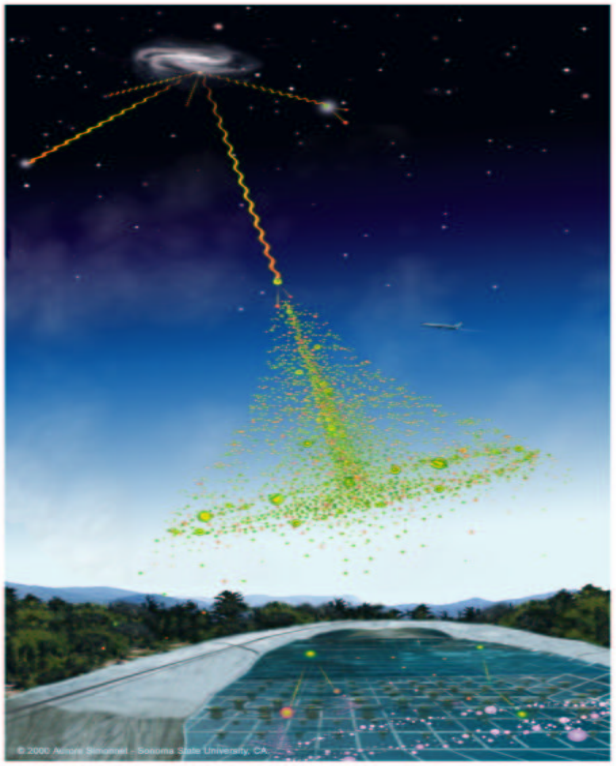
QuarkNet 2002: Cosmic Rays

Anthony Shoup, UCI



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- Outline:
  - History of cosmic rays (CRs)
  - What are cosmic rays anyway? (composition, rates)
  - You've got to be kidding me, right? (sources)
  - How do we know what we know? (detectors)
  - Gamma−Ray Astronomy
  - Neutrino Astronomy

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- History:
  - Prehistory (pre−WWII)
    - (1912) − Victor Hess used "Electroscope" to discover that CRs come from space, not earth

- Took "scope" in balloon flights up to 17500 ft.
- Found that rate of discharge of "scope" increased with increasing altitude.
- Thus CRs were:
  - Charged (mainly)
  - Coming from outer space

"father of cosmic−rays"

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- How an electroscope functions:

Uncharged

Charged

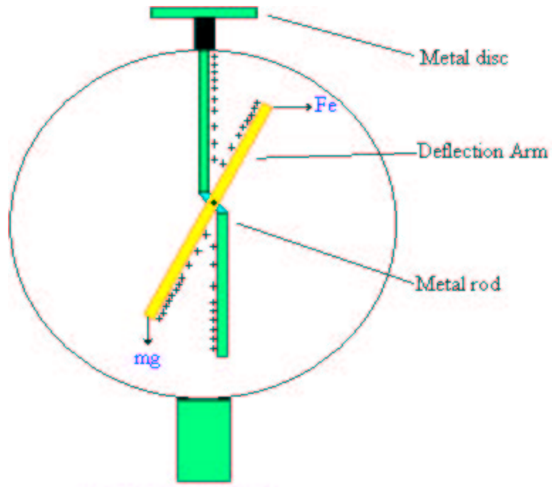

Figure 1: Electroscope

- Charged particle traverses chamber ionizing atoms.
- Freed electrons neutralize positive charge on deflection arm
- Rate of discharge of scope is proportional to CR rate

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- History:
  - Prehistory (pre−WWII)
    - (1912) − Victor Hess used "Electroscope" to discover that CRs come from space, not earth
    - 1930−40's − Compton, Rossi, Vallarta found that rate of CRs depended on lattitude on earth → **+ Charged particles**
    - 1932 − Carl Anderson discovers antimatter (positron) in his "cloud chamber"
    - 1937 − Seth Neddermeyer & Carl Anderson discover the muon (second of a series of subatomic particles discovered using CRs)
    - 1938 − Pierre Auger discovers CR airshowers

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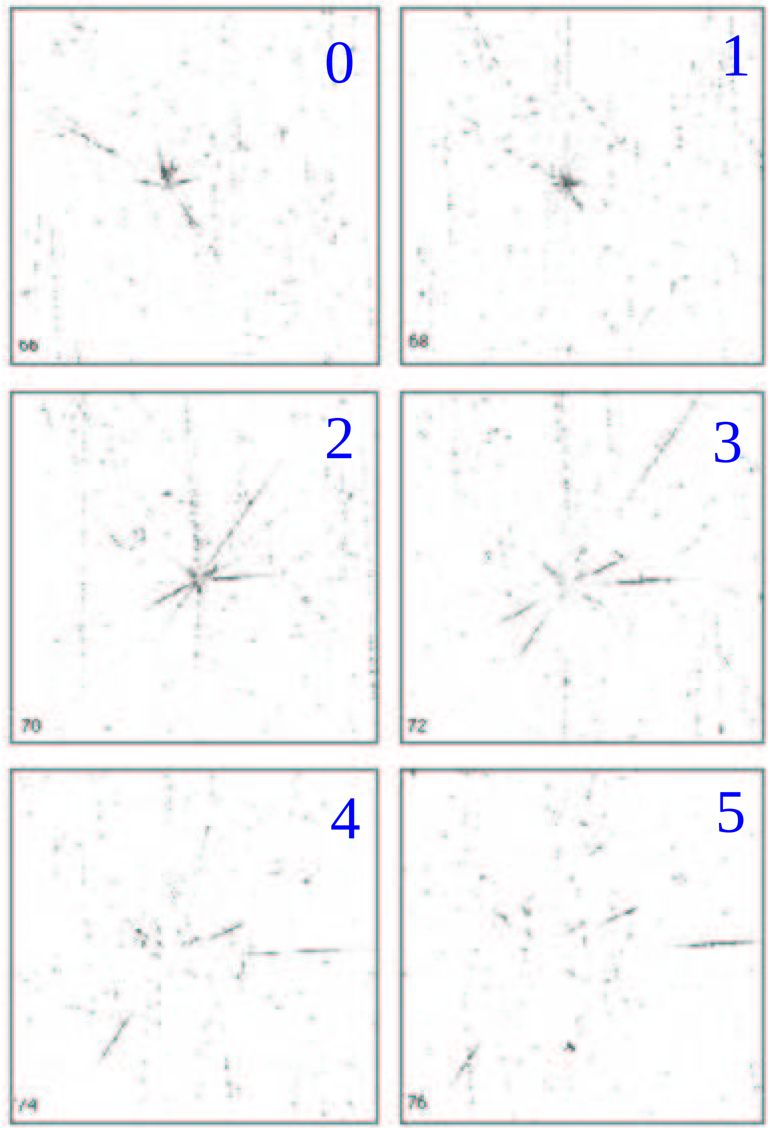
- Example of CR interacting in an emulsion



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- History (continued):
  - Post−WWII (better balloons ⟶ Primary CRs)
    - 1946−1954 Use of emulsions, cloud chambers, and counter telescopes allows the determination of cosmic ray composition
      - Completely ionized H, He, Li, Be, B, and heavier nuclei as well as elementary particles: p, n, e^-, e^+
      - Could reach up to a few GeV
    - 1949 − Enrico Fermi proposes stochastic acceleration of CRs
    - 1954−Present − Air shower arrays at MIT, Japan, Chacaltaya, India, Soviet Union, Australia extend energy reach to > PeV
    - Present:
      - Satellites such as HEAϕ, PROTON, ... provide data supporting "Leaky Box Model of CRs"
      - Underground experiments like KGF, Homestake, MACRO, IMB discover, atmospheric and CR neutrinos

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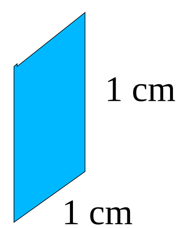
- What are CRs anyway?
  - As stated, they are high energy subatomic particles
  - They have rained down on earth in an ~ constant, isotropic, flux for for millions of years
  - Example:
    - You have just volunteered to be test subject in CR experiment
    - You are put into space with no CR shielding
    - Compute your radiation dosage (**E deposited per gram**):
      - Energetic nuclear CR rate above atmosphere:

$$CR_{rate} \approx \frac{1\ particle}{cm^2\ s\ sr}$$



traversing from all directions $: \quad \frac{6\ part}{s\ cm^2}$

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- Example (continued):
  - Your crossection: $1.8m(height) \times 0.5m(width) = 9000\,cm^2$
  - Rate of particles entering you: $9000\,cm^2 \times \frac{6\,part}{s\,cm^2} = 54{,}000\,part/s$
  - Typical penetration depth: ~ 10cm
  - Energy deposited per particle: ~ 2 MeV/cm => 20 MeV/part
  - Total deposited energy per second:

$$E_{dep} = 20\,\frac{MeV}{part} \times 54{,}000\,\frac{part}{s} \approx 10^6\,MeV/s$$
$$\approx 1.6\,x\,10^{-6}\,ergs/s$$

$$1\,eV = 1.6\,x\,10^{-12}\,ergs$$

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- Example (continued):
  - Compare this to the "Radiation dosage recommendation per year"
    - First need energy deposited per gram:

$$1\,Rad = 6\,x\,10^7\,\frac{MeV}{g}$$

$$\frac{E_{dep}}{g \cdot s} = \frac{10^6\,MeV/s}{7x10^4\,g} = \frac{14\,MeV}{g \cdot s} = 2.3\,x\,10^{-6}\,Rad/s$$

- Dosage in one year:

$$Dosage = \omega_R \times rate \times time = 5 \times 2.3x10^{-6} \times 3.1x10^7$$
$$= 350\,Rad/yr$$

- Max recommended dosage per year: ~ 10 Rad/yr

$$\omega_R \equiv radiation\,weighting\,factor \approx 5$$

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Luckily for us (except perhaps for high energy astronomers) most of the CRs are absorbed by the atmosphere such that CR flux at sea level is ~ 300/(m^2s)

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- So What are CRs?
- Better yet: **Why study CRs at all?**
  - They contribute significantly to the energetics of the galaxy
  - They are messengers for cosmogenic processes which produce the elements of the periodic table
  - Solar CRs from flares and coronal mass ejections (CMEs) influence our ionosphere and can have serious consequences to our satellite communications
  - The highest energy CRs above 10^{20} eV are not understood have give us a glimpse into extremely energtic phenomena which we can't study on earth
  - They (with γ–rays and neutrinos) aid us in studying astrophysical objects such as Active Galactic Nuclei (AGN), supernova explosions, coalascing black holes & neutron stars, and perhaps Gamma Ray Bursts

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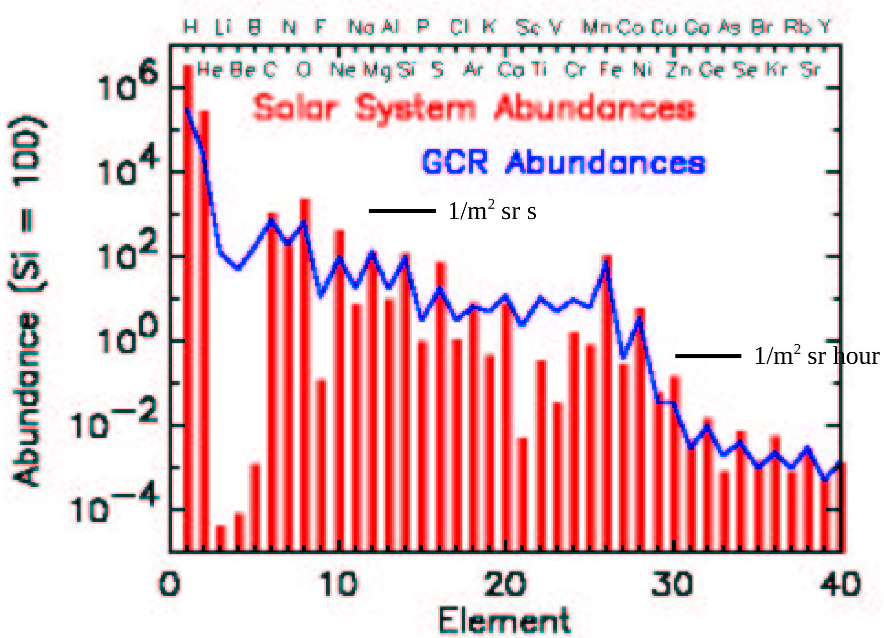
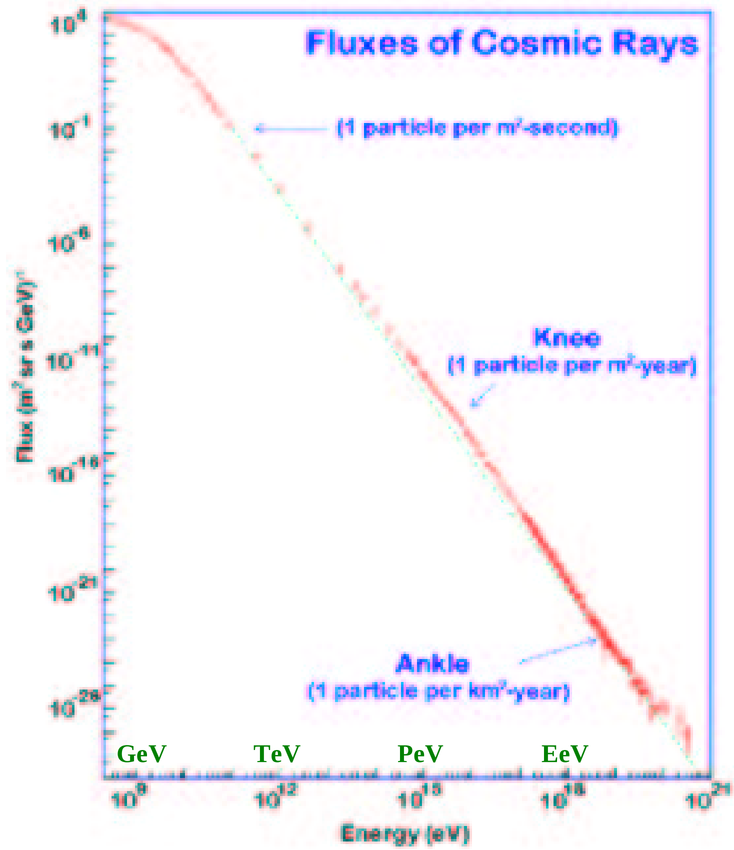
- CR properties:
  - "All particle" spectrum (flux vs. energy) (right)
  - CR Primary composition (below)



(at top of atmosphere)



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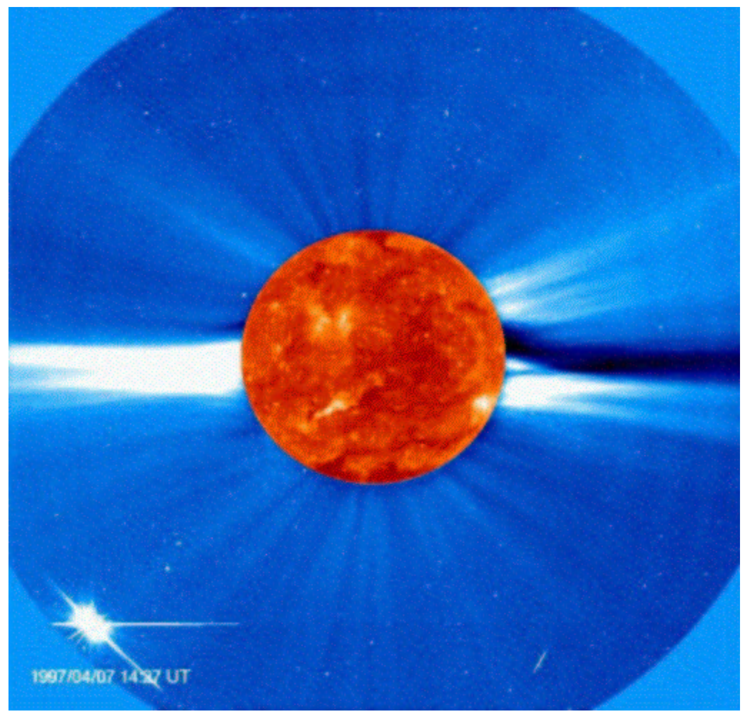
- **Where do they come from and how do they get here?**
  - Sources of CRs
    - Sun and other stars. Particles emitted in solar flares or CMEs mainly protons and nuclei up to iron. E up to ~ 50 GeV?



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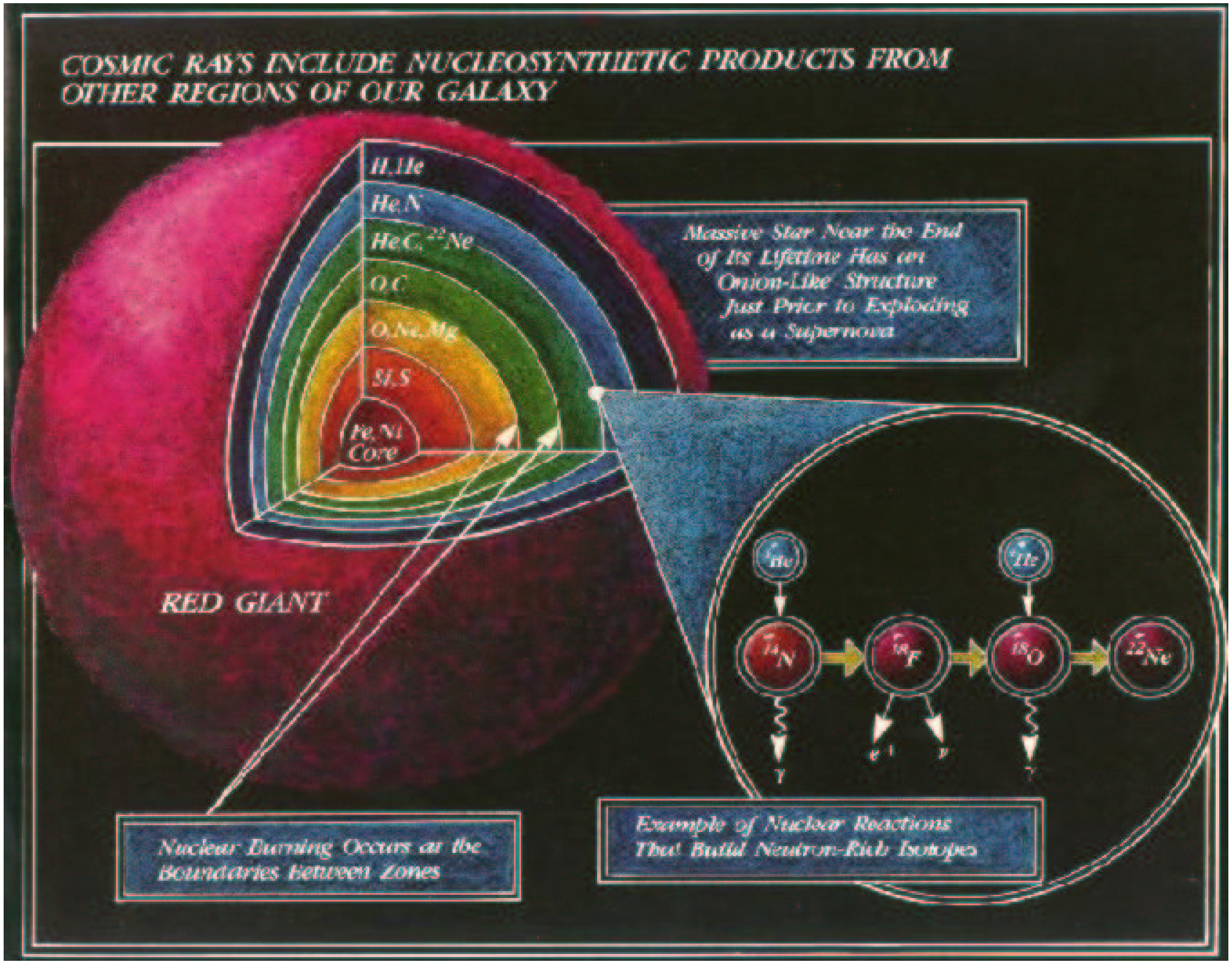

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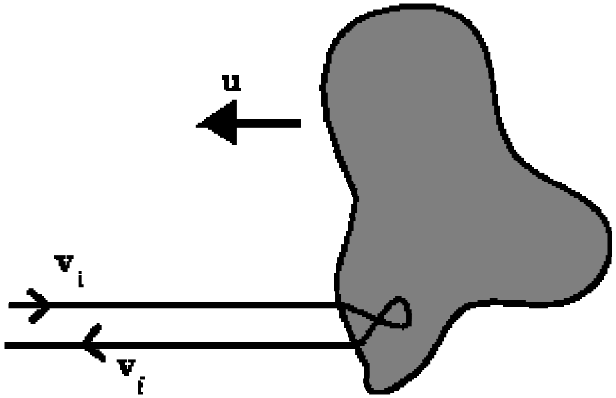
- **Where do they come from and how do they get here?**
  - Sources of CRs
    - Sun and other stars. Particles emitted in solar flares or CMEs mainly protons and nuclei up to iron. **E up to ~ 50 GeV?**
    - Supernova: Stellar explosions of massive stars where matter is ejected into surrounding region and is swept up by outward propagating shocks. **E up to ~ 100 TeV**
      - Nuclei may be accelerated via Fermi Acceleration and/or blast wave acceleration



- Both transits boost CRs energy
- Predicts "power−law" spectrum of ~ right power

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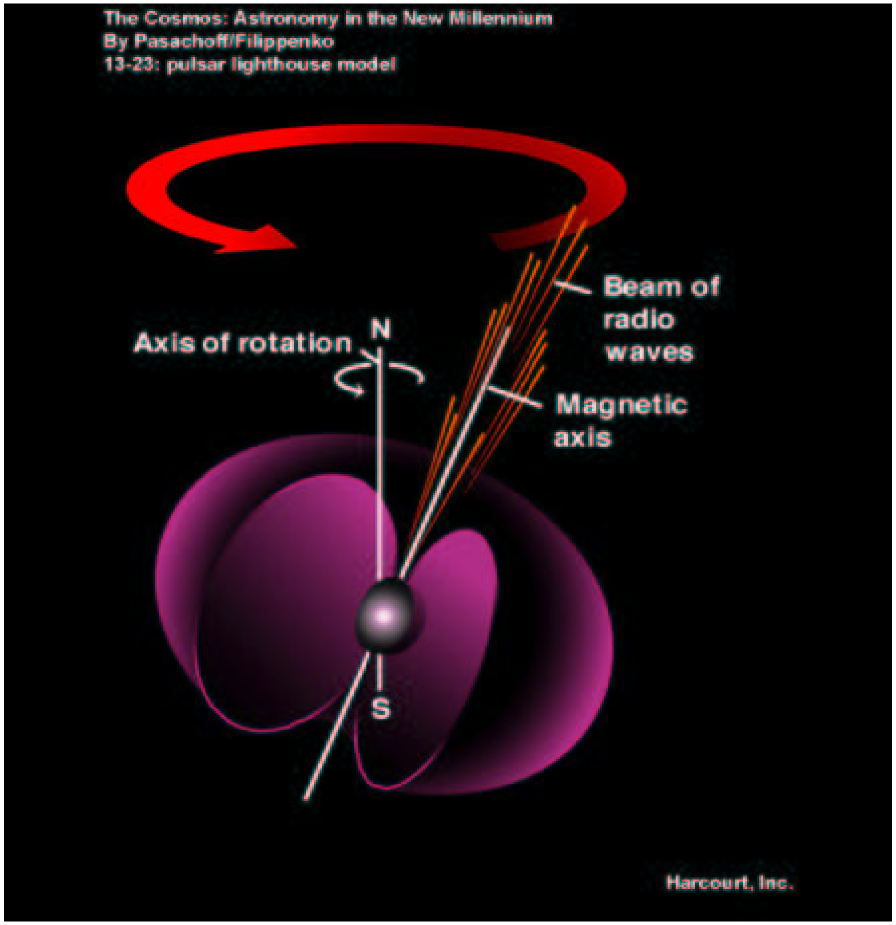
- Pulsar lighhouse model:



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      - Nuclei may be accelerated via Fermi Acceleration and/or blast wave acceleration
    - Pulsars (rotating neutron stars)
    - Active Galactic Nuclei (AGN)

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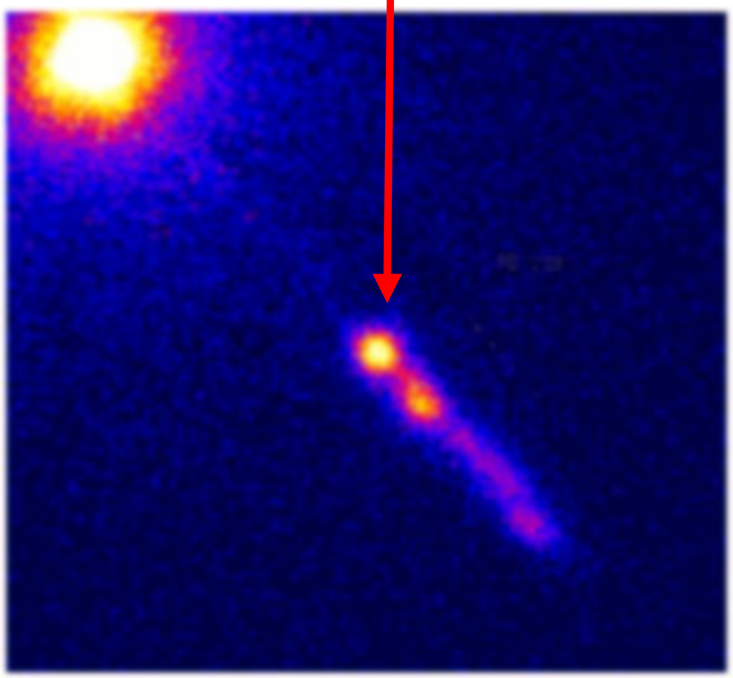
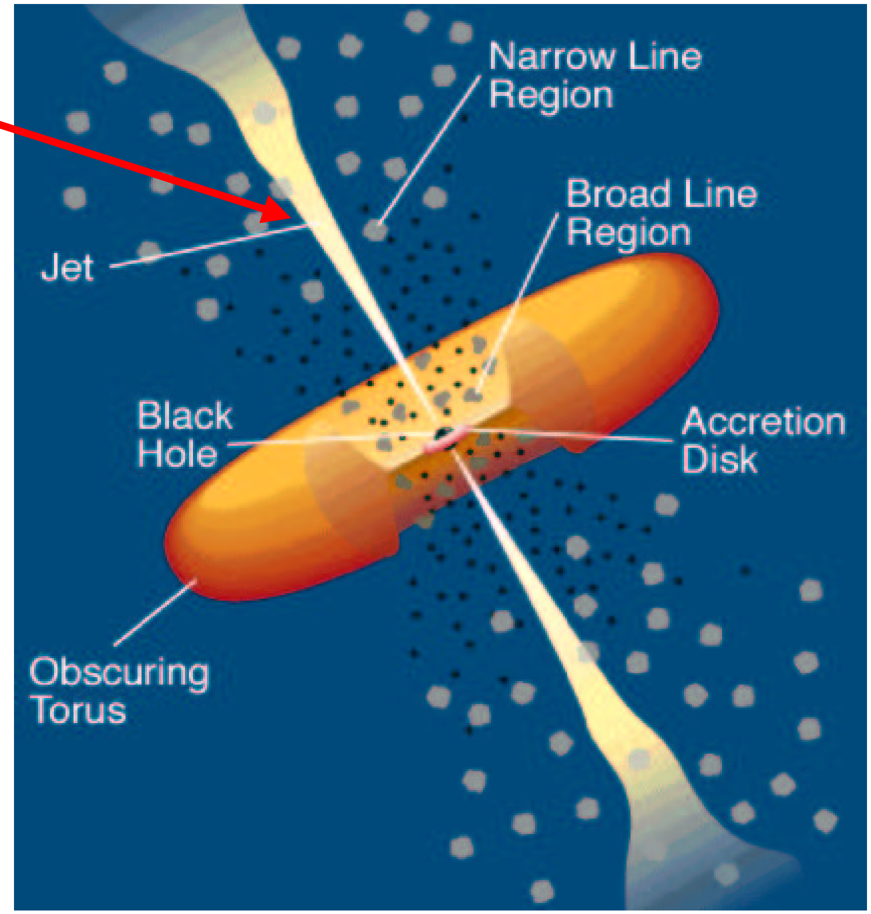
Site of CR acceleration?



Chandra X−Ray image of 3C273 AGN



AGN Model

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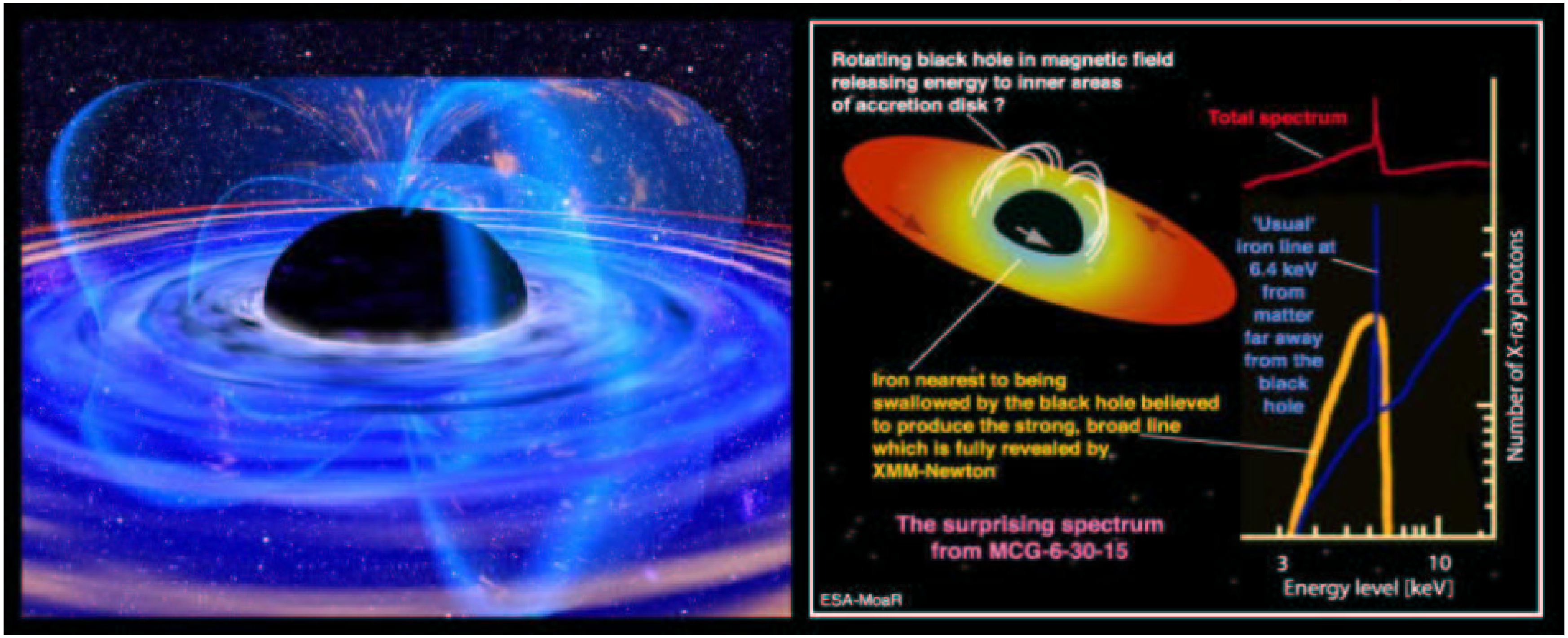
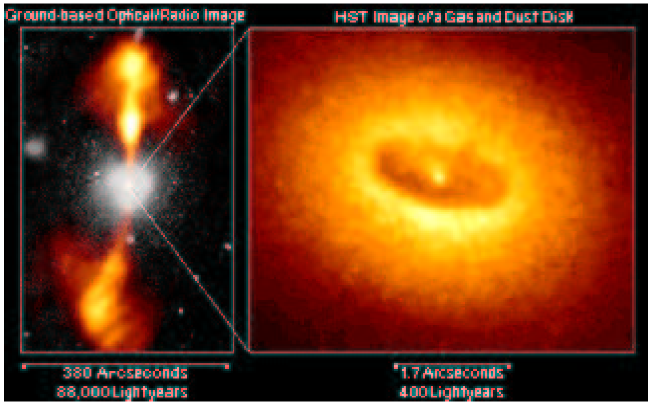


- X−rays from deep within AGN show two largely different regions near black hole. Jets along magnetic axis is where CRs are thought to be accelerated



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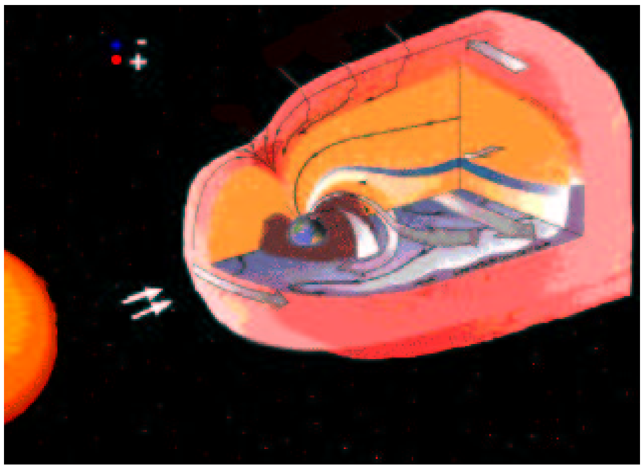
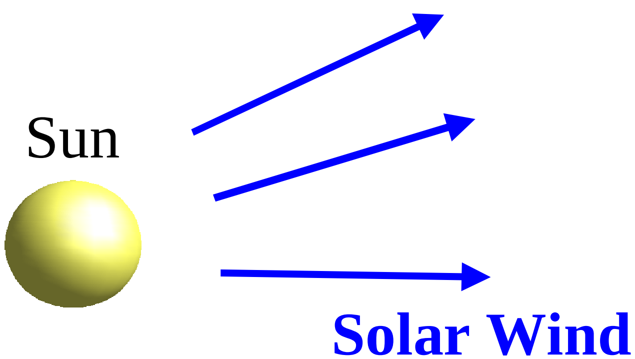
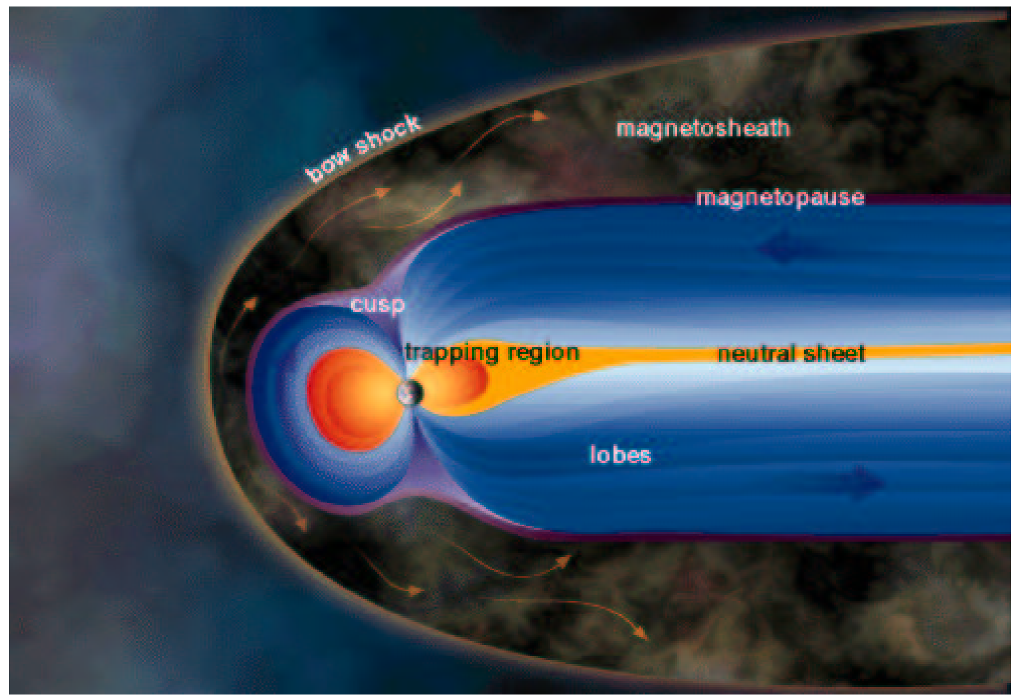
- **Okay, so how do CRs get to us from these supposed souces?**
  - CR propagation
    - Near earth, magnetosphere deflects CRs with E < 5 GeV







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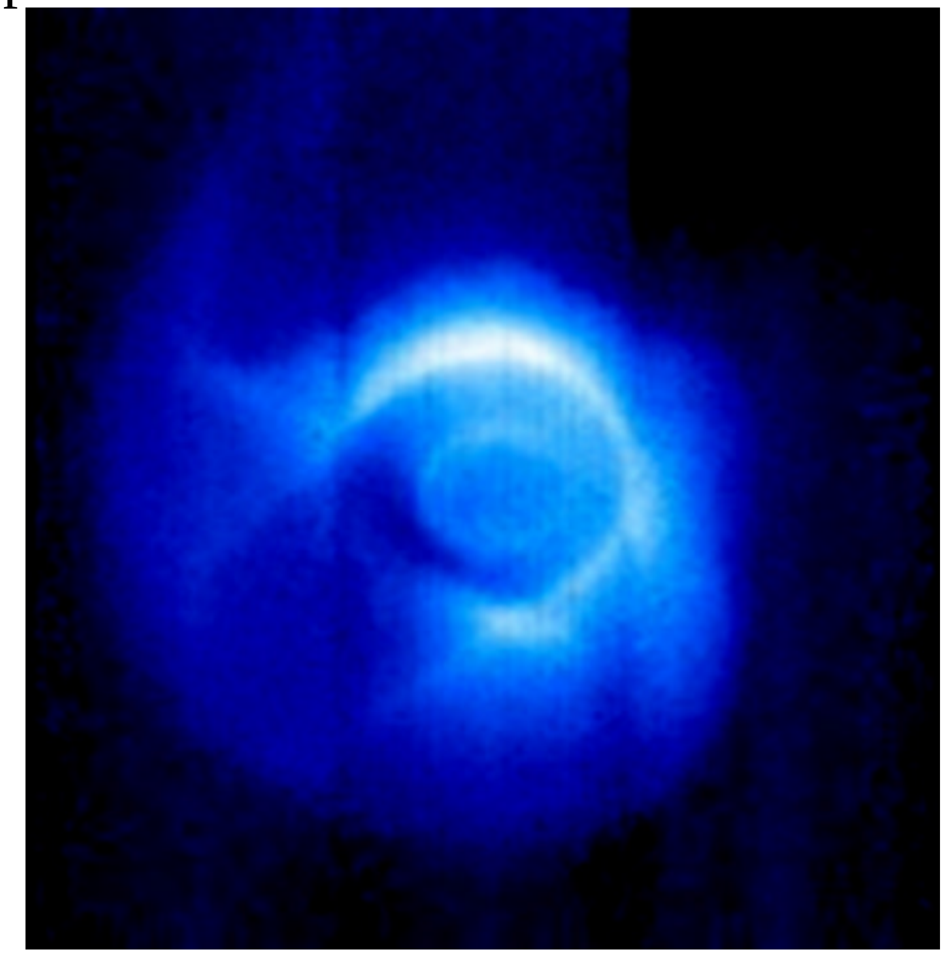
- False color image of the charged plasma from the solar wind trapped by the earth's magnetosphere
  - IMAGE spacecraft, EUV.
  - Earth is in the center, viewed above N. pole
  - Sun is out of picture toward the upper right
  - Faint central ring is Aurora



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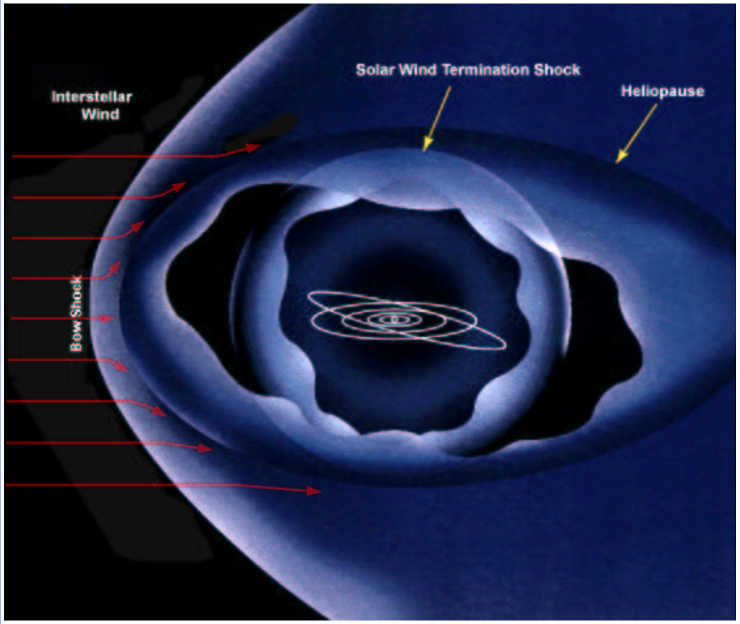
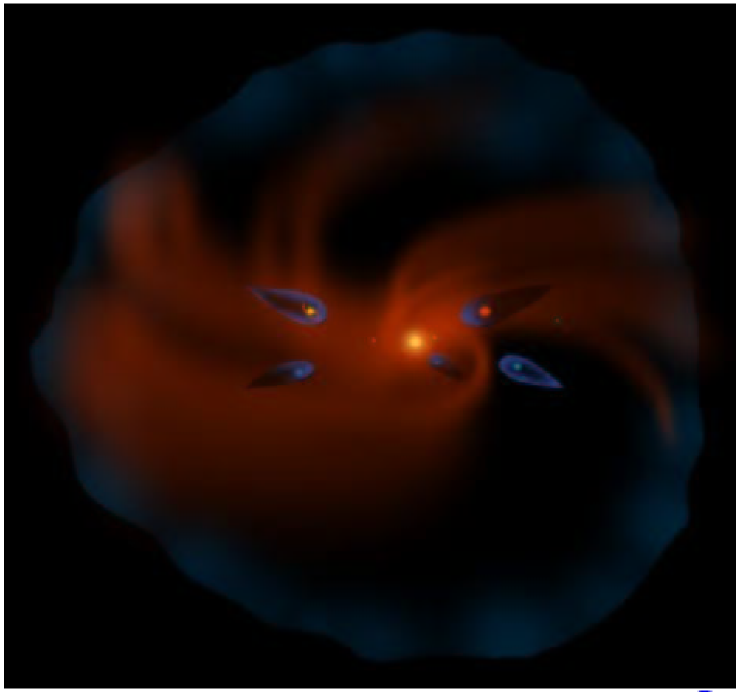
- **Okay, so how do CRs get to us from these supposed souces?**
  - CR propagation (continued)
    - At a few solar system radii scale there is a corresponding magnetic structure called the Heliosphere which effects CR propagation into/out of the solar system



Our Star



Planetary magnetospheres

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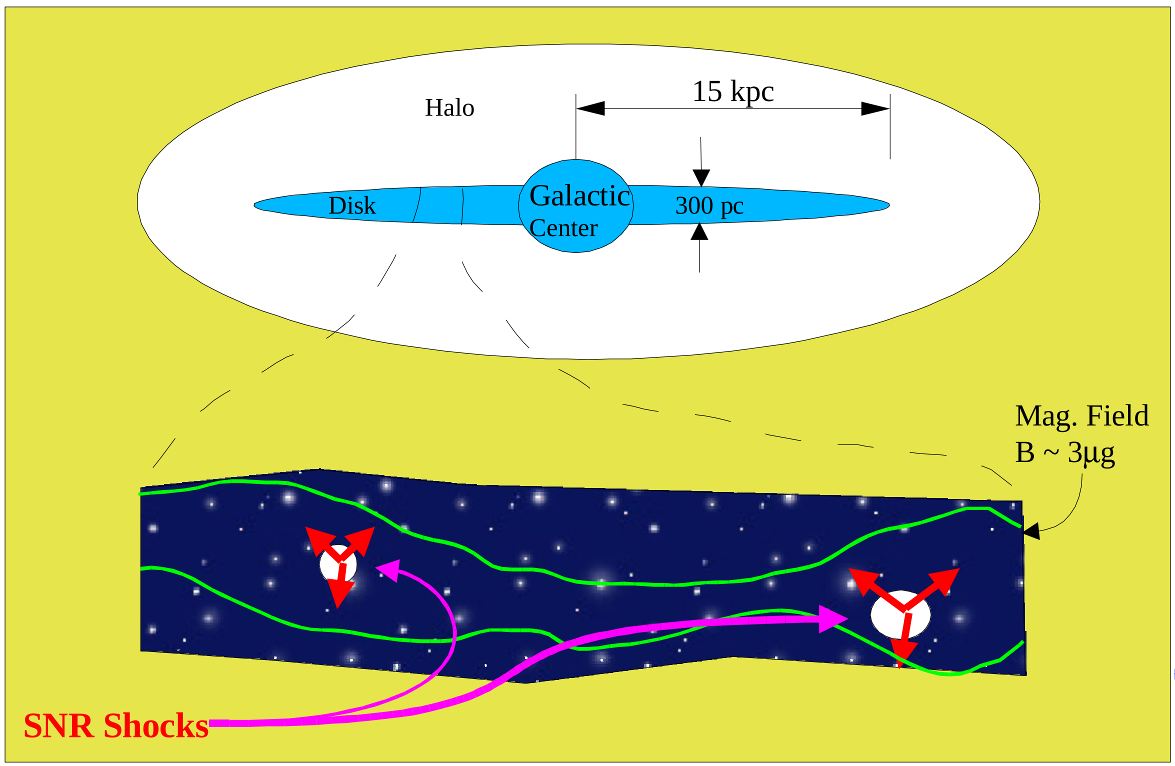
- **Okay, so how do CRs get to us from these supposed souces?**
  - CR propagation (continued)
    - At Galactic scales, semi−ordered galactic magnetic fields (~ 3 µG) influence the propagation of CRs.
    - Below ~ 1 PeV, CRs are "trapped" in galaxy and slowing leak out (Leaky Box Model)

- Use ratio of unstable to stable isotopes (i.e. ^{10}Be)

- Escape time depends on R (rigidity) but on scale of $2x10^7$ years



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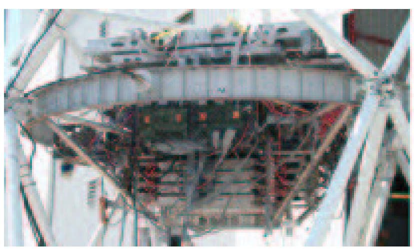
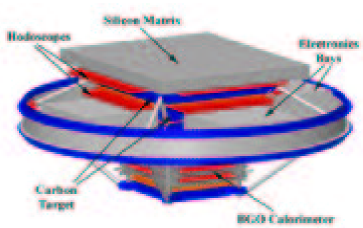
- How do we detect CRs?
  - Low energies (< 1 TeV): Satellites & Balloons

http://atic.phys.lsu.edu/aticweb





ATIC: Advanced Think Ionization Calorimeter

(show movie!)

http://marge.phys.washington.edu/jacee

JACEE:Japanese−American Collaborative Emulsion Experiment

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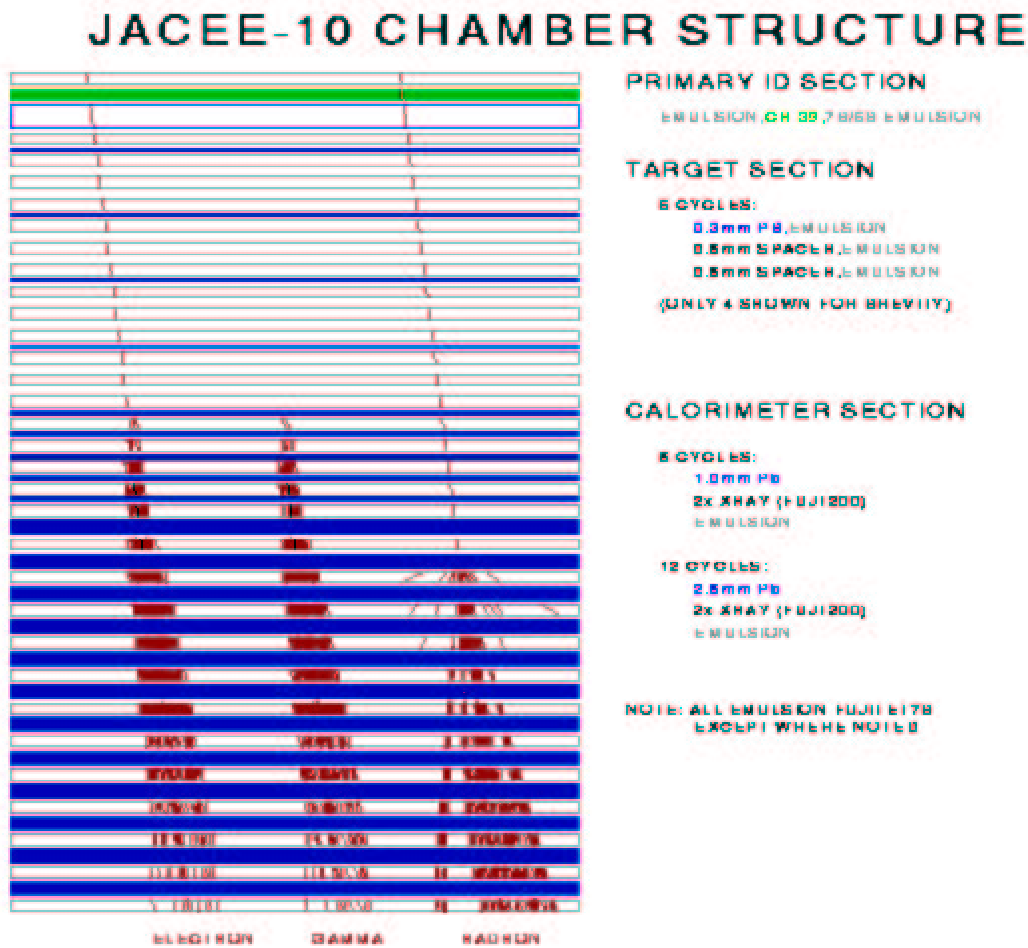
- Schematic of JACEE Emulsion Detector:



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- ACE: Advanced Composition Experiment (satellite)
  - Launched 8/5/97
  - Has multiple instruments

http://www.srl.caltech.edu/ACE

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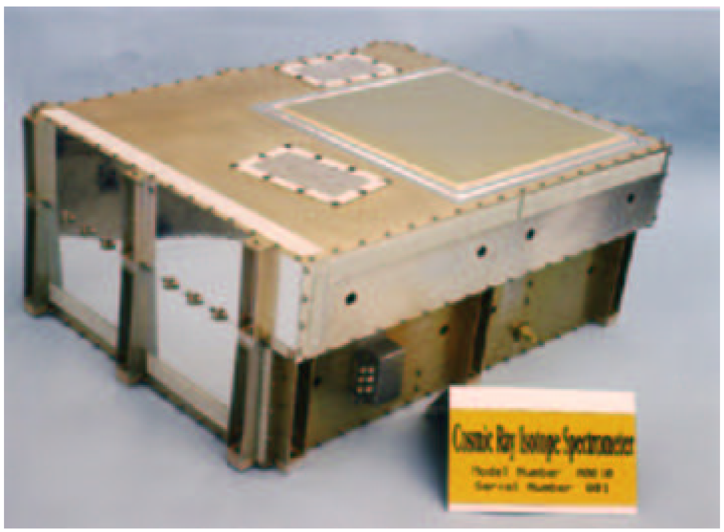
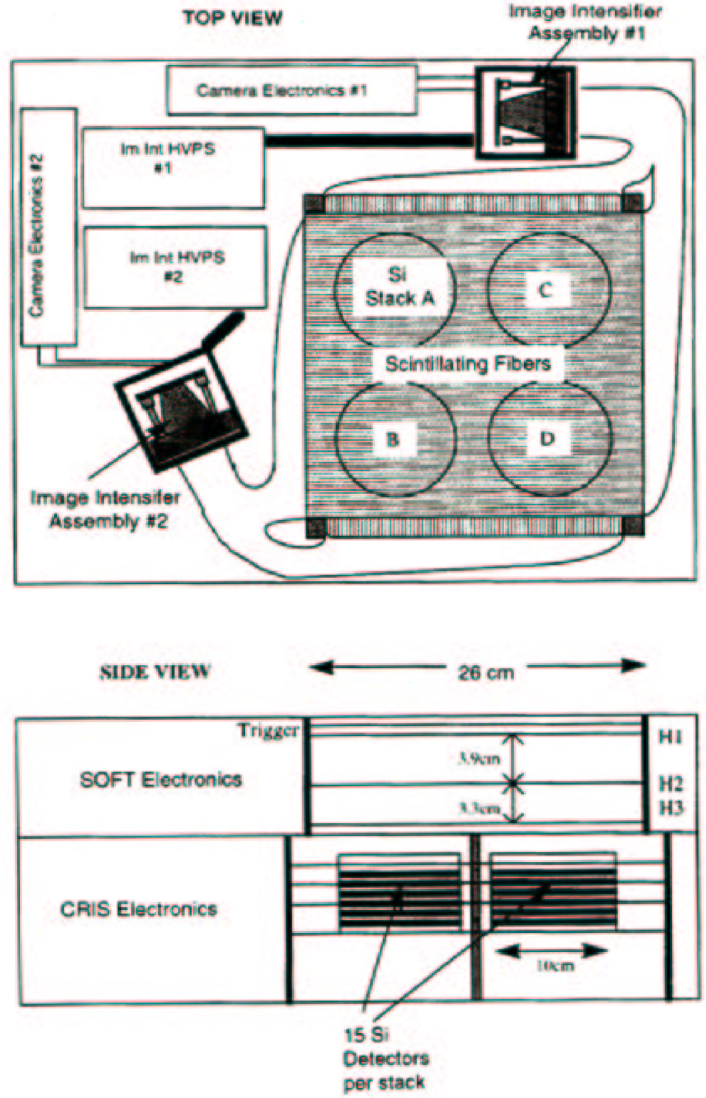
- One example ACE instrument:
  - **CRIS (Cosmic Ray Isotope Spectrometer)**





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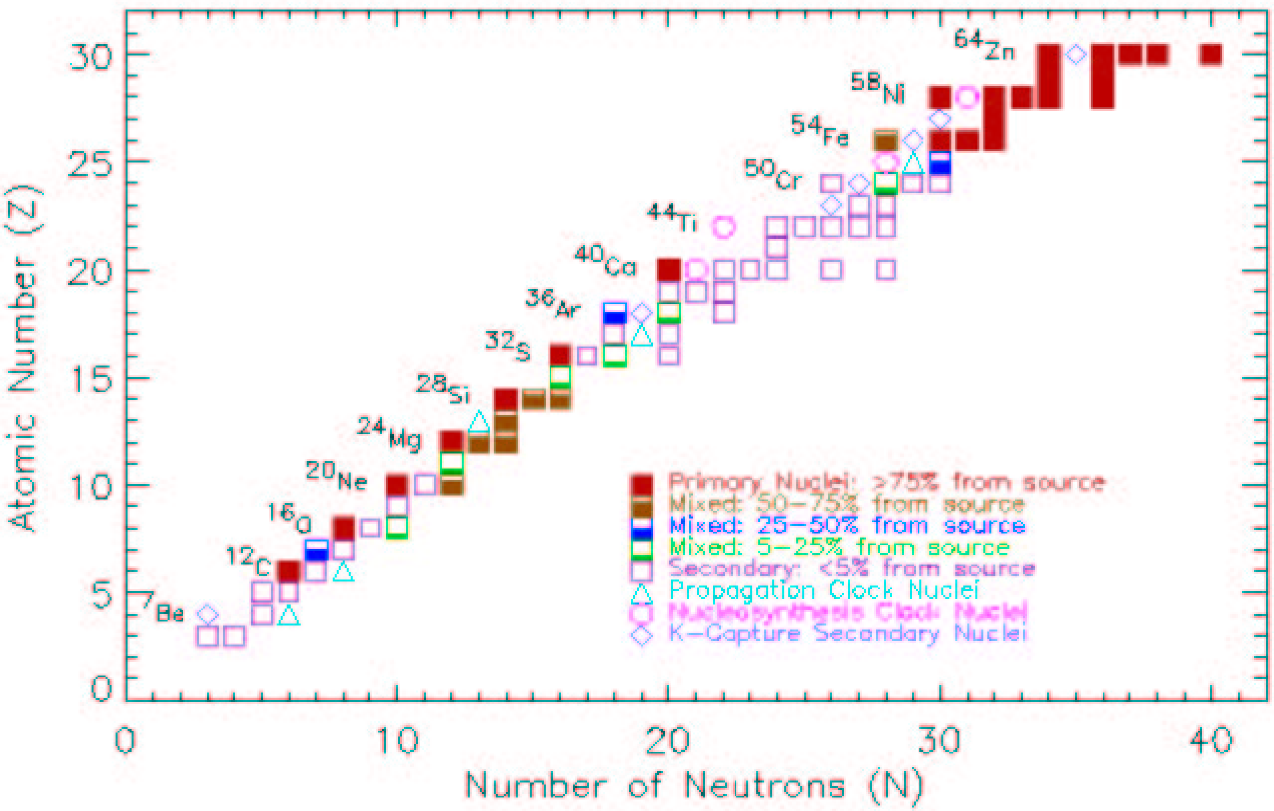
- What CRIS hopes to measure: various isotopes of elements



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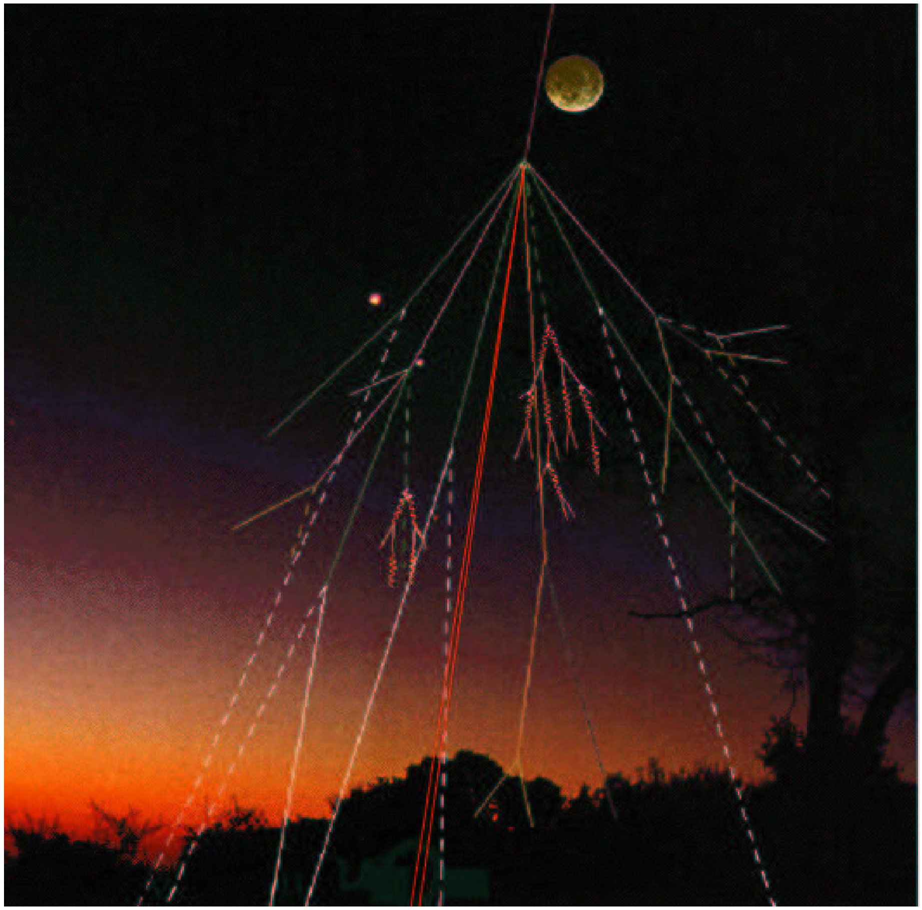
- What if CR rates are too low to be seen by detectors on balloons or satellites?
  - **Detect them through are showers!**



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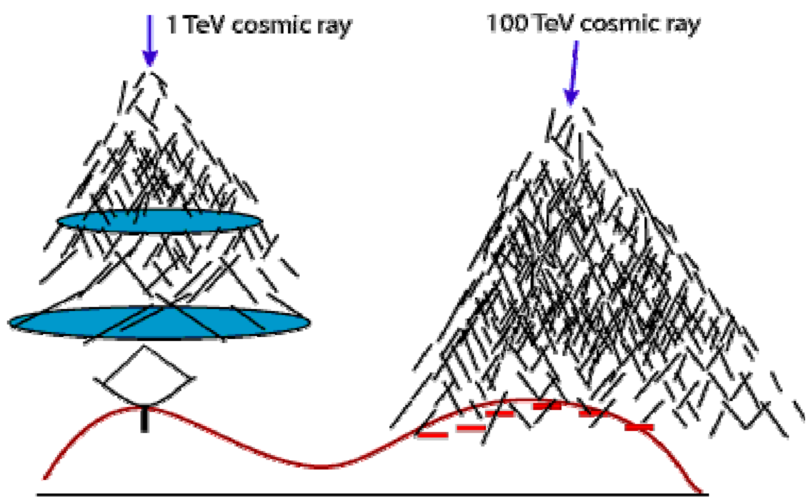
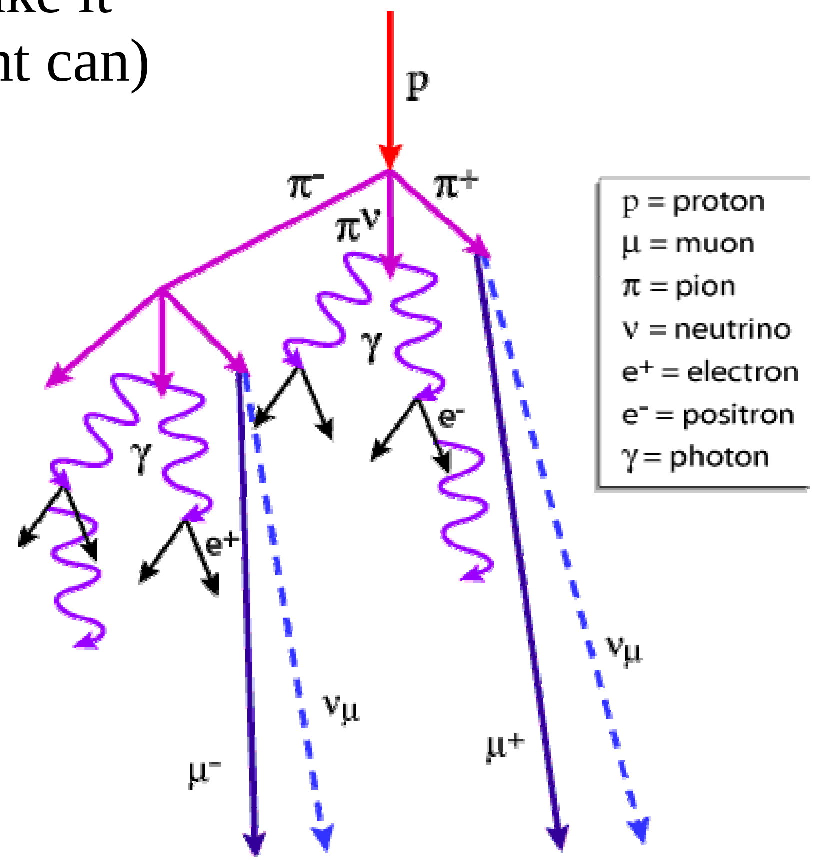
- CR airshower development:
  - If energy too low, no particles make it to the ground (but Cherenkov light can)
  - All particles travel ~ c
  - Secondaries form a thin "pancake"



Air Cherenkov Telescope

Airshower Array



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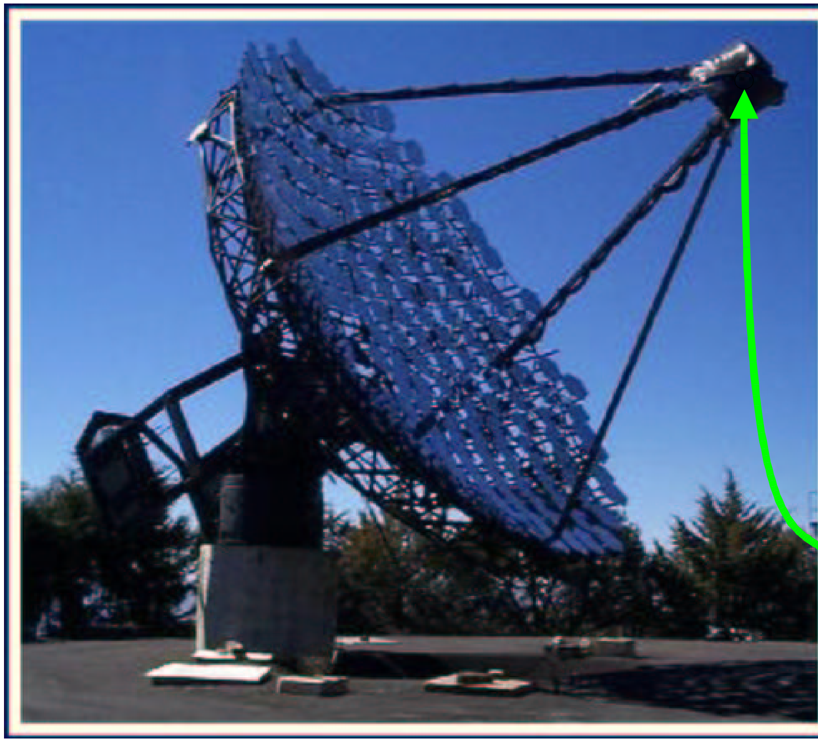
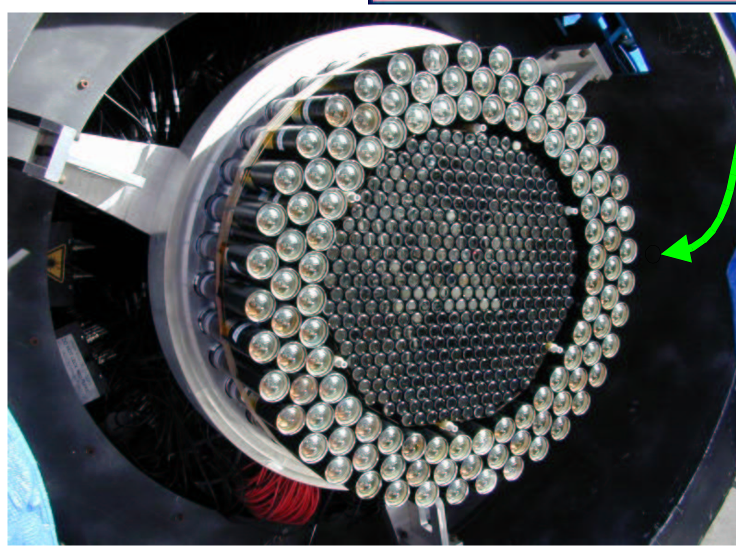
γ −ray Astronomy

- Example Air Cherenkov Telescope:
  - Whipple ACT on MT Hopkins, Arizona
  - 10m multisegmented mirror
  - Light is focused onto "camera" of PMTs
  - Energy threshold: ~ 300 GeV
  - Objects seen:
    - Crab Nebula
    - 4 AGN

http://egret.sao.arizona.edu





490 PMT camera

Are γ−rays tracers for cosmic rays?

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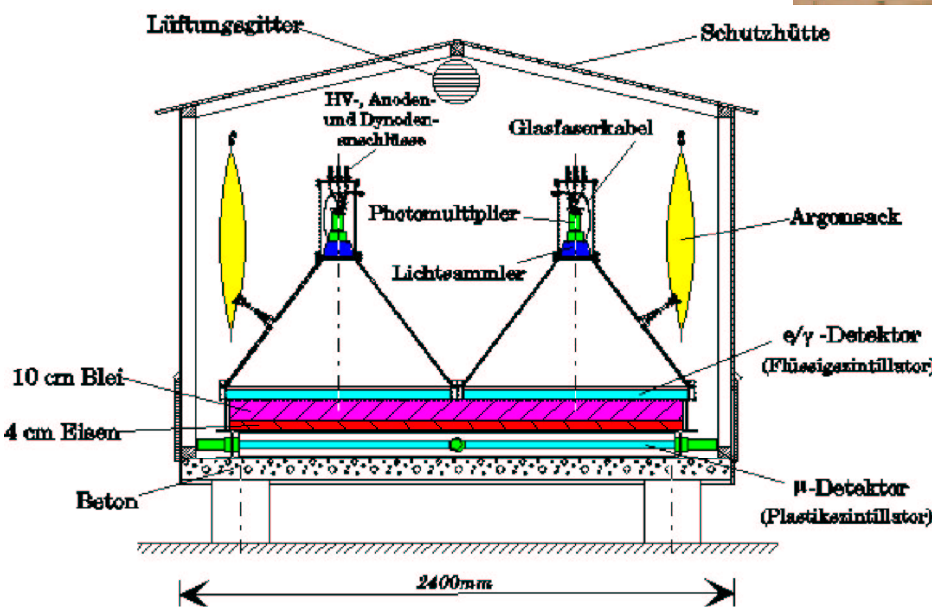
- Example Airshower Array:
  - KASCADE (Karlsruhe Shower Core and Array Detector)
    - Karlsruhe, Germany
    - 252 detectors
    - 40,000 m^2 area



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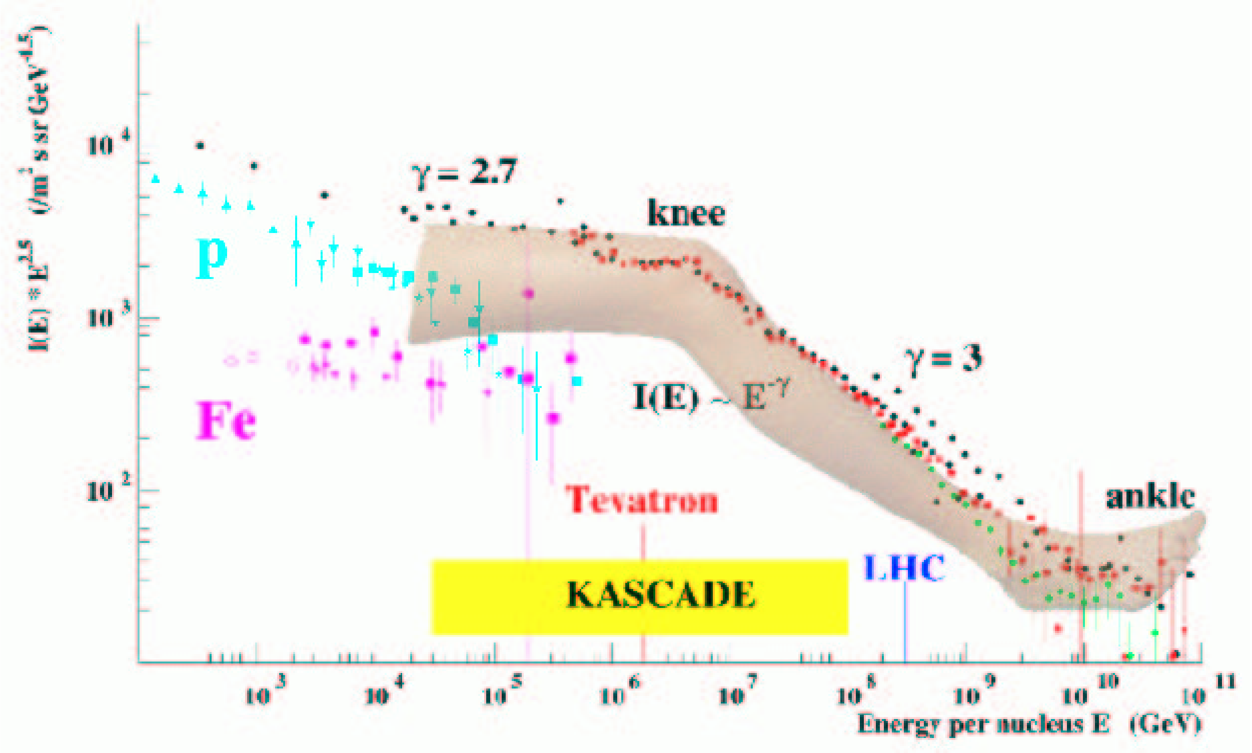
- Example Airshower Array:
  - KASCADE goals



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- Example airshower array for γ−ray astronomy:
  - Milagro
    - Located at 8600’ in Jemez Mtns in NM.
    - Detects CRs with 500 GeV < E < 100 TeV
    - Detects CRs at ~ 1800 per sec. 24/7/365 day per year (~ 95%)
    - 723 8" PMTs and 176 8’ water Cherenkov tanks
    - Has detected TeV level photons from:
      - Crab Nebula, Mrk501 & Mrk421 (AGN)
      - And perhaps 1 Gamma Ray Burst (GRB)

http://www.lanl.gov/milagro

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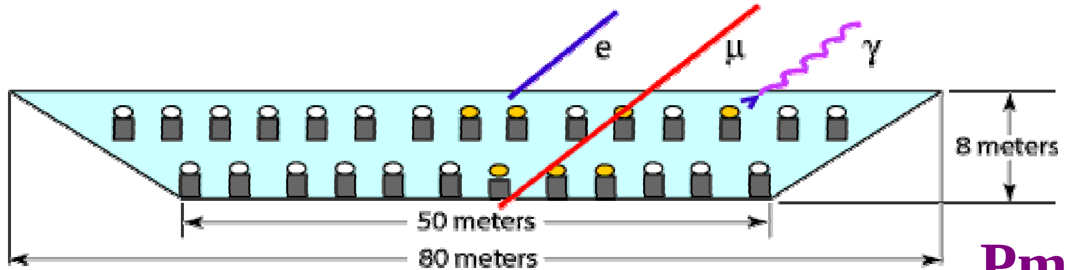
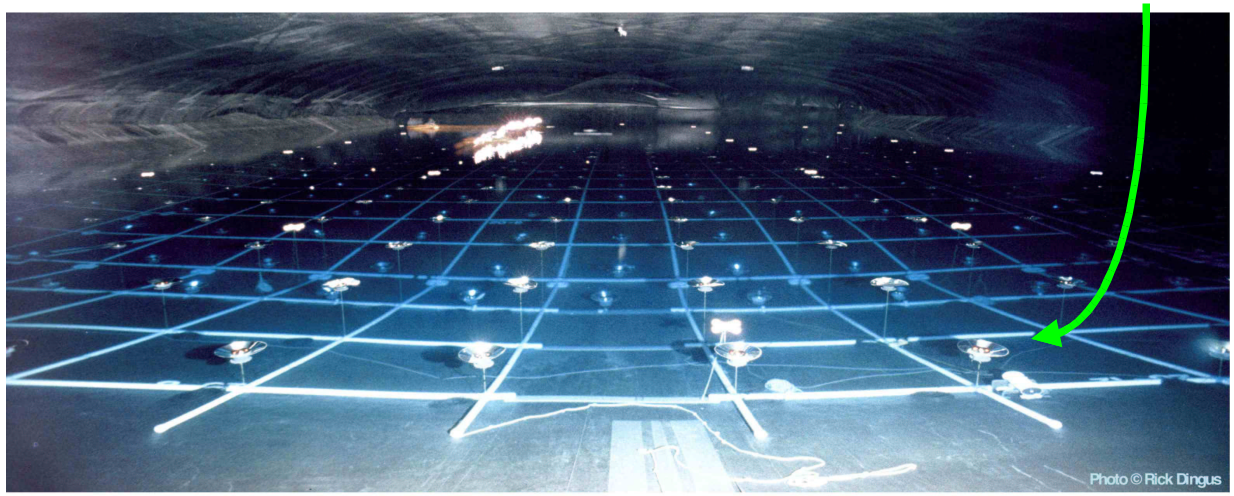
- The Milagro Pond:



Pmts



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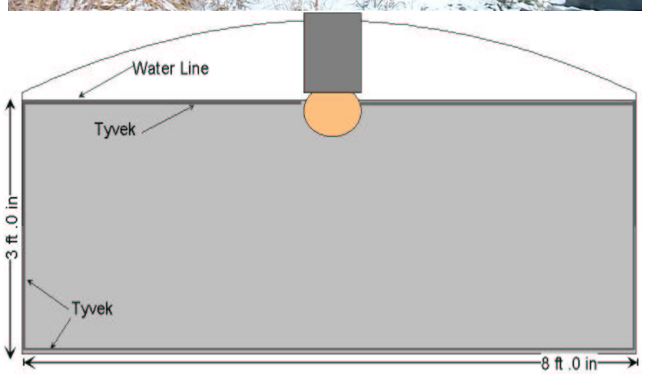
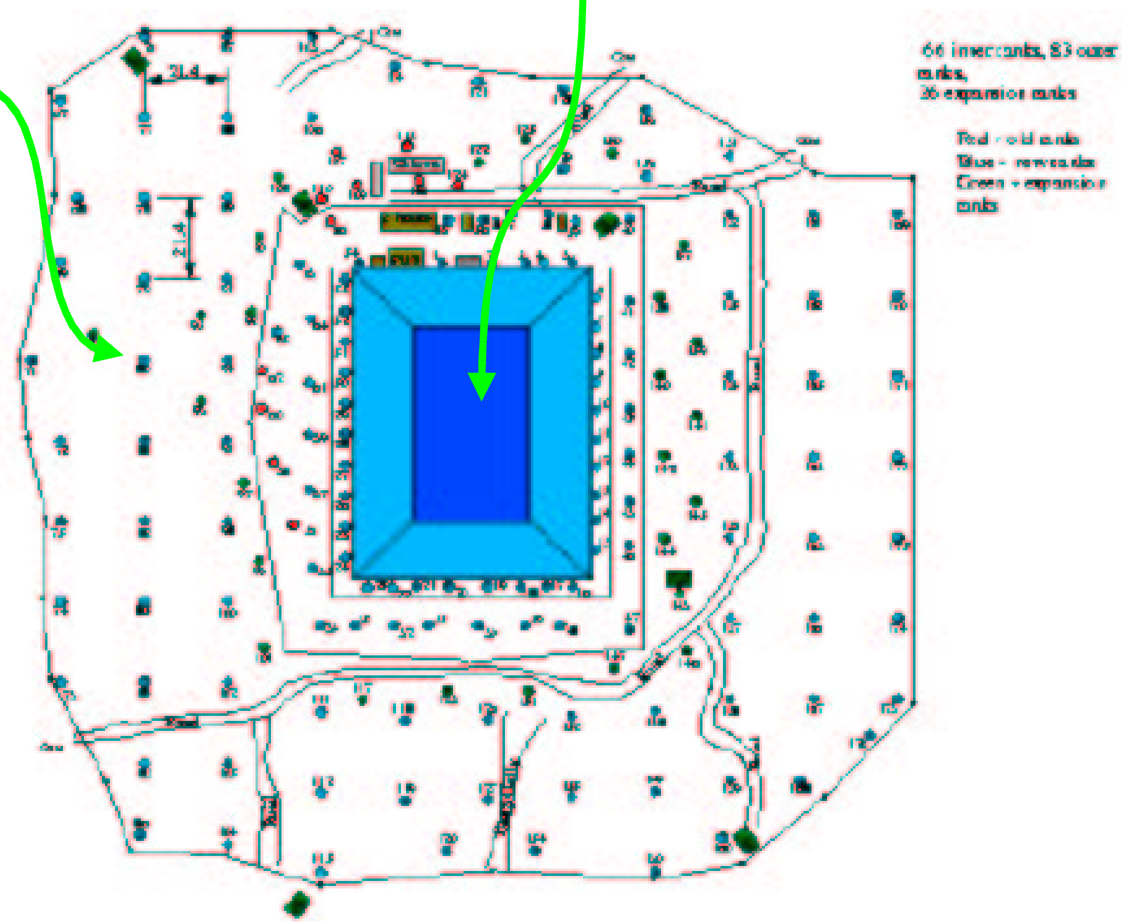
- The Full Milagro Detector:

176 8' x 4' deep water tanks

Pond





200 m

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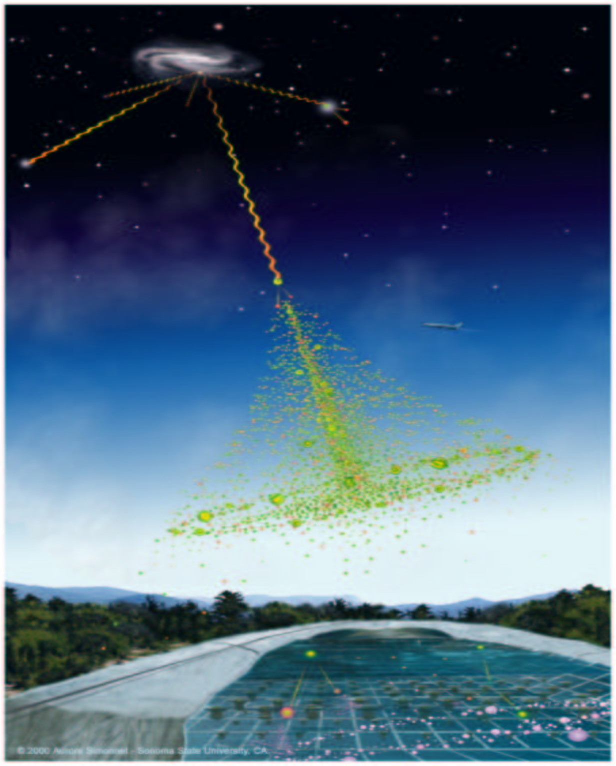
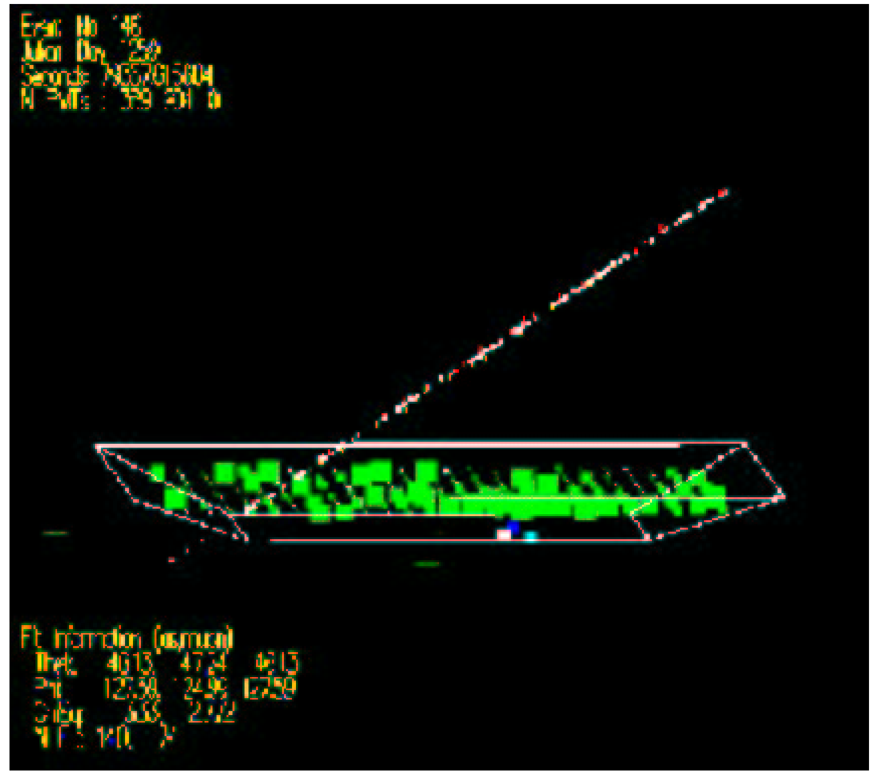
- How Milagro determines CR direction:





(angle formula)

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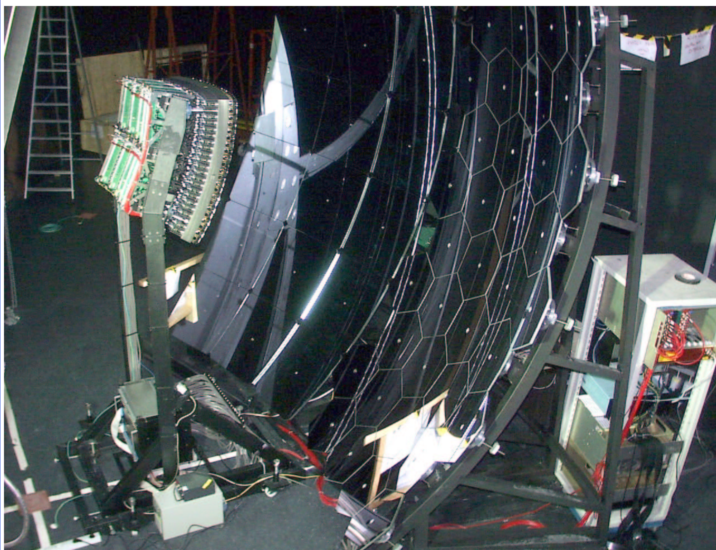
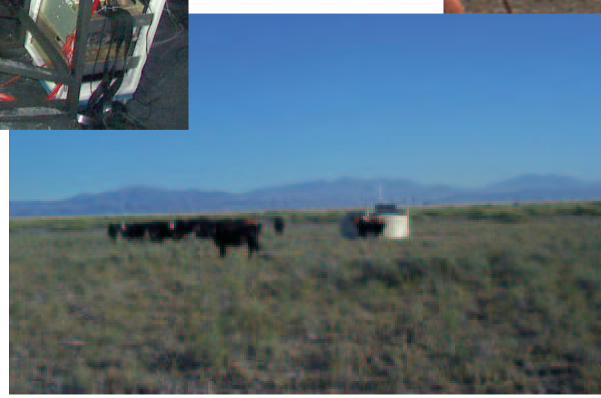
- How do we detect the highest enegy CRs? (> 10^{18} eV)
  - Pierre Auger Project:
    - Located in Malargue, Argentina
    - **1600 water Cherenkov tanks, 1.5 km apart 3000 km^2!**
    - Air fluresence telecope(s)
    - Will detect CRs with E > 10^{18} eV up to highest energies (> 10^{20})





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- Another highest energy CR array closer to home:
  - CHICOS: California HIgh school Cosmic−ray ObServatory
    - CalTech, Cal State Northridge, UCI, local high schools
    - 23 sites deployed
    - Possibility for 1800?
    - Have 2 detectors per school plus computer & electronics

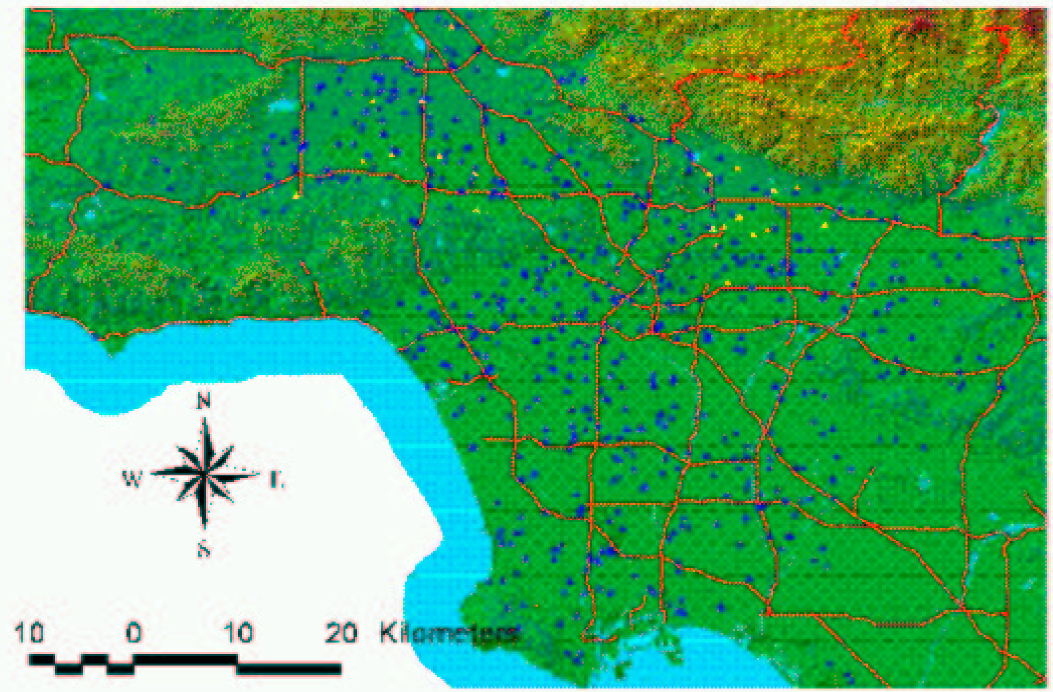

Fig. 5 Operational CHICOS sites are shown as light triangles. Additional potential CHICOS sites (about 800) are shown as darker triangles, although this database is still under development and many additional sites are anticipated in the future.

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- What each school site consists of:

3. Site Hardware

The basic concept for the CHICOS detector station is shown in Fig 3. Each station is configured with 2 detectors to facilitate coincident triggers, and operates autonomously with GPS time stamping (accuracy < 50 nsec). Data are stored and transferred to Caltech via internet once per day (during the night).

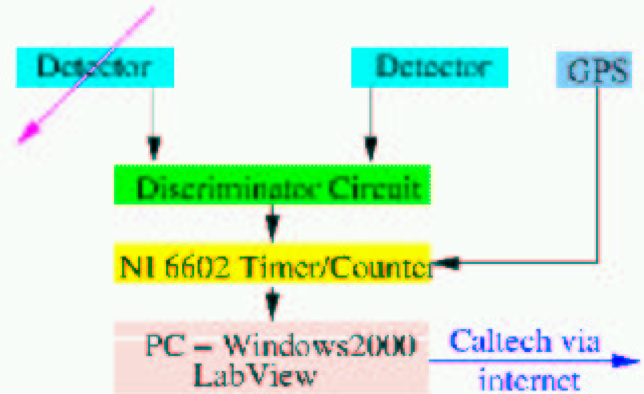

Fig. 3 CHICOS detector station concept.

- What rates we hope to reach:

Energy Threshold	Aperture	Events/year
10^{18} eV	10 km^2-sr	600
10^{19} eV	200 km^2-sr	120
10^{20} eV	500 km^2-sr	3

Table 1. Estimated aperture and event rates for three different threshold energies for an 80 site CHICOS array.

QuarkNet 2002: Cosmic Rays

- What about **neutrinos**?
  - Two catagories:
    - Atmospheric: Produced in CR airshowers
      - **Problem: ratio of ν_e to ν_μ is wrong!**
    - Astrophysical
      - Solar − tell us about nuclear funsion in sun's core
        - **Problem: see too few of them (by factor of ~2)**
      - Galactic and Extragalactic
        - From sources like Supernova, SNR?, Pulsars?, AGN?
  - Detectors:
    - Many but lets talk about:
      - Super−Kamiokande
      - Amanda / Ice−cubed

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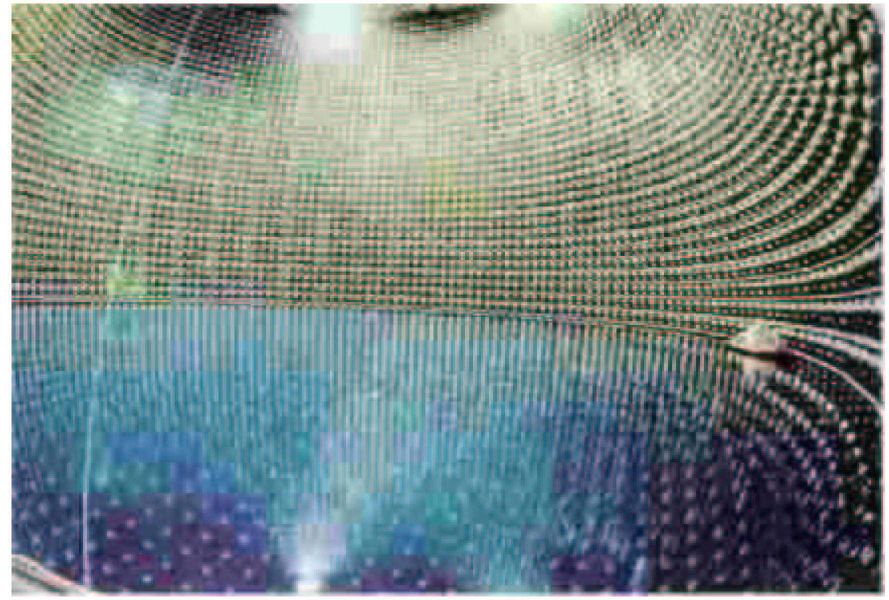
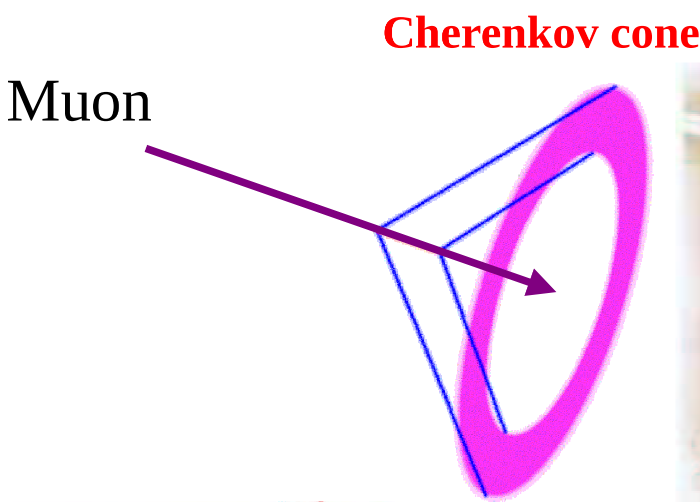
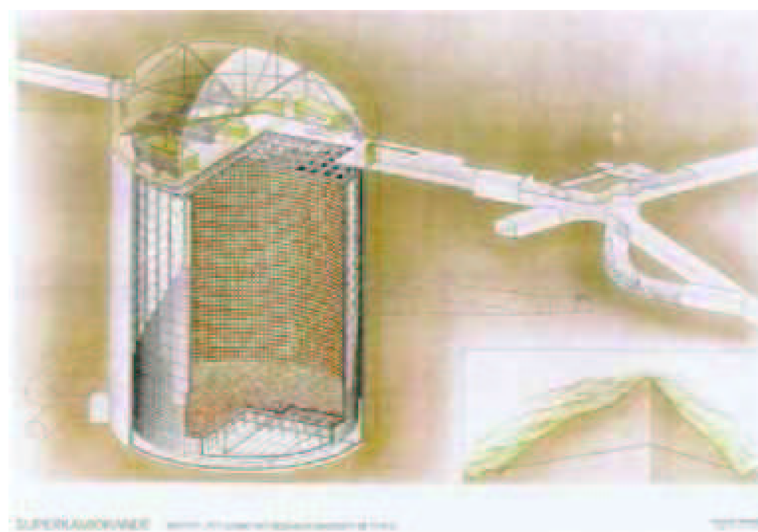
- First SuperK:
  - 50,000 ton tank of purified water, 1km below ground
  - 11,146 50 cm pmts on inside
  - Several thousand 8" pmts on outside







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- First SuperK (continued):
  - Neutrino Oscillations:
    - Concept of one neutrino type spontaneously converting into another
    - Used to explain "missing solar and atmospheric neutrinos

ν_e

- Two requirements:
  - Mixing between neutrino mass and weak interaction eigenstates:

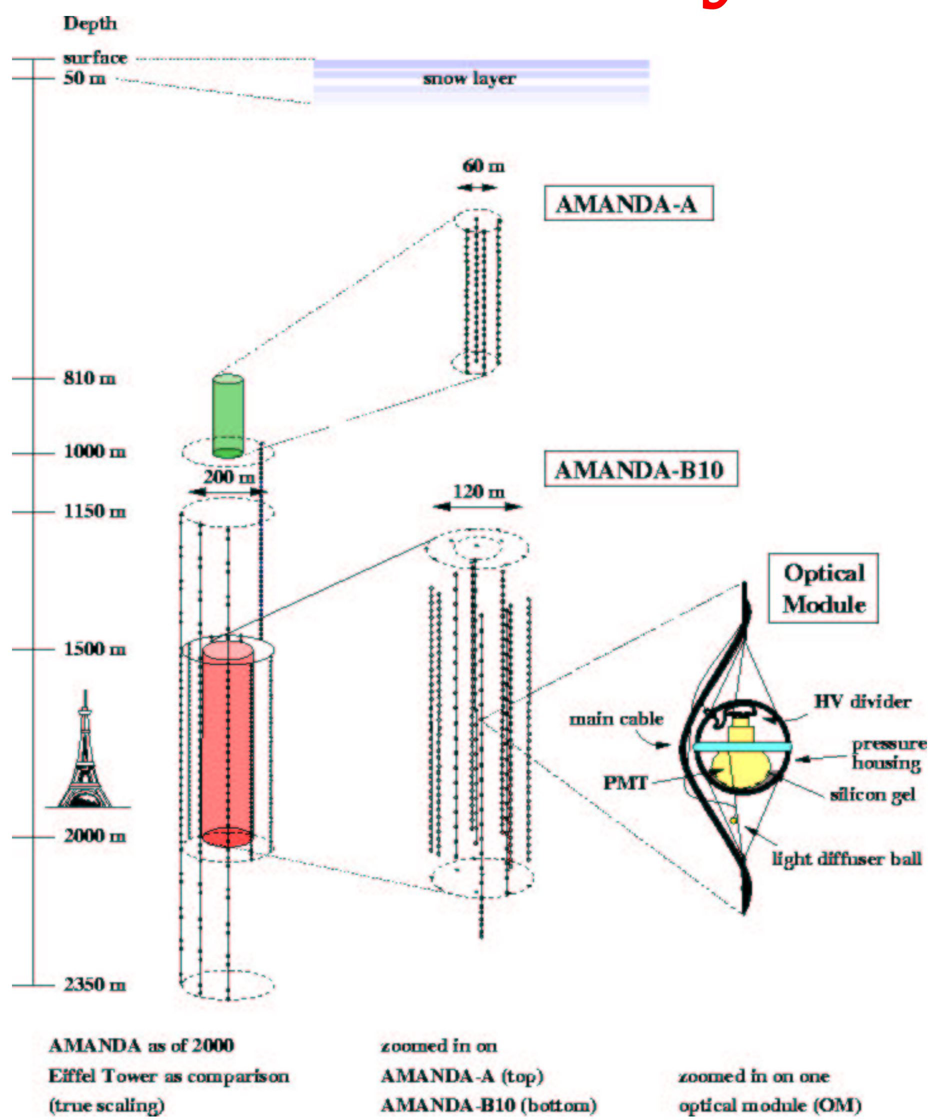
$$\begin{pmatrix} \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} \cos\theta & -\sin\theta \\ \sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \end{pmatrix}$$

  - Difference in mass between neutrino mass eigenstates: $m_1 \neq m_2$

http://www.ps.uci.edu/~superk

QuarkNet 2002: Cosmic Rays

- Now for Amanda (Ice−cubed):
  - 100’s of 8−9" pmts
  - 1800m below ice surface at south pole
  - PMTs detect Cherenkov light from muons traversing ice which were produced from TeV neutrinos rising up through earth



- Sources?:
  - Pulsars?
  - AGN?
  - GRB?

http://amanda.berkeley.edu

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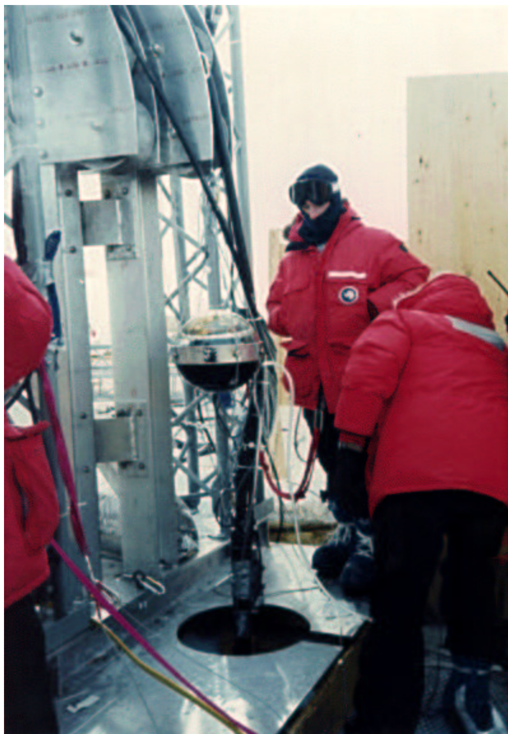
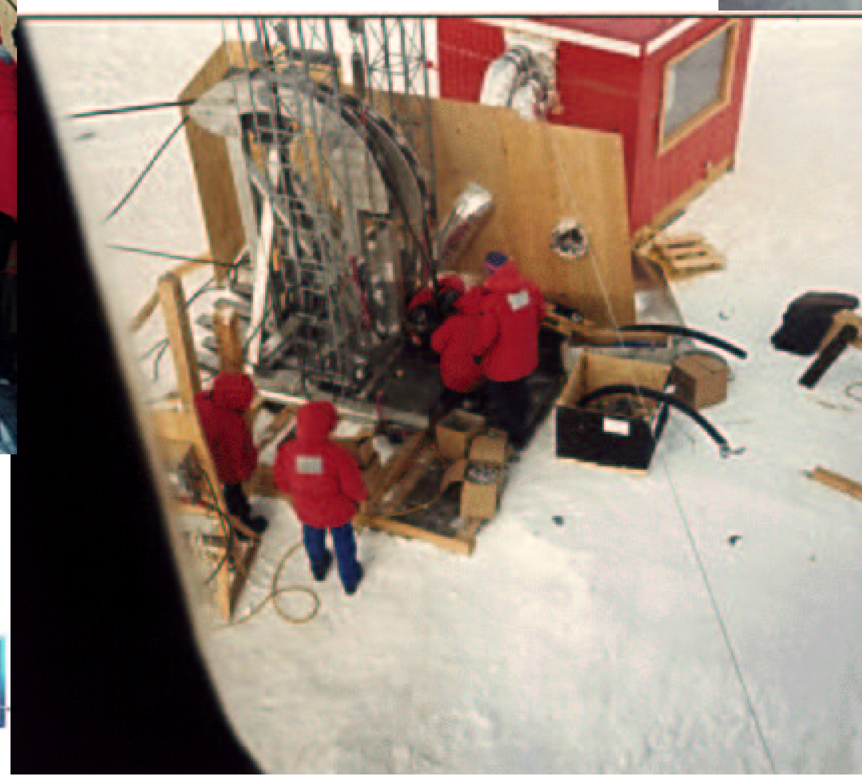
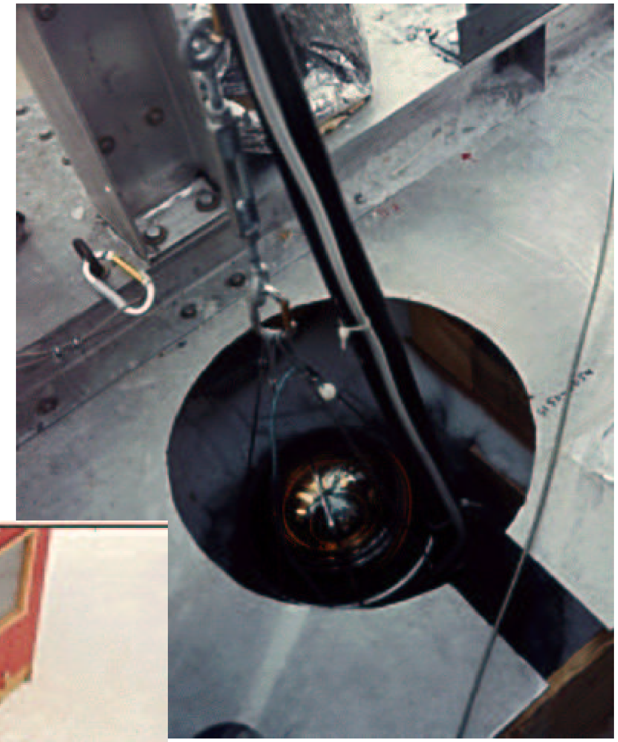
- Amanda deployment pics:







QuarkNet

QuarkNet 2002: Cosmic Rays

- Cosmic Ray Summary:
  - We've know about CRs for almost 100 years
    - Still don't know for sure of their origins
  - First used to explore subatomic particles
  - Significant constituent of solar system and galaxy
  - Messengers from deep space
  - Perhaps were significant in development of life on earth?
  - Still hold many difficult but intriguing mysteries yet to be solved