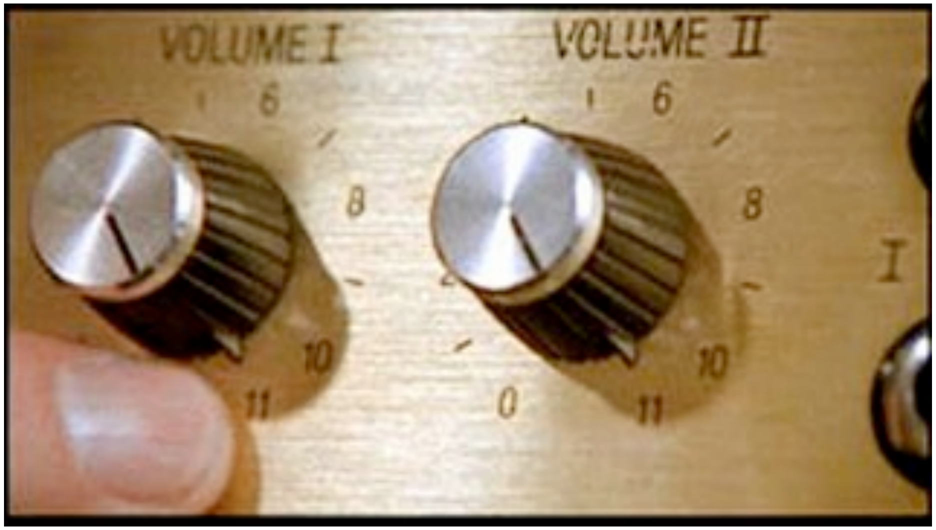
Ultra-High Energy Cosmic Rays

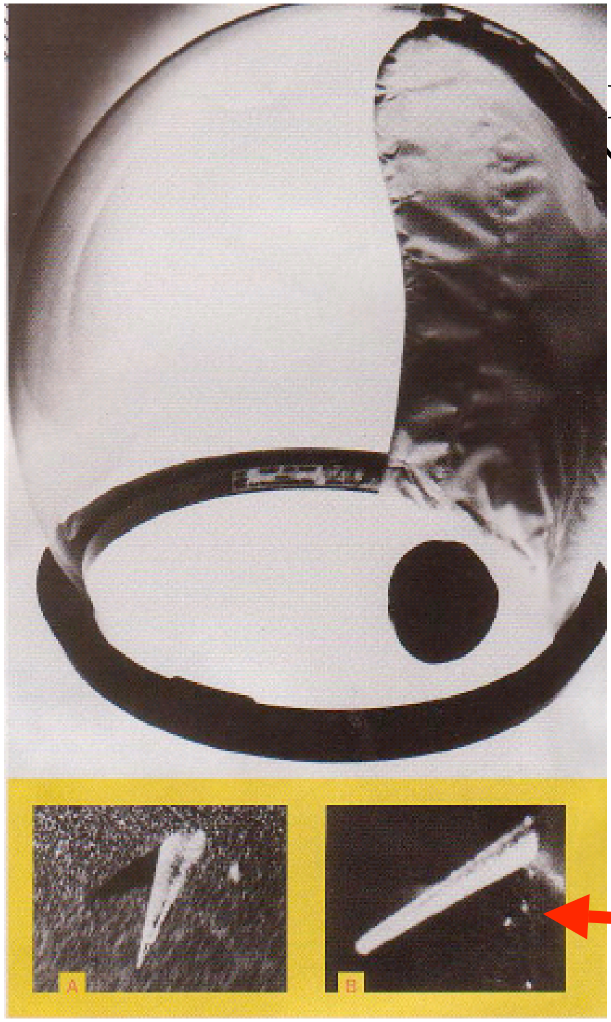


Dalziel Wilson
Physics 135c, 5/25/07

Outline

- Preamble (a disclaimer)
- LE, HE and UHE cosmic rays in context
  - Basic phenomenology
  - Propagation principles
    - The GZK cutoff
  - Theories of origin and their signatures
- Detection methods
  - The extensive air shower
  - Ground arrays, cherenkov light, air fluoresncene
- State of the art experiments
- Recent results (including a very recent first glimpse of the GZK cutoff)

“There’s a hole in the ozone and deadly cosmic rays are getting in…”



~ 500 um track

Apollo 8 (1968) space helmet = plastic track detector

IC RAY DEFLECTION SOCIETY

NORTH AMERICA, INC.

Stopping Power (Bethe Formula):

$$-\frac{dE}{dx} = \frac{4\pi}{m_e c^2}\cdot\frac{nz^2}{\beta^2}\cdot\left(\frac{e^2}{4\pi\varepsilon_0}\right)^2\cdot\left[\ln\left(\frac{2m_e c^2\beta^2}{I\cdot(1-\beta^2)}\right)-\beta^2\right]$$

ρ_{lexan} ~ g/cc, $Z/A|_{\mathrm{lexan}}$ ~ 0.5

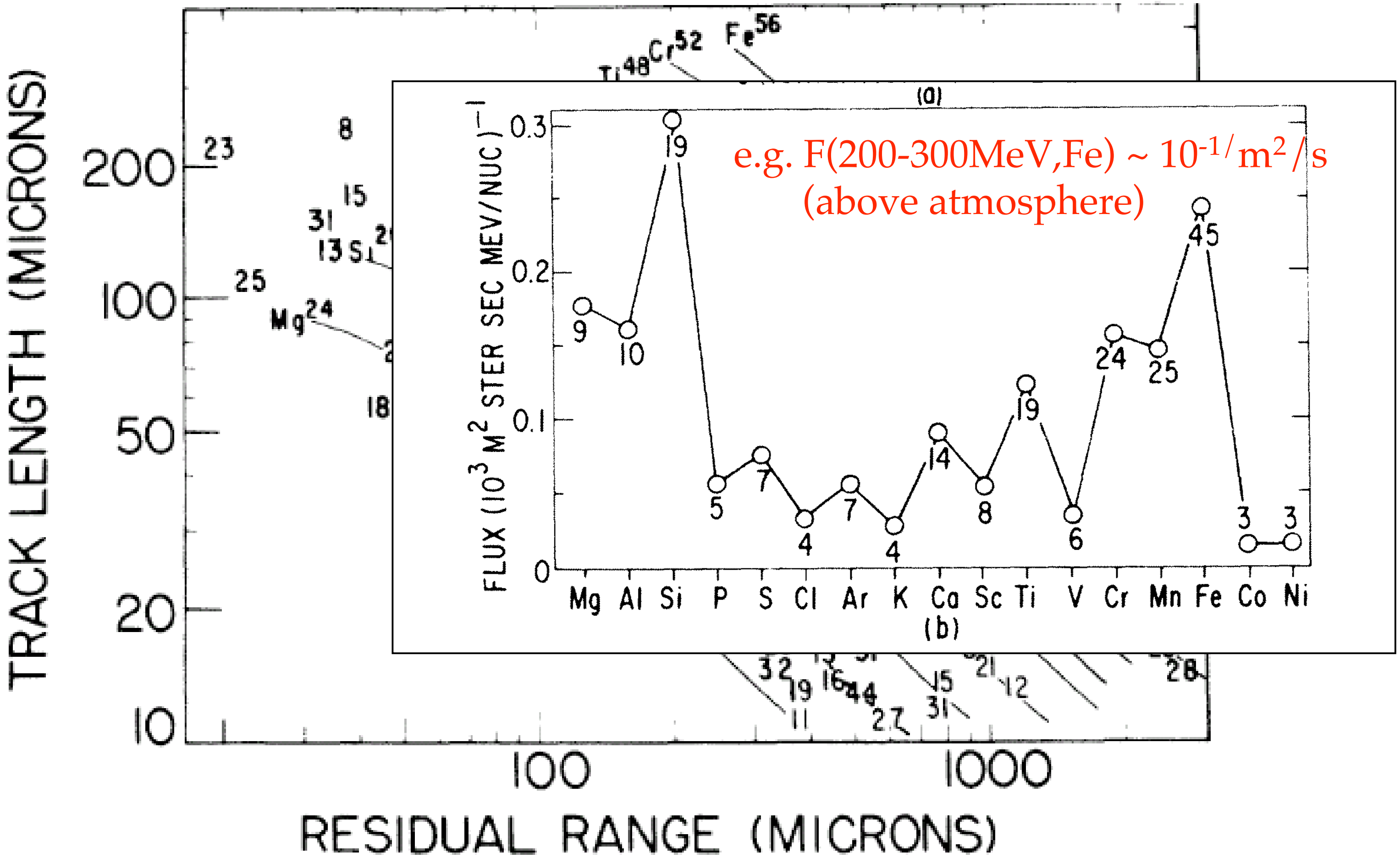
dE/dx ~ 1 GeV/nucleon/cm

z ~10 for nuclei produced by stars

E_{particle}~100 MeV/nuc (~fission energy of U^{235})

Flux(E>100MeV) > 1/m^2/hour

“High-Resolution Study of Low-Energy Heavy Cosmic Rays with Lexan Track Detectors”*



e.g. F(200-300MeV,Fe) ~ $10^{-1}/m^2/s$
(above atmosphere)

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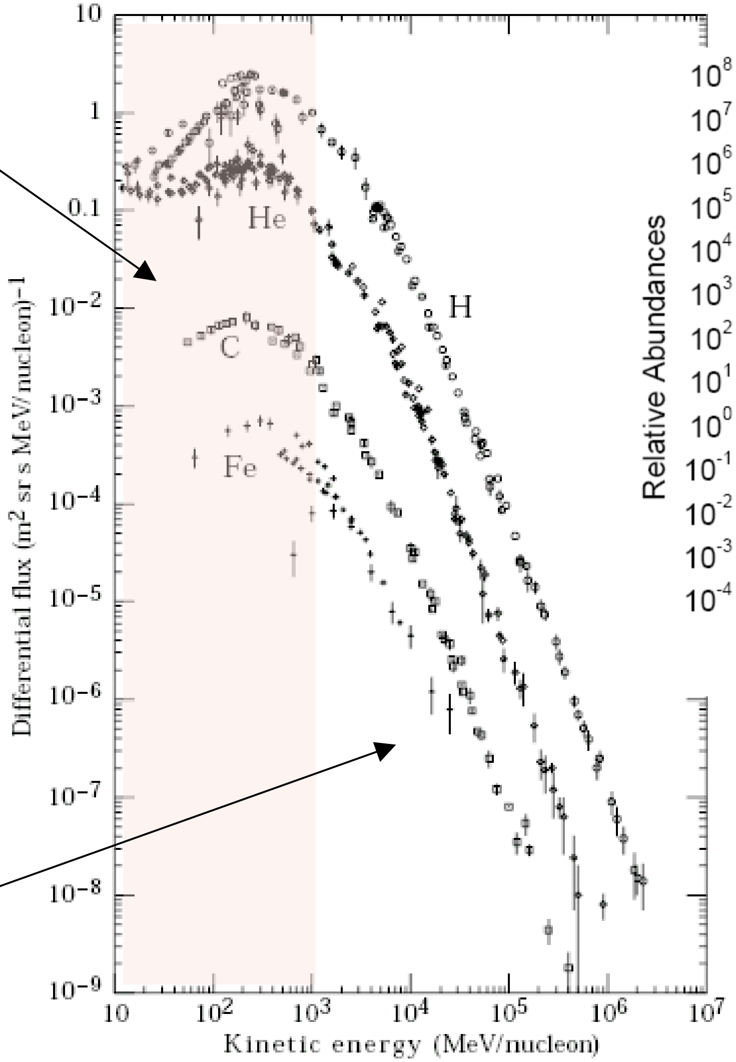
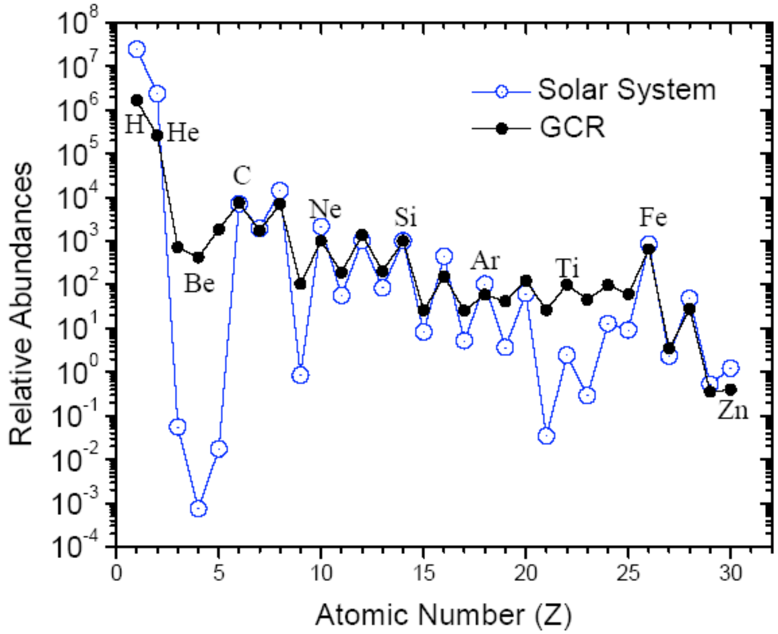
*Price, PRL 21, 630 1968

Low Energy Cosmic Rays (the tip of the iceberg)

Low Cosmic Rays

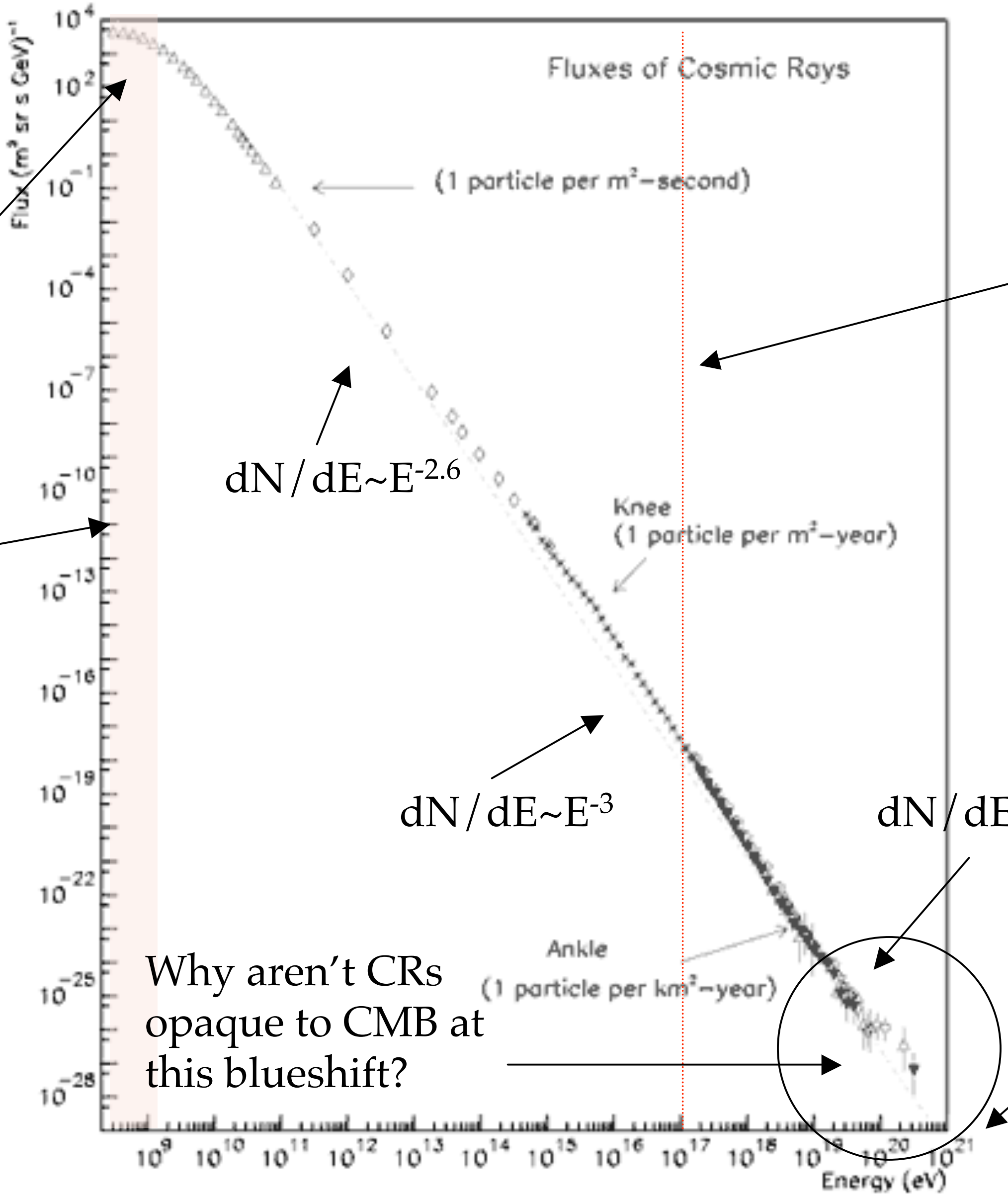


Power law spectra



Stellar abundances, with hints of ‘spallation’

Full Cosmic Ray Spectrum (the much bigger picture)



Bump due to interaction w/ solar wind

Low energy cosmic rays

dN/dE~$E^{-2.6}$

dN/dE~E^{-3}

dN/dE~$E^{-2.5}$?

Fixed proton target
CM energy = 7TeV
(LHC)

100mi/h baseball,
Fixed proton target
CM energy =
140TeV

Why aren't CRs opaque to CMB at this blueshift?

The GZK limit

- CMB = Bath of ~10^{-3} eV photons in cosmic reference frame

  = Bath of ~ $\sqrt{\frac{(1+\beta)}{(1-\beta)}}\cdot\nu \approx (1+\beta)\gamma\nu \approx 2\frac{E}{mc^2}\nu$ photons in rest frame of relativistic cosmic ray.

Photopion production: $\gamma + p \rightarrow n\pi^+, p\pi^0$ $\pi^+ \rightarrow \nu_\mu \mu^+ \rightarrow \nu_\mu \nu_\mu \nu_\mu e^+$

- Photo-pion production becomes important when $E_\gamma \sim m_\pi \approx 160$ MeV, which corresponds to $E_{proton} \sim 10^{20}$ eV
- Photo-pion cross-section at CM energy of 300 MeV is ~ 5×10^{-28} cm^2

$$n_{\gamma CMB} \sim 500/\text{cc (today)} \Rightarrow \text{mfp} = 1/(n\sigma) \sim 5*10^{24}\ \text{cm} < R_{intergalactic} \sim 10^{25}$$

$\Rightarrow$Severe constraints on extragalactic UHECR sources

- Signatures of GZK include: suppression of hadronic nuclei at E > 10 EeV, enhancement of neutrinos at hadronic "dip"

-pair production w/ CMB photons also should produce small dip in proton contribution @ E~10^{19}

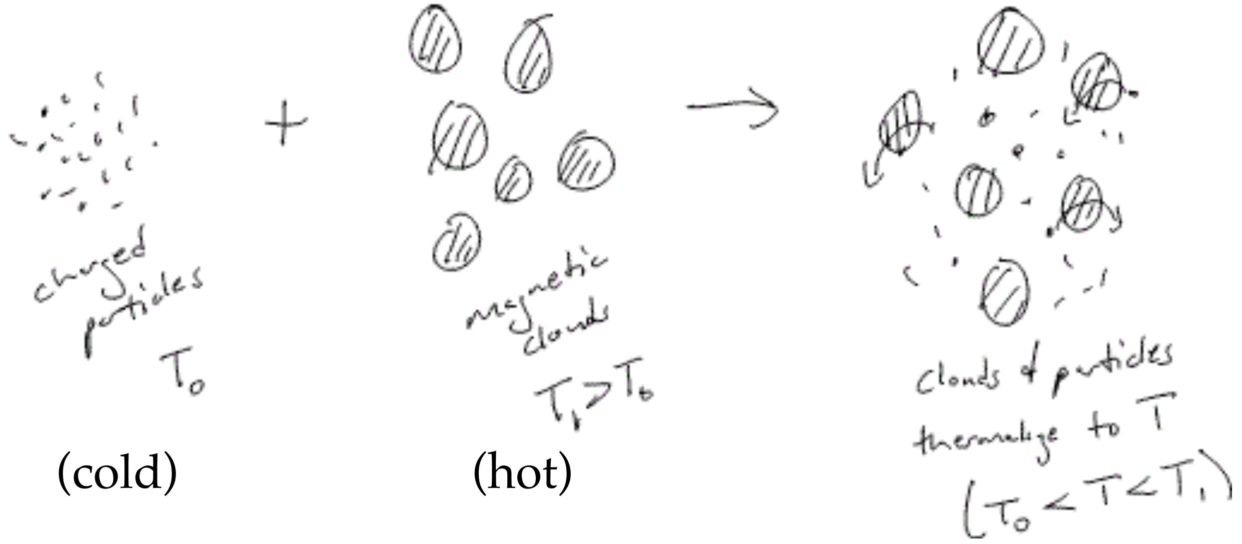
Theories of Origin

- Statistical Acceleration (magnetic clouds, shock fronts)
  - Fermi Model
  - Gradual mechanism, naturally produces power spectrum
  - Hard to account for high energies
- Direct Acceleration (neutron stars, BH accretion disks)
  - May or may not produce power spectrum
  - May imply specific sources
  - Usually high den
- Top-down (topological defects, superheavy relics)
  - Speculative, but accounts for UHE spectrum
  - Signatures in UHECR composition

Statistical Acceleration

<u>Hand-waving model</u>: Energy Equipartition

- particle and magnetic cloud DOFs coupled ⇒ if you wait long enough, energy strata will be diluted. Cold DOFs become warmer, hot DOFs become colder (on average)



(cold) (hot) (warm)

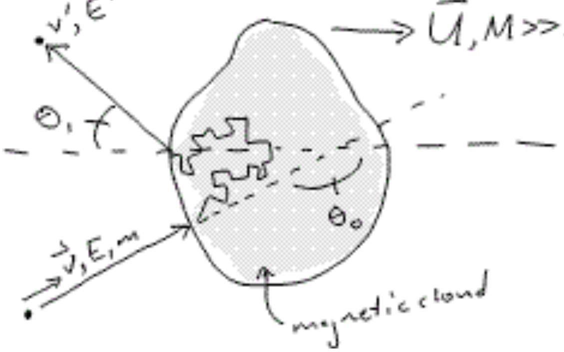
<u>Main assumption</u>: large number of interactions before a particle escapes interaction region

<u>Main conclusion</u>: statistical acceleration increasingly less efficient for "hot" particles

Statistical Acceleration

<u>"Microscopic" Model</u>: Fermi Statistical Acceleration

(1)



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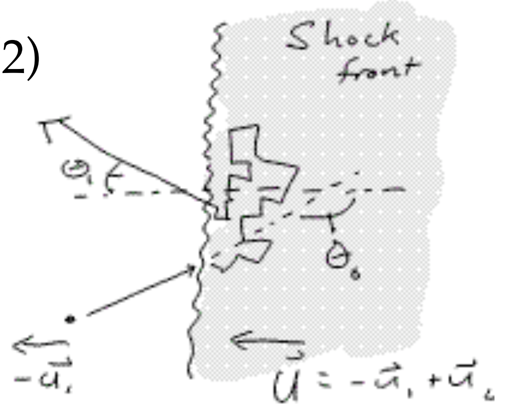


Particle "scatters" repeatedly off magnetic clouds or a shock front. Acceleration occurs if on average it gains a small amount of energy with each pass.

$$\overline{\Delta E} = \lambda E \Rightarrow E_n \cong (1+\lambda)^n E_0 \, , \; P_n = (1-P_{escape})^n$$

$$N(\geq E) \propto \sum_{m=n}^{\infty} P_m \Rightarrow \ldots \Rightarrow \frac{dN}{dE} \propto \frac{1}{P_{esc}}\left(\frac{E}{E_0}\right)^{-\gamma}$$

$$\gamma = \ln\left(\frac{1}{1-P_{esc}}\right) \Big/ \ln(1+\lambda) \approx \frac{P_{esc}}{\lambda}$$

<u>Power Spectrum</u>

$$(1) \;\; \lambda \approx \frac{4}{3}\beta^2, \; P_{esc} \approx \frac{T_{cycle}}{T_{escape}} \approx \frac{1}{\sigma_{cloud}\beta c \rho_{cloud}} \cdot \frac{1}{T_{diffusion}}$$

$$\gamma \approx \frac{1}{(4/3)\beta^2 c \rho_c \sigma_c T_{acc}}$$

$$(2) \;\; \lambda \approx \frac{4}{3}\beta, \; P_{esc} \approx \frac{4 \cdot u_2}{c}, \; \gamma \approx \frac{3}{(u_1/u_2)-1}$$

Numerical Estimates

Galactic Source?

$$L_{CR} = \frac{\rho_{E_{CR}} V_{\text{galactic disk}}}{\tau_{CR}} \sim 10^{41} \text{ erg/sec}$$

$$L_{\text{Type II SN}} \left(M \sim 10 M_\odot,\, u_{\text{shell}} \sim 10^8 \text{ cm/s}\right) \sim 10^{42} \text{ erg/s}$$

$$\Delta E : \lambda E \rightarrow \frac{\Delta E}{\Delta t} = \frac{\lambda}{\Delta t} E \rightarrow \frac{dE}{dt} \approx \frac{\lambda E}{T_{\text{cycle}}}$$

$$T_{\text{cycle}} < \frac{\text{larmor radius}}{u_{\text{shock}}} = \frac{1}{u}\left(\frac{E}{ZeB}\right)$$

$$\Rightarrow \frac{dE}{dt} \sim \lambda u ZeB$$

$$\lambda_{\text{shock front}} \gtrsim u \Rightarrow \boxed{E \sim u^2 ZeBT_{acc}}$$

$\underline{10 M_\odot \text{ SN}}$: $u \sim 10^9$ cm/s, $T_{acc} \sim 10^3$ yrs, $B \sim \mu G$

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

"$\underline{\text{Galactic wind}}$": $u \sim u_{\text{escape from galaxy}} \sim 10^8$ cm/s for MW

$B \sim 0.1\ \mu G$

$T_{acc} \sim 10^{10}$ yr (age of galaxy)

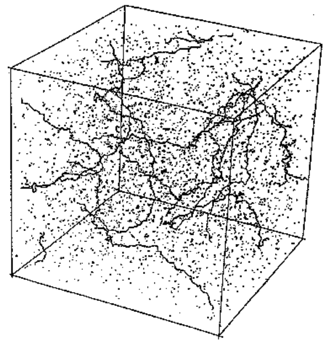
$$\Rightarrow E_{max} \sim Z \times 10^{17} \text{ GeV}$$

$\underline{\text{Pulsar wind shock}}$: $u \sim 10^8$ cm/s, $B = 10 G$, $t = 1$ yr

$$\Rightarrow E_{max} \sim Z \times 10^{15} \text{ GeV}$$

Top-Down Models

- General Idea: Topological defects leading to direct acceleration or superheavy relic particles decay to produce UHECR spectrum
- Motivation:
  - Difficult to account for E>0.1EeV CRs w/ standard astrophysical acceleration models.
  - Circumvents GZK paradox if sources are local
  - Theorists get married("B-violation"), have children to feed.
- Example: Superconducting Cosmic Strings!
  - Large (cosmo scale) loop of heavy fermions, residual from early phase transition in the universe.
  - Loops enclose primordial B-field and to shrink as they radiate EM and G-waves, eventually decay to superheavy fermions @ GUT-scale masses, which quickly decay to produce HE υ,γ,e,p,n
  - Signatures include low weight composition at UHE, no anistropy



Computer simulation of a possible network of cosmic strings. Such extremely massive, one-dimensional defects in space itself may have been the "seeds" needed to trigger galaxy formation.

Detecting UHE cosmic Rays

- Questions to answer:
  - Flux, Composition, and Anisotropy at high energies

- Main Problem: Flux follows a power law
  - $F(E<10^{14}eV) > 10^{7}/m^{2}/yr \Rightarrow$ high enough for direct detection of primary particle (calorimeter)
  - $F(E>10^{17}eV) < 10^{-2}/m^{2}/yr \Rightarrow$ *need a much bigger detector*

Idea#1: Earth as a large space helmet!

- UHE cosmic rays produce air showers with impact cross-section of ~100 m^2 and ~ 10 m longitudinal extent at Earth's surface

$$\Downarrow$$

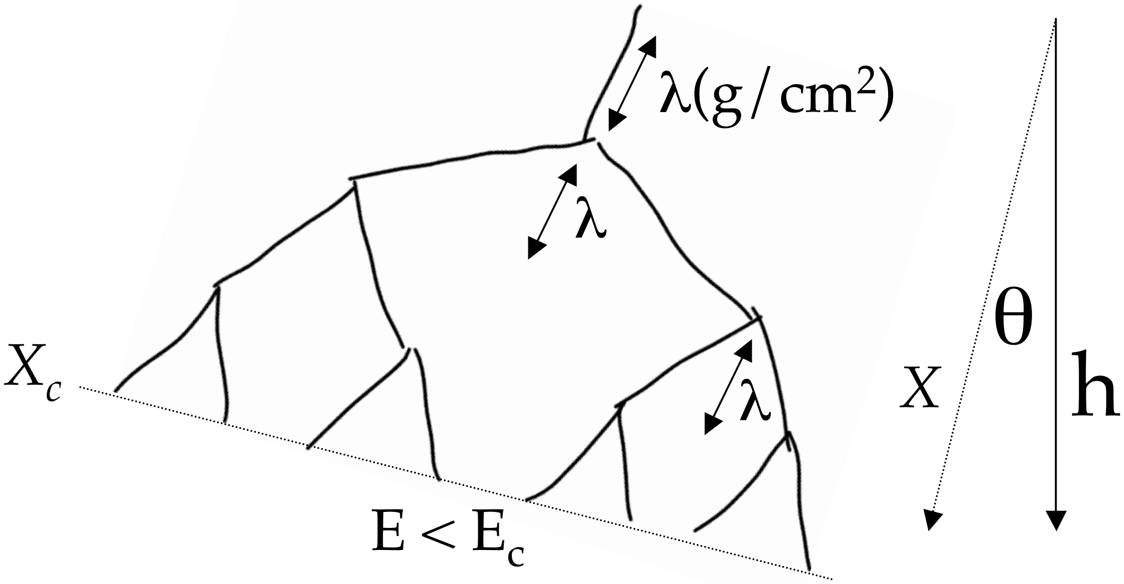
- Use array of detectors spaced by ~$100m^2$ over several km^2. Effective area = A_{array}
  - e.g. Sydney array (1990s) , $A= 100km^2 \Rightarrow Events/yr(E>10^{17}eV) \sim 10^6$

Idea#2: Detect flourencence from air showers

- 10^{8}-10^{10} ionizing particles (300-400nm) at shower maximum. Ionization occurs in ~10ns, ~1km from photodector $\Rightarrow$ (best case) ~10^3 photons/m^2/10ns at detector on top of $\approx 5*10^{4}/m^{2}/10ns$ from starlight (on a dark night)

The Extensive Air Shower

- Baby Model
  - approximates photon primaries (EM shower)



$$X = \int_{h_0}^{\infty} \rho(h\cos\theta)\cos\theta dh$$

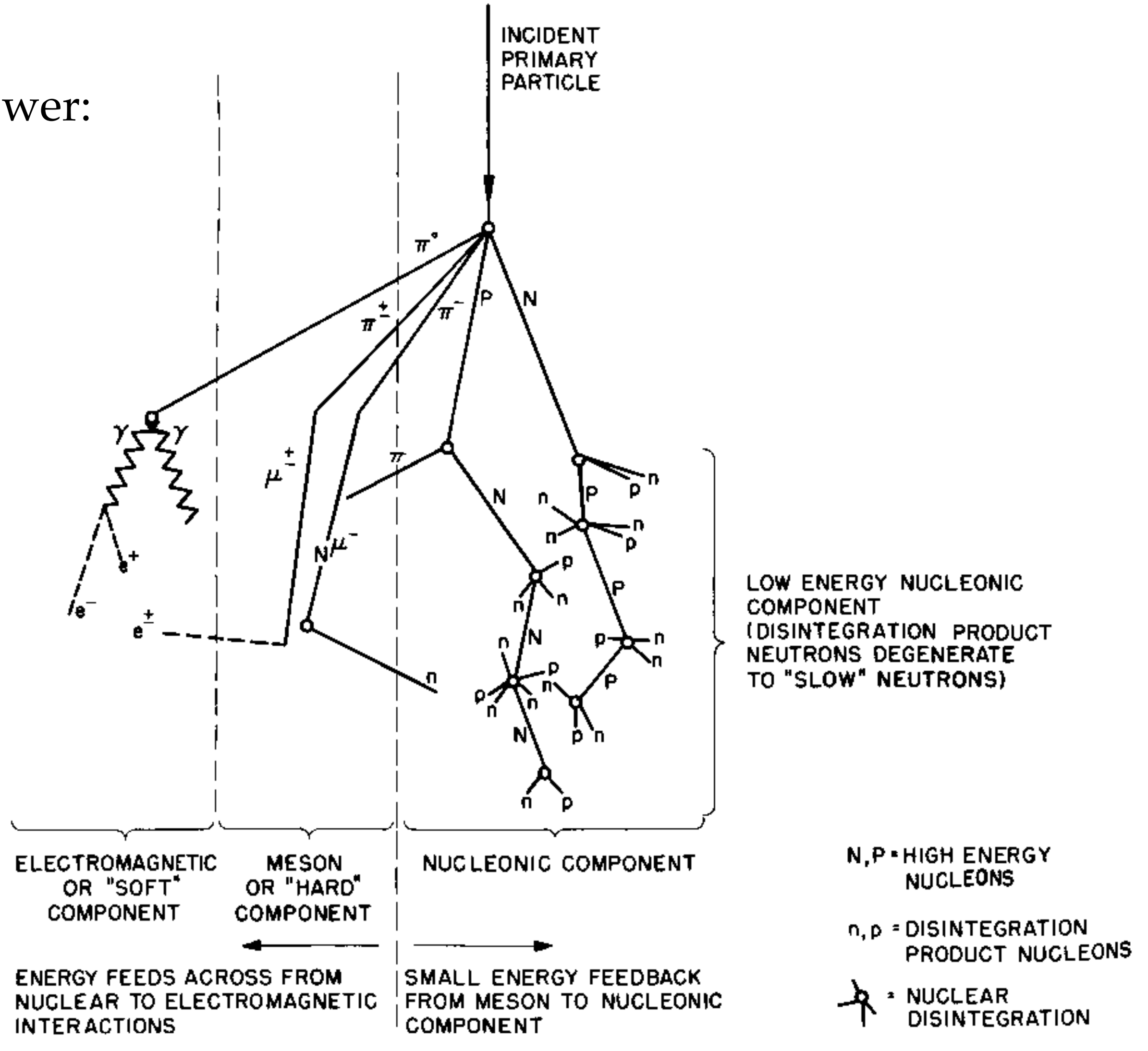
"slant depth"

- Adolescent Model ("superposition model")
  - approximates nuclear primaries (hadronic shower):
  - assume nucleus behaves like A(atomic number) independent nucleons, each giving rise to a toy model spectrum

  ⇒ $\mathbf{X_{max} \propto \lambda \ln(E_0/AE_c)/\ln(2)}$ (stopping power of atmosphere is higher for heavy primaries)

The Extensive Air Shower – Realistic Snapshot

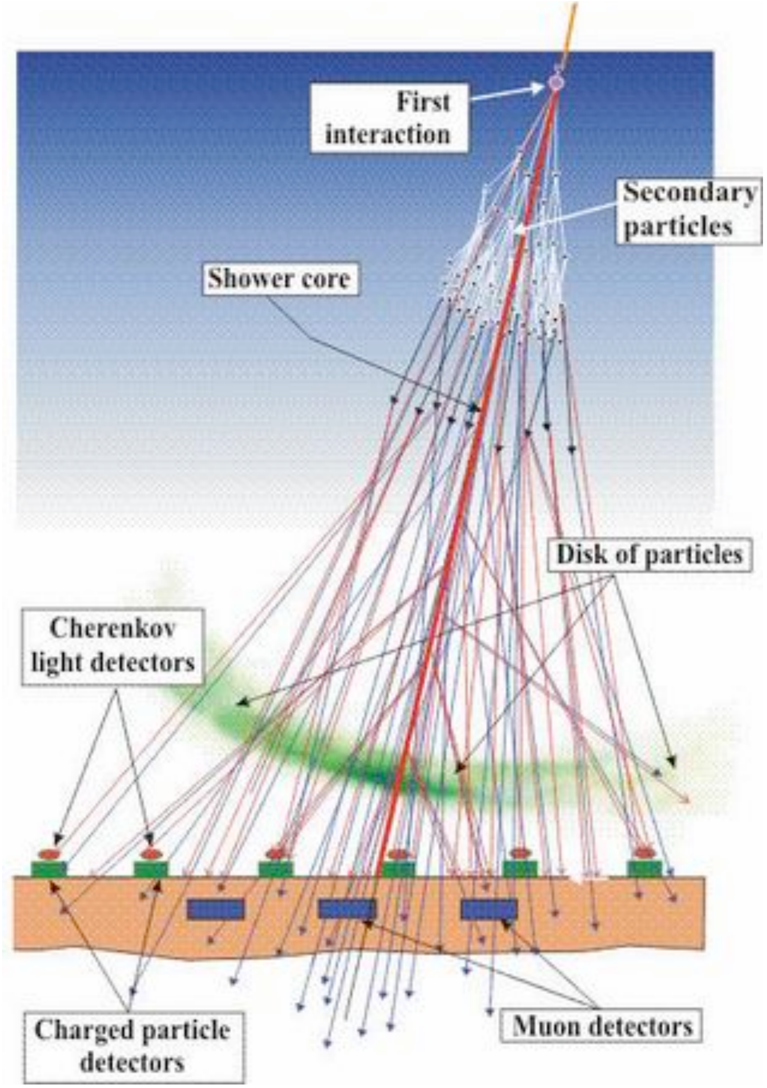
Primary Shower:



Schematic Diagram of Cosmic Ray Shower

The Extensive Air Shower – Realistic Snapshot

Secondary Shower:



Clues to Energy / Composition / Anisotropy

- Lateral particle distribution at earth's surface:
  - charged particles
    - Primarily EM shower products (electrons)
    - Monte Carlo suggests normalized shape of distribution is insensitive to depth of observation (so only have to specify at particular radius)

$$\rho(R) = C(R/R_M)^{-1.2}(1 + R/R_M)^{-(\eta-1.2)}$$

$$\rho(600,\theta) = \rho(600,0)\exp(1018(\sec\theta - 1)/\lambda)$$

$$E_0 = K[\rho(600)]^{\alpha}$$

  - muons
    - Total number at surface highly sensitive to initial shower interactions, and thus to composition of primary
      - Superposition model: $n_{muon}(E) \sim (E/A)^{\alpha}$
      - Emperical model used in ground arrays:

$$N_{\mu}(> E_{\min}) = \frac{K \cdot A\sec\theta}{E_{\min}}\left(\frac{E_{\min}}{E_0 / A}\right)^{\alpha}\left(1 - \frac{E_{\min}}{E_0 / A}\right)^{\beta}$$

- Zenith angle obtained from time profile of wavefront across detector array.

Clues to Energy/Composition/Anisotropy

- Cherenkov light:
  - produced when particle velocity greater than local speed of light, c/n(h).
  - exists critical energy, as a function of elevation, at which electrons cherenkov radiate: E_{min}~0.511/sqrt(1-n(h)) MeV
  - $q_{max}=\cos^{-1}(1/n(h))$ → lateral extent of cherenkov radiation varies with height of shower.

    → A map of the time dependence of the cherenkov wavefront can be used to reconstruct the late longitudinal profile of the shower beyond the critical energy.

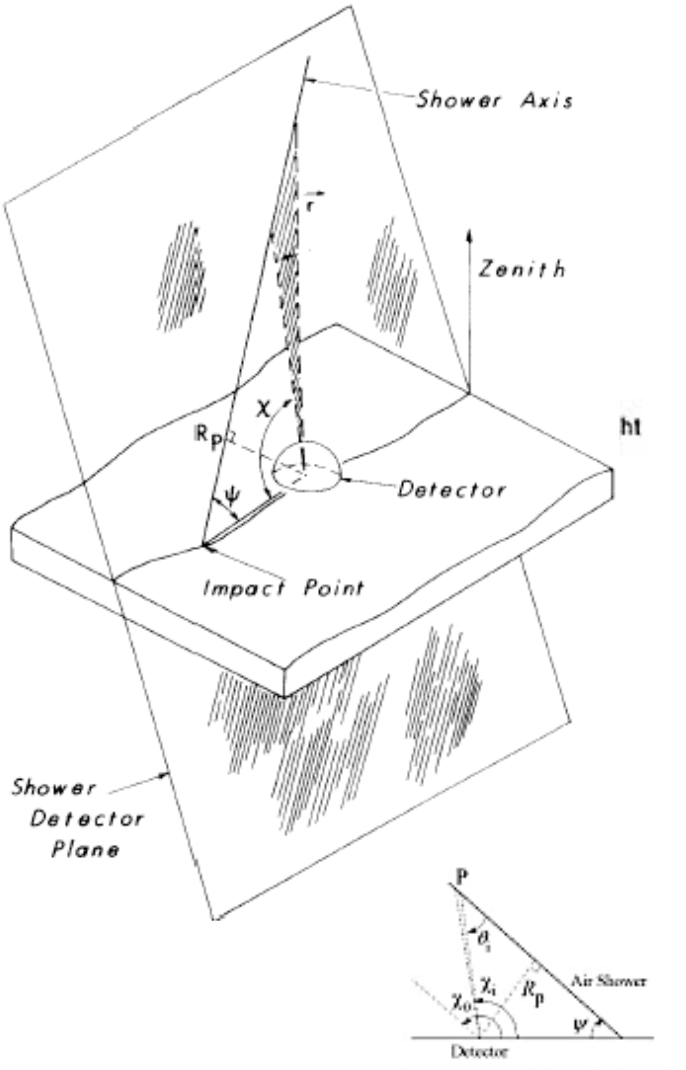
    → X_{max} and therefore E_0 can be estimated
  - Radiation in the short-wave UV, near 300nm
    - Color similar to air flourescence, partially separable because the latter is isotropic and the former subtends an angle of <2° w/ respect to zenith
  - Zenith angle obtained from time profile of wavefront across detector array.

Clues to Energy/Composition/Anisotropy

- Air Flourescense:
  - Ionizing particles excite atmospheric N_{2}, which spontaneously decay in the near UV (220-500nm) with ~10-50ns decay time
  - Flourescent yield insensitive to elevation, >10^8(0.1EeV) ionizing particles, ~5% efficent → ~100–1000 photons/m^2/s

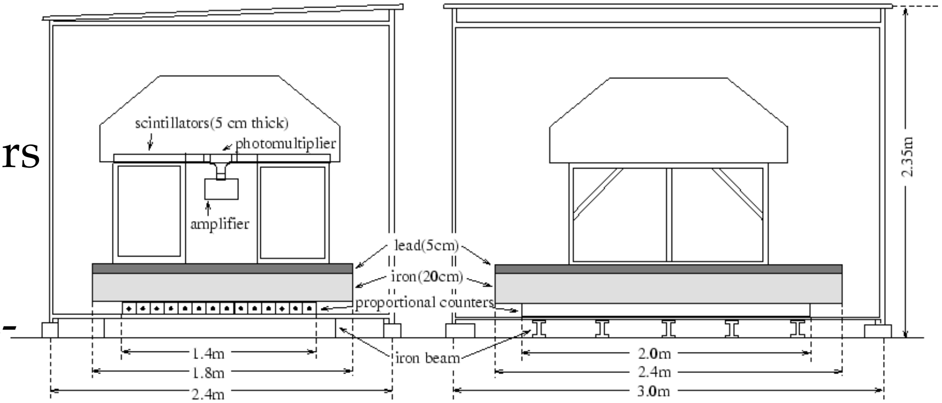
    at detector, atop 10^3 higher background (scattered cherenkov light and starlight)
  - Longitudinal shower development monitored directly via inversion

    of intensity/direction/time profile on hemispheric detector (accounting for cherenkov contribution)
  - Energy of proportional to energy of air flourescence shower (knowing E and X_{max} gives composition)
  - View showers ~15km away (effective 100km^2 detector)



Fit: $t_i = t_0 + (R_p/c)\tan(\chi_0/2 - \chi_i/2)$

Example: Akeno Giant Shower Array (AGASA)



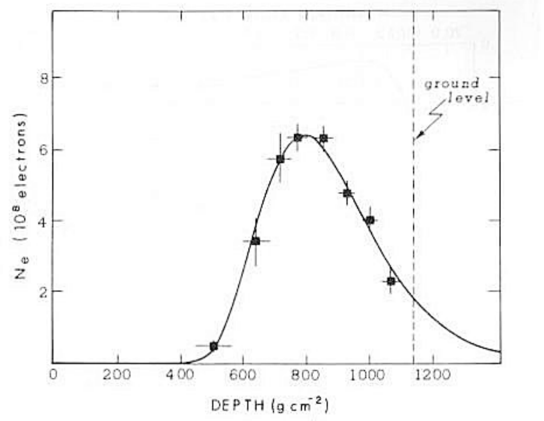
Overview:

- >10 years of data on 111 surface detectors ($2.2m^2$ scintillator) and 27 lead shielded muon detectors spread over $100km^2$
- Energy band: $10^{14.5}$(embedded previous-generation $1km^2$ array) -$10^{20.5}$eV
  - -Method: local particle density at 600m
- Measure composition by comparing muon and electron transverse profiles
- Event rate:~1/yr above 10^{19} eV
- Model-dependent/systematic error in energy measurement:25%/18%

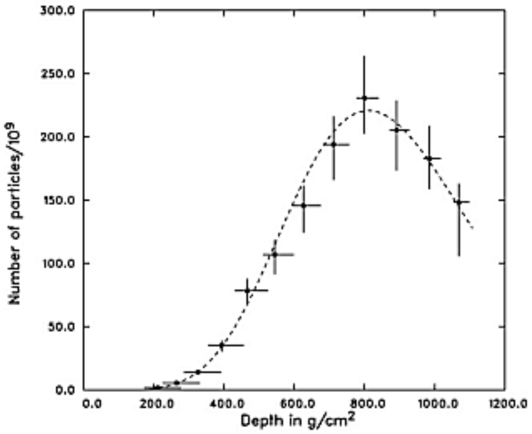
Example: Hi-Resolution Fly's Eye Detector

Overview:

- 2 detector stations 12.6 km apart.
  - 22 and 46 "fly's eye" modules @ respective stations
    - -256 PMTs on 3.6m^2 detection area of each module
    - -field of view is ~1^0 cone/module
- Stereo detection allowed between stations improve angular resolution
- Energy band: 10^{17}-$10^{20.5}$eV
  - -Method: energy of air shower flourescence
- Composition Method:
  - -Independent shower depth and energy measurement
  - Event rate: 4-5 times AGASA (in principle) above 10^{19}eV
  - Flux(systematic)/energy-scale uncertainty = 30%/17%



$8*10^{17}$ eV



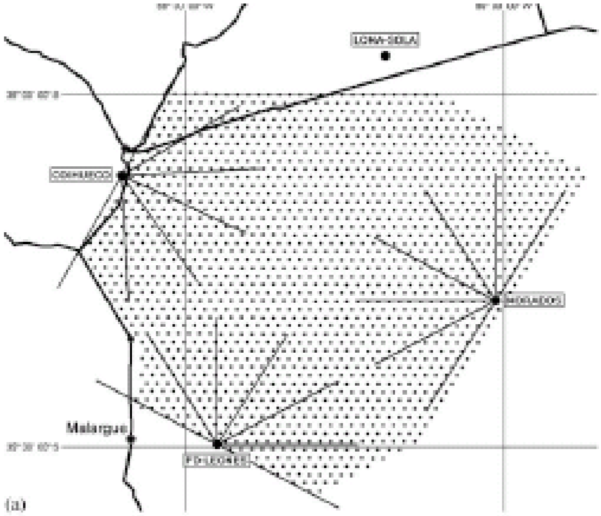
$3*10^{20}$ eV

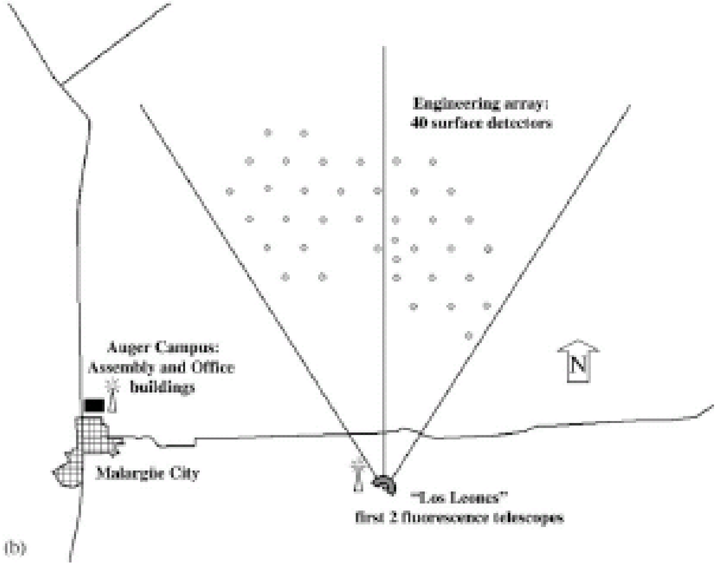
$$E_{fl\_shower} = \frac{E_c}{\lambda}\int N_c(X)dX \propto \int I_\gamma(t,S)dSdt$$

Example: Pierre Auger Cosmic Ray Observatory

Overview:

- Hybrid water cherenkov and Fly’s Eye detector
- 2 arrays, water cherenkov tanks and fly’s eye detectors for $6000km^2$ total coverage
- Energy band: $10^{17.5} – 10^{21}$
  Method: Agasa and Fly’s Eye techniques
- Composition Method: Agasa and Fly’s Eye techniques
- Event rate: >10*AGASA





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