The Niels Bohr International Academy

UNIVERSITY OF COPENHAGEN

Neutrinos and Gamma-Rays as Messengers of Extragalactic Astrophysical Sources

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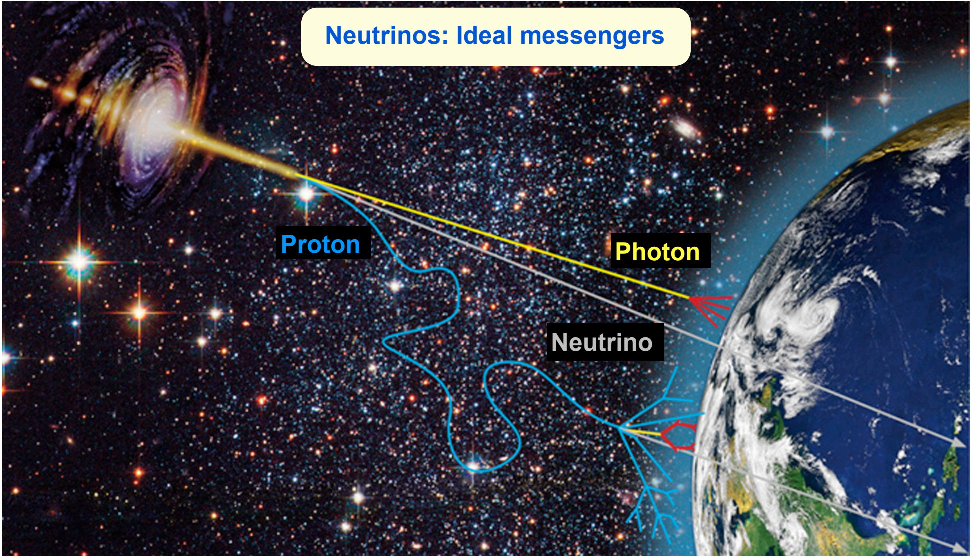
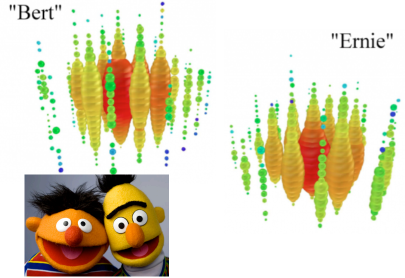
Neutrinos as Cosmic Messengers

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

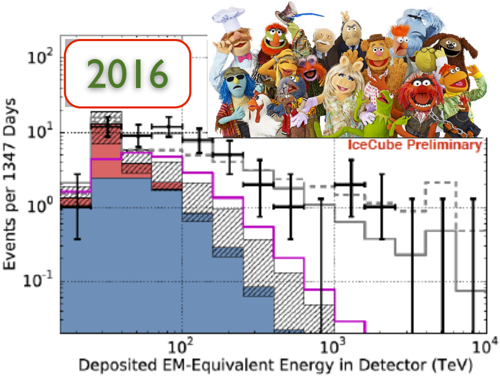


High-Energy Neutrino Astronomy Is Happening!

2013



2016



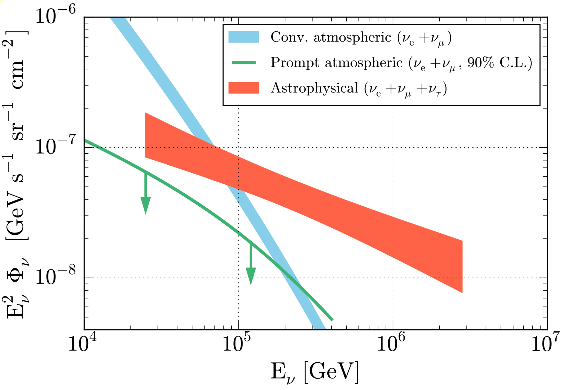
★ IceCube observed 54 events over four years in the 25 TeV-2.8 PeV range.
★ Zenith Distribution compatible with isotropic flux.
★ Flavor distribution consistent with $\nu_e : \nu_\mu : \nu_\tau = 1 : 1 : 1$.

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.

The Measured Astrophysical Flux

Energy spectrum from six data sets combined in a maximum-likelihood analysis [25 TeV-2.8 PeV].



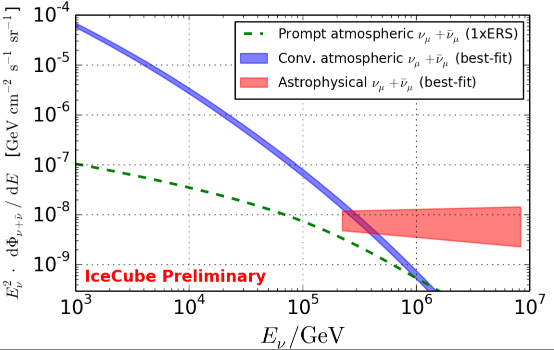
$$\Phi_\nu = 6.7^{+1.1}_{-1.2} \times 10^{-18} \left(\frac{E}{100\ \mathrm{TeV}} \right)^{-2.50 \pm 0.09} \mathrm{GeV^{-1} s^{-1} sr^{-1} cm^{-2}}$$

Soft spectral index driven by low energy bins.

* IceCube Collaboration, ApJ 809 (2015) 1, 98.

The Measured Astrophysical Flux

Analysis six years of IceCube data (2009-2015).



- Atmospheric-only hypothesis excluded by 5.9σ
- Best-fit astrophys. norm. @ 100 TeV:

$$(0.82^{+0.30}_{-0.26}) \times 10^{-18} \frac{1}{\text{GeV cm}^2 \text{ s sr}}$$

- Best-fit spectral index:

$$\gamma_{\text{astro}} = 2.08 \pm 0.13$$

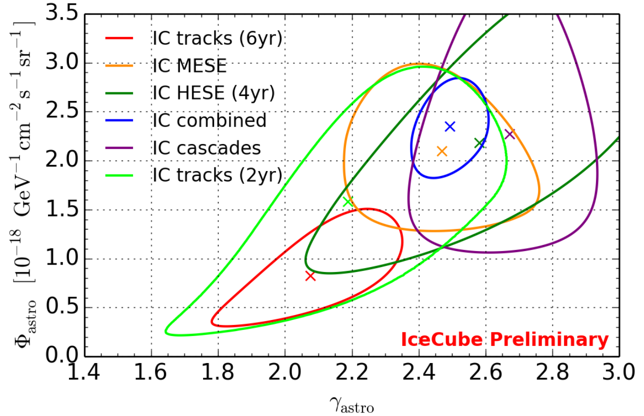
- Energy ranges:

$$220 \text{ TeV} - 8.3 \text{ PeV}$$

- Best fit astrophysical neutrino flux and conventional atmospheric neutrino flux predicted by Honda
- ERS prediction for a prompt atmospheric neutrino flux (best-fit prompt norm. is zero)

* Slide from S. Schoenen @ TeVPa 2015.

The Measured Astrophysical Flux



- 90% C.L. contours of the different IceCube analyses
- Results of IC tracks (6yr) and IC combined analysis (3 yr tracks slightly correlated) not compatible within > 3.6σ (two sided significance)

* Slide from S. Schoenen @ TeVPa 2015.

Where Are These Neutrinos Coming From?

★ New physics?

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

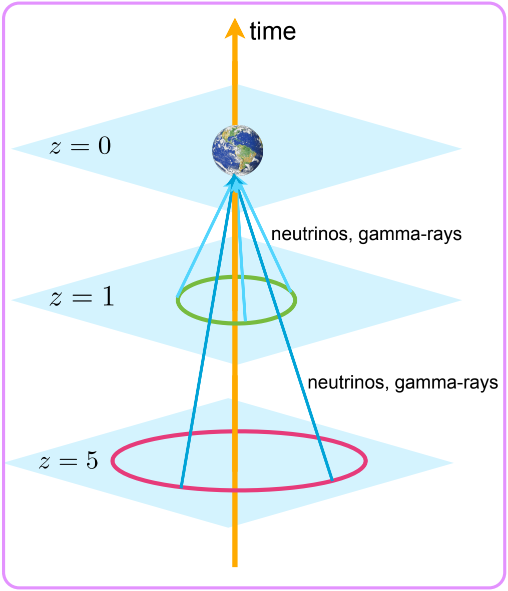
★ **Extragalactic origin [flux compatible with Waxman & Bahcall bound]**

- 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.

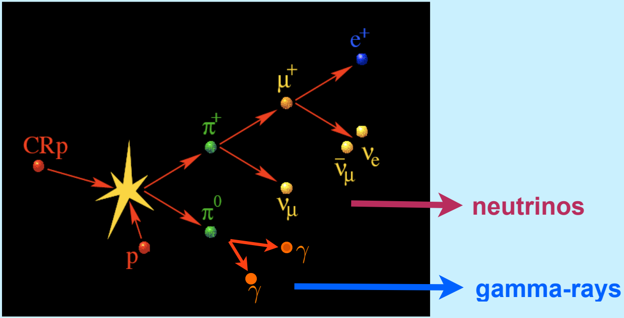
Diffuse Background Ingredients



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

Neutrino Production Mechanisms

Hadronic interactions



Lepto-hadronic interactions

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

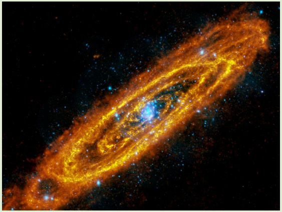
$$\begin{aligned}
\pi^+ &\rightarrow \mu^+ \nu_\mu \ , \\
\mu^+ &\rightarrow \bar{\nu}_\mu + \nu_e + e^+ \\
\pi^- &\rightarrow \mu^- \bar{\nu}_\mu \ , \\
\mu^- &\rightarrow \nu_\mu + \bar{\nu}_e + e^- \\
K^+ &\rightarrow \mu^+ + \nu_\mu \ , \\
n &\rightarrow p + e^- + \bar{\nu}_e
\end{aligned}$$

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

Star-Forming Galaxies

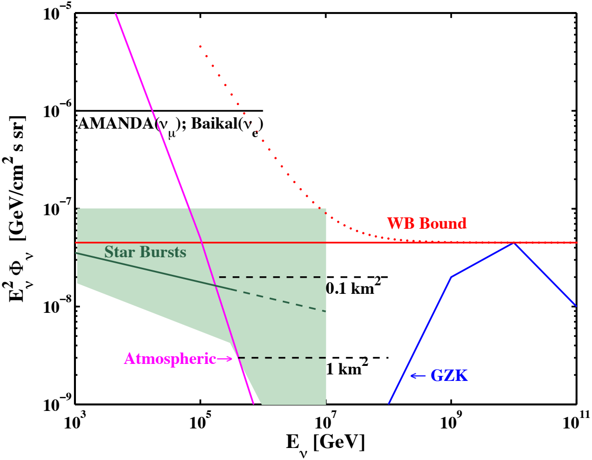
Star-Forming Galaxies

Normal galaxies
(i.e., Milky Way, Andromeda)



Starburst galaxies
(i.e., M82, NGC 253)

Starbursts efficiently produce neutrinos!



* Loeb & Waxman JCAP 0605 (2006) 003. Credits for images: ESA, Hubble, NASA web-sites.

Star-Forming Galaxies

Herschel provides IR luminosity functions for:

Normal galaxies

Starburst galaxies

SF-AGN
(galaxies with dim/low luminosity AGN)

$$I(E_\gamma) = \int_0^{z_{\max}} dz \int_{L_{\gamma,\min}}^{L_{\gamma,\max}} dL_\gamma \boxed{\frac{d^2V}{d\Omega dz}} \sum_X \boxed{\Phi_X(L_\gamma, z)} \boxed{\frac{dN_X(L_\gamma,(1+z)E_\gamma)}{dE_\gamma}} \boxed{e^{-\tau(E_\gamma,z)}}$$

comoving volume

luminosity function
$\Phi_X(L_\gamma, z) = d^2N_X/dV dL_\gamma$

gamma-ray flux

EBL correction

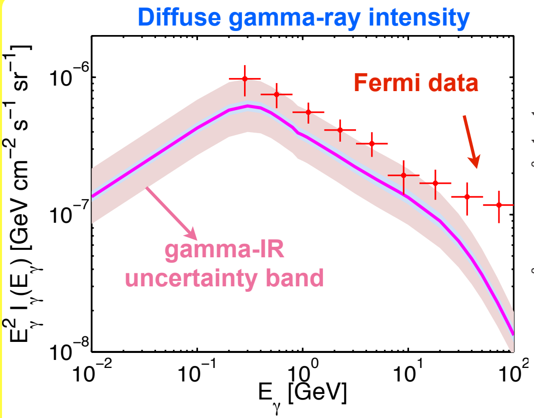
Injection spectral index:
- $\Gamma_{\rm NG} = 2.7$ for normal galaxies
- $\Gamma_{\rm SB} = 2.2$ for starbursts
- SB-like or NG-like according to z for SF-AGN

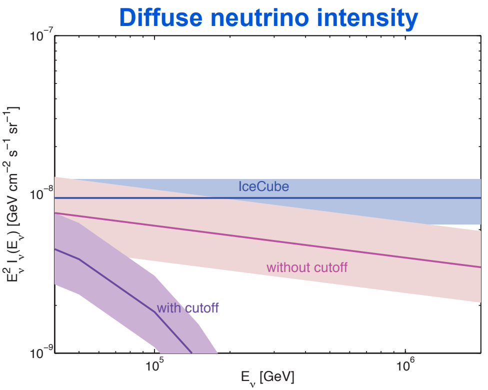
$$\log\left(\frac{L_\gamma}{\rm erg\ s^{-1}}\right) = \alpha \log\left(\frac{L_{\rm IR}}{10^{10} L_\odot}\right) + \beta$$

Gamma-ray-IR linear relation from Fermi data.

* Gruppioni et al., MNRAS 432 (2013) 23. Ackermann et al., ApJ 755 (2012) 164.

Diffuse Emission from Star-Forming Galaxies





Neutrino intensity with its astrophysical uncertainty band within IceCube band for E<0.5 PeV.

* Tamborra, Ando, Murase, JCAP 09 (2014) 043.

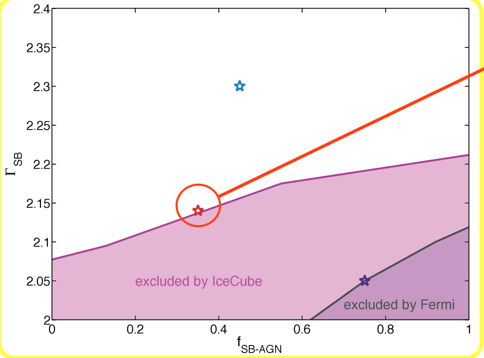
See also: Strong et al. (1976), Thompson et al. (2006), Fields et al. (2010), Makiya et al. (2011), Stecker&Venters(2011). Loeb&Waxman (2006), Lacki et al. (2011), Murase et al. (2013).

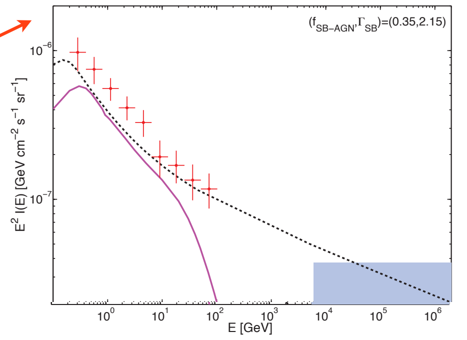
Constraints from Fermi and IceCube Data

Fermi and IceCube data can constrain starburst abundance and their injection spectral index.

$$I_\gamma(E_\gamma) = I_{\gamma,\mathrm{NG}}(E_\gamma) + I_{\gamma,\mathrm{SB}}(E_\gamma, \Gamma_{\mathrm{SB}}) + [f_{\mathrm{SB-AGN}}\ I_{\gamma,\mathrm{SB}}(E_\gamma, \Gamma_{\mathrm{SB}}) + (1 - f_{\mathrm{SB-AGN}})\ I_{\gamma,\mathrm{NG}}(E_\gamma)]$$

SB spectral index and SB-AGN fraction compatible with Fermi and IceCube data

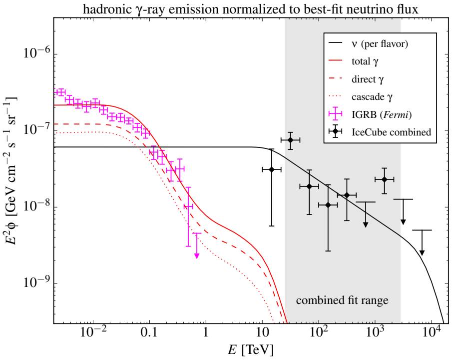


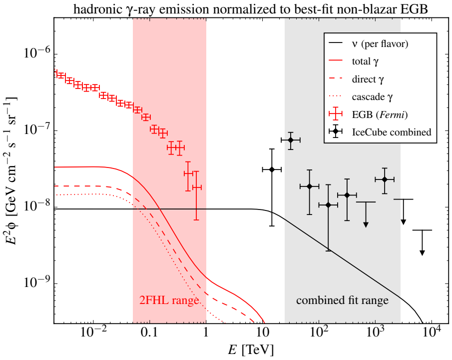


The SB spectral index matching **simultaneously** Fermi and IceCube data is $\Gamma_{SB} \simeq 2.15$.

* Tamborra, Ando, Murase, JCAP 09 (2014) 043.

Diffuse Emission from Star-Forming Galaxies

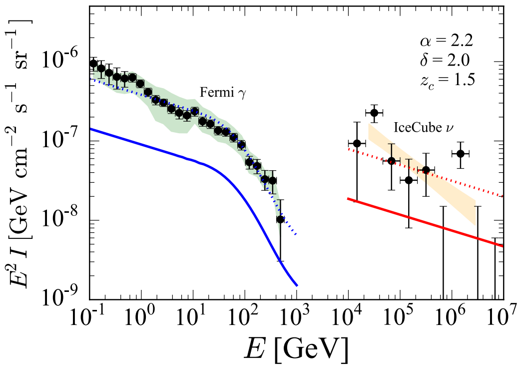


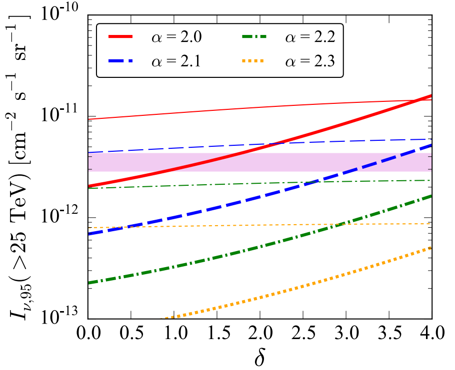


New Fermi study finds that blazars make 86% of the total extra-galactic gamma-ray background. Results in tension with star-forming galaxies as dominant source of the diffuse gamma-ray and neutrino backgrounds.

* Bechtol, Ahlers, Di Mauro, Ajello, Vandenbroucke, arXiv: 1511.00688. Fermi Collaboration, arXiv: 1511.00693.

Tomographic Constraints





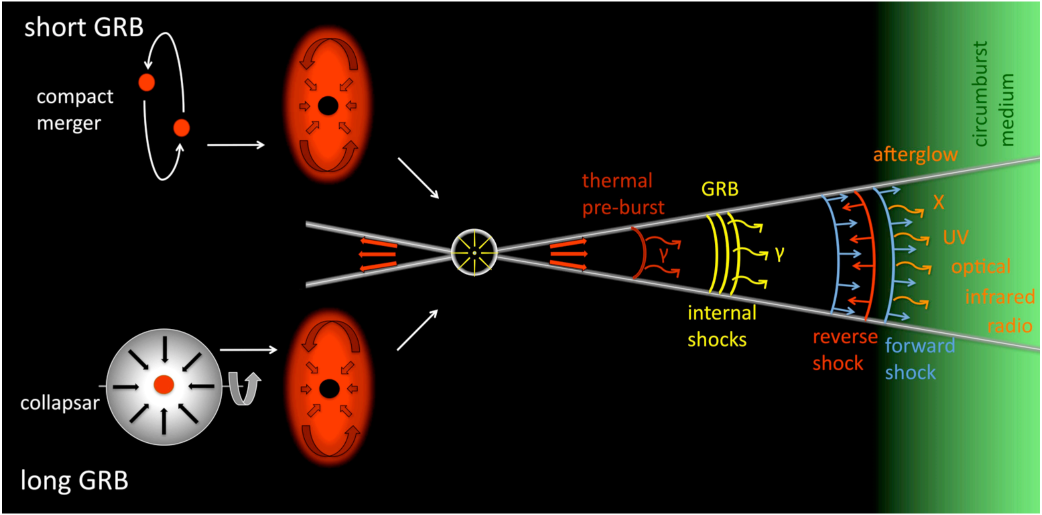
Cross-correlation between GeV gamma rays and galaxy catalogs provides bounds on the neutrino luminosity density up to **one order of magnitude tighter** than those obtained from the energy spectrum.

Any hadro-nuclear source with a spectrum softer than $E^{-2.1}$ and evolution slower than $(1+z)^3$ is excluded.

* Ando, Tamborra, Zandanel, PRL 115 (2015) 22, 221101.

Gamma-Ray Bursts

Neutrino Emission from Gamma-Ray Bursts



* Image credit: Gomboc, Contemp. Phys. 53 (2012) 339.

Neutrino Emission from Gamma-Ray Bursts

Short-duration bursts (t < 2s)

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

Long-duration bursts (t > 2s)

High-luminosity GRBs

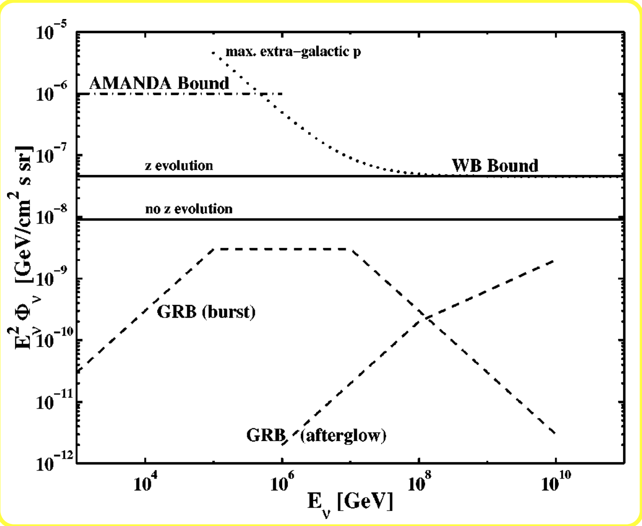
$\tilde{L}_{\rm iso} = 10^{52} {\rm erg/s}$,$\Gamma = 500$, $t_v = 0.1 s$.

Low-luminosity GRBs

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

* Meszaros, Rept. Prog. Phys. 69 (2006) 2259. Credits for images: ESA, Hubble, NASA web-sites.

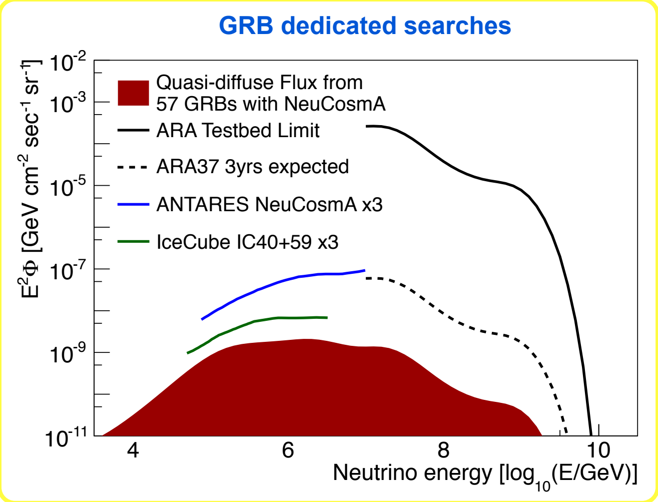
Neutrinos from Ordinary Gamma-Ray Bursts



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.

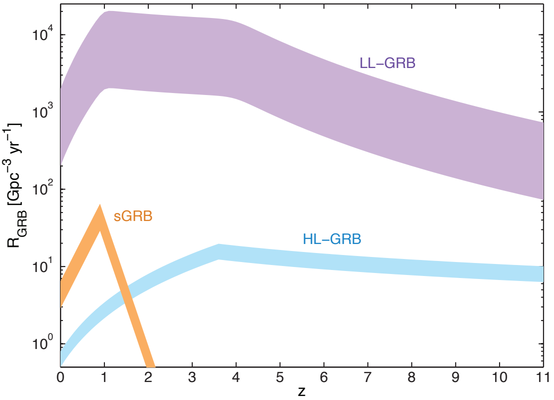
Does the diffuse emission from ALL GRB families contribute to the IceCube flux?

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

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

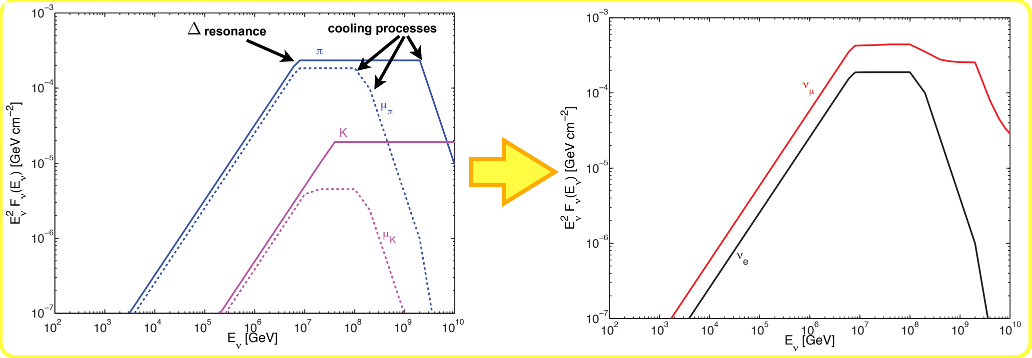
Analytical modeling of the prompt emission from fireballs, involving pion and kaon decays.

* Tamborra & Ando, JCAP 1509 (2015) 09, 036.

Neutrinos Emission from Gamma-Ray Bursts

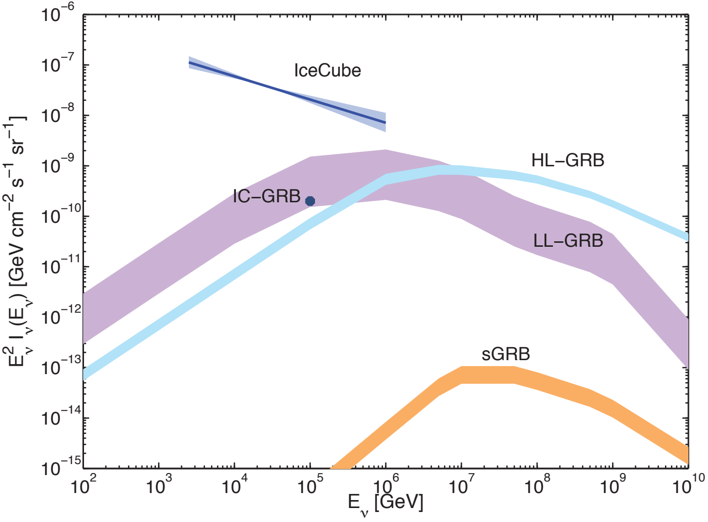
$$\int_0^\infty dE_\nu E_\nu \left(\frac{dN_\nu}{dE_\nu}\right)_{\mathrm{inj},i} = N_i \frac{h_{p,i}}{h_{\gamma p}}[1-(1-\langle\chi_p\rangle)^{\tau_{p\gamma}}] \int_0^\infty dE_\gamma E_\gamma \left(\frac{dN_\gamma}{dE_\gamma}\right)_{\mathrm{inj}}$$

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



* Tamborra & Ando, 1509 (2015) 09, 036.
See also Guetta et al., Astropart. Phys. (2004). Huemmer, Baerwald, Winter, PRL (2012). Li, PRD (2012).

Diffuse Emission from Gamma-Ray Bursts

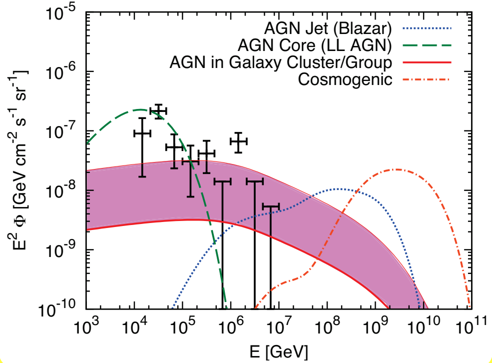


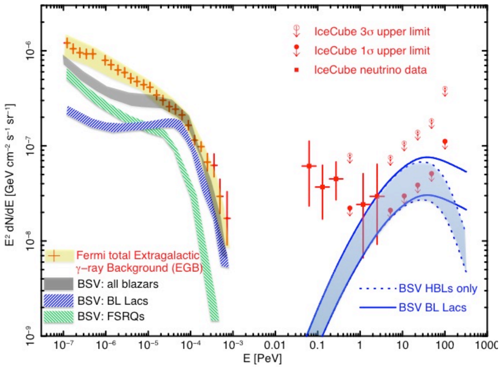
GRBs can make up to few % of the high-energy IceCube flux in the sub-PeV region.
LL-GRBs can be main sources of the IceCube flux in the PeV range.

* Tamborra & Ando, JCAP 1509 (2015) 09, 036. See also: Liu&Wang (2013), Murase&Ioka (2013), Razzaque&Yang (2015).

Active Galactic Nuclei

Active Galactic Nuclei and Blazars





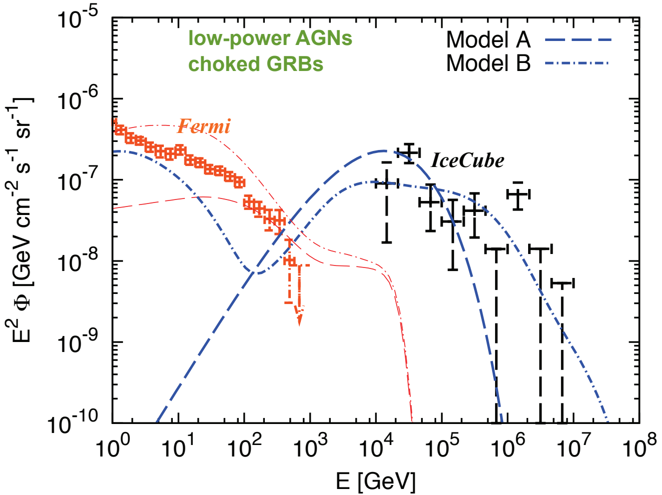
Contribution from AGN is strongly model-dependent, but might be sizable.

Blazars could also contribute to the neutrino background for E>0.5 PeV.

* Padovani, Petropoulou, Giommi, Resconi, MNRAS 452 (2015) 2, 1877. Murase, arXiv: 1511.01590.

Hidden Cosmic Accelerators

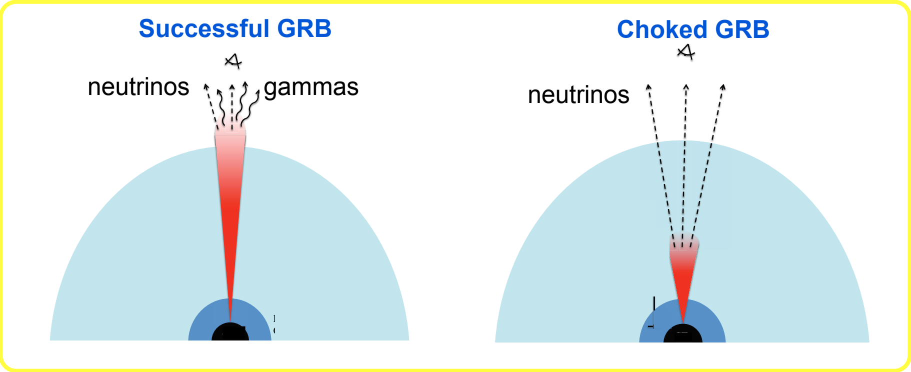
Hidden Cosmic Accelerators



Latest data may point toward a population of CR accelerators hidden in GeV-TeV gamma-ray range. Future searches in the X-ray and MeV bands will address with issue.

* Murase, Guetta, Ahlers, PRL 116 (2016) 7, 071101. Murase & Ioka, PRL (2013).

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. (2016).

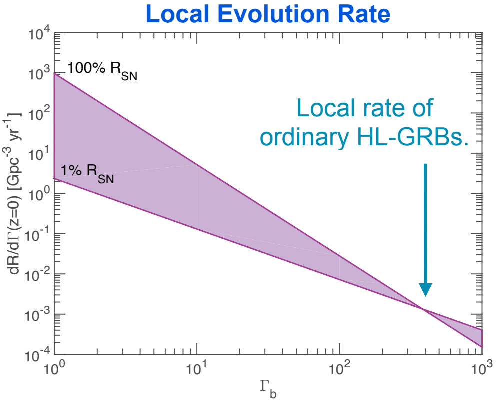
Constraints on the SN-GRB connection

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:

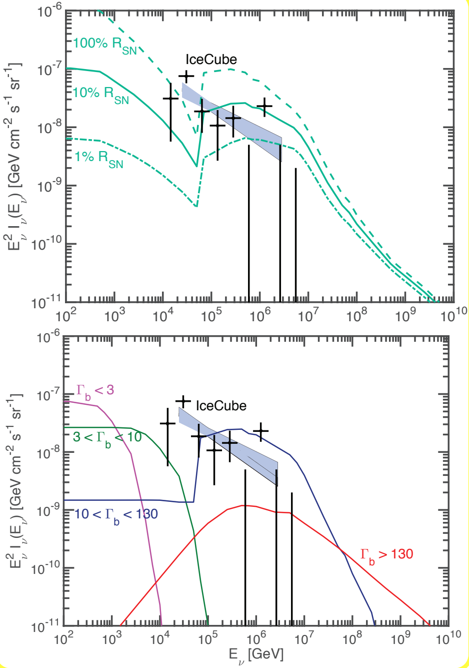
$$\int_1^{10^3} d\Gamma_b \, \Gamma_b^{\alpha_\Gamma} \beta_\Gamma = R_{\rm SN}(0)\zeta_{\rm SN}\frac{\theta_{\rm SN}^2}{2}$$

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



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

Constraints on the SN-GRB Connection



The IceCube flux could be put indirect constraints on the fraction of SNe evolving in choked bursts.

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

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

Conclusions

★ Origin of the IceCube high-energy neutrino flux not yet clear.

★ Multi-messenger approach useful to pinpoint the origin of the IceCube events.

★ Diffuse neutrino flux from starburst-like galaxies is one natural possibility.
Caveats to alleviate tension with Fermi data may be required.

★ 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.

★ Choked or hidden sources may provide a sizable neutrino contribution in the PeV range.

Thank you

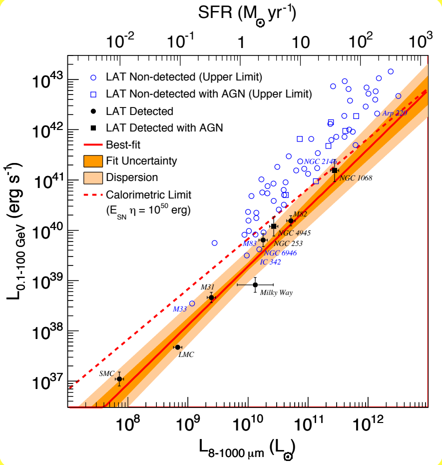
for your attention!

Back-up slides

Diffuse emission from star-forming galaxies

For each population, a parametric estimate of the IR luminosity function provided by Herschel PEP/HerMES survey.

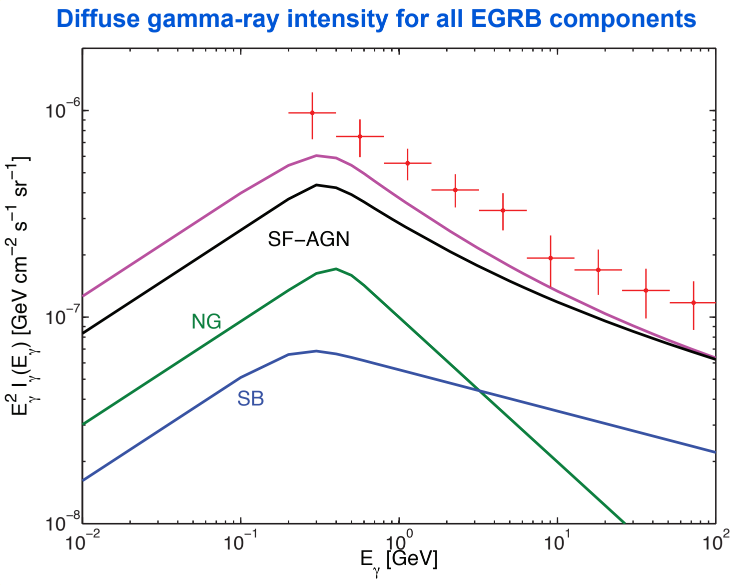
$$\Phi_X(L_{\rm IR})d\log L_{\rm IR} = \Phi_X^*\left(\frac{L_{\rm IR}}{L_X^*}\right)^{1-\alpha_X}\exp\left[-\frac{1}{2\sigma_X^2}\log^2\left(1+\frac{L_{\rm IR}}{L_X^*}\right)\right]d\log L_{\rm IR}$$



The IR luminosity is linearly related to the gamma-ray luminosity.

* C. Gruppioni et al., arXiv: 1302.5209. M. Ackermann et al., arXiv: 1206.1346.

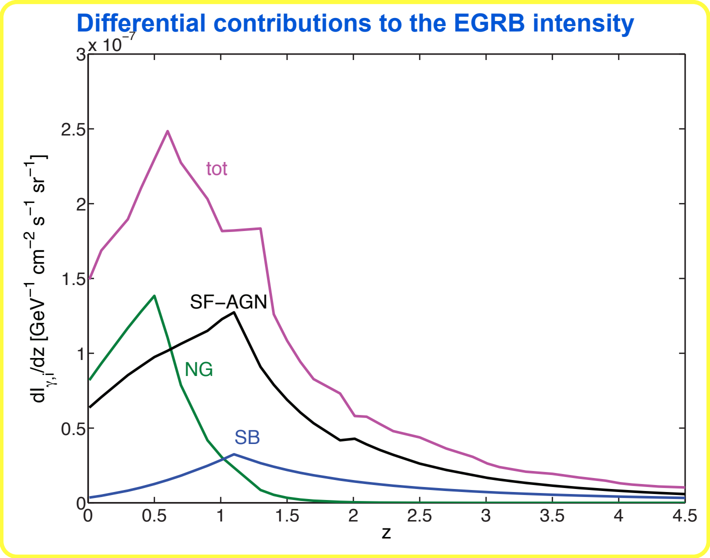
Diffuse emission from star-forming galaxies



SF-AGN give the larger contribution to the total EGRB intensity.

* Tamborra, Ando, Murase, JCAP 09 (2014) 043.

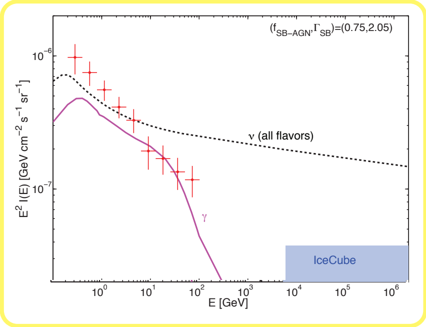
Star-Forming Galaxies

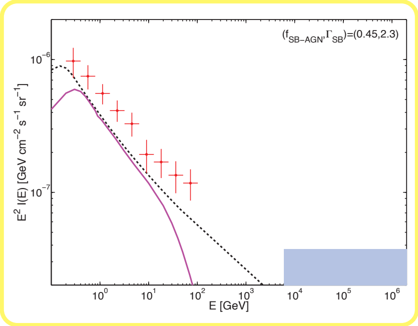


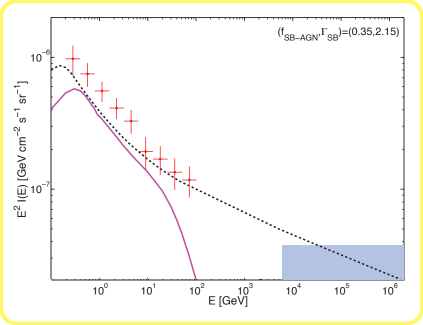
Normal galaxies leading contribution up to z=0.5. SF-AGN and SB dominate at higher z.

* Tamborra, Ando, Murase, JCAP 09 (2014) 043.

Constraints from Fermi and IceCube data



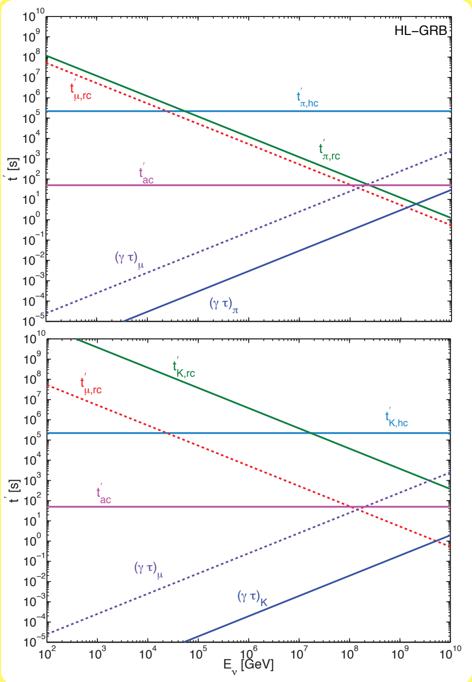




The SB spectral index matching **simultaneously** Fermi and IceCube data is $\Gamma_{SB} \simeq 2.15$.

* Tamborra, Ando, Murase, JCAP 09 (2014) 043.
See also Loeb&Waxman, JCAP 0605 (2006) 003, Murase, Ahlers, Lacki, PRD 88 (2013) 12, 121301.

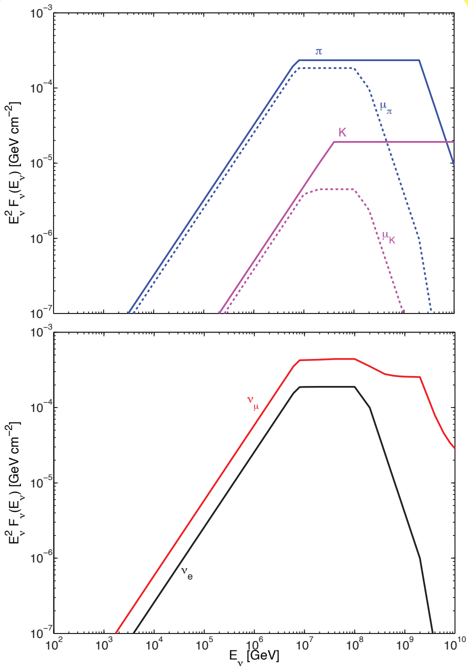
Neutrino emission from gamma-ray bursts



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

* Tamborra, Ando,JCAP (2015).

Neutrino emission from gamma-ray bursts

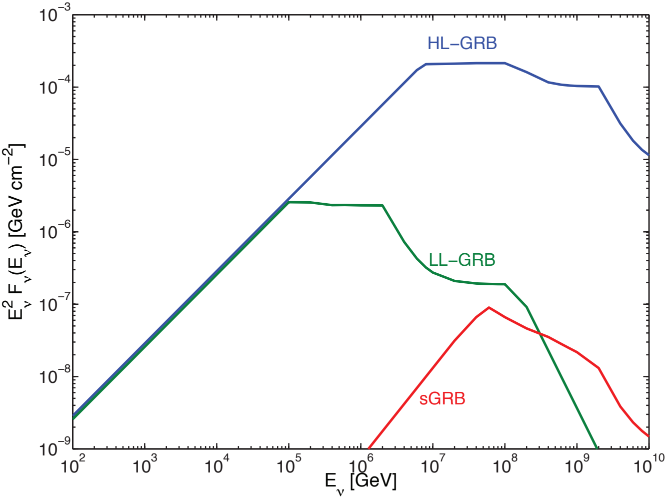


Predicted GRB flux for HL-GRB at z=1 and without flavor oscillations.

* Tamborra, Ando,JCAP (2015).

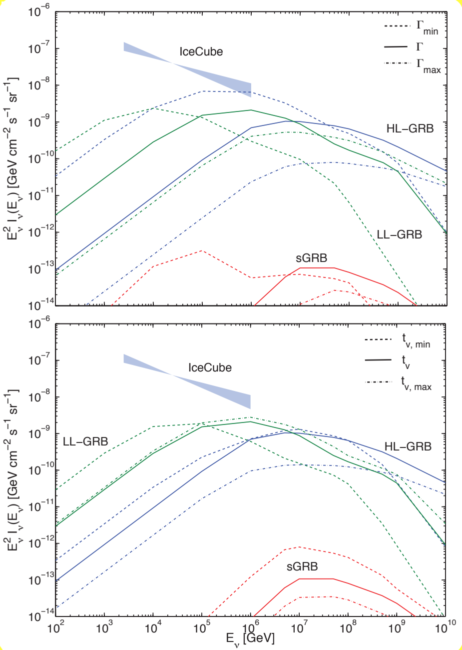
Neutrino emission from gamma-ray bursts

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).

Diffuse emission from gamma-ray bursts



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).

Constraints on the SN-GRB connection