Deep underground detectors

Neutrino experiments

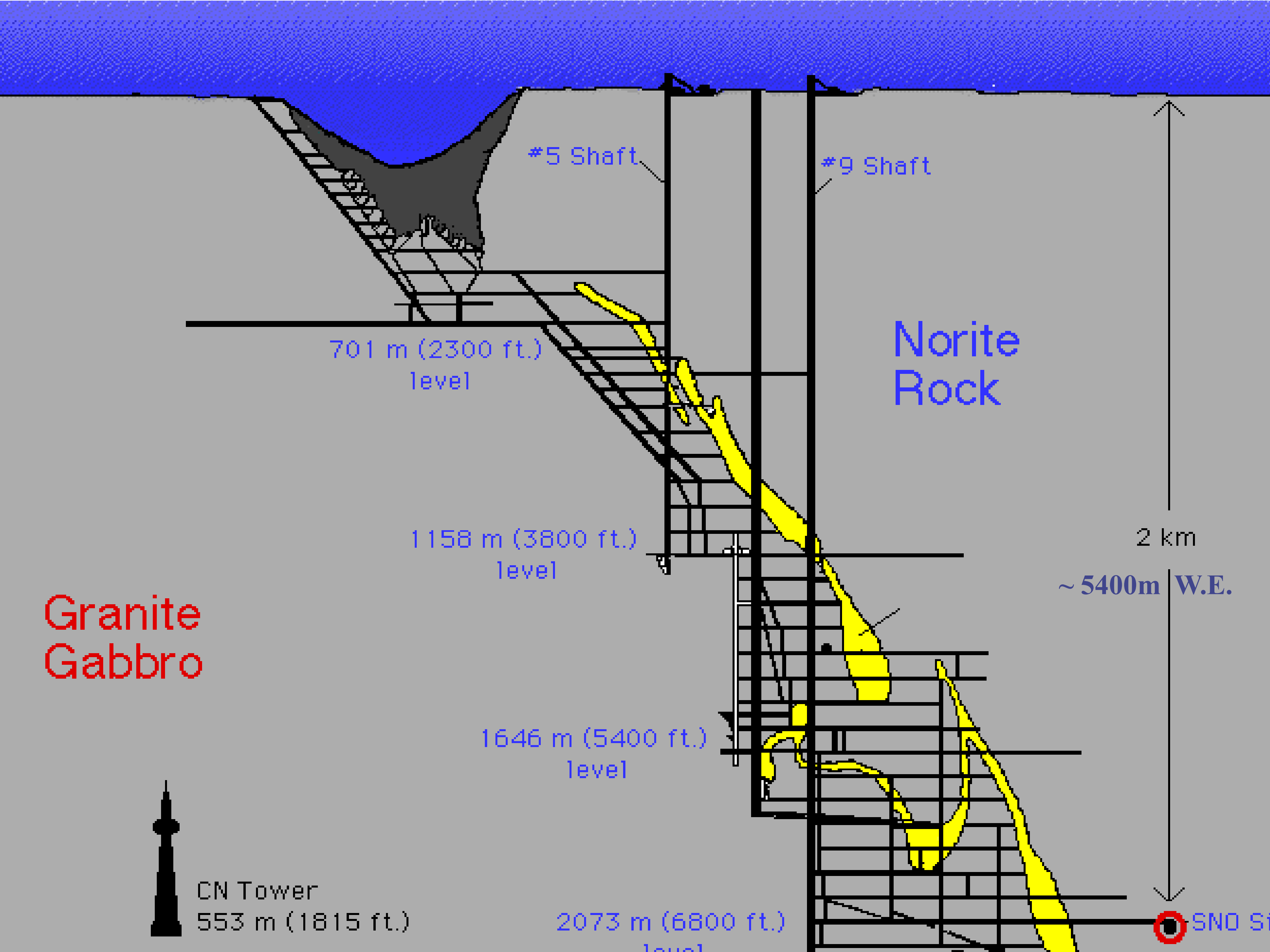
Direct detection of dark matter

Deep underground experiments

Study of rare processes: need to reject reactions caused by unwanted sources – background processes.

Deep underground (1km or more!)

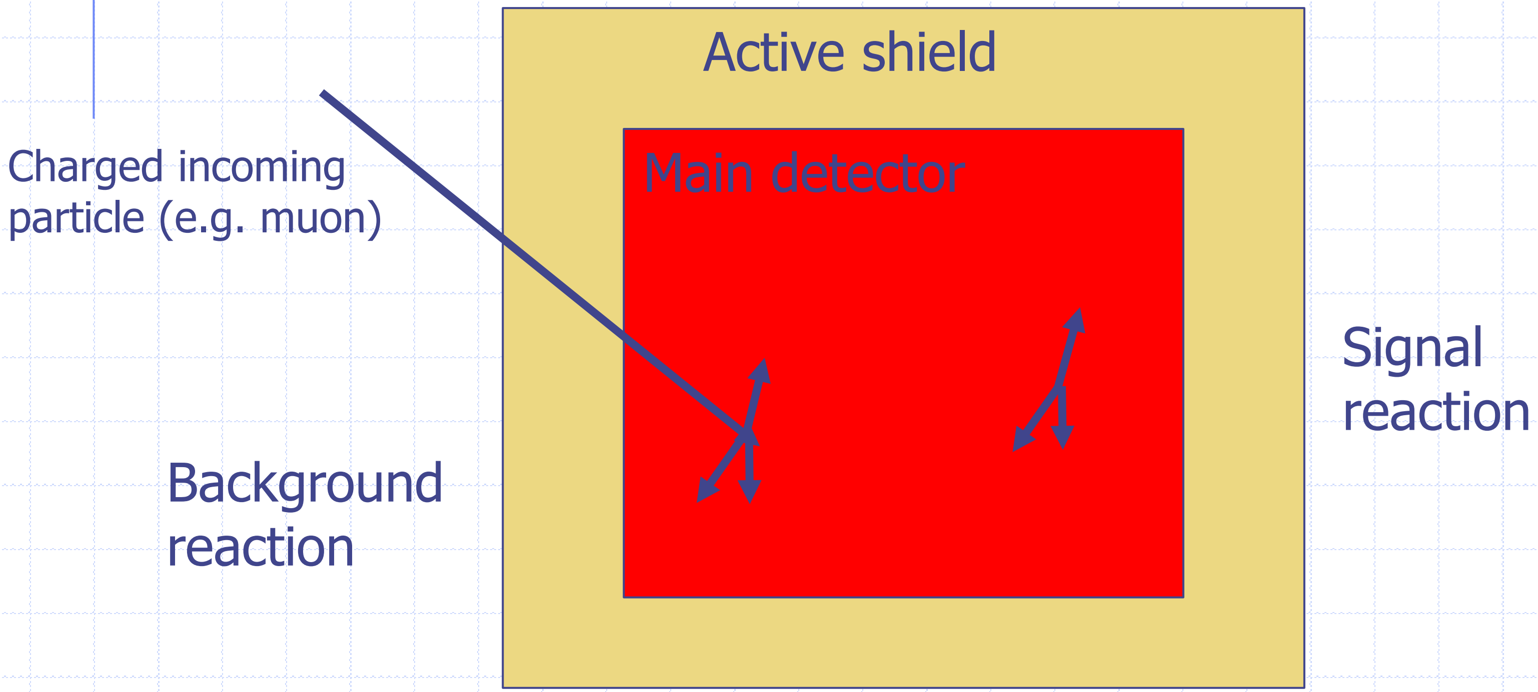
- Reduced cosmic ray flux (muons are quite penetrating)
- Remains: radioactivity in the surrounding rock, in the materials employed in the detector



#5 Shaft
#9 Shaft
Norite Rock
701 m (2300 ft.) level
1158 m (3800 ft.) level
2 km
~ 5400m W.E.
Granite Gabbro
1646 m (5400 ft.) level
CN Tower 553 m (1815 ft.)
2073 m (6800 ft.)

Shielding

- To further reduce the background, employ a two layered detector



Neutrino experiments

For example **neutrino mixing**

Reminder: ν_e and ν_μ are not eigenstates of the free neutrinos (as discussed in Moderna fizika 2), but ν_1 and ν_2 are

$$|\nu_e\rangle = \cos\theta\,|\nu_1\rangle + \sin\theta\,|\nu_2\rangle$$

$$|\nu_\mu\rangle = -\sin\theta\,|\nu_1\rangle + \cos\theta\,|\nu_2\rangle$$

$$|\nu_1(t)\rangle = |\nu_1(t=0)\rangle\, e^{-\frac{iE_1 t}{\hbar}}$$

$$|\nu_2(t)\rangle = |\nu_2(t=0)\rangle\, e^{\frac{-iE_2 t}{\hbar}}$$

$$|\nu_e(t)\rangle = |\nu_1\rangle \cos\theta \exp\left(-\frac{iE_1 t}{\hbar}\right) + \sin\theta\,|\nu_2\rangle \exp\left(-\frac{iE_2 t}{\hbar}\right)$$

Mixing probability $\nu_e \rightarrow \nu_\mu$

$$\boxed{P \propto |\langle \nu_\mu | \nu_e(t)\rangle|^2 = \sin^2(2\theta)\sin^2\left(\frac{E_2 - E_1}{2\hbar}t\right)}$$

$$= \sin^2(2\theta)\sin^2\left(\frac{c^2}{4p\hbar}(m_2^2 - m_1^2)L\right)$$

Neutrino experiments

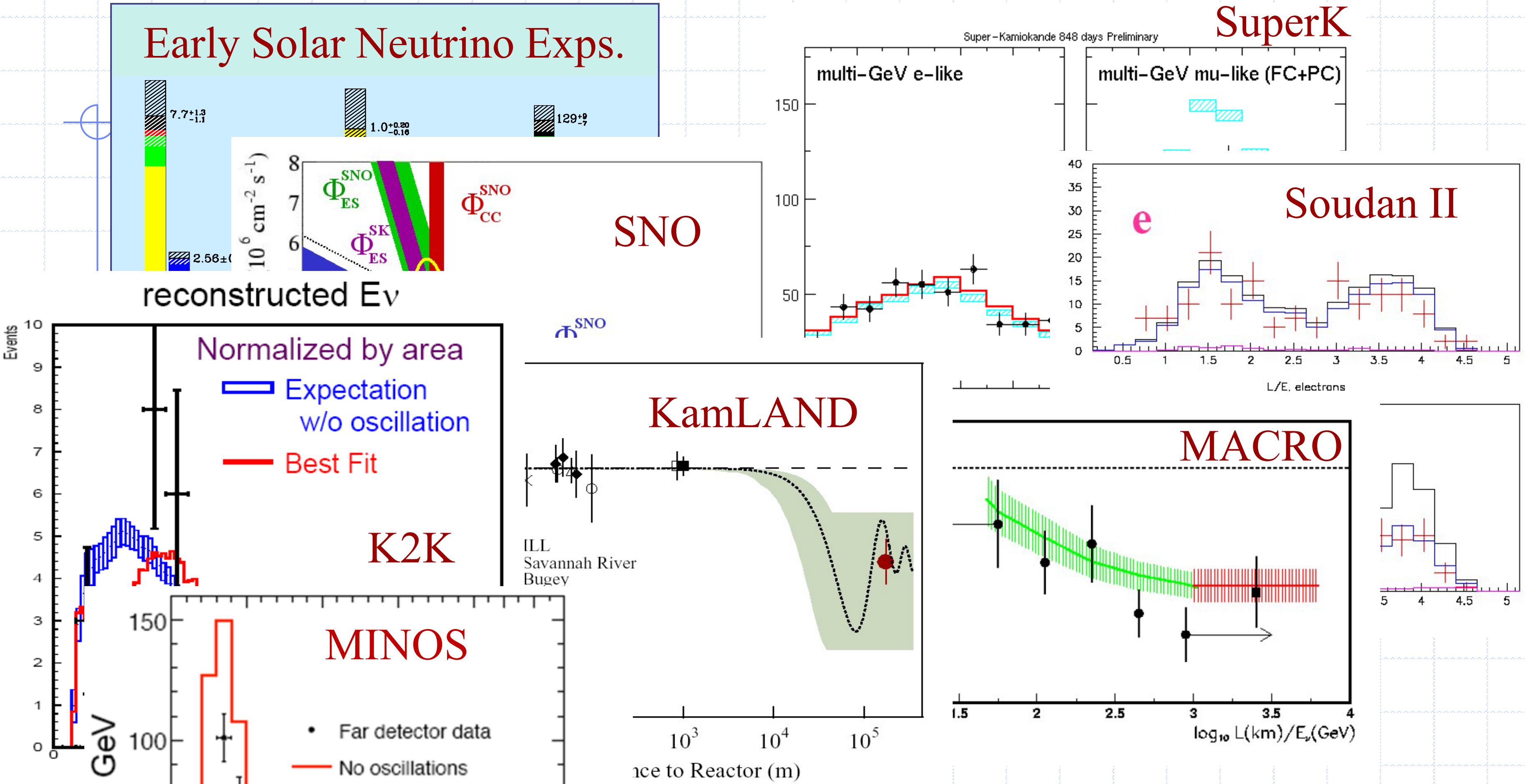
For example neutrino mixing

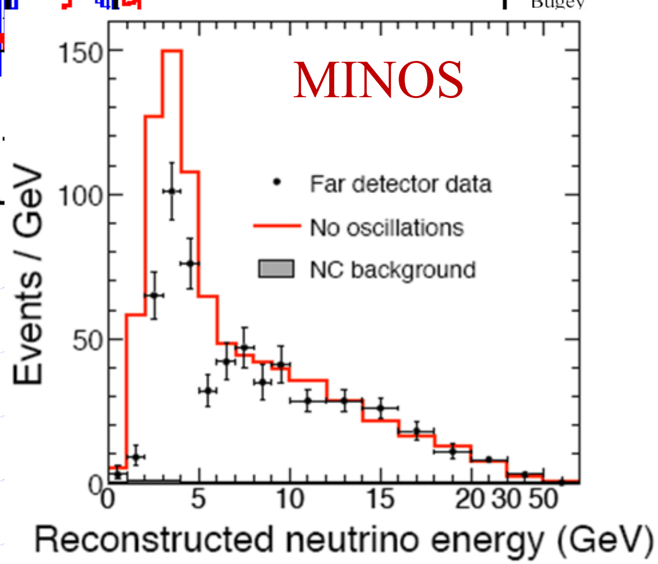
Hard: low cross section for neutrino interaction!

Produce large quantities of neutrinos

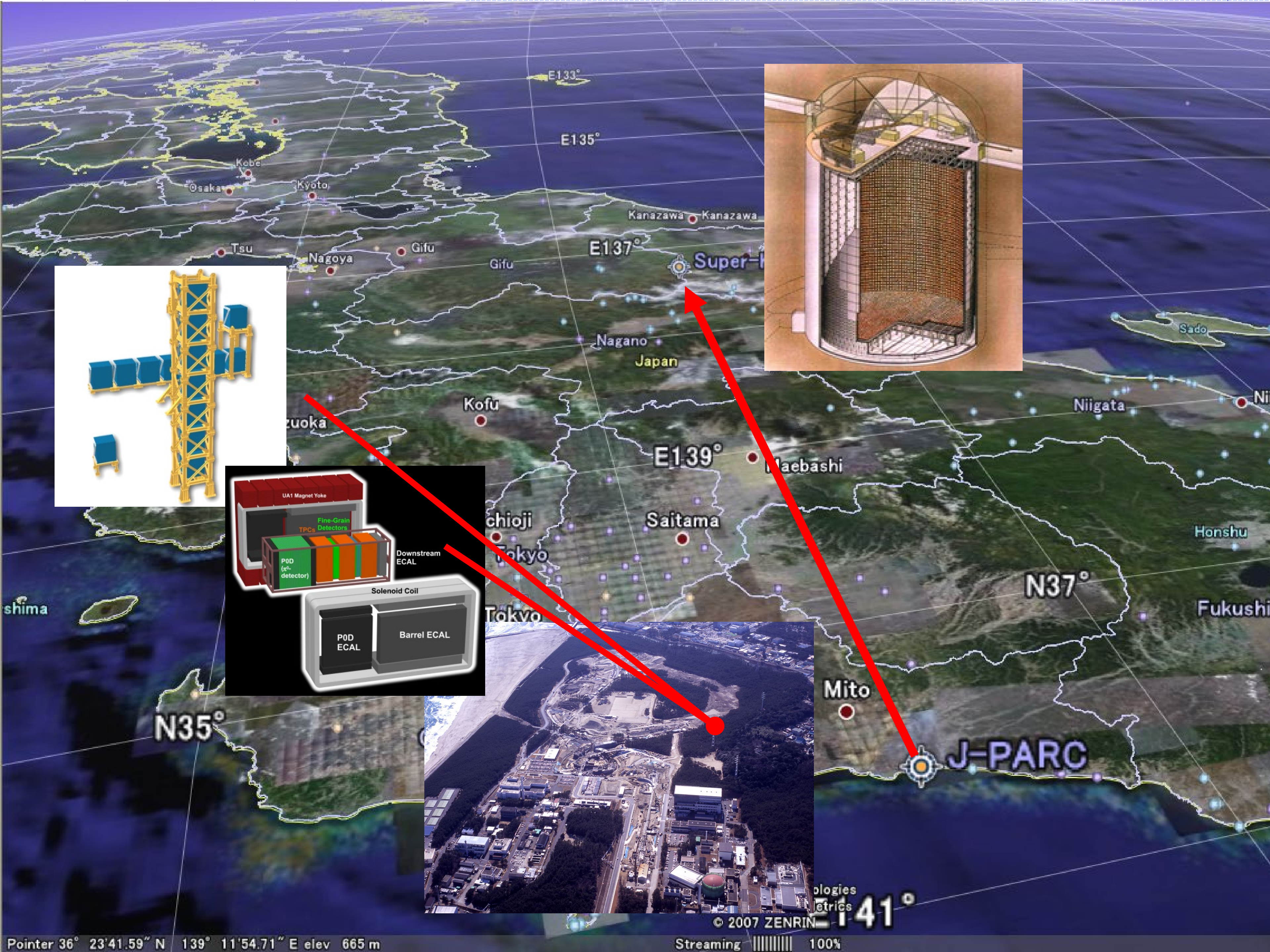
- Accelerator (mainly muon neutrinos and anti-neutrinos)
- Reactor (electron anti-neutrinos)
- Sun (electron neutrinos)
- Atmospheric neutrinos (electron and muon neutrinos)

Evidence for ν oscillations from…





→ **Neutrinos have mass and mix!**


E133°
E135°
Kobe
Osaka
Kyoto
Kanazawa
Kanazawa
Tsu
Nagoya
Gifu
Gifu
E137°
Nagano
Japan
Kofu
E139°
Saitama
Tokyo
Tokyo
Niigata
Sado
Honshu
N37°
Mito
J-PARC
N35°
E141°
UA1 Magnet Yoke
Fine-Grain Detectors
TPCs
Downstream ECAL
P0D (π^0-detector)
Solenoid Coil
P0D ECAL
Barrel ECAL
© 2007 ZENRIN
Pointer 36° 23'41.59" N 139° 11'54.71" E elev 665 m
Streaming 100%

Neutrino detection

Use inverse beta decay

$\nu_e + n \rightarrow p + e^-$

$\bar{\nu}_e + p \rightarrow n + e^+$

$\nu_{\square} + n \rightarrow p + \mu^-$

$\bar{\nu}_\mu + p \rightarrow n + \mu^+$

$\nu_\tau + n \rightarrow p + \tau^-$

$\bar{\nu}_\tau + p \rightarrow n + \tau^+$

However: cross section is very small!

6.4 10^{-44} cm^2 at 1MeV

Probability for interaction in 100m of water = 4 10^{-16}

Neutrino detection - history

$\bar{\nu}_e + p \rightarrow n + e^+$

$e^+ + e^- \rightarrow \gamma\,\gamma$

$n + Cd \rightarrow Cd^* \rightarrow Cd + \gamma$

Reines-Cowan experiment

$\nu_e + n \rightarrow p + e^-$

$\nu_e + {}^{37}Cl \rightarrow {}^{37}Ar^* + e^-$

${}^{37}Ar^* \rightarrow {}^{37}Ar + \gamma$

Davies experiment

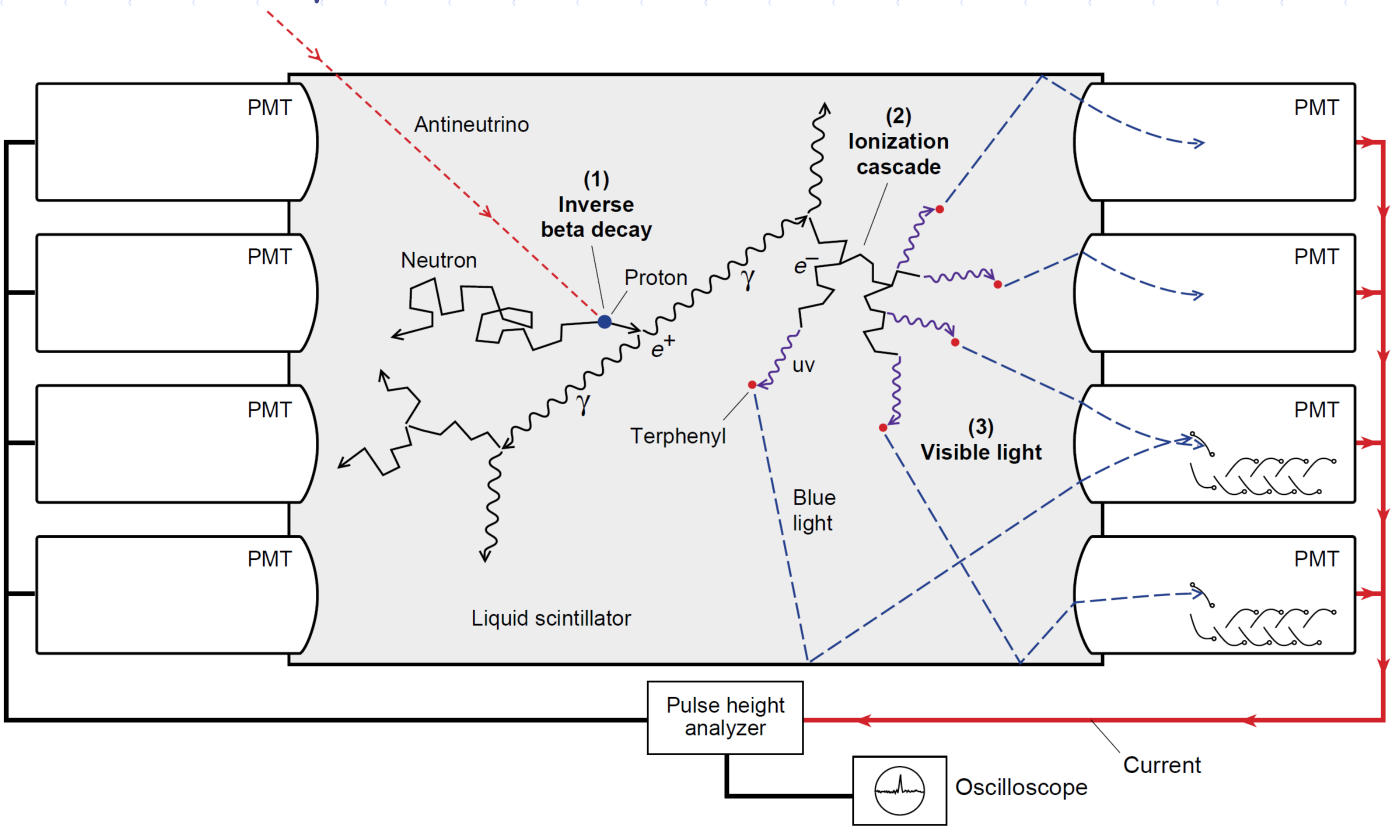
Neutrino detection - history

$\overline{\nu}_e + p \rightarrow n + e^+$

$e^+ + e^- \rightarrow \gamma\,\gamma$

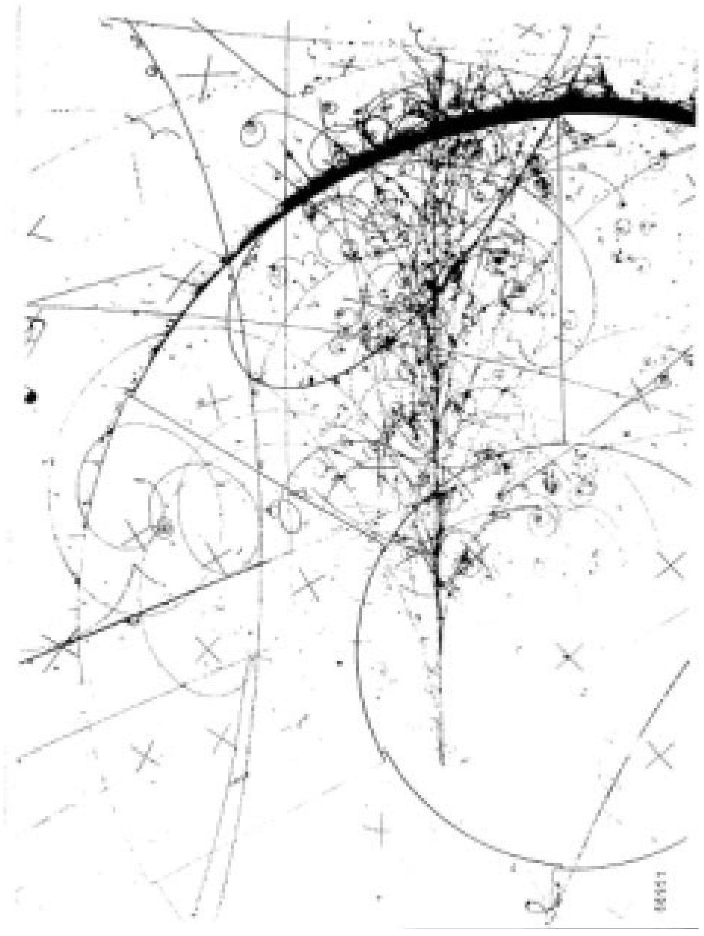
$n + Cd \rightarrow Cd^* \rightarrow Cd + \gamma$

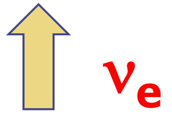
Reines-Cowan experiment



Electron neutrino detected in a bubble chamber

Electron neutrino produces an electron, which then starts a shower. Tracks of the shower are curved in the magnetic field.





Which type of neutrino?

Identify the reaction product, e□□□ and its charge.

Water detectors (e.g. Superkamiokande)

muon: a sharp Cherenkov ring

electron: Cherenkov ring is blurred (e.m. shower development)

tau: decays almost immediately – after a few hundred microns to one or three charged particles

High energy neutrinos

Interaction cross section:

Neutrinos:

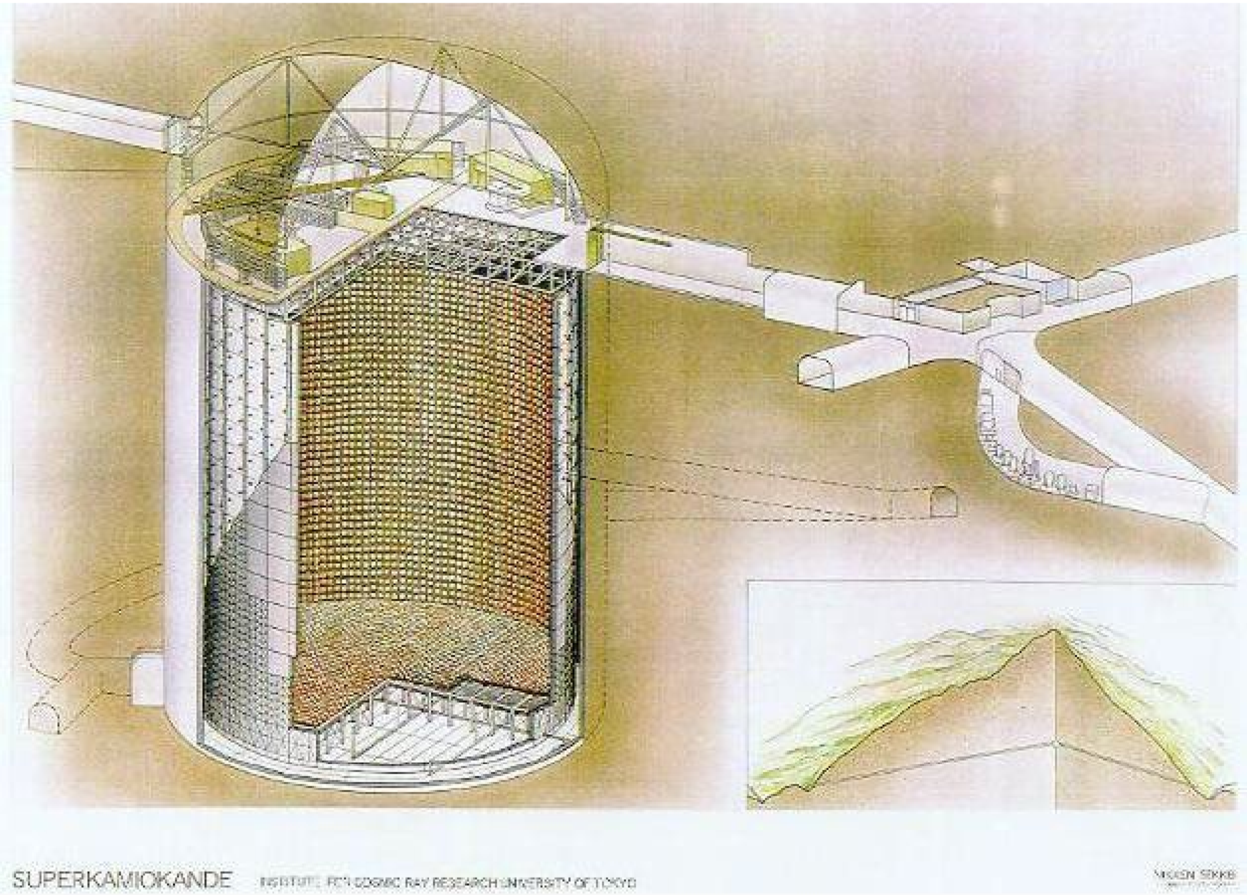
$0.67\ 10^{-38}$ E/1GeV cm^2 per nucleon

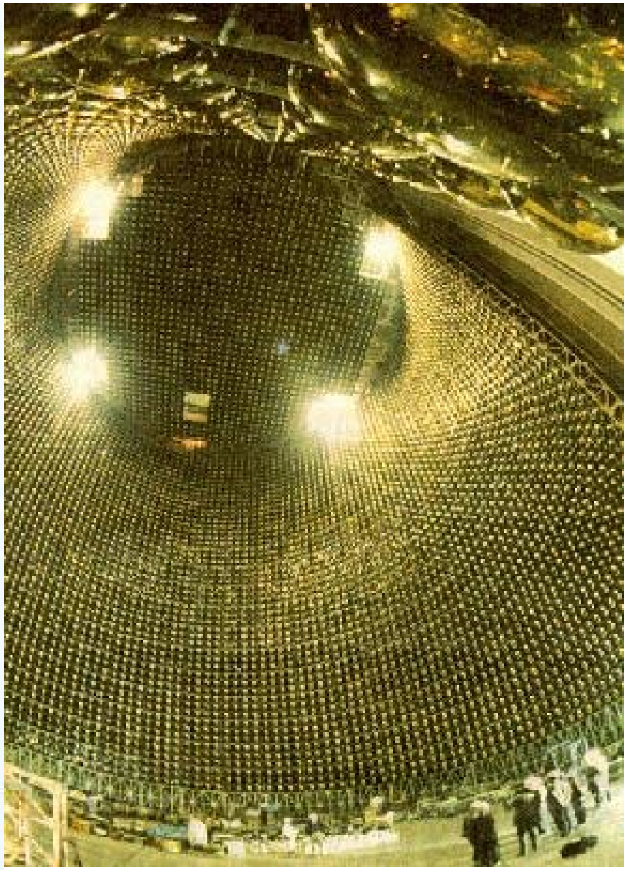
Antineutrinos:

$0.34\ 10^{-38}$ E/1GeV cm^2 per nucleon

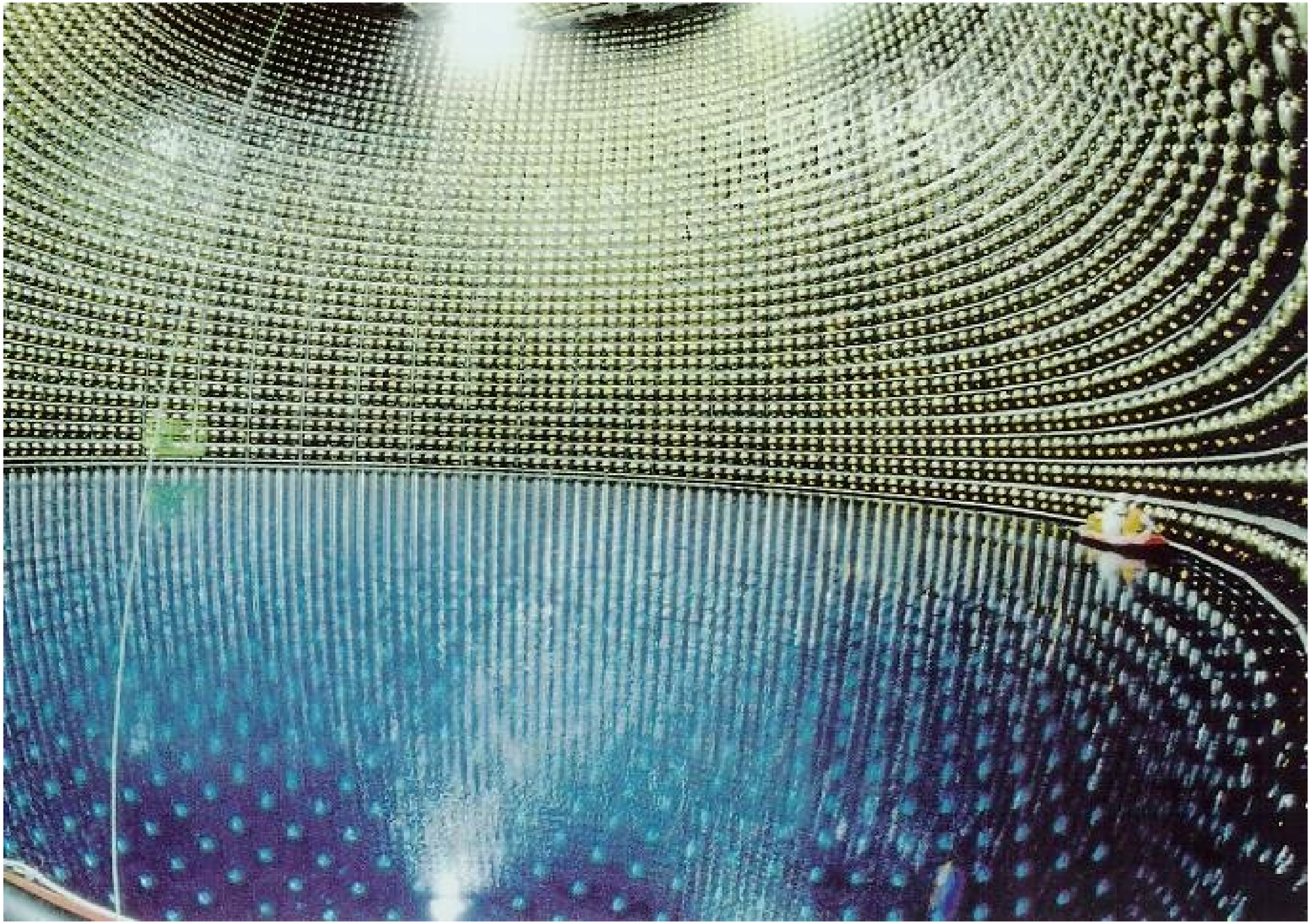
At 100 GeV, still 11 orders below
the proton-proton cross section

Superkamiokande: an example of a neutrino detector



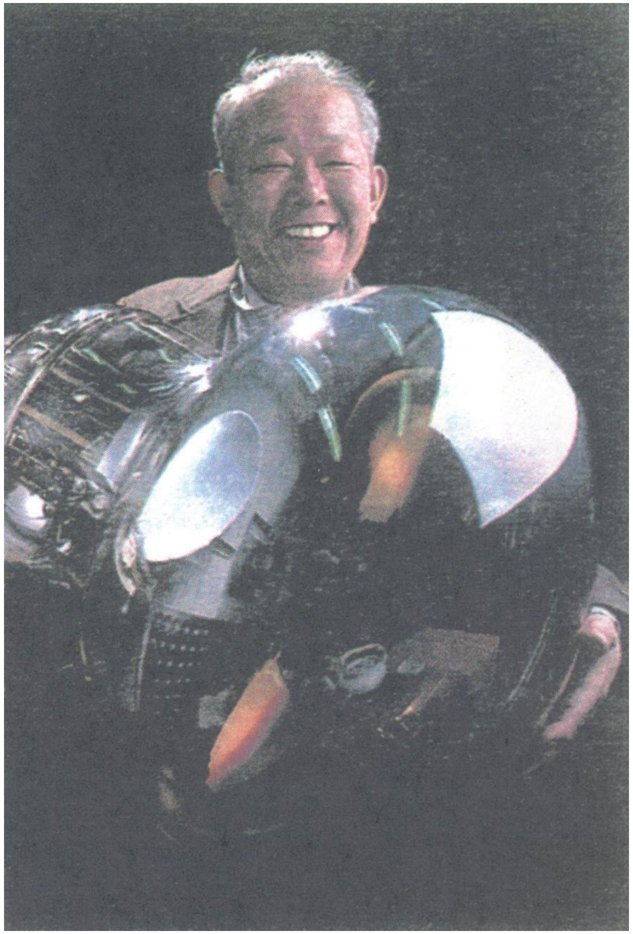


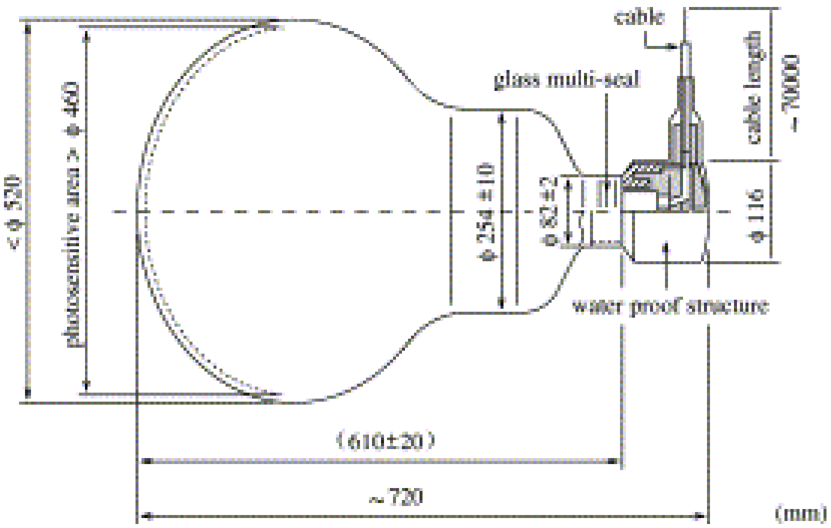
Superkamiokande: an example of a neutrino detector



Superkamiokande: detection of Cherenkov photons

Light sensors: HUGE photomultipler tubes





Masatoshi Koshiba Nobel prize 2002 (together with R. Davis)

Superkamiokande: an example of a neutrino detector

Kamiokande Detector ("Kamioka Nucleon Decay Experiment"):
1000 8" PMTs in 4500-tonne pure water target

Limits on proton decay,
First detection of neutrinos from supernova,
11 events from SN in Large Magellanic Cloud, Feb 23, 1987

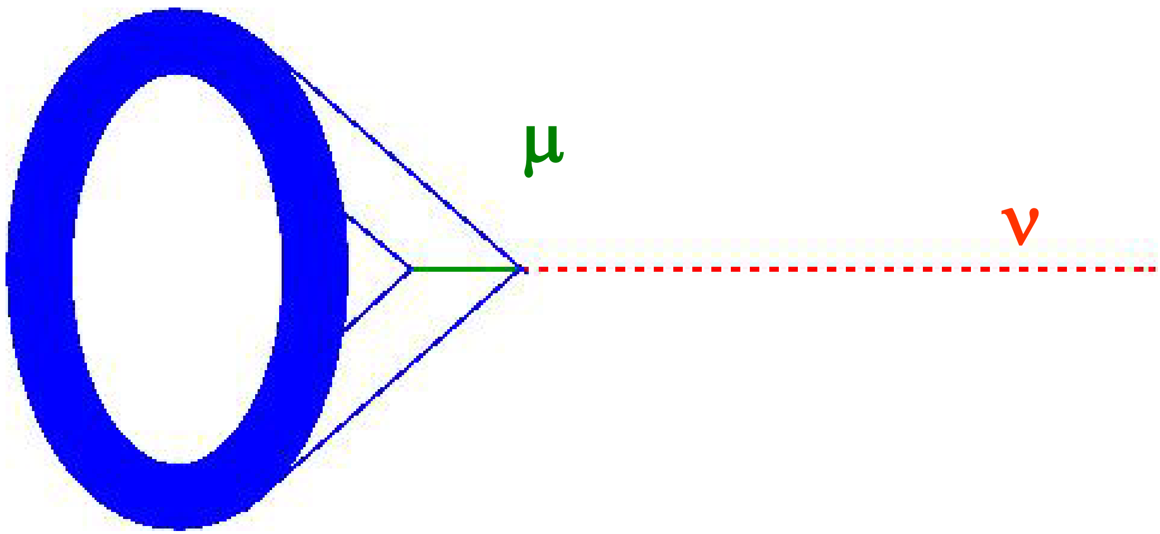
Super-Kamiokande Detector
11000 20" + 1900 8" PMTs in 50000-tonne pure water target

- Operation since 1996, measurements of neutrino oscillations via up down asymmetry in atmospheric ν rate
- Solar ν flux (all types) 45% of that expected

- Accident November 2001: loss of 5000 20" PMTs, replaced after a major effort

Superkamiokande: detection of electrons and muons

How to detect muons or electrons? Again through Cherenkov radiation, this time in the water container. Neutrino turns into an electron or muon.

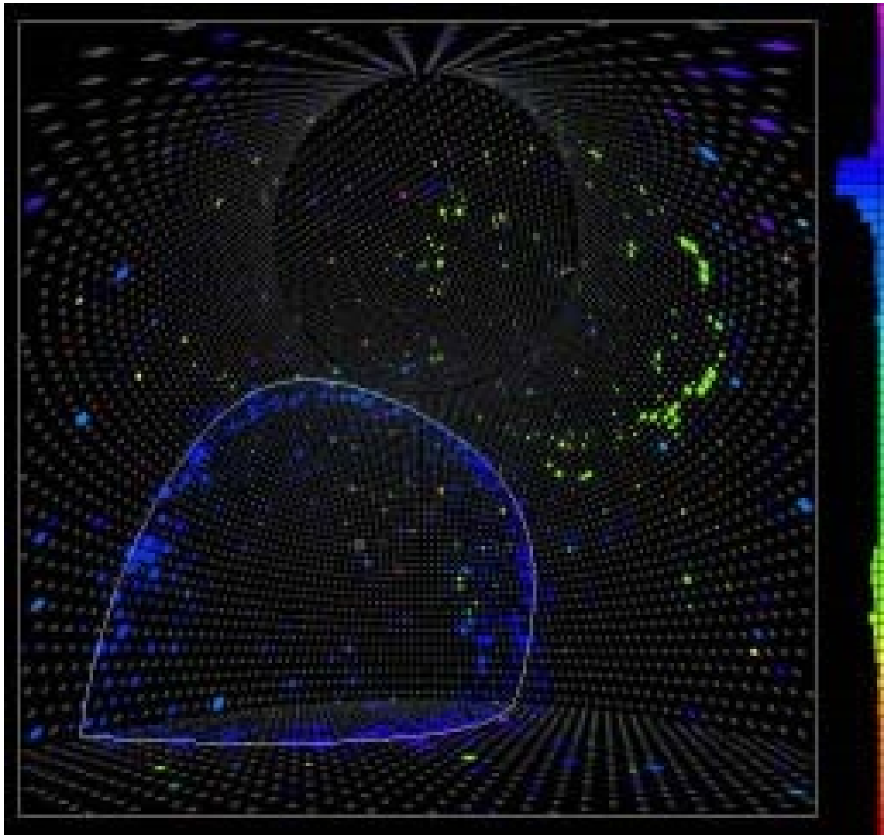


Muons and electrons emit Cherekov photons → ring at the container wals

- Muon ring: sharp edges
- Electron ring: blurred image (bremstrahlung)

Superkamiokande: muon event

Muon 'ring' as seen by the photon detectors



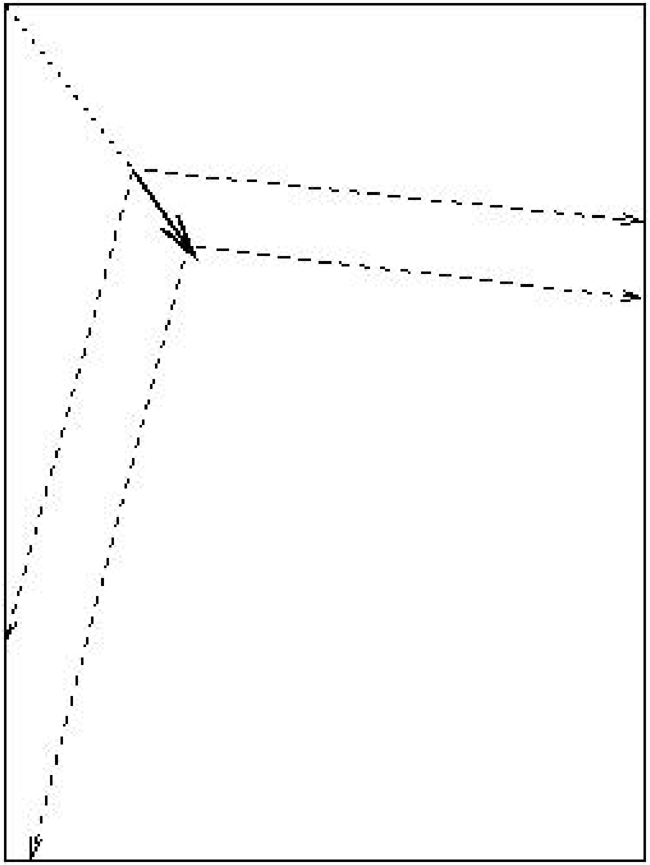
Muon vs electron

Cherenkov photons from a muon track:

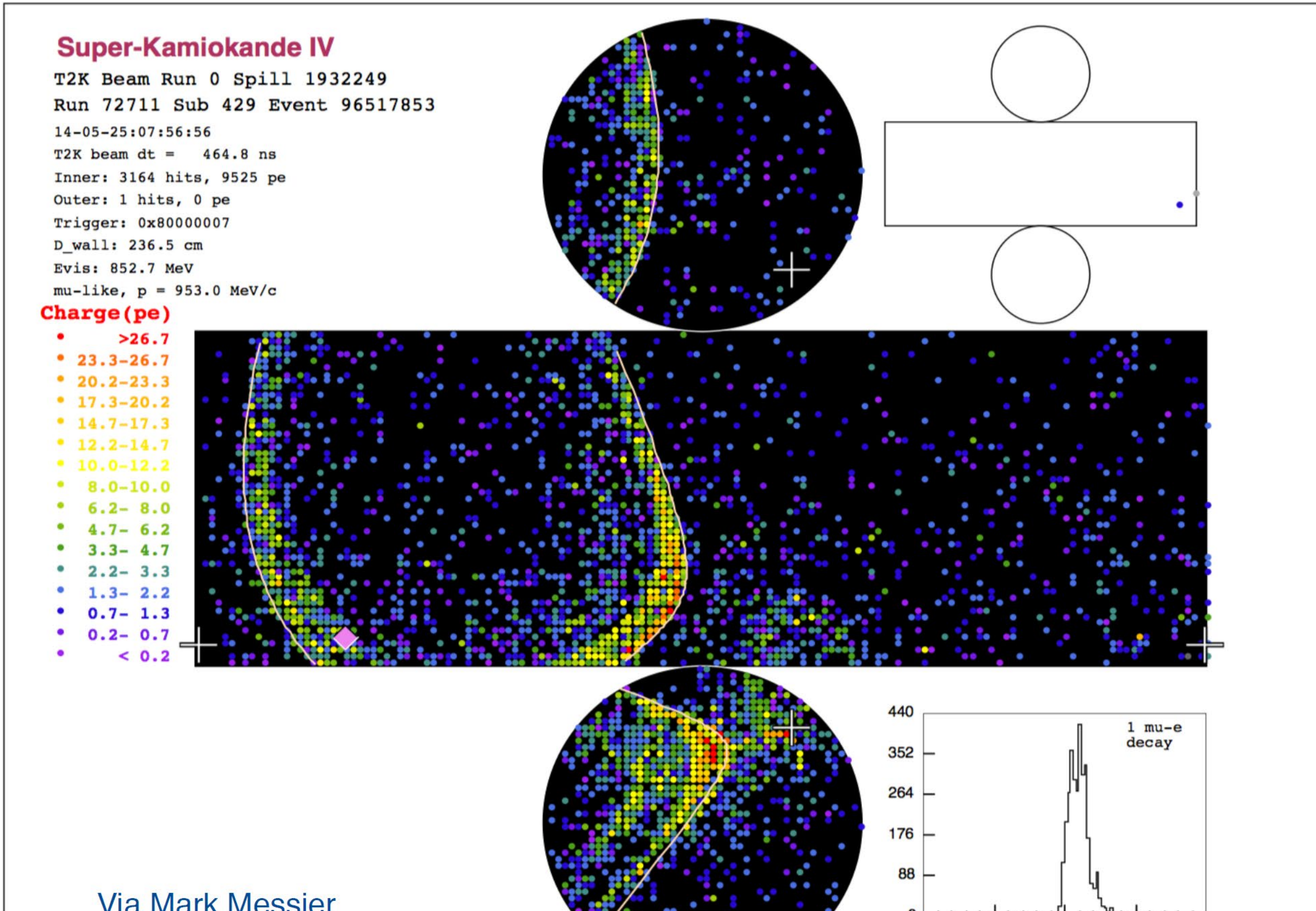
Example: 1GeV muon neutrino

Track length of the resulting muon: $L=E/(dE/dx)=$ $=1GeV/(2MeV/cm)=5m$

→ a well defined “ring” on the walls

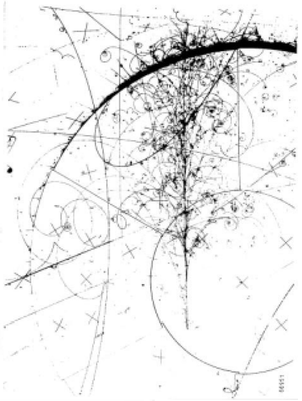


Muon event: photon detector, cillinder walls

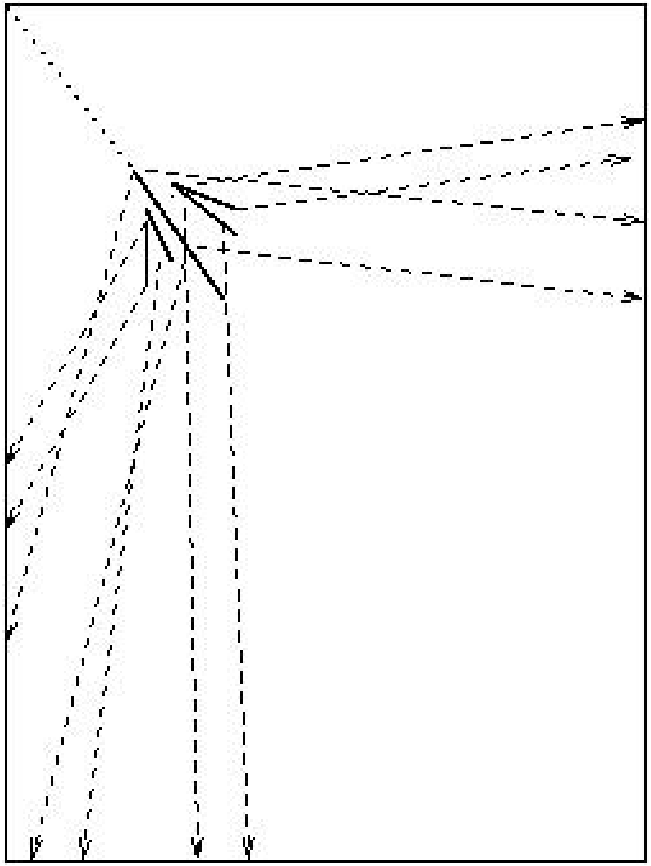


ν_μ charged $-$ current

Cherenkov photons from an electron track

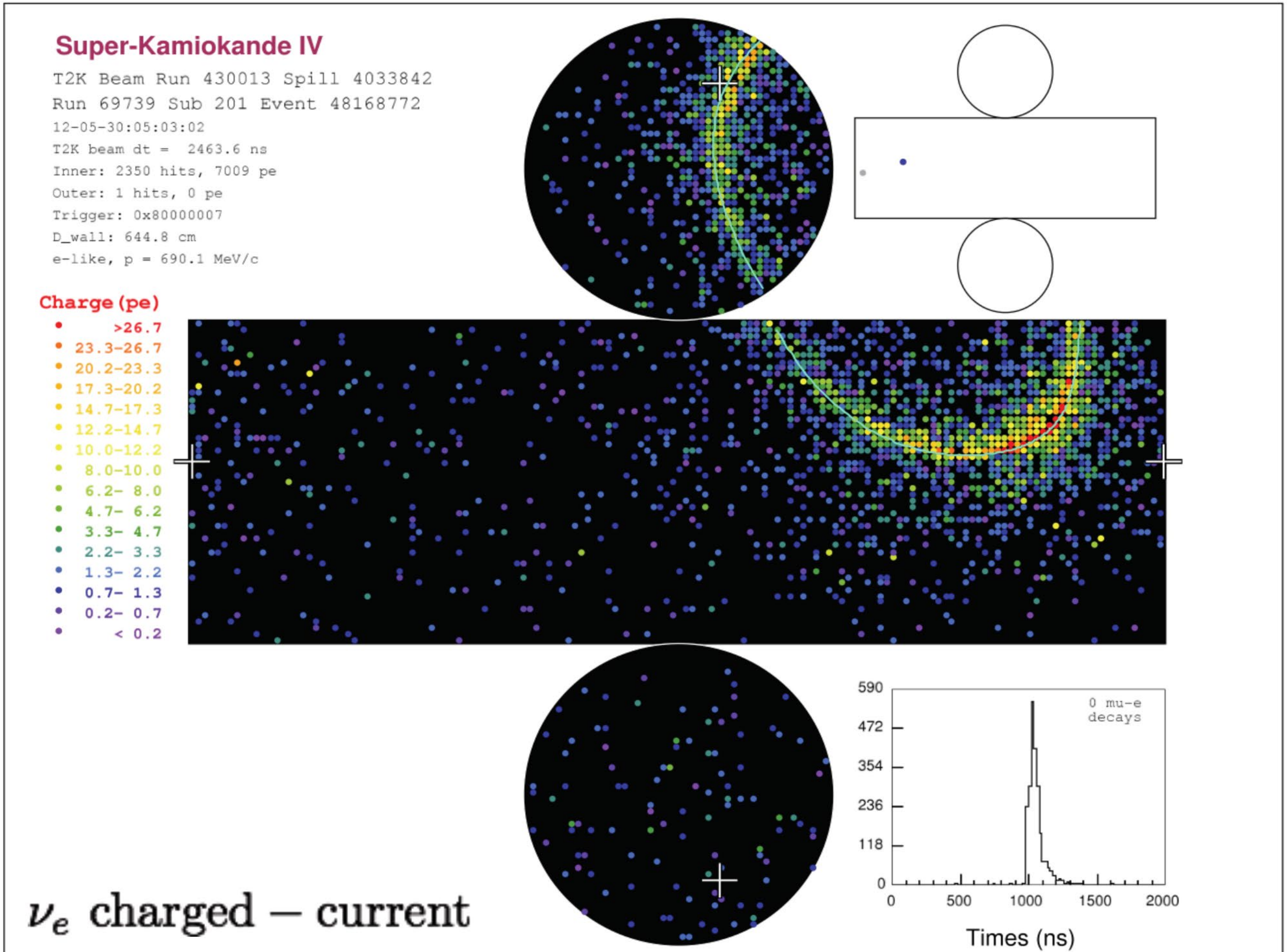


- Electron starts a shower!
- Cherenkov photons from an electron generated shower
- Example: 1GeV el. neutrino
- Shower length:
- $L=X_0*\log_2(E/E_{crit})= 36cm*\log_2(1GeV/10MeV) =2.5m$

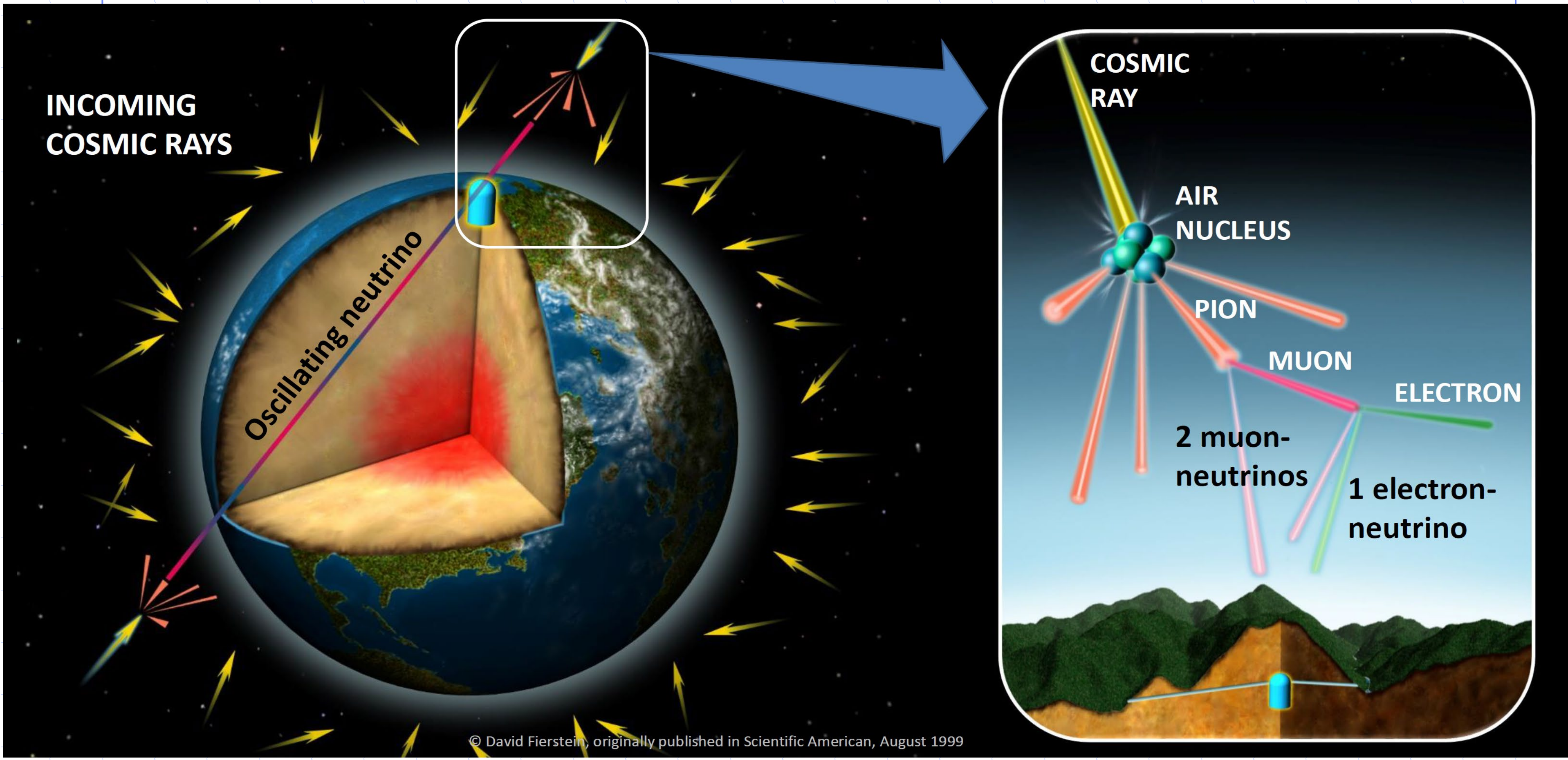


- Shower particles are not parallel to each other
- -> a blurred, less well defined "ring" on the walls

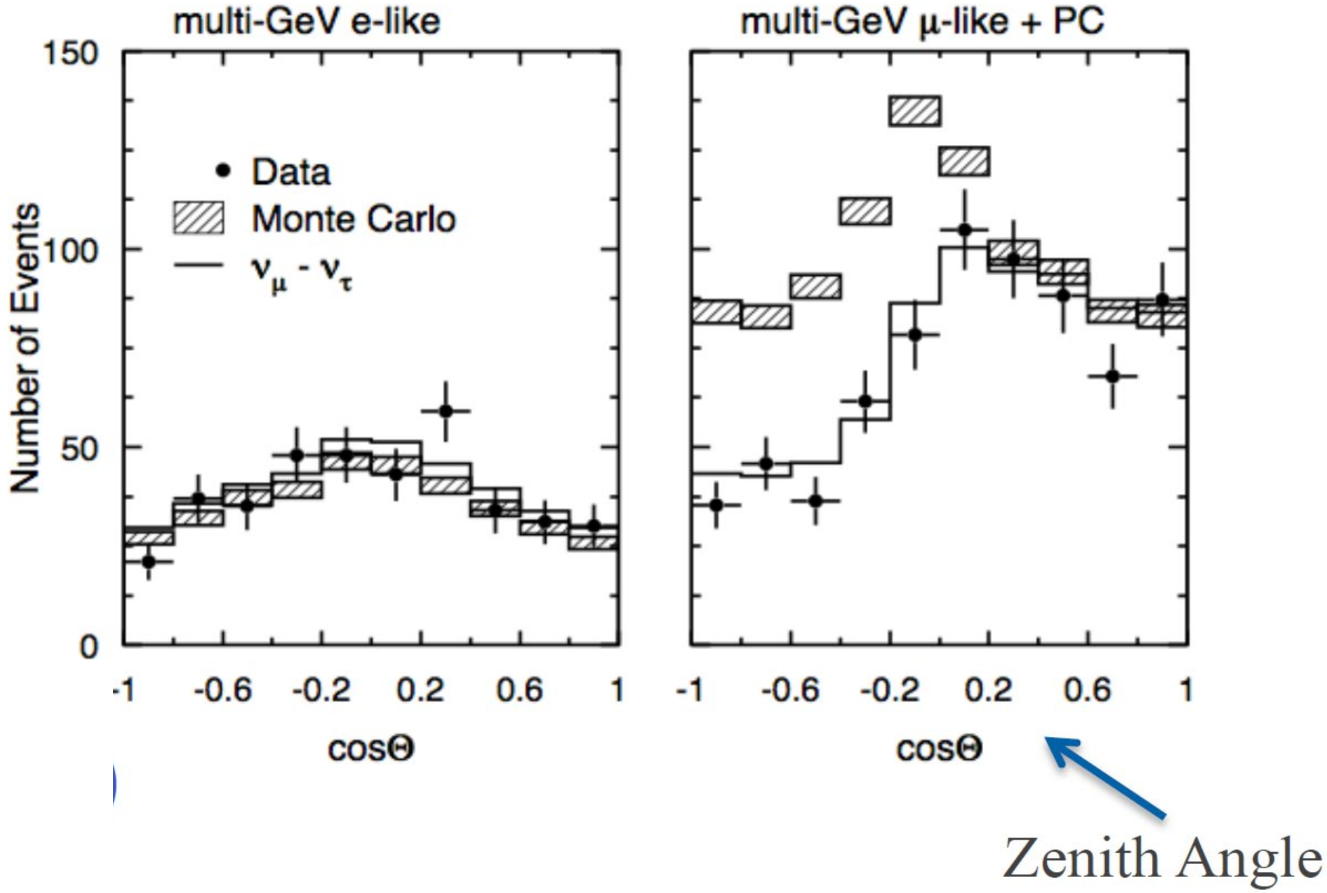
Electron event: blurred ring



Neutrino mixing as observed in atmospehric neutrinos



Neutrino mixing as observed in atmospehric neutrinos



Electron neutrinos: no mixing as they cross the Earth

Mion neutrinos: clear mixing effect for long propagation distances (e.g., for neutrinos with paths across the Earth, cosΘ = -1) → they turn into the third neutrino type ν_τ

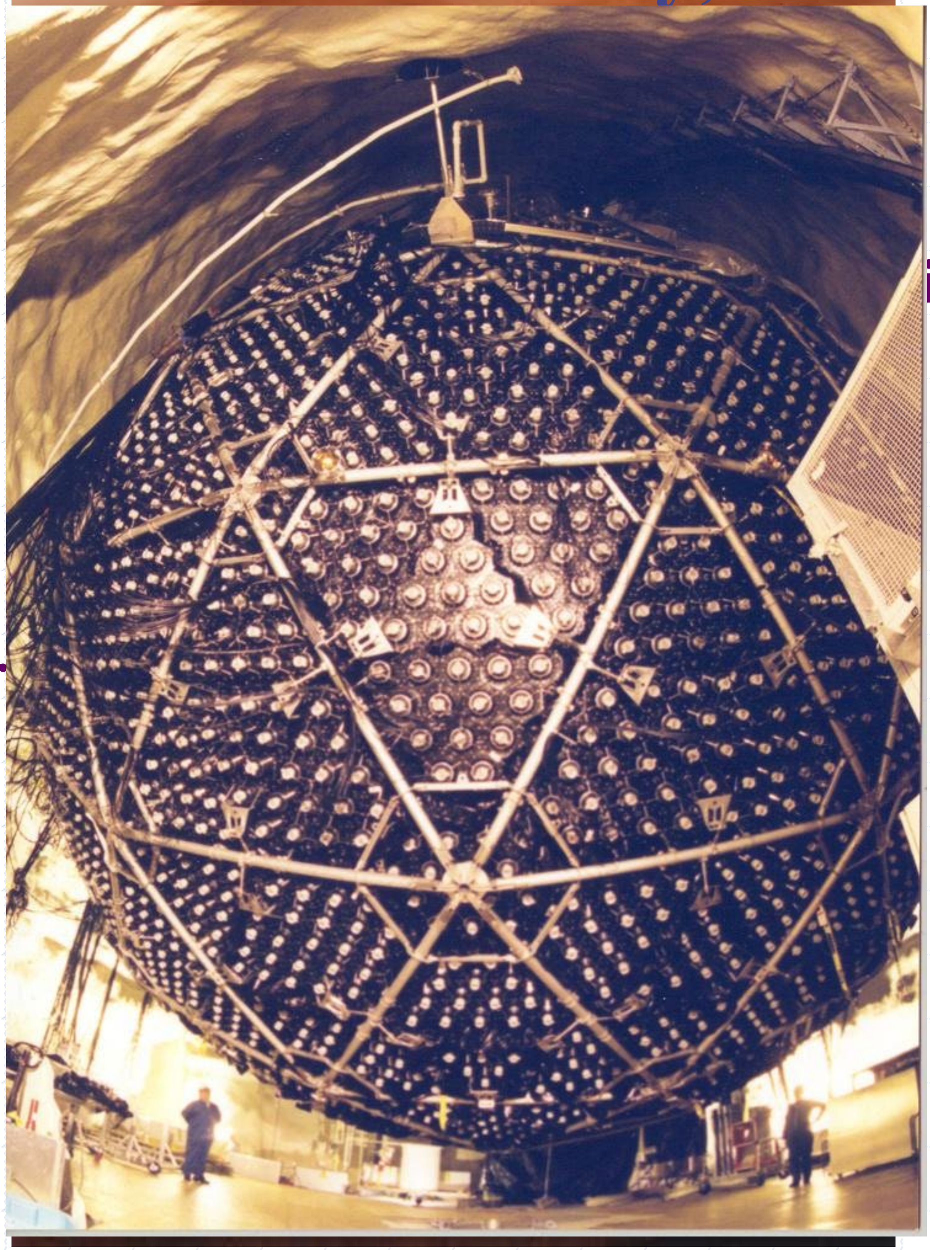
Detection of low energy neutrinos (from sun)

Solution to solar neutrino problem;
  Why is the ν_e flux at the earth's surface (e.g. Homestake) ~ 1/3 that expected from models of solar ν_e production?

Do□ 's oscillate:

change flavour ➔ ν_e
➔ ν_μ
➔ ν_τ

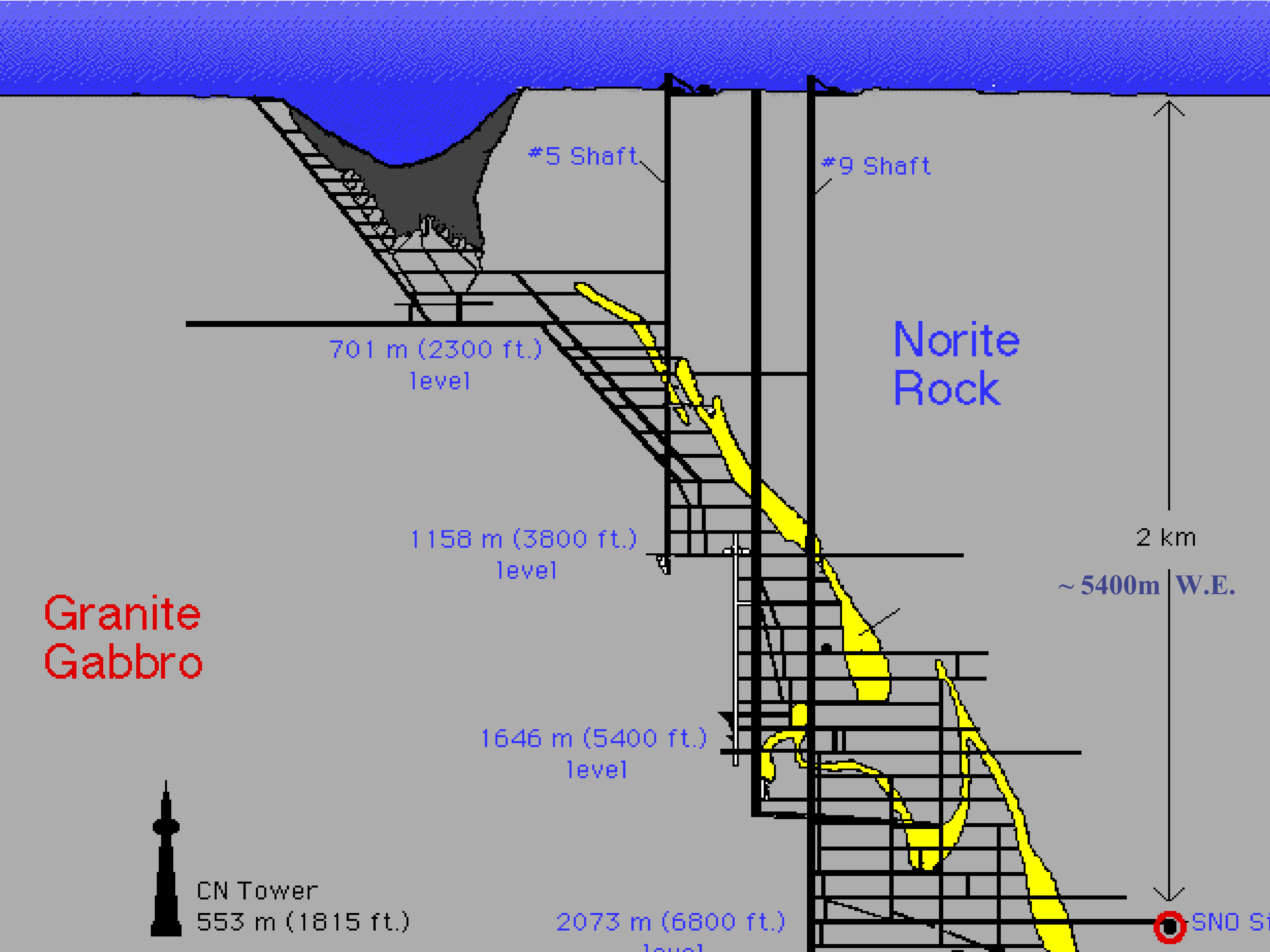
Sudbury Neutrino Observatory, Ontario, Canada



Pure Water
Radiation shield
in cavern Ø 22m,
Height 34m

1000 tonnes
Pure heavy water
in Ø=12m sphere

9456 8” PMTs
(Hamamatsu
R1408:
bi-alkali
photocathode)



#5 Shaft
#9 Shaft
Norite Rock
701 m (2300 ft.) level
1158 m (3800 ft.) level
2 km
~ 5400m W.E.
Granite Gabbro
1646 m (5400 ft.) level
CN Tower
553 m (1815 ft.)
2073 m (6800 ft.)

Sudbury Neutrino Observatory

Due to presence of D_2O, SNO detector sensitive to all 3 neutrino flavours:

ν Reactions in SNO

CC $$\nu_e + d \Rightarrow p + p + e^-$$

-Good measurement of ν_e energy spectrum
-Weak directional sensitivity ∝ 1-1/3cos(θ)
- ν_e only.

⟶ Č light

NC $$\nu_x + d \Rightarrow p + n + \nu_x$$

- Equal cross section for all ν types
- Measure total ^8B ν flux from the sun

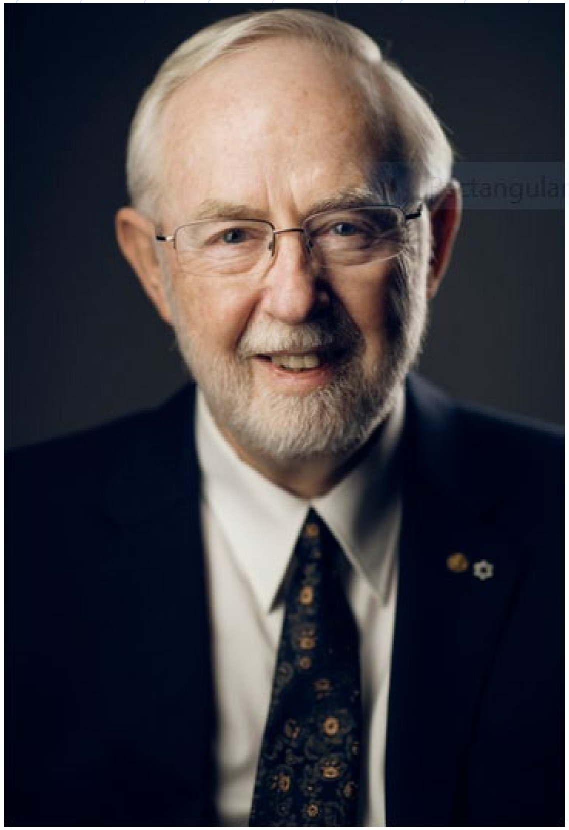
n captured by another deuteron ➔ γ scatters e ➔ Č light

ES $$\nu_x + e^- \Rightarrow \nu_x + e^-$$

⟶ Č light

2015: Nobel prize for neutrino mixing experiments

Takaaki Kajita

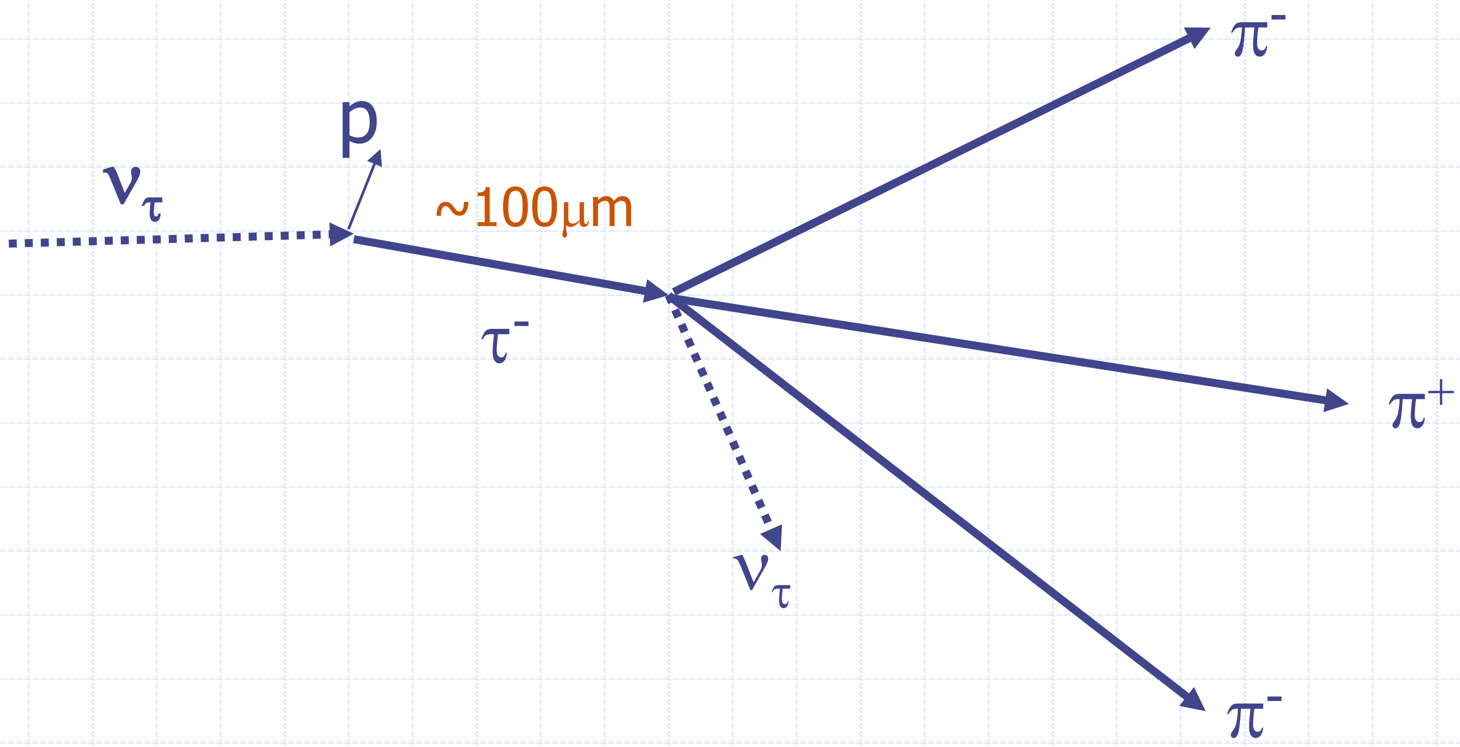


Arthur B. McDonald

Detection of $\boldsymbol{\tau}$ neutrinos 1

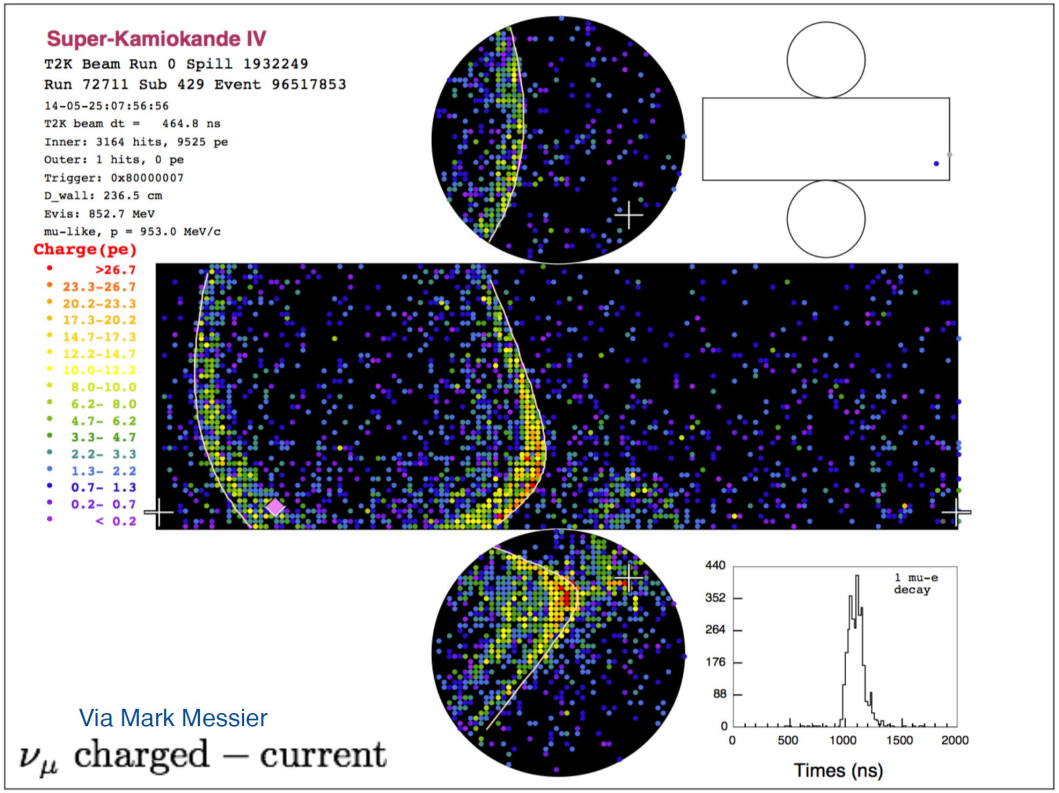
$\nu_{\square} + n \rightarrow p + \tau^-$

$\tau^- \rightarrow \pi^- \pi^- \pi^+ \nu_\tau$



Detection of τ neutrinos in multi-body τ decays

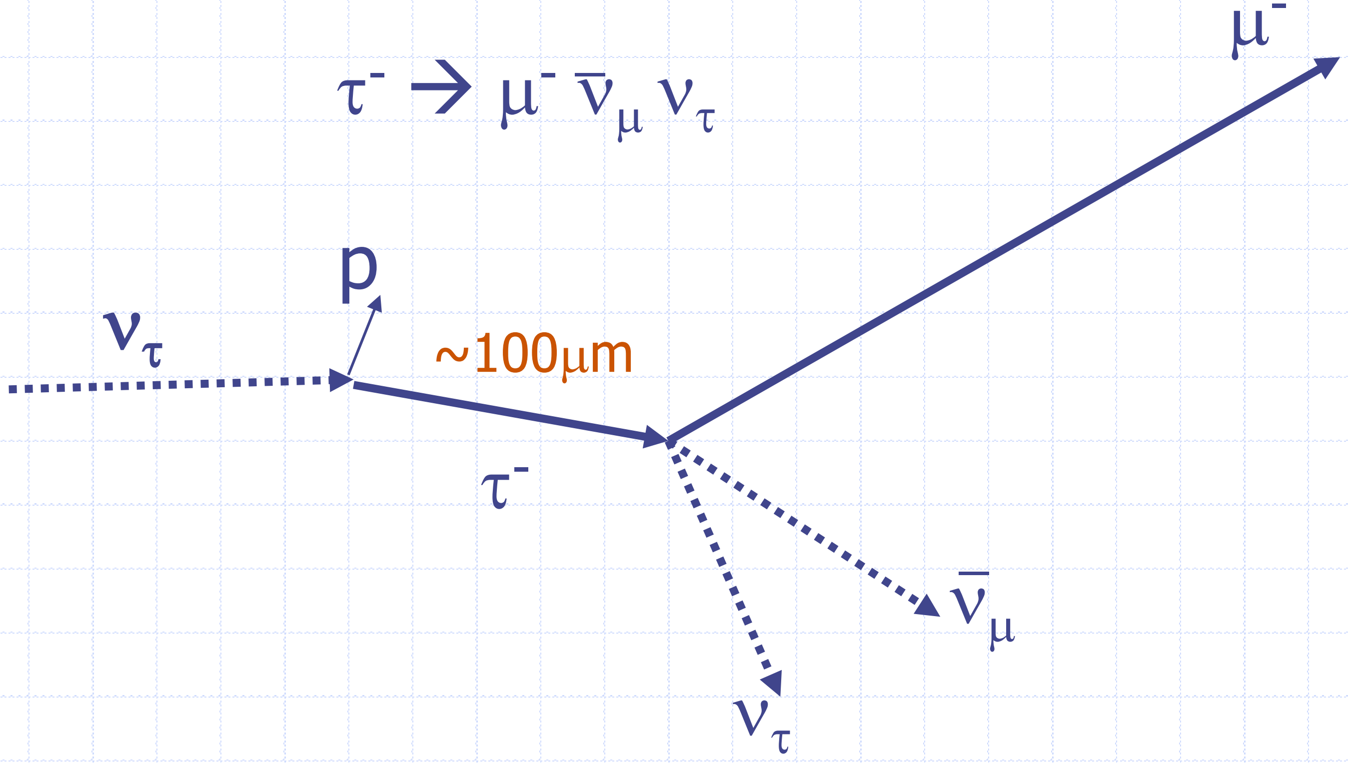
Tau lepton detection from tau neutrino interaction with nuclei in water:
- in $\tau^- \rightarrow \pi^- \pi^- \pi^+ \nu_\tau$ decay: look for 3 muon-like 'rings' (pions produce the same kind of rings as muons)
- in $\tau^- \rightarrow \pi^- \pi^0 \nu_\tau$ decay, $\pi^0 \rightarrow \gamma\gamma$: look for 1 muon-like 'ring' (from π^-) and 2 electron like (from gamma-ray showers)



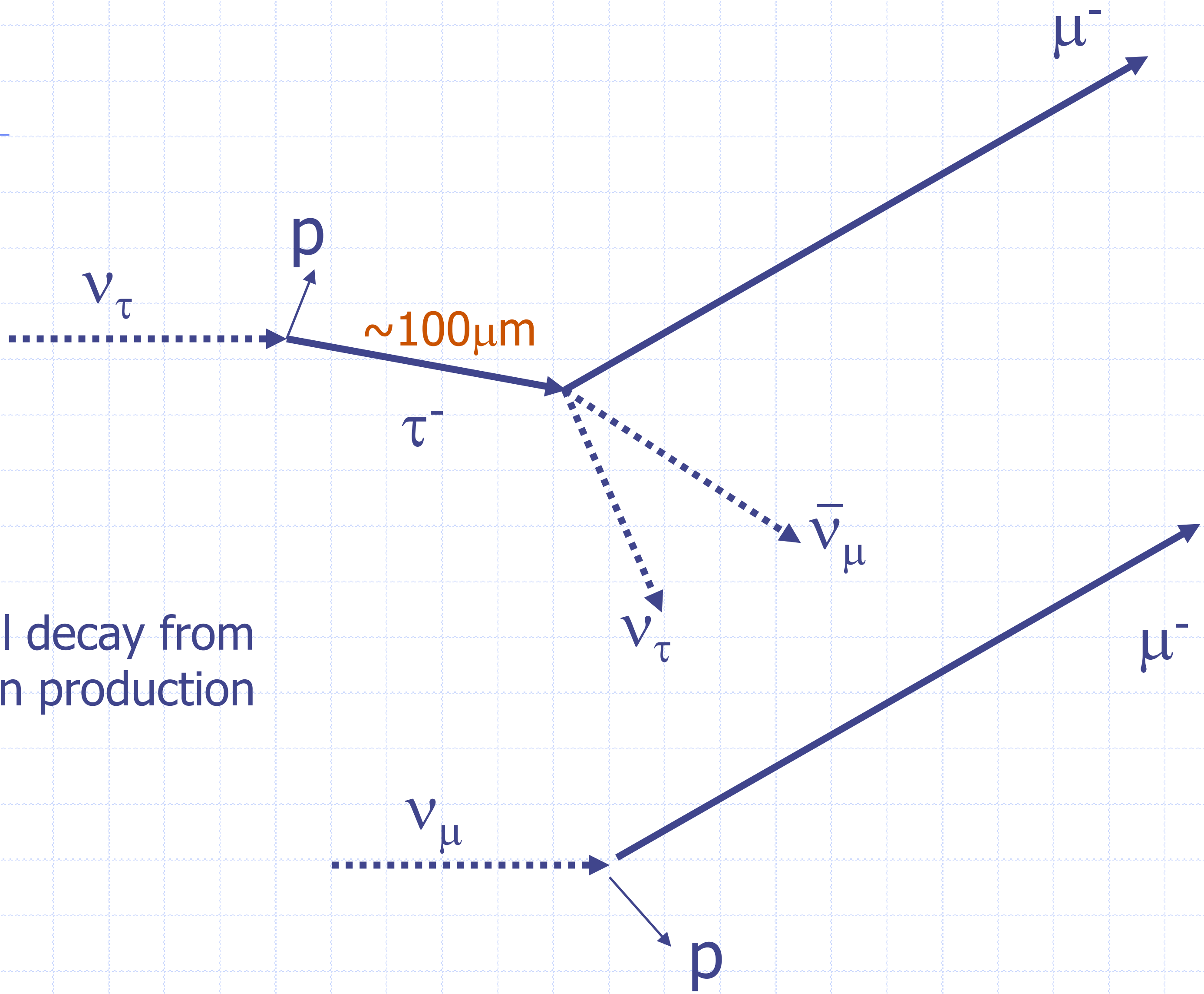
Detection of τ neutrinos 2

$\nu_\tau + n \rightarrow p + \tau^-$

$\tau^- \rightarrow \mu^- \bar{\nu}_\mu \nu_\tau$



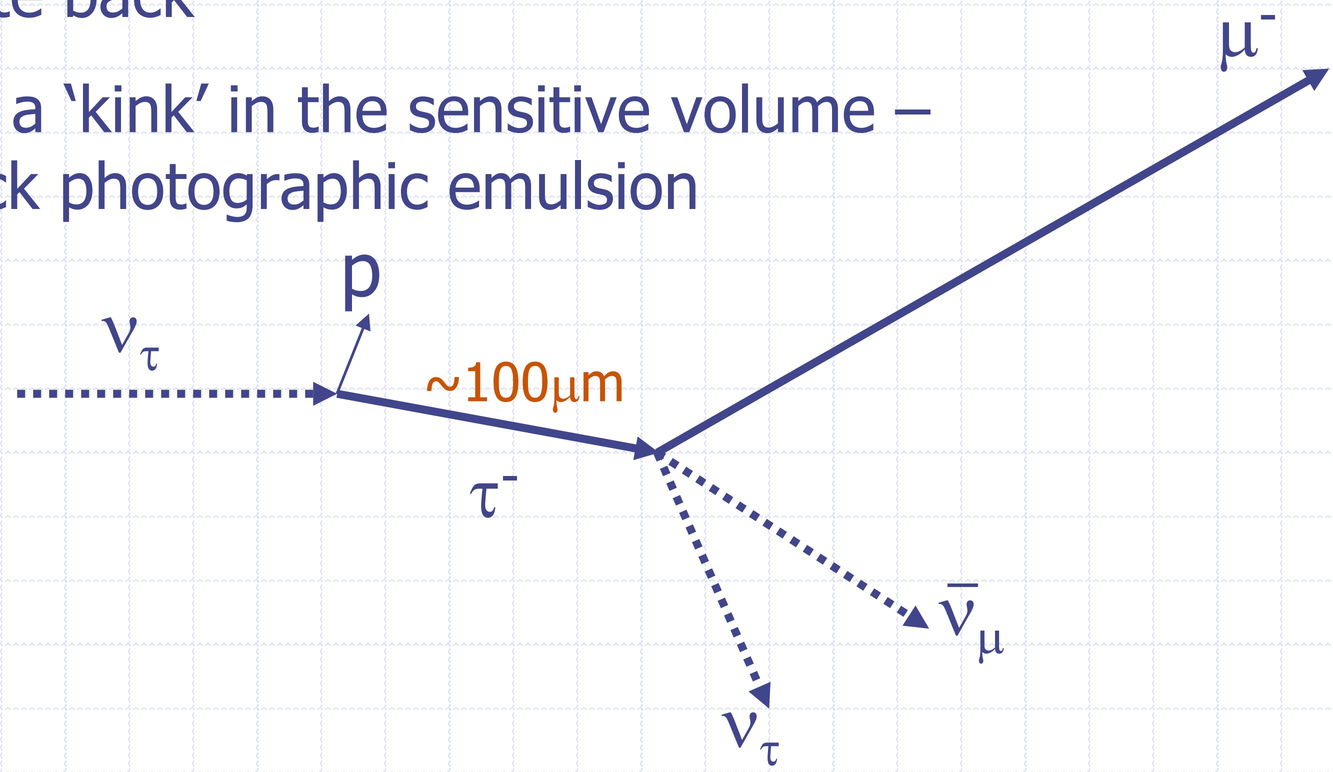
Detection of τ neutrinos 2



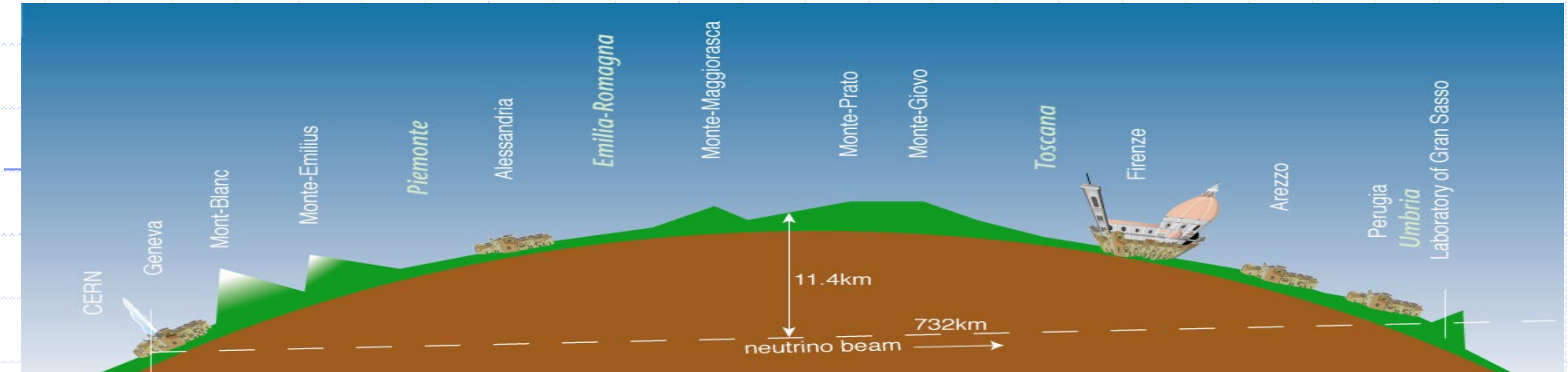
Separate signal decay from the direct muon production

Detection of τ neutrinos 3

- Detect and identifiy mion
- Extrapolate back
- Check for a ‘kink’ in the sensitive volume – e.g. a thick photographic emulsion



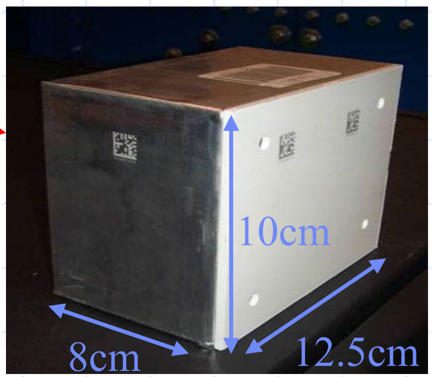
Detection of τ neutrinos: OPERA

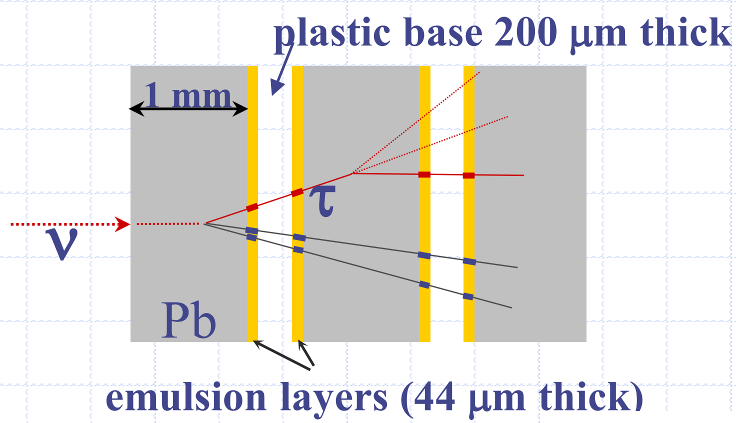


ν

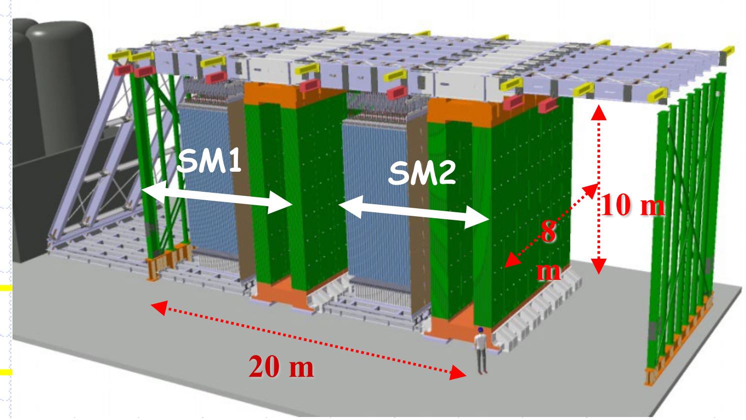
8.3 kg

$10X_0$



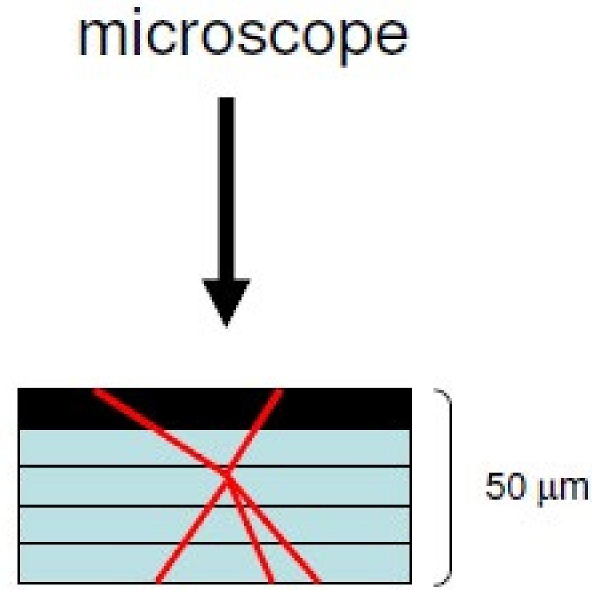


Detection unit: a brick with 56 Pb sheets (1mm) + 57 emulsion films



155000 bricks, detector total mass = 1.35 kton

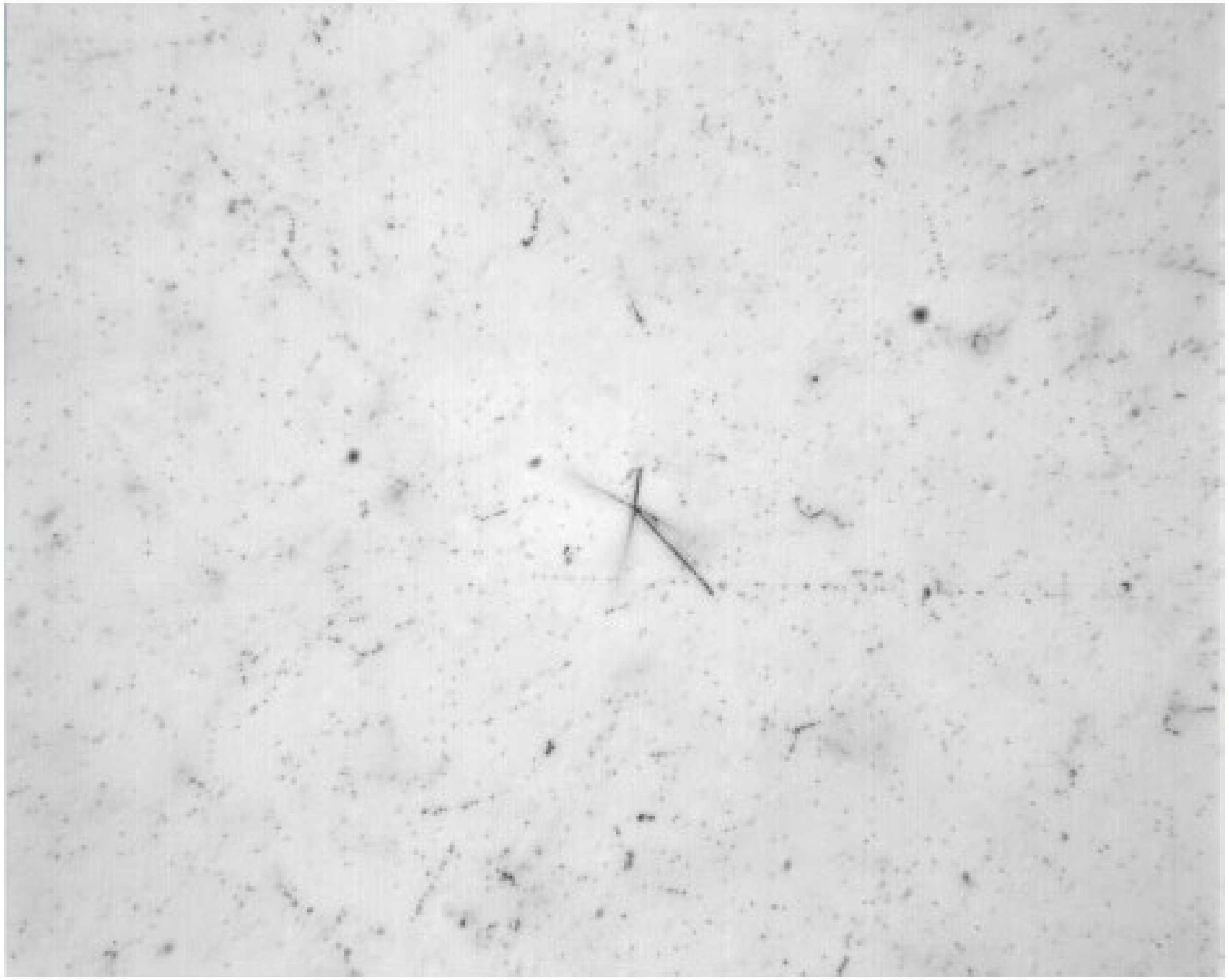
emulsion seen with microscope

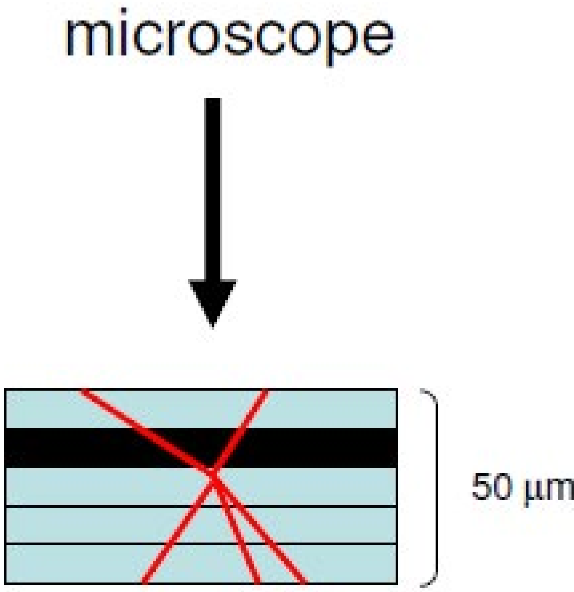


nuclear decay in emulsion

focal depth ~ 5μm

emulsion seen with microscope

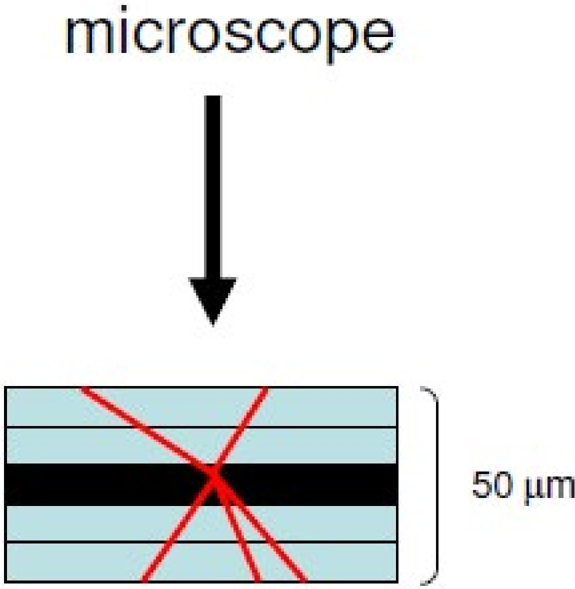




nuclear decay in emulsion

focal depth ~ 5µm

emulsion seen with microscope



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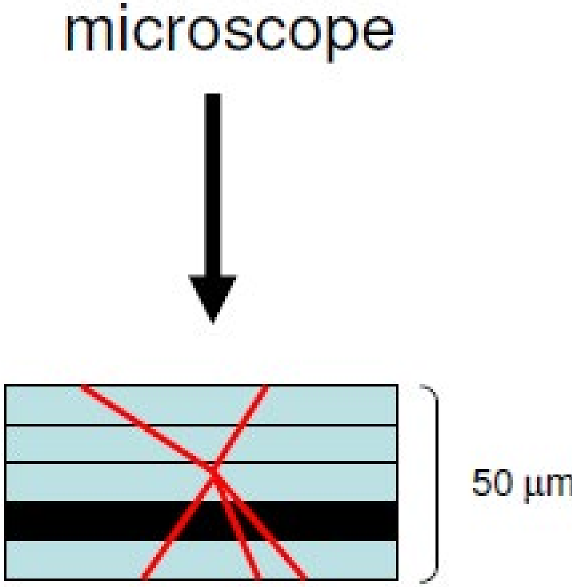
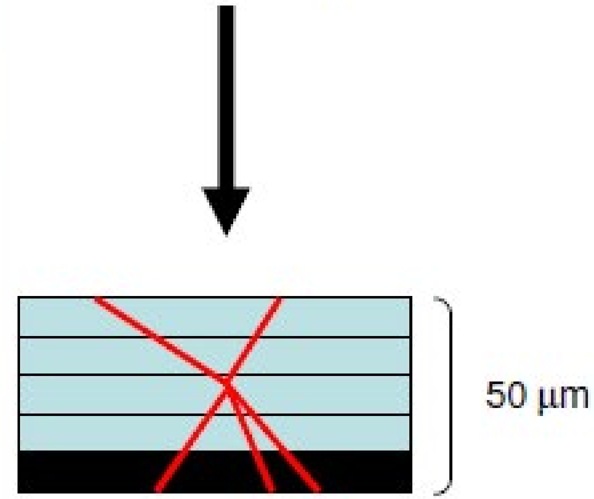


nuclear decay in emulsion

focal depth ~ 5µm

emulsion seen with microscope

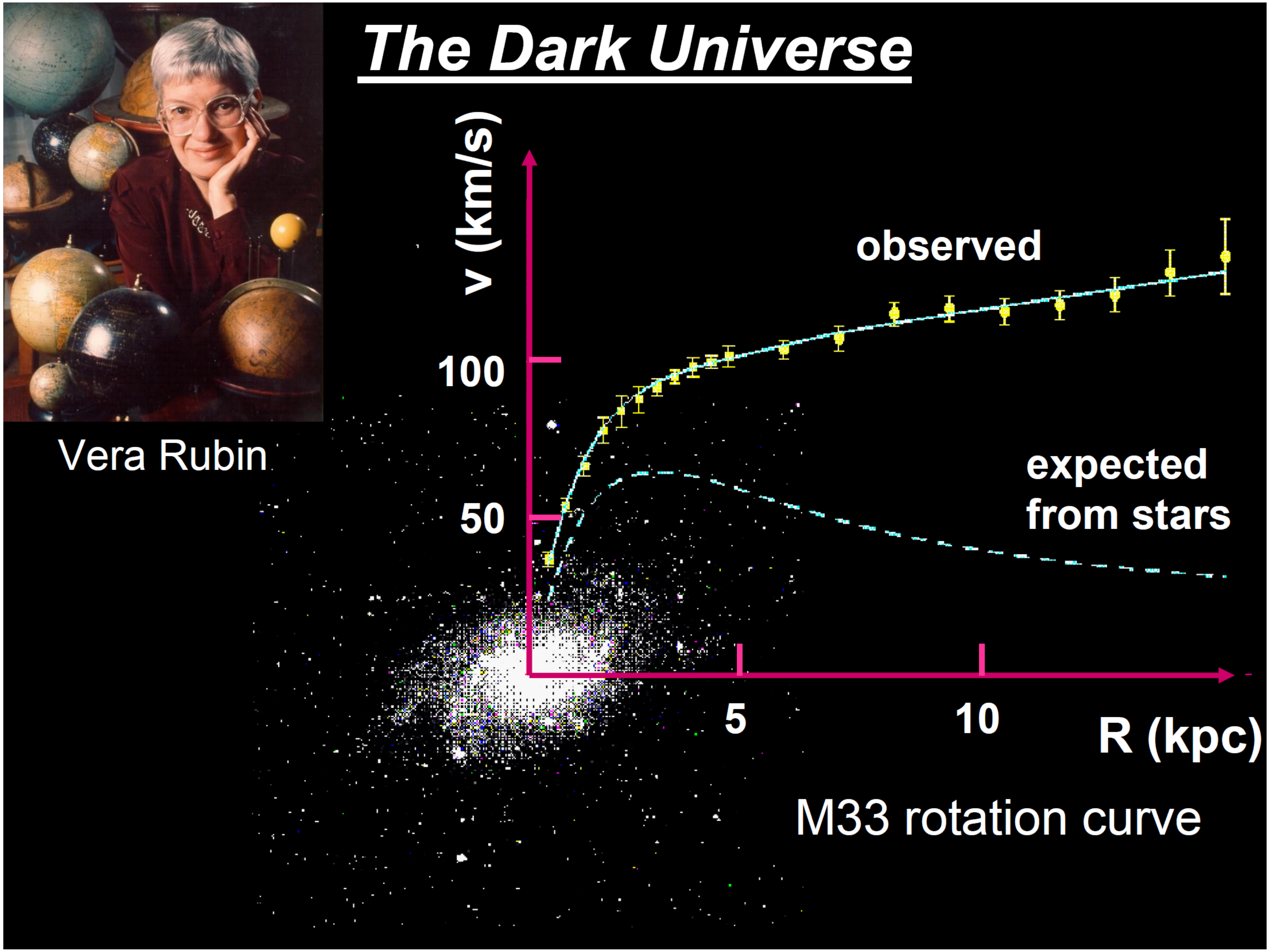
microscope



nuclear decay in emulsion

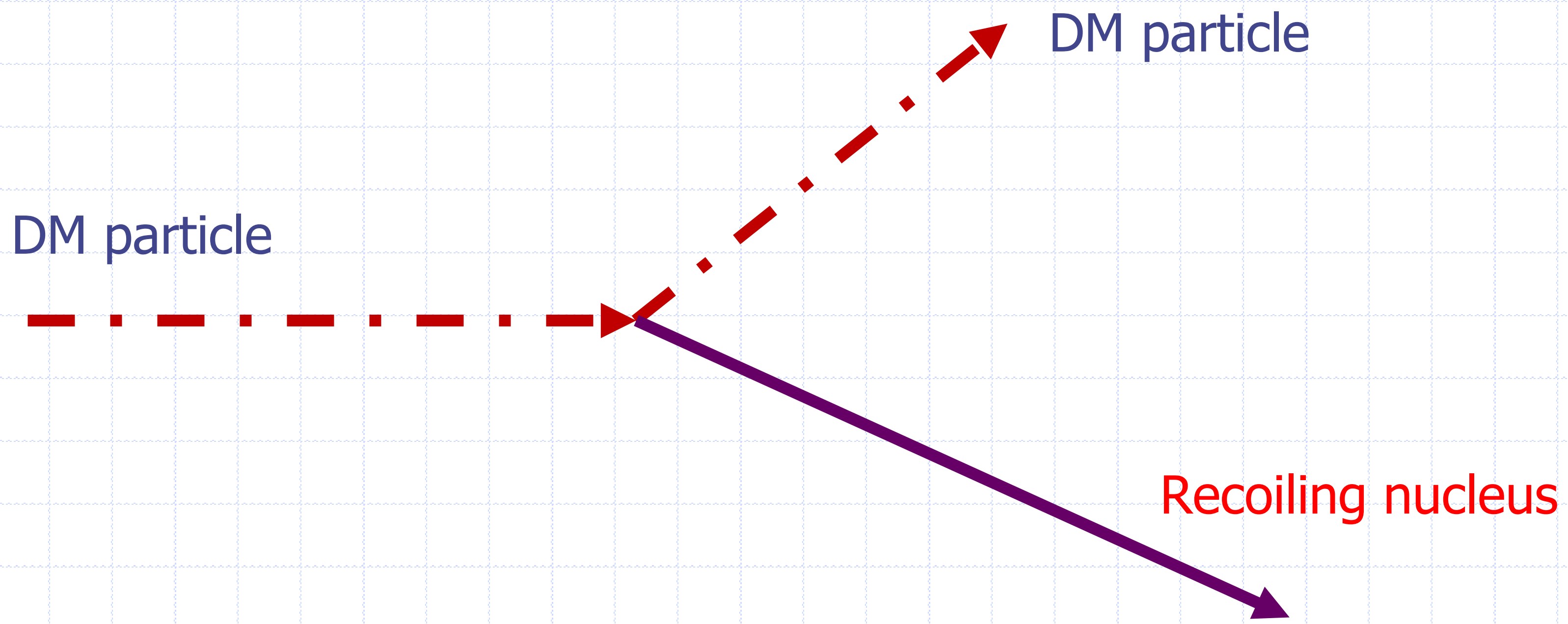
focal depth ~ 5μm

Direct searches for dark matter particles



Direct dark matter detection

A DM particle interacts with a nucleus (e.g., WIMP via weak interaction)



→Detect the recoiling nucleus through:

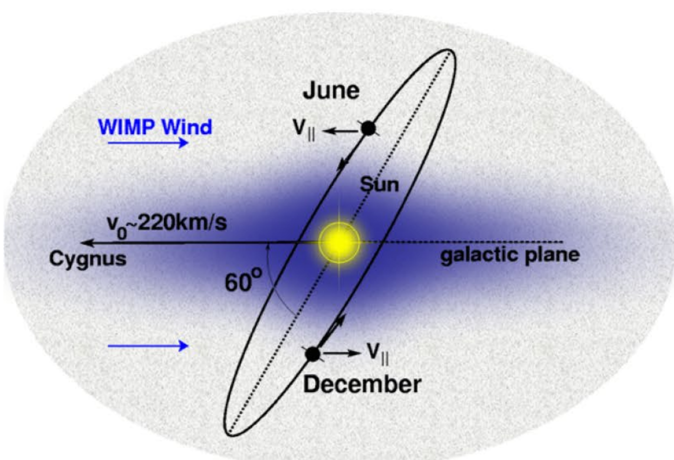
scintillation, ionization, heat deposition (phonons)

Direct dark matter detection

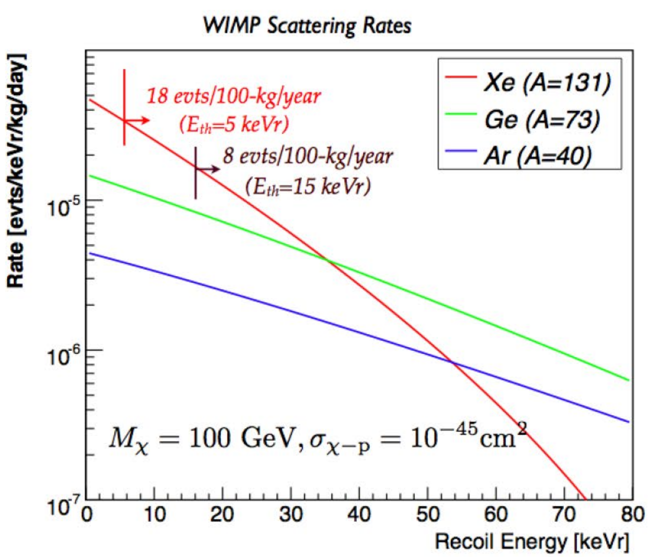
- Requirements for a dark matter detector
  - Large detector mass
  - Low energy threshold $\sim$ few keV's
  - Very low background and/or background discrimination

- Possible signatures of dark matter

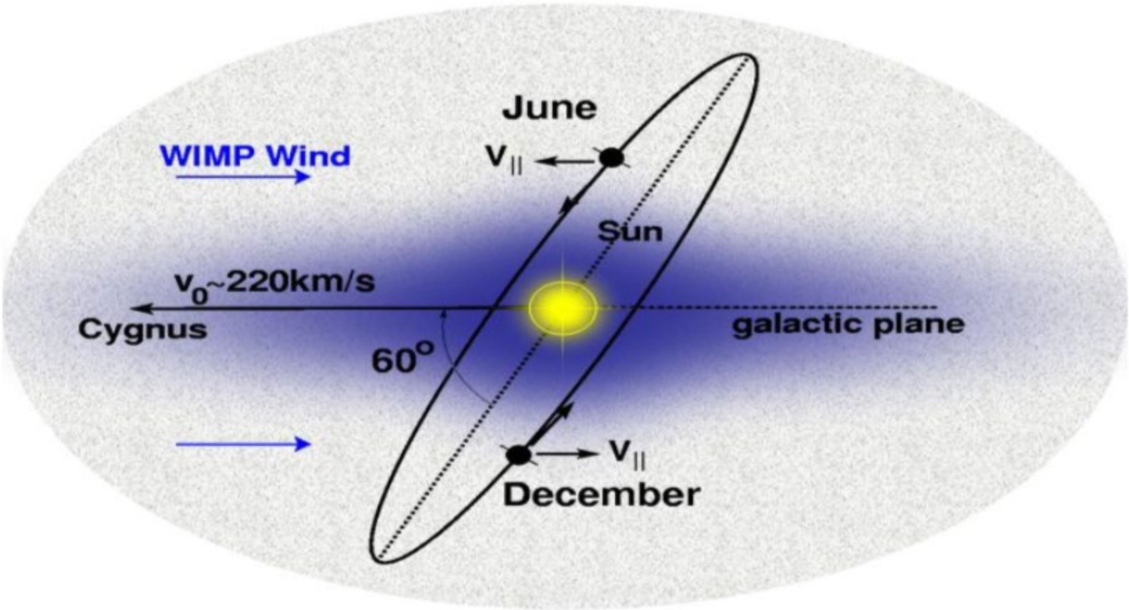
- Annual modulated rate
- Directional dependance



- Nuclear recoil with exponential spectral shape

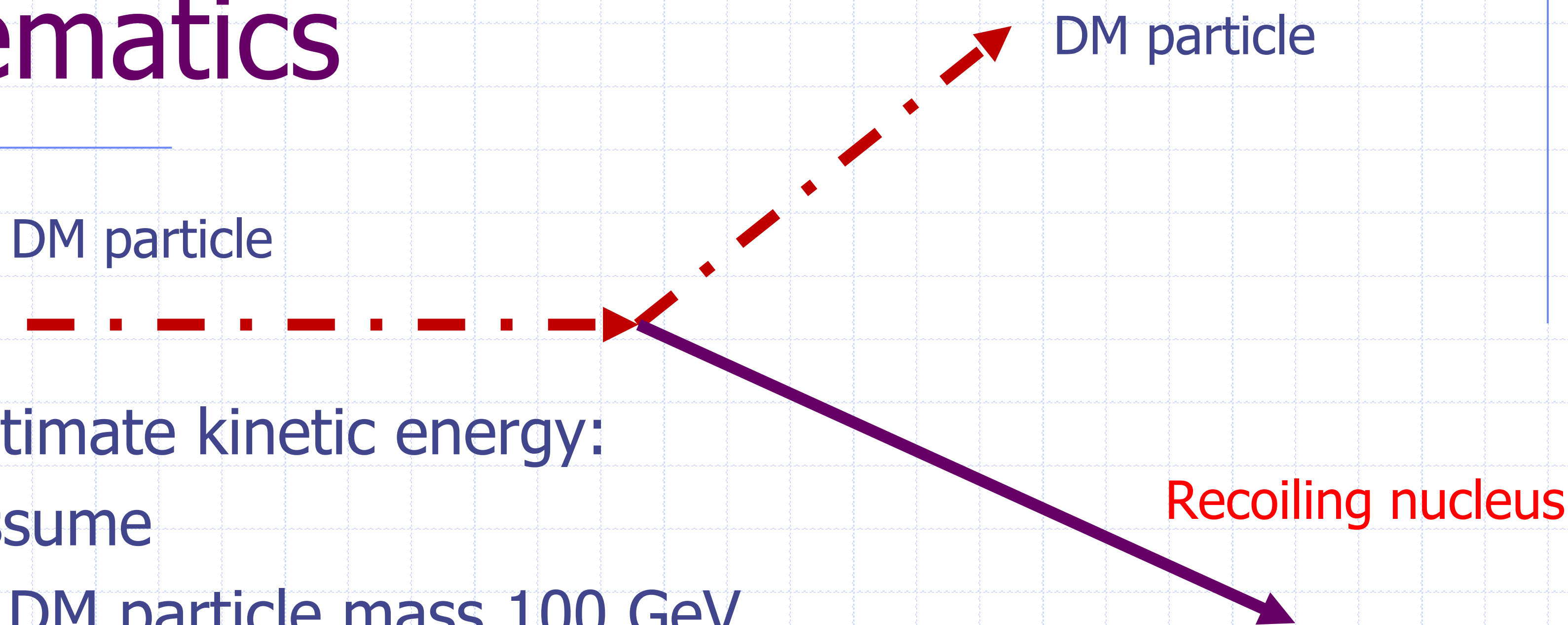


A note on the "dark matter wind"



Why is dark matter at rest, while the Sun and neighbouring stars are moving around the center of the galaxy? Dark matter interacts only gravitationally, so in the absence of (non-gravitational) interactions, the dispersion of the velocity distribution of dark matter is much larger than the total rotational volume. Dark matter cannot collapse on its own because there are no dissipative processes (say radiation) that would reduce the velocity dispersion. Individual particles of dark matter, of course, orbit in quasi-elliptical orbits around the center of gravity, but in very different directions and at different speeds, so on average they are at rest.

Direct dark matter detection - kinematics



Estimate kinetic energy:

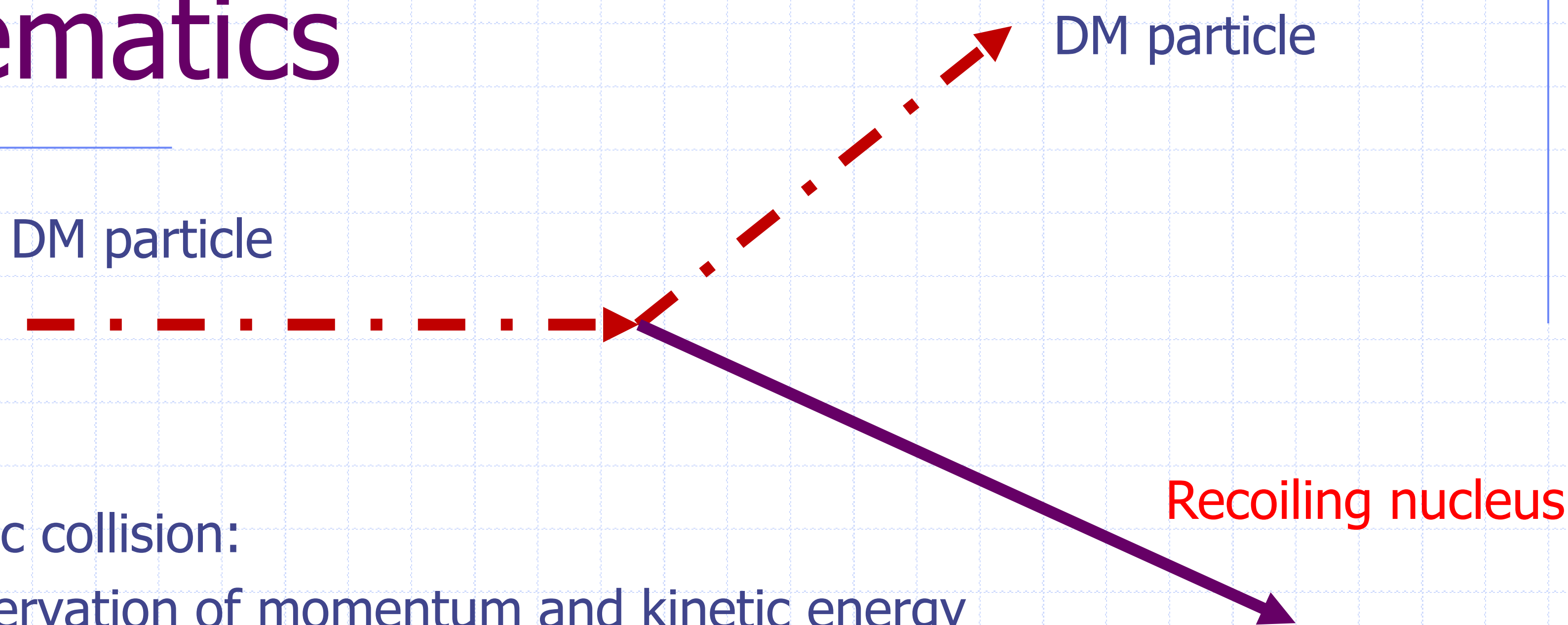
Assume

- DM particle mass 100 GeV
- DM particle velocity 200 km/s
- Central collision

Elastic collision:

Kinetic energy of recoiling nucleus →

Direct dark matter detection - kinematics



Elastic collision:

Conservation of momentum and kinetic energy

To illustrate the kinematics, assume a central collision – all in one dimension

$$m_1 v_1 = m_1 v_1' + m_2 v_2'$$

$$m_1 v_1^2 = m_1 v_1'^2 + m_2 v_2'^2$$

particle 1: DM

particle 2: nucleus

Direct dark matter detection - kinematics

$$m_1 v_1 = m_1 v_1' + m_2 v_2'$$

$$m_1 v_1^2 = m_1 v_1'^2 + m_2 v_2'^2$$

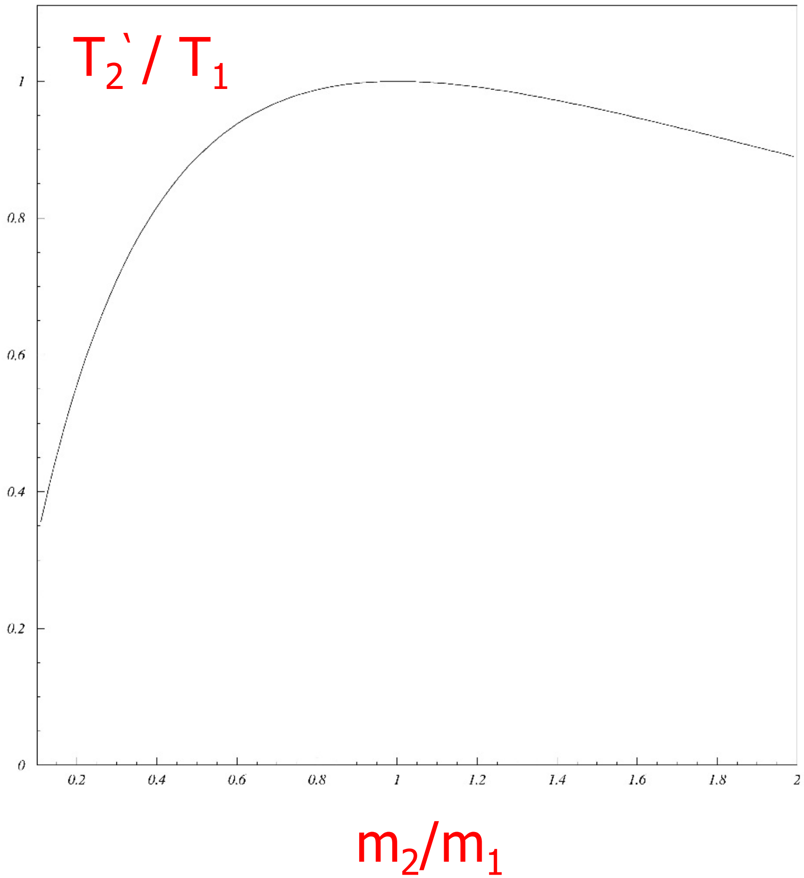
$$m_1^2 (v_1 - v_1')^2 = m_2 m_1 (v_1^2 - v_1'^2)$$

$$v_1' = v_1 \frac{2(m_1 - m_2)}{(m_1 + m_2)}$$

$$v_2 = v_1 \frac{2m_2}{m_1(m_1 + m_2)}$$

$$T_2' = T_1 \frac{4m_2}{m_1(1 + m_2/m_1)^2}$$

Maximize kinetic energy of the recoiling nucleus → m_2 should be close to m_1!



Direct dark matter detection - kinematics

Maximize kinetic energy of the recoiling nucleus → m_2 should be as close as possible to m_1

For a central collision of a

- DM particle mass 100 GeV
- DM particle velocity 200 km/s

DM particle:

$T_1 = 1/2 * 100\ \mathrm{GeV}/c^2\ (200\ \mathrm{km/s})^2 = 2.2\ 10^{-4}\ \mathrm{GeV} = 220\ \mathrm{keV}$

Recoiling nucleus

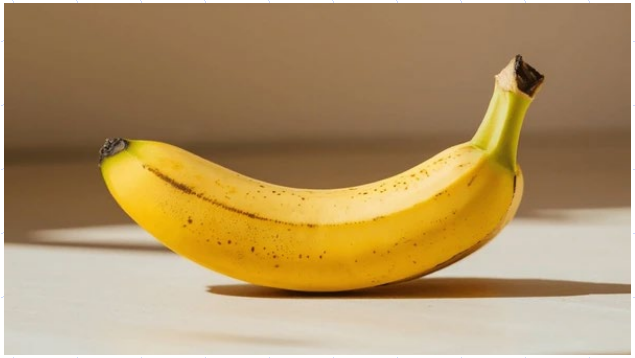
for Xenon (A=131): T_2 = 218 keV for a central collision, for all other collissions lower than that

Background Challenges for Dark Matter Direct Detection

- direct dark matter searches are experiments with low event yield
- typical event yield ~few events/(kg year)
- background rate has to be lower than (expected) signal yield or at least of the same order
- suppression of background essential for success

To illustrate: one of the background sources is the radioisotope ^{40}K

→ 1 banana would contribute ~400 x 10^6 decays/year (E ~ 1.5 MeV)



Background sources

- Natural **U**, **Th** chains and ^{40}**K**
  - Electronic recoils: β's and γ's
  - α's: high energy but still BG in some experiments
- **Neutrons** $\longrightarrow$ nuclear recoils
  - (α, n) reactions and spontaneous fission
  - From muon showers after a spallation process
- **Rn** and ^{85}**Kr**
  - Rn emanation from various detector materials
  - Kr from the air (^{85}Kr produced at nuclear power plants)

$\longrightarrow$ **Background suppression/removal**

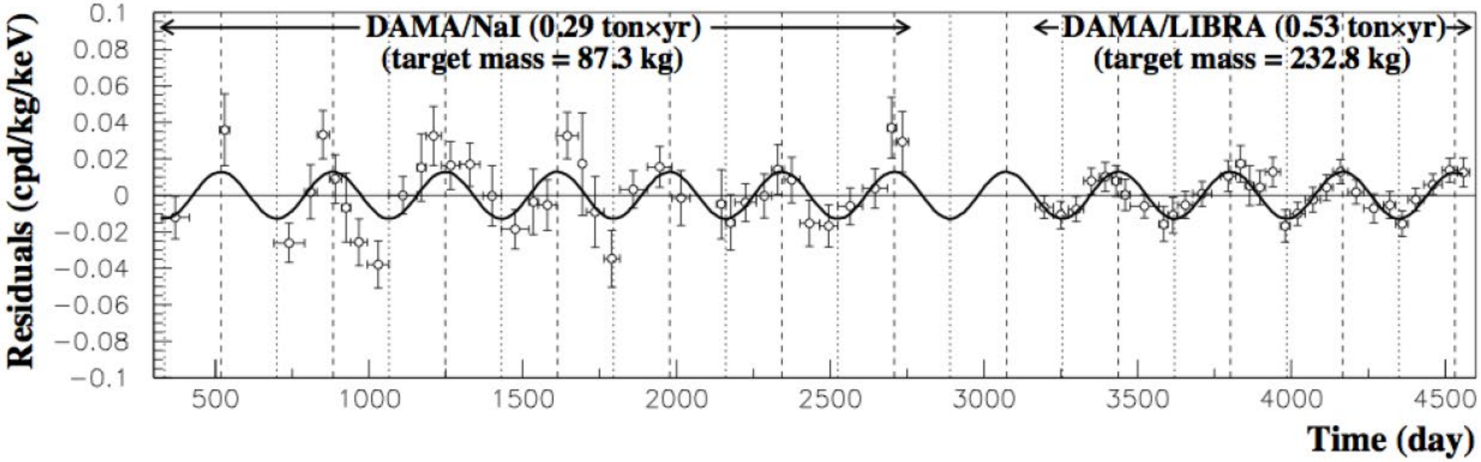
- Material screening and selection
- Removal of Kr or Rn with dedicated devices
- Shielding (underground lab, detector shield, active veto)

Worldwide effort

Annual modulation, DAMA

- Ultra radio-pure NaI crystals
- Annual modulation of the background rate in the energy region $(2-5)\,\mathrm{keV}$

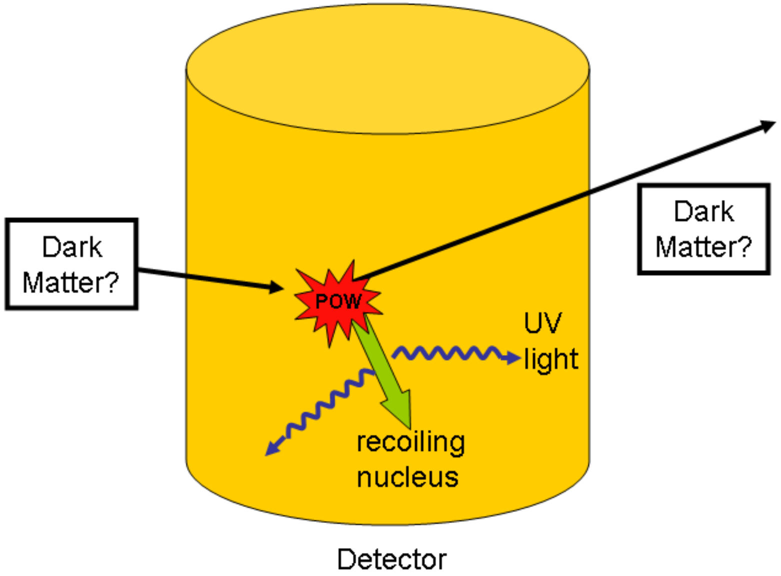
  $8.9\,\sigma$ significance!
- No discrimination of ER from NR



R. Bernabei *et al.*, Eur. Phys. J. C67, 39 (2010)

Dark matter detection - principle

Nuclear recoil: ionizes (electrons and holes/ions) and heats up (phonons) the crystal.

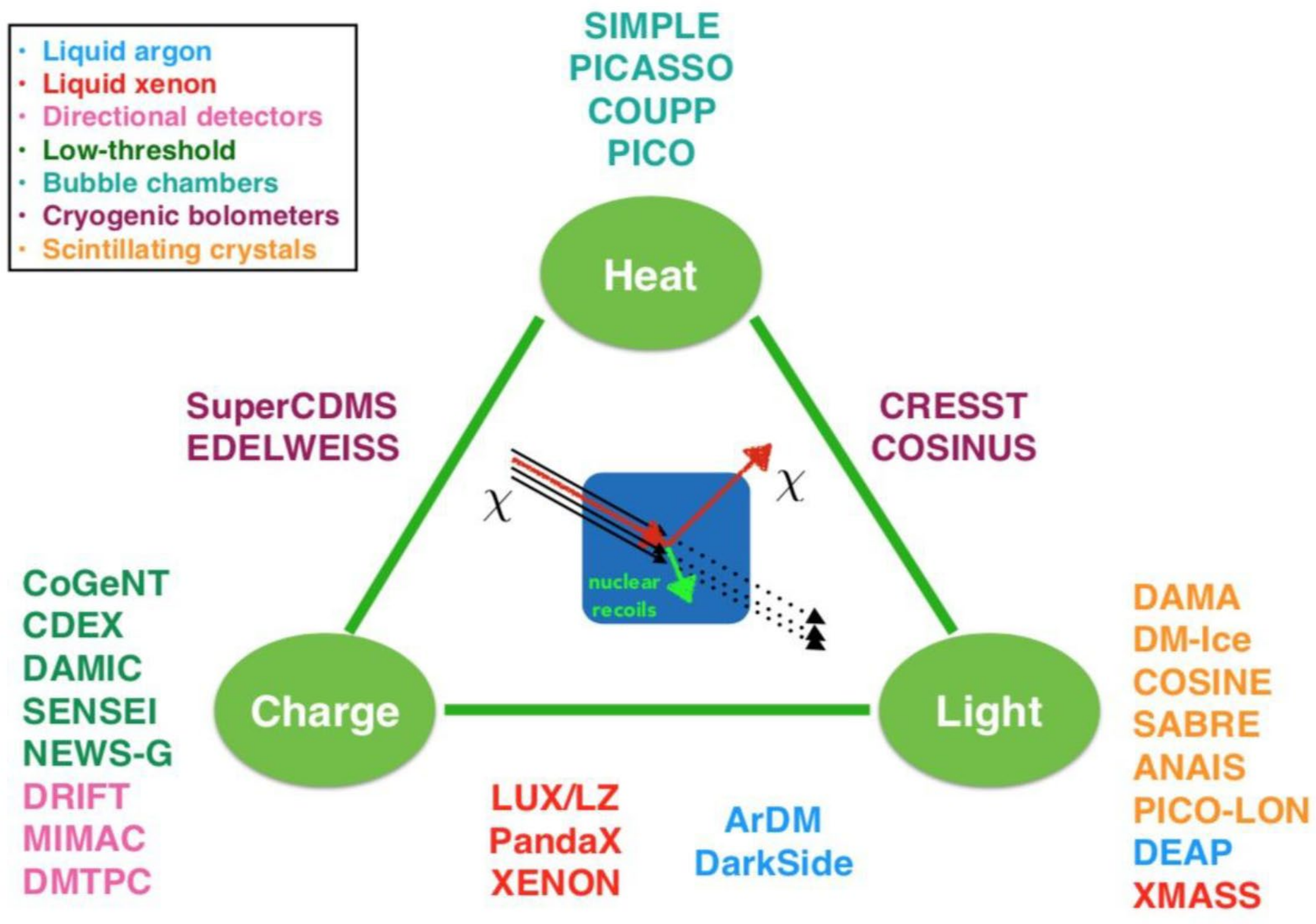


Dark matter detection - principle

DAMA experience: signal could not be reproduced by any other experiment!

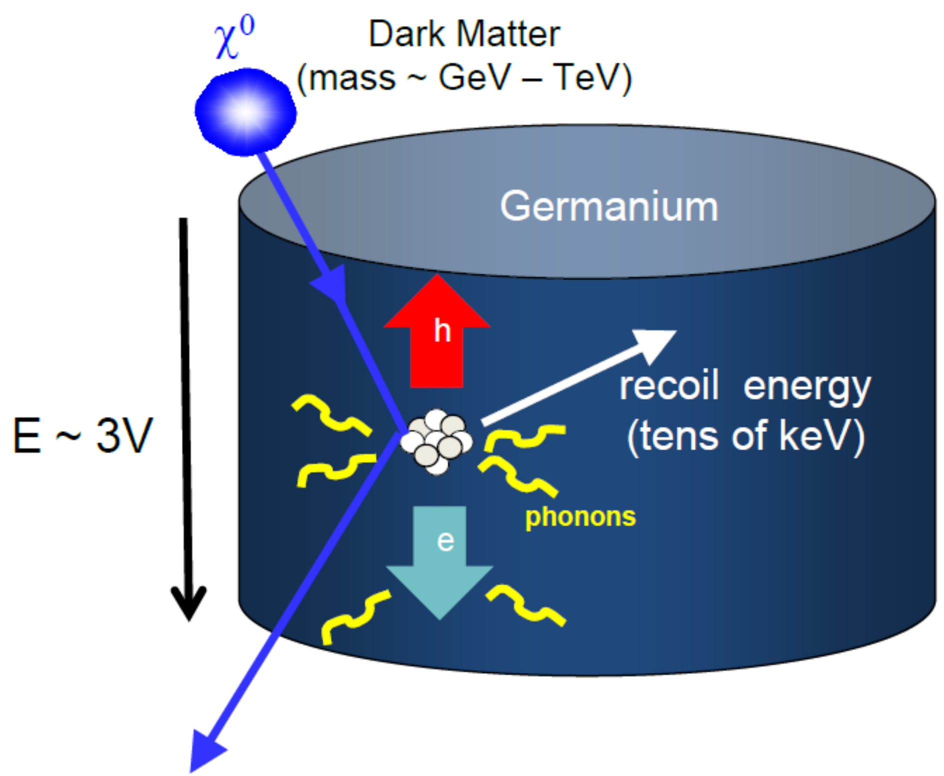
Lesson: to make sure that backgrounds are properly removed, employ at least two different detection mechanisms in the same detector, like

- Scintillation (light) + ionisation (charge)
- Ionisation (charge) + heat (phonons)
- …

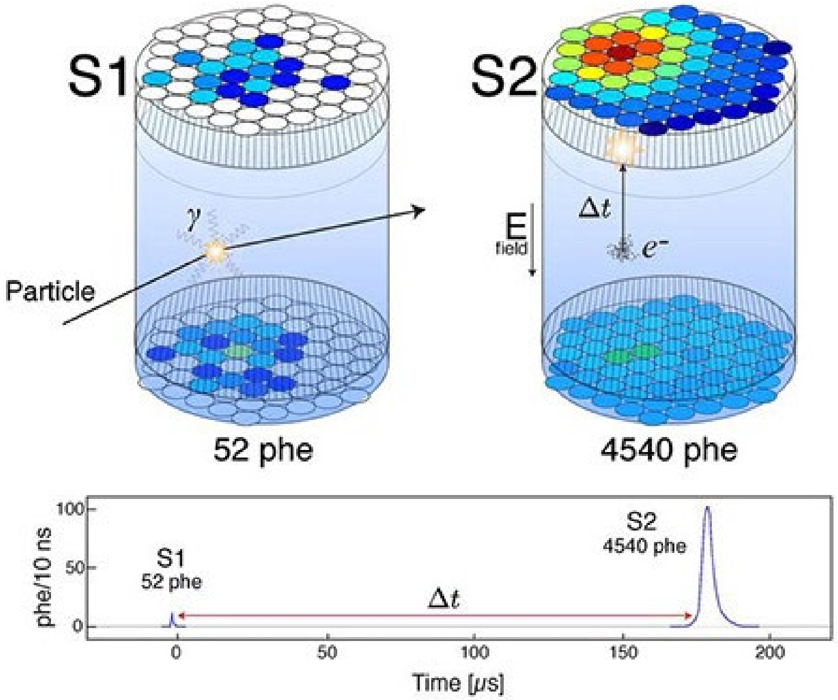

Liquid argon
Liquid xenon
Directional detectors
Low-threshold
Bubble chambers
Cryogenic bolometers
Scintillating crystals
SIMPLE
PICASSO
COUPP
PICO
Heat
SuperCDMS
EDELWEISS
CRESST
COSINUS
χ
χ
nuclear
recoils
CoGeNT
CDEX
DAMIC
SENSEI
NEWS-G
DRIFT
MIMAC
DMTPC
Charge
Light
DAMA
DM-Ice
COSINE
SABRE
ANAIS
PICO-LON
DEAP
XMASS
LUX/LZ
PandaX
XENON
ArDM
DarkSide

Dark matter detection in a semiconductor

- Nuclear recoil: ionizes (electrons and holes) and heats up (phonons) the crystal.



Lux: a huge volume of liquid Xenon + a gas layer



Large Underground Xenon experiment (LUX) in the Homestake mine (South Dakota), the site of the Davis experiment

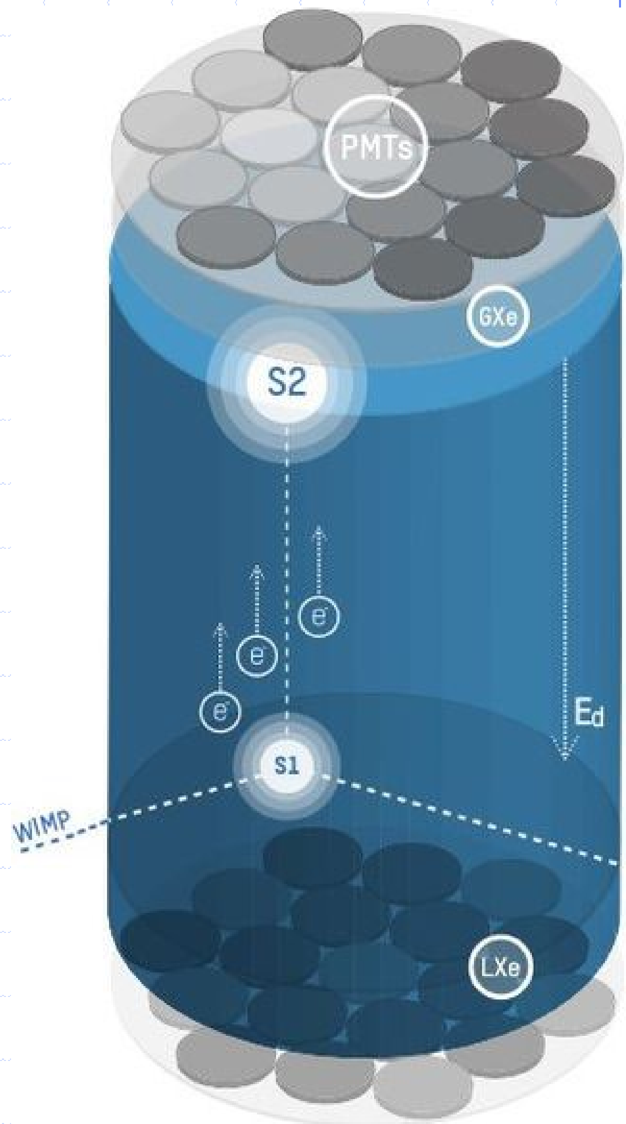
- Container: 1.5m high, 1.5m in diameter
- 370kg liquid Xe
- Sensors, top and bottom: PMTs
- Active shield (water with PMTs)

S1: scintillations in liquid Xenon (small signal, top and bottom)
S2: electroluminescence (large signal, top only)
Time difference: depth of interaction point

XENON1T: the most recent in the series of detectors XENON10, XENON100

- 1 tonne of liquid Xenon + a gas layer
- Gran Sasso Laboratory LNGS

- S1: scintillations in liquid Xenon (small signal, top and bottom)
- S2: scintillations in the gas phase where electrons get accelerated (large signal, top only)
- Time difference: depth of interaction point



XENON1T: results

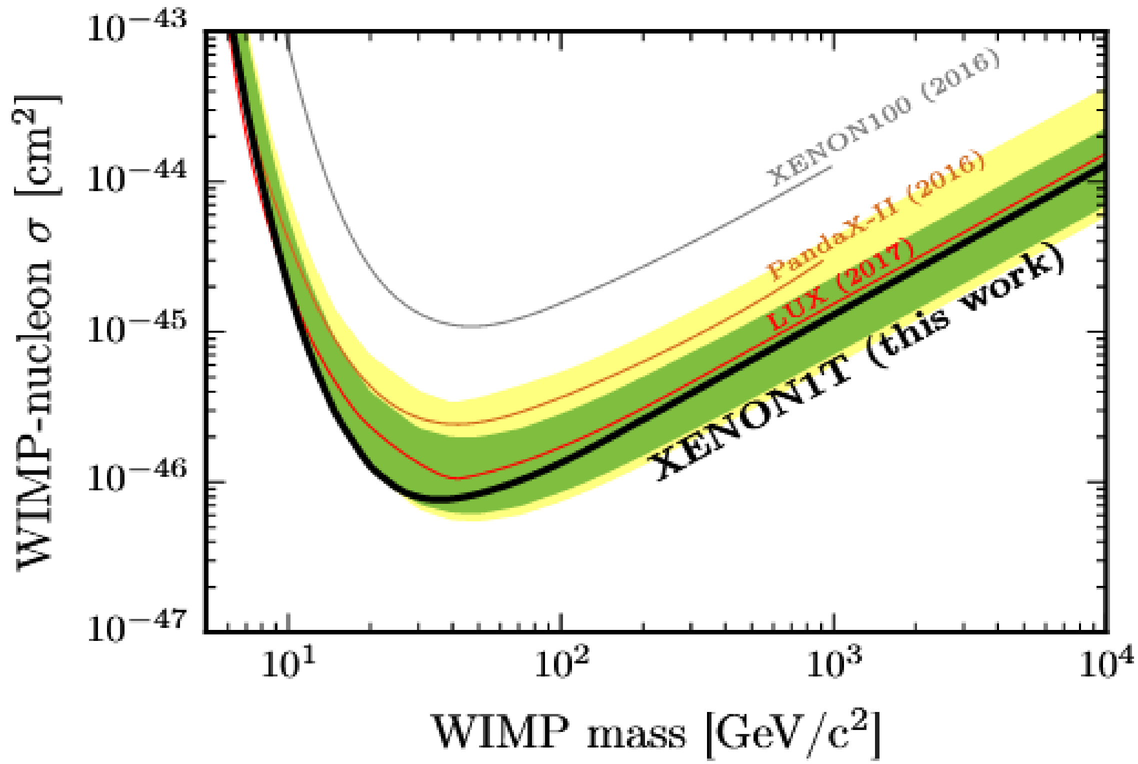
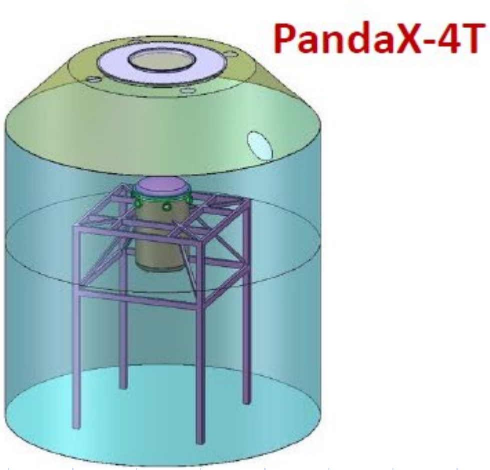
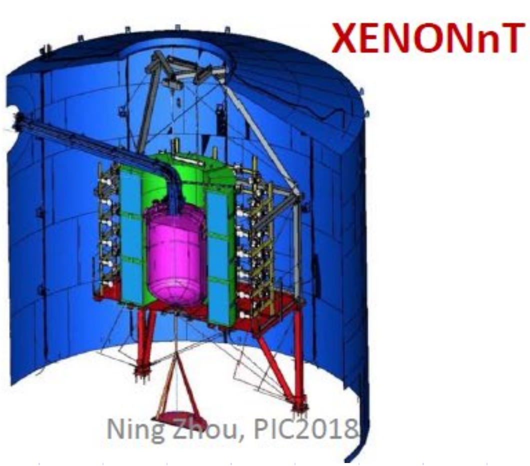


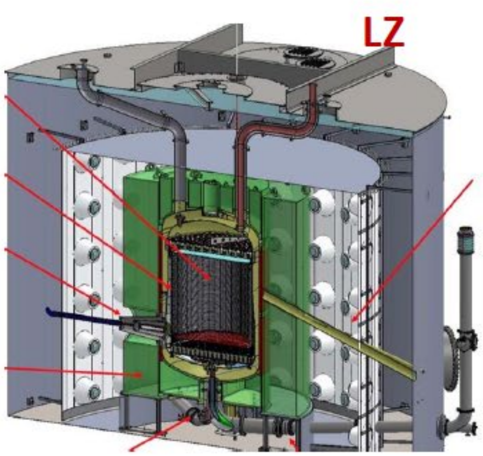
FIG. 4: The spin-independent WIMP-nucleon cross section limits as a function of WIMP mass at 90% confidence level (black) for this run of XENON1T. In green and yellow are the 1- and 2σ sensitivity bands. Results from LUX [27] (red), PandaX-II [28] (brown), and XENON100 [23] (gray) are shown for reference.

Future Xenon Detectors

Experiment	Sensitive Volume	Fiducial Volume	Expected exposure	Expected Sensitivity	Status
PandaX-4T	4 ton	2.8 ton	5 ton-year	10^{-47} cm^2	Commissioning 2020
XENONnT	6 ton	5 ton	20 ton-year	2×10^{-48} cm^2	Commissioning 2019
LZ	7 ton	5.6 ton	20 ton-year	2×10^{-48} cm^2	operations start April 2020
Darwin	40 ton	30 ton	200+ ton-year	Neutrino floor	CDR in 2-3 years







Future Xenon Detectors

- Darwin, with 200+ ton-year, can cover most of the region above neutrino floor for high mass WIMPs