The Niels Bohr International Academy

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The Supernova-GRB Connection and High-Energy Neutrinos

Irene Tamborra

Niels Bohr Institute, University of Copenhagen

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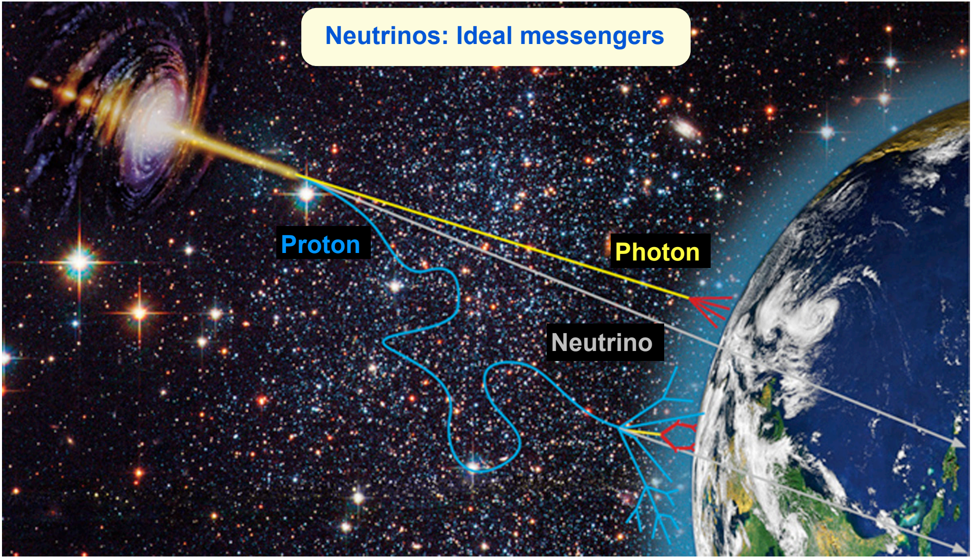
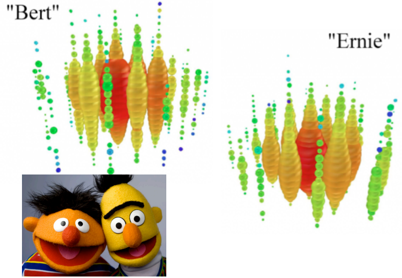
Neutrinos: New Frontier in Astrophysics

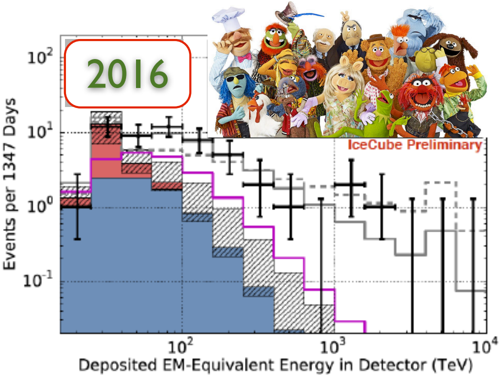
Escaping unimpeded, neutrinos carry information about sources not otherwise accessible.



High-energy neutrino astronomy is happening!

2013





- ★ IceCube observed 54 events over four years in the 25 TeV-2.8 PeV range.
- ★ Zenith Distribution compatible with isotropic flux.
- ★ Flavor distribution consistent with $\nu_e : \nu_\mu : \nu_\tau = 1:1:1$.

7σ evidence for astrophysical flux

* IceCube Collaboration, Science 342 (2013) 6161, PRL 113 (2014) 101101, PRD 91 (2015) 2, 022001.
IceCube Collaboration, ApJ 809 (2015) 1, 98; PRL 115 (2015) 8, 081102.

Where are these neutrinos coming from?

★ New physics?

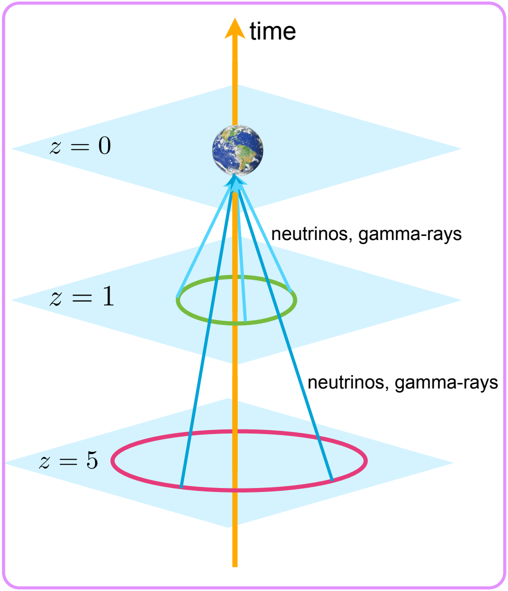
★ Galactic origin [sub-dominant contribution or new unknown sources?]

★ **Extragalactic origin [flux compatible with Waxman & Bahcall bound]**
- Star-forming galaxies
- Gamma-ray bursts
- Active galactic nuclei, blazars
- Low-power or choked sources

Warning: More statistics needed! No strong preference so far.

* Anchordoqui et al., JHEAp 1-2 (2014) 1. Meszaros, arXiv: 1511.01396. Waxman, arXiv: 1511.00815. Murase, arXiv: 1511.01590.

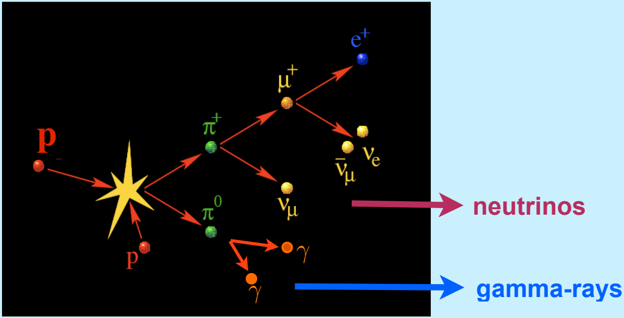
Diffuse background ingredients



- Gamma and neutrino energy fluxes
- Distribution of sources with redshift
- Comoving volume (cosmology)

Neutrino Production Mechanisms

Hadronic interactions



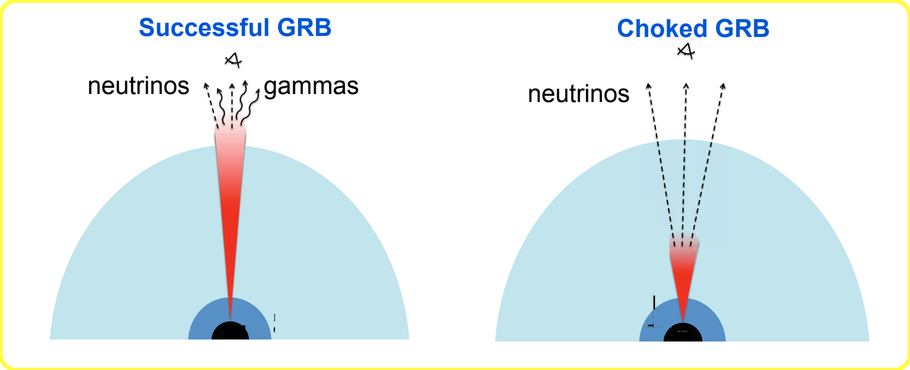
Lepto-hadronic interactions

$$p + \gamma \rightarrow \Delta \rightarrow n + \pi^+, p + \pi^0$$
$$p + \gamma \rightarrow K^+ + \Lambda/\Sigma \ .$$

$$\begin{aligned}
\pi^+ &\rightarrow \mu^+ \nu_\mu \ , \\
\mu^+ &\rightarrow \bar{\nu}_\mu + \nu_e + e^+ \\
\pi^- &\rightarrow \mu^- \bar{\nu}_\mu \ , \\
\mu^- &\rightarrow \nu_\mu + \bar{\nu}_e + e^- \\
K^+ &\rightarrow \mu^+ + \nu_\mu \ , \\
n &\rightarrow p + e^- + \bar{\nu}_e
\end{aligned}$$

* Anchordoqui et al., PLB 600 (2004) 202. Kelner, Aharonian, Bugayov, PRD 74 (2006) 034018.
Kelner, Aharonian, PRD 78 (2008) 034013.

Neutrino emission from gamma-ray bursts

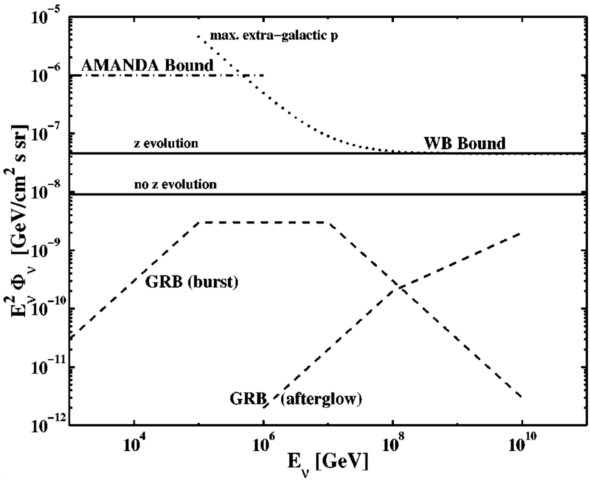


GRBs have rich phenomenology. Still many uncertainties on their physics.

Choked GRBs are especially poorly understood because scarcely (or not) visible in photons.

* Meszaros, Astropart. Phys. (2013). Waxman & Bahcall, PRL (1997). Meszaros & Waxman, PRL (2001). Senno et al. (2015).

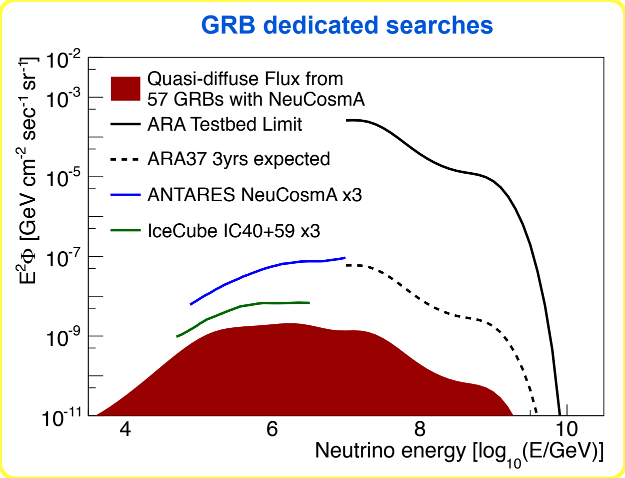
Neutrinos from ordinary gamma-ray bursts



Sizable emission of high-energy neutrinos from gamma-ray bursts expected.

* Waxman & Bahcall, PRL 78 (1997) 2292, PRD 64 (2001) 023002. Guetta et al., Astropart. Phys. 20 (2004) 429.

Neutrinos from ordinary gamma-ray bursts



Dedicated stacking searches on GRBs unsuccessful up to now.

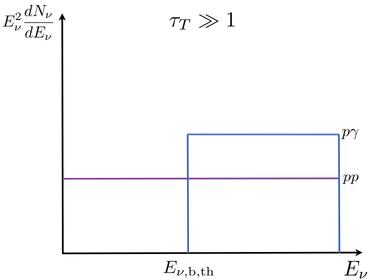
Existing detectors are achieving relevant sensitivity.

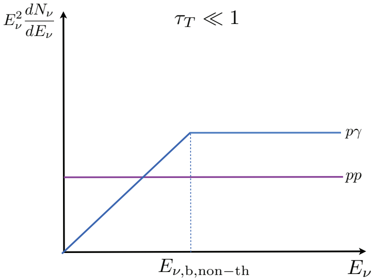
Does the diffuse emission from ANY GRB families contribute to the IceCube flux?

* Allison et al., arXiv: 1507.00100. IceCube Collaboration, ApJ 805 (2015) 1, L5. ANTARES Collaboration, A&A 559 (2013) A9.

Optically thick and thin bursts

Neutrino energy spectrum in absence of meson cooling effects



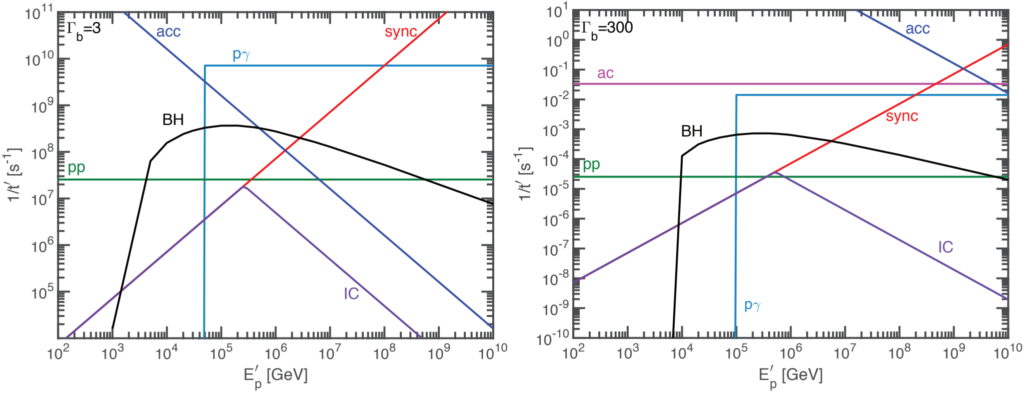


Optically thick sources.

Optically thin sources.

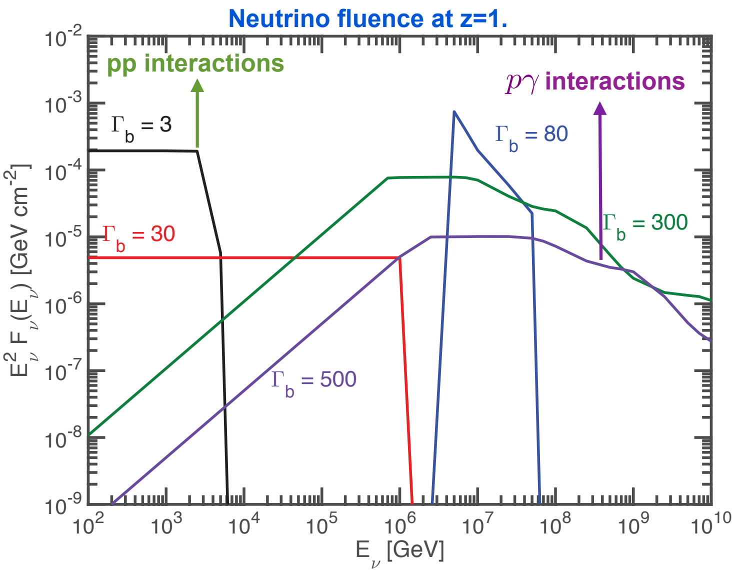
* Tamborra & Ando, PRD 93 (2016) 053010.

Comoving Cooling Times



* Tamborra & Ando, PRD 93 (2016) 053010.

Optically thick and thin bursts



* Tamborra & Ando, PRD 93 (2016) 053010.

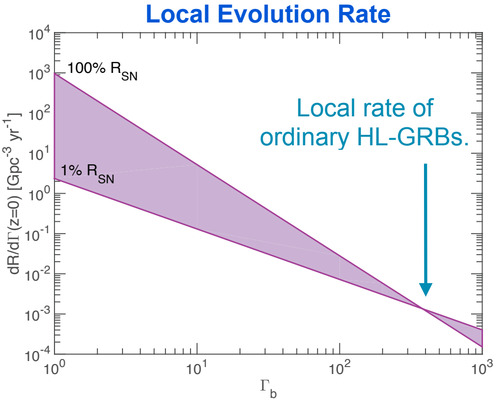
Constraints on the SN-GRB connection

Redshift evolution: $$R(z) \propto \left[(1+z)^{p_1 k} + \left(\frac{1+z}{5000}\right)^{p_2 k} + \left(\frac{1+z}{9}\right)^{p_3 k}\right]^{1/k}$$

Rate evolution with the Lorentz boost factor:

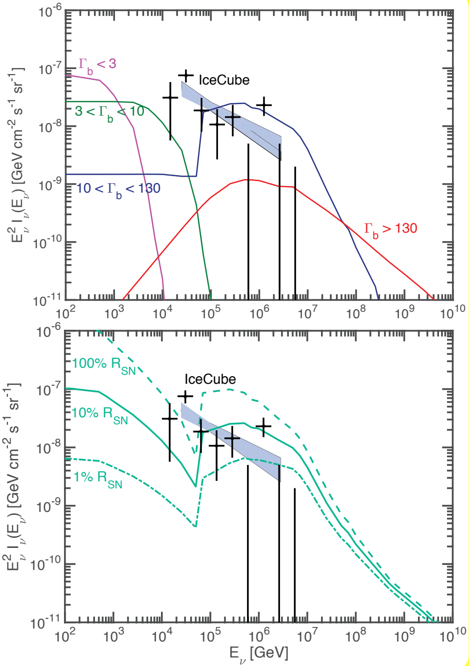
$$\int_1^{10^3} d\Gamma_b \, \Gamma_b^{\alpha_\Gamma} \beta_\Gamma = R_{\rm SN}(0) \zeta_{\rm SN} \frac{\theta_{\rm SN}^2}{2}$$

$$\int_{200}^{10^3} d\Gamma_b \, \Gamma_b^{\alpha_\Gamma} \beta_\Gamma = \rho_{0,\rm HL-GRB} ,$$



* Tamborra & Ando, PRD 93 (2016) 053010.

Constraints on the SN-GRB connection

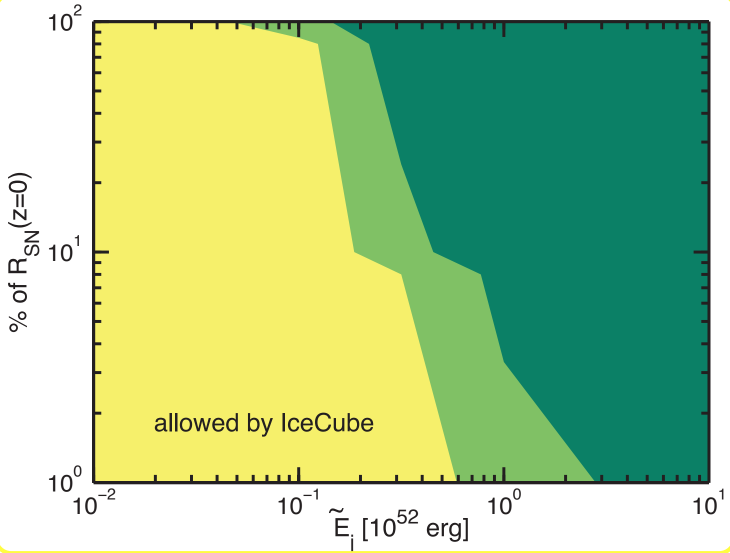


The IceCube flux could be originated by bursts with intermediate values of Lorentz boost factors.

The IceCube flux could indirectly constrain the fraction of SNe evolving in choked bursts.

* Tamborra & Ando, PRD 93 (2016) 053010.

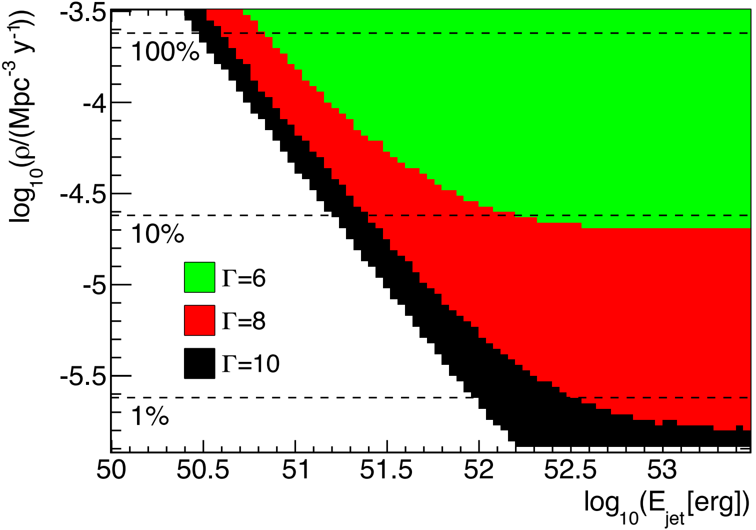
Constraints on the SN-GRB connection



The IceCube flux can already put indirect constraints on the fraction of SNe evolving in choked bursts and their jet energy.

* Tamborra & Ando, PRD 93 (2016) 053010.

Constraints on the SN-GRB connection



* IceCube and ROTSE Collaborations, A&A 539 (2012) A60.

Conclusions

- ★ Origin of the IceCube high-energy neutrino flux not yet clear.
- ★ Diffuse emission from optically thick jets is one natural possibility.
- ★ IceCube high-energy neutrino data indirectly constrain the choked GRB rate to be lower than 10% of the local SN rate.

Thank you
for your attention!