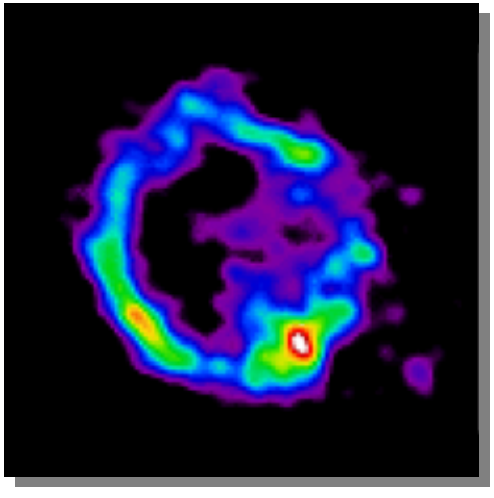
High Resolution Cosmic Ray Measurements using Next Generation Ground-based Gamma Ray Observatories



David Kieda

University of Utah

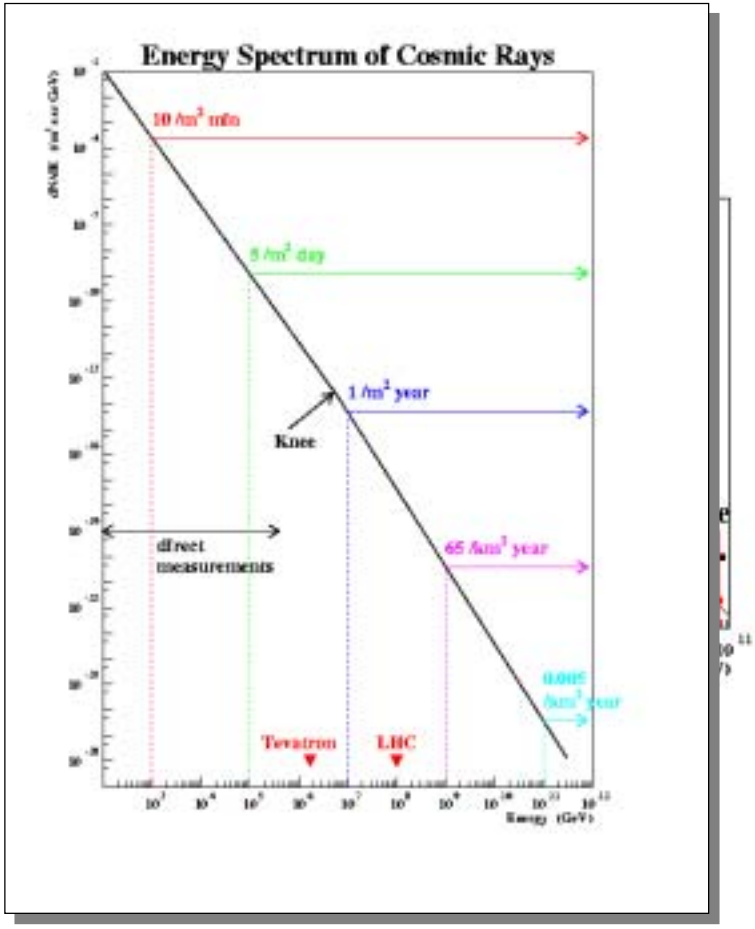
Department of Physics

Kashiwa Gamma Ray Workshop
28 September 2002

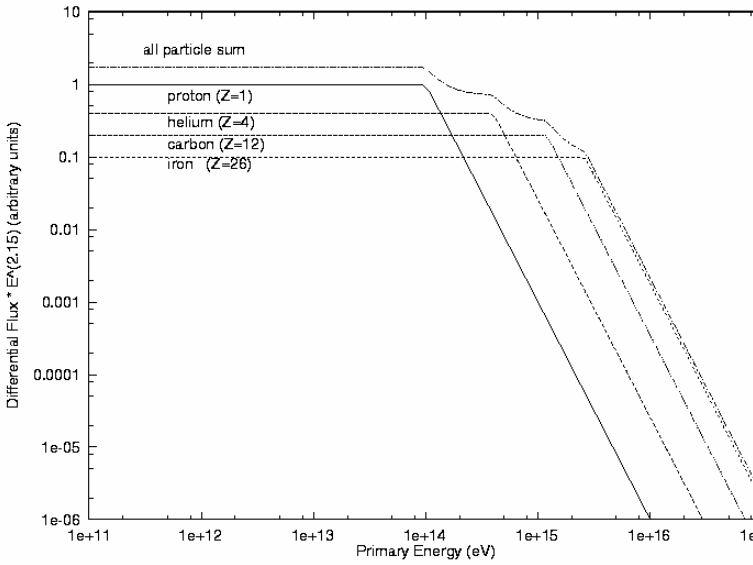
Outline

- Cosmic Ray Origin
- Existing Origin Signatures
  - At Source
  - At Earth
- Potential Contributions of
  - Next Generation γ-Ray Observatories
- New Possibilities

Energy Spectrum and Fluxes



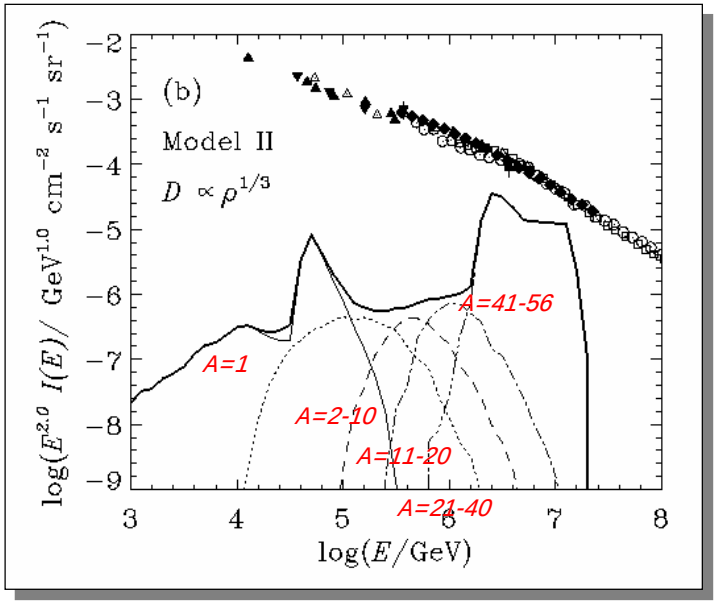
Cosmic Ray Acceleration



Canonical SNR Shock acceleration model

- **Simplified Rigidity dependent acceleration limitation $E_{max} \sim Z \times 10^{14}$ eV**
- **Spectral Steeping with no bump (Knee)**
- **Increasing Energy->Increasing Mass**

γ-Ray Pulsar acceleration



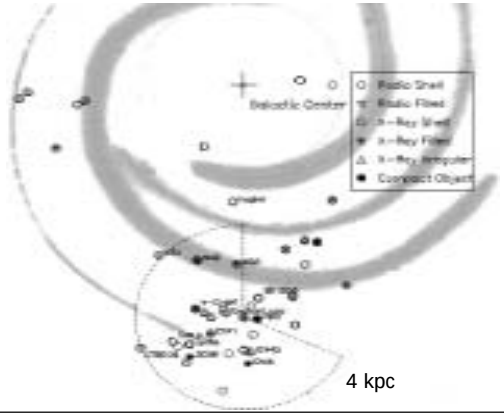
Acceleration of nuclear material from neutron star surface by outer gap electric field of pulsar magnetosphere.

Heavy nuclei injected into medium of expanding Supernova Remnant.

May explain CR origin 10^{15} –10^{17} eV

Bednarek & Protheroe, Ap. Phys. (2001)

Propagation/Escape

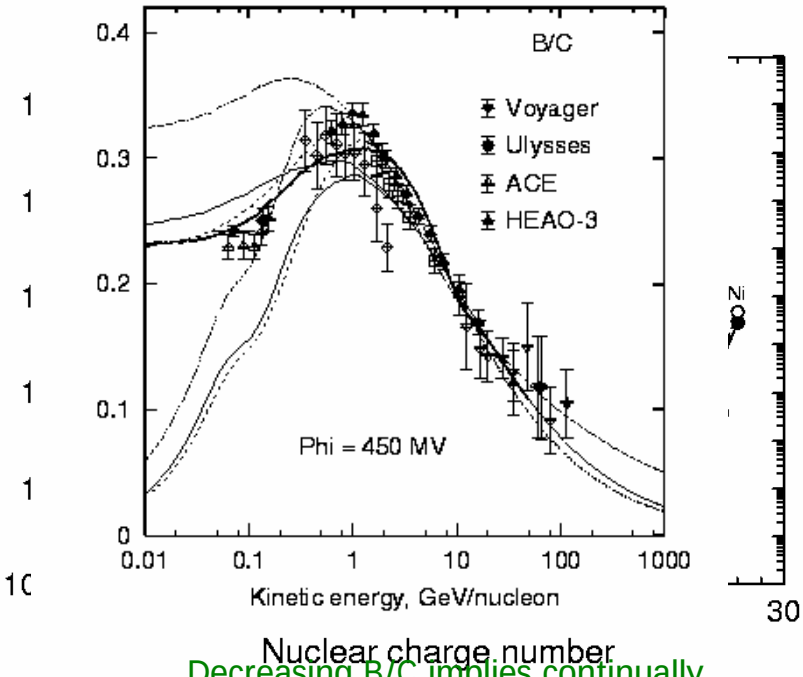


"Leaky Box" model

- **Galactic Magnetic Field**
  - **Charged Particle Trapping**
- **Rigidity-dependent escape**
- **Modifies the power law energy spectrum**
- **Measurable through energy dependence of secondary B/primary C ratio**
- **Interstellar Particle density ~ 1 atom/cm^3**
- **CR has to at least pass out of disk then back in again**
  - **Energy Dependent pathlength with fixed minimum**

$$\lambda_e = \lambda_0 \times \left(R/R_0 \right)^{-\delta} + \lambda_r \quad gm \quad cm^{-2}$$

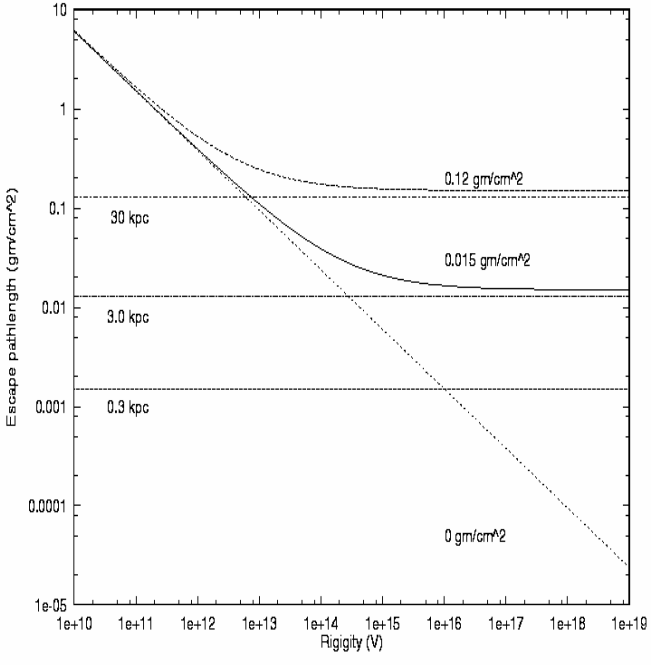
B/C ratio and Propagation



Decreasing B/C implies continually decreasing pathlength with increasing energy.

Moskalenko et al Ap. J. 565,280 (2002)

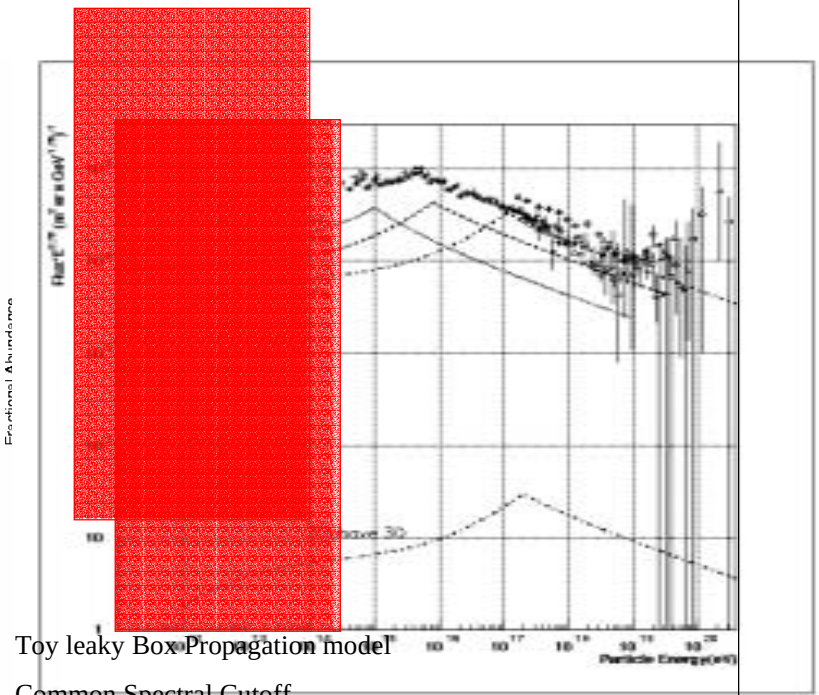
Minimum Pathlength



Pathlength minimum forces higher mass nuclei to breakup into lighter secondary fragments.

Can exact value be extracted from higher energy CR flux normalization w.r.t low energy flux?

"Bump" on the Knee



Toy leaky Box Propagation model

Common Spectral Cutoff

Normalized to JACEE/CRN/HEAO-3 fluxes ~ TeV

Tsao-Silberberg cross sections (Kieda & Swordy 2001)

Λ_ρ=0.015 gm cm^{-2}

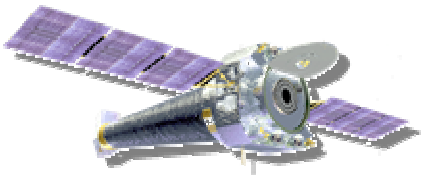
Λ_ρ=0.003 gm cm^{-2}

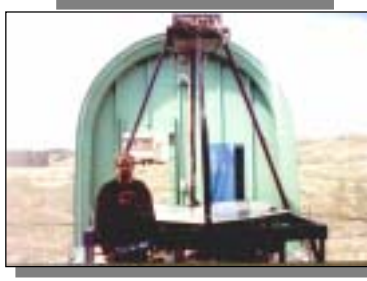
Nuclear flux in red region suppressed somewhat

Almost no nuclei broken up

Indirect Experimental Evidence

No Direct Evidence of origin due to diffusive propagation of charged CR to earth





Emission of Radio/X-Ray/ γ-rays by SNR (at source)

Cosmic Ray Energy spectrum, composition measurements (at Earth)

TeV γ-ray SNR Observations

SN1006 SNR detection

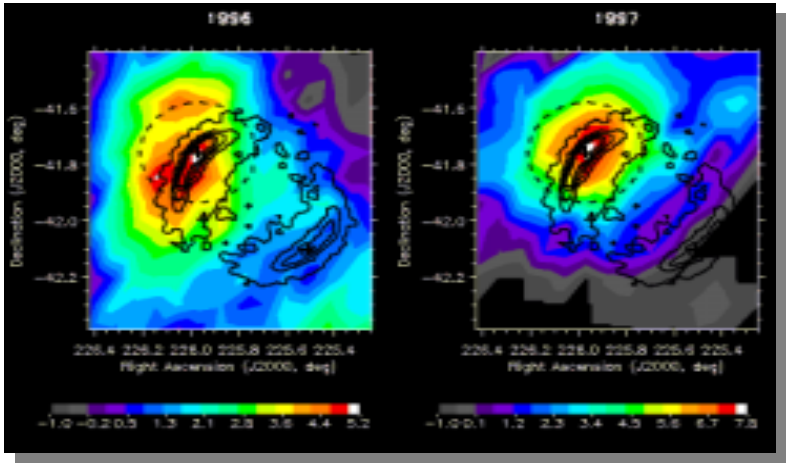
CANGAROO collaboration

Tanimori et al

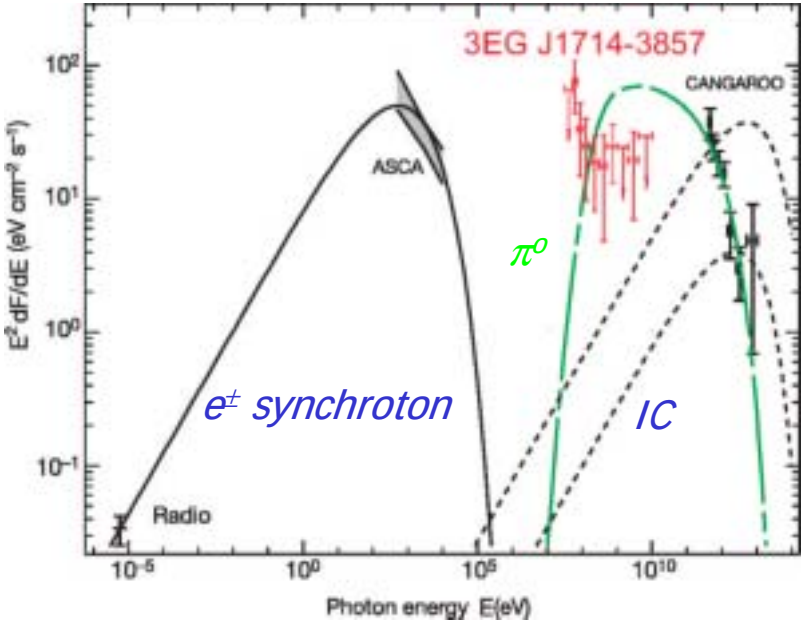
(Ap. J. Lett 497, L25 (1998))

Consistent with IC emission

Hadronic π^0 production/decay not necessary

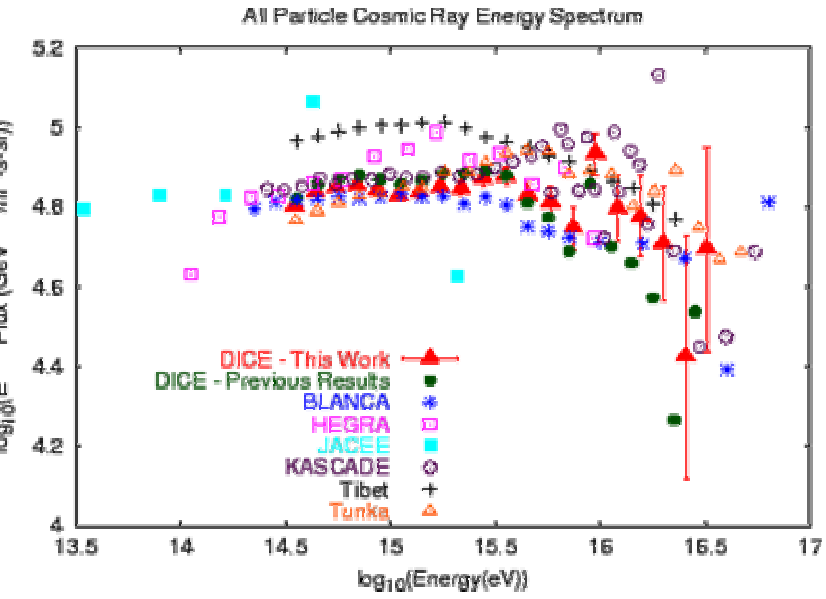


RXJ1713.7-3946



Reimer and Pohl, Astron & Ap. (2002), astro-ph/0205256

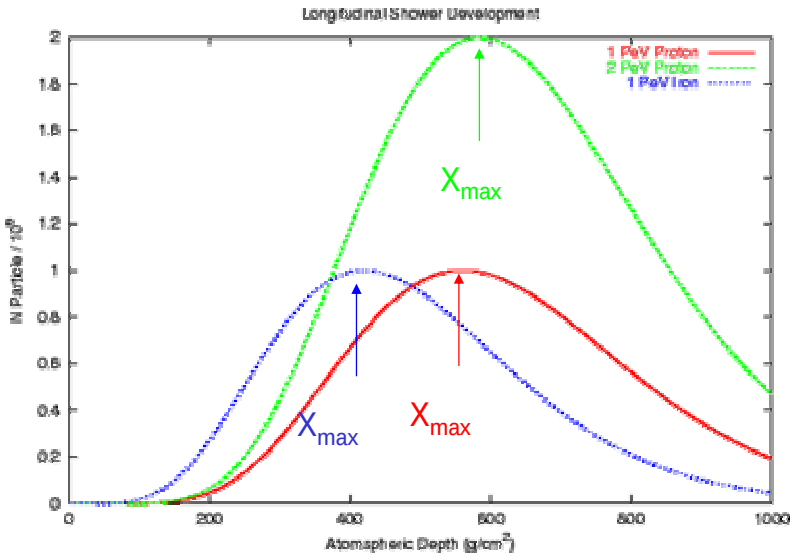
Energy Spectrum



- Location of the Knee?
- Bump on the knee?

(C.G. Larsen et al, Proc. 27th ICRC, Hamburg (2001))

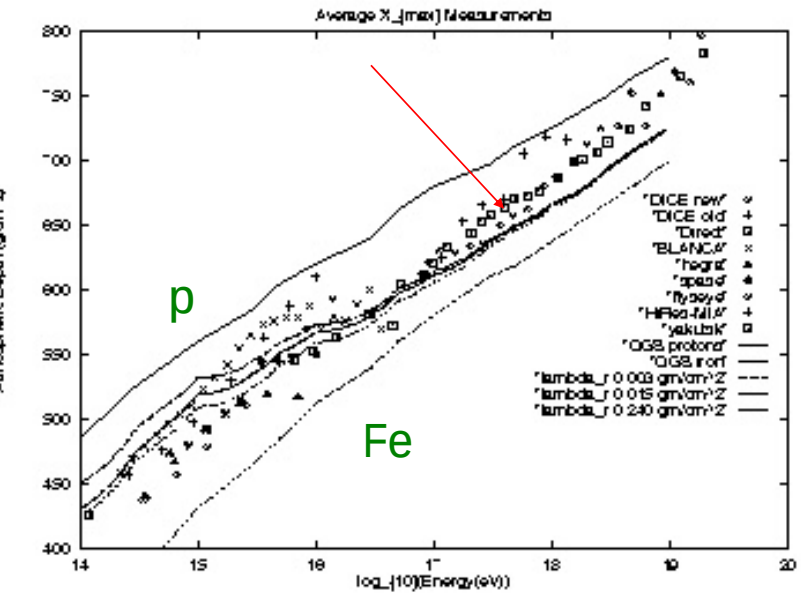
Nuclear Composition



Extensive Air Shower development profile

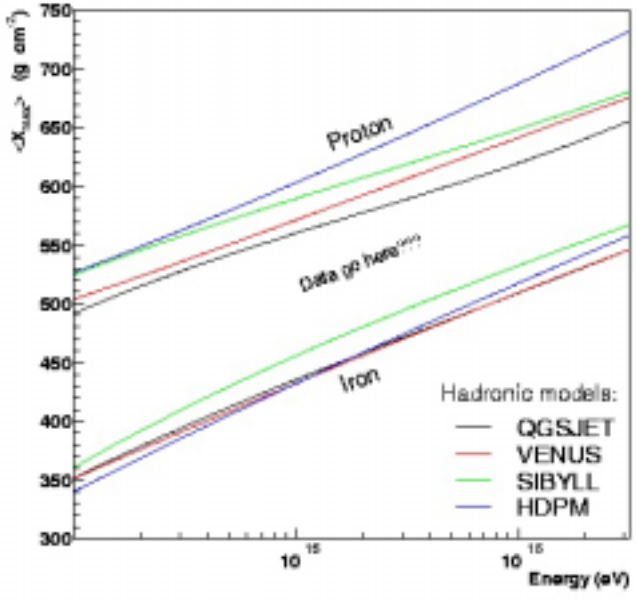
-depth of shower maximum-> primary mass

Nuclear Composition



- Mixed Composition
- Insufficient resolution to examine propagation effects
- New CR source appears above the knee

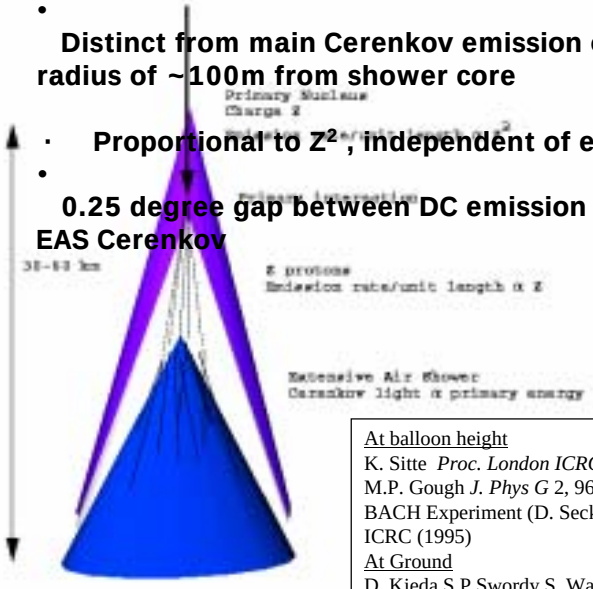
Ground Based Systematics



- **Poor Charge/Energy Resolution**
  Only coarsest origin features barely discernable
- **Energy Dependence of Composition Parameter**
  Error in energy -> error in charge measurement
- **Interaction Model Dependency**
  Clouds any astrophysical interpretations

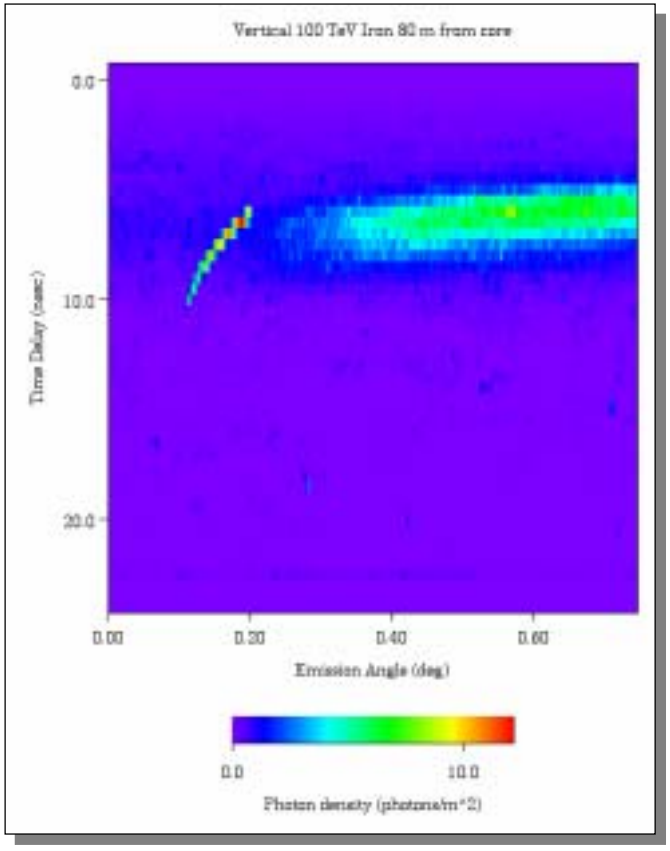
Direct Cherenkov Light

- Emitted before primary CR nuclear interaction
- Narrow angle emission (0.25 degree), distinct from main EAS Cerenkov
- Light arrives 3-6 nsec late compared to main EAS Cerenkov
- Distinct from main Cerenkov emission out to radius of ~100m from shower core
- Proportional to Z^2, independent of energy
- 0.25 degree gap between DC emission and main EAS Cerenkov

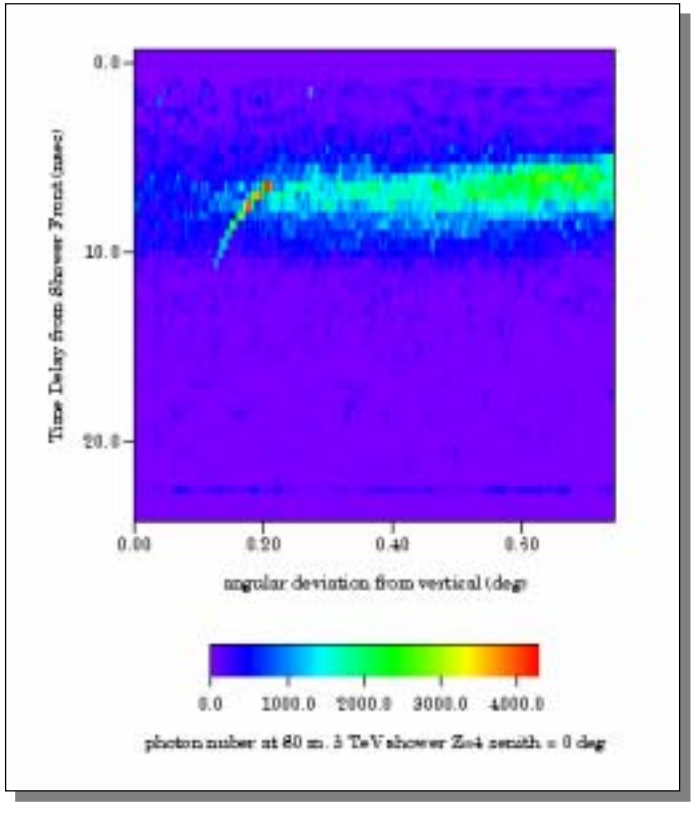


At balloon height
K. Sitte *Proc. London ICRC* (1965)
M.P. Gough *J. Phys G* 2, 965 (1976)
BACH Experiment (D. Seckel et al) Rome ICRC (1995)
At Ground
D. Kieda,S.P Swordy,S. Wakely *Ap.Phys* (2000)

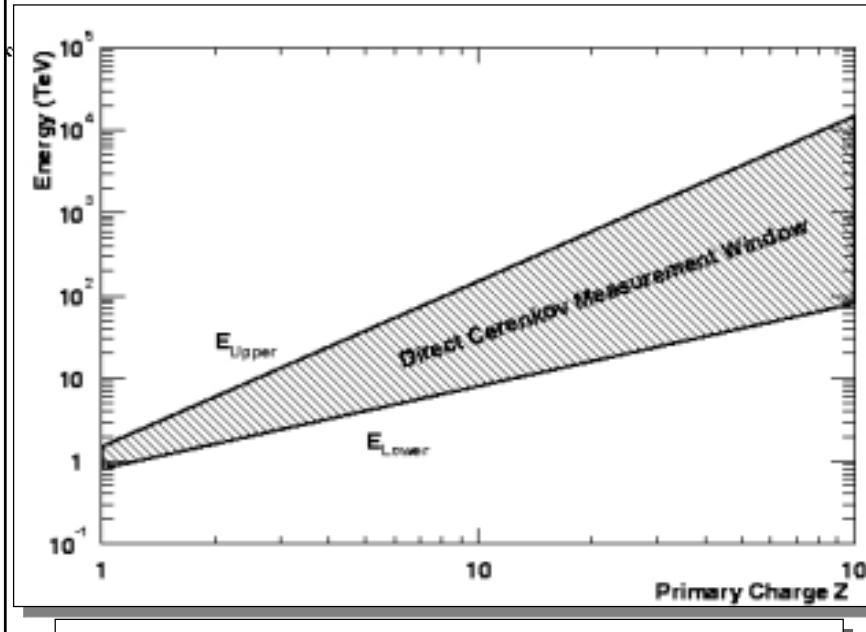
100 TeV Z=26 Vertical



5 TeV Z=4 Vertical

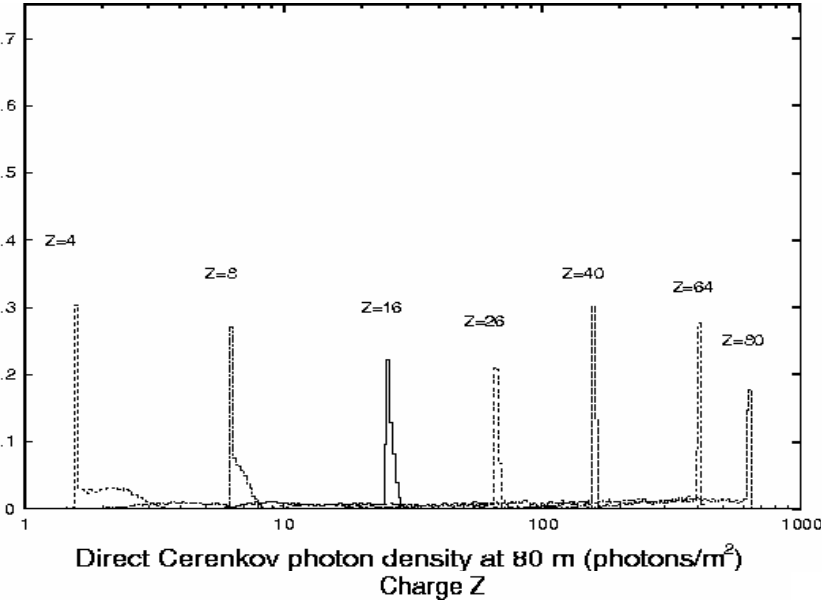


DC Light Emission Threshold



- Lower limit set by Minimum Lorentz factor
- Maximum Energy set by Obscuration by Secondary Cherenkov light
- Measurement window expands with increasing Z

Expected Charge Resolution



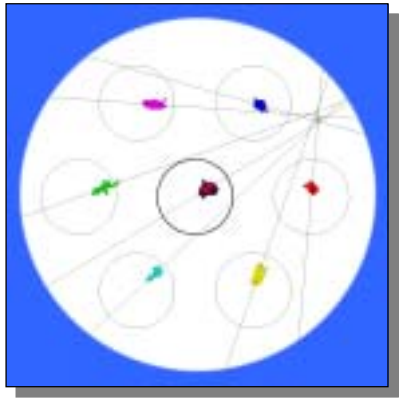
Factors:

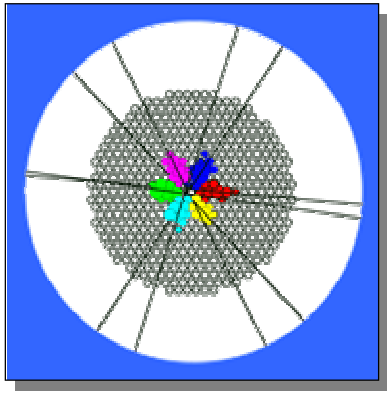
Core Location Error
Secondary Cerenkov Light
First Interaction Fluctuations
Mie/Rayleigh Scattering
Angular Trajectory Error
Night Sky Background
Photostatistics

Existing IACT Array Data

7 Telescope Array (ICRR)

HEGRA Telescopes (Max Planck)





7 Telescope Array Data

Pixel size approaches resolution to posses sensitivity to DC light : (0.25 degree)

Mirror area is small : ~ 10 sq m

Stereo Reconstruction : available

Best chance for success:

Look for Iron nuclei or heavier
Direct Cherenkov Threshold > 10 TeV

Selection criteria:

- **Two or more telescopes**
- **Core distance to each telescope different**
- **Core distance to each telescope 50-120 m**
- **High energy showers (E > 10 TeV)**
- **DC light pixel has large excess (> 2 σ) in geometry predicted location**
- **DC light pixel has gap to main (secondary) Cherenkov light from EAS**
- **Ratio of light at two core distances consistent with expectations from Monte Carlo Simulation**

7 Telescope Array Data

~1000 hours stereo Data :
Reconstruct Core position, direction from stereo imaging

Simple Cuts:

a) 40 m < Core < 150 m

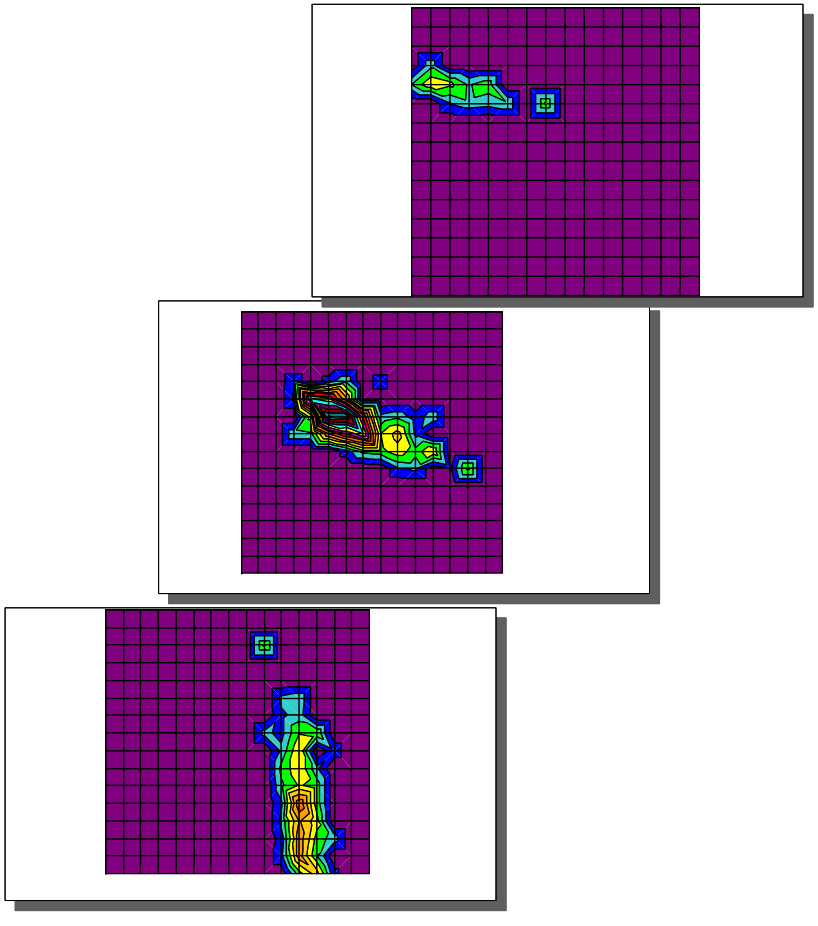
b) 1 pixel with > 70 photons
& surrounding pixels < 20 photons
or
2 adjacent pixel sum > 70 photons
& surrounding pixels < 20 photons each

c) More than 10 pixels/telescope over 10 photons/pixel

d) More than 2 telescopes in event

Cuts 60,000 stereo events -> 10 events
Have not yet exploited additional DC light geometrical constraints

Selected Telescope Array Images



IACT Detection rate

Typical IACT aperture:

1) Require shower to hit within 2° telescope axis
   -> 10^{-3} sr
2) Require core to hit between 60-120 m from central telescope: 8400 m^2
3) 800 hours operation/year
4) Flux of Iron > 20 TeV ~ 1/m^2/day

-> typical IACT telescope array
(VERITAS, HESS, CANGAROOO)
will detect 0.012 iron/hour
or
~ 10 high resolution iron nuclei/year in stereo mode

(Factor of 2x more if telescope pairs point in different directions).

High Resolution Charge Measurements: UH nuclear fluxes

- UH nuclei : r, s in SN Nucleosynthesis
- SNR accelerates swept-up ISM material in vicinity of SNR (concentrated strongly in OB associations)
- Common spectral features between UH nuclei and light nuclei?

  Common Acceleration process?
- UH nuclei inherently fragile (compared to Fe).

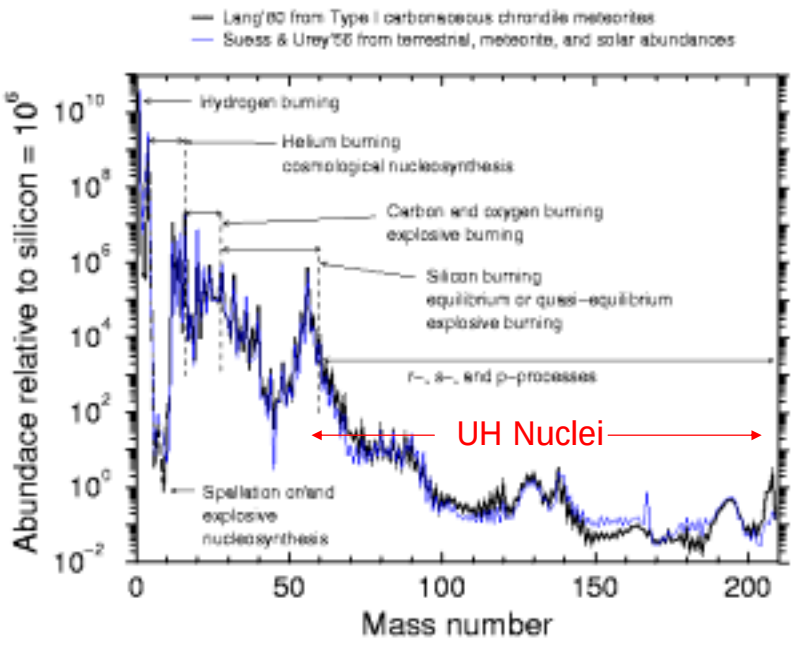
  Can UH nuclei survive the acceleration process?
- Fe to UH ratio probes acceleration process

  short ,fast (superbubbles of multiple SNRs).

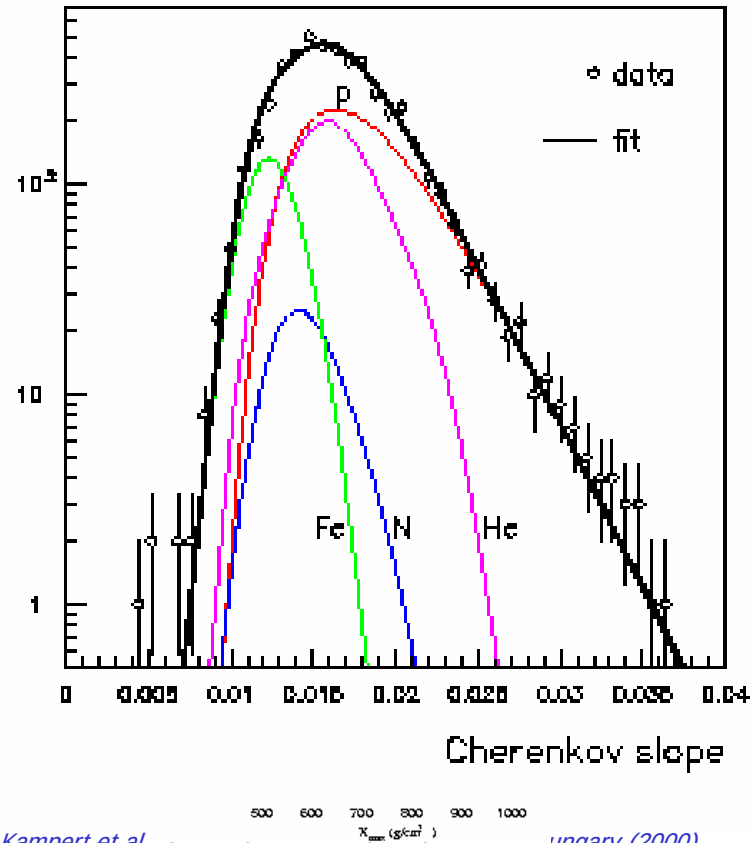
  long,slow (isolated SNR expansion into ISM)
- Probe of acceleration region environment

  photodissociate UH nuclei but not light nuclei

UH nuclear fluxes

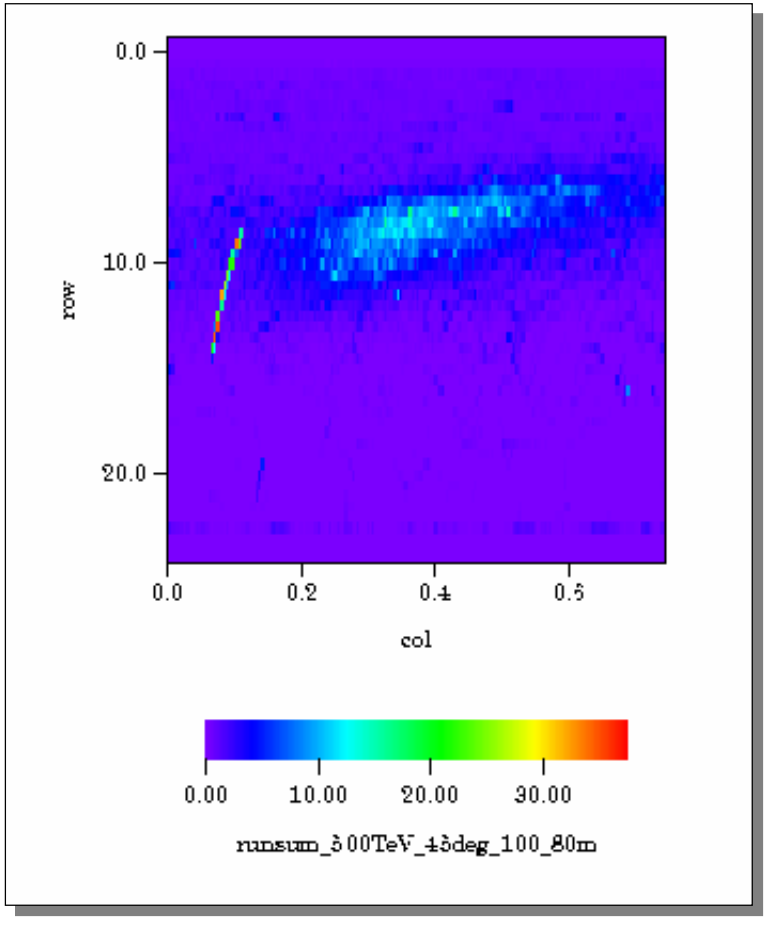


PeV UH nuclear measurements



Kampert et al.
Fowler et al. Ap. Phys 15, 49 (2001)
T. Abu-Zayyad et al. PRL 84,4276(1999)
ungary (2000)

500 TeV Z=100 45 degree zenith



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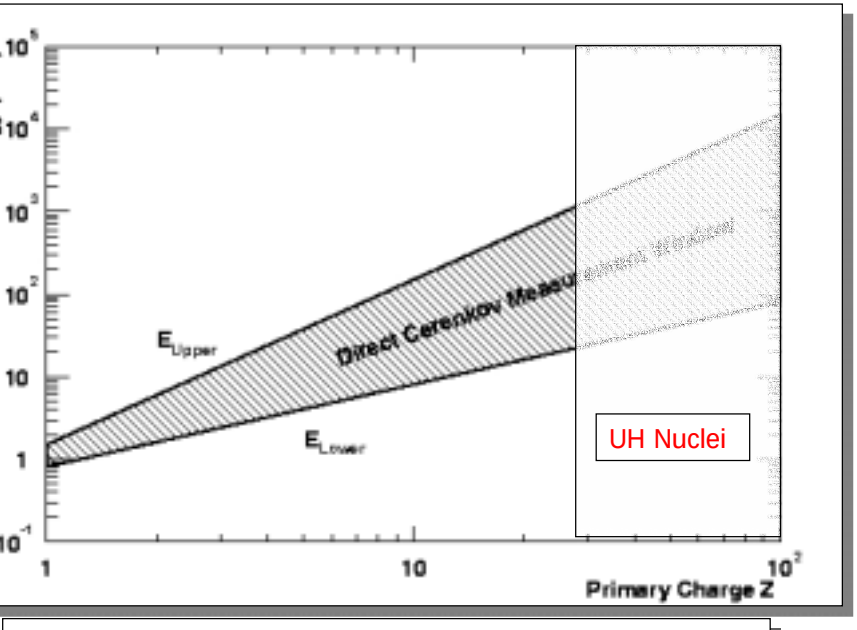
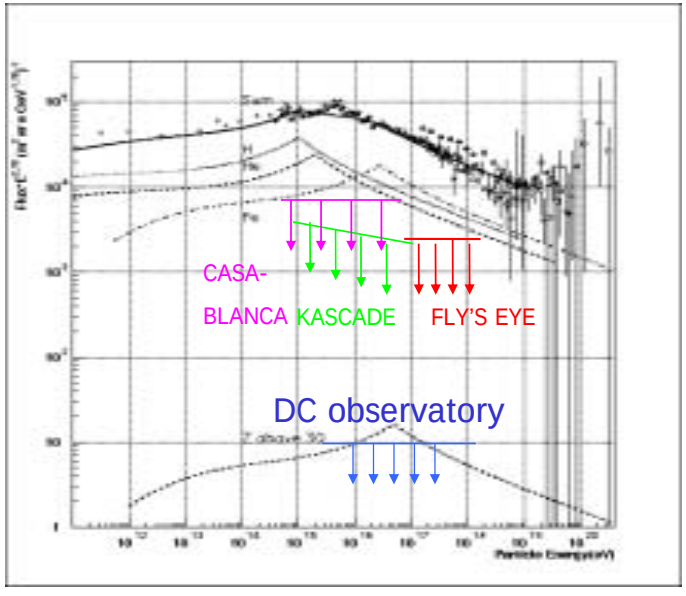


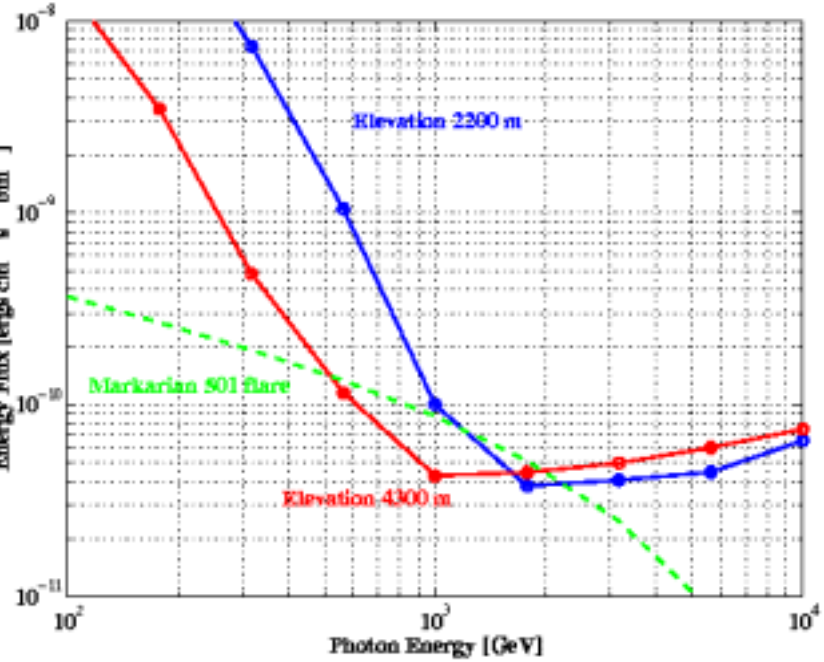
- Low flux of PeV UH nuclei requires extremely large detection area (>20,000 m^2 sr)
- Impossible for satellite/balloon (<100 m^2 sr)
- Only ground based, wide FOV instrument has sufficient aperture

Schematic DC Observatory



-
- Wide Field of View : 45-60 degree
- Multiple stations separated by ~80 m spacing
  - Detect several 1000 Fe/year at knee with 5% charge resolution
  - Detect several UH/year around 1 PeV with 5% charge resolution
  - Wide FOV TeV transient γ–ray monitor
  - Measure Nuclear/Particle Interactions with tagged Z cosmic beam

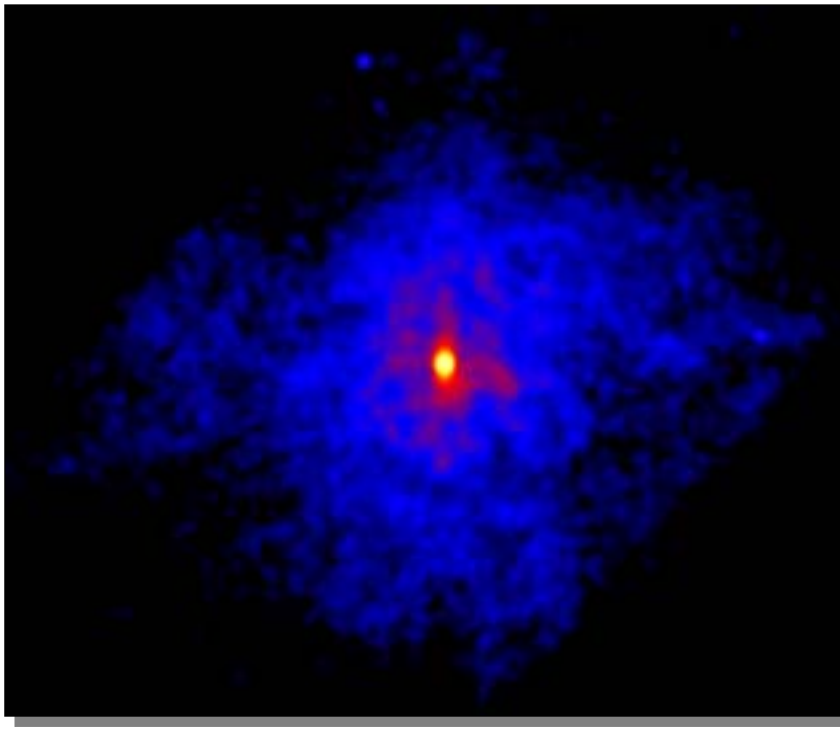
All Sky γ-Ray Monitoring (3m diameter prototype)



CPAX Proposal (NSF 2002) Center for Particle Physics

Emphasize development of next generation HE Ap. Observatories

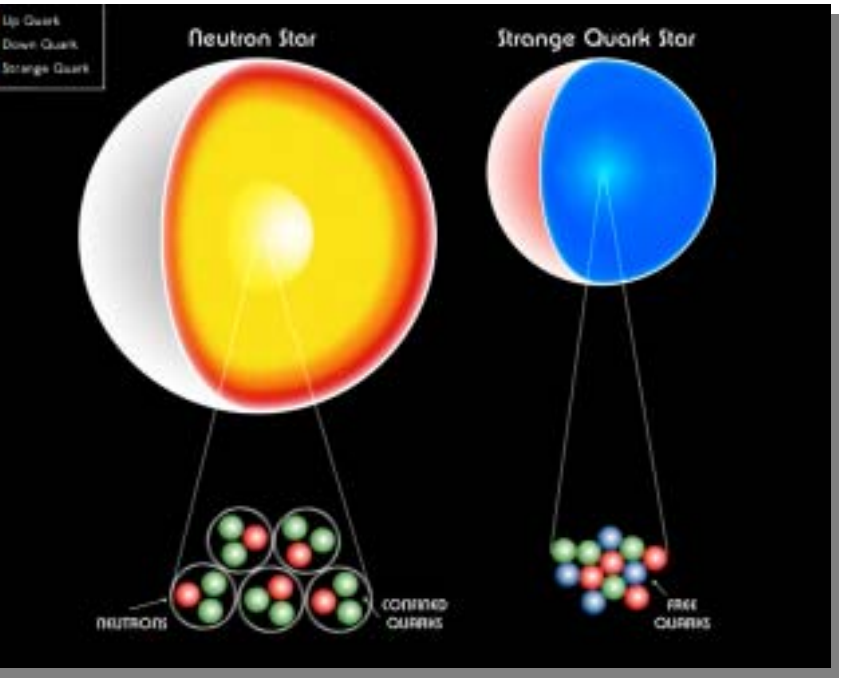
Quark Matter Stars: A new Form of Matter?



Chandra X-ray Image of RXJ1856.5-3754

Is RXJ1856.5-3754 a Quark Star? (Drake et al, AP. J 2002) astro-ph/0204159

Quark Matter Stars: A new Form of Matter?



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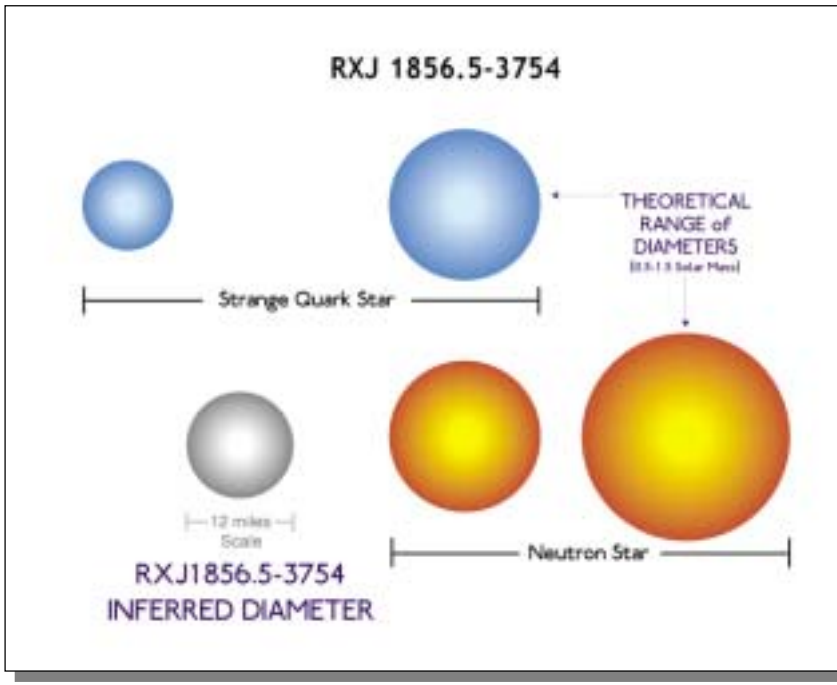
Quark Matter Stars: A new Form of Matter?



Is RXJ1856.5-3754 a Quark Star? (Drake et al, AP. J 2002) astro-ph/0204159

Kashiwa Gamma Ray 28 September 2002 David Kieda, Utah

Summary

- **Cosmic Ray Origin Signatures**
  - **At Source: Particle acceleration observed**
    - **Lepton acceleration certainly present**
    - **Hadronic acceleration controversial**
  - **At Earth: Definitive conclusions are limited by experimental sensitivity, resolution**
- **Next Generation Gamma Instruments**
  - **Probe origin at Source (with radio, x-Ray)**
  - **New Potential for High resolution charge measurement at Earth**
  - **Explore nuclear/particle fragmentation, cross sections with tagged nuclear beam**
  - **Electron/Proton rejection (17m+ mirror)**
- **Future Dedicated Wide FOV Observatory**
  - **Unknown PeV UH nuclei (Z > 30) flux**
  - **Common origin/acceleration with lighter nuclei?**
  - **Can UH nuclei survive acceleration speed/environment?**
  - **All sky gamma monitor for episodic TeV flares/GRBs**
  - **Probe existence of unusual charge states in Cosmic Ray Flux**