Neutrinos and UHECR from GRB multi-collision models

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MNRAS 498 (2020), arxiv 2006.1430

Annika Rudolph
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22.02.2020

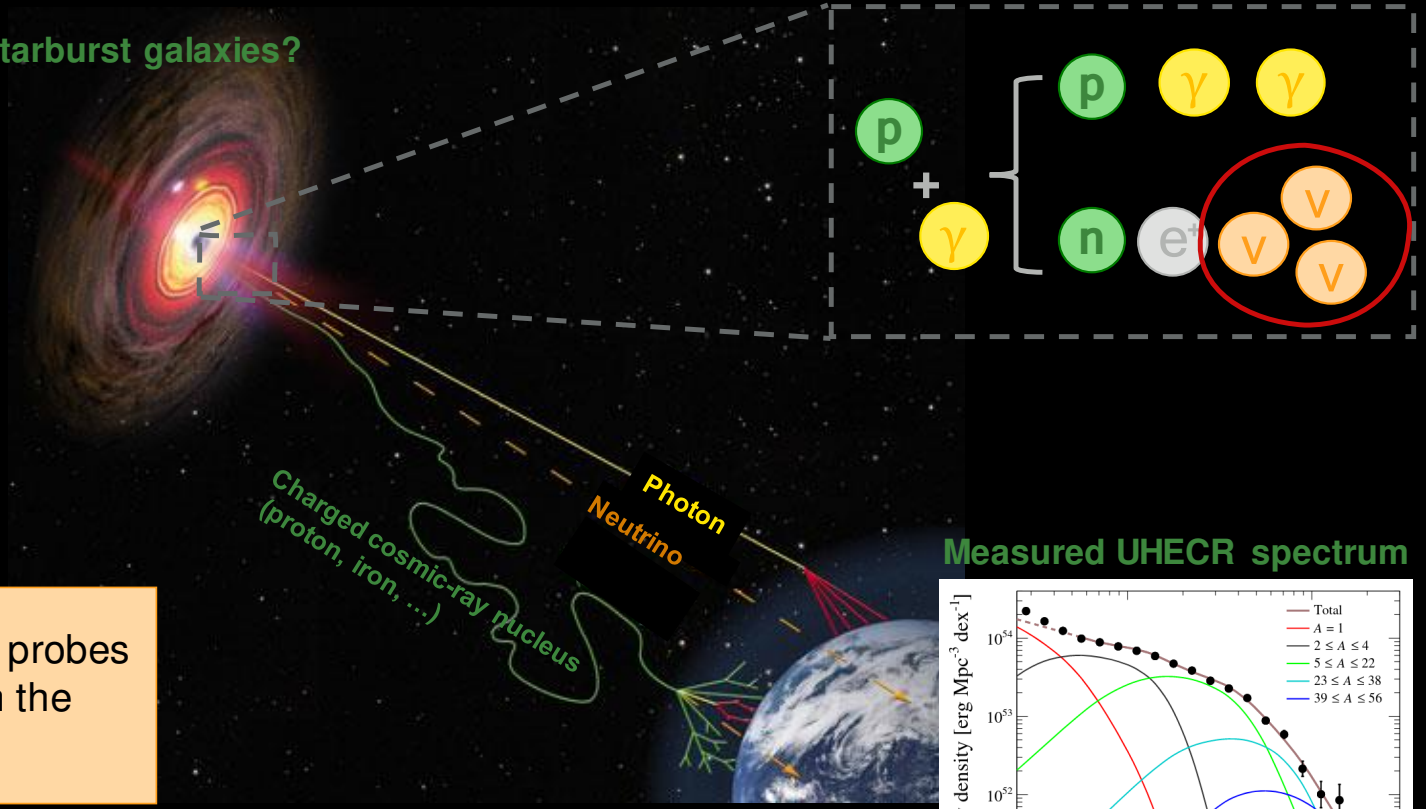
HELMHOLTZ RESEARCH FOR GRAND CHALLENGES

Neutrinos as signatures of Ultra-High-Energy Cosmic-Ray sources

Starburst galaxies?

Gamma-Ray Bursts?

AGN?



Neutrinos are direct probes of cosmic rays in the sources!

Measured UHECR spectrum

Auger Coll 2020 (arxiv 2008.06488)

Gamma-Ray Bursts

A potential source of UHECR?

Observational properties

- Energetic outbursts of gamma-rays
  $$L_{\mathrm{iso},\gamma} \approx 10^{49} - 10^{53}\ \mathrm{erg}\ /\ s$$
- Two main populations by duration:
  - Long GRBs $\rightarrow \sim 10\ - 100\ s$
  - Short GRBs $\rightarrow \sim 0.1\ - 1\ s$
- Large variety of observed **light curves**, fast **time variability t_v**
- Similar spectra (Band function)

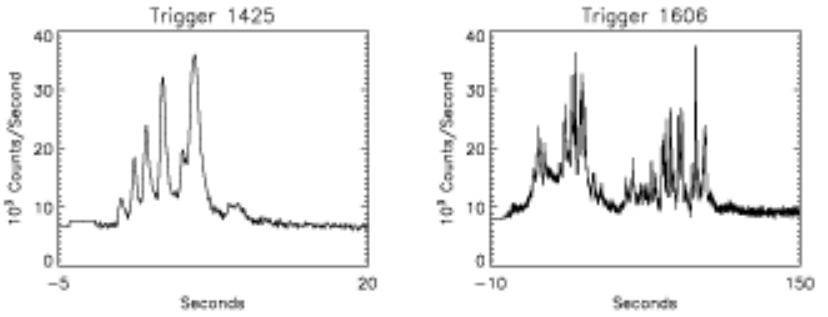
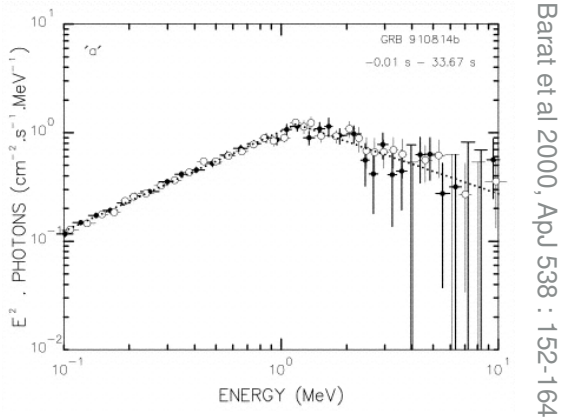


Image credit: J.T. Bonnell (NASA/GSFC)



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

Gamma-Ray Bursts (neutrino limits)

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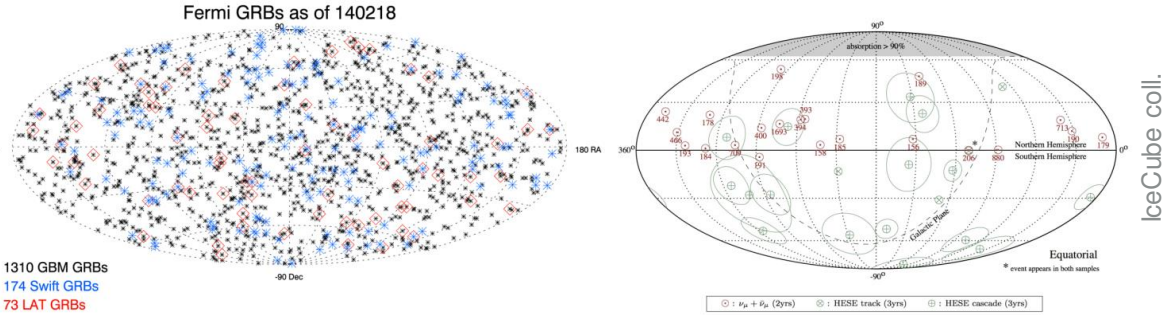
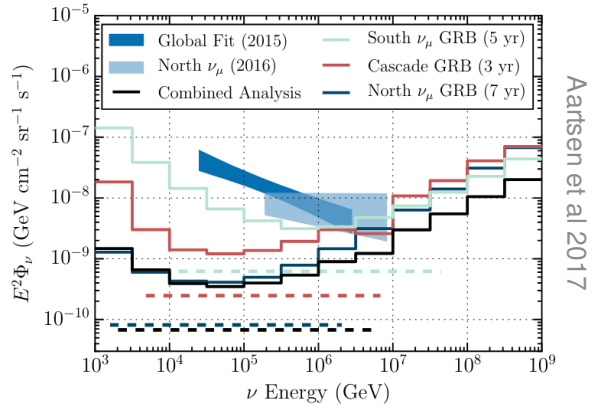
Catalogue of known GRBs

Detected HE neutrnos

Fermi LAT + GBM coll



IceCube coll.



Aartsen et al 2017

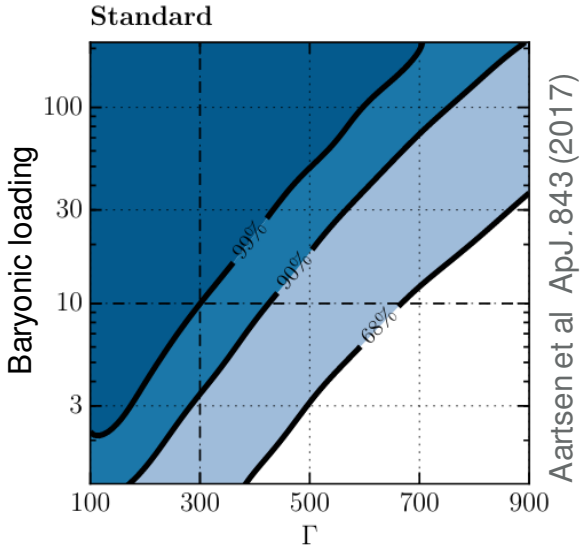
So GRBs can't be UHCER sources?

Interpreting the neutrino limit

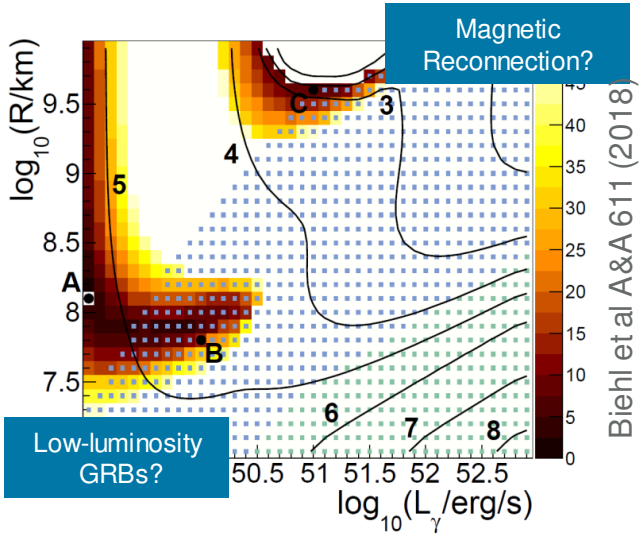
Simplified (one-zone) model

All emission from the same emission region

Degenerate in various parameters
strong limits on baryonic loading/ Lorentz factor/ dissipation radius/ luminosity



Aartsen et al ApJ. 843 (2017)

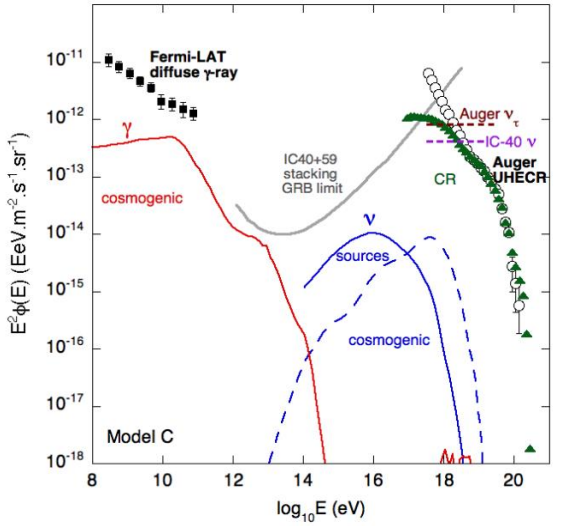


Biehl et al A&A 611 (2018)

Multi-collision model

Emission at different sites along the jet

Properties of the emitting plasma are part of the modeling



Globus et al MNRAS 415 (2015)

Internal shock model

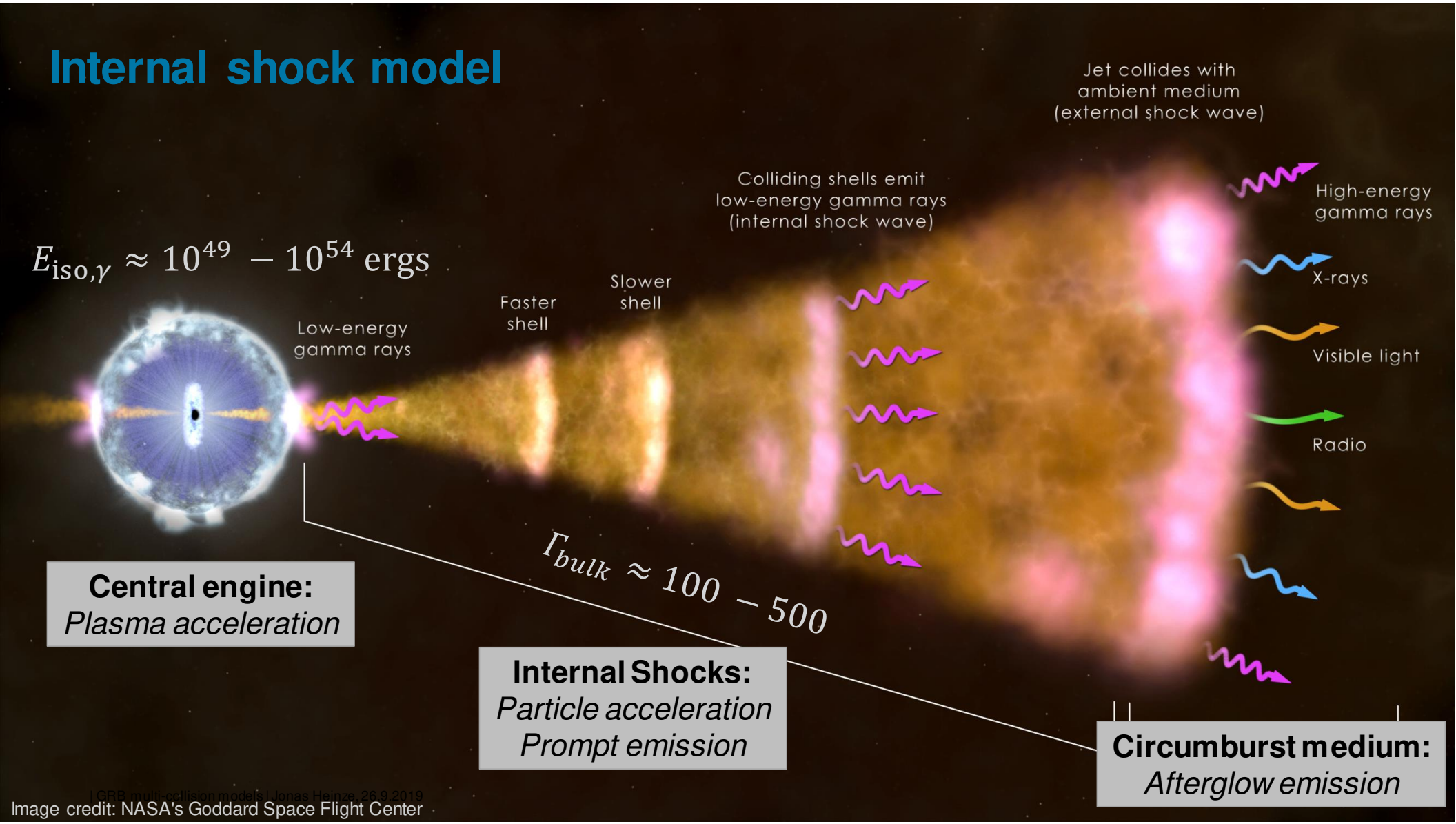


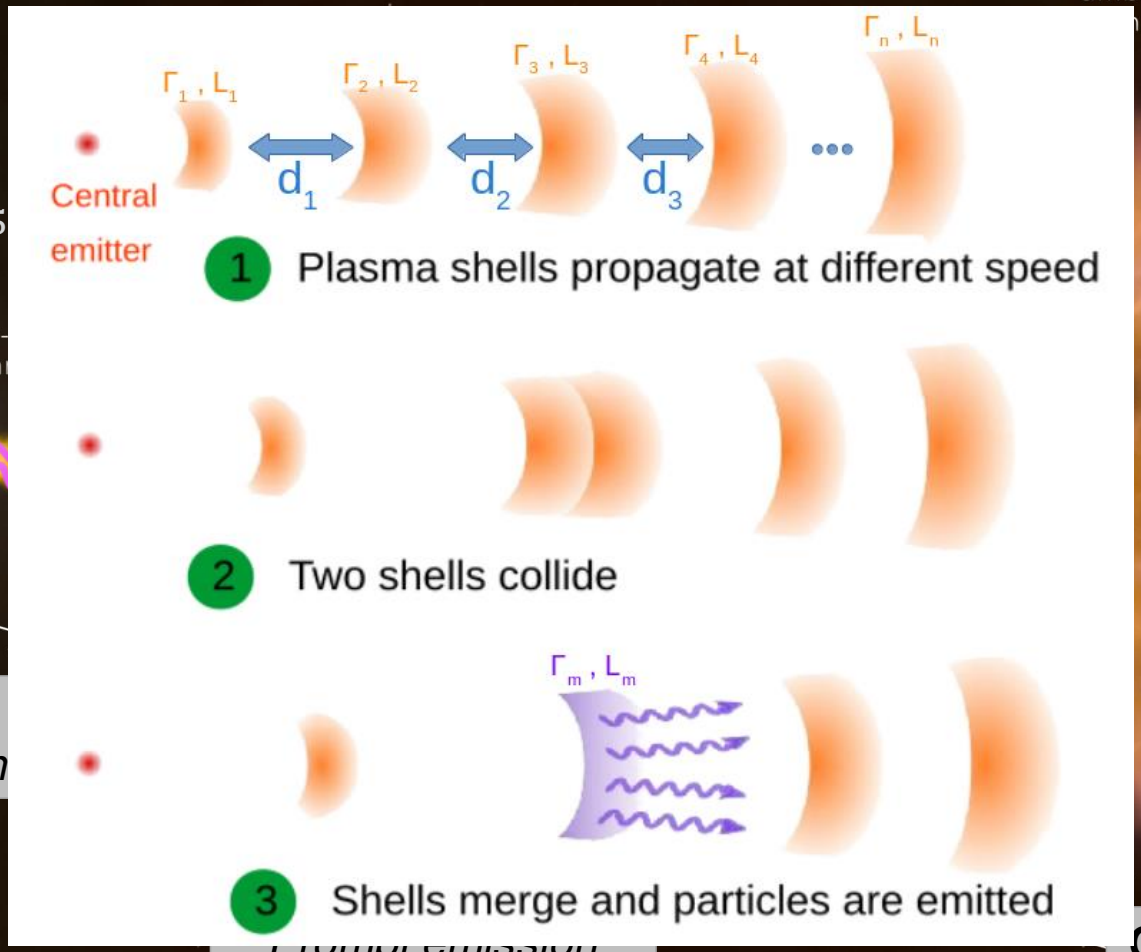
Image credit: NASA's Goddard Space Flight Center

Internal shock model (multiple collisions)

$E_{\mathrm{iso},\gamma} \approx 10^{49} - 10^{5}$

Low-
gam

Central engine:
Plasma acceleration



Prompt emission

Jet collides with ambient medium
al shock wave)

High-energy gamma rays
X-rays
Visible light
Radio

Circumburst medium:
Afterglow emission

Image credit: NASA's Goddard Space Flight Center

Bustamante et al Astrophys.J. 837 (2017)
Rudolph et al Astrophys.J. 893 (2020)

Multi-collision model

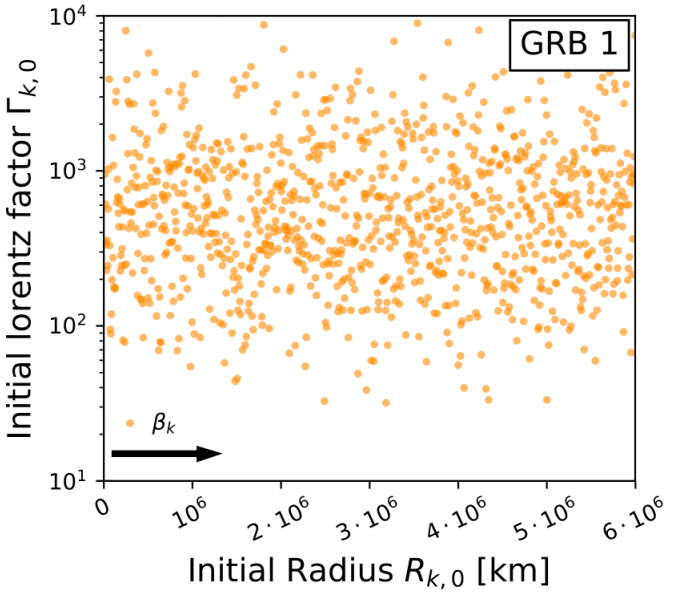
Purely stochastic shell distribution

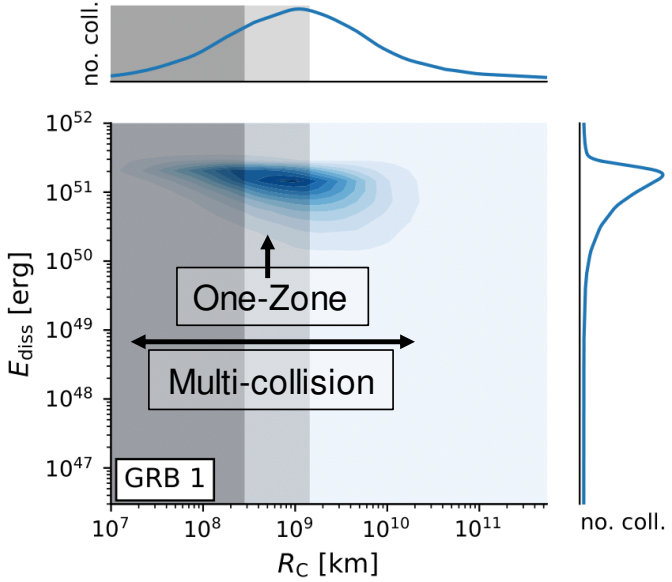
$$\ln\left(\frac{\Gamma_{k,0}-1}{\Gamma_0-1}\right) = A_\Gamma x \qquad P(x)dx = \exp(-x^2)/\sqrt{2\pi}dx$$

Fireball evolution

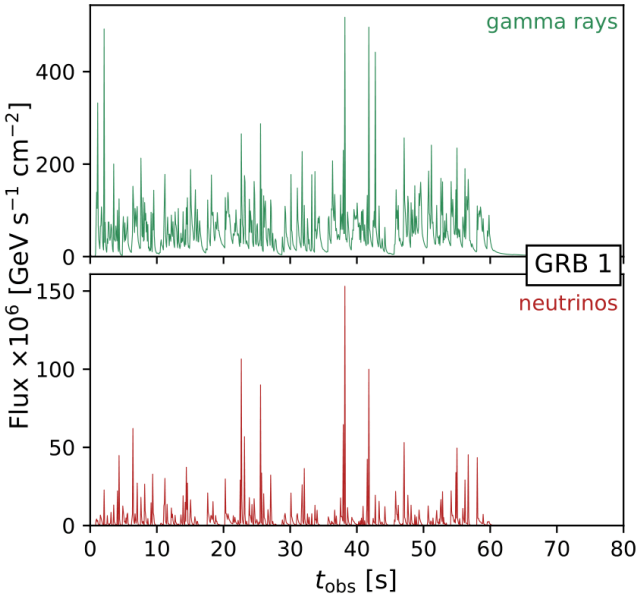
Radiation model

Initial shell distribution → Distribution of collisions → Light curve





Distance from central engine

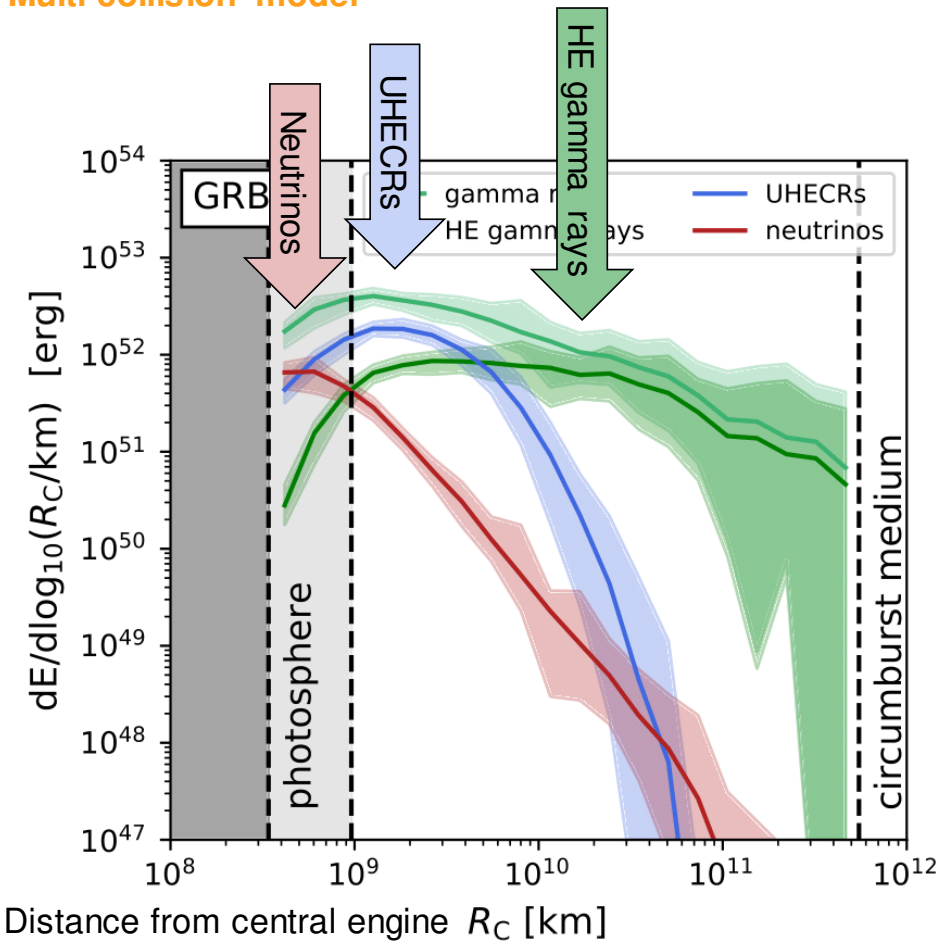


Observed time

Bustamante et al Astrophys.J. 837 (2017)
Rudolph et al Astrophys.J. 893 (2020)

Particle production regions

Multi-collision model



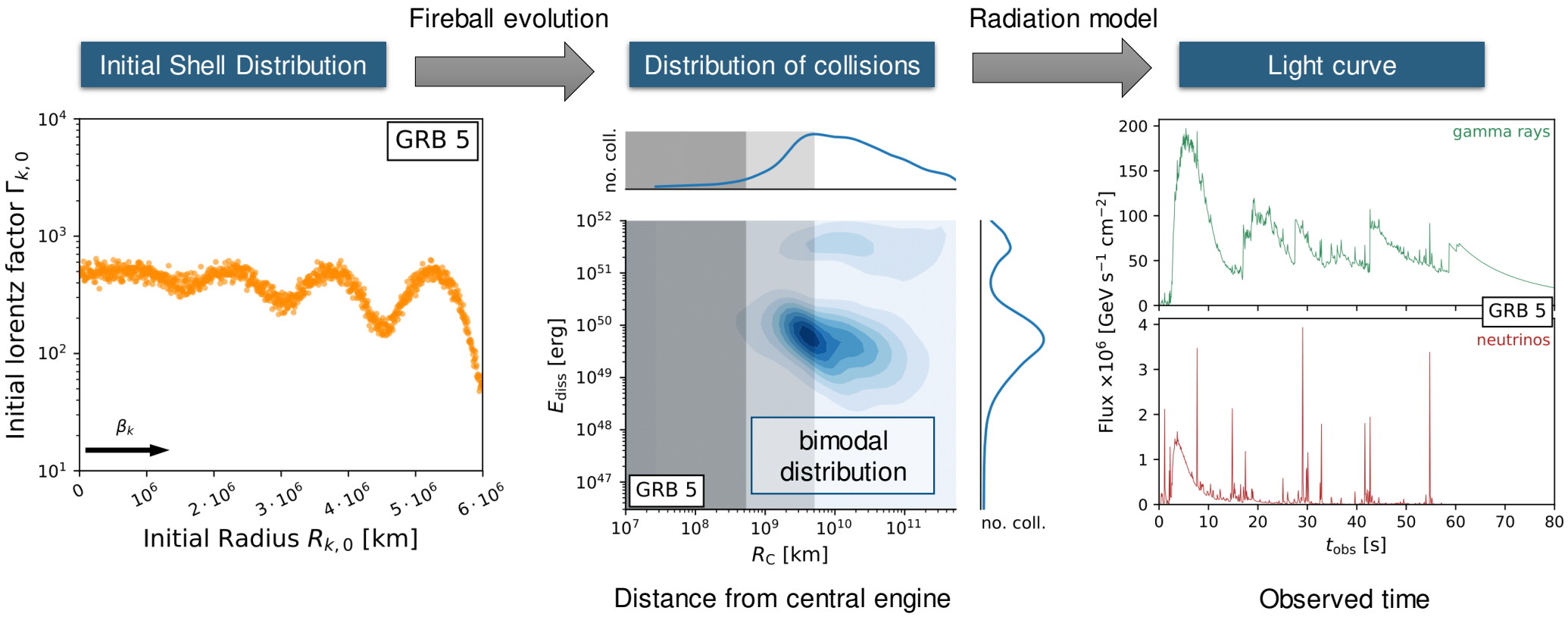
Separates the production regions:

- **Neutrinos** close to the photosphere
- **UHECRs** at intermediate radii
- **(high energy) gamma rays** from all radii

Disciplined (structured) engine

Multi-collision model

Bustamante et al Astrophys.J. 837 (2017)
Rudolph et al Astrophys.J. 893 (2020)



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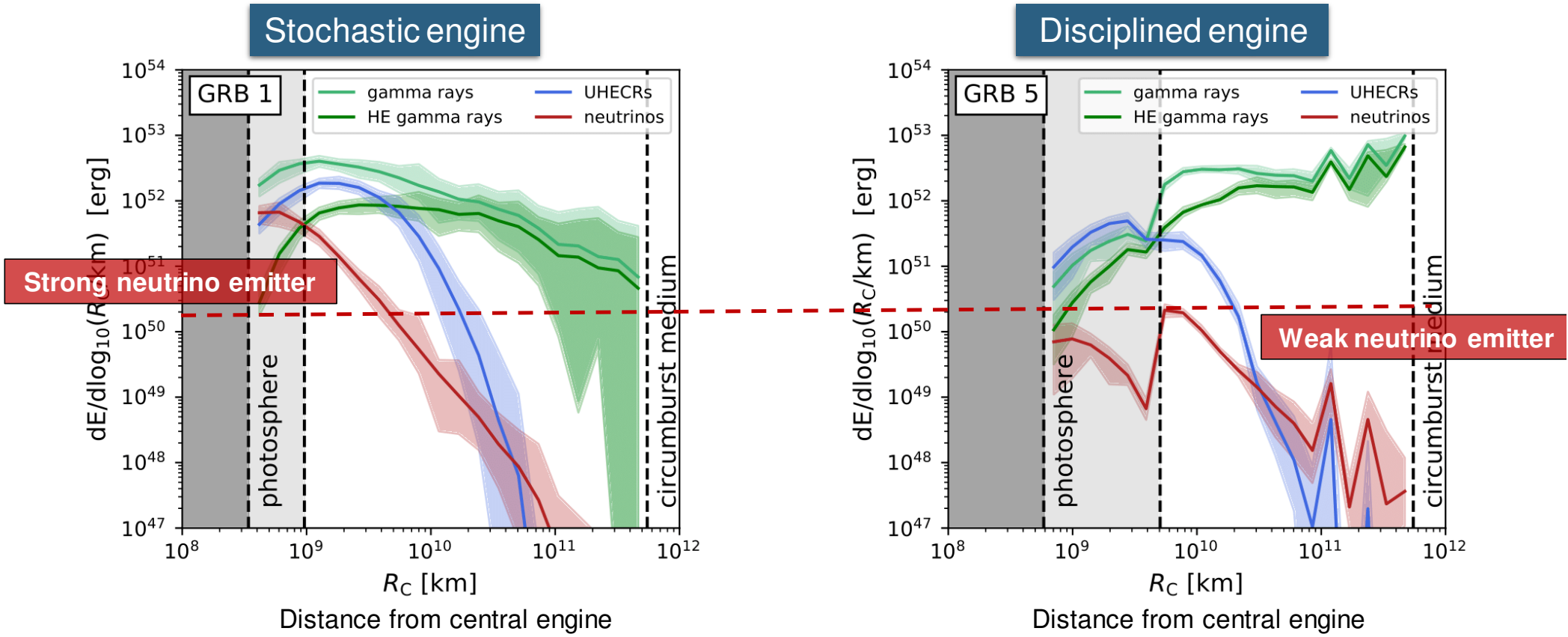
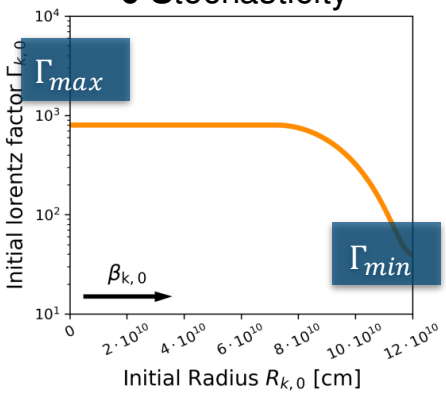


Fitting UHECR data: Exploration of different engine realisations

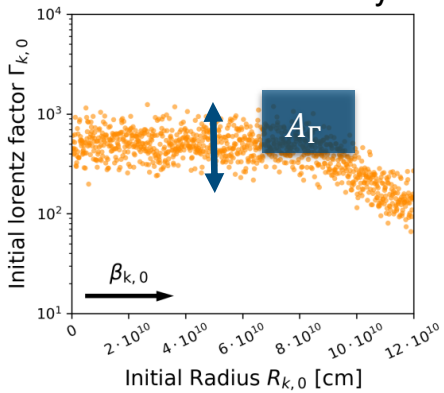
Description of different engine types: from disciplined to stochastic

Initial Lorentz Factors

Strong **R**amp-up
0 Stochasticity



Weak **R**amp-up
Medium **S**tochasticity



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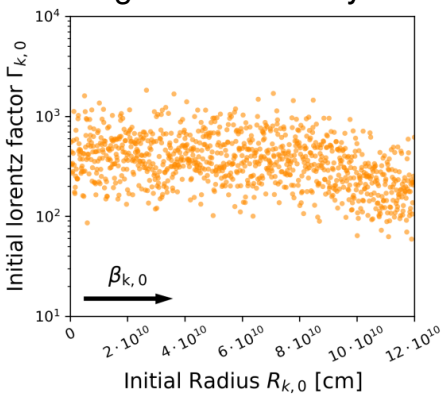

Parameterization similar to
Globus et al. MNRAS. 451 (2015)

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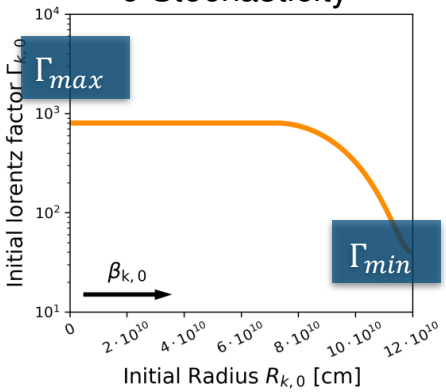

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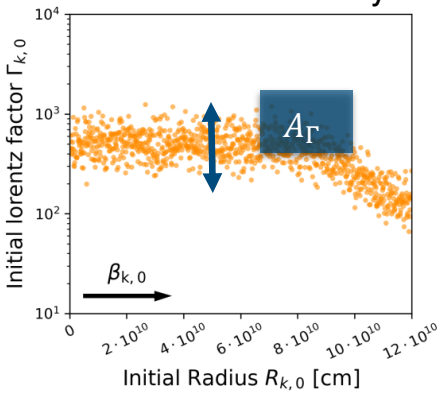

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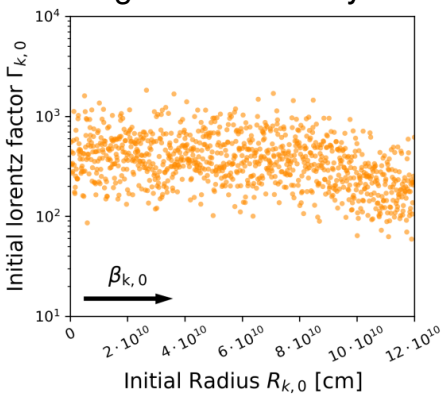
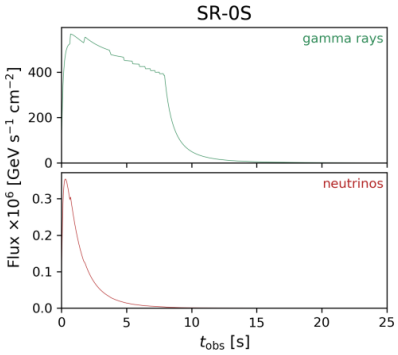
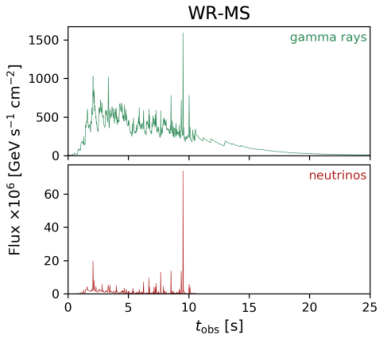
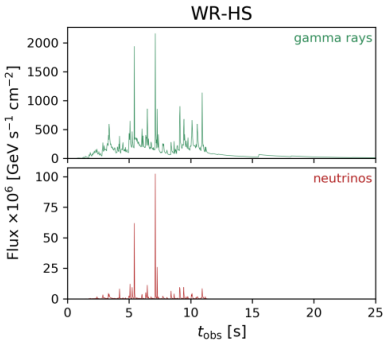


Light curves







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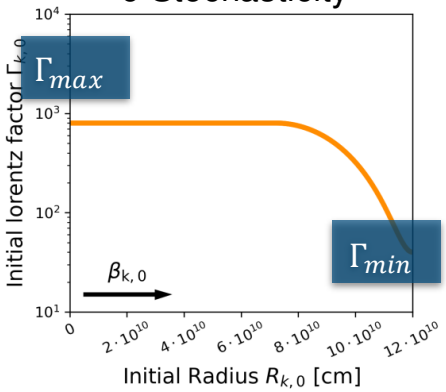

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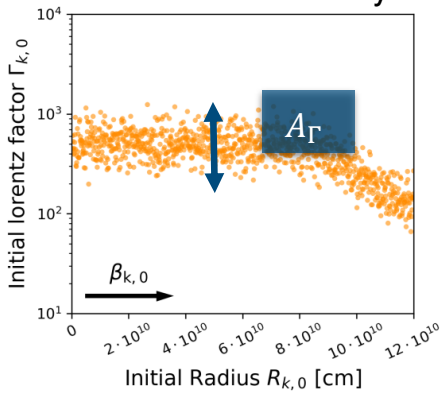

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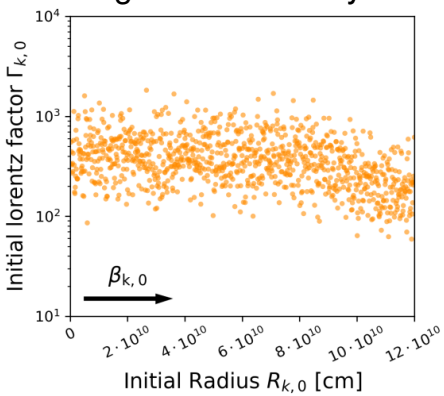
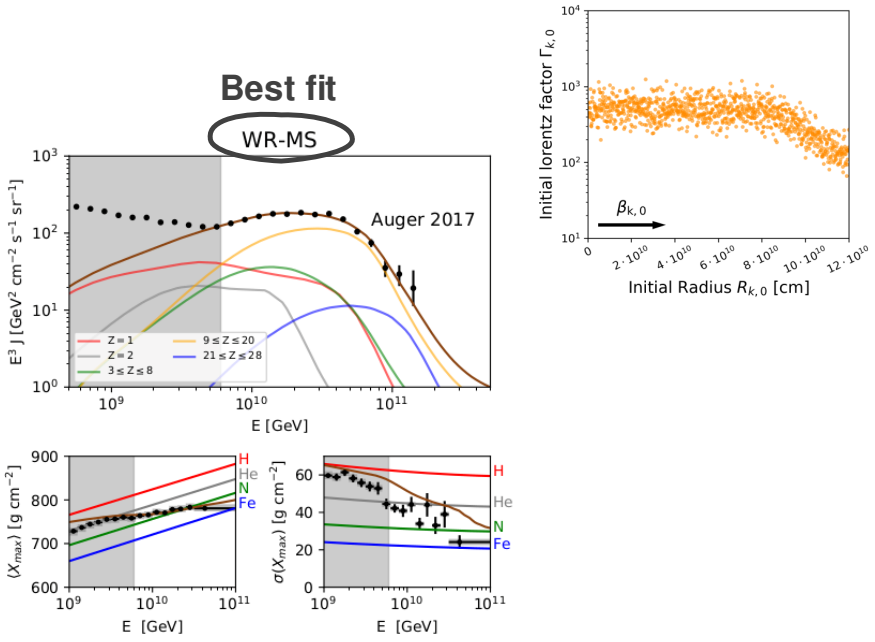


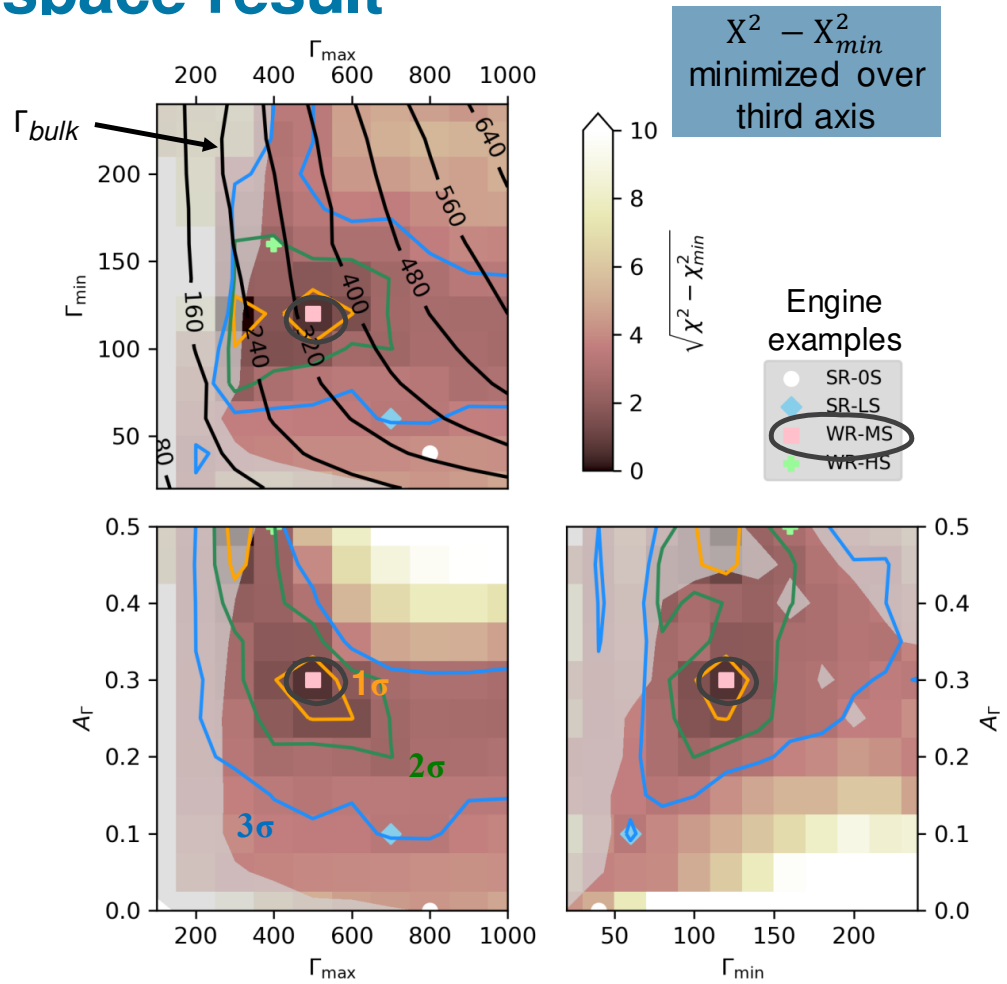
Methods

- 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)

Fitting UHECR data: parameter space result

- **Broad fit region** around best fit (WR-MS)
- Disfavored: low/ no stochasticity,
  Favored: Γ_{bulk} between 200 and 400
- **Large engine kinetic energy required**





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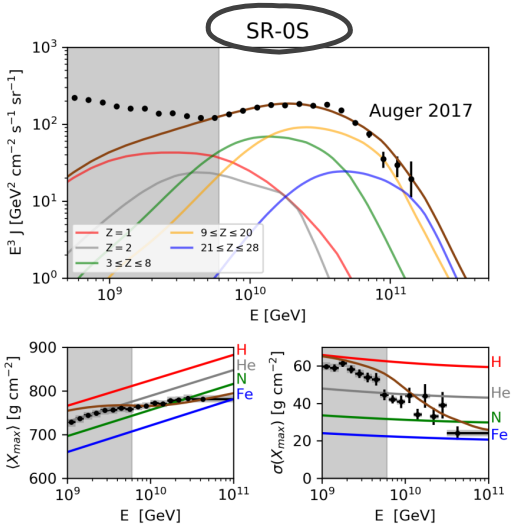
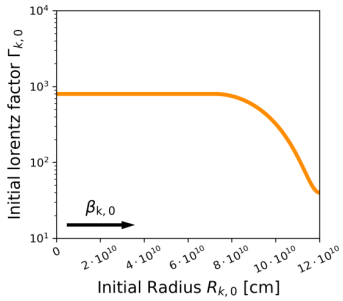
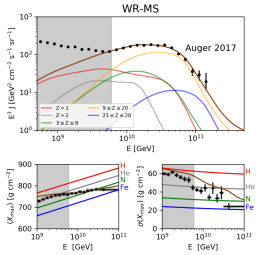
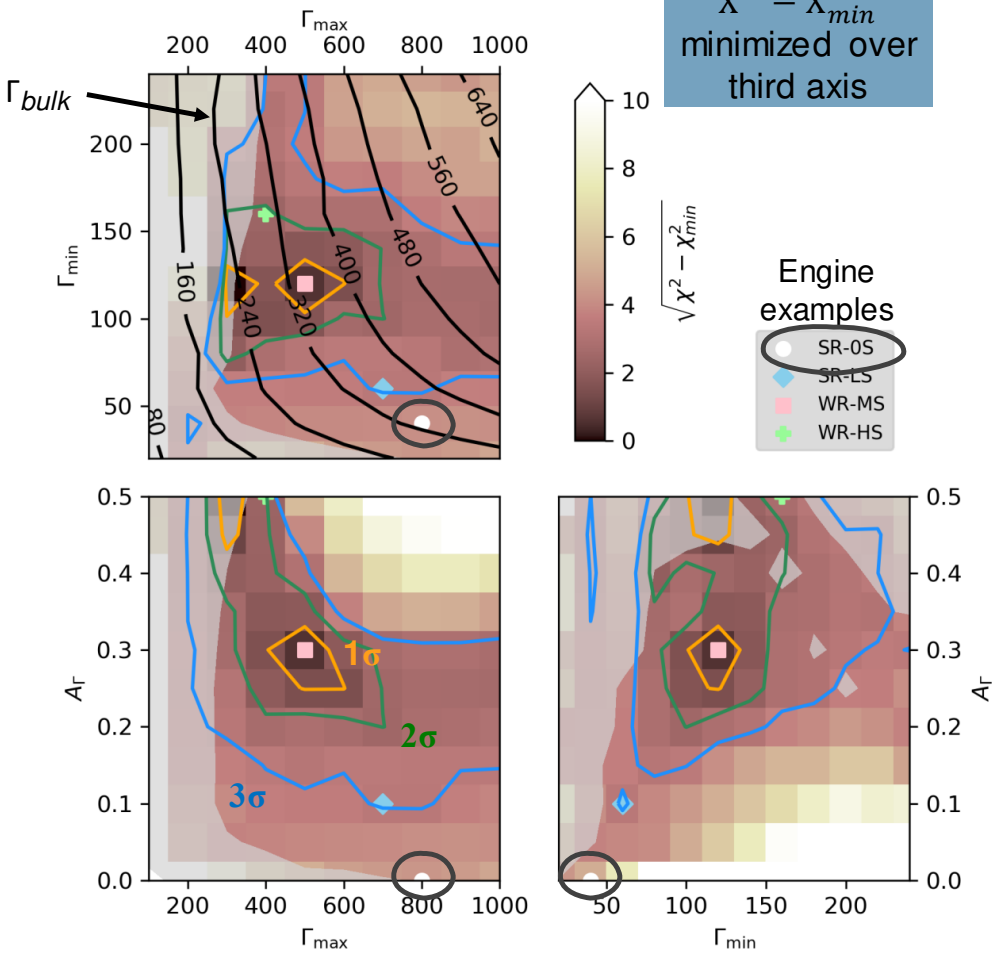




Best fit



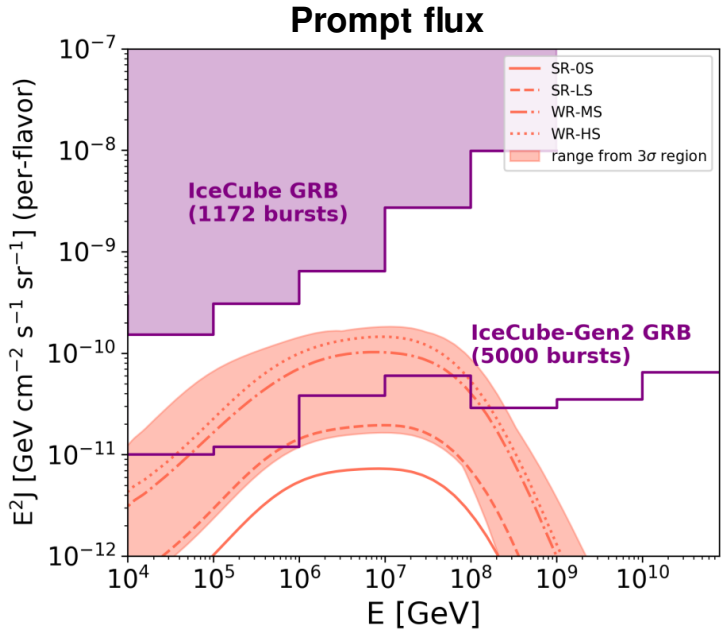
$X^2 - X^2_{min}$ minimized over third axis

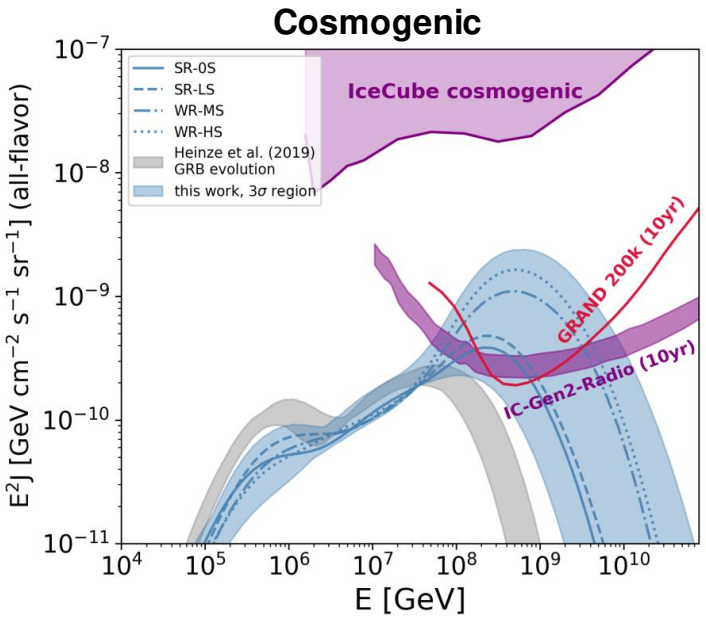


Fitting UHECR data: Neutrino ranges

Multi-collision model – Parameter scan

- Neutrino range for 3σ - contours
- Low Γ_{max} + High A_Γ $\rightarrow$ high neutrino flux
- **Below the IceCube stacking limit ….** but in reach of Gen2





Conclusion

- Multi Collision Models **separate particle production** regions:
  - Neutrinos from small radii; UHECRs from intermediate; gamma-rays from all radii
  - The **observed light curve** indicates UHECR disintegration and neutrino production
- Engine behavior can (partially) **decouple** the **UHECR acceleration/escape** and **neutrino production**

- UHECR fit in principle still viable depending on the engine behavior ....
  … but **stochasticity** of the **engine/light curve limited** by $\sigma(X_{\max})$
- Large engine kinetic energies required (general problem of UHECR fits)
- Heavy mass fraction larger than 70% (95% CL)
- Neutrino flux likely testable in IceCube-Gen2