Gamma-Ray Bursts as sources of UHECRs and HE neutrinos

Second EUCAPT Symposium

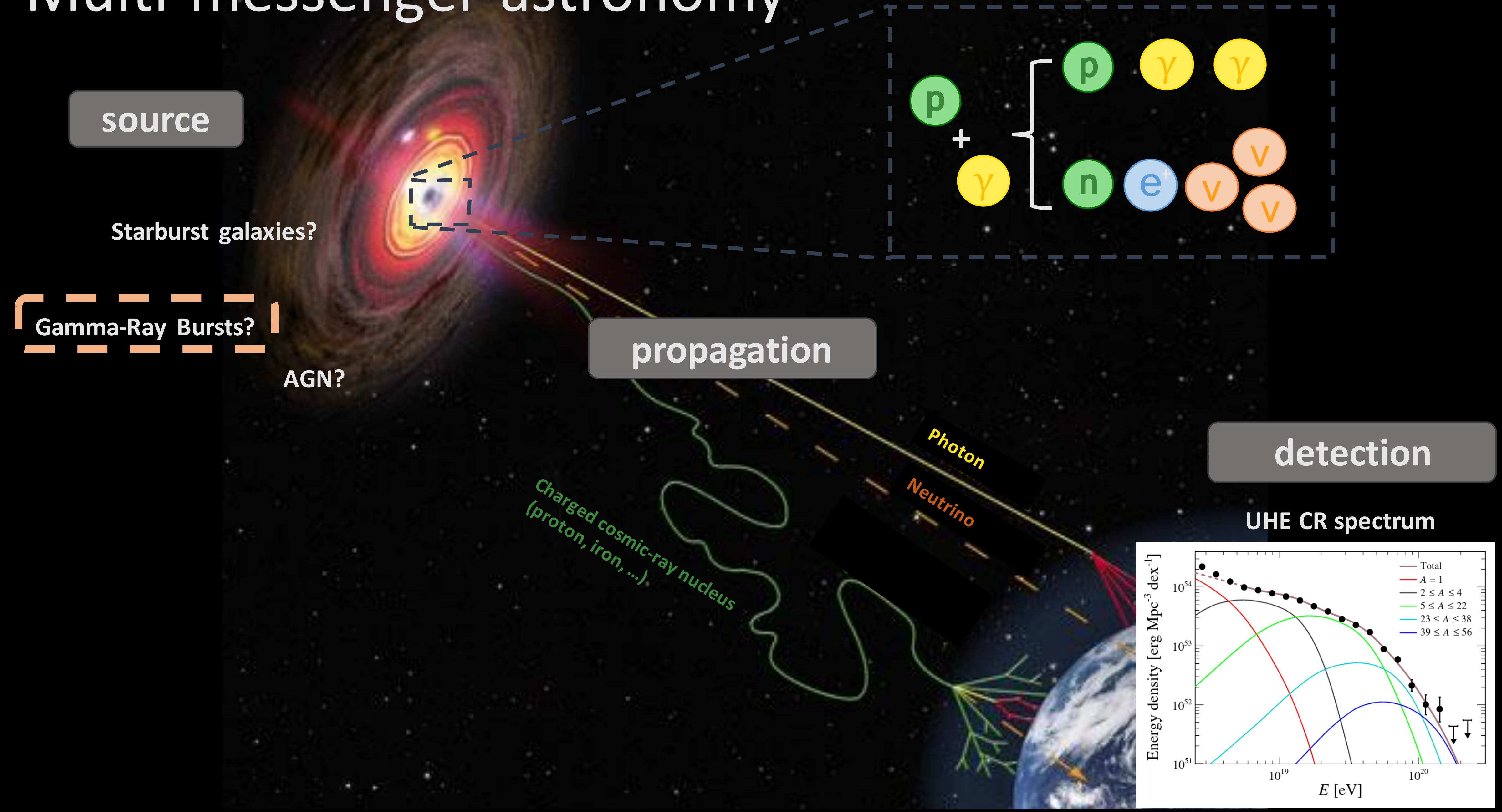
Annika Rudolph

24.05.2022

HELMHOLTZ RESEARCH FOR GRAND CHALLENGES

DESY.

Multi-messenger astronomy



Auger Coll 2020 (arxiv 2008.06488)

Gamma-Ray Bursts

Observational properties of GRBs

- Energetic outbursts of gamma-rays

  $E_{iso} \sim 10^{49} - 10^{55}$ erg
- Two populations by duration:

  (1) Long GRBs : ~ 2 – 100 s

  progenitor: death of massive stars

  (2) Short GRBs: ~ 0.1 – 2 s

  progenitor: merger of 2 compact objects
- Large variety of **light curves with fast time variability**
- **Similar spectra** (narrow broken power law)

Examples of observed light curves

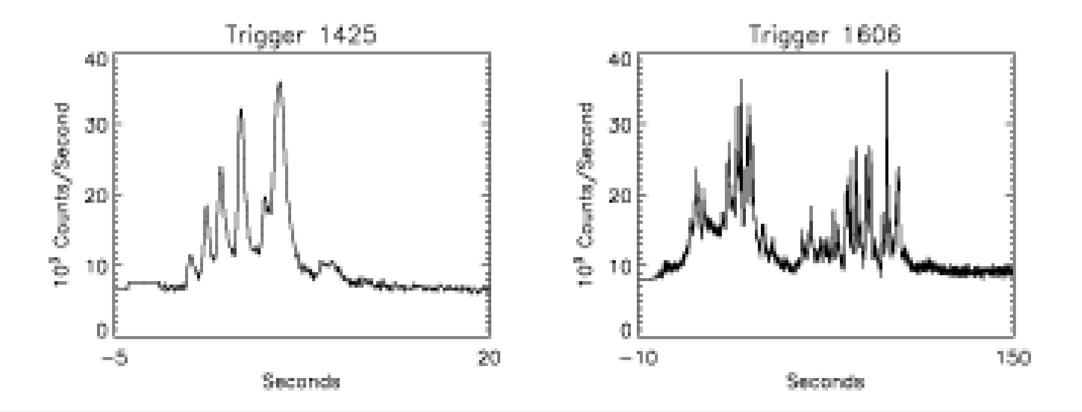
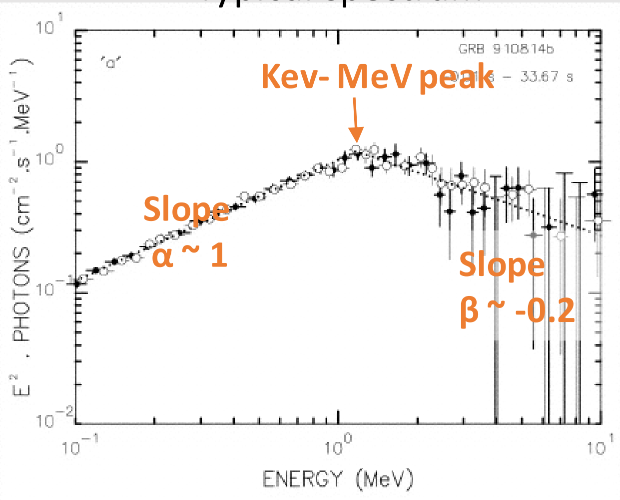


Image credit: J.T. Bonnell (NASA/GSFC)

Typical spectrum



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

Gamma-Ray Bursts

Observational properties of GRBs

- Energetic outbursts of gamma-rays

  $E_{iso} \sim 10^{49} - 10^{55}$ erg
- Two populations by duration:

  (1) Long GRBs : ~ 2 – 100 s

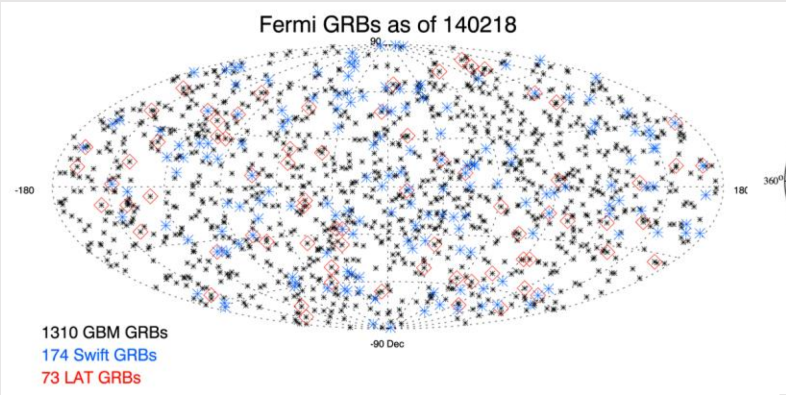
  progenitor: death of massive stars

  (2) Short GRBs: ~ 0.1 – 2 s

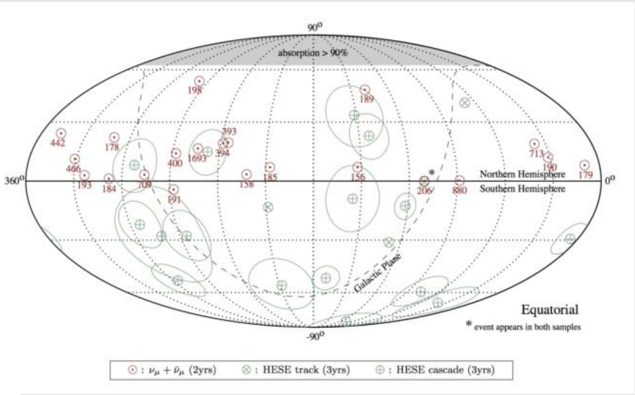
  progenitor: merger of 2 compact objects
- Large variety of **light curves with fast time variability**
- **Similar spectra** (narrow broken power law)
- **No correlation between observed GRBs and HE neutrinos (-> limits neutrino production efficiency in GRBs)**

Catalogue of known GRBs

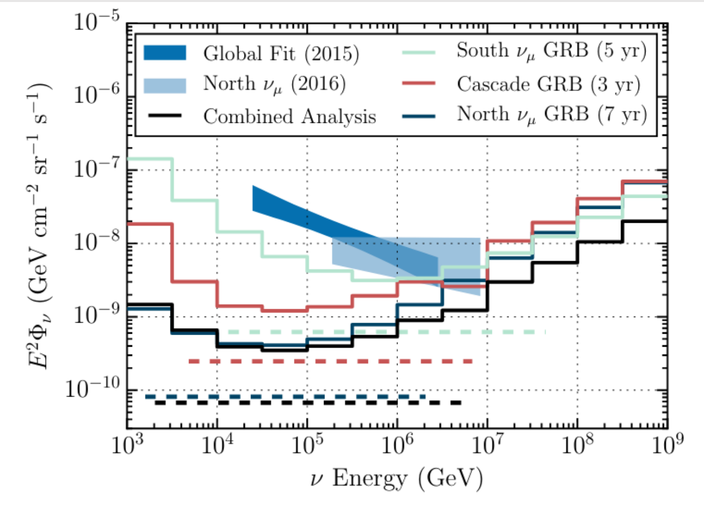
Fermi LAT + GBM coll



Detected HE neutrinos



IceCube coll.



Aartsen et al 2017

The Fireball model

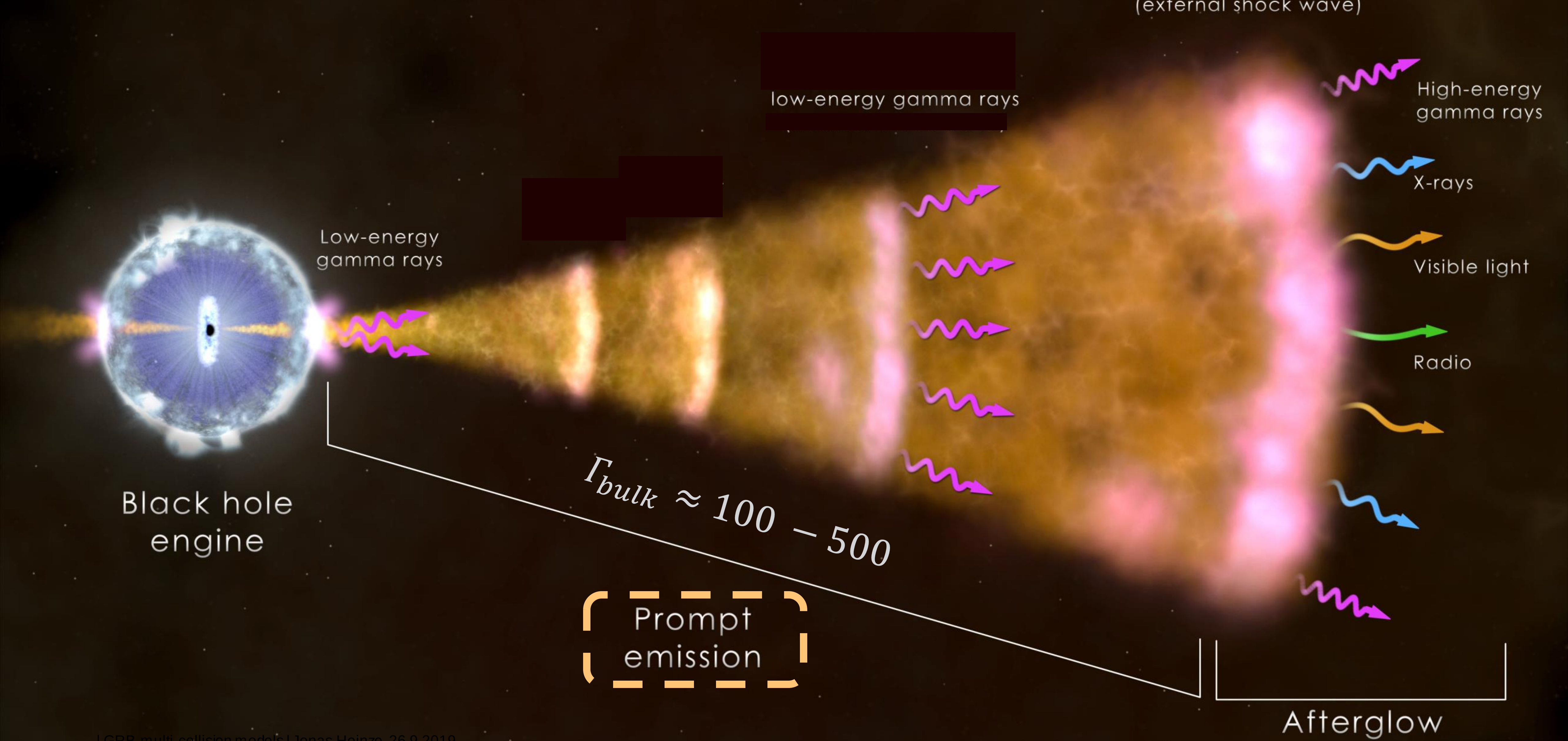
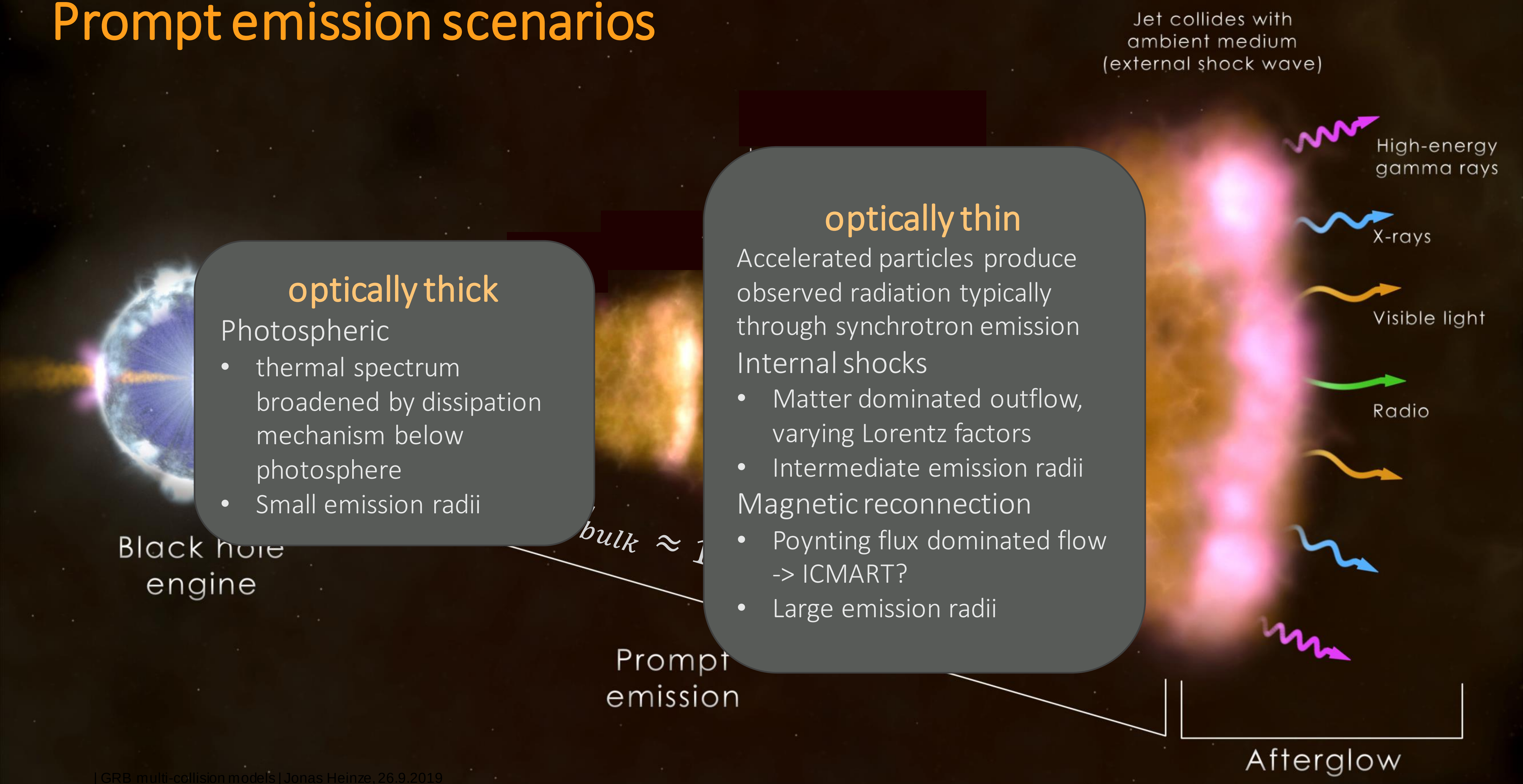


Image credit: NASA's Goddard Space Flight Center

Prompt emission scenarios



optically thick

Photospheric

- thermal spectrum broadened by dissipation mechanism below photosphere
- Small emission radii

optically thin

Accelerated particles produce observed radiation typically through synchrotron emission

Internal shocks

- Matter dominated outflow, varying Lorentz factors
- Intermediate emission radii

Magnetic reconnection

- Poynting flux dominated flow -> ICMART?
- Large emission radii

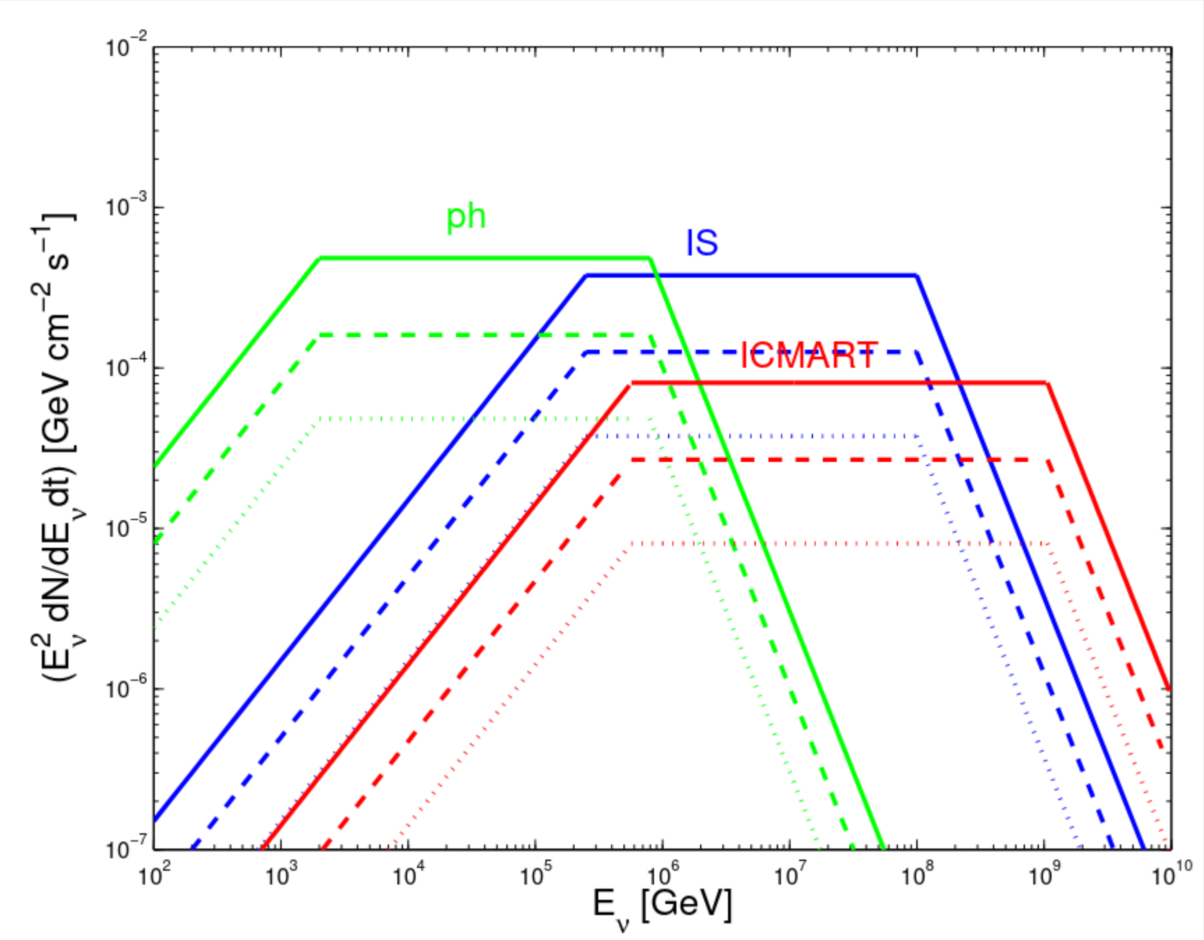
Model-dependent neutrino fluxes

Neutrinos from photo-hadronic interactions:
production rate depends on number **density**

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

Radius from central engine

Comoving width of region



Zhang & Kumar, PRL 110 (2013)

For neutrino production in different models see also eg.
Gao et al JCAP 11 (2012), Hummer et al PRL 118 (2012)
Baerwald et al Astropart.Phys. 62 (2015), Pitik et al JCAP 05 (2021)

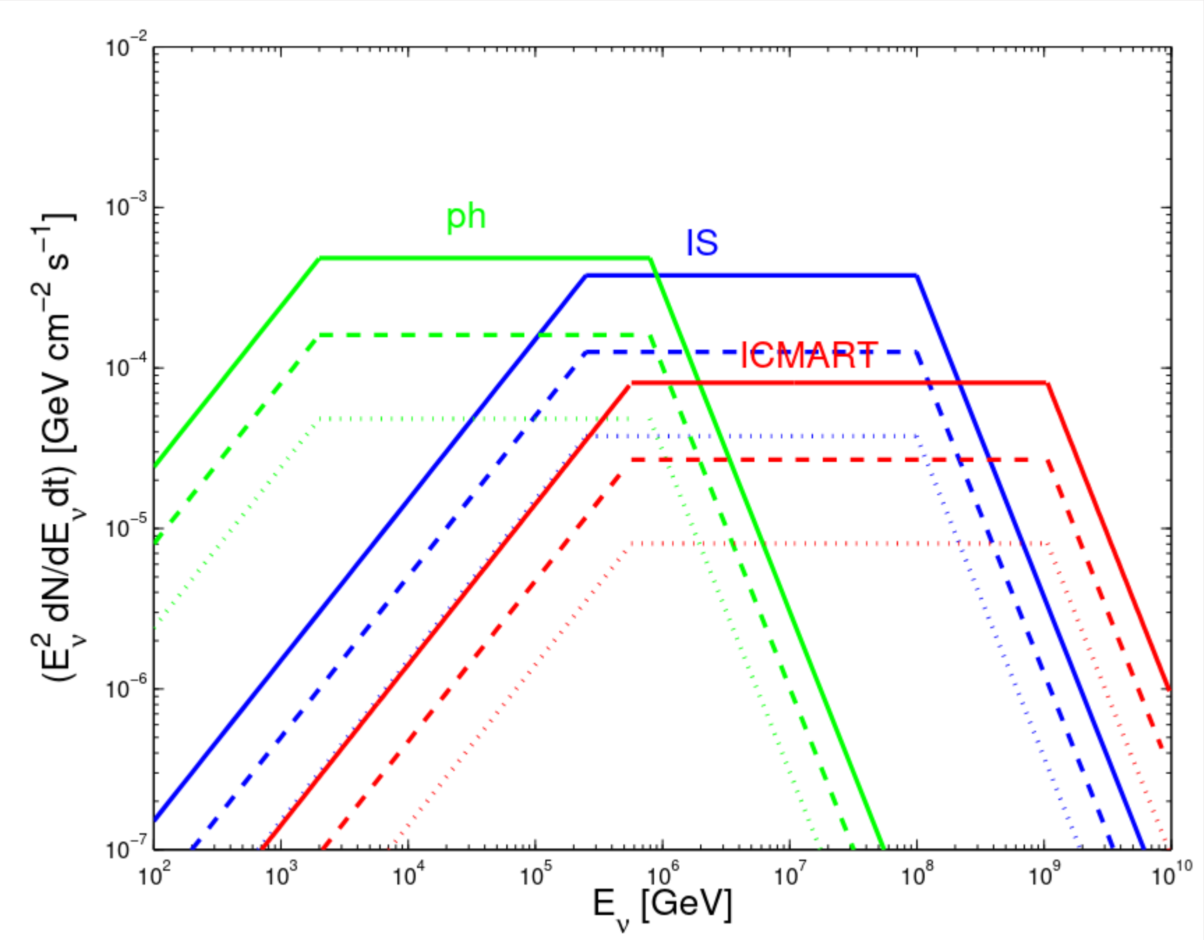
Model-dependent neutrino fluxes

Neutrinos from photo-hadronic interactions:
production rate depends on number **density**

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

Typical radii:

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



Zhang & Kumar, PRL 110 (2013)

For neutrino production in different models see also eg.
Gao et al JCAP 11 (2012), Hummer et al PRL 118 (2012)
Baerwald et al Astropart.Phys. 62 (2015), Pitik et al JCAP 05 (2021)

Model-dependent neutrino fluxes

Neutrinos from photo-hadronic interactions: production rate depends on number **density**

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

N depends on energy transferred to cosmic rays, scales with:
(1) Total energy budget
(2) '**baryonic loading**':

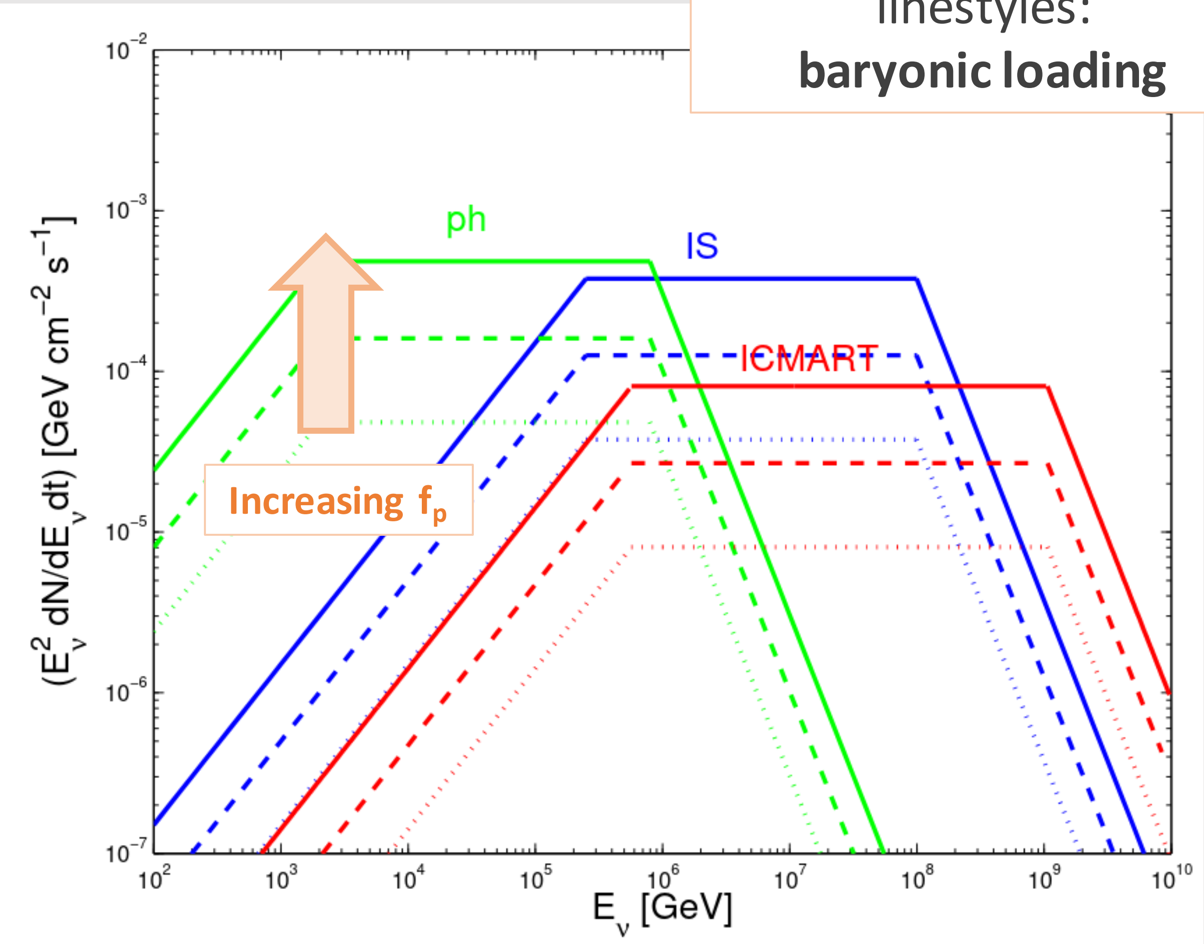
$$f_p = \frac{U_p}{U_e}$$

energy density of accelerated cosmic rays

energy density of accelerated electrons

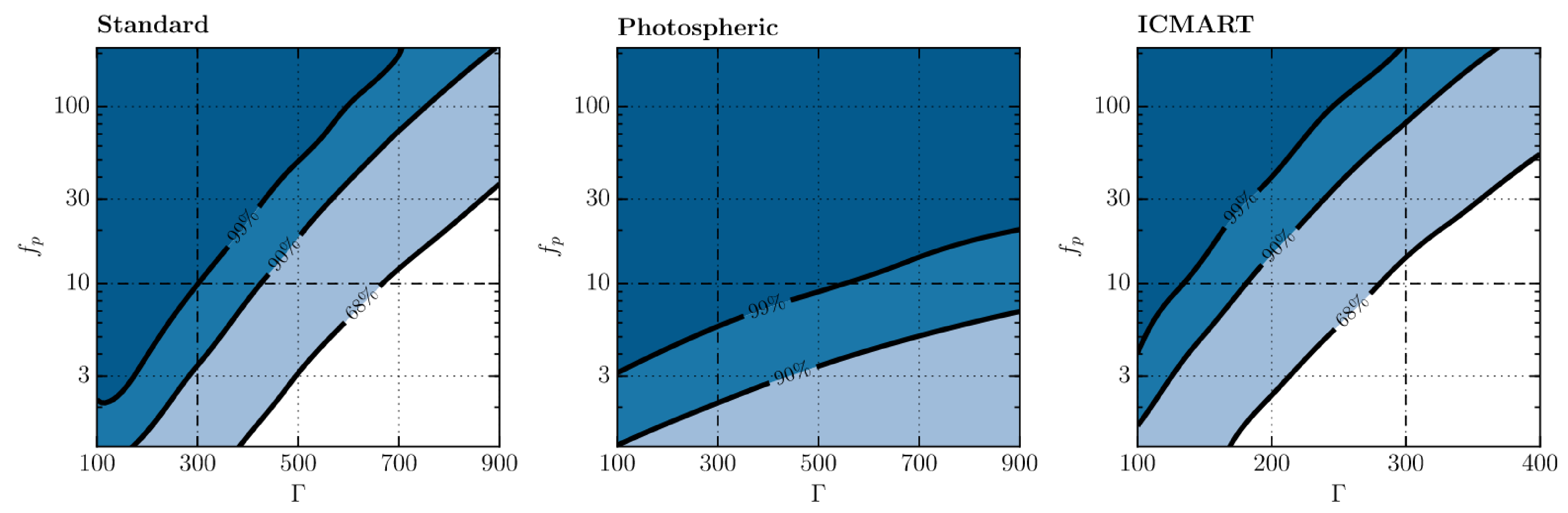
For neutrino production in different models see also eg.
Gao et al JCAP 11 (2012), Hummer et al PRL 118 (2012)
Baerwald et al Astropart.Phys. 62 (2015), Pitik et al JCAP 05 (2021)

linestyles:
baryonic loading



Zhang & Kumar, PRL 110 (2013)

Interpreting the IceCube neutrino limit



Aartsen et al ApJ. 843 (2017)

- Calculate neutrino fluxes for different models and parameter sets, compare to IceCube limits
- For internal shock and ICMART, moderate baryonic loading possible for high Lorentz factors

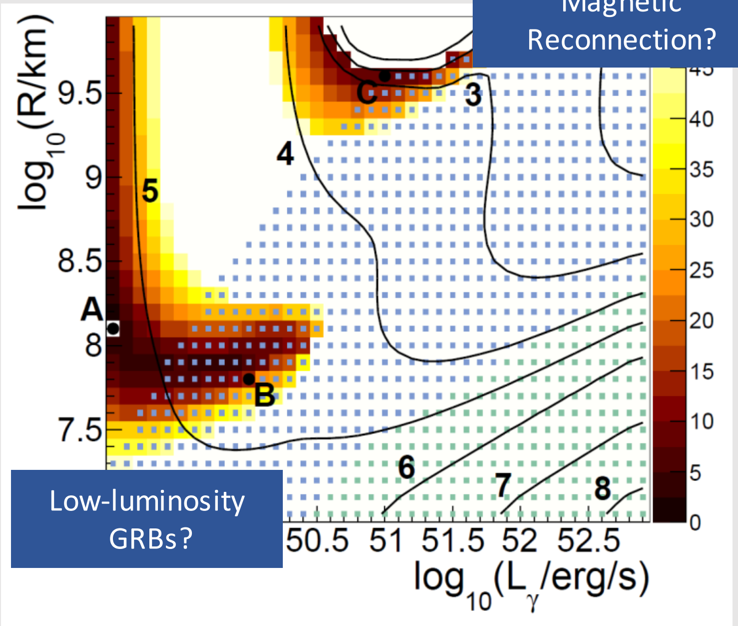
So GRBs can't be UHCER sources?

One-zone model

All emission from the same emission region

→ **degenerate in various parameters** (baryonic loading/ Lorentz factor/ dissipation radius/ luminosity)

Fit to UHECR data



Biehl et al A&A 611 (2018)

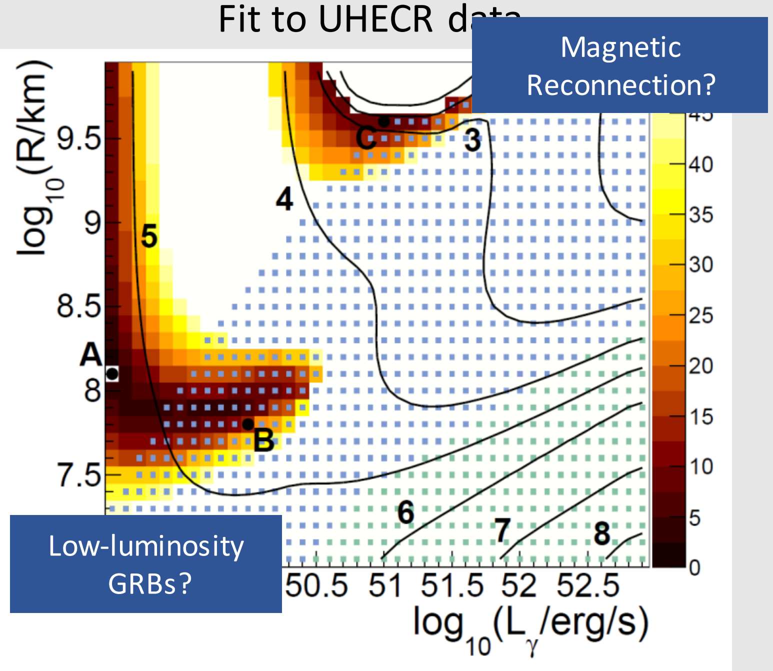
So GRBs can't be UHCER sources?

One-zone model

All emission from the same emission region

→ **degenerate in various parameters** (baryonic loading/ Lorentz factor/ dissipation radius/ luminosity)

Fit to UHECR data



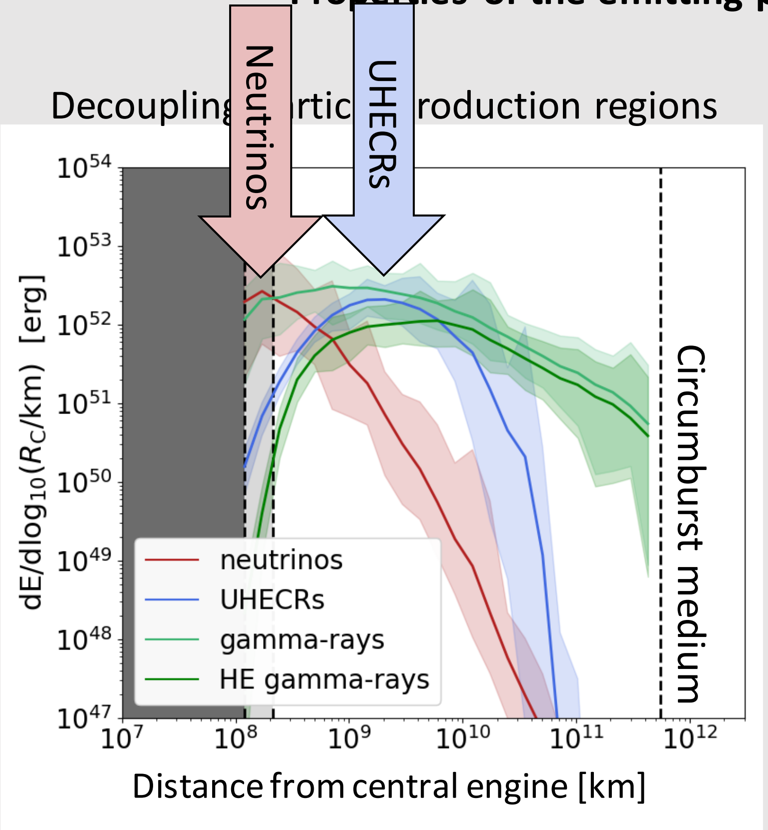
Biehl et al A&A 611 (2018)

Multi-zone model

Emission from different sites along the jet

Properties of the emitting plasma are part of the modeling

Decoupling rtic roduction regions



AR et al, ApJ 893 (2020)

See also:
Bustamante et al Nature Comm. 6 (2015)
Bustamante et al ApJ 837 (2017)

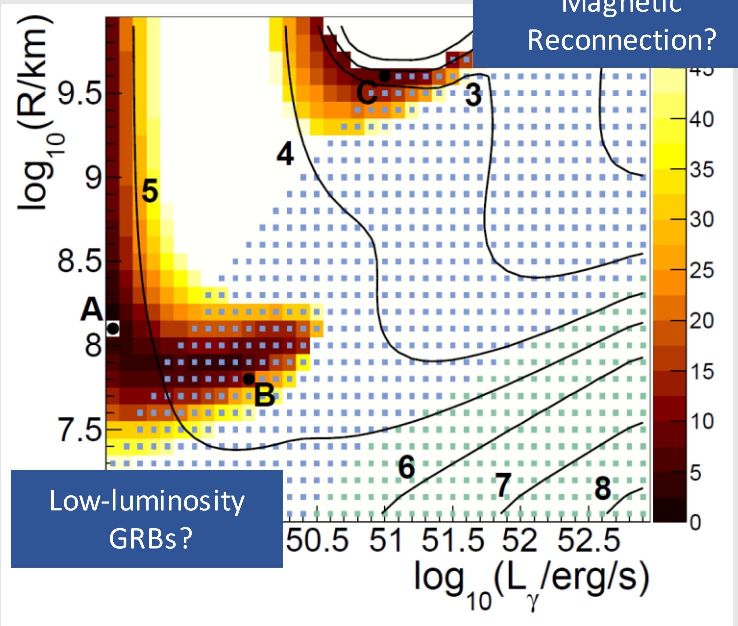
So GRBs can't be UHCER sources?

One-zone model

All emission from the same emission region

→ **degenerate in various parameters** (baryonic loading/ Lorentz factor/ dissipation radius/ luminosity)

Fit to UHECR data



Magnetic Reconnection?

Low-luminosity GRBs?

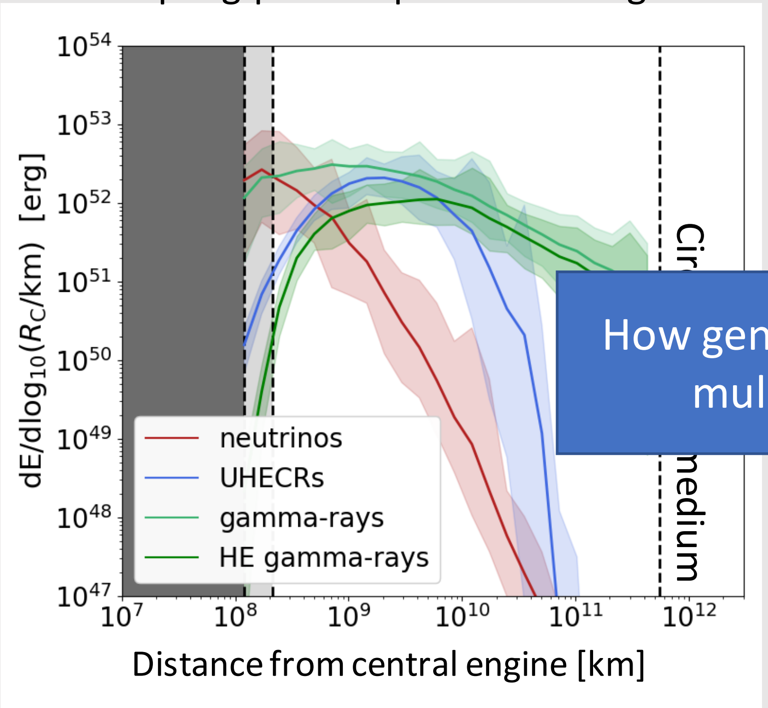
Biehl et al A&A 611 (2018)

Multi-zone model

Emission from different sites along the jet

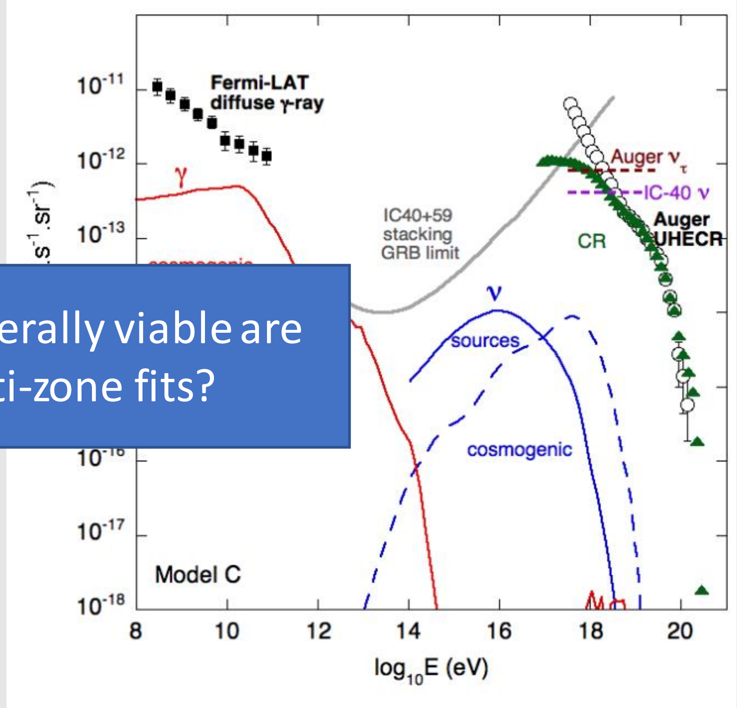
Properties of the emitting plasma are part of the modeling

Decoupling particle production regions



AR et al, ApJ 893 (2020)

Fit to UHECR data



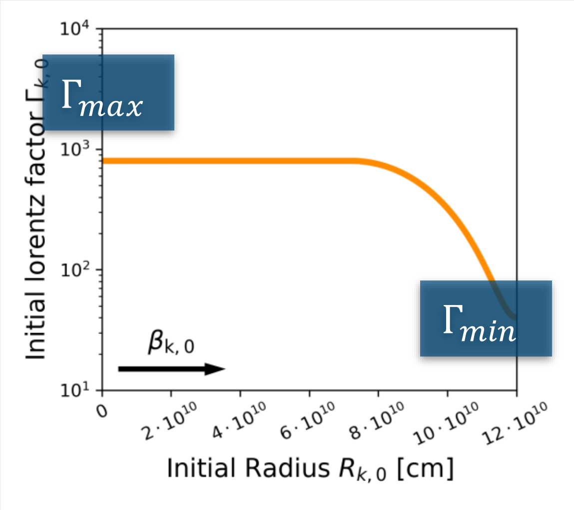
How generally viable are multi-zone fits?

Globus et al MNRAS 415 (2015)

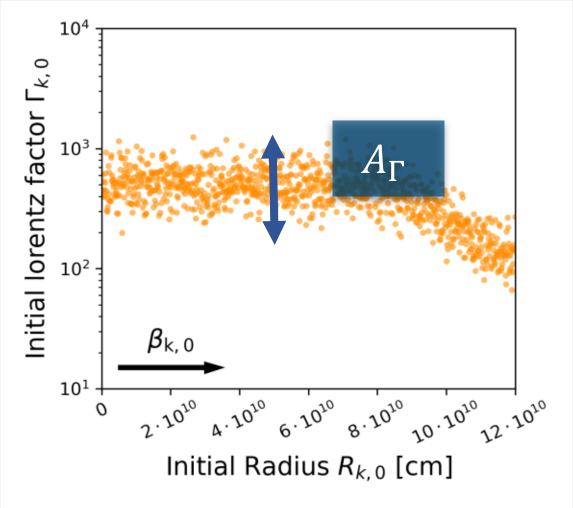
Fitting UHECR data in a multi-zone model: Connection to engine setup & light curves

Initial Lorentz Factors

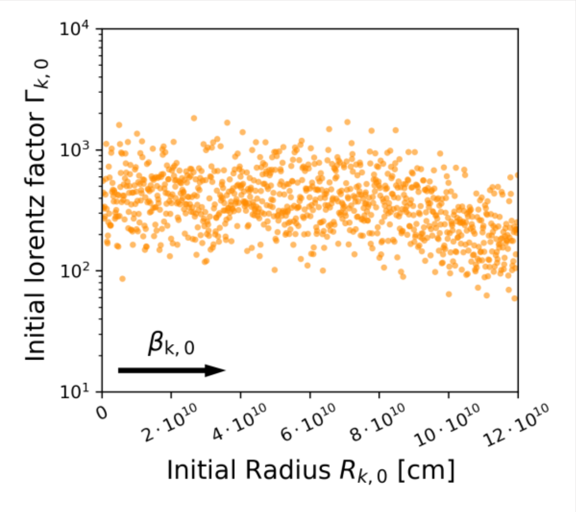
No stochasticity



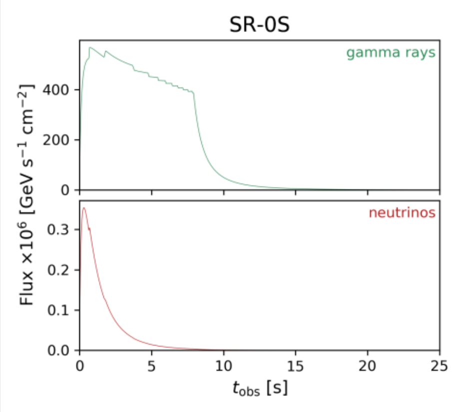
Medium stochasticity

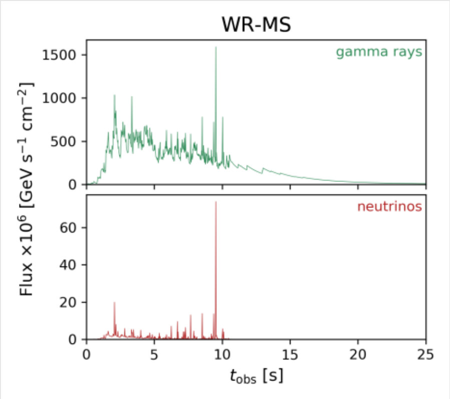


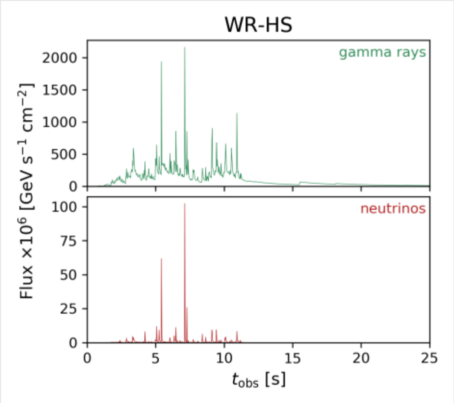
High stochasticity



Light curves

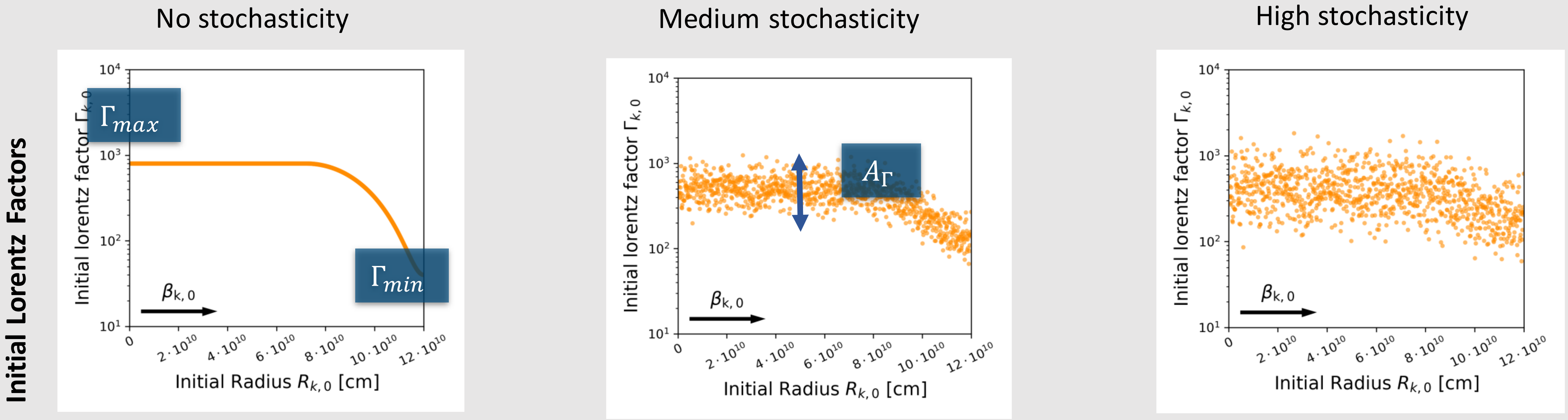






Heinze, AR et al *MNRAS* 498 (2020)

Fitting UHECR data in a multi-zone model: Connection to engine setup & light curves



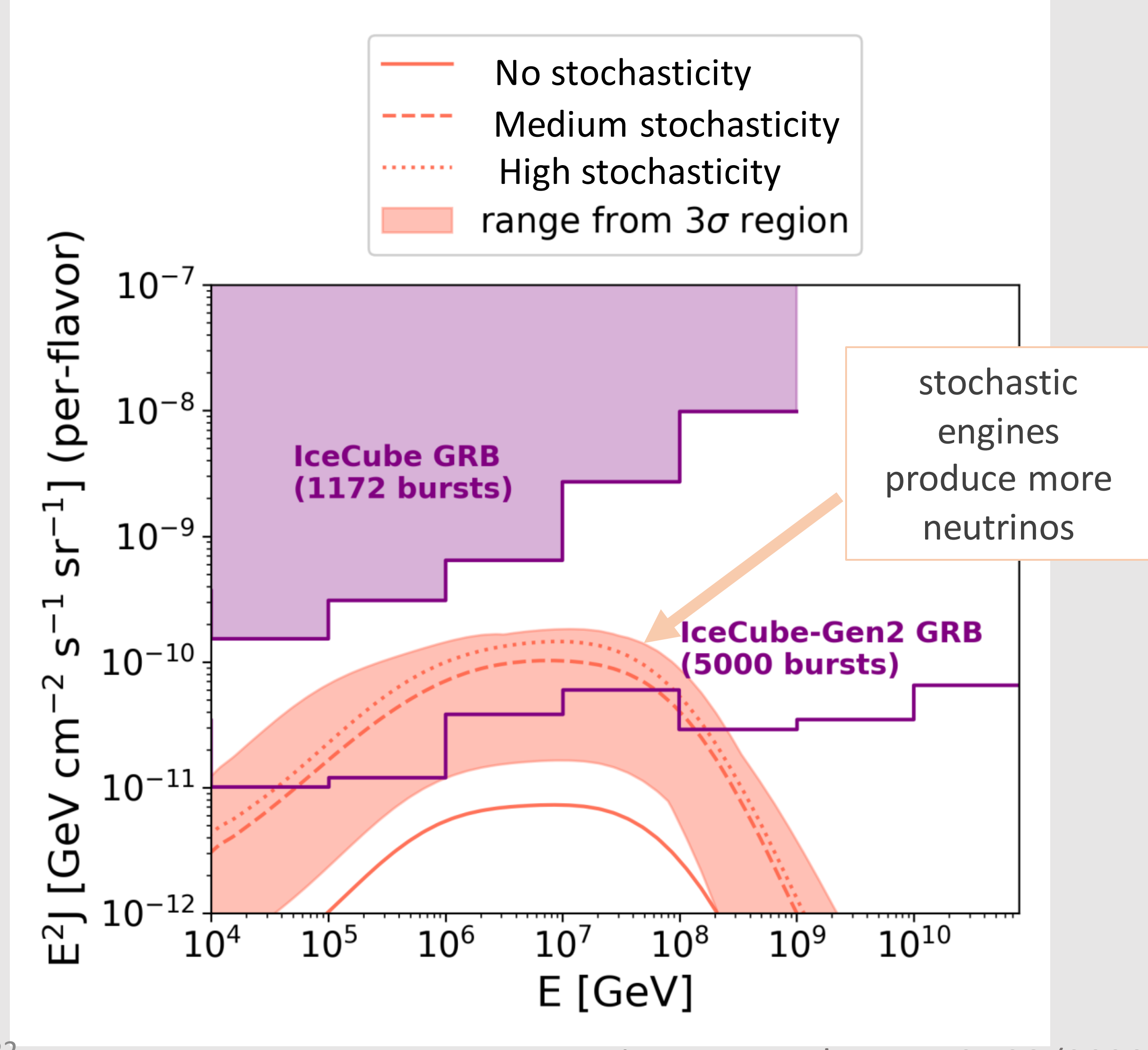
Methods

- Radiation modeling: **Fix band-like photon spectrum** and calculate cosmic ray interactions and escape with NeuCosmA – Code (Biehl et al 2017)
- Propagate using GRB-redshift-distribution: Wanderman, Piran, MNRAS 406 (2010)
  Extragalactic propagation with PriNCe Heinze et al, ApJ 873 (2019), 83
- Fit to **UHECR spectrum and $\langle X_{max} \rangle$, Free injection composition and baryonic loading** (determined by fit)

Heinze, AR et al *MNRAS* 498 (2020)

Fitting UHECR data: neutrino fluxes for different engine realisations/light curves

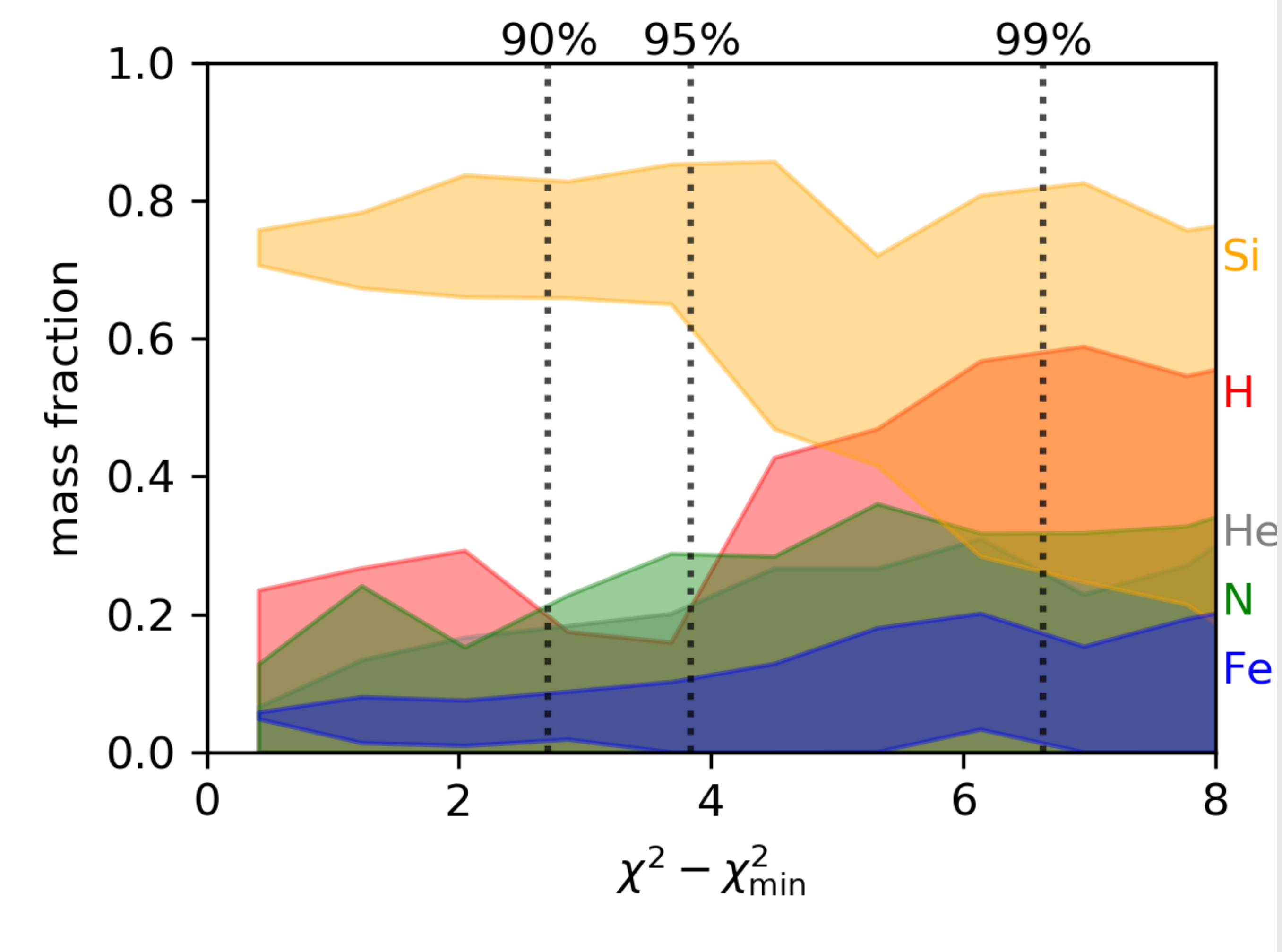
- Broad fit region around best fit
  Disfavored: low/ no stochasticity,
  Favored: Γ_{bulk} between 200 and 400
- Large engine kinetic energy required
- Required baryonic loading: 10 – 100
- Potential issue: Composition!



Heinze, AR et al *MNRAS* 498 (2020)

Fitting UHECR data: fraction of heavy nuclei at base of the jet

- Fit parameters were injected isotope fractions at the base of the jet
- Can determine mass fractions for fit regions!
- at 95% CL: Heavy mass fraction (> He) needs to be > 70 %

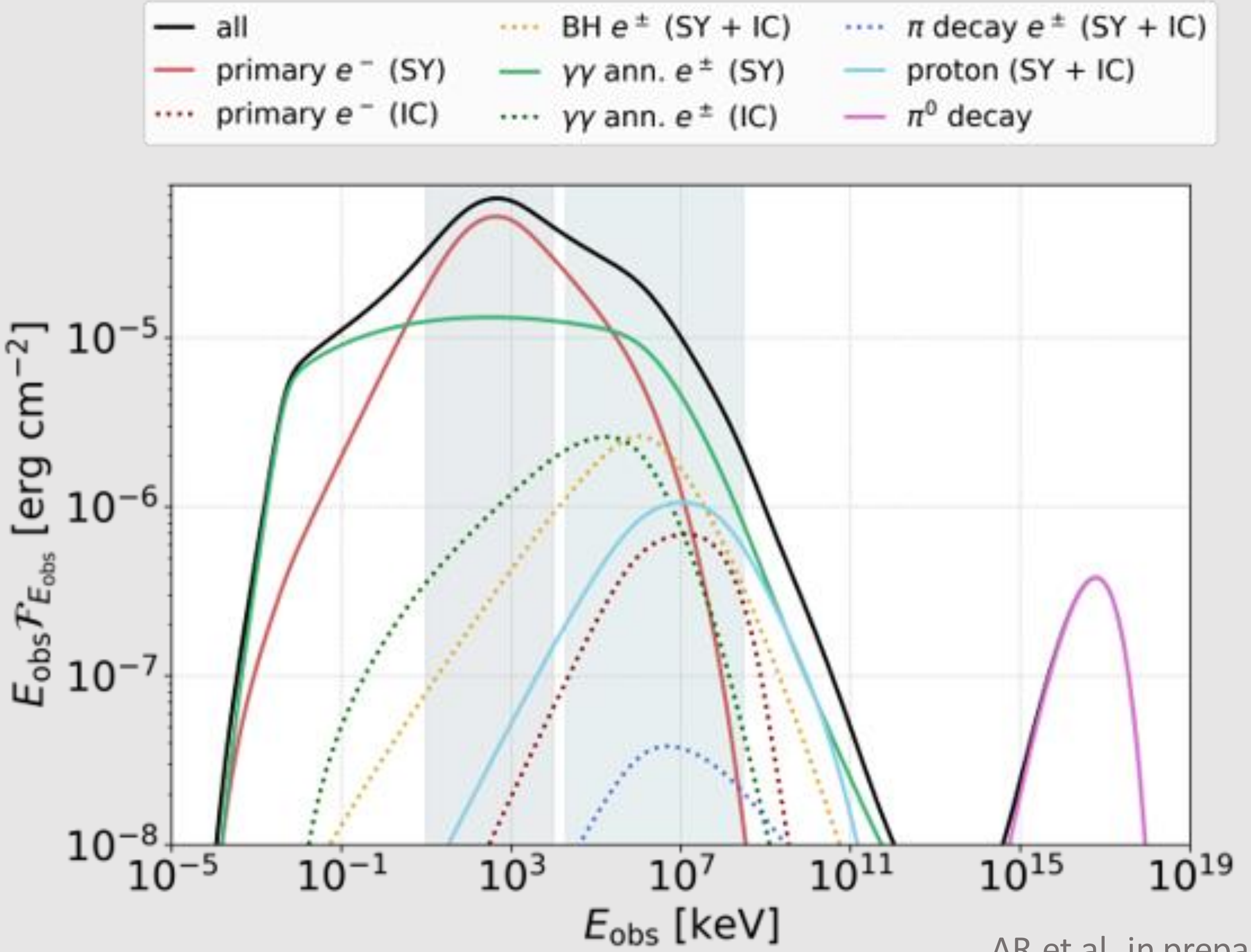


Heinze, AR et al *MNRAS* 498 (2020)

Exploring photon signatures of cosmic rays

photo-hadronic interactions also leave signatures in the photon spectra!

(1) Direct signatures:
photons from pion decays
(2) Cascade signatures:
photons from secondary lepton cascade



AR et al, in preparation

Exploring photon signatures of cosmic rays

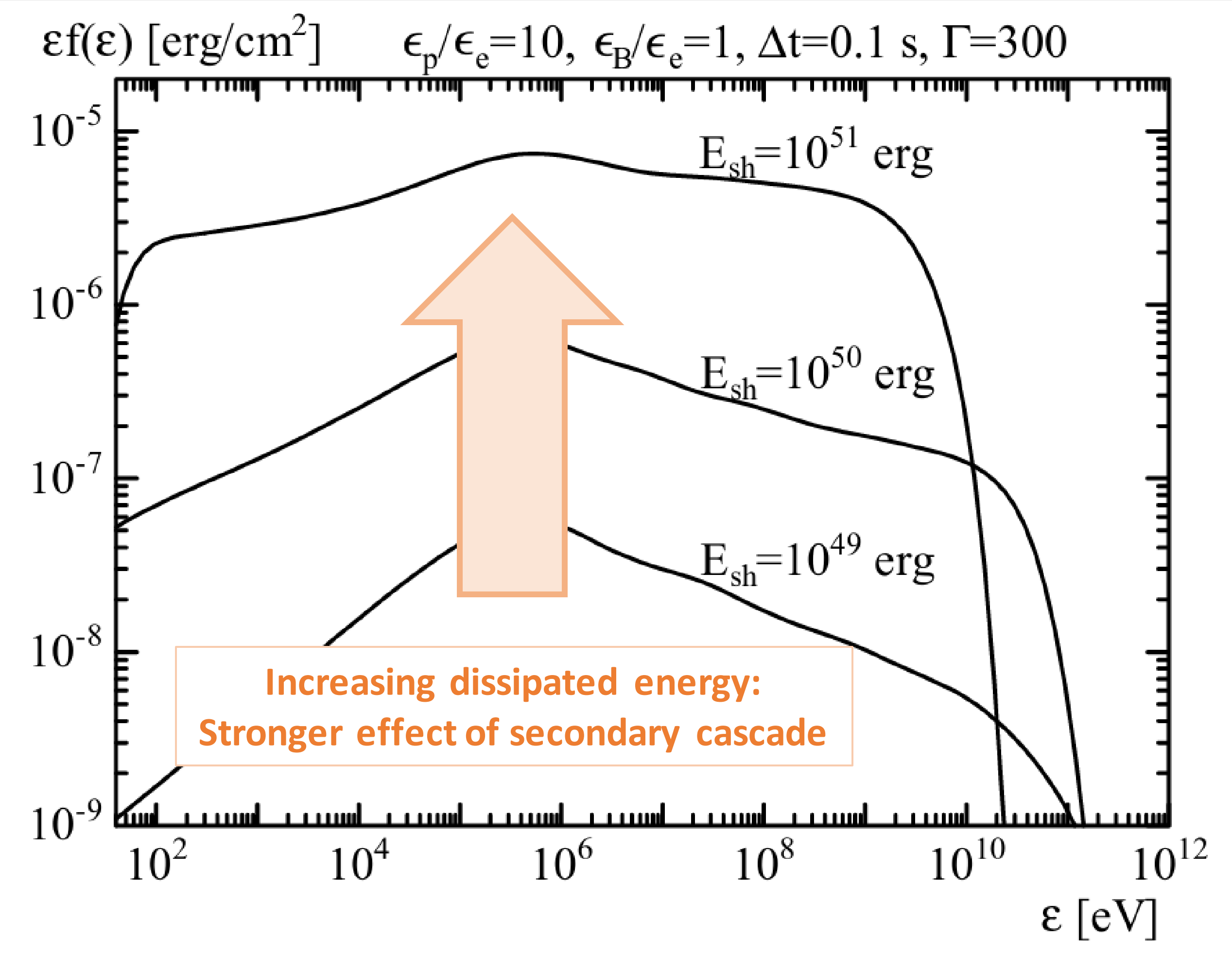
Intensity of signatures again depends on efficiency of photo-hadronic interactions

-> density!

Degenerate in various parameters:

- dissipated energy (E_{sh})
- Lorentz factor
- baryonic loading
- radius

See also: Asano et al ApJ 671 (2007), Asano et al ApJ 757 (2012), Wang et al ApJ 857 (2018)



Asano et al ApJ 699 (2009)

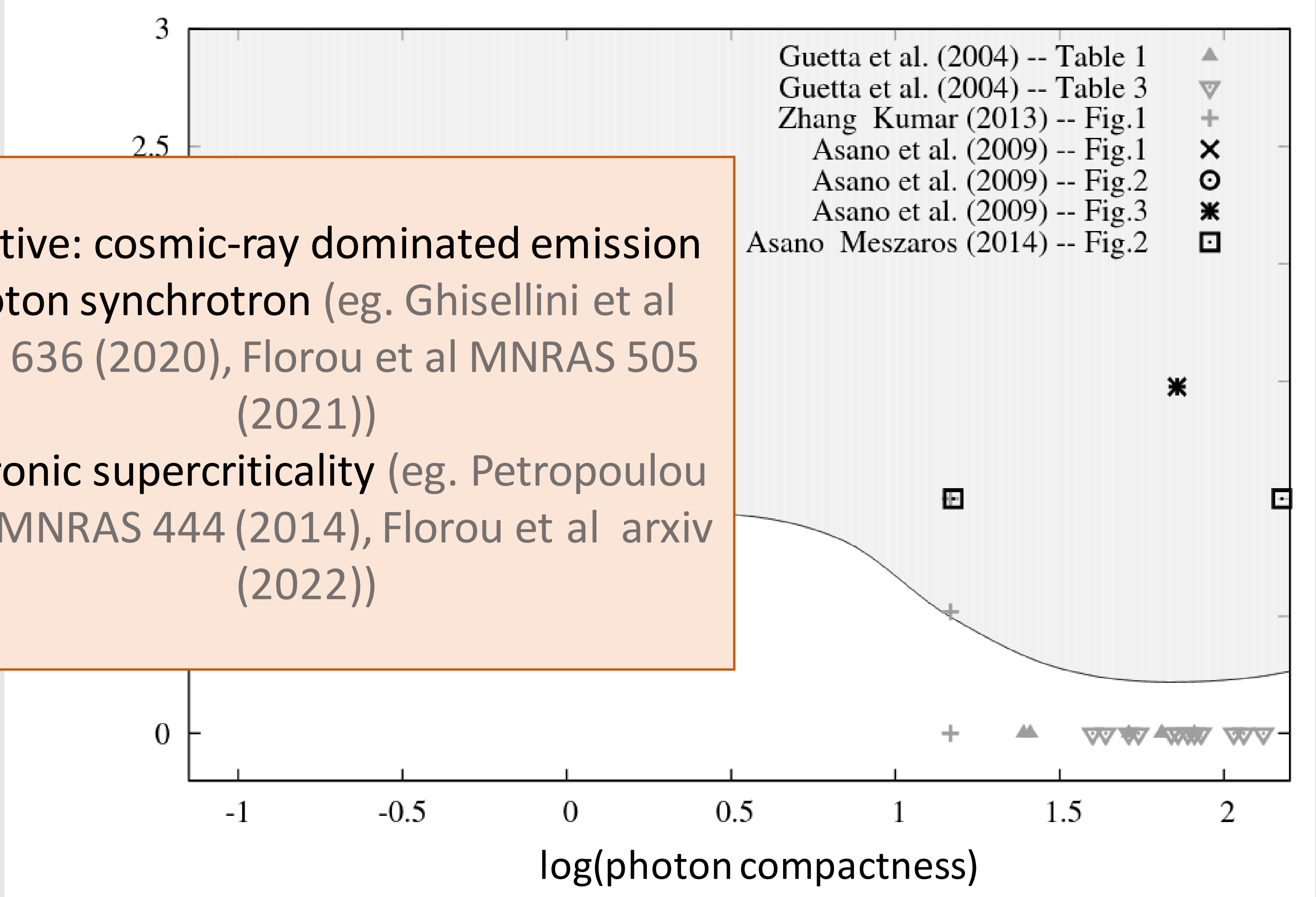
Exploring photon signatures of cosmic rays

Efficiency of photo-hadronic interactions depend on densi

-> explore maximal baryonic loading for which the signatu don't outshine the original spectrum as a function of **ph compactness**

$$\ell_\gamma = \frac{\sigma_T L_\gamma}{4\pi r_b \Gamma^4 m_e c^3}$$

accounts for volume!

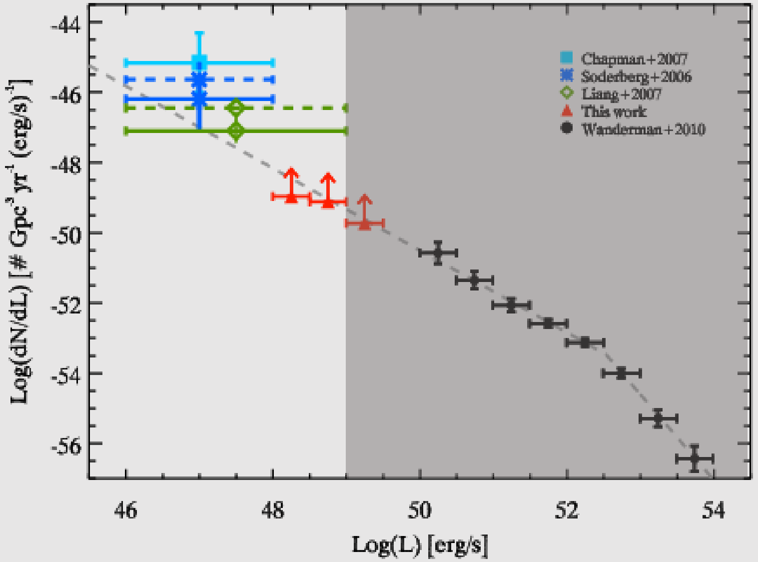


Petropoulou MNRAS 442 (2014)

Alternative: cosmic-ray dominated emission

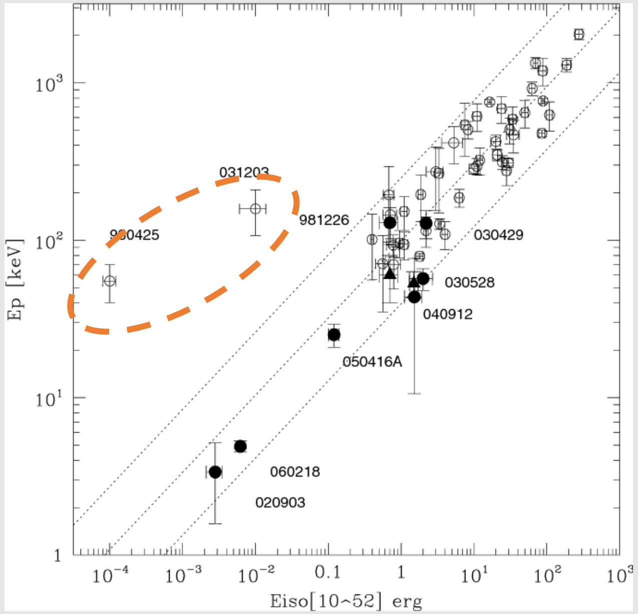
- Proton synchrotron (eg. Ghisellini et al A&A 636 (2020), Florou et al MNRAS 505 (2021))
- Hadronic supercriticality (eg. Petropoulou et al MNRAS 444 (2014), Florou et al arxiv (2022))

A different region of the parameter space:
Low-Luminosity GRBs



Pescalli et al 2015

- Subclass of GRBs but with very low isotropic Luminosities 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)*
- (Some) LL-GRBs are **outliers to known correlations**

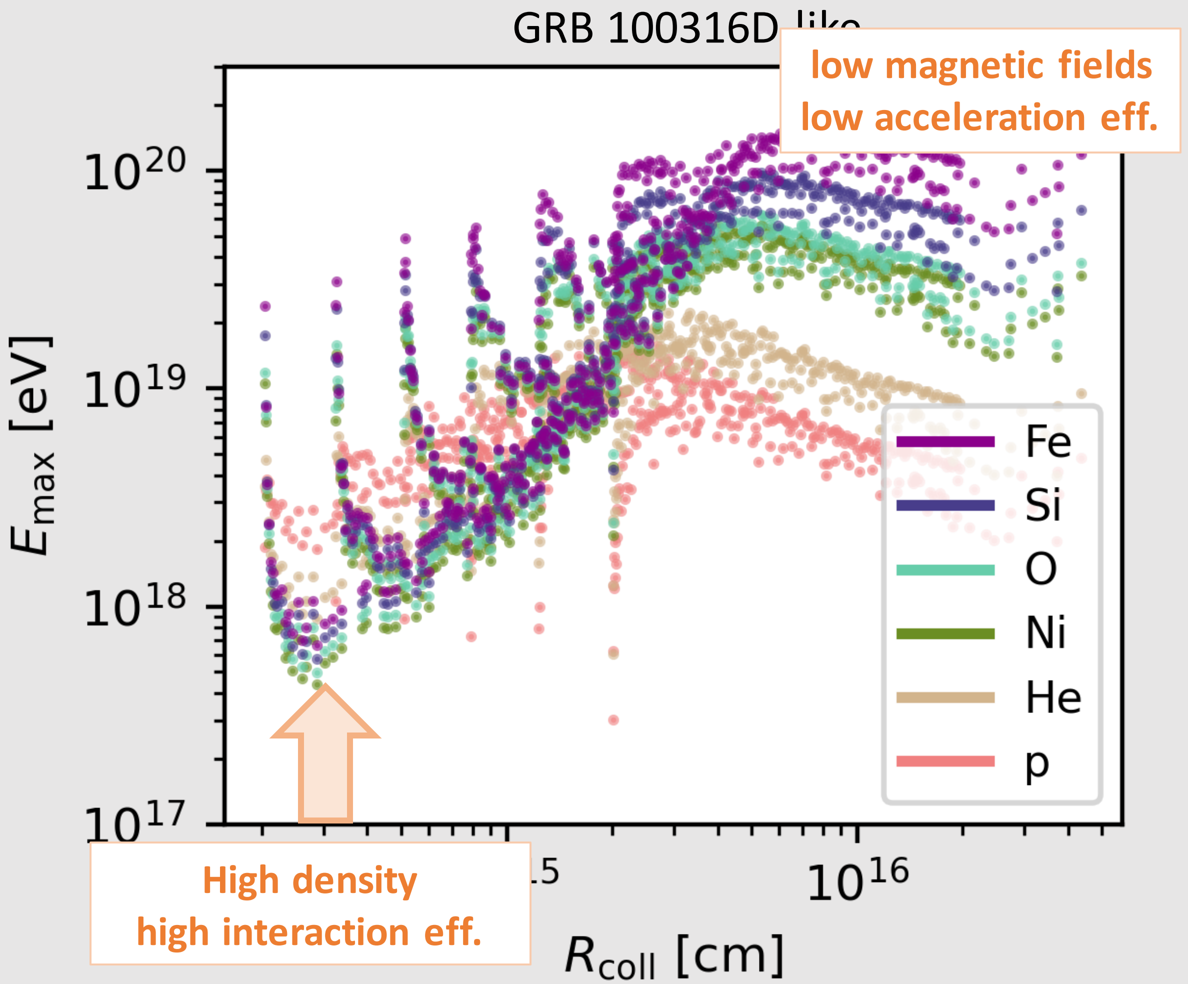


Stratta et al 2007

- **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))*

Can LL-GRBs accelerate cosmic rays to the highest energies?

- Procedure: leptonic radiation modelling for prototypes with properties similar to observed events
- Multi-zone internal shock model
- Calculate maximal energies balancing acceleration with losses
- Findings: for strong magnetic fields, cosmic rays could be accelerated to UHECR energies
- Similar discussion with one-zone internal shock model: Samuelsson et al ApJ 902 (2020)



AR et al, MNRAS 511 (2022)

Summary & Conclusions

- IceCube neutrino limits put strong constraints on the neutrino production efficiency
- In one zone models, UHECR fit only possible in parameter space region of low luminosities/large radii
- Multi-zone models:
  - **decouple production regions** of different particle species: Neutrinos from small, UHECR from intermediate, gamma-rays from large radii
  - UHECR fit still possible, neutrino fluxes testable by IceCube Gen2
- Further constraints come from feedback of cosmic rays on photon spectra
- Low-luminosity GRBs as distinct source class: potential sources of UHECRs and HE neutrinos