Gamma-ray bursts: sources of ultra-high-energy cosmic rays and neutrinos

Mauricio Bustamante

Center for Cosmology and Astroparticle Physics (CCAPP)
The Ohio State University

Latin American Webinars on Physics

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Two fifty-year-old mysteries

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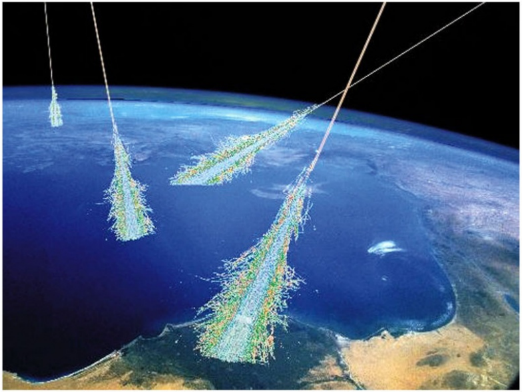
ultra-high-energy cosmic rays (UHECRs)



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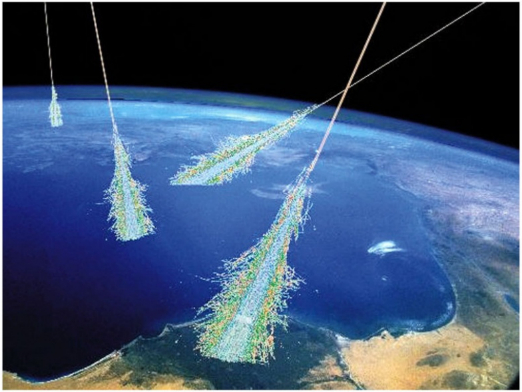

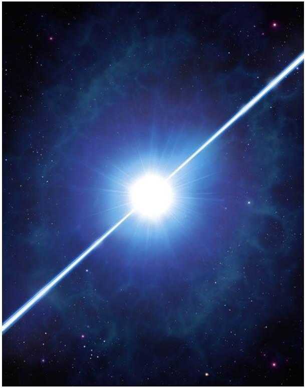

Two fifty-year-old mysteries

ultra-high-energy cosmic rays (UHECRs)

gamma-ray bursts (GRBs)

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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The mystery

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Our hypothesis

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

Our result

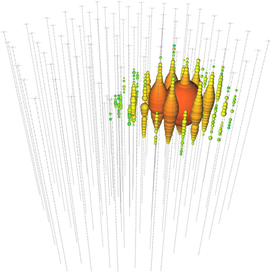
It is possible, *and testable*, but the connection between UHECRs, GRBs, and neutrinos is **not** as simple as we thought

UHE neutrinos – they are real and they are here

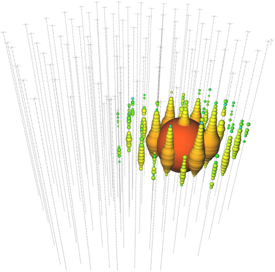
The era of neutrino astronomy has begun!

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

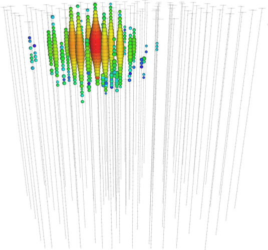
“Bert”, 1.04 PeV



“Ernie”, 1.14 PeV



“Big Bird”, 2 PeV



. . . and 34 more events < 385 TeV

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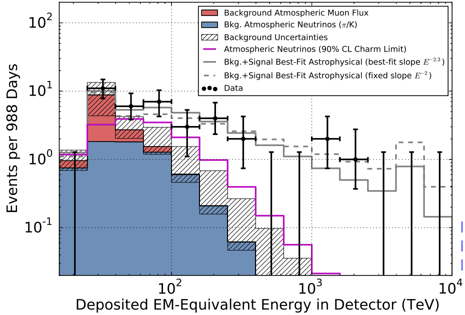

IceCube, *PRL* **111**, 021103 (2013)
IceCube, *Science* **342**, 1242856 (2013)
IceCube, *PRL* **113**, 101101 (2014)

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

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

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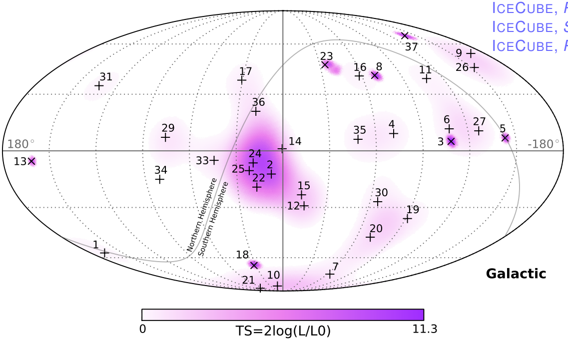
Arrival directions compatible with an isotropic distribution –

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



+: shower
×: muon track

– no association with sources found yet

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!

GRBs – good candidates for UHE CR & ν sources

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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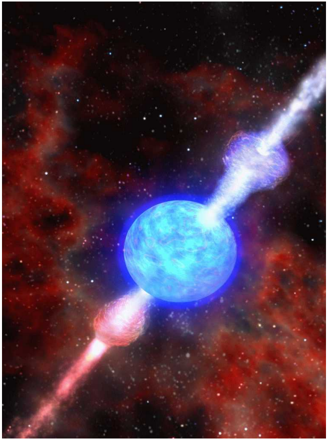
GRBs – what are they?

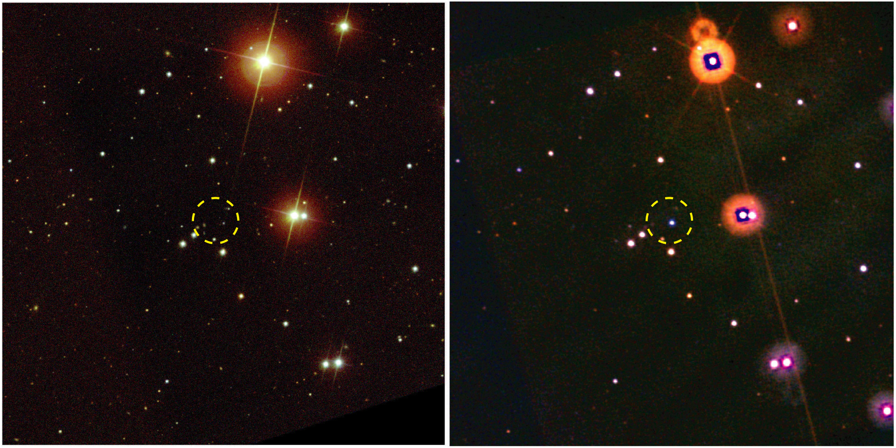
GRBs: the most luminous explosions in the Universe

- **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**: ~ 0.3 Gpc^{-3} yr^{-1}
- two populations:
  - **short-duration (< 2 s):** neutron star-neutron star or NS-black hole mergers
  - **long-duration (> 2 s):** associated to hypernovae
- powered by matter accretion onto a black hole



What do they *look* like?

e.g., GRB060218 seen by *Swift*

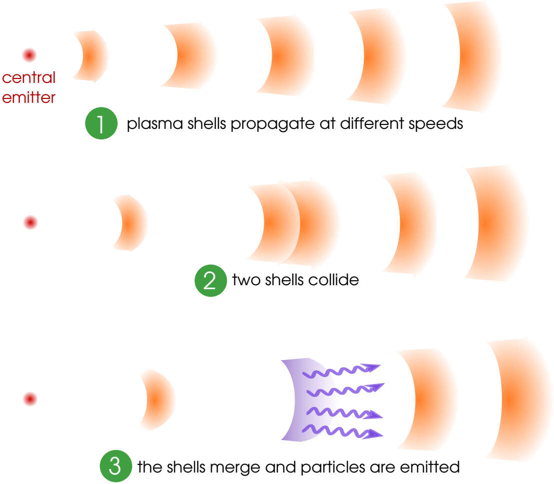


SDSS, Swift Collab., Sloan Foundation, NSF, NASA

GRBs 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

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

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

broken power law

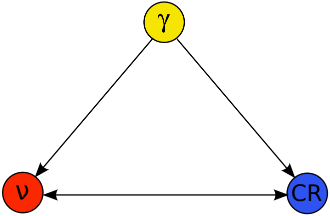
$$p\;\gamma \to \Delta^+(1232) \to \begin{cases} n\pi^+ \,, & \mathrm{BR} = 1/3 \\ p\pi^0 \,, & \mathrm{BR} = 2/3 \end{cases}$$

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

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

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

(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")

This neutron model of CR emission is now strongly disfavoured

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

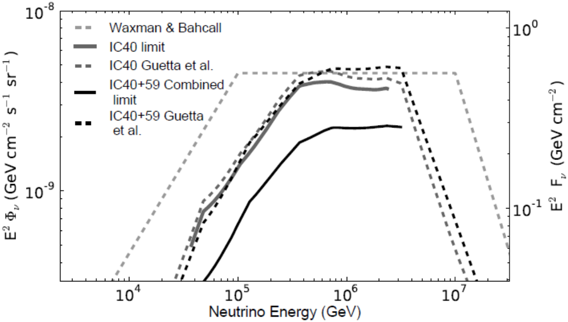
The neutron model under tension?

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

NeuCosmA: (revised) GRB particle emission – I

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

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

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

NeuCosmA: (revised) GRB particle emission – II

Normalise the densities at the source – for one collision:

- Photons:

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

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

- Protons:

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

NeuCosmA: (revised) GRB particle emission – III

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

$x \equiv E'/E'_p$

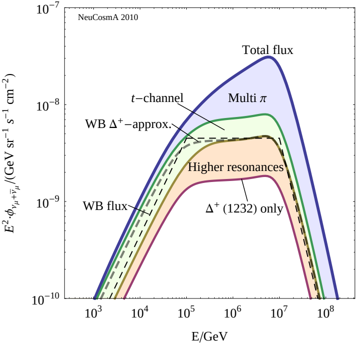
$y \equiv E'_p E'_\gamma / \left(m_p c^2\right)$

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

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



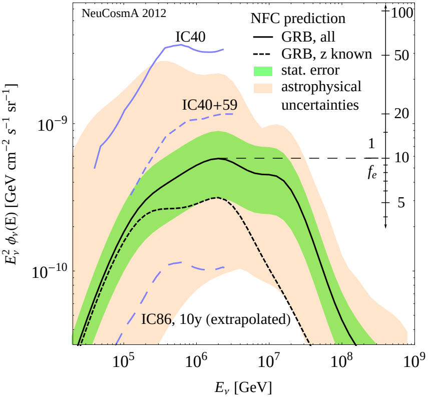
The new prediction of the quasi-diffuse GRB ν flux

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 $\sim$ 1 order of magnitude lower!



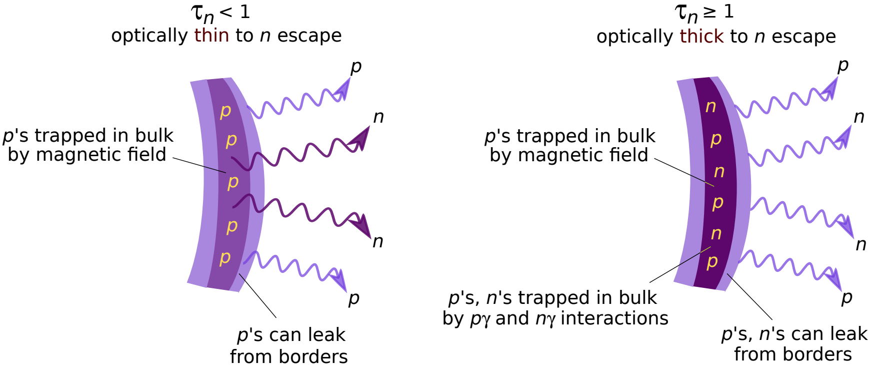
S. Hümmer, P. Baerwald, and W. Winter, *Phys. Rev. Lett.* **108**, 231101 (2012)

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

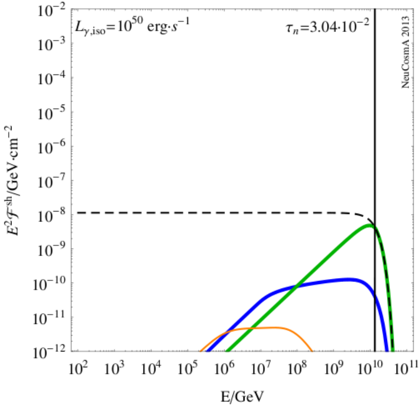
Relative contributions determined by $\tau_n \equiv \left(t_{p\gamma}^{-1} / t_{\mathrm{dyn}}^{-1} \right)\Big|_{E'_{p,\mathrm{max}}}$



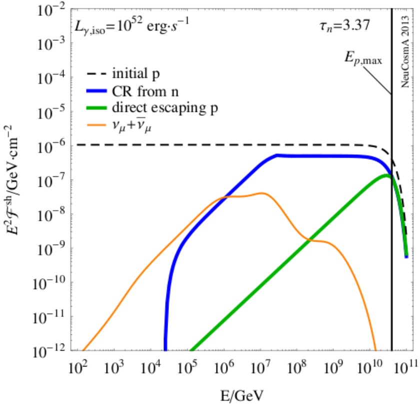
A two-component model of UHECR emission

Sample neutrino fluences –

Optically **thin** source

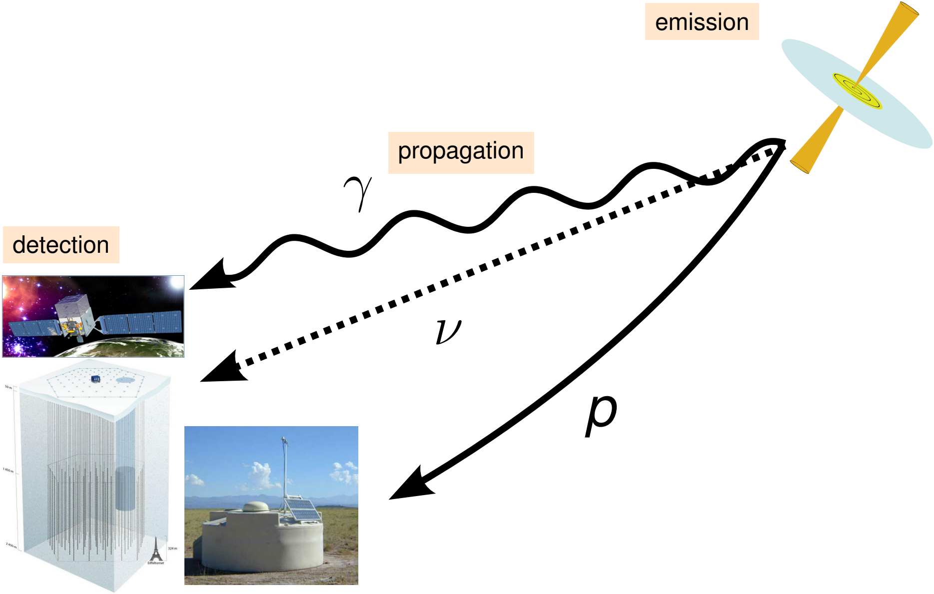


Optically **thick** source



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

From the sources to us



emission

propagation

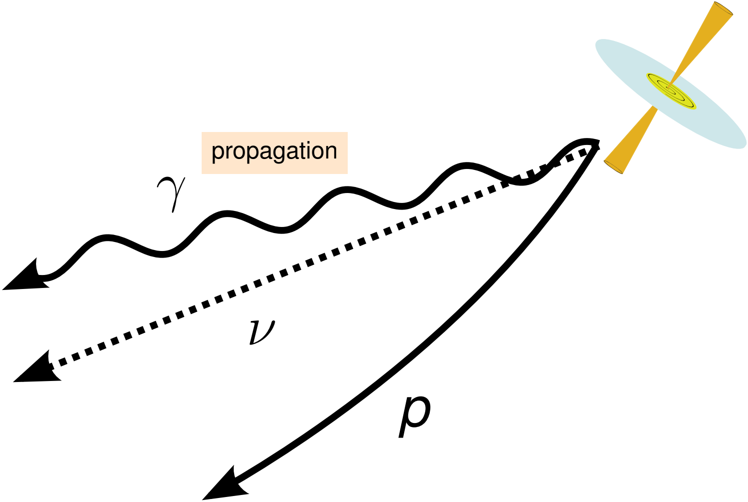
detection

γ

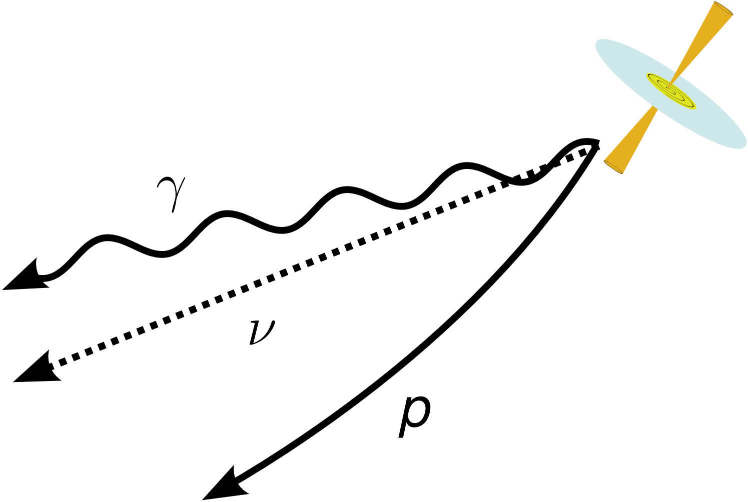
ν

p

From the sources to us



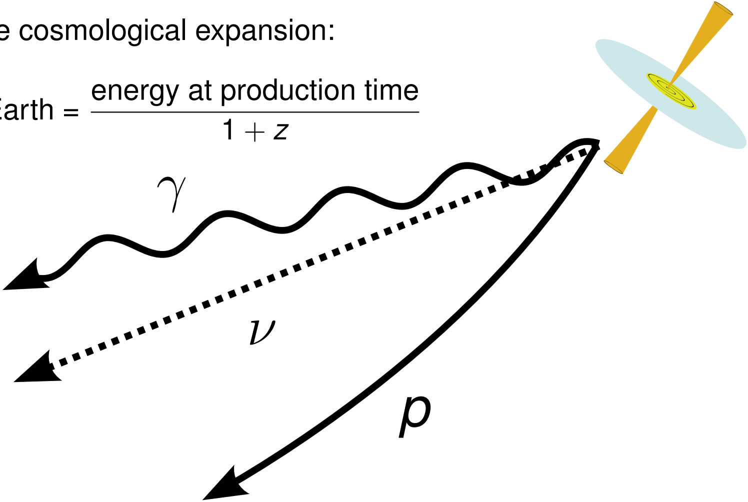
From the sources to us



From the sources to us

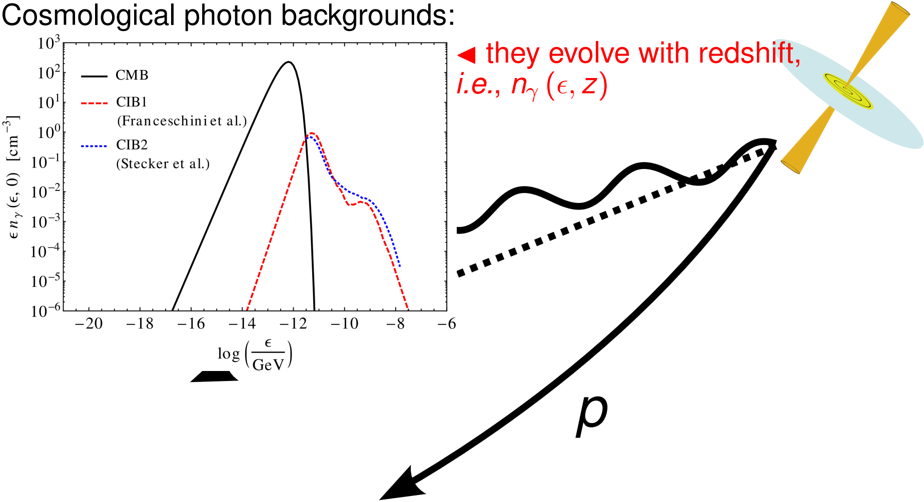
Because of the cosmological expansion:

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



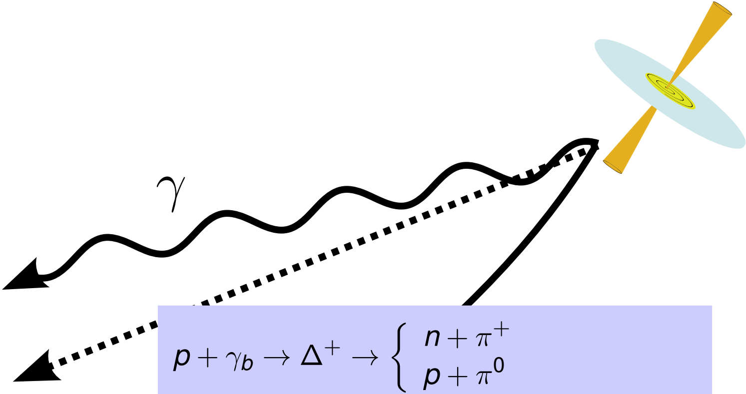
From the sources to us

Cosmological photon backgrounds:



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

From the sources to us



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

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

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

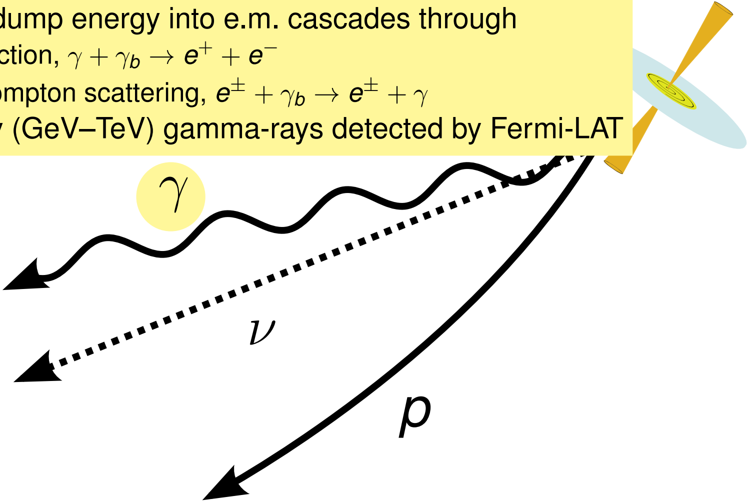
$$n \to p + e^- + \bar{\nu}_e$$

From the sources to us

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

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

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



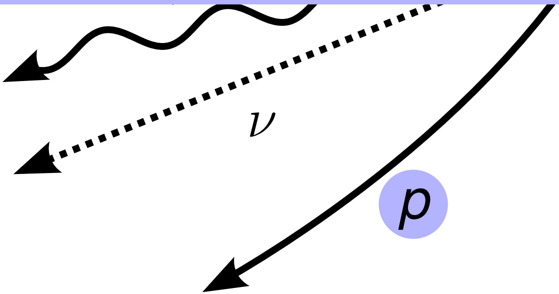
From the sources to us

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

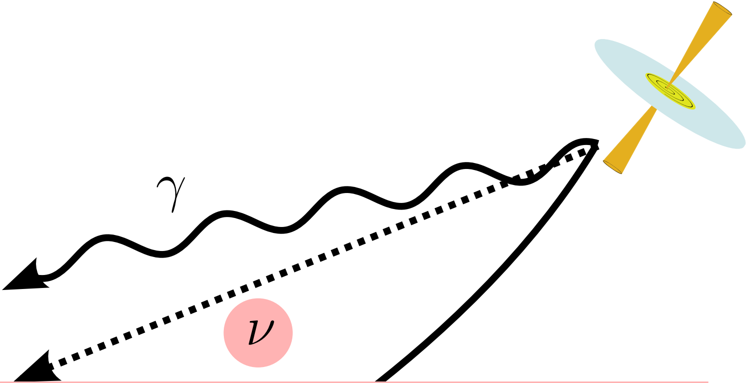
They lose energy through:

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

$\Big\}$ depend on the redshift evolution of the cosmological γ backgrounds



From the sources to us



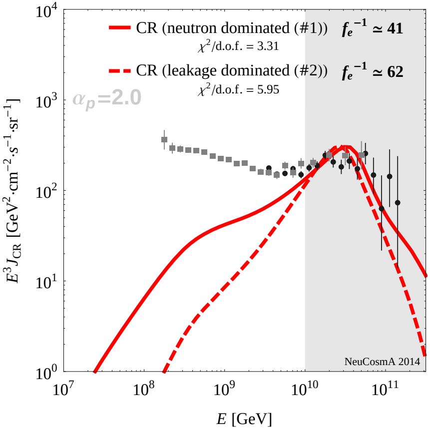
Initial UHE ν flavour fluxes: $\nu_e : \nu_\mu : \nu_\tau = 1 : 2 : 0$

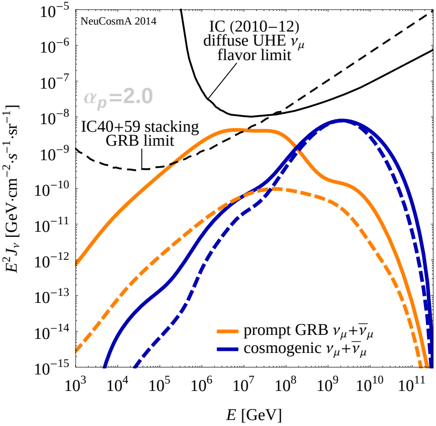
Probability of $\nu_\alpha \to \nu_\beta$ transition: $P_{\alpha\beta}(E_0, z)$

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

What do the fluxes look at Earth, then?

Diffuse UHECR and neutrino predictions –

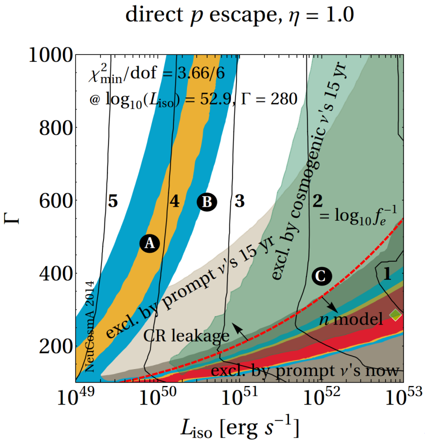




P. Baerwald, MB, and W. Winter, *ApJ* **768**, 186 (2013)
P. Baerwald, MB, and W. Winter, *Astropart. Phys.* **62**, 66 (2015)
See also: H. He *et al.*, *ApJ* **752**, 29 (2012)

Constraints from experimental data

Fit the UHECR flux to Telescope Array data & enforce the IceCube GRB ν and cosmogenic ν upper bounds –



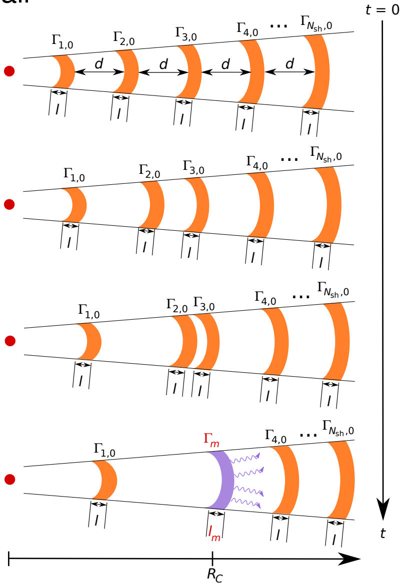
P. Baerwald, MB, and W. Winter, *Astropart. Phys.* **62**, 66 (2015)

more relativistic (higher Γ) GRBs are needed

Going further: a dynamical burst model

We have considered a dynamical fireball –

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



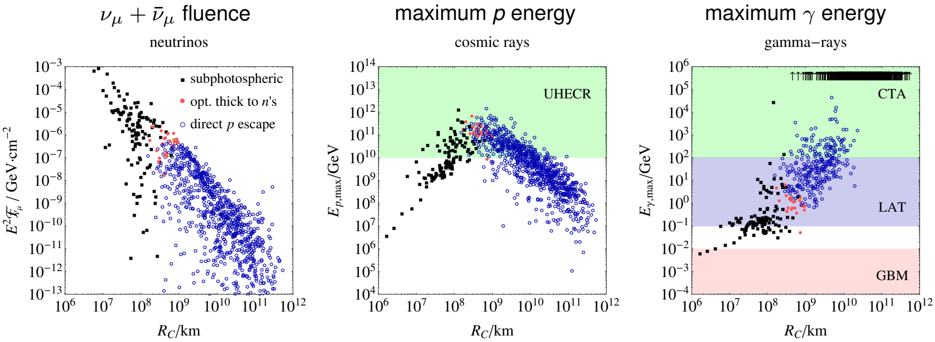
Why does this matter?

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

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

Tracking each collision individually

Each collision occurs in a different emission regime –

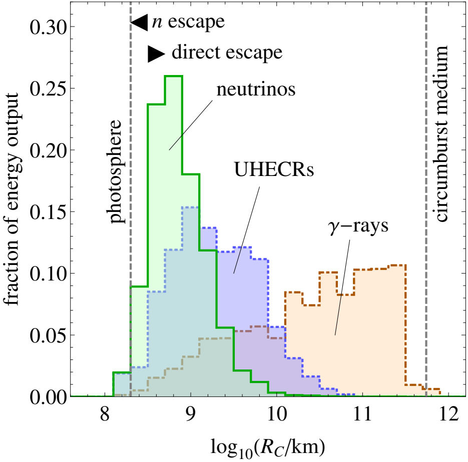


(observer's frame) (source frame)

MB, P. Baerwald, K. Murase, and W. Winter, 1409.2874
(Accepted for publication in Nature Commun.)

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

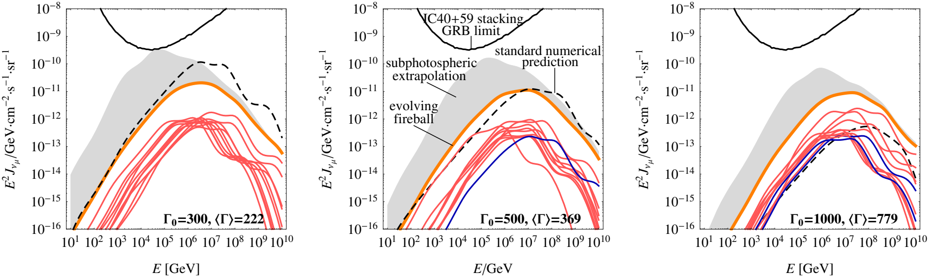
Why does it matter?

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

MB, P. Baerwald, K. Murase, and W. Winter, 1409.2874
(Accepted for publication in Nature Commun.)

A new, robust minimal ν flux from the dynamical burst

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



MB, P. Baerwald, K. Murase, and W. Winter, 1409.2874
(Accepted for publication in Nature Commun.)

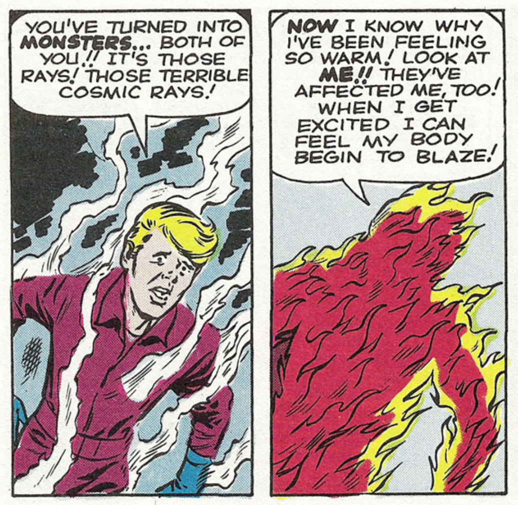
we find a minimal ν flux of $\sim 10^{-11}$ GeV cm^{-2} s^{-1} sr^{-1},
independently of Γ and baryonic loading

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

Conclusions . . . and the future

- GRBs *are* good UHECR and ν source candidates
- *But* the CR-ν-γ connection is trickier than originally thought
- They will contribute to the diffuse UHE 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

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



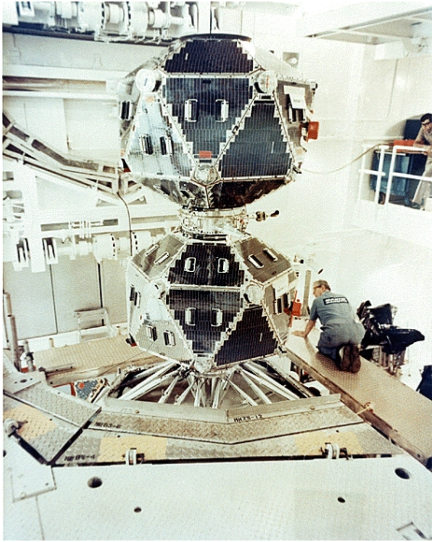
S. LEE AND J. KIRBY, *Fantastic Four* **1** (1961)

Backup slides

GRBs – discovery – I

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

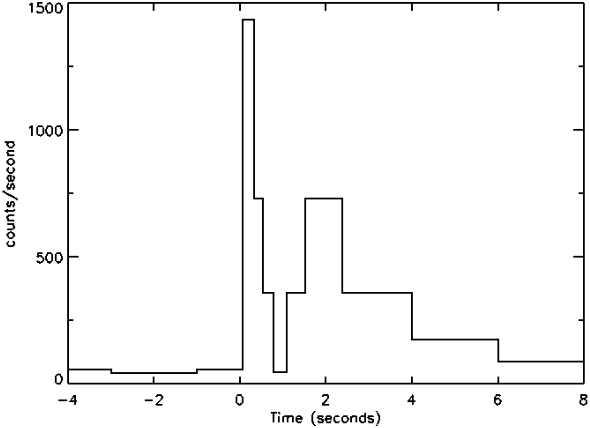
- They carried X-ray, gamma-ray, and neutron detectors
- *Vela* 5a-b had enough spatial resolution to pinpoint the direction of events
- Intense gamma-ray emission from a nuclear explosion lasts $\lesssim 10^{-6}$ s . . .
- . . . however, longer-lasting emissions were detected



VELA 5A/B SATELLITES (NASA)

GRBs – discovery – II

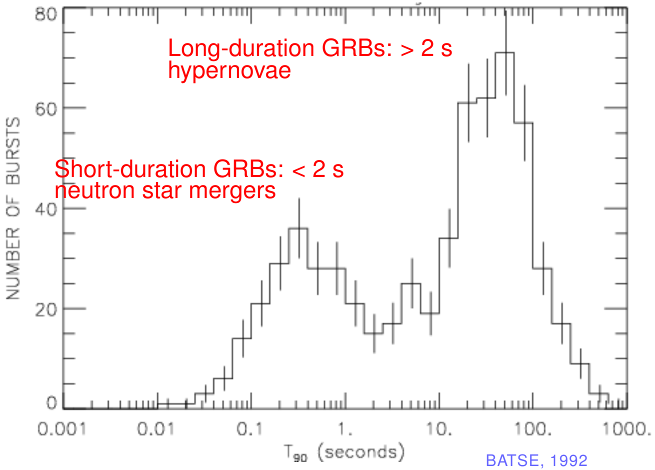
First GRB detected: July 2, 1967, 14:19 UTC



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

GRBs – two populations

Two populations of GRBs:

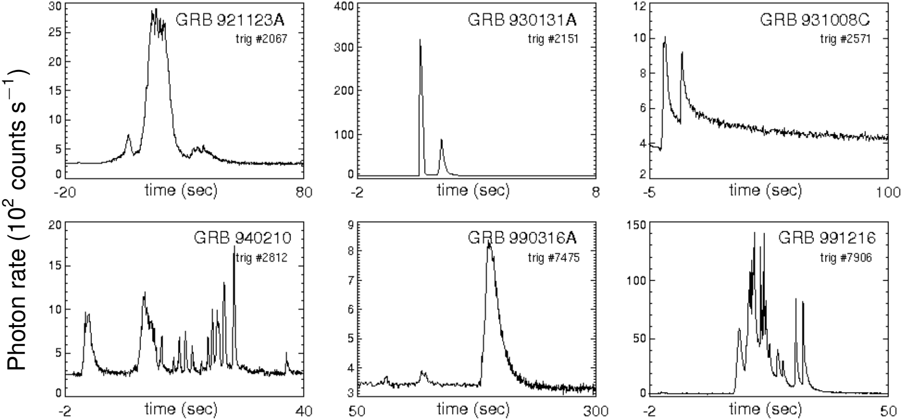


BATSE, 1992

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) $\equiv t_v \approx 1$ 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

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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, 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:

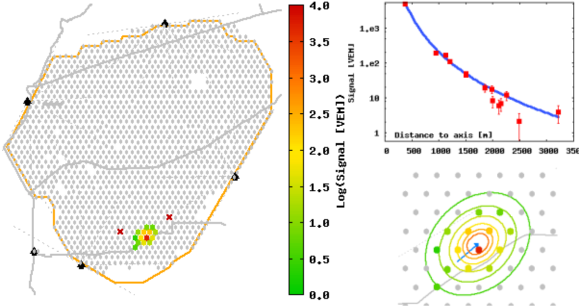
$$p(d) \approx \exp\left(\frac{-d}{6.6\text{ Mpc}}\right) \Rightarrow p(d) < 10^{-4} \text{ for } d = 50 \text{ Mpc}$$

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 – I

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 ± 1.9 EeV
Theta	40.2 ± 0.2 deg
Phi	-139.2 ± 0.2 deg
Curvature	10.9 ± 0.5 km
Core Easting	476053 ± 19 m
Core Northing	6079248 ± 12 m
Reduced Chi^2	8.36

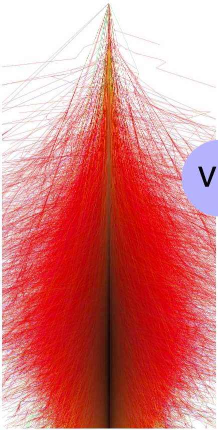
Problem:
So how is the identity of the primary reconstructed from this?

UHECRs – composition – II

Answer:

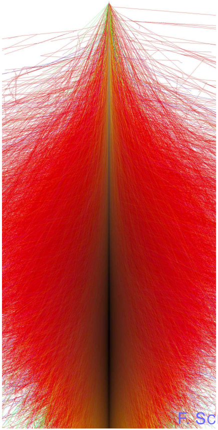
use longitudinal air shower development information from the fluorescence detectors

10^6 GeV proton



vs.

10^6 GeV Fe-56 nucleus



F. SCHMID, UNIV. LEEDS

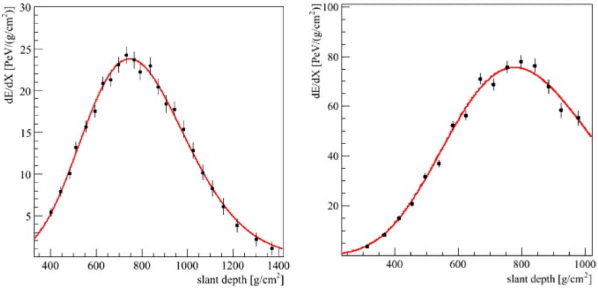
UHECRs – composition – III

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

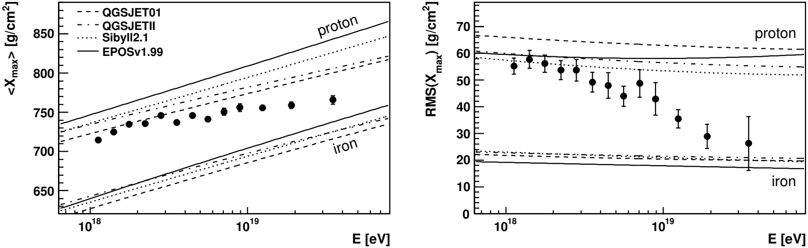
Using the FDs, measure $N(x)$, $x_{\max}$ for each shower:



UHECRs – composition – IV

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

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



Auger

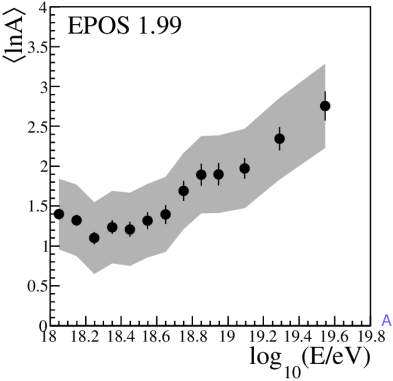
There is a tendency towards heavier composition at very high energies

UHECRs – composition – V

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

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

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



AUGER

The Hillas criterion – I

Two considerations:

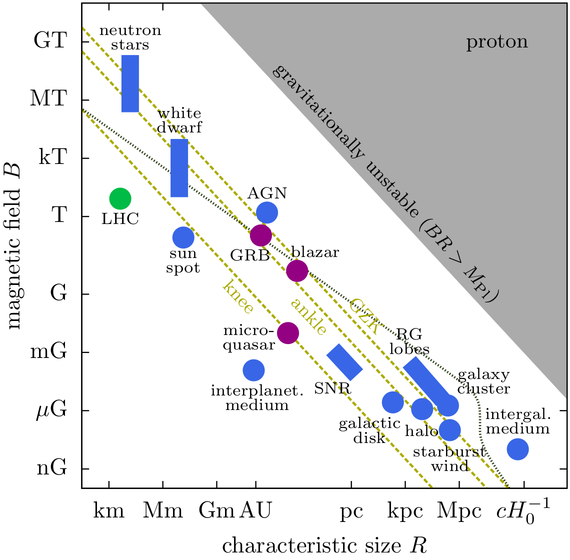
1. Charged particles (Z) are assumed to be accelerated by intense magnetic fields in astrphysical sources
2. For the acceleration to be mantained, the gyroradius should be smaller than the size of the acceleration region

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

Hillas criterion: $R_L < R$
This limits the maximum energy:

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

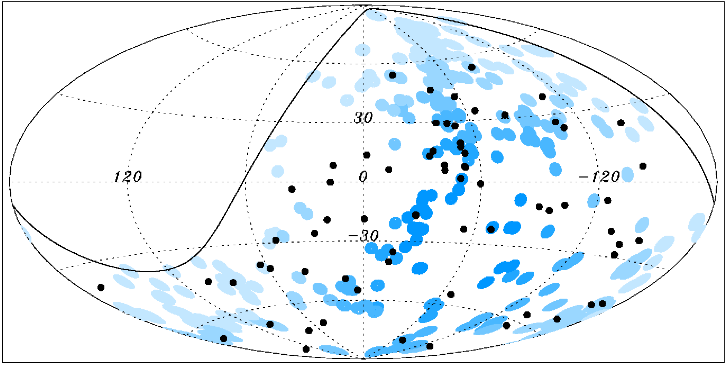
The Hillas criterion – I



UHECRs – correlation with known sources – I

- 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)

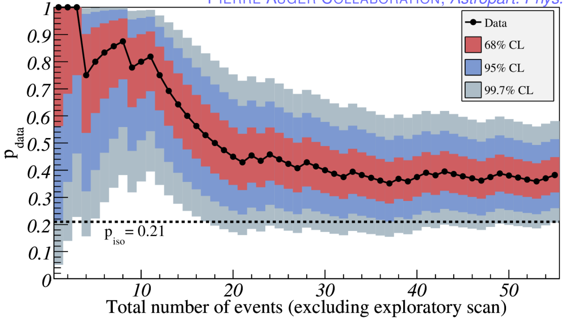
UHECRs – correlation with known sources – II

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 – I

Two important points:

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

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

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

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

A two-component model of CR emission – II

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}:

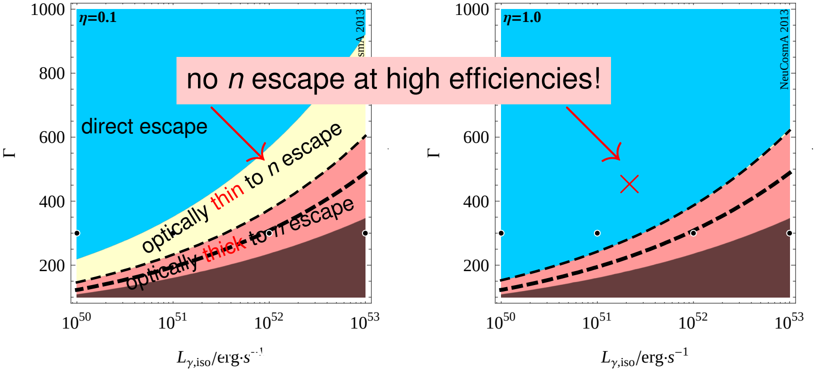
$$\left.\begin{array}{l} \lambda'_{p,\text{mfp}}\left(E'\right) = \min\left[\Delta r', R'_L\left(E'\right), ct'_{p\gamma}\left(E'\right)\right] \\ \lambda'_{n,\text{mfp}}\left(E'\right) = \min\left[\Delta r', ct'_{p\gamma}\left(E'\right)\right] \end{array}\right\} f_{\text{esc}} = \frac{\lambda'_{\text{mfp}}}{\Delta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

fraction of escaping particles

We *need* direct proton escape

Scan of the GRB emission parameter space –

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

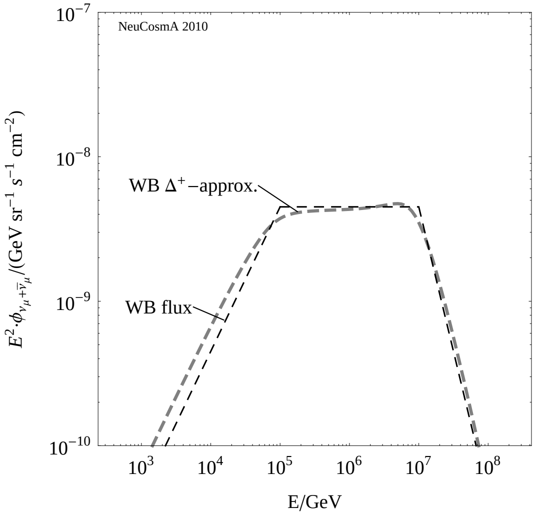


no *n* escape at high efficiencies!

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

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

NeuCosmA – the full photohadronic cross section

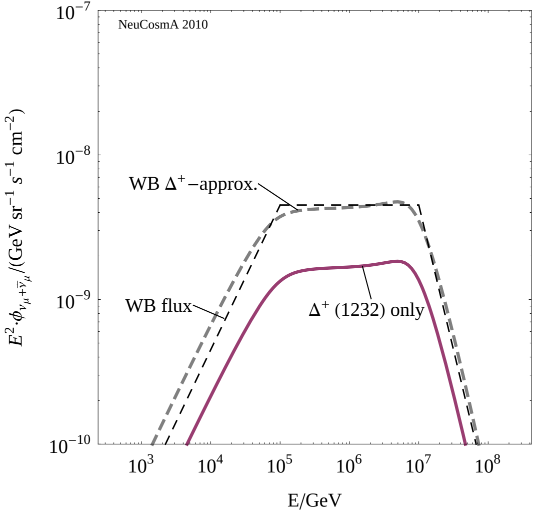


NeuCosmA – the full photohadronic cross section

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

- Δ(1232)-resonance

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

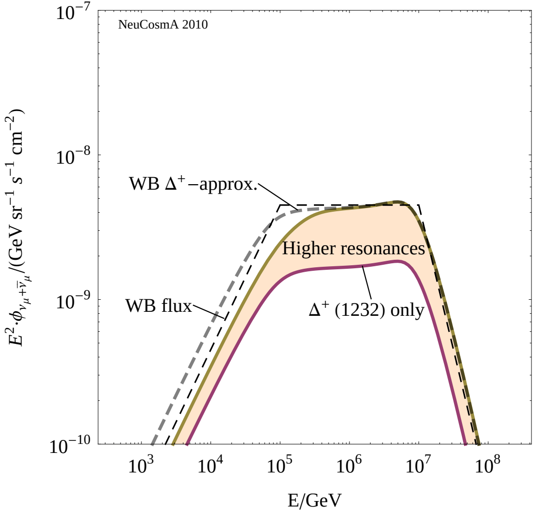


NeuCosmA – the full photohadronic cross section

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

- Δ(1232)-resonance
- Higher resonances

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



NeuCosmA – the full photohadronic cross section

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

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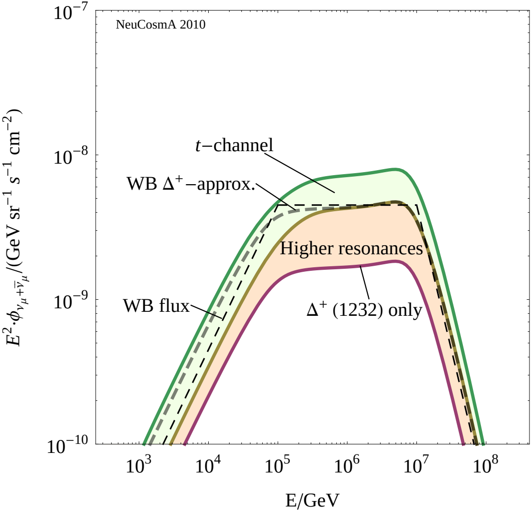
- *t*-channel
  (direct production)

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

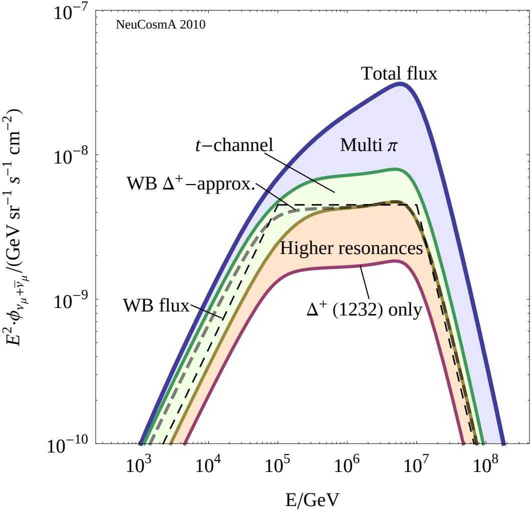


NeuCosmA – the full photohadronic cross section

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

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

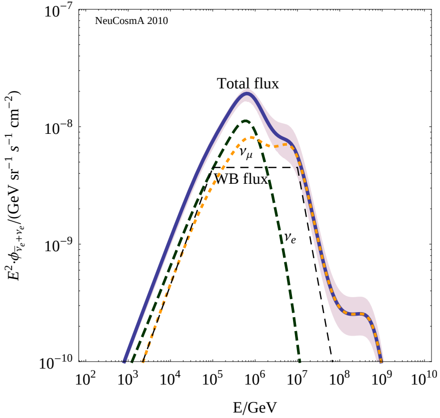
P. Baerwald, S. Hümmer, and W. Winter, *Phys. Rev.* **D83**, 067303 (2011)



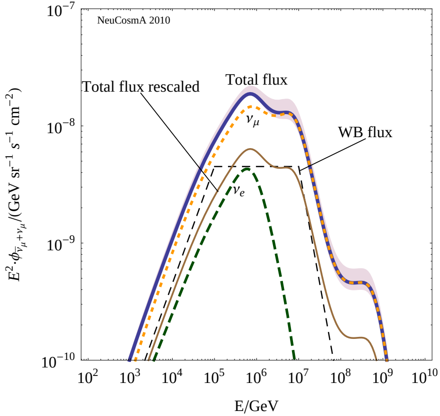
Especially "Multi π" contribution leads to change of flux shape; neutrino flux higher by up to a factor of 3 compared to WB treatment

NeuCosmA – neutrino spectra including flavour mixing

Electron neutrino spectrum



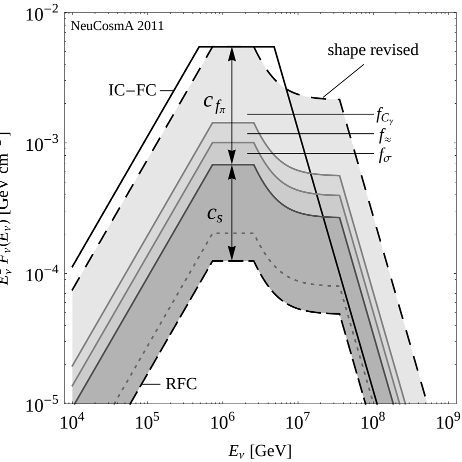
Muon neutrino spectrum



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

NeuCosmA – how the neutrino spectrum changes – I

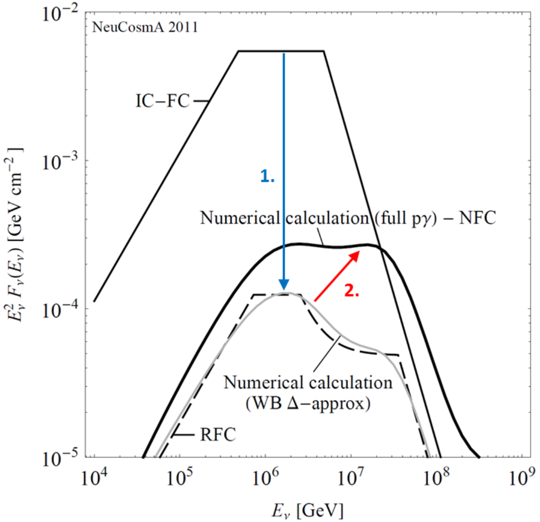


S. Hümmer, P. Baerwald, and W. Winter, *Phys. Rev. Lett.* **108**, 231101 (2012)

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

NeuCosmA – how the neutrino spectrum changes – II



For example, GRB080603A:

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

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

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

NeuCosmA – further particle decays

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

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

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

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

NeuCosmA – further particle decays

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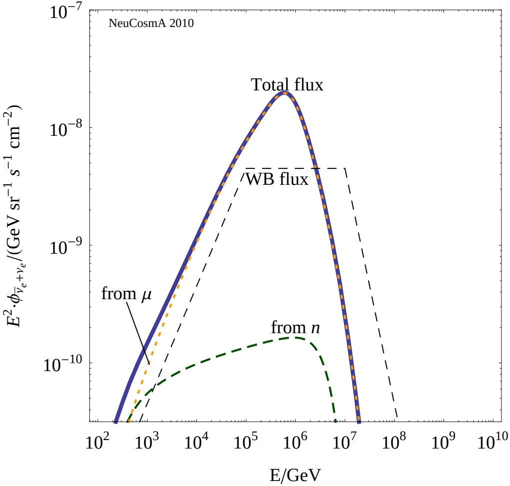
$$K^+ \rightarrow \mu^+ + \nu_\mu$$

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

Resulting ν_e flux (at the observer)

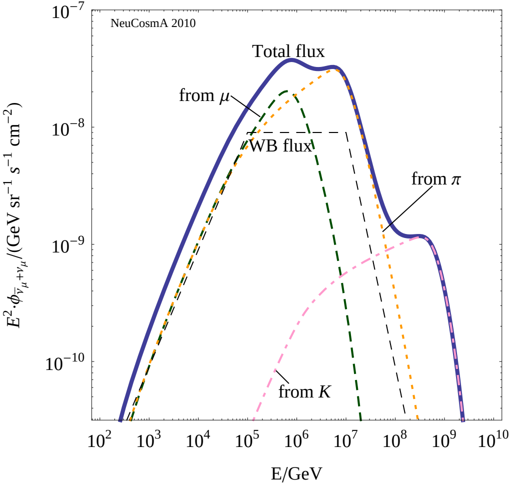


P. BAERWALD, S. HÜMMER, AND W. WINTER, *Phys. Rev.* **D83**, 067303 (2011)

NeuCosmA – further particle decays

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

Resulting ν_μ flux (at the observer)



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

Propagating the UHECRs to Earth

We use a Boltzmann equation to transport protons to Earth:

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

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

  with n_p the real number density

- Transport equation (comoving source frame):

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

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

The need for km-scale neutrino telescopes

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

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

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):

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

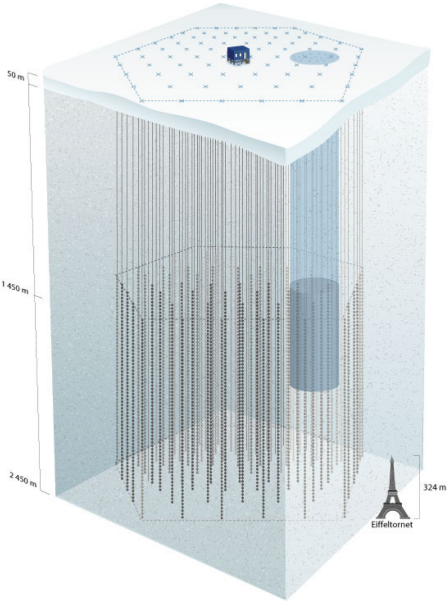
where A_{eff} is the effective area of the detector

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

Detecting the neutrinos – IceCube



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

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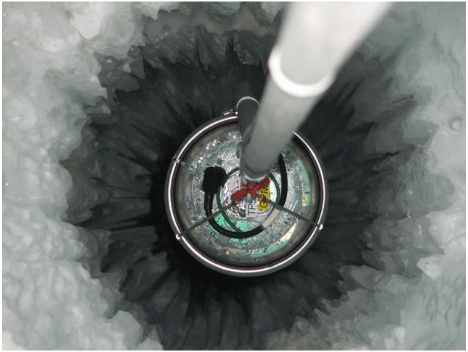
Detecting the neutrinos – IceCube



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

Cosmogenic neutrinos

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

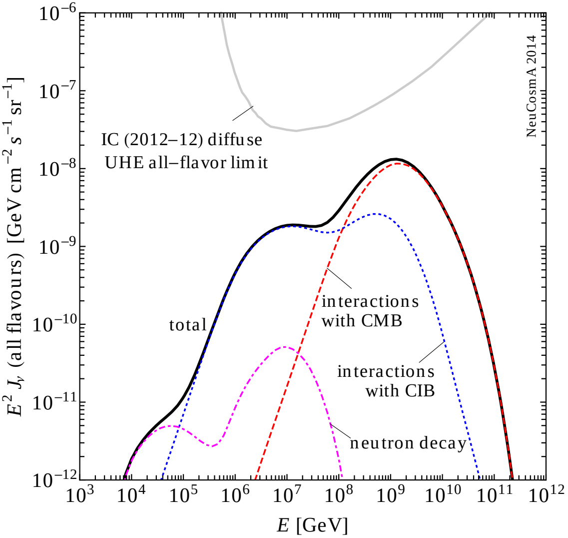
$$p + \gamma \to \Delta^+ \to \pi^+ + n \, ,$$

and neutrinos are created in the decays of the secondaries:

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

These are called *cosmogenic neutrinos*

Cosmogenic neutrinos



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

Interaction with the photon backgrounds – I

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

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

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

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

  - n_γ: isotropic photon background ($\text{GeV}^{-1}\ \text{cm}^{-3}$)
  - 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):

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

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

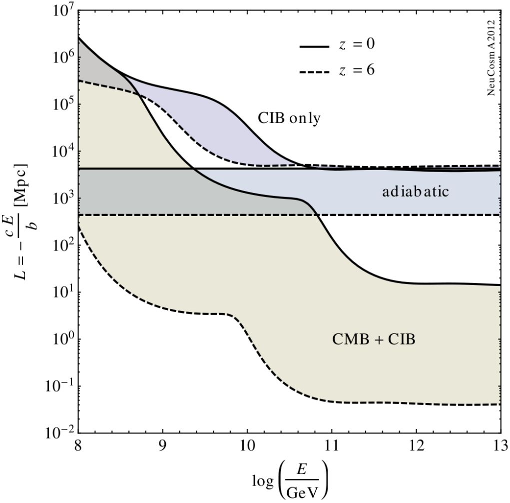
   $$t_{p\gamma}^{-1}\left(E,z\right) = \sum_{i}^{\text{all channels}} \Gamma_{p\to p}^{i}\left(E,z\right) K^i ,$$

   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, $\partial_E\left(b_{p\gamma} Y_p\right)$.

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

Interaction lengths

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



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

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

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

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

UHE ν's in the GRB internal shock model

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

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

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

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

- Proton density:

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

Maximum proton energy limited by energy losses:

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

UHE ν's in the GRB internal shock model

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

$$Q'\left(E'\right) = \int_{E'}^{\infty} \frac{dE_p'}{E_p'} N_p'\left(E_p'\right) \int_0^{\infty} c d\varepsilon' N_\gamma'\left(\varepsilon'\right) R\left(E', E_p', \varepsilon'\right)$$

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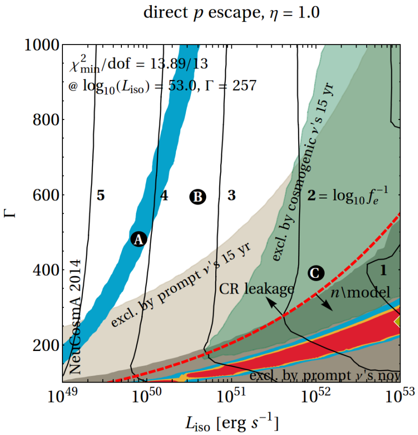
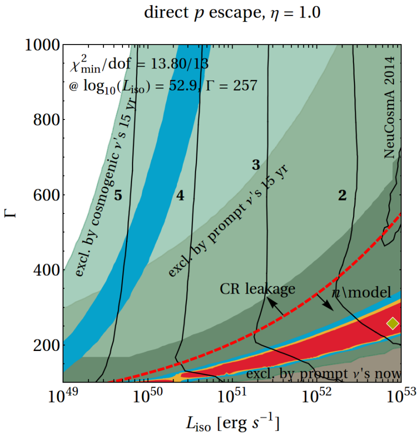
Constraints: SFR vs. GRB redshift evolution

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



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

(star formation rate)

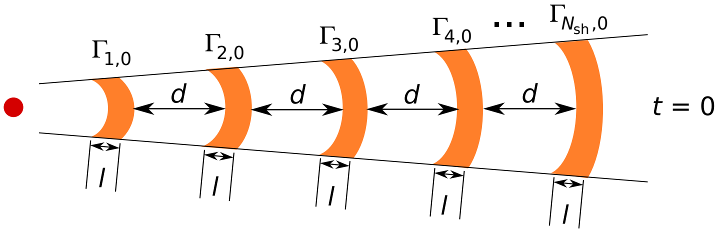


$n_{\rm GRB}(z) \propto \rho_{\rm SFR}(z) \times (1+z)^{1.2}$

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

Dynamical burst – initialisation

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



Initial values of shell parameters:

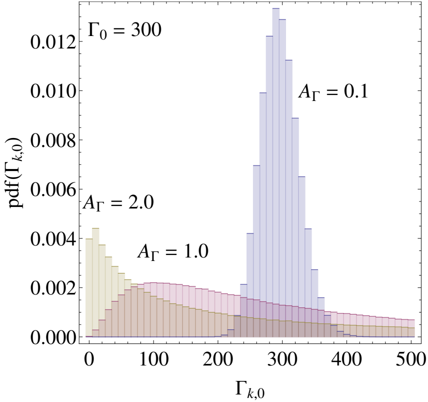
- Separation between shells: $d = l$
- Kinetic energy $E_{\text{kin},0}^{\text{iso}}$ equal for all collisions ($\sim 10^{52}$ erg)
- Speeds $\Gamma_{k,0}$ follow a distribution (see backup)
- Masses: $m_{k,0} = E_{\text{kin},0}^{\text{iso}}/(\Gamma_{k,0}c^2)$

Dynamical burst – 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

$A_\Gamma \gg 1$

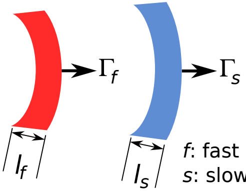
spread too large, too many collisions at low radii

$A_\Gamma \approx 1$

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

Dynamical burst – anatomy of an internal collision

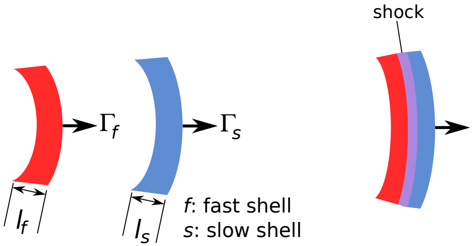
① Propagation



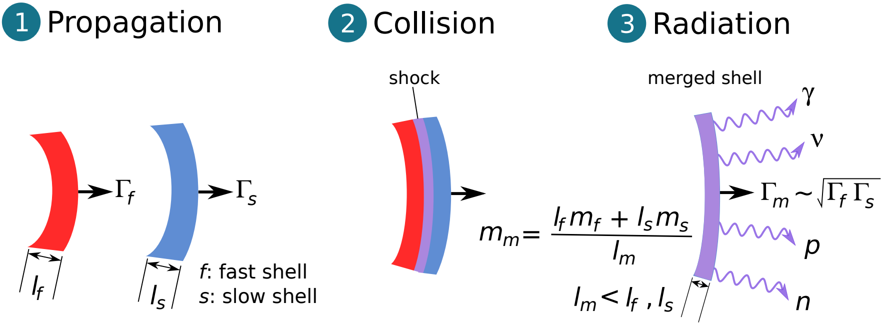
f: fast shell
s: slow shell

Dynamical burst – anatomy of an internal collision

① Propagation ② Collision



Dynamical burst – anatomy of an internal collision



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

$$l_m < l_f \, , l_s$$

$$\Gamma_m \sim \sqrt{\Gamma_f \, \Gamma_s}$$

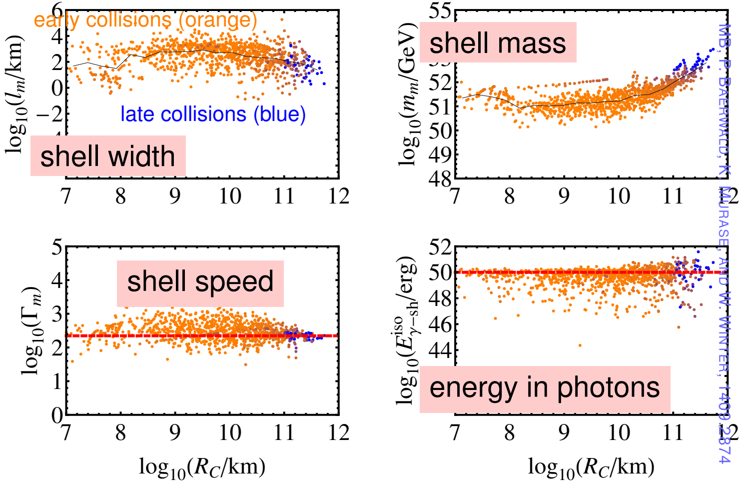
Part of the initial kinetic energy radiated as γ's, ν's, *p*'s, and *n*'s:

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

$$\underbrace{\overset{\boxed{1/12}}{E^{\text{iso}}_{\gamma-\text{sh}}} \equiv \epsilon_e E^{\text{iso}}_{\text{coll}}}_{\text{energy in photons}} \qquad \underbrace{\overset{\boxed{1/12}}{\epsilon_B E^{\text{iso}}_{\text{coll}}}}_{\text{energy in magnetic fields}} \qquad \underbrace{\overset{\boxed{5/6}}{\epsilon_p E^{\text{iso}}_{\text{coll}}}}_{\text{energy in baryons}}$$

Dynamical burst – evolution of collision parameters

We keep track of collision parameters as the fireball expands:



shell width

shell mass

shell speed

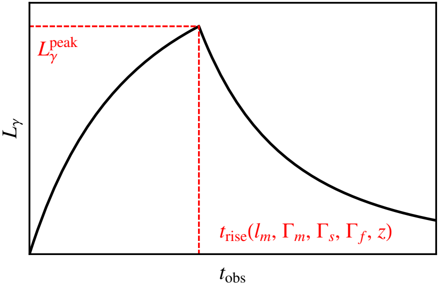
energy in photons

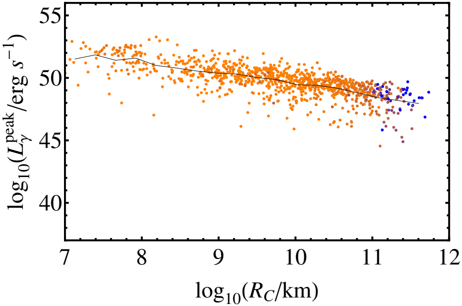
MB, P. BAERWALD, K. MURASE, AND W. WINTER, 1409.2874

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

Dynamical burst – GRB light curve: γ-ray/ν pulses

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





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