High-energy neutrinos, cosmic rays, and gamma rays from gamma-ray bursts

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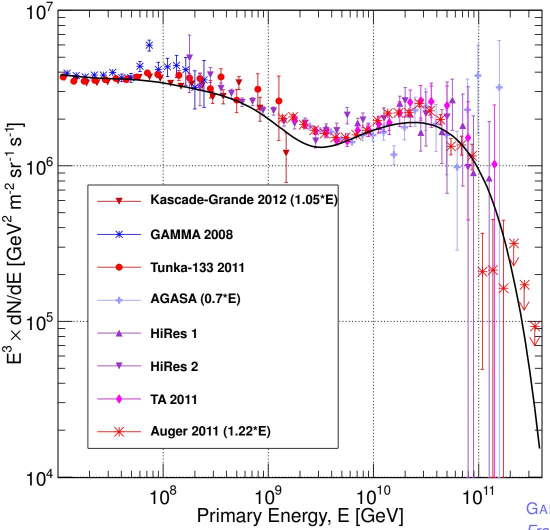
The Ohio State University

Astrophysics Seminar

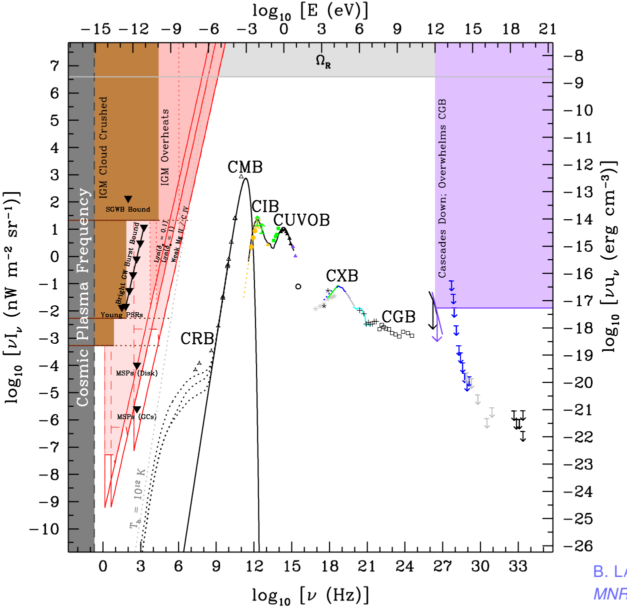
Purdue University — March 06, 2017

After 50+ years of UHECR measurements —



GAISSER, STANEV, TILAV, *Front. Phys. China* **8**, 748 (2013)

The electromagnetic sky

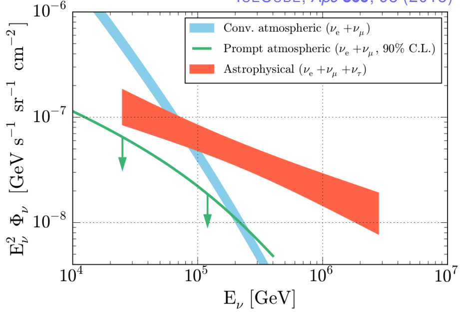


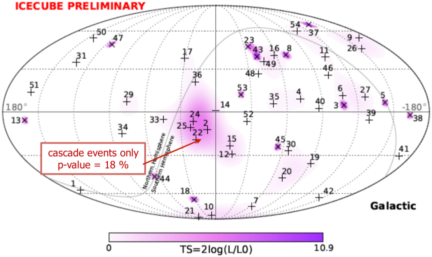
B. Lacki, *MNRAS* **406**, 863 (2010)

A discovery and a mystery

IceCube has discovered a diffuse astrophysical neutrino flux —

IceCube, *ApJ* **809**, 98 (2015)





O. Botner, IPA 2015

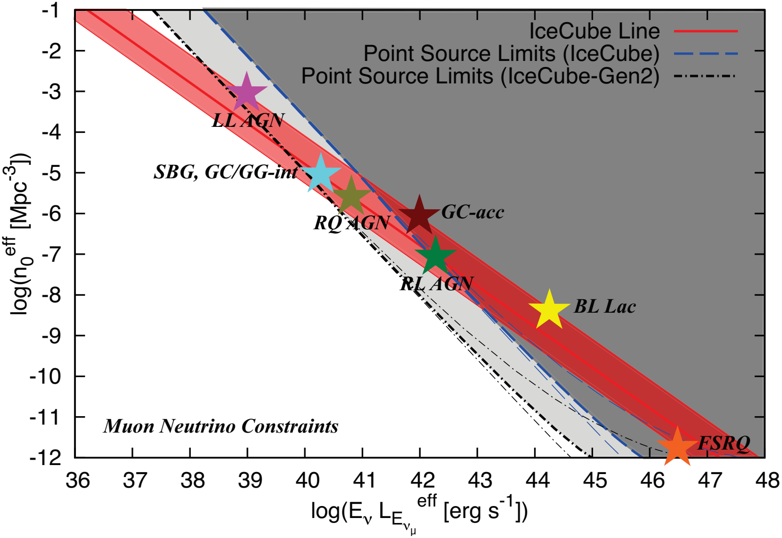
Energies: 25 TeV – 2 PeV

Isotropy of arrivals hints at extragalactic sources

No sources identified yet

Needed: many weak (steady) sources

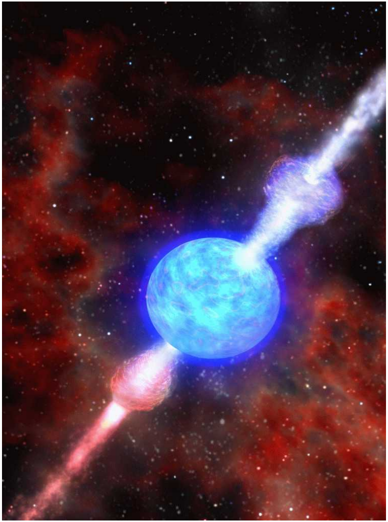
So far, neutrinos are *not* correlated to a few bright steady sources —



MURASE & WAXMAN, *PRD* 2016 [1607.01601]

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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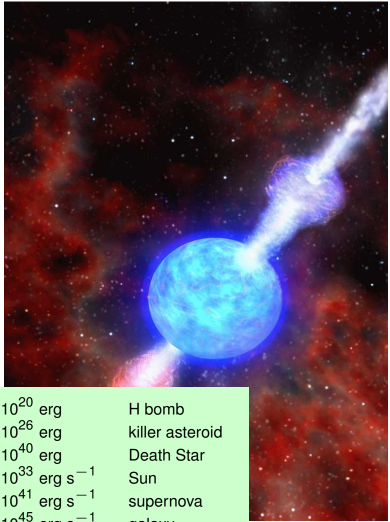


10^{20} erg	H bomb
10^{26} erg	killer asteroid
10^{40} erg	Death Star
10^{33} erg s^{-1}	Sun
10^{41} erg s^{-1}	supernova
10^{45} erg s^{-1}	galaxy

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
   - Gamma-ray emission has features at 0.01 s scale
   - Physics happens inside compact regions

   Implies high proton and photon number densities

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

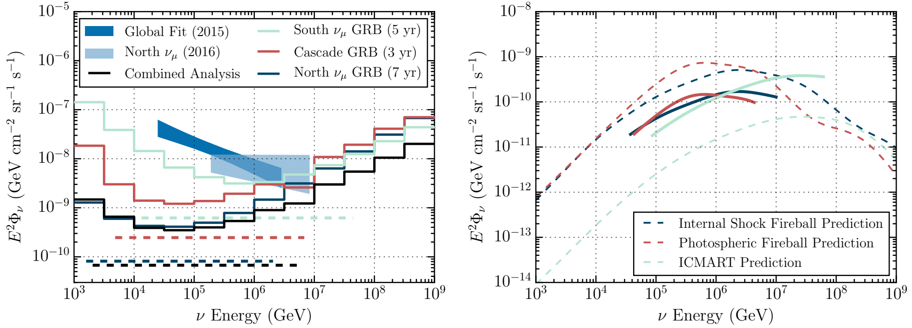
(But they are far and relatively rare)

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
- Catalog of 1172 bursts
- No statistically significant coincidence

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



IceCube, 1702.06868

(Though limits are on one-zone emission models only — more on this later)

The elephant 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]

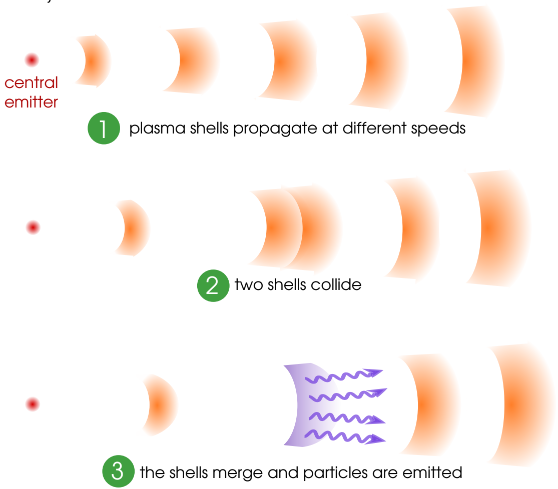
4. Neutrinos from GRB afterglows expected at $\sim$ EeV

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

So, every bit of insight into how GRBs make neutrinos is essential

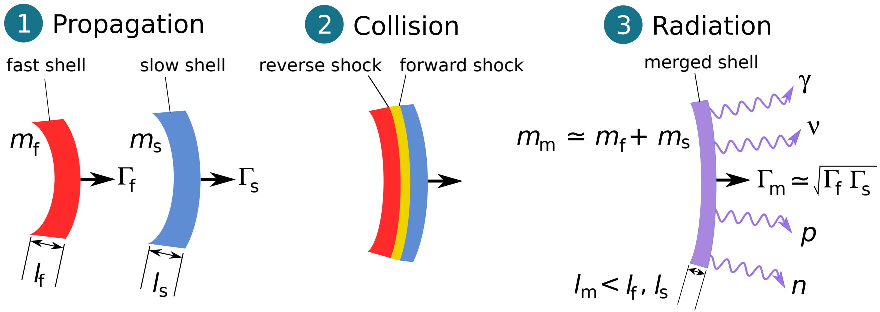
The fireball model — internal collisions

Relativistic blobs of plasma collide, merge, and emit high-energy photons, protons, and neutrinos —



Developed by Mészáros, Reese, Goodman, Pachinsky, *et al.* in the 1990s

Anatomy of an internal collision



Part of the initial kinetic energy radiated as γ's, ν's, p's, and n's:

$$E_{\rm coll}^{\rm iso} = \left(E_{{\rm kin},f}^{\rm iso} - E_{{\rm kin},m}^{\rm iso}\right) + \left(E_{{\rm kin},m}^{\rm iso} - E_{{\rm kin},s}^{\rm iso}\right)$$

1/12 $\underbrace{\epsilon_e E_{\rm coll}^{\rm iso}}$ energy in photons

1/12 $\underbrace{\epsilon_B E_{\rm coll}^{\rm iso}}$ energy in magnetic fields

5/6 $\underbrace{\epsilon_p E_{\rm coll}^{\rm iso}}$ energy in baryons

Producing the UHE ν's, CRs, γ rays – a first look

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

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

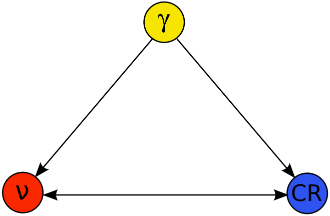
$$p\,\gamma \rightarrow \Delta^+(1232) \rightarrow \begin{cases} n\pi^+\,, & \mathrm{BR} = 1/3 \\ p\pi^0\,, & \mathrm{BR} = 2/3 \end{cases}$$

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

$$\pi^0 \rightarrow \gamma\gamma$$

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

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



After propagation, with flavor mixing:

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

("one ν_μ per cosmic ray")

(This neutron model of CR emission is now strongly disfavored)

IceCube, *Nature* **484**, 351 (2012)
M. Ahlers *et al. Astropart. Phys.* **35**, 87 (2011)

What are the ingredients?

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

- Its gamma-ray luminosity $L_\gamma^{\rm iso}$ [erg s^{-1}] [measured]
- Its variability timescale t_v [s], from the light curve [measured]
- Break energy of its photon spectrum $\epsilon_{\gamma,\rm break}$ [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 ▶

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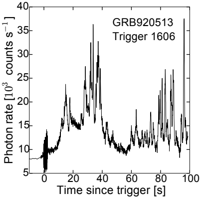

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Now let us cook up the neutrinos ▶

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

Cooking up the neutrinos

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

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

+

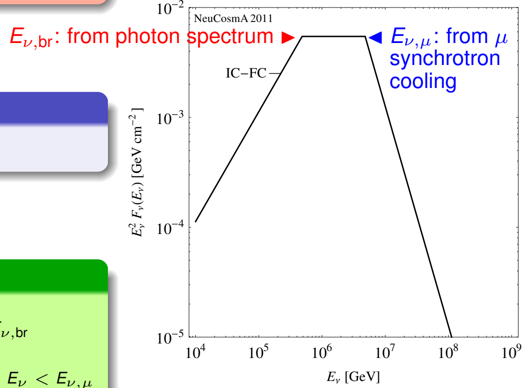
Assumed proton spectrum in the source

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

=

Neutrinos from $p\gamma$, via Δ resonance

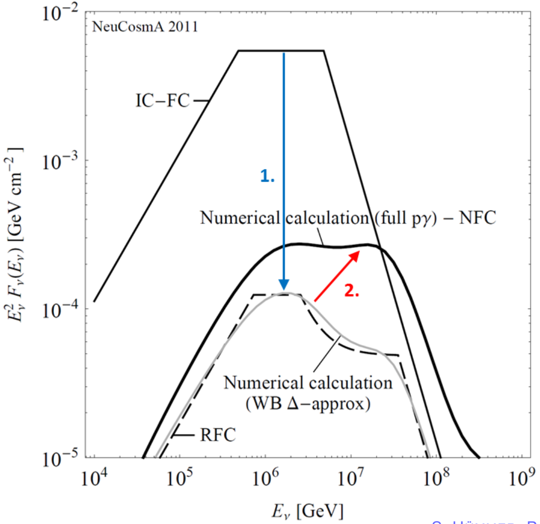
$$F_\nu(E_\nu) \propto \begin{cases} \left(\frac{E_\nu}{E_{\nu,\mathrm{br}}}\right)^{-\alpha_\nu} & , E_\nu < E_{\nu,\mathrm{br}} \\ \left(\frac{E_\nu}{E_{\nu,\mathrm{br}}}\right)^{-\beta_\nu} & , E_{\nu,\mathrm{br}} \leq E_\nu < E_{\nu,\mu} \\ \left(\frac{E_\nu}{E_{\nu,\mathrm{br}}}\right)^{-\beta_\nu}\left(\frac{E_\nu}{E_{\nu,\mu}}\right)^{-2}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



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 $\rightarrow$ RFC)

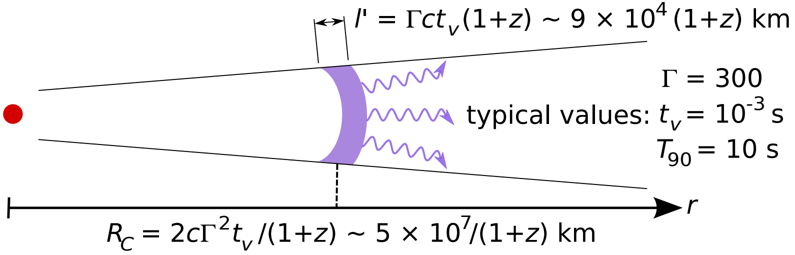
2. Change due to full numerical calculation

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

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

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

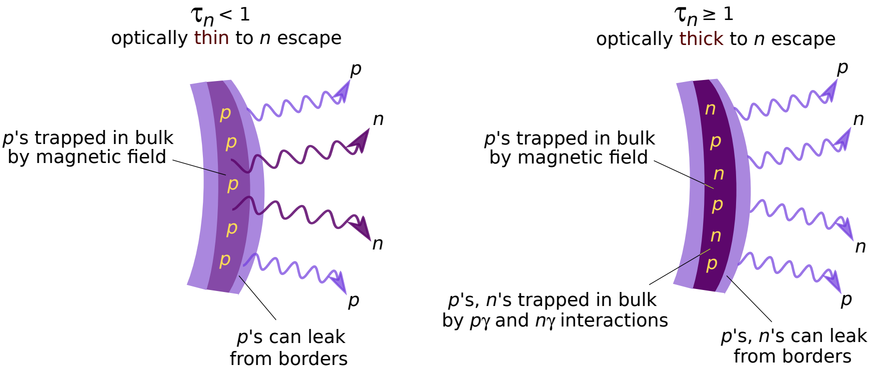
- Calculate particle emission spectra once
- Then multiply by $N_{\rm coll}$
- Γ is the average speed of shells

Going beyond the neutron model

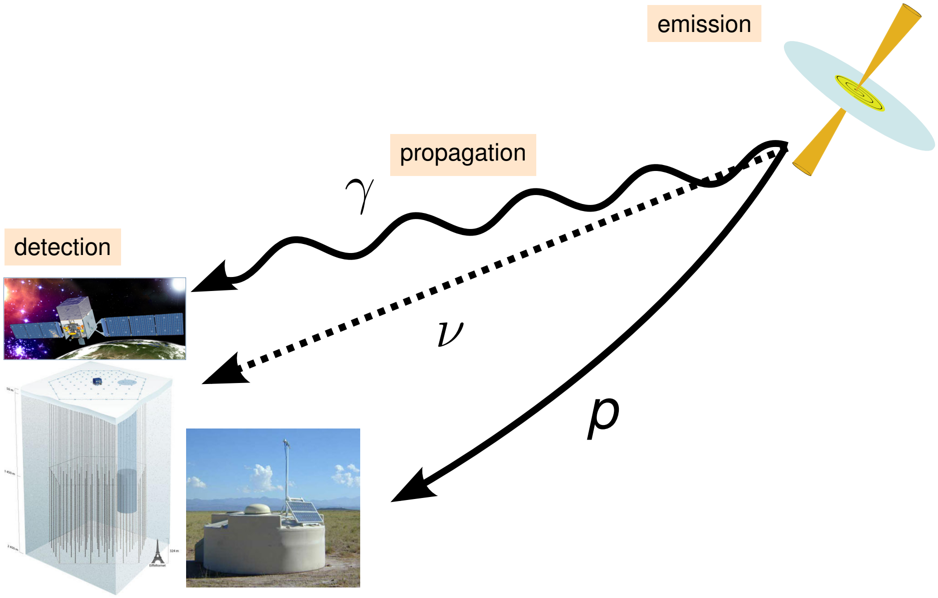
We allow UHECRs to escape as either:

- Neutrons, which decay into protons outside the source; or
- Protons that leak out without interacting inside the source

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



From the sources to us



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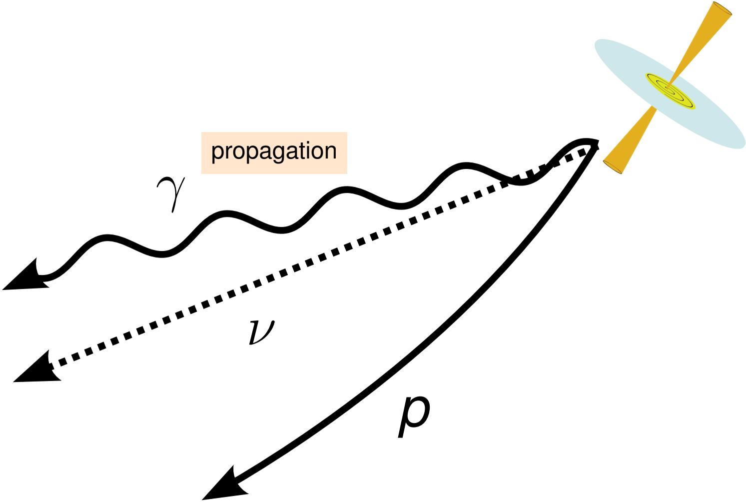
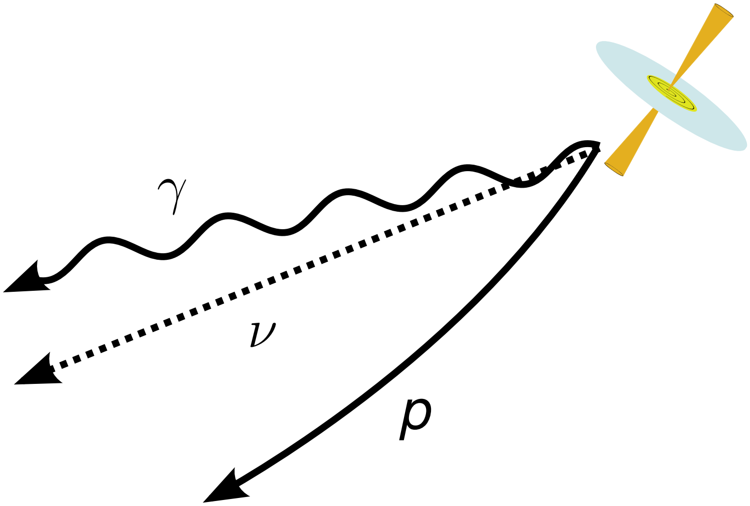


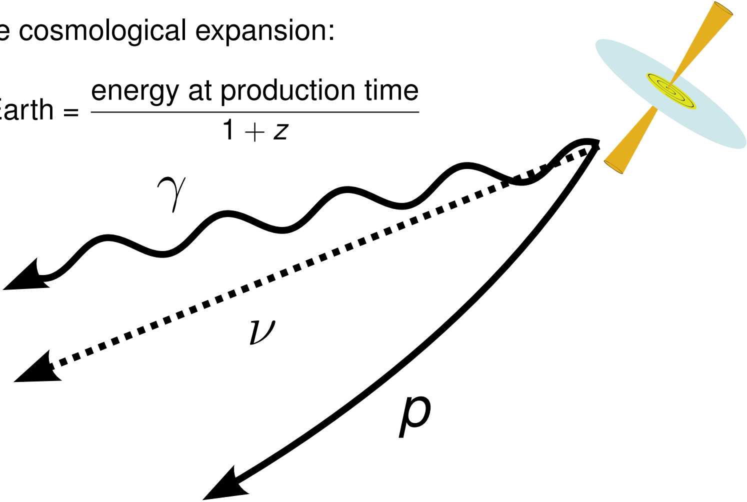
From the sources to us



From the sources to us

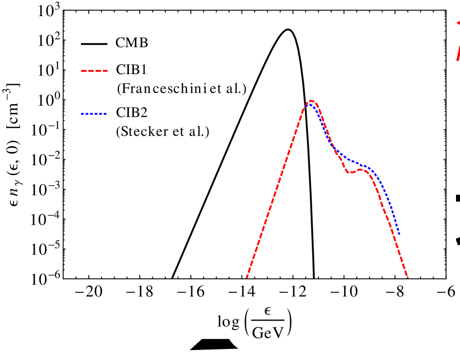
Because of the cosmological expansion:

$$\text{energy at Earth} = \frac{\text{energy at production time}}{1+z}$$

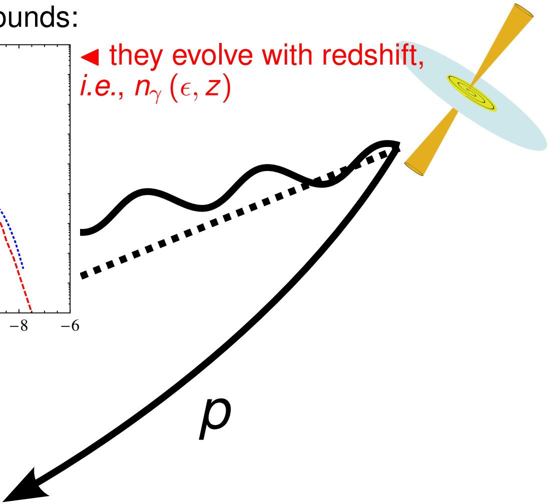


From the sources to us

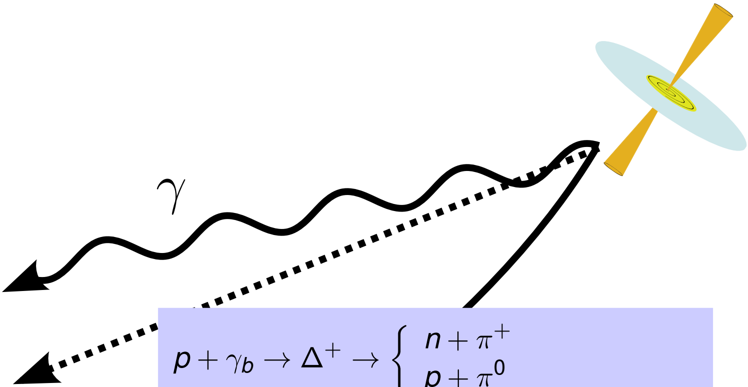
Cosmological photon backgrounds:



◀ they evolve with redshift, *i.e.*, $n_\gamma(\epsilon, z)$



From the sources to us



$$p + \gamma_b \to \Delta^+ \to \begin{cases} n + \pi^+ \\ p + \pi^0 \end{cases}$$

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

Cosmogenic ν's: $\pi^+ \to e^+ + \nu_e + \bar{\nu}_\mu + \nu_\mu$

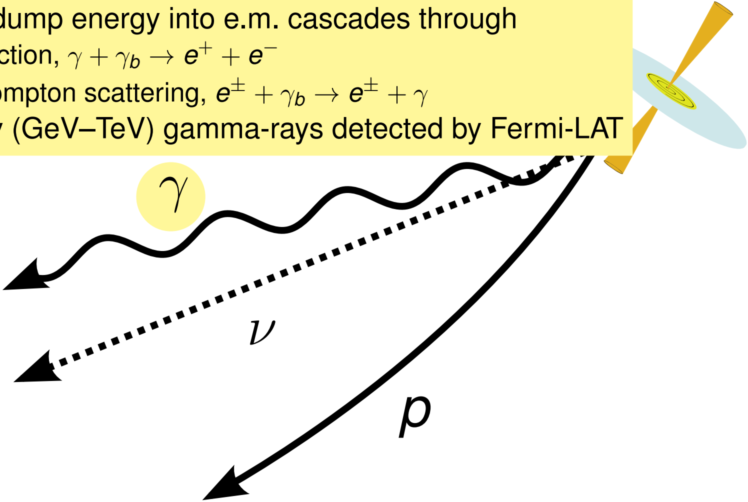
$$n \to p + e^- + \bar{\nu}_e$$

From the sources to us

γ's and $e^{\pm}$'s dump energy into e.m. cascades through

- pair production, $\gamma + \gamma_b \to e^+ + e^-$
- inverse Compton scattering, $e^{\pm} + \gamma_b \to e^{\pm} + \gamma$

Lower-energy (GeV–TeV) gamma-rays detected by Fermi-LAT



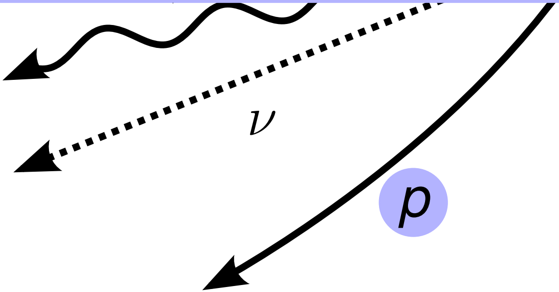
From the sources to us

p's are deflected by extragalactic magnetic fields
$\Rightarrow$ except for the most energetic ones, they are **not** expected to point back to the sources — Pierre Auger found weak correlation with known AGN positions

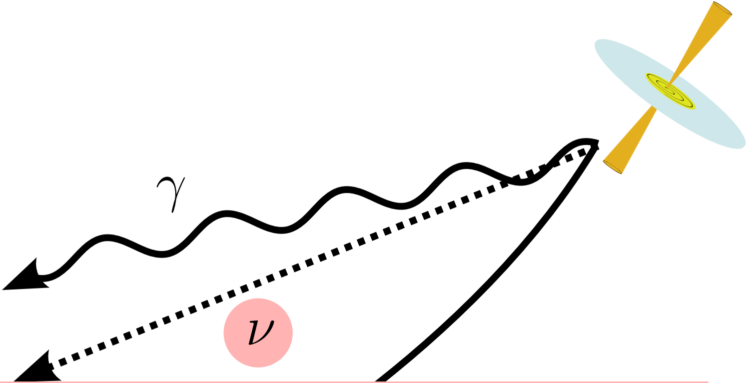
They lose energy through:

- pair production, $p + \gamma_b \to p + e^+ + e^-$
- photohadronic interactions, $p\gamma_b$

depend on the redshift evolution of the cosmological γ backgrounds



From the sources to us



Initial UHE ν flavor fluxes: $\nu_e : \nu_\mu : \nu_\tau = 1 : 2 : 0$

Probability of $\nu_\alpha \to \nu_\beta$ transition: $P_{\alpha\beta}(E_0, z)$

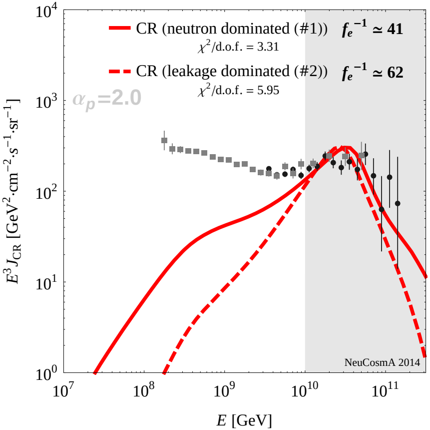
Flavor oscillations redistribute the fluxes

MB, Beacom, Winter, *PRL* **115**, 161302 (2015)

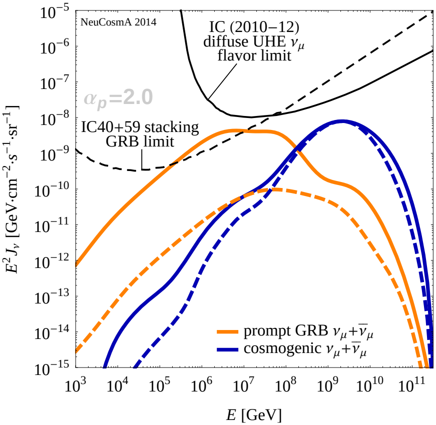
– at Earth: $\nu_e : \nu_\mu : \nu_\tau \approx 1 : 1 : 1$ (might be changed by exotic physics!)

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

UHECRs



Neutrinos



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)

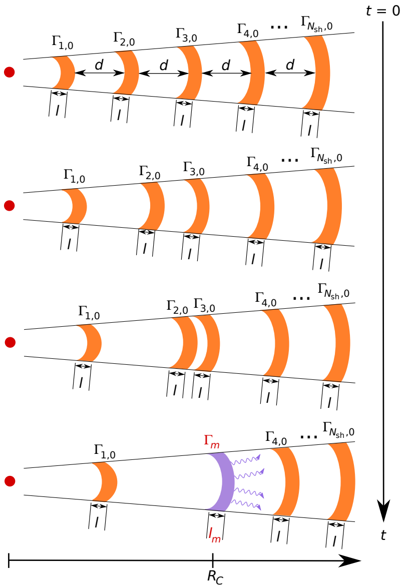
No more identical collisions

Consider an evolving fireball –

- The fireball expands with time
- $\sim$ 1000 shells, different speeds
- They have different masses
- They collide at different radii (collisions no longer identical)

What is different?

The particle (γ, p) densities fall as the fireball expands – particle production conditions change with time/radius



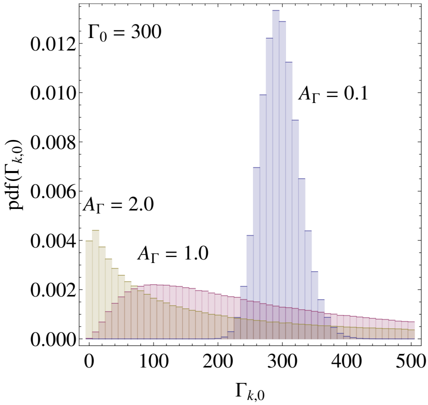
S. Kobayashi, T. Piran, R. Sari, *ApJ* **490**, 92 (1997)
F. Daigne, R. Mochkovitch, *MNRAS* **296**, 275 (1998)

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

Tracking each collision individually

Each collision occurs in a different emission regime –

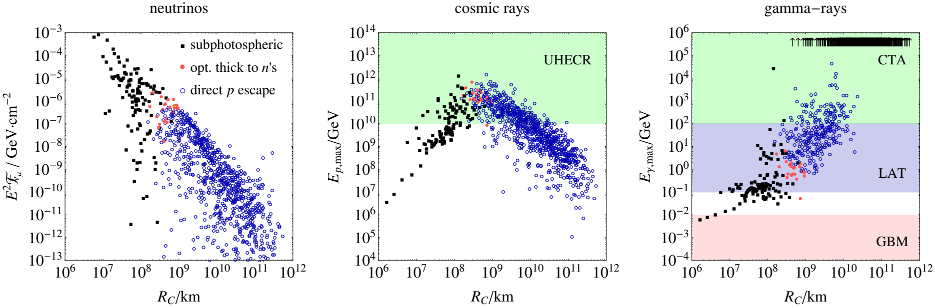
Sub-photospheric: $\tau_{e\gamma} > 1$

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

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

maximum p energy

maximum γ energy



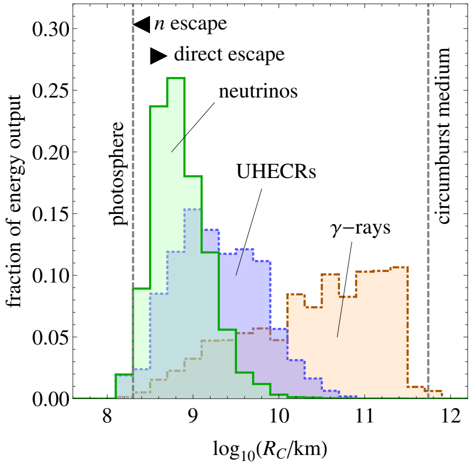
(observer's frame)

(source frame)

MB, P. Baerwald, K. Murase, W. Winter, *Nat. Commun.* **6**, 6783 (2015)

Different particles come from different jet regions

Emission of different species peaks at different collision radii –



Why?

As the fireball expands, photon and proton densities fall

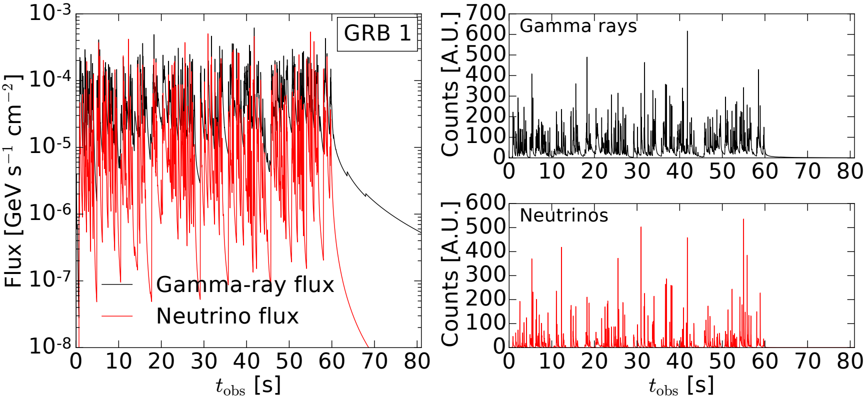
Why does it matter?

GRB parameters derived from gamma-ray observations might bias ν and UHECR predictions

MB, P. Baerwald, K. Murase, W. Winter, *Nat. Commun.* **6**, 6783 (2015)

Synthetic light curves

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



MB, P. Baerwald, K. Murase, W. Winter
Nature Commun. **6**, 6783 (2015)

Synthetic light curves

Each collision emits a particle pulse
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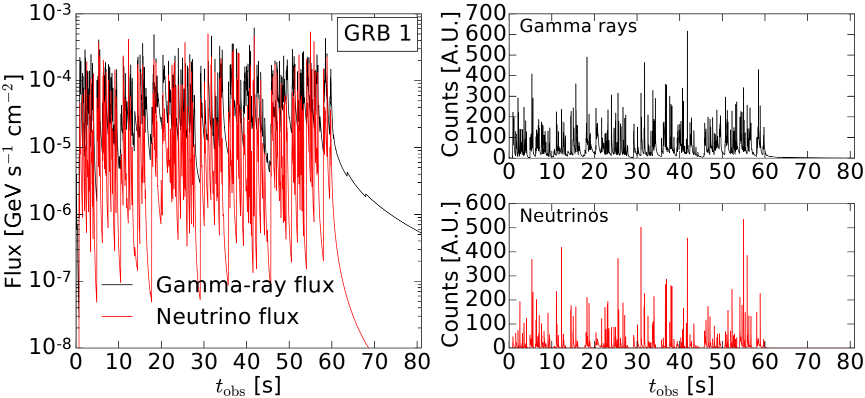
Energy in gamma-rays: $E_{\gamma,\mathrm{tot}}^{\mathrm{iso}} = 10^{53}$ erg



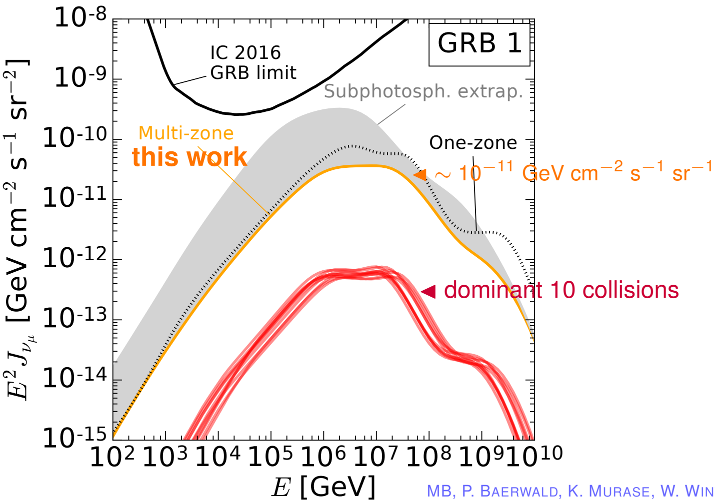
$T_{90} \approx 59$ s

1000 initial shells $\mapsto$ 987 collisions

MB, P. Baerwald, K. Murase, W. Winter
Nature Commun. **6**, 6783 (2015)

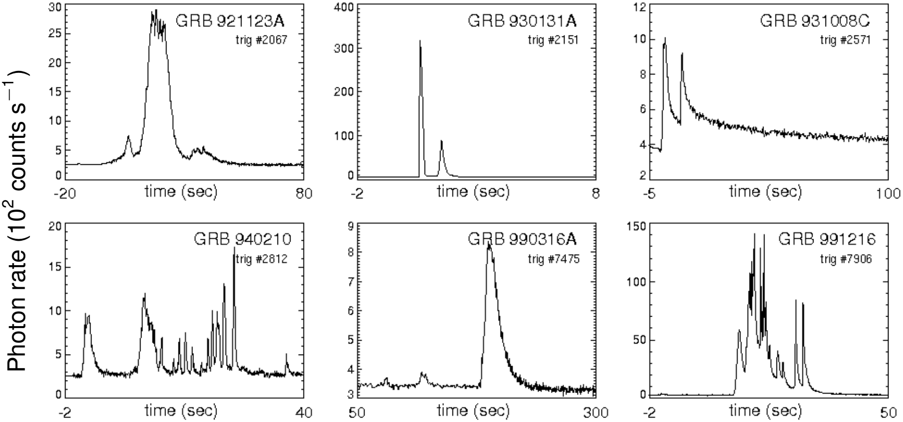
A robust minimal diffuse ν flux from GRBs

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



MB, P. Baerwald, K. Murase, W. Winter
Nature Commun. **6**, 6783 (2015)

GRBs – a zoo of light curves

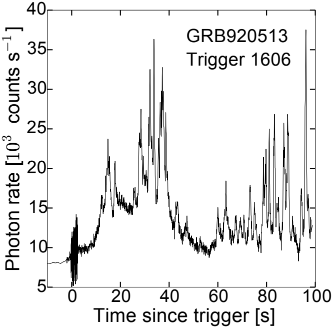


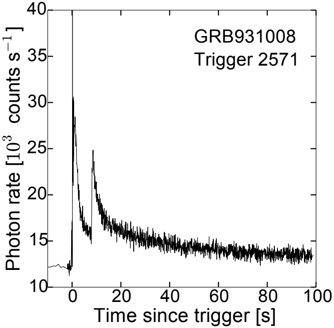
BATSE

variability timescale (width of pulses) $\equiv t_v \approx 0.01$ s

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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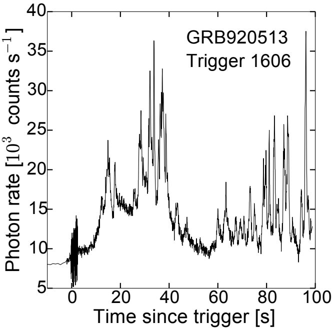
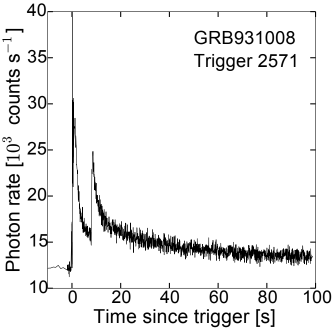


Fast time variability



Slow pulse + fast variability

can we tell which GRB is likely bright in neutrinos?

Which GRB is brighter in neutrinos?

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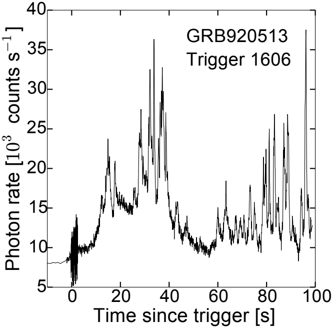
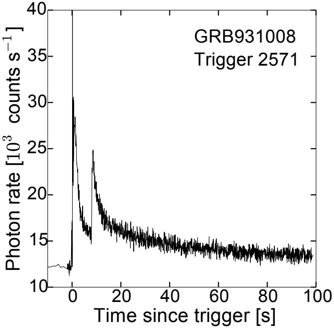


Fast time variability



Slow pulse + fast variability

can we tell which GRB is likely bright in neutrinos?

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

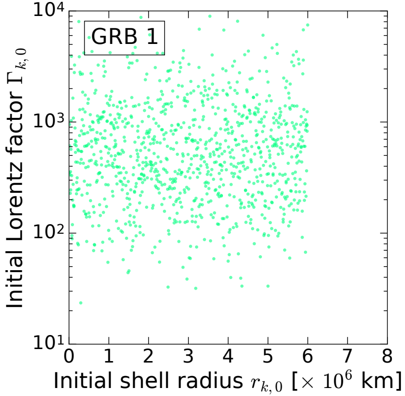
What makes a GRB bright in neutrinos?

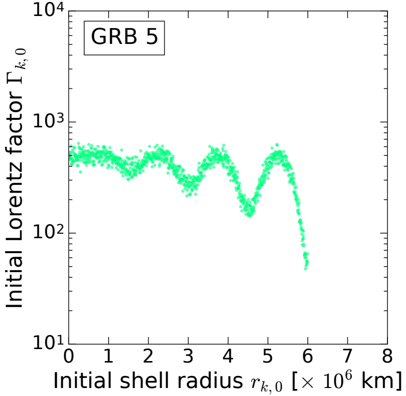
Undisciplined GRB engine

- 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 [1606.02325]

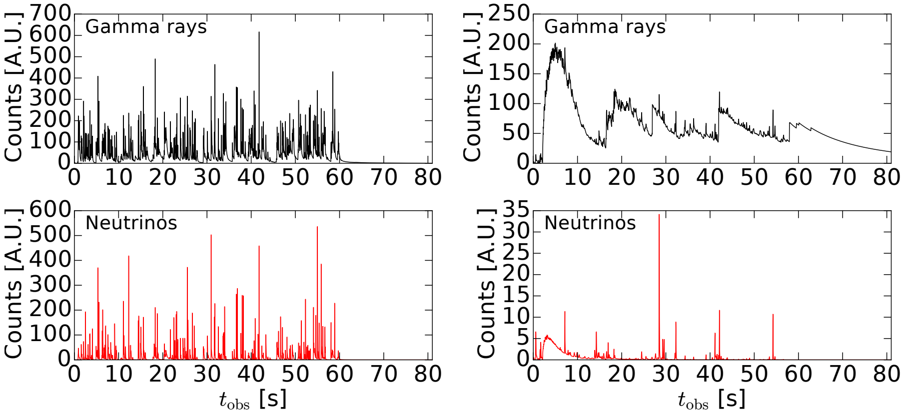
Light curves

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 [1606.02325]

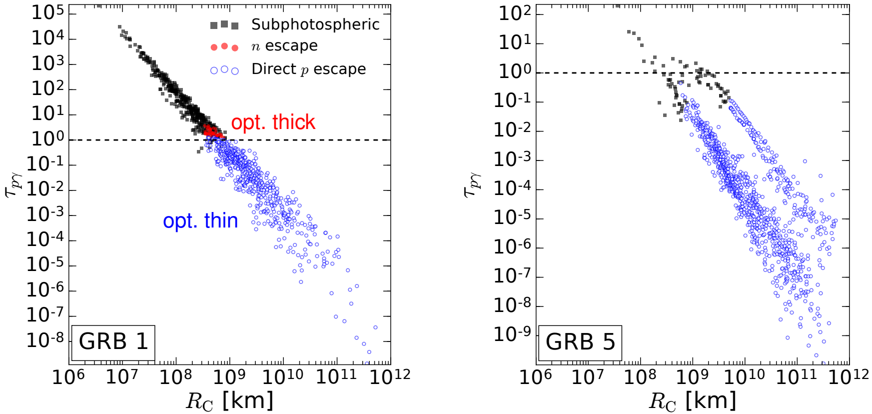
How many optically thick collisions?

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

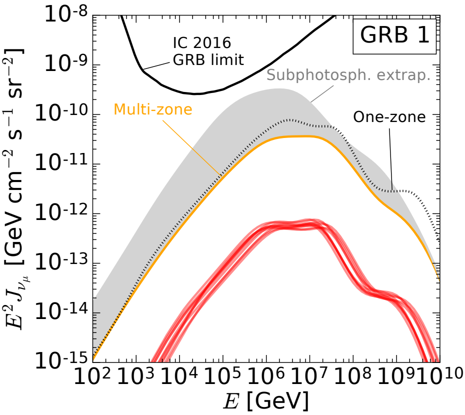


MB, Heinze, Murase, Winter, *ApJ* 2017 [1606.02325]

So which burst is neutrino-bright?

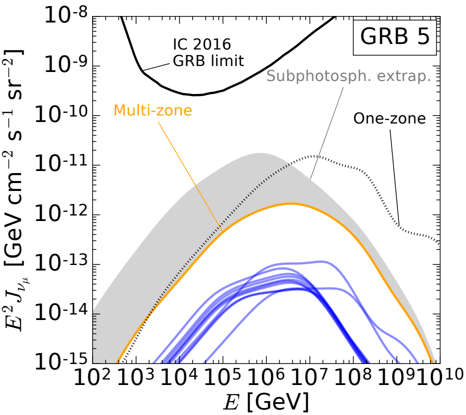
Undisciplined GRB engine

$\sim 10^{-11}$ GeV cm^{-1} s^{-1} sr^{-1}



Disciplined GRB engine

$\sim 10^{-12}$ GeV cm^{-1} s^{-1} sr^{-1}



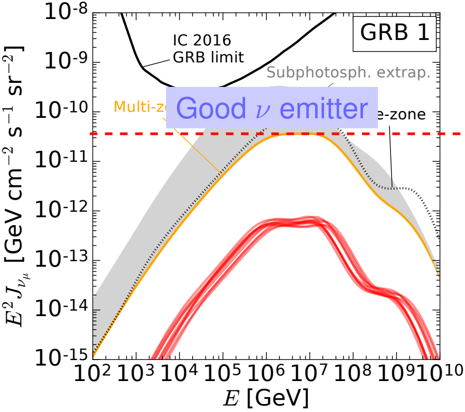
So which burst is neutrino-bright?

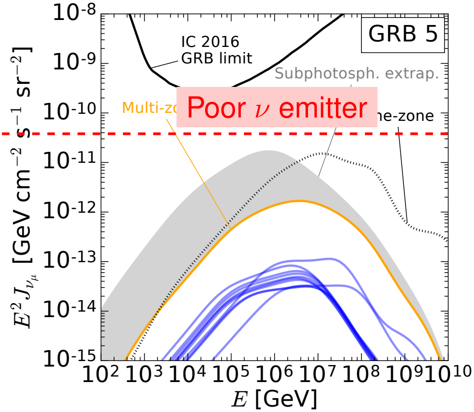
Undisciplined GRB engine

$\sim 10^{-11}$ GeV cm^{-1} s^{-1} sr^{-1}

Disciplined GRB engine

$\sim 10^{-12}$ GeV cm^{-1} s^{-1} sr^{-1}





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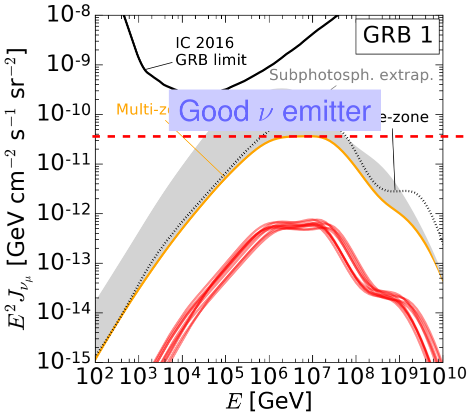
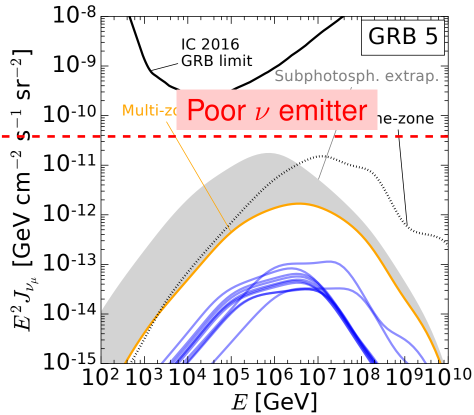
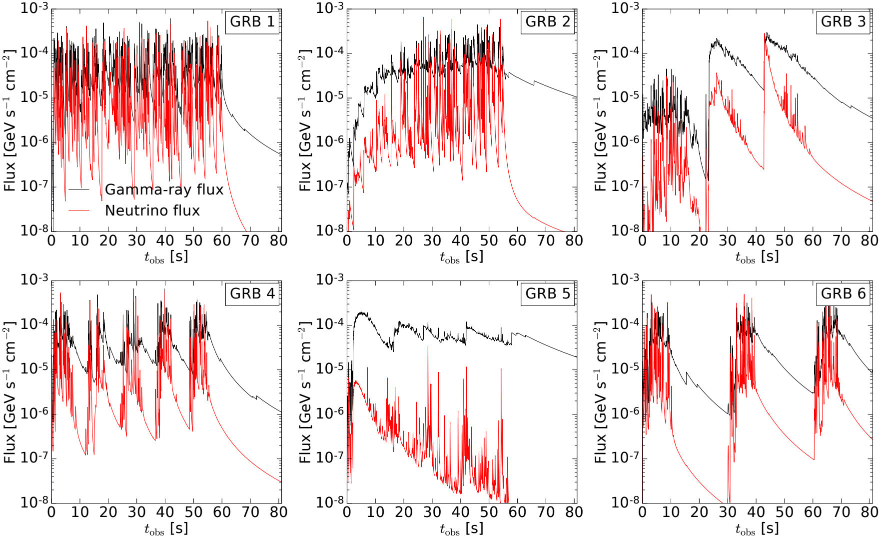




An undisciplined engine makes a GRB neutrino-bright

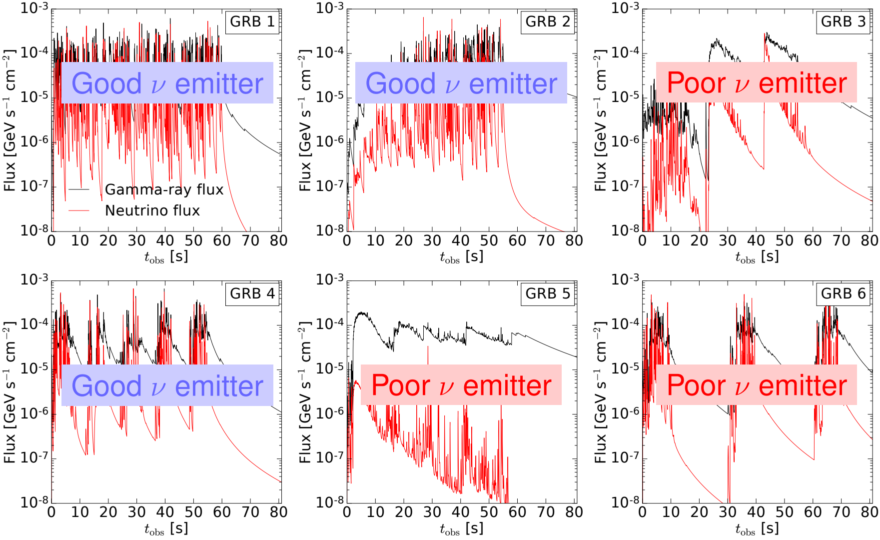
Using our new insight

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



Using our new insight

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



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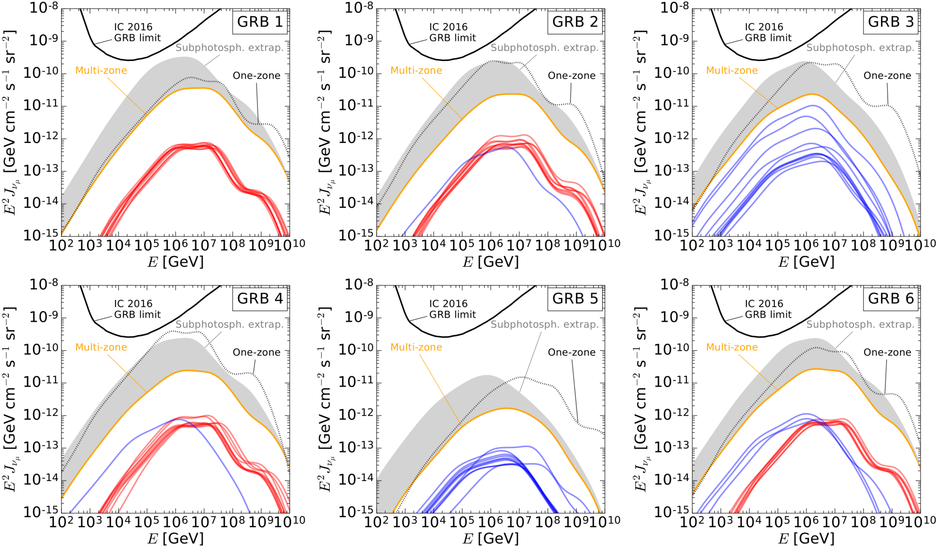

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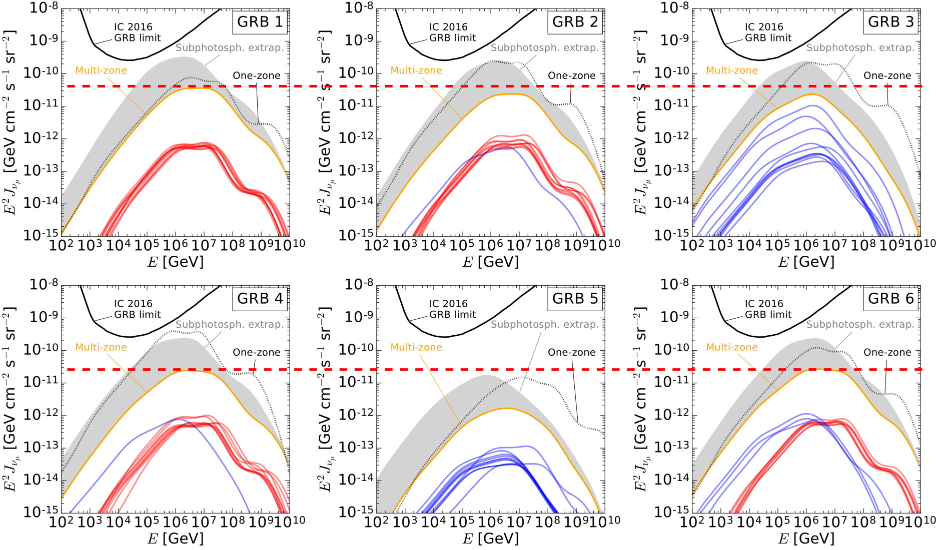
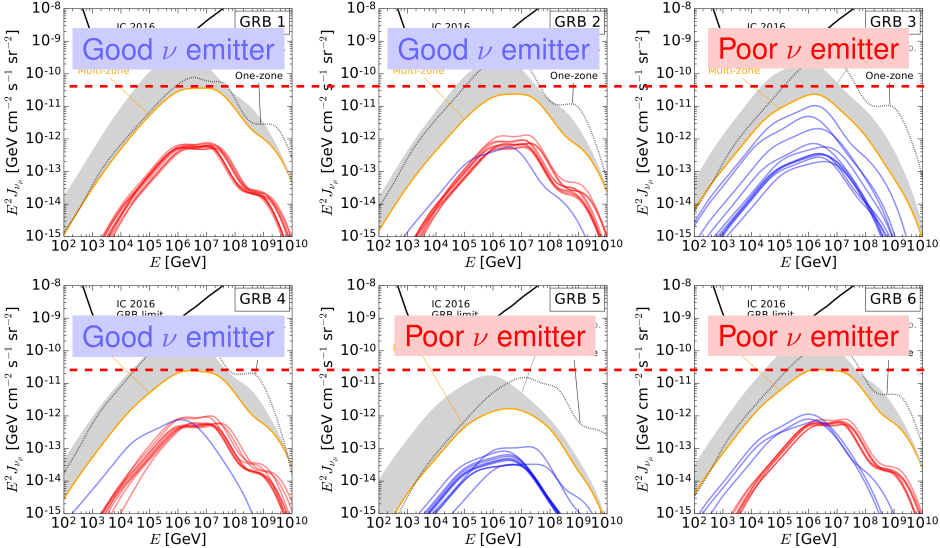


Using our new insight

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



Using our new insight

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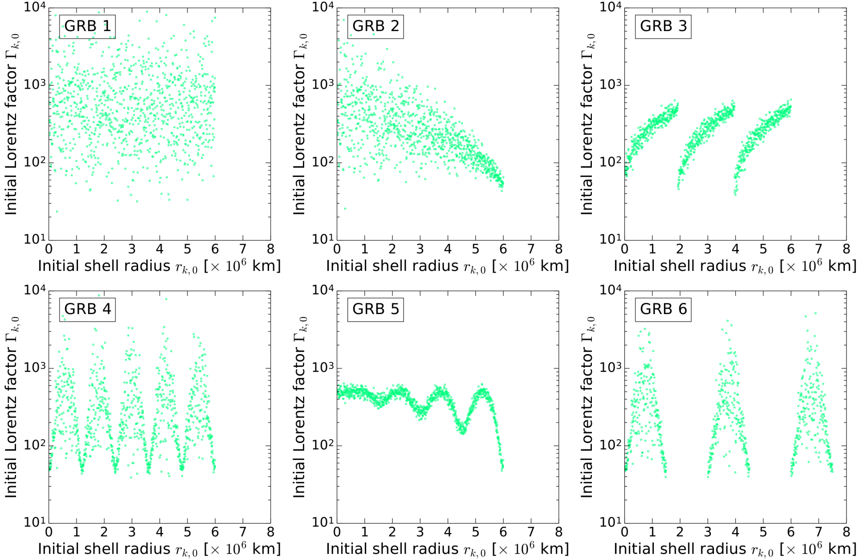
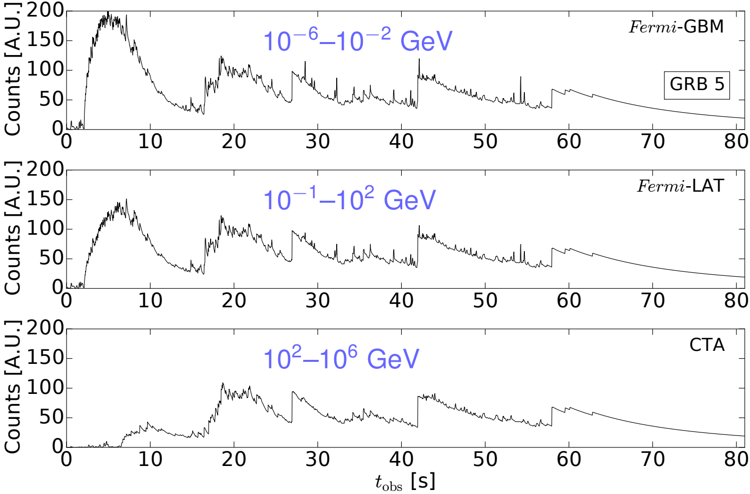


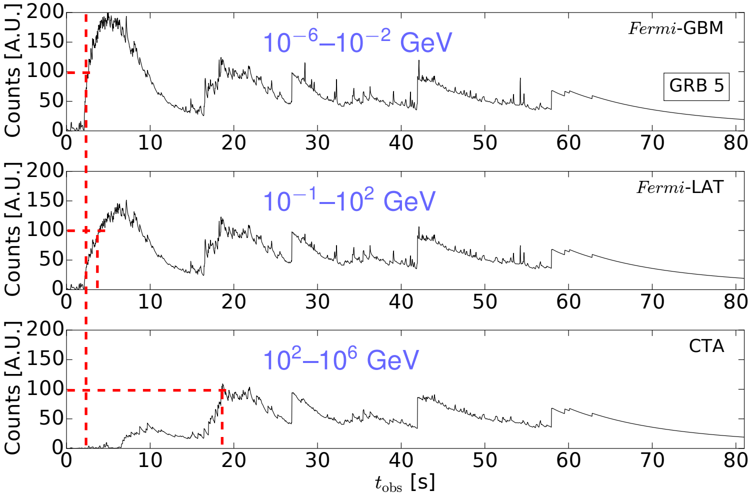
Neutrino-weak bursts show time delays in different energy bands —



MB, Heinze, Murase, Winter, *ApJ* 2017 [1606.02325]
See also: Bošnjak, Daigne, *A&A* 2014 [1404.4577]

Time delays in gamma-ray light curves

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

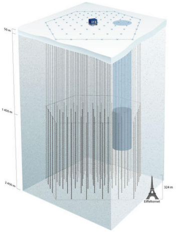


MB, Heinze, Murase, Winter, *ApJ* 2017 [1606.02325]
See also: Bošnjak, Daigne, *A&A* 2014 [1404.4577]

Why is *now* a good time to do this?

better, bigger detectors + loads of data + bright future

Neutrinos



- IceCube: diffuse flux of HE astrophysical ν's
- No point sources *yet*
- GRBs: low bg due to time and direction cuts
- IceCube-Gen2

GRBs

- *Fermi*: $\sim$ 250 GRBs yr^{-1} in 8 keV – 40 MeV
- $\sim$ 12 GRBs yr^{-1} in 20 MeV – 300 GeV
- Different wavelengths: INTEGRAL, *Swift*
- 1000's GRBs detected so far

UHECRs

- Auger + TA: 200 events above 57 EeV
- Surface + fluorescence
- Future: LHAASO, JEM-EUSO

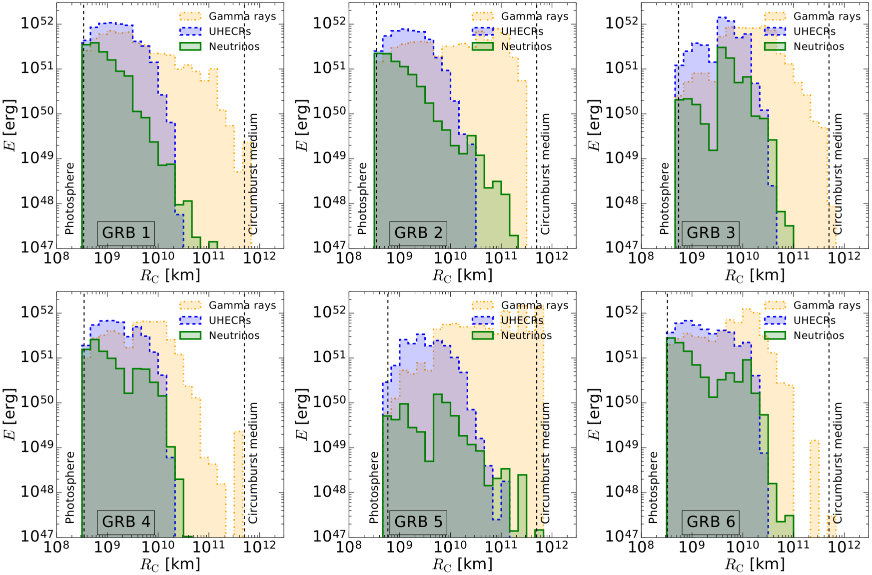
Conclusions . . . and the future

- Neutrino emission from bright GRBs is lower than we expected
- Still candidates for joint e.m.-ν detection, UHECR production
- Likely to be the first neutrino sources to be resolved
- We have a new criterion to select promising GRBs
- We need next-gen neutrino telescopes (IceCube-Gen2, KM3NeT)

The mystery should **not** last another fifty years

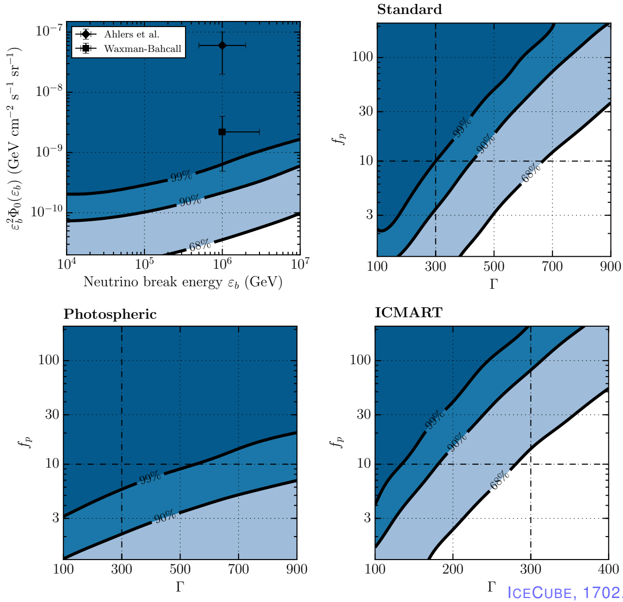
Backup slides

Particle production inside the GRB jet



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

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):

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

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

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

- 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 – II

Normalize the particle densities at the source —

- Photons:

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

- Protons:

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

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

NeuCosmA: (revised) GRB particle emission – III

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

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

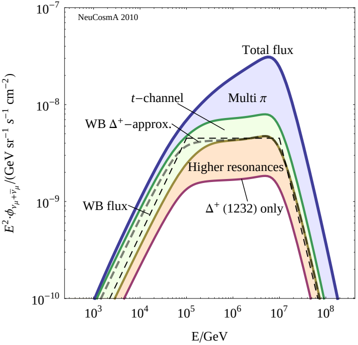
$$Q'\left(E'\right) = \int_{E'}^{\infty} \frac{dE'_p}{E'_p} N'_p\left(E'_p\right) \int_0^{\infty} c\, dE'_\gamma\, N'_\gamma\left(E'_\gamma\right) R\left(x, y\right)$$

response function

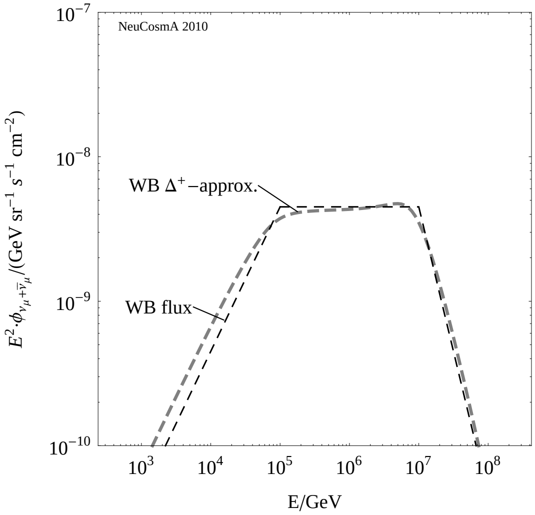
R contains cross sections, multiplicities for different channels

What does NeuCosmA include?

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



NeuCosmA – the full photohadronic cross section

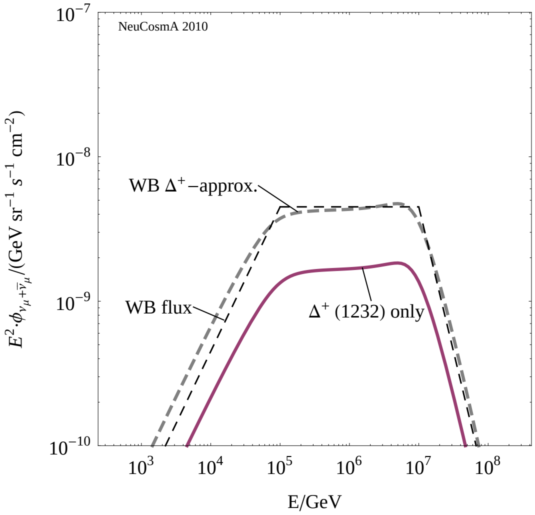


NeuCosmA – the full photohadronic cross section

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

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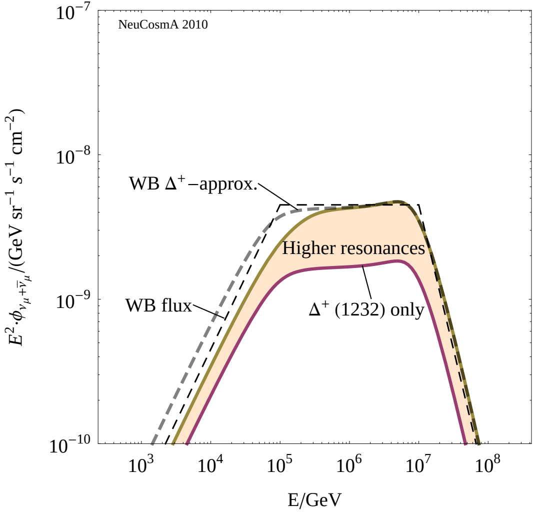
- Higher resonances

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



NeuCosmA – the full photohadronic cross section

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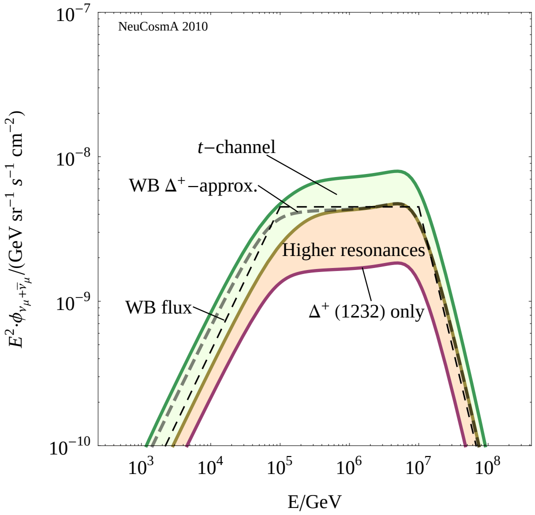
P. BAERWALD, S. HÜMMER, AND W. WINTER, *Phys. Rev.* **D83**, 067303 (2011)



NeuCosmA – the full photohadronic cross section

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

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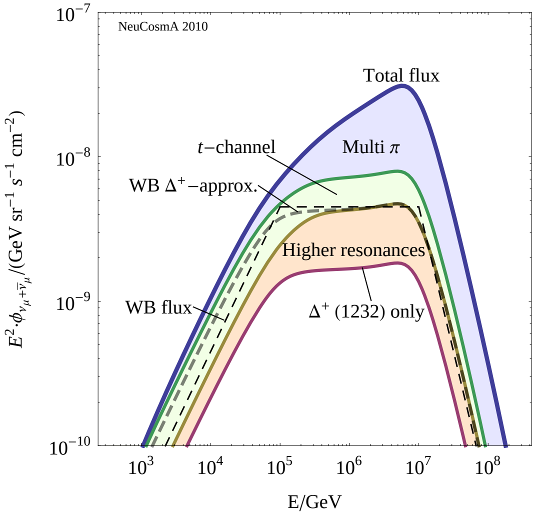
- Higher resonances
- *t*-channel
  (direct production)
- High energy processes
  (multiple π)

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

$$\begin{aligned}\pi^+ &\rightarrow \mu^+ + \nu_\mu \\ &\qquad \mu^+ \rightarrow e^+ + \nu_e + \bar{\nu}_\mu\end{aligned}$$

$$\begin{aligned}\pi^- &\rightarrow \mu^- + \bar{\nu}_\mu \\ &\qquad \mu^- \rightarrow e^- + \bar{\nu}_e + \nu_\mu\end{aligned}$$

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

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

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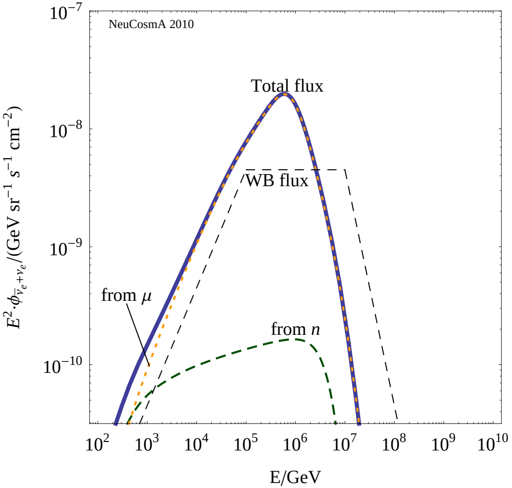
$$\mu^- \rightarrow e^- + \bar{\nu}_e + \nu_\mu$$

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

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

Resulting ν_e flux (at the observer)



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

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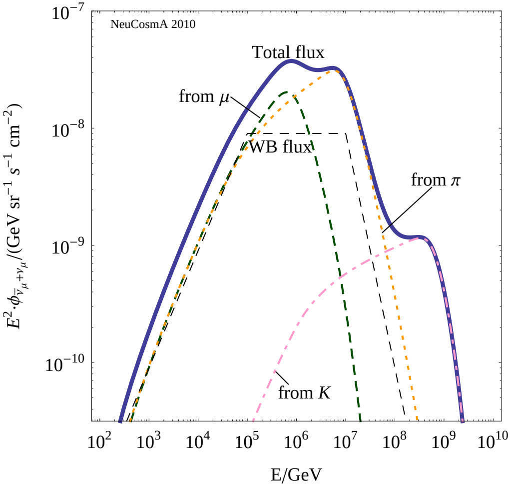
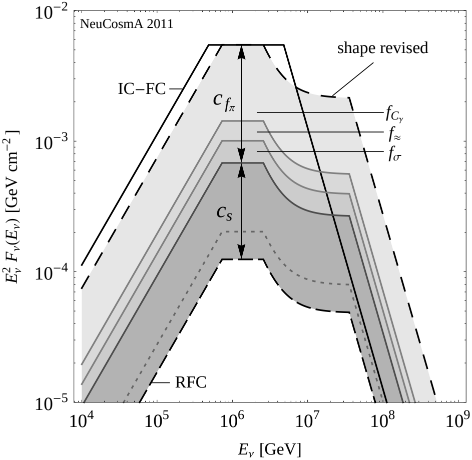
Resulting ν_μ flux (at the observer)



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

NeuCosmA – how the neutrino spectrum changes – I



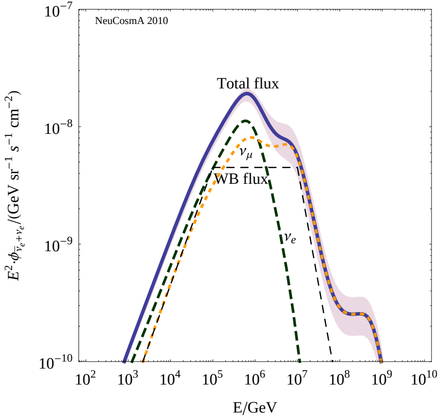
S. Hümmer, P. Baerwald, W. Winter, *Phys. Rev. Lett.* **108**, 231101 (2012)

Corrections to the analytical model:

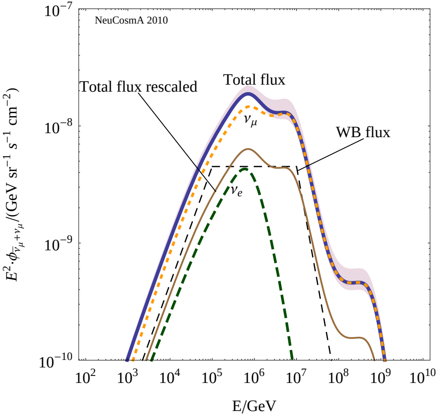
- shape revised:
  - shift of first break (correction of photohadronic threshold)
  - different cooling breaks for μ's and π's
  - $(1+z)$ correction on the variability scale of the GRB
- Correction cf_π to π prod. efficiency:
  - f_{C_γ}: full spectral shape of photons
  - $f_\approx = 0.69$: rounding 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

Electron neutrino spectrum



Muon neutrino spectrum



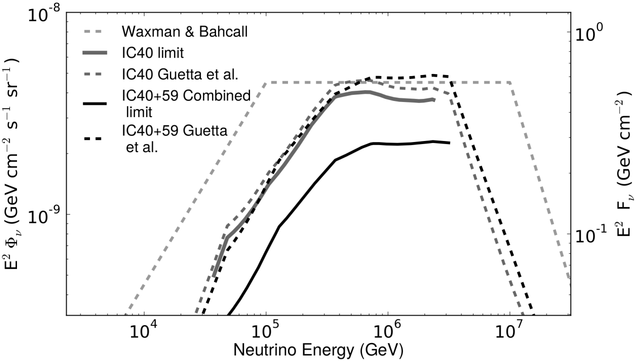
P. BAERWALD, S. HÜMMER, W. WINTER, *Phys. Rev.* **D83**, 067303 (2011)

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)

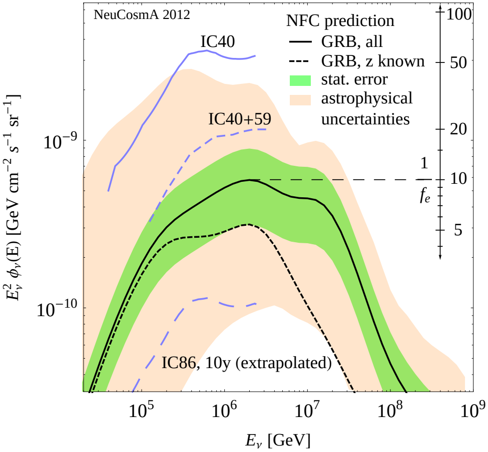
The new prediction of the quasi-diffuse GRB ν flux

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 $\sim$ 1 order of magnitude lower!



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

A two-component model of CR emission

Optical depth:

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

Particles can escape from within a shell of thickness λ'_{mfp}:

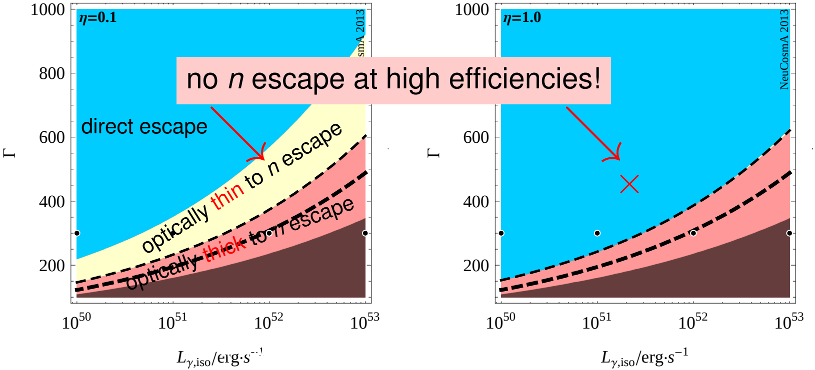
$$\left.\begin{array}{l} \lambda'_{p,\mathrm{mfp}}\left(E'\right) = \min\left[\Delta r', R'_L\left(E'\right), ct'_{p\gamma}\left(E'\right)\right] \\ \lambda'_{n,\mathrm{mfp}}\left(E'\right) = \min\left[\Delta r', ct'_{p\gamma}\left(E'\right)\right] \end{array}\right\} f_{\mathrm{esc}} = \frac{\lambda'_{\mathrm{mfp}}}{\Delta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

fraction of escaping particles

We *need* direct proton escape

Scan of the GRB emission parameter space –

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

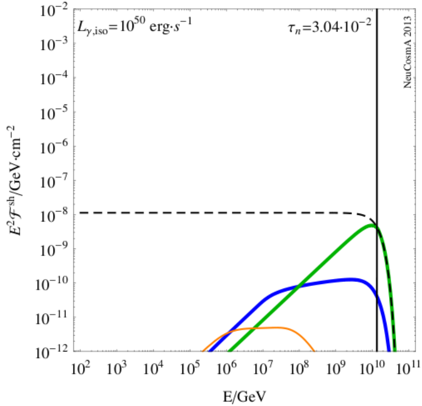


P. BAERWALD, MB, AND W. WINTER, *ApJ* **768**, 186 (2013)

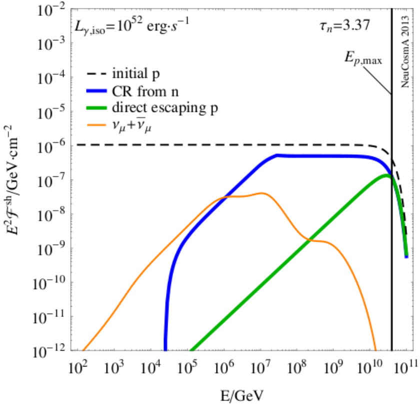
we need high efficiencies $\Rightarrow$ direct proton escape *is* required

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.*,

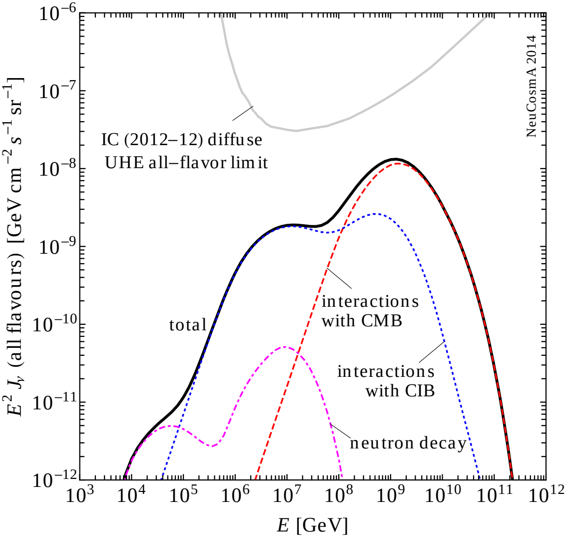
$$p + \gamma \to \Delta^+ \to \pi^+ + n \, ,$$

and neutrinos are created in the decays of the secondaries:

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

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

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

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

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

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

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

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

- Proton density:

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

Maximum proton energy limited by energy losses:

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

ν's in the GRB internal shock model

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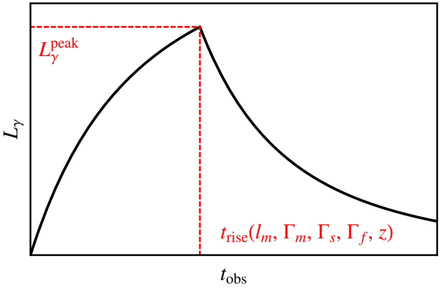
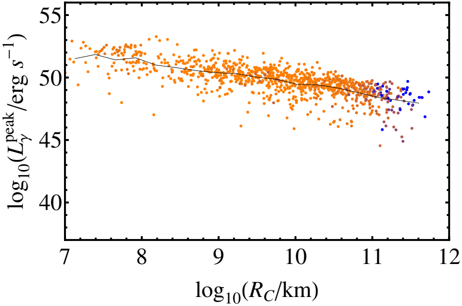
Fluence per shell, at Earth (GeV^{-1} cm^{-2})

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

Gamma-ray and neutrino pulses

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

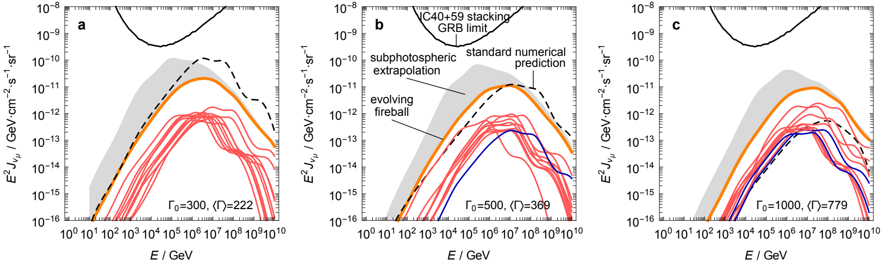




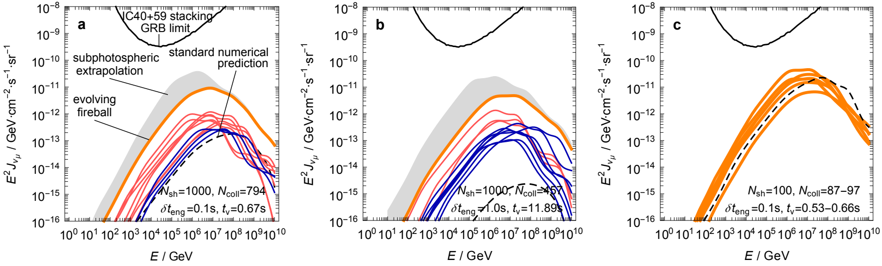
$$L_\gamma^{\rm peak} \sim R_C^{-2}$$

The prediction *is* robust

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

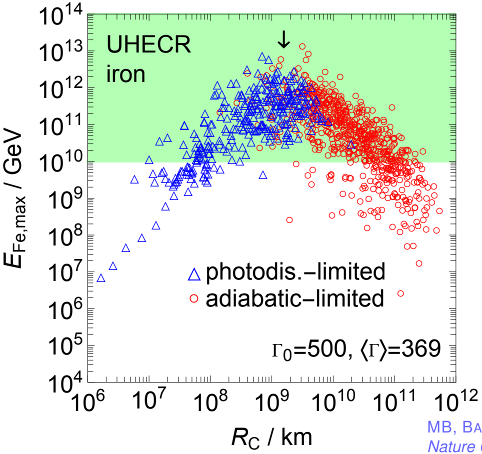


… and on the GRB engine variability time $\delta t_{\rm eng}$



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)

Propagating the UHECRs to Earth

We use a Boltzmann equation to transport protons to Earth:

- Comoving number density of protons ($\text{GeV}^{-1}\ \text{cm}^{-3}$):

$$Y_p(E, z) = n_p(E, z) / (1 + z)^3 \ ,$$

with n_p the real number density

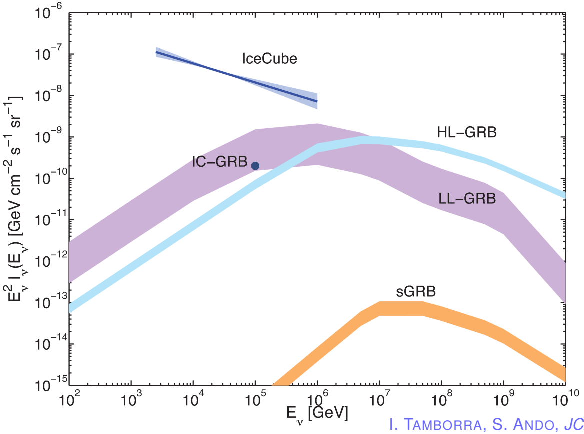
- Transport equation (comoving source frame):

$$\dot{Y}_p = \underbrace{\partial_E (HEY_p)}_{\text{adiabatic losses}} + \underbrace{\partial_E (b_{e^+e^-} Y_p)}_{\text{pair production losses}} + \underbrace{\partial_E (b_{p\gamma} Y_p)}_{\text{photohadronic losses}} + \underbrace{\mathcal{L}_{\text{CR}}}_{\text{CR injection from sources}}$$

$$Q_{\text{CR}}(E) \propto E^{-\alpha_p} e^{-E/E_{p,\text{max}}}$$

Contribution of GRBs to the diffuse ν flux

- Three populations: high-luminosity long GRBs (HL-GRB), low-luminosity long GRBs (LL-GRB), short GRBs (sGRB)
- Sub-PeV: GRBs contribute a few % to the IceCube diffuse flux
- PeV: contribution could be higher



I. Tamborra, S. Ando, *JCAP* **1509**, 036 (2015)

Using UHECR + neutrino constraints

We can already limit the parameter space by using the UHECR observations and ν upper bounds:

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

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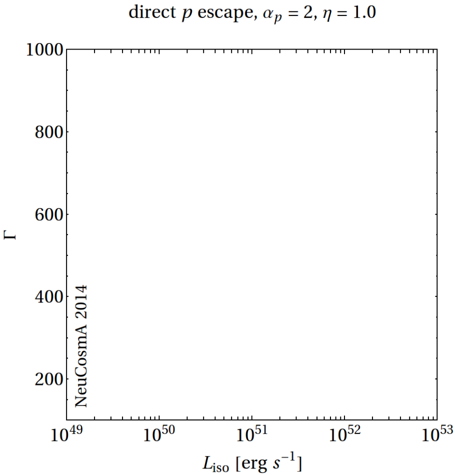
We can already limit the parameter space by using the UHECR observations and ν upper bounds:

1. Generate the UHECR spectrum at every point in parameter space (*e.g.*, in Γ vs. L_{iso})



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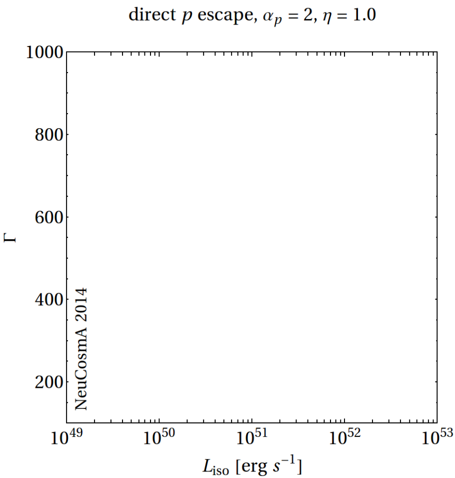

P. Baerwald, MB, W. Winter, *Astropart. Phys.* **62**, 66 (2015)

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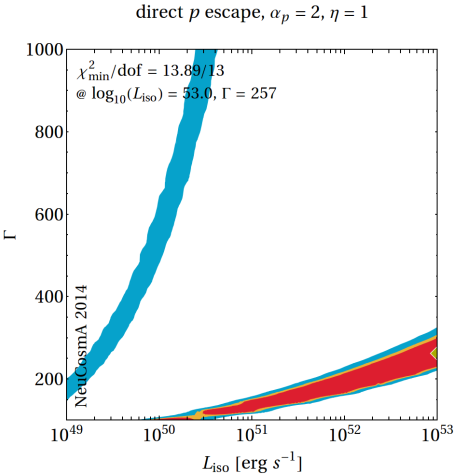
3. Find the best-fit point (diamond), and the 90% (red), 95% (yellow), and 99% (blue) C.L. regions



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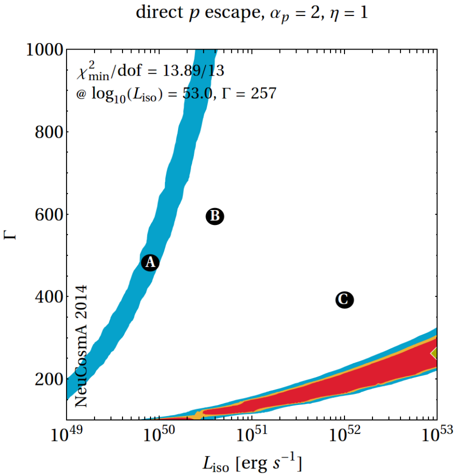

P. Baerwald, MB, W. Winter, *Astropart. Phys.* **62**, 66 (2015)

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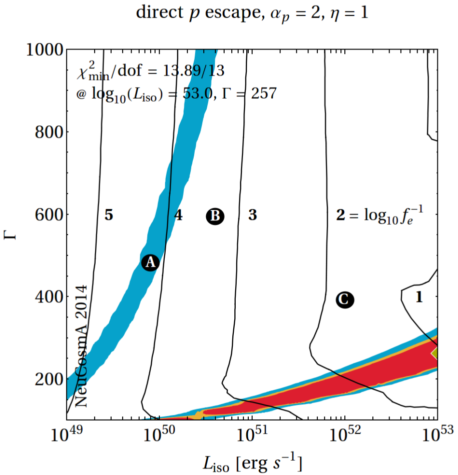

P. Baerwald, MB, W. Winter, *Astropart. Phys.* **62**, 66 (2015)

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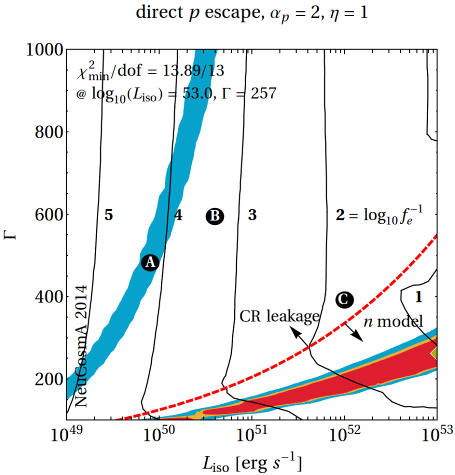
4. Find the baryonic loading (*i.e.*, relative energy of p's to e's) at each point
5. Identify the region corresponding to pure n escape and to n escape + CR leakage



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

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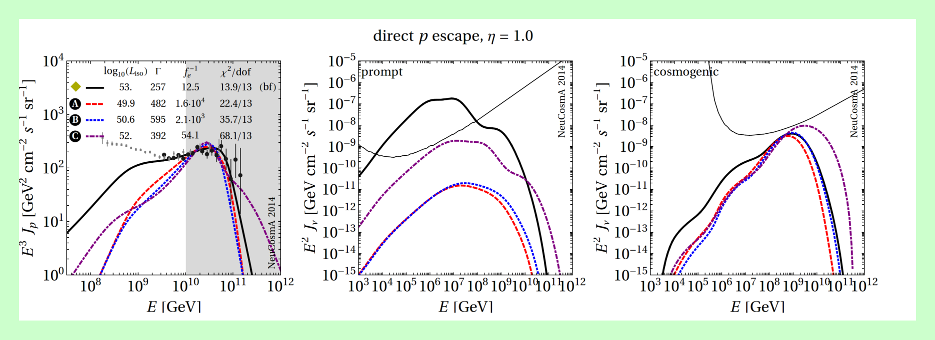
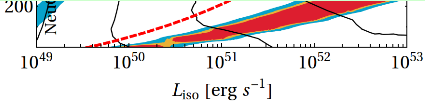
direct p escape, $\alpha_p = 2$, $\eta = 1$





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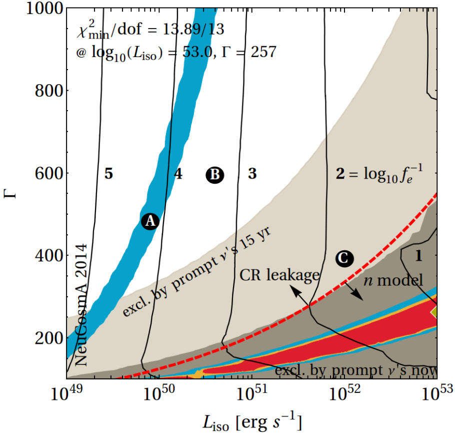
6. Find the region where the number of prompt ν_μ's is > 2.44, *i.e.*, the excluded region at 90% C.L.

direct p escape, $\alpha_p = 2$, $\eta = 1.0$



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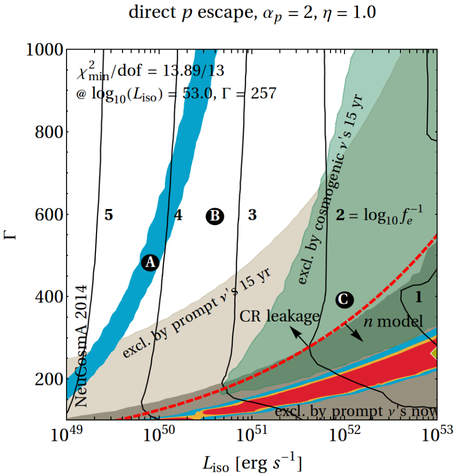
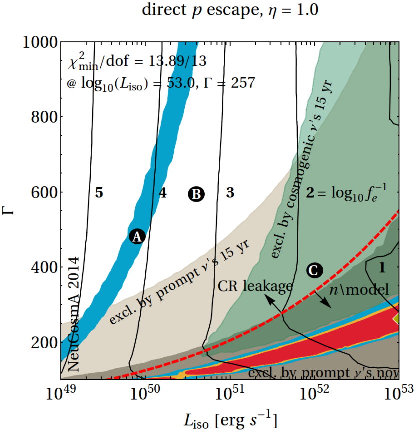
5. Identify the region corresponding to pure n escape and to n escape + CR leakage
6. Find the region where the number of prompt ν_μ's is > 2.44, *i.e.*, the excluded region at 90% C.L.
7. After 15 yr of exposure and no detection, cosmogenic neutrinos also exclude

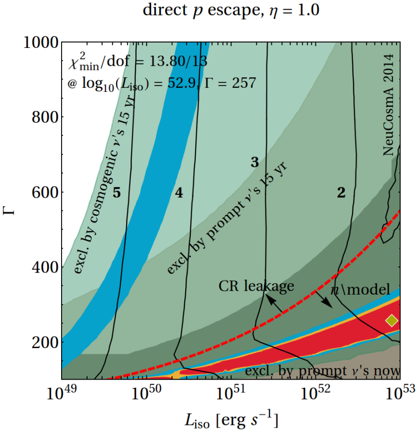


P. Baerwald, MB, W. Winter, *Astropart. Phys.* **62**, 66 (2015)

Star-formation-rate vs. GRB redshift evolution

The exclusion from cosmogenic ν's grows if the number of GRBs evolves more strongly with redshift:



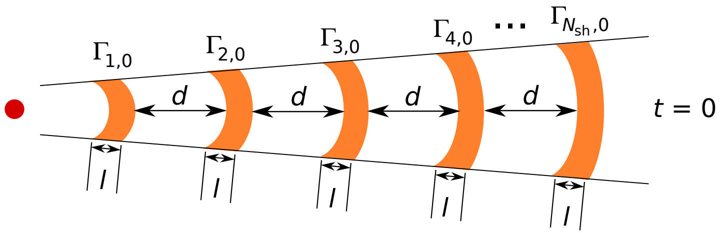


$n_{\rm GRB}(z) \propto \rho_{\rm SFR}(z)$
(star formation rate)

$n_{\rm GRB}(z) \propto \rho_{\rm SFR}(z) \times (1+z)^{1.2}$

Initialising the burst simulation

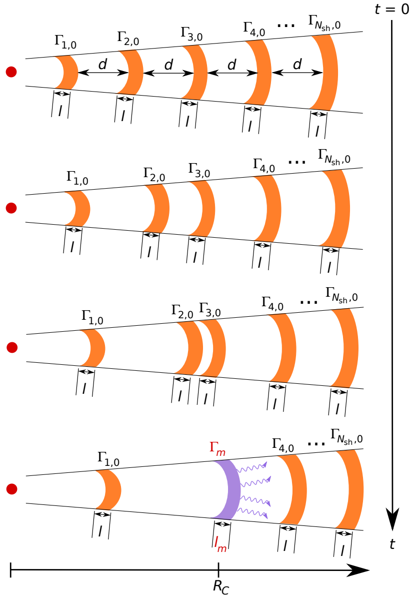
Initial number of plasma shells in the jet: $\gtrsim 1000$



Initial values of shell parameters:

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

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:

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

  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:

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

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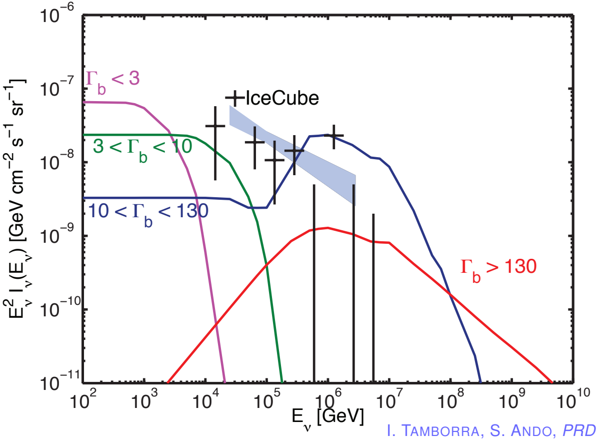
- Compare to standard predictions, which have a $\langle\Gamma\rangle^{-4}$ dependence
- Raising ϵ_p automatically decreases ϵ_e, so the photosphere grows, but still ~ 10 photospheric collisions dominate

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)