Neutrino constraints from Gamma-Ray Bursts

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'Here, There and Everywhere' Neutrino Summer School

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Niels Bohr Institutet

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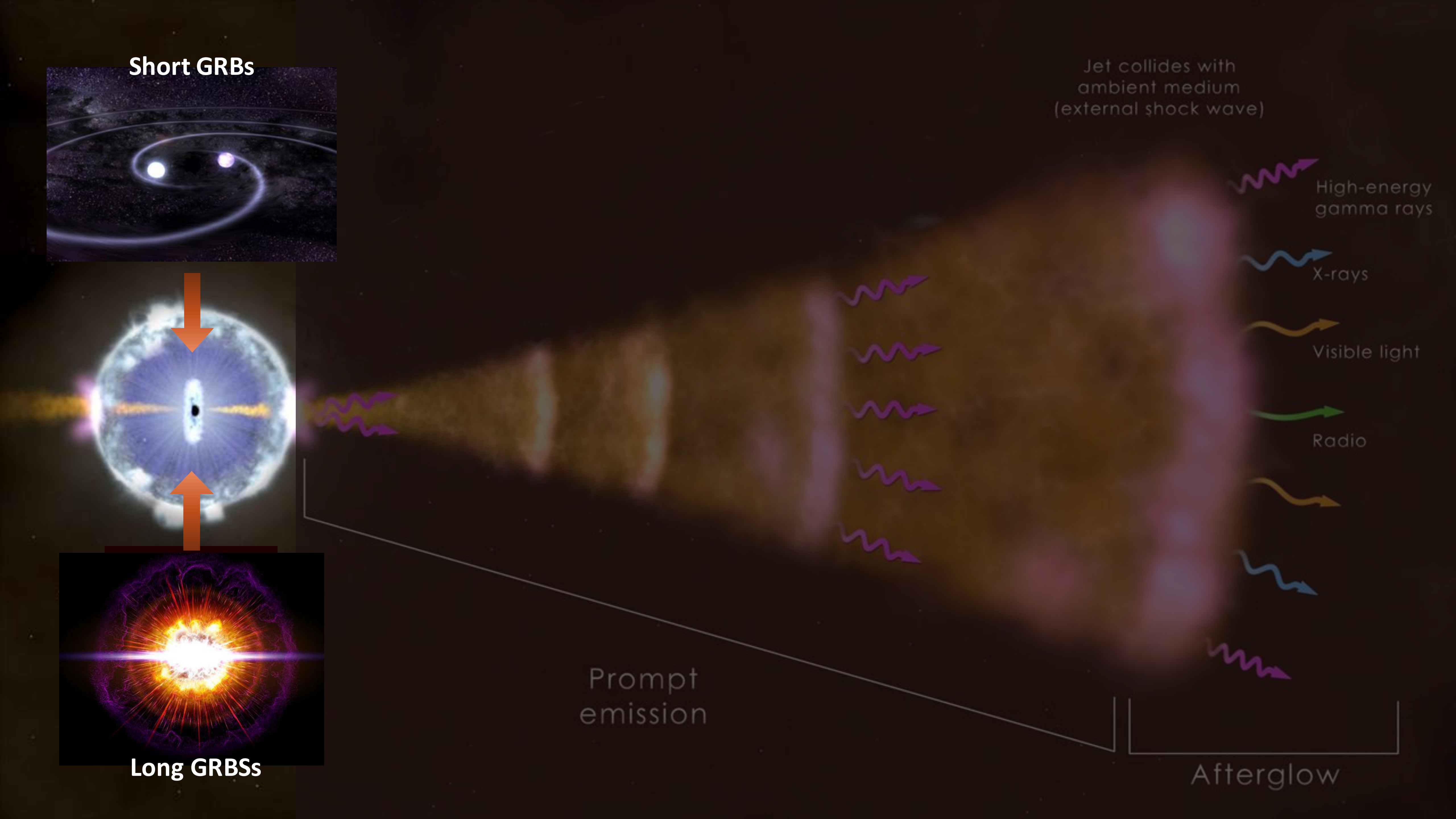
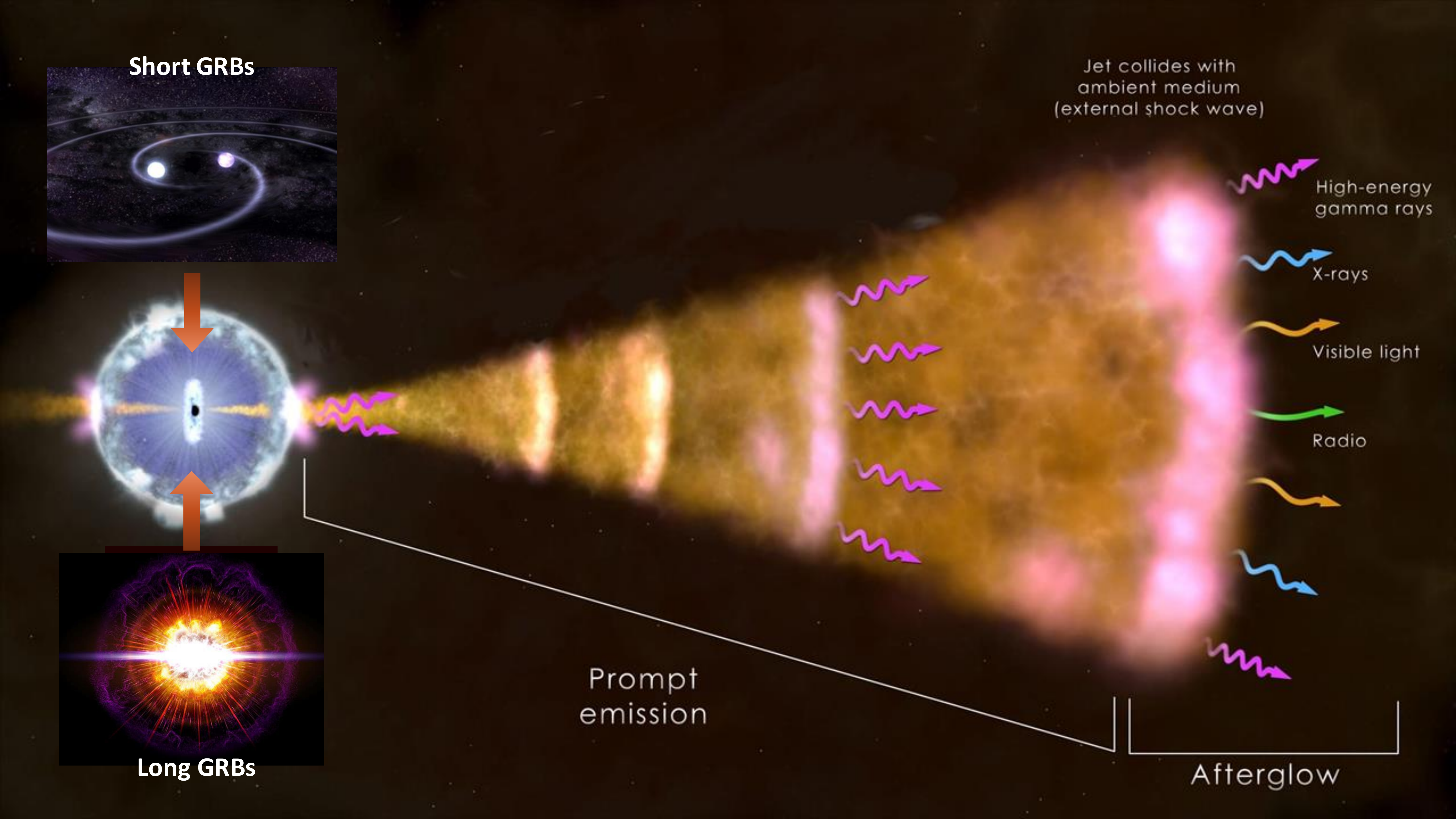
Interpreting neutrino (and multi-messenger) constraints for specific sources: Can we put limits on the amount of (accelerated) baryons in a specific gamma-ray burst?

Outline:

- General GRB picture & current neutrino limits
- Prompt emission models
- Application example: Modelling GRB 221009A in the internal shock scenario


Short GRBs
Long GRBSs
Jet collides with
ambient medium
(external shock wave)
High-energy
gamma rays
X-rays
Visible light
Radio
Prompt
emission
Afterglow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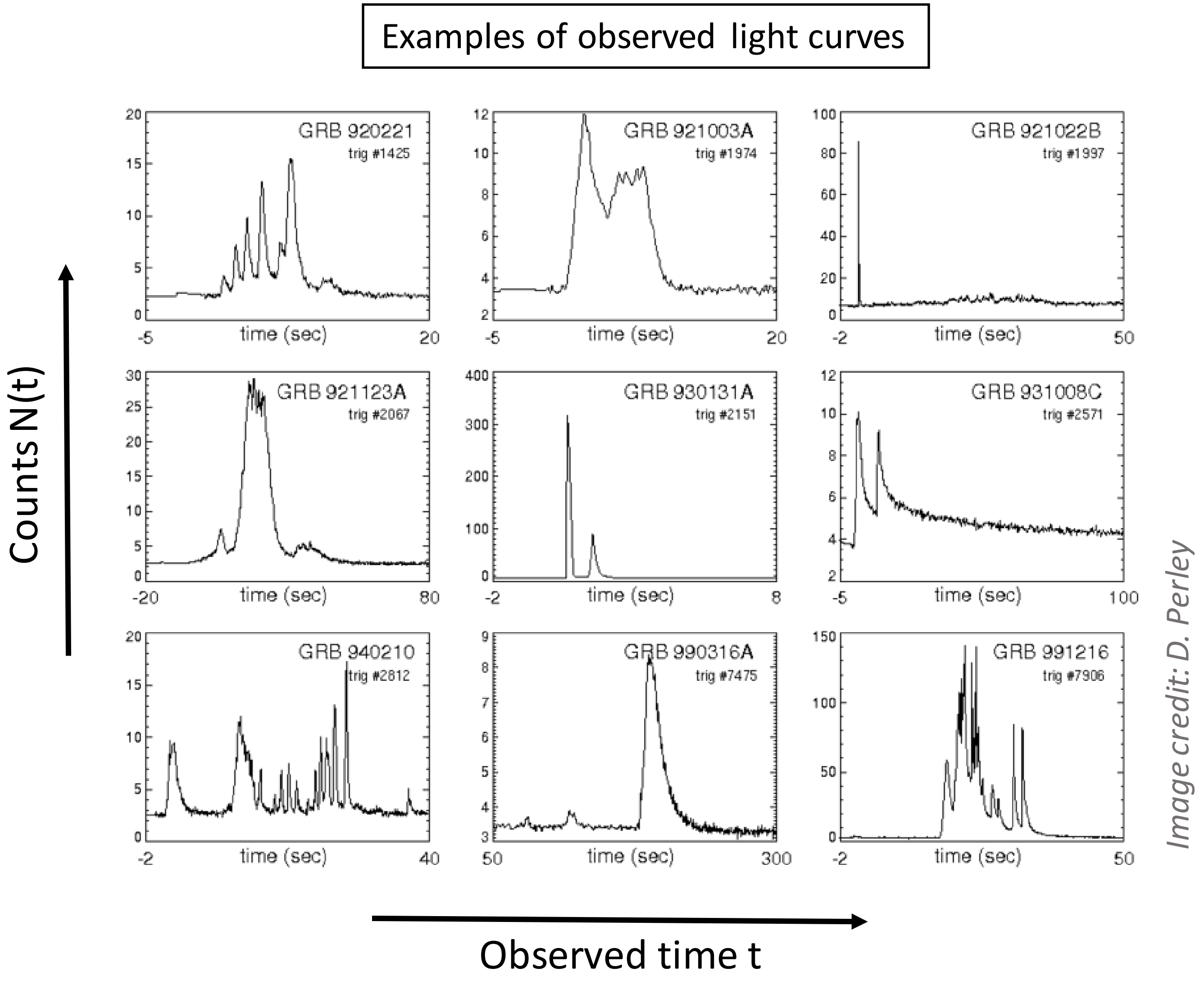
Prompt phase characteristics

- Released energy:

  $E_{iso} = 10^{49} – 10^{55}$ ergs (but opening angle of few degrees)
- Cosmological distances:

  typical z ~ 2
- Large variety of **light curves with fast time variability**



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  $E_{iso} = 10^{49} – 10^{55}$ ergs (but opening angle of few degrees)
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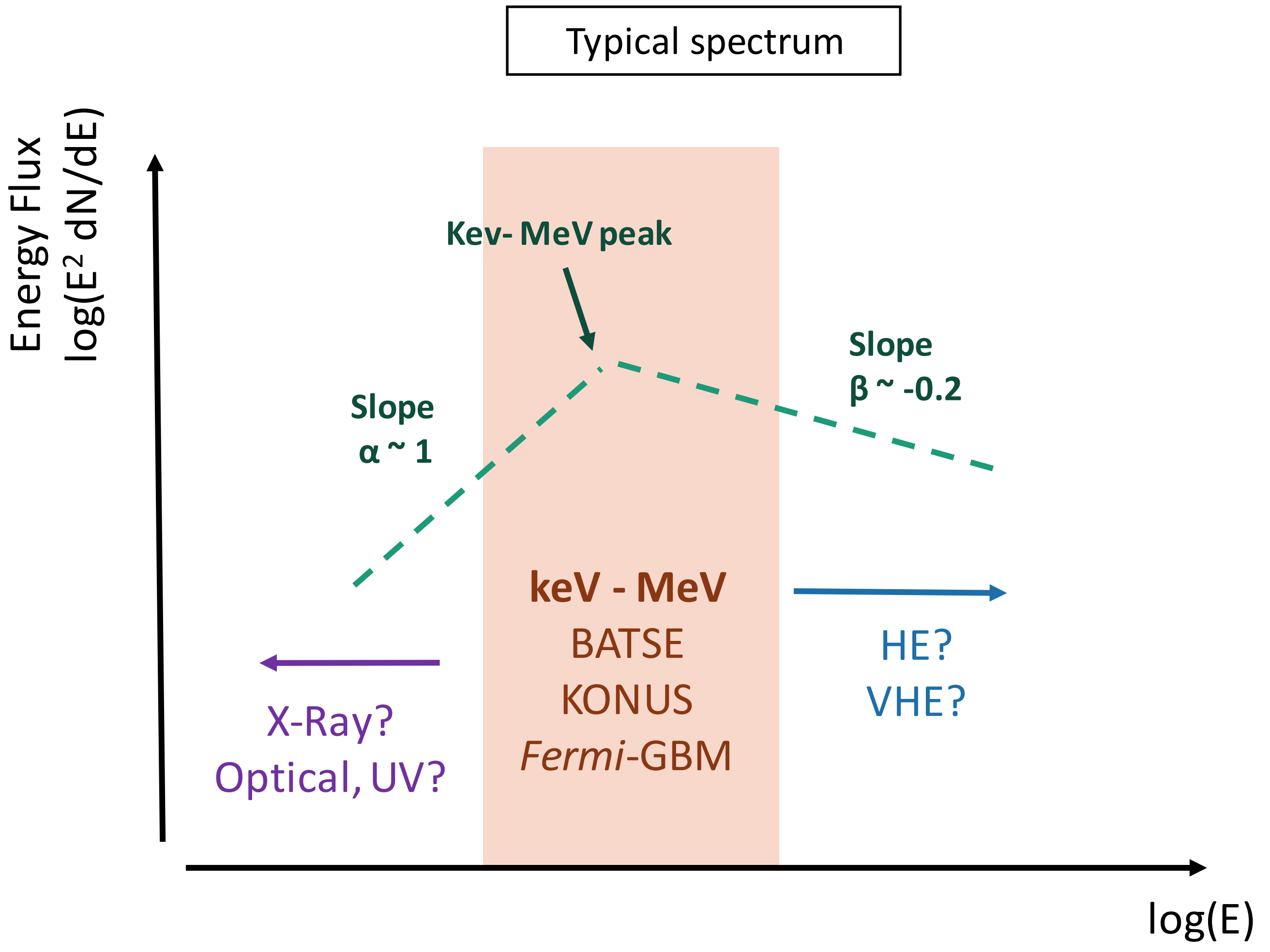
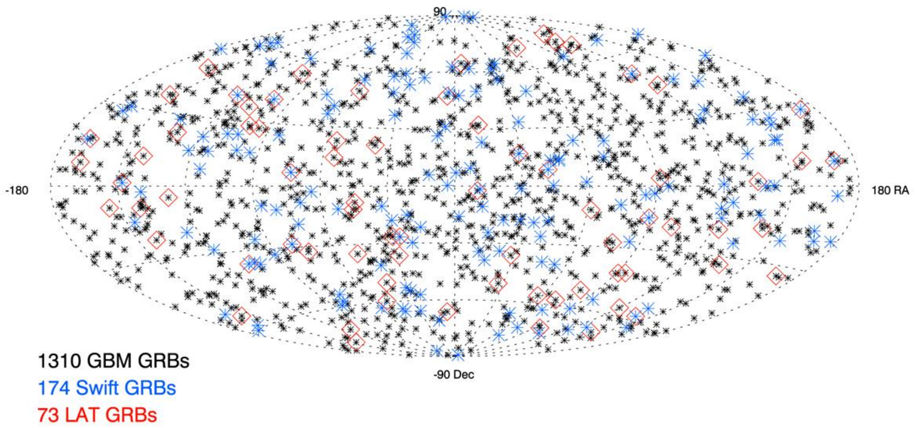
- Large variety of **light curves with fast time variability**
- **Similar spectra** (narrow broken power law, 'Band function')



GRBs as high-energy neutrino sources?

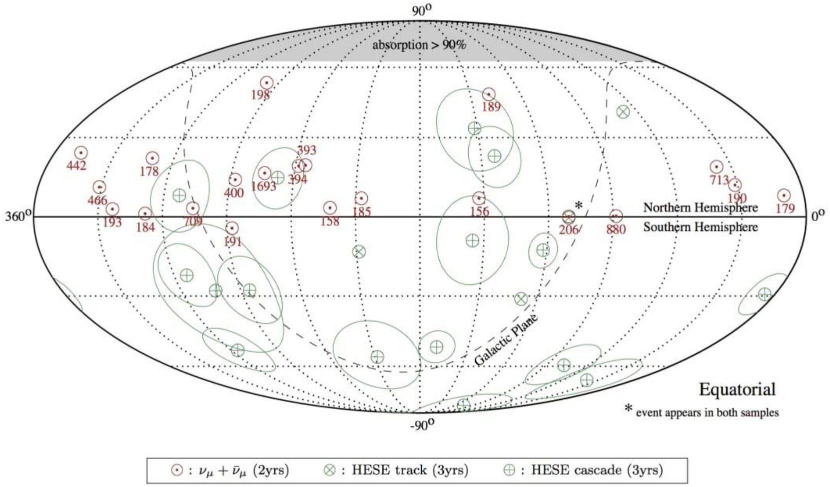
Catalogue of known GRBs

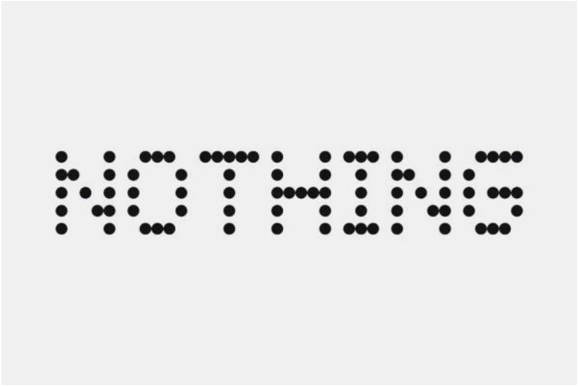
Fermi LAT + GBM coll



Detected HE neutrinos

IceCube coll.





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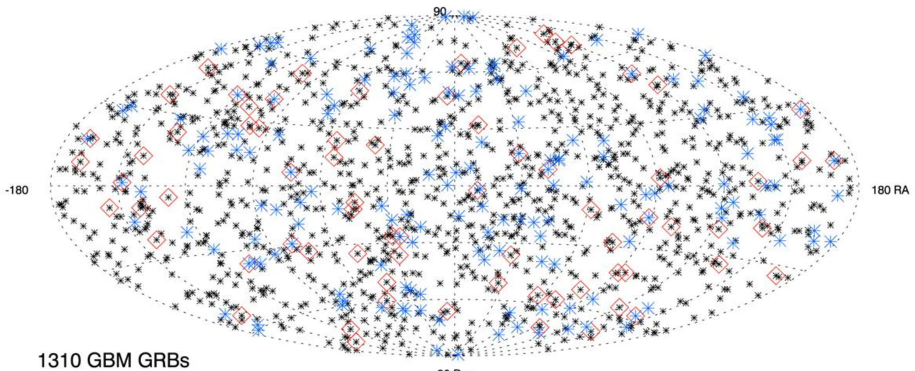

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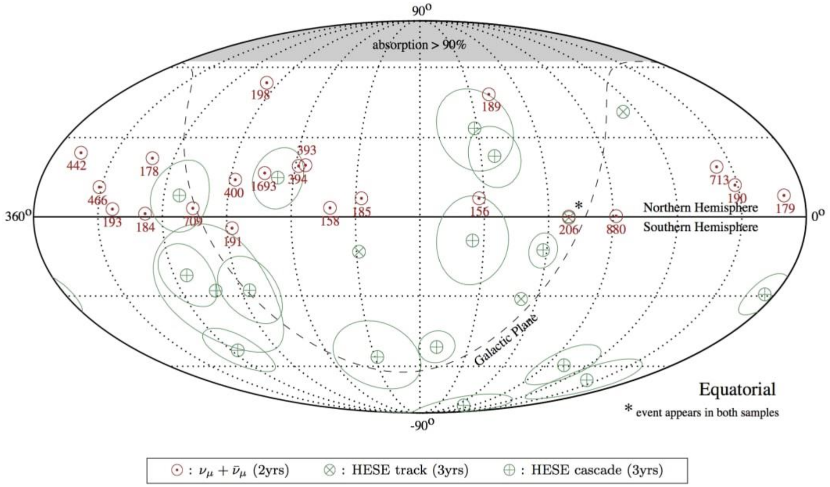
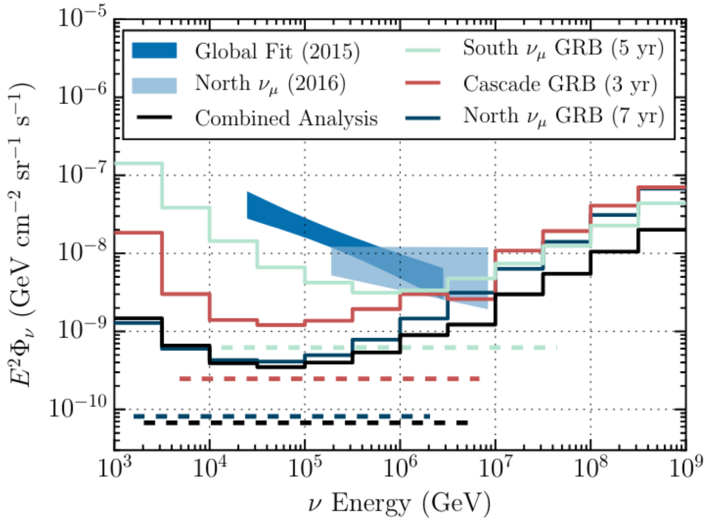


IceCube coll.

upper limit on fluence from **single sources** (powerful for energetic events)

➕

upper limit on **diffuse neutrino flux**



Aartsen et al 2017

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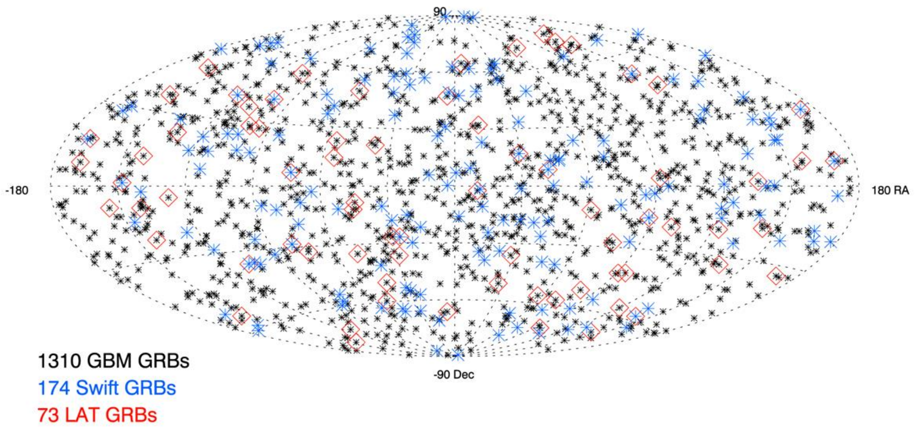

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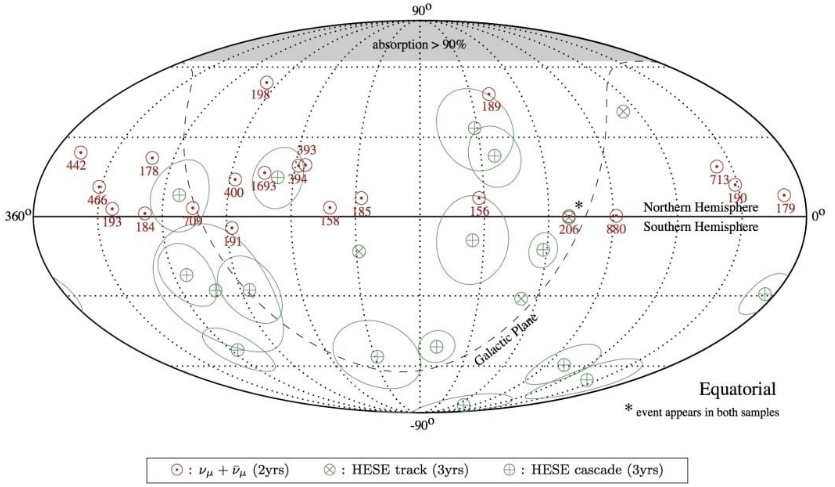
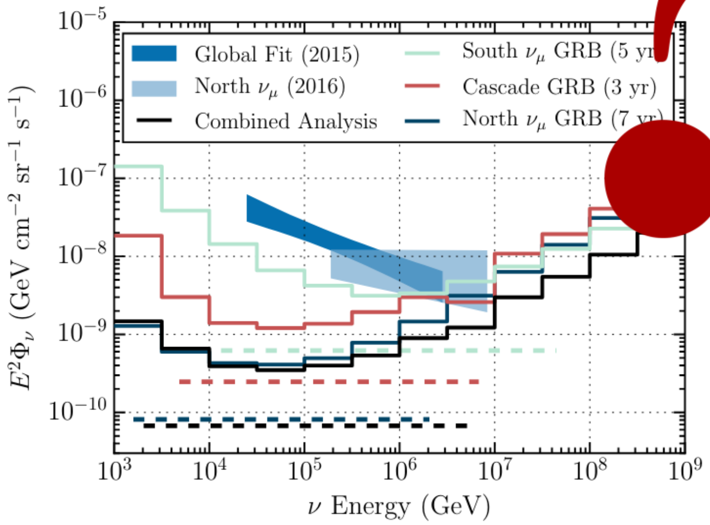


IceCube coll.

upper limit on fluence from **single sources** (powerful for energetic events)

+

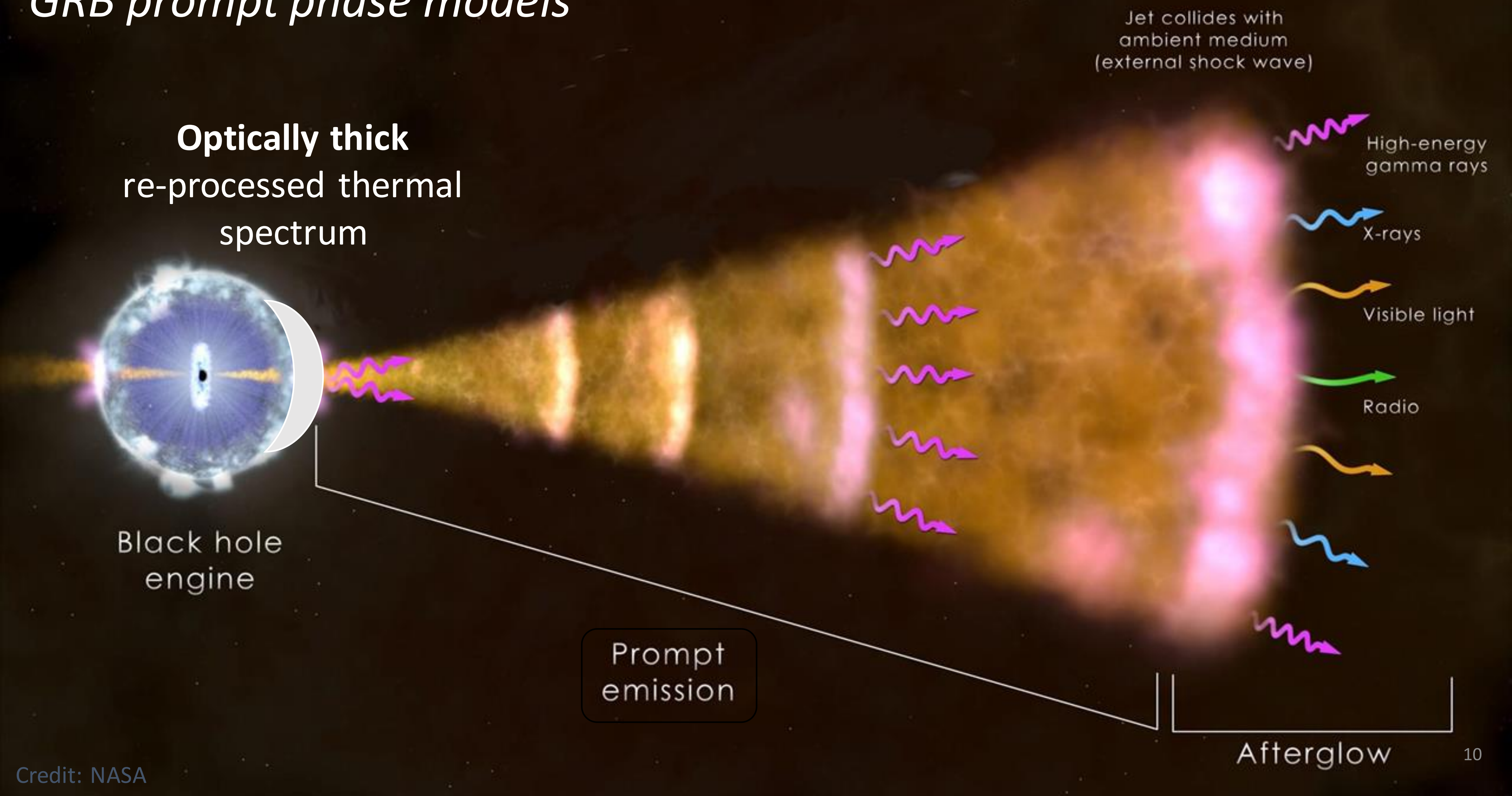
upper limit on **diffuse neutrino flux**



Aartsen et al 2017

GRB prompt phase models

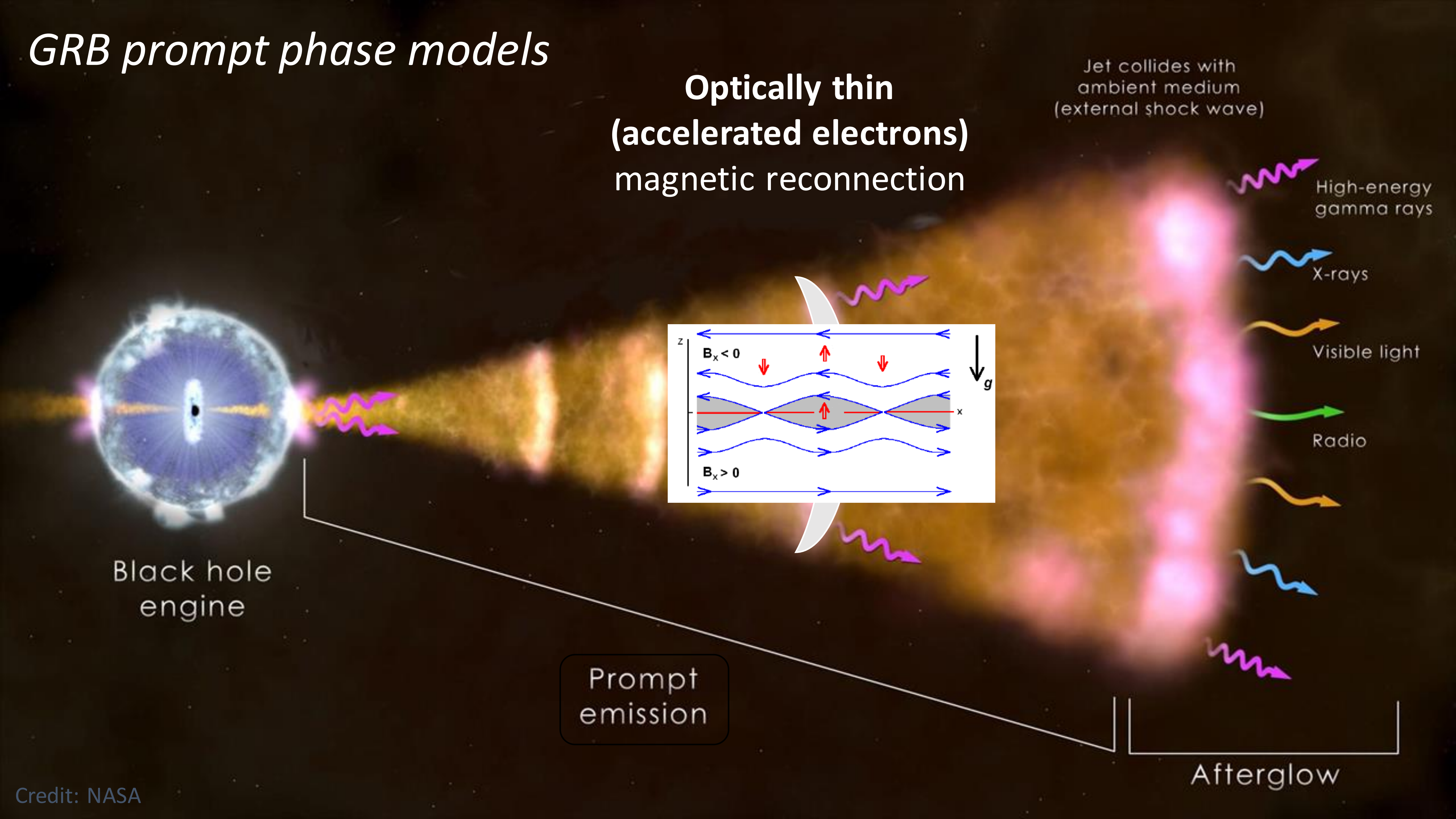
Optically thick
re-processed thermal spectrum



Credit: NASA

GRB prompt phase models

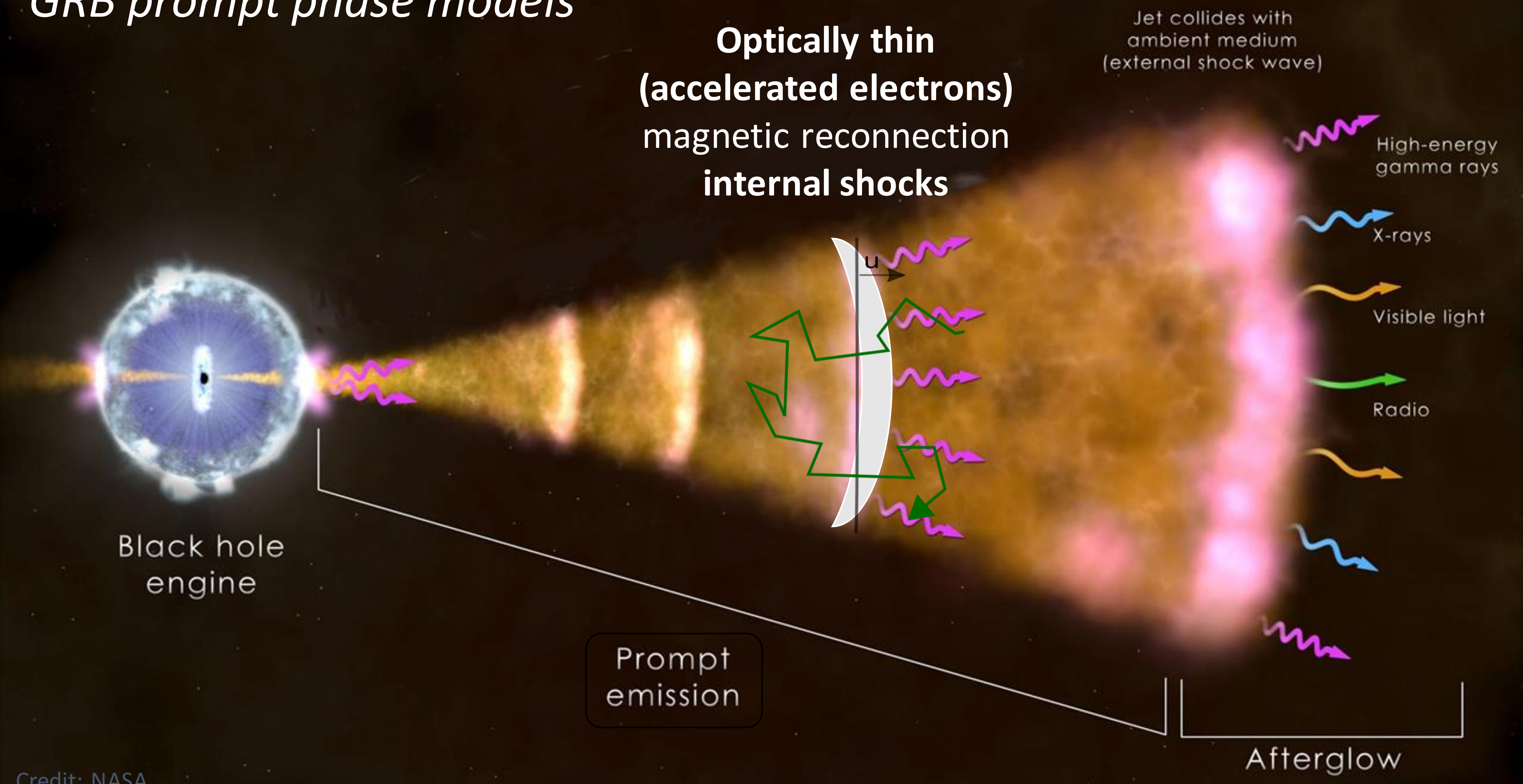
Optically thin
(accelerated electrons)
magnetic reconnection



Credit: NASA

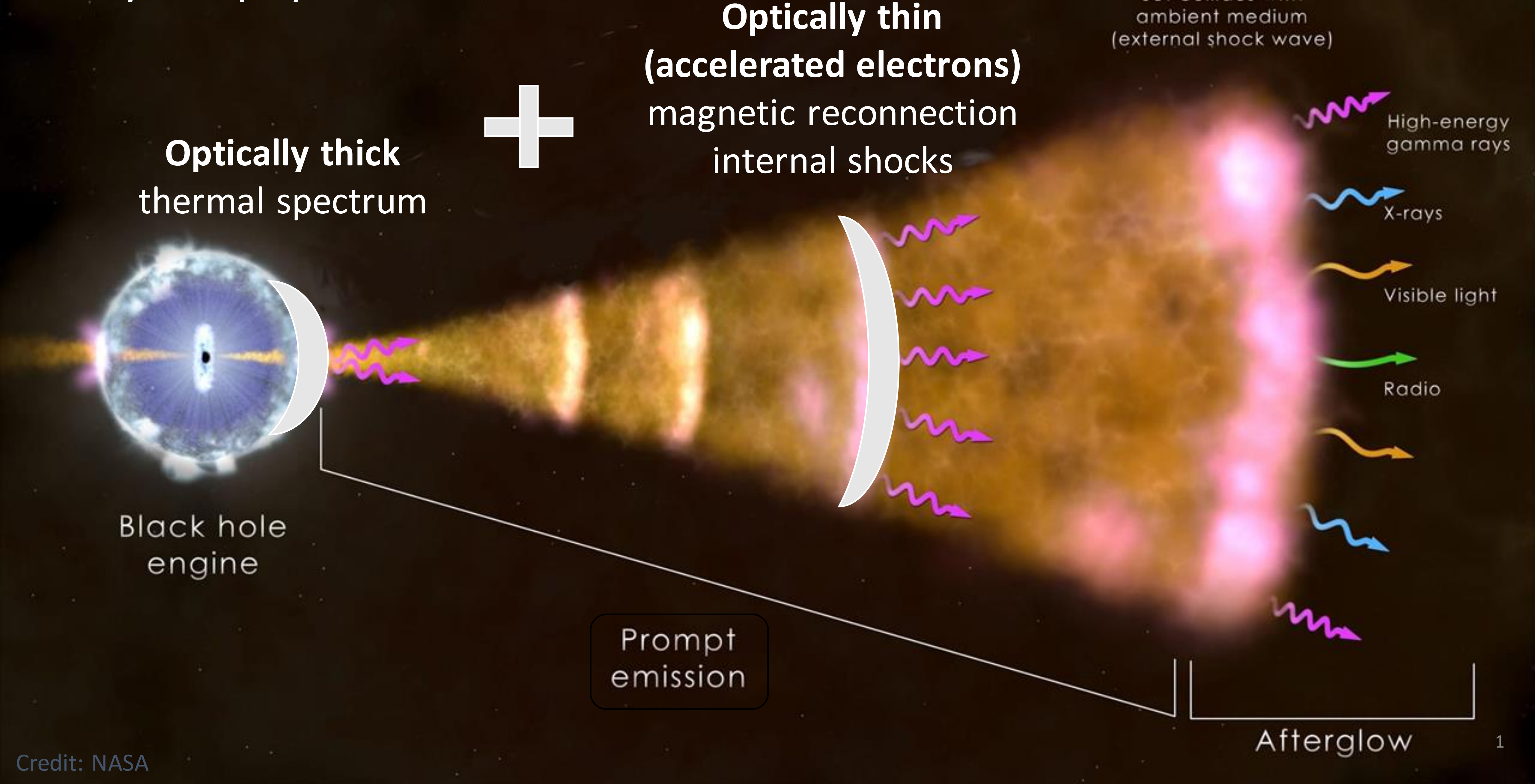
GRB prompt phase models

Optically thin
(accelerated electrons)
magnetic reconnection
internal shocks



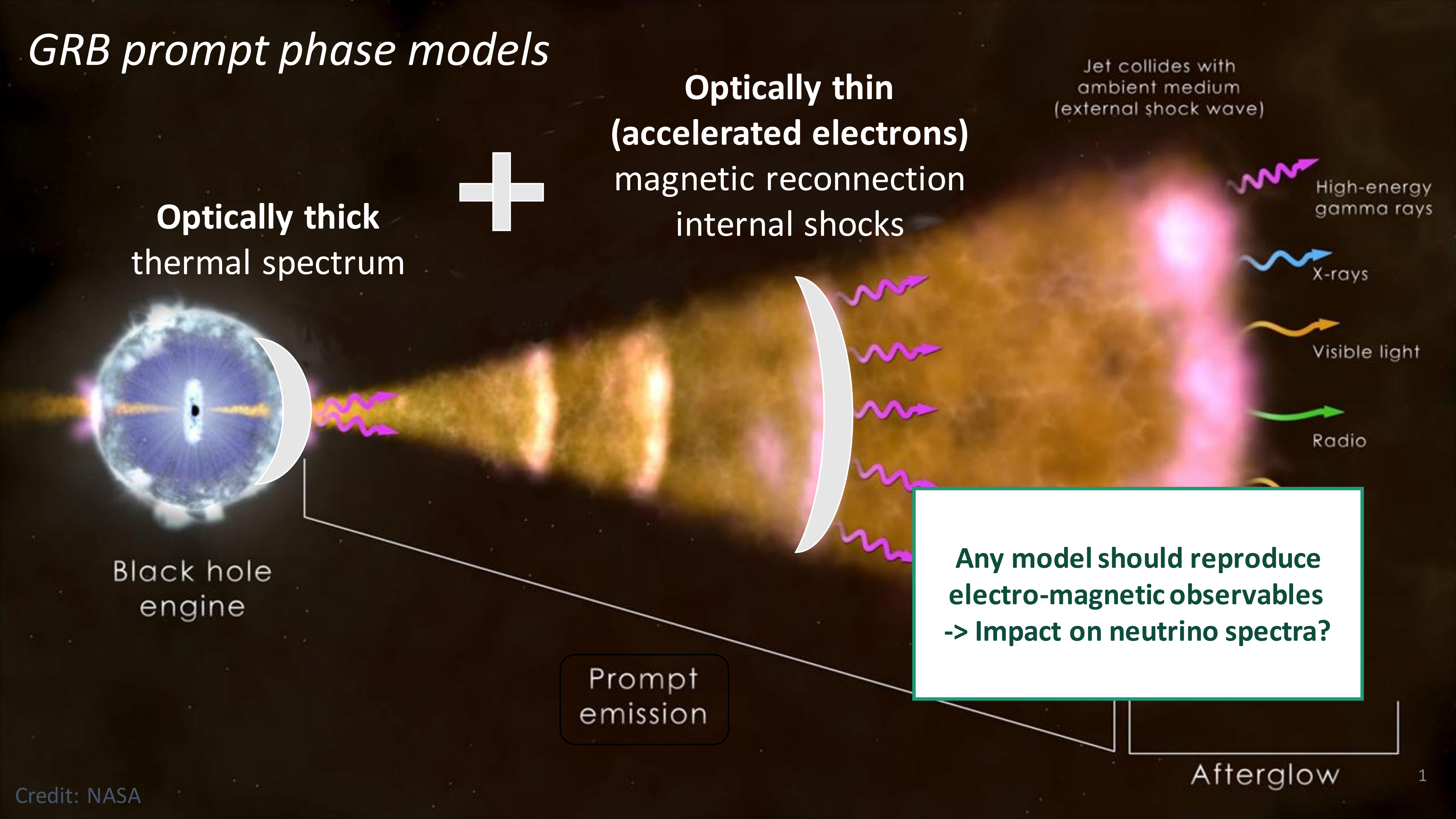
Credit: NASA

GRB prompt phase models



Credit: NASA

GRB prompt phase models



Any model should reproduce electro-magnetic observables
-> Impact on neutrino spectra?

Credit: NASA

Neutrino flux model dependance

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

number of particles

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

Radius from central engine

Comoving width of region

The dissipation model impacts eg:

- Dissipation radius R
- Efficiency: $E_{kin, jet}$ -> $E_{non\text{-}thermal\ particles}$
- Jet composition
- Properties of accelerated particle distributions:
  - $E_{p, min}$ & E_{p_max} + slope of power-law
  - $f_{p/e} = E_{p, non\text{-}th} / E_{e, non\text{-}th}$

Don't forget: Cooling of (intermediate) particles and threshold effects!

Neutrino flux model dependence

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production rate scales with **number density**

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Radius from central engine

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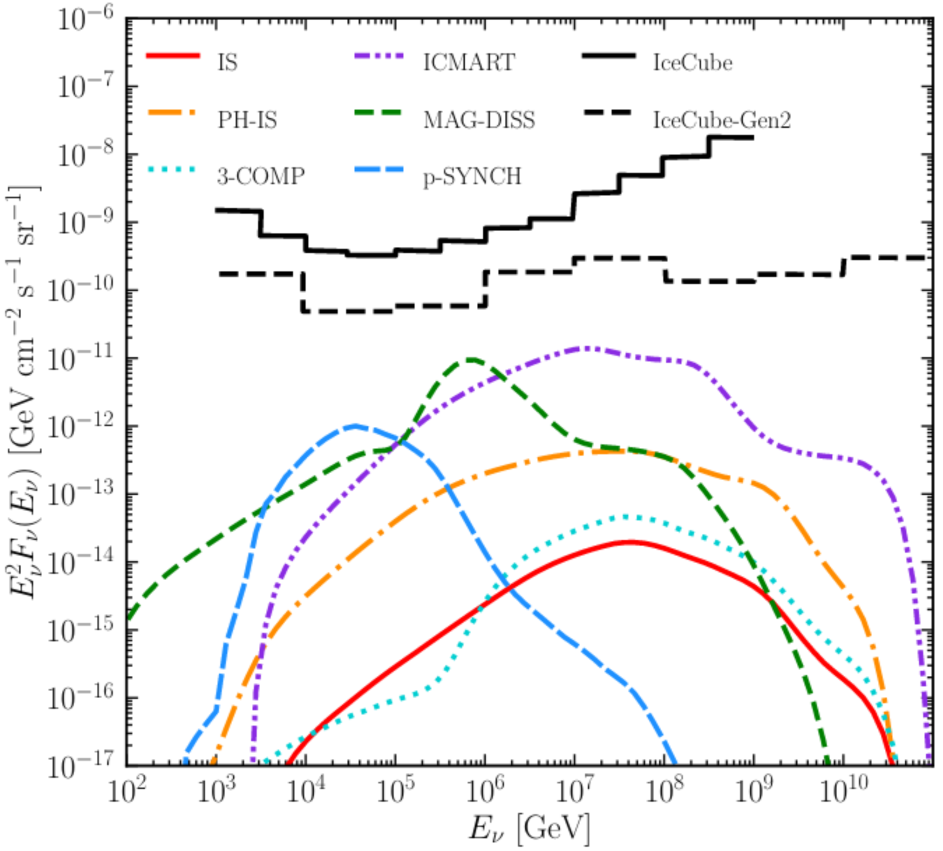
For neutrino production in different models see also eg.
Gao et al JCAP 11 (2012),
Hummer et al PRL 118 (2012),
Zhang & Kumar, PRL 110 (2013),
Baerwald et al Astropart.Phys. 62 (2015)

Model dependence of neutrino fluxes



Pitik et al JCAP 05 (2021)

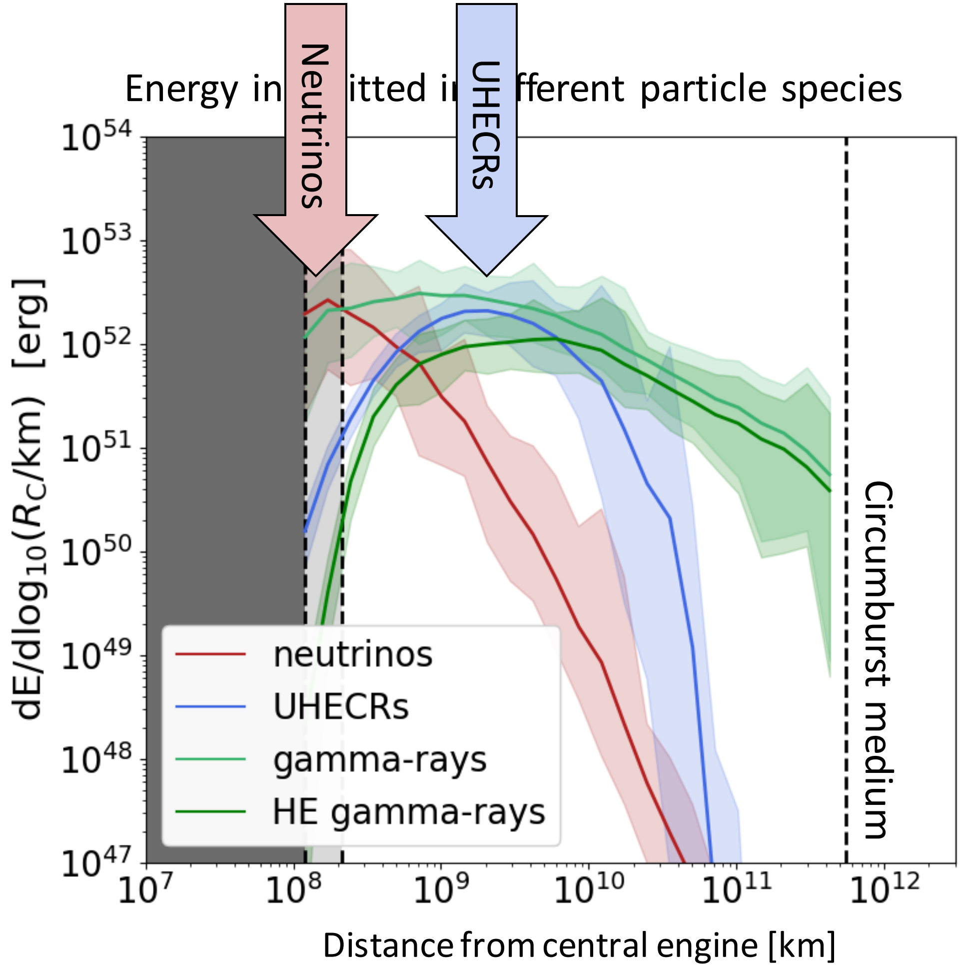
Side note: multiple emission regions

One-zone models:

- A single emission region representative for complete burst

Multi-zone models:

- Multiple emission regions along the jet with varying properties (densities)
- 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)



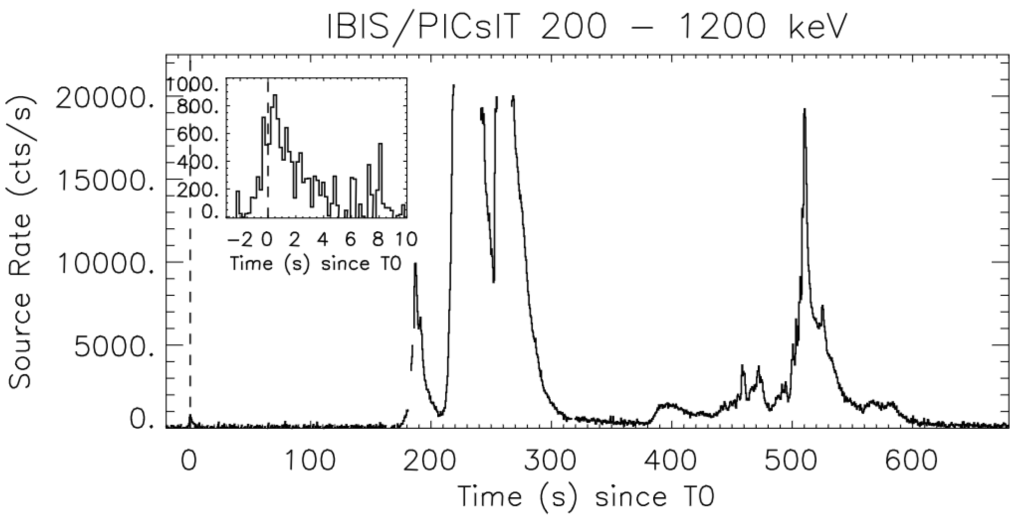
AR et al, ApJ 893 (2020)

Modelling GRB 221009A in the internal shock scenario

GRB 221009A: The BOAT

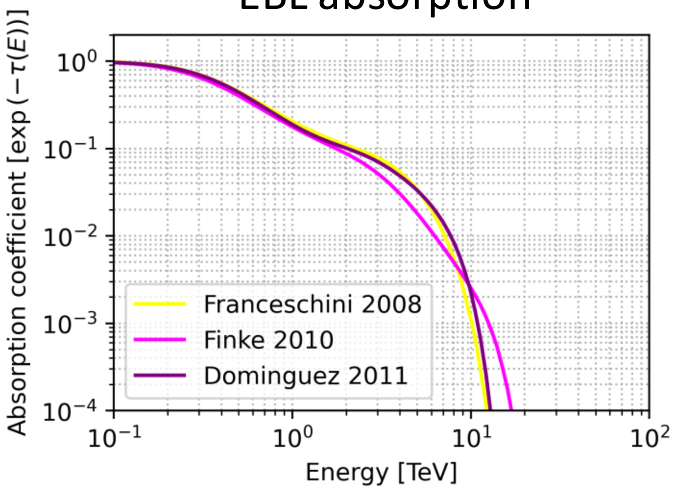
- Very energetic: E_{iso} ~ 10^{55} erg
  + super close: z ~ 0.151
  -> this combination: Once in 10.000 years
- seen by all major instruments and up to VHE (saturation & pile-up effects in many detectors)
- **No neutrinos**
- Peculiarity: LHAASO 18 TeV photon (BSM physics? Prompt/reverse shock/afterglow? *Produced as a UHECR propagation effect?*)

Light curve



Rodi & Umbertini 2023

EBL absorption



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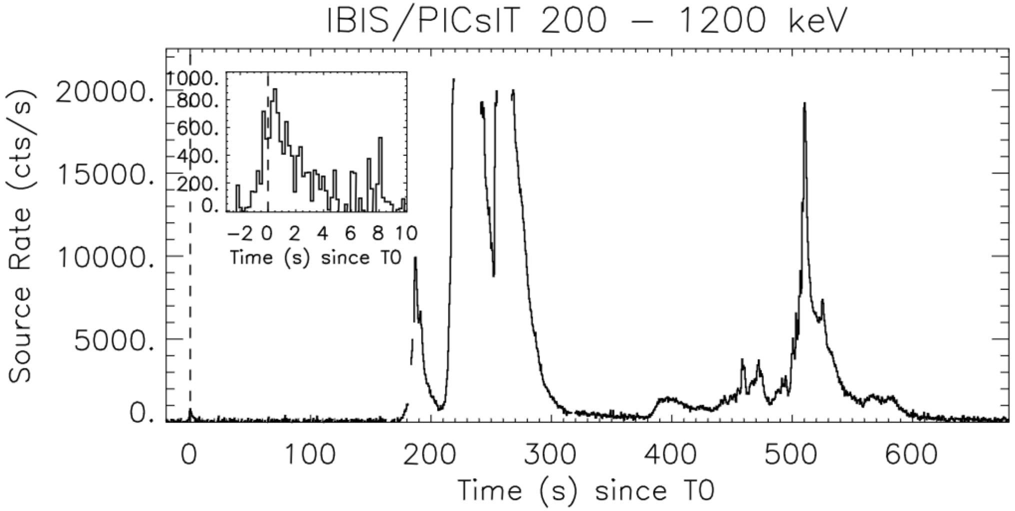
Can we model the event in the internal shock scenario?
What can we learn from neutrino constraints?

Light curve



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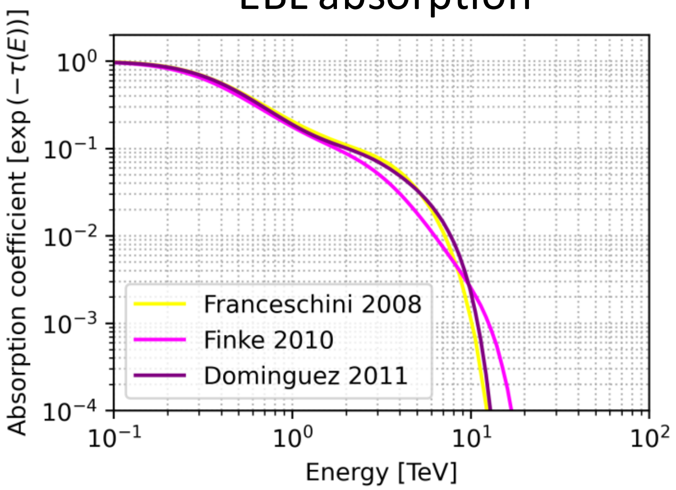
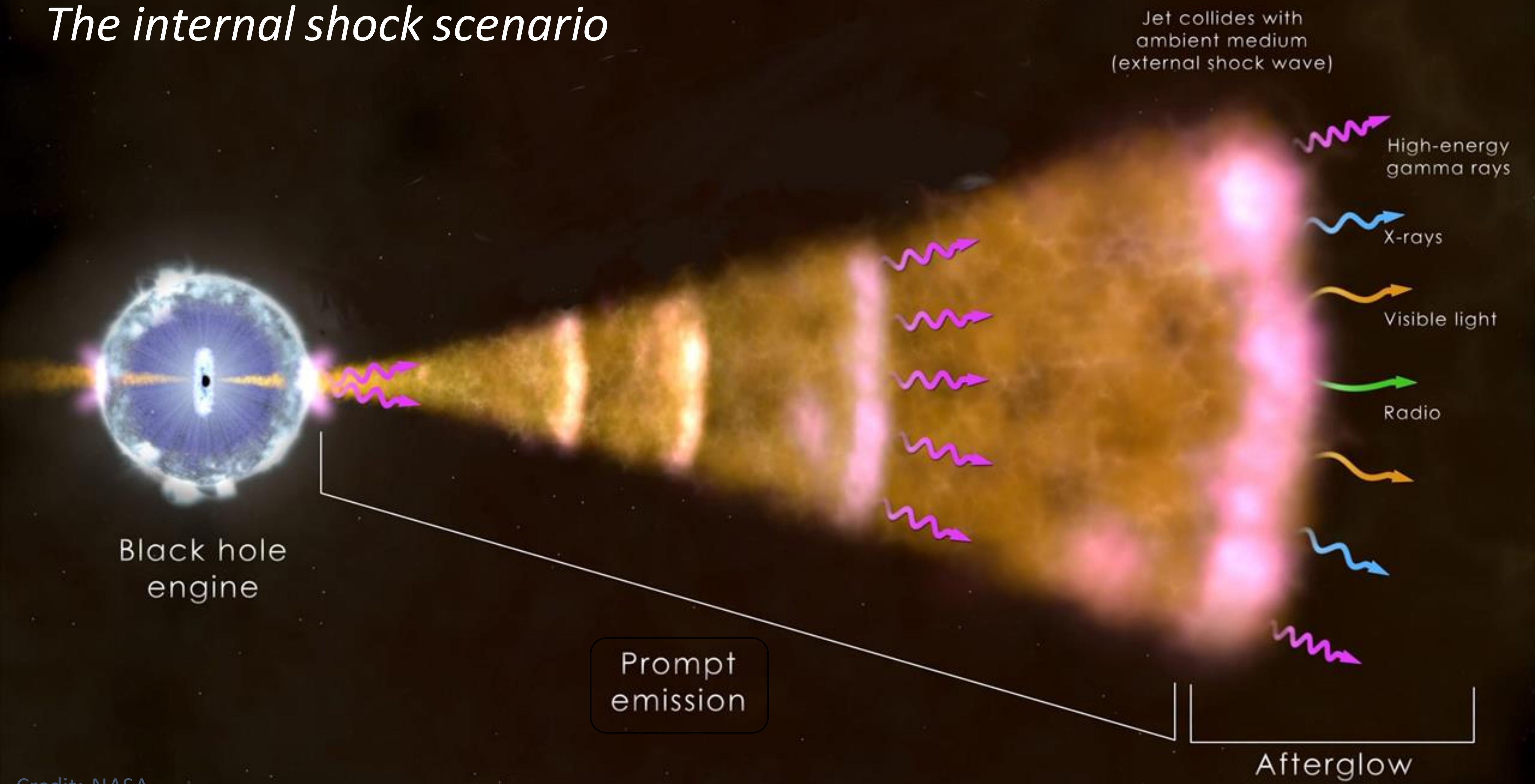


The internal shock scenario



Credit: NASA

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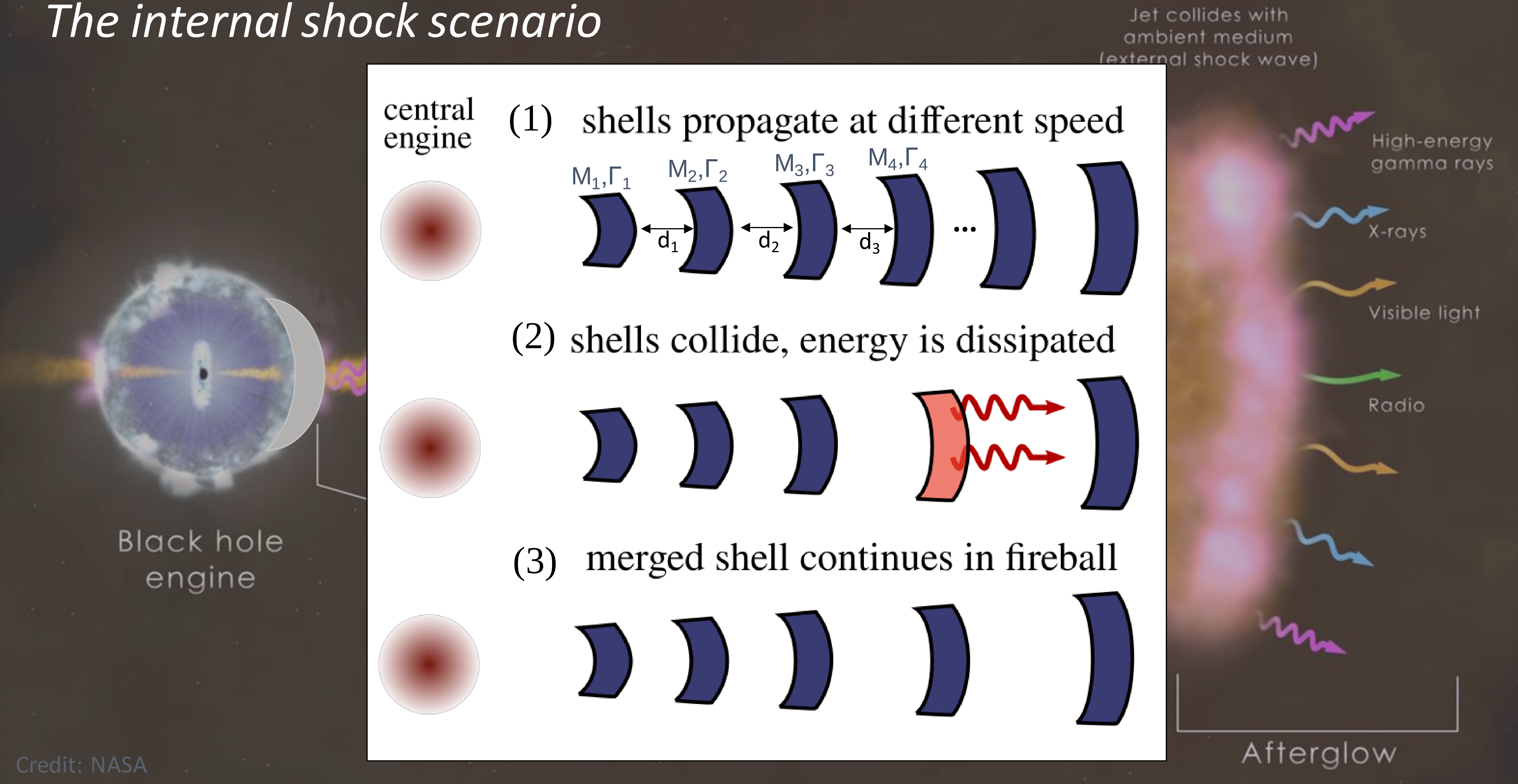
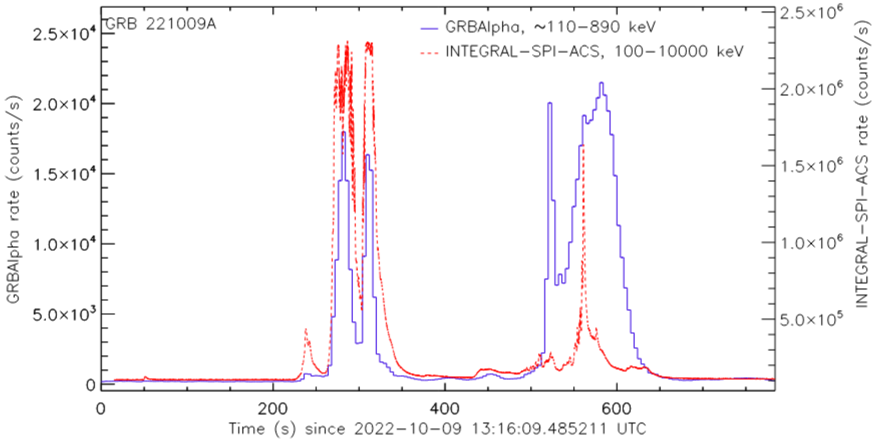


Credit: NASA

Modelling GRB 221009A

$$\langle R \rangle = 2\langle \Gamma \rangle^2 c\delta t_{var}$$

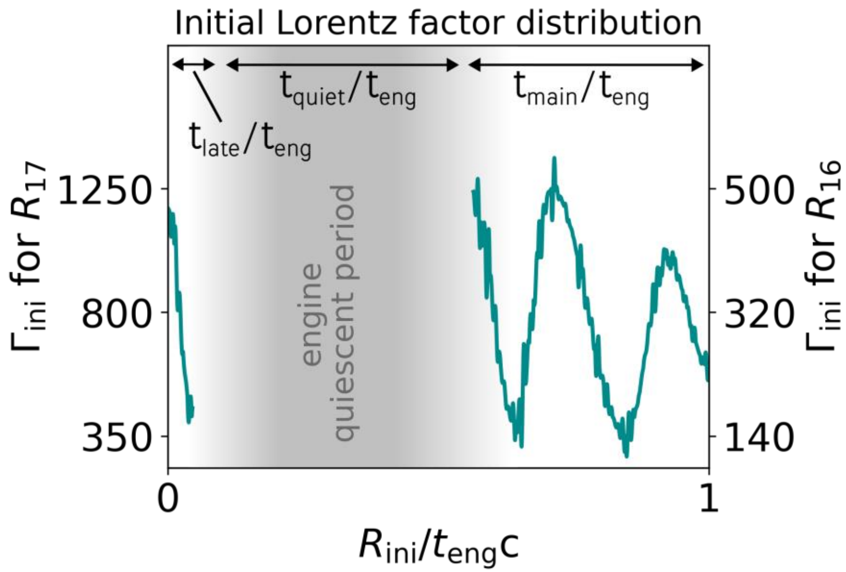
From observations...



+ preliminary analysis:

- $E_{iso} \sim 3\ 10^{54}$ erg
- $E_{peak} \sim 1$ MeV

... to initial conditions



+ assumptions on

- initial jet kinetic energy
- magnetic field
- accelerated particle spectra

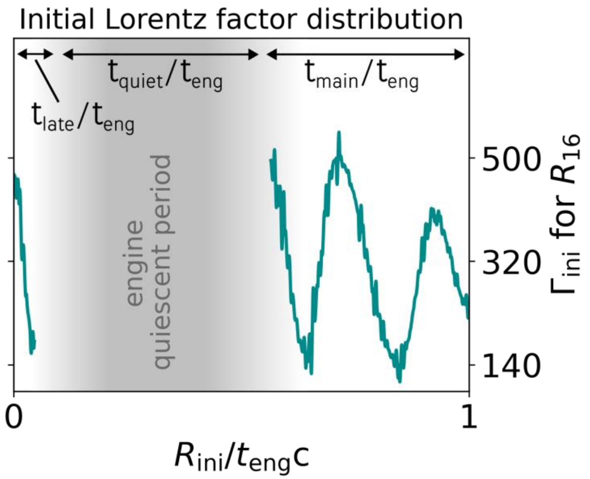
AR et al ApJL 944 (2023)

GRB 221009A

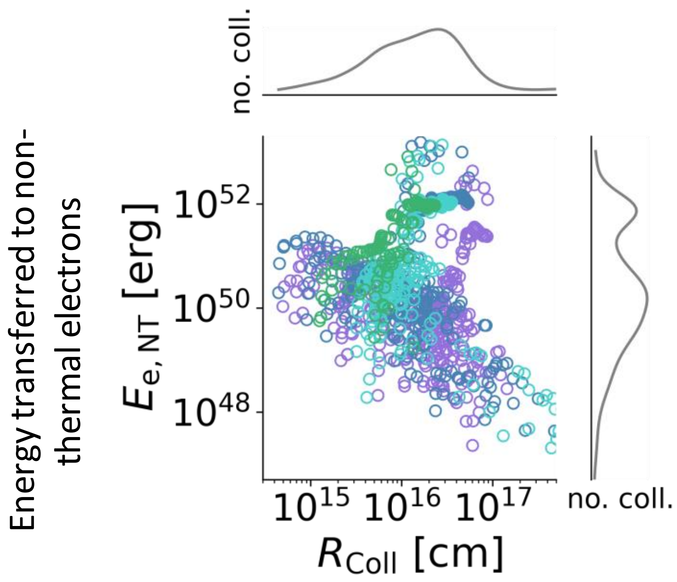
From the initial shell distribution to observable quantities

Fireball evolution

Initial shell distribution → Distribution of collisions



Distance from central engine



Distance from central engine

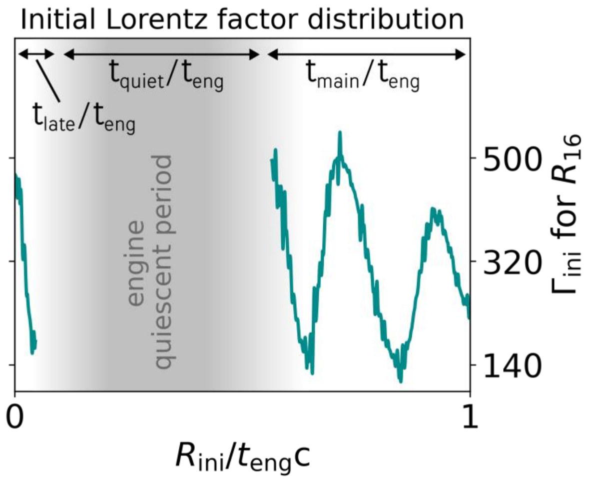
AR et al ApJL 944 (2023)

GRB 221009A

From the initial shell distribution to observable quantities

Initial shell distribution → Fireball evolution → Distribution of collisions → Radiation model

- Emission from each collision
- Solve coupled, non-linear PDEs



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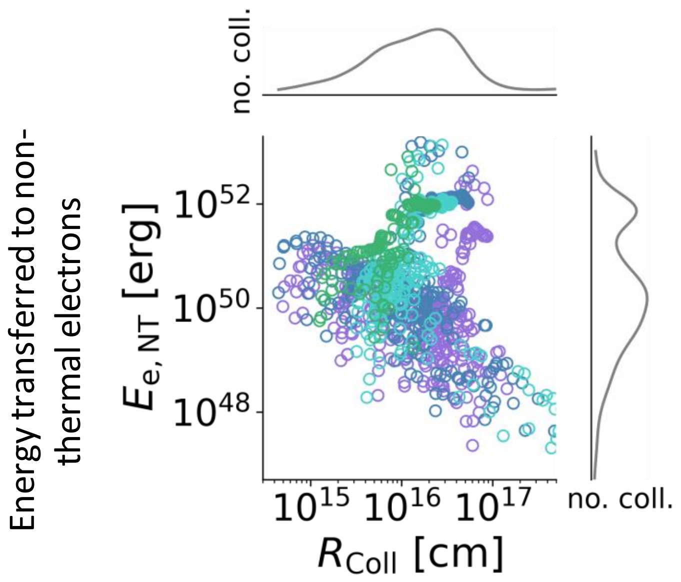
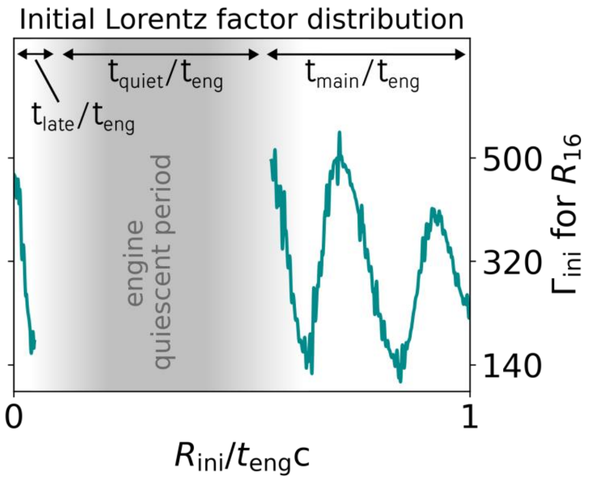


Distance from central engine

GRB 221009A

From the initial shell distribution to observable quantities

Initial shell distribution → Fireball evolution → Distribution of collisions → Radiation model → Particle emission



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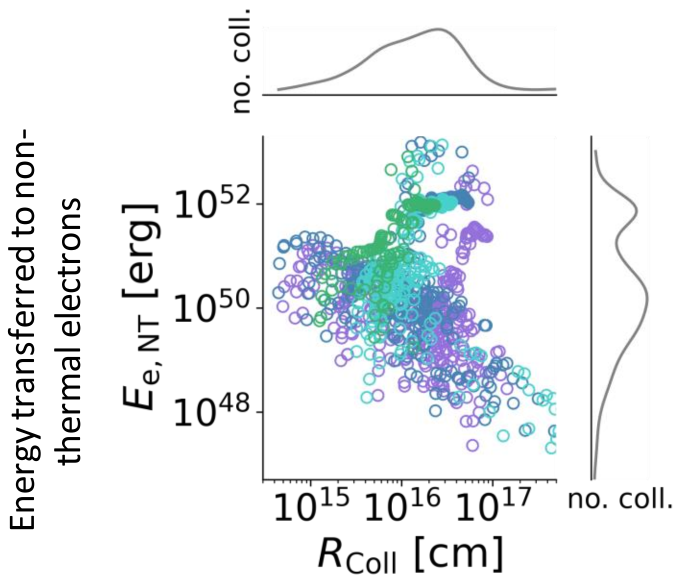

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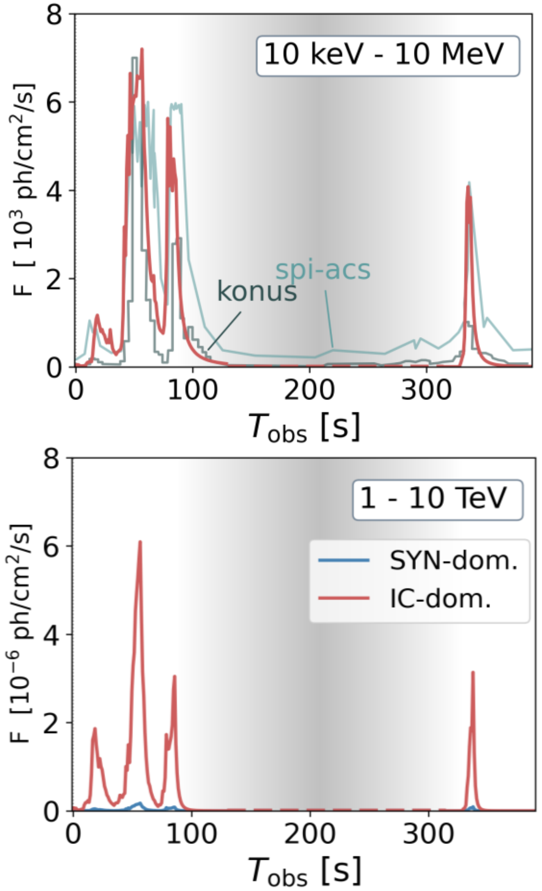

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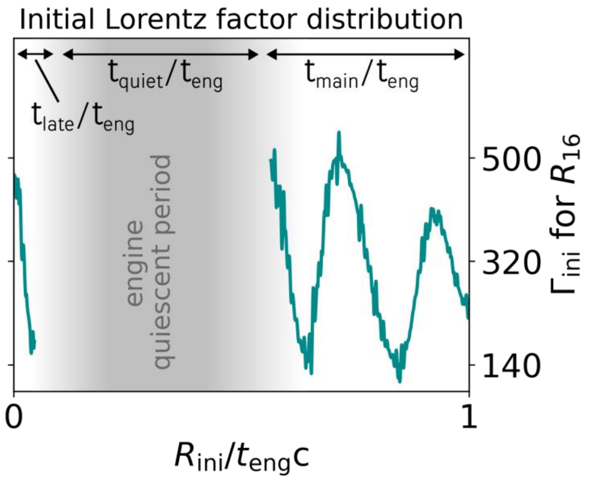

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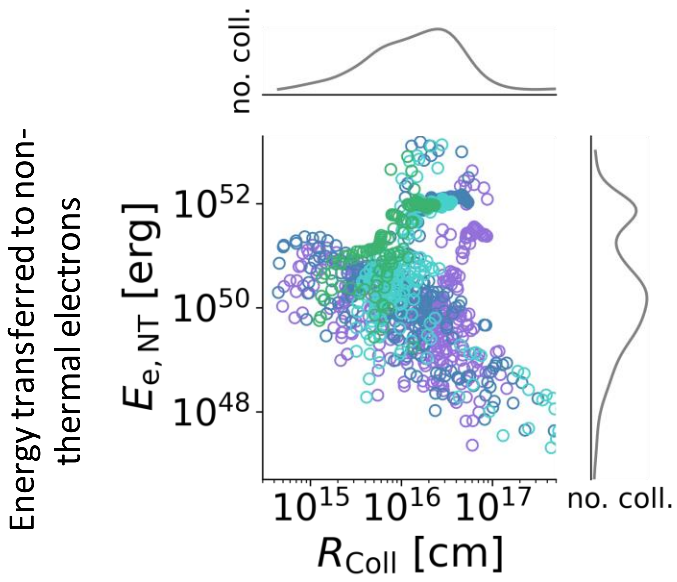

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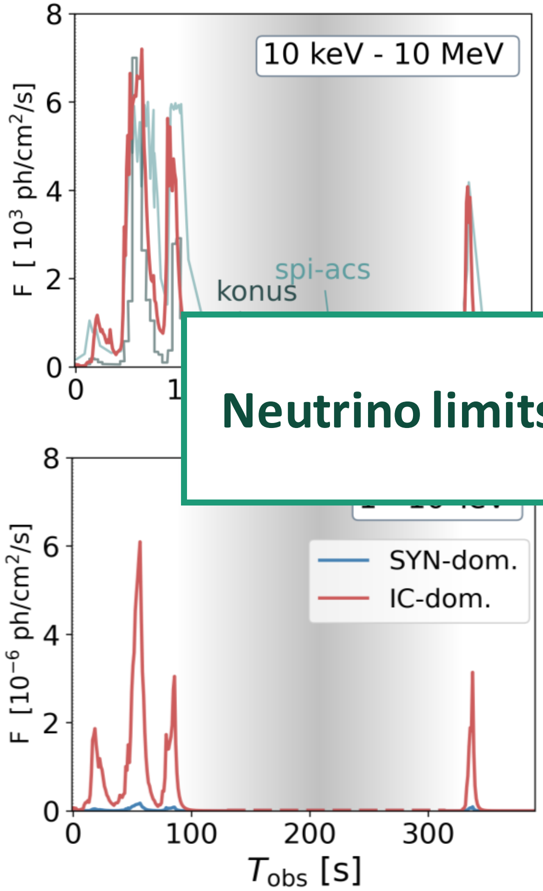
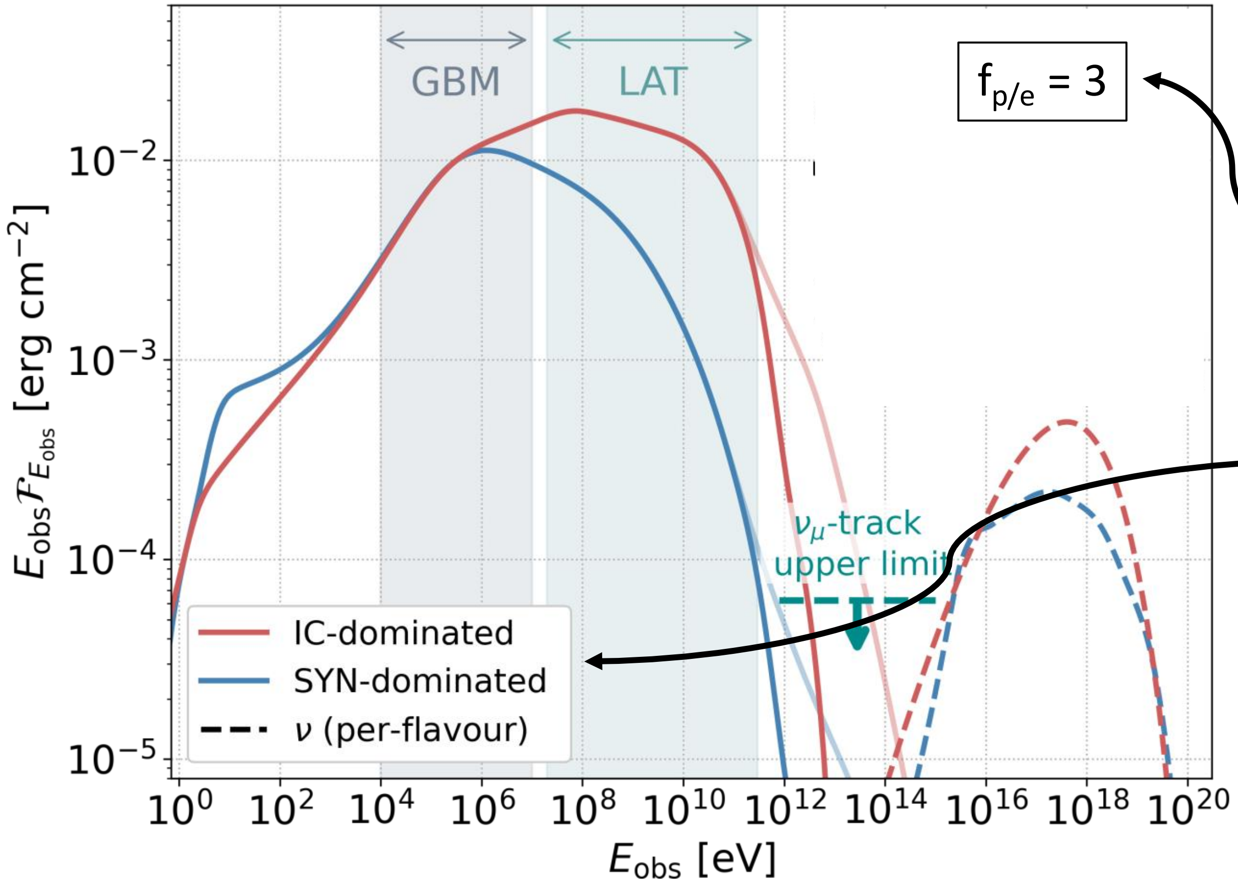


Neutrino limits?

Multi-wavelength & neutrino picture

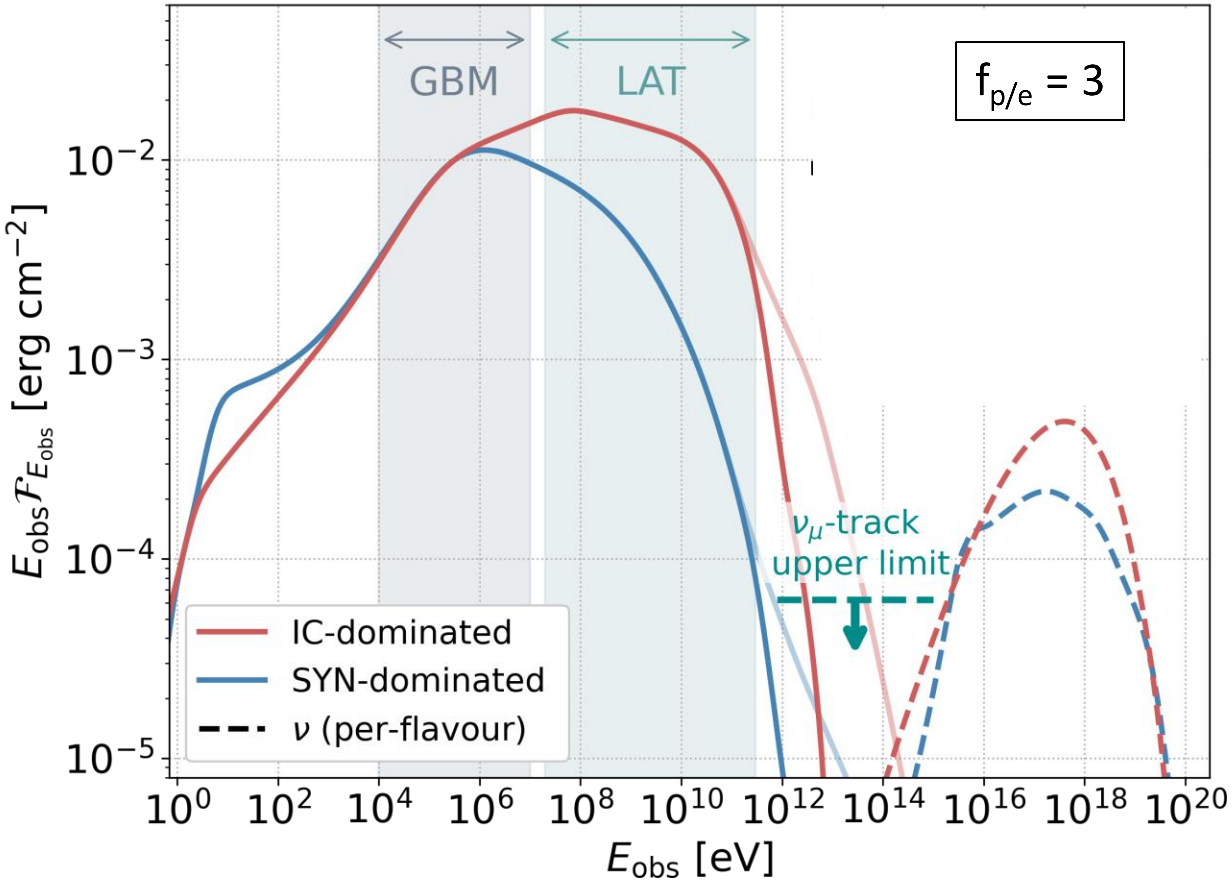


(1) Model assumptions:

1. 3 x more energy into protons than into electrons
   (consistent with source energetics)
2. Strong magnetic fields:
   "Synchrotron - dominated"
   Weak magnetic fields:
   "Inverse Compton – dominated"

AR et al ApJL 944 (2023)

Multi-wavelength & neutrino picture

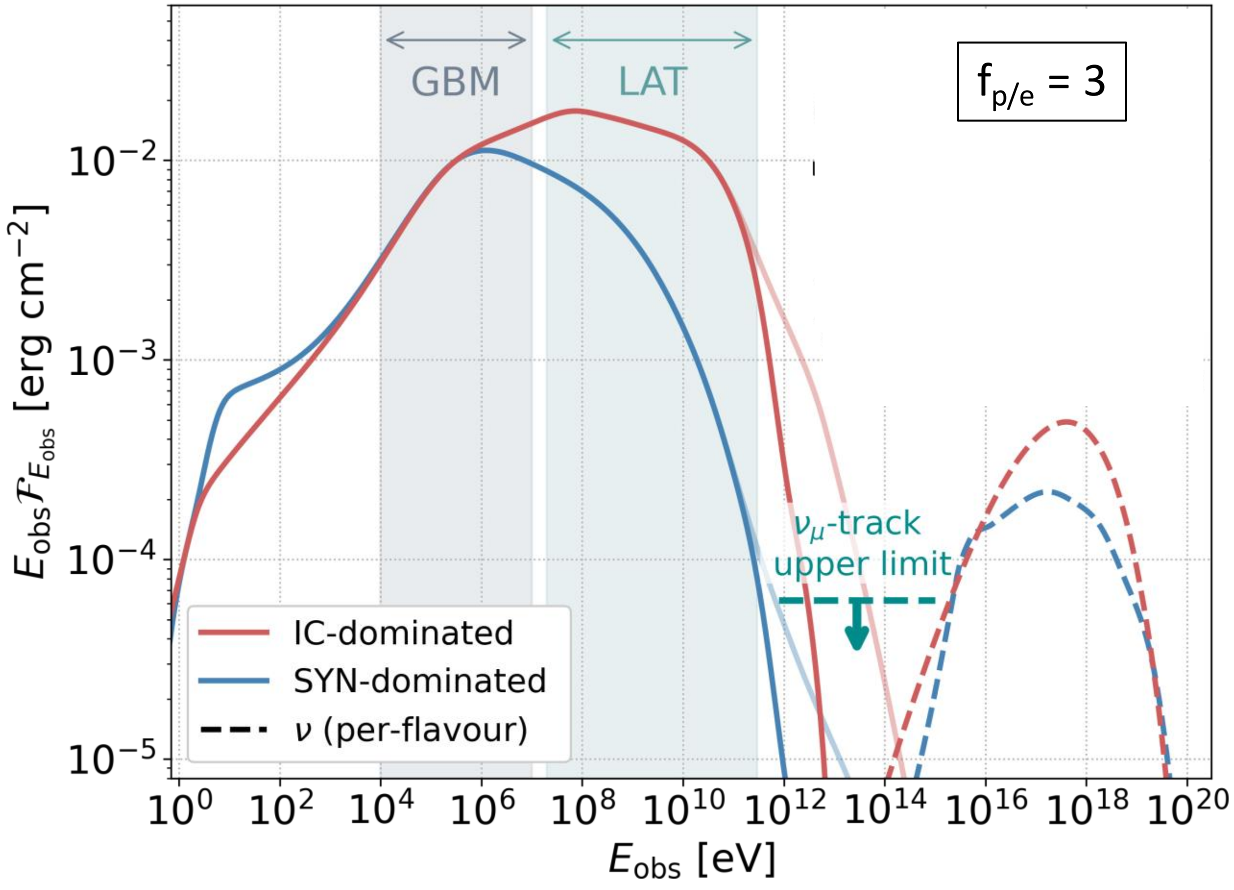


(2) Multi – wavelength predictions

1. Below the MeV-peak similar predictions, differences in LAT band
2. Comparison to photon observations: Too wide around MeV peak?
3. Above ~TeV: suppression due to EBL
4. **(Almost) no signatures from baryons**
   -> source-internal absorption!

AR et al ApJL 944 (2023)

Multi-wavelength & neutrino picture



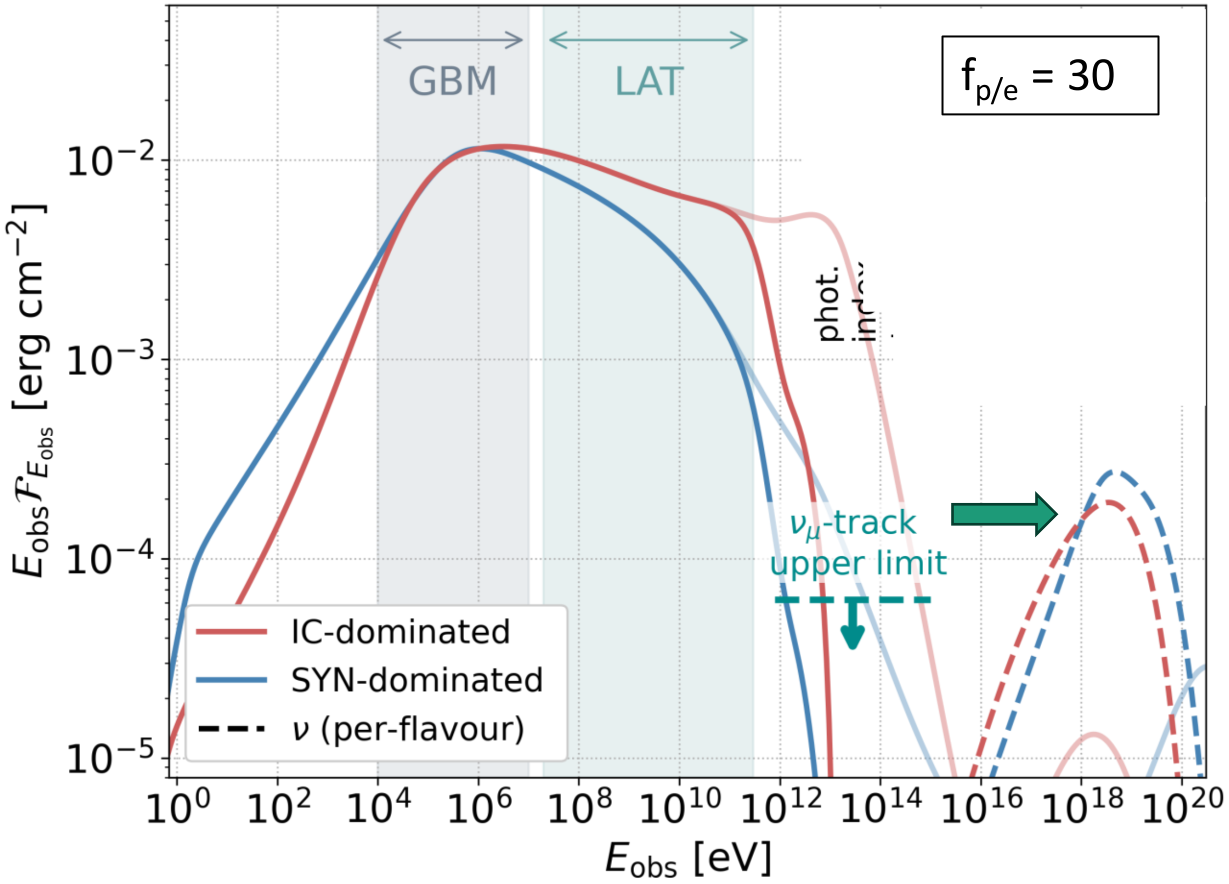
(3) Neutrino predictions

1. Neutrino limits not violated! :)
2. Peak in EeV regime
   -> radio arrays?

AR et al ApJL 944 (2023)

Multi-wavelength & neutrino picture

Emission radius 10x larger



(3) Neutrino predictions

1. Neutrino limits not violated! :)
2. Peak in EeV regime -> radio arrays?
3. **Neutrino fluxes/energies are sensitive to $f_{p/e}$ & dissipation radius** (-> Lorentz factor and variability timescale)

Model-dependent constraints: eg. Ai + Gao ApJ 944 (2023)

AR et al ApJL 944 (2023)

Conclusions

- No neutrinos from GRBs: single source and stacking limits
- Predicted neutrino fluxes depend on **density of emitting region** -> model-dependent!
- Multi-zone models **decouple production regions** of different particle species
- Interpreting neutrino limits of GRB 221009A:
  - consistency with moderate baryon acceleration in the internal shock model for large radii
  - weak photon signatures of baryons. Beware of the cascade!
- Further topics: GRBs as UHECR sources despite stacking limits?