Fizyka cząstek:

detektory

prof. dr hab. A.F.Żarnecki

Zakład Cząstek i Oddziaływań Fundamentalnych IFD

Wykład VIII

Eksperymenty nieakceleratorowe

- Pierre Auger
- Fermi
- Poszukiewanie ciemnej materii

Promieniowanie kosmiczne

Promieniowanie pierwotne - obserwowane poza atmosferą ziemską

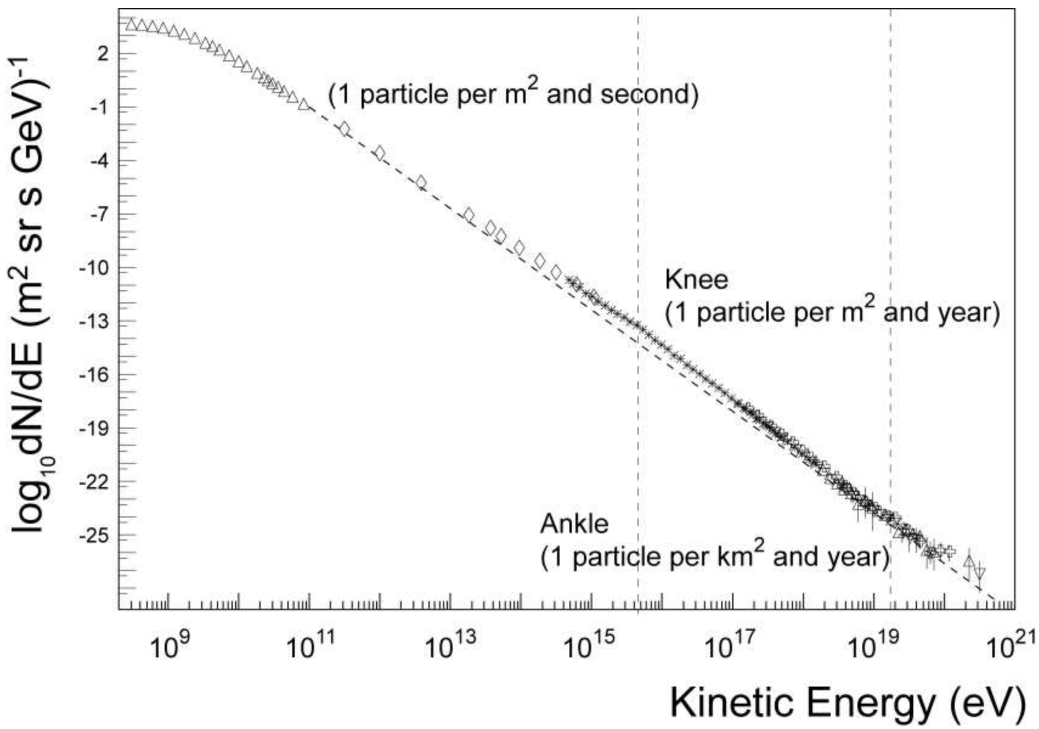
Energie dochodzące do 10^{12} GeV.

Skład (pomijając neutrina):

- protony (jądra H) $\sim$ 86%
- cząstki α (jądra He) $\sim$ 13%
- cięższe jądra $\sim$ 1%
- neutrony, elektrony, fotony $\ll$ 1%

Wciąż nie rozumiemy skąd to promieniowanie pochodzi:

- supernowe
- aktywne jądra galaktyk
- ???



Nie rozumiemy dlaczego dociera do Ziemi !...

(powyżej $5 \cdot 10^{19}$ eV powinno być pochłaniane w oddziaływaniu z mikrofalowym promieniowaniem tła)

Promieniowanie kosmiczne

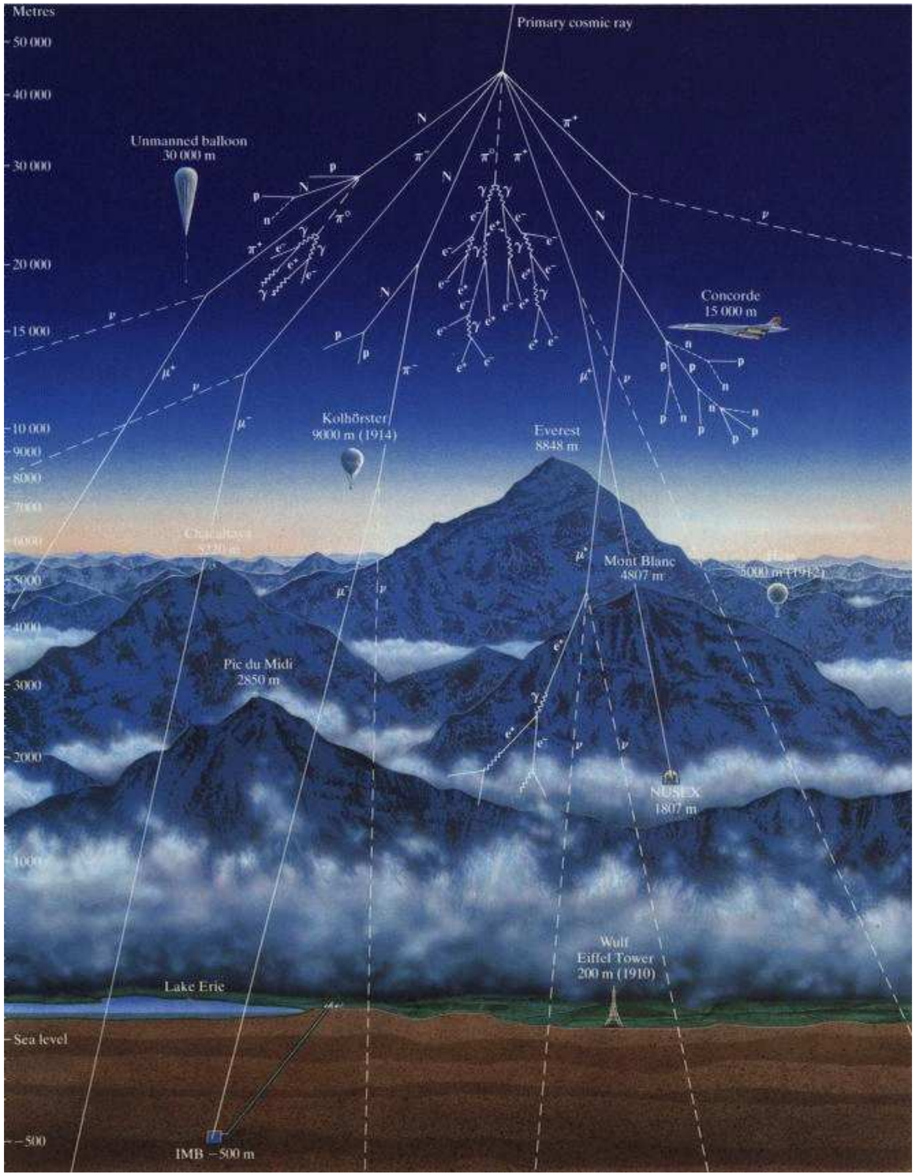
Wtórne promieniowanie kosmiczne

Promieniowanie pierwotne oddziałuje w atmosferze Ziemi. Produkowane są liczne cząstki wtórne, głównie piony i kaony:

$$p + N \;\rightarrow\; X + \mathrm{n}\,\pi + \mathrm{m}\,K + \ldots$$

$$\pi^- \;\rightarrow\; \mu^- + \bar{\nu}_\mu$$

$$\mu^- \;\rightarrow\; e^- + \nu_\mu + \bar{\nu}_e$$



Docierają do powierzchni Ziemi

- miony $\mu^{\pm}$ ~70%
- elektrony $e^{\pm}$ ~25%
- protony, piony $\pi^{\pm}$ ~3%

Łącznie około 180 na $m^2 \cdot s$

Promieniowanie kosmiczne

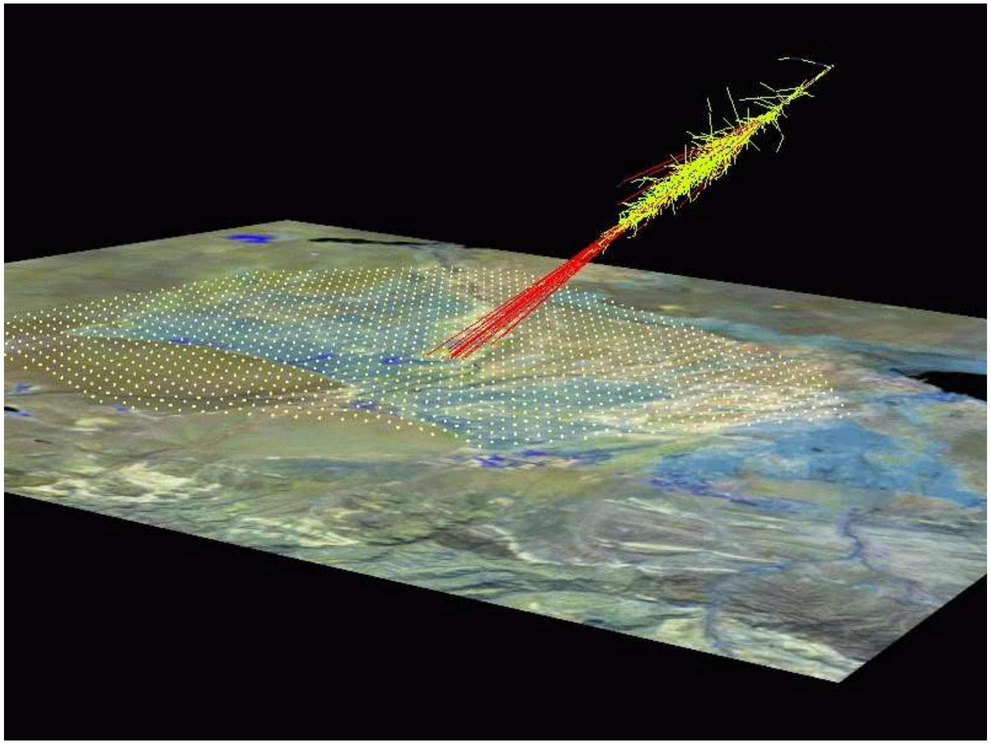
Wykorzystanie

Do lat 50 XX w. badanie oddziaływań promieniowania kosmicznego z materią było jednym z głównych kierunków badań.

Wciąż pozostaje ważnym źródłem danych.

Budowane są coraz większe detektory do pomiaru promieniowania kosmicznego najwyższych energii.

Ważne narzędzie kalibracji detektorów.



Projekt “Pierre Auger Observatory”:
obserwacja promieniowania czerenkowa i fluorescencji kaskady w atmosferze.
1600 detektorów rozmieszczonych na obszarze 3000 km^2

Obserwatorium Pierre Auger

Badanie promieni kosmicznych w zakresie najwyższych obserwowanych energii, E > 10 EeV (>10^{19} eV):

składad
	lekkie czy ciężkie jądra, fotony, neutrina, ??

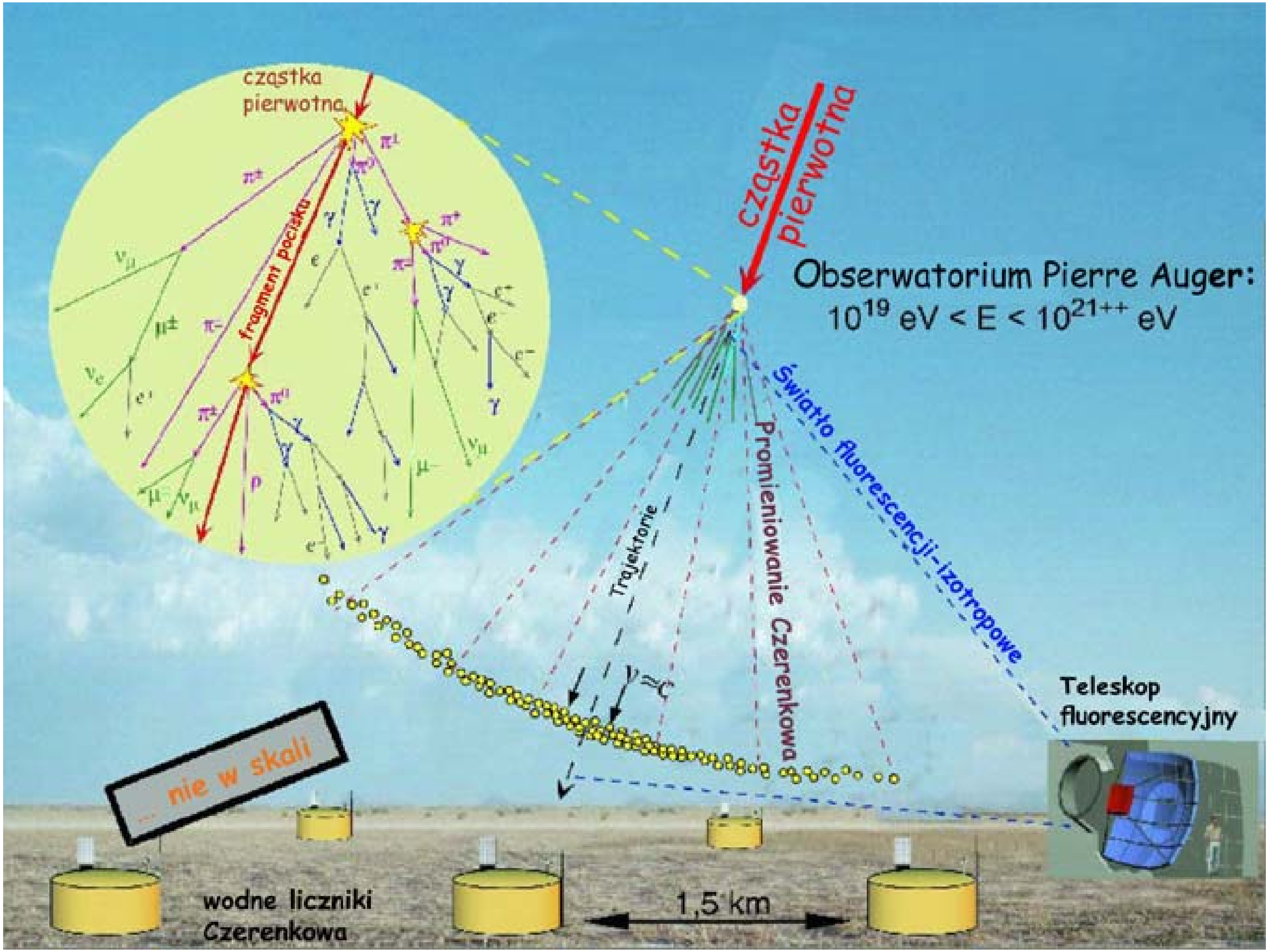
widmo energii
	kształt widma w zakresie efektu GZK

rozkład kierunkowy
	anizotropia, źródła punktowe

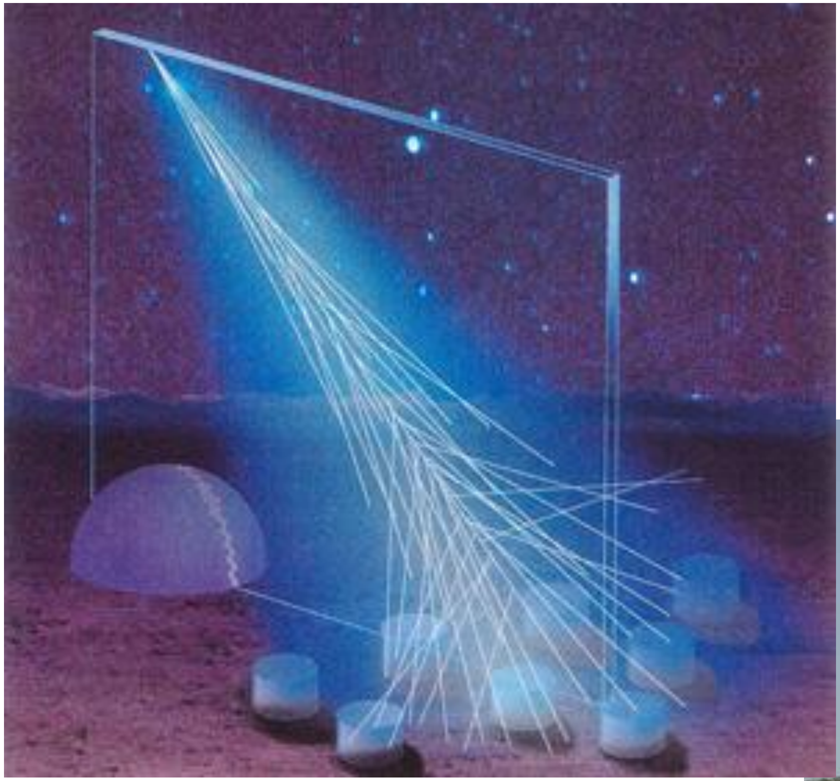
$\rightarrow$ wyjaśnienie ich pochodzenia ???

- obserwacja całego nieba – detektory w Argentynie i w USA
- 2 * 3000 km^2 $\rightarrow$ duża statystyka danych
- hybrydowa detekcja wielkich pęków: dwa układy detektorów

Wielki pęk atmosferyczny



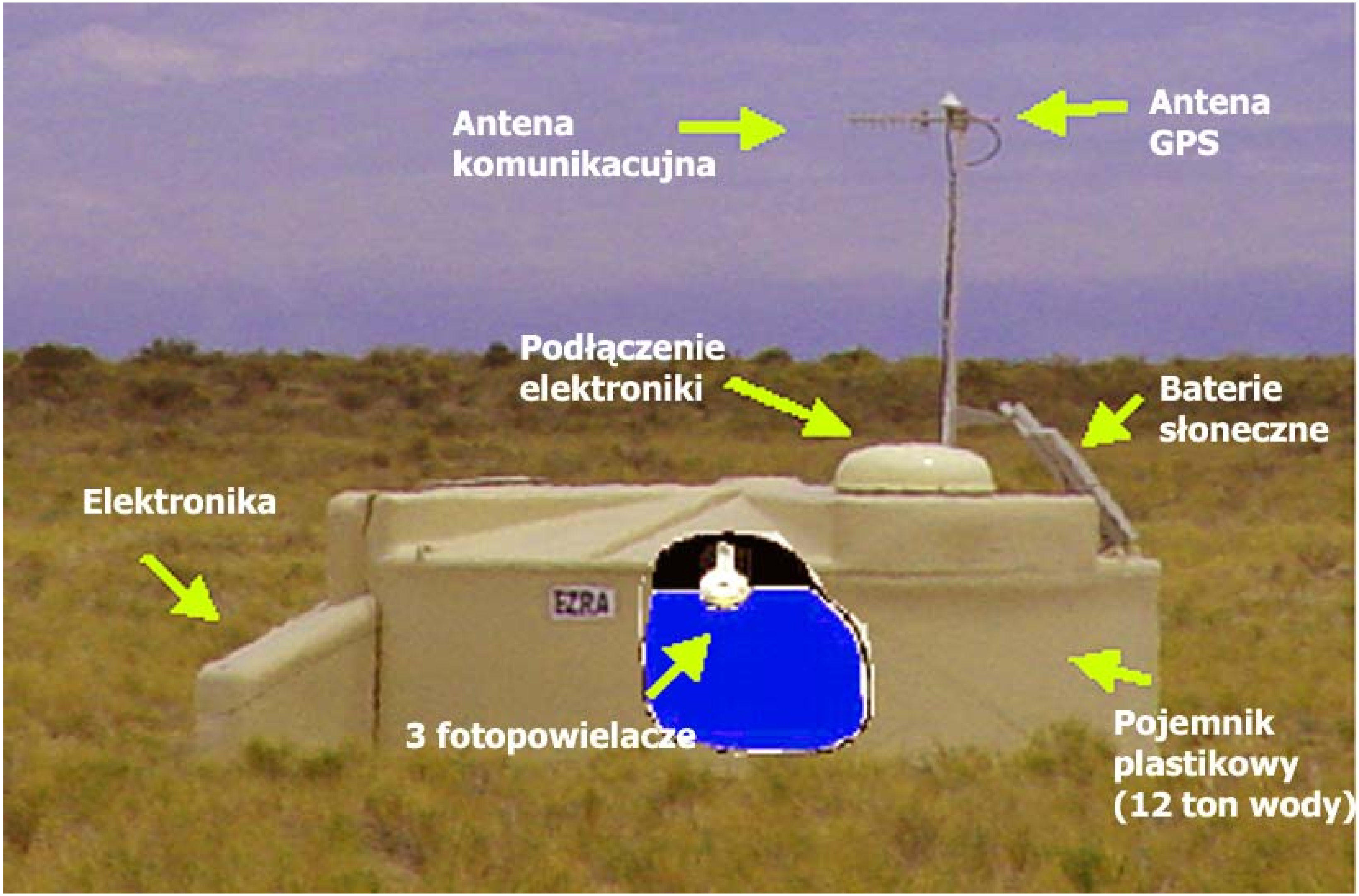
Pierre Auger Cosmic Ray Observatory



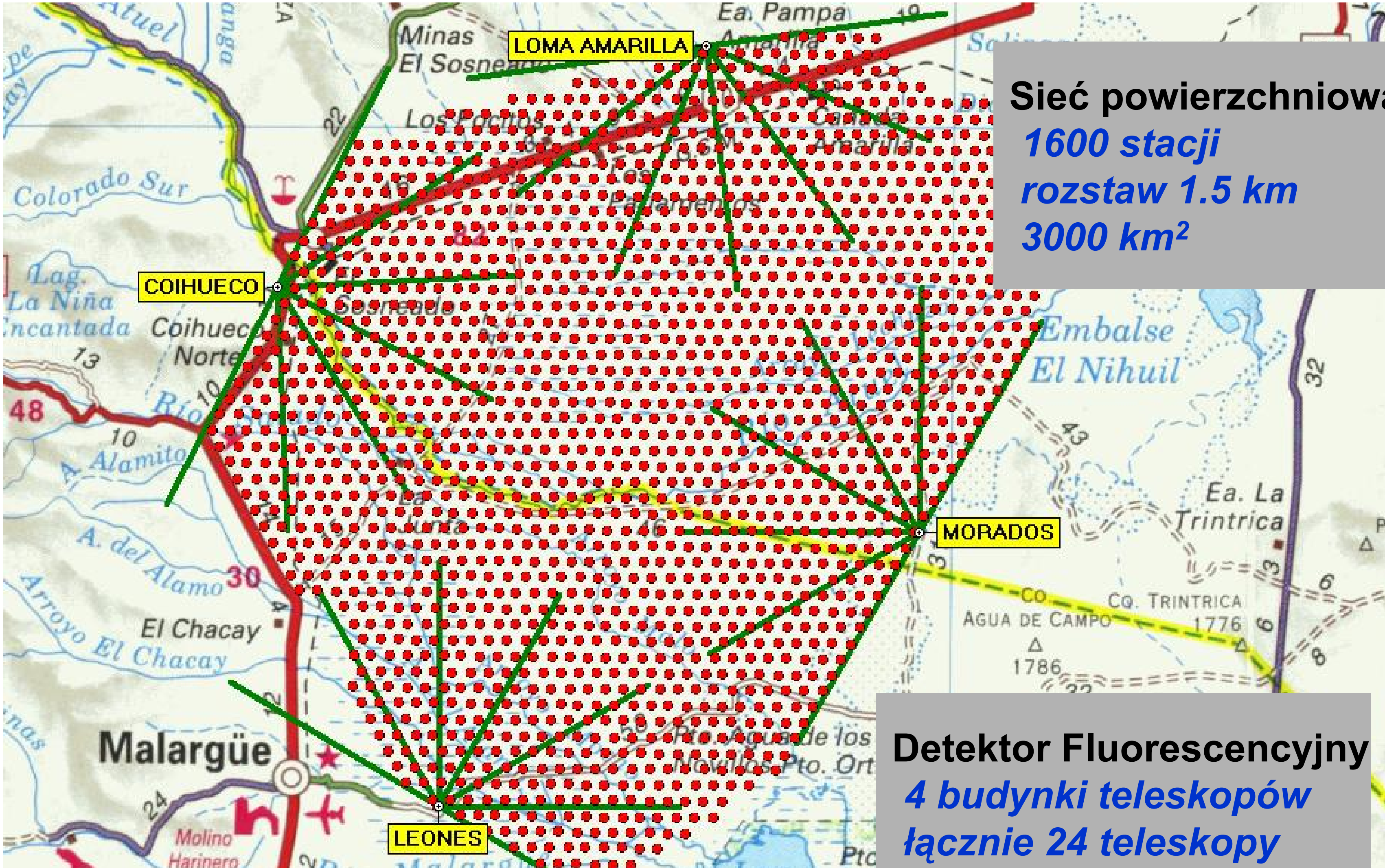
Use earth's atmosphere as a calorimeter. 1600 water Cherenkov detectors with 1.5km distance.

Placed in the Pampa Amarilla in western Argentina.

Detektor naziemny



Obserwatorium Pierre Auger



Sieć powierzchniowa

1600 stacji

rozstaw 1.5 km

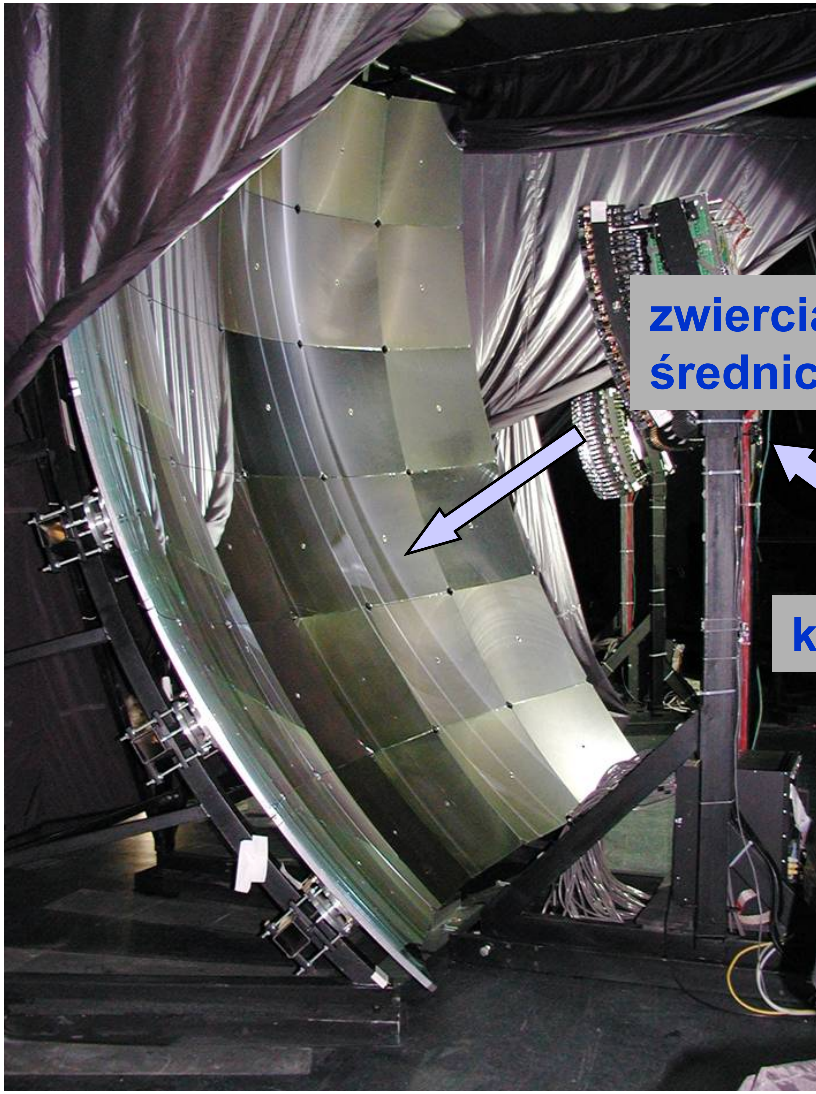
3000 km²

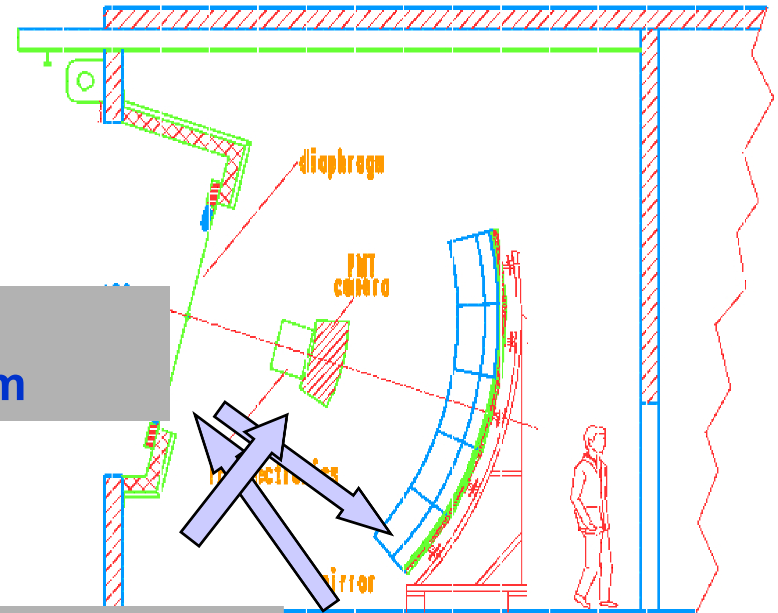
Detektor Fluorescencyjny

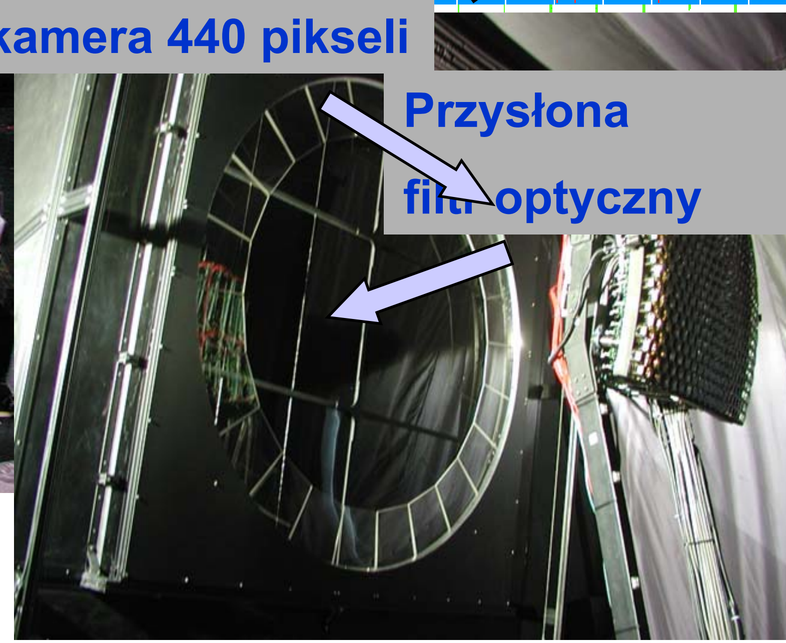
4 budynki teleskopów

łącznie 24 teleskopy

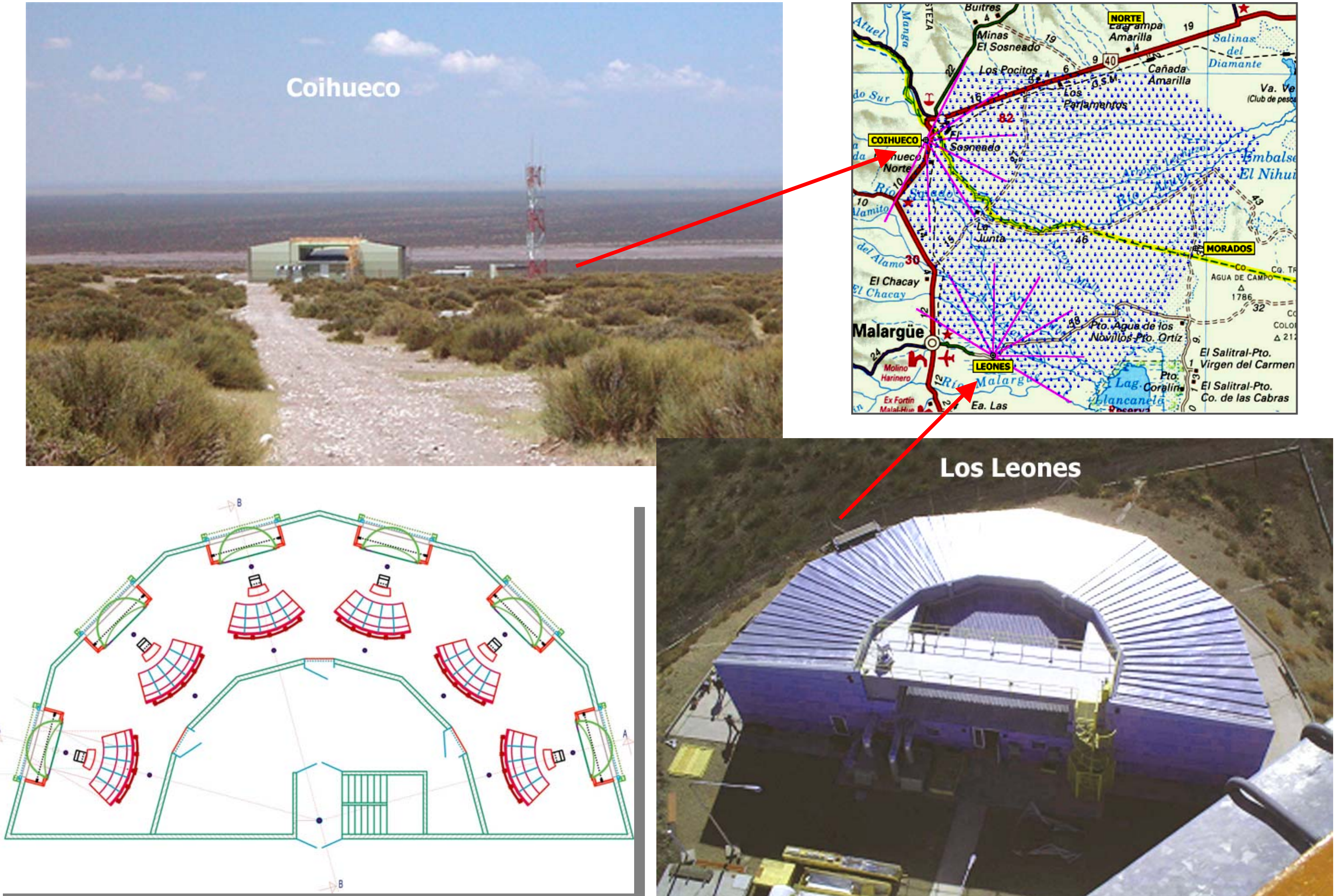
Detektor Fluorescencyjny



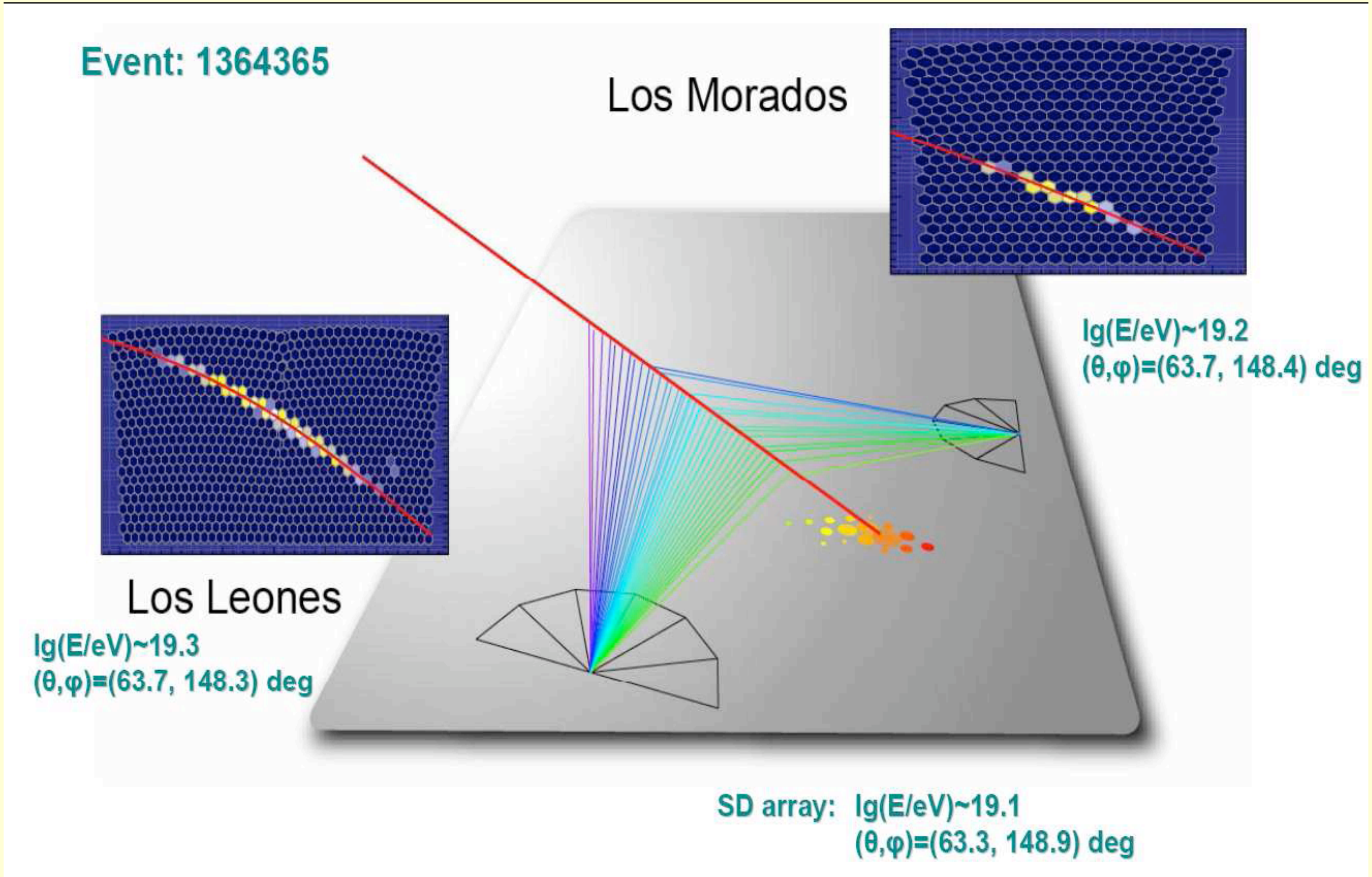




Detektory fluorescencyjne



Przykład rzeczywistego pęku



Goals of the Observatory

Detection with high statistics of cosmic rays with energies >10^{19}eV.

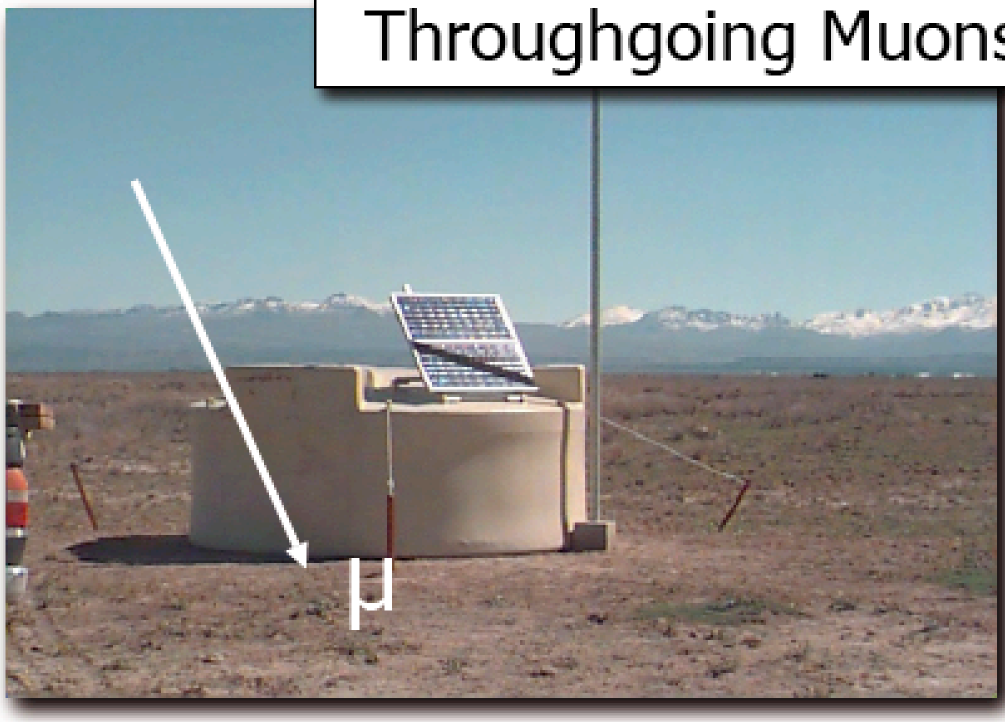
- Spectrum
  - ➡ Requiers a good energy determination ≈ 20 - 30 %
- Arrival directions
  - ➡ Angular resolution ≈1°
- Composition
  - ➡ Fast electronics to measure details of the shower front (SD)
  - ➡ Field of view to observe shower development (FD)

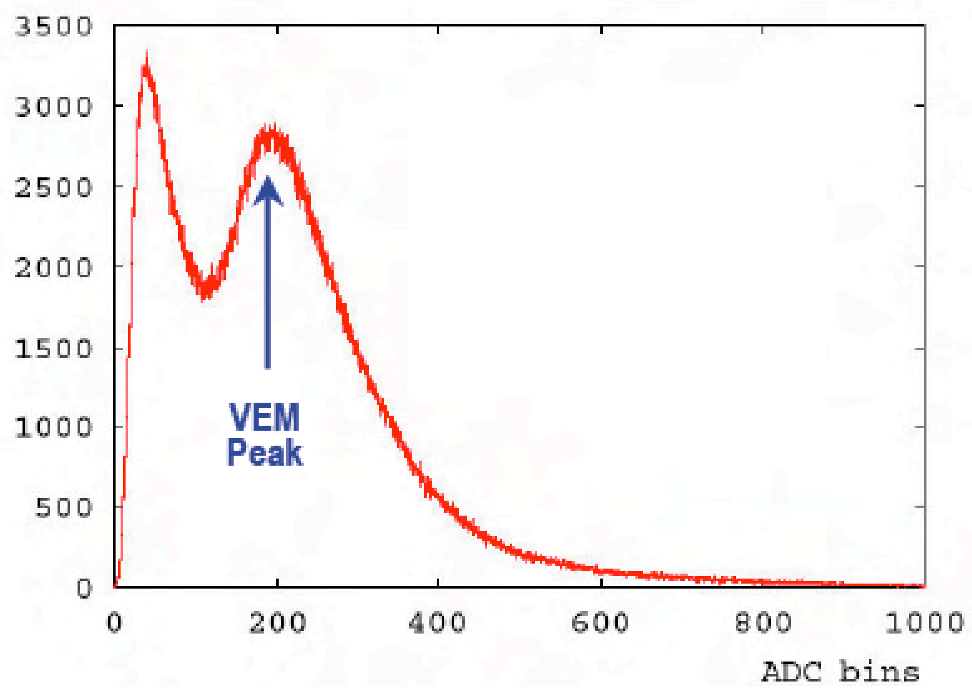
➡ Science results

Detector Calibration

Ground-Array

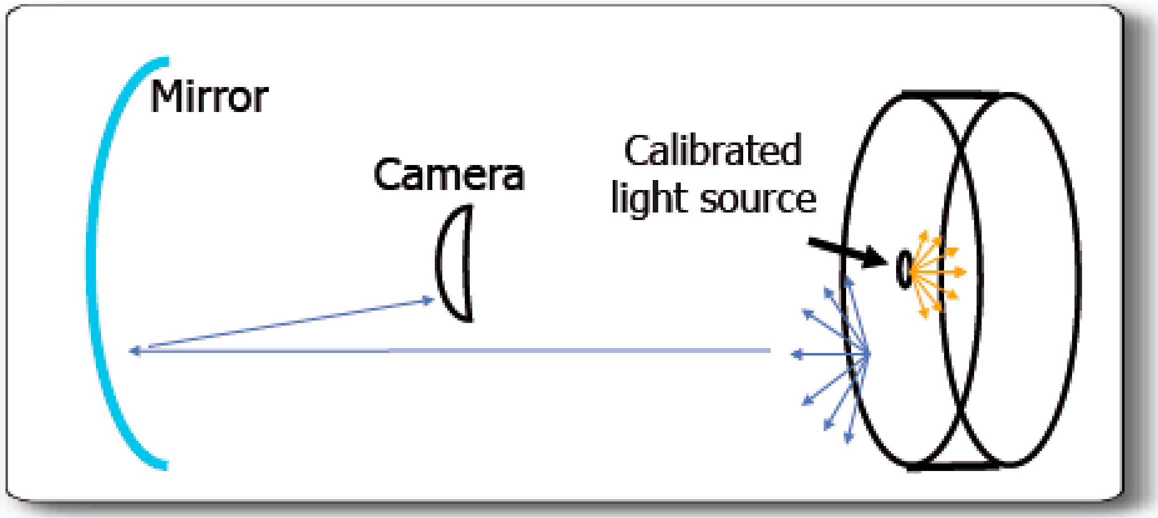
Throughgoing Muons





Fluorescence Telescopes

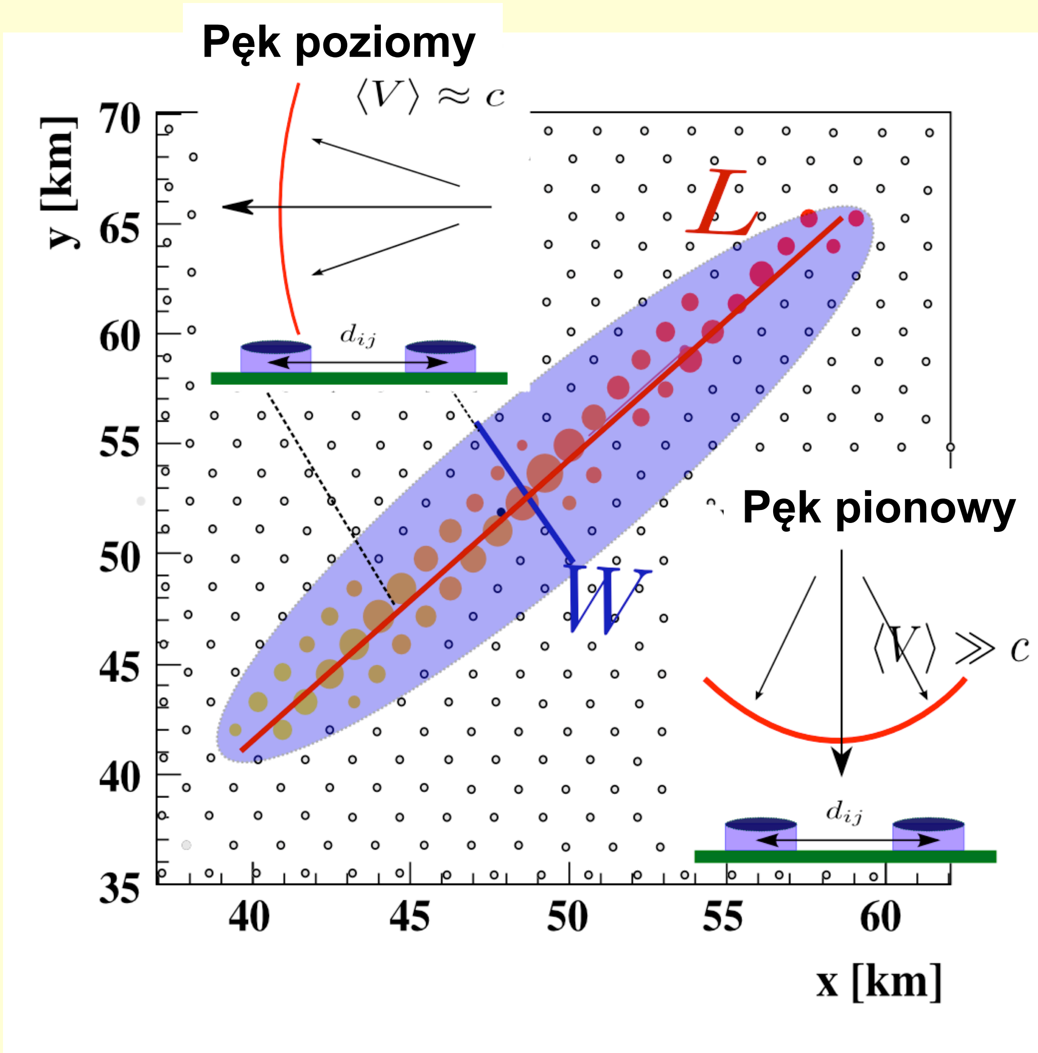
Diffuse Lightsource



Obserwable
(analiza śladu pęku widzianego przez detektor powierzchniowy)

(P. Billoir, O. Blanch Bigas, Nucl. Phys. Proc. Suppl. 168 (2007) 225-231)

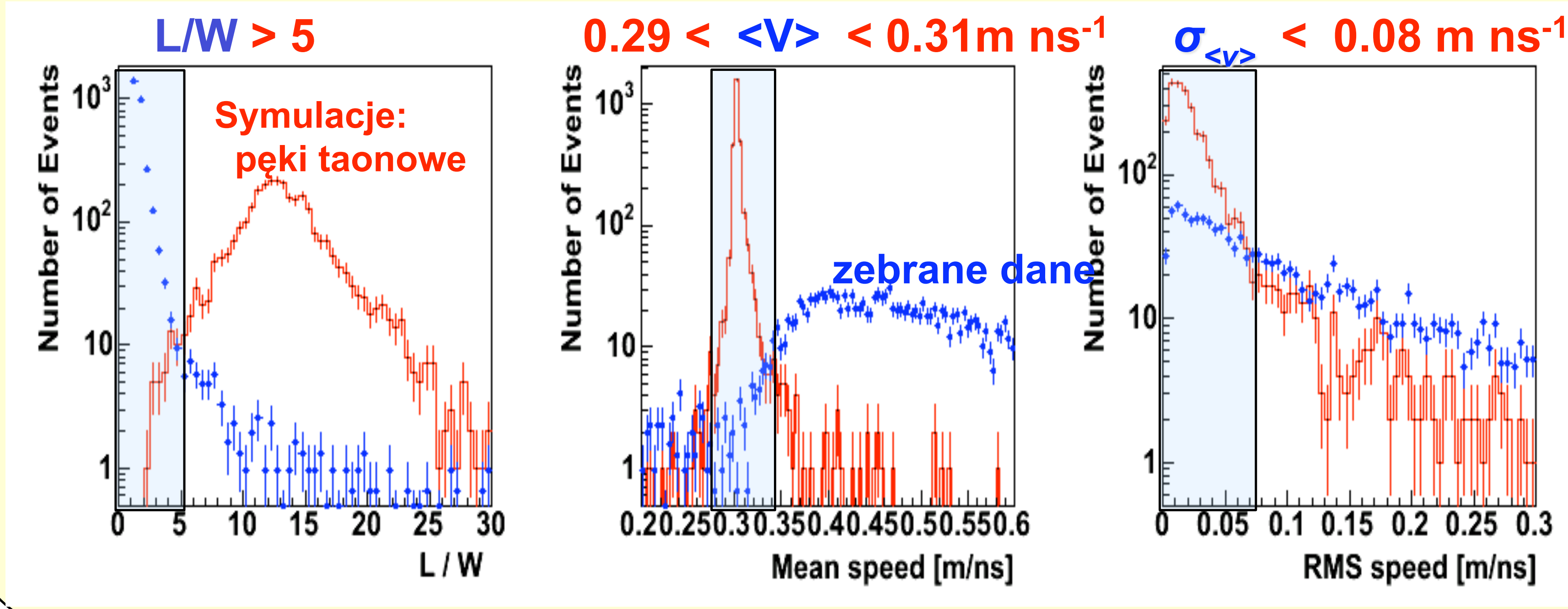
- **długość L i szerokość W: główna i boczna oś elipsoidy inercji ważonej przez sygnał stacji.**
- **prędkość efektywna <V>: dla każdej pary stacji (odległość zrzutowana na główną oś elipsoidy/ różnica pomiędzy czasem triggera)**
- **odchylenie standartowe prędkości efektywnej $\sigma_{<V>}$**



Kryteria selekcji neutrinowych pęków

(dla pęków lecących z dołu , dla obserwatorium Auger)

Selekcja pęków poziomych



Selekcja pęków z silną składową EM

60% stacji z sygnałem ToT

- powyższe kryterium + dane z obs. Auger 01/2004-08/2007 => 0 kandydatów

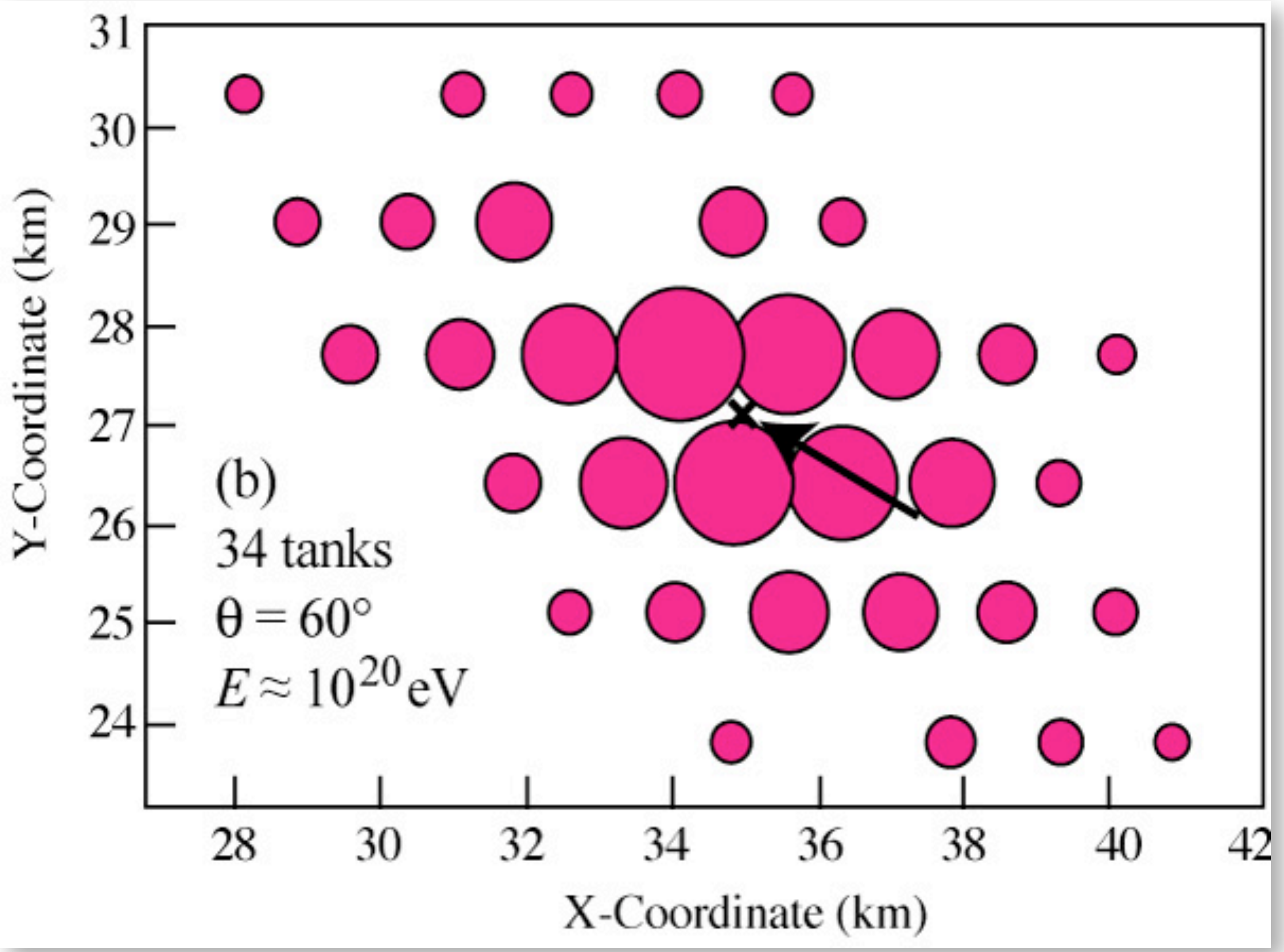
  The Pieer Auger Collaboration, *Phys. Rev. Lett.* 100, 211101 (2008)

- aktualizacja: powyższe kryterium+dane 01/2004-02/2009 => znów 0 kandydatów

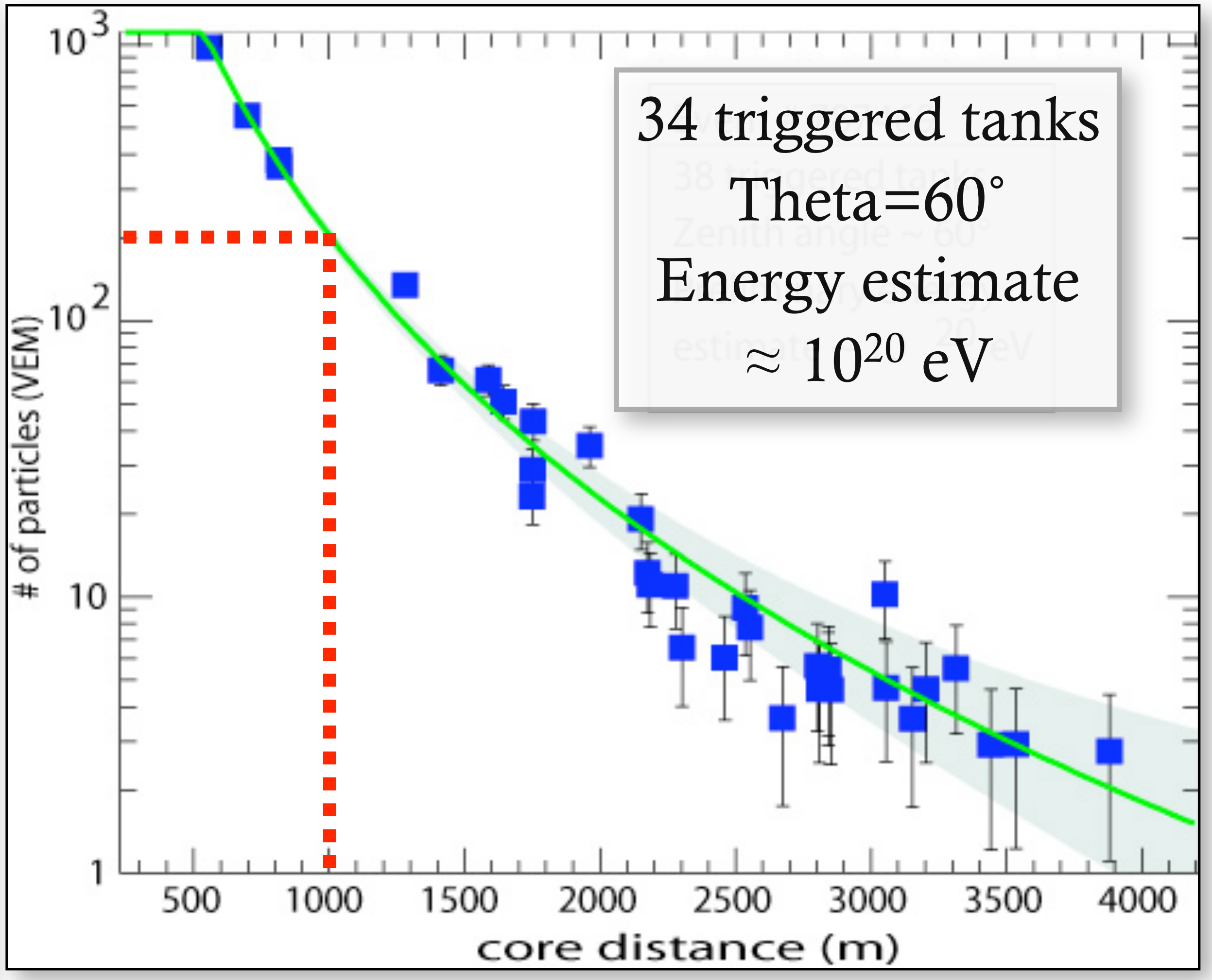
  The Pierre Auger Collaboration, *Phys. Rev. D 79, 102001* (2009)

Primary energy determination: SD

SD measures the lateral structure of the shower at ground



One event seen by SD



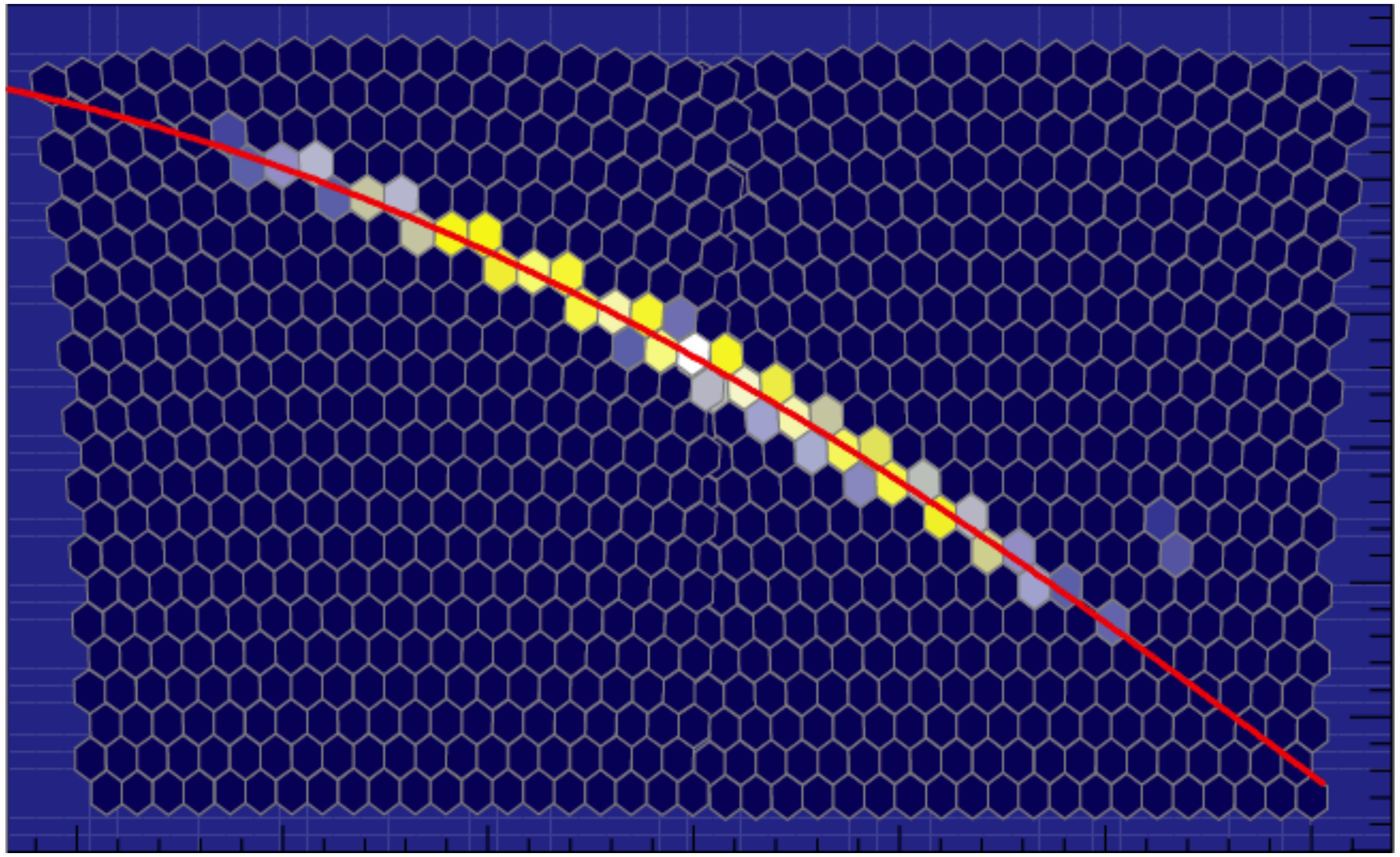
Particle lateral distribution

- Reconstruct geometry (arrival direction & impact point)
- Fit particle lateral distribution (LDF)
- S(1000) [signal at 1000 m] is the Auger energy estimator

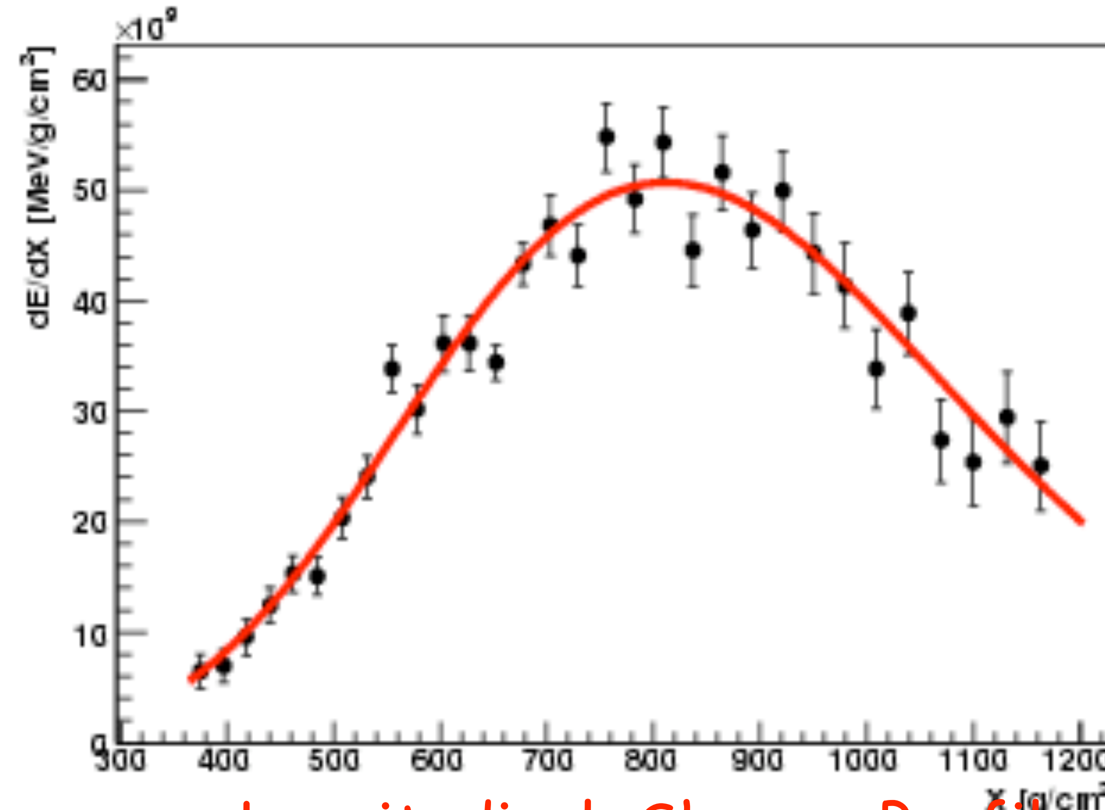
  ("ideal" distance depends on detectors spacing)

Primary energy determination: FD

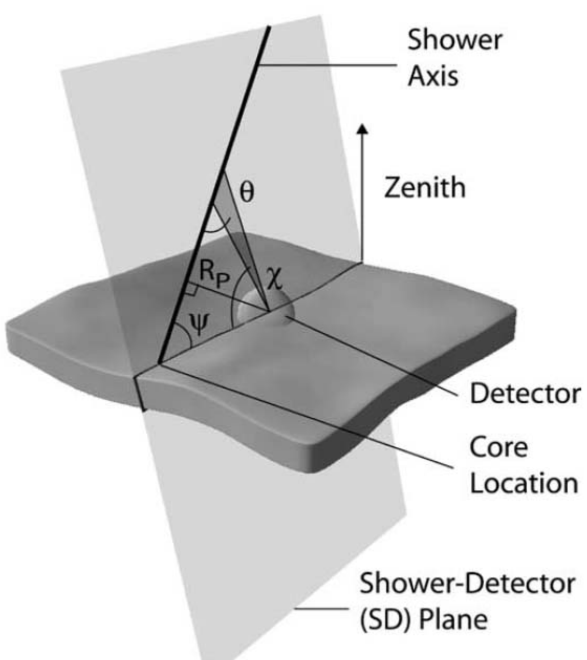
FD records the longitudinal profile of the shower during its development in atmosphere



One event seen by FD



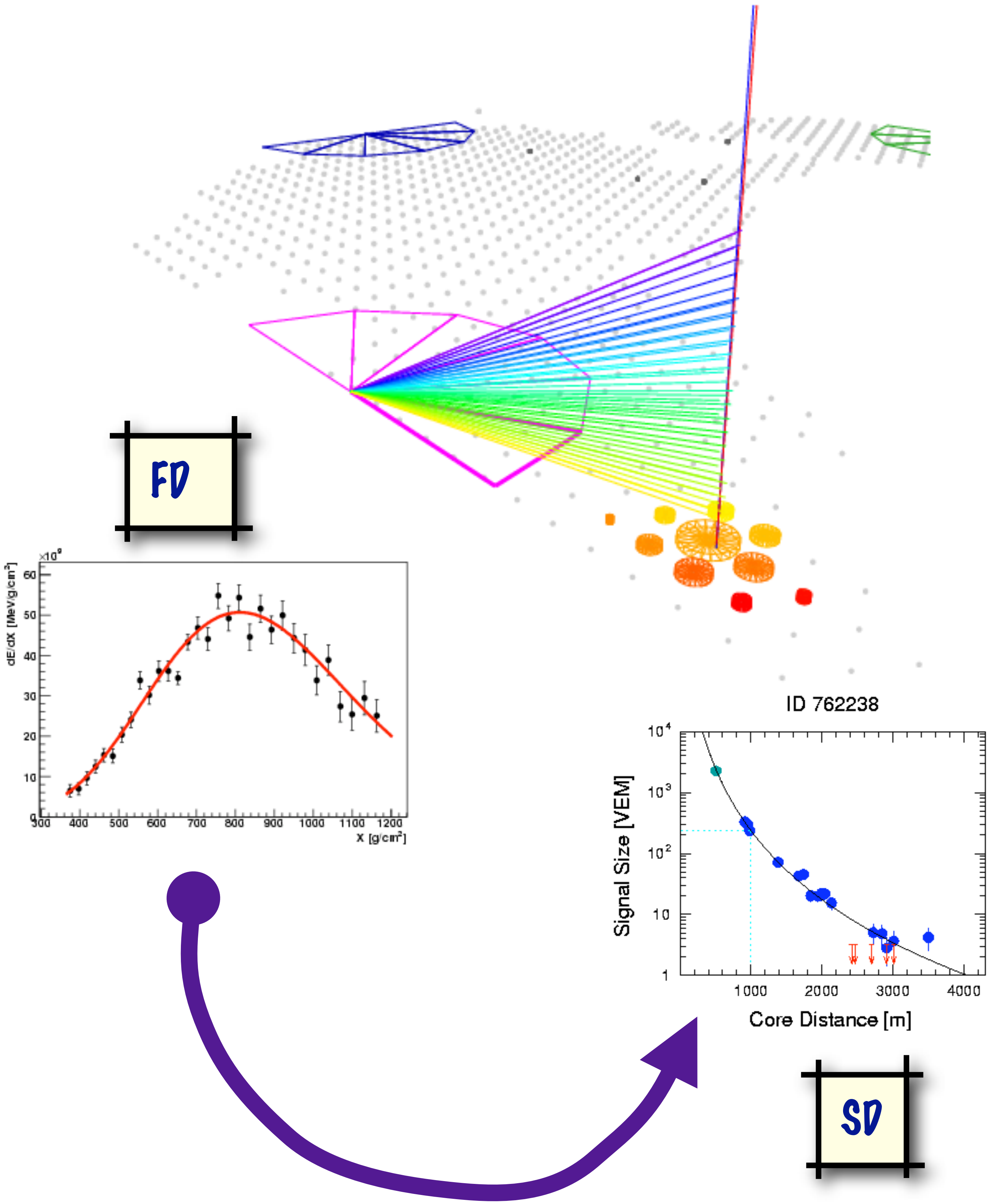
Longitudinal Shower Profile



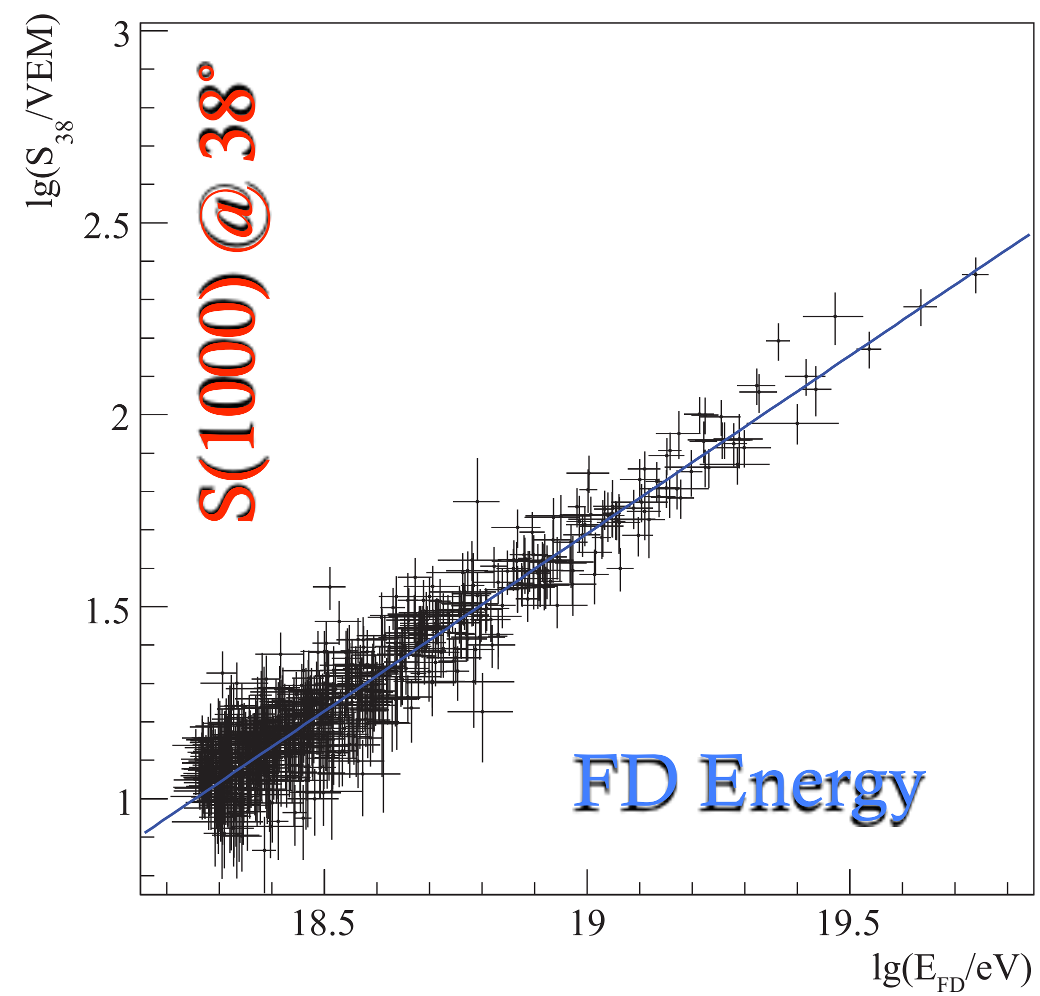
- Reconstruct geometry (shower detector plane, SDP, and shower axis in SDP)
- Fit longitudinal shower profile
- E ∝ area under the curve
- Calorimetric measurement

$$\int \frac{dE}{dX} dX \sim E$$

Primary energy determination: SD+FD



Hybrid Events are used to calibrate the SD energy estimator, S(1000) (converted to the median zenith angle, S38) from the FD calorimetric energy



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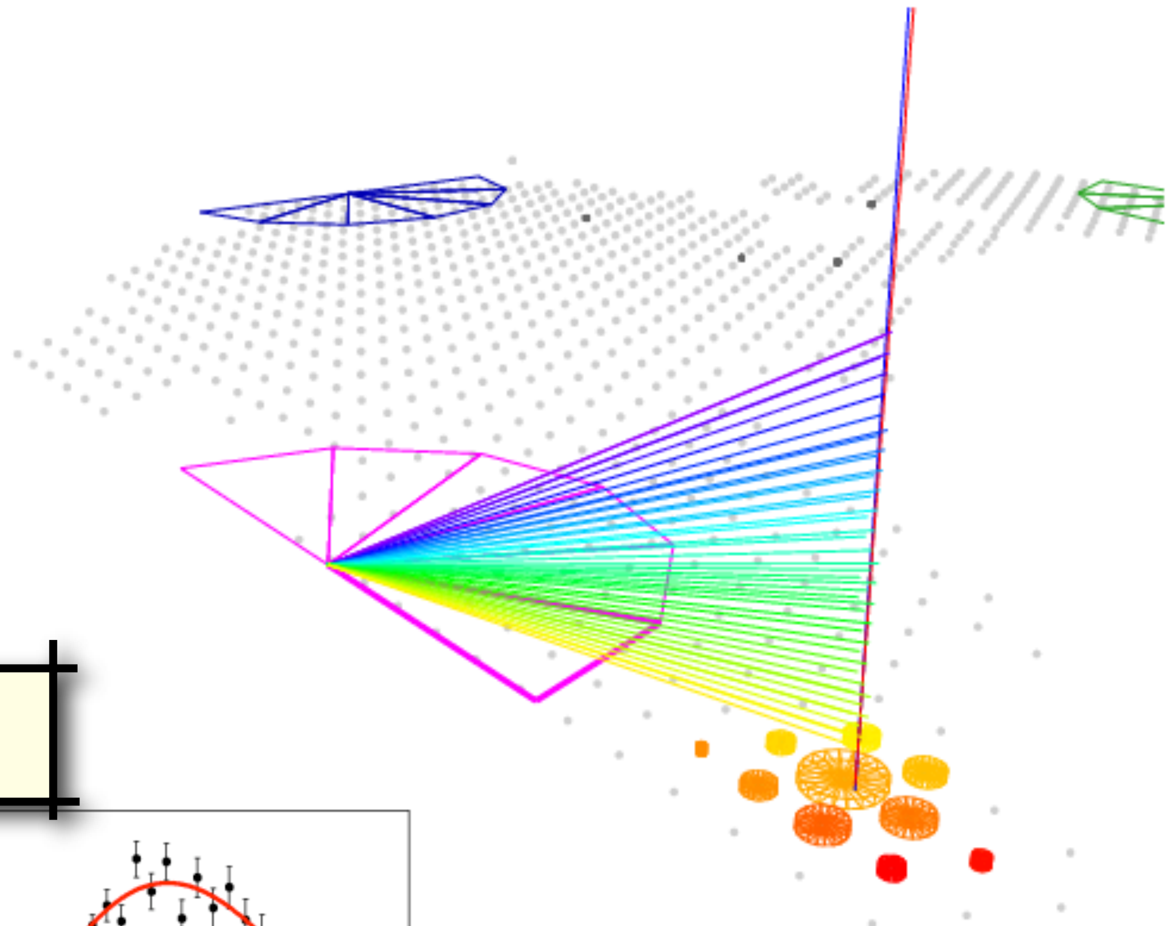
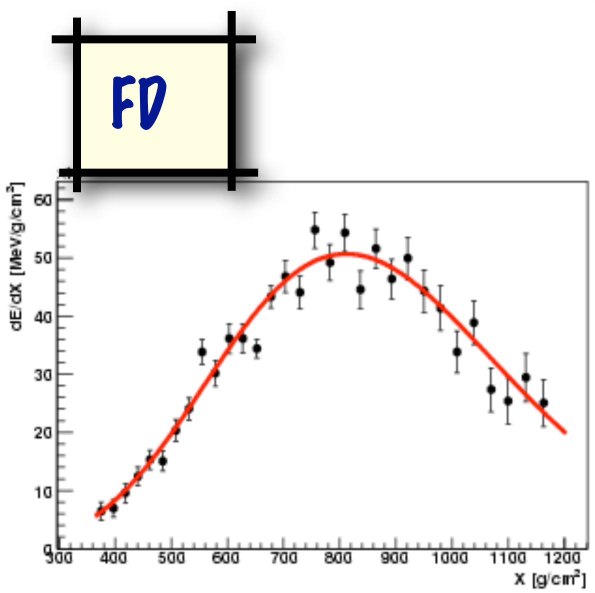
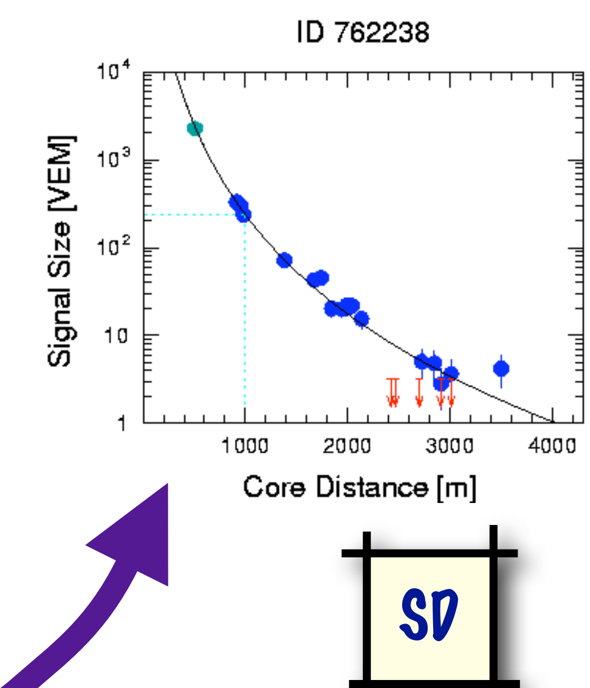
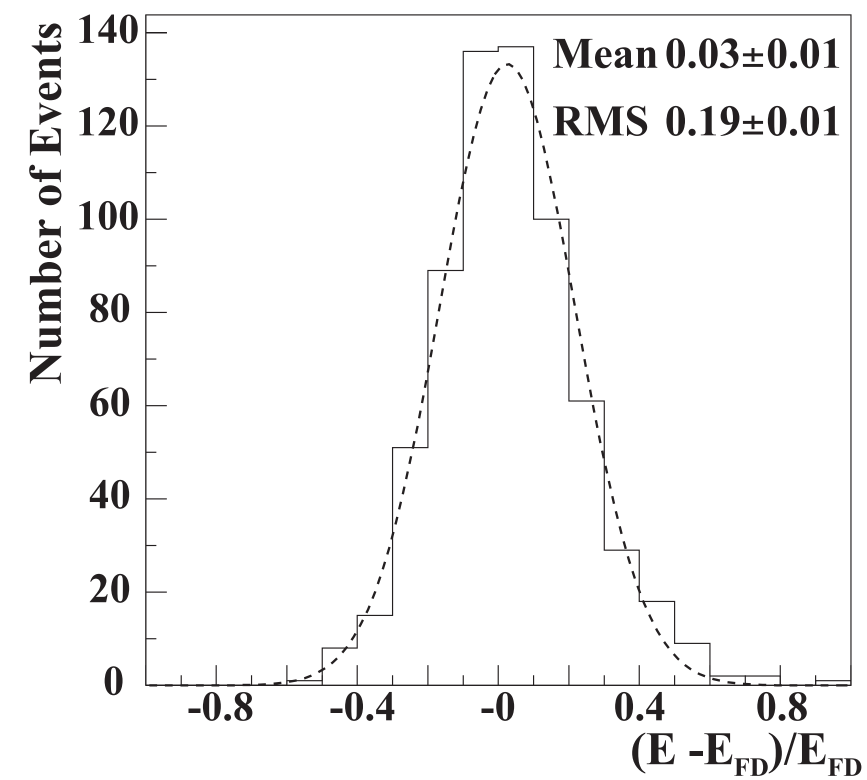


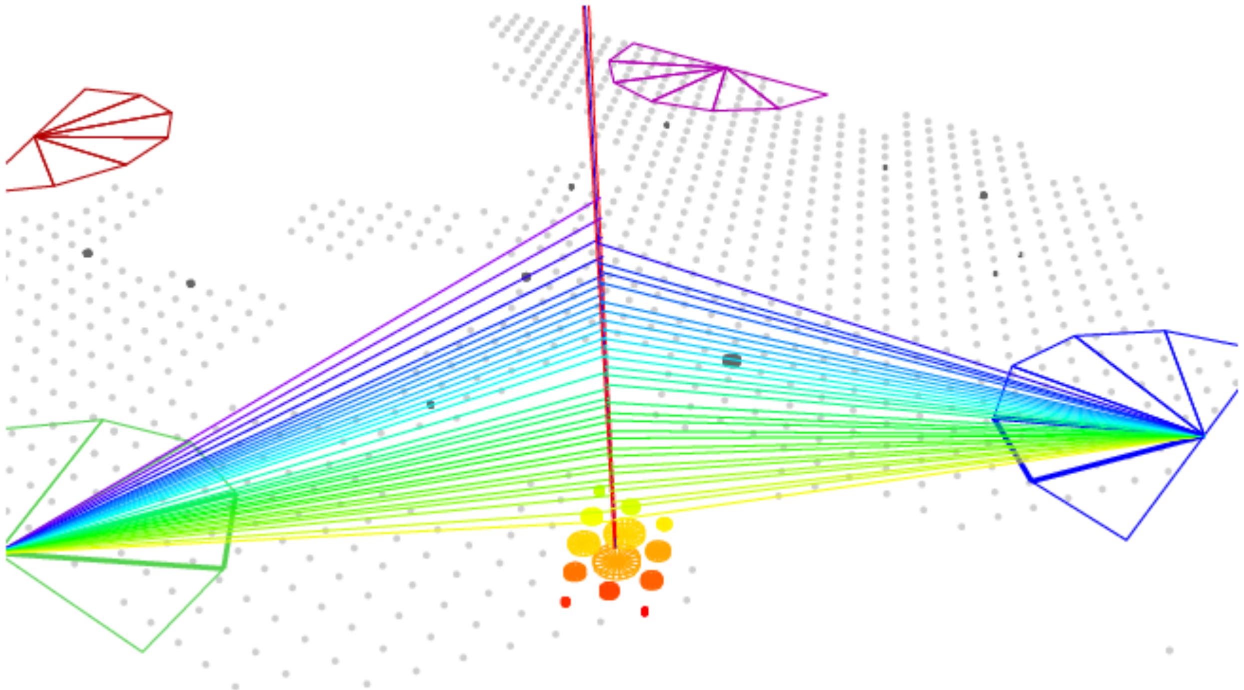






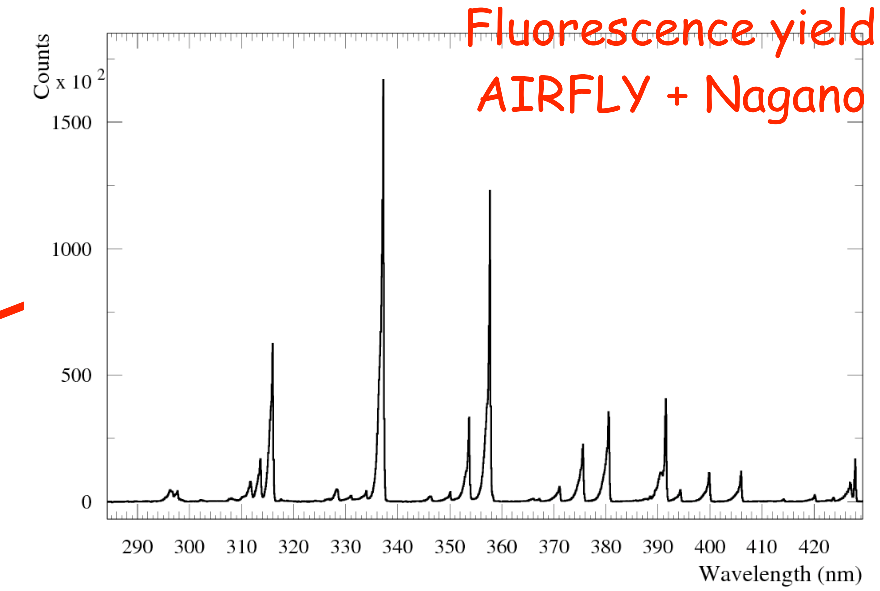
Energy resolution: statistical ≈ 19%

FD Energy systematic uncertainty



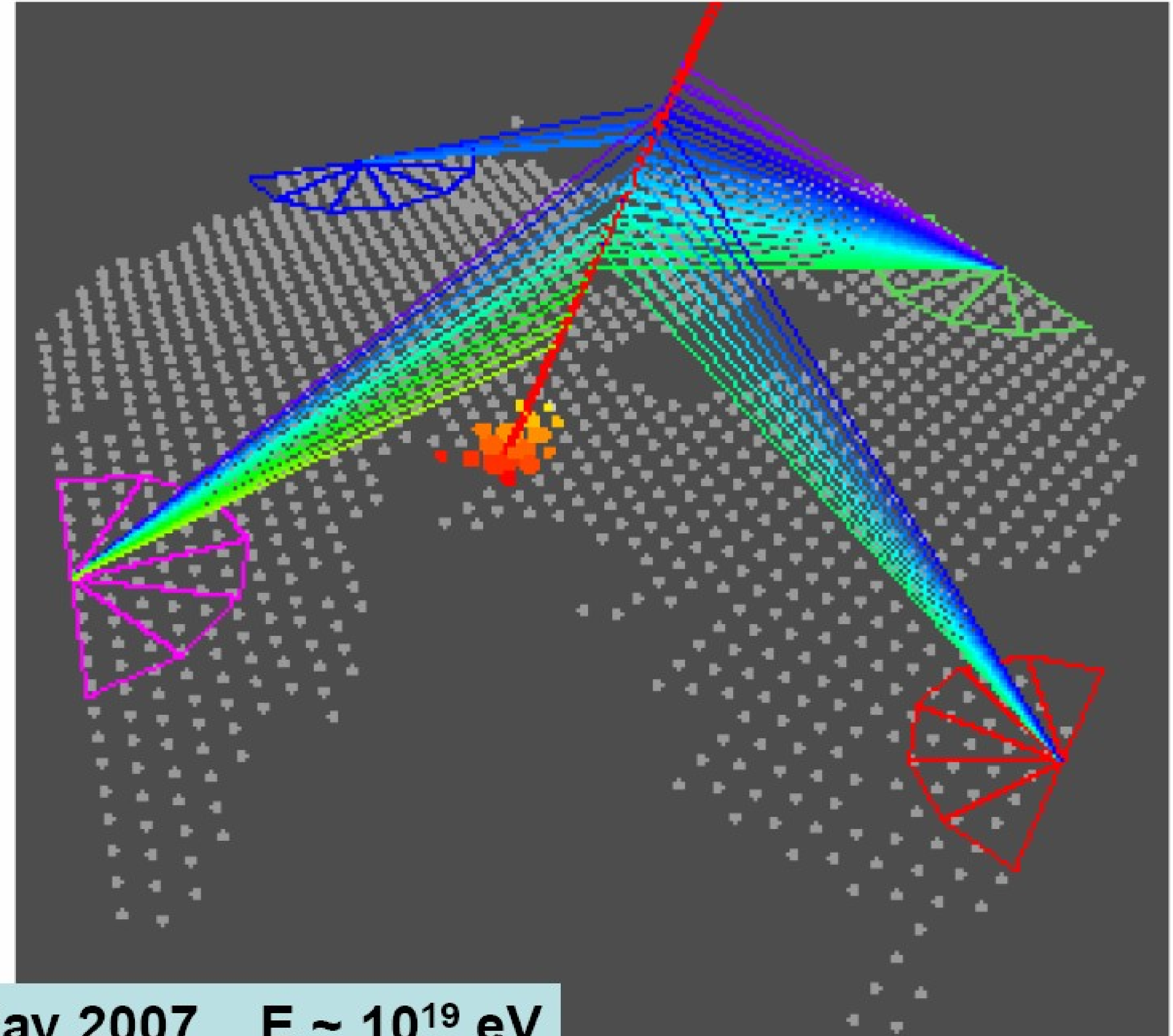
Stereo events
⇒ reconstruction uncertainty

- 10%, consistent with MC



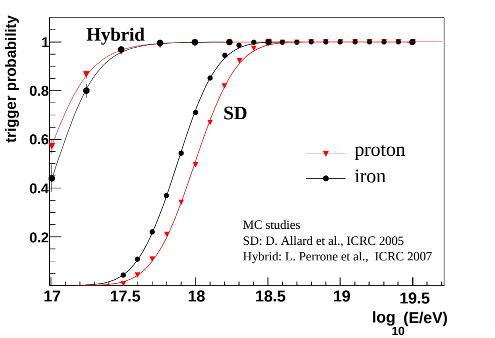
Source	Systematic uncertainty
Fluorescence yield	14%
P,T and humidity effects on yield	7%
Calibration	9.5%
Atmosphere	4%
Reconstruction	10%
Invisible energy	4%
TOTAL	22%

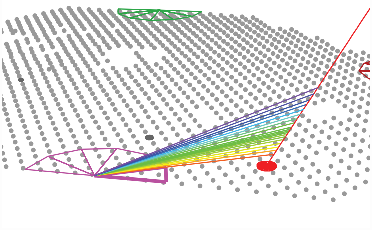
Total FD E uncertainty: 22%



20 May 2007 E ~ 10^{19} eV

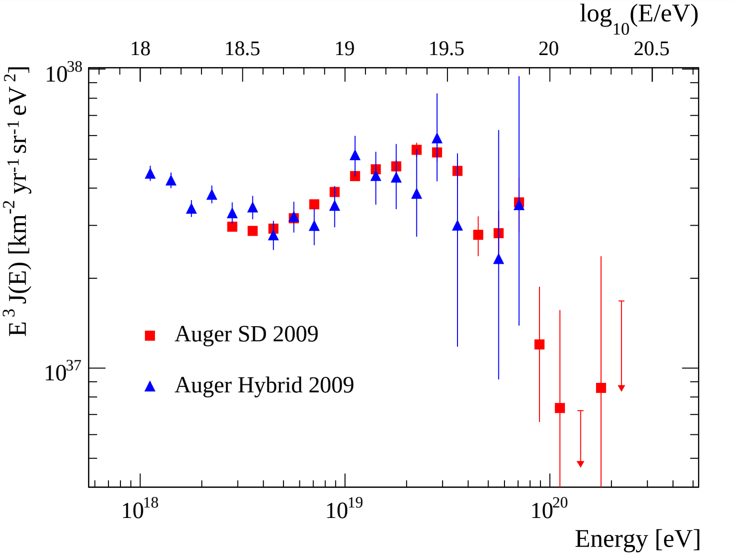
Extending the energy range with hybrid events





- energy threshold $10^{18}\,\mathrm{eV}$ covering the ankle region
- good energy resolution $\sigma(E)/E < 10\%$
- calorimetric energy measurement

Energy spectrum from hybrid data



FERMI: A NEW VIEW OF THE HIGH ENERGY UNIVERSE

LARGE AREA TELESCOPE: INTRODUCTION AND SCIENCE HIGHLIGHTS

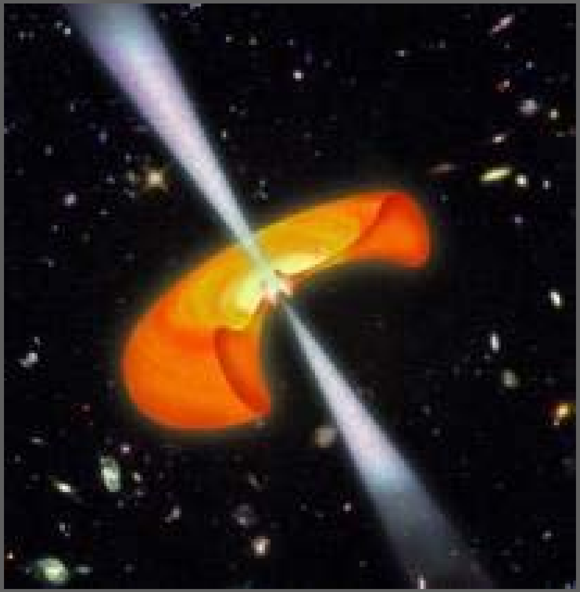
Peter F. Michelson
Stanford University

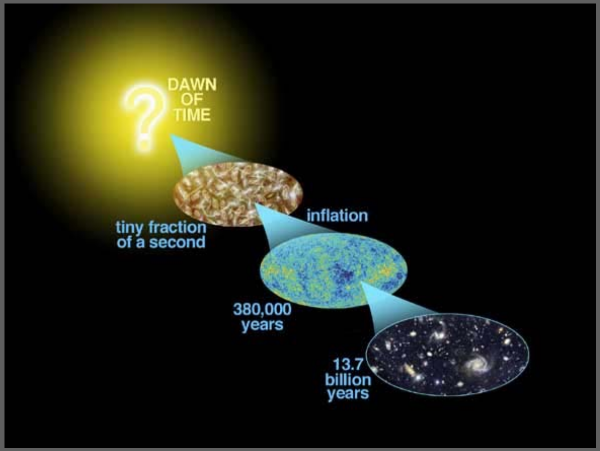
Principal Investigator, Large Area Telescope Collaboration

on behalf of the Fermi LAT Collaboration and the Fermi mission

Characteristics of γ rays

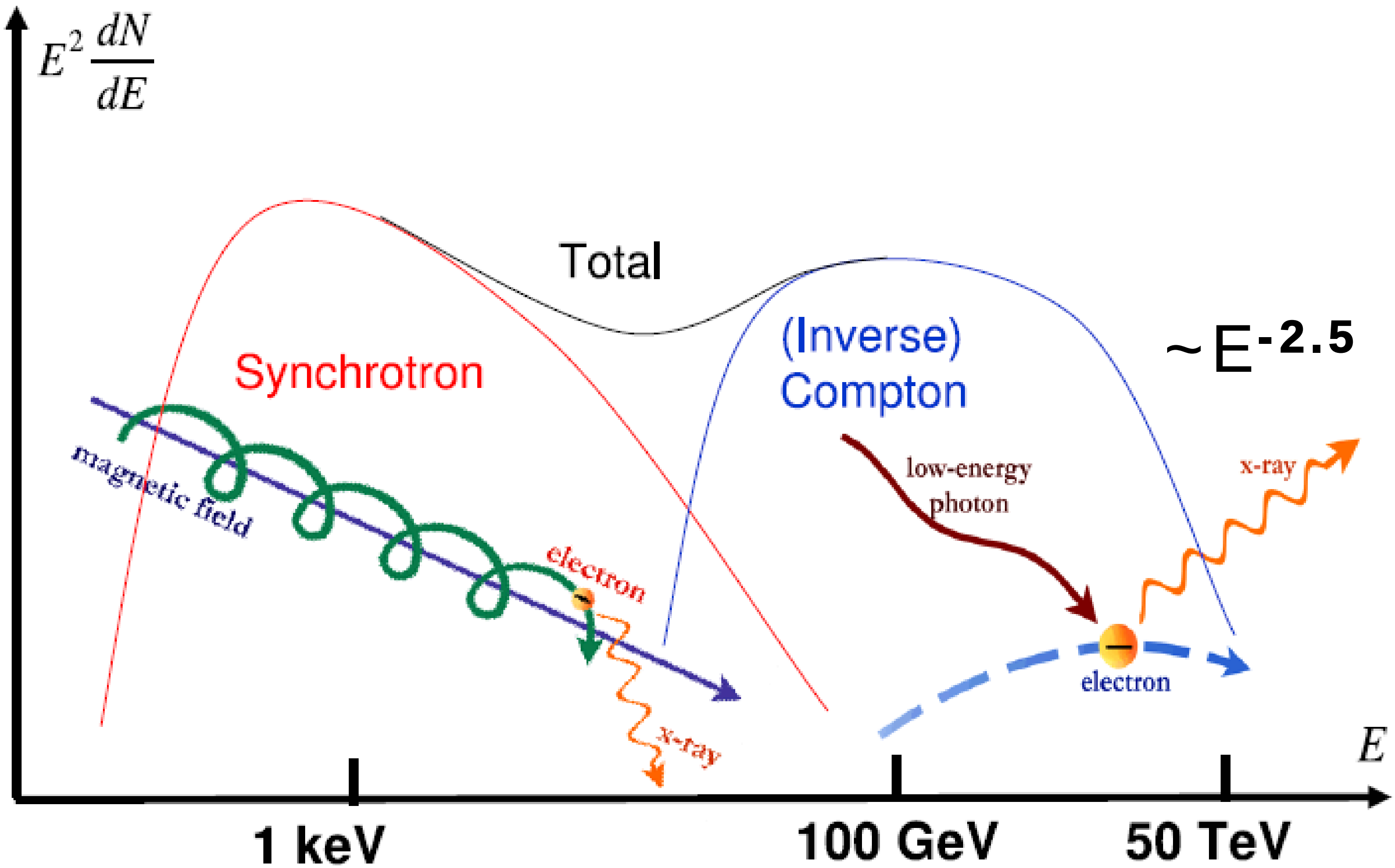
- Most violent processes in the Universe
  - Extreme conditions in Nature
- Non thermal emission
  - Acceleration on several distance and time scales
- Direct information from the source
  - Neutral particles
- Universe is transparent to gamma rays
  - Opacity is energy dependent





SSC: a (minimal) standard model

SSC explains most observations, not necessarily the most interesting…

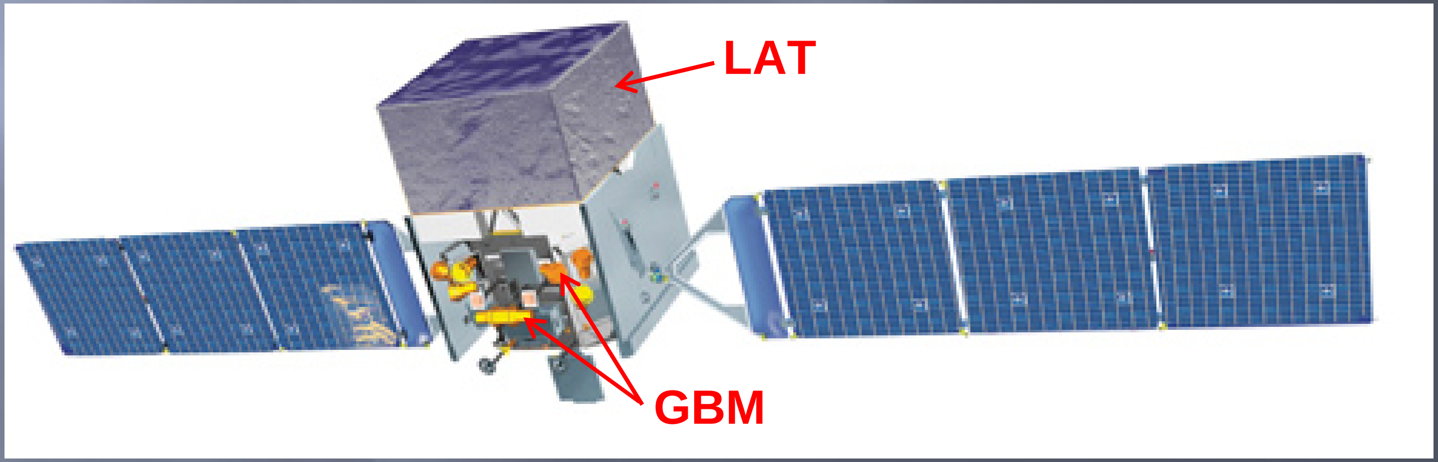


Exploring the High-Energy Universe

- gamma rays provide a direct view into Nature's largest accelerators (neutron stars, black holes)

- gamma rays probe cosmological distances
  (e.g., $\gamma + \gamma_{EBL} \rightarrow e^{+} + e^{-}$)

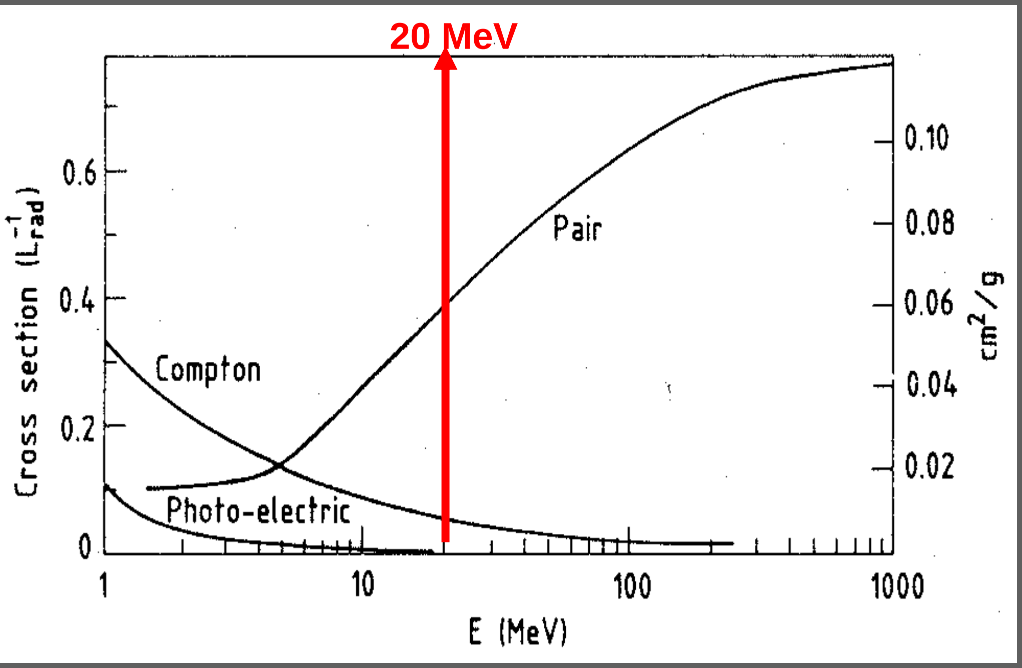
- huge leap in key capabilities, including a largely unexplored energy range; great potential for discovery: e.g. dark matter



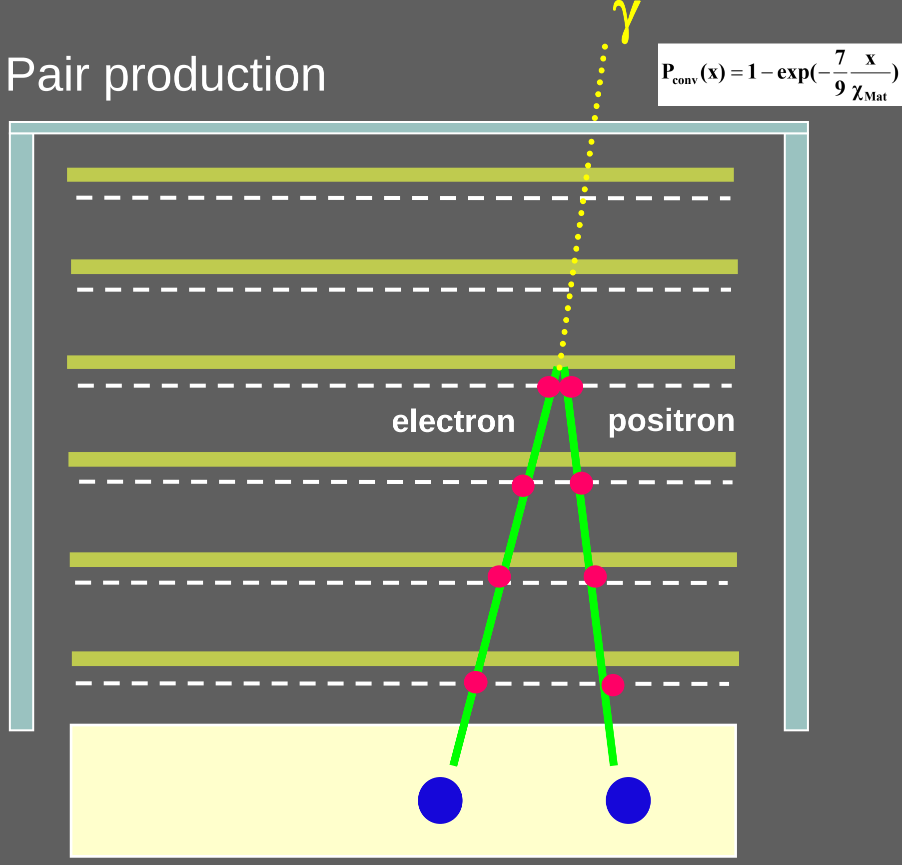
Two instruments: Large Area Telescope (LAT), 20 MeV - >300 GeV
Gamma-ray Burst Monitor (GBM), 10 keV - 25 MeV

Gamma Ray Space Telescopes

- **Short wavelength**
  - **Radiation cannot be focused**
- **Cross section increases ~ 20 MeV**
  - **Pair production dominates**



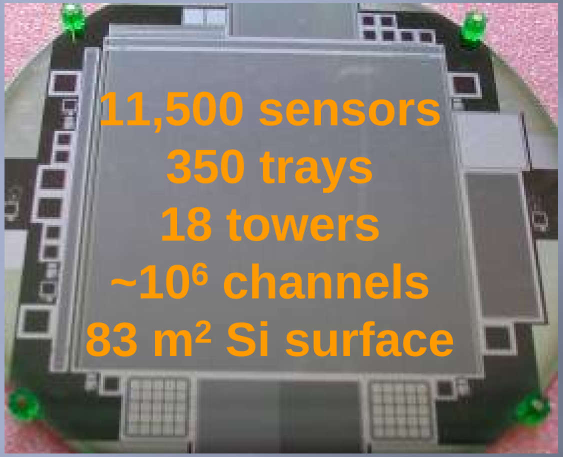
Pair production

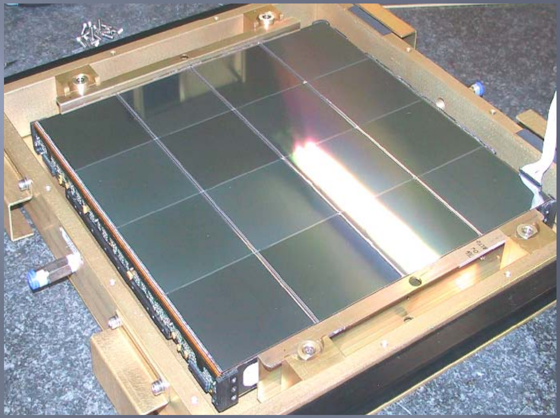


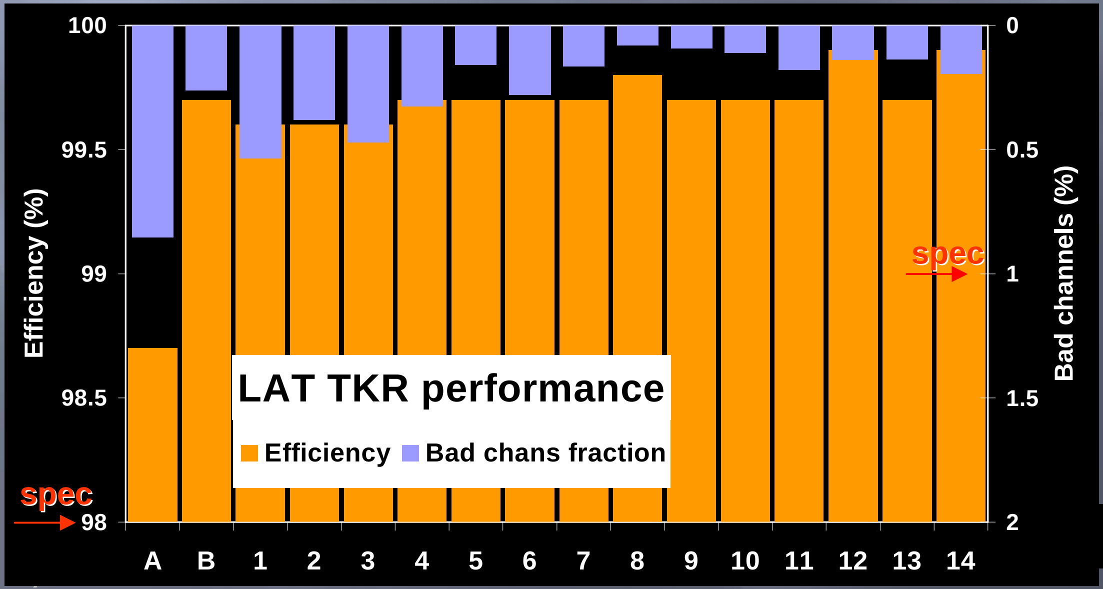
$$A_{eff} \cong A_{Geo} \cdot P_{conv} \cdot \varepsilon_{Ana}$$

LAT Silicon Tracker

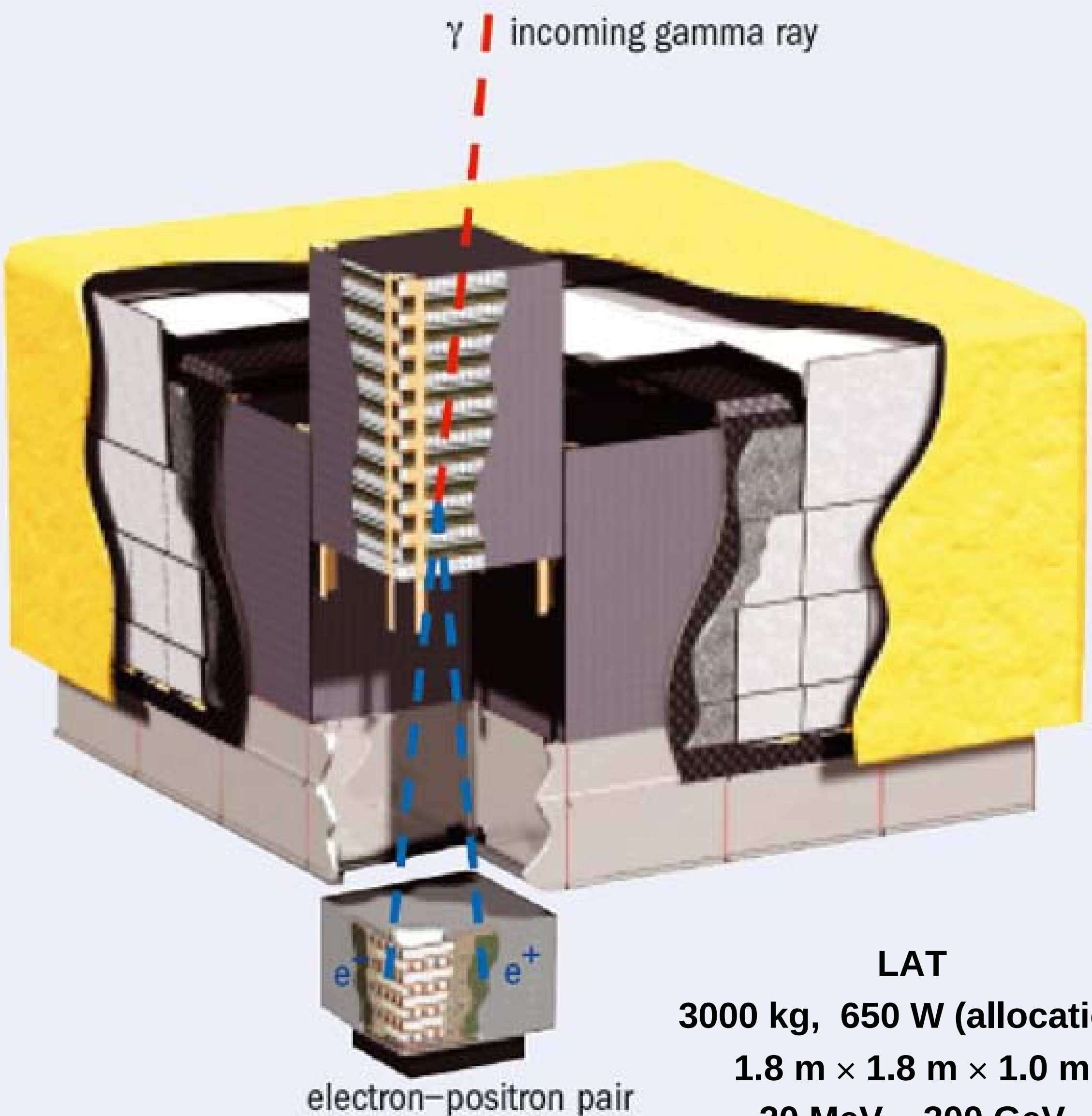
Silicon strip detectors from Hamamatsu Photonics and Japan GLAST Collaboration are a key part of LAT's success







Large Area Telescope



LAT

3000 kg, 650 W (allocation)

1.8 m × 1.8 m × 1.0 m

20 MeV – 300 GeV

Tracker

γ direction and identification

Calorimeter

γ energy

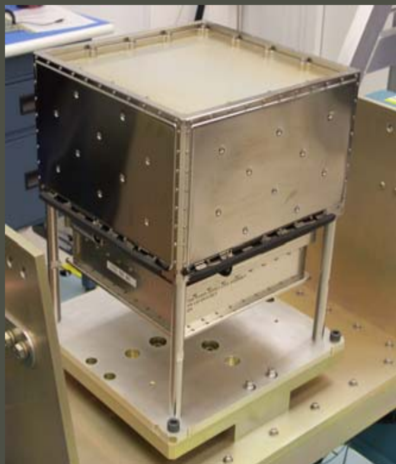
image particle showers

Anti-coincidence detector

Background rejection

segmentation reduces self-veto at high energies

LAT Integration and Tests at SLAC

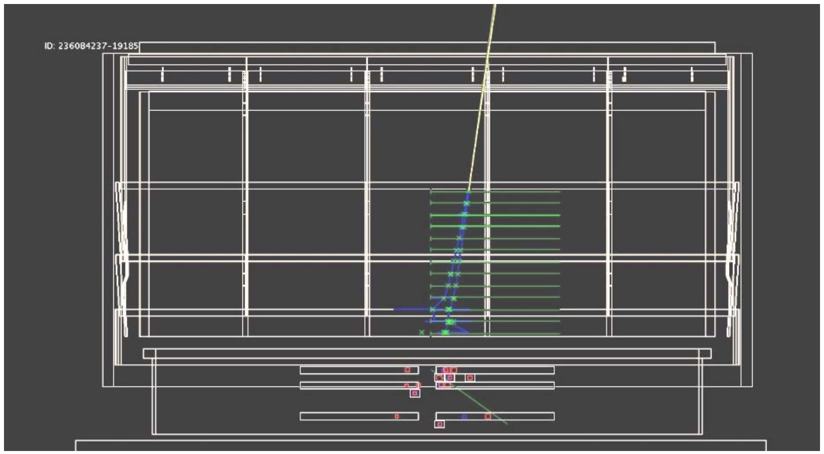


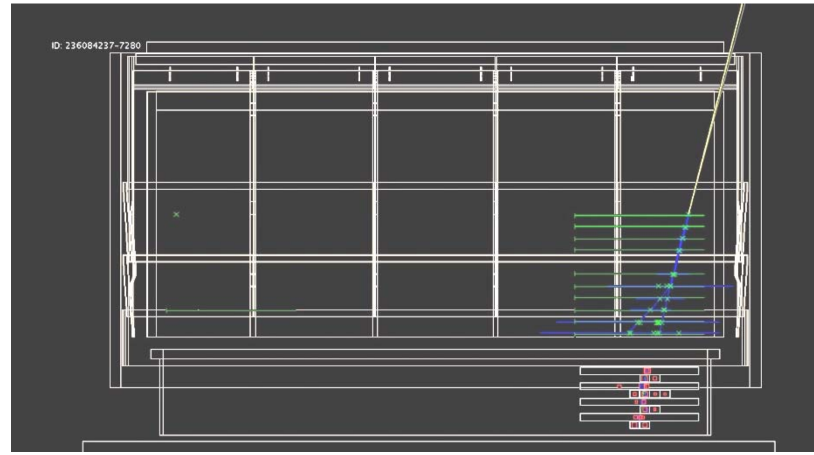
Calorimeter

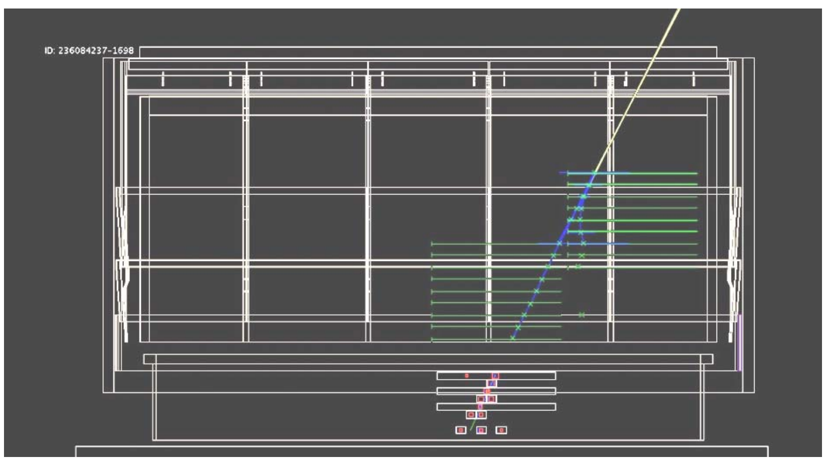
Tracker

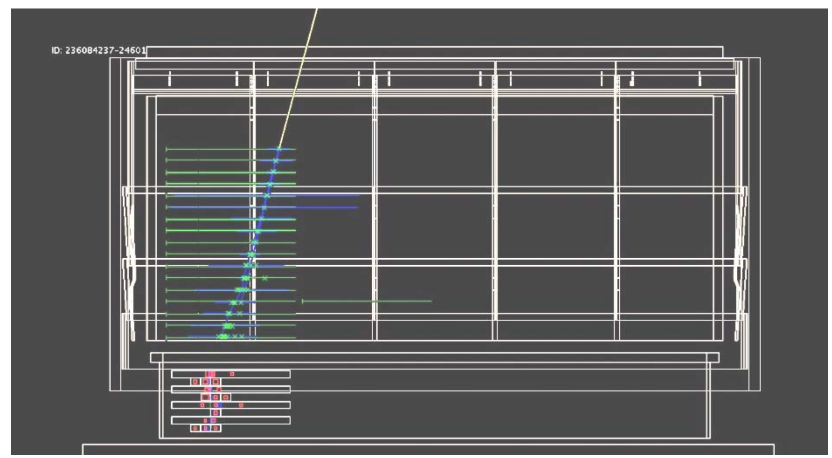
Integration of anti-coincidence detector with 16 towers

LAT Gamma Candidate Events







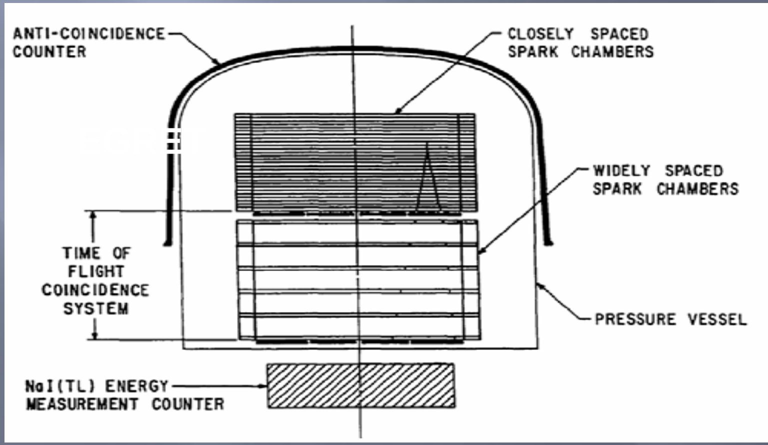


The green crosses show the detected positions of the charged particles, the blue lines show the reconstructed track trajectories, and the yellow line shows the candidate gamma-ray estimated direction. The red crosses show the detected energy depositions in the calorimeter.

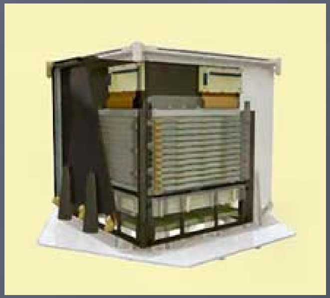
LAT as a Telescope

	Years	Ang. Res. (100 MeV)	Ang. Res. (10 GeV)	Eng. Rng. (GeV)	A_{eff} Ω (cm^2 sr)	# γ-rays
EGRET	**1991–00**	**5.8°**	**0.5°**	**0.03–10**	**750**	**1.4 × 10^6/yr**
AGILE	**2007–**	**4.7°**	**0.2°**	**0.03–50**	**1,500**	**4 × 10^6/yr**
***Fermi* LAT**	**2008–**	**3.5°**	**0.1°**	**0.02–300**	**25,000**	**1 × 10^8/yr**

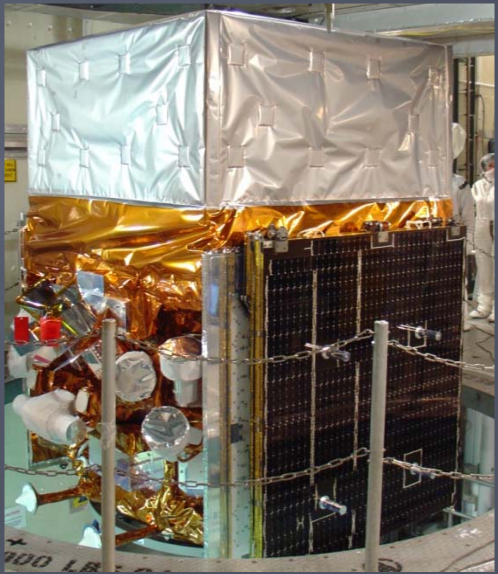
- LAT has already surpassed EGRET and AGILE celestial gamma-ray totals
- Unlike EGRET and AGILE, LAT is an effective All-Sky Monitor
  whole sky every ~3 hours



CGRO EGRET



AGILE (ASI)



Fermi / LAT

GBM Detectors

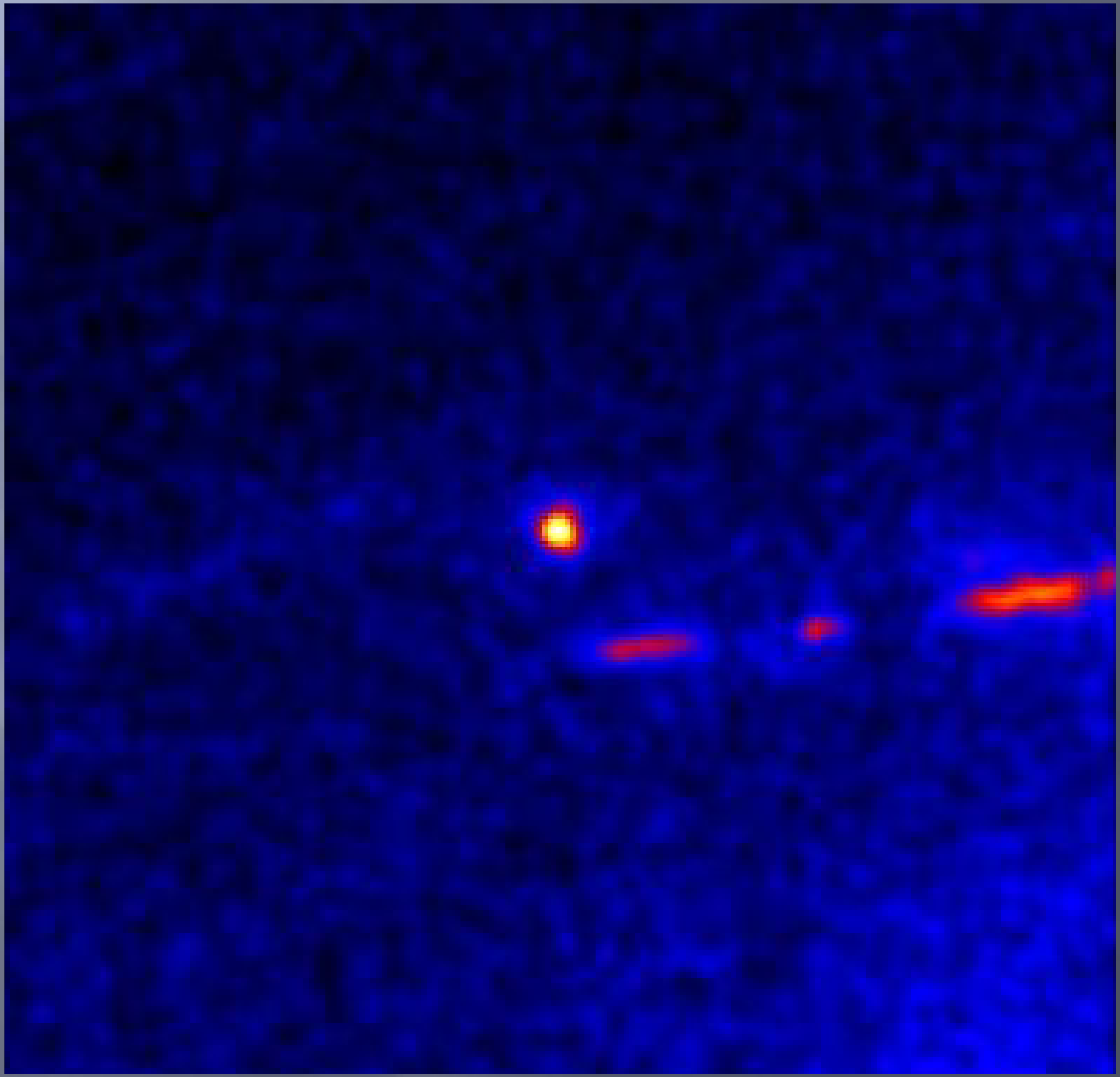
- *Placement of detectors to view entire sky while maximizing sensitivity to events seen in common with the LAT.*
- *4 x 3 NaI Detectors with different orientations.*
- *2 x 1 BGO Detector either side of spacecraft.*

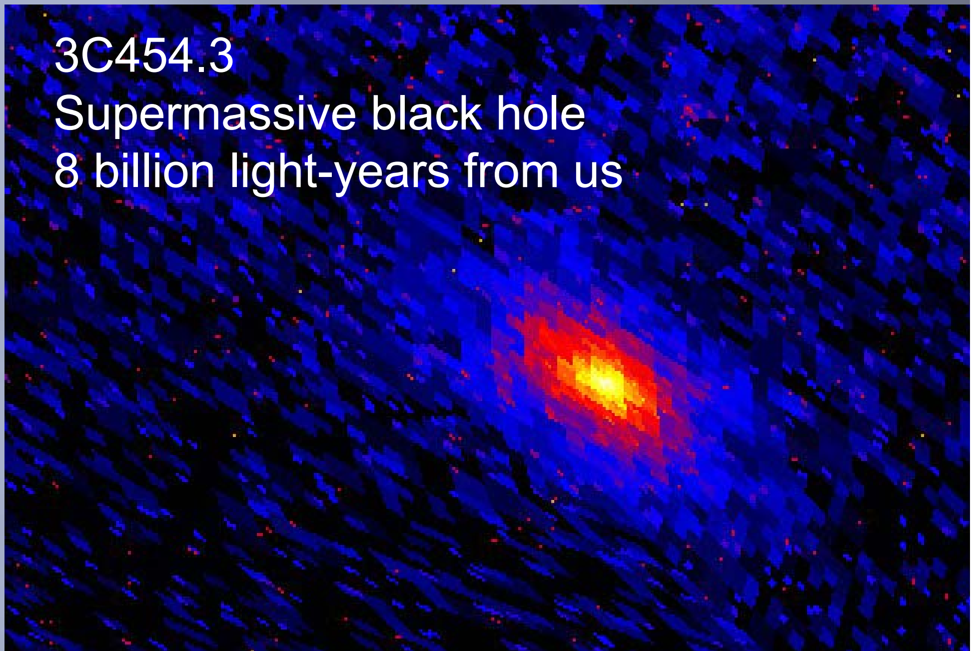
BGO detector.
200 keV -- 40 MeV
Spectroscopy
Bridges gap between NaI and LAT.

NaI detector.
8 keV -- 1000 keV.
Triggering, localization, spectroscopy.

Fermi detects the Sun

July 1 – Sept 24, 2008





GLAST-LAT detection of extraordinary gamma-ray activity in 3C 454.3

ATel #1628; G. Tosti (Univ/INFN-Perugia) , J. Chiang (SLAC), B. Lott (CENBG/Bordeaux), E. do Couto e Silva (SLAC), J. E. Grove (NRL/Washington), J. G. Thayer (SLAC) on behalf of the GLAST Large Area Telescope Collaboration
on ***24 Jul 2008; 14:25 UT***
Password Certification: Gino Tosti (tosti@pg.infn.it)

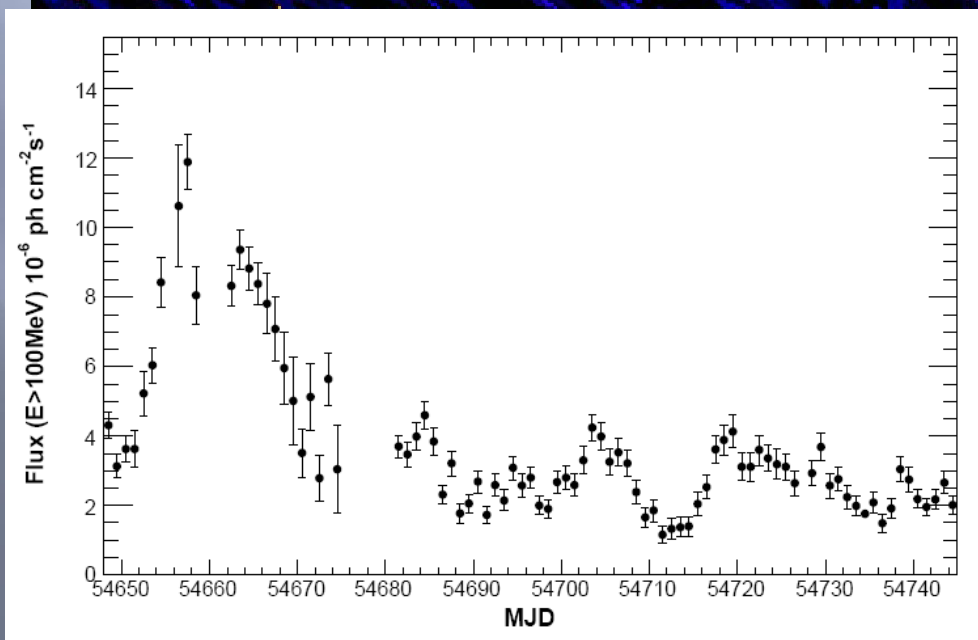
Subjects: Gamma Ray, >GeV, AGN, Quasars

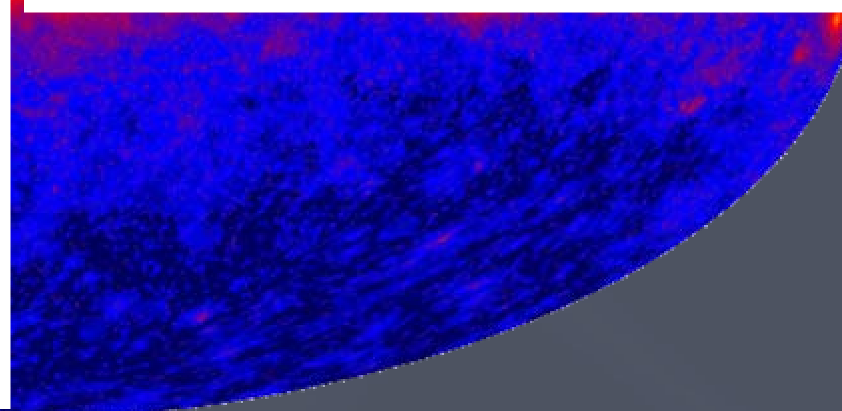
The Large Area Telescope (LAT), one of two instruments on the Gamma-ray Large Area Space Telescope (GLAST) (launched June 11, 2008), which is still in its post-launch commissioning and checkout phase has been monitoring extraordinarily high flux from the gamma-ray blazar 3C 454.3 since June 28, 2008. This confirms the bright state of the source reported by AGILE (see ATel #1592) and by the optical-to-radio observers of the GASP-WEBT Project (ATel #1625).

3C 454.3 has been detected on time scales of hours with high significance (> 5 sigma) by the LAT Automatic Science Processing (ASP) pipeline and the daily light curve (E>100 MeV) indicates that the source flux has increased from the initial measurements on June 28. Although in-flight calibration is still ongoing, preliminary analysis indicates that in the period July 10-21, 2008 the source has been in a very high state with a flux (E>100MeV) that is well above all previously published values reported by both EGRET (Hartman et al. 1999, ApJS, 123,79) and AGILE (see e.g. ATel #1592 and Vercellone et al. 2008, ApJ,676,L13).

Because GLAST will continue with calibration activities, regular monitoring of this source cannot be pursued. Monitoring by the LAT is expected to resume in early August. In consideration of the ongoing activity of this source we strongly encourage multiwavelength observations of 3C 454.3.

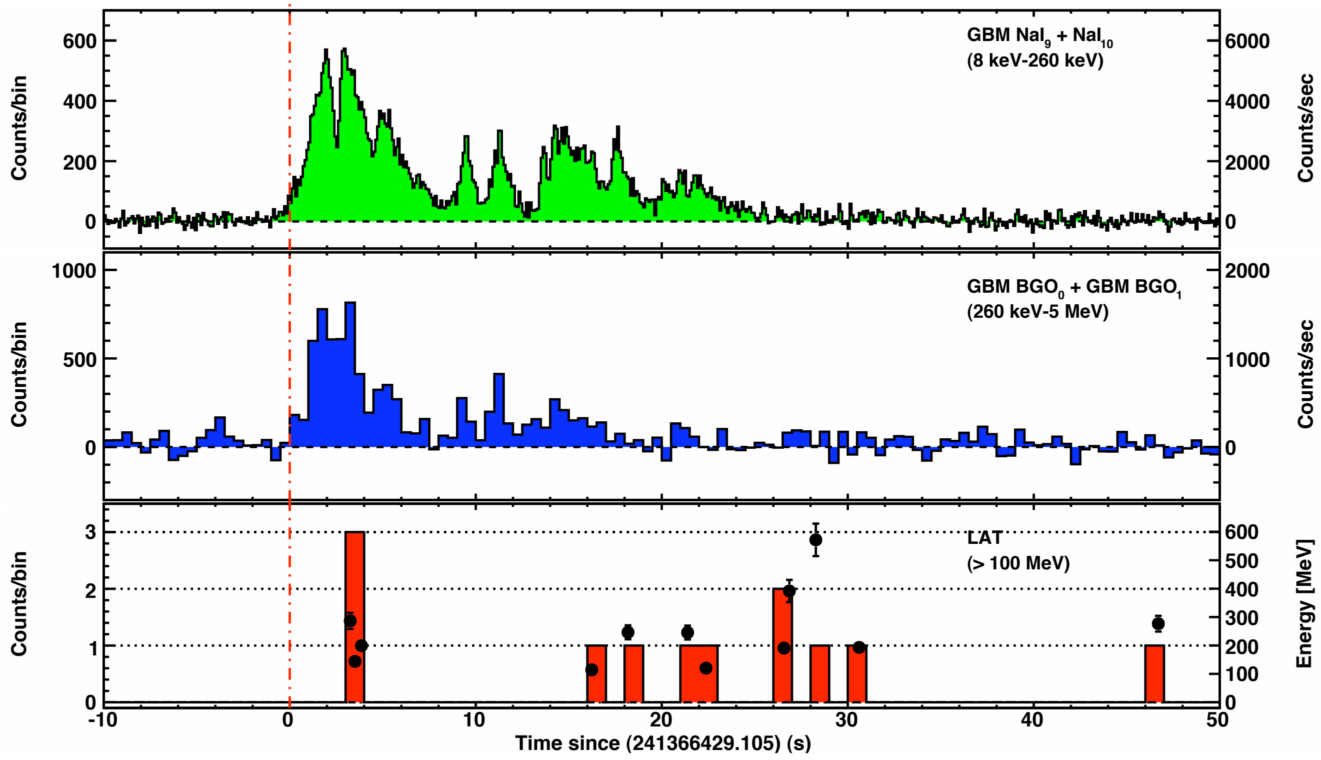
The GLAST LAT is a pair conversion telescope designed to cover the energy band from 20 MeV to greater than 300 GeV. It is the product of an international collaboration between NASA and DOE in the U.S. and many scientific institutions across France, Italy, Japan and Sweden.

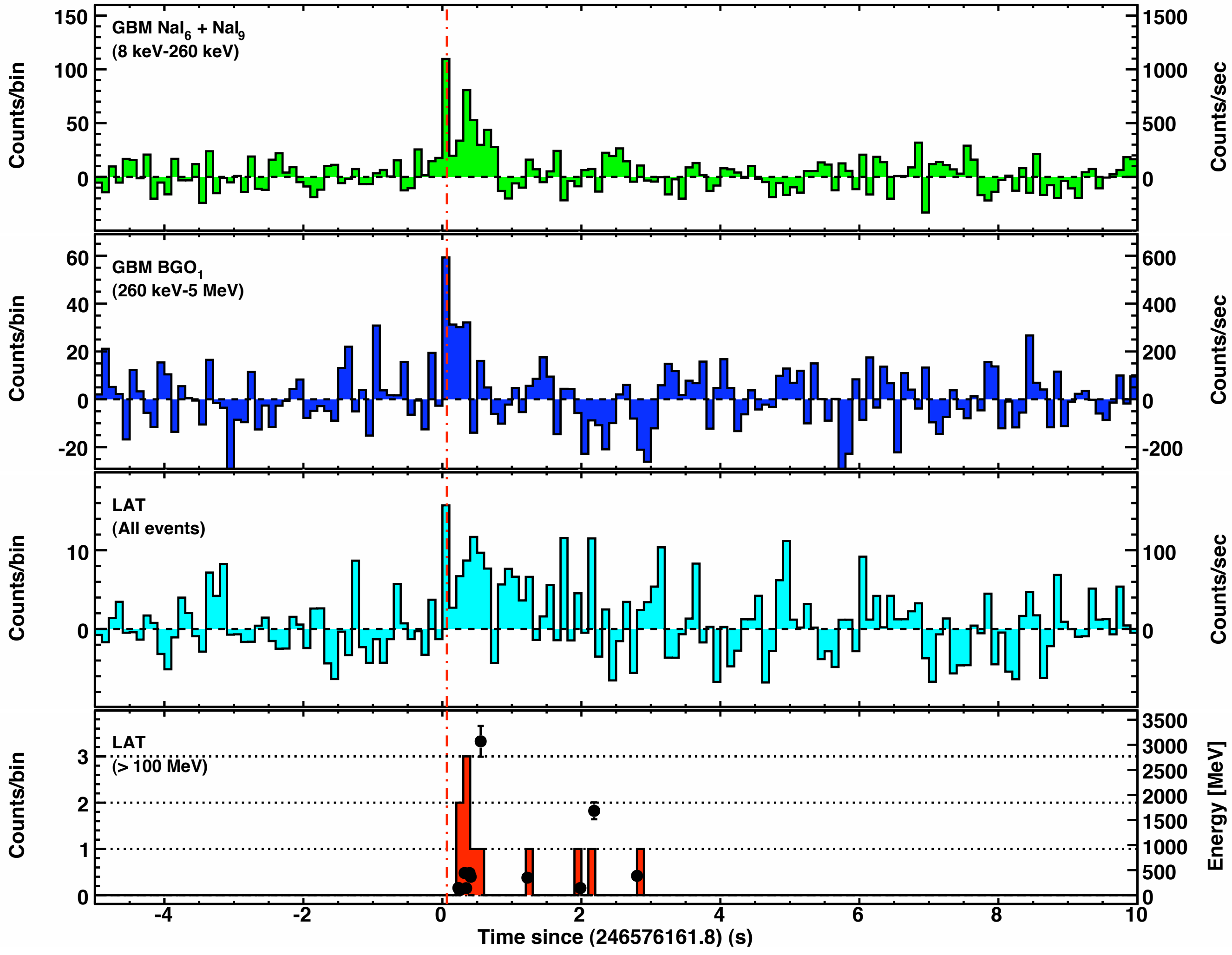


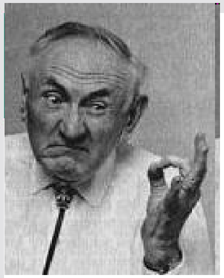


Lightcurves for Other LAT GRBs

- ✤ **Similar features**
  - ❖ **Apparent delay of high-energy emissions**
  - ❖ **Highest energy is very late (GRB080825C)**
    - No detectable low energy emissions

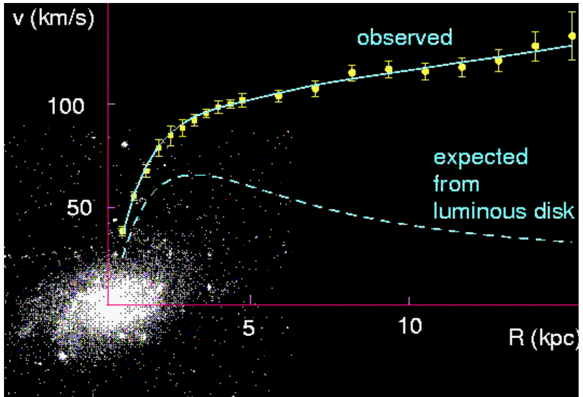






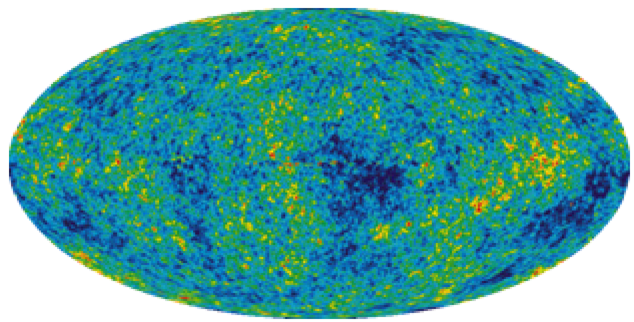
F. Zwicky
1898-1974

Dark Matter: Why and How?



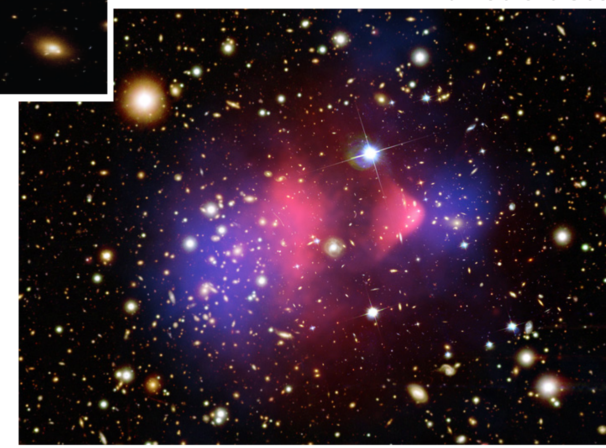
M33 rotation curve


strong gravitational lensing: galaxy cluster CL0024+17

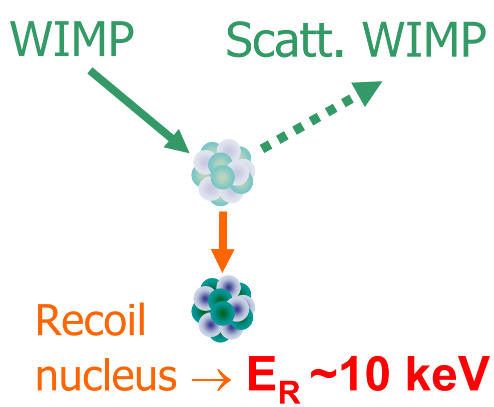


DM searches:
Prof. E. Aprile,
Tue 21st, 9:00

Bullet cluster



Direct detection of WIMPs (Weakly Interacting Massive Particles):



Count rate:

< 10^{-2} evt/kg/day!

Challanges to overcome:

- α, β, γ ;
- **Neutrons;**
- **μ-induced events;**

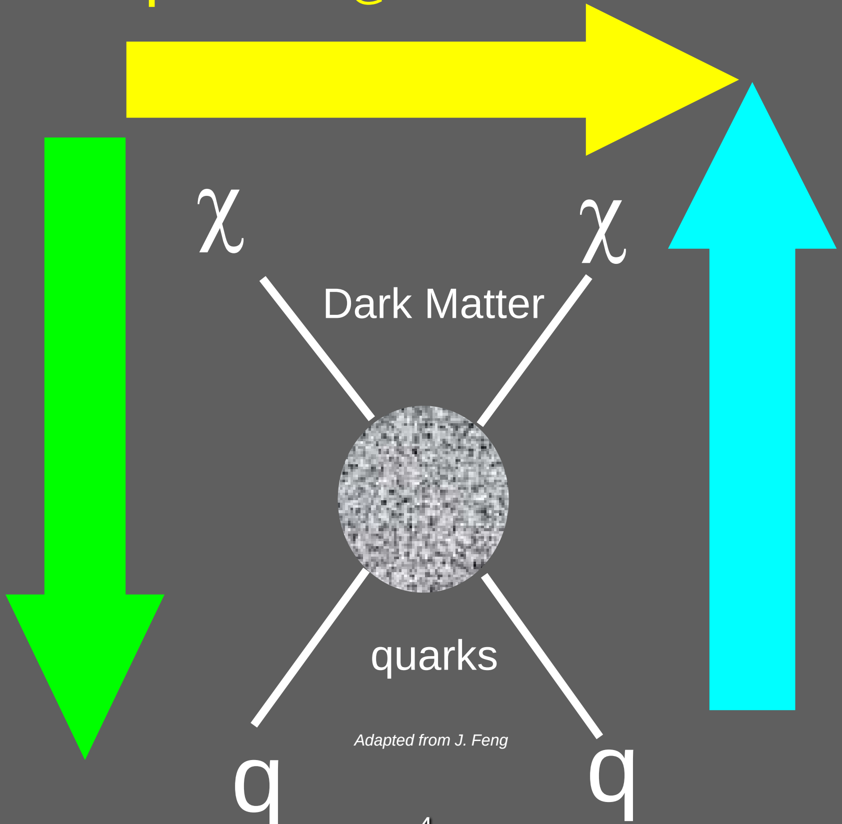
Way to go:

- **low radioactivity;**
- **powerful rejection;**
- **background knowledge;**

Comprehensive Dark Matter Searches at SLAC

Direct Searches

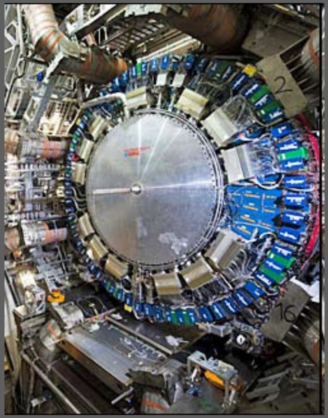
UNDERGROUND
superCDMS @ SNOLAB/DUSEL



Indirect Searches

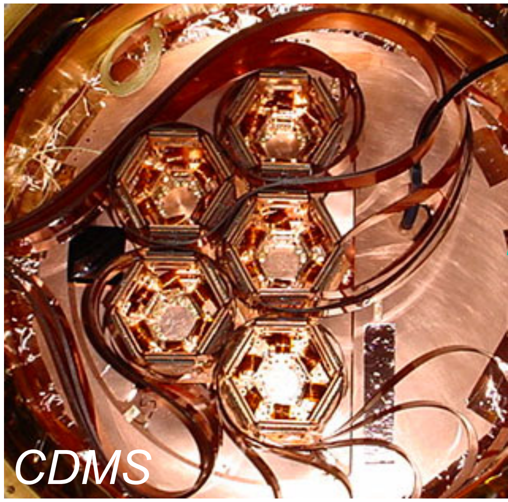
SPACE
Fermi Telescope

Collider Searches

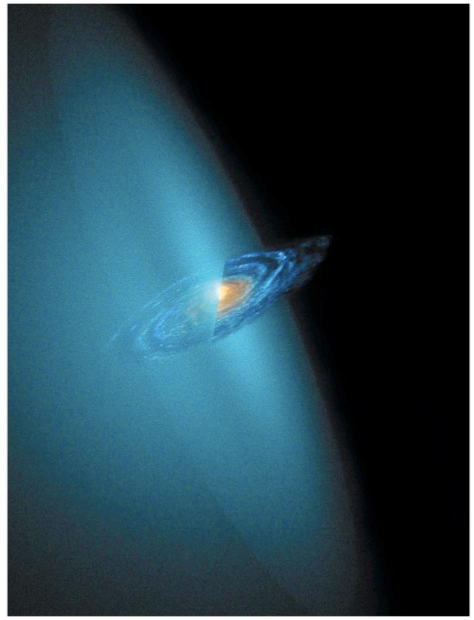


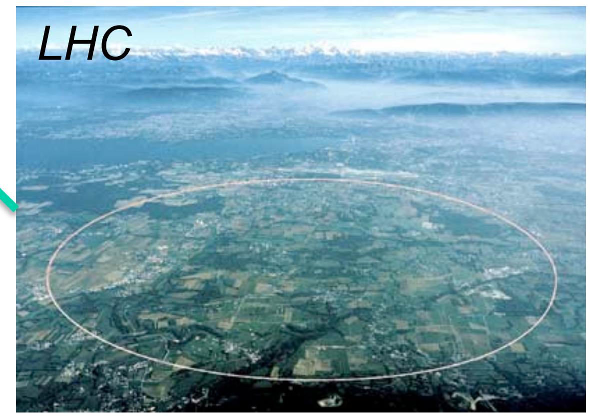
COLLIDER
ATLAS @ LHC

How to detect WIMPs?

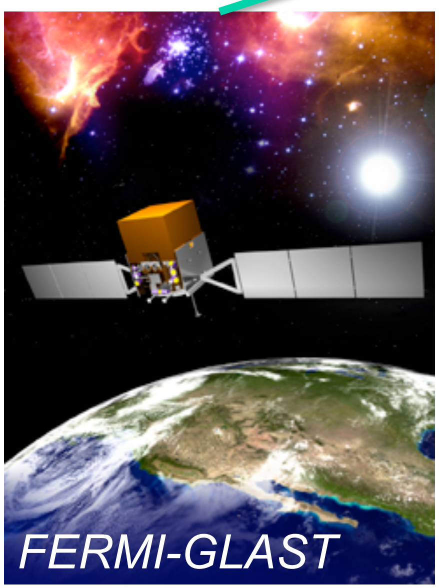


WIMP scattering on Earth

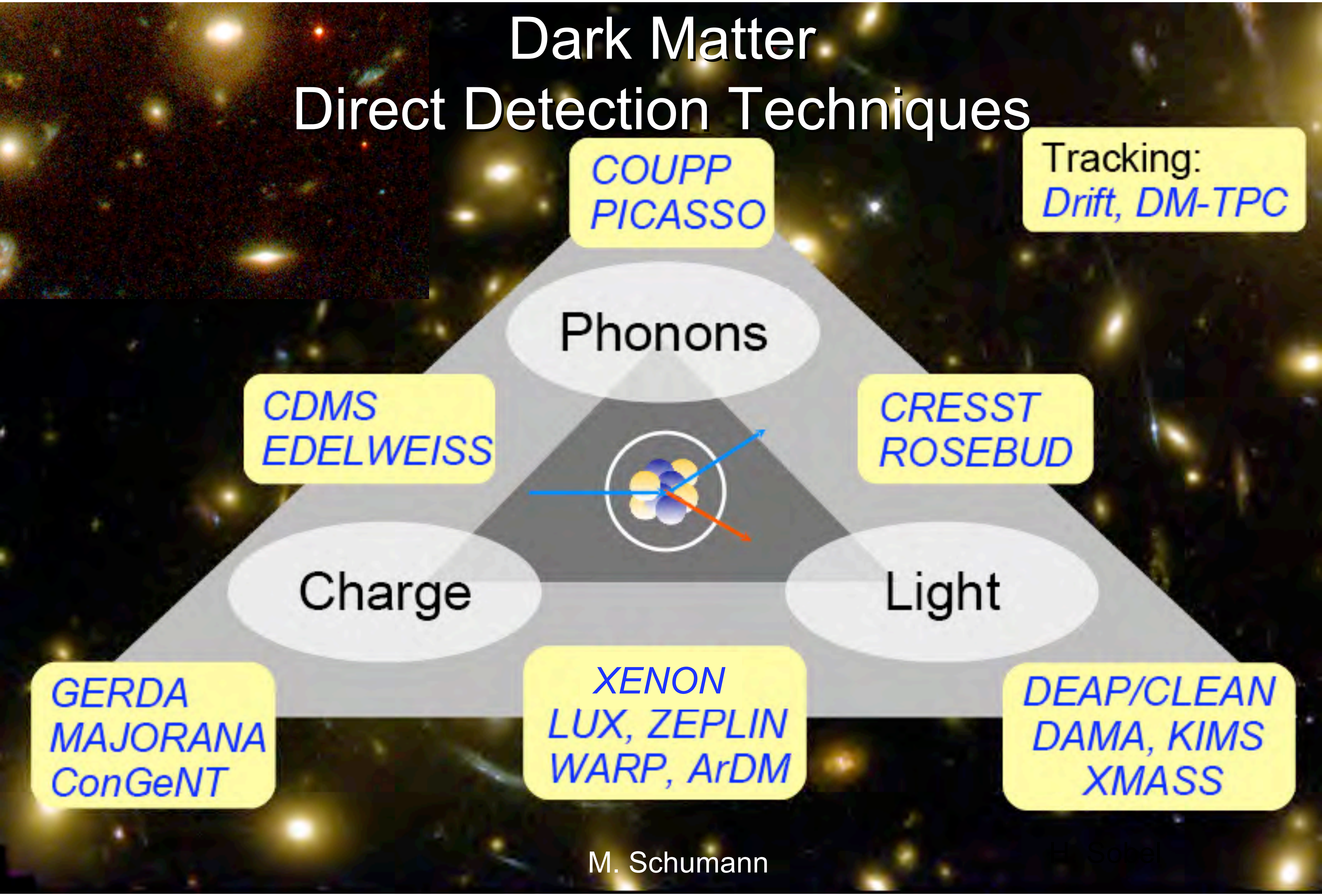




WIMP production on Earth

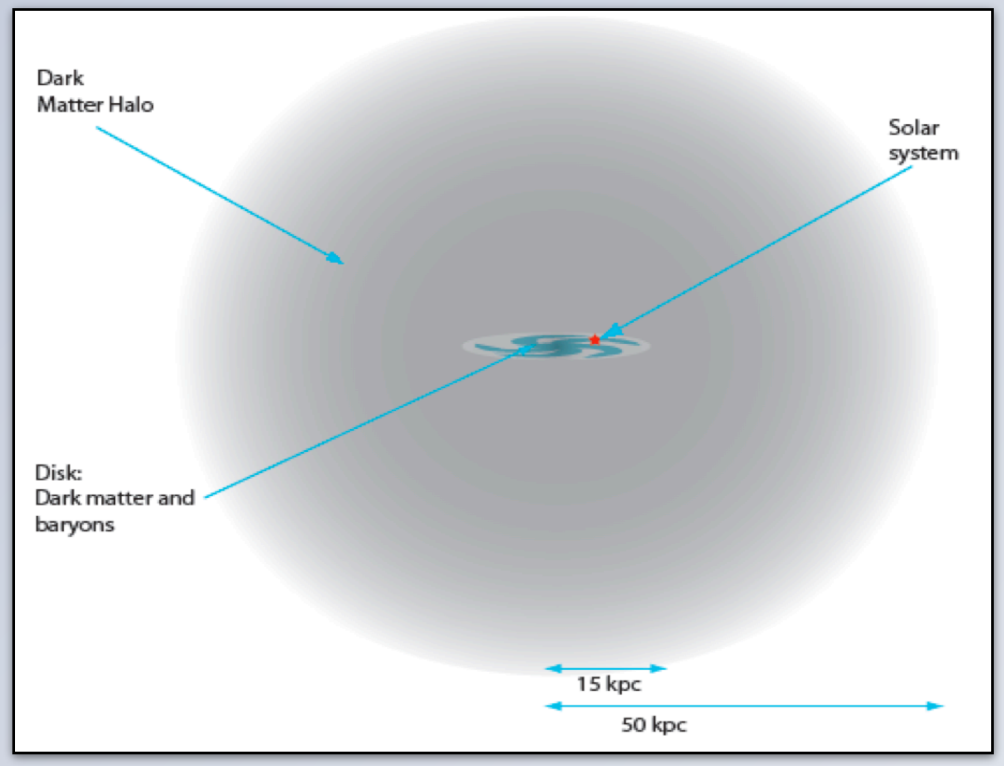


WIMP annihilation in the cosmos

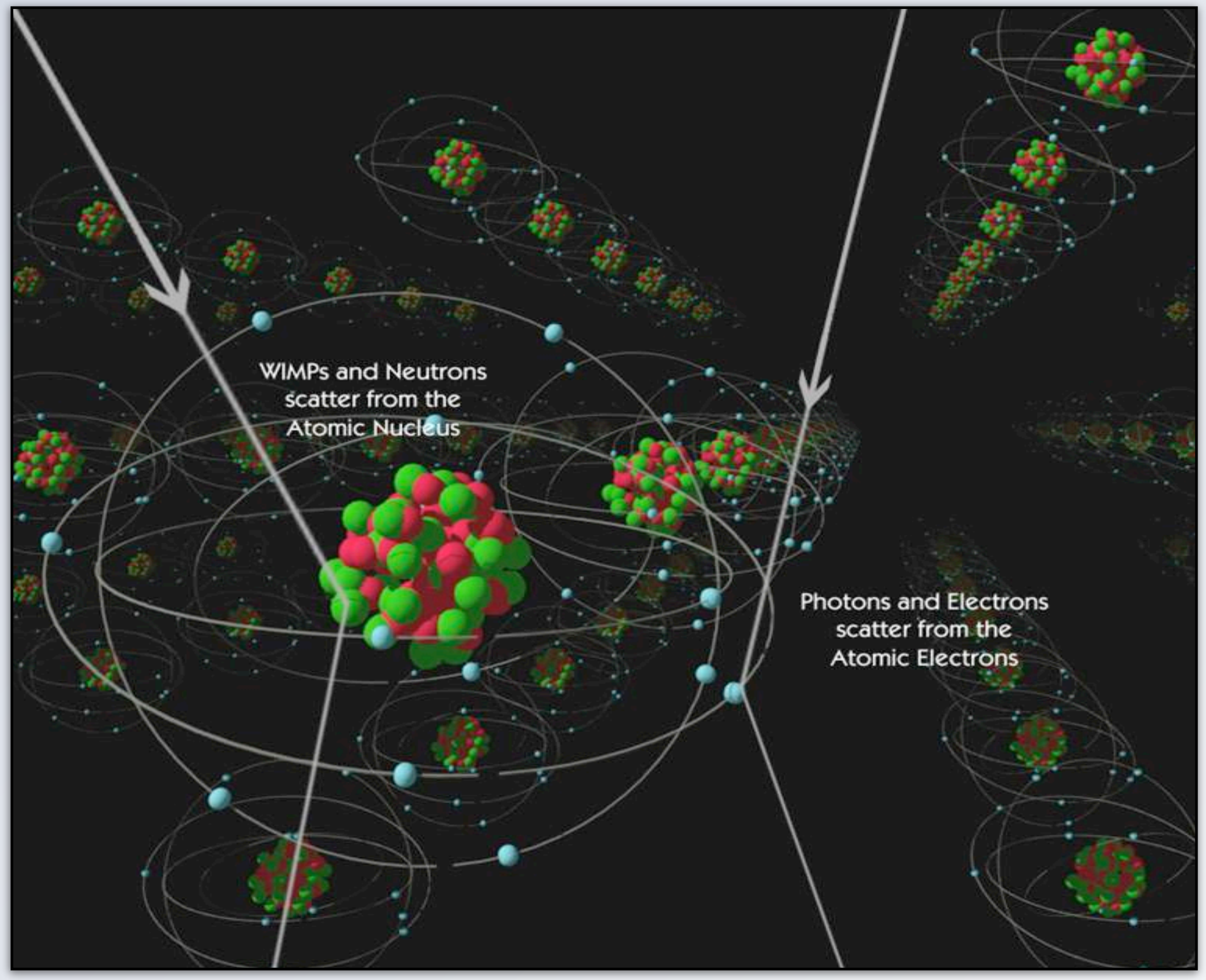


Szukamy bardzo rzadkiego procesu: konieczna koincydencja dwoch sygnatur.

Direct Detection of WIMPs



Spherical Isothermal Halo
Max. Boltz. *v* distribution,
<v>~230km/s



RARE EVENT SEARCH

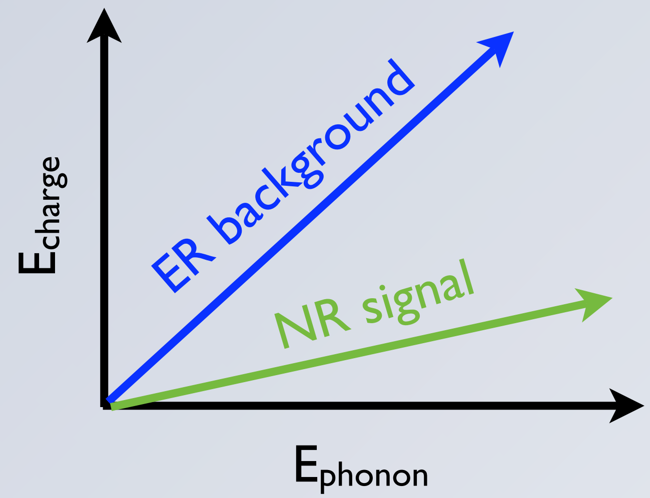
Build a good mousetrap!

- Choose target material to "see" recoils
- Discriminate NRs from ERs
- Reduce background

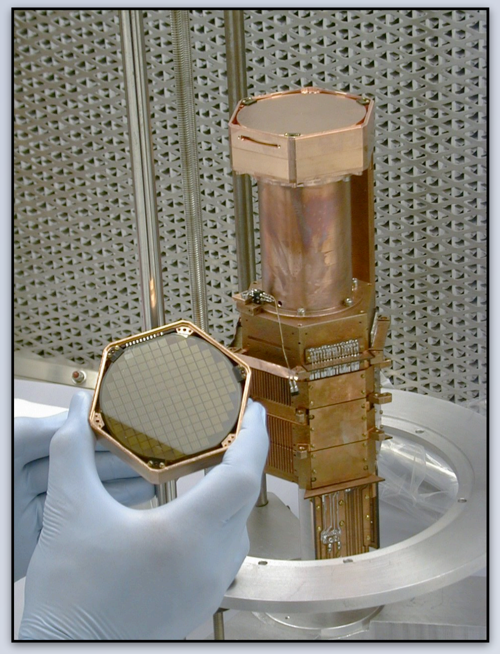
"See" Nuclear Recoils
$\langle E_r \rangle$~30 keV, < ~1event/kg/100days

CDMS-2 in a nutshell

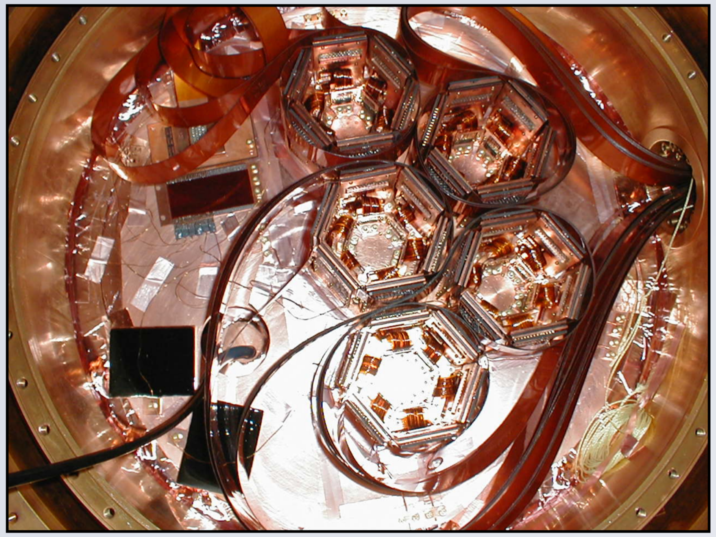
Ge & **Si** target masses



Allow <1 background event to maximize discovery potential



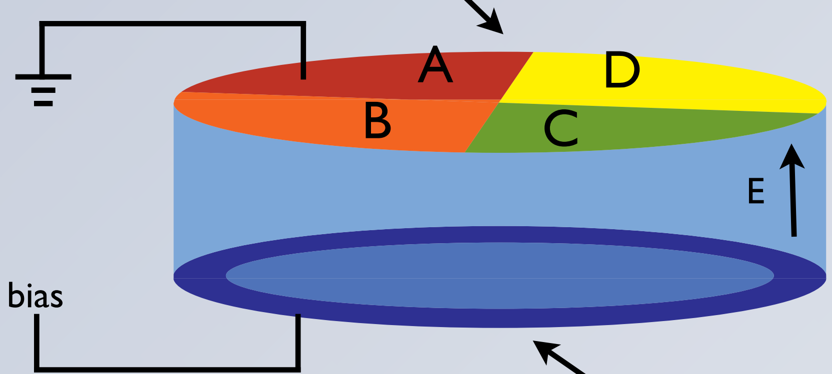
Event by event **discrimination** of nuclear and electron recoils using **ionization** and **phonon** signals

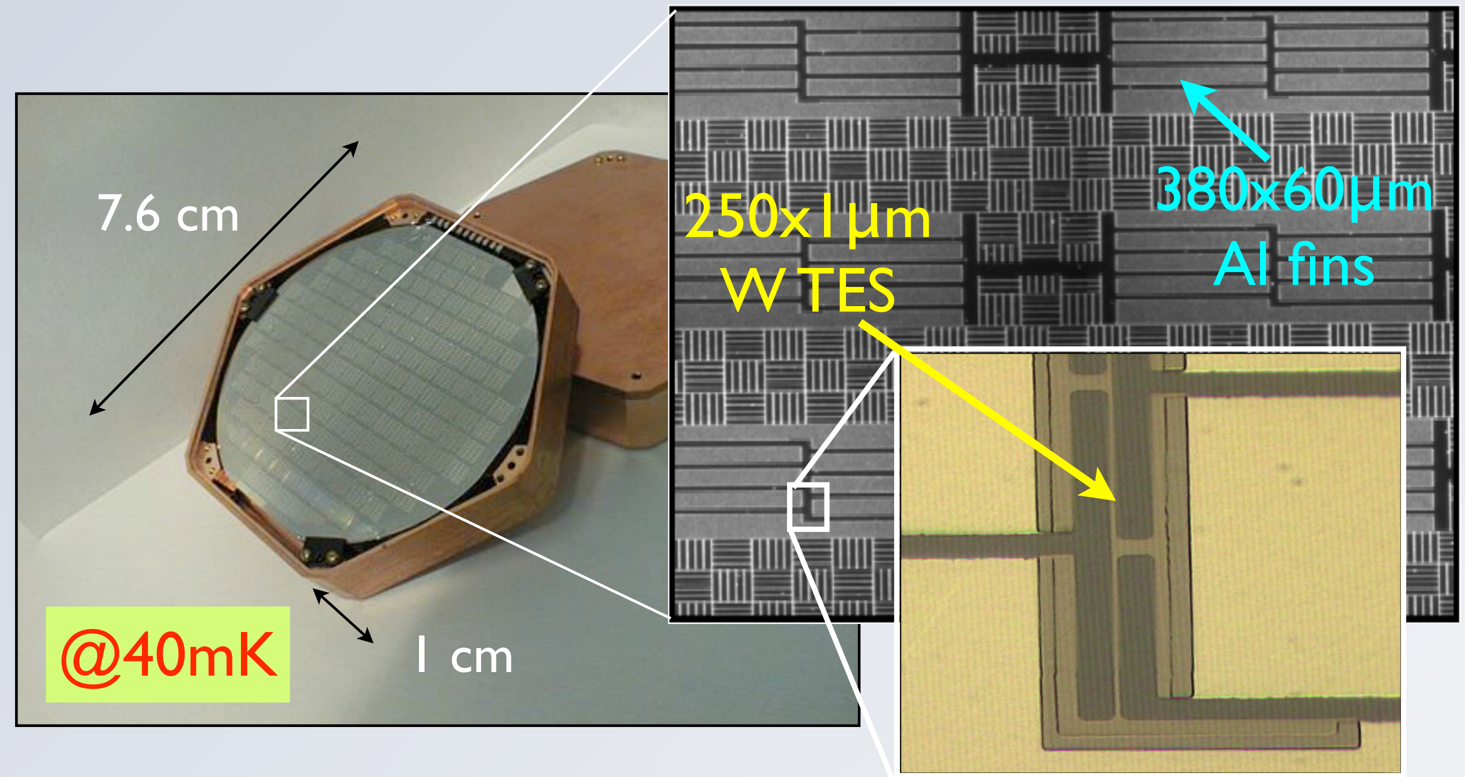


Control Backgrounds by going underground, using clean materials and shielding

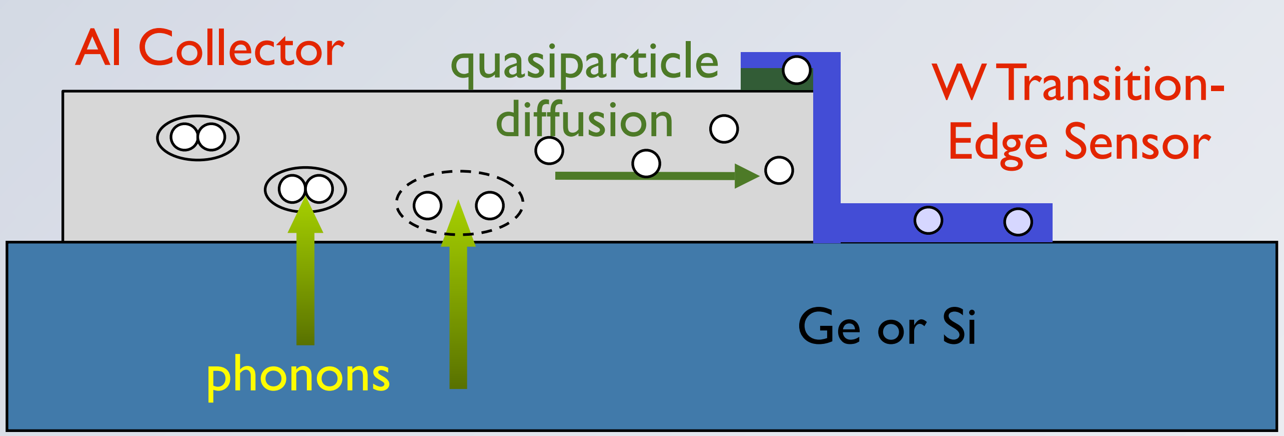
ZIP: Z-sensitive Ionization & Phonon Detectors

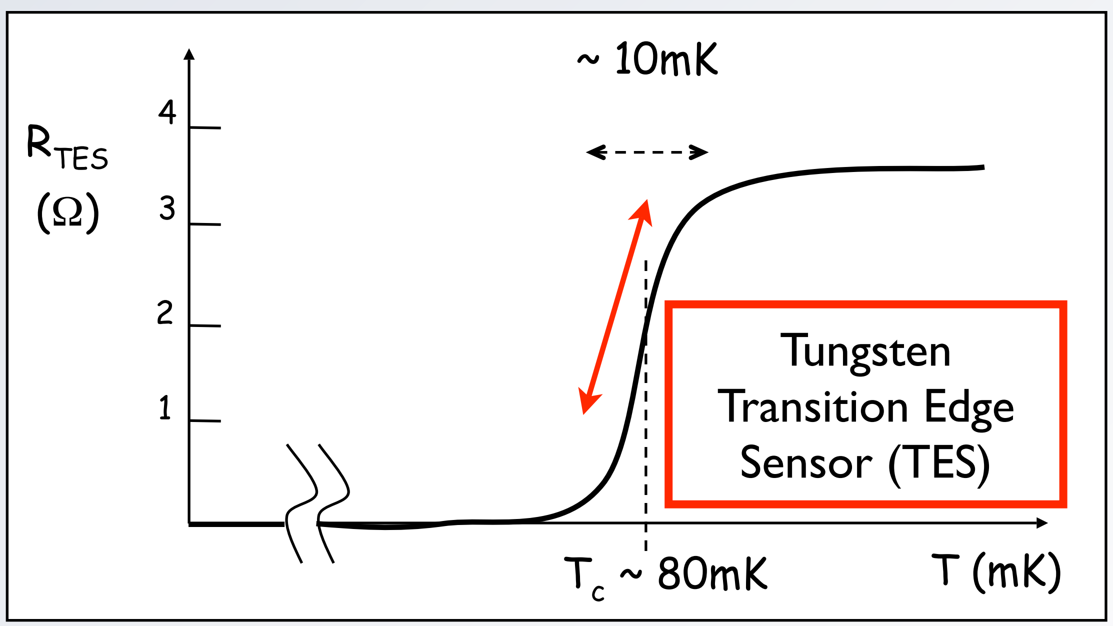
Phonon readout: 4 quadrants of superconducting *Al phonon absorbers* and *W Transition-Edge Sensors*





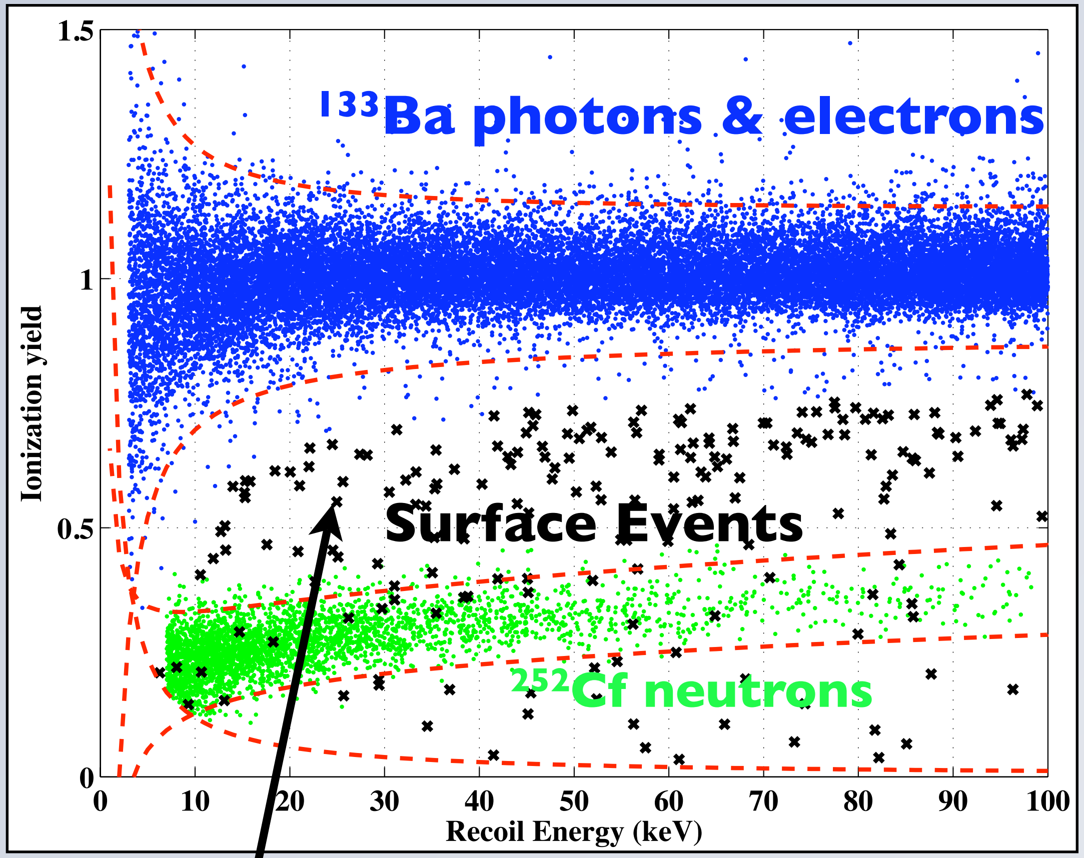
Charge readout: 2 concentric electrodes for measurement and fiducial volume



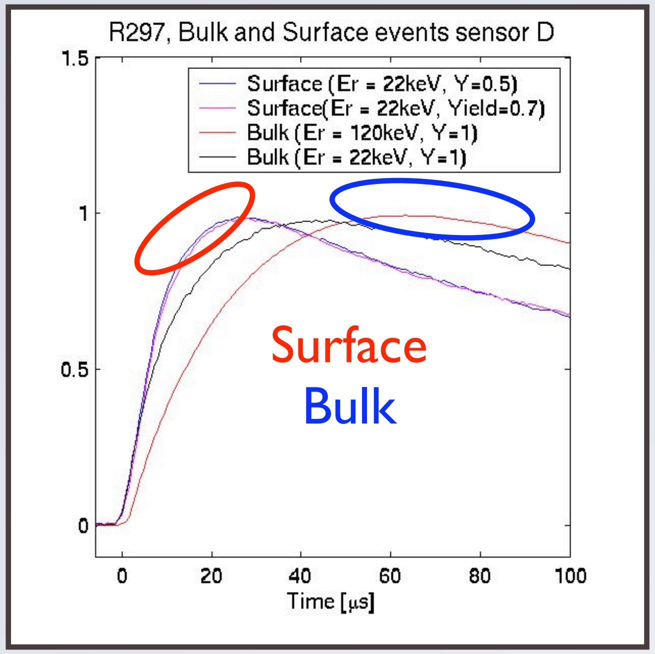


Basic Discrimination principles

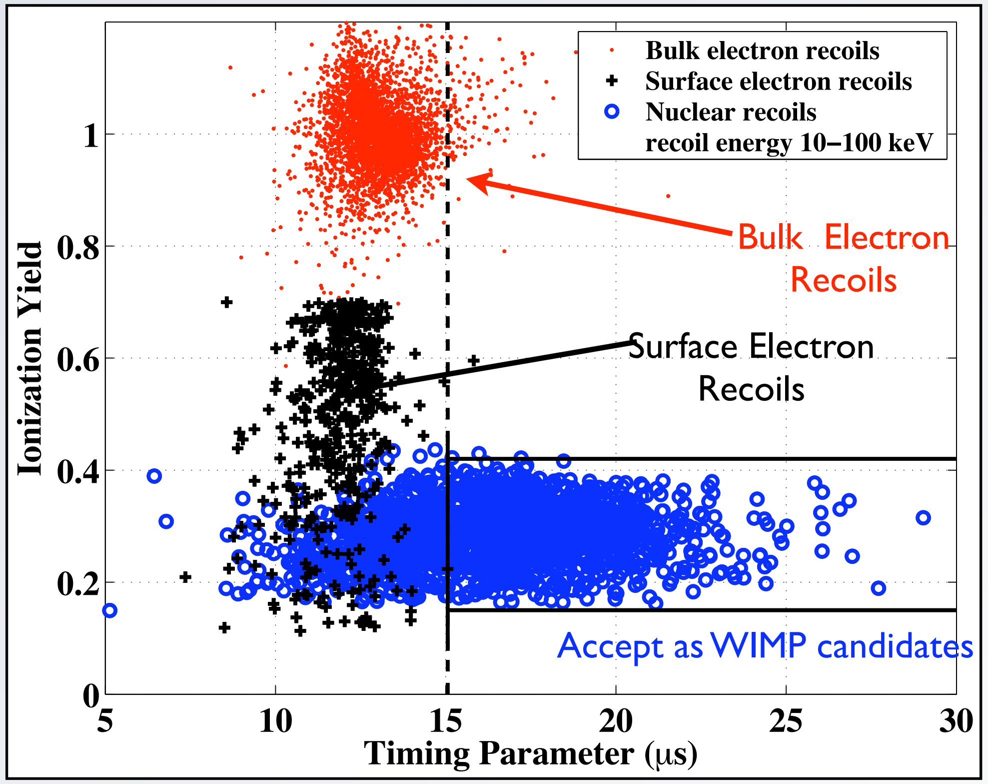
Reject bulk electron recoils using $y=Q/E_{recoil}$



- Events within 10 micron "dead layer" have poor charge collection
- Electrons, x-rays low energy gammas from contamination of surfaces surrounding detectors



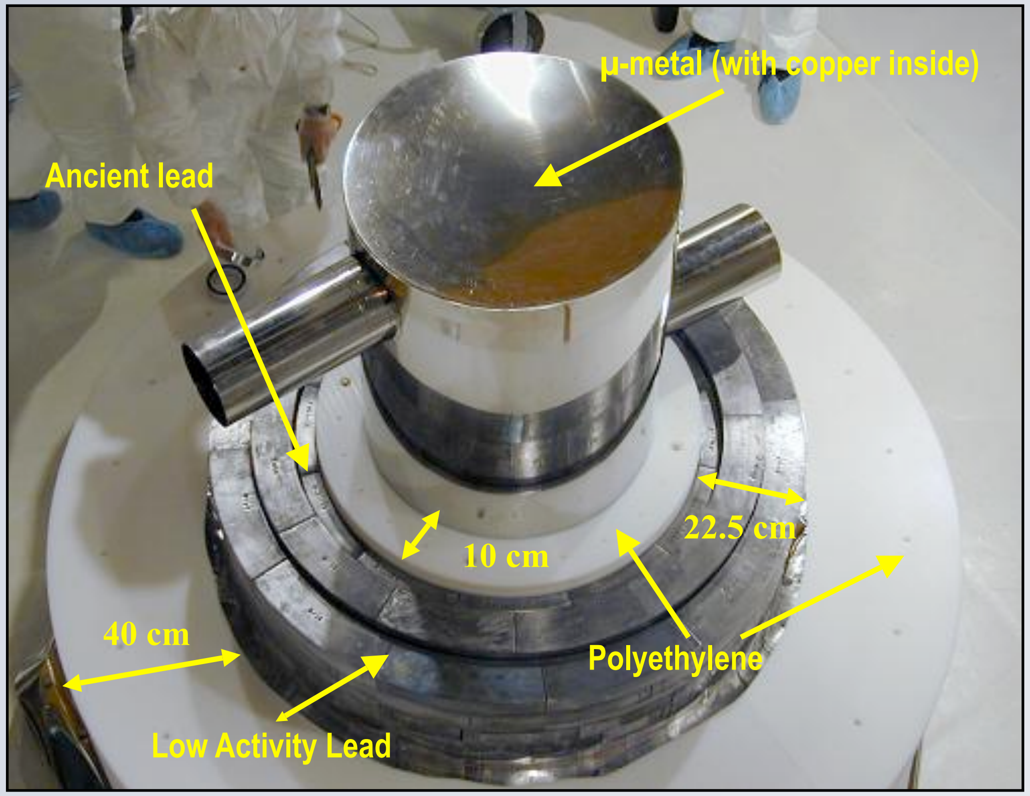
Reject surface events using promptness of phonon pulse



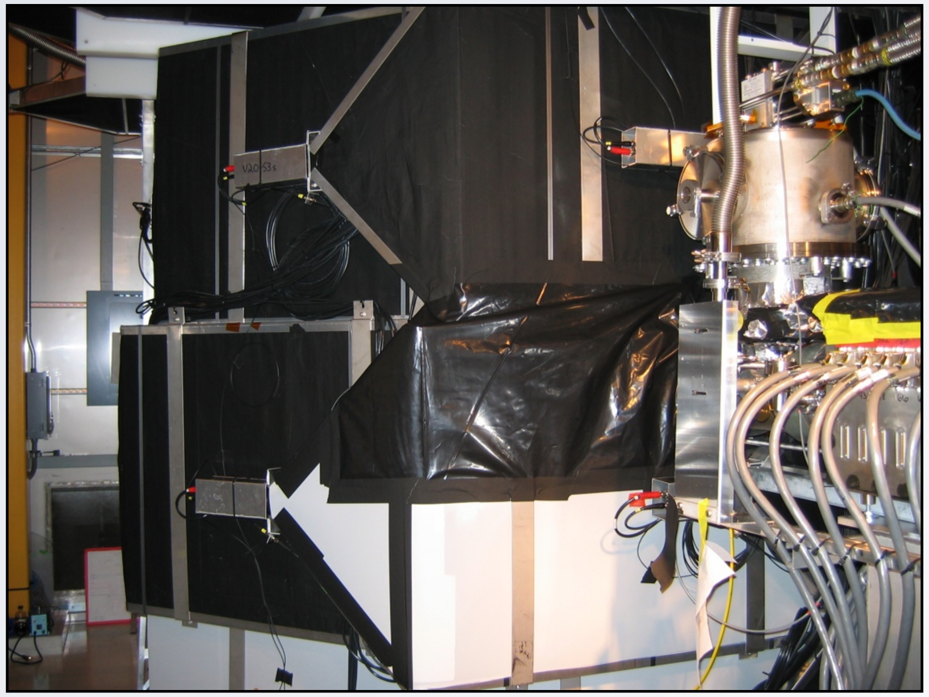
Background Control in CDMS-2

Soudan Underground Lab

RF shielded class 10,000 clean room

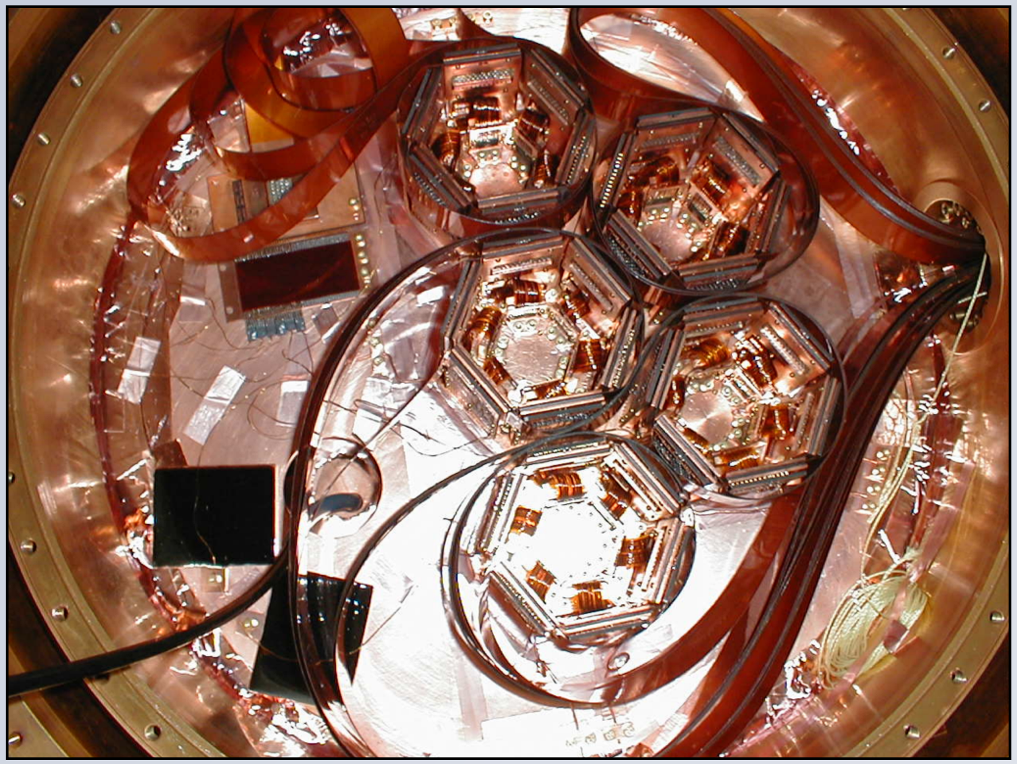


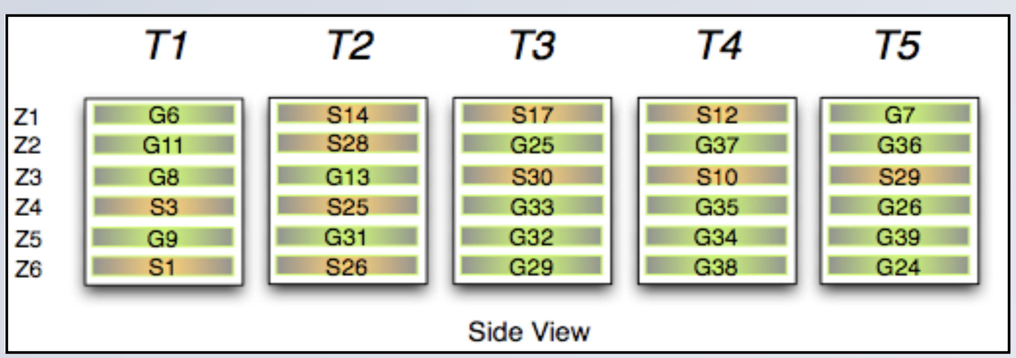
Passive shielding



Plastic scintillator muon veto

CDMS-2 @ Soudan



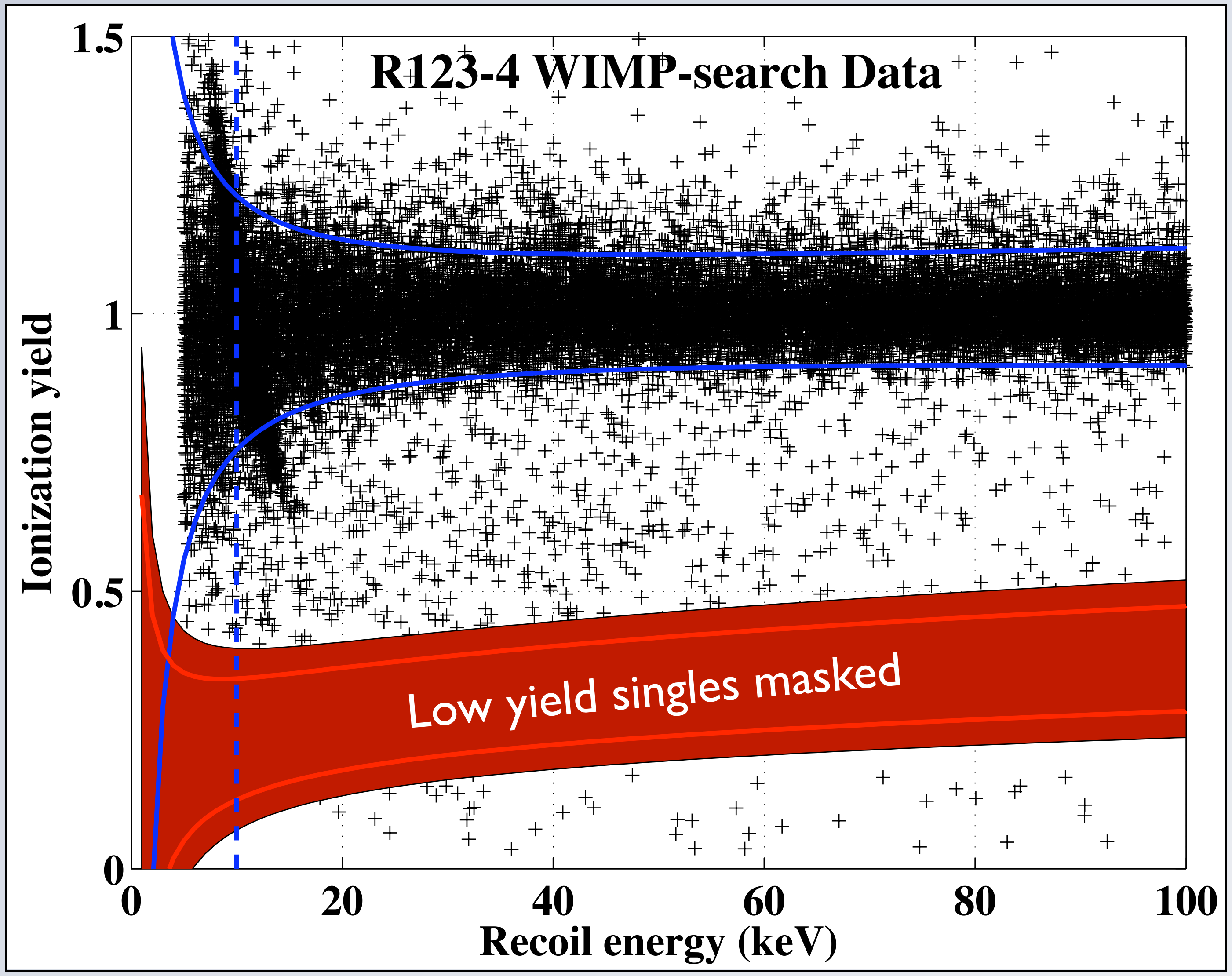


- **30 detectors installed and operating in Soudan since June 2006.**
  - **4.75 kg of Ge, 1.1 kg of Si**
- **Seven Total Data Runs:**
  - **R123 - R124:**
    - **taken: (10/06 - 3/07) (4/07 - 7/07)**
    - **exposure: ~400 kg-d (Ge "raw")**
    - **PRL 102, 011301 (2009)**
  - **R125 - R128**
    - **taken: (7/07 - 1/08) (1/08 - 4/08) (5/08 - 8/08) (8/08 - 9/08)**
    - **exposure: ~ 750 kg-d (Ge "raw")**
    - **Under Analysis**
  - **R129:**
    - **taken: (11/08 - 3/09)**

CDMS-2 : First Five Tower Result

PRL 102, 011301 (2009)

Blind Analysis:
Event selection and efficiencies were calculated without looking at the signal region of the WIMP-search data.



Event Selection:

- Energy threshold (*10-100 keV*)
- Veto-anticoincident
- Single-scatter
- Inside fiducial volume
- 2-sigma Nuclear Recoil
- Phonon timing

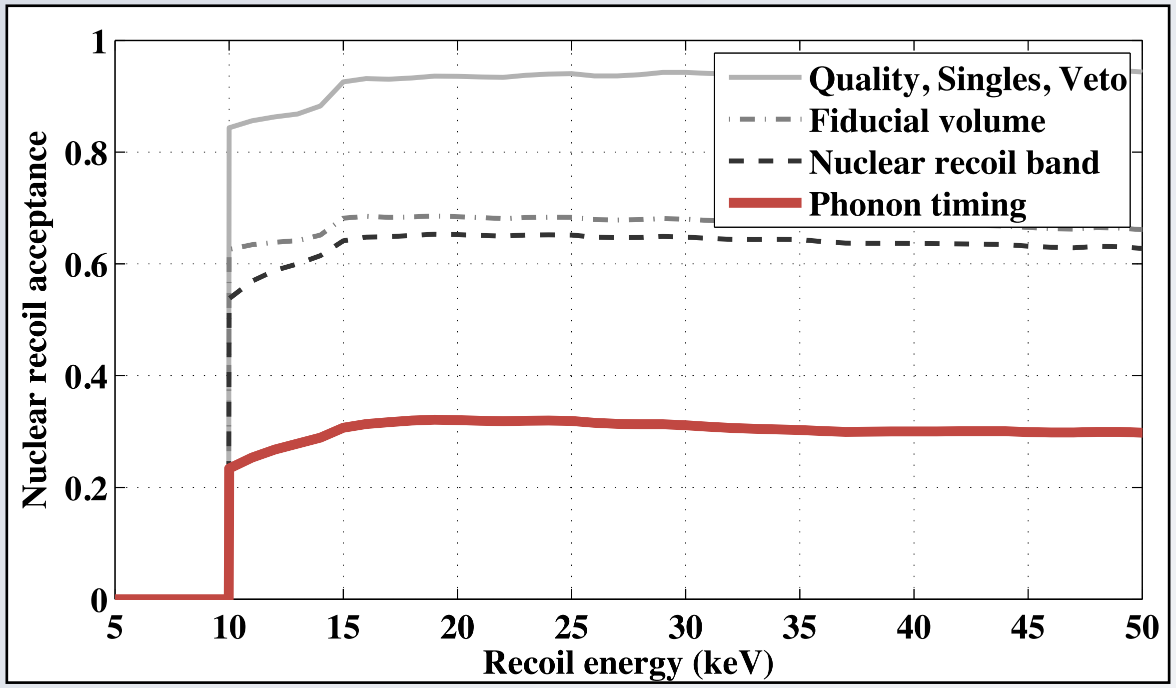
CDMS-2 : First Five Tower Result

PRL 102, 011301 (2009)

Surface Background

Estimated number of background events to pass surface cut in Ge

$$0.6^{+0.5}_{-0.3}(stat.)^{+0.3}_{-0.2}(syst.)$$



Neutron Backround

Poly Cu (α,n): < 0.03

Pb (fission): < 0.1

Cosmogenic: < 0.1 (MC 0.03-0.05)

398 raw kg-d

121 kg-d WIMP equiv. @ 60 GeV/c^2 (10 - 100 keV analysis energy range)

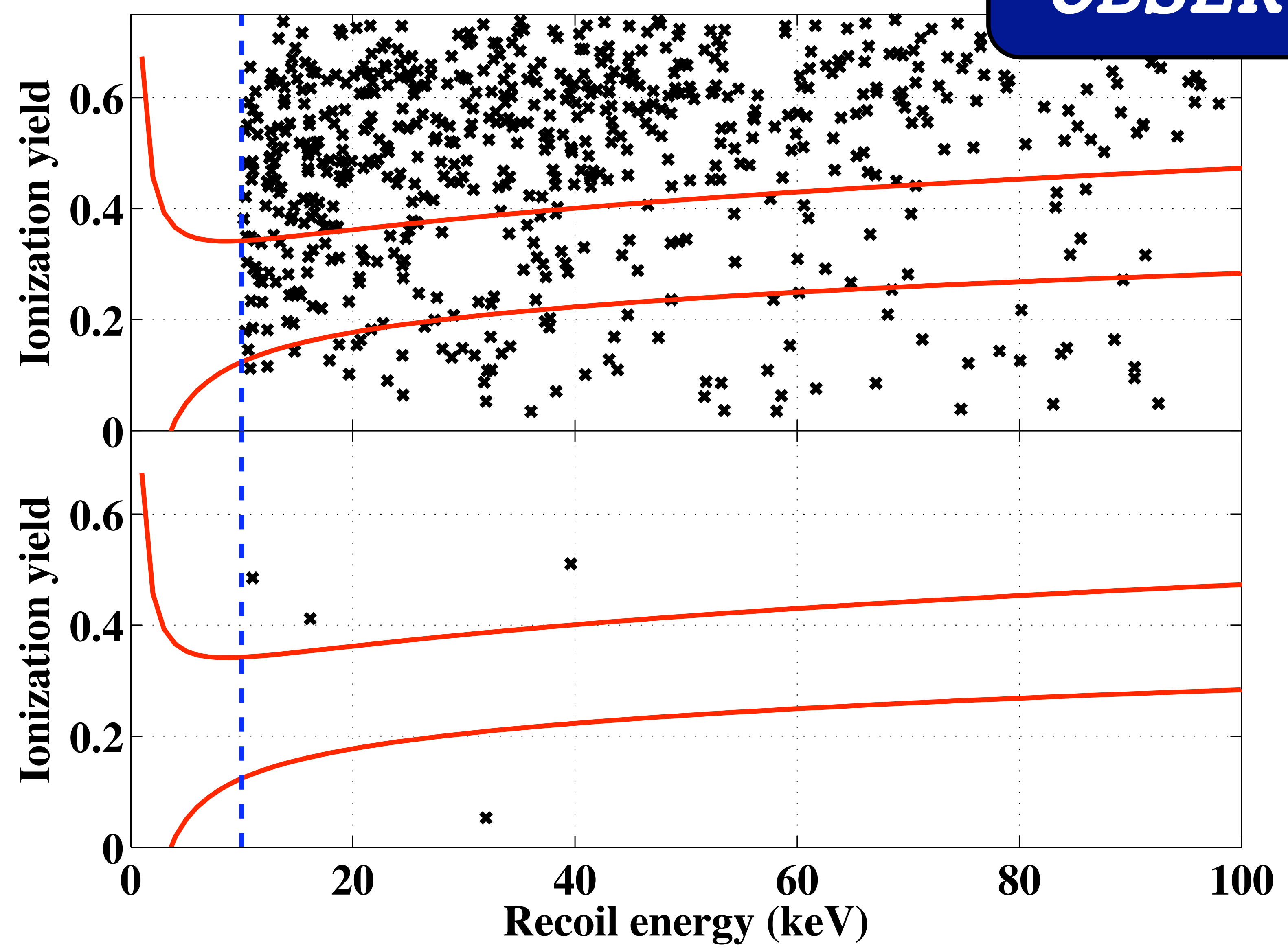
CDMS-2 : First Five Tower Result

PRL 102, 011301 (2009)

NO EVENTS OBSERVED!

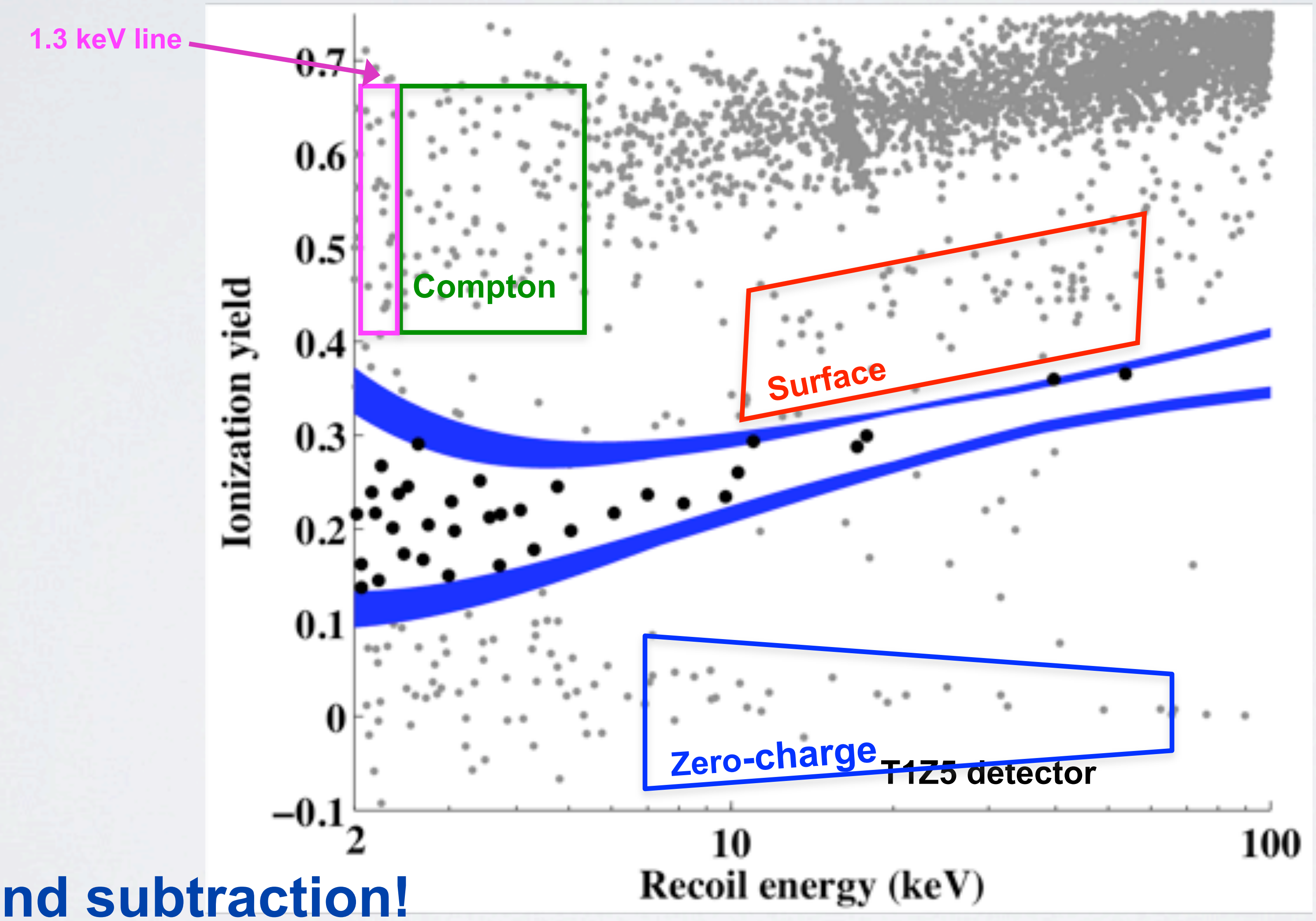
FAIL
timing cut

PASS
timing cut



LOW THRESHOLD ANALYSIS

- NR band (+1.25,-0.5)σ
- Maximizes sensitivity to nuclear recoils while minimizing expected backgrounds



NO background subtraction!

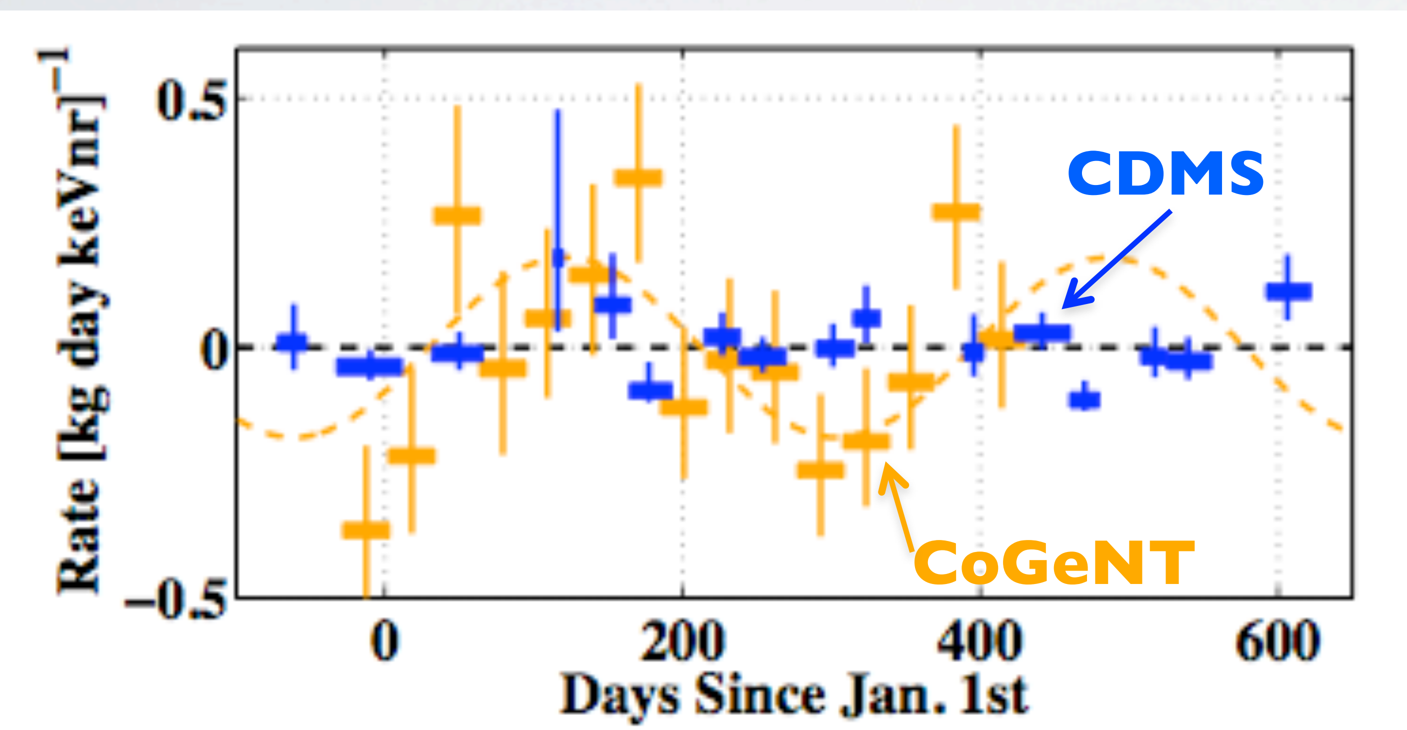
•**Limits set using optimum interval method: *S. Yellin, PRD, 66, 032005 (2002);* arXiv:0709.2701v1 (2007)**

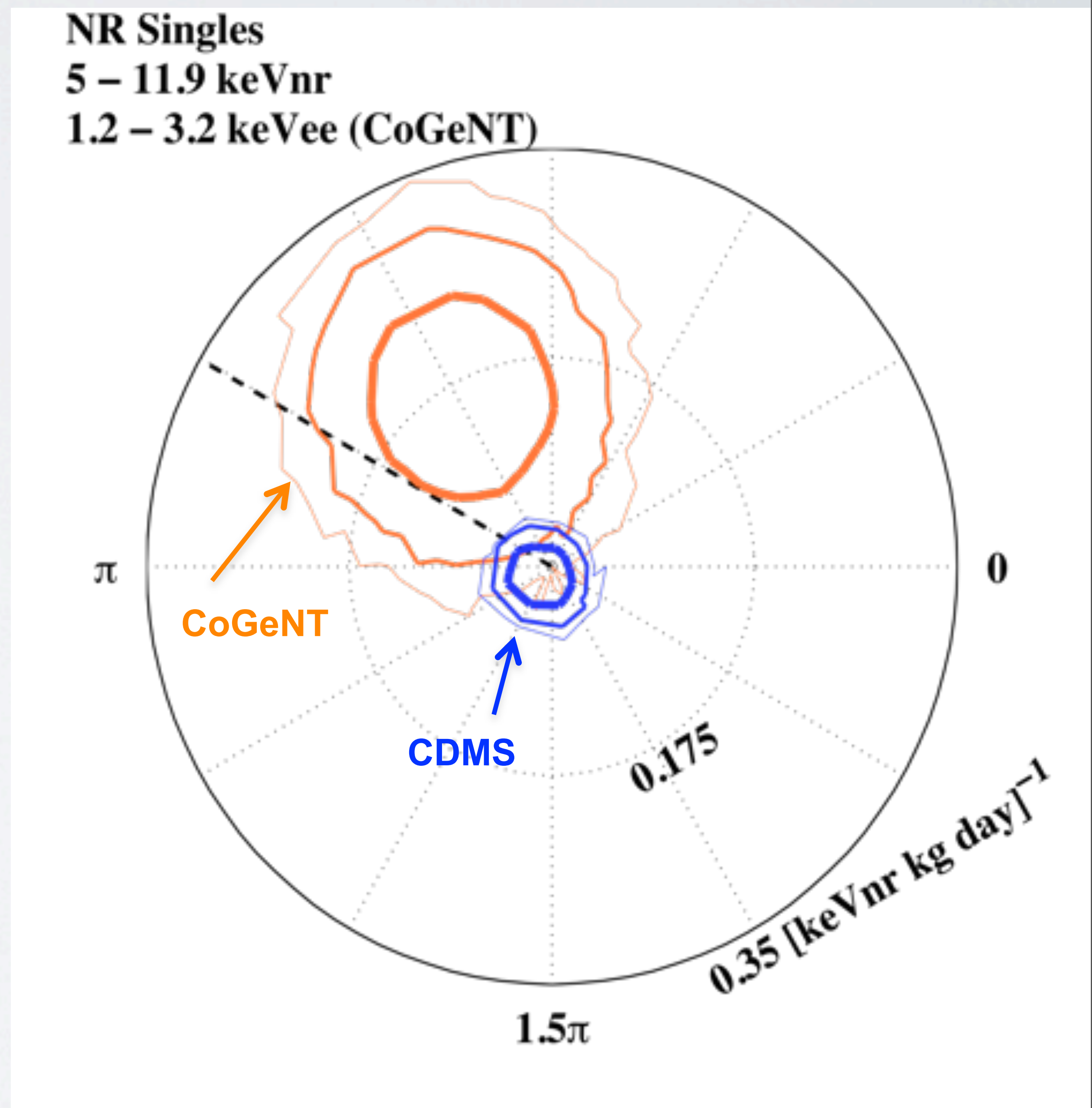
RESULTS FOR **NR** SINGLES

- No annual modulation in the energy interval between 5 keV_{nr} and 11.9 keV_{nr}

- Annual Modulation signal of CoGeNT and CDMS II are incompatible at >95% CL

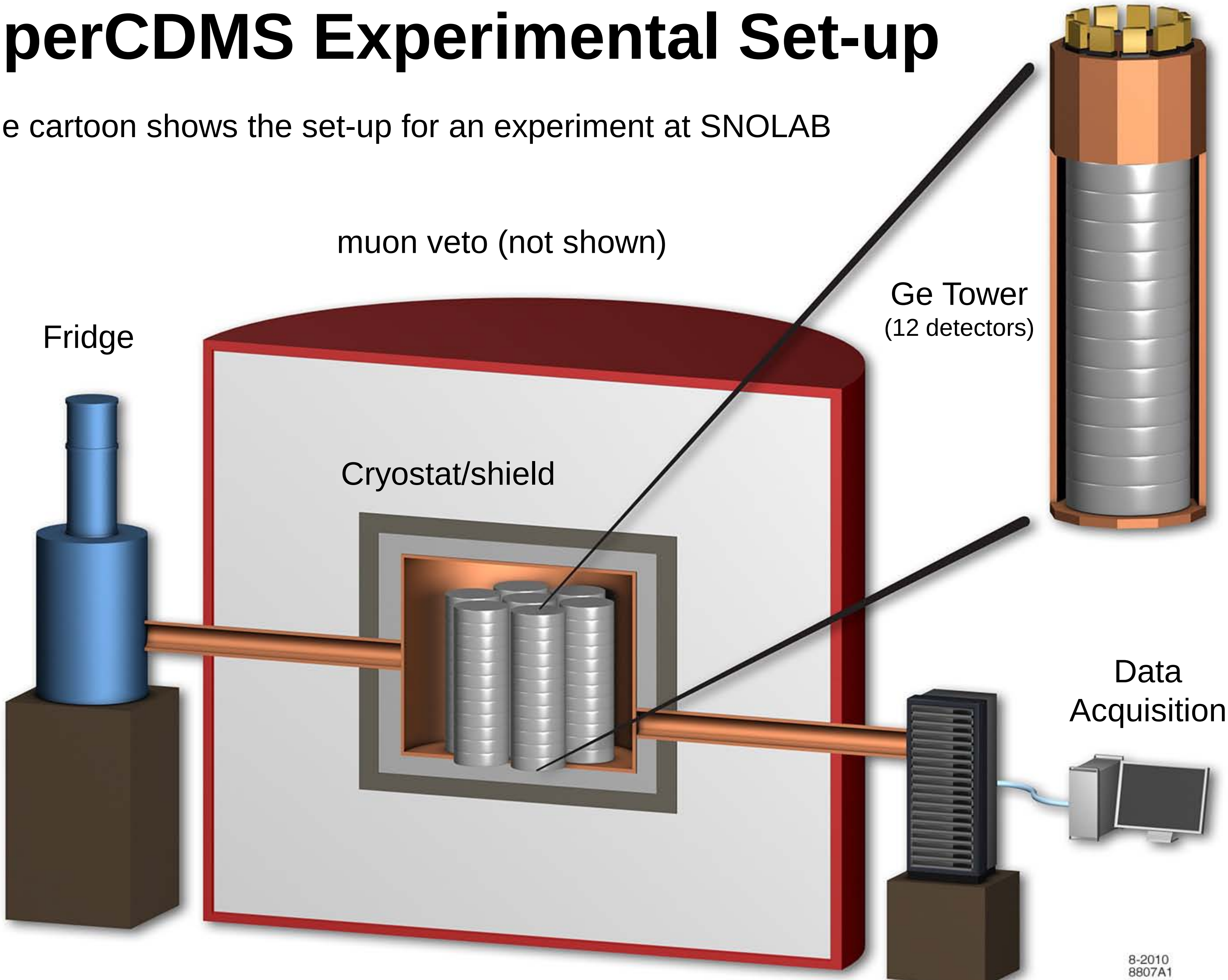
- Would require modulation fraction in CDMS of nearly 100% (same for full energy range)



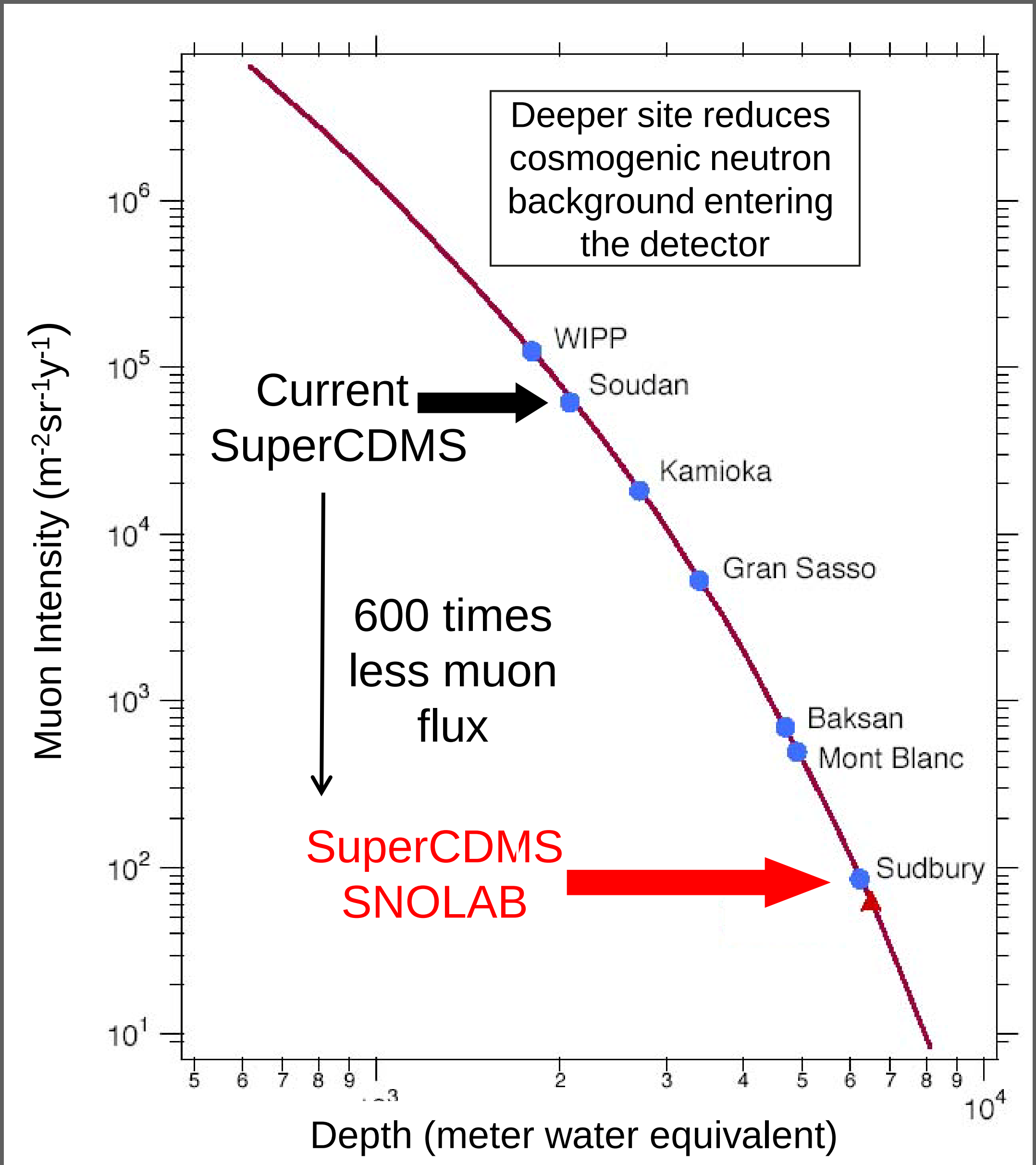


SuperCDMS Experimental Set-up

the cartoon shows the set-up for an experiment at SNOLAB

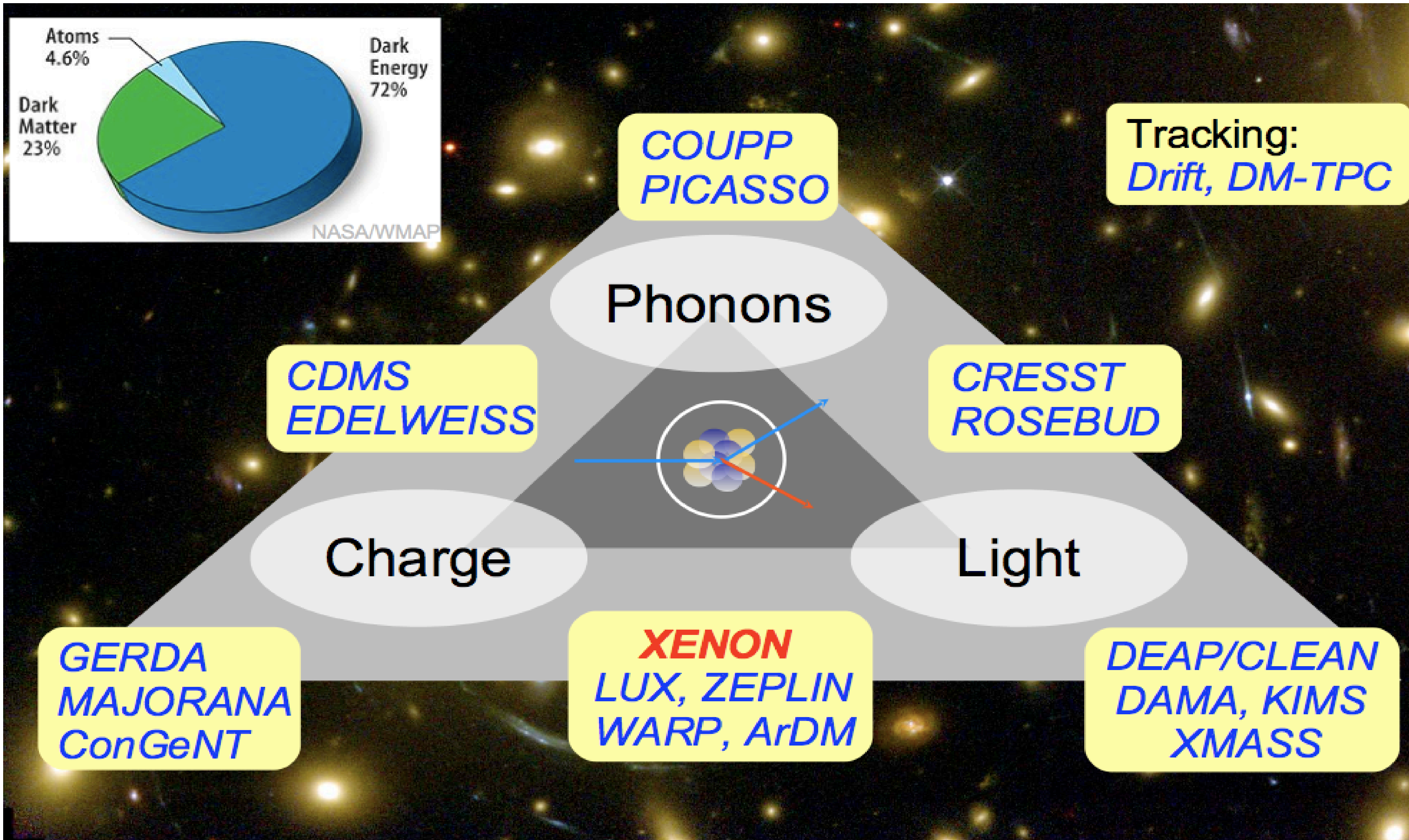


Operate Underground to Reduce Backgrounds



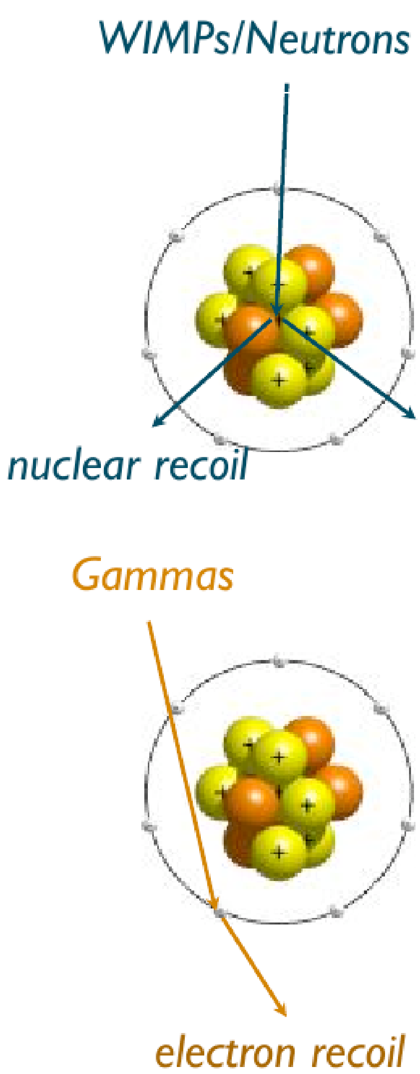
- **Soudan**
  - **< 1 unvetoed neutron for ~ 7000 kg-days**
  - **2090 mwe ~ 0.7 km**
- **SNOLAB**
  - **1 neutron / year / ton**
  - **6060 mwe ~ 2 km**
- **DUSEL**
  7100 mwe

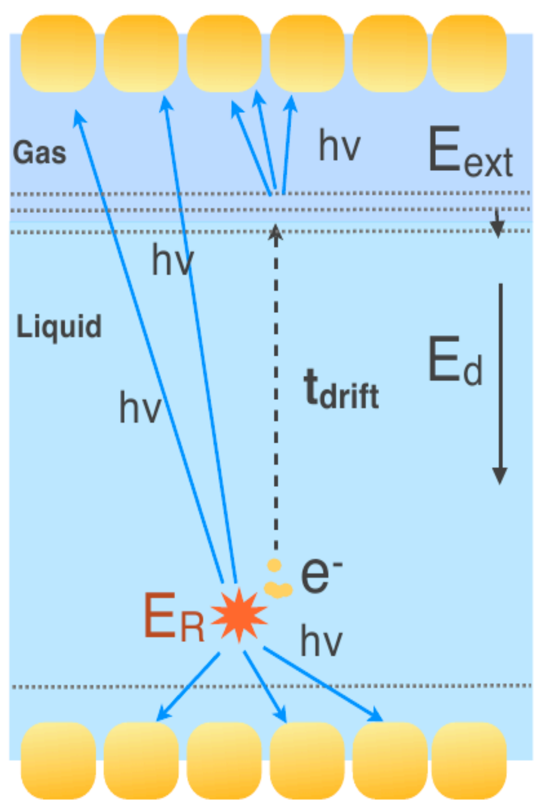
Dark Matter Direct Detection

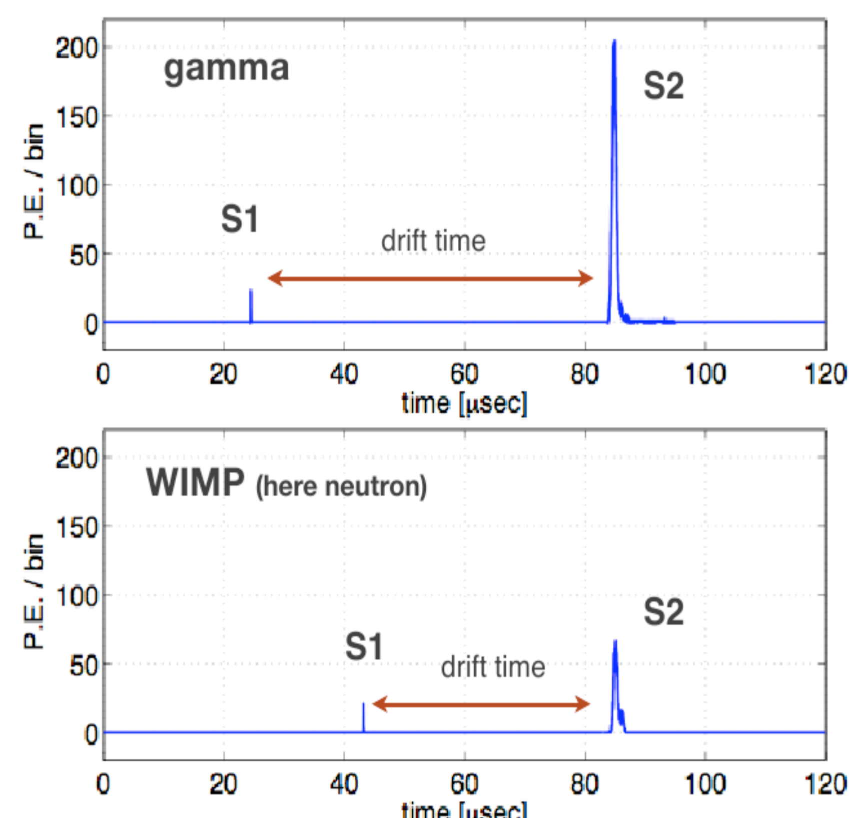


Double phase TPC

- Primary scintillation signal (S1)
- Electrons drift over 30 cm max distance
- Electrons are extracted and accelerated generating secondary scintillation signal
- The time difference between the two signals gives information on event position in z

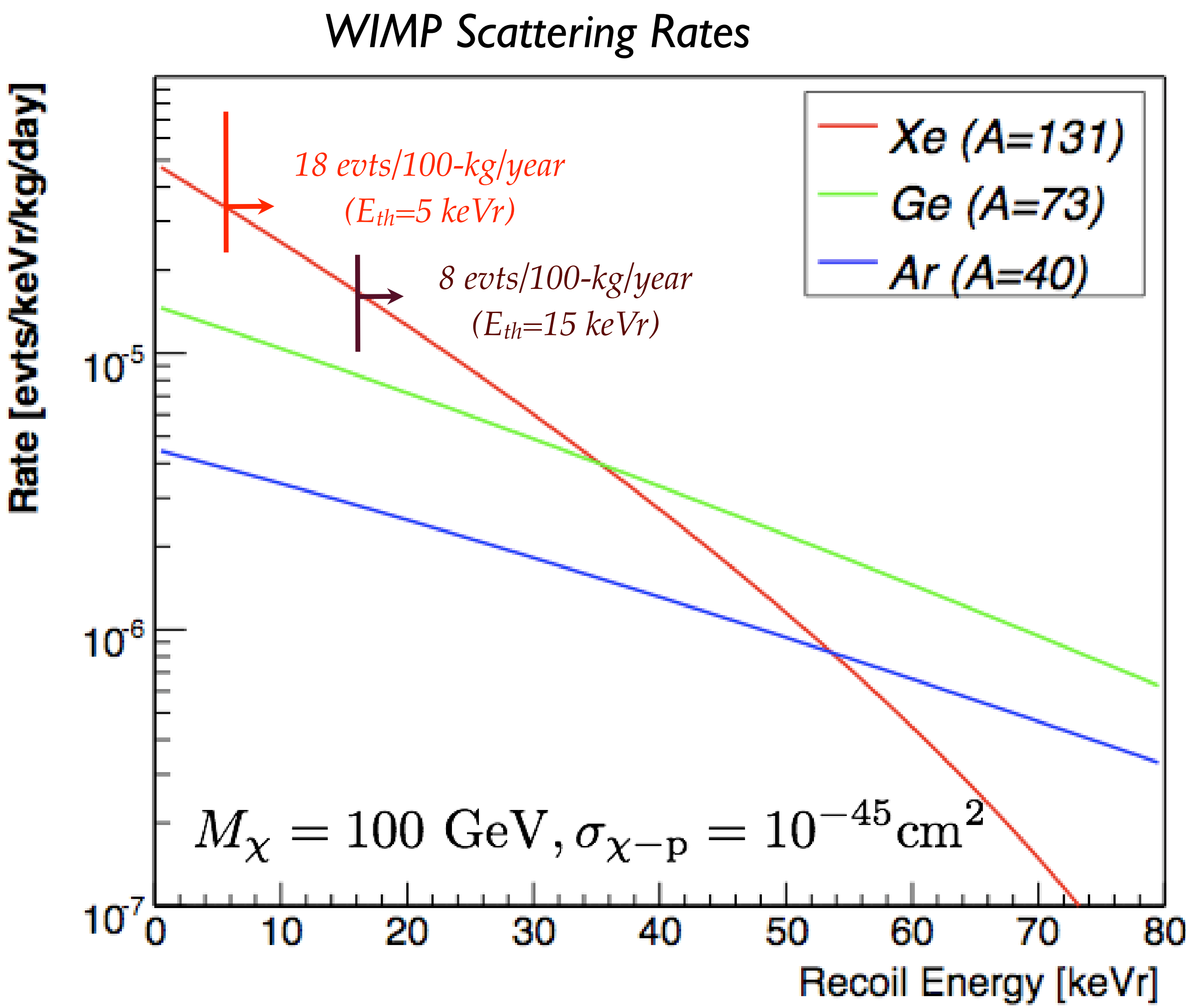






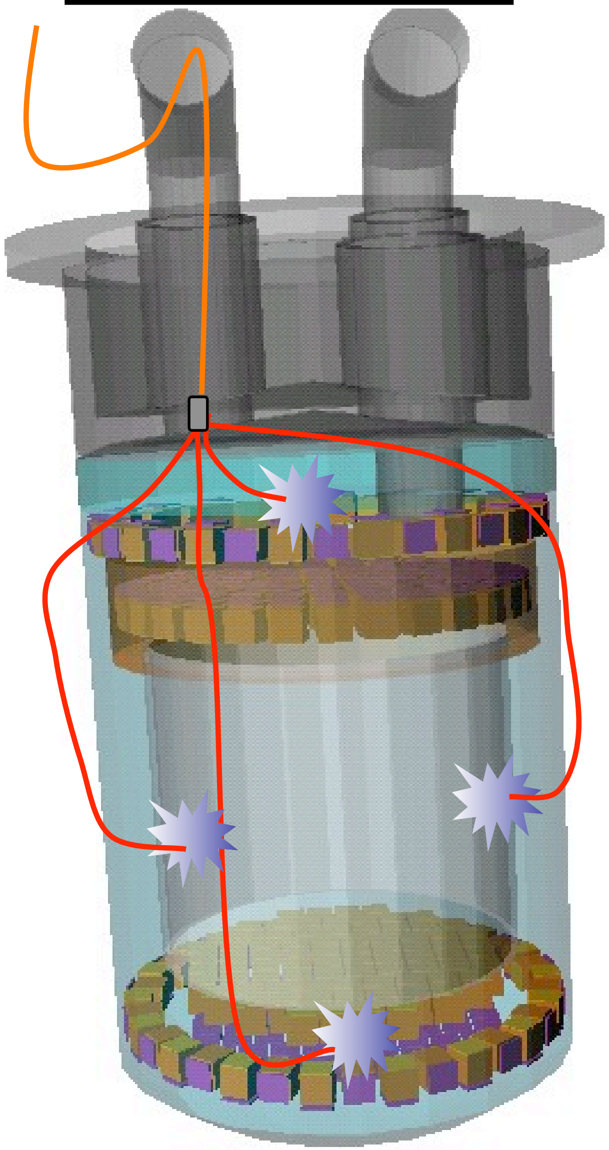
Why Liquid Xenon?

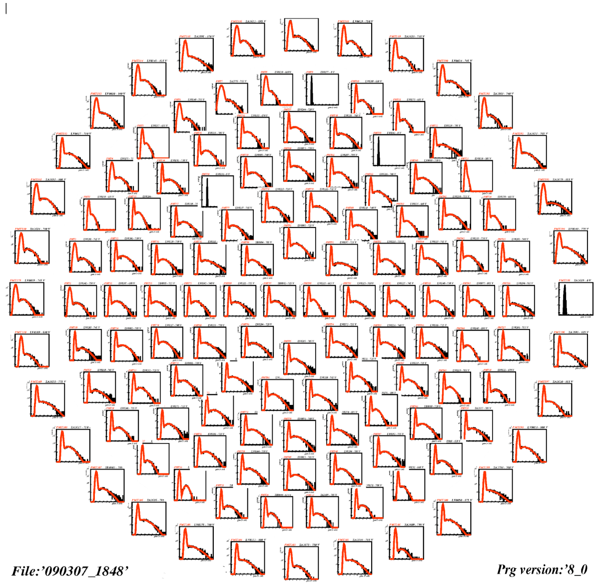
- ✓ large mass (ton scale)
- ✓ easy cryogenics
- ✓ low energy threshold (a few keV)
- ✓ A~131 (good for SI)
- ✓ ~50% odd isotopes (SD)
- ✓ background suppression
  - good self shielding features (~3 g/cm^3)
  - low intrinsic radioactivity
  - gamma background discrimination
  - position sensitive (TPC mode)

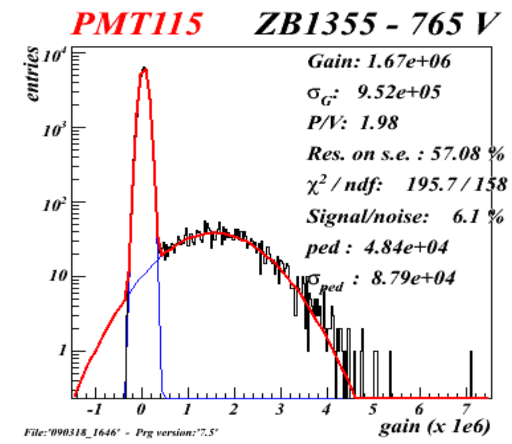


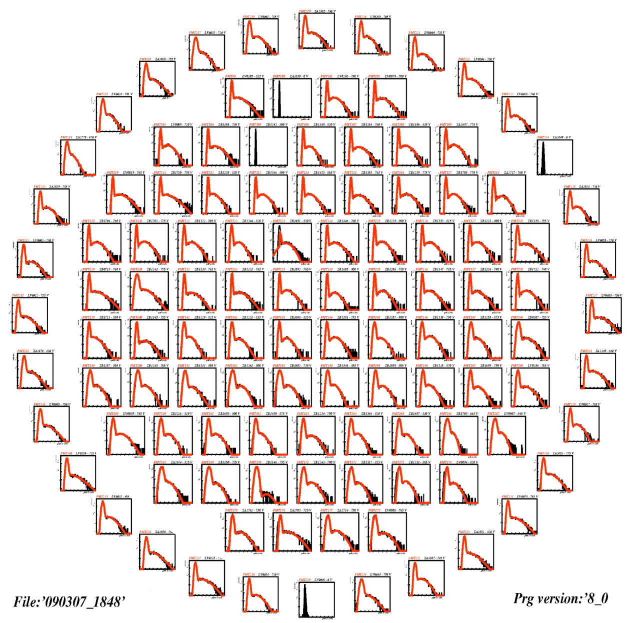
Xenon100: PMT light calibration

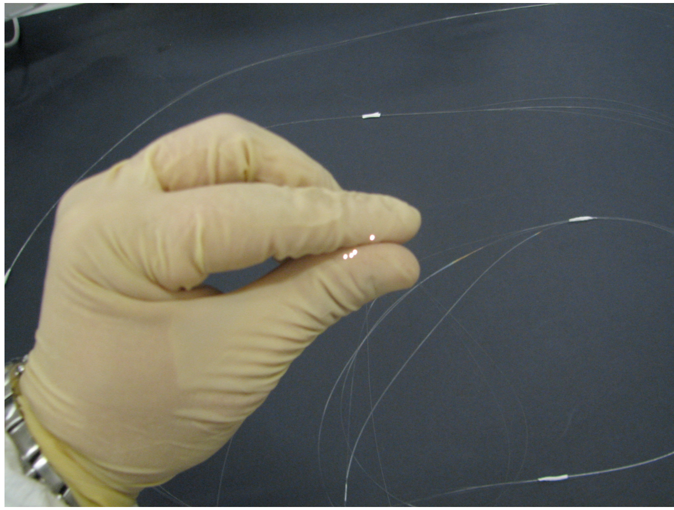
4 optical fibers



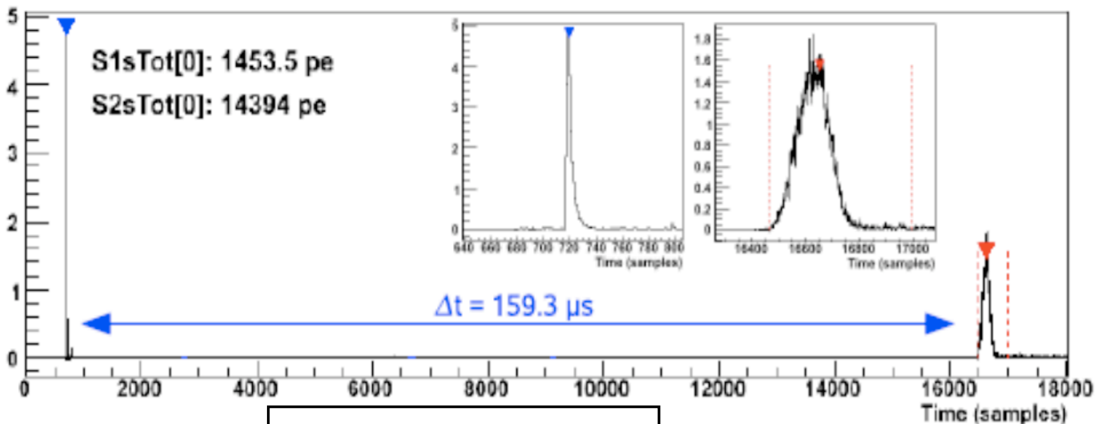




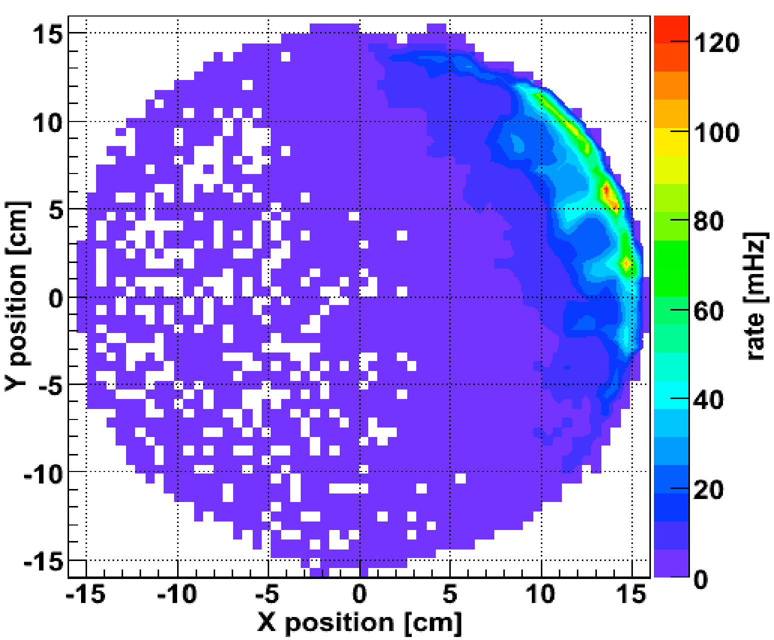




Xenon100: Position reconstruction

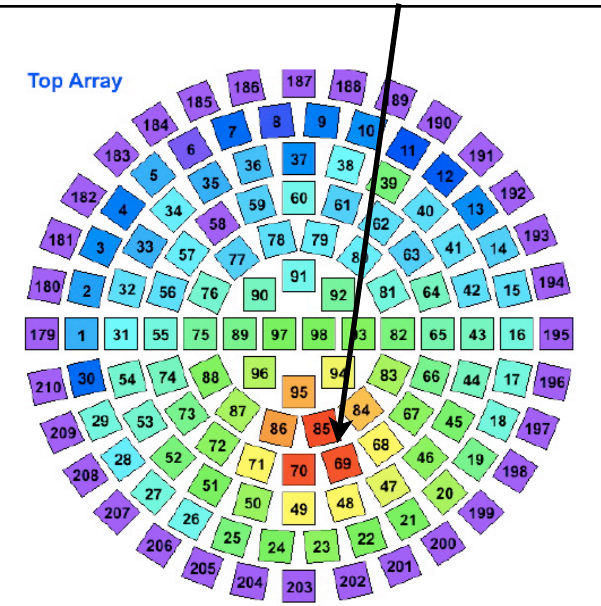


drift time -> z



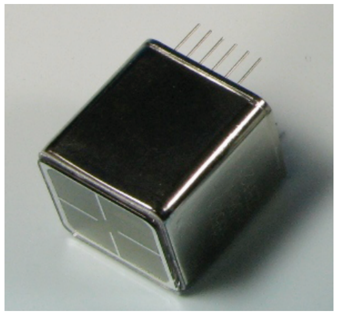
Cs137 from the side

Very localized S2 hit pattern (xy position information)

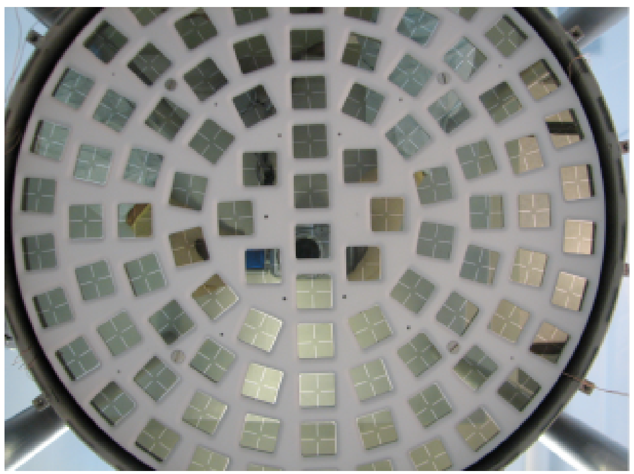


3 different methods for xy position reconstruction:
neural network
support vector machine
Least squares minimization

What is inside has to be carefully selected

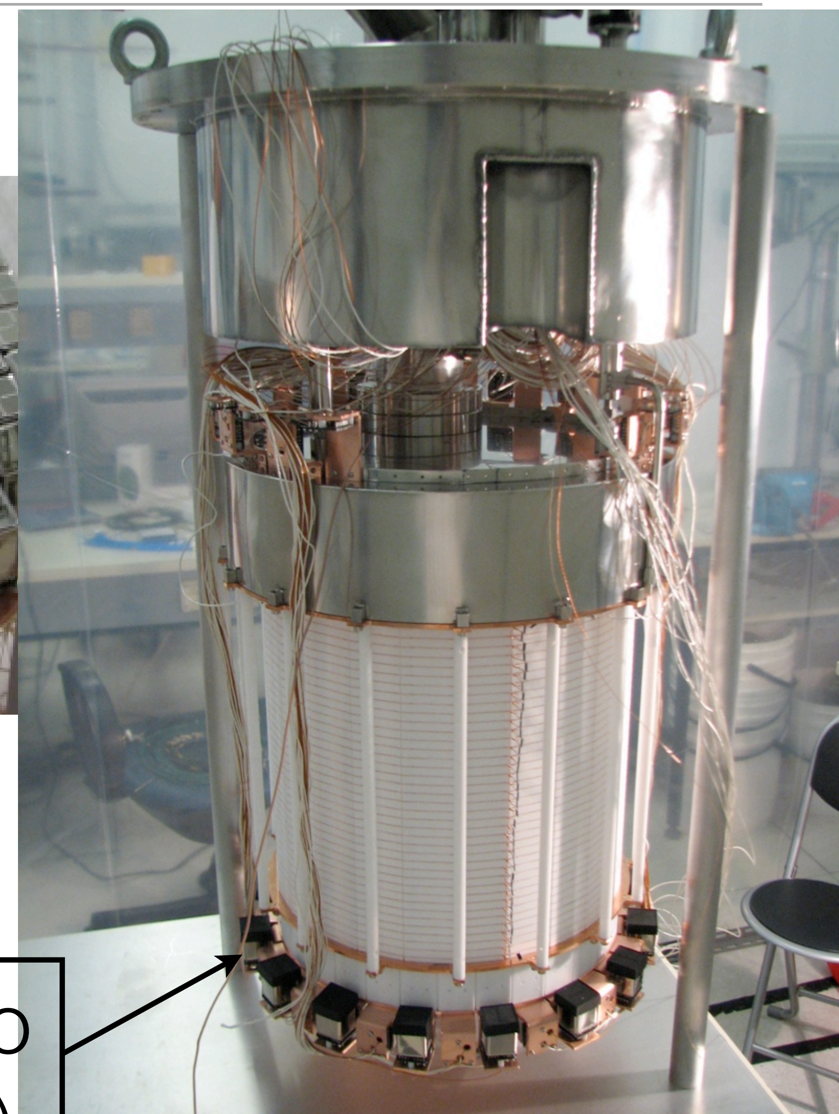


242 (Hamamatsu R8520) 1"x1"
low radioactivity PMTs

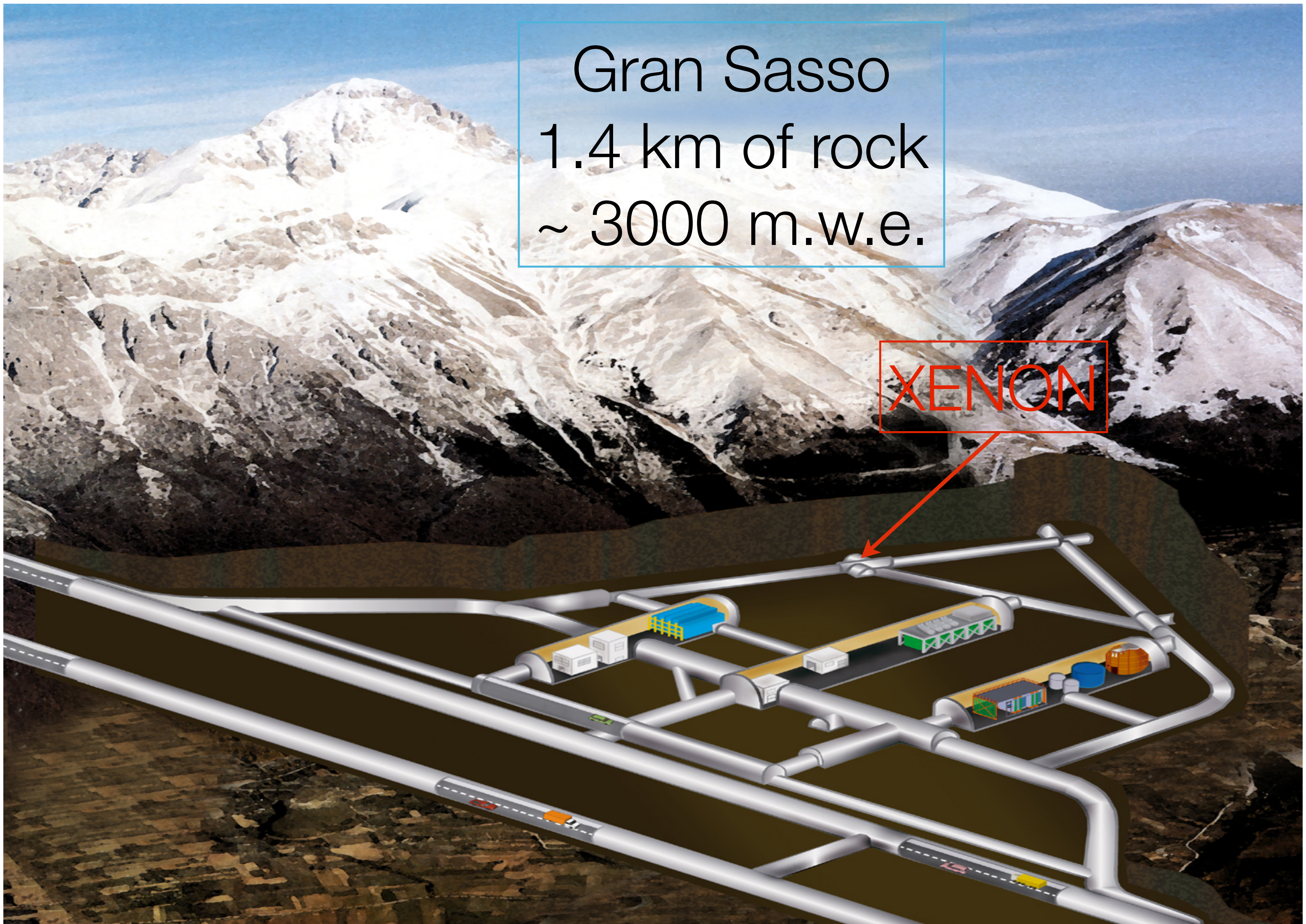


SS
PTFE
Copper
Cables
Screws

100 kg LXe Active veto
(side, top and bottom)

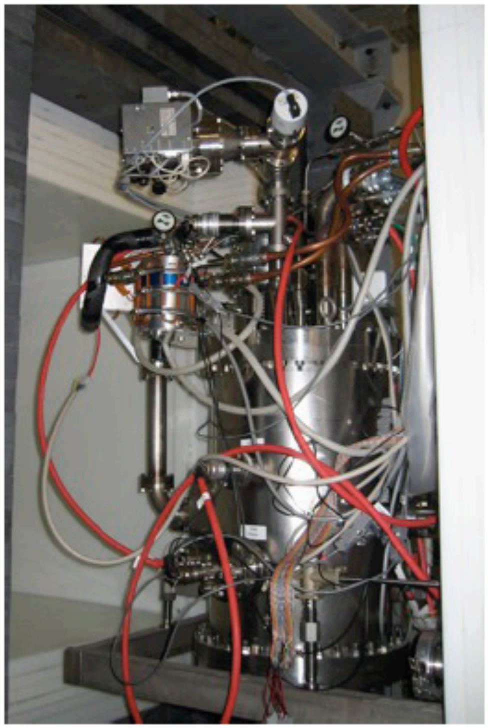


Install the detector underground...



The XENON Roadmap

past (2005 - 2007)	current (2008-2010)	future (2011- 2015)



XENON10

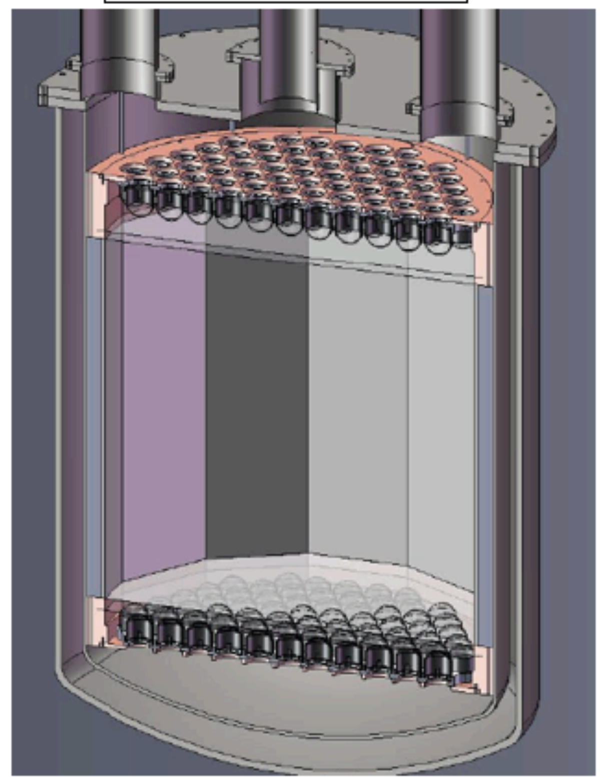
Achieved (2007) σ_{SI}=8.8 x10^{-44} cm^2

Phys. Rev. Lett. **100**, 021303 (2008)

Phys. Rev. Lett. **101**, 091301 (2008

XENON100

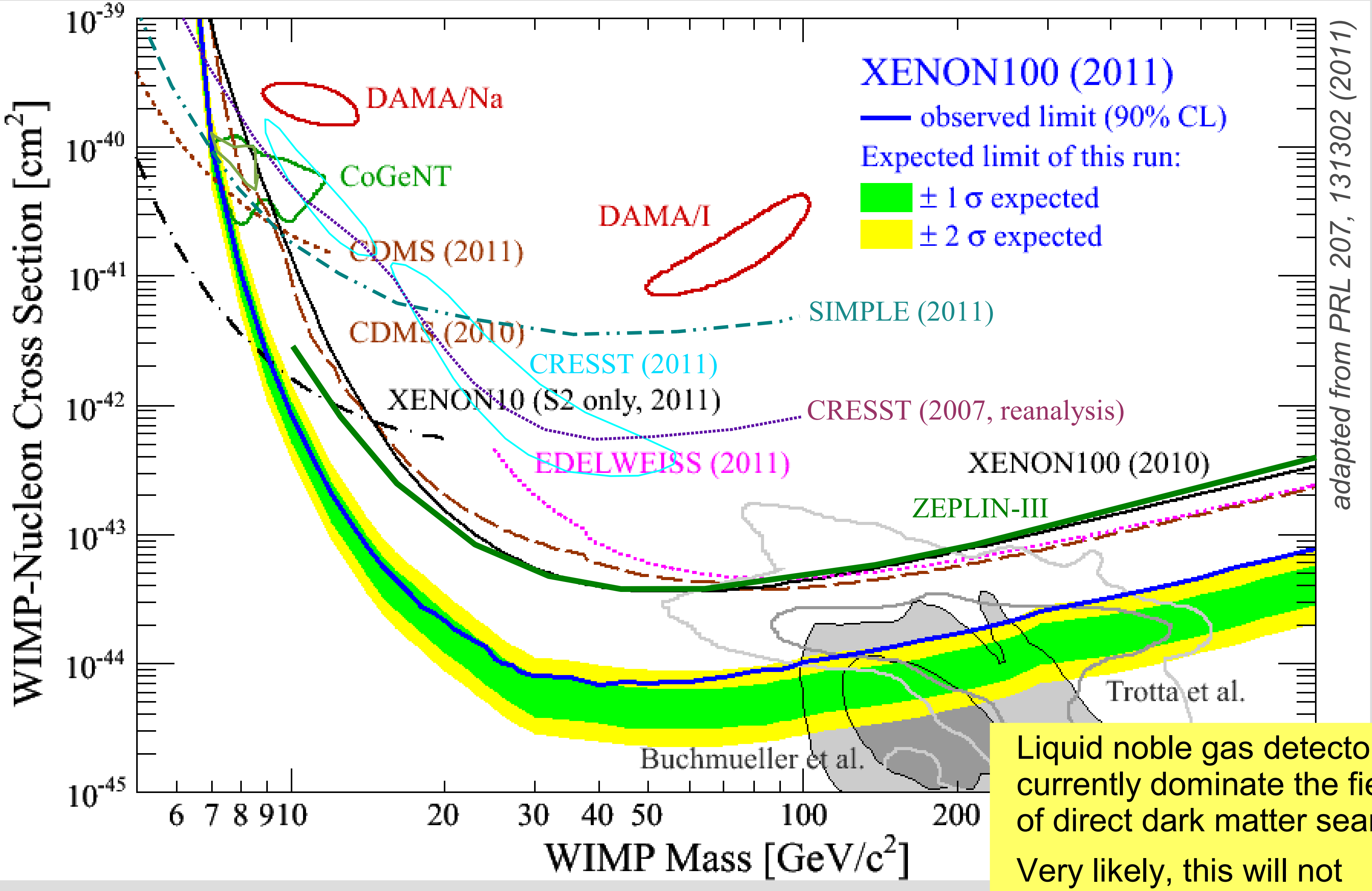
Projected (2010) σ_{SI}~2x10^{-45} cm^2



XENON1T

Goal: σ_{SI} <10^{-46} cm^2

Summary



Liquid noble gas detectors currently dominate the field of direct dark matter searches

Very likely, this will not change in the future.