UHECR and neutrino production in GRB multi-collision models

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Gamma Ray Bursts

Prompt emission

- Energetic outbursts of gamma-rays
  $$L_{\mathrm{iso},\gamma} \approx 10^{49} - 10^{53}\ \mathrm{erg}\ /\ \mathrm{s}$$
- Two main populations by duration:
  - **Long GRBs** $\rightarrow \sim 10\ - 100\ s$
    core-collapse supernovae?
  - **Short GRBs** $\rightarrow \sim 0.1\ - 1\ s$
    neutron star mergers? *(GW170817A !)*
- Large variety of observed **light curves**
  - Fast **time variability** t_ν
    Internal shocks?
    Magnetic Reconnection?
    Photospheric emissions?

Sources of UHECRs?
Neutrino production?

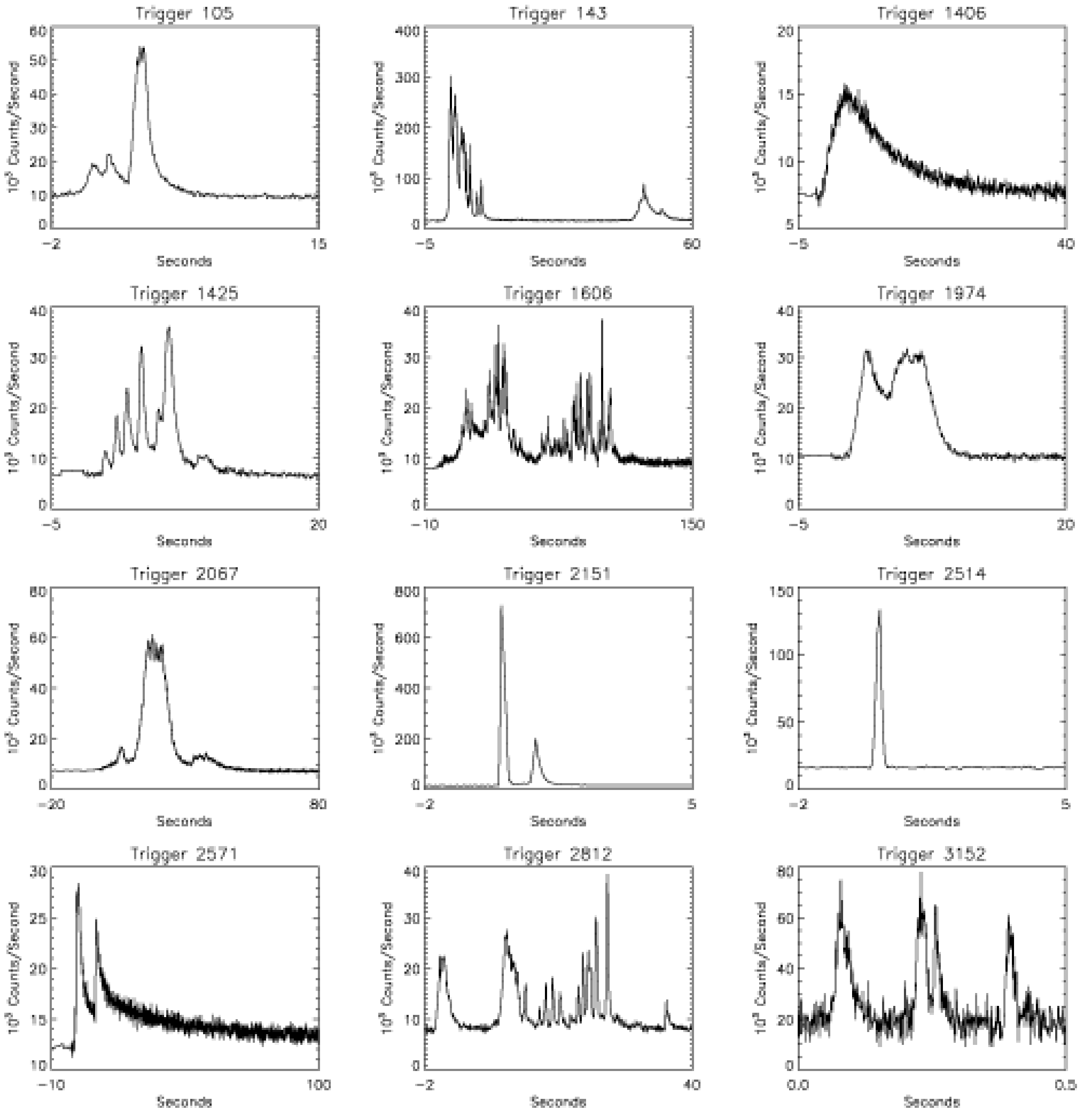
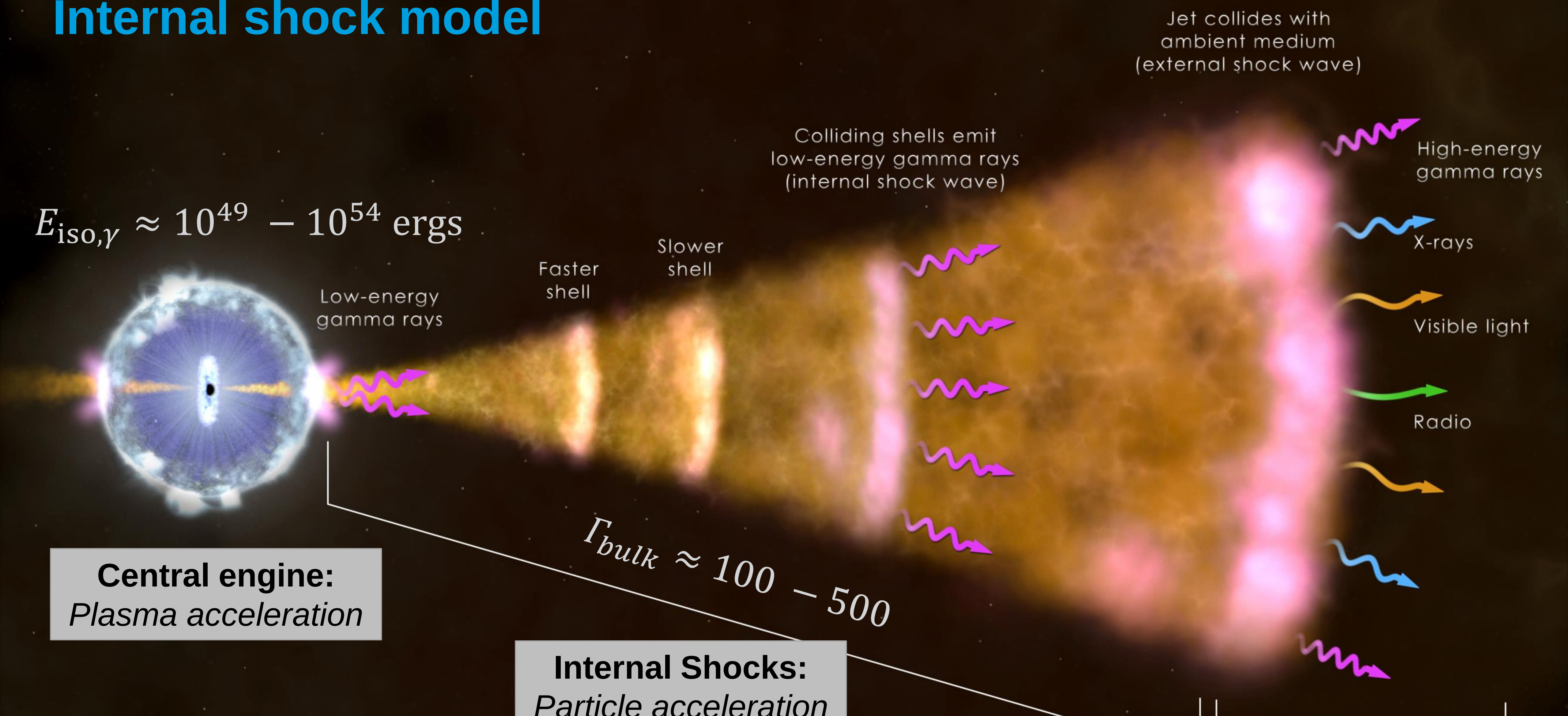


Image credit: J.T. Bonnell (NASA/GSFC)

Internal shock model

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

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

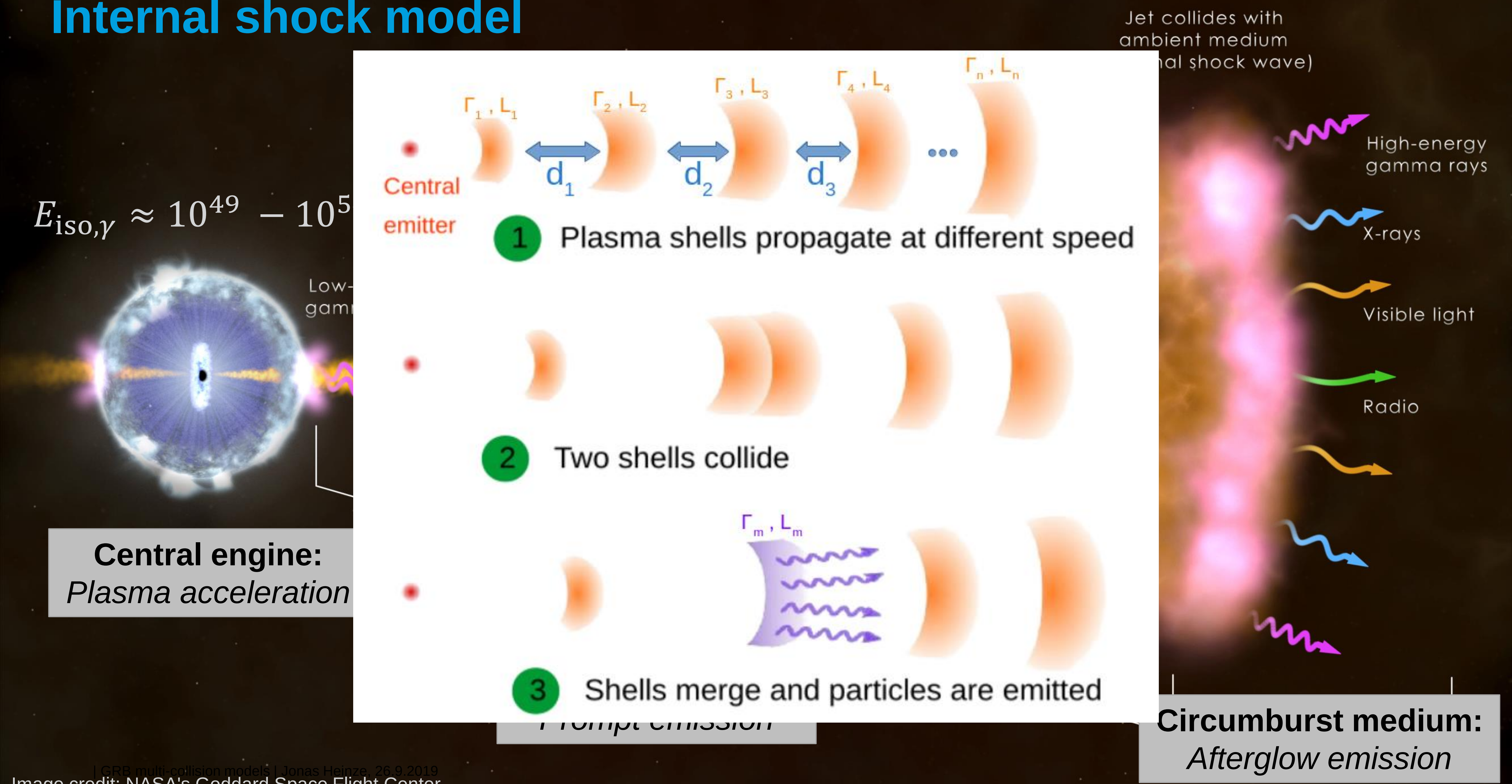


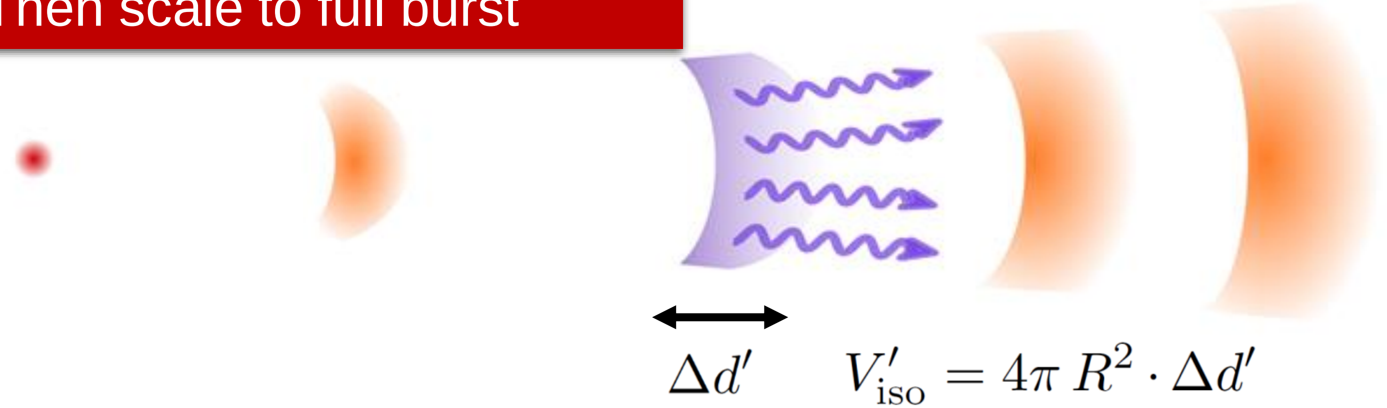
Image credit: NASA's Goddard Space Flight Center

One Zone radiation model

UHECR acceleration and neutrino production

Compute single average collision!
→ Then scale to full burst

$$N_{\mathrm{coll}} \simeq T_{90}/t_v$$



$$V'_{\mathrm{iso}} = 4\pi\, R^2 \cdot \Delta d'$$

Isotropic radiation zone
Geometry estimates

$$R \simeq 2\,\Gamma^2\,\frac{c\,t_v}{1+z}$$

$$\Delta d' \simeq \Gamma\,\frac{ct_v}{1+z}$$

Photon energy density:

$$u'_\gamma \equiv \int \varepsilon' N'_\gamma(\varepsilon')\mathrm{d}\varepsilon' = \frac{L_\gamma\,\Delta d'/c}{\Gamma^2\,V'_{\mathrm{iso}}} = \frac{L_\gamma}{4\pi c\Gamma^2 R^2}$$

Photon Field:
Broken power law

→ Scales with R^{-2}

Nuclei injection density:

$$\int_0^{10\,E'_{i,\mathrm{max}}} E'_i\,Q'_i(E'_i)\,\mathrm{d}E'_i = \xi_i \cdot u'_\gamma \cdot \frac{c}{\Delta d'}$$

Nuclei Injection

Baryonic Loading

Assume fixed peak energy – 1 keV

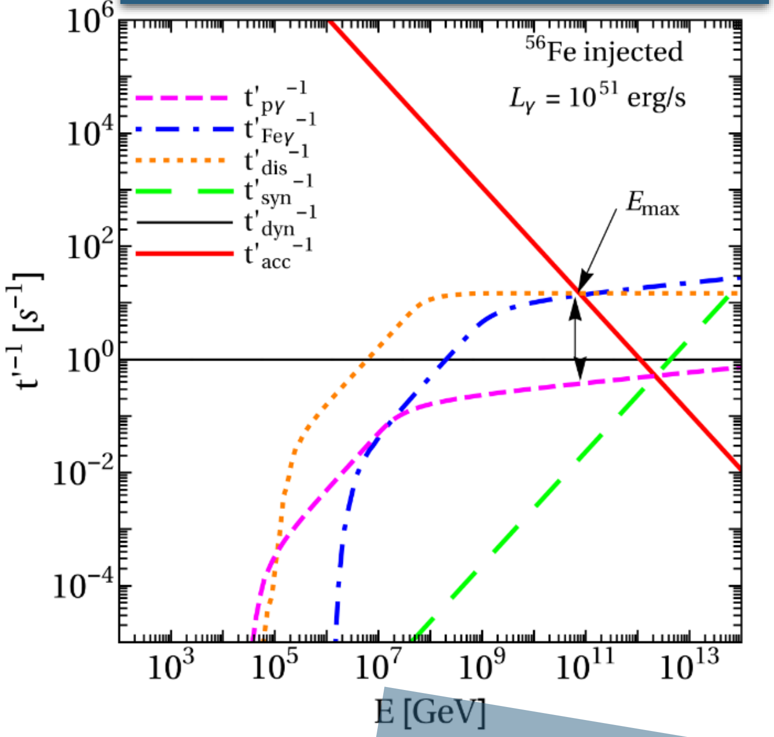
→ Photo-disintegration / Photo-pion-production

→ Secondary neutrinos

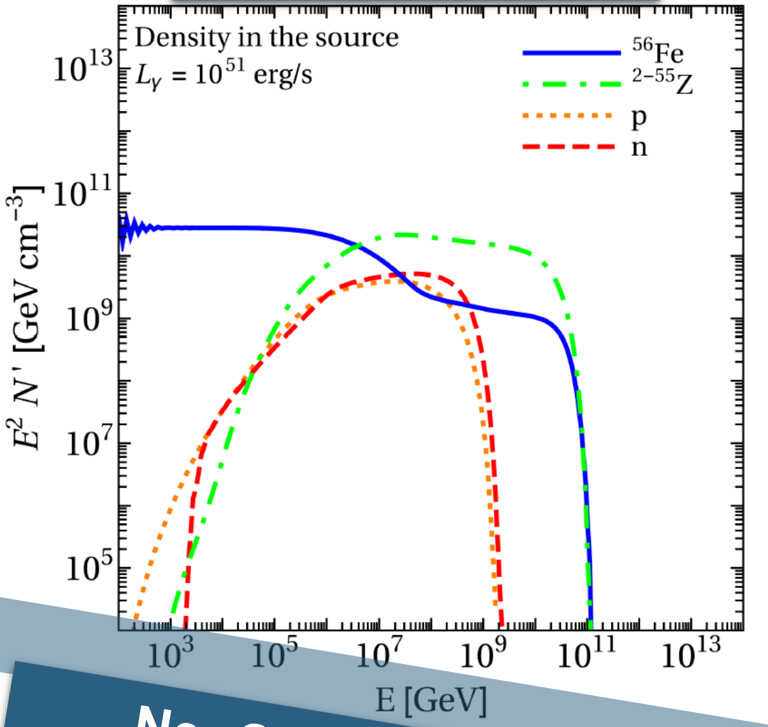
Biehl, Boncioli, Fedynitch, Winter, Astron.Astrophys. 611 (2018)

One Zone radiation model

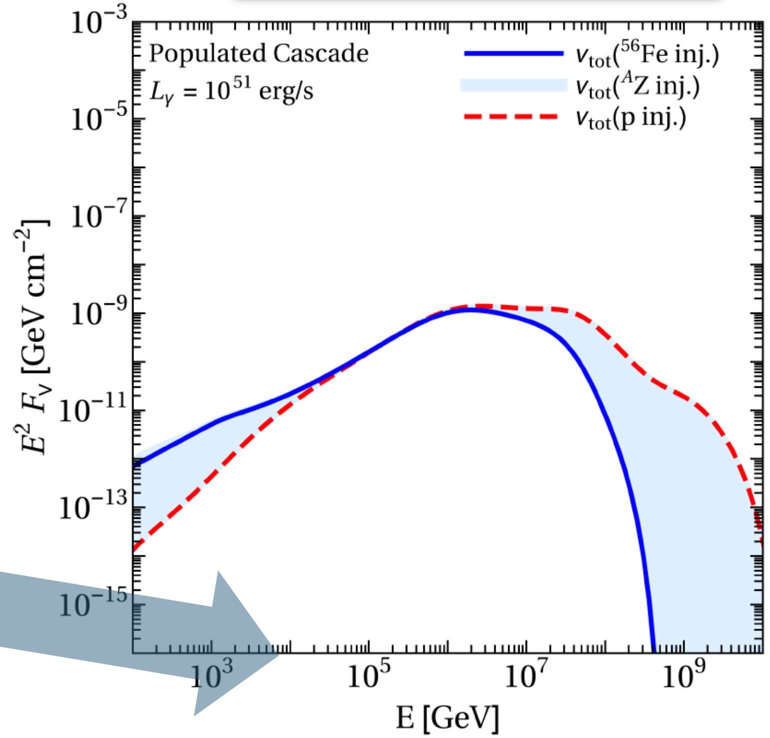
Determined **maximal Energy**
From interaction rates



Cosmic ray spectrum
From time evolution



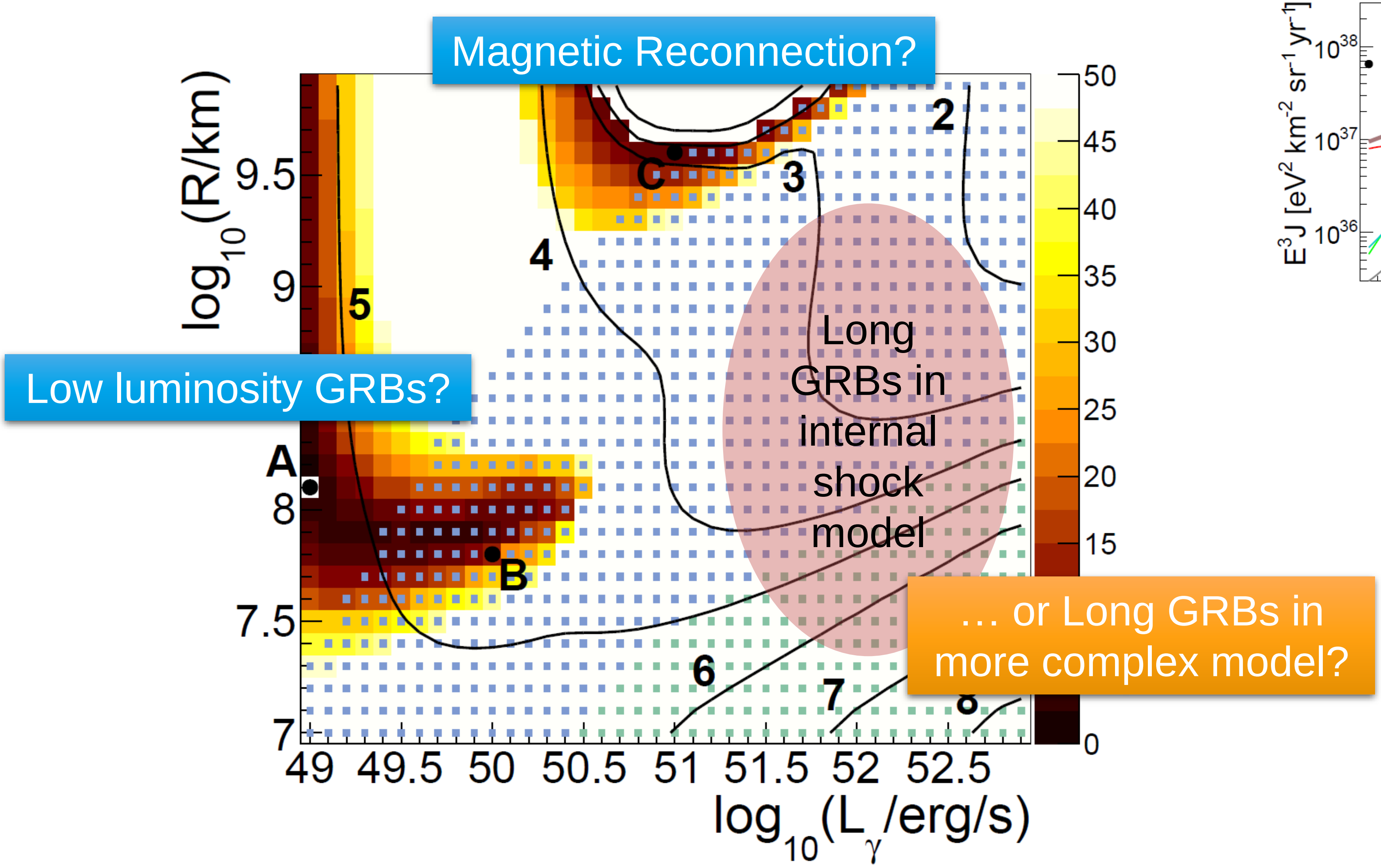
Neutrino spectrum

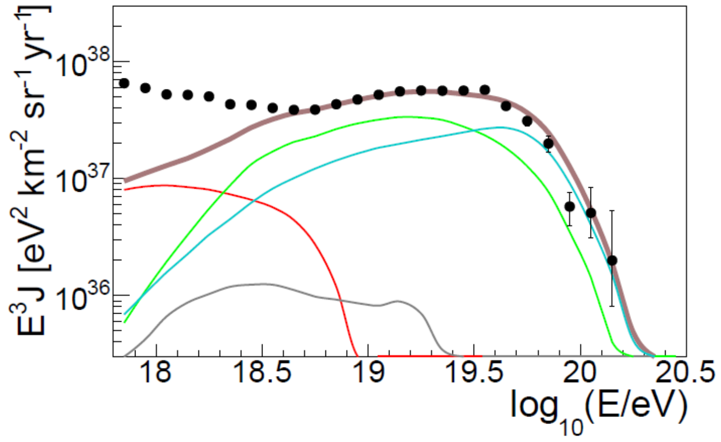


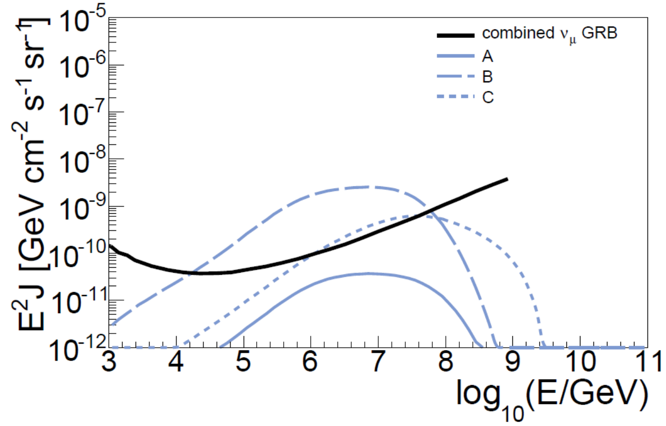
NeuCosmA
radiation code

One Zone model – extragalactic Propagation

Fit to UHECR data and neutrino constraints







Multi Collision model

Bustamante, JH, Murase, Winter, Astrophys.J. 837 (2017)
Rudolph, JH, Fedynitch, Winter arXiv: 1907.10633

Compute the full jet evolution now!

- Merged Lorentz Factor:

$$\Gamma_m = \sqrt{\frac{m_r\Gamma_r + m_s\Gamma_s}{m_r/\Gamma_r + m_s/\Gamma_s}}$$

- Available internal energy:

$$E_{\text{int},m} = m_r\Gamma_r + m_s\Gamma_s - (m_r + m_s)\Gamma_m$$

- Dissipated energy:

$$E_{\text{diss},m} = \eta\, E_{\text{int},m} \text{ with } \eta = 1$$

- Timescale and thickness from shock speed:

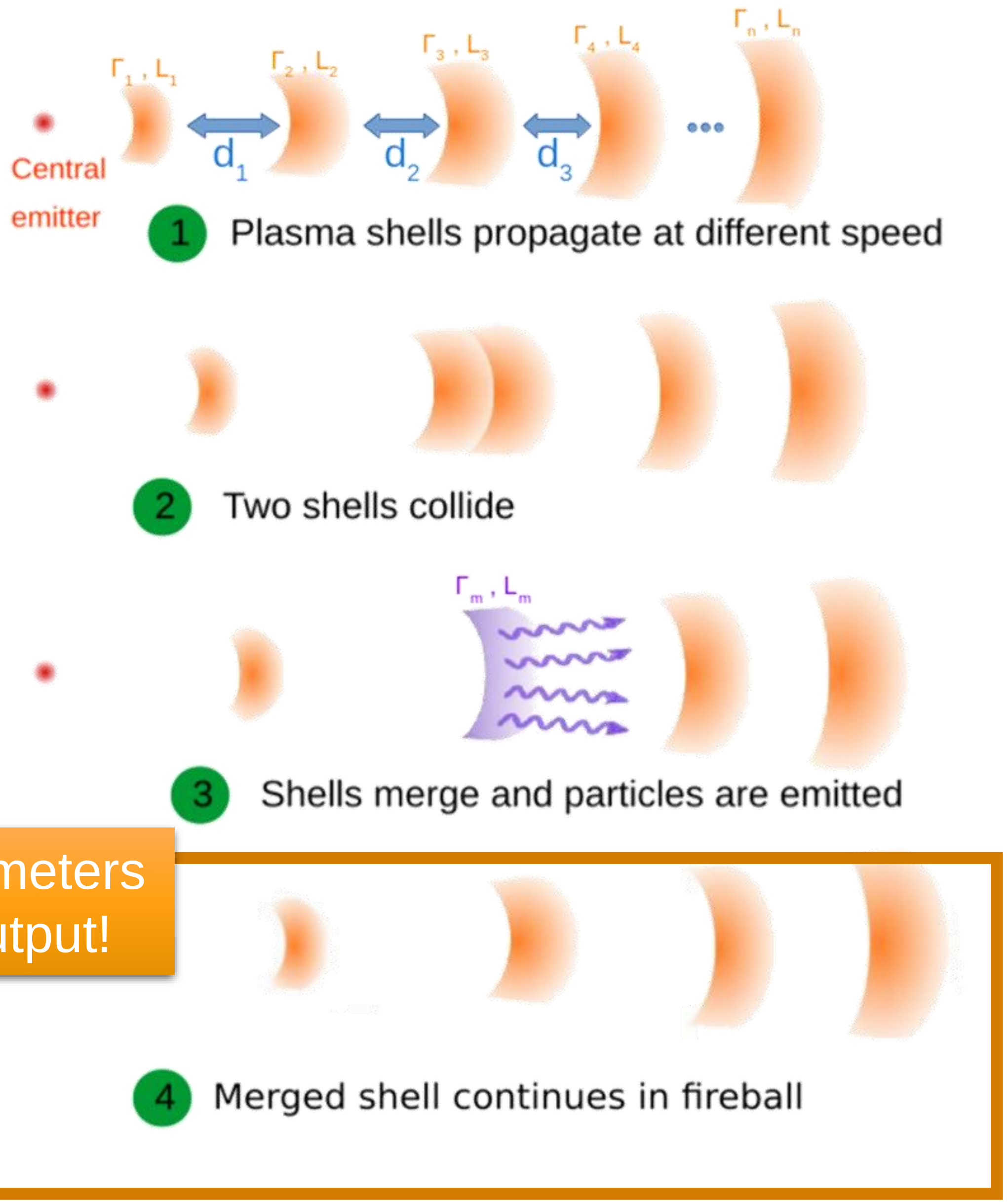
$$\delta t_{\text{em}} = \frac{l_r}{\beta_r - \beta_{\text{rs}}} \qquad l_m = l_s \frac{\beta_{\text{fs}} - \beta_m}{\beta_{\text{fs}} - \beta_s} + l_r \frac{\beta_m - \beta_{\text{rs}}}{\beta_r - \beta_{\text{rs}}}$$

- Collision model originally proposed by:

Kobayshi, Piran, Sari, ApJ 490 (1997)
Daigne, Mochkovitch, MNRAS 296 (1998)

- Alternative collision models:

Rudolph, JH, Fedynitch, Winter arXiv: 1907.10633



Radiation zone parameters are now a model output!

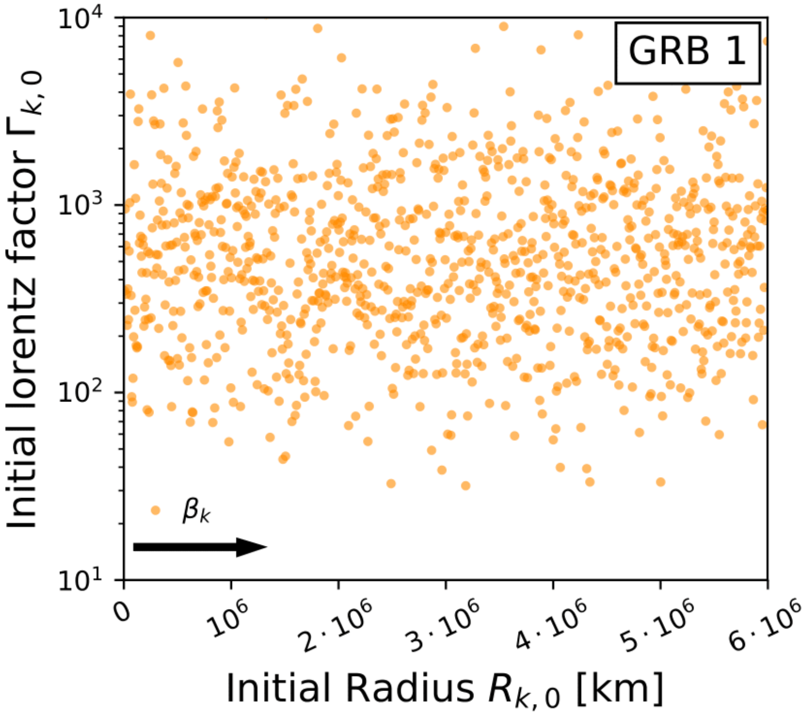
Bustamante, JH, Murase, Winter, Astrophys.J. 837 (2017)
Rudolph, JH, Fedynitch, Winter arXiv: 1907.10633

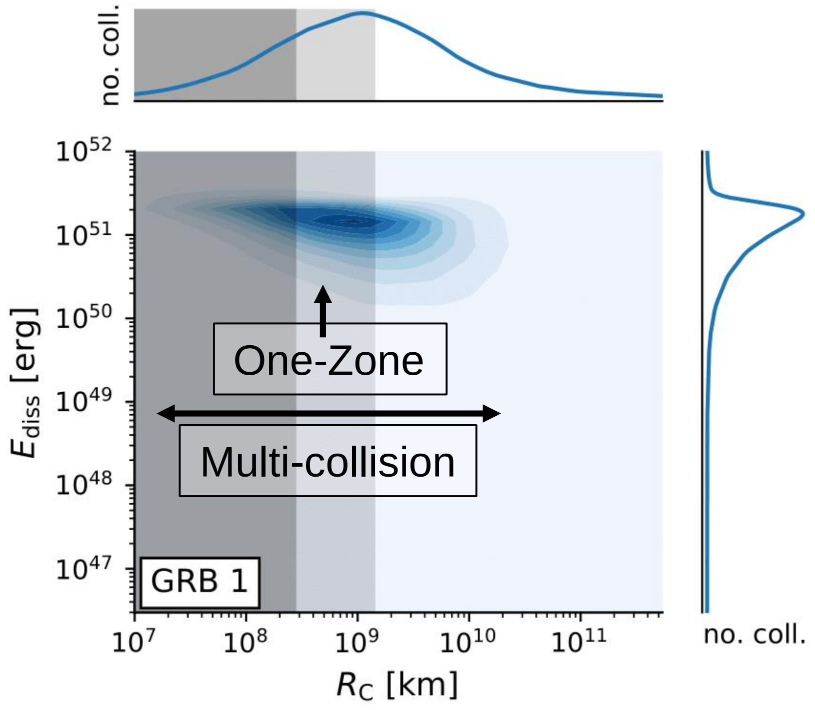
Multi Collision model

Purely stochastic shell distribution

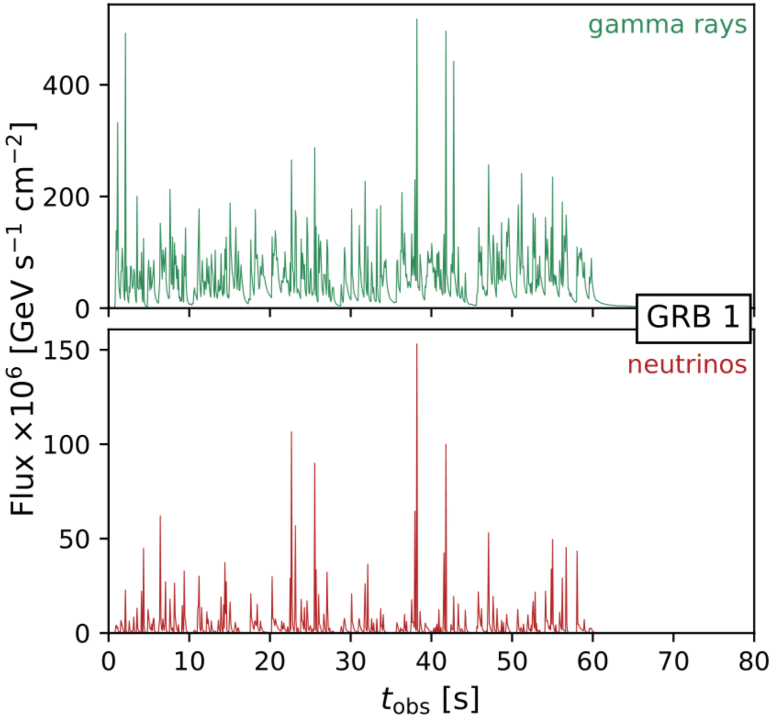
$$\ln\left(\frac{\Gamma_{k,0}-1}{\Gamma_0-1}\right) = A_\Gamma x \qquad P(x)dx \;=\; \exp(-x^2)/\sqrt{2\pi}dx$$

Initial Shell Distribution → (Fireball evolution) → Distribution of collisions → (Radiation model) → Light curve





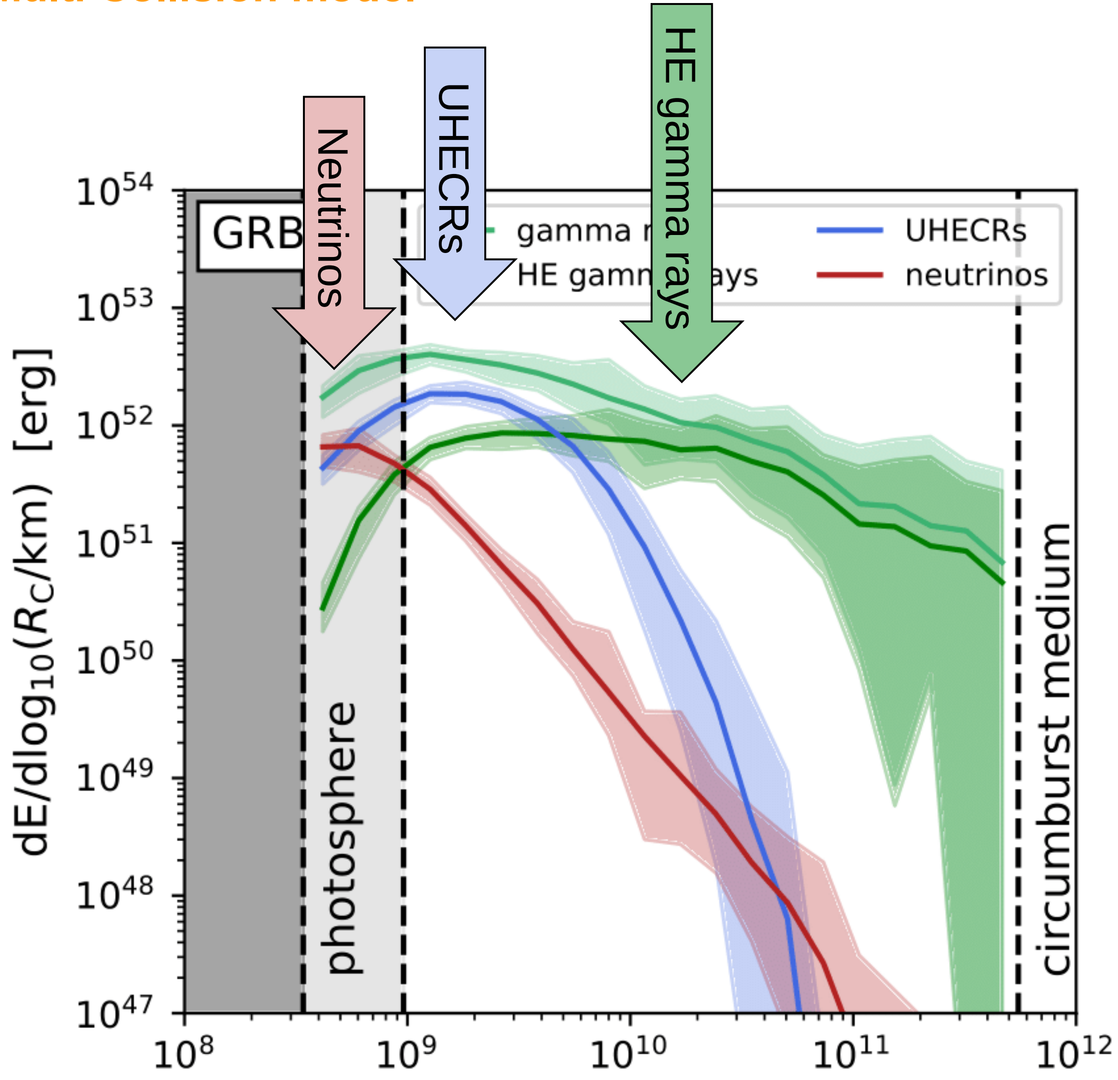
Distance from central engine



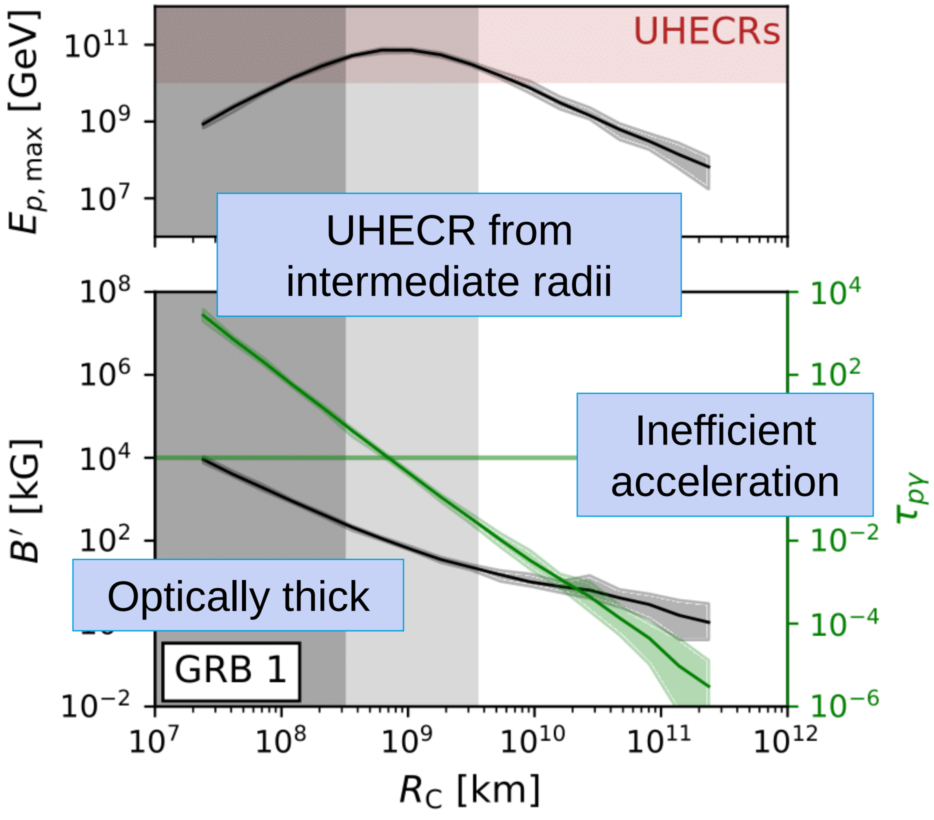
Observed time

Particle Production regions

Multi Collision model



Distance from central engine R_C [km]



Bustamante, JH, Murase, Winter, Astrophys.J. 837 (2017)
Rudolph, JH, Fedynitch, Winter arXiv: 1907.10633

Separates the production regions:

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

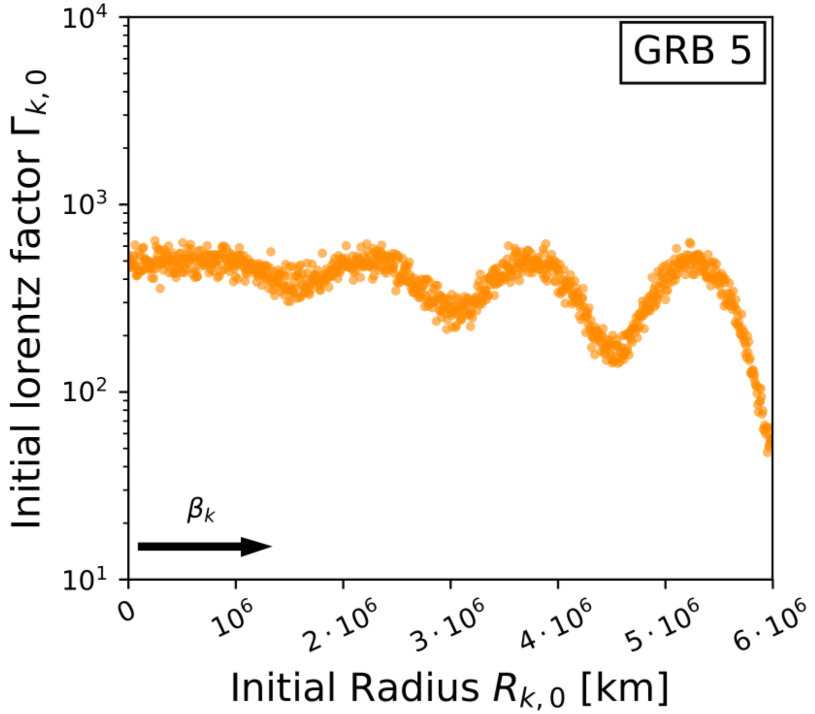
Bustamante, JH, Murase, Winter, Astrophys.J. 837 (2017)
Rudolph, JH, Fedynitch, Winter arXiv: 1907.10633

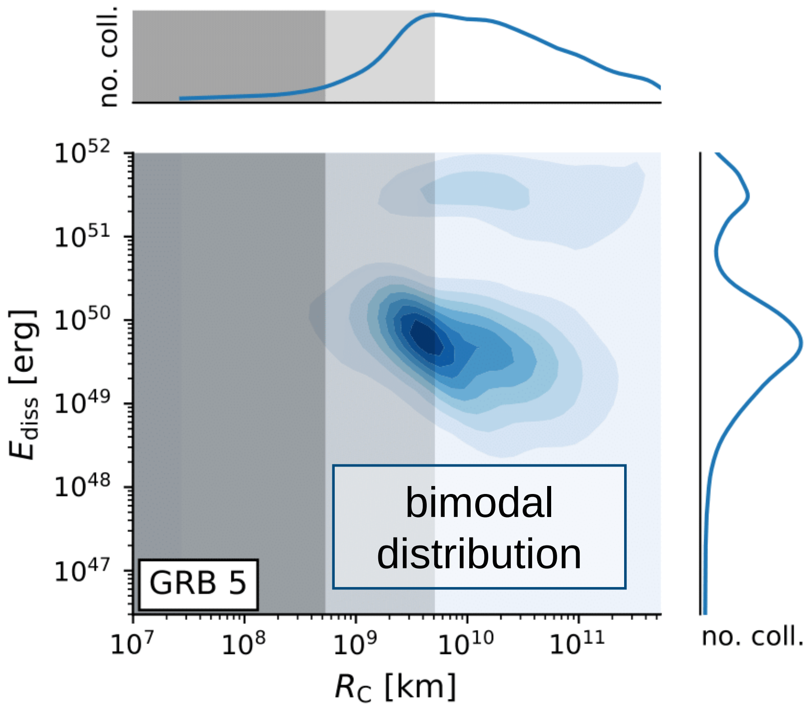
Disciplined (structured) engine

Multi Collision model

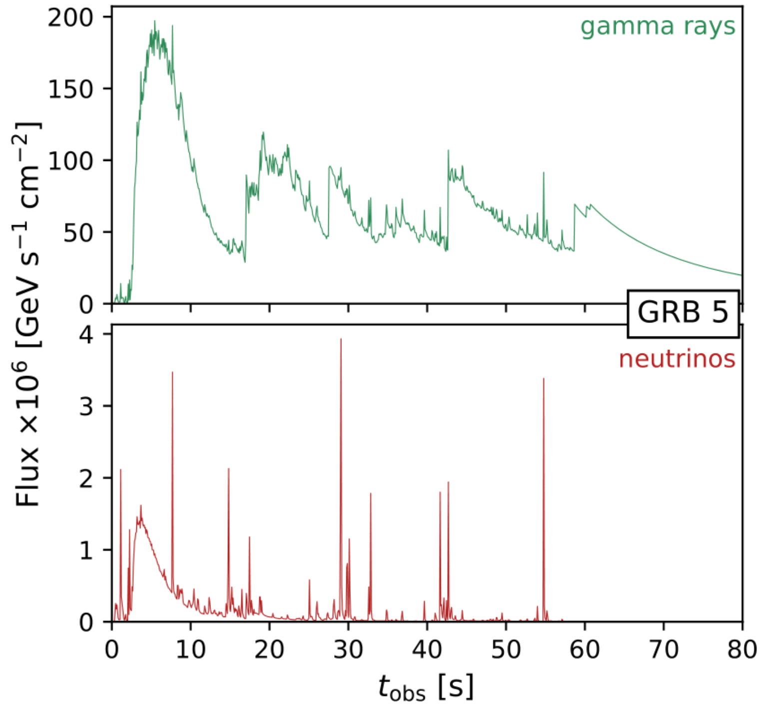
Fireball evolution | Radiation model

Initial Shell Distribution → Distribution of collisions → Light curve





Distance from central engine



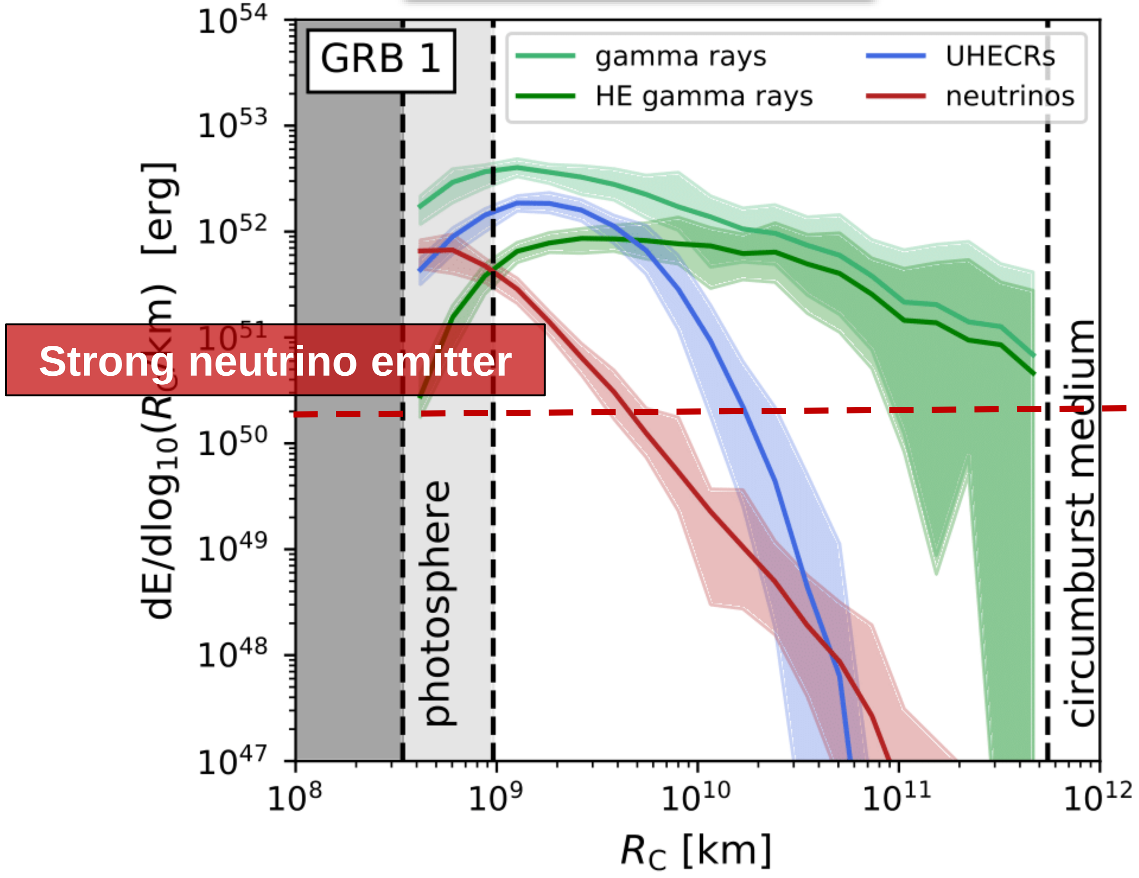
Observed time

Bustamante, JH, Murase, Winter, Astrophys.J. 837 (2017)
Rudolph, JH, Fedynitch, Winter arXiv: 1907.10633

Particle production regions

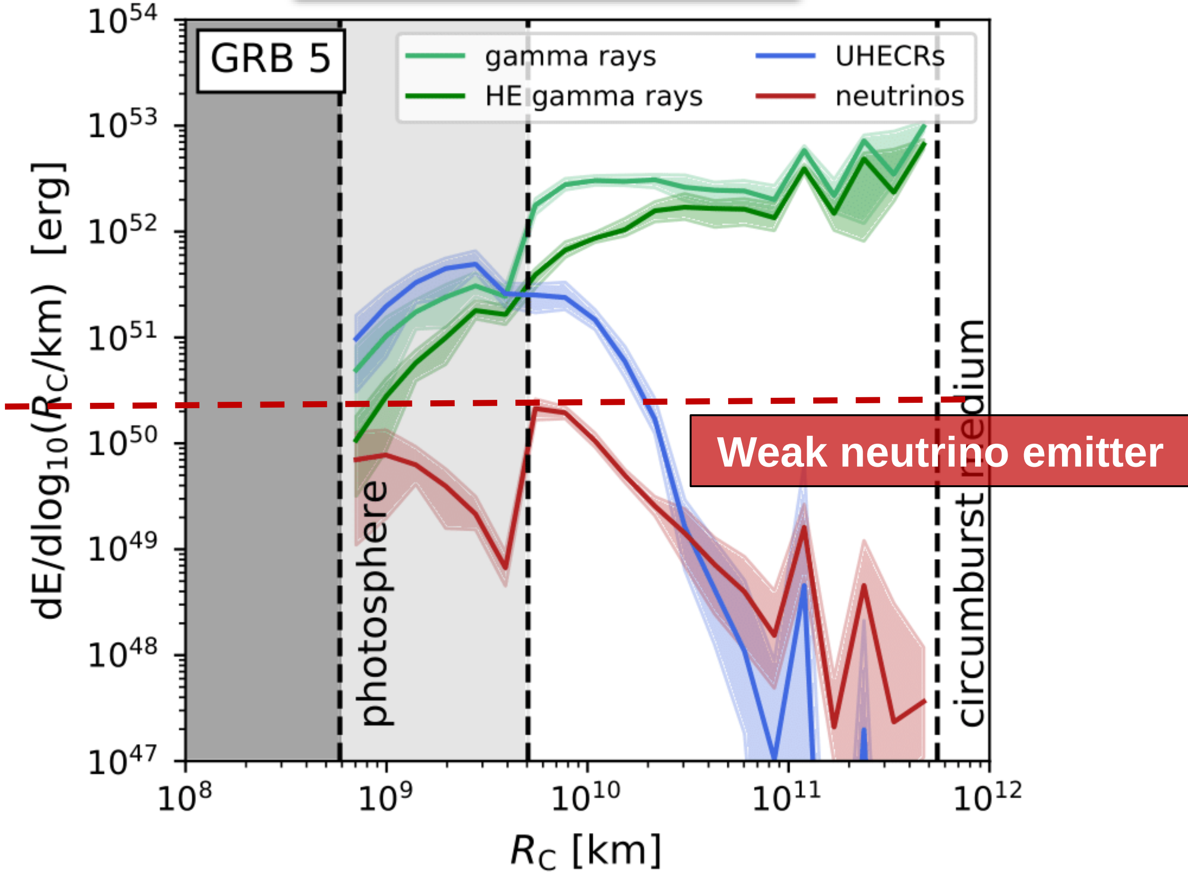
Multi Collision model

Stochastic engine



Distance from central engine

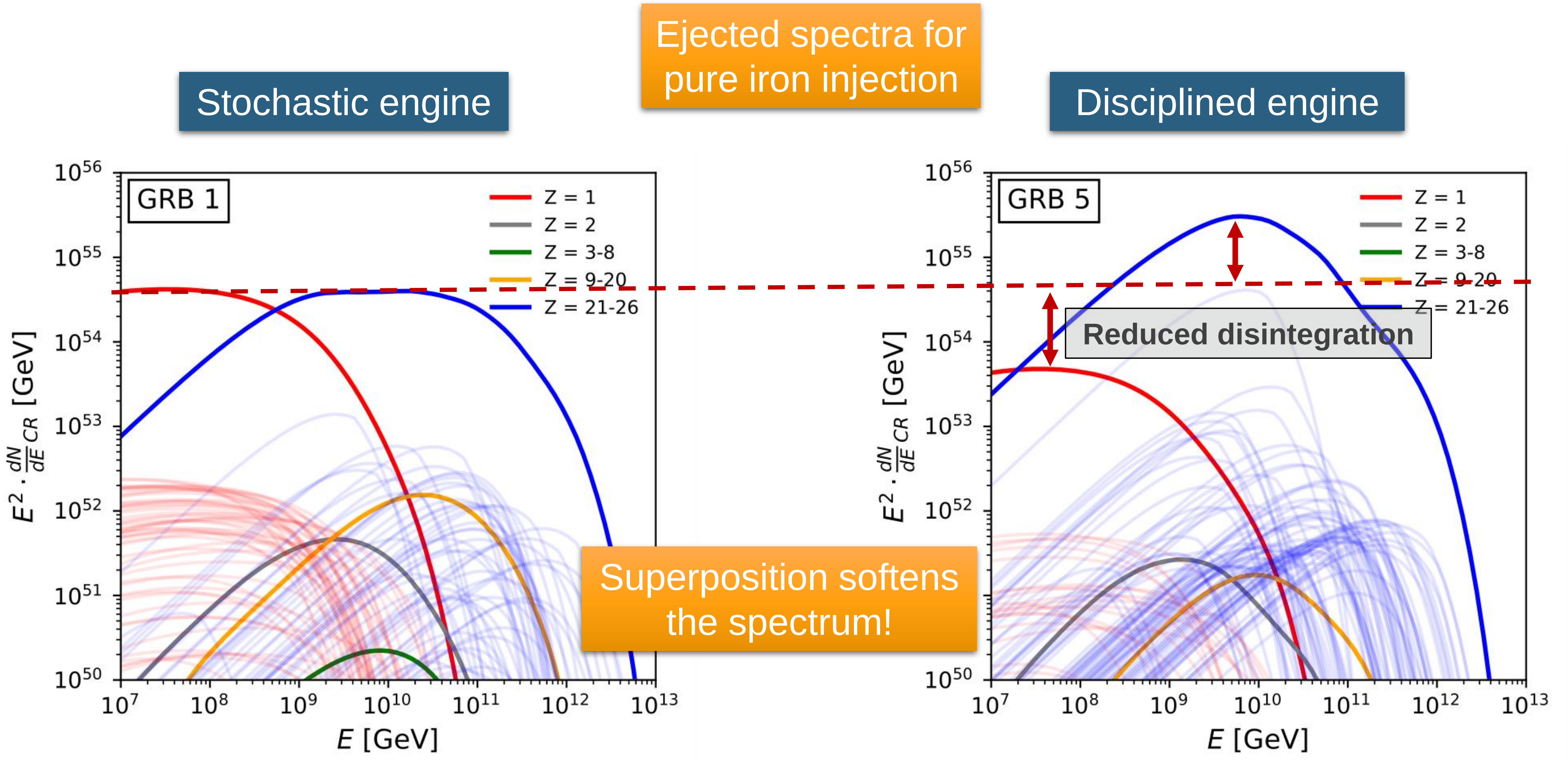
Disciplined engine



Distance from central engine

UHECR escape: Engine comparison

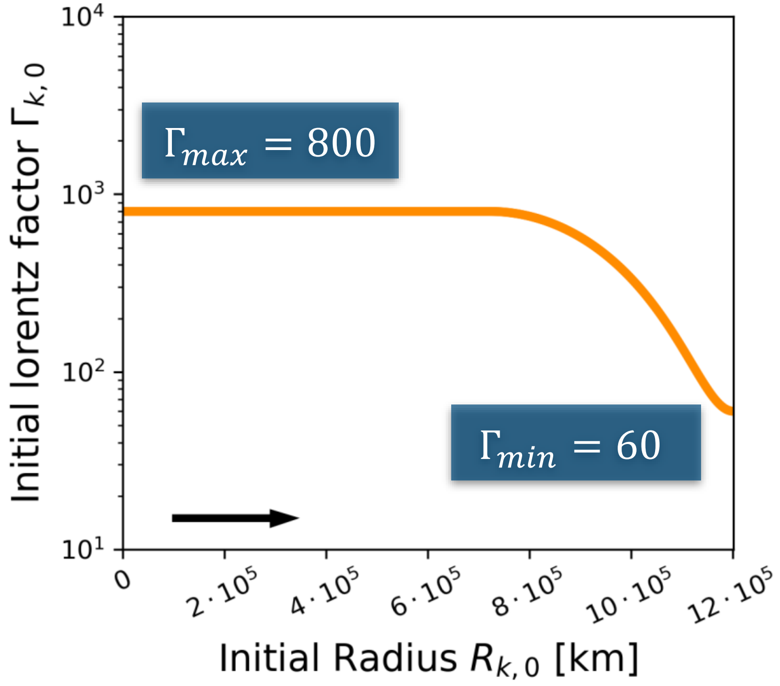
Multi Collision model

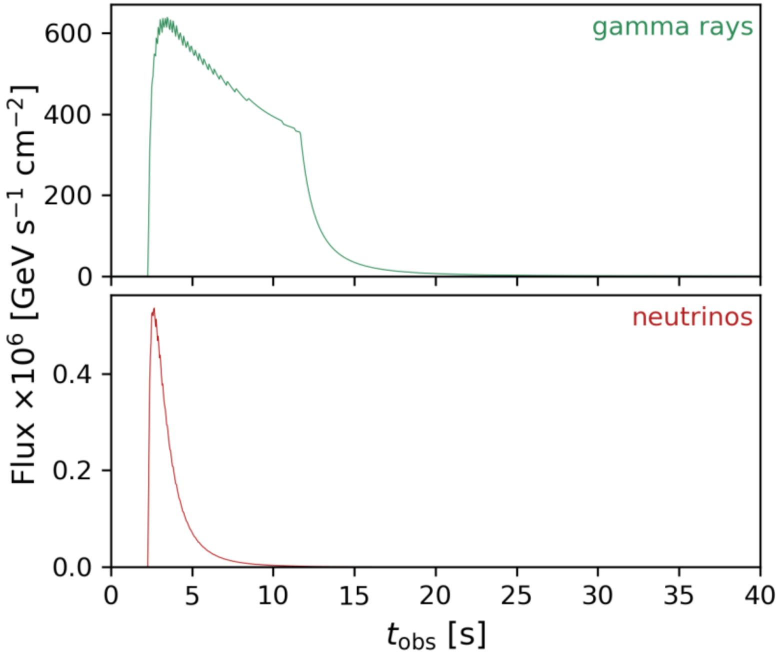


Fit to UHECR data – Input parameters

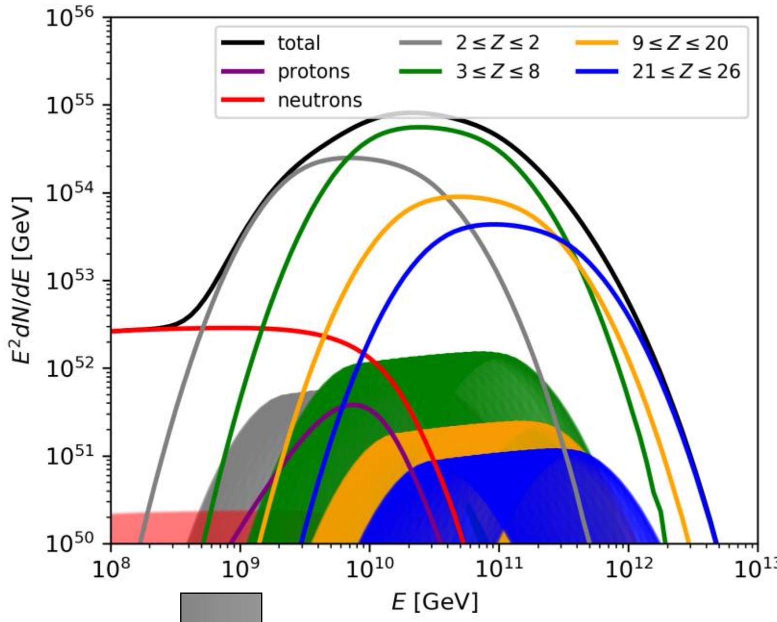
Initial Shell Distribution → Fireball evolution → Lightcurve → Radiation model → UHECR source spectrum (fixed inj. composition)

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





Observed time



↓

Extragalactic Propagation with PriNCe

JH, Fedynitch, Boncioli, Winter, ApJ 873 (2019), 88

Fit to UHECR data – Input parameters

Fireball evolution

Radiation model

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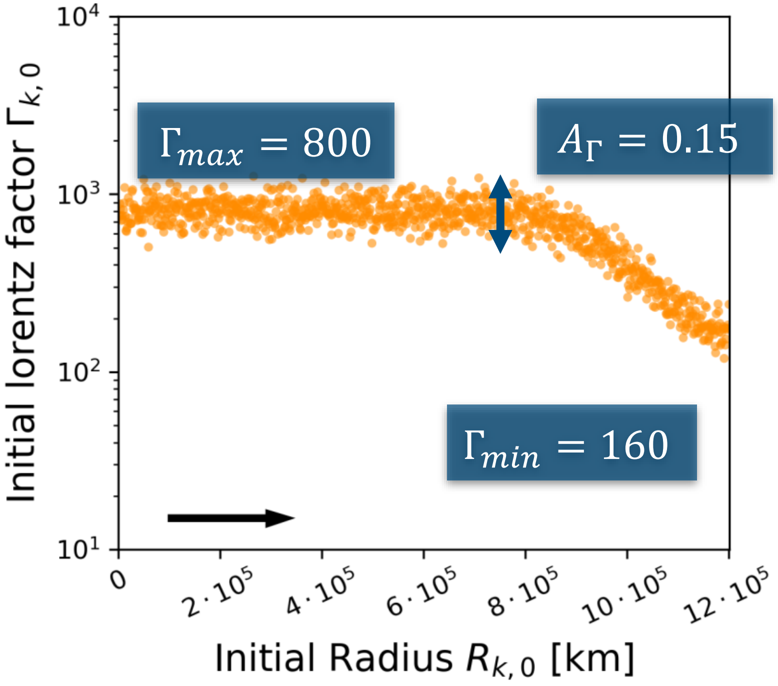
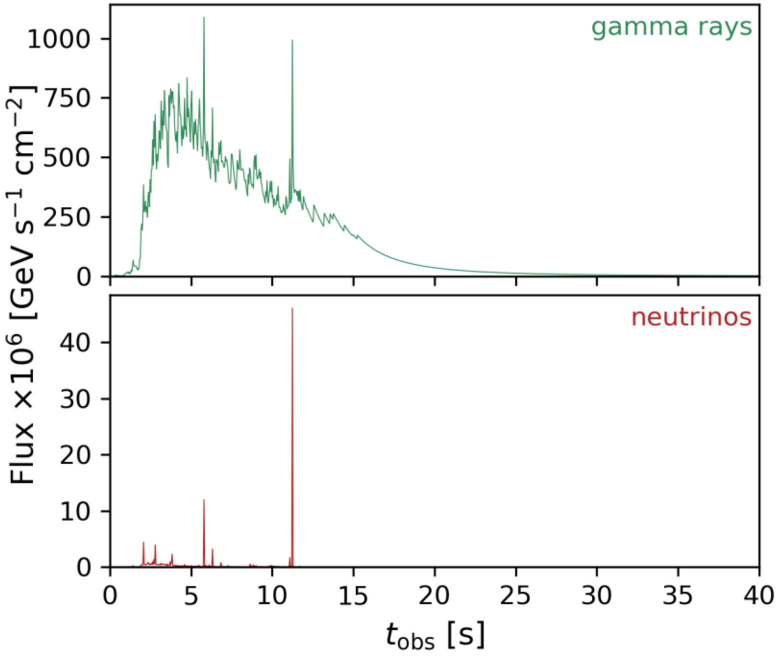
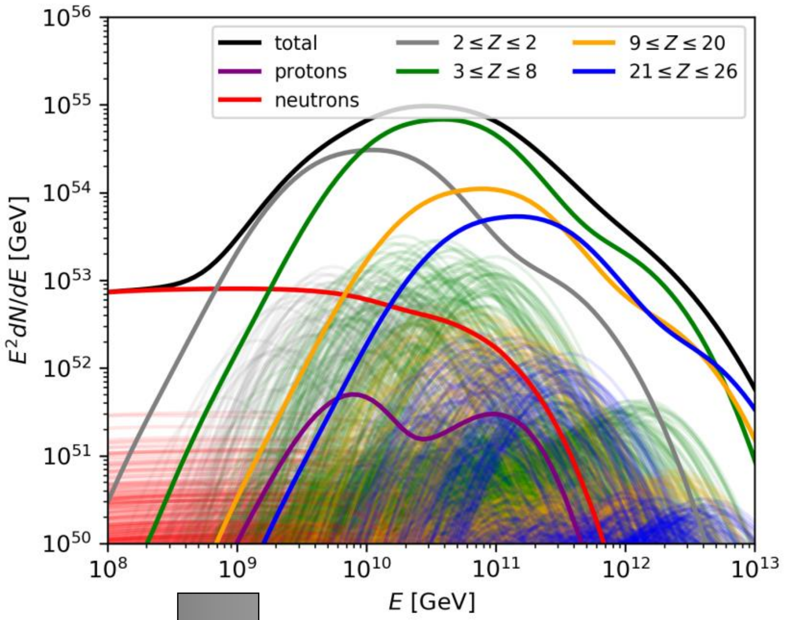




Observed time



Extragalactic Propagation with PriNCe

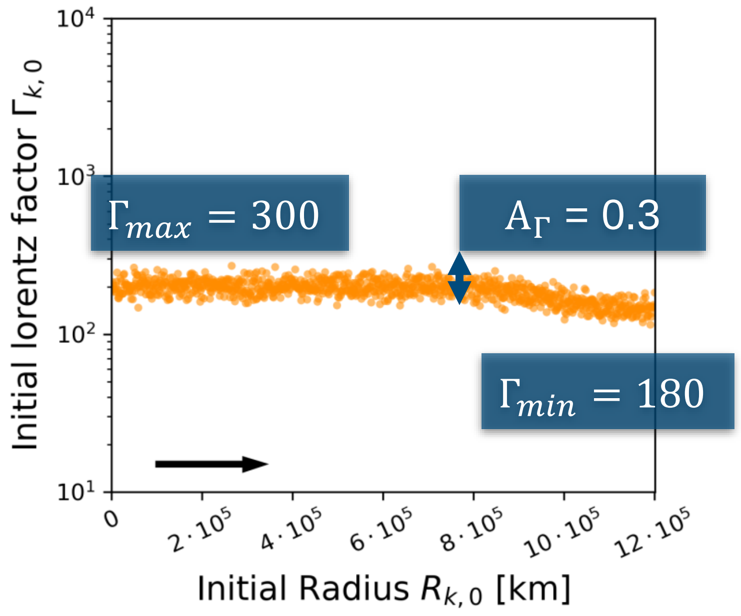
JH, Fedynitch, Boncioli, Winter, ApJ 873 (2019), 88

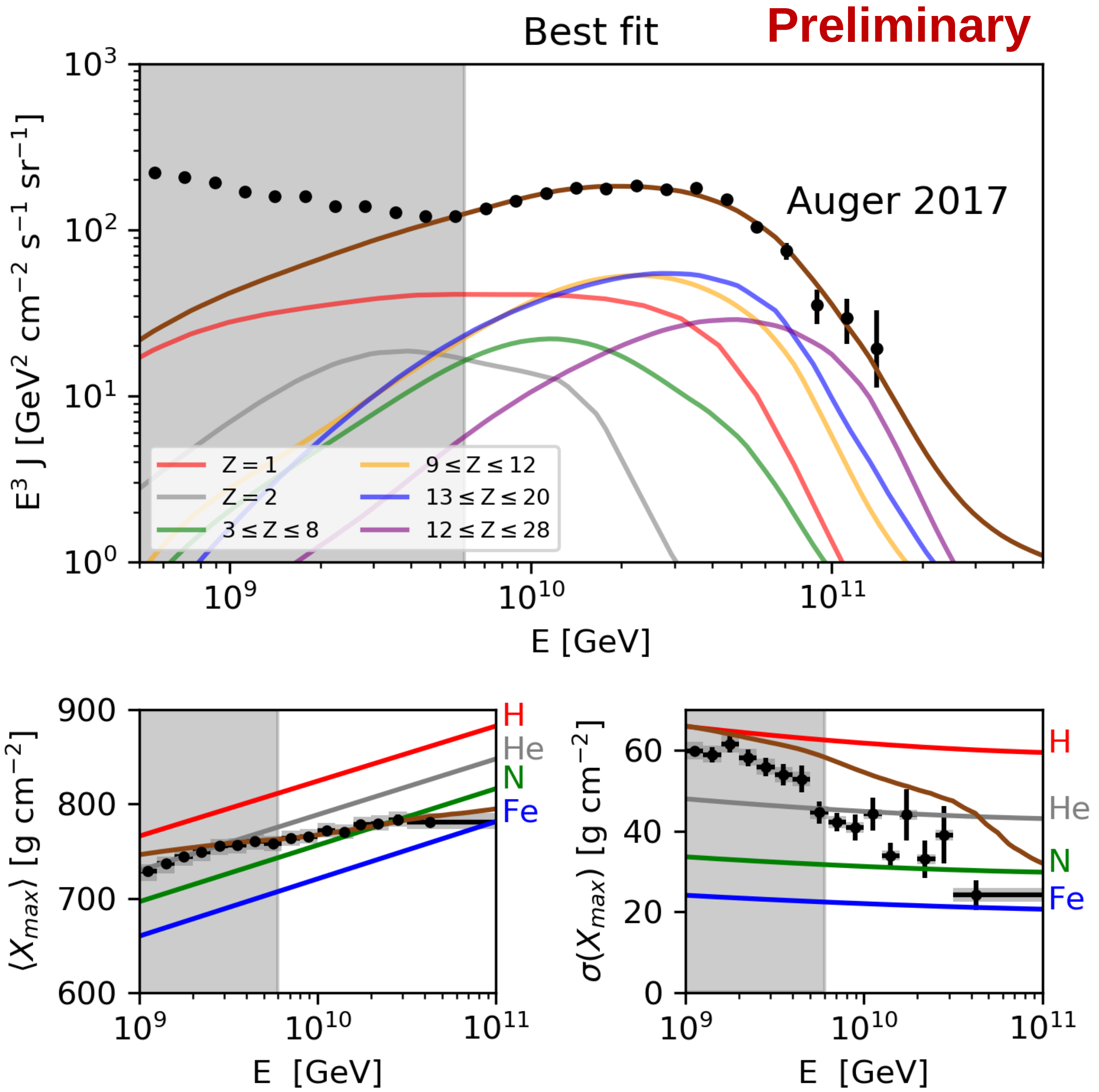
Fit to UHECR data

Best-fit spectrum

- Propagate using GRB-redshift-distribution: Wanderman, Piran, MNRAS 406 (2010)
- Fit to **UHECR spectrum and** $\langle X_{max} \rangle$
- Best fit – **χ^2 / dof = 21 / 16**
- **Injection composition:** (determined by fit)

H – 19%	He – 12%
Si – 58%	Fe – 11%



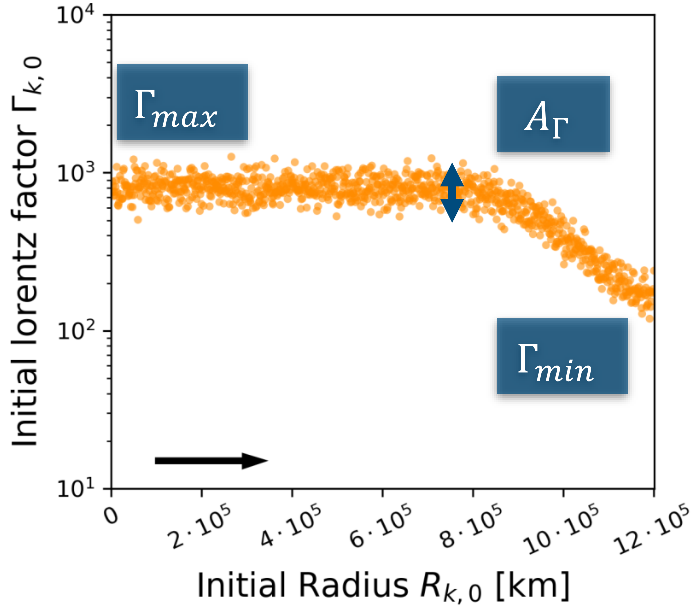


JH, Biehl, Rudolph,, Boncioli, Fedynitch, Winter in preparation

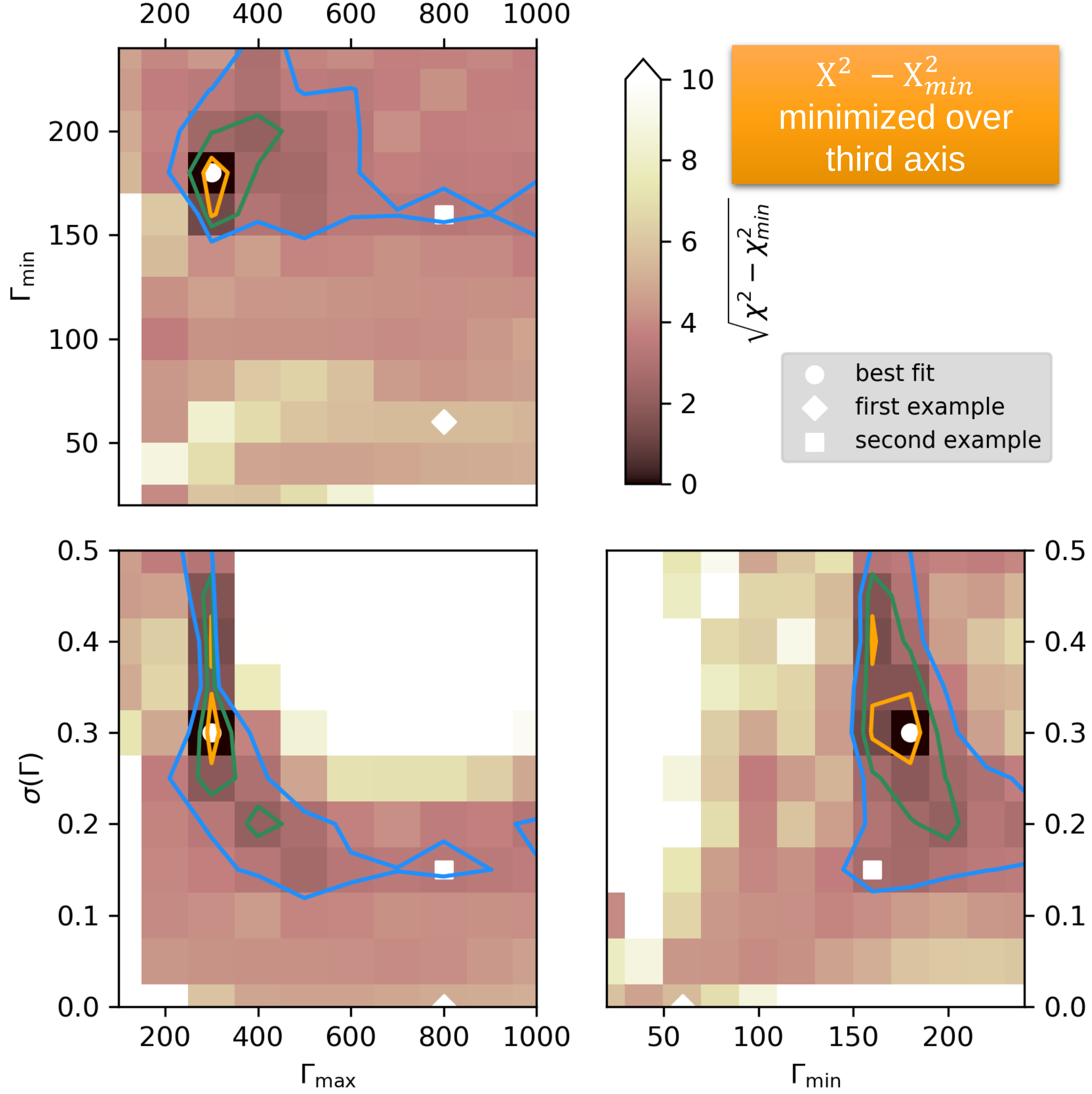
Fit to UHECR data

Parameter space

- Propagate using GRB-redshift-distribution: Wanderman, Piran, MNRAS 406 (2010)
- Fit to **UHECR spectrum and $\langle X_{max} \rangle$**
- **Free injection composition** (determined by fit)
- Baryonic loading: 40 – 130



Preliminary

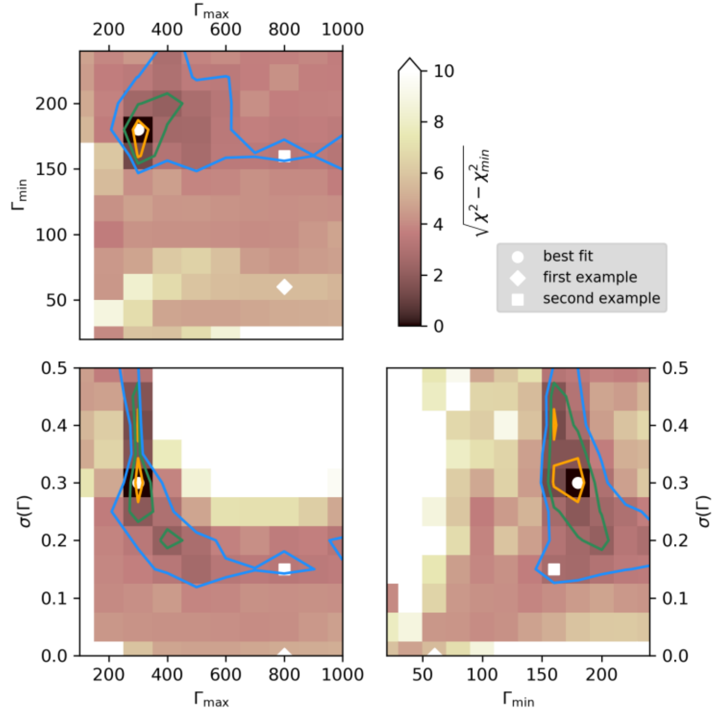


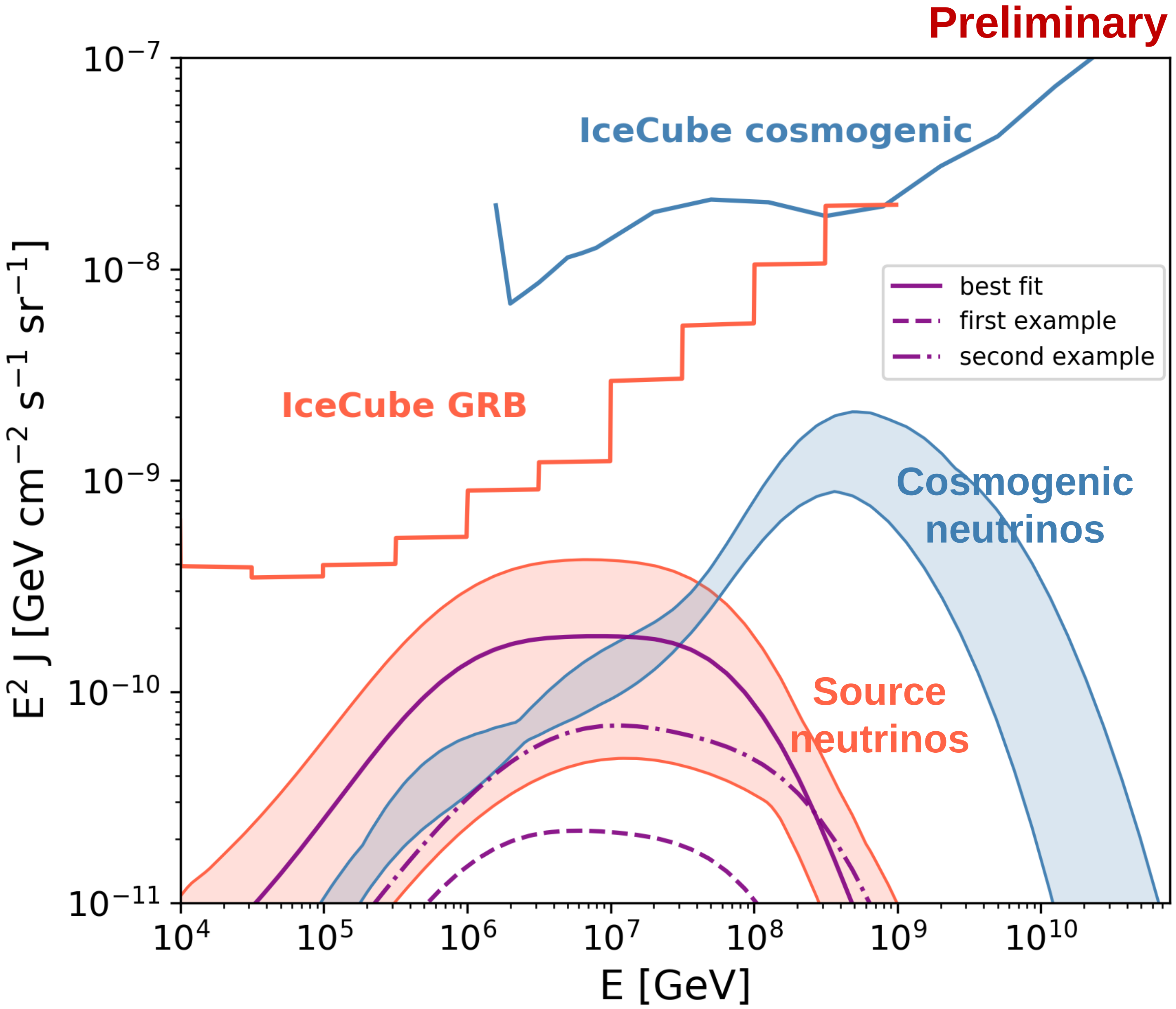
JH, Biehl, Rudolph, Boncioli, Fedynitch, Winter in preparation

Fit to 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





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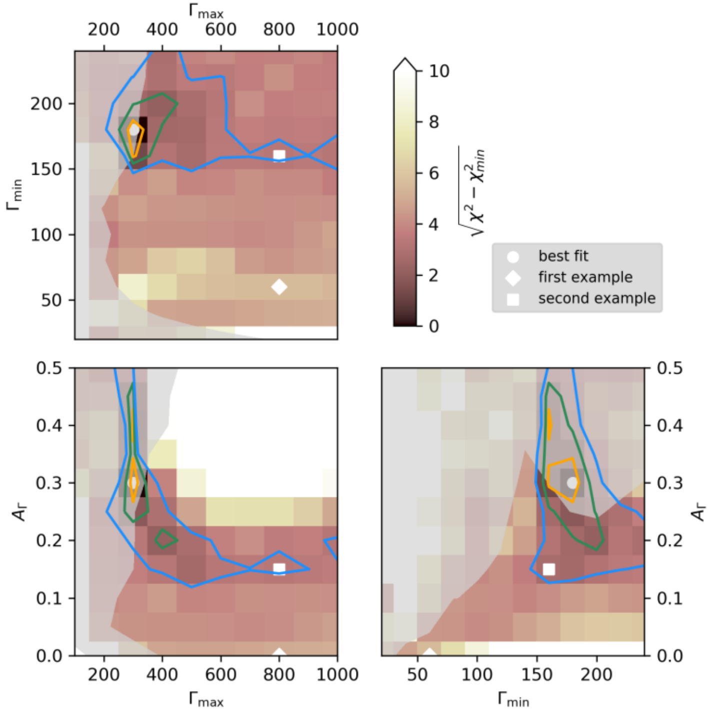
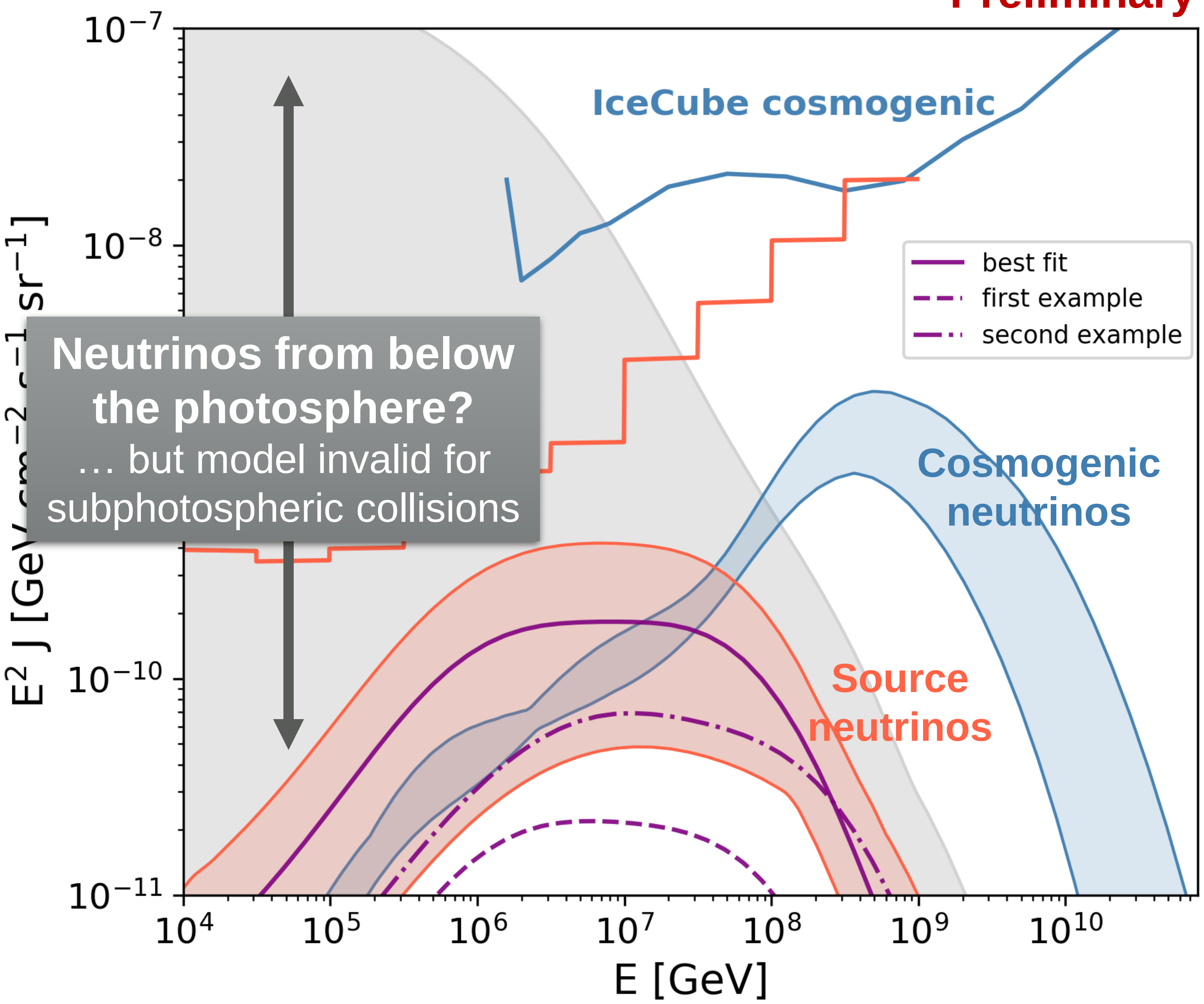




JH, Biehl, Rudolph,, Boncioli, Fedynitch, Winter in preparation

Conclusion

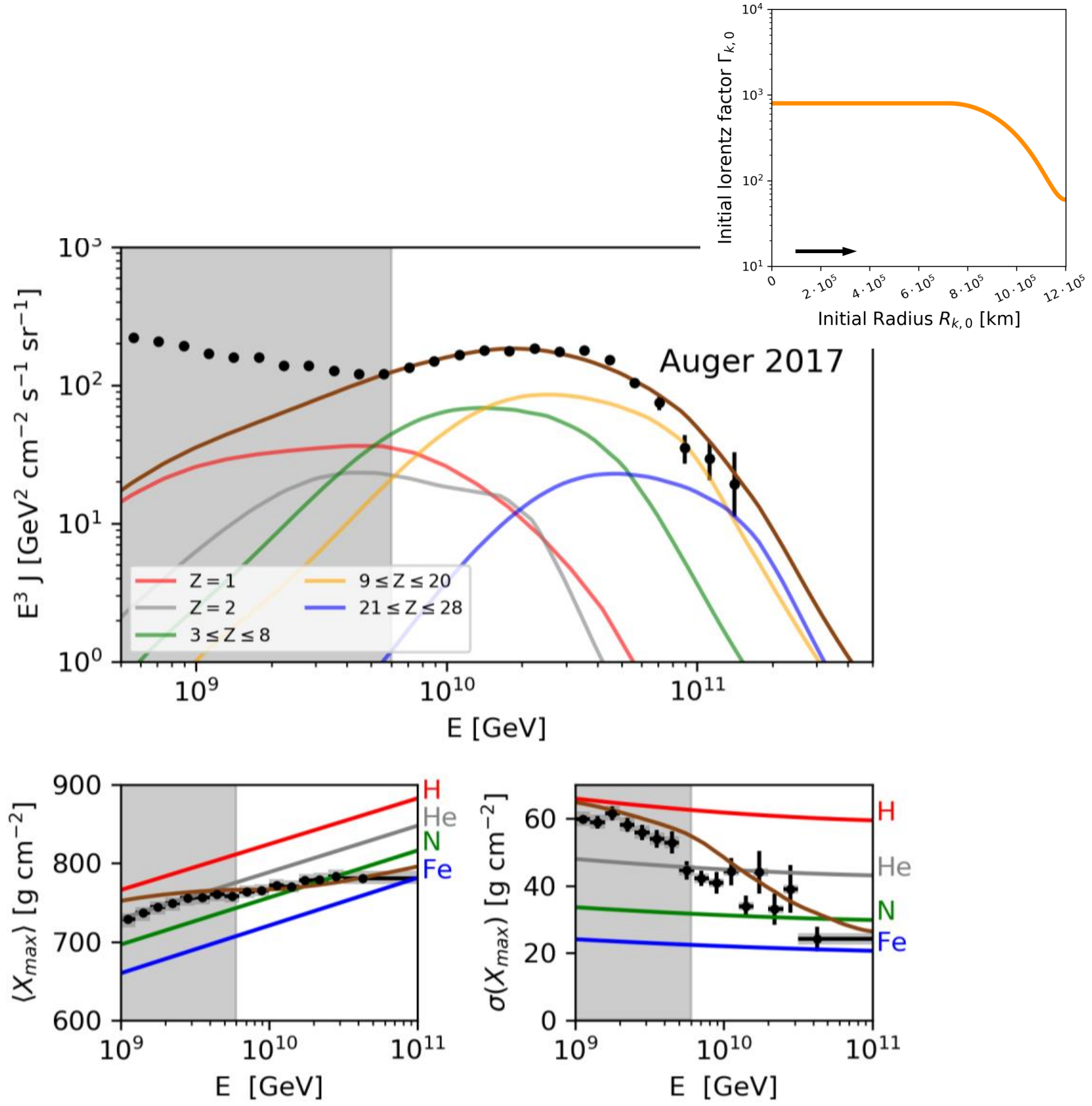
- One-zone GRB models require low luminosity and/or large collision radii

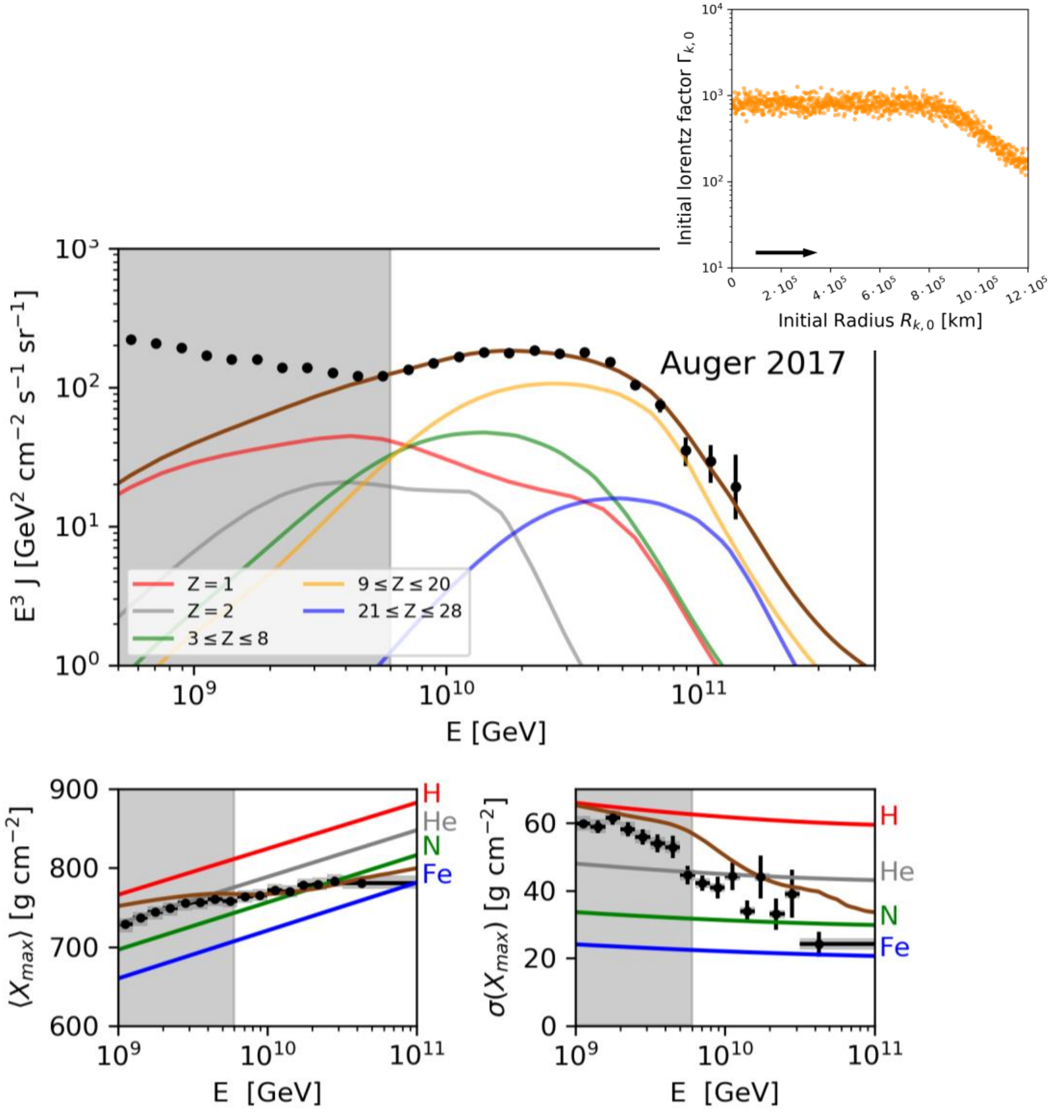
- Multi Collision Models **separate particle production** regions:
  - Neutrinos from small radii; UHECRs from intermediate; gamma-rays from all radii
  - The **observed light curve** indicates UHECR disintegration and neutrino production
- Engine behavior can (partially) **decouple** the **UHECR acceleration/escape**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

- UHECR fit in principle still viable depending on the engine behavior ....
  … but **stochasticity** of the **engine/light curve limited** by $\sigma(X_{\mathrm{max}})$
- Neutrino flux likely testable in IceCube-Gen2

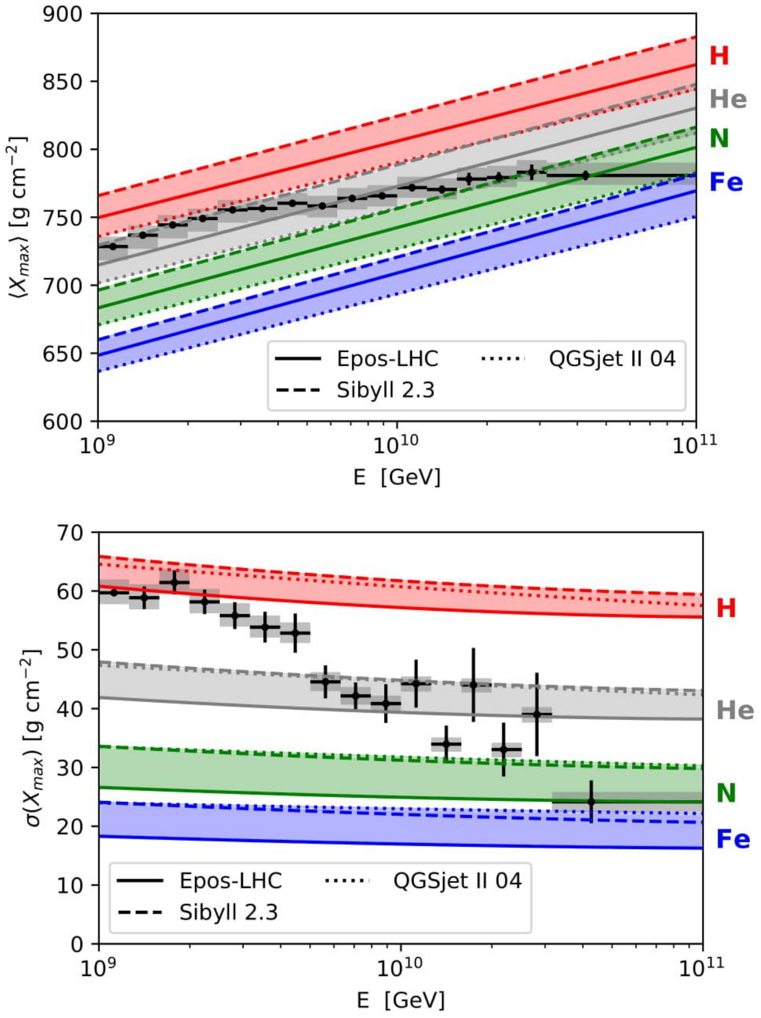
Backup Slides

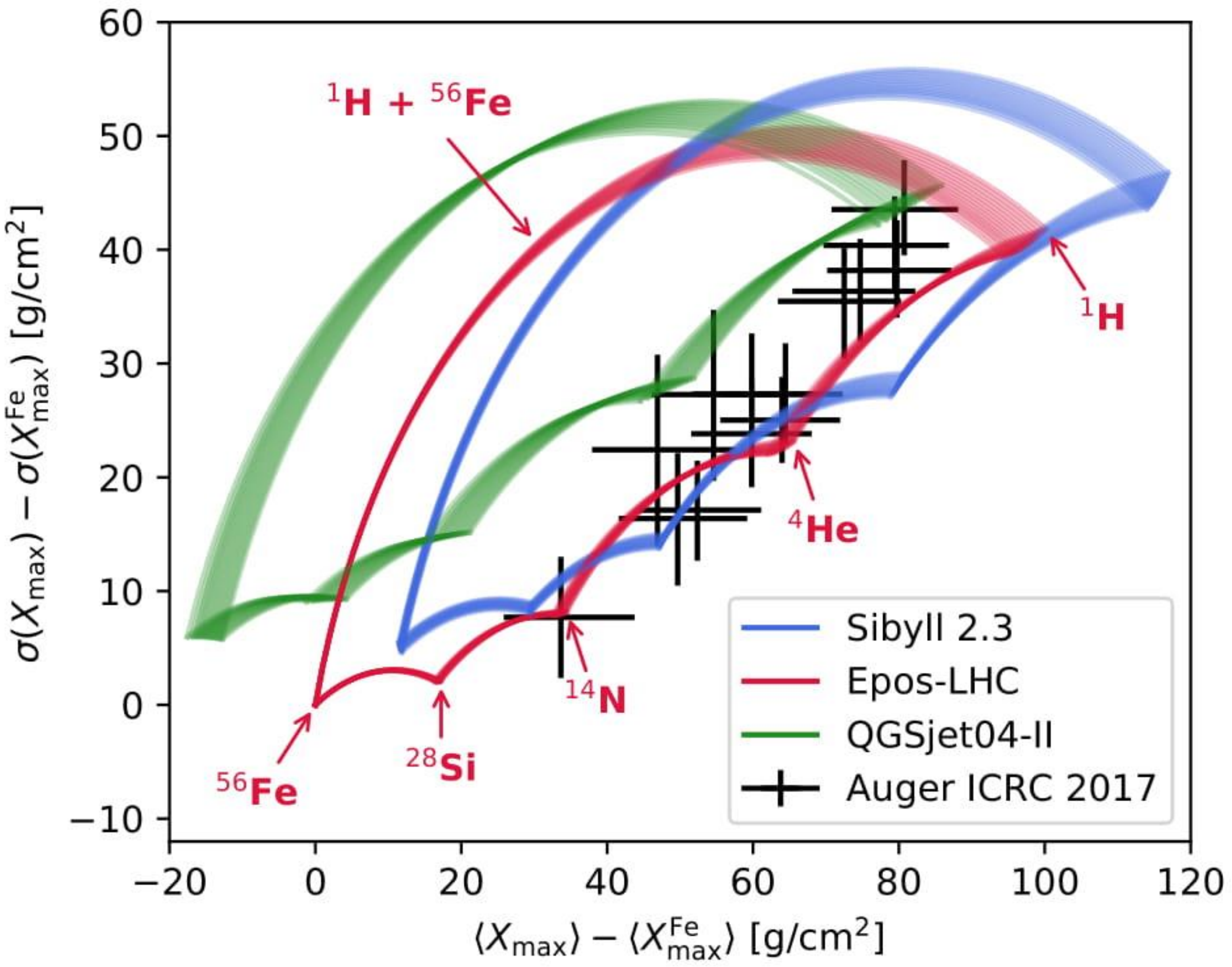
Multi-collision fit to UHECR data





X_{max} and air-shower models



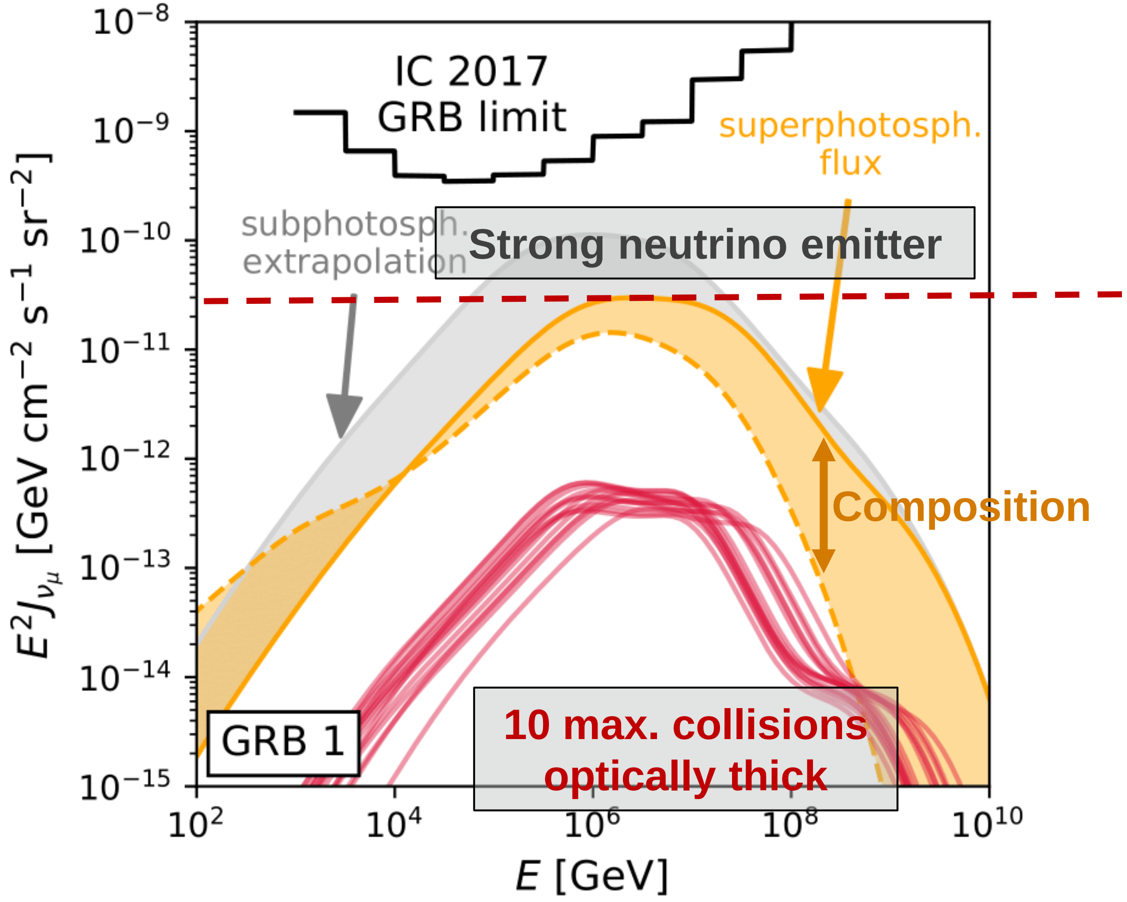


Neutrino fluxes: Engine comparison

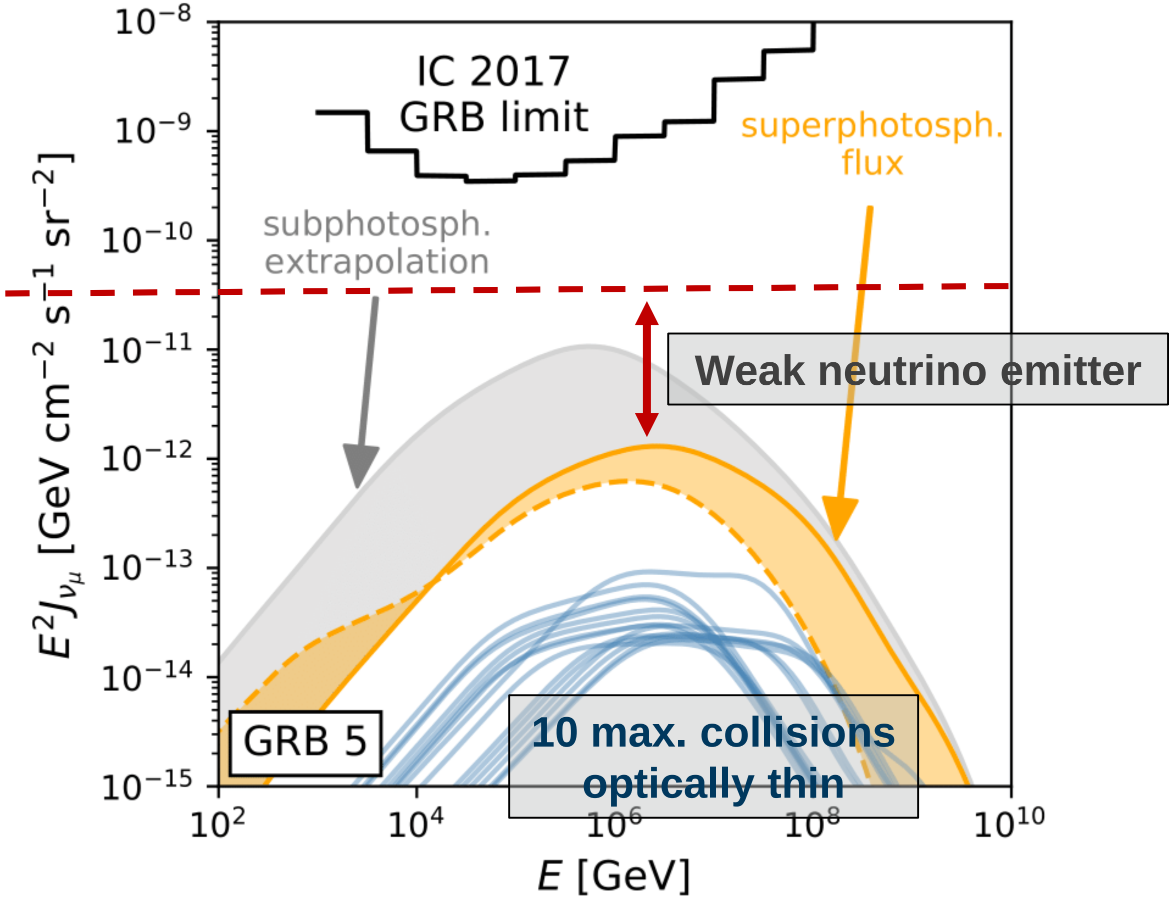
Multi Collision model

Flux for fixed GRB number at z = 2

Stochastic engine



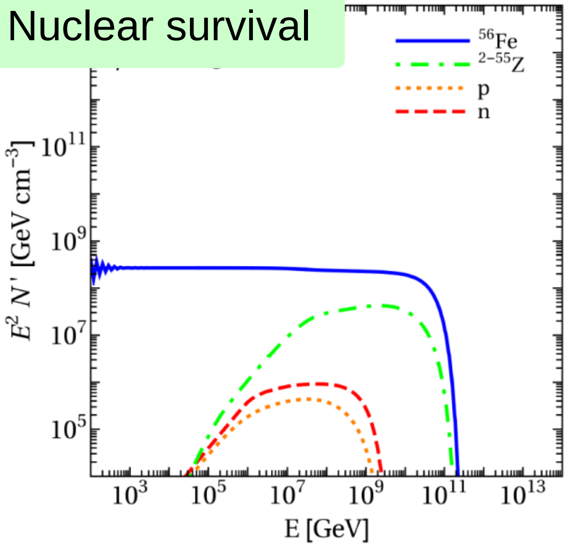
Disciplined engine

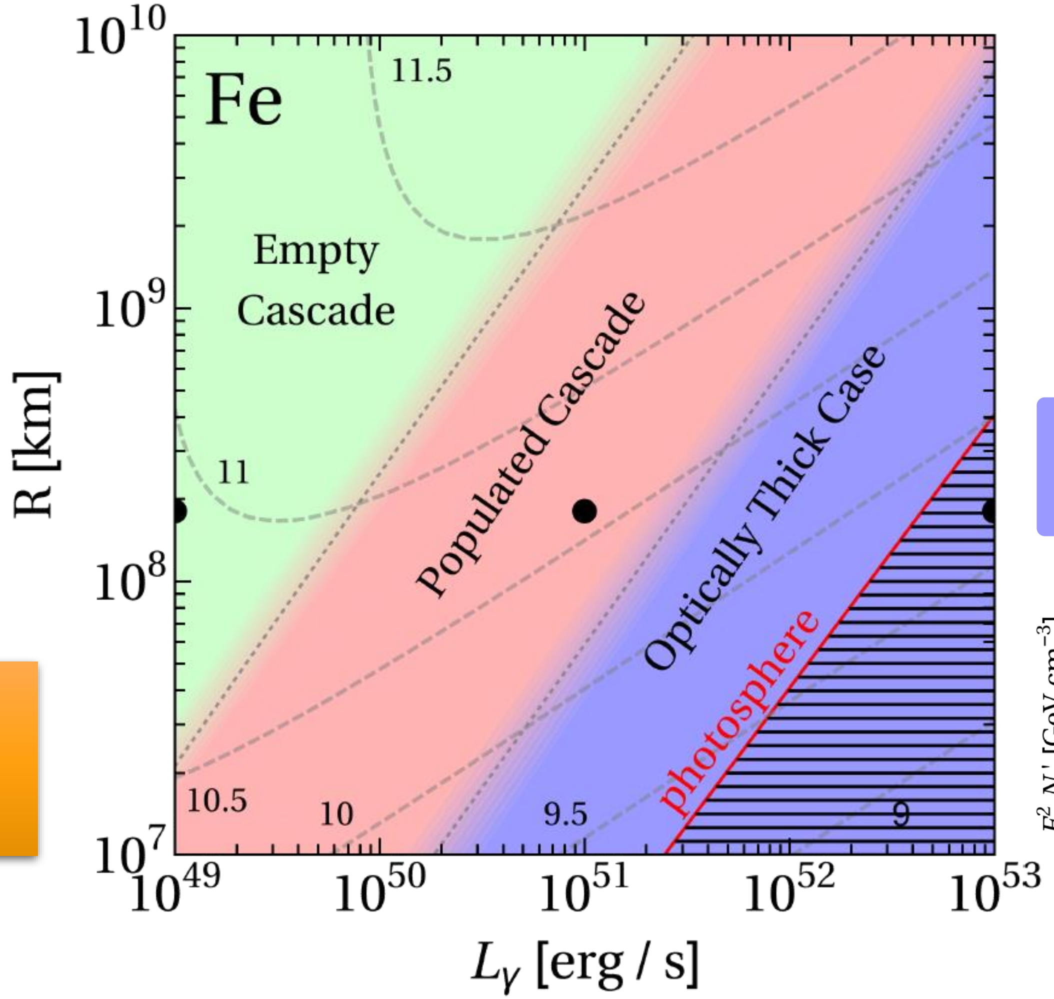


One Zone model: UHECRs

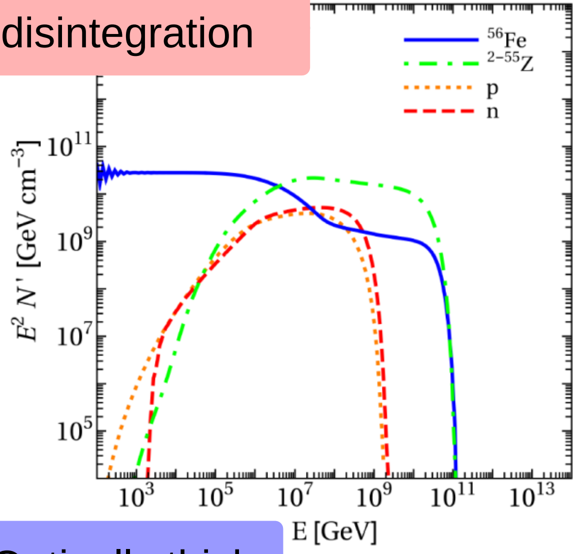
In source UHECR spectra

Nuclear survival

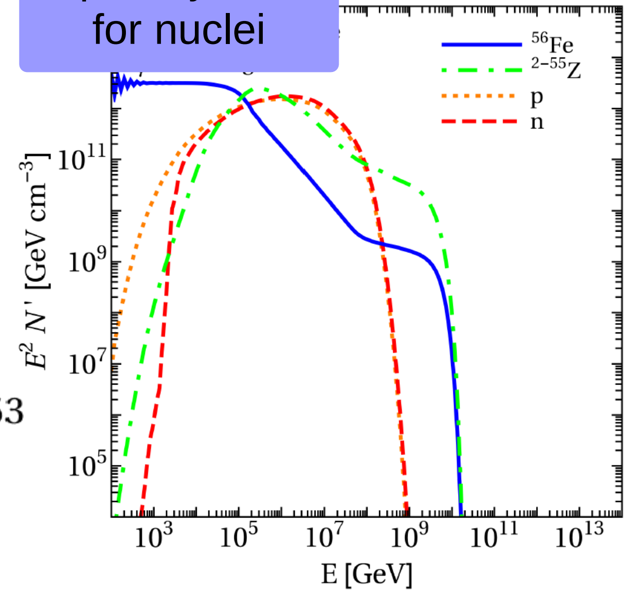




Partial disintegration



Optically thick for nuclei



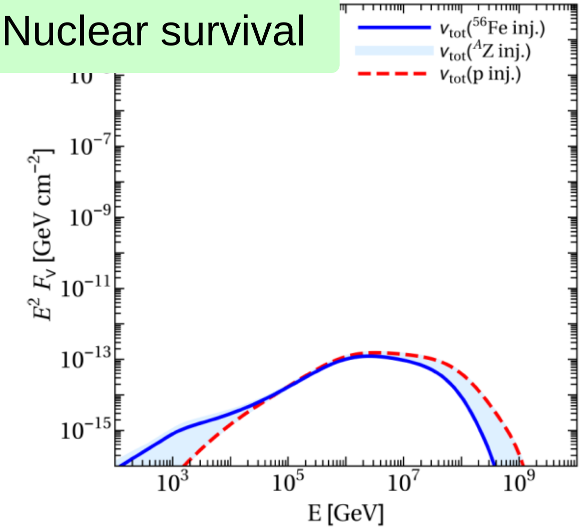
Disintegration rate scales with radius and luminosity

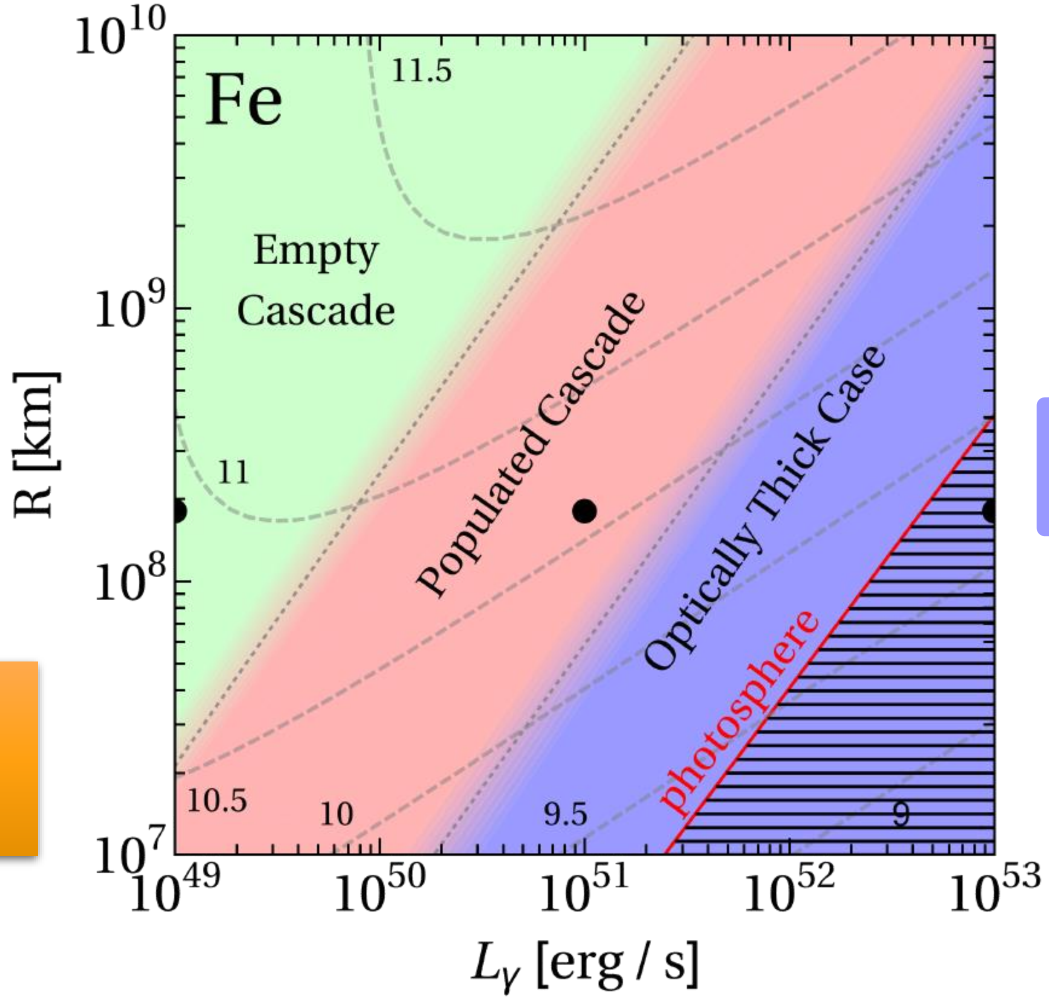
$$u'_\gamma = \frac{L_\gamma}{4\pi c \Gamma^2 R^2}$$

One Zone model: Neutrinos

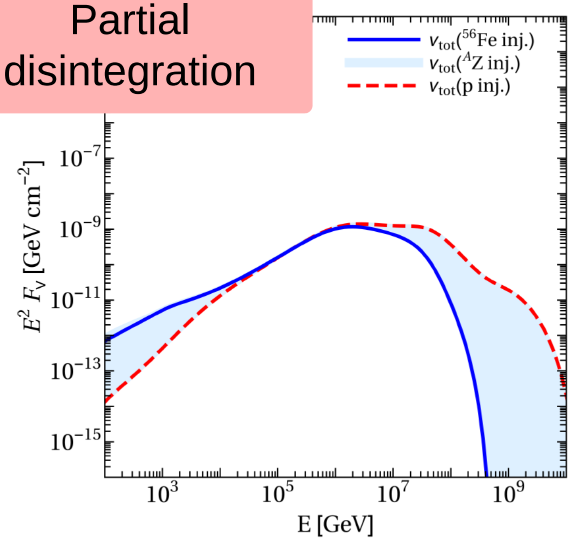
Neutrino flux

Nuclear survival





Partial disintegration



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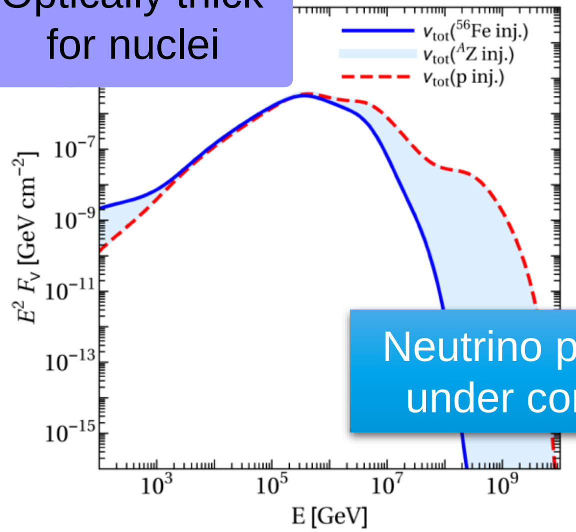
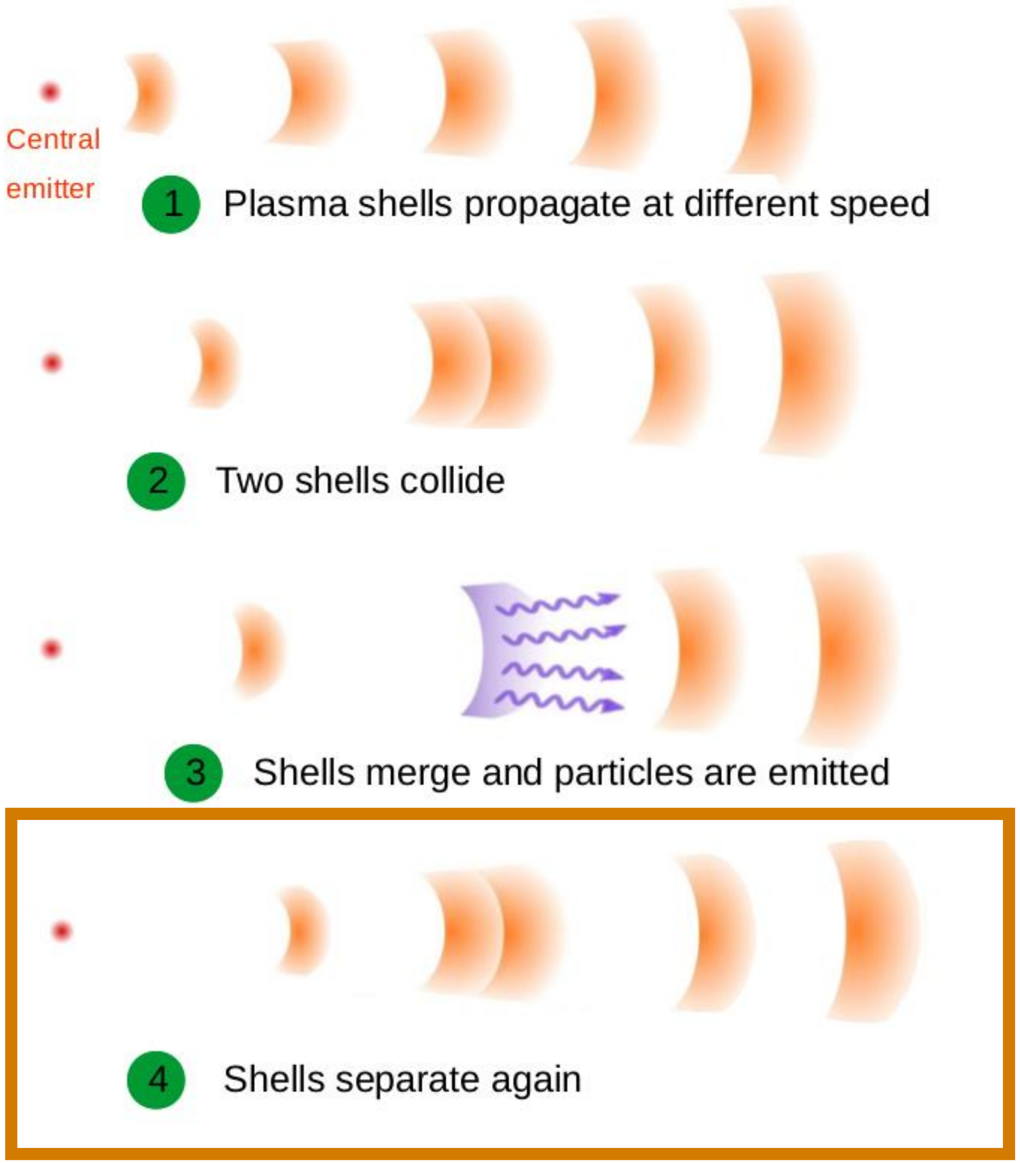


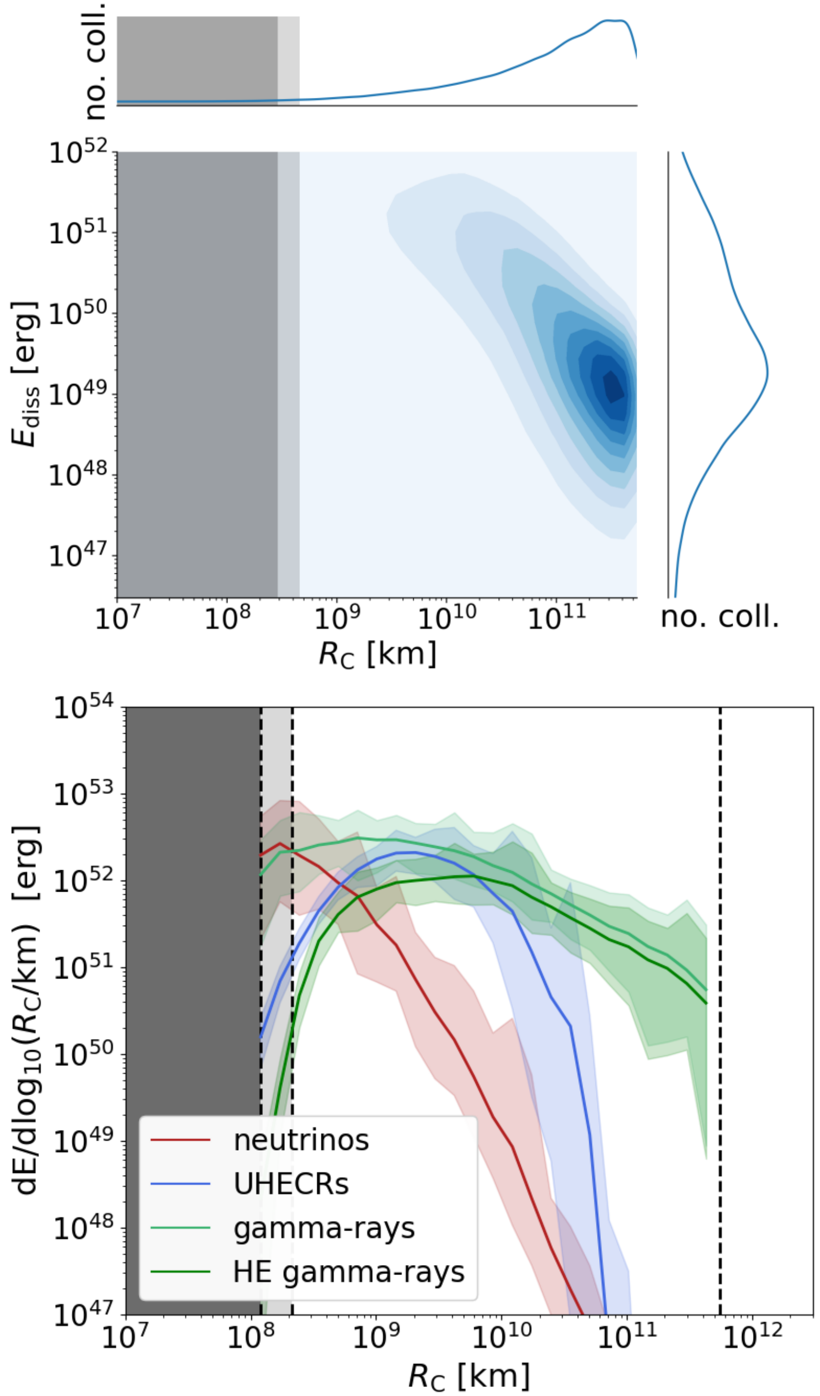
Neutrino peak robust under composition

Neutrino production scales similarly to Disintegration rate!

$$u'_\gamma = \frac{L_\gamma}{4\pi c \Gamma^2 R^2}$$

Ultra-efficient collision model

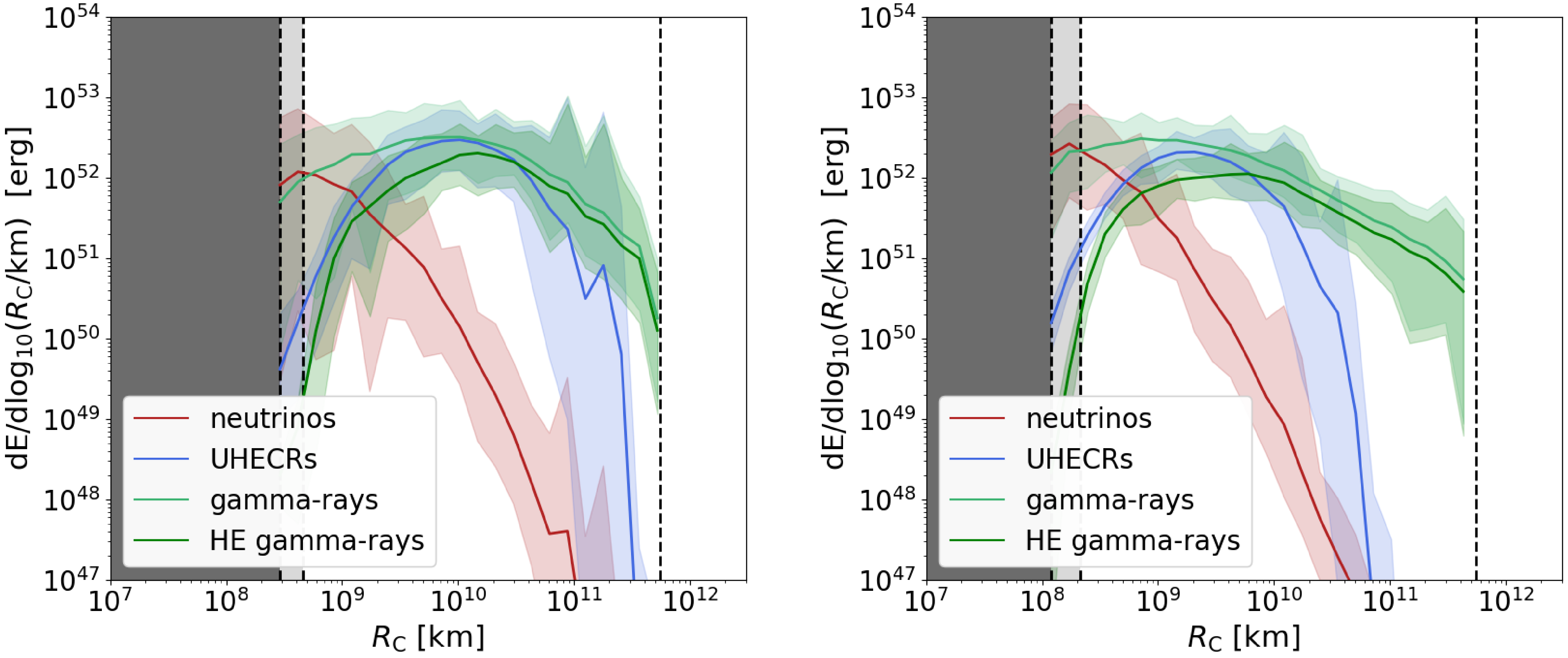




Rudolph, JH, Fedynitch, Winter arXiv: 1907.10633

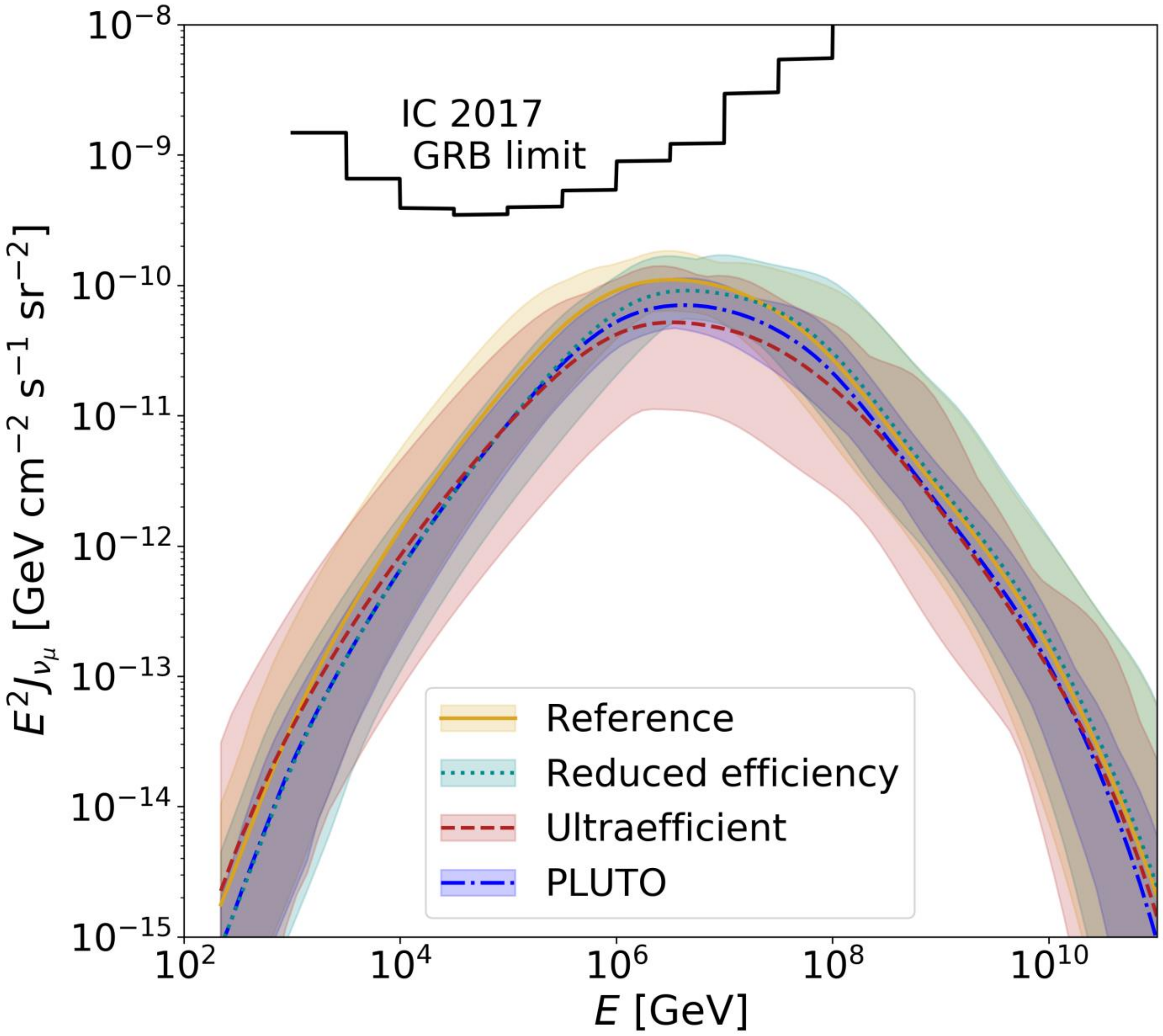
Ultra-efficient vs. baseline

Particle production regions



Rudolph, JH, Fedynitch, Winter arXiv: 1907.10633

Alternative collision models - neutrino fluxes



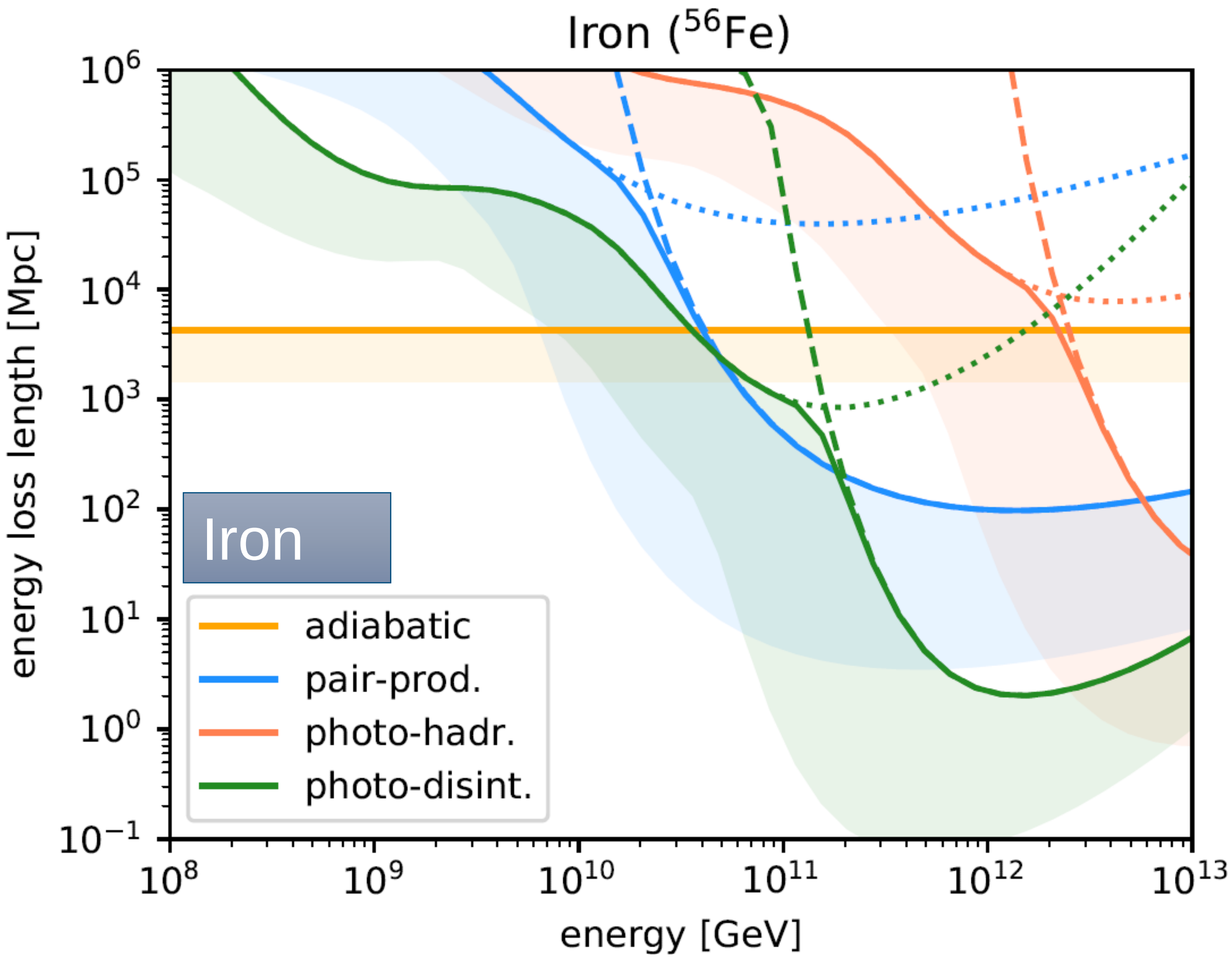
Rudolph, JH, Fedynitch, Winter arXiv: 1907.10633

UHECR Transport Equation

- About 50 × number of E-bins coupled differential equations
- All coefficients time and energy dependent

- Fast computation times needed to study cross-section / photon-field uncertainties

We have developed a new Code:
(with Anatoli Fedynitch)
PriNCe



$$\partial_t Y_i(E,z) = +\partial_E(HEY_i) - \partial_E\left(\frac{dE}{dt}Y_i\right) - \Gamma_i Y_i + \sum_j Q_{j\to i} + \mathcal{L}_i$$

adiabatic cooling | pair - production | photo-hadronic + disintegration | Injection

Propagation Code - PriNCe

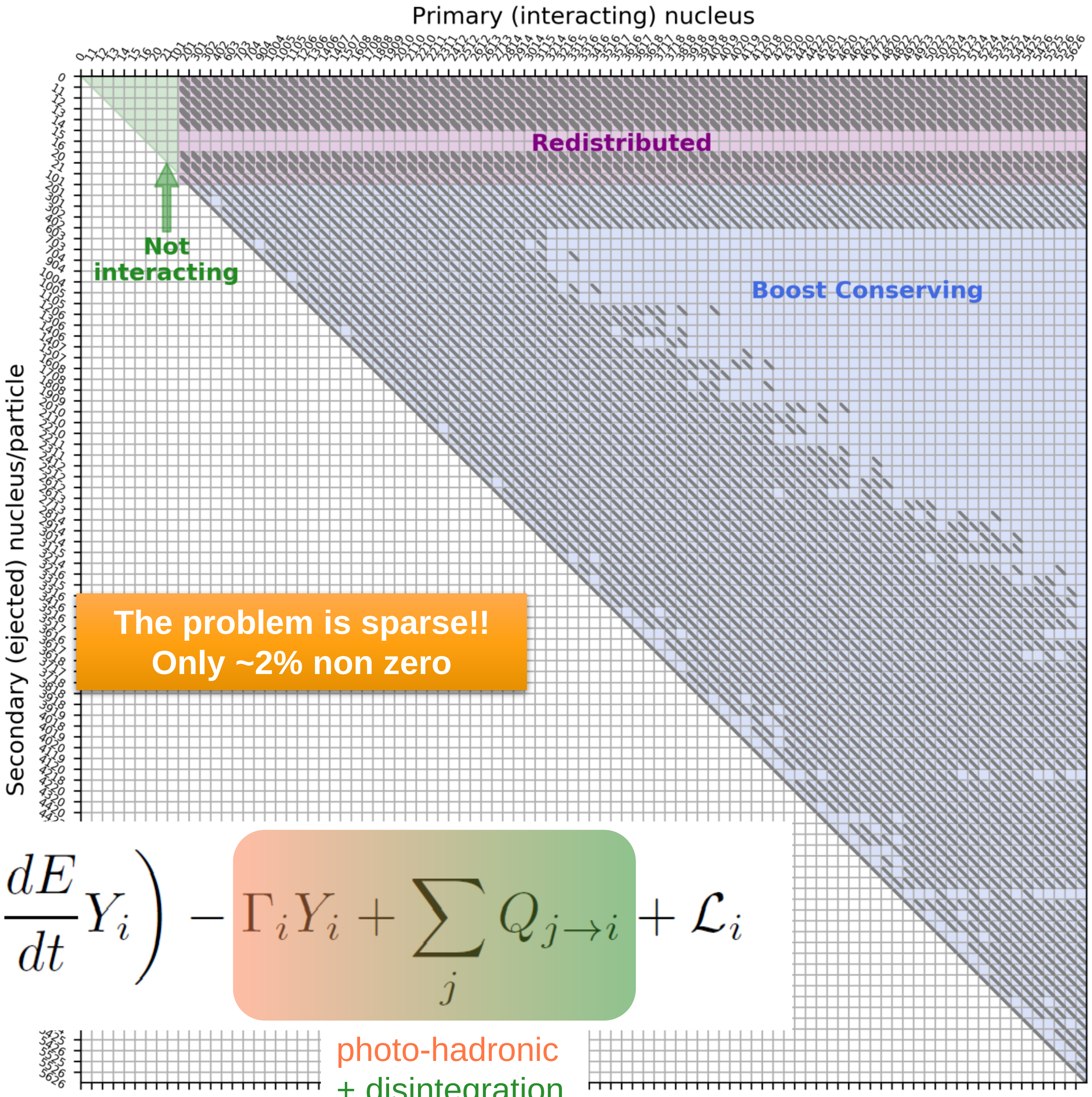
Propagation including Nuclear Cascade

- Written in pure Python using Numpy and Scipy
- Specifically makes use of sparse matrix structure

$$\partial_t \vec{Y} = \Phi \times \vec{Y} + \vec{J}$$

format	full matrix size [MB]	full matrix speed [ms]	only nuclear species size [MB]	only nuclear species speed [ms]
CSR	24.3	2.35	4.19	0.33
CSC	24.3	1.71	4.19	0.29
BSR	21.8	2.57	4.19	0.33
COO	32.3	5.13	5.55	0.75
DIA	184.00	10.00	38.00	1.67
dense	511.00	39.10	417	3100

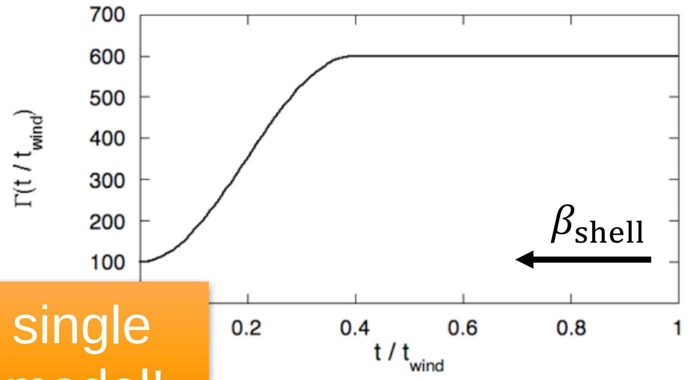
- Speed: **20s – 40s** for single spectrum (depending on number of system species)



$$\partial_t Y_i(E,z) = +\partial_E(HEY_i) - \partial_E\left(\frac{dE}{dt}Y_i\right) - \Gamma_i Y_i + \sum_j Q_{j\to i} + \mathcal{L}_i$$

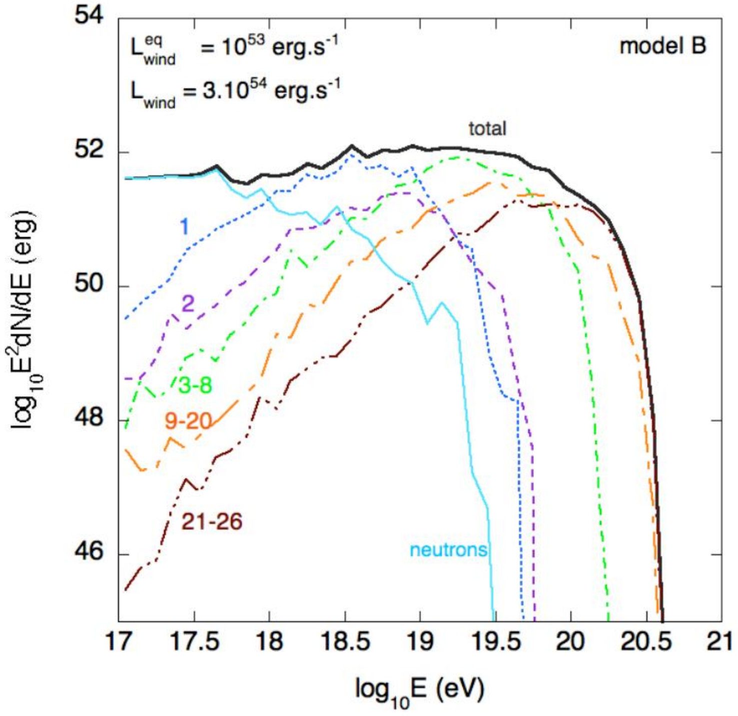
Multi Collision model - Fit to UHECR data

Globus, Allard, Mochkovitch, Parizot, Mon.Not.Roy.Astron.Soc. 451 (2015)
Globus, Allard, Parizot, Phys.Rev. D92 (2015)

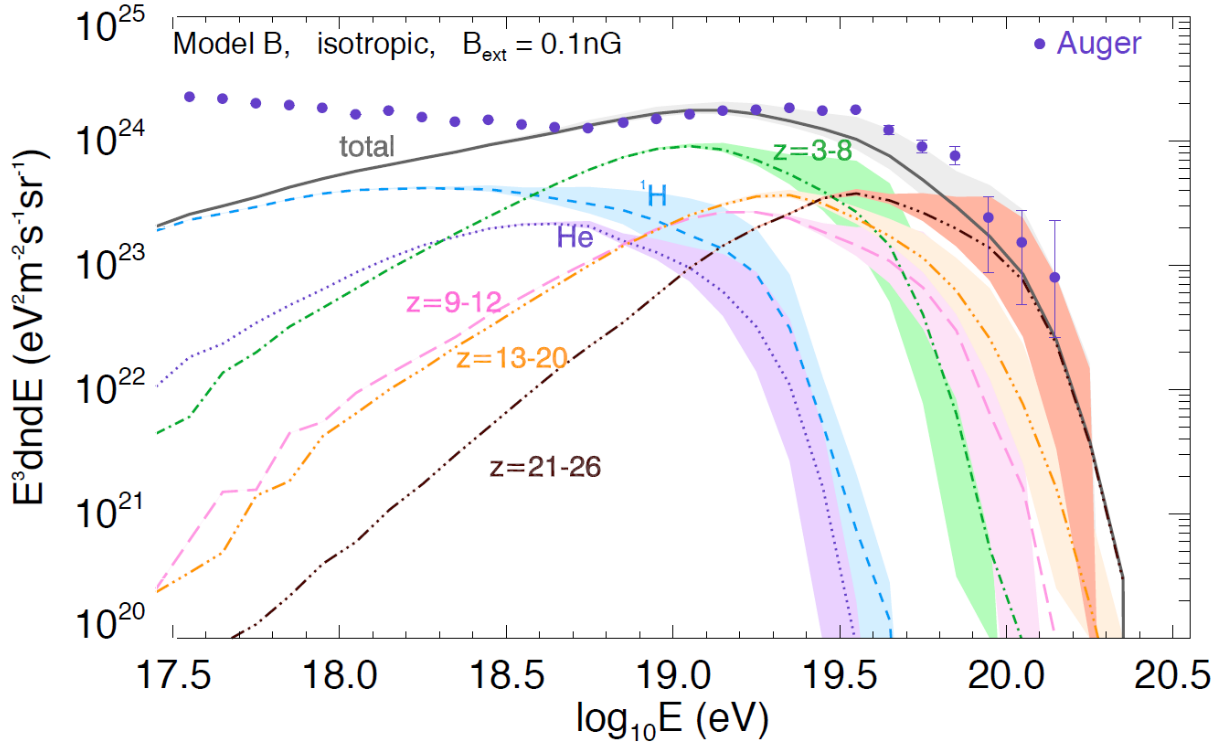


Only a single engine model!

- Disciplined engine → controlled collision radius
- **Hard spectra** (good for UHECR fit)
- … **but no stochasticity** in light curve



Extragalactic propagation



Multi-collision fit to UHECR data

Globus, Allard, Parizot, Phys.Rev. D92 (2015)