

Rethinking GRBs as sources of high-energy neutrinos

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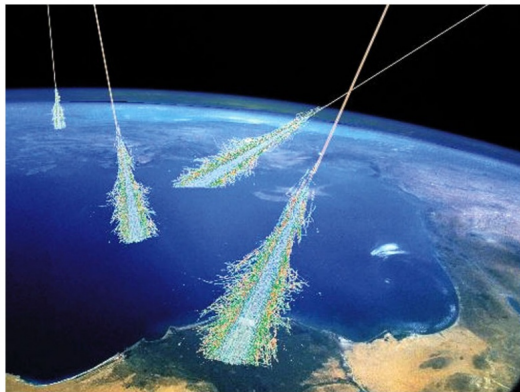
THE OHIO STATE UNIVERSITY



Two fifty-year-old mysteries

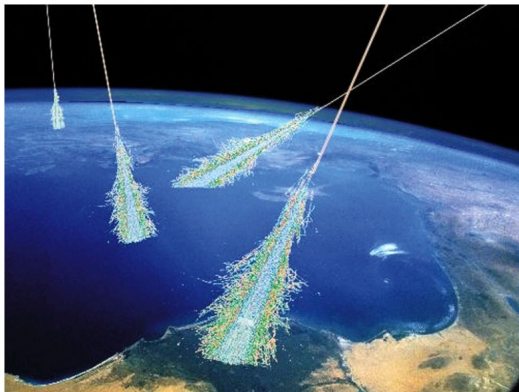
Two fifty-year-old mysteries

ultra-high-energy cosmic rays (UHECRs)

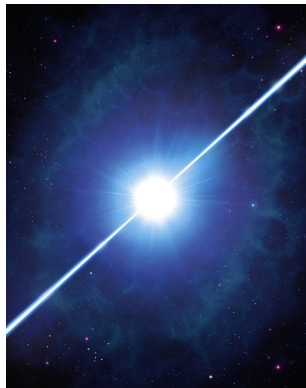


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gamma-ray bursts (GRBs)



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The mystery

We do not know the origin of UHECRs and GRBs

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Our hypothesis

GRBs are the sources of the UHECRs
– and neutrinos are the smoking gun

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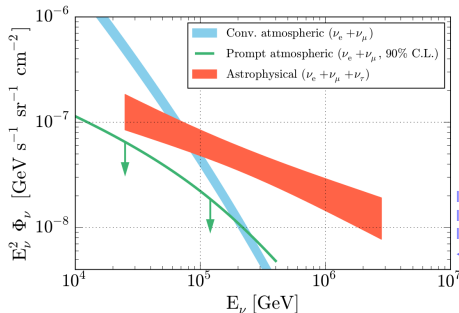
Our result

It is possible, *and testable*, but the connection between UHECRs, GRBs, and neutrinos is **not** as simple as we thought

A new player: high-energy astrophysical neutrinos

The era of neutrino astronomy has begun!

– IceCube has reported 54 events with 30 TeV – 2 PeV in 4 years



IceCube, *PRL* **111**, 021103 (2013)
IceCube, *Science* **342**, 1242856 (2013)
IceCube, *PRL* **113**, 101101 (2014)
◀ IceCube, *ApJ* **809**, 98 (2015)

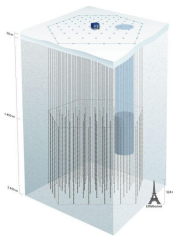
Diffuse per-flavor astrophysical flux [IceCube 2015]:

$$\Phi_\nu = \left(6.7^{+1.1}_{-1.2} \cdot 10^{-18}\right) \left(\frac{E}{100 \text{ TeV}}\right)^{-(2.5 \pm 0.09)} \text{ GeV}^{-1} \text{ cm}^{-2} \text{ s}^{-1} \text{ sr}^{-1}$$

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*: ~ 250 GRBs yr^{-1} in 8 keV – 40 MeV
- ▶ ~ 12 GRBs yr^{-1} in 20 MeV – 300 GeV
- ▶ different wavelengths: *INTEGRAL*, *Swift*
- ▶ 1000's GRBs detected so far

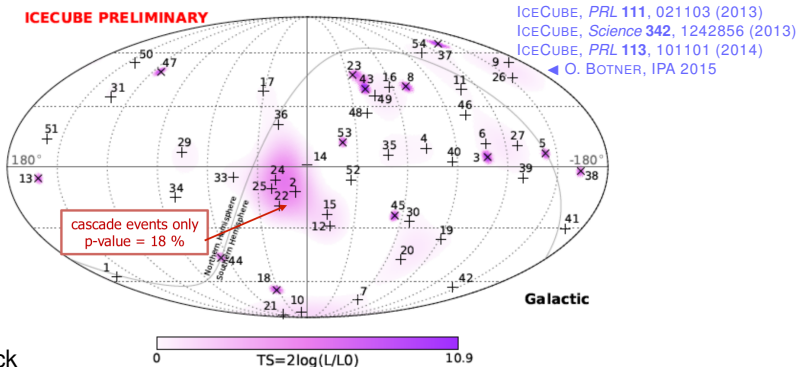
UHECRs



- ▶ Auger: 69 events > 57 EeV
- ▶ Telescope Array: 72 events
- ▶ surface + fluorescence
- ▶ future: LHAASO, JEM-EUSO

What about the sources of HE neutrinos?

Arrival directions compatible with an **isotropic** distribution –



– no association with sources found **yet**

- ▶ GRB searches by IceCube (2012, 2014): no associated ν 's found
- ▶ GRBs contribute only few % of the observed diffuse flux

[I. TAMBORRA, S. ANDO, *JCAP* **1509**, 036 (2015)]

Why is it still interesting to study GRBs?

- 1 They are the best candidates for detection of coincident high-energy e.m.–neutrino emission at PeV ν energies
- 2 Neutrinos from GRB afterglows are expected to be important at EeV energies (observable by radio neutrino detectors)

[K. MURASE, *PRD* **76**, 123001 (2007)] [S. RAZZAQUE, L. YANG, *PRD* **91**, 043003 (2015)]

- 3 Dark, “failed” GRBs might contribute an important part to the diffuse flux seen by IceCube

[P. MÉSZAROS, E. WAXMAN, *PRL* **87**, 171102 (2001)]

Here we will focus on issue 1
and explore the prompt emission of neutrinos in GRBs

GRBs – good candidates for UHE CR & ν sources

GRBs are among the best candidate sources for CRs *and* ν 's:

- ▶ radiated energy of $\sim 10^{52} - 10^{53}$ erg
- ▶ intense magnetic fields of $\sim 10^5$ G
- ▶ magnetically-confined p 's shock-accelerated to $\sim 10^{12}$ GeV
- ▶ plus: low backgrounds (for ν 's) due to small time window

Problem: experiments (IceCube, ANTARES) are starting to strongly constrain the simplest joint emission models

Solution: we need to build more realistic models!

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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

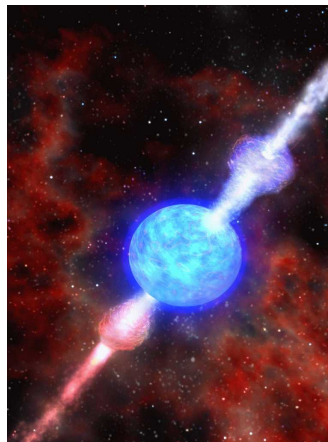
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GRBs – what are they?

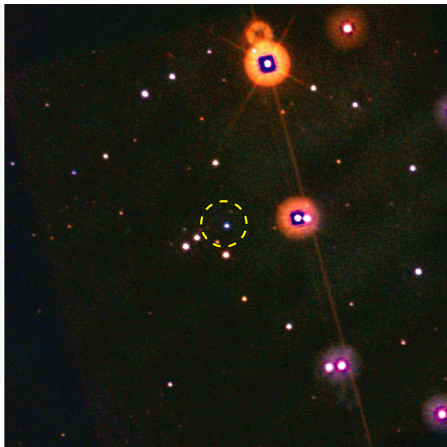
GRBs: the most luminous explosions in the Universe

- ▶ **brief** flashes of gamma rays:
from 0.1 s to few 100's s
- ▶ isotropically distributed in the sky
- ▶ they are **far**: most occur
at ~ 1 Gpc from us ($z \approx 2$)
- ▶ they are **rare**: $\sim 0.3 \text{ Gpc}^{-3} \text{ yr}^{-1}$
- ▶ two populations:
 - ▶ **short-duration** ($< 2 \text{ s}$): neutron star-neutron star or NS-black hole mergers
 - ▶ **long-duration** ($> 2 \text{ s}$): associated to hypernovae
- ▶ powered by matter accretion
onto a black hole



What do they *look* like?

e.g., GRB060218 seen by *Swift*

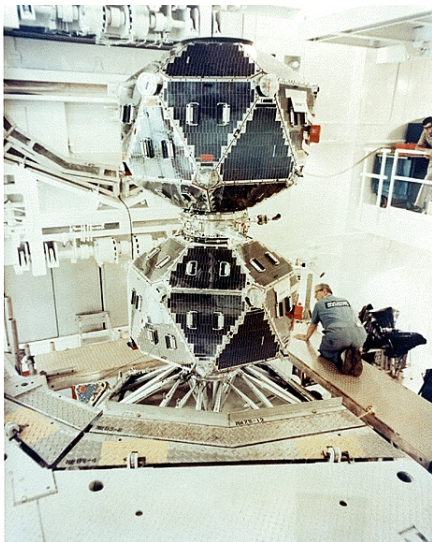


SDSS, SWIFT COLLAB., SLOAN FOUNDATION, NSF, NASA

GRBs – an accidental discovery

After the 1963 Nuclear Test Ban Treaty, the U.S. launched six pairs of *Vela* satellites:

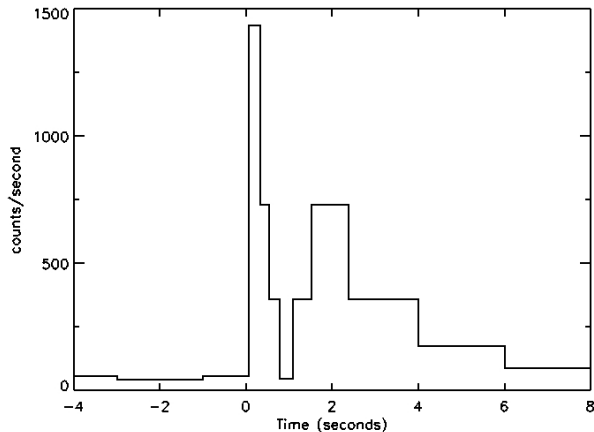
- ▶ They carried X-ray, gamma-ray, and neutron detectors
- ▶ *Vela* 5a-b had enough spatial resolution to pinpoint the direction of events
- ▶ Intense gamma-ray emission from a nuclear explosion lasts $\approx 10^{-6}$ s ...
- ▶ ... however, longer-lasting emissions were detected



VELA 5A/B SATELLITES (NASA)

GRBs – the first one detected

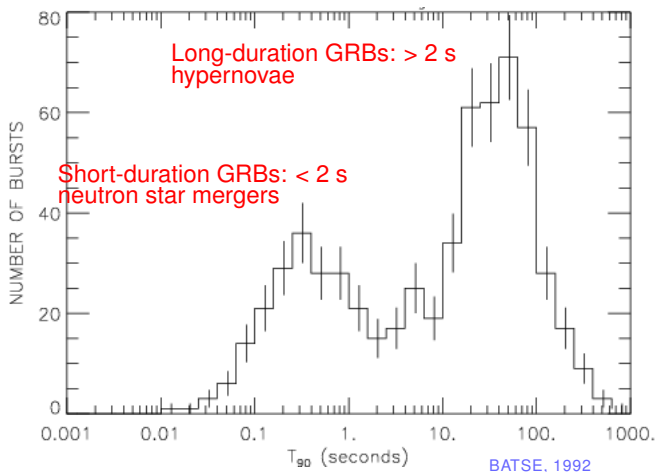
First GRB detected: July 2, 1967, 14:19 UTC



Detected by *Vela* 3, 4a, 4b (found on archival data)

GRBs – two populations

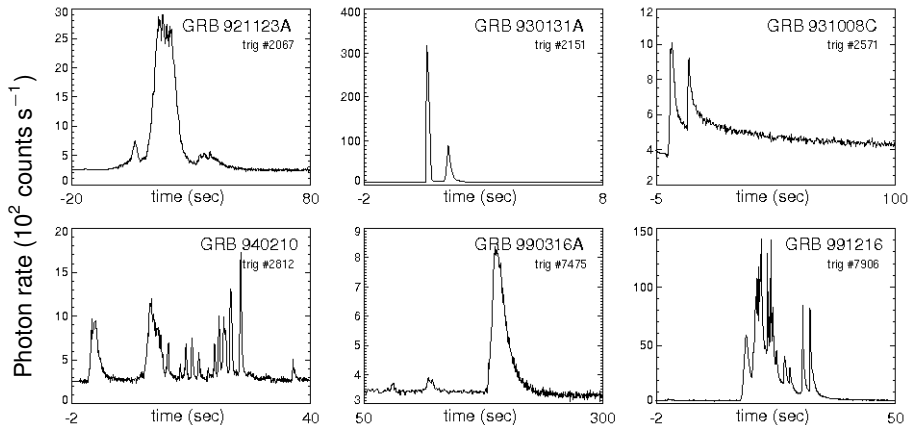
Two populations of GRBs:



T_{90} : time during which 90% of gamma-ray energy is recorded

GRBs – a zoo of light curves

GRB light curves come in different shapes:

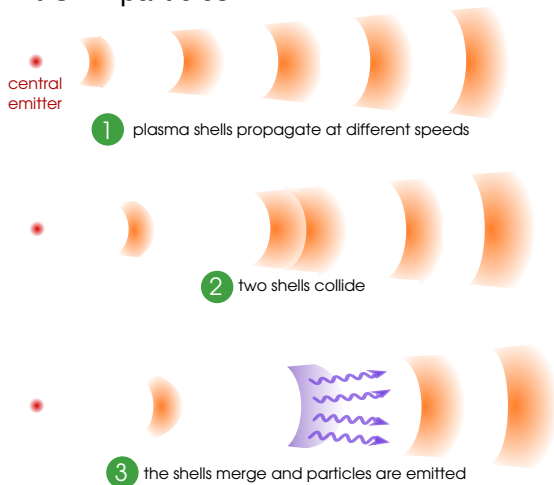


BATSE

variability timescale (width of pulses) $\equiv t_v \approx 1 \text{ ms}$

GRBs explained – the fireball model

Fireball model: our current paradigm of how a GRB works
– relativistically-expanding blobs of plasma collide with each other, merge, and emit UHE particles



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

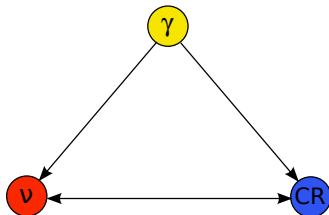
$$p \gamma \rightarrow \Delta^+(1232) \rightarrow \begin{cases} n\pi^+, & \text{BR} = 1/3 \\ p\pi^0, & \text{BR} = 2/3 \end{cases}$$

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

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

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

(Δ^+ : $\sim 50\%$ 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 disfavoured

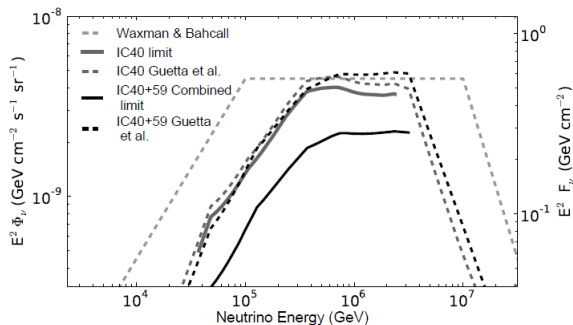
ICECUBE, *Nature* **484**, 351 (2012)

M. AHLERS *et al.* *Astropart. Phys.* **35**, 87 (2011)

The neutron model under tension?

In 2012, IceCube ruled out (a simple version of) the neutron model –

- ▶ per-GRB ν flux normalised to observed γ -ray fluence:
energy in neutrinos $\propto$ energy in gamma-rays
- ▶ extrapolated diffuse ν flux from 117 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)

NeuCosmA: (revised) GRB particle emission – I

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

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

NeuCosmA
 $\otimes$

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

► From Fermi shock acceleration: $N'_p(E'_p) \propto E_p'^{-\alpha_p} e^{-E'_p/E'_{p,\max}}$

► Photon density at source has same shape as observed:

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

$$\alpha_\gamma = 1, \beta_\gamma = 2.2, E'_{\gamma,\min} = 0.2 \text{ eV}, E'_{\gamma,\text{break}} = 1 \text{ keV}$$

Normalise the densities at the source – for one collision:

► Photons:

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

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

► Protons:

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

NeuCosmA: (revised) GRB particle emission – III

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

$$x \equiv E' / E_p'$$

$$y \equiv E_p' E_\gamma' / (m_p c^2)$$

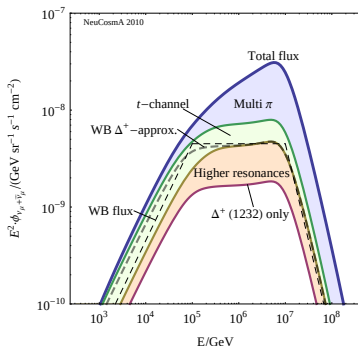
$$Q'(E') = \int_{E'}^{\infty} \frac{dE_p'}{E_p'} N_p'(E_p') \int_0^{\infty} c dE_\gamma' N_\gamma'(E_\gamma') R(x, y)$$

response function

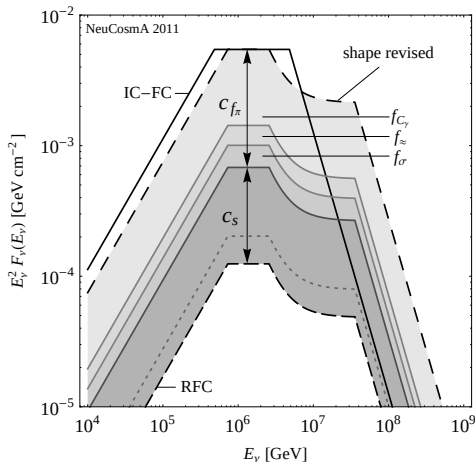
R contains cross sections, multiplicities for different channels

What does NeuCosmA include?

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



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

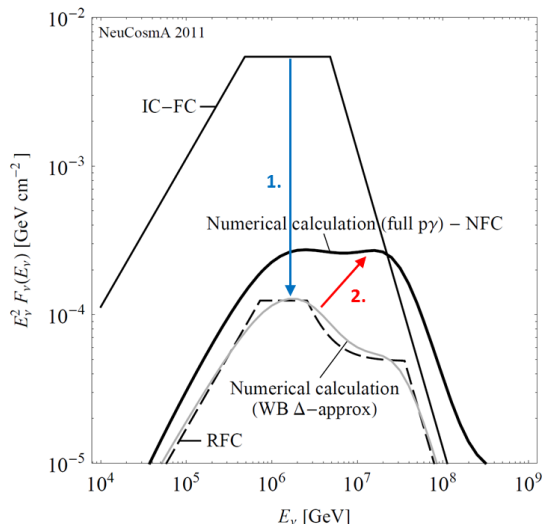
► Correction c_{f_π} to π prod. efficiency:

- 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 – how the neutrino spectrum changes – II



For example, GRB080603A:

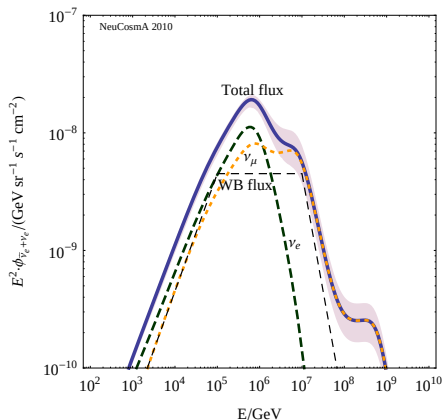
1. Correction to analytical model (IC-FC $\rightarrow$ RFC)
2. Change due to full numerical calculation

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

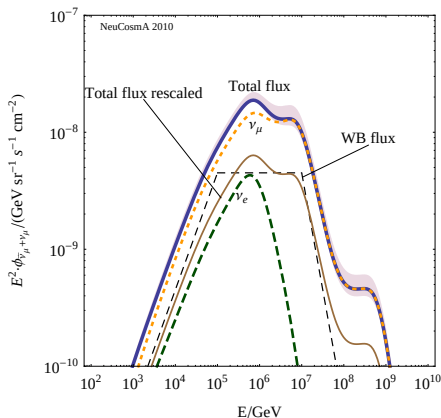
S. HÜMMER, P. BAERWALD, W. WINTER, *Phys. Rev. Lett.* **108**, 231101 (2012)

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

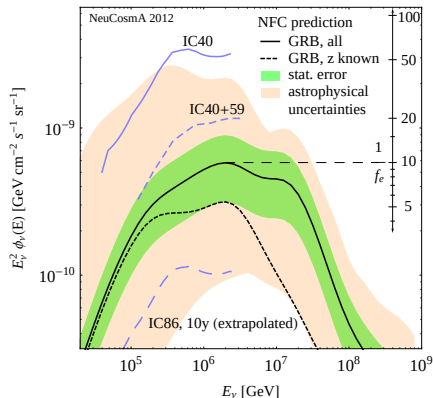
The new prediction of the quasi-diffuse GRB ν flux

Repeat the IceCube GRB neutrino analysis, with NeuCosmA –

- ▶ Same GRB sample and parameters as used by IceCube
- ▶ Calculate the associated neutrino flux for each burst and the stacked flux $F_\nu(E_\nu)$
- ▶ Quasidiffuse flux:

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

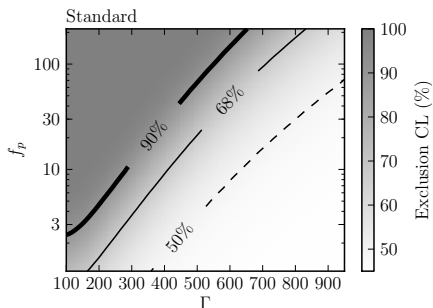
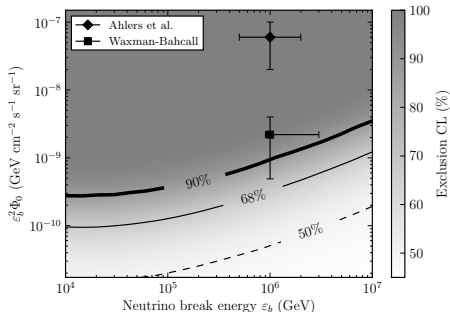
ν flux ~ 1 order of magnitude lower!



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

Improved IceCube bounds (2014)

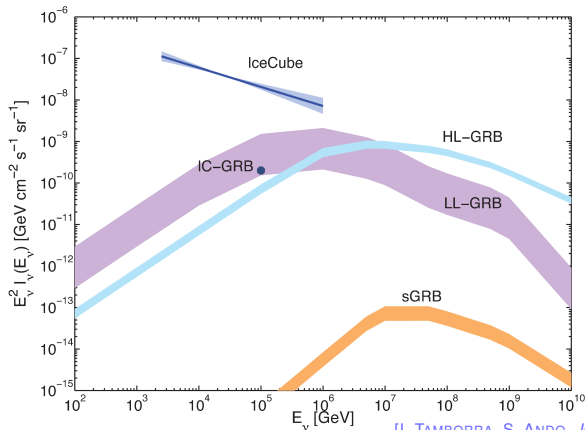
- ▶ Only upgoing ν_μ 's with > 1 TeV used
- ▶ Four years of data (IC-40, -59, -79, -86)
- ▶ Larger GRB catalogue (506 bursts)
- ▶ One coincident event found, with low statistical significance
- ▶ $\lesssim 1\%$ of the diffuse flux can be from prompt GRB emission



[ICECUBE, *ApJ* 805, L5 (2015)]

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)]

Going beyond the neutron model

The neutron model hinges on:

- 1 p 's magnetically confined, only n 's escape
- 2 p 's interact at most once, n 's do not (*optically thin source*)

However, under the “one ν_μ per CR” hypothesis, GRBs are disfavored as the sole sources of UHECRs (AHLERS *et al.*).

M. AHLERS, M. GONZÁLEZ-GARCÍA, F. HALZEN *Astropart. Phys.* **35**, 87 (2011)

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What if 1 and 2 are violated?

- ▶ p 's “leak out”, not accompanied by (direct) ν production
- ▶ multiple p interactions enhance the ν flux
- ▶ in *optically thick sources*, only n 's at the borders escape

M. AHLERS, M. GONZÁLEZ-GARCÍA, F. HALZEN *Astropart. Phys.* **35**, 87 (2011)

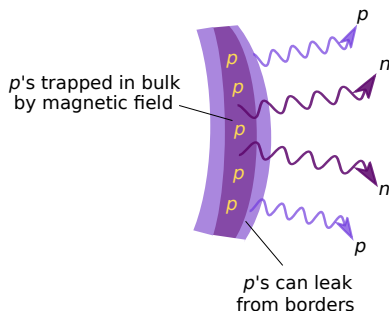
Going beyond the neutron model

We have improved the model – now UHECRs escape as either:

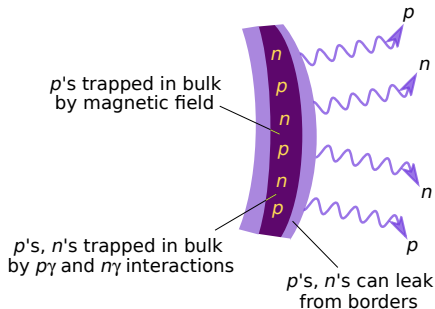
- ▶ **neutrons**, which decay into protons outside the source; or
- ▶ **protons** that leak out without interacting inside the source

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

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



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



A two-component model of UHECR emission

Two important points:

- 1 $E'_{p,\max}$ is determined by energy-loss processes:

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

- 2 Photons can be trapped in the source by pair production:

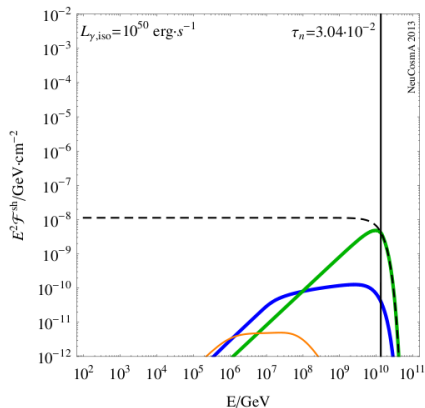
$$\gamma + \gamma \rightarrow e^+ + e^-$$

Photosphere: radius where $\tau_{\gamma\gamma}(E'_\gamma) = 1$ for all E'_γ

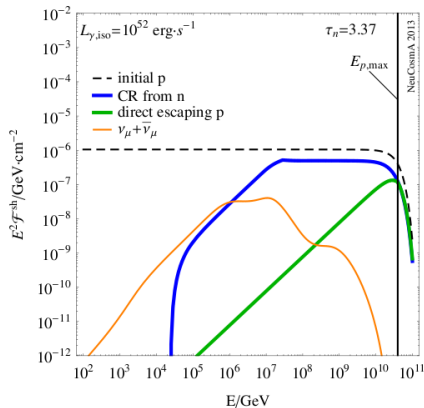
A two-component model of UHECR emission

Sample neutrino fluences –

Optically **thin** source

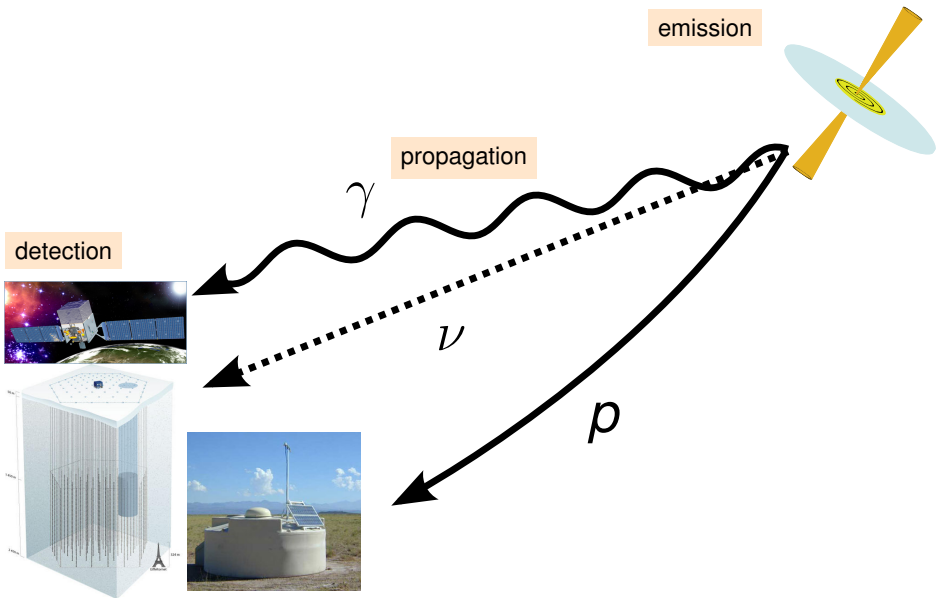


Optically **thick** source

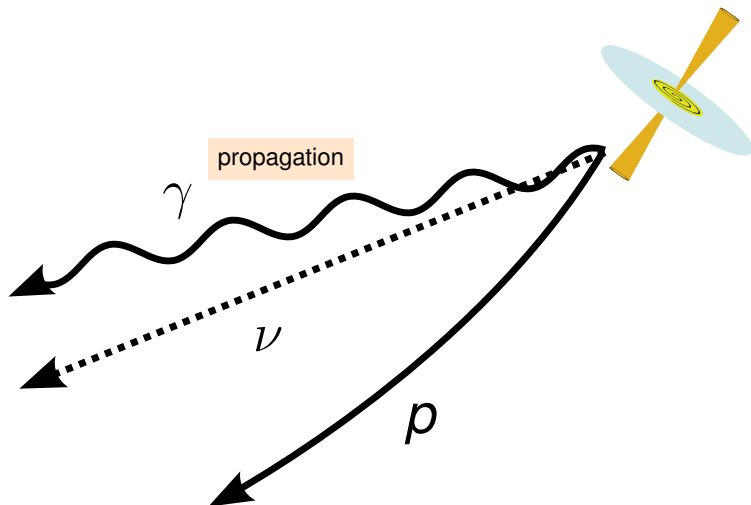


P. BAERWALD, MB, W. WINTER, *ApJ* **768**, 186 (2013)

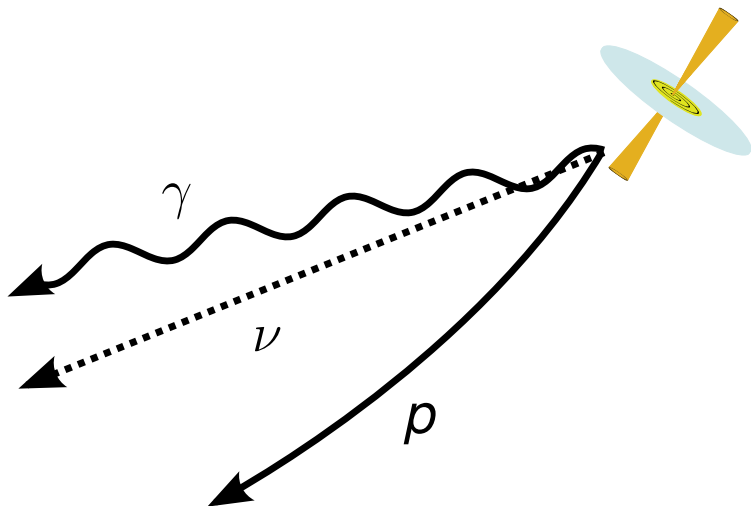
From the sources to us



From the sources to us



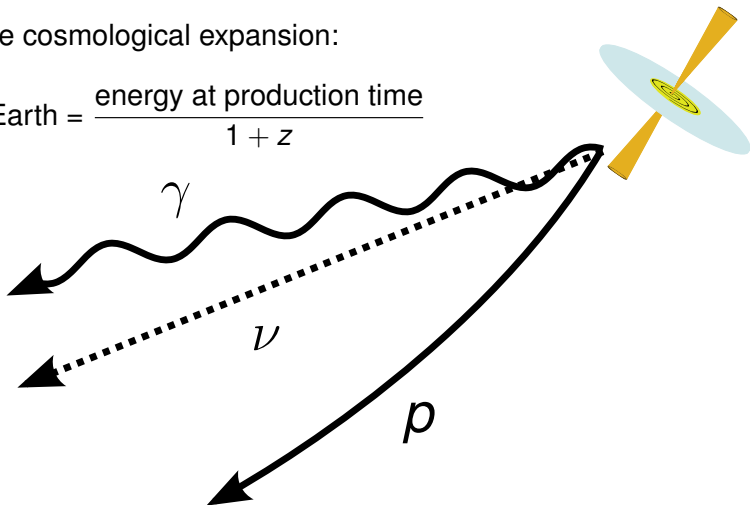
From the sources to us



From the sources to us

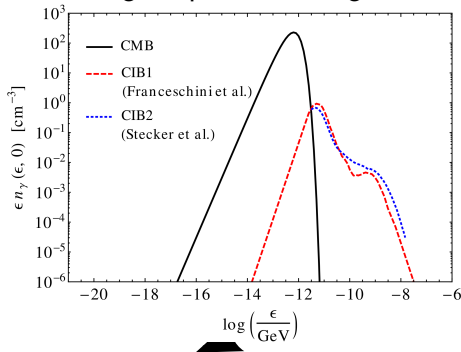
Because of the cosmological expansion:

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

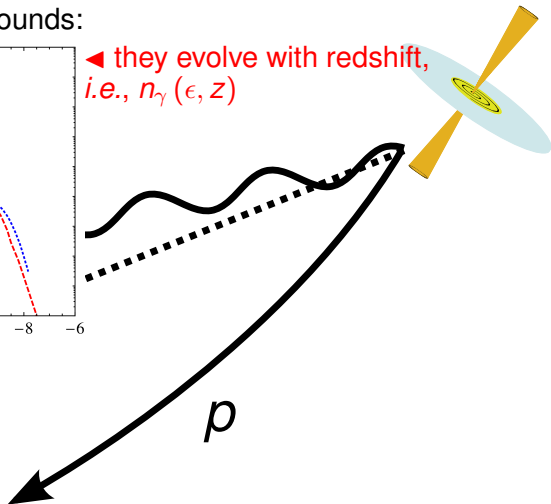


From the sources to us

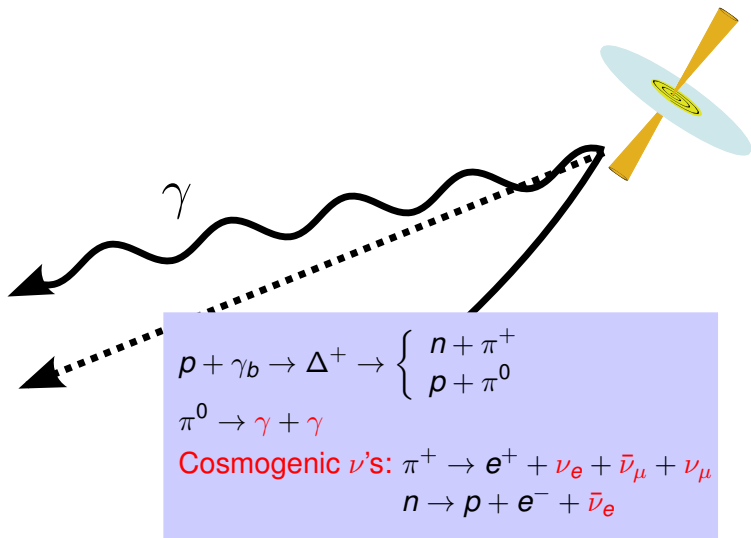
Cosmological photon backgrounds:



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



From the sources to us

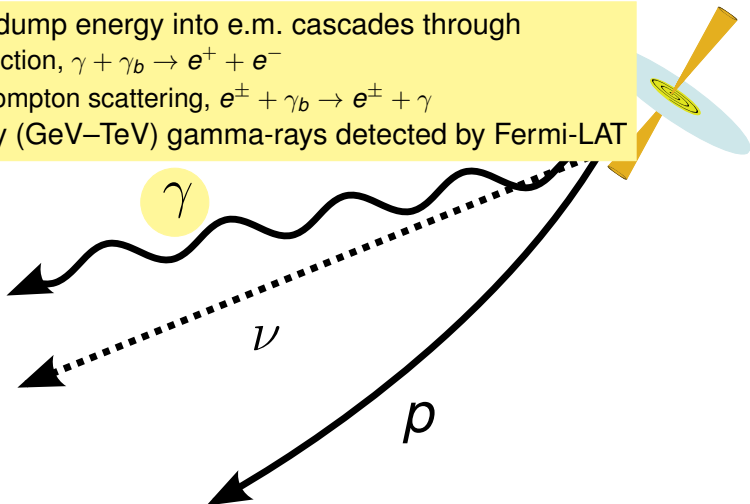


From the sources to us

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

- ▶ pair production, $\gamma + \gamma_b \rightarrow e^+ + e^-$
- ▶ inverse Compton scattering, $e^\pm + \gamma_b \rightarrow e^\pm + \gamma$

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



From the sources to us

p 's are deflected by extragalactic magnetic fields

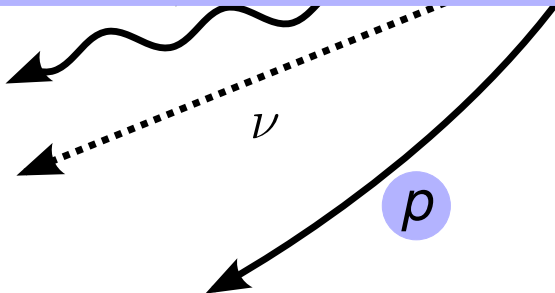
⇒ except for the most energetic ones, they are **not** expected to point back to the sources

} Pierre Auger found weak correlation with known AGN positions

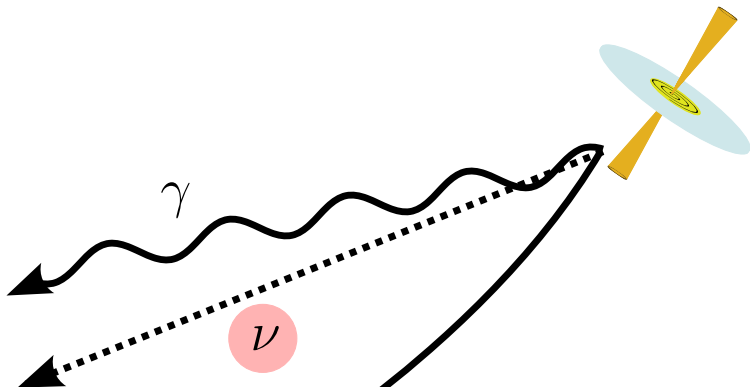
They lose energy through:

- ▶ pair production, $p + \gamma_b \rightarrow p + e^+ + e^-$
- ▶ 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 $\nu_\alpha \rightarrow \nu_\beta$ transition: $P_{\alpha\beta}(E_0, z)$

Flavor oscillations redistribute the fluxes

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

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):

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

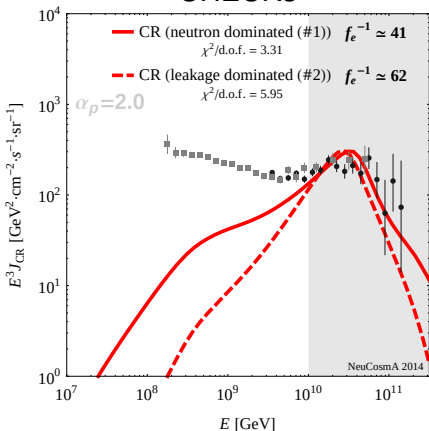
$Q_{\text{CR}}(E) \propto E^{-\alpha_p} e^{-E/E_{p,\text{max}}}$

What do the diffuse fluxes look at Earth, then?

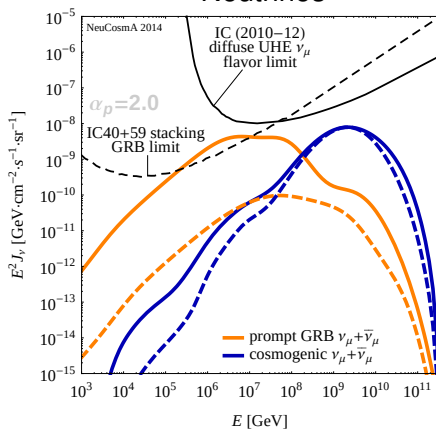
Neutron model vs. two-component model:

prompt and **cosmogenic** ν 's

UHECRs

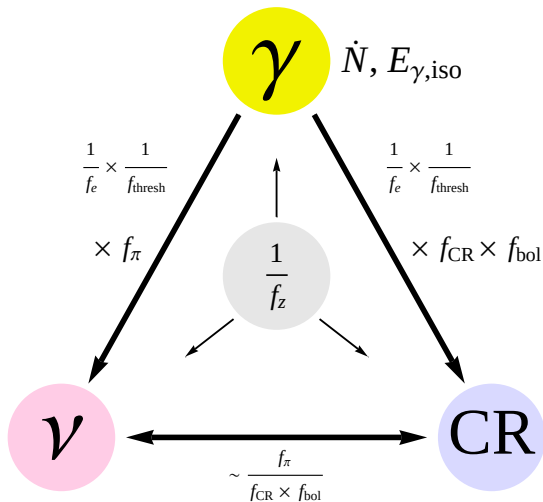


Neutrinos



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)

The big (multi-messenger) picture



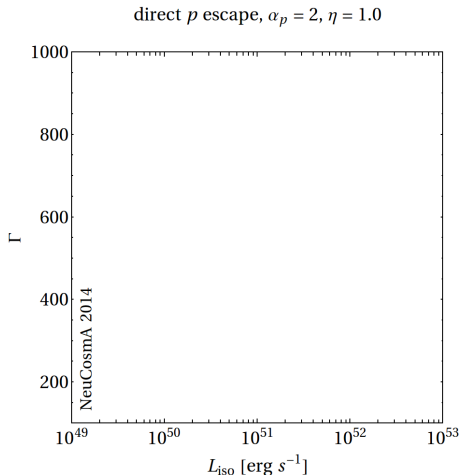
Using UHECR + neutrino constraints

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

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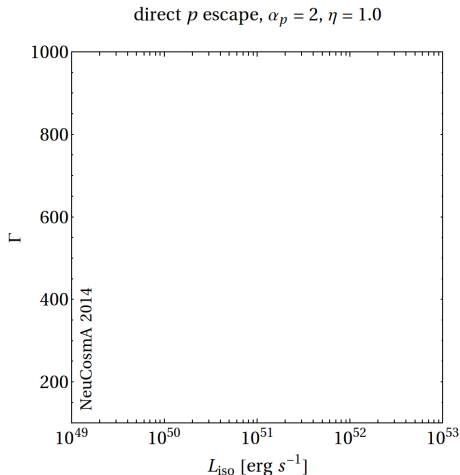


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- 2 Fit each spectrum to UHECR data (TA, PAO, HiRes)

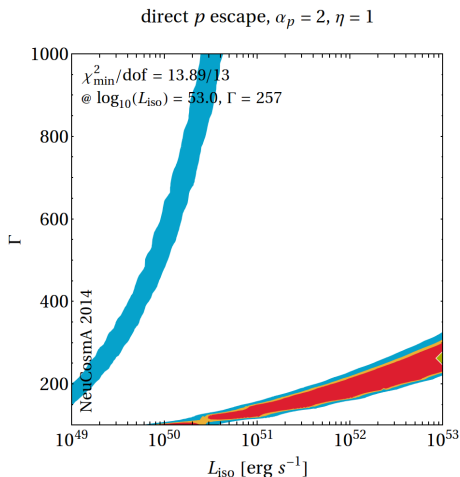


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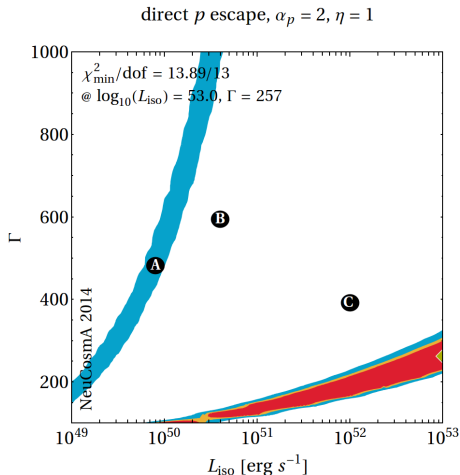


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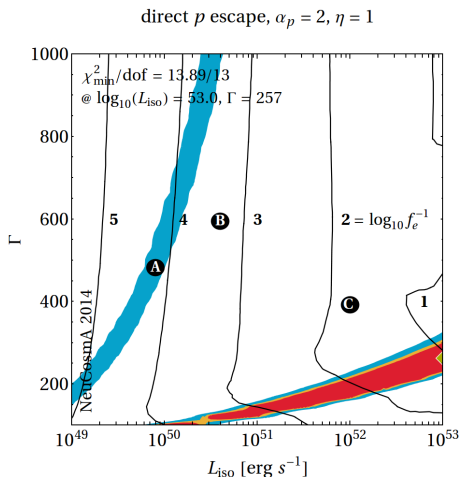


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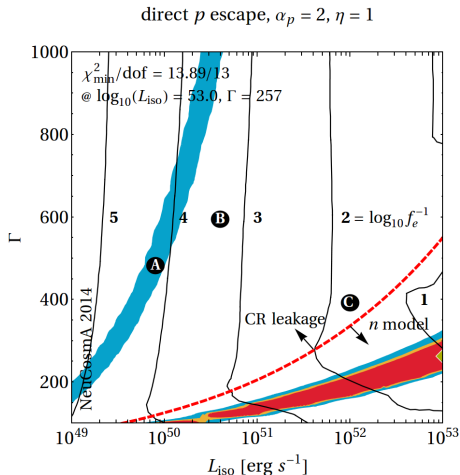


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- 5 Identify the region corresponding to pure n escape and to n escape + CR leakage



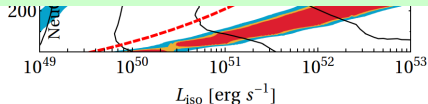
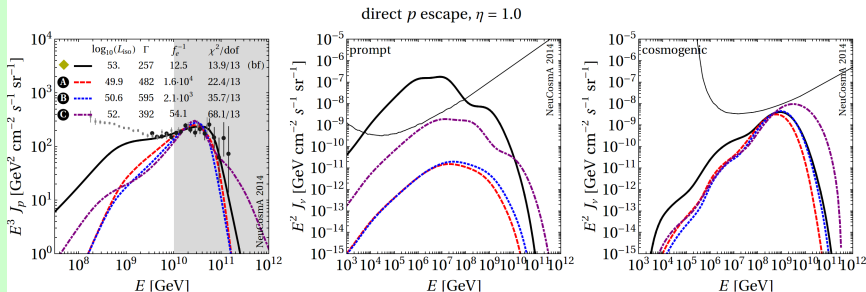
P. BAERWALD, MB, W. WINTER, *Astropart. Phys.* **62**, 66 (2015)

Using UHECR + neutrino constraints

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

1 Generate the UHECR spectrum at every

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

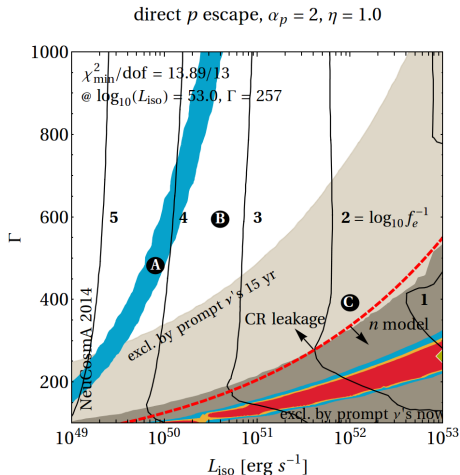


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- 5 Identify the region corresponding to pure n escape and to n escape + CR leakage
- 6 Find the region where the number of prompt ν_μ 's is > 2.44 , i.e., the excluded region at 90% C.L.

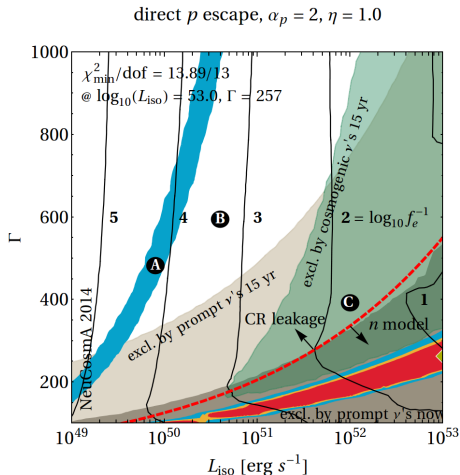


P. BAERWALD, MB, W. WINTER, *Astropart. Phys.* **62**, 66 (2015)

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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.
- 7 After 15 yr of exposure and no detection, cosmogenic neutrinos also exclude

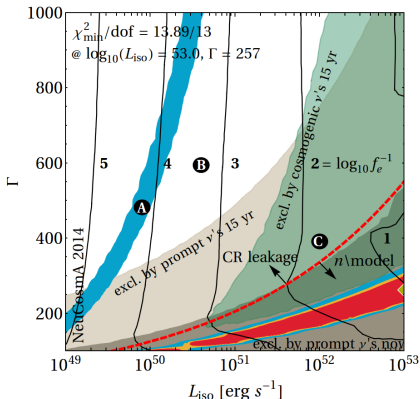


P. BAERWALD, MB, W. WINTER, *Astropart. Phys.* **62**, 66 (2015)

Star-formation-rate vs. GRB redshift evolution

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

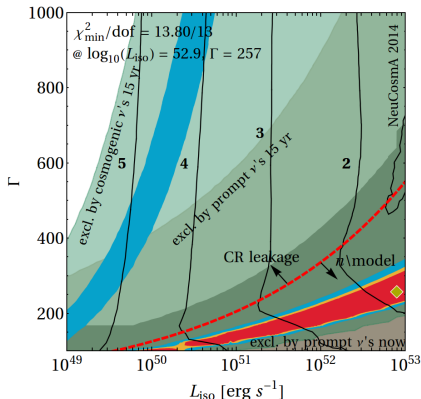
direct p escape, $\eta = 1.0$



$$n_{\text{GRB}}(z) \propto \rho_{\text{SFR}}(z)$$

(star formation rate)

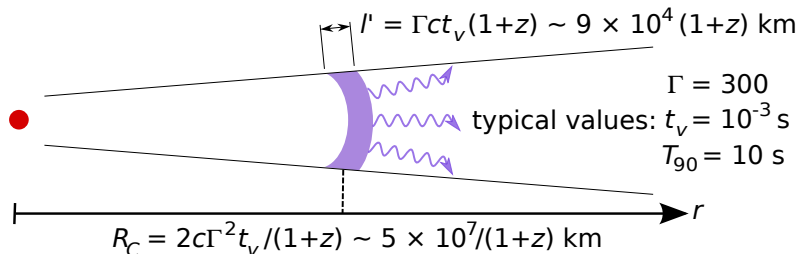
direct p escape, $\eta = 1.0$



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

The *static* burst

So far, we have taken *all* internal collisions to occur at the *same* radius:



- ▶ *average* speed Γ inferred from afterglow observations
- ▶ “variability timescale” t_v measured from the light curve
- ▶ redshift z measured for the host galaxy

Static burst: made up of $T_{90}/t_v \sim 100 - 1000$ identical collisions

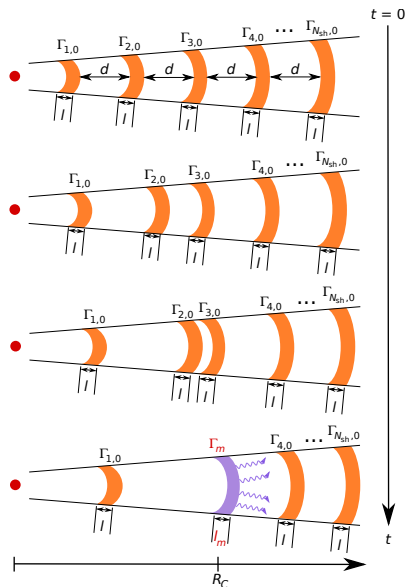
Going further: an evolving burst

Consider an evolving fireball –

- ▶ the fireball expands with time
- ▶ ~ 1000 shells propagate with different speeds
- ▶ they have different masses
- ▶ they collide at different radii
(collisions no longer identical)

Why does this matter?

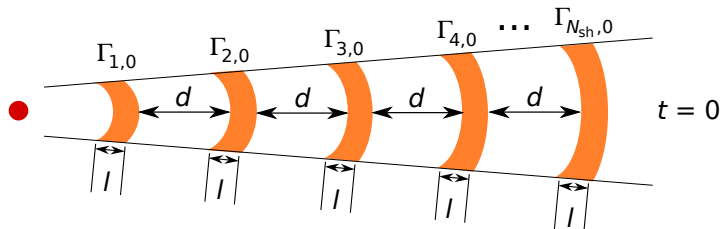
The particle (γ , p) densities fall as the fireball expands – particle production conditions change with time/radius



S. KOBAYASHI, T. PIRAN, R. SARI, *ApJ* **490**, 92 (1997)
F. DAIGNE, R. MOCHKOVITCH, *MNRAS* **296**, 275 (1998)

Initialising the burst simulation

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



Initial values of shell parameters:

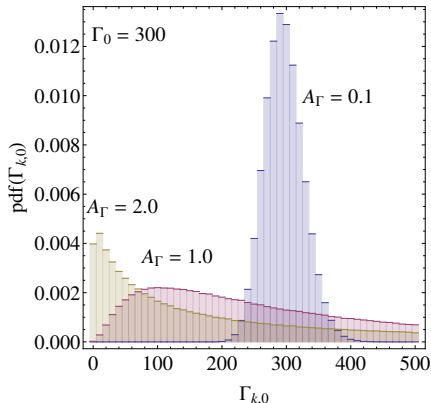
- ▶ Width of shells and separation between them: $l = d = c \cdot \delta t_{\text{eng}}$
- ▶ Equal kinetic energy for all shells ($\sim 10^{52}$ erg)
- ▶ Shell speeds $\Gamma_{k,0}$ follow a distribution (log-normal or other)

Initial distribution of shell speeds

Distribution of initial shell speeds (Lorentz factors):

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

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

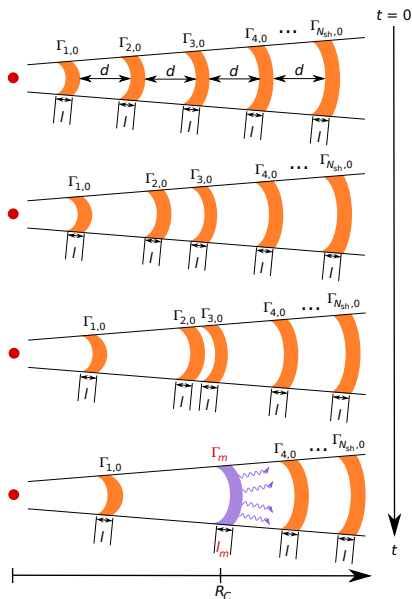
$$A_\Gamma \gg 1$$

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

$\approx$

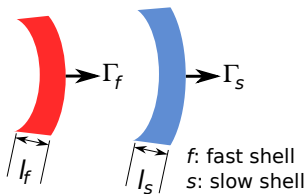
number of initial shells ($\gtrsim 1000$)

S. KOBAYASHI, T. PIRAN, R. SARI, *ApJ* **490**, 92 (1997)

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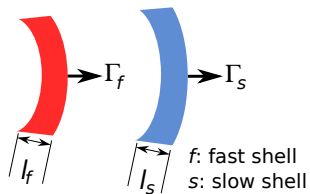
Anatomy of an internal collision

1 Propagation

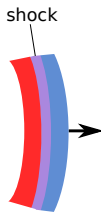


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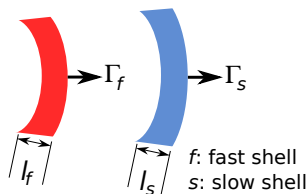


2 Collision

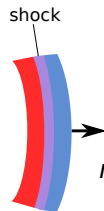


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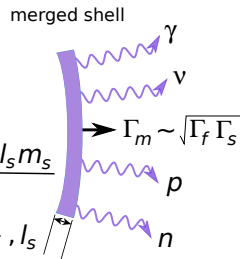
2 Collision



$$m_m = \frac{l_f m_f + l_s m_s}{l_m}$$

$l_m < l_f, l_s$

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

$$\epsilon_e E_{\text{coll}}^{\text{iso}}$$

energy in photons

1/12

$$\epsilon_B E_{\text{coll}}^{\text{iso}}$$

energy in magnetic fields

5/6

$$\epsilon_p E_{\text{coll}}^{\text{iso}}$$

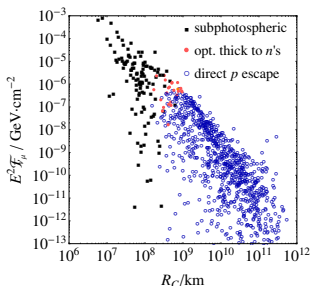
energy in baryons

Tracking each collision individually

Each collision occurs in a different emission regime –

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

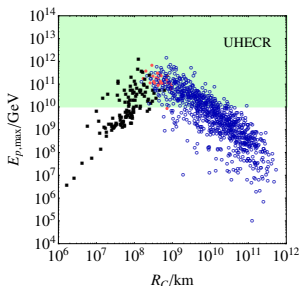
neutrinos



(observer's frame)

maximum p energy

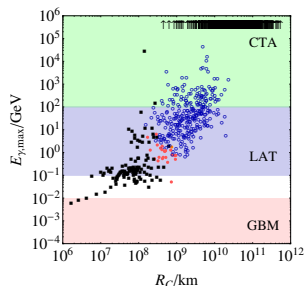
cosmic rays



(source frame)

maximum γ energy

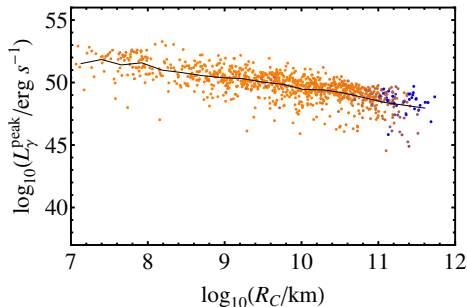
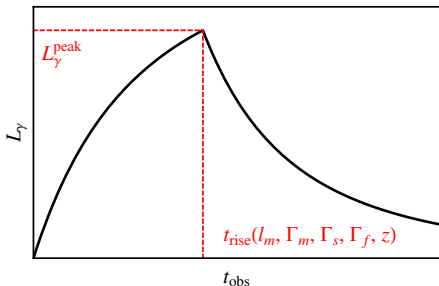
gamma-rays



[MB, P. BAERWALD, K. MURASE, W. WINTER, *Nat. Commun.* 6, 6783 (2015)]

Gamma-ray and neutrino pulses

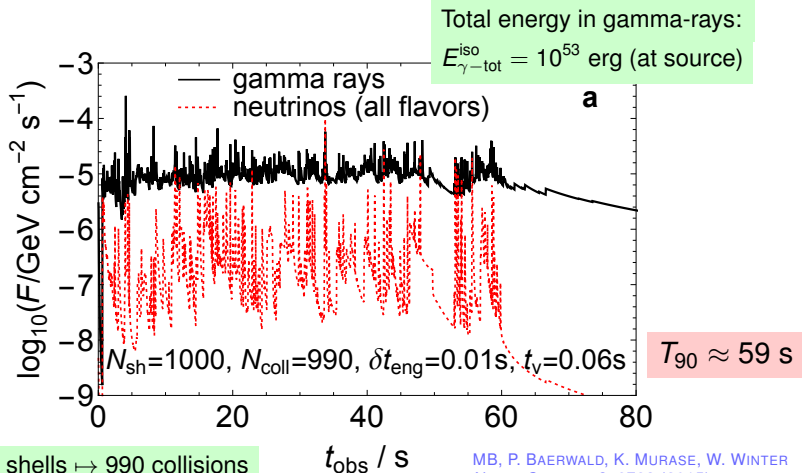
A fast-rise-exponential-decay (FRED) gamma-ray pulse is emitted in every collision:



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

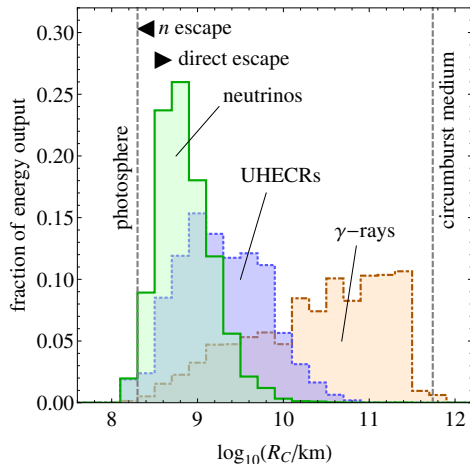
Synthetic light curves

- An emission pulse is assigned to each collision
– their superposition yields a **synthetic light curve**:



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

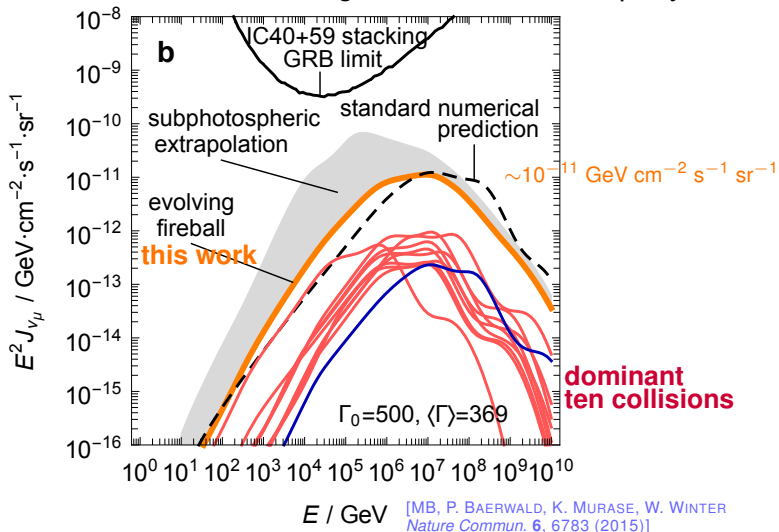
Why does it matter?

GRB parameters derived from gamma-ray observations might not be adequate to describe ν and UHECR emission

[MB, P. BAERWALD, K. MURASE, W. WINTER, *Nat. 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:



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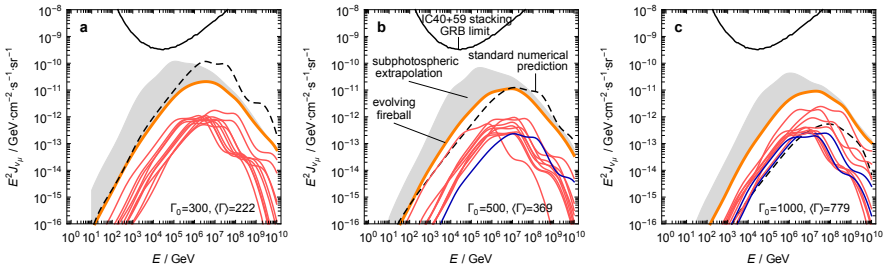
- ▶ $\Rightarrow$ Time-integrated neutrino fluence dominated is independent of Γ :

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

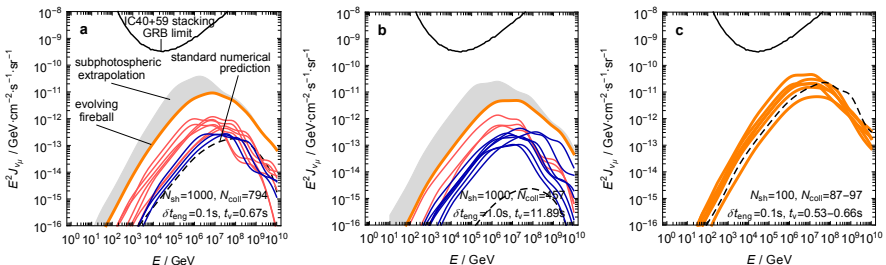
- ▶ Compare to standard predictions, which have a $\langle \Gamma \rangle^{-4}$ dependence
- ▶ Raising ϵ_p automatically decreases ϵ_e , so the photosphere grows, but still ~ 10 photospheric collisions dominate

The prediction *is* robust

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

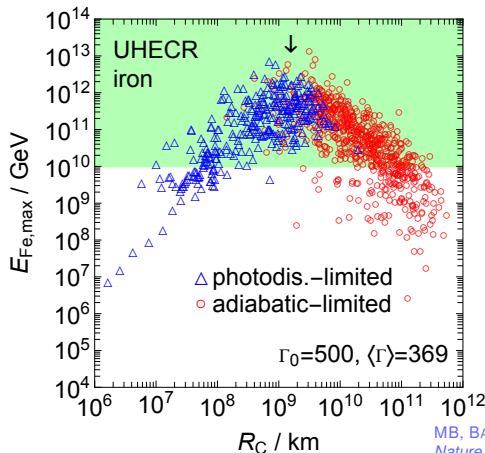


... and on the GRB engine variability time δt_{eng}



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:



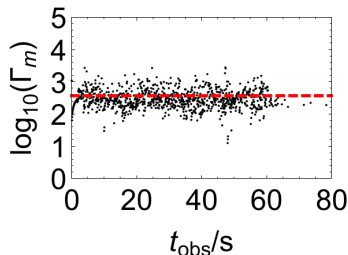
MB, BAERWALD, MURASE, WINTER
Nature Commun. **6**, 6783 (2015)

What makes a GRB bright in neutrinos? (Preliminary)

- ▶ **Goal:** to use the morphology of the GRB gamma-ray light curve alone to assess whether the burst is neutrino-bright
- ▶ The central engine determines the features of the light curve

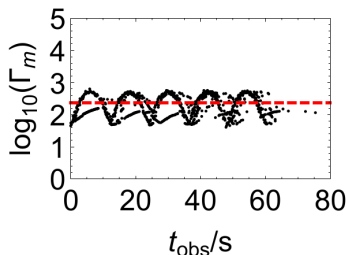
GRB A: undisciplined engine

- ▶ Engine emits shells with log-normal distribution of Γ
- ▶ Broad Γ distribution ($A_\Gamma = 1$)



GRB B: disciplined engine

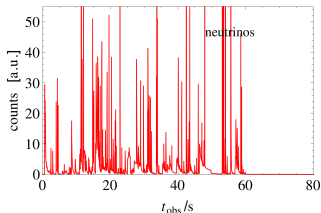
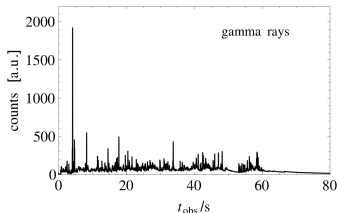
- ▶ Engine emits shells with oscillating Γ
- ▶ Narrow Γ distribution ($A_\Gamma = 0.1$)



How do the gamma-ray and neutrino light curves look?

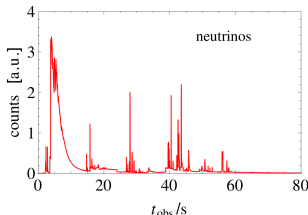
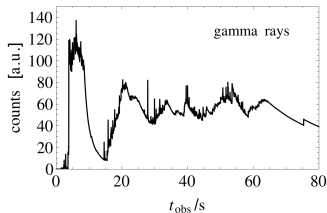
GRB A: undisciplined engine

- ▶ Fast variability dominates
- ▶ No broad pulses



GRB B: disciplined engine

- ▶ Broad pulses dominate
- ▶ Fast variability on top



So which burst is neutrino-bright?

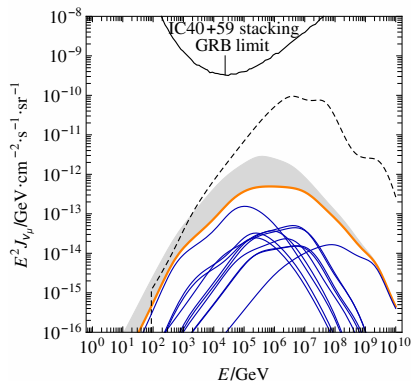
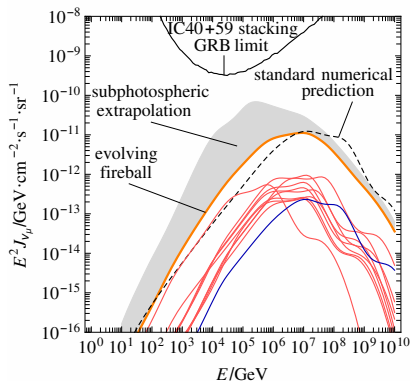
Compare the quasi-diffuse neutrino fluxes:

GRB A: undisciplined engine

$$\sim 10^{-11} \text{ GeV cm}^{-2} \text{ s}^{-1} \text{ sr}^{-1}$$

GRB B: disciplined engine

$$\sim 5 \cdot 10^{-13} \text{ GeV cm}^{-2} \text{ s}^{-1} \text{ sr}^{-1}$$

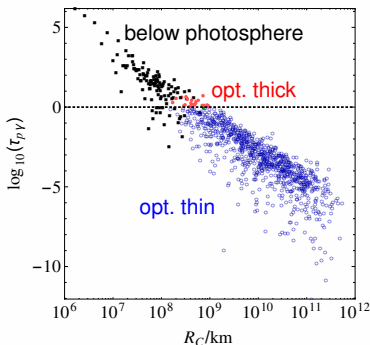


$\therefore$ An undisciplined engine makes a GRB neutrino-bright

Why?

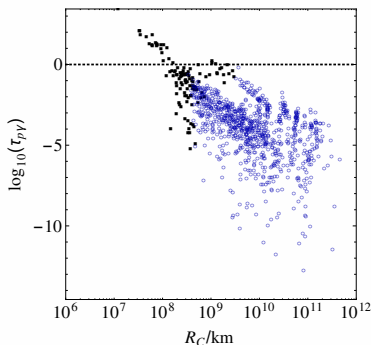
GRB A: undisciplined engine

- ▶ Shells have very different speeds
- ▶ Collide quickly, close to engine
- ▶ High p and γ densities
- ▶ ~ 10 optically-thick bursts near the photosphere



GRB B: disciplined engine

- ▶ Shells have similar speeds
- ▶ Collide far from engine
- ▶ Low p and γ densities
- ▶ All (superphotospheric) collisions are optically thin



Conclusions ... and the future

- ▶ GRBs *are* good UHECR and ν source candidates
- ▶ *But* the CR- ν - γ connection is trickier than originally thought
- ▶ Contribute to the diffuse HE astrophysical ν flux at the few % level
- ▶ Likely to be the first point neutrino sources to be resolved
- ▶ Need *next-gen* neutrino telescopes (IceCube-Gen2, KM3NeT) ...
- ▶ ... while Auger, Telescope Array, CTA, *etc.* gather extensive UHECR statistics
- ▶ By exploiting gamma-ray light curve morphology, we may be able to improve selection cuts

Backup slides

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} :

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

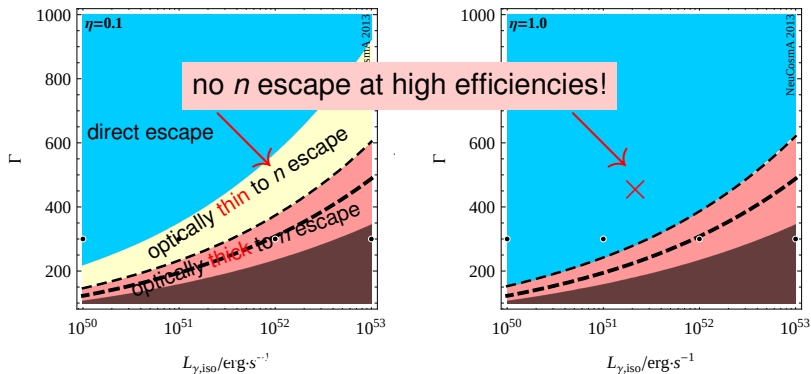
fraction of escaping particles

We *need* direct proton escape

Scan of the GRB emission parameter space –

acceleration efficiency $\longrightarrow \eta = 0.1$

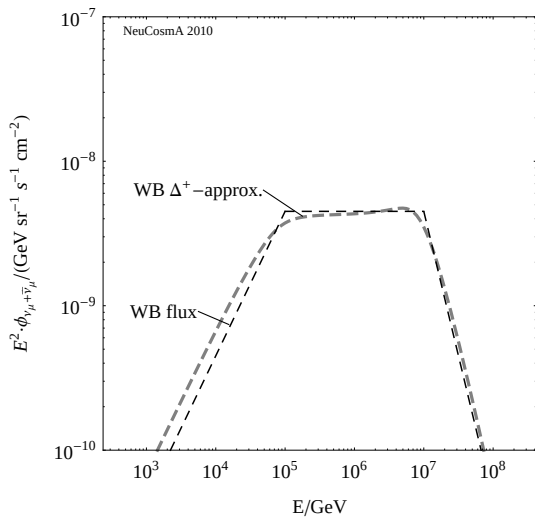
$\eta = 1.0$



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

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

NeuCosmA – the full photohadronic cross section

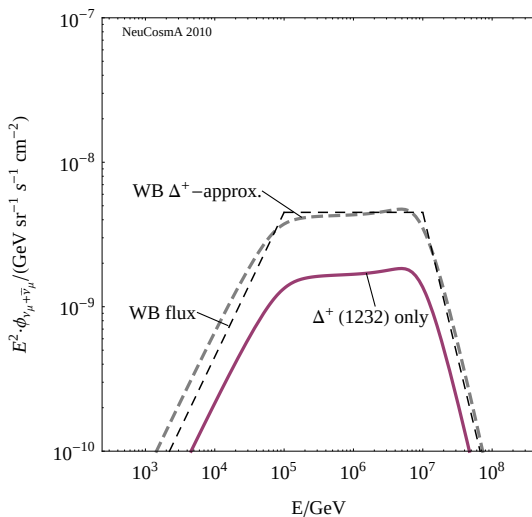


NeuCosmA – the full photohadronic cross section

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)

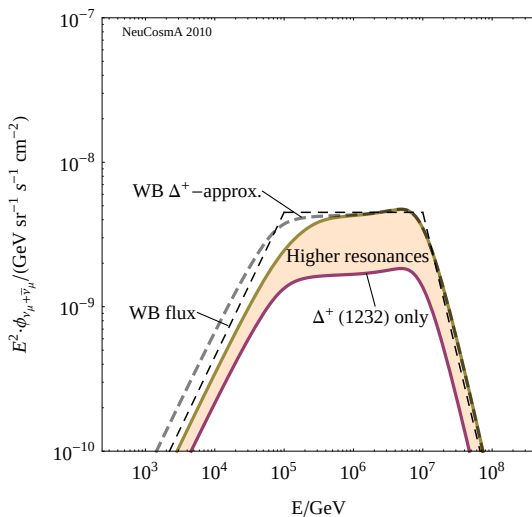


NeuCosmA – the full photohadronic cross section

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,
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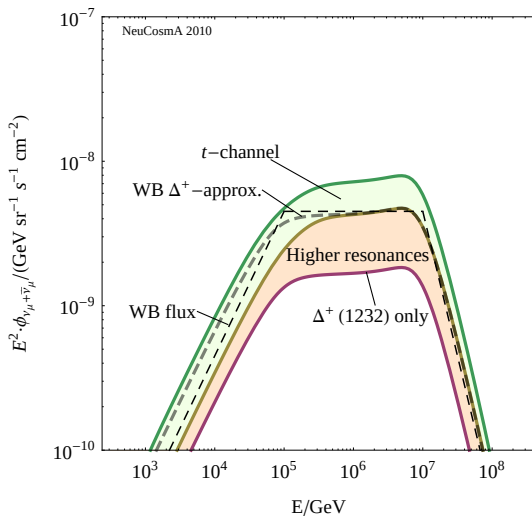


NeuCosmA – the full photohadronic cross section

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)

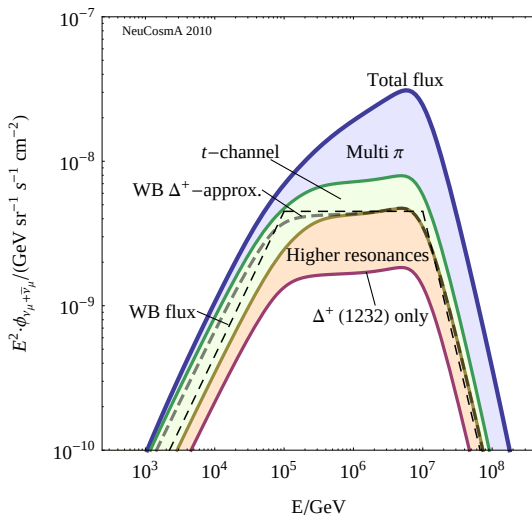


NeuCosmA – the full photohadronic cross section

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

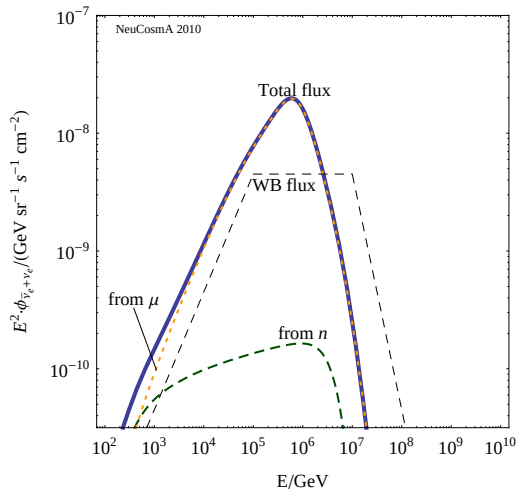
$$\begin{aligned}\pi^+ &\rightarrow \mu^+ + \nu_\mu \\ \mu^+ &\rightarrow e^+ + \nu_e + \bar{\nu}_\mu\end{aligned}$$

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

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

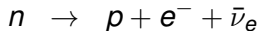
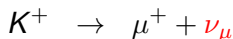
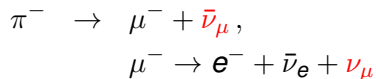
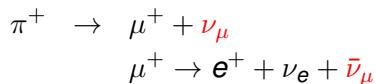
$$n \rightarrow p + e^- + \bar{\nu}_e$$

Resulting ν_e flux (at the observer)

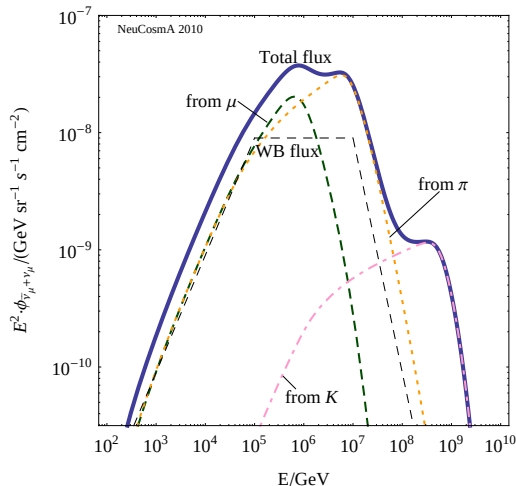


P. BAERWALD, S. HÜMMER, AND W. WINTER, *Phys. Rev. D* **83**, 067303 (2011)

NeuCosmA – further particle decays



Resulting ν_μ flux (at the observer)



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

The need for km-scale neutrino telescopes

Expected ν flux from cosmological accelerators (Waxman & Bahcall 1997 & 1998):

$$E^2 \Phi_\nu \sim 10^{-8} \frac{f_\pi}{0.2} \left(\frac{\dot{\epsilon}_{\text{CR}}^{[10^{10}, 10^{12}]}}{10^{44} \text{ erg Mpc}^{-3} \text{ yr}^{-1}} \right) \text{ GeV cm}^{-2} \text{ s}^{-1} \text{ sr}^{-1}$$

Integrated flux above 1 PeV:

$$\Phi_\nu (> 1 \text{ PeV}) \sim \int_{1 \text{ PeV}}^{\infty} \frac{10^{-8}}{E^2} dE \sim 10^{-20} \text{ cm}^{-2} \text{ s}^{-1} \text{ sr}^{-1}$$

Number of events from half of the sky (2π):

$$N_\nu \simeq 2\pi \cdot \Phi_\nu (> 1 \text{ PeV}) \cdot 1 \text{ yr} \cdot A_{\text{eff}} \approx (2.4 \times 10^{-10} \text{ cm}^{-2}) A_{\text{eff}},$$

where A_{eff} is the effective area of the detector

To detect $N_\nu > 1$ events per year, we need an area of

$$A_{\text{eff}} \gtrsim 0.4 \text{ km}^2$$

Therefore, we need km-scale detectors, like IceCube

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:

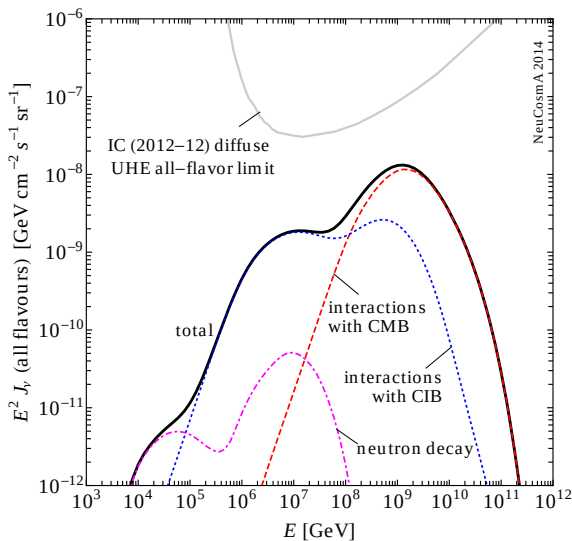
$$\pi^+ \rightarrow \mu^+ + \nu_\mu$$

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

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

These are called *cosmogenic neutrinos*

Cosmogenic neutrinos



P. BAERWALD, MB, W. WINTER, *Astropart. Phys.* **62**, 66 (2015)

Interaction with the photon backgrounds – I

- ▶ Energy loss rate (GeV s^{-1}):

$$b(E) \equiv \frac{dE}{dt}$$

- ▶ For pair production $p\gamma \longrightarrow pe^+e^-$:

$$b_{e^+e^-}(E, z) = -\alpha r_0^2 (m_e c^2)^2 c \int_2^\infty d\xi n_\gamma \left(\frac{\xi m_e c^2}{2\gamma}, z \right) \frac{\phi(\xi)}{\xi^2}$$

- ▶ n_γ : isotropic photon background ($\text{GeV}^{-1} \text{ cm}^{-3}$)
- ▶ ξ : photon energy in units of $m_e c^2$
- ▶ proton energy: $E = \gamma m_p c^2$ ($\gamma \gg 1$)
- ▶ $\phi(\xi)$: (tabulated) integral in energy of outgoing e^-

G. BLUMENTHAL, *Phys. Rev.* **D 1**, 1596 (1970)

H. BETHE, W. HEITLER, *Proc. Roy. Soc.* **A146**, 83 (1934)

Interaction with the photon backgrounds – II

Photohadronic interactions – $p\gamma$ interaction rate (s^{-1} per particle):

$$\Gamma_{p\gamma \rightarrow p'b}(E, z) = \frac{1}{2} \frac{m_p^2}{E^2} \int_{\frac{\epsilon_{\text{th}} m_p}{2E}}^{\infty} d\epsilon \frac{n_\gamma(\epsilon, z)}{\epsilon^2} \int_{\epsilon_{\text{th}}}^{2E\epsilon/m_p} d\epsilon_r \epsilon_r \sigma_{p\gamma \rightarrow p'b}^{\text{tot}}(\epsilon_r)$$

- 1 For given values of E and z , [NeuCosmA](#) calculates the cooling rate $t_{p\gamma}^{-1} \equiv -(1/E) b_{p\gamma} (\text{s}^{-1})$ as

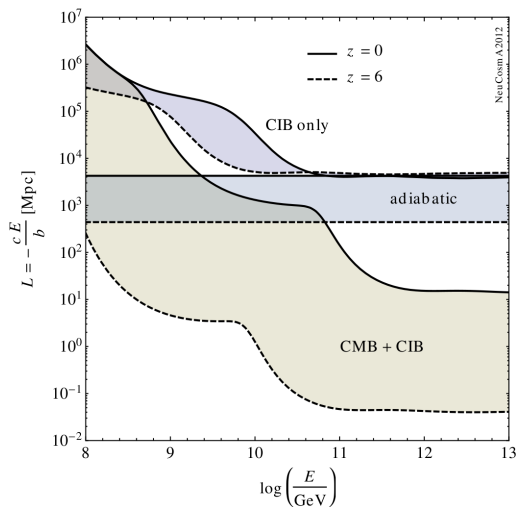
$$t_{p\gamma}^{-1}(E, z) = \sum_i^{\text{all channels}} \Gamma_{p \rightarrow p}^i(E, z) K^i,$$

with $K^i E$ the loss of energy per interaction

- 2 From this, we calculate back $b_{p\gamma} (\text{GeV s}^{-1}) \dots$
- 3 ... and the corresponding energy-loss term in the transport equation, $\partial_E (b_{p\gamma} Y_p)$.

Interaction lengths

Note that $L_{\text{CIB}} \gg L_{\text{CMB}}$:



Matches, e.g., H. TAKAMI, K. MURASE, S. NAGATAKI, K. SATO, *Astropart. Phys.* **31**, 201 (2009) [0704.0979]

UHE 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 ($\text{GeV}^{-1} \text{ cm}^{-2}$)

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

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

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

► Proton density:

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

Maximum proton energy limited by energy losses:

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

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

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