ApJ 538 : 152-164,

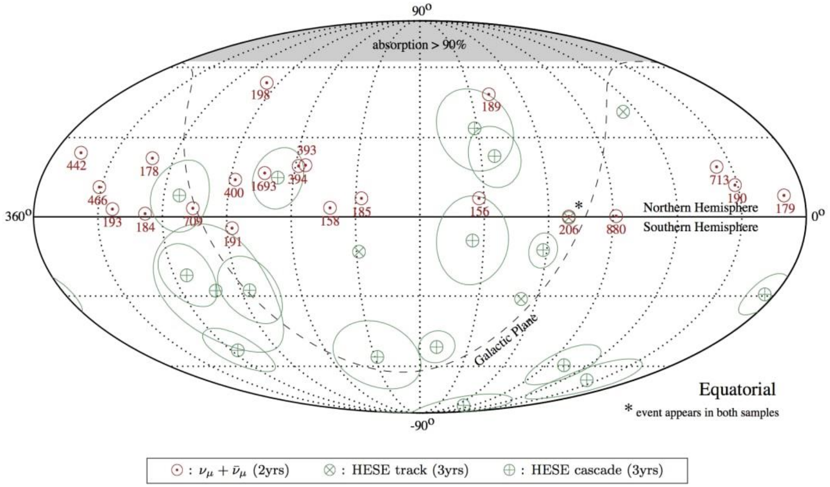
Gamma-Ray Bursts

Catalogue of known GRBs



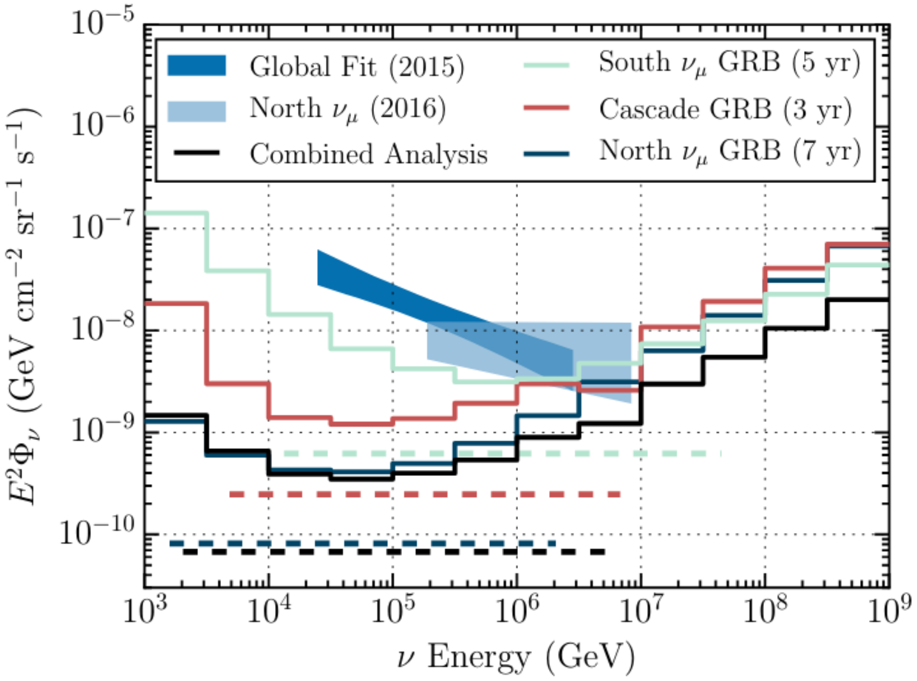
Fermi LAT + GBM coll

Detected HE neutrinos



IceCube coll.

No correlation between observed GRBs and HE neutrinos
-> limits neutrino production efficiency in GRBs



Aartsen et al 2017

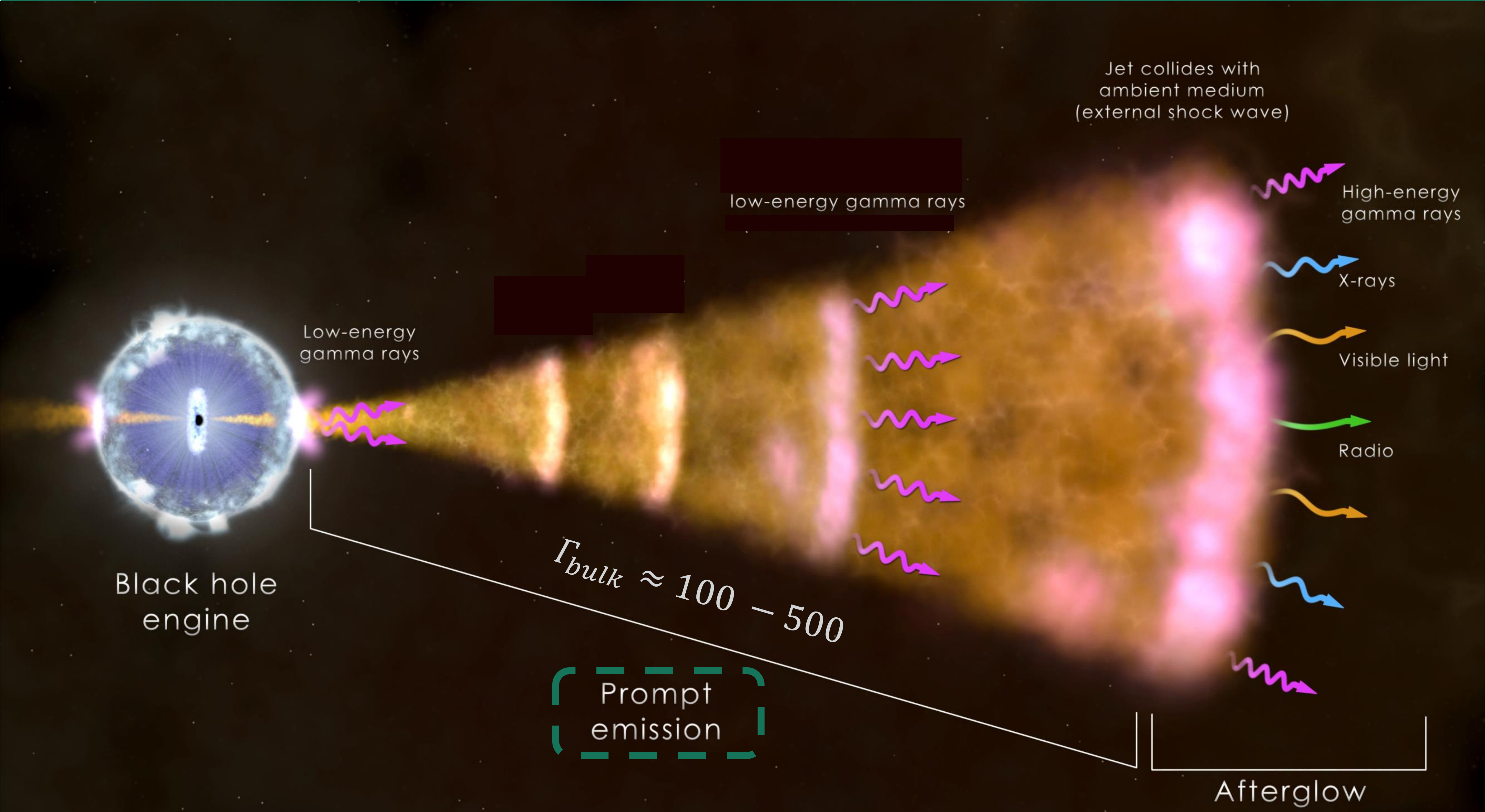


Image credit: NASA's Goddard Space Flight Center

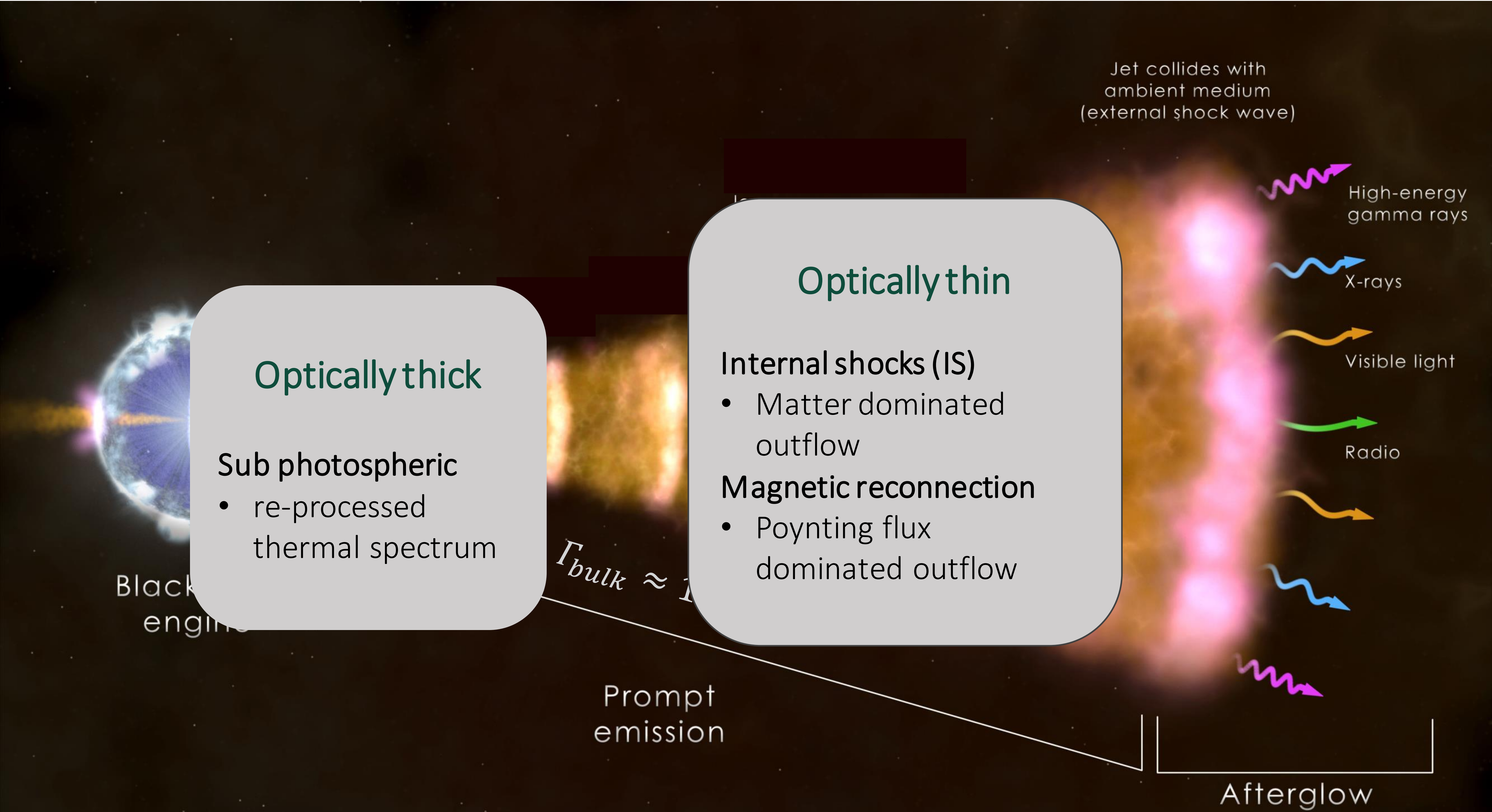


Image credit: NASA's Goddard Space Flight Center

Neutrino flux dependence on parameters

Neutrinos from photo-hadronic interactions:
production rate scales with number **density**

$$n' = \frac{N}{4\pi R^2 \Delta\Gamma}$$

Radius from central engine

Comoving width of region

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Typical radii

Photospheric $10^{11} - 10^{12}$ cm
Internal Shocks $10^{13} - 10^{14}$ cm
Magnetic reconnection (ICMART) 10^{15} cm

Small radii -> large densities -> many neutrinos

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N depends on energy transferred to cosmic rays, scales with:
(1) Total energy budget
(2) '**baryonic loading**': $f_p = \frac{U_p}{U_e}$

U_p: energy density of accelerated cosmic rays

U_e: energy density of accelerated electrons

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- Baryon acceleration efficiency may be model-dependent
- Peak energy/ production efficiency affected by typical proton+photon energies (cross section!)

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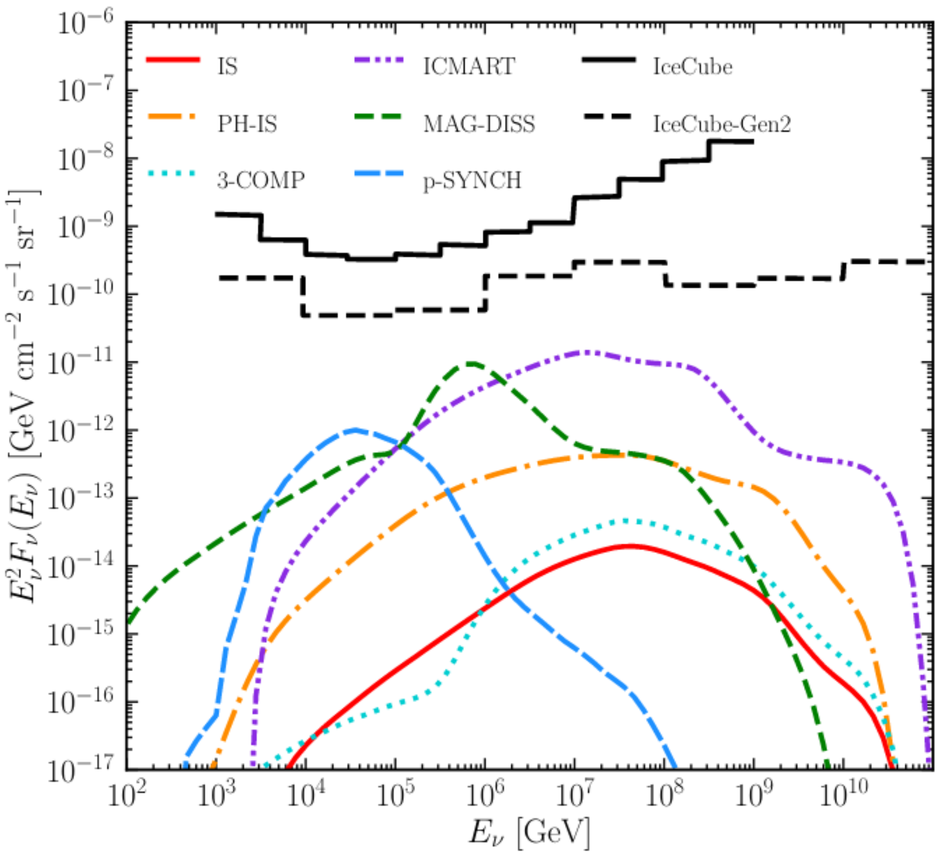
For neutrino production in different models see also eg.
Gao et al JCAP 11 (2012),
Hummer et al PRL 118 (2012),
Zhang & Kumar, PRL 110 (2013),
Baerwald et al Astropart.Phys. 62 (2015)

Model dependance of neutrino fluxes



Pitik et al JCAP 05 (2021)

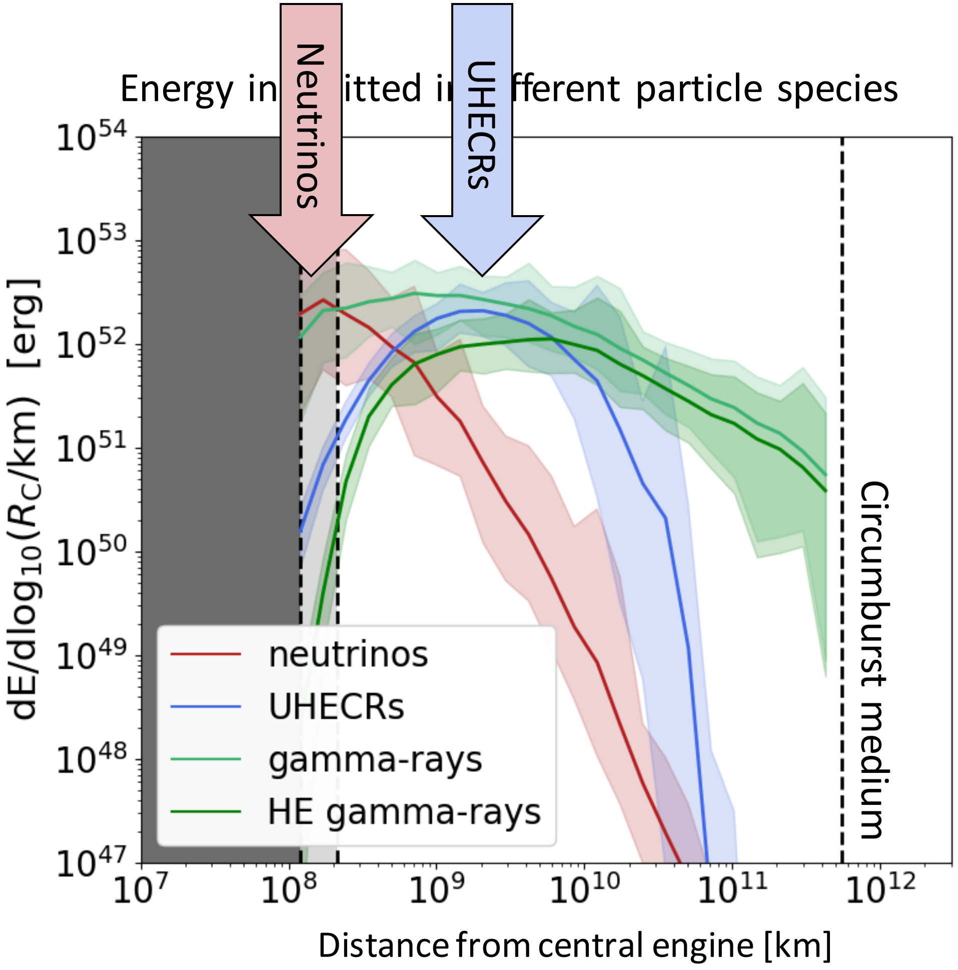
Internal shock models

One-zone models:

- A single emission region representative for complete burst

Multi-zone models:

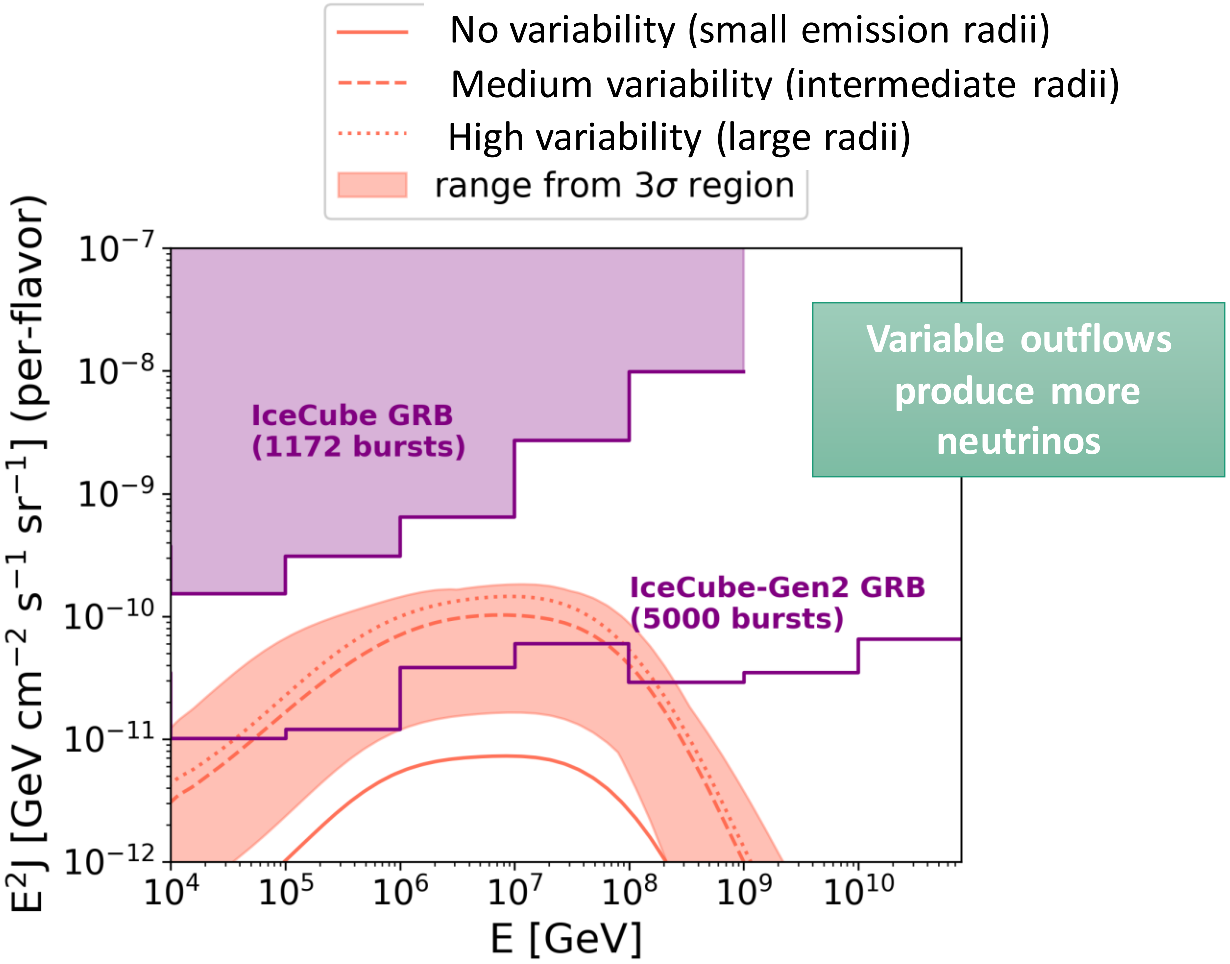
- Many emission regions along the jet
- Simple parametrisation of multiple shocks
  Daigne & Mochkovitch MNRAS 296 (1998)
  Kobayashi, Piran & Sari ApJ 490 (1997)
- Decoupling of emission regions for different particle species -> typically lower neutrino predictions
  Bustamante et al Nature Comm. 6 (2015)
  Bustamante et al ApJ 837 (2017)



AR et al, ApJ 893 (2020)

Diffuse neutrino flux: Fit to UHECR data

- **Methods:**
  - Multi-zone internal shock model with different initial jet configurations
  - Fit to UHECR data (energy spectrum + composition)
- **Results:**
  - Fit possible in large parameter space
  - Neutrino fluxes testable by IceCube Gen2

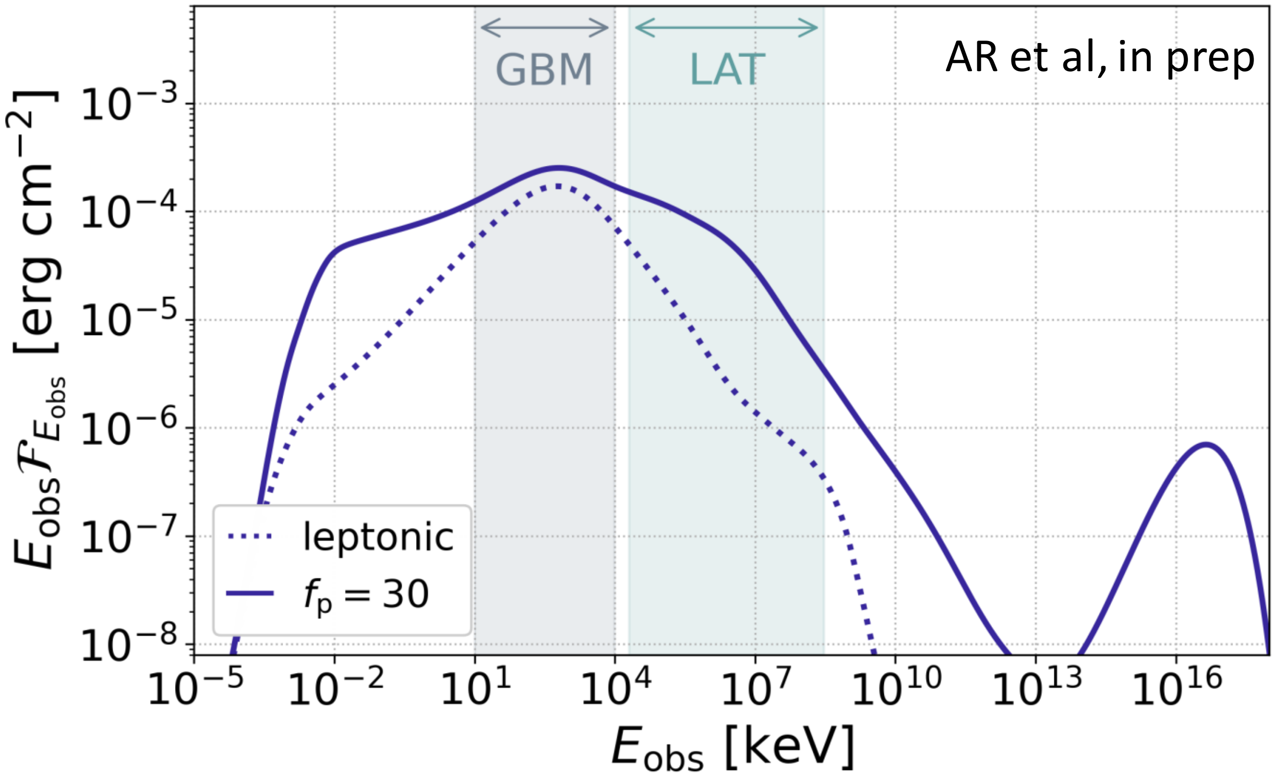


Heinze, AR et al MNRAS 498 (2020)

Hadronic signatures in energetic GRBs

- Large emitted energy: single event neutrino constraints!
  GRB 160625B Fraija et al ApJ 848 (2017)
  GRB 130427A Gao et al ApJL 772 (2013)
- Some seen in HE by *Fermi*-LAT
  -> hadronic component?/multi-messenger?

Toy GRB @ z = 2 (no EBL)
Simulated Spectral Energy Distribution



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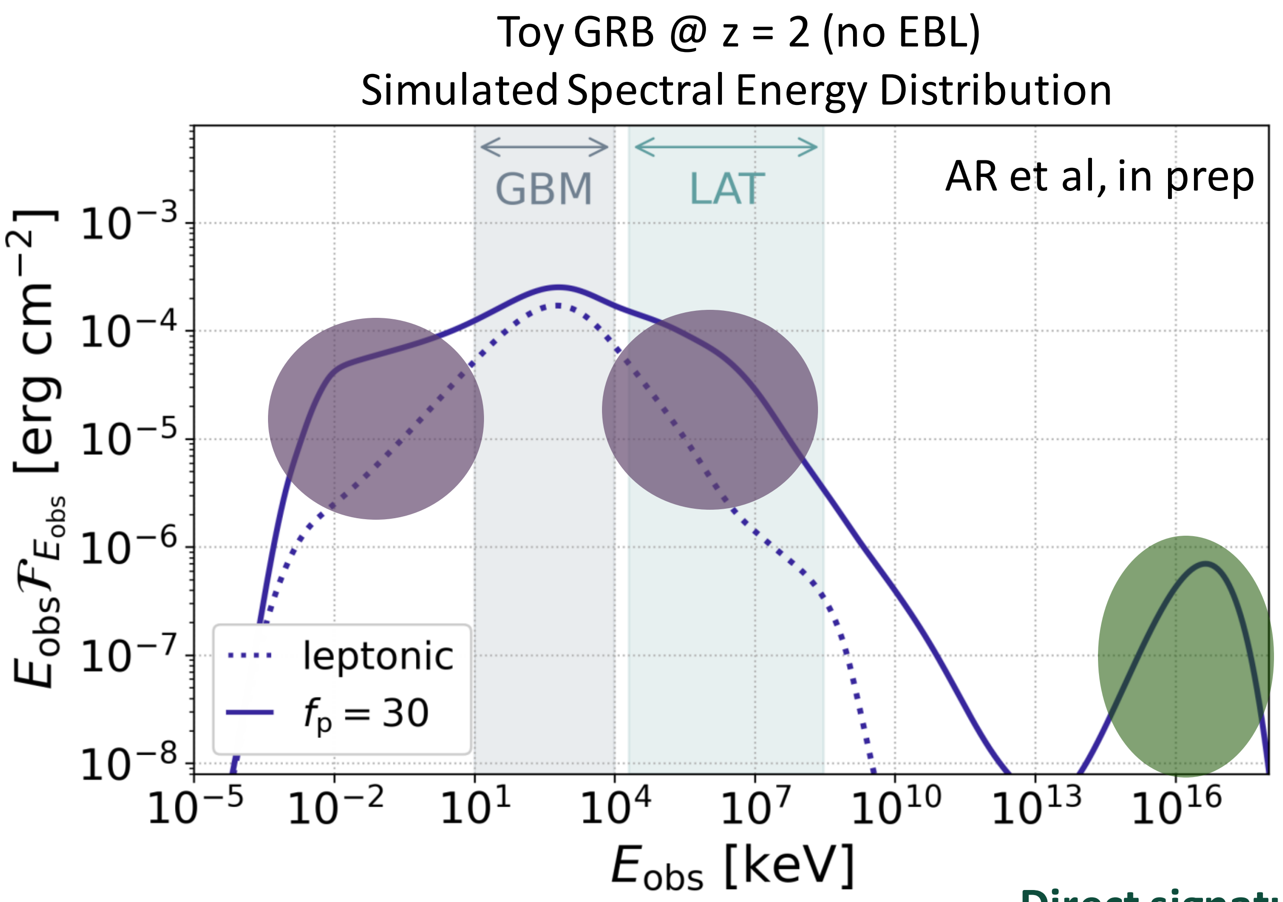

Indirect signature:
Secondary lepton cascade

Direct signature:
Decay of neutral pions
Absorbed during propagation

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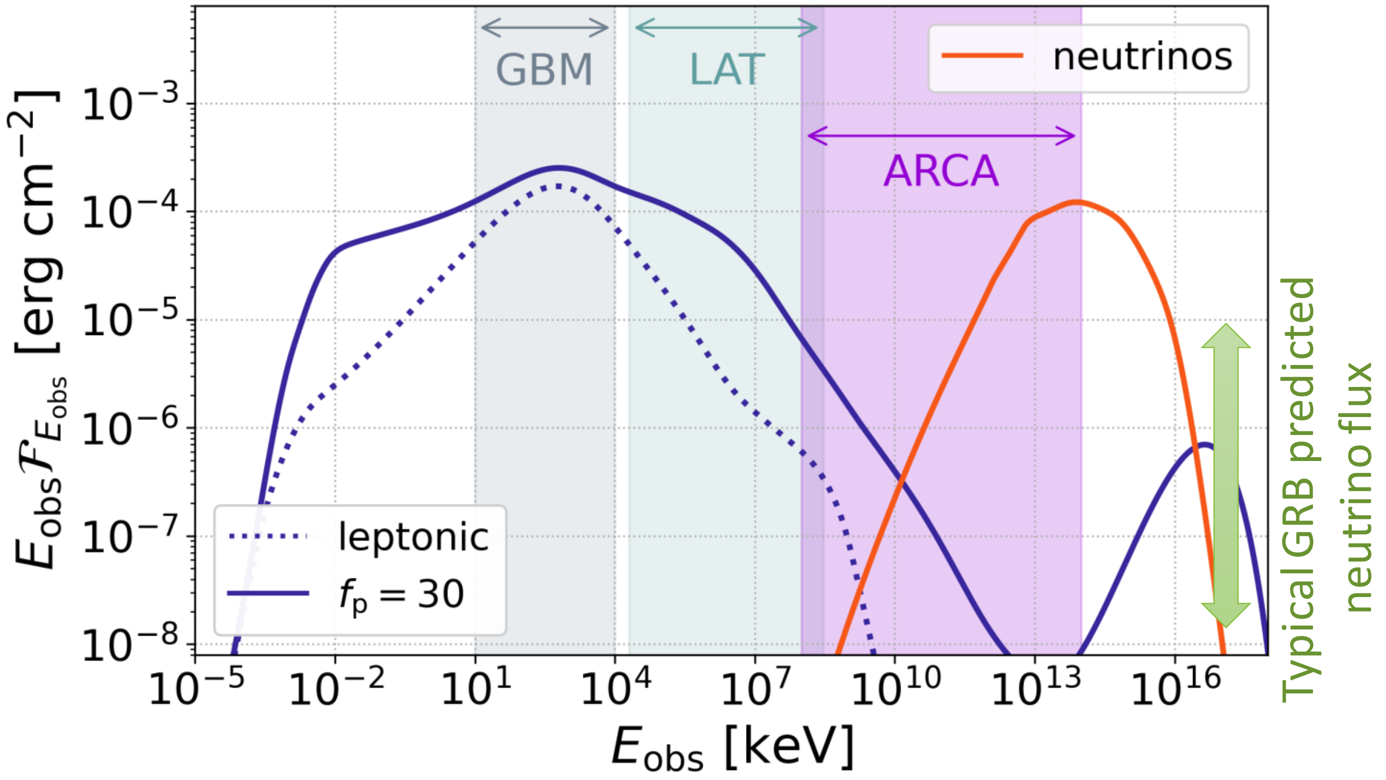

hadronic signatures scale with typical emission radius & f_p !

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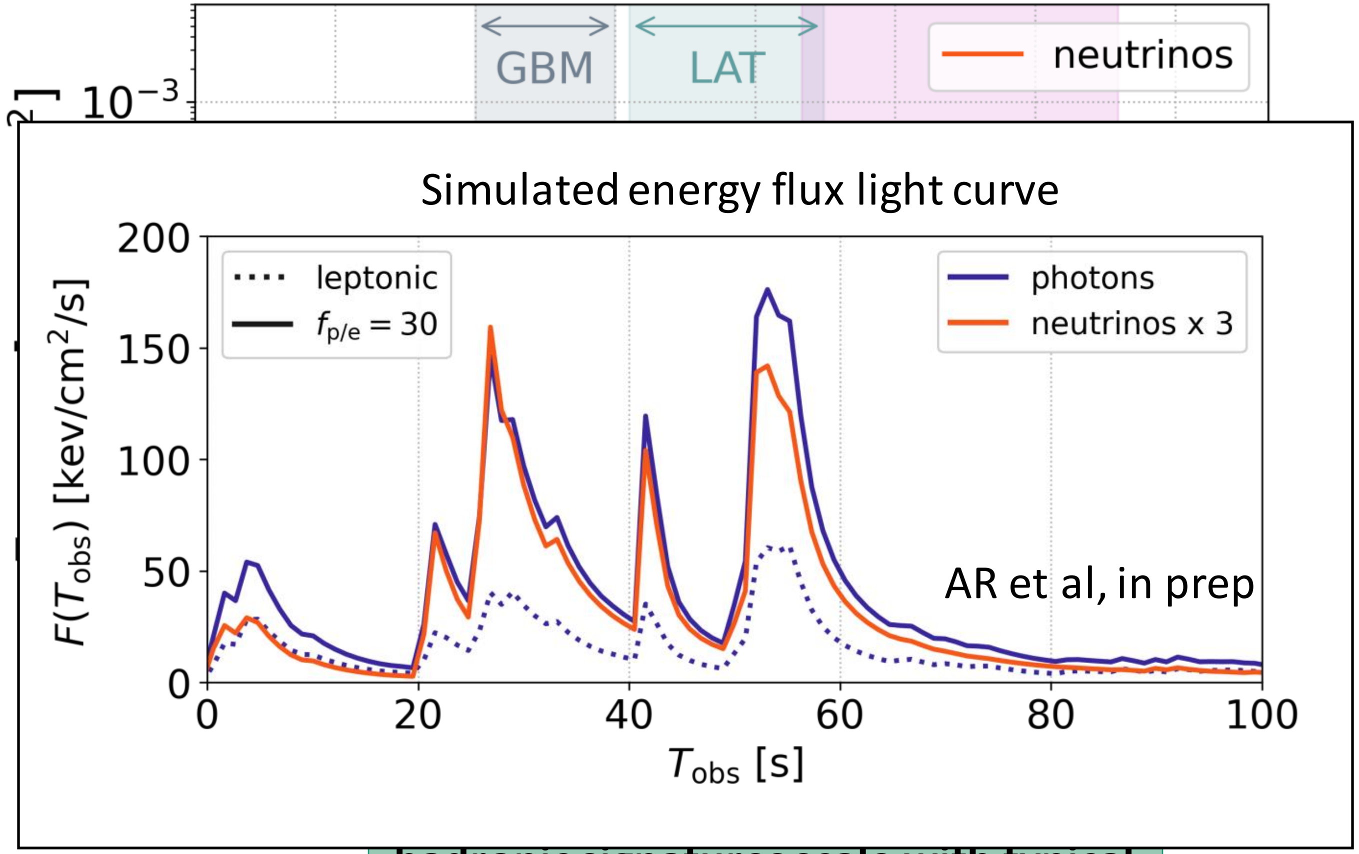

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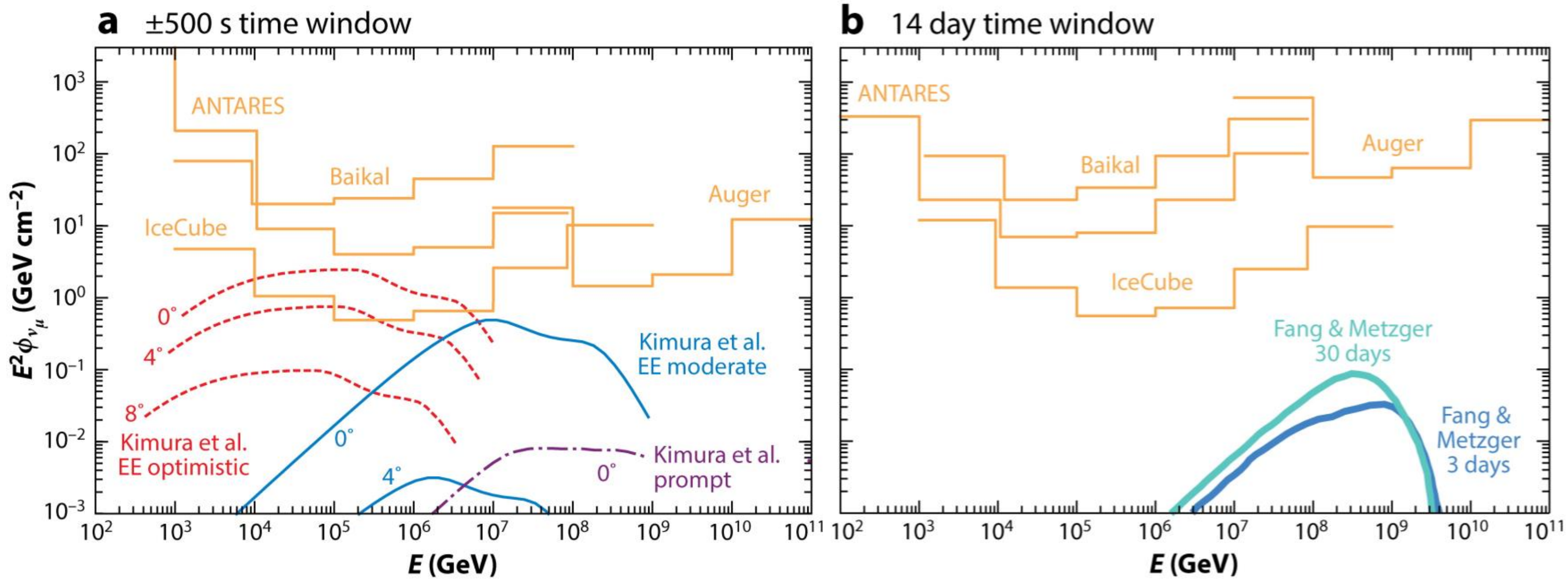
High-Energy Neutrinos from GRB 170817A?

- No neutrinos from prompt phase detected
- Neutrinos from:
  - late engine activity
  - choked jets
  - long-lived ms magnetar
- Neutrino triggers for position



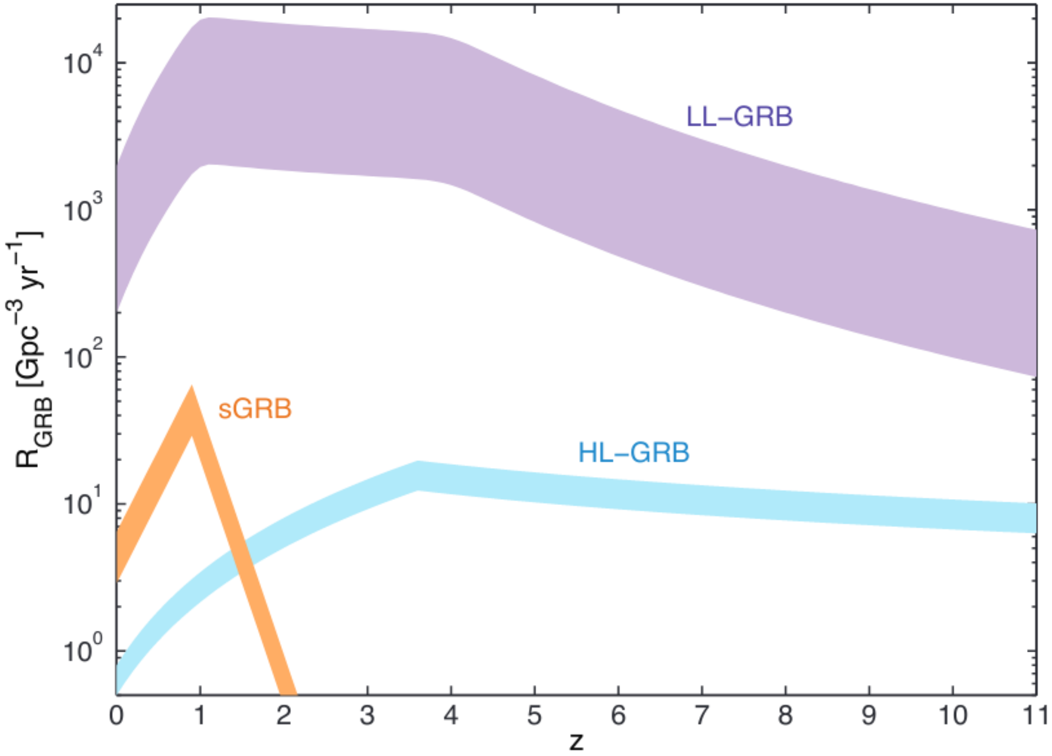
Fang & Murase Ann.Rev.Nucl.Part.Sci. 69 (2019),
Albert et al ApJL 850 (2017)

Kimura et al ApJL 848 (2017), Fang & Metzger ApJ 849 (2017), Kimura et al PRD 98 (2018), Biehl et al MNRAS 476 (2018), Gottlieb & Globus ApJL 915 (2021)

Low-Luminosity GRBs

- **L_{iso} ~ 10^{46} – 10^{49} erg/s**
- **Sources of UHECR** (and HE neutrinos)? *(Boncioli et al ApJ. 872 (2019), Samuelsson et al ApJ. 876 (2018), Samuelsson et al ApJ. 902 (2020), Zhang et al PRD 97 (2018)), Tamborra & Ando JCAP 09 (2015)*
- **High local density** when compared to high-luminosity GRBs
- **Theoretical models:**
  off-axis *(Pescalli et al MNRAS 447 (2015), Aloy et al MNRAS 478 (2018))*
  shock-breakout *(eg. Waxman et al ApJ 667 (2007), Nakar ApJ 807(2015))*
  intrinsically dim *(eg. Daigne & Mochkovitch A&A 465 (2007))*

Rate of different GRB populations

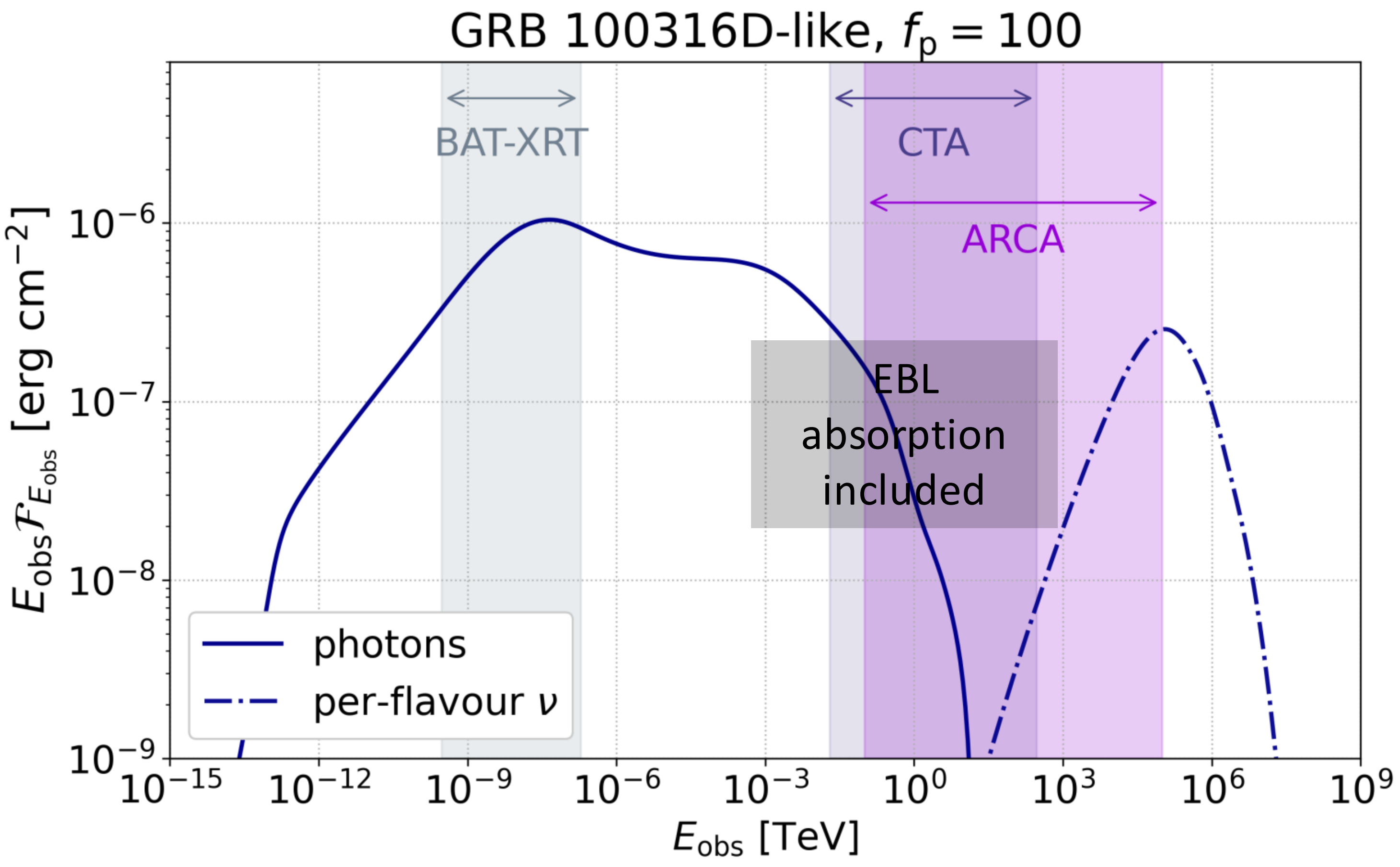


Tamborra et al JCAP 09 (2015)

Modeling an Ultra-Long LL - GRB

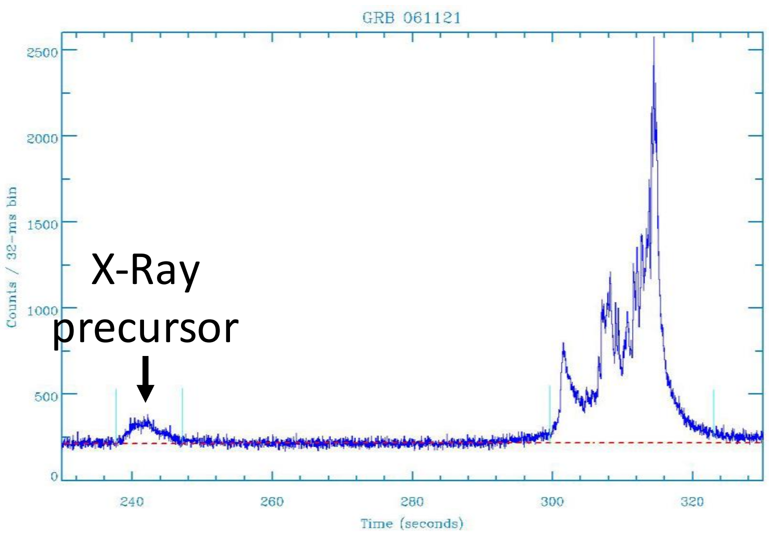
- Ultra-Long LL-GRBs: sub-class, duration 10^3 s
- Standard IS model (weak jet)
- **Neutrinos:**
  - low per-event flux
  - model-dependent predictions?
- **Multi-messenger**: Targets for IACTS? *See AR et al, MNRAS 511 (2022)*

GRB similar to detected event, z = 0.059
Self-consistent photon and neutrino spectrum



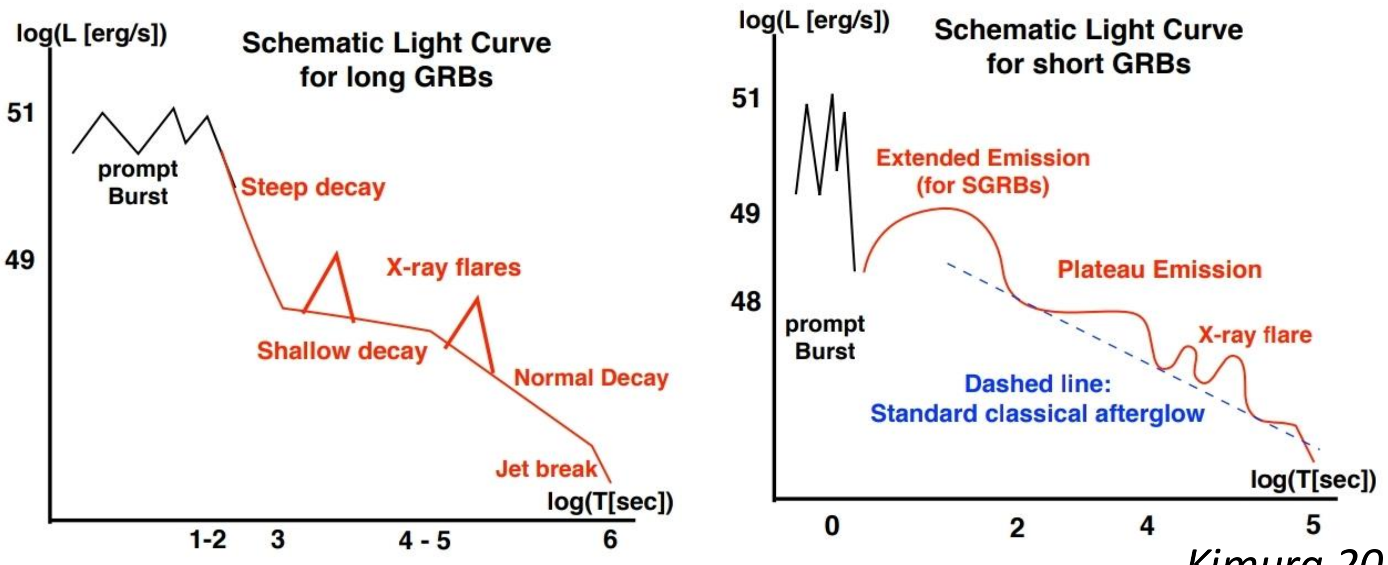
Multiple Emission Epochs in GRBs?

Precursor



- Photon precursor catalogues *eg. Coppin et al PRD 102 (2020)*
- pure neutrino precursor?

Variety of afterglow phenomena



Kimura 2022

- Simple afterglow: detection unlikely? *eg. Thomas et al PRD 96 (2017)*
- Alternatives: Flares (X-Ray / optical *eg Murase& Nagataki PRL 97(2007), Guarini et al JCAP 06 (2022)*), EE (-> GRB 170817A)

IceCube, extended time windows: arXiv 2205.11410

Conclusions

- Current neutrino limits: strong constraints on the neutrino production efficiency in GRBs
- Predicted neutrino fluxes depend on **density of emitting region**
- Multi-zone models **decouple production regions** of different particle species
- Diffuse flux: **UHECR fit still possible,** neutrino fluxes testable by next generation telescopes
- **Single events, energetic GRBs**: point-source neutrino constraints, multi-wavelength signatures of hadrons
- BNS-mergers as MM sources: various neutrino production sites
- **Low-luminosity GRBs**: potential sources of UHECRs and HE neutrinos + targets for IACTs
- Extending the time window: precursor to afterglow