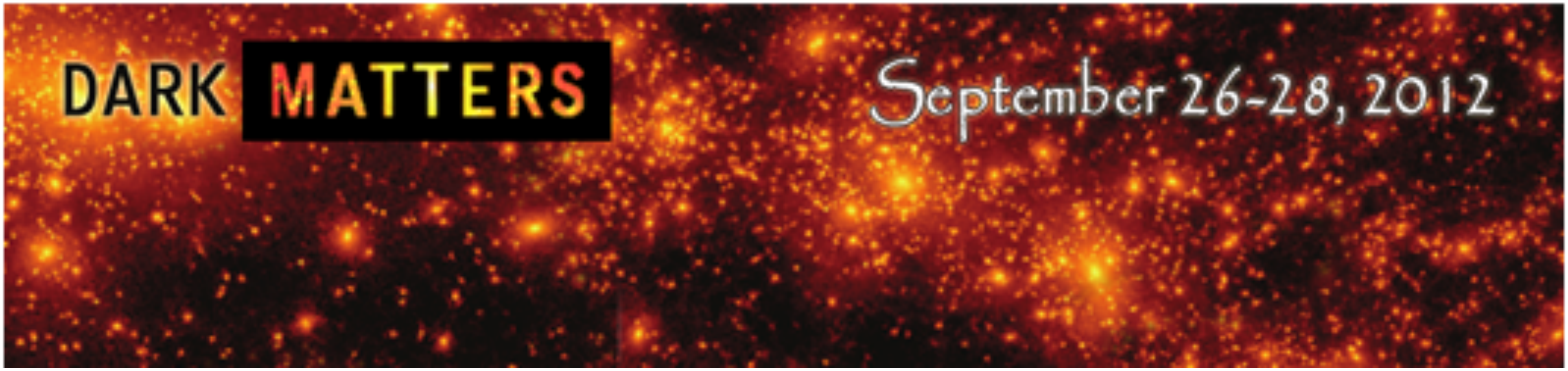


Detectors Fundamentals

(for Dark Matter)

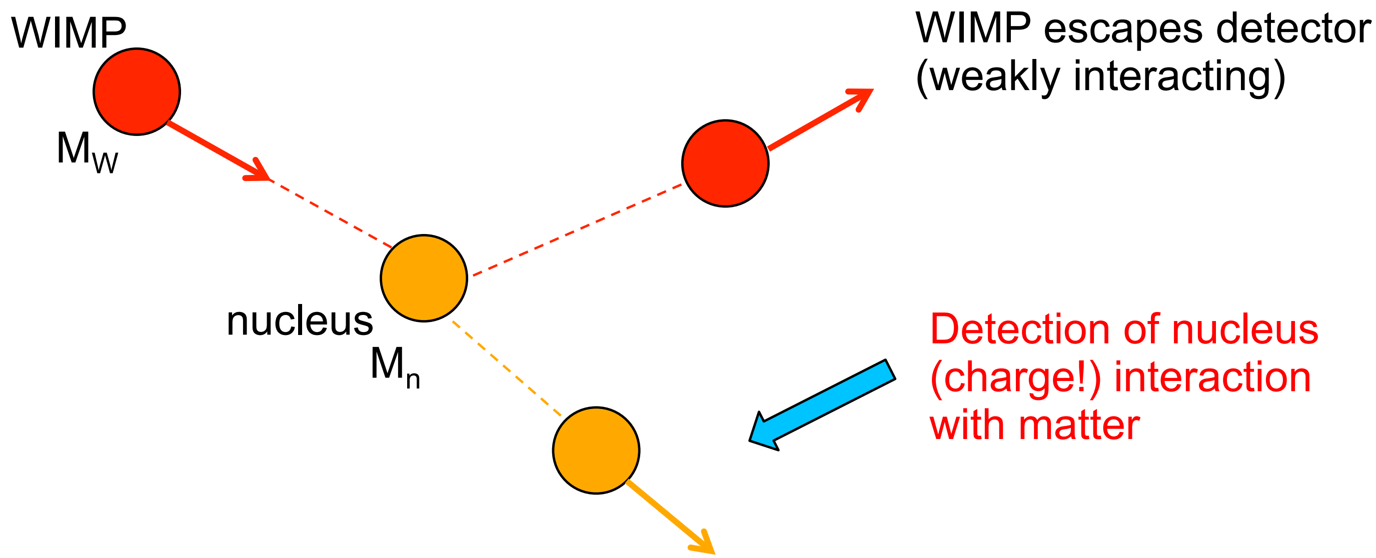
Paolo Privitera

KICP Kavli Institute for Cosmological Physics
at the University of Chicago

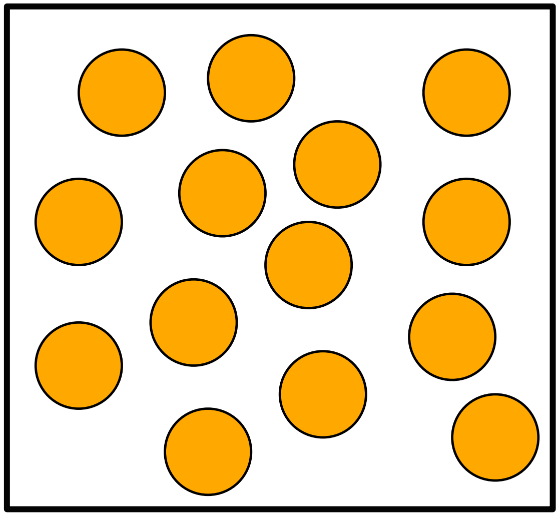
Detection of Dark Matter particles

- Weak Interacting Massive Particles:
  - weakly interacting → extremely low rates
  - electrically neutral → does not ionize directly
  - massive (> GeV)
  - non relativistic – low velocity

- WIMP interaction with matter
  - extremely low rates
  - does not ionize directly
  - low energy elastic scattering with nuclei (WIMP and nucleus do not change their identity)



Interaction of Dark Matter particles



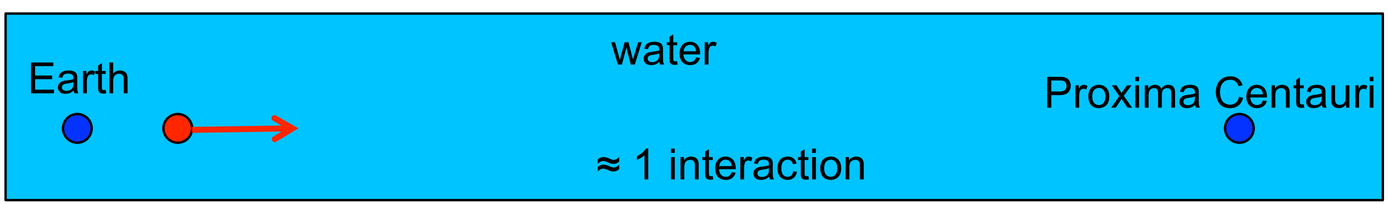
σ = area of target particle disk

A = total area

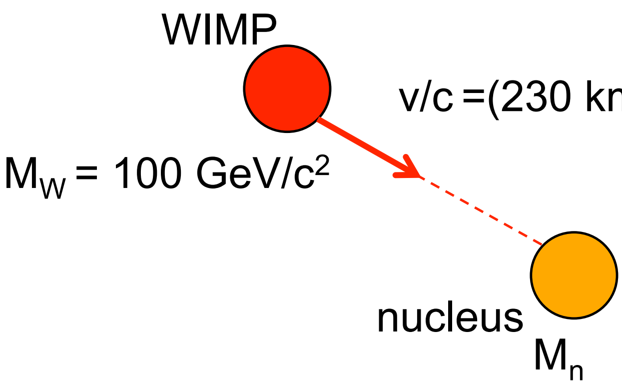
N = n. of target nuclei in A

Cross section, σ

$$\frac{N\sigma}{A} = \text{Probability of interaction}$$



WIMP-nucleus elastic scattering



$v/c = (230 \text{ km/s}) / (300\,000 \text{ km/s}) \approx 10^{-3}$

De Broglie wavelength

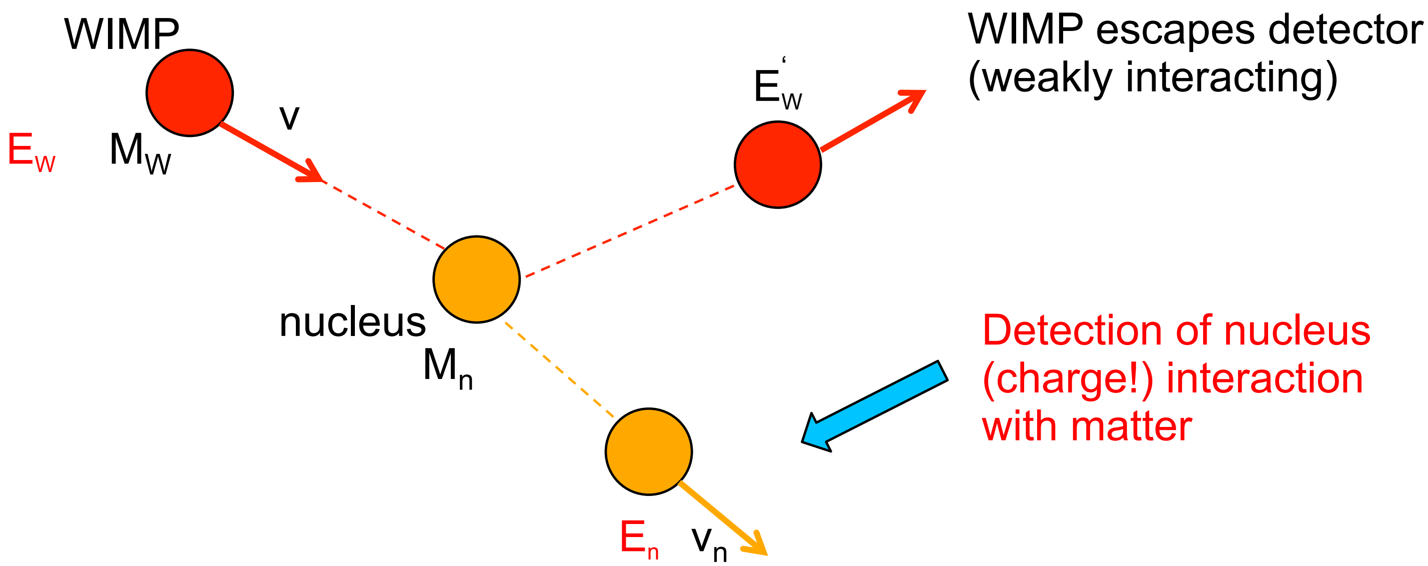
$$\lambda_W = \frac{hc}{pc} = \frac{1240 \text{ nm}}{pc(\text{eV})}$$

$$pc = M_W\, v\, c = M_W\, c^2\, (v/c) = 10^{11} \cdot 10^{-3} = 10^8 \text{ eV}$$

$\lambda_W \approx 10$ F $\approx$ size of the nucleus

The WIMP cannot “see” inside the nucleus, thus elastic scattering

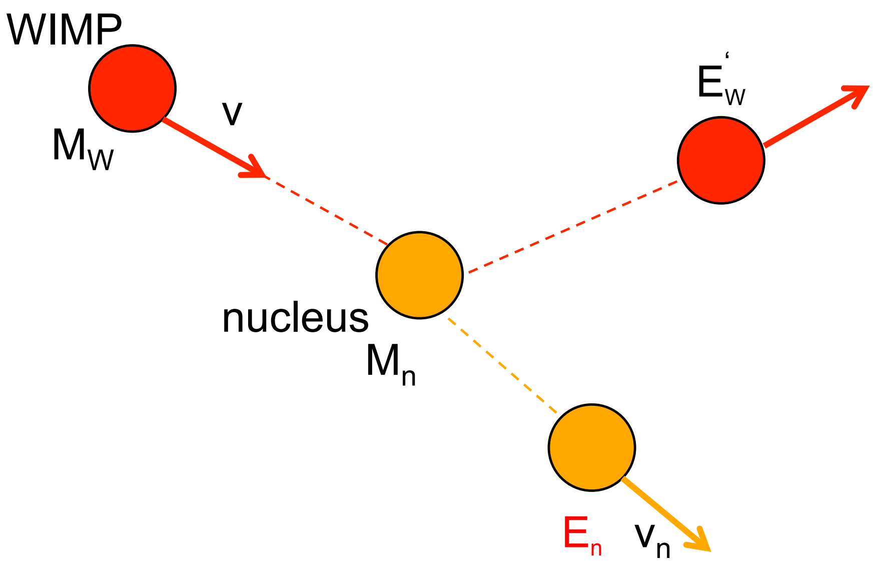
WIMP-nucleus elastic scattering



$$E_W = \frac{1}{2} M_W v^2 = \frac{1}{2} M_W c^2 (v/c)^2 = 50{,}000 \text{ eV}$$

$$E_W = E_W^{'} + E_n \Longrightarrow E_n \approx \text{thousands of eV}$$

WIMP-nucleus elastic scattering

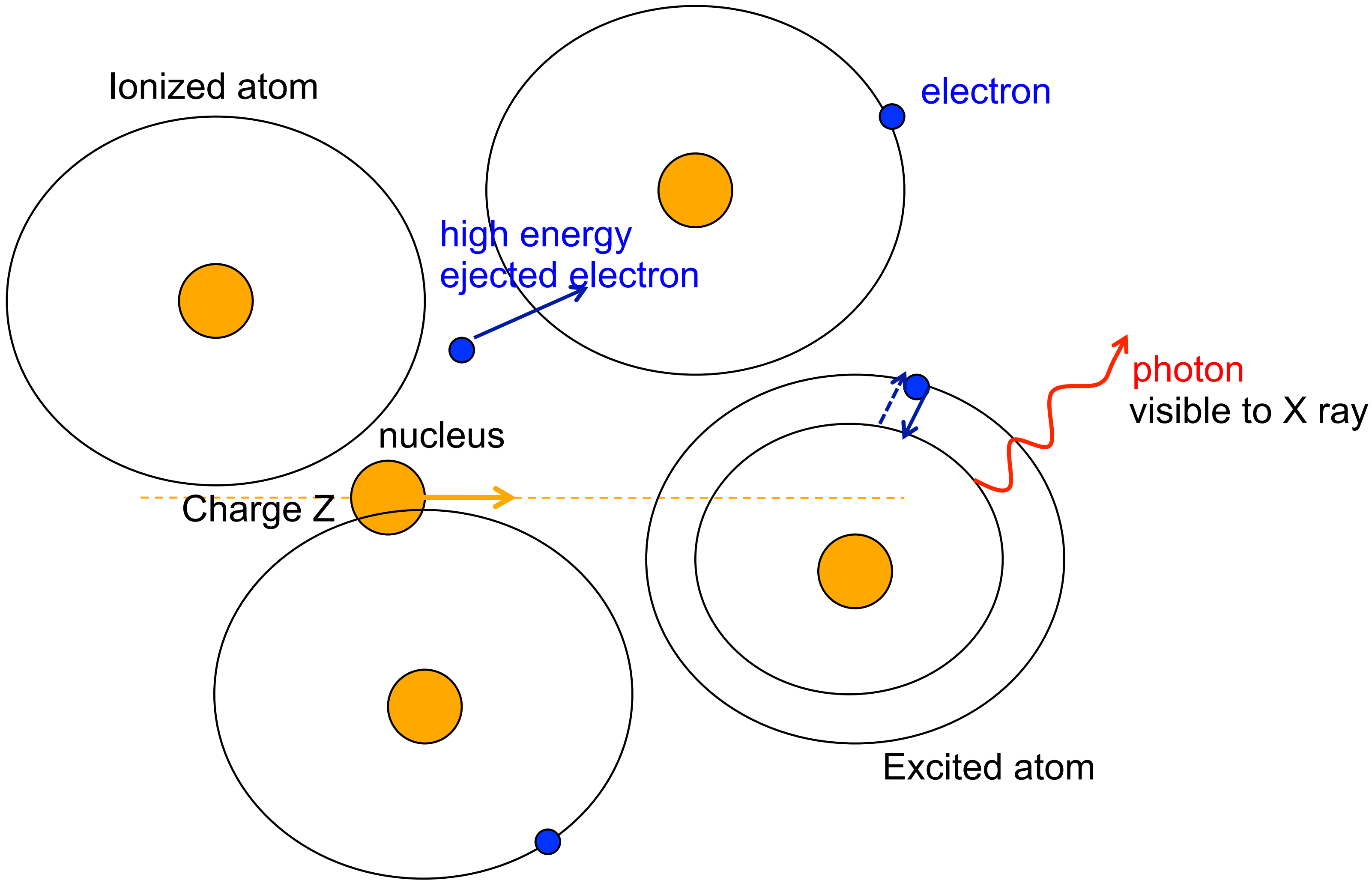


If $M_W \approx M_n$, maximum energy for the recoil nucleus (billiard ball on a billiard ball)

If $M_W < M_n$, low energy for the recoil nucleus (table tennis ball on a billiard ball)

Important to detect the lowest possible recoil energy

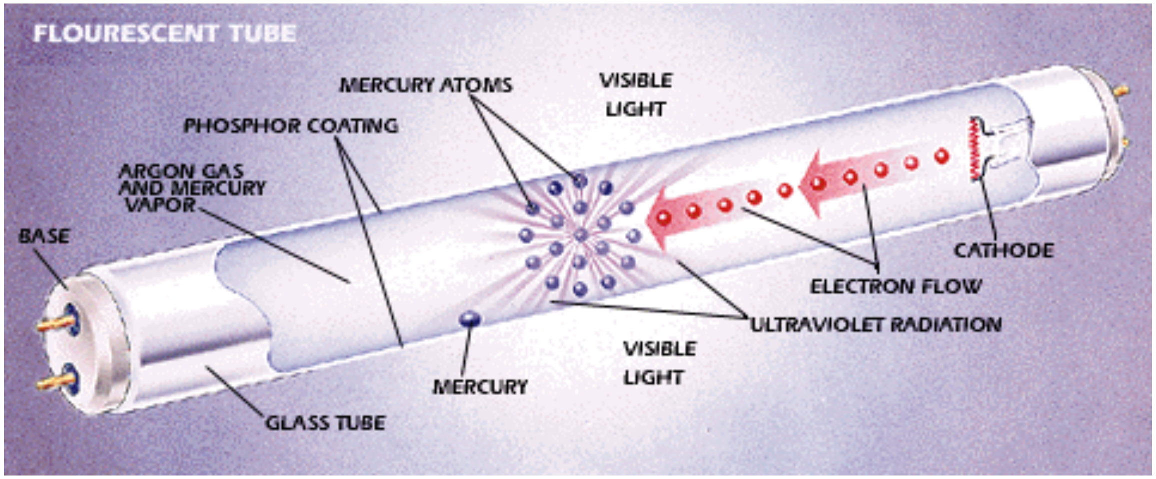
Nucleus interaction in matter



The nucleus electromagnetic interactions produce electrons and photons which can be detected

Ionization and scintillation

Fluorescent lamp 110 V



Typically tens of eV to ionize an atom, hydrogen atom 13.6 eV

Argon: ≈ 30 eV / ion-electron pair   ,   ≈ 30 eV / scintillation photon

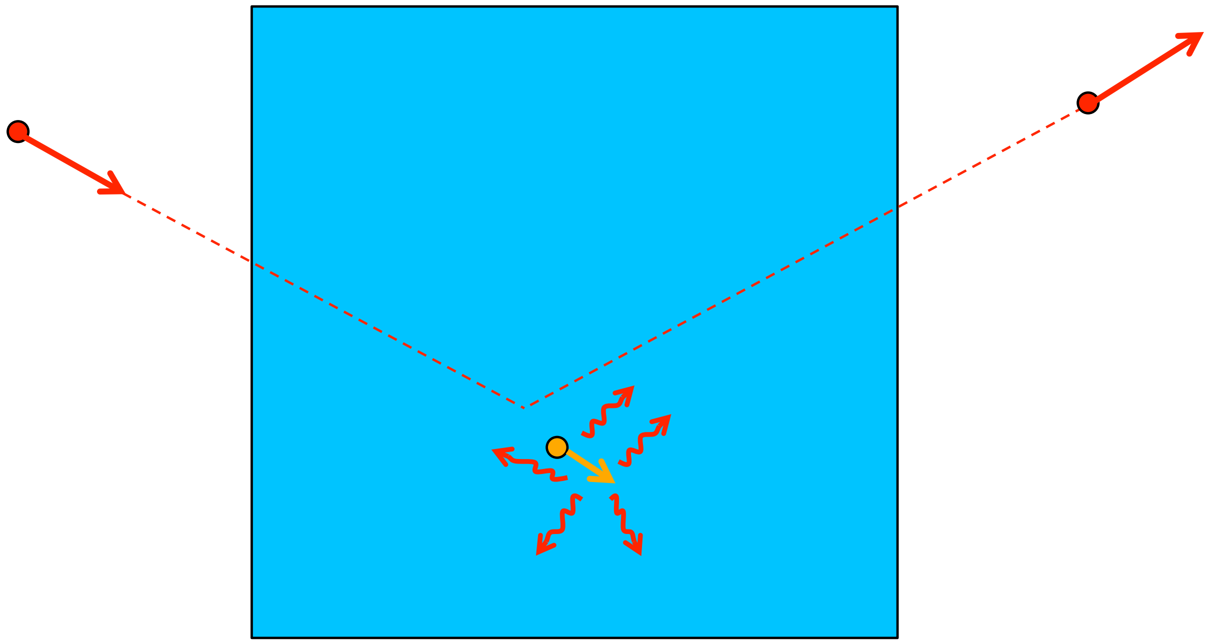
A WIMP will produce:

E_n / E_{ion} ≈ 3 keV / 30 eV = 100 ionizations or photons

A very small charge or n. of photons to detect!

Concept of a Dark Matter detector

Photon detection



1) Choose a dense material with high scintillation yield

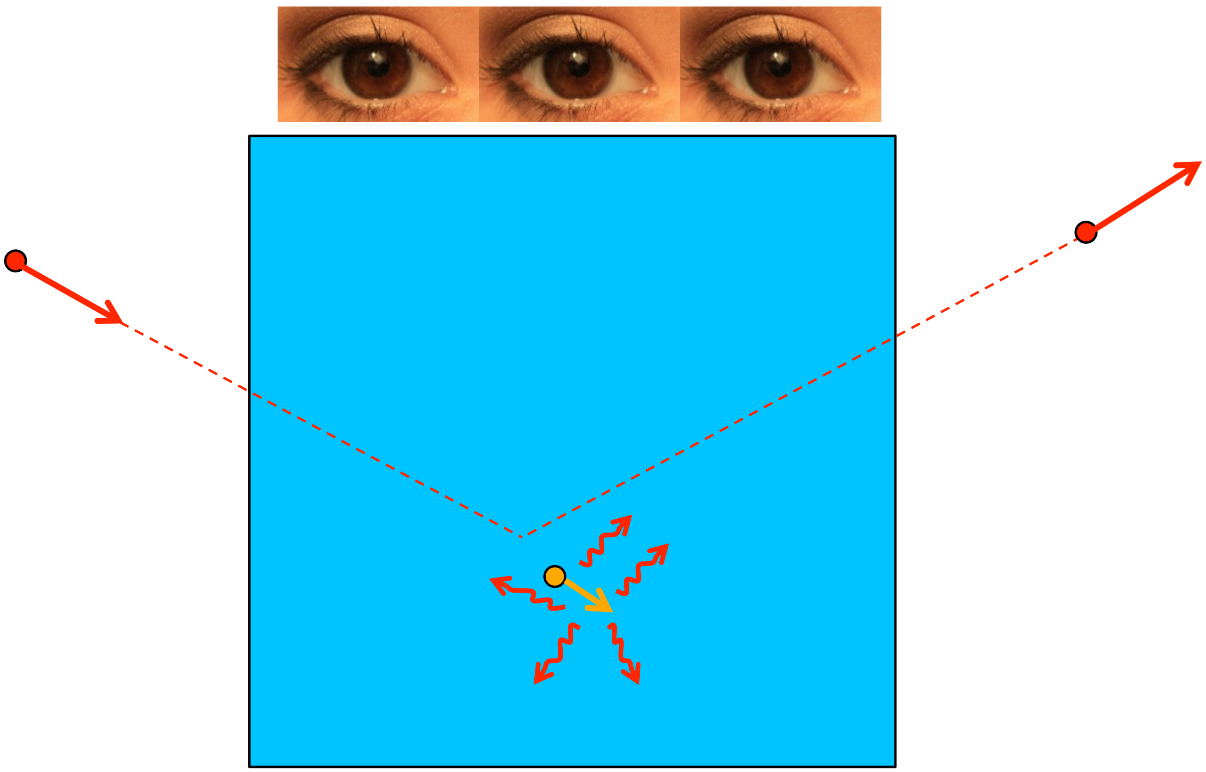
Scintillator	NaI(Tl)	Liquid Argon	Liquid Xenon
Photon Yield [ph/MeV]	4.3×10^4	4.0×10^4	4.2×10^4

Scintillator crystals

Noble liquids

Concept of a Dark Matter detector

Photon detection



Human eye: sensitive to 100 photons in 100 ms

Photomultiplier tube (PMT): electronic eye sensitive to a single photon

Photomultiplier tubes

Photon detection

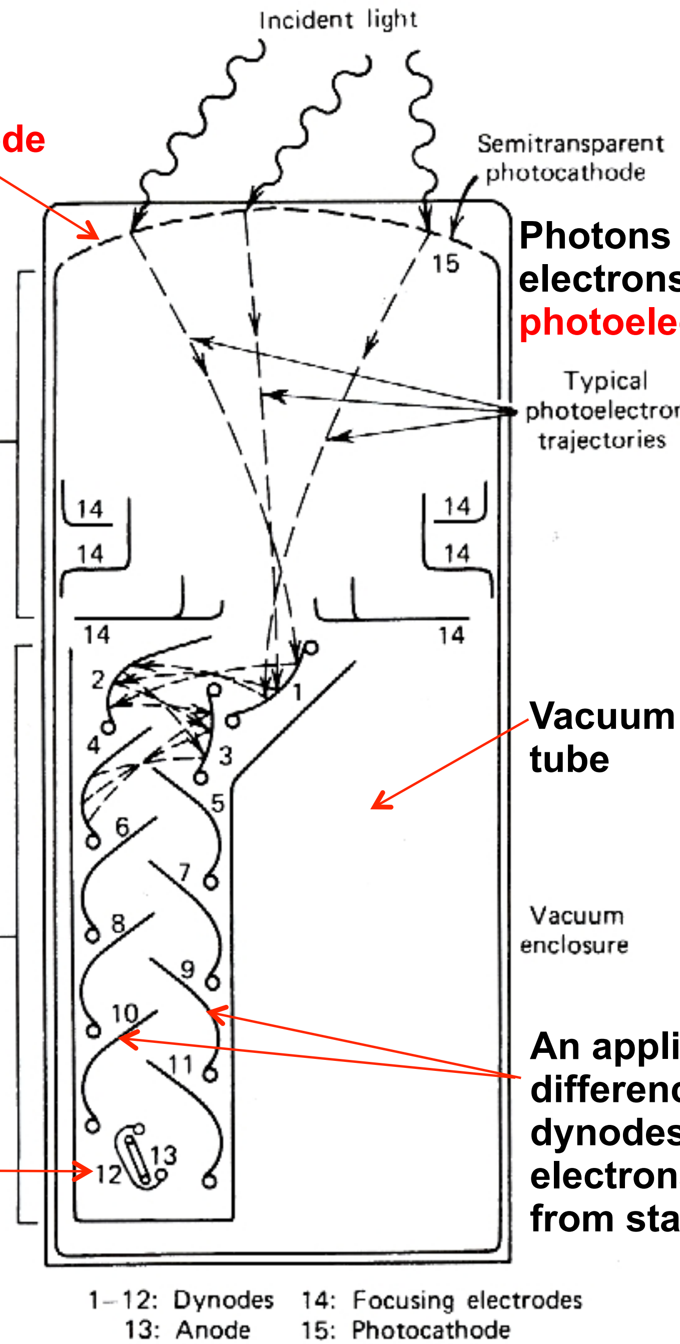
Hamamatsu

PMT

Quantum efficiency

≈ 25% of incident photons produce a photoelectron

Photocathode



Photons eject electrons via photoelectric effect

Vacuum inside tube

≈ 1000 V

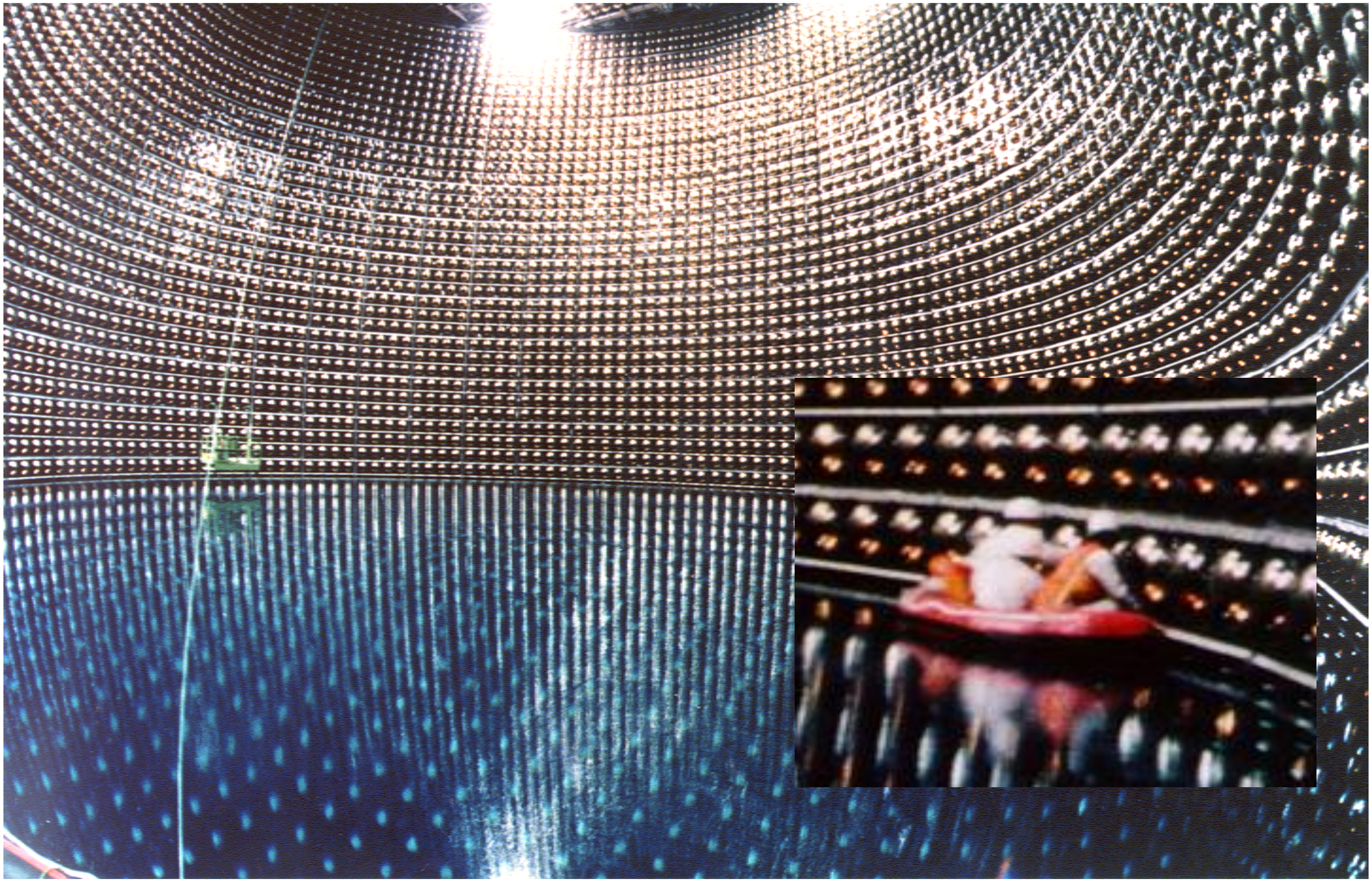
Each incident electron ejects about 4 new electrons at each dynode stage

Gain

"Multiplied" signal comes out here (4^{12} = 16 million!) to oscilloscope or electronics

An applied voltage difference between dynodes (≈100 V) makes electrons accelerate from stage to stage

PMT: a ubiquitous detector



42 m

Super-Kamiokande Neutrino physics

PMT: a *sensitive* detector

CERN COURIER

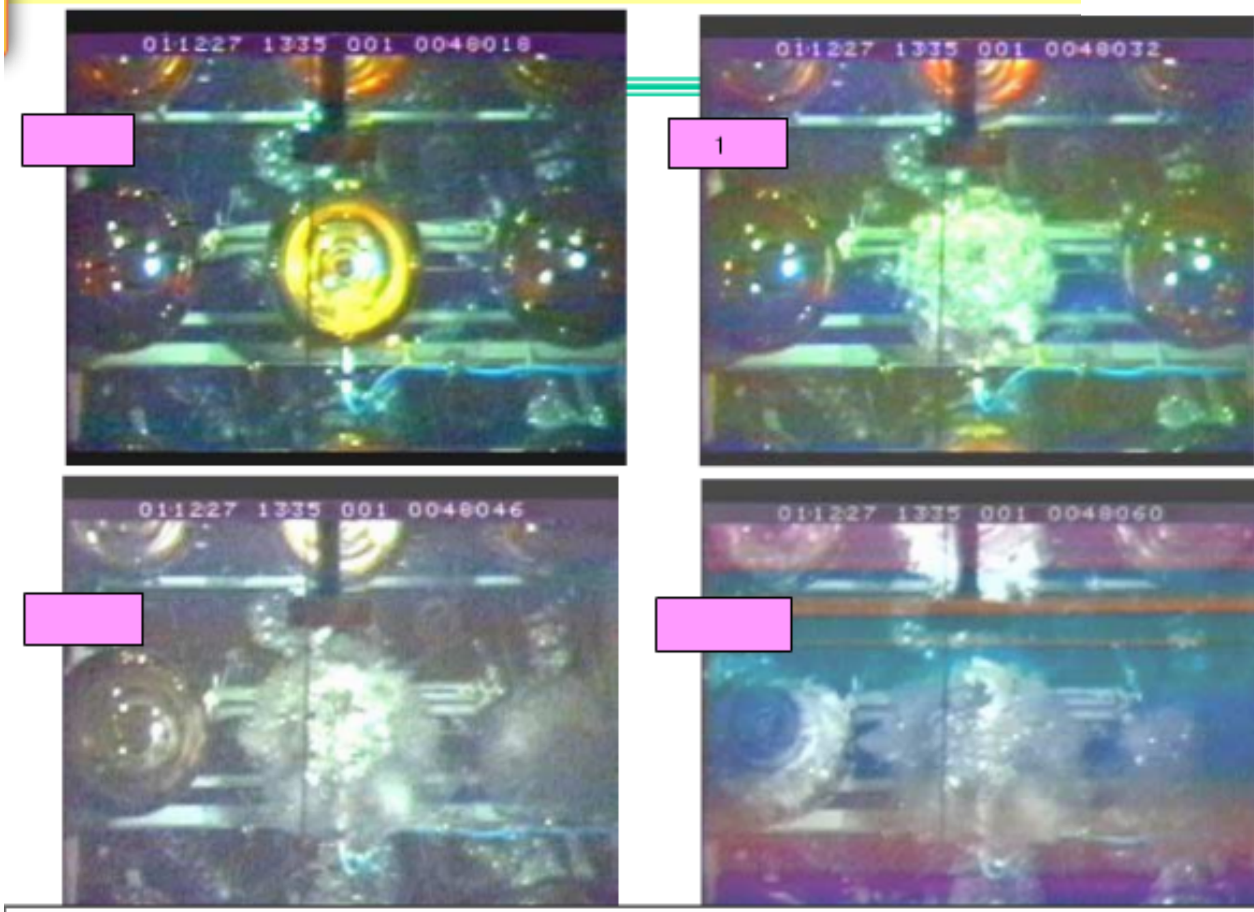
Jan 24, 2002

Accident at major detector in Japan

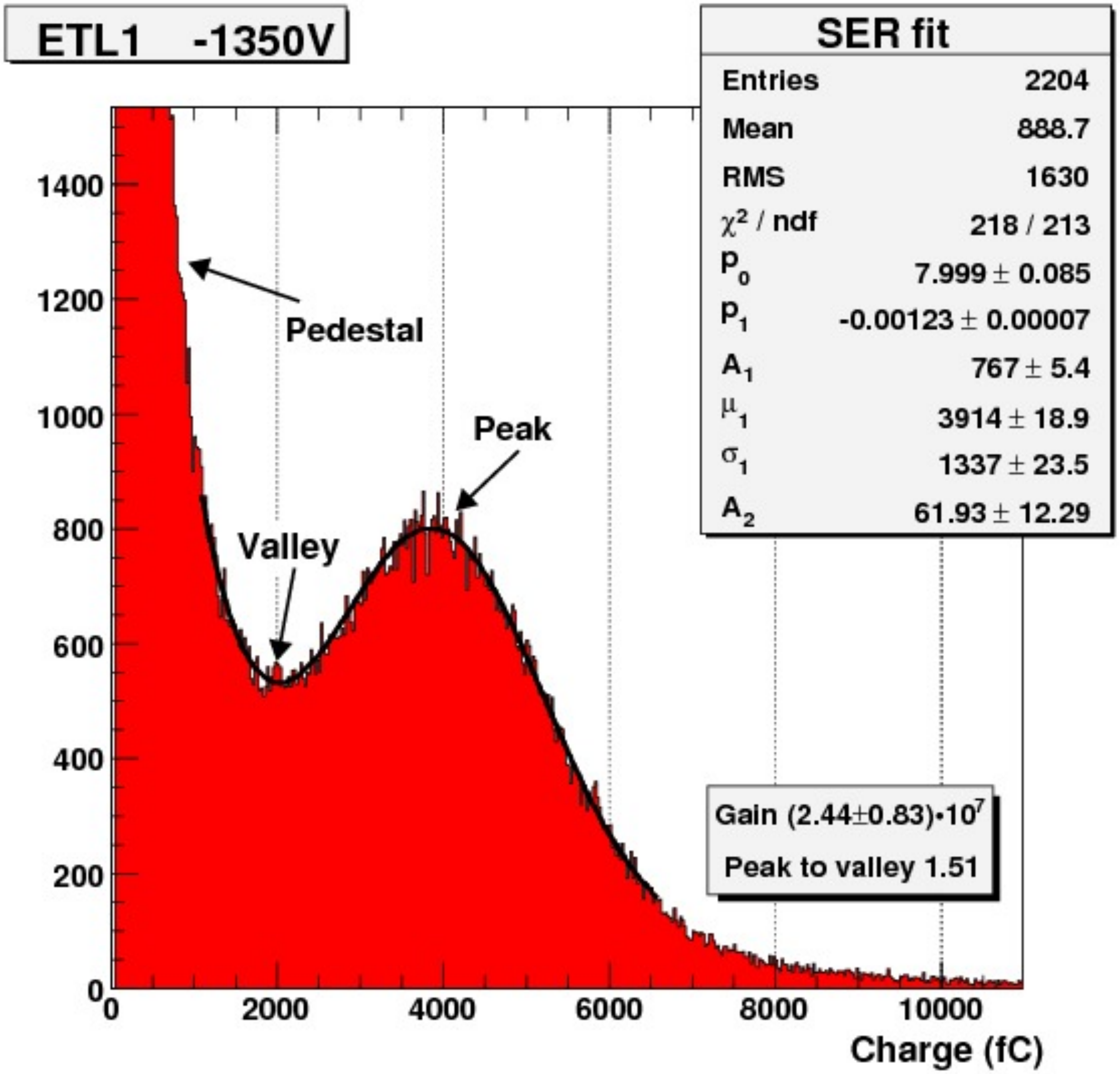
Super-Kamiokande debris

On 12 November, as reported briefly in *CERN Courier* December 2001, several thousand large photomultiplier tubes imploded in the huge Super-Kamiokande underground neutrino detector in Japan. The extent of the damage suggested some kind of chain reaction in the tubes, with one implosion setting off the next. It happened as the detector was being refilled with water after routine maintenance.

A test of a chain reaction with 9 PMT modules, caused by the implosion of

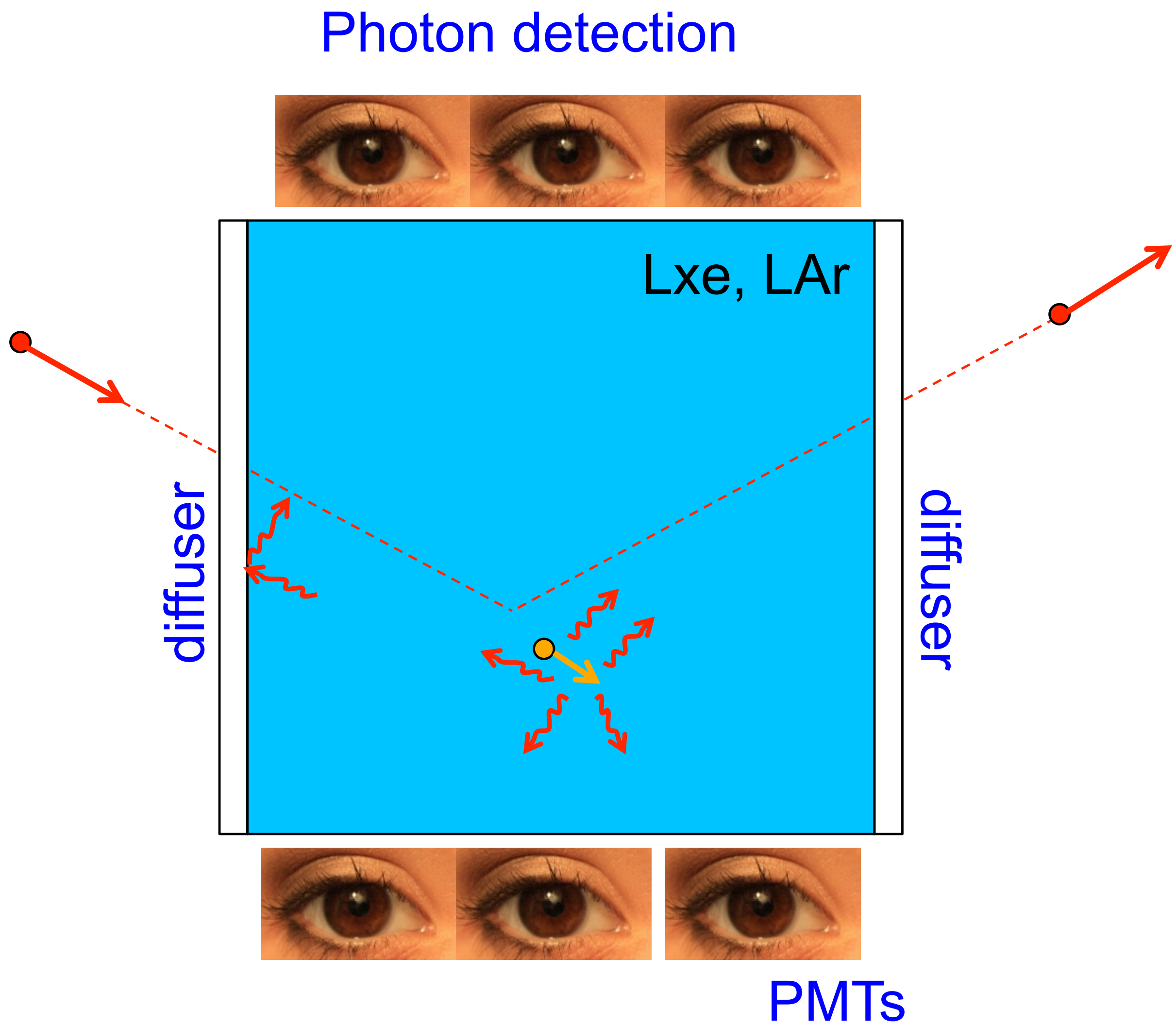


Single Electron Response SER



Pulse charge measurement with ADC

A noble liquid detector

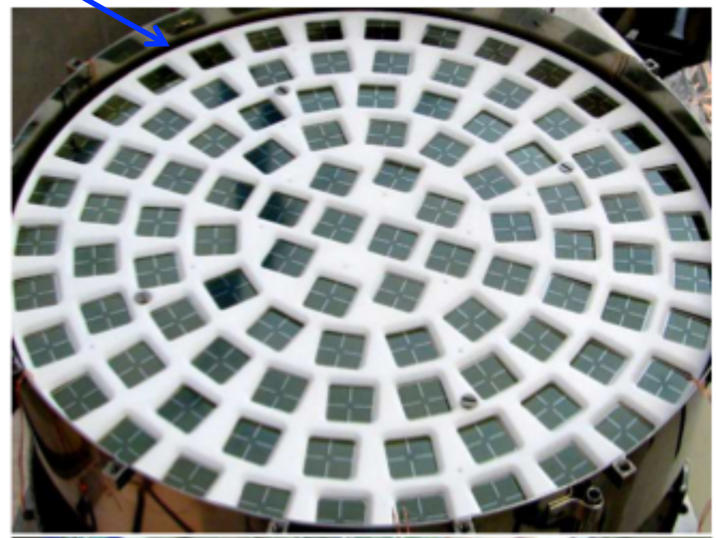


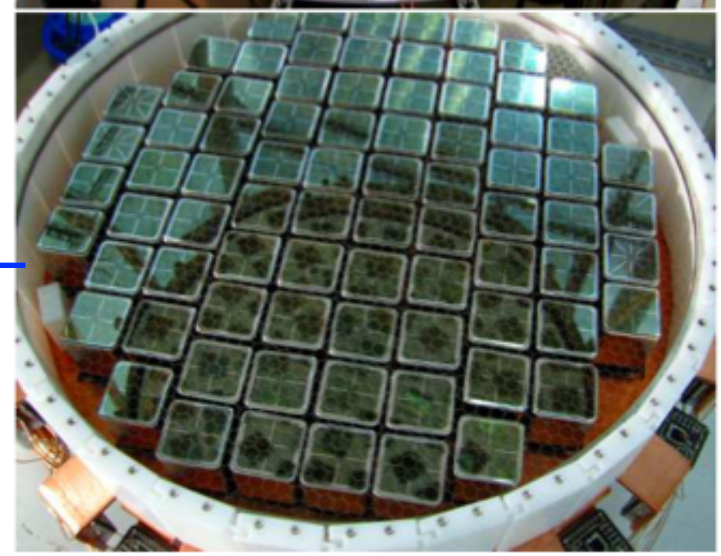
Xenon-100

60 kg of Liquid Xenon as a target for WIMP
Cryogenic temperatures

Gran Sasso Laboratory
Dual-phase detector (see later)

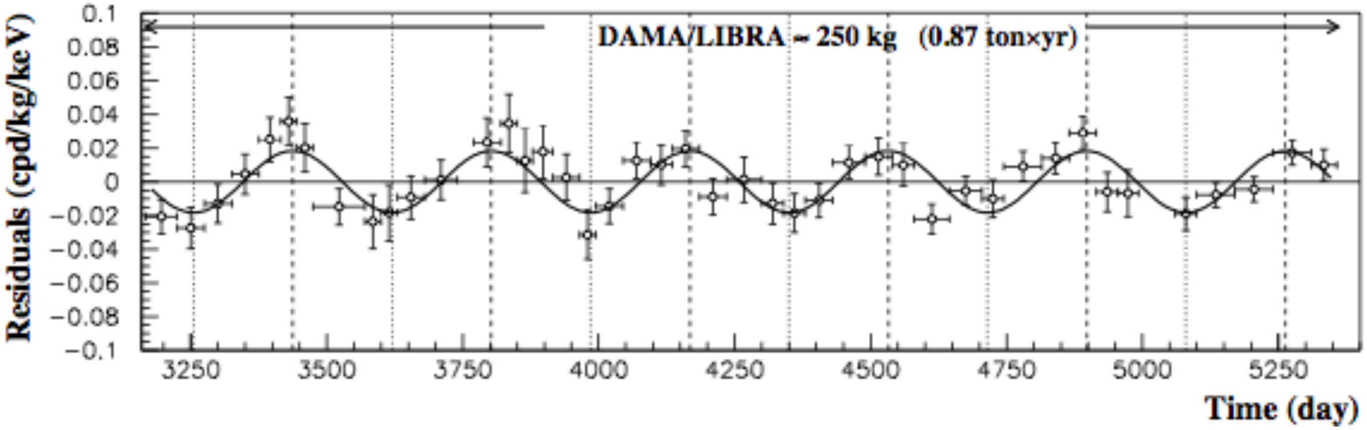
PTFE light diffuser





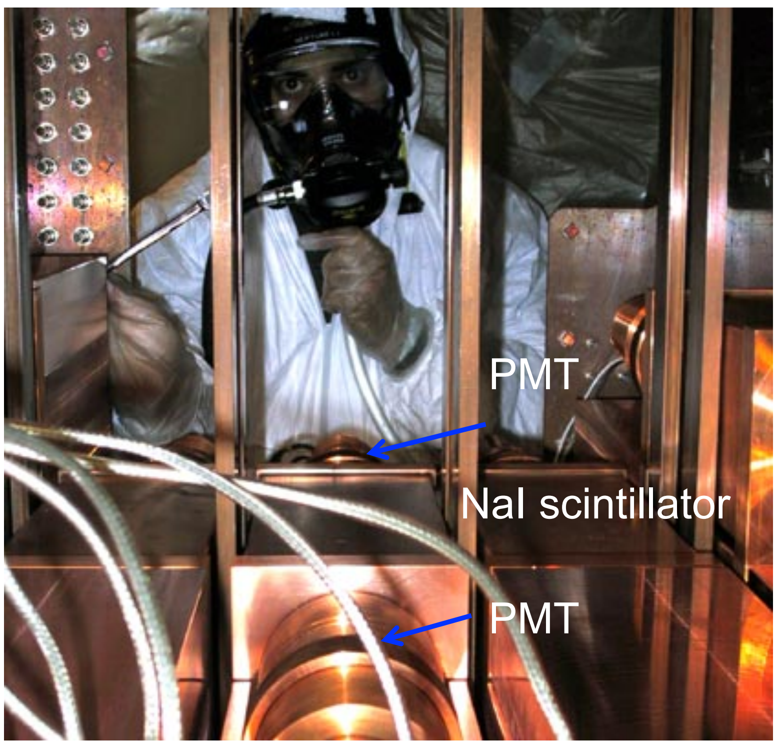
3 photoelectrons/keV

Dark matter signal from Annual Modulation (see Collar lecture)



DAMA/ LIBRA

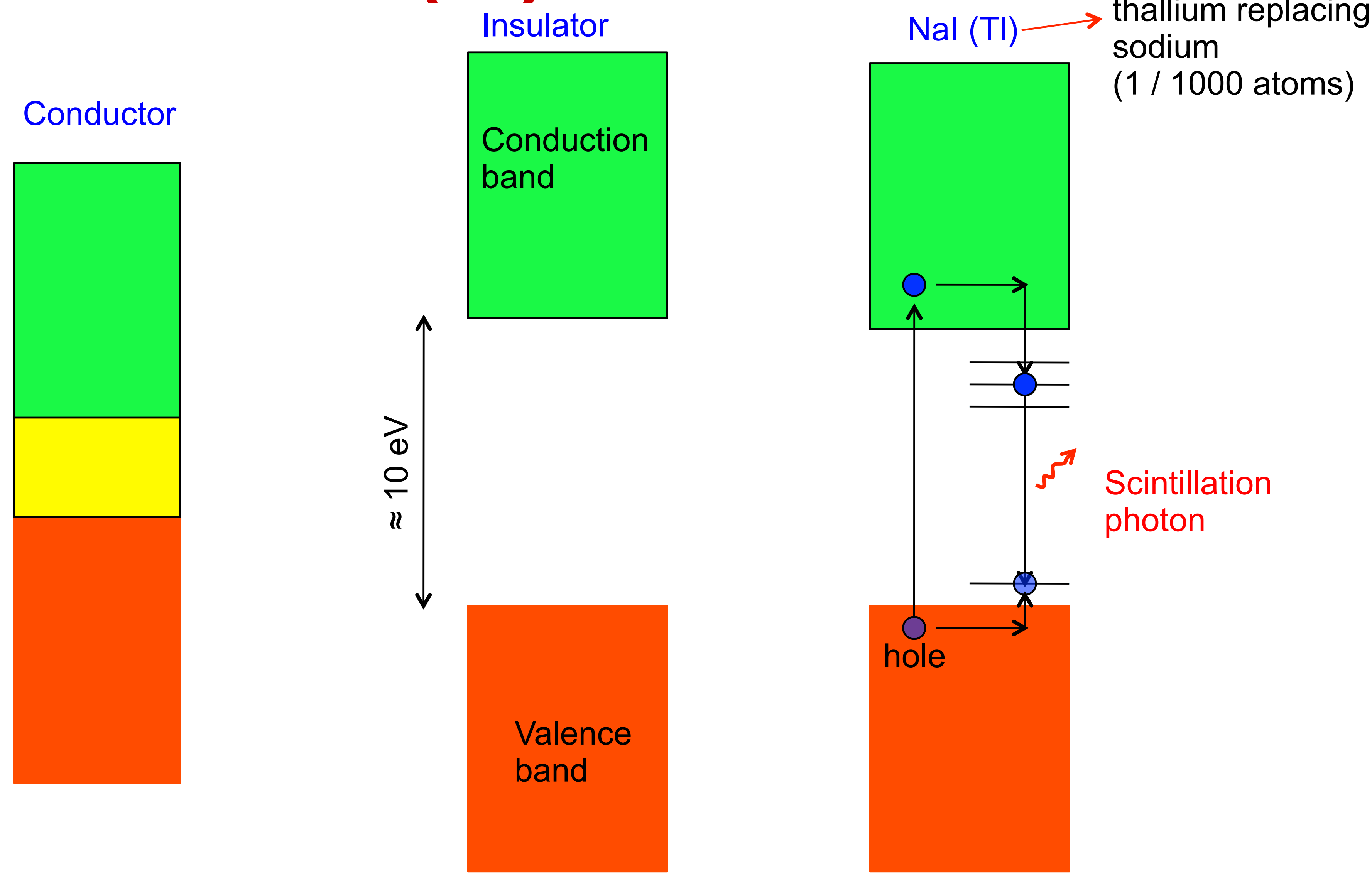
Gran Sasso Laboratory



- 25 NaI(Tl) ultra-pure scintillator crystals (each ≈ 10 Kg)

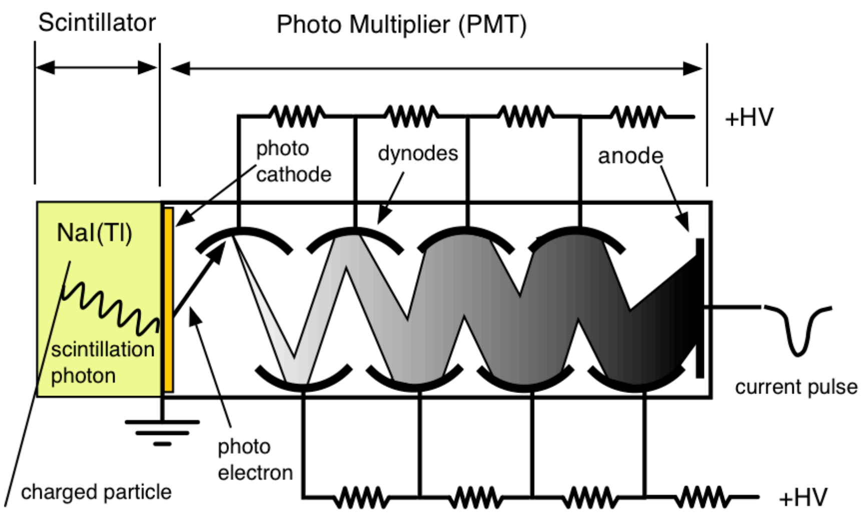
- Two PMTs, one at each end of the NaI crystal, detect scintillation photons produced by nuclear recoil (induced by a DM particle or a neutron) or e.m. backgrounds

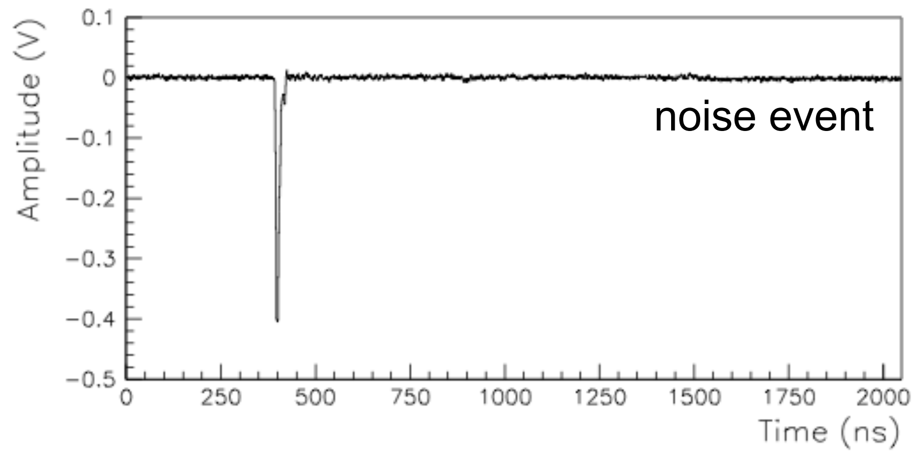
NaI(Tl) scintillation

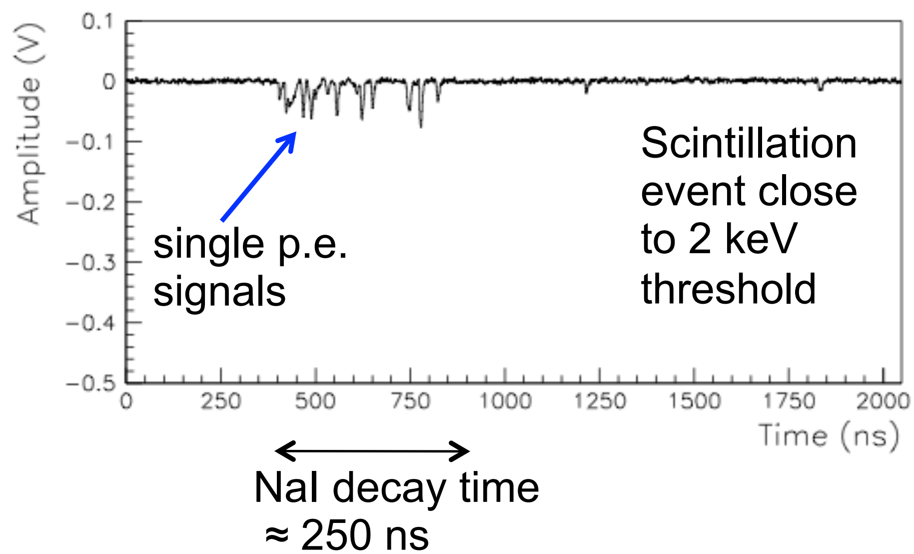


Thallium impurities generate orbitals within the gap, allowing electrons moved by ionization to the conduction band to go back into the valence band, with an emission of a scintillation photon

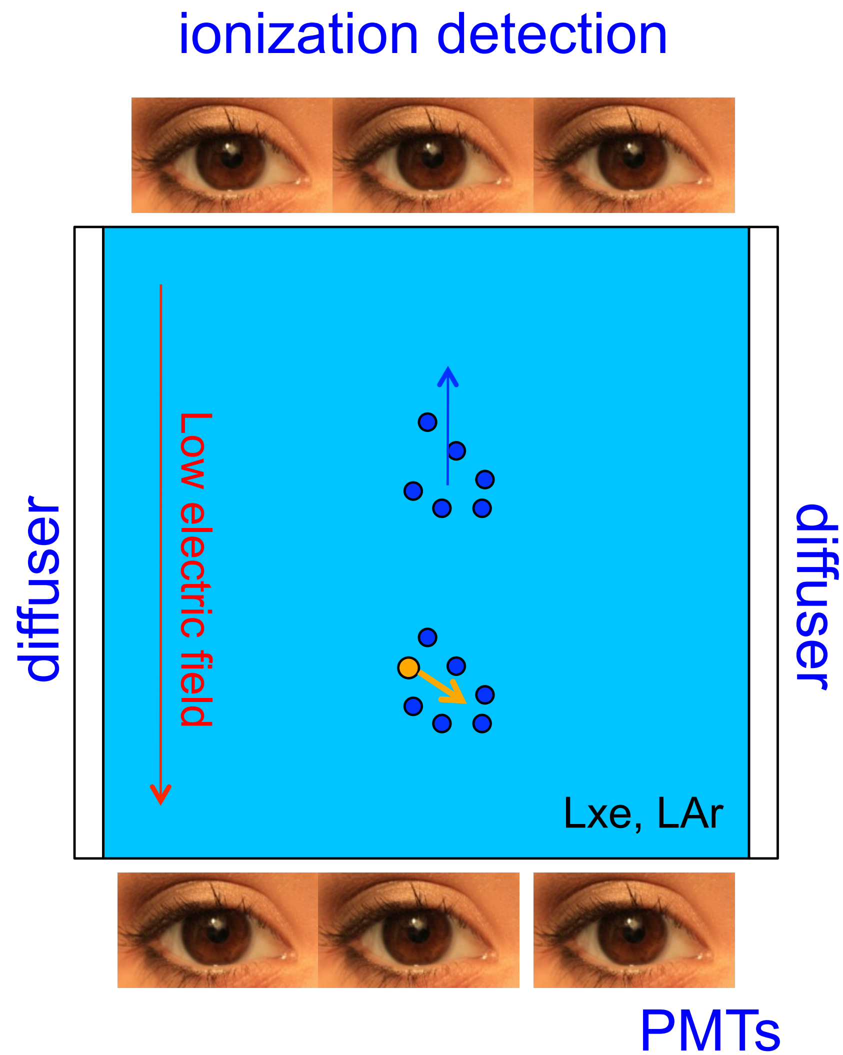
DAMA/LIBRA


Scintillator
Photo Multiplier (PMT)
+HV
photo cathode
dynodes
anode
NaI(Tl)
scintillation photon
current pulse
photo electron
charged particle
+HV


0.1
0
−0.1
−0.2
−0.3
−0.4
−0.5
Amplitude (V)
0 250 500 750 1000 1250 1500 1750 2000
Time (ns)
noise event


0.1
0
−0.1
−0.2
−0.3
−0.4
−0.5
Amplitude (V)
0 250 500 750 1000 1250 1500 1750 2000
Time (ns)
single p.e. signals
Scintillation event close to 2 keV threshold
NaI decay time ≈ 250 ns

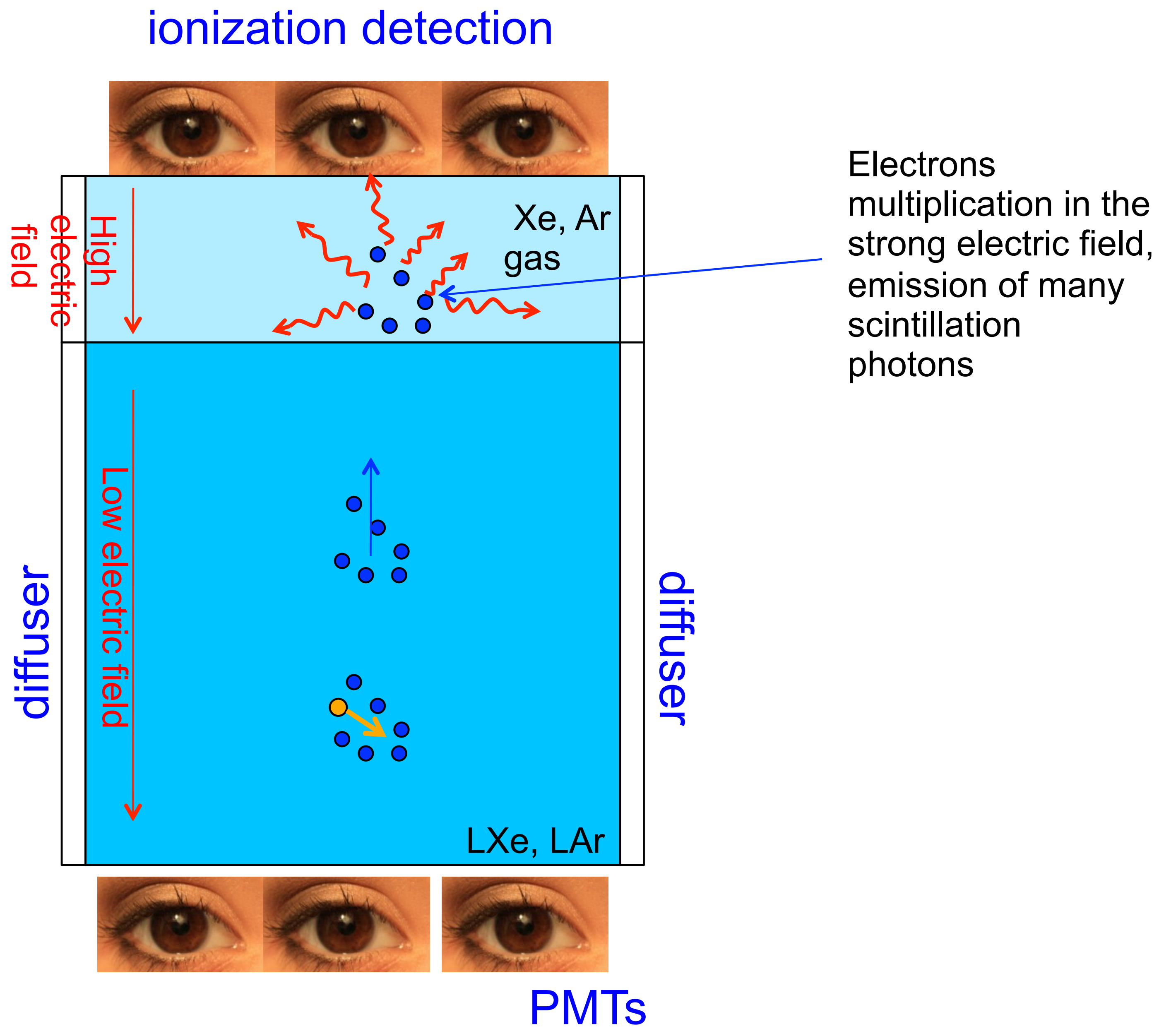
What about ionization?



- Take the ionization electrons out of the target volume

- Noble gas/liquid: orbitals filled with electrons, so drifting electrons from ionization are not ‘attached’ (purity is fundamental.

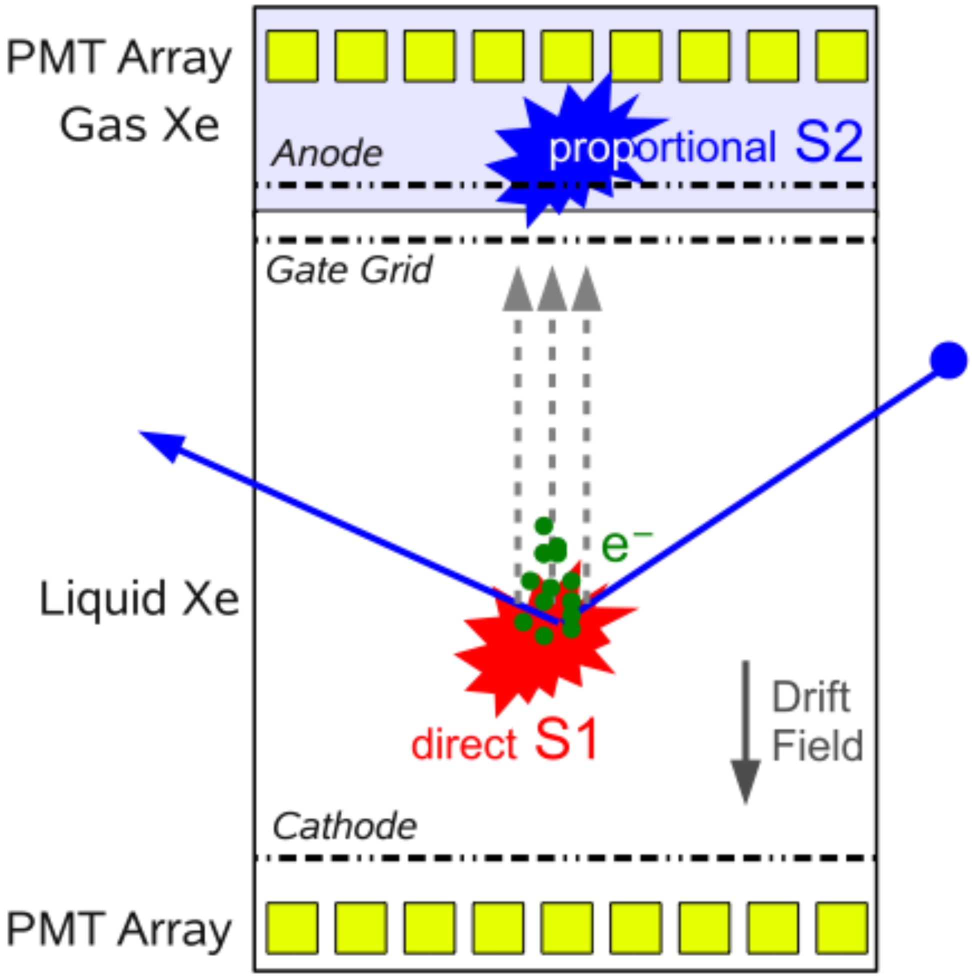
Dual phase Noble Liquid TPC

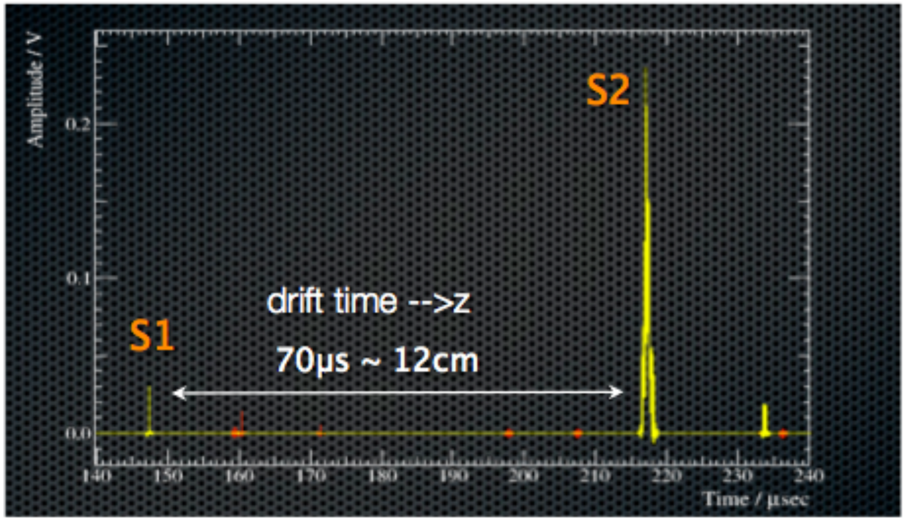


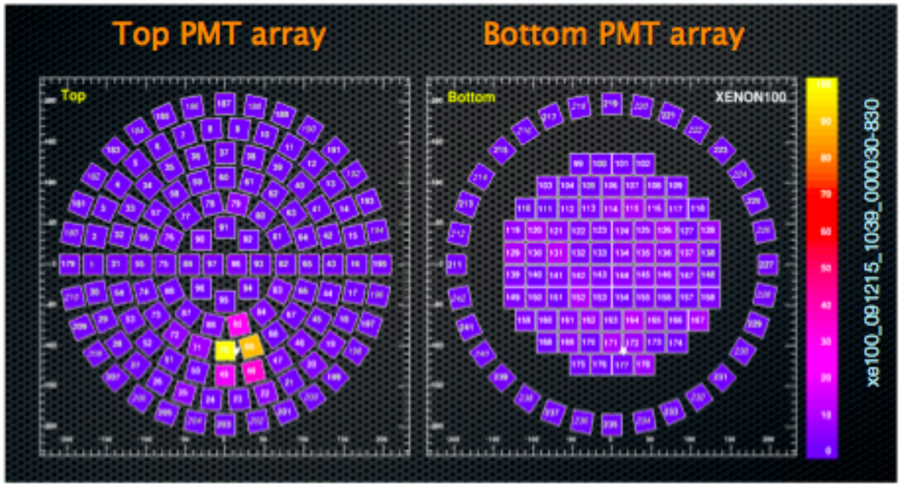
Dual phase Noble Liquid TPC

Ar, Xe

Time Projection Chamber



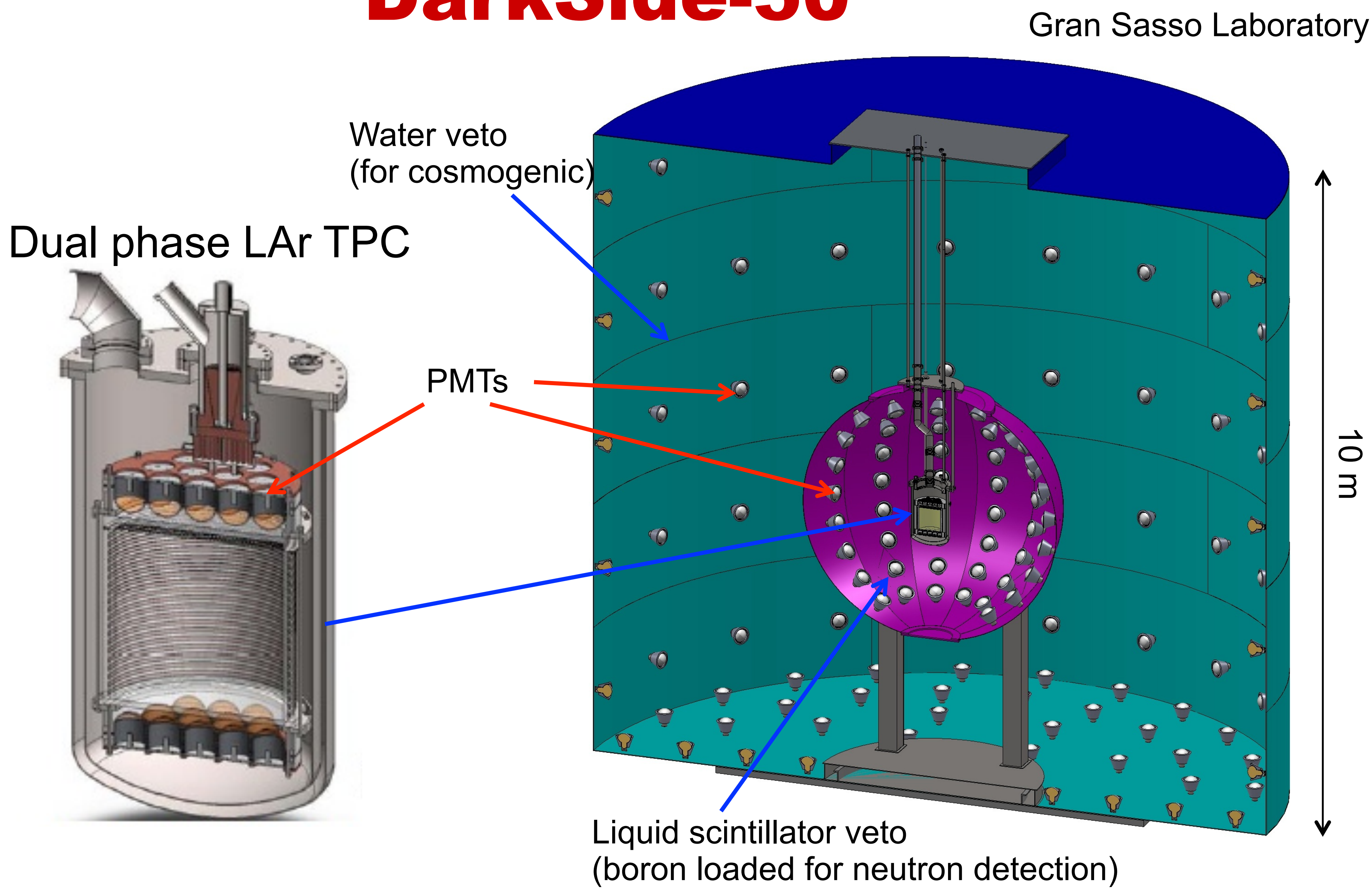




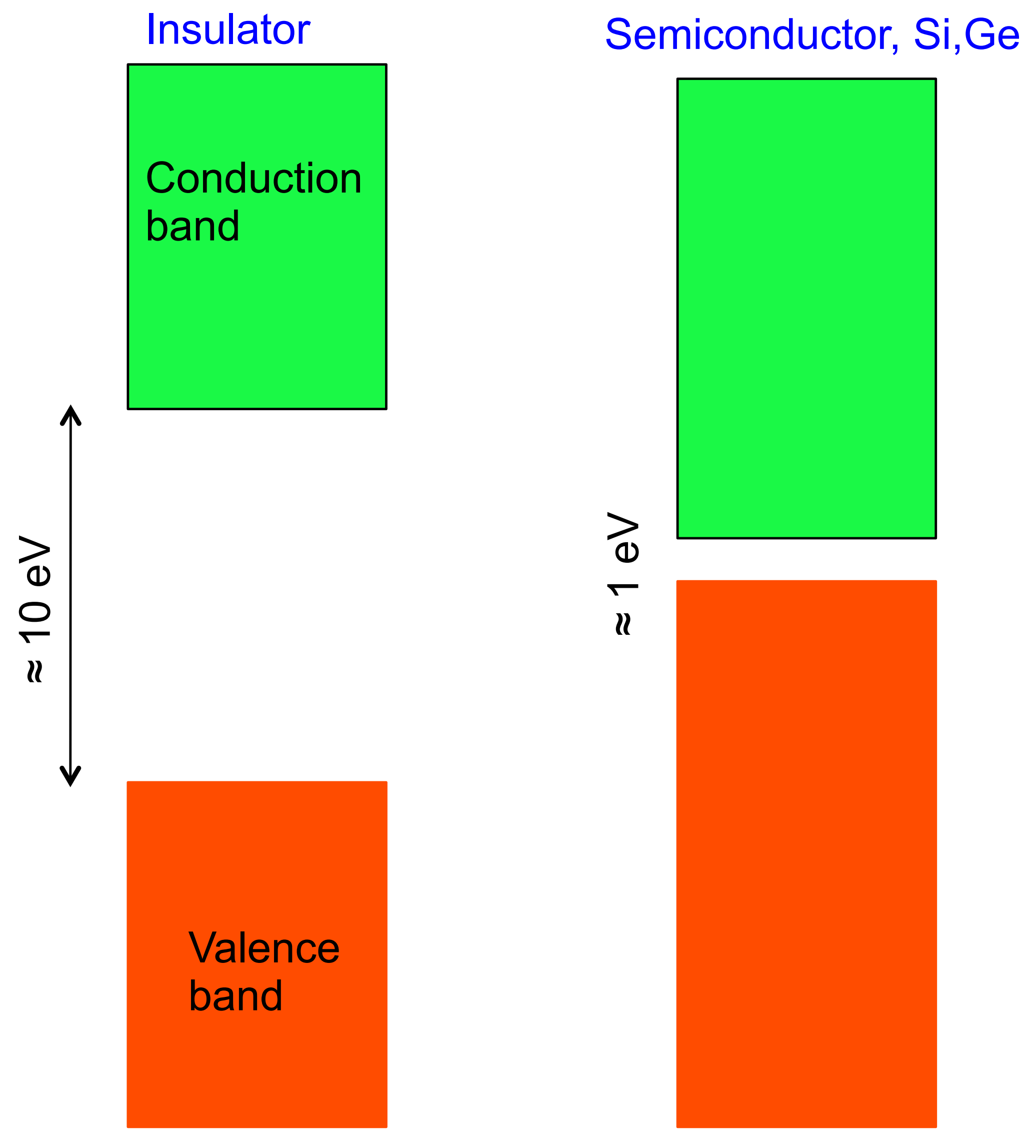
Today lab, small gas chamber

Xenon 100 event

DarkSide-50


Gran Sasso Laboratory
Water veto
(for cosmogenic)
Dual phase LAr TPC
PMTs
10 m
Liquid scintillator veto
(boron loaded for neutron detection)

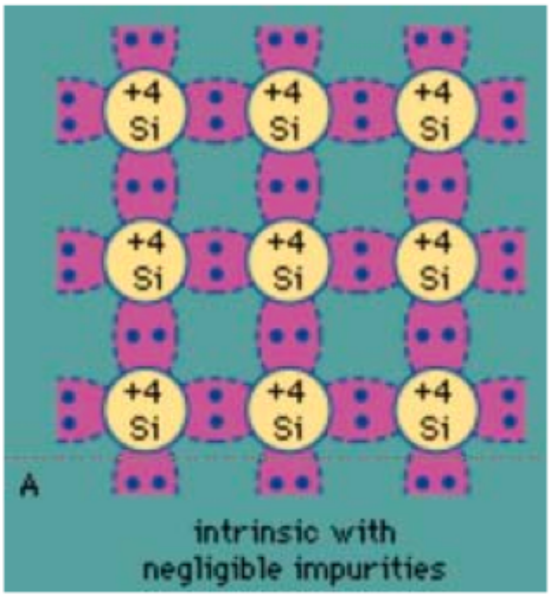
Semiconductor detectors

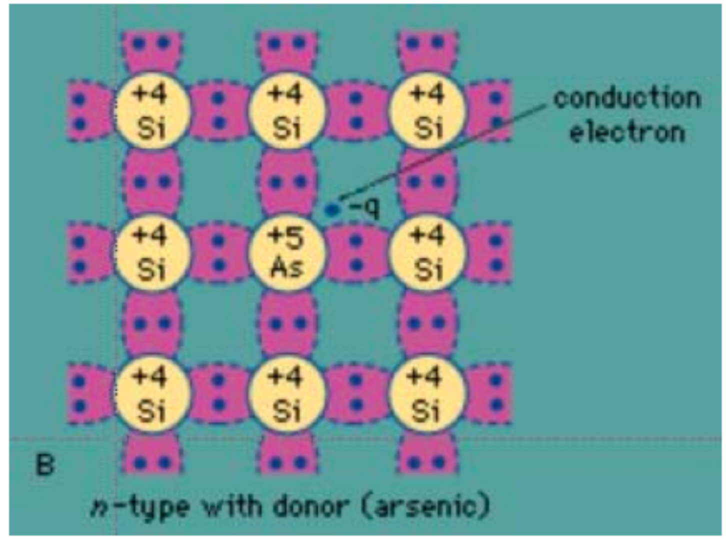


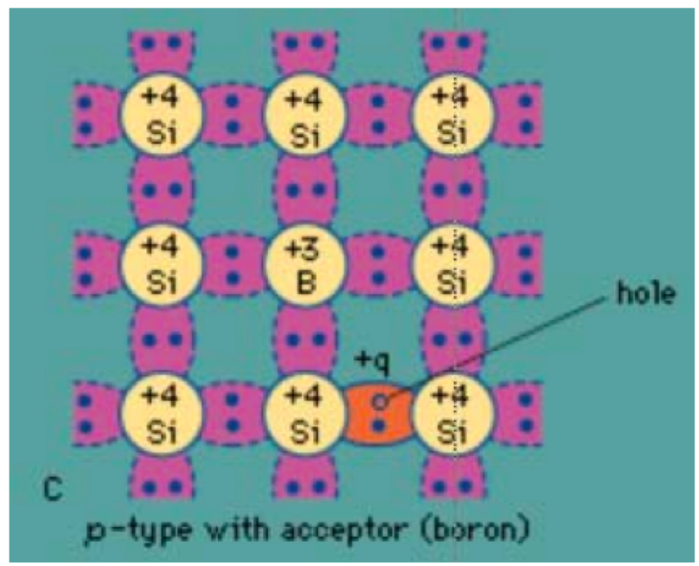
1) Energy to produce a ionization (electron-hole pair) ≈ 3 eV
Compare with ionization in gas 30 eV

2) To measure an electric signal, electrons must go into the conduction band. Easier for semiconductors due to the small energy gap. But must be cooled otherwise large leakage current.

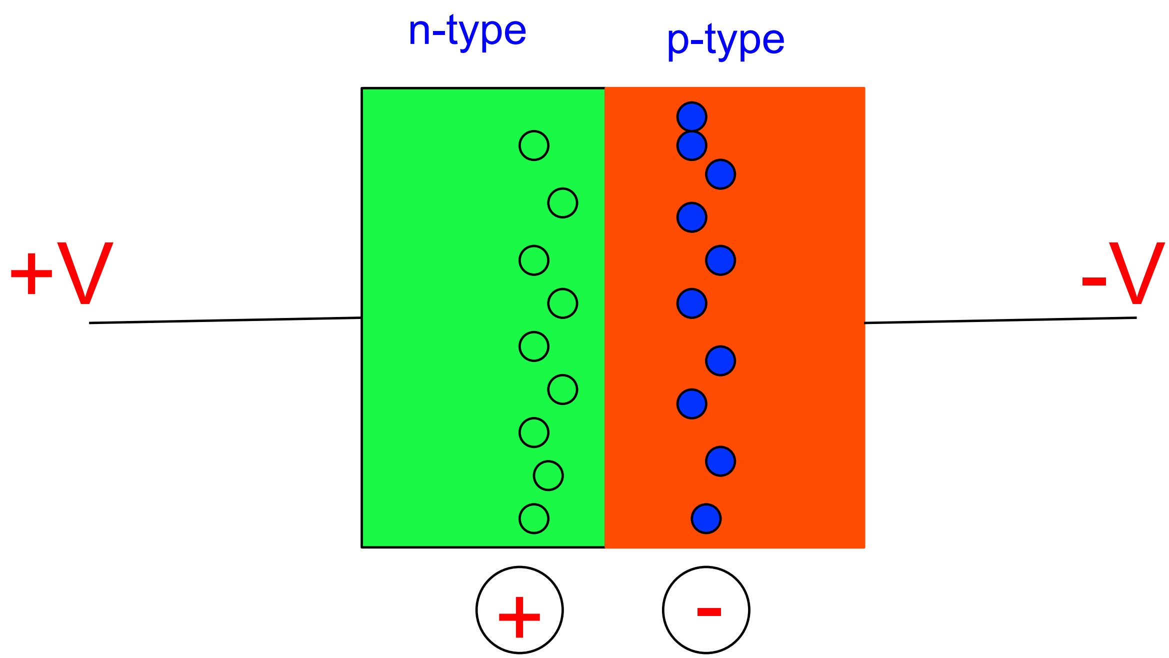
Doped semiconductor





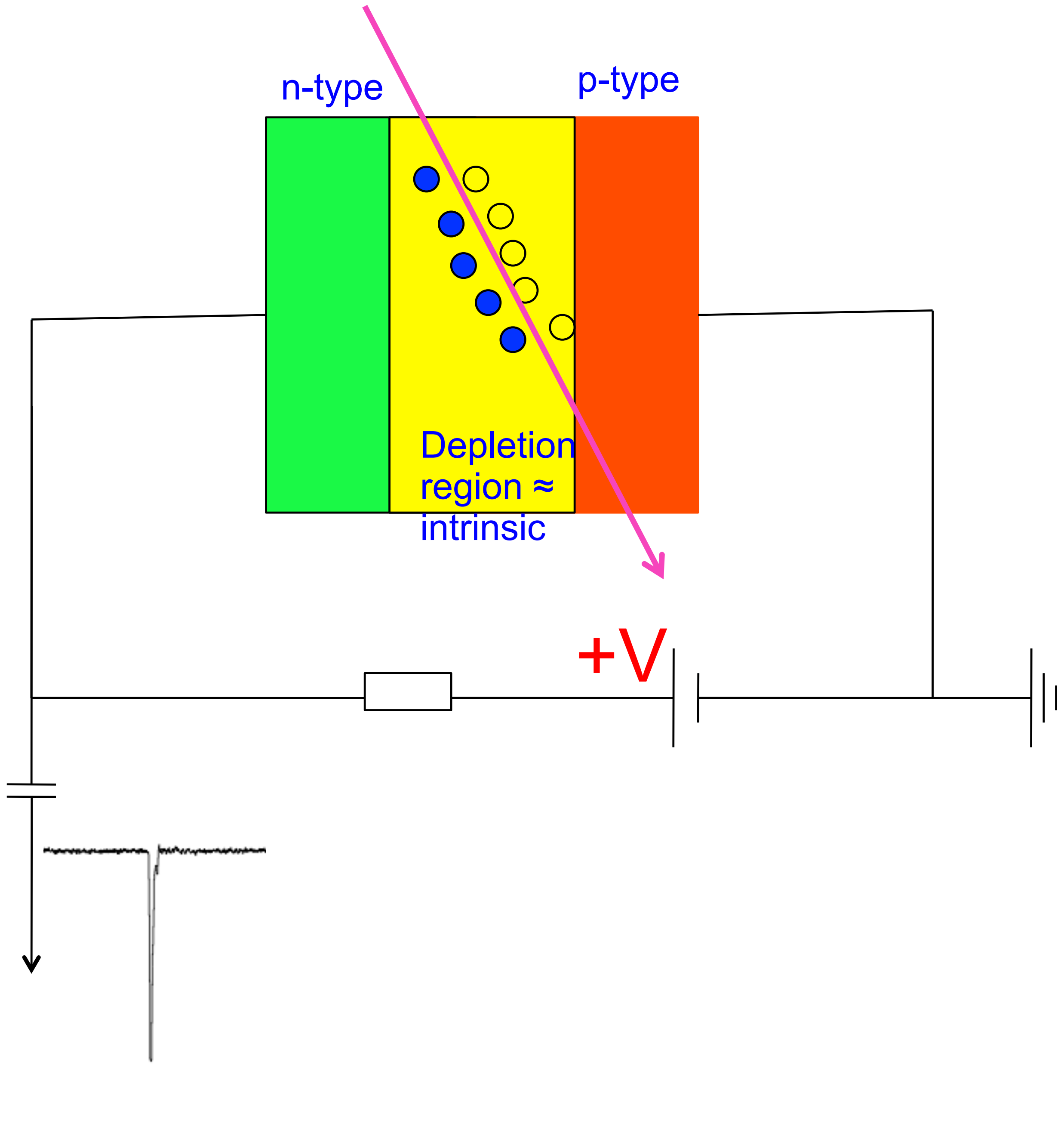


Semiconductor diode detector



1) At the contact, diffusion of holes from p to n , and of electrons from n to p.
2) A positive space charge builds up in the n-type side, a negative space charge in the p-type side.
3) Around the contact, a depletion region is formed, depleted of holes and electrons.
4) By reverse bias (apply +V on the n-type side, -V on the p-type side), the depletion region is increased.

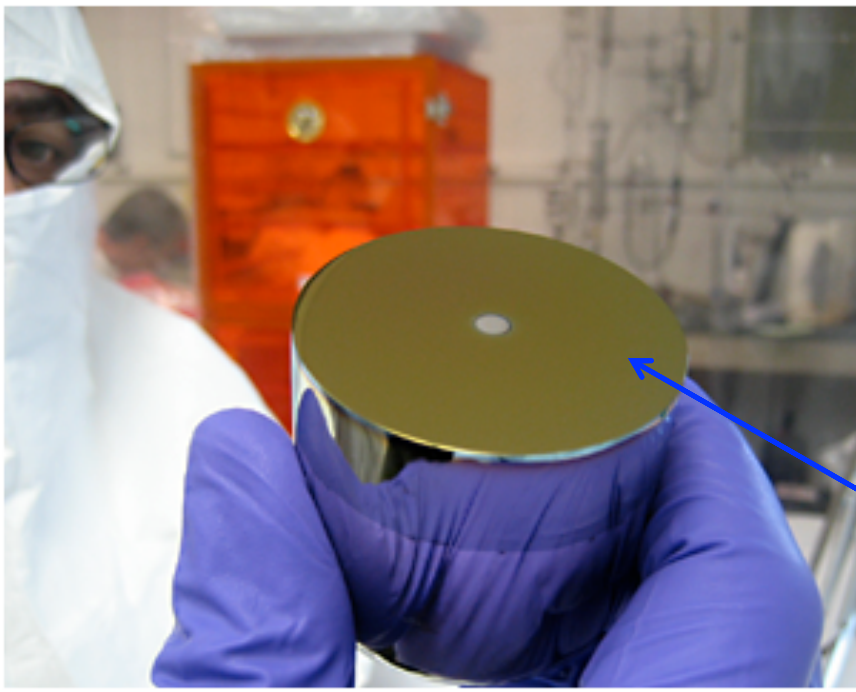
Semiconductor diode detector



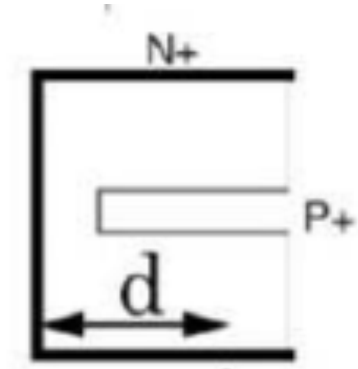
High Purity Germanium detector

Big Ge crystals – 100s g - can be grown

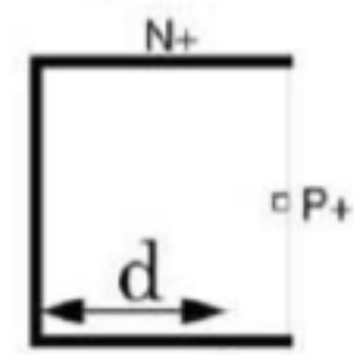
p-type point contact HPGe



CoGeNT experiment

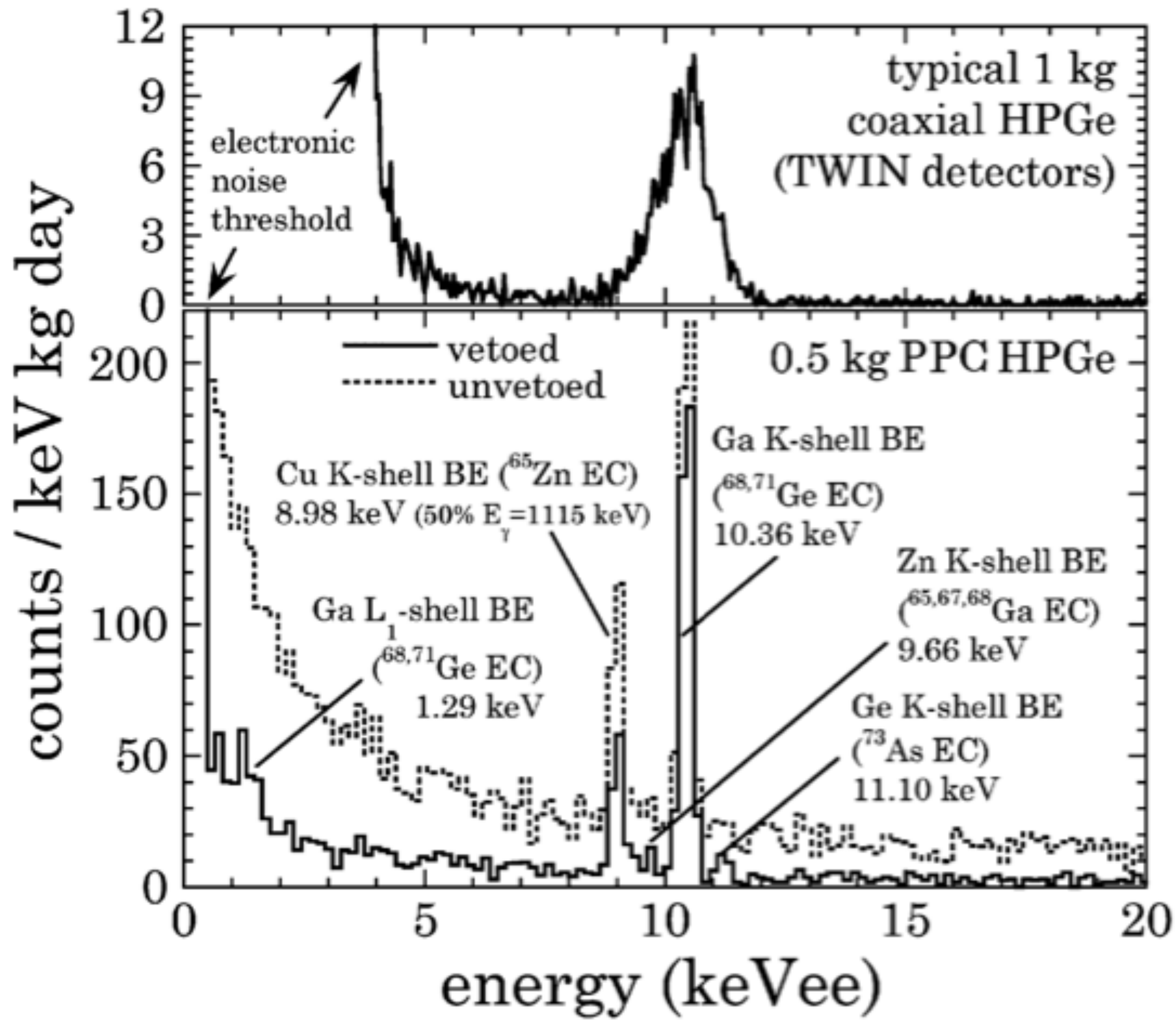


Standard coaxial detector



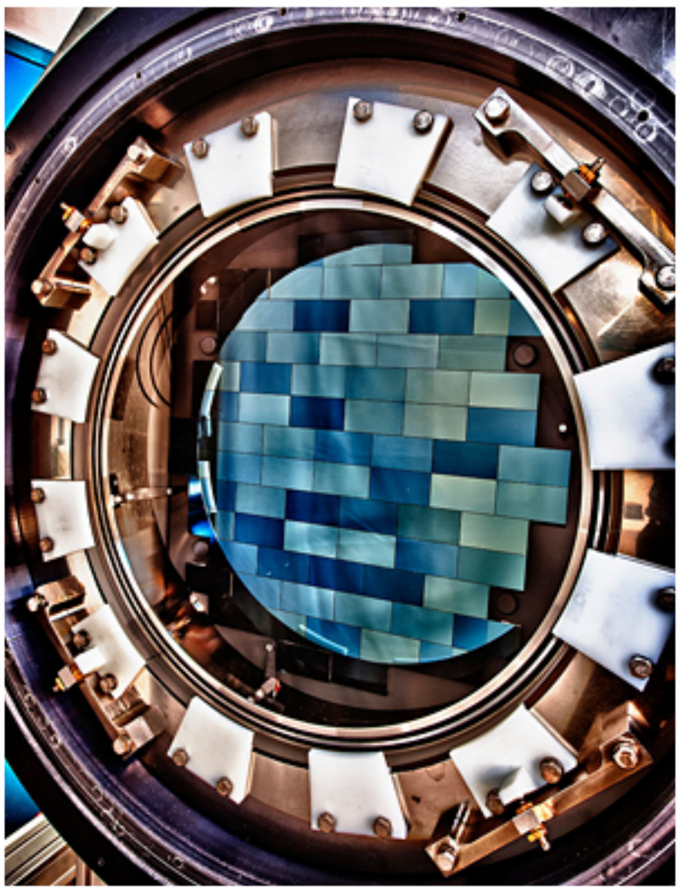
Much smaller capacitance, noise improvement

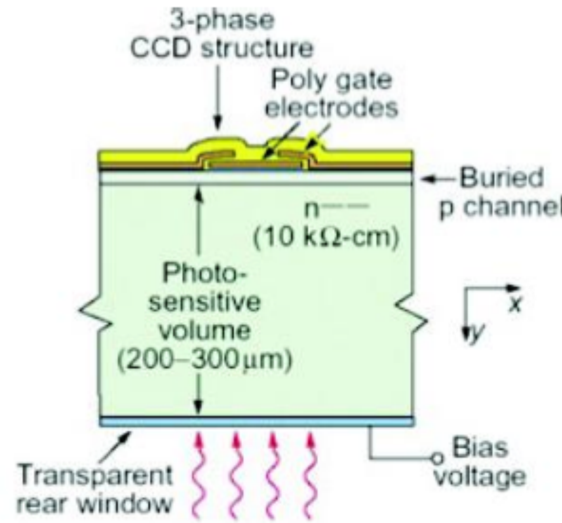
High Purity Germanium detector



CCDs for Dark Matter

Dark Energy Survey camera use thick
 CCDs to enhance the efficiency in the
infrared
(normal CCD only tens of microns)

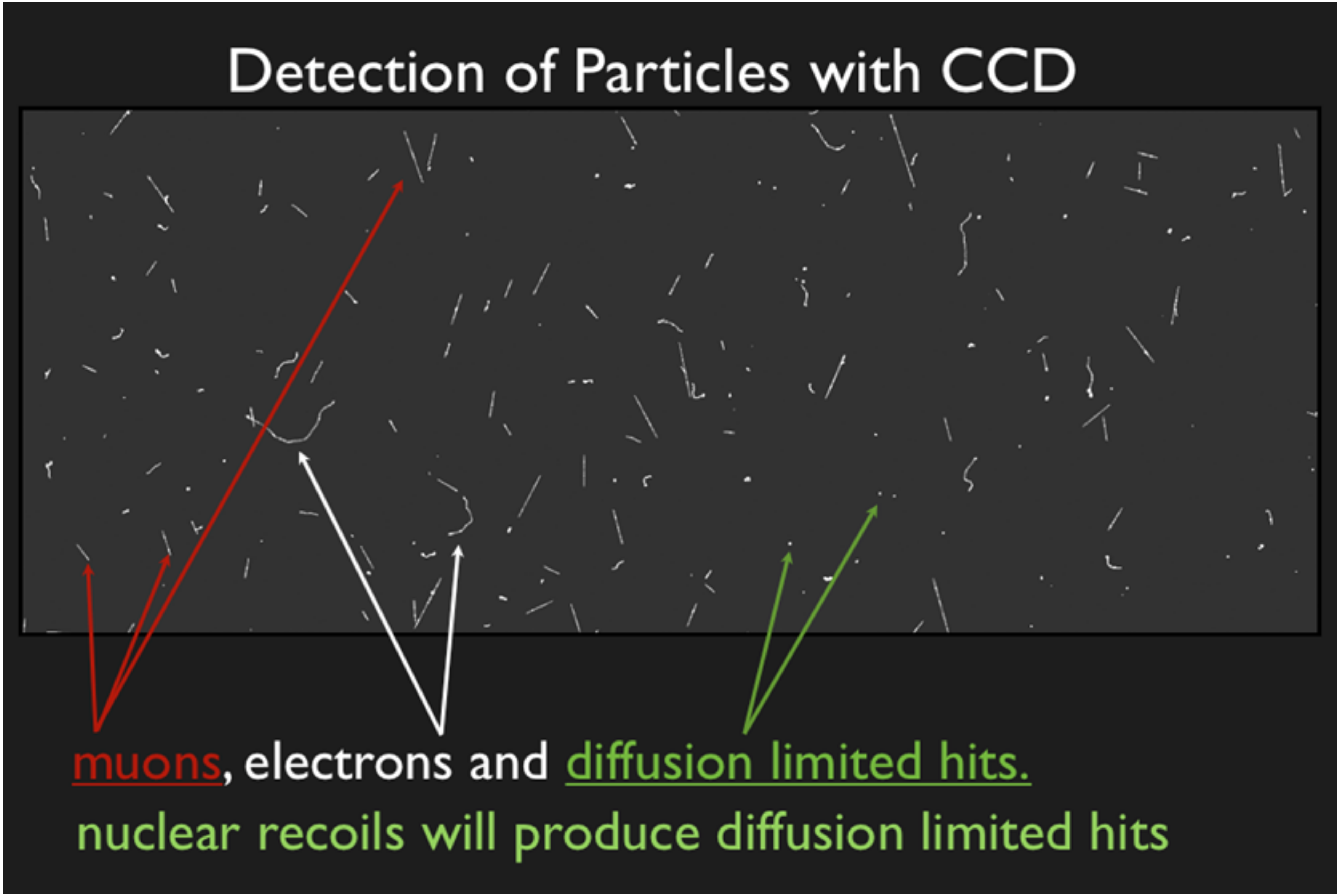




6 cm

1 gram of Si per board

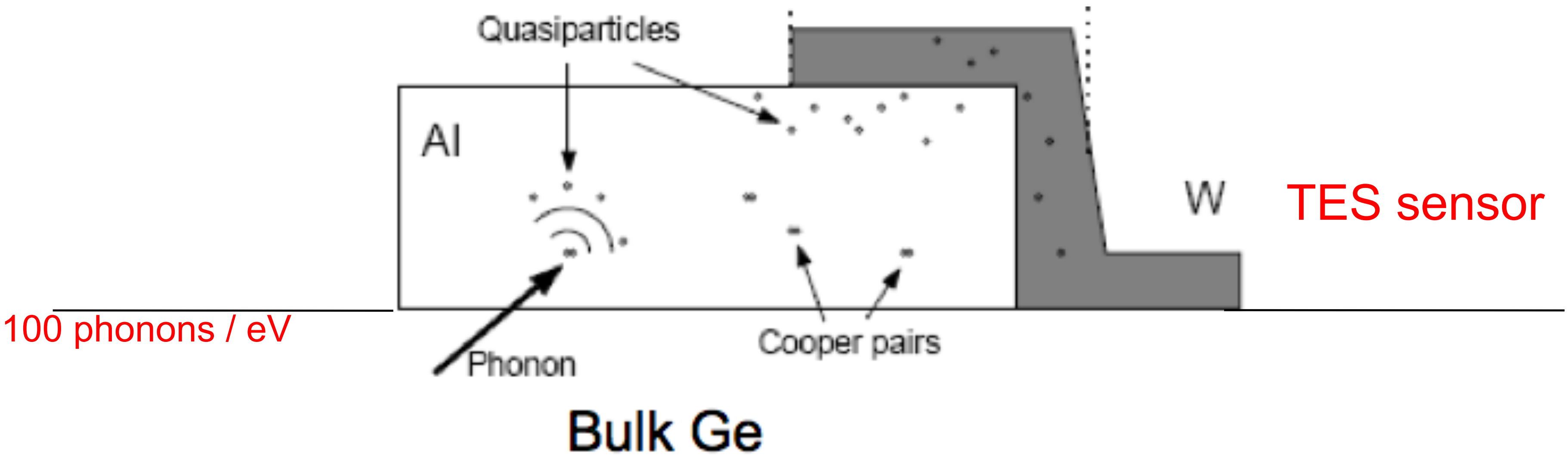
15 micron pixel size

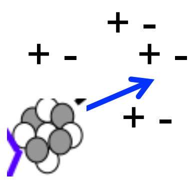


Several hours exposure of a CCD, DAMIC experiment soon at SNOLAB

Phonons.....

CDMS experiment



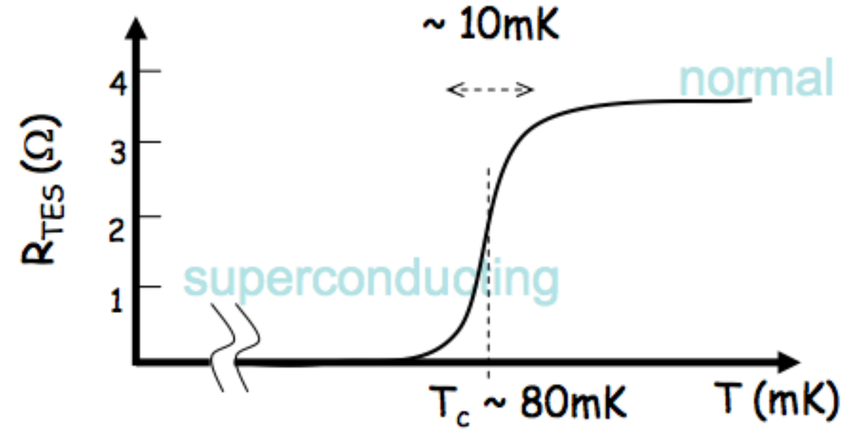


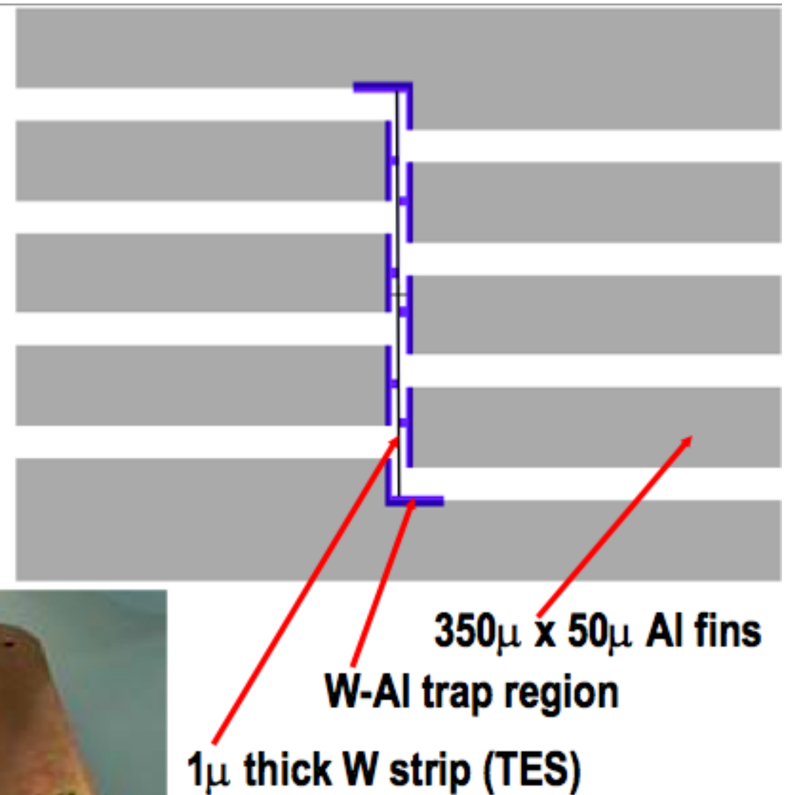
1 electron-hole / 3 eV

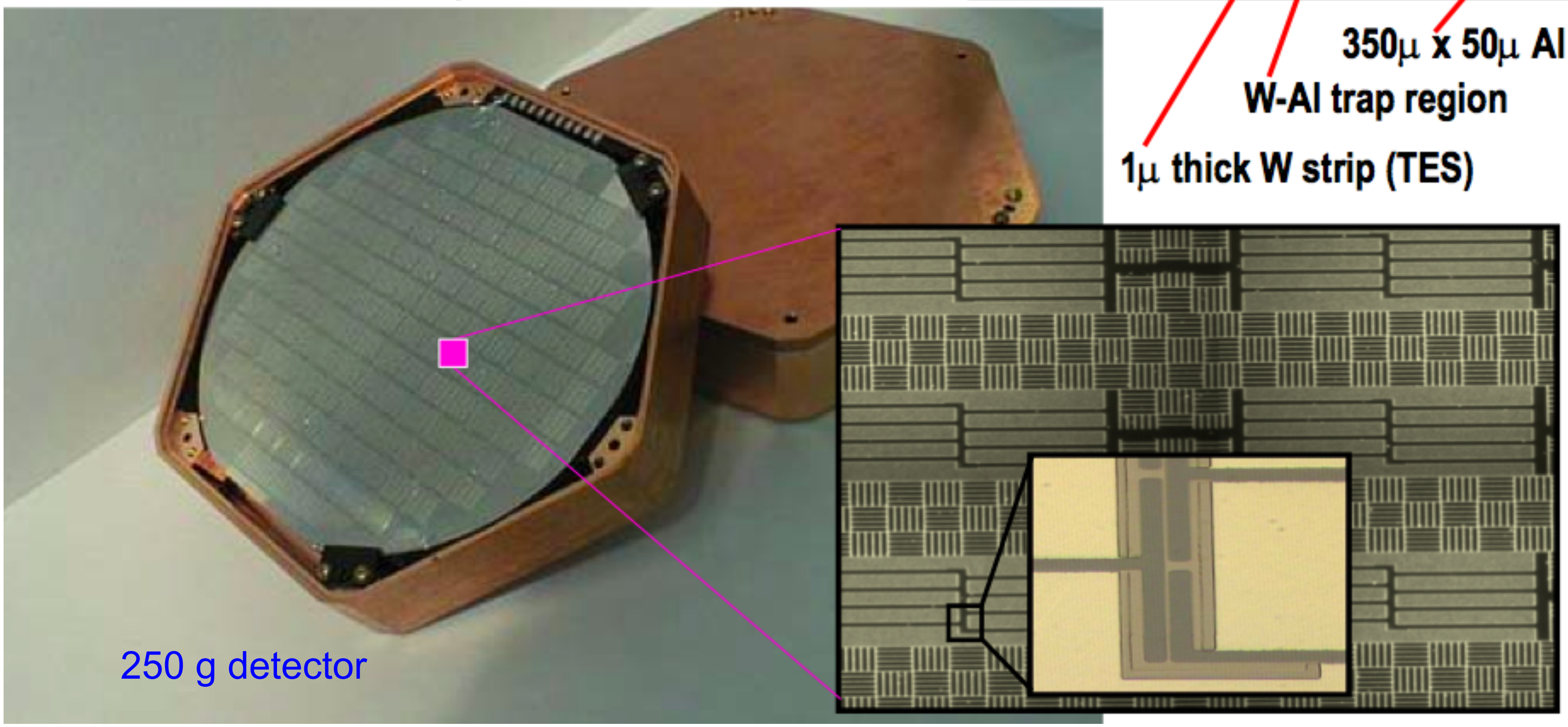
Also charge detection

Phonons from vibrations of the crystal lattice induced by scattering with nucleus. Reach surface and give energy in the Al breaking Cooper pairs. These electrons diffuse to the tungsten strip, where they release energy.

QET: Transition Edge Sensor





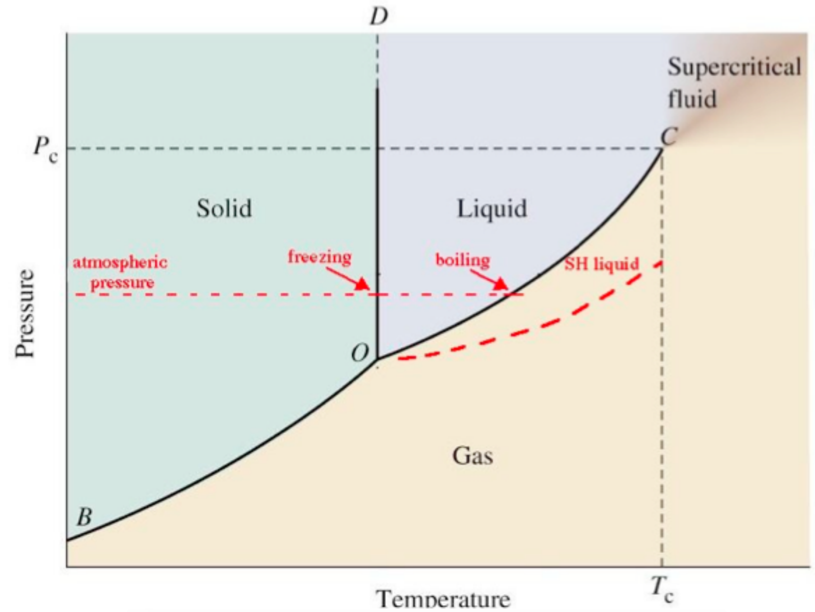


COUPP

J. Collar

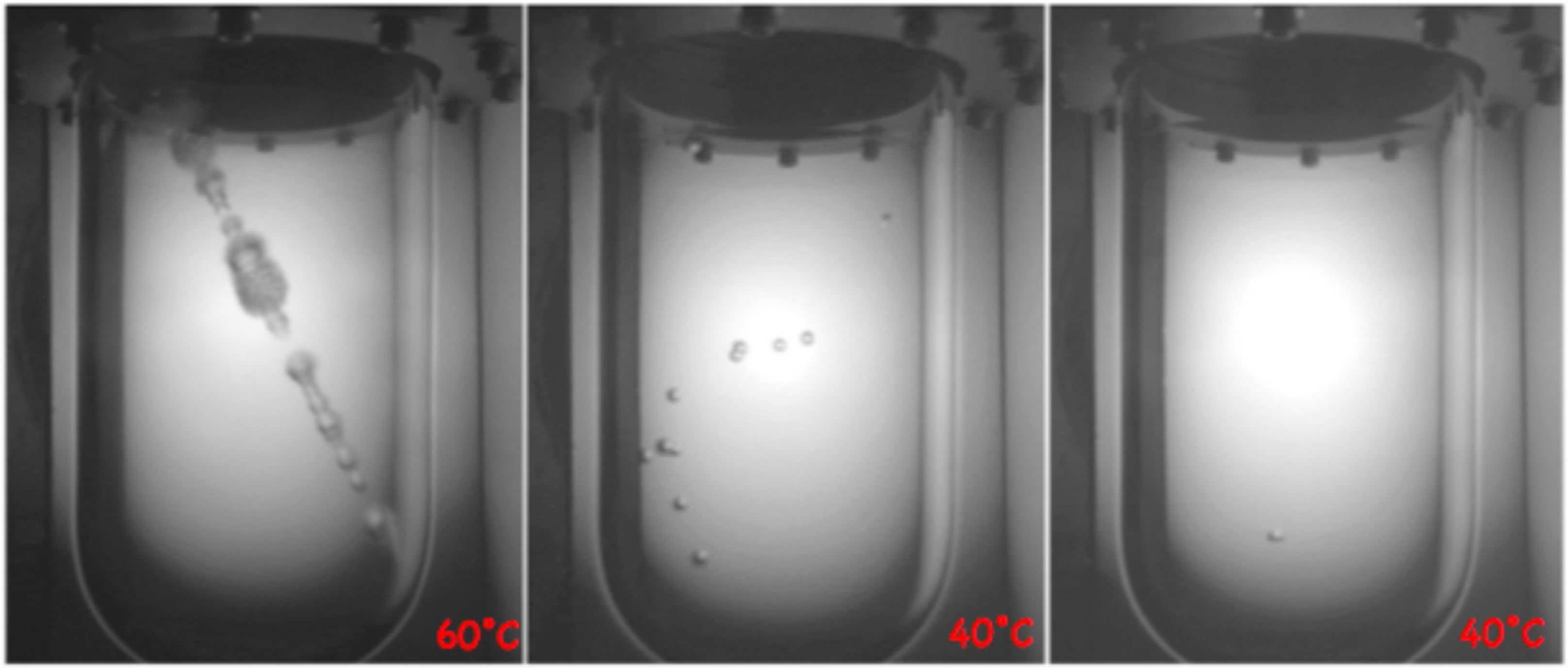
Chicagoland Observatory for Underground Particle Physics

Bubble chamber



Conventional BC operation
(high superheat, MIP sensitive)

Low degree of superheat, sensitive to nuclear recoils only

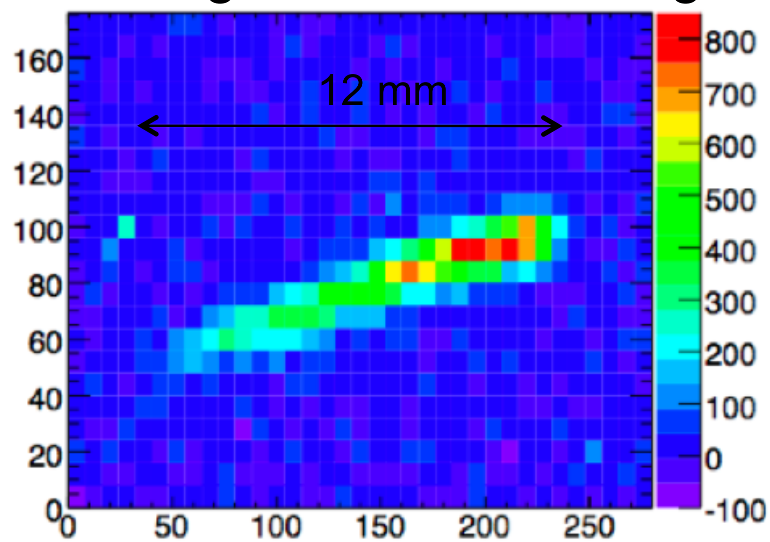


muon

Neutron

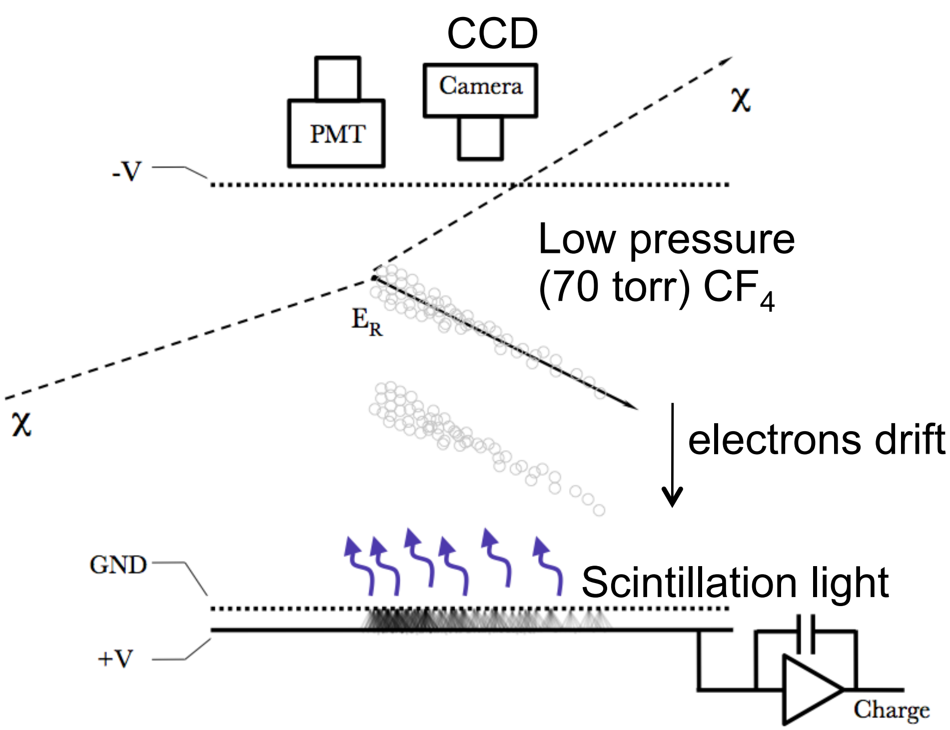
WIMP

CCD image of scintillation light



DMTPC

A directional DM detector



Detectors (for Dark Matter)

- Dark matter detectors challenges: mass, energy threshold and resolution

- Many different detectors: dark matter is elusive, detection will be convincing only if several independent experiments (with different systematics) will agree.

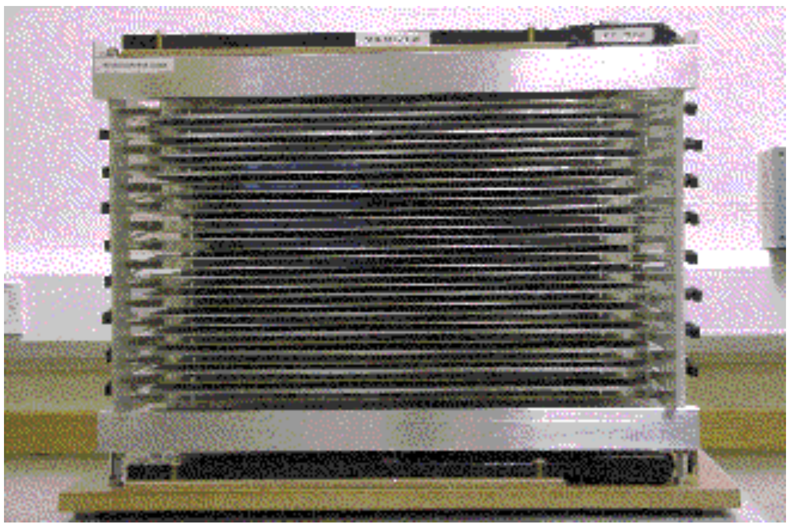
- Techniques developed across fields (e.g. liquid Argon for neutrino detection, TES for CMB)

- Dark matter special: background rejection….

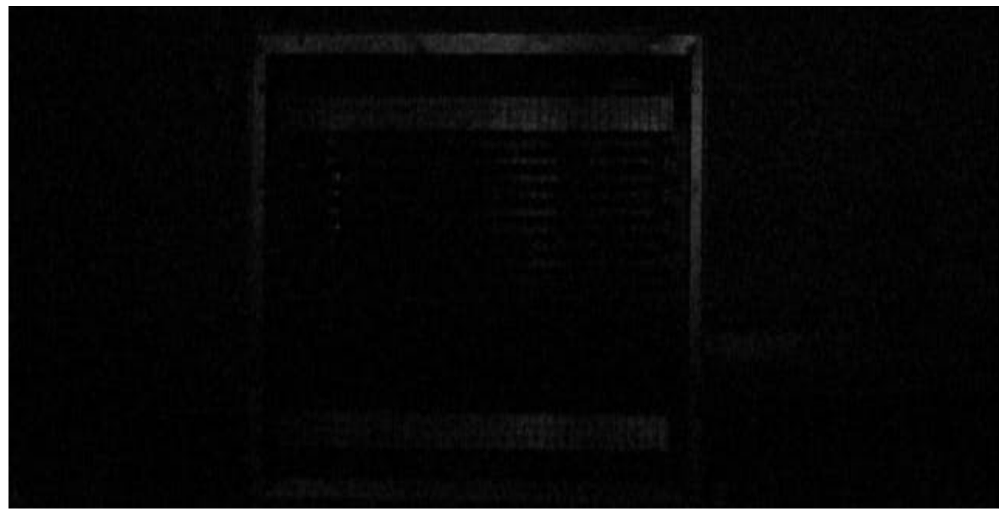
- Could detectors be integrated in your programs/ exhibitions?

Dark Matter - Cosmic Rays

Show that we are bombarded by cosmic particles –
Dark Matter may be a very rare kind of cosmic particle



A particle detector: the Spark Chamber
(courtesy University of Birmingham)



Rate of cosmic rays at ground ≈ 1 / cm^2 / minute

Other cosmic rays exhibits

Fermilab Take a Cosmic Ray Shower

Fermilab deputy director Young-Kee Kim takes a cosmic ray shower at the grand opening of the new exhibit.

Wonderlab Museum, Bloomington IN

COSMIC RAY TO OPEN PLANETARIUM TONIGHT

Caught by Delicate Apparatus, It Will Switch On Stars in 'Artificial Heaven.'

A cosmic ray, messenger from interstellar space, will switch on the stars tonight, promptly at 9 o'clock, in New York's first "artificial heaven," at the opening of the Hayden Planetarium of the American Museum of Natural History.

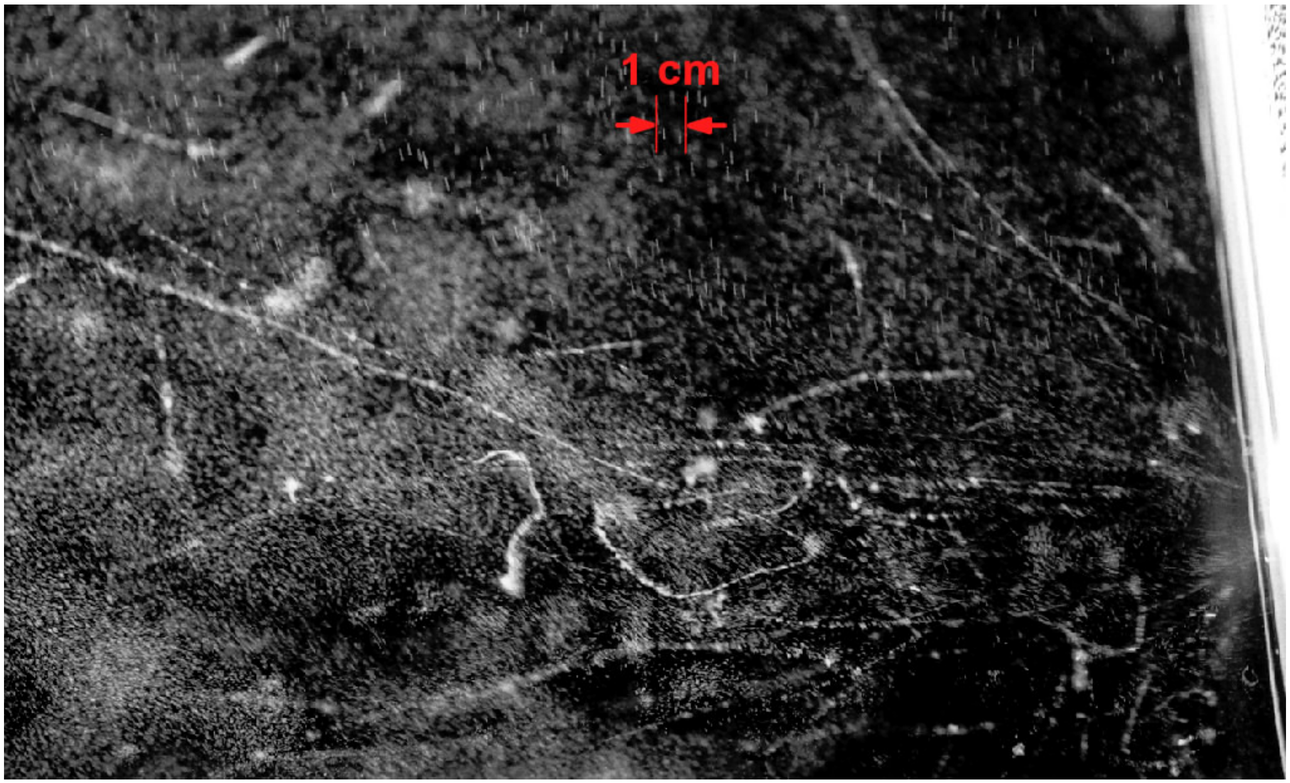
So far as is known, this will be the first time that a cosmic ray, most powerful "electrical bullets" found in nature, will be made to perform a useful task at the bidding of man.

The cosmic ray will be trapped by delicate electrical apparatus and made to provide the impulse that will switch on the great planetarium projector with its 9,000 stars. This was announced yesterday by Dr. Clyde Fisher, curator of New York's "Theatre of the Stars."

New York Times, Oct. 2, 1935
Opening of the Hayden Planetarium at the American Museum of Natural History

Cloud chamber

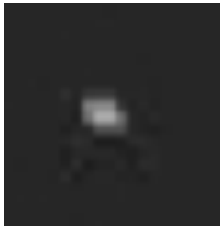
Supersaturated vapor condensation along the ionization trail left by the particle



Explain different types of interactions (and bkg to DM searches)

Several commercial options

CCD



Explain different types of interactions (and bkg to DM searches)

With some tuning, possible with digital camera

Take a picture, explore it, count the n. of muons, etc.