Ultra-high energy astrophysical cosmic rays and neutrinos: a half-century mystery

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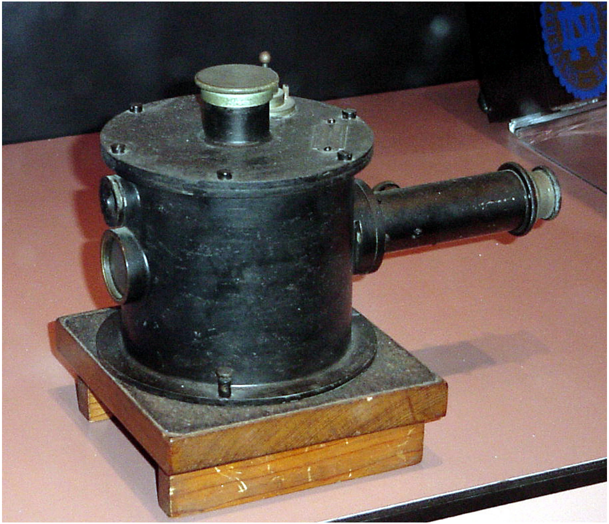
Cosmic rays discovered

1911–1913: the Austrian physicist Victor Hess made balloon flights up to an altitude of 5.3 km

What he found would eventually be known as *cosmic rays*

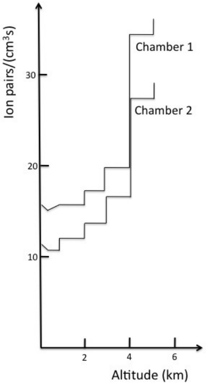
Cosmic rays discovered

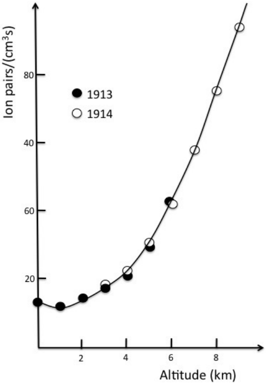


Original electograph used by Hess in 1911-1912

What did Hess find?

- ionising radiation decreases up to $\sim$ 1 km of altitude
- then it rises!





$\therefore$ The ionising radiation was not coming from Earth
(nor the Sun!)

Cosmic rays discovered

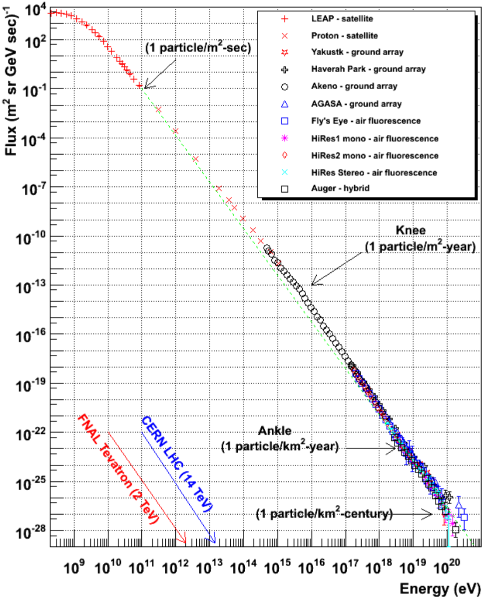
Quoting Hess:

"The results of my observation are best explained by the assumption that a radiation of very great penetrating power enters our atmosphere from above."

1920s: Robert Millikan coined the term "cosmic ray"

1936: Nobel Prize in Physics 1936 to Hess, "for his discovery of cosmic radiation"

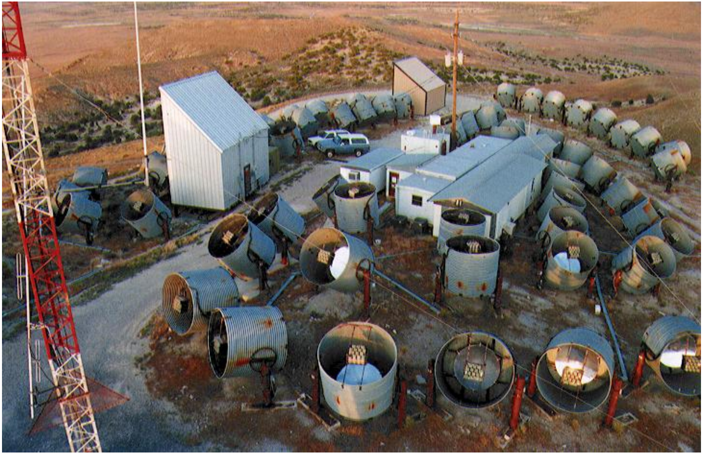
Cosmic rays: 102 years later



- they are mostly protons
- they span 12 orders of magnitude in energy
- spectrum is a power-law with two breaks: knee and ankle
- low energy: from the Sun
- higher energy: from Milky Way
- highest energy: extragalactic?

Cosmic rays: 102 years later

Our cosmic-ray detectors have also changed:



Cosmic rays: 102 years later

Our cosmic-ray detectors have also changed:

Cosmic rays: 102 years later

Our cosmic-ray detectors have also changed:

UHECRs – discovery

1962: discovery of UHECRs (ultra-high energy cosmic rays) at the Park Ranch Experiment, New Mexico

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

UHECRs – discovery

"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

UHECRs – discovery

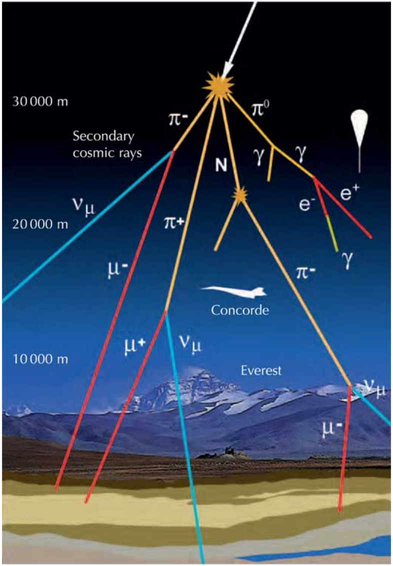
After fifty years, UHECRs are still a mystery:

- *where* are they produced?
- *how* are they produced?
- *what* are they (protons, atomic nuclei)?

We are now in a position to start giving definite answers

Neutrinos (and gamma-rays) are key to solving the mystery

UHECRs – giant air showers and detection



UHECRs – giant air showers and detection

The flux of UHECRs is *very* low: 1 particle / km^2 / century

Modern experiments detect the secondary particles of the air showers, not the primary

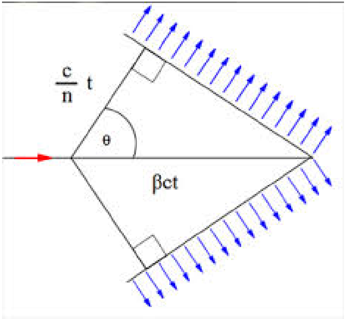
Two main detection methods:

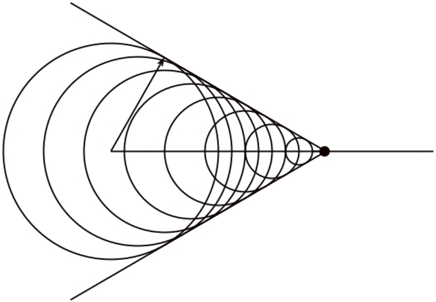
- in water: Cherenkov light inside water tanks
- in air: detection of fluorescence emission

Let us take a short detour about Cherenkov radiation ▶

Cherenkov radiation

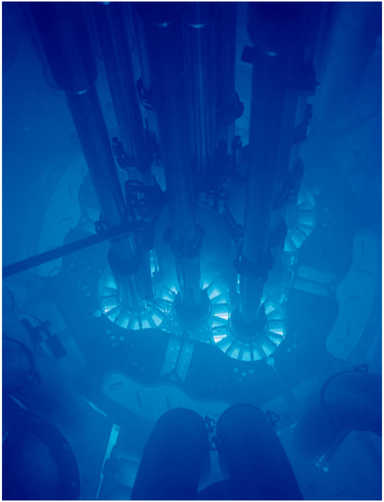
Occurs when a charged particle travels faster than light in a medium:



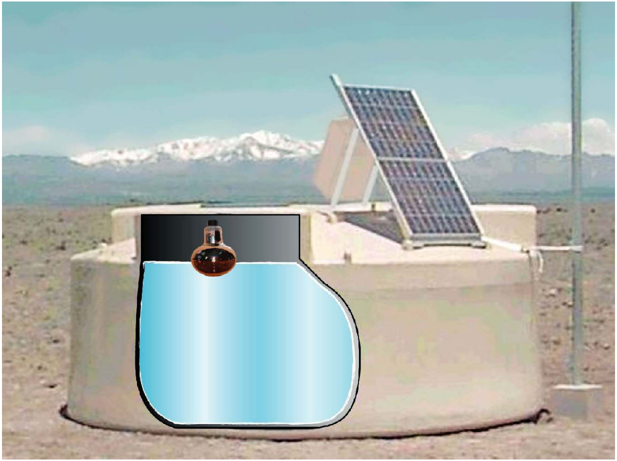


Cherenkov radiation

Cherenkov radiation

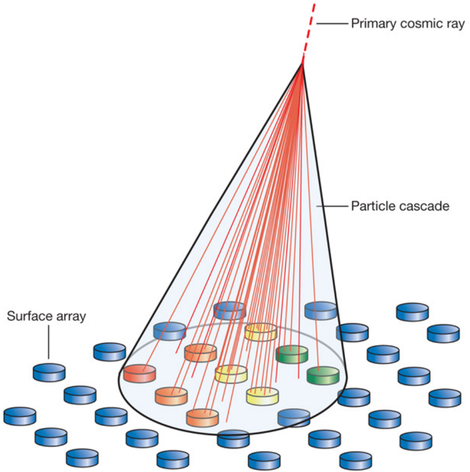


Surface CR detectors



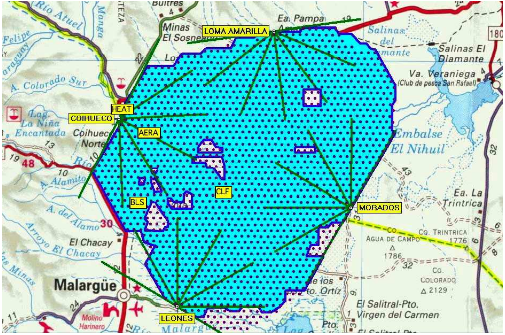
Pierre Auger Observatory

Surface CR detectors



Nature

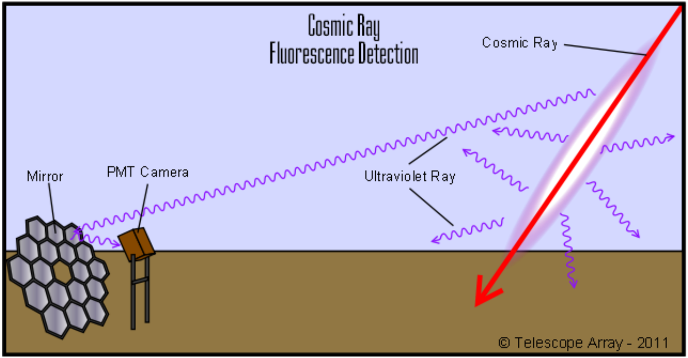
Surface CR detectors

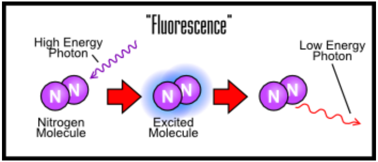


Pierre Auger Observatory:

- In Malargüe, Argentina
- 1600 water tanks
- Each one holds 1200 L of water
- Distance between tanks: 1.5 km
- 3000 km^2 of instrumented area
- Plus four air fluorescence detectors (FDs)

Fluorescence detectors



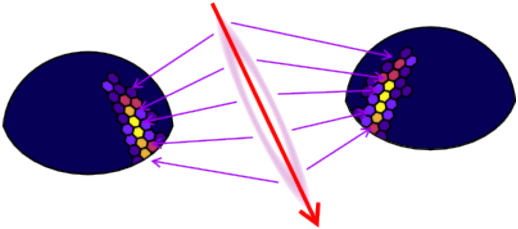


At Auger: 330-380 nm UV

Fluorescence detectors

Telescope Array

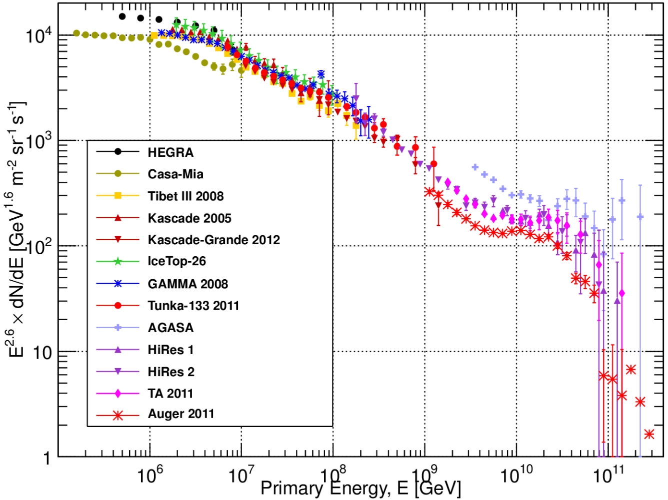
Fluorescence detectors



Telescope Array

UHECRs – shape of the spectrum

Using a combination of both methods, air-shower detectors have measured the UHECR spectrum:



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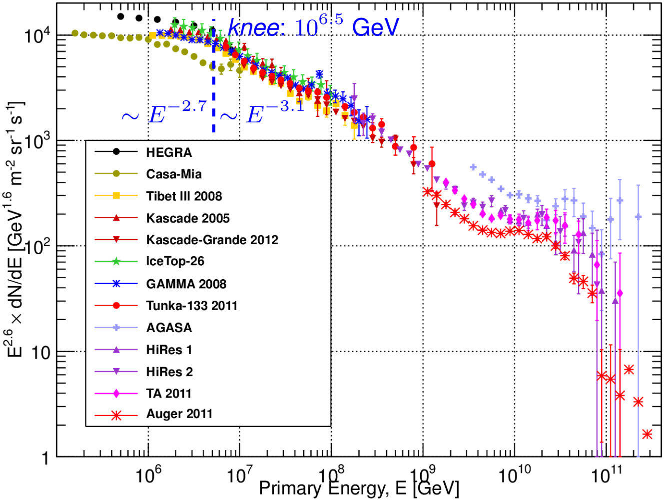

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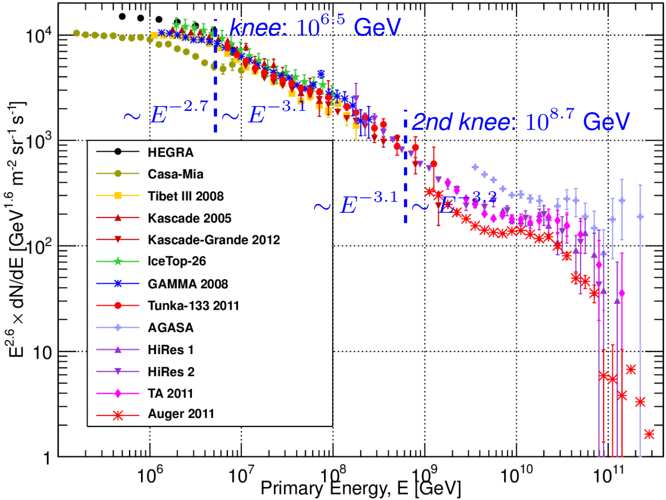

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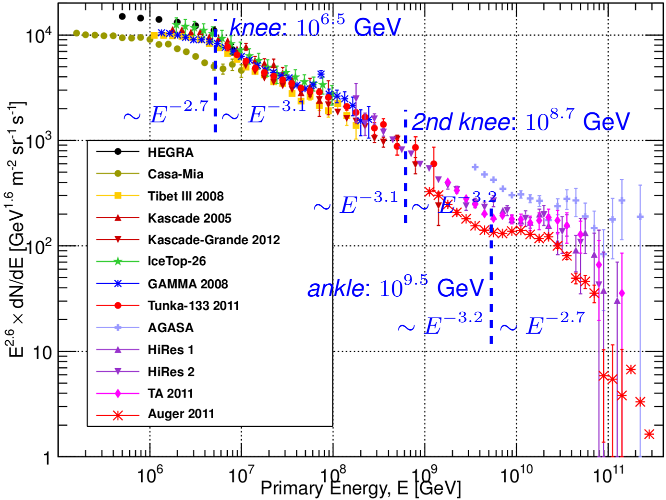

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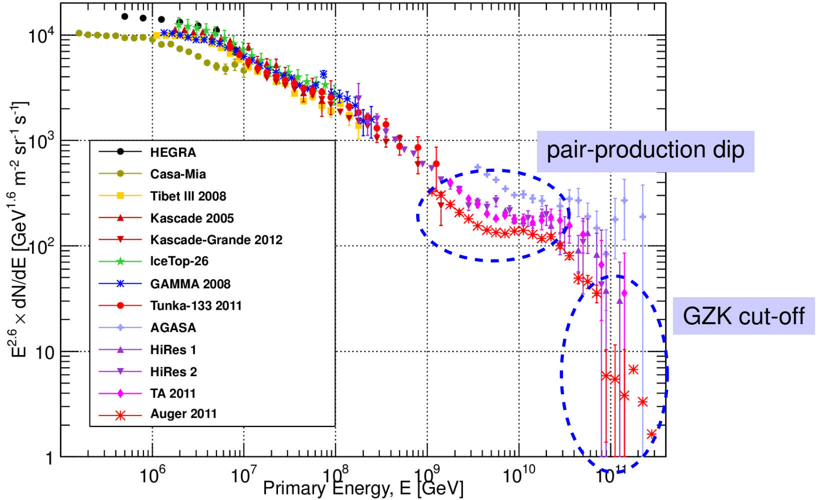
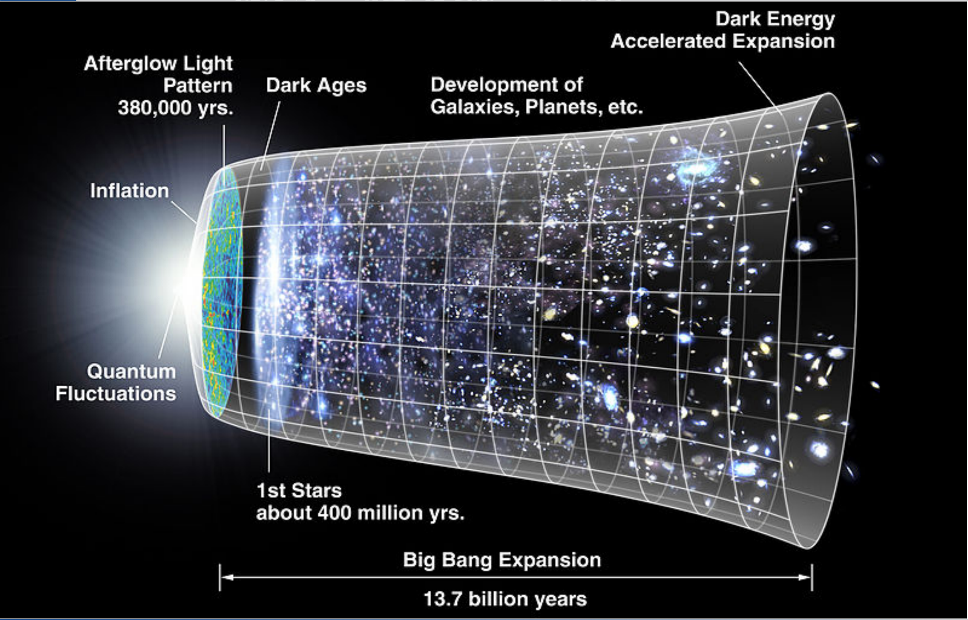


Detour: some necessary cosmology



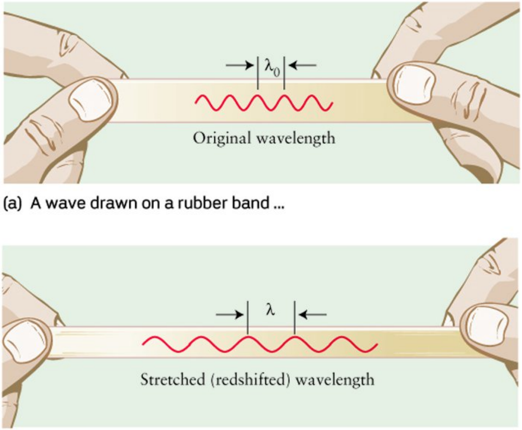
Cosmological redshift

Fact: the Universe is expanding

Assume that a photon has a wavelength

- $\lambda_{\rm emit}$ at emission time; and
- $\lambda_{\rm obs}$ when observed, today at Earth

Cosmological redshift



(a) A wave drawn on a rubber band ...

(b) ... increases in wavelength as the rubber band is stretched.

Cosmological redshift

The redshift z measures how much the wavelength is stretched:

$$1 + z = \lambda_{\text{obs}} / \lambda_{\text{emit}}$$

Because energy $E \propto 1/\lambda$, the photon cools down as the Universe expands, *i.e.*,

$$E_{\text{obs}}(z) = E_{\text{emit}} / (1 + z)$$

and . . .

the higher z, the further back in time we look ($t_{\text{emit}} \propto (1 + z)^{-3/2}$).

The cosmic microwave background (CMB)

Shortly after the Big Bang, the Universe was so hot (> 4000 K) that the following process occurred back and forth:

$$H + \gamma \longleftrightarrow p + e^- \quad (E_\gamma = 13.6 \text{ eV})$$

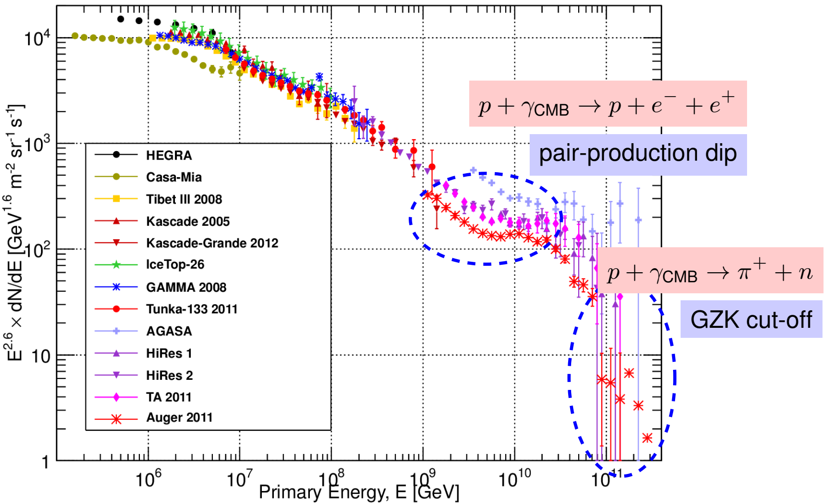
Recombination epoch: 378 000 years later (z = 1100)

- cooled photons are no longer able to ionise the hydrogen
- $\therefore$ the Universe becomes transparent

Today, these first photons are in the microwave range:
cosmic microwave background (CMB)

UHECR – shape of the spectrum

So now we know the origin of the UHECR features:



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:

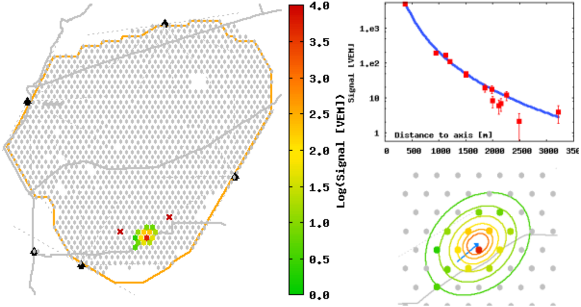
$$p(d) \approx \exp\left(\frac{-d}{6.6\ \text{Mpc}}\right) \Rightarrow p(d) < 10^{-4} \text{ for } d = 50 \text{ Mpc}$$

Two conclusions

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

UHECRs – what are they, anyway?

This is what a UHE event looks like in Auger:



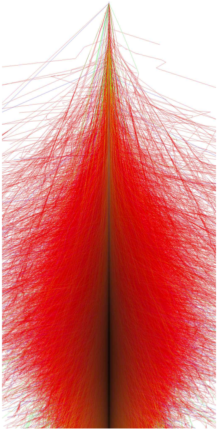
Ide	10485600
Date	Tue Oct 26 17:39:16 2010
No. of stations	14
Energy	49.7 $\pm$ 1.9 EeV
Theta	40.2 $\pm$ 0.2 deg
Phi	-139.2 $\pm$ 0.2 deg
Curvature	10.9 $\pm$ 0.5 km
Core Easting	476053 $\pm$ 19 m
Core Northing	6079248 $\pm$ 12 m
Reduced Chi^2	8.36

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

UHECRs – what are they, anyway?

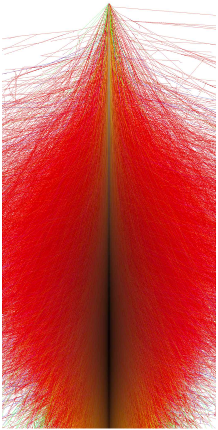
Answer:
use longitudinal air shower development information
from the fluorescence detectors

10^6 GeV proton



vs.

10^6 GeV Fe-56 nucleus



F. Schmid, Univ. Leeds

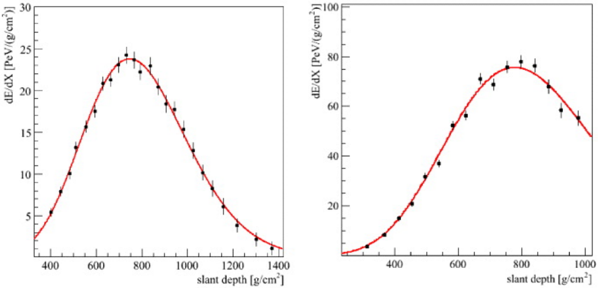
UHECRs – what are they, anyway?

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

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

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

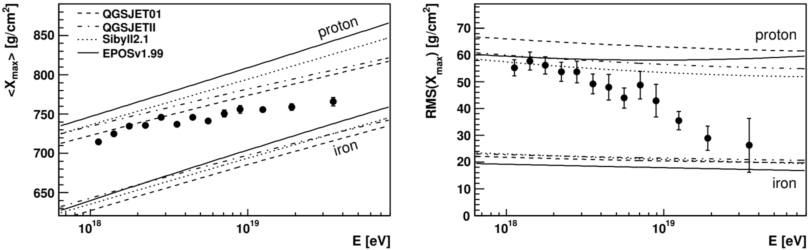
Using the FDs, measure $N(x)$, $x_{\rm max}$ for each shower:



UHECRs – what are they, anyway?

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

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



AUGER

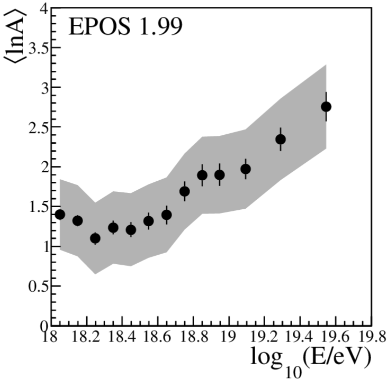
There is a tendency towards heavier composition at very high energies

UHECRs – what are they, anyway?

$\langle x_{\text{max}} \rangle$ 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

Two considerations:

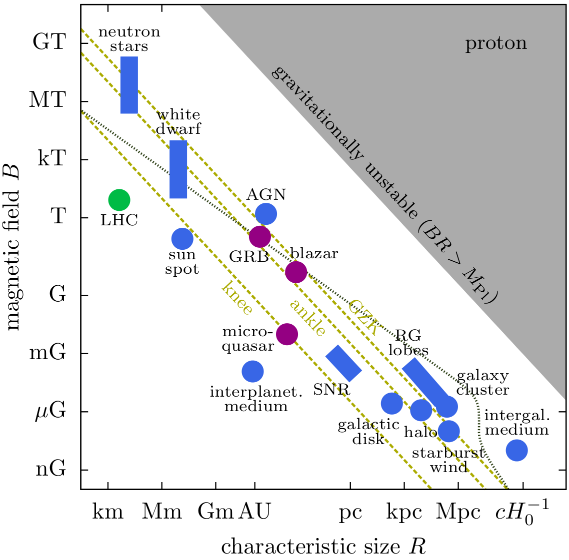
1. Charged particles (Z) are assumed to be accelerated by intense magnetic fields in astrphysical sources
2. For the acceleration to be mantained, the gyroradius should be smaller than the size of the acceleration region

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

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

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

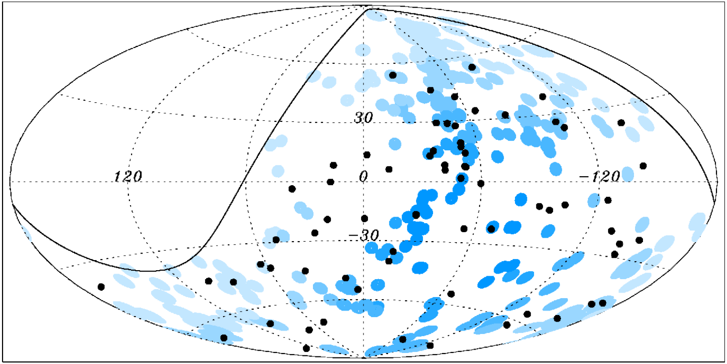
The Hillas criterion



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)

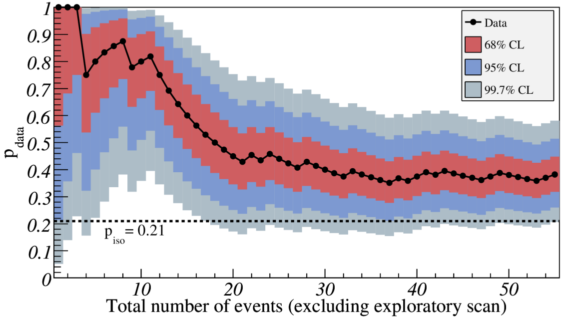
UHECRs – correlation with known sources

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

k: number of UHECRs correlated to sources

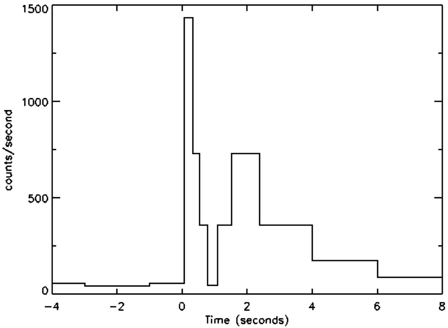
N: total number of UHECRs

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, $p_{\text{iso}} = 0.21$

1967: the nuclear-test-monitoring satellites Vela discover the following gamma-ray-pulse



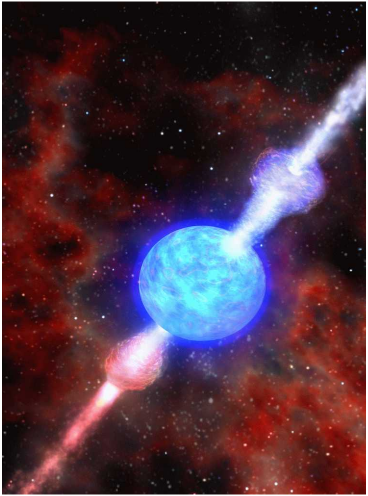
What is was not:

- a nuclear explosion (too long)
- a solar flare
- a new supernova

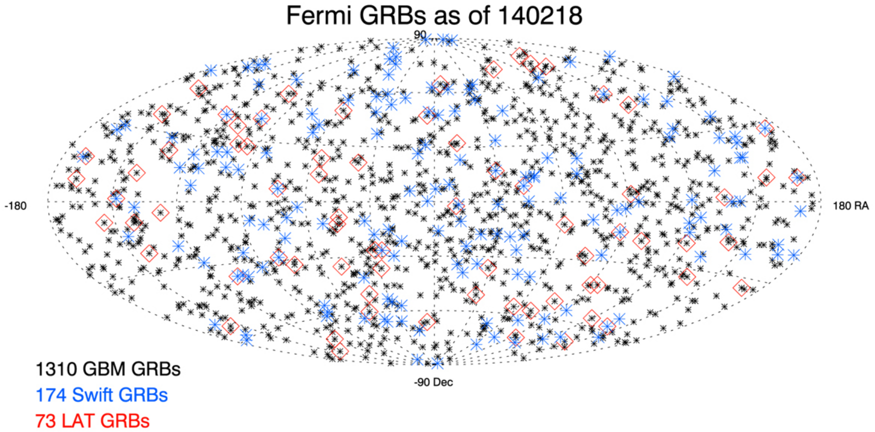
So what was it?

Gamma-ray bursts (GRBs)

Probably something like this . . .

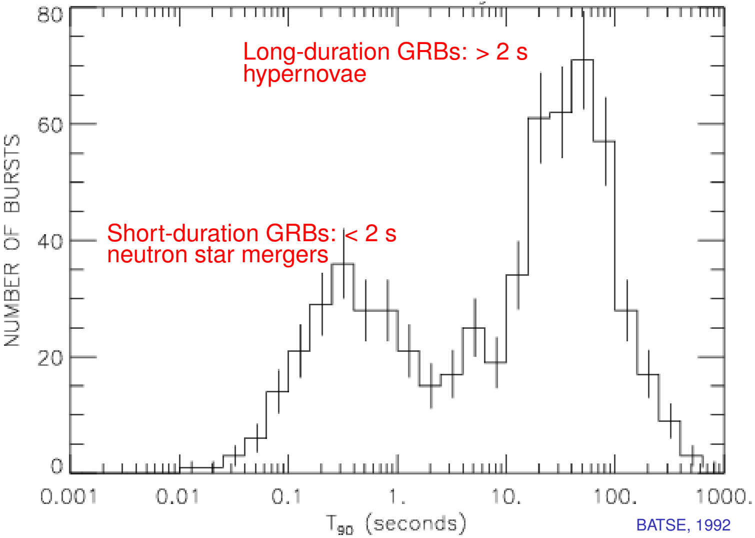


Gamma-ray bursts (GRBs)



Gamma-ray bursts (GRBs)

Two populations of GRBs:



BATSE, 1992

Gamma-ray bursts (GRBs)

GRBs are among the best candidate UHECR sources:

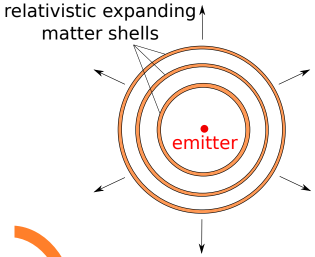
- radiated energy of $\sim 10^{52} - 10^{53}$ erg
- intense magnetic fields of $\sim 10^{5}$ G
- magnetically-confined p's shock-accelerated to $\sim 10^{12}$ GeV

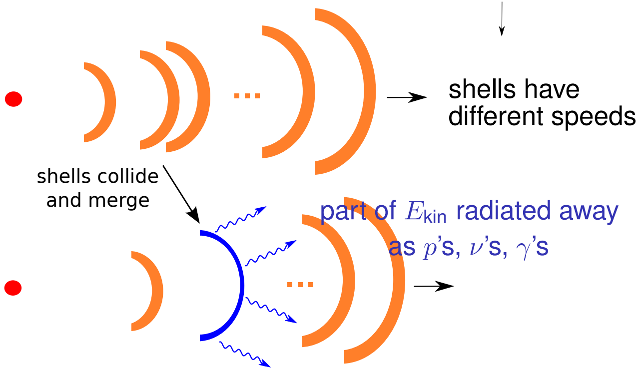
Problem: experiments (IceCube, ANTARES) are starting to strongly constrain the simplest emission models

Solution: we need to build more realistic models!

Internal shocks in the fireball model

Long-duration GRB ($\geq$ 2 s):
a compact object ($\sim 10^3$ km) emits relativistically expanding baryonic-loaded matter ejecta





The standard "neutron model" of emission

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

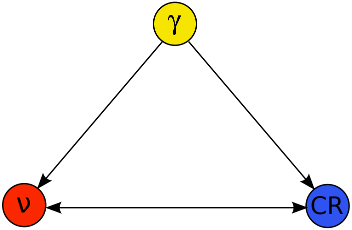
$$p\gamma \to \Delta^+(1232) \to \begin{cases} n\pi^+ , & \text{BR} = 1/3 \\ p\pi^0 , & \text{BR} = 2/3 \end{cases}$$

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

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

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

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



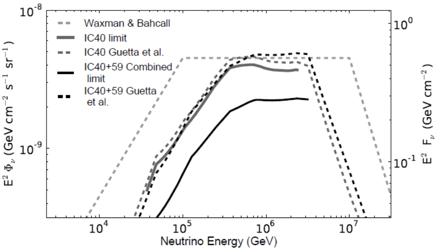
After propagation, with flavour mixing:

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

("one ν_μ per cosmic ray")

The *simplest* neutron model is now strongly disfavoured ▸

The neutron model under tension?



IceCube Collaboration:

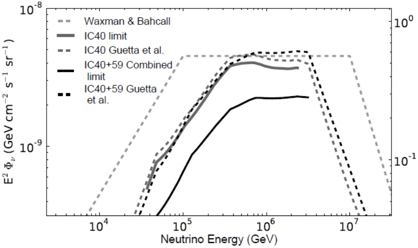
- ν flux normalised to GRB γ fluence:

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

- 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)

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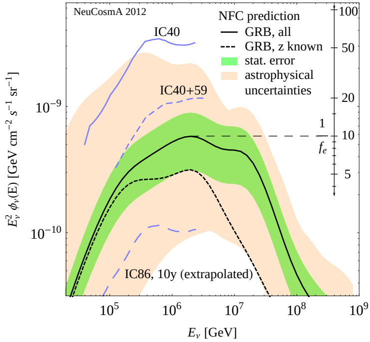
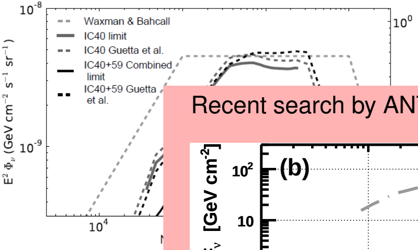


The neutron model under tension?



More detailed particle physics (NeuCosmA):

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

ude lower

31101 (2012)

12)

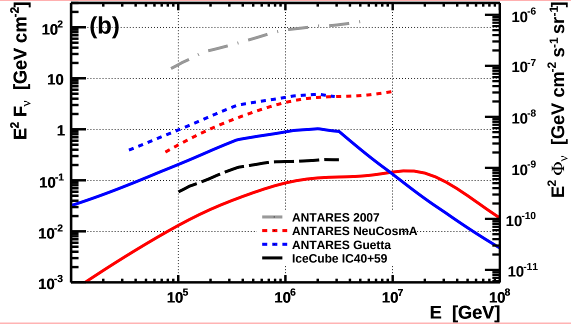
IceCube Collabor

- ν flux norm

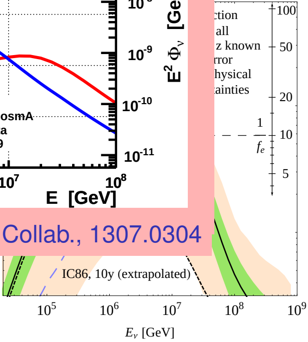
$$\int_0^\infty dE_\nu E_\nu I$$

- quasi-diffus
- analytical c
  upper bour

Recent search by ANTARES optimised for NeuCosmA:



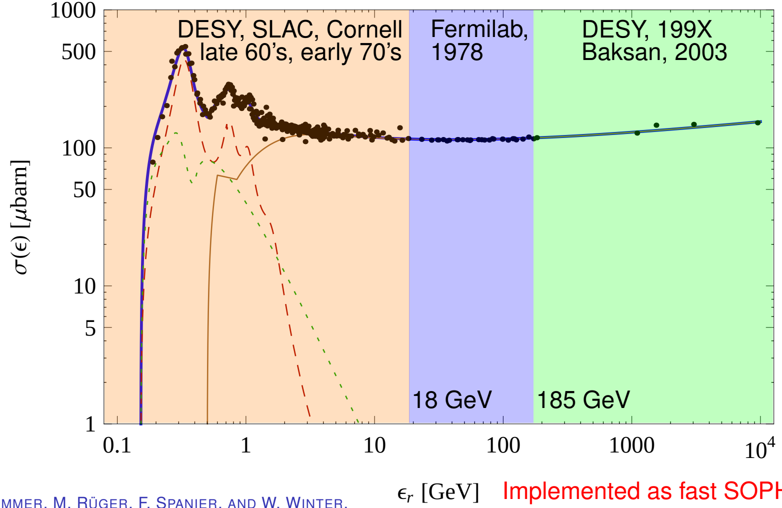
ANTARES Collab., 1307.0304



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

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

The UHECR and UHE ν fluxes at Earth

We use a Boltzmann equation to transport protons to Earth:

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

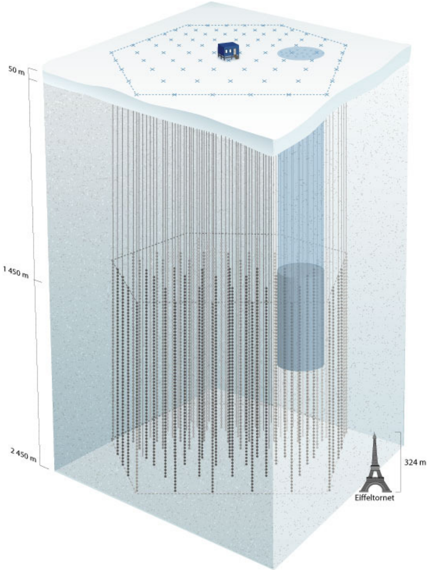
- Transport equation (comoving source frame):

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

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

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

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

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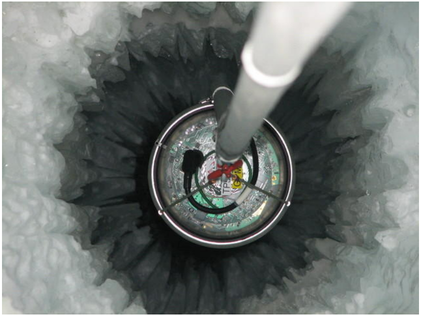

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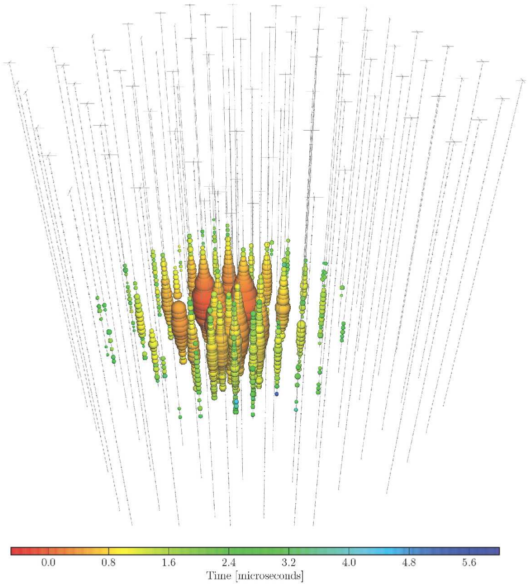
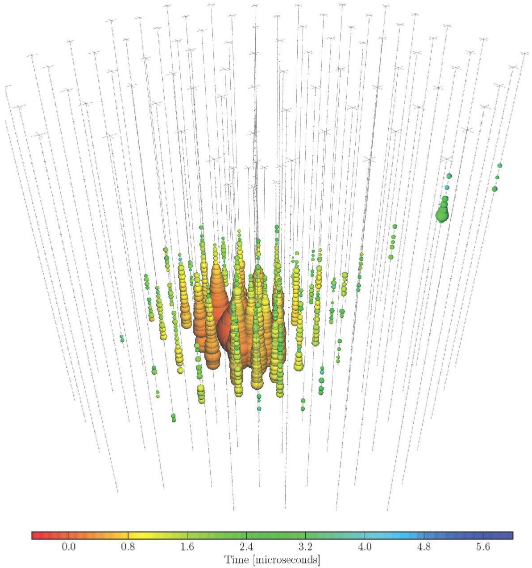


Detecting the neutrinos



Cosmogenic neutrinos

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

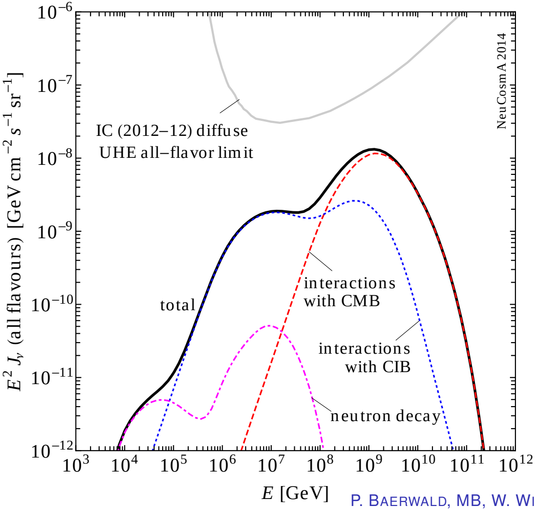
$$p + \gamma \to \Delta^+ \to \pi^+ + n \ ,$$

and neutrinos are created in the decays of the secondaries:

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

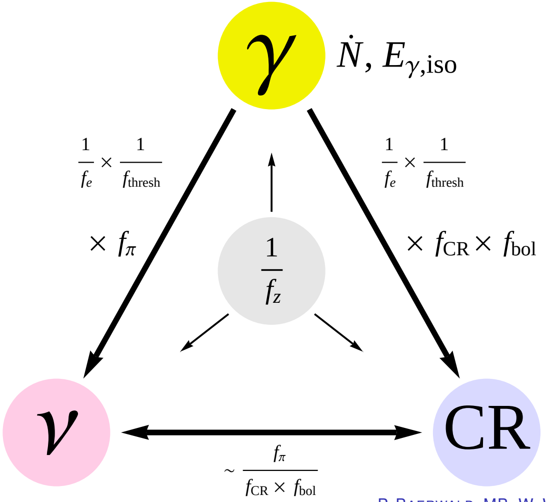
These are called *cosmogenic neutrinos*

Cosmogenic neutrinos



P. Baerwald, MB, W. Winter, arXiv:1401.1820

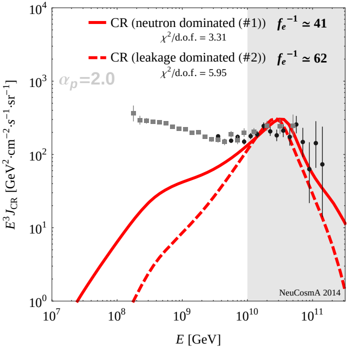
The big (multi-messenger) picture:

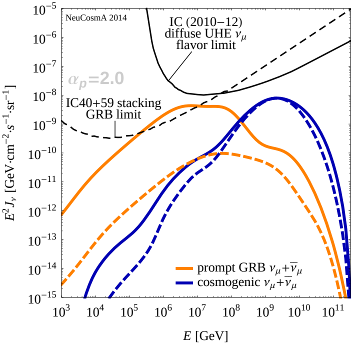


P. Baerwald, MB, W. Winter, arXiv:1401.1820

UHECRs and UHE neutrinos

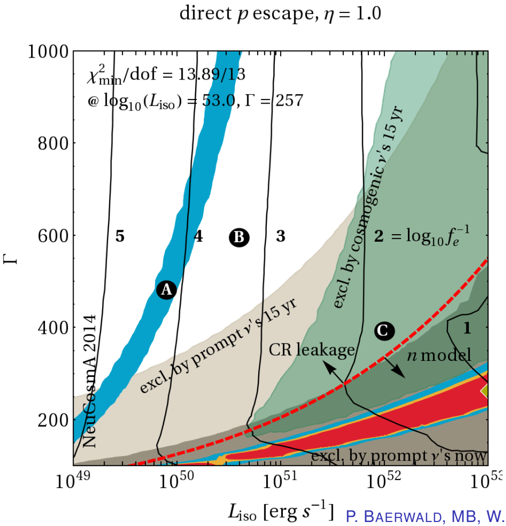
- Propagate protons to generate a diffuse UHECR flux
- Normalise to experimental data (shown: HiRes)
- Carry the normalisation to the prompt and cosmogenic ν fluxes
- Compare to the neutrino upper bounds by IceCube





P. Baerwald, MB, W. Winter, *Astrophys. J.* **768**, 186 (2013)
P. Baerwald, MB, W. Winter, arXiv:1401.1820

If the ν fluxes exceed the bounds, exclude this parameter space point:



P. Baerwald, MB, W. Winter, arXiv:1401.1820

What is in store for the future?

- Auger will continue taking data:
  - better composition determination
  - updates on correlation with sources
  - more precise determination of the spectrum
- Perhaps Auger North will be built
- Hopefully a satellite to observe atmospheric fluoresence, *e.g.*, JEM-EUSO on the ISS
- IceCube has started detecting EHE events: correlations with GRBs in the future?
- The KM3NeT neutrino telescope might be built in the Mediterranean Sea

The future for UHECR and neutrino research looks bright
Stay tuned!

Backup slides

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

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

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

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

Three emission regimes

Optically thin to neutron escape regime

- the standard emission scenario
- p's magnetically confined: n's and ν's from $p\gamma$ interactions
- n's escape and decay to produce UHECRs

Direct escape regime

- directly-escaping p's from the borders dominate
- subdominant n production
- more CRs emitted, so "one ν_μ per CR" no longer valid

Optically thick to neutron escape regime

- n's and p's in the bulk trapped by multiple $p\gamma$ interactions
- they only escape from the borders
- ν production enhanced

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

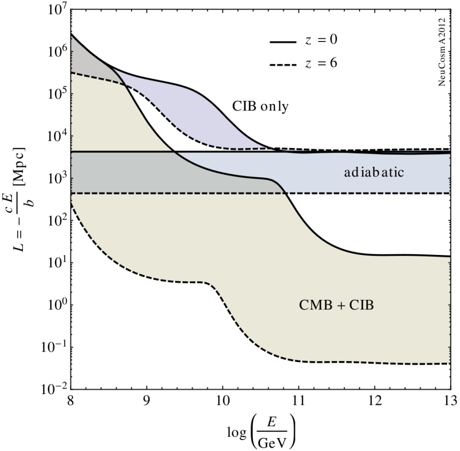
$$t_{p\gamma}^{-1}(E,z) = \sum_i^{\text{all channels}} \Gamma_{p\to p}^i(E,z)\, K^i \,,$$

   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]

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]

Interaction lengths

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

P. Baerwald, MB, W. Winter, arXiv:1401.1820

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

P. BAERWALD, MB, W. WINTER, ARXIV:1401.1820

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P. Baerwald, MB, W. Winter, arXiv:1401.1820

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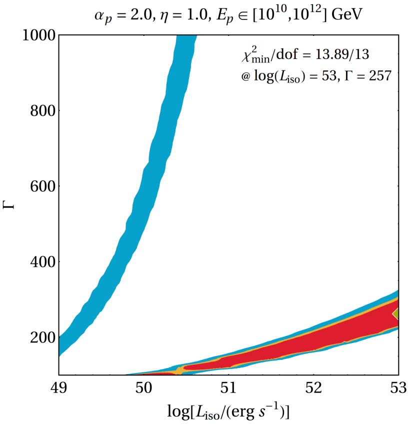
2. Fit each spectrum to the HiRes data
3. Find the best-fit point (diamond), and the 90% (red), 95% (yellow), and 99% (blue) C.L. regions



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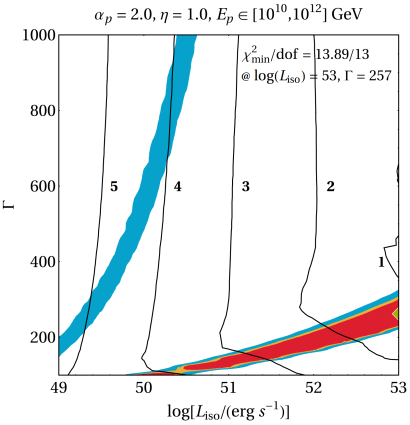
4. Find the baryonic loading (*i.e.*, relative energy of p's to e's) at each point



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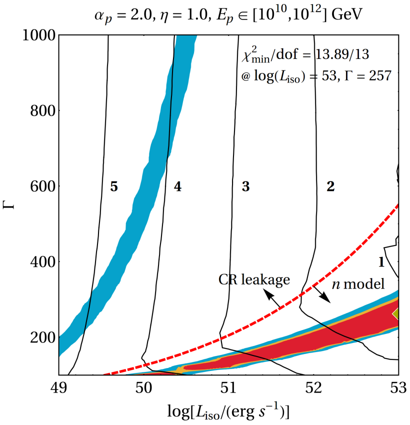
4. Find the baryonic loading (*i.e.*, relative energy of p's to e's) at each point
5. Identify the region corresponding to pure n escape and to n escape + CR leakage



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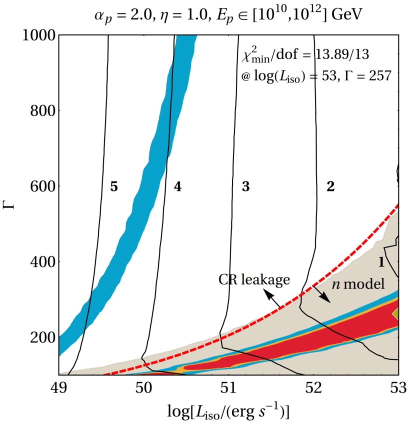
6. Find the region where the number of prompt ν_μ's is > 2.44, *i.e.*, the excluded region at 90% C.L.



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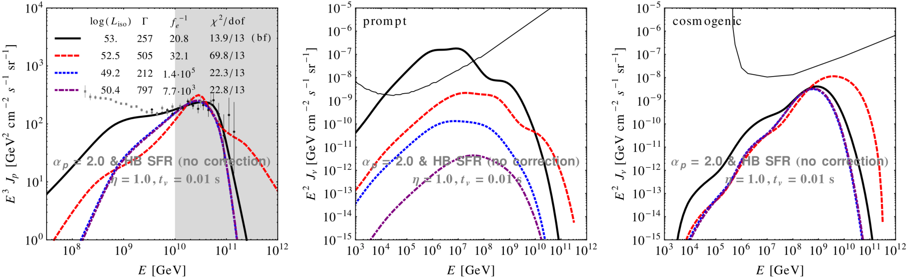

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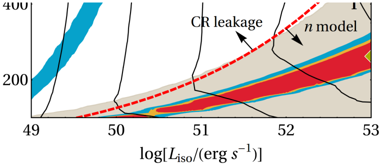

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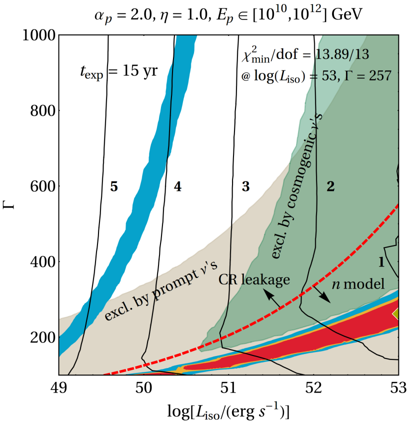
7. After 15 yr of exposure and no detection, cosmogenic neutrinos also exclude



P. Baerwald, MB, W. Winter, arXiv:1401.1820