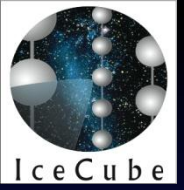




# COSMIC RAY PHYSICS WITH ICECUBE

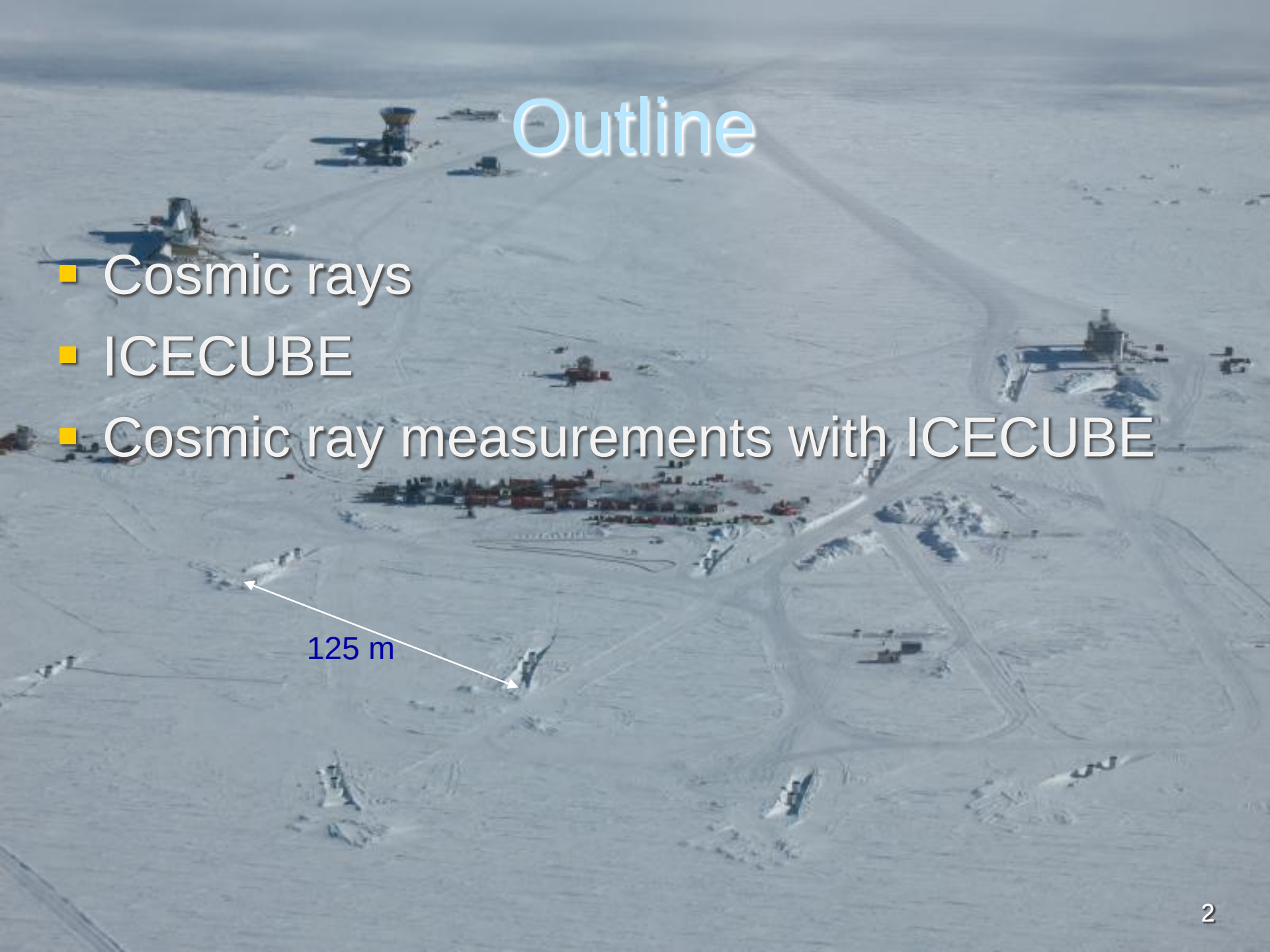
**Shahid Hussain**
**for the ICECUBE collaboration**

**University of Delaware, USA**

March 02, 2011

# Outline

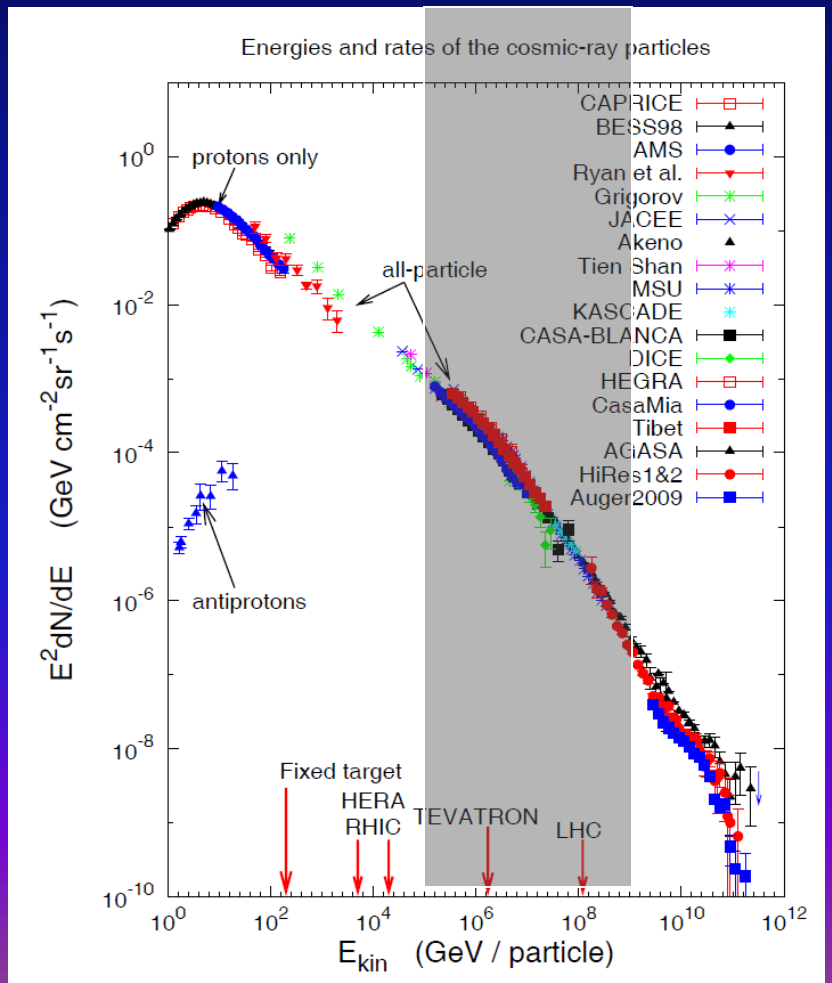
- Cosmic rays
- ICECUBE
- Cosmic ray measurements with ICECUBE

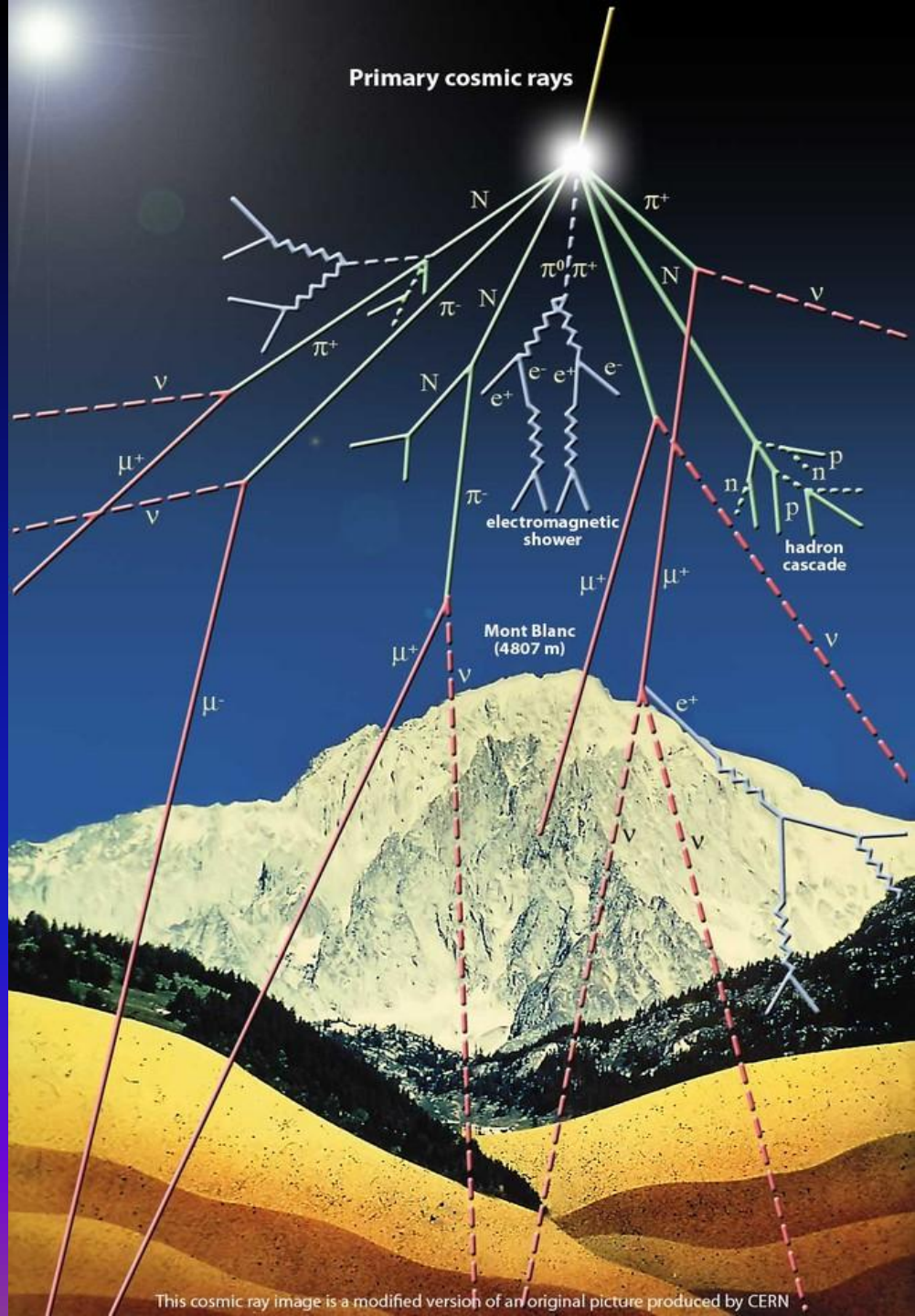


# cosmic rays Produce air showers

Radiation from space discovered by Victor Hess (1912)

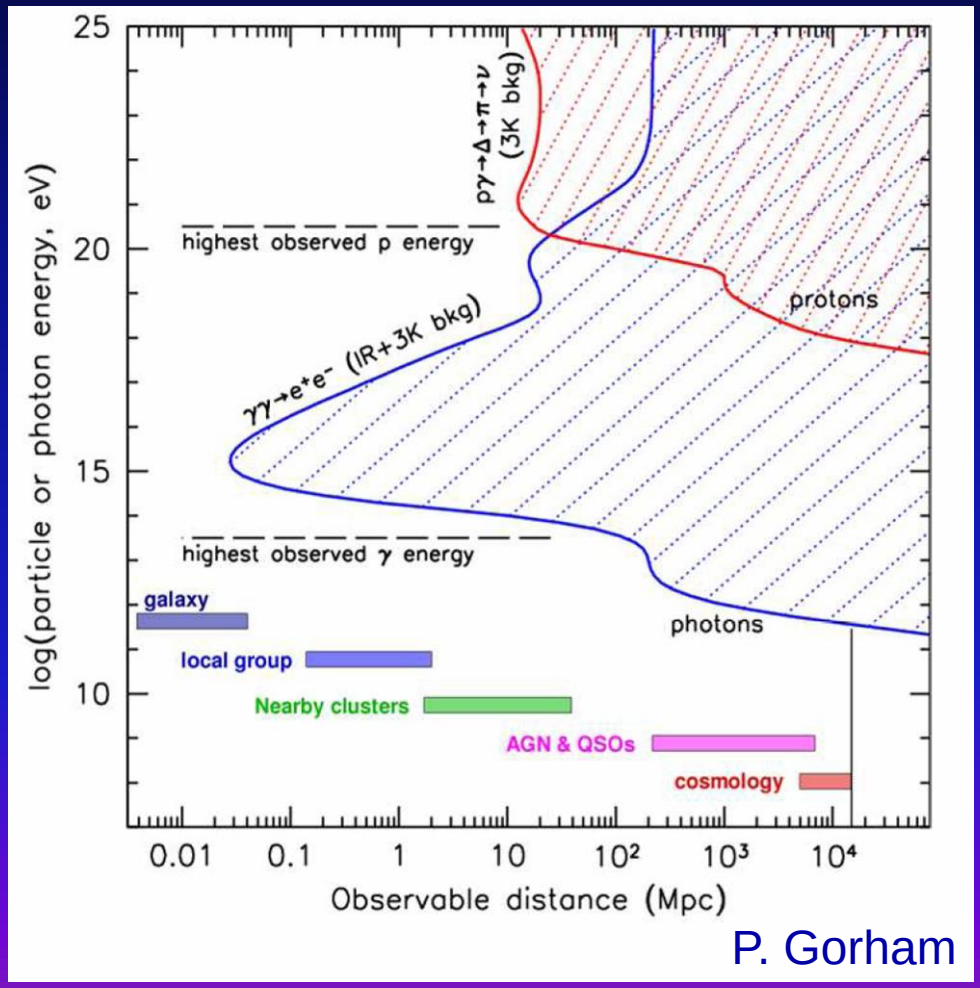
- Direct/indirect detection
  - Direction, spectrum, composition
- Physics questions
  - Sources?
  - Acceleration mechanism?



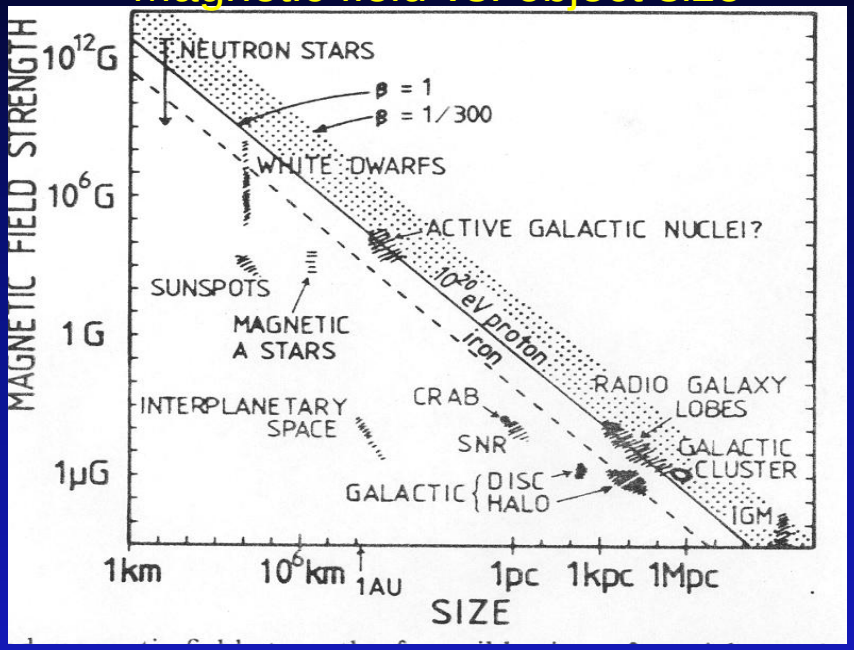
# Cosmic ray sources?

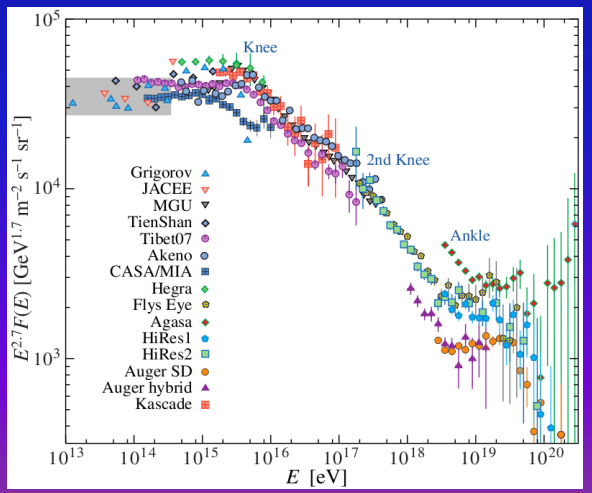
Transparency of the Universe:
Particle energy vs. Object distance



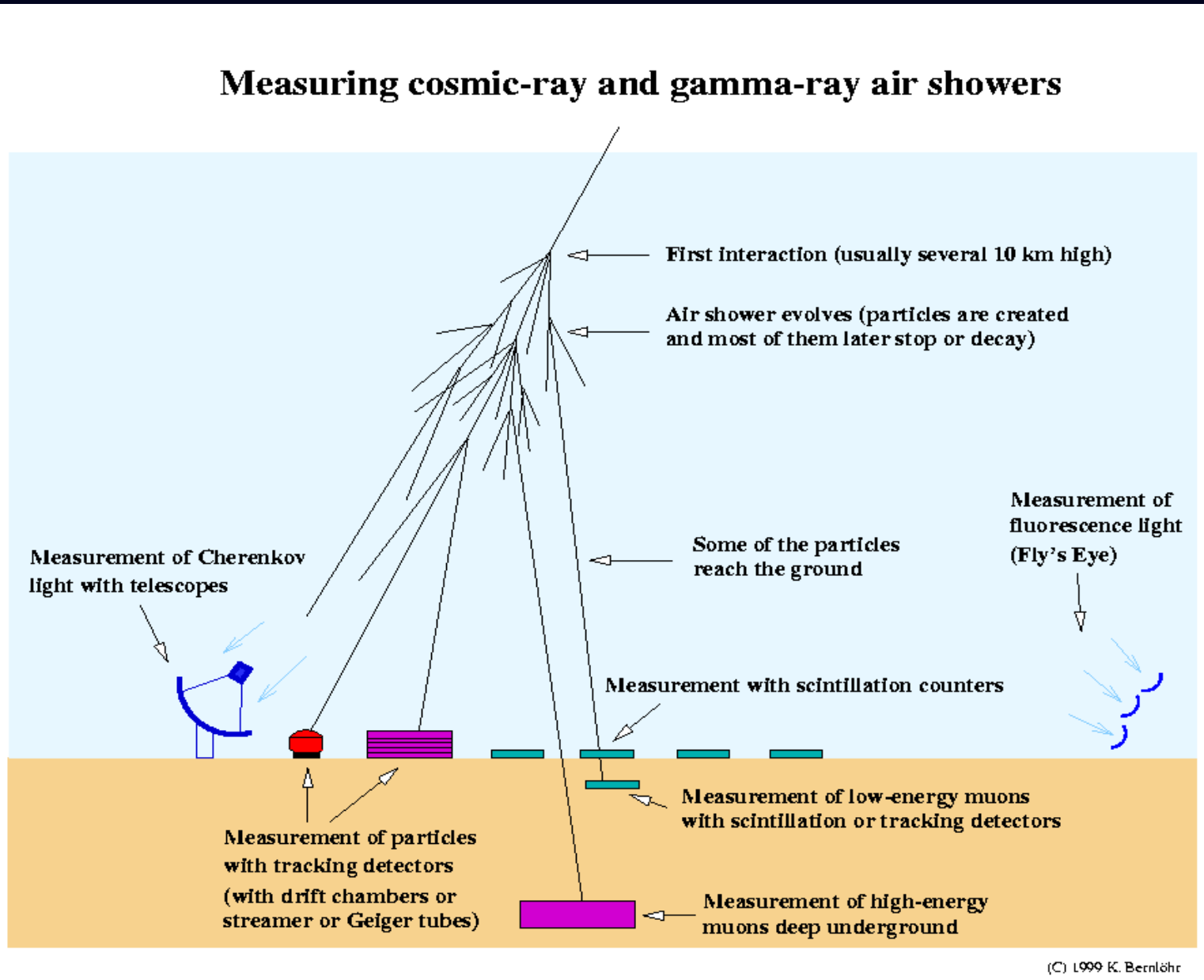

P. Gorham

**Hillas plot**
Astrophysical objects:
Magnetic field vs. object size



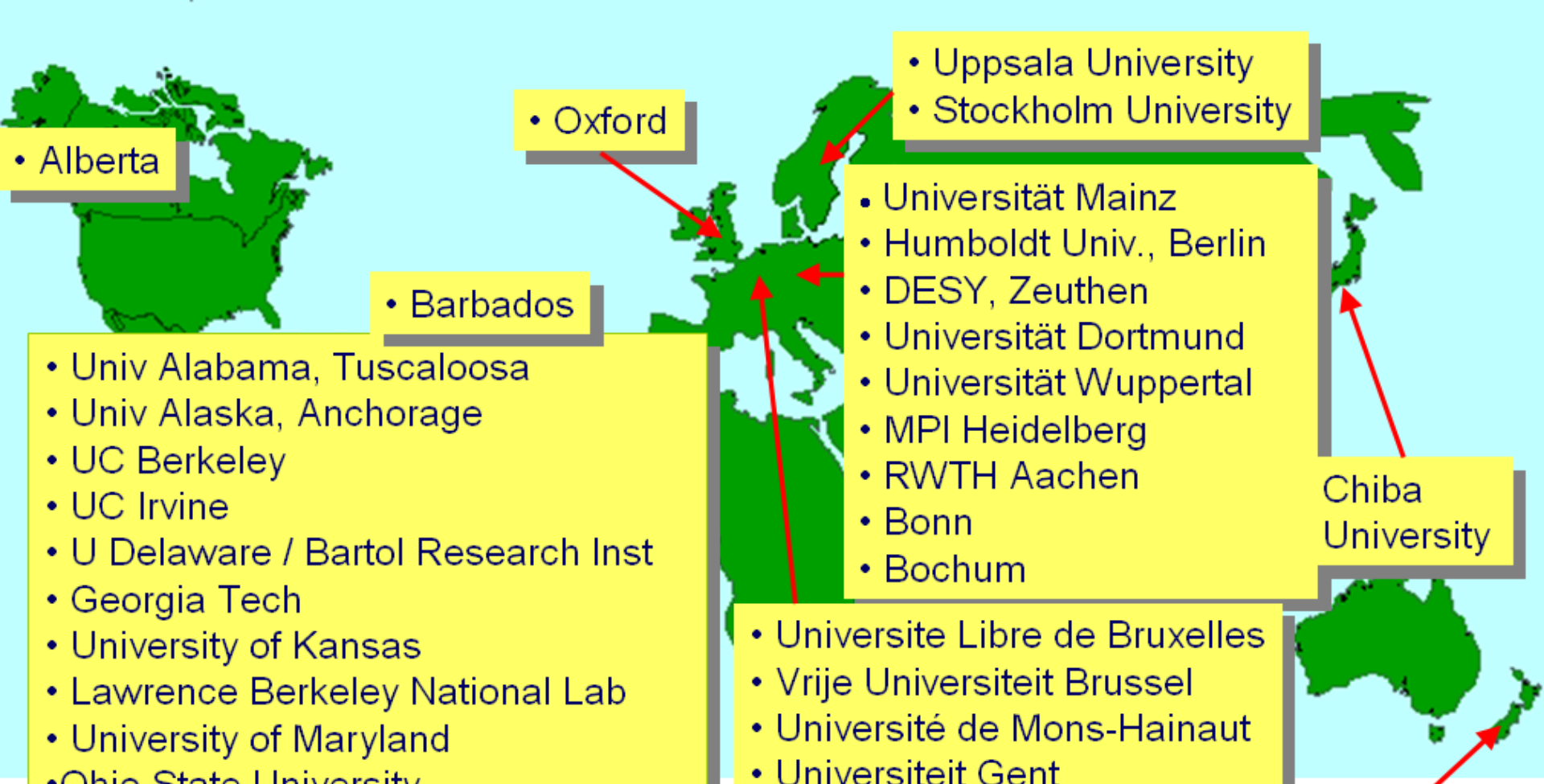



# Air showers-- detection methods



# ICECUBE

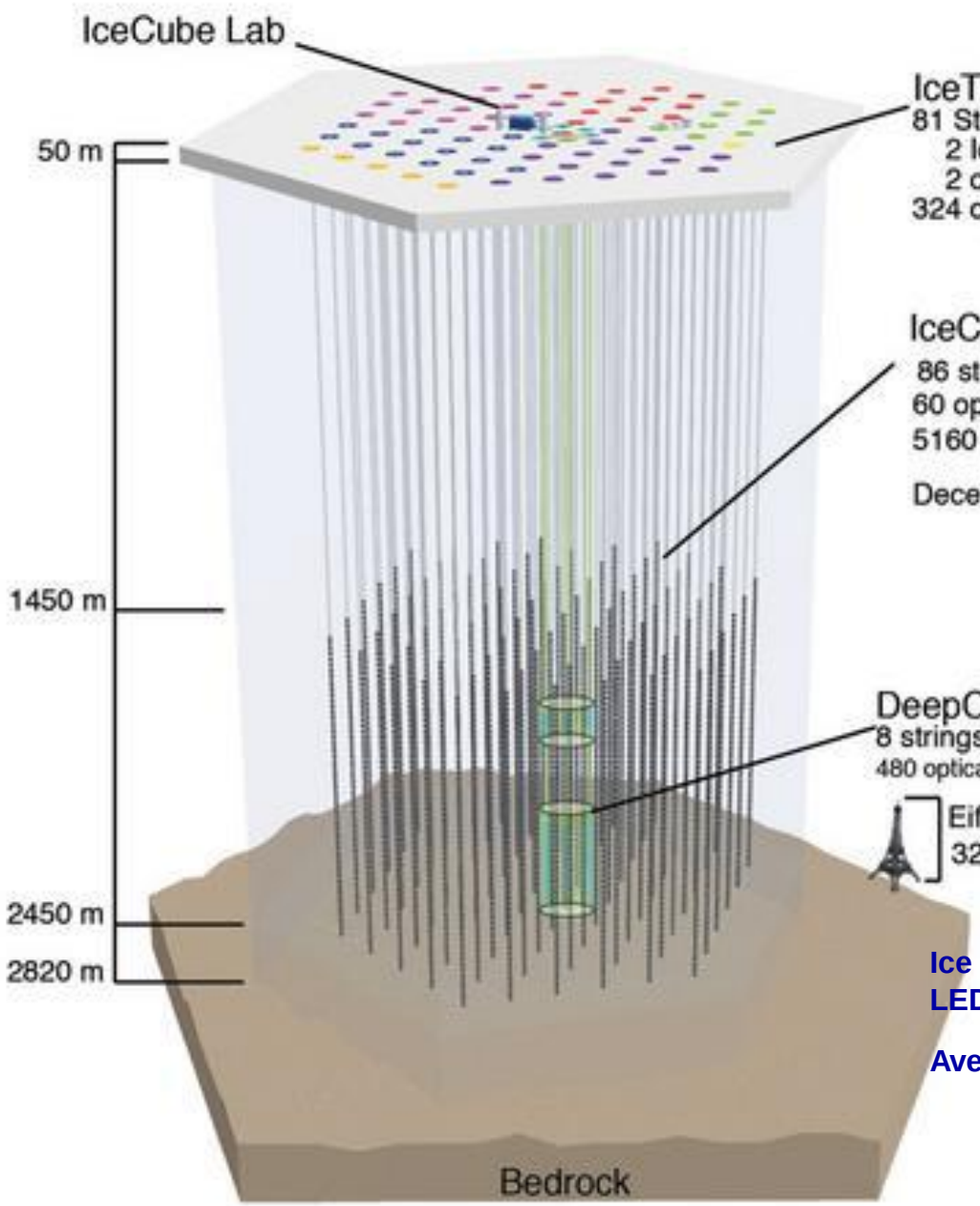
- Detection principle: optical Cherenkov radiation
- Detector medium: South Pole ice
- Physics
  - Neutrinos: Main discovery target is astrophysical neutrinos
  - Cosmic rays (~100 TeV to ~1 EeV)
  - Dark matter (indirect search)
  - Monopoles and other exotic particles
  - Cross sections (neutrino-nucleon, air showers)
- Animations:
  - ICECUBE geometry  Downward event  Upward event




# The IceCube Collaboration

**250 scientists, 36 institutions**

# ICECUBE: 3D view




**IceTop**
81 Stations, each with
2 IceTop Cherenkov detector tanks
2 optical sensors per tank
324 optical sensors

**IceCube Array**
86 strings including 8 DeepCore strings
60 optical sensors on each string
5160 optical sensors

December, 2010: Project completed, 86 strings

**DeepCore**
8 strings-spacing optimized for lower energies
480 optical sensors

Eiffel Tower
324 m

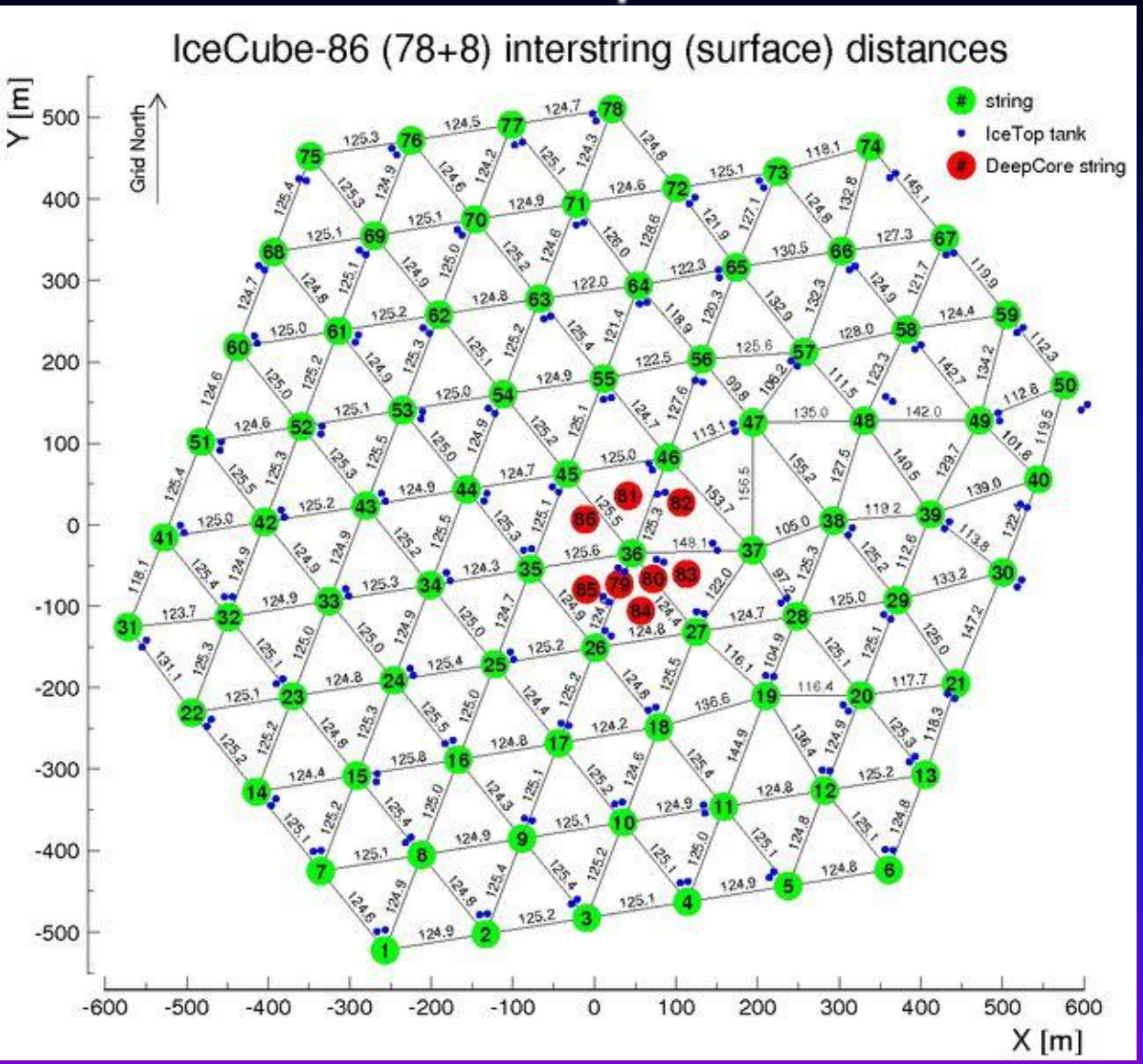
**Ice properties measured with LED and LASER sources**

**Average optical parameters at 400 nm:**

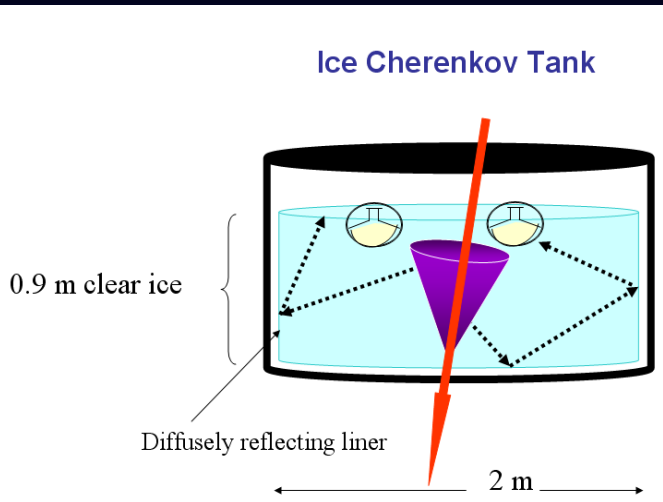
**$\lambda_{abs}$ ~110 m, $\lambda_{sca}$ ~20 m above the dust layer**

**$\lambda_{abs}$ ~220 m, $\lambda_{sca}$ ~40 m below the dust layer**

# ICECUBE- top view

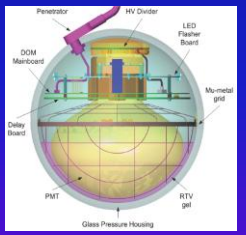



## IceTop Tank

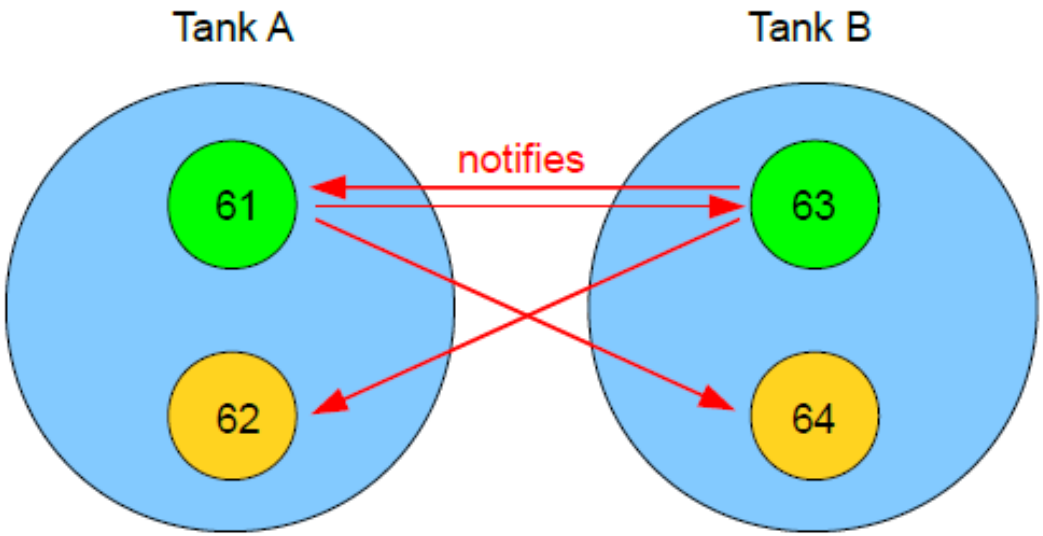



## DOMs in a Tank

## Digital optical module (DOM)



# Local Coincidence and Trigger



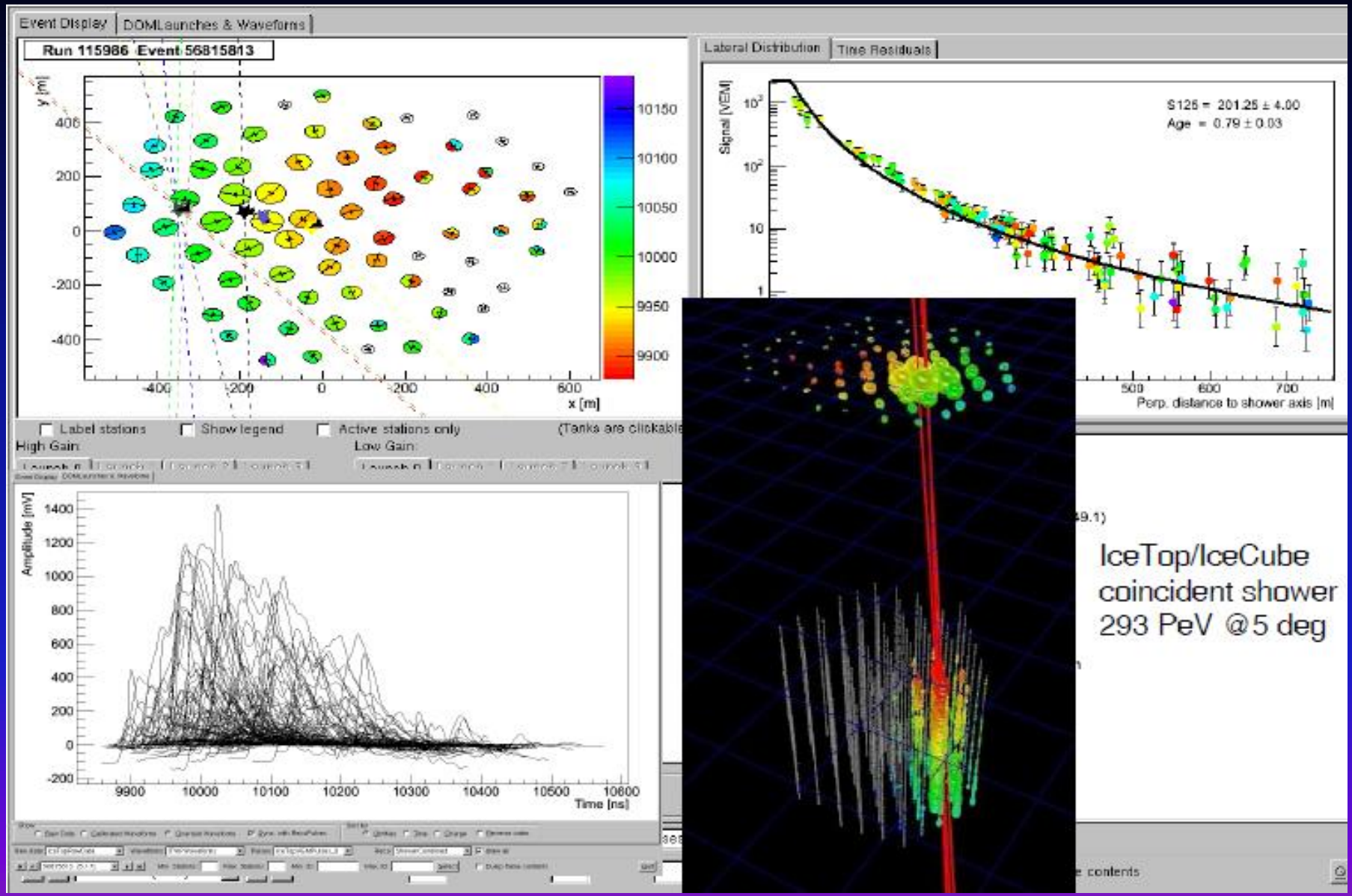

LC-Window: ± 250ns

Simple Majority Trigger condition:

6 LC-hits within 5 µs *(Readout window: ±10 µs, IC59-Rate: 22 Hz)*

Tilo W.

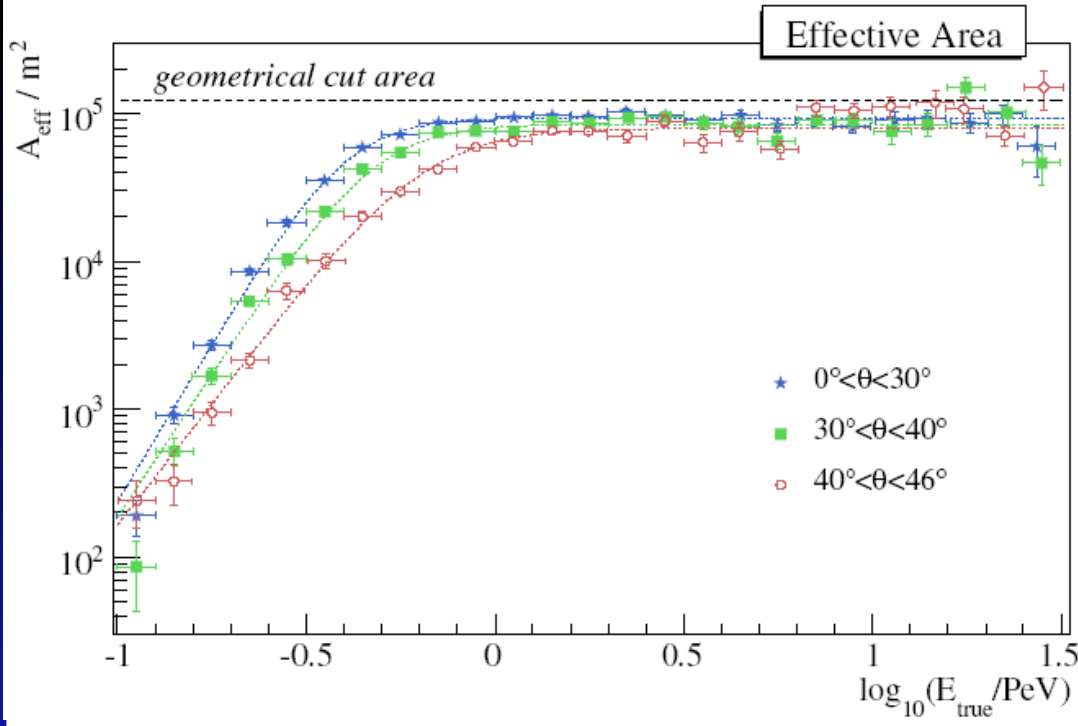
# Event example: June 2010 data

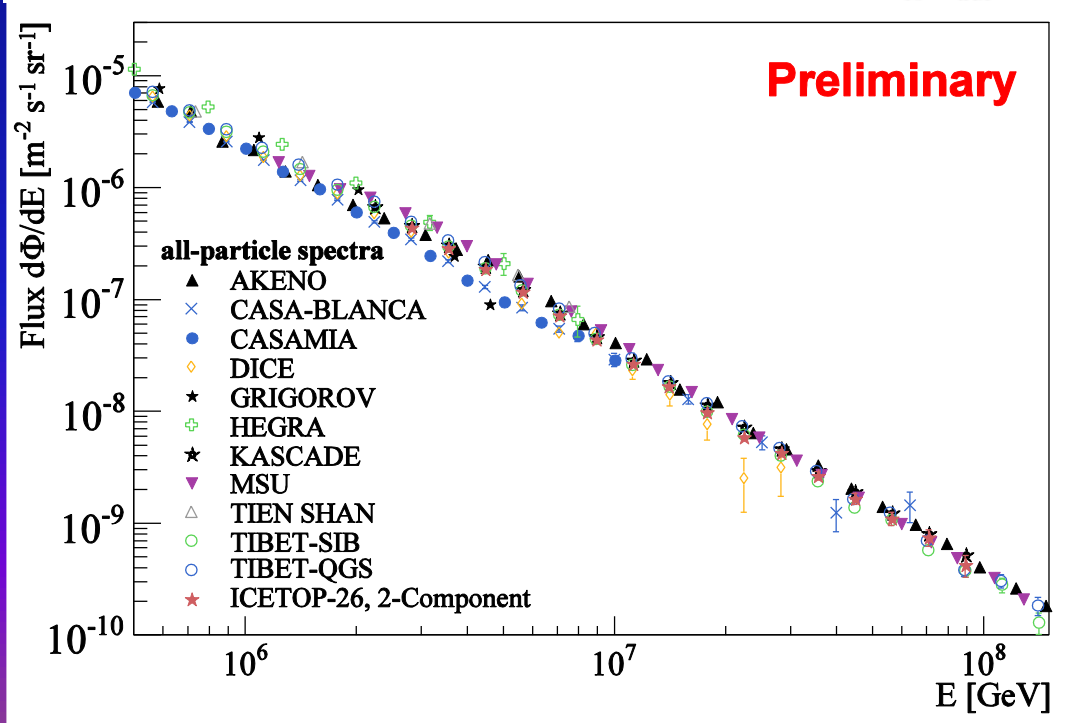


# IceTop-only (26 stations) analysis example

Effective area and resolution

| | |
|---|---|
| direction | ≈1.5° |
| core | ≈ 9 m |
| energy | ≈ 0.06 (in $\log_{10}$) |

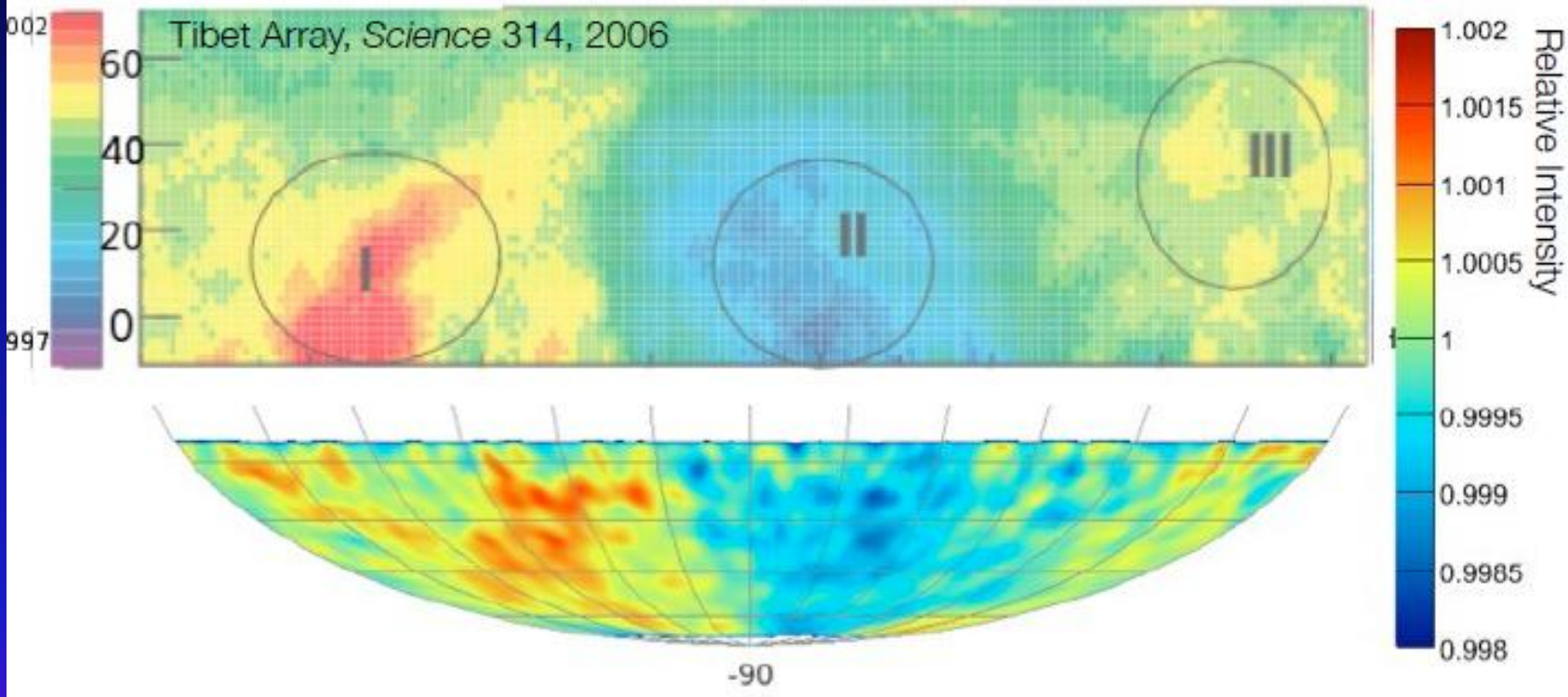


# Example of an InIce-only analysis

## Anisotropy in TeV-Scale Cosmic Rays

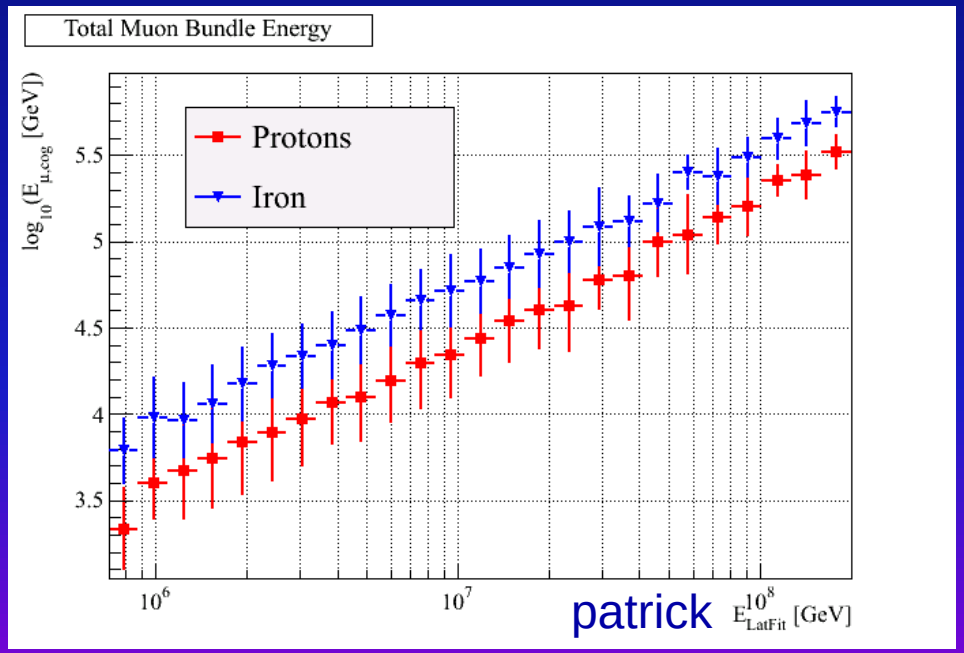
arXiv:1005.2960, accepted *Astrophys. J. Lett.*

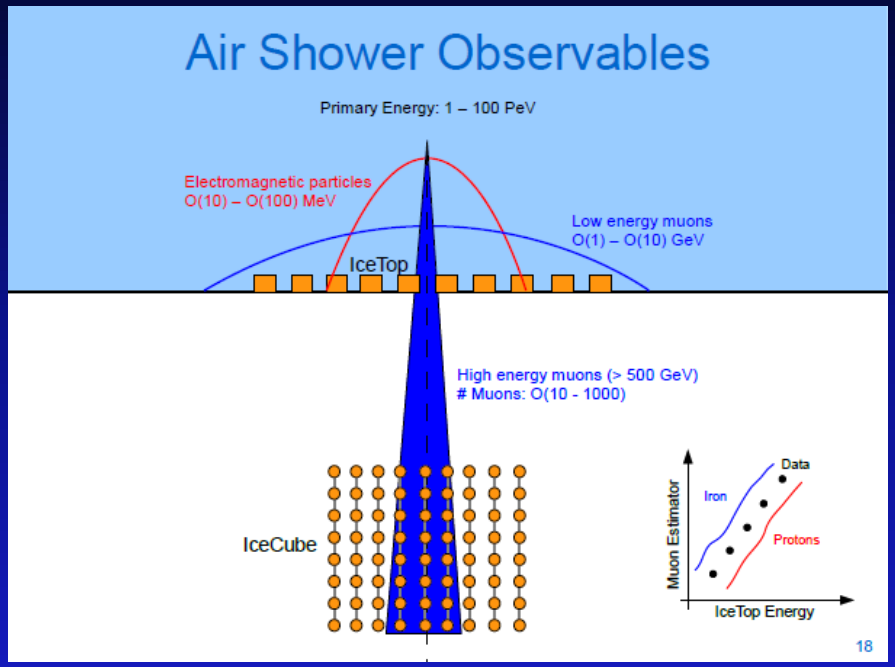



Appears consistent with an extension of Northern anisotropy previously reported by Tibet and Milagro

# Several analyses underway: Combine surface and InIce information

- Composition analysis
- Analyze small showers for comparison with direct measurements
- Search for PeV gamma rays
- Search for Muons with large transverse momentum




**Simulations: correlation between surface and InIce energy deposition; sensitivity to composition.**

# Summary– ICECUBE as a cosmic ray observatory

- ICECUBE is now fully deployed; data analyses underway
- Energy range covered ~100 TeV-1 EeV
  - Overlap with direct measurements
  - Main goal is to understand galactic to extra-galactic transition region
- Energy estimation
  - em and mu components with IceTop
  - Muon component InIce
- Direction measurement
  - both IceTop and InIce
- Cosmic ray composition resolution
  - Combined information from IceTop, InIce, and angular distribution of events

# Extra slides

# Event reconstruction (IceTop only): Likelihood function

**Lateral distribution function**

$$S(R) = S_{R_0} \left(\frac{R}{R_0}\right)^{-\beta-\kappa \log_{10}\left(\frac{R}{R_0}\right)}$$

**toprec likelihood function:**

$$\mathcal{L} = \mathcal{L}_S + \mathcal{L}_0 + \mathcal{L}_t$$

**Charge likelihood function:**

$$\mathcal{L}_S = \sum_i \frac{\left(\log_{10}(S_i) - \log_{10}(S_{\text{fit}}^{(i)})\right)^2}{2\sigma_S(S_{\text{fit}}^{(i)})^2} + \sum_i \log(\sigma_S(S_{\text{fit}}^{(i)}))$$

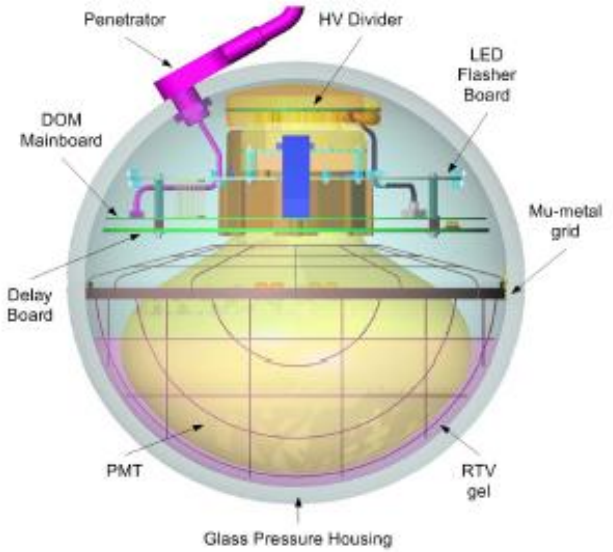
**L0 involves:**

$$\frac{1}{\sqrt{2\pi}\sigma_0} \int_{-\infty}^{S_{thr}} \exp\left(-\frac{(\log_{10}(S_j) - \log_{10}(S_{\text{fit}}^{(j)}))^2}{2\sigma_0^2}\right) \mathrm{d}\log_{10} S$$

**Time likelihood function:**

$$\mathcal{L}_t = \sum_i \frac{(t_i - t_{\text{fit}}^{(i)})^2}{2\sigma_t(R_i)^2} + \sum_i \log(\sigma_t(R_i))$$

# Digtial Optical Module





Design Requirements:

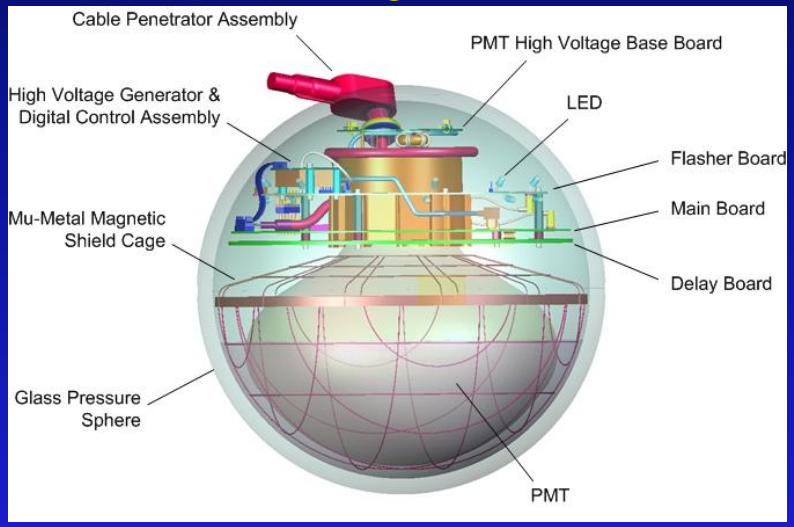
- Minimal signal loss
- Minimal number of channels *(cables)*
- Minimal data traffic

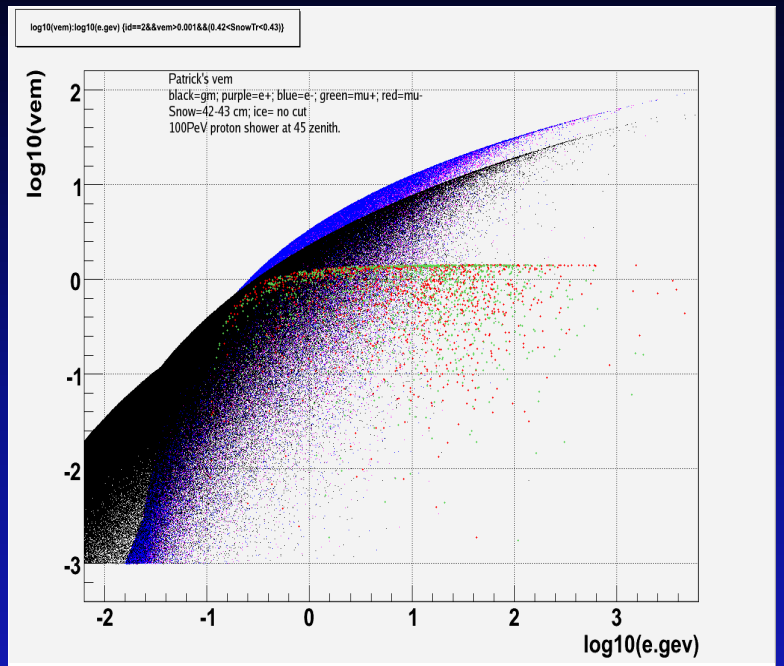
- PMT with integrated HV-converter
- Onboard Digitalisation
  - ATWD, 128 Samples in 422 ns
  - fADC, 256 samples in 6.4 µs
- Local Coincidence with neighbors *(noise suppression)*
- Onboard calibration and tests
- Autonomous operation

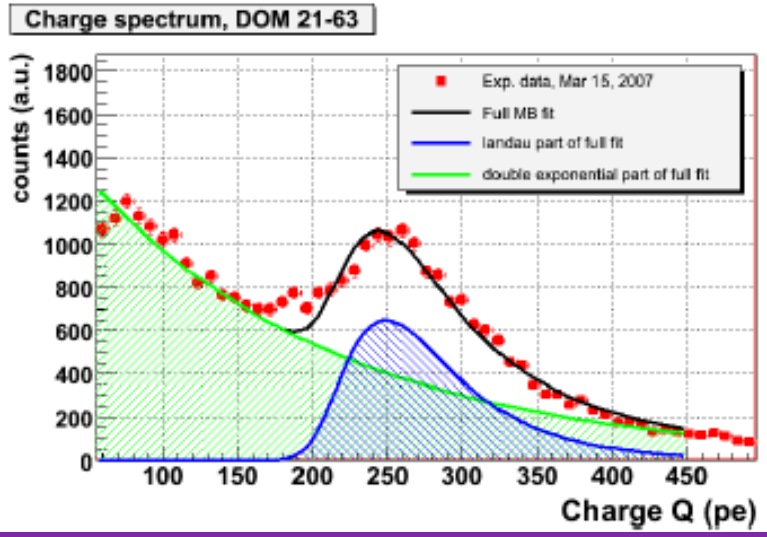
Tilo W.

# VEM definition and DOM Calibration

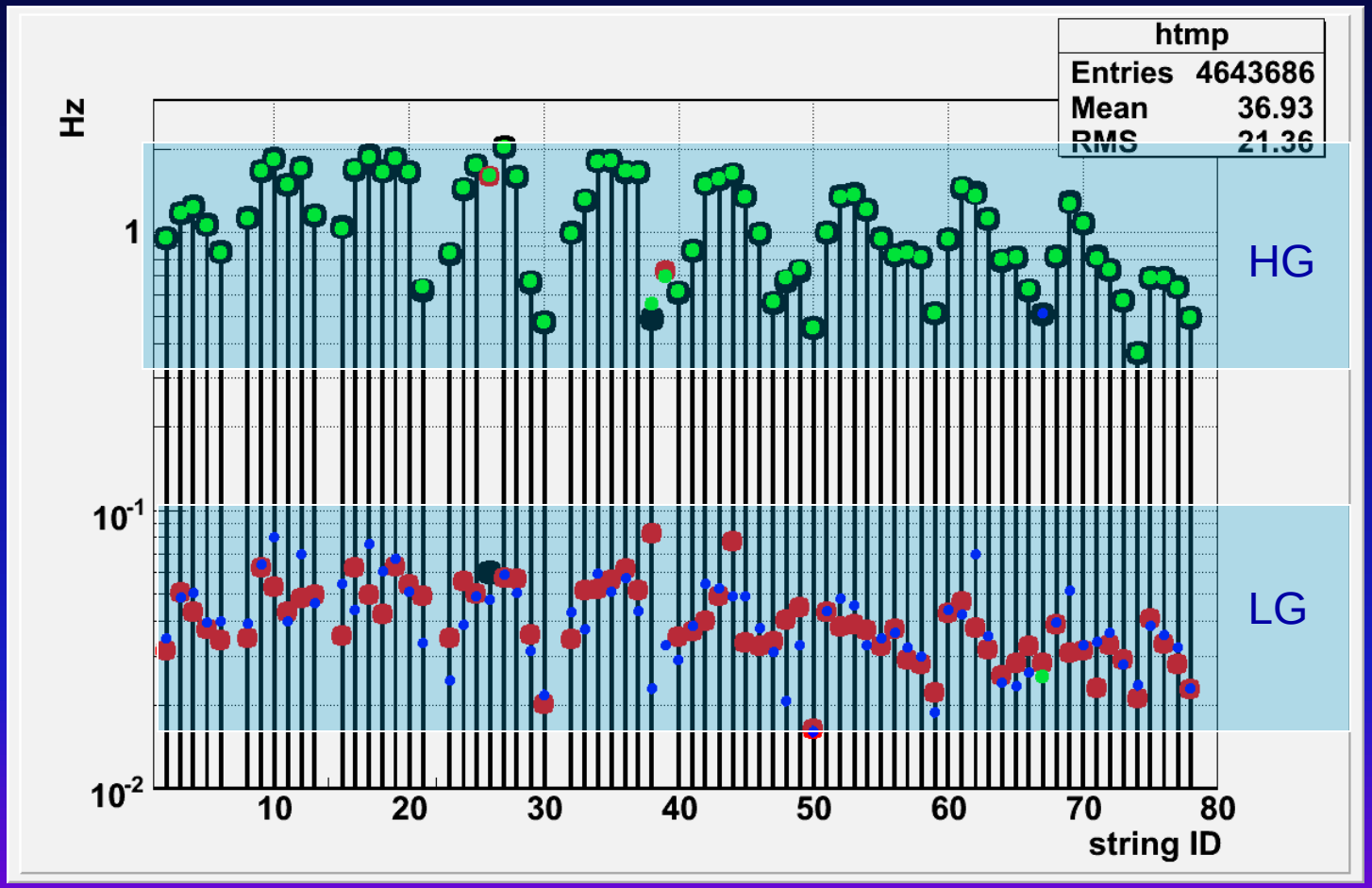
## DOM



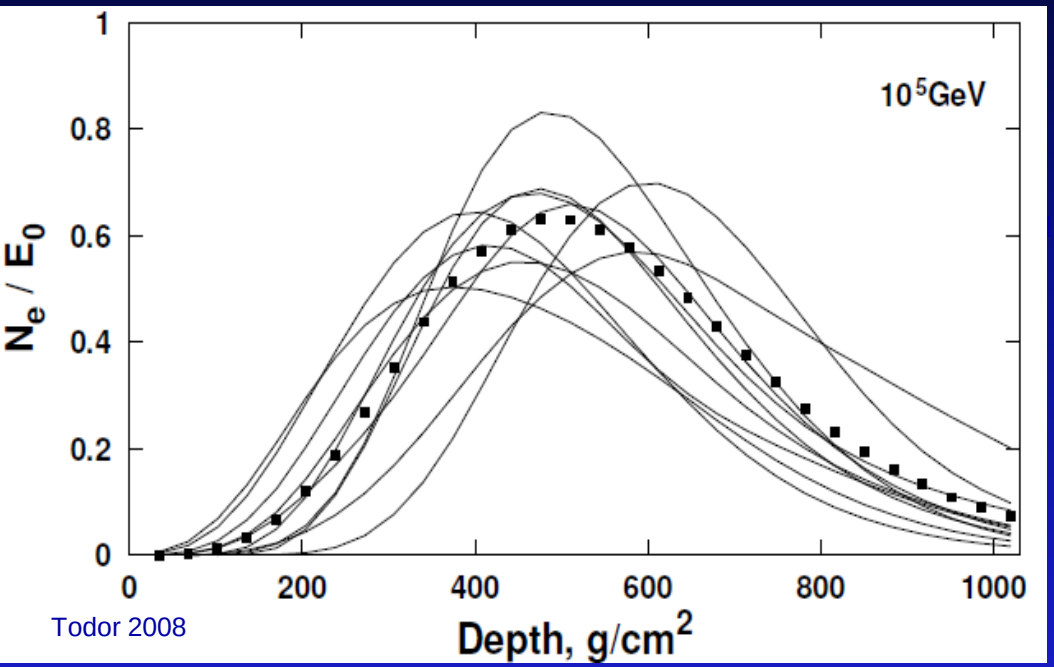



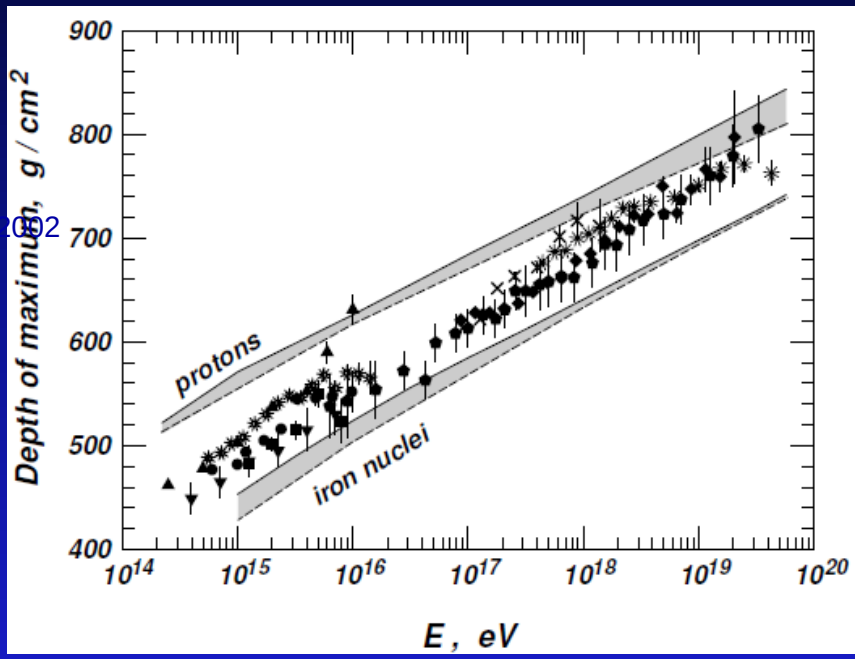
# DOM launch rates due to air showers



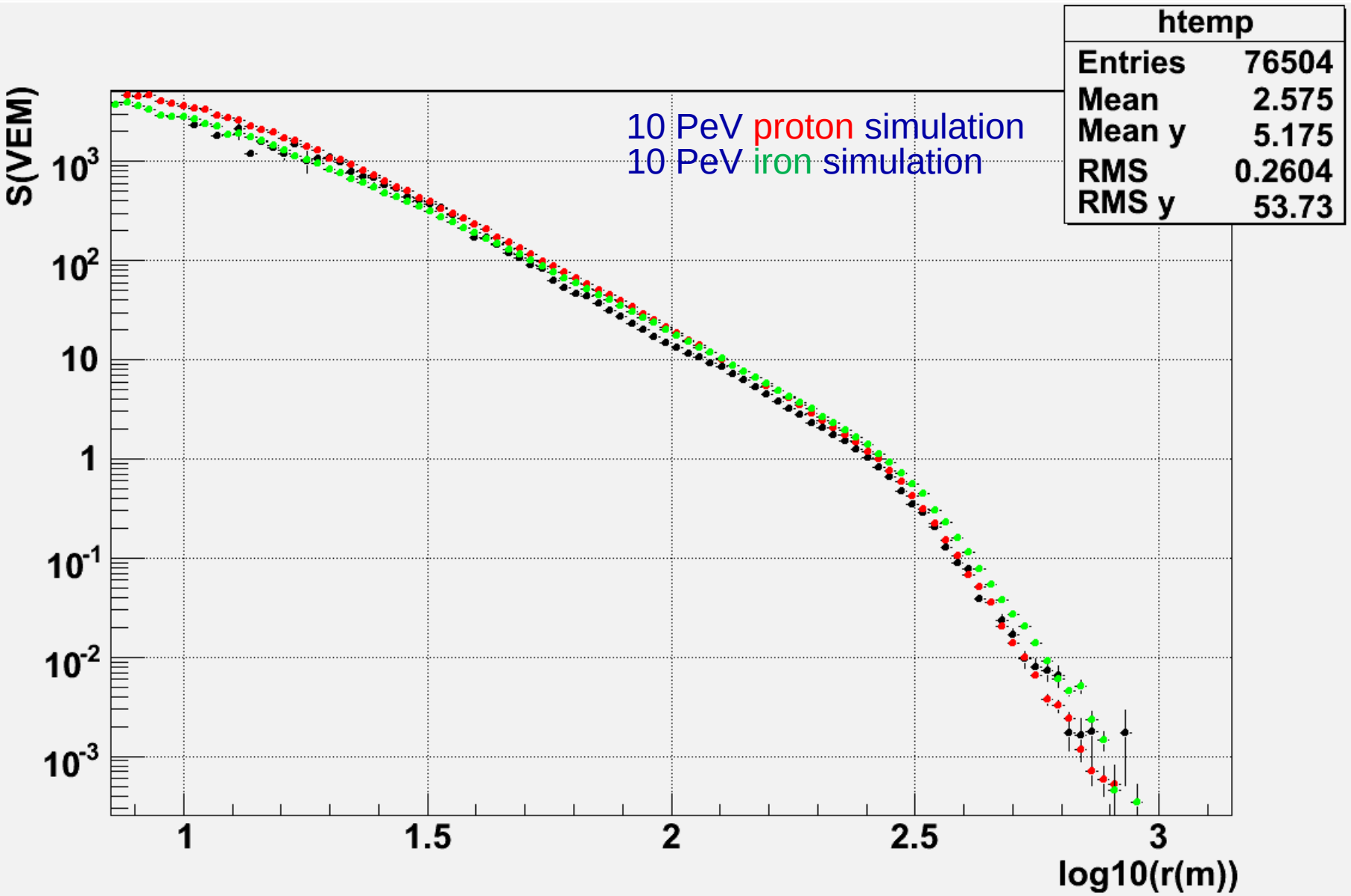
# Air showers– longitudinal profiles



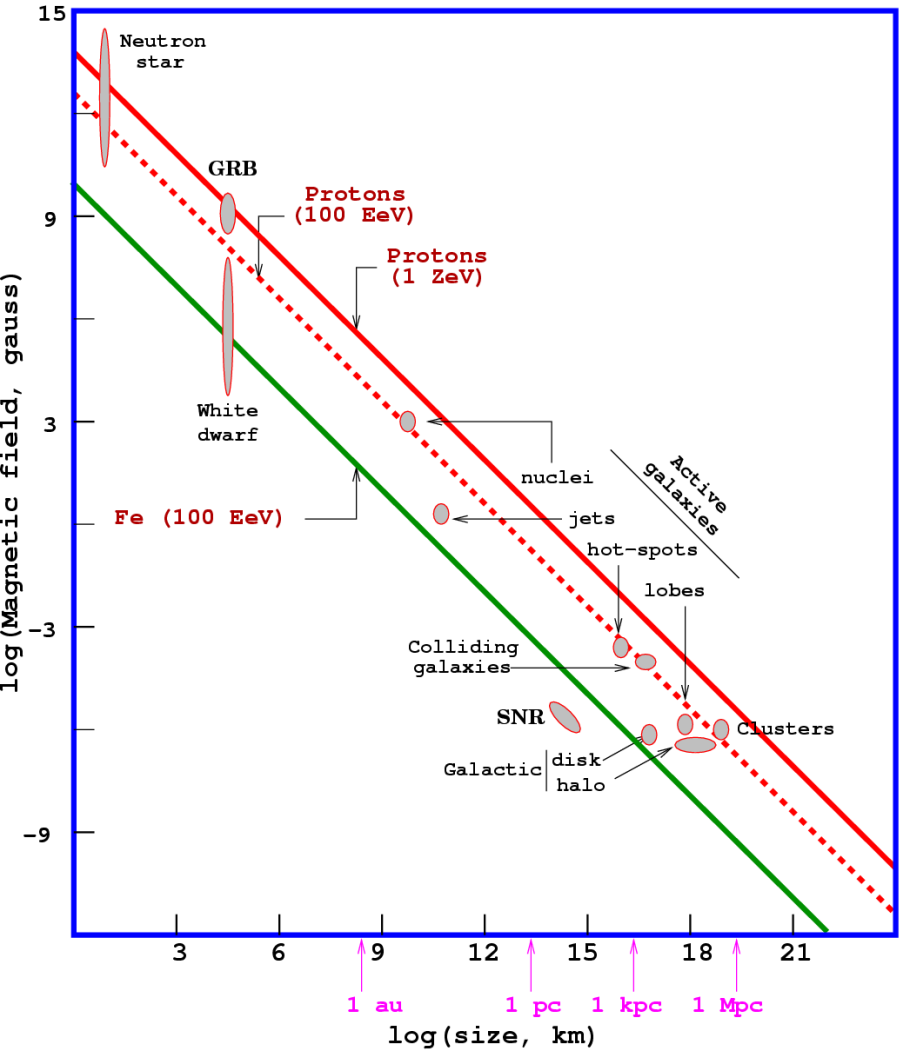

Todor 2008



# Lateral profile of air shower signals measured with IceTop



## Hillas-plot
## (candidate sites for E=100 EeV and E=1 ZeV)



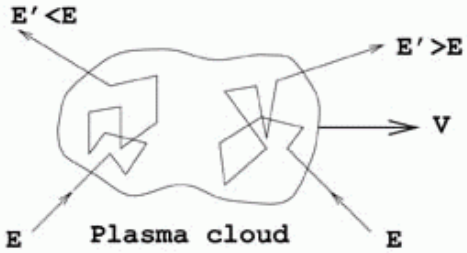

$E_{max} \sim ZBL$ (Fermi)

$E_{max} \sim ZBL\,\Gamma$ (Ultra-relativistic shocks-GRB)

## Fermi Acceleration Mechanism

Stochastic energy gain in collisions with plasma clouds

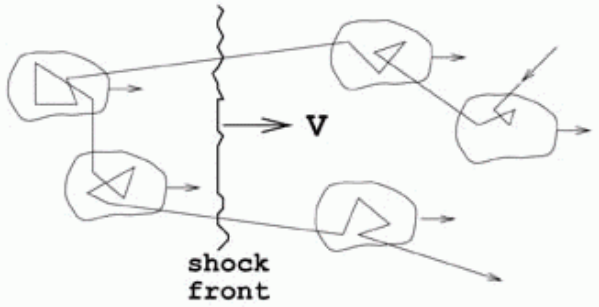
2nd order :
randomly distributed magnetic mirrors




$$\frac{\Delta E}{E} \sim \beta^2 \qquad \beta = \frac{V}{c} \lesssim 10^{-4}$$

[Slow and inefficient]

1st order :
acceleration in strong shock waves
(supernova ejecta, RG hot spots...)




$$\frac{\Delta E}{E} \sim \beta \qquad \beta = \frac{V}{c} \lesssim 10^{-1}$$

# Fit Procedure and Resolutions

- Negative Log-Likelihood minimization including charge, timing and silent stations
- Seven parameters: x, y, θ, φ, $S_{125}$, β, $t_0$
- Minimum of 5 stations (10 tanks) required.