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# Diffuse Emission of High-energy Neutrinos from Cosmic Bursts

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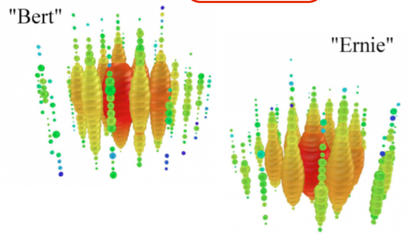
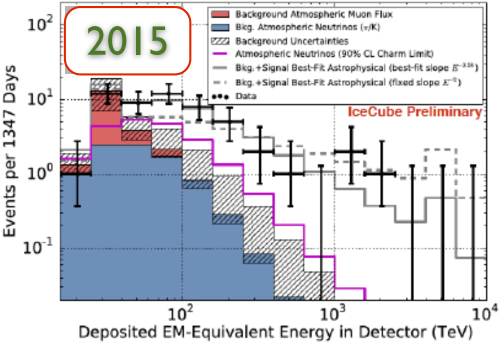
# Outline

- ★ High energy IceCube neutrino flux
- ★ Neutrino emission from star-forming galaxies
- ★ Neutrino emission from gamma-ray bursts
- ★ Conclusions

# The high-energy neutrino astronomy era has begun!

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 $\nu_e : \nu_\mu : \nu_\tau = 1:1:1$.

$7\sigma$ 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, arXiv: 1507.03991, arXiv: 1507.04005.

**Where are these neutrinos coming from?**

# Where are these neutrinos coming from?

★ New physics?

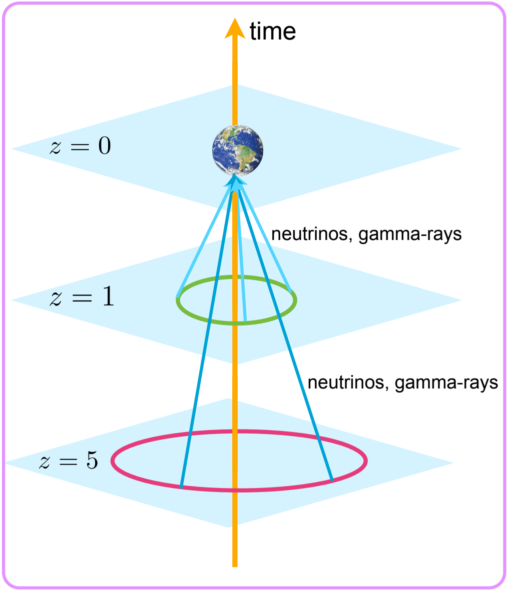
★ Galactic origin [sub-dominant contribution or new unknown sources?]

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

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

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

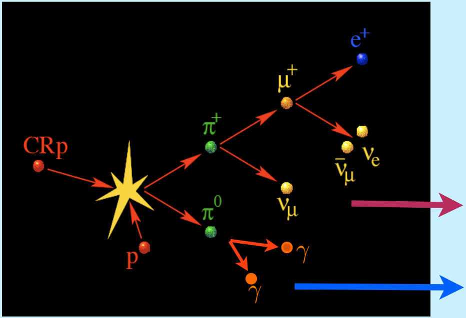
# Diffuse background ingredients




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

# Neutrino Production Mechanisms

## Hadronic interactions




neutrinos

gamma-rays

## Lepto-hadronic interactions

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

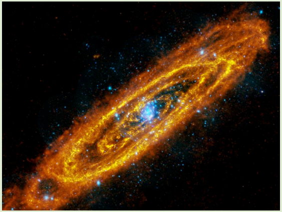
$$\begin{aligned}
\pi^+ &\to \mu^+ \nu_\mu \ , \\
\mu^+ &\to \bar{\nu}_\mu + \nu_e + e^+ \\
\pi^- &\to \mu^- \bar{\nu}_\mu \ , \\
\mu^- &\to \nu_\mu + \bar{\nu}_e + e^- \\
K^+ &\to \mu^+ + \nu_\mu \ , \\
n &\to p + e^- + \bar{\nu}_e
\end{aligned}$$


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

# Star-forming galaxies

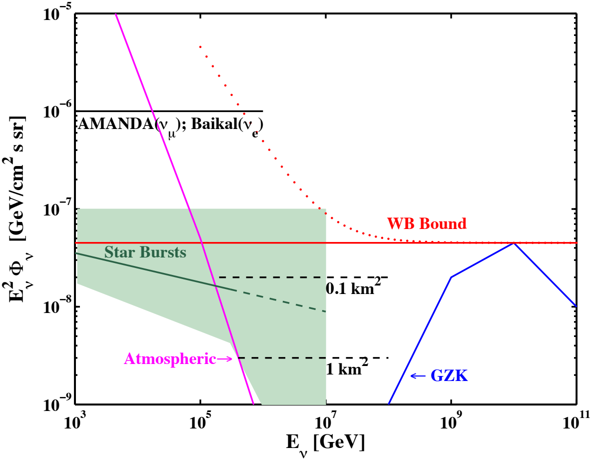
# Star-forming galaxies

**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
$\Phi_X(L_\gamma, z) = d^2N_X/dVdL_\gamma$

gamma-ray flux

EBL correction

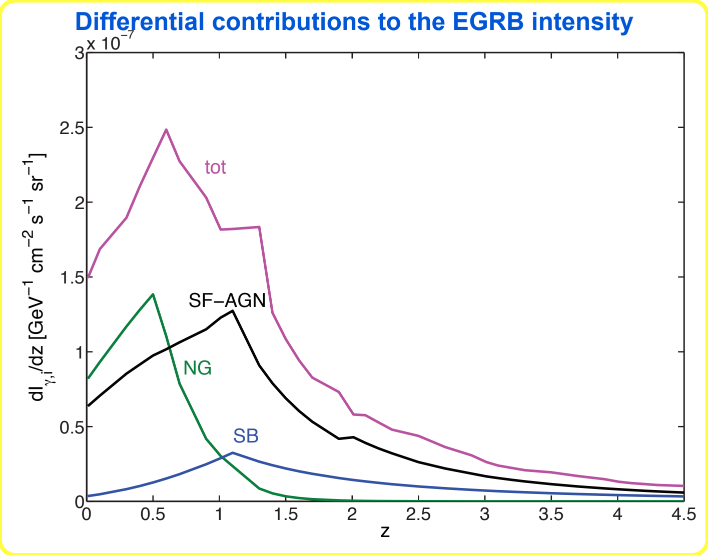
Injection spectral index:
- $\Gamma_{\mathrm{NG}} = 2.7$ for normal galaxies
- $\Gamma_{\mathrm{SB}} = 2.2$ for starbursts
- SB-like or NG-like according to z for SF-AGN

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

Gamma-ray-IR linear relation from Fermi data.

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

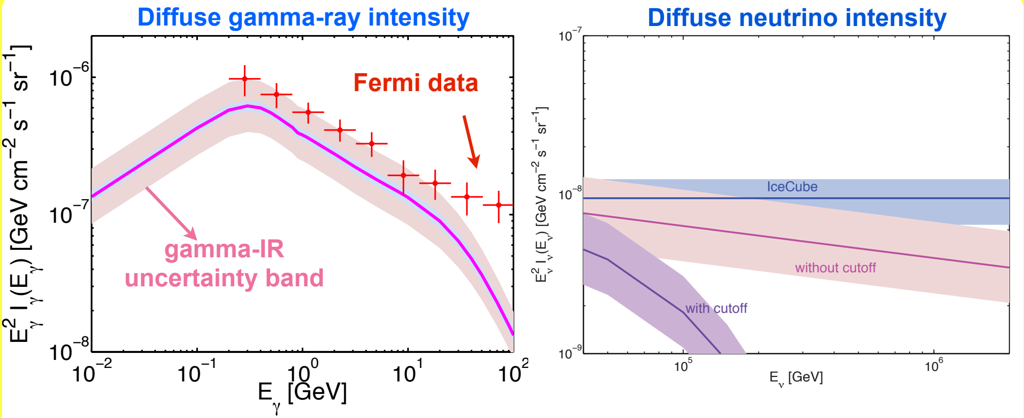
# Star-forming galaxies




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

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

# 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.

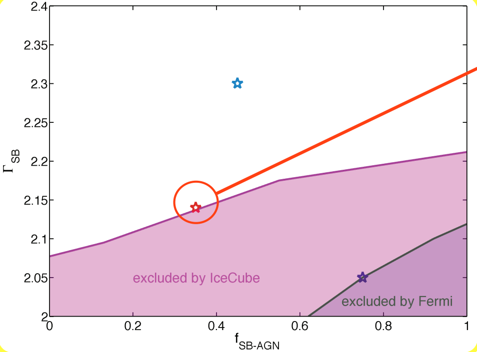
See also: Strong et al. (1976), Thompson et al. (2006), Fields et al. (2010), Makiya et al. (2011), Stecker&Venters(2011). Loeb&Waxman (2006), Lacki et al. (2011), Murase et al. (2013).

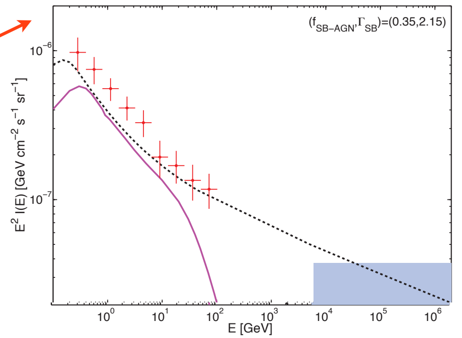
# Constraints from Fermi and IceCube data

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



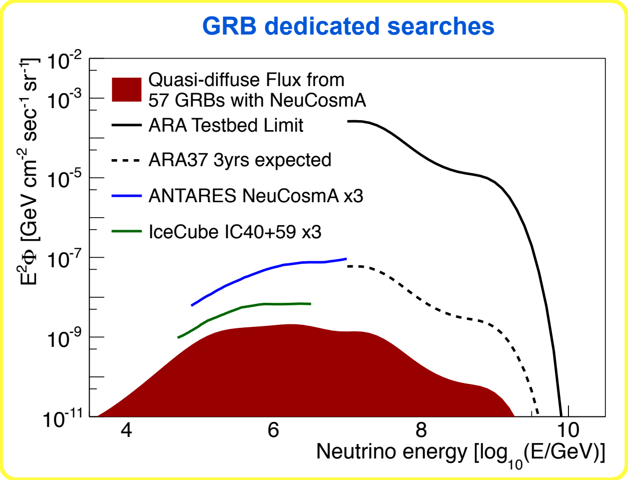




The SB spectral index matching **simultaneously** Fermi and IceCube data is $\Gamma_{SB} \simeq 2.15$.

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

# Gamma-ray bursts

# Neutrinos from gamma-ray bursts




Dedicated stacking searches on GRBs unsuccessful up to now.

Existing detectors are achieving relevant sensitivity.

* 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

**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**

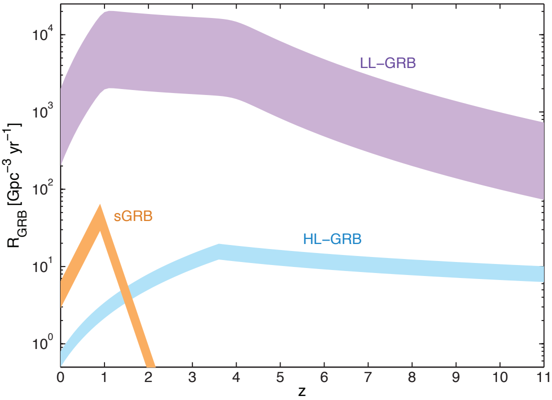
$\tilde{L}_{\rm iso} = 10^{48}{\rm erg/s}$ , $\Gamma = 5$, $t_v = 100s$ .

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

# Diffuse emission from gamma-ray bursts

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

**GRB redshift distribution**




**luminosity function**

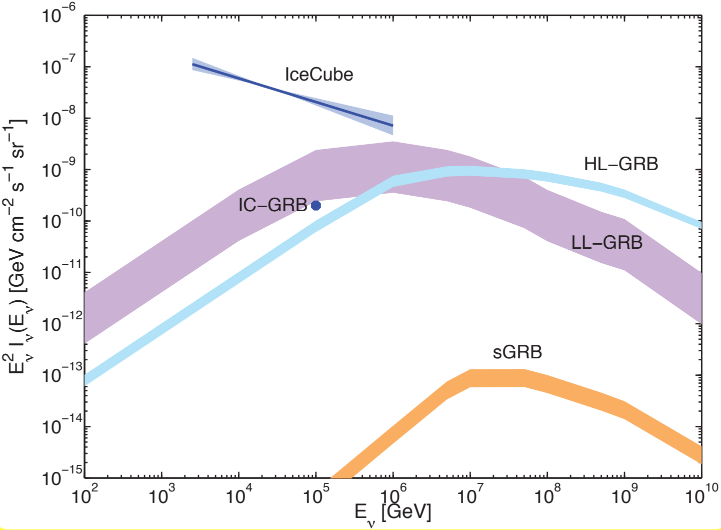
Recent work based on BATSE, Fermi and Swift data.

**neutrino flux**

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

* Tamborra & Ando, arXiv: 1504.00107.

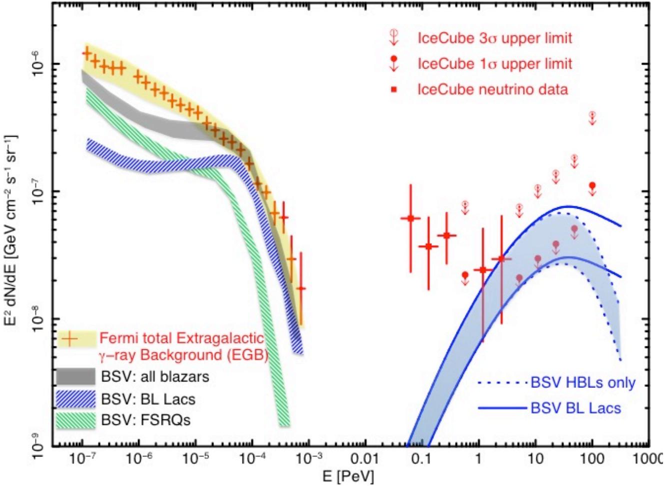
# Diffuse emission from gamma-ray bursts




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, arXiv: 1504.00107.
See also: Liu&Wang (2013), Murase&Ioka (2013), Razzaque & Yang (2015), Baerwald, Bustamante, Winter (2015).

# Blazars




Besides GRBs, blazars could also contribute to the neutrino background for E>0.5 PeV.

* Padovani, Petropoulou, Giommi, Resconi, arXiv:1506.09135.

# Conclusions

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

★ Diffuse neutrino flux from starburst-like galaxies is one natural possibility for E < 0.5 PeV.

★ Spectral index matching **simultaneously** Fermi and IceCube data ~$\Gamma_{SB} \simeq 2.15$.

★ 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.

Thank you

for your attention!