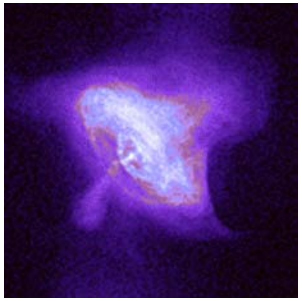
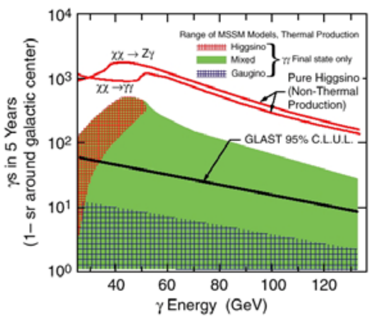
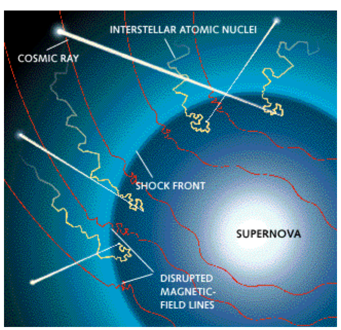
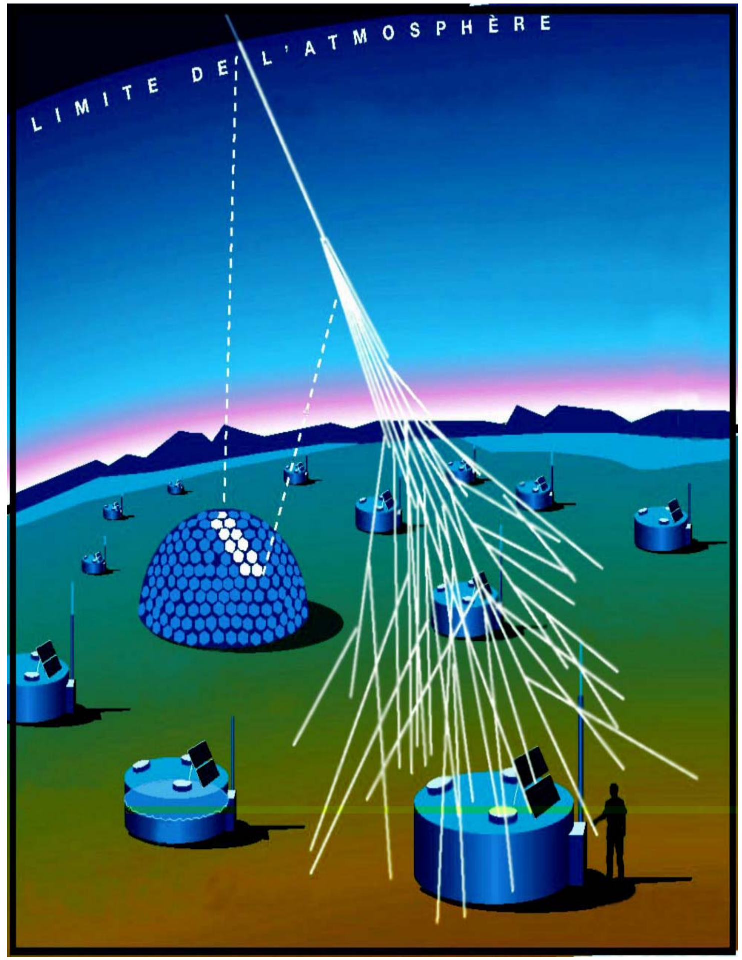
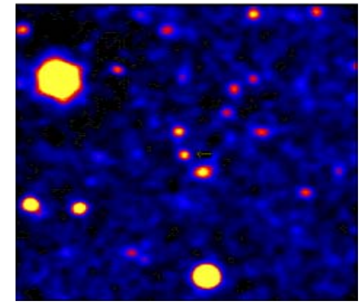
HIGH-ENERGY COSMIC RAYS

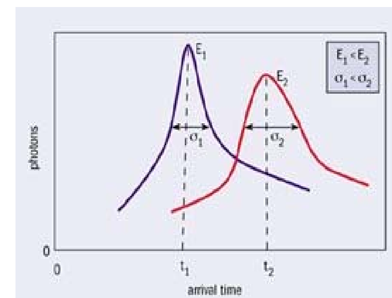


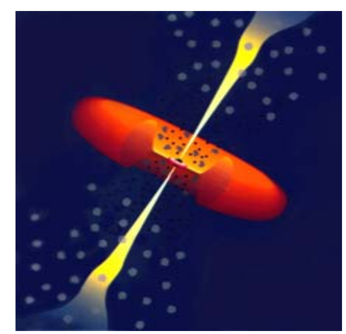












Rene A. Ong
University of California, Los Angeles

SLAC Summer Institute
1 August 2003

OUTLINE

- Introduction
  - **Messengers, observables, questions.**
- Detection of HE particles
  - **Early history.**
  - **Satellite & ground-based.**
  - **Particle physics techniques!**
- Physics: Origin of HE particles
  - **Power sources & particle acceleration.**
  - **The general picture → many questions.**

OUTLINE

- Astrophysics: Known HE Sources
  - **γ-ray, CR, and ν skies.**
  - **Point and diffuse sources.**

- Connection to Part. Physics & Cosmology
  - **VHE/UHE radiation as probes of space.**
  - **Relic particles & top-down models.**

- Summary – the next 5 years

INTRODUCTION

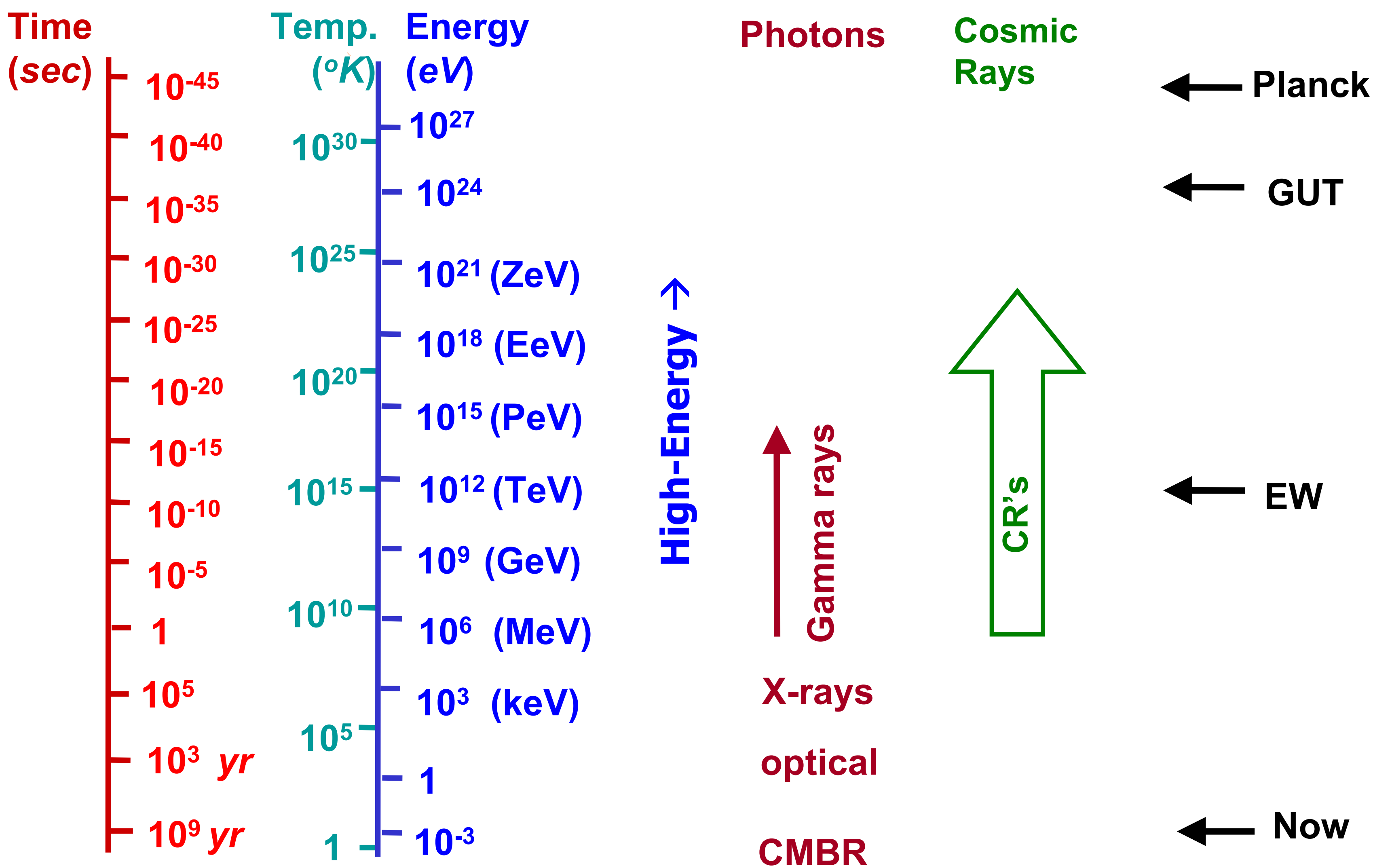
Cosmic Messengers

We know about the Universe from 4 messengers:

	Particles	charge	status
1.	**Photons**	neutral	crucial
2.	**Cosmic Rays**	charged	v. important
3.	**Neutrinos**	neutral	developing
4.	**Grav. Waves**	neutral	infancy
5.	**(New stable particle)**		

These lectures concentrate on 1-3 at high-energy.

Energy Scales

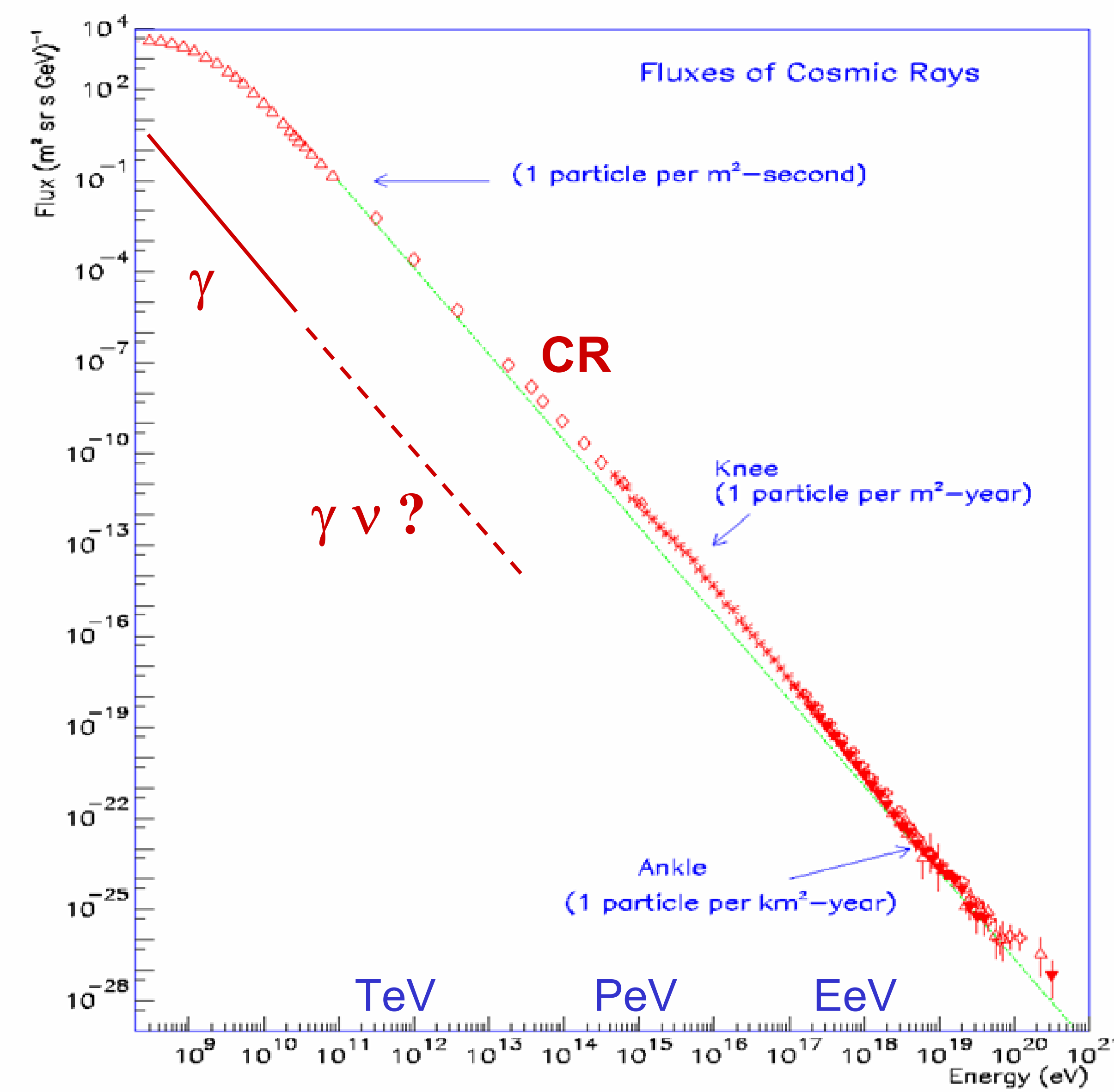


Observables

• Particle Type: CR, γ, ν, g	**Composition**
• Energy	**Spectrum**
• Arrival Direction	**Anisotropy**
• Variability	**Light Curve**

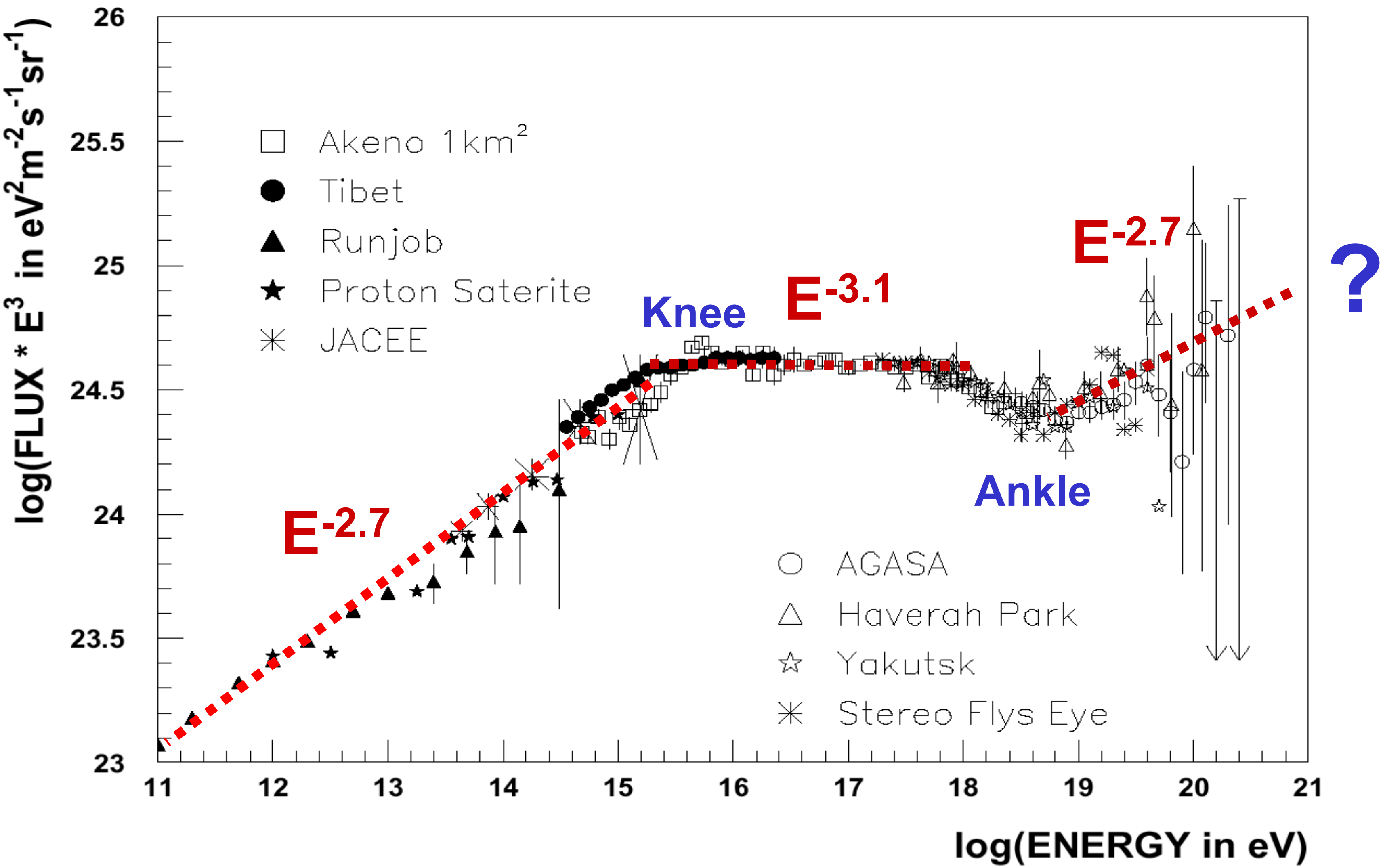
(Polarization)

Energy Spectrum

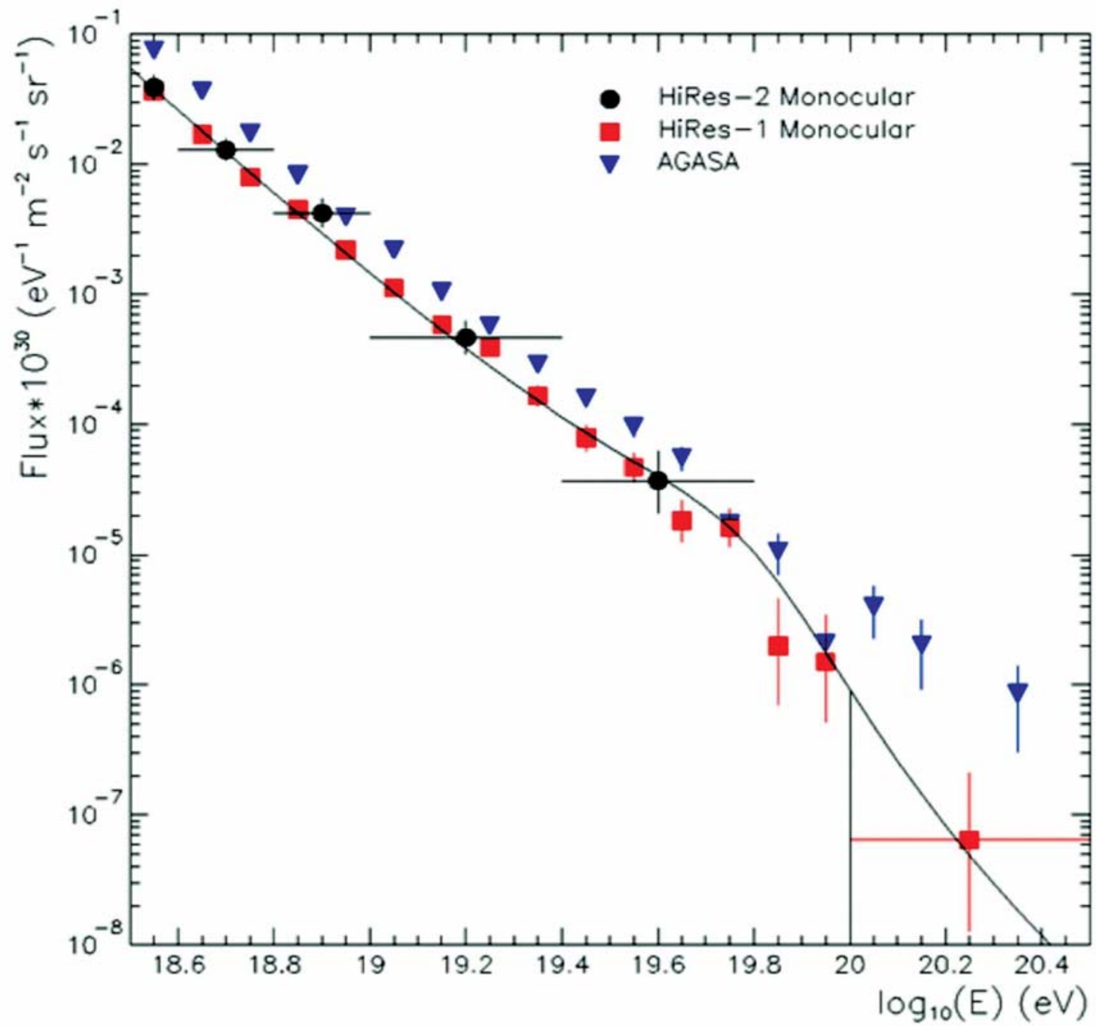


- Total,diffuse spectrum individual species not resolved.
- Power-law spectrum E^{-3} differential.
- $E > 10^{20}$ eV.
- Energy density ~ 1 eV / cm^3.
- Diffuse ν not (yet) seen.

Energy Spectrum (Flattened)



At the Highest Energies



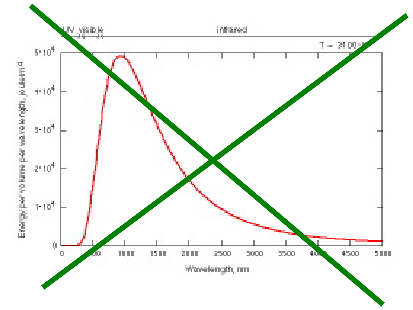
Particles E > 10^{20} eV are <u>not</u> expected:

1. Very hard to accelerate to these energies.
2. Nuclei cannot travel beyond 100 Mpc

   $p\ \gamma_{cmbr} \rightarrow \Delta^{+} \rightarrow \pi$'s

What are these particles and where do they come from ??

HE Implications



Phenomenological

Energy scale is reached by either:

1. Non-thermal, radiative processes (**Astrophysics**).
2. Decays, interactions from higher mass scale (**Particle Physics**).

Experimental

1. Particles are detected by total absorption.
2. We are required to measure tiny fluxes. (< 1 /km^2/century at highest energies)

Other Properties

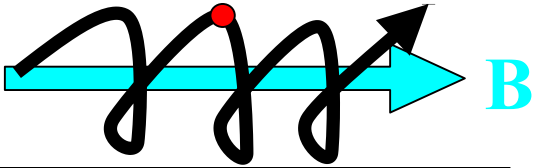
- Composition
  - Charged nuclei (P, He, C … Fe).
  - Total energy measured.

- Anisotropy
  - Very little detected – μG galactic magnetic field.

- Variability
  - Not detected at HE.

Origin of HE cosmic rays remains mysterious !

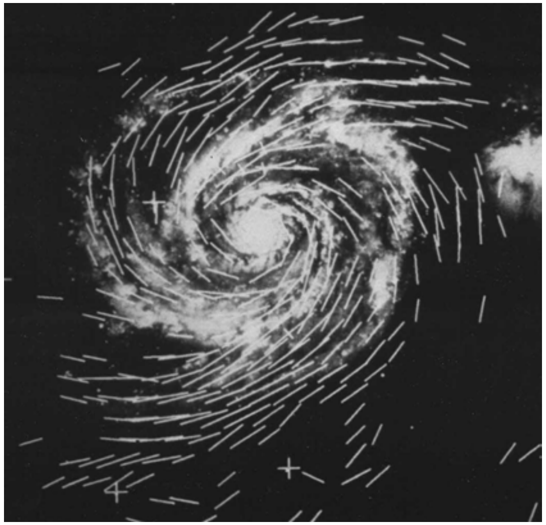
Magnetic Fields



1. Galaxies have magnetic fields.
   - Protons and nuclei will be deflected by the B ~ 5 μG galactic field.

   Larmor radius r = R/cB

R	r
10^{15} eV	0.3 pc
10^{20} eV	30 kpc ← size of galaxy



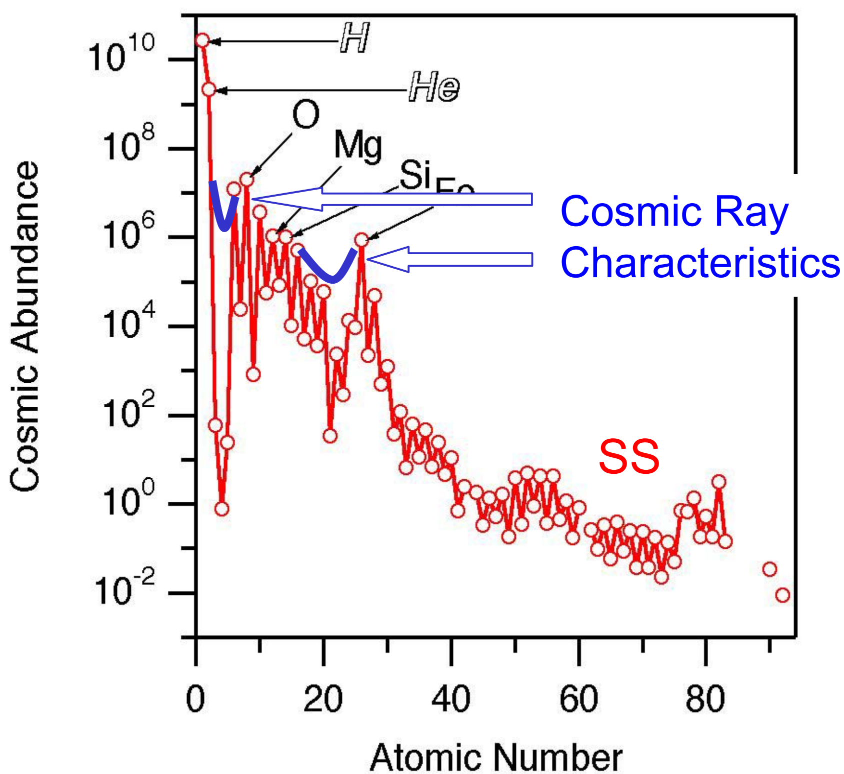
M51

2. Intergalactic fields may also be significant
   - Clusters (e.g. Coma) have field strengths B ~ 0.1 – 2 μG, perhaps extending out along sheets and filaments.

Charged CR directions will be scrambled by B fields.
But we can still learn a lot from their composition.

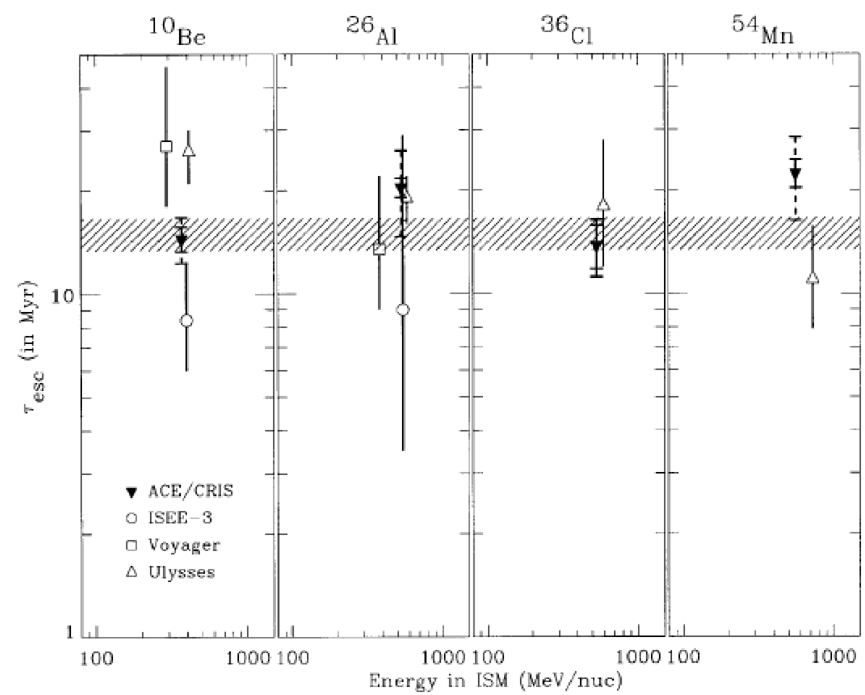
Low-Energy CR's

Elemental Abundances



Generally agrees with local material.
Excess for light elements and near Fe.

Radioactive Clock Isotopes



Mean CR lifetime ~ 15 Myrs.
Required Luminosity $L > 10^{40}$ ergs/s

Questions I

What is the nature and the origins of this diffuse flux of cosmic-ray particles?

- Abundant, extremely energetic particles that play an important role in dynamics of galaxy.
- Sources must be powerful and renewable.
- At highest energies – we have no understanding of how they can be produced.

Do these particles provide clues about the early Universe or about the physics at higher mass scales?

Questions II

What can we learn from Astronomy at very high energies?

- New wavebands/messenengers → New Physics
- Gamma-rays, ν's point directly back to sites of extreme particle acceleration or unexpected phenomena.
- VHE particles can be used to probe radiation fields and the fabric of space-time.

These are the major themes for this talk.

DETECTION OF VHE/UHE PARTICLES

Early History

Discovery of “Hohenstrahlung” (1912)

- Electroscopes in balloons (Hess, Kohlhoerster).

Identifying the nature of CR’s (1933-1937)

- Penetrating nature (Rossi) .
- Latitude effect → charged particles (Compton).
- East-West effect → positively charged (Rossi, Compton, Alvarez).
- Positron & muon (Anderson etc.).

Reaching extreme energies (1938)

- Extensive air showers (Auger).
- Power law spectrum with energies to > 10^{14} eV.
- Clearly differentiated between primary/secondary CR’s.

"Hohenstrahlung"

Electroscope

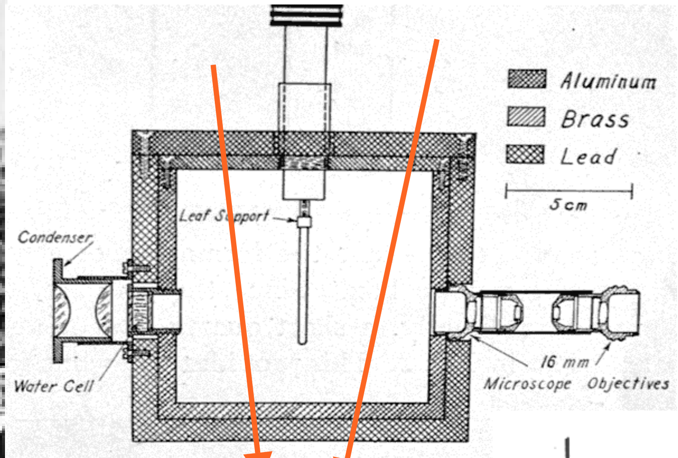
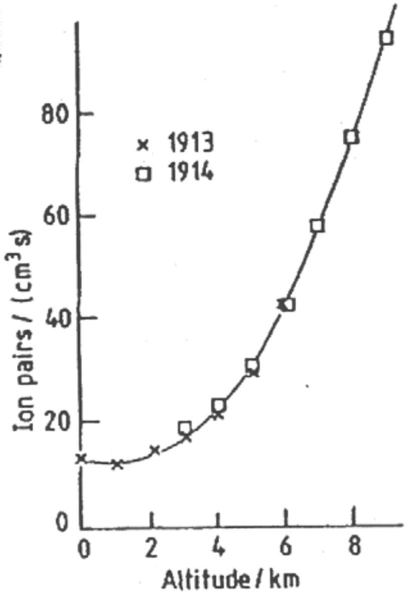


FIG. 1. Cross-section of electroscope

Viktor Hess

Ionization Rate



Deciphering Cosmic Rays

Robert Millikan

These facts, combined with the further observations … all this constitutes pretty un-ambiguous evidence that the high altitude rays do not originate in our atmosphere… and justifies the designation "cosmic rays" …

Nature, 121, 19 (1928).

The New York Times

VOL. LXXXII...No. 27,370. December 31, 1932

MILLIKAN RETORTS HOTLY TO COMPTON IN COSMIC RAY CLASH

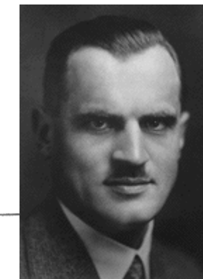
Debate of Rival Theorists Brings Drama to Session of Nation's Scientists.

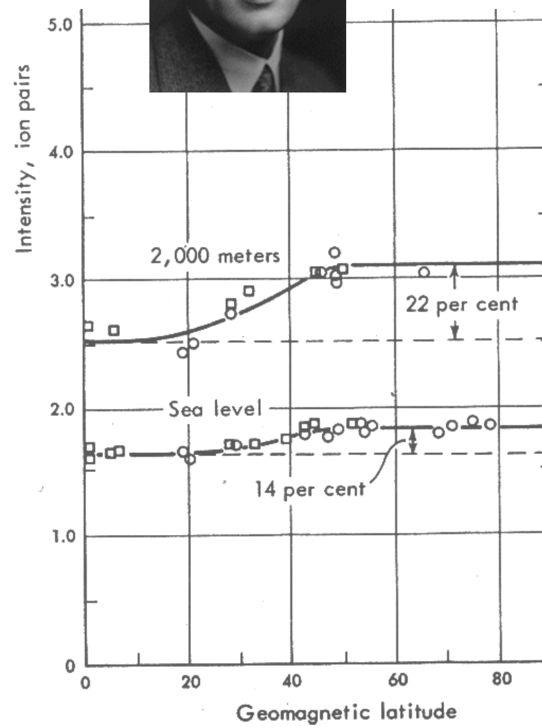
THEIR DATA AT VARIANCE

New Findings of His Ex-Pupil Lead to Thrust by Millikan at 'Less Cautious' Work.

γ-ray or particle ?

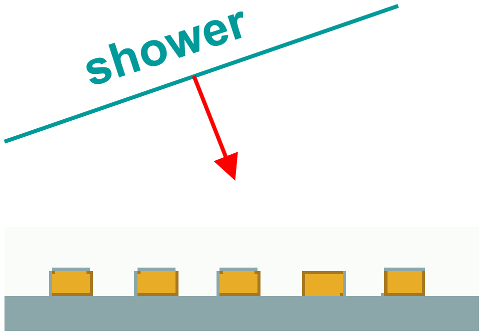
Arthur Compton



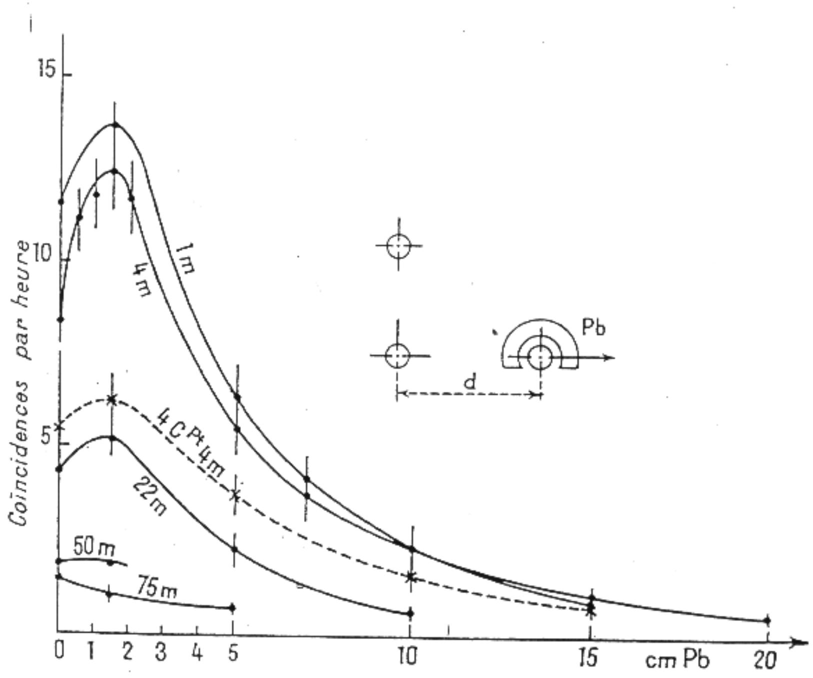


Extensive Air Showers

Pierre Auger



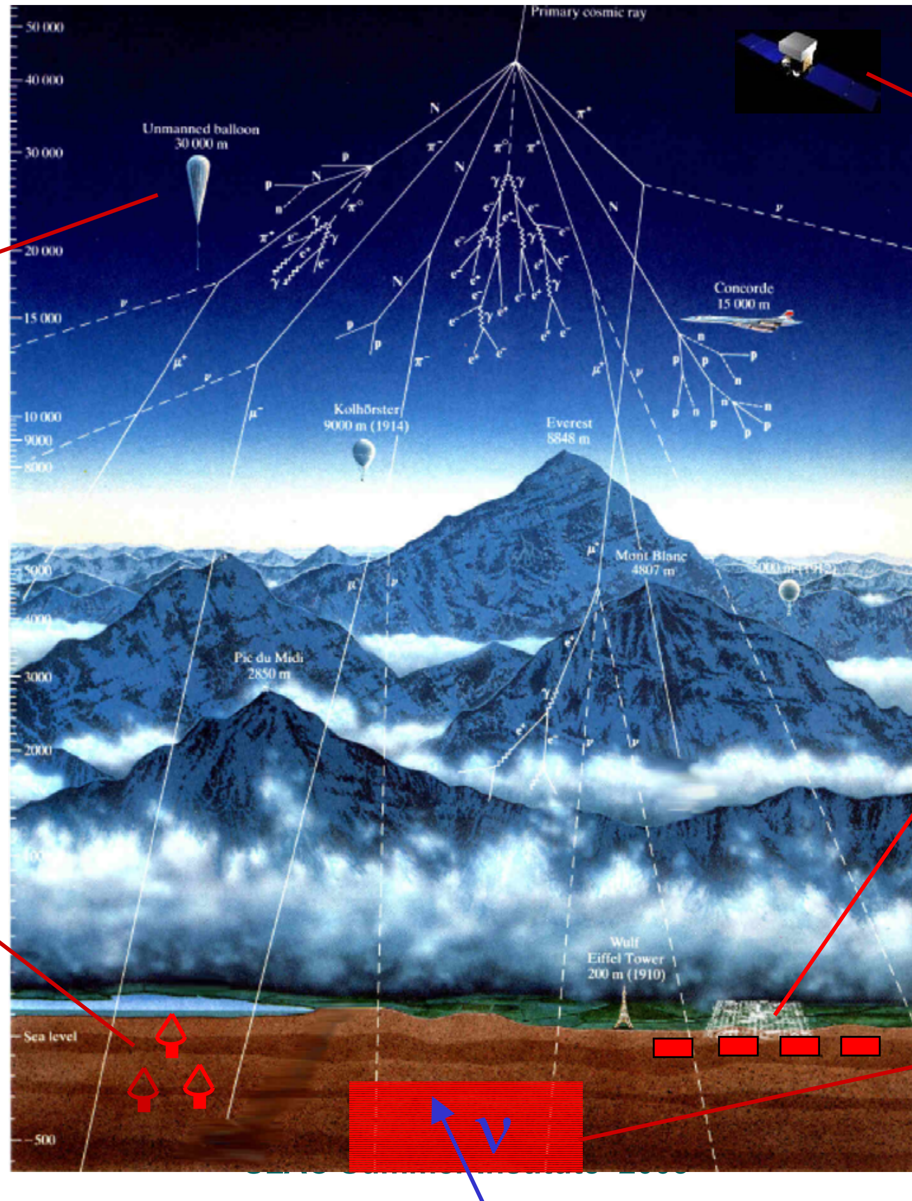
pour les écrans interposés. On peut voir là une indication de l'énergie moindre des électrons géométriquement très écartés des condensations ou les particules les plus énergiques sont présentes (courbe 5).



Courbe 5.

Lateral distribution

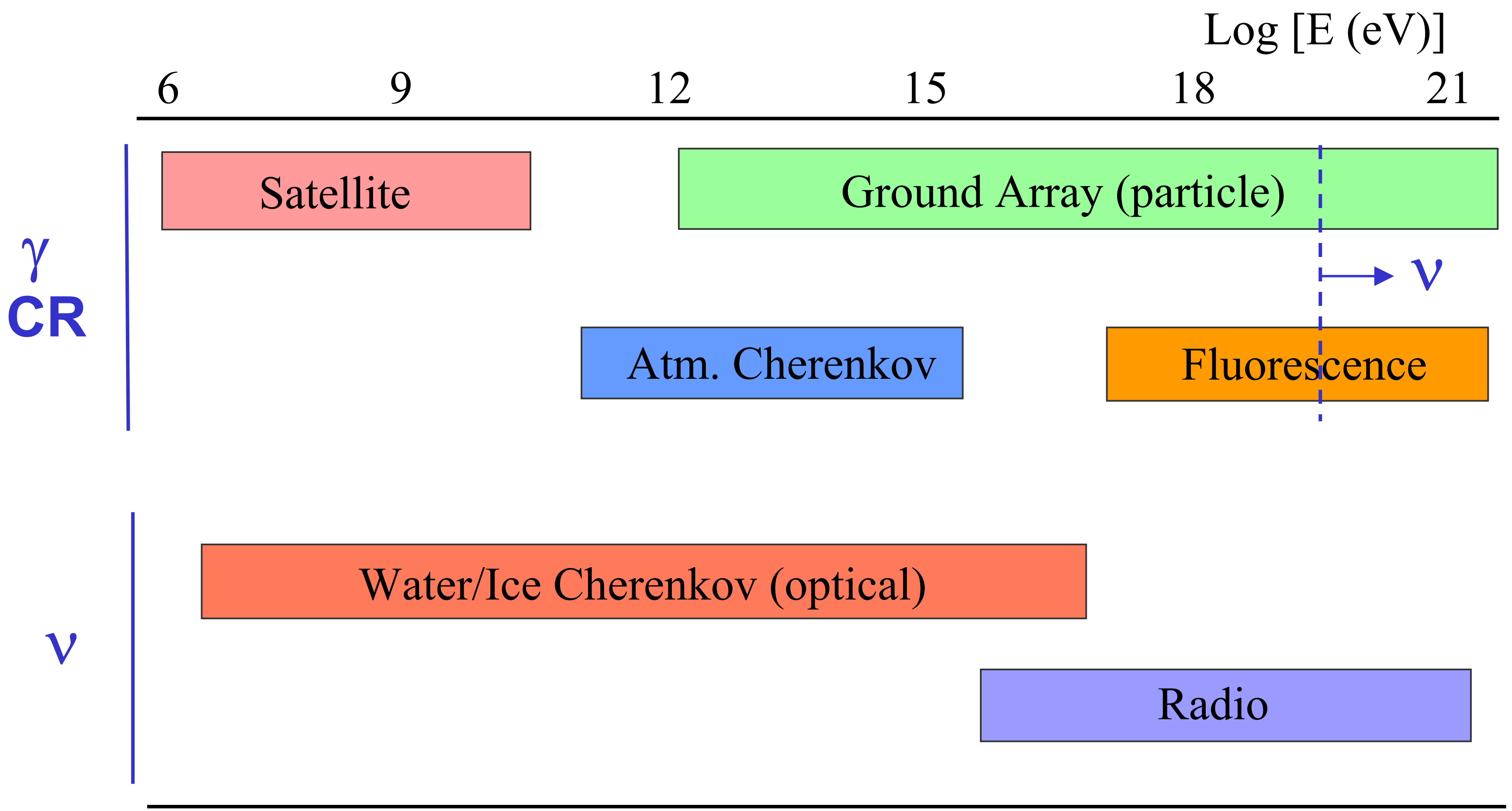
Experimental Techniques



Giant Air Showers

Picture of Giant Air Shower

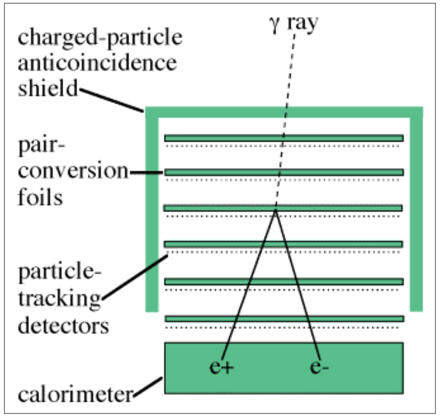
Experimental Techniques



Satellite

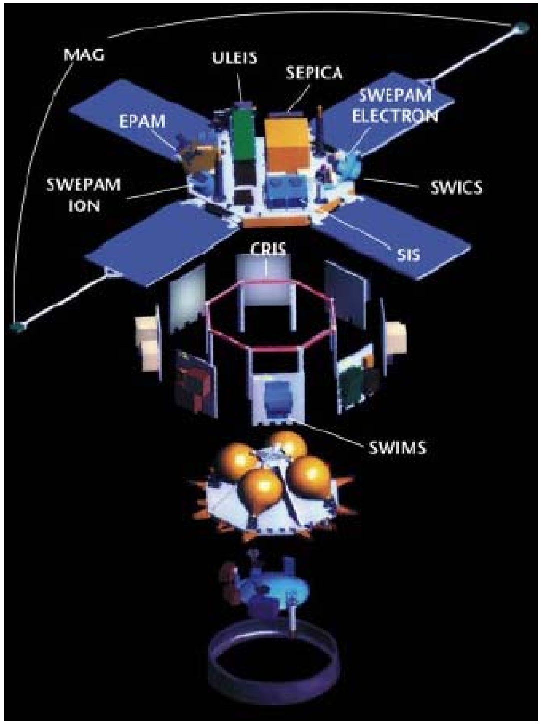
γ-ray: pair production

EGRET



- Excellent background rejection
- Full-sky coverage
- Limited collection area < 1 m^2

CR's: direct detection

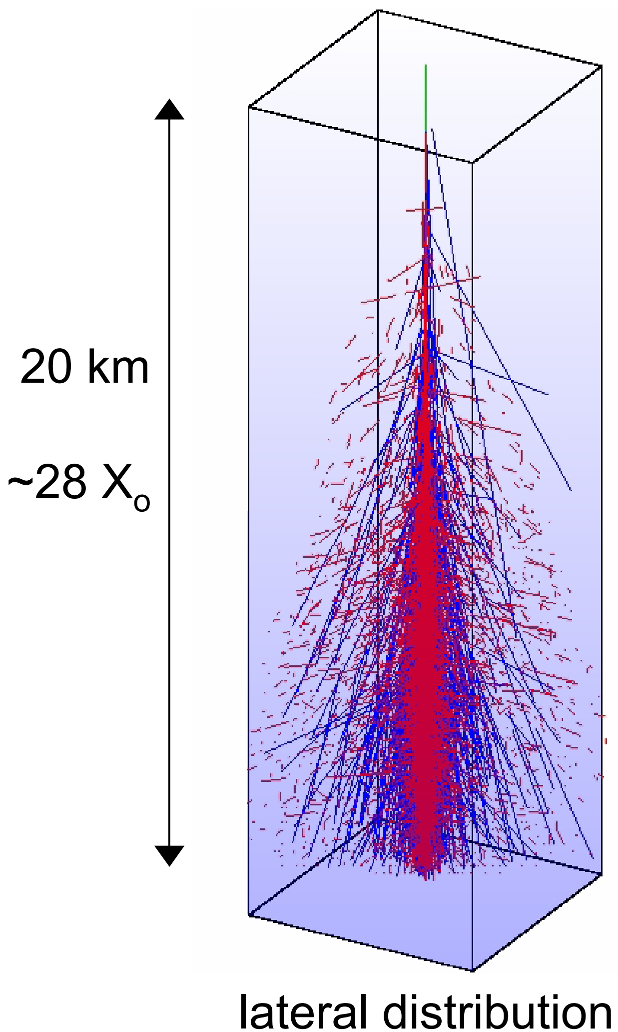


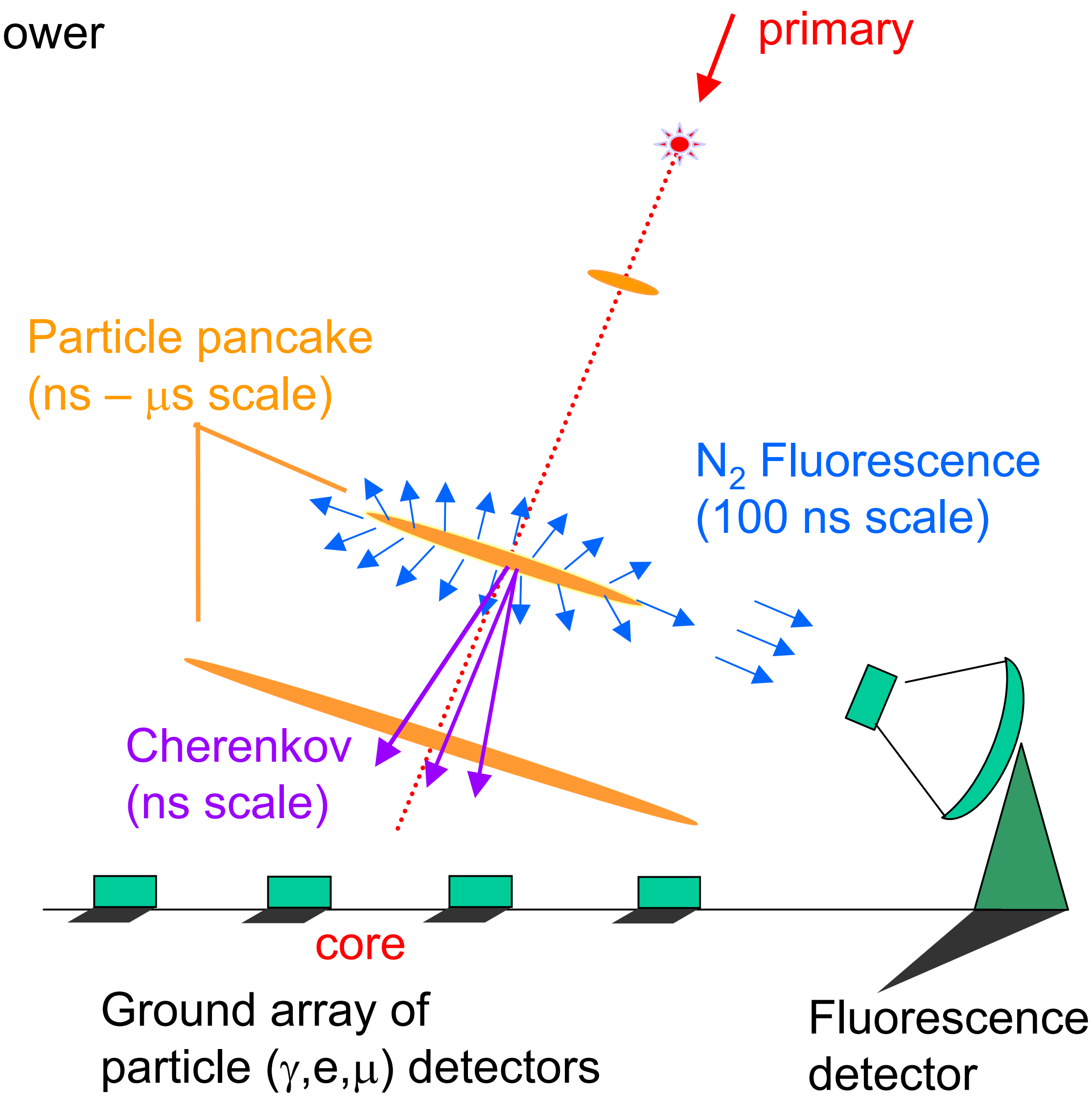
ACE

- GCR / Solar energetic part.
- Elemental / isotopic meas.

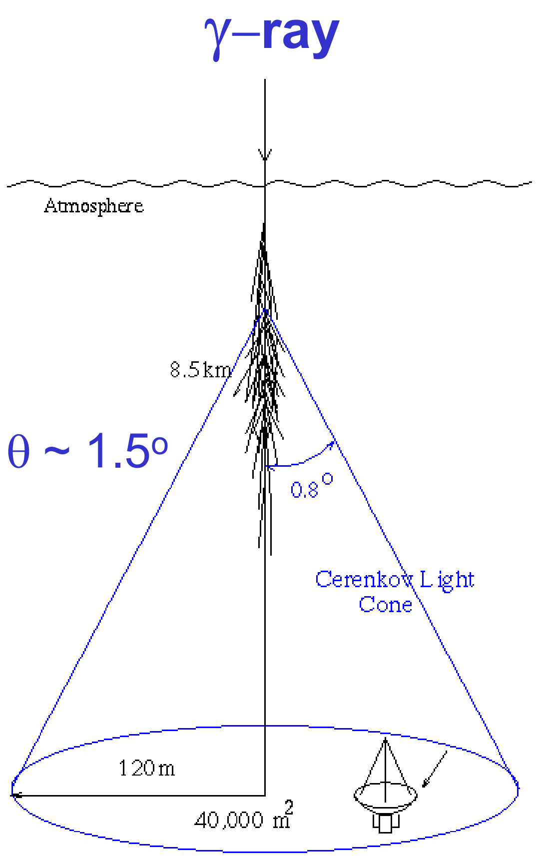
Air Shower Detection

10^{18}eV Proton → 10^9 e in shower





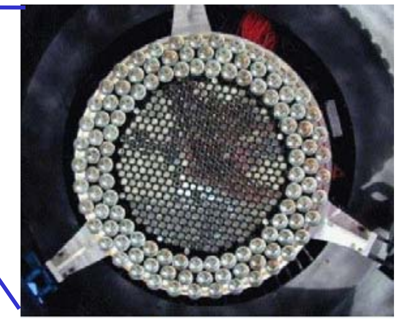
Atmospheric Cherenkov



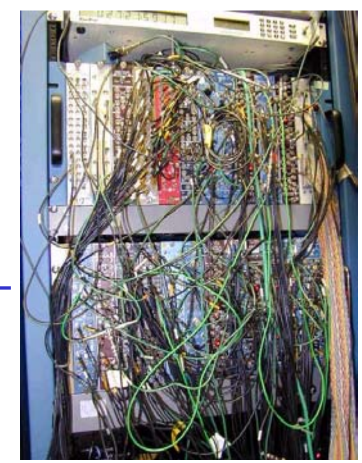
Area = $10^4 - 10^5$ m^2

~60 optical photons/m^2/TeV

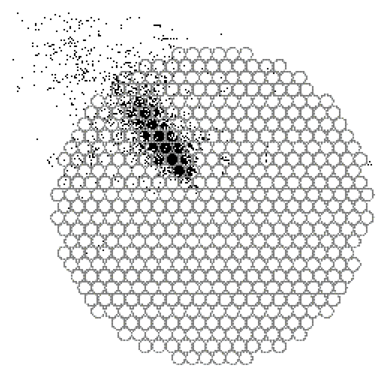
Whipple 10m (Arizona)



PMT camera

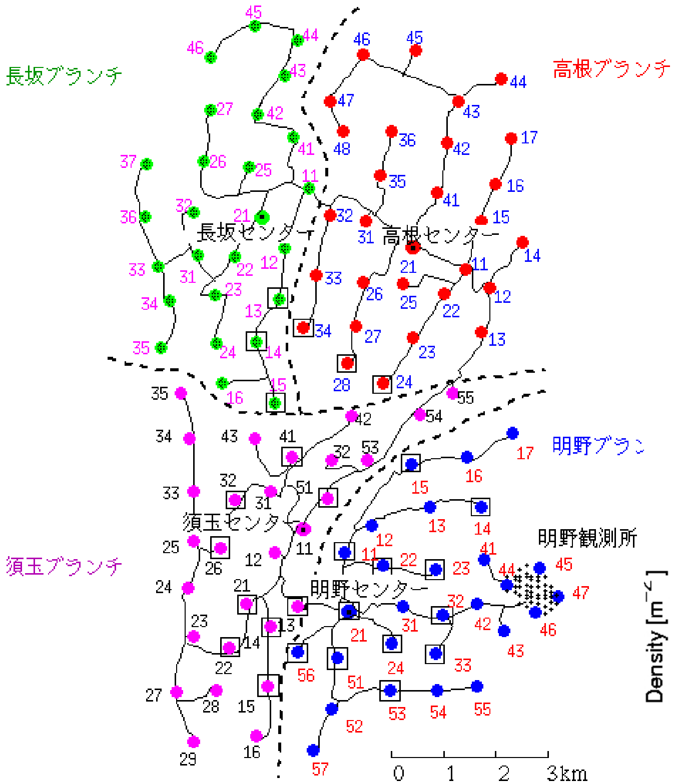


ns electronics



Cherenkov image

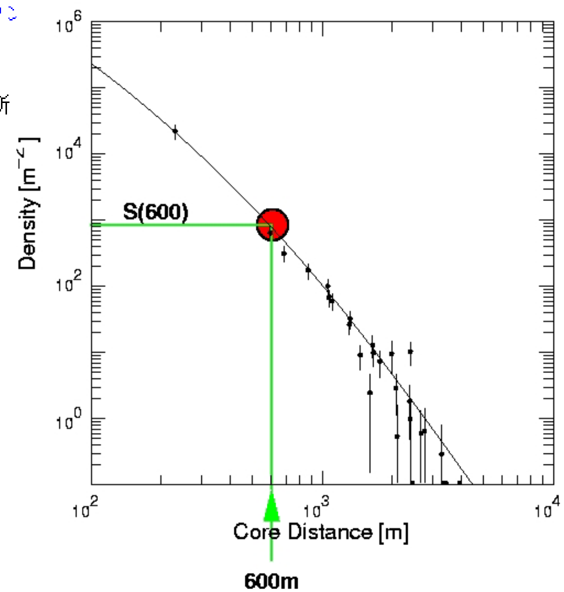
Ground Arrays



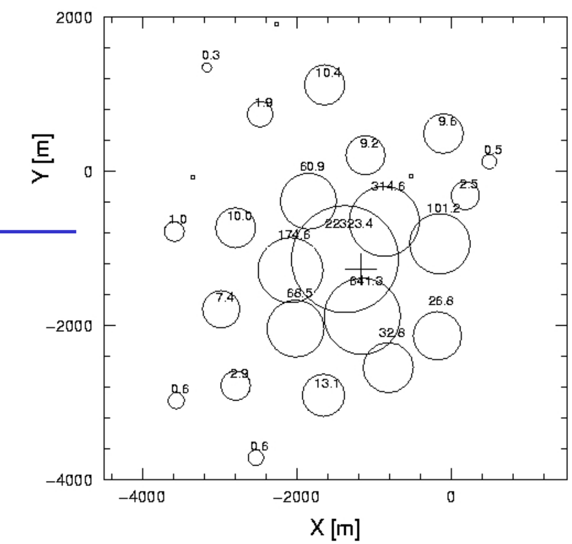
AGASA (Japan)

~ 100 km² area

Absorber & charged particle detectors modest timing req.

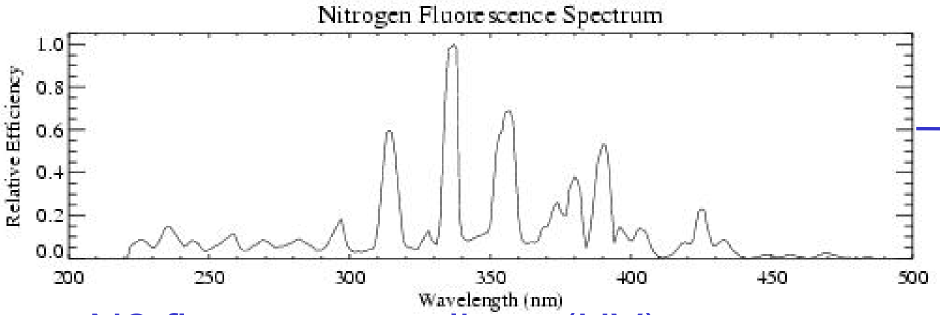


Energy estimation S(600)

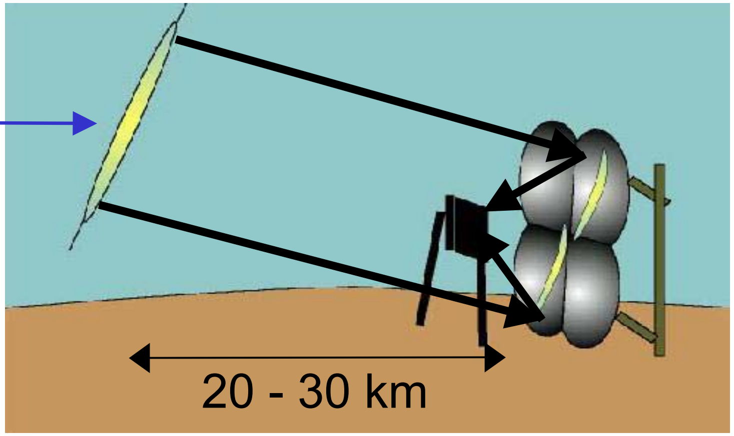


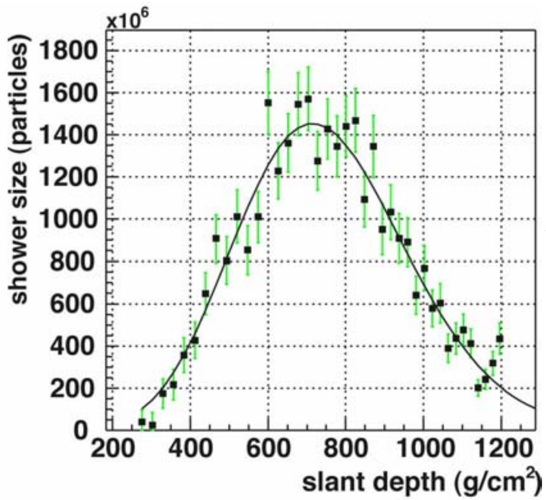
Lateral intensity

Fluorescence detection

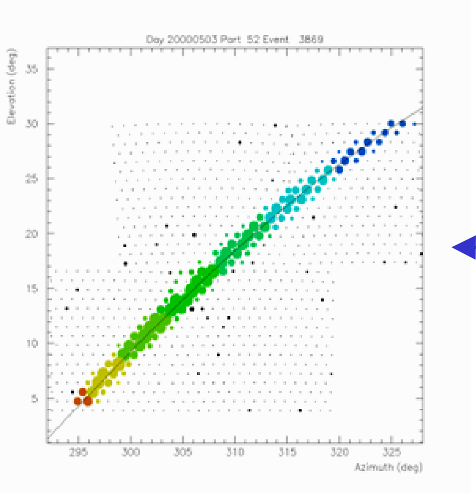


N2 fluorescence lines (UV)
decay ~ 100 ns, ~4 photons/m/e$^-$





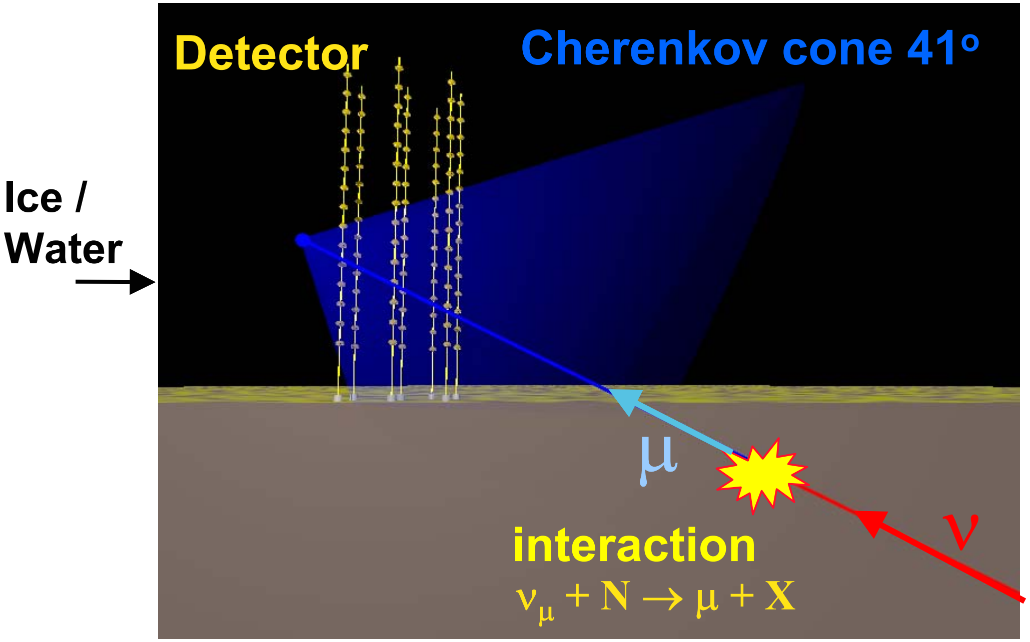
Longitudinal distribution
→ E, shower max

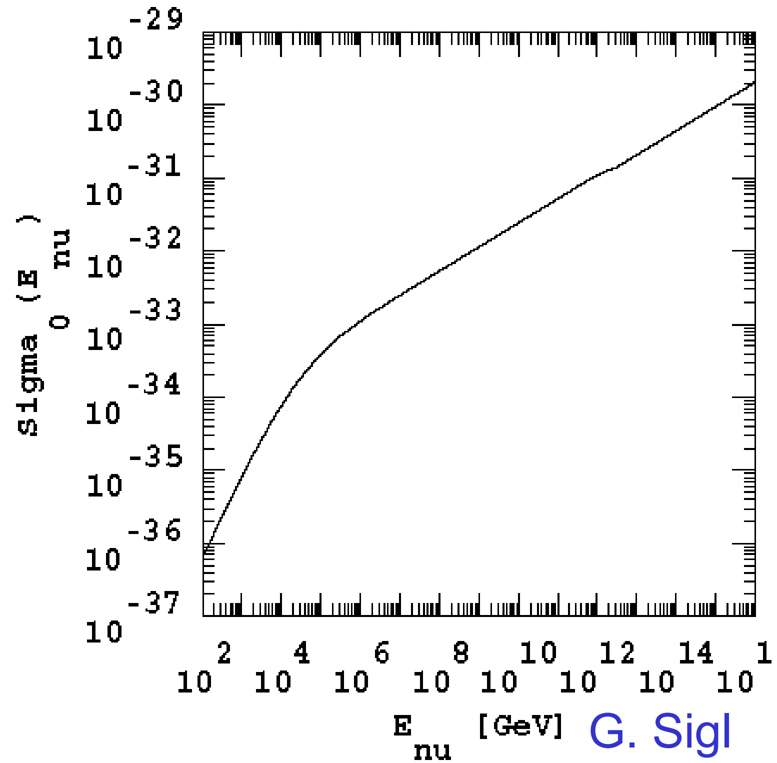


Shower intensity image

Fly's Eye HiRes
(Utah)

ν Detection (optical)





G. Sigl

Two signatures:

- Muon track: CC interaction

  ~7km, 20x min.i. (10 TeV)
- Casade: CC or NC interaction

$$\nu_{(e,\tau,)} + N \rightarrow (e, \tau) + X$$

$$\nu_x + N \rightarrow \nu_x + X$$

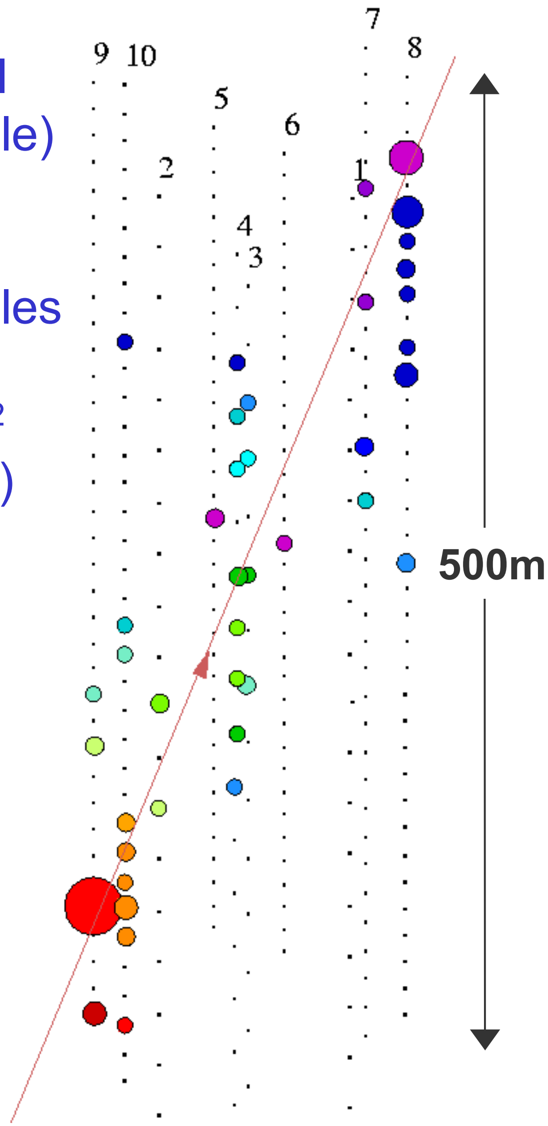
Neutrino cross sections have some uncertainty (~ 50% in PeV-EeV range).

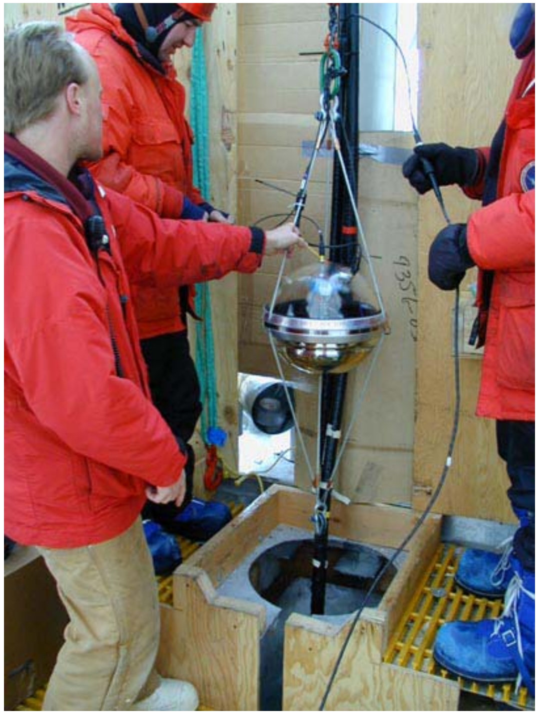
ν Detection (optical)

Amanda-II
(South Pole)

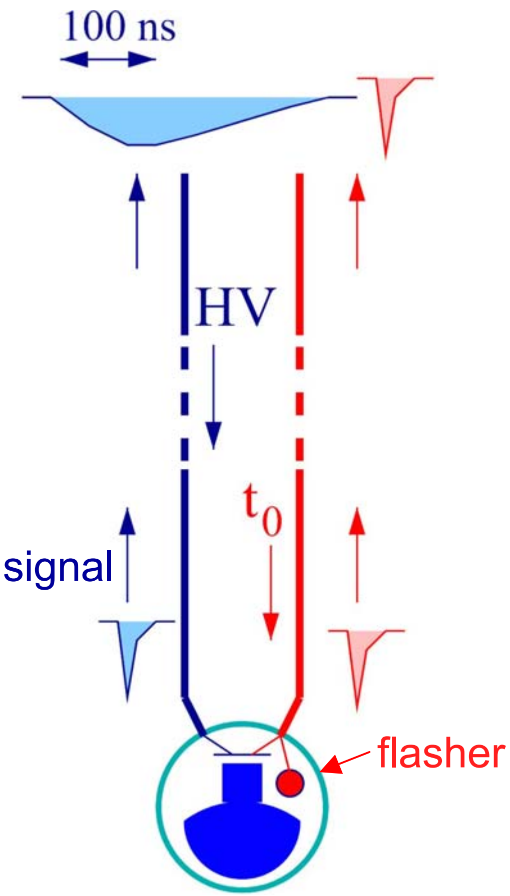
19 strings
677 modules

25,000 m^2
(10 TeV)



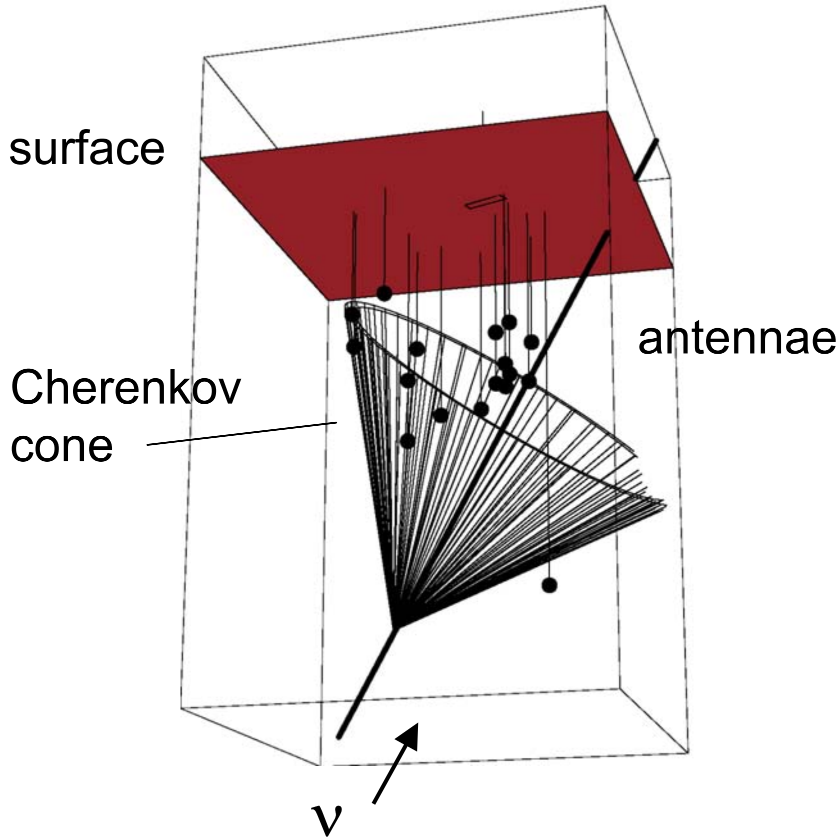


Deploying optical modules

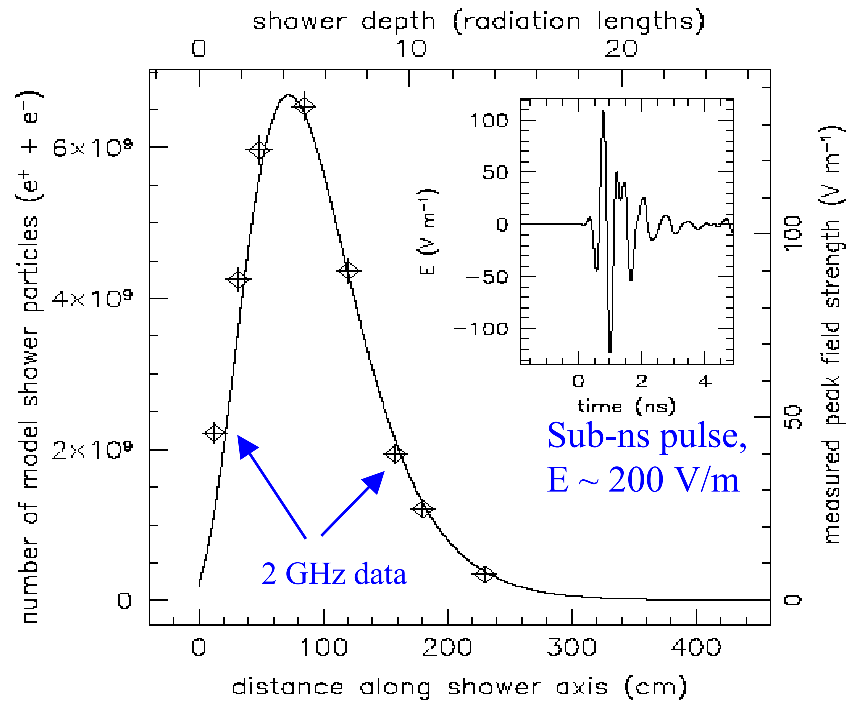


Readout strategy

ν Detection (radio)



RICE concept (South Pole)



Coherent Cherenkov radio signal observed (SLAC):

- e^- beam into sand, rock salt

Comparison of Techniques

Subjective (!) comparison:

Particle	Technique	Area	Duty cycle FOV	Part. ID	Ang. Res.	E Res.
CR, γ	Satellite	small	wide	excellent	excellent	v. good
γ	At. Cherenk.	large	narrow	v. good	v. good	good
CR, γ	Ground array	v. large	wide	modest	o.k.	o.k.
CR, γ	N_2 fluoresc.	v. large	wide (low dc)	good	o.k.	good
ν	Ice/water	v. large	wide	good	modest	modest

ORIGIN OF
HE PARTICLES

General Approaches

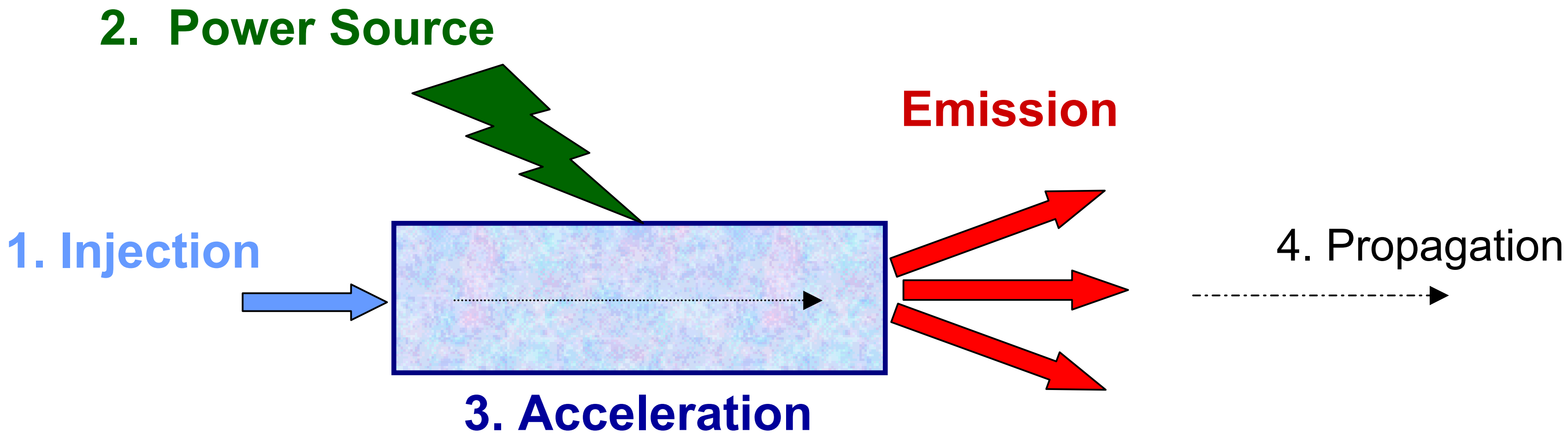
We hypothesize of two broad origins for HE particles:

1. Astrophysical Particle Acceleration (“bottom up”):
   - Non-thermal acceleration at source.
   - Emission into ISM and propagation to us.

2. New Particle Physics (“top down”):
   - New particle from EW or GUT scale interaction.
   - Relic produced in early Universe.

Cosmic Acceleration

To build a HE cosmic accelerator, we need the following parts:



1. Injection

Acceleration is done on charged particles. γ-rays and ν's are secondaries. What is the source material for charged particles? At least three possibilities:

- Low-mass stars – coronal activity injects material into ISM.
- Dust in the ISM – ionized and then accelerated.
- High-mass stars – explode and recycle material.

Strong (inverse) correlation between:

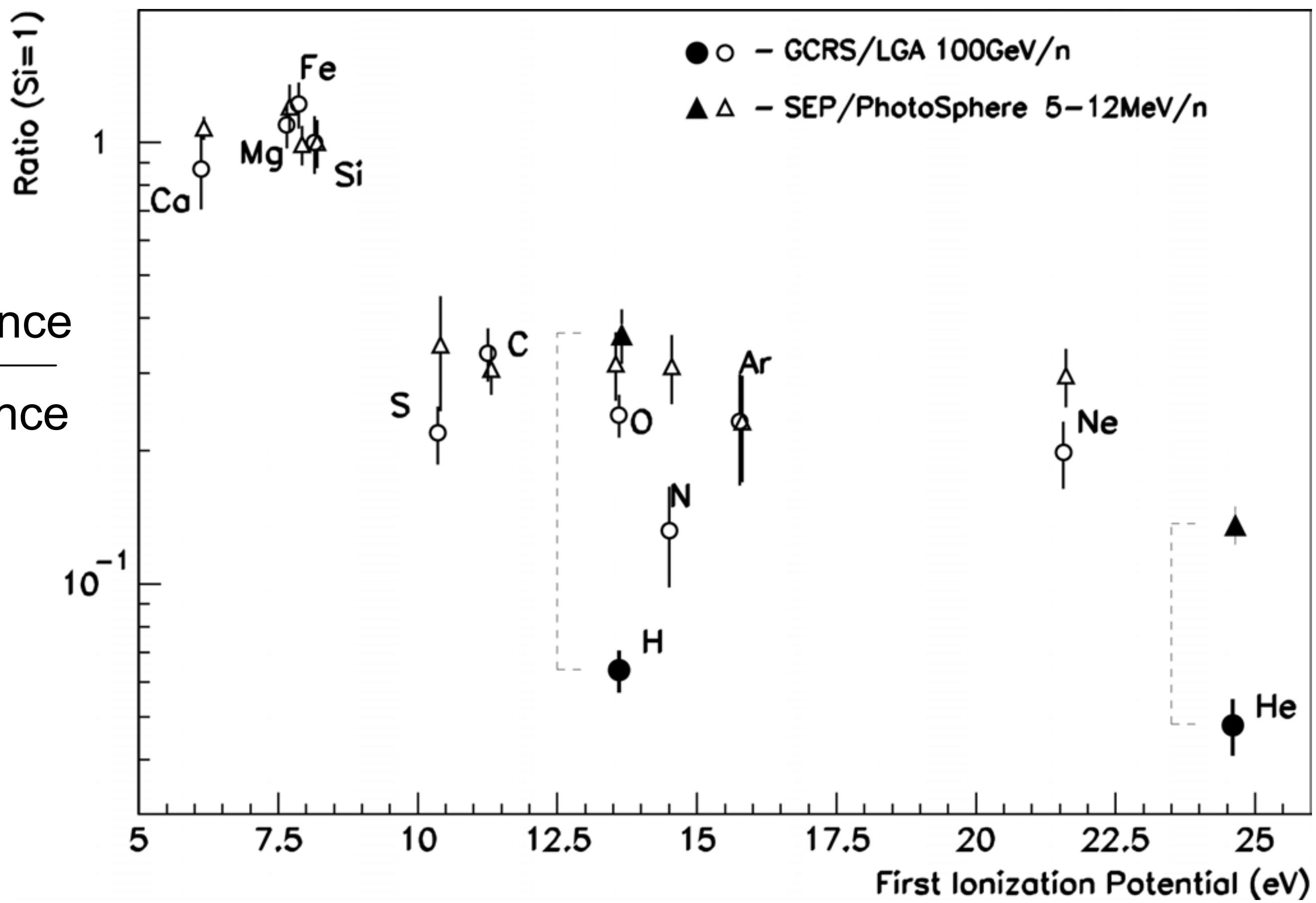
CR elemental abundances $\leftarrow\rightarrow$ Atomic ionization scale

larger abundances small ionization potential

Even after great acceleration, the energetic CR's retain knowledge of their initial origin!

Ionization Potential Dependence

CR Abundance / SS Abundance



Atomic ionization scale

2. Power Sources

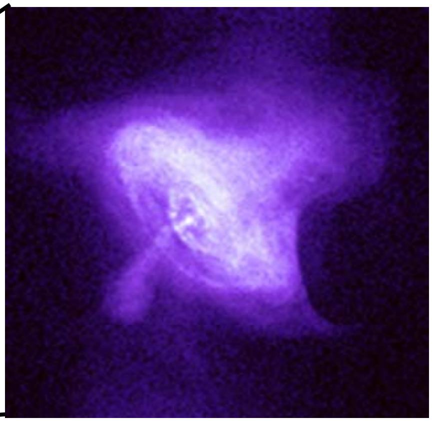
Broadly speaking, there are two types of sources:

1. Electromagnetic
   - Rotating highly magnetized object (Pulsar)

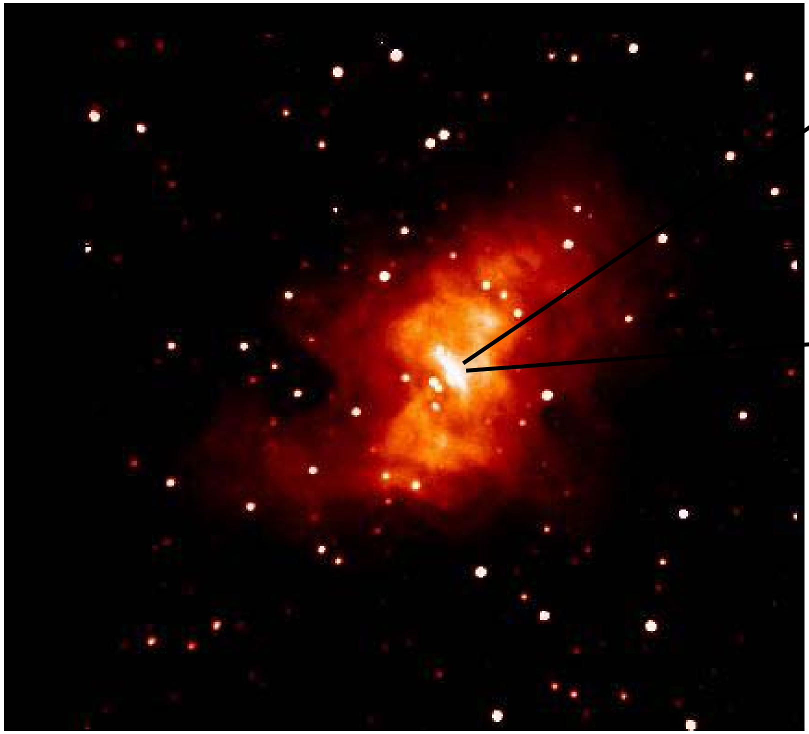
2. Gravitational
   - Core collapse of a massive star – SN and its remnant
     – Gamma-ray Bursts
   - Accretion onto a compact object (BH, NS, etc.)
   - other…

Somewhat intertwined – eventually acceleration is done electromagnetically, and often both are involved.

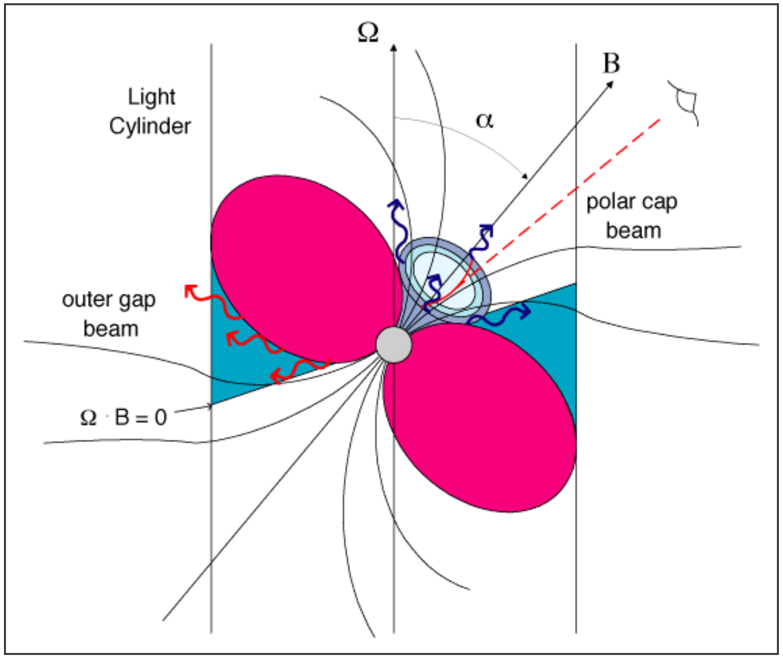
Power Source: Pulsar



Pulsar

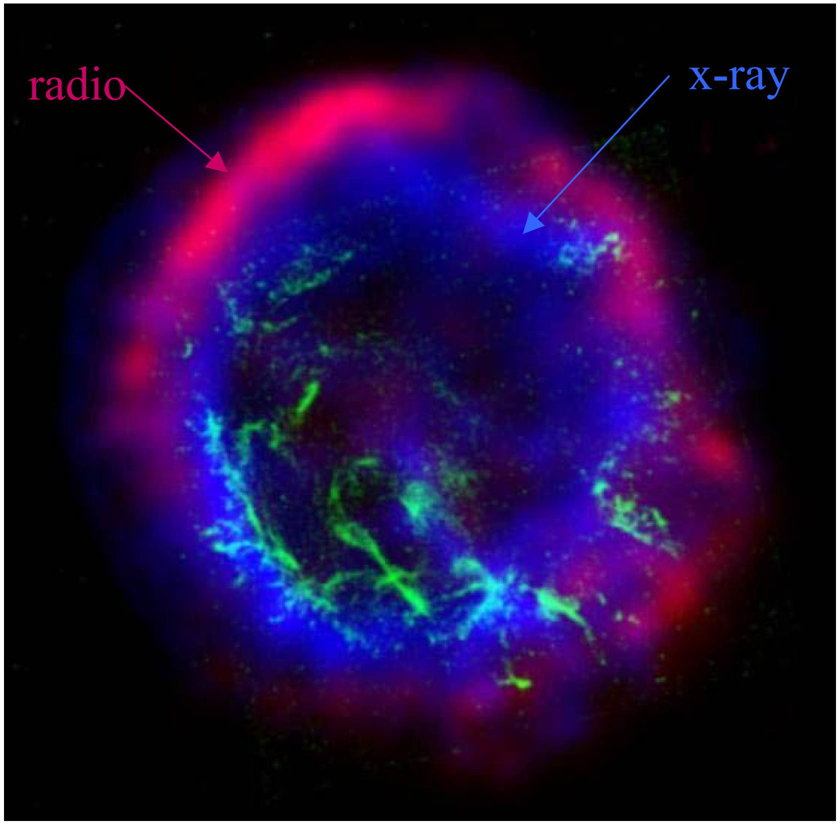


Crab Nebula



Emitted beams

Power Source: SN Remnant



SNR E102

- Collapse of massive star.
- Outer layers ejected with
  v ~ 1-2 x 10^4 km/s.
- Shell expands and shock front forms as it sweeps up material from ISM.
- In ~ 10^4 yrs, blast wave begins to deccelerate (Sedov phase) and slowly dissipate.

SN Energetics

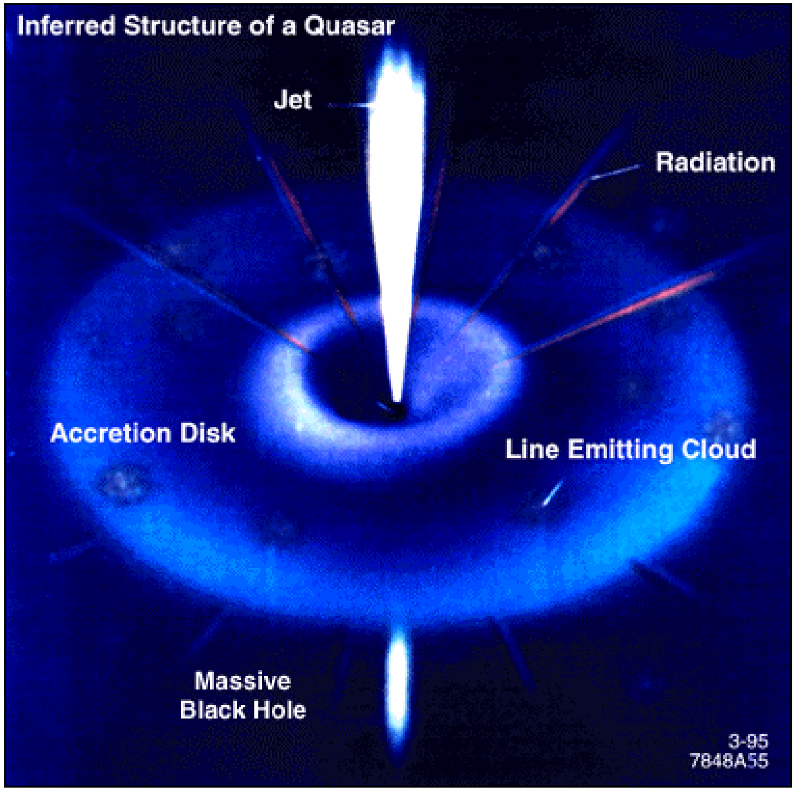
Supernovae are very attractive sites for cosmic ray acceleration:

- Natural source of highly evolved material.
- We see strong evidence for non-thermal populations of electrons.
- Energetics seem viable:

Rate of SN in galaxy		~	1 / 40 yr	
Energy released		~	10^{51} erg / SN	
SN Luminosity	L	~	10^{42} erg/s	(CR L > 10^{40} erg/s)

SN can power the CR's if KE in blast is converted into particle acceleration with $\varepsilon \sim$ few %.

Power Source: BH Accretion



AGN model

- AGN are likely powered by accretion onto BH's of mass between $10^6 – 10^9$ solar masses.
- Matter falling in towards BH piles up in a rotating accretion disk.
- Released energy powers a broad spectrum of strong emission and jets of relativistic outflow.

Compact Accretion

Accretion basics:

For particle falling in from infinity: $\frac{1}{2} m v^2 = G M m / R$

KE is dissipated at surface at rate: $L = \frac{1}{2} \dot{m} v^2 = \frac{1}{2} (r_s/R) \dot{m} c^2$

Luminosity: $L = \varepsilon \dot{m} c^2$ where ε is some efficiency factor.

For pp-chain $\varepsilon \sim 7 \times 10^{-2}$
NS $\varepsilon \sim 0.1$
BH $\varepsilon \sim 0.06$ (S) – 0.40 (K)

Compact accretion is much more efficient than nuclear energy!

(For BH's, a bit tricky because no solid surface – practically, we consider situation with angular mom. → accretion disk around BH.)

Accretion Limit

An important limit comes from the balance of material infall and outgoing radiation pressure.

Eddington Luminosity = Maximum luminosity for spherically symmetric accreting source (steady state).

Gravitational force (protons): $F_{grav} = G M m_{\mathbf{p}} / r^2$

Radiation force (plasma): $F_{rad} = \sigma_{\mathbf{T}} N_\gamma h\nu / c \qquad N_\gamma = L / 4\pi r^2 h\nu$

Eddington:

$$L_{\mathbf{E}} = 2\pi r_{\mathbf{s}} m_{\mathbf{p}} c^3 / \sigma_T \sim 10^{38} \, (M/M_s) \text{ ergs/s}$$

For AGN, situation is much more complicated, but this provides a crude benchmark.

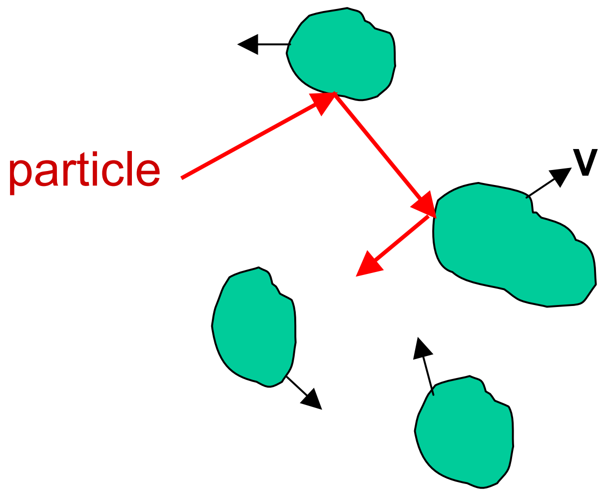
3. Acceleration

A variety of mechanisms have been proposed to explain how HE particles are accelerated in astrophysical environments.

Leading contender: Fermi acceleration (various forms)

Original Form (1949):

- Charged particles reflected off irregularities in galactic B field.
- Particles gain energy statistically.
  Energy gain: $\Delta E / E \sim (V / c)^2$
- If particles remain in region for time T_{esc}, a power law form of energies results.



Fermi Acceleration I

Why does the Fermi mechanism naturally give a power-law spectrum?

Let $E = \beta E_o$ energy after one collision

P = probability of particle remaining in accelerating region

After ***k*** collisions:

$N = N_o P^{k}$ number of particles with $E = E_o \beta^{k}$

Thus: $N / N_o = (E / E_o)^{\ln P / \ln \beta}$

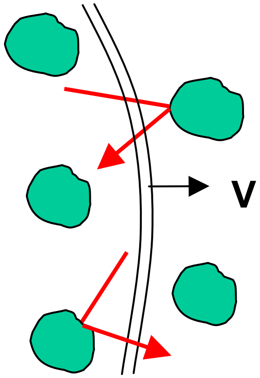
But, Fermi's original theory was not able to explain origin of CR's.

- Random motion of interstellar clouds is too small.
- Collisions too infrequent (MFP ~ 1 pc).
- Acceleration must be quick enough to overcome ionization losses.
- Theory did not explain the power-law index.

Fermi Acceleration II

In late 1970's, the Fermi acceleration mechanism was substantially improved upon for the case of strong shock waves.

- Shock move rapidly through ISM.
- HE particles move back and forth across shock boundary, gaining energy with each crossing. First-order Fermi acceleration ~(V/c).
- Naturally get differential power-law index of $\alpha = 2$.



Applied to SN remnants, acceleration time ~ 10^4 yrs, we reach a limiting energy:

$$E_{max} < Z \times 10^{14}\ \text{eV}$$

(good thing!)

CR's: Galactic Origin?

The clues from low-energy point towards a galactic origin for CR's:

- Energy density 1 eV/cm^3 → CR's cannot be universal.
- Magnetic fields will trap and contain charged particles that are produced in the galaxy.
- Abundances → CR's interact with material in galaxy to produce secondary elements not found in solar system.
- CR material most consistent with highly evolved stellar systems (e.g. Supernovae).
- CR ages → continual renewal of energetic particles.

General Picture: bulk of CR's are produced in a number of (discrete) galactic sources (SN's?) that fill the galaxy with energetic particles. This seems fine at "low" energy (< 10^{15} eV), but …

Reaching Higher Energies

Large industry developing acceleration models to extend to much higher energies. Somewhat successful.

Some possibilities:

- Pulsars – like Crab, but accelerating iron.
- Magnetars – pulsars with B ~ 10^{15} G.
- Induction from spinning (supermassive) black holes

- Multiple SN's, or a SN explosion into a strong wind.
- Galactic shock waves.
- AGN (radio jet termination, quasar jets).
- Gamma-ray bursts – extreme Lorentz factors.

In general, difficult to reach 10^{19} eV, let alone 10^{20} eV!

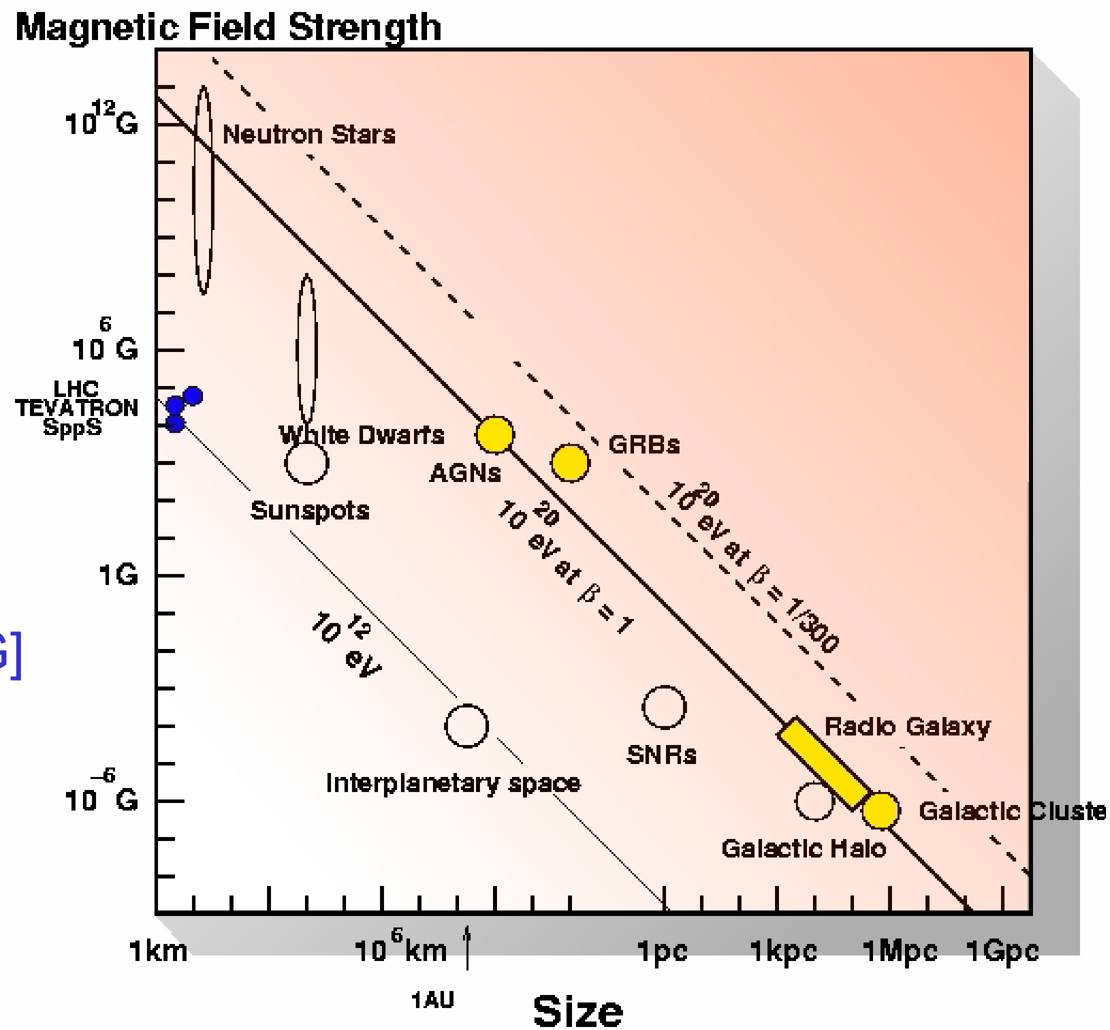
Magnetic Confinement

"Hillas Plot"

Minimum size of B field to contain particles being accelerated.

Achievable energy:

E [EeV] ~ Z R [kpc] B [μG]



4. Propagation

How particles propagate depends on their type and energy.

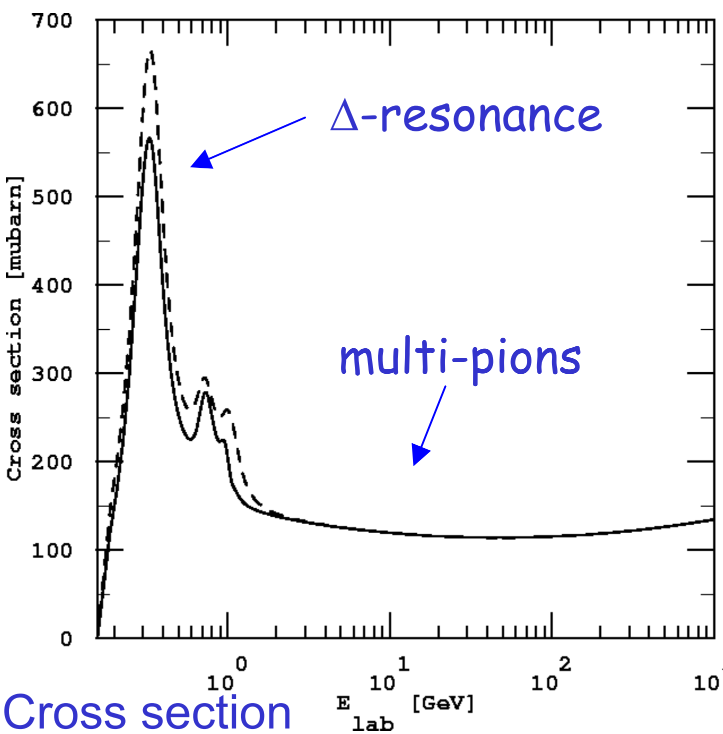
Particle	Deflected ?	Interactions
Protons	yes	ISM (~ 10 g/cm^2) - spallation
Nuclei		CMBR $p\,\gamma_{cmbr} \rightarrow \Delta^+ \rightarrow \pi$'s
Gamma rays	no	Intergalactic radiation
		$\gamma\,\gamma \rightarrow e^+\,e^-$ (CMBR, CIR, etc.)
Neutrinos	no	~ None

Cosmic Ray Horizon

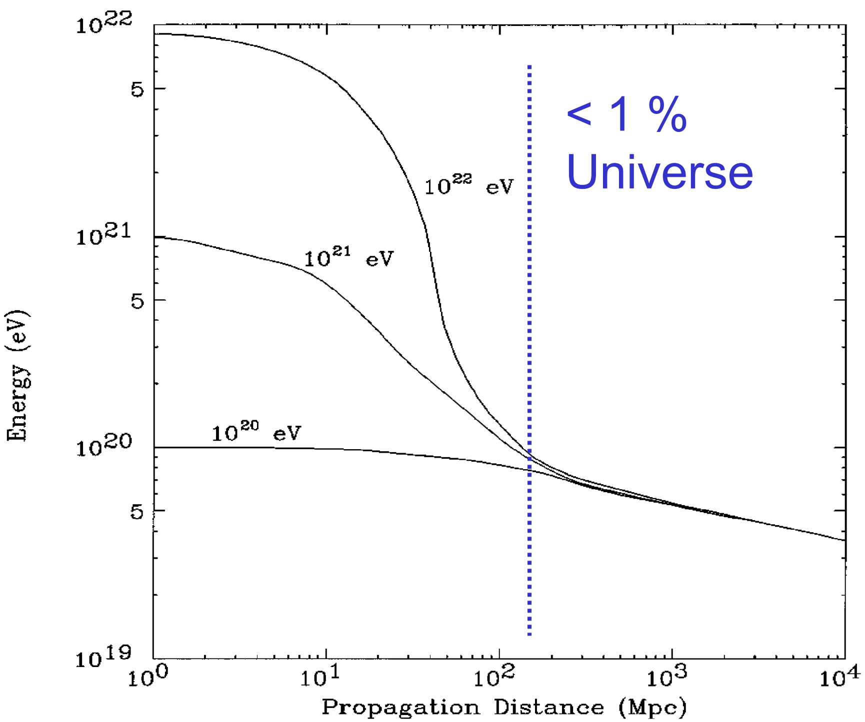
Soon after the discovery of the CMBR, it was pointed out that protons would be absorbed while traversing intergalactic space.

"GZK Cut-off" $\mathbf{P} + \gamma_{\mathbf{cmb}} \rightarrow \Delta^{+} \rightarrow \mathbf{p} + \pi^{0}$

$\rightarrow \mathbf{n} + \pi^{+}$

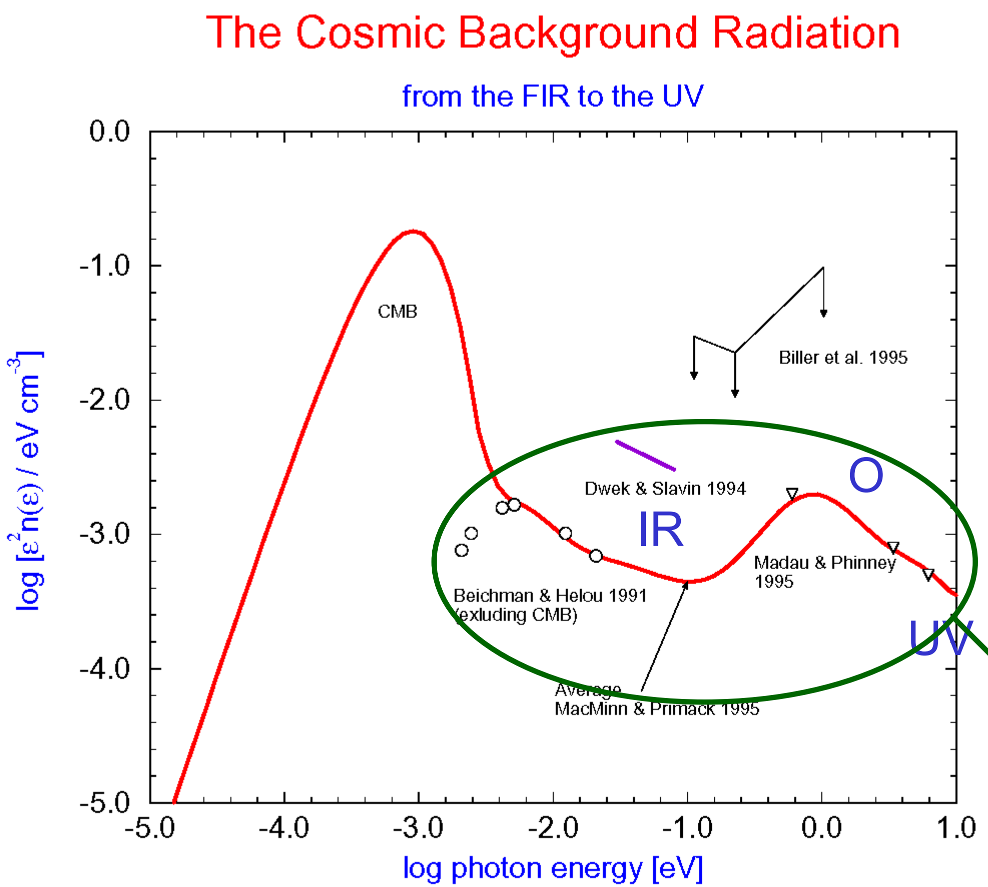


Cross section



Gamma-Ray Horizon

Gamma-rays will pair-produce off intergalactic radiation fields.



- The photon density of the CMBR is well known, but at other λ, it is more poorly understood.
- Would like to turn this around to use absorption spectra to measure the CIR (more on this later).

Poorly understood

Gamma-Ray Horizon

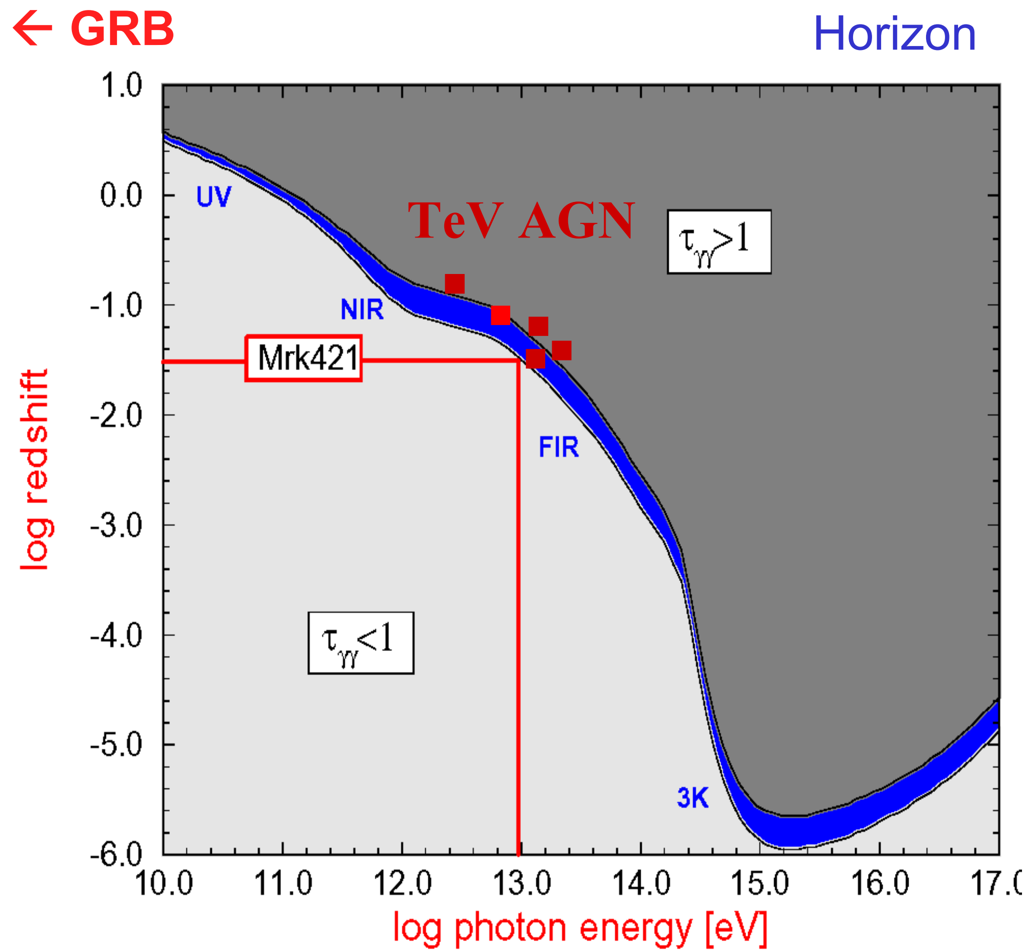
For n_{ir} = density of cosmic IR, the optical depth is:

$$\tau \sim n_{ir} \; \sigma_{\gamma\gamma} \; D(z)$$

For $E = (1+z)E_o$ γ-ray energy
$\varepsilon = (1+z)\varepsilon_o$ IR energy
threshold for absorption is:

$$\mathrm{sqrt}(\varepsilon E) > 2 m_e c^2$$

Allows us to calculate the γ-ray horizon. Universe is transparent below E ~ GeV.



Energy Spectrum (Redux)