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

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)

[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

\[ R \approx 2\Gamma^2 c t_v \]

- Black hole engine
- \( L_{\gamma} \sim 10^{49} - 10^{53} \) erg/s
- \( \Gamma \sim 100 - 1000 \)
- Prompt emission
- \( R \sim 10^{12} - 10^{15} \) cm

Jet collides with ambient medium (external shock wave)

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

Increasing luminosity (Γ, R const.)

Photo-disintegration in (conventional) GRBs
Reproducing the ankle with cosmic ray interactions

- 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!

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 $\sim 10^5$ → challenging...

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

LLGRBs as sources of UHECRs across the ankle

Model ingredients and assumptions

LLGRBs as a distinct population

- Low luminosity $\sim 10^{46} - 10^{49}$ erg/s, durations up to $10^3 - 10^4$ s and beyond
- Intermediate / heavy injection composition: 60% O, 40% Si

$$m \times H_{\text{SFR}}(z) \text{ with } 0 < m < 1$$

- Low energy component:
  - $A = 28$
  - $\alpha = 4.2$
  - 78% fraction of the flux at $10^{17.5}$ eV

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

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

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

Cosmogenic neutrinos expected with future instruments

Heavy galactic plus light extragalactic below the ankle

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!

Conclusion

GRBs as sources of UHECRs across the ankle

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]
LLGRBs as a distinct population

LLGRB population model

Model parameters:

\[ \alpha_1^{HL} = 0.65, \alpha_2^{HL} = 2.3, L_0^{HL} = 2.25 \times 10^{52} \text{ erg s}^{-1} \]
\[ \rho_0^{HL} = 1.2 \text{ Gpc}^{-3} \text{ yr}^{-1} \]

\[ \alpha_1^{LL} = 0.00, \alpha_2^{LL} = 3.0, L_0^{LL} = 1 \times 10^{47} \text{ erg s}^{-1} \]
\[ \rho_0^{LL} = 364 \text{ Gpc}^{-3} \text{ yr}^{-1} \]

Low-luminosity Gamma-Ray Bursts (LLGRBs)

Parameter space scan of UHECR fit

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 $\xi_A \sim 10$

UHECR fit for conventional GRBs

Parameter space scan

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

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

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!

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)]
Main ingredients of our simulation
Parameters, assumptions, composition

Details on the model

- Internal shock scenario connecting radius and time variability by $R \sim 2\Gamma^2ct$
- Static broken power law target photon field assumed
- Efficient Fermi shock acceleration of nuclei, injection follows spectral index $\sim 2$ 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)]

**Population model in a nutshell**

**Cosmological rate of TDEs**

\[
\dot{\rho}(z, M) = \dot{N}_{TD}(M) f_{occ}(M) \phi(z, M)
\]

- Rate of disruptions per black hole
- Occupation fraction
- Black hole mass function

**Negative source evolution**

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

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 $G \sim 540$, varying the baryonic loading and randomly drawing from a set of sources corresponding to the resulting rate gives a probability < 50%

Multi-zone models
Multipllet constraints in the context of our model

1. Plasma shells propagate at different speed
2. Two shells collide
3. Shells merge and particles are emitted
4. Merged shell continues in fireball

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, ...

[Disciplined: \[10^3\] vs. \[10^2\] \( R_{\text{shell}} [10^5 \text{ km}] \)]

[Stochastic: \[10^3\] \( R_{\text{shell}} [10^5 \text{ km}] \)]
Impact of the collision model

Ultra-efficient shocks as an example

- 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.

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

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: a simple estimate

Prompt emission from a single source

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

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