UHECR from high- and low-luminosity GRBs

J. Heinze, D. Biehl, A. Fedynitch, D. Boncioli, A. Rudolph, W. Winter – MNRAS 498 (2020) arxiv 2006.1430

A. Rudolph, Z. Bosnjak, I. Sadeh, A. Palladino, W. Winter – arxiv 2107.04612

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International Cosmic Ray Conference (ICRC)
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HELMHOLTZ RESEARCH FOR GRAND CHALLENGES

Gamma-Ray Bursts

A potential source of UHECR?

Observational properties of GRBs

- Energetic outbursts of gamma-rays

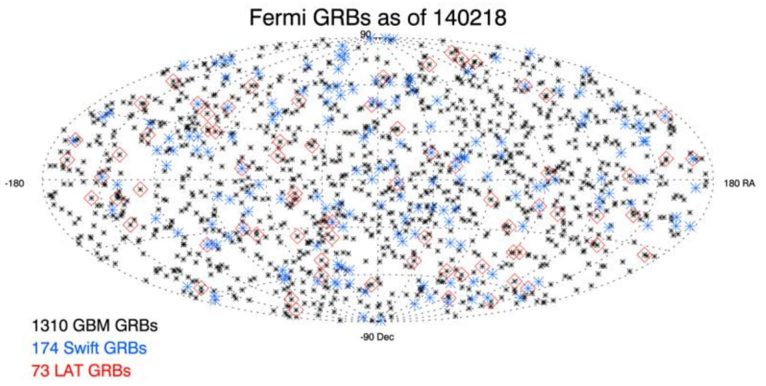
  $E_{iso} \sim 10^{49} – 10^{54}$ ergs
- Two populations by duration:

  (1) Long GRBs : ≥ 2s

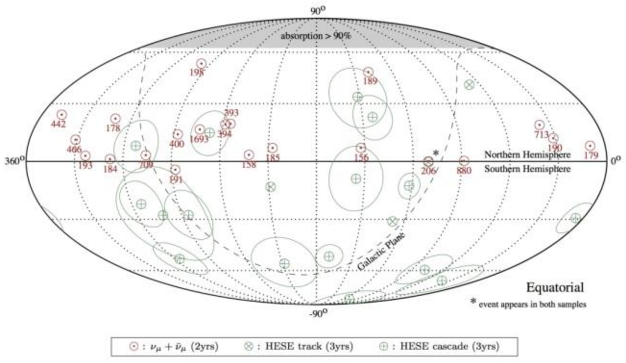
  (2) Short GRBs: ≤ 2s
- Large variety of **light curves with fast time variability**
- **Similar spectra** (Band function)
- **No correlation between observed GRBs and HE neutrinos (-> Stacking limits)**

Catalogue of known GRBs

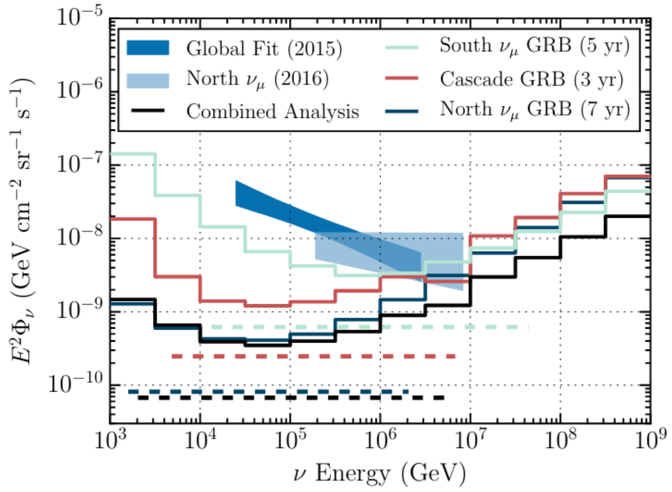
Fermi LAT + GBM coll



Detected HE neutrnos



IceCube coll.



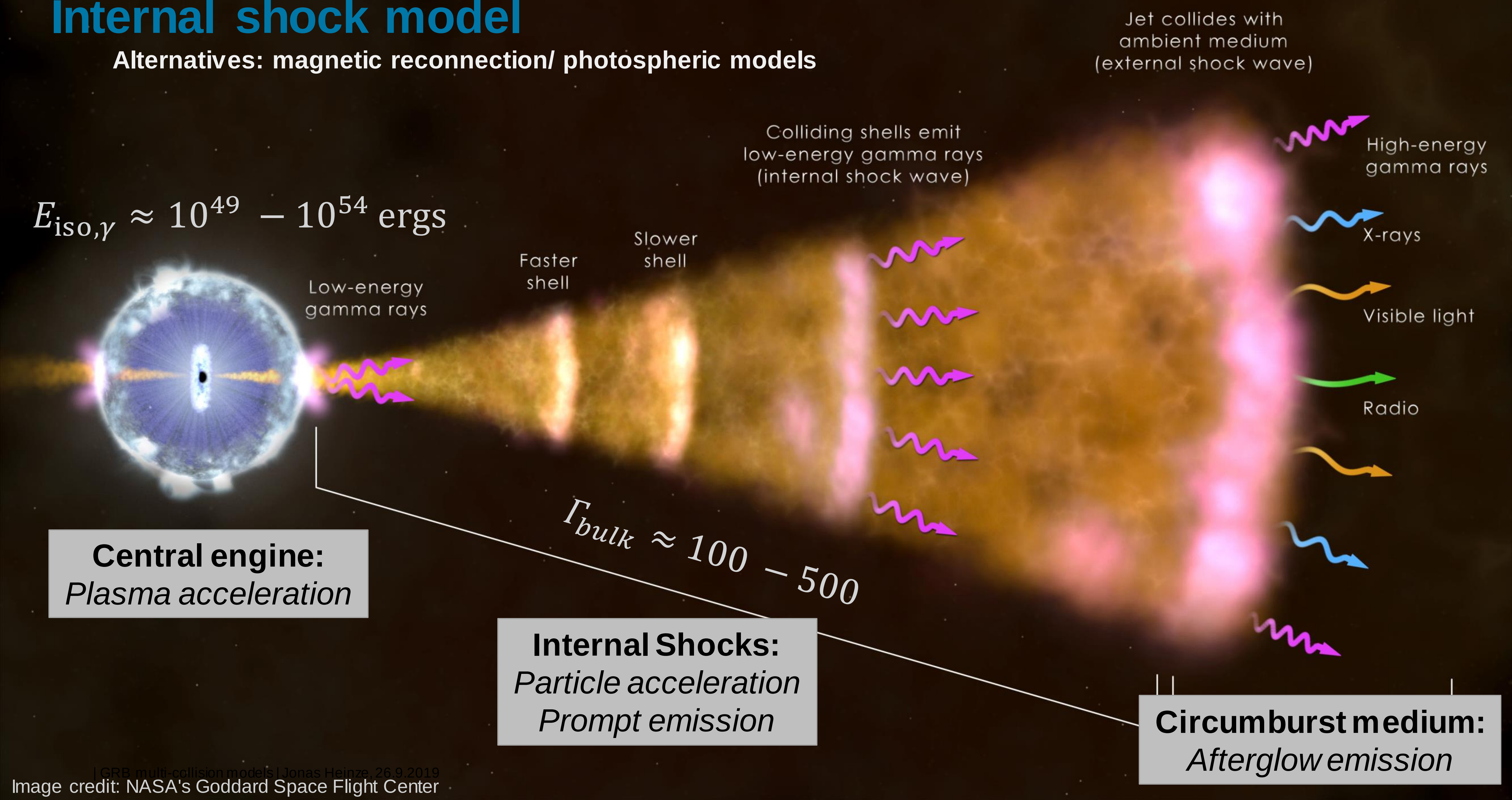
Aartsen et al 2017

Most simple GRB models ruled out as UHECR sources.
Need refined models / specific part of the parameter space
This talk: Multi-zone model & Low-Luminosity GRBs

Internal shock model

Alternatives: magnetic reconnection/ photospheric models

$$E_{iso,\gamma} \approx 10^{49} - 10^{54} \text{ ergs}$$



$$\Gamma_{bulk} \approx 100 - 500$$

Central engine:
Plasma acceleration

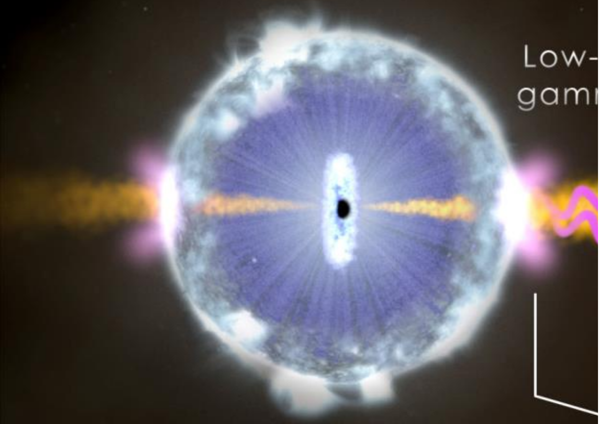
Internal Shocks:
Particle acceleration
Prompt emission

Circumburst medium:
Afterglow emission

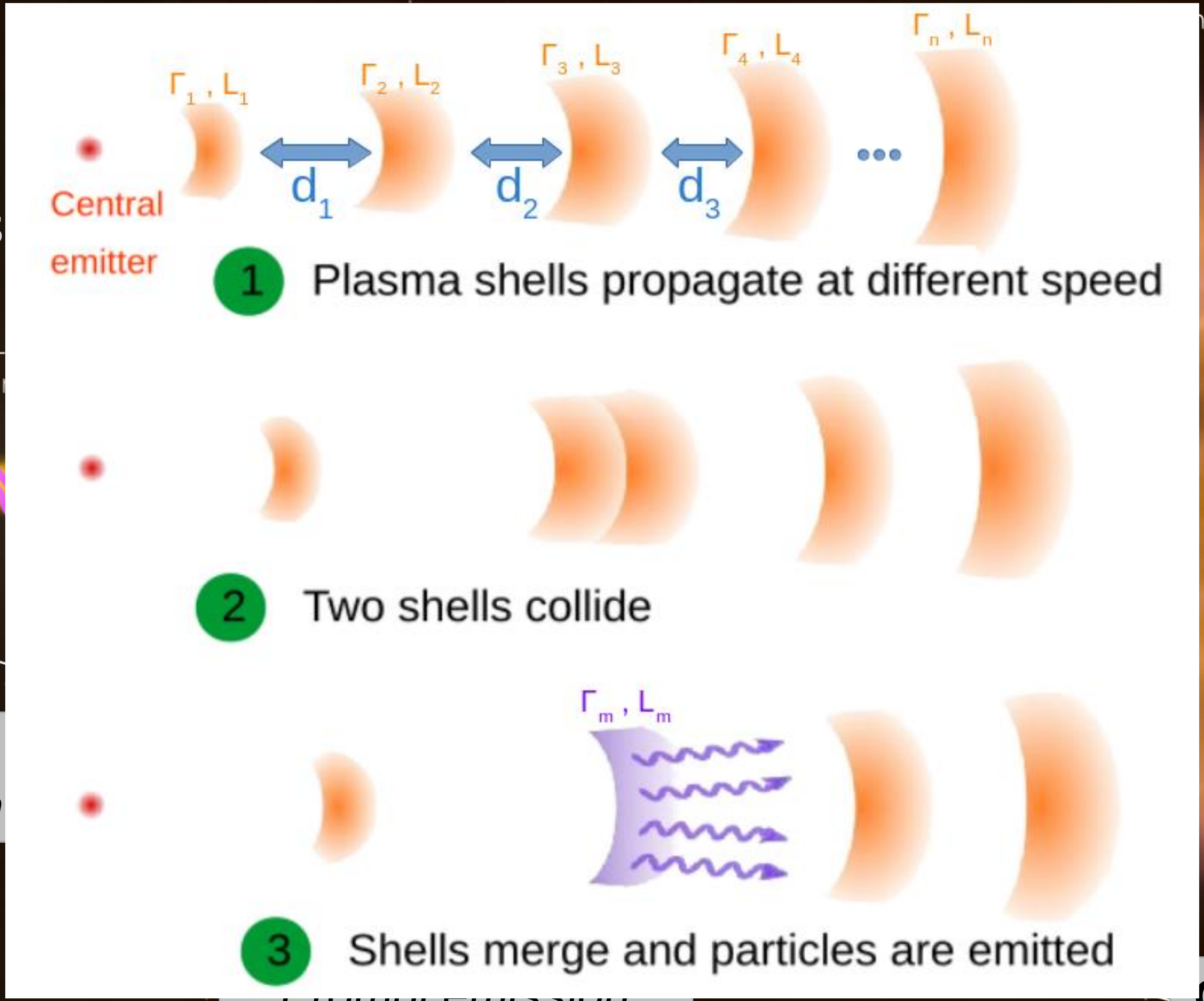
Image credit: NASA's Goddard Space Flight Center

Internal shock model

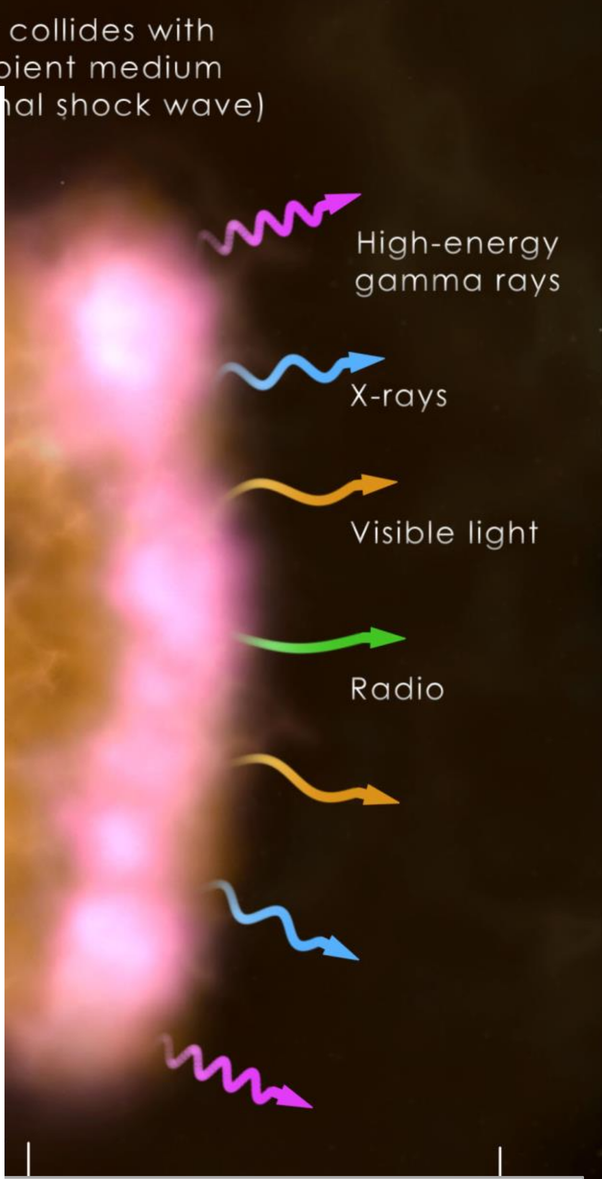
$E_{\mathrm{iso},\gamma} \approx 10^{49} - 10^{5}$



Central engine:
Plasma acceleration



Prompt emission



Circumburst medium:
Afterglow emission

Image credit: NASA's Goddard Space Flight Center

Fitting the UHECR spectrum in a parameter scan over engine realisations

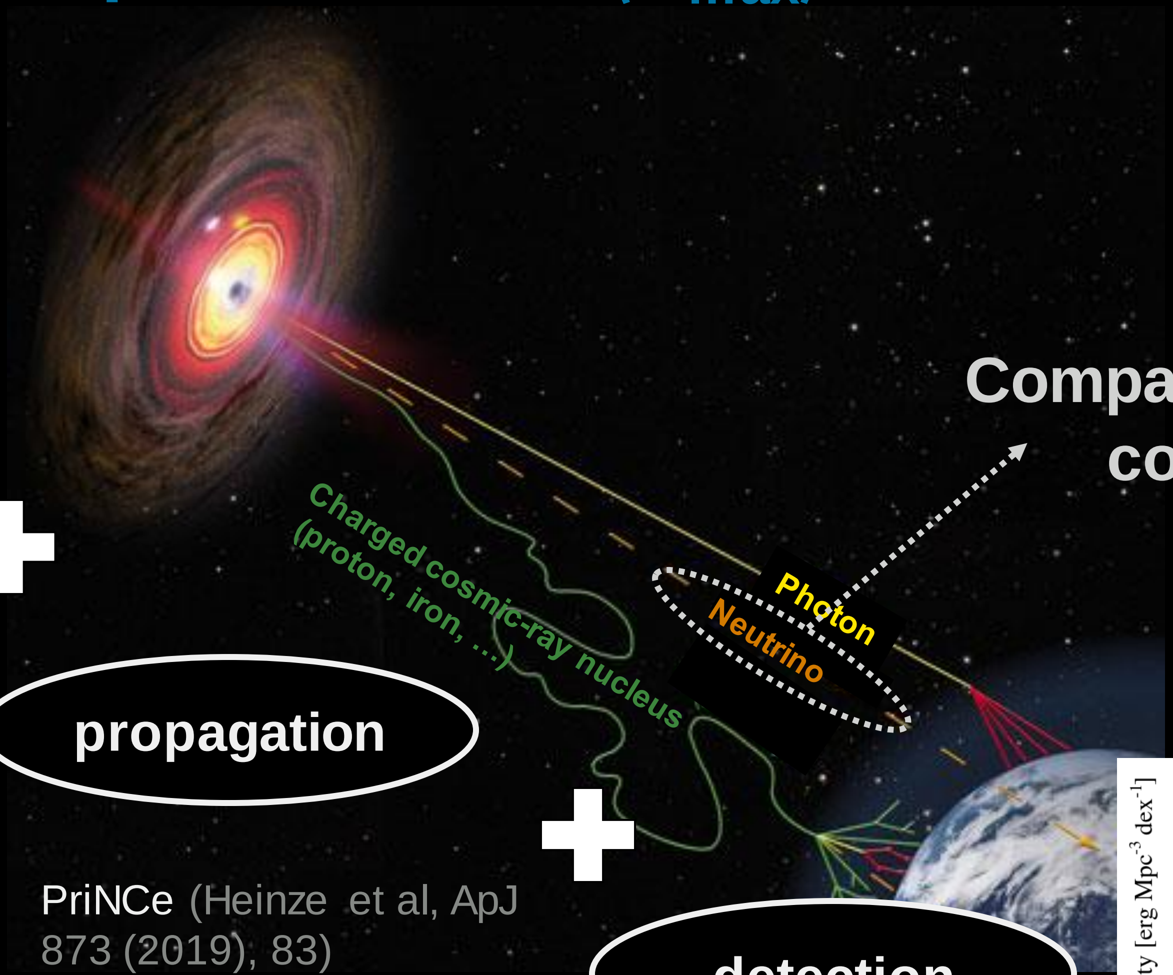
MNRAS 498 (2020) arxiv 2006.1430

Fitting the UHECR spectrum and $\langle X_{max} \rangle$ with GRBs

Combined Model

source

- Remus – Code
  Multi-zone internal shock model
- NeuCosmA – Code
  in-source disintegration/ interactions
- **Parameter scan over different engine realisations**
- **Fit parameters: injection composition, baryonic loading**



+

propagation

- PriNCe (Heinze et al, ApJ 873 (2019), 83)
- GRB distribution (Wanderman, Piran, MNRAS 406 (2010)

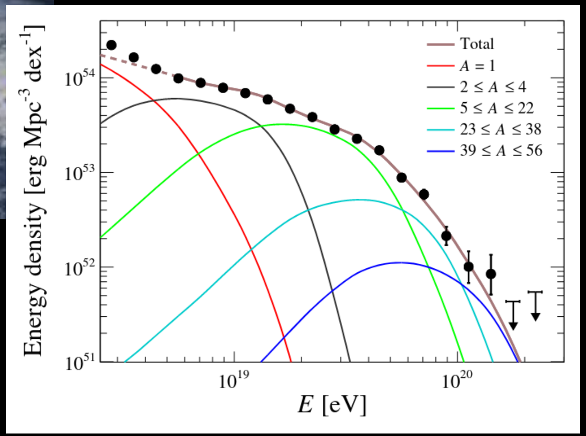
+

detection

- **Fit to UHECR spectrum and $\langle X_{max} \rangle$ (Auger)**

Compare to neutrino constraints

UHECR spectrum



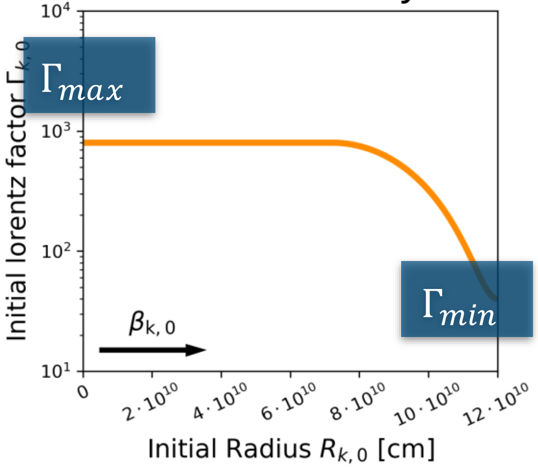
Auger Coll 2020 (arxiv 2008.06488)

Fitting UHECR data: Exploration of different engine realisations

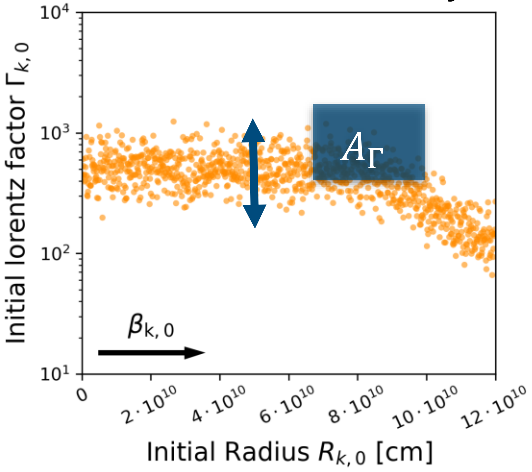
Description of different engine types: from disciplined to stochastic

Initial Lorentz Factors

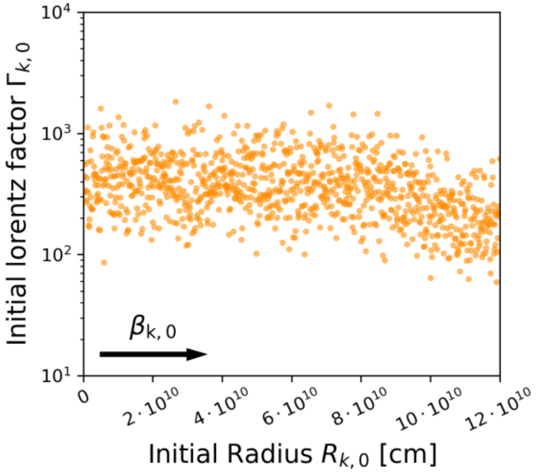
Strong Ramp-up
0 Stochasticity



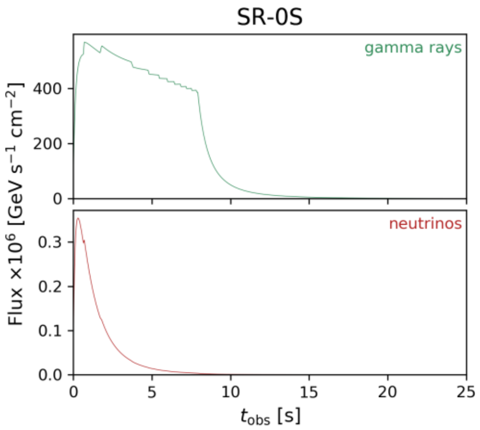
Weak Ramp-up
Medium Stochasticity

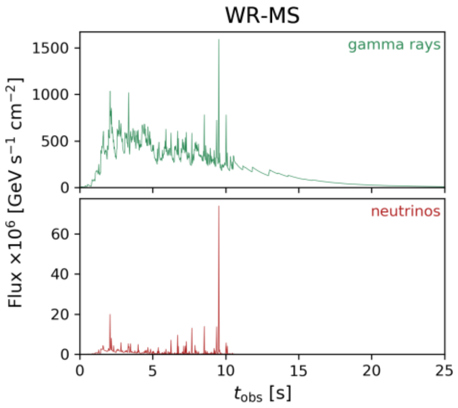


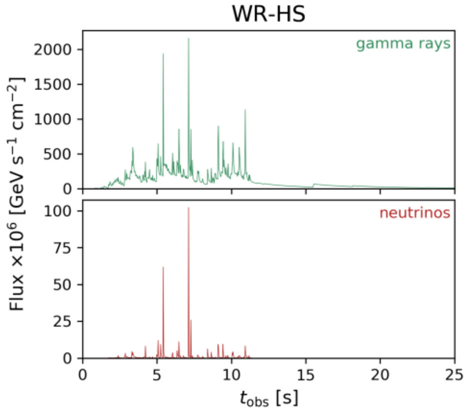
Weak Ramp-up
High Stochasticity



Light curves







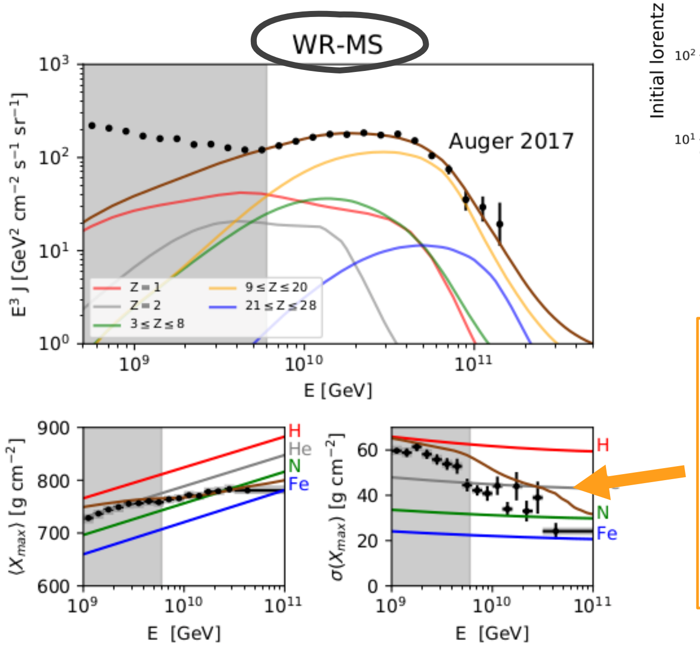
Parameterization similar to Globus et al. MNRAS. 451 (2015)

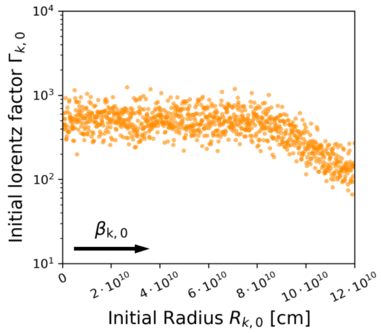
Fitting UHECR data: parameter space result

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

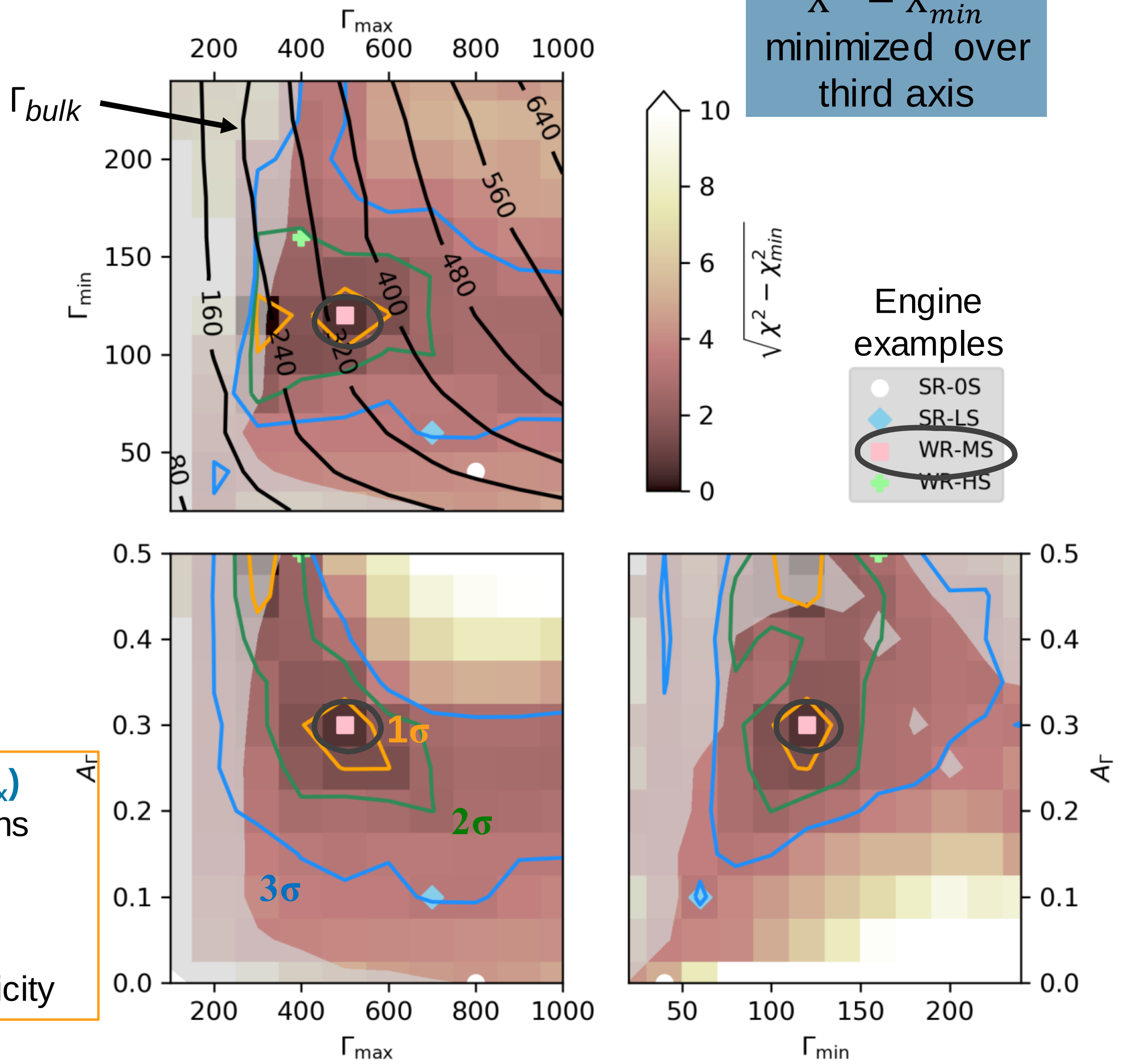
$X^2 - X^2_{min}$ minimized over third axis

Best fit





No good fit for $\sigma(X_{max})$
overlapping contributions
in and from
single collisions
→soft spectra,
better fit for low stochasticity



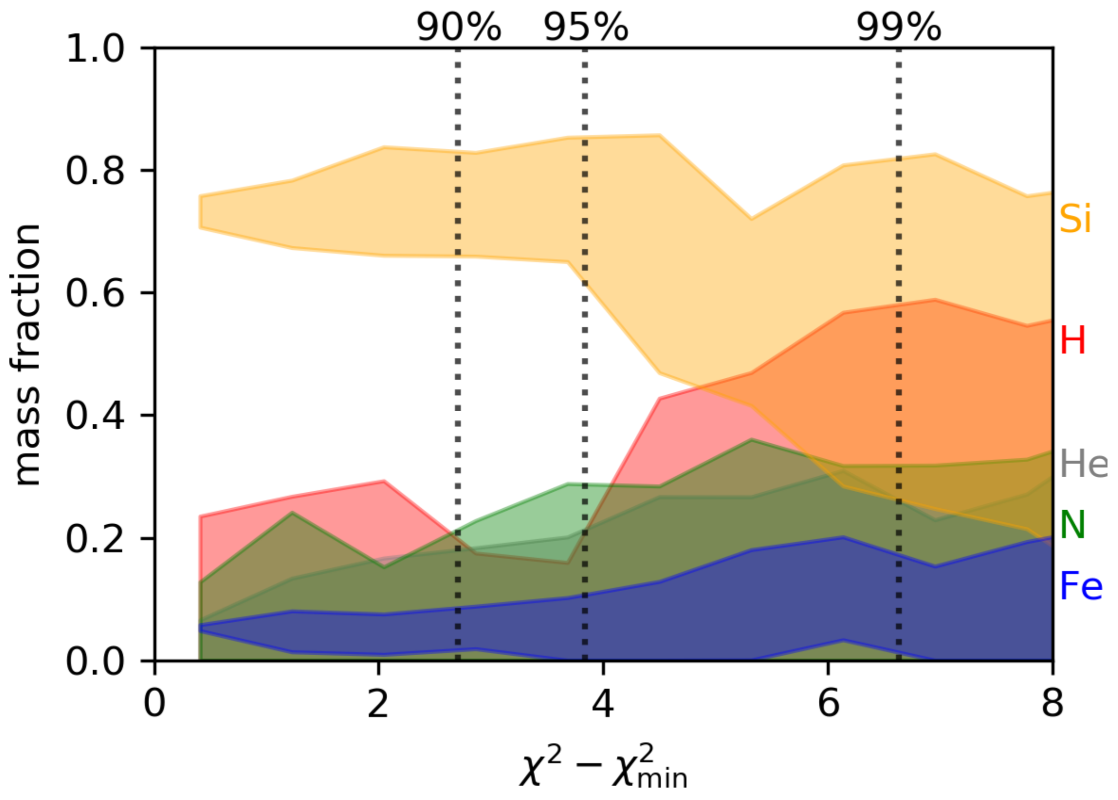
Fitting UHECR data: Metallicity

How large is the fraction of heavy elements injected at the source?

Define injected integral mass fraction (per element):

$$I_A \equiv \frac{\int_{1\,\mathrm{GeV}}^{\infty} \frac{dN'}{dE'_{\mathrm{CR}}} E'_{\mathrm{CR}} dE'_{\mathrm{CR}}}{\sum_A \int_{1\,\mathrm{GeV}}^{\infty} \frac{dN'}{dE'_{\mathrm{CR}}} E'_{\mathrm{CR}} dE'_{\mathrm{CR}}} .$$

	SR-0S	SR-LS	WR-MS	WR-HS
$\Gamma_{\max}$	800	700	500	400
$\Gamma_{\min}$	40	60	120	160
A_Γ	0.0	0.1	0.3	0.5
χ^2	51.0	34.3	23.4	30.7
χ^2/dof	3.9	2.6	1.8	2.4
Baryonic loading f_b	80.1	67.1	59.5	108.4
Energy shift δ_E	0.14	-0.14	-0.14	-0.14
Dissipation efficiency ϵ_{diss}	0.28	0.22	0.13	0.14
Fraction super-photospheric f_{sup}	0.67	0.80	0.82	0.43
E_γ	$6.67 \cdot 10^{52}$ erg	$8.00 \cdot 10^{52}$ erg	$8.21 \cdot 10^{52}$ erg	$4.27 \cdot 10^{52}$ erg
$E^{\mathrm{esc}}_{\mathrm{UHECR}}$ (escape)	$2.01 \cdot 10^{53}$ erg	$2.10 \cdot 10^{53}$ erg	$1.85 \cdot 10^{53}$ erg	$1.69 \cdot 10^{53}$ erg
$E^{\mathrm{src}}_{\mathrm{CR}}$ (in-source)	$5.11 \cdot 10^{54}$ erg	$5.13 \cdot 10^{54}$ erg	$4.62 \cdot 10^{54}$ erg	$4.36 \cdot 10^{54}$ erg
$E^{\mathrm{src}}_{\mathrm{UHECR}}$ (in-source, UHECR)	$3.70 \cdot 10^{53}$ erg	$4.46 \cdot 10^{53}$ erg	$3.97 \cdot 10^{53}$ erg	$3.57 \cdot 10^{53}$ erg
E_ν	$7.81 \cdot 10^{49}$ erg	$2.18 \cdot 10^{50}$ erg	$1.28 \cdot 10^{51}$ erg	$1.79 \cdot 10^{51}$ erg
$E_{\mathrm{kin,init}}$	$2.90 \cdot 10^{55}$ erg	$3.03 \cdot 10^{55}$ erg	$4.50 \cdot 10^{55}$ erg	$7.81 \cdot 10^{55}$ erg
Fraction I_{H}	$0.22^{+0.04}_{-0.05}$	$0.00^{+0.10}_{-0.00}$	$0.00^{+0.06}_{-0.00}$	$0.01^{+0.07}_{-0.01}$
Fraction I_{He}	$0.00^{+0.01}_{-0.00}$	$0.07^{+0.04}_{-0.05}$	$0.07^{+0.07}_{-0.07}$	$0.27^{+0.05}_{-0.05}$
Fraction I_{N}	$0.39^{+0.04}_{-0.04}$	$0.29^{+0.06}_{-0.08}$	$0.13^{+0.11}_{-0.13}$	$0.00^{+0.09}_{-0.00}$
Fraction I_{Si}	$0.33^{+0.03}_{-0.04}$	$0.63^{+0.03}_{-0.03}$	$0.76^{+0.03}_{-0.03}$	$0.53^{+0.03}_{-0.03}$
Fraction I_{Fe}	$0.06^{+0.02}_{-0.02}$	$0.01^{+0.02}_{-0.01}$	$0.05^{+0.03}_{-0.03}$	$0.19^{+0.02}_{-0.03}$
Heavy mass fraction	$0.78^{+0.22}_{-0.10}$	$0.93^{+0.07}_{-0.13}$	$0.93^{+0.07}_{-0.19}$	$0.72^{+0.28}_{-0.06}$

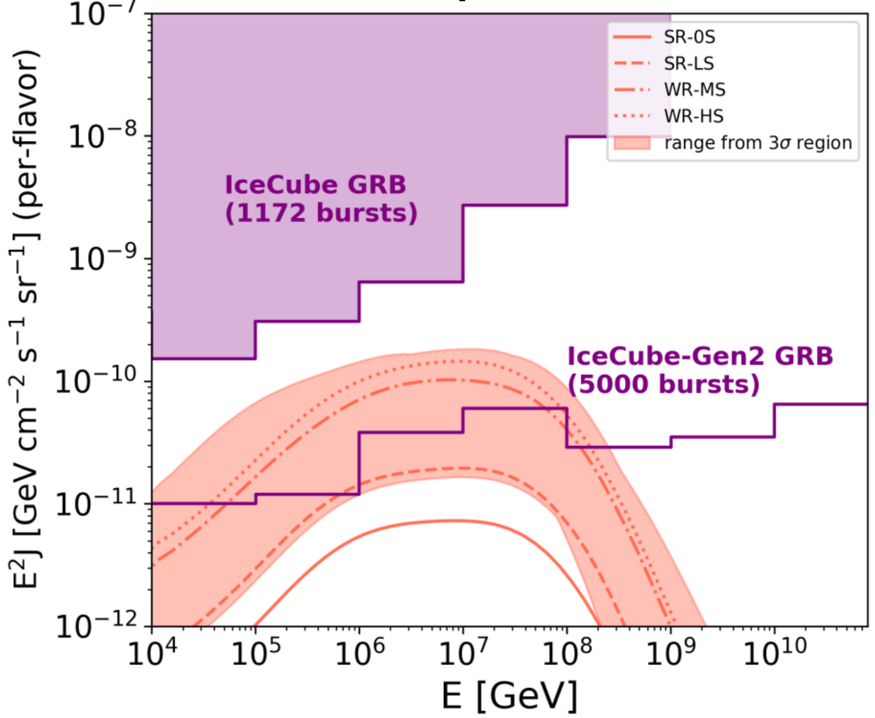


Fitting UHECR data: Neutrino ranges

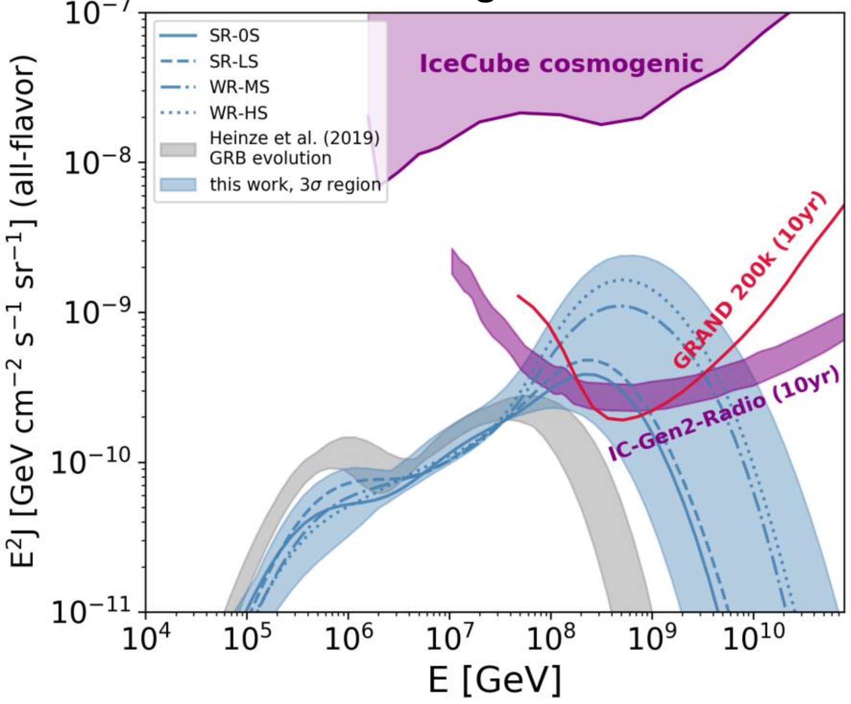
Multi-collision model – Parameter scan

- 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

Prompt flux



Cosmogenic

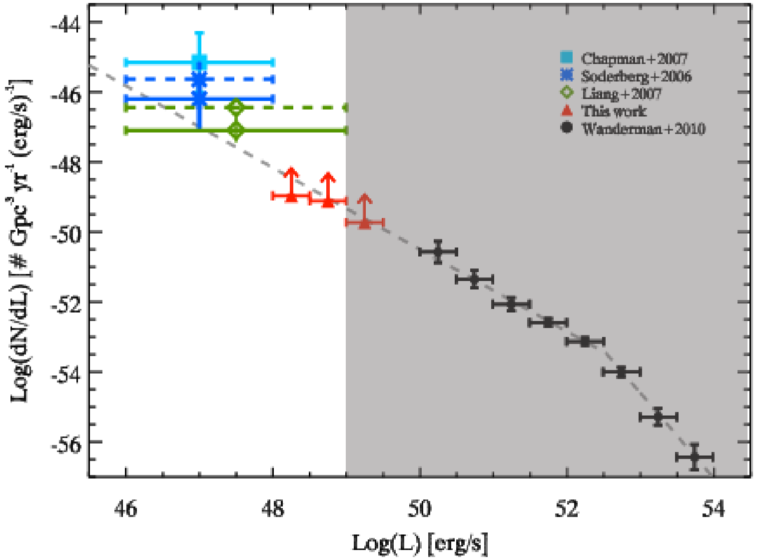


Exploring LL-GRBs as sources of UHECR and VHE gamma-ray radiation

arxiv 2107.04612

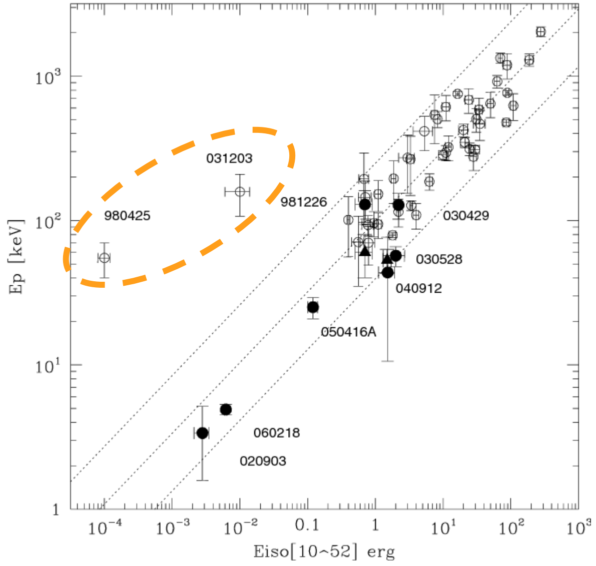
Low-Luminosity GRBs

Properties and recent discussions



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 2018, Samuelsson et al 2018 & 2020, Zhang et al 2017)*



Stratta et al 2007

- **High local density** when compared to high-luminosity GRBs, but so far less then 20 LL GRBs observed → could we detect more of them with future instruments like CTA?
- (Some) LL-GRBs seem to be **outliers to known correlations**

Choosing two exemplary LL - GRBs

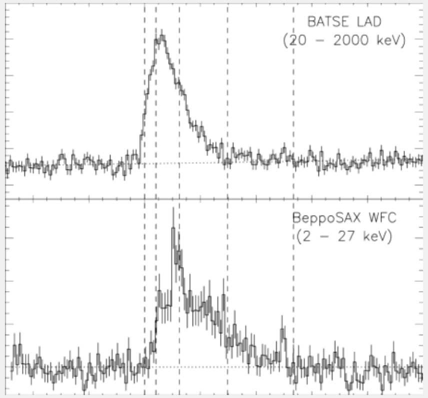
Outflow model: Daigne et al 1998
Radiative Code: AM3 (Gao et al 2016)

Fact sheets observed properties

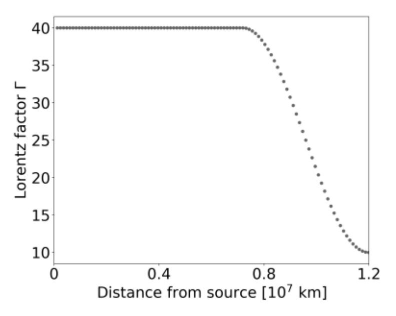
GRB 980425

$E_{iso} = 1.6\ 10^{48}$ erg
$L_{iso} = 4.6\ 10^{46}$ erg/s
$T_{90} = 35$ s
$E_{peak} = 122$ keV
$z = 0.0085$

Observed light curve



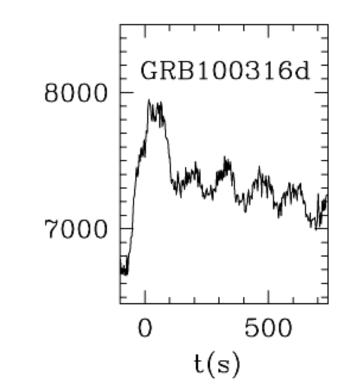
$L_{wind} = 2.5\ 10^{48}$ ergs
for $t_{engine} = 40$ s



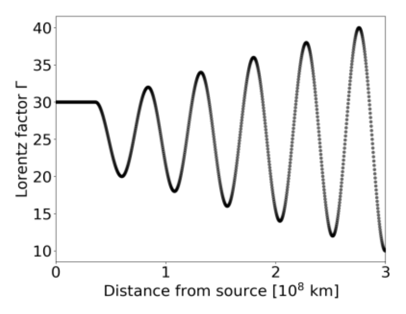
GRB 100316D

$E_{iso} = 3.9\ 10^{49}$
$L_{iso} = 1.2\ 10^{47}$ erg/s
$T_{90} = 1300$ s
$E_{peak} = 30$ keV
$z = 0.059$

Observed light curve



$L_{wind} = 5.8\ 10^{48}$ ergs
for $t_{engine} = 1000$ s



Explore impact of magnetic field
→adjust fraction of accelerated
electrons (ζ) to fit observed peak

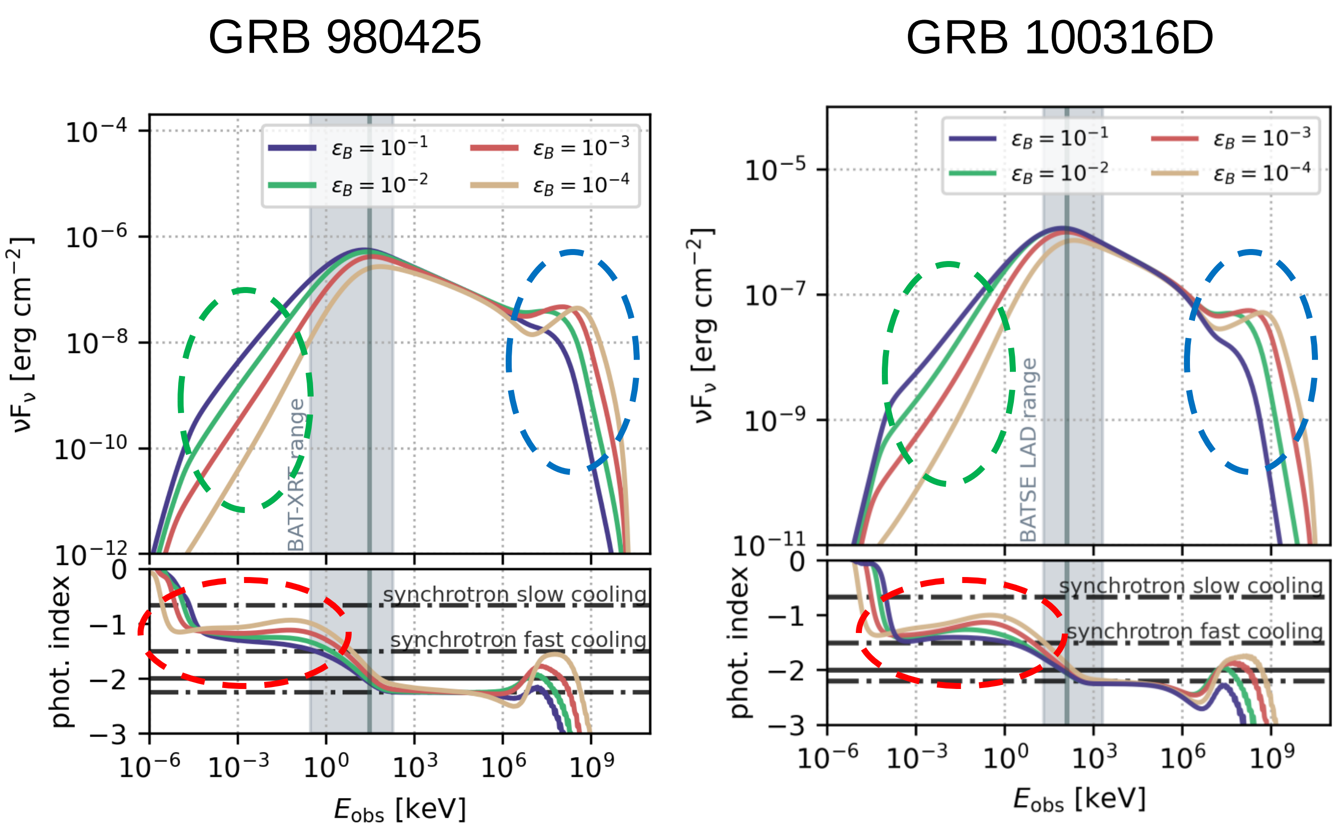
Simulated spectra (observer frame)

Purely leptonic radiation modeling

- **Fixed dynamical properties of the outflow** (density, dissipated energy and Lorentz factor as a fct of collision radius and time from multi-collision internal shock model)
- Reproduce light curve structure, observed fluence and E_{peak} of reference events
- **Vary magnetic field via ε_B**

  in each collision $B' = \sqrt{8\pi\epsilon_B \rho' \epsilon'_{diss}}$
- **Low ε_B:** large α, small optical/ UV flux, large VHE component
- Radiative efficiency can put lower bounds on ε_B ($\varepsilon_B \geq 10^{-3}$)

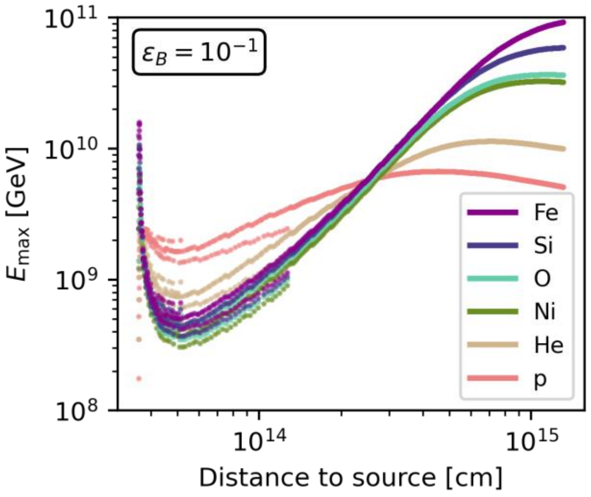
Simulated spectra

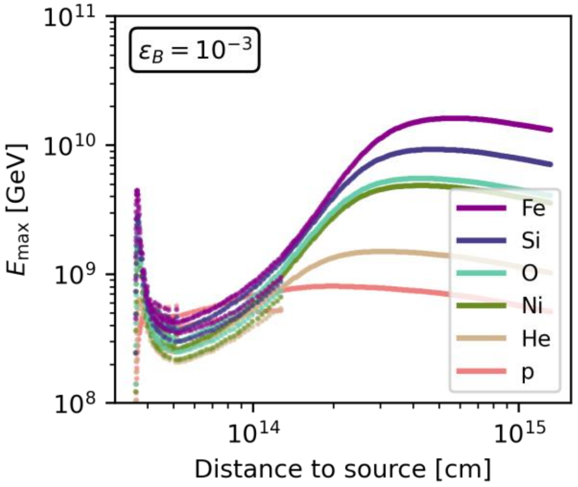


Maximal energies of cosmic-ray nuclei (source frame)

Using the dynamical evolution of the jet & results of the leptonic radiation modeling

GRB 980425





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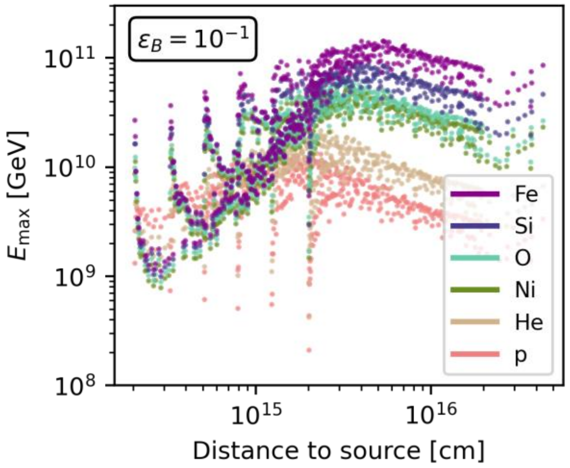

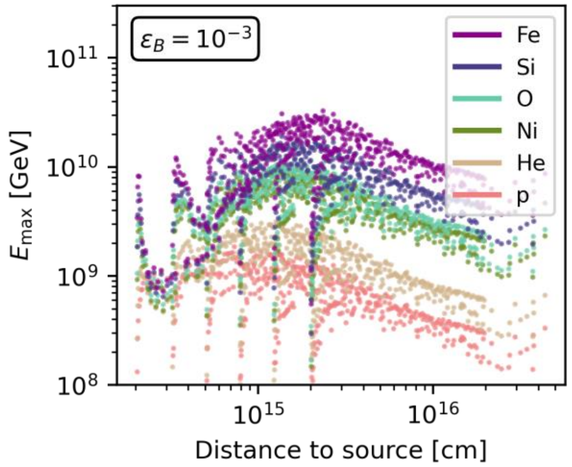

- E_{max} calculated balancing losses and acceleration (NeuCosmA Code, Biehl et al 2017)
- **Boncioli et al (2018)** Best Fit Parameters: L_{iso} ~ 5 10^{46} erg/s Emax, Si ~ $10^{9.7}$ GeV (shock rest frame) R ~ 10^{14} cm

→We reach high enough energies and results are (roughly) compatible!

Conclusion

UHECR in GRBs: IceCube Neutrino limits exclude most simple internal shock models. Need more refined models or specific region of the parameter space

- **Multi-collision models** separate particle production regions
- Engine behaviour/ stochasticity reflects in time variability of the light curve
- UHECR fit in principle still viable, depending on the engine realisation...
  … but **stochasticity of the engine/ light curve is limited by $\sigma(X_{max})$**
- **Large engine kinetic energies neccessary (general problem of UHECR fits)**
- Required heavy mass fraction at injection > 75% (95% CL)
- Neutrino flux likely testable by IceCube Gen2

- **LL-GRBs** Self-consistent (leptonic) radiation modeling of selected events in the internal shock model
- For low magnetic fields (low ε_B):
  VHE component potentially in reach of ground-based instruments (CTA)
- Maximal energies (in the source frame) for **iron** can be up to **10^{11} GeV**, for **protons** up to **10^9 GeV**. High ε_B yield high maximal energies!