Ultra-high-energy neutrinos and cosmic rays from gamma-ray bursts: exploring and updating the connections

Mauricio Bustamante

Inst. für Theoretische Physik und Astrophysik, Uni. Würzburg &
Deutsches Elektronen-Synchrotron DESY, Zeuthen

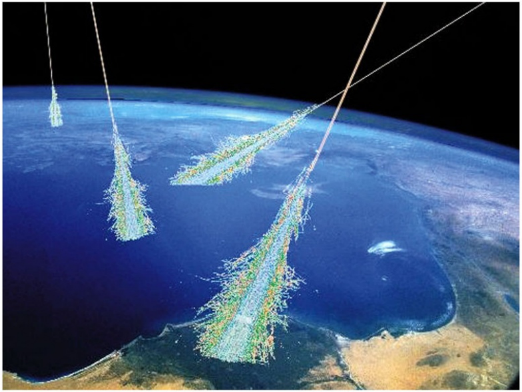
Promotionskolloquium
Würzburg, September 22, 2014

Introduction – the mystery

Two of the biggest mysteries –

Two of the biggest mysteries –

ultra-high-energy cosmic rays (UHECRs)

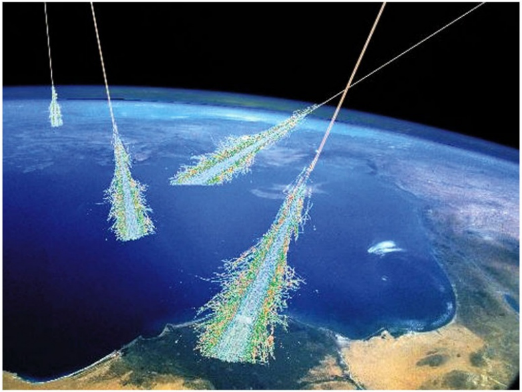


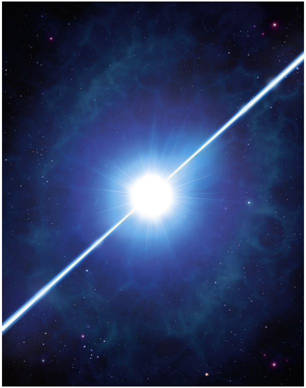
Introduction – the mystery

Two of the biggest mysteries –

ultra-high-energy cosmic rays (UHECRs)

gamma-ray bursts (GRBs)





Introduction – the mystery

Two of the biggest mysteries –

ultra-high-energy cosmic rays (UHECRs)

gamma-ray bursts (GRBs)

The mystery

We do not know the origin of UHECRs and GRBs

Introduction – the mystery

Two of the biggest mysteries –

ultra-high-energy cosmic rays (UHECRs)   gamma-ray bursts (GRBs)

The mystery

We do not know the origin of UHECRs and GRBs

Our hypothesis

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

Introduction – the mystery

Two of the biggest mysteries –

ultra-high-energy cosmic rays (UHECRs) gamma-ray bursts (GRBs)

The mystery

We do not know the origin of UHECRs and GRBs

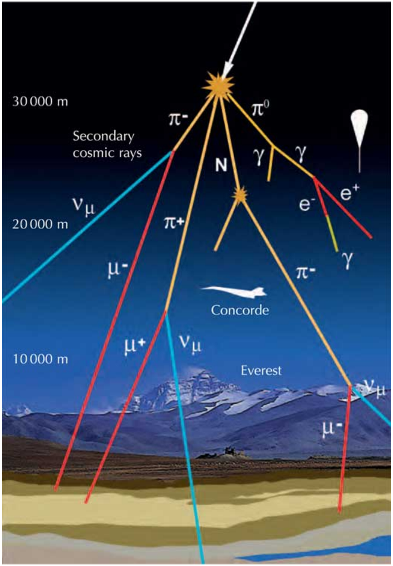
Our hypothesis

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

Our result

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

Introduction – UHECRs



Introduction – UHECRs

1962: discovery of UHECRs at the Volcano Ranch Experiment, New Mexico

$> 10^{18}$ eV – most energetic particles in known Universe

Introduction – UHECRs

“Oh-my-God particle”: $\sim$ 3 $\cdot 10^{20}$ eV $\equiv$ 50 J

(Fly’s Eye experiment, Utah, 1991)

This is equivalent to . . .

- a baseball (142 g) travelling at 94 km h^{-1}; or
- a football (410 g) travelling at 55 km h^{-1},

. . . but concentrated in a volume of radius 1 fm $\equiv 10^{-15}$ m

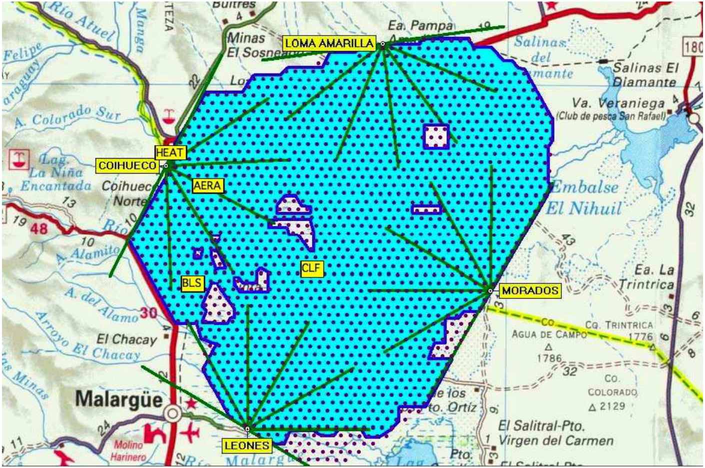
Approximate speed:

$$0.9999999999999999999999951c = (1 - 4.9 \cdot 10^{-24})c$$

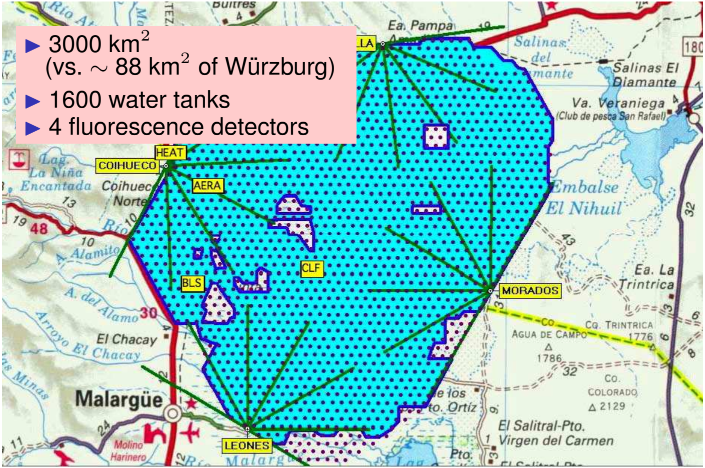
$\sim$ 40 million times higher than a 7 TeV proton at the LHC

They are *very* rare: only a few dozen observed so far

We now have much larger detectors
– *e.g.*, Pierre Auger Observatory, in Argentina



We now have much larger detectors
– *e.g.*, Pierre Auger Observatory, in Argentina

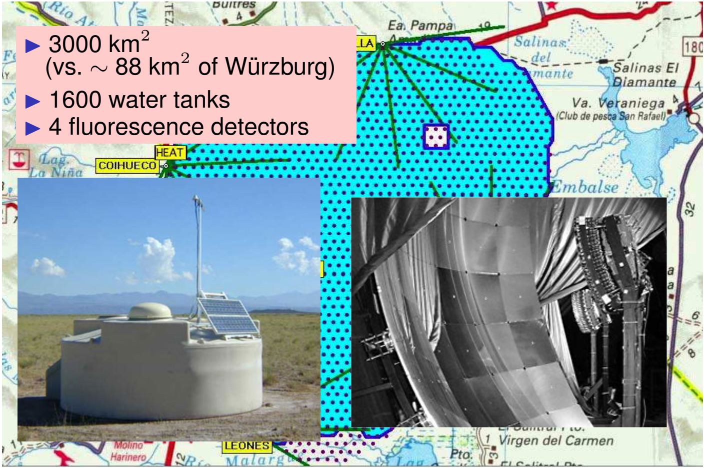


- ▶ 3000 km^2
  (vs. $\sim$ 88 km^2 of Würzburg)
- ▶ 1600 water tanks
- ▶ 4 fluorescence detectors

Introduction – UHECRs

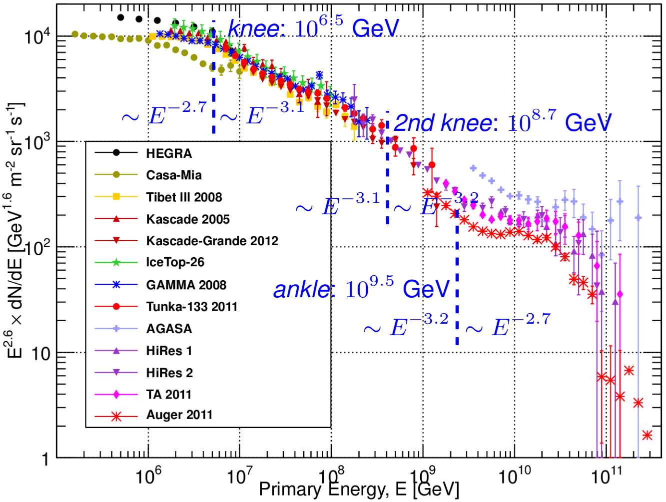
We now have much larger detectors
– *e.g.*, Pierre Auger Observatory, in Argentina

- 3000 km^2
  (vs. $\sim$ 88 km^2 of Würzburg)
- 1600 water tanks
- 4 fluorescence detectors



Introduction – UHECRs

After 102 years of the discovery of CRs, this is what we know –



THE ASTROPHYSICAL JOURNAL, **182**: L85–L88, 1973 June 1

OBSERVATIONS OF GAMMA-RAY BURSTS OF COSMIC ORIGIN

RAY W. KLEBESADEL, IAN B. STRONG, AND ROY A. OLSON

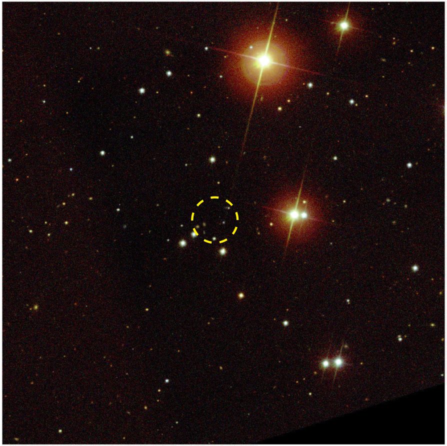
University of California, Los Alamos Scientific Laboratory, Los Alamos, New Mexico
Received 1973 March 16; revised 1973 April 2

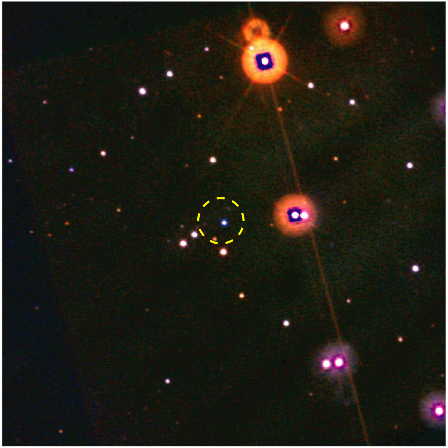
ABSTRACT

Sixteen short bursts of photons in the energy range 0.2–1.5 MeV have been observed between 1969 July and 1972 July using widely separated spacecraft. Burst durations ranged from less than 0.1 s to ~30 s, and time-integrated flux densities from $\sim 10^{-5}$ ergs cm^{-2} to $\sim 2 \times 10^{-4}$ ergs cm^{-2} in the energy range given. Significant time structure within bursts was observed. Directional information eliminates the Earth and Sun as sources.

Subject headings: gamma rays — X-rays — variable stars

What does a GRB look like? *e.g.*, GRB060218 seen by *Swift*

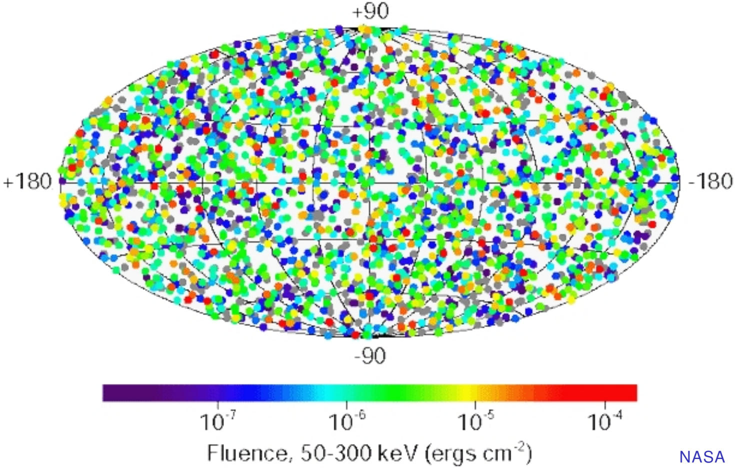




SDSS, Swift Collab., Sloan Foundation, NSF, NASA

Introduction – GRBs

Dedicated missions were flown – *e.g.*, BATSE detected 2704 GRBs between 1991 and 2000



NASA

What makes GRBs good candidates?

If the sources of UHECRs are extragalactic, they must satisfy:

1. Sources should produce protons with a local ($z = 0$) energy injection input of $\approx 10^{44}$ erg Mpc^{-3} yr^{-1}
2. Density of sources should be $n_s > 10^{-4}$ Mpc^{-3}
3. Power output of individual sources should satisfy $L \gtrsim 10^{45.5}\,\Gamma^2$ erg s^{-1}
4. Plasma flows should be relativistic: $\Gamma \gtrsim 100\,(\delta t/10$ ms$)^{-1/4}$

This leaves as candidates:

- (some) AGN flares
- GRBs, with typical $L \sim 10^{52}$ erg s^{-1}, $\Gamma \gtrsim 300$

E. Waxman in *Astronomy at the Frontiers of Science*, Springer (2011)

Still not convinced?

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

better, bigger detectors + loads of data + bright future

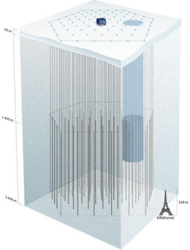
UHECRs

- Auger: 69 events > 57 EeV
- Telescope Array: 72 events
- surface + fluorescence
- from space: JEM-EUSO (?)
  – $\times$ 10 event rate

GRBs

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

neutrinos



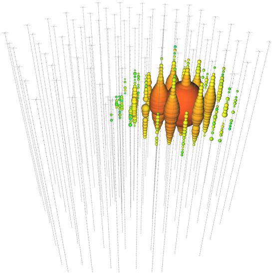
- IceCube: 1 km^3 Antarctic ice
- detection: νN interactions
- sensitive to predicted UHE astrophysical flux
- see sources after 10-15 yr?

Still not convinced?

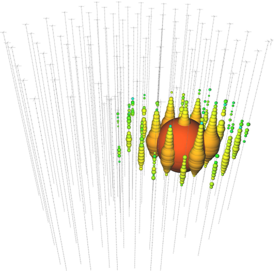
The era of neutrino astronomy has begun!

– IceCube (2010-2013) detected 37 events with 30 TeV – 2 PeV

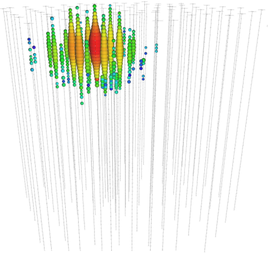
“Bert”, 1.04 PeV



“Ernie”, 1.14 PeV



“Big Bird”, 2 PeV

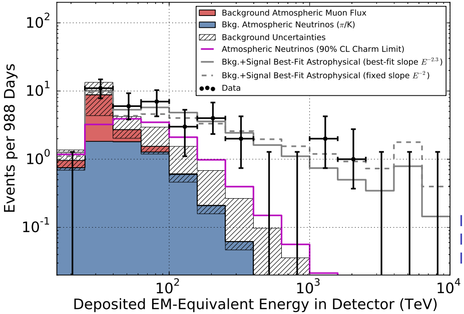


. . . and 34 more events < 385 TeV

Still not convinced?

The era of neutrino astronomy has begun!

– IceCube (2010-2013) detected 37 events with 30 TeV – 2 PeV



ICECUBE, *PRL* **111**, 021103 (2013)
ICECUBE, *Science* **342**, 1242856 (2013)
ICECUBE, *PRL* **113**, 101101 (2014)

Flux compatible with extragalactic origin (Waxman & Bahcall 1997):

$$E^2\Phi_\nu = (0.95 \pm 0.3) \times 10^{-8} \text{ GeV cm}^{-2} \text{ s}^{-1} \text{ sr}^{-1} \text{ (per flavour)}$$

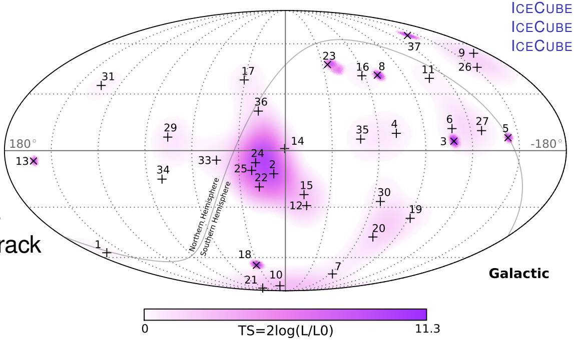
Still not convinced?

The era of neutrino astronomy has begun!

– IceCube (2010-2013) detected 37 events with 30 TeV – 2 PeV

Arrival directions compatible with an isotropic distribution –

ICECUBE, *PRL* **111**, 021103 (2013)
ICECUBE, *Science* **342**, 1242856 (2013)
ICECUBE, *PRL* **113**, 101101 (2014)

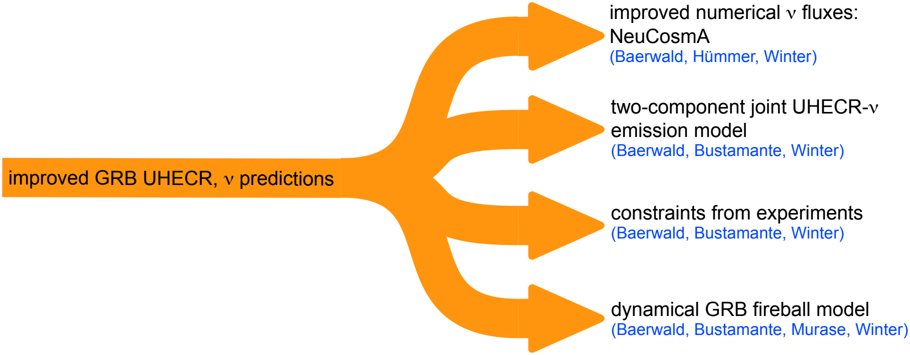


+: shower
×: muon track

– no association with sources found yet

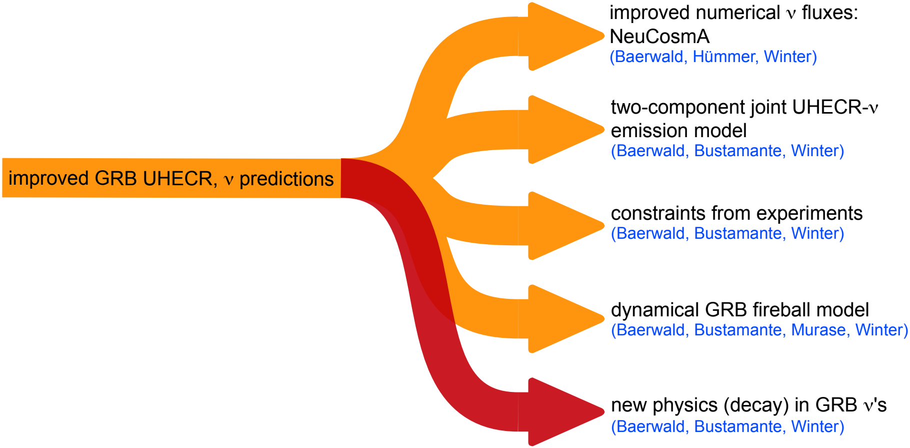
Our plan of attack

A four-pronged plan of attack –



Our plan of attack

A five-pronged plan of attack –



GRBs as sources of UHE CRs and ν's

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

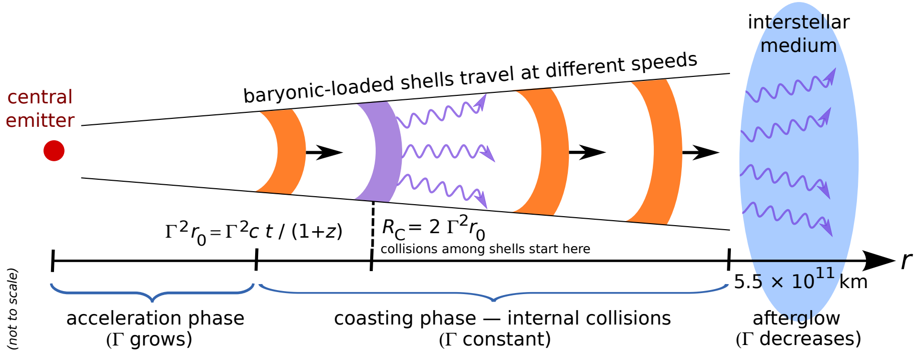
Problem: experiments (IceCube, ANTARES) are starting to strongly constrain the simplest joint emission models

Solution: we need to build more realistic models!

The GRB fireball model

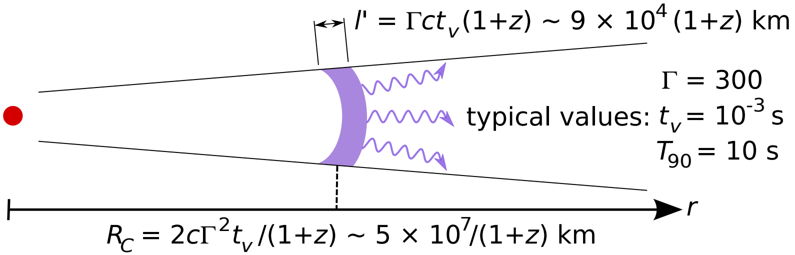
Fireball model: our current paradigm of how a GRB works

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



The GRB fireball model – a *static* burst

The static fireball picture: all collisions 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

A common origin for UHE particles

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

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

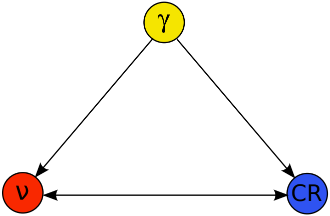
$$p\,\gamma \rightarrow \Delta^+(1232) \rightarrow \begin{cases} n\pi^+ \,, & \text{BR} = 1/3 \\ p\pi^0 \,, & \text{BR} = 2/3 \end{cases}$$

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

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

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

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



After propagation, with flavour mixing:

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

("one ν_μ per cosmic ray")

CR emission by n escape only is now strongly disfavoured

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

Particle emission from a collision

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

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

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

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

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

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

Particle emission from a collision

Normalise the densities at the source – for one collision:

- Photons:

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

- Protons:

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

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

Particle emission from a collision

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

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

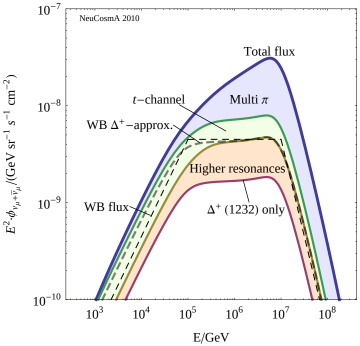
$$Q'\left(E'\right) = \int_{E'}^{\infty} \frac{dE'_p}{E'_p} N'_p\left(E'_p\right) \int_0^{\infty} c\, dE'_\gamma\, N'_\gamma\left(E'_\gamma\right) R\left(x, y\right)$$

response function

R contains cross sections, multiplicities for different channels

What does NeuCosmA include?

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

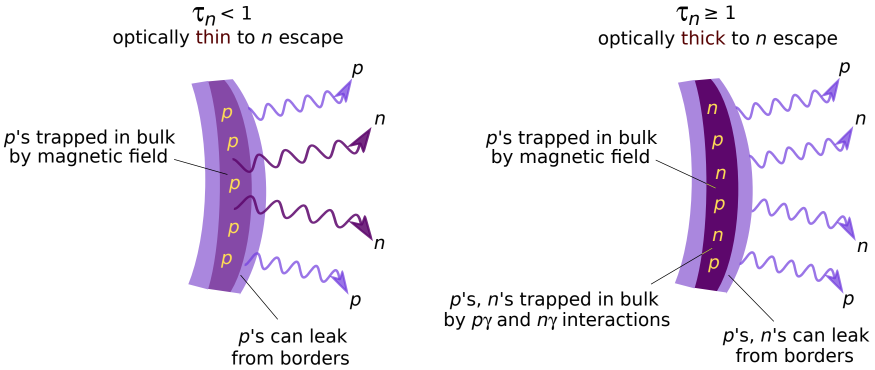


A two-component model of CR emission

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

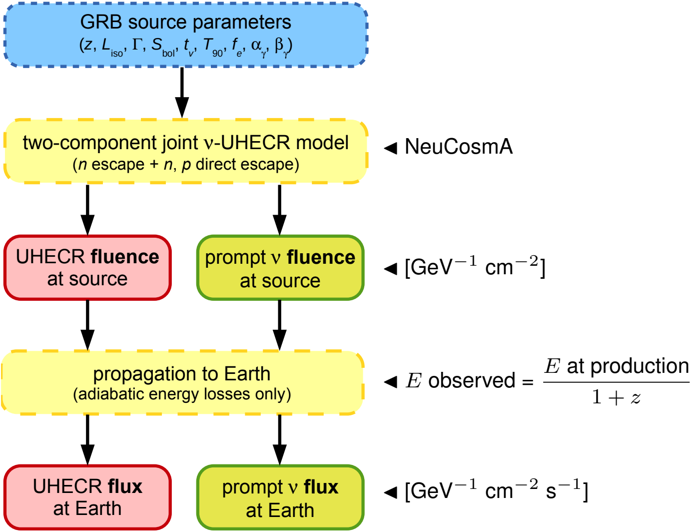
Relative contributions determined by $\tau_n \equiv \left(t_{p\gamma}^{-1} / t_{\text{dyn}}^{-1}\right)\Big|_{E'_{p,\max}}$



Julius-Maximilians-
UNIVERSITÄT
WÜRZBURG

A two-component model of CR emission

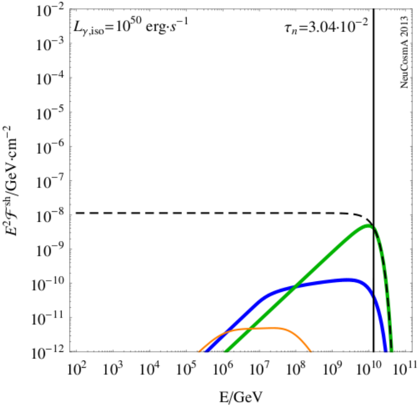
Calculation of UHECR and neutrino fluxes from one GRB –



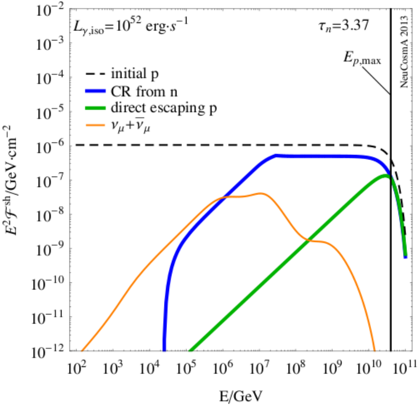
A two-component model of CR emission

Sample neutrino fluences –

Optically **thin** source



Optically **thick** source

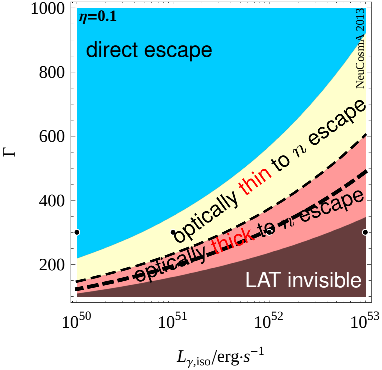


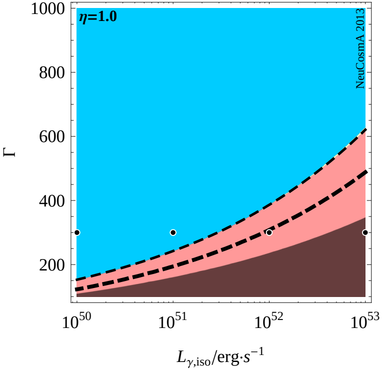
P. BAERWALD, MB, AND W. WINTER, *ApJ* **768**, 186 (2013)

A two-component model of CR emission

Scan of the GRB emission parameter space –

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





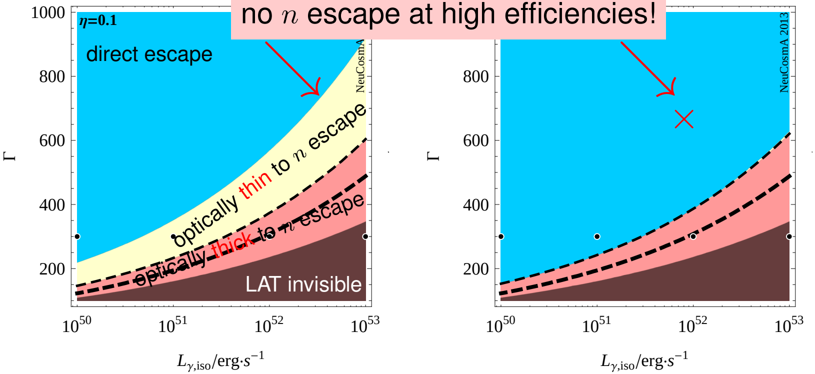
P. Baerwald, MB, and W. Winter, *ApJ* **768**, 186 (2013)

A two-component model of CR emission

Scan of the GRB emission parameter space –

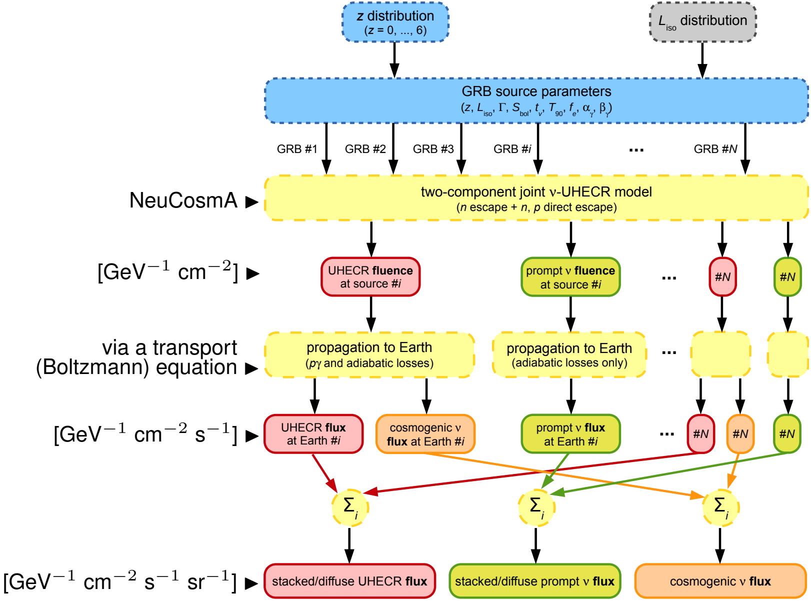
acceleration efficiency ⟶ $\eta = 0.1$ $\eta = 1.0$

no n escape at high efficiencies!



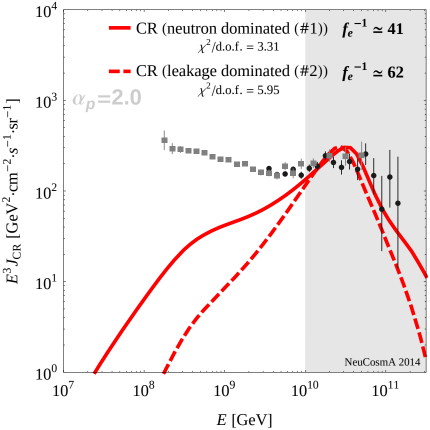
P. BAERWALD, MB, AND W. WINTER, *ApJ* **768**, 186 (2013)

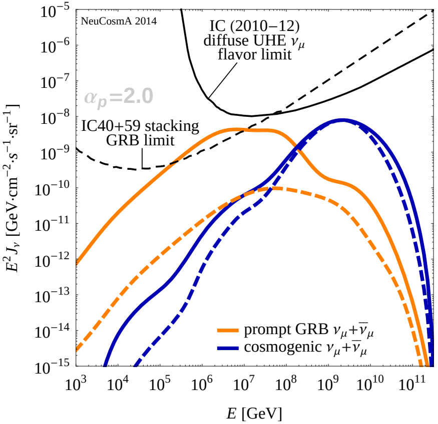
Fluxes from a population of GRBs



Fluxes from a population of GRBs

Diffuse UHECR and neutrino predictions –





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

Constraining the model with data

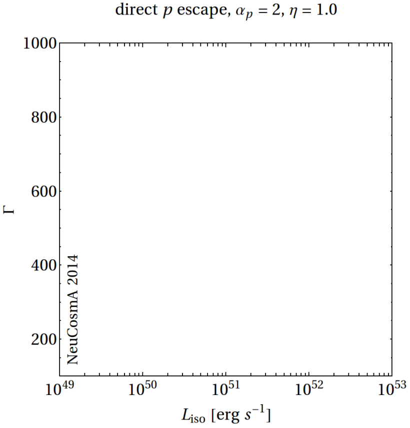
We can already limit the parameter space by using the UHECR observations and ν upper bounds:

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

Constraining the model with data

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

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

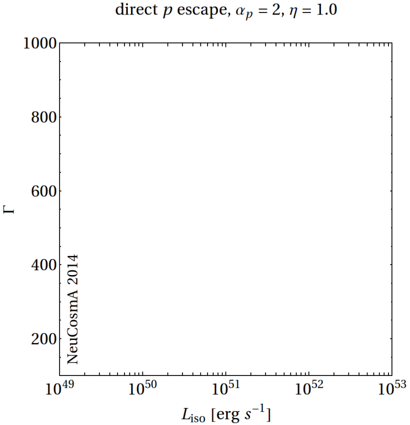


P. BAERWALD, MB, AND W. WINTER, *Astropart. Phys.* **62**, 66 (2015)

Constraining the model with data

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

1. Generate the UHECR spectrum at every point in parameter space (*e.g.*, in Γ vs. $L_{\rm iso}$)
2. Fit each spectrum to HiRes data (or TA, PAO)

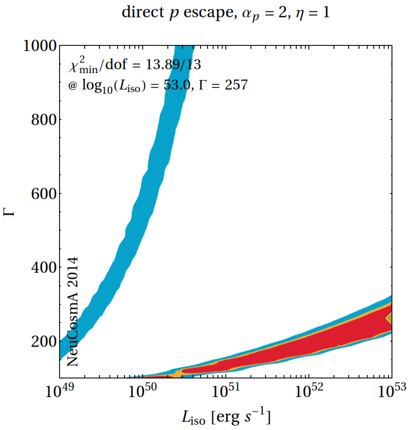


P. Baerwald, MB, and W. Winter, *Astropart. Phys.* **62**, 66 (2015)

Constraining the model with data

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

1. Generate the UHECR spectrum at every point in parameter space (*e.g.*, in Γ vs. $L_{\rm iso}$)
2. Fit each spectrum to HiRes data (or TA, PAO)
3. Find the best-fit point (diamond), and the 90% (red), 95% (yellow), and 99% (blue) C.L. regions

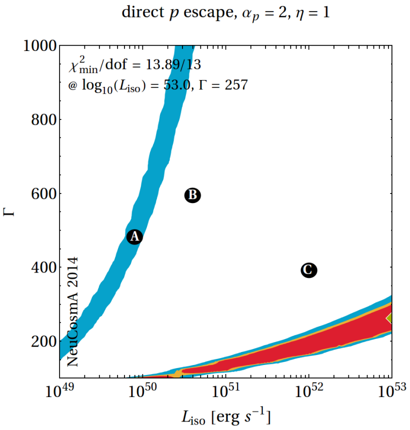


P. Baerwald, MB, and W. Winter, *Astropart. Phys.* **62**, 66 (2015)

Constraining the model with data

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

1. Generate the UHECR spectrum at every point in parameter space (*e.g.*, in Γ vs. $L_{\rm iso}$)
2. Fit each spectrum to HiRes data (or TA, PAO)
3. Find the best-fit point (diamond), and the 90% (red), 95% (yellow), and 99% (blue) C.L. regions

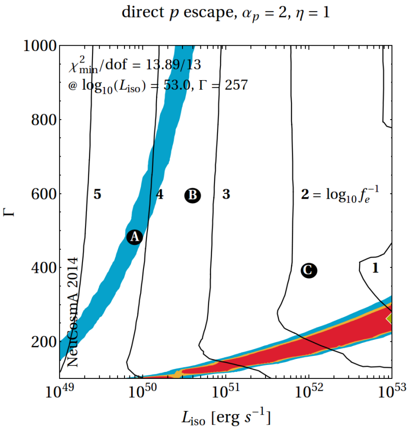


P. Baerwald, MB, and W. Winter, *Astropart. Phys.* **62**, 66 (2015)

Constraining the model with data

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

1. Generate the UHECR spectrum at every point in parameter space (*e.g.*, in Γ vs. $L_{\rm iso}$)
2. Fit each spectrum to HiRes data (or TA, PAO)
3. Find the best-fit point (diamond), and the 90% (red), 95% (yellow), and 99% (blue) C.L. regions
4. Find the baryonic loading (*i.e.*, relative energy of p's to e's) at each point

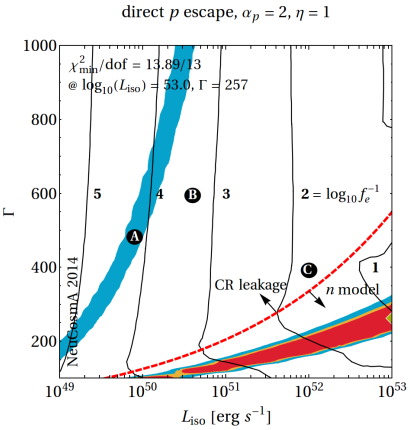


P. Baerwald, MB, and W. Winter, *Astropart. Phys.* **62**, 66 (2015)

Constraining the model with data

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

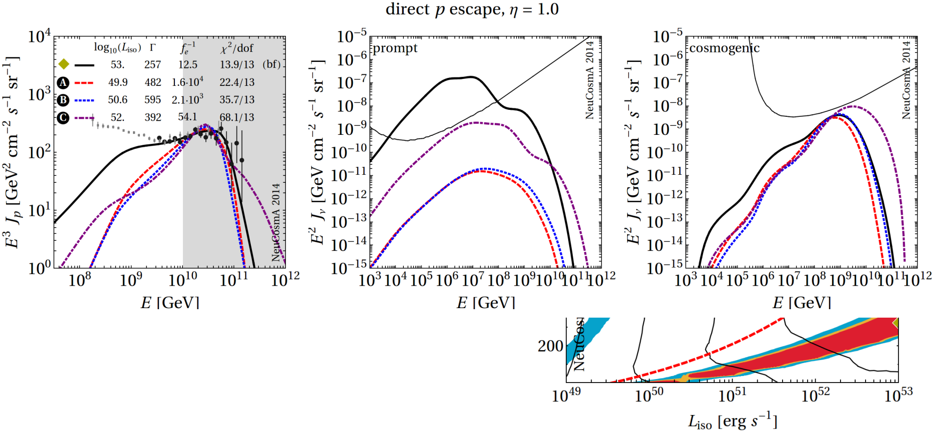
1. Generate the UHECR spectrum at every point in parameter space (*e.g.*, in Γ vs. $L_{\rm iso}$)
2. Fit each spectrum to HiRes data (or TA, PAO)
3. Find the best-fit point (diamond), and the 90% (red), 95% (yellow), and 99% (blue) C.L. regions
4. Find the baryonic loading (*i.e.*, relative energy of p's to e's) at each point
5. Identify the region corresponding to pure n escape and to n escape + CR leakage



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

Constraining the model with data

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

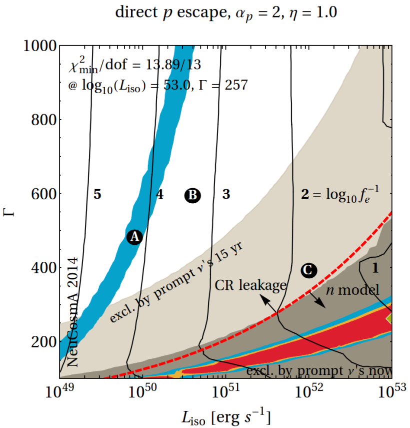


P. Baerwald, MB, and W. Winter, *Astropart. Phys.* **62**, 66 (2015)

Constraining the model with data

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

1. Generate the UHECR spectrum at every point in parameter space (*e.g.*, in Γ vs. $L_{\rm iso}$)
2. Fit each spectrum to HiRes data (or TA, PAO)
3. Find the best-fit point (diamond), and the 90% (red), 95% (yellow), and 99% (blue) C.L. regions
4. Find the baryonic loading (*i.e.*, relative energy of p's to e's) at each point
5. Identify the region corresponding to pure n escape and to n escape + CR leakage
6. Find the region where the number of prompt ν_μ's is > 2.44, *i.e.*, the excluded region at 90% C.L.

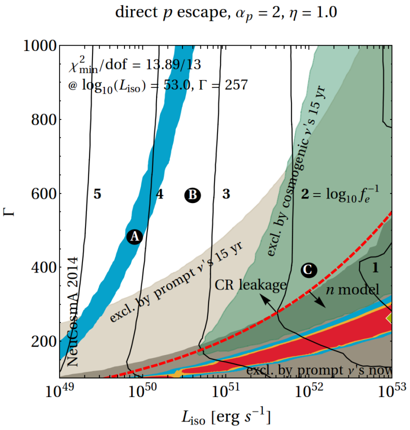


P. Baerwald, MB, and W. Winter, *Astropart. Phys.* **62**, 66 (2015)

Constraining the model with data

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

1. Generate the UHECR spectrum at every point in parameter space (*e.g.*, in Γ vs. L_{iso})
2. Fit each spectrum to HiRes data (or TA, PAO)
3. Find the best-fit point (diamond), and the 90% (red), 95% (yellow), and 99% (blue) C.L. regions
4. Find the baryonic loading (*i.e.*, relative energy of p's to e's) at each point
5. Identify the region corresponding to pure n escape and to n escape + CR leakage
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, and W. Winter, *Astropart. Phys.* **62**, 66 (2015)

An evolving, dynamical burst

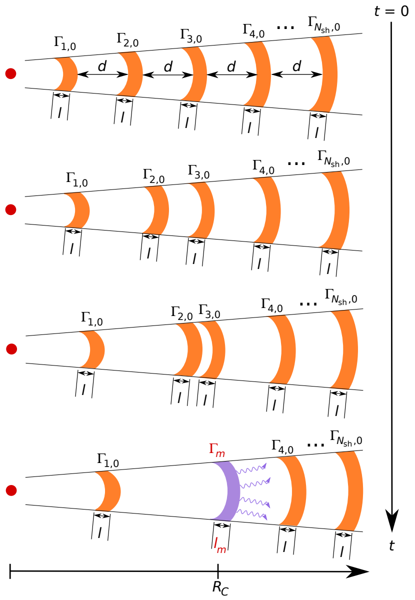
We have considered a dynamical fireball instead:

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

Why is this important?

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

Evolving the fireball



During propagation:

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

Evolution stops when either:

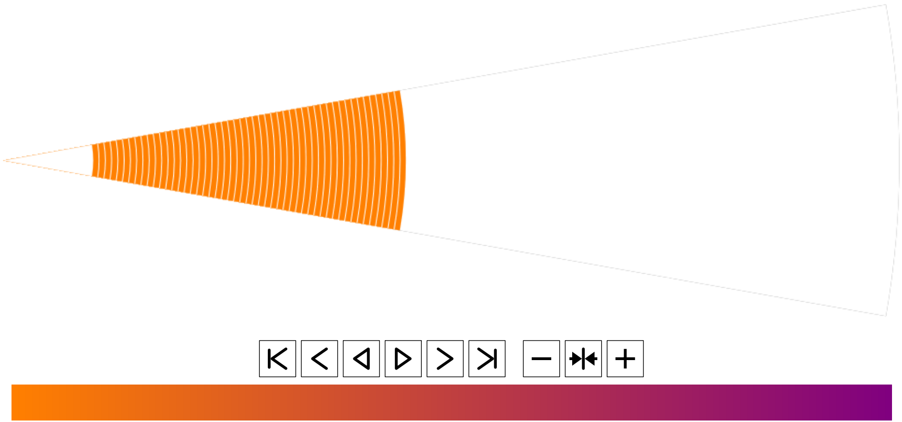
- a single shell is left; or
- all remaining shells have reached the circumburst medium ($\geq 5.5 \times 10^{11}$ km)

final number of collisions
$\approx$
number of initial shells ($\gtrsim$ 1000)

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

Evolving the fireball

Let's look at a sample animated fireball –

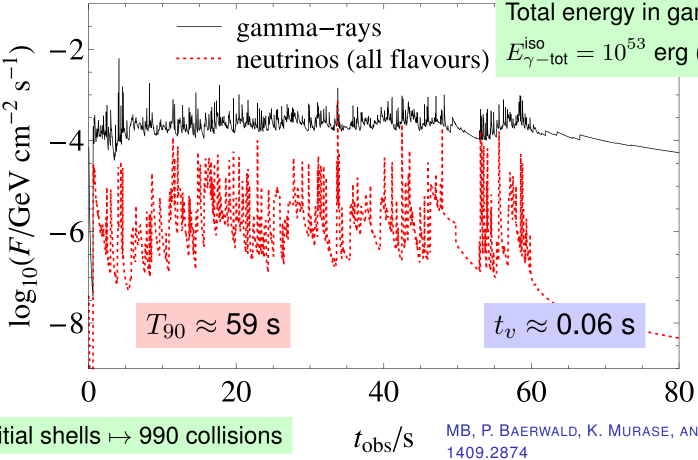


▲ shell has not collided

shell has collided many times ▲

Synthetic light curves

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



Total energy in gamma-rays:
$E^{\mathrm{iso}}_{\gamma-\mathrm{tot}} = 10^{53}$ erg (at source)

$T_{90} \approx 59$ s

$t_v \approx 0.06$ s

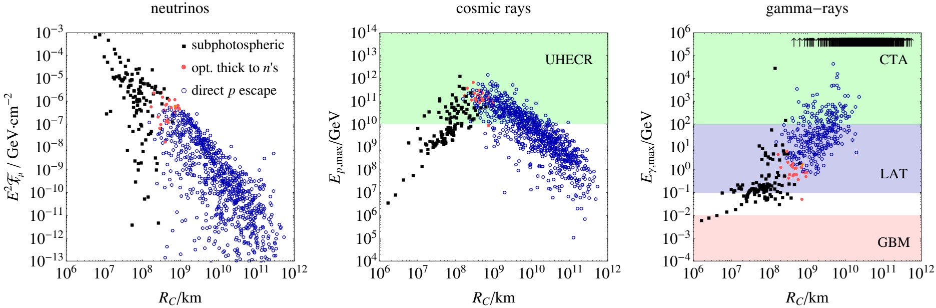
1000 initial shells $\mapsto$ 990 collisions

MB, P. Baerwald, K. Murase, and W. Winter, 1409.2874

Particle emission from a dynamical fireball

Each collision occurs in a different emission regime –

$\nu_\mu + \bar{\nu}_\mu$ fluence | maximum p energy | maximum γ energy

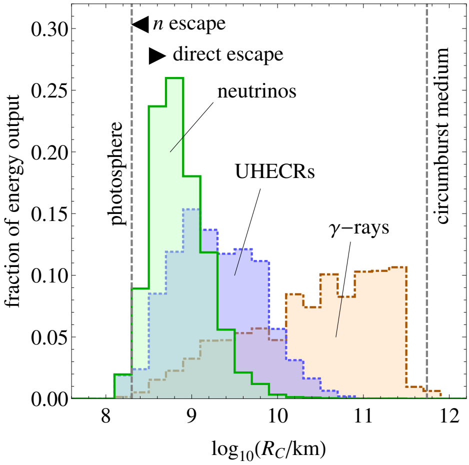


(observer's frame) (source frame)

MB, P. Baerwald, K. Murase, and W. Winter, 1409.2874

Particle emission from a dynamical fireball

Emission of different species peaks at different collision radii –



MB, P. Baerwald, K. Murase, and W. Winter, 1409.2874

Why?

As the fireball expands, photon and proton densities fall

Why does it matter?

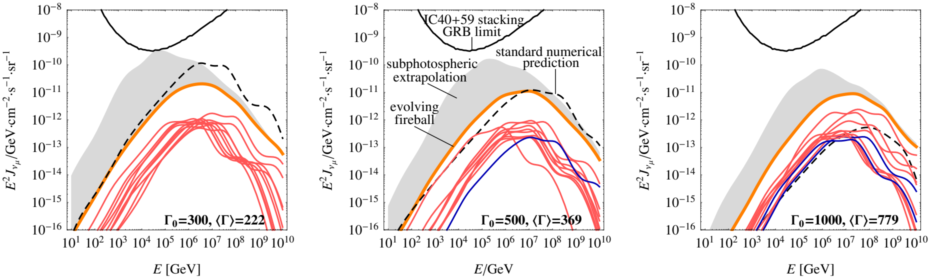
GRB parameters derived from gamma-ray observations might not be adequate to describe ν and UHECR emission

So what?

So the following happens . . .

Particle emission from a dynamical fireball

Quasi-diffuse neutrino flux, assuming 667 GRBs per year –



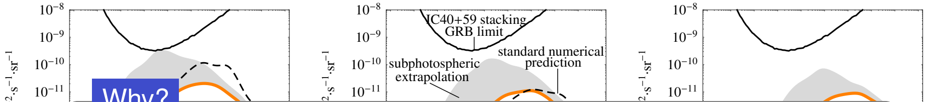
MB, P. Baerwald, K. Murase, and W. Winter, 1409.2874

we find a minimal ν flux of $\sim 10^{-11}$ GeV cm^{-2} s^{-1} sr^{-1}, independently of Γ and baryonic loading

in contrast with traditional predictions, with a Γ^{-4} dependence

Particle emission from a dynamical fireball

Quasi-diffuse neutrino flux, assuming 667 GRBs per year –



Why?

- ν emission comes mostly from $\sim$ 10 photospheric collisions, regardless of model parameters . . .
- time-integrated neutrino fluence:

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

independently of Γ and baryonic loading

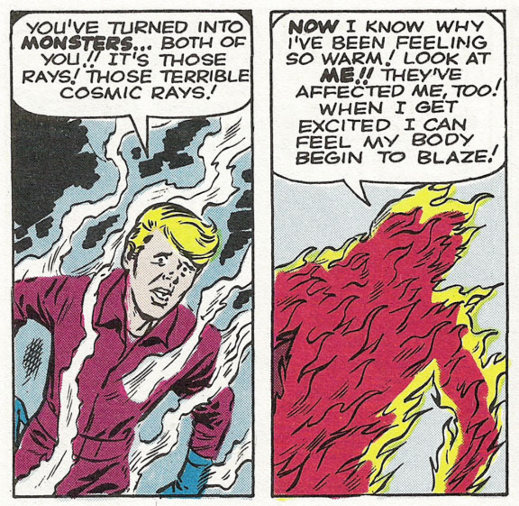
in contrast with traditional predictions, with a Γ^{-4} dependence

Summary and conclusions

We have revised the UHECR and ν predictions from GRBs:

1. Refined the ν yields from $p\gamma$ interactions
2. Introduced a two-component UHECR-ν production model
   – direct p escape required at high acceleration efficiency
3. Constrained the model by using UHECR and neutrino data
   – n escape domination disfavoured by current ν bounds
   – baryonic loading can be inferred from the fits
4. Explored a dynamical fireball model
   – different particle species come from different collision radii
   – found a minimal neutrino flux from GRBs

The coming years should provide much more data on the UHE messengers to put the theories to further test



S. Lee and J. Kirby, *Fantastic Four* **1** (1961)

Backup slides

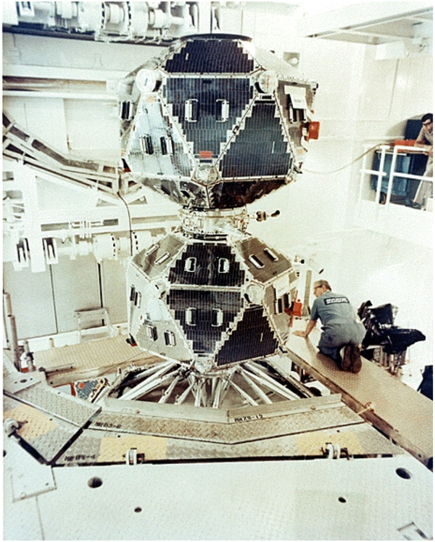
Outlook

Several ongoing projects, in different stages of progress:

- **Fireball evolution:** different GRB parameter sets, include nuclei
  P. Baerwald (Penn State), MB, K. Murase (IAS Princeton), W. Winter (DESY)
- **Seesaw and heavy neutrino decay detection in IceCube**
  MB, C. de los Heros (Uppsala Univ.), J. Jones (PUCP Lima), P. Ferrario (IFIC Valencia)
- **Lorentz invariance violation in cosmogenic neutrinos**
  MB, P. Mehta (Univ. Delhi), W. Winter (DESY)
- **Decay of UHE astrophysical neutrinos:** use the latest IceCube data to constrain the ν lifetime (based on *JCAP* **1210**, 020 (2012), P. Baerwald, MB, W. Winter)
  MB, K. Murase (IAS Princeton)
- **Prospects for correlations between UHECRs and neutrinos:** both in position and energy
  C. Argüelles (WIPAC Wisconsin), MB, J. Carpio (PUCP Lima), A. Gago (PUCP Lima), J. Salvadó (WIPAC Wisconsin)

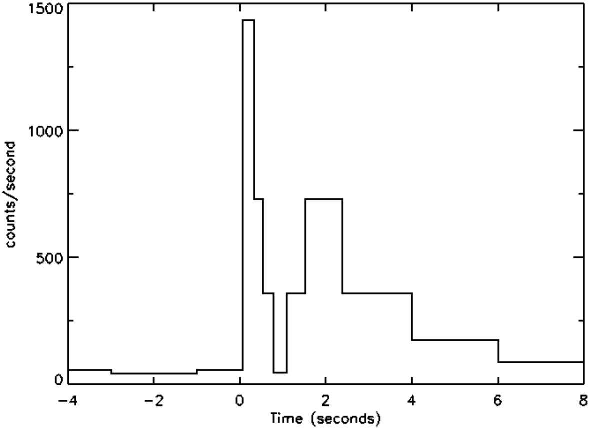
After the 1963 Nuclear Test Ban Treaty, the U.S. launched six pairs of *Vela* satellites:

- 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 $\lesssim 10^{-6}$ s . . .
- . . . however, longer-lasting emissions were detected



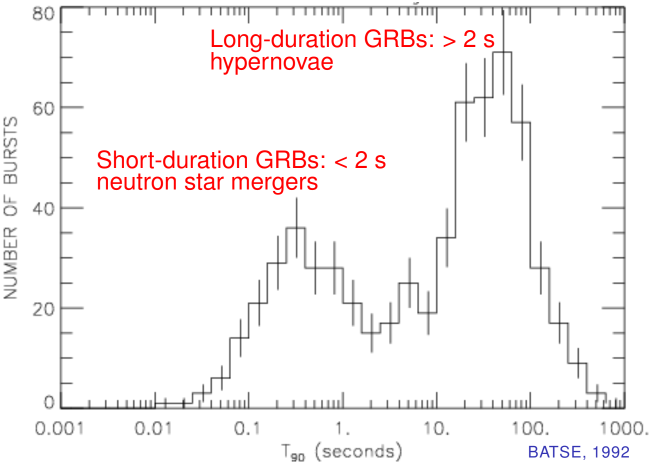
VELA 5A/B SATELLITES (NASA)

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



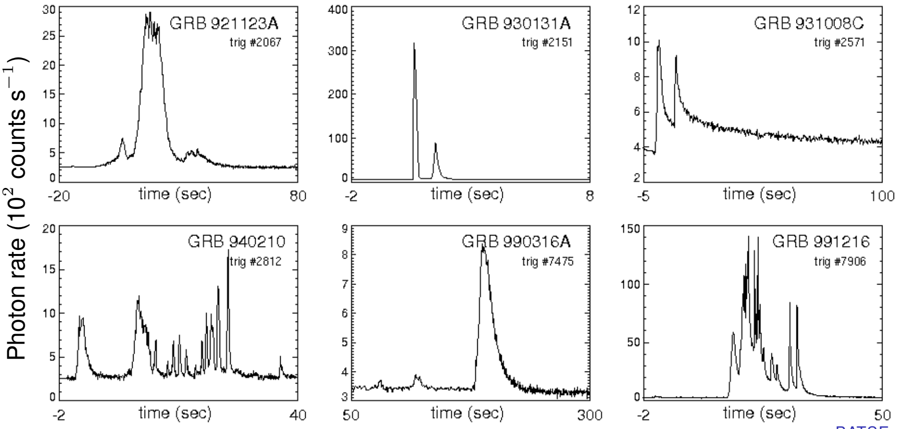
Detected by *Vela* 3, 4a, 4b (found on archival data)

Two populations of GRBs:



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

GRB light curves come in different shapes:



BATSE

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

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 disfavoured to be the sole source of UHECRs (AHLERS *et al.*).

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

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 disfavoured to be the sole source of UHECRs (AHLERS *et al.*).

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, AND F. HALZEN *Astropart. Phys.* **35**, 87 (2011)

The GZK cut-off

GZK $\equiv$ Greisen-Zatsepin-Kuzmin (1966)

The process $p + \gamma_{\text{CMB}} \to \Delta^{+}(1232) \to \pi^{+} + n$ has a threshold

$$E_{\text{GZK}}^{\text{th}} = \frac{m_\pi (m_p + m_\pi/2)}{\epsilon_{\text{CMB}}} \approx 6.8 \cdot 10^{10} \left(\frac{\epsilon_{\text{CMB}}}{10^{-3}\ \text{eV}} \right) \text{ GeV}$$

Survival probability of a 10^{11} GeV propagating for a distance d:

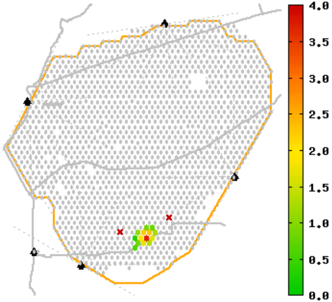
$$p(d) \approx \exp\left(\frac{-d}{6.6\ \text{Mpc}} \right) \Rightarrow p(d) < 10^{-4} \text{ for } d = 50 \text{ Mpc}$$

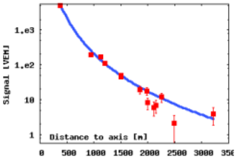
Two conclusions

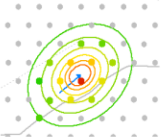
1. The maximum CR energy is $\sim 10^{11}$ GeV
2. UHECRs are created relatively close to us ($\lesssim 50$ Mpc)

UHECRs – composition

This is what a UHE event looks like in Auger:







Ide	10485600
Date	Tue Oct 26 17:39:16 2010
No. of stations	14
Energy	49.7 $\pm$ 1.9 EeV
Theta	40.2 $\pm$ 0.2 deg
Phi	-139.2 $\pm$ 0.2 deg
Curvature	10.9 $\pm$ 0.5 km
Core Easting	476053 $\pm$ 19 m
Core Northing	6079248 $\pm$ 12 m
Reduced Chi^2	8.36

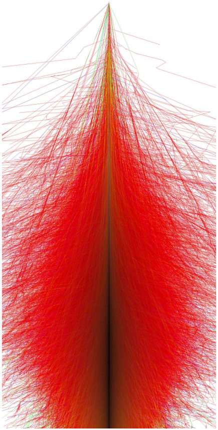
Problem:

So how is the identity of the primary reconstructed from this?

UHECRs – composition

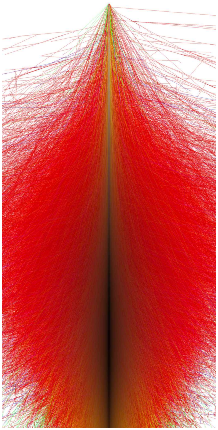
Answer:
use longitudinal air shower development information
from the fluorescence detectors

10^6 GeV proton



vs.

10^6 GeV Fe-56 nucleus



F. Schmid, Univ. Leeds

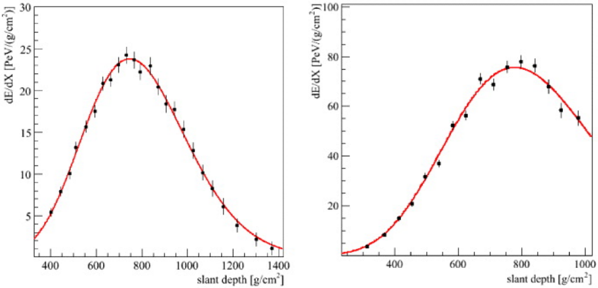
UHECRs – composition

Number of cascading particles evolves as (Gaisser & Hillas):

$$N(x) = N_{\max} \left(\frac{x - x_0}{x_{\max} - x_0} \right)^{(x_{\max} - x_0/\Lambda)} \exp\left(\frac{x_{\max} - x}{\Lambda} \right)$$

x: *slant depth*, *i.e.*, column density traversed (g cm^{-2})
$x_{\max}$: depth of shower maximum
x_0: related to depth of first interaction in the atmosphere

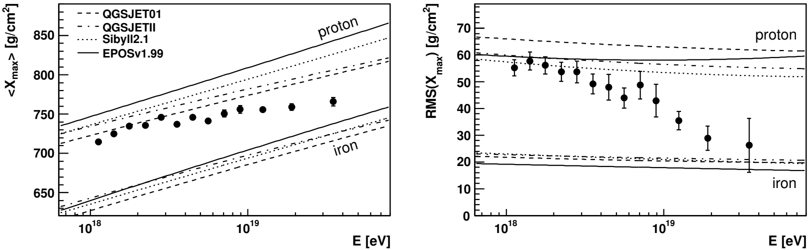
Using the FDs, measure $N(x)$, $x_{\max}$ for each shower:



UHECRs – composition

$\langle x_{\text{max}} \rangle$: average value of x_{max} among all showers

Compare these data to the simulated $\langle x_{\text{max}} \rangle$ assuming a proton or Fe primary:



AUGER

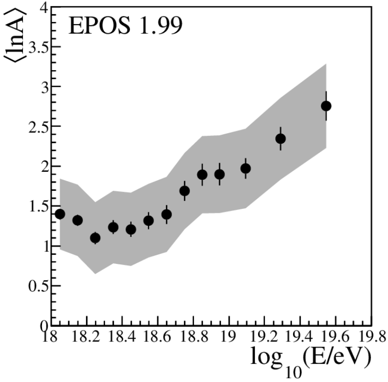
There is a tendency towards heavier composition at very high energies

UHECRs – composition

$\langle x_{\mathrm{max}} \rangle$ is related to the average mass number $\langle \ln A \rangle$ (Heitler-Matthews model):

$$\langle x_{\mathrm{max}} \rangle = \alpha \left(\ln E - \langle \ln A \rangle \right) + \beta$$

α, β: from hadronic interactions (cross section, multiplicity, etc.)



AUGER

The Hillas criterion

Two considerations:

1. Charged particles (Z) are assumed to be accelerated by intense magnetic fields in astrphysical sources
2. For the acceleration to be mantained, the gyroradius should be smaller than the size of the acceleration region

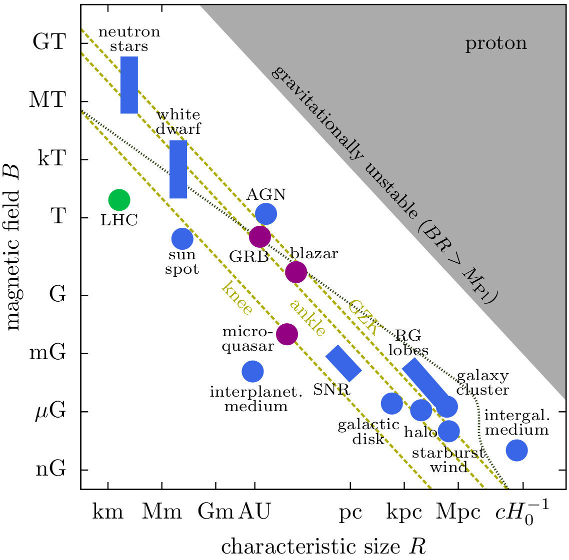
$$\text{Larmor radius: } R_L = \frac{1.1}{Z}\left(\frac{E}{\text{EeV}}\right)\left(\frac{B}{\mu\text{G}}\right)^{-1}$$

Hillas criterion: $R_L < R$

This limits the maximum energy:

$$E_{\text{max}} \simeq Z\left(\frac{B}{\mu\text{G}}\right)\left(\frac{R}{\text{kpc}}\right) \cdot 10^9 \text{ GeV}$$

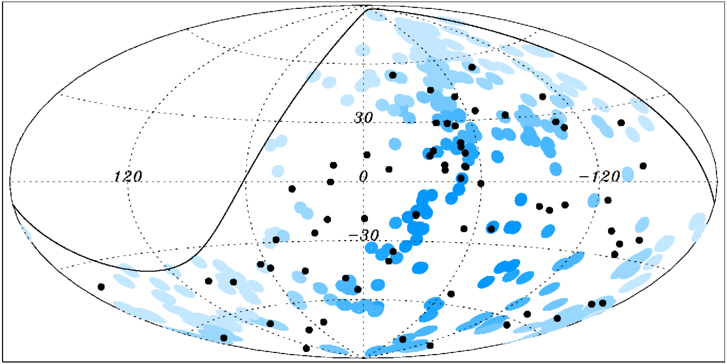
The Hillas criterion



UHECRs – correlation with known sources

- 69 CRs with > 55 EeV observed at Auger
- Compare arrival directions to positions of 318 known AGN within 75 Mpc

Circles of 3.1° centered around each source



PIERRE AUGER COLLABORATION, *Astropart. Phys.* **34**, 314 (2010)

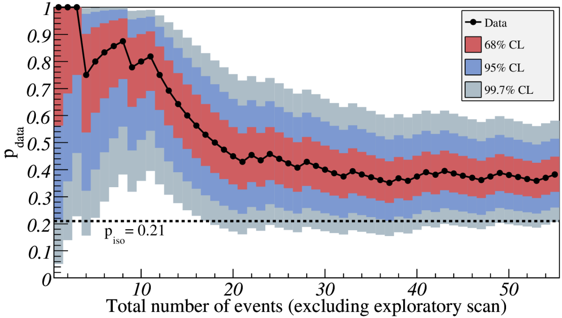
UHECRs – correlation with known sources

Degree of correlation: $p_{\text{data}} = k/N$

k: number of UHECRs correlated to sources

N: total number of UHECRs

PIERRE AUGER COLLABORATION, *Astropart. Phys.* **34**, 314 (2010)



Auger found $p_{\text{data}} = 0.38^{+0.07}_{-0.06}$ – inconclusive when compared to the value for an isotropic distribution of sources, $p_{\text{iso}} = 0.21$

A two-component model of CR emission

Two important points:

1. $E'_{p,\max}$ is determined by energy-loss processes:
$t'_{\text{acc}}\left(E'_{p,\max}\right) = \min\left[t'_{\text{dyn}}, t'_{\text{syn}}\left(E'_{p,\max}\right), t'_{p\gamma}\left(E'_{p,\max}\right)\right]$

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

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

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

A two-component model of CR emission

Optical depth:

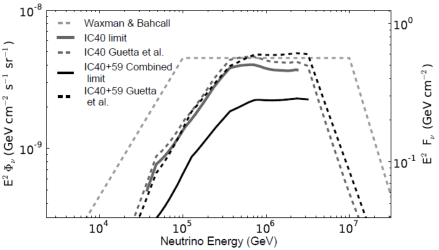
$$\tau_n = \left.\frac{t_{p\gamma}^{-1}}{t_{\text{dyn}}^{-1}}\right|_{E_{p,\max}} = \begin{cases} \lesssim 1\,, & \text{optically } \textbf{thin} \text{ source} \\ > 1\,, & \text{optically } \textbf{thick} \text{ source} \end{cases}$$

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

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

fraction of escaping particles

The neutron model under tension?



IceCube Collaboration:

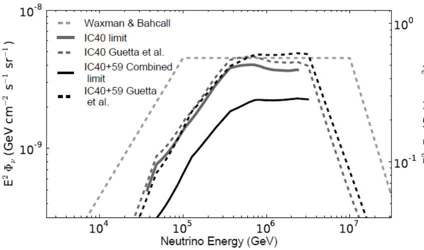
- ν flux normalised to GRB γ fluence:

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

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

IceCube Coll., *Nature* **484**, 351 (2012)
Ahlers et al. *Astropart. Phys.* **35**, 87 (2011)
Guetta et al. *Astropart. Phys.* **20**, 429 (2004)

The neutron model under tension?



More detailed particle physics (NeuCosmA):

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

ν flux $\sim$ one order of magnitude lower

BAERWALD, HÜMMER, WINTER, *PRL* **108**, 231101 (2012)

See also: HE, LIU, WANG, *ApJ* **752**, 29 (2012)

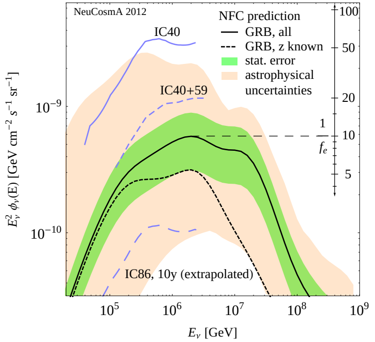
IceCube Collaboration:

- ν flux normalised to GRB γ fluence:

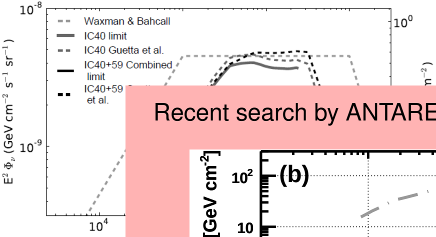
$$\int_0^\infty dE_\nu E_\nu F_\nu(E_\nu) \propto \int_{1\text{ keV}}^{10\text{ MeV}} d\varepsilon_\gamma \varepsilon_\gamma F_\gamma(\varepsilon_\gamma)$$

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

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



The neutron model under tension?



More detailed particle physics (NeuCosmA):

- ► extra multi-π, K, n production modes
- ► synchrotron losses of secondaries

lower

1 (2012)

IceCube Coll

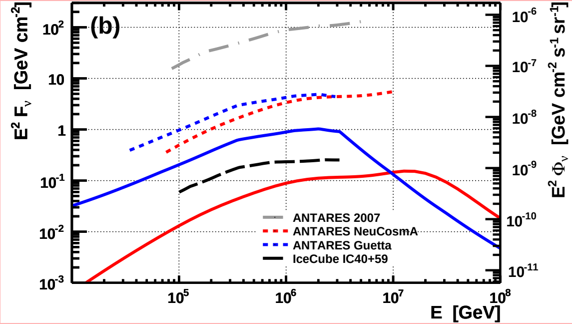
- ► ν flux r

$$\int_0^\infty dE_\nu$$

- ► quasi-d
- ► analyti upper l

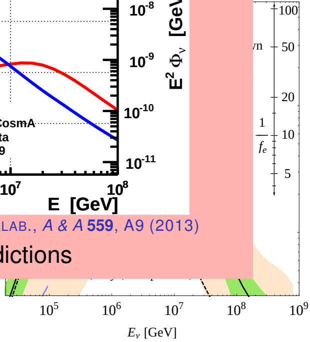
IceCube Coll.,
Ahlers et al. *Astropart. Phys.* **35**, 87 (2011)
Guetta et al. *Astropart. Phys.* **20**, 429 (2004)

Recent search by ANTARES optimised for NeuCosmA:



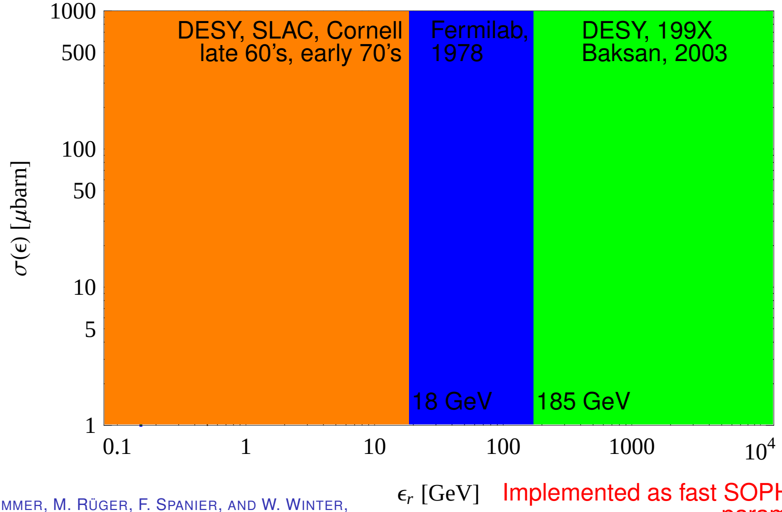
Antares Collab., *A & A* **559**, A9 (2013)

► IceCube is also revising its GRB predictions



Revising the neutron model: NeuCosmA

• Detailed $p\gamma$ cross section

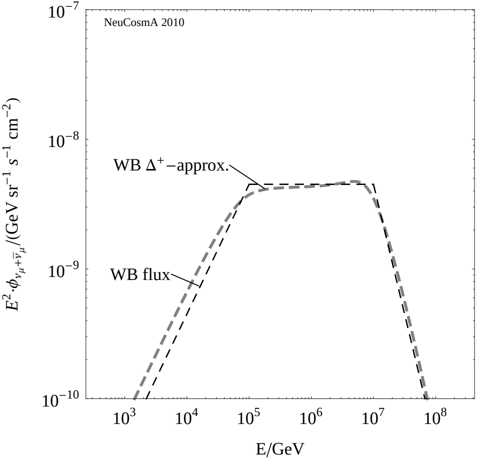


S. Hümmer, M. Rüger, F. Spanier, and W. Winter, *Astrophys. J.* **721**, 630 (2010)

Implemented as fast SOPHIA-based parametrisation

Revising the neutron model: NeuCosmA

- Contributions to the full photohadronic cross section



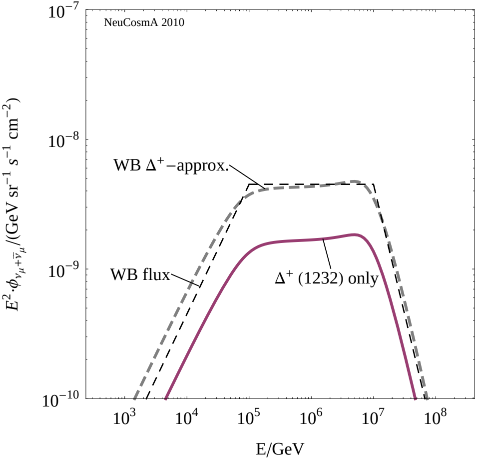
Revising the neutron model: NeuCosmA

• Contributions to the full photohadronic cross section

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

- $\Delta(1232)$-resonance

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



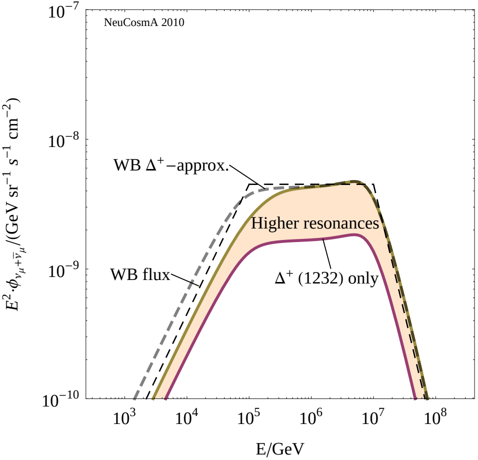
Revising the neutron model: NeuCosmA

• Contributions to the full photohadronic cross section

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

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

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



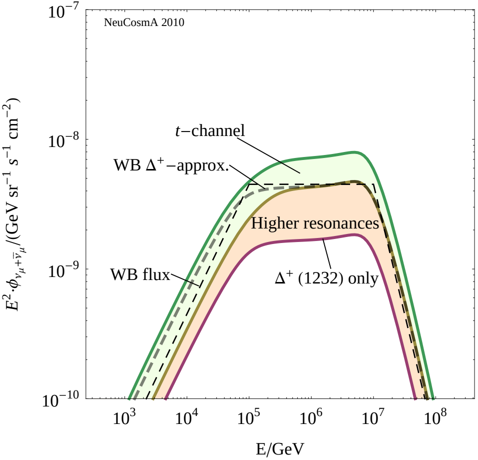
Revising the neutron model: NeuCosmA

• Contributions to 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.* **D83**, 067303 (2011)



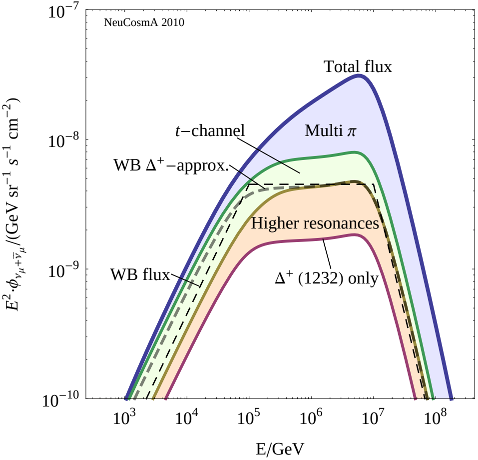
Revising the neutron model: NeuCosmA

• Contributions to the full photohadronic cross section

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

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

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

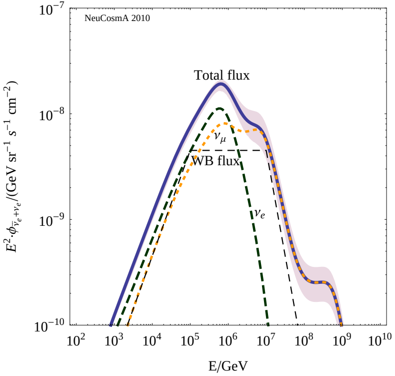


Especially "Multi π" contribution leads to change of flux shape; neutrino flux higher by up to a factor of 3 compared to WB treatment

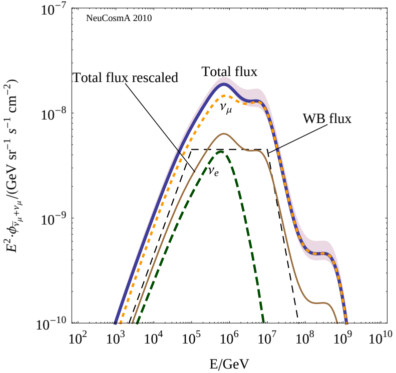
Revising the neutron model: NeuCosmA

• Neutrino spectra including flavour mixing

Electron neutrino spectrum



Muon neutrino spectrum

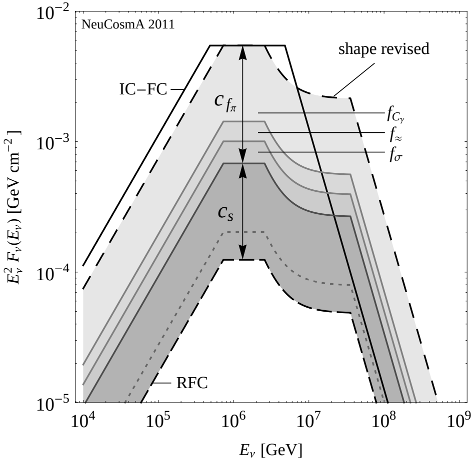


P. Baerwald, S. Hümmer, and W. Winter, *Phys. Rev.* **D83**, 067303 (2011)

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

Revising the neutron model: NeuCosmA

• How the spectrum changes...



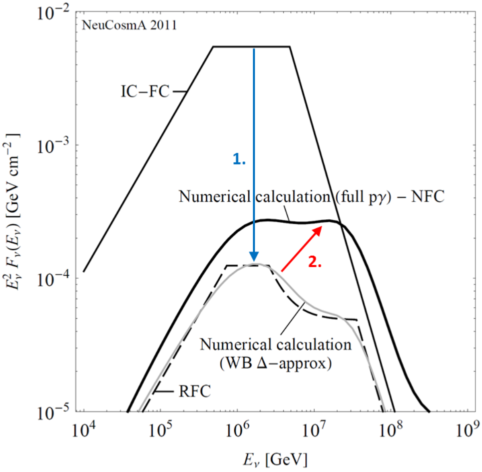
S. HÜMMER, P. BAERWALD, AND W. WINTER, *Phys. Rev. Lett.* **108**, 231101 (2012)

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

Revising the neutron model: NeuCosmA

• How the spectrum changes ... (cont.)



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, and W. Winter, *Phys. Rev. Lett.* **108**, 231101 (2012)

Revising the neutron model: NeuCosmA

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

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

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

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

Revising the neutron model: NeuCosmA

• Further particle decays

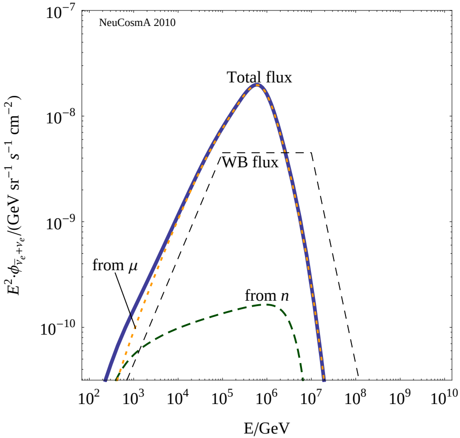
$$\pi^+ \rightarrow \mu^+ + \nu_\mu$$
$$\mu^+ \rightarrow e^+ + \nu_e + \bar{\nu}_\mu$$

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

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

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

Resulting ν_e flux (at the observer)



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

Revising the neutron model: NeuCosmA

• Further particle decays

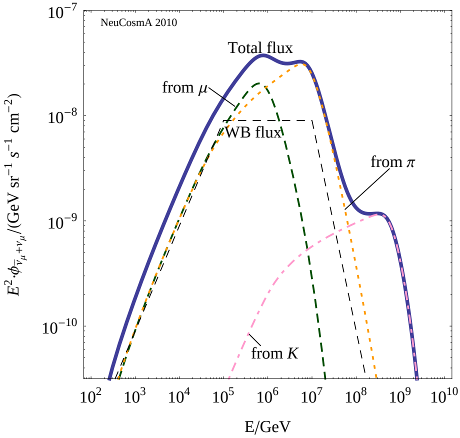
$$\pi^+ \rightarrow \mu^+ + \nu_\mu$$
$$\mu^+ \rightarrow e^+ + \nu_e + \bar{\nu}_\mu$$

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

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

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

Resulting ν_μ flux (at the observer)



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

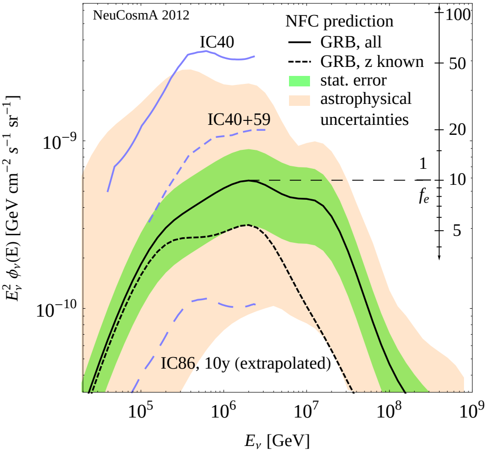
Revising the neutron model: NeuCosmA

• The new prediction of the quasi-diffuse GRB ν flux

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

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

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



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

Revising the neutron model: NeuCosmA

- The new prediction of the quasi-diffuse GRB ν flux

We use a Boltzmann equation to transport protons to Earth:

- Comoving number density of protons (GeV^{-1} 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):

$$\dot{Y}_p = \partial_E(HEY_p) + \partial_E(b_{e^+e^-}Y_p) + \partial_E(b_{p\gamma}Y_p) + \mathcal{L}_{\text{CR}}$$

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

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

Detecting the neutrinos

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

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

Integrated flux above 1 PeV:

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

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

$$N_\nu \simeq 2\pi\cdot\Phi_\nu\,(>1\ \mathrm{PeV})\cdot 1\ \mathrm{yr}\cdot A_{\mathrm{eff}} \approx \left(2.4\times10^{-10}\ \mathrm{cm^{-2}}\right)A_{\mathrm{eff}}\ ,$$

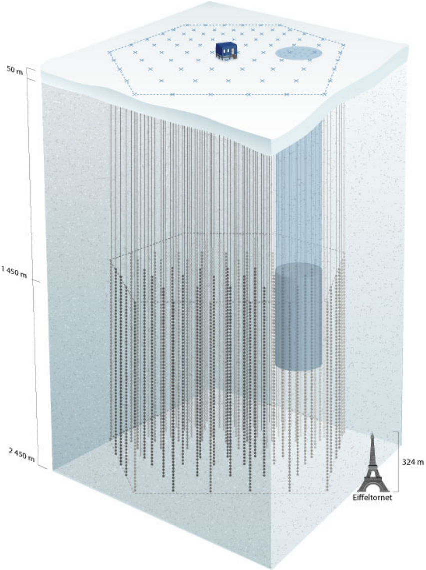
where A_{eff} is the effective area of the detector

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

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

Therefore, we need km-scale detectors, like IceCube

Detecting the neutrinos



IceCube: km^3 in-ice South Pole Čerenkov detector

Neutrinos detected through νN interactions ($N = n, p$)

- Neutral current: all flavours produce hadronic showers
- Charged current: ν_μ's leave muon tracks; $\nu_{e/\tau}$ produce showers

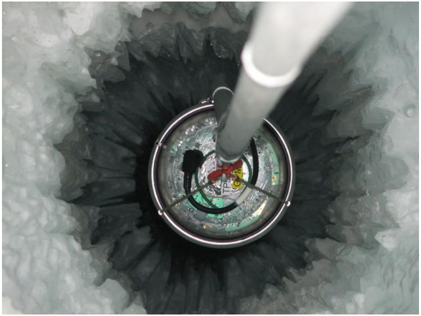
Detecting the neutrinos

IceCube: km^3 in-ice South Pole Čerenkov detector

Neutrinos detected through νN interactions ($N = n, p$)

- Neutral current: all flavours produce hadronic showers
- Charged current: ν_μ's leave muon tracks; $\nu_{e/\tau}$ produce showers

Detecting the neutrinos

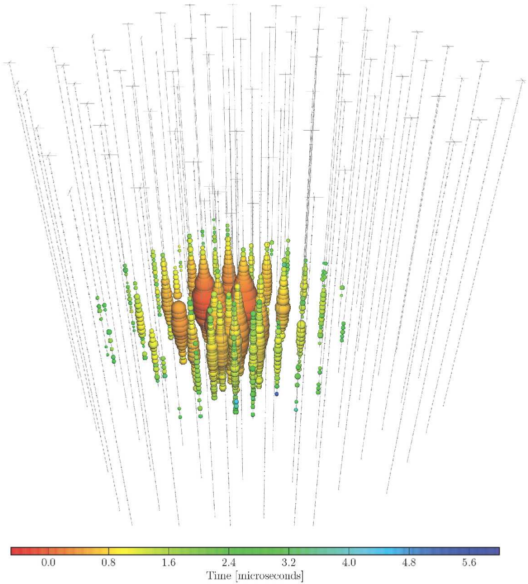


IceCube: km^3 in-ice South Pole Čerenkov detector

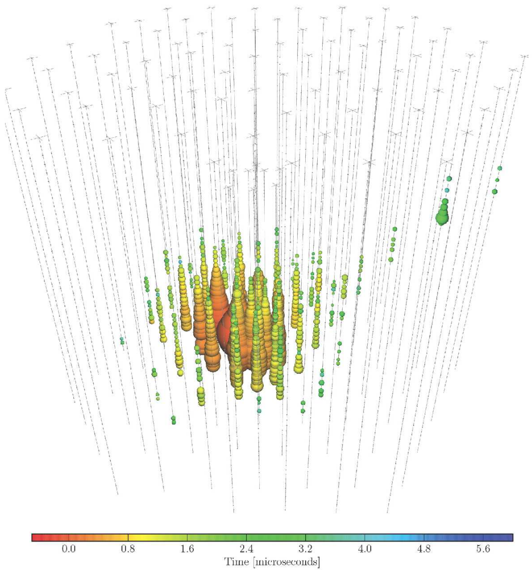
Neutrinos detected through νN interactions ($N = n, p$)

- Neutral current: all flavours produce hadronic showers
- Charged current: ν_μ's leave muon tracks; $\nu_{e/\tau}$ produce showers

Detecting the neutrinos



Detecting the neutrinos



Cosmogenic neutrinos

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

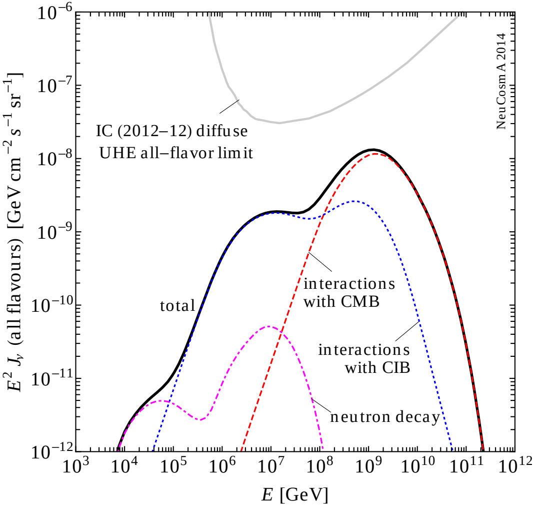
$$p + \gamma \to \Delta^+ \to \pi^+ + n \ ,$$

and neutrinos are created in the decays of the secondaries:

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

These are called *cosmogenic neutrinos*

Cosmogenic neutrinos



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

Interaction with the photon backgrounds

- Energy loss rate (GeV s^{-1}):

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

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

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

  - n_γ: isotropic photon background (GeV^{-1} 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

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

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

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

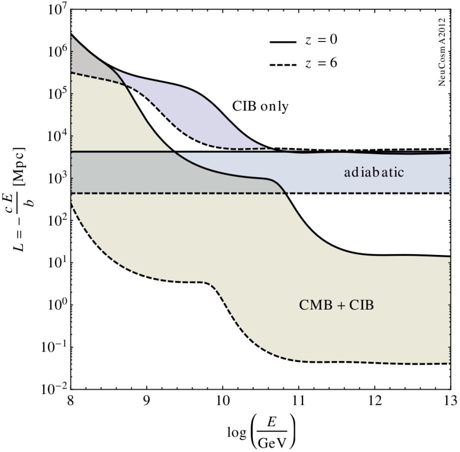
$$t_{p\gamma}^{-1}(E,z) = \sum_i^{\text{all channels}} \Gamma_{p\to p}^i(E,z)\, K^i ,$$

   with $K^i E$ the loss of energy per interaction
2. From this, we calculate back $b_{p\gamma}$ (GeV s^{-1}) ...
3. ...and the corresponding energy-loss term in the transport equation, $\partial_E(b_{p\gamma}Y_p)$.

S. Hümmer, M. Rüger, F. Spanier, W. Winter, *Astrophys. J.* **721**, 630 (2010) [1002.1310]

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 (GeV^{-1} cm^{-3} s^{-1})

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

Normalisation to the observed GRB photon flux F_γ

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

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

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

UHE ν's in the GRB internal shock model

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

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

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

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

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

- Proton density:

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

Maximum proton energy limited by energy losses:

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

UHE ν's in the GRB internal shock model

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

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

Normalisation to the observed GRB photon flux F_γ

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

UHE ν's in the GRB internal shock model

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

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

Normalisation to the observed GRB photon flux F_γ

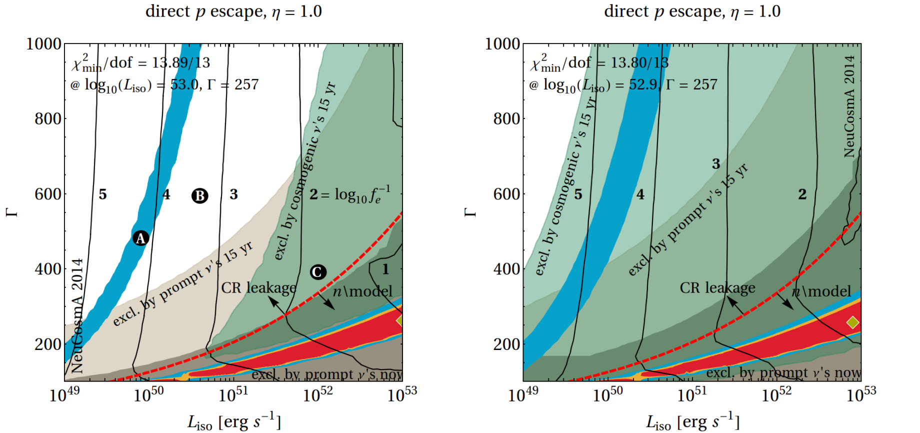
$$\int \varepsilon' N'_\gamma\left(\varepsilon'\right) d\varepsilon' = \frac{E'^{\rm sh}_{\rm iso}}{V'_{\rm iso}} \propto F_\gamma \ , \quad \int E'_p N'_p\left(E'_p\right) dE'_p = \frac{1}{f_e} \frac{E'^{\rm sh}_{\rm iso}}{V'_{\rm iso}} \propto \frac{F_\gamma}{f_e}$$

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

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

Constraints: SFR vs. GRB redshift evolution

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



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

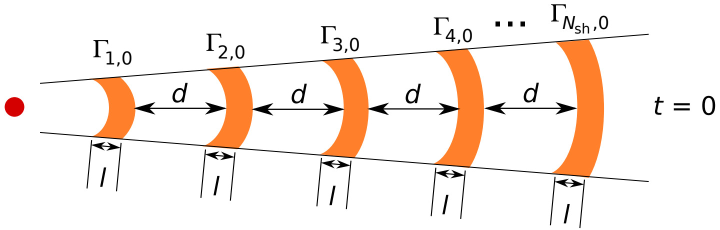
(star formation rate)

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

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

Initialising the dynamical burst

Initial number of shells: $N_{\text{sh}} \gtrsim 1000$



Initial values of shell parameters:

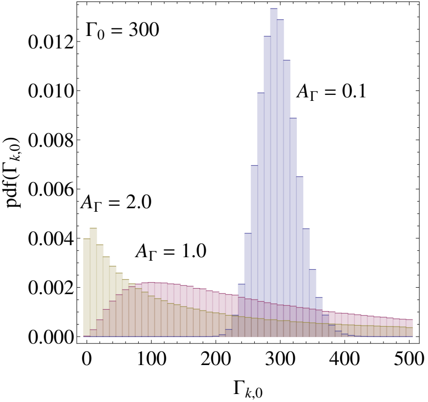
- Separation between shells: $d = l$
- Kinetic energy $E_{\text{kin},0}^{\text{iso}}$ equal for all collisions ($\sim 10^{52}$ erg)
- Speeds $\Gamma_{k,0}$ follow a distribution (see backup)
- Masses: $m_{k,0} = E_{\text{kin},0}^{\text{iso}}/(\Gamma_{k,0}c^2)$

Initialising the dynamical burst

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

$A_\Gamma \gg 1$

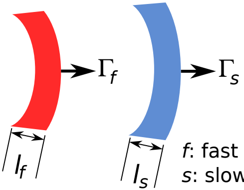
spread too large, too many collisions at low radii

$A_\Gamma \approx 1$

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

Anatomy of an internal collision

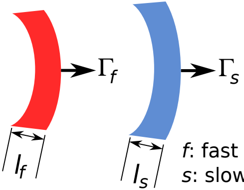
1 Propagation



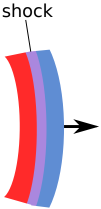
f: fast shell
s: slow shell

Anatomy of an internal collision

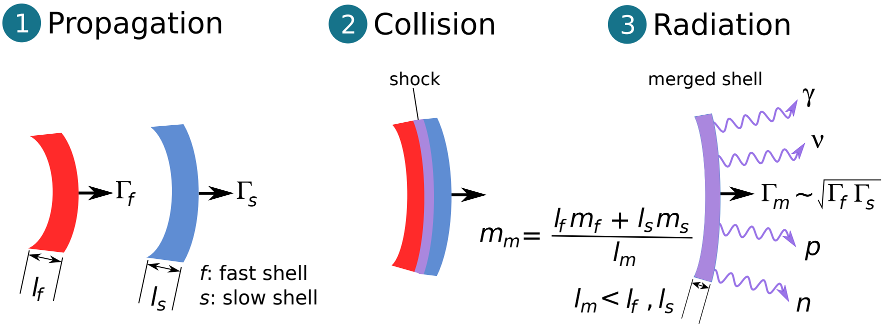
1 Propagation



2 Collision



Anatomy of an internal collision



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

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

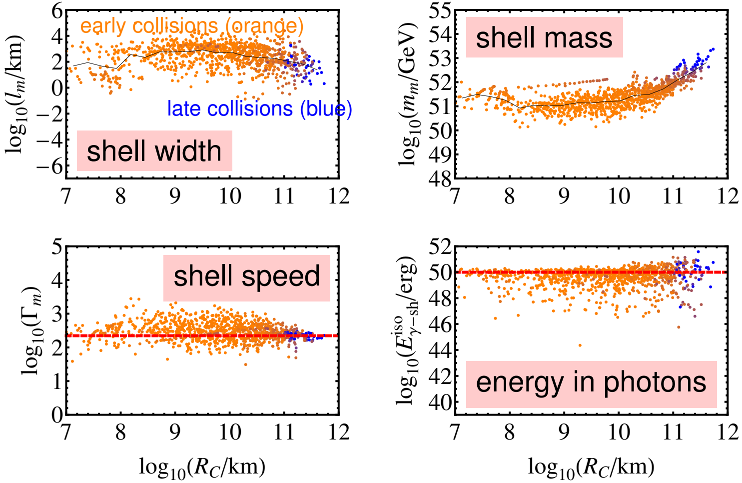
1/12: $\underbrace{E_{\gamma-\text{sh}}^{\text{iso}} \equiv \epsilon_e E_{\text{coll}}^{\text{iso}}}_{\text{energy in photons}}$

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

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

A dynamical burst

We keep track of collision parameters as the fireball expands:

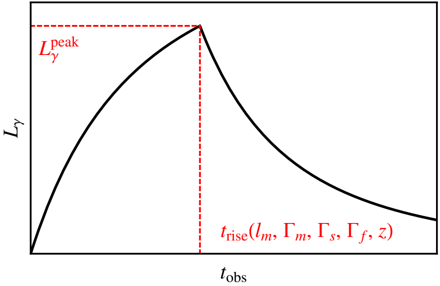


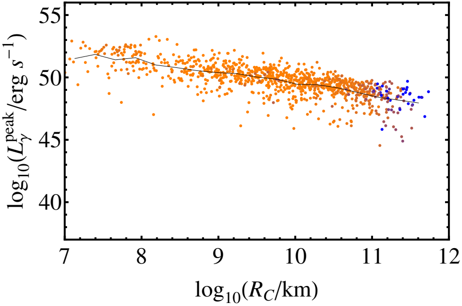
MB, P. Baerwald, K. Murase, and W. Winter, 1409.2874

(For this burst: $N_{\text{sh}} = 1000$, $N_{\text{coll}} = 990$, $\Gamma_0 = 300$, $A_\Gamma = 1$, $E^{\text{iso}}_{\gamma-\text{tot}} = 10^{53}$ erg)

GRB light curve: gamma-ray/neutrino pulses

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





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

Neutrino decay

Neutrinos are stable particles . . . *are they?*

So far, they seem to be

Bounds on "lifetimes" $\kappa^{-1} \equiv \tau_0/m$ of eigenstates $\nu_{1,2,3}$:

- $\kappa_1^{-1} \gtrsim 10^5$ s eV^{-1} (from SN 1987A)
- $\kappa_2^{-1} \gtrsim 10^{-4}$ s eV^{-1} (from solar ν's)
- $\kappa_3^{-1} \gtrsim 10^{-10}$ s eV^{-1} (from atm. and long-baseline)

Very long baselines might reveal their true unstable nature

$\Rightarrow$ cosmological neutrinos

If $\nu_{1,2,3}$ decay, their populations are governed by

$$\frac{dN_i}{dt} = -\lambda_i N_i$$

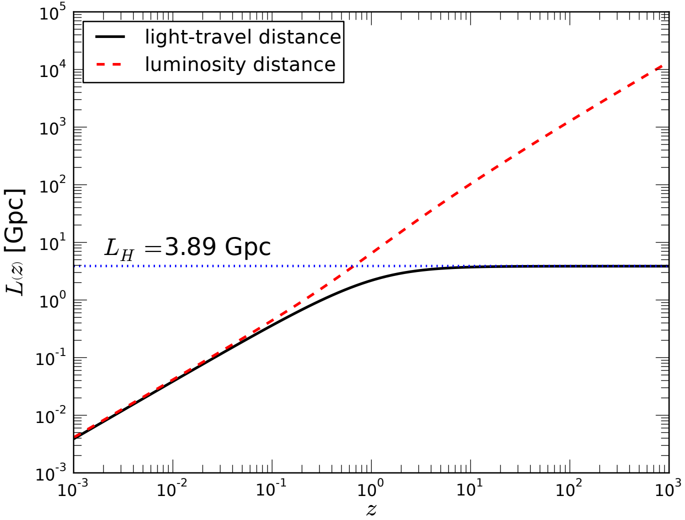
with the decay rate (s^{-1})

$$\lambda_i \equiv \frac{1}{\tau_i} = \frac{m_i}{\tau_{i,0}} \frac{1}{E} \equiv \frac{\kappa_i}{E}$$

Consider only decay into products invisible to the detector

Neutrinos are ultra-relativistic, so $t \approx L$
— if they are produced at a source with redshift z,

$L(z) \equiv$ light-travel, or lookback distance


light-travel distance
luminosity distance
L_H =3.89 Gpc
$L(z)$ [Gpc]
z
10^{5}
10^{4}
10^{3}
10^{2}
10^{1}
10^{0}
10^{-1}
10^{-2}
10^{-3}
10^{-3}
10^{-2}
10^{-1}
10^{0}
10^{1}
10^{2}
10^{3}

$\nu_\alpha \to \nu_\beta$ flavour-transition probability, oscillations washed out:

$$P_{\alpha\beta} = \sum_{i=1}^{3} |U_{\alpha i}|^2 \, |U_{\beta i}|^2 \qquad (\alpha, \beta = e, \mu, \tau)$$

What if neutrinos decay?

$$P_{\alpha\beta}(E_0, z) = \sum_{i=1}^{3} |U_{\alpha i}|^2 \, |U_{\beta i}|^2 \underbrace{\frac{N_i(E_0, z)}{N_i^0(E_0)}}_{D_i(E_0, z) \leq 1}$$

Damping factor $D_i(E_0, z)$ found by solving the decay equation

When solving, take into account:

1. $L = L(z)$ is the light-travel distance
2. Cosmological expansion: $E(z) = (1+z) E_0 \Rightarrow \lambda_i(z) = \frac{\kappa_i}{E_0 (1+z)}$

The traditional, simplified solution

$$\frac{dN_i}{dt} = -\lambda_i N_i \xrightarrow{\text{assume } \lambda_i \text{ constant}} N_i(t) = N_i^0 e^{-\lambda_i t}$$

Only now introduce the z-dependence of λ_i and L:

$$e^{-\lambda_i t} \longrightarrow D_i(E_0, z) = [\mathcal{Z}_1(z)]^{-\kappa_i L_H / E_0}$$

vs.

The proper solution

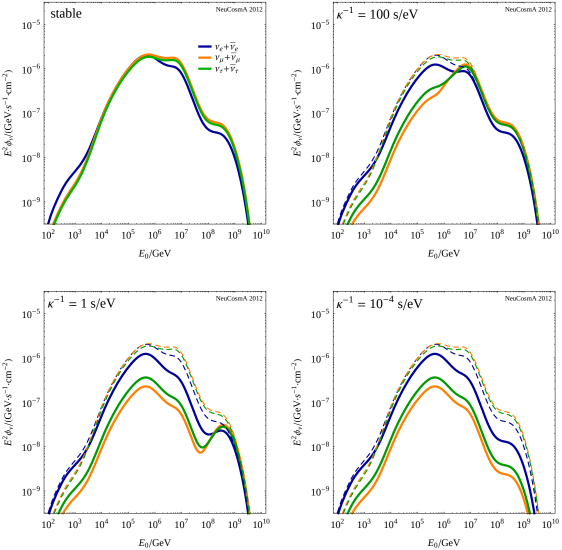
Rewrite the decay equation in terms of z from the start,

$$\frac{dN_i(E_0, z)}{dz} = -\frac{\kappa_i}{E_0} \frac{dL}{dz} \frac{N_i(E_0, z)}{1+z}$$

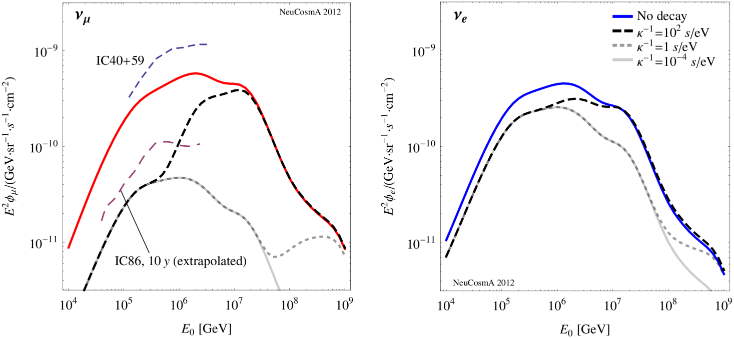
and then solve it:

$$D_i(z) = [\mathcal{Z}_2(z)]^{-\kappa_i L_H / E_0}$$

Now keep ν_1 stable (from SN 1987A) and let $\nu_{2,3}$ decay:



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



No neutrinos found because they decay, or because the baryonic loading in GRBs is smaller than anticipated?

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