Low-energy and low-background methods: from techniques to the most enigmatic particle physics

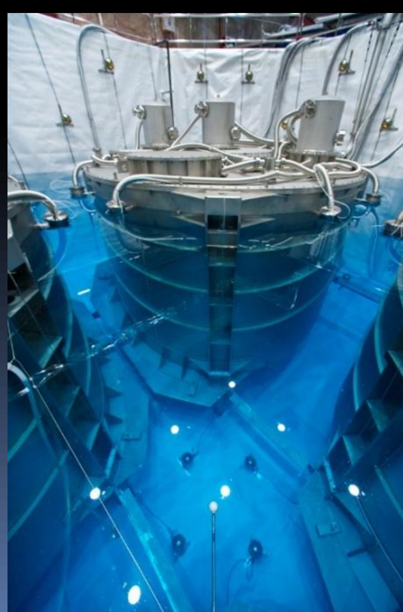
Jianglai Liu
Shanghai Jiao Tong University

I am an experimental physicist working at the intersection of nuclear physics, particle physics, and astrophysics.

G0 experiment at Jefferson Lab

UCNA spectrometer at Los Alamos

Daya Bay Neutrino Experiment



PandaX Dark Matter Experiment

Low-energy and low-background methods

- You are probably here for “high energy physics”: at the highest energy regime, events are “clean” and “rare”
- Low-energy: ~<10 MeV characteristic energy. This is an energy overlapping with typical nuclear-levels
- Intrinsically dirty!
- However, we need to find/study the rarest interactions in this regime

Outline

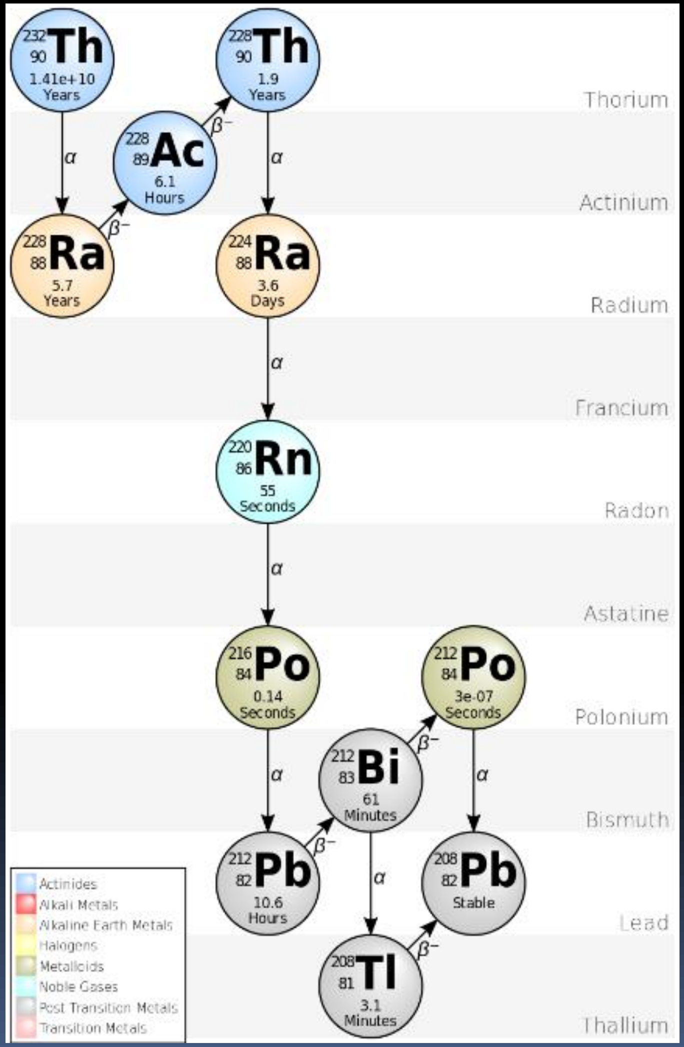
- Unit 1: Detector and low background techniques 101
- Unit 2: Neutrinos, weak interactions
- Unit 3: Neutrino oscillations
- Unit 4: From neutrino coherent scattering to dark matter detection
- Unit 5: Neutrinoless double beta-decays

Outline

- Unit 1: Detector and low background techniques 101
- Unit 2: Neutrinos, weak interactions
- Unit 3: Neutrino oscillations
- Unit 4: From neutrino coherent scattering to dark matter detection
- Unit 5: Neutrinoless double beta-decays

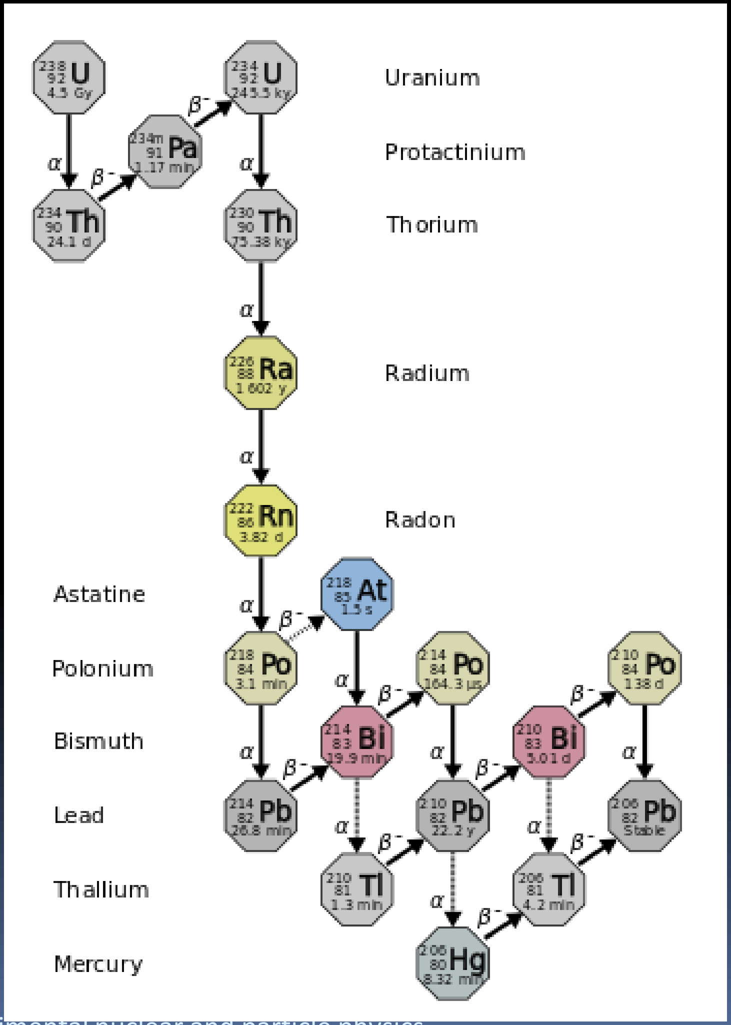
Four naturally-occurring long-lived chains

^{232}Th: 1.4×10^{10} y



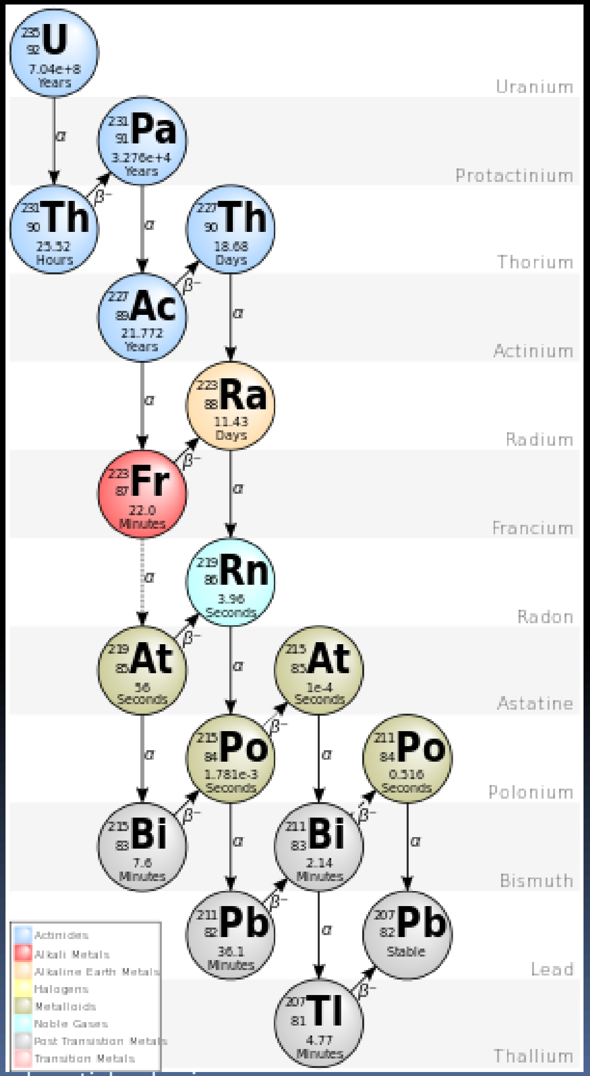
Four long-lived chains

^{238}U: $4.5x10^9$ y



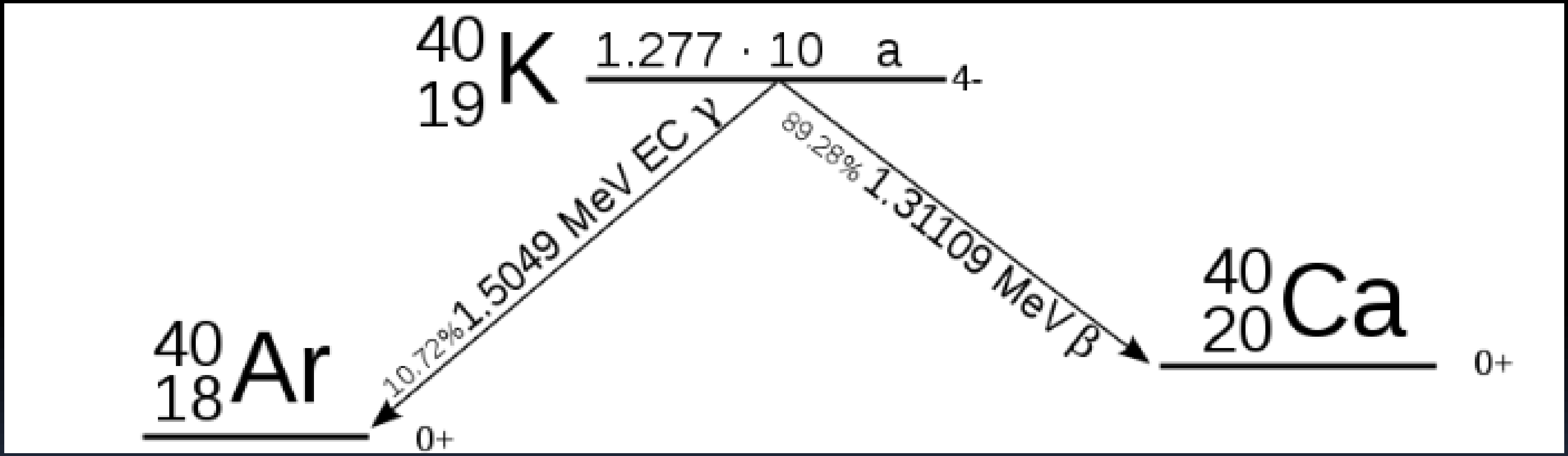
Four long-lived chains

^{235}U: 7.1×10^{8} y



Four long-lived decay chains in nature

^{40}K： 1.3x10^{9} y



Secular equilibrium (assumption)

- $A \rightarrow B \rightarrow C$ 。。。
- $N_A = N_A^0 \, e^{-t/\tau_A}$
- $dN_B/dt = N_A/\tau_A - N_B/\tau_B$
  - Note: $R_A = N_A/\tau_A$, $R_B = N_B/\tau_B$
- Condition for a constant decay rate for B: $dN_B/dt = 0$
  - $N_A/\tau_A = N_B/\tau_B$
  - When $\tau_A >> \tau_B$, this condition quickly met when $\tau_A >> t >> \tau_B$

Particle energy loss mechanisms

- Heavy charged particles (through ionization)
- Interaction of electrons/positrons
- Photon interaction
- Neutron interaction
- Optical photons produced in these processes

Particle energy loss mechanisms

- Heavy charged particles (through ionization)
- Interaction of electrons/positrons
- Photon interaction
- Neutron interaction
- Optical photons produced in these processes

Bethe and Bloch

Bethe-Bloch equation

$$-\frac{dE}{dx} = Kz^2 \frac{Z}{A} \rho \frac{1}{\beta^2} \left[\frac{1}{2} \ln \frac{2 m_e c^2 \beta^2 \gamma^2 T_{max}}{I^2} - \beta^2 - \frac{\delta}{2} \right]$$

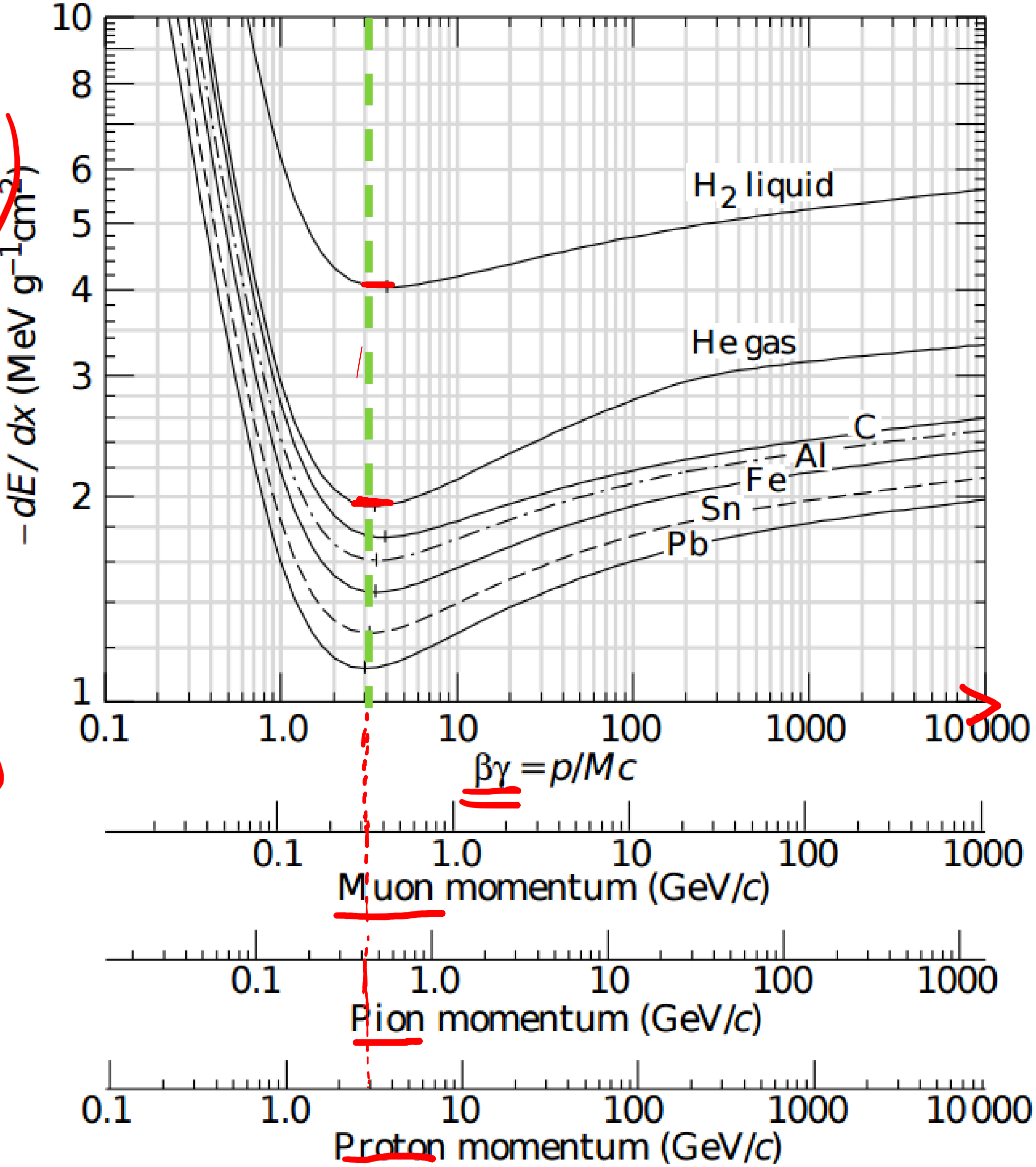
$\frac{K}{A} = \frac{4\pi N_A r_e^2 m_e c^2}{A}$ with classical electron radius $r_e = \frac{e^2}{m_e c^2}$

$T_{max} \approx 2 m_e c^2 \beta^2 \gamma^2$ max. energy transfer in a single collision, for $M \gg m_e$

$I = (10 \pm 1) \cdot Z$ eV mean excitation energy (for elements beyond oxygen)

and 'density correction' $\delta/2$: with increasing particle energy $\rightarrow$ Lorentz contraction of electric field, corresponding to increase of contribution from large b with $\ln \beta\gamma$

- z: charge of incident particle, Z: charge of absorber, ρ: density of absorber

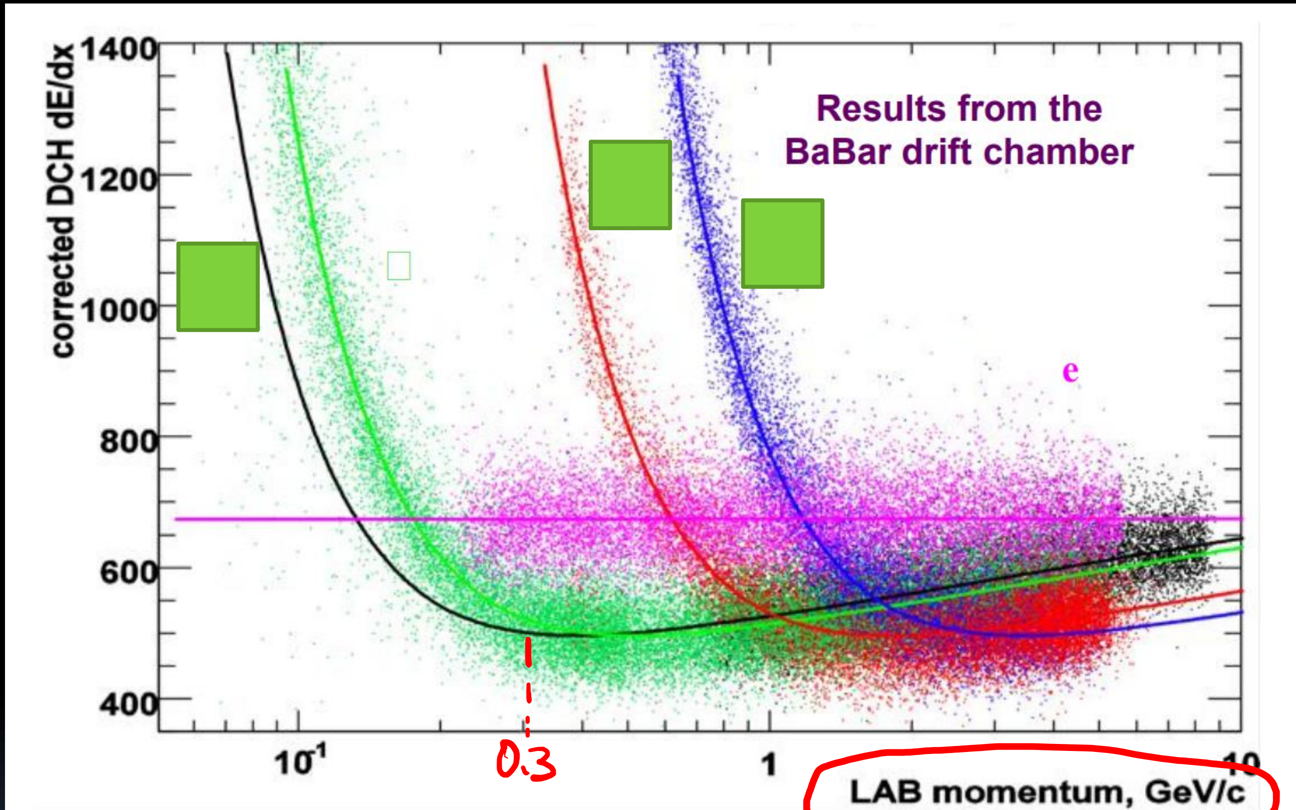

10
8
6
5
4
3
2
1
−dE/dx (MeV g⁻¹cm²)
H2 liquid
He gas
C
Al
Fe
Sn
Pb
0.1
1.0
10
100
1000
10000
βγ = p/Mc
Muon momentum (GeV/c)
Pion momentum (GeV/c)
Proton momentum (GeV/c)

Ionization threshold energy and W value

- I_0 :ionization threshold energy for the molecule
  - also ionization of inner shells
- Ni = ΔE/W where W is an average value of energy to produce an electron/ion pair
  - excitation that may not lead to ionization

	I_0 (eV)	W (eV)
H_2	15.4	37
N_2	15.5	35
O_2	12.2	31
Ne	21.6	36
Ar	15.8	26
Kr	14.0	24
Xe	12.1	22
CO_2	13.7	33
CH_4	13.1	28
		in gases $\approx$ 30 eV

Particle ID



A simultaneous measurement of dE/dx and momentum can provide particle identification.

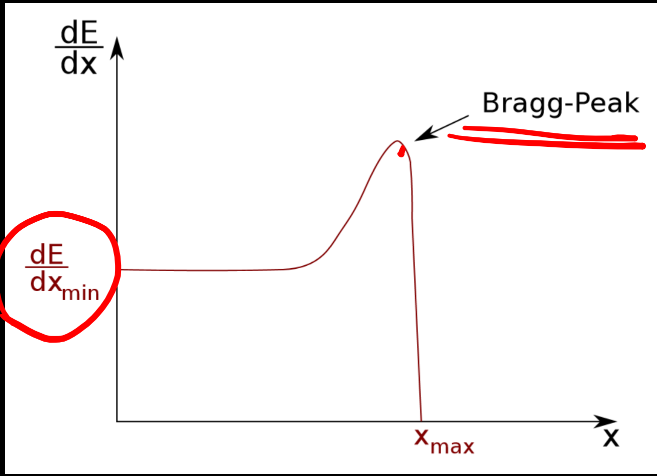
$\beta\gamma = 3$

$\frac{p}{M} = 3$

$\frac{0.3}{m} = 3$

$m = 100\ \mathrm{MeV}$

Bragg peak



- When a fast charged particle moves through matter, it ionizes atoms of the material and deposits a dose along its path.
- Energy lost by charged particles is inversely proportional to the square of their velocity (Bragg peak)

An ideal imaging detector

Particle energy loss mechanisms

- Heavy charged particles (through ionization)
- Interaction of electrons/positrons
- Photon interaction
- Neutron interaction
- Optical photons produced in these processes

Soft and hard collisions

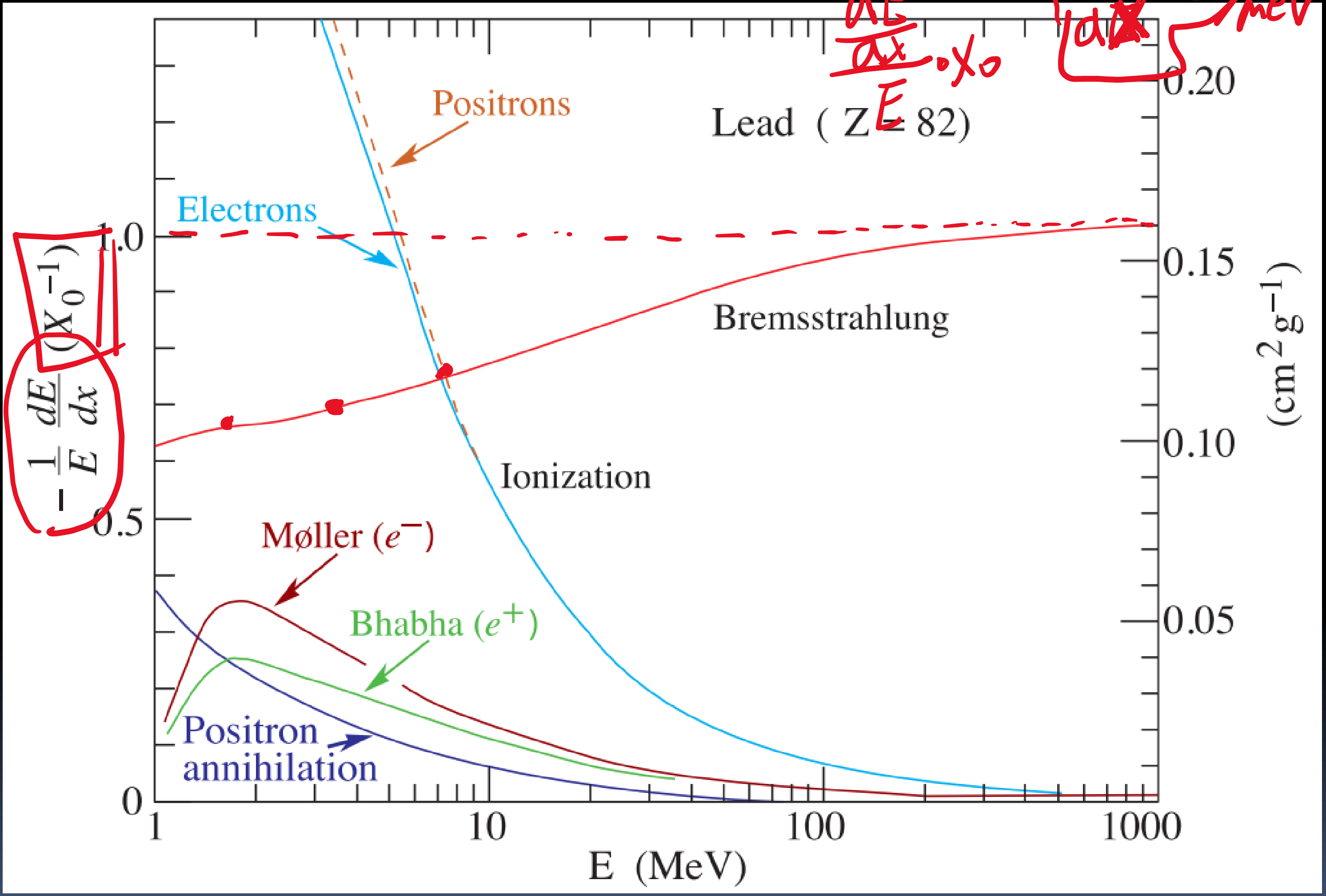
- Similar to heavy charged particles, electron energy loss process also contains
  - soft collision (ionization)
  - Hard collision (Moller scattering) ⇔ delta rays
  - Radiation (Bremstrahlung)

ee elastic

e^+e^-

Famous PDG curve

What is this strange unit?



X_0 is the famous "radiation length"

Interpretation

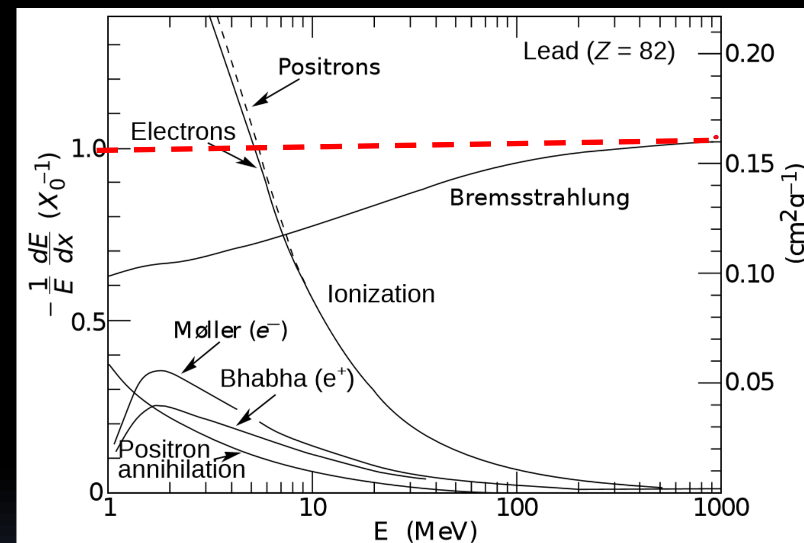
For high E, $\frac{dE/dx}{E} \cdot X_0 = 1$

$E_f = E_i e^{-x/\lambda}$

$\frac{dE_f}{dx} = -\frac{1}{\lambda} E_f$

- $1/E\ dE/dx\ (X_0^{-1})$ is the fractional energy loss per radiation length!

  $\equiv (dE/dx \times X_0)/E$
- High E: $(dE/dx \times X_0)/E \sim 1$



Physical meaning of X_0:

Consider an exponential attenuation of energy $E(x) = E\, e^{-x/\lambda}$

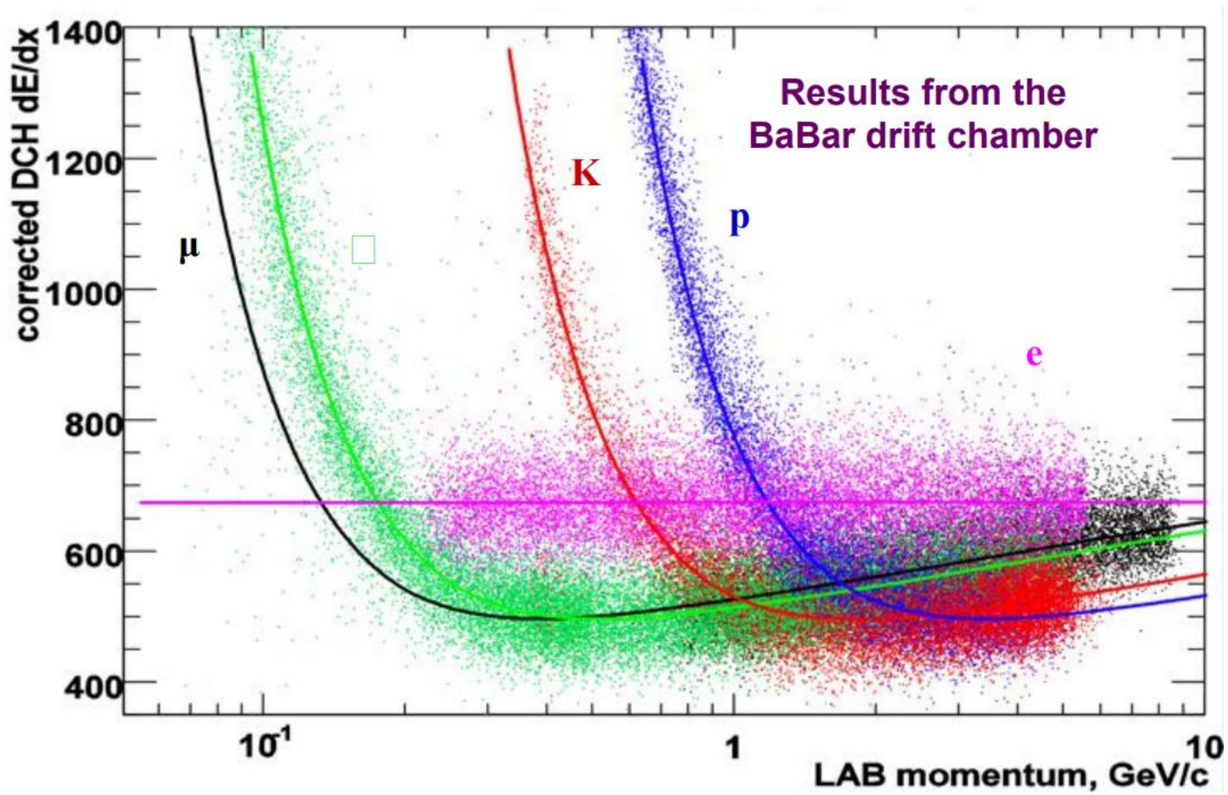
$dE/dx = -1/\lambda\ E(x)$

Radiation length

- X_0, fundamental property of material, just like density
- Several interpretations:
  - the mean distance over which a high-energy electron loses all but 1/e of its energy by bremsstrahlung
  - Estimate energy loss of a 1 GeV electron in 2 cm LH2
  - 7/9 of the mean free path for pair production by a high-energy photon (discuss later)
  - Note also Moliere's formula for multiscattering angle

	ρ (g/cm^3)	X_0 (cm)
liq H_2	0.071	865
C	2.27	18.8
Fe	7.87	1.76
Pb	11.35	0.56
air	0.0012	30 420

So does this make sense for electron?



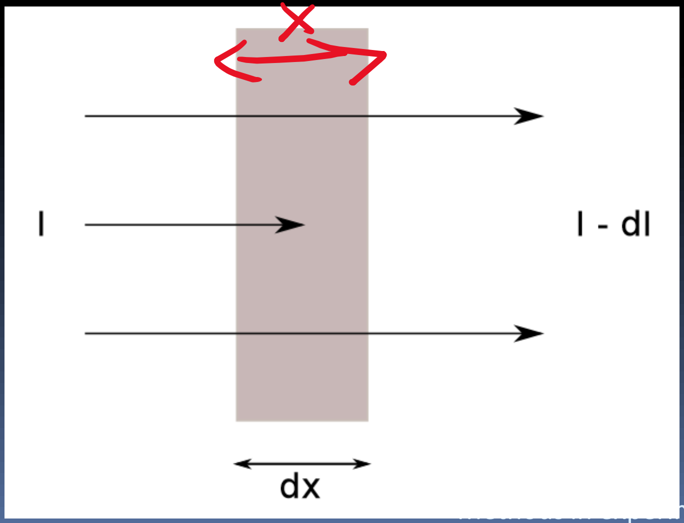
A simultaneous measurement of dE/dx and momentum can provide particle identification.

Particle energy loss mechanisms

- Heavy charged particles (through ionization)
- Interaction of electrons/positrons
- Photon interaction
- Neutron interaction
- Optical photons produced in these processes

Mean free path

- Unlike charged particles, photon loses energy in a non-continuous fashion
- Useful to consider mean free path (λ): average material a gamma traverse before the first scatter

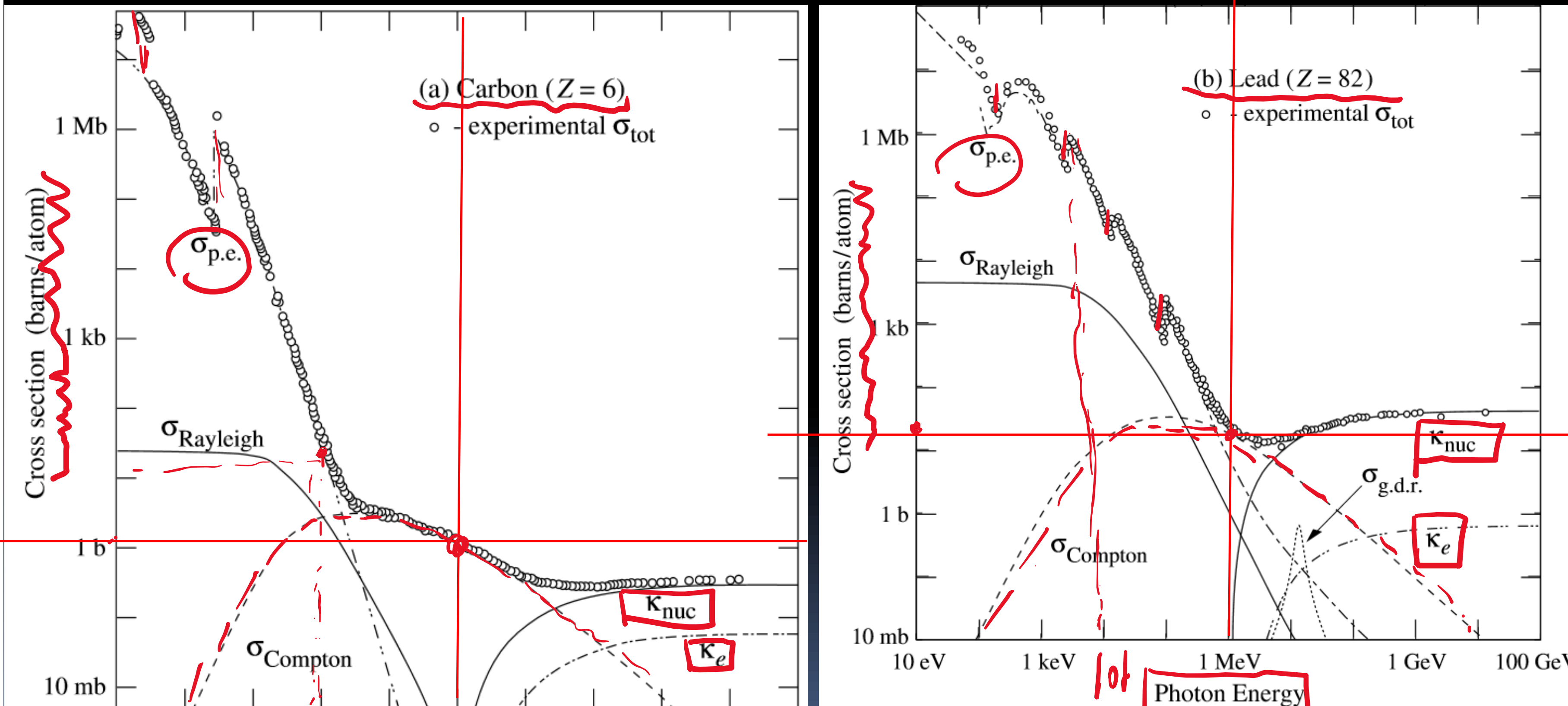


Quiz: how to relate scattering cross section with λ?

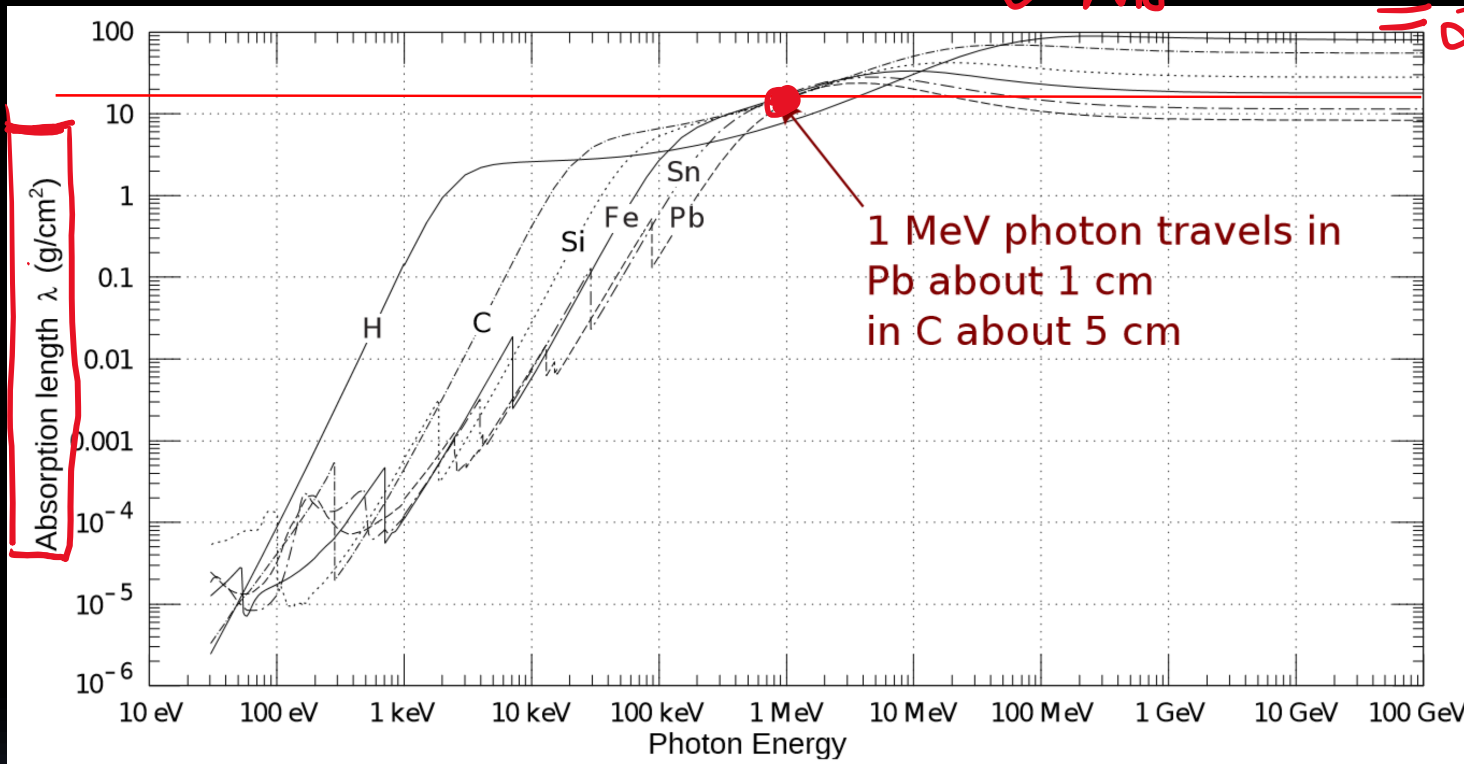
Underlining processes

- Growing importance with increasing energy
  - Photoelectric effects ✓ photoabsorption
  - Compton scattering ✓
  - Pair production ✓
- Other processes
  - Rayleigh scattering (coherently with an atom)

Famous PDG figure



Mean free path



Quiz: based on the gamma-Pb and gamma-C cross section from PDG, can you estimate the mean free path for a 1 MeV gamma. Why they are roughly the same at 1 MeV?

Particle energy loss mechanisms

- Heavy charged particles (through ionization)
- Interaction of electrons/positrons
- Photon interaction
- Neutron interaction
- Optical photons produced in these processes

How to make neutrons

- Neutrons are around us
- Produced via
  - Spontaneous fission of U238

E(level) (MeV)	Jπ	Δ(MeV)	$T_{1/2}$	Abundance	Decay Modes
0.0	0+	47.3077	4.468×10^{9} y *6*	99.2742% *10*	α : 100.00 % SF : 5.4E-5 %

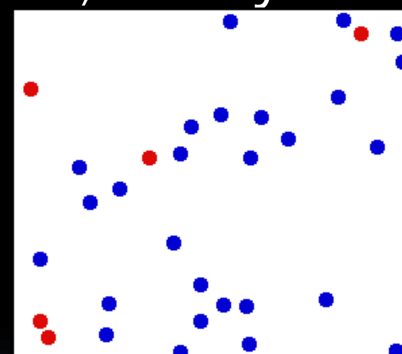
  - Estimate the # of n/s for a 1 gram of U238
  - (alpha, n) reaction on light elements
  - Cosmic ray bombardment
  - Nuclear reactors (fission of heavy elements)
- These neutrons are "high energy" neutrons or some times called "fast" neutrons >~ MeV

Moderators and thermal neutrons

- Light nuclei + low absorption.
- Elastic collisions between the nucleus and the neutron
- Moderated neutrons take on the average kinetic energy of the moderator, set by its *T*.

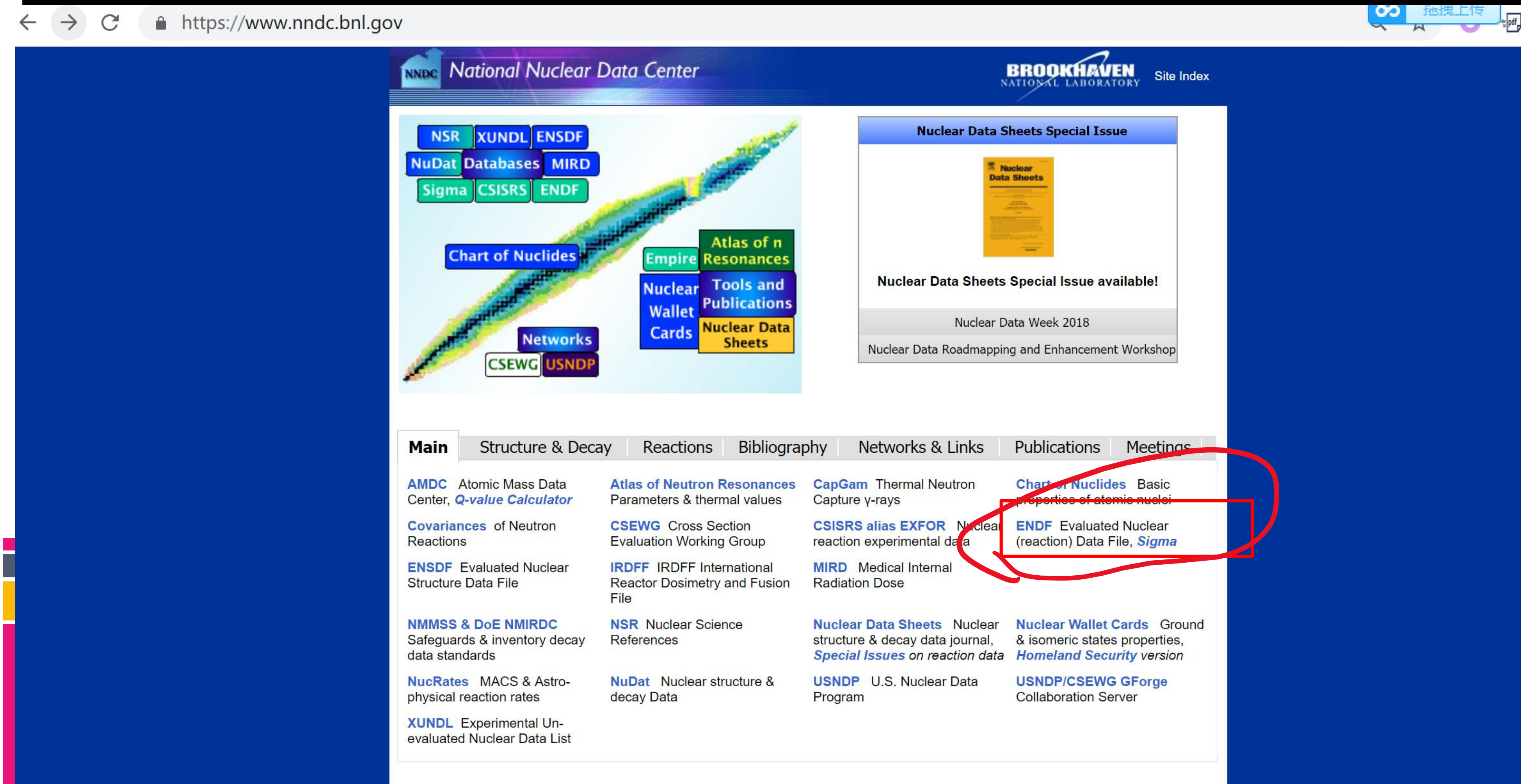
$$E = \frac{1}{2}mv^2$$

$$E = k_B T$$

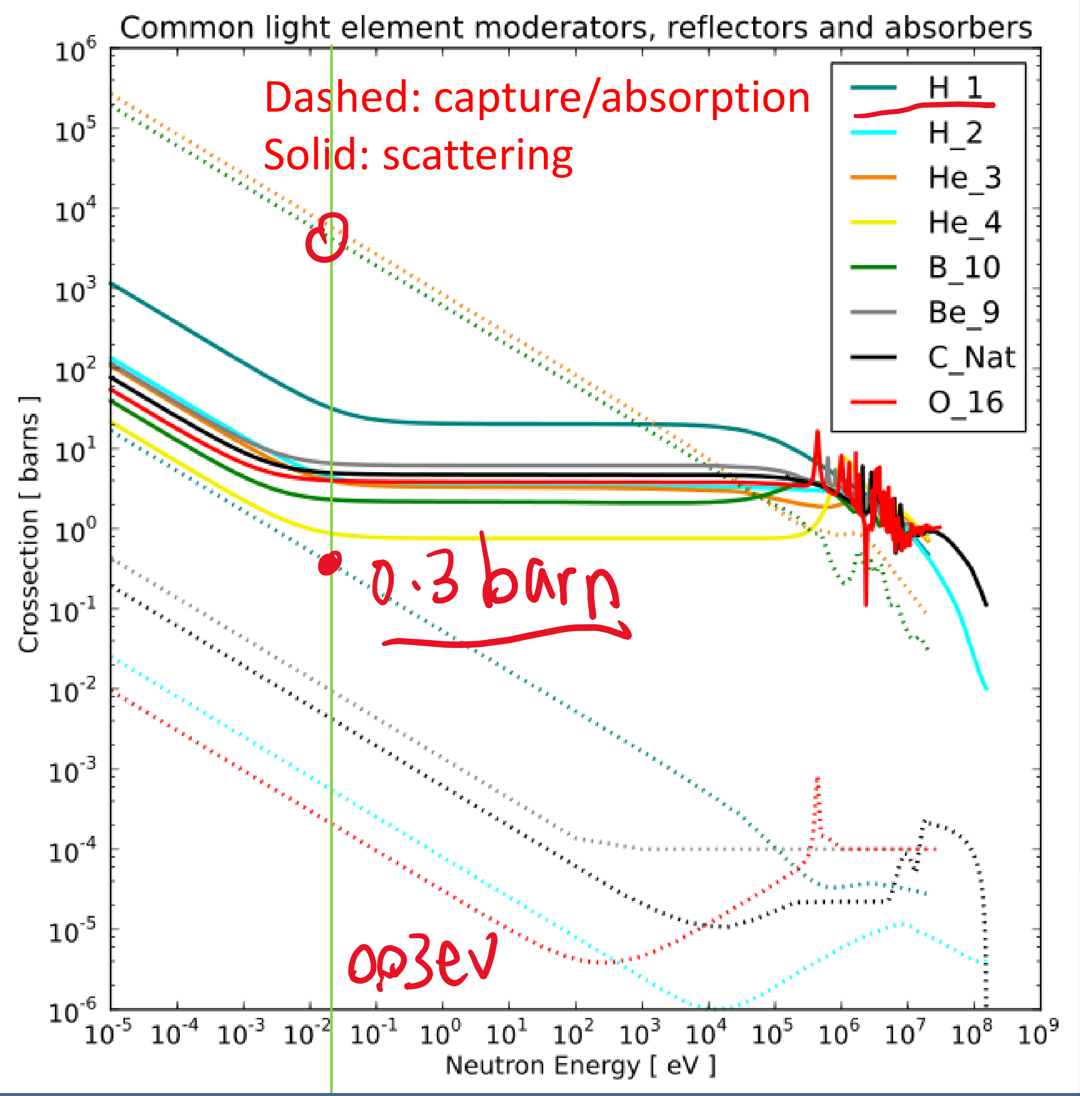


- At room temperature, neutron on average do not gain or lose energy, therefore becomes "thermal"
- Calculate the KE of thermal neutrons
- What is its speed?
- Calculate the wavelength of thermal neutrons

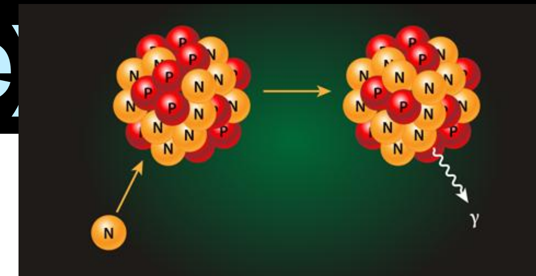
Neutron interaction database

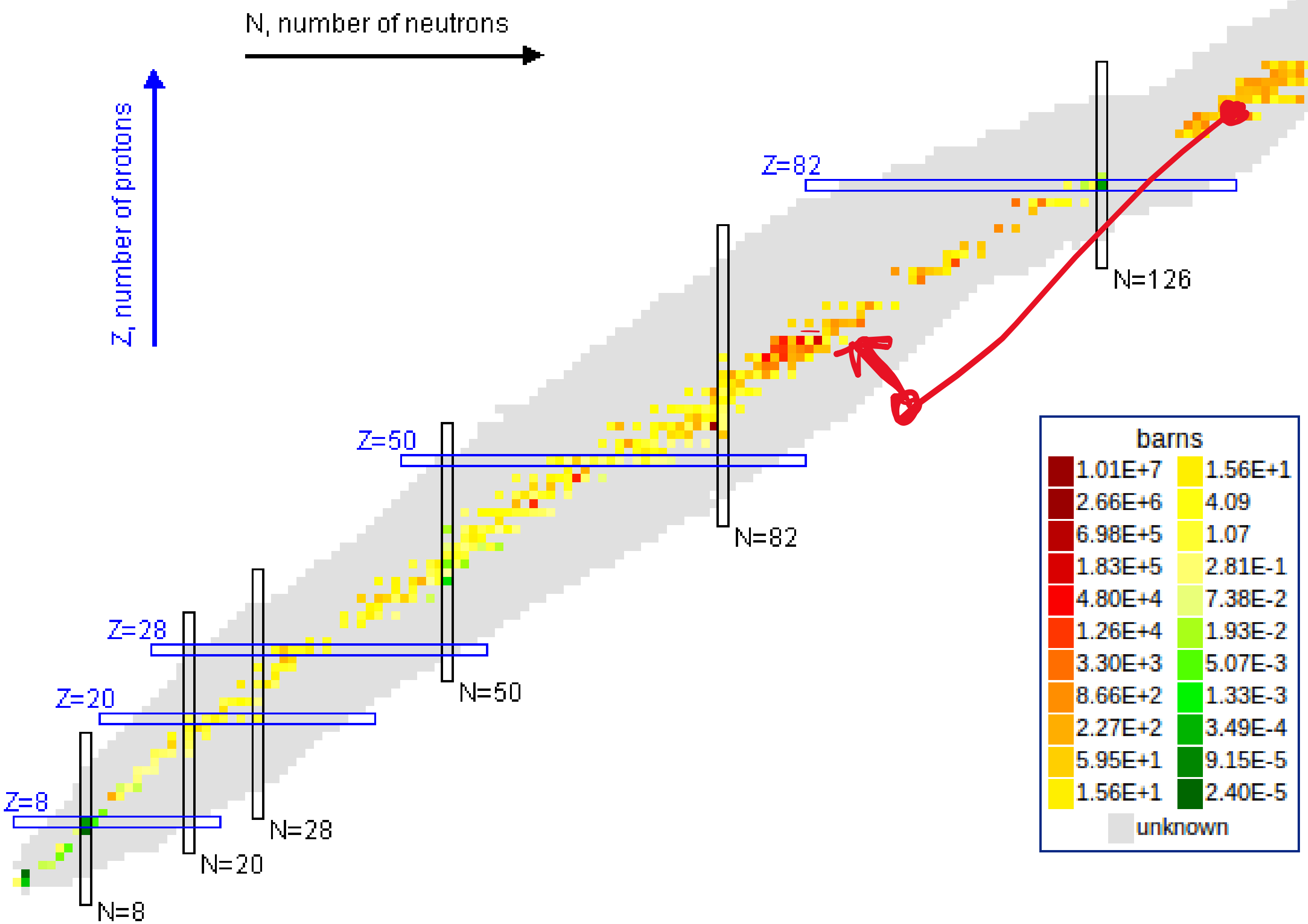


Neutron interaction cross section



Neutron absorption (capture)





Thermal neutron capture cross section by element

Element	$\sigma_{capture}$ (barn)
H	0.3
Xe	23.9
B	767
Cd	2450
Gd	49000

Neutron capture examples

- Neutron capture: the neutron capture cross section increases as 1/v.
  - E.g. n+p -> D + 2.2 MeV (gamma)
  - There are also resonances with certain nuclei such as Cd and In.
  - In capture can be used to measure the flux of epithermal neutrons (1 eV): n+ ^{115}In -> ^{116}In*->^{116}Sn+e (54m).

Neutron reaction

- Nuclear reaction: transformation of the n and colliding nucleus to something else
  - E.g. neutron activation:

    $$\text{n} + A \rightarrow B$$

    to study trace of U/Th

NAA

Particle energy loss mechanisms

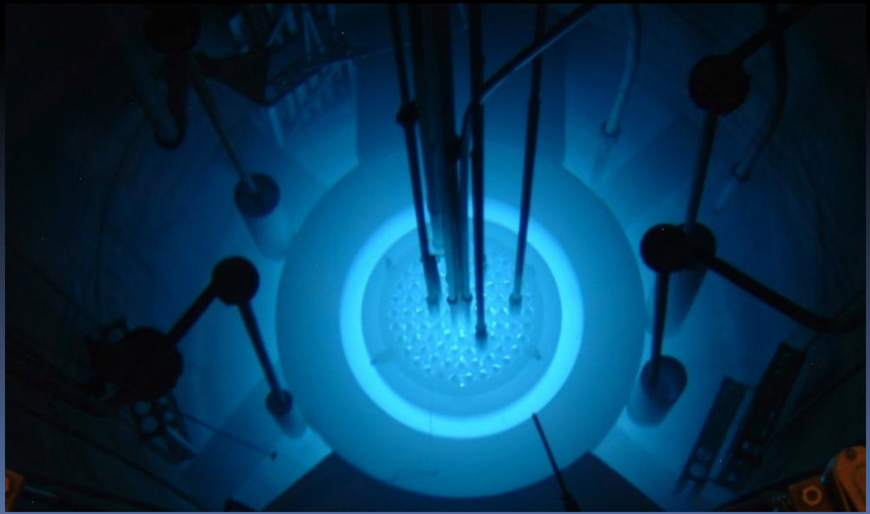
- Heavy charged particles (through ionization)
- Interaction of electrons/positrons
- Photon interaction
- Neutron interaction
- Optical photons produced in these processes

Optical photons

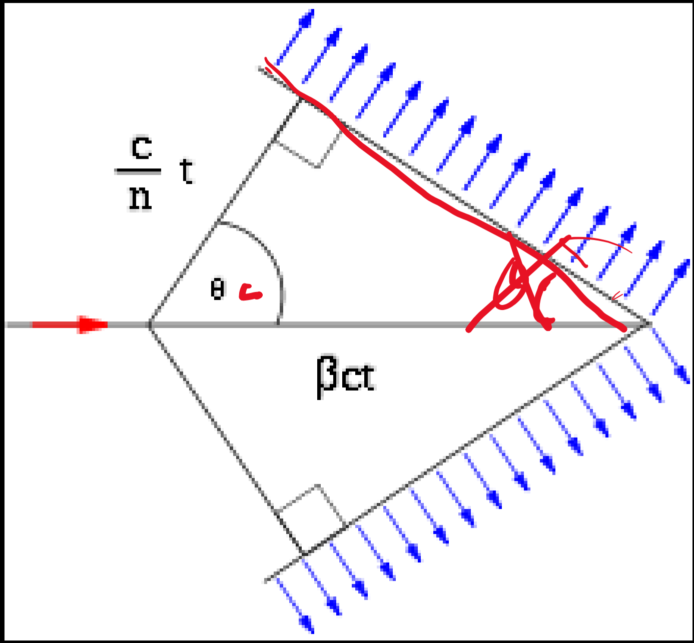
- Differs from "gamma" ray in that they are normally about ~eV energy related to the ionization energy of electrons, thus the name "optical"
  - Scintillation is the main process produced together with ionization, but we will leave this discussion to later
  - Cerenkov radiation and Cerenkov photons (Noble prize 1958). Unimportant for eloss, but important for detection!

Cerenkov radiation

- Energetic charged particle traveling through the medium displaces electrons in some atoms along its path => EM radiation by displaced electrons
- Condition: $v_{photon} < v_{charged}$



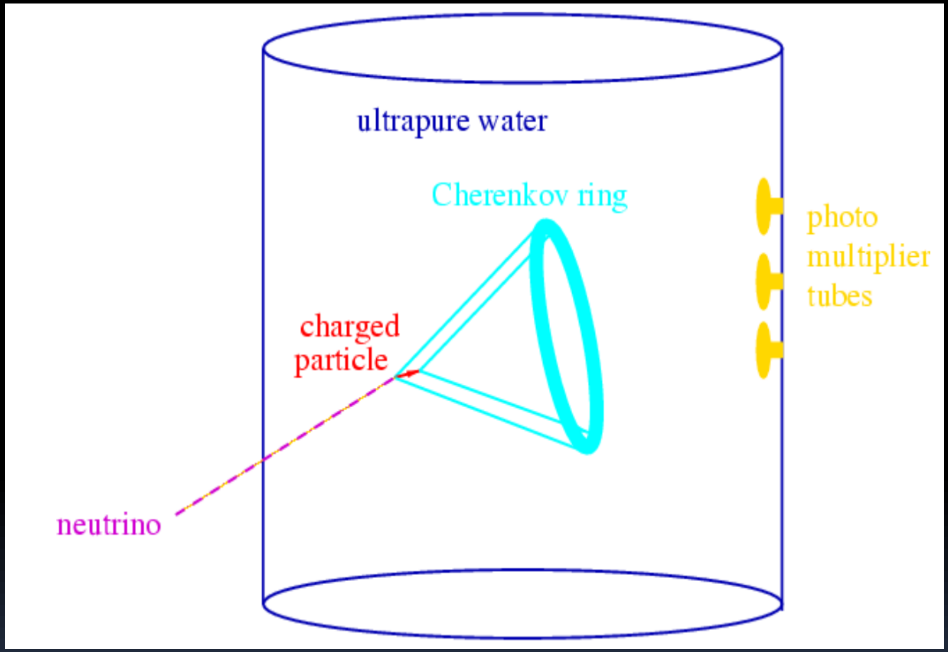
Cerenkov radiation



$\cos\theta = 1/(n\beta)$

- $\beta_{thre} = 1/n$, at which point $\theta = 0$ deg
- When $\beta = 1$, $\theta_{max} = \cos^{-1}(1/n)$

Reconstruction



- PMT timing: "vertex"
- Direction of particle: based on the charge pattern (cone)
- Total detected photons $\propto$ energy loss (approximately, see later)

Radiation spectrum

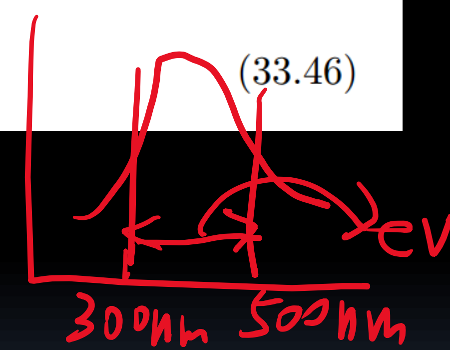
The number of photons produced per unit path length of a particle with charge ze and per unit energy interval of the photons is

$$\frac{d^2N}{dEdx} = \frac{\alpha z^2}{\hbar c}\sin^2\theta_c = \frac{\alpha^2 z^2}{r_e\, m_e c^2}\left(1 - \frac{1}{\beta^2 n^2(E)}\right)$$

$$\approx 370 \sin^2\theta_c(E)\ \mathrm{eV^{-1}cm^{-1}} \qquad (z = 1)\ , \tag{33.45}$$

or, equivalently,

$$\frac{d^2N}{dxd\lambda} = \frac{2\pi\alpha z^2}{\lambda^2}\left(1 - \frac{1}{\beta^2 n^2(\lambda)}\right)\ . \tag{33.46}$$



- UV and blue dominated
- Very fast (promptly produced)
- Total energy deposition approximately scale with the total photon detected

Careful designs give $\langle\epsilon_{\mathrm{coll}}\rangle \gtrsim 90\%$. For a photomultiplier with a typical bialkali cathode, $\int \epsilon_{\mathrm{det}}dE \approx 0.27$ eV, so that

$$N_{\mathrm{p.e.}}/L \approx 90\ \mathrm{cm^{-1}}\ \langle\sin^2\theta_c\rangle \qquad (i.e.,\ N_0 = 90\ \mathrm{cm^{-1}})\ . \tag{34.8}$$

Three main types of detectors

- Charge-collecting gas detector
- Solid state charge detector
- Scintillator

Charge-collecting gas detectors

- Collecting electrons and ions produced by the passage of a particle in a gas or liquid
- Chamber containing inert gas and two electrodes (cathode and anode).
- Anode: collect electrons which drift though the chamber much more rapidly, the signal can be amplified.
- The average energy for producing an electron-ion pair is about 30 ± 10eV.

Table 5.1 Values of the Energy Dissipation per Ion Pair (the *W*-Value) for Different Gases[a]

Gas	First Ionization Potential (eV)	*W*-Value (eV/ion pair)	
		Fast Electrons	Alpha Particles
Ar	15.7	26.4	26.3
He	24.5	41.3	42.7
H_2	15.6	36.5	36.4
N_2	15.5	34.8	36.4
Air		33.8	35.1
O_2	12.5	30.8	32.2
CH_4	14.5	27.3	29.1

[a] Values for *W* from ICRU Report 31, "Average Energy Required to Produce an Ion Pair," International Commission on Radiation Units and Measurements, Washington, DC, 1979.

Different regions of gas detector

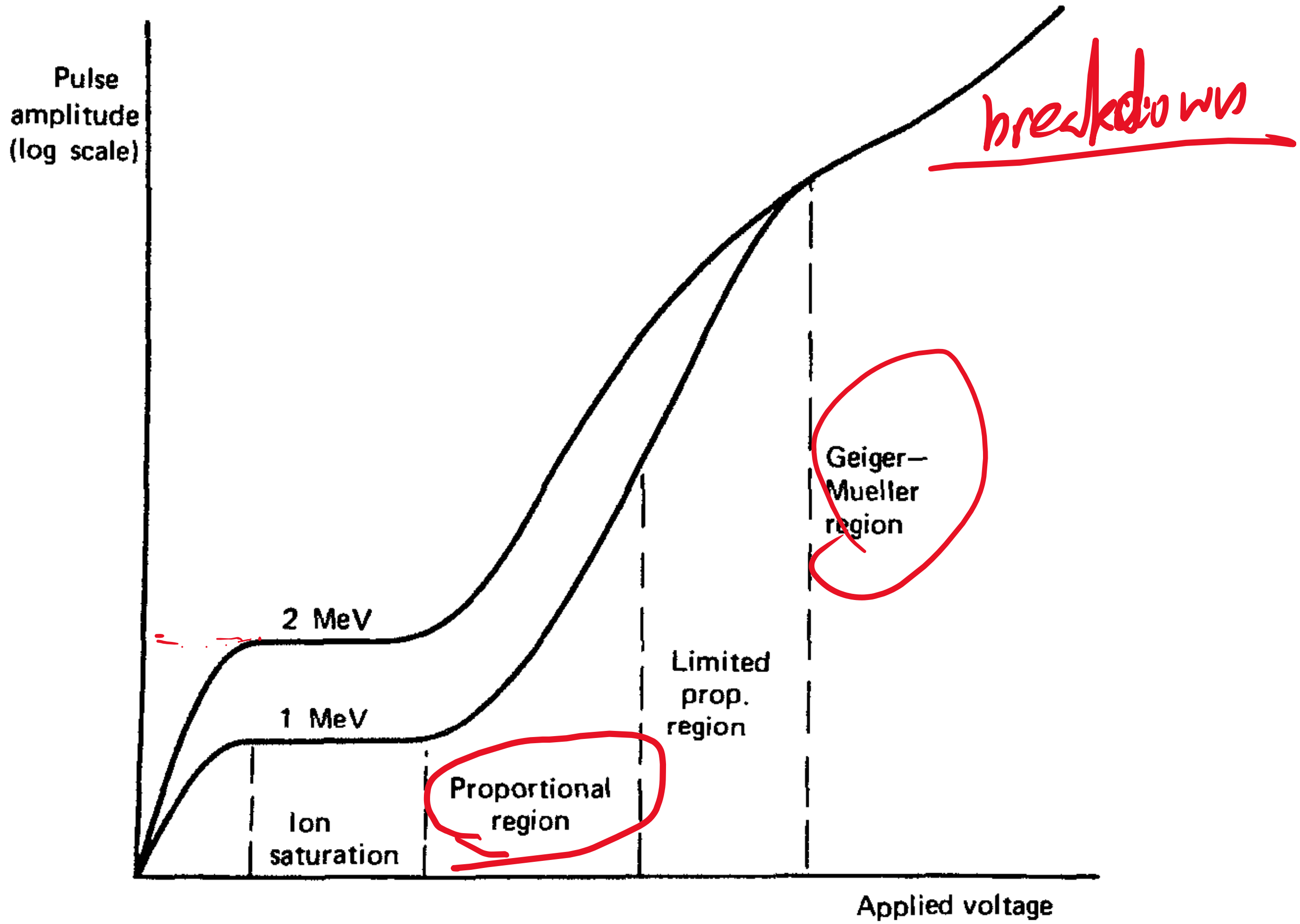


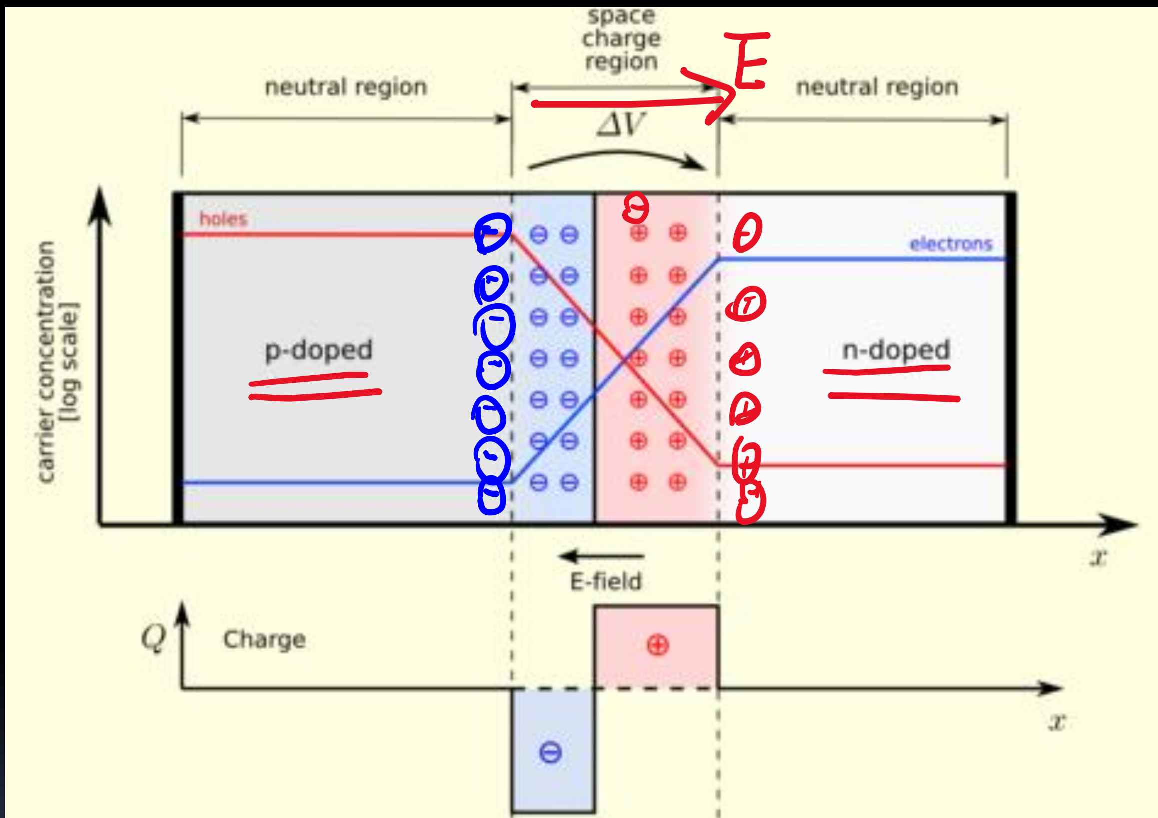
Figure 6.2 The different regions of operation of gas-filled detectors. The observed pulse amplitude is plotted for events depositing two different amounts of energy within the gas.

Silicon and Germanium: two typical semi-conductors

Table 11.1 Properties of Intrinsic Silicon and Germanium

	Si	Ge
Atomic number	14	32
Atomic weight	28.09	72.60
Stable isotope mass numbers	28-29-30	70-72-73-74-76
Density (300 K); g/cm^3	2.33	5.32
$Atoms/cm^3$	4.96×10^{22}	4.41×10^{22}
Dielectric constant (relative to vacuum)	12	16
Forbidden energy gap (300 K); eV	1.115	0.665
Forbidden energy gap (0 K); eV	1.165	0.746
Intrinsic carrier density (300 K); cm^{-3}	1.5×10^{10}	2.4×10^{13}
Intrinsic resistivity (300 K); $\Omega \cdot cm$	2.3×10^{5}	47
Electron mobility (300 K); $cm^2/V \cdot s$	1350	3900
Hole mobility (300 K); $cm^2/V \cdot s$	480	1900
Electron mobility (77 K); $cm^2/V \cdot s$	2.1×10^{4}	3.6×10^{4}
Hole mobility (77 K); $cm^2/V \cdot s$	1.1×10^{4}	4.2×10^{4}
Energy per electron–hole pair (300 K); eV	3.62	
Energy per electron–hole pair (77 K); eV	3.76	2.96
Fano factor (77 K)	0.143 (Ref. 7)	0.129 (Ref. 9)
	0.084 (Ref. 8)	0.08 (Ref. 10)
	0.085 to 0.137 (Ref. 12)	< 0.11 (Ref. 11)
		0.057 0.064 (Ref. 12)
	0.16 (Ref. 13)	0.058 (Ref. 14)

Need for a depleted zone (P-N junction)



Depleted zone:

- excess of electrons and holes builds up across the junction (radiation detector)
- with reverse biasing, the bulk material can be the detector

Based on these, which side should apply positive voltage? Which side collects electron and which side collects hole?

Spectrum comparison

- HPGe: excellent energy resolution
- Very useful in gamma ray tracing

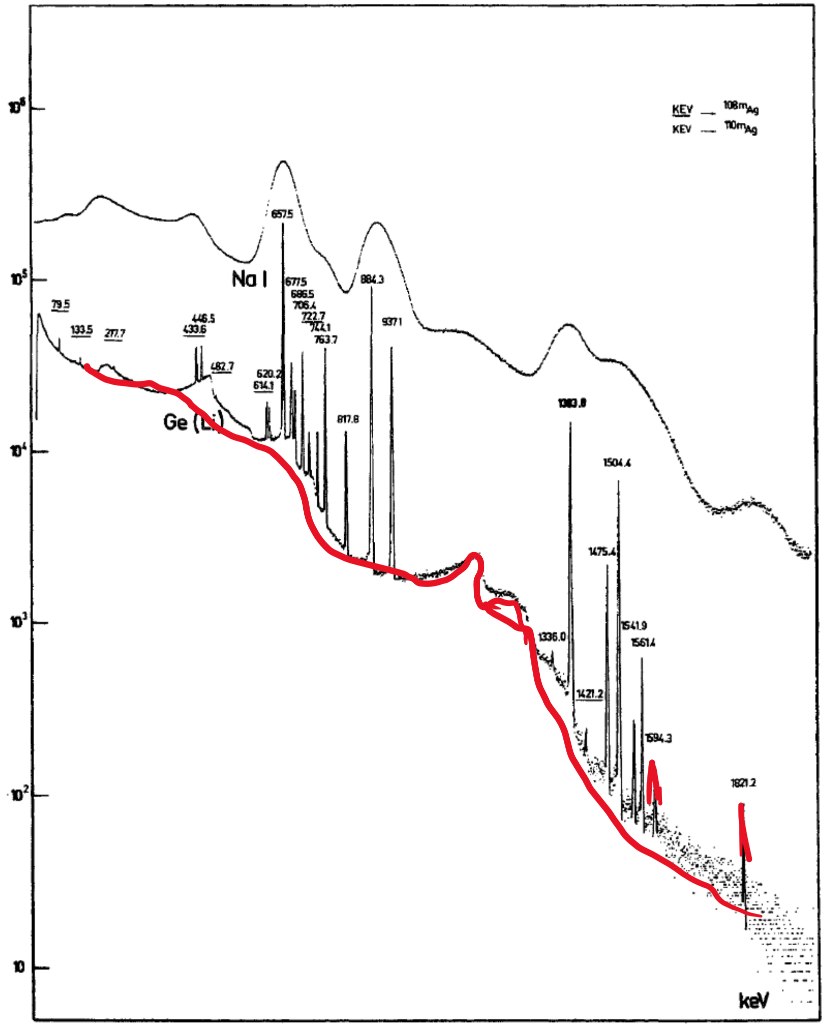
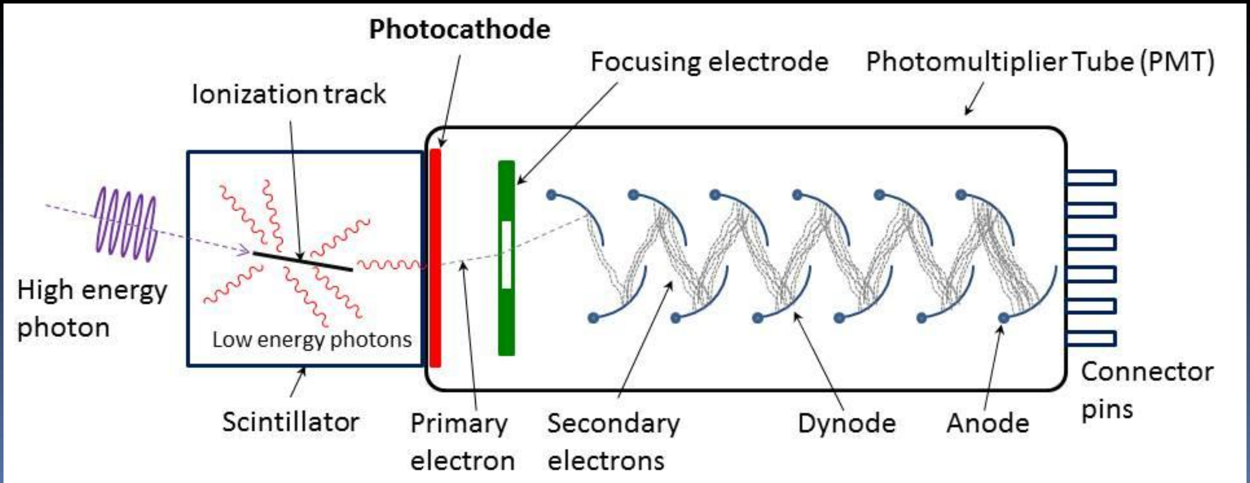


Figure 12.7 Comparative pulse height spectra recorded using a sodium iodide scintillator and a Ge(Li) detector. The source was gamma radiation from the decay of ^{108m}Ag and ^{110m}Ag. Energies of peaks are labeled in keV. (From Philippot.[13])

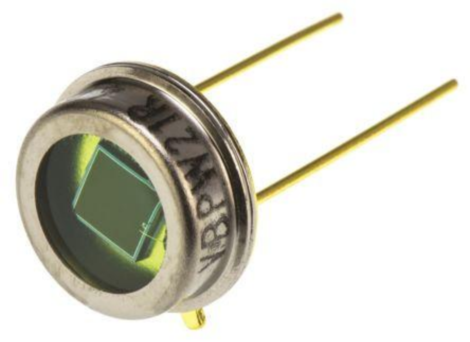
Scintillating detectors

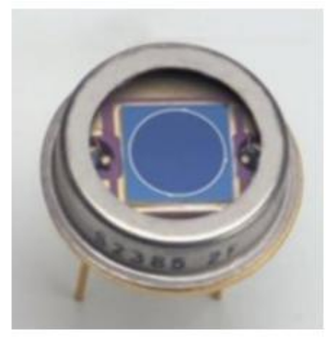
- Detection of radiation using scintillation light is an old technology.
  - Energy $\propto$ photons
  - Transparent!
  - Decay time of induced luminescence short
- Organic or crystal

Photosensors

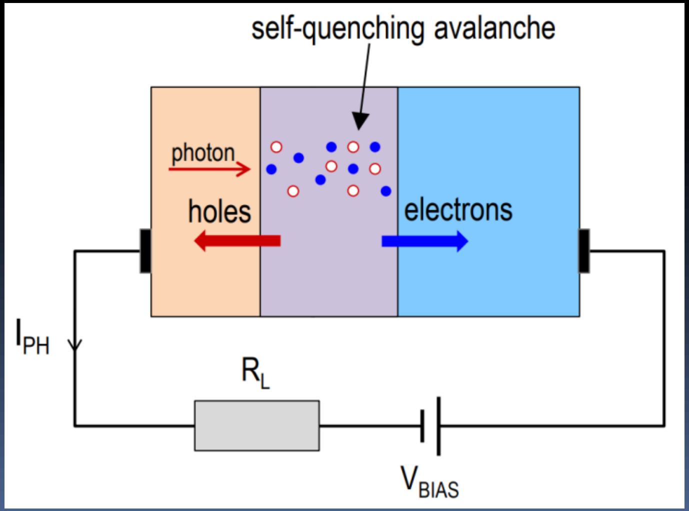


Semi-conductor photosensors (PD & APD)

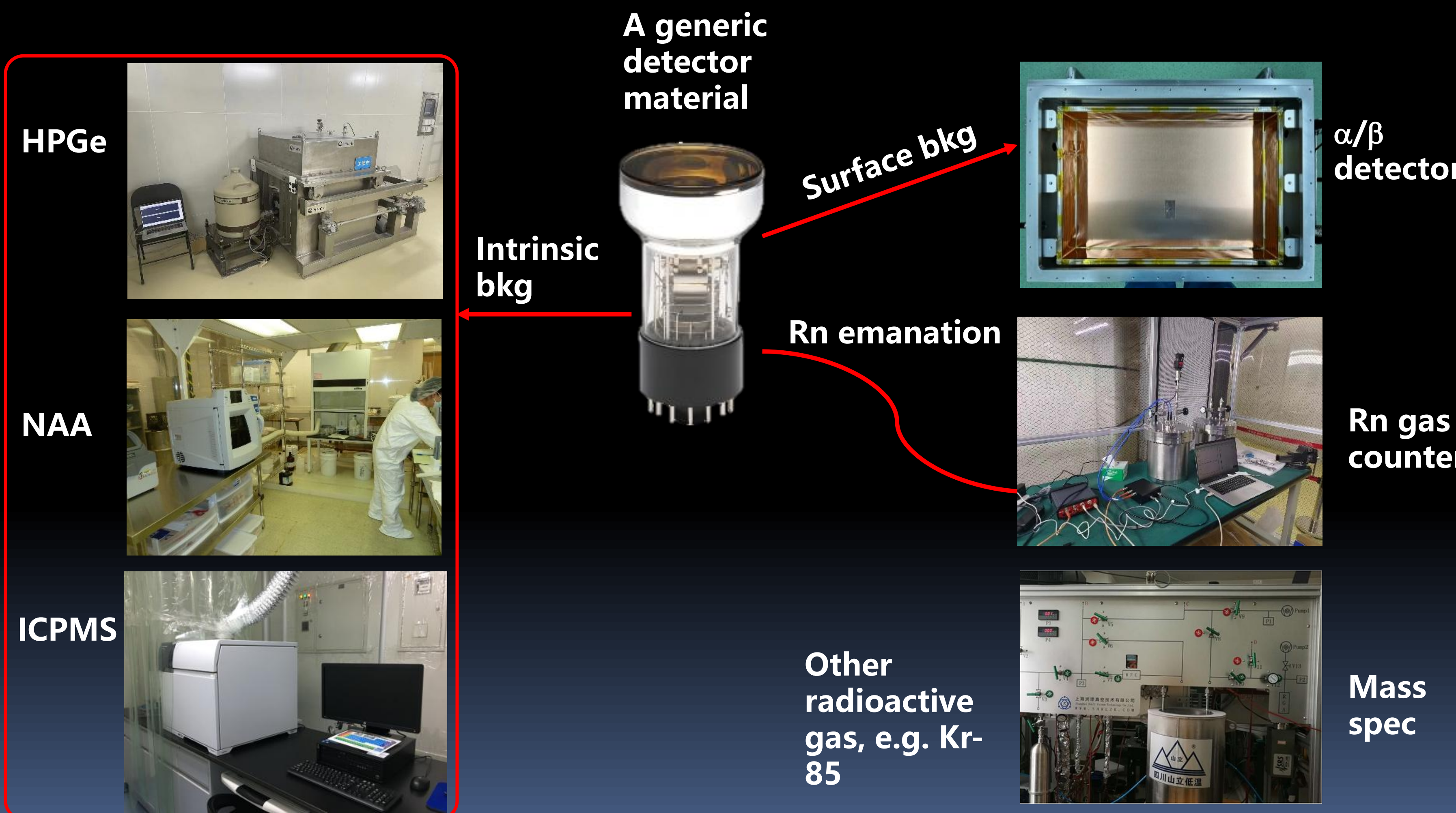




- Solid state instead of vacuum tube technology
- APD: biased to produce avalanche but below breakdown
- Gain can be up to 100
- Similarity with gas proportional counter!



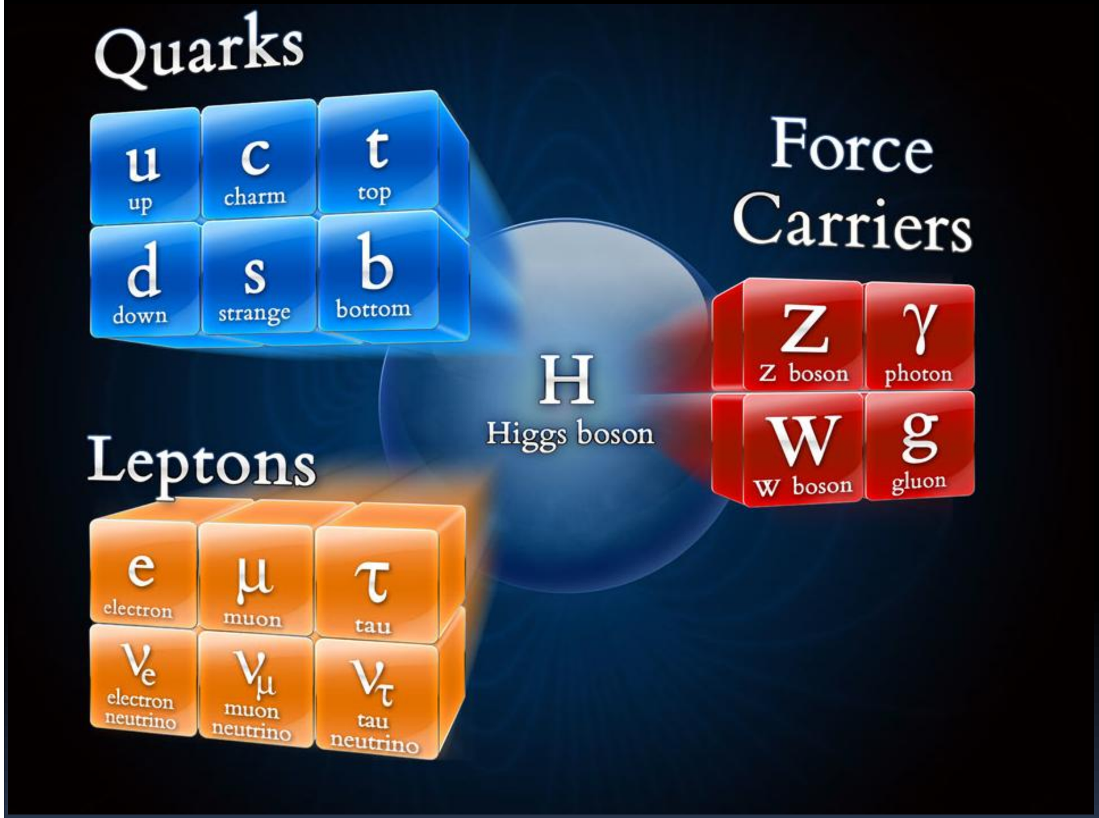
Low background techniques



Outline

- Unit 1: Detector and low background techniques 101
- Unit 2: Neutrinos, weak interactions
- Unit 3: Neutrino oscillations
- Unit 4: From neutrino coherent scattering to dark matter detection
- Unit 5: Neutrinoless double beta-decays

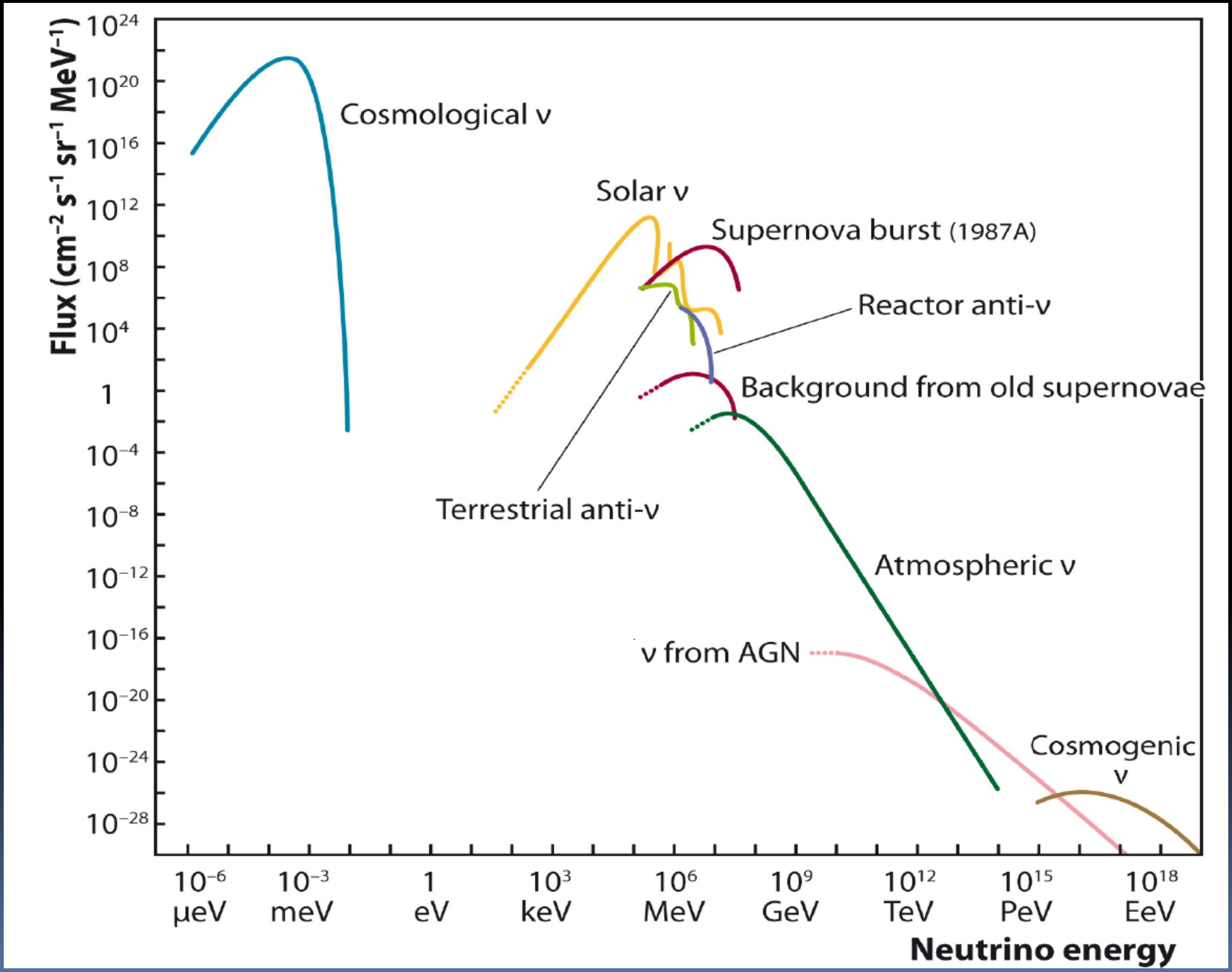
Standard Model of Particle Physics



$\nu_e, \bar{\nu}_e; \quad \nu_\mu, \bar{\nu}_\mu; \quad \nu_\tau, \bar{\nu}_\tau$

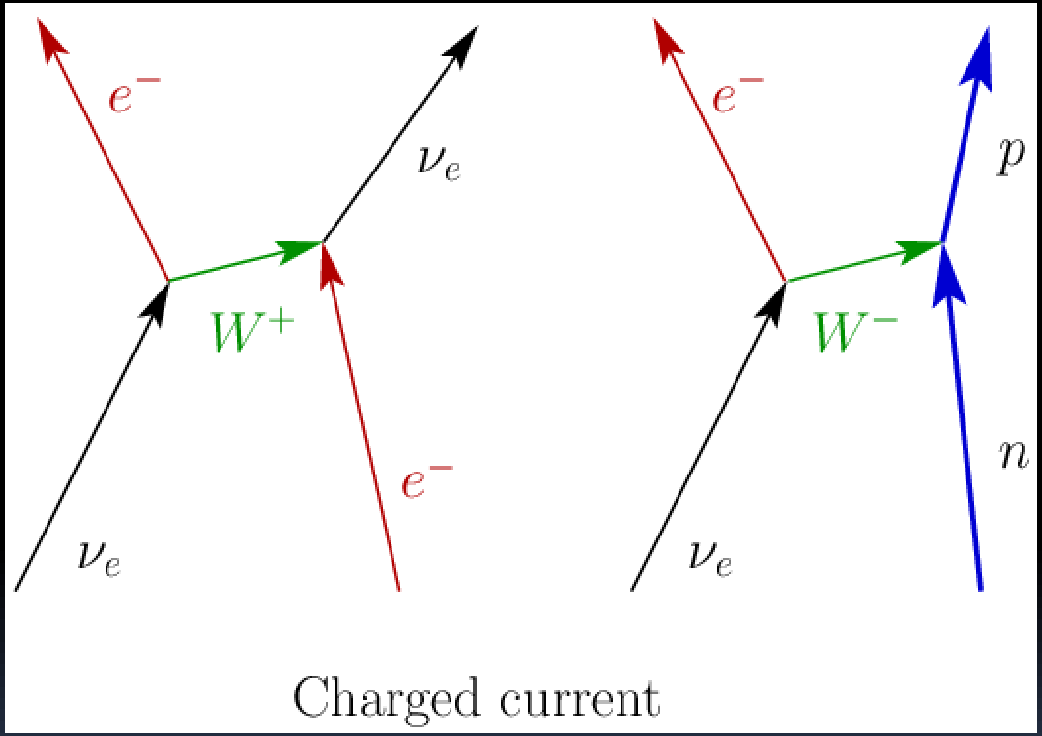
Three flavors
Weak interactions “only”
“No” mass

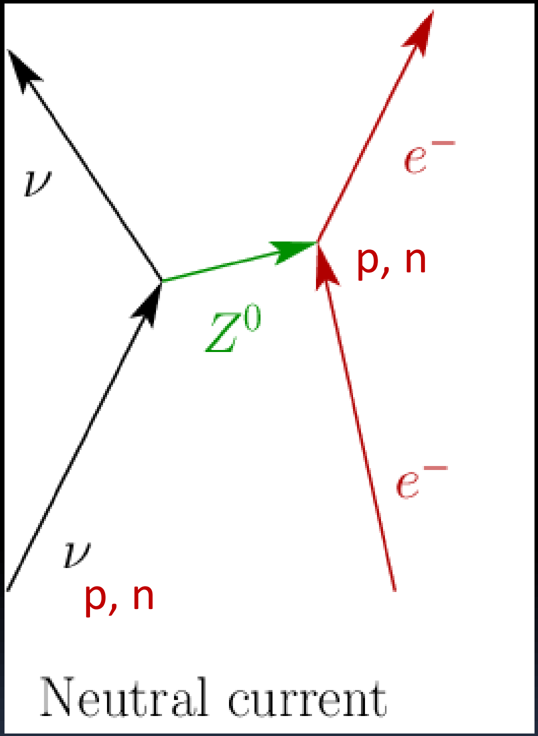
Everywhere!



Flux (cm⁻² s⁻¹ sr⁻¹ MeV⁻¹)
10²⁴
10²⁰
10¹⁶
10¹²
10⁸
10⁴
1
10⁻⁴
10⁻⁸
10⁻¹²
10⁻¹⁶
10⁻²⁰
10⁻²⁴
10⁻²⁸
Cosmological ν
Solar ν
Supernova burst (1987A)
Reactor anti-ν
Background from old supernovae
Terrestrial anti-ν
Atmospheric ν
ν from AGN
Cosmogenic ν
10⁻⁶ μeV
10⁻³ meV
1 eV
10³ keV
10⁶ MeV
10⁹ GeV
10¹² TeV
10¹⁵ PeV
10¹⁸ EeV
Neutrino energy

Weak interactions





First proposal of neutrino "detection"

Indirect Detection (Kan Chang Wang, 1941)

Physical Review 61 (1–2): 97

A Suggestion on the Detection of the Neutrino

Kan Chang Wang

Department of Physics, National University of Chekiang Tsunyi, Kweichow, China

October 13, 1941

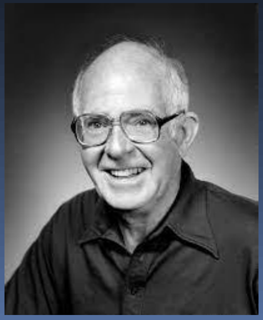
$$Be^7 + e_K \rightarrow Li^7 + \eta + (1\ \text{Mev})$$

and

$$Be^7 + e_K \rightarrow (Li^7)^* + \eta + (0.55\ \text{Mev}),$$
$$(Li^7)^* \rightarrow Li^7 + h\nu + 0.45\ \text{Mev}.$$

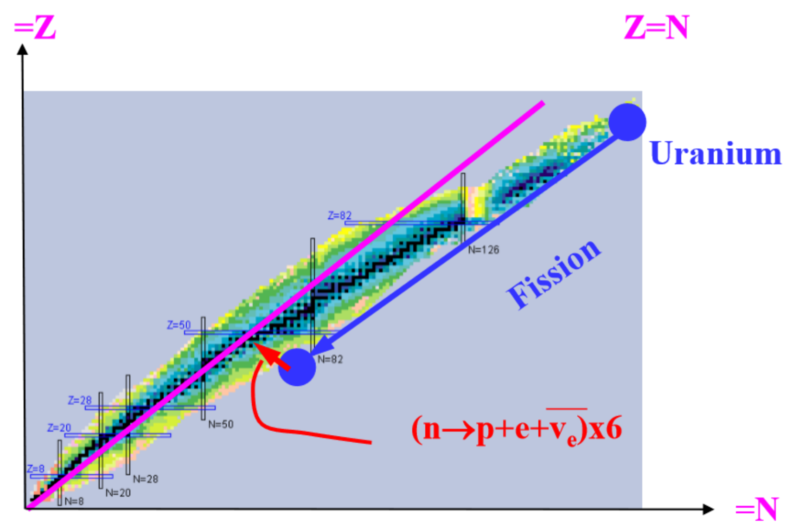
My first successful experiment was a study of the recoil energy of a ^{7}Li nucleus resulting from the electron-capture decay of ^{7}Be. In ^{7}Be decay, a single monoenergetic neutrino is emitted with an energy of 0.862 MeV, and the resulting ^{7}Li nucleus should recoil with a characteristic energy of 57 eV. A measurement of this process provides evidence for the existence of the neutrino. In my experiment, the energy spectrum of a recoiling ^{7}Li ion from a surface deposit of ^{7}Be was measured and found to agree with that expected from the emission of a single neutrino (Davis, 1952). This was a very nice result, but I was scooped by a group from the University of Illinois (Smith and Allen, 1951).

Ray Davis, Nobel lecture



Man-made neutrinos: nuclear reactors/bombs

Nuclear Reactors: Source of $\overline{\nu}_e$

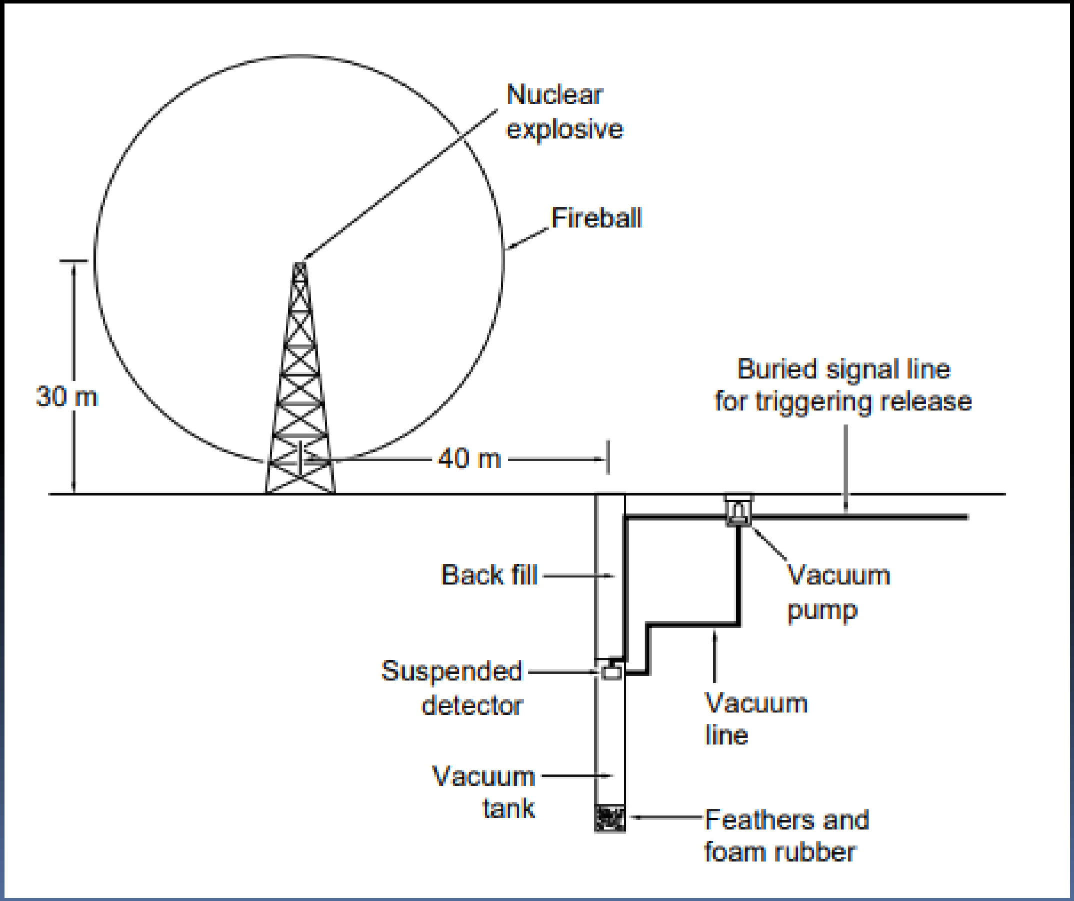


1 Fission $\Leftrightarrow$ 200 MeV $\Leftrightarrow$ 6 $\overline{\nu}_e$

So 1 GWth (typical power reactor) $\Rightarrow$ 2×10^{20} $\overline{\nu}_e$ /s

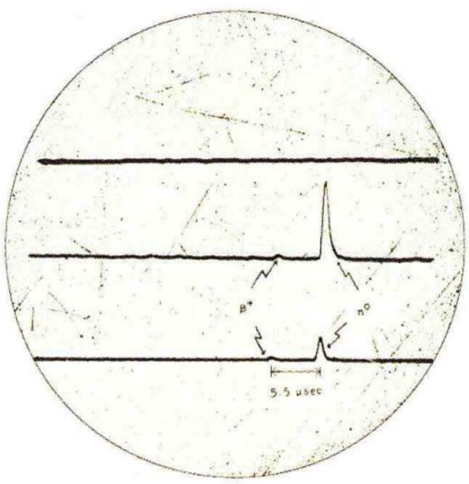
Proposal to directly measure neutrinos

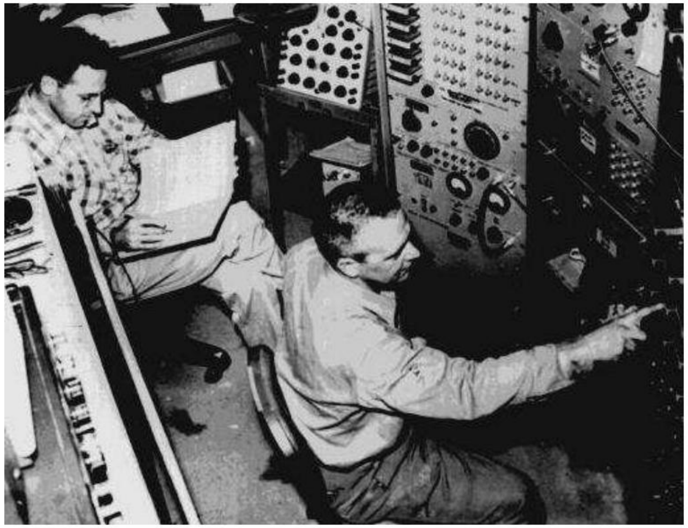
Direct measurement   Fred Reines, Cowan

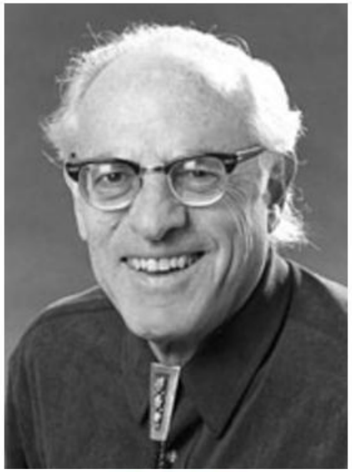


1953-1955: inverse beta decay (actually worked!)

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







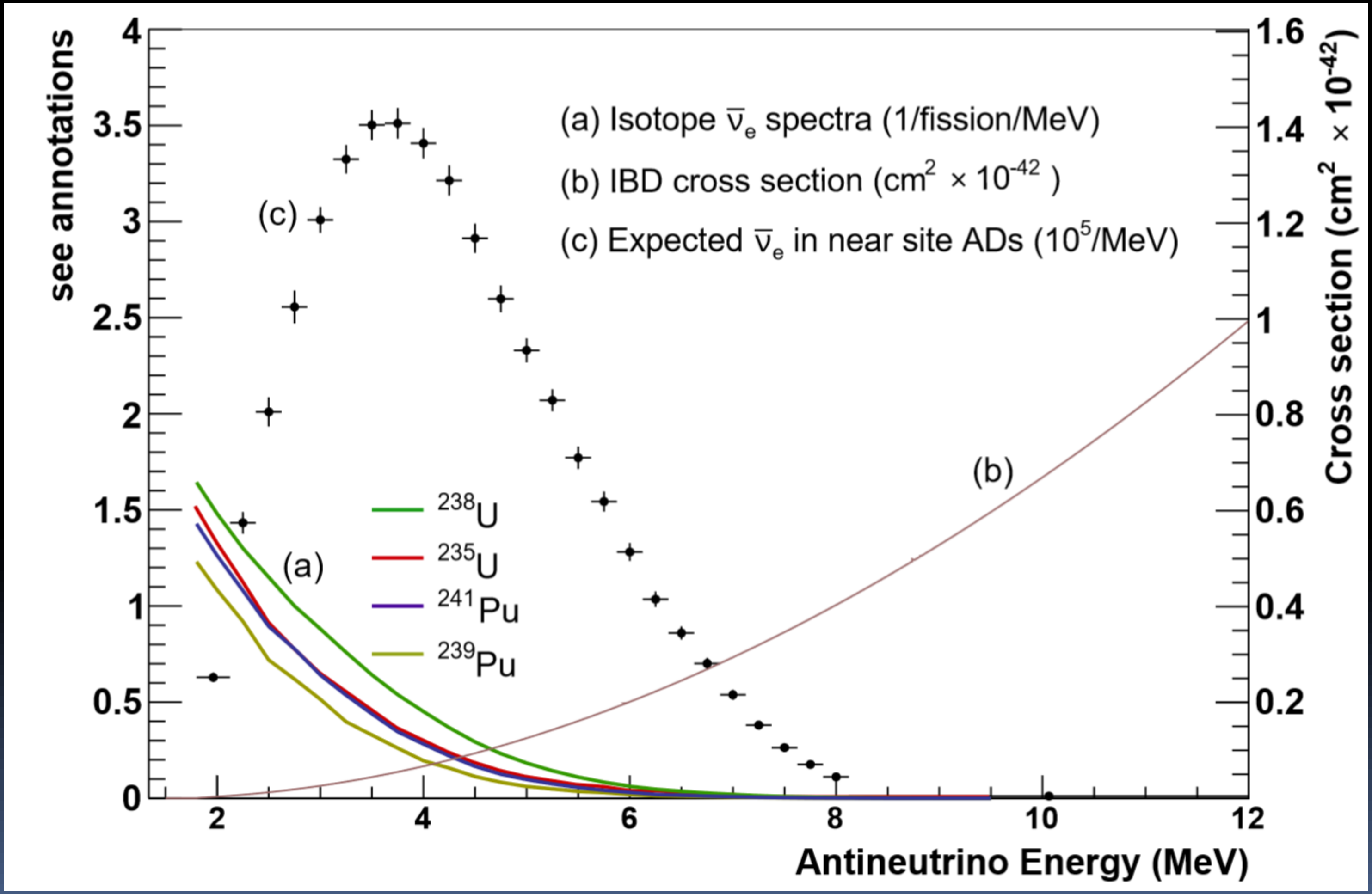
Fred Reines 1995

Detection of the Free Neutrino*

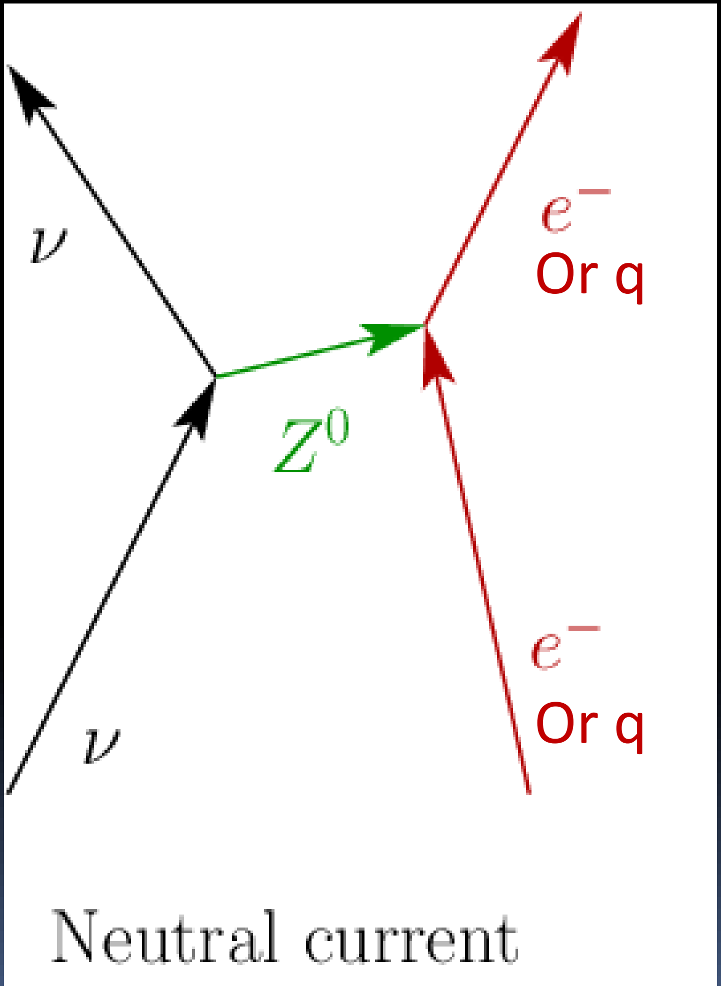
F. Reines and C. L. Cowan, Jr.
Los Alamos Scientific Laboratory, University of California, Los Alamos, New Mexico

(Received July 9, 1953; revised manuscript received September 14, 1953)

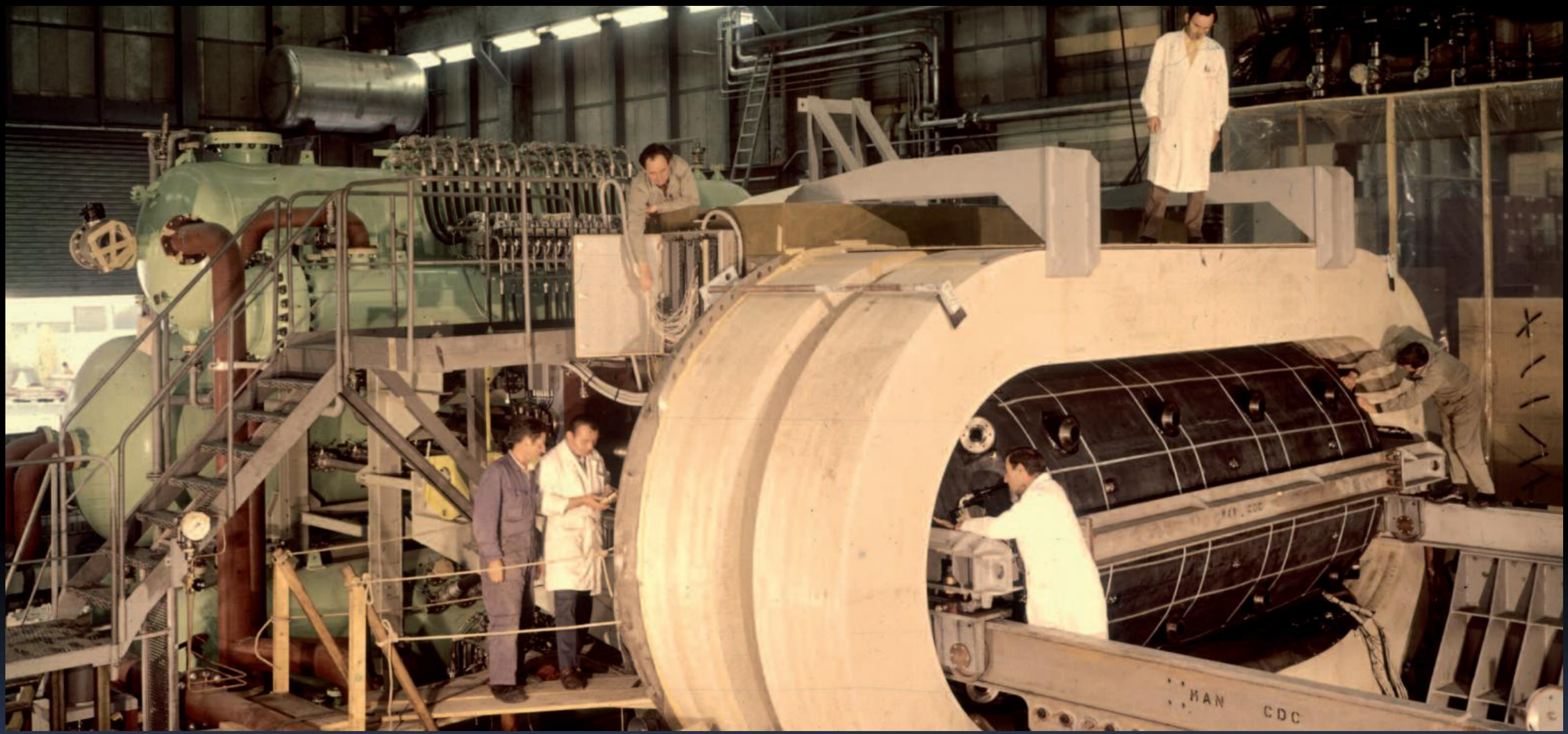
Inverse beta decay cross section



What about neutral current interaction?



What about neutral current interaction Gargamelle @ CERN (late 60's to 70's)



12 m^3 heavy-liquid Freon bubble chamber CF_3Br.

Bubble chamber

- The bubble chamber, invented by Donald Glaser in 1952, consists of a tank of unstable (superheated) transparent liquid
- Sensitive to the passage of charged particles $\Rightarrow$ boiling as a result of the energy they deposit by ionizing the atoms along the track

First leptonic NC events

360000 pictures scanned

Isolated forward e observed

at Aachen Dec 1972.

Interpretation:

$$\overline{\nu}_\mu e \rightarrow \overline{\nu}_\mu e$$

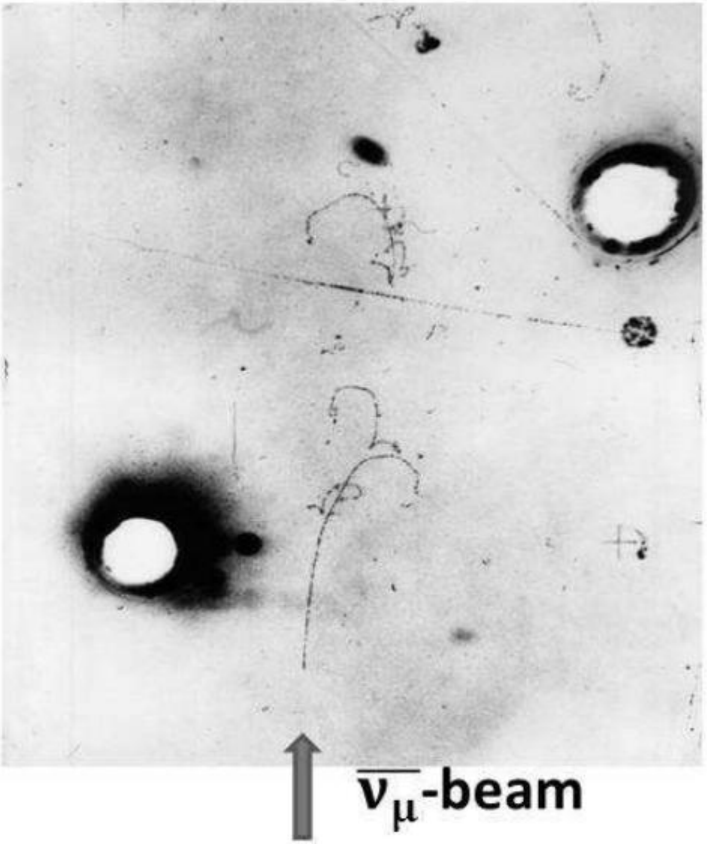
Properties of electron :

- **Identification** : unique by bremsstrahlung and curling
- **Energy** 385±100 MeV
- **Angle** 1.4 ± 1.4 degree

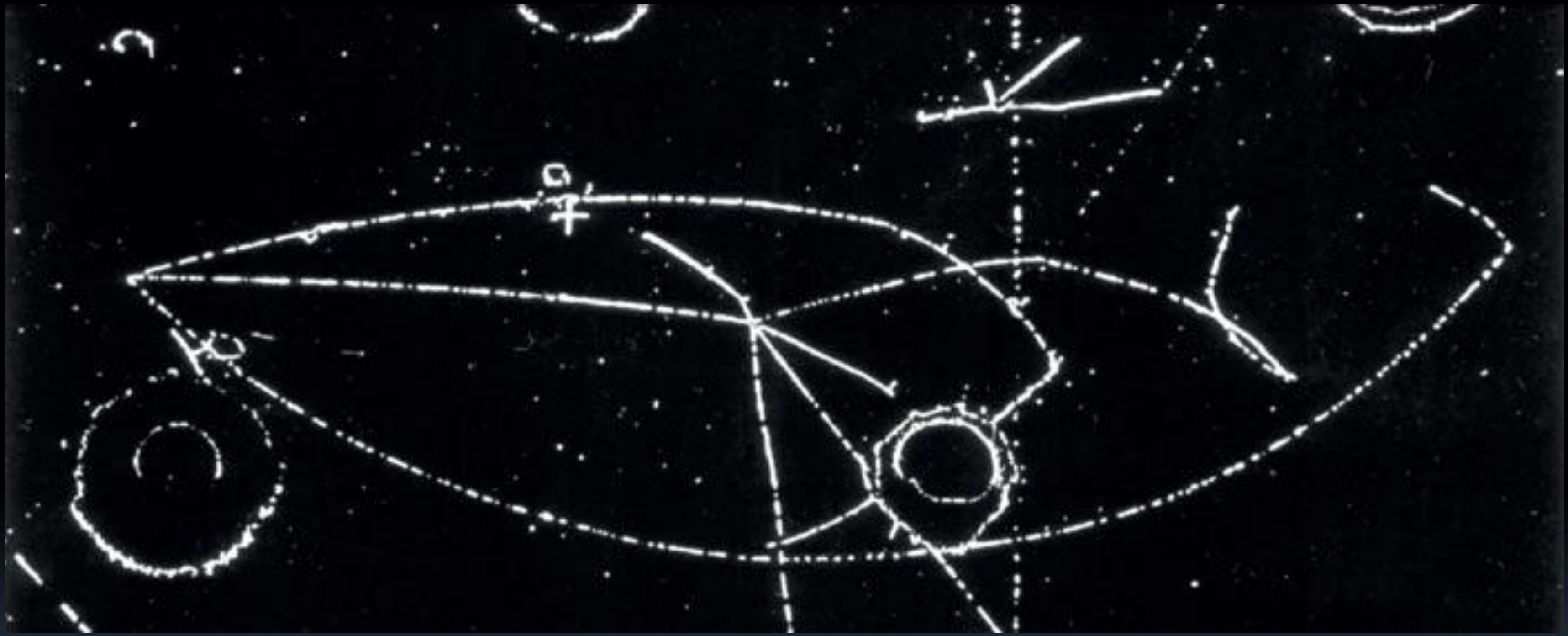
Background : 0.03 ±0.02

$$\nu_e\, n \rightarrow e + p$$

(proton invisible)



First hadronic NC events



How do we tell a hadronic vertex from a leptonic vertex?

Volume 46B, number 1 PHYSICS LETTERS 3 September 1973

OBSERVATION OF NEUTRINO-LIKE INTERACTIONS WITHOUT MUON OR ELECTRON IN THE GARGAMELLE NEUTRINO EXPERIMENT

F.J. HASERT, S. KABE, W. KRENZ, J. Von KROGH, D. LANSKE, J. MORFIN, K. SCHULTZE and H. WEERTS

III. Physikalisches Institut der Technischen Hochschule, Aachen, Germany

G.H. BERTRAND-COREMANS, J. SACTON, W. Van DONINCK and P. VILAIN*[1]

Interuniversity Institute for High Energies, U.L.B., V.U.B. Brussels, Belgium

U. CAMERINI*[2], D.C. CUNDY, R. BALDI, I. DANILCHENKO*[3], W.F. FRY*[2], D. HAIDT, S. NATALI*[4], P. MUSSET, B. OSCULATI, R. PALMER*[4], J.B.M. PATTISON, D.H. PERKINS*[6], A. PULLIA, A. ROUSSET, W. VENUS*[7] and H. WACHSMUTH

CERN, Geneva, Switzerland

V. BRISSON, B. DEGRANGE, M. HAGUENAUER, L. KLUBERG, U. NGUYEN-KHAC and P. PETIAU

Laboratoire de Physique Nucléaire des Hautes Energies, Ecole Polytechnique, Paris, France

E. BELOTTI, S. BONETTI, D. CAVALLI, C. CONTA*[8]. E. FIORINI and M. ROLLIER

Istituto di Fisica dell'Università, Milano and I.N.F.N. Milano, Italy

B. AUBERT, D. BLUM, L.M. CHOUNET, P. HEUSSE, A. LAGARRIGUE, A.M. LUTZ, A. ORKIN-LECOURTOIS and J.P. VIALLE

Laboratoire de l'Accélérateur Linéaire, Orsay, France

F.W. BULLOCK, M.J. ESTEN, T.W. JONES, J. McKENZIE, A.G. MICHETTE*[9] G. MYATT* and W.G. SCOTT*[6],*[9]

University College, London, England

Energy production from the sun

- Sun: mass = $2x10^{30}$ kg
- Known: Energy is released via proton-proton fuse into He4 in the core, about 10% of the mass
- Known: Sun will burn for 10 billion years (1e10)

Neutrino flux from the sun

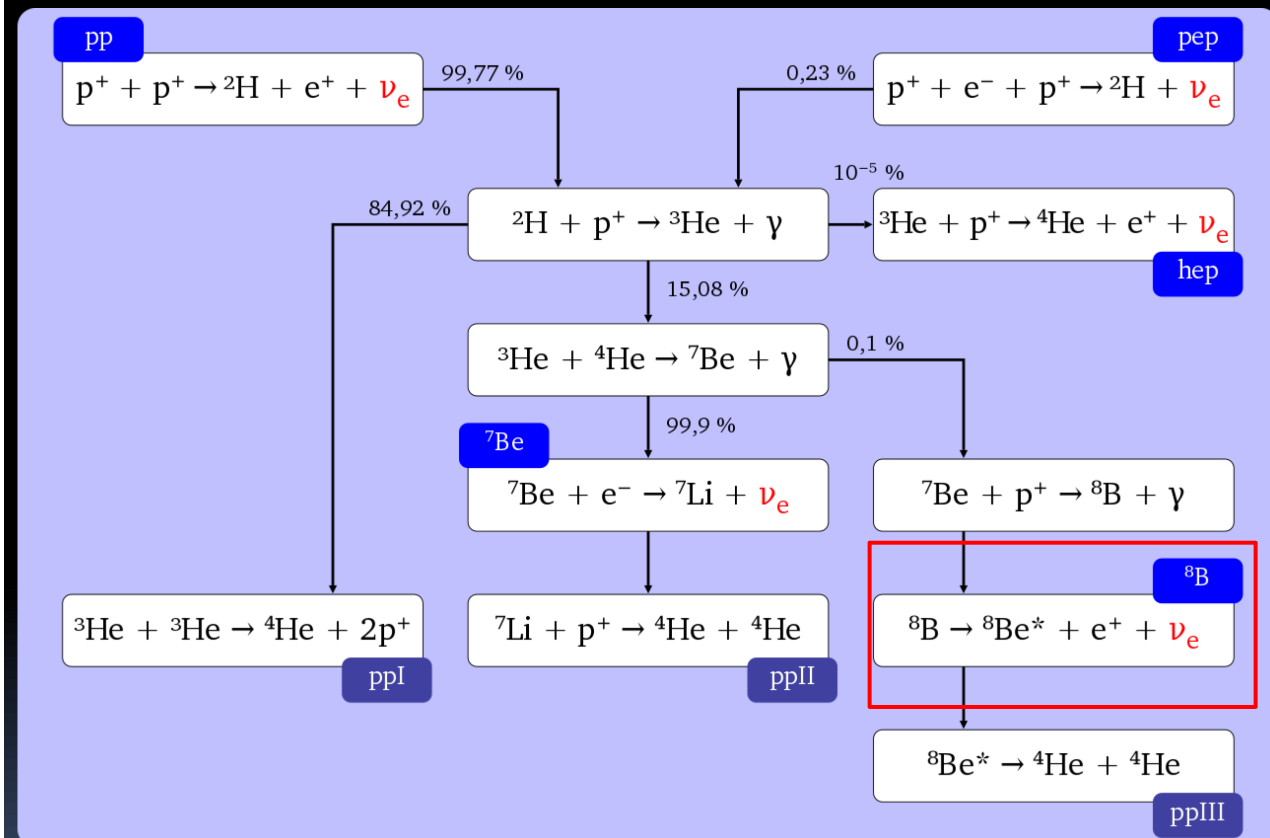
- Mostly p+p+p+p $\Rightarrow$ He4
  - Change 2 p into 2 n, each is giving out an electron neutrino!
  - $p + p + p + p \Rightarrow \alpha + e^{+} + e^{+} + v_e + v_e$
- Quiz: can you estimate electron neutrino per sec created from the sun?

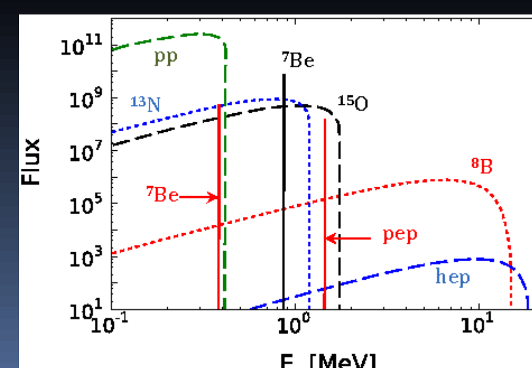
• Sun: mass = 2×10^{30} kg (homework #1)

• Known: Energy is released via proton-proton fuse into He4 in the core, about 10% of the mass

• Known: Sun will burn for 10 billion years (1e10)

Standard solar model (John Bahcall)





Pontecorvo

- Italian born physicist. Fermi's student
- Theoretical physicists with fundamental contributions to neutrinos

On a method of detecting free neutrinos (1946)

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

Ar37

- (P,N) = (20, 17)
- Decay mode: electron capture!
  - Ar37 + e = Cl37 + ve
- Half-life: 35 days
- 2.8 keV x-ray

What does it take?

- Expected Ar37 atom: ~2e-3 per day/ton
- Get a big chunk of Cl37
- Go deep underground to reduce background
- Ultrapure environment
- High and known efficiency to extract Ar37
- High and known efficiency to measured Ar37

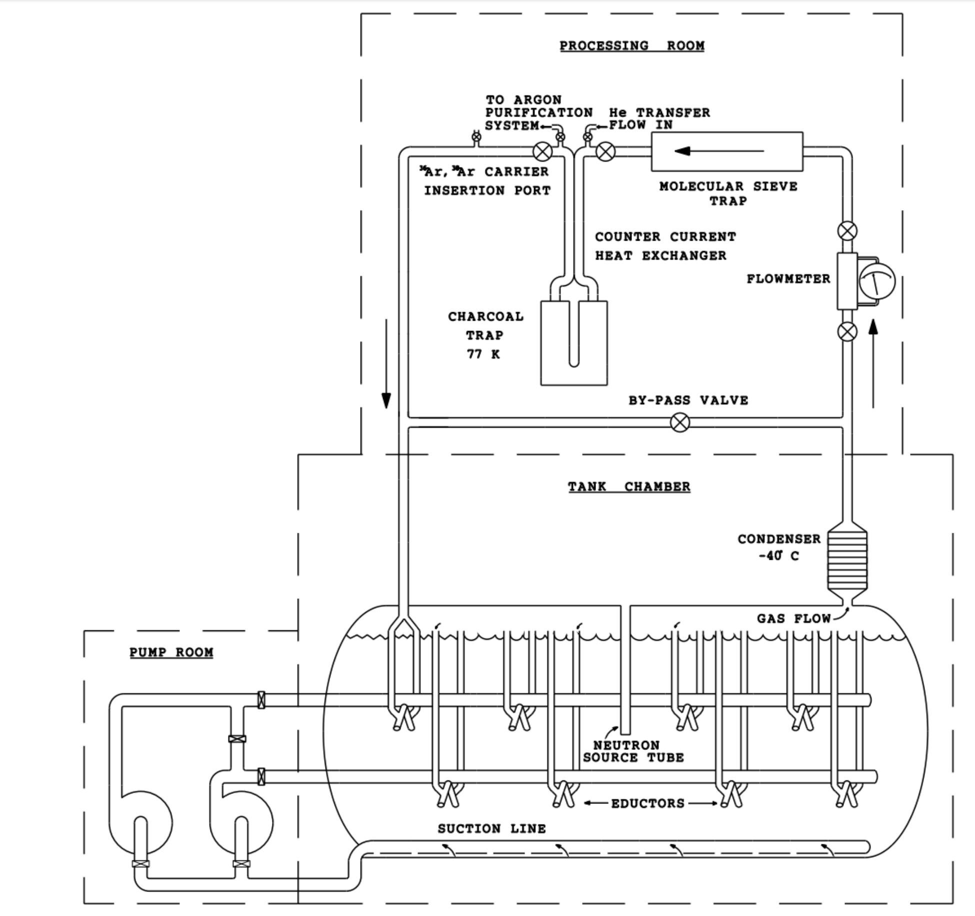
Hunters for solar neutrino

Also >50 years ago, Baksan observatory got started. Many interesting experiments since then. The Sage experiment using the electron-capture of Ge71 was another crucial player in the field!

30 years of solar neutrino measurement

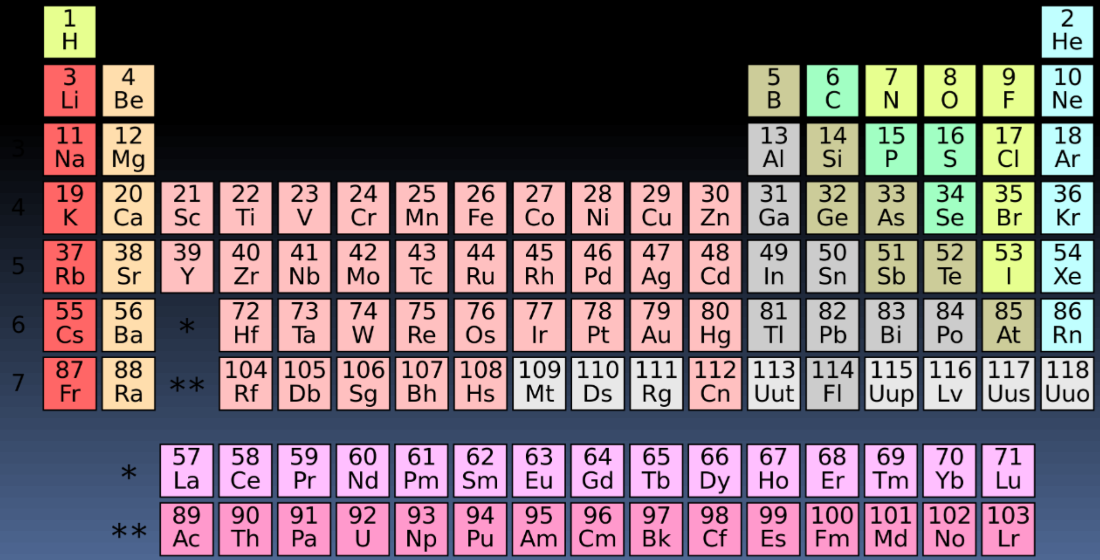
$$\nu_e + {}^{37}\mathrm{Cl} \rightarrow {}^{37}\mathrm{Ar} + e^-$$

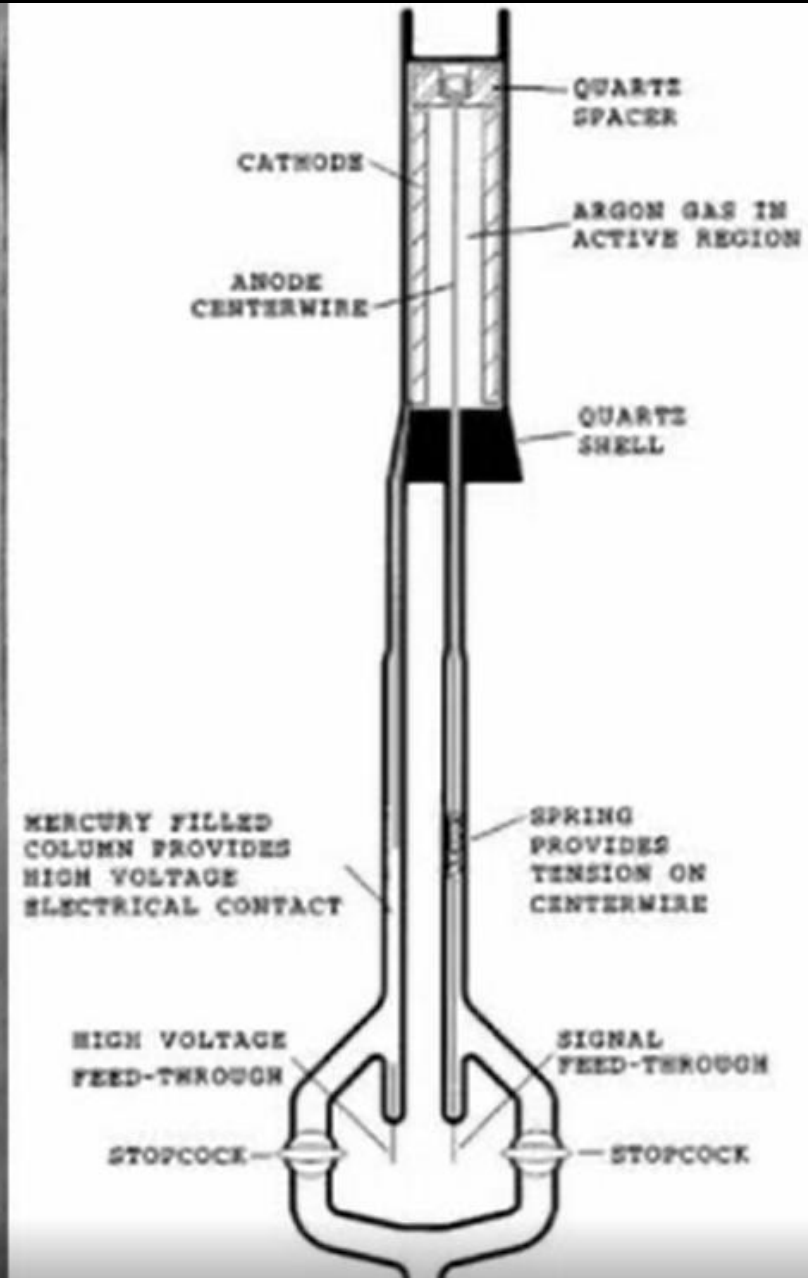
615 T of C_2Cl_4
tetrachloroethylene



How it worked

- He4 bubbles the Ar out of the detector
- Ar trapped by LN2 cooled charcoal
- Ar released into a ionization gas detector to measured Ar37 one by one!




QUARTZ SPACER
CATHODE
ARGON GAS IN ACTIVE REGION
ANODE CENTERWIRE
QUARTZ SHELL
MERCURY FILLED COLUMN PROVIDES HIGH VOLTAGE ELECTRICAL CONTACT
SPRING PROVIDES TENSION ON CENTERWIRE
HIGH VOLTAGE FEED-THROUGH
SIGNAL FEED-THROUGH
STOPCOCK
STOPCOCK

The first exposure was 48 days. The tank was purged with 0.50 million liters of helium. A volume of 1.27 std cc of argon was recovered from the tank, and this volume contained 94 % of the carrier Ar^{36} introduced at the start of the exposure. It was counted for 39 days and the total number of counts observed in the Ar^{37} peak position (full width at half-maximum) in the pulse-height spectrum was 22 counts. This rate is to be compared with a background rate of 31 ± 10 counts for this period. The neutrino-capture rate in the tank deduced from the exposure, counter efficiency, and argon recovery from this experiment was (-1.1 ± 1.4) per day.

First search of solar neutrinos

- https://journals.aps.org/prl/pdf/10.1103/PhysRevLett.20.1205

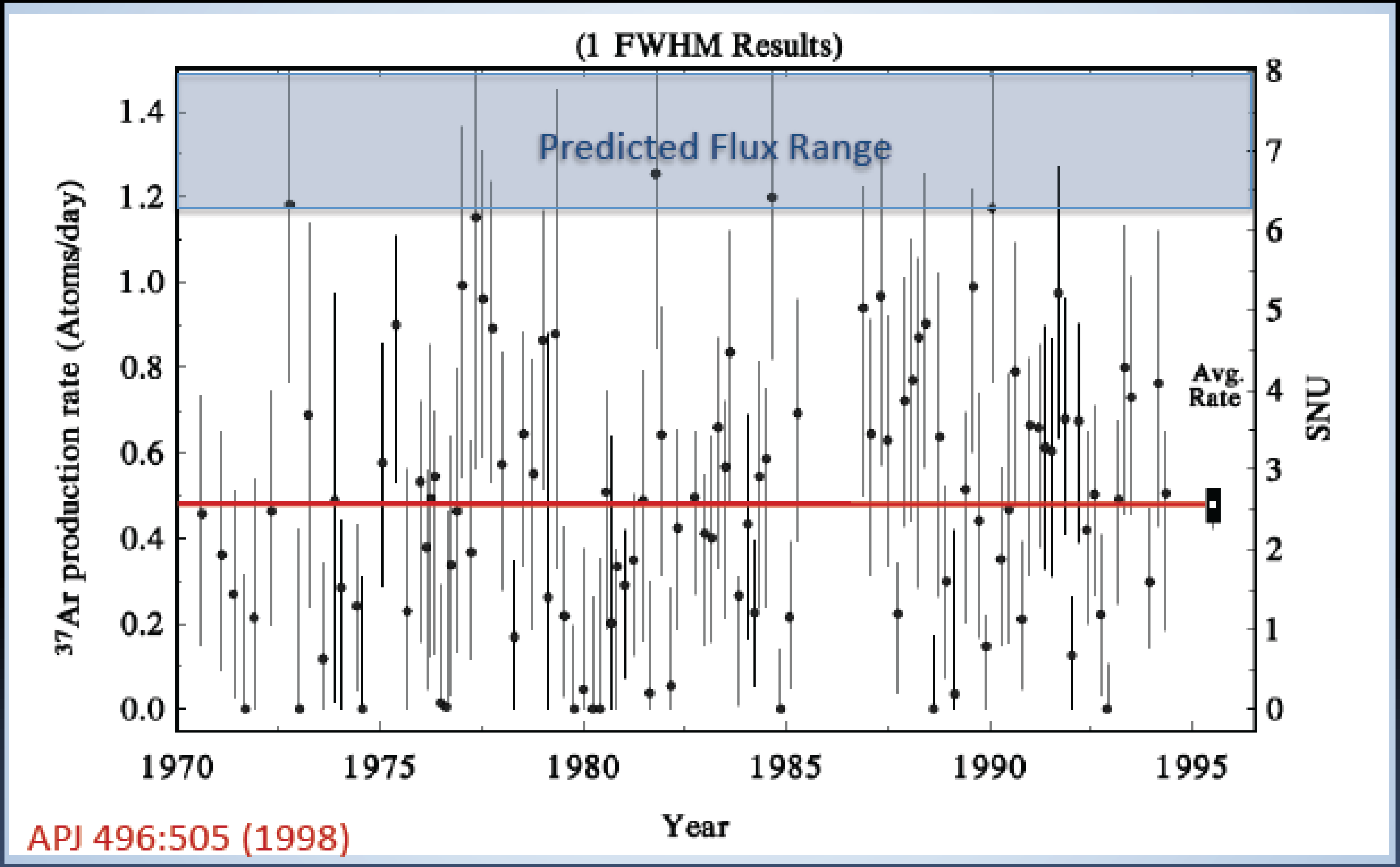
VOLUME 20, NUMBER 21 PHYSICAL REVIEW LETTERS 20 MAY 1968

SEARCH FOR NEUTRINOS FROM THE SUN*

Raymond Davis, Jr., Don S. Harmer,† and Kenneth C. Hoffman
Brookhaven National Laboratory, Upton, New York 11973
(Received 16 April 1968)

A search was made for solar neutrinos with a detector based upon the reaction $Cl^{37}(\nu, e^-)Ar^{37}$. The upper limit of the product of the neutrino flux and the cross sections for all sources of neutrinos was 3×10^{-36} sec^{-1} per Cl^{37} atom. It was concluded specifically that the flux of neutrinos from B^8 decay in the sun was equal to or less than 2×10^6 cm^{-2} sec^{-1} at the earth, and that less than 9% of the sun's energy is produced by the carbon-nitrogen cycle.

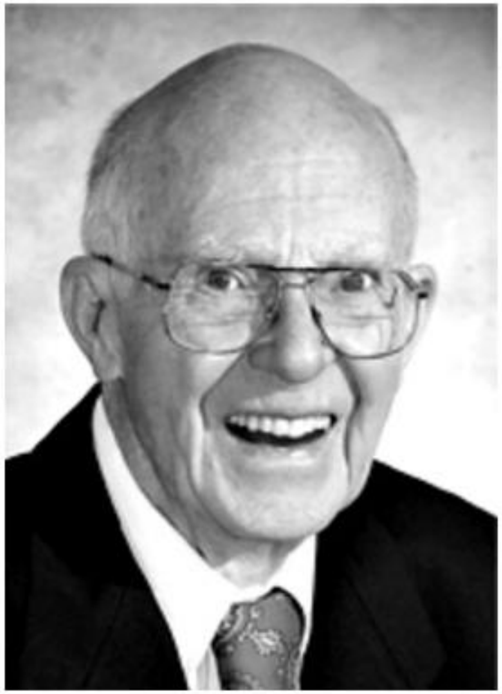
Solar neutrino detection and “problem”



Solar neutrino problem

- Davis is WRONG?
- Bahall is WRONG? (many places can be wrong, the flux, the cross section, etc …)
- Or both of them are WRONG?

But: 2002 Nobel Prize



Raymond Davis Jr.
Prize share: 1/4

Masatoshi Koshiba
Prize share: 1/4

The Nobel Prize in Physics 2002 was divided, one half jointly to Raymond Davis Jr. and Masatoshi Koshiba *"for pioneering contributions to astrophysics, in particular for the detection of cosmic neutrinos"* …

Cheat sheet: neutrino interaction scattering cross sections

- http://cupp.oulu.fi/neutrino/nd-cross.html

Antineutrino-nucleon

$$\sigma_{\bar{\nu}_e p \to e^+ n} = \frac{G_F^2 E_\nu^2 (\hbar c)^2}{\pi}(g_V^2 + 3g_A^2)\left(1 - \frac{Q}{E_\nu}\right)\sqrt{1 - 2\frac{Q}{E_\nu} + \frac{Q^2 - m_e^2}{E_\nu^2}}\,\theta(E - Q)$$

$$\frac{G_F^2 E_\nu^2 (\hbar c)^2}{\pi}(g_V^2 + 3g_A^2) = 9.3 \cdot 10^{-48}\ \mathrm{m}^2 \left(\frac{E_\nu}{1\ \mathrm{MeV}}\right)^2$$

Elastic scattering

$$\sigma_{\nu_e e^- \to \nu_e e^-} = \frac{G_F^2 s}{\pi}\left[\left(\frac{1}{2} + \xi\right)^2 + \frac{1}{3}\xi^2\right] \approx 9.5 \cdot 10^{-49}\ \mathrm{m}^2 \left(\frac{E_\nu}{1\ \mathrm{MeV}}\right)$$

$$\sigma_{\bar{\nu}_e e^- \to \bar{\nu}_e e^-} = \frac{G_F^2 s}{\pi}\left[\frac{1}{3}\left(\frac{1}{2} + \xi\right)^2 + \xi^2\right] \approx 4.0 \cdot 10^{-49}\ \mathrm{m}^2 \left(\frac{E_\nu}{1\ \mathrm{MeV}}\right)$$

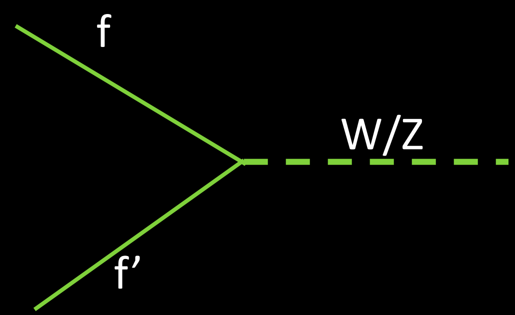
Neutrino-nucleon elastic c.s.

$$\sigma_{\nu n \to \nu n}(E) = \frac{G_F^2 E_\nu^2 (\hbar c)^2}{\pi}(1 + 3g_A^2) \approx 9.3 \cdot 10^{-48}\ \mathrm{m}^2 \left(\frac{E_\nu}{1\ \mathrm{MeV}}\right)^2.$$

$$\sigma_{\nu p \to \nu p}(E) = \frac{G_F^2 E_\nu^2 (\hbar c)^2}{4\pi}\left((16\xi^2 - 8\xi + 1)(1 + 3g_A^2)\right) \approx 6.0 \cdot 10^{-50}\ \mathrm{m}^2 \left(\frac{E_\nu}{1\ \mathrm{MeV}}\right)^2.$$

- For proton, IBD highest
- Neutrino-neutron cross section also "big" (but difficult to measure due to small recoils)

Insights: coupling in neutrino interactions



W vertices

$$\frac{-ig_W}{2\sqrt{2}}\gamma^\mu(1-\gamma^5)$$

Z vertices

$$\frac{-ig_Z}{2}\gamma^\mu(c_V^f - c_A^f\gamma^5)$$

$$g_Z = \frac{g_W}{\cos\theta_W}$$

$$M_Z = \frac{M_W}{\cos\theta_W}$$

$\sin^2\theta_W = 0.2312$

	c_V	c_A
ν_e, ν_μ, ν_τ	$\frac{1}{2}$	$\frac{1}{2}$
e, μ, τ	$-\frac{1}{2}+2\sin^2\theta_W$	$-\frac{1}{2}$
u, c, t	$\frac{1}{2}-\frac{4}{3}\sin^2\theta_W$	$\frac{1}{2}$
d, s, b	$-\frac{1}{2}+\frac{2}{3}\sin^2\theta_W$	$-\frac{1}{2}$

$C_v(p) = -C_v(e)$
$= -1/12\ C_v(n)$
$= 1/12\ C_v(\nu)$!!!

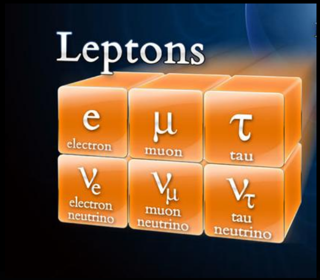
Neutrons and neutrinos see more weak force than proton and electrons!

Outline

- Unit 1: Detector and low background techniques 101
- Unit 2: Neutrinos, weak interactions
- Unit 3: Neutrino oscillations
- Unit 4: From neutrino coherent scattering to dark matter detection
- Unit 5: Neutrinoless double beta-decays

Pontecorvo Explanation

- Neutrino can change species: neutrino oscillation!
  - Electron neutrino may have oscillated into other species!



20. B. Pontecorvo, "Mesonium and antimesonium," *Zhurnal Eksperimental'noi i Teoreticheskoi Fiziki*, vol. 33, p. 549, 1957, *Soviet Physics—JETP*, vol. 6, p. 429, 1958. View at Google Scholar

21. B. Pontecorvo, "Inverse beta processes and nonconservation of lepton charge," *Zhurnal Eksperimental'noi i Teoreticheskoi Fiziki*, vol. 34, p. 247, 1957, *Soviet Physics—JETP, vol.7, pp. 172-173, 1958.* View at Google Scholar

Origin of SNO

Herbert Chen, 陈华森, 1942-1987

VOLUME 55, NUMBER 14 PHYSICAL REVIEW LETTERS 30 SEPTEMBER 1985

Direct Approach to Resolve the Solar-Neutrino Problem

Herbert H. Chen
Department of Physics, University of California, Irvine, California 92717
(Received 27 June 1985)

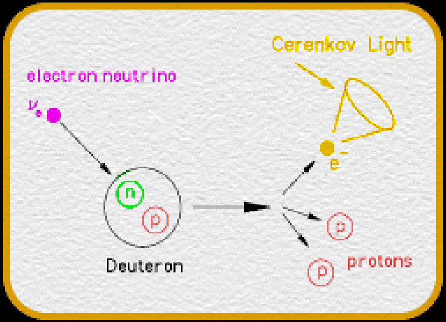
A direct approach to resolve the solar-neutrino problem would be to observe neutrinos by use of both neutral-current and charged-current reactions. Then, the total neutrino flux and the electron-neutrino flux would be separately determined to provide independent tests of the neutrino-oscillation hypothesis and the standard solar model. A large heavy-water Cherenkov detector, sensitive to neutrinos from ^{8}B decay via the neutral-curent reaction $\nu + d \rightarrow \nu + p + n$ and the charged-current reaction $\nu_e + d \rightarrow e^- + p + p$, is suggested for this purpose.

PACS numbers: 96.60.Kx, 14.60.Gh

Three detection channels in SNO

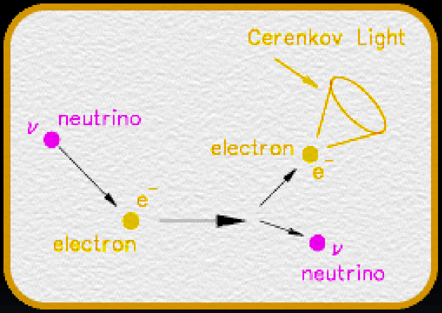
Let us call the flux of ve "e", other neutrinos "x:

$$\nu_e + {}^2H \rightarrow e^- + p + p \quad (\mathrm{CC})$$



CC ∝ e

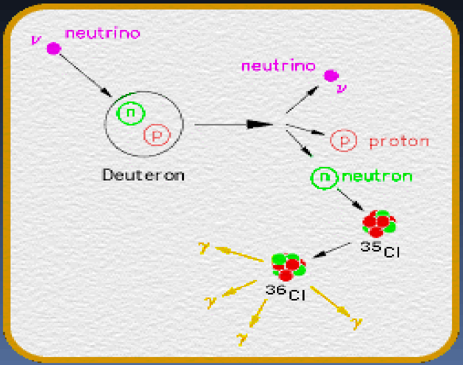
$$\nu_x + e^- \rightarrow \nu_x + e^- \quad (\mathrm{ES})$$



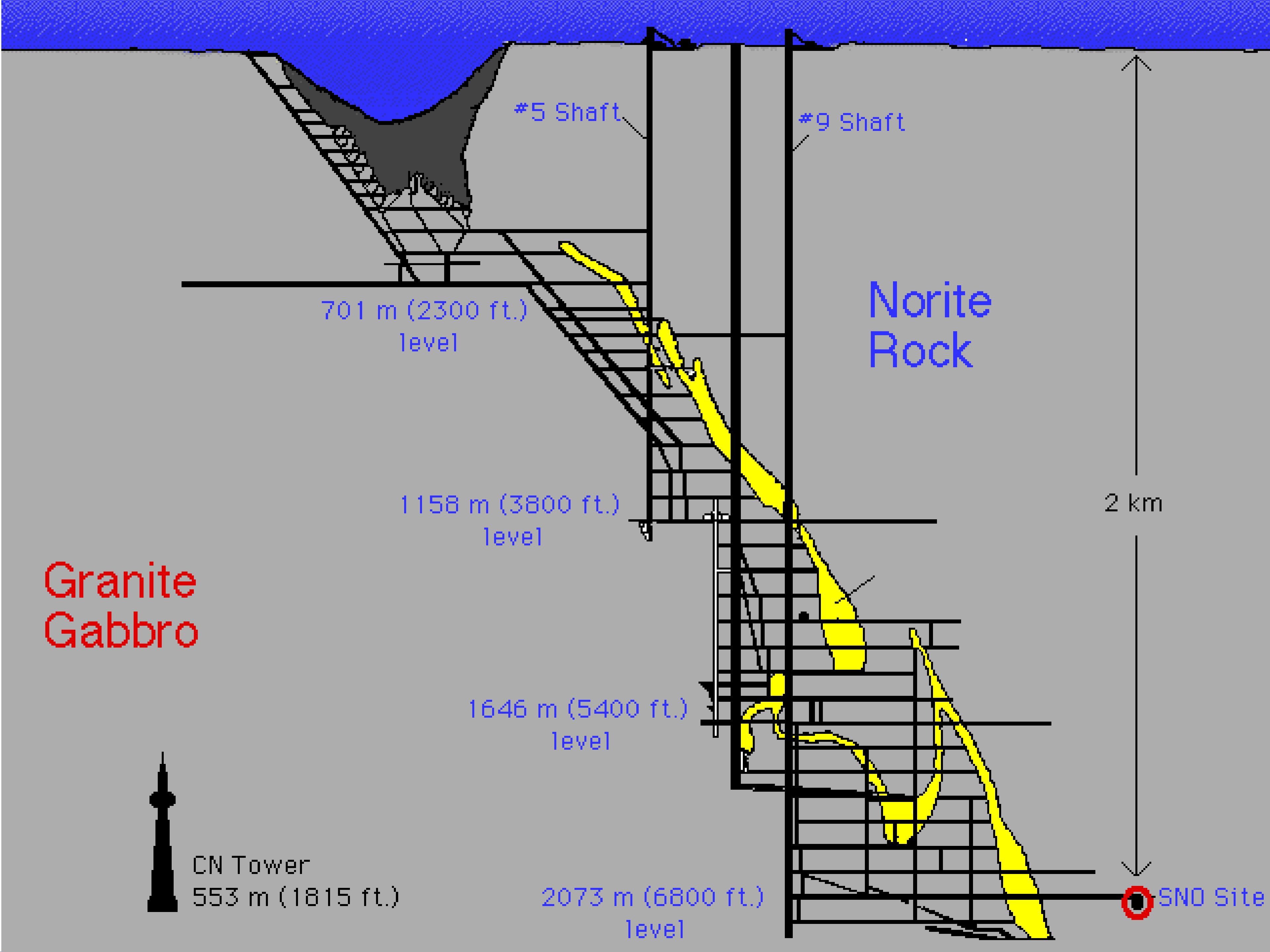
ES ∝ 1 e + 1/7 x

What are the actual interactions?
Can you explain why "x" is suppressed?

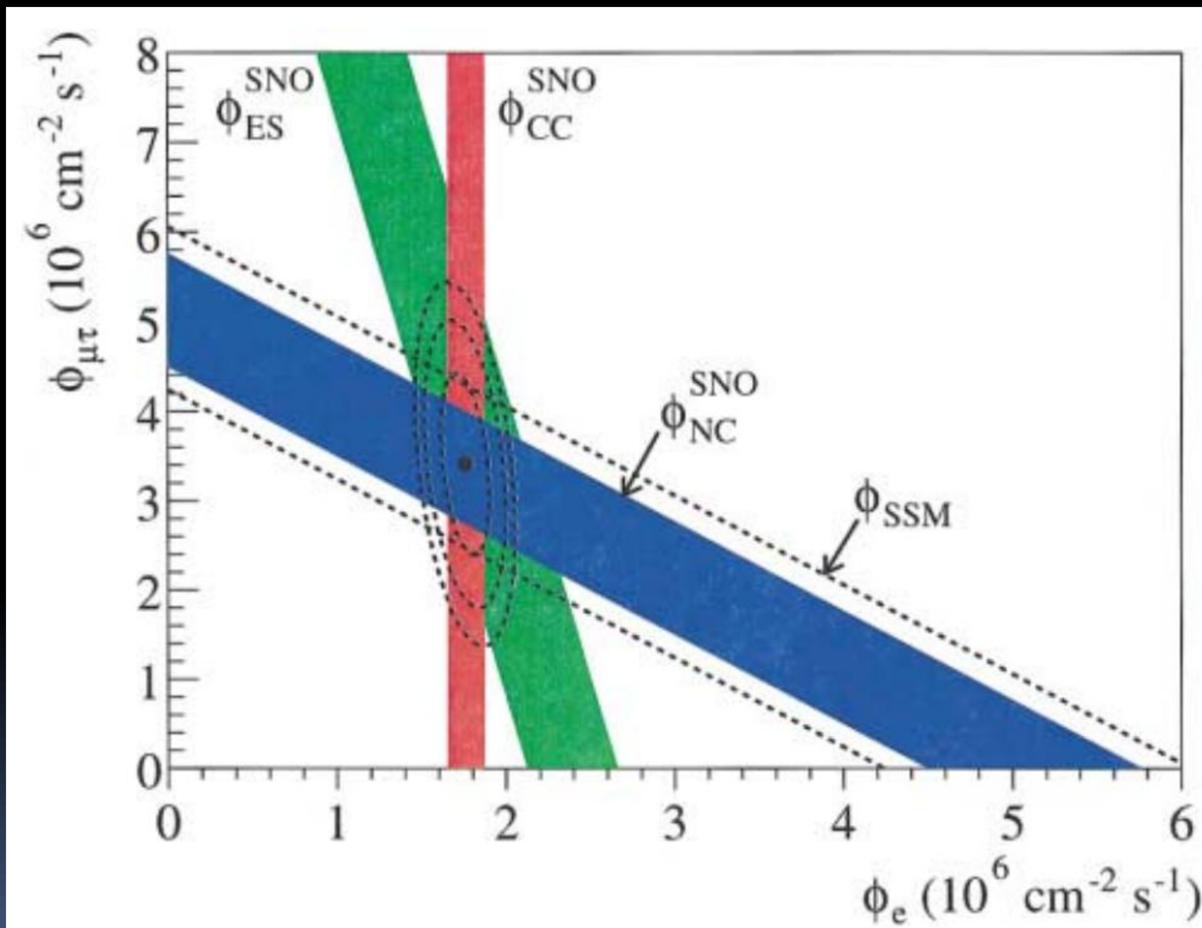
$$\nu_x + {}^2H \rightarrow \nu_x + p + n \quad (\mathrm{NC})$$



NC ∝ 1 e + 1 x


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

SNO solving solar neutrino mystery



Art McDonald

2015年诺奖

- CC ∝ e
- ES ∝ 1 e + 1/7 x
- NC ∝ 1 e + 1 x

Neutrino Oscillation

Source	Fly In Space	Detection

Source:

$$|\nu(x_0)\rangle = |\nu_A\rangle = \cos\theta|\nu_1\rangle + \sin\theta|\nu_2\rangle$$

Fly In Space:

$$|\nu(\vec{x},t)\rangle = \cos\theta|\nu_1\rangle e^{i(Et-\vec{k}_1\cdot\vec{x})} + \sin\theta|\nu_2\rangle e^{i(Et-\vec{k}_2\cdot\vec{x})}$$

Detection:

$$P(\nu_A \to \nu_A) = |\langle \nu_A | \nu(t)\rangle|^2$$

Linear Light → Birefringent Crystal → Analyzer

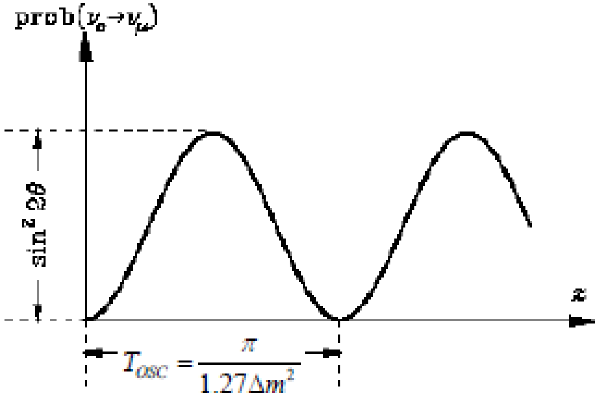
Two-flavor Neutrino Oscillation in Vacuum

$$\begin{pmatrix} \nu_A \\ \nu_B \end{pmatrix} = \begin{bmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{bmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \end{pmatrix}$$

P(A→B, appearance) = $\sin^2 2\theta \sin^2(1.27\Delta m^2 L/E)$

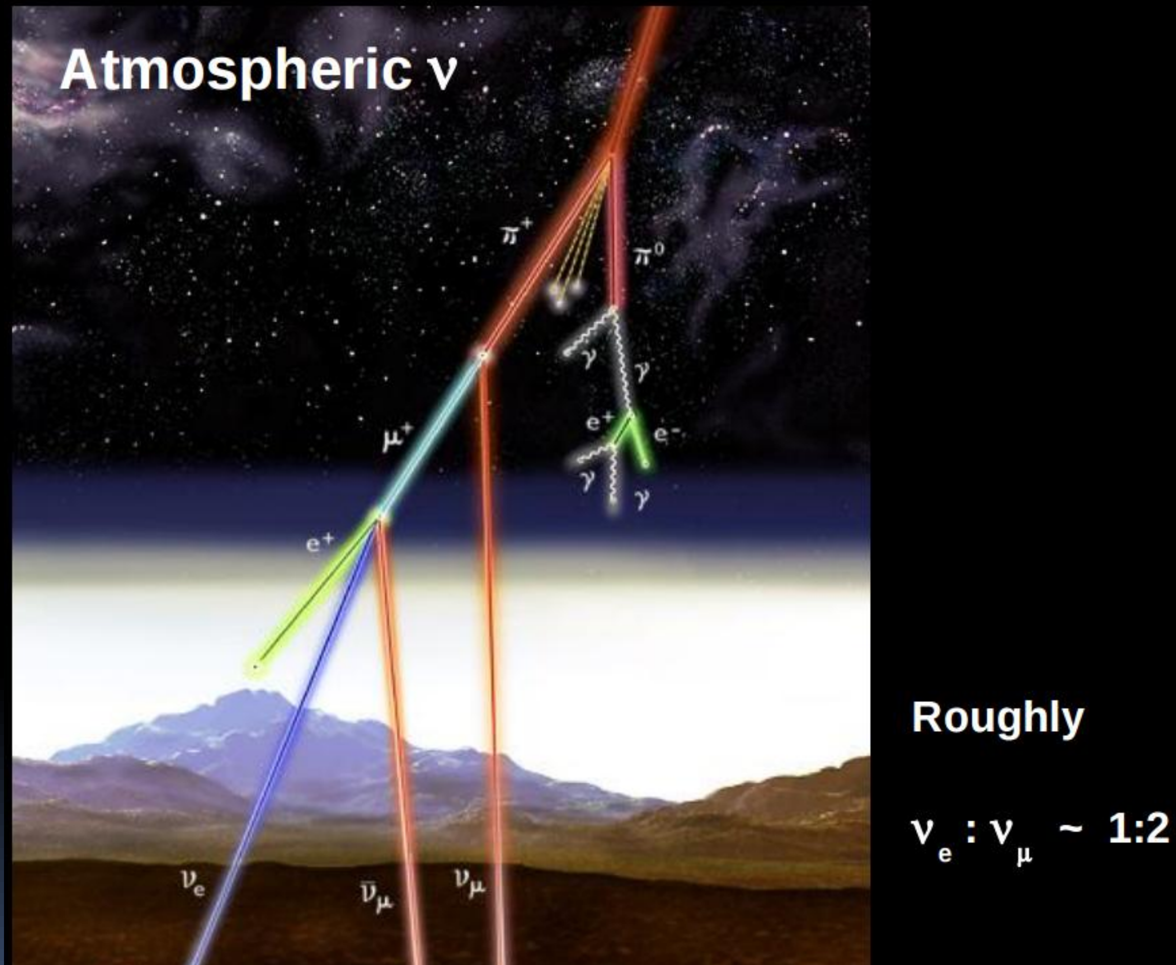
P(A→A, survival) = $1 - \sin^2 2\theta \sin^2(1.27\Delta m^2 L/E)$

$\Delta m^2 = m_1^2 - m_2^2$ in eV^2
L in m, E in MeV



Given L/E sensitive to a range of Δm^2: MeV neutrino & 1000 m ⇒ $\Delta m^2 \sim 10^{-3} eV^2$

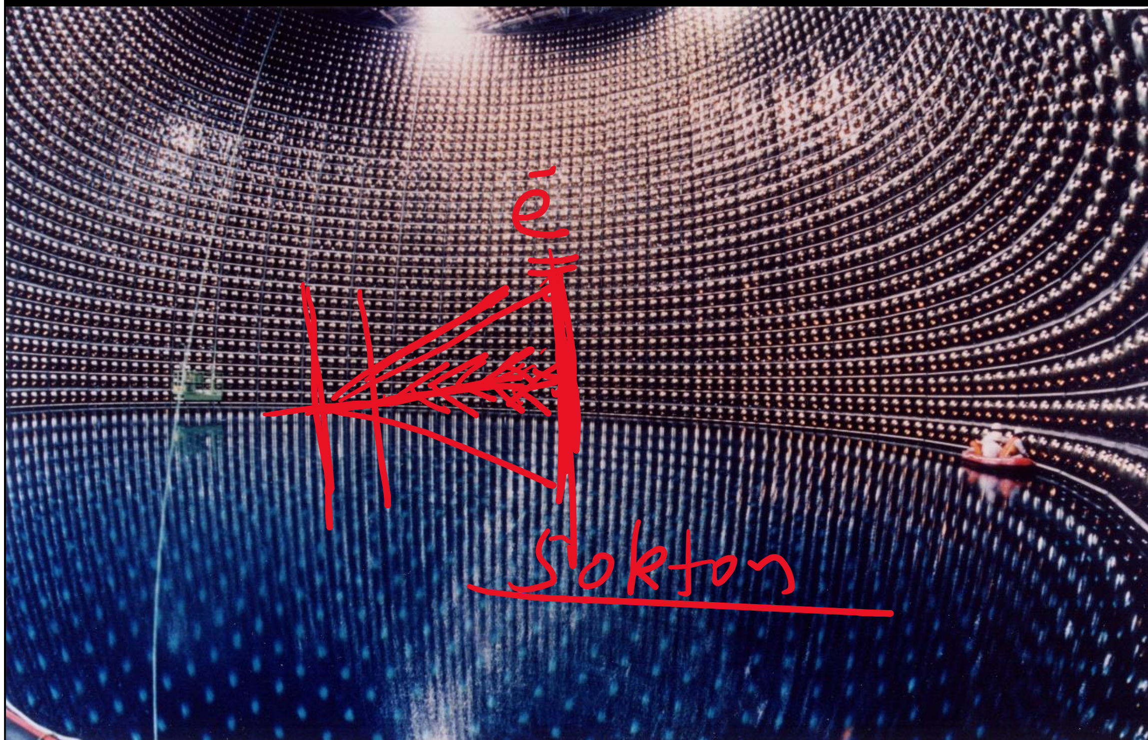
Atmospheric neutrinos

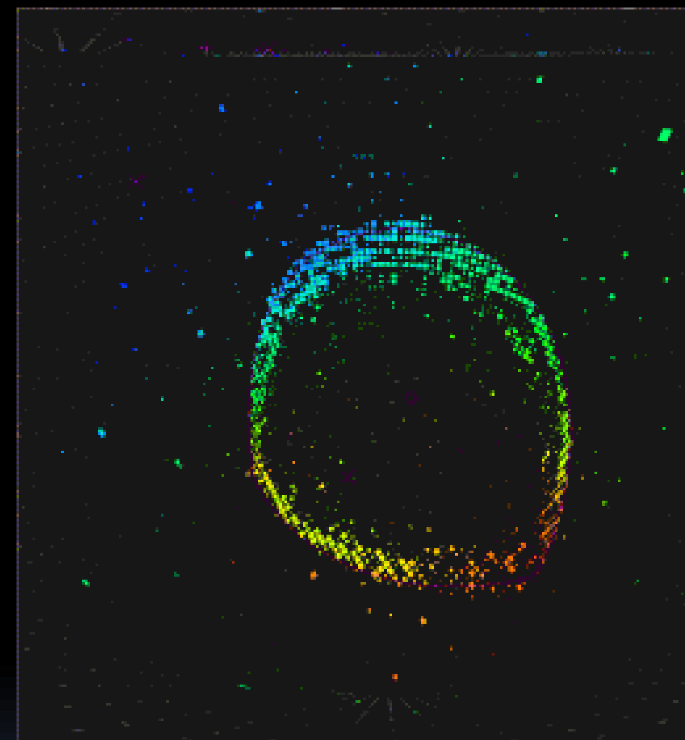


Quiz: pi+ = $(u\bar{d})$, can you draw the Feynman diagram of its decay? How about mu+?

Note that Pi+ decays into e+ is hugely suppressed due to the so-called helicity suppression

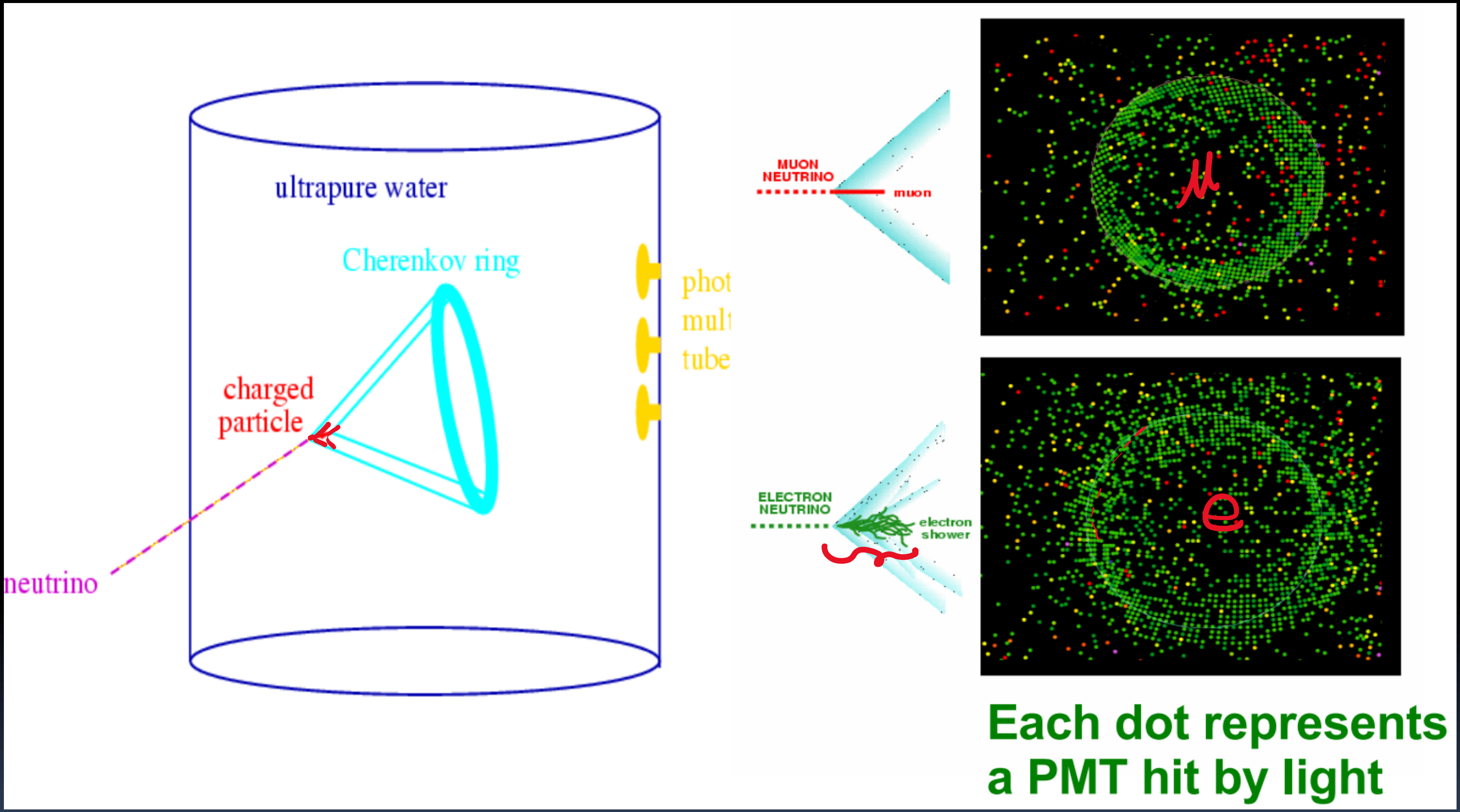
Super Kamiokande



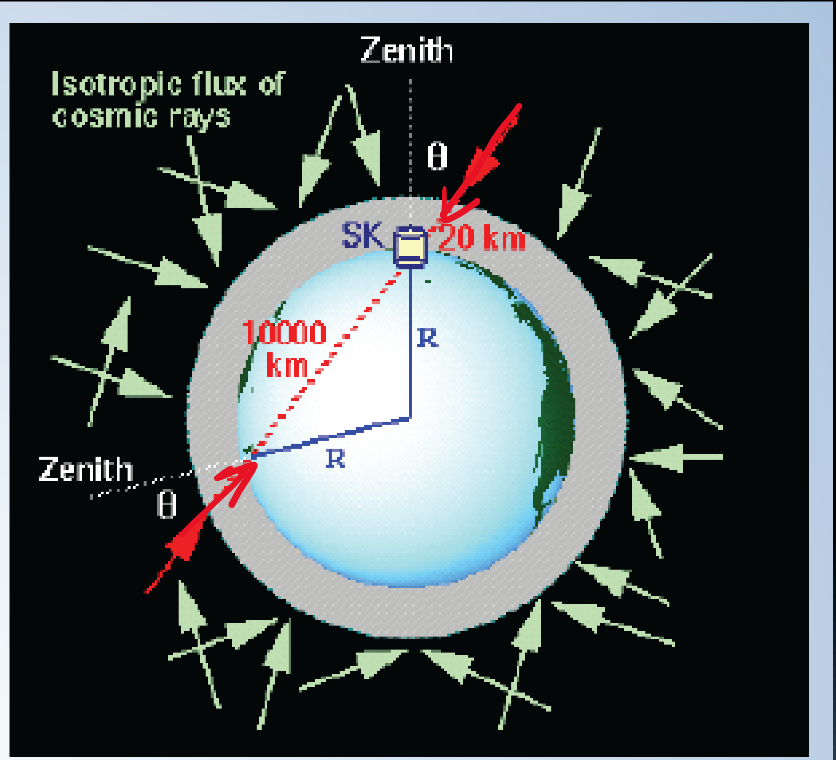


How did the “ring” form????

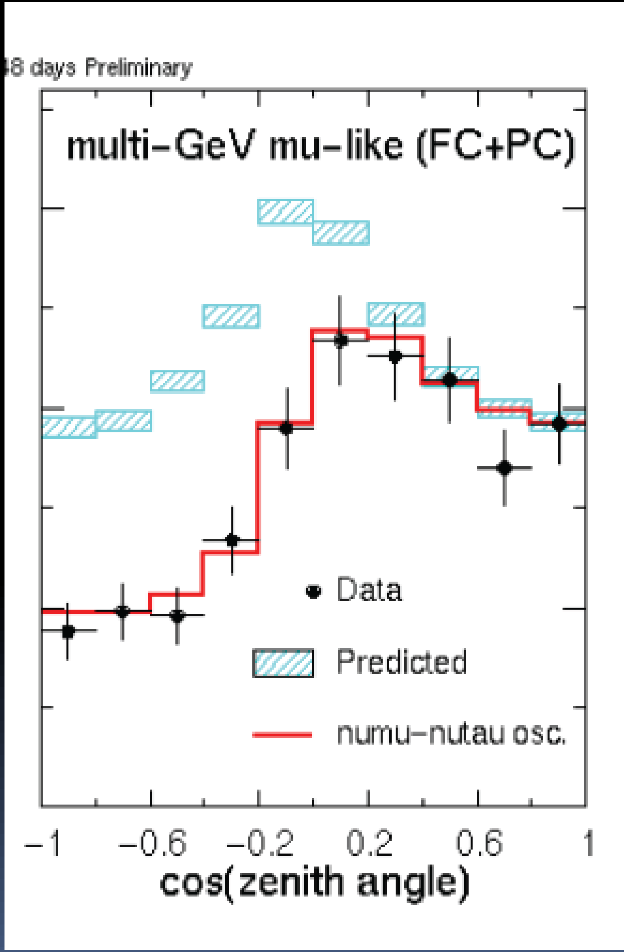
Events in Super K



Neutrino oscillation smoking gun from Super K



http://hep.bu.edu/~superk/atmnu/



Neutrino mixing

Transformation from mass to weak eigenstates

$\Delta m^2_{atm} = 2.4\times10^{-3}\ eV^2$

$\Delta m^2_{sol} \sim 7.6\times10^{-5}\ eV^2$

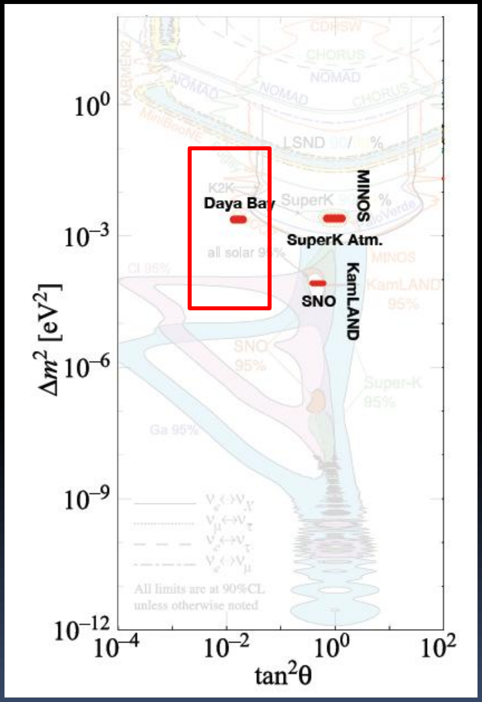
Solar: θ_{12}~32°   Atmospheric: θ_{23}~45°

$$U_{PMNS} = \begin{pmatrix} \cos\theta_{12} & \sin\theta_{12} & 0 \\ -\sin\theta_{12} & \cos\theta_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \times \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_{23} & \sin\theta_{23} \\ 0 & -\sin\theta_{23} & \cos\theta_{23} \end{pmatrix}$$

$$\times \begin{pmatrix} \cos\theta_{13} & 0 & \sin\theta_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -\sin\theta_{13}e^{i\delta} & 0 & \cos\theta_{13} \end{pmatrix} \times \begin{pmatrix} e^{i\alpha_1/2} & 0 & 0 \\ 0 & e^{i\alpha_2/2} & 0 \\ 0 & 0 & 0 \end{pmatrix}$$

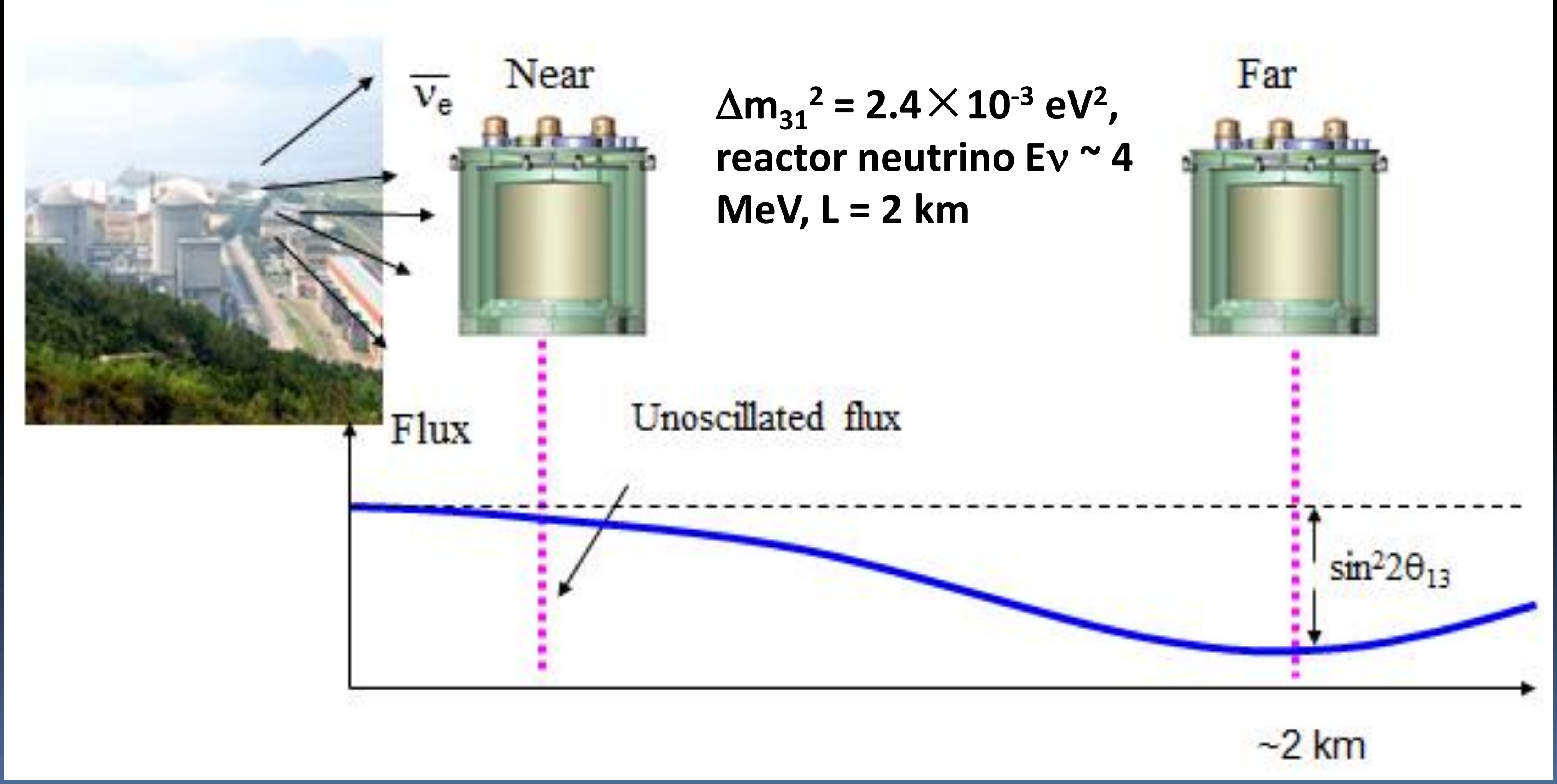
θ_{13}~9°

δ: CP Violation Phase



The last mixing angles θ_{13}

$$P(\nu_e \to \nu_e) = 1 - \sin^2 2\theta_{13}(\cos^2\theta_{12}\sin^2\Delta_{31} + \sin^2\theta_{12}\sin^2\Delta_{32}) - \cos^4\theta_{13}\sin^2 2\theta_{12}\sin^2\Delta_{12}$$

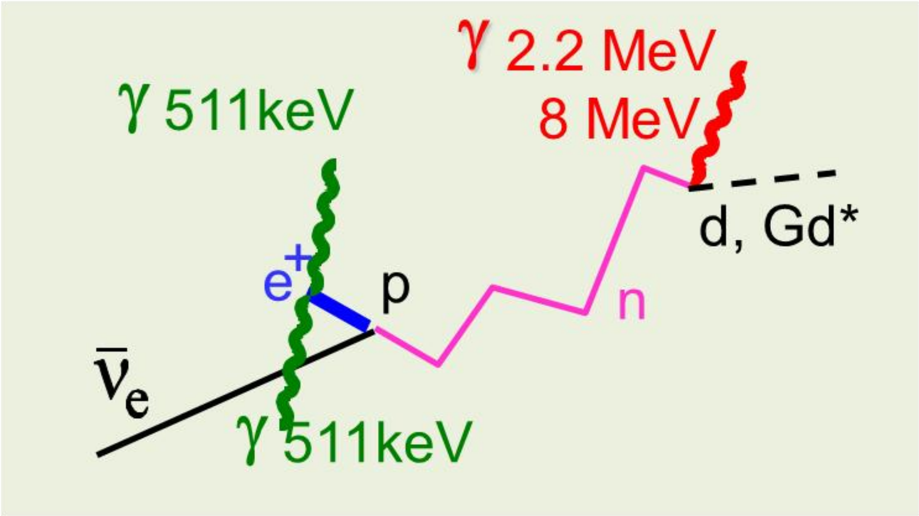


Daya Bay Experiment

Inverse Beta Decay

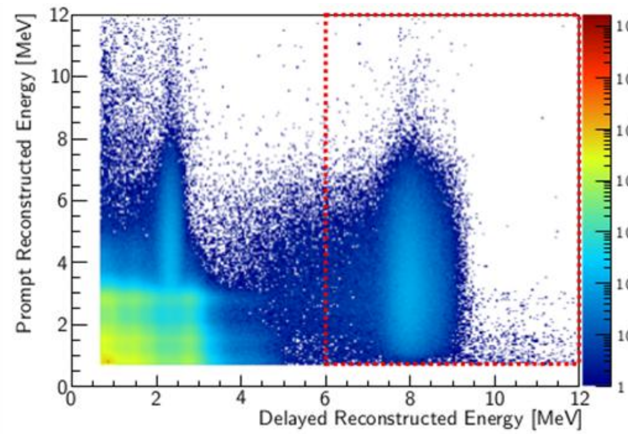
$$\bar{\nu}_e + p \rightarrow n + e^+$$

Use liquid scintillator doped with Gd



Coincidence signal: detect

- **Prompt**: e^+ annihilation $E_\nu = KE_{e+} + 1.8$ MeV
- **Delayed**: **n** capture on proton (2.2 MeV) or Gd (8 MeV)
- Δt (delayed-prompt) ~ 28 usec for 0.1% Gd-doped LS



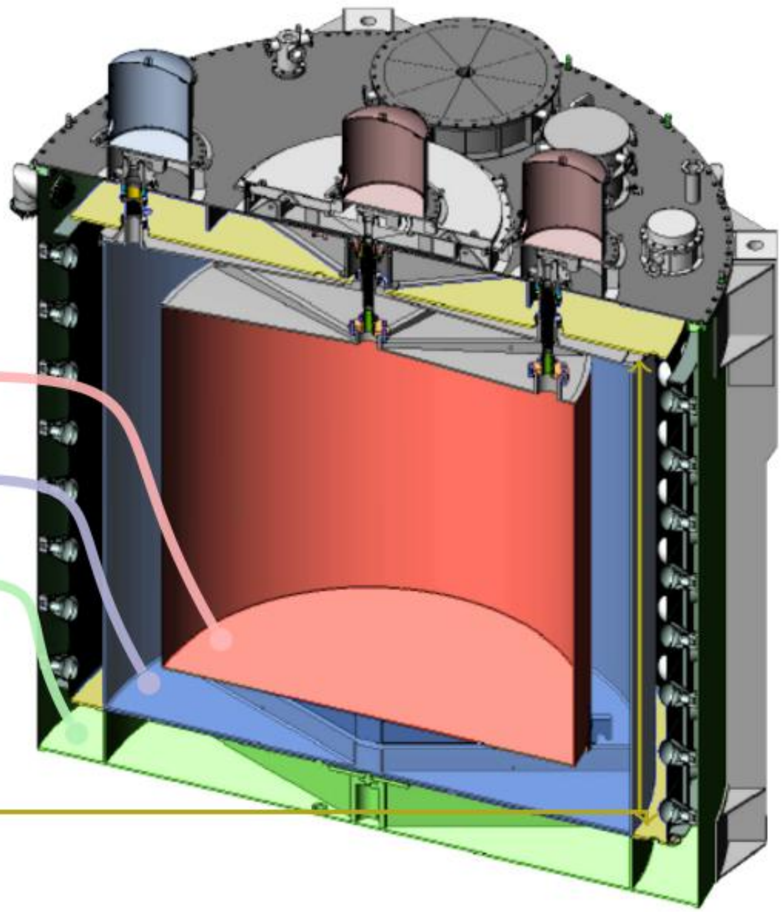
大亚湾中微子探测器

8 functionally identical detectors
reduce systematic uncertainties

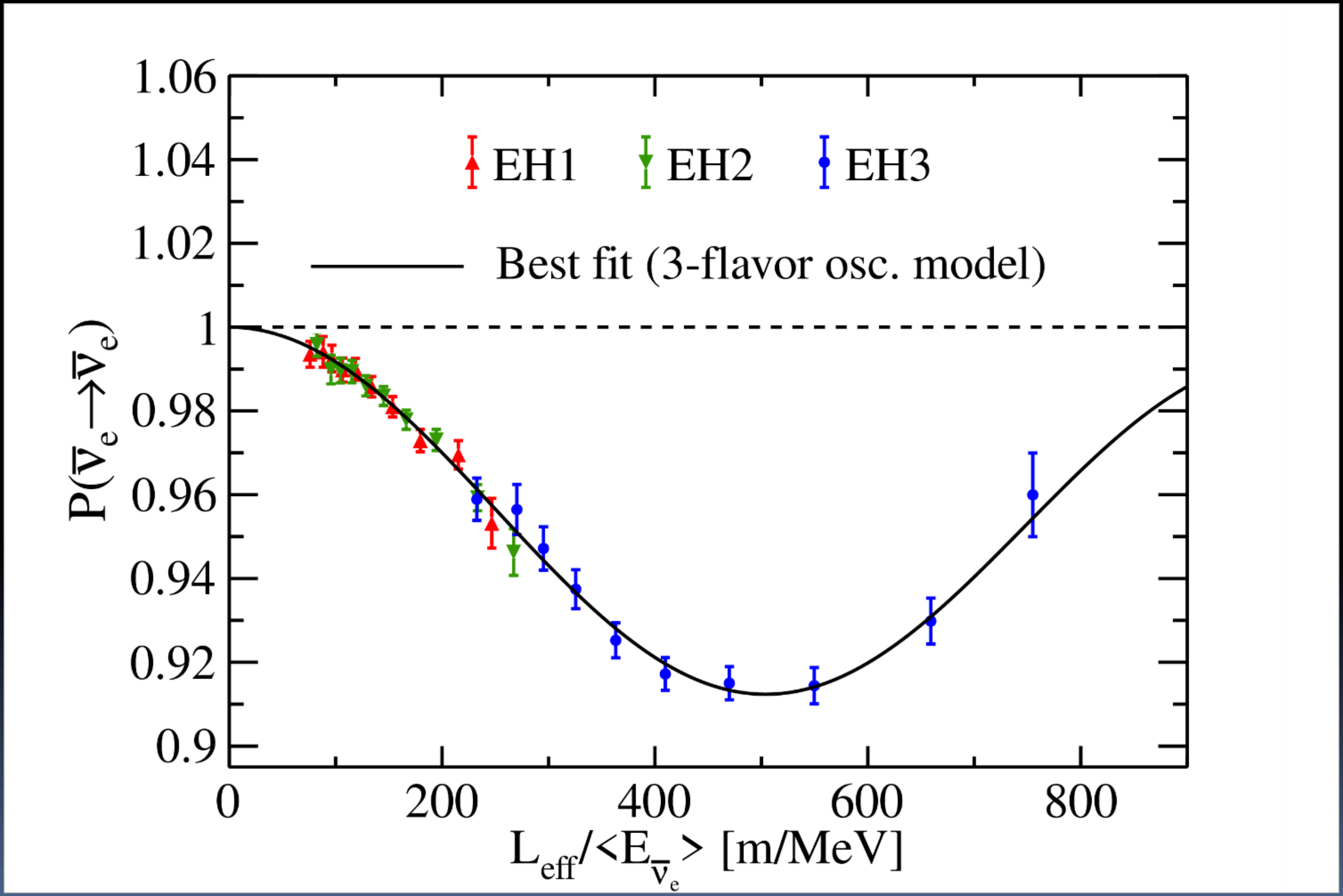
	3 zone cylindrical vessels		
	Liquid	Mass	Function
Inner acrylic	Gd-doped liquid scint.	20 t	Antineutrino target
Outer acrylic	Liquid scintillator	20 t	Gamma catcher
Stainless steel	Mineral oil	40 t	Radiation shielding

192 8 inch PMTs in each detector

Top and bottom reflectors increase light yield
and flatten detector response



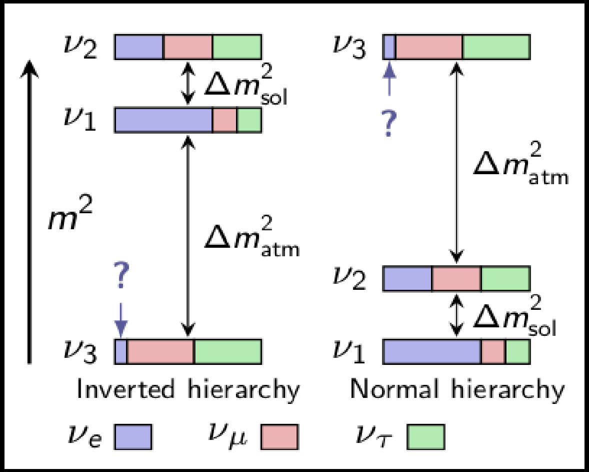
L/E final data set

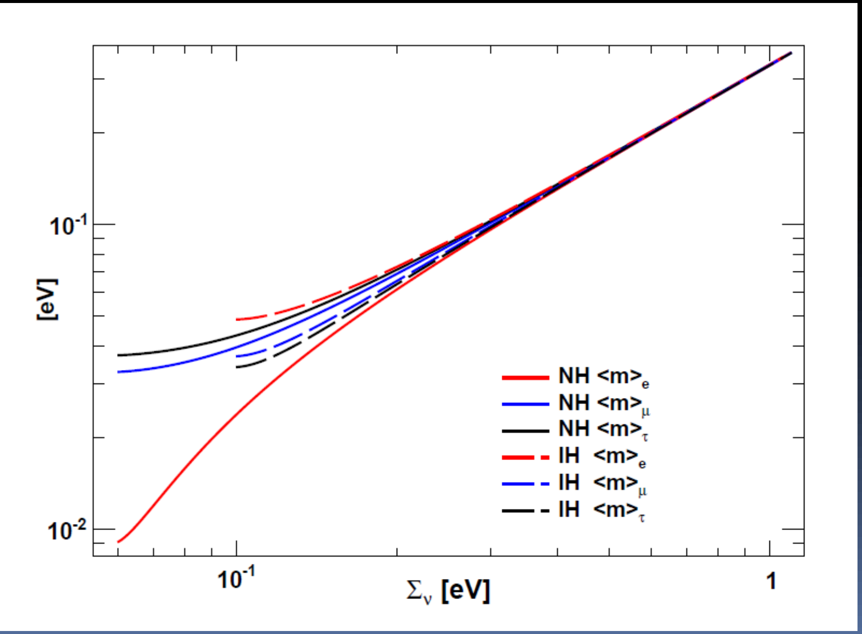


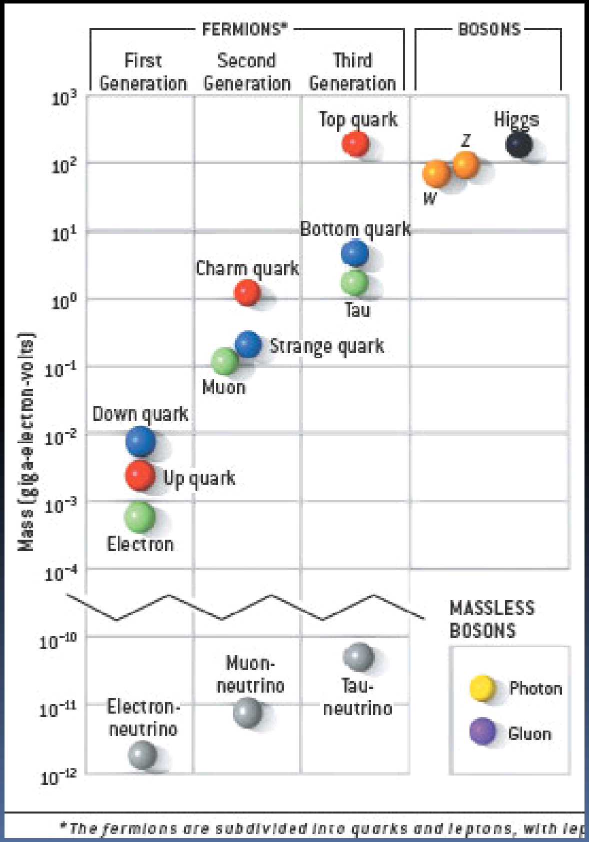
Another big question: Mass ordering???

- $|\Delta m_{31}^2| = 2.4\times10^{-3}\ eV^2$, $\Delta m_{21}^2 = 7.5\times10^{-5}\ eV^2$
- Mass hierarchy:

  Is m_1 the lightest (normal) or m_3 the lightest (inverted)?







An “upgrade” of Daya Bay Experiment

$$P(\bar{\nu}_e \to \bar{\nu}_e) = 1 - \cos^4\theta_{13}\ \sin^2 2\theta_{12}\ \sin^2\Delta_{21} - \sin^2 2\theta_{13}\ \left(\cos^2\theta_{12}\ \sin^2\Delta_{31} + \sin^2\theta_{12}\ \sin^2\Delta_{32}\right)$$

$$\approx 1 - \cos^4\theta_{13}\ \sin^2 2\theta_{12}\ \sin^2\Delta_{21} - \sin^2 2\theta_{13}\ \sin^2\Delta_{ee}$$

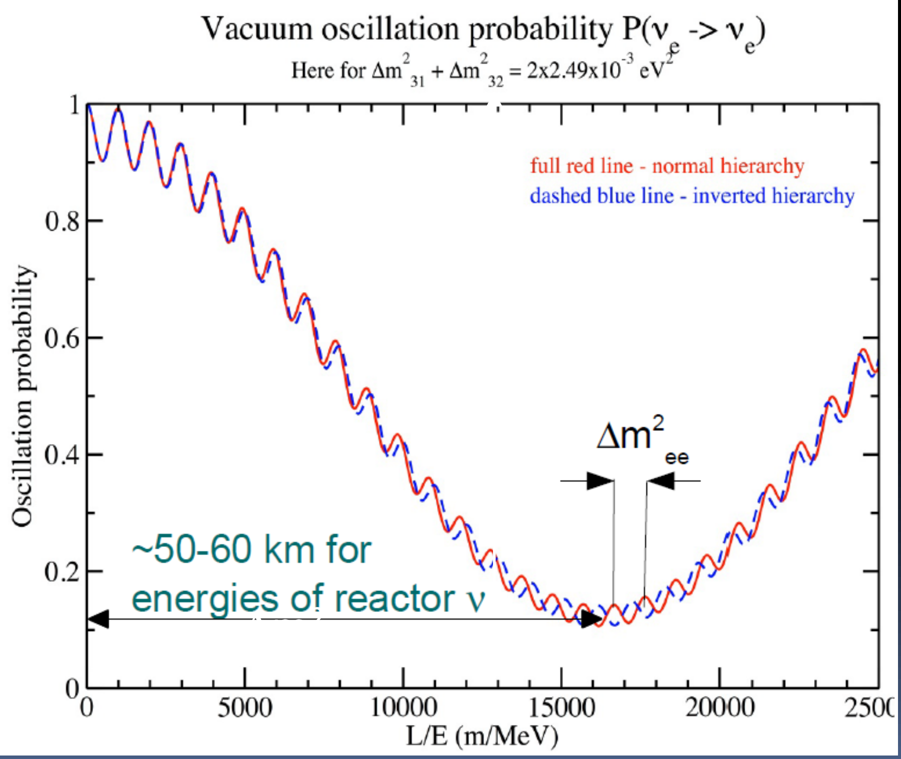
$$\Delta_{ij} = \Delta m^2_{ij}\frac{L}{4E}$$

Δm^2_{ee} = effective neutrino mass-squared difference
(beat frequency)

$$\Delta m^2_{31} = \Delta m^2_{32} + \Delta m^2_{21}$$
$$\text{NH}: |\Delta m^2_{31}| = |\Delta m^2_{32}| + |\Delta m^2_{21}|$$
$$\text{IH}: |\Delta m^2_{31}| = |\Delta m^2_{32}| - |\Delta m^2_{21}|$$

with $\Delta m^2_{12} << \Delta m^2_{32}$

→ different beat frequency (Δm^2_{ee}) for both hierarchies



JUNO Experiment

Outline

- Unit 1: Detector and low background techniques 101
- Unit 2: Neutrinos, weak interactions
- Unit 3: Neutrino oscillations
- Unit 4: From neutrino coherent scattering to dark matter detection
- Unit 5: Neutrinoless double beta-decays

Coherent elastic neutrino-nucleus scattering (CEvNS)

Quantum mechanics: 200 MeV ~ 1 fm
So MeV neutrino cannot resolve nucleons in nucleus

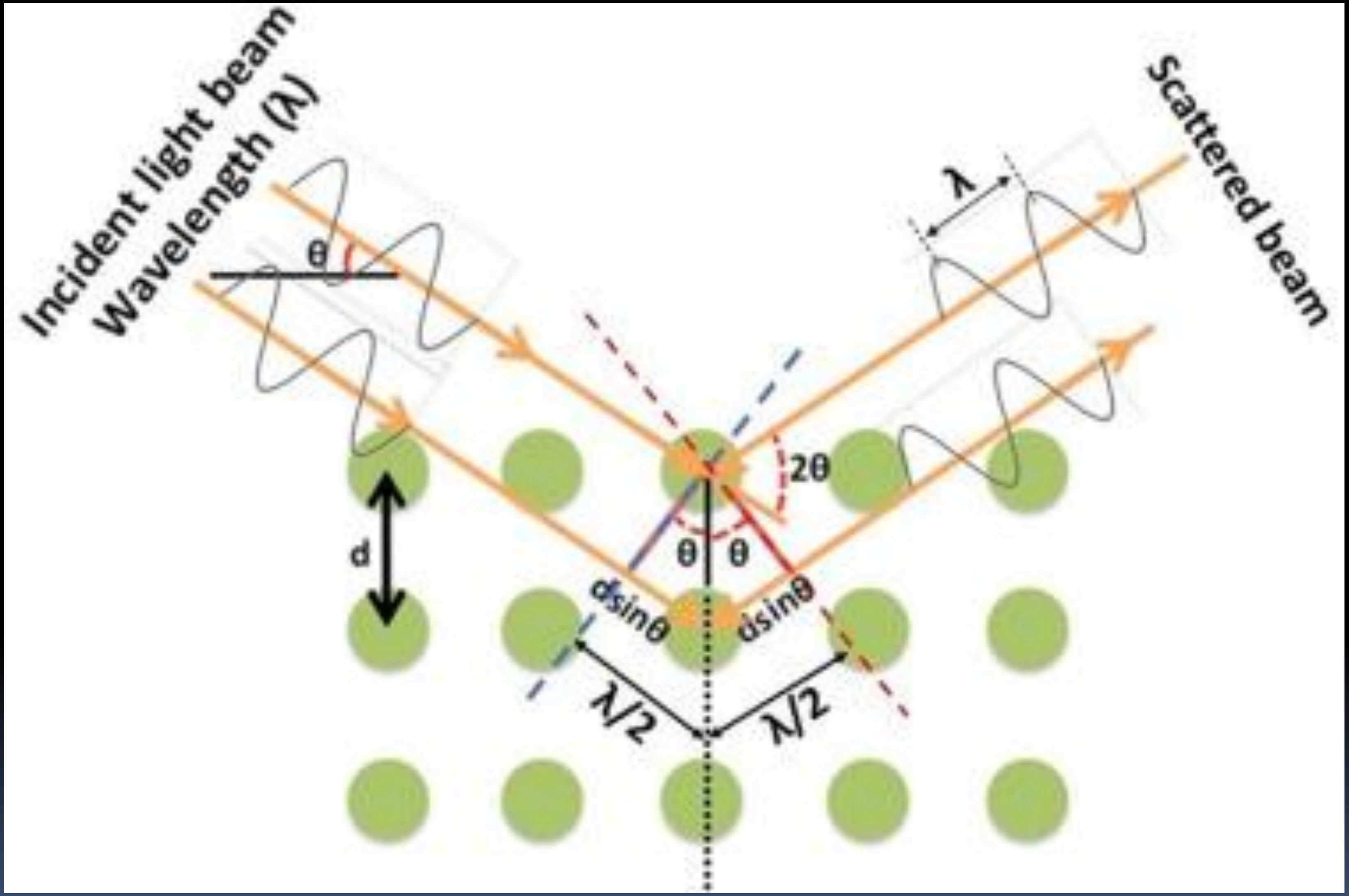
Coherent effects of a weak neutral current

Daniel Z. Freedman
Phys. Rev. D **9**, 1389 – Published 1 March 1974

Article | References | Citing Articles (412) | PDF | Export Citation

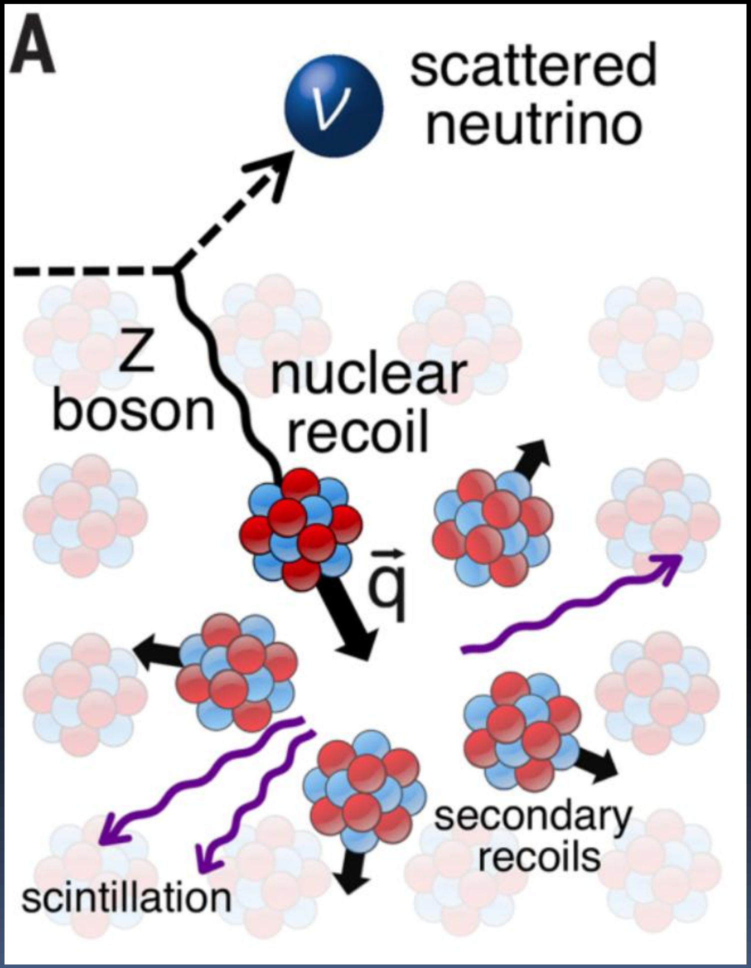
ABSTRACT

If there is a weak neutral current, then the elastic scattering process $\nu + A \to \nu + A$ should have a sharp coherent forward peak just as $e + A \to e + A$ does. Experiments to observe this peak can give important information on the isospin structure of the neutral current. The experiments are very difficult, although the estimated cross sections (about 10^{-38} cm^2 on carbon) are favorable. The coherent cross sections (in contrast to incoherent) are almost energy-independent. Therefore, energies as low as 100 MeV may be suitable. Quasi-coherent nuclear excitation processes $\nu + A \to \nu + A^*$ provide possible tests of the conservation of the weak neutral current. Because of strong coherent effects at very low energies, the nuclear elastic scattering process may be important in inhibiting cooling by neutrino emission in stellar collapse and neutron stars.


Incident light beam
Wavelength (λ)
θ
Scattered beam
λ
2θ
d
θ
θ
dsinθ
dsinθ
λ/2
λ/2

CEvNS

Approximation, N=num neutrons



$$\sigma = \frac{G^2}{16\pi} N^2 \Delta_{max}{}^2 = \frac{G^2 N^2}{4\pi} E^2 .$$

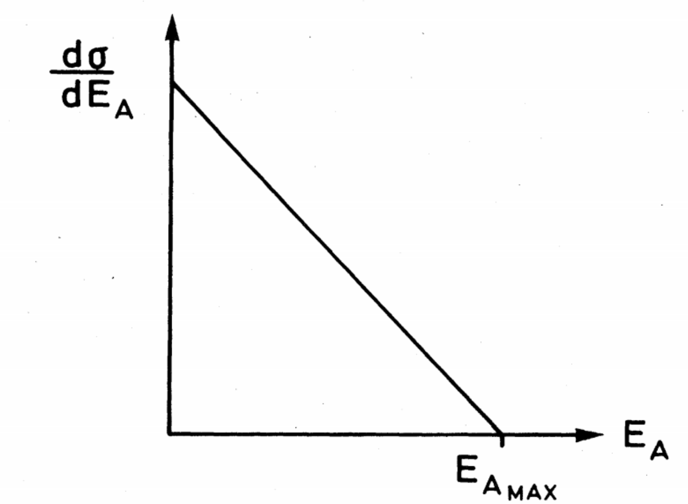
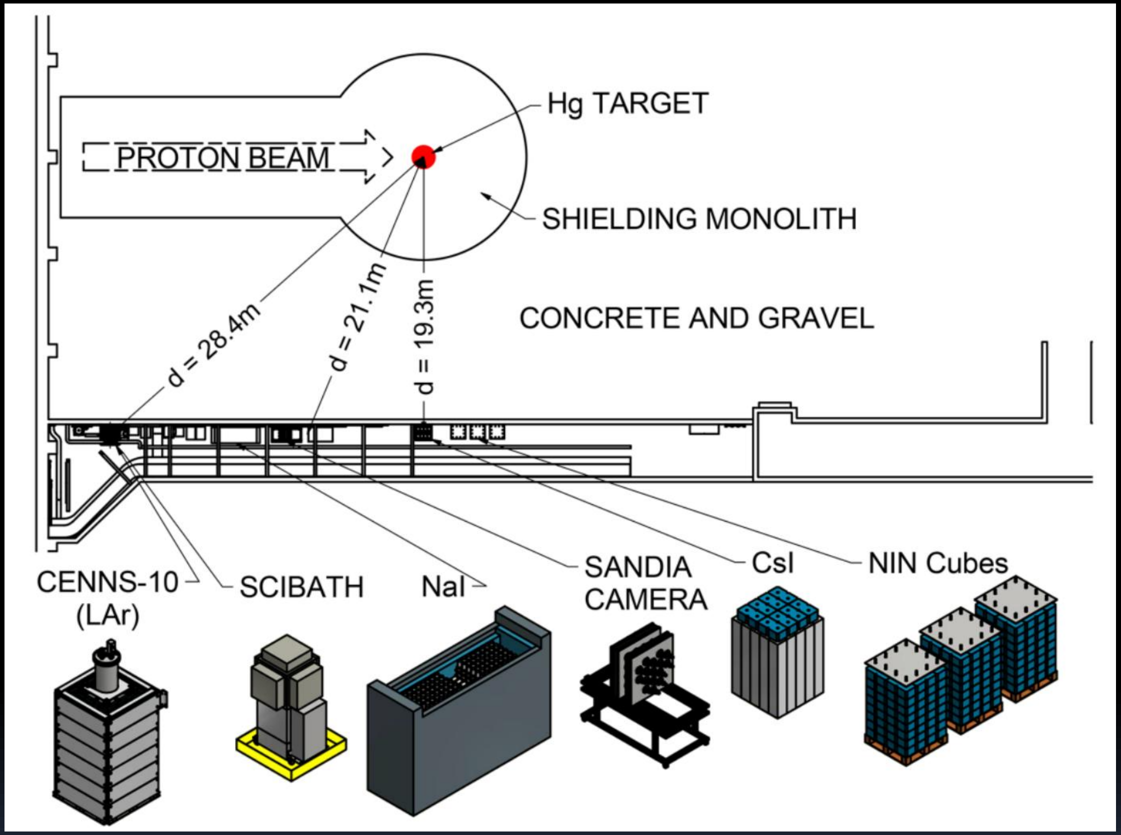


FIG. 1. Recoil-energy spectrum of the struck nucleus A in elastic neutrino scattering.

$$\bar{E}_A = \frac{2}{3A} (E/1\ \mathrm{MeV})^2\ \mathrm{keV}$$

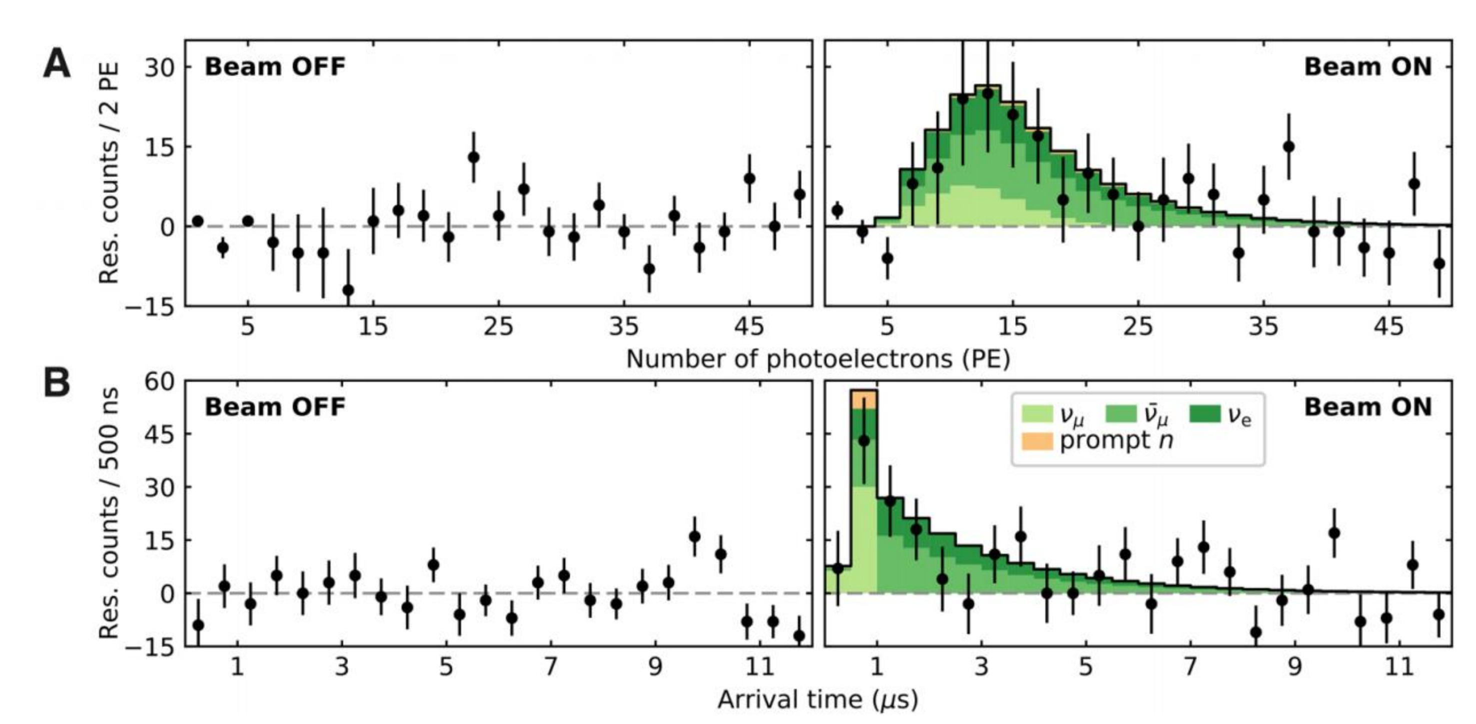
COHERENT Experiment



- Oak Ridge
- Proton beam：1 GeV，pulsed
- Neutrino energy：16-53 MeV
- Live time：154 days

Results

Light yield ~1.17 PE/keV_{nr}



Science REPORTS

Cite as: D. Akimov *et al.*, *Science* 10.1126/science.aao0990 (2017).

Observation of coherent elastic neutrino-nucleus scattering

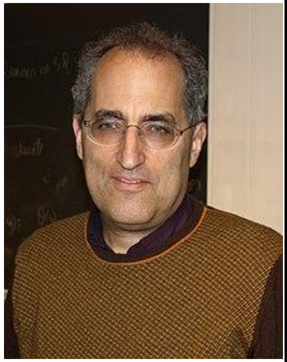
"Application" of a low E neutral current detector

PHYSICAL REVIEW D VOLUME 31, NUMBER 12 15 JUNE 1985

Detectability of certain dark-matter candidates

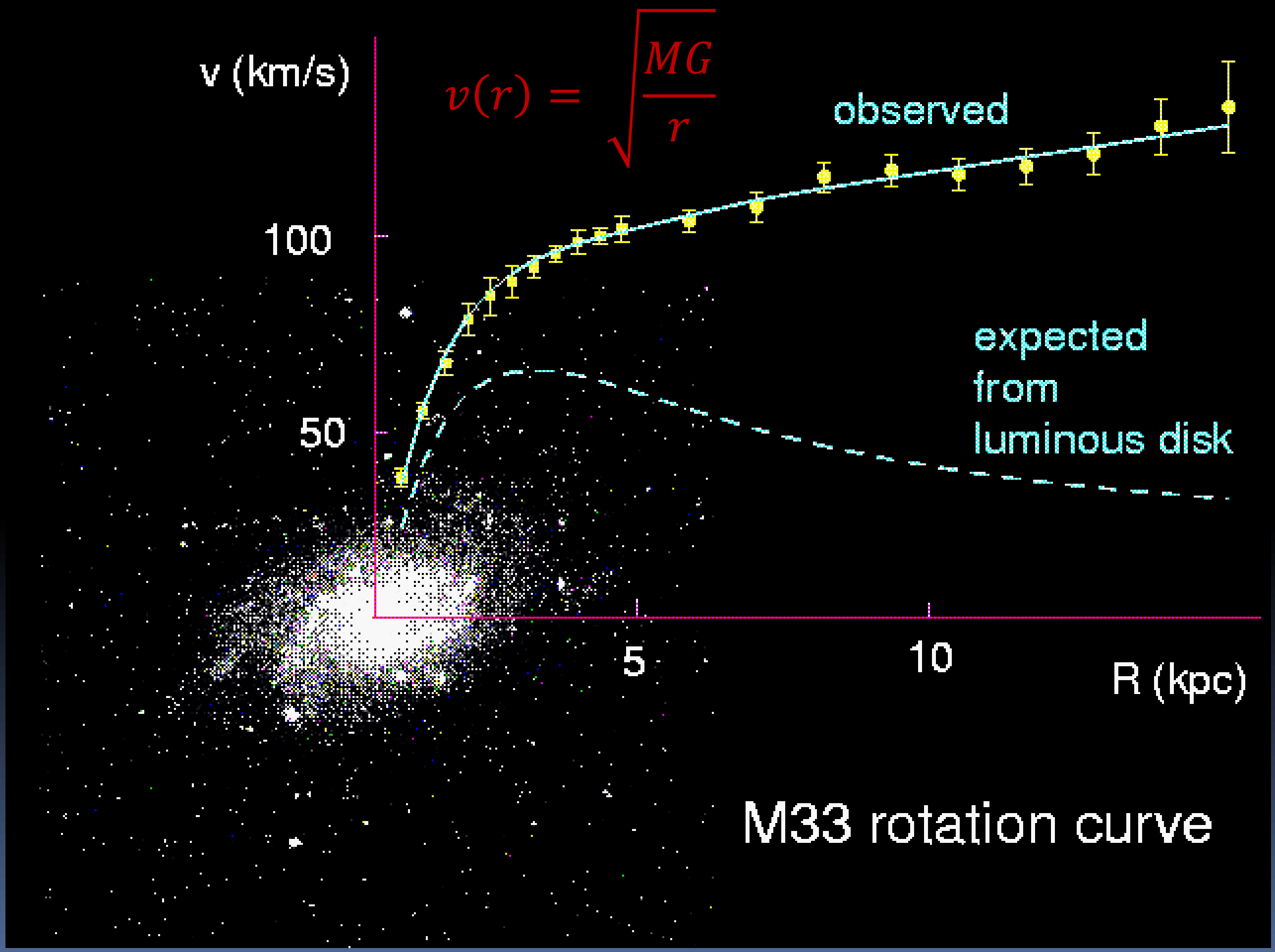
Mark W. Goodman and Edward Witten
Joseph Henry Laboratories, Princeton University, Princeton, New Jersey 08544
(Received 7 January 1985)

We consider the possibility that the neutral-current neutrino detector recently proposed by Drukier and Stodolsky could be used to detect some possible candidates for the dark matter in galactic halos. This may be feasible if the galactic halos are made of particles with coherent weak interactions and masses $1-10^6$ GeV; particles with spin-dependent interactions of typical weak strength and masses $1-10^2$ GeV; or strongly interacting particles of masses $1-10^{13}$ GeV.



In this paper, we will calculate the sensitivity of the detector considered in Ref. 5 to various dark-matter candidates. Although this detector is not very sensitive to

Discoveries by astronomers

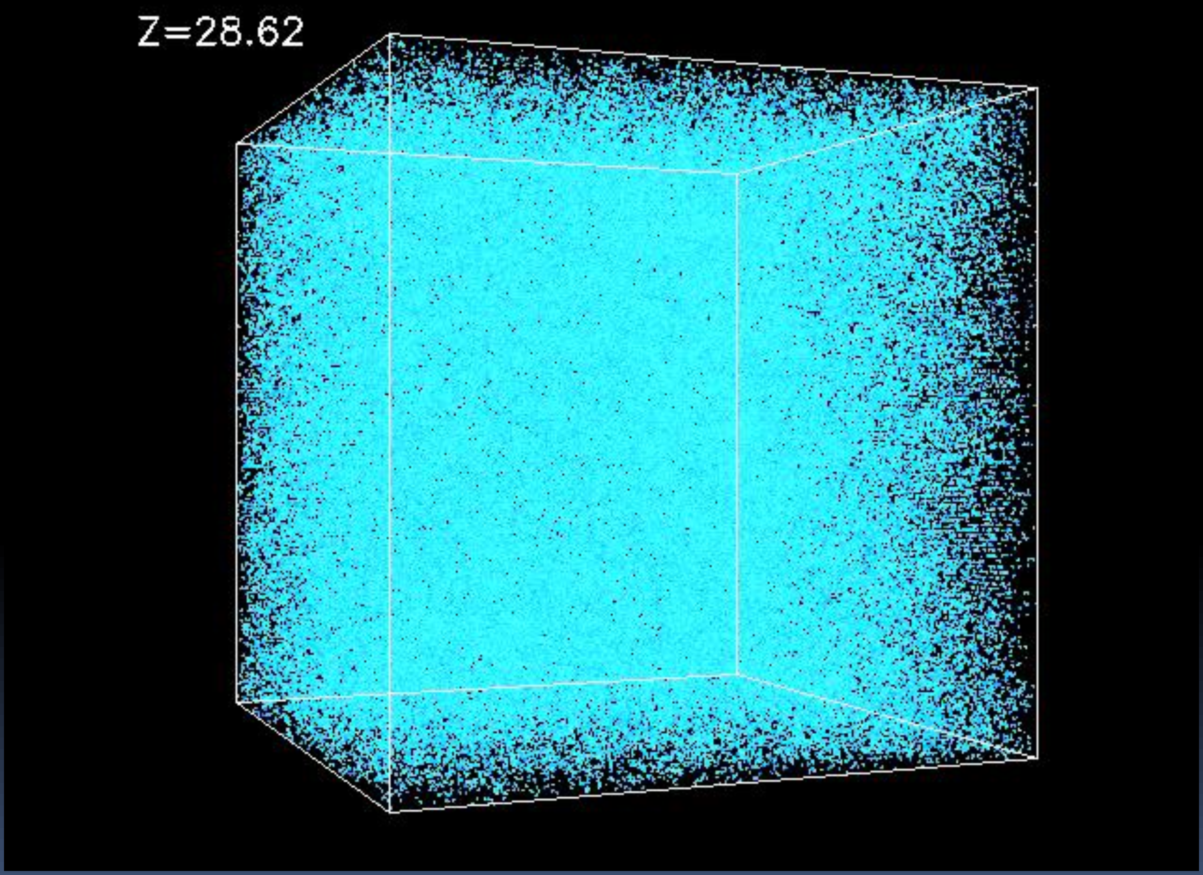


Fritz Zwicky

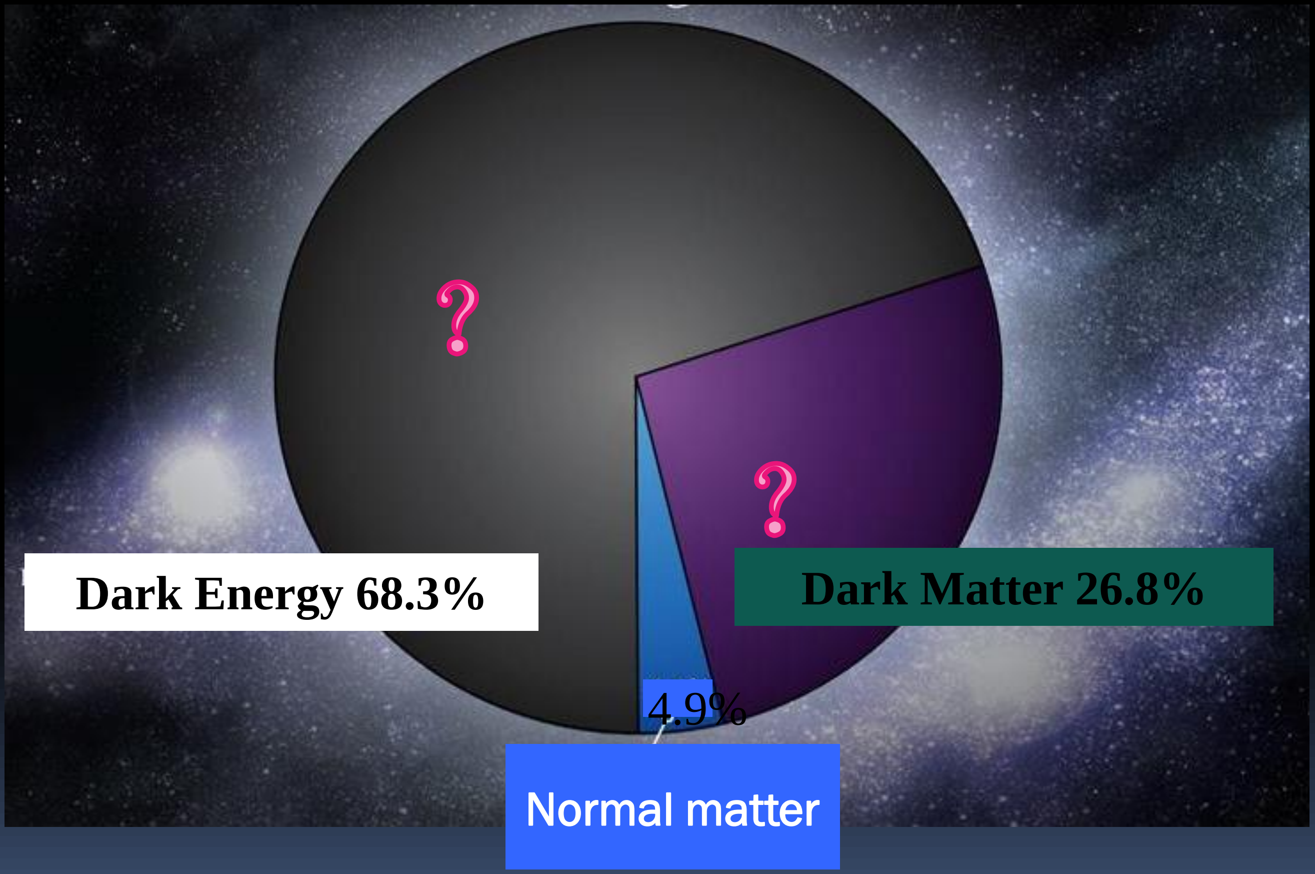
Vera Rubin

Vera Cooper Rubin at the Lowell Observatory. Kent Ford has his back to us.

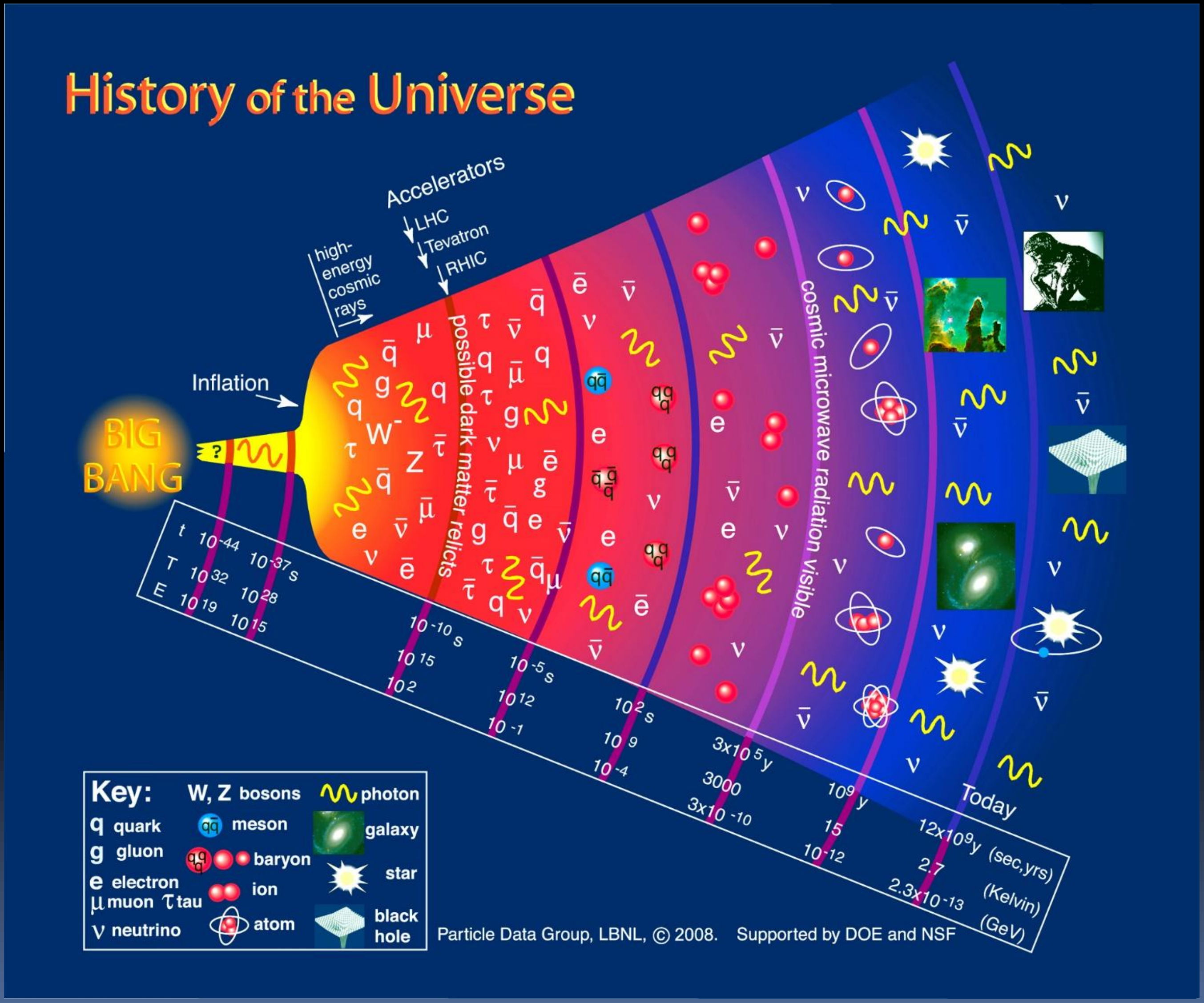
Large scale structure of the universe



Standard Cosmology: ΛCDM



Expanding and cooling universe

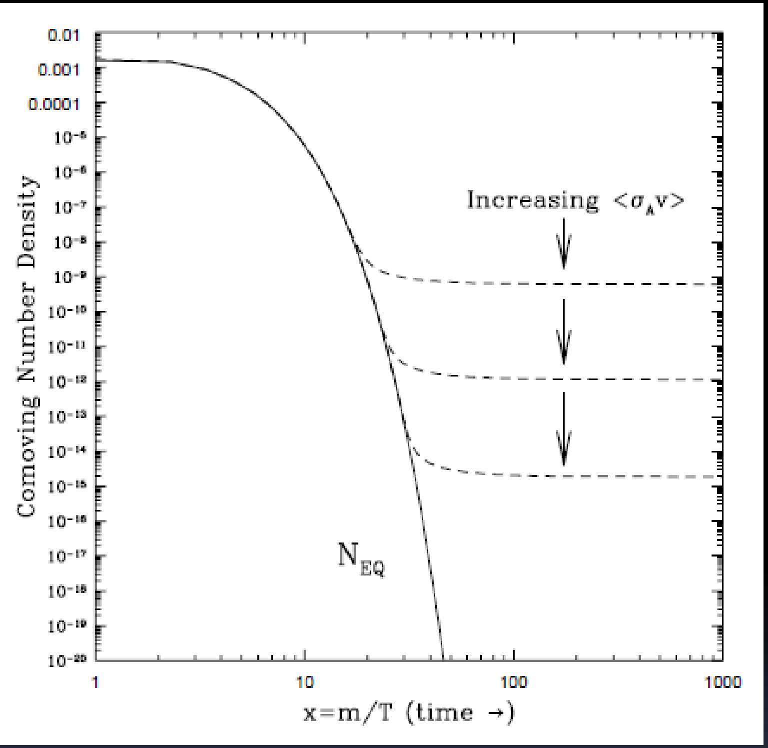


Dark matter and known matter: fossils from the earliest soup!

- Known matter forms atoms
- DM: cannot be made by known particles!
- “Lucky guess” of DM mass: 100 GeV-10TeV
- In thermal equilibrium with known matter in early universe

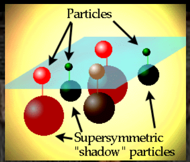
$$X\bar{X} \leftrightarrow Y\bar{Y}$$

Dark matter "freeze-out"



- Universe cools => DM can not be created
- Universe expands => DM cannot find a DM to annihilate either
- "Eternity!": a constant relic!

Comoving: a volume which increases as the universe expands



Heavy BSM particles (weakly-interacting massive particles)

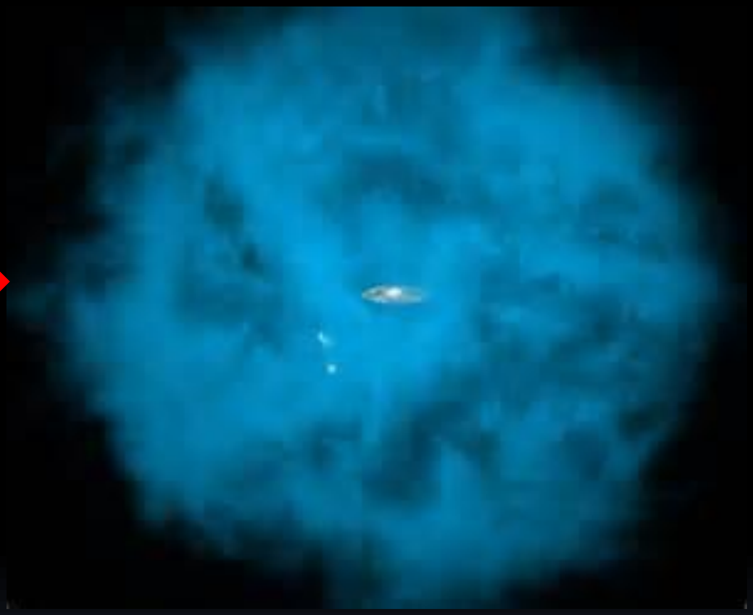
→

Observed relic density

WIMP Miracle! ! !

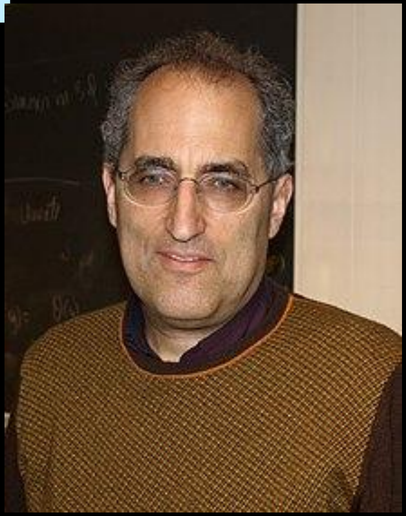
There are other highly motivated models: axions, sterile neutrinos, even primordial black holes..., but none leads to convincing signals so far ...

Dark matter: dominating aggregator of our own galaxy



Quite accurately measured by gravitational dynamics:
DM mass density around us: 0.3 GeV/cm^3

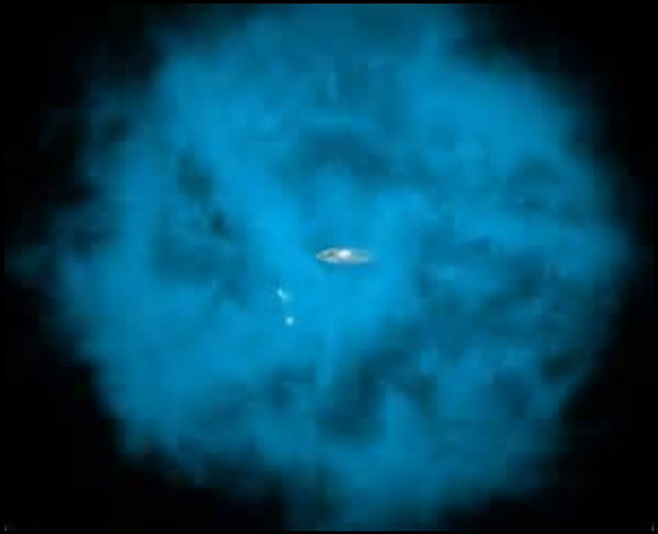
So back to Witten's proposal



- The solar system is cycling the center of galaxy with 220 km/s speed
- DM direct detection: wait for DM interacting atomic nucleus in the detector, and detect its recoil (Goodman & Witten, 1985)

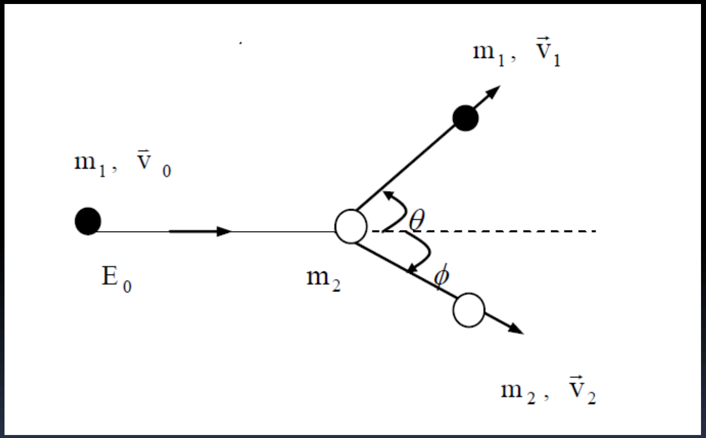
Dark matter beam

- Local density of DM: 0.3 GeV/cm^3
- Mass of DM = Mx, then DM particle incoming flux J = 0.3 GeV/Mx *220 km/s
- Quiz: compute the flux of 100 GeV DM



Elastic scattering

- If the DM particle scatters with ordinary matter through some interactions, it can interact with both electrons and nuclei.



Collision energy

- Use energy and momentum conservation, kinetic energy of the particles after collisions

$$T = E_2 = \frac{4A}{(1+A)^2} E_0 \cos^2 \phi$$

where $A = m_2/m_1$.

- Collision with atomic nuclei.
  - A=1, T reaches maximum
  - $T_{max} = E_0$ when the collision angle is either 0 or 180 degree.

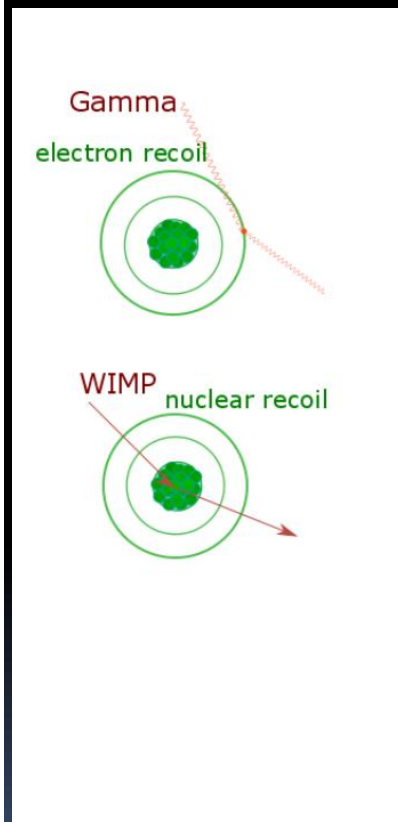
Xenon

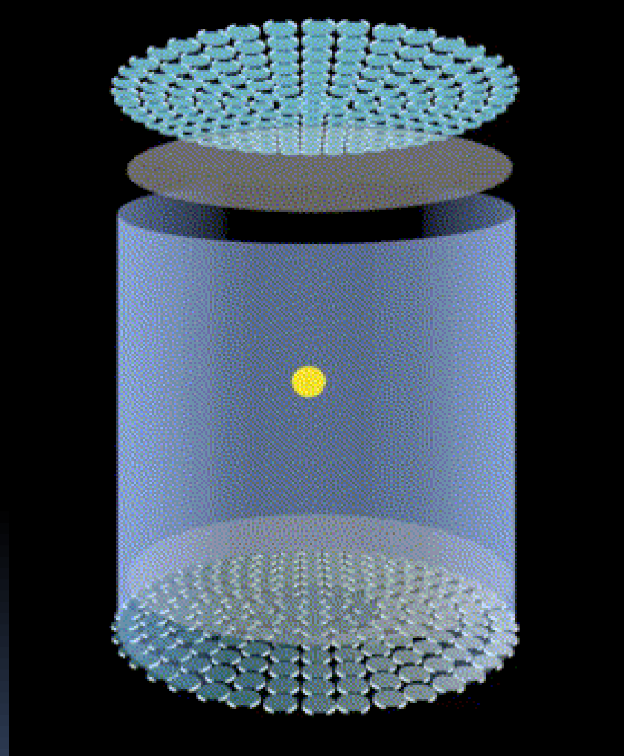
Liquid density:3 g/cc

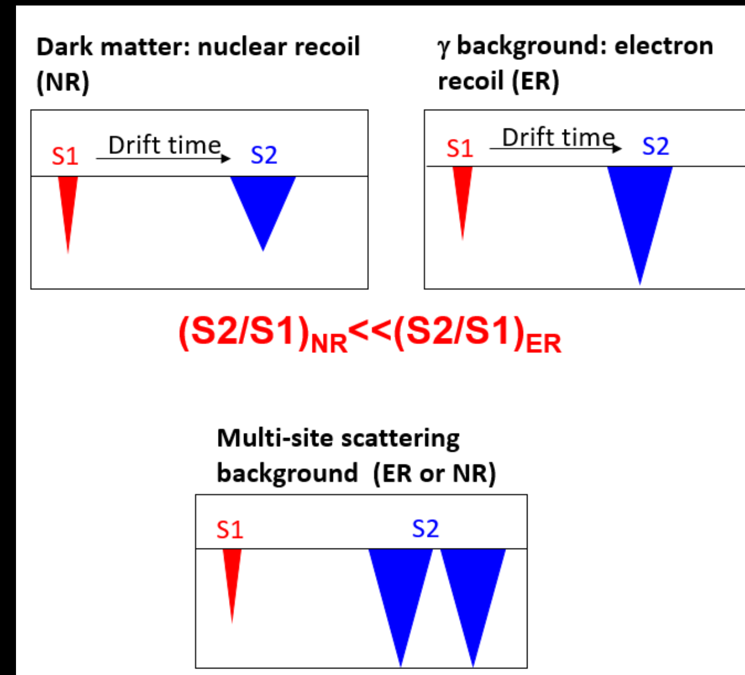
Boiling pt: -100C

Annual production: ~100 ton

Dual-phase time projection chamber



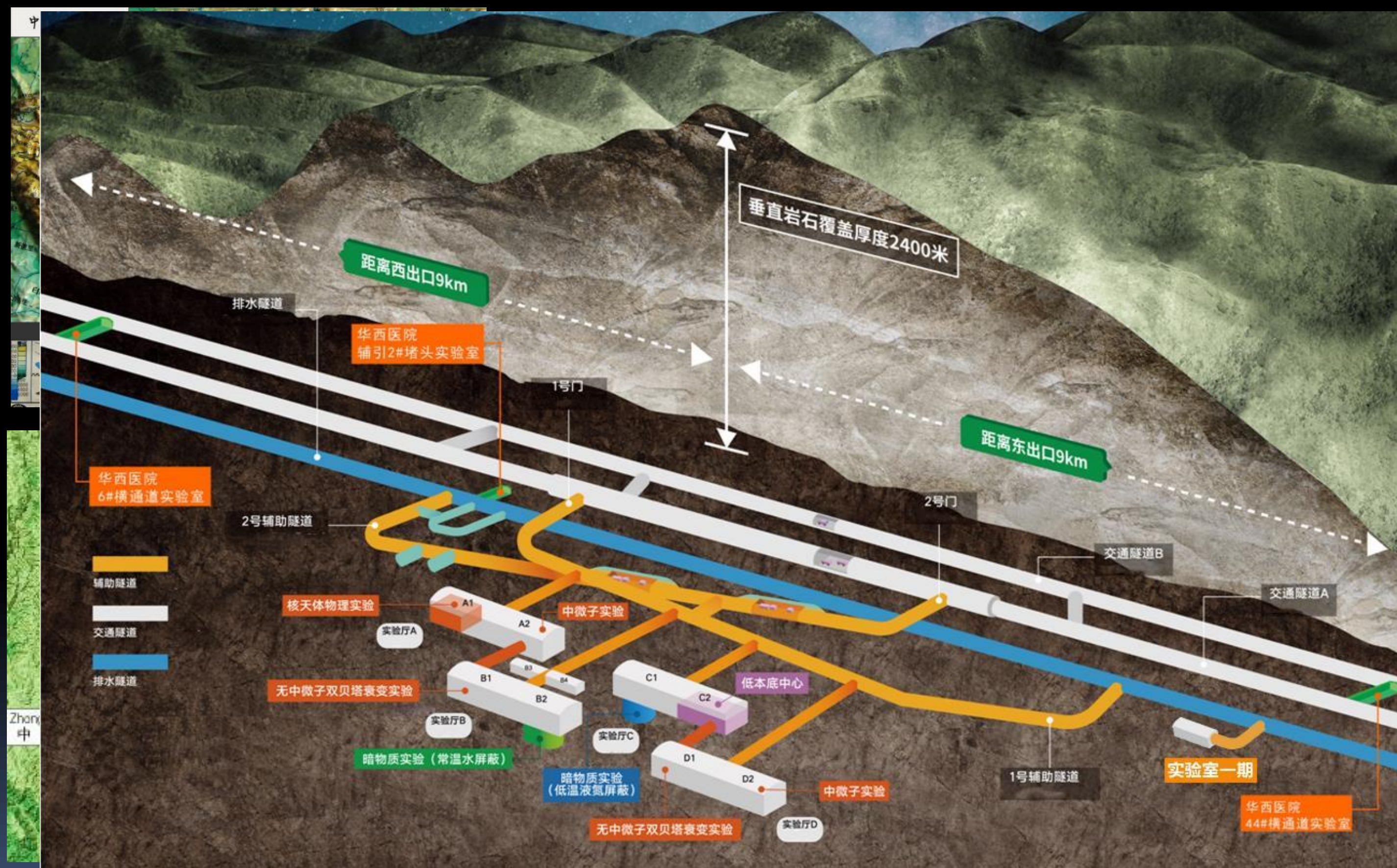




Detector capability:

- Large monolithic target
- 3D reconstruction and fiducialization
- Good ER/NR rejection
- Calorimeter capable of seeing a couple of photons/electrons

China Jinping underground Laboratory



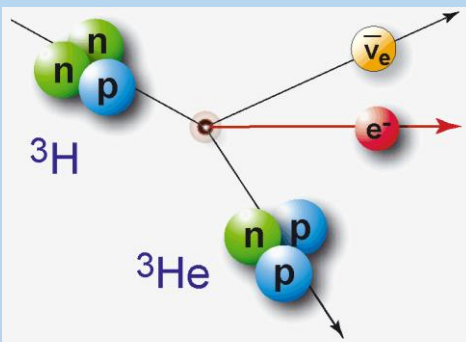
2018.4 water tank construction

2019.8 PandaX-4T instllation

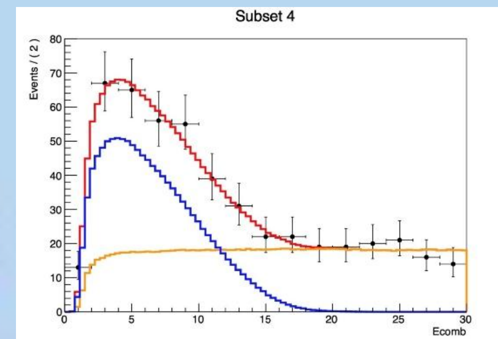
2020.5 liquid xenon filling

2020/6-2020/11 integration tests

Background: name of the game



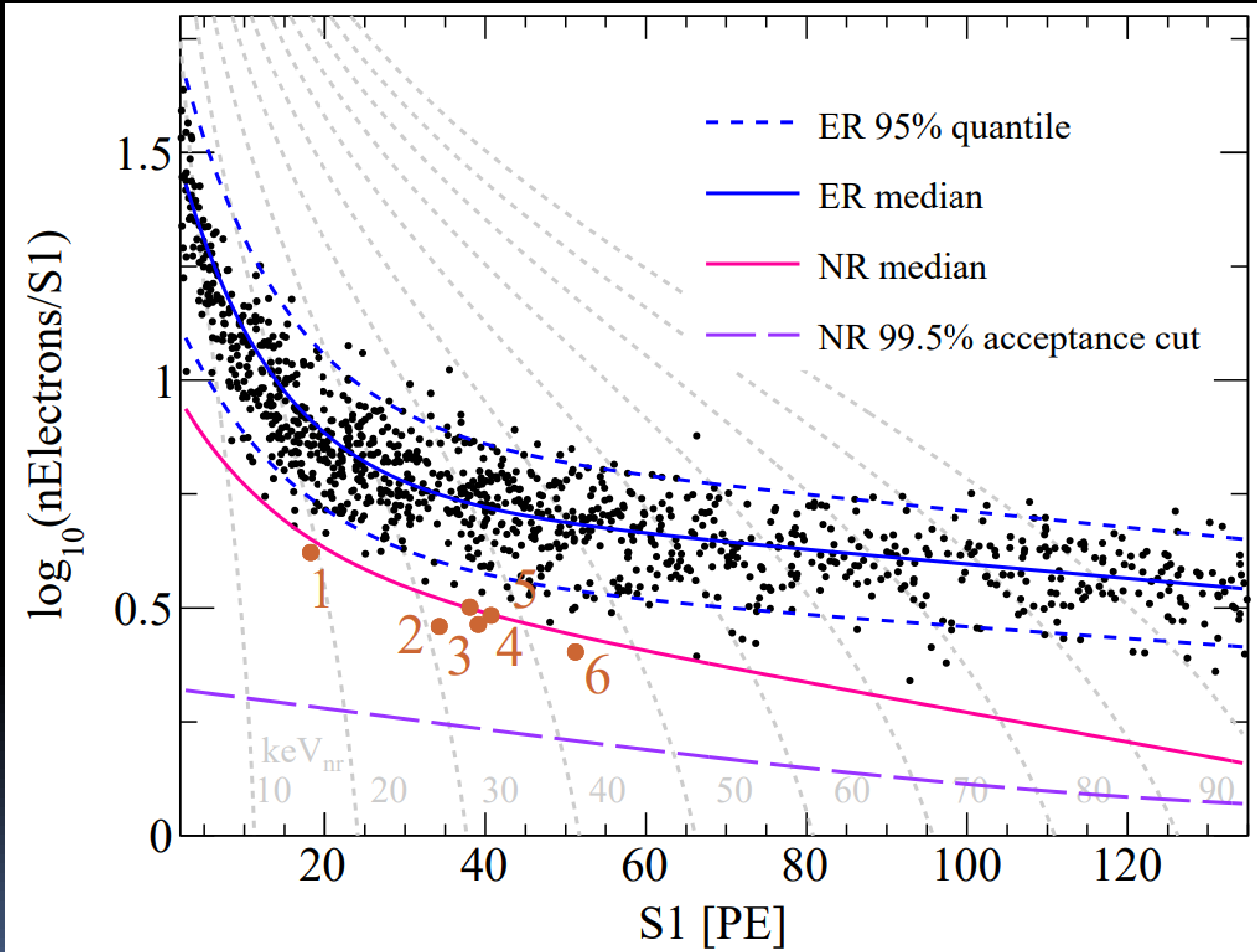
氚：^3H



每公斤氙中20个！

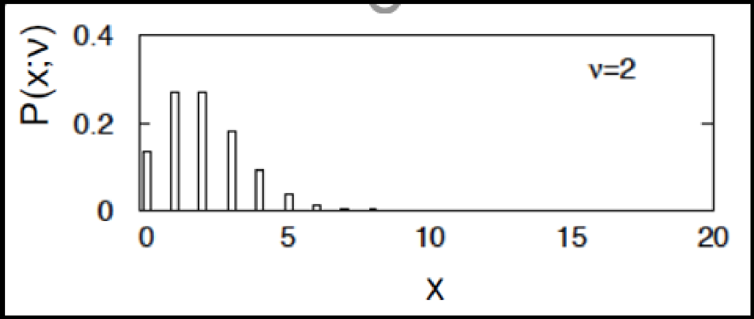
Tritium: lifetime 18 years

We discovered a tritium level of 20/kg-of-xenon! Now managed to reduce it to 2/kg-of-xenon …

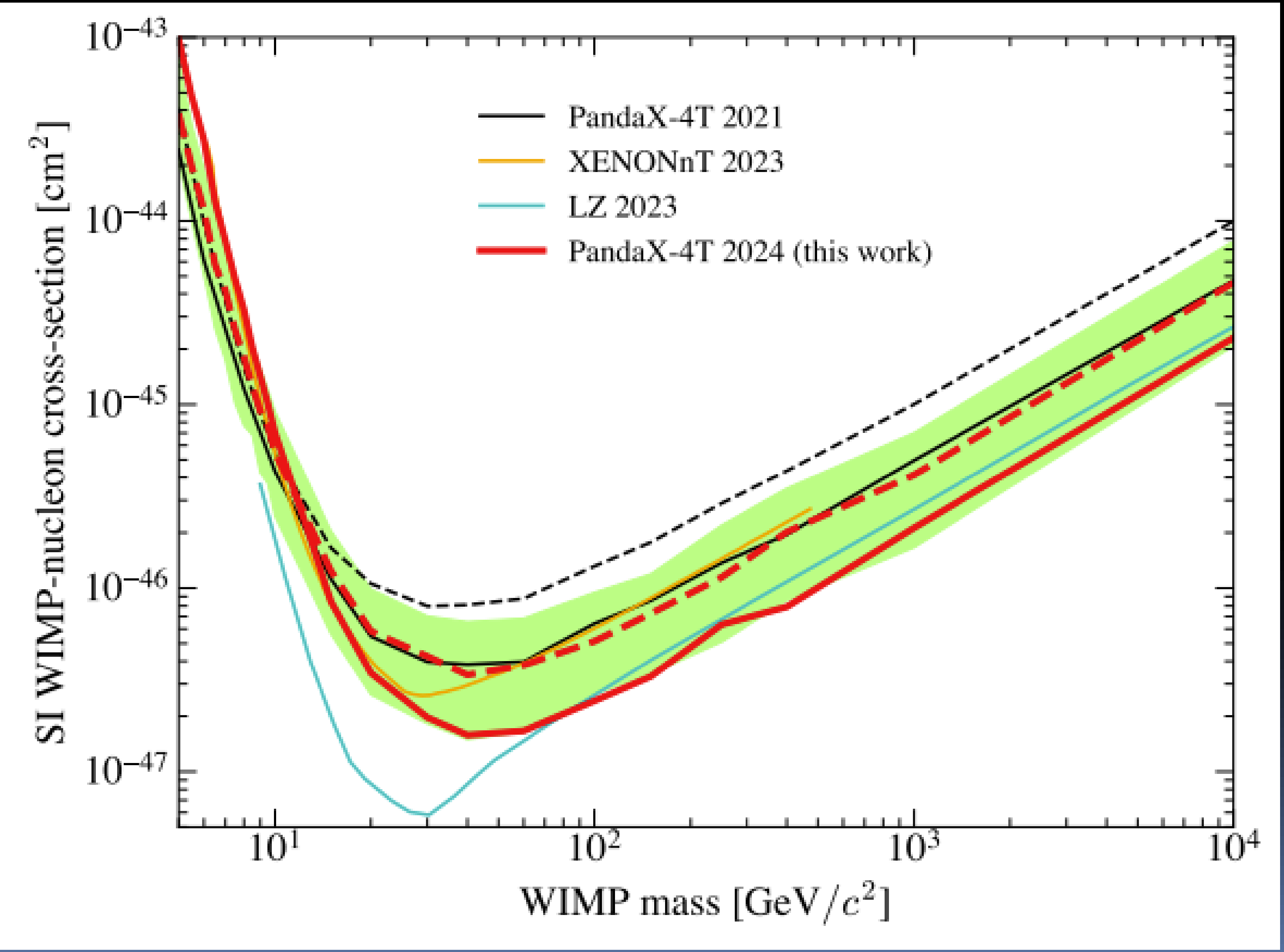

ER 95% quantile
ER median
NR median
NR 99.5% acceptance cut
log10(nElectrons/S1)
1.5
1
0.5
0
20
40
60
80
100
120
S1 [PE]
keVnr
10
20
30
40
50
60
70
80
90
1
2
3
4
5
6

Upper limit : "Nothing" is still meaningful

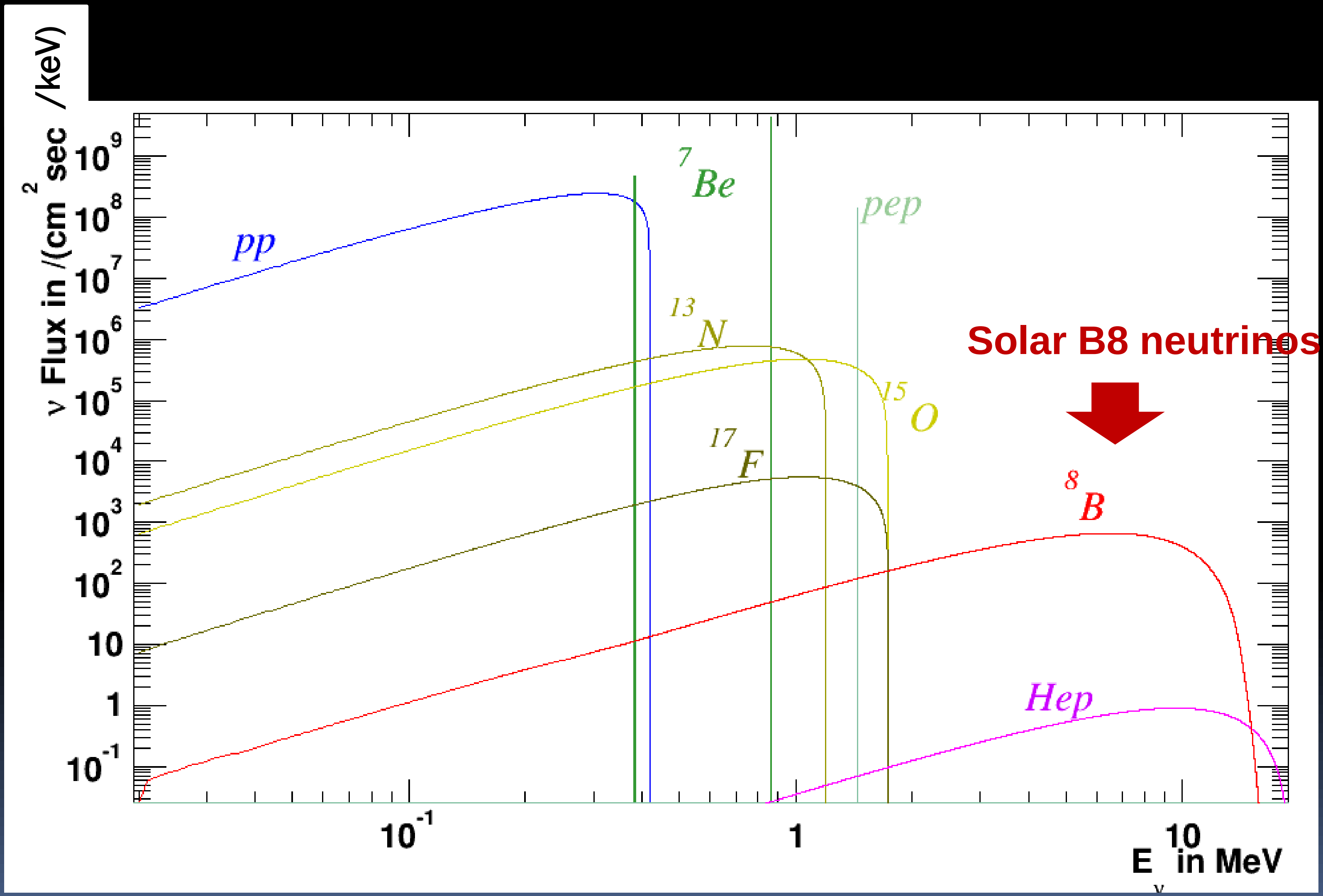
- For a Poisson distribution, if we measure 0
  - If mean value = 2.3, 10% of the probability of measuring 0!
  - So we usually say 2.3 is the (90%) upper limit when we measure NOTHING

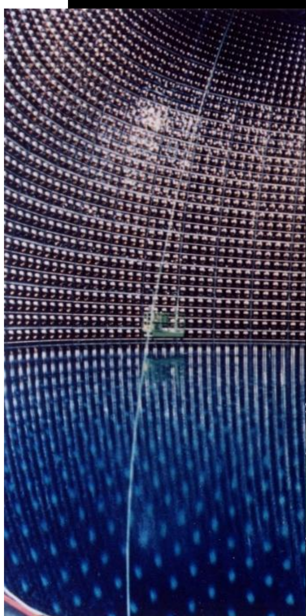


Turning the absence of DM into a limit

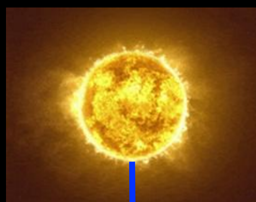


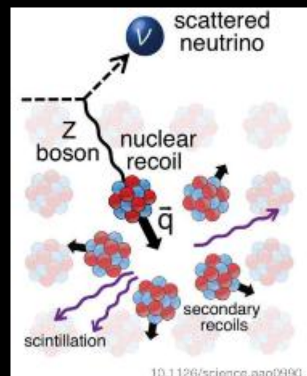
Solar neutrinos again



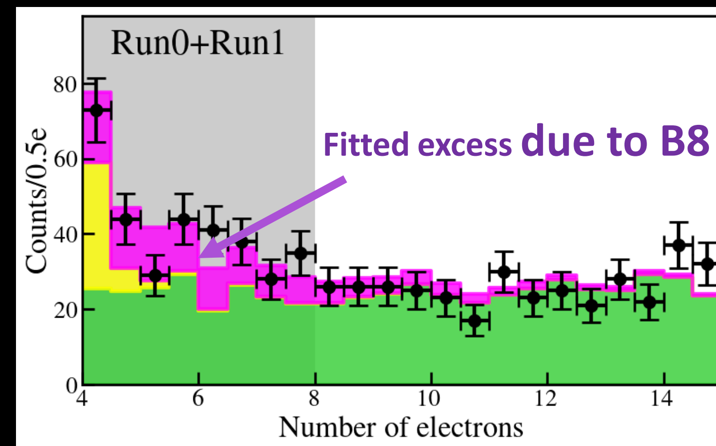


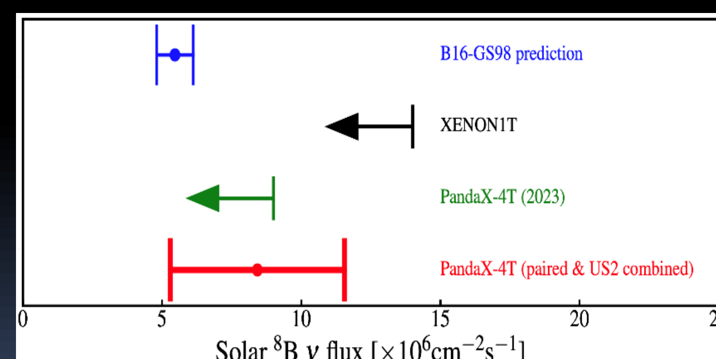
A 4-ton detector, but with CEvNS





ν





A 4-ton detector, but with CEvNS

PHYSICAL REVIEW LETTERS

Accepted Paper

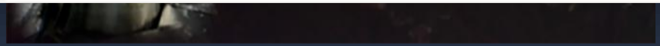
First indication of solar ^{8}B neutrinos through coherent elastic neutrino-nucleus scattering in PandaX-4T

Phys. Rev. Lett.

Zihao Bo et al.

Accepted

11 September 2024



PHYSICAL REVIEW LETTERS

Accepted Paper

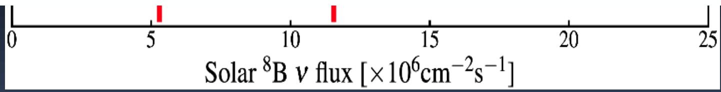
First indication of solar ^{8}B neutrinos via coherent elastic neutrino-nucleus scattering with XENONnT

Phys. Rev. Lett.

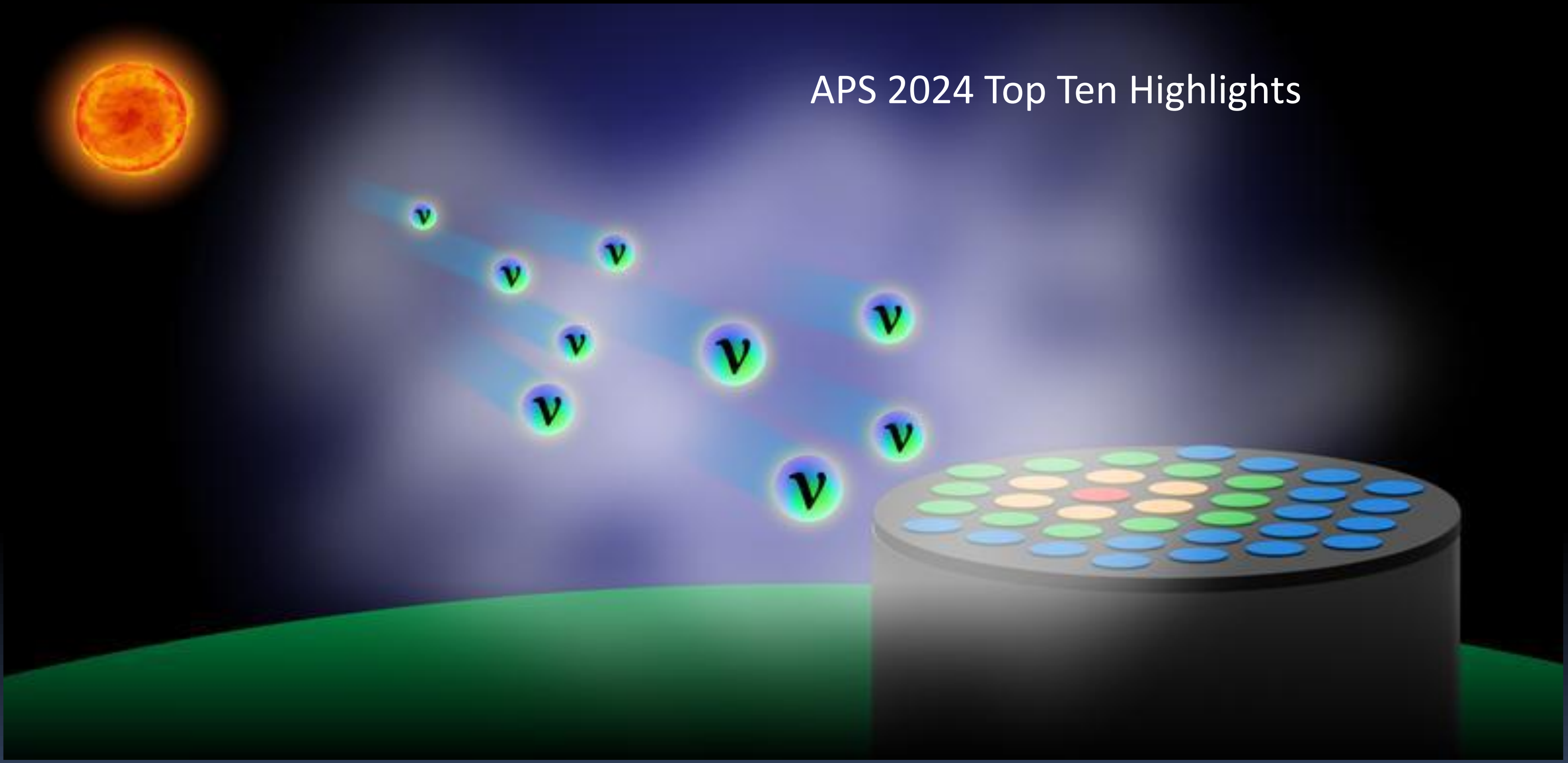
E. Aprile et al.

Accepted

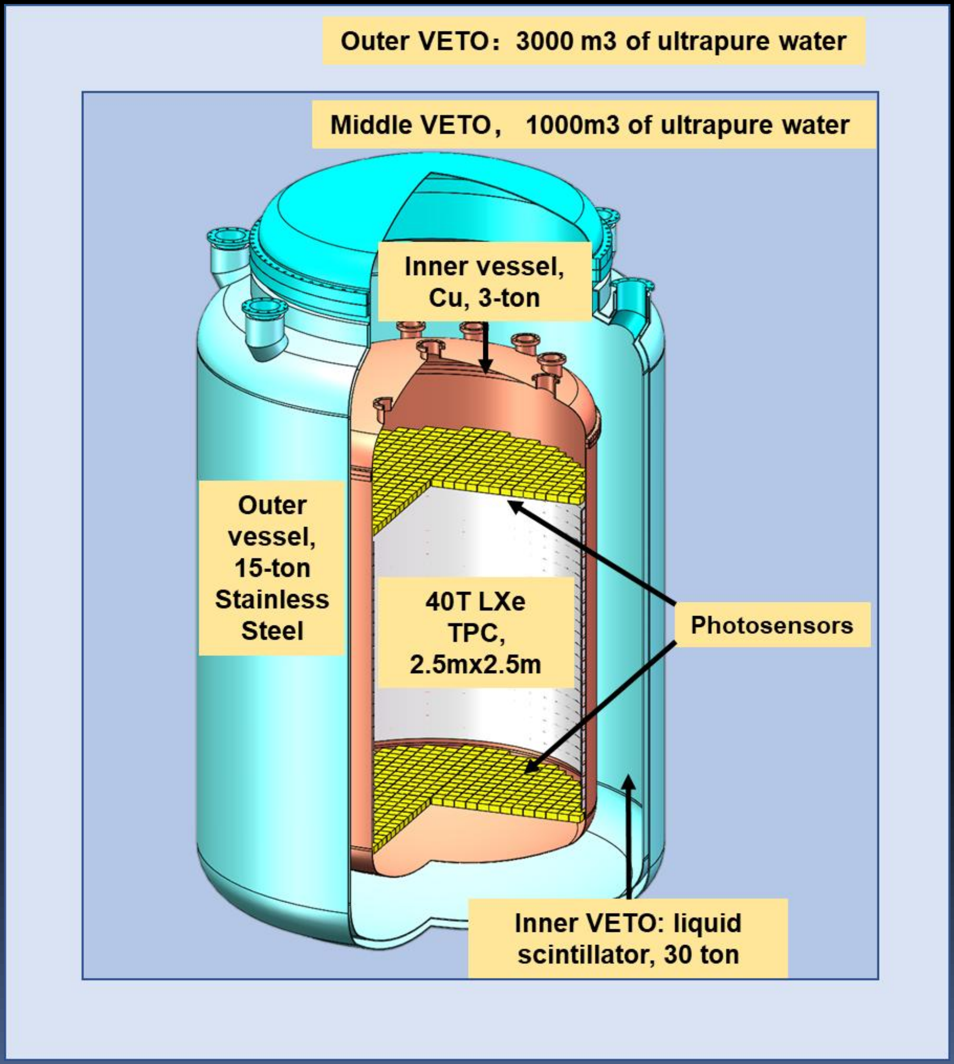
25 September 2024



A 4-ton detector, but with CEvNS



Future: PandaX-xT



- 47-ton xenon, including
  43-ton sensitive volume
  - 2.7 meters in diameter and height
  - Eliminate LXe veto
  - Cold LS veto right outside Cu cryostat
  - Staged and upgradable

Outline

- Unit 1: Detector and low background techniques 101
- Unit 2: Neutrinos, weak interactions
- Unit 3: Neutrino oscillations
- Unit 4: From neutrino coherent scattering to dark matter detection
- Unit 5: Neutrinoless double beta-decays

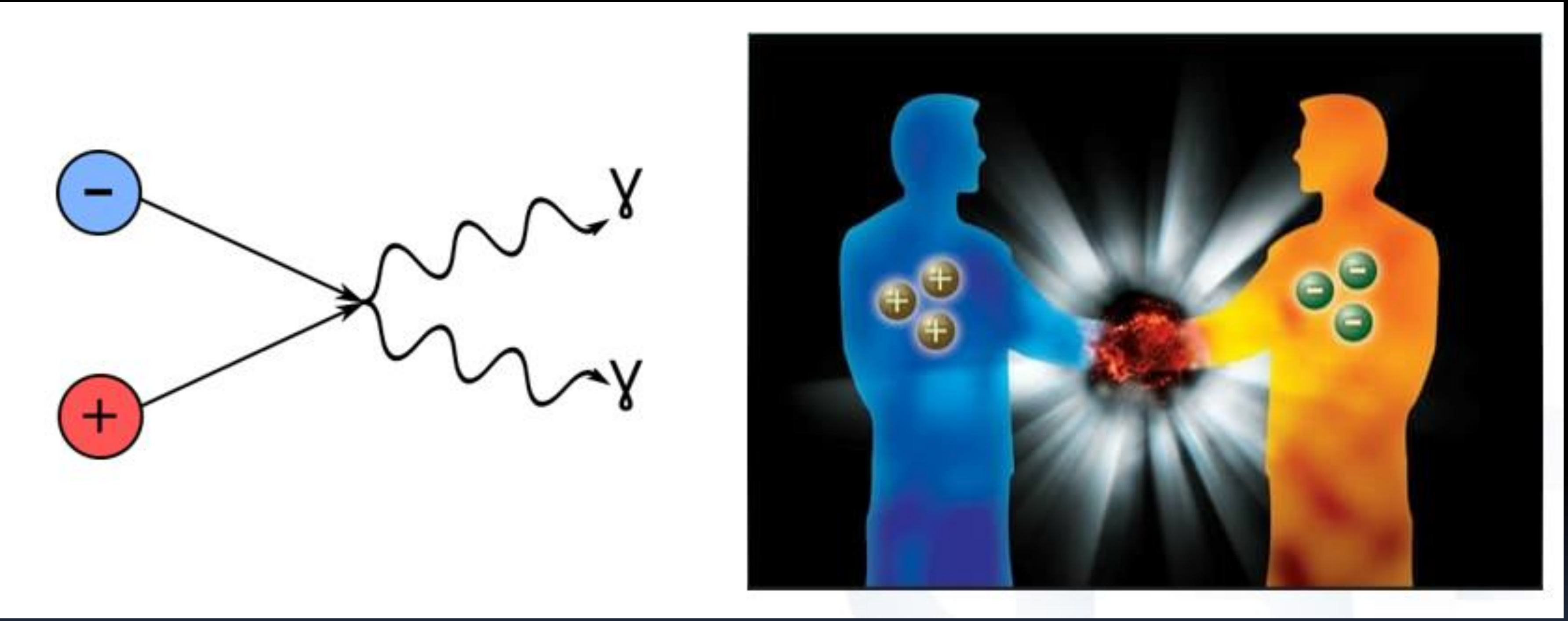
Majorana particles

Majorana mass term:

$$m_R \, \overline{\nu_R{}^C} \, \nu_R$$

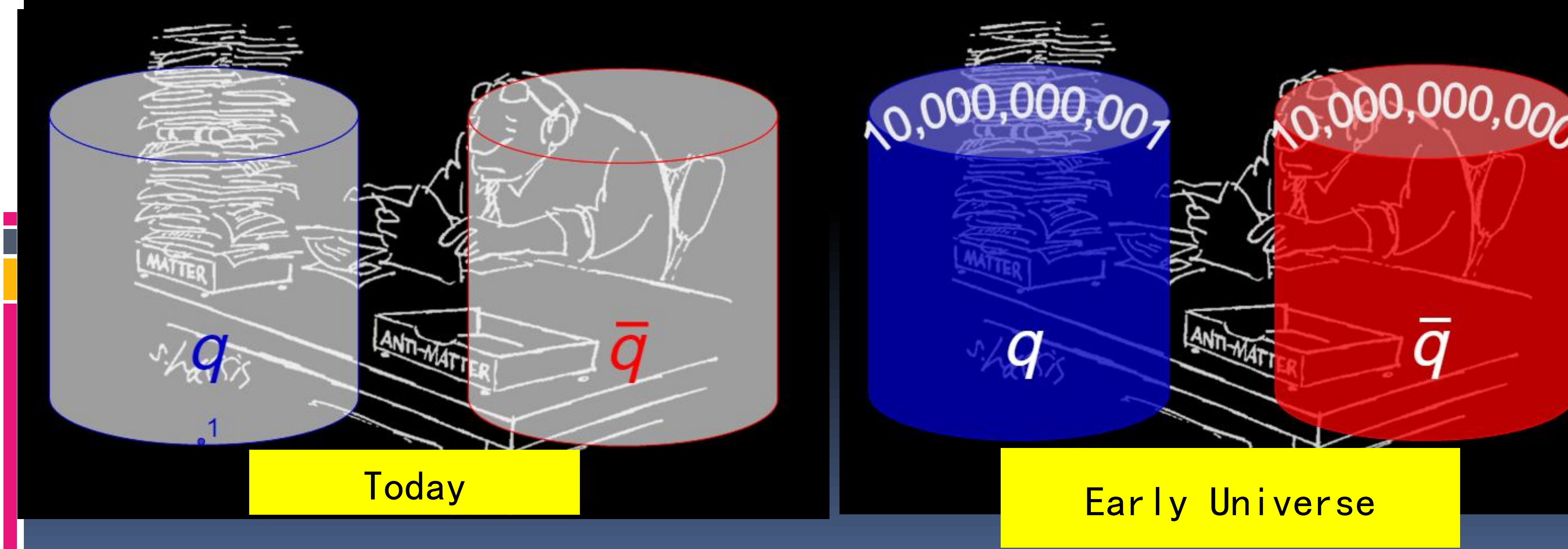
- Majorana, 1937
- Can be tested via neutrinoless double β decay, W. Furry, 1939

What happens with matter-antimatter meet?



Another big mystery: why Universe almost has no anti-matter?

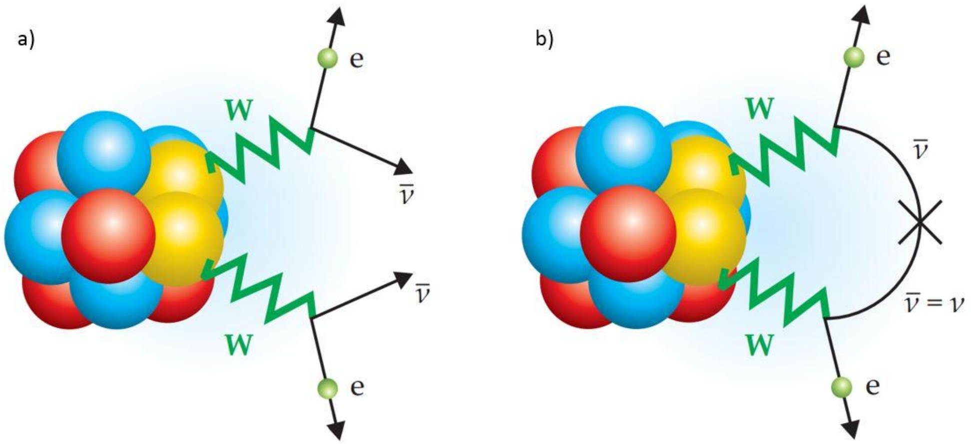
$$\eta = \frac{n_B - n_{\overline{B}}}{n_\gamma} \simeq 5 \times 10^{-10}$$

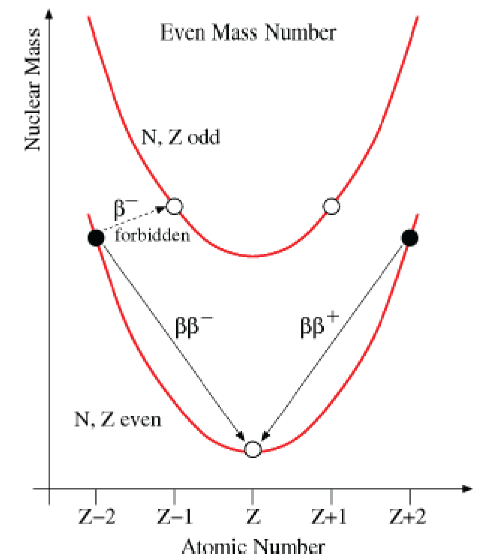


One promising theory: leptongenesis

- If neutrino is Majorana, then it “may” be able to explain the 10^{-9} asymmetry produced in the early universe

Neutrinoless double beta decay

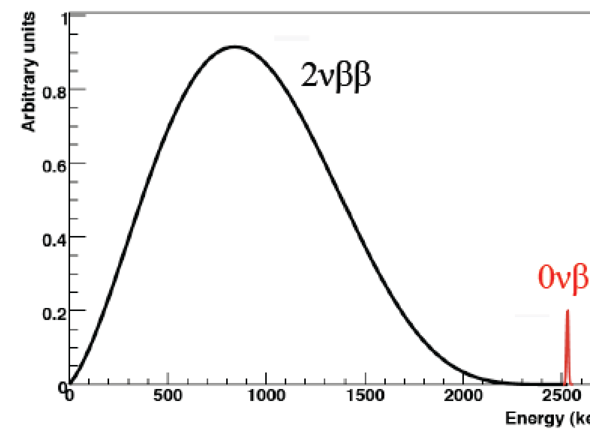




- Neutrinoless double beta decay
  - The nature of neutrinos, Dirac or Majorana
  - lepton number violation
- Extremely rare events T > 10^{24} year.

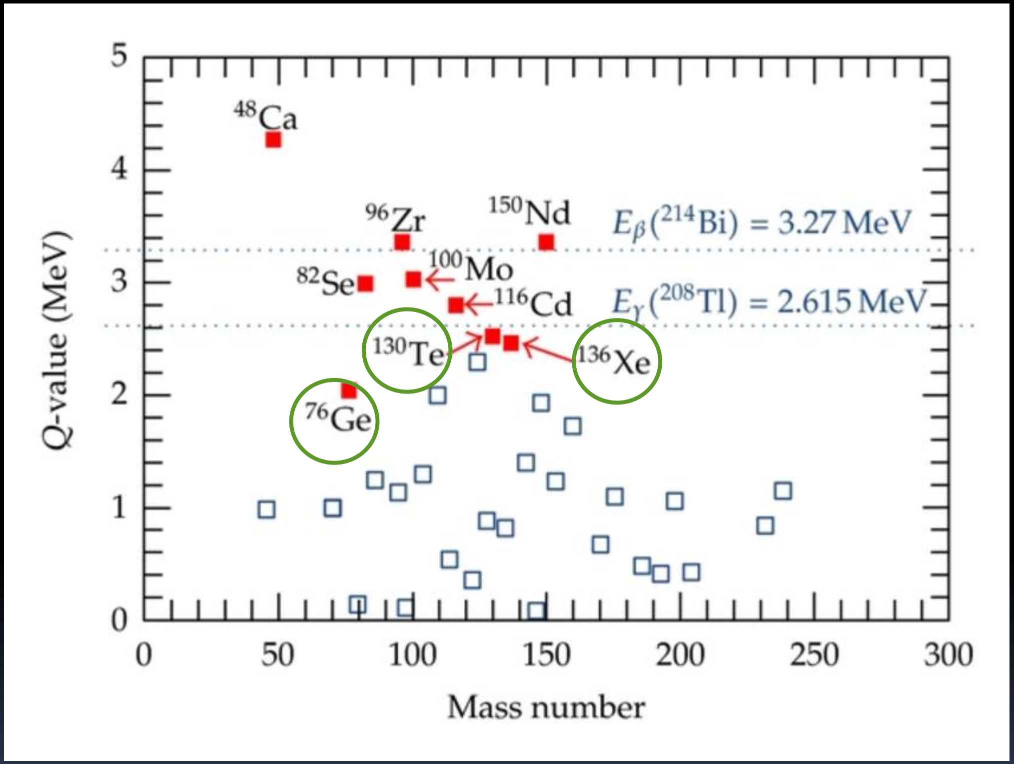
$$(T^{0\nu}_{1/2})^{-1} = G^{0\nu}(Q,Z)\ |M^{0\nu}|^2\ \frac{|\langle m_{\beta\beta}\rangle|^2}{m_e^2}$$

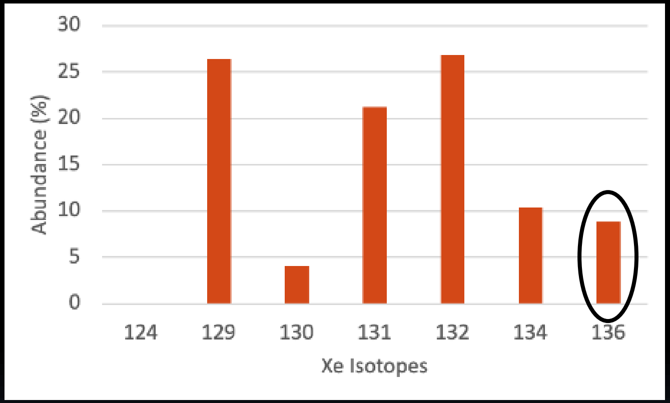
$$m_{\beta\beta} \equiv \left|\sum_{i=1}^{3} U_{ei}^2\, m_i\right|.$$



Sum of electrons energy

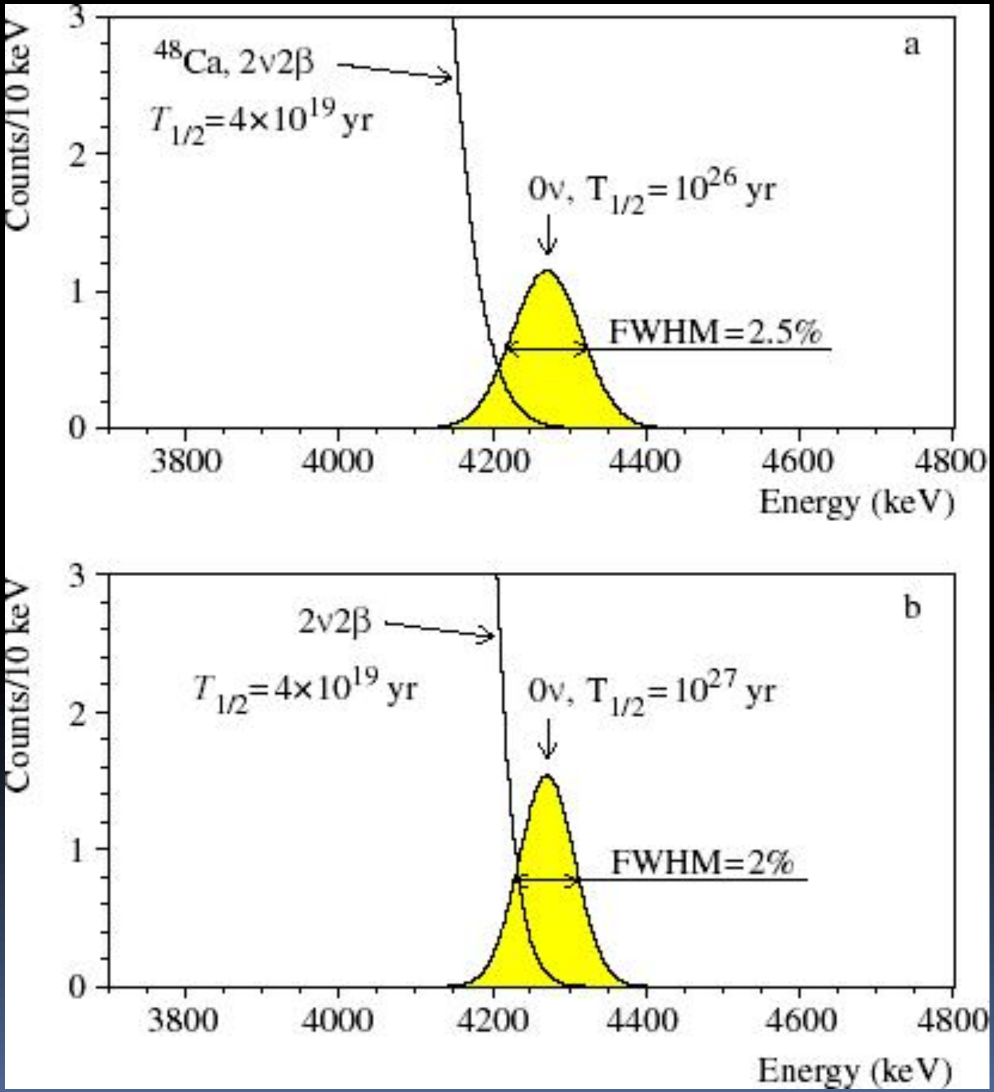
"The Magnificent Nine"





Advances in High Energy Physics Vol 2012, 857016

Needle from a haystack

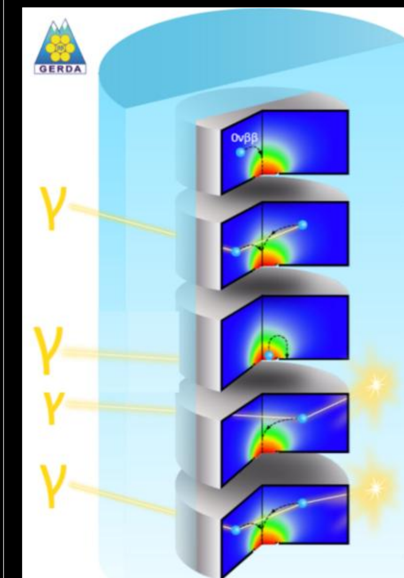


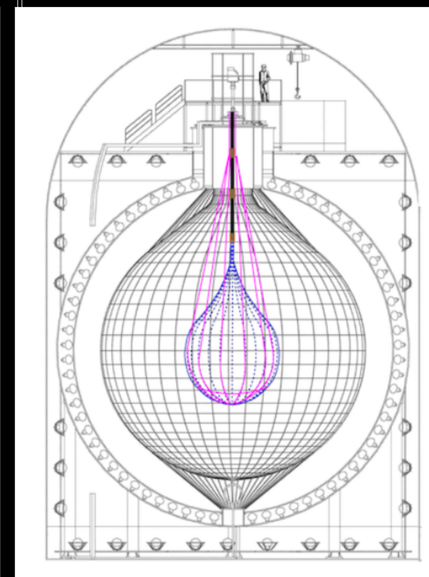
Front runners

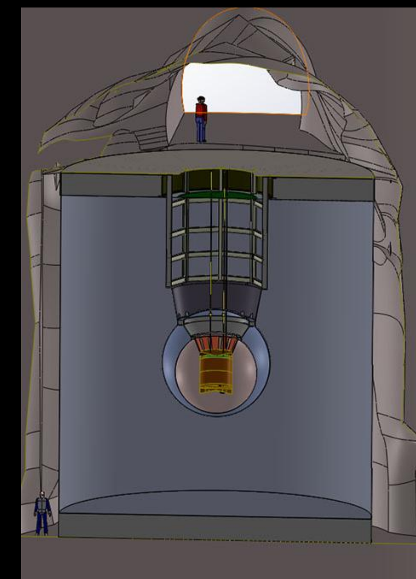
Experiment	Isotope	Resolution (keV)	Efficiency	Phase	Mass (kg)	Exposure (kg·year)	Background rate (counts/(keV · kg · y))	Sensitivity (meV)
CUORE	^{130}Te	5	0.8	2015–2017 (I) 2018–2020 (II)	200 200	600 600	10^{-1} 4×10^{-2}	140 85
EXO	^{136}Xe	100	0.7	2012–2014 (I) (II) 2016–2020	160 160	480 800	7×10^{-3} 5×10^{-3}	185 150
GERDA	^{76}Ge	5	0.8	2012–2014 (I) 2016–2020 (II)	18 35	54 175	10^{-2} 10^{-3}	214 112
KamLAND-Zen	^{136}Xe	250	0.8	2013–2015 (I) 2017–2020 (II)	360 35	1440 2700	10^{-3} 5×10^{-4}	97 60

Table 1.1: Proposals considered in the $m_{\beta\beta}$ sensitivity comparison. For each proposal, the isotope that will be used, together with estimates for detector performance parameters — FWHM energy resolution, detection efficiency and background rate per unit of energy, time and $\beta\beta$ isotope mass — are given. Two possible operation phases, with estimates for the detector mass and the background rate achieved, are given for each experiment.

Experimental techniques

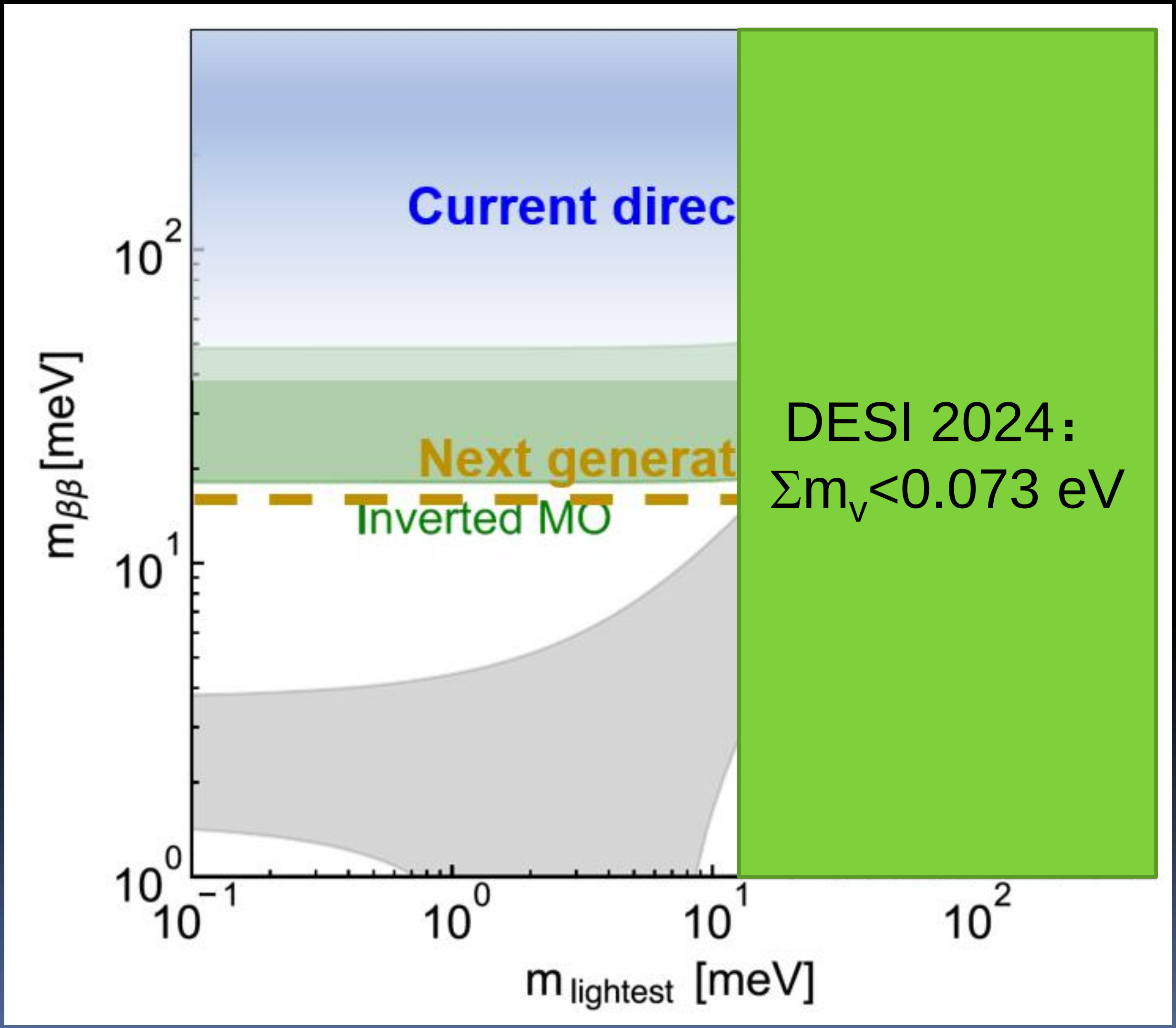






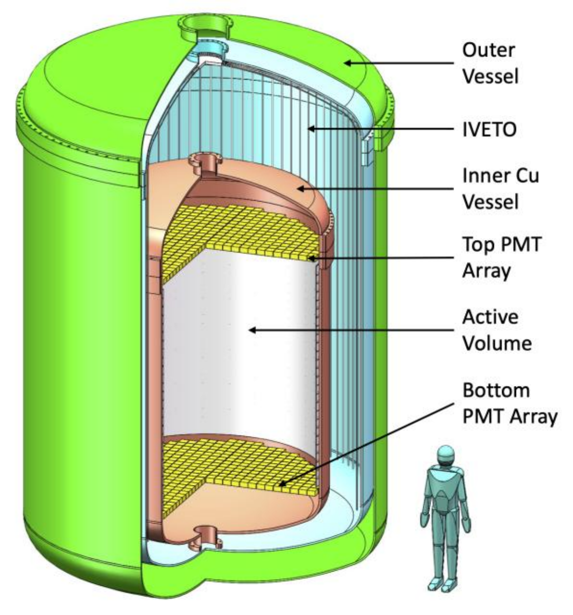
^{130}Te/^{100}Mo	^{76}Ge	^{136}Xe (8.9% natural abd.)	
CUORE/CUPID	LEGEND family	KamLAND-ZEN	EXO/nEXO
Microcalorimeter	Ionization	Liquid scintillator [181]	Time projection chamber

Where we expect the signal?

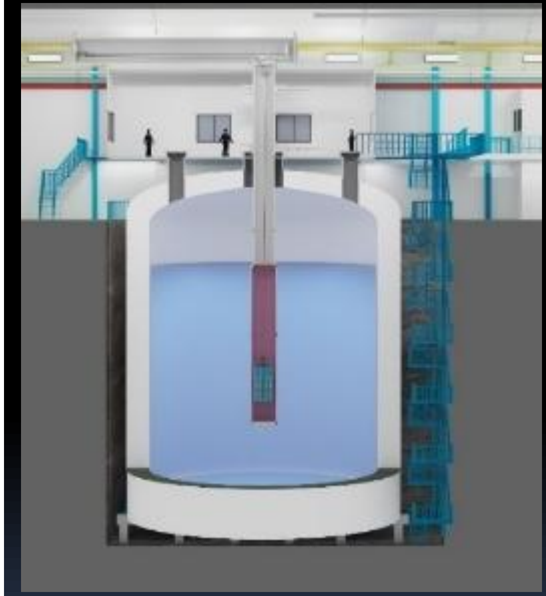


Potential new comers

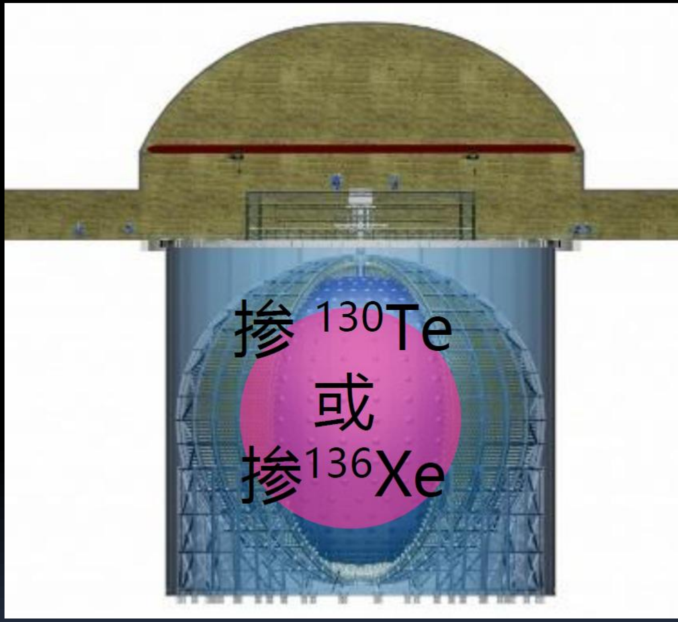
PandaX-xT



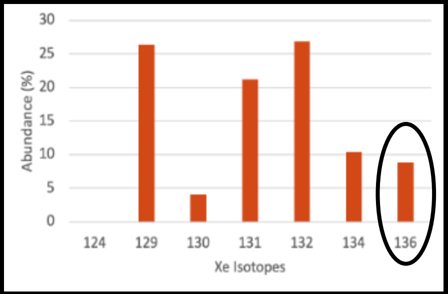
CDEX-1T

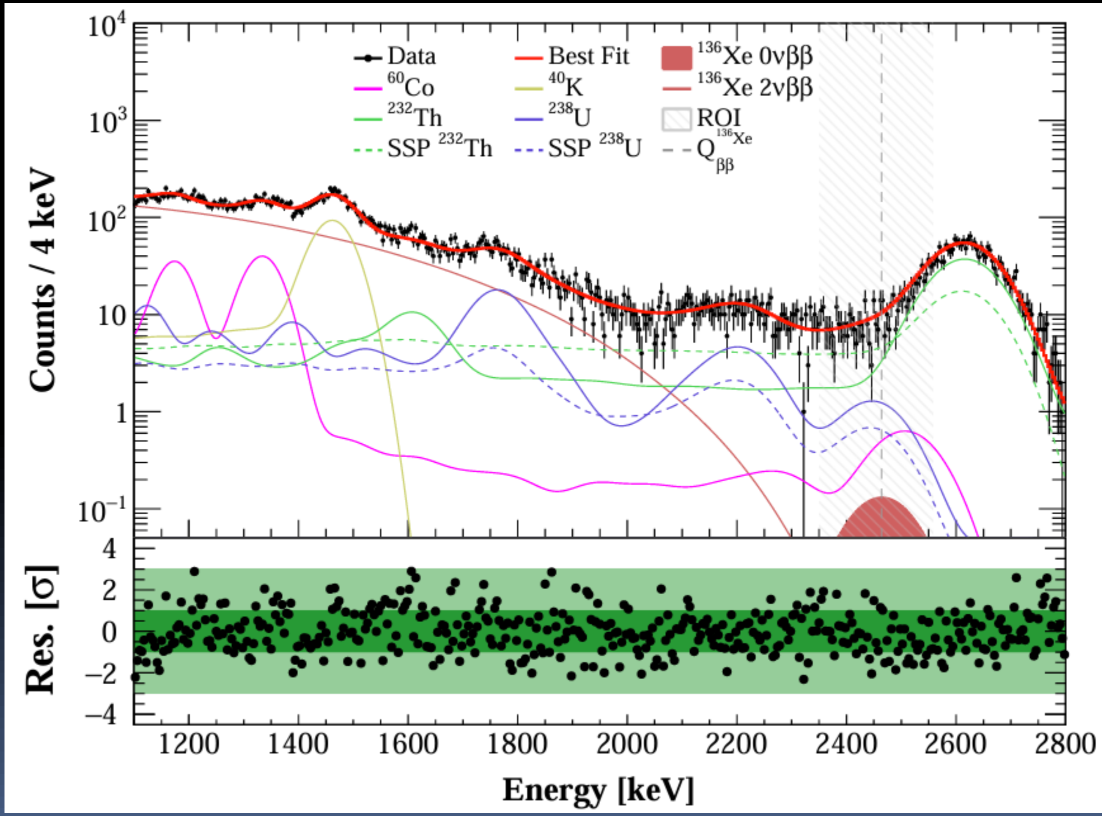


JUNO-DBD



PandaX-4T latest result



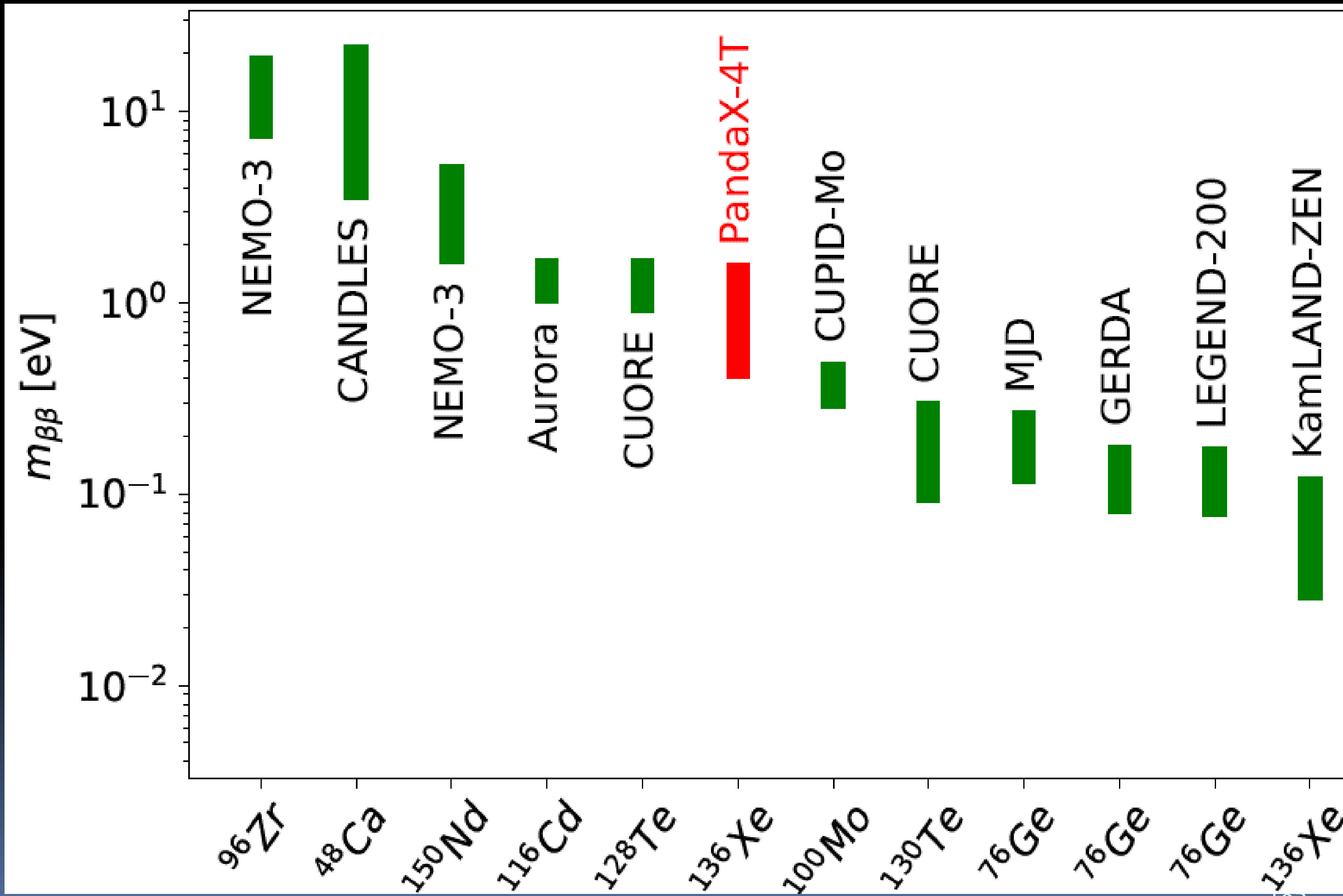


arXiv:2412.13979

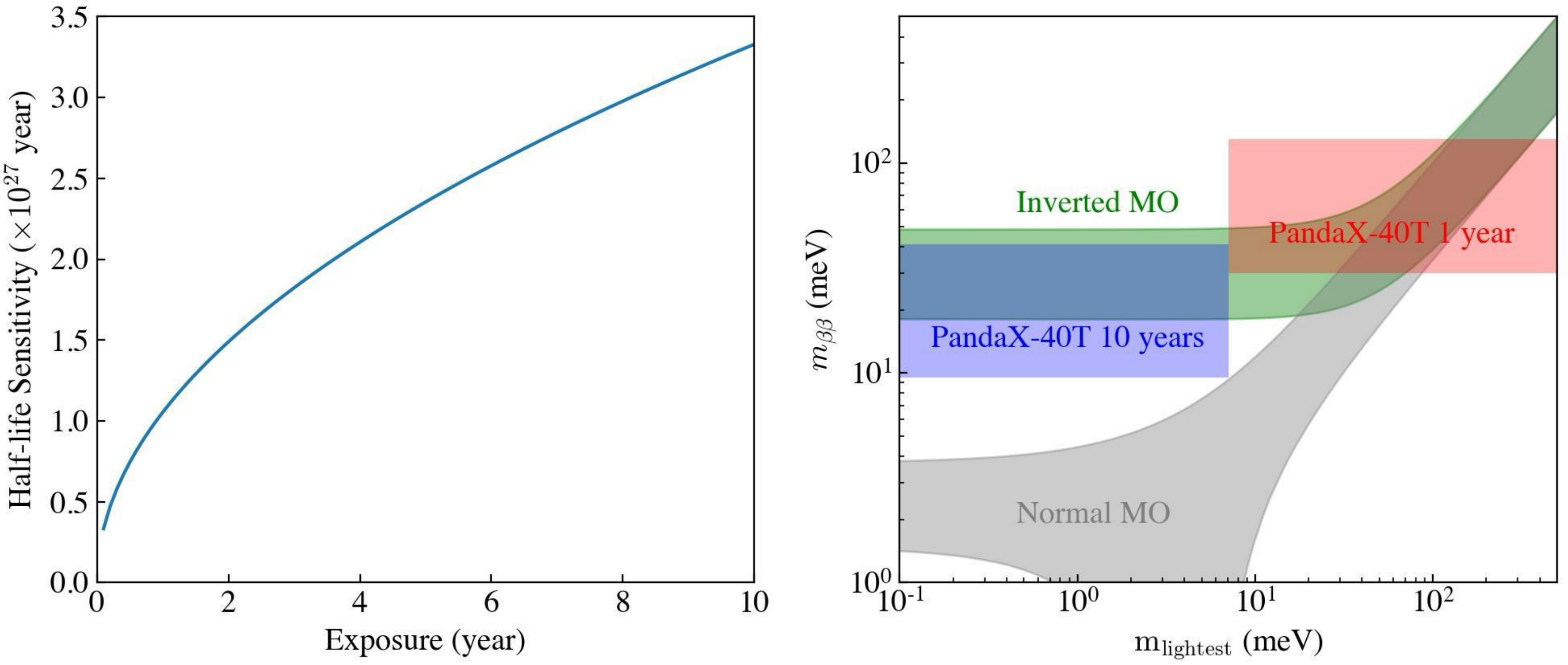
Lifetime
$> 2.1 \times 10^{24}$year
90% CL

Median sensitivity
2.7×10^{24}year

Global race

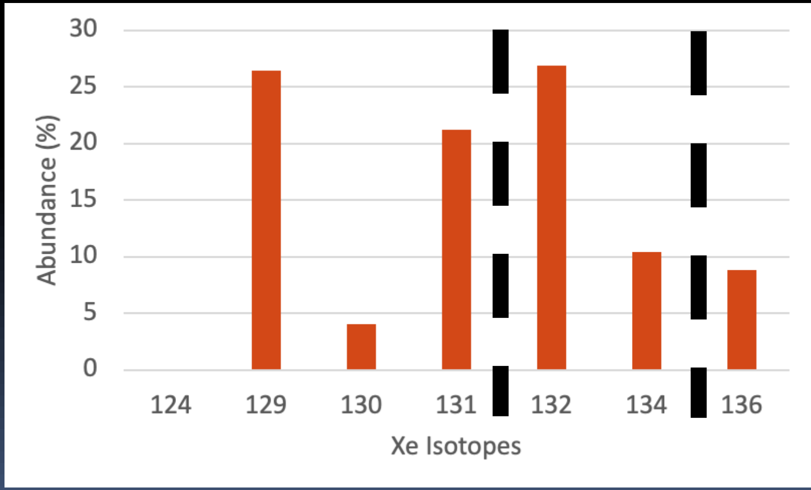

$m_{\beta\beta}$ [eV]
10^1
10^0
10^{-1}
10^{-2}
NEMO-3
CANDLES
NEMO-3
Aurora
CUORE
PandaX-4T
CUPID-Mo
CUORE
MJD
GERDA
LEGEND-200
KamLAND-ZEN
^{96}Zr
^{48}Ca
^{150}Nd
^{116}Cd
^{128}Te
^{136}Xe
^{100}Mo
^{130}Te
^{76}Ge
^{76}Ge
^{76}Ge
^{136}Xe

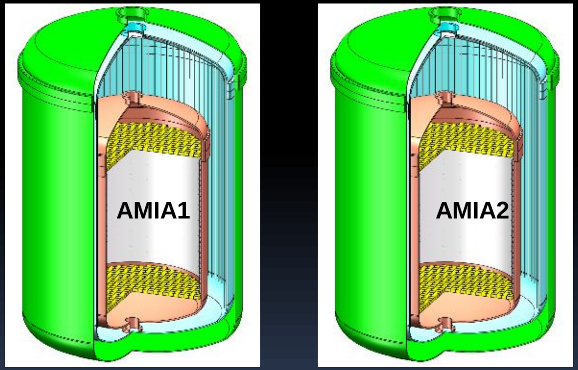
Projection for PandaX-40T



Even future development

Xenon with artificially modified isotopic abundance (AMIA), either via a split of odd and even nuclei, or further enrichment of ^{136}Xe, to improve sensitivity to spin-dependence of DM-nucleon interactions and NLDBD (Y. Suzuki, arXiv:hep-ph/0008296, 2000)





Discovery smoking gun!


上海交通大學
SHANGHAI JIAO TONG UNIVERSITY
李政道研究所
TSUNG-DAO LEE INSTITUTE
https://tdli.sjtu.edu.cn/EN/
Accelerator
Large-Scale Structure of The Universe
Astrophysics
Black Hole
Laboratory Astrophysics
Physics Beyond the Standard Model
Multi-Messenger Astronomy
Gravitational Wave Muon Exoplanet
Neutrino Dark Matter
Gravitational Lens Dark Energy
Quantum Computing Condensed Matter
Anyon Quantum Information
Topological Effect in Condensed Matter
2024-25 Admission Majorana
Complex System
Tsung-Dao Lee Institute PhD Program
in Physics and Astronomy
Open to applicants with either a bachelor's or master's degree.