Ultra-high energy neutrinos and cosmic rays from gamma-ray bursts

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THE OHIO STATE UNIVERSITY

CCAPP

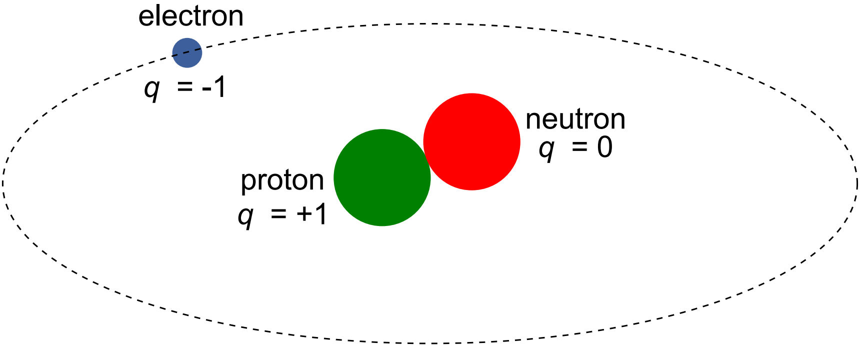
Plan of attack:

1. **Neutrinos** – what are they? where do they come from?
2. **Cosmic rays** – what do we know / don't know about them
3. **Gamma-ray bursts (GRBs)** – the most luminous explosions in the Universe
4. GRBs as **sources** of neutrinos and cosmic rays
5. **The future** – more data, better detectors

Neutrinos

Neutrinos – what are they?

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



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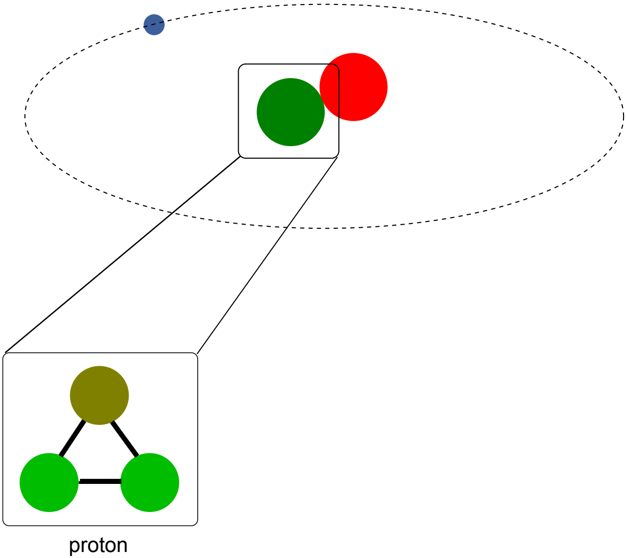

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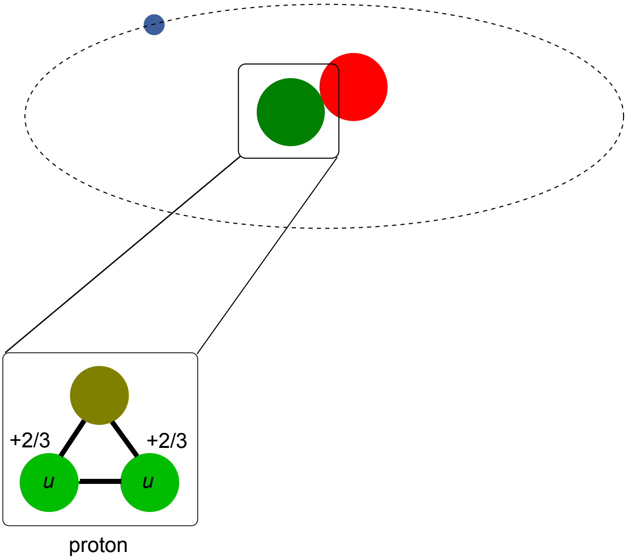

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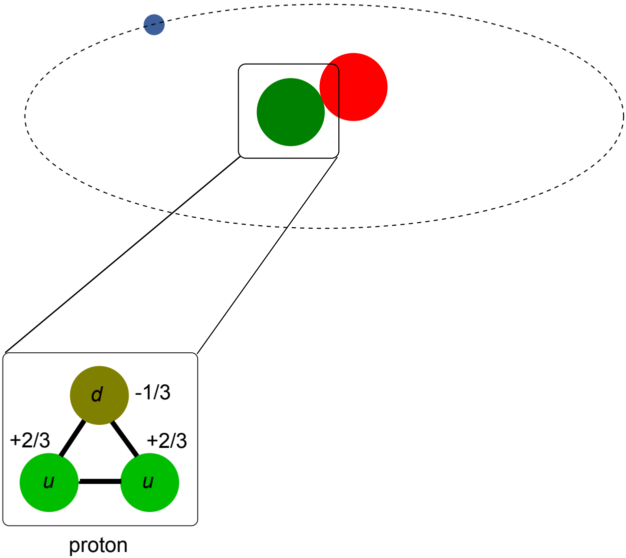

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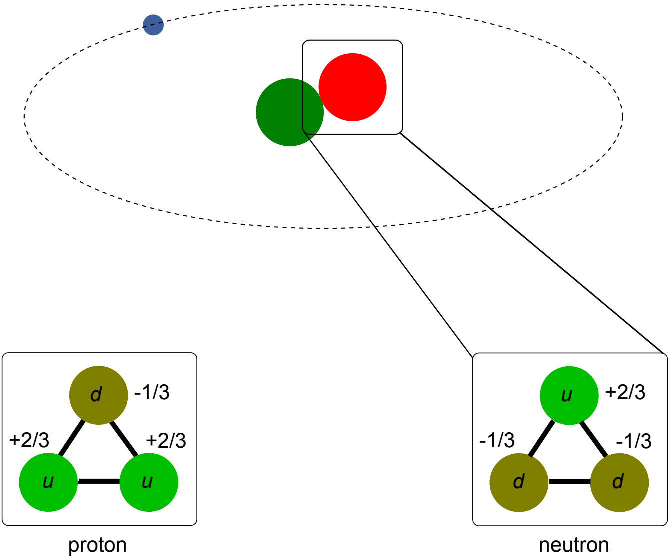

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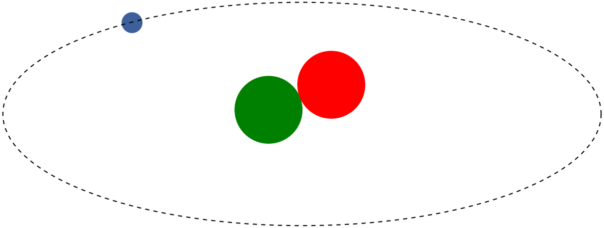

Six quarks, grouped in three families:

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

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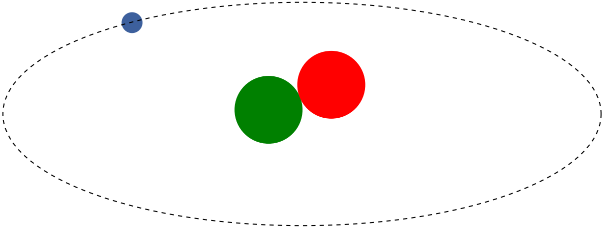

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mass

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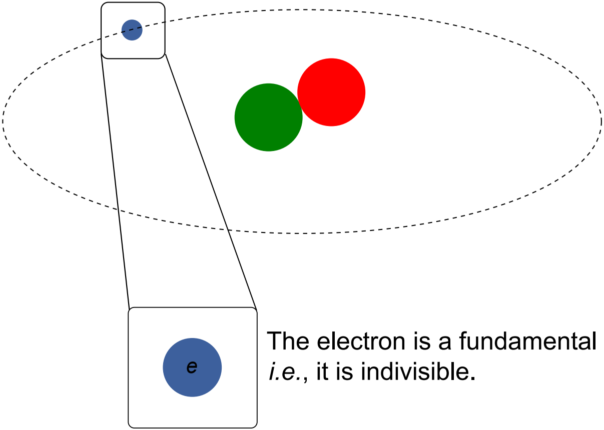
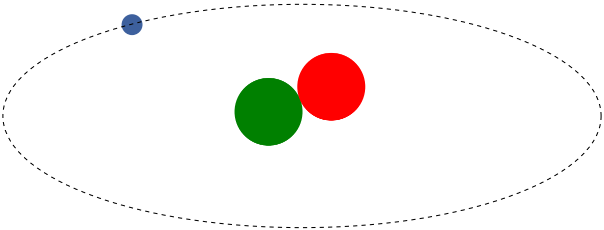
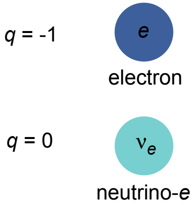


The electron is a fundamental particle,
i.e., it is indivisible.

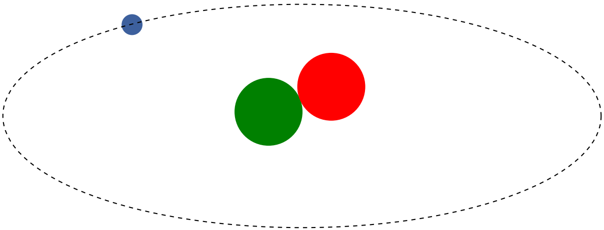
Neutrinos – what are they?





The electron and the neutrino are *leptons*.

Neutrinos – what are they?



Leptons are also grouped in three families:

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

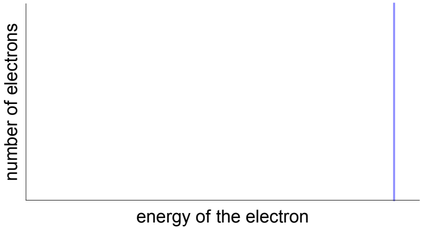
mass

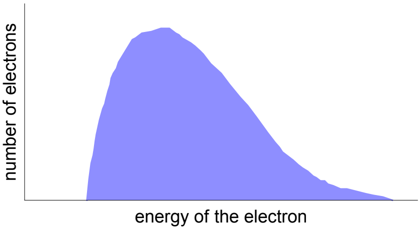
Neutrinos – how where they discovered?

<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:

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

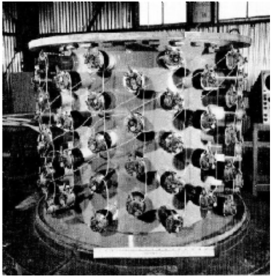
Neutrinos – how where they discovered?

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

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

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

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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  (10^{-11} times the intensity of the electromagnetic force);

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

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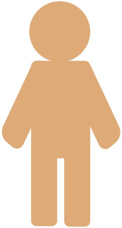
Neutrinos are generated in ...

- nuclear processes in the Sun
- nuclear reactors
- supernovae
- particle accelerators
- high atmosphere
- extragalactic objects
  (*e.g.*, active galactic nuclei, *gamma-ray bursts*)

Even in the human body:



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

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

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

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

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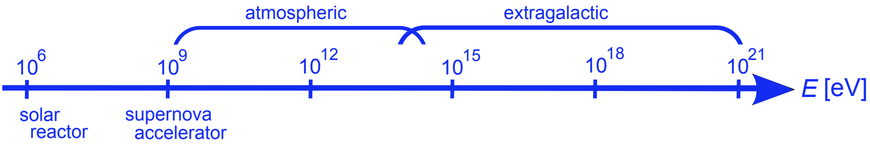

$$1 \text{ eV} \approx 1.6 \times 10^{-19} \text{ J}$$

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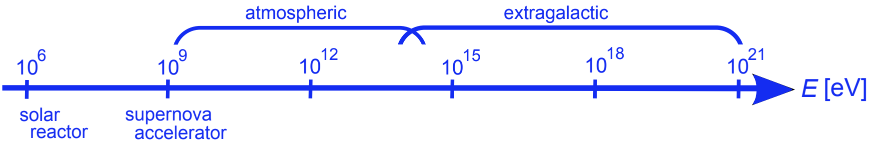

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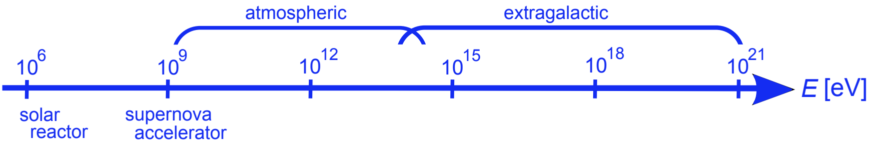

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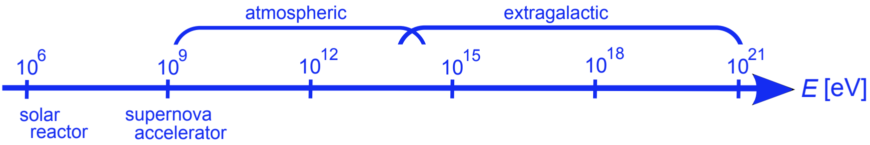

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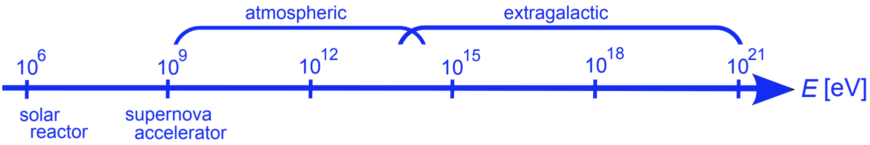

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- $\sim$ 624 EeV (6.24×10^{20} eV): energy needed to light a bulb of 100 W for 1 s

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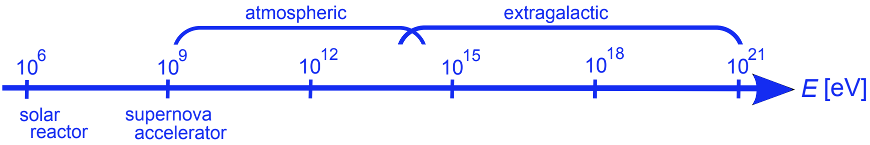


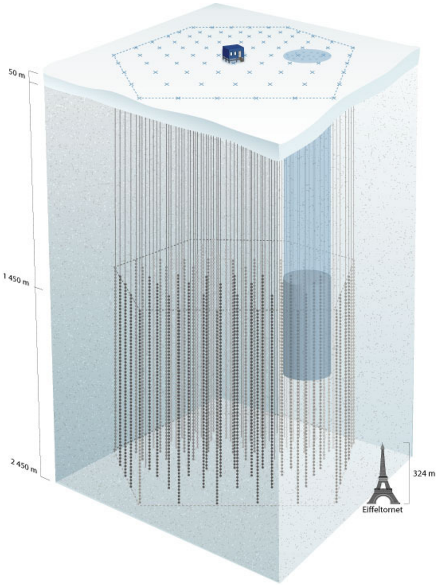
The higher the neutrino energy,
the larger the probability to detect it.

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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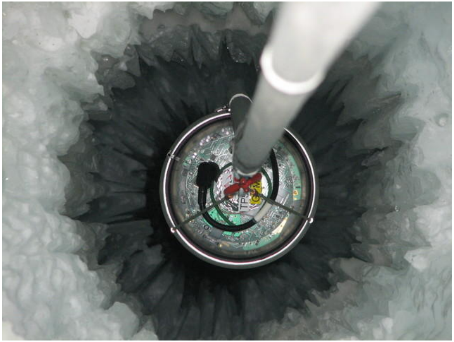

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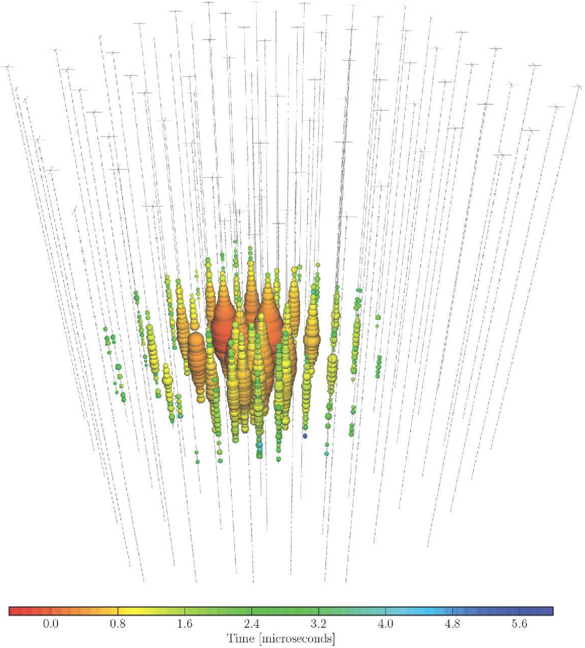
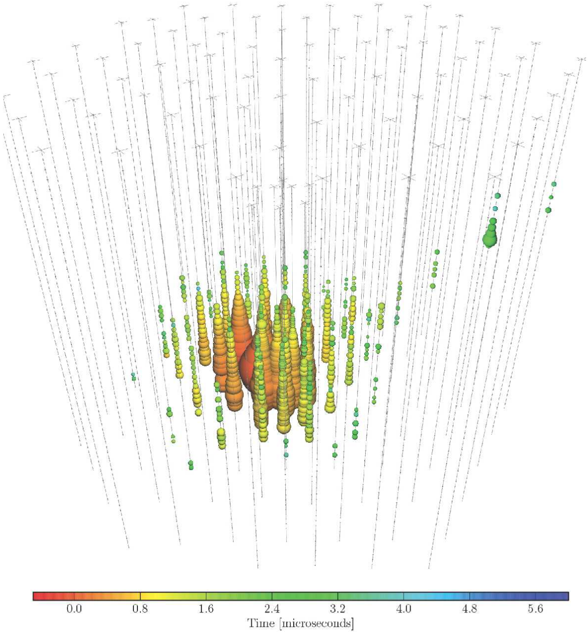

0.0
0.8
1.6
2.4
3.2
4.0
4.8
5.6
Time [microseconds]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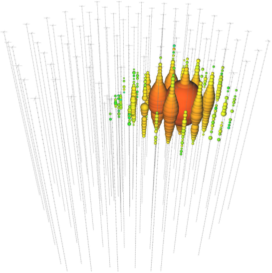
Time [microseconds]

Neutrinos – how are UHE ν's detected?

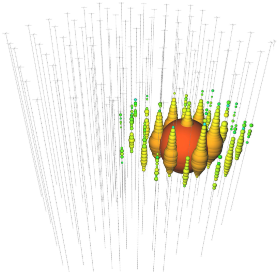
The era of neutrino astronomy has begun!

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

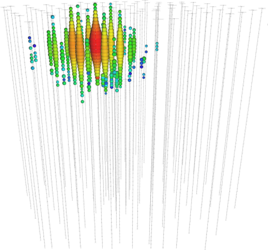
"Bert", 1.04 PeV



"Ernie", 1.14 PeV



"Big Bird", 2 PeV



. . . and 34 more events < 385 TeV

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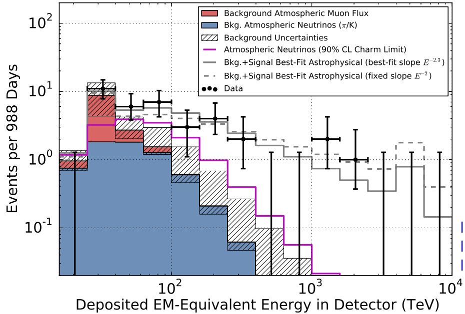

IceCube, *PRL* **111**, 021103 (2013)
IceCube, *Science* **342**, 1242856 (2013)
IceCube, *PRL* **113**, 101101 (2014)

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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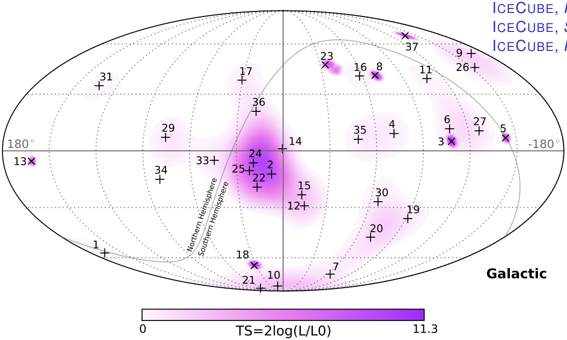
Arrival directions compatible with an isotropic distribution –

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

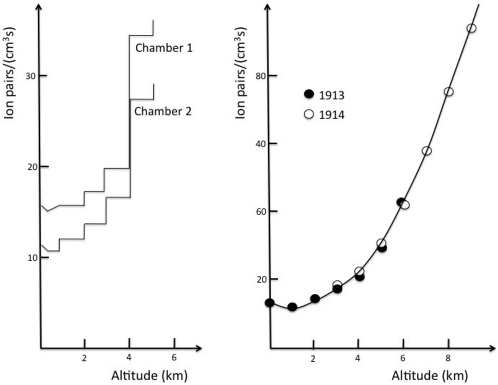
1911–1913: the Austrian physicist Victor Hess made balloon flights up to an altitude of 5.3 km

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

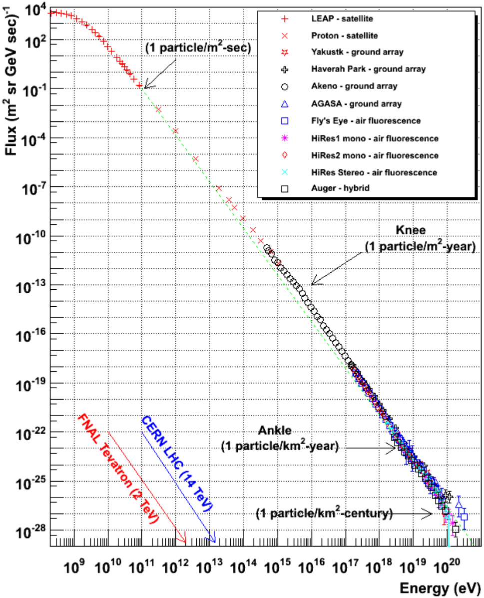
Quoting Hess:

> *"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"

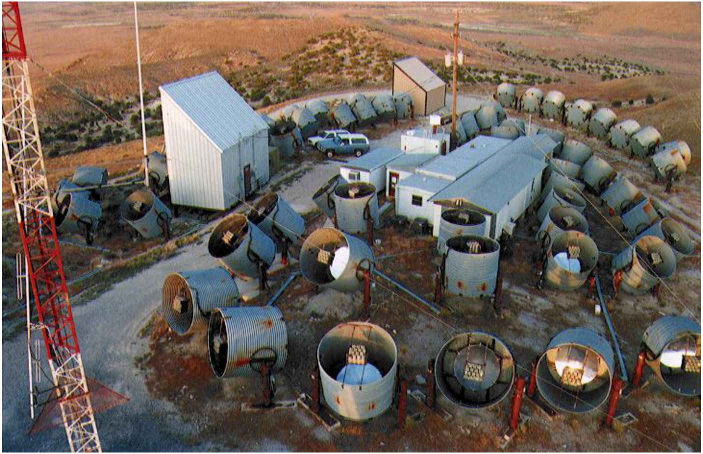
1936: Nobel Prize in Physics 1936 to Hess, "for his discovery of cosmic radiation"

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?

Our cosmic-ray detectors have also changed:



Cosmic rays: 102 years later

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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

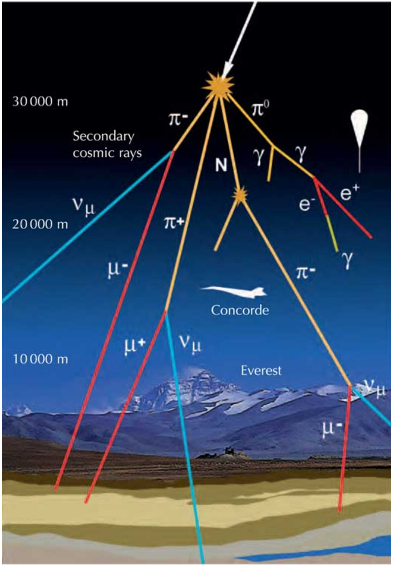
After fifty years, UHECRs are still a mystery:

- *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

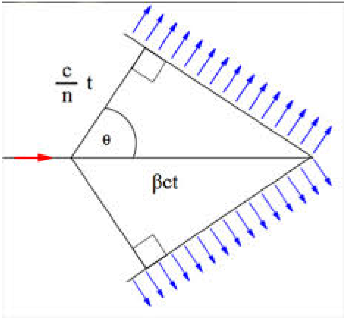
Modern experiments detect the secondary particles of the air showers, not the primary

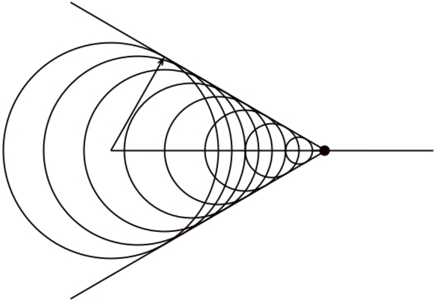
Two main detection methods:

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

Let us take a short detour about Cherenkov radiation ▶

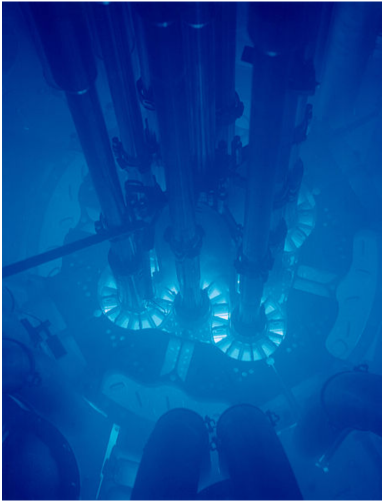
Occurs when a charged particle travels faster than light in a medium:



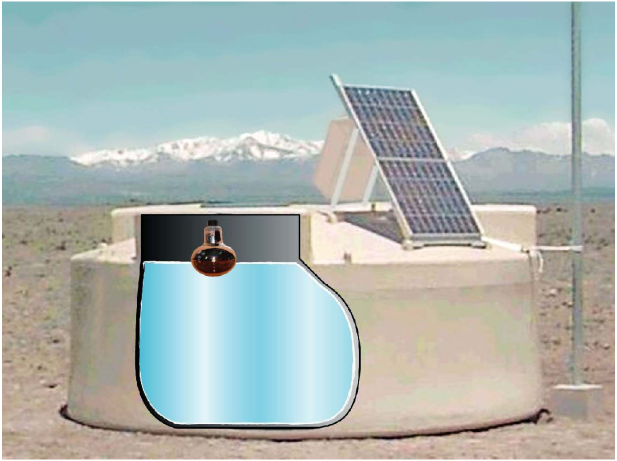


Cherenkov radiation

Cherenkov radiation

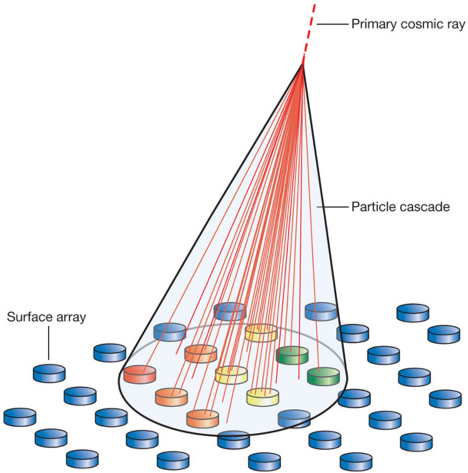


Surface CR detectors



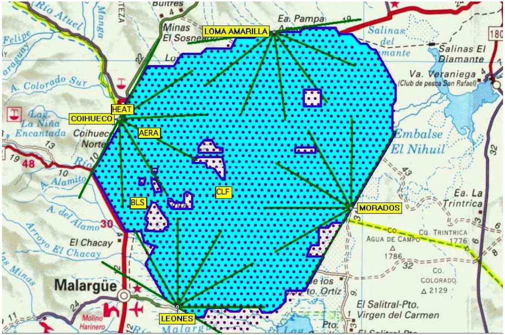
Pierre Auger Observatory

Surface CR detectors



Nature

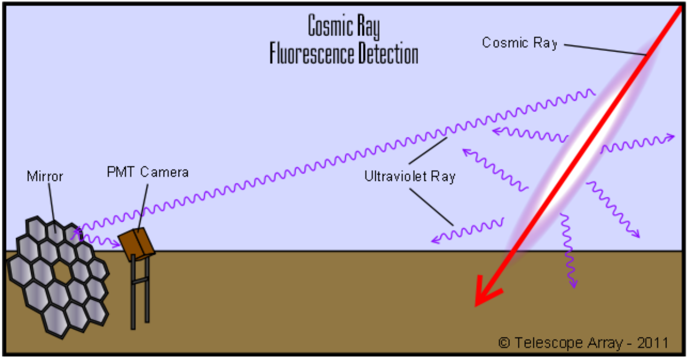
Surface CR detectors

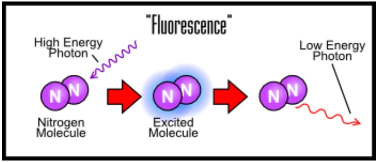


Pierre Auger Observatory:

- 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



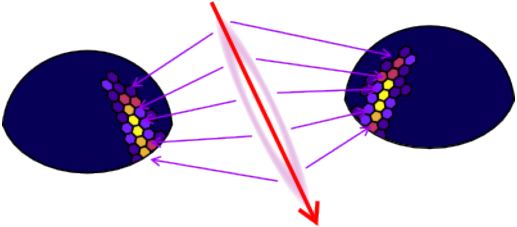


At Auger: 330-380 nm UV

Fluorescence detectors

Telescope Array

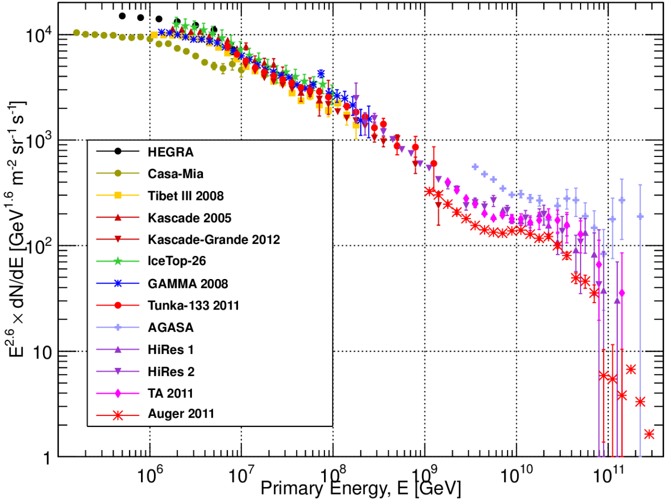
Fluorescence detectors



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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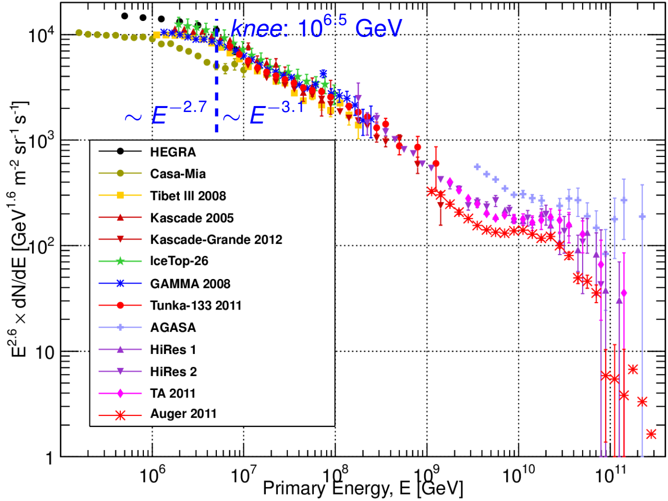

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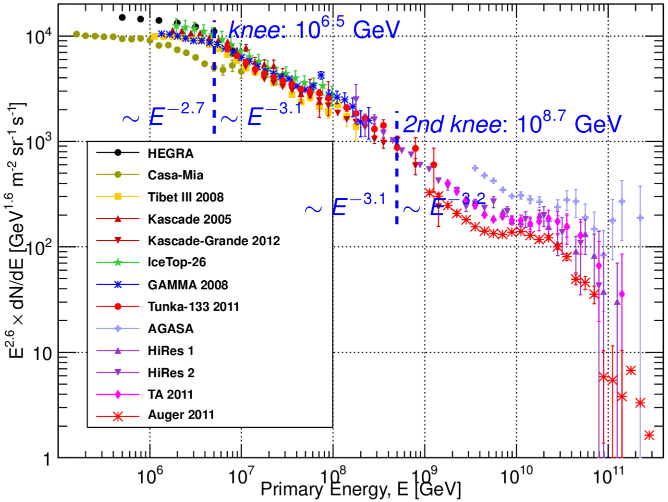

UHECRs – shape of the spectrum

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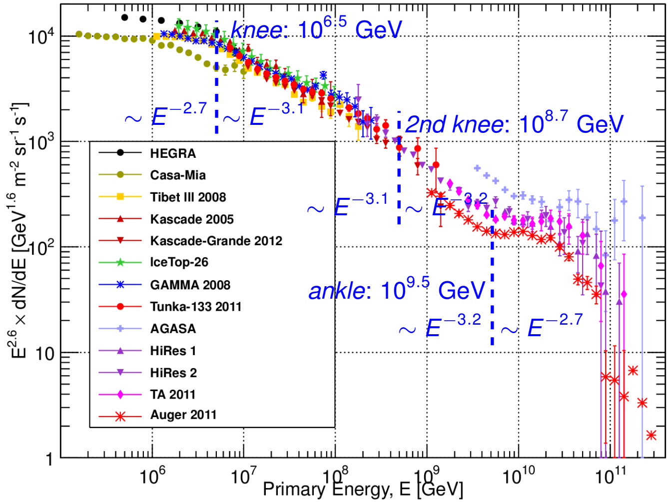

UHECRs – shape of the spectrum

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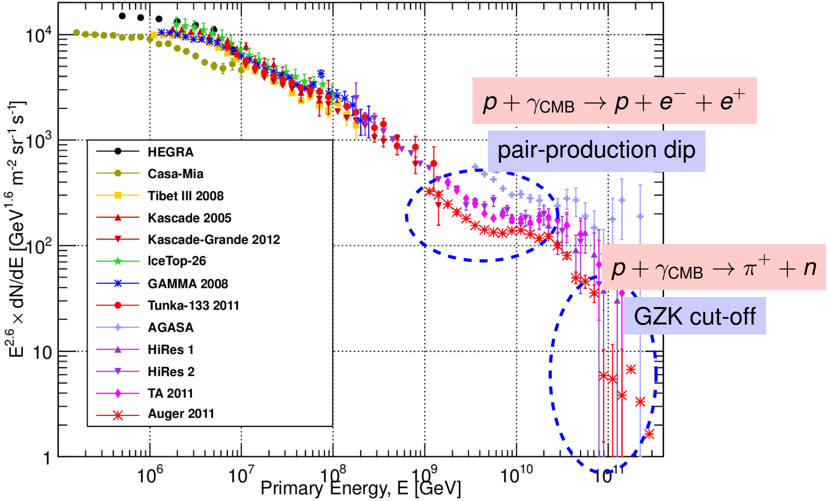


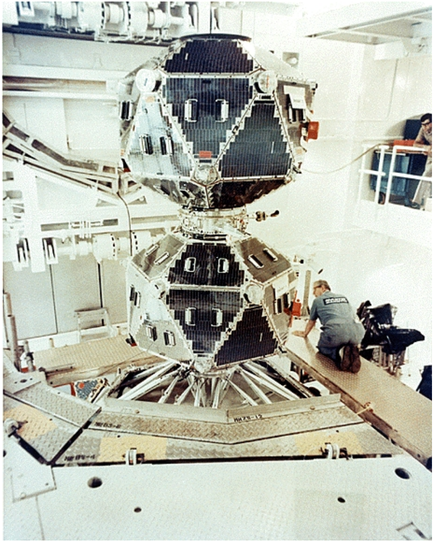
Gamma-ray bursts

GRBs – an accidental discovery

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 – an accidental discovery

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

OBSERVATIONS OF GAMMA-RAY BURSTS OF COSMIC ORIGIN

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

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

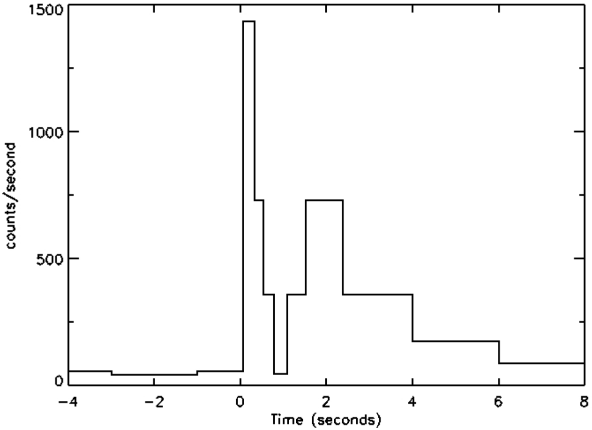
ABSTRACT

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

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

GRBs – an accidental discovery

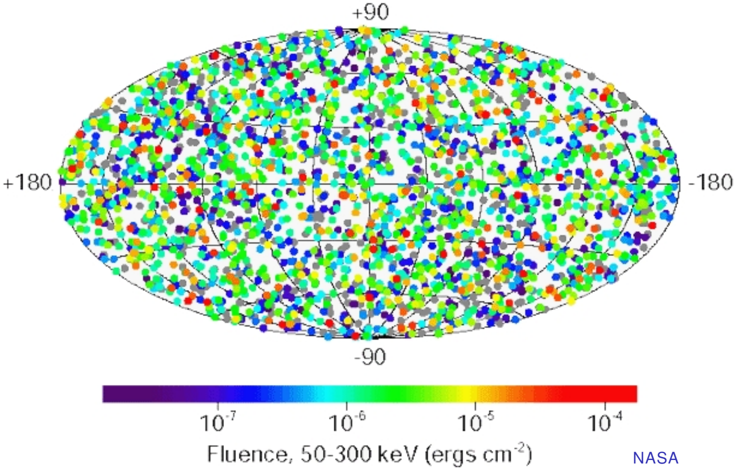
First GRB detected: July 2, 1967, 14:19 UTC



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

GRBs studied

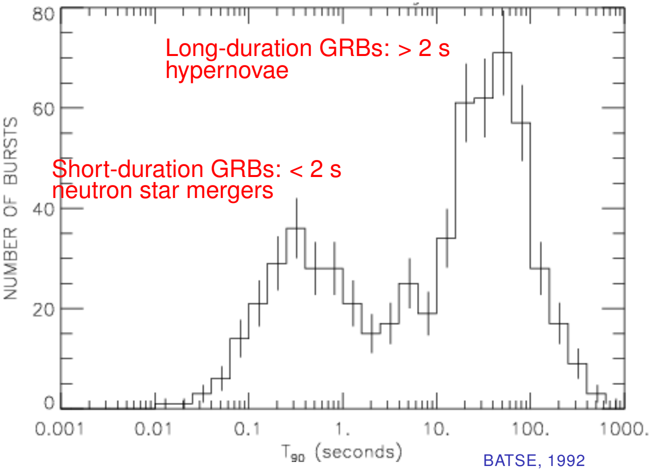
Dedicated missions were flown – *e.g.*, BATSE detected 2704 GRBs between 1991 and 2000



NASA

GRBs studied

Two populations of GRBs:

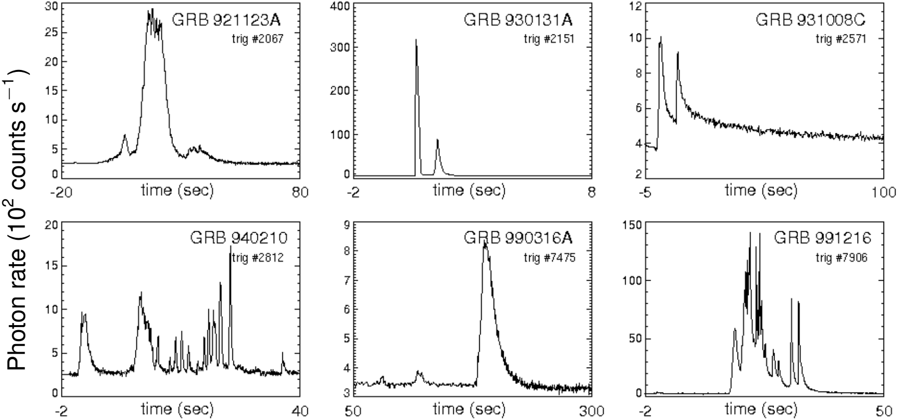


BATSE, 1992

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

GRBs studied

GRB light curves come in different shapes:

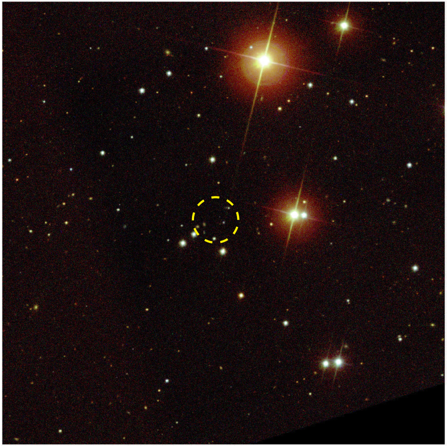


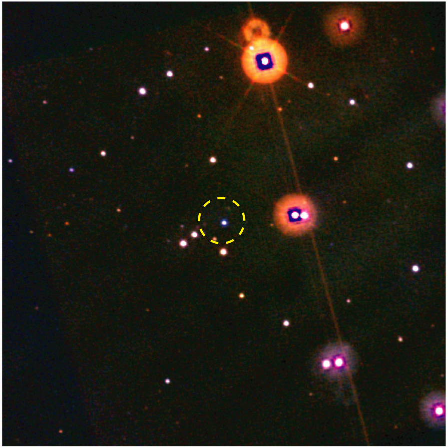
BATSE

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

GRBs studied

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

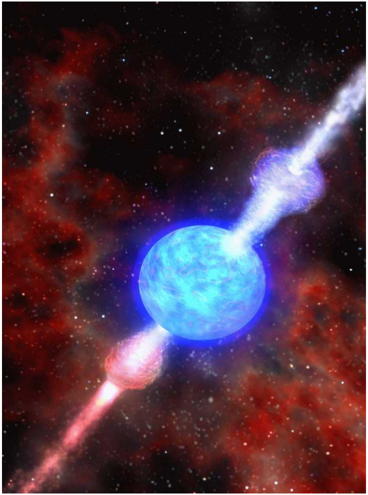




SDSS, Swift Collab., Sloan Foundation, NSF, NASA

GRBs explained – the fireball model

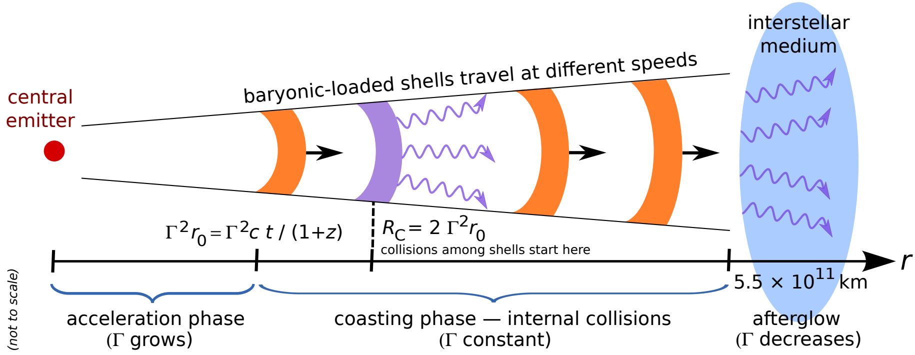
GRBs probably look something like this . . .



GRBs explained – the fireball model

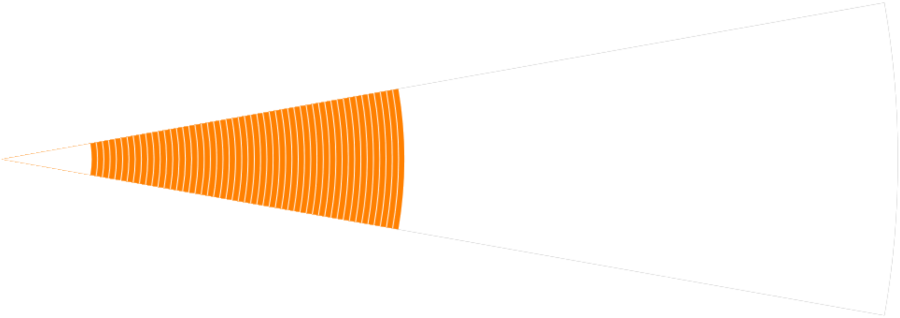
Fireball model: our current paradigm of how a GRB works

– 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 –

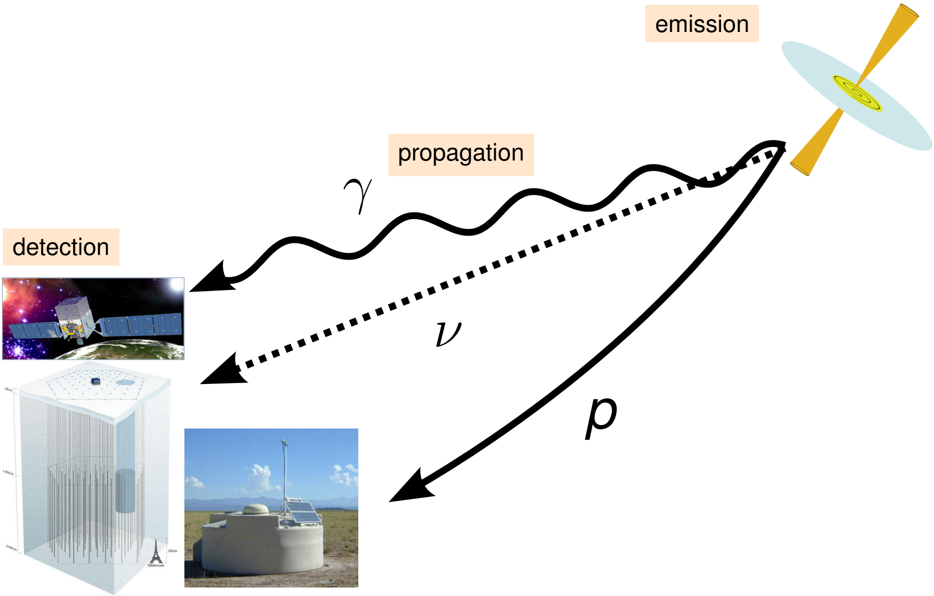


▲ shell has not collided

shell has collided many times ▲

GRBs: sources of UHE neutrinos and cosmic rays?

Emission–propagation–detection



GRBs as sources of UHE ν's, CRs, γ rays

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

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

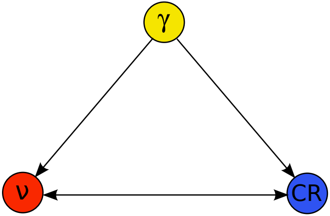
$$p\,\gamma \rightarrow \Delta^+(1232) \rightarrow \begin{cases} n\pi^+\,, & \mathrm{BR} = 1/3 \\ p\pi^0\,, & \mathrm{BR} = 2/3 \end{cases}$$

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

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

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

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



After propagation, with flavour mixing:

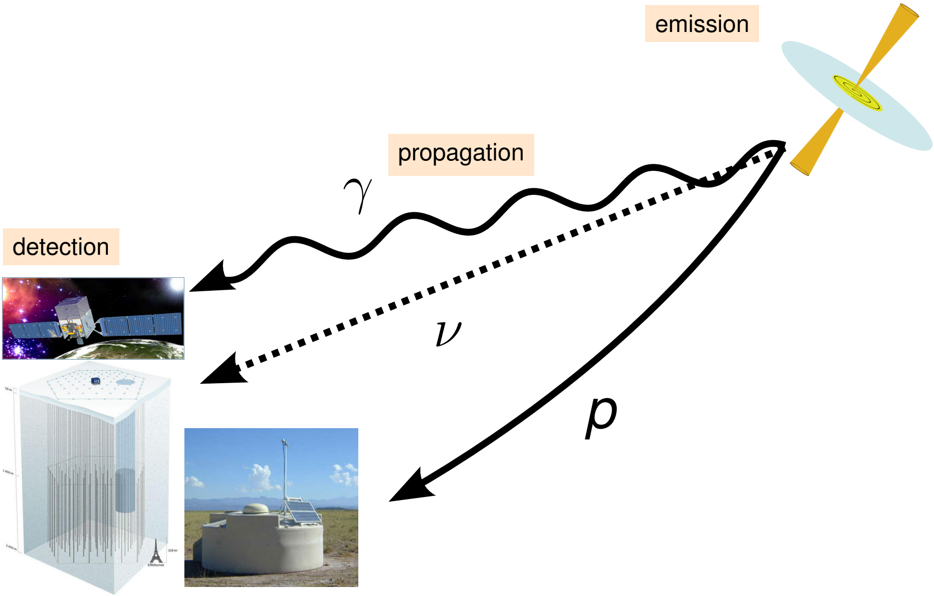
$$\nu_e : \nu_\mu : \nu_\tau : p = 1 : 1 : 1 : 1$$

("one ν_μ per cosmic ray")

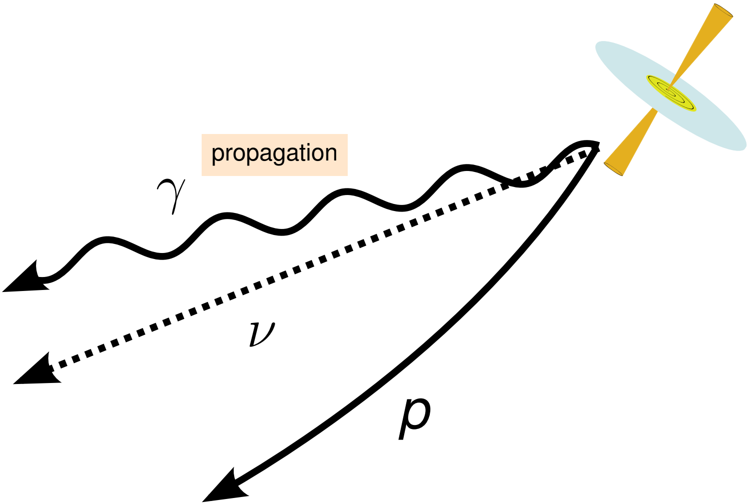
CR emission by *n* escape only is now strongly disfavoured

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

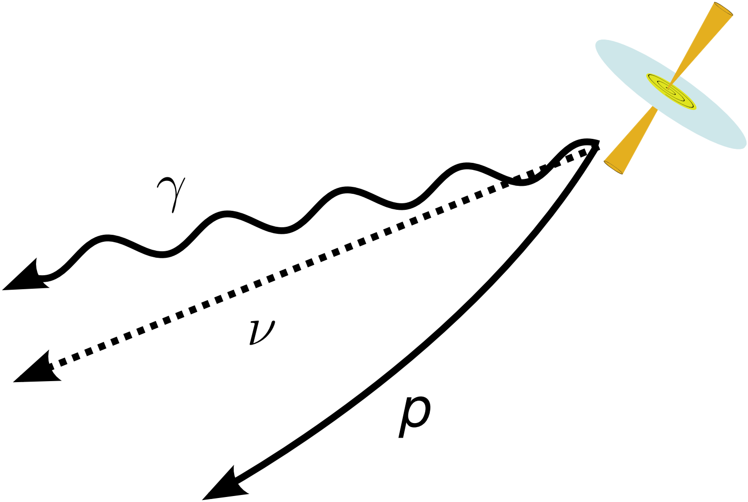
GRBs as sources of UHE ν's, CRs, γ rays



GRBs as sources of UHE ν's, CRs, γ rays



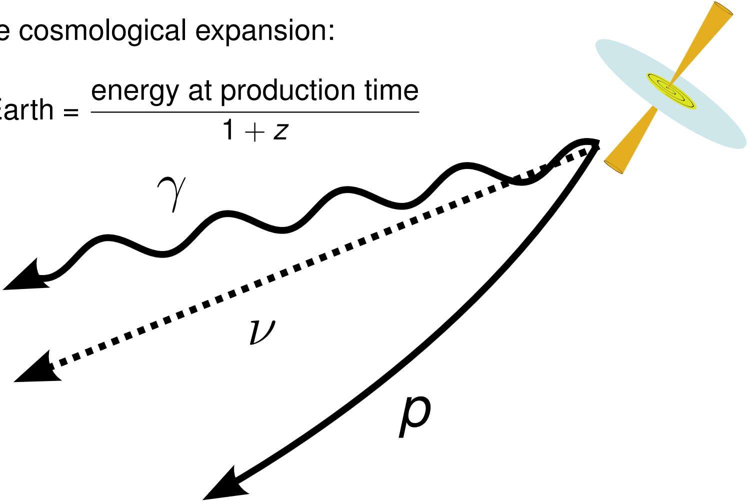
GRBs as sources of UHE ν's, CRs, γ rays



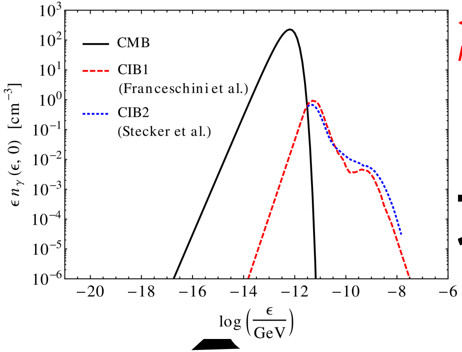
GRBs as sources of UHE ν's, CRs, γ rays

Because of the cosmological expansion:

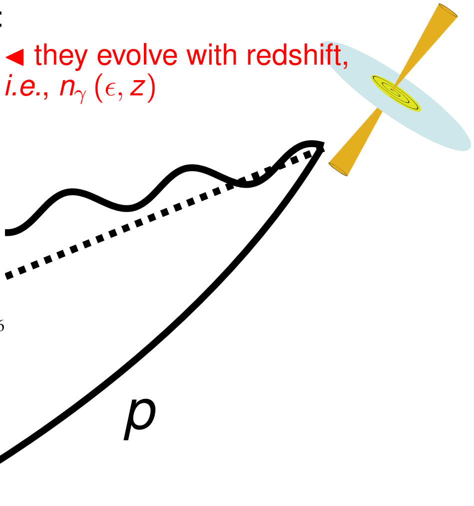
$$\text{energy at Earth} = \frac{\text{energy at production time}}{1+z}$$



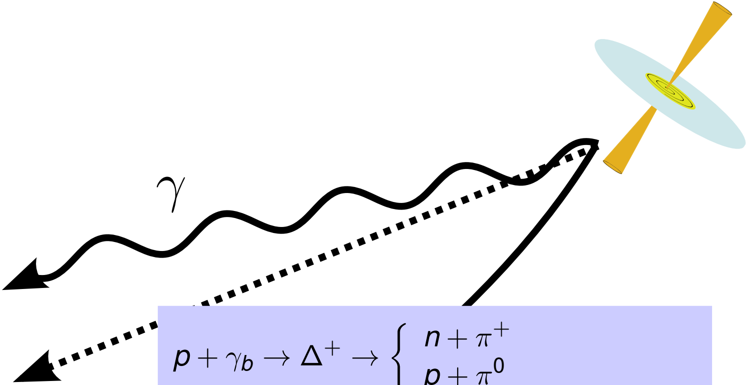
Cosmological photon backgrounds:



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



GRBs as sources 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: $\pi^+ \to e^+ + \nu_e + \bar{\nu}_\mu + \nu_\mu$

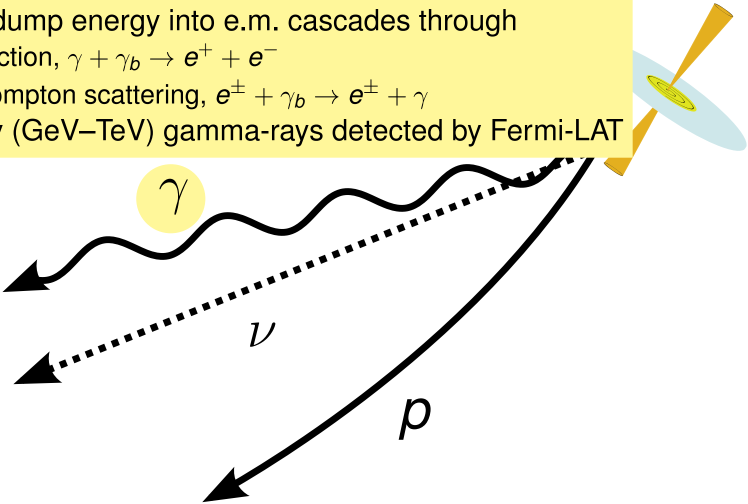
$n \to p + e^- + \bar{\nu}_e$

GRBs as sources 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



GRBs as sources of UHE ν's, CRs, γ rays

p's are deflected by extragalactic magnetic fields

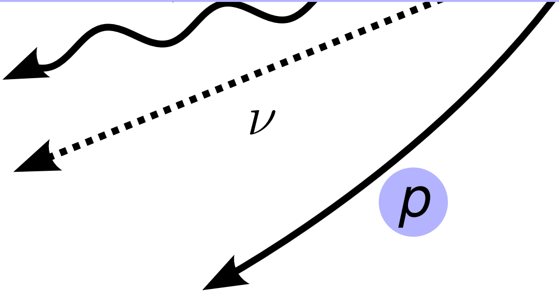
$\Rightarrow$ except for the most energetic ones, they are **not** expected to point back to the sources

Pierre Auger found weak correlation with known AGN positions

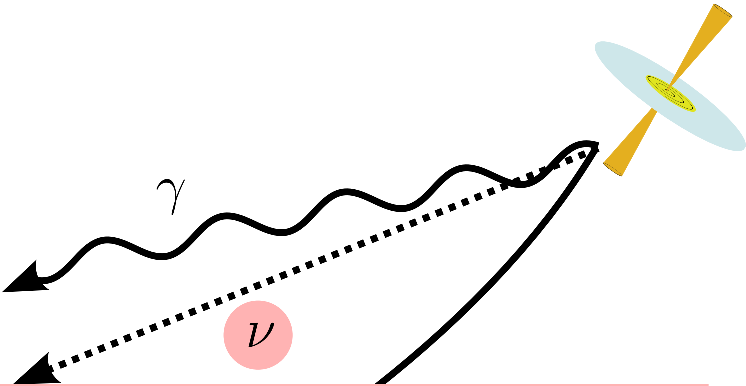
They lose energy through:

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

depend on the redshift evolution of the cosmological γ backgrounds



GRBs as sources of UHE ν's, CRs, γ rays



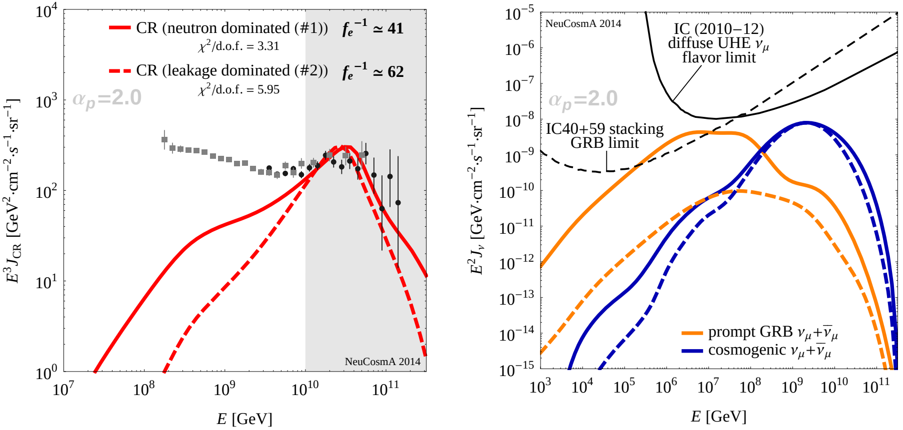
Initial UHE ν flavour fluxes: $\nu_e : \nu_\mu : \nu_\tau = 1 : 2 : 0$

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!)

UHE ν and CR fluxes at Earth

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

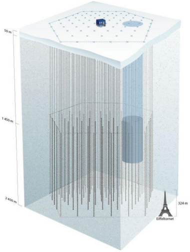
UHECRs

- 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.*:

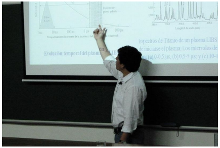
bustamanteramirez.1@osu.edu

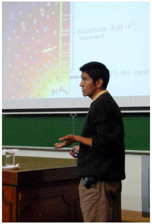
Ongoing and coming events

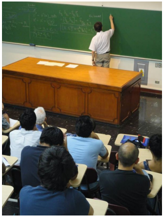
PUCP COLOQUIOS DE FÍSICA

- 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

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

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

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

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

- Photon density at source has same shape as observed:

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

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

Normalise the densities at the source – for one collision:

- Photons:

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

- Protons:

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

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

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

$x \equiv E'/E'_p$

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

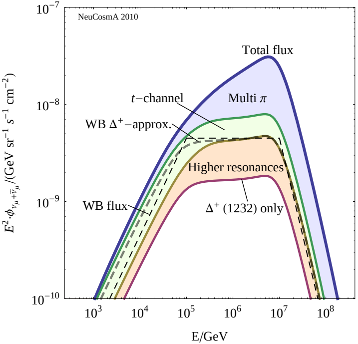
$$Q'\left(E'\right) = \int_{E'}^{\infty} \frac{dE'_p}{E'_p} N'_p\left(E'_p\right) \int_0^{\infty} c\, dE'_\gamma\, N'_\gamma\left(E'_\gamma\right) R\left(x, y\right)$$

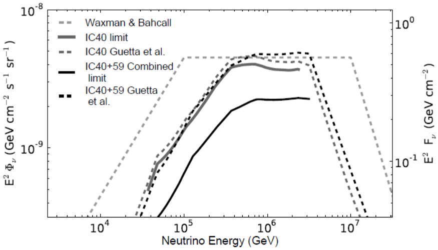
response function

R contains cross sections, multiplicities for different channels

What does NeuCosmA include?

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





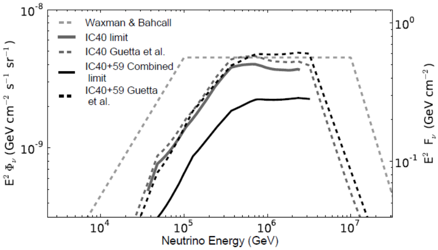
IceCube Collaboration:

- ν flux normalised to GRB γ fluence:

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

- 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)



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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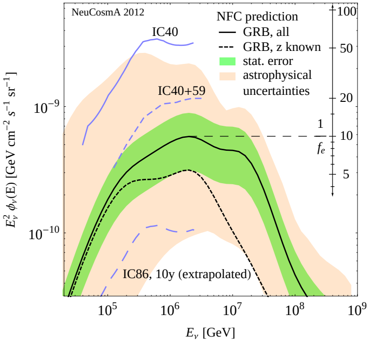
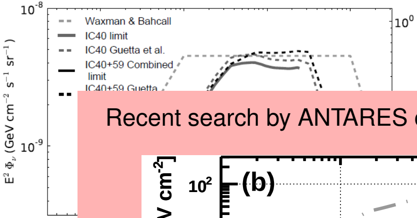
AHLERS ET AL. *Astropart. Phys.* **35**, 87 (2011)
GUETTA ET AL. *Astropart. Phys.* **20**, 429 (2004)





More detailed particle physics (NeuCosmA):

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

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(2012)

IceCube C

- ν flu

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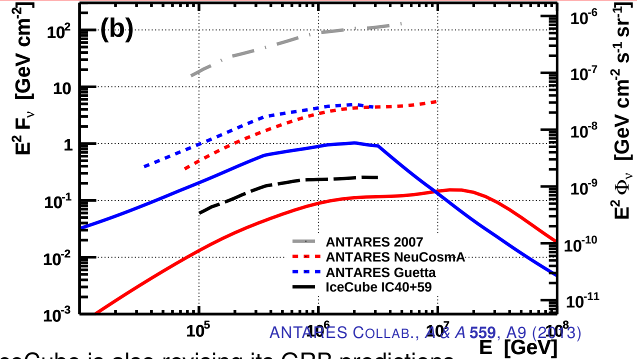
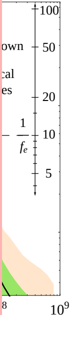
Recent search by ANTARES optimised for NeuCosmA:



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

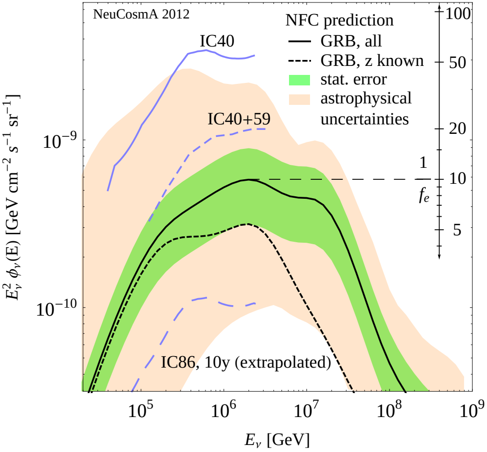
► IceCube is also revising its GRB predictions



- 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:
  - $0.001 \leq t_v\,[\mathrm{s}] \leq 0.1$
  - $200 \leq \Gamma \leq 500$
  - $1.8 \leq \alpha_p \leq 2.2$
  - $0.1 \leq \epsilon_e/\epsilon_B \leq 10$



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