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High-Energy Neutrinos from Gamma-Ray Burst Fireballs

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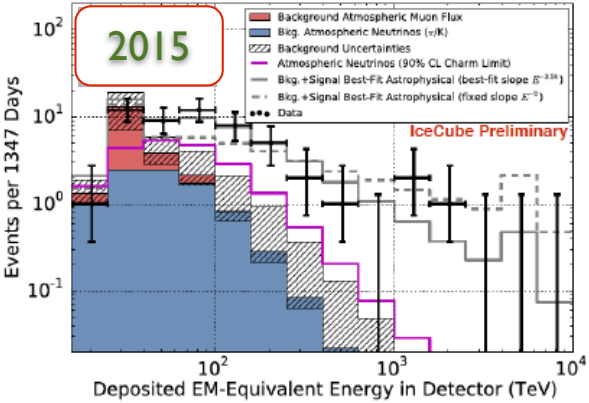
Outline

- ★ IceCube detection of high-energy neutrinos
- ★ Neutrinos from gamma-ray burst fireballs
- ★ Diffuse emission from gamma-ray bursts
- ★ Conclusions

This talk is based on work in collaboration with Shin'ichiro Ando, arXiv: 1504.00107, JCAP (2015, in press).

High-energy neutrino astronomy is happening!



talk by Karle

- ★ 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.
F. Halzen @ INvISIBLES 2015. See also: IceCube Collaboration, ApJ 809 (2015) 1, 98, PRL 115 (2015) 8, 081102.

Where are these neutrinos coming from?

★ New physics?

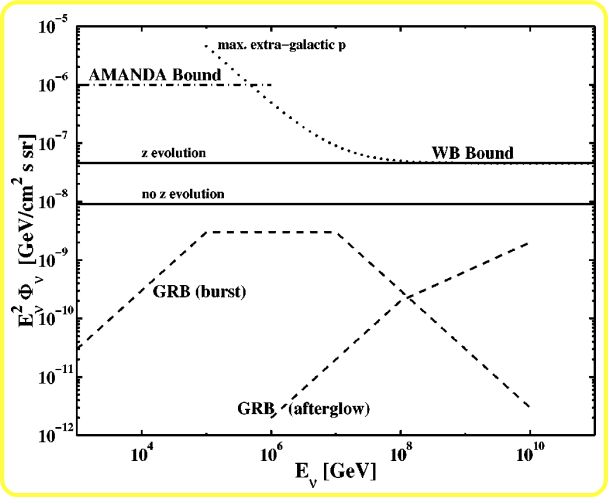
★ Galactic origin [sub-dominant contribution or new unknown sources?]

★ **Extragalactic origin [flux compatible with Waxman&Bahcall bound]**
- Star-forming galaxies
- Active galactic nuclei
- **Gamma-ray bursts**

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

* Anchordoqui et al., JHEAp 1-2 (2014) 1.

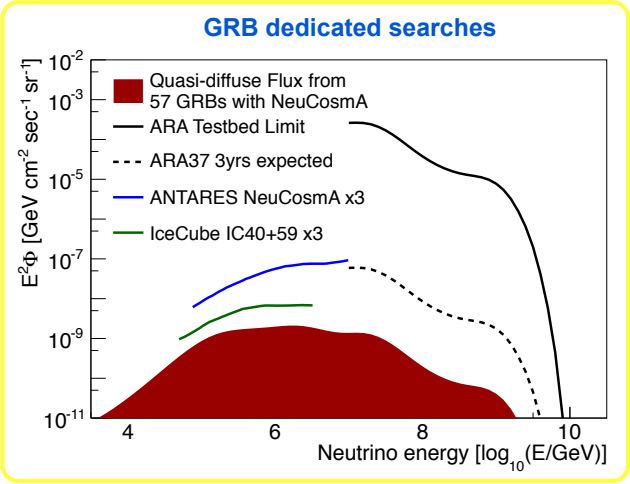
Neutrinos from gamma-ray bursts



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 gamma-ray bursts



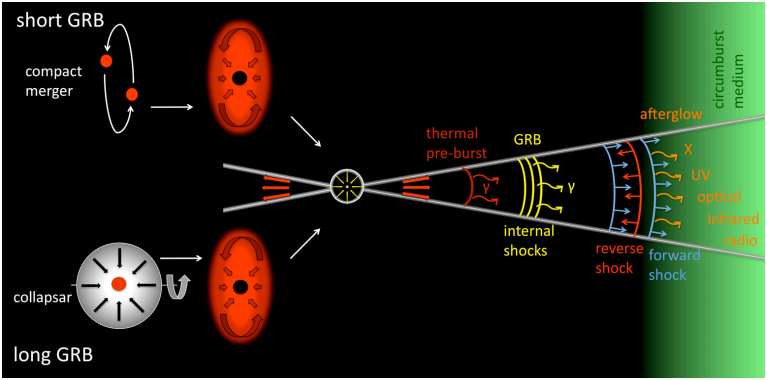
Dedicated stacking searches on GRBs unsuccessful up to now.

Existing detectors are achieving relevant sensitivity.

Does the diffuse emission from ALL 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.

Neutrino emission from gamma-ray bursts



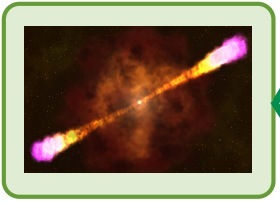
High energy neutrinos are produced through the following reactions:

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

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

* Image credit: Gomboc, Contemp. Phys. 53 (2012) 339.
* Kelner, Aharonian, PRD 78 (2008) 034013.

Neutrinos emission from gamma-ray bursts



Short-duration bursts (t < 2s)

$\tilde{L}_{\rm iso} = 10^{51}{\rm erg/s}\,,\,\Gamma = 650\,,\;t_v = 0.01s.$

Long-duration bursts (t > 2s)

High-luminosity GRBs

$\tilde{L}_{\rm iso} = 10^{52}{\rm erg/s}\,,\Gamma = 500,\;t_v = 0.1s.$

Low-luminosity GRBs

$\tilde{L}_{\rm iso} = 10^{48}{\rm erg/s}\,,\,\Gamma = 5,\;t_v = 100s.$

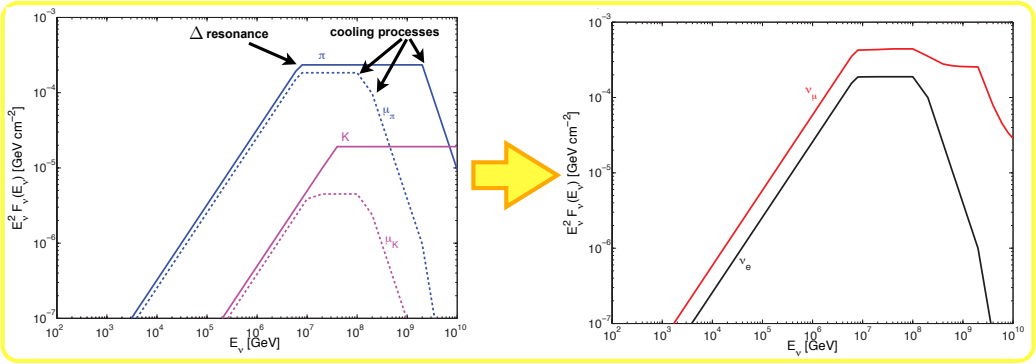
* Meszaros, Rept. Prog. Phys. 69 (2006) 2259. Image credit: NASA web-site.

Neutrino emission from gamma-ray bursts

We revisited the analytical modeling of prompt emission from fireballs, including pion and kaon decays as well as adiabatic, radiative and hadronic cooling processes.
Neutrino spectrum normalized in terms of the photon fluence:

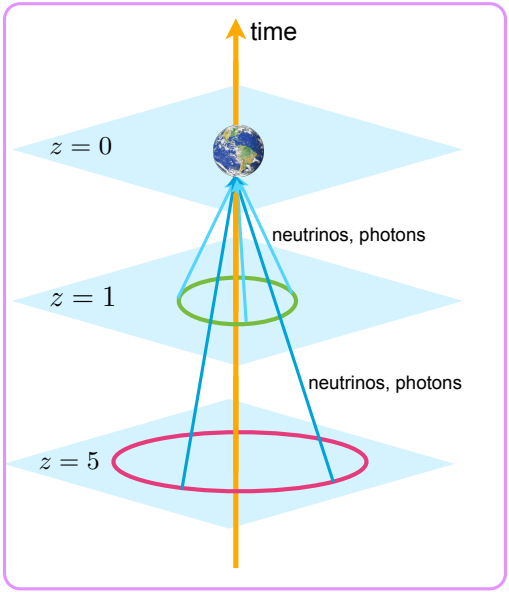
$$\int_0^\infty dE_\nu E_\nu \left(\frac{dN_\nu}{dE_\nu}\right)_{\mathrm{inj},i} = N_i \frac{h_{p,i}}{h_{\gamma p}}[1-(1-\langle\chi_p\rangle)^{\tau_{p\gamma}}] \int_0^\infty dE_\gamma E_\gamma \left(\frac{dN_\gamma}{dE_\gamma}\right)_{\mathrm{inj}}$$

Example of predicted HL-GRB flux w/o flavor oscillations at z=1.



* Tamborra, Ando, JCAP (2015).
See also Guetta et al., Astropart. Phys. (2004). Huemmer, Baerwald, Winter, PRL (2012). Li, PRD (2012).

Diffuse background ingredients

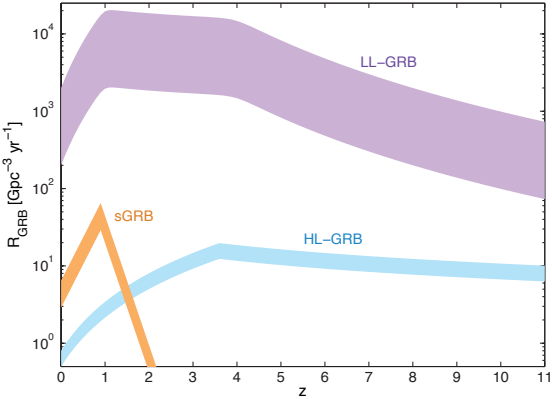


- Gamma and neutrino energy fluxes
- Distribution of sources with redshift
- Comoving volume (cosmology)

Diffuse emission from gamma-ray bursts

$$I_X(E_\nu) = \int_{z_{\min}}^{z_{\max}} dz \int_{\tilde{L}_{\min}}^{\tilde{L}_{\max}} d\tilde{L}_{\rm iso} \frac{c}{4\pi H_0 \Gamma} \frac{1}{\sqrt{\Omega_M (1+z)^3 + \Omega_\Lambda}} R_X(z) \Phi_X(\tilde{L}_{\rm iso}) \left(\frac{dN_{\nu_\mu}}{dE'_\nu}\right)_{\rm osc}$$

GRB redshift distribution



luminosity function

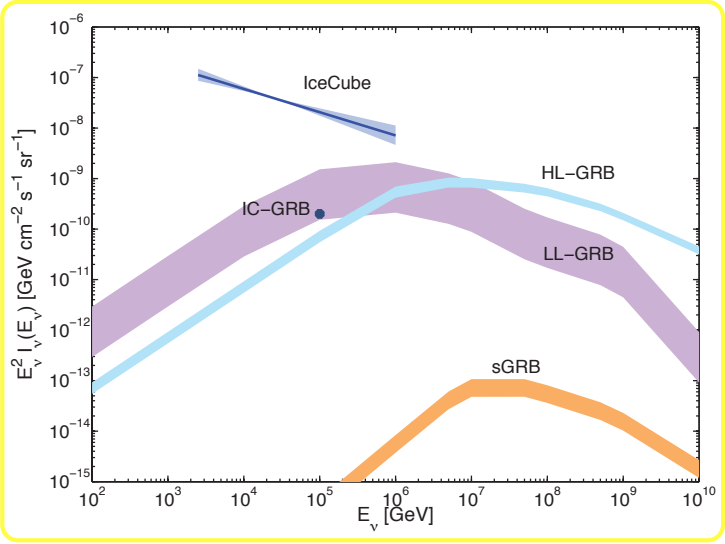
Recent work based on BATSE, Fermi and Swift data.

neutrino flux

Analytical modeling of the prompt emission from fireballs.

* Tamborra & Ando, JCAP (2015).

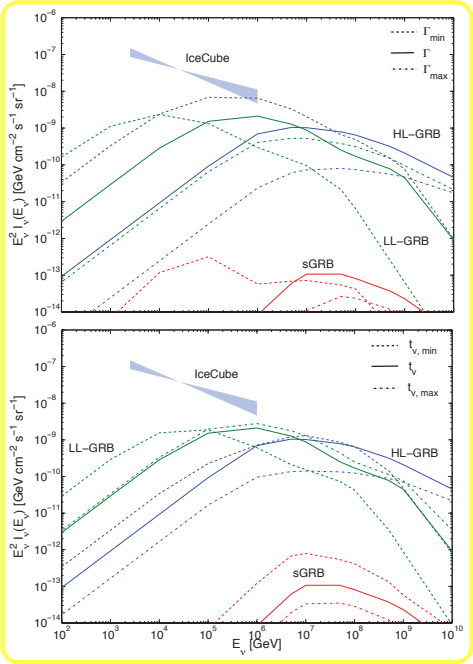
Diffuse emission from gamma-ray bursts



GRBs can make up to few % of the high-energy IceCube flux in the sub-PeV region.
LL-GRBs can be main sources of the IceCube flux in the PeV range.

* Tamborra & Ando, JCAP (2015).
See also: Liu & Wang (2013), Murase & Ioka (2013), Razzaque & Yang (2015), Baerwald, Bustamante, Winter (2015).

Diffuse emission from gamma-ray bursts



	$\Gamma_{\rm min}$	Γ	$\Gamma_{\rm max}$	$t_{v,\rm min}$	t_v	$t_{v,\rm max}$
HL-GRB	100	500	1000	10^{-3}	0.1	1
LL-GRB	2	5	20	10	100	200
sGRB	100	650	1000	10^{-3}	10^{-2}	0.05

Conclusions robust with respect to variation of model parameters.

GRBs cannot explain the IceCube flux for sub-PeV energies, but could contribute around PeV energies for certain choices of the model parameters.

* Tamborra & Ando, JCAP (2015).

Conclusions

★ Gamma-ray bursts account up to few % of the observed IceCube flux for E< 1 PeV.
Low-luminosity gamma-ray bursts dominate the diffuse emission in the PeV range.

★ High-luminosity and low-luminosity GRBs have comparable intensities, while the contribution from the short-duration component is small.

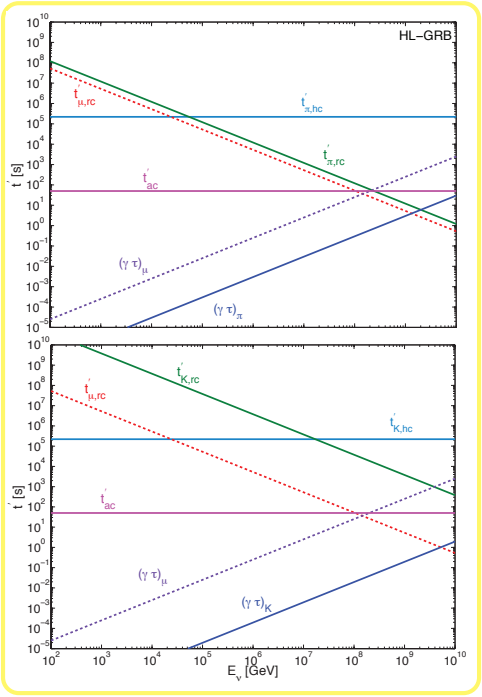
★ Our findings confirm the most-recent IceCube results on GRB searches.
Larger exposure is mandatory to detect neutrinos from high-luminosity GRBs.

Thank you

for your attention!

Back-up slides

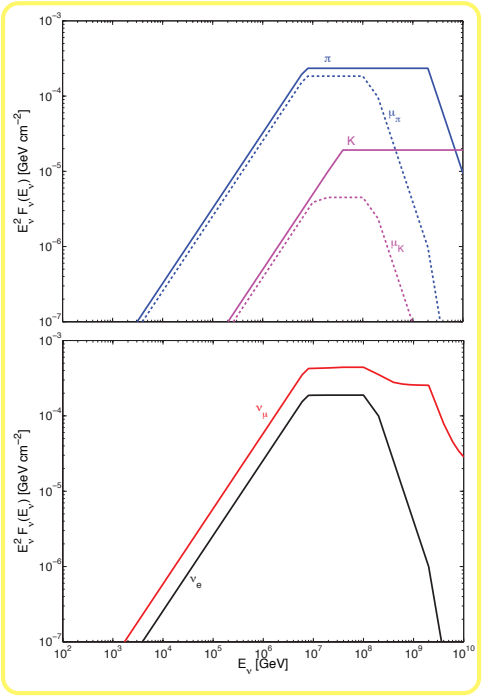
Neutrino emission from gamma-ray bursts



Cooling times in the jet comoving frame for HL-GRBs.

* Tamborra, Ando,JCAP (2015).

Neutrino emission from gamma-ray bursts

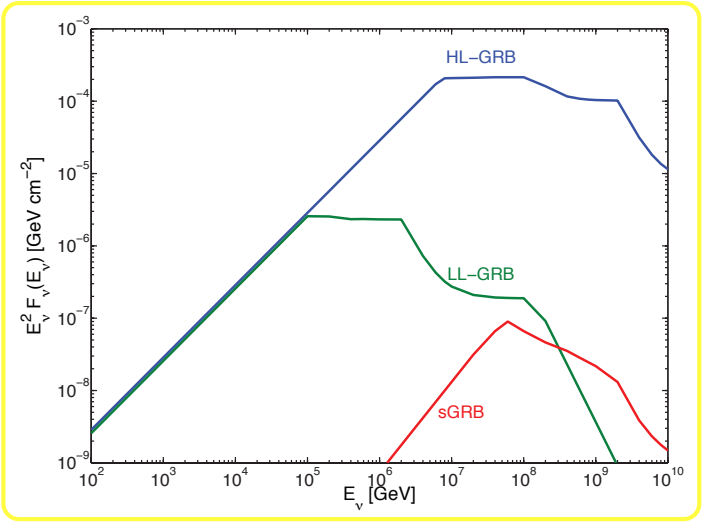


Predicted GRB flux for HL-GRB at z=1 and without flavor oscillations.

* Tamborra, Ando,JCAP (2015).

Neutrino emission from gamma-ray bursts

Predicted GRB flux with flavor oscillations at z=1.



* Tamborra, Ando, JCAP (2015).
See also Guetta et al., Astropart. Phys. (2004). Huemmer, Baerwald, Winter, PRL (2012). Li, PRD (2012).