Gamma-Ray Bursts

as sources of ultra-high energy cosmic rays across the ankle

Credit: NASA/Swift/Cruz deWilde

Daniel Biehl
ICRC 2019
July 29, 2019

HELMHOLTZ RESEARCH FOR GRAND CHALLENGES

based on [**DB**, D. Boncioli, A. Fedynitch, W. Winter – Astron.Astrophys. 611 (2018) A101]
[D. Boncioli, **DB**, W. Winter – Astrophys.J. 872 (2019) no.1, 110]

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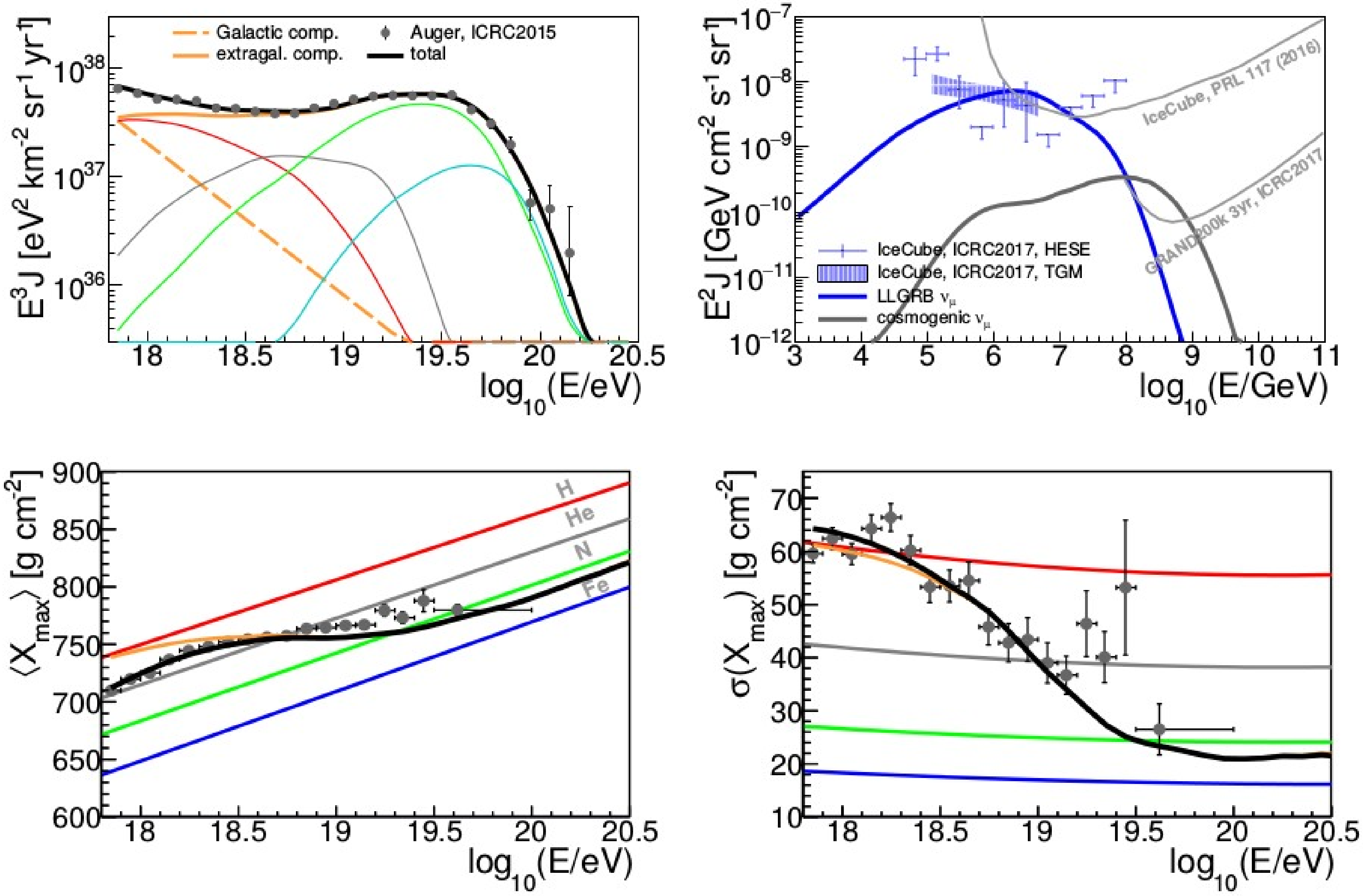


[Boncioli, **DB**, Winter, ApJ (2019)]

Generating the ankle due to photo-disintegration

The sub-ankle extragalactic proton component

A natural explanation of the ankle feature

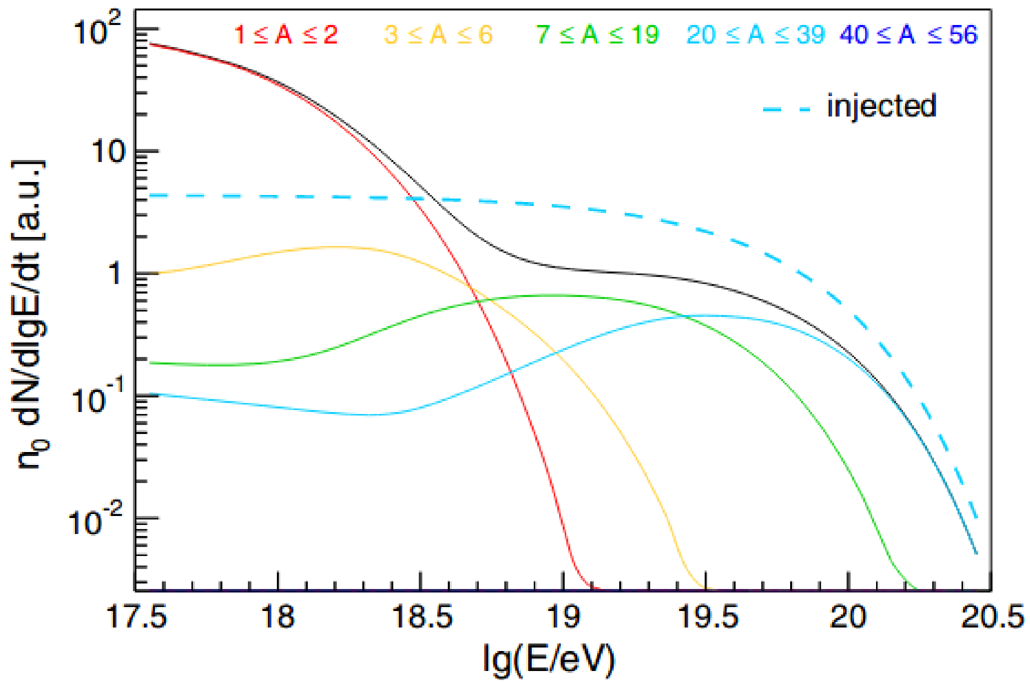
- High energy particles are likely to disintegrate as the corresponding rate increases with the cosmic ray energy

- Secondary nucleons are produced by photo-disintegration which leads to a second peak at lower energies

- Escape from the source is most efficient for the highest energies (direct escape, diffusive escape, escape-limited)

[Ohira, Murase, Yamazaki, A&A 2010]
[Baerwald, Bustamante, Winter, ApJ 2013]
[Unger, Farrar, Anchordoqui, PRD 2015]

- Application to specific sources including the explicit computation of all nuclear processes, i.e., nucleon (and neutrino) production in the nuclear cascade



[Unger, Farrar, Anchordoqui, PRD 2015]

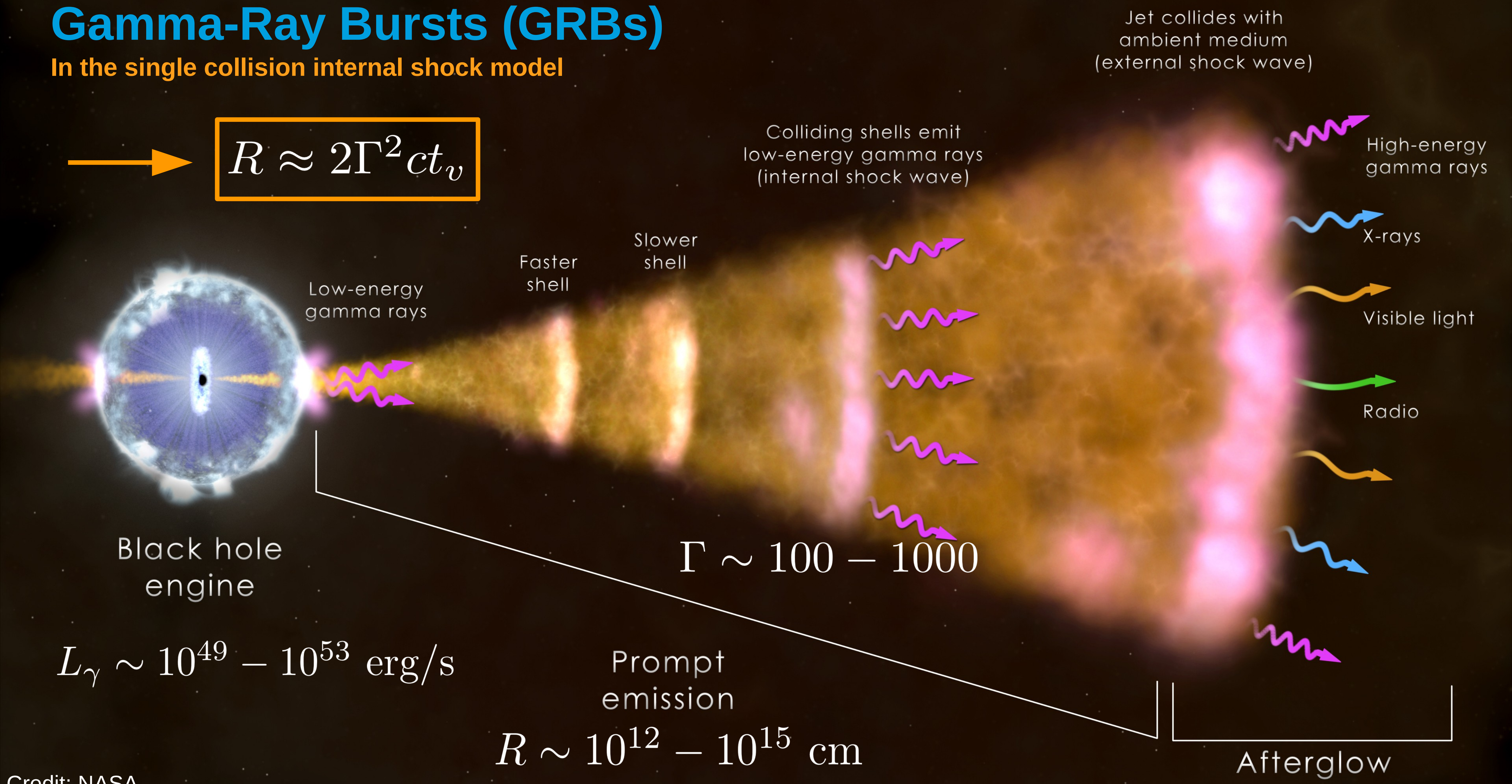
Update: [Muzio, Unger, Farrar, 1906.06233]

See also: [**DB**, Boncioli, Fedynitch, Winter, A&A 2018]

Gamma-Ray Bursts (GRBs)

In the single collision internal shock model

$$R \approx 2\Gamma^2 c t_v$$



Credit: NASA

Development of the nuclear cascade

Production of light nucleons in cosmic ray interactions

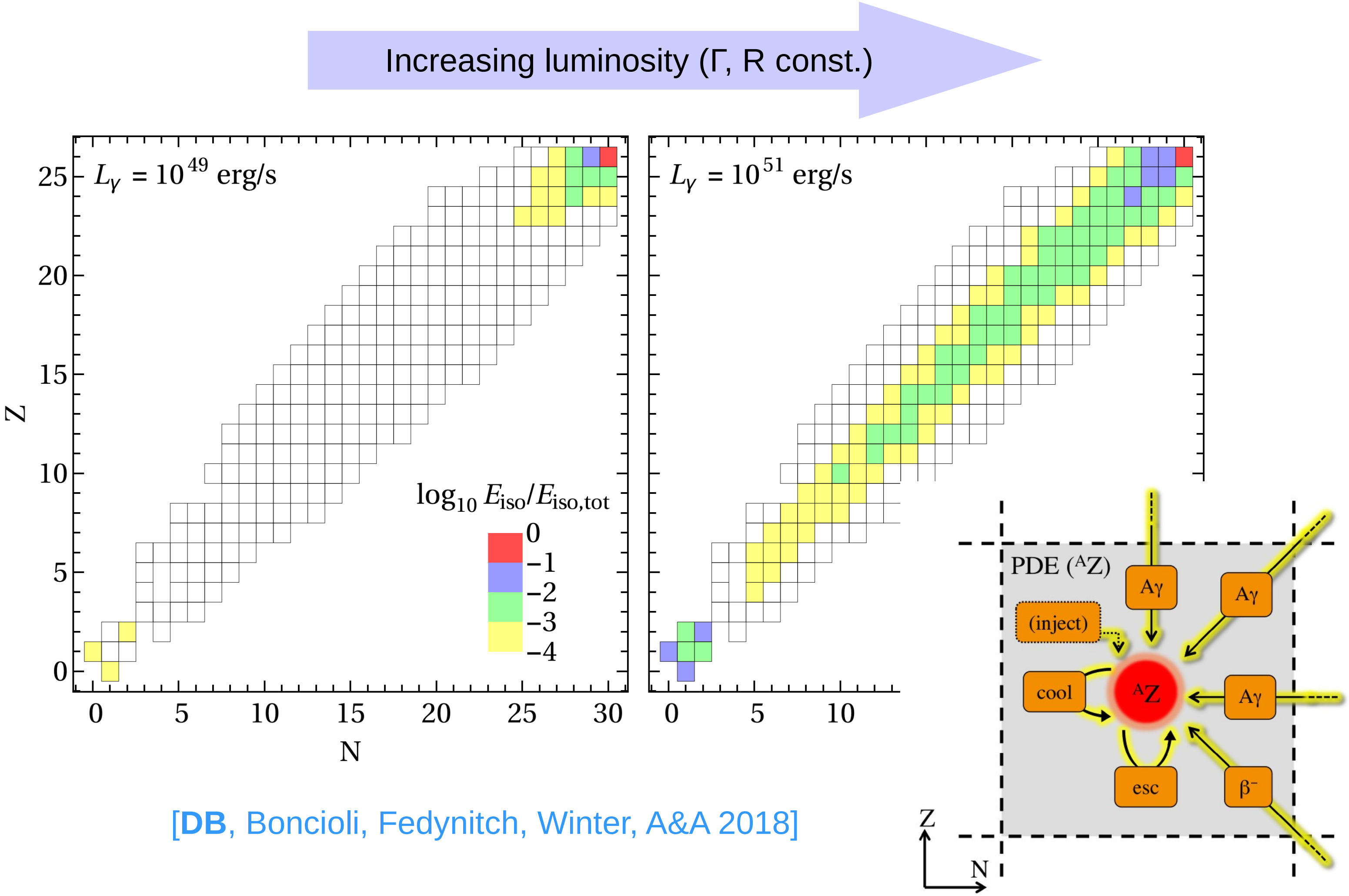
- Photo-disintegration initiates a nuclear cascade due to subsequent interactions
- Neutrino production via photo-meson production and subsequent pion decay

$$p + \gamma \rightarrow \Delta^+ \rightarrow \pi^+ + n \rightarrow \mu^+ + \nu_\mu$$

- Nuclear cascade and neutrino production scale with the radiation density

$$u'_\gamma \sim \frac{L_\gamma}{\Gamma^2 R^2}$$

→ **Production radius R and luminosity L are the main control parameters for the nuclear cascade and neutrino production**

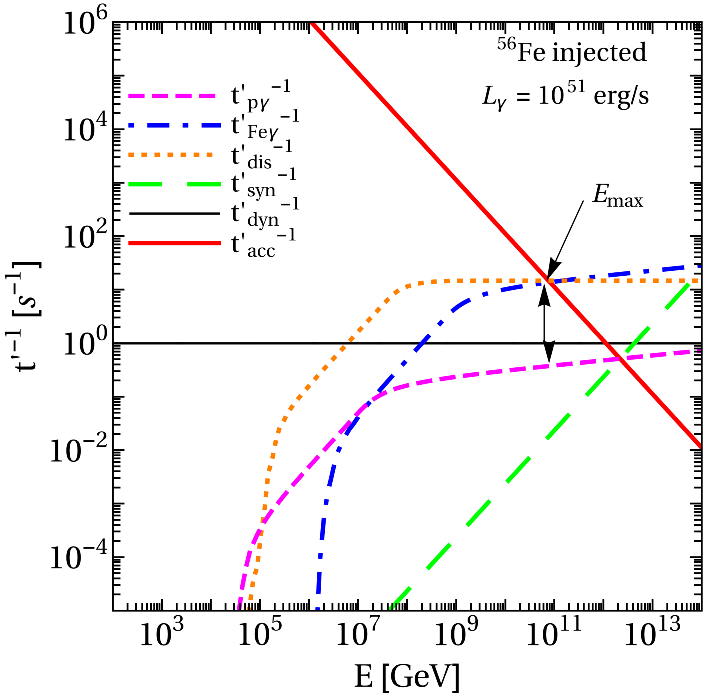


[**DB**, Boncioli, Fedynitch, Winter, A&A 2018]

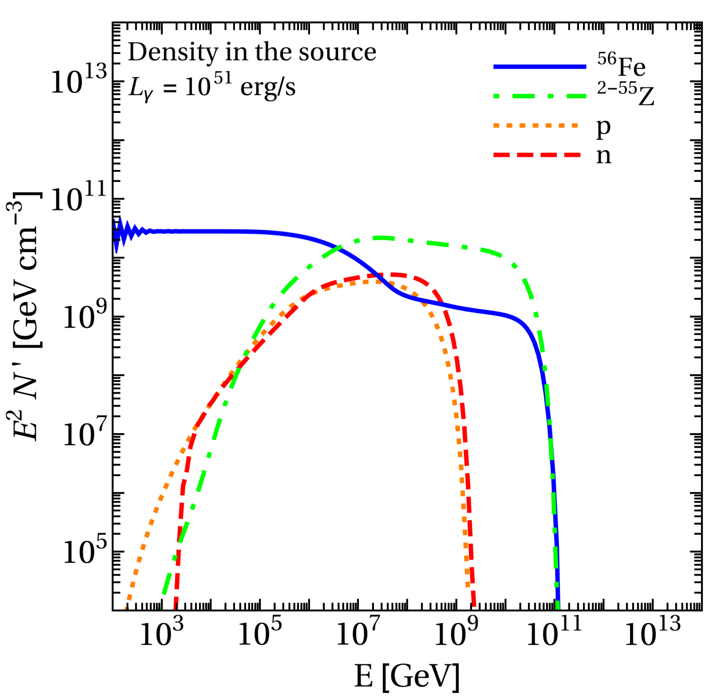
Photo-disintegration in (conventional) GRBs

Reproducing the ankle with cosmic ray interactions

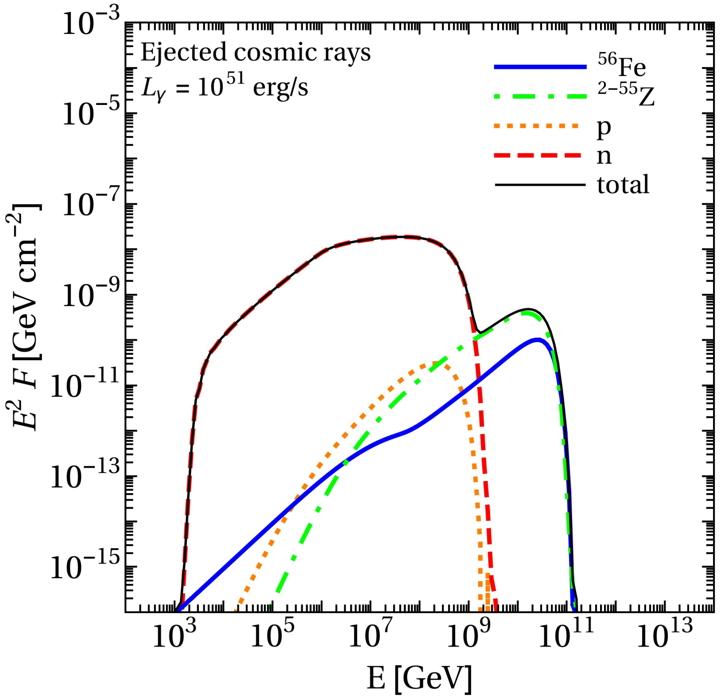
Interaction rates



Accelerated spectrum



Escaping spectrum



- As disintegration becomes efficient, heavy cosmic rays are depleted and light secondary nucleons are produced
- Mostly high energy cosmic rays escape as their Larmor radius is large enough to reach the boundary of the region
- All neutrons escape as they are electrically neutral → the amount of disintegration will determine the fit!

[**DB**, Boncioli, Fedynitch, Winter, A&A 2018]

Description of UHECR data by conventional GRBs

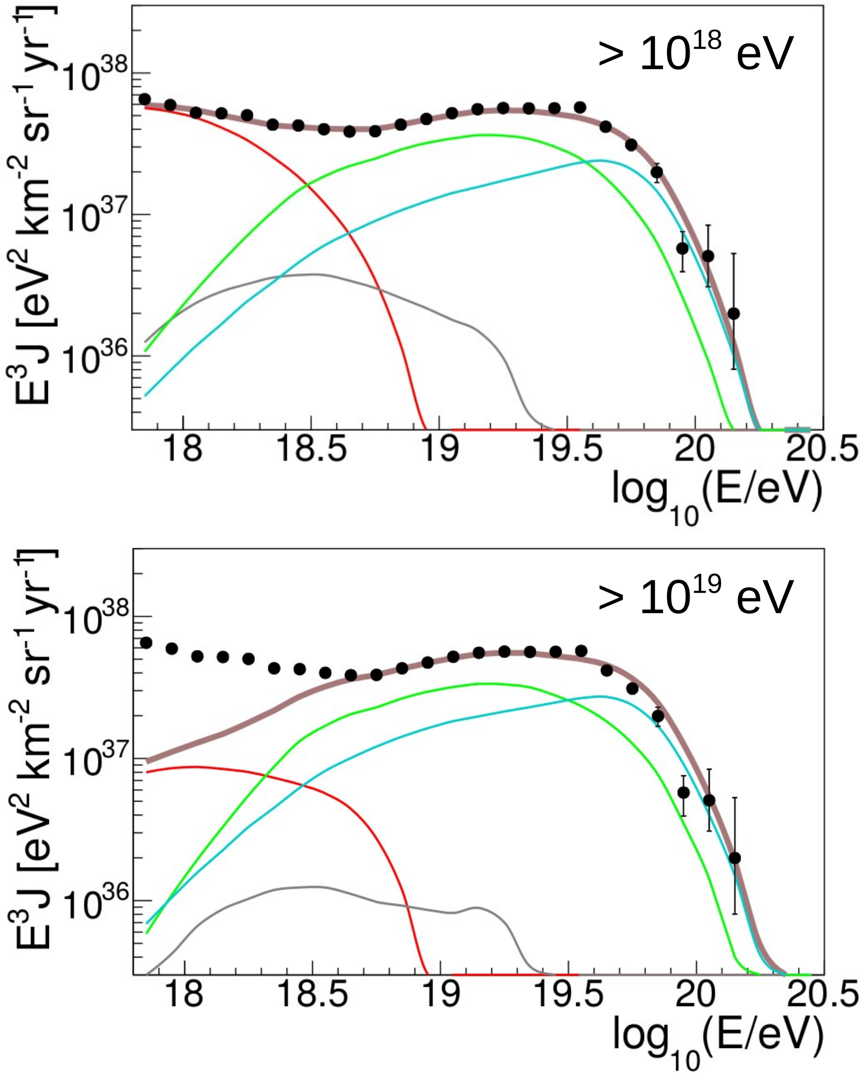
Best fit across and above the ankle

The GRB-UHECR paradigm

- Fit across the ankle requires intermediate radiation densities, however this leads to an excess in co-produced neutrinos, no other solutions found in extensive parameter space scans
  → **already excluded!**

- Fit above the ankle still viable, but only for low radiation densities indicating low-luminosity scenarios; still comes with the disadvantage of very high baryonic loadings around ~ 10^5
  → **challenging...**

- Possible solution: low-luminosity GRBs (LLGRBs) including a low energy Galactic power law for a consistent description



[**DB**, Boncioli, Fedynitch, Winter, A&A 2018]

LLGRBs as sources of UHECRs across the ankle

Model ingredients and assumptions

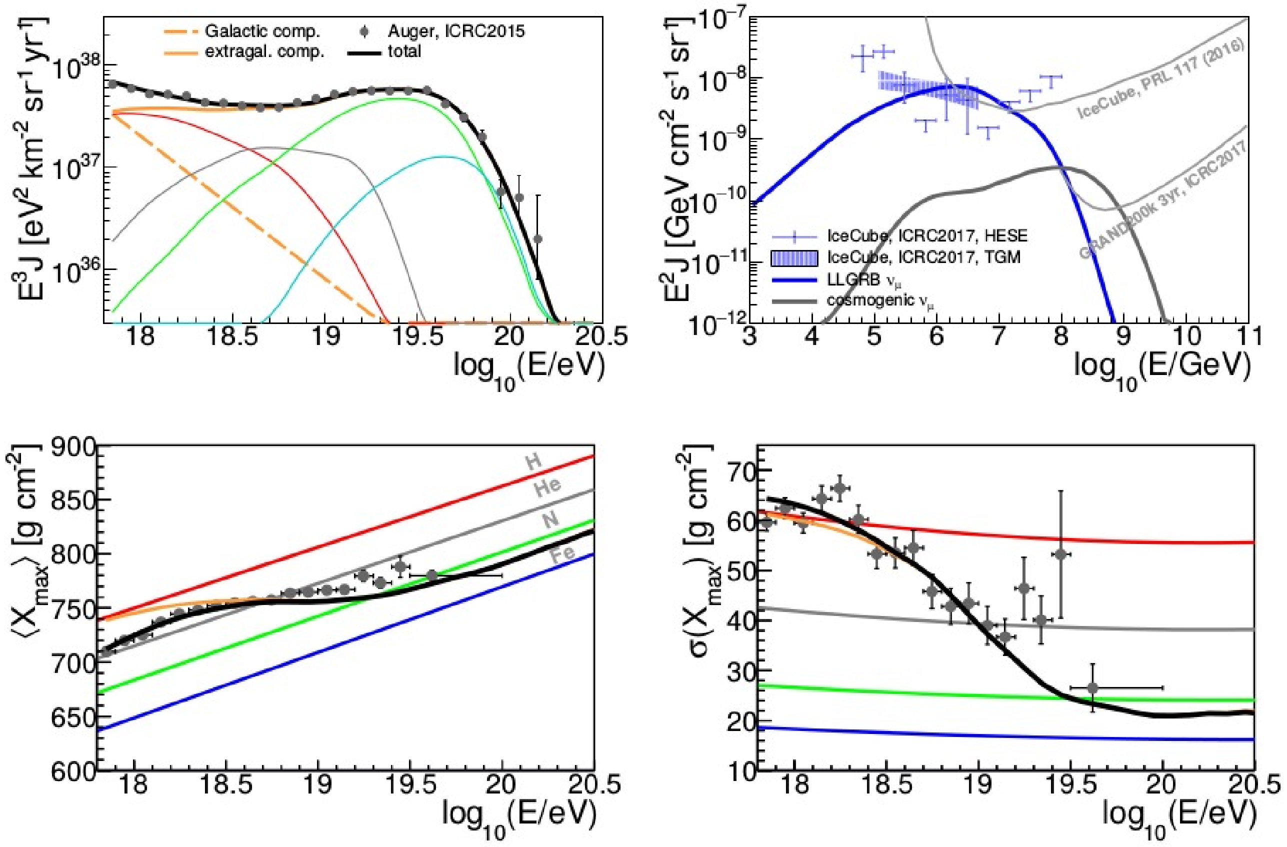
LLGRBs as a distinct population

- Low luminosity ~ 10^{46} – 10^{49} erg/s, durations up to 10^{3} – 10^{4} s and beyond
- Intermediate / heavy injection composition: 60% O, 40% Si [Zhang++, PRD 2018]

- Source evolution $(1+z)^m \times H_{SFR}(z)$ with $0 < m < 1$
- Low energy component:
  - A = 28
  - α = 4.2
  - 78% fraction of the flux at $10^{17.5}$ eV

  Similar to [Unger, Farrar, Anchordoqui, PRD 2015]

- Best fit yields a baryonic loading $\xi_A \sim 10$

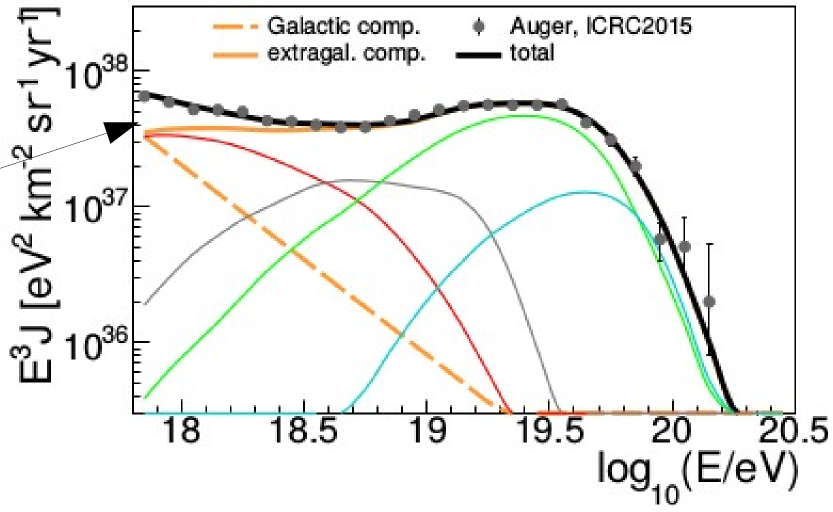


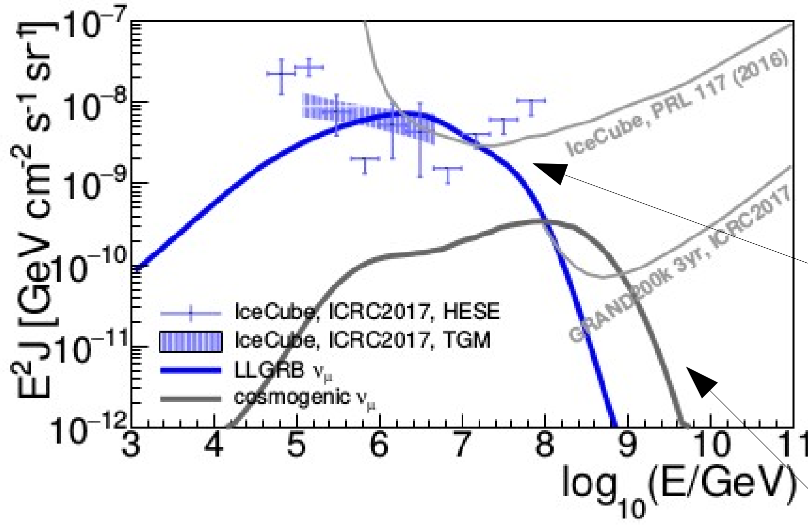
[D. Boncioli, **DB**, W. Winter – ApJ (2019)]

Best fit for UHECR spectrum, composition & neutrinos

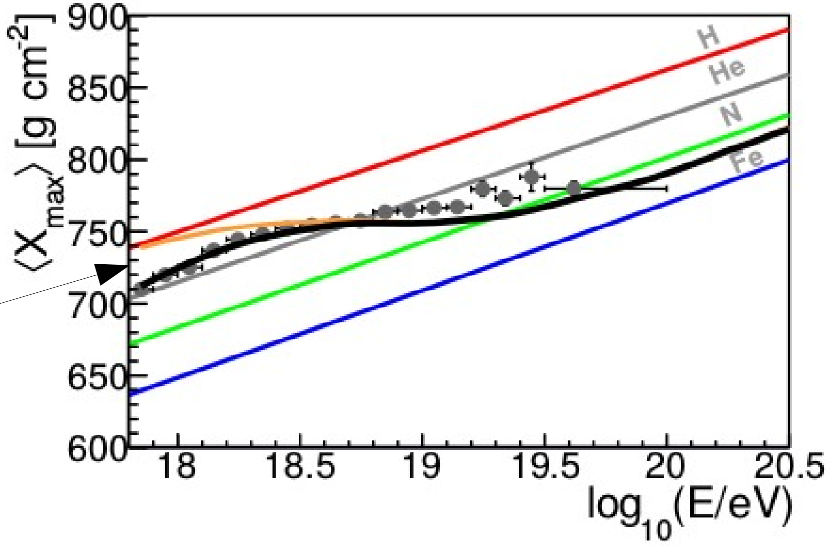
A complete, consistent picture for LLGRBs

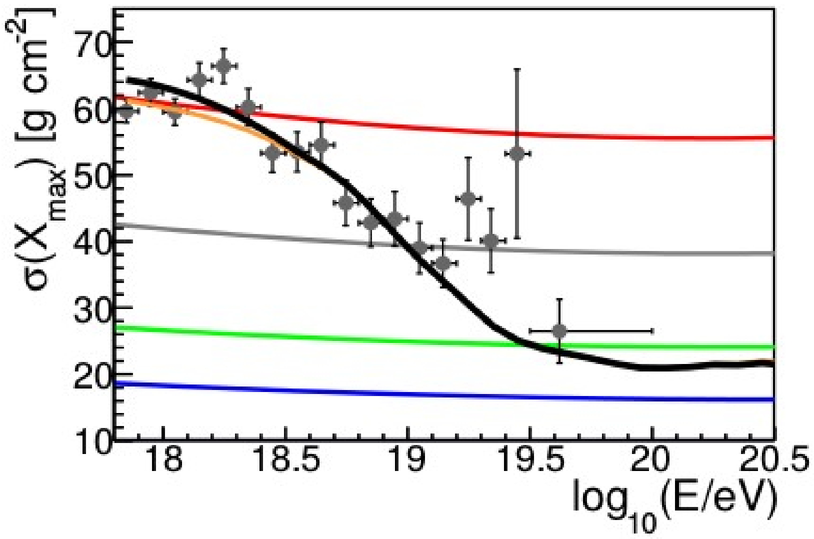
Nuclear cascade controls the sub-ankle region, almost perfect description with additional low energy power law





PeV neutrino data in IceCube can be addressed





Heavy galactic plus light extra-galactic below the ankle

Cosmogenic neutrinos expected with future instruments

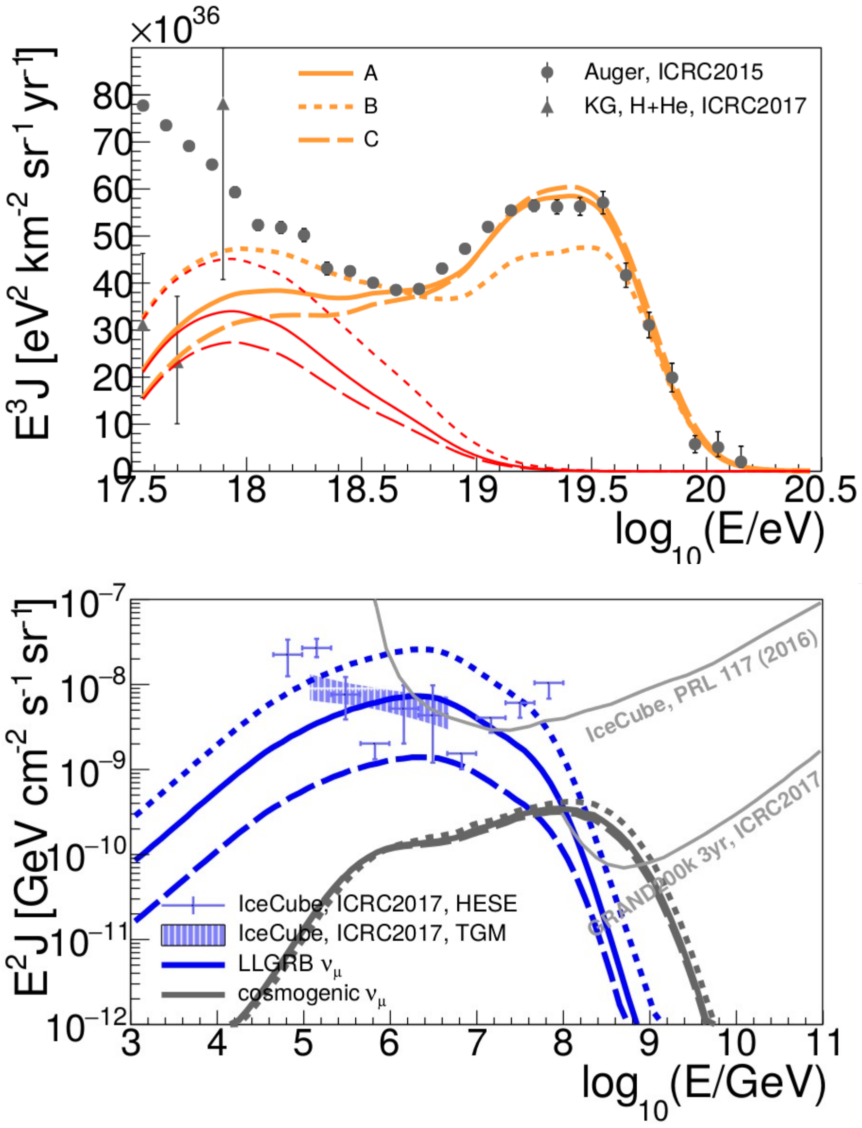
[D. Boncioli, **DB**, W. Winter – ApJ (2019)]

Extragalactic sub-ankle component

The link to the nuclear cascade

(Lower energy) nucleon production in the source

- Cannot be taken into account in propagation only models, i.e., if source interactions are neglected
- Directly depends on the radiation parameters and therefore on the development of the nuclear cascade
- Bench marks with similar maximum energy and therefore similar cosmogenic neutrino flux
  - Best fit point A
  - Higher radiation density point B
  - Lower radiation density point C
- The nuclear cascade breaks the degeneracy between different source scenarios by neutrino data!



[D. Boncioli, **DB**, W. Winter – ApJ (2019)]

Conclusion

GRBs as sources of UHECRs across the ankle

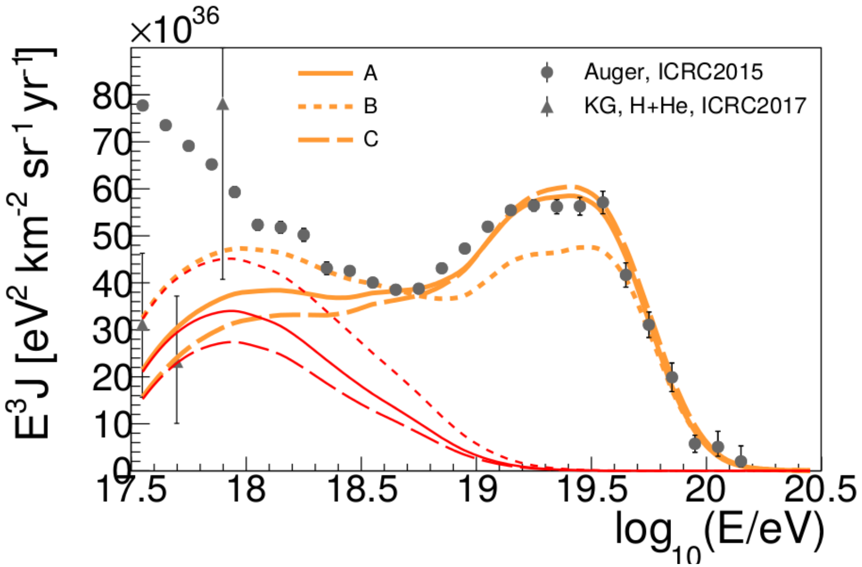
[D. Boncioli, **DB**, W. Winter – ApJ (2019)]

Summary

- The nuclear cascade controls the production of nucleons and neutrinos by photo-disintegration of cosmic rays in the source; subtle balance between too strong and too weak disintegration

- We can reproduce UHECR spectrum and composition across the ankle with LLGRBs while conventional GRBs are disfavored

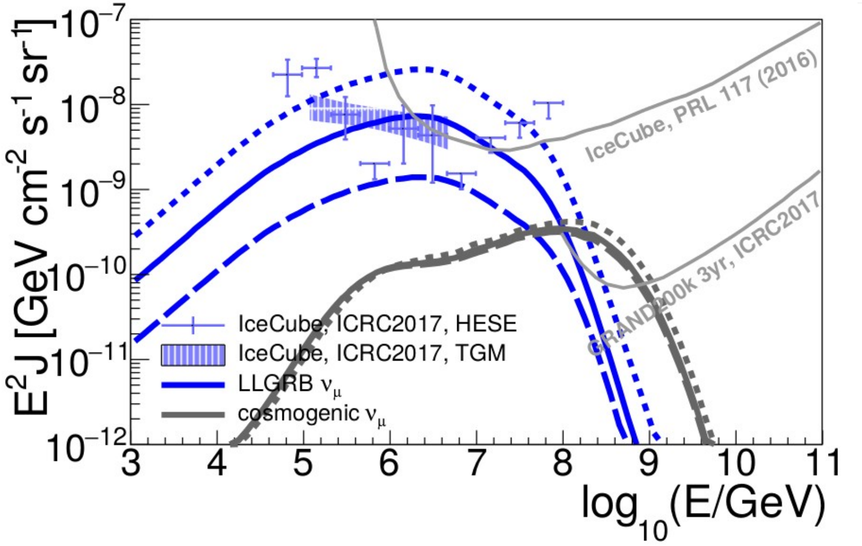
- Neutrinos are important as they can ultimately test these models!



Outlook

- TDEs: can describe UHECRs as well! Discrimination possible via cosmogenic neutrinos [**DB**, Boncioli, Lunardini, Winter, Sci. Rep. 2018]

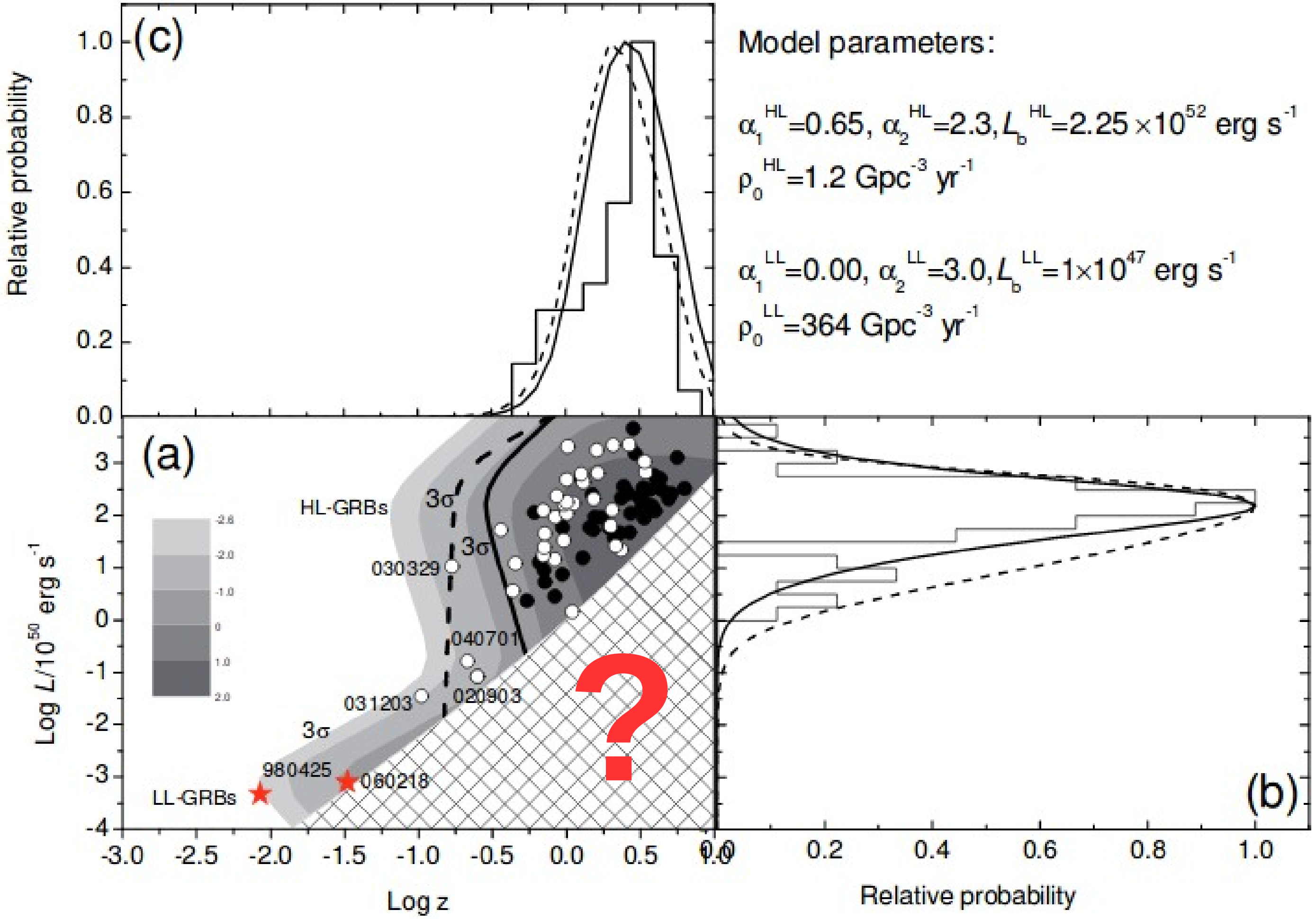
- Multi-zone models: studies on engine behavior and collision dynamics
  [Rudolph, Heinze, Fedynitch, Winter, to be submitted]
  [Heinze, **DB**, Boncioli, Fedynitch, Winter, in preparation]



BACKUP

LLGRBs as a distinct population

LLGRB population model



Model parameters:

α_1^{HL}=0.65, α_2^{HL}=2.3, L_b^{HL}=2.25×10^{52} erg s^{-1}
ρ_0^{HL}=1.2 Gpc^{-3} yr^{-1}

α_1^{LL}=0.00, α_2^{LL}=3.0, L_b^{LL}=1×10^{47} erg s^{-1}
ρ_0^{LL}=364 Gpc^{-3} yr^{-1}

[Liang, Zhang, Virgili, Dai, ApJ 2007]

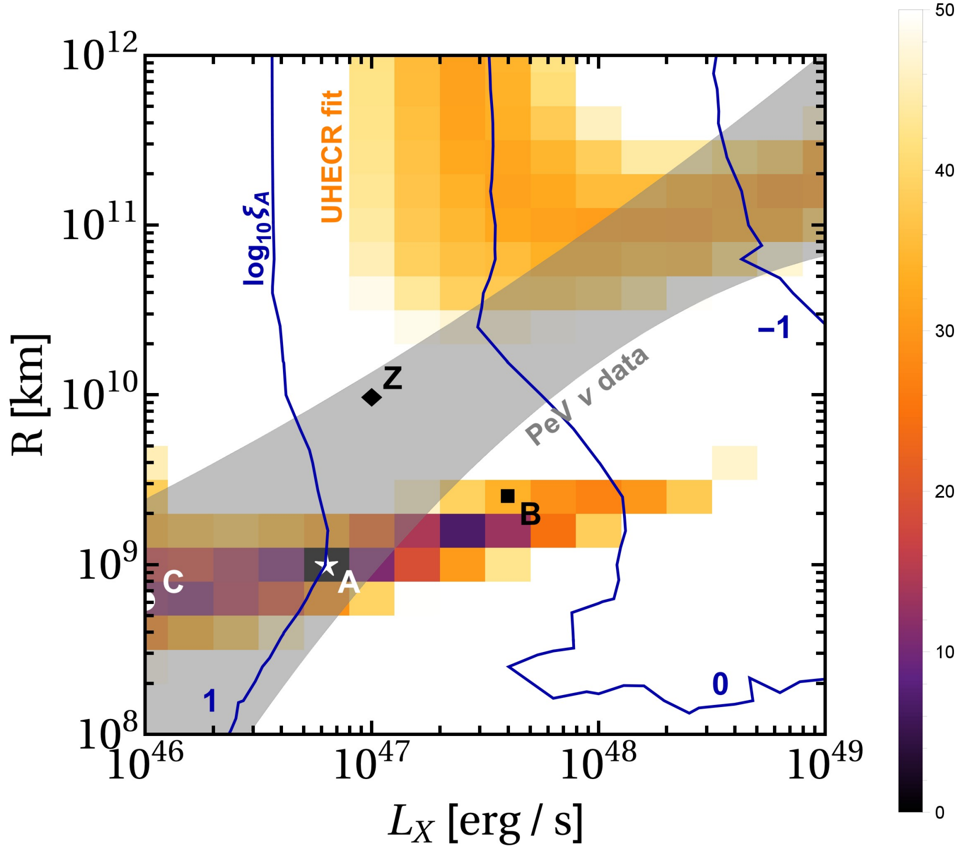
Low-luminosity Gamma-Ray Bursts (LLGRBs)

Parameter space scan of UHECR fit

Color code: χ^2

LLGRBs as a distinct population from conventional GRBs

- Long duration makes background suppression less efficient, low luminosity limits detection of resolved sources
- Cosmic ray fit follows maximum energy, degenerate with composition, acceleration efficiency, energy scale uncertainty
- Neutrino band corresponds to through-going muon data set, follows required radiation density, photo-hadronic interactions efficient for heavy nuclei
- It is possible to find a common fit region, best fit yields a baryonic loading $\xi_A \sim 10$

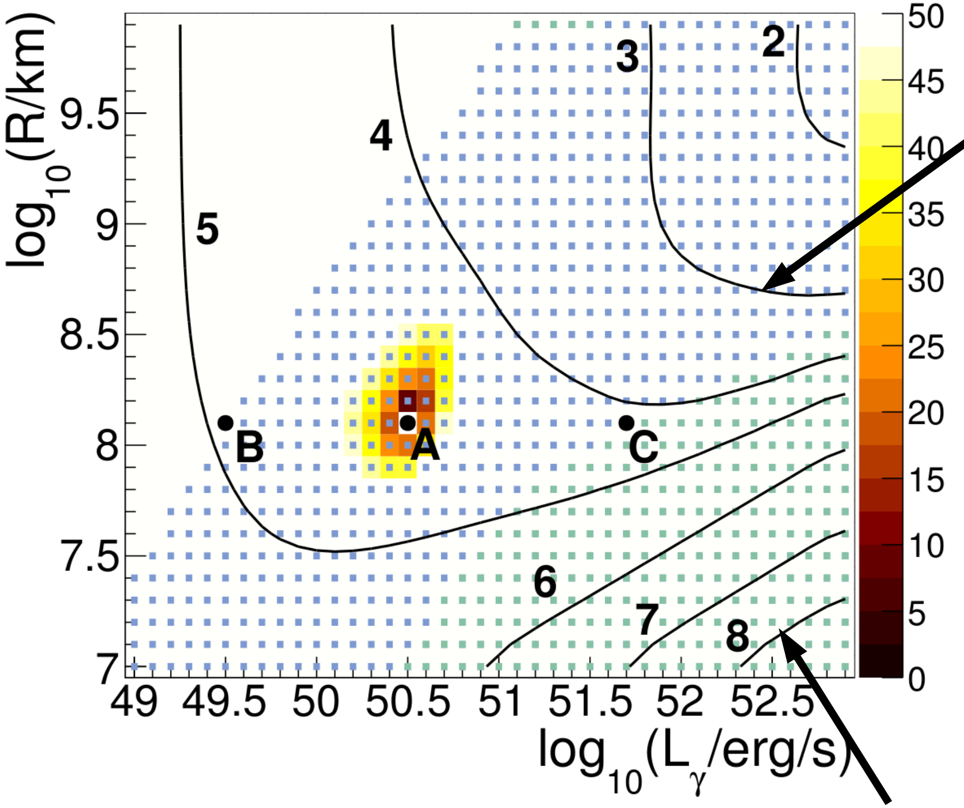


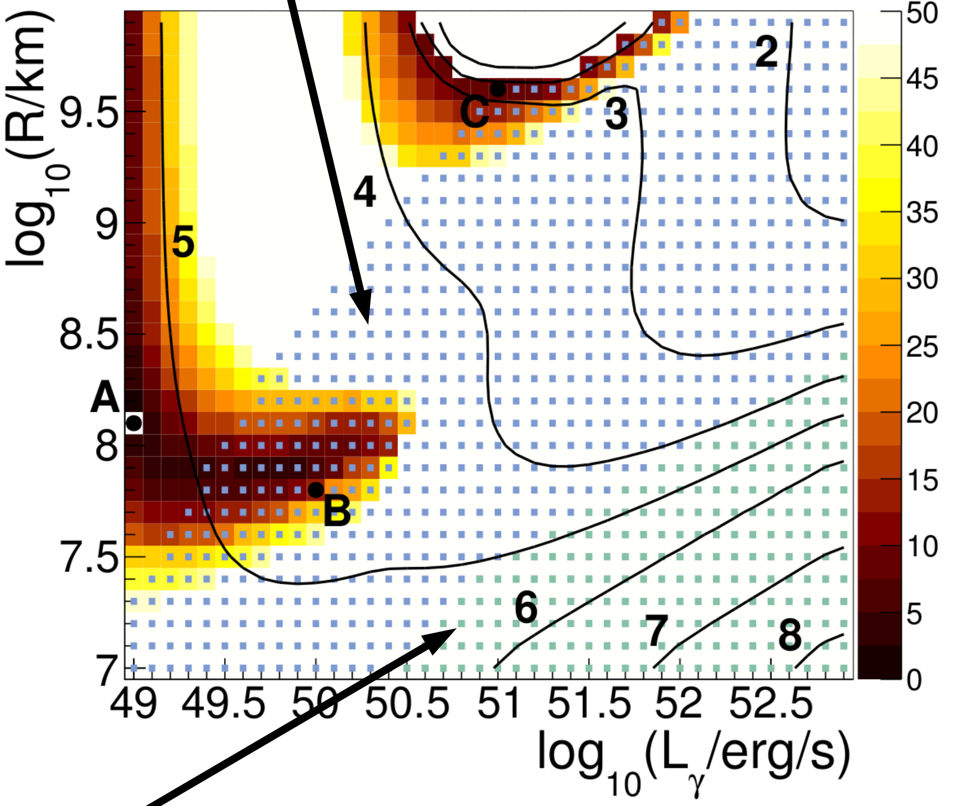
[D. Boncioli, **DB**, W. Winter – Astrophys.J. 872 (2019) no.1, 110]

UHECR fit for conventional GRBs

Parameter space scan

IceCube excluded region
from GRB stacking analysis,
Aartsen et al 2017





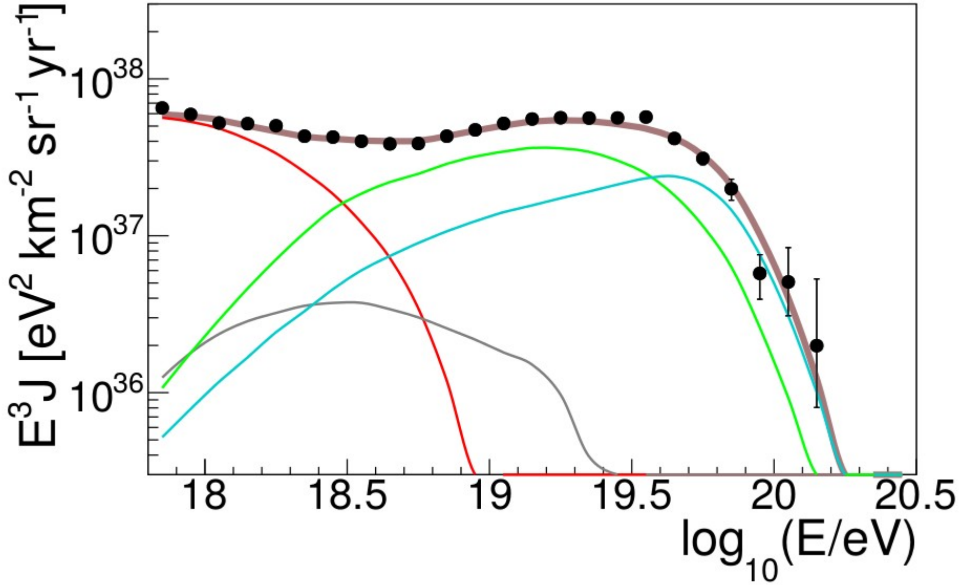
Fit of UHECR data above 10^{18} eV → including ankle

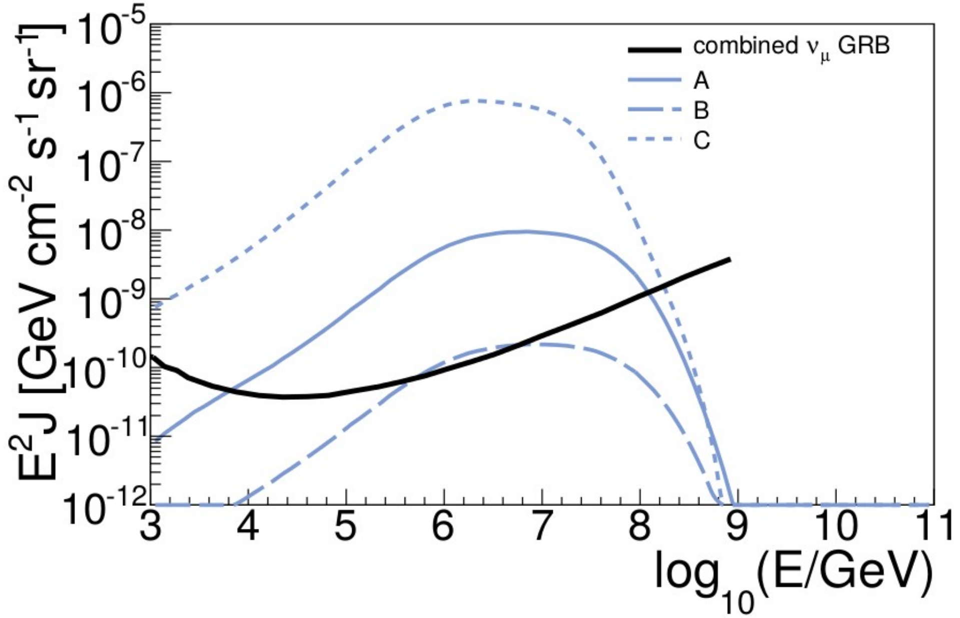
IceCube excluded region
from cosmogenic neutrinos,
Aartsen et al 2016

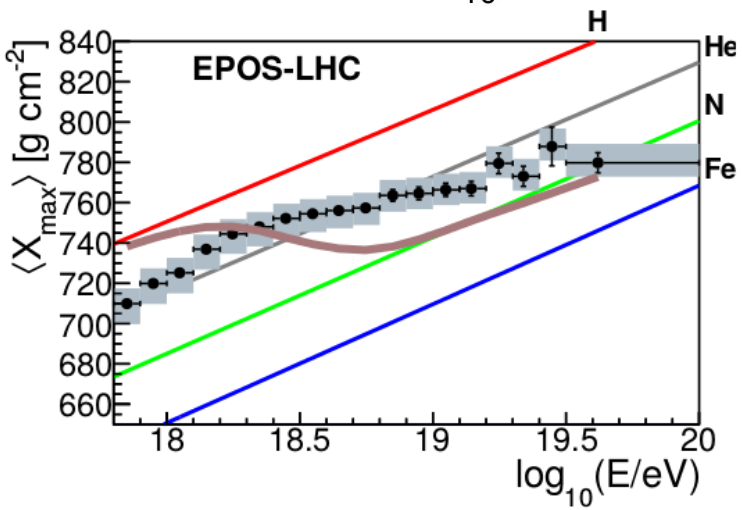
Fit of UHECR data above 10^{19} eV → excluding ankle

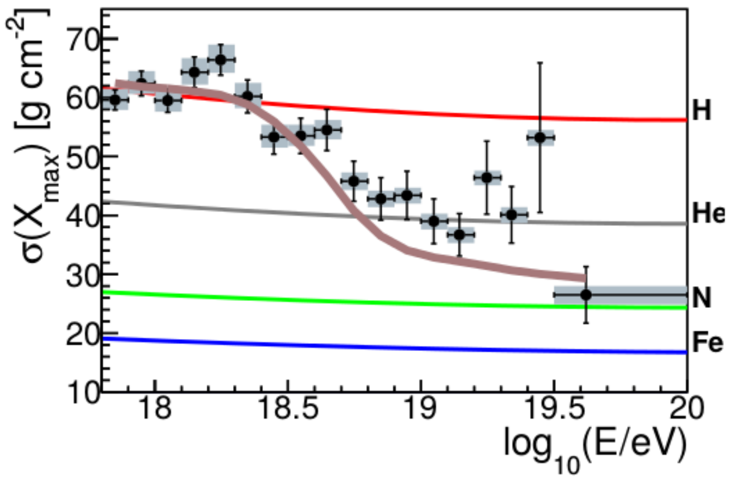
UHECR fit for conventional GRBs

Best fit for spectrum and composition across the ankle



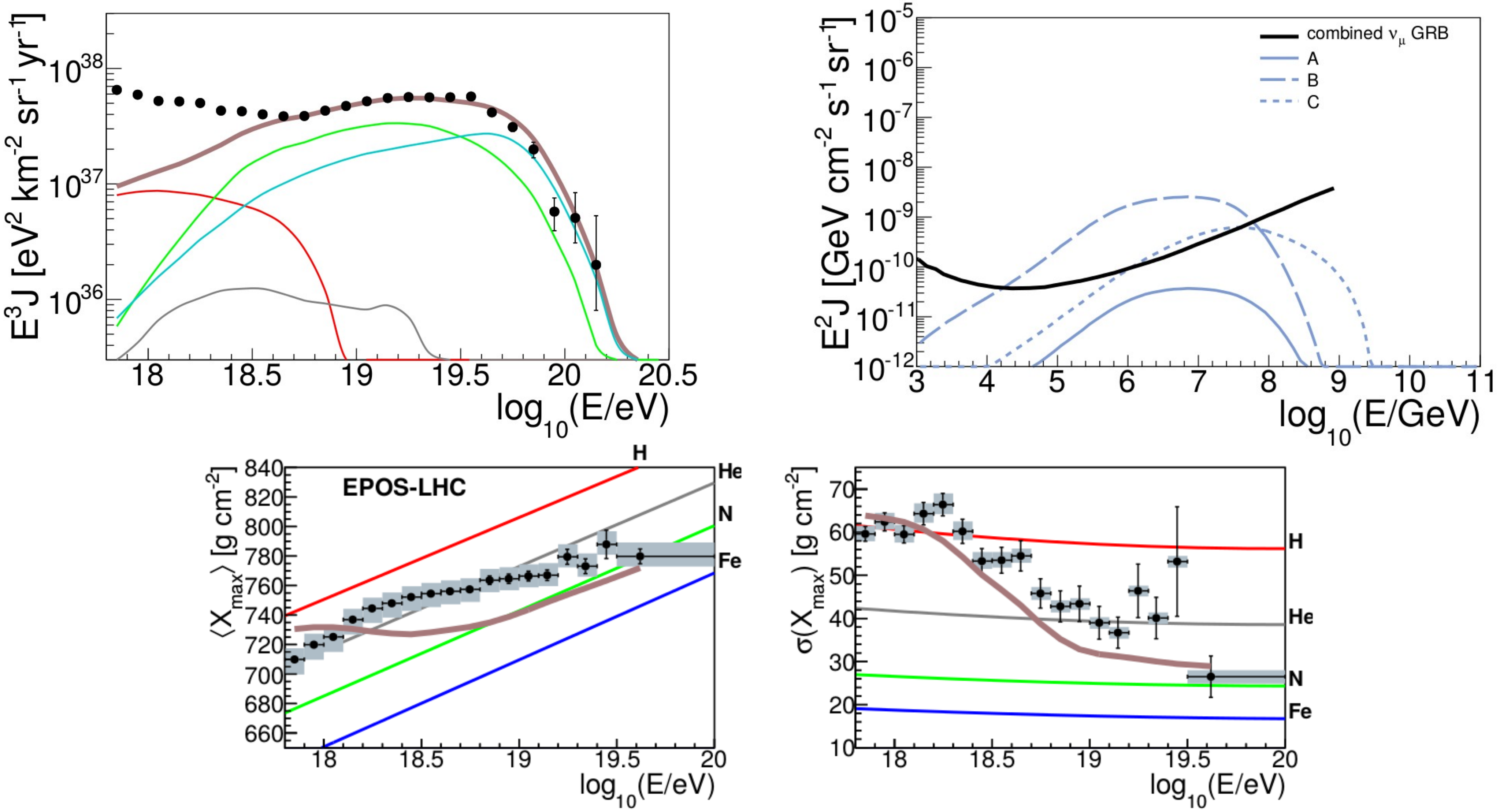






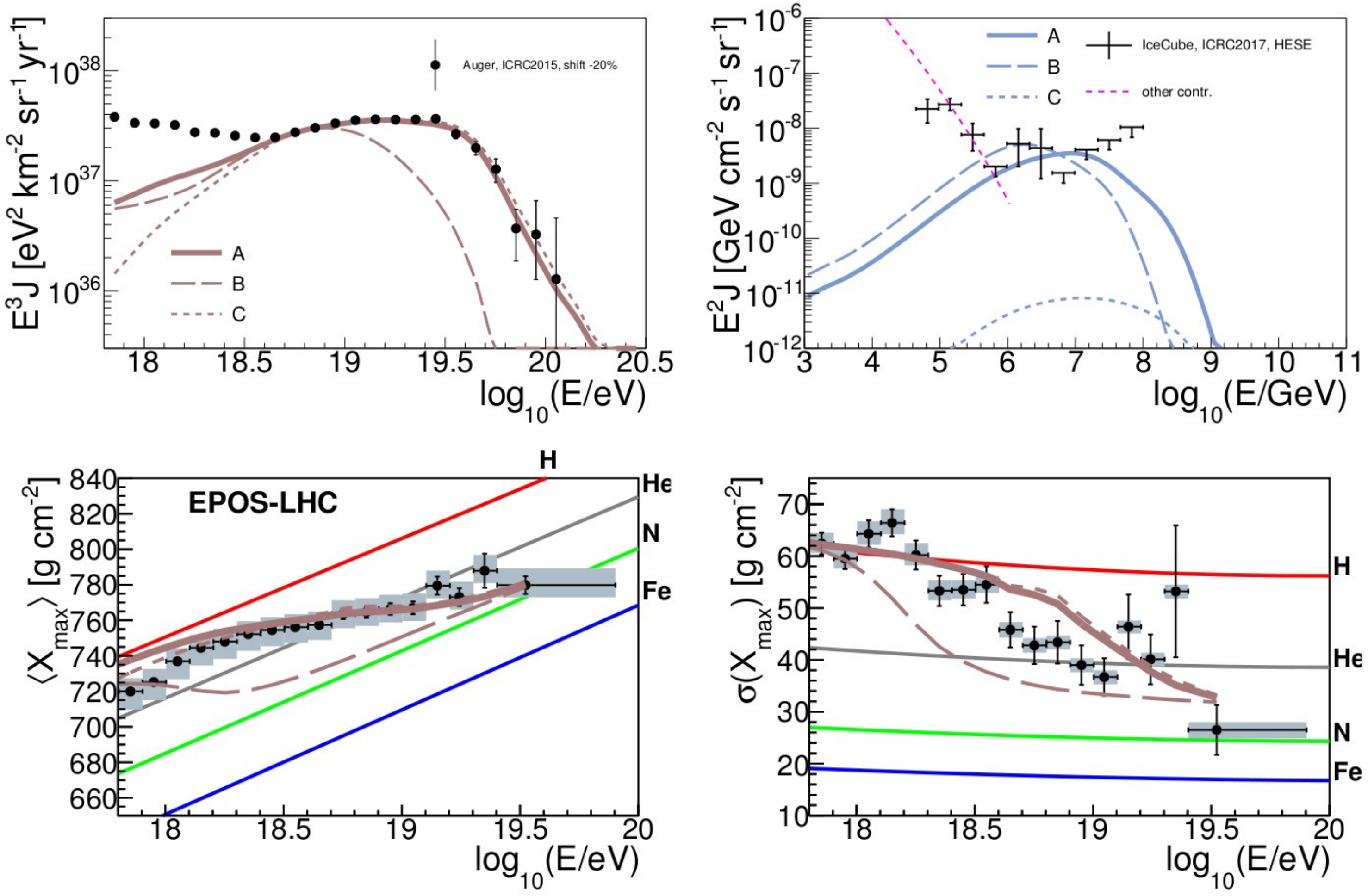
UHECR fit for conventional GRBs

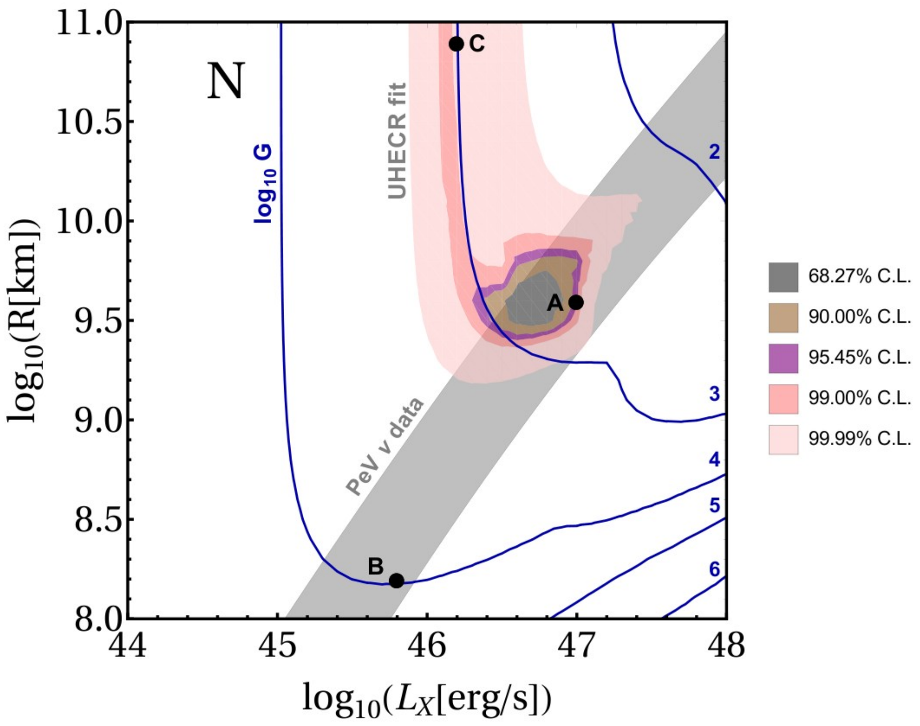
Best fit for spectrum and composition above the ankle



Single messenger best fit points

Fitting either cosmic ray or neutrino data





It is possible to fit both within the 1σ region of each other!

[D. Biehl, D. Boncioli, C. Lunardini, W. Winter – Sci.Rep. 8 (2018) no.1, 10828]

Possible scenarios for the progenitor system

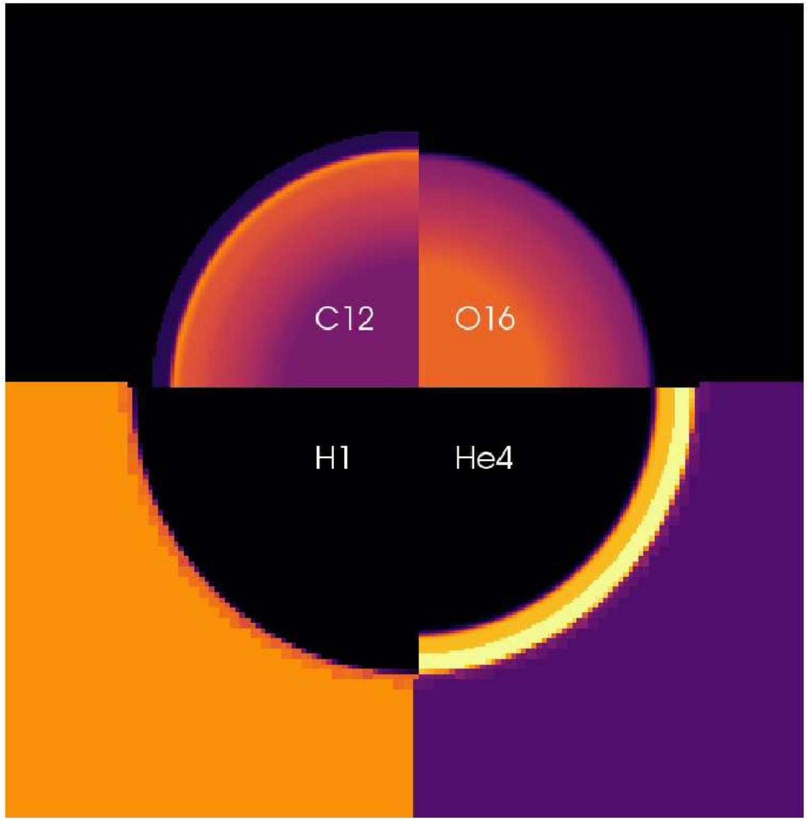
A diverse population of TDEs

Binaries of black holes and stars

- Three jet-hosting TDEs have been identified so far, the observations are consistent with [D. N. Burrows et al. (2011)] [S. B. Cenko et al. (2012)]
  - Supermassive black hole, M > 10^5 solar masses, disrupting main sequence star [J. S. Bloom et al. (2012)]
  - Intermediate mass black hole, 10^3 > M > 10^5 solar masses, disrupting white dwarf (WD)
- Other scenarios are possible as well, e.g. tidal forces triggering the burning of elements which may normally not happen due to the mass of the star [R. Alves Batista, J. Silk (2017)]
- Presence of intermediate mass isotopes motivated by the disruption of white dwarfs, ONeMg white dwarfs from past supernovae or explosive nuclear burning

[B. T. Zhang, K. Murase, F. Oikonomou, Z. Li (2017)]

[P. Anninos et al. (2018)]



Cross-section of typical white dwarf

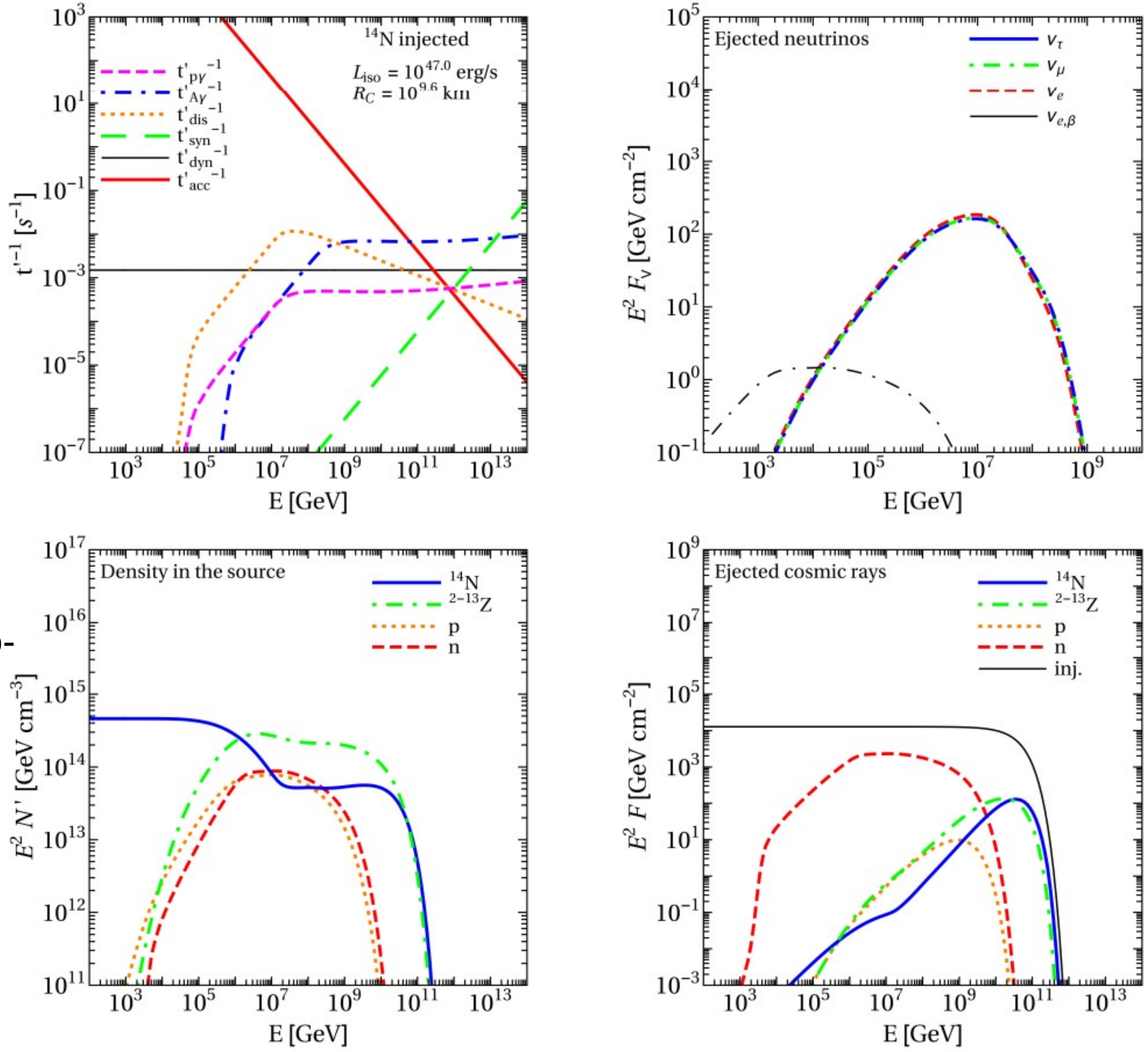
Main ingredients of our simulation

Parameters, assumptions, composition

Details on the model

- Internal shock scenario connecting radius and time variability by $R \sim 2\Gamma^2 ct$
- Static broken power law target photon field assumed
- Efficient Fermi shock acceleration of nuclei, injection follows spectral index ~ 2 up to a maximum energy
- Direct UHECR escape mechanism leads to harder escaping spectra with respect to the injection
- Photo-disintegration based on TALYS + CRPropa, Photo-Meson production based on SOPHIA
- Pure nitrogen injection motivated by the disruption of carbon-oxygen white dwarfs and the observation of nitrogen emission lines

[S. B. Cenko et al. (2016)]
[J. S. Brown et al. (2017)]



[D. Biehl, D. Boncioli, C. Lunardini, W. Winter – Sci.Rep. 8 (2018) no.1, 10828]

Population model in a nutshell

Cosmological rate of TDEs

$$\dot{\rho}(z, M) = \dot{N}_{\mathrm{TD}}(M) f_{\mathrm{occc}}(M) \phi(z, M)$$

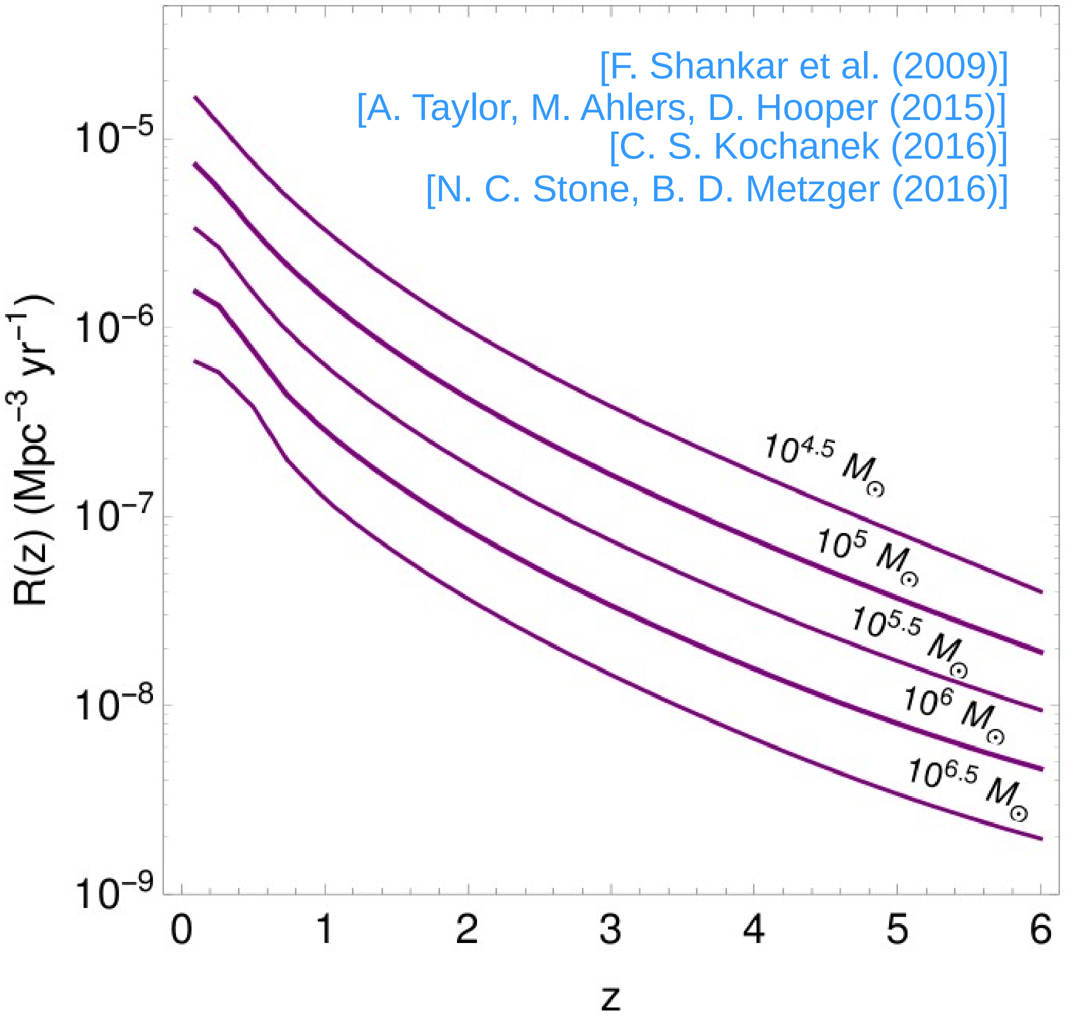
Rate of disruptions per black hole

Occupation fraction

Black hole mass function

Negative source evolution

- Follows mainly black hole mass function Φ(z,M)
  - declines with z roughly as $(1+z)^{-3}$
- Close sources dominate, i.e. less cosmogenic neutrinos and diffuse gamma-ray photons, heavier composition



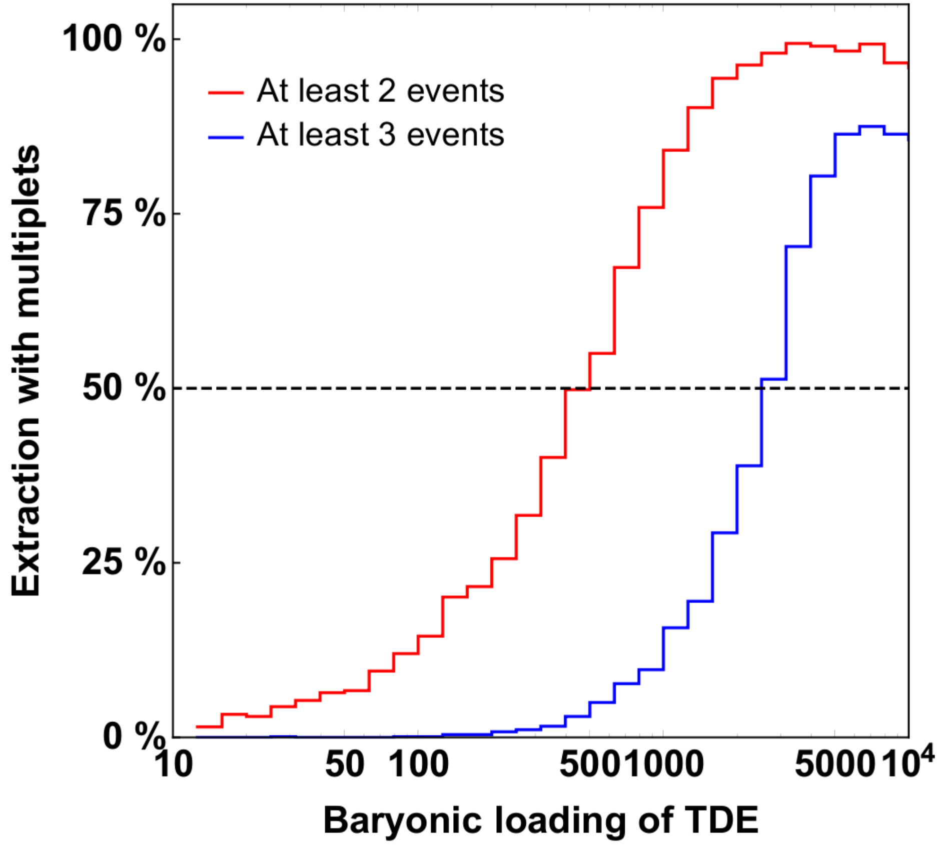
[C. Lunardini, W. Winter, PRD 95, 123001 (2017)]

Neutrino multiplets from jetted TDEs

Multiplet constraints in the context of our model

Our results are consistent with current observations

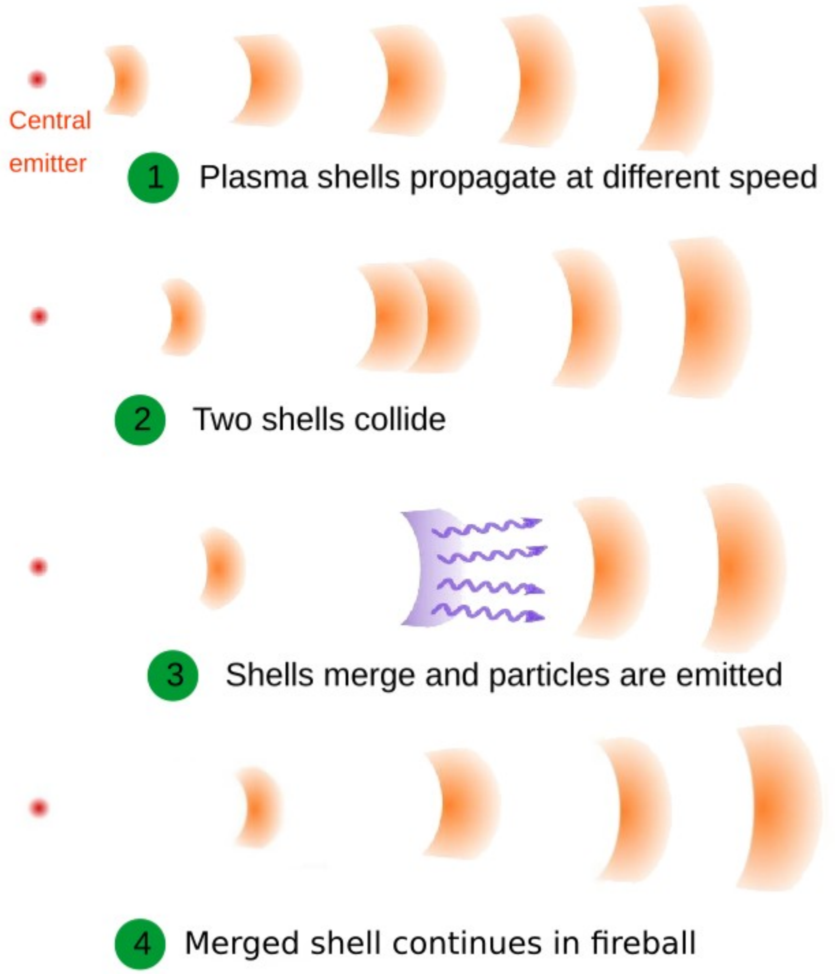
- Neutrino multiplets can test this model, as the baryonic loading and the rate both cannot be too high
- Main difference: we describe only PeV data, where statistics are low (~ 3 events), spectral shape different
- Best fit yields G ~ 540, varying the baryonic loading and randomly drawing from a set of sources corresponding to the resulting rate gives a probability < 50%

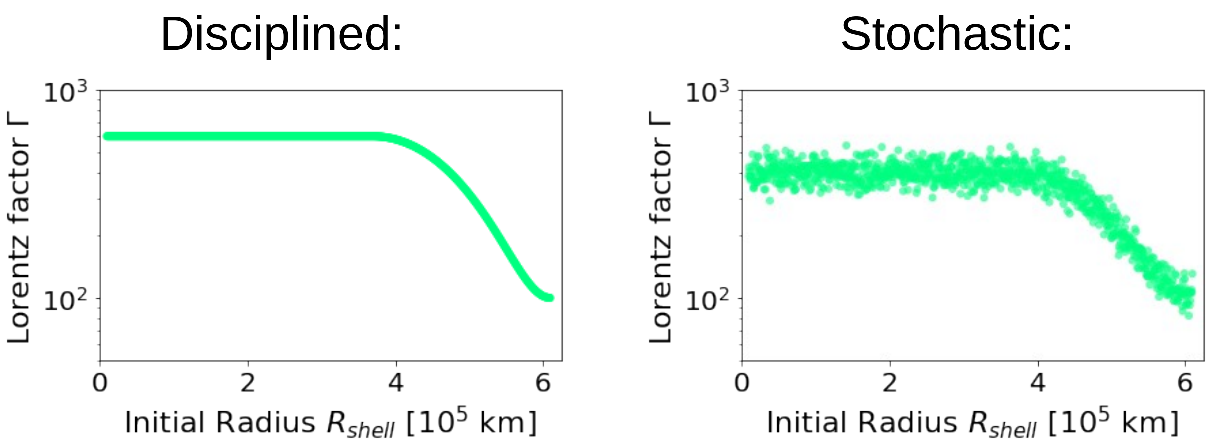


[A. Palladino, W. Winter, Astron.Astrophys. 615 (2018) A168]

Multi-zone models

Multiplet constraints in the context of our model





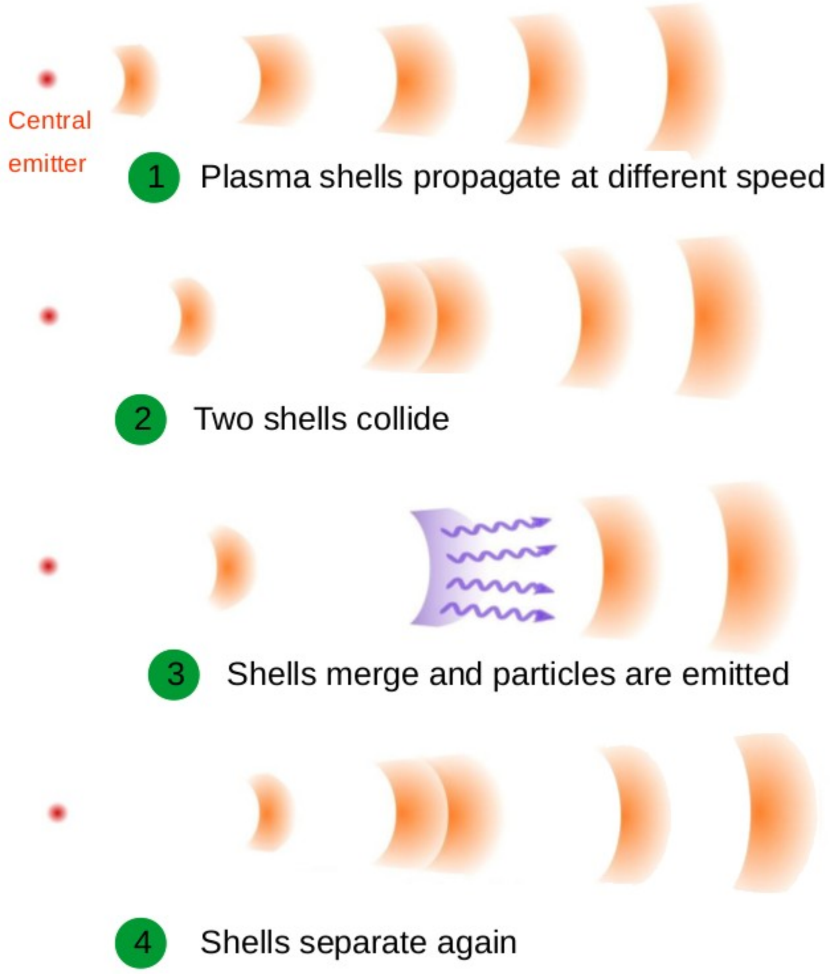
Results depend on the engine behaviour

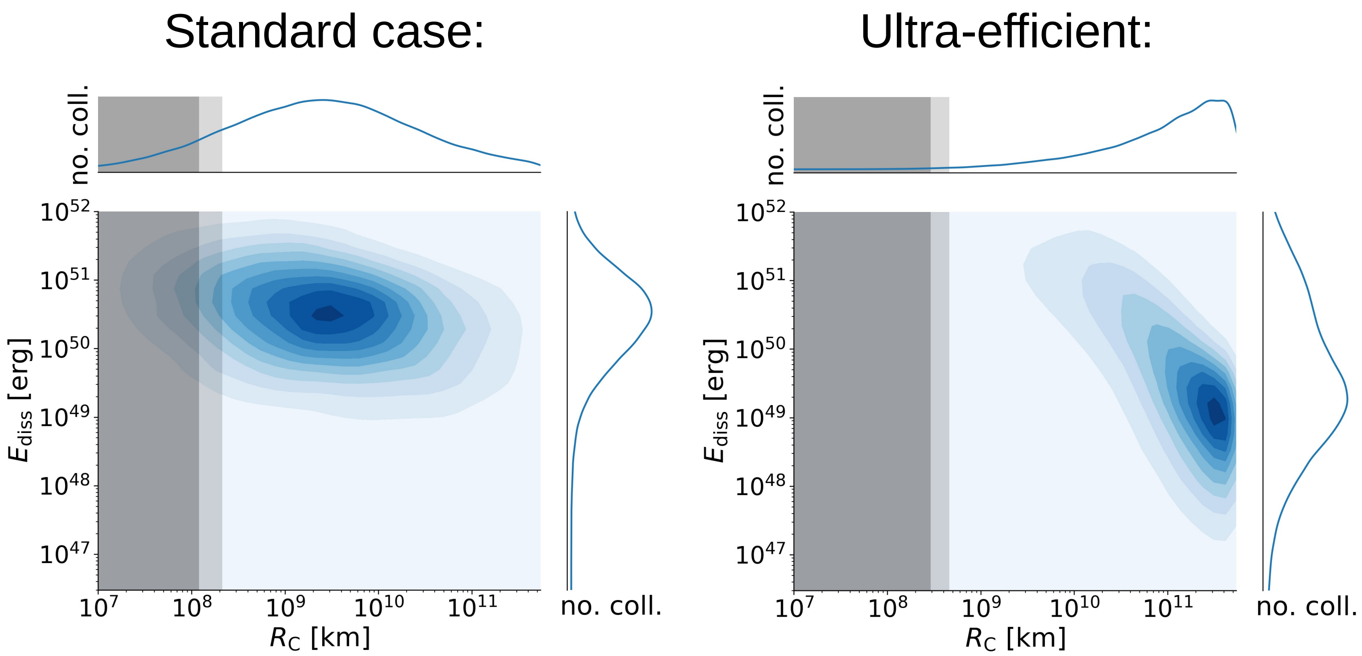
- Engine behavior is characterized by initial Lorentz factor distribution, e.g.
  - Shape of the distribution
  - Disciplined vs. stochastic
  - Separation between shells
  - Average Lorentz factor
- Resulting distribution of collision radii should match the required maximum energy, optical thickness, ...

Impact of the collision model

Ultra-efficient shocks as an example

[A. Rudolph, J. Heinze, A. Fedynitch, W. Winter – to be submitted]





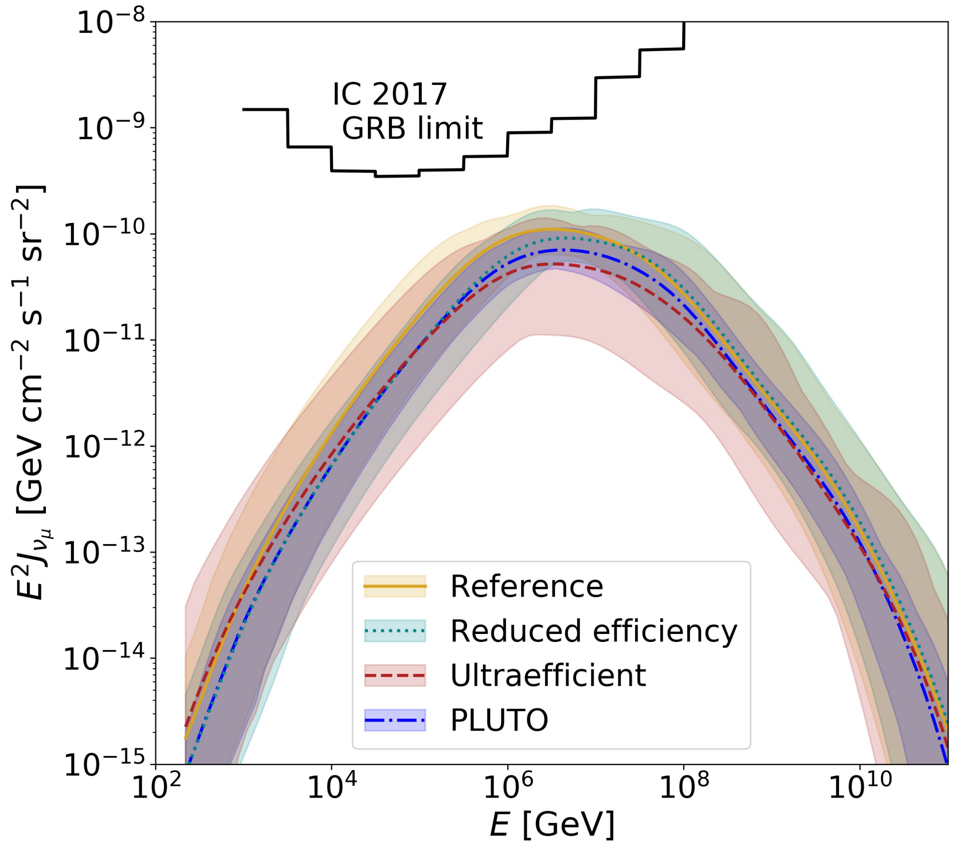
- Distribution of collisions shifts to higher radii as there are more shells available to collide further outside
- For high radii, the relative Lorentz factors will be small due to preceding collisions
- The dissipated energy is still dominated by intermediate collision radii, i.e., comparable neutrino fluxes are expected

Neutrino fluxes for different collision dynamics

In the multi-zone model for GRBs

Similar predictions for different dynamics

- Neutrino fluxes do not change considerably, i.e., neutrino limits will test the GRB-UHECR paradigm regardless of the collision dynamics
- PLUTO simulations suggest that the ultra-efficient shock scenario requires very specific collision parameters
→ occurs only in ~ 10% of all collisions
- The standard assumption of inelastic shell collisions seems to yield reliable results
- Other model components, as e.g. the escape mechanism, may have a much larger influence on the results



[A. Rudolph, J. Heinze, A. Fedynitch, W. Winter – to be submitted]

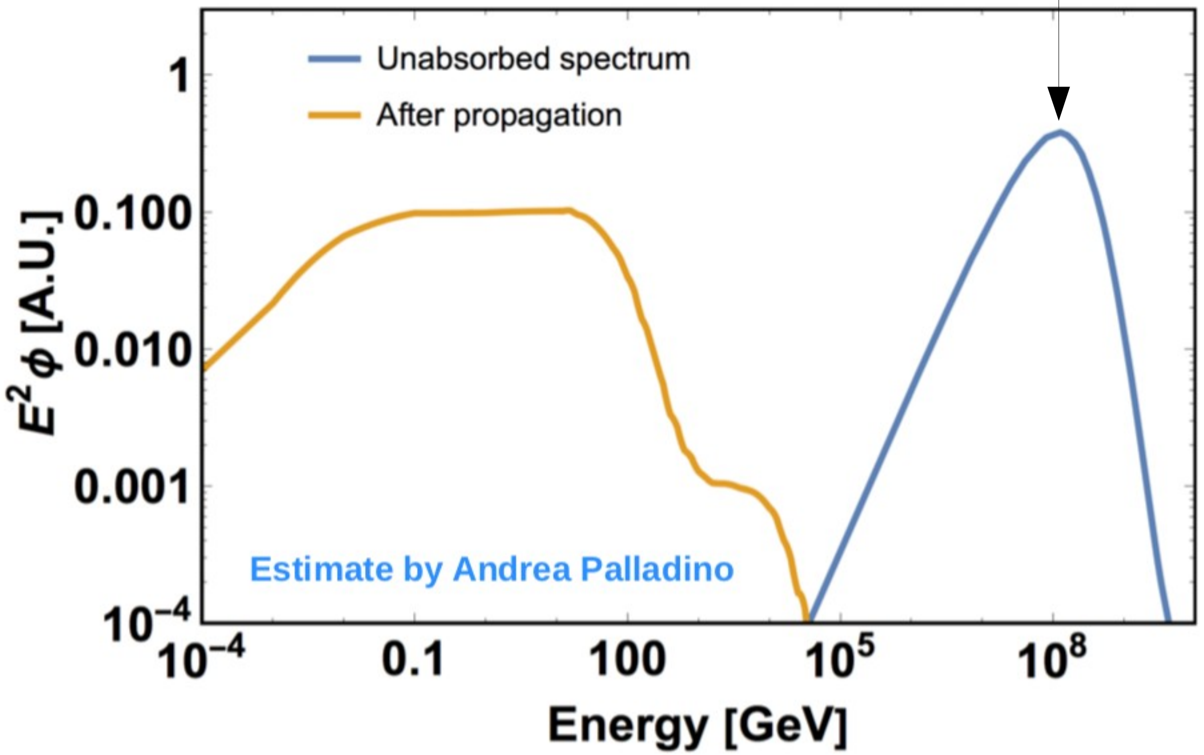
High-energy gamma rays: a simple estimate

Contribution to diffuse flux

Importance from a theory perspective

- Observation of LLGRBs in gamma-rays essential to test the model and constrain parameter space
- (Unabsorbed) gamma-ray spectrum from neutral pion decay from hadronic interactions, i.e. proportional to the efficiency of interactions, no leptonic contribution!
- Source evolution needed for absolute normalization → work in progress
- Diffuse flux vs. flux from single event to compare to sensitivity, time delay → work in progress

High-energy gamma-rays from π^0 decay

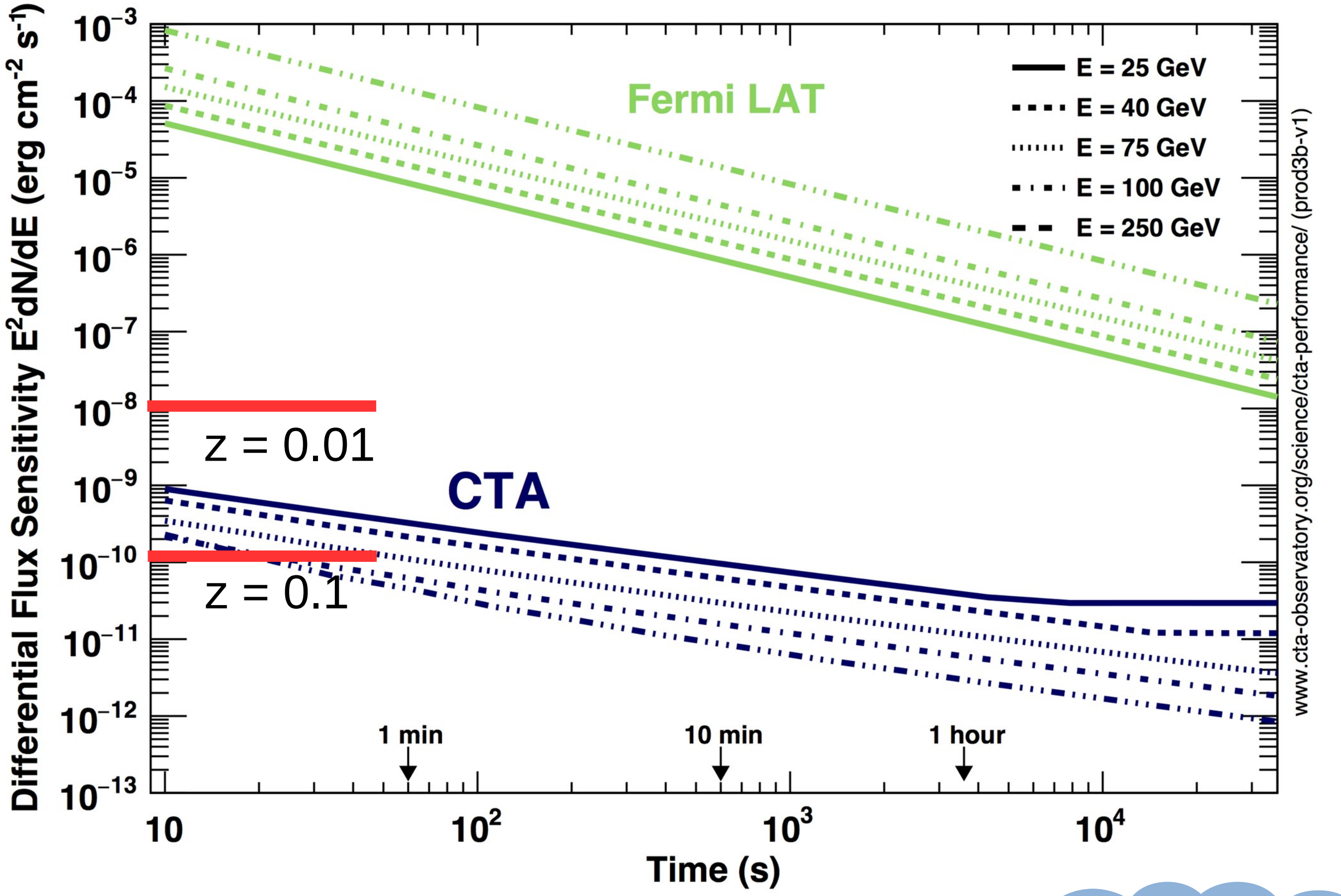


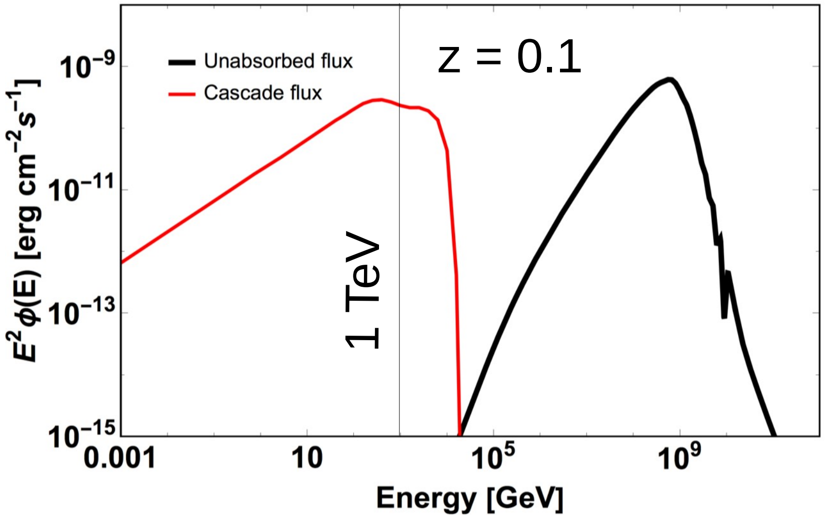
[based on the model in D. Boncioli, **DB**, W. Winter – arXiv:1808.07481]

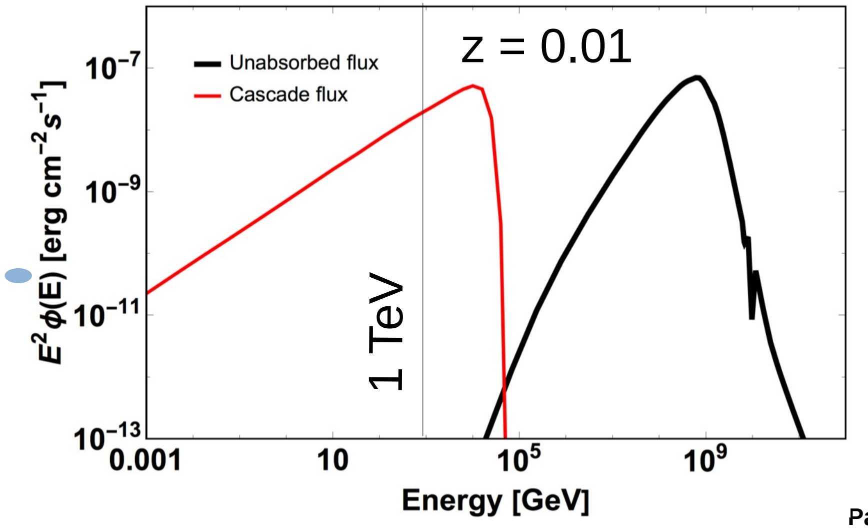
High-energy gamma rays: a simple estimate

Prompt emission from a single source

Propagation by Andrea Palladino, based on the model in [D. Boncioli, **DB**, W. Winter – arXiv:1808.07481]







Time delay?

W O R K I N P R O G R E S S

High-energy gamma rays: a simple estimate

Light curves from multiple internal shocks

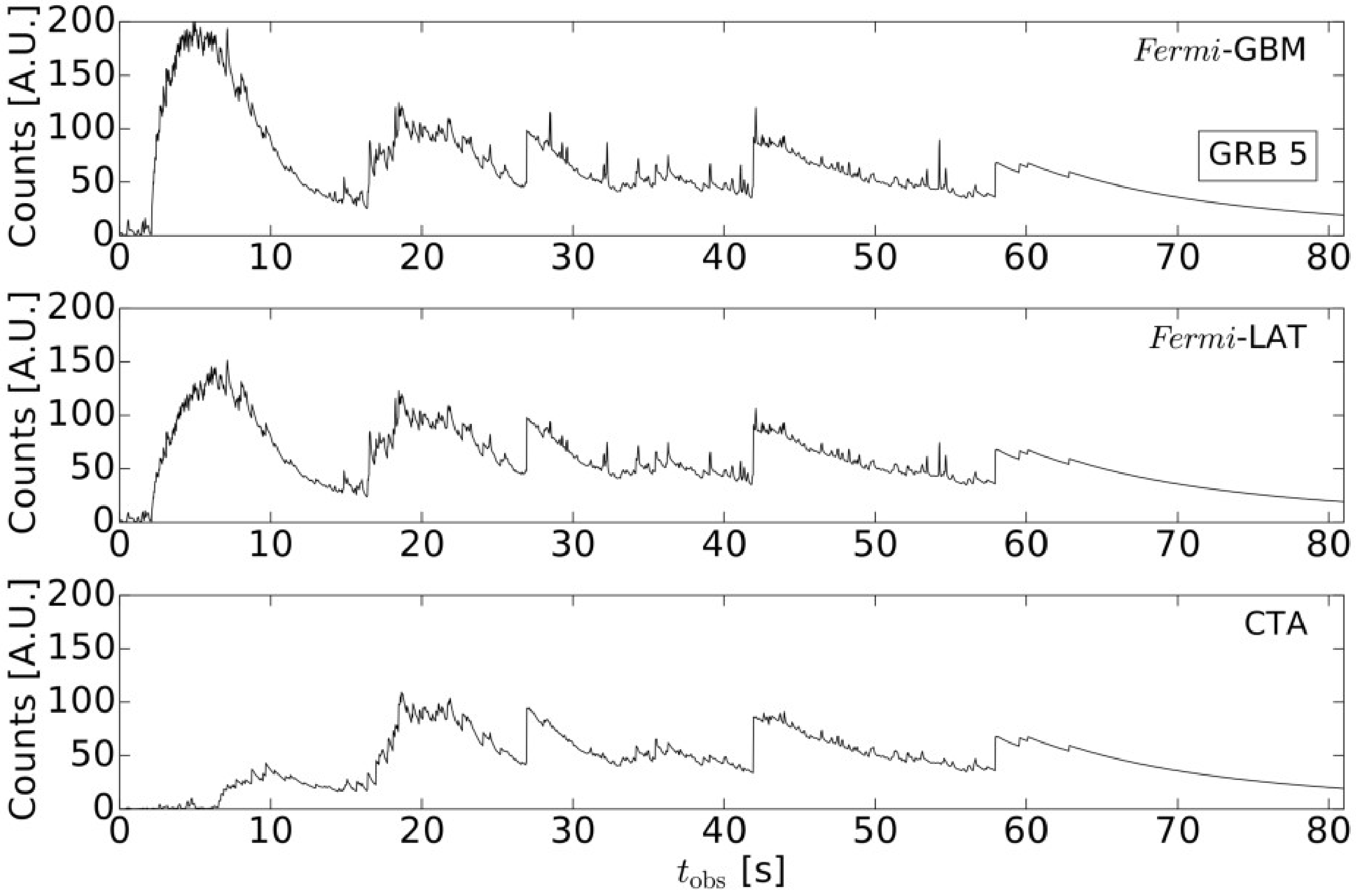
A possible future application

- By allowing for multiple shocks, i.e. varying collision radii and parameters, light curves can be predicted

- Features in the light curve represent behavior of the engine

- LLGRBs have a more smooth light curve → disciplined engine?

- Light curves can serve as a first hint on the neutrino production efficiency



[M. Bustamante, J. Heinze, K. Murase, W. Winter, ApJ (2017)]

[**DB**, J. Heinze, A. Fedynitch, W. Winter – in preparation]