Gamma rays, cosmic rays, and neutrinos: windows into the ultra-high-energy Universe

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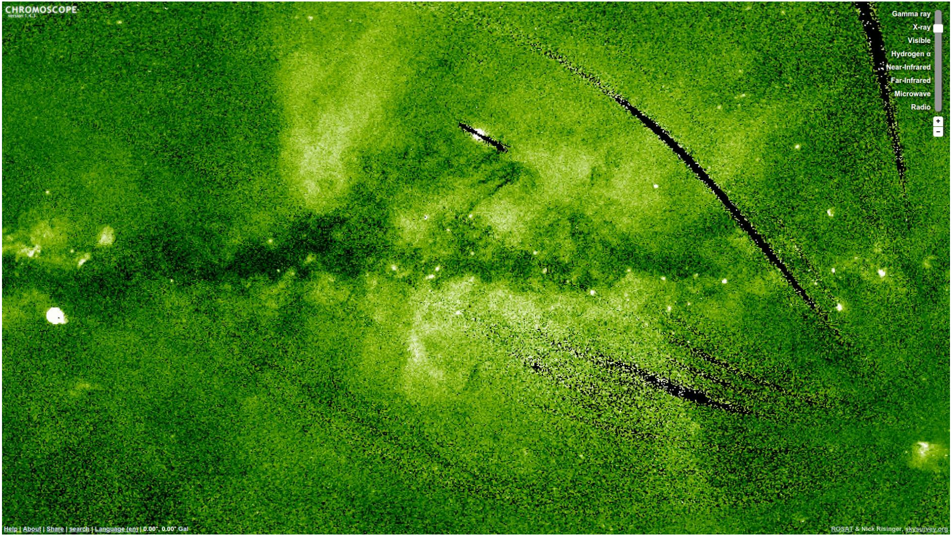
THE OHIO STATE UNIVERSITY

CCAPP

Milky Way in **visible light** (551, 658 nm $\equiv$ 2.25, 1.88 eV):

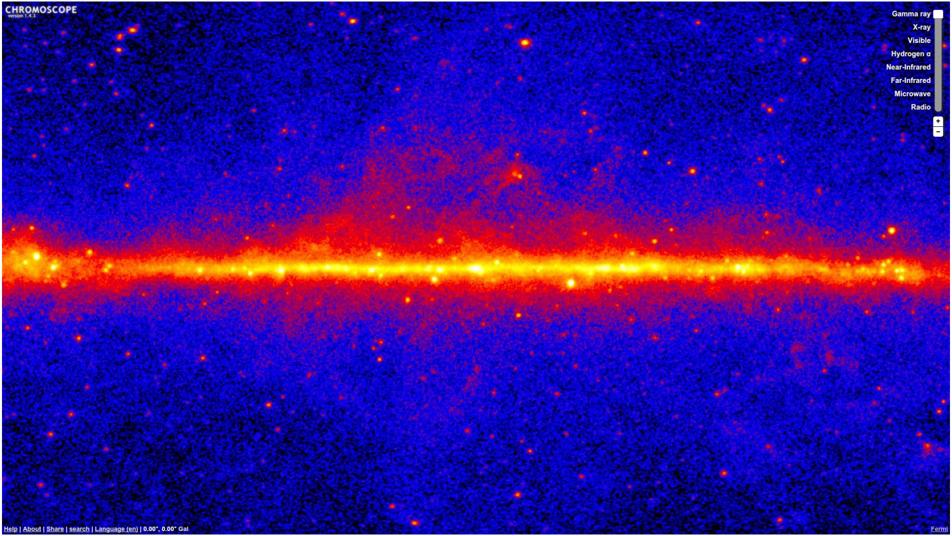
Chromoscope – Nick Risinger, skysurvey.org

Milky Way in **X rays** (0.1 – 2 keV):



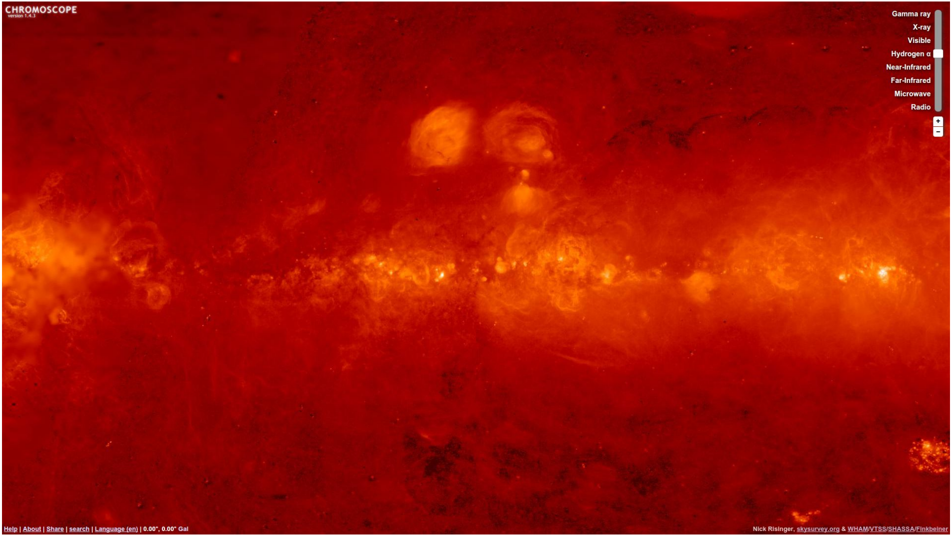
Chromoscope – ROSAT & Nick Risinger, skysurvey.org

Milky Way in **gamma rays** (10 keV – 300 GeV):



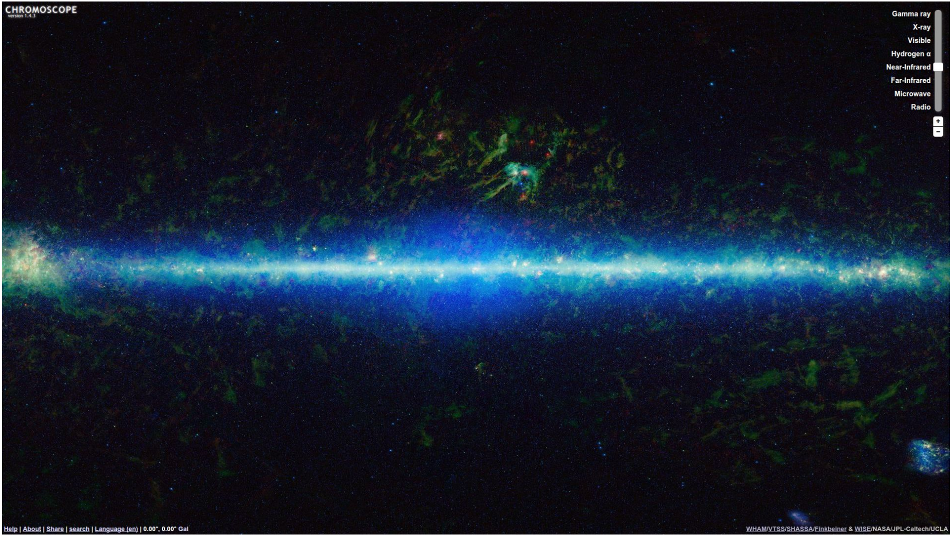
Chromoscope – Fermi

Milky Way in Hα (656.3 nm ≡ 1.89 eV):



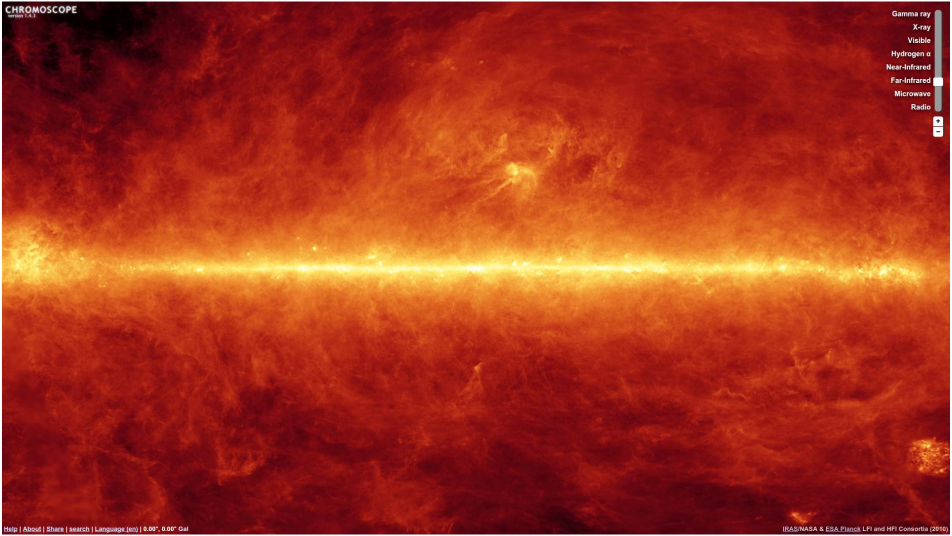
Chromoscope – Nick Risinger, WHAM / SHASSA / VTSS / Finkbeiner

Milky Way in **near infrared** (750–2500 nm $\equiv$ 1.65–0.496 eV):



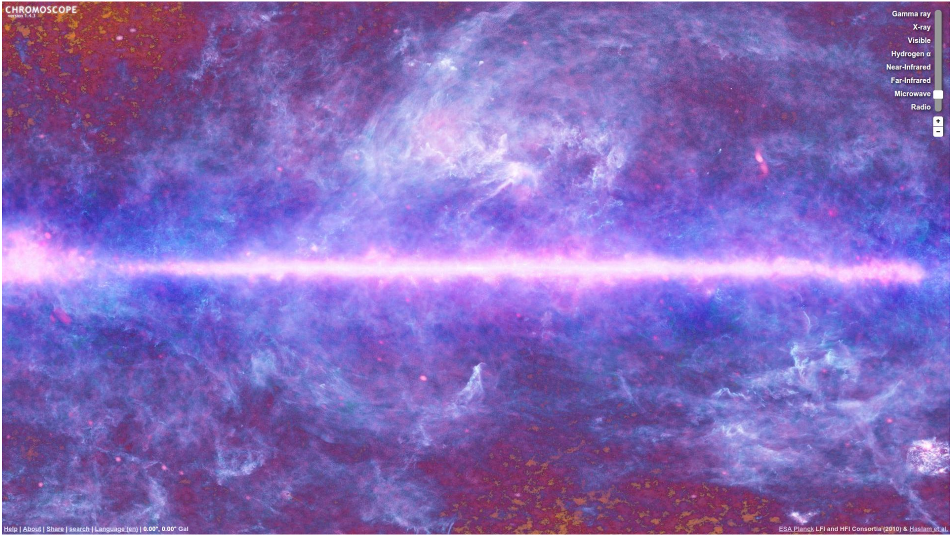
Chromoscope – WHAM / SHASSA / VTSS / Finkbeiner

Milky Way in **far infrared** (10–100 μm $\equiv$ 124–12.4 meV):



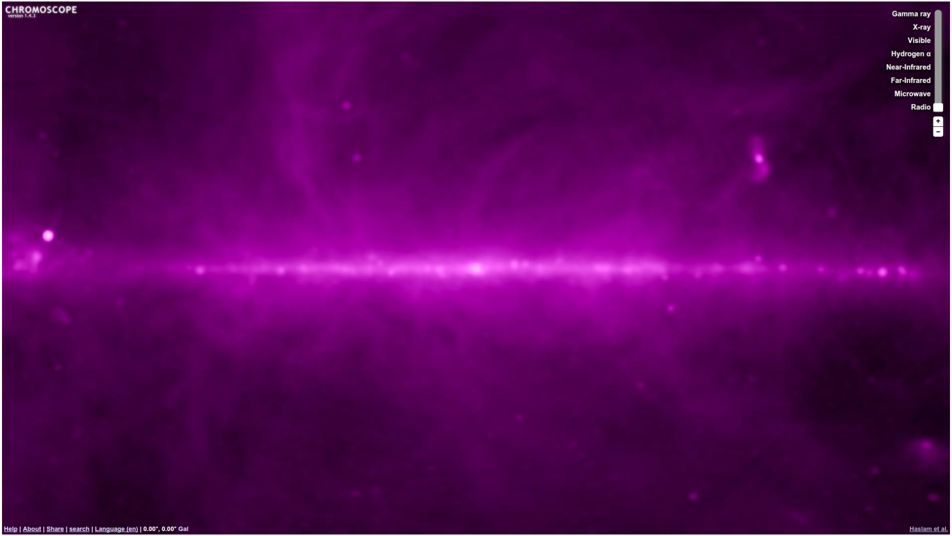
Chromoscope – Fermi

Milky Way in **microwaves** (0.35, 10 mm $\equiv$ 3.54, 1.24 meV):



Chromoscope – Planck

Milky Way in **radio** (408 Mhz $\equiv$ 1.69 meV):



Chromoscope – Haslam *et al.*

But the Universe is **not** static

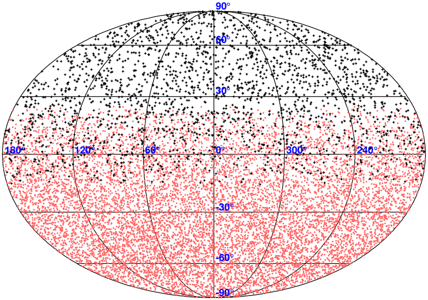
e.g., 500 gamma-ray bursts seen by the *Swift* satellite (2004–2013) –

Swift/NASA

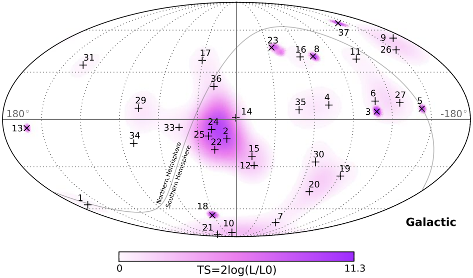
Also, light is **not** the only lens with which to see the Universe
– there are other cosmic messengers:

ultra-high-energy cosmic rays

ultra-high-energy neutrinos



Auger/TA



IceCube

We will take a closer look at both of them . . .

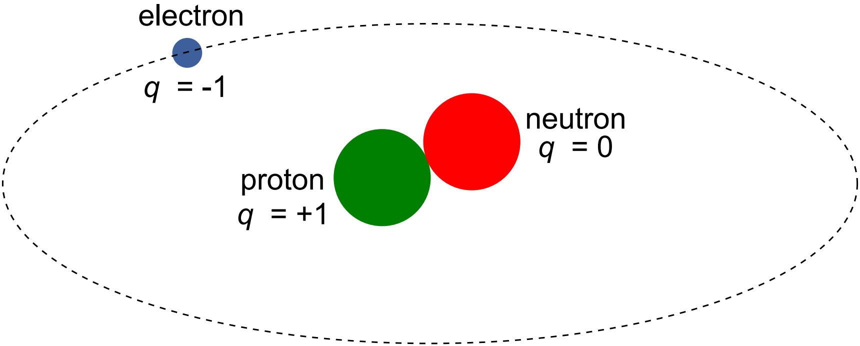
Plan of attack:

1. **Neutrinos** – what are they? where do they come from?
2. **Cosmic rays** – what we know / don't know about them
3. What are the **sources** of the UHE messengers?
4. **The future** – more data, better detectors

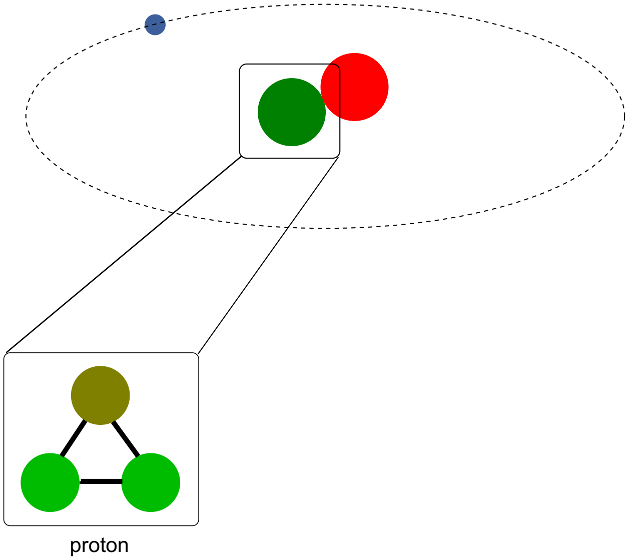
Neutrinos

Neutrinos – what are they?

An atom of deuterium, ${}^{2}_{1}$H:



Neutrinos – what are they?



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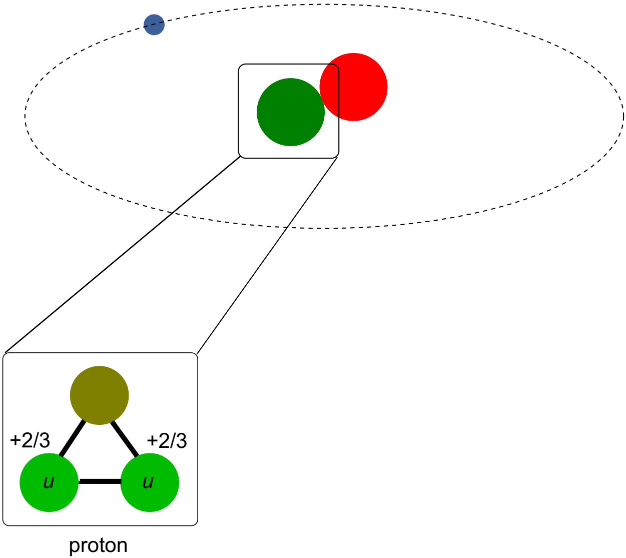

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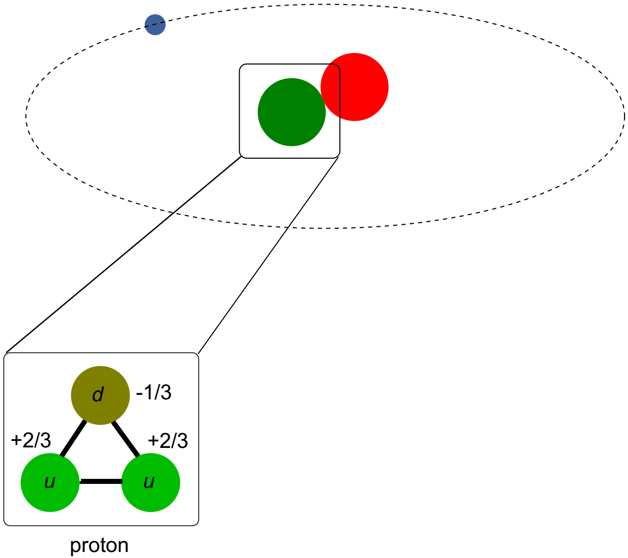

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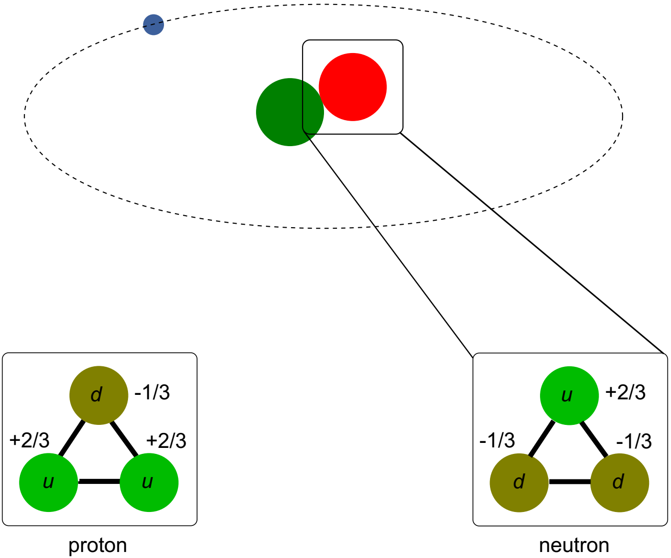

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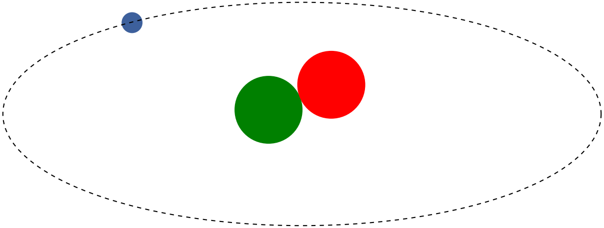

Six quarks, grouped in three families:

-1/3	*d* down	*s* strange	*b* bottom
+2/3	*u* up	*c* charm	*t* top

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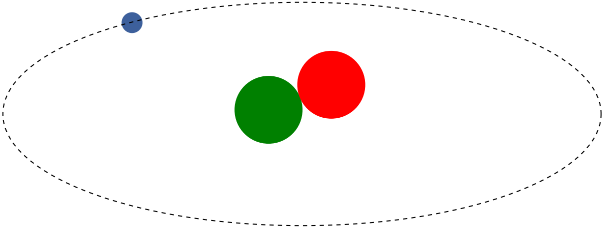

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mass →

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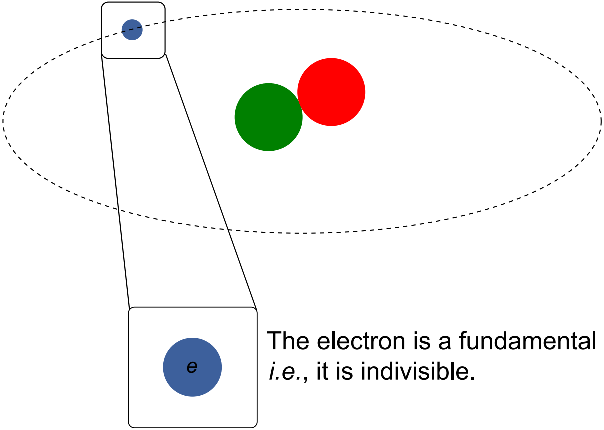
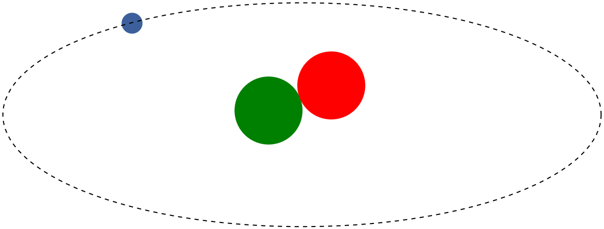
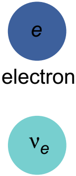


The electron is a fundamental particle,
i.e., it is indivisible.

Neutrinos – what are they?



q = -1



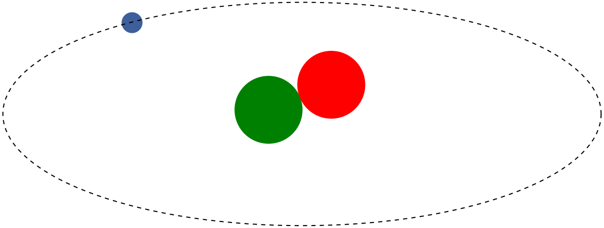
electron

q = 0

neutrino-*e*

The electron and the neutrino are *leptons*.

Neutrinos – what are they?



Leptons are also grouped in three families:

-1	e electron	μ muon	τ tau
0	ν_e neutrino-e	ν_μ neutrino-μ	ν_τ neutrino-τ

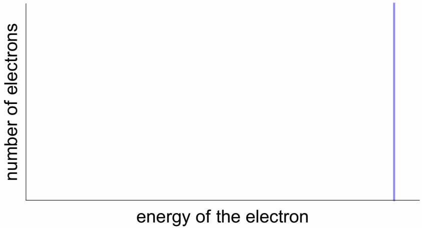
→ mass

Neutrinos – how where they discovered?

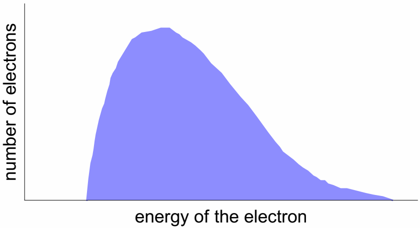
<1930: β decay was understood as

$$n^0 \rightarrow p^+ + e^-$$

We expected to see ...



... but we found



Bohr proposed to weaken the principle of conservation of energy.

1930: Pauli postulated the neutrino to maintain energy and momentum conservation in β decay:

$$n^0 \rightarrow p^+ + e^- + \bar{\nu}_e$$

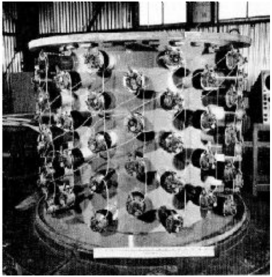
Neutrinos – how where they discovered?

1956: Cowan and Reines detect the $\bar{\nu}_e$ through

$$\bar{\nu}_e + p^+ \rightarrow n^0 + e^+$$

$$(1) \quad e^+ + e^- \rightarrow \gamma + \gamma \qquad (2) \quad n^0 + N_i \rightarrow \gamma + N_f$$

The coincidence of both emissions reveals that a $\bar{\nu}_e$ interacted.



Neutrinos – what do we know about them today?

1962: Lederman, Schwartz, and Steinberger detect the ν_μ

1975: τ lepton discovered at the Stanford Linear Accelerator Center

2000: detection of the ν_τ by the DONUT collaboration at Fermilab

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  (*e.g.*, active galactic nuclei, *gamma-ray bursts*)

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- nuclear reactors
- supernovae
- particle accelerators
- high atmosphere
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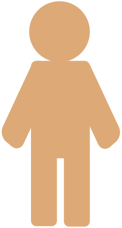
Even in the human body:



Potasium-40 is radioactive, with $\tau_{1/2} = 1.25 \times 10^9$ years

$$\left.\begin{array}{r} e^- + {}^{40}_{19}\text{K} \to {}^{40}_{18}\text{Ar} + \nu_e \ \ (e^- \text{ capture}) \\ {}^{40}_{19}\text{K} \to {}^{40}_{18}\text{Ar} + e^+ + \nu_e + \gamma \ \ (\beta^+ \text{ decay}) \end{array}\right\} \ 11.2\%$$

$${}^{40}_{19}\text{K} \to {}^{40}_{20}\text{Ca} + e^- + \bar{\nu}_e \ \ (\text{decaimiento } \beta) \qquad \} \ 88.8\%$$

$\sim$ 4400 $(\nu_e + \bar{\nu}_e)$ emitted s^{-1} by a 70 kg person

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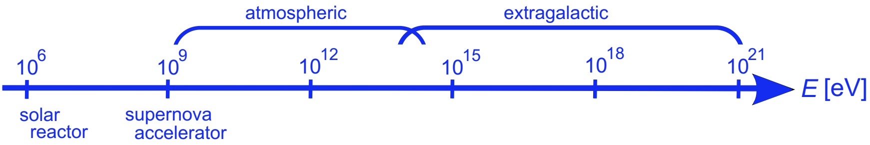

$$1 \text{ eV} \approx 1.6 \times 10^{-19} \text{ J}$$

$$1 \text{ eV}/c^2 \approx 1.7 \times 10^{-36} \text{ kg}$$

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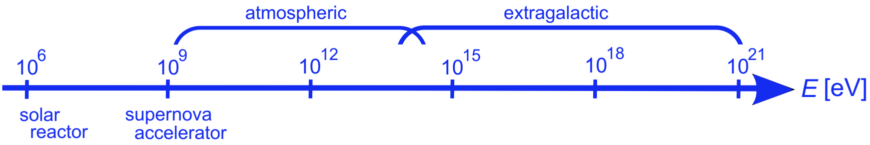

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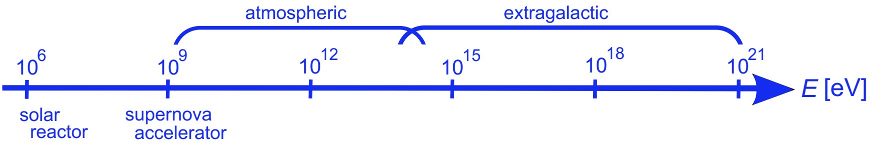

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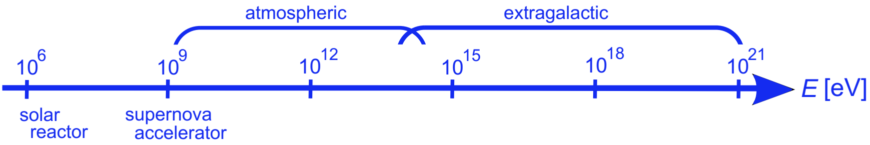

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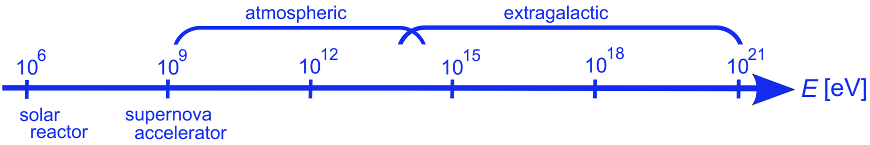

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- $\sim$ 624 EeV (6.24×10^{20} eV): energy needed to light a bulb of 100 W for 1 s

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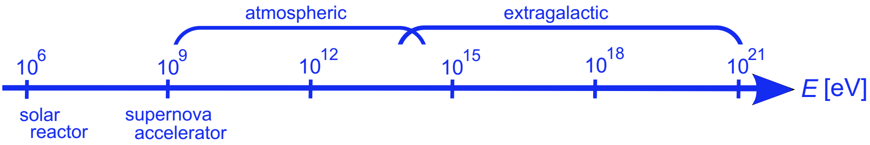


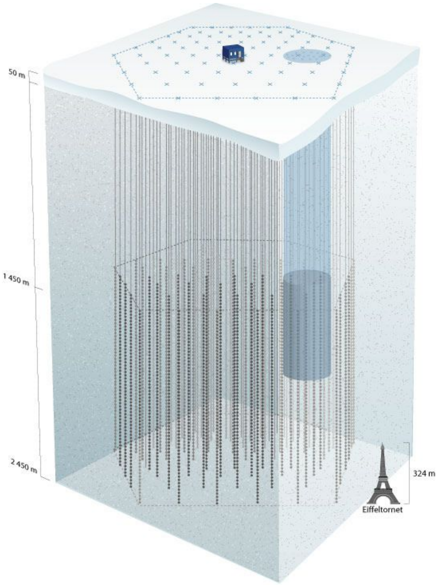
The higher the neutrino energy,
the larger the probability to detect it.

Cross section ν–p (elastic):

$$\sigma_{\nu p \to \nu p}(E) \approx 6 \times 10^{-46} \left(\frac{E}{1 \text{ MeV}} \right)^2 \text{ cm}^2$$

probability of detection $\propto \sigma$

Neutrinos – how are UHE ν's detected?



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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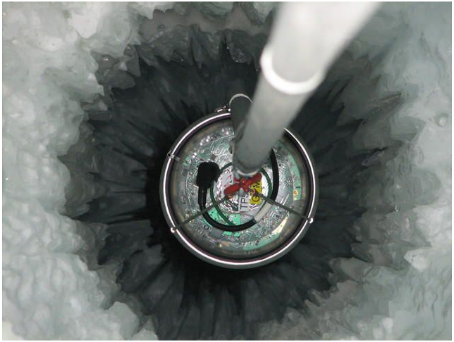

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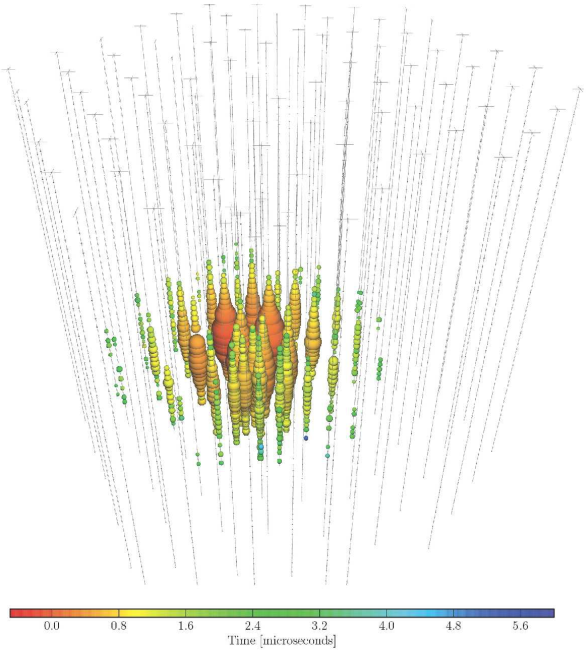
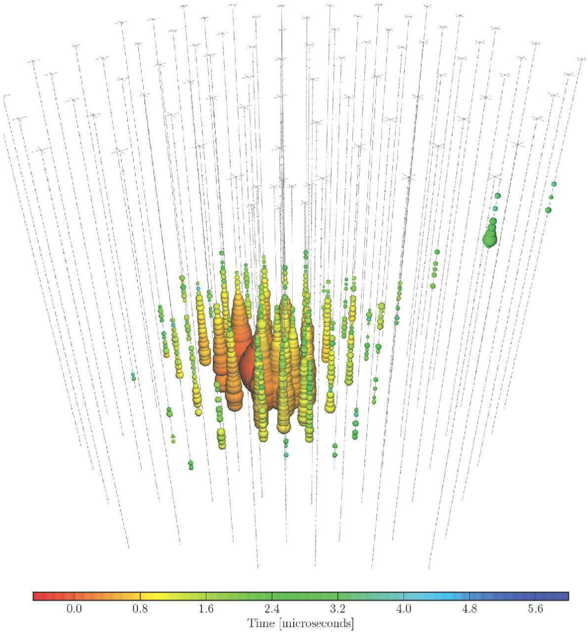

0.0
0.8
1.6
2.4
3.2
4.0
4.8
5.6
Time [microseconds]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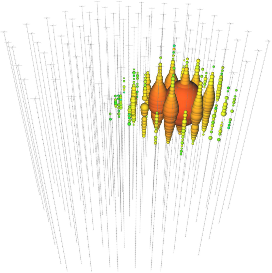
Neutrinos – how are UHE ν's detected?

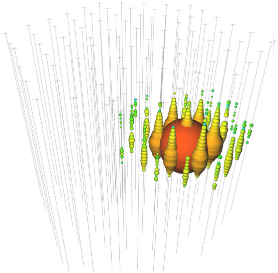
The era of neutrino astronomy has begun!

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

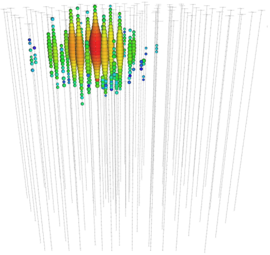
"Bert", 1.04 PeV



"Ernie", 1.14 PeV



"Big Bird", 2 PeV



. . . and 34 more events < 385 TeV

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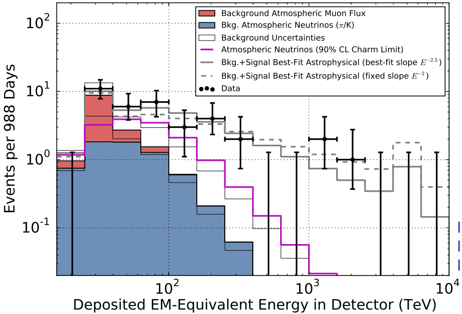

IceCube, *PRL* **111**, 021103 (2013)
IceCube, *Science* **342**, 1242856 (2013)
IceCube, *PRL* **113**, 101101 (2014)

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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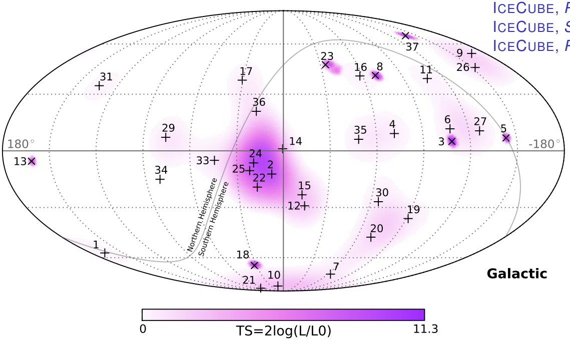
Arrival directions compatible with an isotropic distribution –

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



+: shower
×: muon track

– no association with sources found yet

Cosmic rays

Cosmic rays discovered

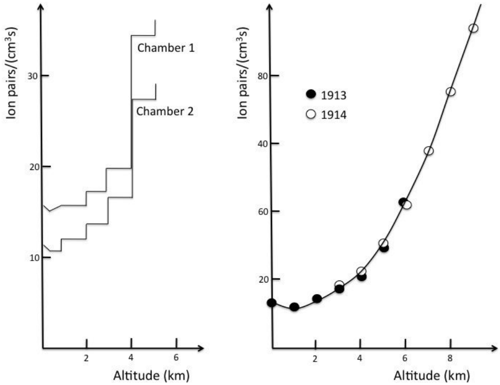
1911–1913: the Austrian physicist Victor Hess made balloon flights up to an altitude of 5.3 km

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

Cosmic rays discovered

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

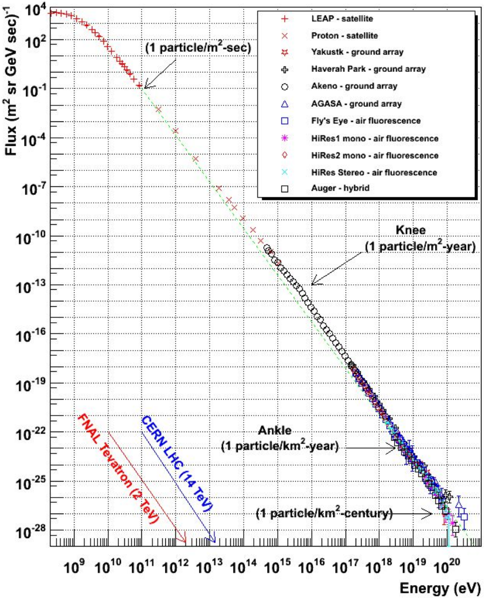
Quoting Hess:

“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

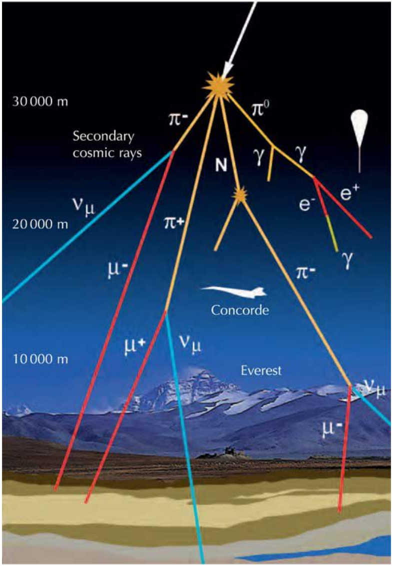
After fifty years, UHECRs are still a mystery:

- *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

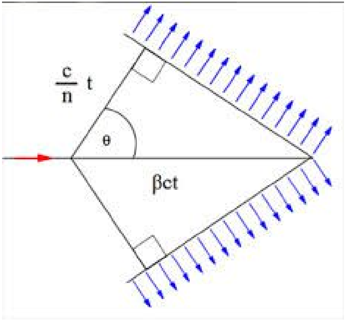
Two main detection methods:

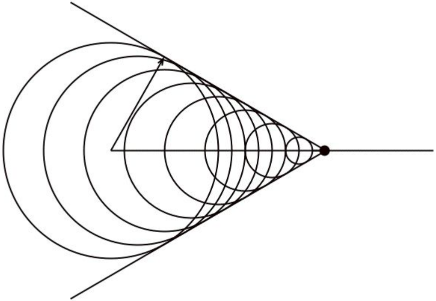
- in water: Cherenkov light inside water tanks
- in air: detection of fluorescence emission

Let us take a short detour about Cherenkov radiation ▶

Cherenkov radiation

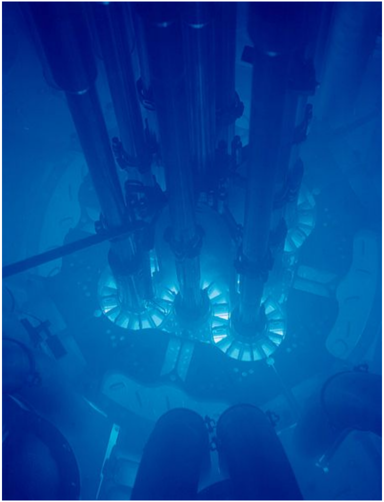
Occurs when a charged particle travels faster than light in a medium:



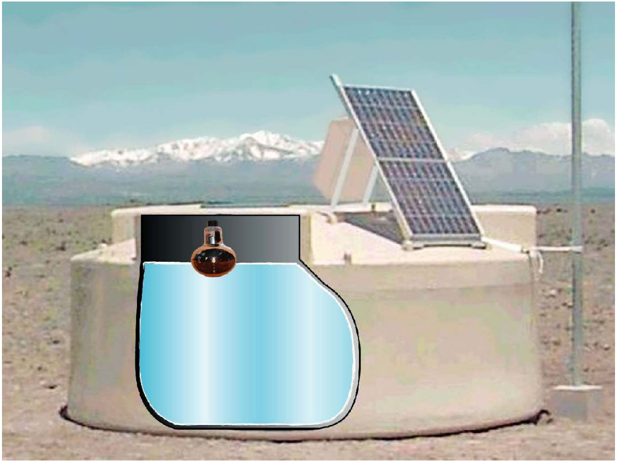


Cherenkov radiation

Cherenkov radiation

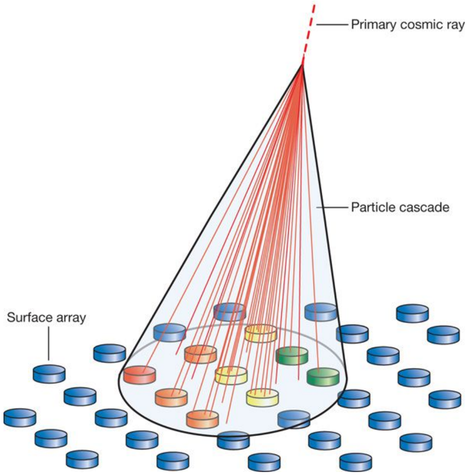


Surface CR detectors



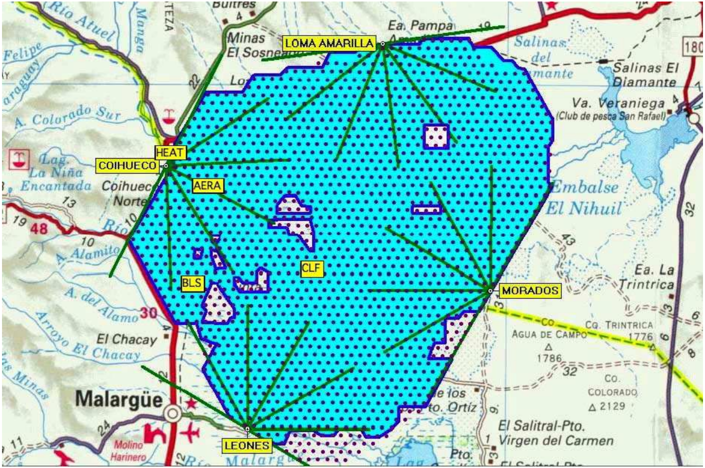
Pierre Auger Observatory

Surface CR detectors



Nature

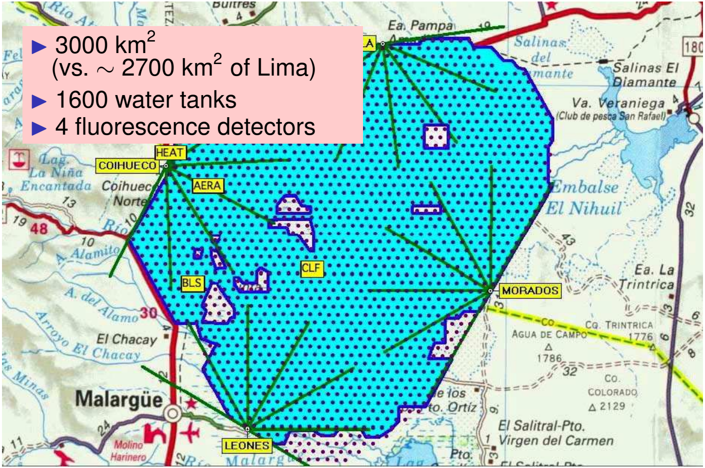
We now have much larger detectors
– *e.g.*, Pierre Auger Observatory, in Argentina



Surface CR detectors

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

- 3000 km^2
  (vs. $\sim$ 2700 km^2 of Lima)
- 1600 water tanks
- 4 fluorescence detectors



Surface CR detectors

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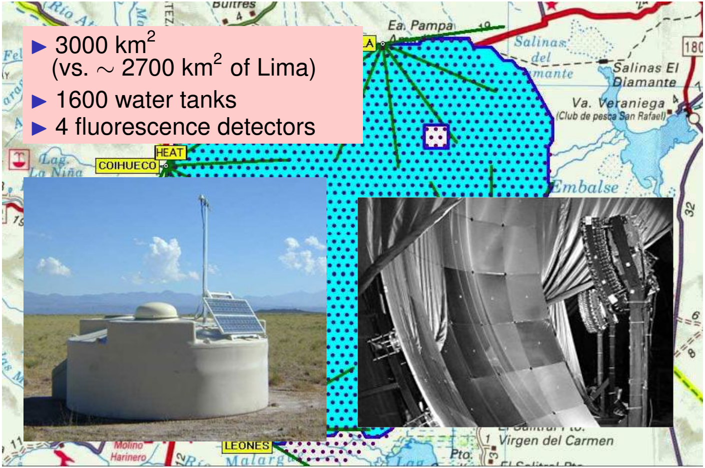
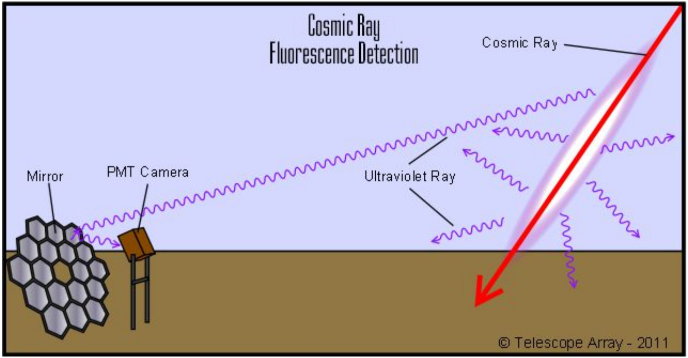
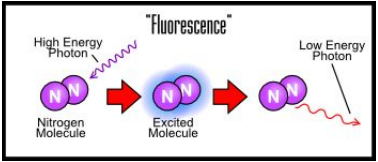


Fluorescence detectors



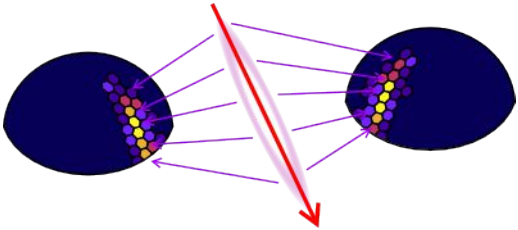


At Auger: 330-380 nm UV

Fluorescence detectors

Telescope Array

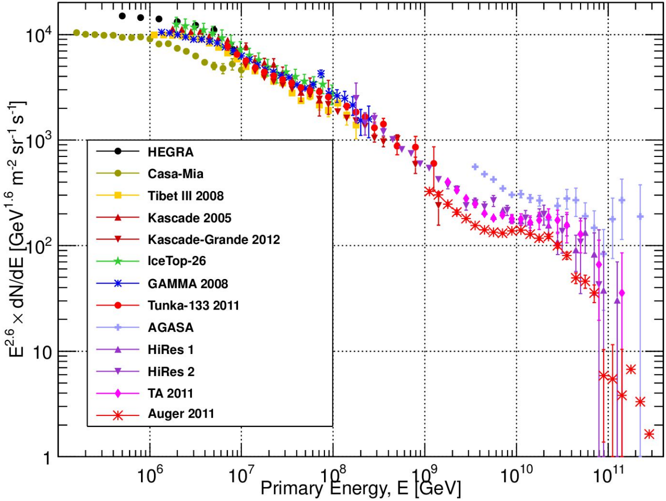
Fluorescence detectors



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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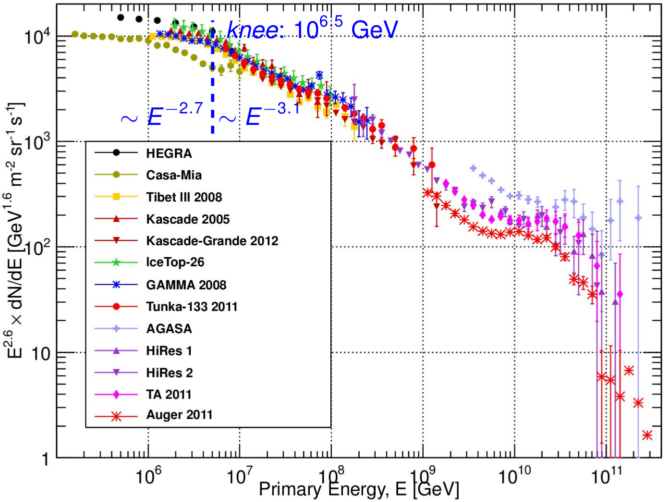

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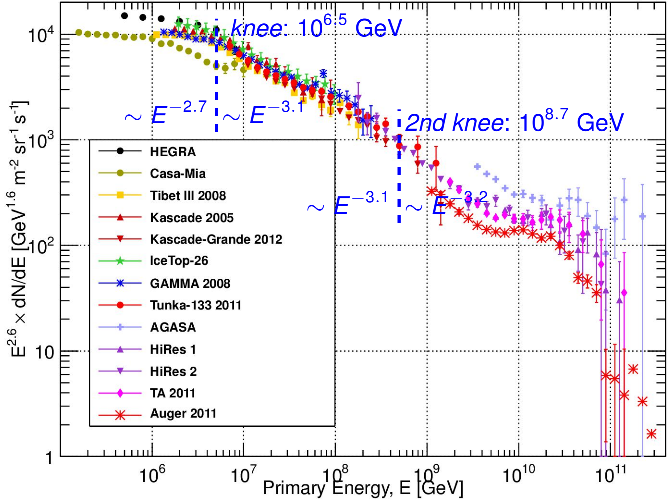

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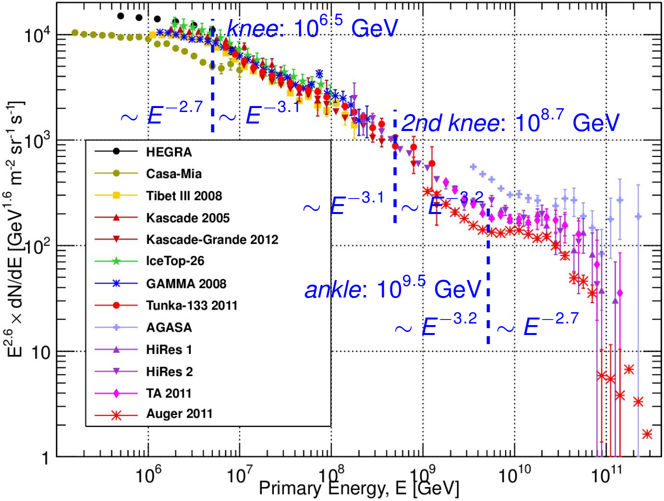

UHECRs – shape of the spectrum

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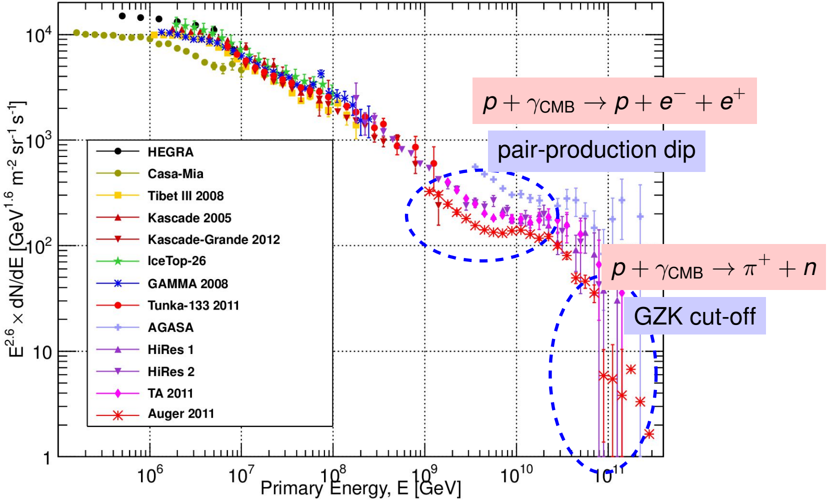


Detour: the cosmic microwave background (CMB)

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)

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

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

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

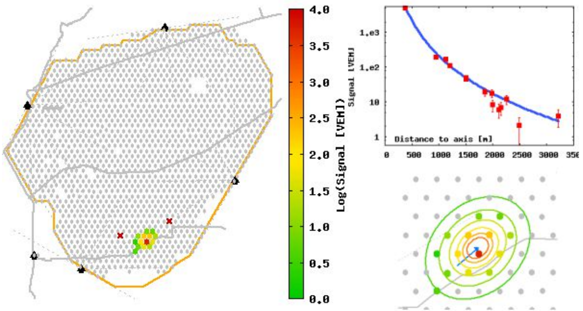
$$p\left(d\right) \approx \exp\left(\frac{-d}{6.6\ \text{Mpc}}\right) \Rightarrow p\left(d\right) < 10^{-4} \text{ for } d = 50\ \text{Mpc}$$

Two conclusions

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

UHECRs – finding their 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:

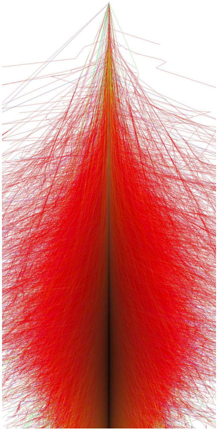
So how is the identity of the primary reconstructed from this?

UHECRs – finding their composition

Answer:

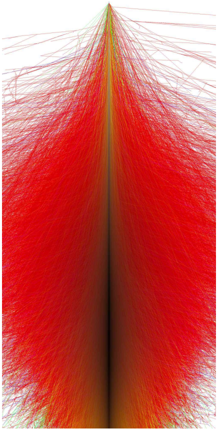
use longitudinal air shower development information from the fluorescence detectors

10^6 GeV proton



vs.

10^6 GeV Fe-56 nucleus

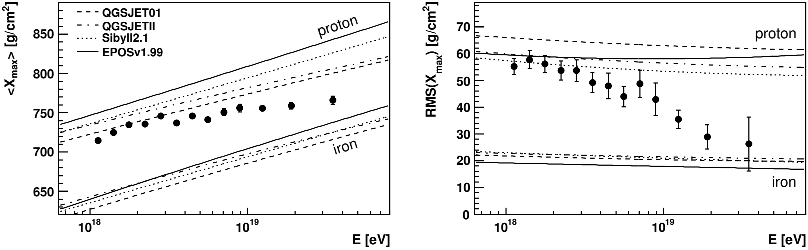


F. Schmid, Univ. Leeds

UHECRs – finding their composition

$\langle x_{max} \rangle$: 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

What are the sources of the UHE messengers?

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Short answer – we do not know (yet)

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Longer answer – we do not know,
but we have a few good candidates

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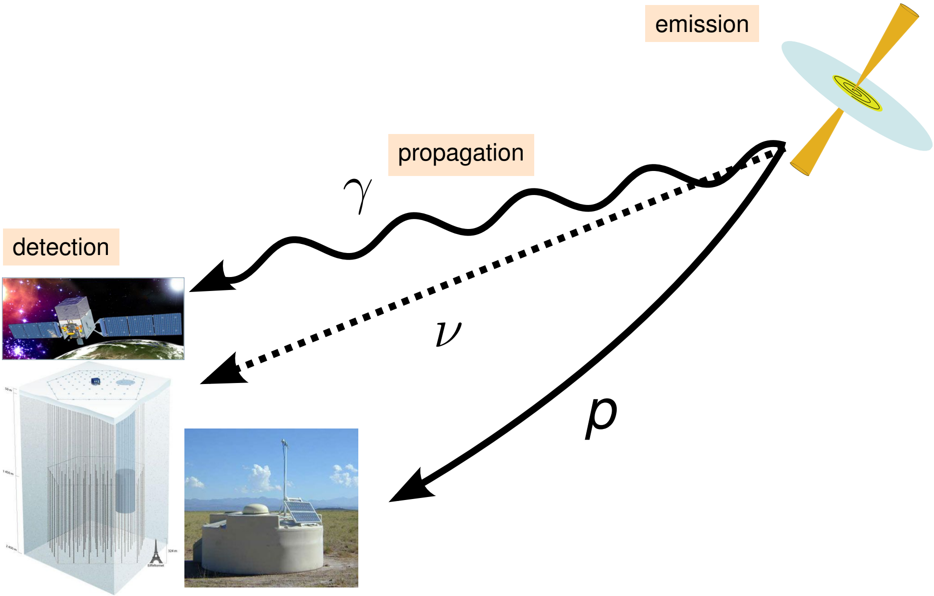
Short answer – we do not know (yet)

Longer answer – we do not know,
but we have a few good candidates

Let us look at some general constraints on the nature of the sources,
and some candidates ▶

Emission–propagation–detection



Hillas criterion: UHECR sources must be extragalactic

Two considerations:

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

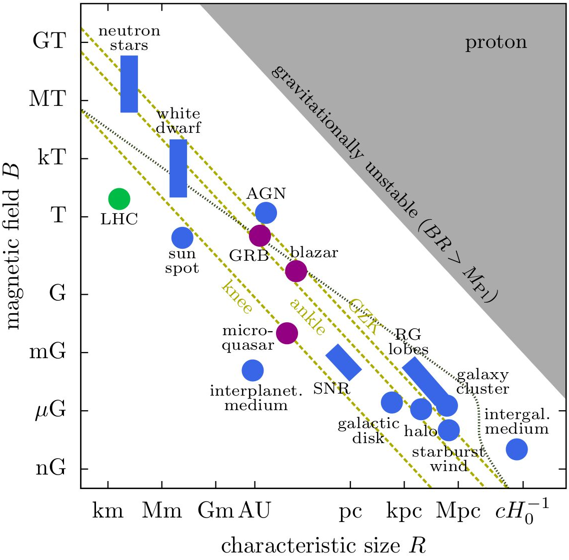
$$\text{Larmor radius:}\ \ R_L = \frac{1.1}{Z}\left(\frac{E}{\text{EeV}}\right)\left(\frac{B}{\mu\text{G}}\right)^{-1}$$

Hillas criterion: $R_L < R$

This limits the maximum energy:

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

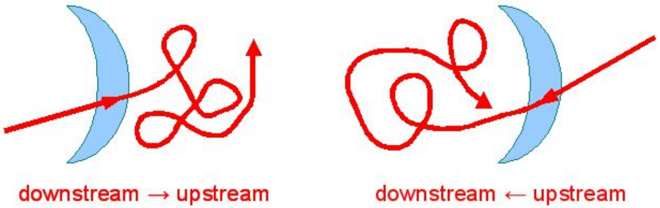
Hillas criterion: UHECR sources must be extragalactic



How are UHECRs accelerated at the sources?

First order Fermi acceleration:

- Relativistic particles, supersonic magnetic shocks
- Energy gain per crossing $\propto v/c$
- Average energy after one collision: $E = \beta E_o$

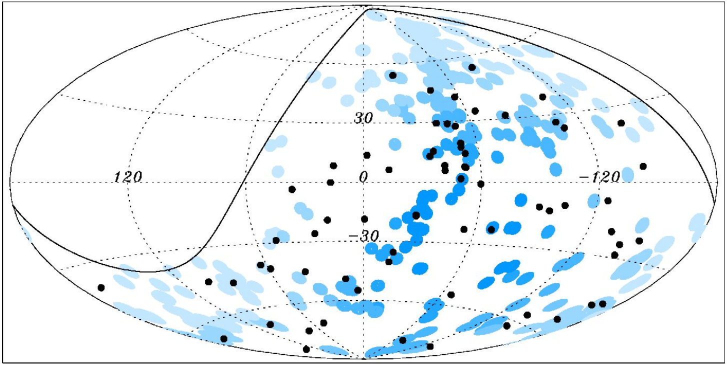


- Same energy gain in downstream $\rightarrow$ upstream and upstream $\rightarrow$ downstream crossing

UHECRs – correlations 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)

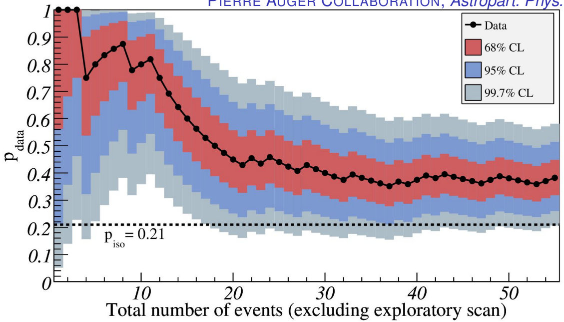
UHECRs – correlations with known sources

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

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

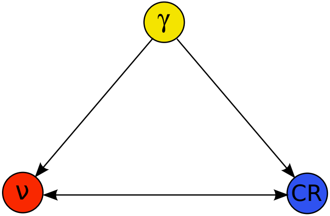
$$p\,\gamma \to \Delta^+(1232) \to \begin{cases} n\pi^+ , & \text{BR} = 1/3 \\ p\pi^0 , & \text{BR} = 2/3 \end{cases}$$

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

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

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

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



After propagation, with flavour mixing:

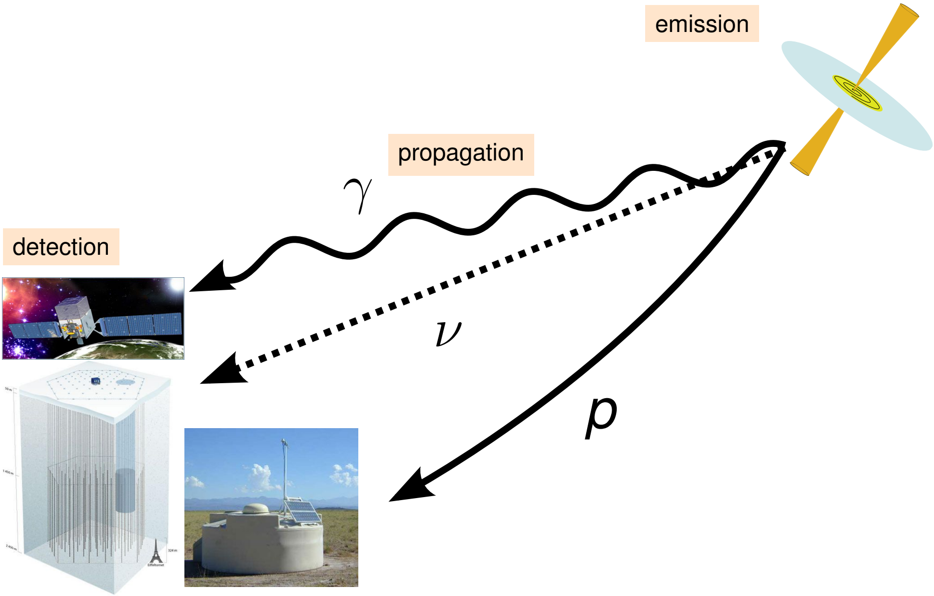
$$\nu_e : \nu_\mu : \nu_\tau : p = 1 : 1 : 1 : 1$$

("one ν_μ per cosmic ray")

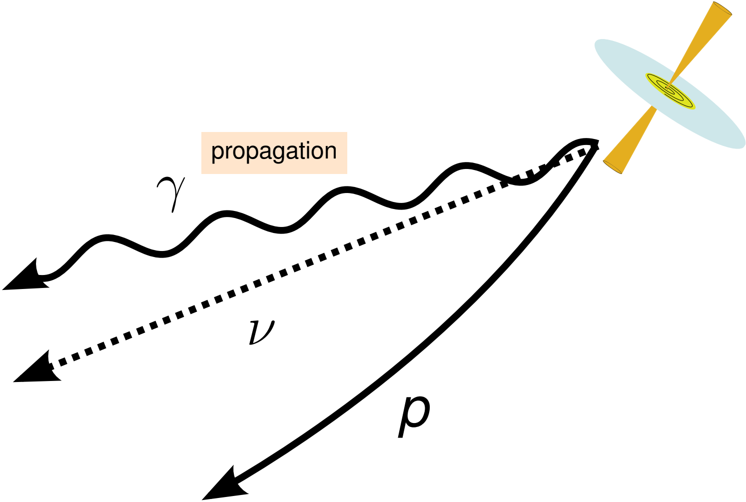
CR emission by *n* escape only is now strongly disfavoured

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

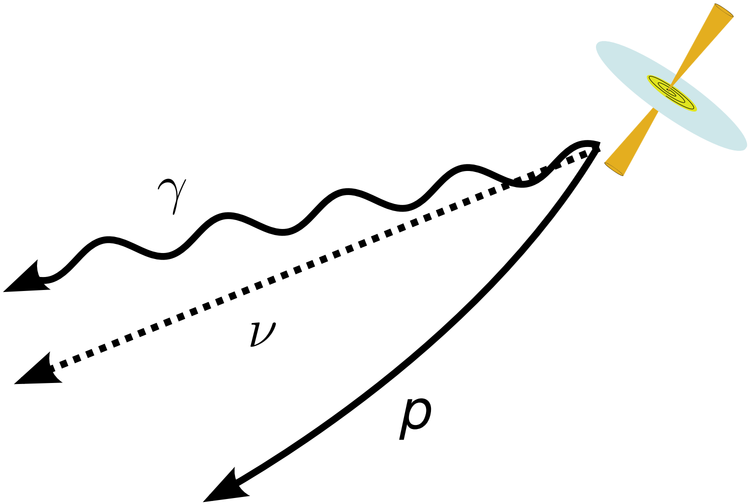
Production & propagation of UHE ν's, CRs, γ rays



Production & propagation of UHE ν's, CRs, γ rays

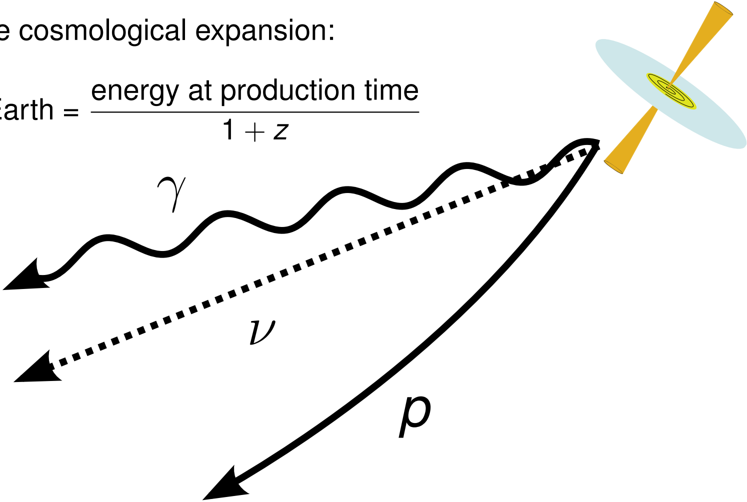


Production & propagation of UHE ν's, CRs, γ rays



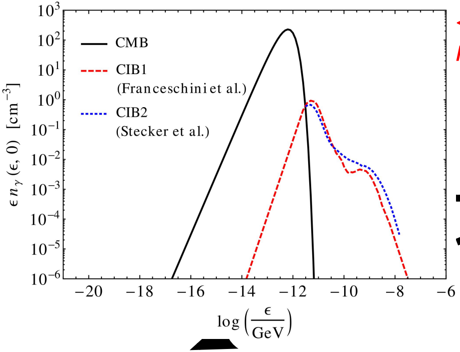
Because of the cosmological expansion:

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

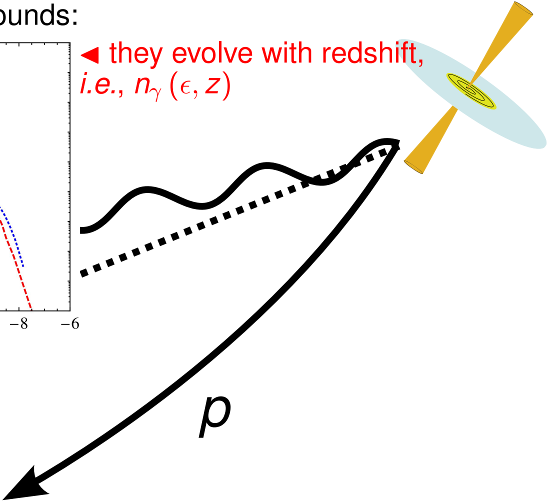


Production & propagation of UHE ν's, CRs, γ rays

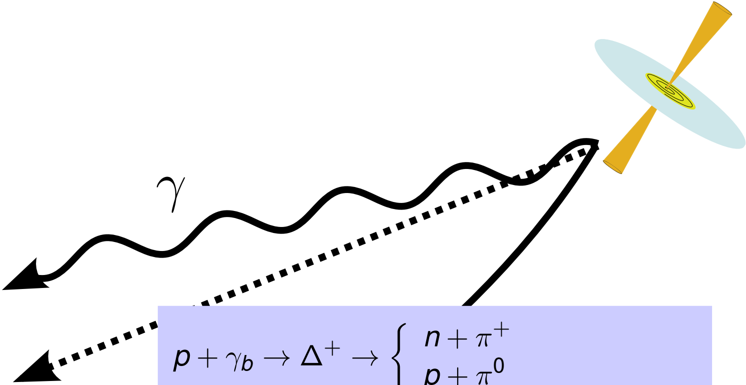
Cosmological photon backgrounds:



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



Production & propagation of UHE ν's, CRs, γ rays



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

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

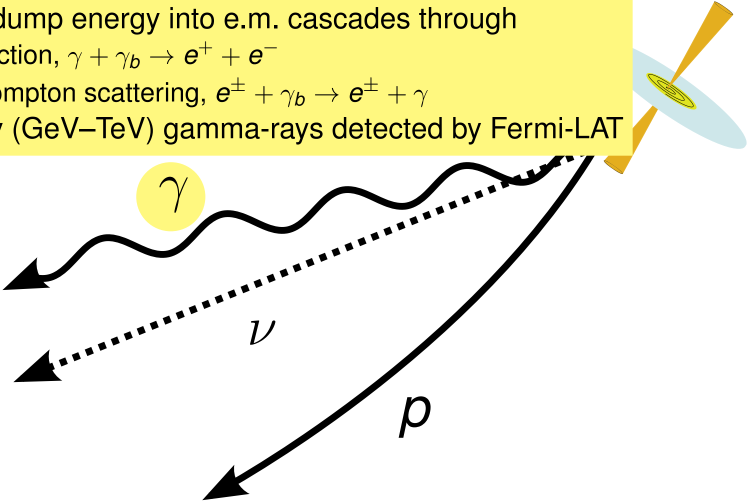
Cosmogenic ν's: $\pi^+ \to e^+ + \nu_e + \bar{\nu}_\mu + \nu_\mu$

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

Production & propagation of UHE ν's, CRs, γ rays

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



Production & propagation of UHE ν's, CRs, γ rays

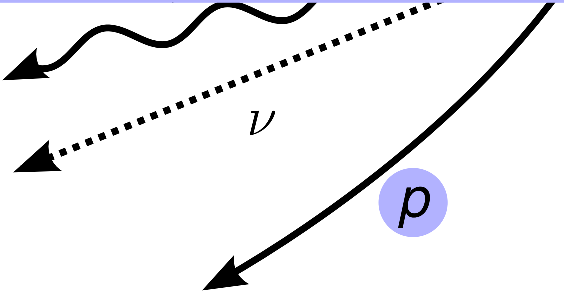
p's are deflected by extragalactic magnetic fields

$\Rightarrow$ except for the most energetic ones, they are **not** expected to point back to the sources } Pierre Auger found weak correlation with known AGN positions

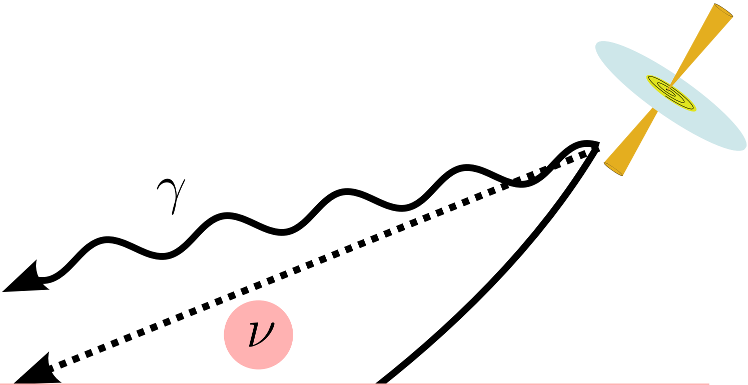
They lose energy through:

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

} depend on the redshift evolution of the cosmological γ backgrounds



Production & propagation of UHE ν's, CRs, γ rays



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 makes a good candidate UHECR source?

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: $\Gamma \gtrsim 100\,(\delta t/10\text{ ms})^{-1/4}$

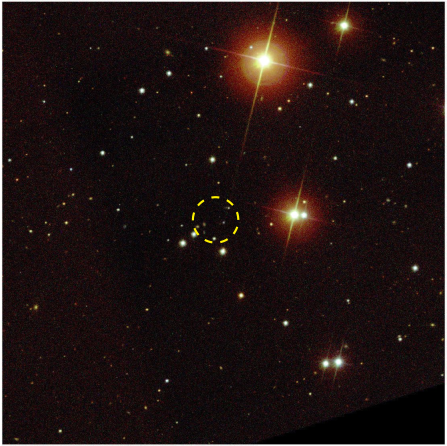
This leaves as candidates:

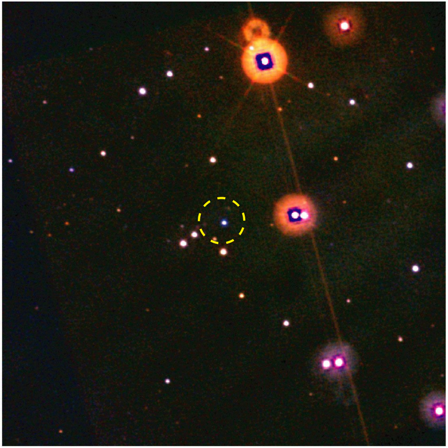
- (some) AGN flares
- GRBs, with typical $L \sim 10^{52}$ erg s^{-1}, $\Gamma \gtrsim 300$

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

Gamma-ray bursts

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



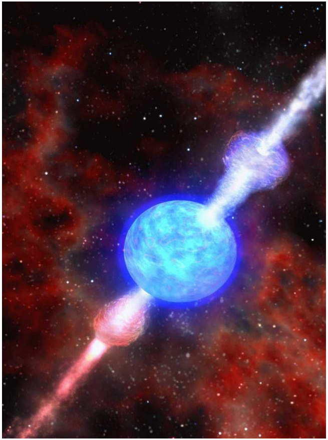


SDSS, Swift Collab., Sloan Foundation, NSF, NASA

Gamma-ray bursts – 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 $\sim$ 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



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

GRBs are among the best candidate sour[ces]

- 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

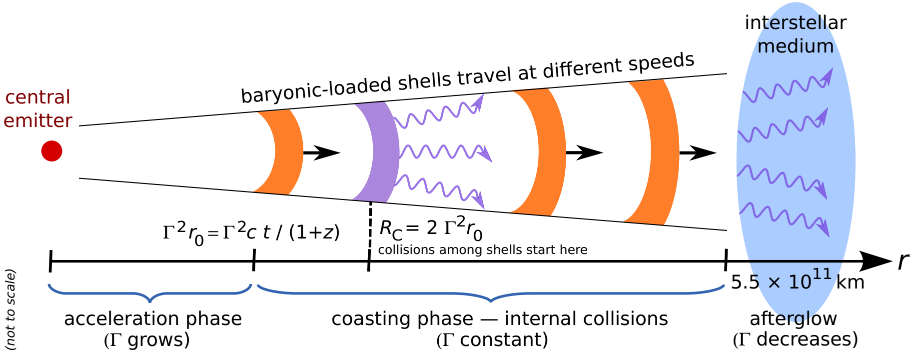
Problem: experiments (IceCube, ANTARES) are starting to strongly constrain the simplest joint emission models

Solution: we need to build more realistic models!

GRBs explained – the 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



GRBs explained – the fireball model

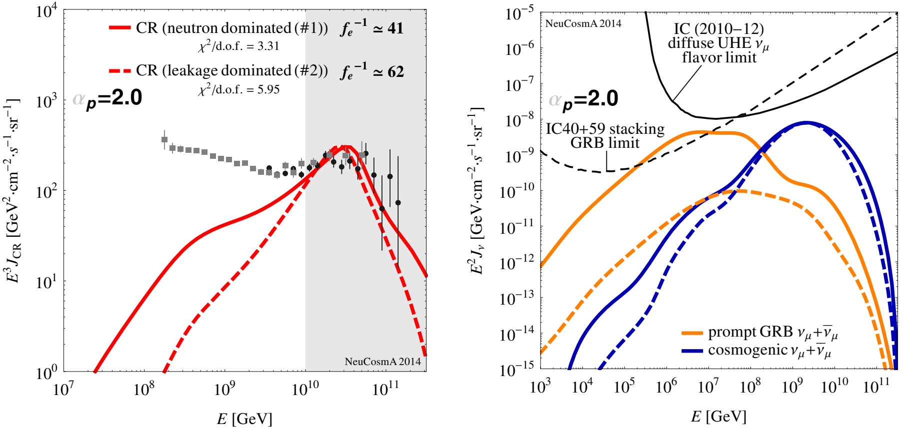
Let’s look at a sample animated fireball –

▲ shell has not collided

shell has collided many times ▲

UHE ν and CR fluxes at Earth from 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)

The future

The future

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

better, bigger detectors + loads of data + bright future

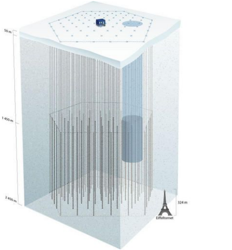
UHECRs

- 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?

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!

Questions, *etc*.:

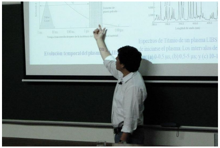
bustamanteramirez.1@osu.edu

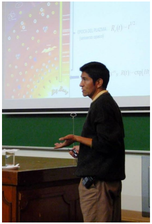
Ongoing and coming events

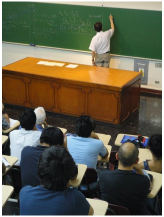
PUCP COLOQUIOS DE FÍSICA

- Jueves 12:30 p.m.,
  Auditorio de Física PUCP
- Ponentes nacionales e internacionales
- Diversas áreas de Física, otras ciencias e ingenierías
- **Transmisión en vivo:** envivo.pucp.edu.pe/fisica
- > **cien** coloquios grabados
- **Página web:** sites.google.com/site/fisicapucp/
- **Ingreso libre para todos**
- **Facebook** y **Twitter**
- coloquios@fisica.pucp.edu.pe









I Escuela Peruana de Física de Altas Energías y Cosmología (EPFAEC 2015)

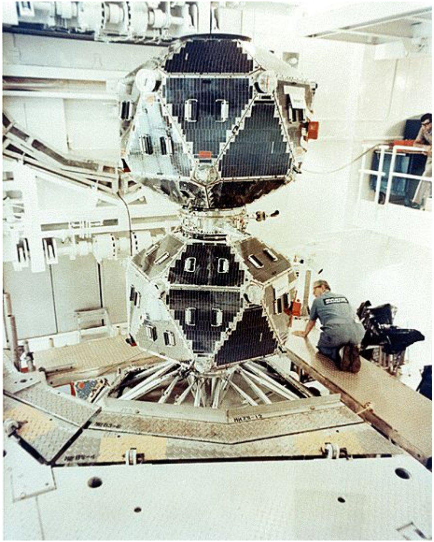
- 22–26 de Junio 2015
- Dirigido a estudiantes, profesores e investigadores en Física
- Lugar: UNI
- Tres expertos internacionales
- Clases + sesiones de discusión:
  - física de partículas y teoría cuántica de campos
  - física de neutrinos
  - cosmología
- **Sin costo de inscripción**
- **Registro hasta 30 de Abril**
- Más información y registro en línea: fc.uni.edu.pe/epfaec2015

Backup slides

GRBs – an accidental discovery

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

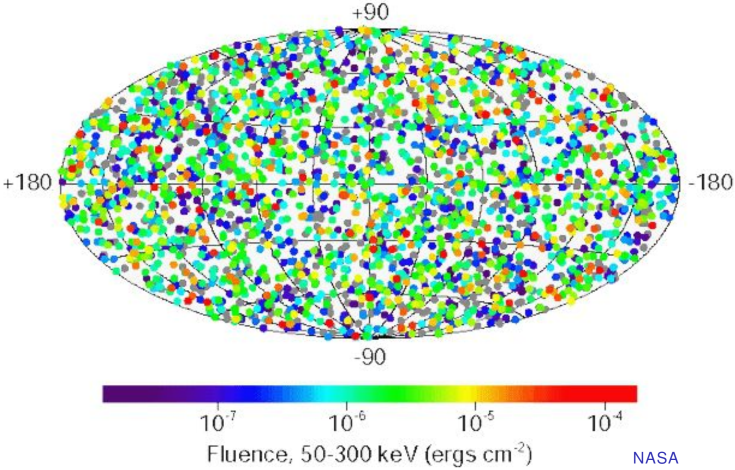
- They carried X-ray, gamma-ray, and neutron detectors
- *Vela* 5a-b had enough spatial resolution to pinpoint the direction of events
- Intense gamma-ray emission from a nuclear explosion lasts $\lesssim 10^{-6}$ s ...
- ... however, longer-lasting emissions were detected



VELA 5A/B SATELLITES (NASA)

GRBs studied

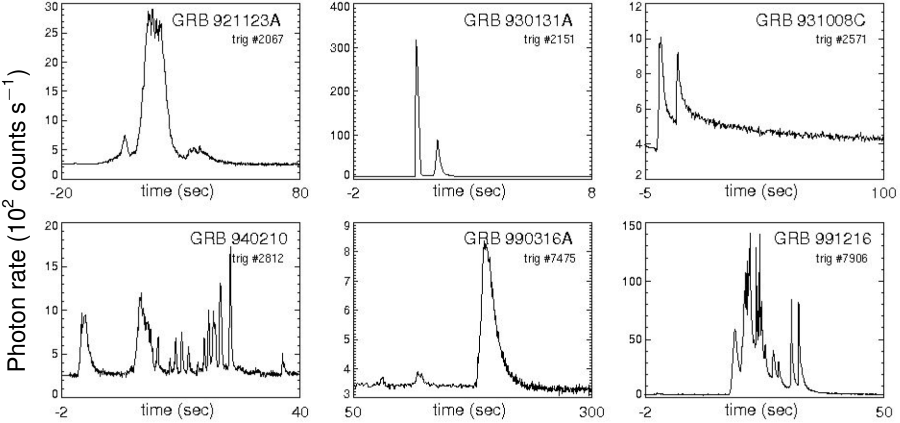
Dedicated missions were flown – *e.g.*, BATSE detected 2704 GRBs between 1991 and 2000



NASA

GRBs studied

GRB light curves come in different shapes:

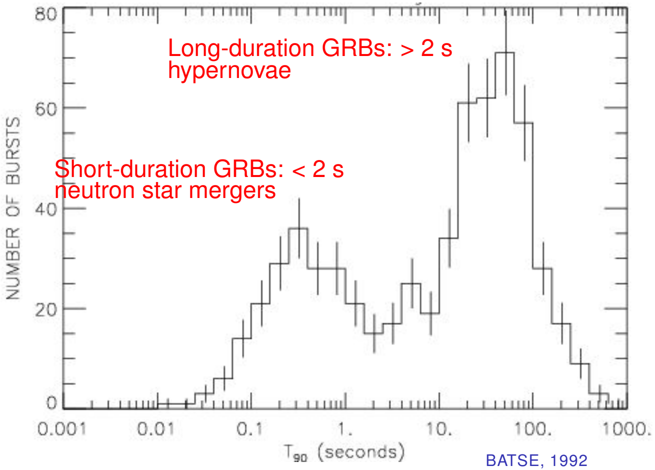


BATSE

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

GRBs – two different populations

Two populations of GRBs:

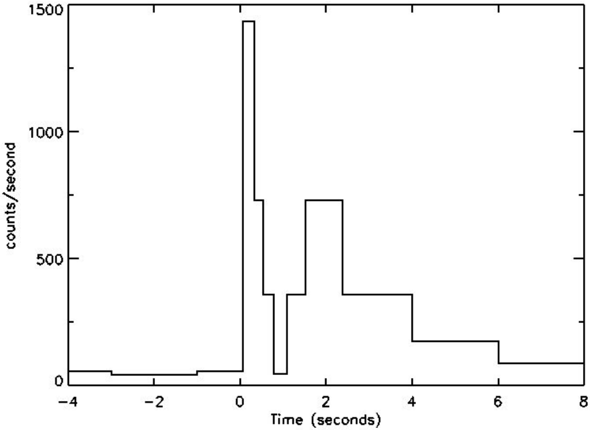


BATSE, 1992

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

GRBs – an accidental discovery

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



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

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

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

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

Particle emission from a collision

Normalise the densities at the source – for one collision:

- Photons:

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

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

- Protons:

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

Particle emission from a collision

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

$x \equiv E'/E'_p$

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

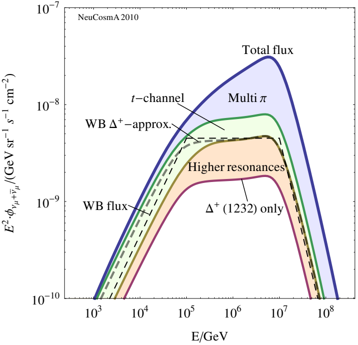
$$Q'(E') = \int_{E'}^{\infty} \frac{dE'_p}{E'_p} N'_p(E'_p) \int_0^{\infty} c \, dE'_\gamma \, N'_\gamma(E'_\gamma) \, R(x, y)$$

response function

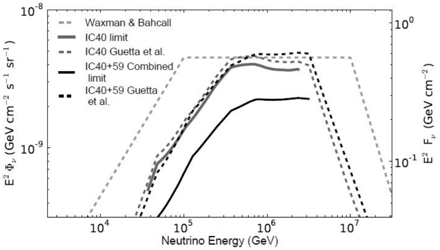
R contains cross sections, multiplicities for different channels

What does NeuCosmA include?

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



The neutron model under tension?



IceCube Collaboration:

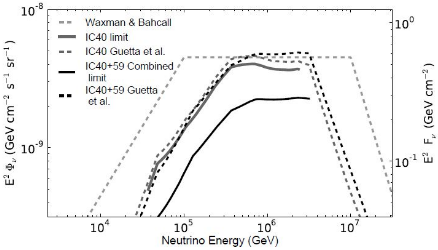
- ν flux normalised to GRB γ fluence:

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

- 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:

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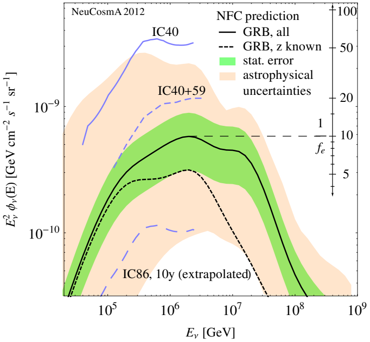
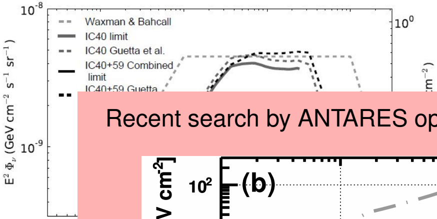


The neutron model under tension?



More detailed particle physics (NeuCosmA):

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

...wer

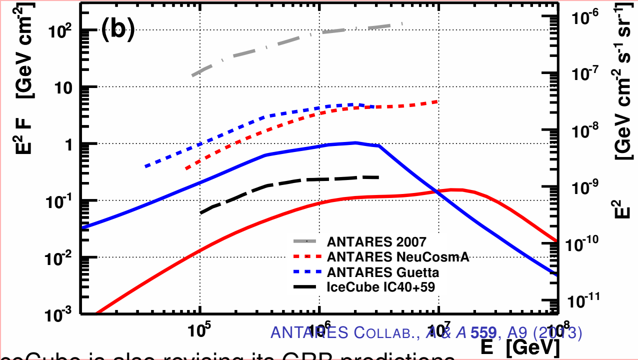
(2012)

IceCube C...

- ν flu...
- quas...
- anal... bour...

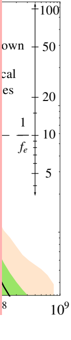
ICECUBE COL...
AHLERS ET AL...
GUETTA ET AL...

Recent search by ANTARES optimised for NeuCosmA:



ANTARES COLLAB., *A & A* **559**, A9 (2013)

► IceCube is also revising its GRB predictions

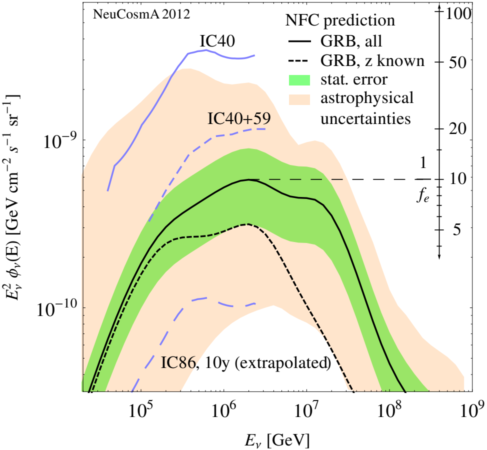


The new prediction of the quasi-diffuse GRB ν flux

- 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)