UHECR science with ground-based imaging atmospheric Cherenkov telescopes

- **Direct measurements with IACTs:**
  - **VERITAS CR electron spectrum.**
  - **VERITAS CR iron spectrum.**
- **Indirect measurements:**
  - **Low-luminosity GRBs as potential sources of UHECRs.**

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October 2018

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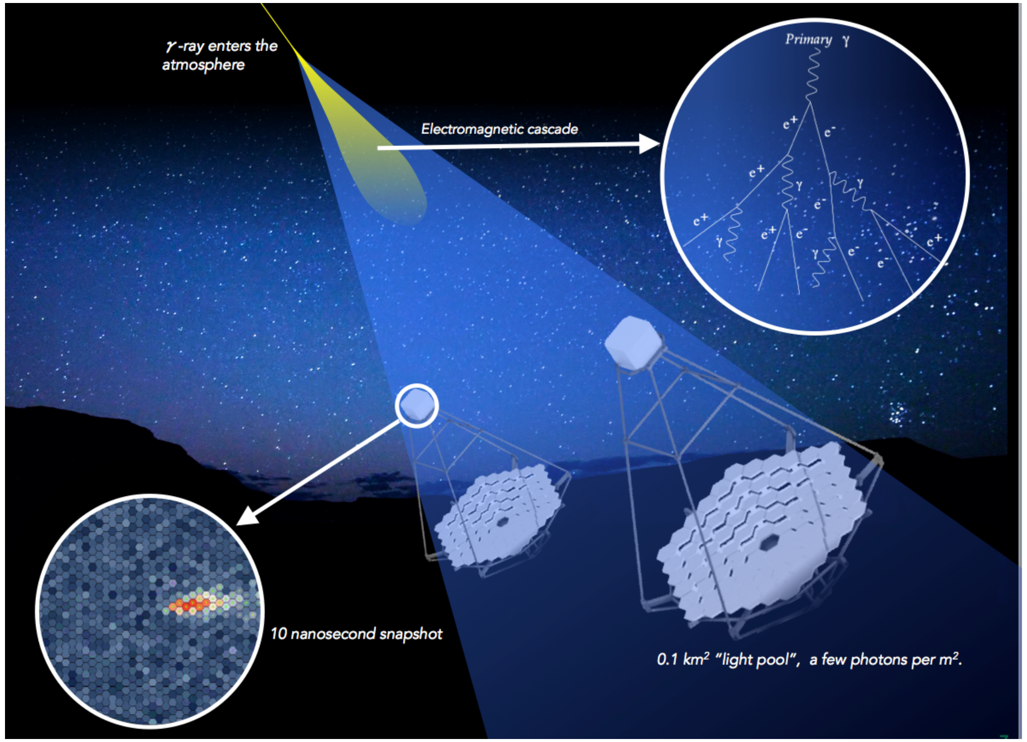
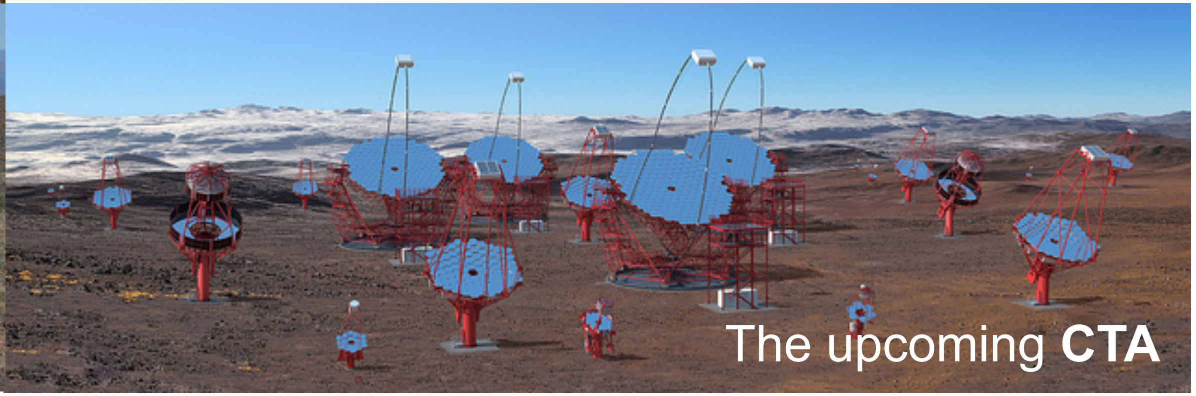
Imaging Atmospheric Cherenkov Telescopes (IACTs)

- Detecting the Cherenkov light of air showers with ground-based IACTs.

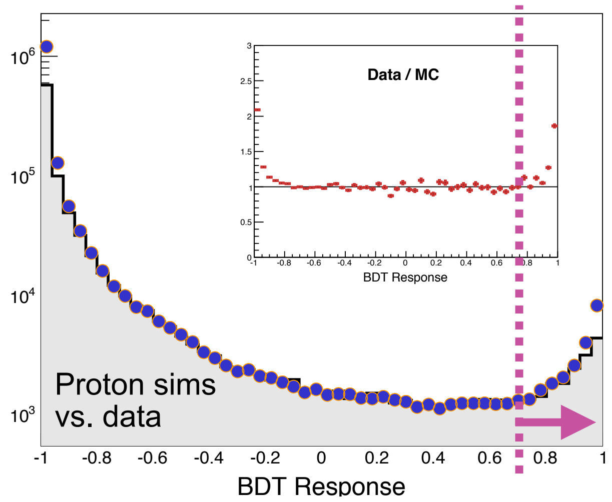


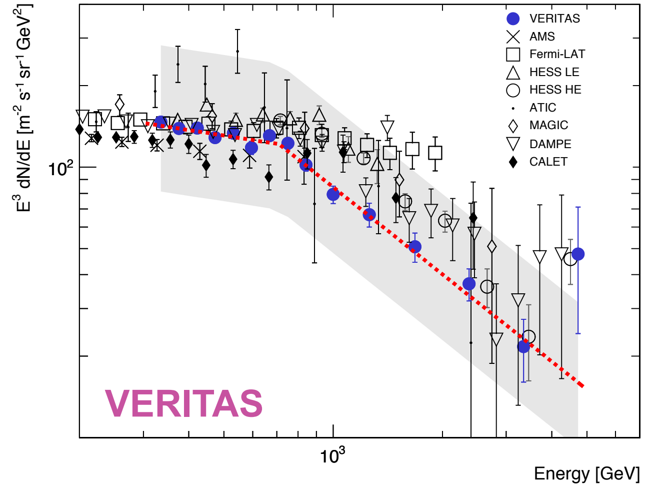


Direct measurements of VHE CRs with IACTs

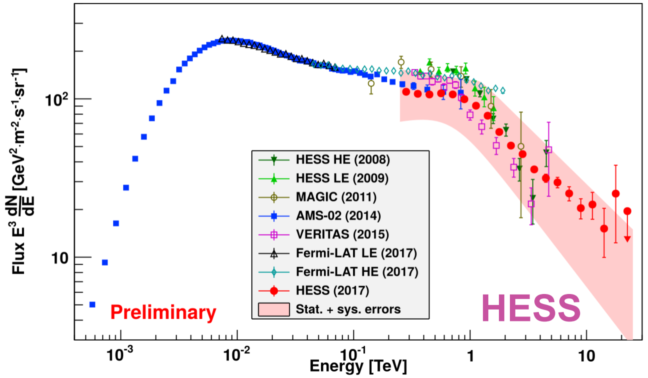
VERITAS electron spectrum

- Backgrounds to IACT analyses:
  - γ-rays and e± showers can not be distinguished on an event-by-event basis:
    - Known γ-ray sources - masked.
    - Extra-galactic diffuse γ-ray background (Γ~2.3 PL; 250 GeV exponential cutoff) ➜ excluded.
  - Hadronic CRs:
    - Some hadron showers mimic EM showers (classification uncertainties) ➜ BDT response.
- 2018 VERITAS analysis:
  - 296 hours (post-T1 move, pre-camera upgrade) of data at 0.3-5 TeV.
  - Proton simulations ➜ low BDT score excess due to Helium and higher-Z elements. • High BDT score excess due to electrons.
  - Results: Binned likelihood fit for [BDT > 0.7]: Broken PL with a break at 710 ± 40(stat) ± 140(sys) GeV. • Index transition at the break, Γ = (3.2 ➜ 4.1) ± 0.1. • Best fit for two PLs with a break, but a single-PL + exponential cutoff is still allowed.
- Interpretation: TeV break connected to the distribution of sources (possibly Geminga, Monogem etc.). • Lack of features (TeV bumps) excludes some nearby sources. • Cutoff hints at diffuse propagation. • More data needed (e.g., CTA) to effectively constrain the sources.





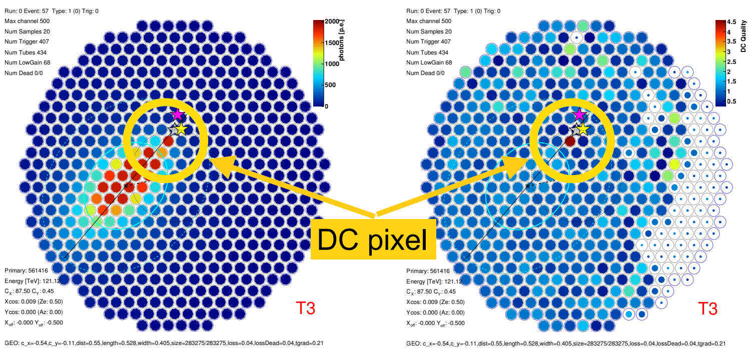
VERITAS col. (2018) arxiv:1808.10028

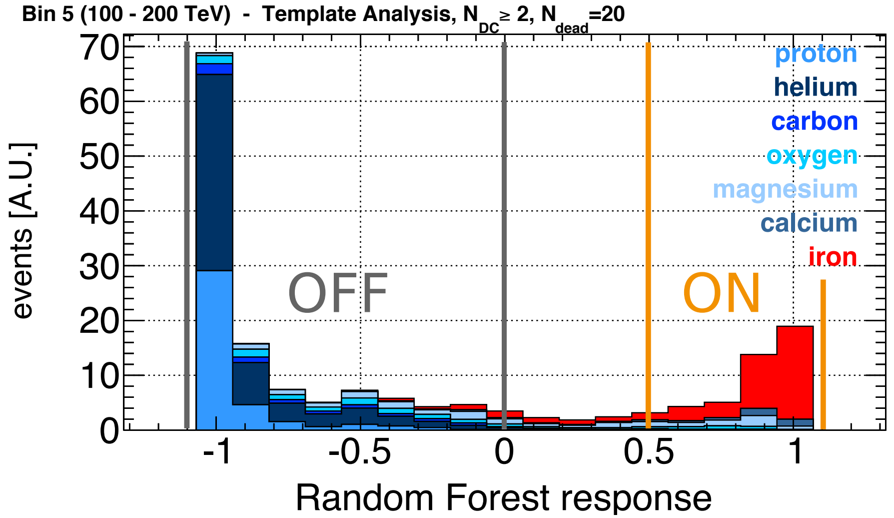


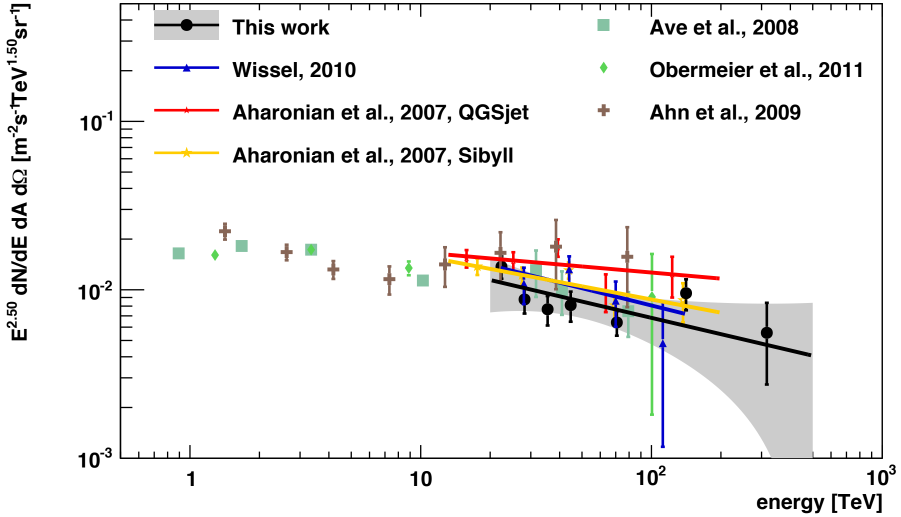
HESS col. (2017) HESS homepage

VERITAS iron spectrum

- Backgrounds to IACT analyses:
  - Known γ-ray sources.
  - Hadronic CRs from other elements.
- 2018 VERITAS analysis:
  - Direct Cherenkov (DC) light emitted by cosmic ray primaries in the atmosphere before the first interaction ➜ DC Intensity proportional to Z^2.
  - Image template fitting to select & reconstruct (energy; direction) DC images. • Strict quality cuts for a pure sample.
  - Random forests to estimate background from non-iron CRs.
  - Results: 71 hours (post-T1 move, pre-camera upgrade) of data at 20-500 TeV ➜ PL with index, $\Gamma = 2.82 \pm 0.3(\text{stat})\ [+0.24\ -0.27](\text{sys})$.







VERITAS col. (2017) arxiv:1807.08010

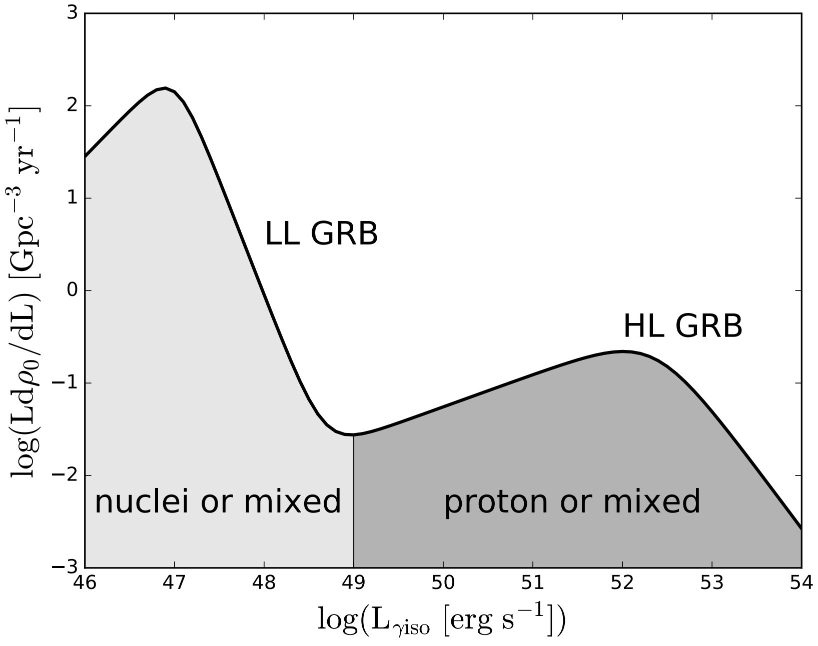
Indirect measurements -

Low-luminosity GRBs as potential sources of UHECRs

What are long low-luminosity GRBs?

- LL-GRBs are typically defined by isotropic-equivalent luminosities, **$10^{46} < L_{\gamma,iso} < 10^{48\text{-}50}$ erg s^{-1}** (several dex lower than “regular” HL-GRBs).
- LL-GRBs have energies, $10^{48} < E_{iso} < 10^{51}$ erg s^{-1}, some are SN of high energies, $E_{SN} \sim 10^{52}$ erg (hypernovae/broad-line SN Ic).
- Only a few ($\lesssim$ 20) LL-GRBs detected so far, due to experimental limitations (e.g., peak energies, E_p, nominally too low for Swift/GBM). • Discoveries keep coming in, see **today’s arXiv**, D’Elia et al (2018) arxiv:1810.03339 .
- A small number (~3) are famously ultra-long, but usually they have durations akin to long HL-GRBs ($T_{90} < 100$ s).
- LL-GRBs are generally assumed to be similar to HL-GRBs, **but could have** unusual properties, e.g., different combinations of:
  - Lower Lorentz factors (5-100). • Lower E_p values. • Choked jets. • High baryon fractions. • Wide opening angles. • Low radiation-conversion efficiencies. • …

Zhang et al (2017) arxiv:1712.09984



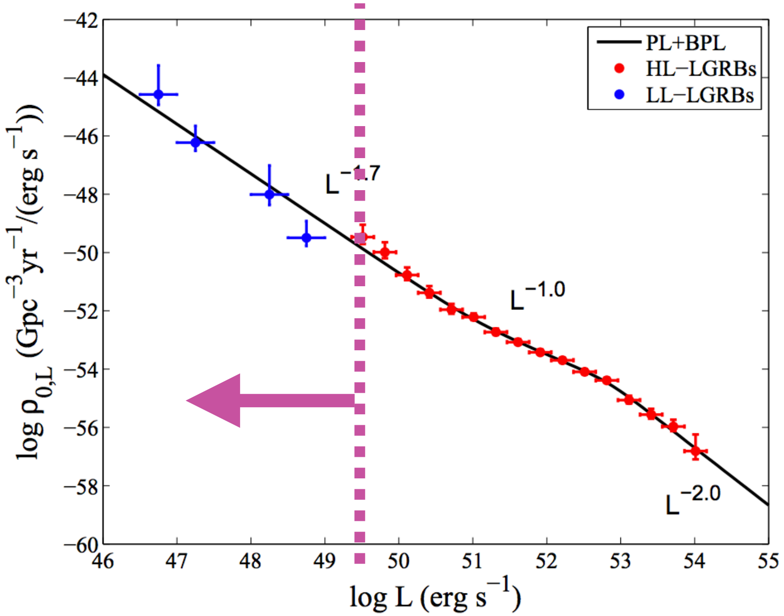
- LL-GRBs could advance SN science; help explain UHECRs & the diffuse IceCube astrophysical HE neutrinos flux.
- Anecdotally, off-axis/structured jets (short/long) GRBs & kilonovae may be observed as LL, e.g., GW170817 (40 Mpc; $L_{iso} \sim 10^{47}$ erg s^{-1}) ➜ same search methodologies…

The luminosity function of LL-GRBs

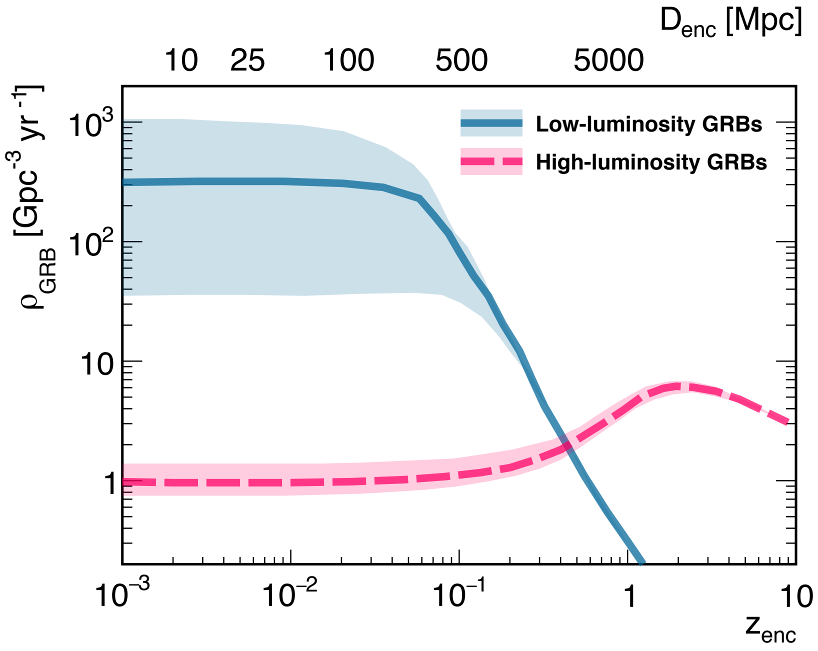
- Their density in the local universe (z < 1) is expected to be much higher (**x100**) than for HL-GRBs.
- Usually (Liang et al (2007)) a double broken PL luminosity function (LF) describes the local event rate density, $\rho_{0,L}$, using a "break luminosity" (L_b ~ **5×10^{49}** erg s^{-1}):

$$\rho_{0,L} \equiv \frac{d\rho_0}{dL} \propto \rho_0 \left[\left(\frac{L}{L_b}\right)^{\omega\alpha_1} + \left(\frac{L}{L_b}\right)^{\omega\alpha_2} \right]^{-1/\omega}$$

- A triple LF by Sun connects LL- & HL-GRBs smoothly from L_{iso} ~ 10^{51} erg s^{-1}.



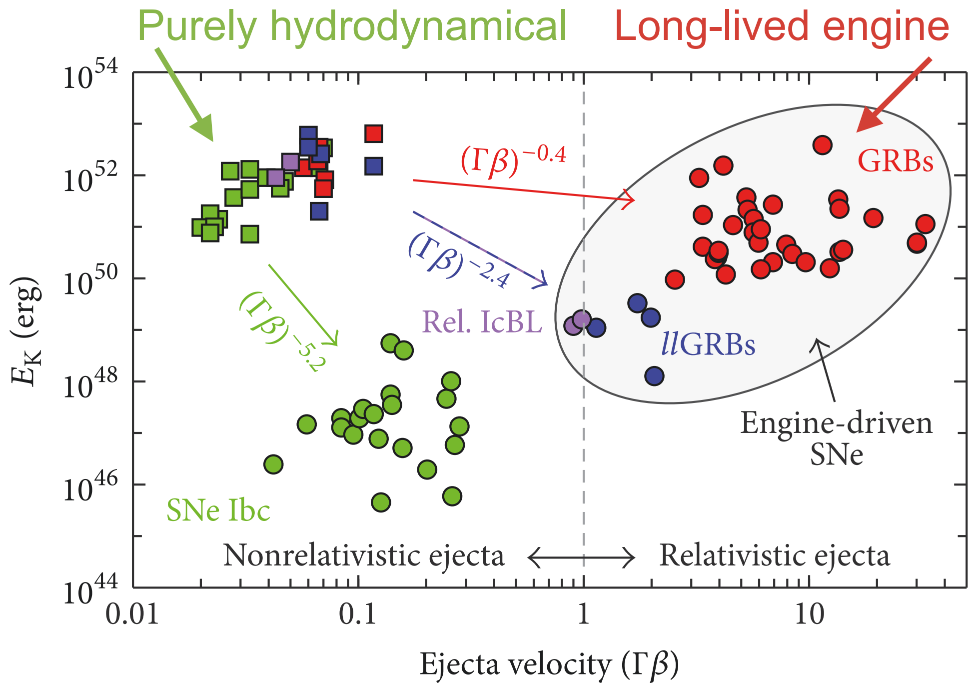
Sun et al (2015) arxiv:1509.01592



Liang et al (2007) arxiv:0605200

Possible source models - Collapsar model / SN connection

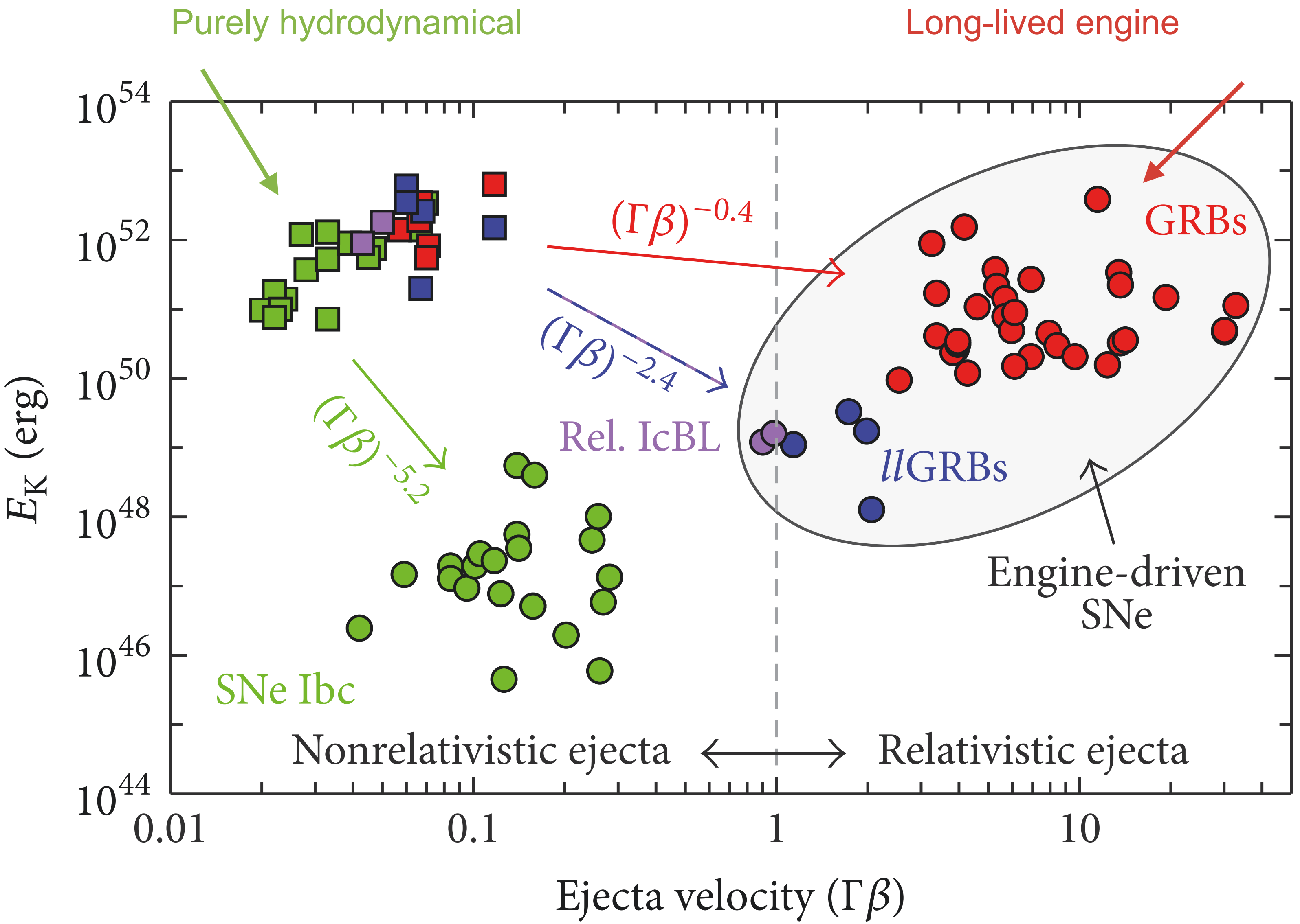
- Likely… type Ic core-collapse supernovae; massive; low metallicity; WR stars (compact envelopes impede jets less).
- These are "hypernovae", ~1% of SN Ic, broad-line relativistic SN, that lack H, He in their spectra ➜ two component types:
  - Relativistic comp. ($\Gamma \lesssim 100$, $v \sim 10^4$ km s^{-1}) for the GRB.
  - Slow ejecta for the SN.
- The prompt spectrum may be compatible with:
  - A standard non-thermal synchrotron emission (collision of fast-moving shells within the jet)
  - (Sometimes) a thermal component - shock breakout (SBO)?.
- The central engine of the GRB may be triggering the SN (Barnes et al (2017) arxiv:1708.02630). • Possibly all SN Ic-BL have jets; some we don't detect due to low-energy (De Colle et al (2018) arxiv:1803.00602), e.g., a possible failed jet/SBO in SN 2008D.



Margutti et al (2014) arxiv:1402.6344
Cano et al (2016) arxiv:1604.03549

Possible source models - Collapsar model / SN connection

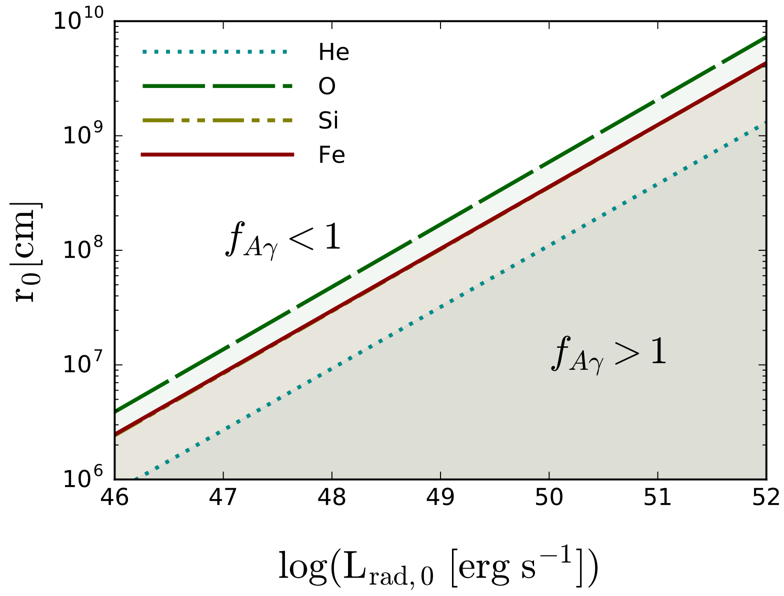
- "**Rel. IcBL**": events with the features of a GRB (in radio and optical), but no prompt stage.
- LL to HL-GRBs have increasingly more relativistic ejecta ➜ Indicates a continuum of SN Ic where the jet fails or succeeds in breaking out.
- May be due to engine duration/ strength or to progenitor prop. (high metallicity; Helium-rich).



Margutti et al (2014) arxiv:1402.6344 ; Cano et al (2016) arxiv:1604.03549

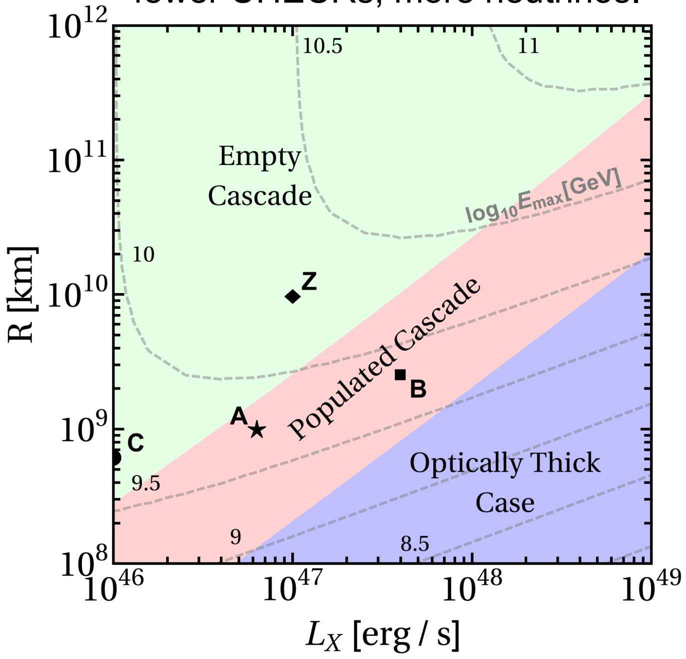
LL-GRBs as sources of UHECRs & neutrinos

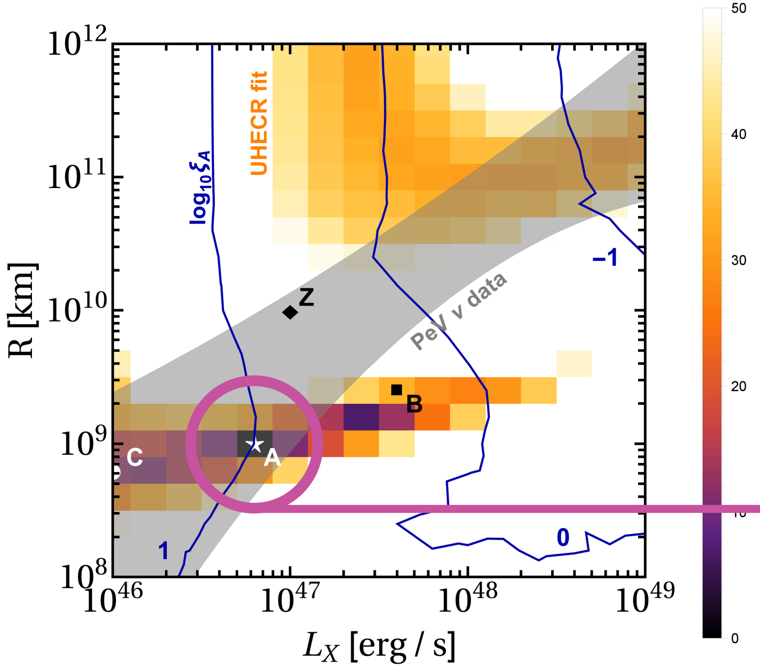
- If UHECRs are produced in GRBs, these are likely LL-GRBs!
- Source material can be rich in heavy nuclei.
- LL-GRBs are energetic enough to accelerate nuclei to UHE (10^{20} eV).
- Source env. is optimal for nuclei to survive (not too dense).
- Just enough LL-GRBs expected within ~100 Mpc to satisfy the obs. UHECR spectrum (much higher or much lower rates disfavoured).

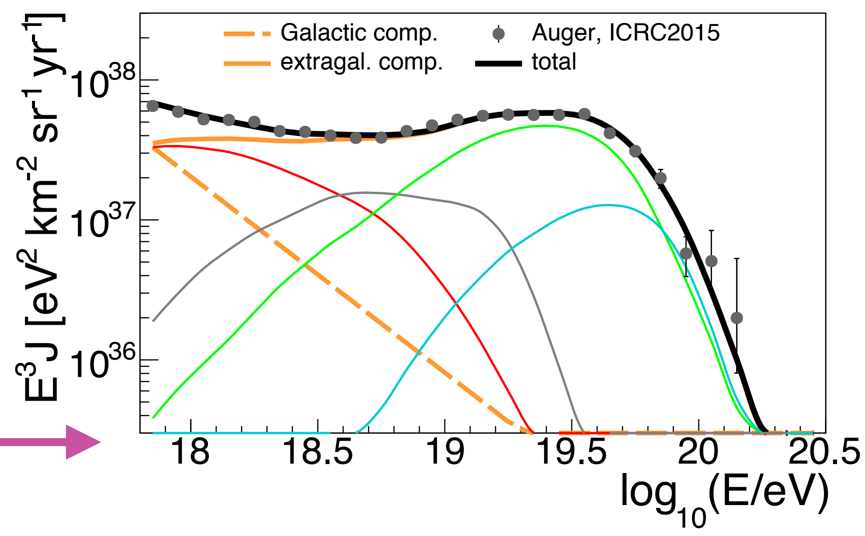


Zhang et al (2017) arxiv:1712.09984

Darker shade ➜ more photo-disintegration; fewer UHECRs; more neutrinos.





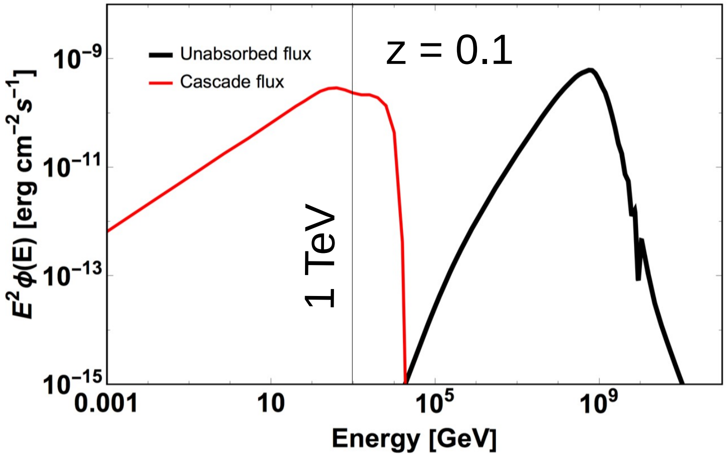


Boncioli et al (2018) arxiv:1808.07481

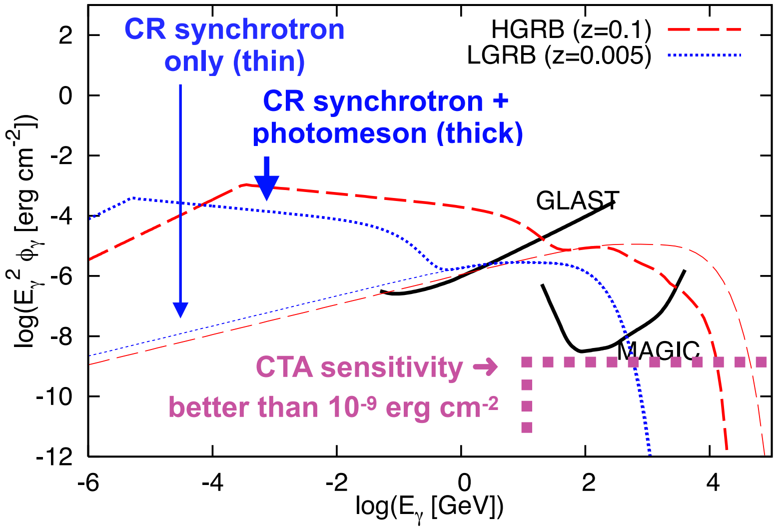
Expected VHE γ-ray signal from LL-GRBs

- $f_{A\gamma}$: Lower optical depth for γ-rays ➜ higher chance of γs escaping the source for larger radii / lower luminosities. • For large $f_{A\gamma}$, we can also expect proton-induced cascaded γ-ray signals.
- γ-ray production mechanisms:
  - Leptonic: synchrotron, & synchrotron Self-Compton (SSC) of e± • SSC enhanced for low E_p ➜ detectable >GeV energies.
  - Hadronic: UHECRs ➜ Proton Synchrotron; γs from neutral/charged pions, muons and e± pairs generated via photomeson production, E_γ > 10 PeV, cascaded down by the EBL to detectable GeV-TeV energies.

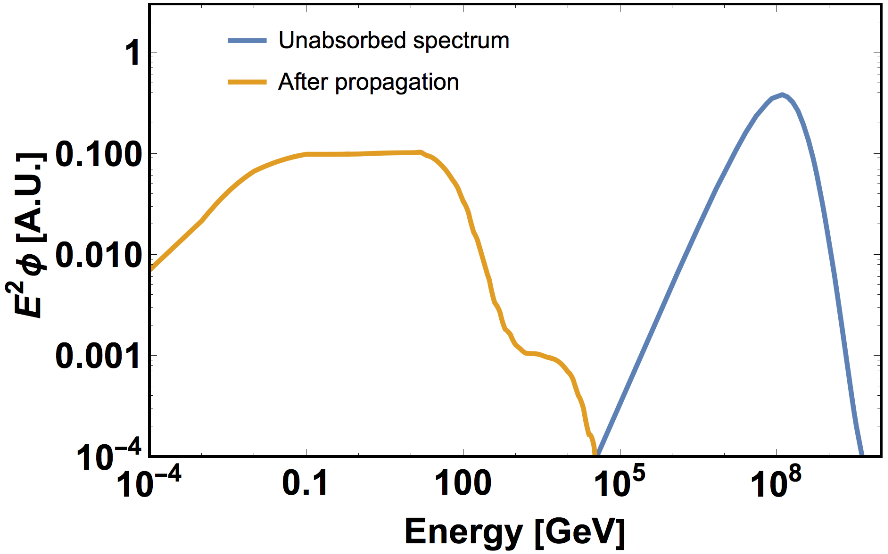
(Preliminary attempt at…)
Prompt γ-rays from a single LL-GRB

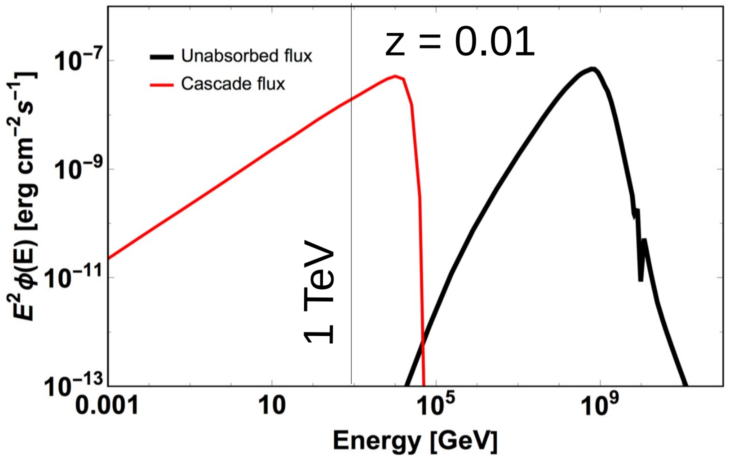


γ-rays from a single H/LL-GRB



(Preliminary attempt at…) **Diffuse** γ-rays from all LL-GRBs



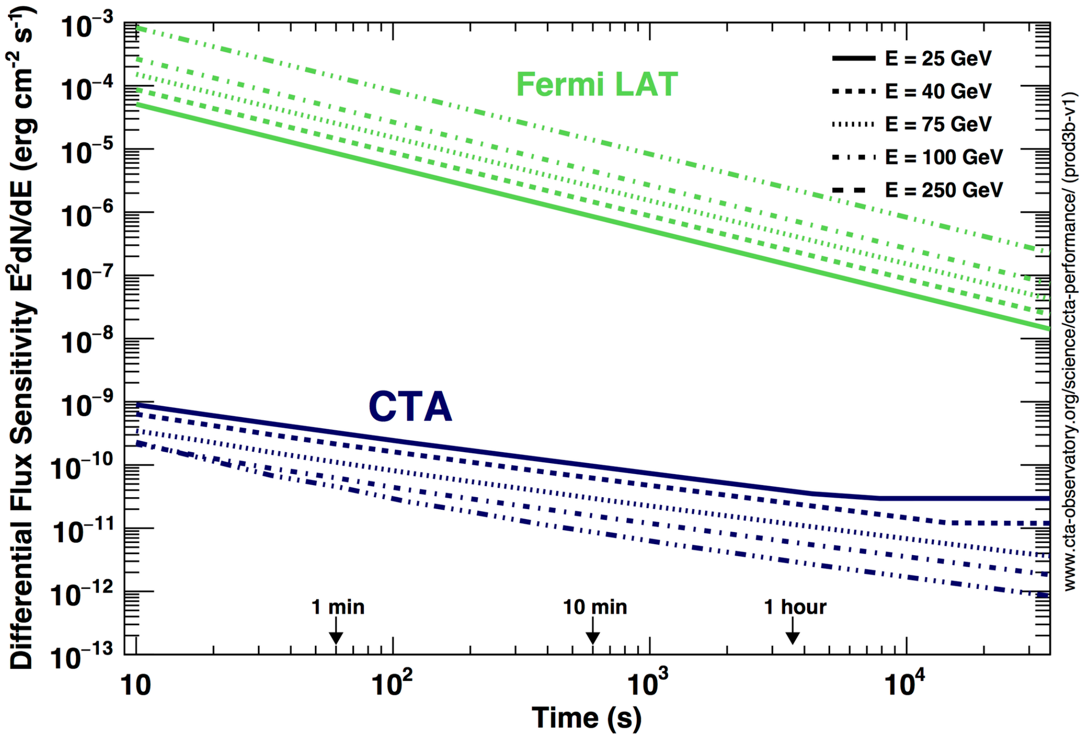


Murase et al (2008) arxiv:0801.2861: $E_{iso} = 10^{50}$ erg (e.g., $L_{iso} \sim 2\times10^{48}$ erg s^{-1} for z = 0.05; T_{90} = 50 s).

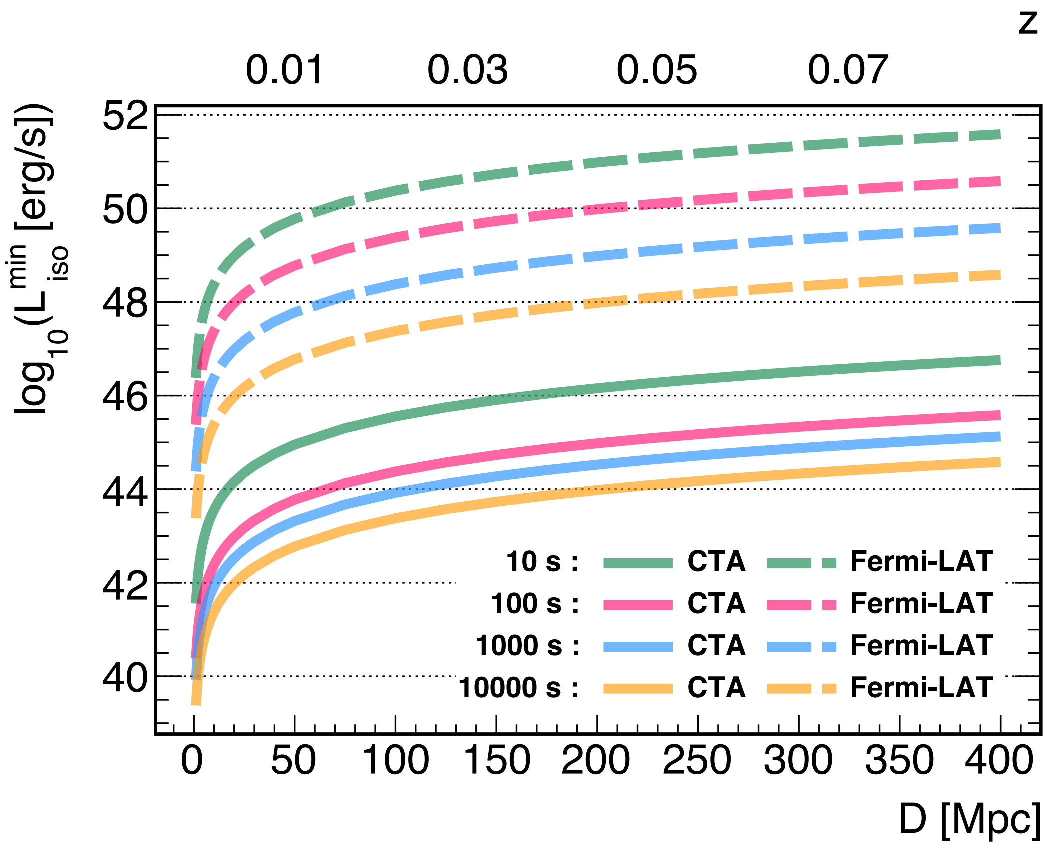
Estimate by A. Palladino, based on the results of Boncioli et al (2018) arxiv:1808.07481

The nominal CTA detection strategy for GRBs

1. Slew as quickly as possible following an external trigger.
2. Serendipitously detect extreme upward fluctuation in the FoV (only HL-GRB considered in the past).



- Sensitivity as a function of exposure time for different energies.



- Detectable-source luminosity vs. distance for different exposures (5σ for 40 GeV γ-rays).

LL-GRB detection prospects with CTA

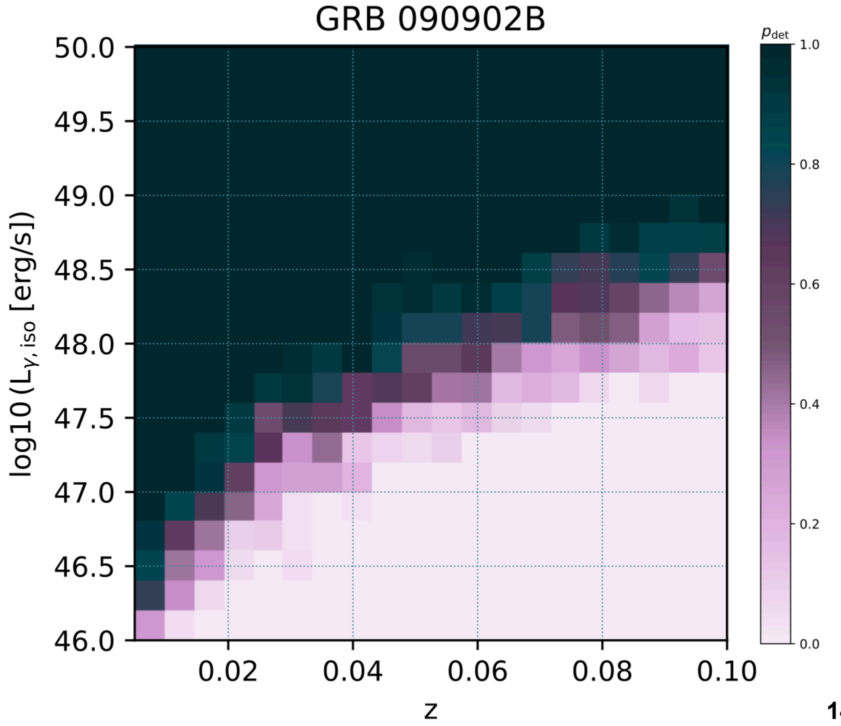
Preliminary

The objective: given LL-GRBs exist, would we see them? (no assumption on rates)

- **Detection strategy:**
  - Blind search - not dependent on external triggers (LL-GRBs are unlikely to have an external trigger).
  - Continuous searches within the current FoV.
  - Short integration windows (promising results for 0.5-1 sec time spans).
  - Optimise the search algorithm for the highest (post-trails) test-statistic, TS_{pt} (currently for 100 hours of observing, and a benchmark of $TS_{pt} > 25$).
- **Initial feasibility study:**
  - Scan the phase space ➜ which kinds of LL-GRBs can we detect (high confidence & low fake-rate)?
  - Defining a "detectability" metric:

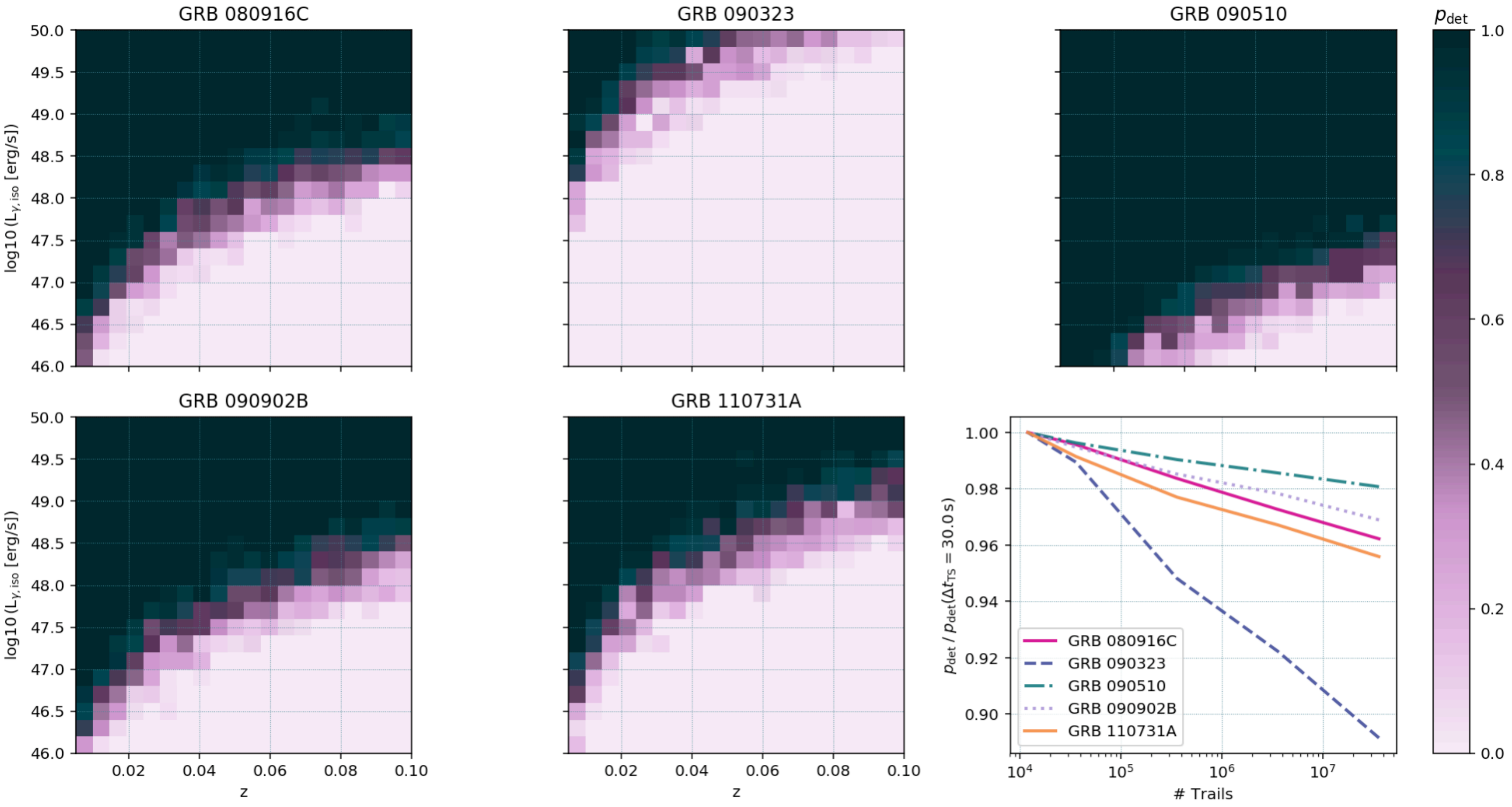
$$p_{\mathrm{det}} = \begin{cases} 0\,, & \mathrm{TS}_{\mathrm{pt}} < 25 \\ 1\,, & \mathrm{TS}_{\mathrm{pt}} \geq 25 \end{cases}$$

  - The plot shows p_{det}, averaged over many GRB sims; a proxy for the detection probability per {L_{iso} , z} bin.



LL-GRB detection prospects with CTA

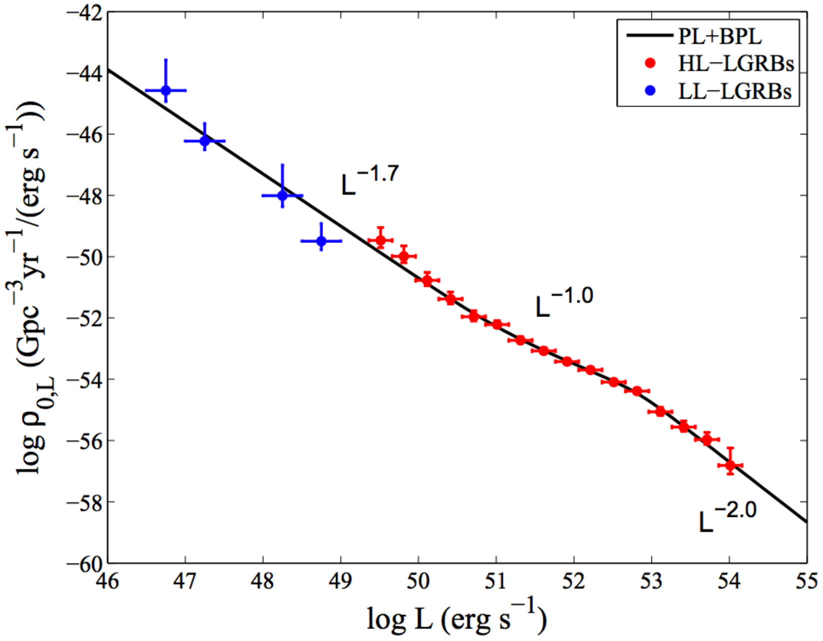
Preliminary

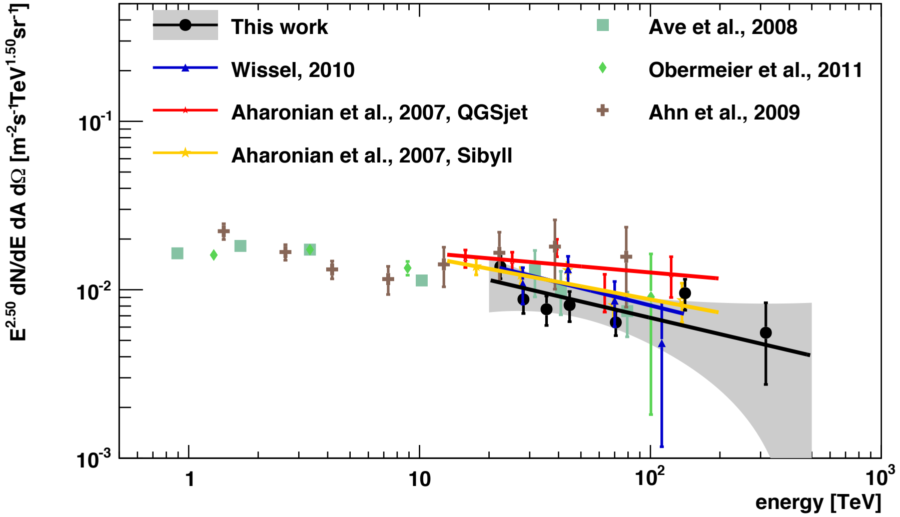


Closing remarks

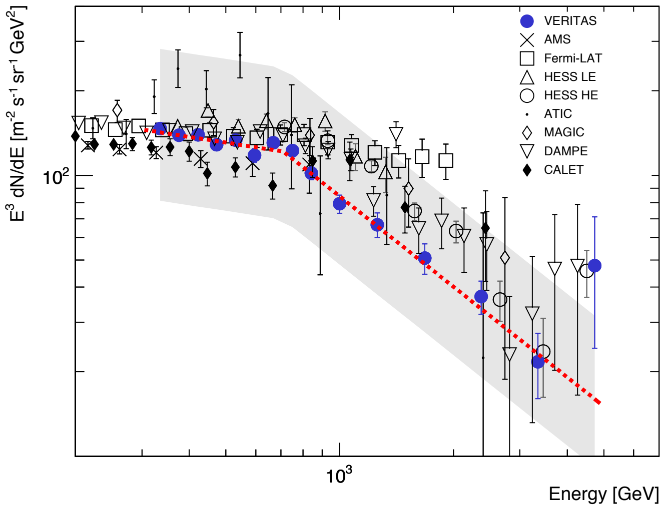
- HE-CR electrons and nuclei can be observed directly by IACTs; much improvement foreseen for the upcoming CTA.
- LL-GRBs are emerging as promising candidates for being sources of UHECRs and neutrinos. • Having potentially high rates, CTA could be used to constrain their source population.

Sun et al (2015) [arxiv:1509.01592](https://arxiv.org/abs/1509.01592)

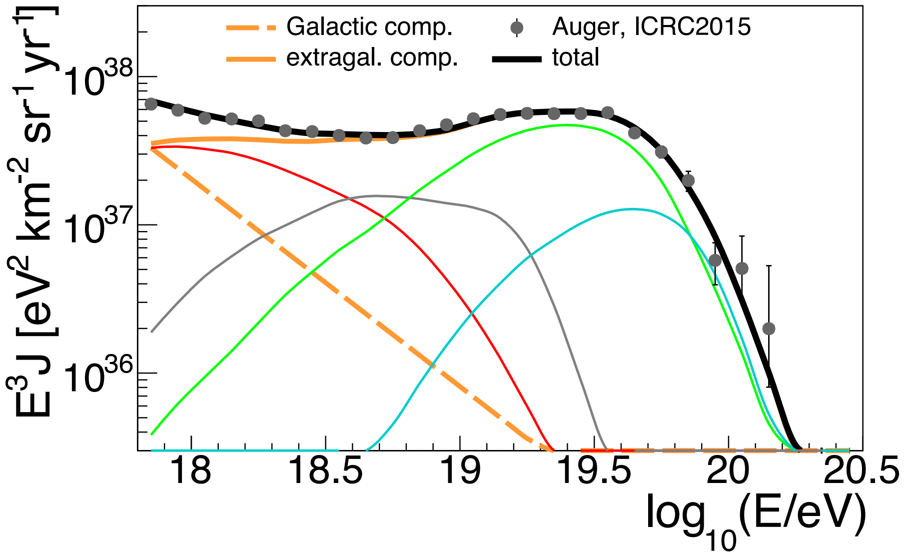




VERITAS col. (2017) [arxiv:1807.08010](https://arxiv.org/abs/1807.08010)



VERITAS col. (2018) [arxiv:1808.10028](https://arxiv.org/abs/1808.10028)



Boncioli et al (2018) [arxiv:1808.07481](https://arxiv.org/abs/1808.07481)

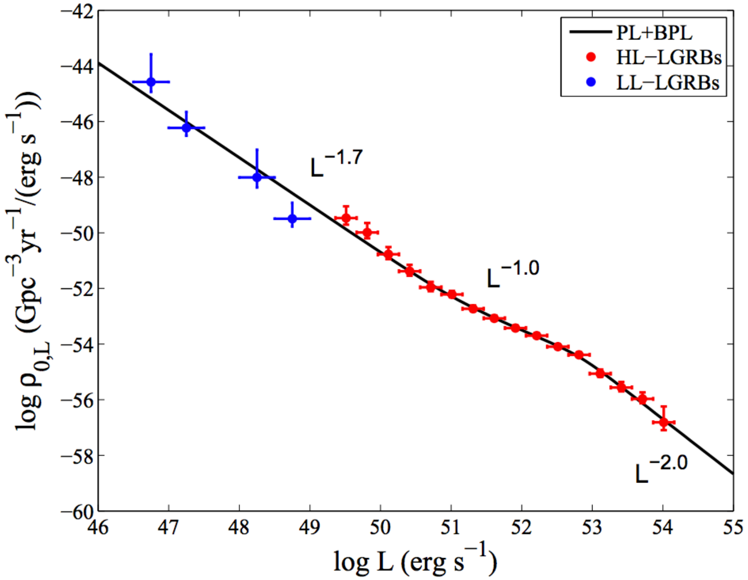
Additional material

Are LL-GRBs simply off-axis HL-GRBs?

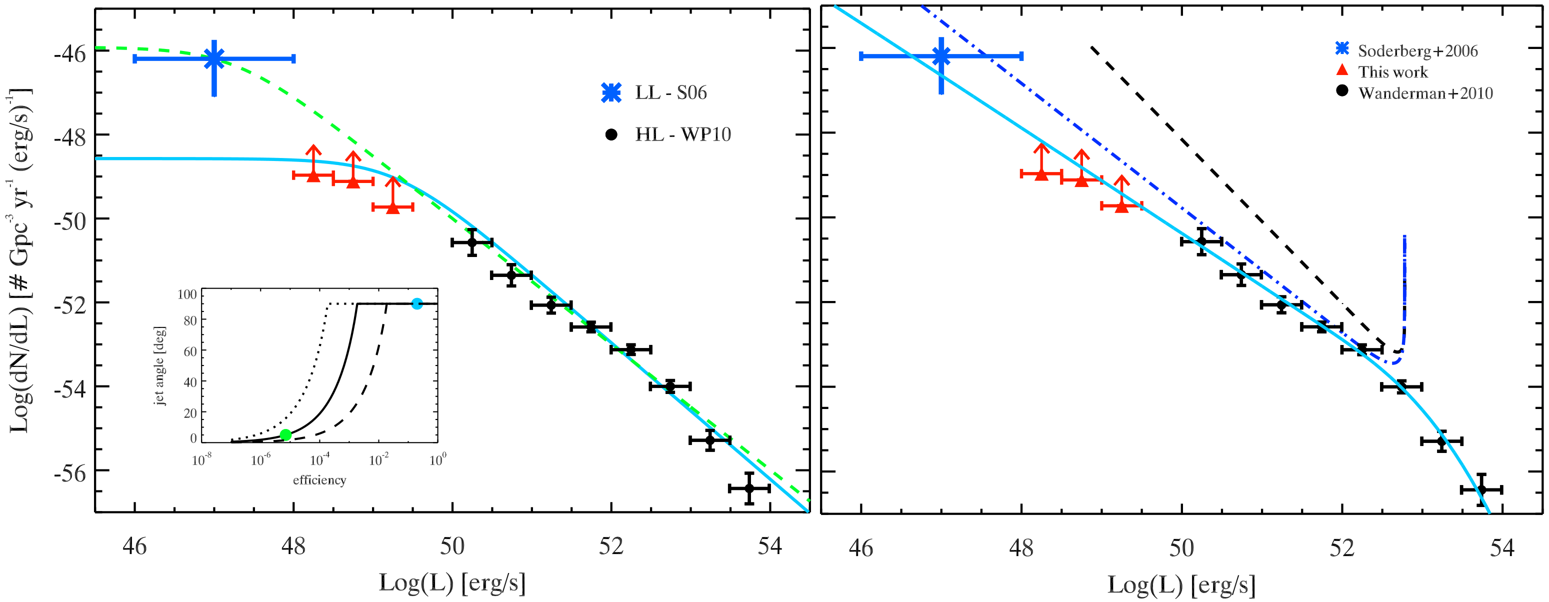
- Assume a simple model: threshold lumi., $L_{iso,min} \sim 10^{50}$ erg s^{-1} for jet success, and a viewing/jet opening angle, θ_j:

$$\rho_{0,L} \propto \begin{cases} \text{const}\,, & L_{\rm iso} \ll \epsilon_\gamma L_{\rm iso,min}/(1-\cos\theta_j) \\ L_{\rm iso}^{-k}\,, & L_{\rm iso} \gg \epsilon_\gamma L_{\rm iso,min}/(1-\cos\theta_j) \end{cases}$$

Sun et al (2015) arxiv:1509.01592



Pescalli et al (2014) arxiv:1409.1213



- Only works for unrealistically-low values of the radiation efficiency; or with “structured jets”.
- The cost for simplifying the LF is the need for fine-tuning: added complexity of new parameters; the need for very steep jet structure…
- ➜ If we have to accept a complicated scenario, then just as well to assume that LL-GRBs are unique.

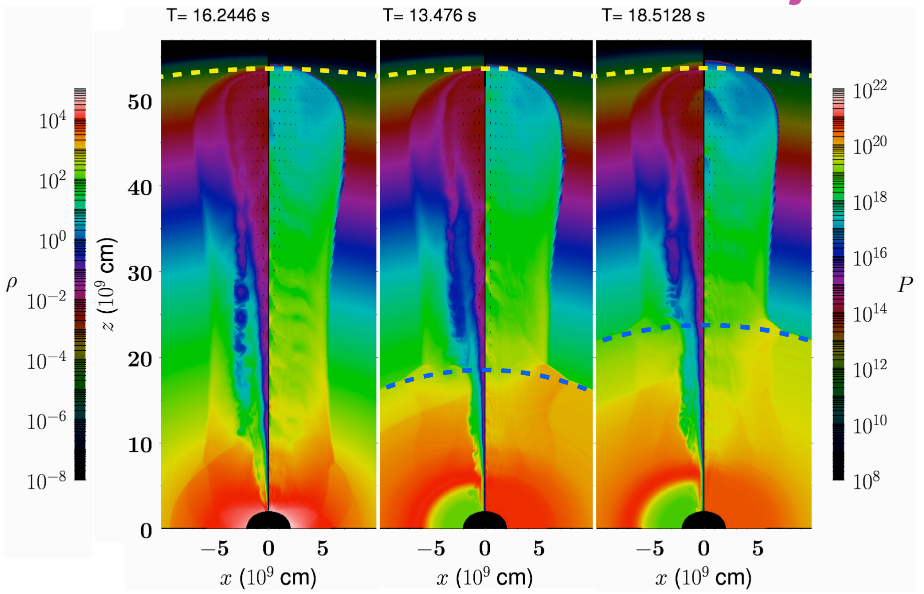
Failed jets

- Regardless of the existence of SBOs, low-energy jets may fail…
- Energetics between the jet/cocoon system and the environment of the SN ➜ The observed luminosity may be lower than the intrinsic luminosity…
- The BO timing condition ($t_E > t_{SBO}$) seems to be slightly relaxed.
- A SN shock wave (“piston” model) may reduce the pressure/density in the progenitor ➜ lower $L_{\gamma,iso,BO}$.
- Threshold for LL-jets:

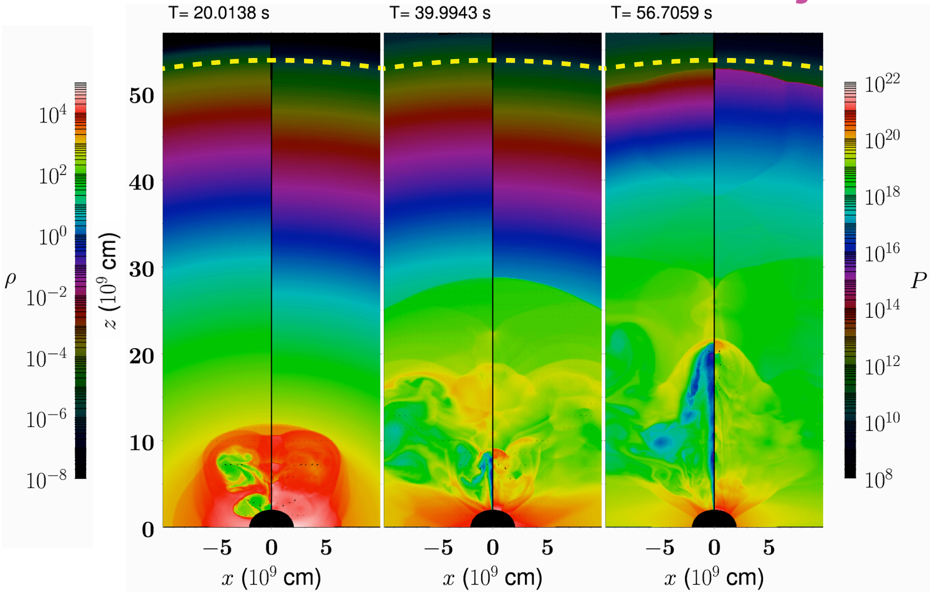
$$L_{\gamma,\mathrm{iso,BO}} \geq 1.5 \times 10^{48} \left(\frac{\epsilon_\gamma}{0.01}\right) \left(\frac{R_j}{2\times 10^9\,\mathrm{cm}}\right)^2 \left(\frac{\theta_j}{2^\circ}\frac{35^\circ}{\theta_{\mathrm{BO}}}\right)^2 \times \left(\frac{p_a}{1.8\times 10^{22}\,\mathrm{erg\,cm^{-3}}}\right) \mathrm{erg\,s^{-1}}$$

  - Intrinsic jet angle, $\theta_j \sim 2°$, where what we observe is the breakout angle, $\theta_{BO} \gtrsim 35°$ (decreasing with time).
  - Radiation conversion efficiency, $\varepsilon_\gamma \lesssim 1$ %.

Successful jet



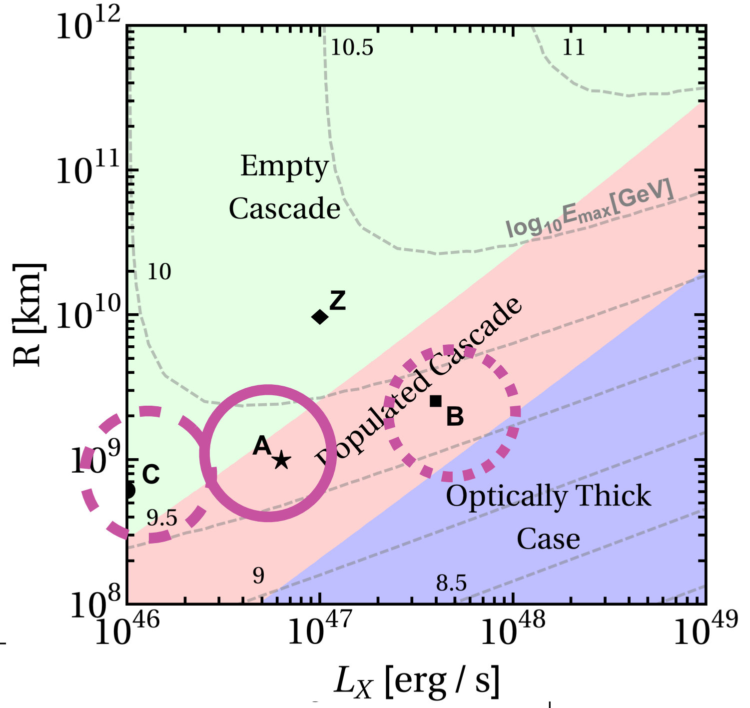
Failed jet

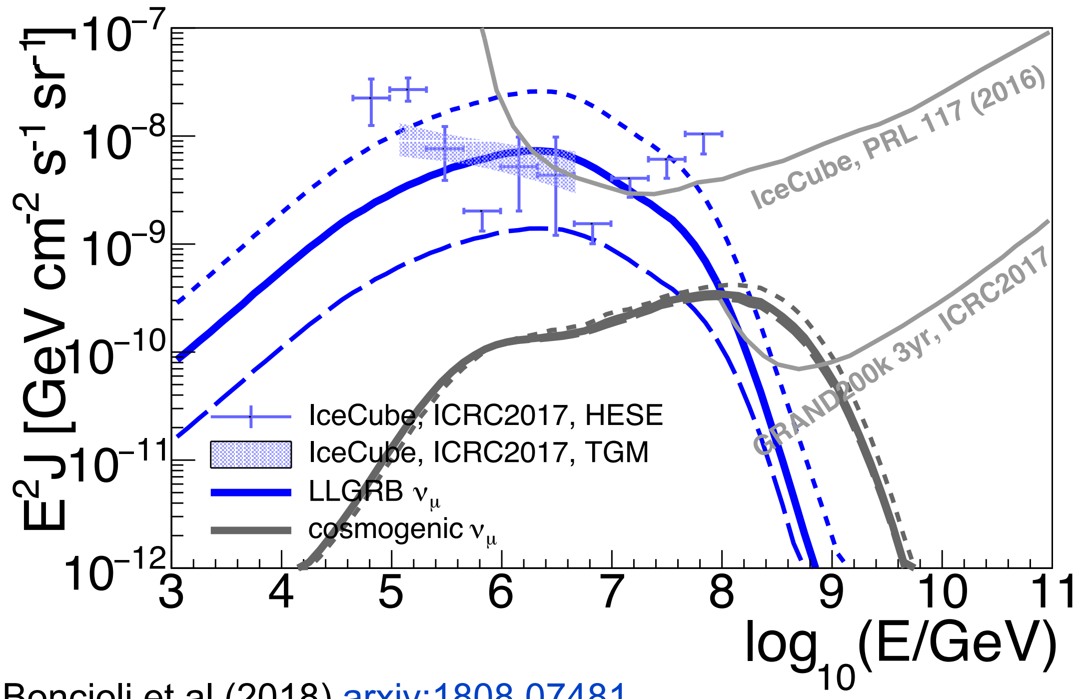


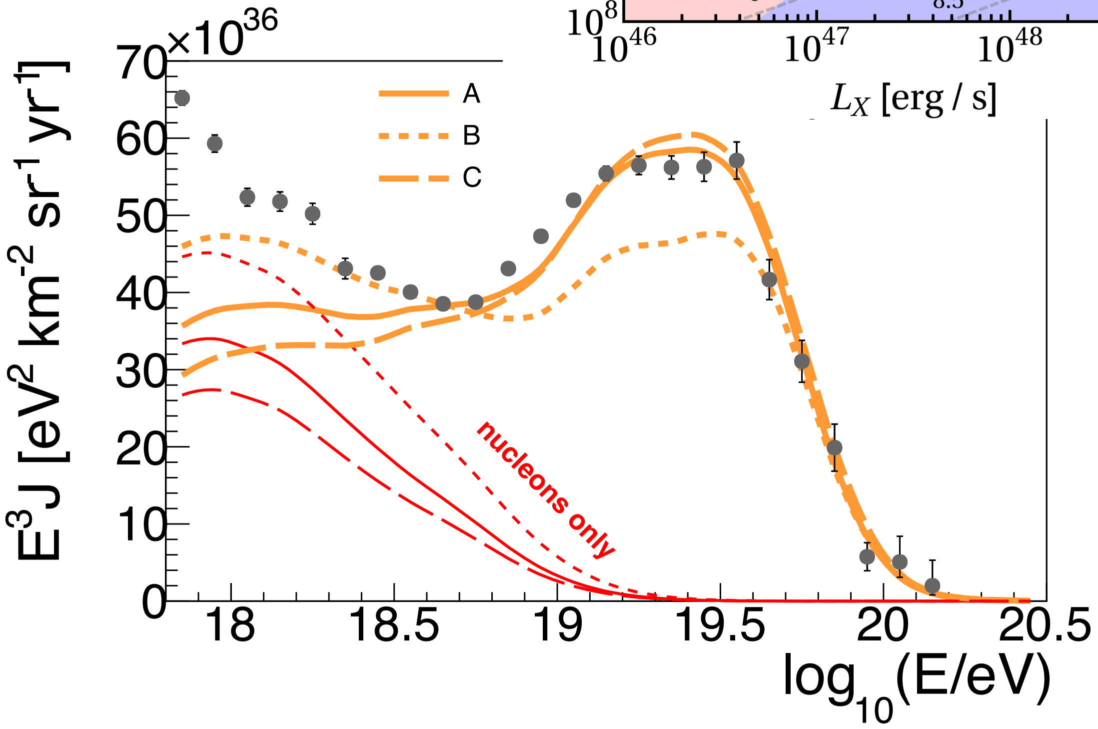
Aloy et al (2018) arxiv:1801.06186

UHECRs and neutrinos from LL-GRBs

- A, B, C: cases with similar cutoff energy at the source, but different values for the luminosity and the radius ➜ different strength of the nuclear cascade.
- Increased photo-disintegration results in more neutrinos and less CRs.
- A galactic(?) component is always needed below the ankle ($10^{18.6}$ eV).







DESY. Boncioli et al (2018) arxiv:1808.07481