High-energy neutrinos, cosmic rays, and gamma rays from GRBs

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IceCube Particle Astrophysics

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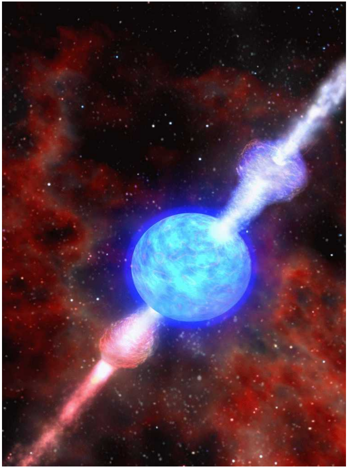
THE OHIO STATE UNIVERSITY

CENTER FOR COSMOLOGY AND ASTROPARTICLE PHYSICS

Why are GRBs natural ν source candidates?



1. They are bright
   - $10^{52} - 10^{53}$ erg in gamma rays
   - Gamma rays up to $\sim$ 100 GeV

   Implies possible acceleration of protons to high energies

2. They have fast time-variability
   - Structure at 0.01 s scale
   - Compact objects

   Implies high proton and photon number densities

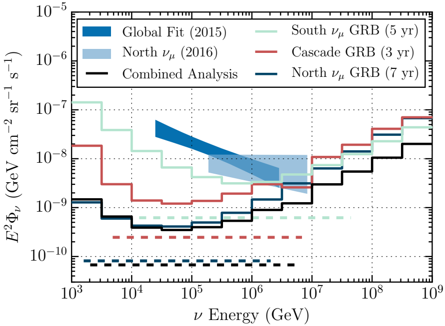
Original expectation:
GRBs produce copious high-energy neutrinos via $p\gamma$ interactions

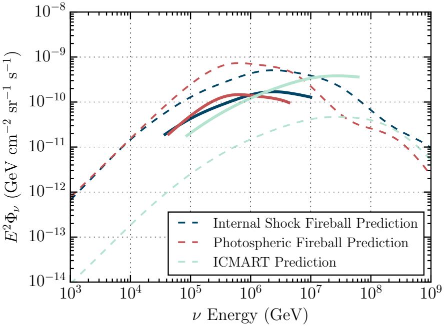
Our expectations, unrewarded?

IceCube has not found neutrinos associated to GRBs

- 3 yr of showers (all flavors) + 7 yr of upgoing tracks + 5 of downgoing tracks
- 1172 GRBs
- No statistically significant coincidence

Only $\lesssim$ 0.4% of the diffuse flux can be from prompt GRB emission





IceCube, 1702.06868

The  in the room

Why is it still interesting to look for GRB neutrinos?

1. Best candidates for joint high-energy e.m.–neutrino emission
2. Potential sources of ultra-high-energy cosmic rays

Also . . .

3. "Choked" bursts might contribute sizeably to the diffuse flux

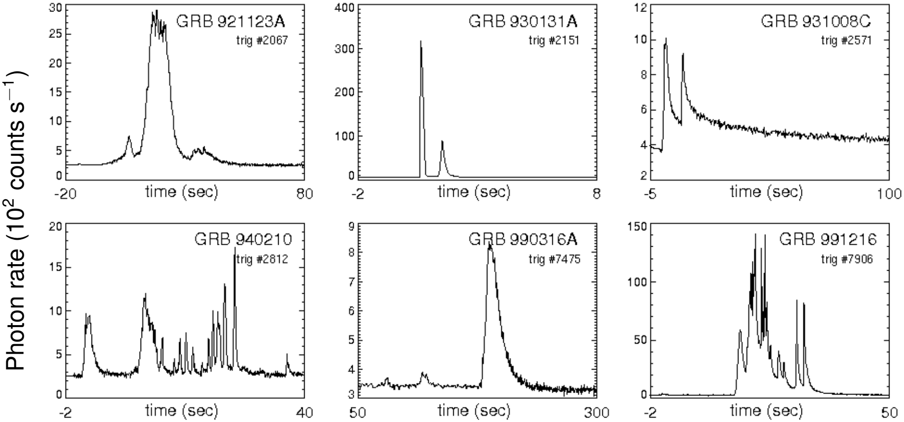
   e.g., [P. Mészaros, E. Waxman 2001] [N. Senno, K. Murase, P. Mészaros 2016] [I. Tamborra, S. Ando 2016]

4. Neutrinos from GRB afterglows expected at $\sim$ EeV

   e.g., [K. Murase 2007] [S. Razzaque, L. Yang 2015]

So, every bit of insight into how GRBs make neutrinos helps

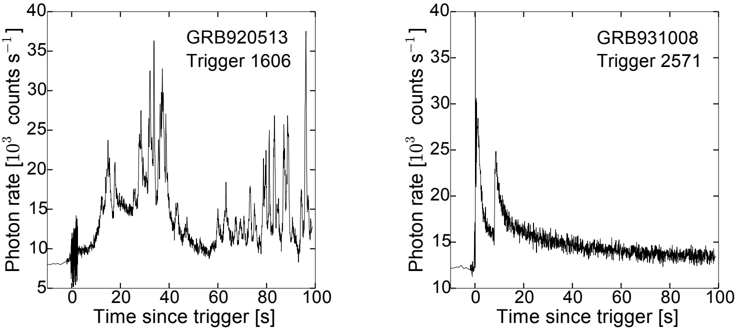
GRBs — a zoo of light curves



BATSE

Which GRB is brighter in neutrinos?

Just from looking at these gamma-ray light curves,



can we tell which GRB is likely bright in neutrinos?

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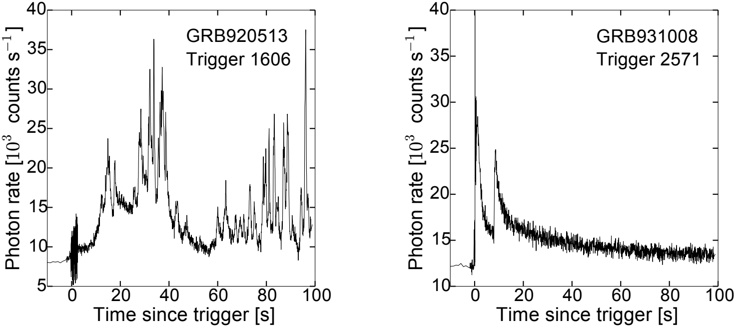

Fast time variability | Slow pulse + fast variability

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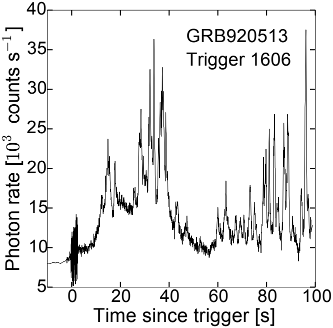
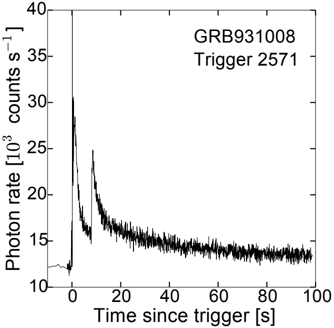


Fast time variability

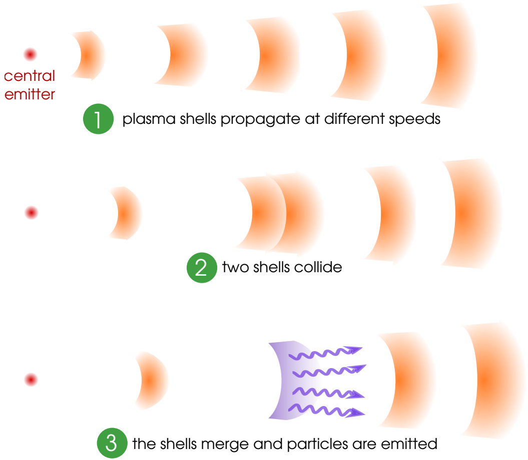


Slow pulse + fast variability

can we tell which GRB is likely bright in neutrinos?

(**Answer:** yes, the one on the left)

The fireball model — internal collisions



Energy in photons and electrons $\approx$ Energy in magnetic fields

Energy in relativistic protons $\gtrsim 10 \times$ Energy in photons and electrons

Producing ν's, CRs, γ rays

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

broken power law

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

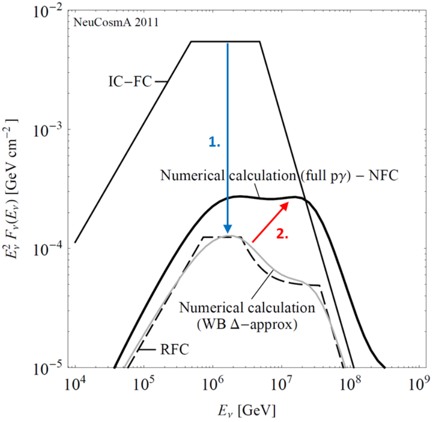
$$\pi^+ \to \mu^+\nu_\mu \to \bar{\nu}_\mu e^+ \nu_e \nu_\mu$$

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

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

We use NeuCosmA:

- More production channels
- Detailed particle interactions
- Flavor mixing



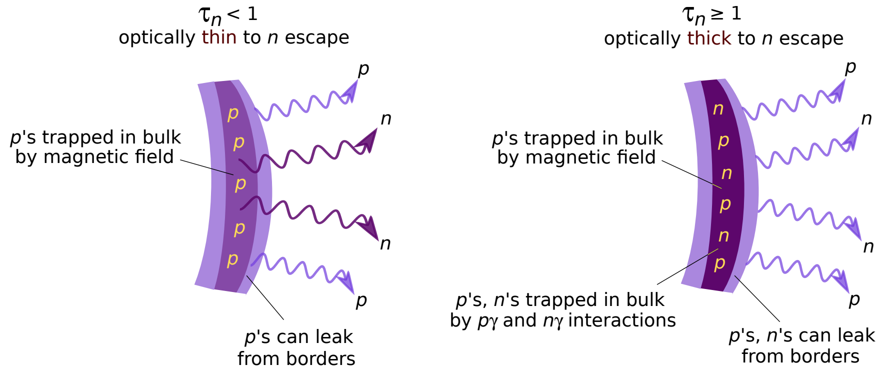
energy in neutrinos $\propto$ energy in gamma rays

S. Hümmer, P. Baerwald, W. Winter, *PRL* **108**, 231101 (2012)

Two forms of UHECR escape

- Neutrons, produced together with ν's; or
- Protons that leak out without producing ν's in the source

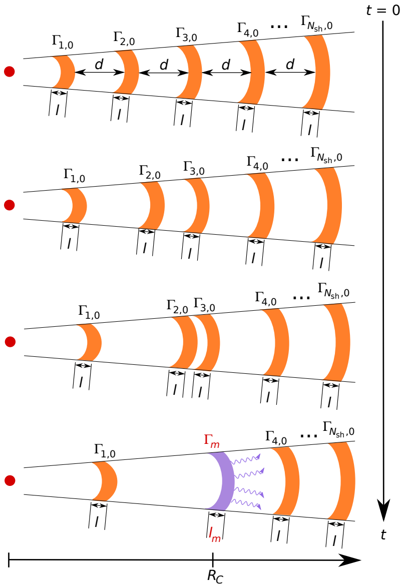
Relative contributions determined by $\tau_n \equiv \left(t_{p\gamma}^{-1} / t_{\mathrm{dyn}}^{-1} \right) \Big|_{E'_{p,\max}}$



P. Baerwald, MB, W. Winter, *ApJ* **768**, 186 (2013)
P. Baerwald, MB, W. Winter, *Astropart. Phys.* **62**, 66 (2015)
See also: H. He *et al.*, *ApJ* **752**, 29 (2012)

An evolving fireball

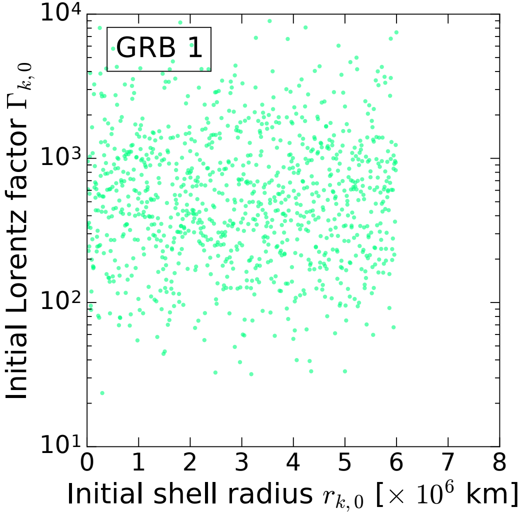
- The fireball expands with time
- Particle densities $\propto R_C^{-2}$
- $\sim$ 1000 shells
- Different speeds, masses
- They collide at different radii



S. Kobayashi, T. Piran, R. Sari, *ApJ* **490**, 92 (1997)
F. Daigne, R. Mochkovitch, *MNRAS* **296**, 275 (1998)

Initial distribution of shell speeds

Broad distribution — slow and fast shells fast each other early



MB, Baerwald, Murase, Winter, *Nat. Commun.* 2015

Tracking each collision individually

Each collision occurs in a different emission regime —

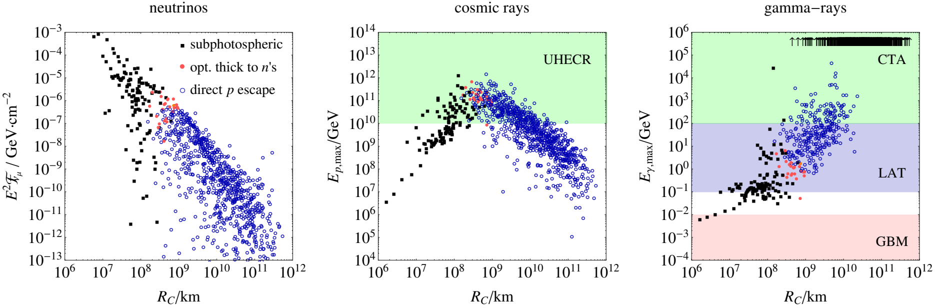
Sub-photospheric: $\tau_{e\gamma} > 1$

$\nu_\mu + \bar{\nu}_\mu$ fluence

maximum p energy

Limited by $\gamma + \gamma \to e^+ + e^-$

maximum γ energy

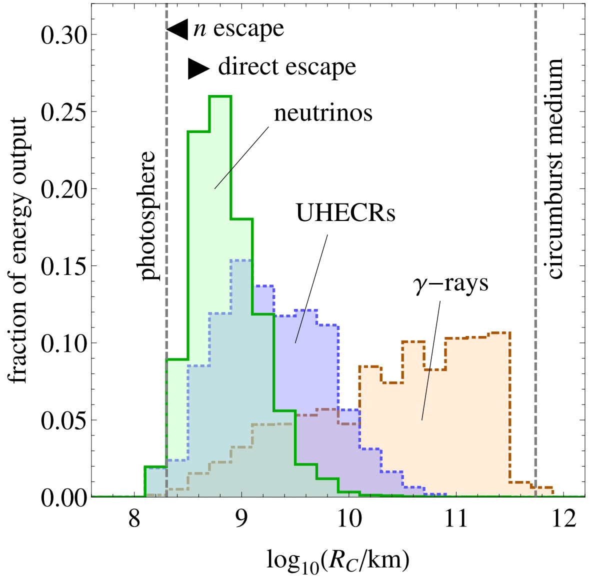


(observer's frame)

(source frame)

MB, BAERWALD, MURASE, WINTER, *Nat. Commun.* 2015

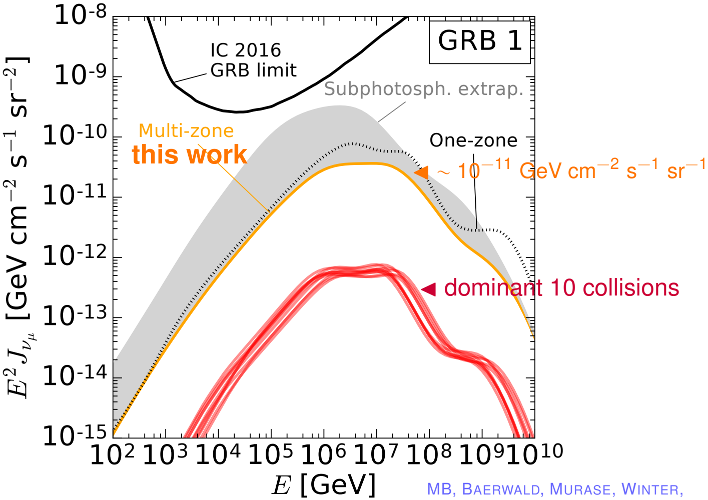
Different particles come from different jet regions



MB, Baerwald, Murase, Winter, *Nat. Commun.* 2015

A robust minimal diffuse ν flux from GRBs

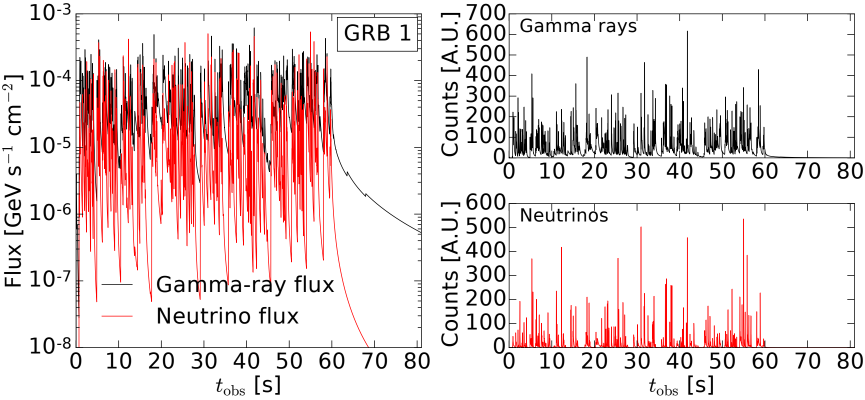
- Take the simulated burst as stereotypical
- Quasi-diffuse neutrino flux, assuming 667 identical GRBs per year:



MB, Baerwald, Murase, Winter, *Nature Commun.* 2015

Synthetic light curves

Each collision emits a particle pulse
— their superposition yields a synthetic light curve:



MB, BAERWALD, MURASE, WINTER
Nature Commun. 2015

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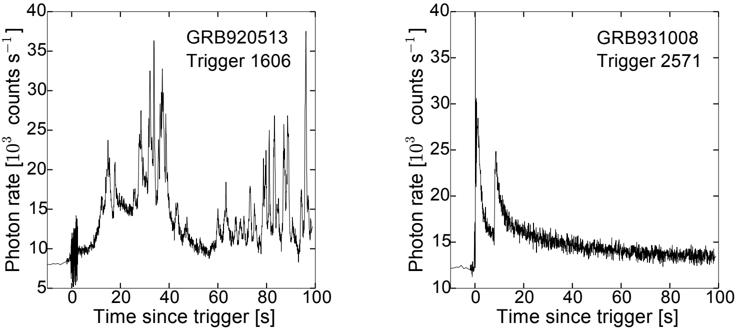

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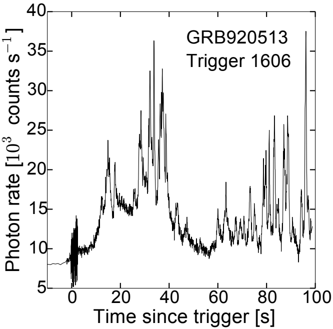
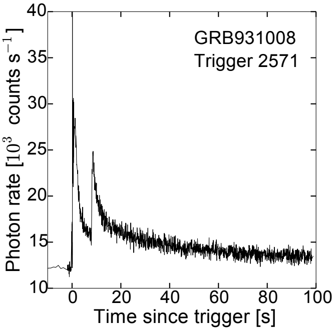


Fast time variability



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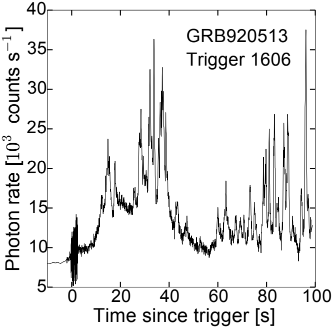

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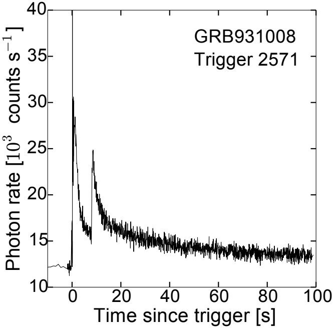

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Answer: yes, the one on the left

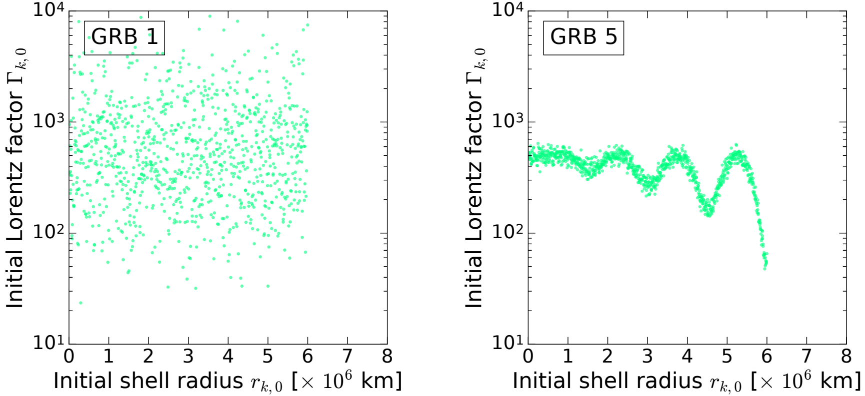
What makes a GRB bright in neutrinos?

Undisciplined GRB engine

- Broad Γ distribution
- *E.g.*, engine emits shells with log-normal Γ distribution

Disciplined GRB engine

- Narrow Γ distribution
- *E.g.*, engine emits shells with oscillating Γ



MB, Heinze, Murase, Winter, *ApJ* 2017

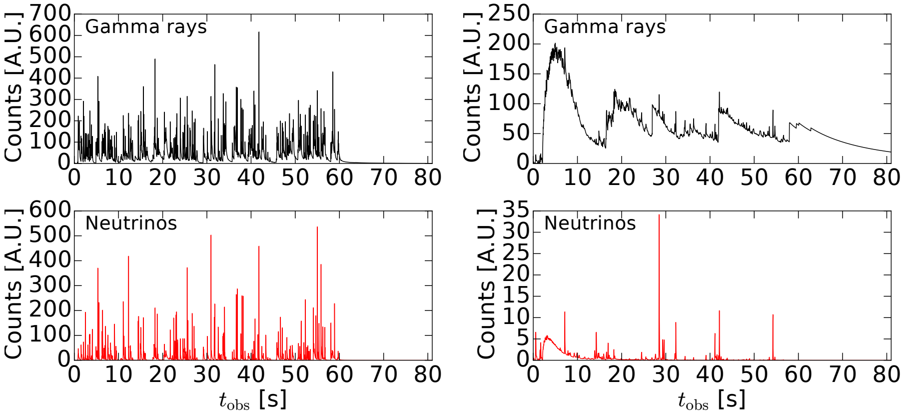
Light curves

Undisciplined GRB engine

- Fast variability dominates
- No broad pulses

Disciplined GRB engine

- Broad pulses dominate
- Fast variability on top



MB, Heinze, Murase, Winter, *ApJ* 2017

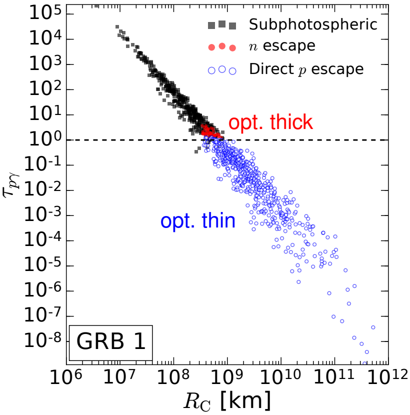
How many optically thick collisions?

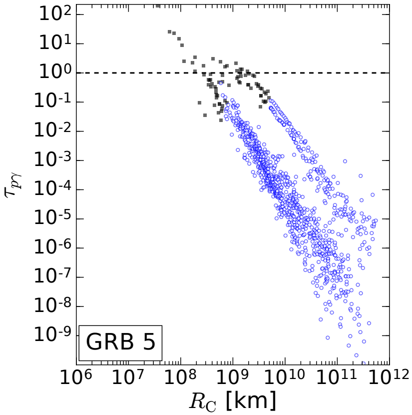
Undisciplined GRB engine

- Shells with very different speeds
- Collide quickly, close to center
- High p and γ densities
- Some optically thick collisions

Disciplined GRB engine

- Shells with similar speeds
- Collide far from center
- Low p and γ densities
- No optically thick collisions

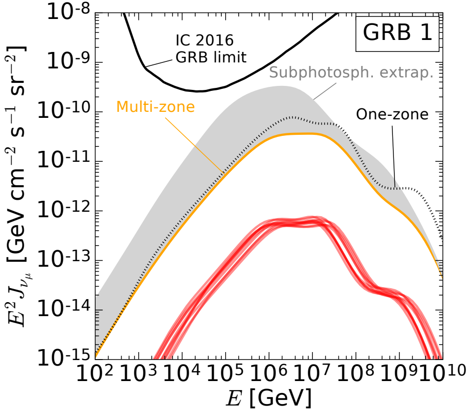


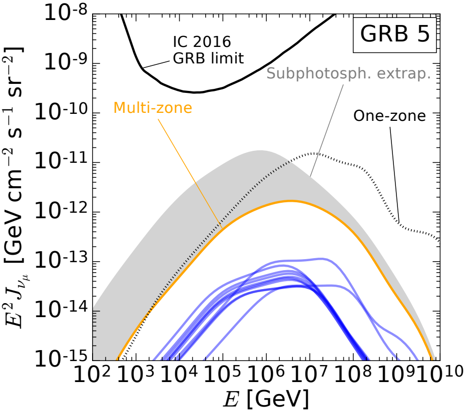


MB, Heinze, Murase, Winter, *ApJ* 2017

So which burst is neutrino-bright?

Undisciplined GRB engine	Disciplined GRB engine
$\sim 10^{-11}$ GeV cm^{-1} s^{-1} sr^{-1}	$\sim 10^{-12}$ GeV cm^{-1} s^{-1} sr^{-1}





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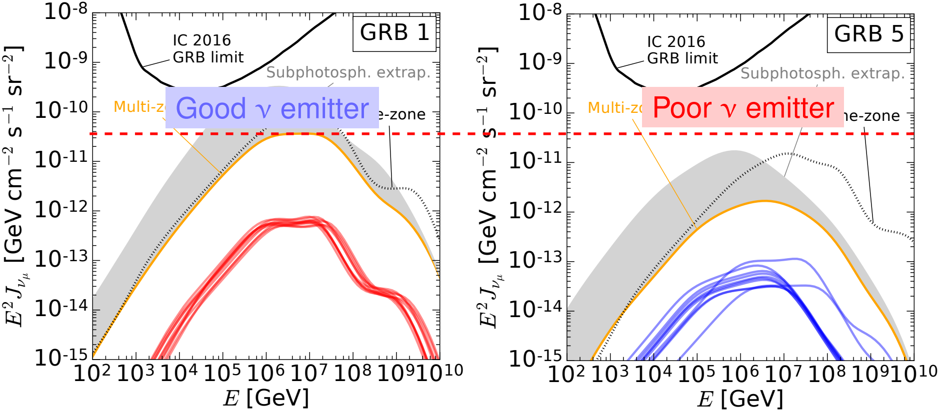

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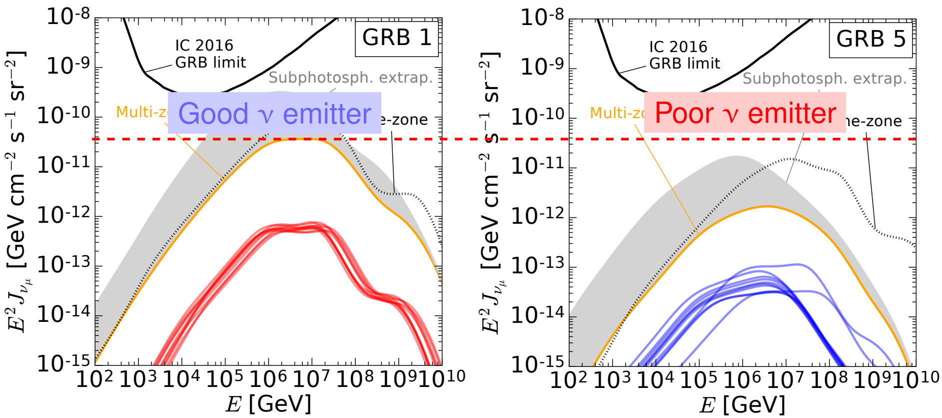
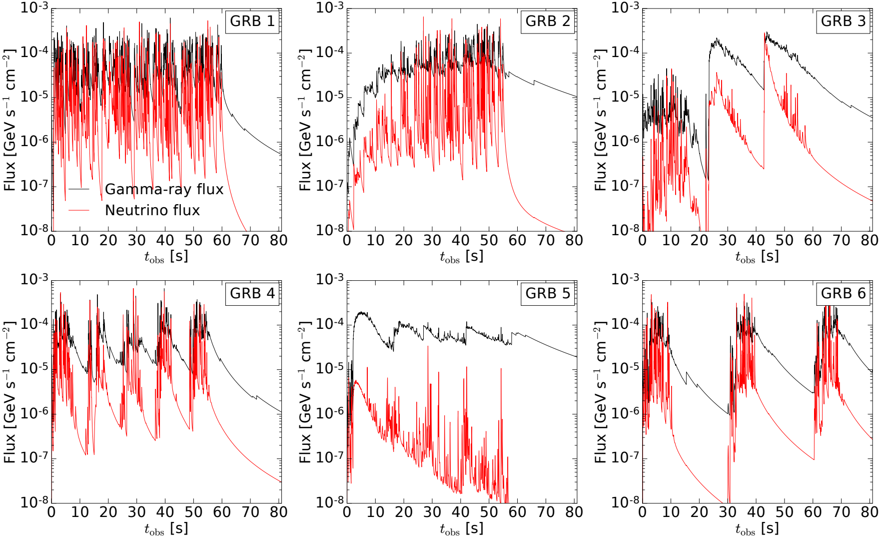


An undisciplined engine makes a GRB neutrino-bright

Using our new insight

MB, Heinze, Murase, Winter, *ApJ* 2017



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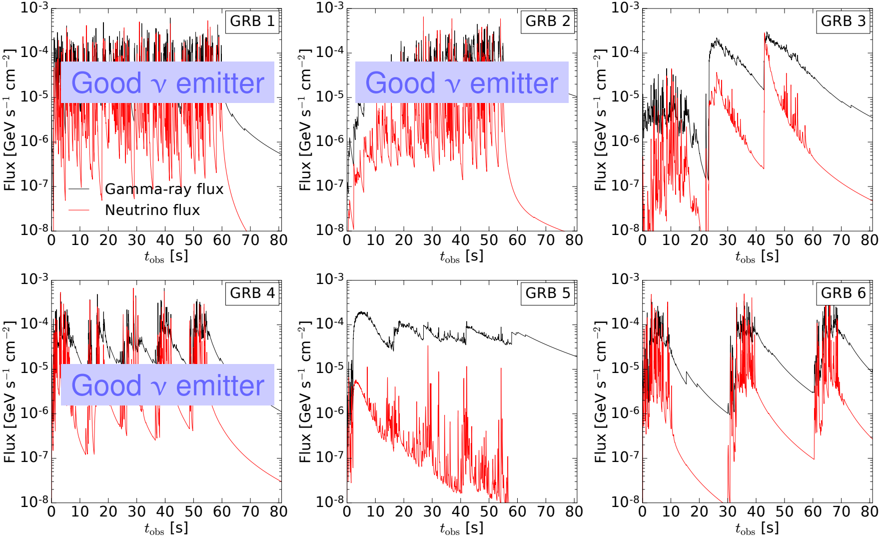

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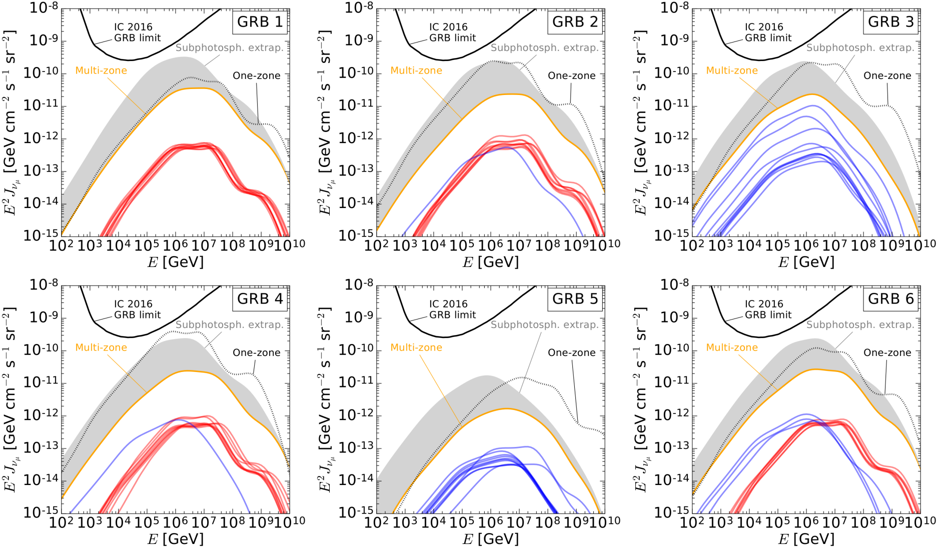
MB, Heinze, Murase, Winter, *ApJ* 2017



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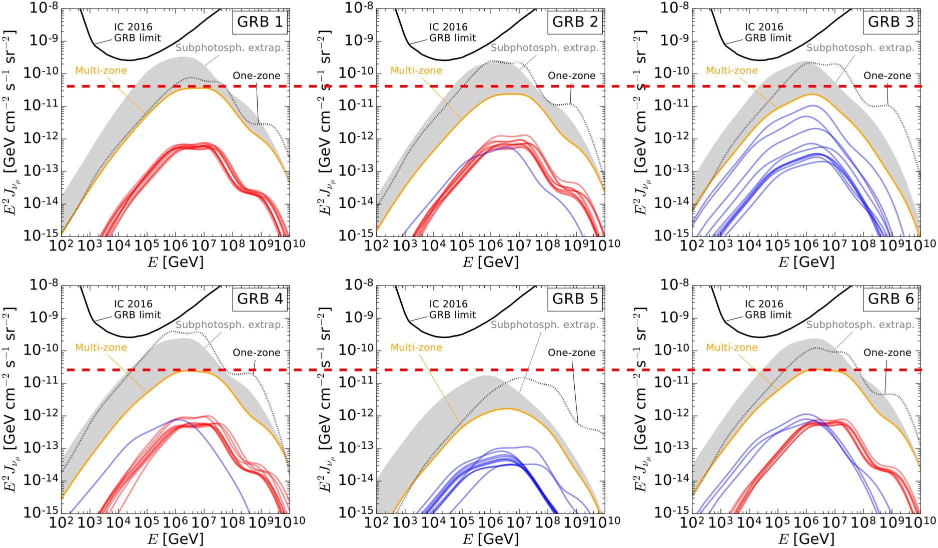
MB, Heinze, Murase, Winter, *ApJ* 2017



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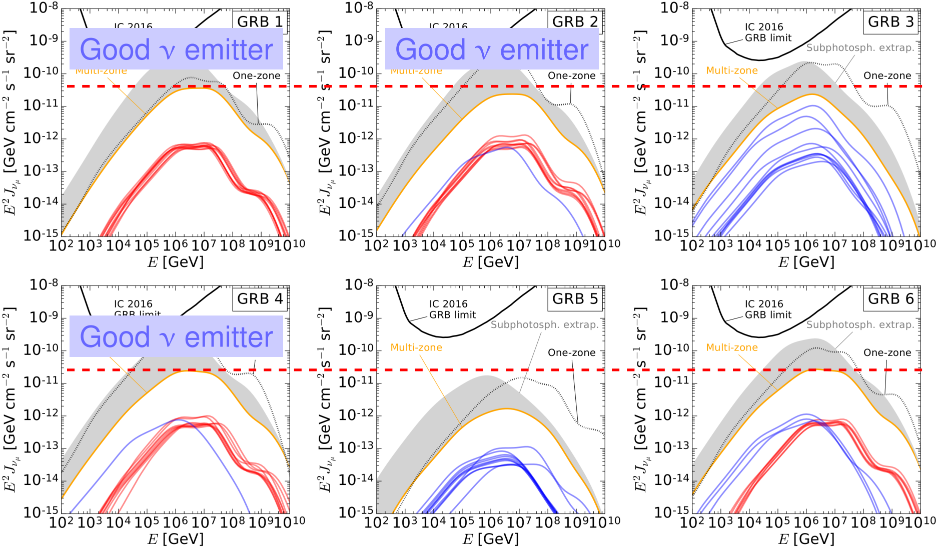

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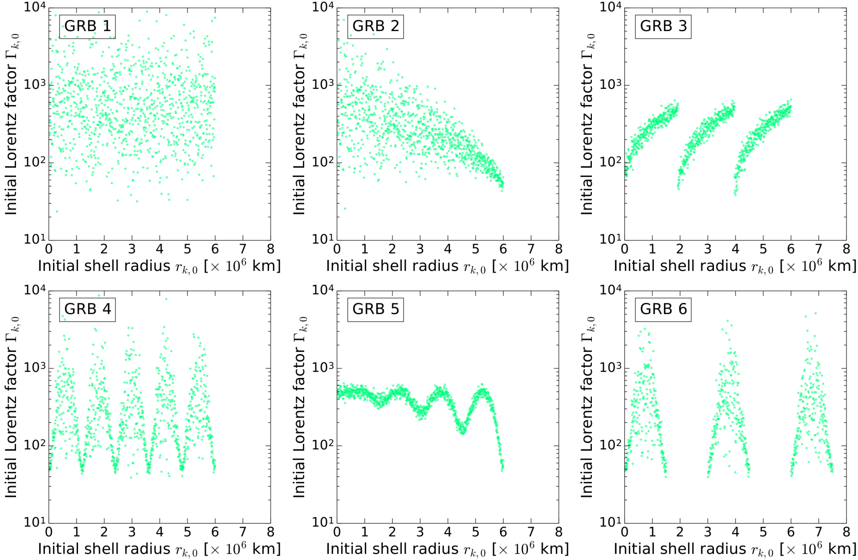
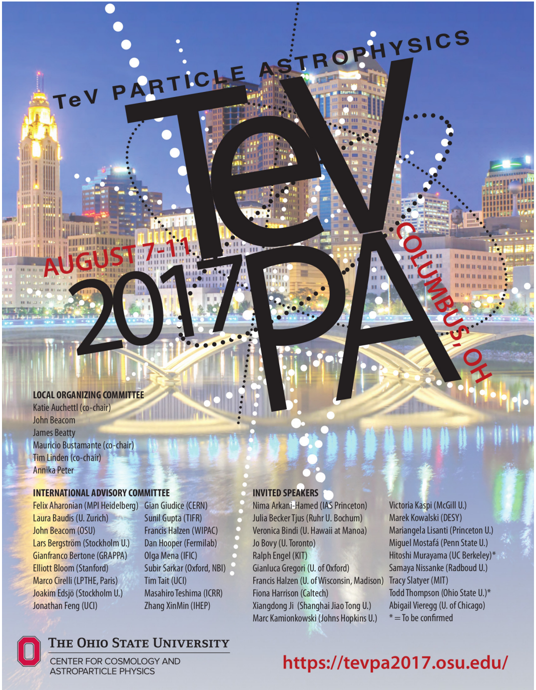


Conclusions . . . and the future

- Neutrino emission from bright GRBs is lower than we expected
- Still candidates for joint e.m.-ν detection, UHECR production
- Possibly the first neutrino sources to be resolved
- More realistic understanding of GRB ν production
- We need next-gen neutrino telescopes (IceCube-Gen2, KM3NeT)



TeVPA 2017

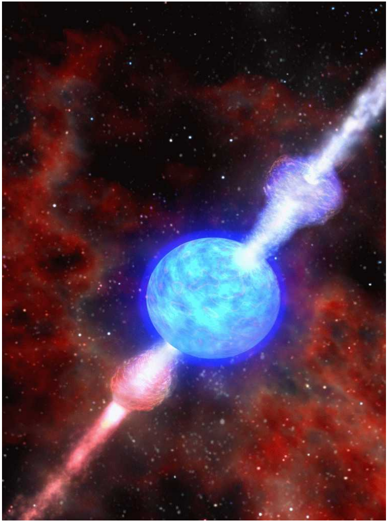
tevpa2017.osu.edu

- August 7–11, Columbus, OH
- Registration and abstract submission are **open**
- Pre-meeting mini-workshops on Sunday, August 7
- Ample room for parallels: **we welcome your talks!**

Backup slides

GRBs at a glance

- Duration: 0.1 s to > 100 s
- Two populations:
  - Short (< 2 s): NS, BH mergers
  - Long (> 2 s): hypernovae
- Accretion onto a compact object
- Isotropically distributed
- Far: most at a few Gpc ($z \approx 1$)
- Gamma-ray energies: > 1 keV
- Radiated energy: 10^{52}–10^{53} erg



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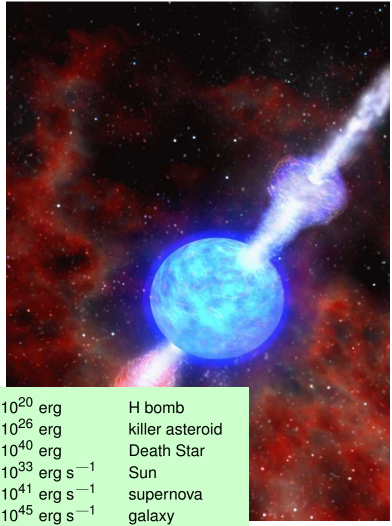
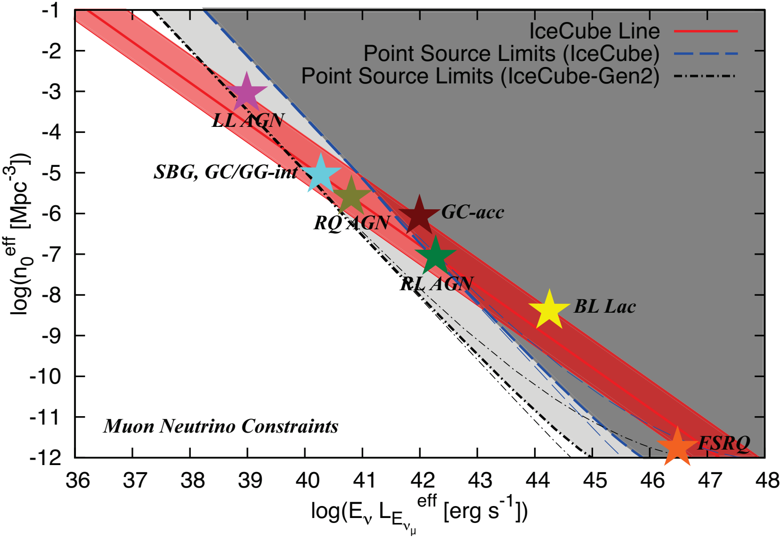


10^{20} erg	H bomb
10^{26} erg	killer asteroid
10^{40} erg	Death Star
10^{33} erg s^{-1}	Sun
10^{41} erg s^{-1}	supernova
10^{45} erg s^{-1}	galaxy

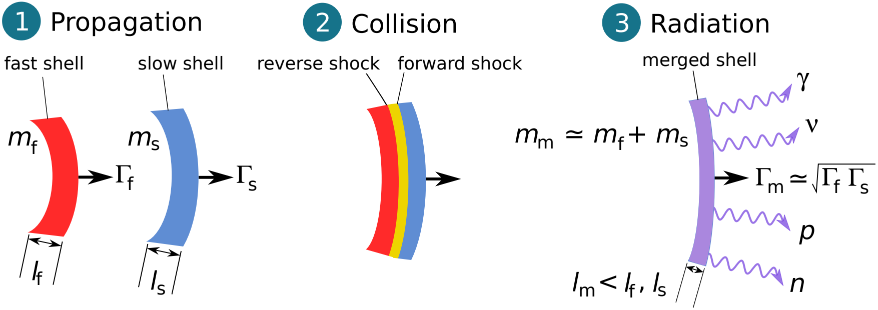
Needed: many weak (steady) sources

So far, neutrinos are *not* correlated to a few bright steady sources —



MURASE & WAXMAN, *PRD* 2016 [1607.01601]

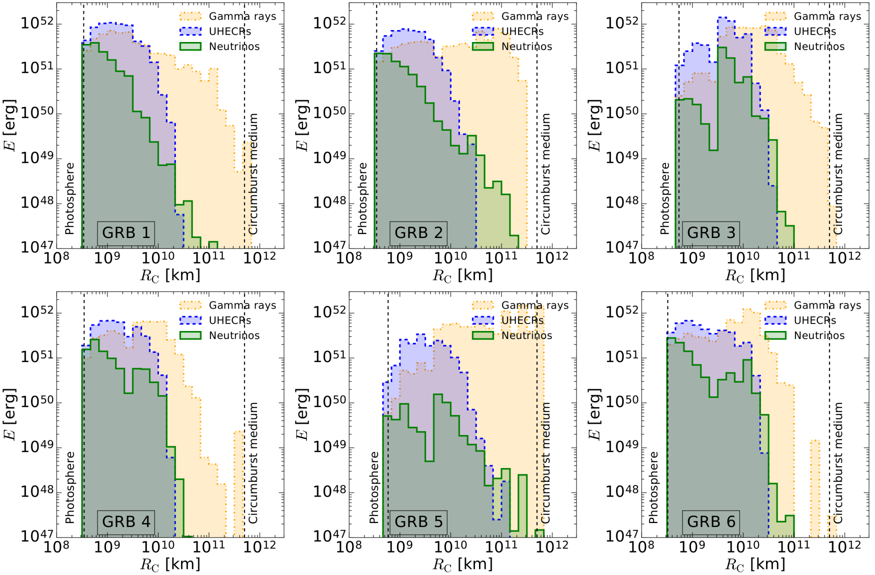
Anatomy of an internal collision



Energy in photons and electrons $\approx$ Energy in magnetic fields

Energy in relativistic protons $\gtrsim 10 \times$ Energy in photons and electrons

Particle production inside the GRB jet



MB, Heinze, Murase, Winter, *ApJ* 2017 [1606.02325]

Normalizing neutrinos with observed gamma rays

For each GRB,

energy in neutrinos $\propto$ energy in gamma rays

$$\int_0^\infty dE_\nu E_\nu F_\nu(E_\nu) = \frac{1}{8} \underbrace{\left[1 - \left(1 - \langle x_{p\to\pi}\rangle\right)^{\Delta R/\lambda_{p\gamma}}\right]}_{f_\pi\text{: fraction of total } p \text{ energy given to } \pi\text{'s}} \frac{1}{f_e} \int_{1\ \text{keV}}^{10\ \text{MeV}} d\epsilon_\gamma \epsilon_\gamma F_\gamma(\epsilon_\gamma)$$

ΔR: size of the emitting region
$\lambda_{p\gamma}$: mean free path for $p\gamma$ interactions
$\langle x_{p\to\pi}\rangle$: avg. fraction of p energy transferred to a π in one interaction
f_e^{-1}: ratio of energy in protons to energy in photons ("baryonic loading")

Optical depth to $p\gamma$: $$\frac{\Delta R}{\lambda_{p\gamma}} = \left(\frac{L_\gamma^{\rm iso}}{10^{52}\ \text{erg s}^{-1}}\right)\left(\frac{0.01}{t_v}\right)\left(\frac{10^{2.5}}{\Gamma}\right)^4\left(\frac{\text{MeV}}{\varepsilon_{\gamma,\text{break}}}\right)$$

Cooking up the neutrinos

Observed gamma-ray fluence [$\mathrm{GeV}^{-1}\ \mathrm{cm}^{-2}$]

$$F_\gamma(\varepsilon_\gamma) \propto \begin{cases} (\varepsilon_\gamma/\varepsilon_{\gamma,\mathrm{br}})^{-1} & , \varepsilon_\gamma < \varepsilon_{\gamma,\mathrm{br}} = 1\ \mathrm{MeV} \\ (\varepsilon_\gamma/\varepsilon_{\gamma,\mathrm{br}})^{-2.2} & , \varepsilon_\gamma \geqslant \varepsilon_{\gamma,\mathrm{br}} \end{cases}$$

+

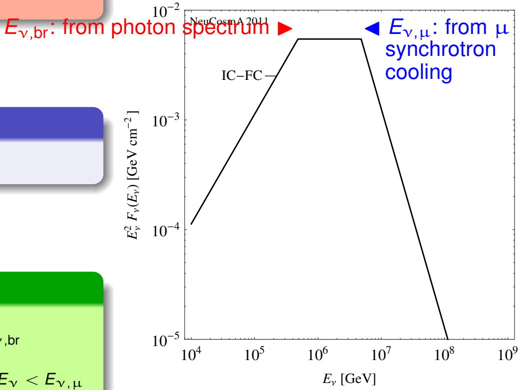
Assumed proton spectrum in the source

$$N'_p(E_p) \propto E'^{-2}_p$$

=

Neutrinos from $p\gamma$, via Δ resonance

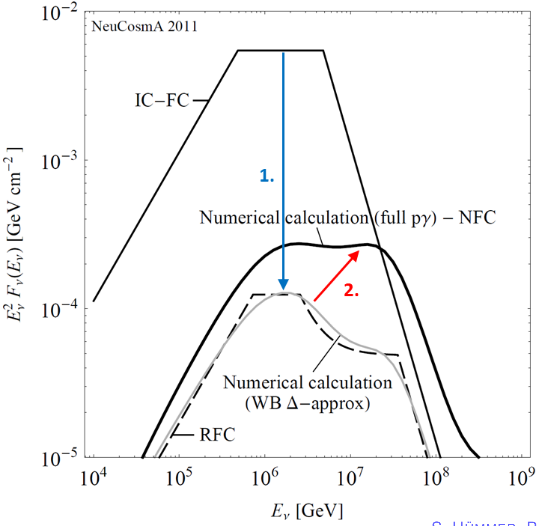
$$F_\nu(E_\nu) \propto \begin{cases} \left(\frac{E_\nu}{E_{\nu,\mathrm{br}}}\right)^{-\alpha_\nu} & , E_\nu < E_{\nu,\mathrm{br}} \\ \left(\frac{E_\nu}{E_{\nu,\mathrm{br}}}\right)^{-\beta_\nu} & , E_{\nu,\mathrm{br}} \leqslant E_\nu < E_{\nu,\mu} \\ \left(\frac{E_\nu}{E_{\nu,\mathrm{br}}}\right)^{-\beta_\nu}\left(\frac{E_\nu}{E_{\nu,\mu}}\right)^{-2} & , E_\nu \geqslant E_{\nu,\mu} \end{cases}$$



E. Waxman, J. N. Bahcall, *PRL* **78**, 2292 (1997)
D. Guetta *et al.*, *Astropart. Phys.* **20**, 429 (2004)

Refining the neutrino spectrum — NeuCosmA

More production channels, more complete particle-physics treatment



For example, GRB080603A:

1. Correction to analytical model (IC-FC → RFC)
2. Change due to full numerical calculation

IC-FC: IceCube-Fireball Calculation
RFC: Revised Fireball Calculation
NFC: Numerical Fireball Calculation

S. Hümmer, P. Baerwald, W. Winter, *PRL* **108**, 231101 (2012)

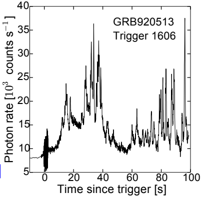
What are the ingredients?

To calculate the ν flux from a GRB, we need:

- Its gamma-ray luminosity L_γ^{iso} [erg s^{-1}] [measured]
- Its variability timescale t_v [s], from the light curve [measured]
- Break energy of its photon spectrum $\epsilon_{\gamma,\mathrm{break}}$ [MeV] [measured]
- Its redshift z [(sometimes) measured]
- The bulk Lorentz factor of its jet Γ [estimated]
- The energy in electrons, magnetic field, protons [estimated]

Now let us cook up the neutrinos ▶

What are the ingredients?



To calculate the ν flux from a GRB, we need:

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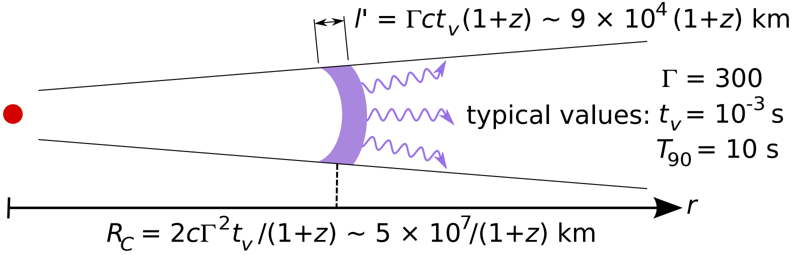
- Break energy of its photon spectrum $\epsilon_{\gamma,\text{break}}$ [MeV] [measured]
- Its redshift z [(sometimes) measured]
- The bulk Lorentz factor of its jet Γ [estimated]
- The energy in electrons, magnetic field, protons [estimated]

Now let us cook up the neutrinos ▶

A simplifying assumption: identical collisions

All internal collisions are identical and occur at the same radius —

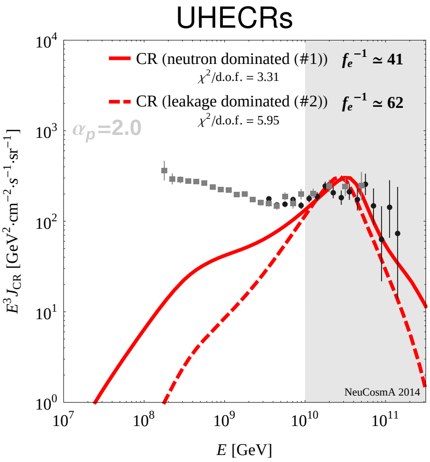


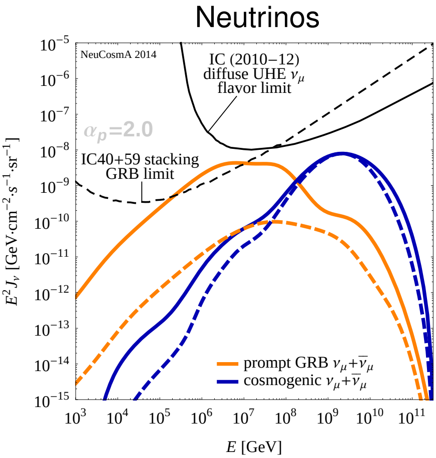
$N_{\rm coll} \approx T_{90}/t_v \sim 100\text{–}1000$ identical collisions

- Calculate particle emission spectra once
- Then multiply by $N_{\rm coll}$
- Γ is the average speed of shells

Diffuse fluxes at Earth

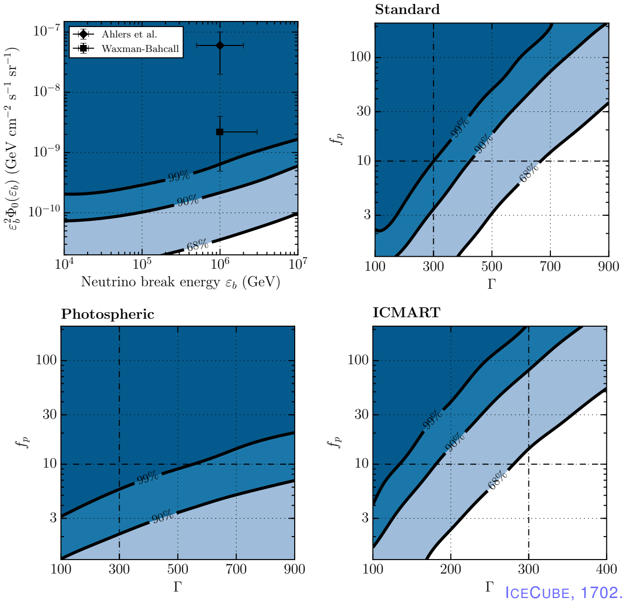
Neutron model vs. two-component model:
prompt and cosmogenic ν's





P. Baerwald, MB, W. Winter, *ApJ* **768**, 186 (2013)
P. Baerwald, MB, W. Winter, *Astropart. Phys.* **62**, 66 (2015)
See also: H. He *et al.*, *ApJ* **752**, 29 (2012)

Limits on GRB ν production model parameters



ICECUBE, 1702.06868

NeuCosmA: (revised) GRB particle emission – I

Two ingredients:

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

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

▶ Photons (same shape as observed at Earth):

$$N'_\gamma\left(E'_\gamma\right) = \begin{cases} \left(E'_\gamma/E'_{\gamma,\text{break}}\right)^{-1} & , \ E'_{\gamma,\text{min}} = 0.2 \text{ eV} \leqslant E'_\gamma < E'_{\gamma,\text{break}} = 1 \text{ keV} \\ \left(E'_\gamma/E'_{\gamma,\text{break}}\right)^{-2.2} & , \ E'_\gamma \geqslant E'_{\gamma,\text{break}} \\ 0 & , \ \text{otherwise} \end{cases}$$

▶ Protons: $N'_p\left(E'_p\right) \propto E_p'^{-\alpha_p} e^{-E'_p/E'_{p,\text{max}}} \quad \left(\alpha_p \gtrsim 2\right)$

NeuCosmA: (revised) GRB particle emission – I

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$$t'_{\mathrm{acc}}\left(E'_{p,\mathrm{max}}\right) = \min\left[t'_{\mathrm{dyn}}, t'_{\mathrm{syn}}\left(E'_{p,\mathrm{max}}\right), t'_{p\gamma}\left(E'_{p,\mathrm{max}}\right)\right]$$

▶ Protons: $N'_p\left(E'_p\right) \propto E'^{-\alpha_p}_p e^{-E'_p/E'_{p,\mathrm{max}}} \quad \left(\alpha_p \gtrsim 2\right)$

NeuCosmA: (revised) GRB particle emission – II

Normalize the particle densities at the source —

- Photons:

$$\underbrace{\text{photon energy density per collision}}_{\int E'_\gamma \, N'_\gamma\left(E'_\gamma\right) \, dE'_\gamma} = \frac{\overbrace{\text{total gamma-ray energy of burst}}^{E^{\mathrm{iso},\prime}_{\gamma,\mathrm{tot}} \sim 10^{53} \text{ erg (from observed fluence)}}}{\underbrace{\text{number of collisions}}_{N_{\mathrm{coll}}} \cdot \underbrace{\text{volume of one collision}}_{V'_{\mathrm{iso}}}}$$

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

$$\underbrace{\text{proton energy density per collision}}_{\int E'_p \, N'_p\left(E'_p\right) \, dE'_p} = \frac{1}{f_e} \cdot \text{photon energy density per collision}$$

NeuCosmA: (revised) GRB particle emission – III

Injected/ejected spectrum of secondaries (π, K, n, ν, etc.):

$x \equiv E'/E'_p$

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

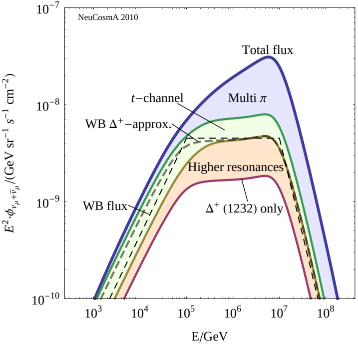
$$Q'(E') = \int_{E'}^{\infty} \frac{dE'_p}{E'_p} N'_p(E'_p) \int_0^{\infty} c\, dE'_\gamma\, N'_\gamma(E'_\gamma)\, R(x, y)$$

response function

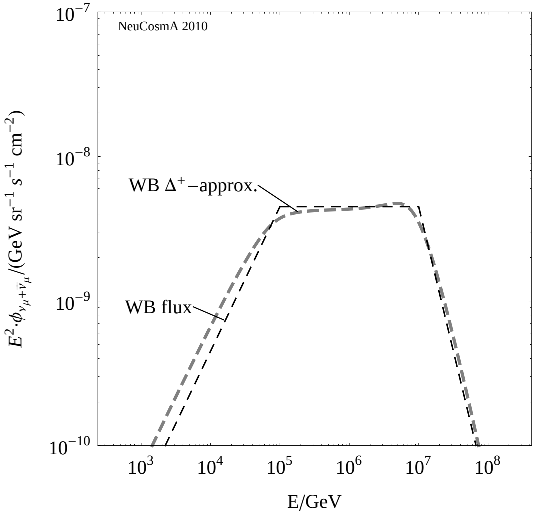
R contains cross sections, multiplicities for different channels

What does NeuCosmA include?

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



NeuCosmA – the full photohadronic cross section

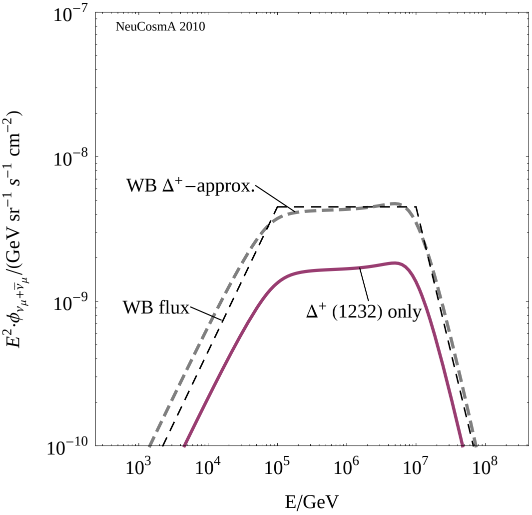


NeuCosmA – the full photohadronic cross section

Contributions to $(\nu_\mu + \bar{\nu}_\mu)$ flux from $\pi^\pm$ decay divided in:

- $\Delta(1232)$-resonance

P. Baerwald, S. Hümmer, and W. Winter, *Phys. Rev.* **D83**, 067303 (2011)

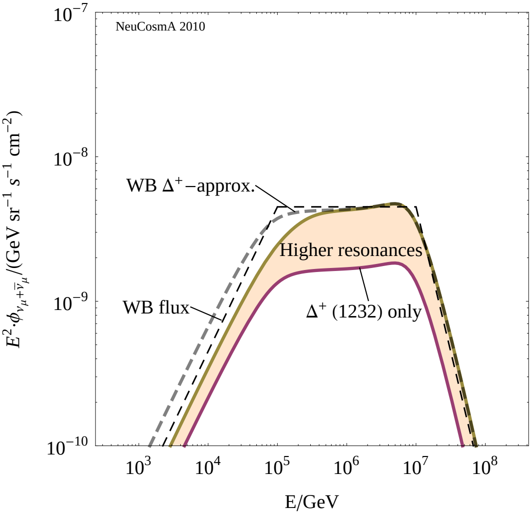


NeuCosmA – the full photohadronic cross section

Contributions to $(\nu_\mu + \bar{\nu}_\mu)$ flux from $\pi^\pm$ decay divided in:

- $\Delta(1232)$-resonance
- Higher resonances

P. Baerwald, S. Hümmer, and W. Winter, *Phys. Rev.* **D83**, 067303 (2011)



NeuCosmA – the full photohadronic cross section

Contributions to $(\nu_\mu + \bar{\nu}_\mu)$ flux from $\pi^\pm$ decay divided in:

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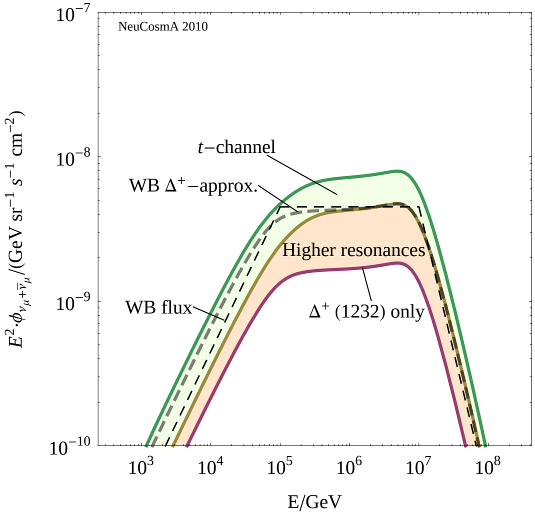
P. Baerwald, S. Hümmer, and W. Winter, *Phys. Rev.* **D83**, 067303 (2011)

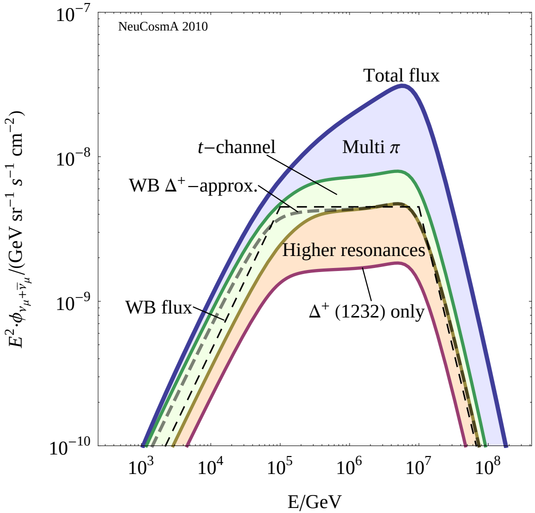


NeuCosmA – the full photohadronic cross section

Contributions to $(\nu_\mu + \bar{\nu}_\mu)$ flux from $\pi^\pm$ decay divided in:

- $\Delta(1232)$-resonance
- Higher resonances
- *t*-channel (direct production)
- High energy processes (multiple π)

P. Baerwald, S. Hümmer, and W. Winter, *Phys. Rev.* **D83**, 067303 (2011)



Especially "Multi π" contribution leads to change of flux shape; neutrino flux higher by up to a factor of 3 compared to WB treatment

NeuCosmA – further particle decays

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

NeuCosmA – further particle decays

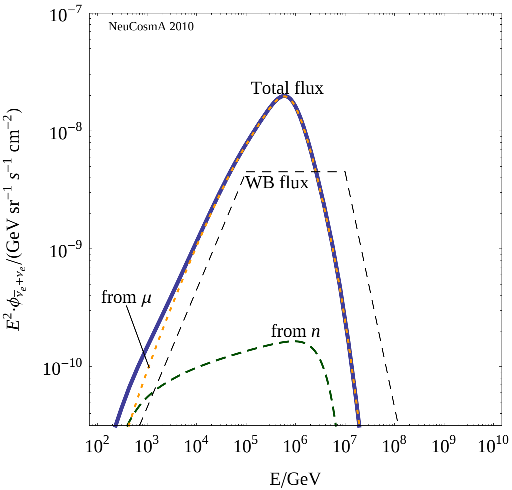
$$\pi^+ \rightarrow \mu^+ + \nu_\mu$$
$$\mu^+ \rightarrow e^+ + \nu_e + \bar{\nu}_\mu$$

$$\pi^- \rightarrow \mu^- + \bar{\nu}_\mu$$
$$\mu^- \rightarrow e^- + \bar{\nu}_e + \nu_\mu$$

$$K^+ \rightarrow \mu^+ + \nu_\mu$$

$$n \rightarrow p + e^- + \bar{\nu}_e$$

Resulting ν_e flux (at the observer)



P. Baerwald, S. Hümmer, and W. Winter, *Phys. Rev.* **D83**, 067303 (2011)

NeuCosmA – further particle decays

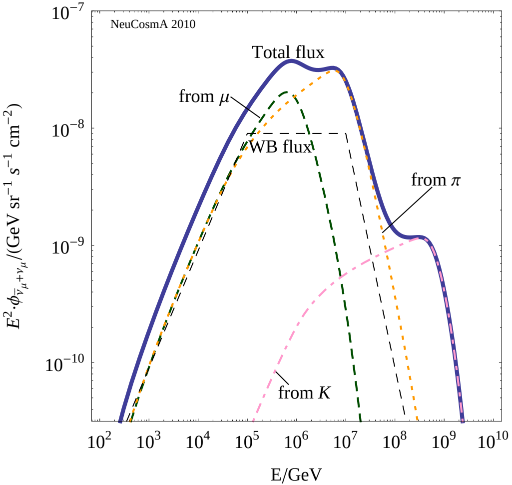
$$\pi^+ \rightarrow \mu^+ + \nu_\mu$$
$$\mu^+ \rightarrow e^+ + \nu_e + \bar{\nu}_\mu$$

$$\pi^- \rightarrow \mu^- + \bar{\nu}_\mu\,,$$
$$\mu^- \rightarrow e^- + \bar{\nu}_e + \nu_\mu$$

$$K^+ \rightarrow \mu^+ + \nu_\mu$$

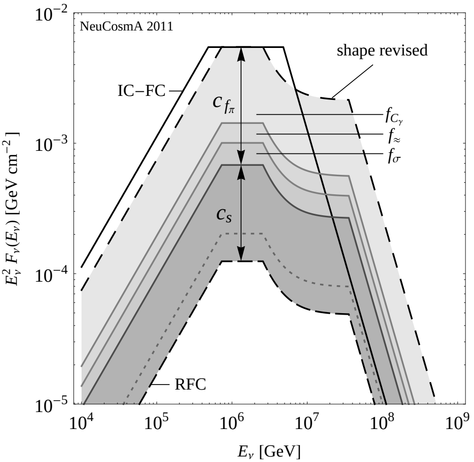
$$n \rightarrow p + e^- + \bar{\nu}_e$$

Resulting ν_μ flux (at the observer)



P. BAERWALD, S. HÜMMER, AND W. WINTER, *Phys. Rev.* **D83**, 067303 (2011)

NeuCosmA – how the neutrino spectrum changes – I

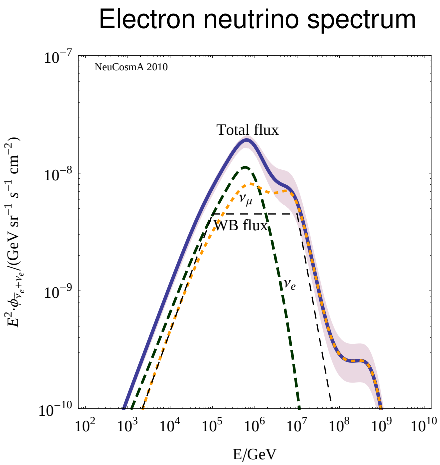


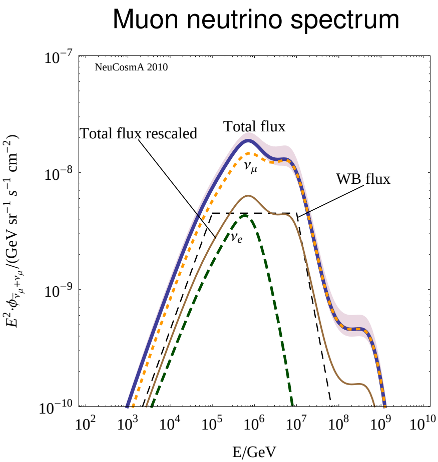
S. Hümmer, P. Baerwald, W. Winter, *Phys. Rev. Lett.* **108**, 231101 (2012)

Corrections to the analytical model:

- shape revised:
  - shift of first break (correction of photohadronic threshold)
  - different cooling breaks for μ's and π's
  - $(1+z)$ correction on the variability scale of the GRB
- Correction cf_π to π prod. efficiency:
  - f_{C_γ} : full spectral shape of photons
  - $f_\approx = 0.69$: rounding error in analytical calculation
  - $f_\sigma \simeq 2/3$: from neglecting the width of the Δ-resonance
- Correction c_S:
  - energy losses of secondaries
  - energy dependence of the mean free path of protons

NeuCosmA – neutrino spectra including flavor mixing





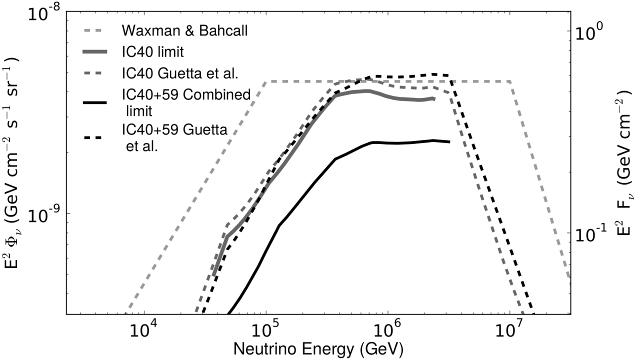
P. Baerwald, S. Hümmer, W. Winter, *Phys. Rev.* **D83**, 067303 (2011)

Characteristic double peak structure from μ and π decay in both flavors, additional peak from K^+ decay at 10^8 to 10^9 GeV

Neutron model of UHECR emission under tension?

In 2012, IceCube ruled this analytical version of the fireball model –

- assumed a fixed baryonic loading of 10
- extrapolated diffuse ν flux from 117–215 GRBs ("quasi-diffuse")
- analytical calculation – in tension with upper bounds



ICECUBE, *Nature* **484**, 351 (2012)
M. AHLERS *et al. Astropart. Phys.* **35**, 87 (2011)
D. GUETTA *et al. Astropart. Phys.* **20**, 429 (2004)

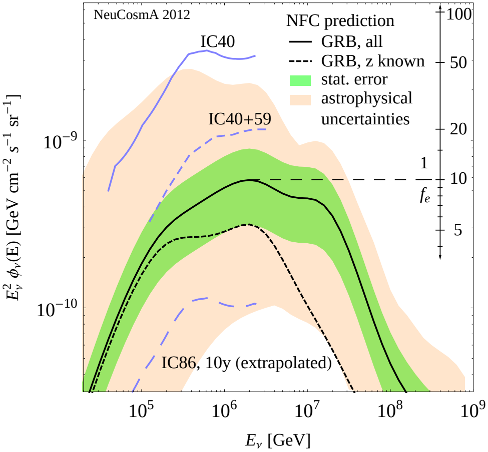
The new prediction of the quasi-diffuse GRB ν flux

Repeat the IceCube GRB neutrino analysis, with NeuCosmA —

- Same GRB sample and parameters
- Calculate ν fluence for each burst and stacked fluence $F_\nu(E_\nu)$
- Quasi-diffuse flux ($N_{\mathrm{GRB}} = 117$):

$$\phi_\nu(E_\nu) = F_\nu(E_\nu)\,\frac{1}{4\pi}\,\frac{1}{N_{\mathrm{GRB}}}\,\frac{667\ \text{bursts}}{\text{yr}}$$

Flux ~ 1 order of magnitude lower!



S. Hümmer, P. Baerwald, W. Winter, *PRL* **108**, 231101 (2012)

A two-component model of CR emission

Optical depth:

$$\tau_n = \left.\frac{t_{p\gamma}^{-1}}{t_{\rm dyn}^{-1}}\right|_{E_{p,\rm max}} = \begin{cases} \lesssim 1\,, & \text{optically } \textbf{thin} \text{ source} \\ > 1\,, & \text{optically } \textbf{thick} \text{ source} \end{cases}$$

Particles can escape from within a shell of thickness $\lambda'_{\rm mfp}$:

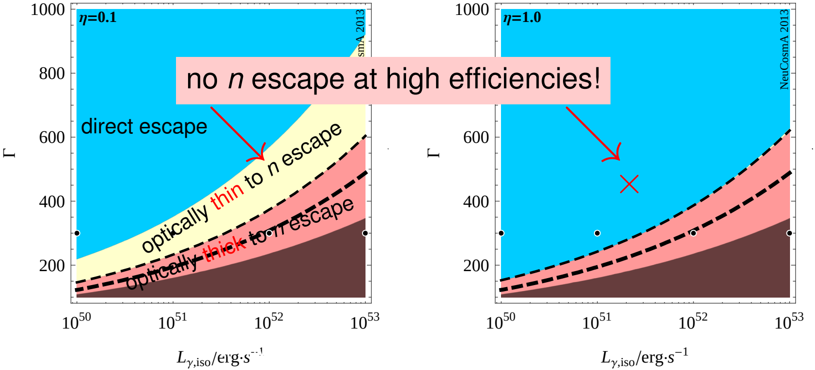
$$\left.\begin{aligned} \lambda'_{p,\rm mfp}(E') &= \min\left[\Delta r', R'_L(E'), ct'_{p\gamma}(E')\right] \\ \lambda'_{n,\rm mfp}(E') &= \min\left[\Delta r', ct'_{p\gamma}(E')\right] \end{aligned}\right\} f_{\rm esc} = \frac{\lambda'_{\rm mfp}}{\Delta r'}$$

fraction of escaping particles

We *need* direct proton escape

Scan of the GRB emission parameter space –

acceleration efficiency ⟶ $\eta = 0.1$ $\eta = 1.0$



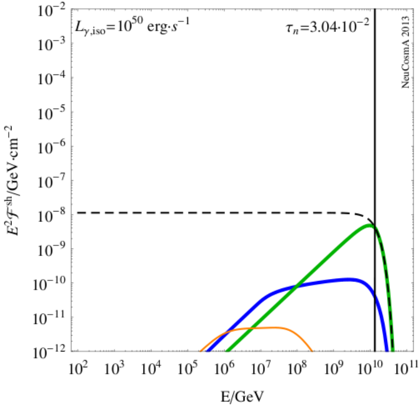
P. Baerwald, MB, and W. Winter, *ApJ* **768**, 186 (2013)

we need high efficiencies ⇒ direct proton escape *is* required

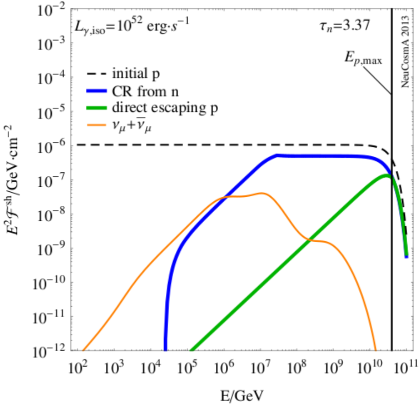
A two-component model of UHECR emission

Sample neutrino fluences –

Optically **thin** source



Optically **thick** source



P. Baerwald, MB, W. Winter, *ApJ* **768**, 186 (2013)

Cosmogenic neutrinos

We have seen that protons interact with the cosmological photon fields (CMB, etc.), *e.g.*,

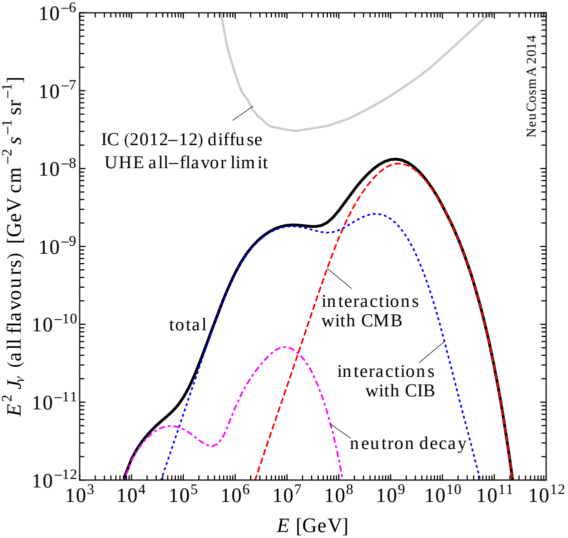
$$p + \gamma \rightarrow \Delta^+ \rightarrow \pi^+ + n \,,$$

and neutrinos are created in the decays of the secondaries:

$$\pi^+ \rightarrow \mu^+ + \nu_\mu$$
$$\mu^+ \rightarrow \bar{\nu}_\mu + \nu_e + e^+$$
$$n \rightarrow p + e^- + \bar{\nu}_e$$

These are called *cosmogenic neutrinos*

Cosmogenic neutrinos



P. Baerwald, MB, W. Winter, *Astropart. Phys.* **62**, 66 (2015)

ν's in the GRB internal shock model

Secondary injection of neutrons, neutrinos (GeV^{-1} cm^{-3} s^{-1})

$$Q'\left(E'\right) = \int_{E'}^{\infty} \frac{dE'_p}{E'_p} N'_p\left(E'_p\right) \int_0^{\infty} c\,d\varepsilon' N'_\gamma\left(\varepsilon'\right) R\left(E', E'_p, \varepsilon'\right)$$

Normalisation to the observed GRB photon flux F_γ

$$\int \varepsilon' N'_\gamma\left(\varepsilon'\right) d\varepsilon' = \frac{E'^{\rm sh}_{\rm iso}}{V'_{\rm iso}} \propto F_\gamma\ , \quad \int E'_p N'_p\left(E'_p\right) dE'_p = \frac{1}{f_e}\frac{E'^{\rm sh}_{\rm iso}}{V'_{\rm iso}} \propto \frac{F_\gamma}{f_e}$$

Fluence per shell, at Earth (GeV^{-1} cm^{-2})

$$\mathcal{F}^{\rm sh} = t_v V'_{\rm iso} \frac{\left(1+z\right)^2}{4\pi d_L^2} Q'$$

ν's in the GRB internal shock model

Secondary injection of neutrons, neutrinos ($\mathrm{GeV}^{-1}\ \mathrm{cm}^{-3}\ \mathrm{s}^{-1}$)

$$Q'\left(E'\right) = \int_{E'}^{\infty} \frac{dE'_p}{E'_p} N'_p\left(E'_p\right) \int_0^{\infty} c\,d\varepsilon'\, N'_\gamma\left(\varepsilon'\right) R\left(E', E'_p, \varepsilon'\right)$$

- Photon density, shock rest frame ($\mathrm{GeV}^{-1}\ \mathrm{cm}^{-3}$):

$$N'_\gamma\left(\varepsilon'\right) \propto \begin{cases} \left(\varepsilon'\right)^{-\alpha_\gamma}, & \varepsilon'_{\gamma,\mathrm{min}} = 0.2\ \mathrm{eV} \leqslant \varepsilon' \leqslant \varepsilon'_{\gamma,\mathrm{break}} \\ \left(\varepsilon'\right)^{-\beta_\gamma}, & \varepsilon'_{\gamma,\mathrm{break}} \leqslant \varepsilon' \leqslant \varepsilon'_{\gamma,\mathrm{max}} = 300 \times \varepsilon'_{\gamma,\mathrm{min}} \end{cases}$$

$$\varepsilon'_{\gamma,\mathrm{break}} = \mathcal{O}\left(\mathrm{keV}\right), \alpha_\gamma \approx 1, \beta_\gamma \approx 2$$

- Proton density:

$$N'_p\left(E'_p\right) \propto \left(E'_p\right)^{-\alpha_p} \times \exp\left[-\left(E'_p/E'_{p,\mathrm{max}}\right)^2\right] \quad \left(\alpha_p \approx 2\right)$$

Maximum proton energy limited by energy losses:

$$t'_{\mathrm{acc}}\left(E'_{p,\mathrm{max}}\right) = \min\left[t'_{\mathrm{dyn}}, t'_{\mathrm{syn}}\left(E'_{p,\mathrm{max}}\right), t'_{p\gamma}\left(E'_{p,\mathrm{max}}\right)\right]$$

ν's in the GRB internal shock model

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ν's in the GRB internal shock model

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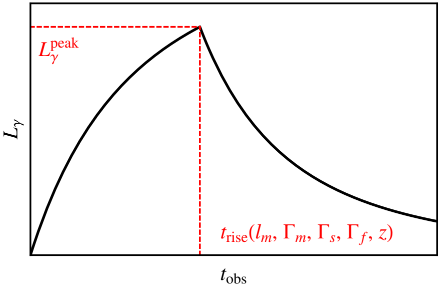
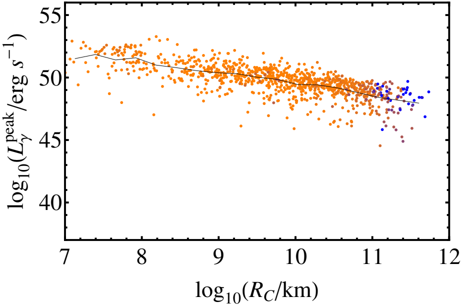
Fluence per shell, at Earth (GeV^{-1} cm^{-2})

$$\mathcal{F}^{\mathrm{sh}} = t_v V'_{\mathrm{iso}} \frac{(1+z)^2}{4\pi d_L^2} Q'$$

Gamma-ray and neutrino pulses

A fast-rise-exponential-decay (FRED) gamma-ray pulse is emitted in every collision:

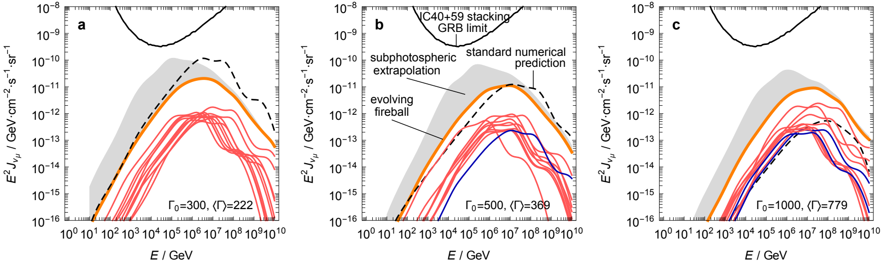




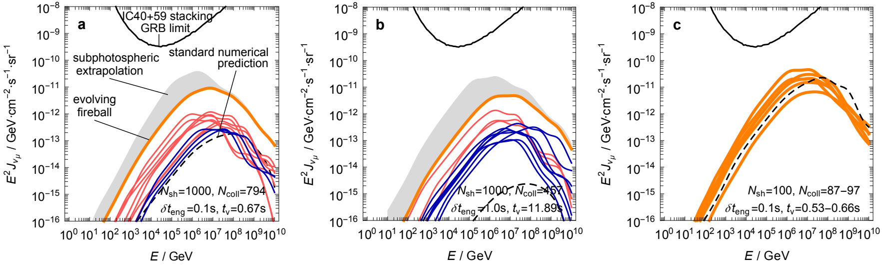
$L_\gamma^{\rm peak} \sim R_C^{-2}$

The prediction *is* robust

Simulations show only weak dependence of the **flux** on the boost Γ . . .

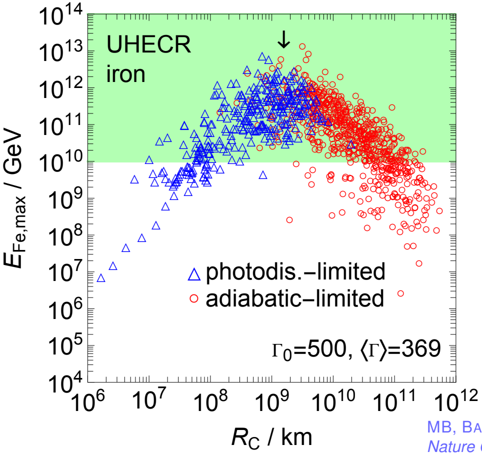


. . . and on the GRB engine variability time δt_{eng}



Accelerating iron

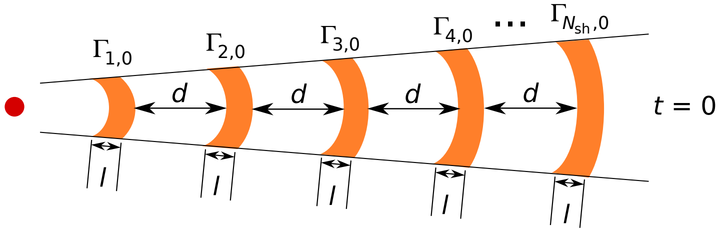
- Photodisintegration destroys nuclei close to the center ($\sim 10^8$ km)
  e.g., ANCHORDOQUI *et al.*, *Astropart. Phys.* **29**, 1 (2008)
- However, they can survive at large radii:



MB, BAERWALD, MURASE, WINTER
Nature Commun. **6**, 6783 (2015)

Initialising the burst simulation

Initial number of plasma shells in the jet: $\gtrsim 1000$



Initial values of shell parameters:

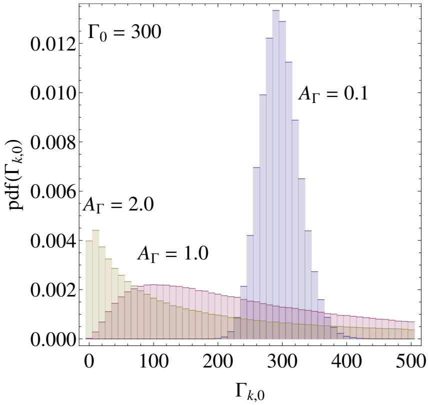
- Width of shells and separation between them: $l = d = c \cdot \delta t_{eng}$
- Equal kinetic energy for all shells ($\sim 10^{52}$ erg)
- Shell speeds $\Gamma_{k,0}$ follow a distribution (log-normal or other)

Initial distribution of shell speeds

Distribution of initial shell speeds (Lorentz factors):

$$\ln\left(\frac{\Gamma_{k,0}-1}{\Gamma_0-1}\right) = A_\Gamma \cdot x$$

x follows a Gaussian distribution, $P(x)\,dx = dx\ e^{-x^2/2}/\sqrt{2\pi}$



$A_\Gamma < 1$

Speeds too similar, collisions only at large radii

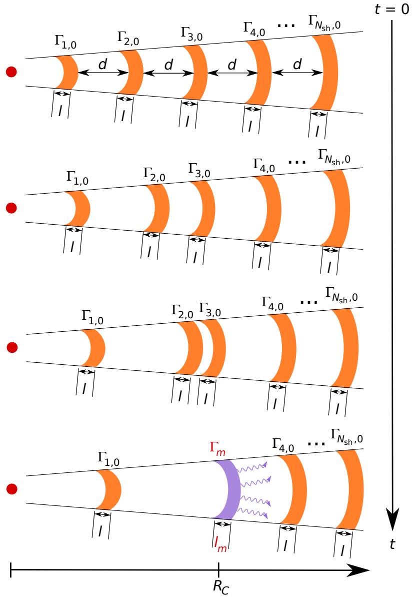
$A_\Gamma \gg 1$

Spread too large, too many collisions at low radii

$A_\Gamma \approx 1$

Just right, burst has high efficiency of conversion of kinetic to radiated energy

Propagating and colliding the shells



During propagation:

- speeds, masses, widths do not change (only in collisions)
- the new, merged shells continue propagating and can collide again

Evolution stops when either:

- a single shell is left; or
- all remaining shells have reached the circumburst medium ($\gtrsim 6 \times 10^{11}$ km)

final number of collisions

$\approx$

number of initial shells ($\gtrsim 1000$)

S. Kobayashi, T. Piran, R. Sari, *ApJ* **490**, 92 (1997)
F. Daigne, R. Mochkovitch, *MNRAS* **296**, 275 (1998)

How is the new prediction different?

- The top-contributing collisions are at the photosphere
- Pion production efficiency there is independent of Γ:

$$f_{p\gamma}^{\mathrm{ph}} \sim 5 \cdot \frac{\varepsilon}{0.25} \cdot \frac{\epsilon_e}{0.1} \cdot \frac{1\ \mathrm{keV}}{\epsilon'_{\gamma,\mathrm{break}}}$$

ε: energy dissipation efficiency
ϵ_e: fraction of dissipated energy as e.m. output (photons)

- $\Rightarrow$ Time-integrated neutrino fluence dominated is independent of Γ:

$$\mathcal{F}_\nu \propto \frac{N_{\mathrm{coll}}\left(f_{p\gamma} \gtrsim 1\right)}{N_{\mathrm{coll}}^{\mathrm{tot}}} \times \min\left[1, f_{p\gamma}^{\mathrm{ph}}\right] \times \frac{\epsilon_p}{\epsilon_e} \times E_{\gamma-\mathrm{tot}}^{\mathrm{iso}}$$

- Compare to standard predictions, which have a $\langle\Gamma\rangle^{-4}$ dependence
- Raising ϵ_p automatically decreases ϵ_e, so the photosphere grows, but still ~ 10 photospheric collisions dominate

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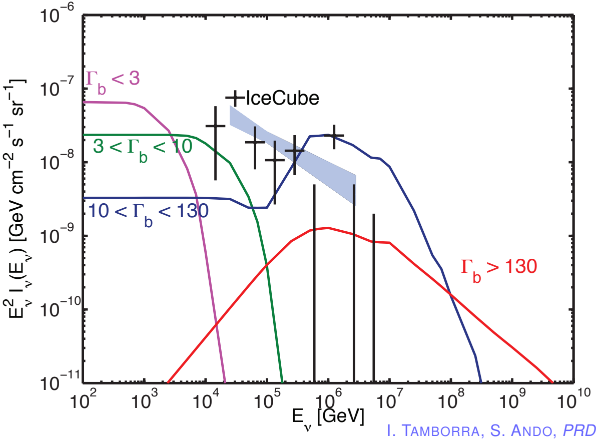
What about low-luminosity and choked GRBs?

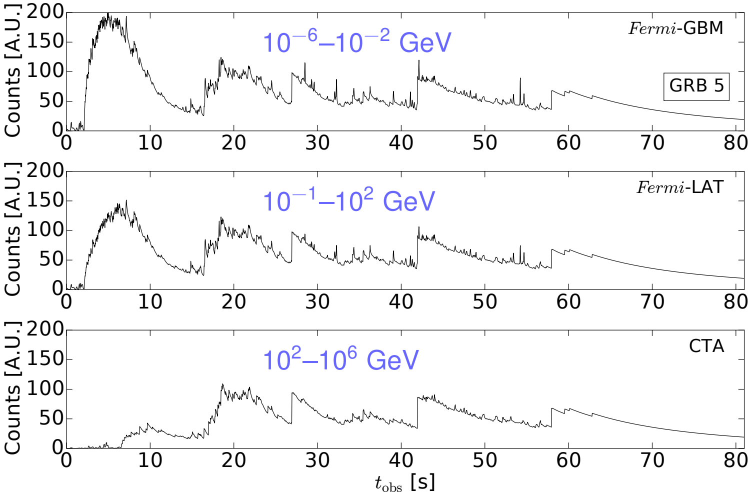
- Low-luminosity and choked GRBs might be in the same family as high-luminosity long GRBs
- Due to lower jet speeds (Γ_b), they do not break out
- They might explain the TeV region of the IceCube diffuse ν flux:



I. Tamborra, S. Ando, *PRD* **93**, 053010 (2016)

Time delays in gamma-ray light curves

Neutrino-weak bursts show time delays in different energy bands —



MB, HEINZE, MURASE, WINTER, *ApJ* 2017 [1606.02325]
See also: BOŠNJAK, DAIGNE, *A&A* 2014 [1404.4577]

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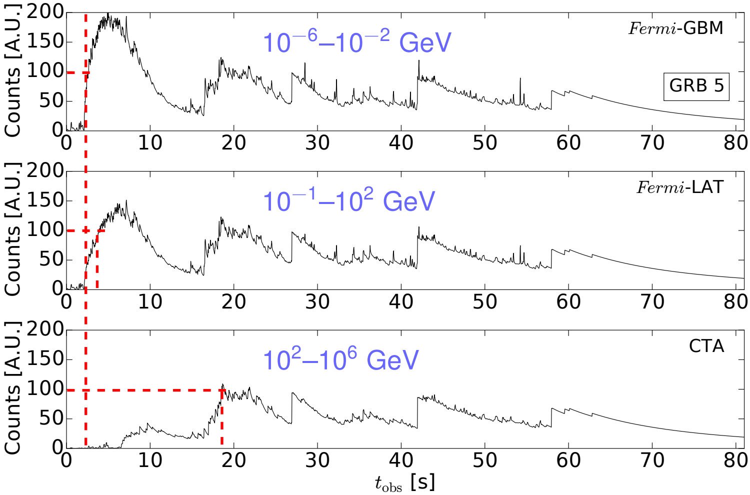

MB, Heinze, Murase, Winter, *ApJ* 2017 [1606.02325]
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