

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

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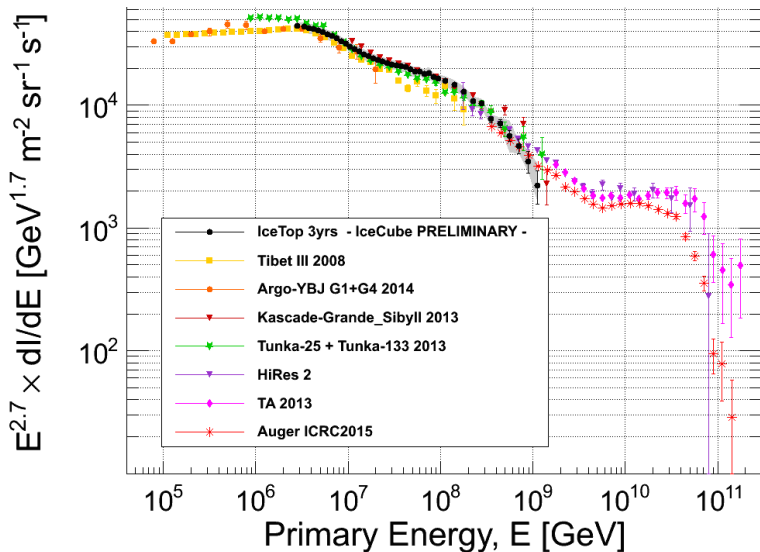


THE OHIO STATE UNIVERSITY

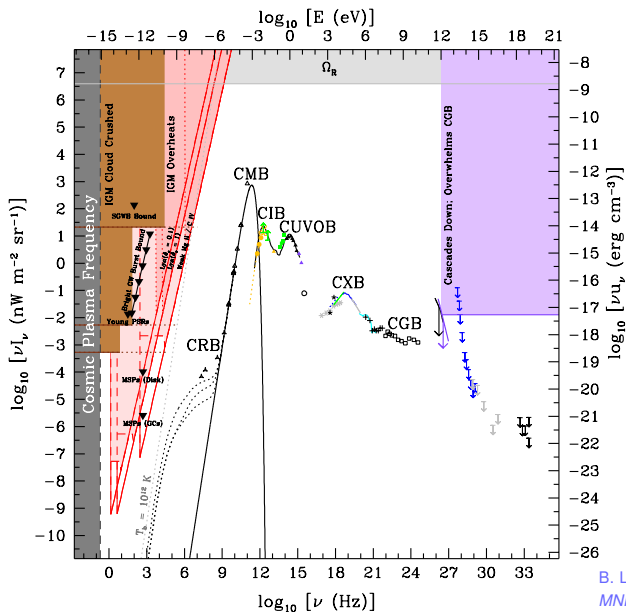
CENTER FOR COSMOLOGY AND
ASTROPARTICLE PHYSICS

Ultra-high-energy cosmic rays

After 50+ years of UHECR measurements —



The electromagnetic sky

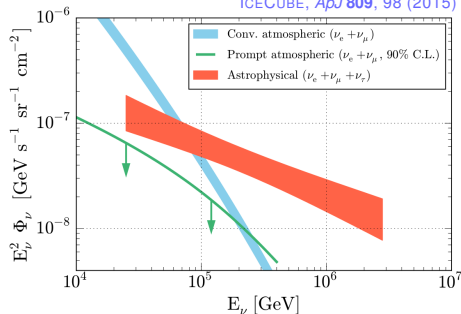


B. LACKI,
MNRAS 406, 863 (2010)

A discovery and a mystery

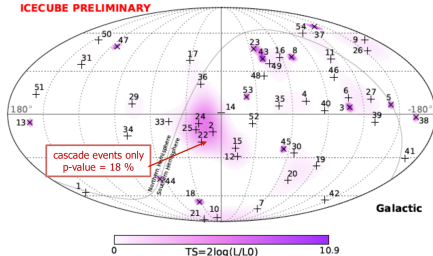
IceCube has discovered a diffuse astrophysical neutrino flux —

ICECUBE, *ApJ* 809, 98 (2015)



Energies: 25 TeV – 2 PeV

ICECUBE PRELIMINARY



O. BOTNER, IPA 2015

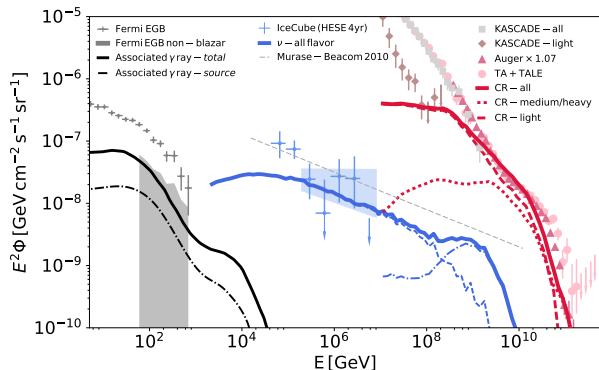
Isotropy of arrivals hints at
extragalactic sources

No sources identified yet

Two profound observations from the discovery

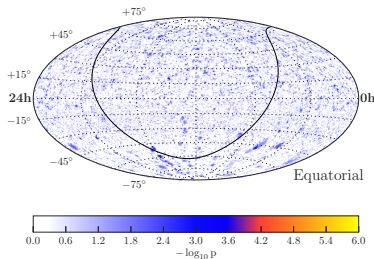
- 1 Diffuse fluxes of gamma rays, UHECRs, neutrinos are comparable

FANG & MURASE, 1704.00015 ►

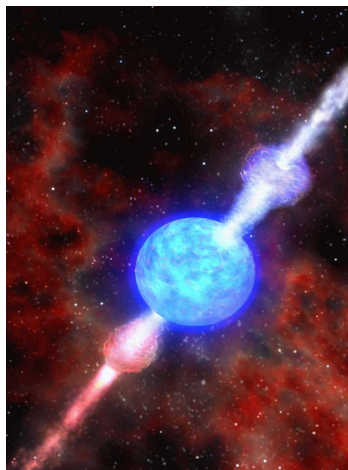


- 2 There is no (evident) dominant neutrino-bright source or few sources

ICECUBE, *ApJ* 2017 [1609.04981]



Why are GRBs natural ν source candidates?



① They are **bright**

- ▶ $10^{52} - 10^{53}$ erg in gamma rays
- ▶ Gamma rays up to ~ 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:

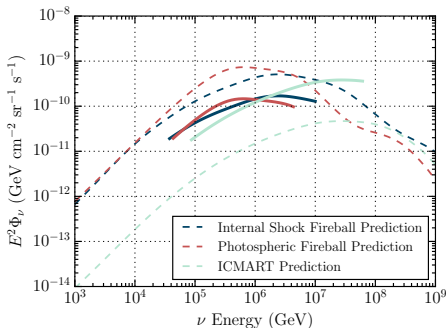
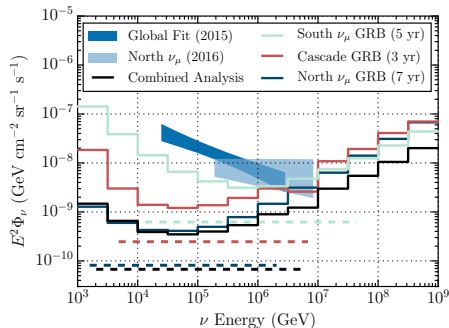
GRBs produce copious high-energy neutrinos via $p\gamma$ interactions

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?

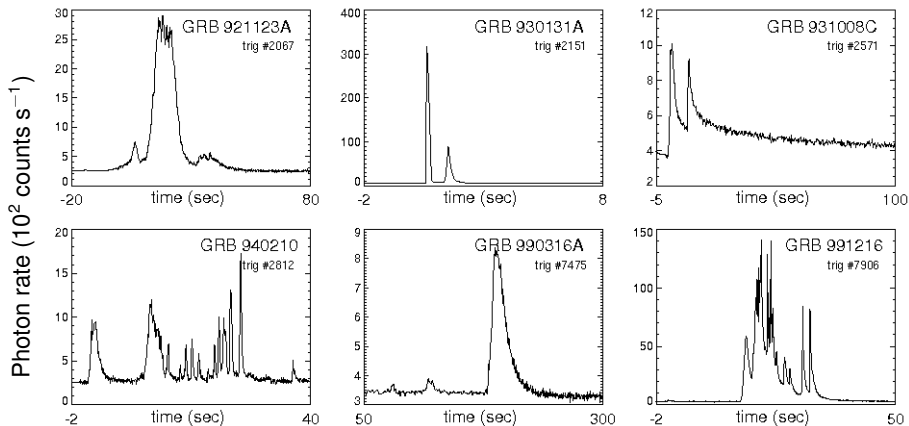
- 1 Best candidates for joint high-energy e.m.–neutrino emission
- 2 Potential sources of ultra-high-energy cosmic rays

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

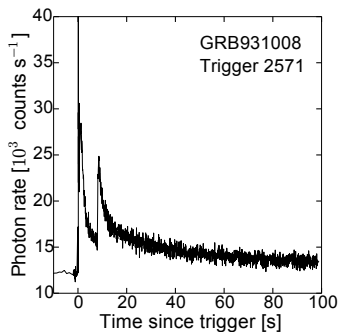
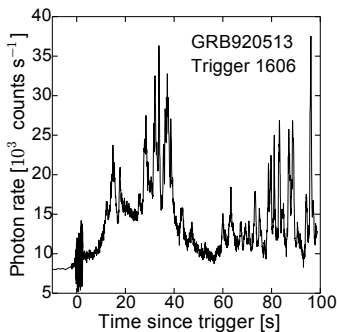
GRBs — a zoo of light curves



BATSE

Which GRB is brighter in neutrinos?

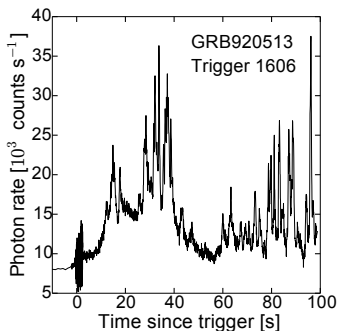
Just from looking at these gamma-ray light curves,



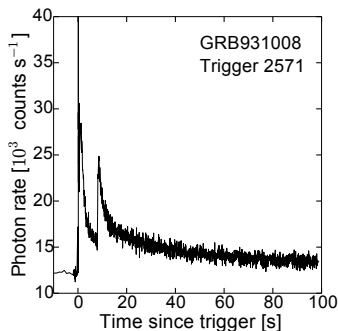
can we tell which GRB is likely bright in neutrinos?

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Fast time variability

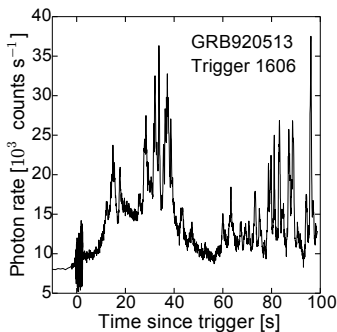


Slow pulse + fast variability

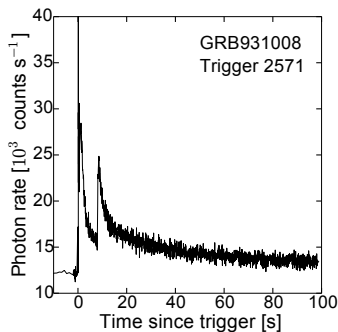
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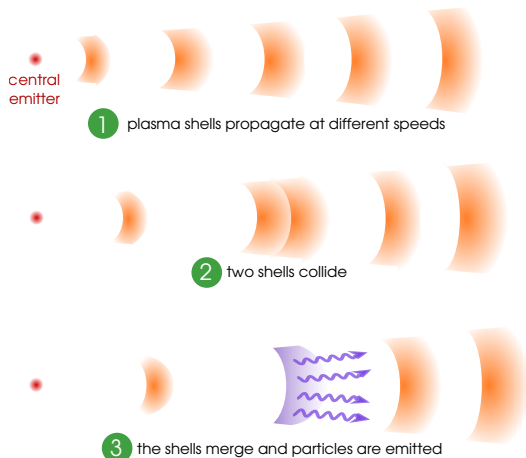


Slow pulse + fast variability

can we tell which GRB is likely bright in neutrinos?

(Answer: yes, the one on the left)

The fireball model — internal collisions

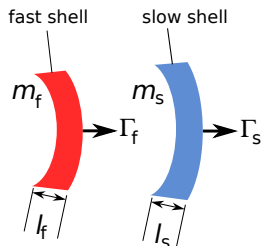


Energy in photons and electrons $\approx$ Energy in magnetic fields

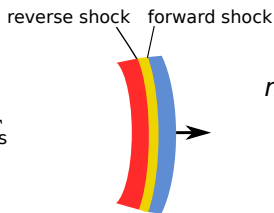
Energy in relativistic protons $\gtrsim 10 \times$ Energy in photons and electrons

Anatomy of an internal collision

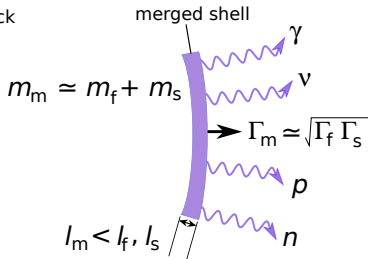
1 Propagation



2 Collision



3 Radiation



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

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

1/12

$$\underbrace{\epsilon_e E_{\text{coll}}^{\text{iso}}}_{\text{energy in photons}}$$

energy in photons

1/12

$$\underbrace{\epsilon_B E_{\text{coll}}^{\text{iso}}}_{\text{energy in magnetic fields}}$$

energy in magnetic fields

5/6

$$\underbrace{\epsilon_p E_{\text{coll}}^{\text{iso}}}_{\text{energy in baryons}}$$

energy in baryons

Producing ν 's, CRs, γ rays

power law $\sim E^{-\alpha p}$

broken power law

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

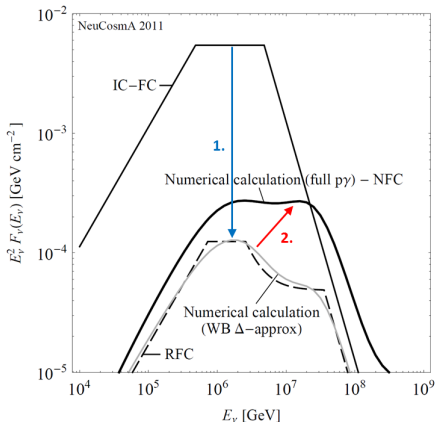
$$\pi^+ \rightarrow \mu^+ \nu_\mu \rightarrow \bar{\nu}_\mu e^+ \nu_e \nu_\mu$$

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

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

We use NeuCosmA:

- ▶ More production channels
- ▶ Detailed particle interactions
- ▶ Flavor mixing



energy in neutrinos $\propto$ energy in gamma rays

What are the ingredients?

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

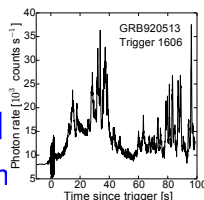
- ▶ Its gamma-ray luminosity L_{γ}^{iso} [erg s $^{-1}$] [measured]
- ▶ Its variability timescale t_{ν} [s], from the light curve [measured]
- ▶ Break energy of its photon spectrum $\epsilon_{\gamma,\text{break}}$ [MeV] [measured]
- ▶ Its redshift z [(sometimes) measured]
- ▶ The bulk Lorentz factor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

Now let us cook up the neutrinos ►

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_{ν} [s], from the light curve [n]
- ▶ 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 ▶

Normalizing neutrinos with observed gamma rays

For each GRB,

$$\text{energy in neutrinos} \propto \text{energy in gamma rays}$$

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

ΔR : size of the emitting region

$\lambda_{p\gamma}$: mean free path for $p\gamma$ interactions

$\langle x_{p \rightarrow \pi} \rangle$: 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”)

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

Cooking up the neutrinos (simple example)

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

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

+

Assumed proton spectrum in the source

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

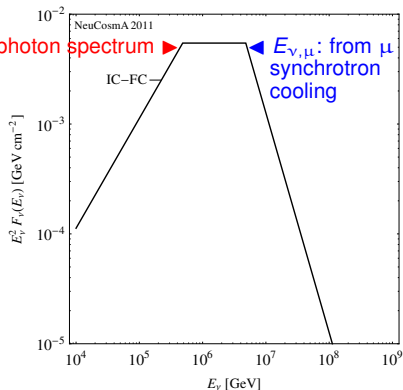
=

Neutrinos from $p\gamma$, via Δ resonance

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

$E_{\nu,\text{br}}$: from photon spectrum

$E_{\nu,\mu}$: from μ synchrotron cooling



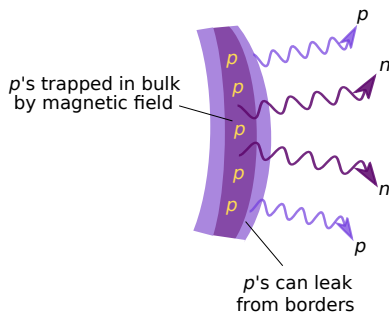
E. WAXMAN, J. N. BAHCALL, *PRL* **78**, 2292 (1997)
D. GUETTA *et al.*, *Astropart. Phys.* **20**, 429 (2004)

Two forms of UHECR escape

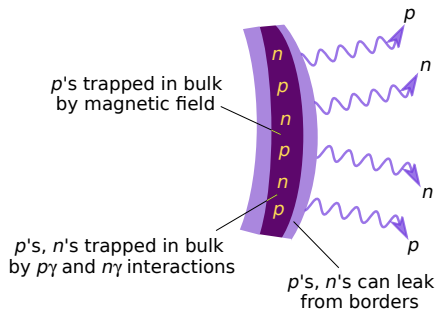
- ▶ **Neutrons**, produced together with ν 's; or
- ▶ **Protons** that leak out without producing ν 's in the source

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

$\tau_n < 1$
optically **thin** to n escape



$\tau_n \geq 1$
optically **thick** to n escape

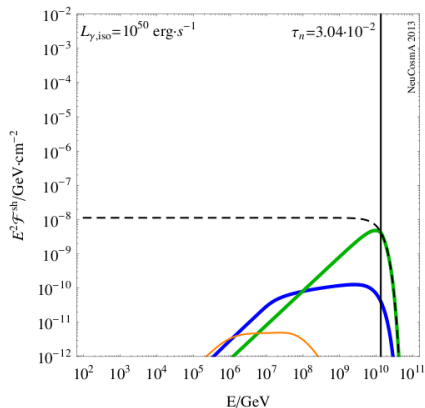


P. BAERWALD, MB, W. WINTER, *ApJ* **768**, 186 (2013)
P. BAERWALD, MB, W. WINTER, *Astropart. Phys.* **62**, 66 (2015)
See also: H. HE *et al.*, *ApJ* **752**, 29 (2012)

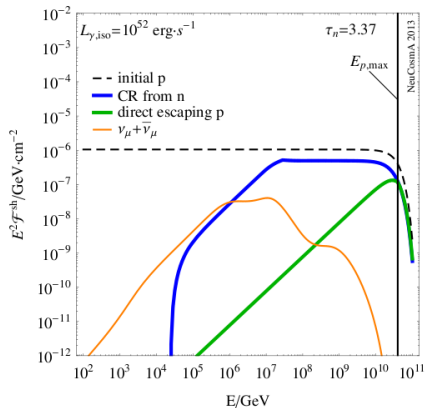
A two-component model of UHECR emission

Sample neutrino fluences —

Optically **thin** source



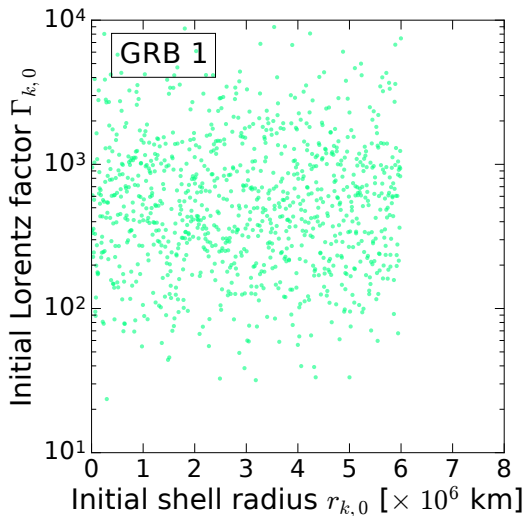
Optically **thick** source



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

Initial distribution of shell speeds

Broad distribution — slow and fast shells find each other early



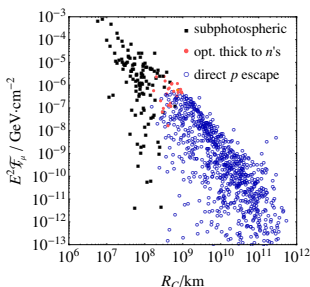
Tracking each collision individually

Each collision occurs in a different emission regime —

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

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

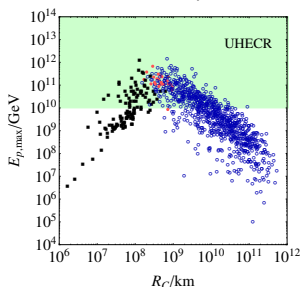
neutrinos



(observer's frame)

maximum p energy

cosmic rays

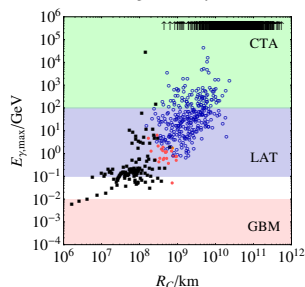


(source frame)

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

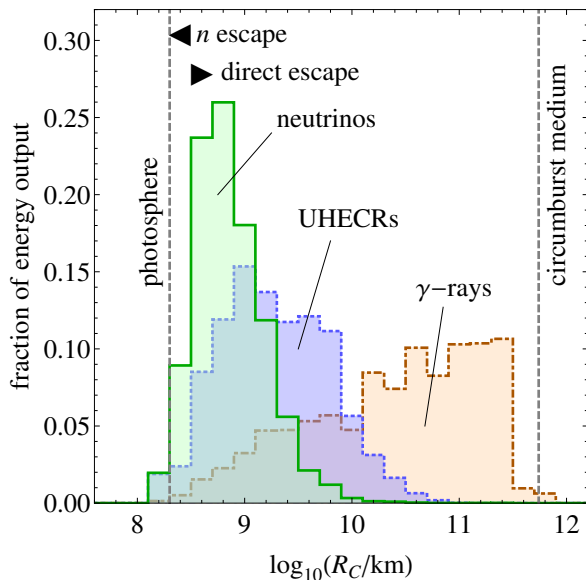
maximum γ energy

gamma-rays



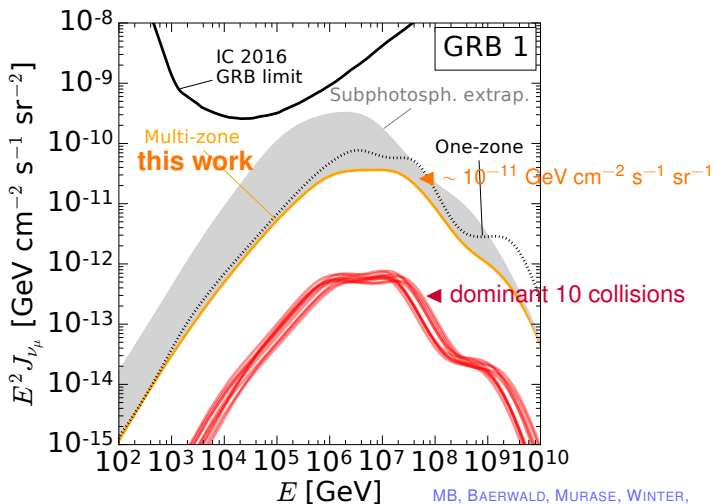
MB, BAERWALD, MURASE, WINTER, *Nat. Commun.* 2015

Different particles come from different jet regions



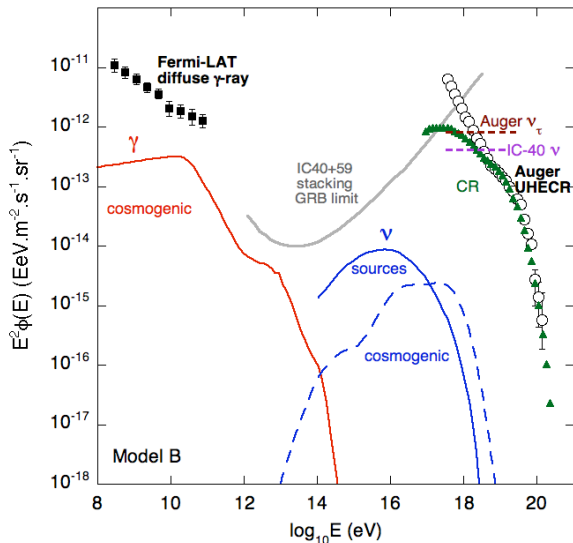
A robust minimal diffuse ν flux from GRBs

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



A detailed treatment of UHECR acceleration

From GLOBUS, ALLARD, MOCHKOVITCH, PARIZOT *MNRAS* 2015 —

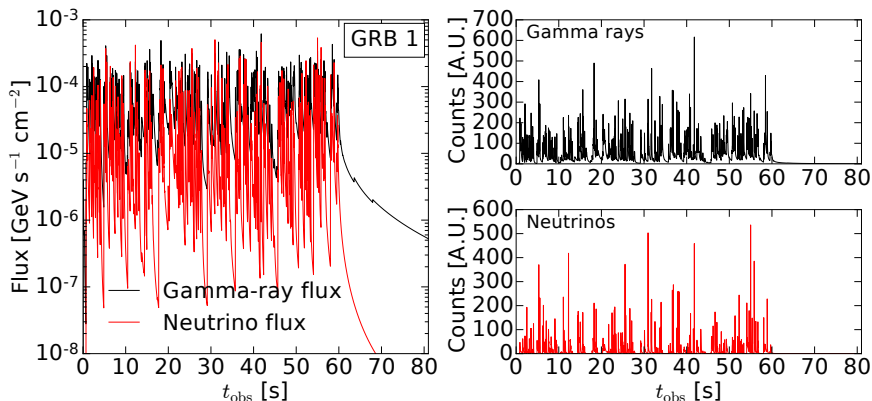


- ▶ Multiple internal collisions
- ▶ Numerical simulation of CR acceleration at mildly relativistic shocks
- ▶ Accelerated p to Fe
- ▶ γ spectrum harder as shock propagates
- ▶ Results compatible with Bustamante+ 2015

Synthetic light curves

Each collision emits a particle pulse

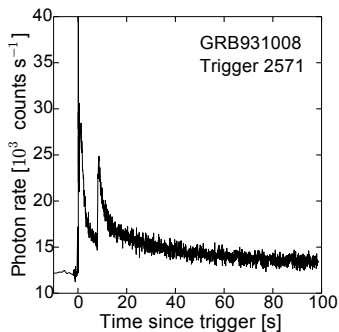
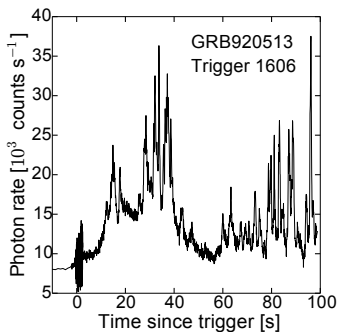
— their superposition yields a **synthetic light curve**:



MB, BAERWALD, MURASE, WINTER
Nature Commun. 2015

Which GRB is brighter in neutrinos?

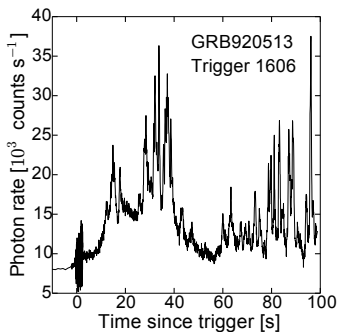
Just from looking at these gamma-ray light curves,



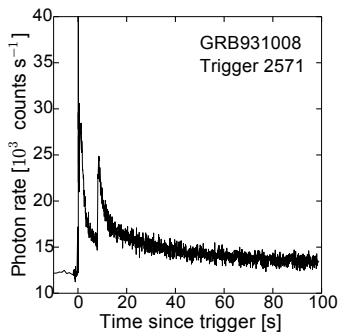
can we tell which GRB is likely bright in neutrinos?

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Fast time variability

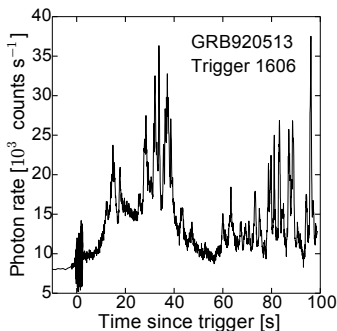


Slow pulse + fast variability

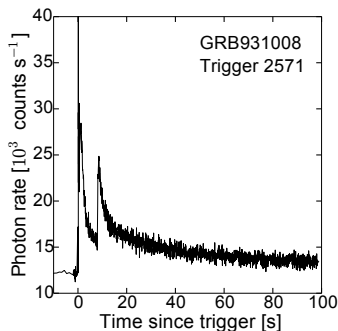
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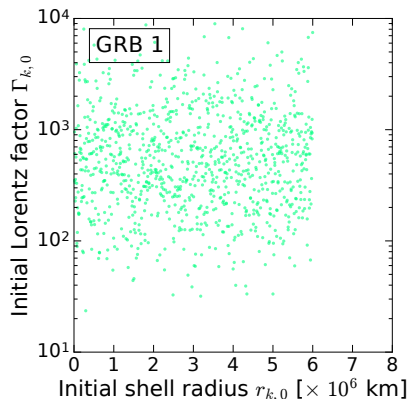
can we tell which GRB is likely bright in neutrinos?

Answer: yes, the one on the left

What makes a GRB bright in neutrinos?

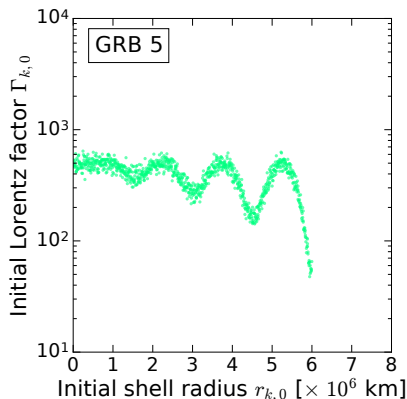
Undisciplined GRB engine

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



Disciplined GRB engine

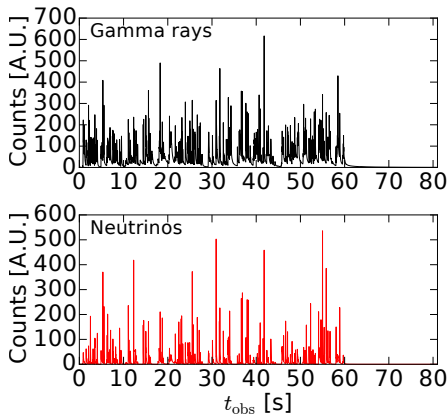
- ▶ Narrow Γ distribution
- ▶ *E.g.*, engine emits shells with oscillating Γ



Light curves

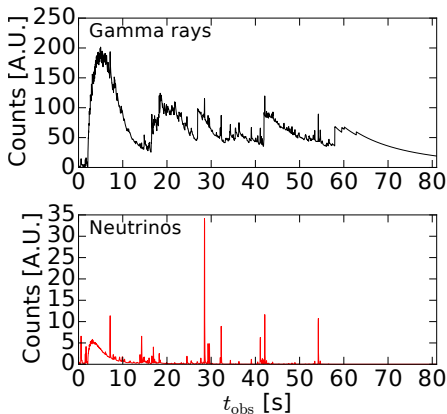
Undisciplined GRB engine

- ▶ Fast variability dominates
- ▶ No broad pulses



Disciplined GRB engine

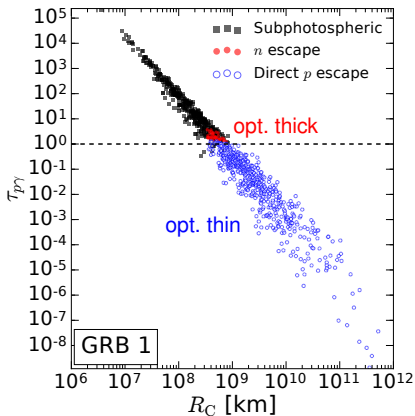
- ▶ Broad pulses dominate
- ▶ Fast variability on top



How many optically thick collisions?

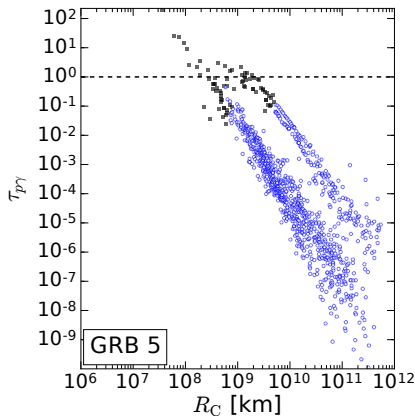
Undisciplined GRB engine

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



Disciplined GRB engine

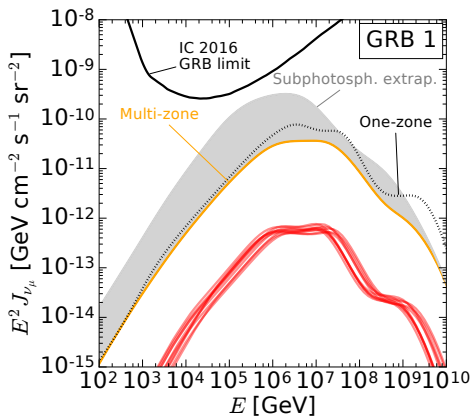
- ▶ Shells with similar speeds
- ▶ Collide far from center
- ▶ Low p and γ densities
- ▶ No optically thick collisions



So which burst is neutrino-bright?

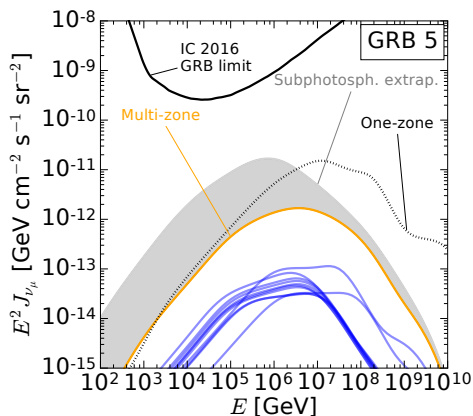
Undisciplined GRB engine

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



Disciplined GRB engine

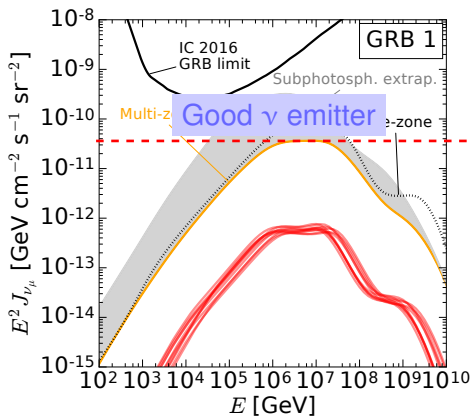
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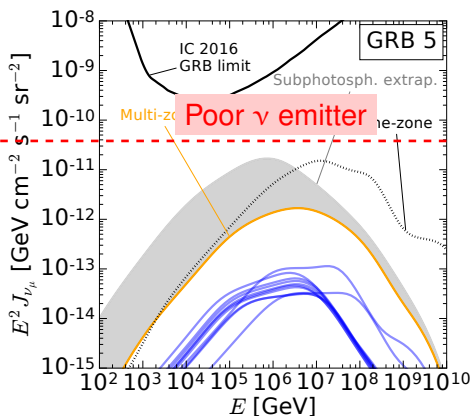
Undisciplined GRB engine

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Disciplined GRB engine

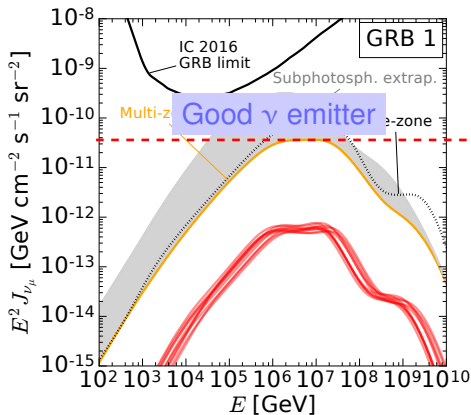
$$\sim 10^{-12} \text{ GeV cm}^{-1} \text{ s}^{-1} \text{ sr}^{-1}$$



So which burst is neutrino-bright?

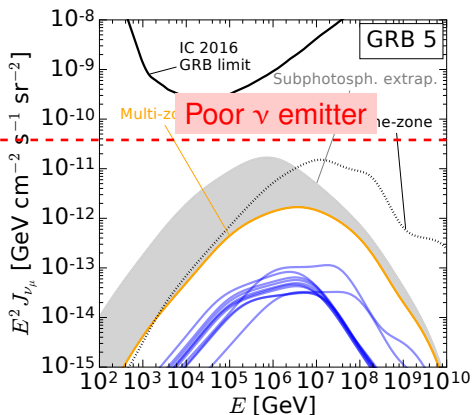
Undisciplined GRB engine

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



Disciplined GRB engine

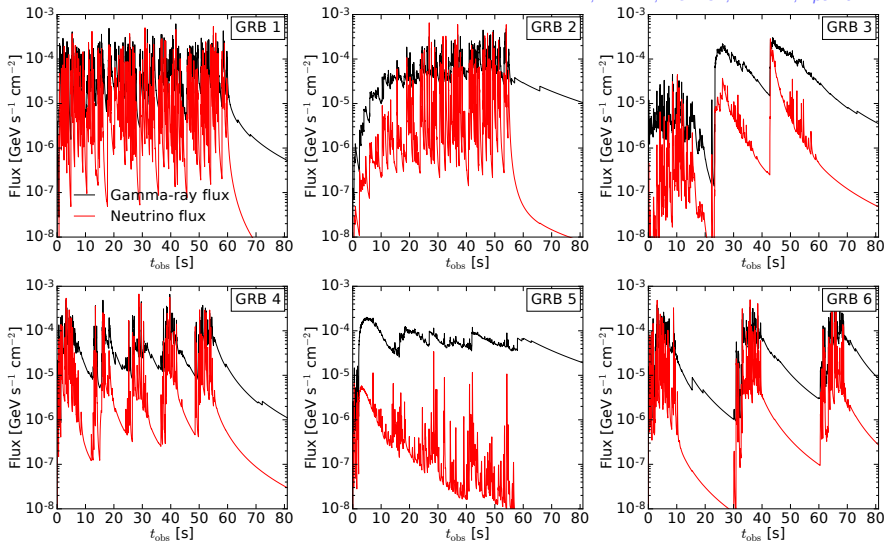
$$\sim 10^{-12} \text{ GeV cm}^{-1} \text{ s}^{-1} \text{ sr}^{-1}$$



An undisciplined engine makes a GRB neutrino-bright

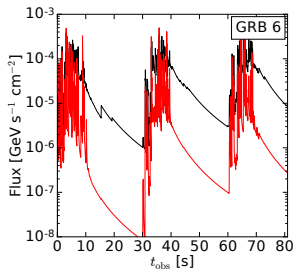
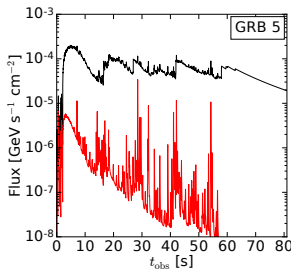
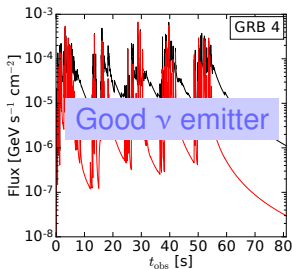
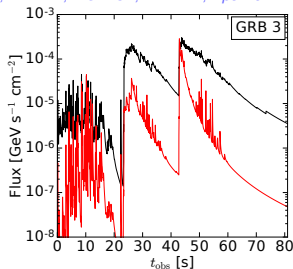
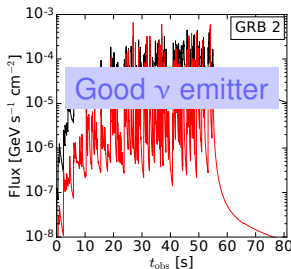
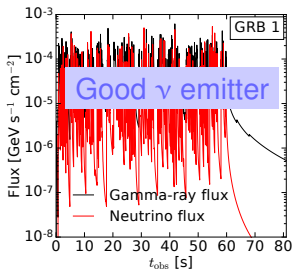
Using our new insight

MB, HEINZE, MURASE, WINTER, *ApJ* 2017



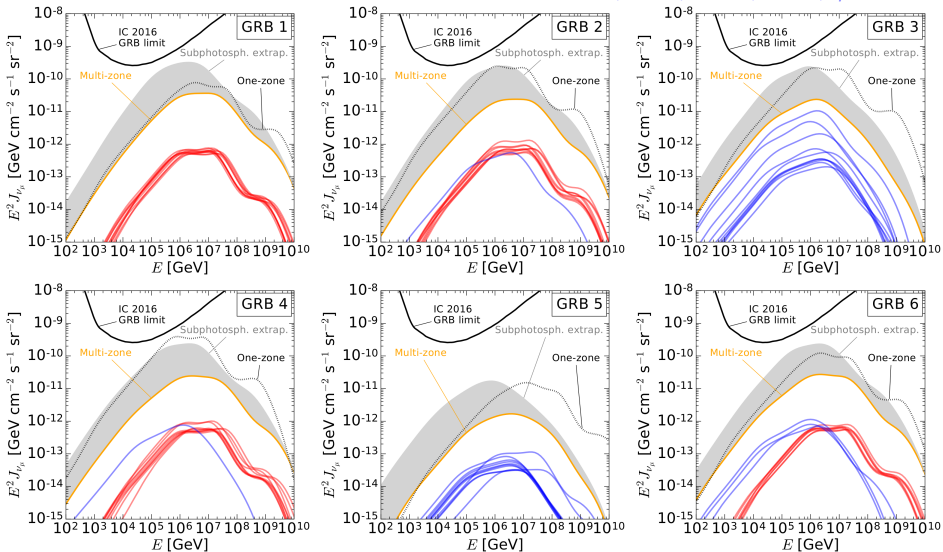
Using our new insight

MB, HEINZE, MURASE, WINTER, *ApJ* 2017



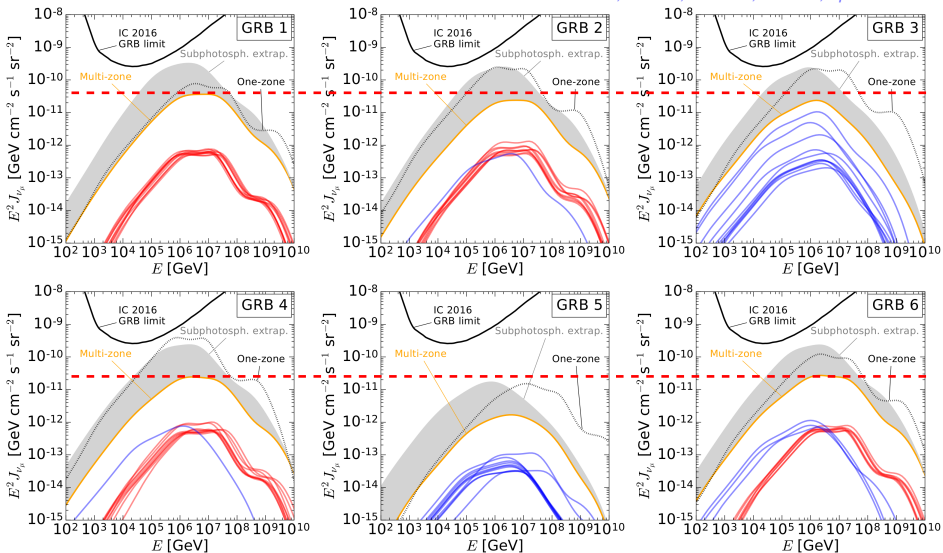
Using our new insight

MB, HEINZE, MURASE, WINTER, *ApJ* 2017



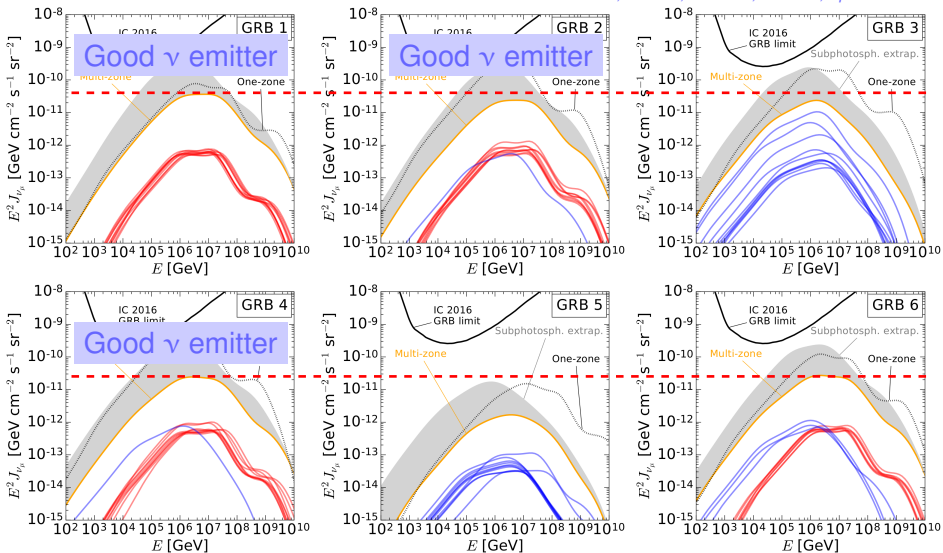
Using our new insight

MB, HEINZE, MURASE, WINTER, *ApJ* 2017



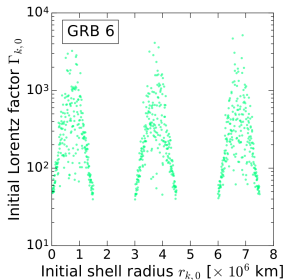
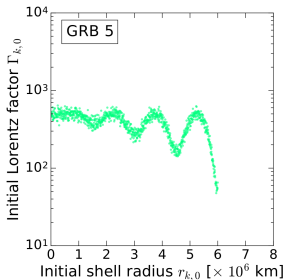
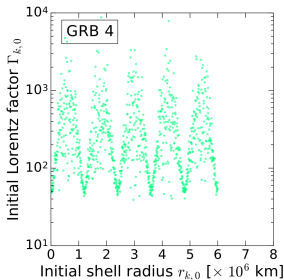
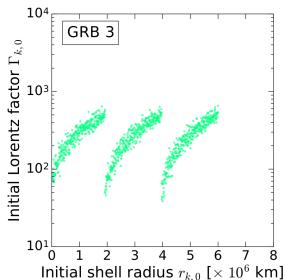
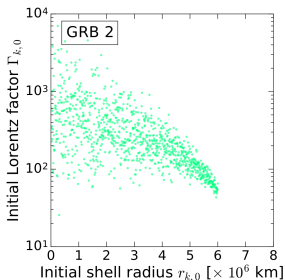
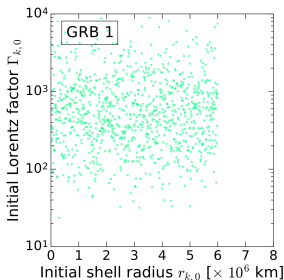
Using our new insight

MB, HEINZE, MURASE, WINTER, *ApJ* 2017



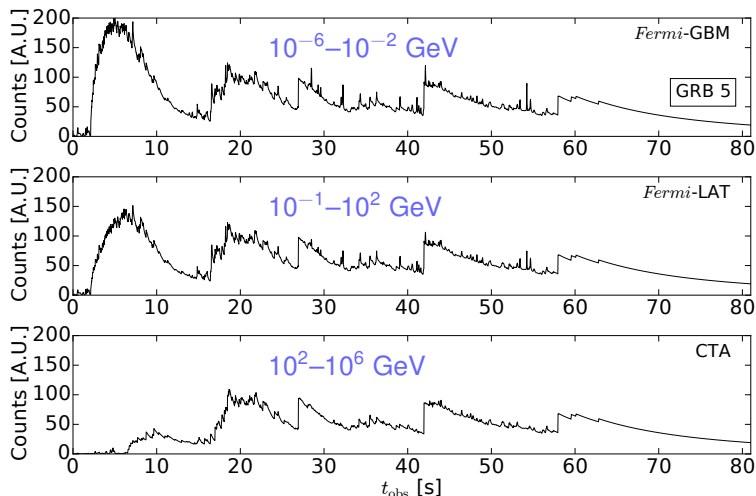
Using our new insight

MB, HEINZE, MURASE, WINTER, *ApJ* 2017



Time delays in gamma-ray light curves

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

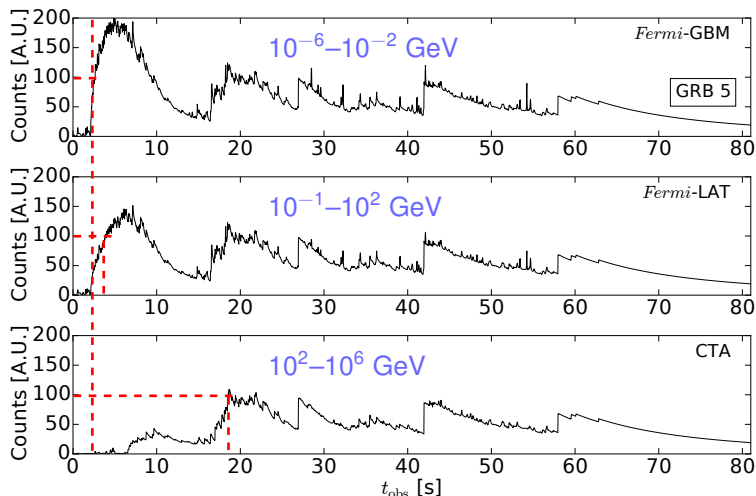


MB, HEINZE, MURASE, WINTER, *ApJ* 2017 [1606.02325]

See also: BOŠNJAK, DAIGNE, *A&A* 2014 [1404.4577]

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]

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 extragalactic neutrino sources to be resolved
- ▶ More realistic understanding of GRB ν production
- ▶ We **need** next-gen neutrino telescopes (IceCube-Gen2, KM3NeT)

TeV PARTICLE ASTROPHYSICS

TeVPA

AUGUST 7-11 2017

COLUMBUS, OH

LOCAL ORGANIZING COMMITTEE
 Katie Auchetti (co-chair)
 John Beacom
 James Beatty
 Mauricio Bustamante (co-chair)
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INTERNATIONAL ADVISORY COMMITTEE
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 Gian Giudice (CERN)
 Supriya Gupta (TIFR)
 Francis Halzen (WIPAC)
 Dan Hooper (Fermilab)
 Olga Mena (IFIC)
 Subir Sarkar (Oxford, NBI)
 Tim Tait (UCI)
 Masahiro Teshima (ICRR)
 Zhang XinMin (IHEP)

INVITED SPEAKERS
 Nima Arkani-Hamed (IAS Princeton)
 Julia Becker-Tjus (Ruhr U. Bochum)
 Veronica Bindi (U. Hawaii at Manoa)
 Jo Bovy (U. Toronto)
 Ralph Engel (KIT)
 Gianluca Gregori (U. of Oxford)
 Francis Halzen (U. of Wisconsin, Madison)
 Fiona Harrison (Caltech)
 Xiangdong Ji (Shanghai Jiao Tong U.)
 Marc Kamionkowski (Johns Hopkins U.)
 Victoria Kaspi (McGill U.)
 Marek Kowalski (DES)
 Mariangela Lisanti (Princeton U.)
 Miguel Mostafá (Penn State U.)
 Hitoshi Murayama (UC Berkeley)*
 Samaya Nissanka (Radboud U.)
 Tracy Slatyer (MIT)
 Todd Thompson (Ohio State U.)*
 Abigail Vieregg (U. of Chicago)
 * = To be confirmed

THE OHIO STATE UNIVERSITY
 CENTER FOR COSMOLOGY AND
 ASTROPARTICLE PHYSICS

<https://tevpa2017.osu.edu/>

TeVPA 2017

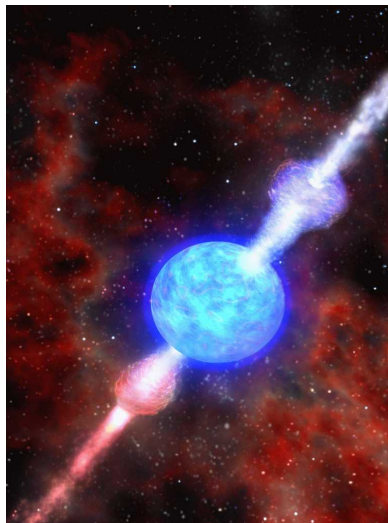
tevpa2017.osu.edu

- ▶ August 7–11, Columbus, OH
- ▶ Deadline for registration and abstract submission: **June 2**
- ▶ Pre-meeting mini-workshops on Sunday, August 7
- ▶ Ample room for parallels: *we welcome your talks!*

Backup slides

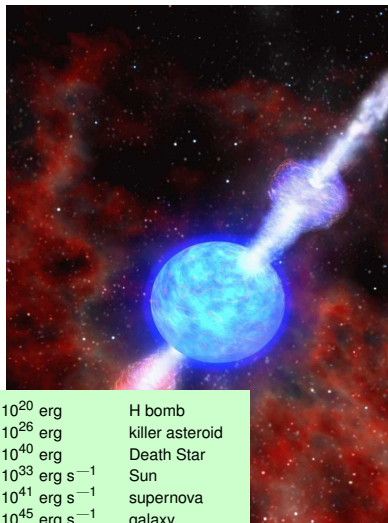
GRBs at a glance

- ▶ **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



GRBs at a glance

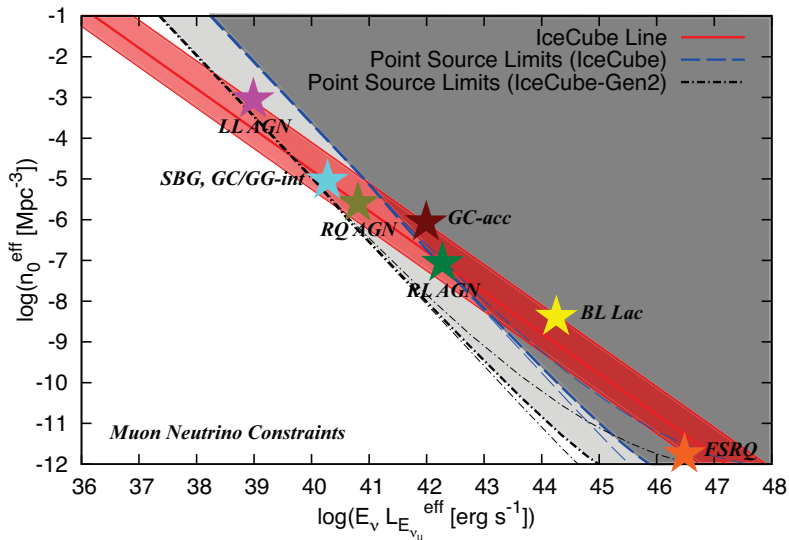
- ▶ **Duration:** 0.1 s to > 100 s
- ▶ Two populations:
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- ▶ Accretion onto a compact object
- ▶ Isotropically distributed
- ▶ Far: most at a few Gpc ($z \approx 1$)
- ▶ Gamma-ray energies: > 1 keV
- ▶ Radiated energy: 10^{52} – 10^{53} erg



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

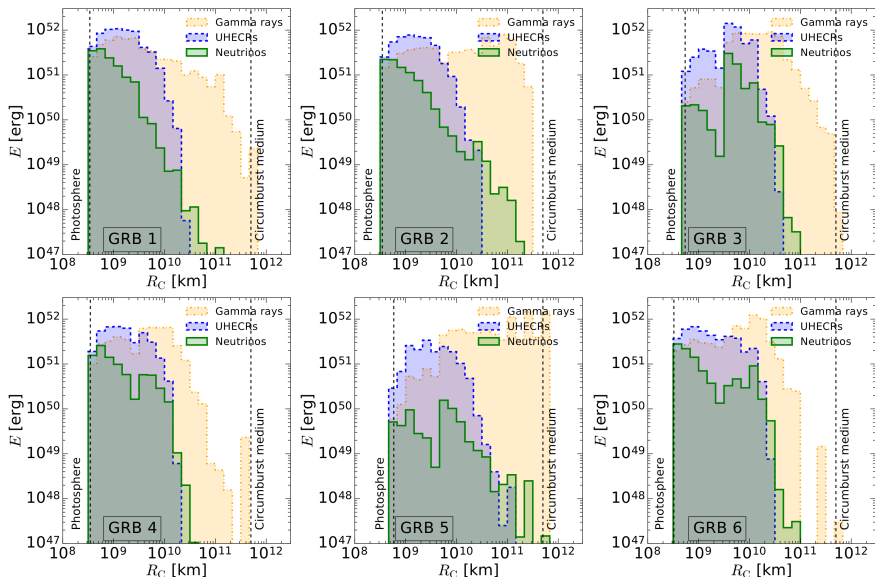
Needed: many weak (steady) sources

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



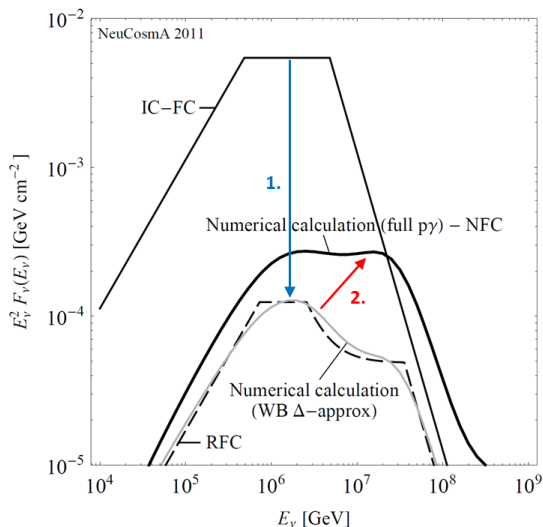
MURASE & WAXMAN, *PRD* 2016 [1607.01601]

Particle production inside the GRB jet



Refining the neutrino spectrum — NeuCosmA

More production channels, more complete particle-physics treatment



For example, GRB080603A:

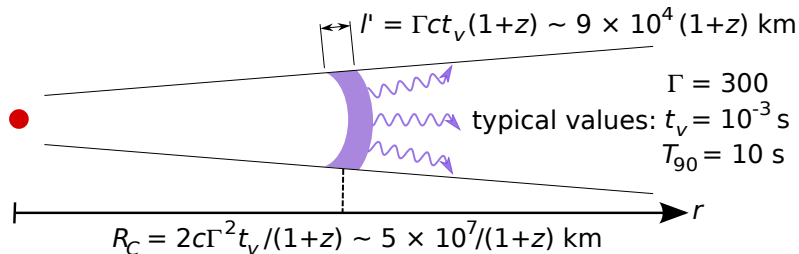
1. Correction to analytical model (IC-FC $\rightarrow$ RFC)
2. Change due to full numerical calculation

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 —



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

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

A two-component model of CR emission

Optical depth:

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

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

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

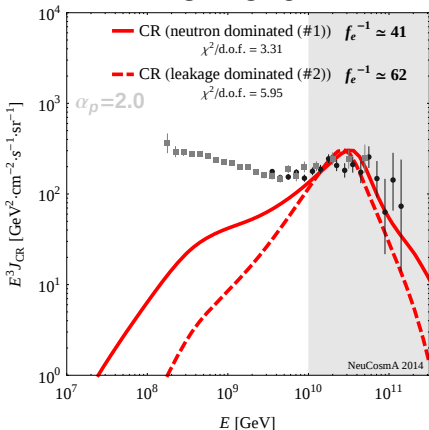
fraction of escaping particles

Diffuse fluxes at Earth

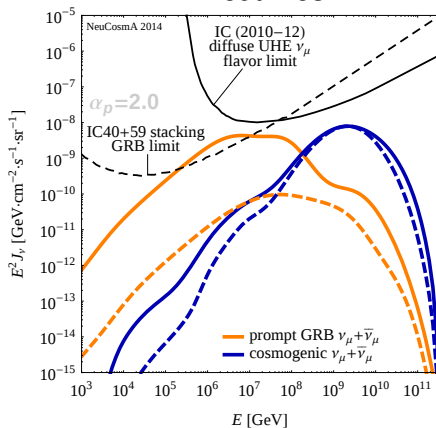
Neutron model vs. two-component model:

prompt and **cosmogenic** ν 's

UHECRs

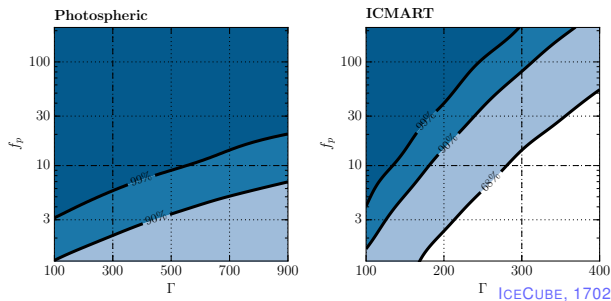
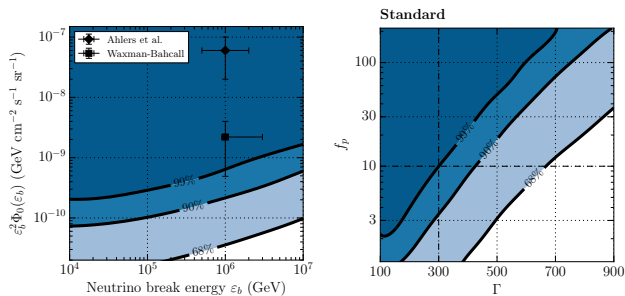


Neutrinos



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)

Limits on GRB ν production model parameters



ICECUBE, 1702.06868

NeuCosmA: (revised) GRB particle emission – I

Two ingredients:

$$\underbrace{N'_p(E'_p)}_{\text{proton density at the source } [\text{GeV}^{-1} \text{ cm}^{-3}]} \overset{\text{NeuCosmA}}{\otimes} \underbrace{N'_\gamma(E'_\gamma)}_{\text{photon density at the source}} = \underbrace{Q'_\nu(E'_\nu)}_{\text{emitted neutrino spectrum } [\text{GeV}^{-1} \text{ cm}^{-3} \text{ s}^{-1}]}$$

► Photons (same shape as observed at Earth):

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

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

NeuCosmA: (revised) GRB particle emission – I

Two ingredients:

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

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

► Photons (same shape as observed at Earth):

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

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

NeuCosmA: (revised) GRB particle emission – II

Normalize the particle densities at the source —

► Photons:

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

► Protons:

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

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

NeuCosmA: (revised) GRB particle emission – III

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

$$x \equiv E' / E'_p$$

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

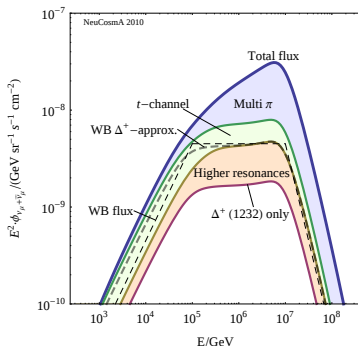
$$Q'(E') = \int_{E'}^{\infty} \frac{dE'_p}{E'_p} N'_p(E'_p) \int_0^{\infty} c dE'_\gamma N'_\gamma(E'_\gamma) R(x, y)$$

response function

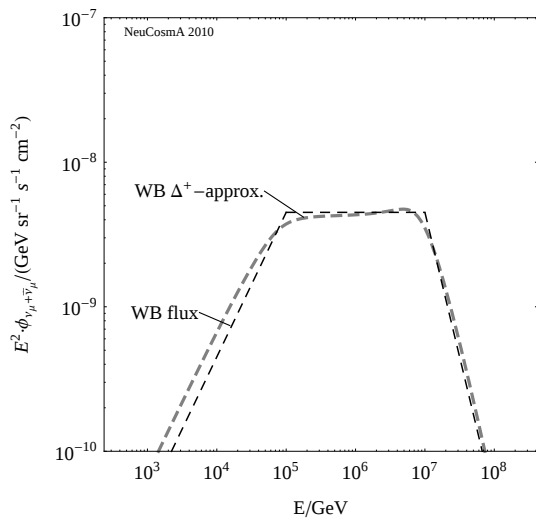
R contains cross sections, multiplicities for different channels

What does NeuCosmA include?

- ▶ $p\gamma \rightarrow \Delta^+(1232) \rightarrow \pi^0, \pi^+, \dots$
- ▶ 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

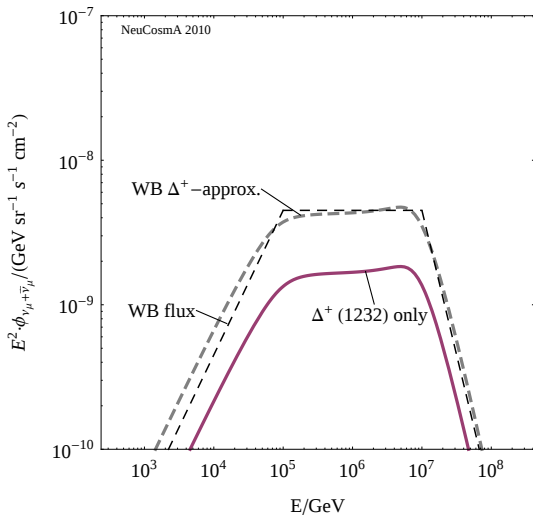


NeuCosmA – the full photohadronic cross section

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. D **83**, 067303 (2011)

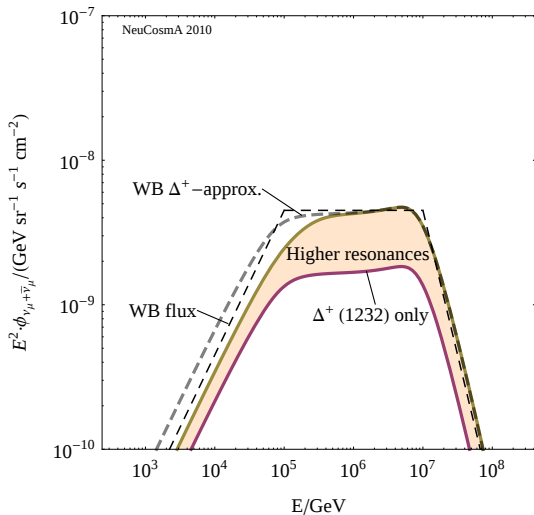


NeuCosmA – the full photohadronic cross section

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. D **83**, 067303 (2011)

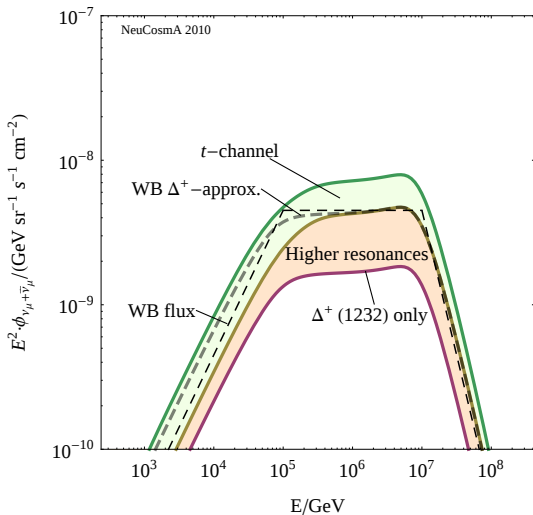


NeuCosmA – the full photohadronic cross section

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

- ▶ $\Delta(1232)$ -resonance
- ▶ Higher resonances
- ▶ t -channel (direct production)

P. BAERWALD, S. HÜMMER, AND W. WINTER,
Phys. Rev. D **83**, 067303 (2011)

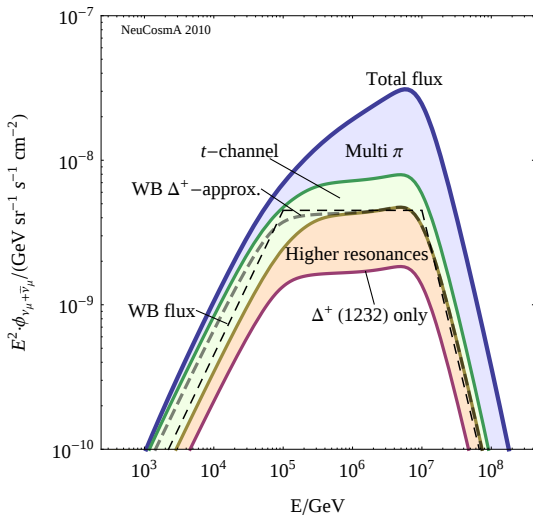


NeuCosmA – the full photohadronic cross section

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. D **83**, 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

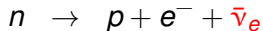
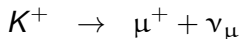
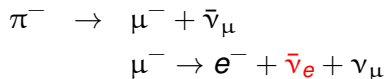
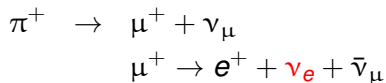
$$\begin{aligned}\pi^+ &\rightarrow \mu^+ + \nu_\mu \\ \mu^+ &\rightarrow e^+ + \nu_e + \bar{\nu}_\mu\end{aligned}$$

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

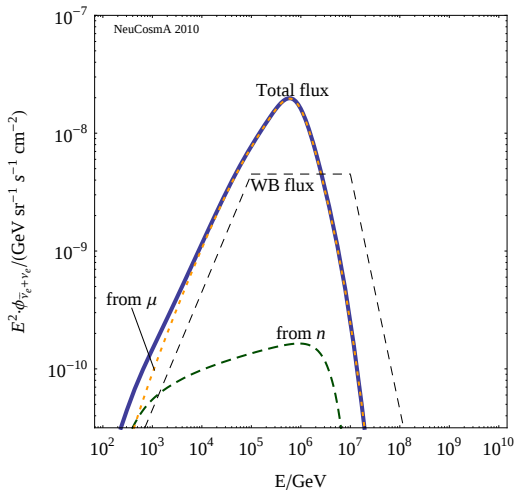
$$K^+ \rightarrow \mu^+ + \nu_\mu$$

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

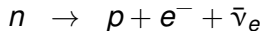
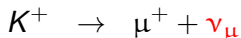
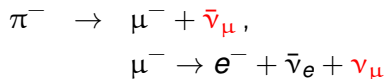
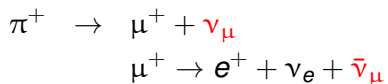
NeuCosmA – further particle decays



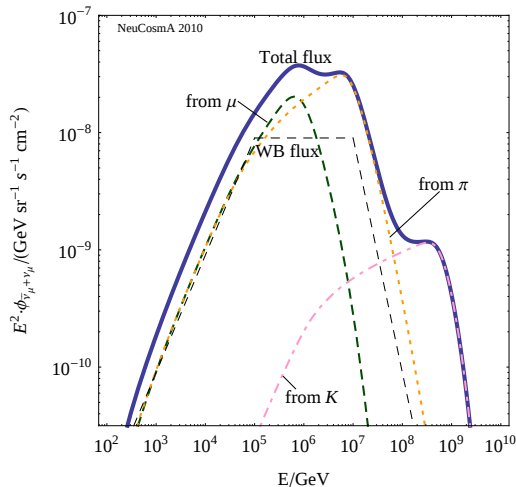
Resulting ν_e flux (at the observer)



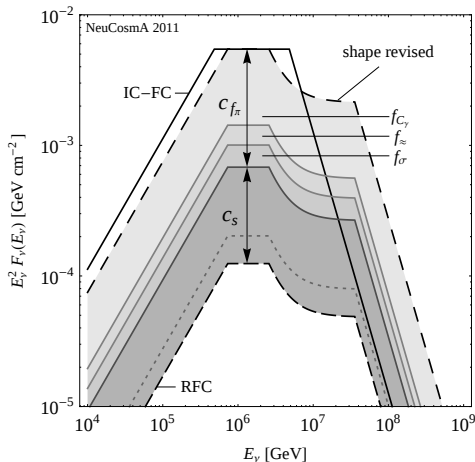
NeuCosmA – further particle decays



Resulting ν_μ flux (at the observer)



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:

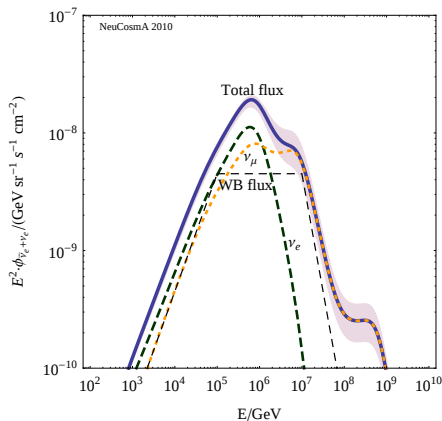
- f_{C_γ} : full spectral shape of photons
- $f_{\approx} = 0.69$: rounding error in analytical calculation
- $f_\sigma \simeq 2/3$: from neglecting the width of the Δ -resonance

► Correction c_s :

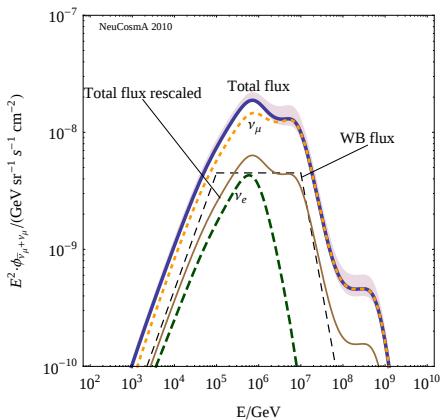
- energy losses of secondaries
- energy dependence of the mean free path of protons

NeuCosmA – neutrino spectra including flavor mixing

Electron neutrino spectrum



Muon neutrino spectrum



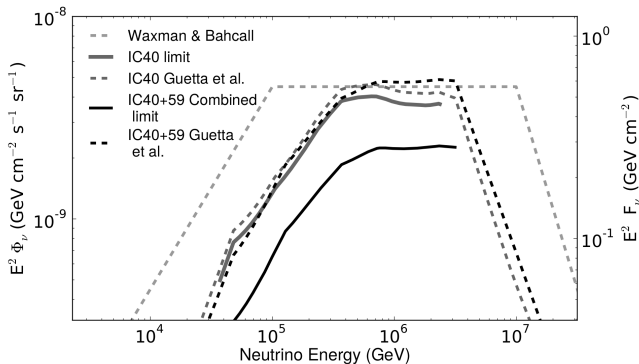
P. BAERWALD, S. HÜMMER, W. WINTER, *Phys. Rev.* **D83**, 067303 (2011)

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 —

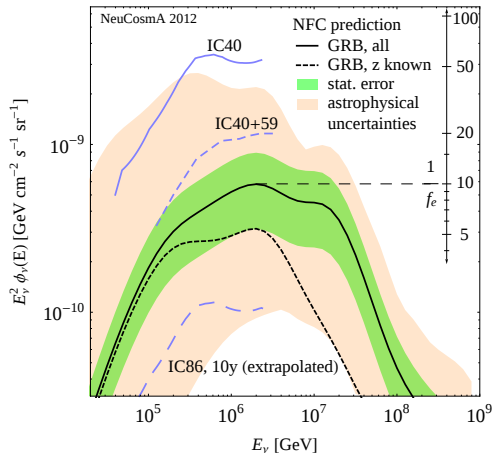
► Same GRB sample and parameters

► Calculate ν fluence for each burst and stacked fluence $F_\nu(E_\nu)$

► Quasi-diffuse flux ($N_{\text{GRB}} = 117$):

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

Flux ~ 1 order of magnitude lower!



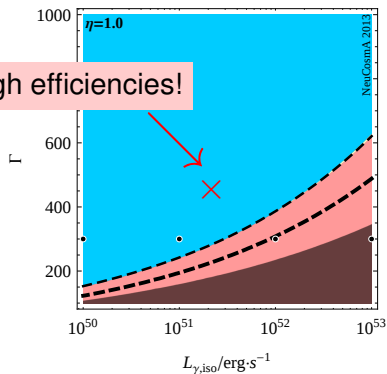
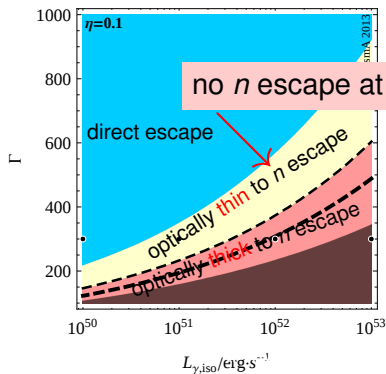
S. HÜMMER, P. BAERWALD, W. WINTER,
PRL **108**, 231101 (2012)

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

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:

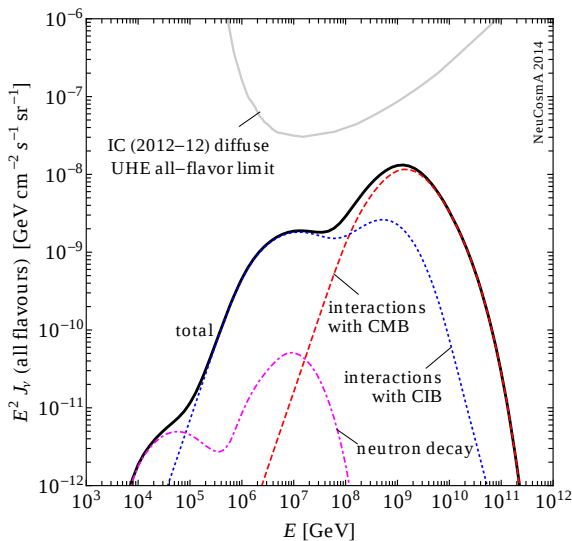
$$\pi^+ \rightarrow \mu^+ + \nu_\mu$$

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

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

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 ($\text{GeV}^{-1} \text{ cm}^{-3} \text{ s}^{-1}$)

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

Normalisation to the observed GRB photon flux F_γ

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

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

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

ν 's in the GRB internal shock model

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

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

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

$$N'_\gamma(\varepsilon') \propto \begin{cases} (\varepsilon')^{-\alpha_\gamma}, & \varepsilon'_{\gamma,\text{min}} = 0.2 \text{ eV} \leq \varepsilon' \leq \varepsilon'_{\gamma,\text{break}} \\ (\varepsilon')^{-\beta_\gamma}, & \varepsilon'_{\gamma,\text{break}} \leq \varepsilon' \leq \varepsilon'_{\gamma,\text{max}} = 300 \times \varepsilon'_{\gamma,\text{min}} \end{cases}$$
$$\varepsilon'_{\gamma,\text{break}} = \mathcal{O}(\text{keV}), \alpha_\gamma \approx 1, \beta_\gamma \approx 2$$

► Proton density:

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

Maximum proton energy limited by energy losses:

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

ν 's in the GRB internal shock model

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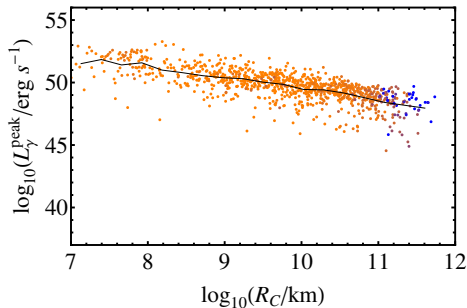
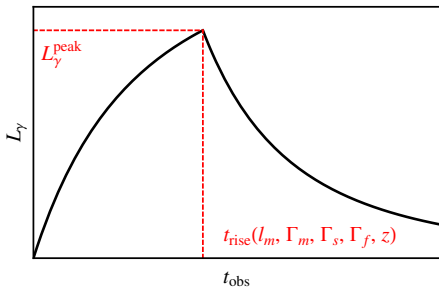
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Gamma-ray and neutrino pulses

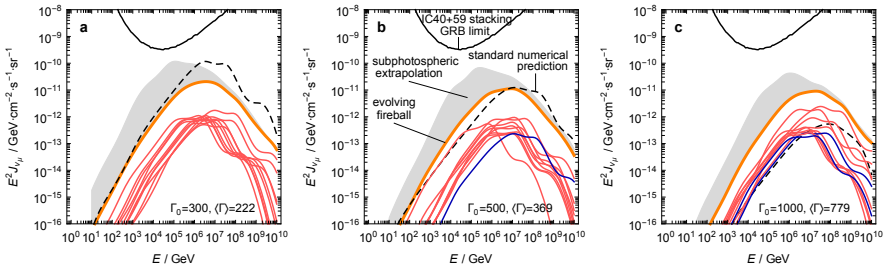
A fast-rise-exponential-decay (FRED) gamma-ray pulse is emitted in every collision:



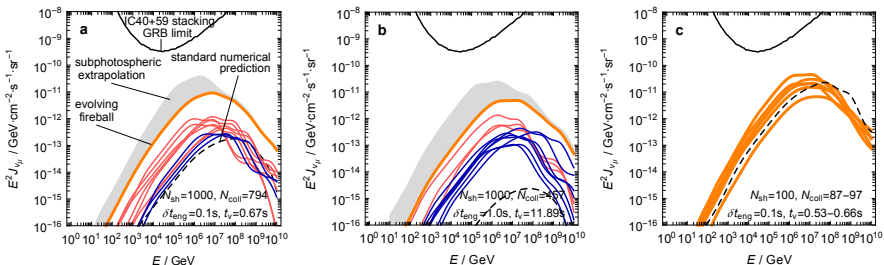
$$L_\gamma^{\text{peak}} \sim R_C^{-2}$$

The prediction *is* robust

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

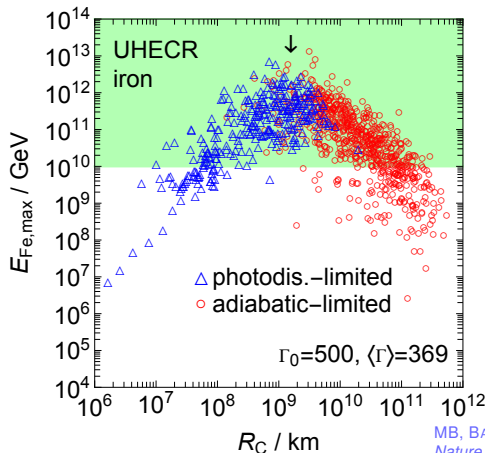


... and on the GRB engine variability time δt_{eng}



Accelerating iron

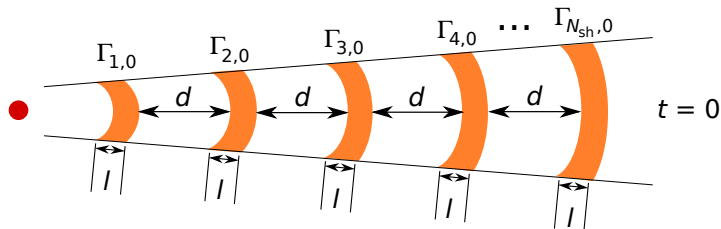
- ▶ Photodisintegration destroys nuclei close to the center ($\sim 10^8$ km)
e.g., [ANCHORDOQUI *et al.*, *Astropart. Phys.* **29**, 1 \(2008\)](#)
- ▶ However, they can survive at large radii:



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:

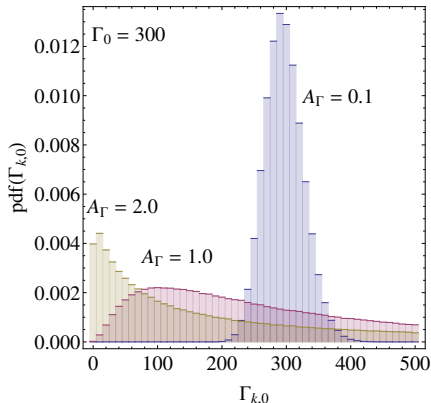
- ▶ Width of shells and separation between them: $l = d = c \cdot \delta t_{\text{eng}}$
- ▶ Equal kinetic energy for all shells ($\sim 10^{52}$ erg)
- ▶ Shell speeds $\Gamma_{k,0}$ follow a distribution (log-normal or other)

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

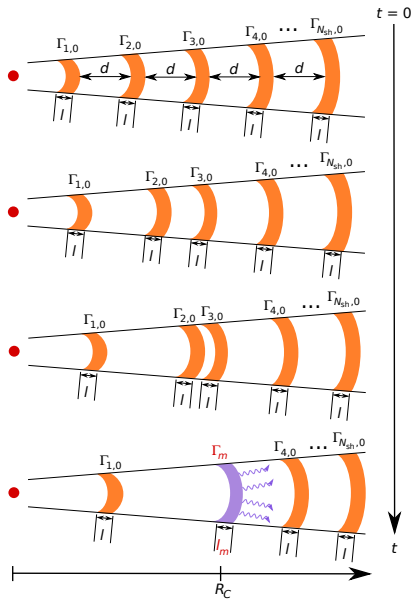
$$A_\Gamma \gg 1$$

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** :

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

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 :

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

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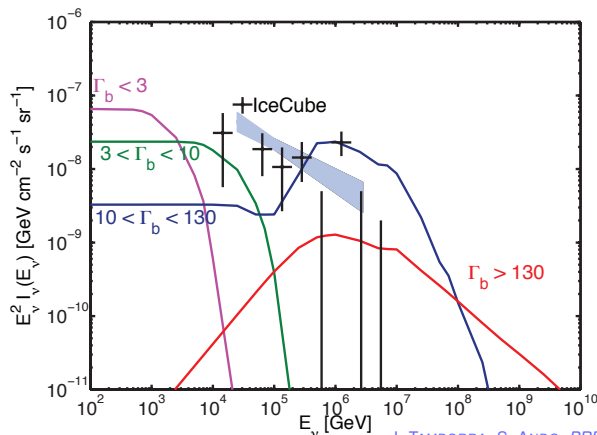
- ▶ $\Rightarrow$ Time-integrated neutrino fluence dominated is independent of Γ :

$$\mathcal{F}_\nu \propto \frac{\overset{\sim 10}{N_{\text{coll}} (f_{p\gamma} \gtrsim 1)}}{\underset{\sim 1000}{N_{\text{coll}}^{\text{tot}}}} \times \min \left[1, f_{p\gamma}^{\text{ph}} \right] \times \left(\frac{\epsilon_p}{\epsilon_e} \right) \times \overset{10}{10^{53} \text{ erg}} E_{\gamma-\text{tot}}^{\text{iso}}$$

- ▶ 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

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)