Neutrino decays over cosmological distances: GRBs

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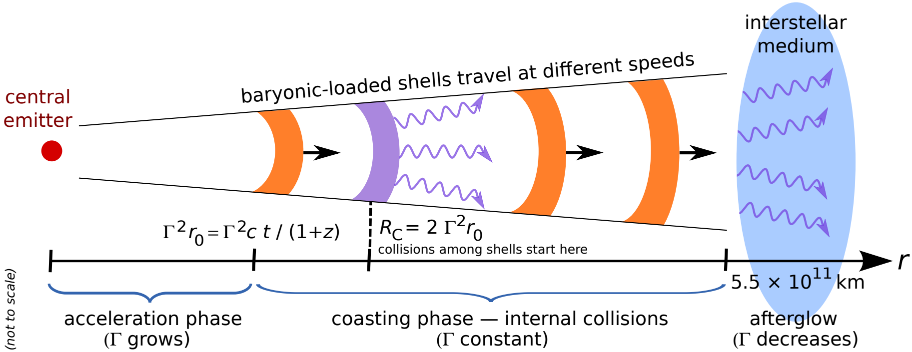
THE OHIO STATE UNIVERSITY

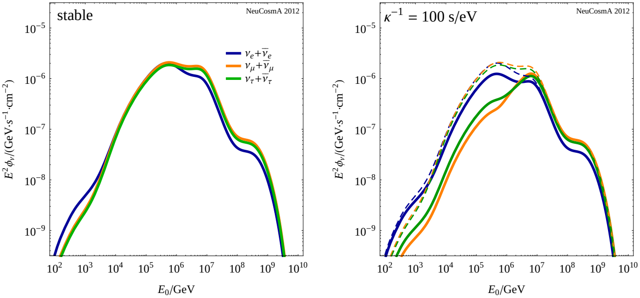
CCAPP

Fireball model: our current paradigm of how a GRB works

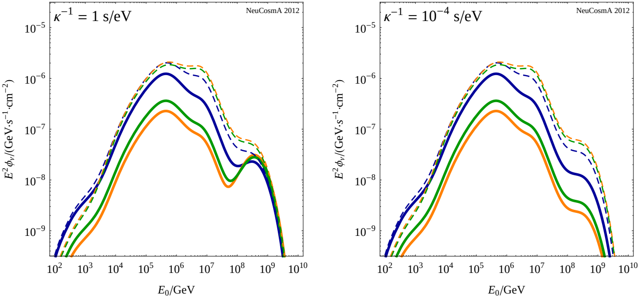
– relativistically-expanding blobs of plasma collide with each other and, in the process, emit UHE particles



UHE ν flux from a standard burst (ν_1 stable and $\nu_{2,3}$ unstable):

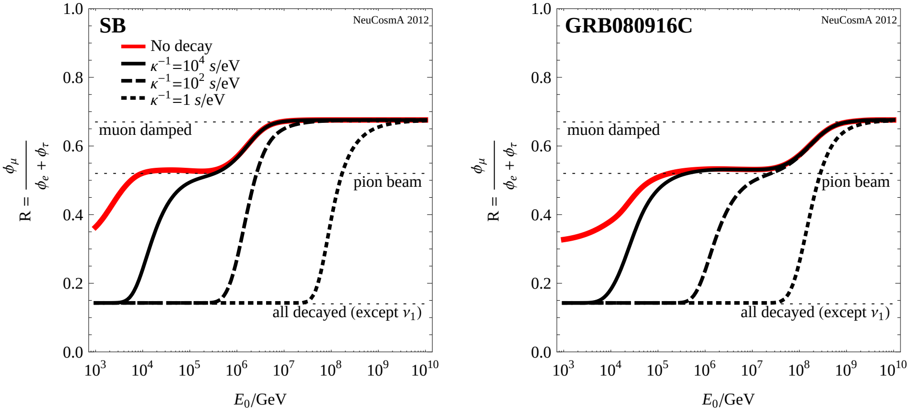


P. Baerwald, MB, W. Winter, *JCAP* **1210**, 020 (2012) [arXiv:1208.4600]



Flavour ratio:

$$R = \frac{\phi_\mu}{\phi_e + \phi_\tau} \approx \frac{\text{number of muon tracks}}{\text{number of cascades}}$$



P. Baerwald, MB, W. Winter, *JCAP* **1210**, 020 (2012) [arXiv:1208.4600]

Quasi-diffuse flux (stacking the same 117 GRBs from IC-40 analysis):

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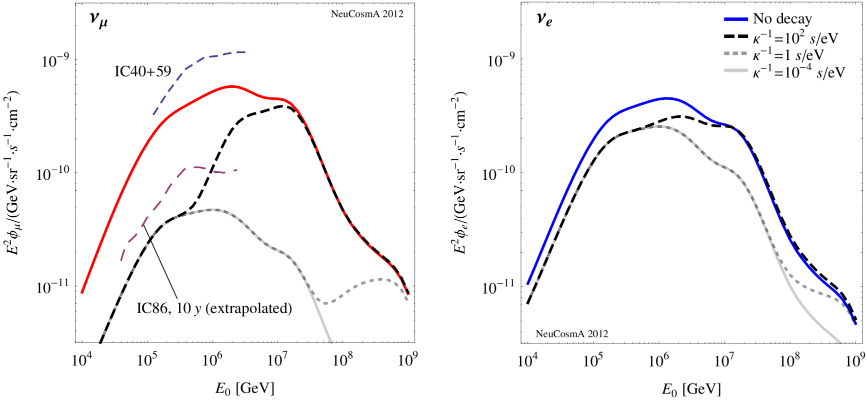


Fewer muon tracks found because they decayed?

No reliable information on astrophysical neutrino sources can be obtained from muon tracks only

Backup slides

Joint production of UHECRs, ν's, and γ's:

power law $\sim E^{-\alpha_p}$

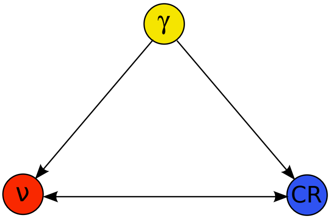
broken power law

$$p\,\gamma \to \Delta^+(1232) \to \begin{cases} n\pi^+ , & \mathrm{BR} = 1/3 \\ p\pi^0 , & \mathrm{BR} = 2/3 \end{cases}$$

$$\pi^+ \to \mu^+\nu_\mu \to \bar{\nu}_\mu e^+ \nu_e \nu_\mu$$

$$\pi^0 \to \gamma\gamma$$

$$n \text{ (escapes)} \to p e^- \bar{\nu}_e$$



(Δ^+: ~50% of all $p\gamma$ interactions)

After propagation, with flavour mixing:

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

("one ν_μ per cosmic ray")

CR emission by n escape only is now strongly disfavoured

ICECUBE COLL., *Nature* **484**, 351 (2012)
AHLERS ET AL. *Astropart. Phys.* **35**, 87 (2011)

In a collision, UHE protons, photons, and neutrinos are emitted:

$$\underbrace{N_p'\left(E_p'\right)}_{\text{proton density at the source [GeV}^{-1}\text{ cm}^{-3}]} \overset{\text{NeuCosmA}}{\otimes} \underbrace{N_\gamma'\left(E_\gamma'\right)}_{\text{photon density at the source}}$$

$$= \underbrace{Q_\nu'\left(E_\nu'\right)}_{\text{ejected neutrino spectrum [GeV}^{-1}\text{ cm}^{-3}\text{ s}^{-1}]}$$

- From Fermi shock acceleration: $N_p'\left(E_p'\right) \propto E_p'^{-\alpha_p} e^{-E_p'/E_{p,\mathrm{max}}'}$
- Photon density at source has same shape as observed:

$$N_\gamma'\left(E_\gamma'\right) = \begin{cases} \left(E_\gamma'/E_{\gamma,\mathrm{break}}'\right)^{-\alpha_\gamma} & , \ E_{\gamma,\mathrm{min}}' \leq E_\gamma' < E_{\gamma,\mathrm{break}}' \\ \left(E_\gamma'/E_{\gamma,\mathrm{break}}'\right)^{-\beta_\gamma} & , \ E_\gamma' \geq E_{\gamma,\mathrm{break}}' \\ 0 & , \ \text{otherwise} \end{cases}$$

$$\alpha_\gamma = 1,\ \beta_\gamma = 2.2,\ E_{\gamma,\mathrm{min}}' = 0.2\ \mathrm{eV},\ E_{\gamma,\mathrm{break}}' = 1\ \mathrm{keV}$$

Normalise the densities at the source – for one collision:

- Photons:

$$\underbrace{\int E'_\gamma \, N'_\gamma \left(E'_\gamma\right) \, dE'_\gamma}_{\text{total energy density in photons}} = \frac{E'^{\text{iso}}_{\gamma-\text{sh}}}{V'_{\text{iso}}}$$

- Protons:

baryonic loading (energy in p's / energy in e's + γ's), *e.g.*, 10

$$\underbrace{\int E'_p \, N'_p \left(E'_p\right) \, dE'_p}_{\text{total energy density in protons}} = \boxed{\frac{1}{f_e}} \frac{E'^{\text{iso}}_{\gamma-\text{sh}}}{V'_{\text{iso}}}$$

NeuCosmA calculates the injected/ejected spectrum of secondaries (π, K, n, ν, etc.):

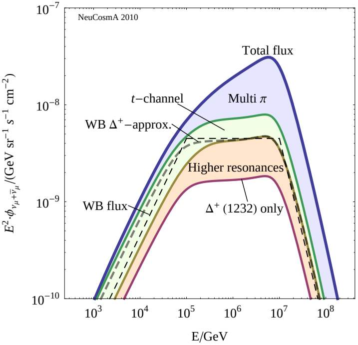
$x \equiv E'/E'_p$ $\quad$ $y \equiv E'_p E'_\gamma / \left(m_p c^2\right)$

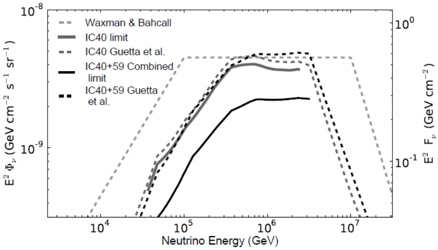
$$Q'\left(E'\right) = \int_{E'}^{\infty} \frac{dE'_p}{E'_p} N'_p\left(E'_p\right) \int_0^{\infty} c \, dE'_\gamma \, N'_\gamma\left(E'_\gamma\right) \underbrace{R}_{\text{response function}} \left(x, y\right)$$

R contains cross sections, multiplicities for different channels

What does NeuCosmA include?

- $p\gamma \to \Delta^+(1232) \to \pi^0, \pi^+, \ldots$
- extra K, n, π^-, multi-π production modes
- synchrotron losses of secondaries
- adiabatic cooling
- full photon spectrum
- neutrino flavour transitions





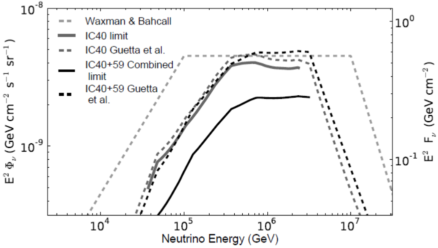
IceCube Collaboration:

- ν flux normalised to GRB γ fluence:

$$\int_0^\infty dE_\nu E_\nu F_\nu\,(E_\nu) \propto \int_{1\text{ keV}}^{10\text{ MeV}} d\varepsilon_\gamma \varepsilon_\gamma F_\gamma\,(\varepsilon_\gamma)$$

- quasi-diffuse ν flux from 117 GRBs
- analytical calculation – in tension with upper bounds

ICECUBE COLL., *Nature* **484**, 351 (2012)
AHLERS ET AL. *Astropart. Phys.* **35**, 87 (2011)
GUETTA ET AL. *Astropart. Phys.* **20**, 429 (2004)



More detailed particle physics (NeuCosmA):

- extra multi-π, K, n production modes
- synchrotron losses of secondaries
- adiabatic cooling
- full photon spectrum, etc.

ν flux $\sim$ one order of magnitude lower

Baerwald, Hümmer, Winter, *PRL* **108**, 231101 (2012)

See also: He, Liu, Wang, *ApJ* **752**, 29 (2012)

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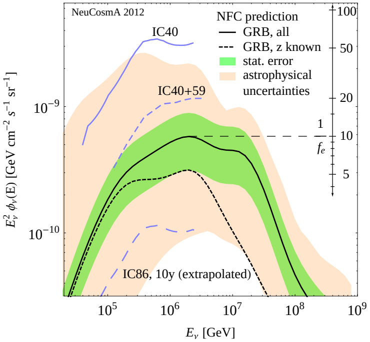

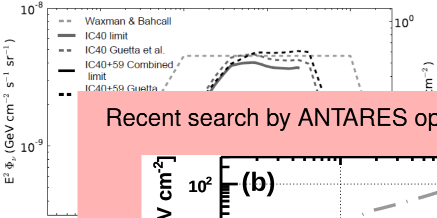

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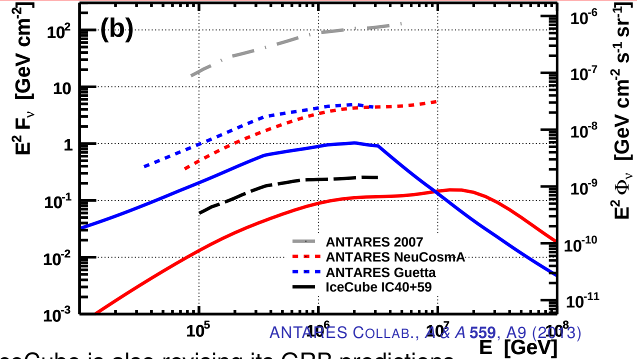
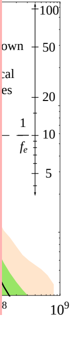
Recent search by ANTARES optimised for NeuCosmA:



ANTARES COLLAB., *A & A* **559**, A9 (2013)

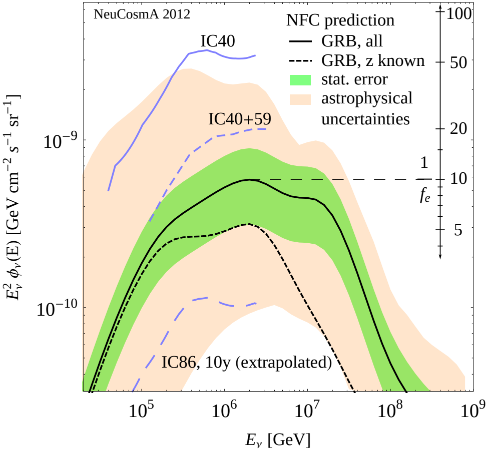
► IceCube is also revising its GRB predictions



- Same $n = 117$ GRBs, effective area, and parameters as used by the IC-40 analysis
- Calculate the associated neutrino flux for each burst and the stacked flux $F_\nu(E_\nu)$
- Quasidiffuse flux:

$$\phi_\nu(E_\nu) = F_\nu(E_\nu) \frac{1}{4\pi} \frac{1}{n} \frac{667 \text{ bursts}}{\text{yr}}$$

- Statistical uncertainty: extrapolation of a few bursts to a quasidiffuse flux
- Astrophysical uncertainty:
  - $0.001 \leq t_v \text{ [s]} \leq 0.1$
  - $200 \leq \Gamma \leq 500$
  - $1.8 \leq \alpha_p \leq 2.2$
  - $0.1 \leq \epsilon_e/\epsilon_B \leq 10$



S. Hümmer, P. Baerwald, and W. Winter, *Phys. Rev. Lett.* **108**, 231101 (2012)