Physics with calorimeters

Calor 2008

Pavia 26-30.May 2008

K.Pretzl

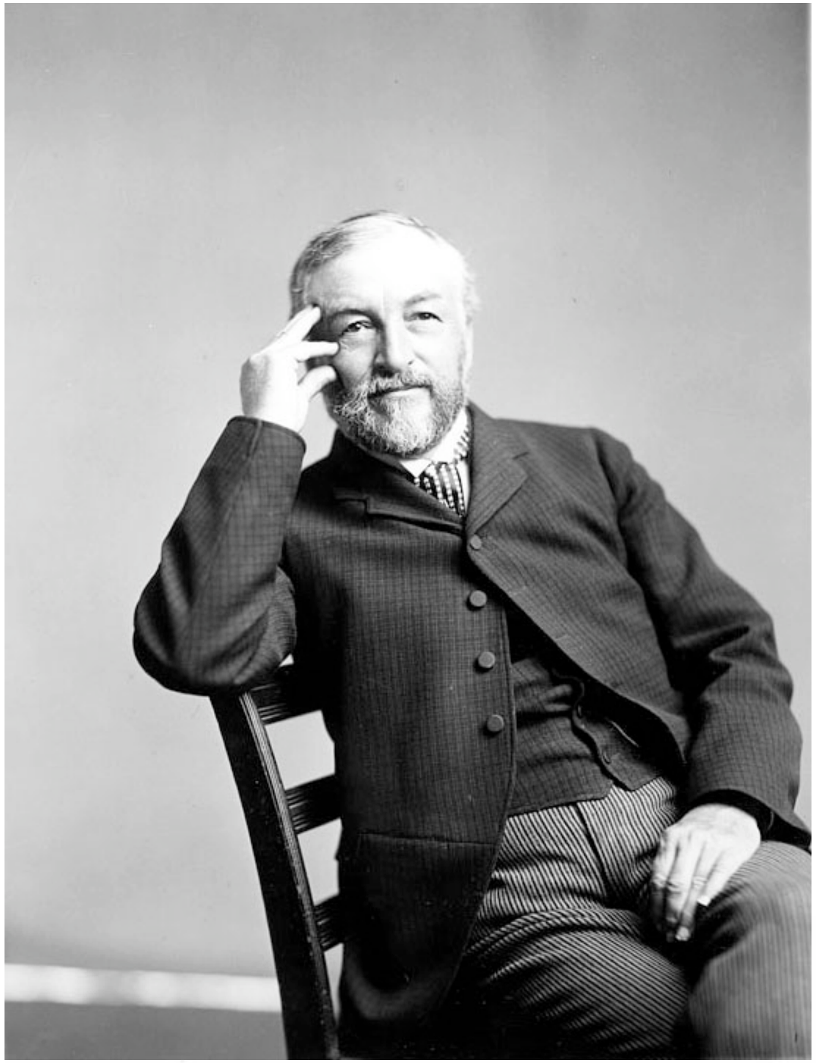
Historical remarks

The early days of jet physics

Direct dark matter searches

Neutrinoless double beta decay

Direct neutrino mass measurement



Samuel Pierpot Langley (1834-1906)

Astronomer

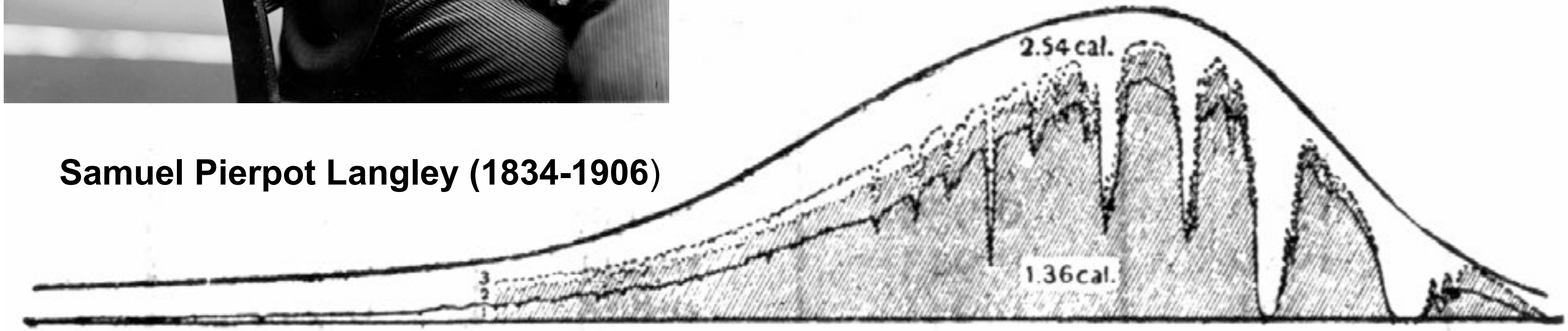
Inventor of bolometer 1878

Pioneer of aviation

Solar constant measured
on Mount Whitney by Langley

2.54 cal / min cm^2 = 1.77 kW / m^2

Actual average value =1.37 kW / m^2



1903 first attempt to measure the energy released in radioactive decays by P. Curie and A. Laborde with a calorimeter.

1927 C.D. Ellis and A. Wooster developed a micro-calorimeter to measure the beta decay of ^{210}Bi.

W. Orthmann and L. Meitner measured 1930 the average electron energy to 0.337 MeV with 6% accuracy of the ^{210}Bi beta decay.

Notion of a continuous beta spectrum was leading to W.Pauli's neutrino hypothesis.

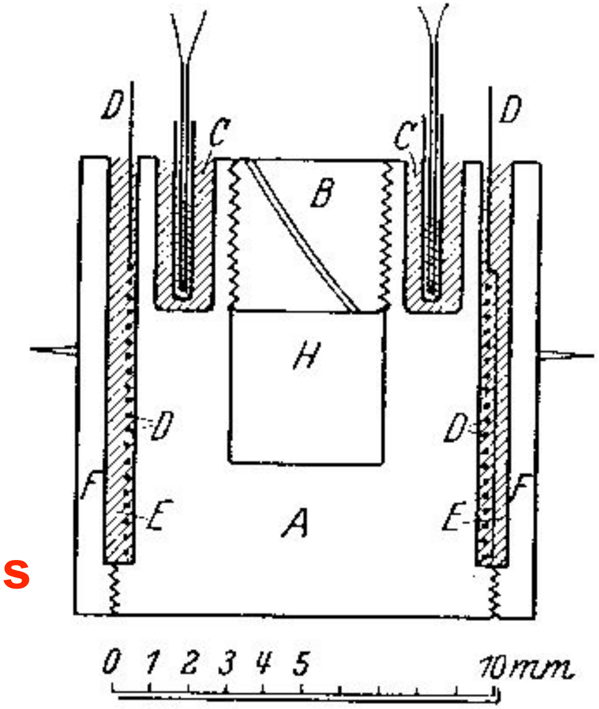


Fig. 1.
Längsschnitt durch ein Kalorimetergefäß.
▨ Woodsches Metall.

1954: N.L.Grigorov put foreward the idea of sampling calorimeters using ionisation chambers (proportinal counters) to measure cosmic ray particles with energies

$E>10^{14}$ eV

N.L. Grigorov et al. Zh.Eksp.Teor.Fiz.34 (1954)506

V.S.Murzin, Prog.Elem.Part.Cosmic Ray Phys. 9 (1967) 247-303

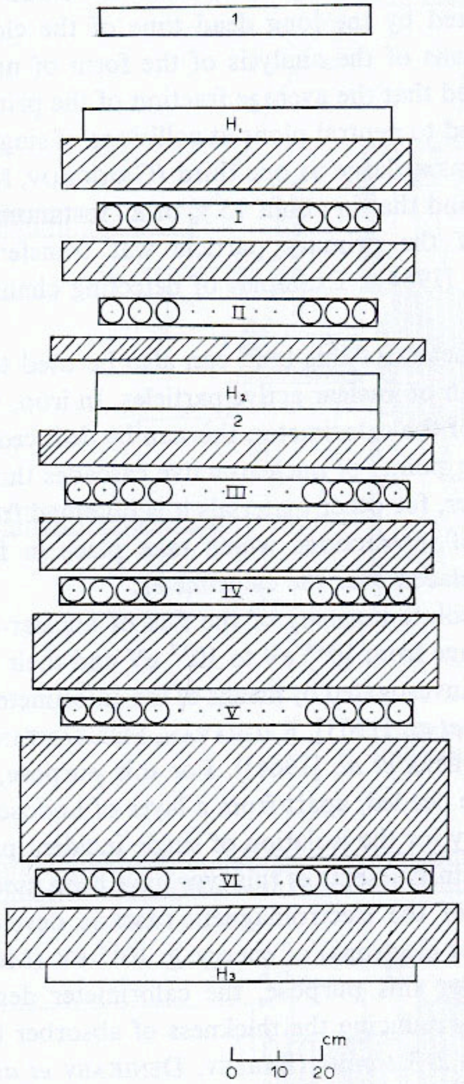
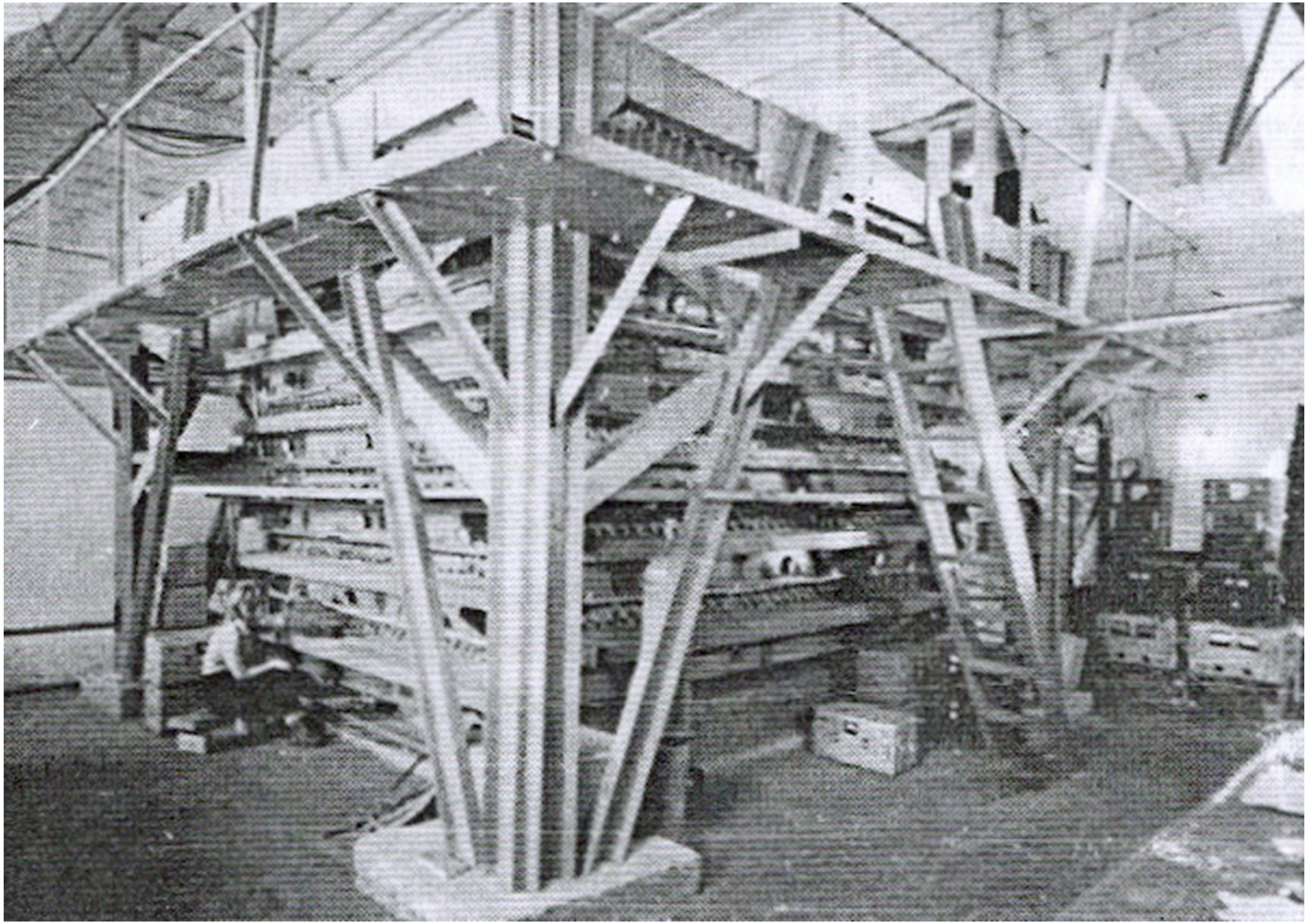


Fig. 14. Schematic diagram of the first ionization calorimeter (GRIGOROV, MURZIN and RAPOPORT [1958]). The shaded areas represent absorber. Layers 1 and 2 are the rows of counters forming the controlling telescope. Layers H_1, H_2, H_3 are hodoscoped counters, while layers I, . . ., VI are the detectors (ionization chambers) of the calorimeter.

N.Grigorov, V.Murzin and I.Rapoport calorimeter erected 1957 in the Pamir Mountains at 3860m above sea level



1969 e-p scattering experiments at SLAC suggest point like structure of the nucleon (Friedman, Kendall, Taylor)

1969 Feynman introduces the parton model of the nucleon

1971 The 63 GeV ISR begins operation at CERN

1973 Fritzsch, Gell-Mann, Leutwyler introduce color octet of gluons leading to a theory of strong interactions (QCD)

1972 400 GeV Proton Synchrotron at Fermi-Lab. starts operation

1972 The SPEAR electron positron collider at SLAC is completed

1973 Discovery of neutral currents with GARGAMELLE at CERN

1974 The DORIS electron-positron collider at DESY begins operation

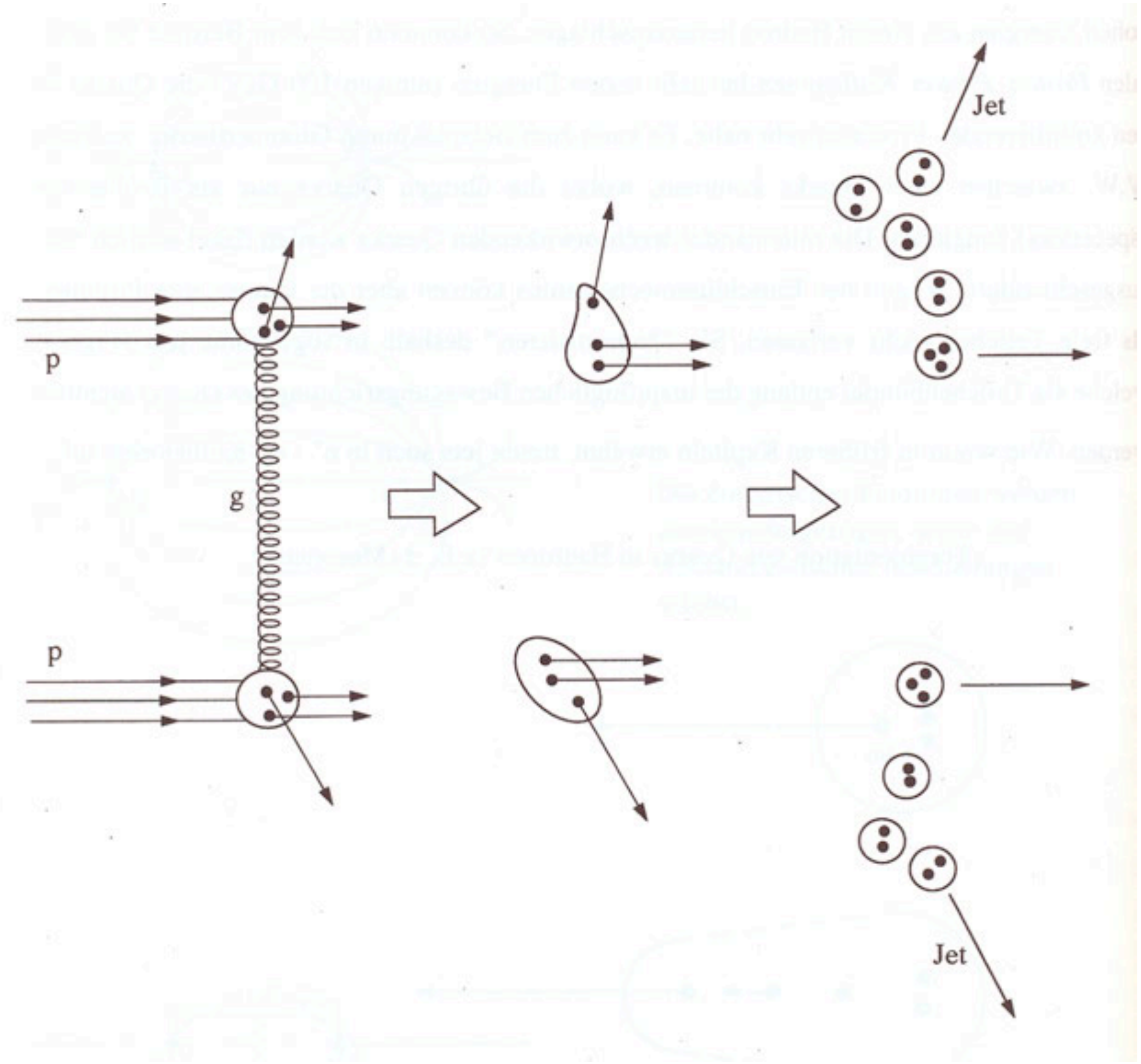
1974 Discovery of the J/ψ in BNL and SLAC (Ting, Richter)

1975 Evidence of jet like structure in e^+-e^- annihilations at SLAC

1976 Discovery of charm mesons at SLAC (Goldhaber)

1976 The 450 GeV SPS at CERN starts up operation

The early days of jet physics in hadron collisions at SPS energies $\sqrt{s} = 24 GeV$



Physics questions asked:

Is there a scaling law?

$$\frac{d\sigma}{dx_c} = \frac{1}{s} F(\theta_1^*, \theta_2^*, x_c)$$

With $x_c = \frac{E_{cal.}}{E_{inc.}}$ and θ_1^* , θ_2^* the minimum and maximum CM angles of the calorimeter.

Are there jets?

How do they look like ?

Are there heavy objects which decay into jets?

NA5 Experiment at the SPS $\sqrt{s} = 24 GeV$

EXPERIMENTAL LAY - OUT HORIZONTAL

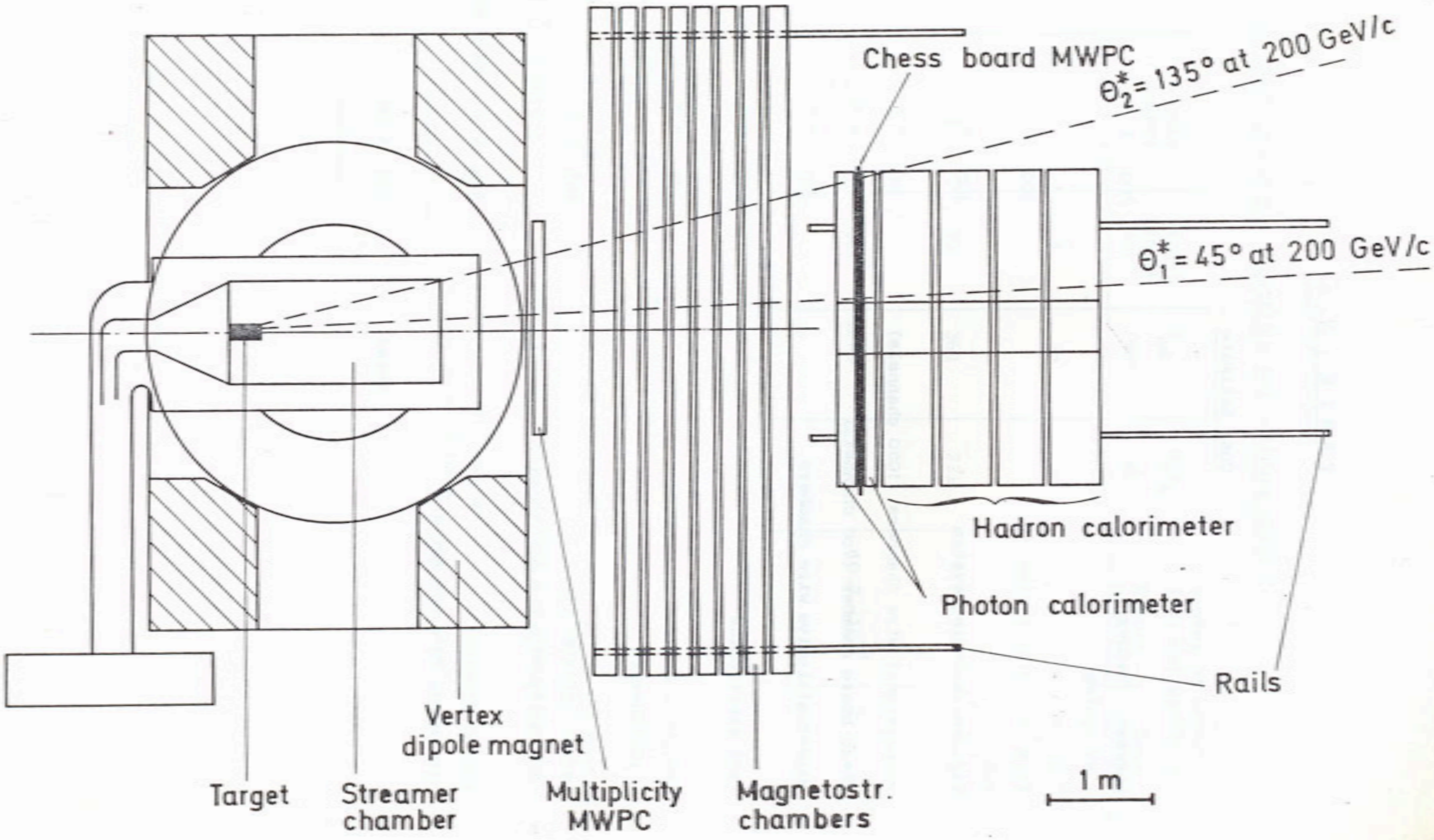
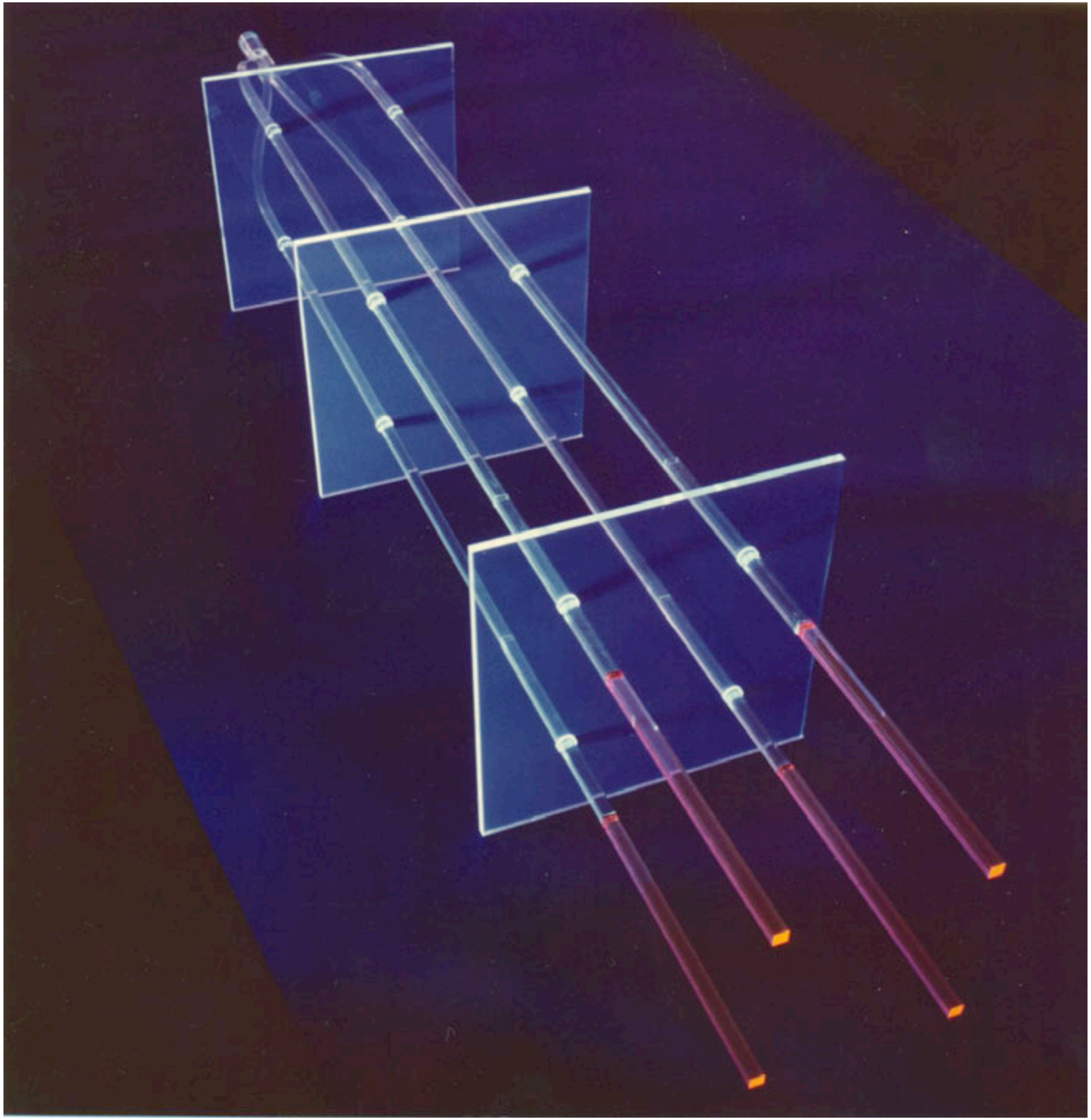


FIG. 1

NA5 Calorimeter



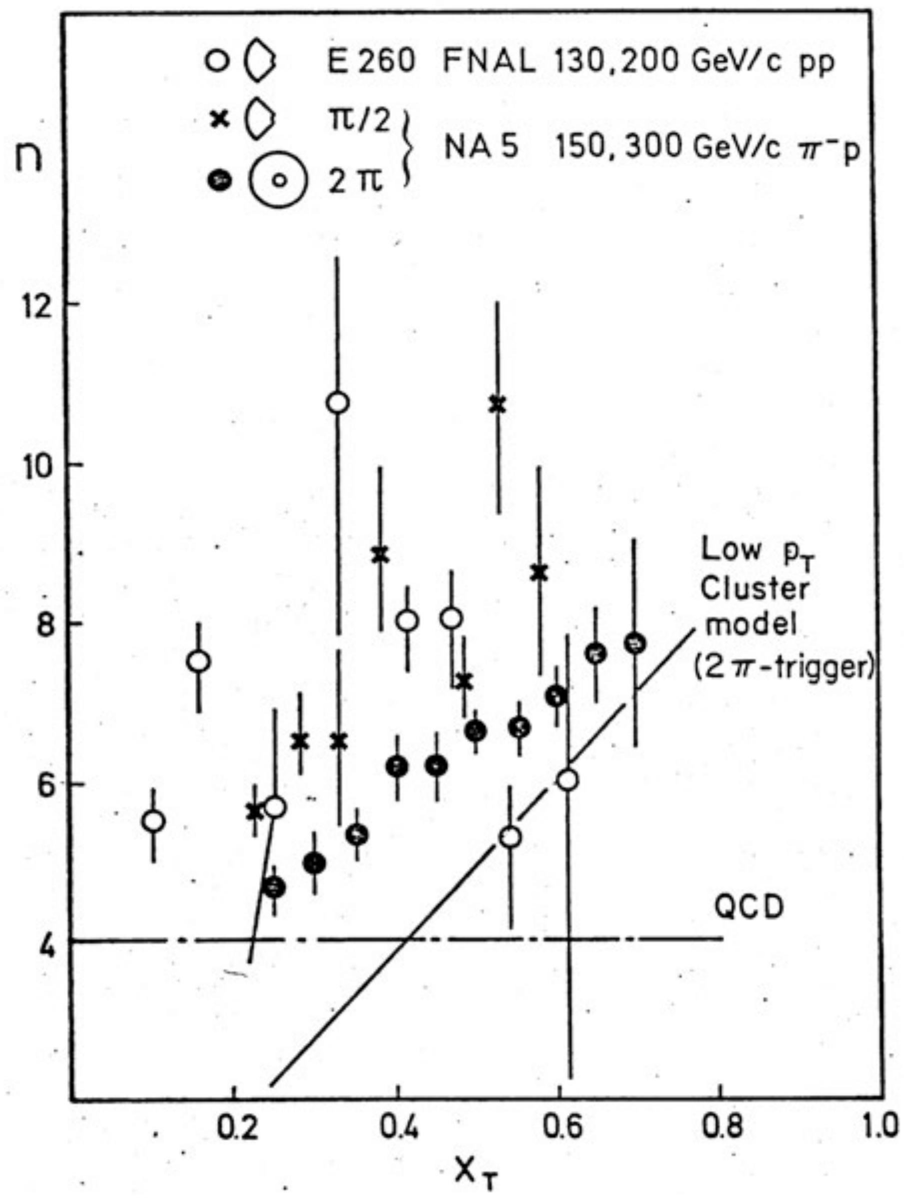


Fig. 9. The scaling behaviour of the cross sections measured with the calorimeter triggers 1 and 3. Two constituent scattering models predict dimensional scaling with n=3 for the trigger 1 and n=4 for trigger 3 cross sections. Results from the FNAL experiment E260[5] are shown for comparison.

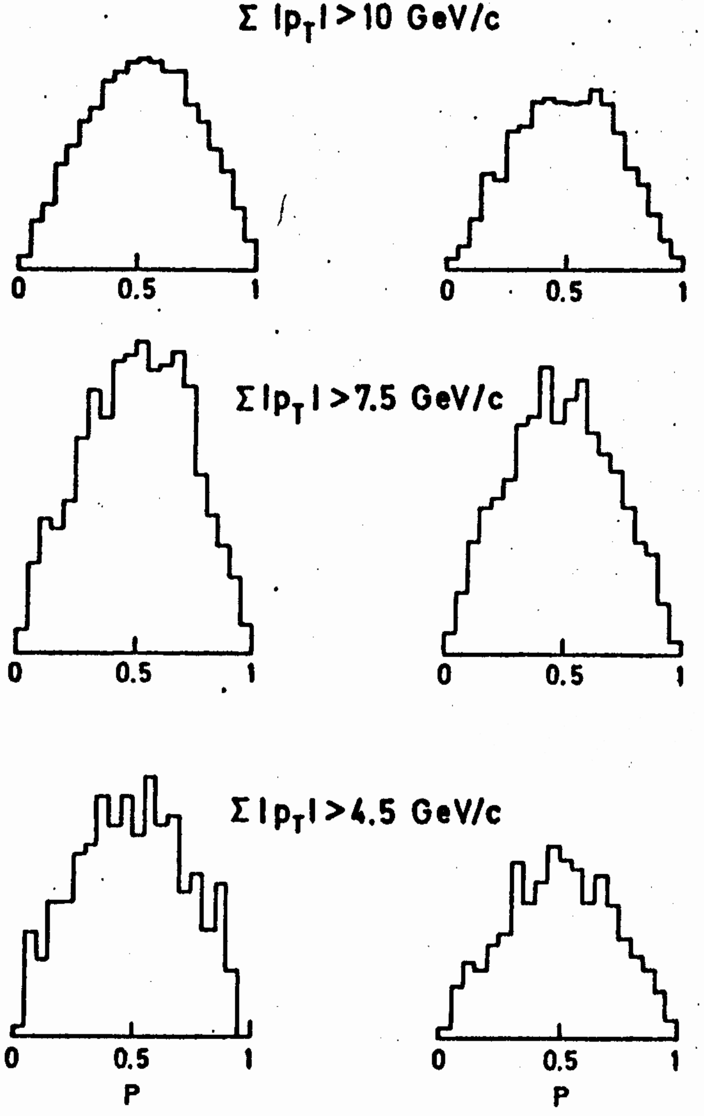
$$\frac{d\sigma}{dp_T^2} \sim p_T^{-n} f(x_T)$$

$$with \;\; x_T = \frac{2p_T}{\sqrt{s}}$$

PLANARITY

300 GeV $\pi^- p$

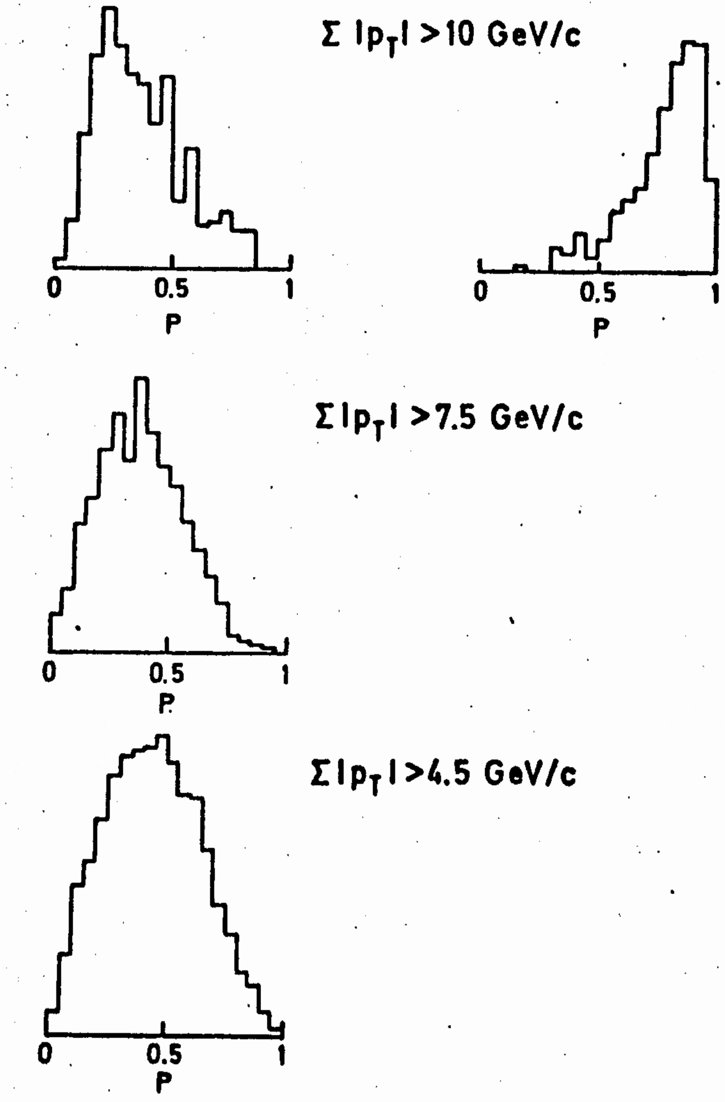
300 GeV pp



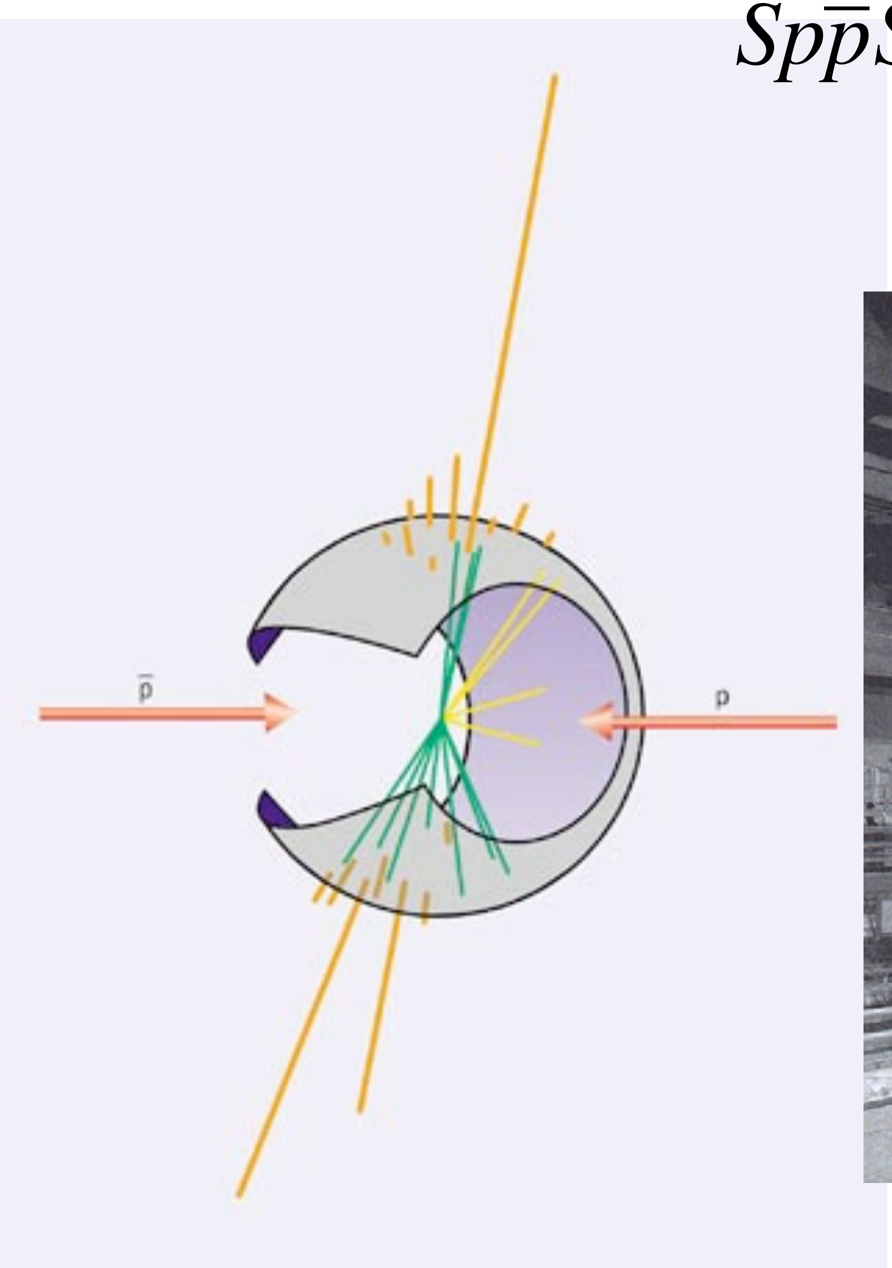
PLANARITY

Low p_T CLUSTER MODEL

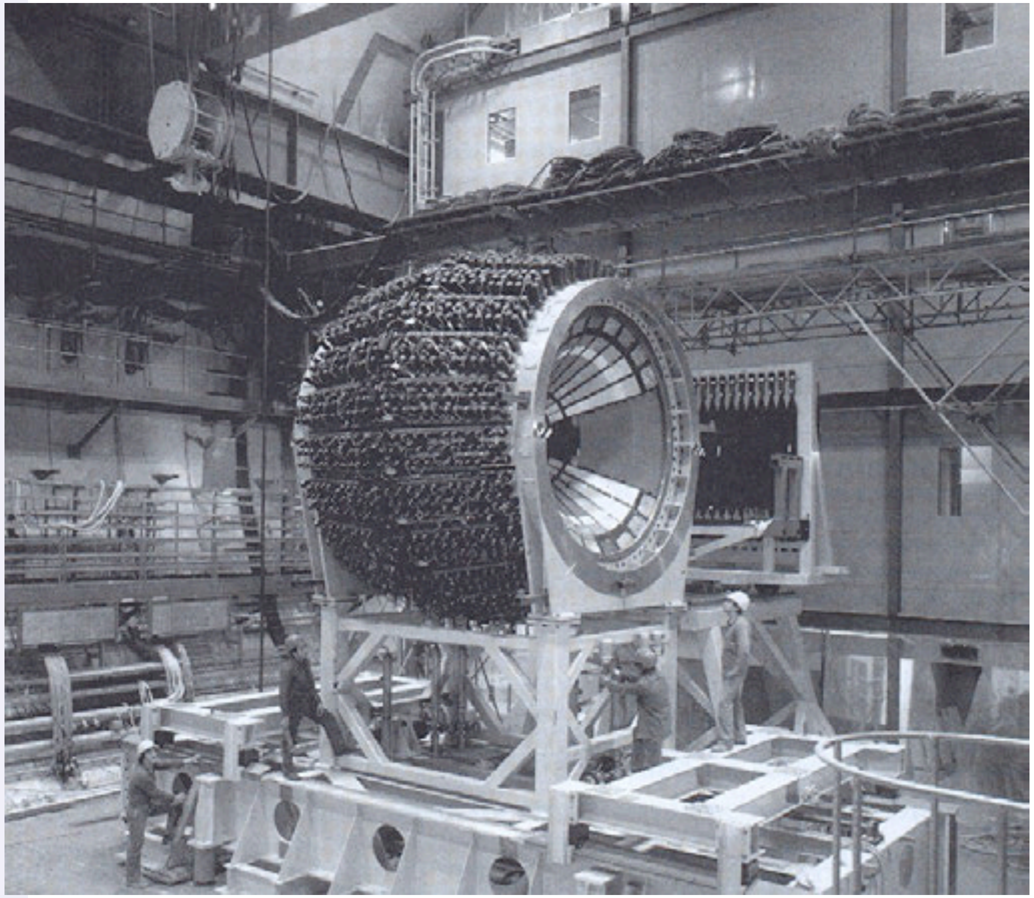
QCD - JET MODEL

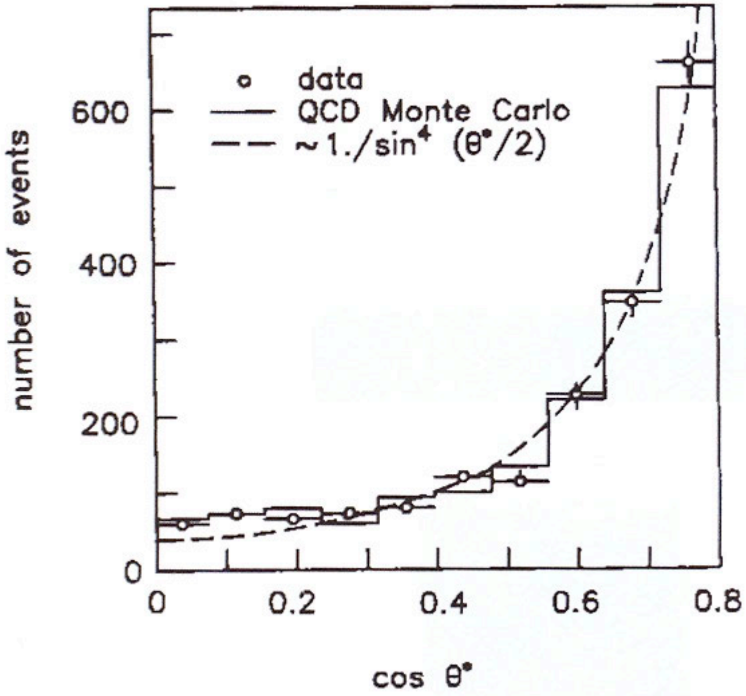


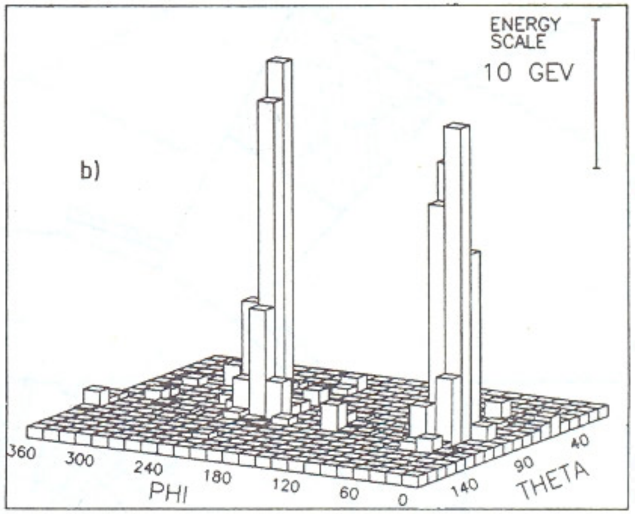
$$Sp\bar{p}S - Collider \quad \sqrt{s} = 630 GeV$$

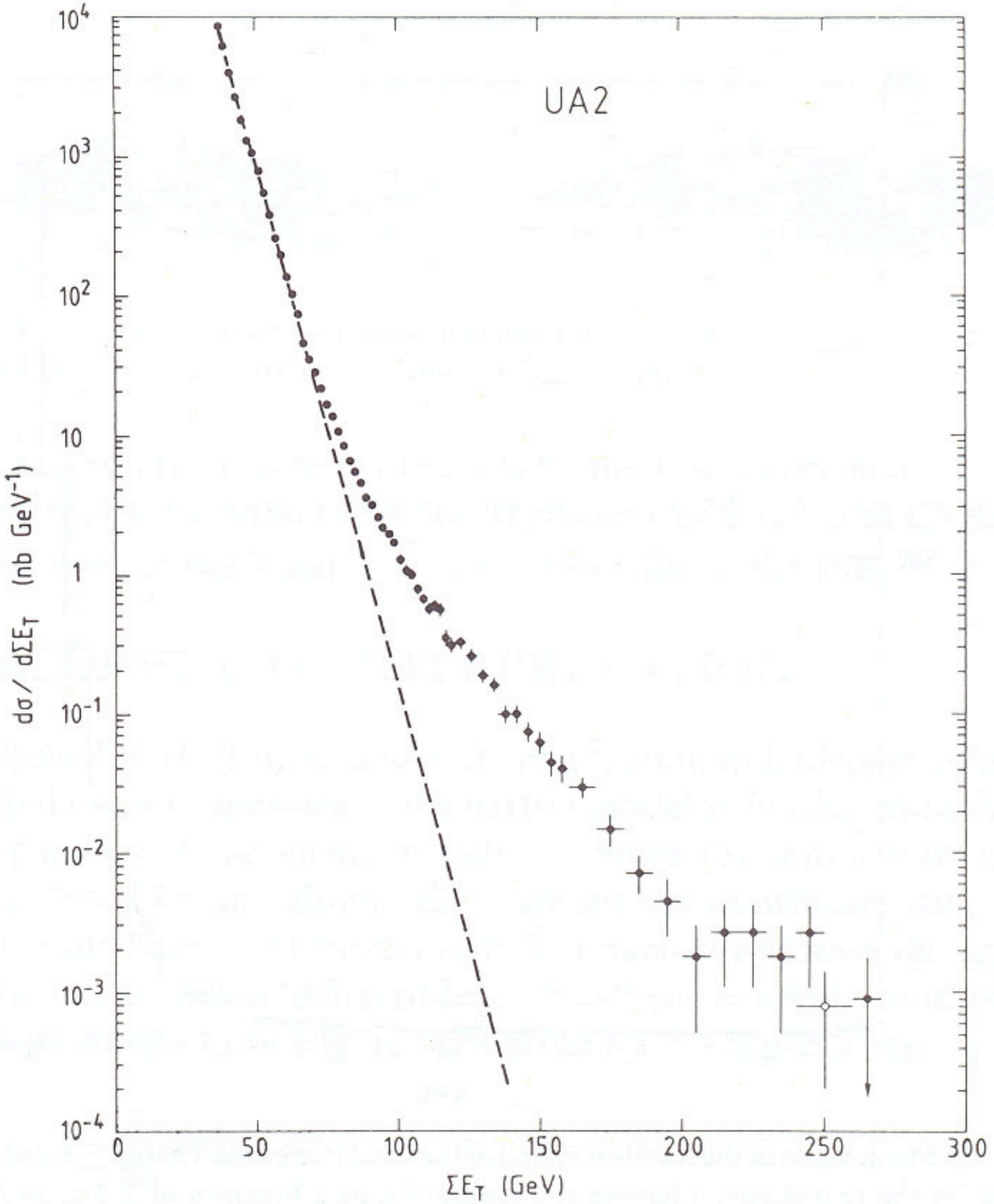


UA2 Calorimeter

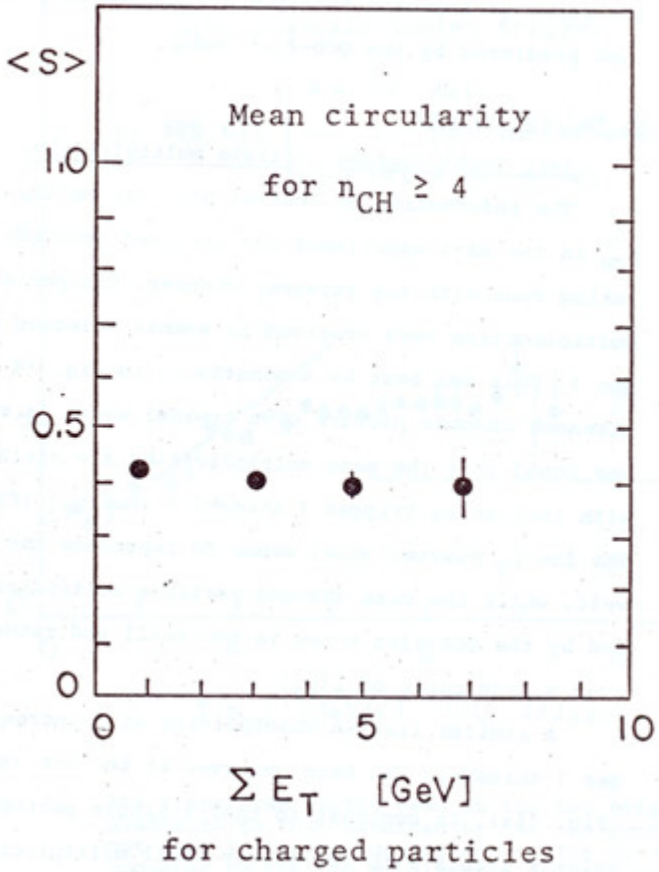


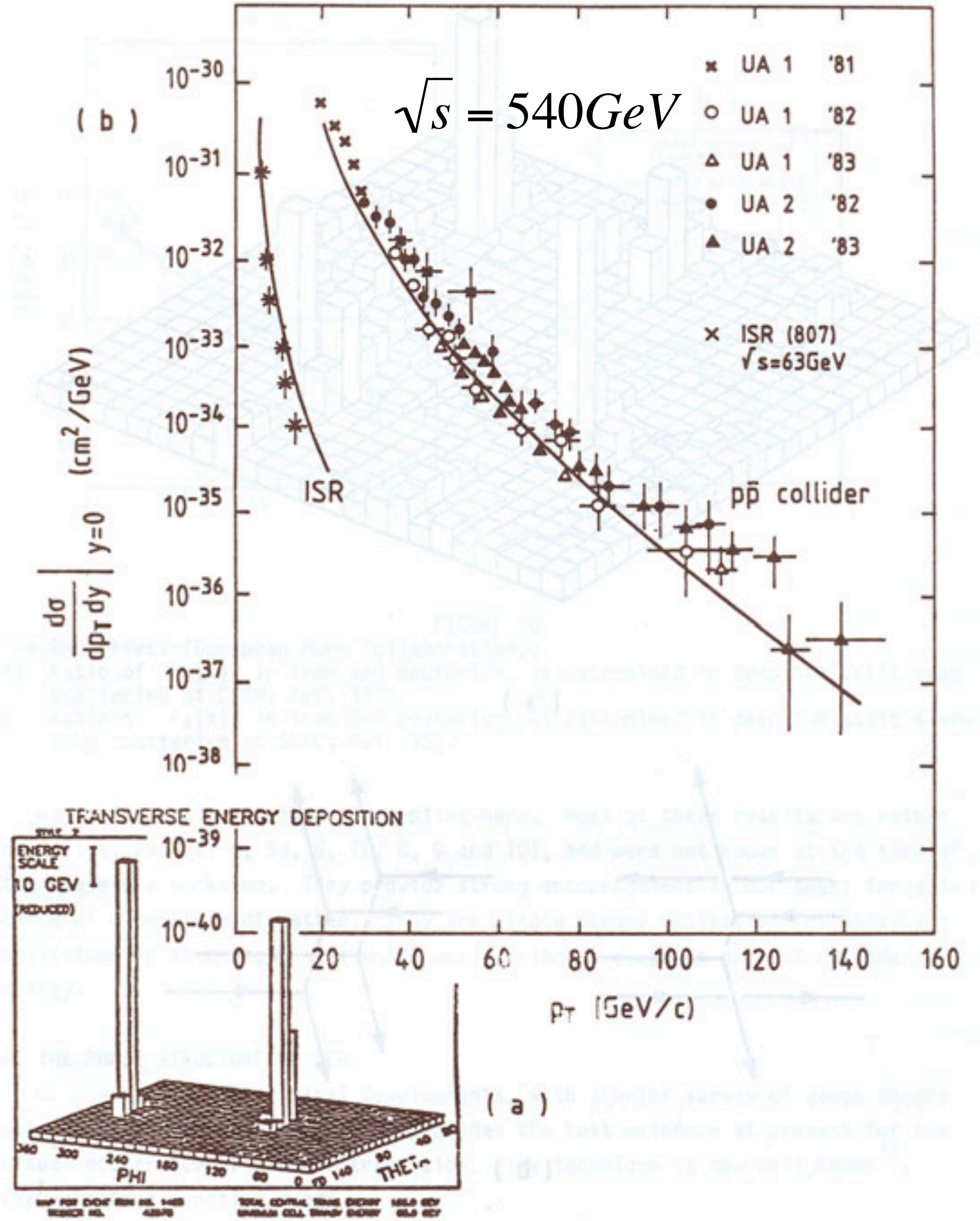

number of events
0
200
400
600
○ data
QCD Monte Carlo
~1./sin⁴ (θ*/2)
0
0.2
0.4
0.6
0.8
cos θ*


ENERGY SCALE
10 GEV
b)
360
300
240
180
120
60
0
PHI
140
90
40
THETA

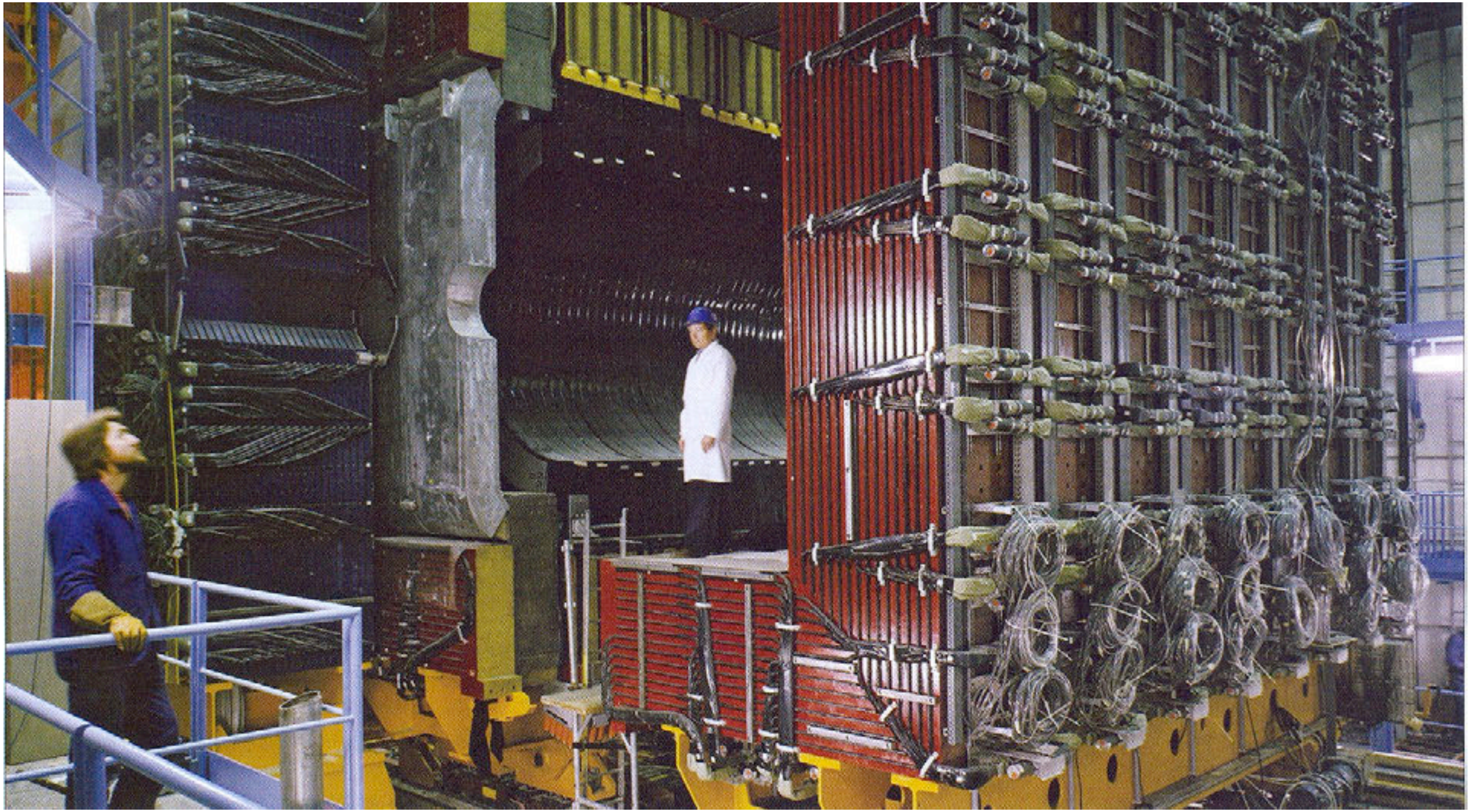

UA2
dσ / dΣE_T (nb GeV⁻¹)
10⁴
10³
10²
10
1
10⁻¹
10⁻²
10⁻³
10⁻⁴
0
50
100
150
200
250
300
ΣE_T (GeV)

ISR $\sqrt{s} = 63GeV$




$\sqrt{s} = 540GeV$

UA1 Experiment



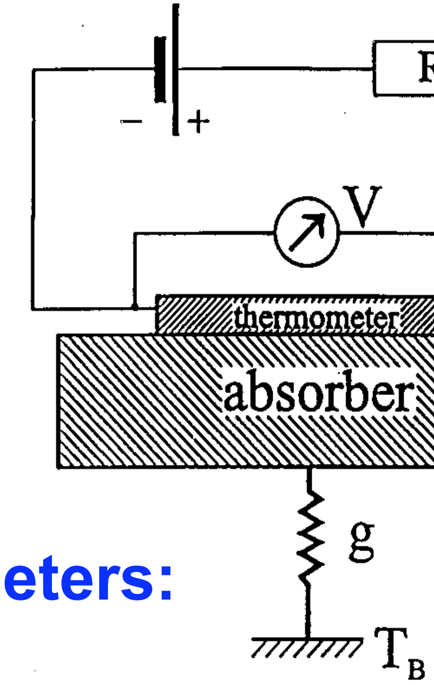
Direct dark matter searches

Neutrinoless double beta decay

Direct neutrino mass measurementss

Cryogenic calorimeters

$$\Delta T = \frac{\Delta E}{C}$$



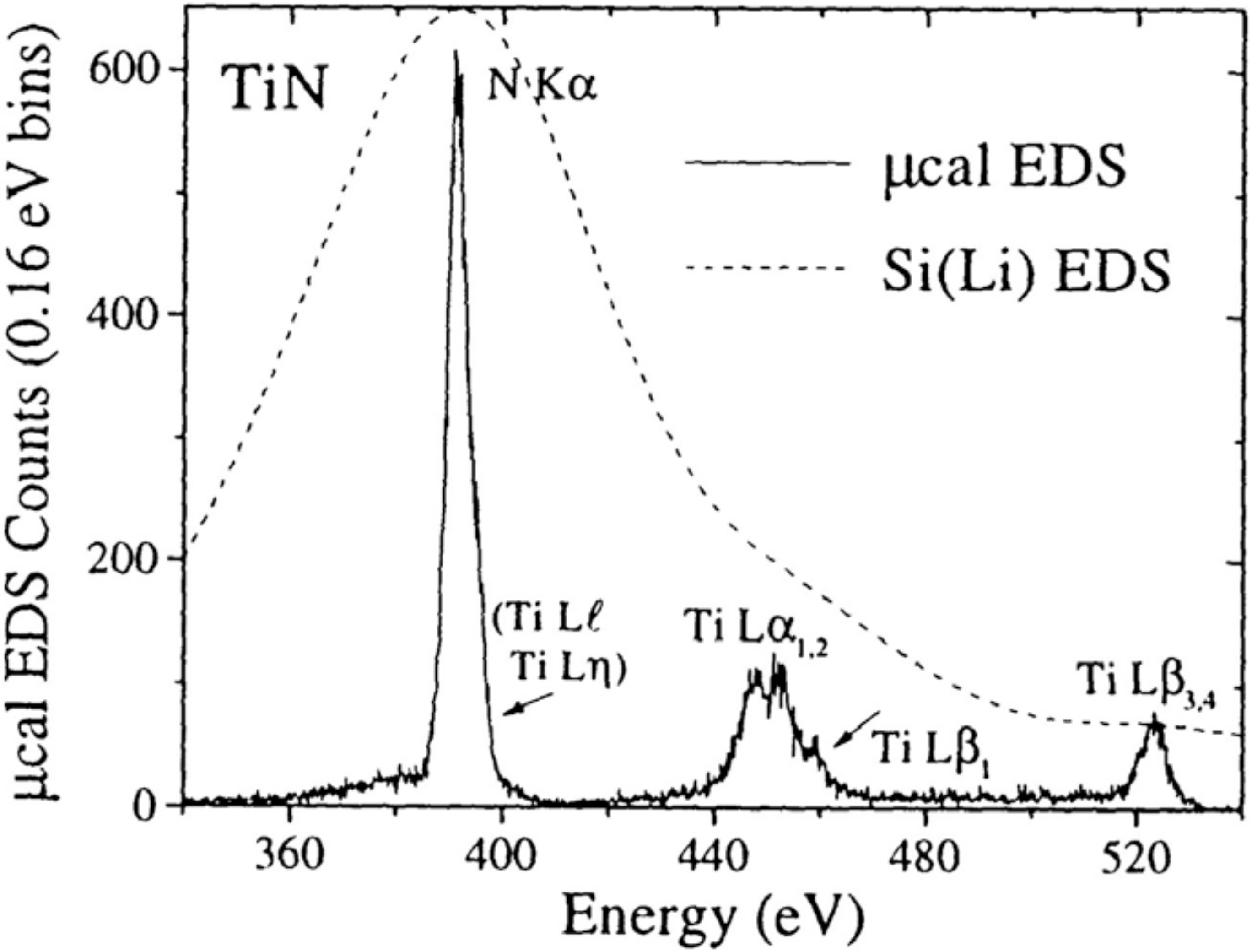
T~100 mK

Most frequently used thermometers:

Semiconducting thermistors

Superconducting Transition Edge Sensors (TES)

$$\Delta E_{FWHM} = 2.35\xi\sqrt{kT^2C} \approx 2eV$$ at 6 KeV


TiN
N Kα
μcal EDS
Si(Li) EDS
(Ti Lℓ
Ti Lη)
Ti Lα1,2
Ti Lβ1
Ti Lβ3,4
μcal EDS Counts (0.16 eV bins)
0
200
400
600
360
400
440
480
520
Energy (eV)

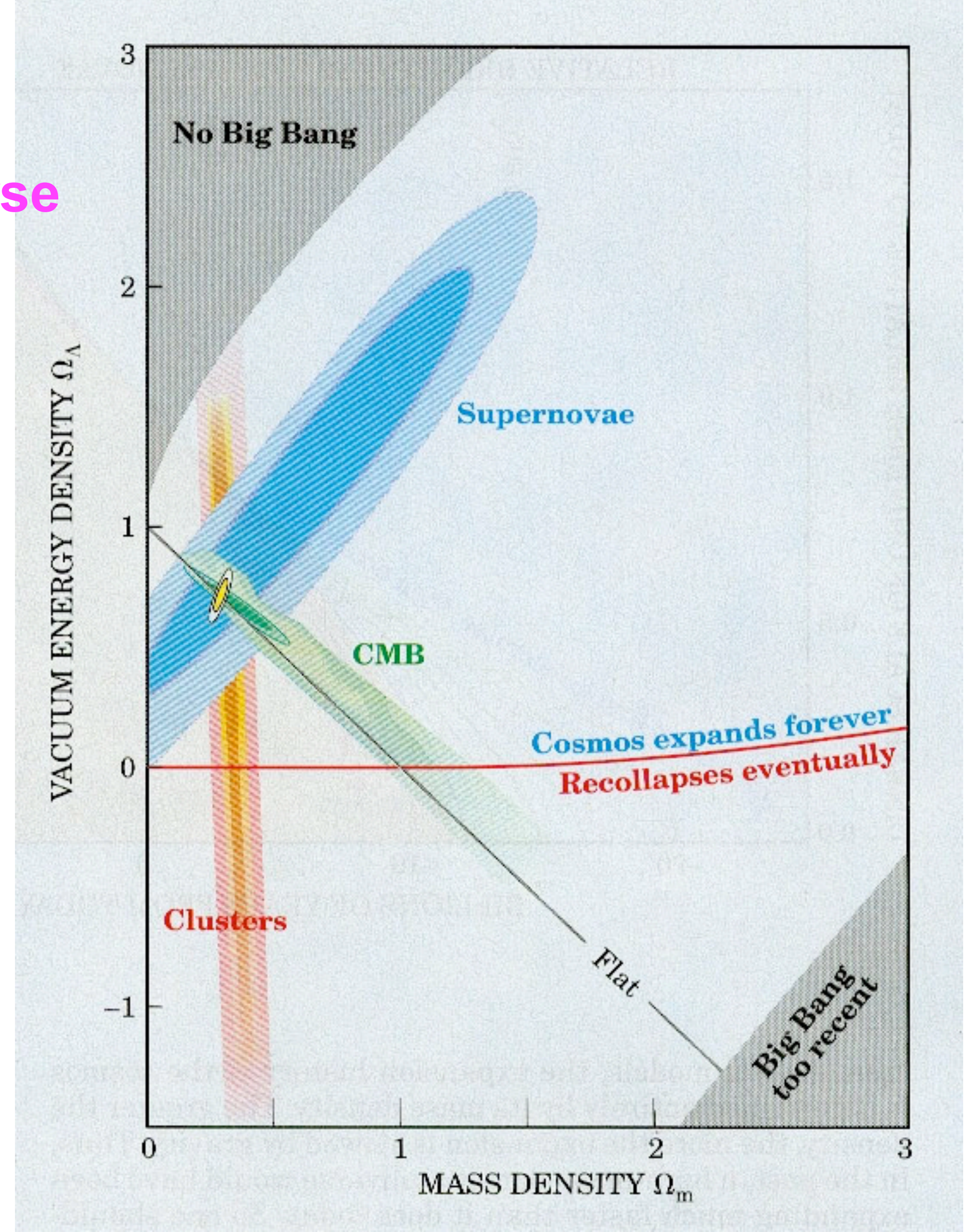
Matter budget of universe

Ω_Λ=72±2 %
Ω_m=28±1 %
Ω_b=4.6±0.3 %
$\Omega_m=\Omega_b+\Omega_{exotic}$

72% dark energy

23% dark matter

95% of universe is
of unknown nature



Dark Matter Candidates:

Massive Neutrinos

Large Scale Structure survey (Ω_ν/Ω_m)and WMAP (Ω_m)

$\sum m_\nu < 0.7$ eV

$$\Omega_\nu h^2 = \frac{\sum m_\nu}{94eV}$$

WIMP’s (Weakly Interacting Massive Particles):
Neutralino most prominent cadidate

AXION’s

Direct WIMP Detection

Measure recoil energy in WIMP-nucleus scattering

Need local shield of radio-poor material

Active background recognition:

Cryogenic detectors (typical mass order of kg) :

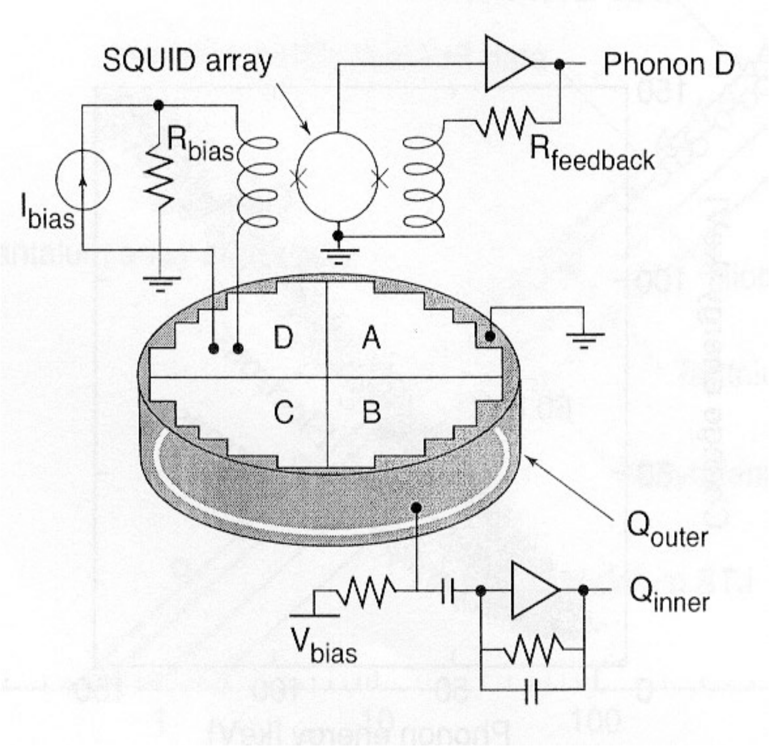
measure phonons and ionization (photons) simultaneously and separat to distinguish

nuclear recoils from Compton electrons and m.i.p.'s

Liquid Xe, LAr, NaI, Ge detectors (large masses ~ ton possible):

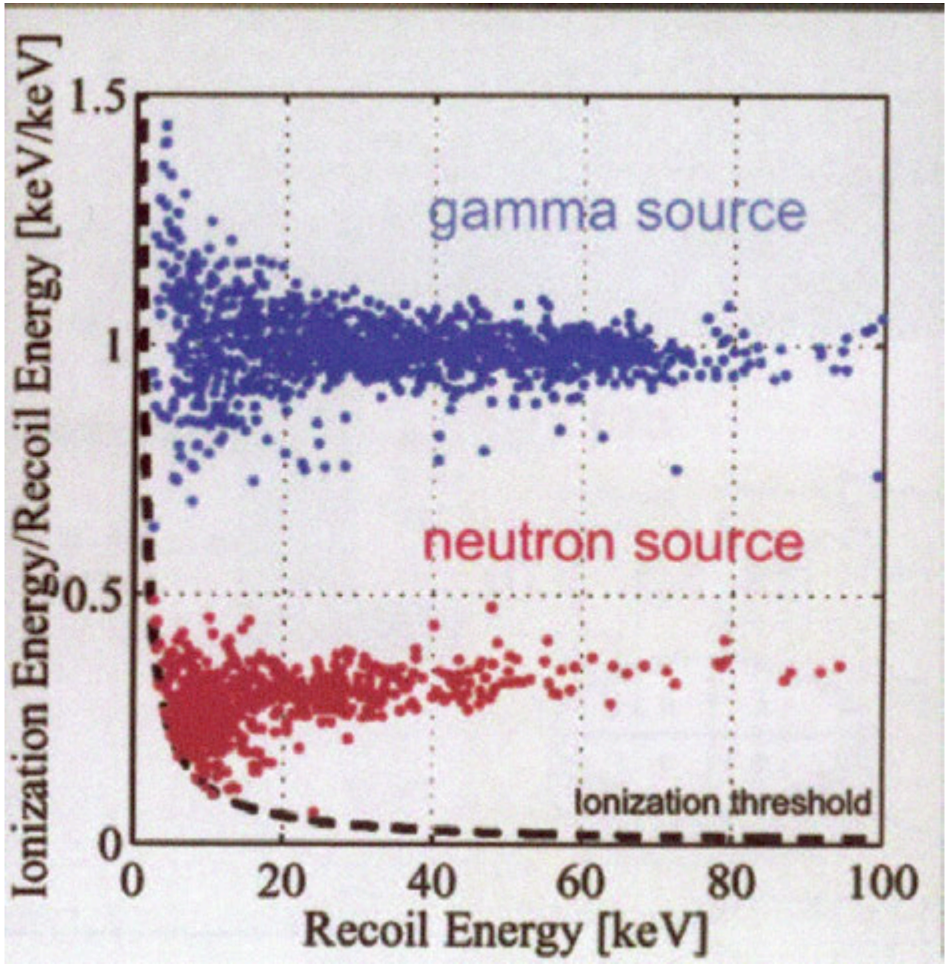
signal shape analysis to reduce background

- **Measure recoil spectrum using different detector materials (model independent identification!)**
- **Observation of signal modulation due to earth motion (model dependent identification!). DAMA experiment!**
- **Observation of recoil direction**



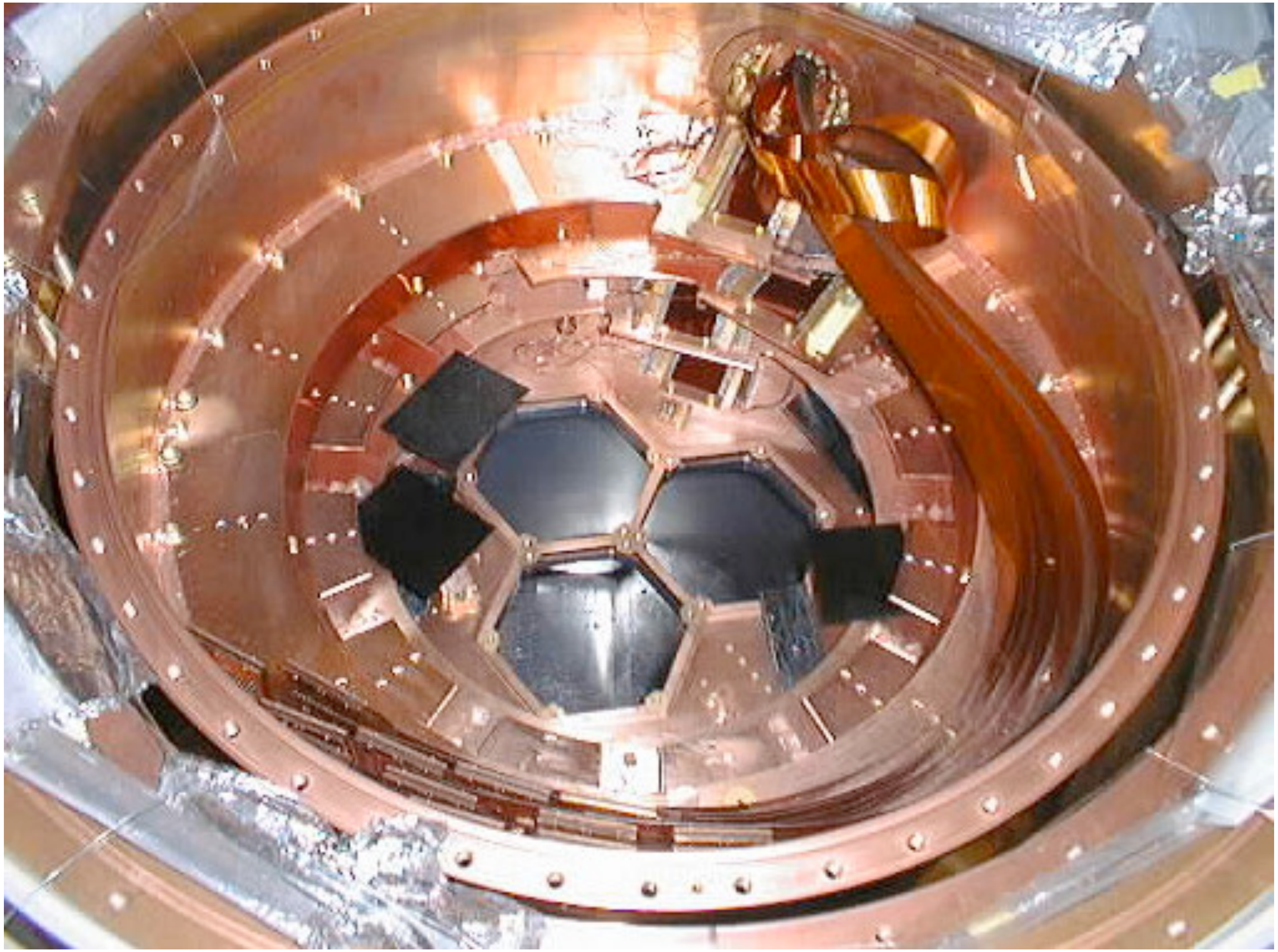
CDMS II (Soudan mine)
19 Ge absorbers (250g each)
11 Si absorbers (100g each)

Edelweiss (Frejus)
3 Ge absorbers (320g each)



CDMS cryogenic detectors

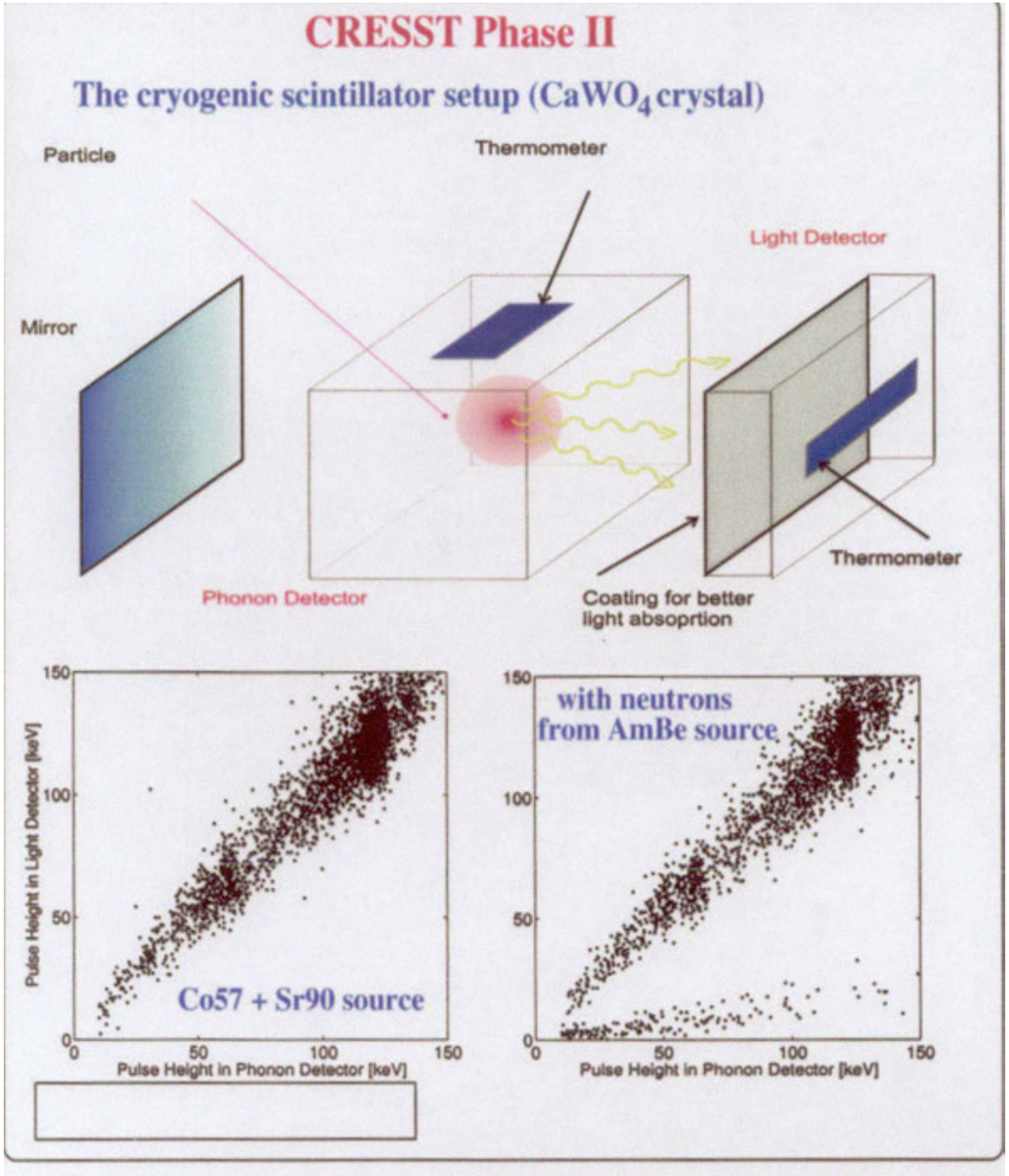
CDMS experiment in the Soudan Mine Minnesota 2090 m.w.e.



CRESST II

Gran Sasso Laboratory

2 $CaWO_4$ absorbers 300g each



CRESST Phase II

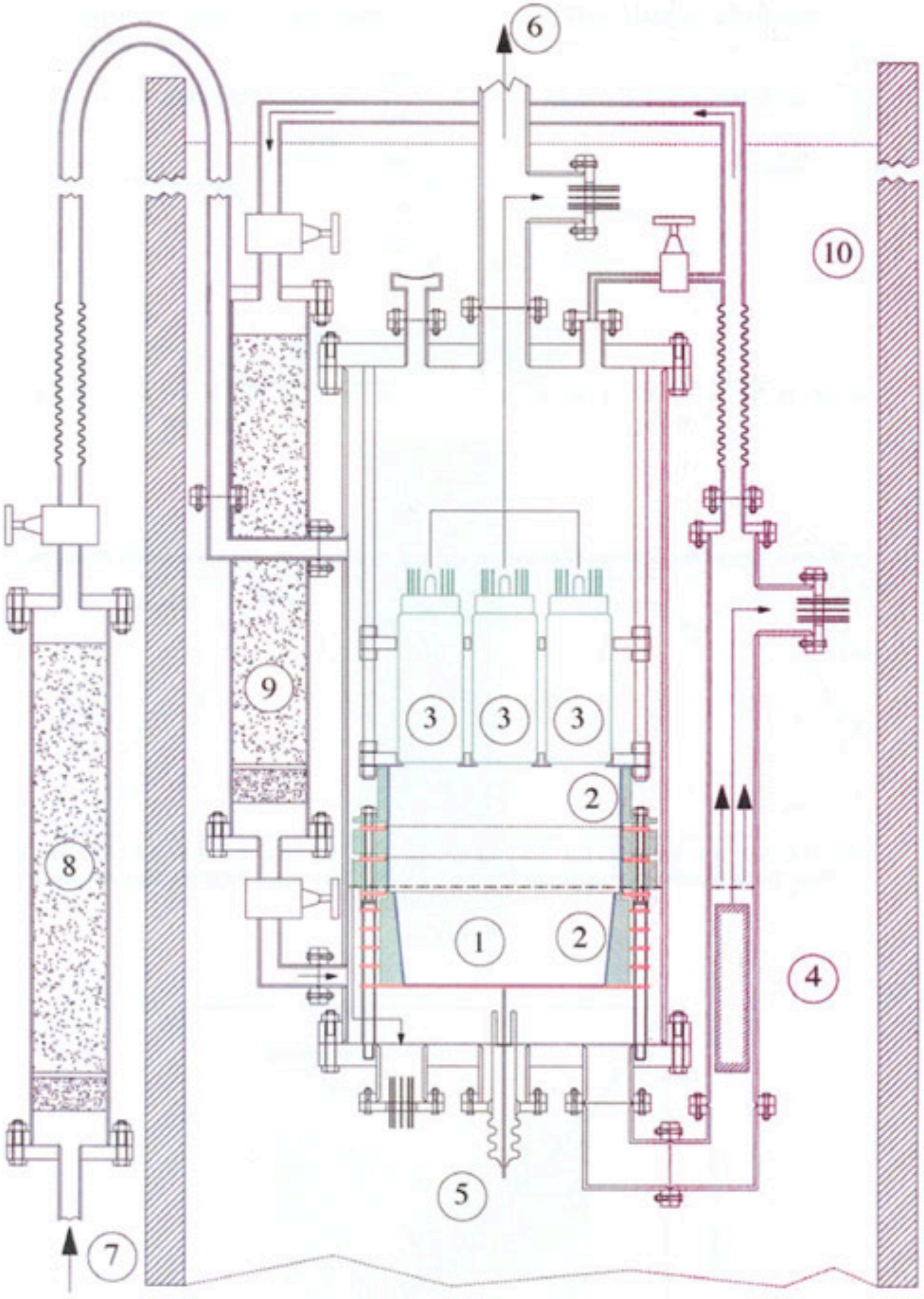
The cryogenic scintillator setup ($CaWO_4$ crystal)

WARP

Gran Sasso Laboratory

2.3 l LAR test chamber

Exposure 100 kgdays



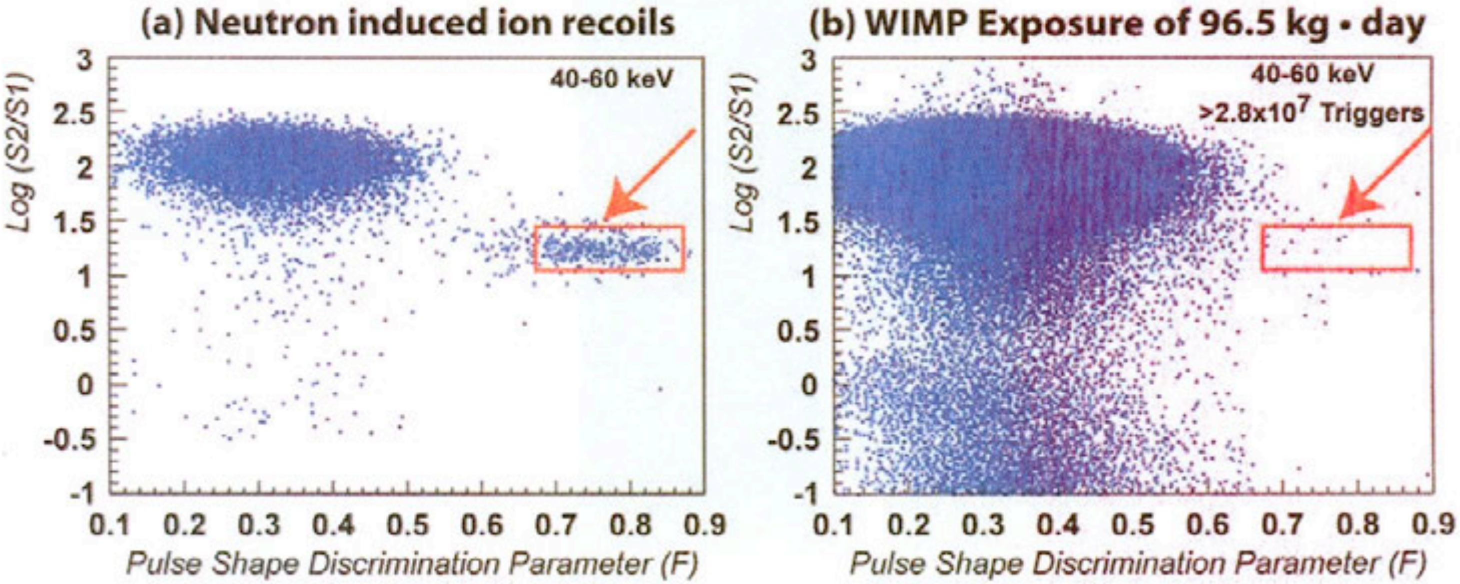
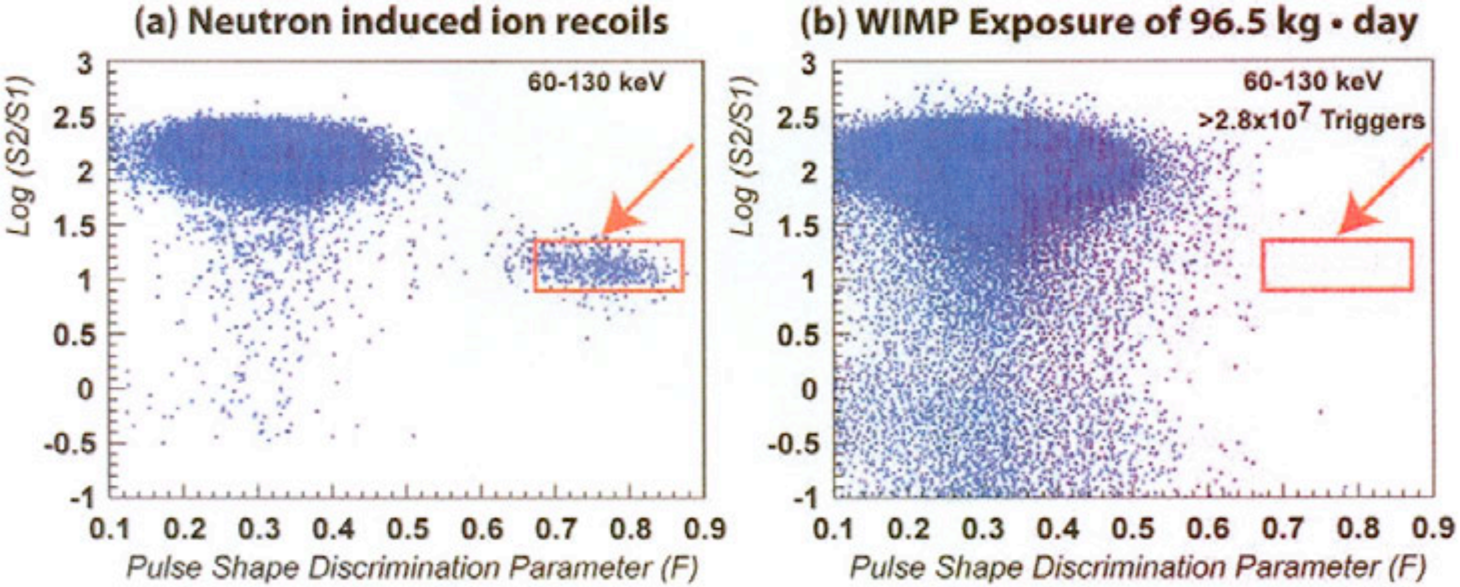
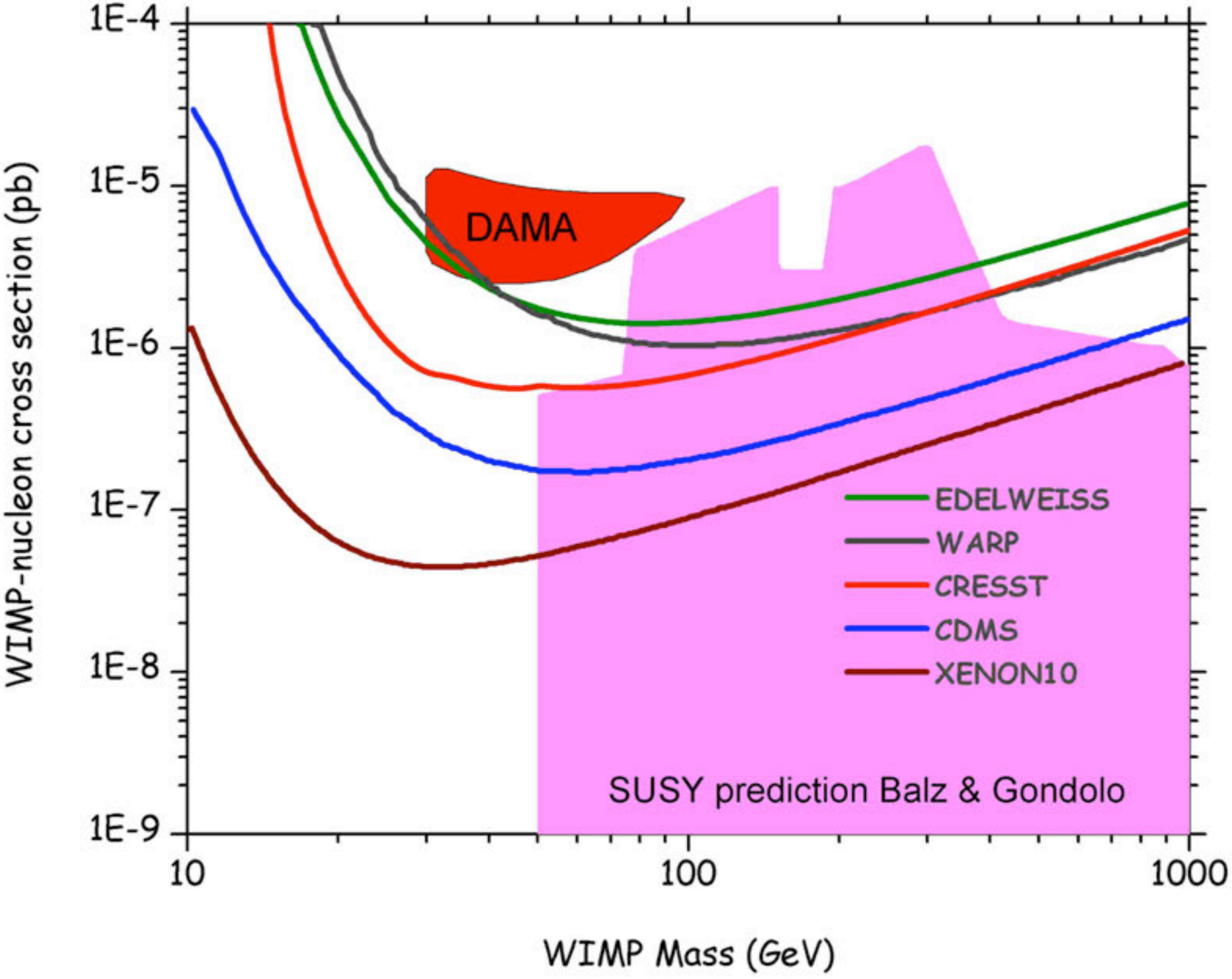

(a) Neutron induced ion recoils
40-60 keV
Log (S2/S1)
3
2.5
2
1.5
1
0.5
0
-0.5
-1
0.1 0.2 0.3 0.4 0.5 0.6 0.7 0.8 0.9
Pulse Shape Discrimination Parameter (F)
(b) WIMP Exposure of 96.5 kg • day
40-60 keV
>2.8x10^7 Triggers
Log (S2/S1)
Pulse Shape Discrimination Parameter (F)

Figure 6


(a) Neutron induced ion recoils
60-130 keV
Log (S2/S1)
3
2.5
2
1.5
1
0.5
0
-0.5
-1
0.1 0.2 0.3 0.4 0.5 0.6 0.7 0.8 0.9
Pulse Shape Discrimination Parameter (F)
(b) WIMP Exposure of 96.5 kg • day
60-130 keV
>2.8x10^7 Triggers
Log (S2/S1)
Pulse Shape Discrimination Parameter (F)

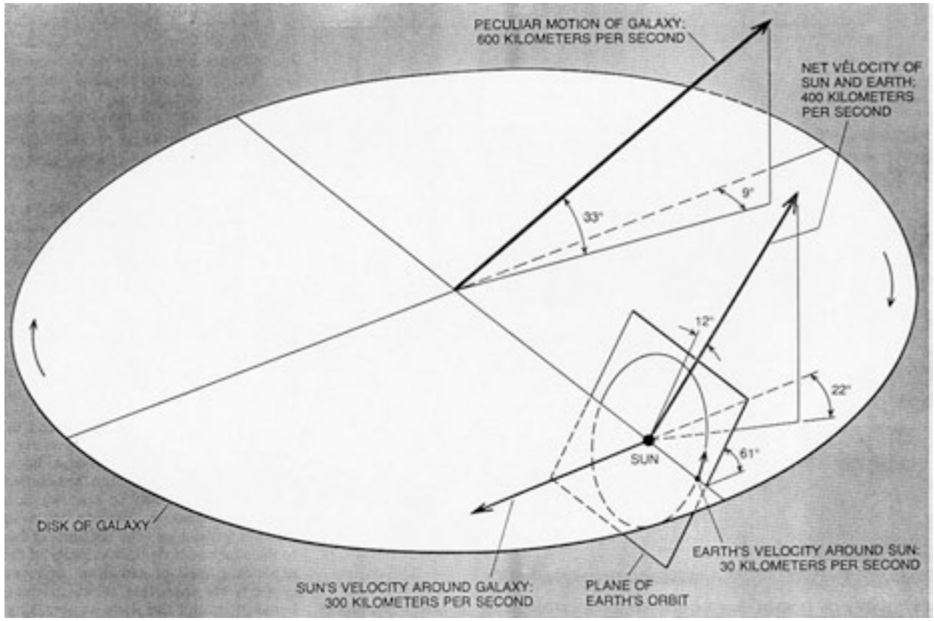
Exclusion plot for spin independent interactions

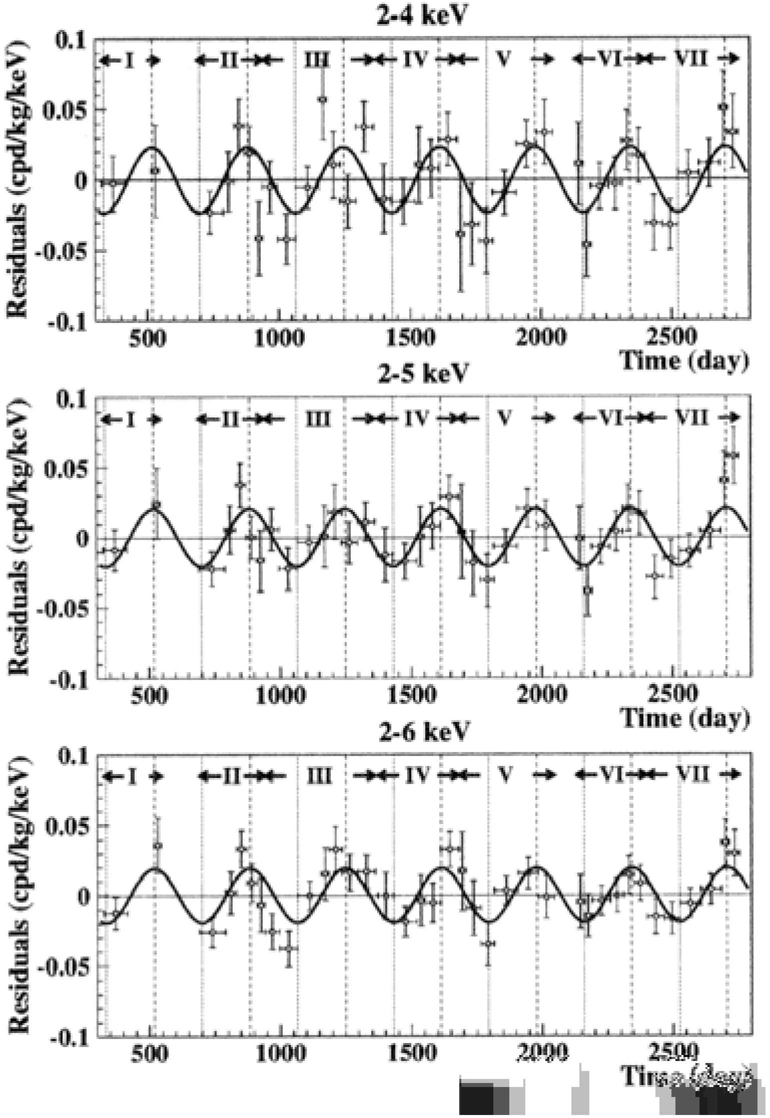


DAMA (Gran Sasso)

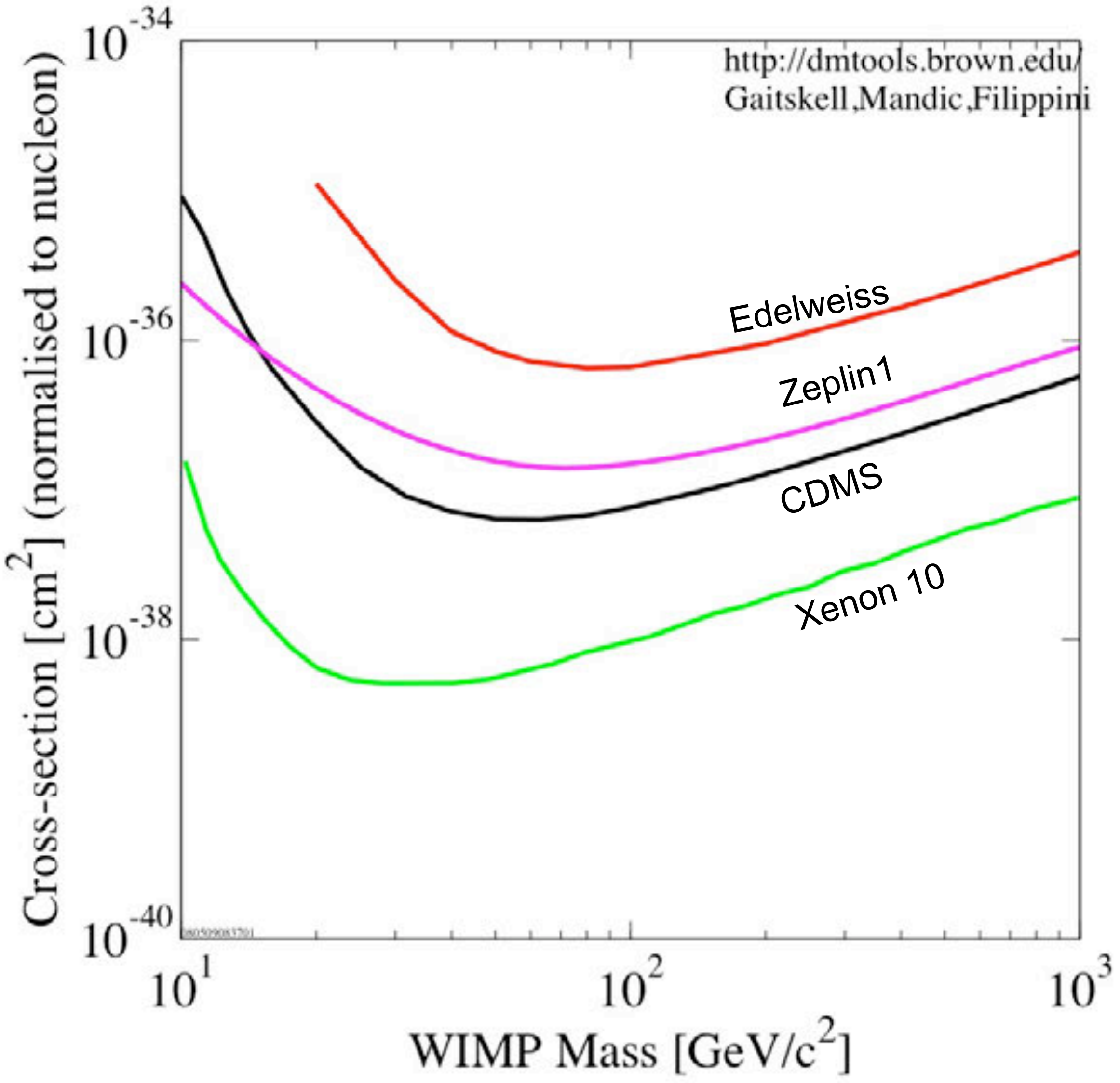
$m_x = 52_{-8}^{+10}$ GeV

$\xi\sigma = 7.2\ 10^{-6}$ pb





Exclusion plot for spin dependent interactions

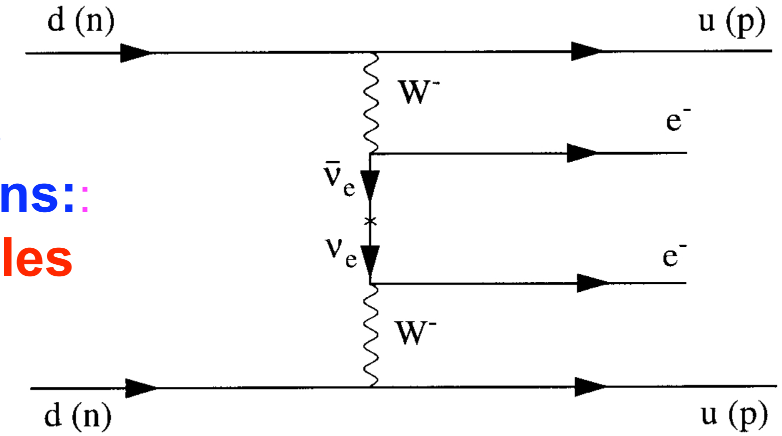


Neutrinoless double beta decay

This lepton number violating process occurs under two necessary conditions::

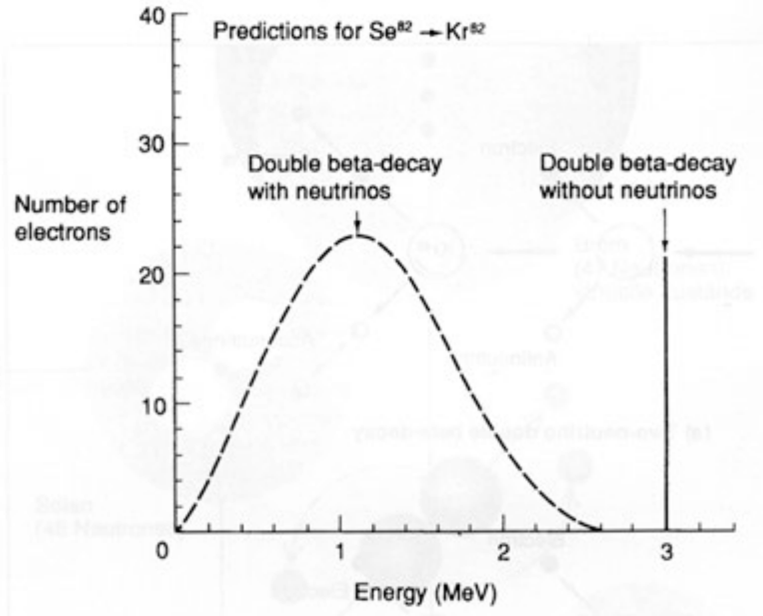
Neutrinos are Majorana particles

Neutrinos have a mass

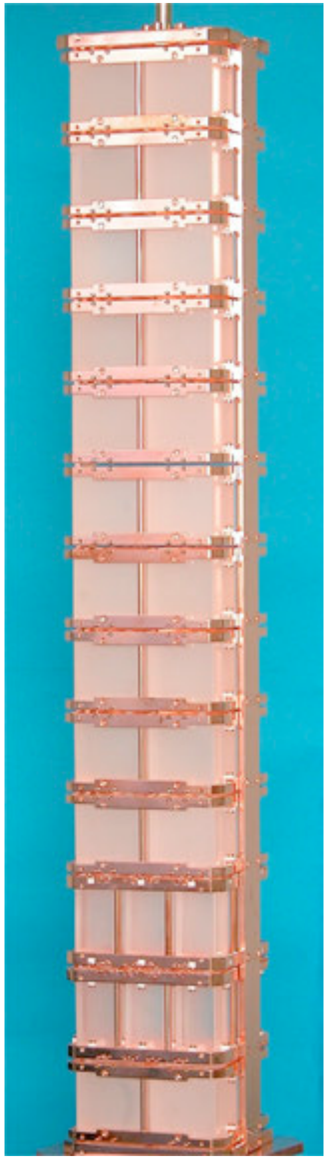


The rate :

$$\left(\frac{1}{T^{0\nu}_{1/2}}\right) = G_{0\nu}\left(E_0,Z\right)\left|M_{0\nu}\right|^2\left\langle m_\nu\right\rangle^2$$



- The use of cryogenic calorimeters for the search of DBD was suggested by
- E. Fiorini and T.Niinikoski NIM 224 (1984) 83
- Excellent energy resolution
- Wide choice of DBD nuclei
- ^{130}Te a good candidate due to
  - high transition energy 2528 keV
  - large isotopic abundance (33.8%)
- Experimental results competitive with Ge DBD experiments
- MIBETA->CUORICINO->CUORE

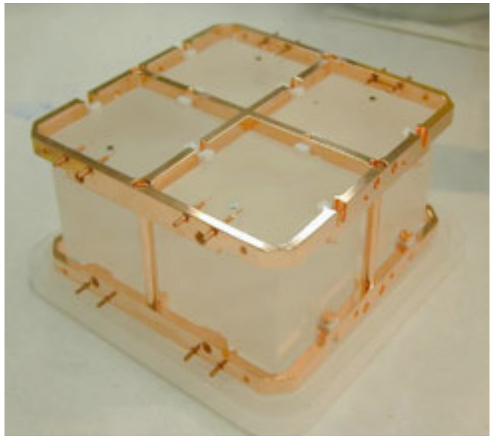


11 modules, 4 detector each,

crystal dimension 5x5x5 cm^3

crystal mass 790 g

4 x 11 x 0.79 = 34.76 kg of TeO_2



2 modules, 9 detector each,

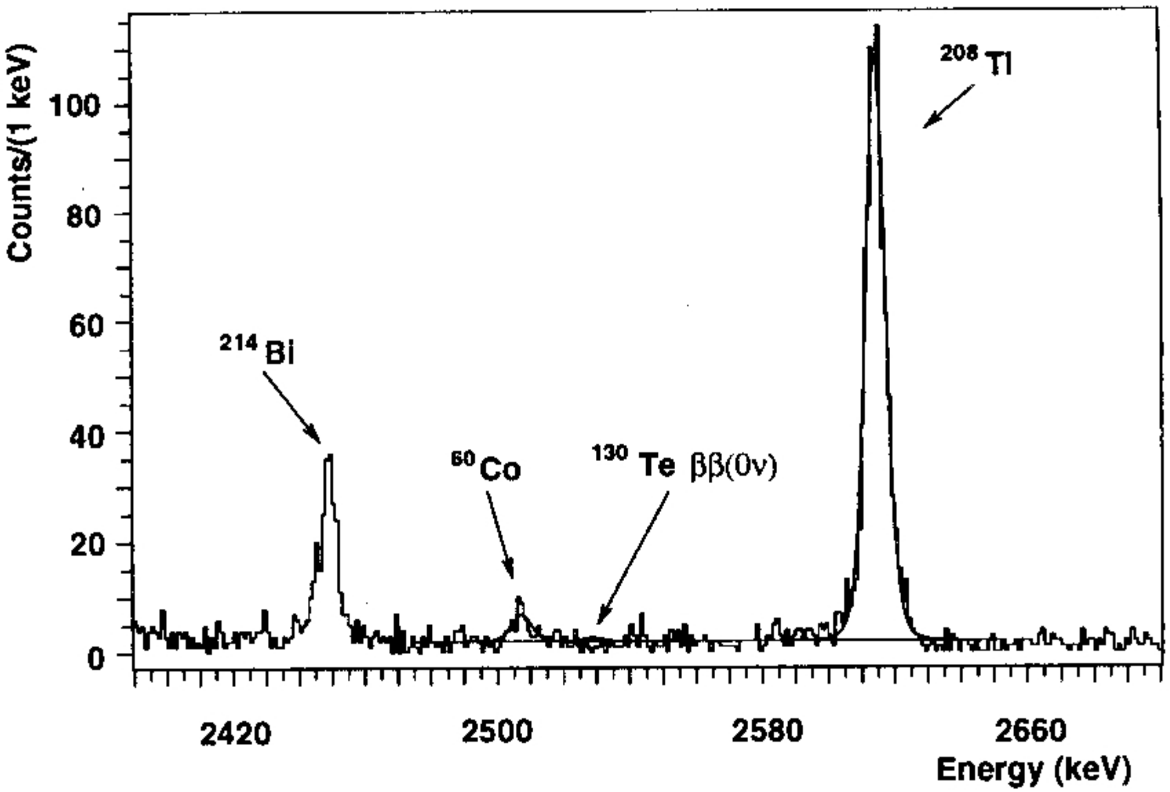
crystal dimension 3x3x6 cm^3

crystal mass 330 g

9 x 2 x 0.33 = 5.94 kg of TeO_2

CUORICINO TOTAL ACTIVE MASS

40.7 kg of TeO_2



Preliminary results from CUORICINO (62 towers): Effective exposure 10.85 kg y

$t_{1/2} > 1.8\text{x}10^{24}$ y **$t_{1/2}$ (^{76}Ge) $> 1.9\text{x}10^{25}$ y (Heidelberg,Moscow)**

$$\langle m_{\beta\beta} \rangle < 0.2eV - 1.1eV \quad \Rightarrow \quad \langle m_{\beta\beta} \rangle \approx 30meV$$

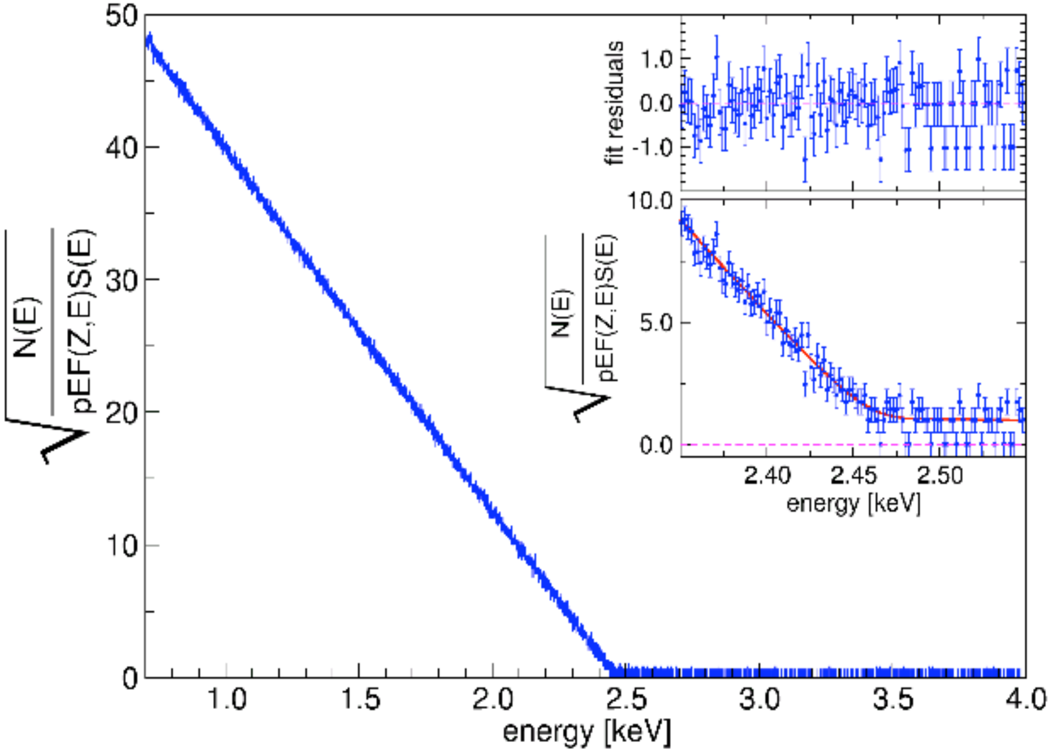
CUORE (988 towers)
750kg

Neutrino Mass Measurements

- Genova group pioneered neutrino mass measurements using
  ^{187}Re β-decay Fontanelli et al.NIM A 370 (1996)247
- Early developments continued by the Milano group
- Advantages of Re:
  - high natural abundance (62%)
  - low endpoint energy (2.64 keV)
- Calorimetric measurement of end point energy is an alternative to tritium decay spectrometry (KATRIN).
- Calorimeter measures total energy including final state interactions.
- No negative values of m^2_ν due to final state interactions (tritium decay spectroscopy).
- However, limited counting rate capability due to slow calorimeter signals (few Hz).

Milano neutrino mass experiment

- total acquired $AgReO_4$ mass: 2.174 mg ⇒ ^{187}Re activity: 1.17 Hz
- total statistics of β decay acquisition: 168 days
  - ⇨ 8751 hours×mg ($AgReO_4$)
  - ⇨ 6.2×10^6 ^{187}Re decays collected above end-point



$m_\nu < 15$ eV (90% C.L.)

Ambitious international project MARE
(Micro-calorimeter Array for a Rhenium Experiment)

Aims to reach a neutrino mass sensitivity of 0.2 eV comparable to the KATRIN Tritium experiment.

10^4 detector elements,

energy resolution of 1 eV

and

timing capability of 1μs

Are necessary to reach the goal

Conclusion:

Calorimeters made major discoveries in physics possible:
Neutral currents in GARGAMELLE
Quark and gluon jets (SPEAR, UA2, UA1 and PETRA)
W, Z bosons (UA1, UA2)
Top quark (CDF, D0)
Neutrino oscillations (SUPER-KAMIOKANDE, SNO)

Calorimeters under development or in operation for future discoveries:
Higgs particle(s) and SUSY (LHC)
Dark matter
Neutrino Physics
Astrophysics
Cosmology (CMB-Polarization)