OVERVIEW OF LABORATORY ASTROPHYSICS

Pisin Chen
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Stanford University

- Introduction
- Calibration of Observations
- Investigation of Dynamics
- Probing Fundamental Physics
- Summary

SABER Workshop
March 15-16, 2006, SLAC

National Research Council Turner Committee:

Connecting Quarks with the Cosmos: Eleven Science Questions for the New Century

Laboratory Astrophysics can address several of these basic questions

- How do cosmic accelerators work and what are they accelerating?
- Are there new states of matter at exceedingly high density and temperature?
- Are there additional space-time dimensions?
- Did Einstein have the last word on gravity?
- Is a new theory of matter and light needed at highest energies?

One of the seven recommendations made by the Turner Committee:

Recommendation On Exploring Physics Under Extreme Conditions In The Laboratory

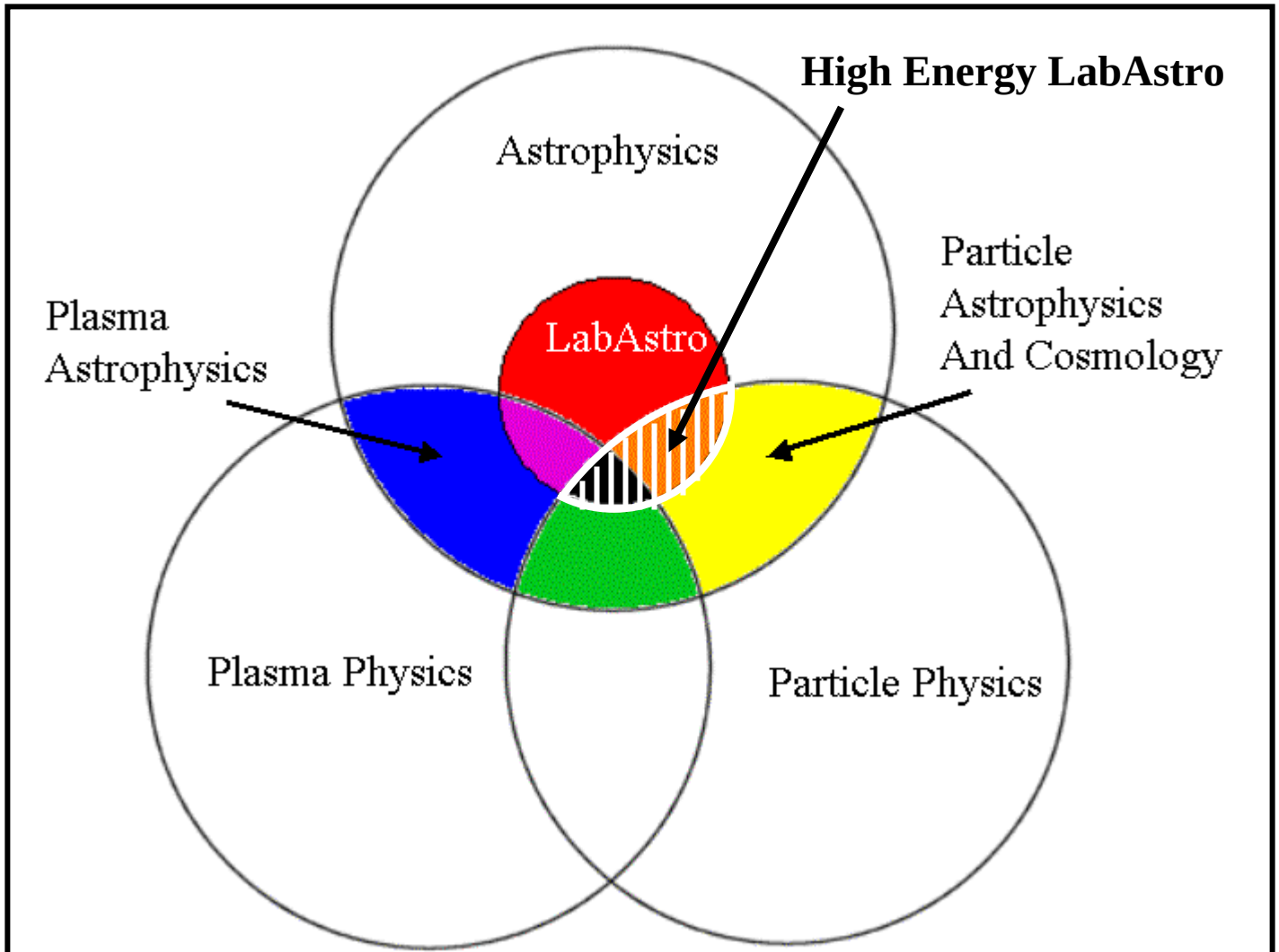
"Discern the physical principles that govern extreme astrophysical environments through the laboratory study of high enrgy-density physics. The Committee recommends that the agencies cooperate in bringing together the different scientific communities that can foster this rapidly developing field."

Connection to Extreme Astrophysical Conditions

- Extremely high energy events, such as ultra high energy cosmic rays (UHECR), neutrinos, and gamma rays
- Very high density, high pressure, and high temperature processes, such as supernova explosions and gamma ray bursts (GRB)
- Super strong field environments, such as that around black holes (BH) and neutron stars (NS)

NRC Davidson Committee Report (2003) "**Frontiers in High Energy Density Physics**" states:
"Detailed understanding of acceleration and propagation of the highest-energy particles ever observed demands a coordinated effort from plasma physics, particle physics and astrophysics communities"

LABORATORY ASTROPHYSICS



P. Chen, *AAPPS Bull.* 13, 3 (2003).

Three Categories of LabAstro

-Using Lasers and Particle Beams as Tools -

1. Calibration of observations

- Precision measurements to calibrate observation processes
- Development of novel approaches to astro-experimentation

→ *Impact on astrophysics is most direct*

2. Investigation of dynamics

- Experiments can model environments not previously accessible in terrestrial conditions
- Many magneto-hydrodynamic and plasma processes scalable by extrapolation

→ *Value lies in validation of astrophysical models*

3. Probing fundamental physics

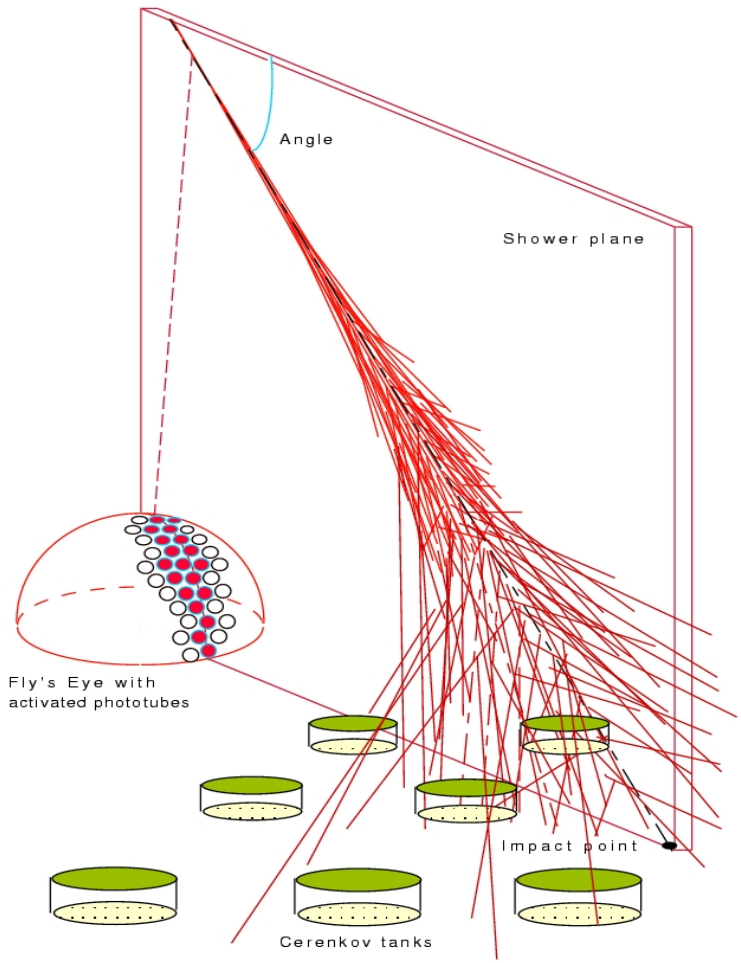
- Surprisingly, issues like quantum gravity, large extra dimensions, and spacetime granularities can be investigated through creative approaches using high intensity/density beams

→ *Potential returns to science are most significant*

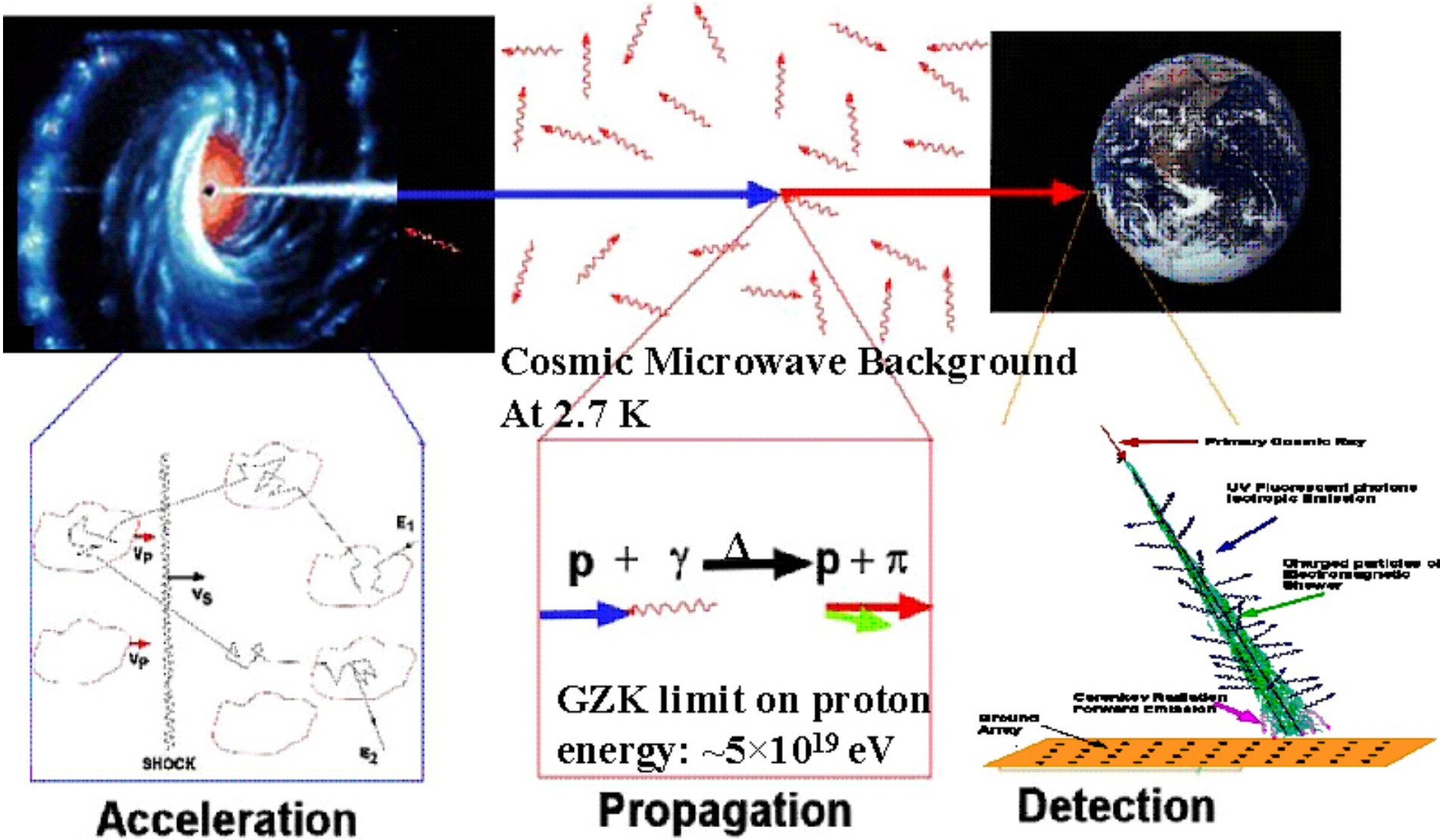
1. Calibration of Observations

1. Fluorescence from UHECR Induced Showers

- Two methods of detec-
  tion: Fly's eye (HiRes)
  & ground array(AGASA)
- Next generation UHECR
  detector *Pierre Auger* invokes
  hybrid detections
- Future space-based
  observatories use fluorescence
  detection



UHECR: Production and Detection



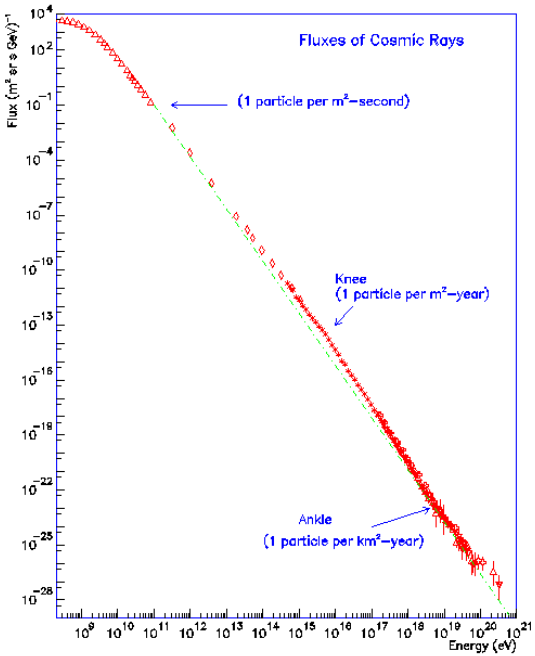
SLAC E-165 Experiment: *Fl*uorescence from *A*ir in *Sh*owers (FLASH)

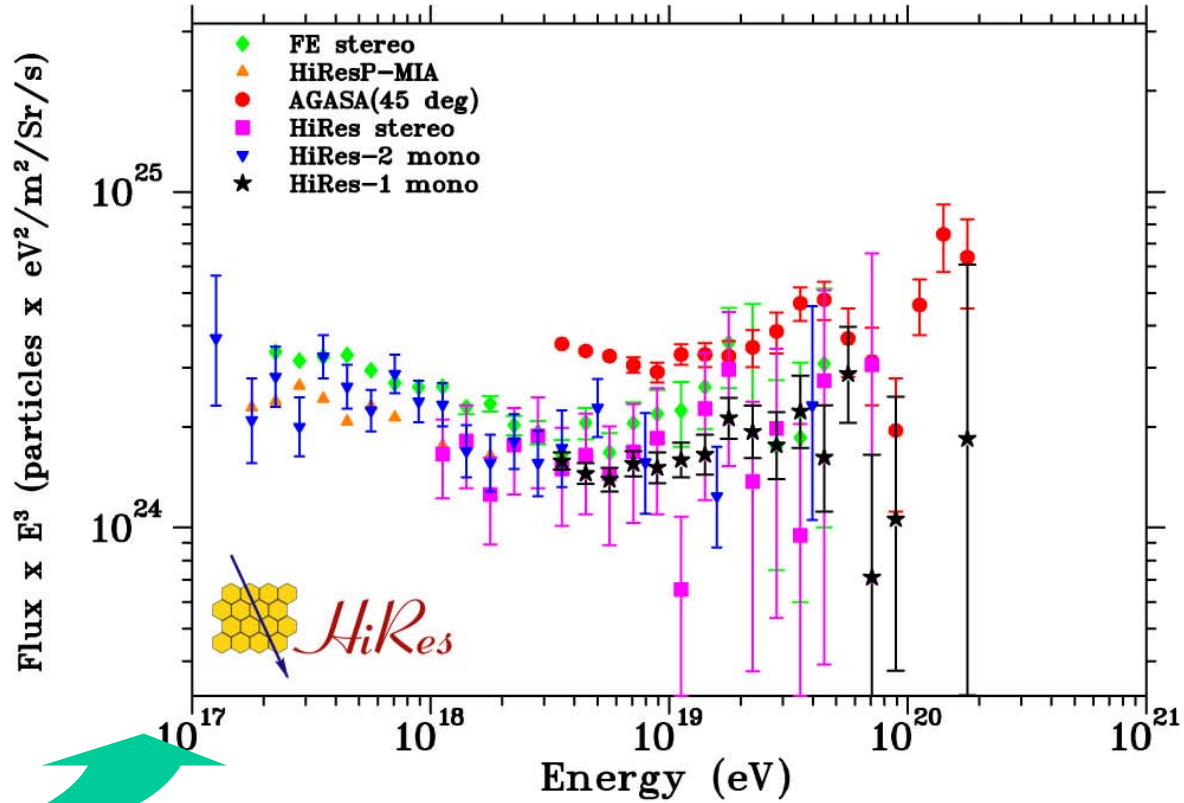
J. Belz[1], Z. Cao[2], F.Y. Chang[4], P. Chen[3*], C.C. Chen[4], C.W. Chen[4], C. Field[3], P. Huentemeyer[2], W-Y. P. Hwang[4], R. Iverson[3], C.C.H. Jui[2], G.-L. Lin[4], E.C. Loh[2], K. Martens[2], J.N. Matthews[2], J.S.T. Ng[3], A. Odian[3], K. Reil[3], J.D. Smith[2], P. Sokolsky[2*], R.W. Springer[2], S.B. Thomas[2], G.B. Thomson[5], D. Walz[3]

[1]University of Montana, Missoula, Montana
[2]University of Utah, Salt Lake City, Utah
[3]Stanford Linear Accelerator Center, Stanford University, CA
[4]Center for Cosmology and Particle Astrophysics (CosPA), Taiwan
[5]Rutgers University, Piscataway, New Jersey

* Collaboration Spokespersons

Motivation for FLASH





- Experiment designed to help resolve discrepancy between measured flux of ultra high energy cosmic rays (UHECR).
- Energy scale of fluorescence technique based upon fluorescence yield (number of photons produced per meter per charged shower particle.
- Provide a precision measurement of the yield.

FLASH Motivation

- At large distances of up to **30 km**, which are typical of the highest energy events seen in a fluorescence detector, knowing the **spectral distribution** of the emitted light becomes essential due to the λ^{-4} attenuation from **Rayleigh scattering**.

Bunner (1967)

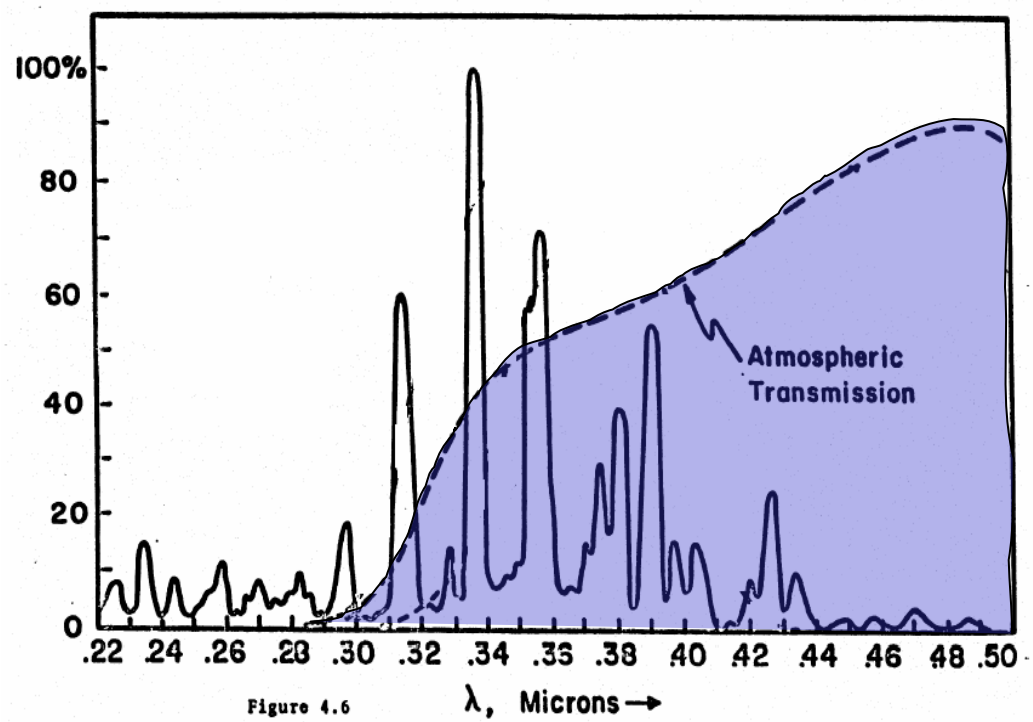


Figure 4.6

Fluorescence in Air from Showers (FLASH)

HiRes-SLAC-CosPA (Taiwan) collaboration

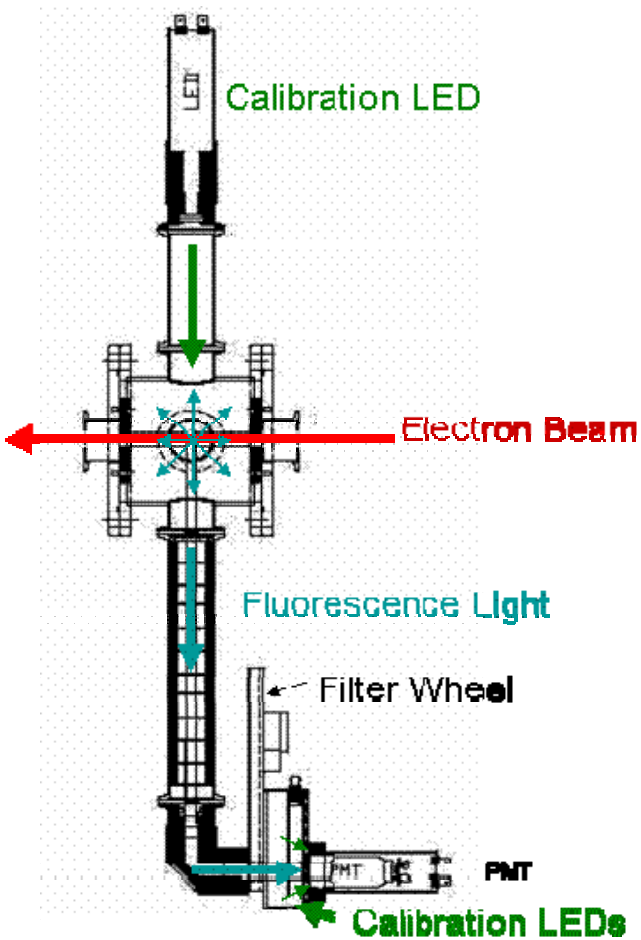
- Spectrally resolved air fluorescence yield in an electromagnetic shower
- Energy dependence of the yield down to ~100 keV
- Aim to help resolve apparent differences between HiRes and AGASA observations

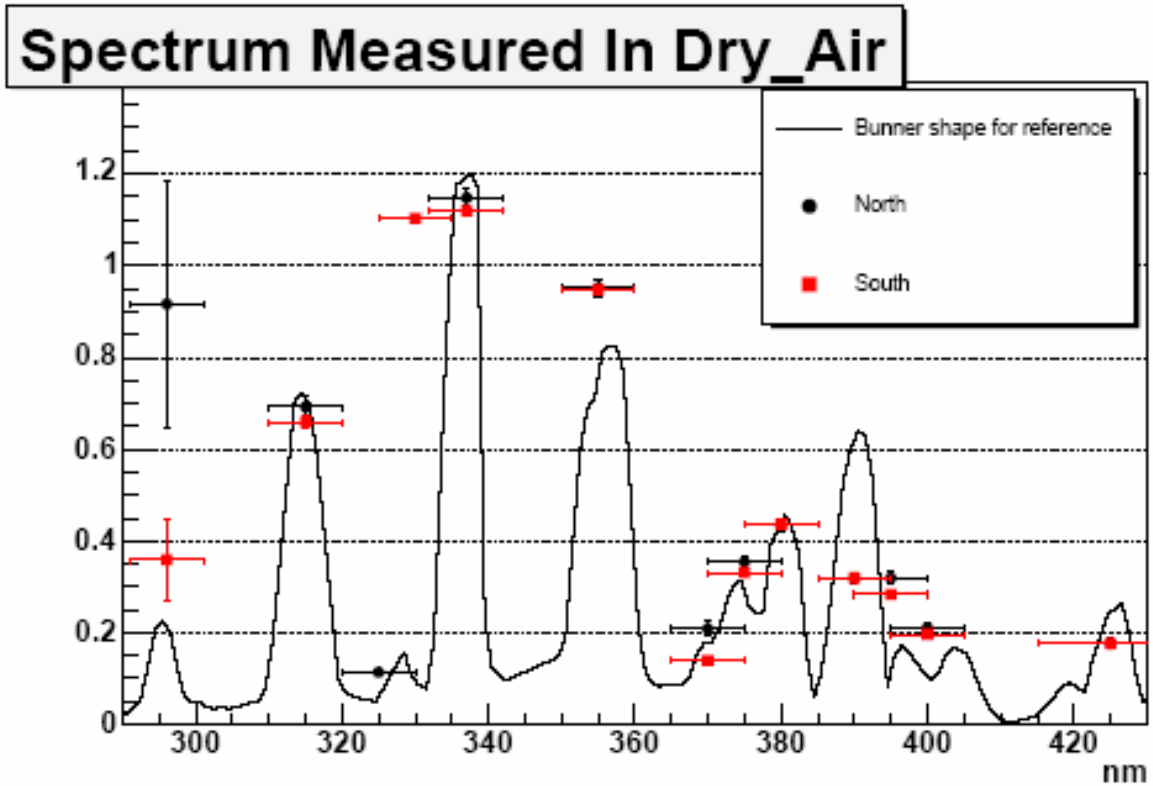
- SLAC E-165 (FLASH) Experiment (2002-2004):

-Two-stage: Thin target and Thick target

-28.5 GeV electrons, 10^7 to 10^9 particles per bunch

FLASH: Thin Target

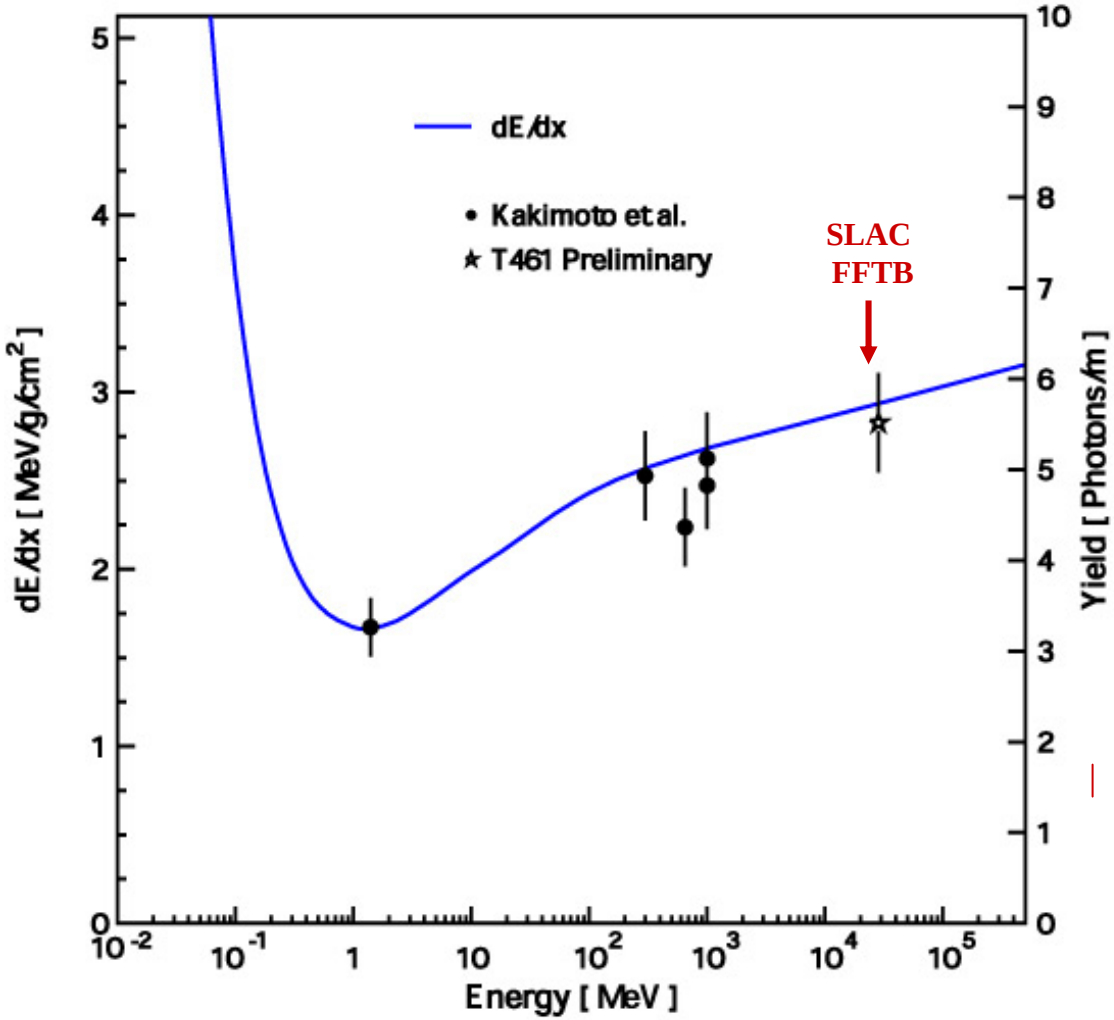




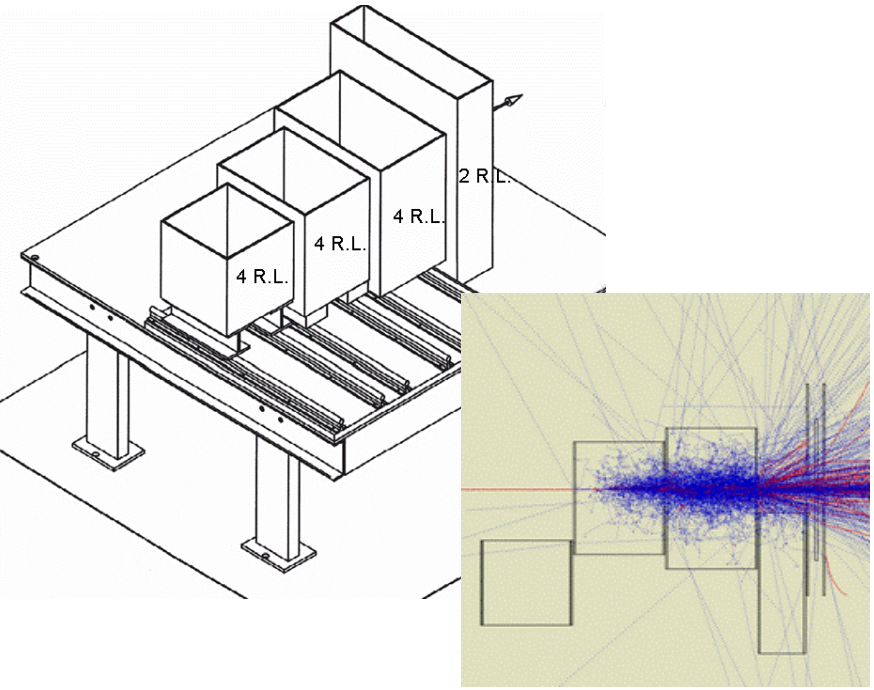
- Precision total yield measurement.
- Spectral measurement made using narrow band filters.

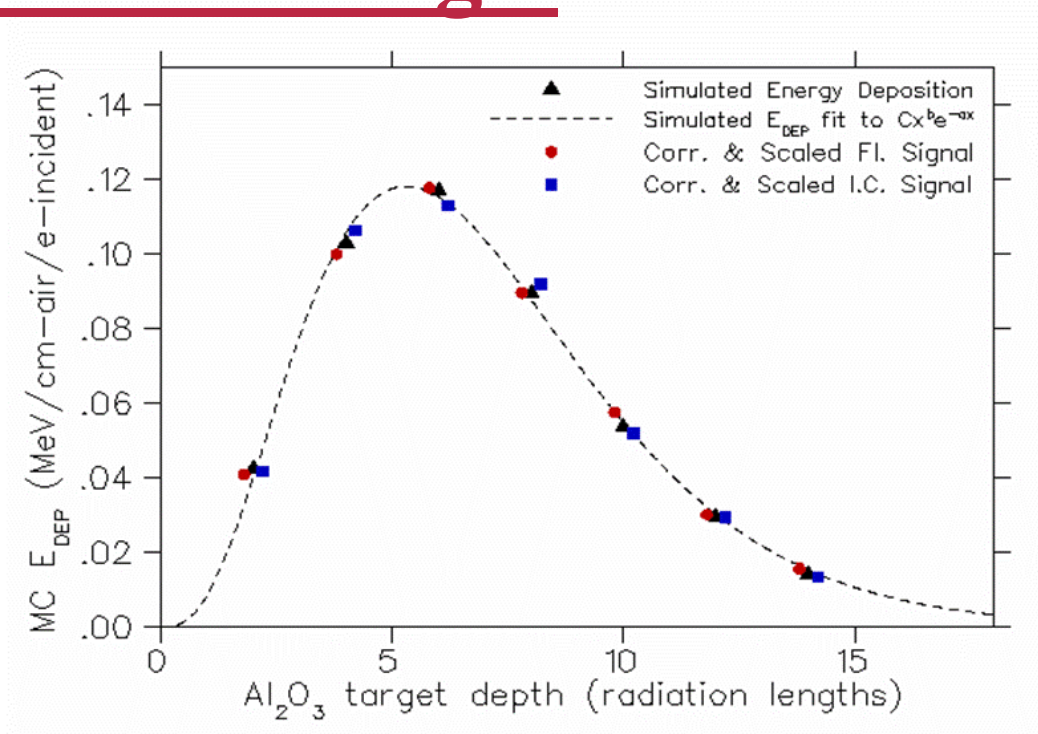
→ Only small corrections to current understanding. Fluorescence technique seems to be built on stable ground!

Air Fluorescence Yield



FLASH: Thick Target





- Electron beam showered with varying shower depths.
- Particle and photon count measured at each shower depth.

➡ Confirm long standing assumption that the total fluorescence light in air-shower is proportional to number of cascade charged particles.

FLASH: Status and Prospects

❖ Publications

- June 2002 data: total yield, pressure dependence, effect of impurity.
  - ➢ J. Belz et al., Astropart. Phys. (2006); astro-ph/0506741
- Thin-target (2003 and 2004 data): precision spectrally resolved yield measurements; humidity dependence.
  - ➢ K. Reil et al., SLAC-PUB-11068, Dec. 2004; Proc of 22nd Texas Symposium, Dec. 2004.
- Thick-target (2004 data): fluorescence and charged particle yields as a function of shower depth and comparison with shower Monte Carlo simulations.
  - ➢ J. Belz et al., Astropart. Phys. (2006); astro-ph/0510375

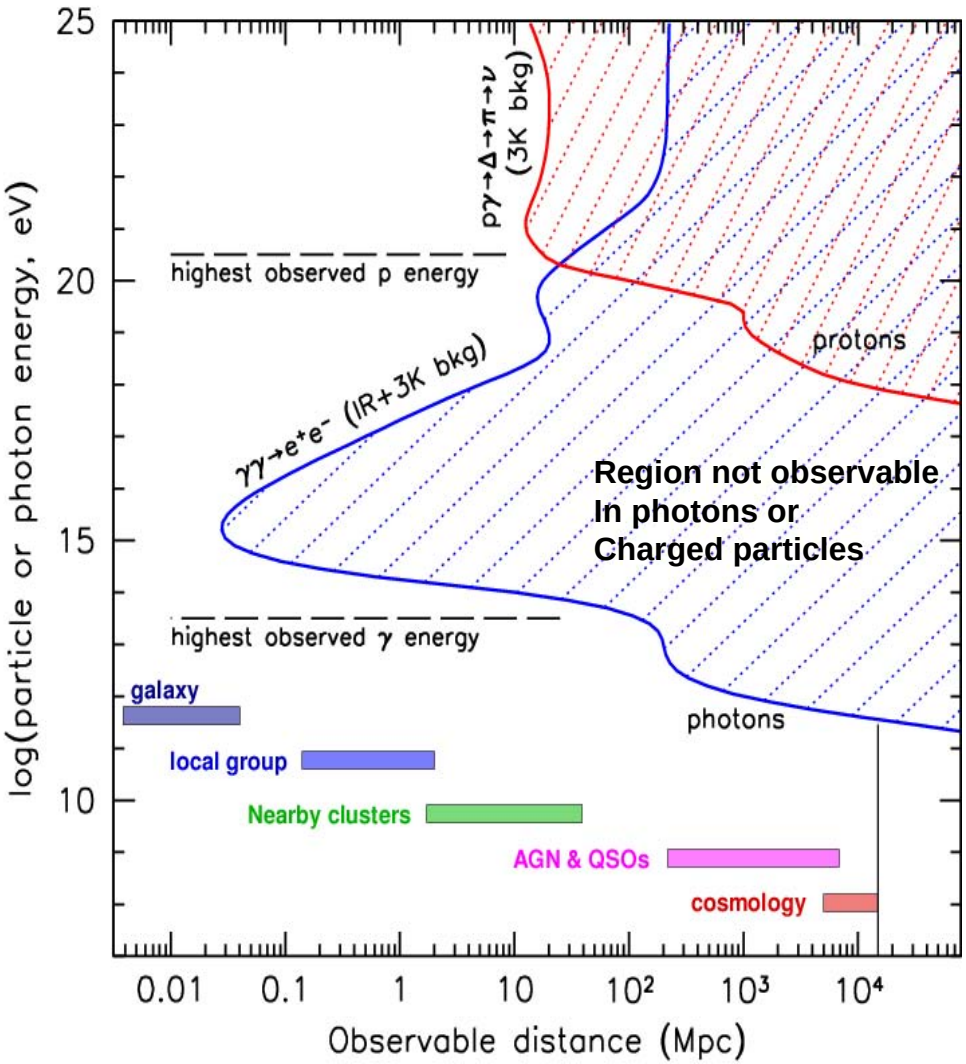
❖ Future Prospects

- – The collaboration is actively assessing whether a next run is needed, pending final outcome of on-going data analysis and publication efforts.

2. Exploring New Techniques for Cosmic Neutrino Detection

- Radio Detection of UHE EAS– **Askaryan effect** (1962)
- First observation at SLAC FFTB by Saltzberg, et al. **SLAC Exp. T444** D. Saltzberg, P.W. Gorham et al. Phys.Rev.Lett.86:2802-2805,2001.
- Search for neutrino interactions in Lunar surface using radio
- Antarctic Ice Experiment – RICE, ANITA
- Underground Saltdome Shower Array (SalSA) for super-GZK cosmic neutrino detection

Neutrinos: The only useful messengers for astrophysics at >PeV energies

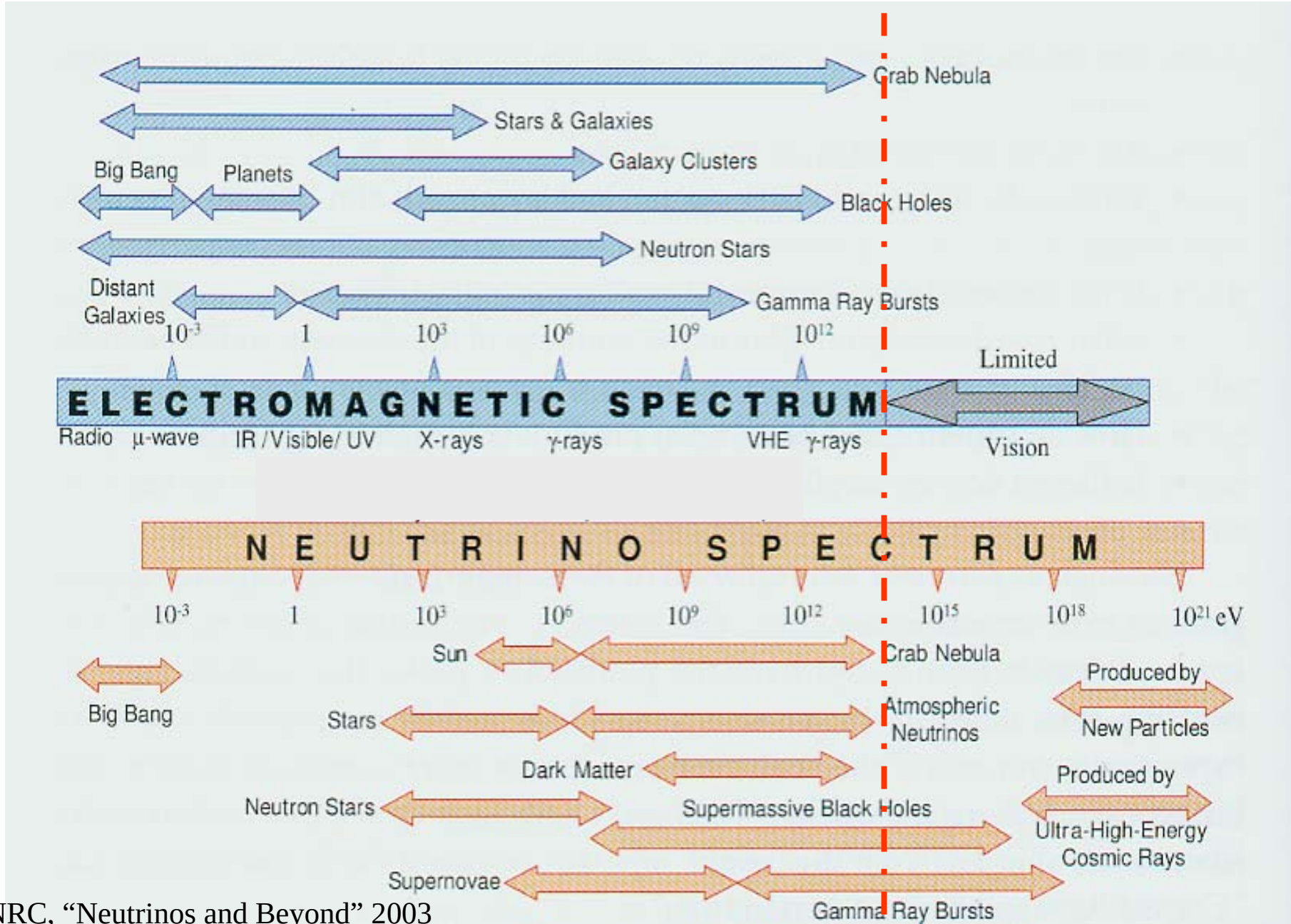


- **Photons lost above 30 TeV:** pair production on IR & μwave background
- **Charged particles:** scattered by B-fields or GZK process at all energies
- But the sources extend to 10^9 TeV !

Conclusion:

- **Study of the highest energy processes and particles throughout the universe *requires* PeV-ZeV neutrino detectors**

Comparison between Cosmic EM and Neutrino Spectrum



NRC, "Neutrinos and Beyond" 2003

UHECR: *"How do cosmic accelerators work and what are they accelerating?"*

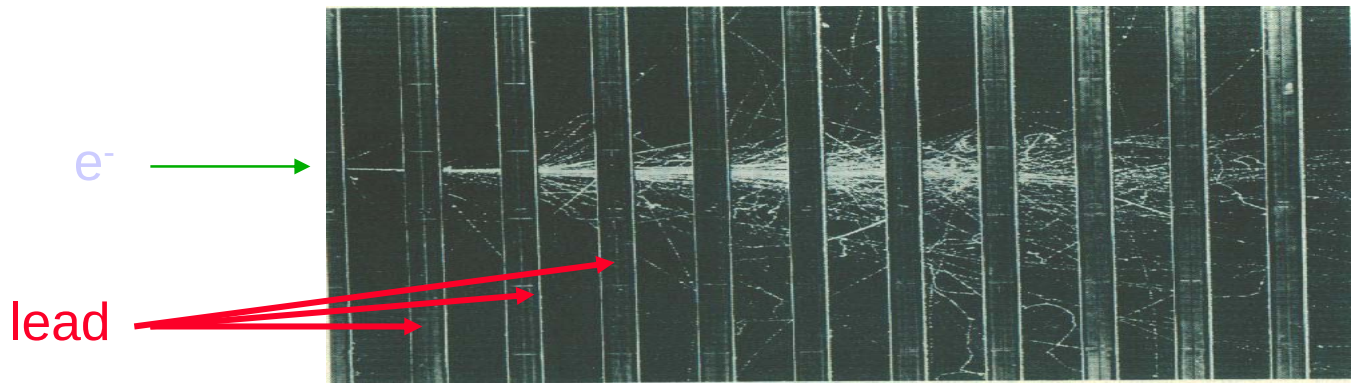
$$p + \gamma_{2.7K} \rightarrow \Delta^* \rightarrow n + \pi^{\pm}$$
$$\hookrightarrow \mu\nu$$
$$\hookrightarrow e\nu\nu$$

Every Neutrino points back to its source !

- UHECR: Top-down or bottom-up?
- If bottom-up, what accelerates the cosmic particles?
- Where are the sources?
- GZK neutrino spectrum and directions indispensable

The Askaryan Effect

UHE event will induce an e/γ shower:



In electron-gamma shower in matter, there will be ~20% more electrons than positrons.

Compton scattering: $\gamma + e^-_{(\text{at rest})} \rightarrow \gamma + e^-$

Positron annihilation: $e^+ + e^-_{(\text{at rest})} \rightarrow \gamma + \gamma$

$$\frac{dP_{CR}}{d\nu} \propto \nu d\nu$$

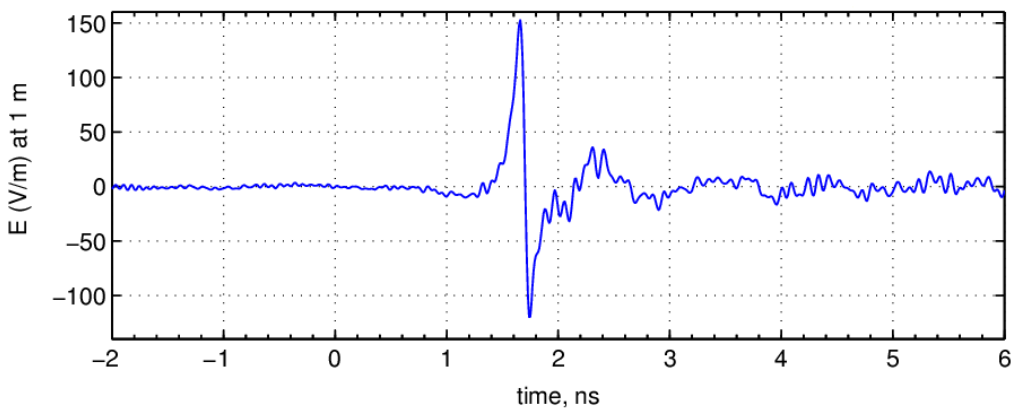
In solid material $R_{Moliere}$~ 10cm.

$\lambda >> R_{Moliere}$ (microwaves), <u>coherent</u>

$\Rightarrow$ **$P \propto N^2$**

SLAC Characterization of Askaryan Effect

Ultra-wideband data on Askaryan pulse



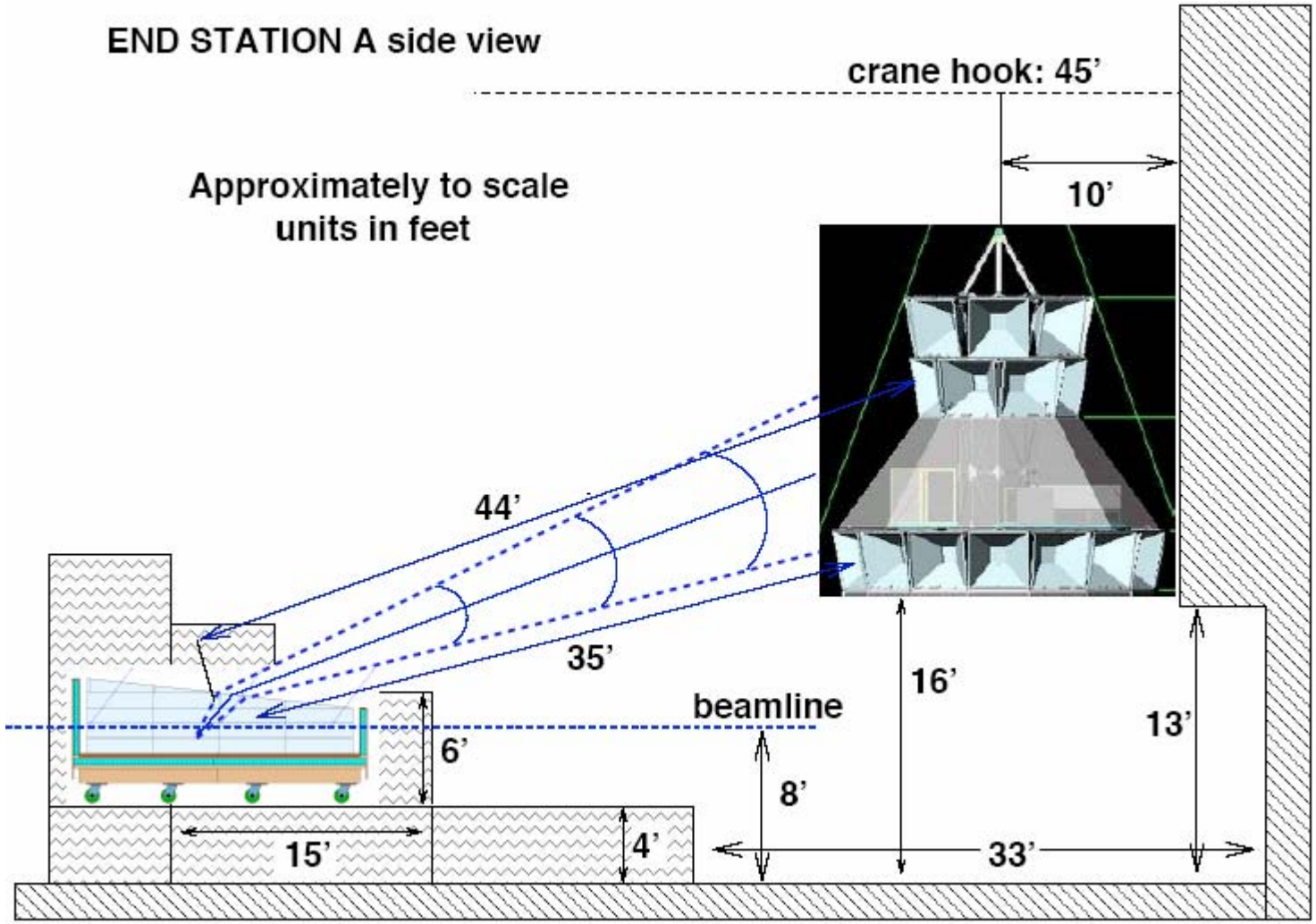
SLAC FFTB

- 2000 & 2002 SLAC Experiments confirm extreme coherence of Askaryan radio pulse
- 60 picosecond pulse widths measured for salt showers. Unique signal reduces background, simplifies triggering, excellent timing for reconstruction.

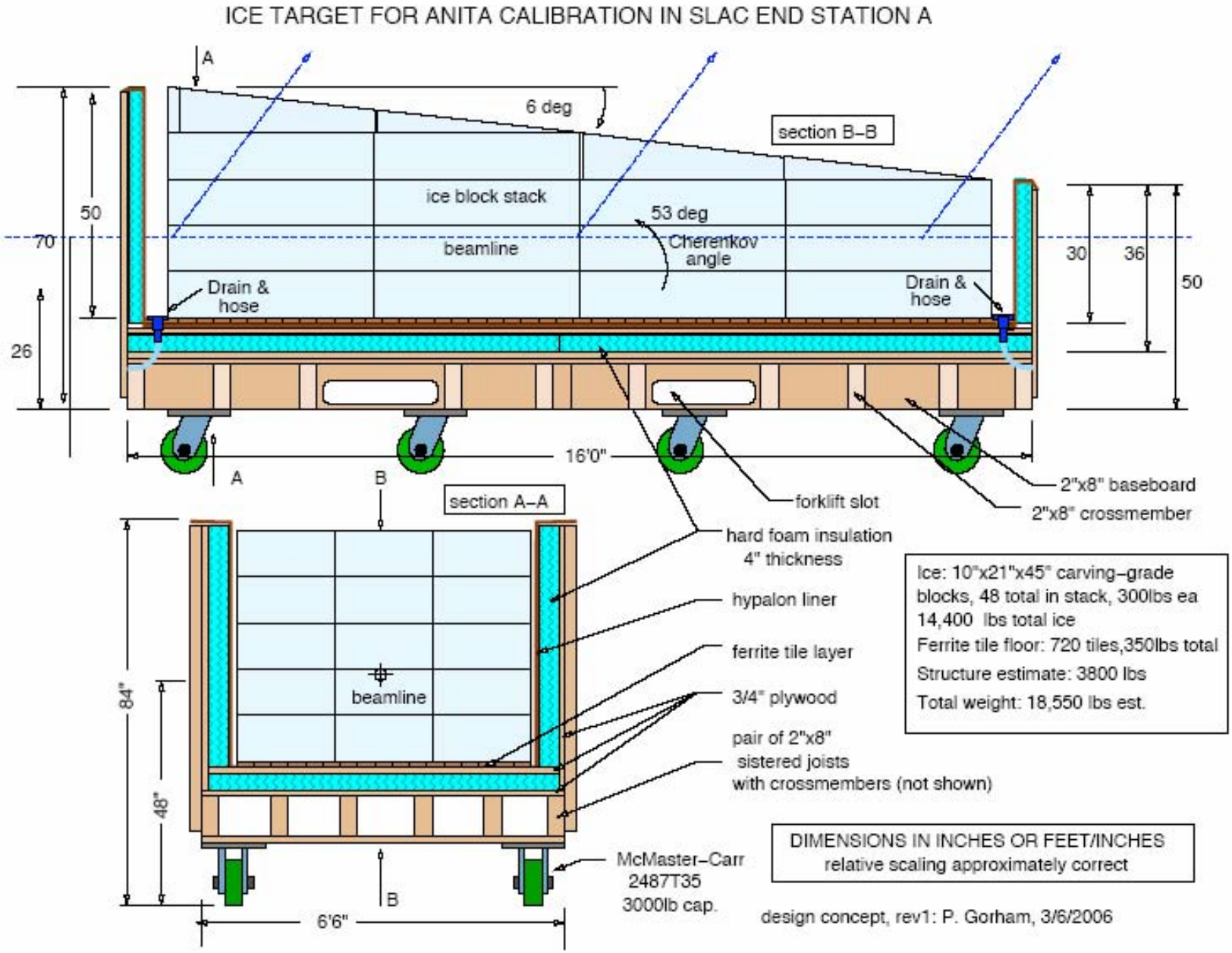
ANITA: Antarctic Neutrino Transient Antenna

ESTA: End Station Test of ANITA

SLAC-ANITA Collaboration Expected date: June 2006

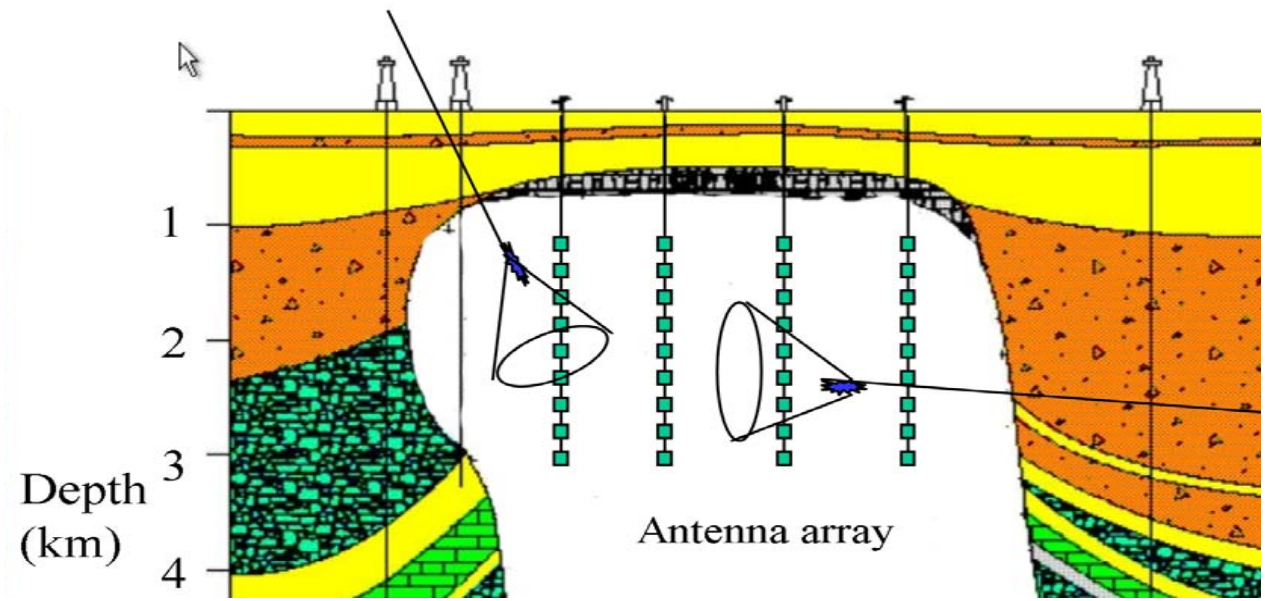


ESTA Ice Target



SalSA: Saltdome Shower Array

A large sample of GZK neutrinos using radio antennas in a 12x12 array of boreholes natural Salt Domes



SalSA sensitivity, 3 yrs live:

70-230 GZK neutrino events

2. Investigation of Dynamics

Length Scales

← *Compton Scale* — *Hydro Scale* →

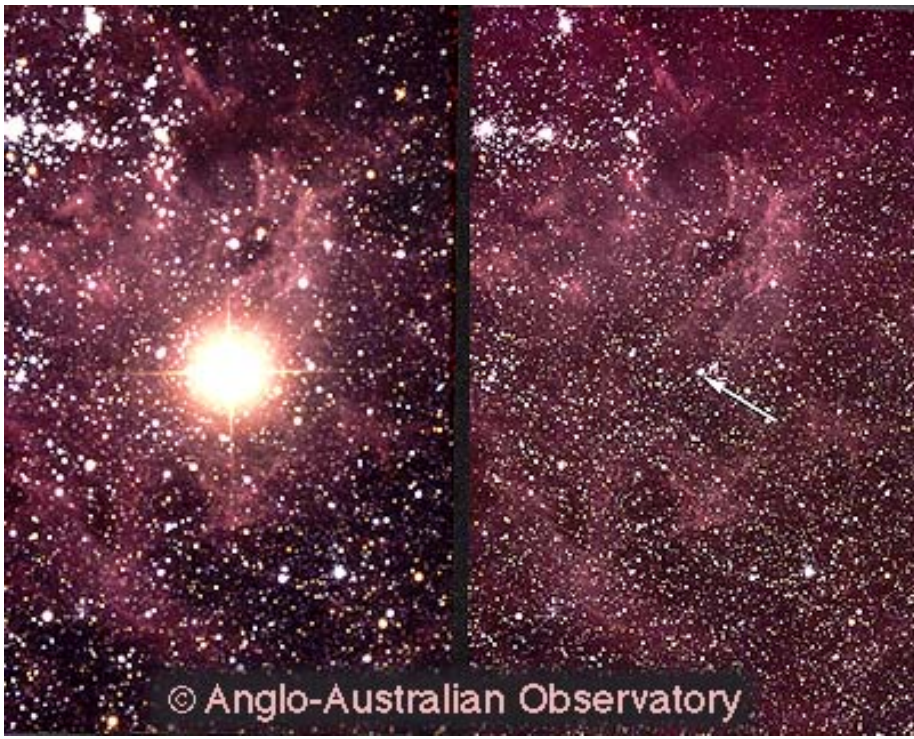
HEP — ***Plasma scale*** — **Shocks**

λ_D, λ_p, r_L

>> 14 orders of magnitude

Can intense neutrino winds drive collective and kinetic mechanisms at the *plasma scale* ?

Bingham, Bethe, Dawson, Su (1994)



Plasma Waves Driven by Different Sources

Equations for electron density perturbation driven by electron beam, photon beam, neutrino beam, and Alfven shocks are similar

Electron beam

$$\left(\partial_t^2 + \omega_{pe0}^2\right)\delta n_e = -\omega_{pe0}^2 n_{e-beam}$$

Photons

$$\left(\partial_t^2 + \omega_{pe0}^2\right)\delta n_e = \frac{\omega_{pe0}^2}{2m_e}\nabla^2 \int \frac{d\mathbf{k}}{(2\pi)^3}\hbar\frac{N_\gamma}{\omega_{\mathbf{k}}}$$

Neutrinos

$$(\partial_t^2 + \omega_{pe0}^2)\delta n_e = \frac{\sqrt{2}n_{e0}G_F}{m_e}\nabla^2 n_\nu$$

where δn_e is the perturbed electron plasma density

Bingham, Dawson, Bethe (1993): Application to NS explosion

Alfven Shocks

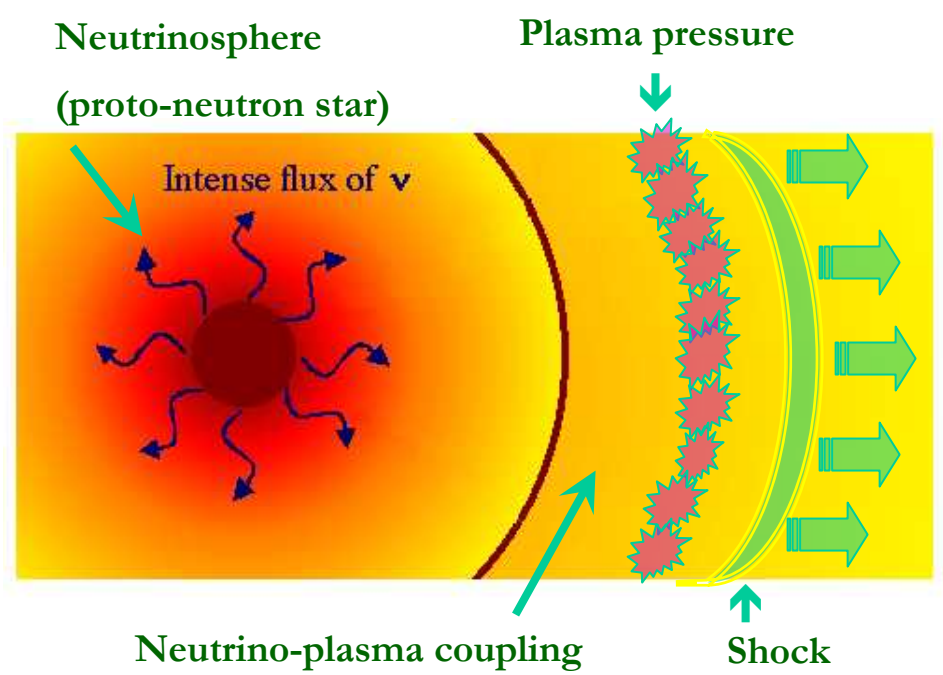
$$\left(\partial_t^2 + \omega_{pe0}^2\right)\delta n_e = \frac{A}{2m_e}\nabla^2 \int \frac{d\mathbf{k}}{(2\pi)^3}\frac{c^2k^2}{\omega_{\mathbf{k}}\,\omega_A}(E_A{}^2 + B_A{}^2)$$

All these processes can in principle occur in astro jets.

1. Supernova Electroweak Plasma Instability

- 99% of SN energy is carried by neutrinos from the core
- Single-particle dynamics unable to explain explosion
- ν-flux induced collective electroweak plasma instabilities load energy to plasma efficiently*

Use laser/*e*-beam to simulate ν- flux induced two-stream instability, Landau damping, and Weibel instability



* R. Bingham, J. M. Dawson, H. Bethe, Phys. Lett. A, 220, 107 (1996)
Phys. Rev. Lett., 88, 2703 (1999)

2. Cosmic Acceleration

- Conventional cosmic acceleration mechanisms encounter limitations:

  - Fermi acceleration (1949) (= stochastic accel. bouncing off B-fields)
  - Diffusive shock acceleration (70s) (a variant of Fermi mechanism)

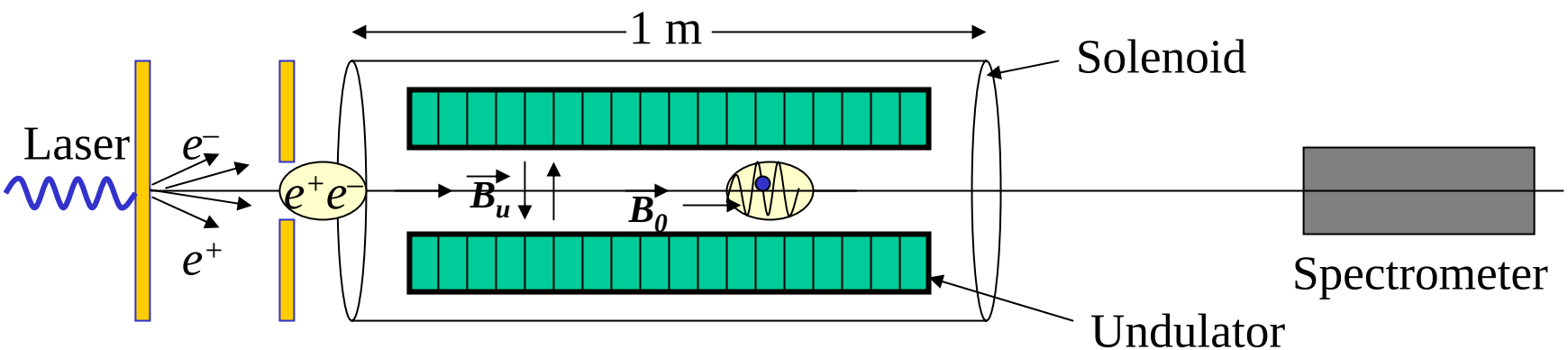
    Limitations for UHE: field strength, diffusive scattering inelastic
  - Eddington acceleration (= acceleration by photon pressure)

    Limitation: acceleration diminishes as $1/\gamma$
- New thinking:

  - Zevatron (= unipolar induction acceleration) (R. Blandford)
  - Alfven-wave induced wakefield acceleration in relativistic plasma (Chen, Tajima, Takahashi, Phys. Rev. Lett. 89 , 161101 (2002).)
  - Weibel instability-induced induction and wakefield acceleration (Ng and Noble, Phys. Rev. Lett., March 2006)
  - Additional ideas by M. Barring, R. Rosner, etc

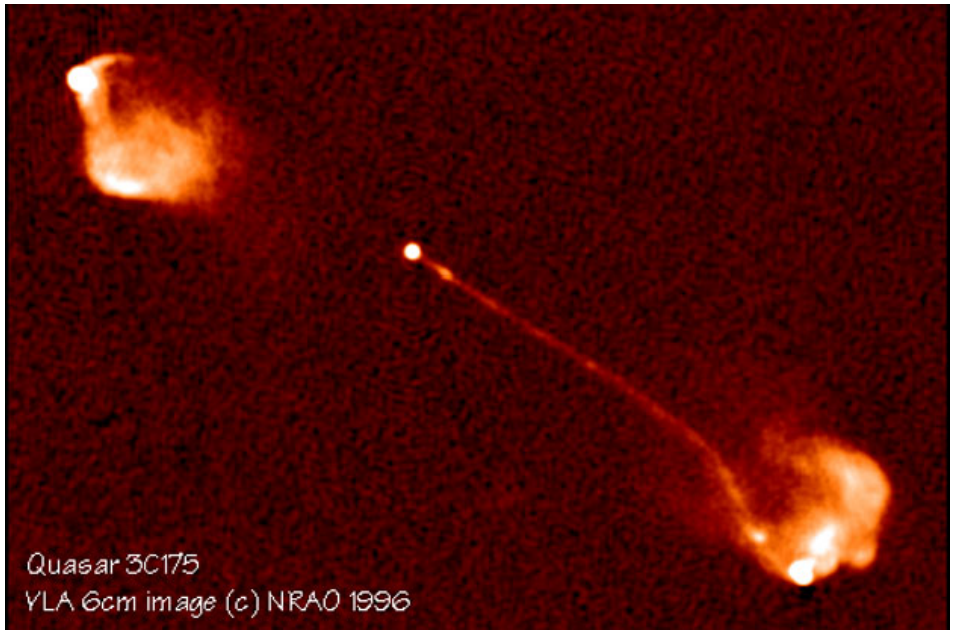
Alfven-Shock Induced Plasma Wakefield Acceleration

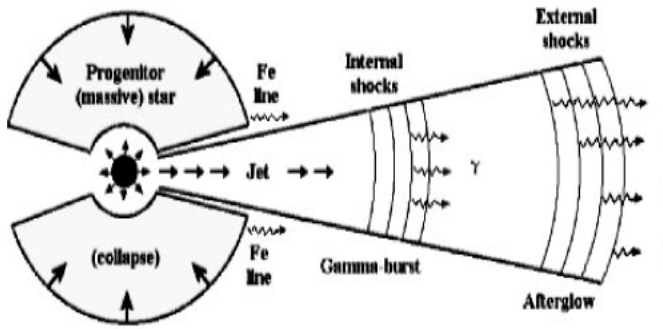
(Chen, Tajima, and Takahashi, PRL, 2001)



- Generation of Alfven waves in relativistic plasma flow
- Inducing high gradient nonlinear plasma wakefields
- Acceleration and deceleration of trapped e^+/e^-
- Power-law (n ~ -2) spectrum due to stochastic acceleration

3. Relativistic Jet-Plasma Dynamics



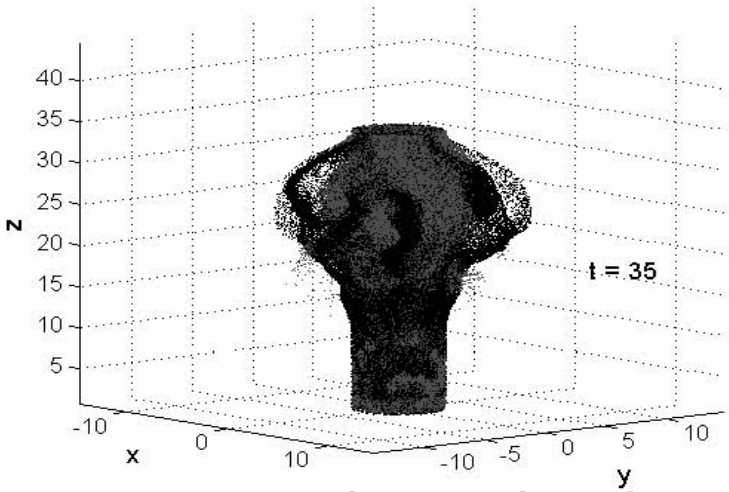


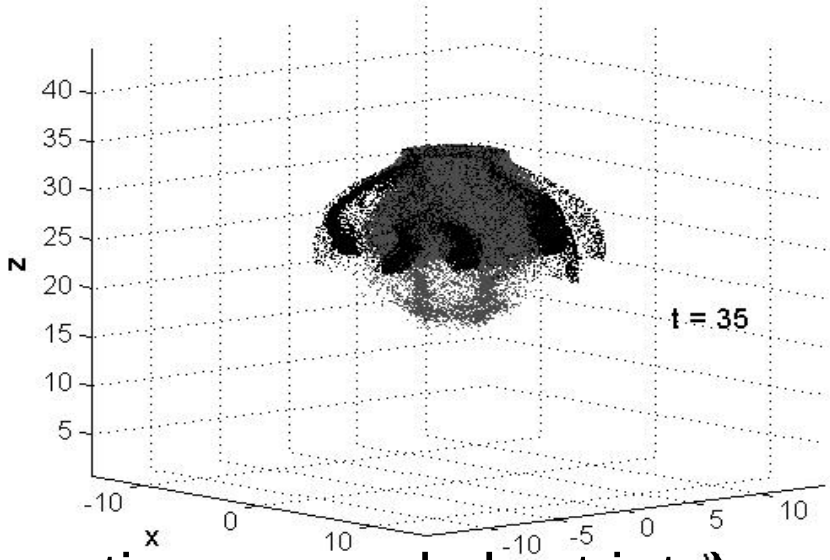
Gamma Ray Burst
Blast Wave Model [Meszaros, 2002]

- Relativistic jets commonly observed in powerful sources
- A key element in models of cosmic acceleration

→ An understanding of their dynamics is crucial.

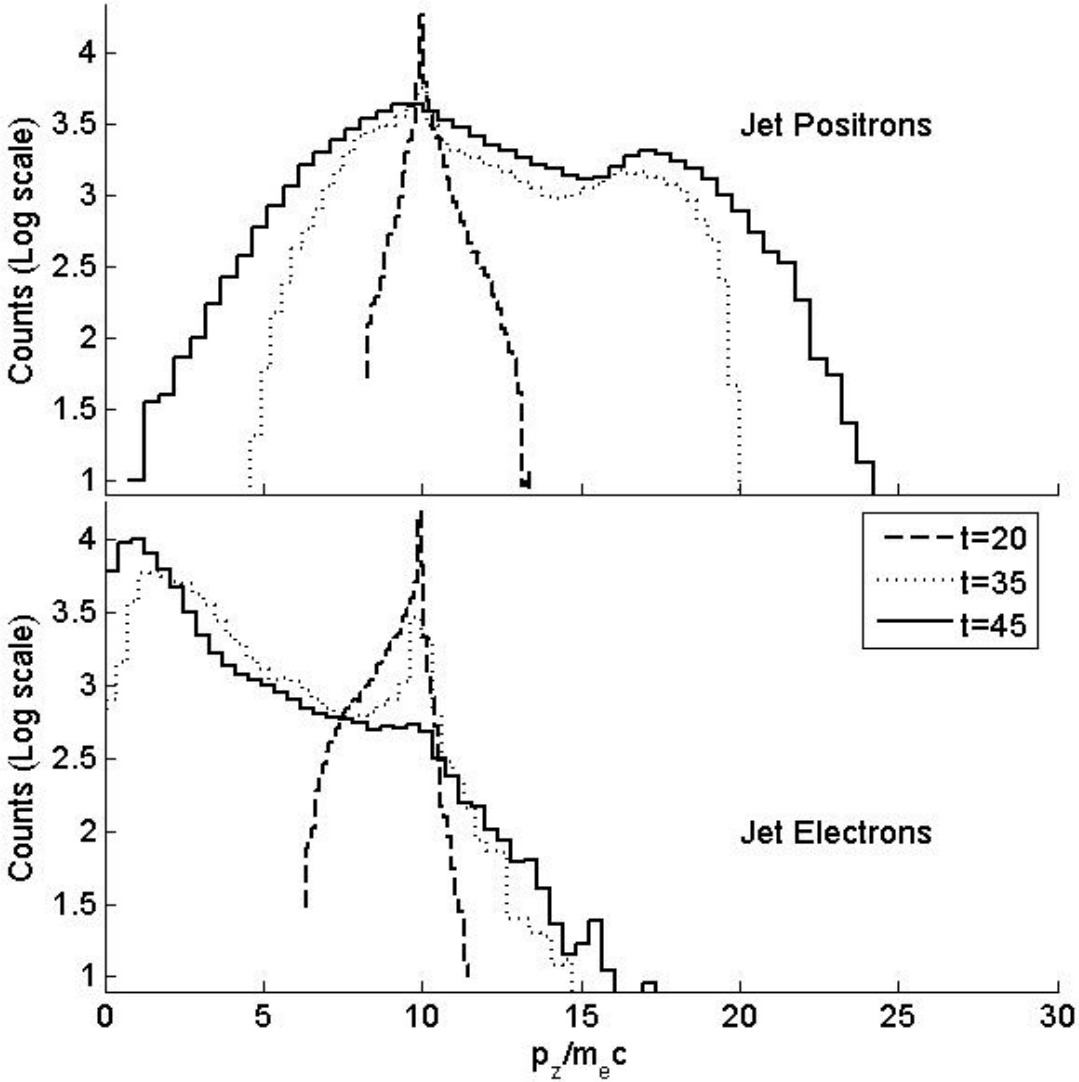
3D PIC Simulation Results: Overview





1. Transverse dynamics (same for continuous and short jets):
   - Magnetic filamentation instability: inductive Ez
   - Positron acceleration; electron deceleration
2. Longitudinal dynamics:
   - Electrostatic “wakefield” generation (stronger in finite-length jet)
   - Persists after jet passes: acceleration over long distances.

Particle Acceleration and Deceleration



Longitudinal momentum distribution of positrons and electrons for a finite-length jet at three simulation time epochs.

t in units of $1/\omega_p$

~ half of positrons gained >50% In longitudinal momentum (p_z)

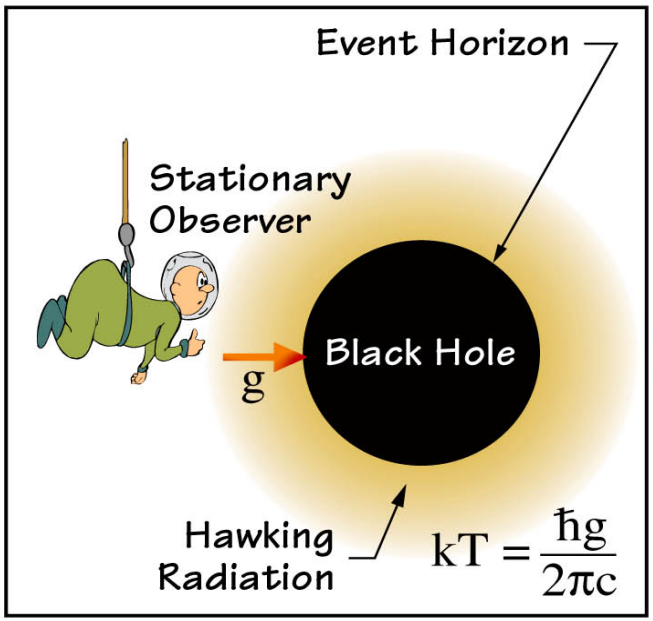
(For details see my talk in Working Group C)

3. Probing Fundamental Physics

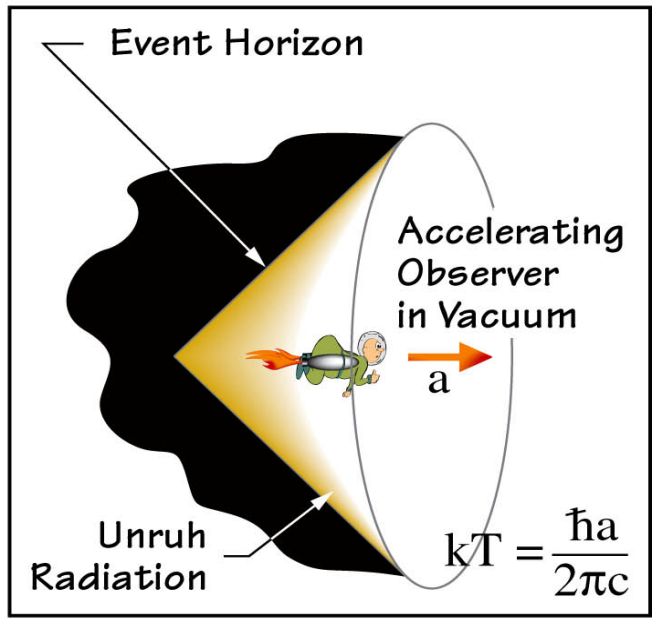
1.Event Horizon Experiment

Chen and Tajima, PRL (1999)

EVENT HORIZONS: From Black Holes to Acceleration



A stationary observer outside the black hole would see the thermal Hawking radiation.



An accelerating observer in vacuum would see a similar Hawking-like radiation called Unruh radiation.

5-2000
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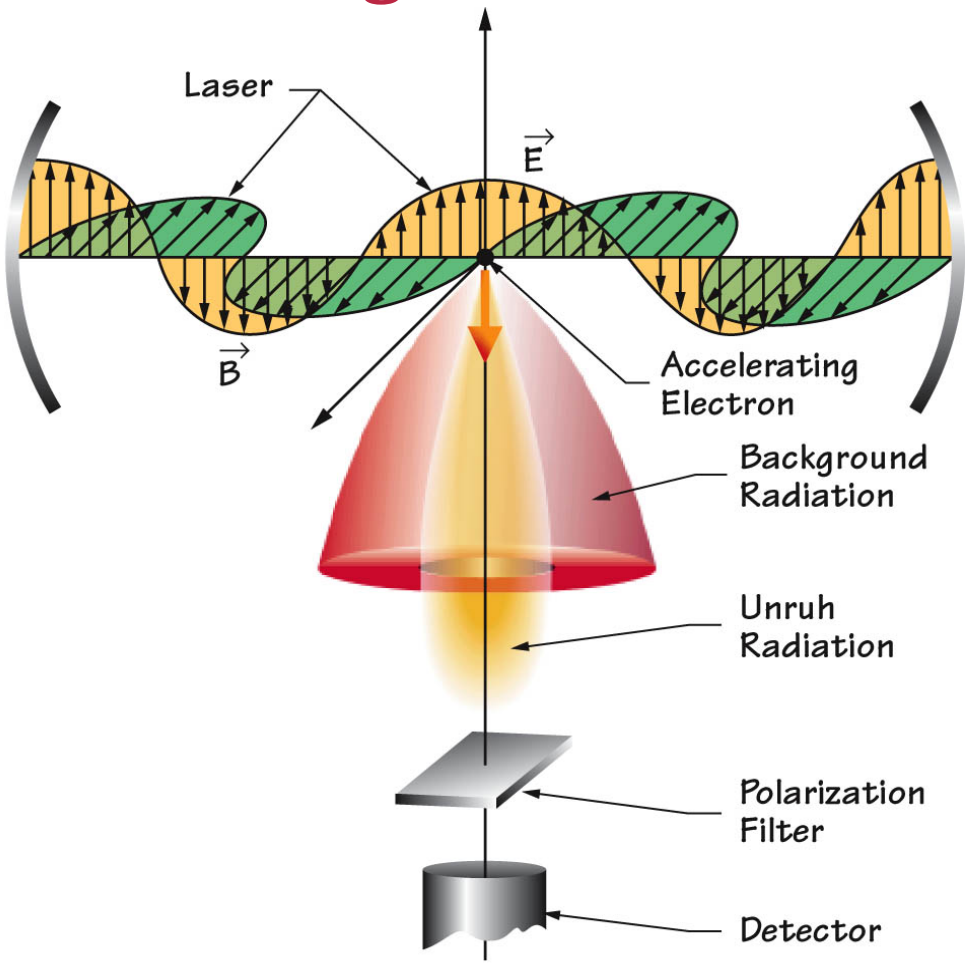
A Conceptual Design of an Experiment for Detecting the Unruh Effect



Schematic Diagram for Detecting Unruh Radiation

5-2000
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2. Probing Extra Spacetime Dimension?

- In standard theory of gravity, the Planck scale is at

$$M_p \sim 10^{19}\,\text{GeV}, \text{ or } L_p \sim 10^{-33}\,\text{cm}.$$

- Assuming large extra dimensions, then $M_p^{\,2} \sim R^n M_*^{\,n+2}$, and

$$R \sim (M_p/M_*)^{(n+2)/n} L_p.$$

- If M_* is identified with the electroweak, or TeV, scale, then

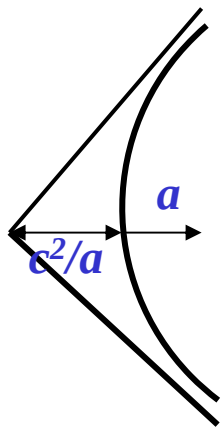
$$R \sim 10^{32/n - 17}\,\text{cm}. \qquad (\text{For } n=6,\ R \sim 10^{-12}\,\text{cm.})$$

- Distance from accelerating detector and the event horizon,

$$d \sim c^2/a \ ,$$

can probe extra spacetime dimension.

- State-of-the art laser can probe up to n=3.



SUMMARY

- History has shown that symbiosis between *direct observation* and *laboratory investigation* instrumental in the progress of astrophysics.
- Recent advancements in *Particle astrophysics and cosmology* have created new questions in physics at the most fundamental level
- Many of these issues overlap with *high energy-density physics.*
- Laboratory experiments can address many of these important issues
- *Laser and particle beams* are powerful tools for Laboratory Astrophysics
- Three categories of LabAstro: *Calibration of observations, Investigation of dynamics,* and *Probing fundamental physics.* Each provides a unique value to astrophysics.

LabAstro Working Group Program

March 15 (Wed.)

WG Parallel Session 1 (11:00-12:00)

Pierre Sokolsky (Utah), "Some Thoughts on the Importance of Accelerator Data for UHE Cosmic Ray Experiments"

Pisin Chen (KIPAC, SLAC), "ESTA: End Station Test of ANITA"

WG Parallel Session 2 (13:30-15:00)

Robert Bingham (RAL, UK), "Tests of Unruh Radiation and Strong Field QED Effects"*

Anatoly Spitkovsky (KIPAC, SLAC), "Pulsars as Laboratories of Relativistic Physics,"

Eduardo de Silva (KIPAC, SLAC), "Can GLAST Provide Hints on GRB Parameters?"

WG Parallel Session 3 (15:30-17:00)

Robert Noble (SLAC), "Simulations of Jet-Plasma Interaction Dynamics"*

Johnny Ng (KIPAC, SLAC), "Astro-Jet-Plasma Dynamics Experiment at SABER"*

Kevin Reil (KIPAC, SLAC), "Simulations of Alfven Induced Plasma Wakefields"*

LabAstro Working Group Program

March 16 (Thur.)

WG Parallel Session 4 (08:30-10:00)

Bruce Remington (LLNL), "Science Outreach on NIF: Possibilities for Astrophysics Experiments"

Bruce Remington (LLNL), "Highlights of the 2006 HEDLA Conference"

Round Table Discussion, "Considerations of Labaratory Astrophysics"

WG Summary Preparation (10:20-12:00)

*Tentative title