Abstract

Long duration gamma-ray bursts (GRBs) have often been considered as the natural evolution of some core-collapse supernova (CCSN) progenitors. However, the fraction of CCSNe linked to astrophysical jets and their properties are still poorly constrained. While any successful astrophysical jet harbored in a CCSN should produce high energy neutrinos, photons may be able to successfully escape the stellar envelope only for a fraction of progenitors, possibly leading to the existence of high-luminosity, low-luminosity and not electromagnetically bright ("choked") GRBs. By postulating a CCSN–GRB connection, we accurately model the jet physics within the internal-shock GRB model and assume scaling relations for the GRB parameters that depend on the Lorentz boost factor Γ. The IceCube high energy neutrino flux is then employed as an upper limit of the neutrino background from electromagnetically bright and choked GRBs to constrain the jet and the progenitor properties. The current IceCube data set is compatible with up to 1% of all CCSNe harboring astrophysical jets. Interestingly, those jets are predominantly choked. Our findings suggest that neutrinos can be powerful probes of the burst physics and can provide major insights on the CCSN–GRB connection.

Supernova – Gamma Ray Burst – Neutrino Connection

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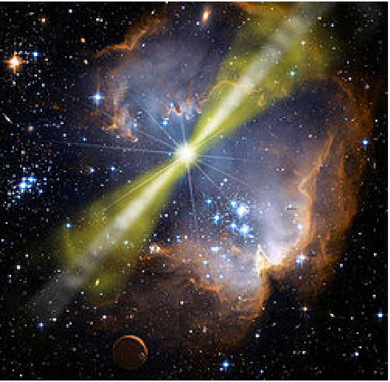
Gamma ray bursts

GRBs are potential UHECR and HEν sources.



- Have observed ~ 1000 GRBs.
- Most luminous events observed
- Photon measurements $\Rightarrow$ high Γ outflow.
- Central engine?
  - CCSN.
  - Binary mergers, ...?
- IceCube has strong constraints from spatial + timing correlations.

IC: 1601.06484

CCSN–GRB connection

Mounting evidence that some or all long duration GRBs are associated with CCSNe.

- Theoretical:

Lazzati, Morsony, Blackwell, Begelman: 1111.0970

Sobacchi, Granot, Bromberg, Sormani: 1705.00281

- Observational:

Paczyński: astro-ph/9710086

Hjorth, Bloom: 1104.2274

Modjaz: 1105.5297

Hjorth: 1304.7736

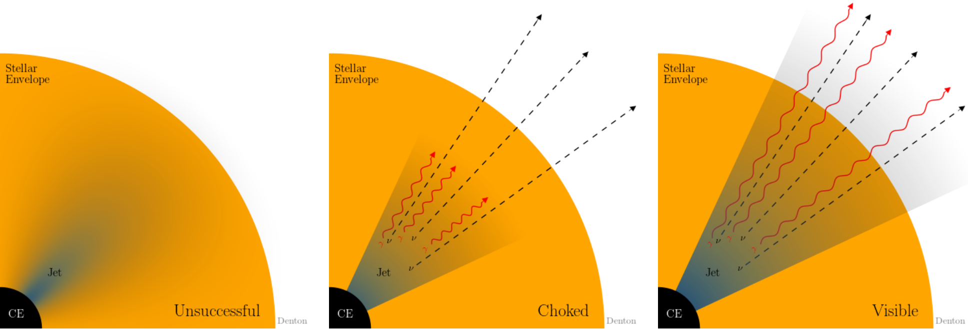
Margutti, et. al.: 1402.6344

CCSN + (rotation, B field) $\Rightarrow$ jet.

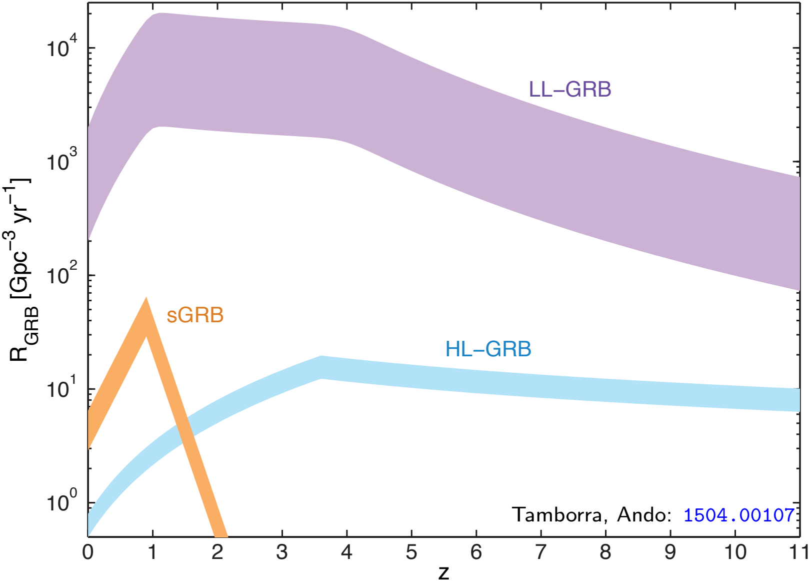
Three kinds of jets

The type of the jet determines the particle output:

- Unsuccessful $\Rightarrow \emptyset$.
- Successful but choked $\Rightarrow \nu$'s.
- Successful and visible $\Rightarrow \nu$'s and γ's.



GRB Rate



10^4
10^3
10^2
10^1
10^0
R_{GRB} [Gpc^{-3} yr^{-1}]
LL−GRB
sGRB
HL−GRB
Tamborra, Ando: 1504.00107
0
1
2
3
4
5
6
7
8
9
10
11
z

Choked GRBs

- Without EM observations, it is possible to write down anything for a choked source.
- We assume that all jets are drawn from the same distribution.
- We match the high luminosity jets to observations.
- One extra parameter $\zeta_{\rm SN}$: fraction of CCSNe that harbor jets.

GRB model: properties

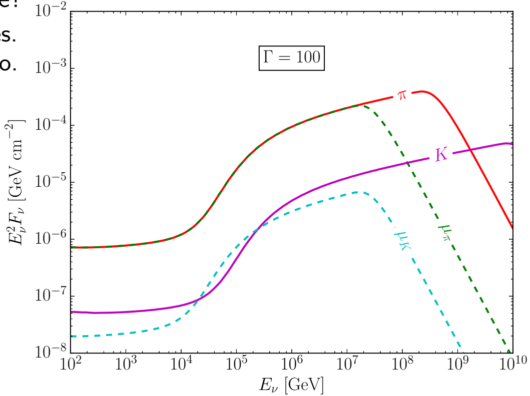
- Protons accelerated by the central engine following Fermi acceleration.
- Photons are measured to have a non-thermal spectrum.

  Band, et. al.: ApJ, 413, 281

  Amati, et. al.: astro-ph/0205230
- Magnetic fields carry $\sim 10\%$ of the total jet energy.
- Jet opening angle is related to the Lorentz boost factor $\theta_j = 1/\Gamma$.
- Variability time t_v scales with Γ:
  ~ 100 s for small Γ down to ~ 0.001 s for $\Gamma \sim 1000$.
- The shock radius of acceleration is $r \propto t_v$.

Particle physics in jets

- $p\gamma$ interactions lead to pions and kaons.
- Pions and kaons quickly decay to muons and neutrinos.
- Muons decay to more neutrinos.
- Protons, pions, kaons, and muons lose energy in the jet,
  - Do they decay in time?
    - Low energy $\Rightarrow$ yes.
    - High energy $\Rightarrow$ no.



Distribution of jets

We consider multiple shocks leading to a random walk with more boosted particles in the middle of the jet.

The observed distribution in Γ's comes from,

- Distribution of jets: power law in $\Gamma_{\rm max}$, and
- Angle of the jets relative to the Earth.

Consider a distribution of jets given instead by a power law in $\Gamma_{\rm max}$:

- $\Gamma = \Gamma_{\rm max}$ along the jet axis.
- Γ falls off as the angle increases with characteristic width $\sigma = 1/\sqrt{\Gamma_{\rm max}}$.
- The total jet opening angle wide enough to contain down to $\Gamma = 1$.

Normalization

Normalize to GRB and CCSNe rates based on Γ along line of sight:

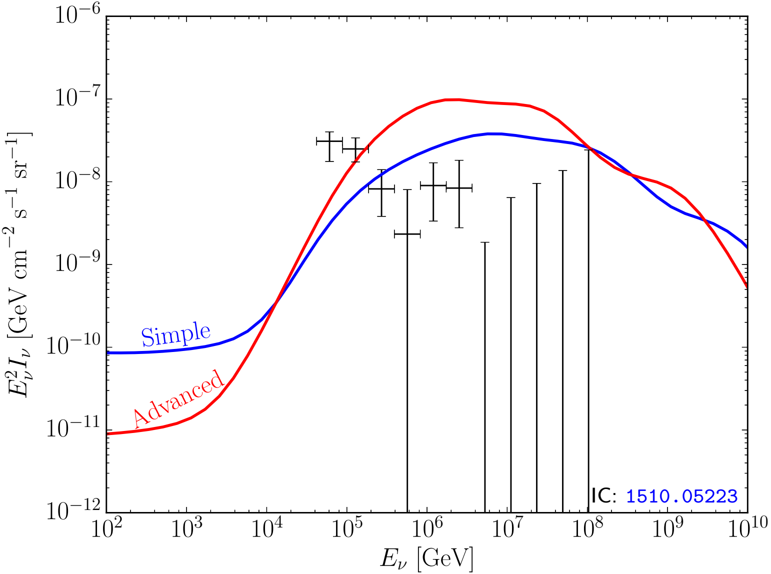
- The CCSNe rate times the fraction ($\zeta_{\rm SN}$) that forms jets normalizes all the jets.
- The HL-GRB rate normalizes the highly relativistic jets ($\Gamma > 200$).

This leads to exponents $\alpha_\Gamma \sim [-1,-3]$ depending on $\zeta_{\rm SN}$.

The redshift evolution follows that of star formation rate not that of GRBs.

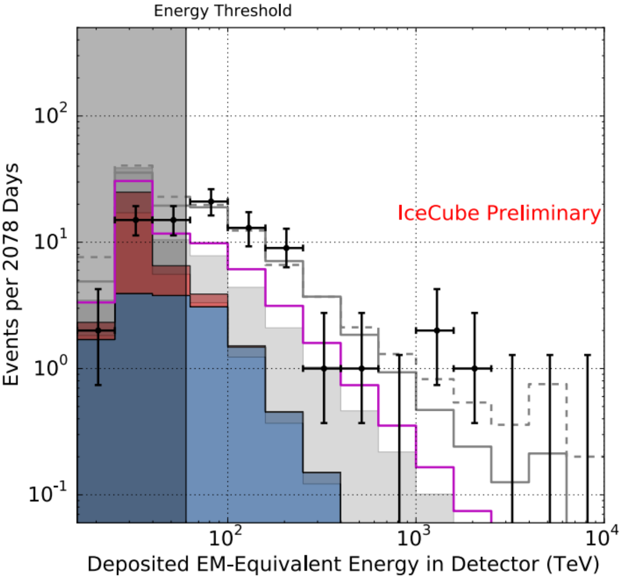
Diffuse intensities

At $\zeta_{\rm SN} = 0.1$ and $\tilde{E}_j = 10^{51}$ erg.

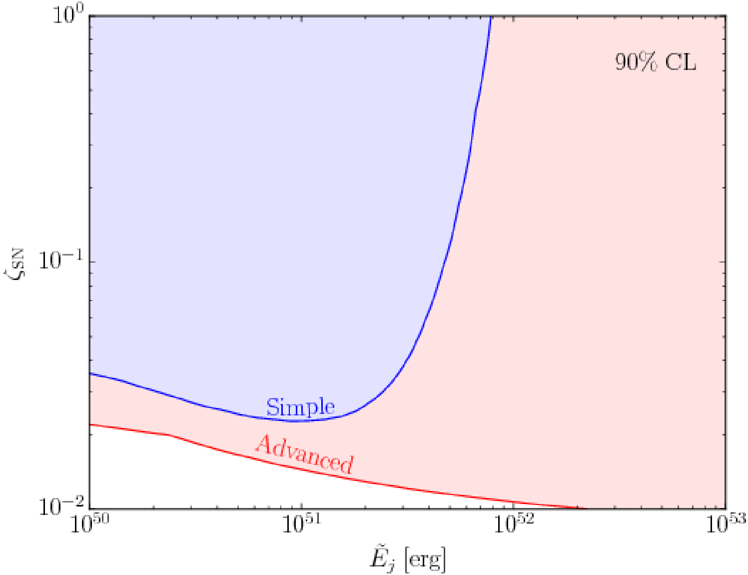


IceCube Detects Astrophysical Neutrinos

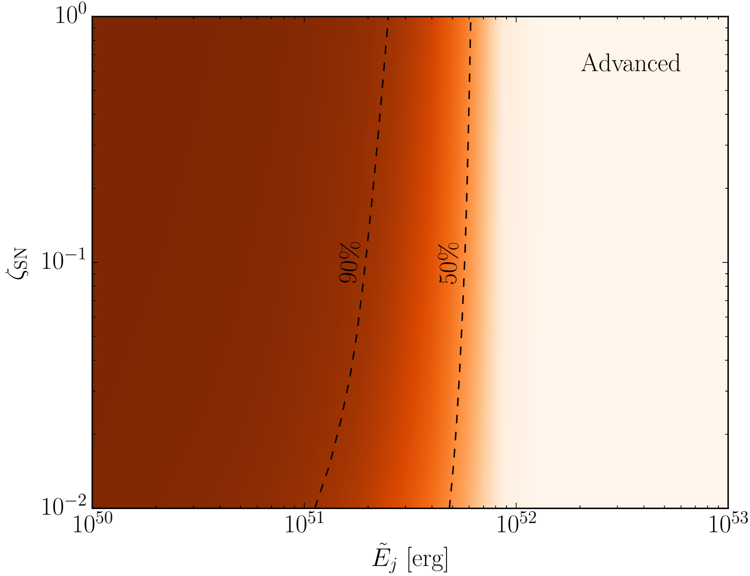
IC's 6 yr HESE: ICRC 2017



Source parameter exclusion limits



Choked fraction



GRB–Supernovae in the literature

- If all Ibc's form a jet, $\lesssim 10\%$ are visible.

  Soderberg, Frail, Wieringa: astro-ph/0402163

  Soderberg, Nakar, Kulkarni: astro-ph/0507147

  Sobacchi, Granot, Bromberg, Sormani: 1705.00281

- $R_{\rm GRB}(0)/R_{\rm Ibc}(0) \sim 0.1 - 1\%$, and Ibc's are $\sim 10\%$ of all CCSNe.

  Grieco, et. al.: 1204.2417

- The subclass broadlined CCSNe linked to GRBs sans gamma rays.

  Podsiadlowski, et. al.: astro-ph/0403399

  Mazzali, et. al.: astro-ph/0505199

  Soderberg, Nakar, Kulkarni: astro-ph/0507147

  Soderberg: astro-ph/0601693

- Example: SN2002ap (Ic) had a jet 90° from observer, $\tilde{E}_j = 5\times10^{50}$ erg.

  Totani: astro-ph/0303621

Conclusions

- IceCube has measured the astrophysical neutrino flux.
- The astrophysical neutrino flux is largely extragalactic.
- GRBs naturally lead to a high neutrino flux.
- Need to consider different classes of jets.
- CCSNe-GRB connection allows for physical constraints on choked GRBs.
- $\lesssim 1\%$ of CCSNe form jets, the majority of which will be choked.
- These could be type Ibc SNe forming jets: unsuccessful, choked, off/on-axis.

Backups

Possible extragalactic sources

- Cosmogenics from UHECR energy loss: wrong energy.

  Berezinsky, Zatsepin: PLB '69

- Point source searches: nothing found.

  IC: 1406.6757

- Catalog correlations: nothing (significant) found.

  Moharana, Britto, Razzaque: 1602.03694

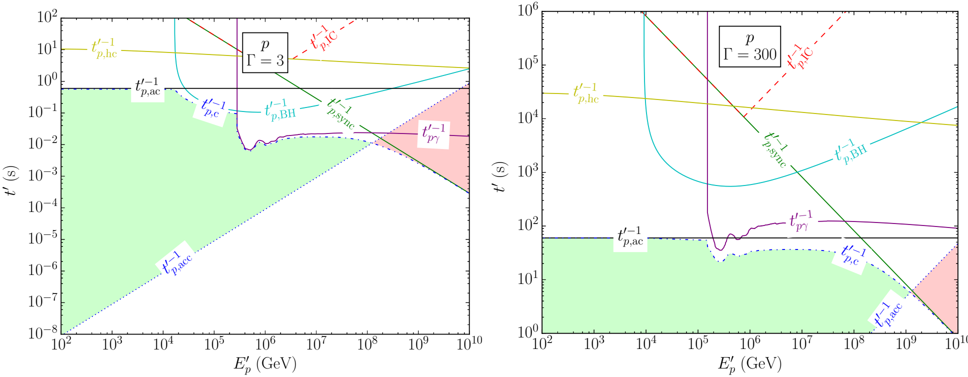
- UHECR correlation: nothing (significant) found.

  IC, Auger, TA: 1511.09408

Seem to be running out of source catalogs to check.

$\therefore$ Move to diffuse backgrounds and use spectral information.

Proton cooling



Muon energy correction

The energy deposited in tracks is not the true neutrino energy because the muon carries some of the energy out of the detector.

- Muon energy loss rate: $\frac{dE_\mu}{d\ell} = -(a + bE_\mu)$.
- Inelasticity parameter $y \equiv E_{\rm had}/E_\nu$.
- For a finite sized detector $\ell_{\sf max} = 1$ km,
  we can relate the deposited and neutrino energies by,

  $$\frac{E_{\rm dep}}{E_\nu} \approx \langle y\rangle + (1 - \langle y\rangle) b\ell_{\sf max}\,,$$

  which is valid in the region of interest.

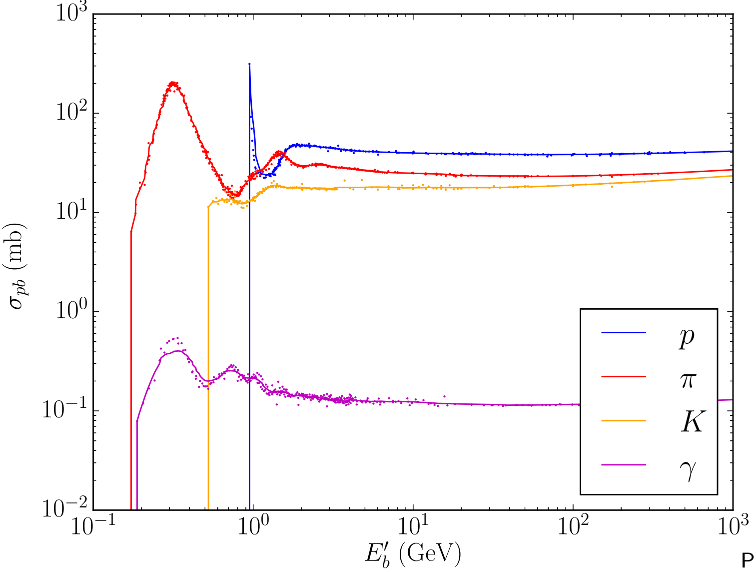
  Anchordoqui, Weiler, et. al.: 1611.07905

- $\langle y\rangle \in [0.25, 0.55]$ for relevant energies.

  Gandhi, Quigg, Reno, Sarcevic: hep-ph/9512364

Cross sections

Use the data for low energies, fits for high energies.



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