10. Detector Systems in Particle and Astroparticle Physics

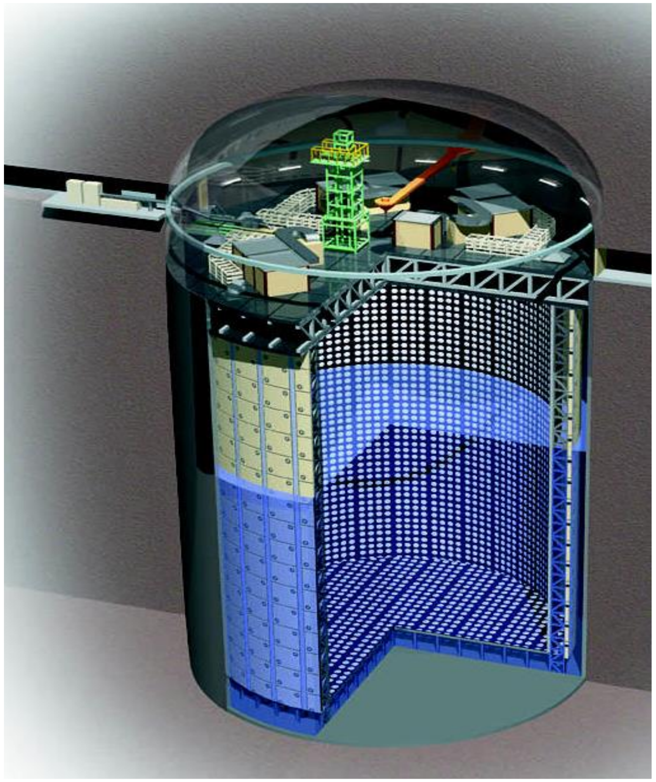
10.1 Introduction

10.2 Fixed Target Experiments (Example COMPASS)

10.3 Neutrino Experiments
(T2K, Kamiokande, ICECUBE)

10.4 Direct Dark Matter detection experiments

10.5 Indirect Dark Matter detection experiments



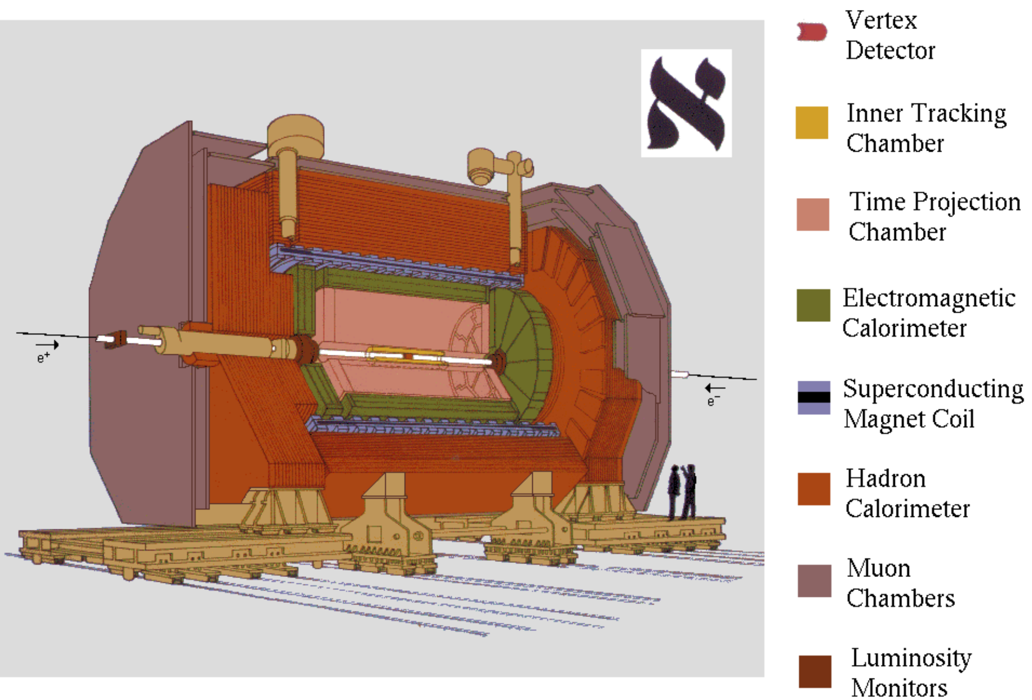
10.1 Introduction

(i) Particle Physics experiments at Colliders (e^+e^- or pp)

- 4π geometry, with a cylindrical central barrel and endcap detectors;
- Centre-of-mass system, symmetric in forward/backward directions
- Most detectors have central solenoidal magnetic field

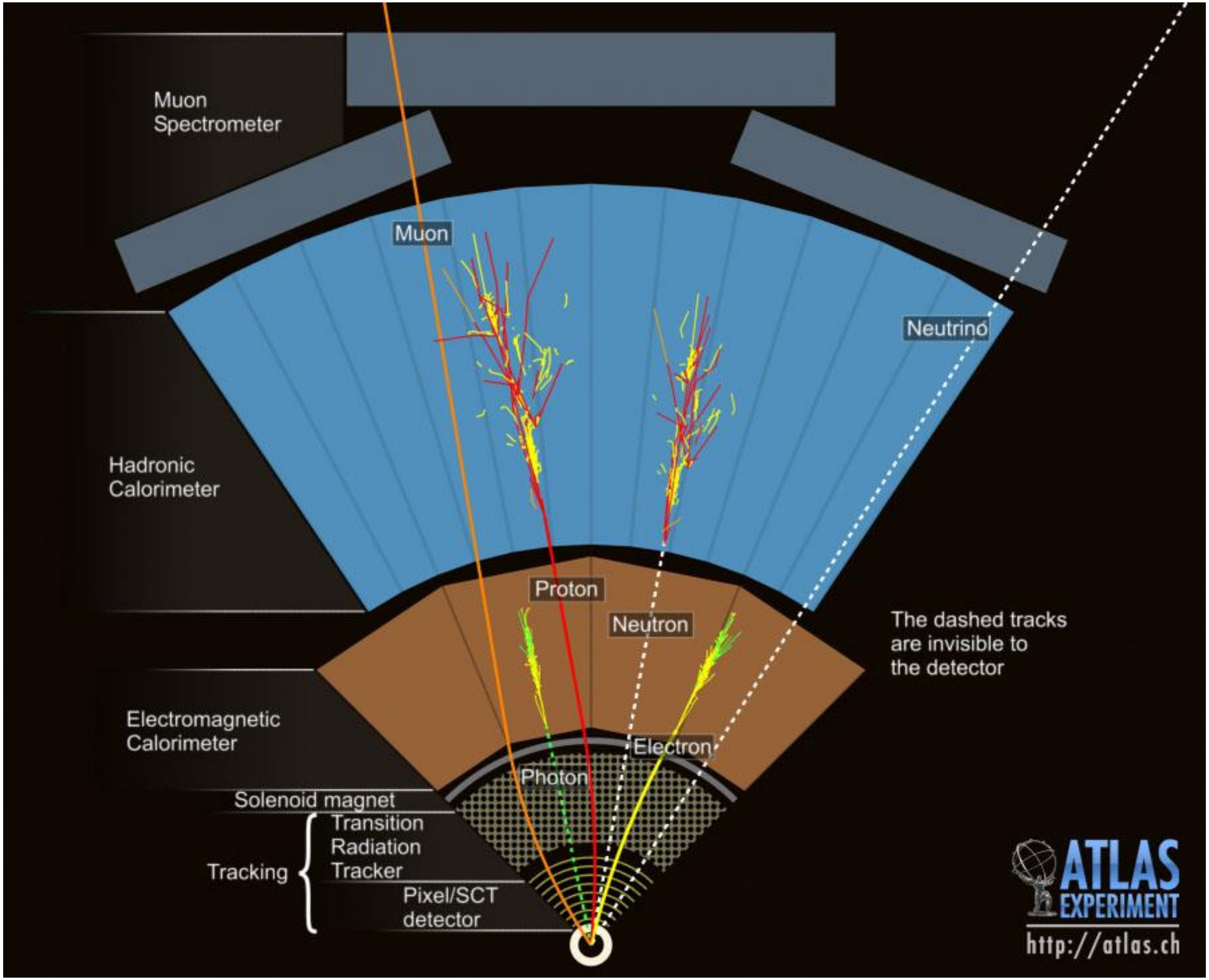
Essential components:

- Tracking detectors, including silicon strip and pixel (vertex) detectors
- Electromagnetic calorimeters
- Hadronic calorimeters
- Muon detectors
- Dedicated particle identification systems normally not required, however, it depends on the physics goals (example: DELPHI at LEP had very good π/K separation with RICH detectors)



The ALEPH Detector

Layers of the ATLAS detector

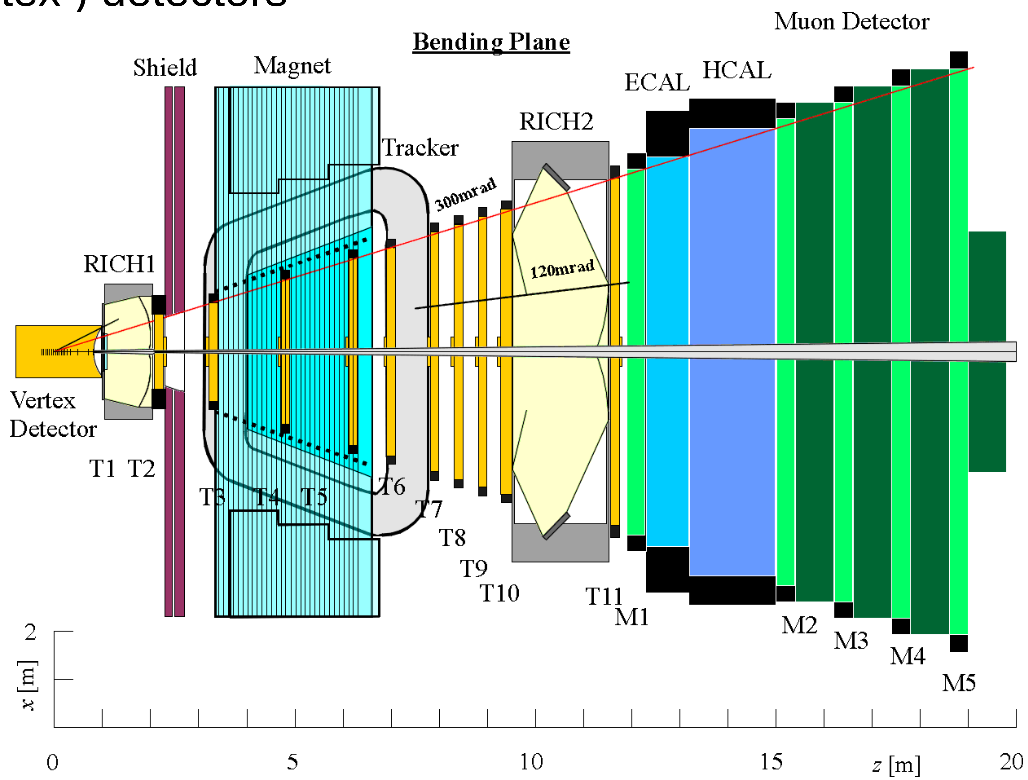


(ii) Fixed Target experiments at accelerators

- "Forward" geometry, lab system, acceptance angle,
  Extended detector systems along the beam axis (z direction)
- Most detectors have dipole magnets

Essential components:

- Tracking detectors (before/after, inside magnets),
  including silicon strip and pixel (vertex) detectors
- Particle Identification systems
  (dE/dx, TOF, Cherenkov,
  Transition radiation)
- Electromagnetic calorimeters
- Hadronic calorimeters
- Muon detectors



(iii) Neutrino experiments at accelerators

- A ν beam, produced at an accelerator (mainly ν_μ) is sent through earth to a far neutrino detector

  So called “Long baseline neutrino experiment”

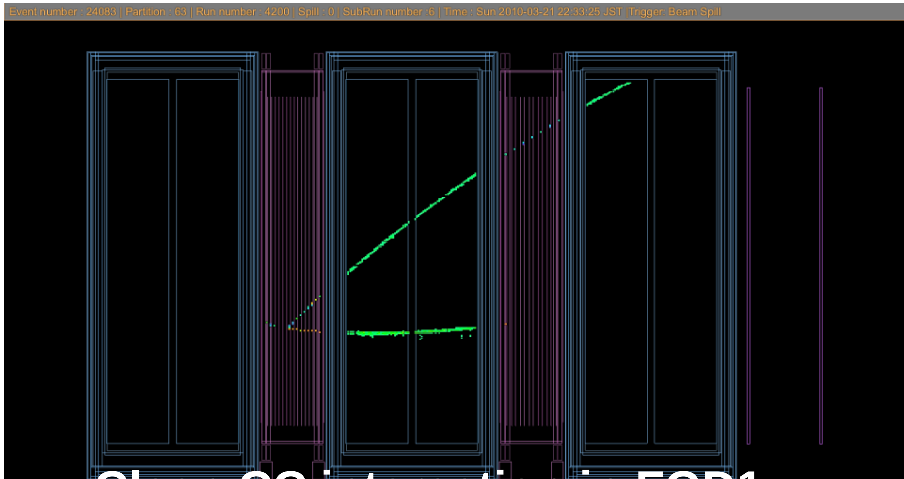
- Long baseline for neutrino oscillations;
  Energy can fixed at accelerator, baseline

Essential components:

- Near Detector (flux measurement, energy spectrum)
  → μ detection (spectrometer, sampling calorimeter)

- Far detector
  (look for changes in flux, appearance of ν_τ or ν_e events)

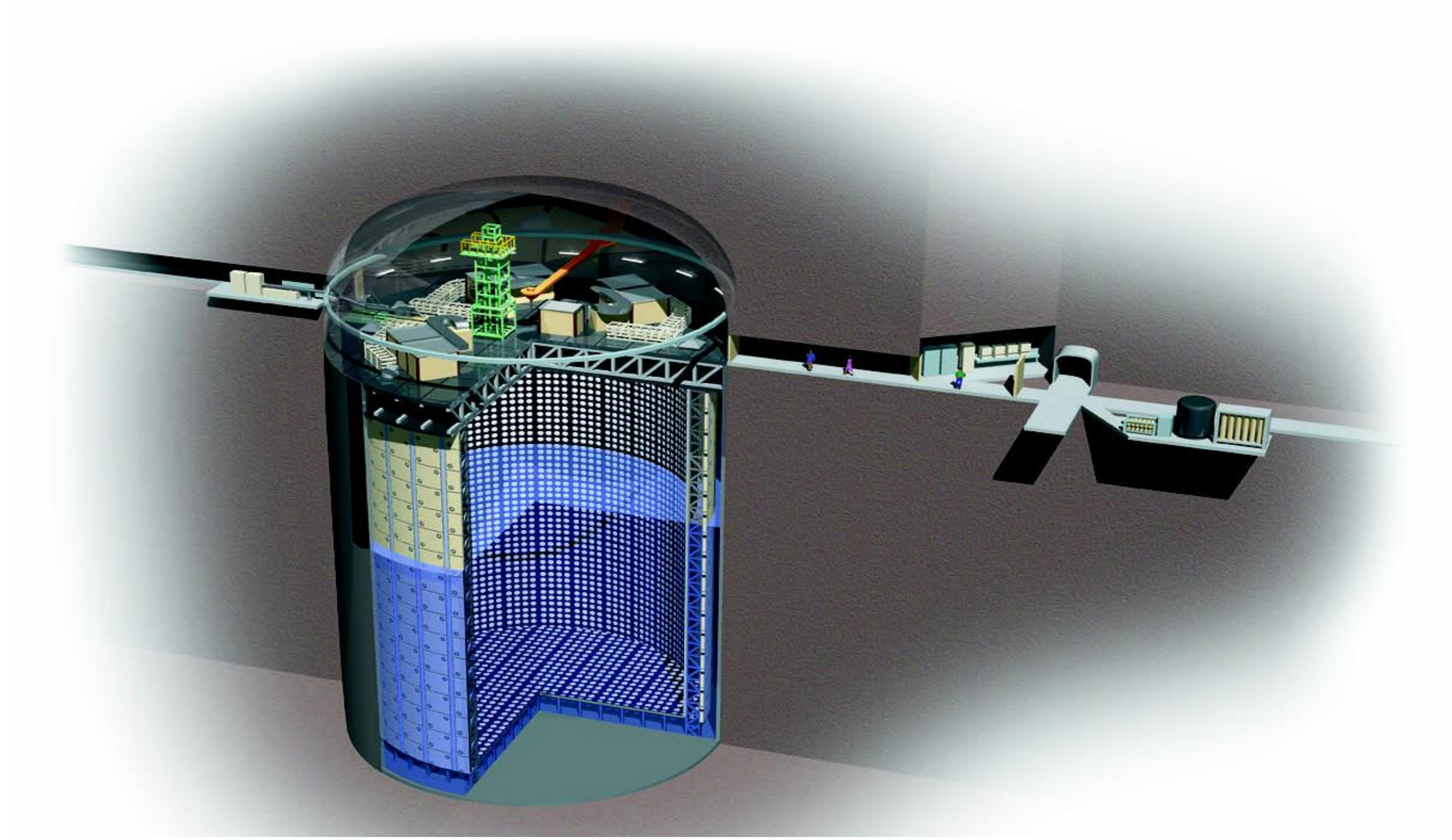
  → μ detection, e detection, (τ detection)



Clean CC interaction in FGD1

(iv) "Underground" Neutrino experiments for atmospheric, solar or cosmic neutrinos

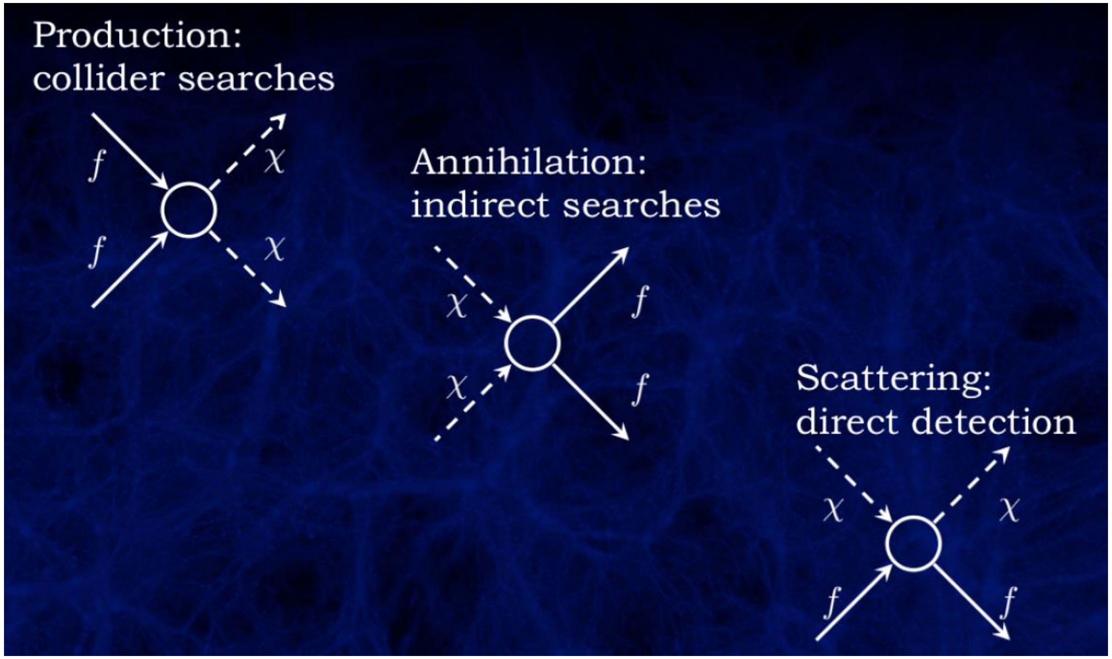
- Deep underground, well protected from cosmic ray background
- Neutrino detection via direct Cherenkov light (directional sensitivity) or via radiochemical extraction

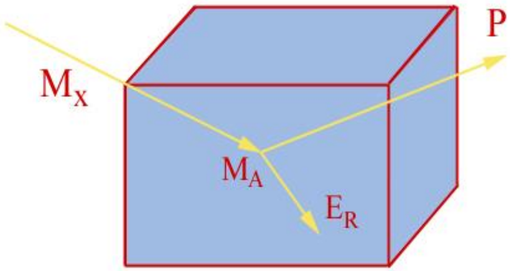


(v) Ground-based Dark Matter Detection experiments

- Search for signals of elastic scattering of WIMPs on nuclei in detectors

i.e. process 3: $\chi + f \rightarrow \chi + f$



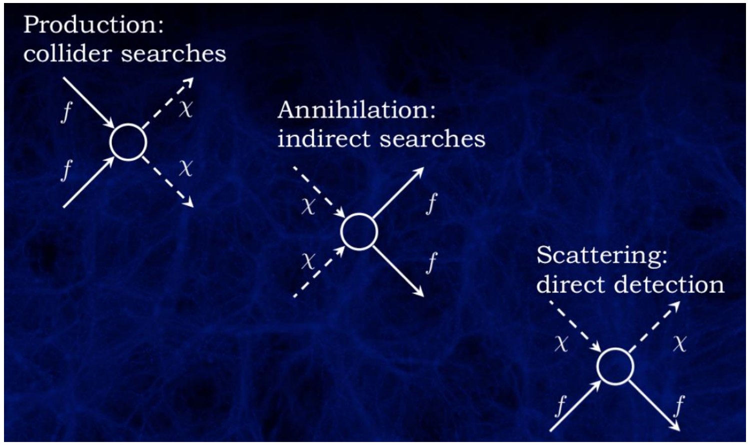


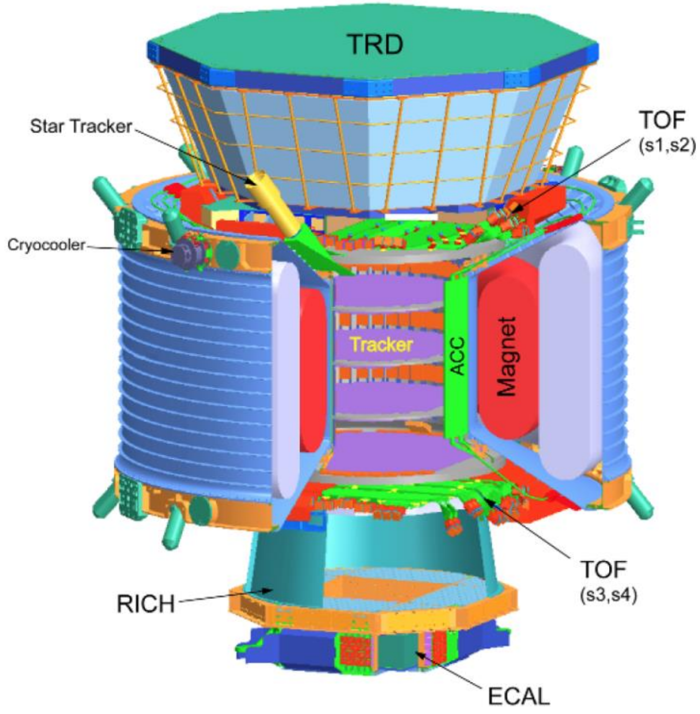
Detector signal: - scintillation light
- ionization signal of recoil particle

(v) Dark Matter Detection experiments in space

- Search for signals of elastic scattering of WIMPs on nuclei in detectors

i.e. process 2: $\chi + \chi \rightarrow f + f$





Detector signal: - annihilation signal of two WIMPs into SM particles
- excess above backgrounds

10.2 Fixed Target Experiments

The COMPASS Experiment at the

CERN Super Proton Synchrotron (SPS)

COmmon

Muon and

Proton

Apparatus for

Structure and

Spectroscopy

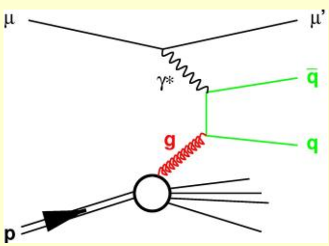
(Fixed Target Experiment)


Jura
Geneva Lake
COMPASS

COMPASS Physics

Hadron structure and Spectroscopy

- Muon beam programme
  - Quark and gluon polarisation in polarised nucleon

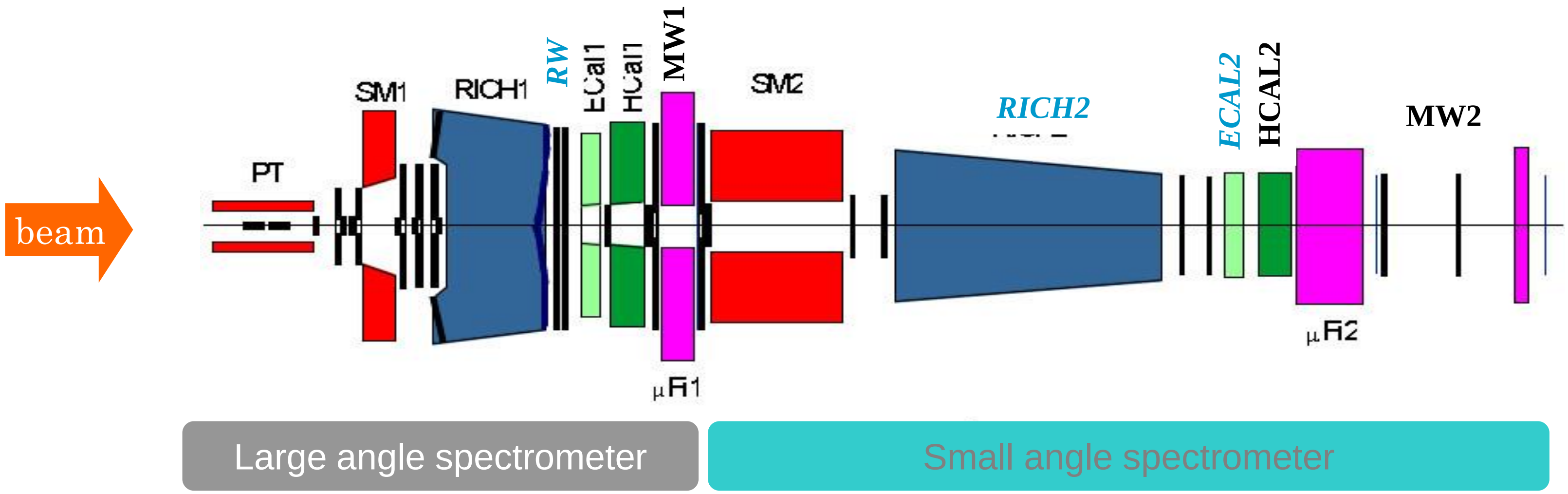


  - Polarisation transfer in fragmentation

- Hadron beam programme
  - Glue balls
  - Semi-leptonic decays of charmed hadrons
  - Double charmed hadrons

Operate in quite different conditions with (μ, p, π) beams

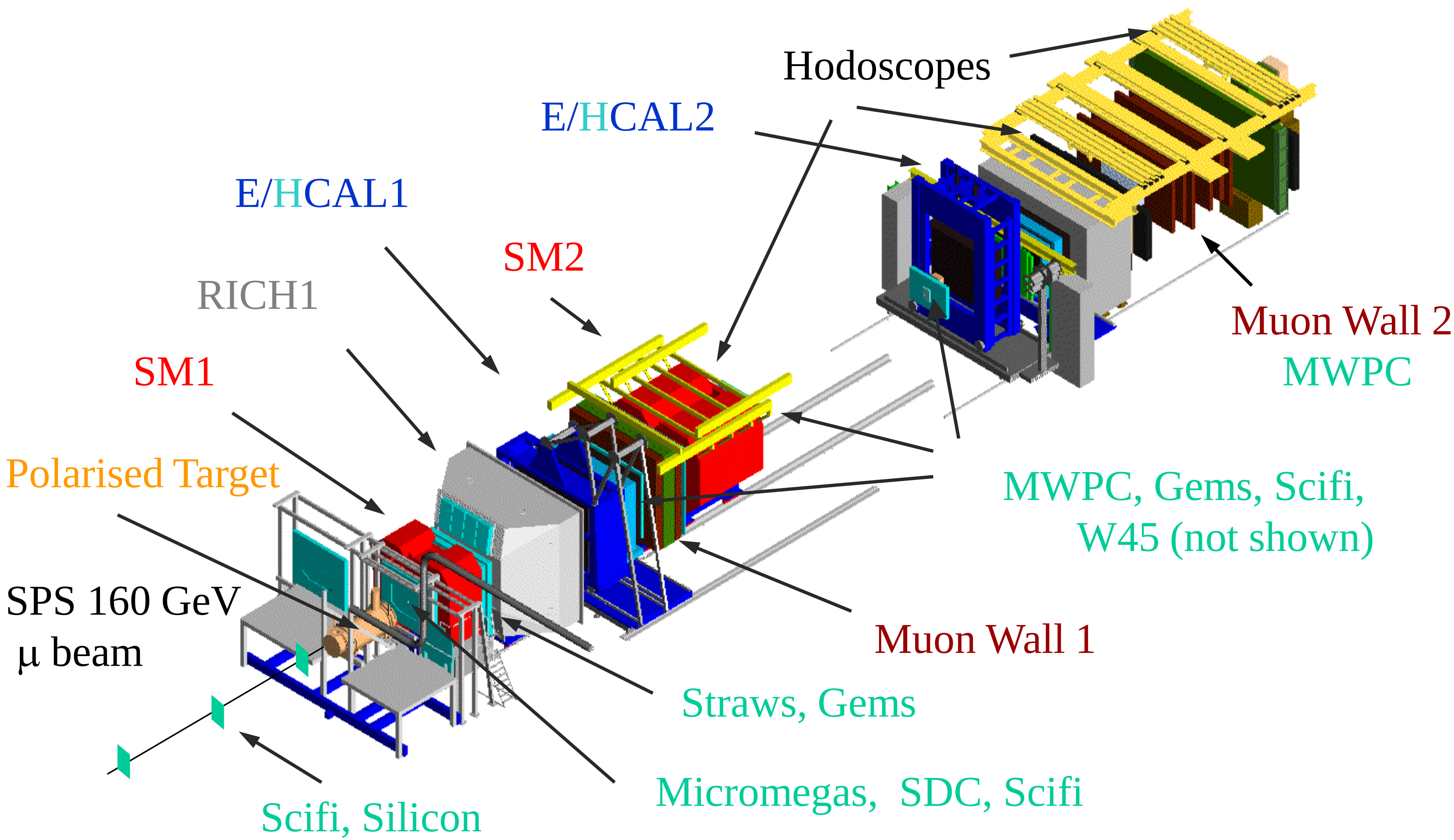
Spectrometer layout



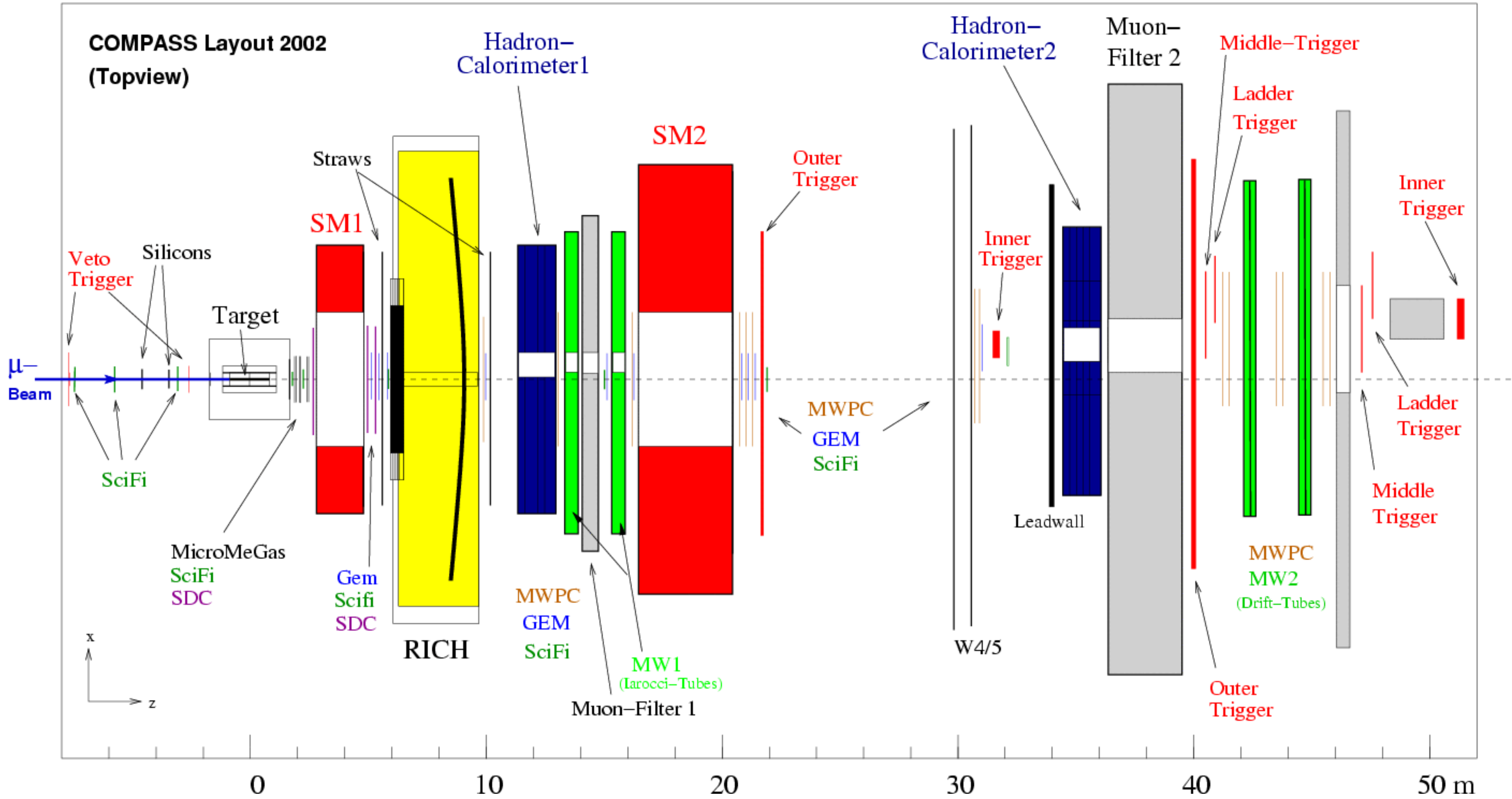
Two-stage spectrometer, each stage comprising

- Small and large area tracking
- Momentum measurement
- Particle ID

The COMPASS Spectrometer



Spectrometer 2002



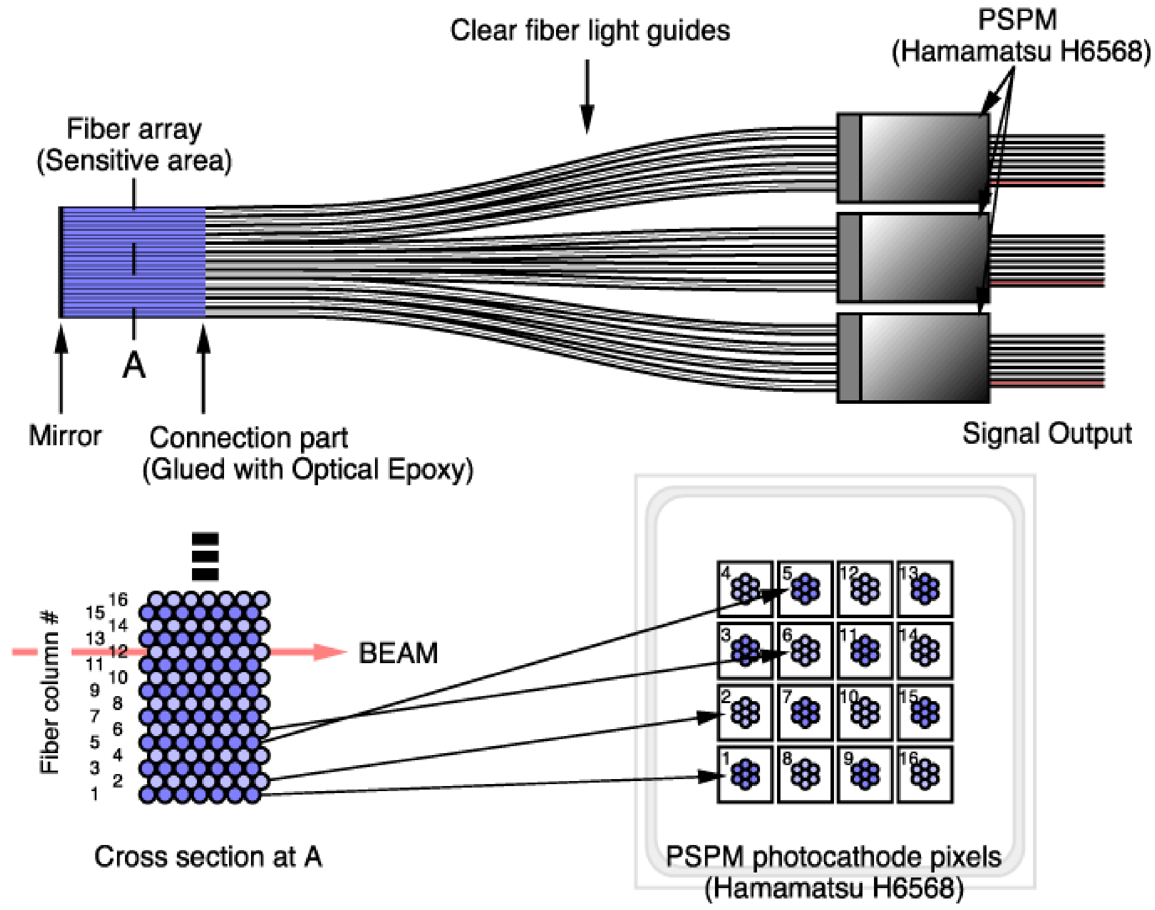
COMPASS Spectrometer

Scintillating Fibre Detector

7 layers of scintillating fibres
with 0.5 – 1 mm diameter,
up to 5 MHz / fibre

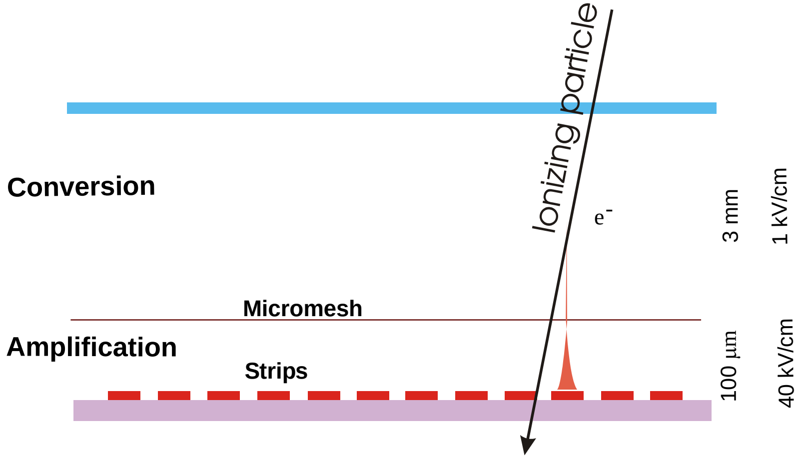
4x4 – 12x12 cm^2
130 – 250 µm space resolution

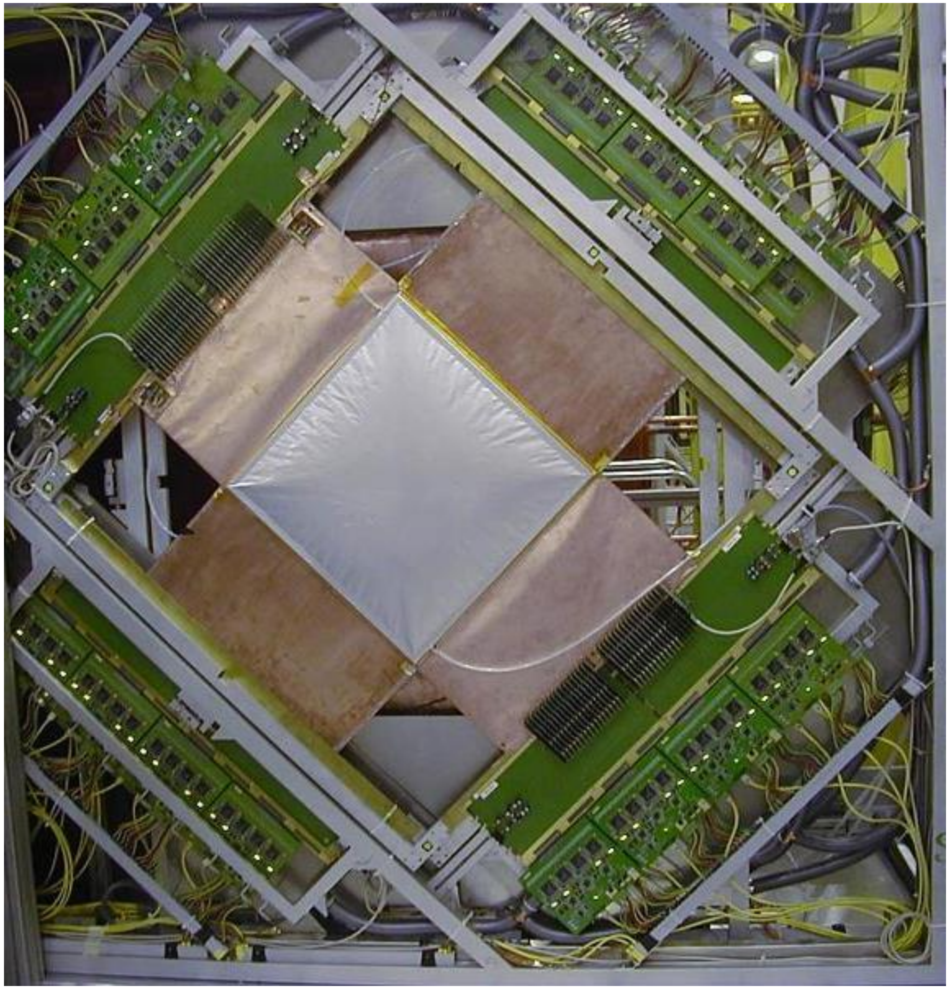
Efficiency ~ 99 %



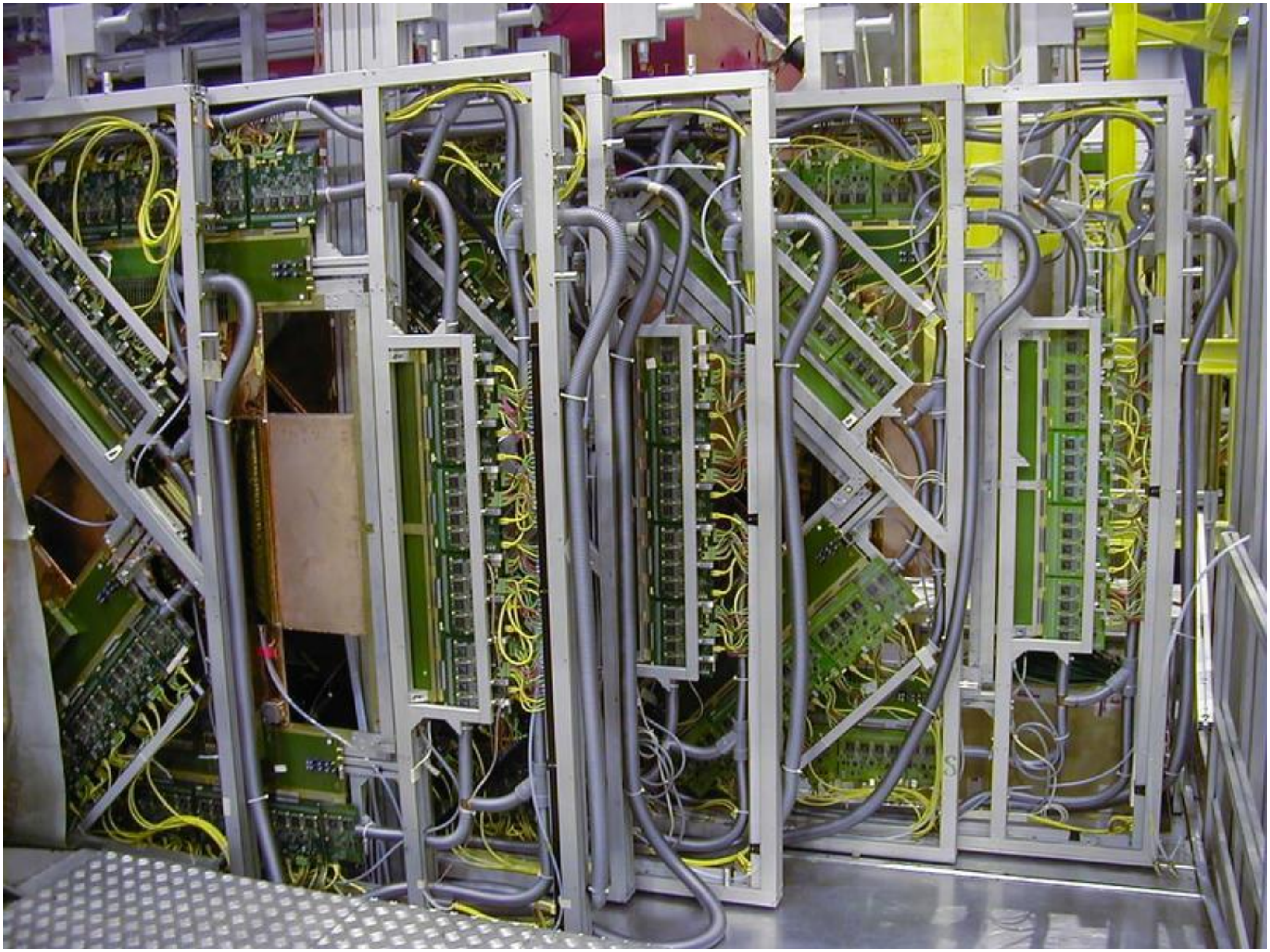
MicroMegas

3 stations, 12 coordinates
Size 40x40 cm^2
Pitch 360 – 420 μm
Time resolution < 10 ns
Space resolution 70 μm
Efficiency > 97%
Gas: $Ne/C_2H_6/CF_4$ 80/10/10 %

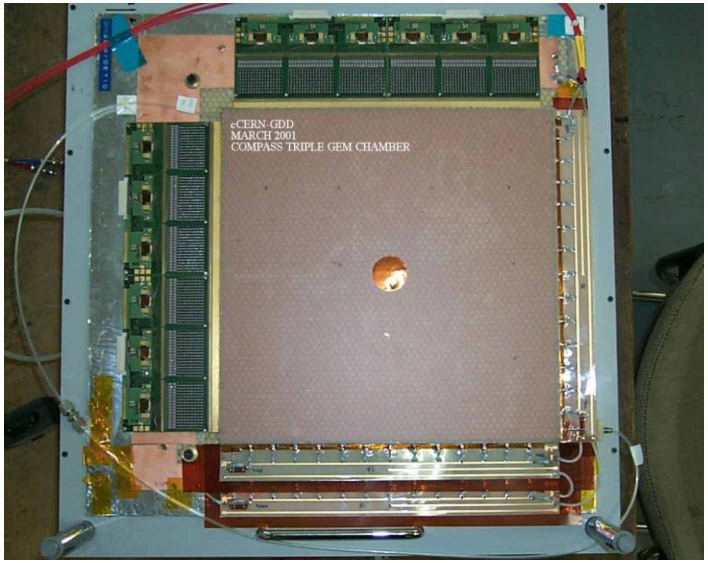




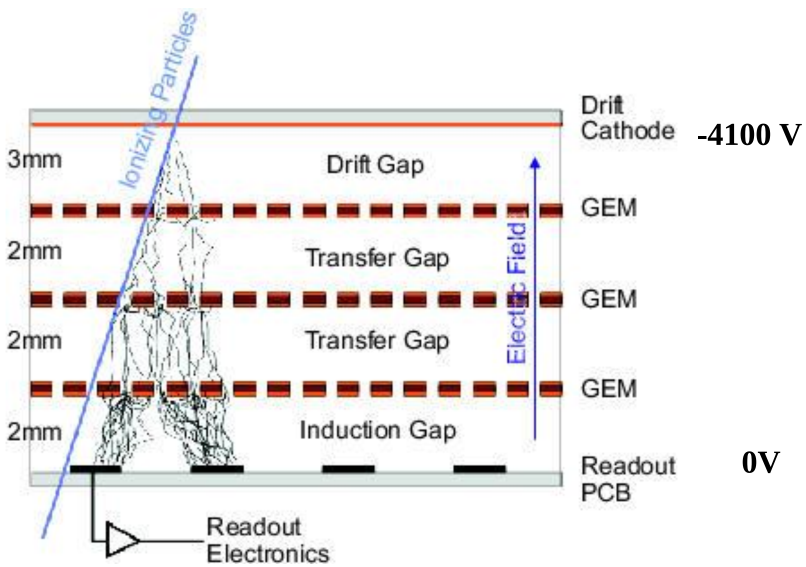
MicroMegas stations



Gems

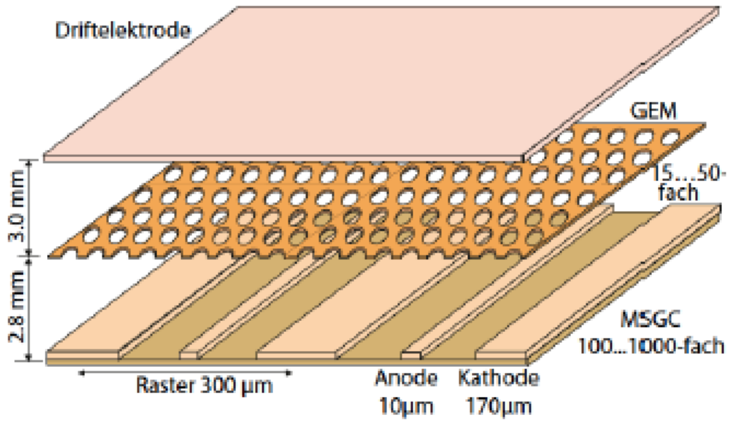


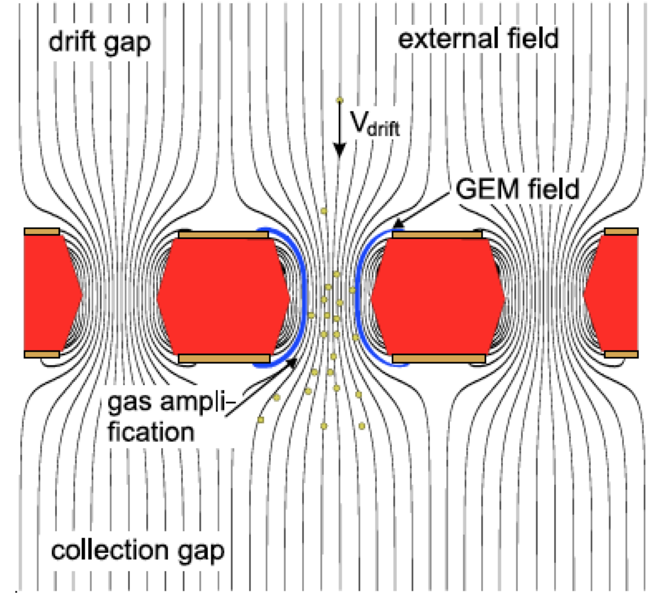
- 20 triple Gems detectors in 10 stations
- 40 coordinates
- Size 30x30 cm^2
- 12 ns time resolution
- 50 μm space resolution
- Efficiency ~ 97 %
- Gas: Ar/CO_2 70/30 %



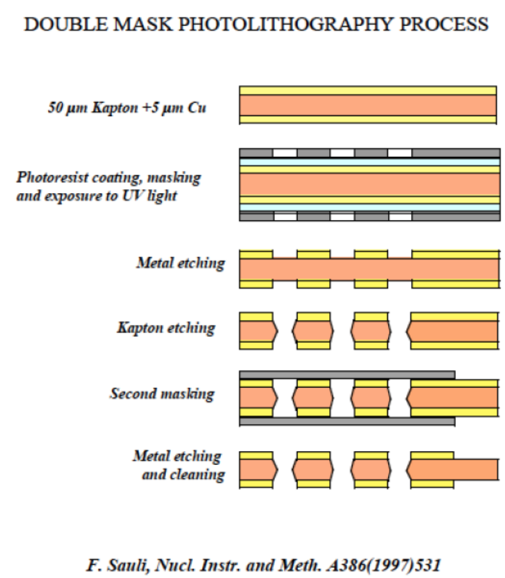
MSGCs with GEMs (Gas Electron Multiplier)

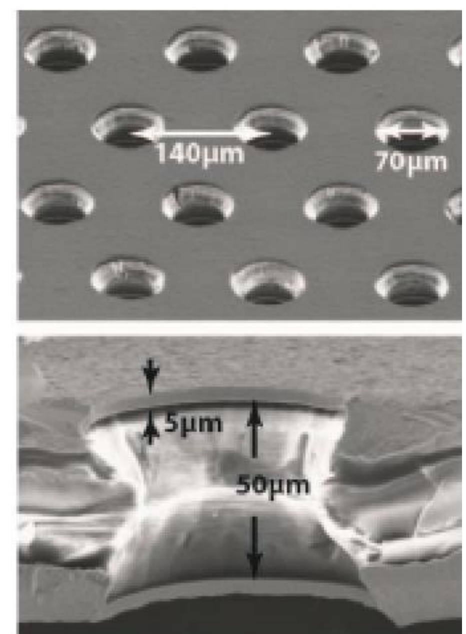
A two step gain reduces the spark probability



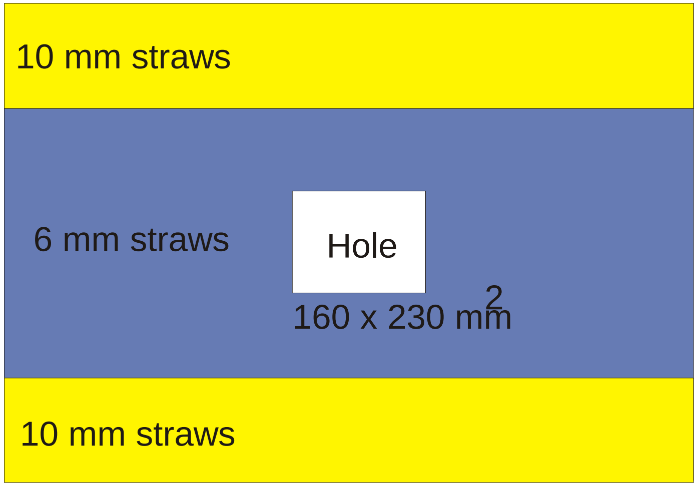


- Electrons are collected on anodes → signal
- Positive Ions are partially collected on the GEM electrodes



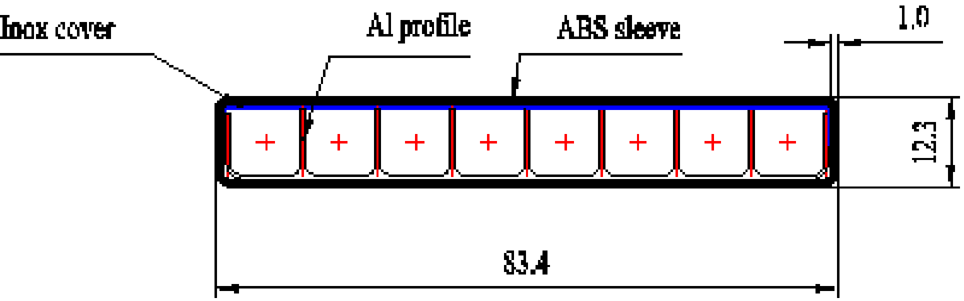


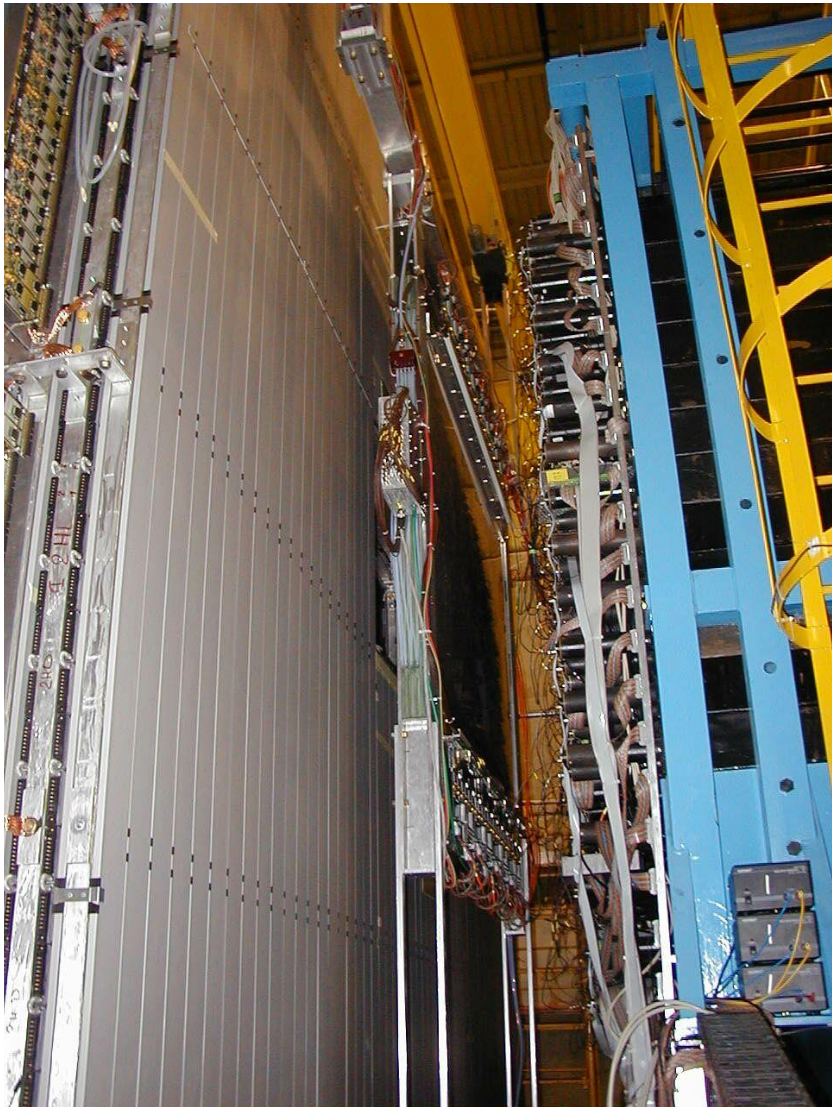
Straw Tube Tracking Detectors



- 15 double layers of 6 and 10 mm straws
- Size 325 x 242 cm^2
- Resolution 270 µm
- Efficiency 85 – 98 %
- $Ar/CF_4/CO_2$ 74/20/6 %

Muon Wall 1





- Size 4 x 2 m^2
- 2 stations sandwiching a 60 cm iron absorber
- 4 double layers per station
- 10 mm pitch

Calorimetry

- ECAL

$$\frac{\sigma}{E} = \frac{5.8\%}{\sqrt{E}} \oplus 2.3\%$$

- Lead glass

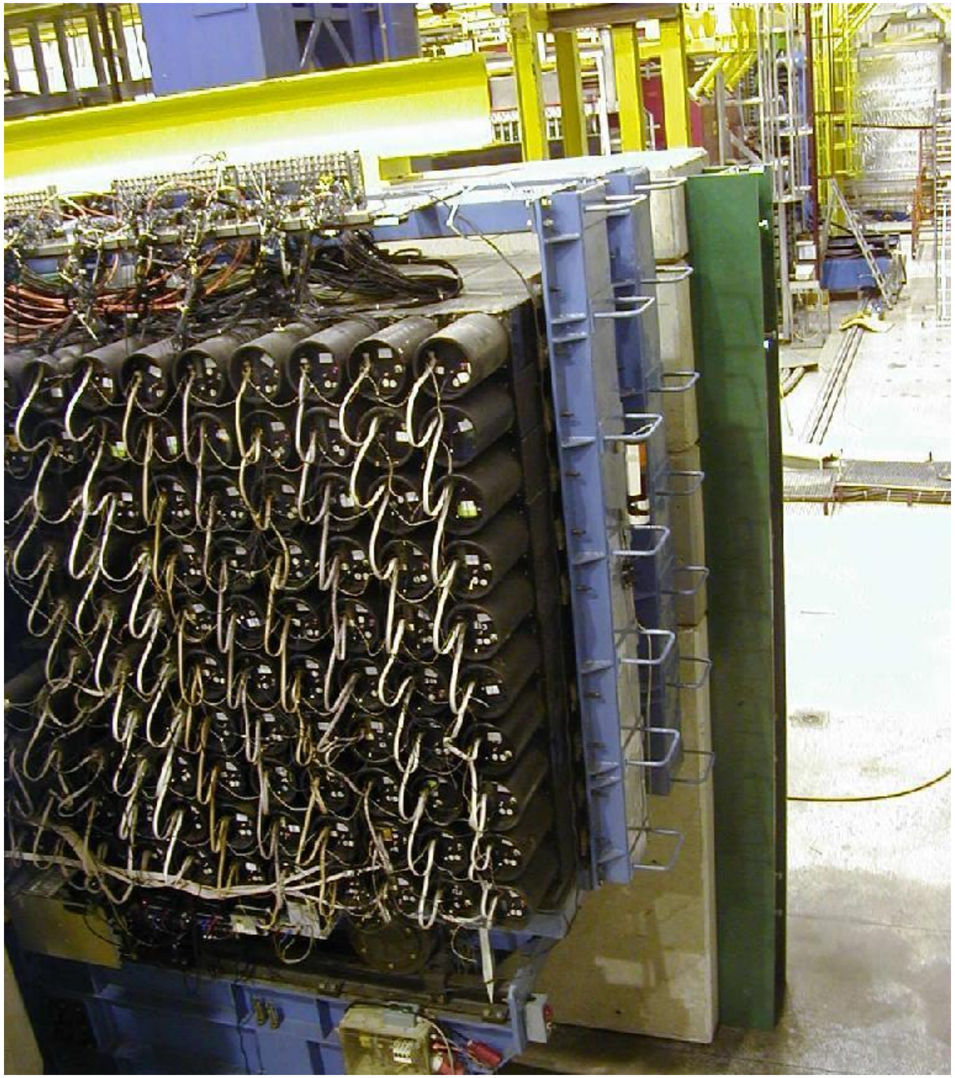
- HCAL 1 (500 channels)
- Sandwich: Fe + scintillator
- Planar WLS read-out

$$\pi : \frac{\sigma}{E} = \frac{59.4\%}{\sqrt{E}} \oplus 7.6\%$$

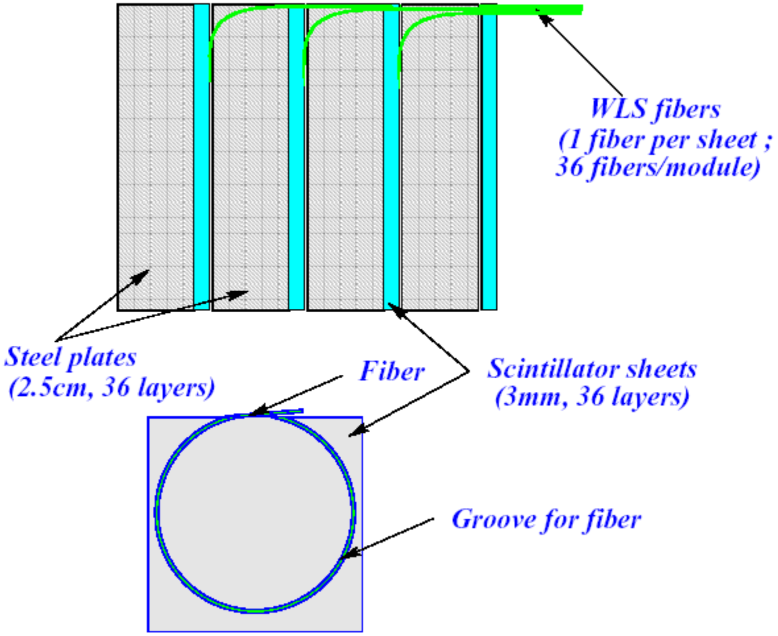
- HCAL 2 (200 channels)
- Sandwich: Fe + scintillator
- WLS fibres read-out

$$\pi : \frac{\sigma}{E} = \frac{65\%}{\sqrt{E}} \oplus 4\%$$

HCAL2

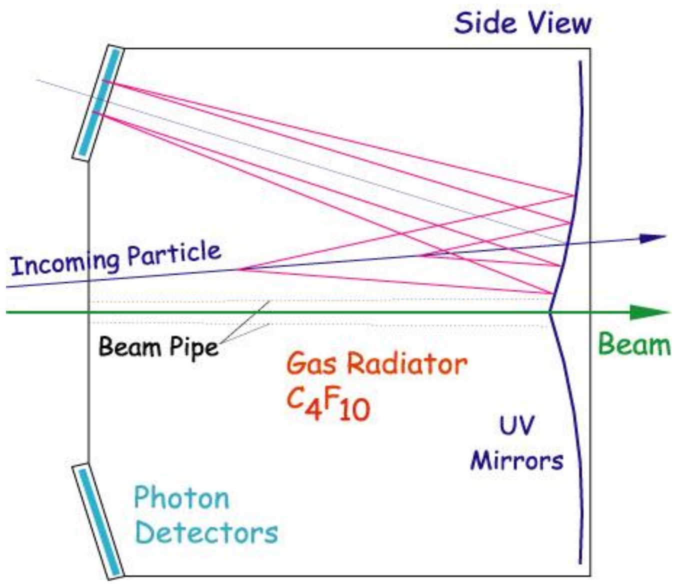


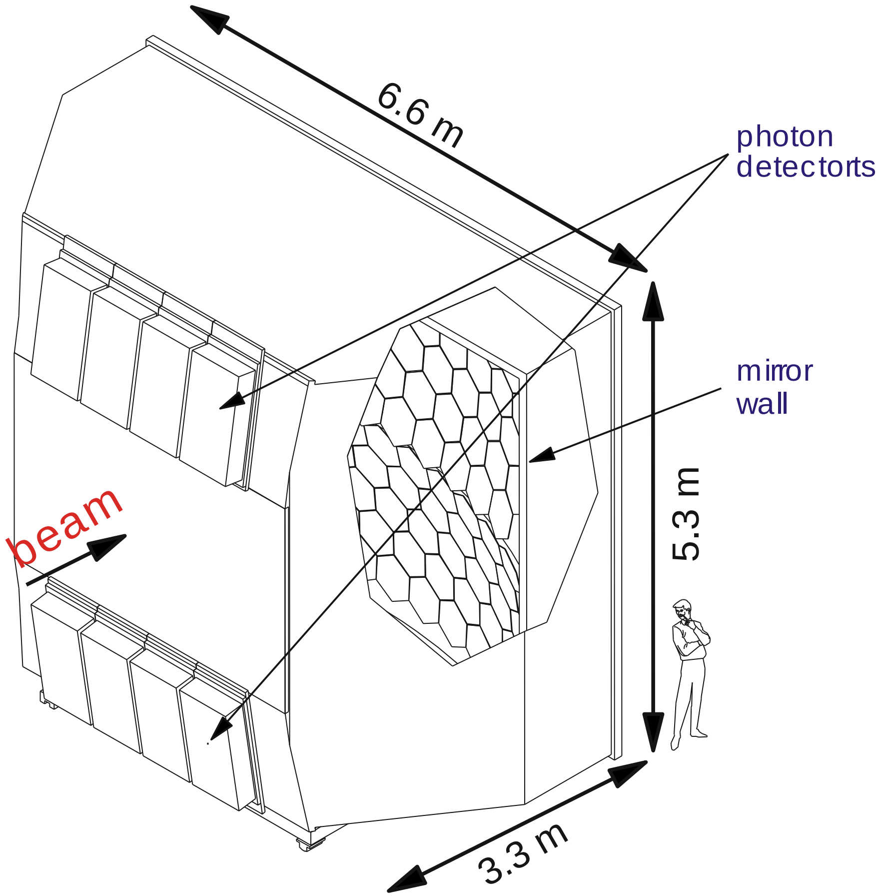
$20x20\ cm^2$ module size



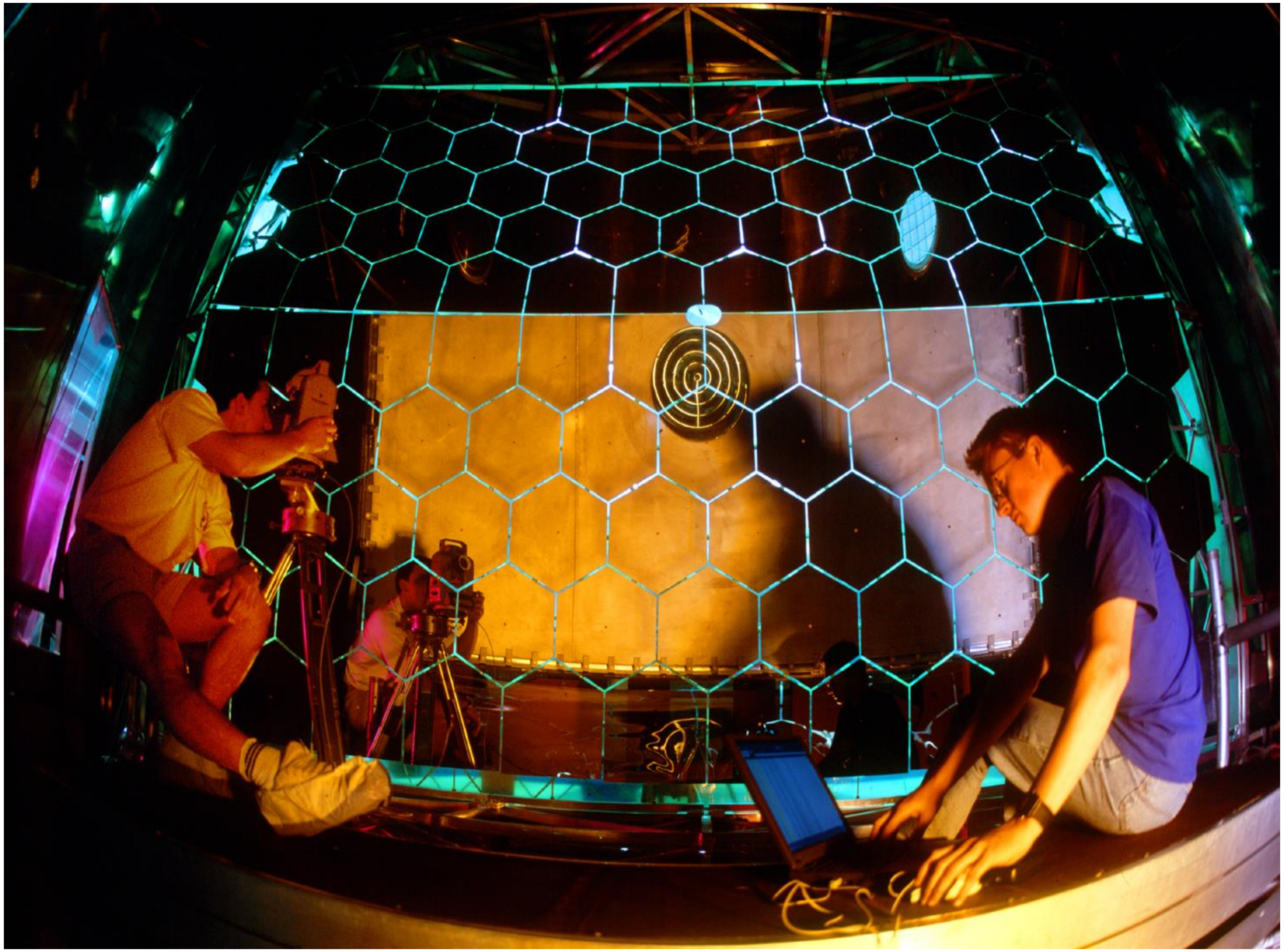
Ring Imaging Cherenkov Counter

- 80 m^3 (3 m C_4F_{10} radiator)
- 116 mirrors
- 5.3 m^2 detectors
  - MWPC CsI photo-sensitive cathodes
  - 8x8 mm^2 pads
- 84k analog readout channels





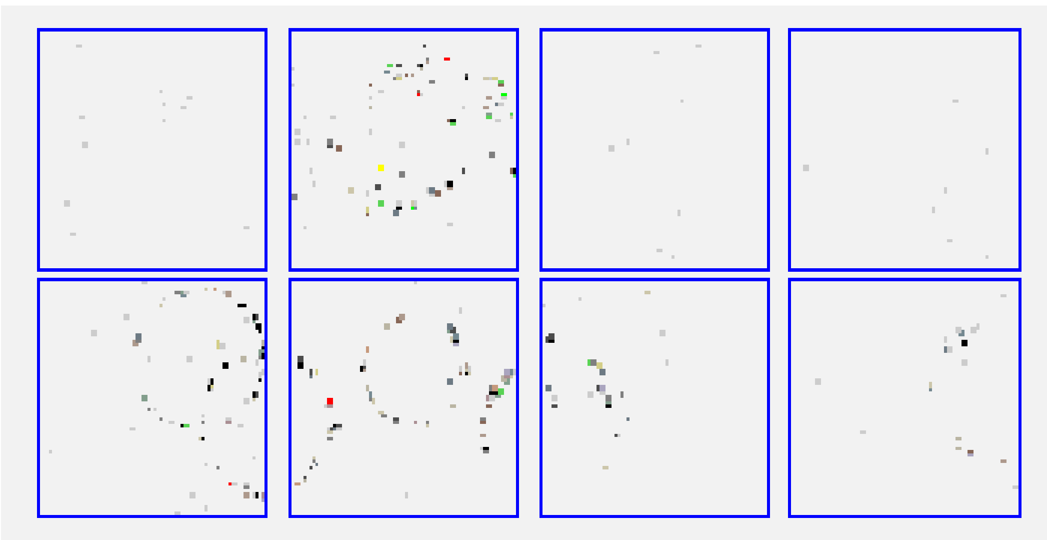
COMPASS RICH (cont.)

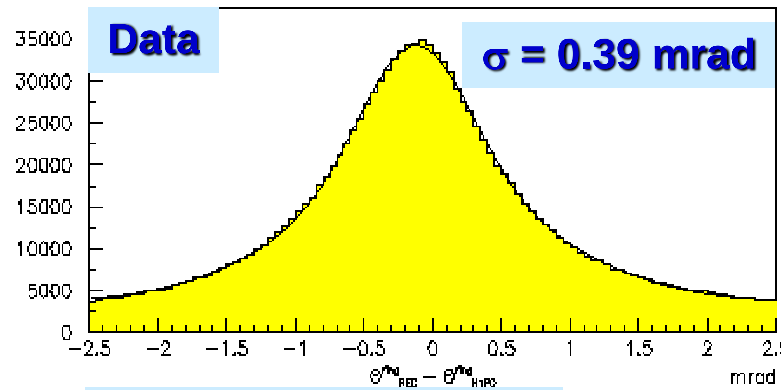


RICH performance

Single event, C_4F_{10}, 2050 V

Cherenkov angle for rings with $\beta \cong 1$





<n> = 15 photons

π / K separation up to 40 GeV/c

10.3 Neutrino Experiments

Different types of neutrino experiments

- Accelerator based neutrino experiments
  (flux of ν_μ neutrinos from accelerator, near detector (flux, beam position), and far detector for rate/oscillation measurements)

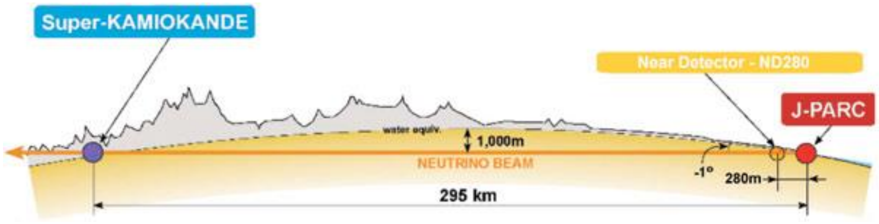
- Reactor neutrino experiments
  (similar in concept as neutrino experiments at accelerators)

- Solar and atmospheric neutrino experiments

- Experiments to measure high energy galactic neutrinos

The T2K ν experiment in Japan

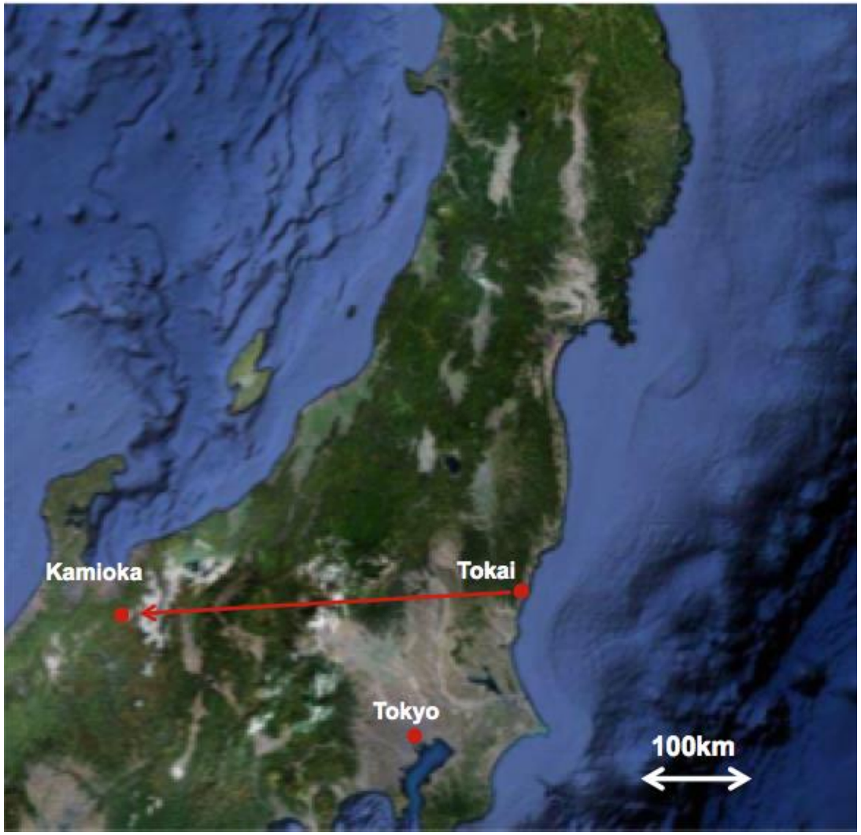
Tokai-to-Kamioka: long-baseline ν experiment with narrow-band beam



- Muon neutrinos produced in J-PARC laboratory in Tokai
  (30 GeV proton beam on a graphite target)

- Near detector: 280 m from the production point to measure the beam profile and flux

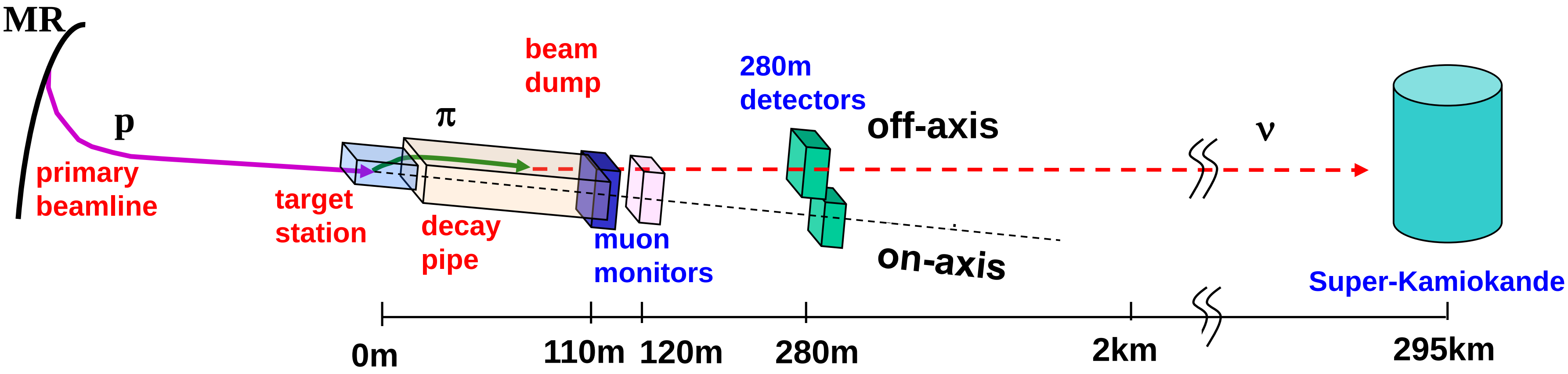
- Far detector (295 km away):
  Super-Kamiokande Detector
  (large water-Cherenkov detector in the Kamioka mine)



Main goal: neutrino oscillation studies

- Muon (anti-)neutrino disappearance
- Electron (anti-)neutrino appearance

T2K Beamline and Detectors



Beamline

- Primary beamline (from accelerator)
- Target station
- Decay pipe
- Beam dump (at 100 m)

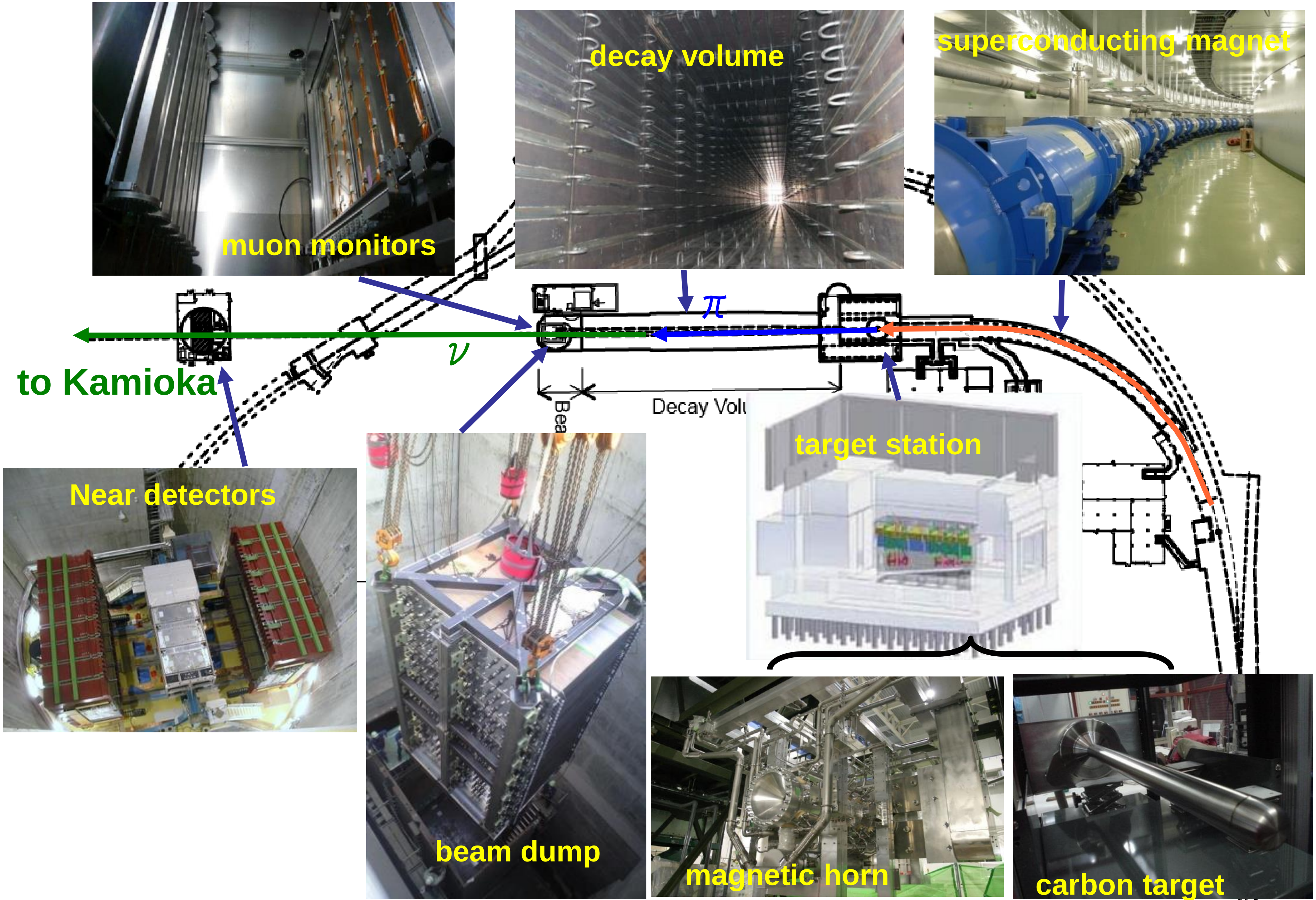
Detectors

- Muon monitors (at 120 m)
- Near detector (at 280 m)
- Far detector Super-Kamiokande (at 295 km)

Off axis beam

The center of the beam direction is adjusted to be 2.5^{o} off from the SK direction

Neutrino beam line and components

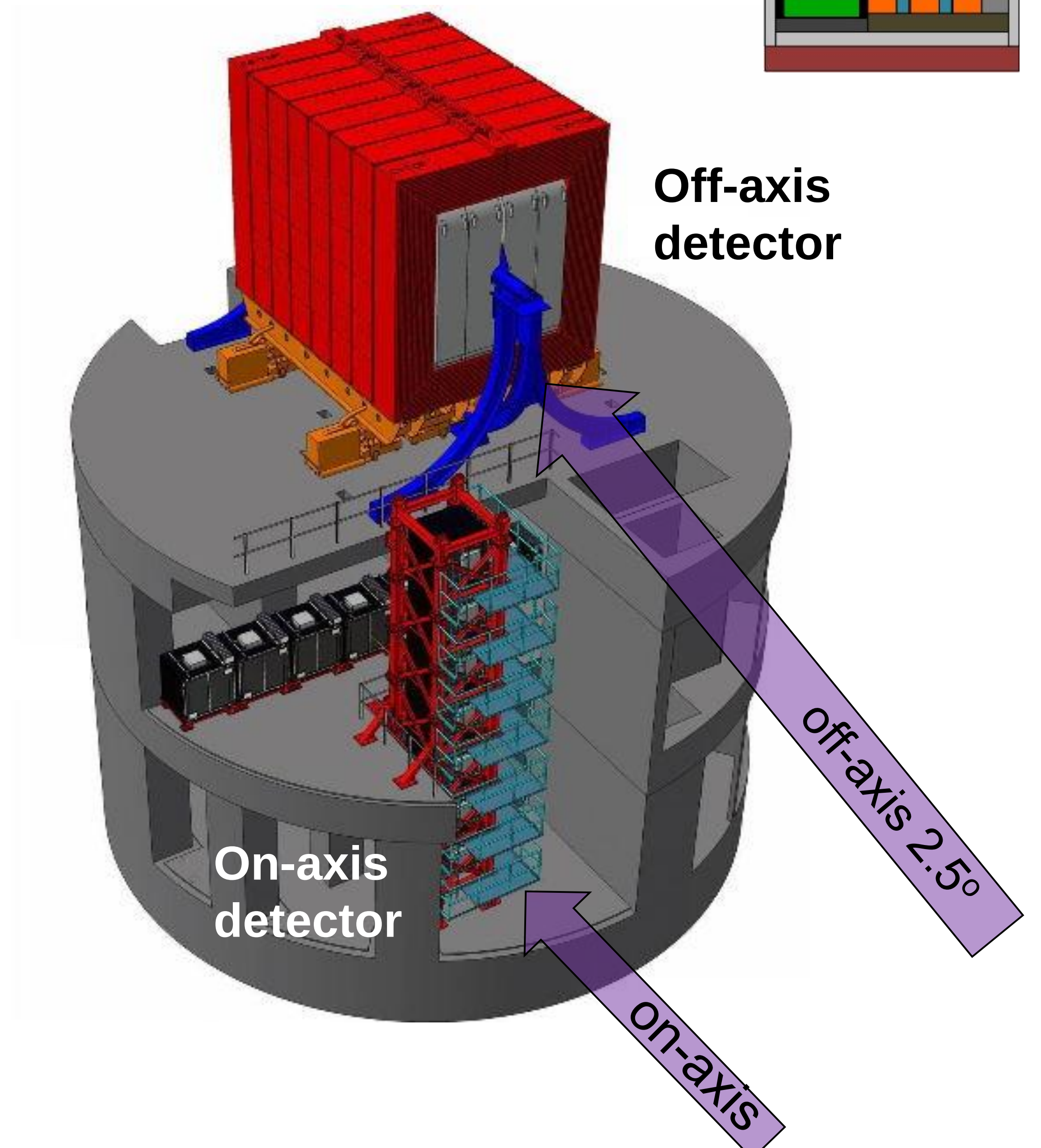


ND280 (The Near Detector at 280 m)

Two detector components:

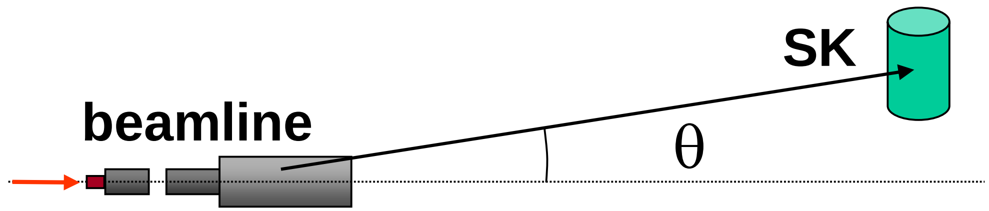
On-axis Detector in the direction of the neutrino beam center

Off-axis Detector in the direction of Super-Kamiokande.

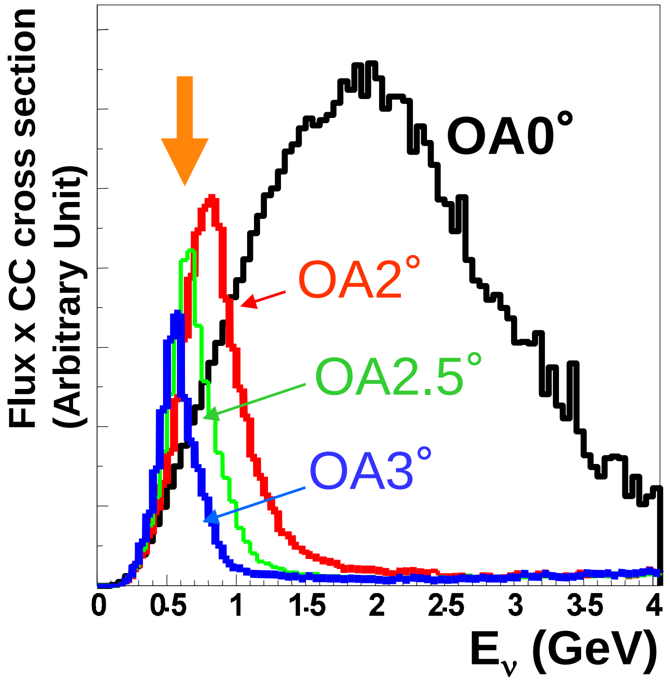


Why an Off-axis beam? or how to adjust the neutrino energy?

- The center of the beam direction is adjusted to $2^o \sim 3^o$ off from the SK direction. Although the number of neutrino events at SK is smaller, the peak energy is lower, with a smaller spread, the high energy neutrinos are suppressed;

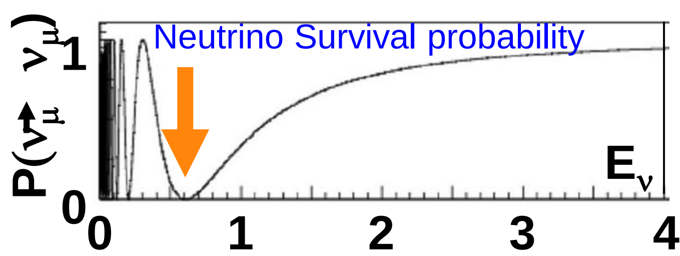


The neutrino energy spectrum is obtained from two-body decay kinematics



- The oscillation study is most effective if the neutrino peak energy is adjusted to the oscillation maximum

- Δm^2_{23} from other experiments was ~ (2~3)x10^{-3} eV^2



On-axis detector (INGRID)

- 16 modules

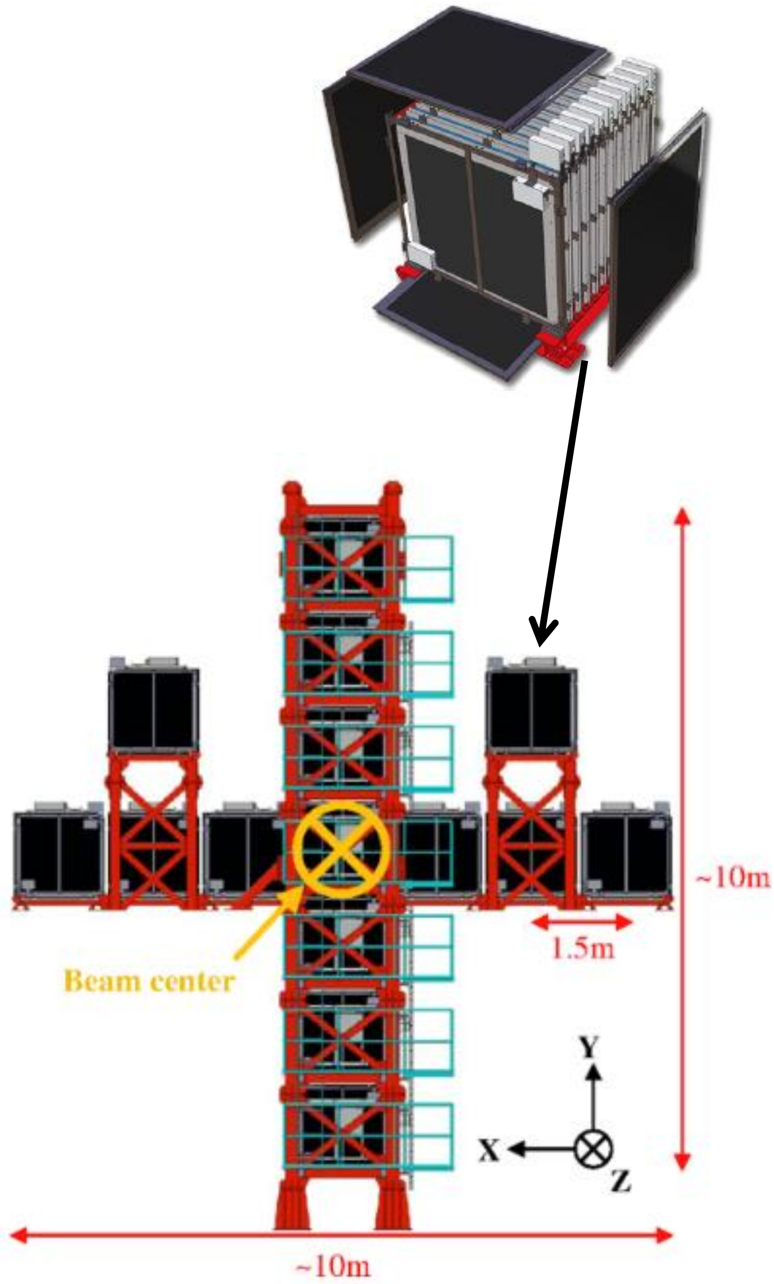
  (7 horizontal, 7 vertical, and 2 off-diagonal)

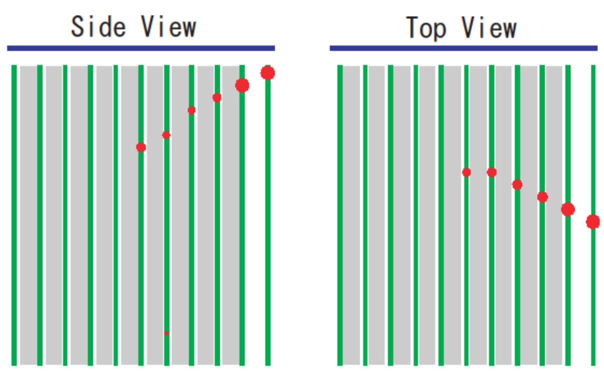
- Each module is 1m x 1m x 1m cube

  Sandwich of 11 scintillator layers and

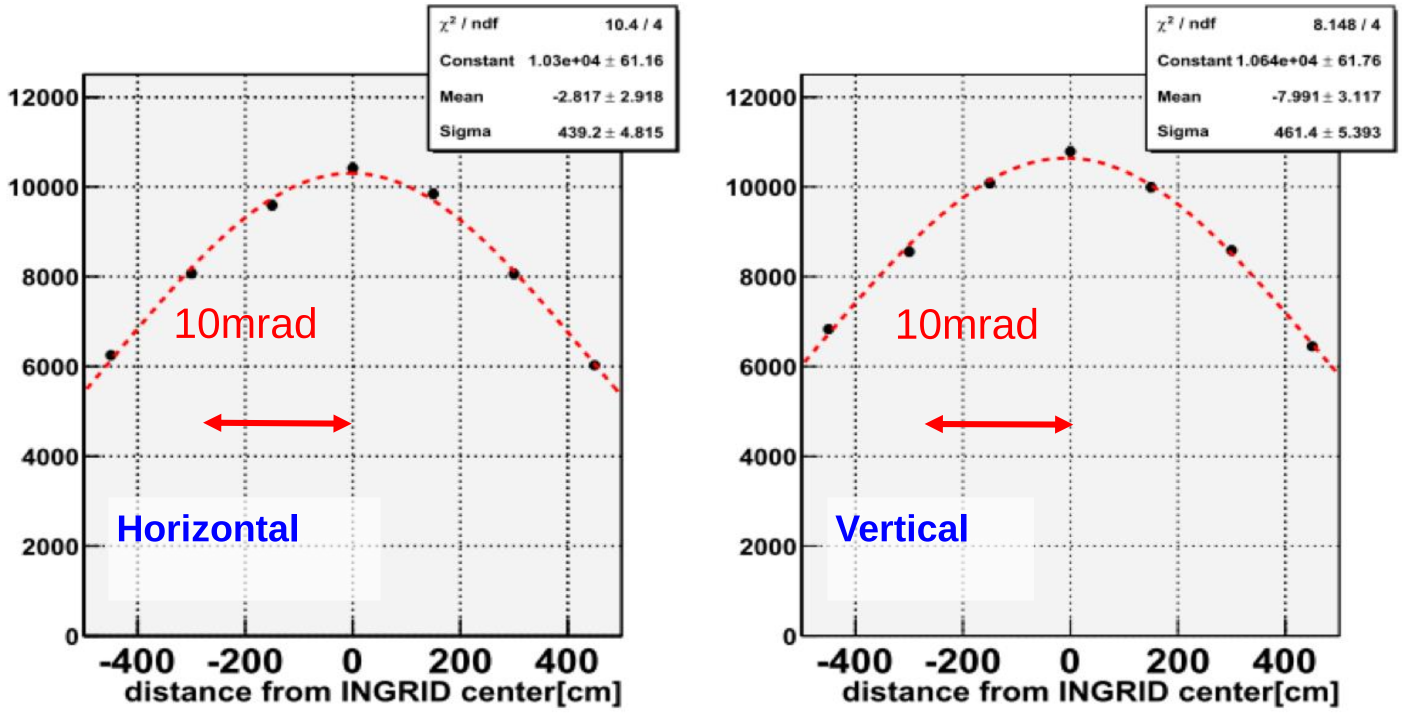
  10 iron layers;

  (surrounded by 4 veto planes)





- The neutrino beam center is calculated from horizontal and vertical distribution of the neutrino event rate.

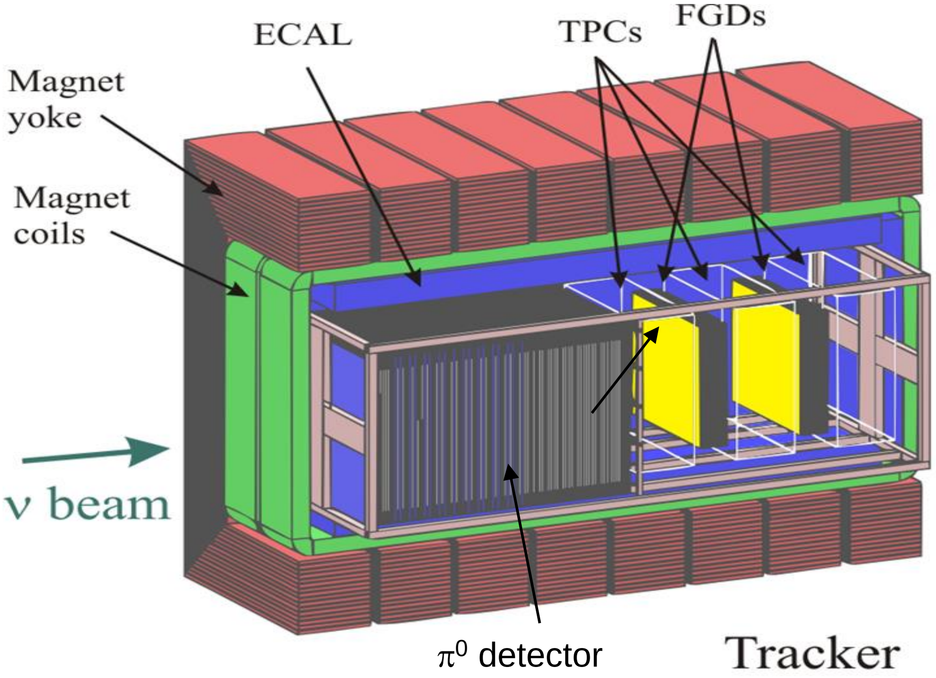


The Off-axis detector

The major tasks of the Off-axis near detector are to measure:

- The energy spectrum of muon neutrinos in the SK direction
- The fraction of electron neutrinos in the beam

Muon detection via the charged-current reaction: $\nu_\mu + n \rightarrow \mu + p$



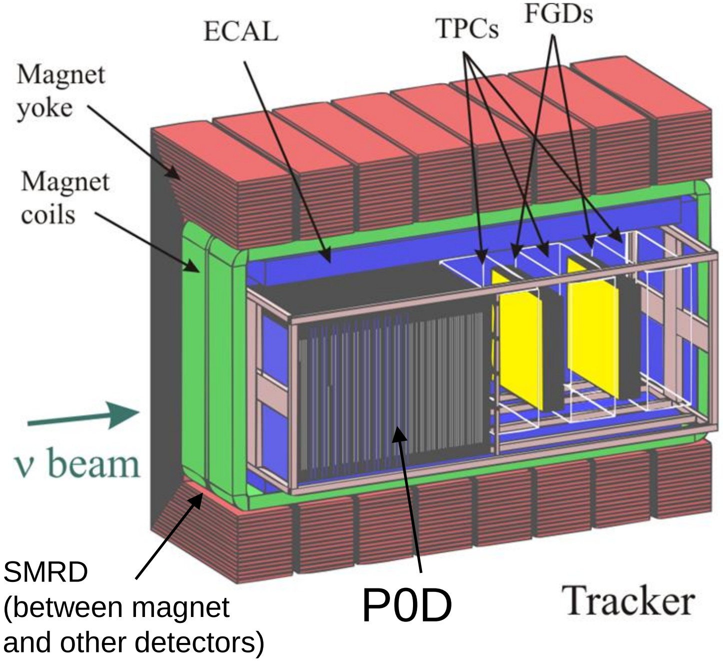
- All detector components are in 0.2 T magnetic field (previous UA1 dipole magnet from CERN)

The Off-axis detector

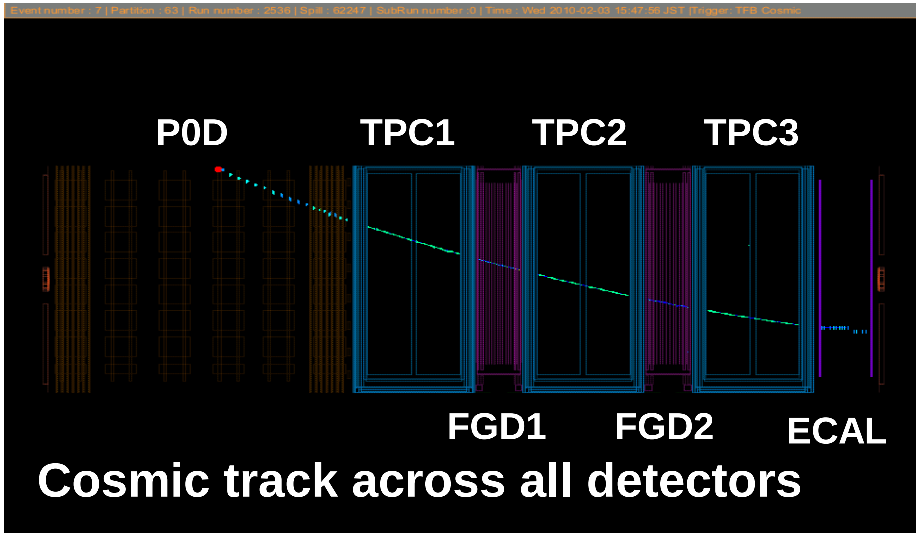
Major detector components:

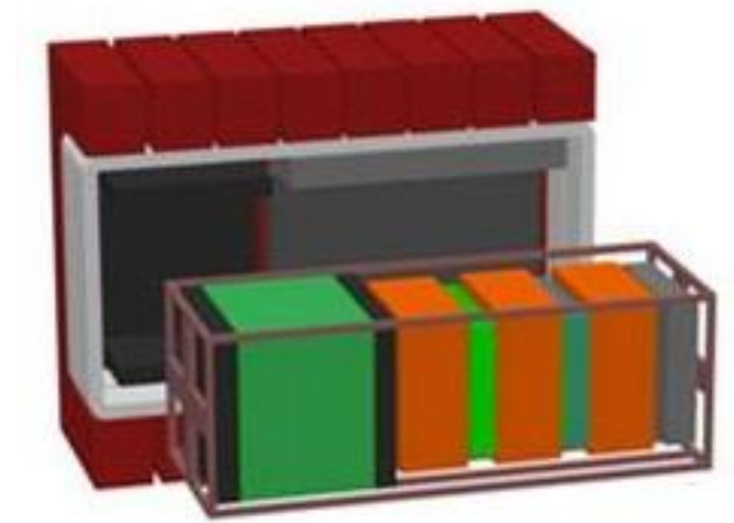
- Tracking detector: 3 TPCs and 2 FGD
  (Fine-grained detector, consisting of
  scintillator and water as target material)

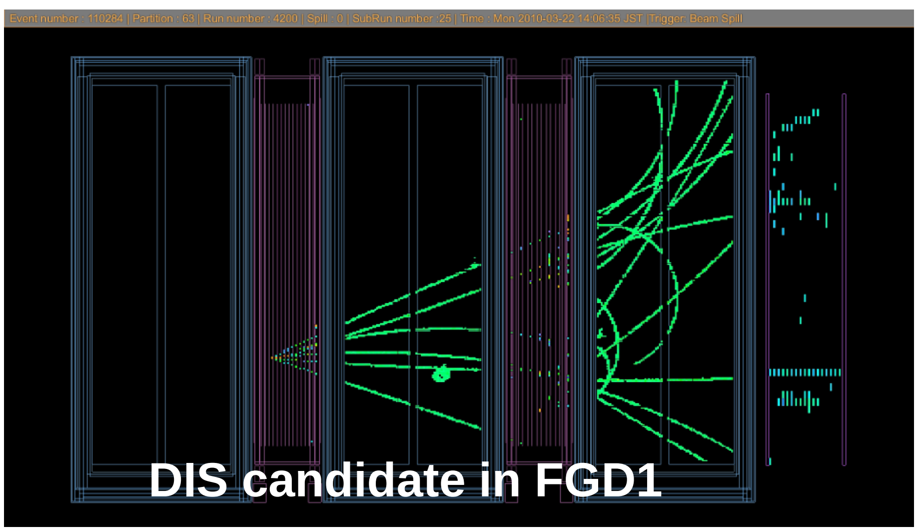
- Measurement of muon momentum;
  → the neutrino energy is obtained from
  two-body kinematics

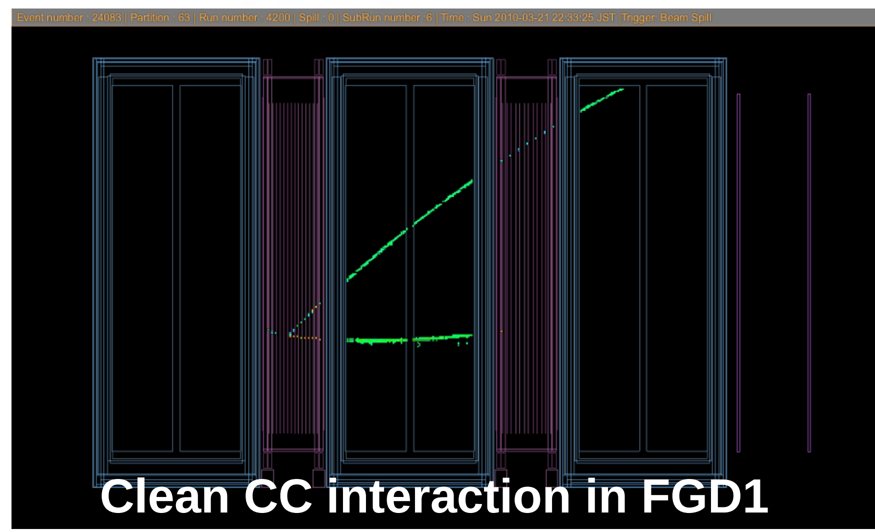


ND280 off-axis neutrino events



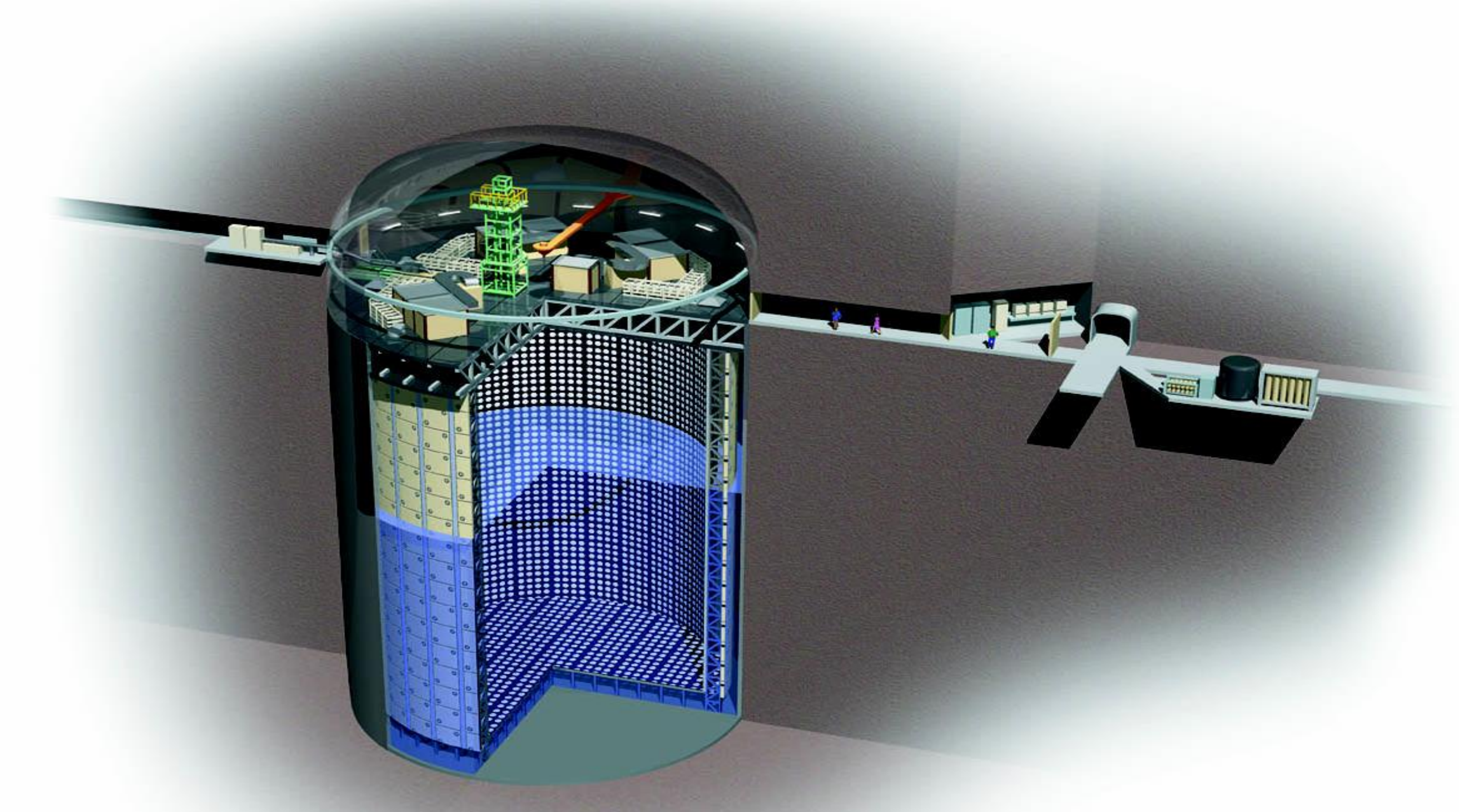




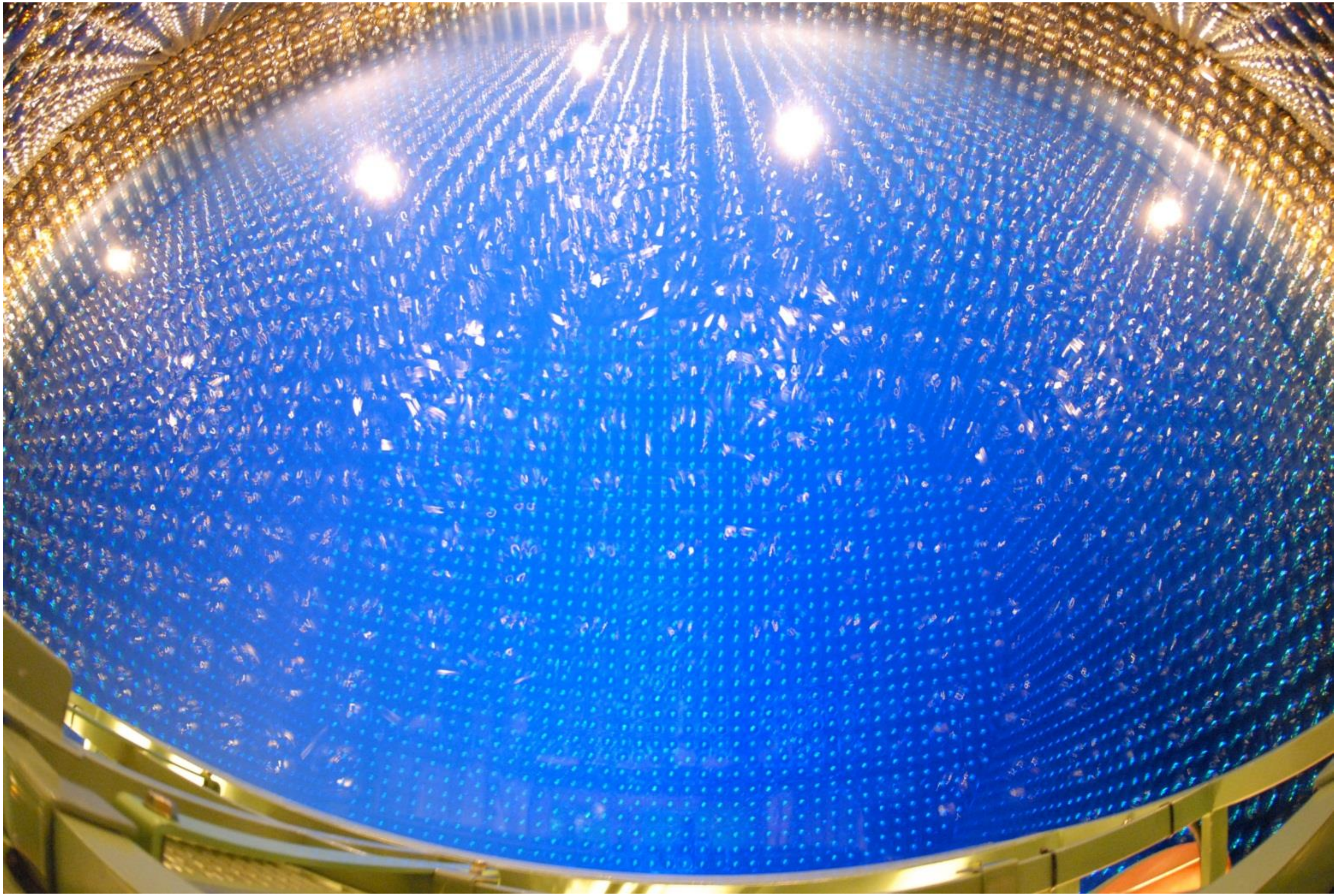


The Super-Kamiokande Experiment

- A 50 kt water Cherenkov detector with 11129 20-inch special photomultipliers; The fiducial volume of the detector is 22.5 kt
- It is located about 1000 m underground in the Kamioka mine (Japan) with a distance to J-PARC of 295 km
- Detection of ν-induced reactions via Cherenkov light (measurement of Cherenkov angle and e/μ separation)



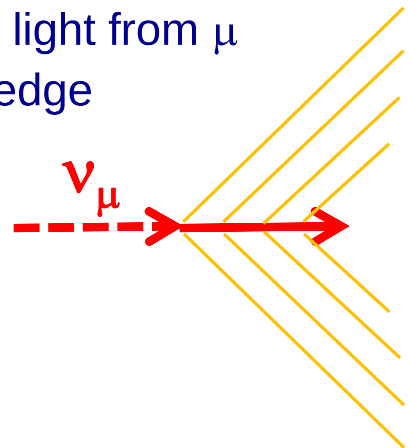
The Super-Kamiokande Experiment



μ/e identification in Super-Kamiokande

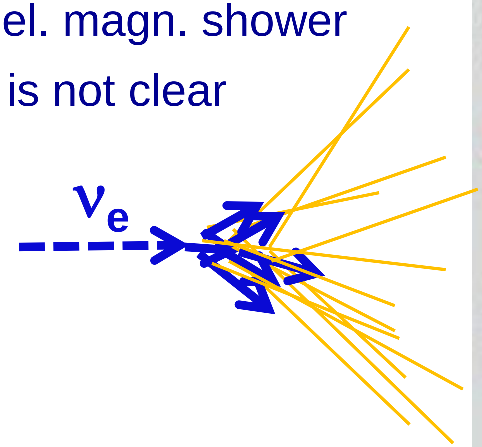
$\nu_\mu \rightarrow \mu$

Only direct Cherenkov light from μ
Clear Cherenkov ring edge

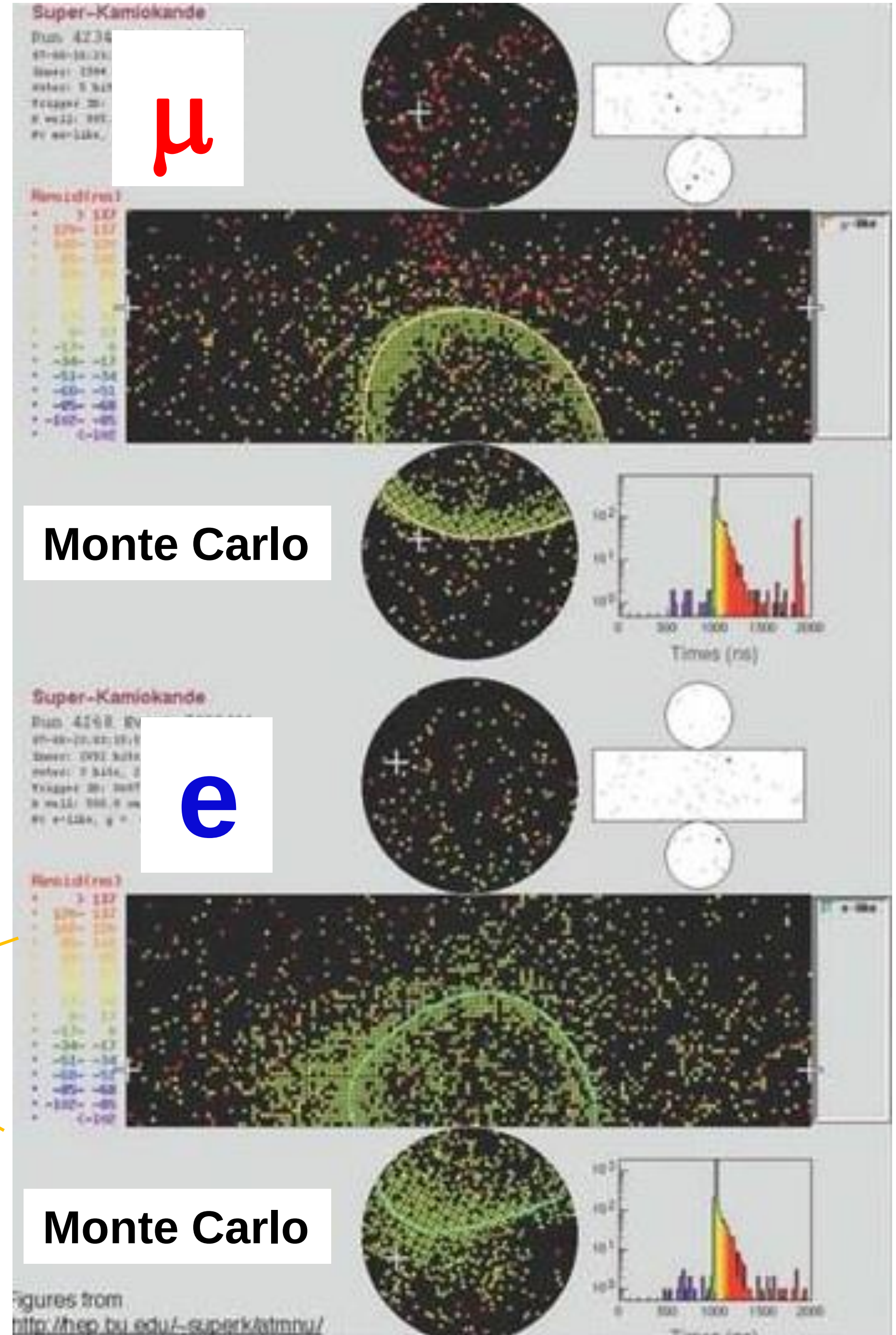


$\nu_e \rightarrow e$

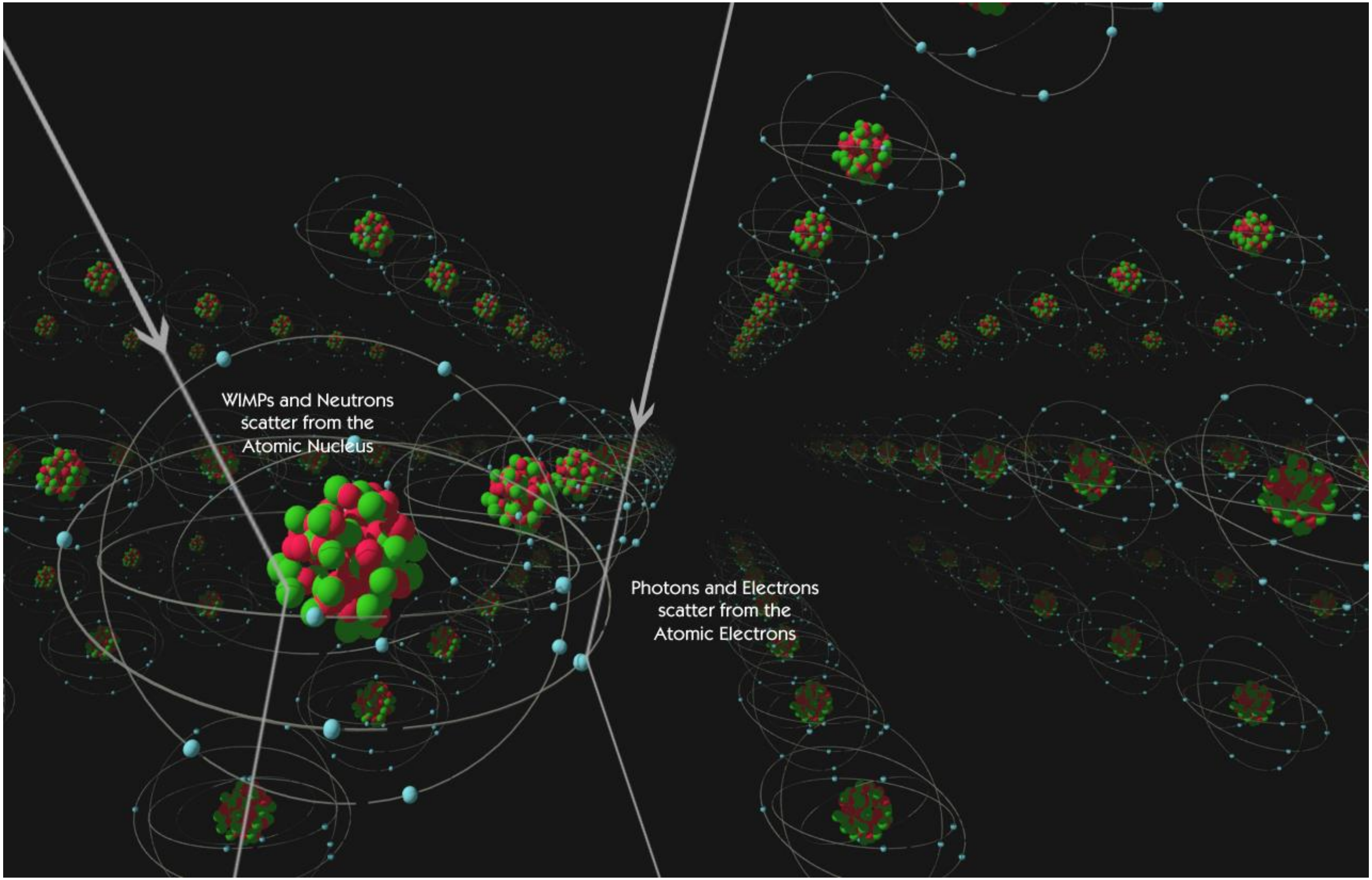
Cherenkov light from el. magn. shower
Cherenkov ring edge is not clear



μ/e misidentification probability
is less than 1%.



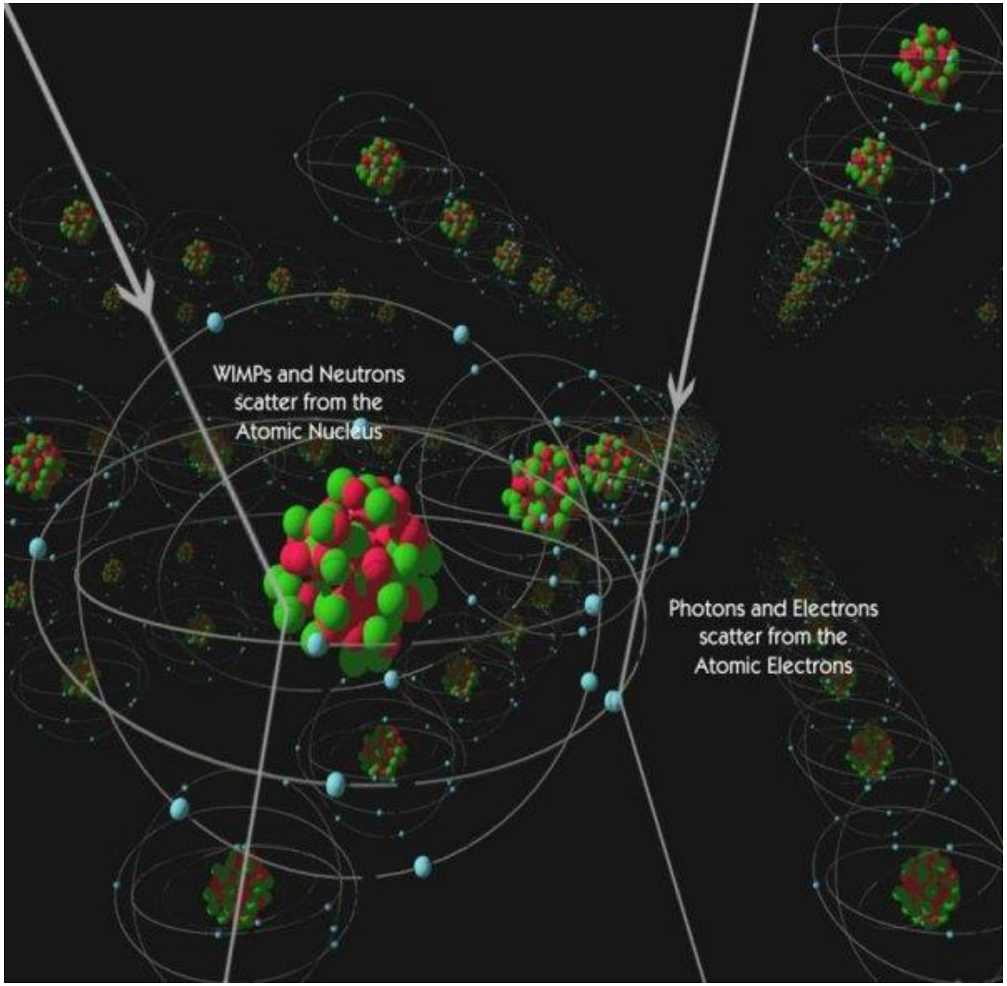
10.4 Direct Dark Matter Detection



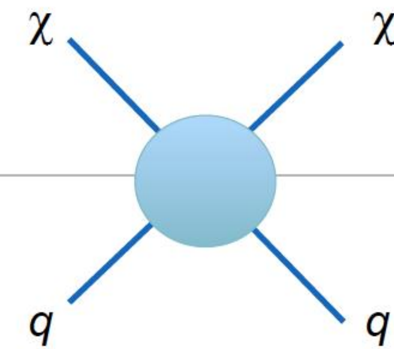
Direct detection : Elastic WIMP-Atom Scattering

Three signals of nuclear recoils are used to search for evidence of WIMP scattering

a) Ionization of target atoms
b) Fluorescence / scintillation light
c) Phonon excitations generated in crystals by the nuclear recoils



Strategy for WIMP Direct Detection



- **Collisions with atomic nuclei**
- Rates depend on: **[m_χ, σ]**, **[f(v), ρ_0]**, **[N, $F^2(E_R)$, E_{th}]** ...

$$\frac{dR}{dE_R} = \frac{\sigma_0 \rho_0}{2 m_\chi \mu^2} F^2(E_R) \int_{v > \sqrt{m_N E_R / 2\mu^2}}^{v_{max}} \frac{f(\vec{v},t)}{v} d^3 v$$

- **Recoil spectrum featureless**

- **With WIMP-nucleon cross sections** $< 10^{-7}$ pb, the expected rates are

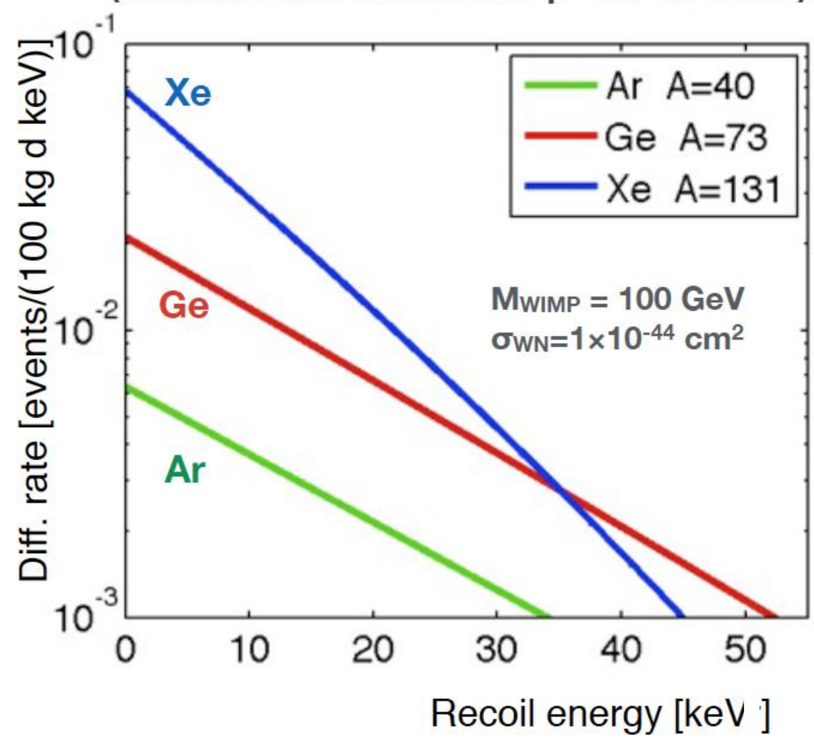
  < 1 event/100kg/day

- **Energy of recoiling nuclei**

$$E_R = \frac{|\vec{q}|^2}{2 m_N} = \frac{\mu^2 v^2}{m_N}(1 - \cos\theta) \leq 50\ keV$$

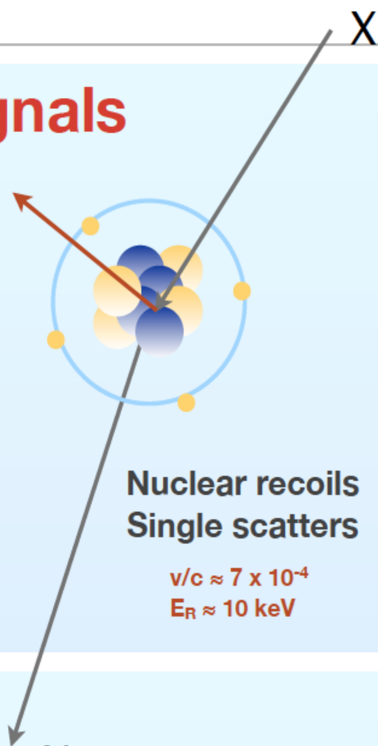
Differential rates (per 100 kg and day) for different targets (Ar, Ge, Xe)

(Standard halo model with ρ= 0.3 GeV/cm³)



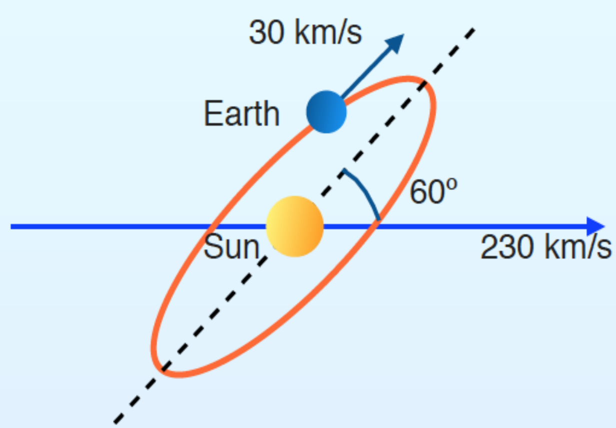
Signals and Backgrounds

Signals

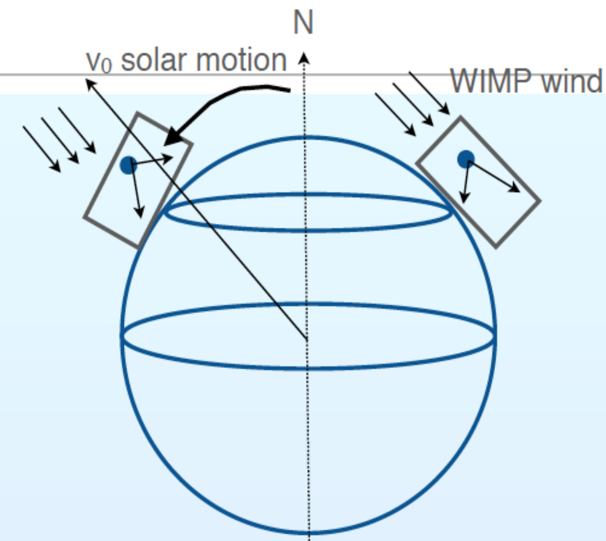


Nuclear recoils
Single scatters

$v/c \approx 7 \times 10^{-4}$
$E_R \approx 10$ keV

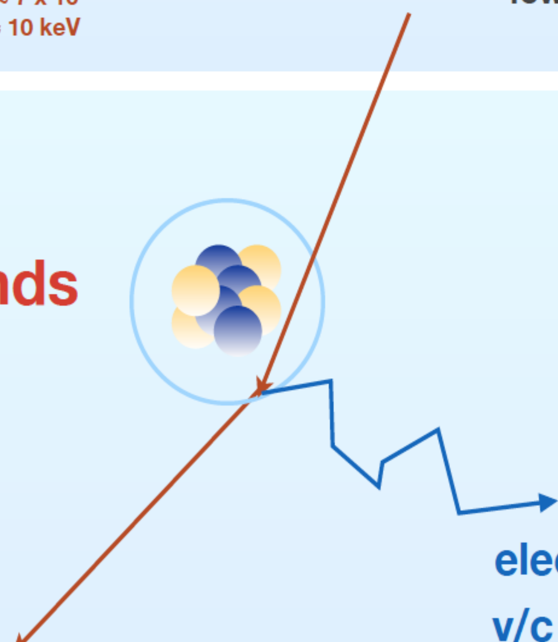


Annual rate variation
~ few % effect



Diurnal directional modulation:
~ 50% effect

Backgrounds



electron
$v/c \approx 0.3$

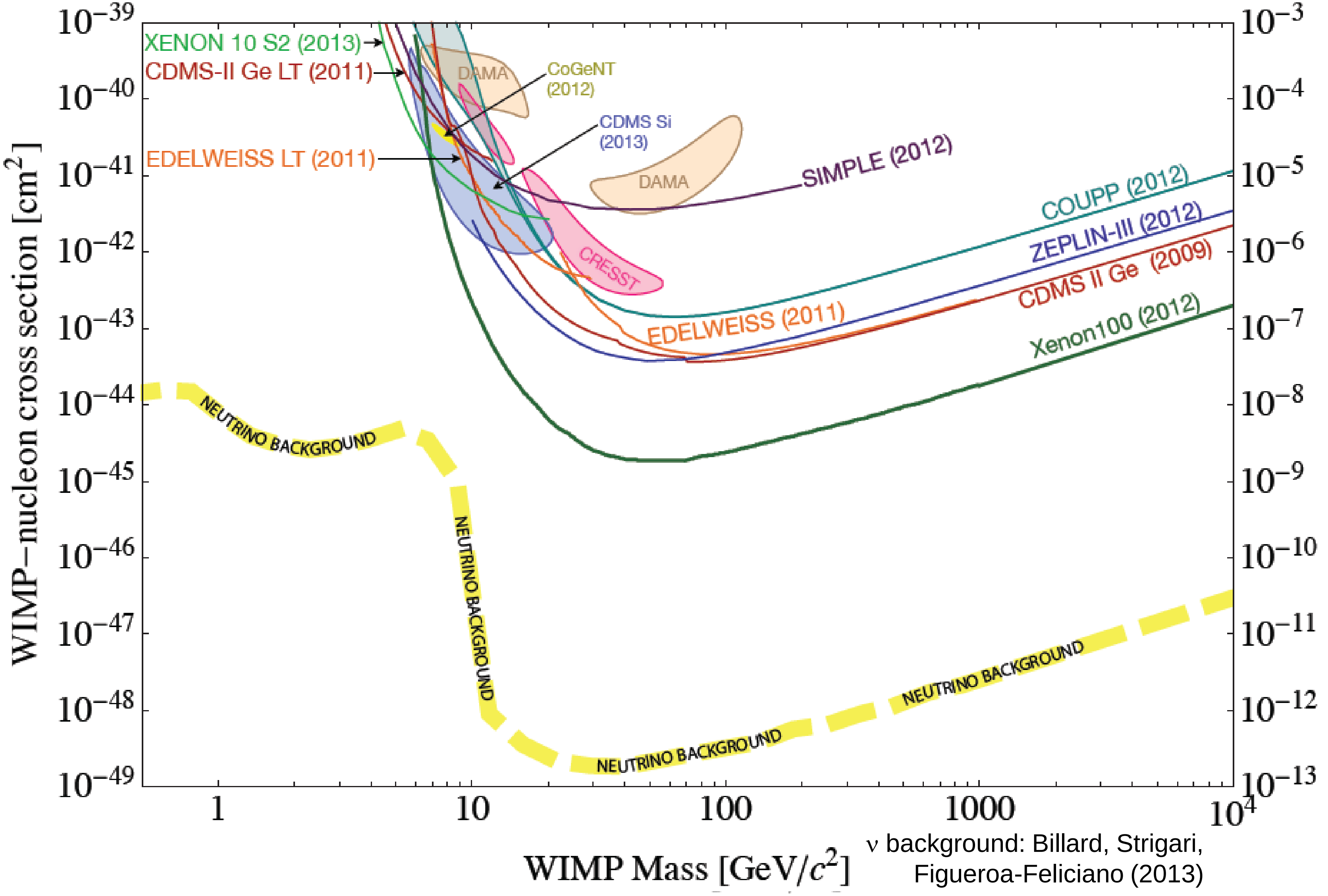
gamma, betas: ER vs NR discrimination and self-shielding

muons: go deep underground, add muon veto

neutrons: NRs, but also capture and multiple scatters

alphas: much higher energy depositions, but recoiling nuclei a problem if α energy not seen in active detector volume

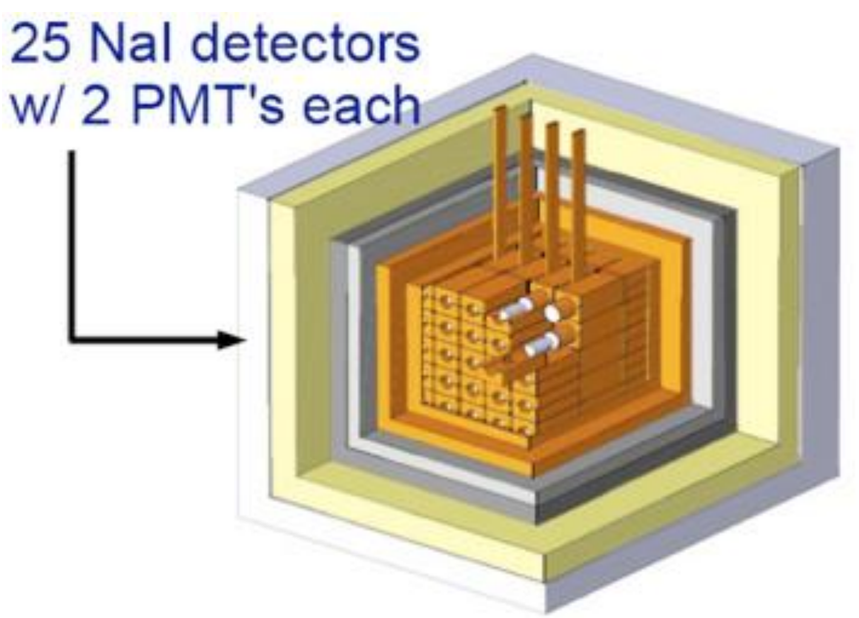
Status on WIMP search (2012)



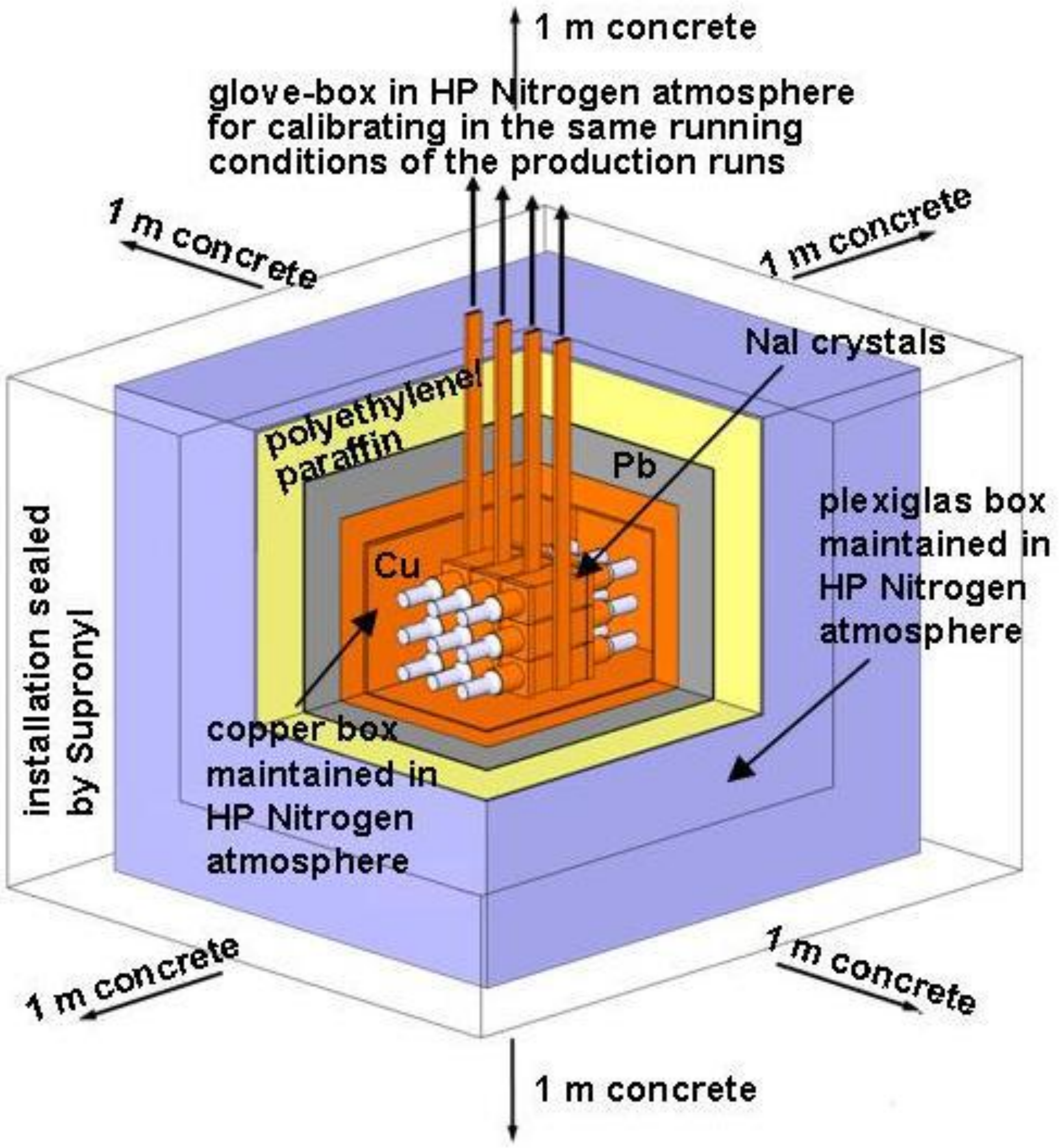
ν background: Billard, Strigari, Figueroa-Feliciano (2013)

Example: The DAMA Experiment

- 1996: Dark Matter Experiment
- Underground, Gran Sasso Laboratoy in Italy
- Use Scintillation light, NaI crystals, target mass of 100 kg,
  Read out with conventional photomultipliers

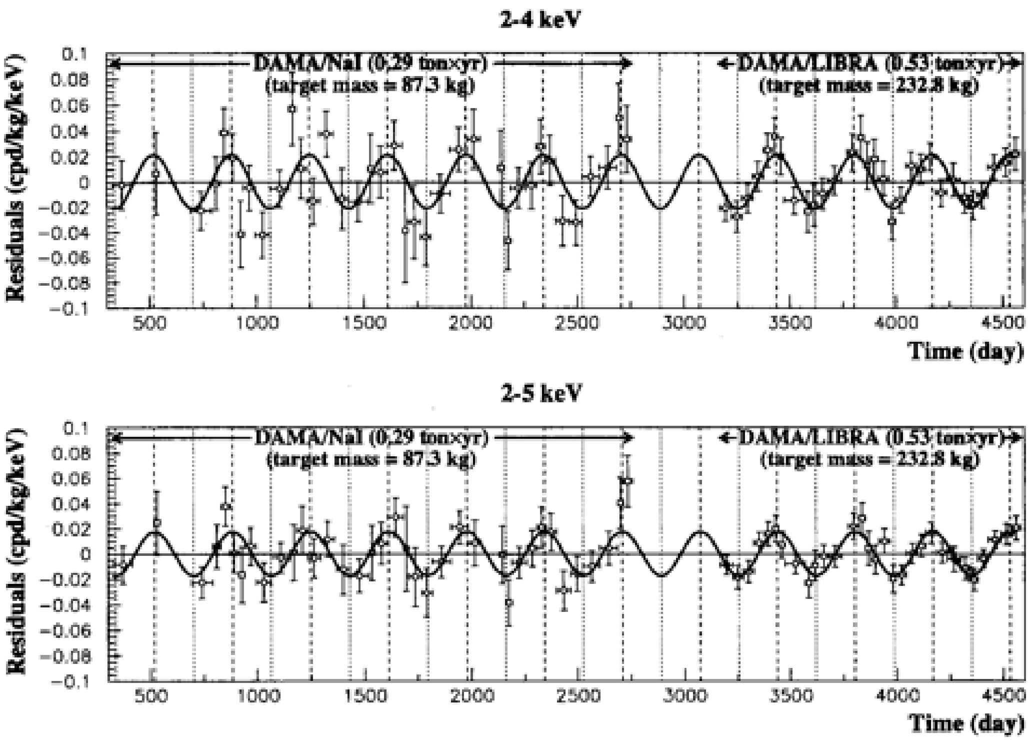


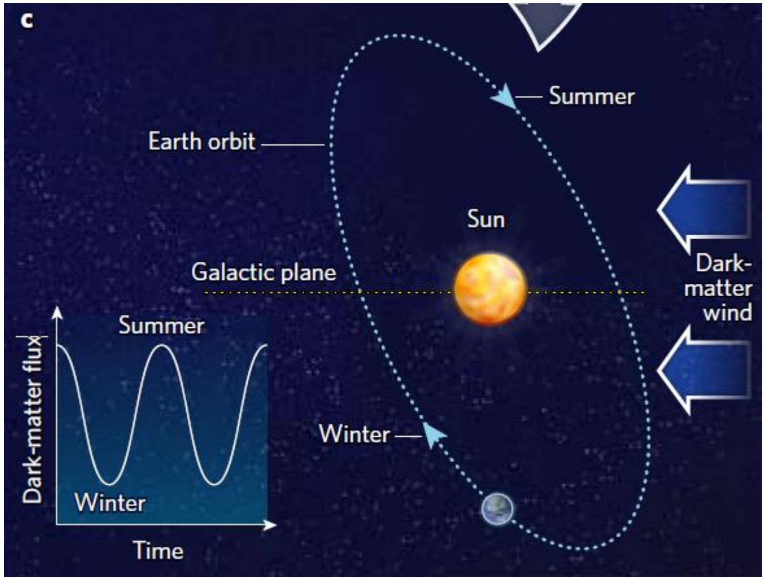
The DAMA Experiment



Simplified schema of ~ 100 kg NaI(Tl) set-up

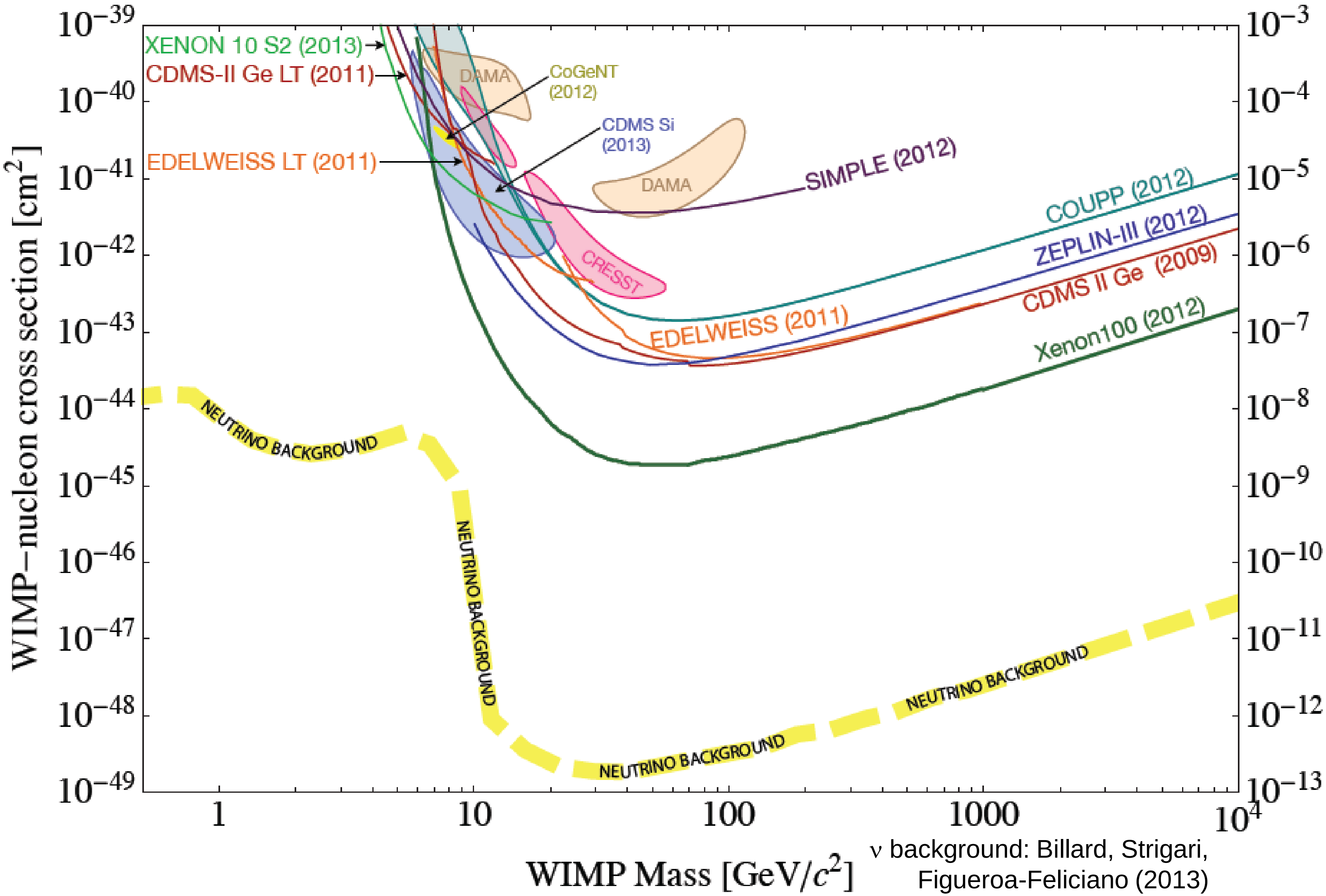
DAMA Experiment





- The DAMA Collaboration has reported direct observation of annual modulation signals at a confidence level of more that 8 standard deviations.
- In conflict with other experimental results

Status on WIMP search (2012)



ν background: Billard, Strigari, Figueroa-Feliciano (2013)

Dark Matter search is one of the most active fields in particle physics today

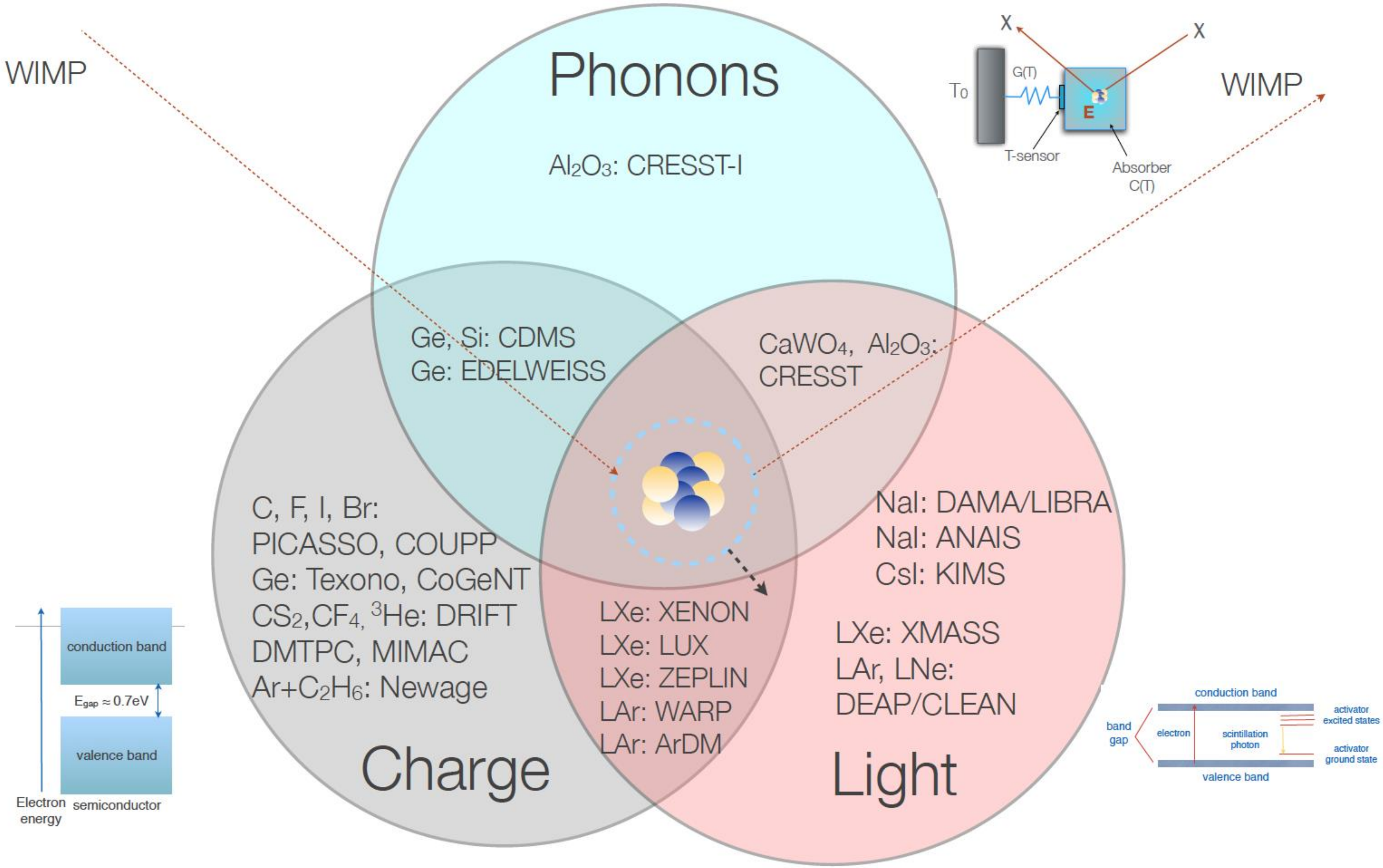
- Many experiments have been designed and built over the past years, to reach lower scattering cross sections

  → Larger target mass

  → Improved sensitivity

- The most sensitive experiments use a “double signature” to discriminate nuclear recoils from electron recoils

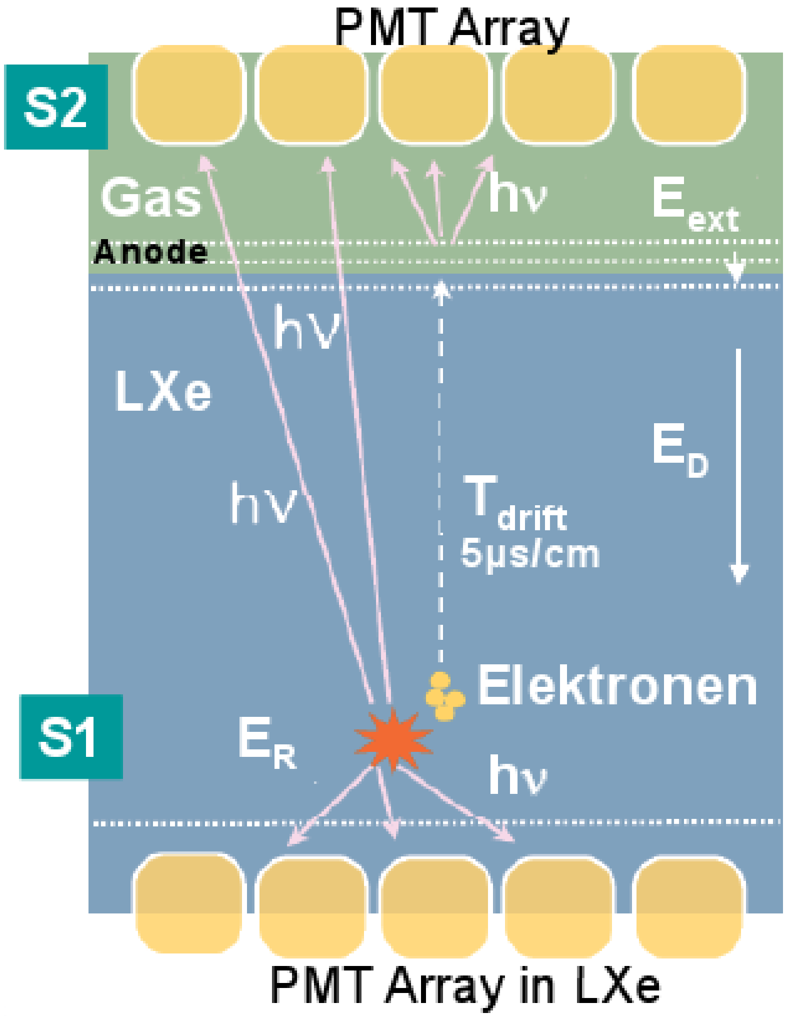
Detection of Multiple Signals



Large Xenon Detectors

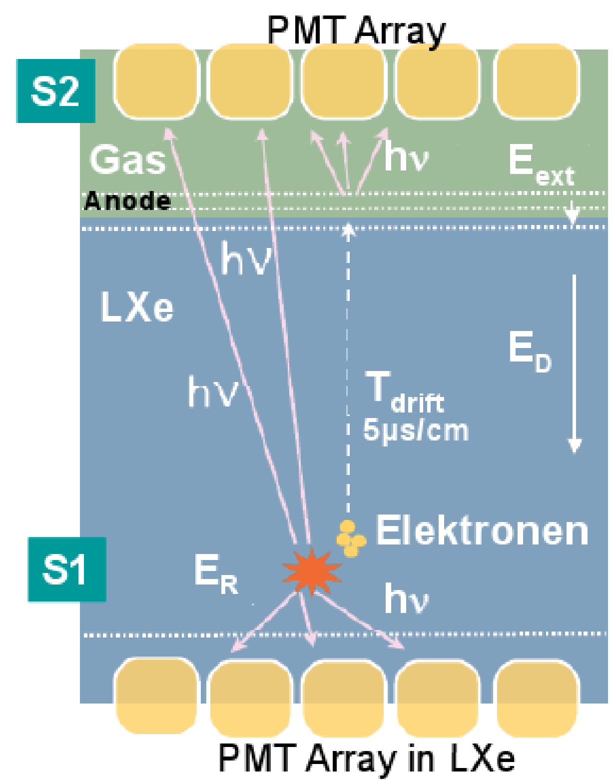
- Large target mass from liquid Xenon
- Use a Time Projection Chamber (TPC) filled with Liquid Xenon

  and Photomultiplier Readout
- Detection of Scintillation Light and Charge (Ionization Signal)

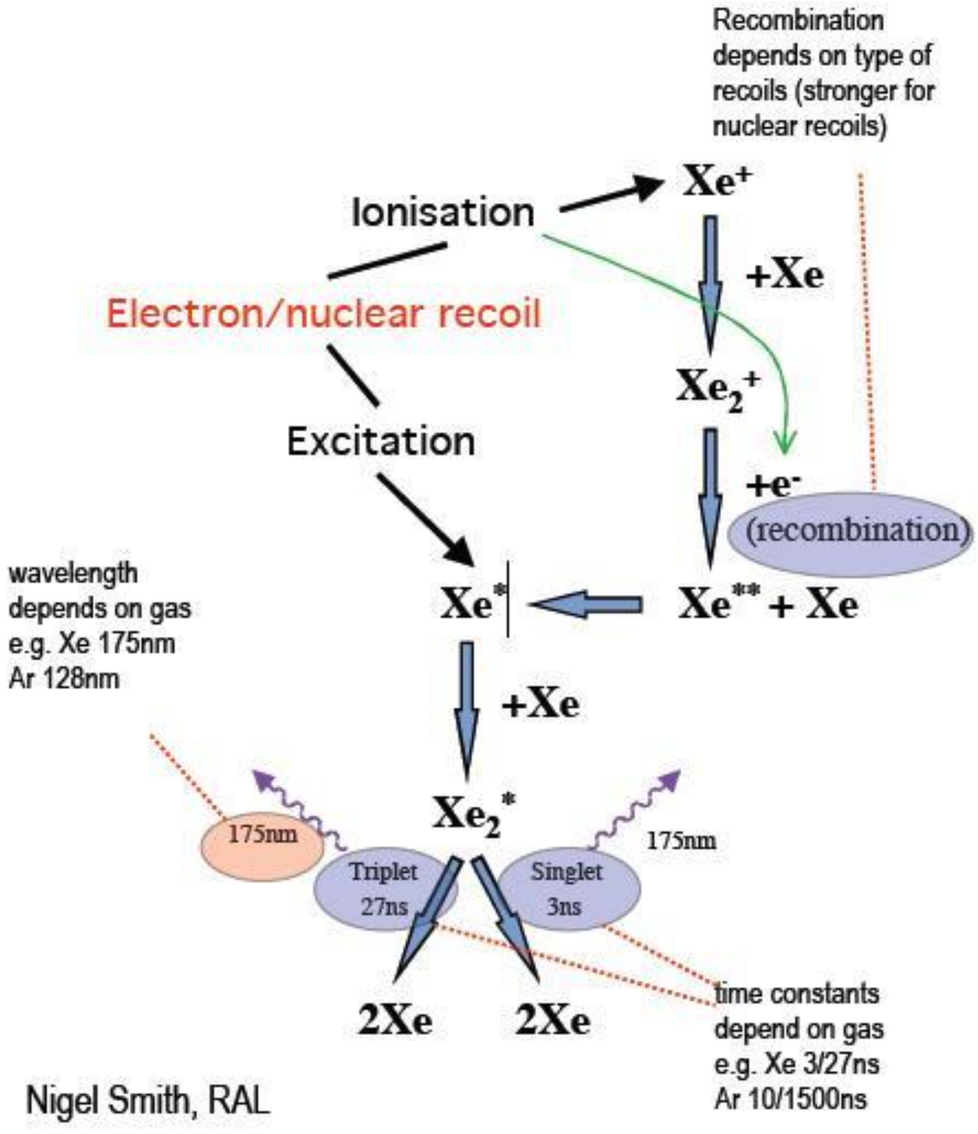


Why Xenon detectors?

- High mass Xe nucleus is a good target for WIMP interactions
- High atomic number (Z = 54) and high density (ρ = 3 g/cm^3) allow for a compact and flexible detector geometry
- High ionization yield (W = 15.6 eV)
- High electron drift velocity and small diffusion in TPC allow for a good space resolution
  → 3D event reconstruction (background rejection)
- In addition: high scintillation yield with fast response
- Distinct charge / light ratio for electron / nuclear energy deposits



Ionization and Excitation Processes in Xenon

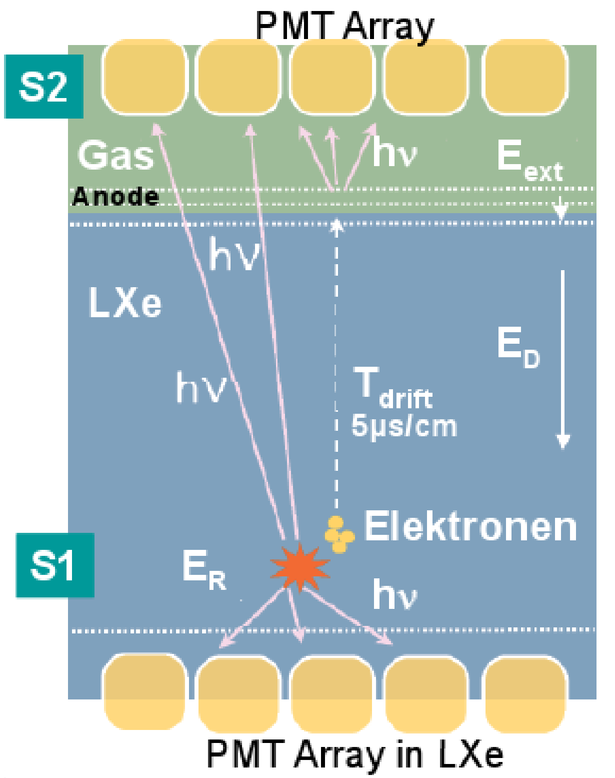


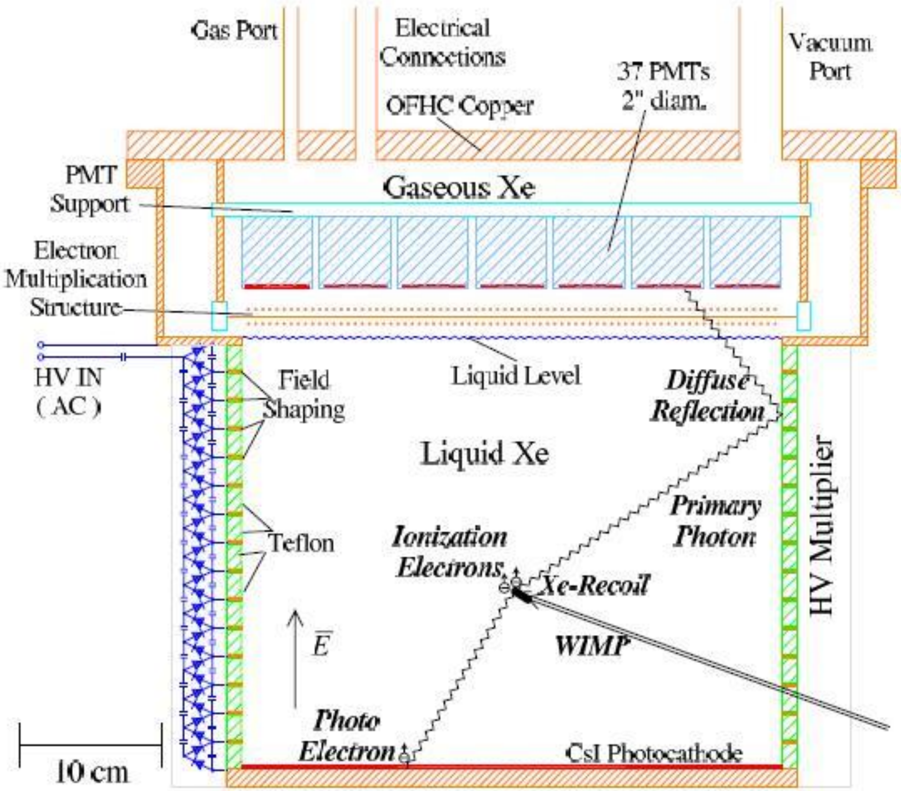
Principle of operation

- WIMP elastic scattering with Xe nucleus → nuclear recoil
- Scintillation light in Xenon → Prompt signal S_1 measured in photomultipliers (in top and bottom arrays)
- Ionization charge in Xenon → drift of electrons to anode (top), extraction of electrons into gas phase (Dual phase TPC) via E_{ext}
- Excitation of gas molecules, scintillation light, below threshold for ionization

  → Signal S_2
- Time difference → drift time → coordinate in z (depth inside the liquid argon volume)

  x,y coordinated from S_2 photomultipliers





- 5 kV/cm drift field to detect small charge from nuclear
- Electron extraction into gas phase to detect charge via proportional scintillation (~1000 UV γ/e/cm) demonstrated
- Internal CsI photocathode with QE~31% to enhance direct light signal and thus lower threshold
- PMTs readout inside the TPC for direct and secondary light
  $\rightarrow$ need PMTs with low activity
  from U / Th / K

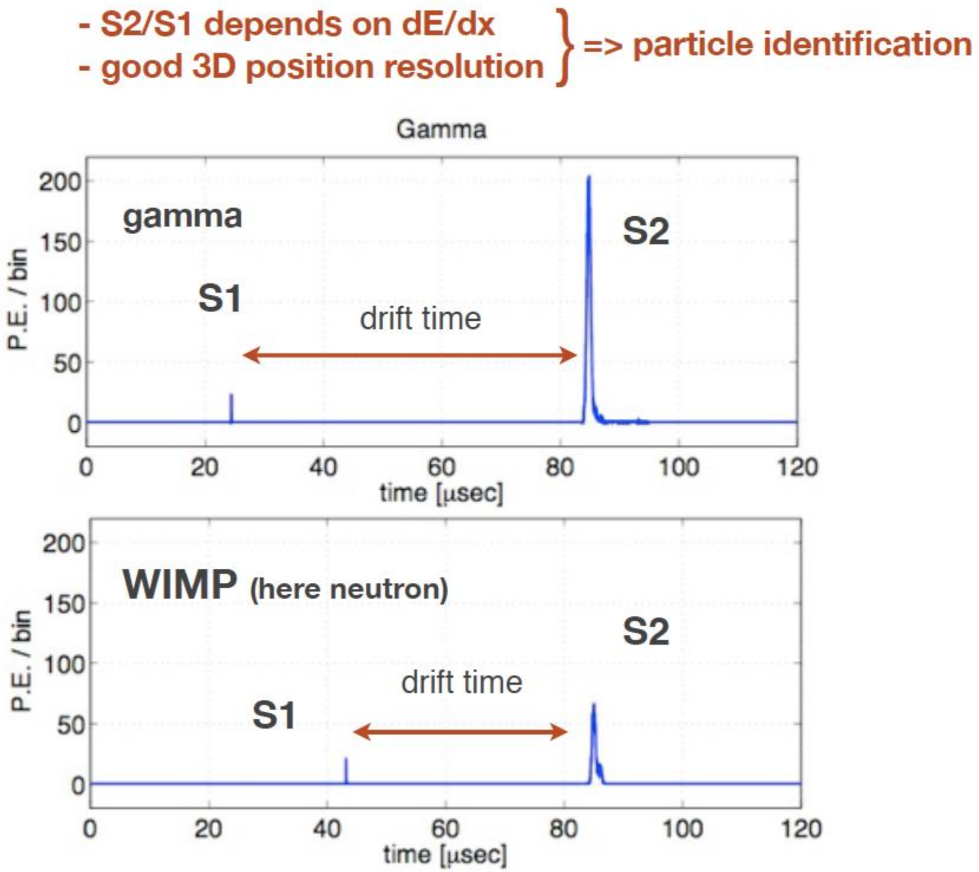
Principle of operation

Discrimination of nuclear recoils from photon processes

via the ratio of S_1 / S_2

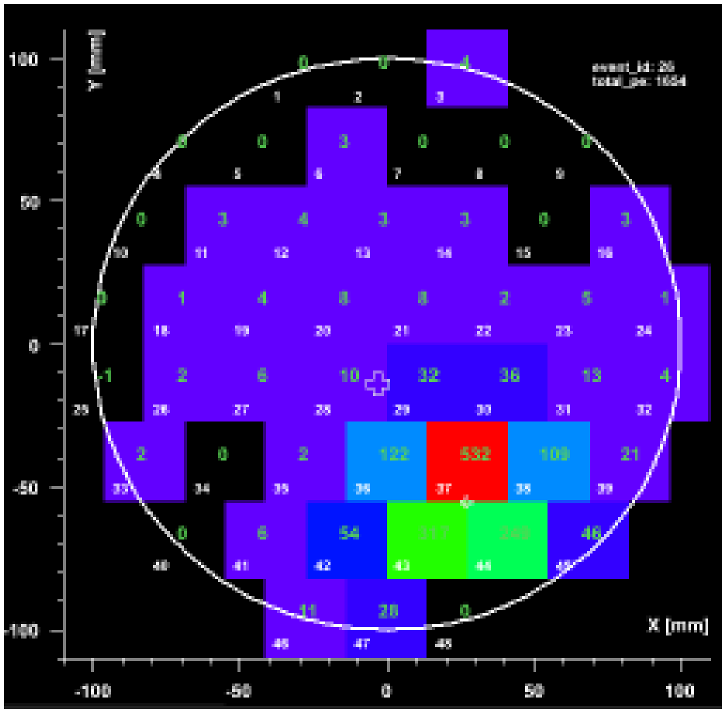
Nuclear recoils (low energy)
→ small ionization signal, but
larger scintillation signal

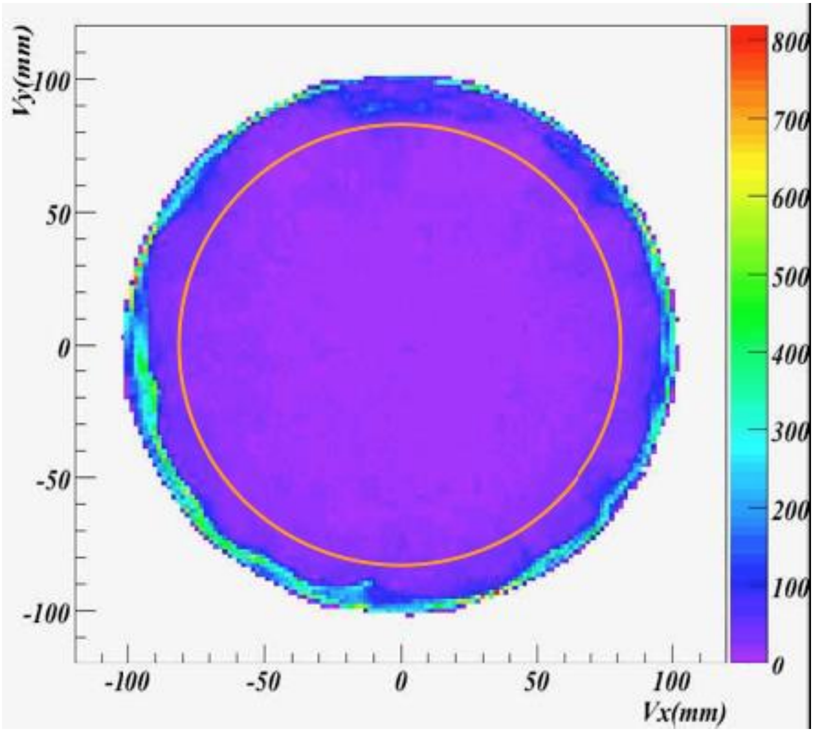
γ absorption is followed by:
- large ionization (via electrons)
  and a smaller scintillation signal



Pattern in Photomultipliers

Hit pattern of top PMTs





→ r-ϕ coordinates
z coordinate from drift time

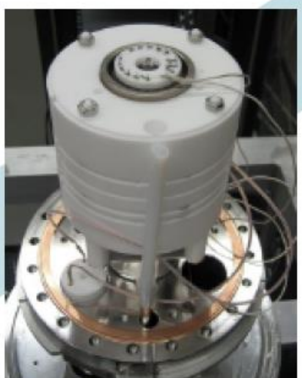
→ r-ϕ distribution of reconstructed events
→ definition of “fiducial volume”
→ background rejection

Major Backgrounds:

- β and γ radioactivity of krypton and radon contamination, Purity required p << 1 ppb
- β decay of ^{136}Xe
- Neutron background
- Residual cosmic rays (muons)
- Radioactivity from surrounding rocks
- Radioactivity from surrounding detector materials

The XENON Program

XENON R&D



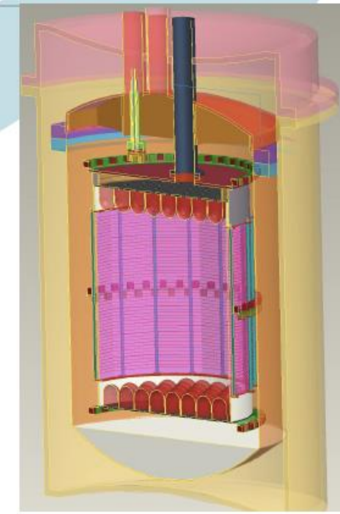
XENON10

2005-2007

XENON100

2008-2010
taking science data

XENON1t

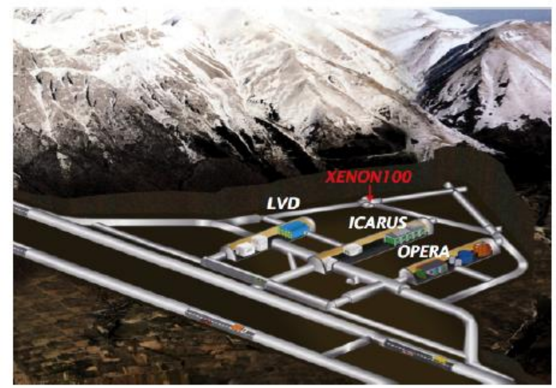


> 2017

studies in progress
technical proposal
submitted to LNGS
end of April, 2010

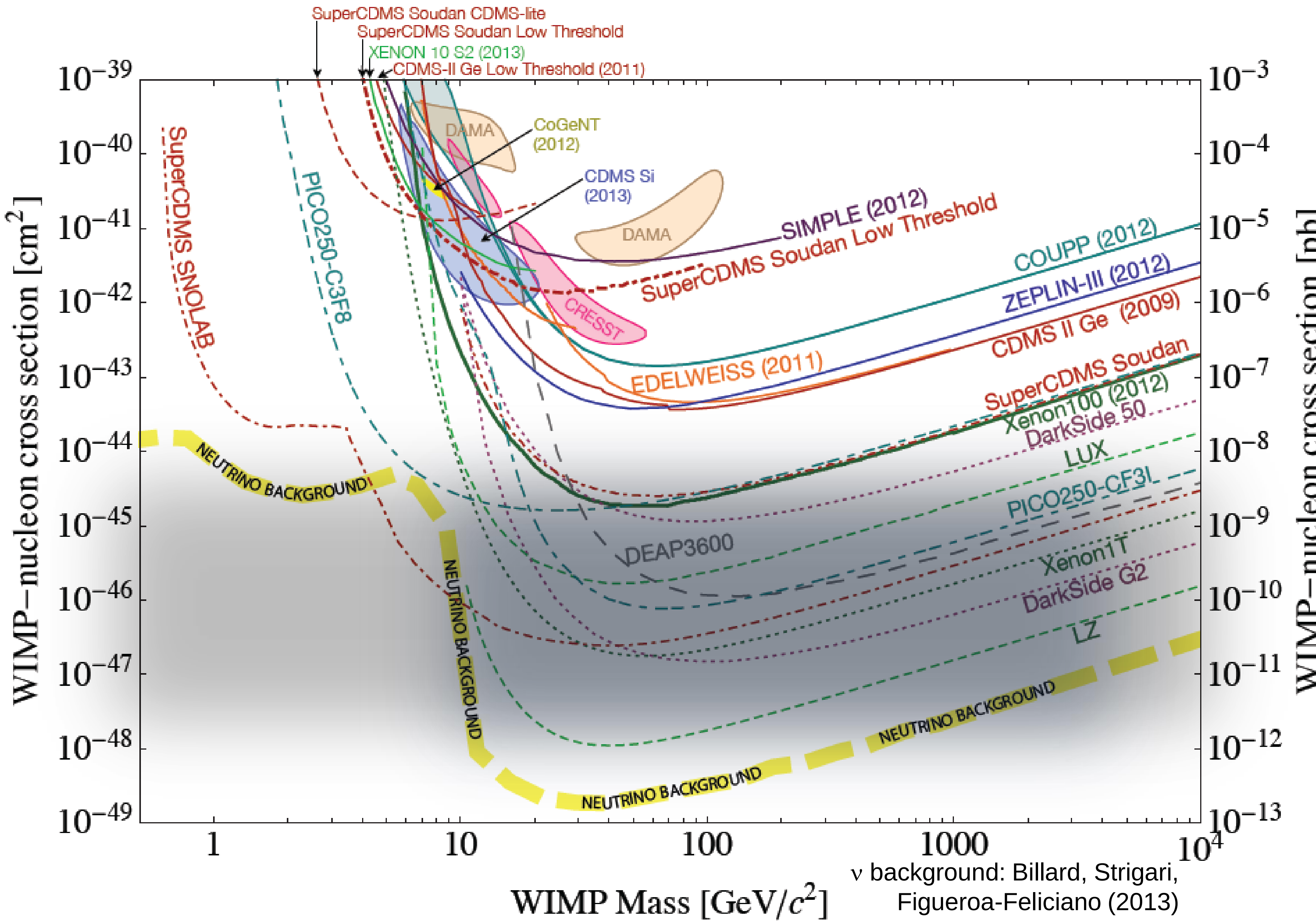
The XENON100 Experiment at LNGS

- 161 kg ultra-pure LXe: 62 kg in the active target surrounded by 99 kg LXe as scintillator veto
- 30 cm drift gap TPC with two PMT arrays to detect both charge and light signals
- 242 1-inch square PMTs with < 1 mBq/PMT in $^{238}U/^{232}Th$ and high QE (25-33%) at 178 nm
- 3D event localization with few mm x-y-z resolution



The XENON100 detector in its low-background shield at LNGS

Current Status and Future Prospects



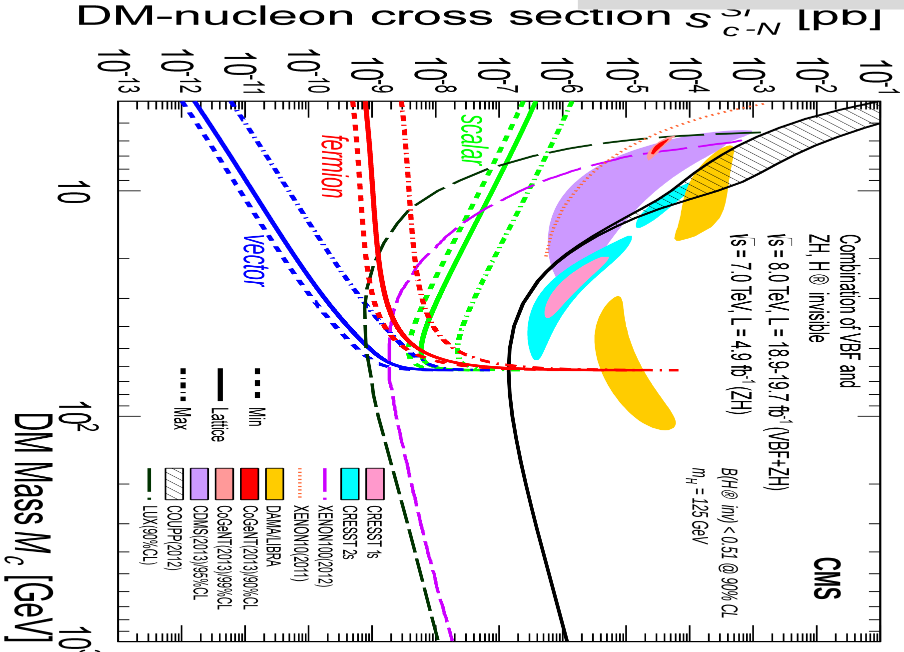
ν background: Billard, Strigari, Figueroa-Feliciano (2013)

ATLAS and CMS contributions to DM search via Higgs decays

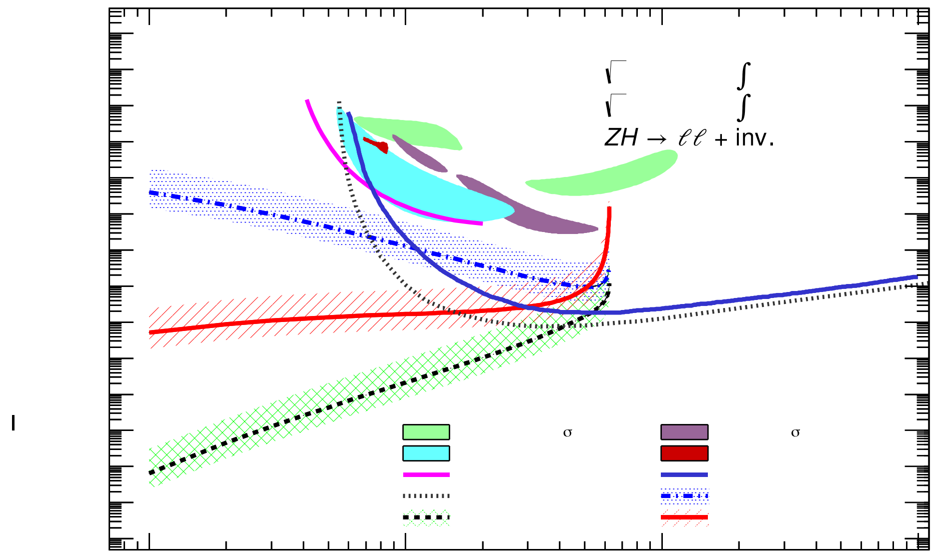
-Stable dark matter particles with couplings to the Higgs boson-

- For $m_\chi < m_H/2$, limits on invisible branching ratios can be translated to the spin-independent DM-nucleon elastic cross section for scalar, vector and fermionic DM particles
- Higgs-nucleon coupling, model dependent: assume $0.33^{+0.30}_{-0.07}$ (lattice calculations)
- Within this model, interesting limits for low m_X masses

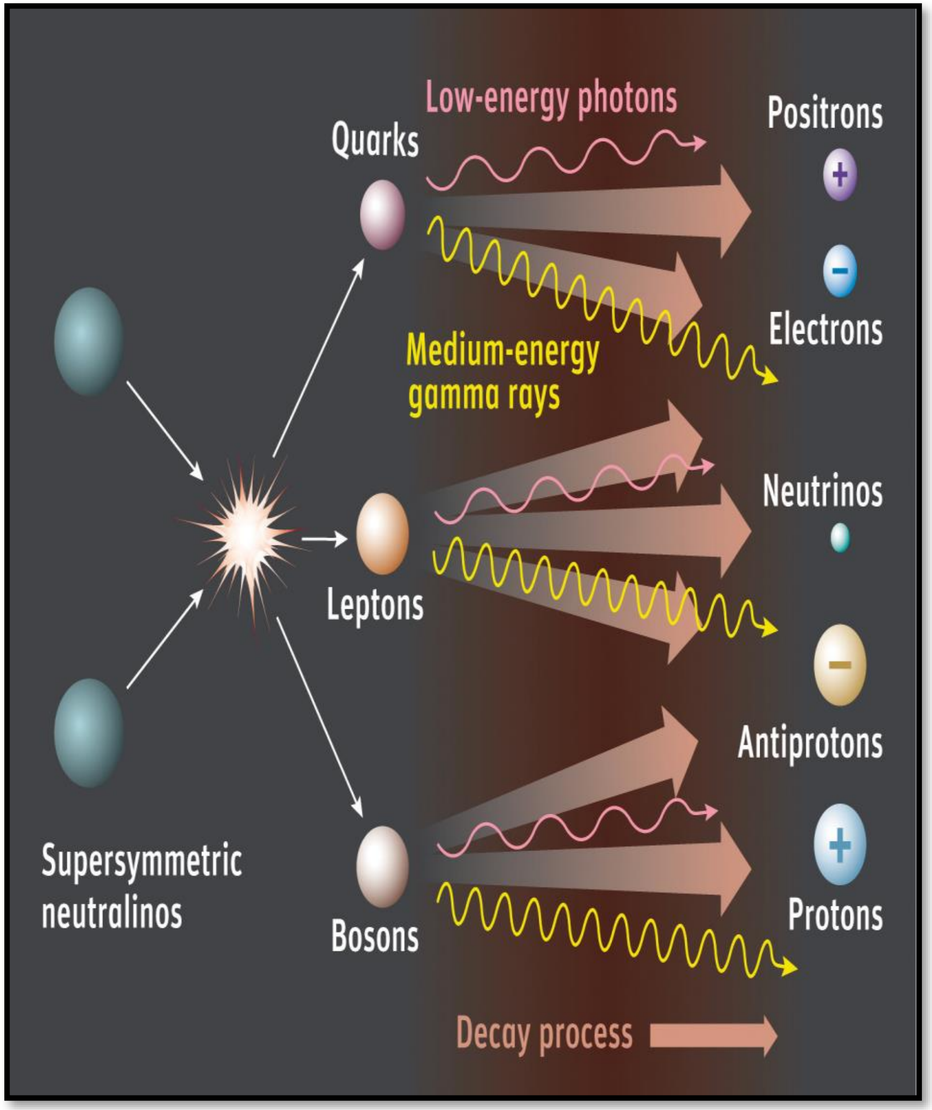
EPJ C74 (2014) 2980



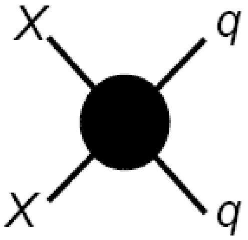
PRL 112 (2014) 201802



10.5 Indirect Dark Matter Detection Experiments

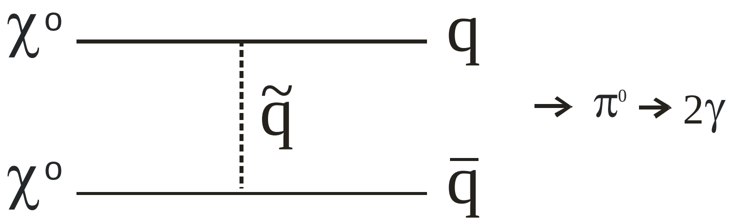


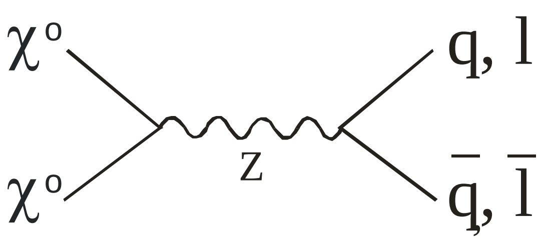
- Dark matter may annihilate in our galactic neighbourhood to
  - Photons
  - Neutrinos
  - Positrons
  - Antiprotons
  - Anti-deuterons

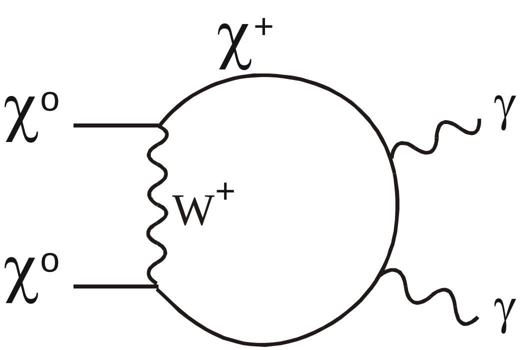


- The relic density provides a target annihilation cross section

- Indirect detection experiments search for the products of WIMP annihilation.
- Two WIMPs colliding could annihilate to produce γ rays or particle-antiparticle pairs. This could produce a significant number of γ rays, antiprotons or positrons in the galactic halo.

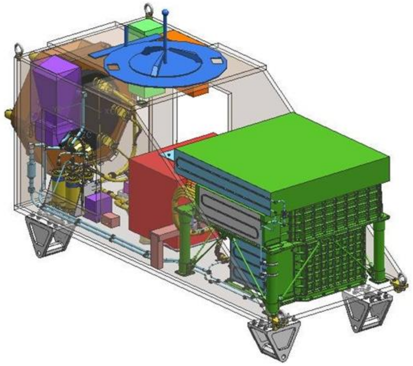




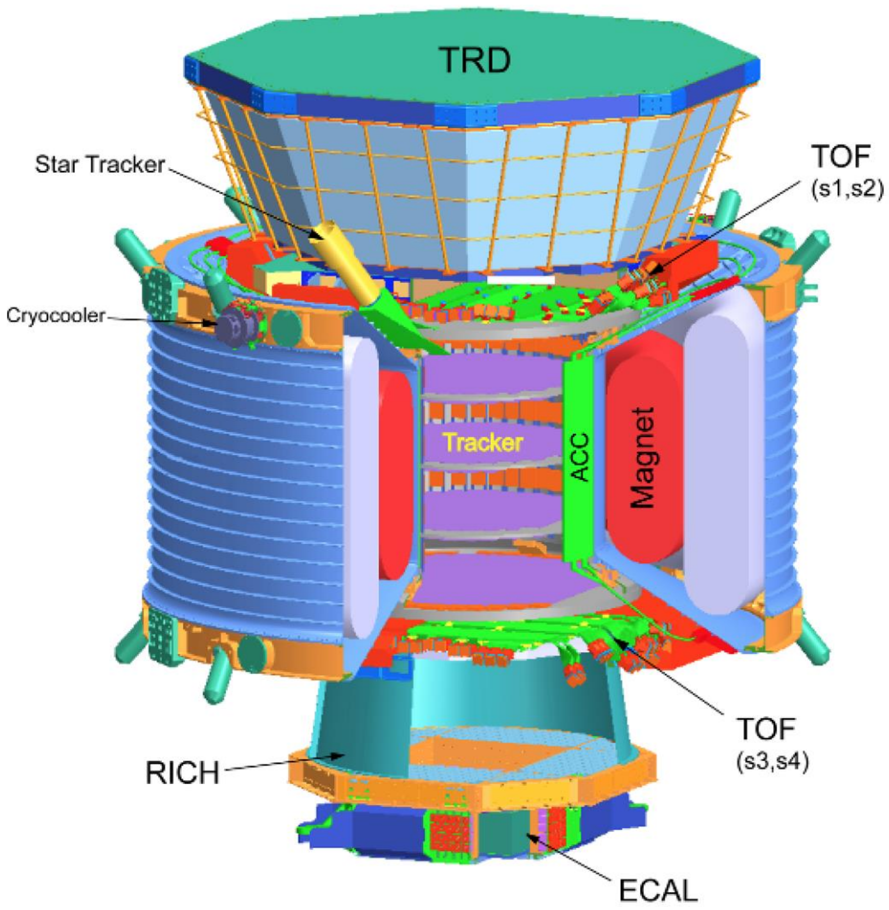


Indirect Detection: Antimatter

- Positrons (PAMELA, Fermi-LAT, AMS, CALET)
- Anti-Protons (PAMELA, AMS)
- Anti-Deuterons (GAPS, AMS)



AMS Experiment on the Space Station



AMS = Alpha Magnetic Spectrometer

Physics goals:

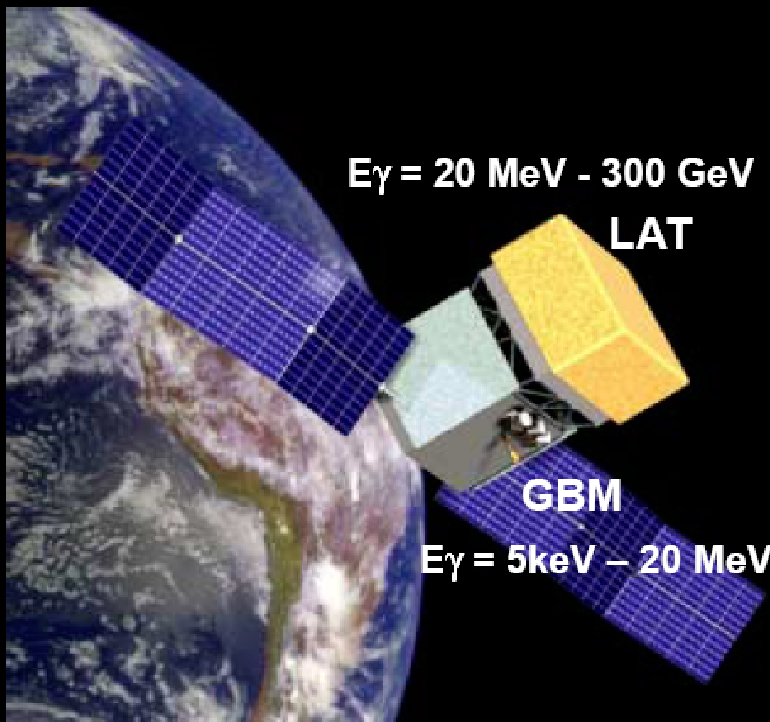
- Study the composition and the energy spectrum of the primary cosmic rays
- Search for Dark Matter annihilation

State-of-the-art particle physics detector in space

- Permanent Magnet B = 0.14 T
- High-precision double-sided silicon tracking detector
- Four dedicated Particle-ID detectors:
  * TRD for electron ID (Straw tubes filled with Xe /CO_2)
  * RICH with aerogel radiator (n=1.03)
  * ToF: four planes of plastic scintillators
  * Sampling el.magn. calorimeter (Lead + scintillating fibres)

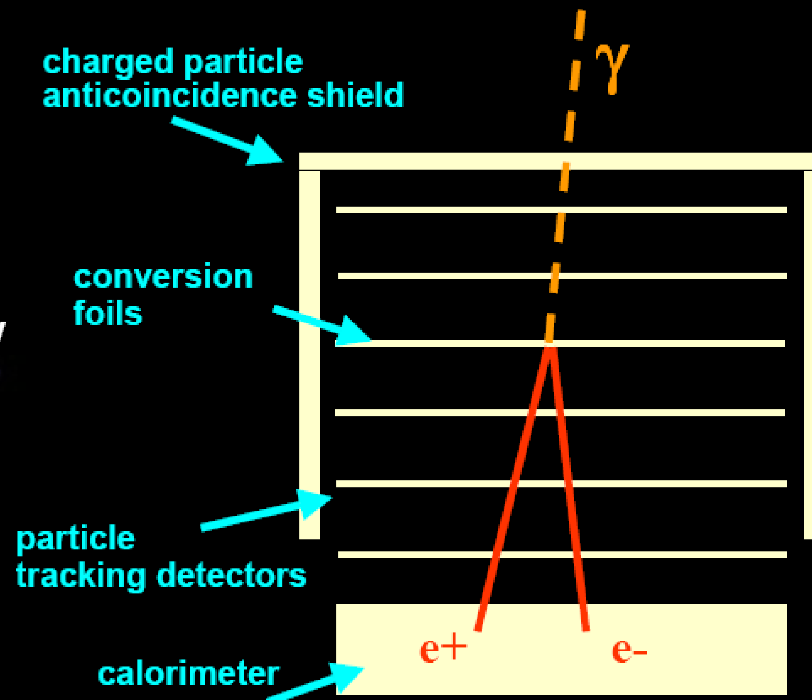
GLAST / FERMI-LAT

Gamma Ray Large Area Space Telescope



Approved by NASA early 2000
to be launched in March 2006

The Large Area Telescope (LAT) uses a pair-conversion technique to detect photons



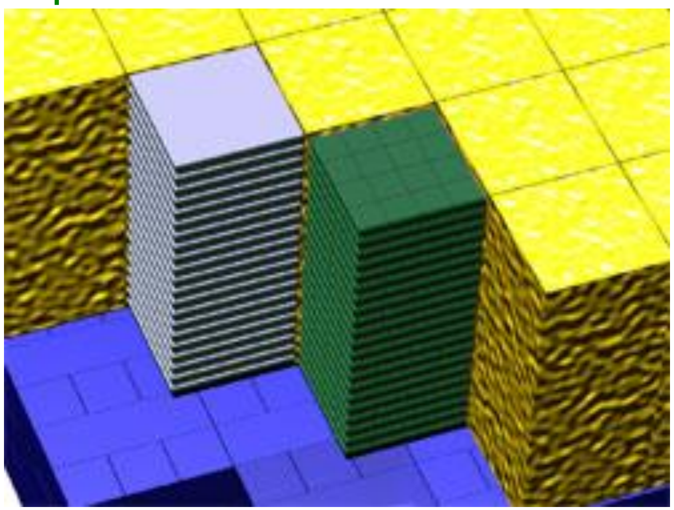
LAT has 16 modules and

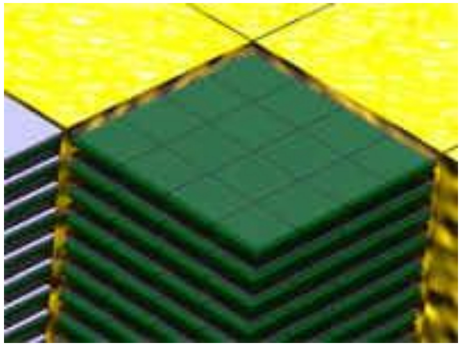
2560 kg, 600 W, $1.73^2 \times 1.06$ m^3

GLAST Detektorkomponenten:

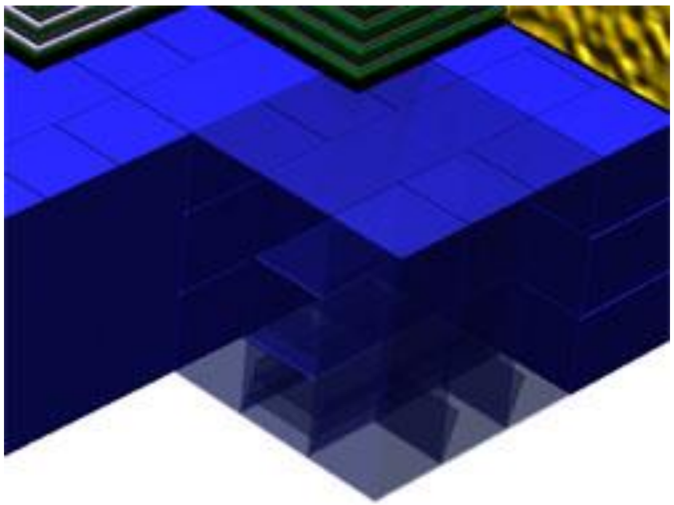
- Präzisionsspurdetektor (Silizium-Streifenzähler)
- CsI Kristallkalorimeter
- Antikoinzidenzzähler (Szintillatoren)
- Trigger- u. Datennahmesystem

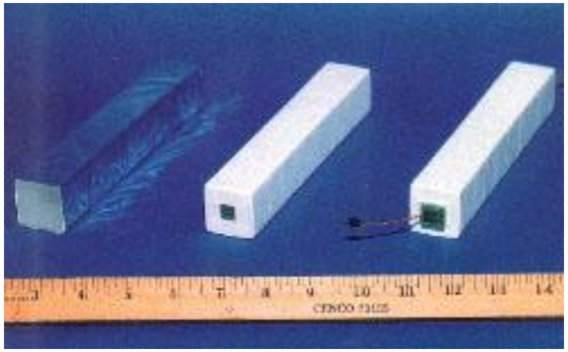
Spurdetektor:





Kalorimeter:





Overview of LAT

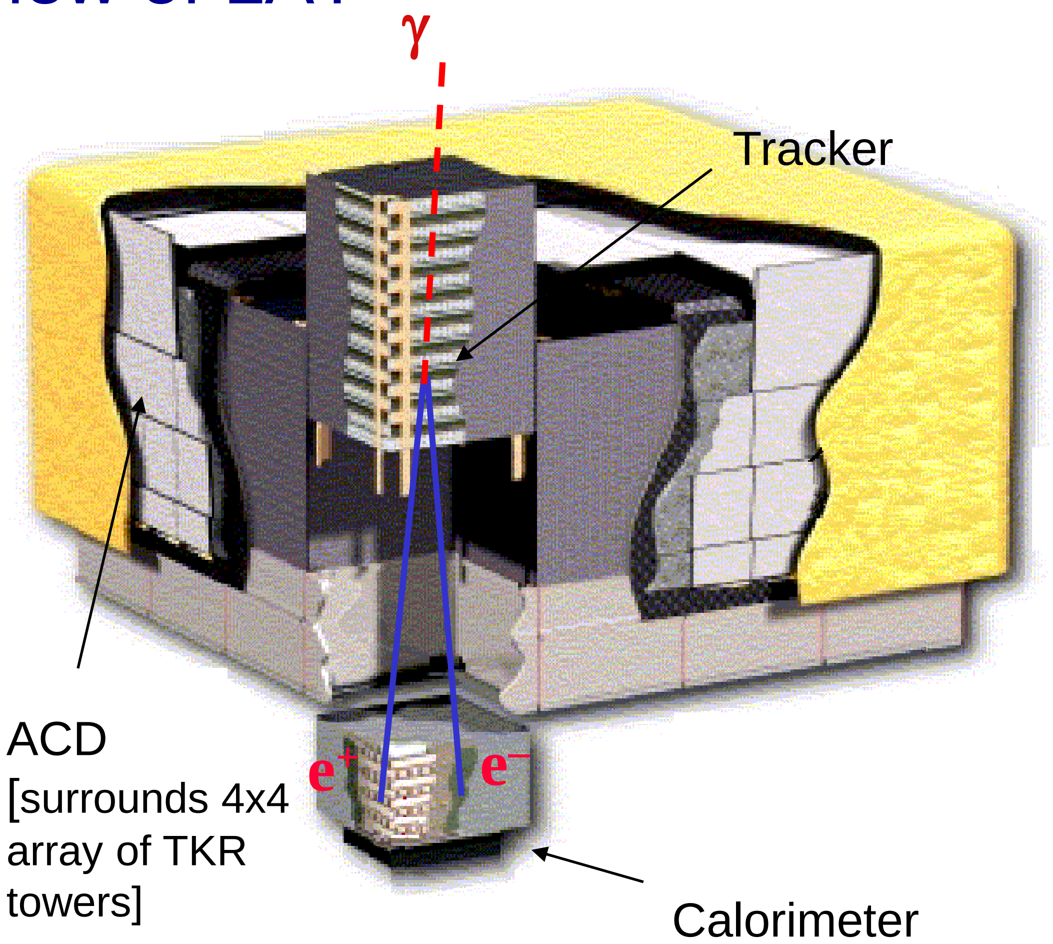
- **<u>Precision Si-strip Tracker (TKR)</u>** **18 XY tracking planes. Single-sided silicon strip detectors (228 μm pitch) Measure the photon direction; gamma ID.**

- **<u>CsI Calorimeter(CAL)</u>**

  Array of 1536 CsI(Tl) crystals in 8 layers. Measure the photon energy; image the shower.

- **<u>Segmented Anticoincidence Detector (ACD)</u> 89 plastic scintillator tiles. Reject background of charged cosmic rays; segmentation removes self-veto effects at high energy.**

- **<u>Electronics System</u> Includes flexible, robust hardware trigger and software filters.**



Systems work together to identify and measure the flux of cosmic gamma rays with energy 20 MeV - >300 GeV.