The Niels Bohr International Academy

VILLUM FONDEN

The High Energy Neutrino Sky

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Astroparticle Theory Seminar

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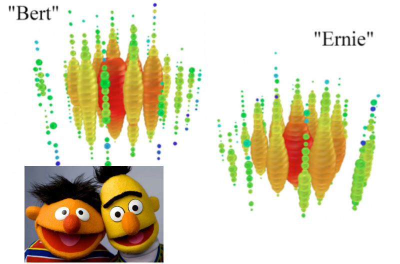
Outline

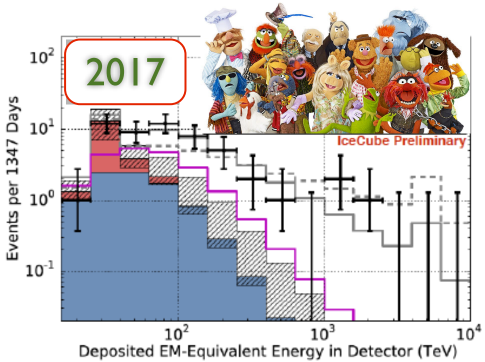
- ★ Features of high energy neutrino flux detected by IceCube
- ★ Neutrino emission from hadro-nuclear and photo-hadronic sources
- ★ Prospects for detection of point sources
- ★ Conclusions

High-energy neutrino astronomy is happening!

2013



2017

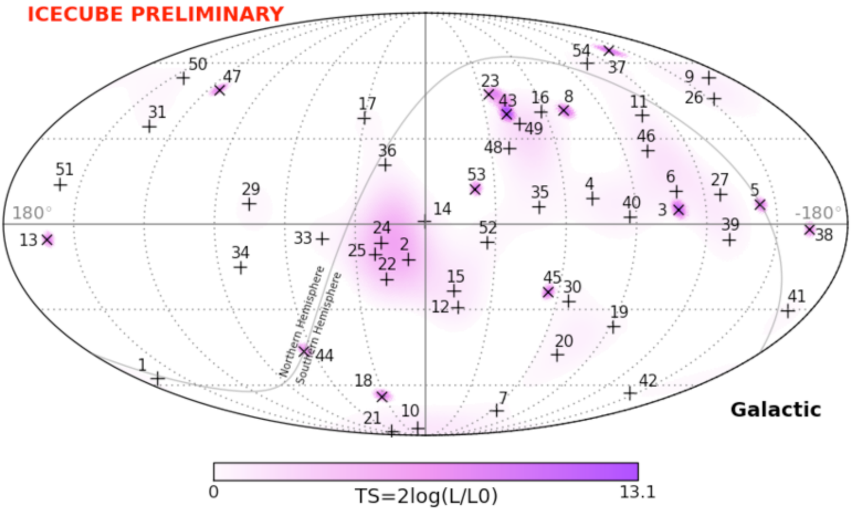


- ★ IceCube observed 54 events over four years in the 25 TeV-2.8 PeV range.
- ★ Zenith Distribution compatible with isotropic flux.
- ★ Flavor distribution consistent with $\nu_e : \nu_\mu : \nu_\tau = 1:1:1$.

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. M. Kowalski @ Neutrino 2016.

Sky Map of 54 High Energy Starting Events

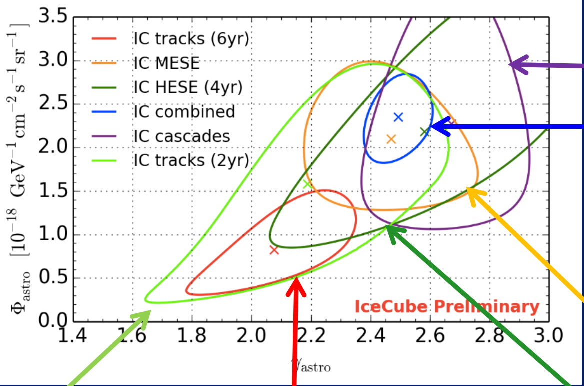


Distribution of events compatible with an isotropic one.
No evidence of (significant) correlation neither spacial nor temporal with known sources.

* Slide adapted from M. Kowalski @ Neutrino 2016.

The measured astrophysical flux

Assumed equal ν flavor ratios $(f_e:f_\mu:f_\tau)_\oplus$ = 1:1:1 at Earth
and single unbroken power-law fit



All Sky Cascades (ν_e+ν_τ) 2yr
E>10 TeV
PoS (ICRC2015) 1109

Combined fit ν_e + ν_μ+ ν_τ
PoS(ICRC2015) 1066

All Sky MESE ν_e + ν_μ+ ν_τ 2yr
E>1 TeV
PRD 91, 022001 (2015)

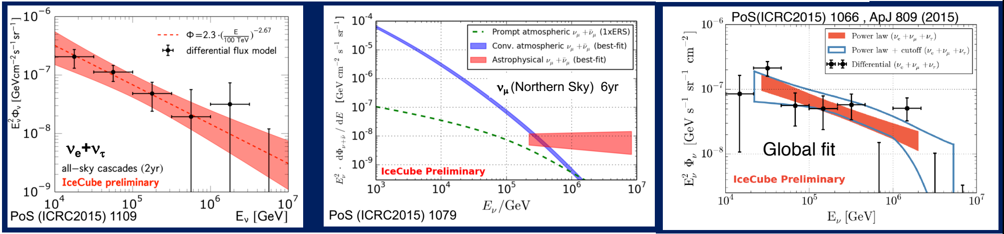
All Sky HESE ν_e + ν_μ+ ν_τ 4yr
E>60 TeV
PoS(ICRC2015) 1081

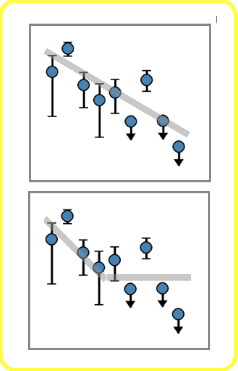
ν_μ (Northern Sky only) 2yr
PRL 115 (2015) 8, 081102

ν_μ (Northern Sky only) 6yr
PoS(ICRC2015) 1079

* Slide adapted from J. Kiryluk @ NOW 2016.

The measured astrophysical flux





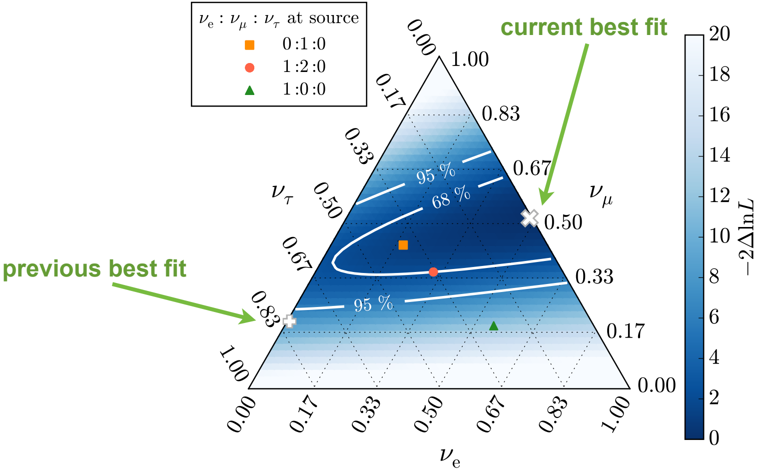
Are we seeing a spectral flattening of energy spectrum?

Combined spectral index: γ=2.50±**0.09**
High-energy tracks: γ=2.13±**0.13**
Prompt component < 1.06 x Enberg et al. (2008)

* Plots adapted from J. Kiryluk's talk @ NOW 2016.

The measured astrophysical flux

Flavor composition at Earth (combined likelihood analysis).



Not yet possible to pinpoint the production mechanism.

* IceCube Collaboration, ApJ 809 (2015) 1, 98.
See also: Bustamante, Beacom, Winter, PRL (2015). Arguelles, Katori, Salvado, PRL (2015). Palladino, Pagliaroli, Villante, Vissani, PRL (2015).

Where are these neutrinos coming from?

Where are these neutrinos coming from?

★ New physics?

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

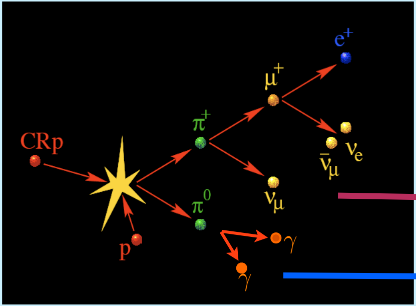
★ **Extragalactic origin [flux compatible with Waxman&Bahcall bound]**
- Star-forming galaxies
- Gamma-ray bursts
- Active galactic nuclei
- Low-power or choked sources

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

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

Neutrino Production Mechanisms

Hadronic interactions



neutrinos

gamma-rays

Lepto-hadronic interactions

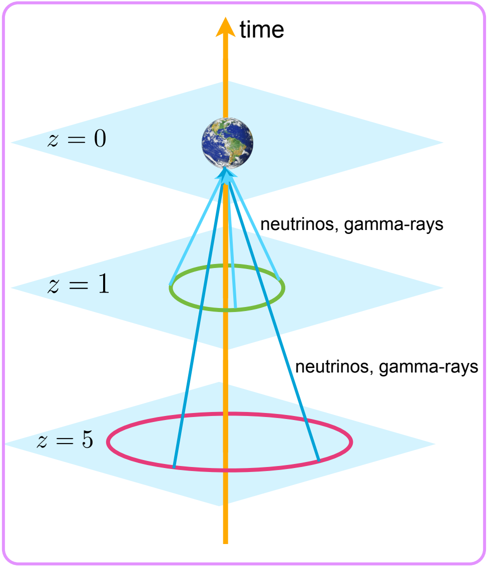
$$p + \gamma \to \Delta \to n + \pi^+, p + \pi^0$$
$$p + \gamma \to K^+ + \Lambda/\Sigma\ .$$

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

* Anchordoqui et al., PLB (2004). Kelner, Aharonian, Bugayov, PRD (2006). Kelner, Aharonian, PRD (2008).

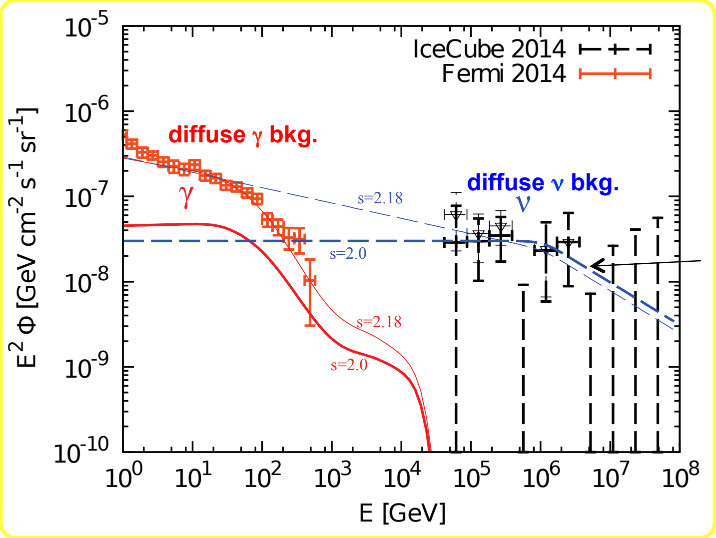
Diffuse backgrounds

Diffuse background ingredients



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

Neutrino-Gamma Connection

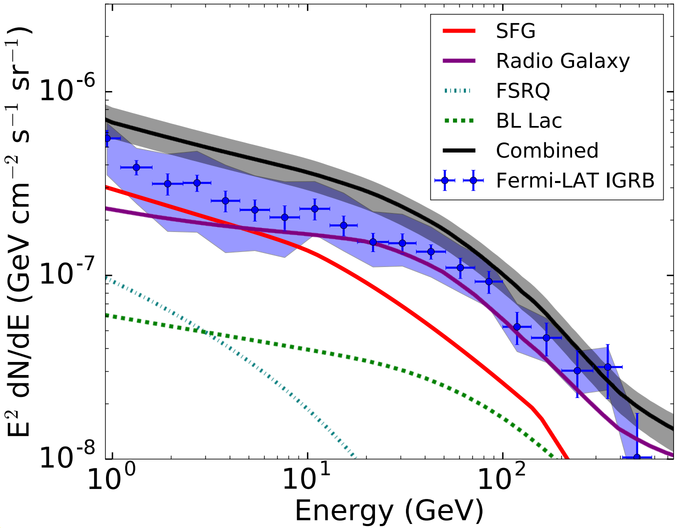


Confined cosmic rays can make both neutrinos and gamma rays.

Are gamma and neutrino backgrounds explained by the same sources?

* Murase, Ahlers, Lacki, PRD (2013). Plot adapted from Murase's talk @ Weizmann workshop 2017.

Isotropic Gamma-Ray Background



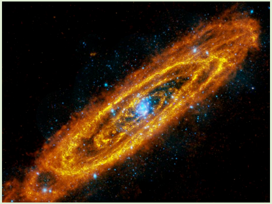
Star-forming galaxies and radio galaxies are among the main contributors to the IGRB.

* Linden, arXiv: 1612.03175.

Star-forming galaxies

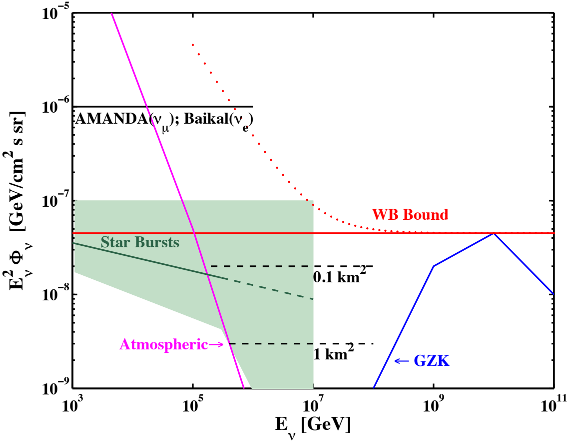
Star-forming galaxies

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



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

Starbursts efficiently produce neutrinos!



* Loeb & Waxman JCAP (2006). 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)

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

EBL correction

comoving volume

gamma-ray flux

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

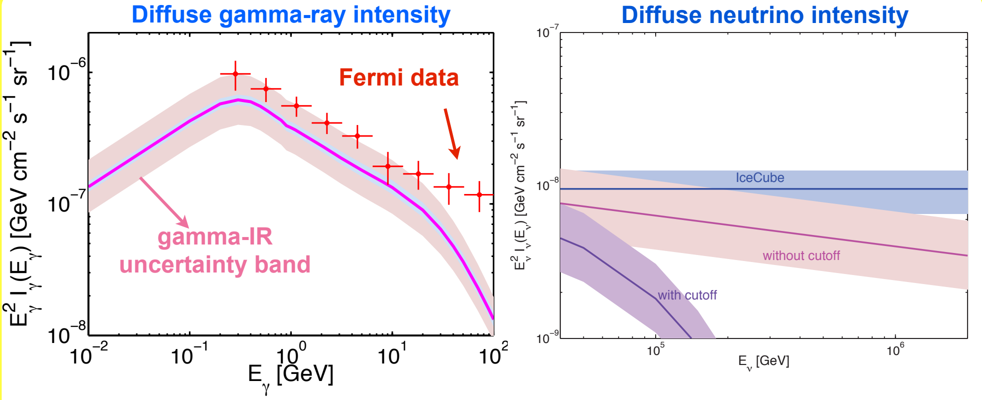
Injection spectral index (Fermi):
- $\Gamma_{\rm NG} = 2.7$ for normal galaxies
- $\Gamma_{\rm SB} = 2.2$ for starbursts

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

Gamma-ray-IR linear relation from Fermi data.

* Gruppioni et al., MNRAS (2013). Ackermann et al., ApJ (2012).

Diffuse emission from star-forming galaxies



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

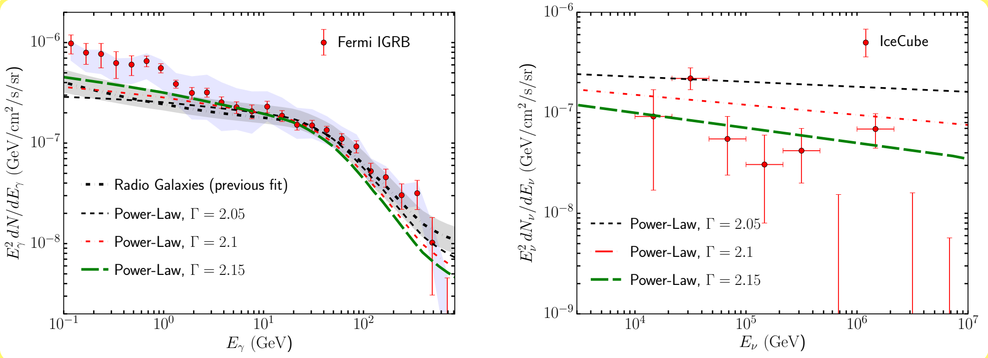
Improved modeling of starburst galaxies may be useful.

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

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).

Radio Galaxies

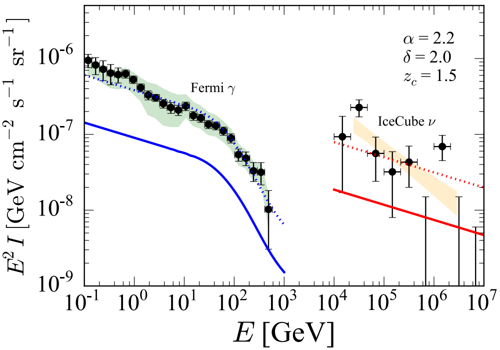
Diffuse emission from radio galaxies

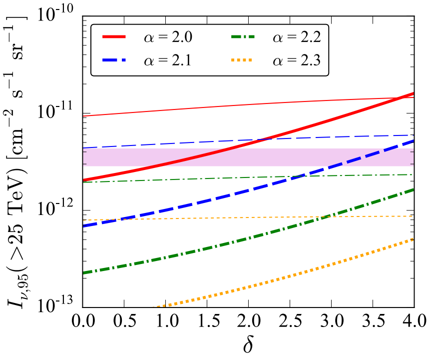


Radio galaxies (active galaxies with mis-aligned jets) can also be primary sources of the diffuse neutrino background.

* Hooper, JCAP (2016).

Tomographic constraints





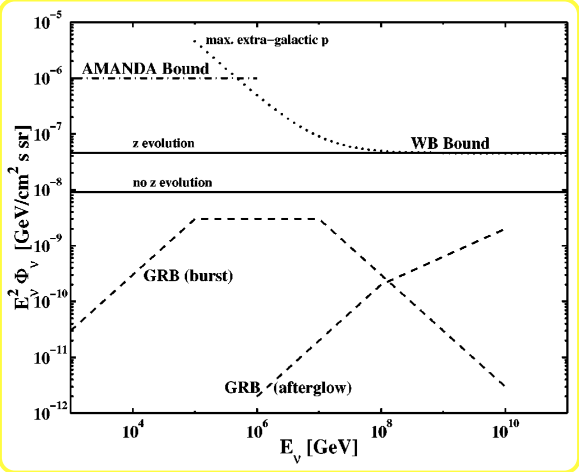
Cross-correlation between GeV gamma rays and galaxy catalogs provide bounds on the neutrino luminosity density up to **one order of magnitude tighter** than those obtained from the energy spectrum.

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 (2015).

Gamma-ray bursts

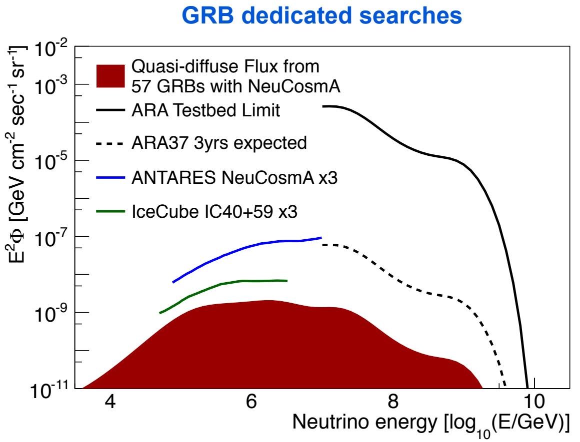
Neutrinos from gamma-ray bursts



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

* Waxman & Bahcall, PRL (1997), PRD (2001). Guetta et al., Astropart. Phys. (2004).

Neutrinos from gamma-ray bursts



Dedicated stacking searches on GRBs unsuccessful up to now.

Existing detectors are achieving relevant sensitivity.

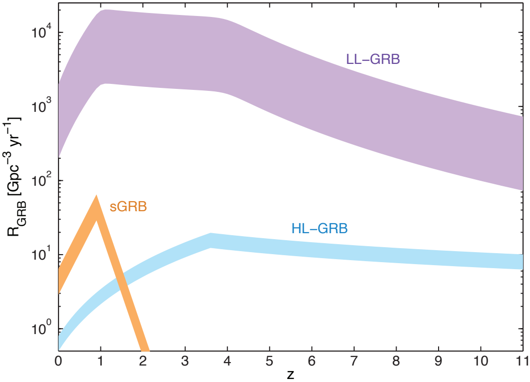
Does the diffuse emission from ALL GRB families contribute to the IceCube flux?

* Allison et al., arXiv: 1507.00100. IceCube Collaboration, ApJ (2015). ANTARES Collaboration, A&A (2013).

Diffuse emission from gamma-ray bursts

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

GRB redshift distribution



luminosity function

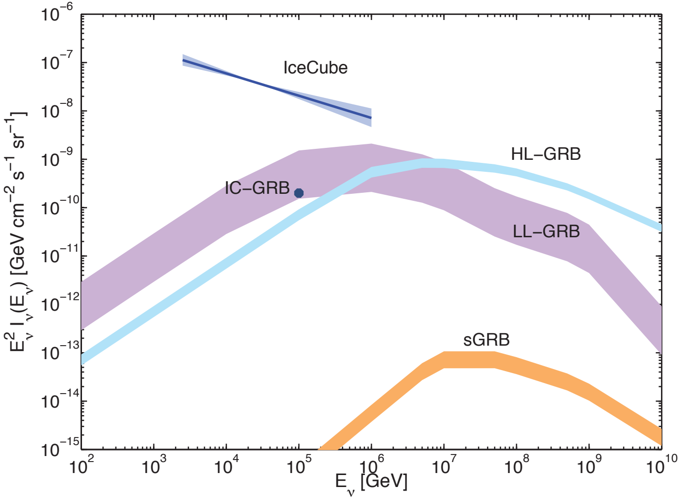
Recent work based on BATSE, Fermi and Swift data.

neutrino flux

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

* Tamborra & Ando, JCAP (2015).

Diffuse emission from gamma-ray bursts

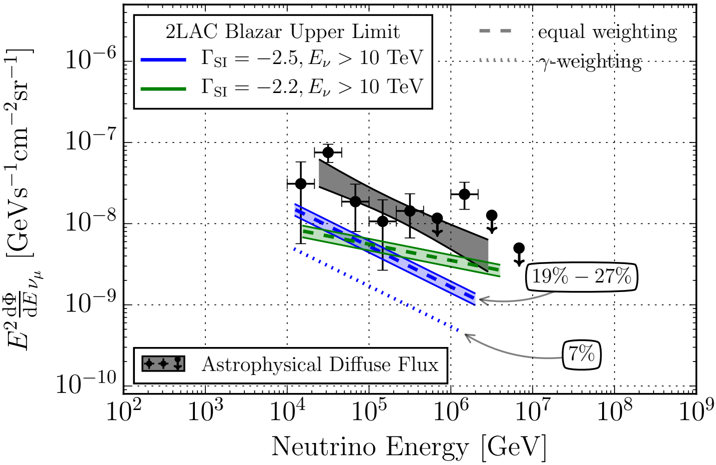


GRBs can make up to few % of the high-energy IceCube flux in the sub-PeV region.
LL-GRBs can be main sources of the IceCube flux in the PeV range.

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

Blazars

Neutrino emission from blazars

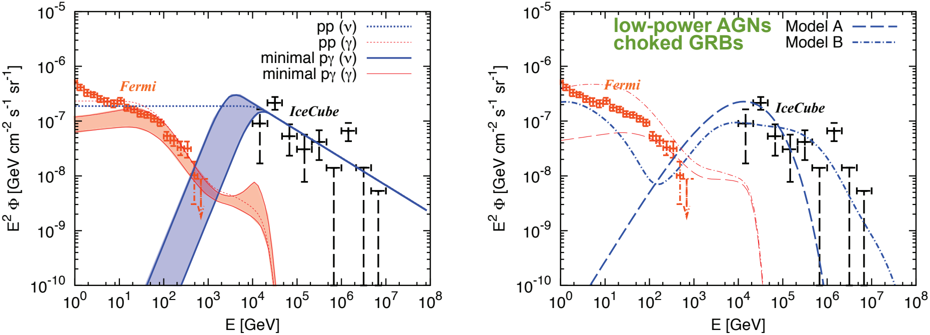


Blazars cannot explain the flux observed by IceCube.
Few PeV events may be associated with distant blazars (still low significance).

* IceCube Coll., arXiv: 1611.03874. Kadler et al., Nature Phys. (2016). Padovani, Resconi, MNRAS (2014).

Choked or low-power sources

Hidden cosmic ray accelerators

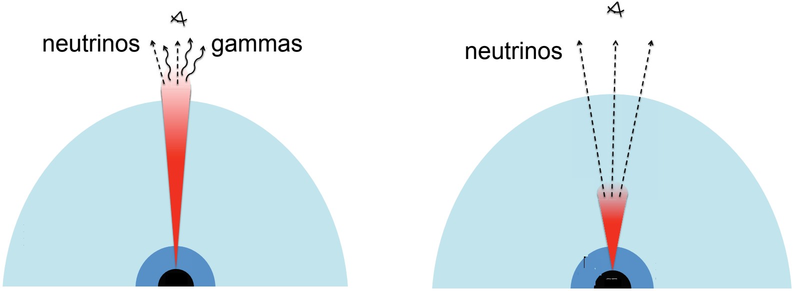


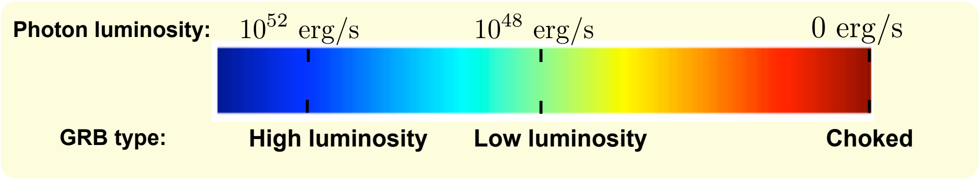
Latest data may point toward a population of CR accelerators hidden in GeV-TeV gamma-ray range. Future searches in the X-ray and MeV bands may address with issue.

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

Neutrinos from Choked Bursts

Successful GRB **Choked GRB**





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

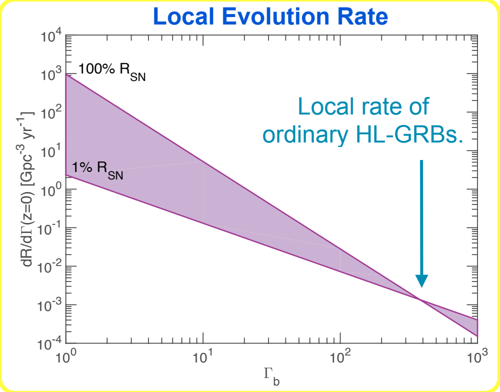
* Meszaros, Astropart. Phys. (2013). Waxman & Bahcall, PRL (1997). Meszaros & Waxman, PRL (2001). Senno et al. (2016).

Constraints on SN-GRB connection

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

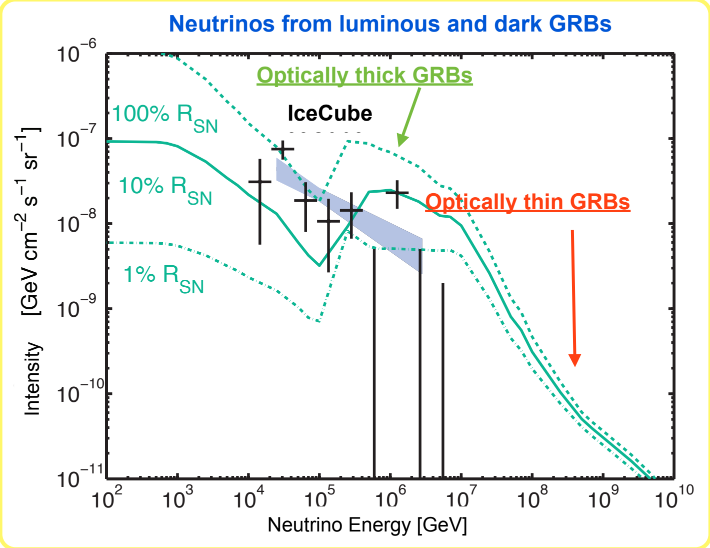
Rate evolution with the Lorentz boost factor:

$$\int_1^{10^3} d\Gamma_b \, \Gamma_b^{\alpha_\Gamma} \beta_\Gamma = R_{\rm SN}(0)\zeta_{\rm SN}\frac{\theta^2_{\rm SN}}{2}$$
$$\int_{200}^{10^3} d\Gamma_b \, \Gamma_b^{\alpha_\Gamma} \beta_\Gamma = \rho_{0,\rm HL-GRB} \, ,$$



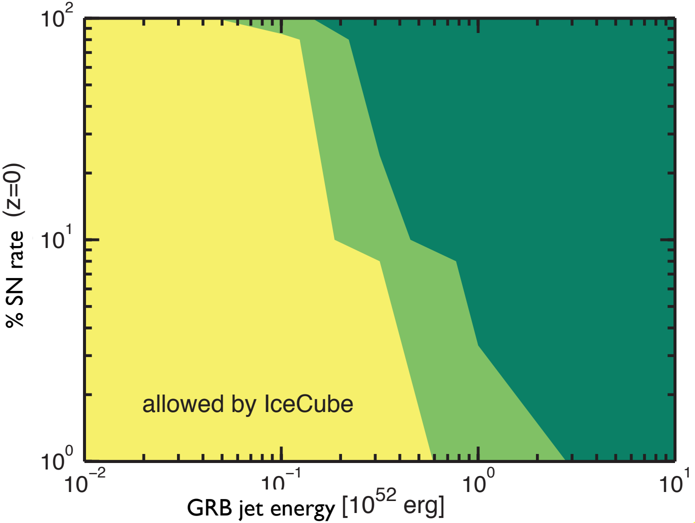
* Tamborra & Ando, PRD (2016).

Neutrinos Production in Dark GRBs



* Tamborra & Ando, PRD (2016). Senno et al. PRD (2016). Meszaros & Waxman, PRL (2001).

Constraints on the SN-GRB connection

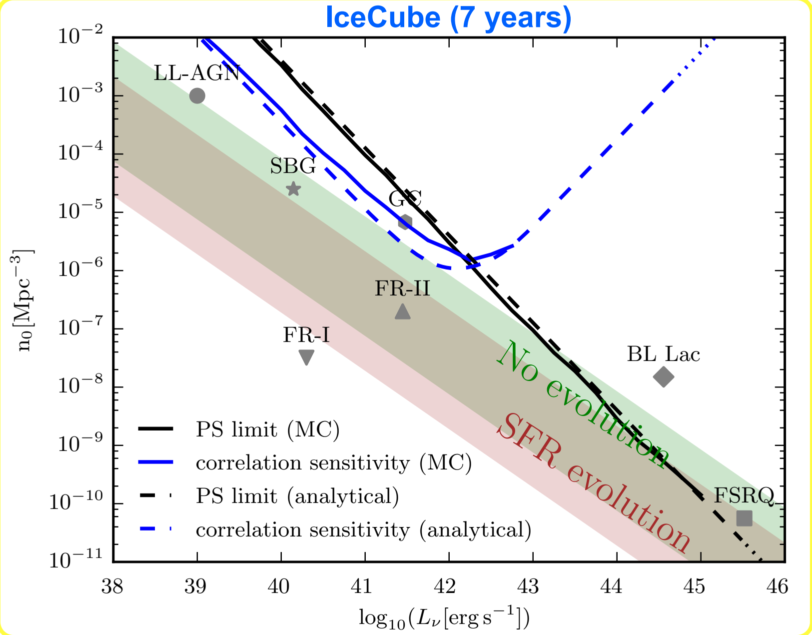


IceCube flux can put indirect constraints on the fraction of SNe evolving in choked bursts and their jet energy.

* Tamborra & Ando, PRD (2016). IceCube and ROTSE Collaborations, A&A (2012).

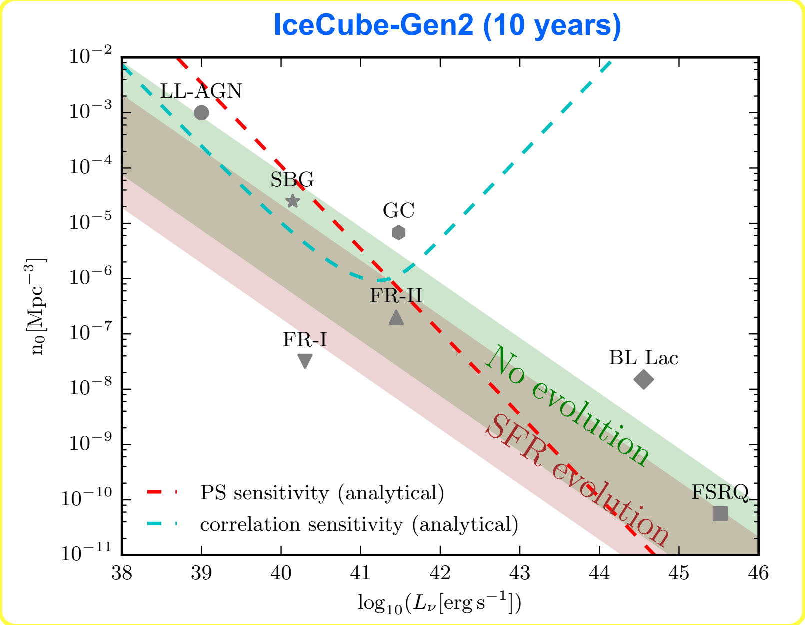
Point Source Detection

Anisotropies of the Local Universe



* Mertsch, Rameez, Tamborra, arXiv: 1612.07311. Murase & Waxman PRD (2016).
Feyereisen,Tamborra, Ando, arXiv:1610.01607.

Anisotropies of the Local Universe



* Mertsch, Rameez, Tamborra, arXiv: 1612.07311. Murase & Waxman PRD (2016).
Feyereisen,Tamborra, Ando, arXiv:1610.01607.

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.
Improved modeling required.

★ Low-luminosity gamma-ray bursts (and blazars) may dominate the PeV energy region.

★ Correlation studies with IceCube and IceCube-Gen2 will allow to place constraints on certain kind of sources provided they have the right local density and luminosity.

Thank you

for your attention!