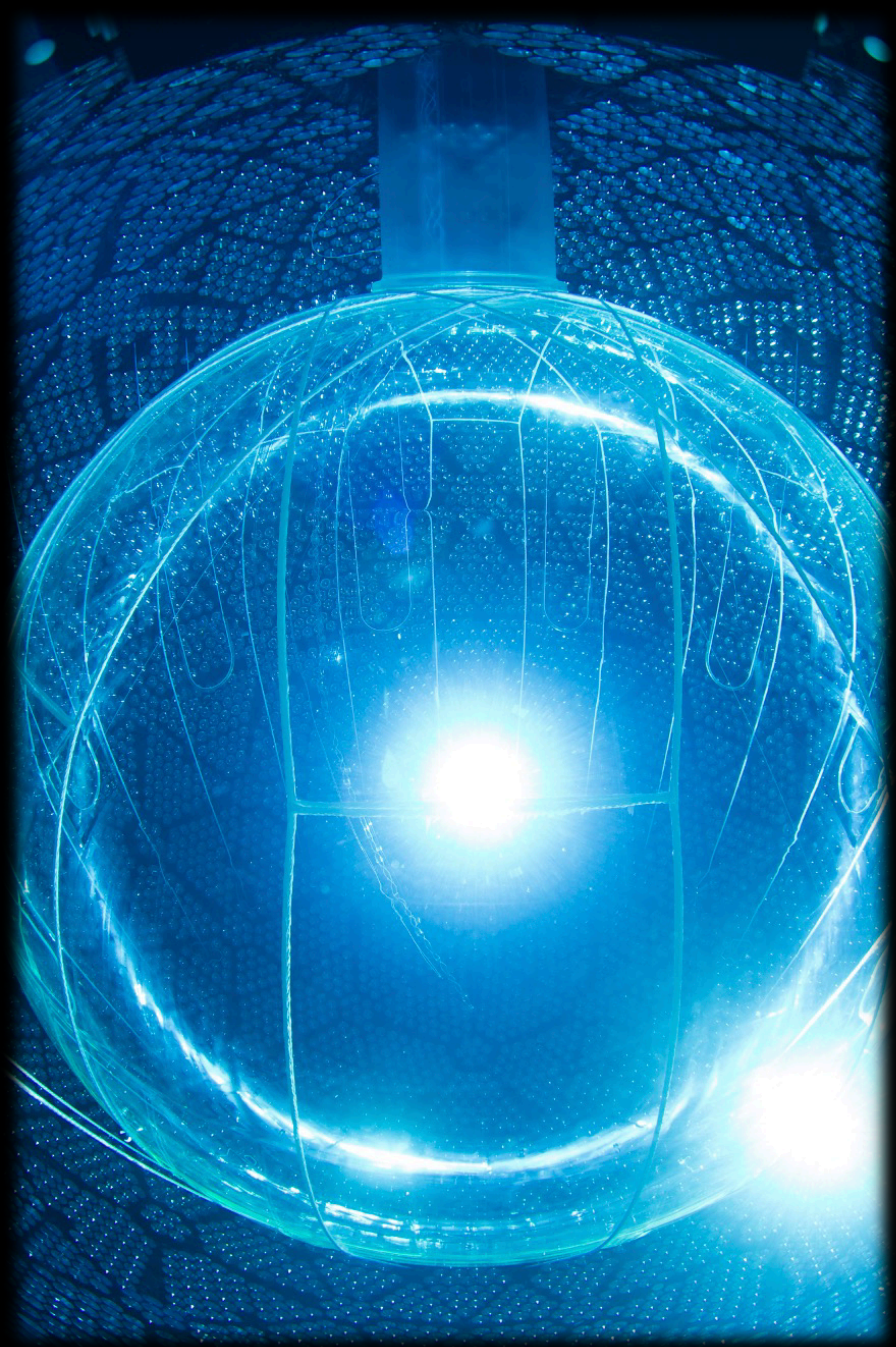

NEUTRINO SCIENCE 2

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SUSI 2024
SNOLAB UNDERGROUND SCIENCE INSTITUTE
JULY 22 - AUGUST 2, 2024 SUDBURY, CANADA

OVERALL PLAN OF THE 5 LECTURES

1. Neutrinos in the Standard Model.
2. Neutrino interactions, detectors. Solar and atmospheric neutrino problems.
3. Neutrino oscillations in 2 flavors. SNO and SK.
4. Neutrino oscillations in 3 flavors. Future experiments.
5. Theory and search for neutrino masses. Neutrinoless double-beta decay. Neutrinos in Cosmology and Astrophysics.

- Theory and experiment will be strongly mingled.
- Every lecture will have some of both.

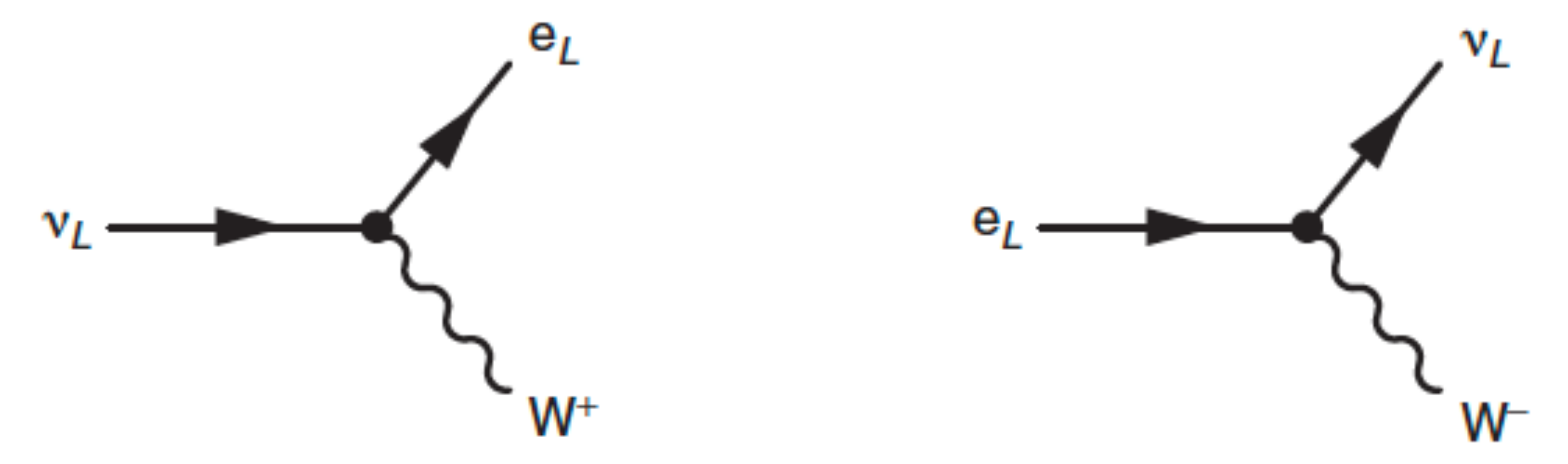
PLAN FOR LECTURE 2

- Neutrino interactions with matter
  - Charged and neutral currents vertices
  - Kinematic considerations
  - Cross sections for lepton and nuclear interactions
- Detectors
- The Solar Neutrino Problem
  - Basics of the Solar Standard Model and production of neutrinos in the Sun
  - Radiochemical experiments: Chlorine & Gallium
  - Kamiokande-II
  - Astrophysical solutions ?
- The atmospheric neutrino anomaly

NEUTRINO INTERACTIONS

RECAP, NEUTRINO INTERACTIONS

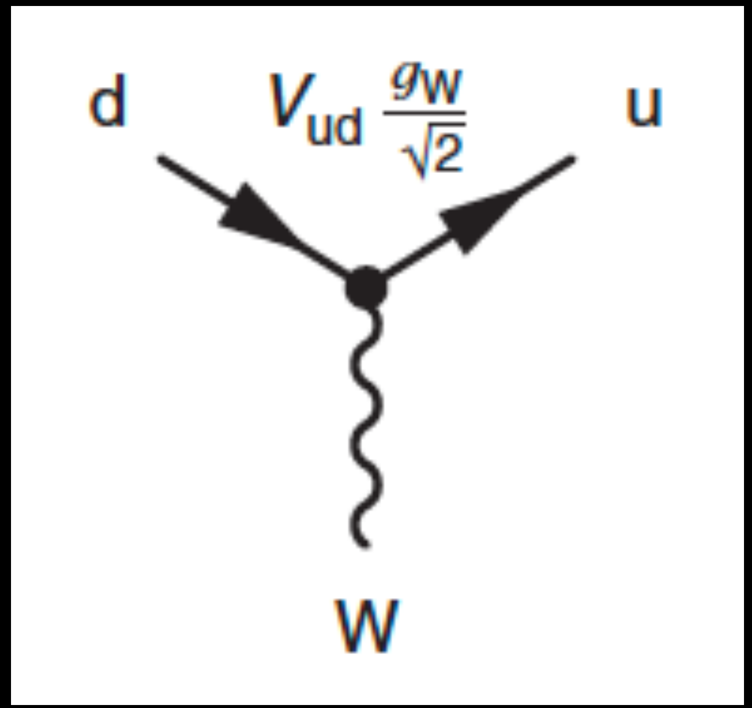
- Charged Current



$$j_+^\mu = \frac{g_W}{\sqrt{2}}\bar{\nu}\gamma^\mu \tfrac{1}{2}(1-\gamma^5)e \quad \text{and} \quad j_-^\mu = \frac{g_W}{\sqrt{2}}\bar{e}\gamma^\mu \tfrac{1}{2}(1-\gamma^5)\nu,$$

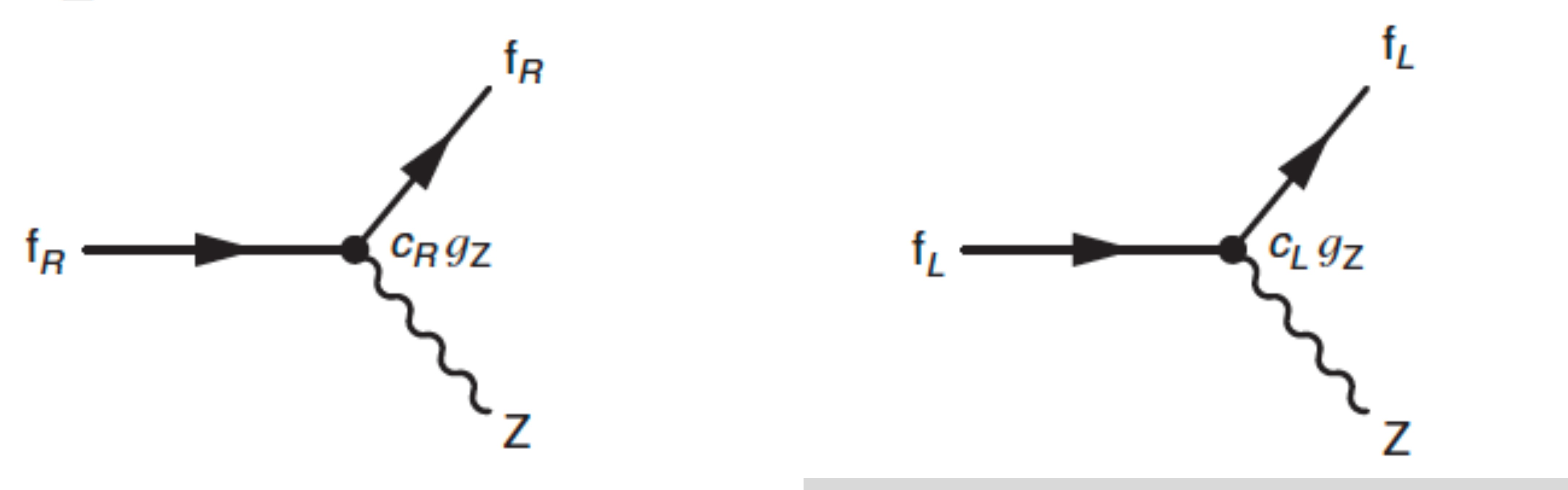
  - only LH particles (RH antiparticles)
  - similar for ν_μ, ν_τ.
  - plus the diagrams for quarks

$$j_{du}^\mu = -i\frac{g_W}{\sqrt{2}}V_{ud}\,\bar{u}\gamma^\mu \tfrac{1}{2}(1-\gamma^5)d.$$



- Neutral Current

$$j_Z^\mu = g_Z\left(c_L\,\bar{u}_L\gamma^\mu u_L + c_R\bar{u}_R\gamma^\mu u_R\right),$$



  - c_R=0 for neutrinos
  - only LH neutrinos (RH antineutrinos)

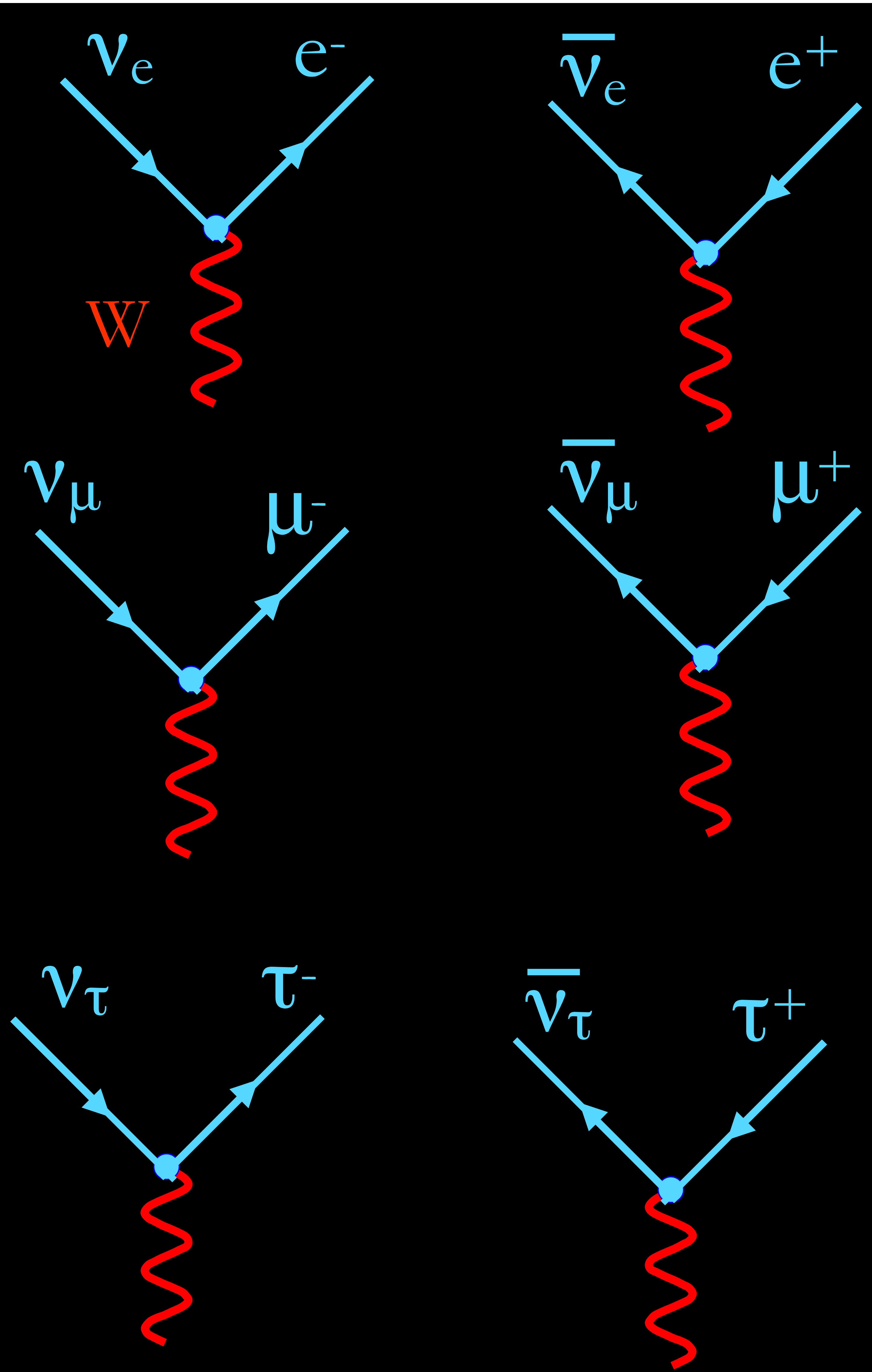
fermion	c_L	c_R
ν_e, ν_μ, ν_τ	$+\frac{1}{2}$	0
e^-, μ^-, τ^-	−0.27	+0.23
u, c, t	+0.35	−0.15
d, s, b	−0.42	+0.08

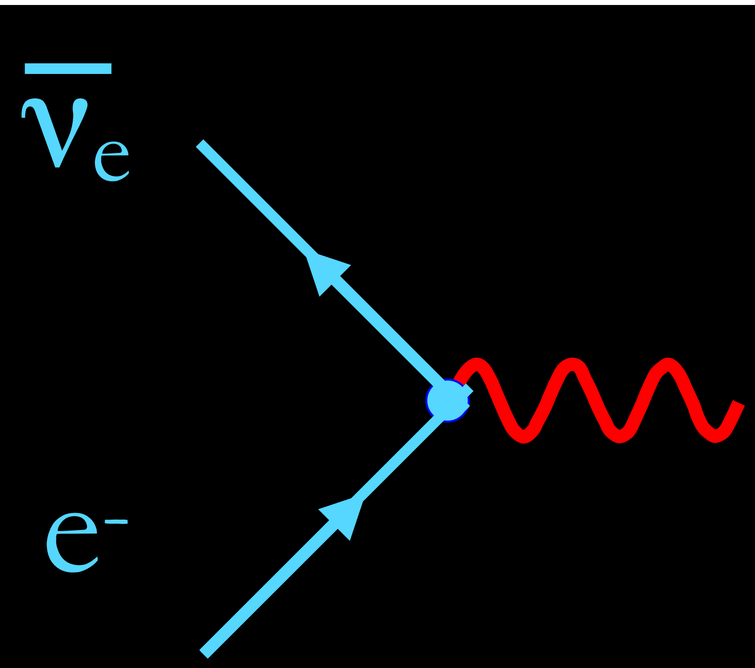
$$g_Z = \frac{g_W}{\cos\theta_W} \equiv \frac{e}{\sin\theta_W\cos\theta_W}$$

- Boson propagators
  - ~$1/m_W^2$ or ~$1/m_Z^2$
  - (if E<< m_W)

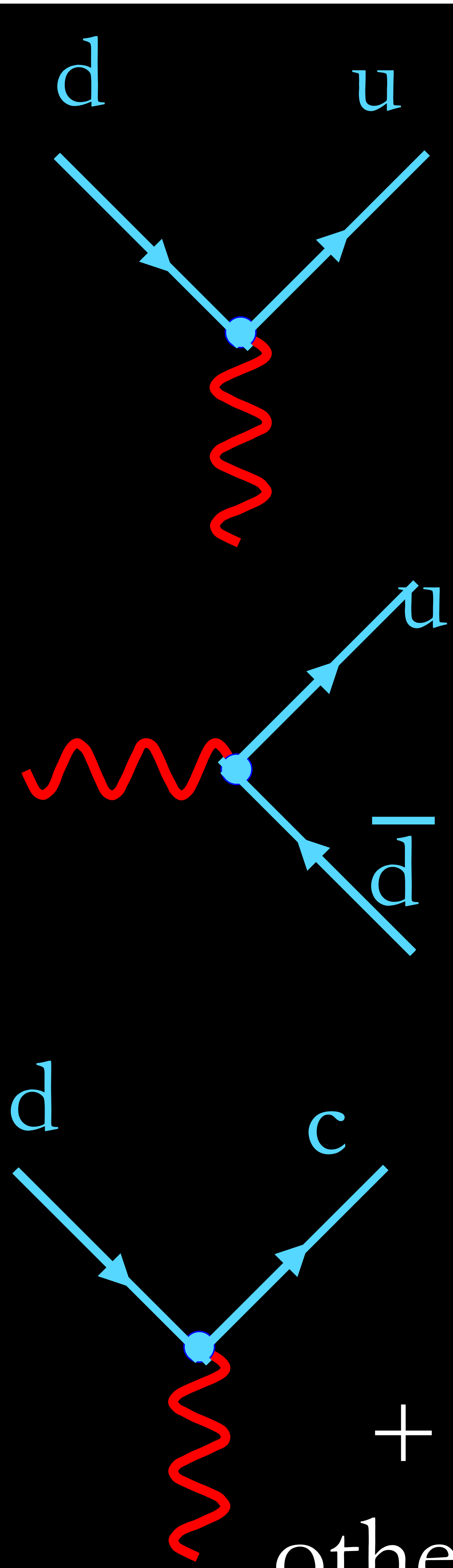
$$\frac{m_W}{m_Z} = \cos\theta_W.$$

VERTICES

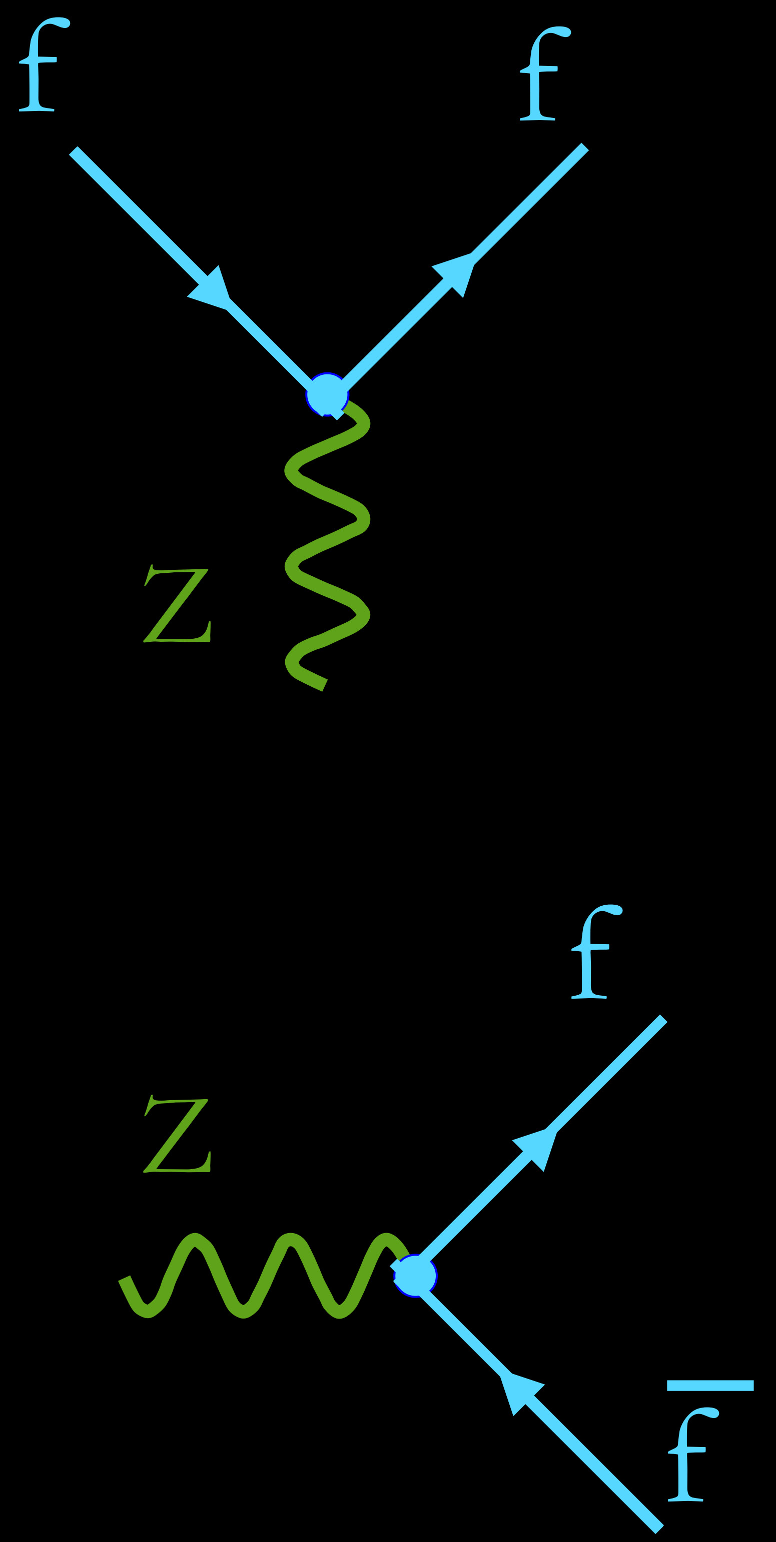




+
others
…



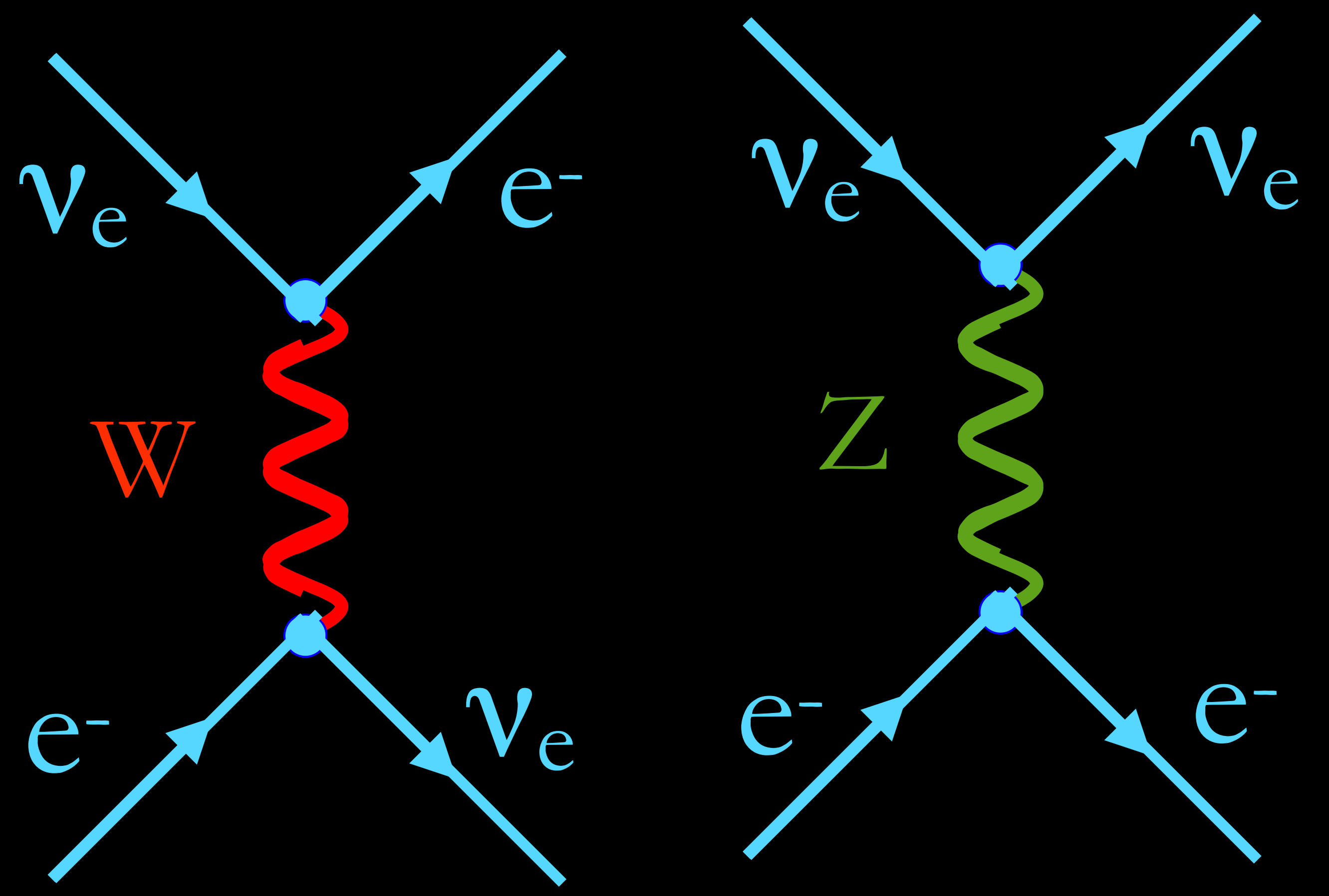
+
others
…



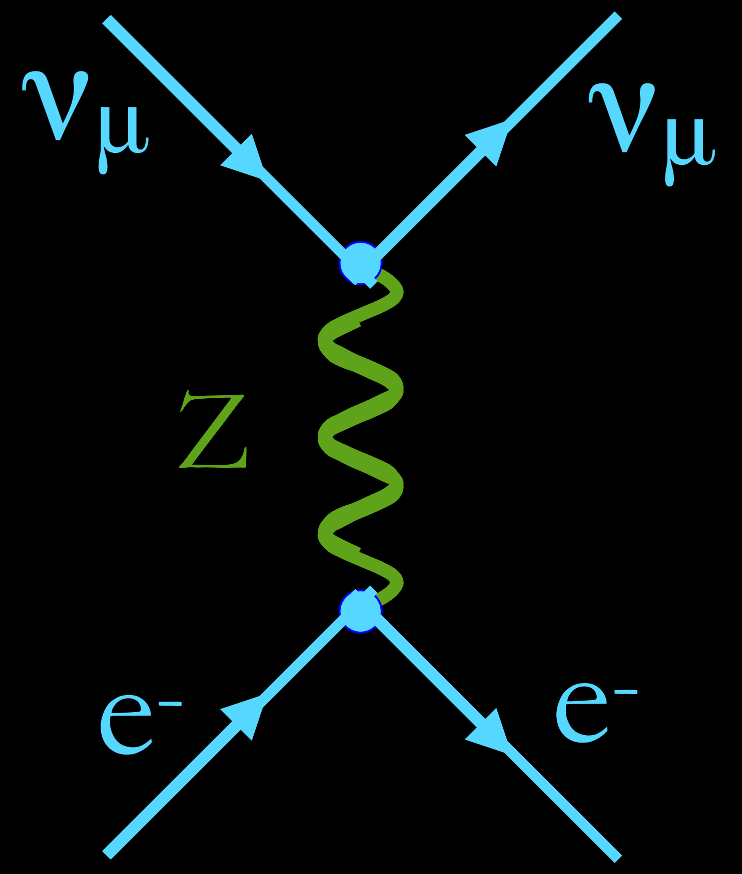
f = any fermion

REACTIONS WITH ELECTRONS

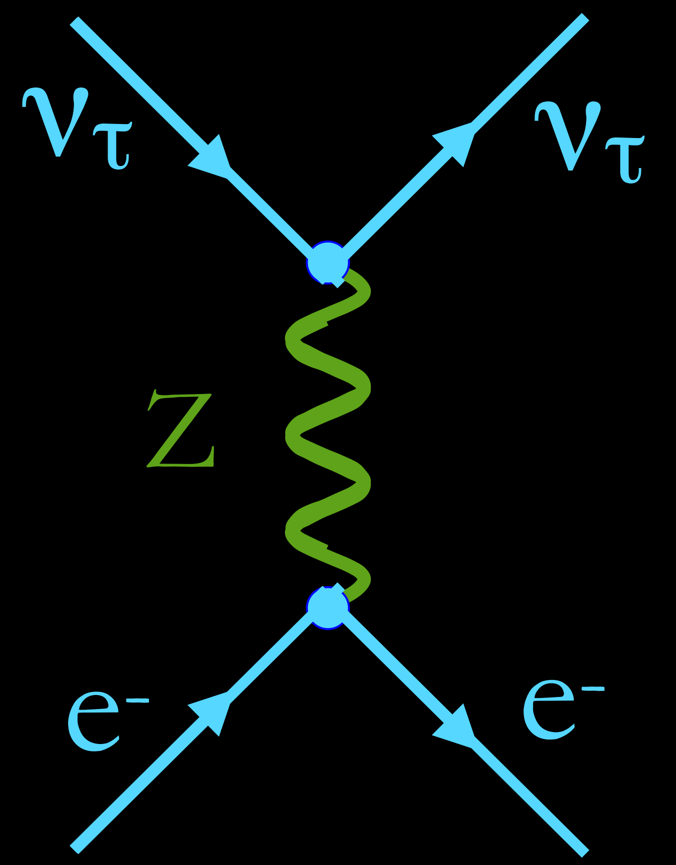
$\nu_e + e^- \rightarrow \nu_e + e^-$



$\nu_\mu + e^- \rightarrow \nu_\mu + e^-$



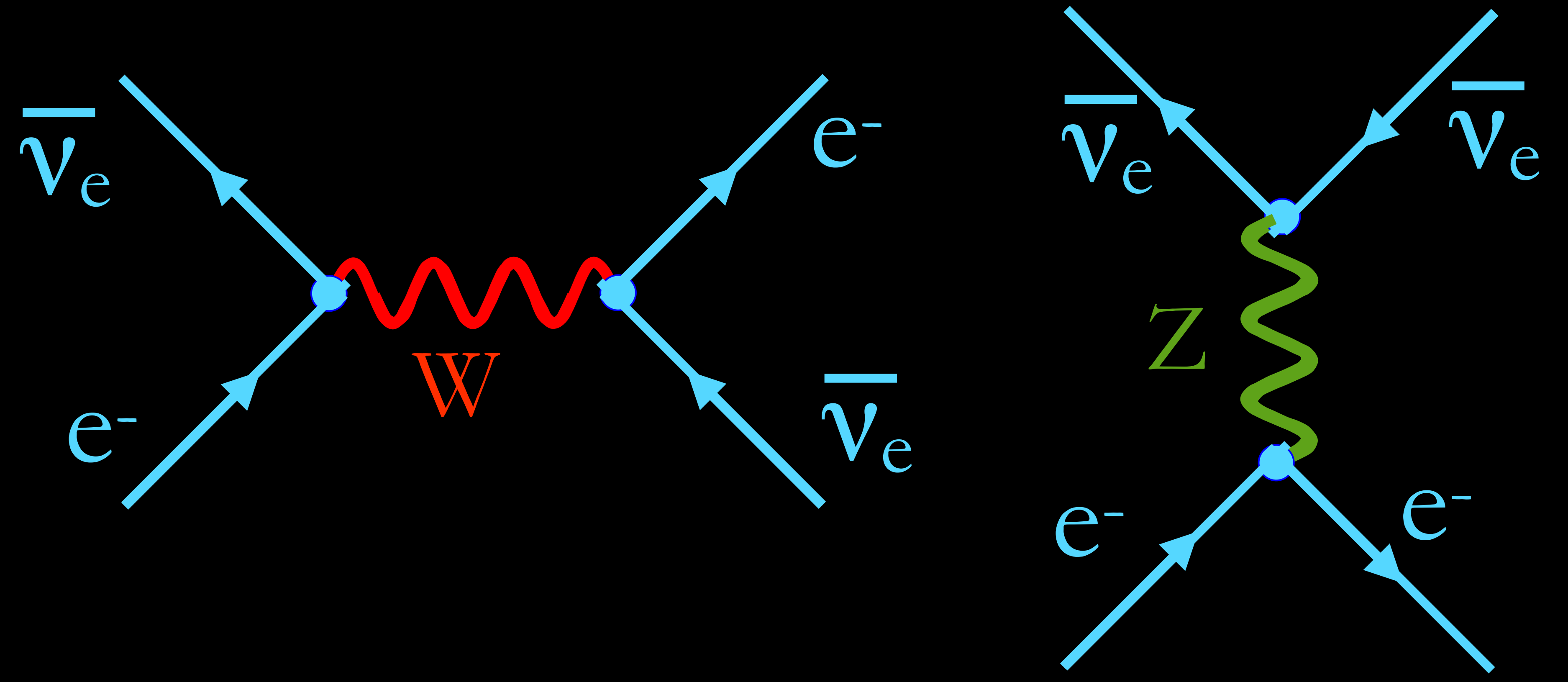
$\nu_\tau + e^- \rightarrow \nu_\tau + e^-$



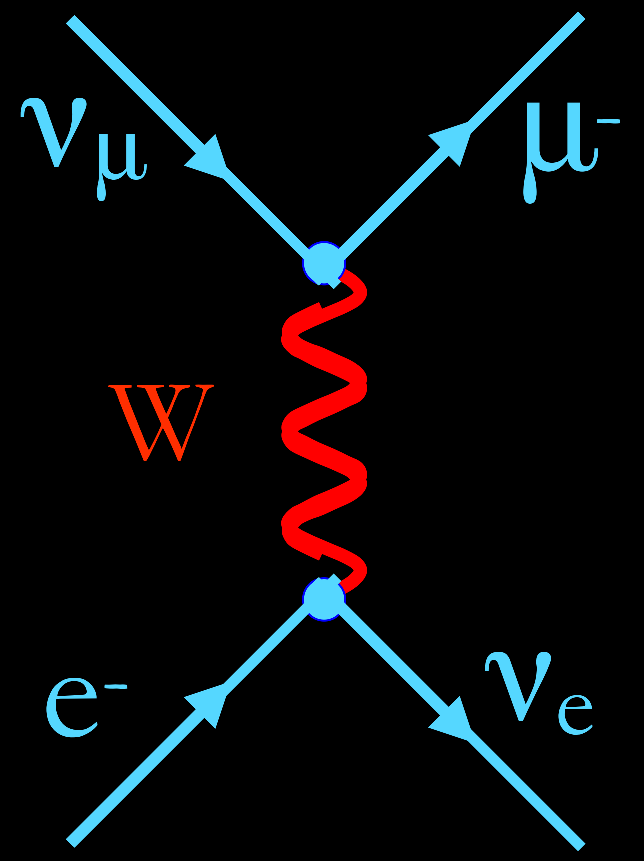
+ similar for $\bar{\nu}_\mu$ $\bar{\nu}_\tau$

Elastic

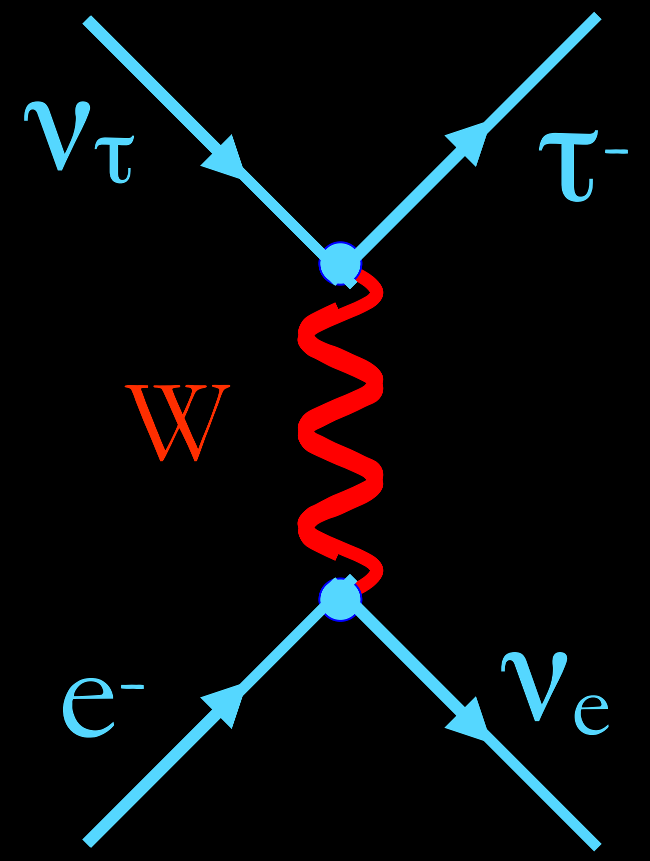
$\bar{\nu}_e + e^- \rightarrow \bar{\nu}_e + e^-$



$\nu_\mu + e^- \rightarrow \nu_e + \mu^-$



$\nu_\tau + e^- \rightarrow \nu_e + \tau^-$

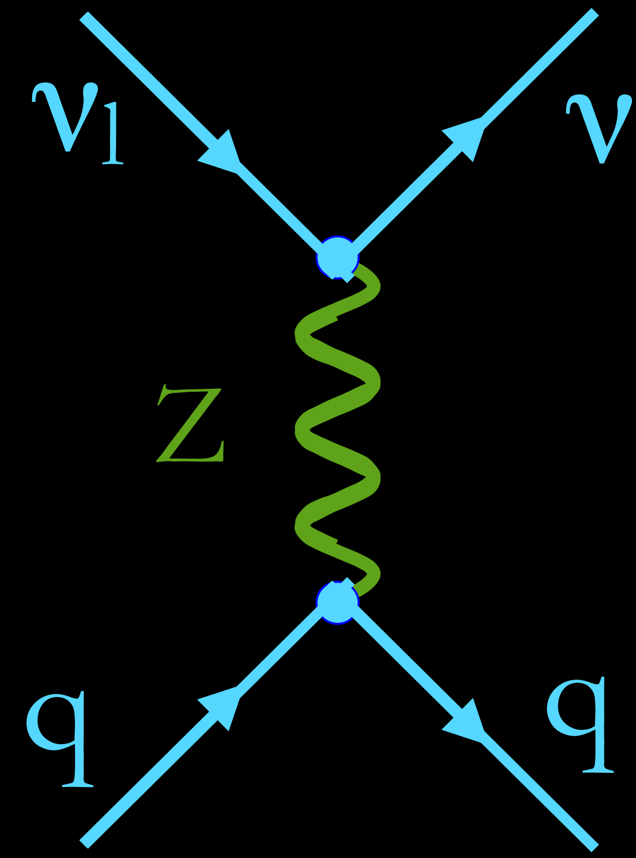


Quasi-elastic

+ similar for $\bar{\nu}_\mu$ $\bar{\nu}_\tau$

REACTIONS WITH QUARKS

$$\nu_l + q \rightarrow \nu_l + q$$



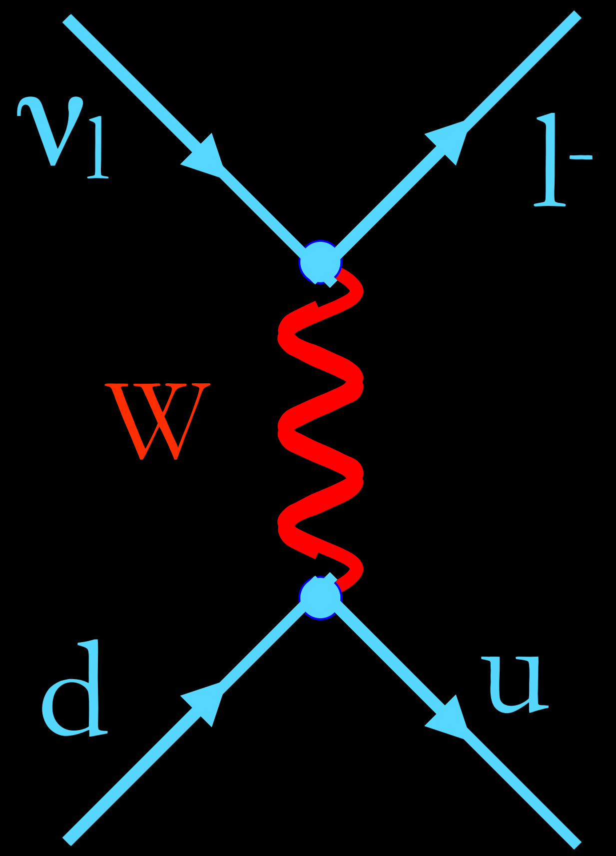
q=any quark

+ similar
for
$\bar{\nu}_e$ $\bar{\nu}_\mu$ $\bar{\nu}_\tau$
$\bar{q}$

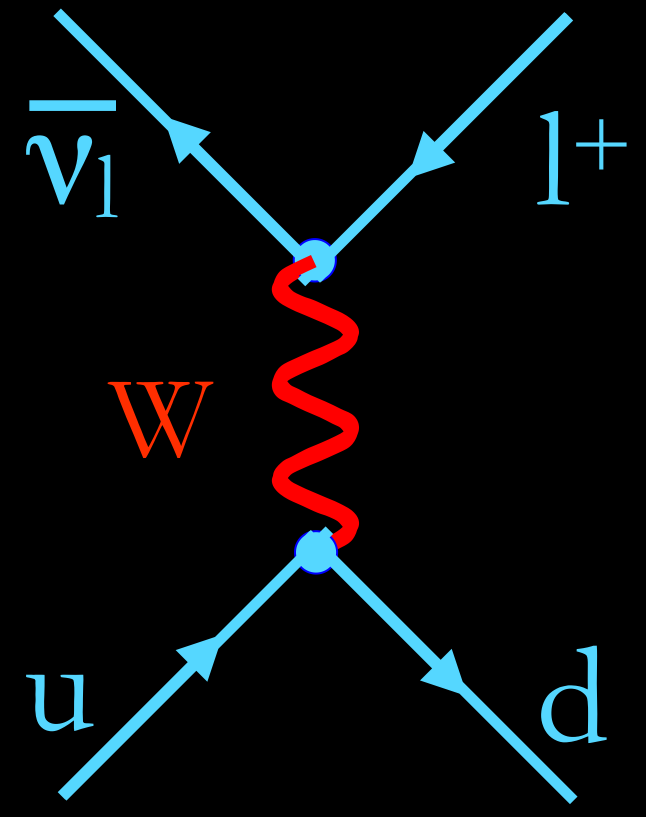
Elastic*

Quasi-elastic*

$$\nu_l + d \rightarrow u + l^-$$



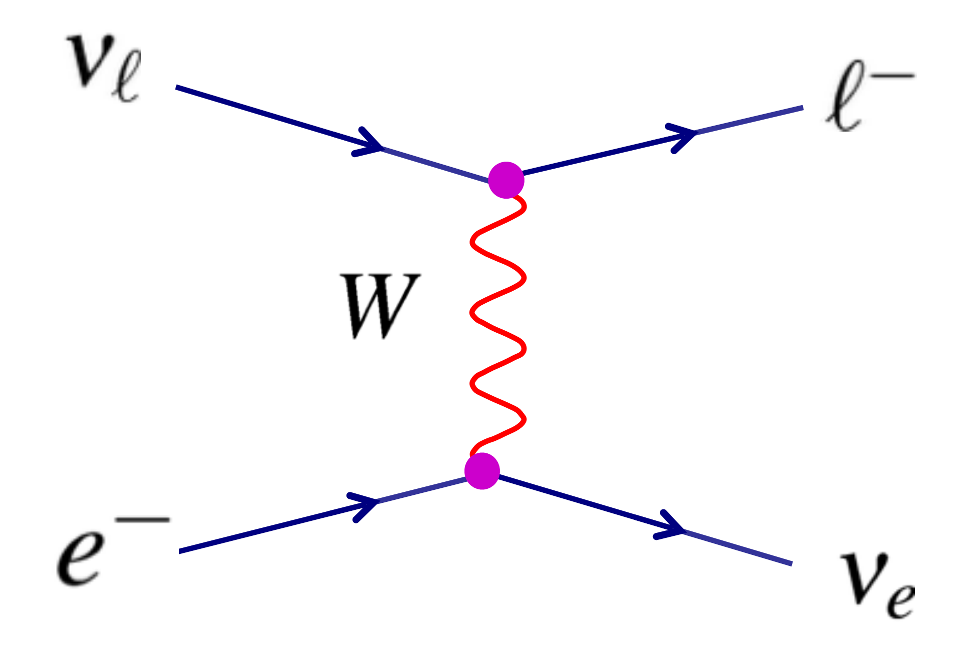
$$\bar{\nu}_l + u \rightarrow d + l^+$$



l=e, μ, τ
+ similar
for other
quarks

*Elastic or quasi-elastic:
only if the nucleon stays intact

INTERACTION THRESHOLDS

- Neutrinos from the Sun ~ 1-10 MeV, from cosmic rays ~1 GeV
- If the neutrino energy is low, some interactions may be kinematically forbidden
- For interactions to occur, there must be enough energy in the center-of-mass to produce the final state particles
- 

$$p_\nu = (E_\nu, 0, 0, E_\nu)$$

$$p_e = (m_e, 0, 0, 0)$$

$$s = (p_\nu + p_e)^2 = (E_\nu + m_e)^2 - E_\nu^2$$

$$s > m_\ell^2$$

Assuming $m_\nu << m_l$

$$\boxed{E_\nu > \left[\left(\frac{m_\ell}{m_e}\right)^2 - 1\right]\frac{m_e}{2}}$$

- Charged current scattering with electrons, thresholds for each flavor

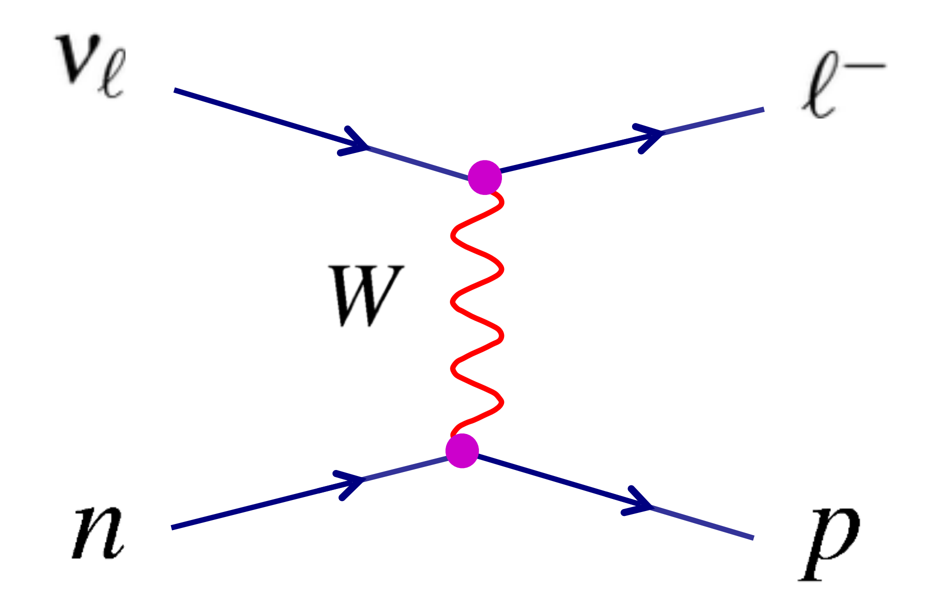
$$E_{\nu_e} > 0 \qquad E_{\nu_\mu} \cancel{>} 11\,\mathrm{GeV} \qquad E_{\nu_\tau} \cancel{>} 3090\,\mathrm{GeV}$$

Only electron solar and atmospheric neutrinos can scatter off electrons via CC

Considering also NC: only elastic scattering with electrons is possible, not quasi-elastic

INTERACTION THRESHOLDS

- Charged Current Scattering off nucleons



$$s = (p_\nu + p_n)^2 = (E_\nu + m_n)^2 - E_\nu^2$$

$$s > (m_\ell + m_p)^2$$

$$E_\nu > \frac{(m_p^2 - m_n^2) + m_\ell^2 + 2m_p m_\ell}{2m_n}$$

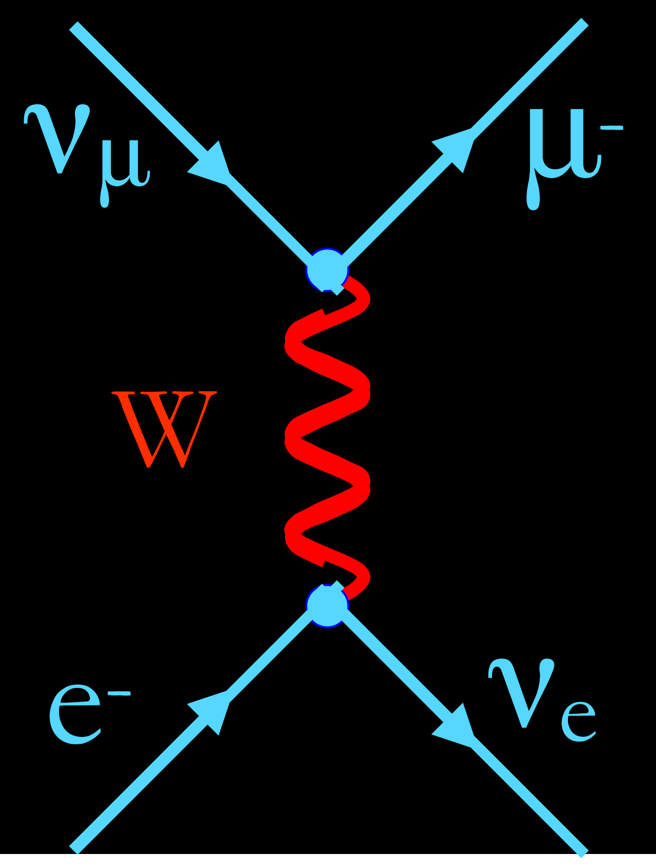
$$E_{\nu_e} > 0 \qquad E_{\nu_\mu} > 110\,\mathrm{MeV} \qquad E_{\nu_\tau} > 3.5\,\mathrm{GeV}$$

- Solar neutrinos (~1-10 MeV) that oscillate to muon or tau can only interact via neutral currents
  - no handle on their flavor
  - elastic scattering cross section is smaller than for ν_e : it seems they “disappear”
- Atmospheric neutrinos of ~ 1 GeV, that oscillate to ν_τ: the same

CROSS SECTIONS

- Simplest reaction, quasi-elastic. Cross section has same form for electrons or nucleon

$$\nu_\mu + e^- \rightarrow \nu_e + \mu^-$$

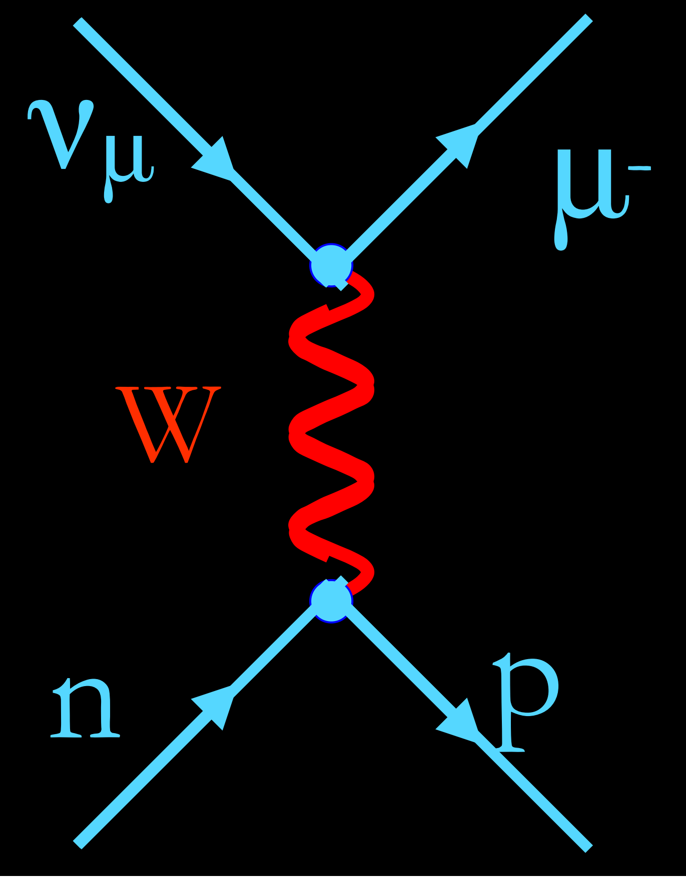


$$\mathcal{M}_{fi} = \frac{g_W^2}{m_W^2}\hat{s},$$

$$\frac{d\sigma_{\nu q}}{d\Omega^*} = \frac{G_F^2}{4\pi^2}\hat{s},$$

$$\boxed{\sigma_{\nu q} = \frac{G_F^2 \hat{s}}{\pi}.}$$

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



$\nu_e + e^- \rightarrow \nu_e + e^-$ has two diagrams, more complex

$$s = (E_\nu + m_e)^2 - E_\nu^2 \approx 2m_e E_\nu$$

$$s = (E_\nu + m_n)^2 - E_\nu^2 \approx 2m_n E_\nu$$

s = center-of-mass energy

But m_n ~2000x larger than m_e!
Cross section much larger for nuclei just due to the heavier target particle

ANTINU CROSS SECTION

neutrino antineutrino

$$\mathcal{M}_{fi} = \frac{g_W^2}{m_W^2}\hat{s},$$

$$\mathcal{M}_{\overline{\nu}q} = \tfrac{1}{2}(1+\cos\theta^*)\frac{g_W^2}{m_W^2}\hat{s},$$

$$\frac{d\sigma_{\nu q}}{d\Omega^*} = \frac{G_F^2}{4\pi^2}\hat{s},$$

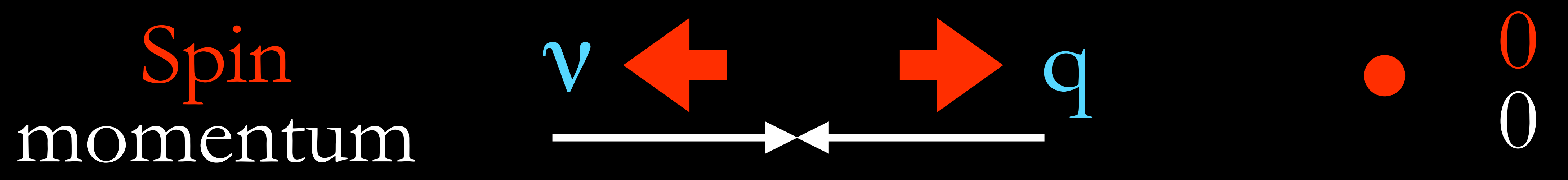
$$\frac{d\sigma_{\overline{\nu}q}}{d\Omega^*} = \tfrac{1}{4}(1+\cos\theta^*)^2\frac{d\sigma_{\nu q}}{d\Omega^*}$$

$$\sigma_{\nu q} = \frac{G_F^2\hat{s}}{\pi}.$$

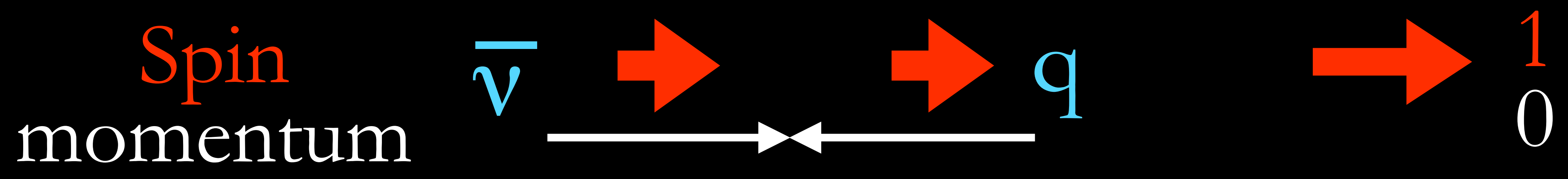
$$\sigma_{\overline{\nu}q} = \frac{G_F^2\hat{s}}{3\pi},$$

$$\frac{\sigma_{\overline{\nu}q}}{\sigma_{\nu q}} = \frac{1}{3}.$$

- Why the matrix element is different?
  - a consequence of the vertex chirality
  - neutrino has to be L. From projection rules*, quark also needs to be L.
  - So their spins are opposed and the interacting states have Sz = 0. null spin, so no preferred direction



  - antinu has to be R. quark continues to have to be L, so the spins are actually aligned. The Mfi will depend on the scattering angle.

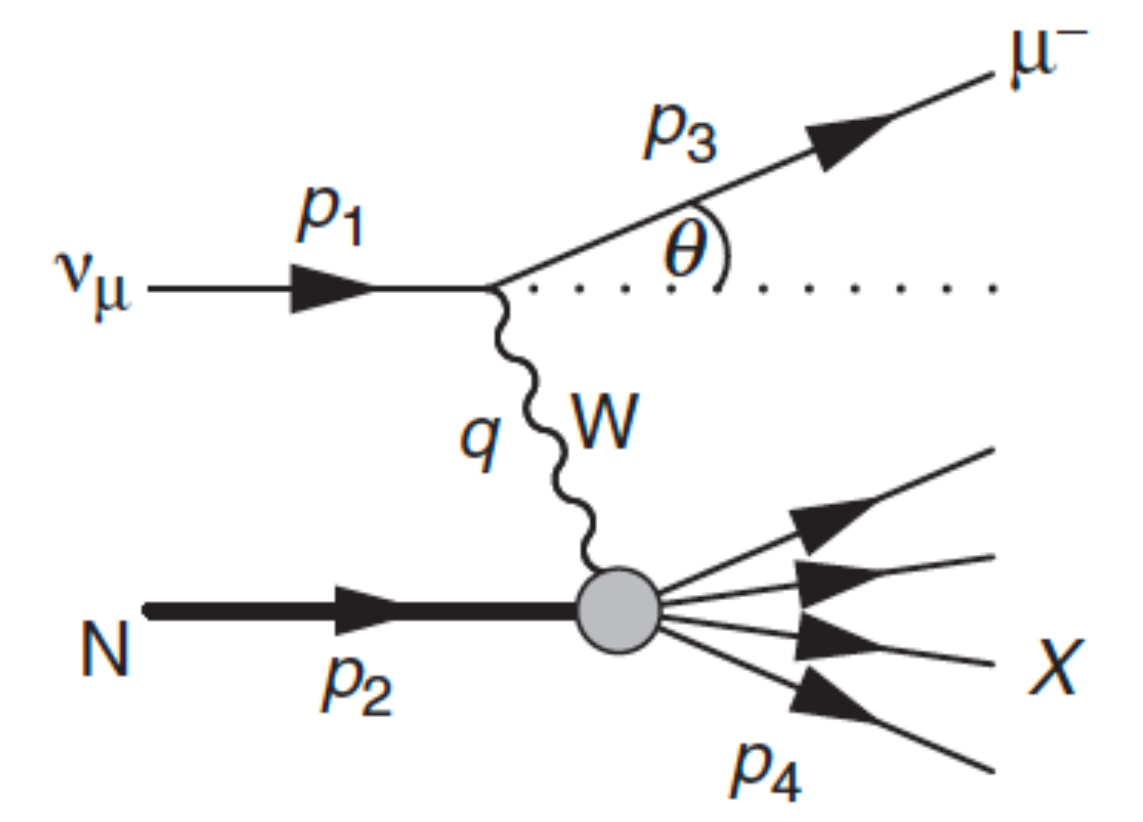


* $\overline{u}_L\gamma^\mu u_R = \overline{u}_R\gamma^\mu u_L = \overline{v}_L\gamma^\mu v_R = \overline{v}_R\gamma^\mu v_L = \overline{v}_L\gamma^\mu u_L = \overline{v}_R\gamma^\mu u_R \equiv 0$

DEEP INELASTIC SCATTERING

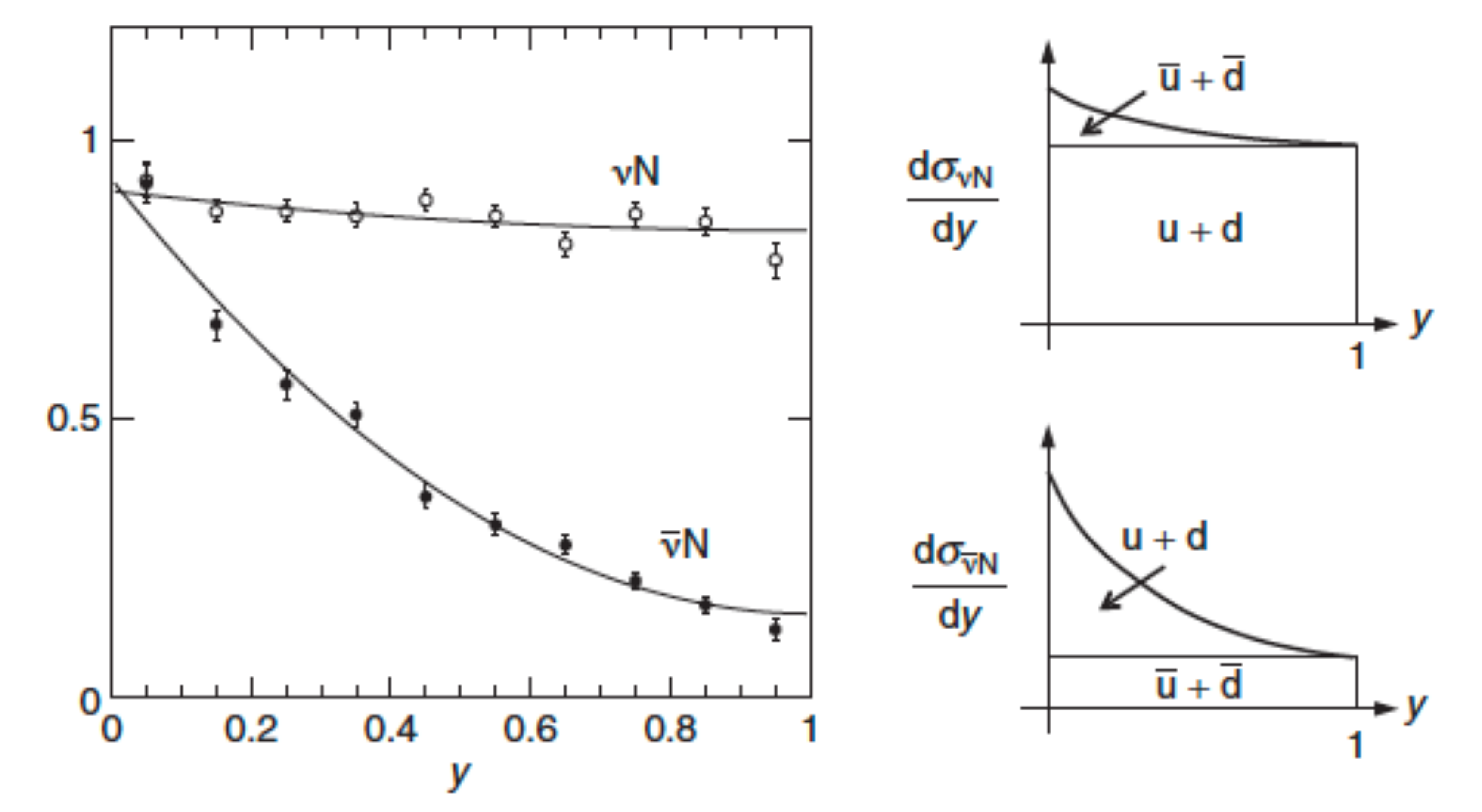
- Cross sections as a function of Lorentz-invariant y

$$y \equiv \frac{p_2 \cdot q}{p_2 \cdot p_1}.$$

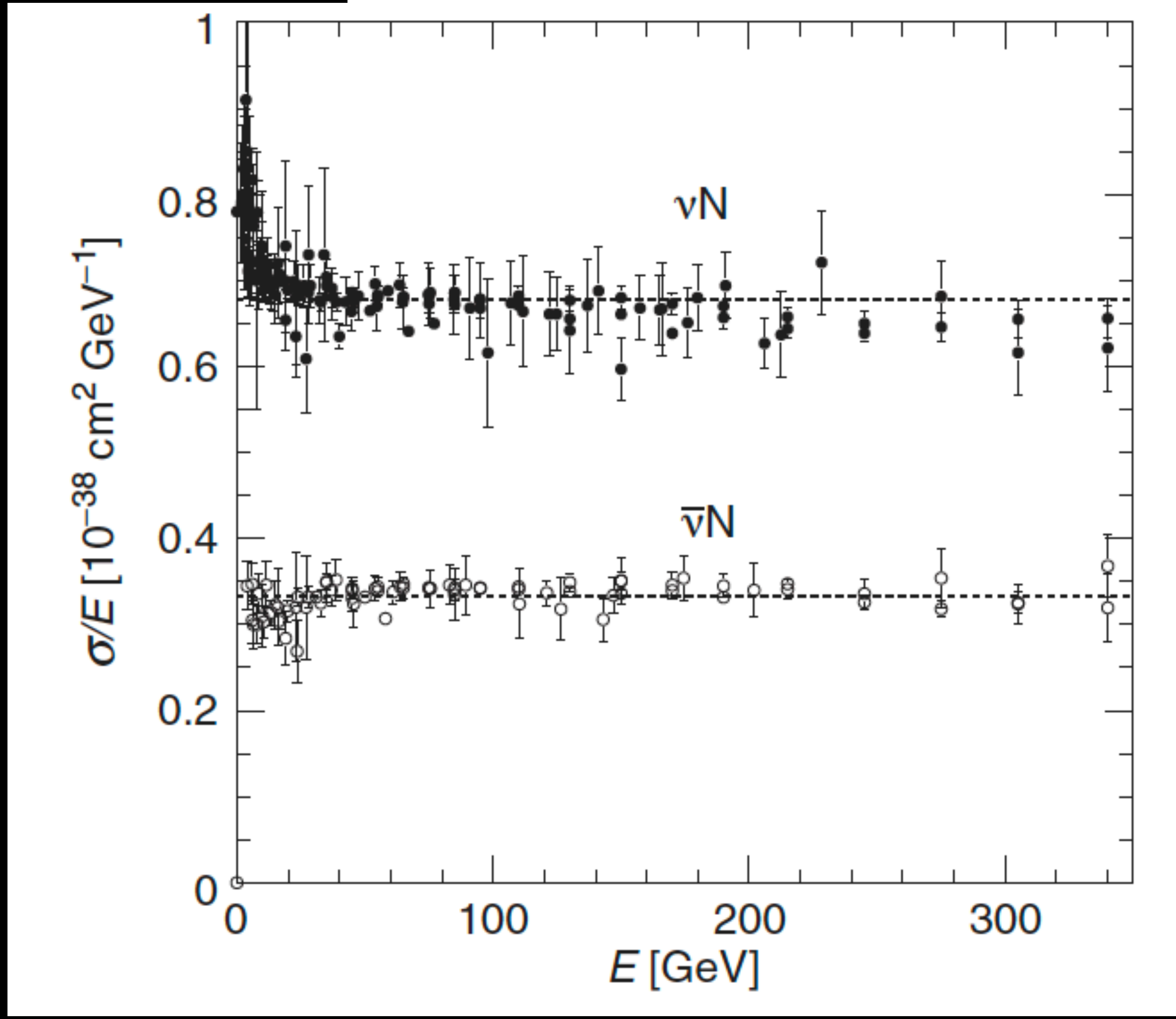


$$\frac{d\sigma_{\nu q}}{dy} = \frac{d\sigma_{\overline{\nu}\overline{q}}}{dy} = \frac{G_F^2}{\pi}\hat{s}. \qquad \frac{d\sigma_{\overline{\nu}q}}{dy} = \frac{d\sigma_{\nu\overline{q}}}{dy} = \frac{G_F^2}{\pi}(1-y)^2\hat{s}.$$

switched for $\overline{q}$



- y-dependent component larger for nu-bar
- Higher σ for nuN because higher σ for valence quarks



$$\sigma^{\nu N} = \frac{G_F^2 m_N E_\nu}{\pi}\left[f_q + \frac{1}{3}f_{\overline{q}}\right].$$

$$\sigma^{\overline{\nu} N} = \frac{G_F^2 m_N E_{\overline{\nu}}}{\pi}\left[\frac{1}{3}f_q + f_{\overline{q}}\right].$$

where f_q and $f_{\overline{q}}$ are the fractions of the nucleon momentum respectively carried by the quarks and the antiquarks,

$$f_q = \int_0^1 x\,[u(x) + d(x)]\,dx \quad \text{and} \quad f_{\overline{q}} = \int_0^1 x\left[\overline{u}(x) + \overline{d}(x)\right]dx.$$

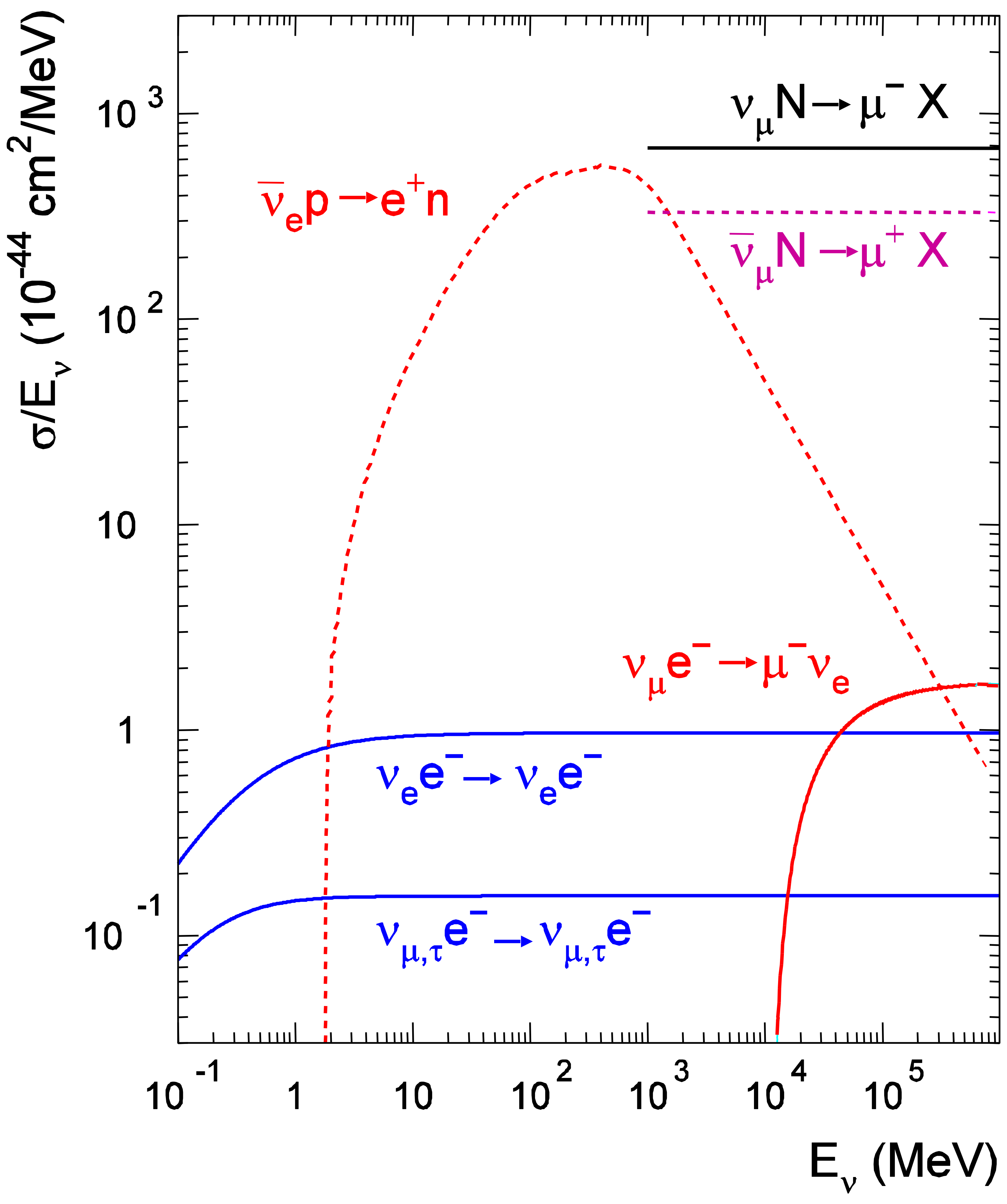
$$\frac{\sigma^{\nu N}}{\sigma^{\overline{\nu} N}} = \frac{3f_q + f_{\overline{q}}}{f_q + 3f_{\overline{q}}}.$$

$$\frac{\sigma^{\nu N}}{\sigma^{\overline{\nu} N}} = 1.984 \pm 0.012.$$

$$f_q \approx 0.41 \quad \text{and} \quad f_{\overline{q}} \approx 0.08.$$

Neutrinos as probes of nucleon structure!

CROSS SECTION SUMMARY



$$\sigma_{\nu_\mu N} = 0.22\frac{2m_pG_F^2E_\nu}{\pi}$$

$$\sigma_{\bar{\nu}_\mu N} = 0.33\frac{2m_pG_F^2E_\nu}{3\pi}$$

Deep Inelastic Scattering

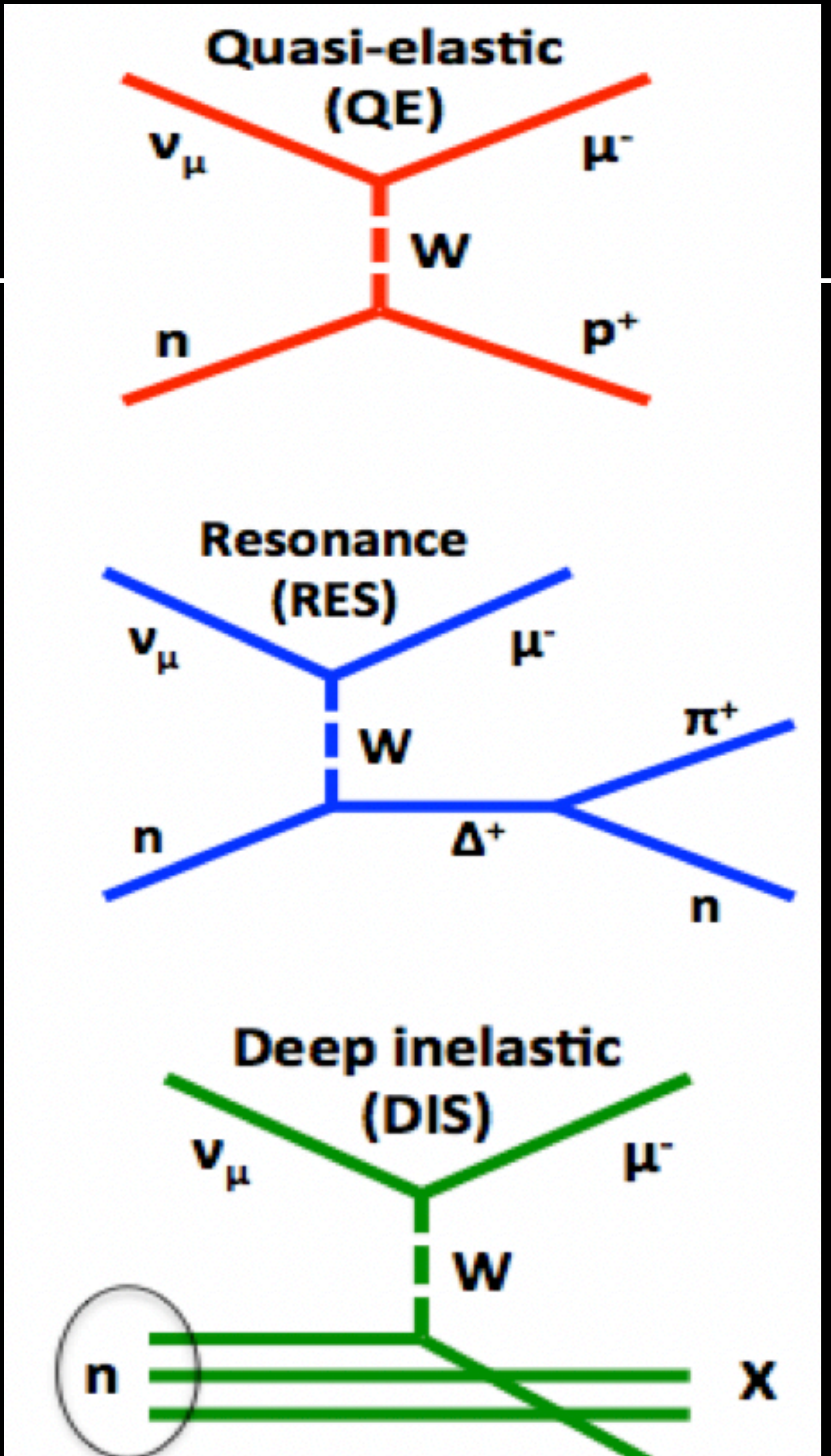
$$\sigma_{\nu_\mu e^-} = \frac{2m_eG_F^2E_\nu}{\pi}$$

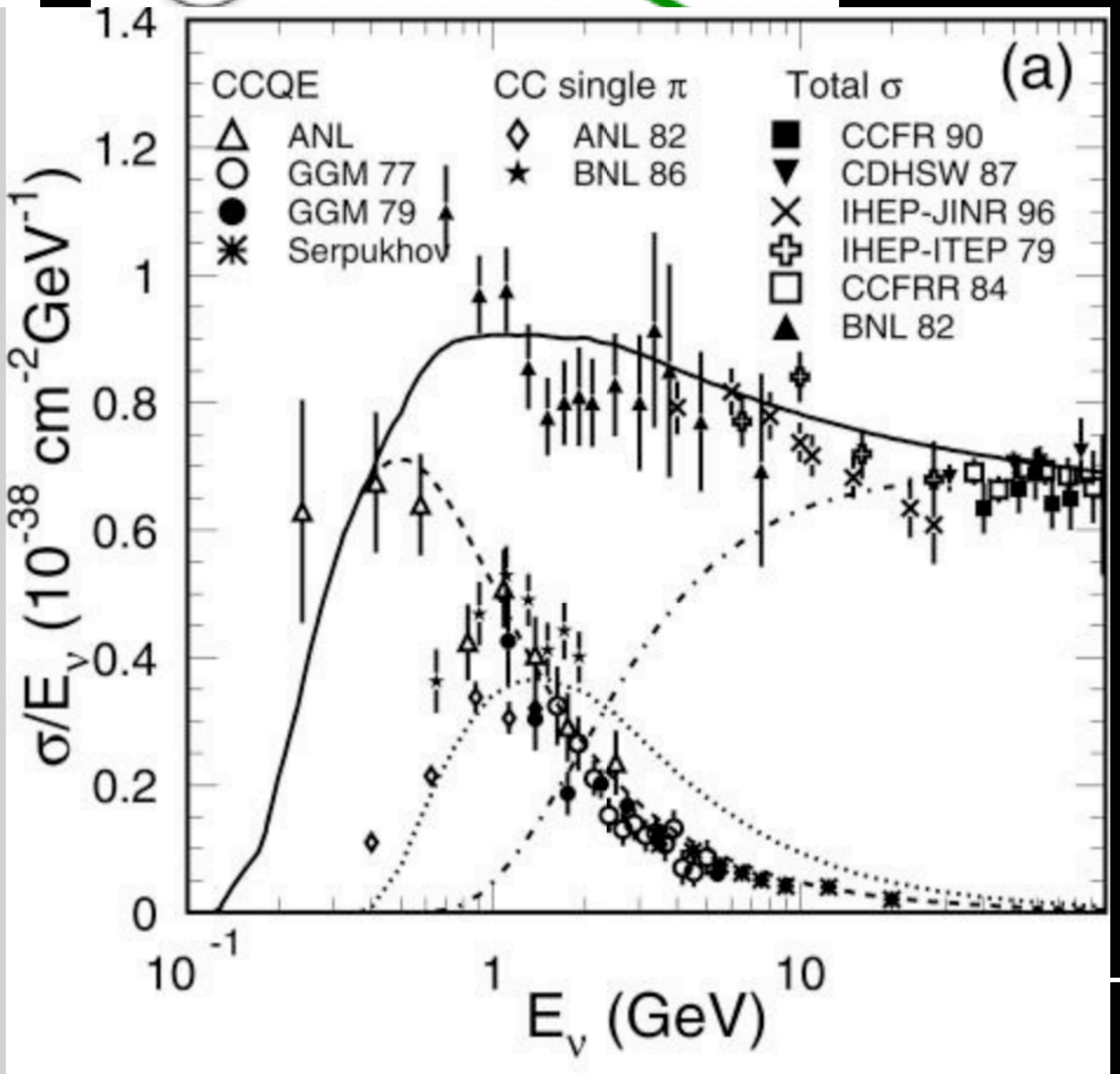
CC only
Threshold 11 GeV

$$\sigma_{\nu_e e^-} \approx 0.6\frac{2m_eG_F^2E_\nu}{\pi}$$

NC + CC

NC only



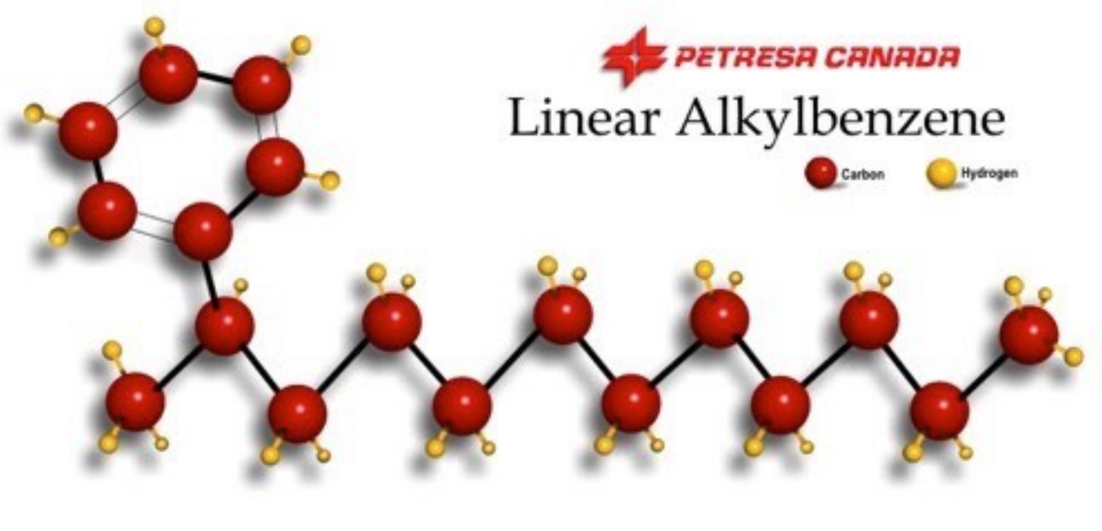


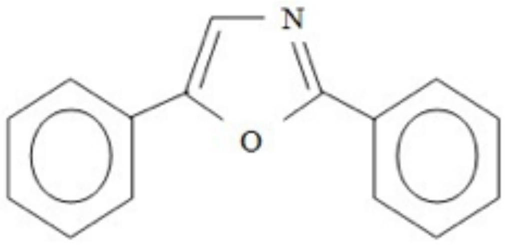
NEUTRINO DETECTORS

HIGH OR LOW ENERGY ?

	TYPICAL SOURCES	ADVANTAGES	DISADVANTAGES
LOW ENERGY	SOLAR REACTOR	HIGH FLUX SIMPLE FINAL STATES WELL-KNOWN CROSS SECCTIONS	RADIOACTIVITY BACKGROUNDS LOWER SIGNAL SMALL EXTENT
HIGH ENERGY	ATMOSPHERIC ACCELERATOR	NO RADIOACTIVITY BACKGROUNDS BETTER PARTICLE ID HIGHER CROSS SECTION	LOW FLUX COMPLEX FINAL STATES UNCERTAINTY IN CROSS SECTIONS

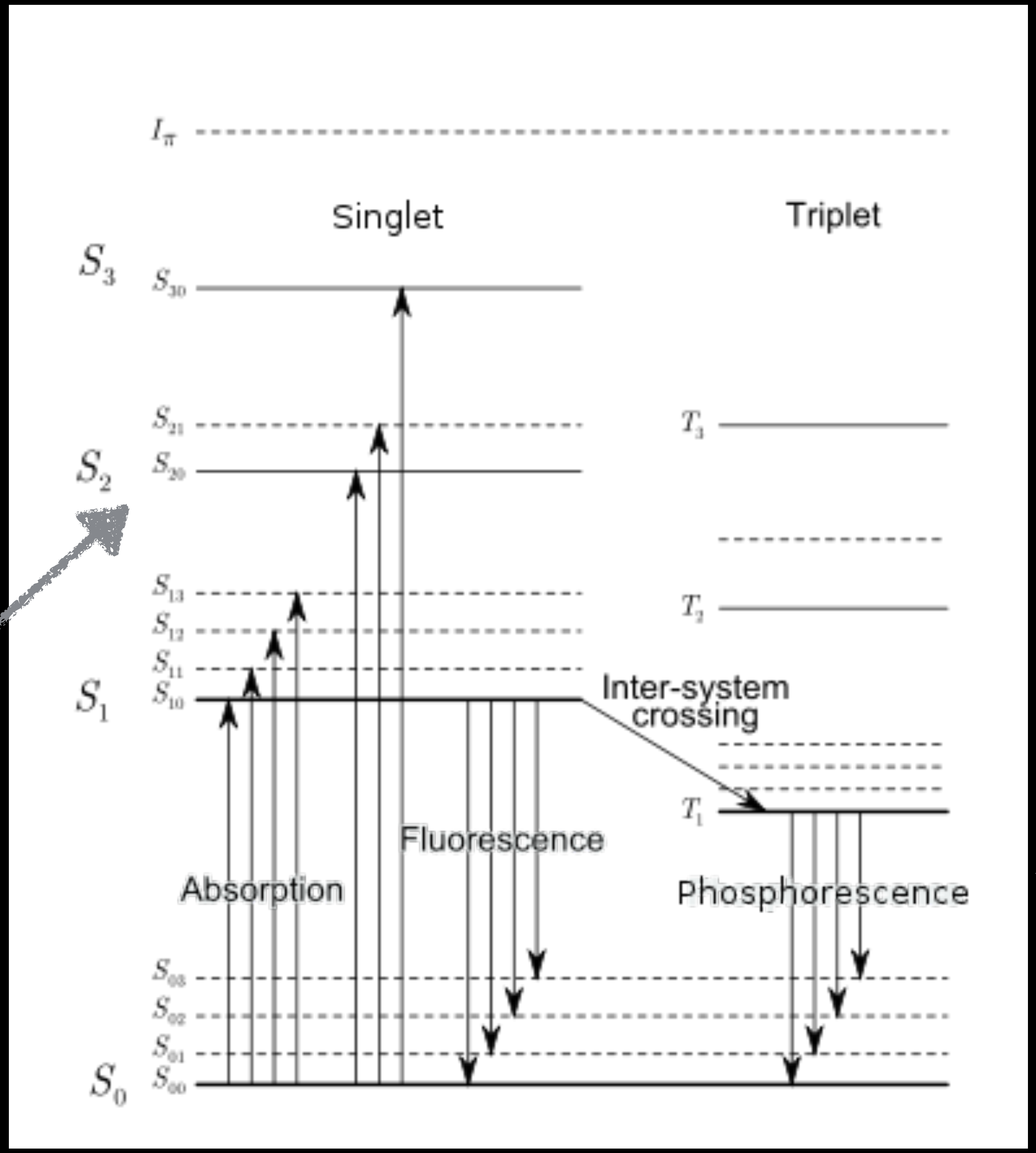
SCINTILLATION DETECTORS



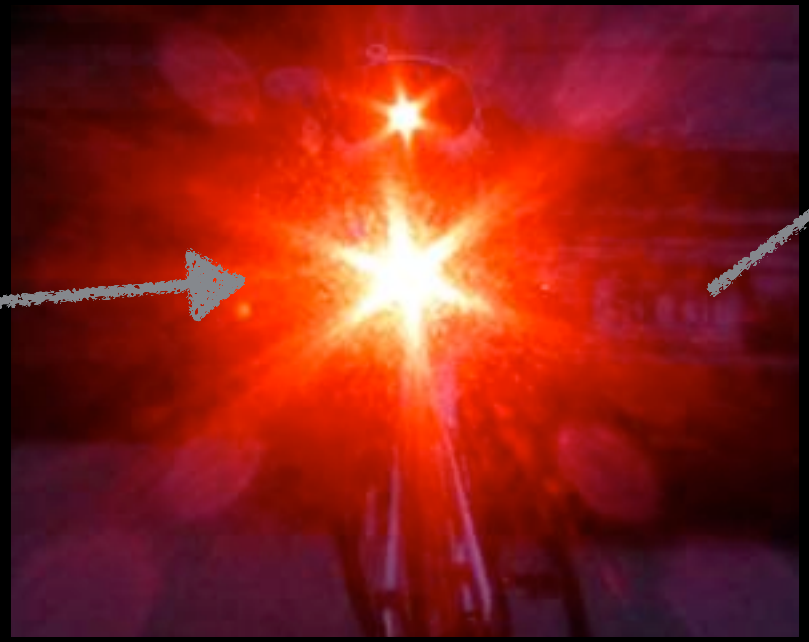


LAB +
2g/l PPO

Charged
particle excites
scintillator
molecules



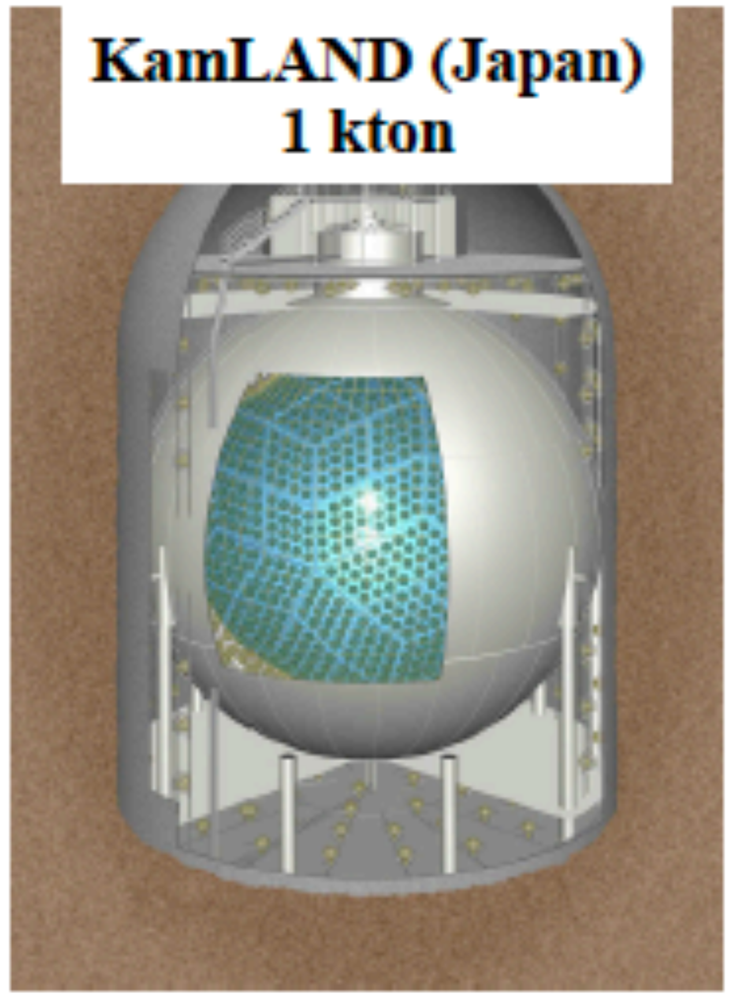
Emission of
fluorescence
light

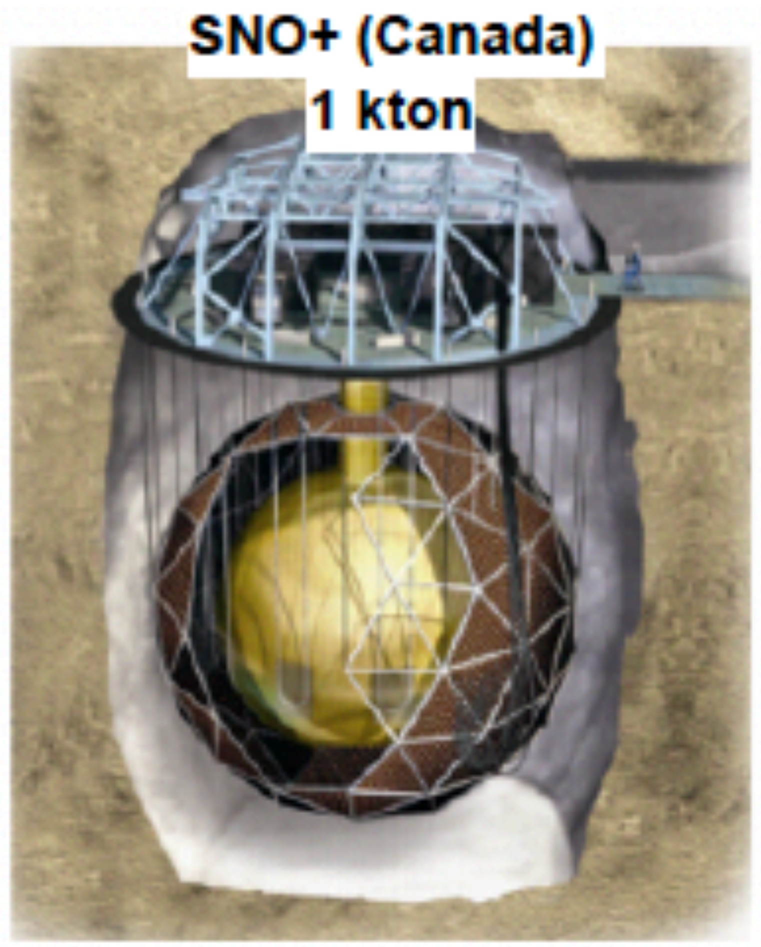


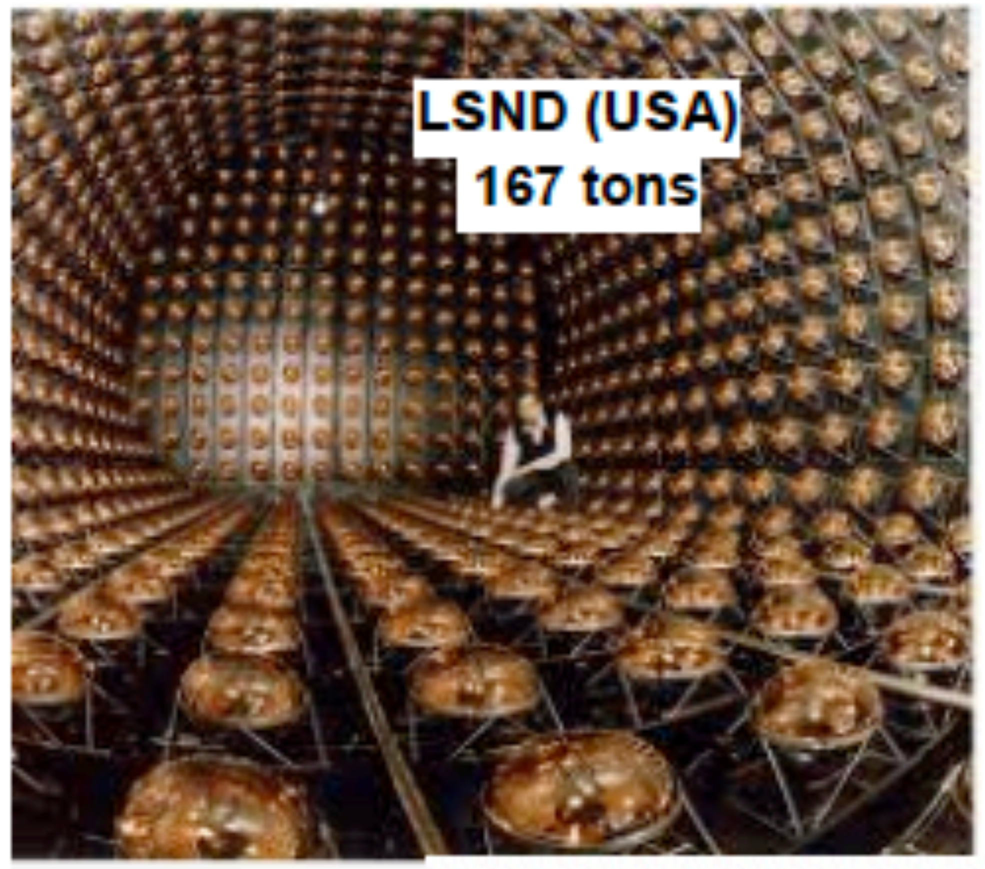
Detected by
photomultiplier

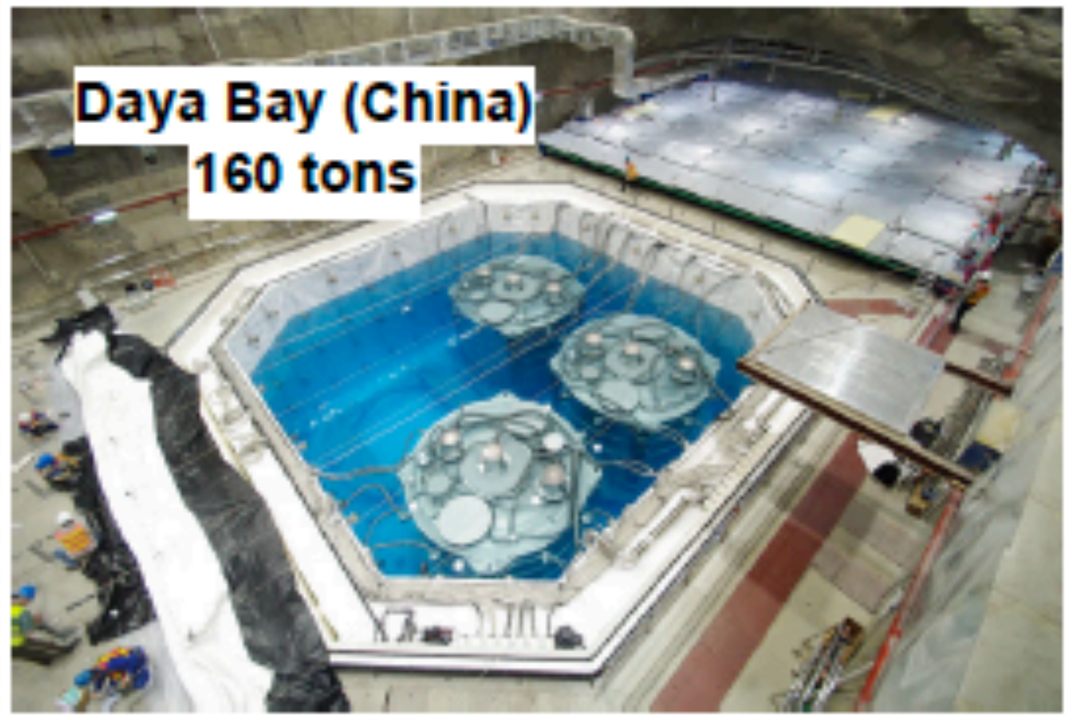
- Liquid scintillators: high light yield (~10k ph./MeV), low radioactivity, fast, good pulse-shape discrimination
- Solid scintillators: easier to build/assemble, good for segmentation, can be denser (shorter radiation length)

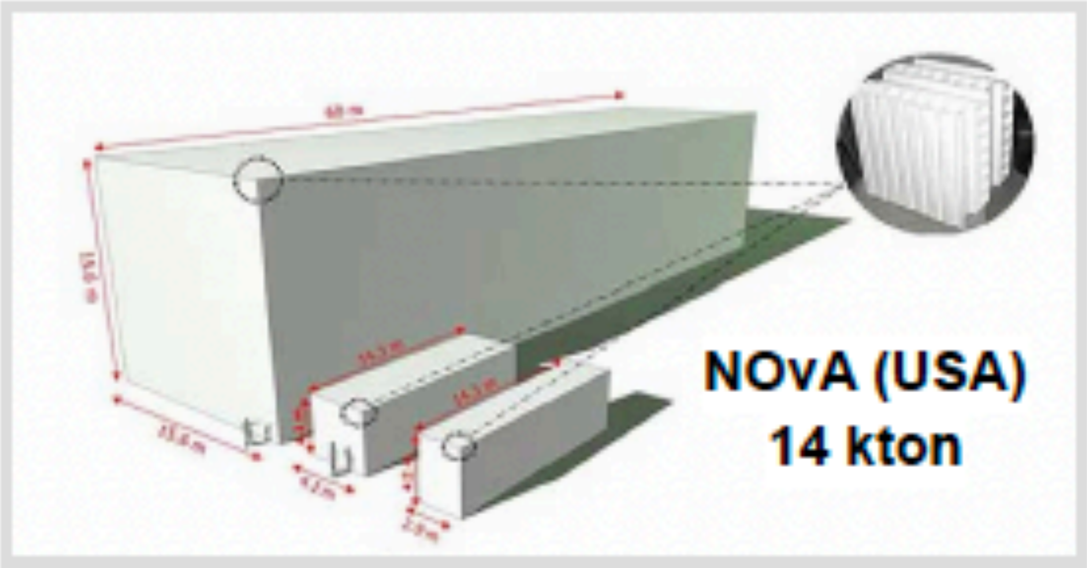
SCINTILLATOR DETECTORS

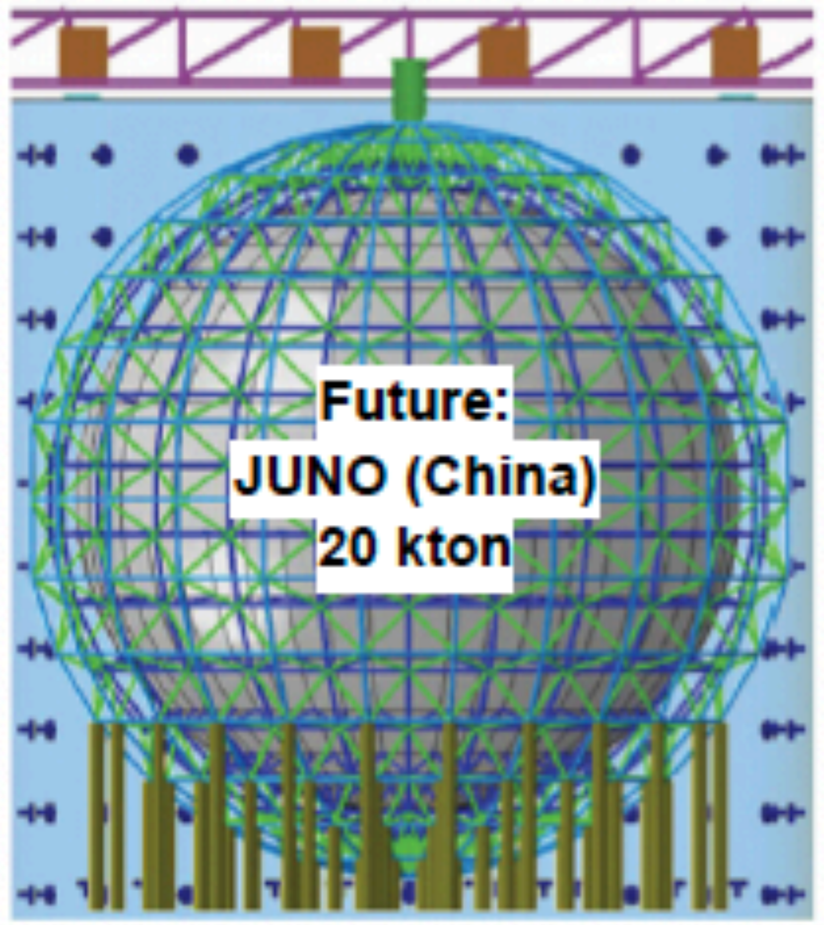

KamLAND (Japan)
1 kton

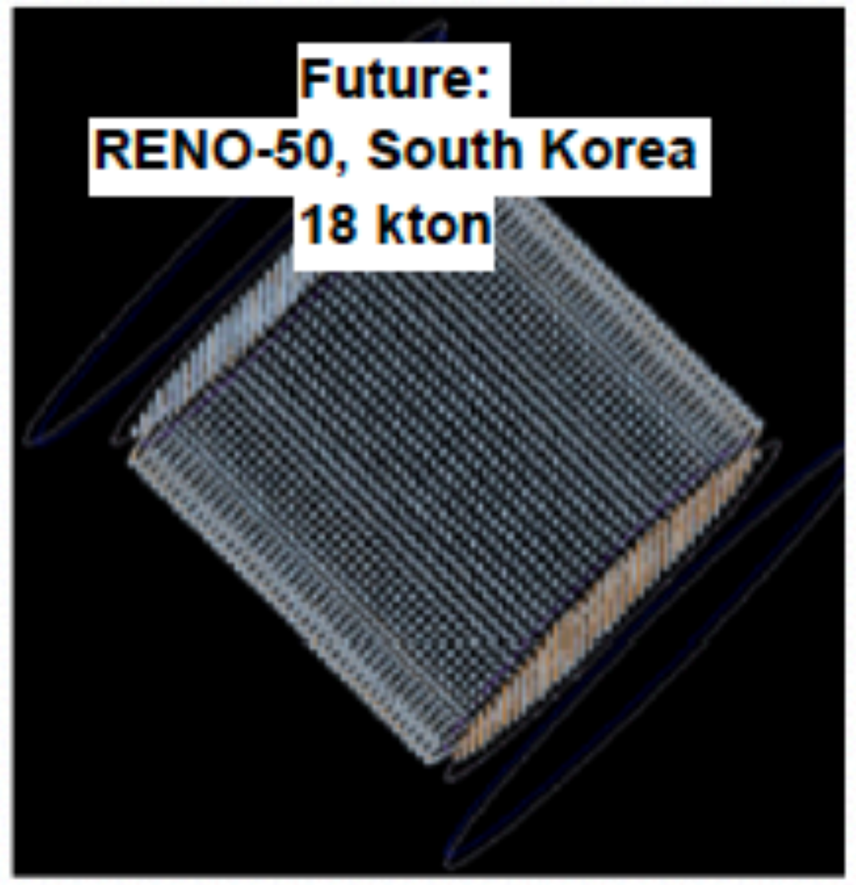

SNO+ (Canada)
1 kton


LSND (USA)
167 tons

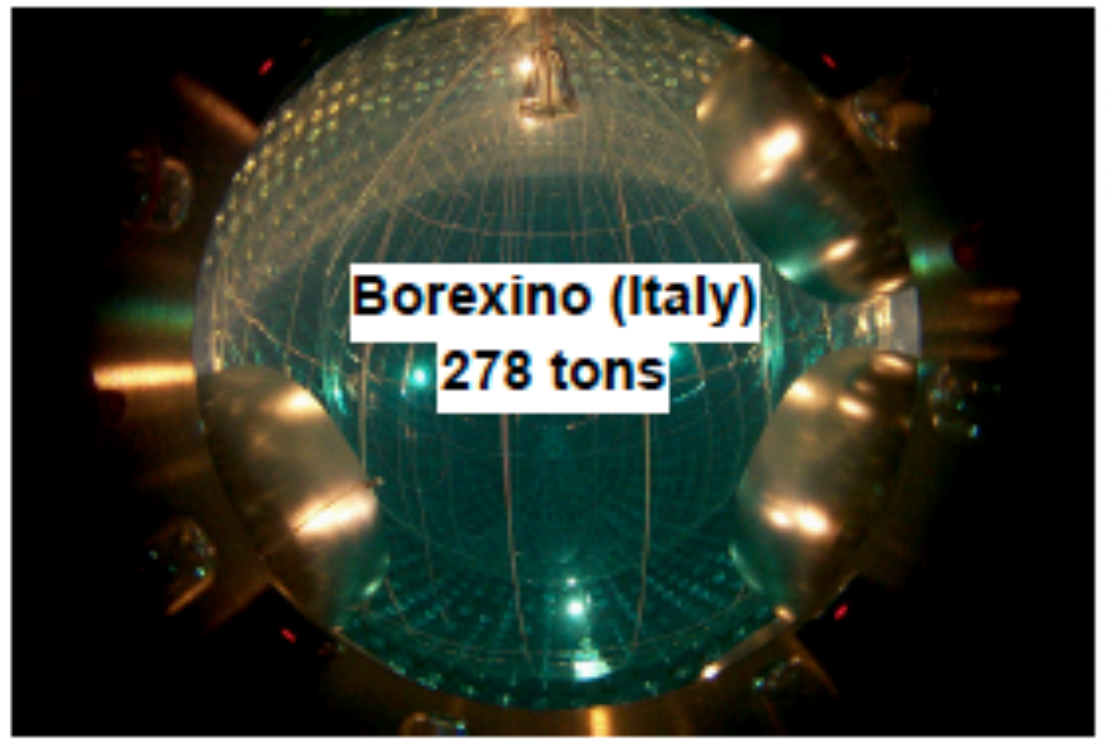

Daya Bay (China)
160 tons


NOvA (USA)
14 kton


Future:
JUNO (China)
20 kton

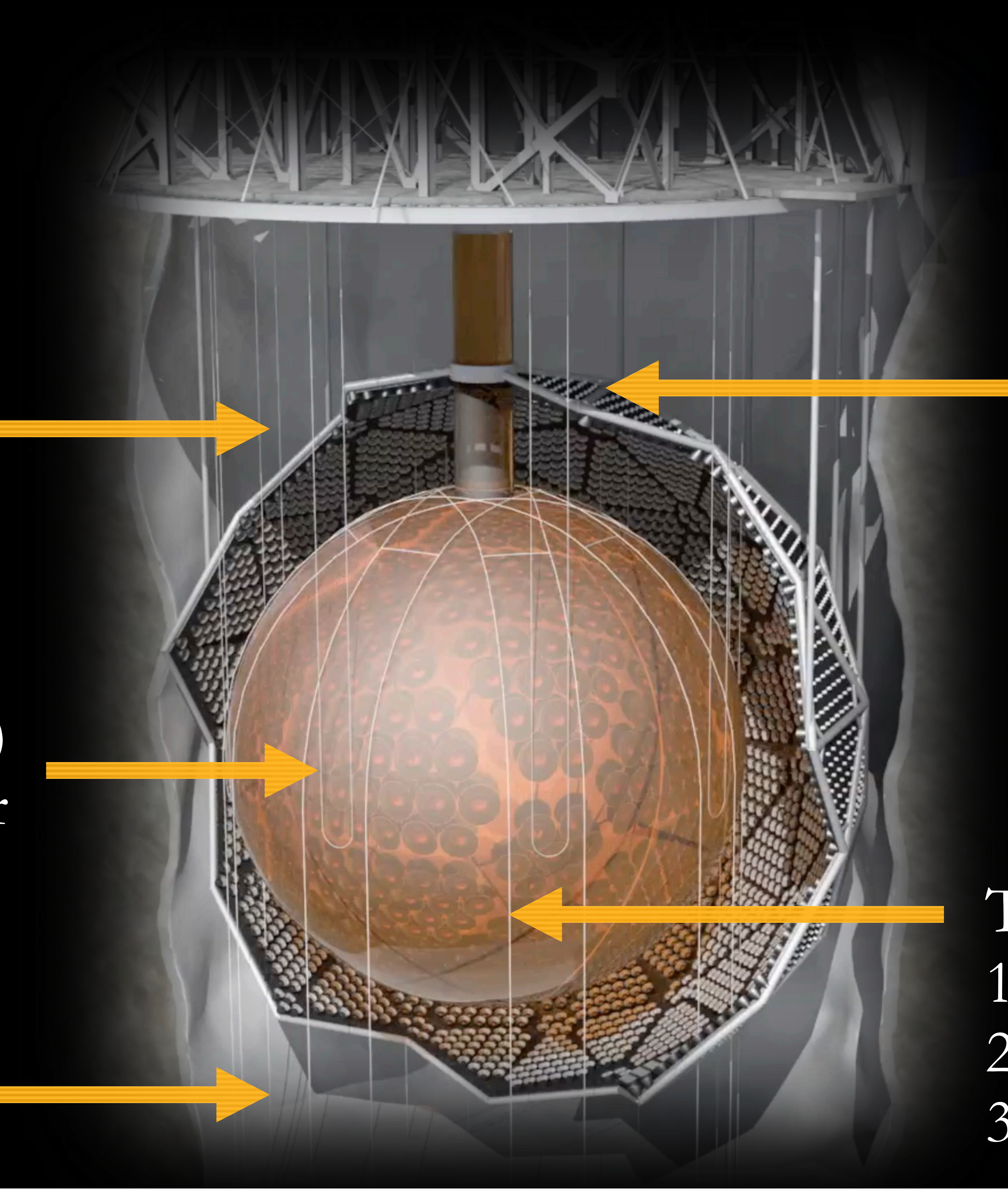

Future:
RENO-50, South Korea
18 kton


Future:
LENA
Finland
50 kton


Borexino (Italy)
278 tons

Plus many (smaller) short baseline detectors at reactors - Poltergeist, Palo Verde, Bugey, Chooz, Double-Chooz, RENO
or beam - MiniBoone

SNO+



2 km underground
~70 muons/day

Rope system
Hold-up and -down
Low Radioactivity

~9300 PMTs

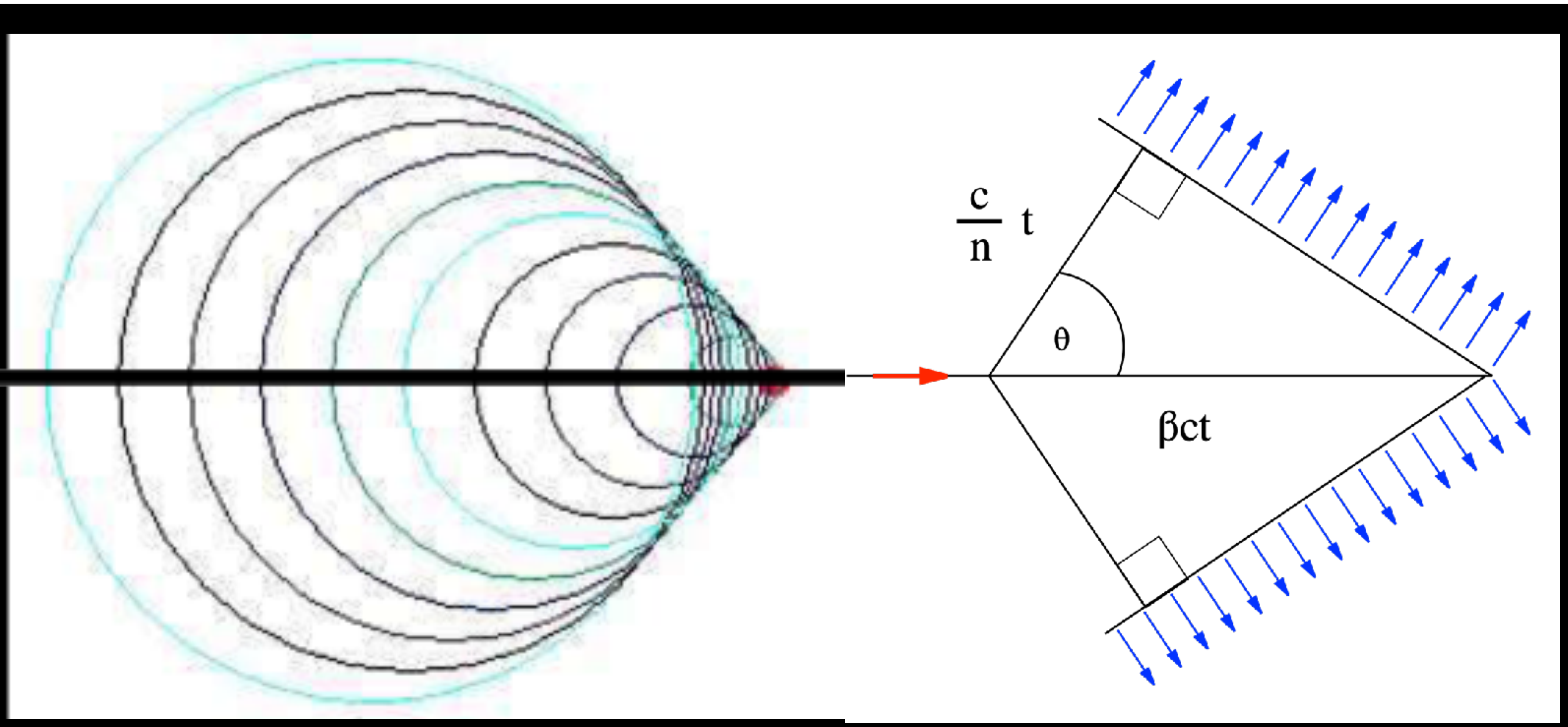
Acrylic Vessel (AV)
12 m diameter

Ultra-Pure
Water

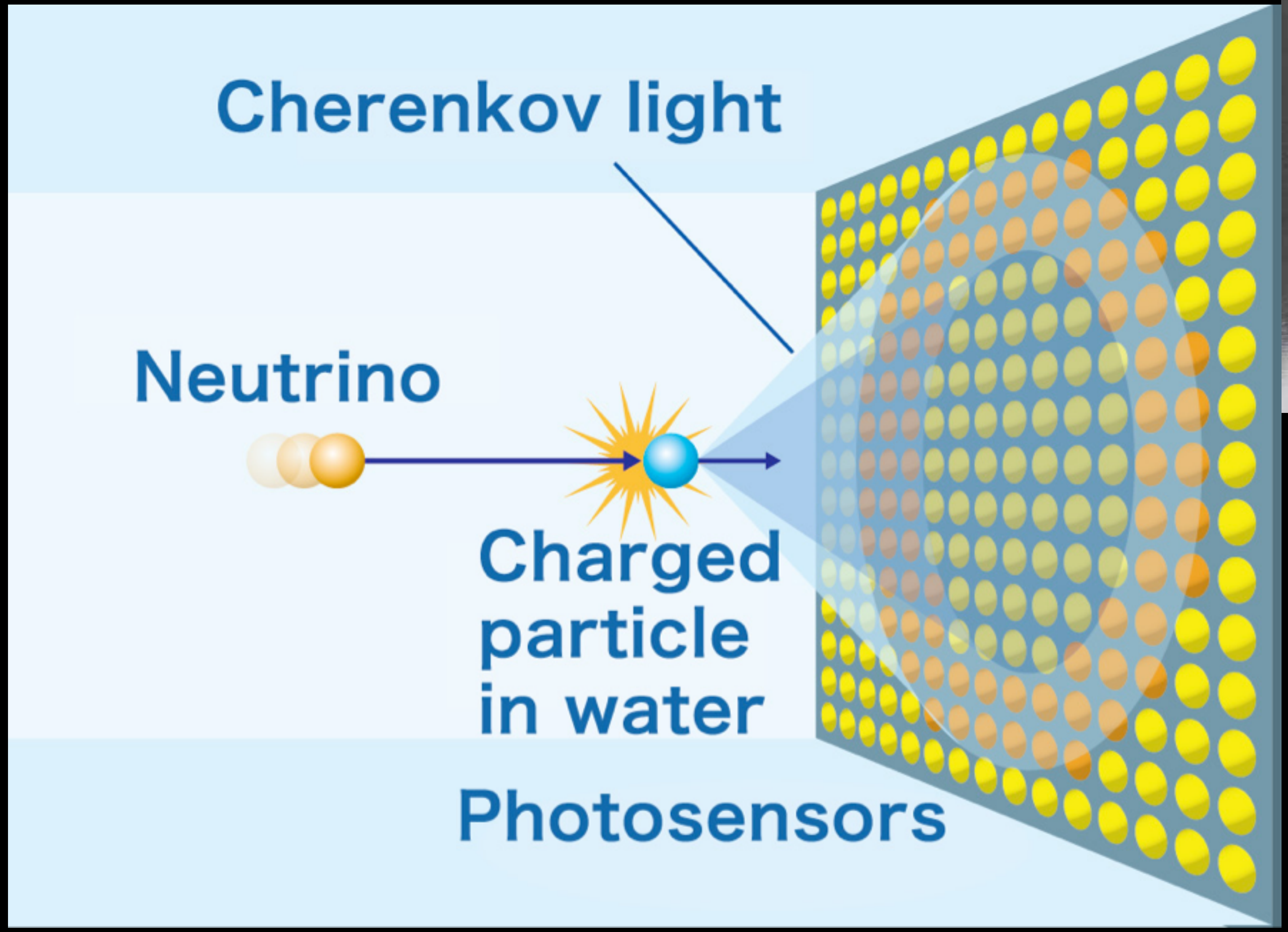
Target Material
1. Water: 905 tonnes
2. LAB Scintillator: 780 tonnes
3. Tellurium loading: +3.9 tonnes

Purification plant

WATER CHERENKOV DETECTORS

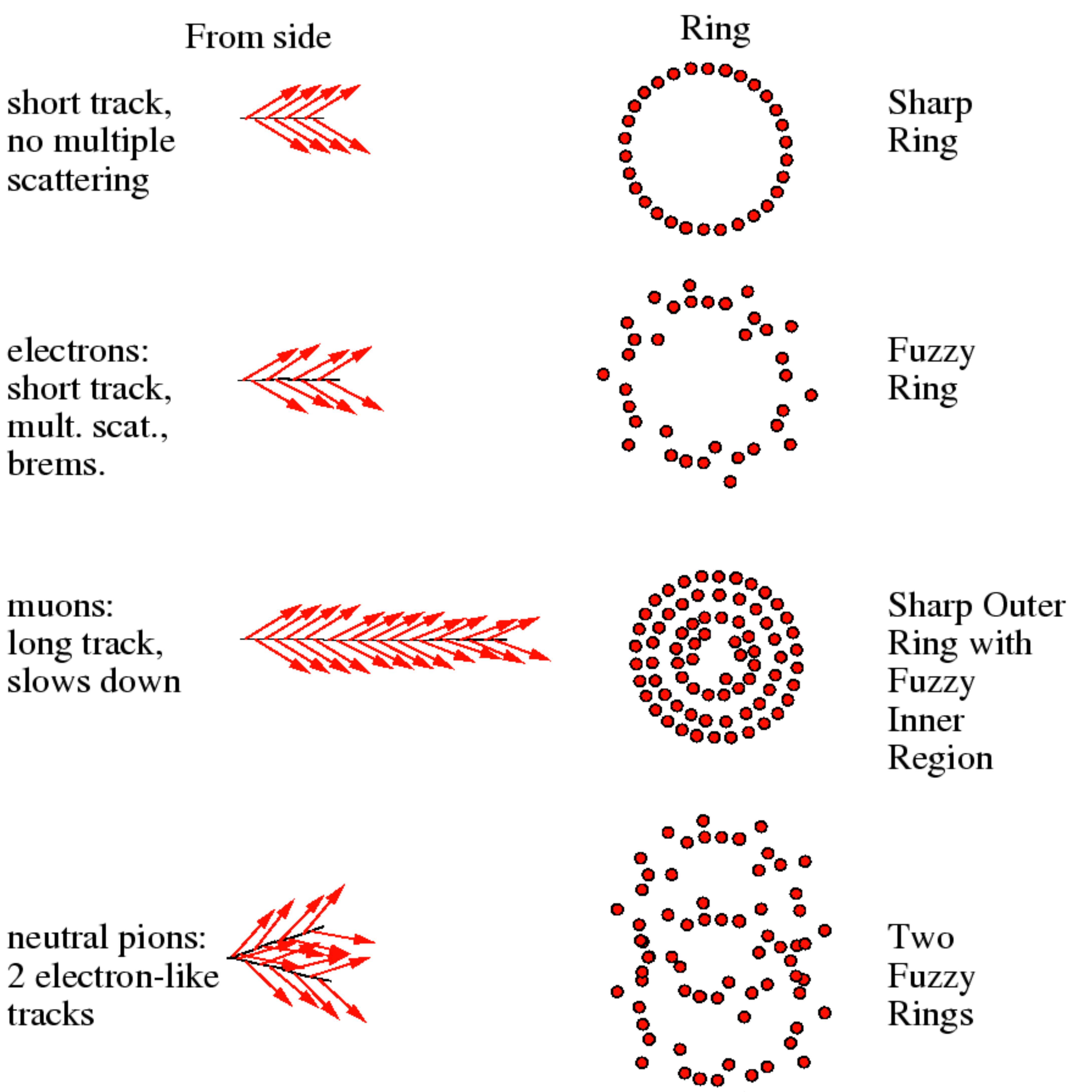


- Cherenkov effect
  - When a particle travels above the speed of light (in a medium with refractive index n, v> c/n), there is constructive interference of wave fronts
  - Emission of light at a fixed angle cos θ =c/nv
  - Similar to waves from boats or sonic boom



- Water Cherenkov detectors
  - Neutrino produces charged particle
  - Cherenkov light forms cone around path
  - PMTs in wall see circle, or ellipse

CHERENKOV PATTERNS



From side

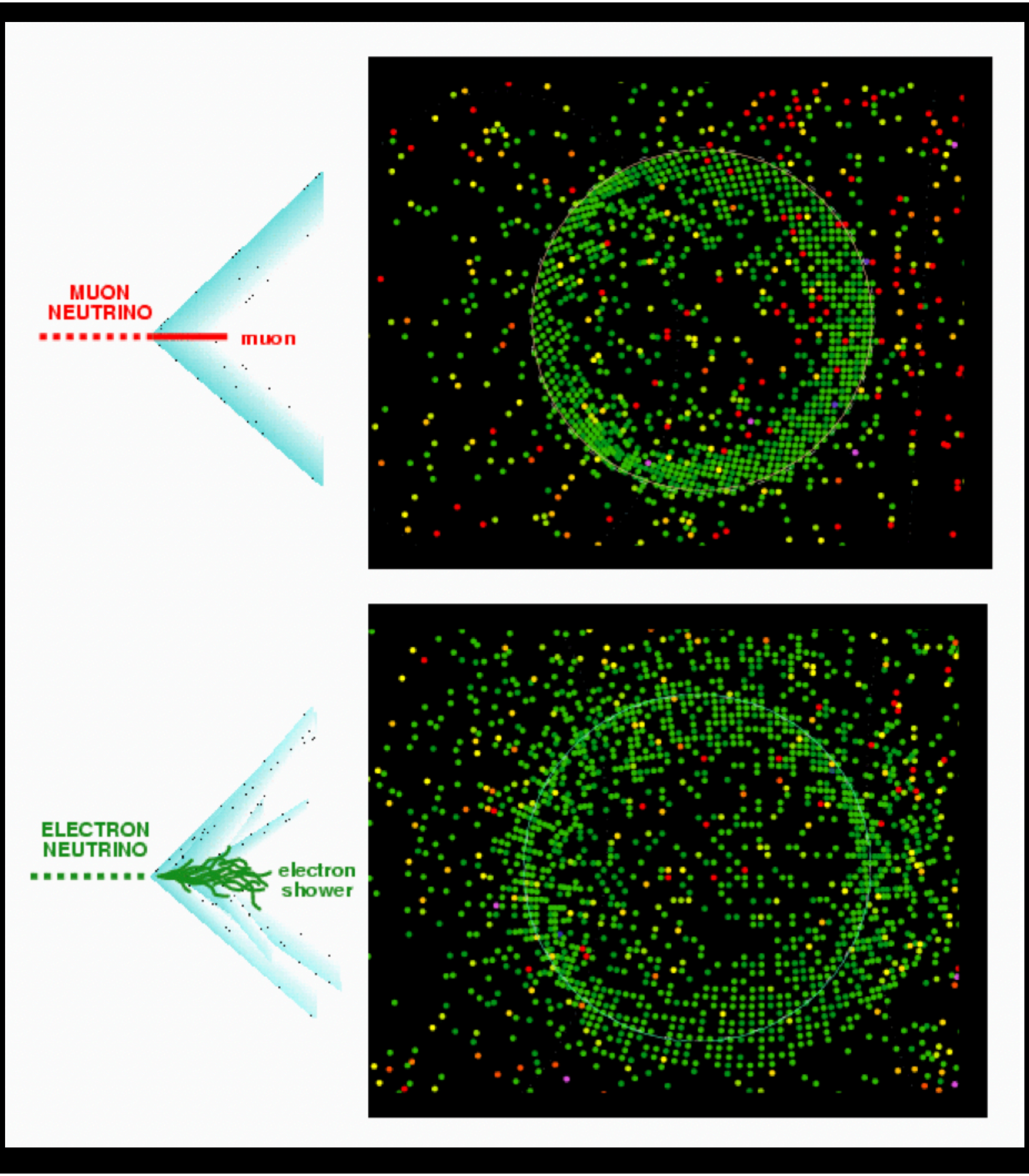
Ring

short track, no multiple scattering — Sharp Ring

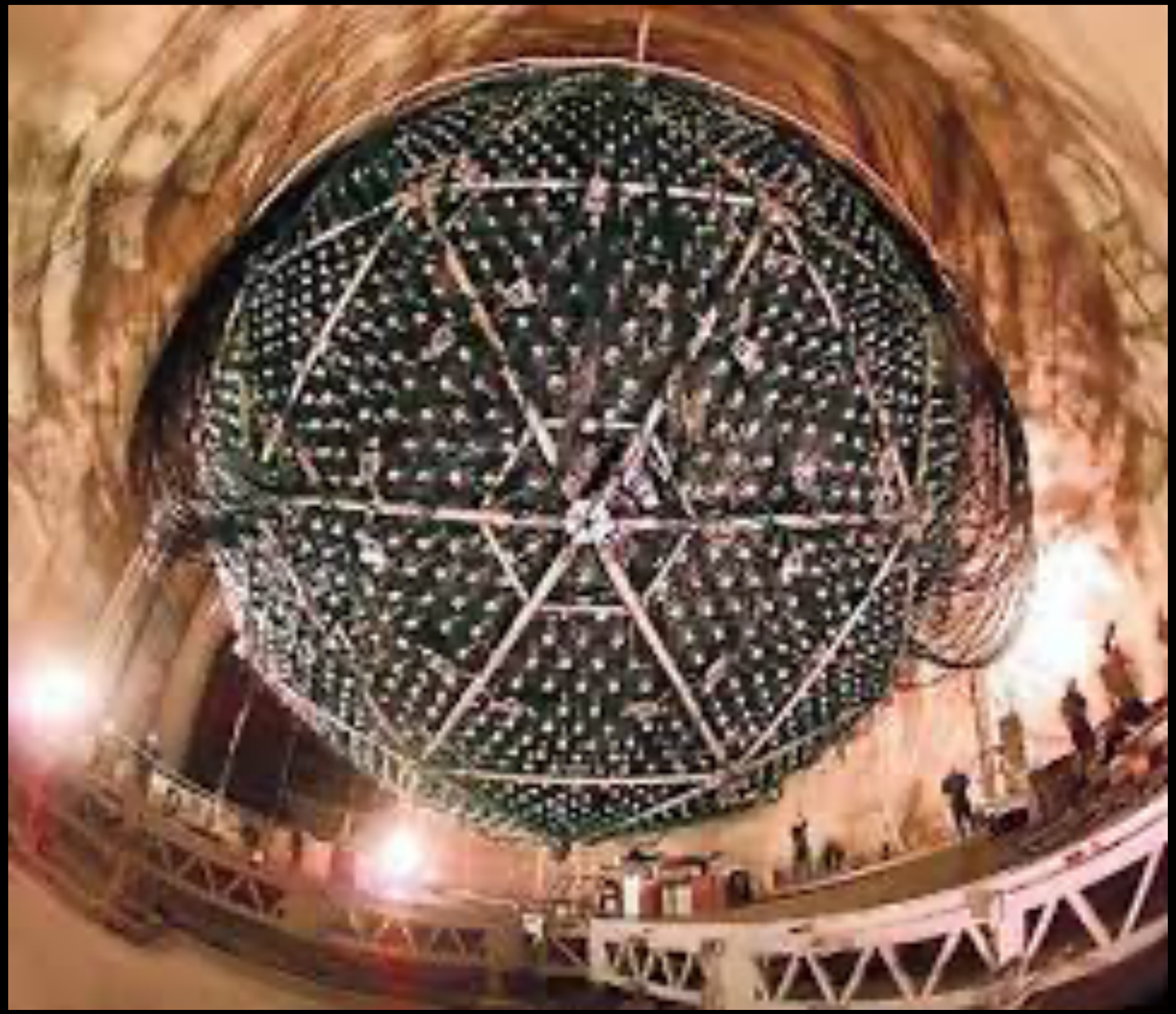
electrons: short track, mult. scat., brems. — Fuzzy Ring

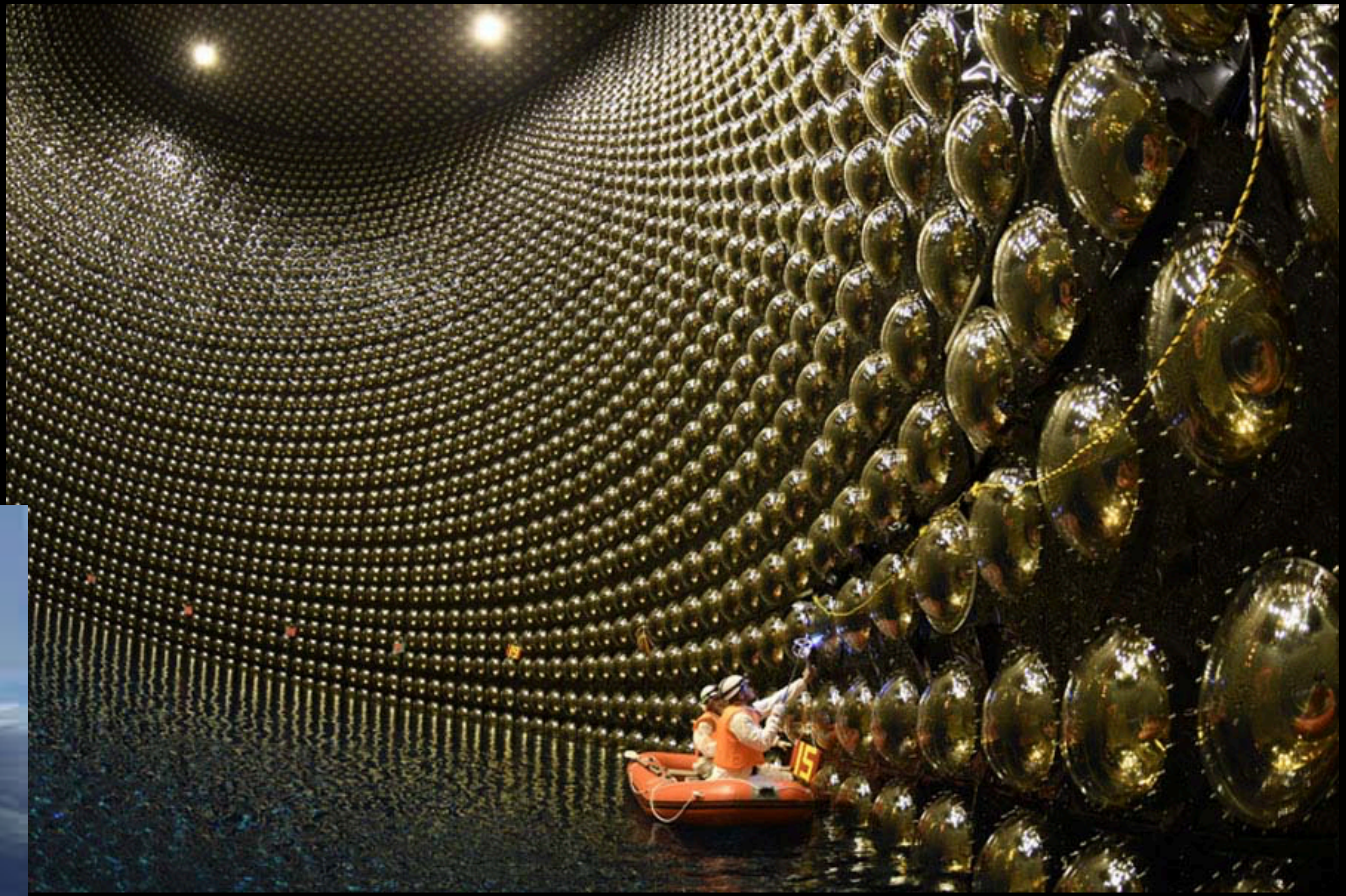
muons: long track, slows down — Sharp Outer Ring with Fuzzy Inner Region

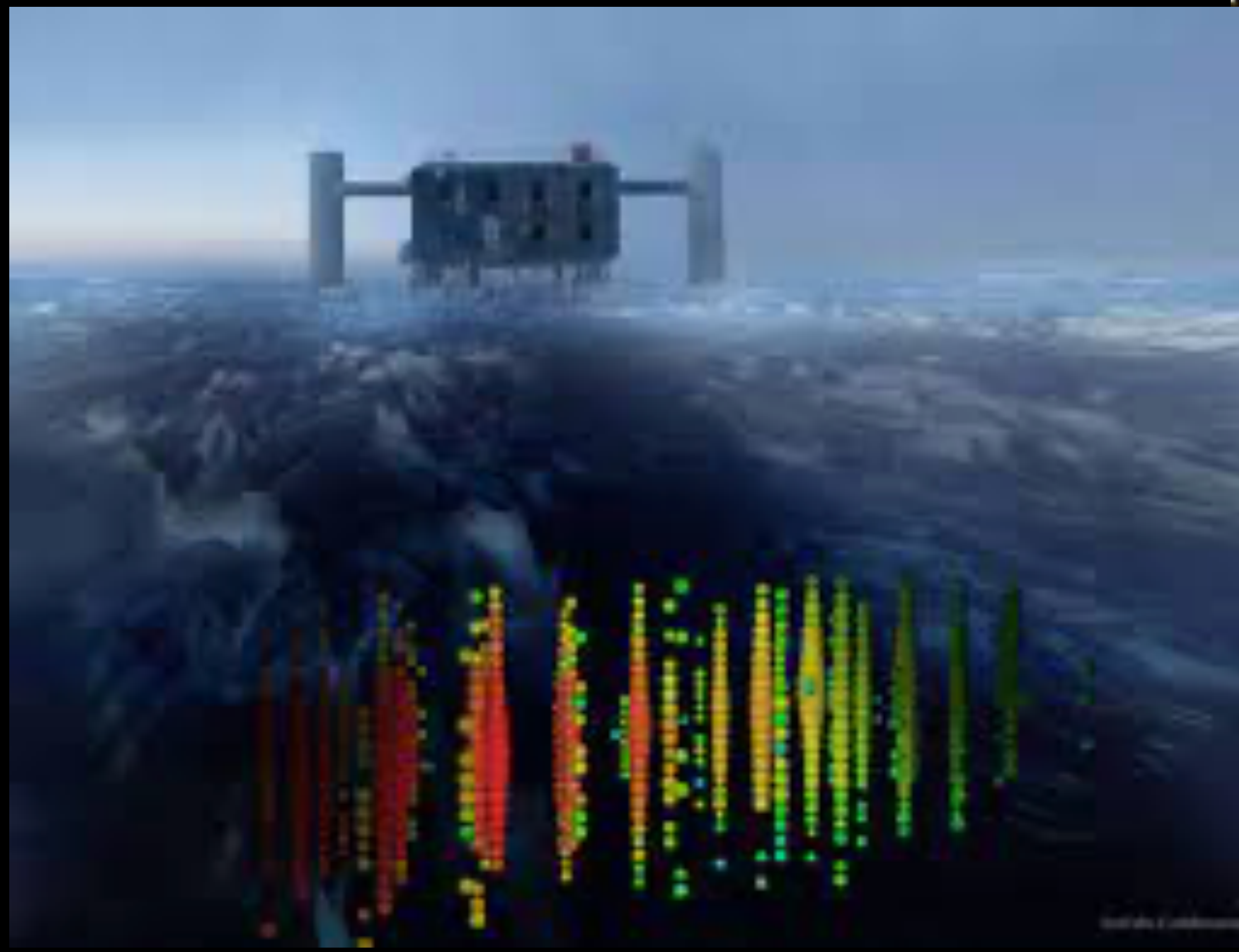
neutral pions: 2 electron-like tracks — Two Fuzzy Rings

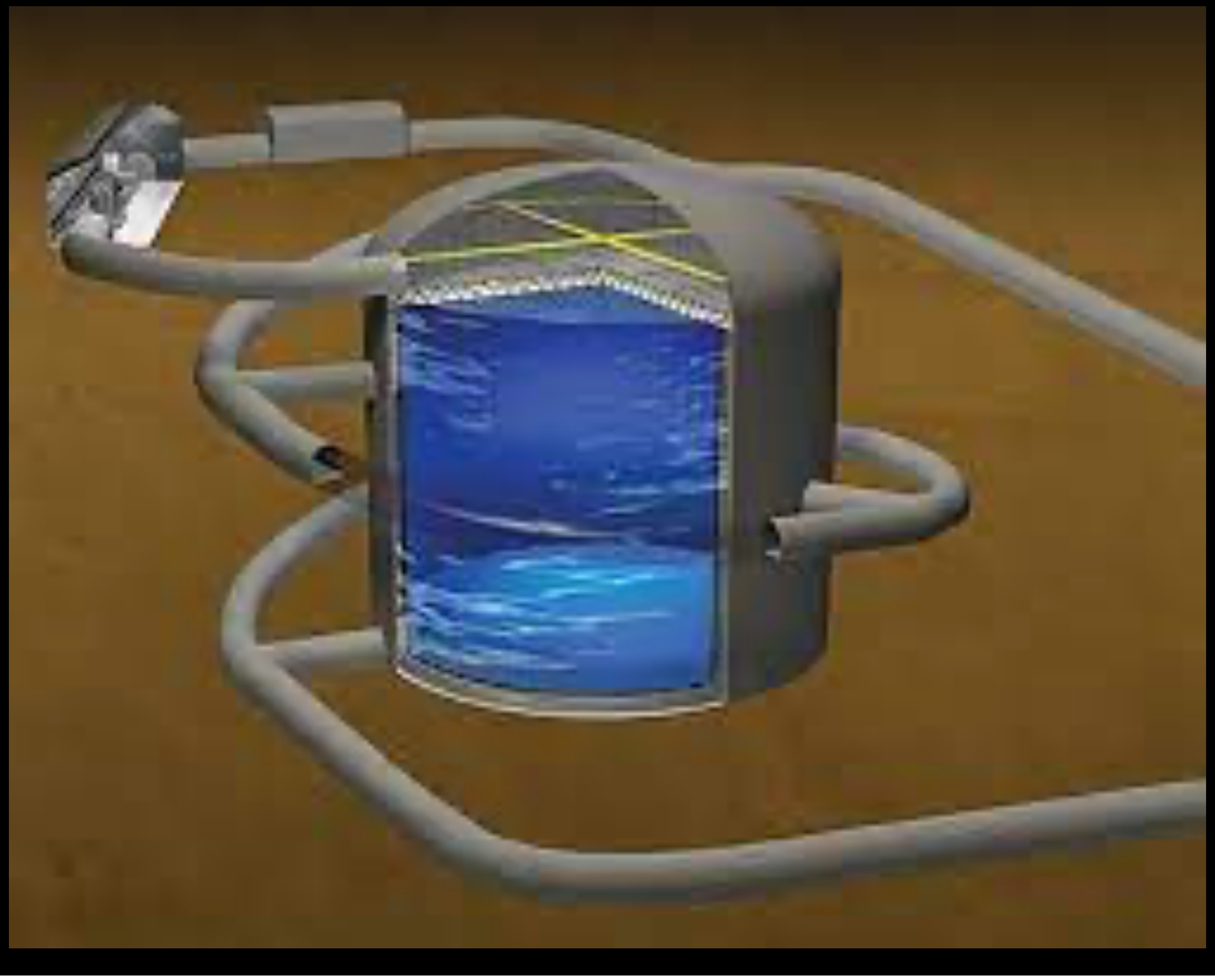


WATER CHERENKOV DETECTORS



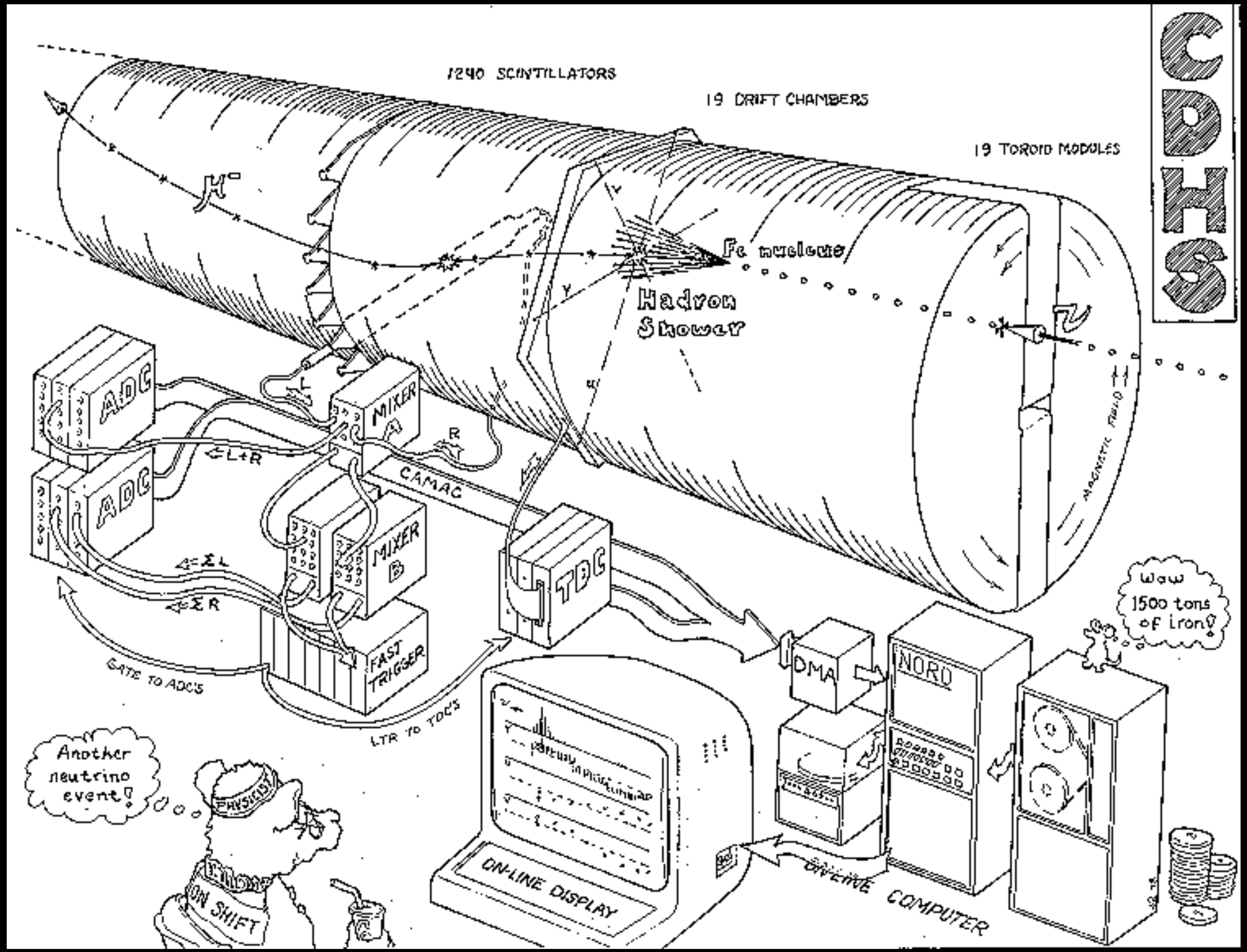


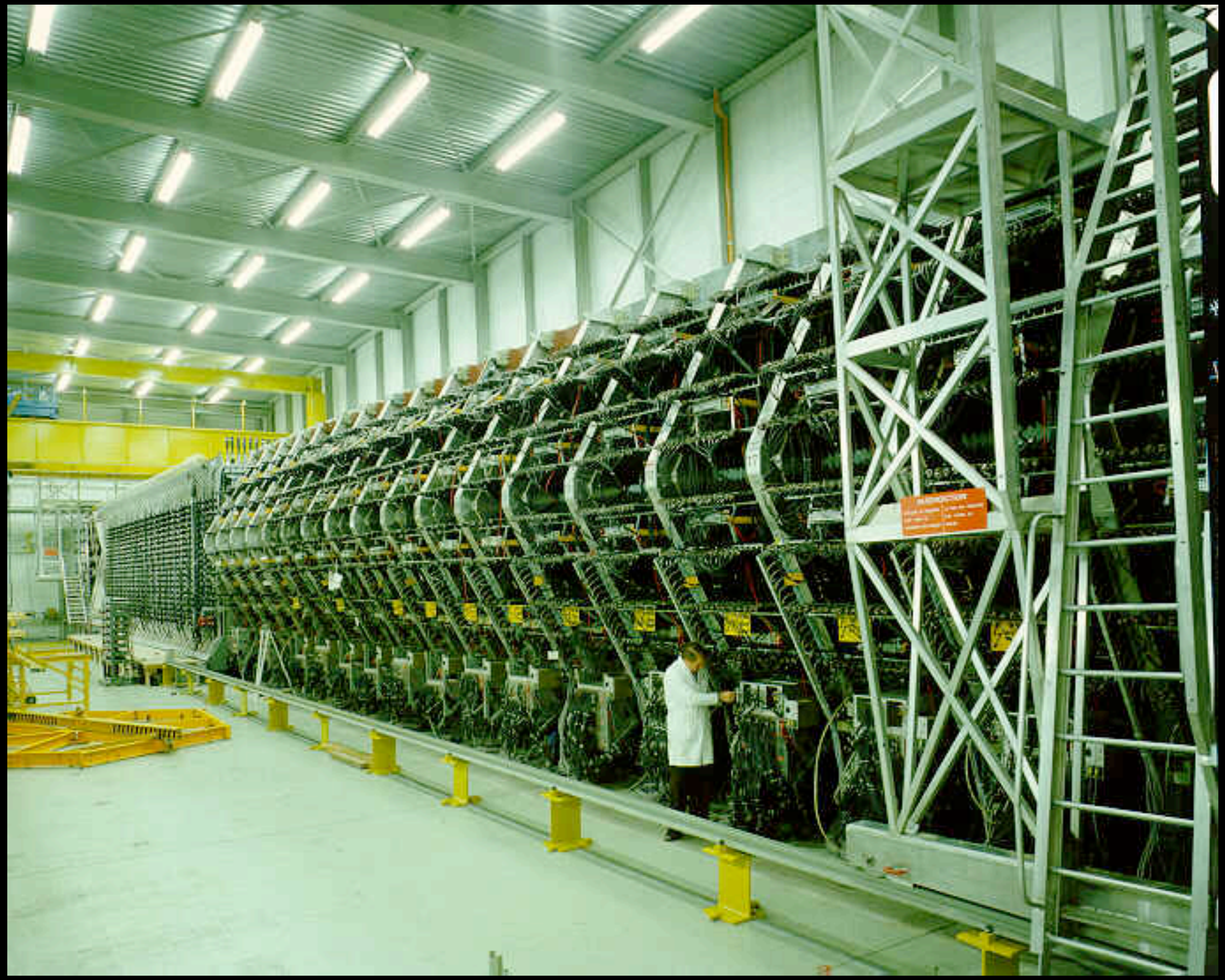




HIGH ENERGY CALORIMETERS

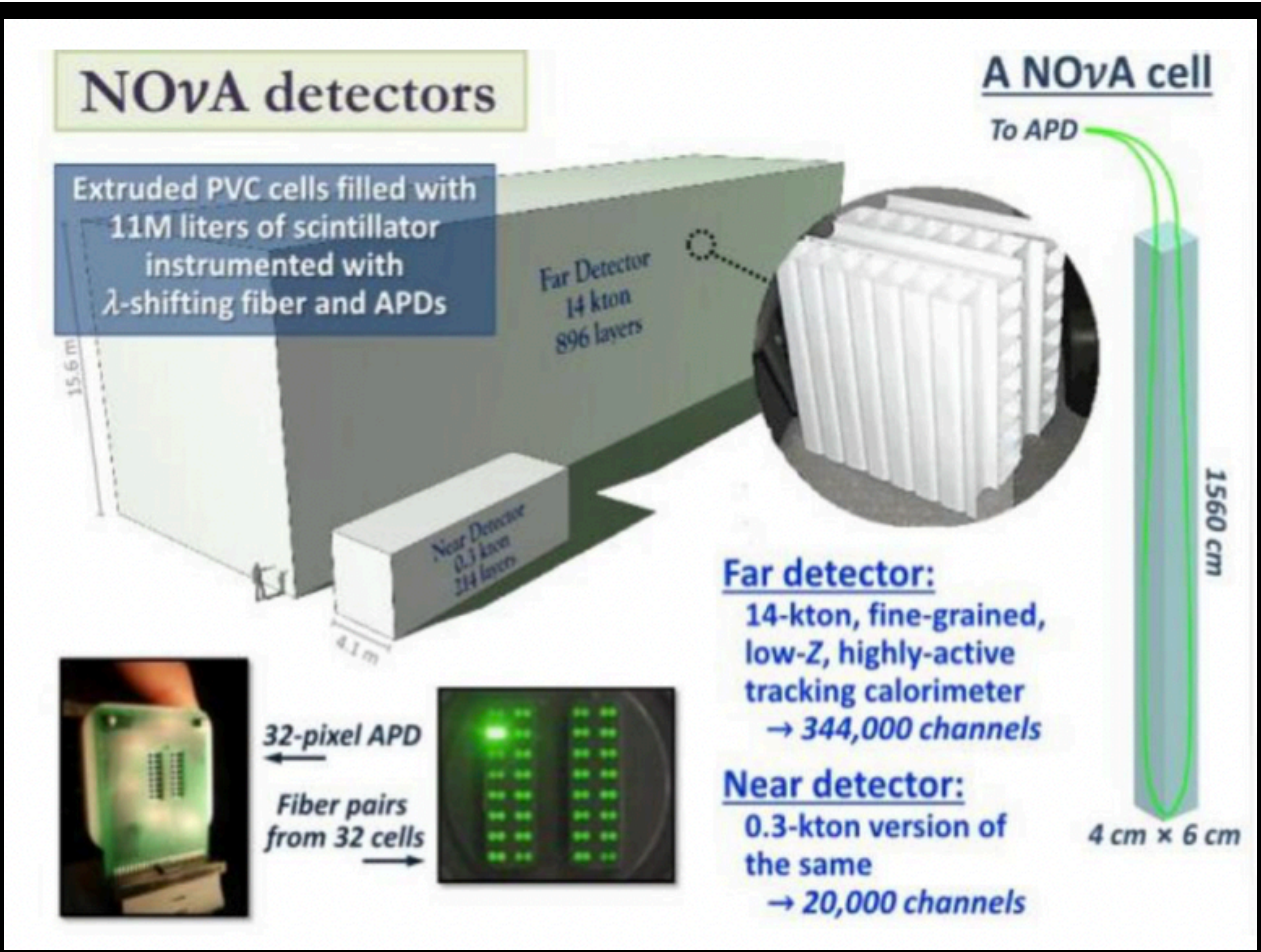
- CDHS experiment at CERN (1976-1984)
  - Goal: study deep inelastic scattering of HE neutrinos
  - Neutrino beam from 400 GeV SPS protons
  - (Massive!) 1500 tons magnetized iron + wire chambers + calorimeters





NOVA

- Oscillation experiment at long baseline (810 km)
- Low flux → high mass 14 kton!

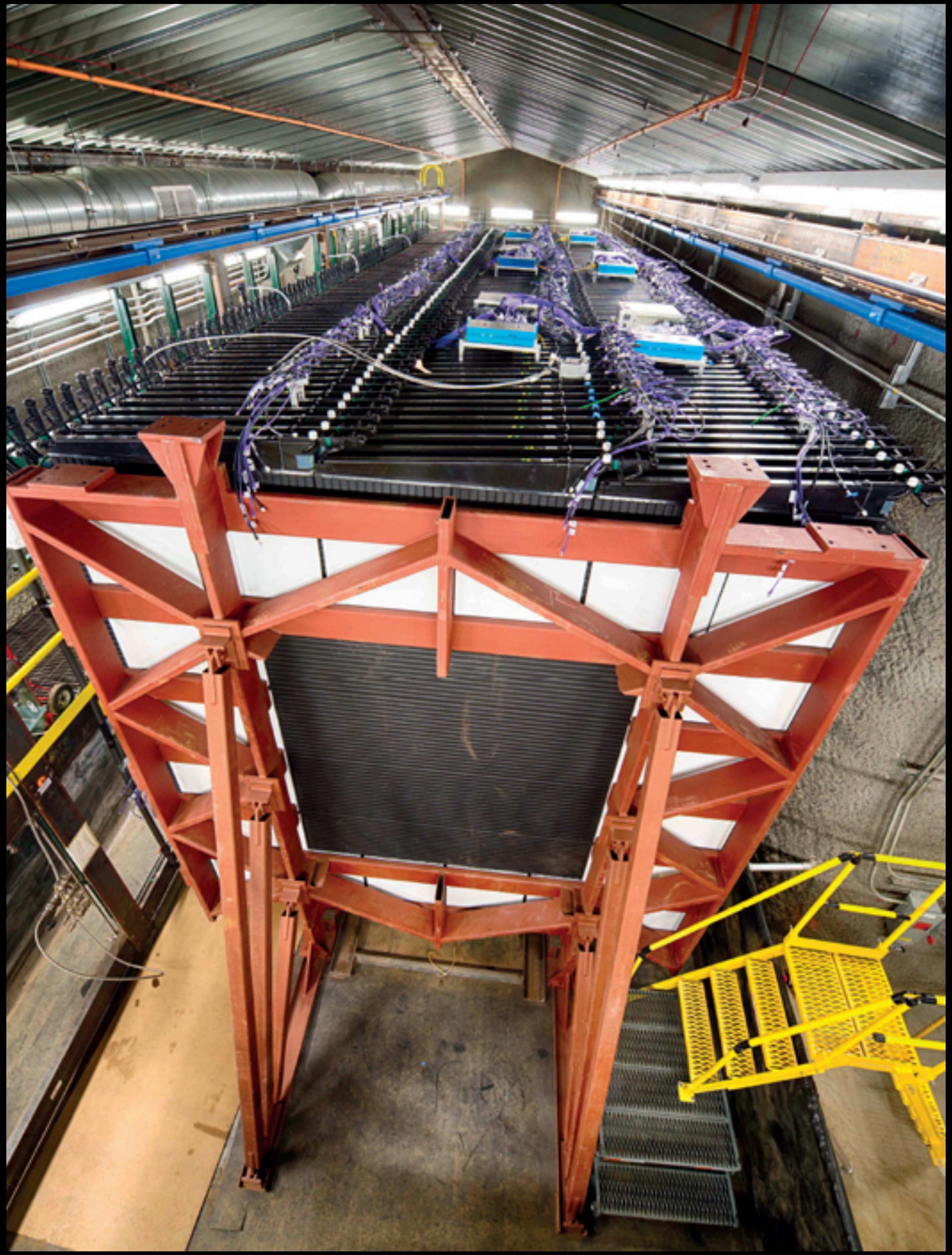


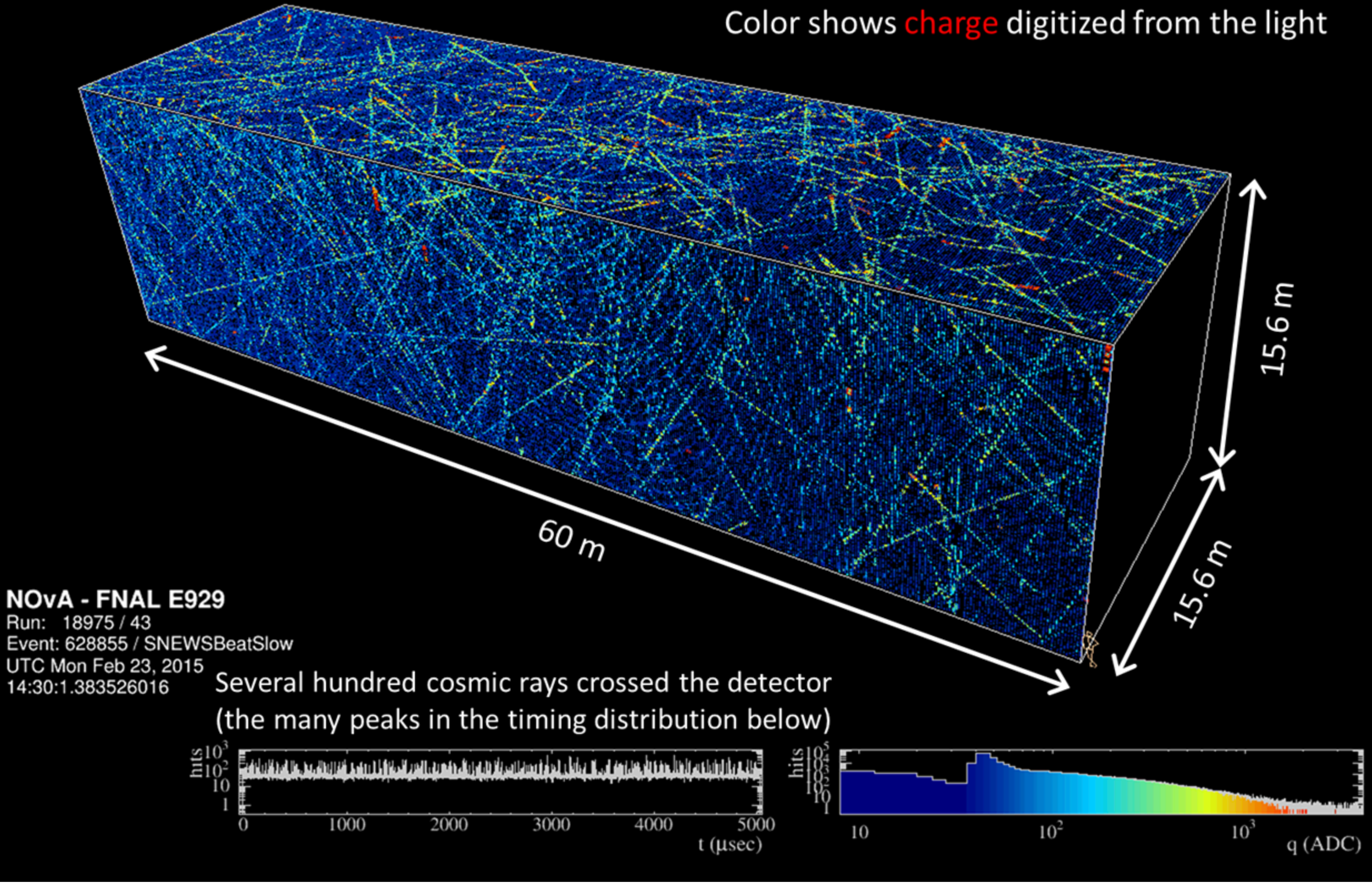
Extruded PVC cells filled with 11M liters of scintillator instrumented with λ-shifting fiber and APDs

Far detector:
14-kton, fine-grained, low-Z, highly-active tracking calorimeter
→ 344,000 channels

Near detector:
0.3-kton version of the same
→ 20,000 channels

NOVA

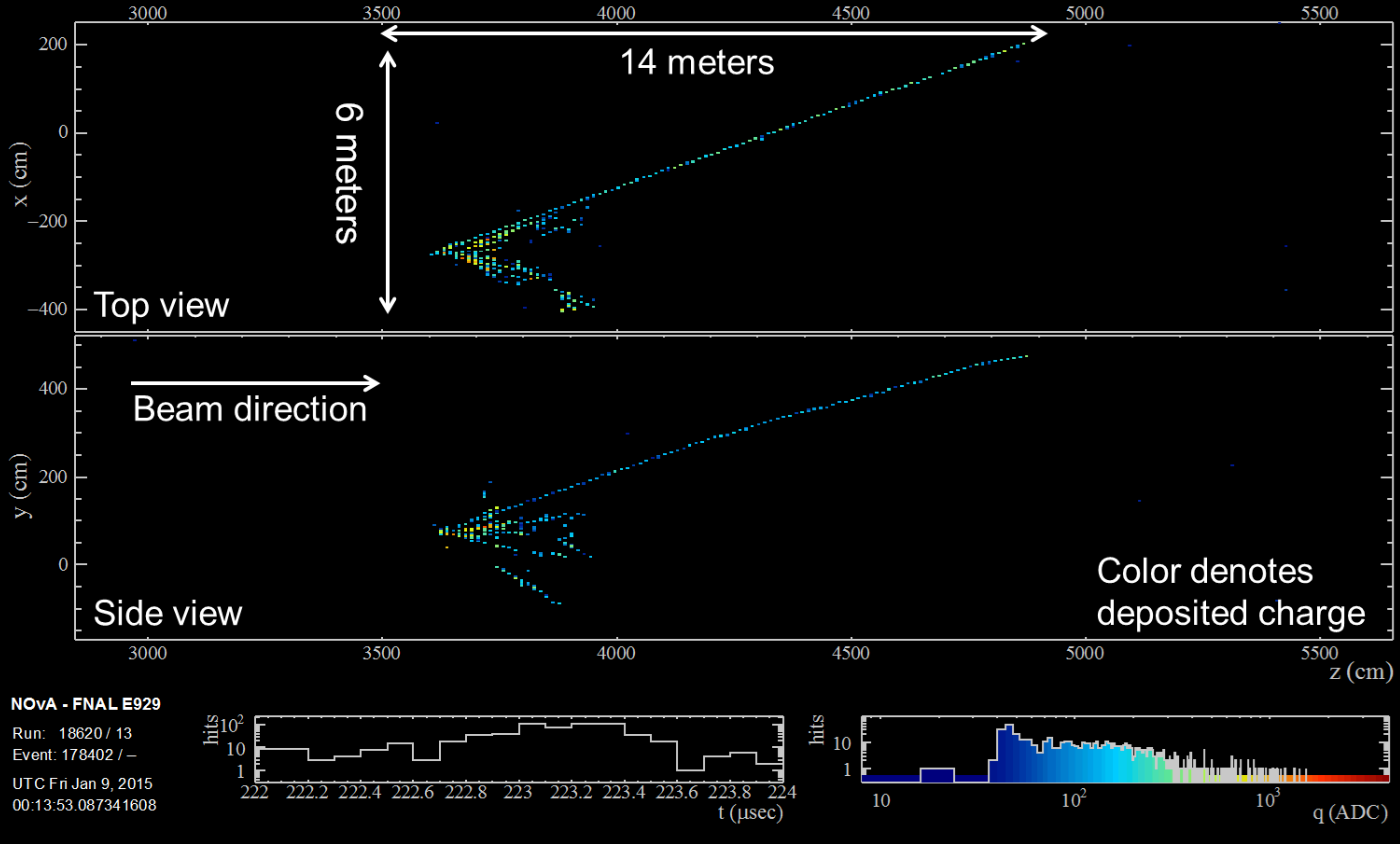




5ms of data at the NOνA Far Detector
Each pixel is one hit cell
Color shows charge digitized from the light

Several hundred cosmic rays crossed the detector
(the many peaks in the timing distribution below)

NOVA RESULTS



14 meters

6 meters

Top view

Beam direction

Side view

Color denotes deposited charge

NOVA RESULTS

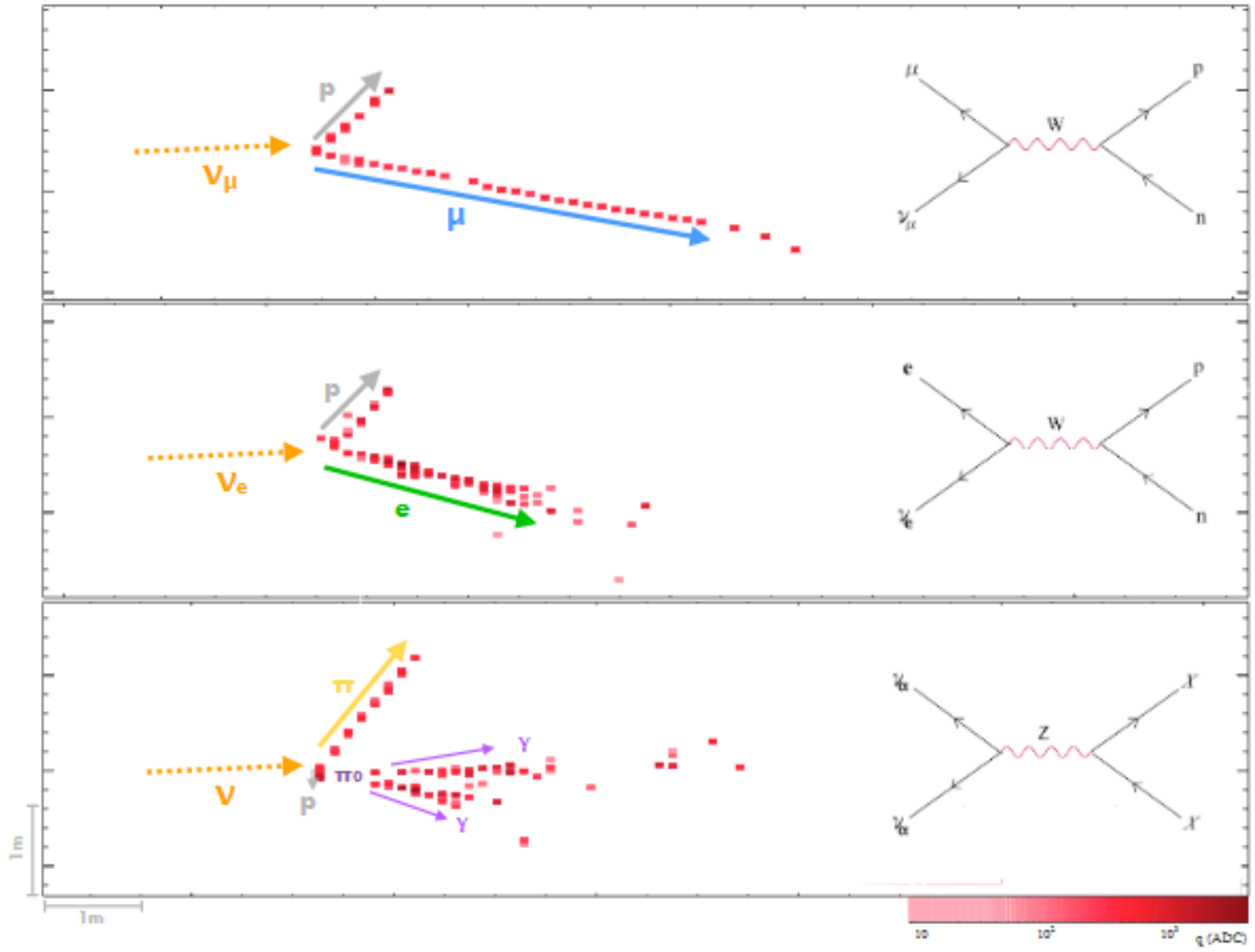
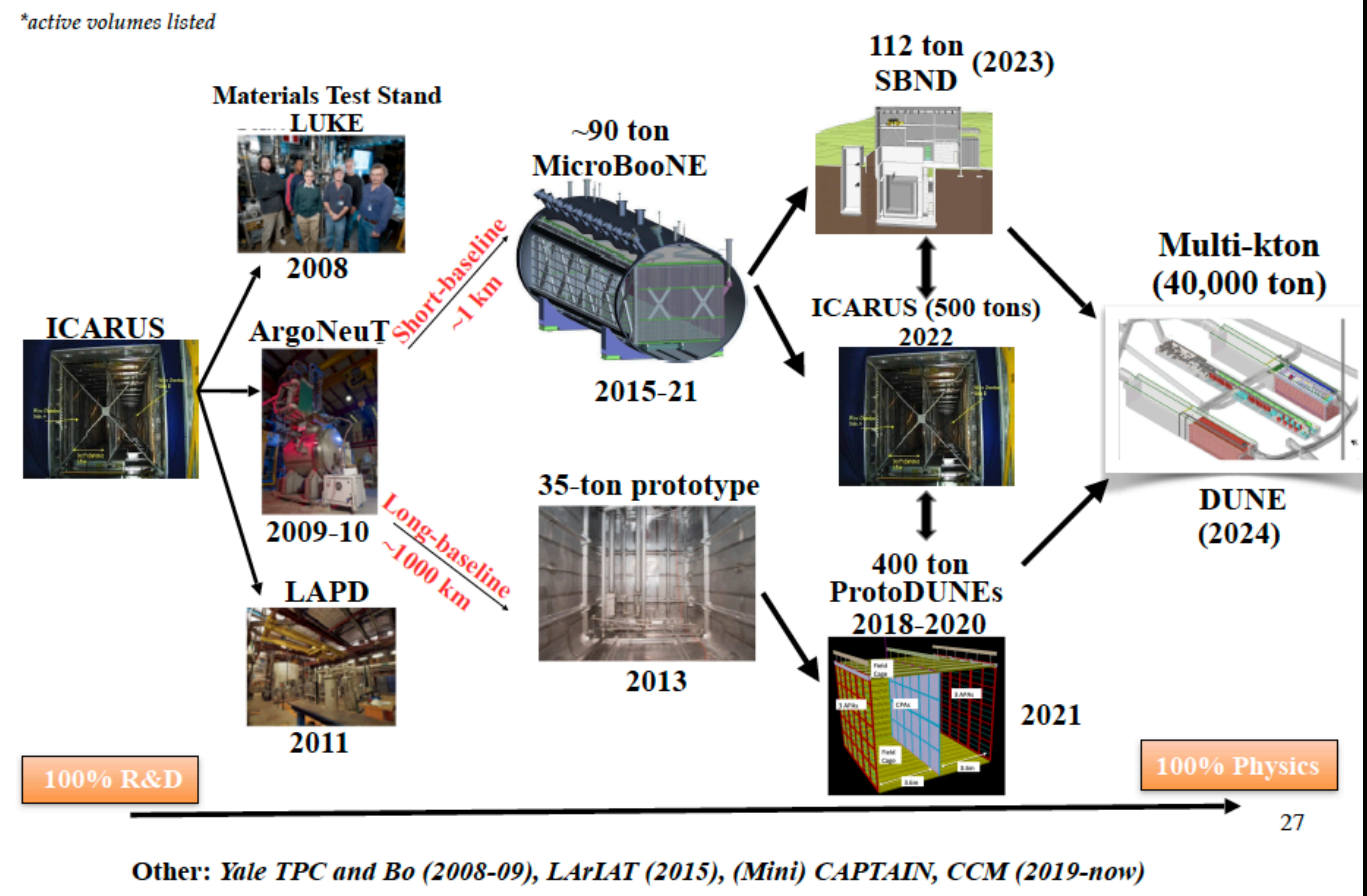


Figure 4.3: Example event topologies from data files. Top: Selected ν_μ ND event. Middle: Selected ν_e ND event. Bottom: Selected π^0 ND event.

LIQUID ARGON

- Noble liquid detectors are the technology of choice for many Dark Matter and Neutrino Physics experiments (LAr has also been employed in HEP (e.g. ATLAS))
- Dark Matter
  - Liquid Xenon: e.g. ZEPLIN, LUX, Xenon, LZ, XLZD
  - Liquid Argon: e.g. ArDM, DEAP, DarkSide, MiniCLEAN (also Liquid Neon)
- Neutrino Experiments
  - Liquid Argon is the chosen target for many ongoing and future neutrino experiments: e.g. ICARUS, ArgoNEUT, MicroBooNE, SBND, ProtoDUNE, DUNE
- Advantages of Liquid Argon Time Projection Chambers
  - Pure - high electron mobility - scalable to very large masses
  - Abundant in the atmosphere (1%), therefore not expensive
  - Bubble chamber quality images, only in HD! — interactions with unprecedented detail
  - Full 3D reconstruction, calorimetry and particle ID
  - Can operate on wide range of energies (MeV to GeV)

LIQUID ARGON, ACTIVE FIELD



active volumes listed

ICARUS

Materials Test Stand LUKE

2008

ArgoNeuT

2009-10

LAPD

2011

Short-baseline ~1 km

Long-baseline ~1000 km

~90 ton MicroBooNE

2015-21

35-ton prototype

2013

112 ton SBND (2023)

ICARUS (500 tons) 2022

400 ton ProtoDUNEs 2018-2020

2021

Multi-kton (40,000 ton)

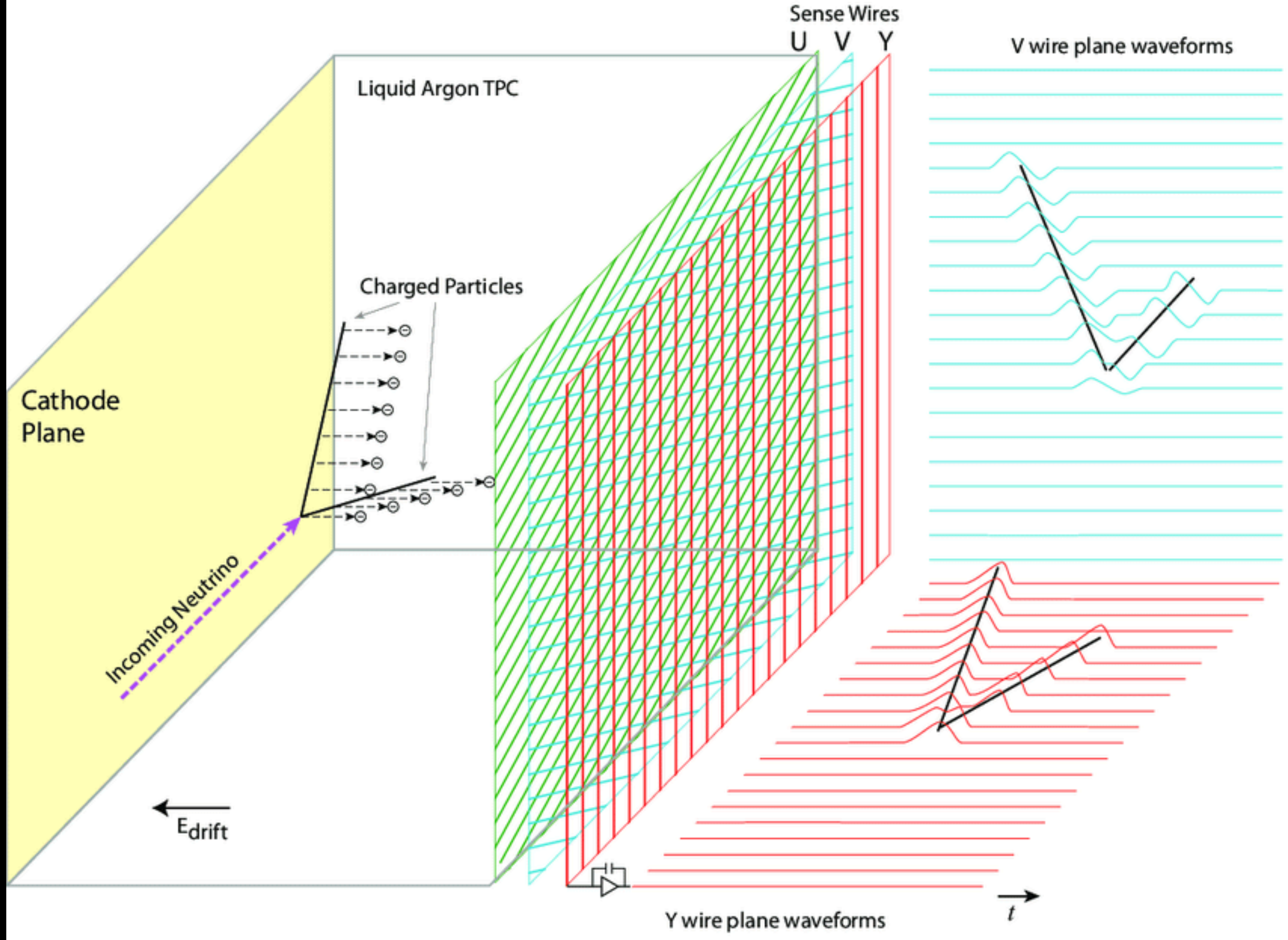
DUNE (2024)

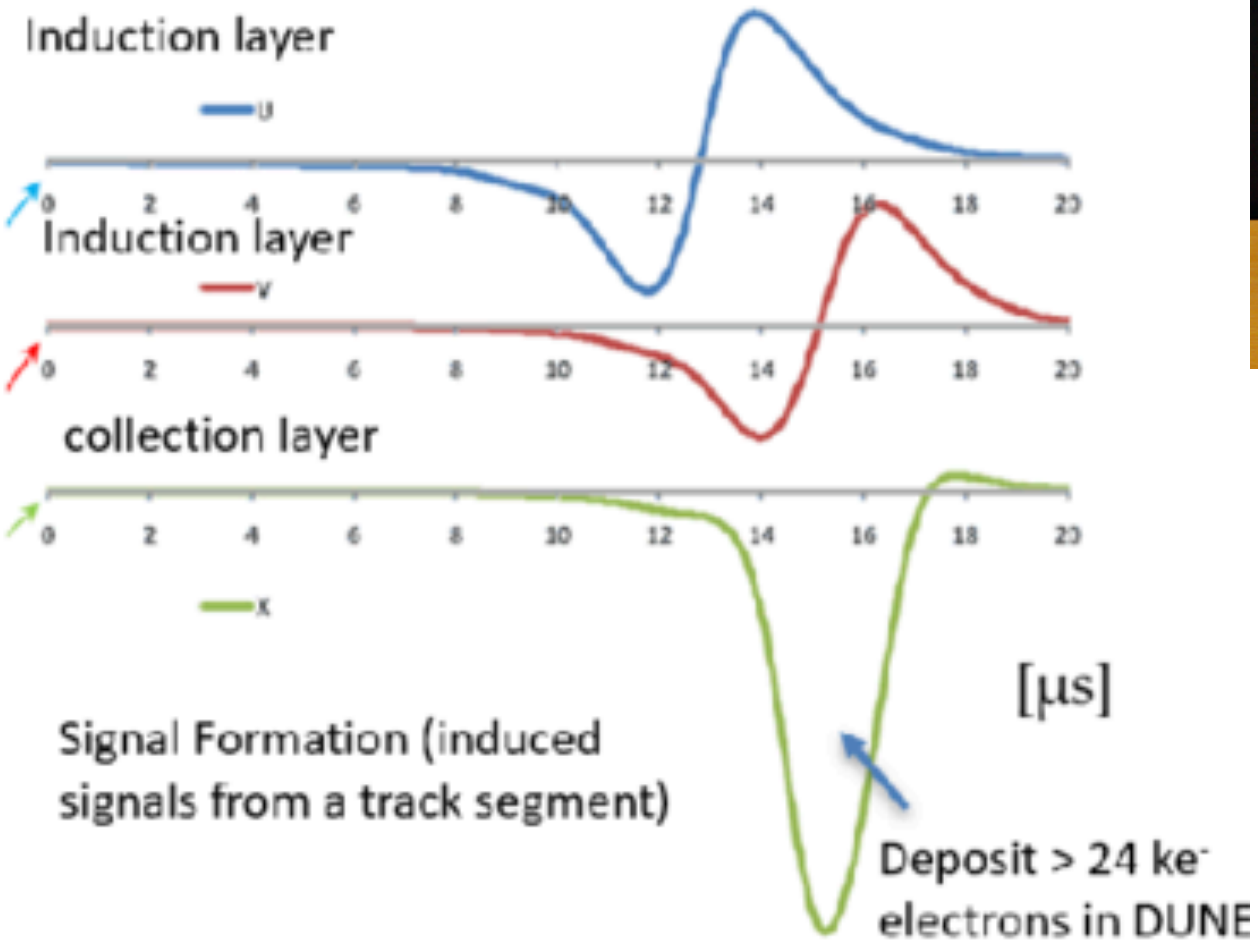
100% R&D

100% Physics

Other: *Yale TPC and Bo (2008-09), LArIAT (2015), (Mini) CAPTAIN, CCM (2019-now)*

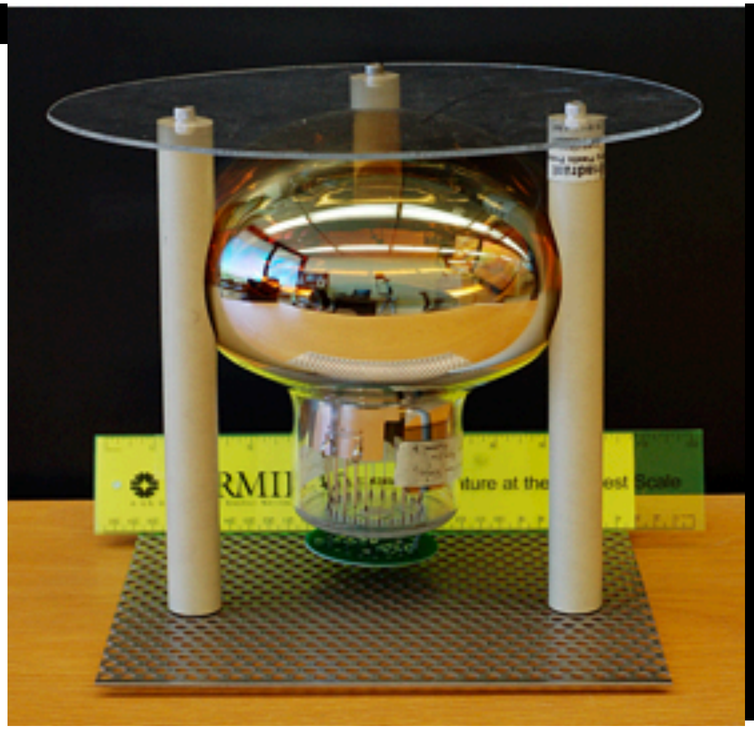
LAR TPC PRINCIPLE

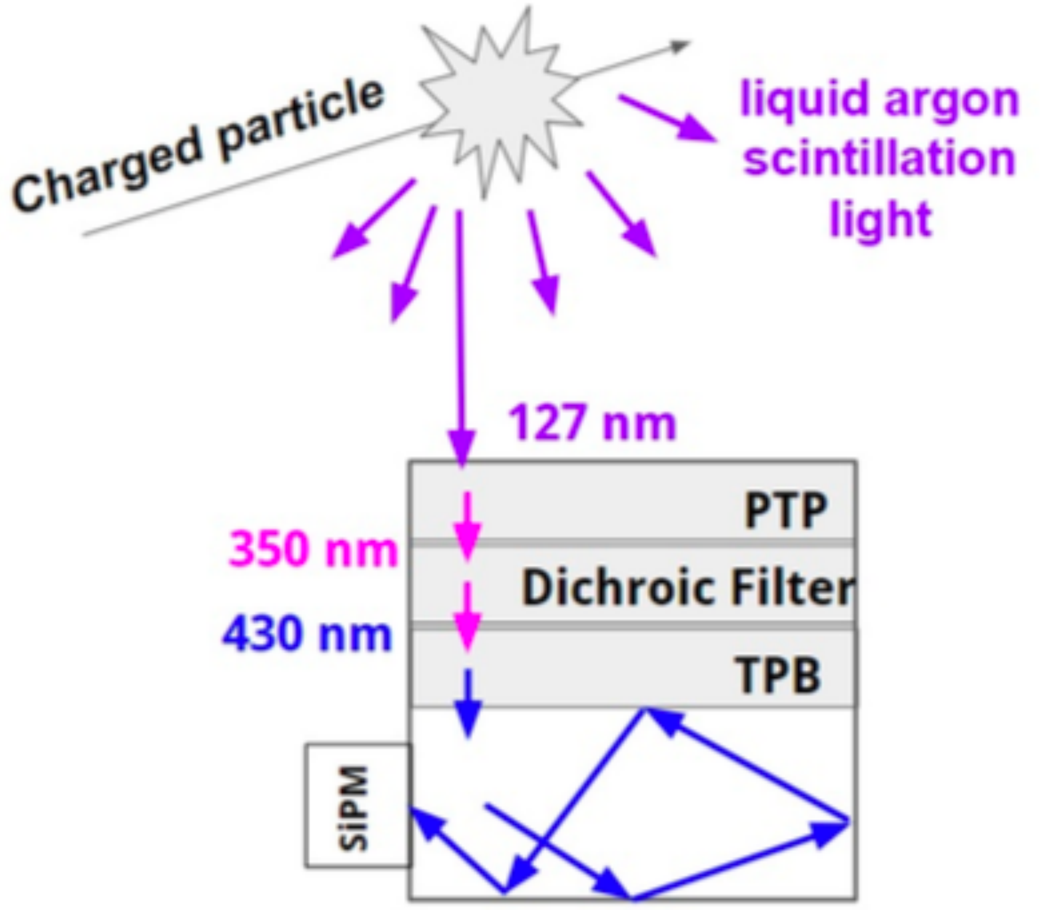




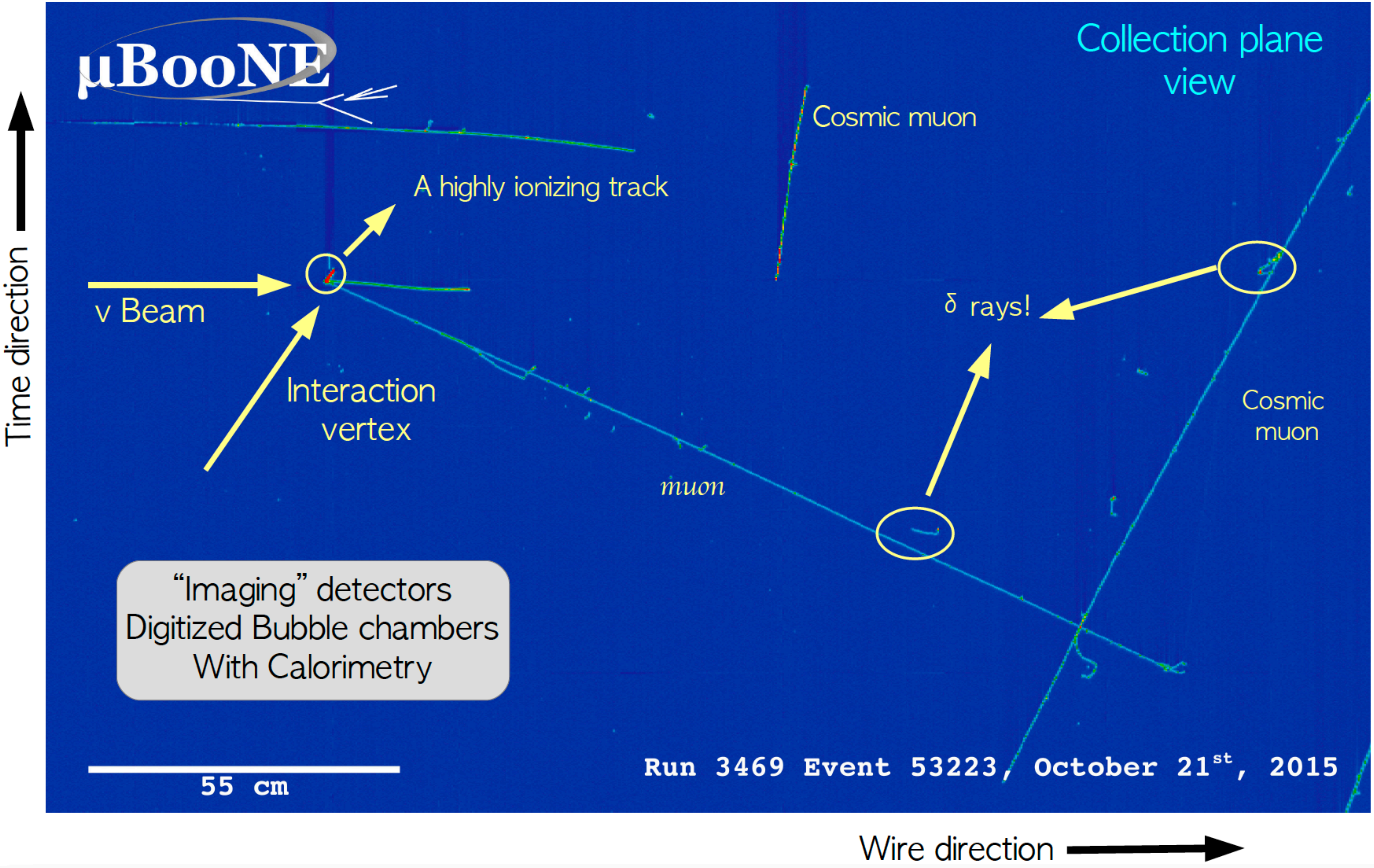
Signal Formation (induced signals from a track segment)

Deposit > 24 ke$^-$ electrons in DUNE



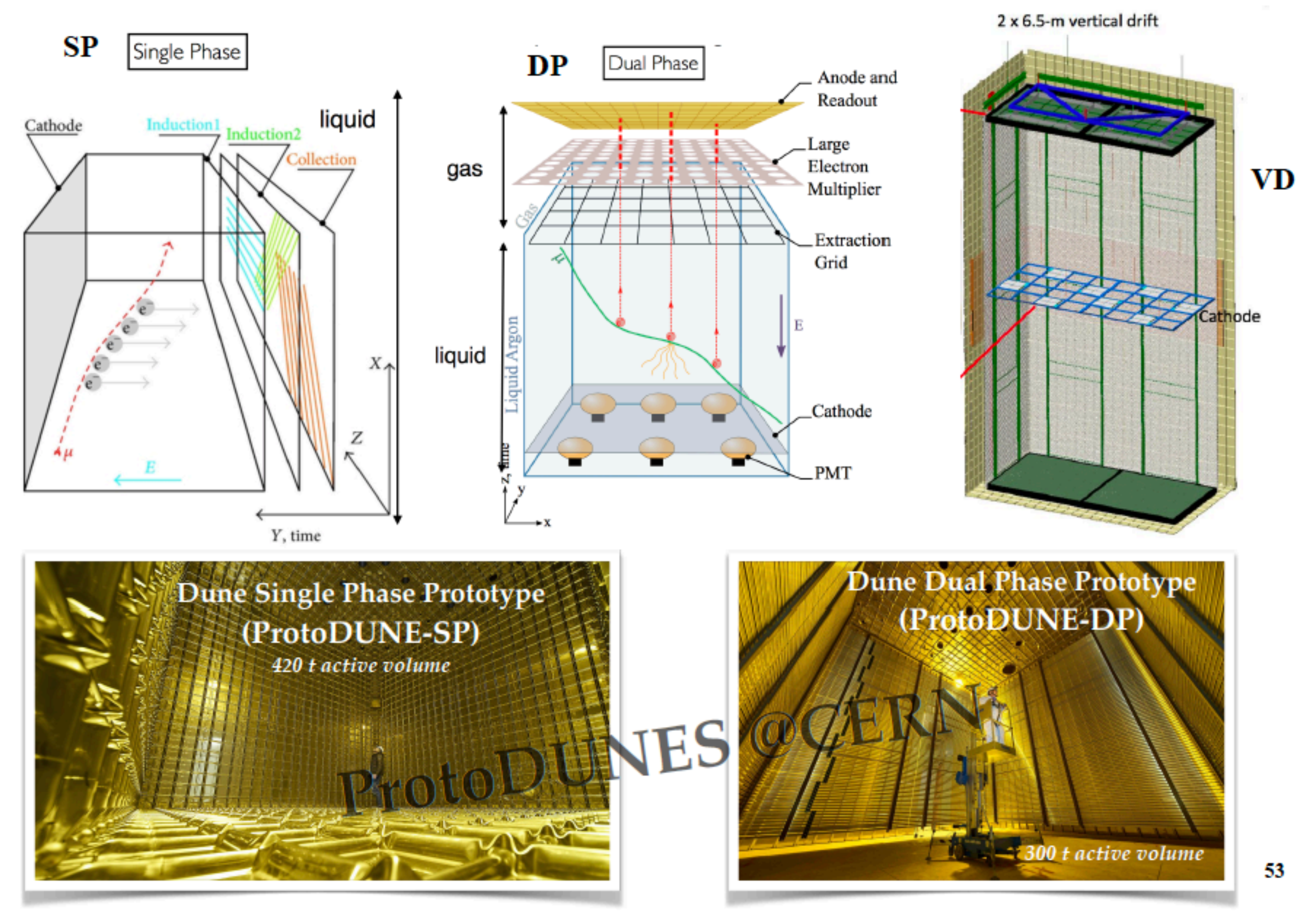


- Ionization charges drift in strong electric field
- Collected in sense plane
- Overlap in 3 sets of wires gives position in plane
- Scintillation light gives ref. time
- Drift time provides 3rd coordinate
- Collected charge provides calorimetry and particle ID



"Imaging" detectors
Digitized Bubble chambers
With Calorimetry

DUNE PROTOTYPES AT CERN



Dune Single Phase Prototype (ProtoDUNE-SP)

420 t active volume

Dune Dual Phase Prototype (ProtoDUNE-DP)

300 t active volume

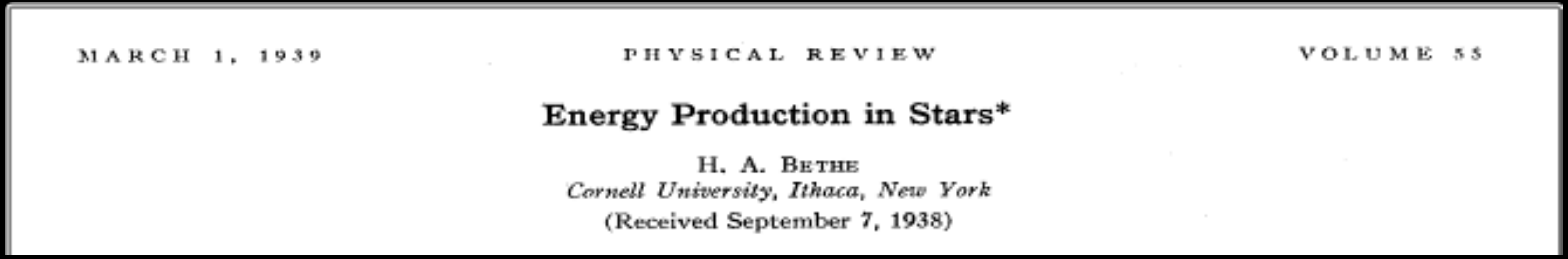
MUCH MORE ON DUNE IN LECTURE 3.

QUESTIONS?

THE SOLAR NEUTRINO PROBLEM

HOW DO STARS SHINE?

- Lord Kelvin (1865)
  - Having excluded chemical energy (enough only for a few thousand years), proposed slow gravitational collapse, estimating 20 Myr for age of the Sun
  - Evidence from geology and evolution of life said it had to be much larger

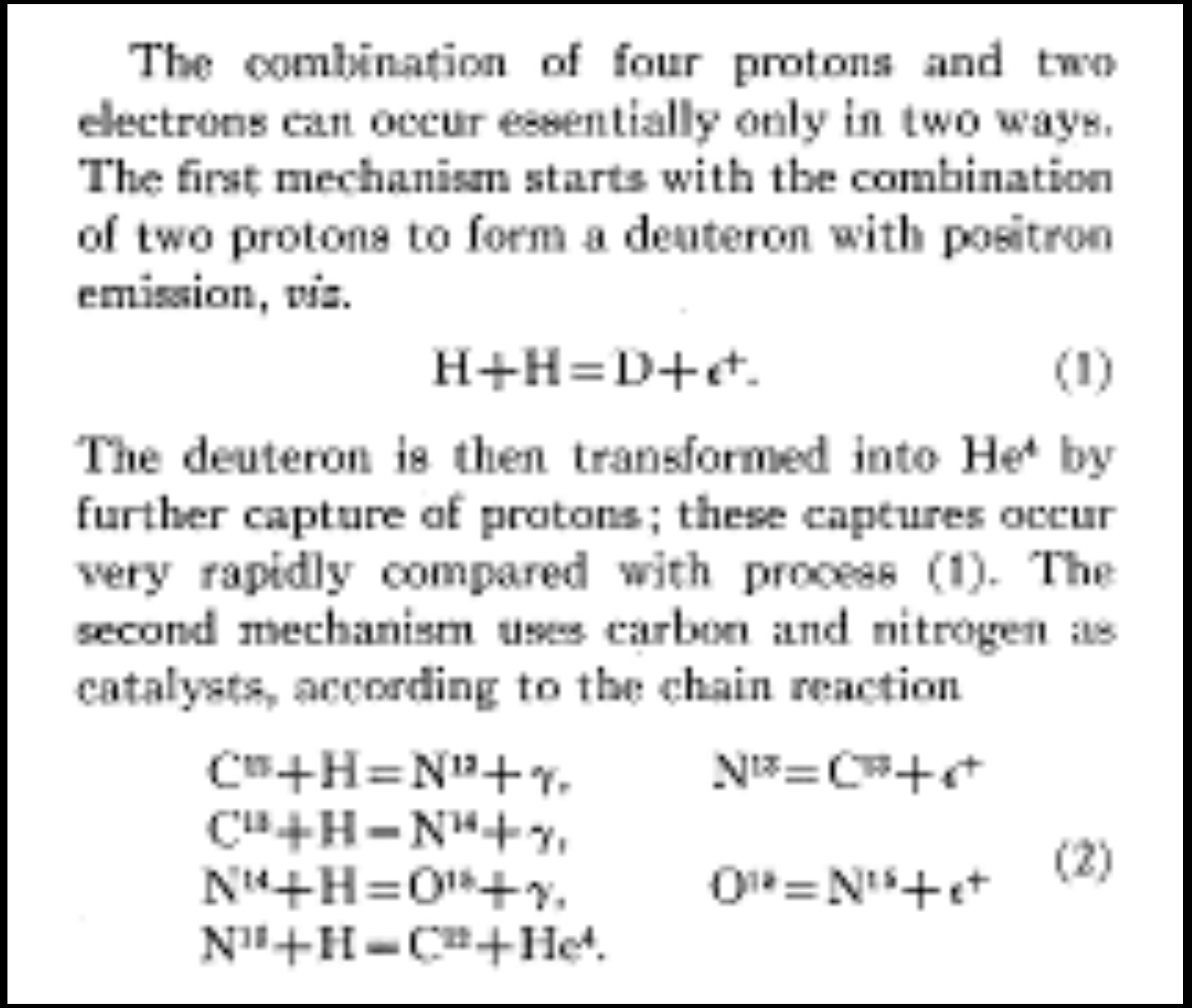


MARCH 1, 1939 PHYSICAL REVIEW VOLUME 55

Energy Production in Stars*

H. A. Bethe
Cornell University, Ithaca, New York
(Received September 7, 1938)

- Hans Bethe (1939)
  - Star's power source is nuclear fusion of 4 protons into He, not chemical or gravitational processes
  - Provides two mechanisms, the pp Chain and the CNO cycle
  - Enough energy for estimated age of the Sun, 4.5 billion years



The combination of four protons and two electrons can occur essentially only in two ways. The first mechanism starts with the combination of two protons to form a deuteron with positron emission, *viz.*

$$H+H=D+\epsilon^{+}. \qquad (1)$$

The deuteron is then transformed into He^4 by further capture of protons; these captures occur very rapidly compared with process (1). The second mechanism uses carbon and nitrogen as catalysts, according to the chain reaction

$$\begin{array}{ll} C^{12}+H=N^{13}+\gamma, & N^{13}=C^{13}+\epsilon^{+} \\ C^{13}+H=N^{14}+\gamma, & \\ N^{14}+H=O^{15}+\gamma, & O^{15}=N^{15}+\epsilon^{+} \\ N^{15}+H=C^{12}+He^{4}. & \end{array} \qquad (2)$$

Note: no mention of neutrinos …

BAHCALL & DAVIS

SOLAR NEUTRINOS. I. THEORETICAL*

John N. Bahcall
California Institute of Technology, Pasadena, California

(Received 6 January 1964)

The principal energy source for main-sequence stars like the sun is believed to be the fusion, in the deep interior of the star, of four protons to form an alpha particle.[1] The fusion reactions are thought to be initiated by the sequence $^1H(p, e^+\nu)^2H(p,\gamma)^3He$ and terminated by the following sequences: (i) $^3He(^3He, 2p)^4He$; (ii) $^3He(\alpha,\gamma)^7Be(e^-\nu)^7Li(p,\alpha)^4He$; and (iii) $^3He(\alpha,\gamma)^7Be(p,\gamma)^8B(e^+\nu)^8Be^*(\alpha)^4He$. No direct evidence for the existence of nuclear reactions in the interiors of stars has yet been obtained because the mean free path for photons emitted in the center of a star is typically less than 10^{-10} of the radius of the star. Only neutrinos, with their extremely small interaction cross sections, can enable us to see into the interior of a star and thus verify directly the hypothesis of nuclear energy generation in stars.

The most promising method[2] for detecting solar neutrinos is based upon the endothermic reaction ($Q = -0.81$ MeV) $^{37}Cl(\nu_{solar}, e^-)^{37}Ar$, which was first discussed as a possible means of detecting neutrinos by Pontecorvo[3] and Alvarez.[4] In this note, we predict the number of absorptions of

VOLUME 12, NUMBER 11 PHYSICAL REVIEW LETTERS 16 MARCH 1964

SOLAR NEUTRINOS. II. EXPERIMENTAL*

Raymond Davis, Jr.
Chemistry Department, Brookhaven National Laboratory, Upton, New York

(Received 6 January 1964)

The prospect of observing solar neutrinos by means of the inverse beta process $^{37}Cl(\nu, e^-)^{37}Ar$ induced us to place the apparatus previously described[1] in a mine and make a preliminary search. This experiment served to place an upper limit on the flux of extraterrestrial neutrinos. These results will be reported, and a discussion will be given of the possibility of extending the sensitivity of the method to a degree capable of measuring the solar neutrino flux calculated by Bahcall in the preceding paper.[2]

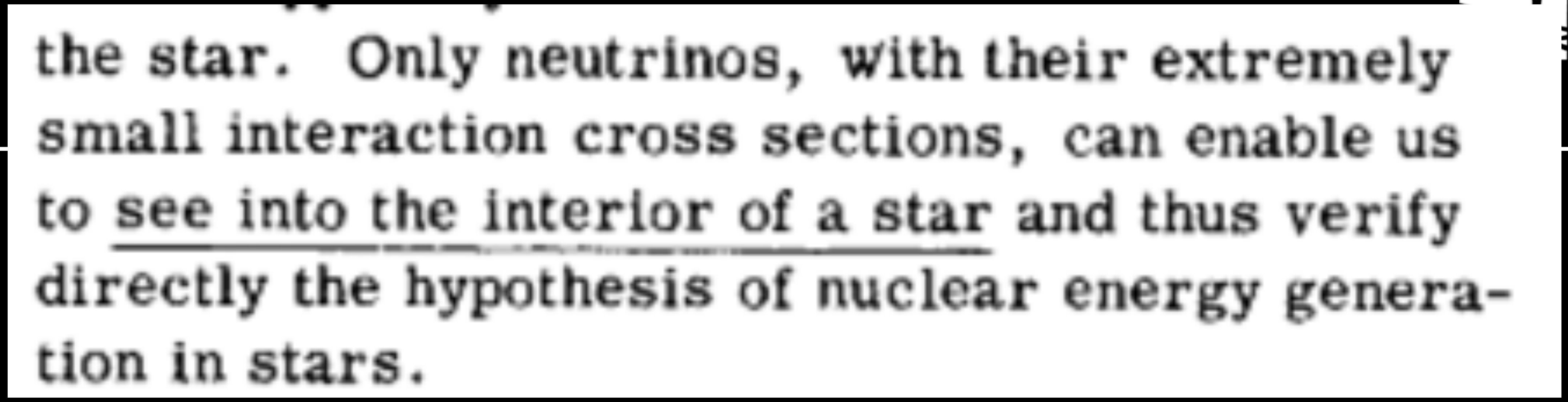
The apparatus consists of two 500-gallon tanks of perchlorethylene, C_2Cl_4, equipped with agitators and an auxiliary system for purging with helium. It is located in a limestone mine 2300 feet below the surface[3] (1800 meters of water equivalent shielding, m.w.e.). Initially the tanks were swept completely free of air argon by purging the tanks with a stream of helium gas. ^{36}Ar carrier (0.10 cm^3) was introduced and the tanks exposed for periods of four months or more to allow the 35-d ^{37}Ar activity to reach nearly the saturation value. Carrier argon along with any ^{37}Ar pro-

3 counts in 18 days is probably entirely due to the background activity. However, if one assumes that this rate corresponds to real events and uses the efficiencies mentioned, the upper limit of the neutrino capture rate in 1000 gallons of C_2Cl_4 is ≤ 0.5 per day or $\varphi\bar{\sigma} \leq 3 \times 10^{-34}$ sec^{-1} (^{37}Cl atom$)^{-1}$. From this value, Bahcall[2] has set an upper limit on the central temperature of the sun and other relevant information.

On the other hand, if one wants to measure the solar neutrino flux by this method one must use a much larger amount of C_2Cl_4, so that the expected ^{37}Ar production rate is well above the background of the counter, 0.2 count per day. Using Bahcall's expression,

$$\sum \varphi_\nu(\text{solar})\,\sigma_{abs} = (4 \pm 2) \times 10^{-35}\ \text{sec}^{-1}\ (^{37}\text{Cl atom})^{-1},$$

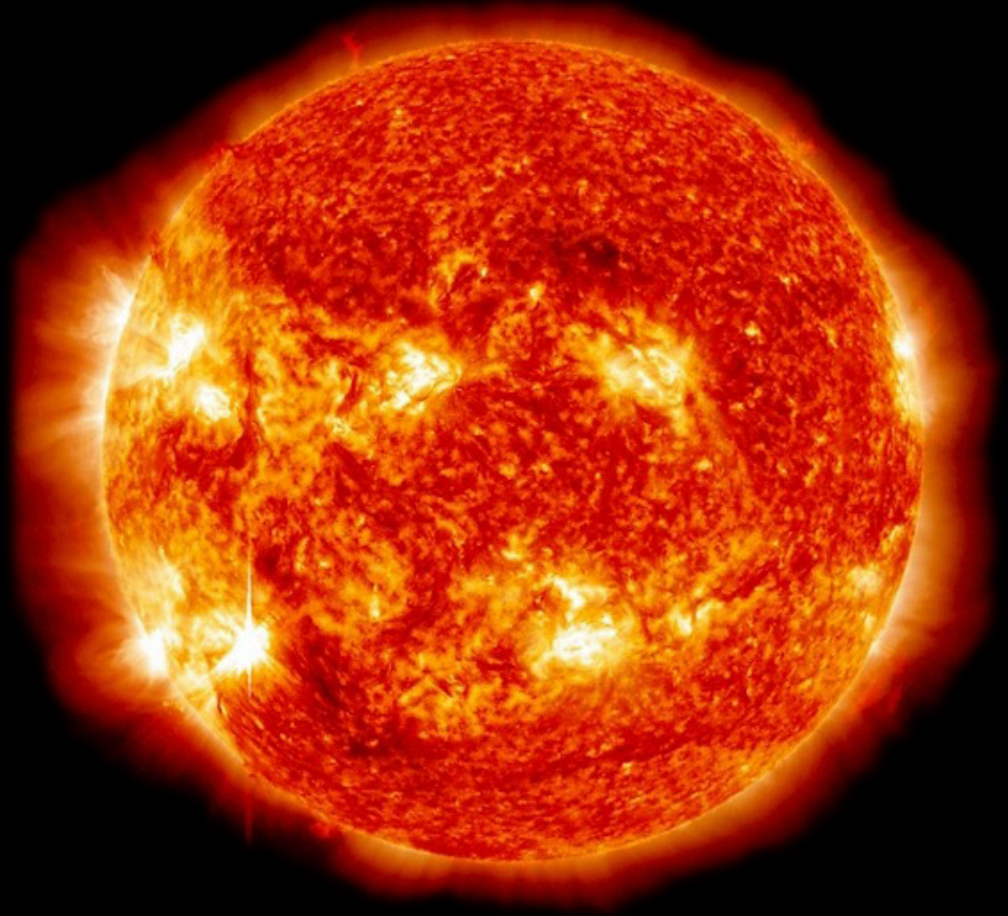
then the expected solar neutrino captures in 100 000 gallons of C_2Cl_4 will be 4 to 11 per day, which is an order of magnitude larger than the counter background. On the basis of experience

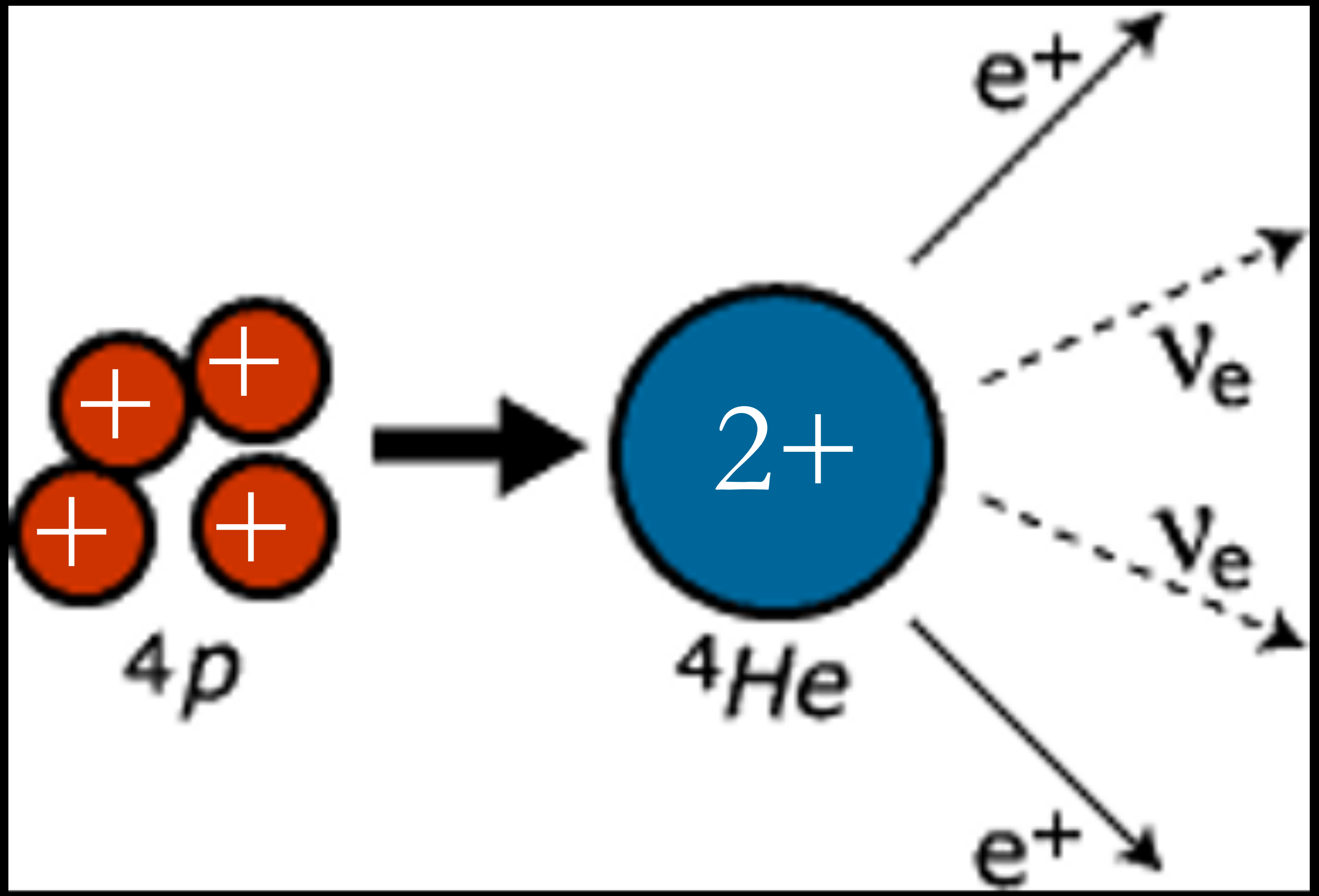


the star. Only neutrinos, with their extremely small interaction cross sections, can enable us to see into the interior of a star and thus verify directly the hypothesis of nuclear energy generation in stars.

- Two landmark papers (1964): the birth of a field
- Bahcall calculated the expected solar neutrino flux
- Davis described his experiment to detect them

HOW MANY NEUTRINOS?





- 1 MeV = 1.6x10^{-13} J

- Sun powered by fusion of protons into Helium. Protons turn into neutrons, so this emits ν_e, not $\bar{\nu}_e$
- For each 4p fusion, 2 ν are emitted, plus 26.7 MeV. So, one neutrino is emitted per each 13.3 MeV (2.1x10^{-12} J) produced
- Sun´s luminosity 3.826 x 10^{26} J/s
  - Neutrinos emitted = **1.8x10^{38} ν/s**
- Flux in the Earth? D=149x10^{6}km=1.5x10^{13}cm
  - **6x10^{10} ν/cm^2/s** (same as near a nuclear reactor)

- Only an overall balance of a sequence of reactions, more complex than this.

SOLAR MODELS

$$\rho = \frac{1}{4\pi r^2}\frac{dM}{dr}.$$

$$\frac{dP}{dr} = -\rho g = -\rho\frac{GM(r)}{r^2}.$$

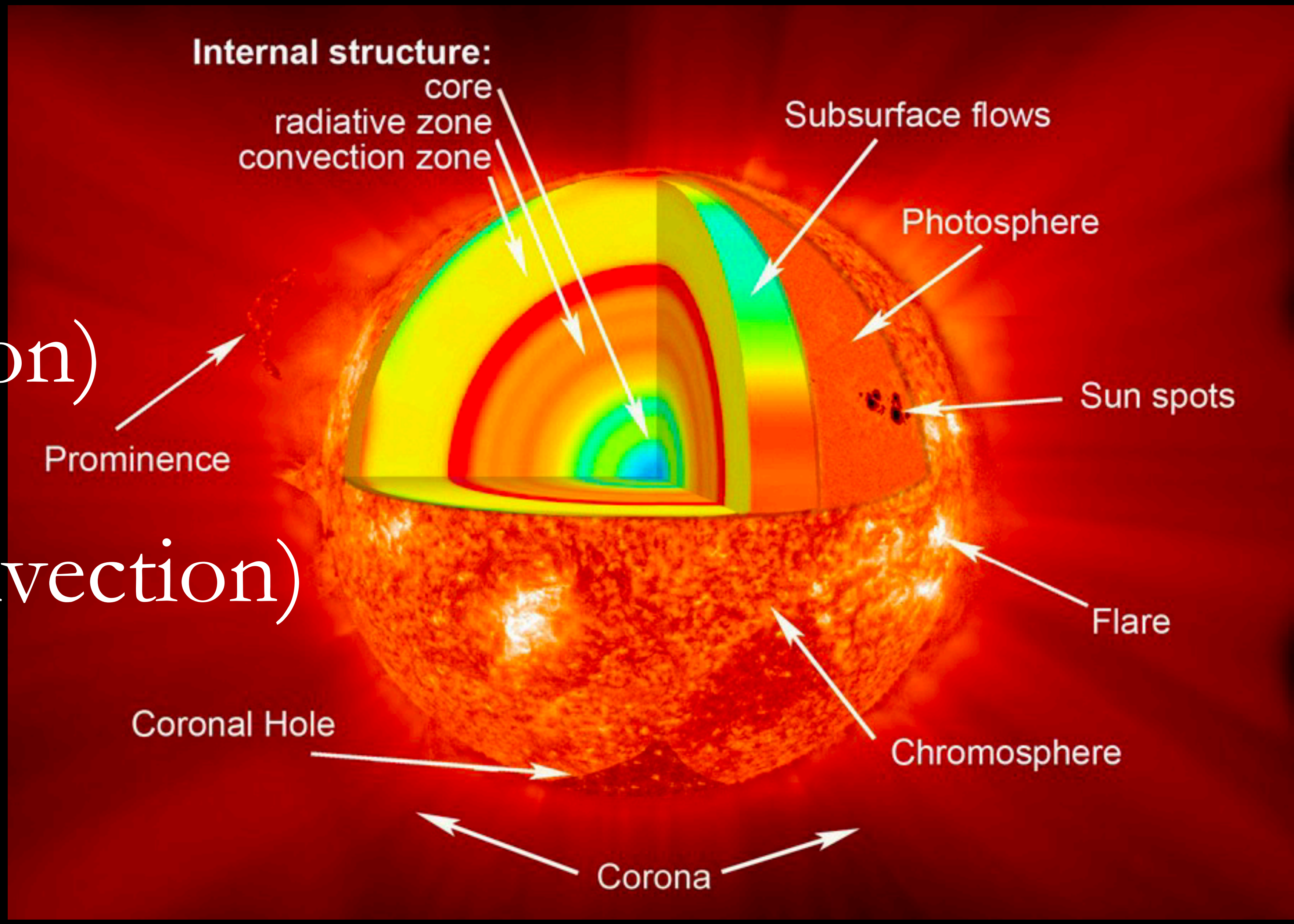
$$P = \frac{\rho k T}{\mu m_H},$$

$$\frac{dL(r)}{dr} = 4\pi r^2 \rho \varepsilon_{nuc}(r).$$

$$\frac{dT}{dr} = -\frac{3}{4ac}\frac{\bar{\kappa}\rho}{T^3}\frac{L(r)}{4\pi r^2},$$

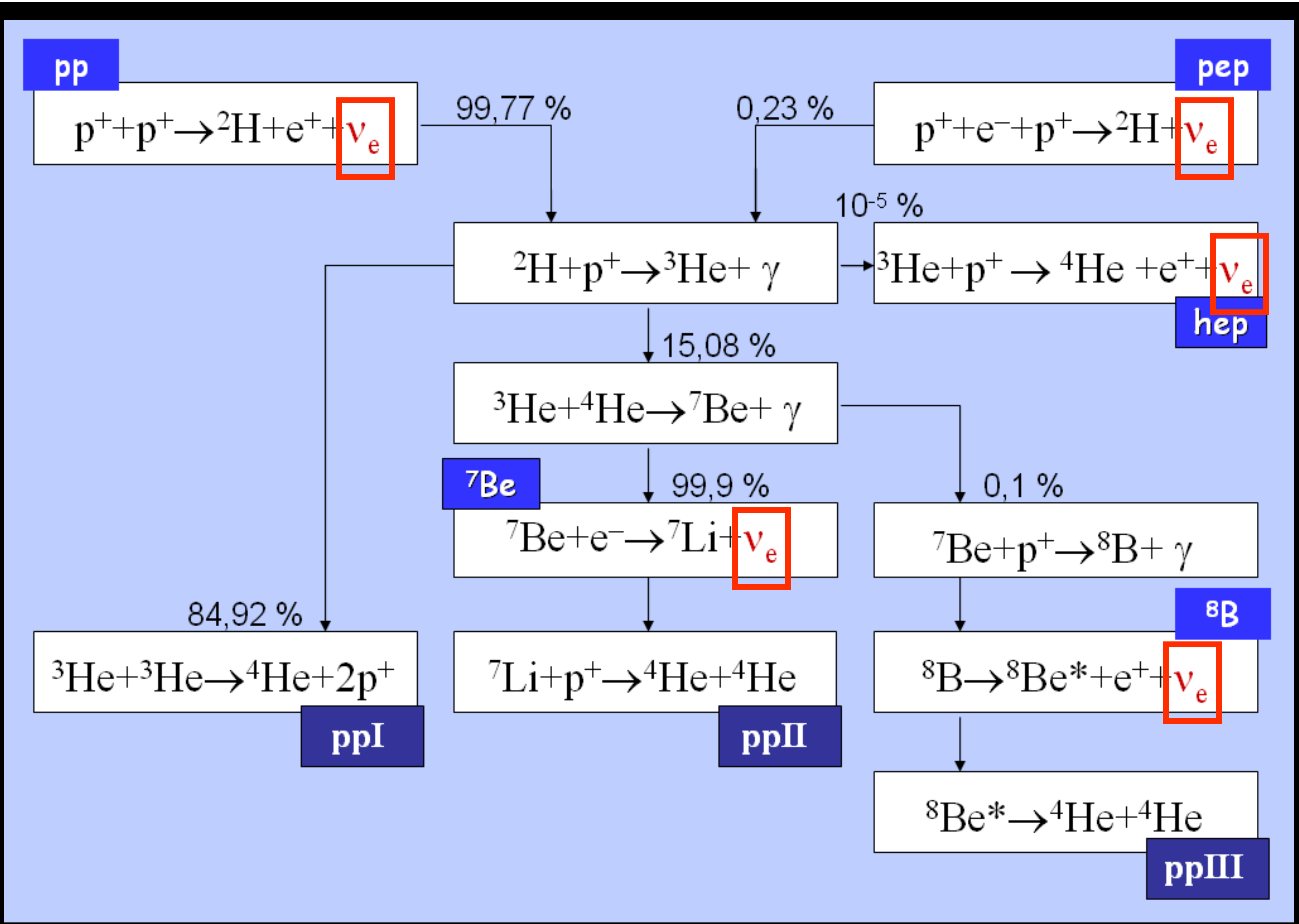
$$\frac{dT}{dr} = -\left(1-\frac{1}{\gamma}\right)\frac{\mu m_H}{k}\frac{GM(r)}{r^2}.$$

- Assumptions
  - Mass conservation
  - Hydrostatic equilibrium
  - Equation of state (gas & radiation)
  - Nuclear energy production
  - Energy transport (radiation, convection)
- Ingredients and constraints
  - Initial composition
  - Mass, luminosity, age
  - Nuclear and atomic cross sections (opacities)



- Predictions
  - Solar neutrino fluxes
  - Surface Helium abundance, depth of convective zone
  - Temperature and sound speed profiles (vs. radius)
  -

PP CHAIN & CNO CYCLE



pp

$p^+ + p^+ \rightarrow {}^2H + e^+ + \nu_e$

99,77 %

0,23 %

pep

$p^+ + e^- + p^+ \rightarrow {}^2H + \nu_e$

$^2H + p^+ \rightarrow {}^3He + \gamma$

10^{-5} %

$^3He + p^+ \rightarrow {}^4He + e^+ + \nu_e$

hep

15,08 %

$^3He + {}^4He \rightarrow {}^7Be + \gamma$

99,9 %

0,1 %

^{7}Be

$^7Be + e^- \rightarrow {}^7Li + \nu_e$

$^7Be + p^+ \rightarrow {}^8B + \gamma$

84,92 %

^{8}B

$^3He + {}^3He \rightarrow {}^4He + 2p^+$

ppI

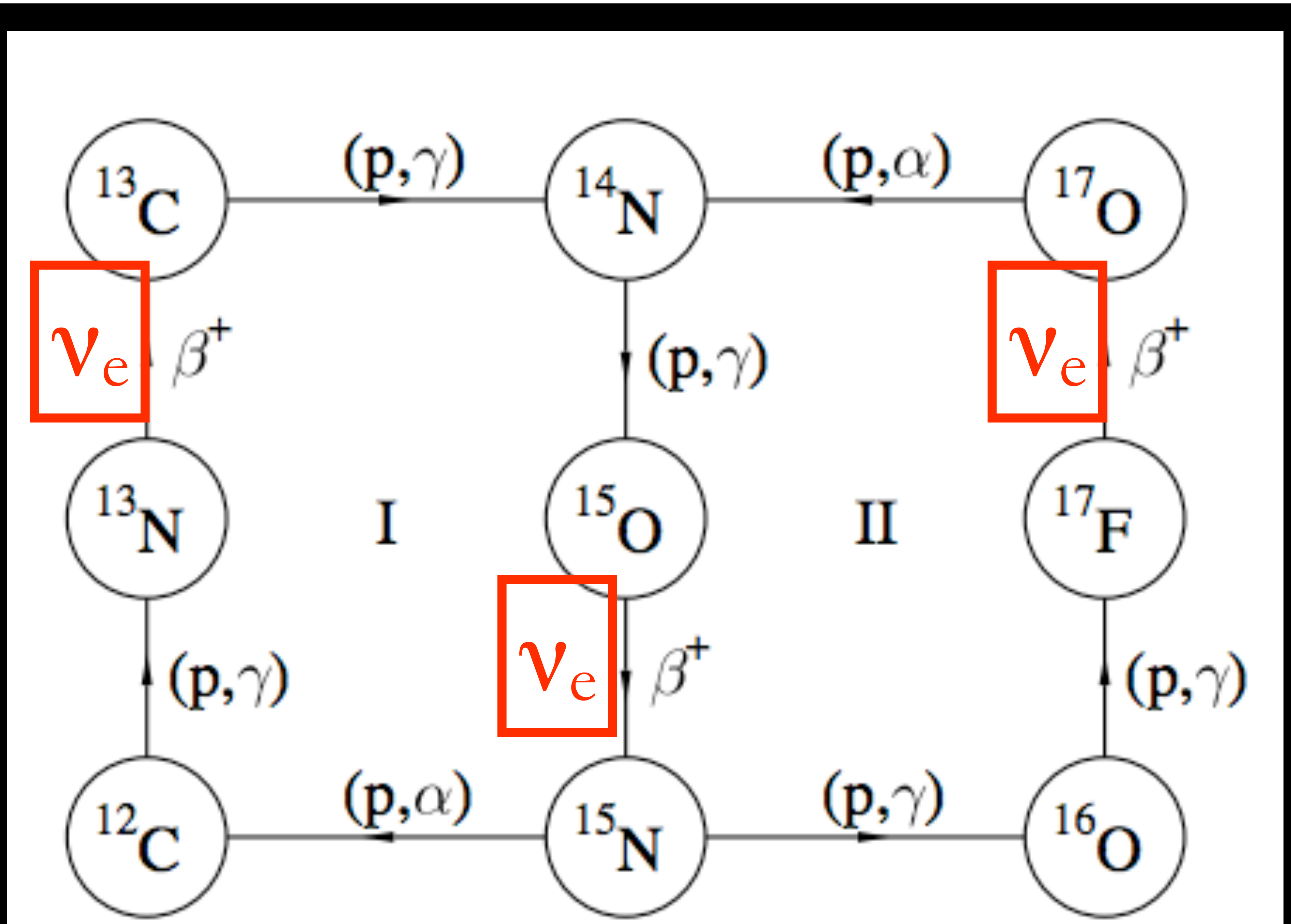
$^7Li + p^+ \rightarrow {}^4He + {}^4He$

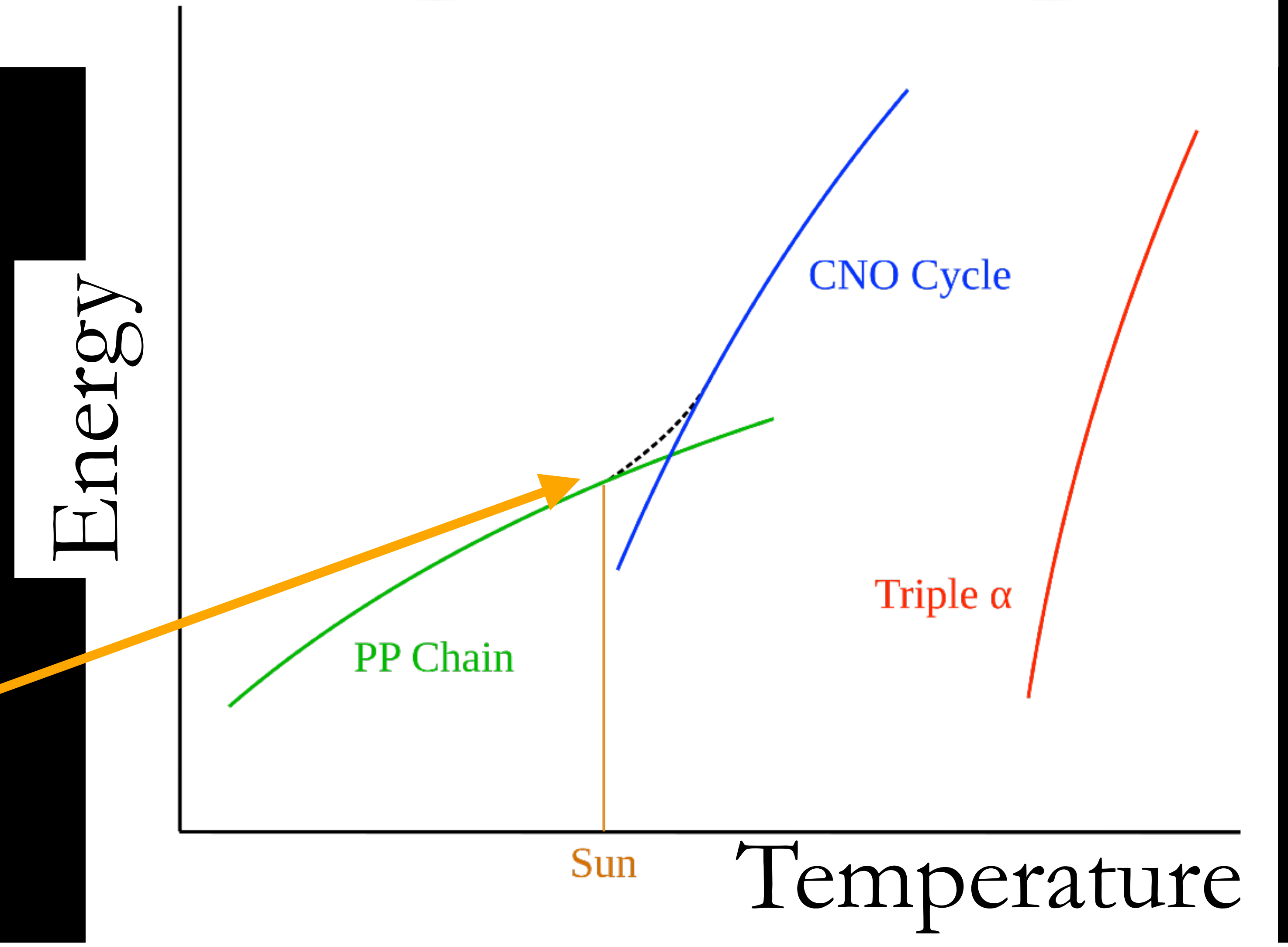
ppII

$^8B \rightarrow {}^8Be^* + e^+ + \nu_e$

$^8Be^* \rightarrow {}^4He + {}^4He$

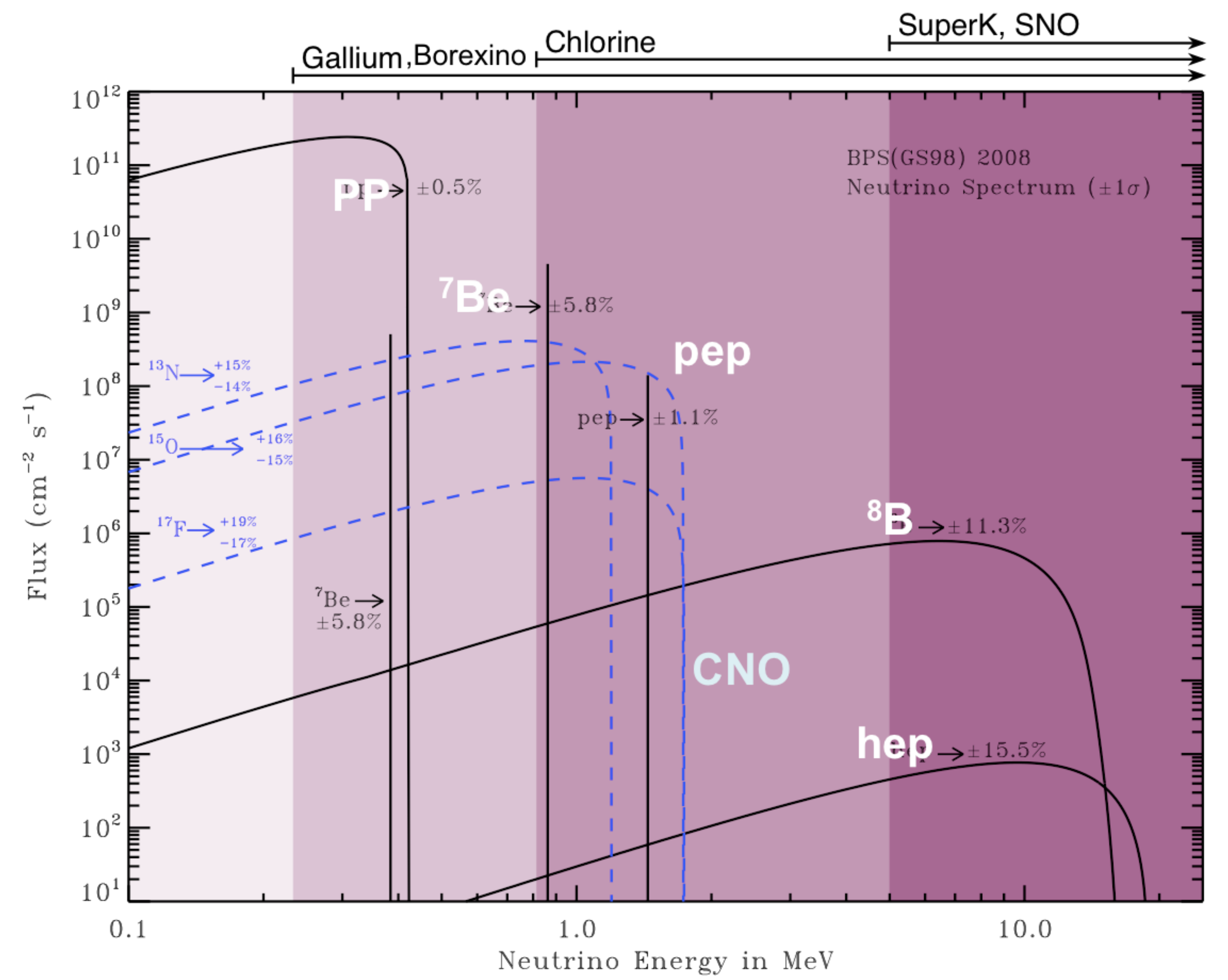
ppIII





PP chain dominates for stars like the Sun

SOLAR NEUTRINO SPECTRUM

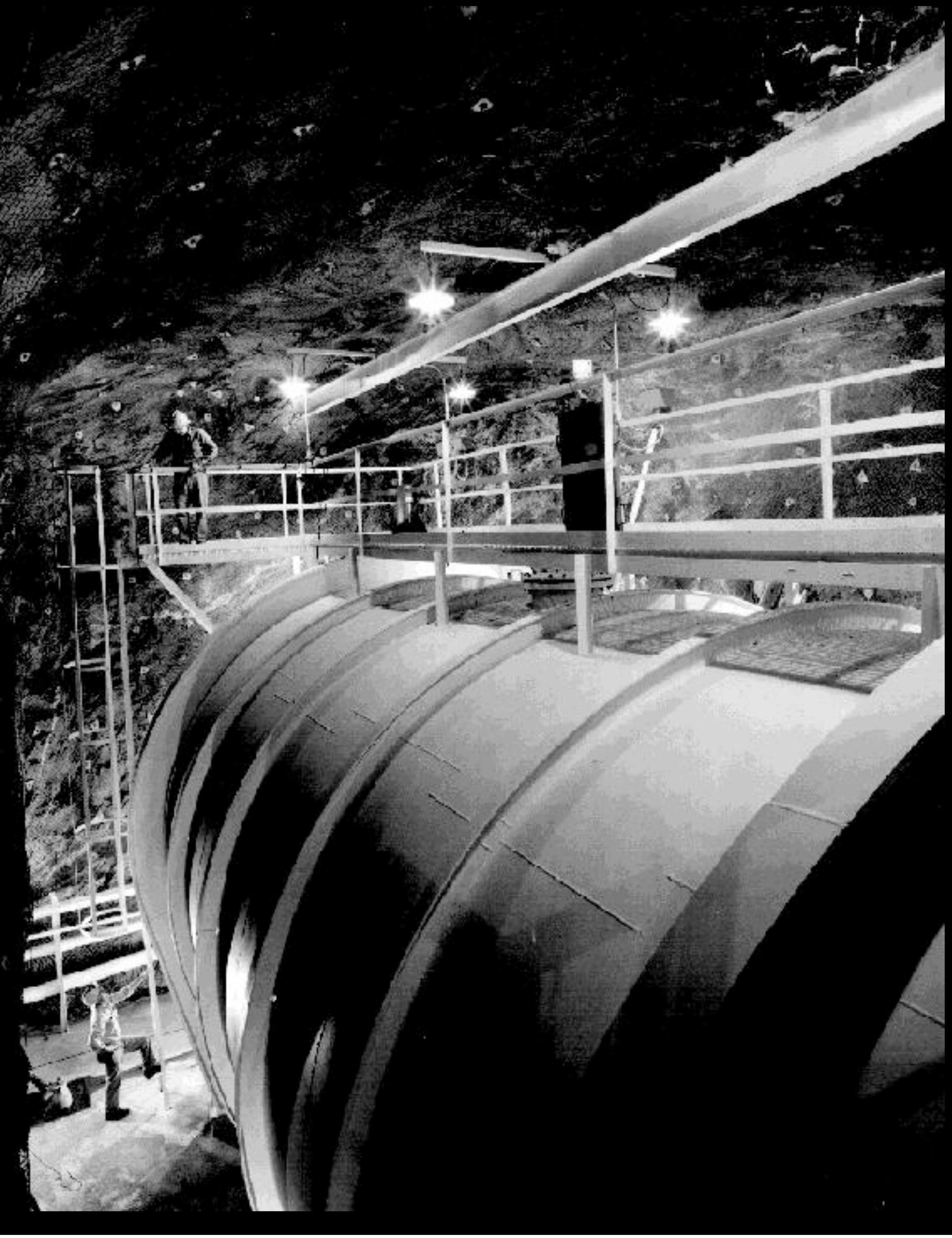


CHLORINE EXPERIMENT

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

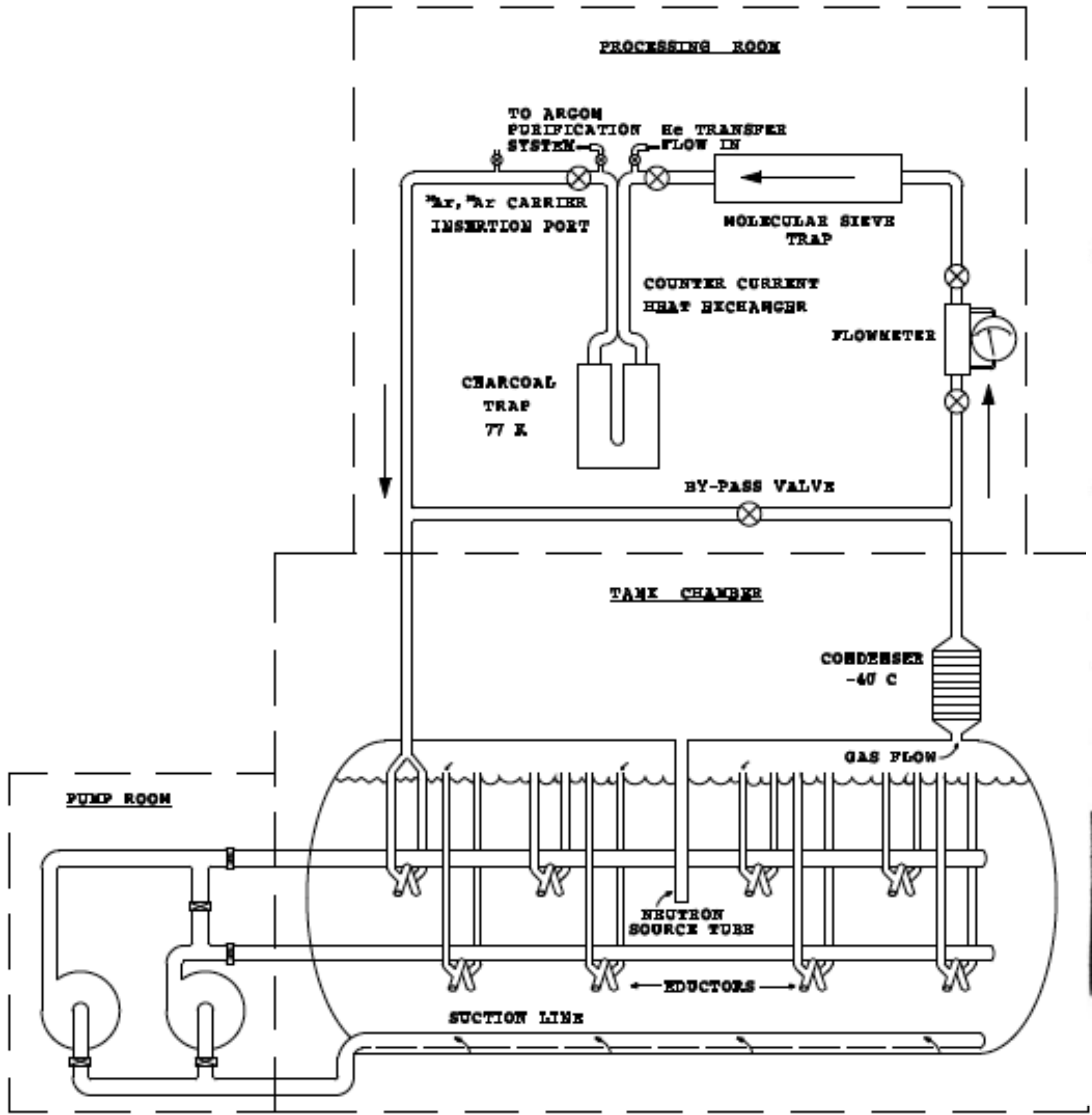
E > 814 keV: sensitive mostly to ^{8}B, ^{7}Be ν

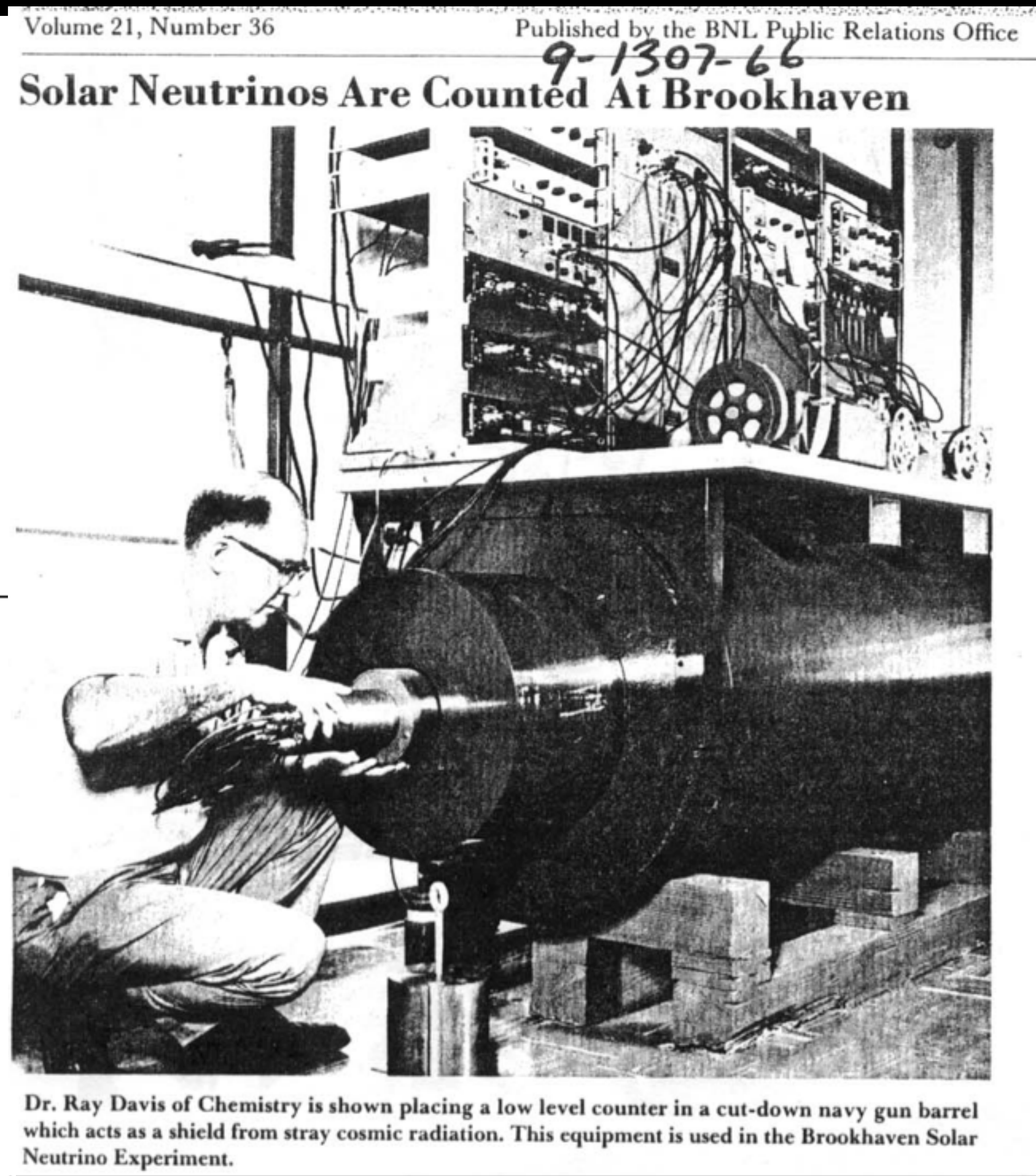
- The pioneering solar neutrino experiment by Ray Davis
- Homestake mine (USA), 1478 m deep
- Big tank with 600 tons of CCl_4 (solvent)
- Chemical extraction of argon from tank (2 atoms/day)!
- Detection of the ^{37}Ar decays



Ray Davis,
Nobel 2002

Radiochemical method proposed by Pontecorvo & Alvarez





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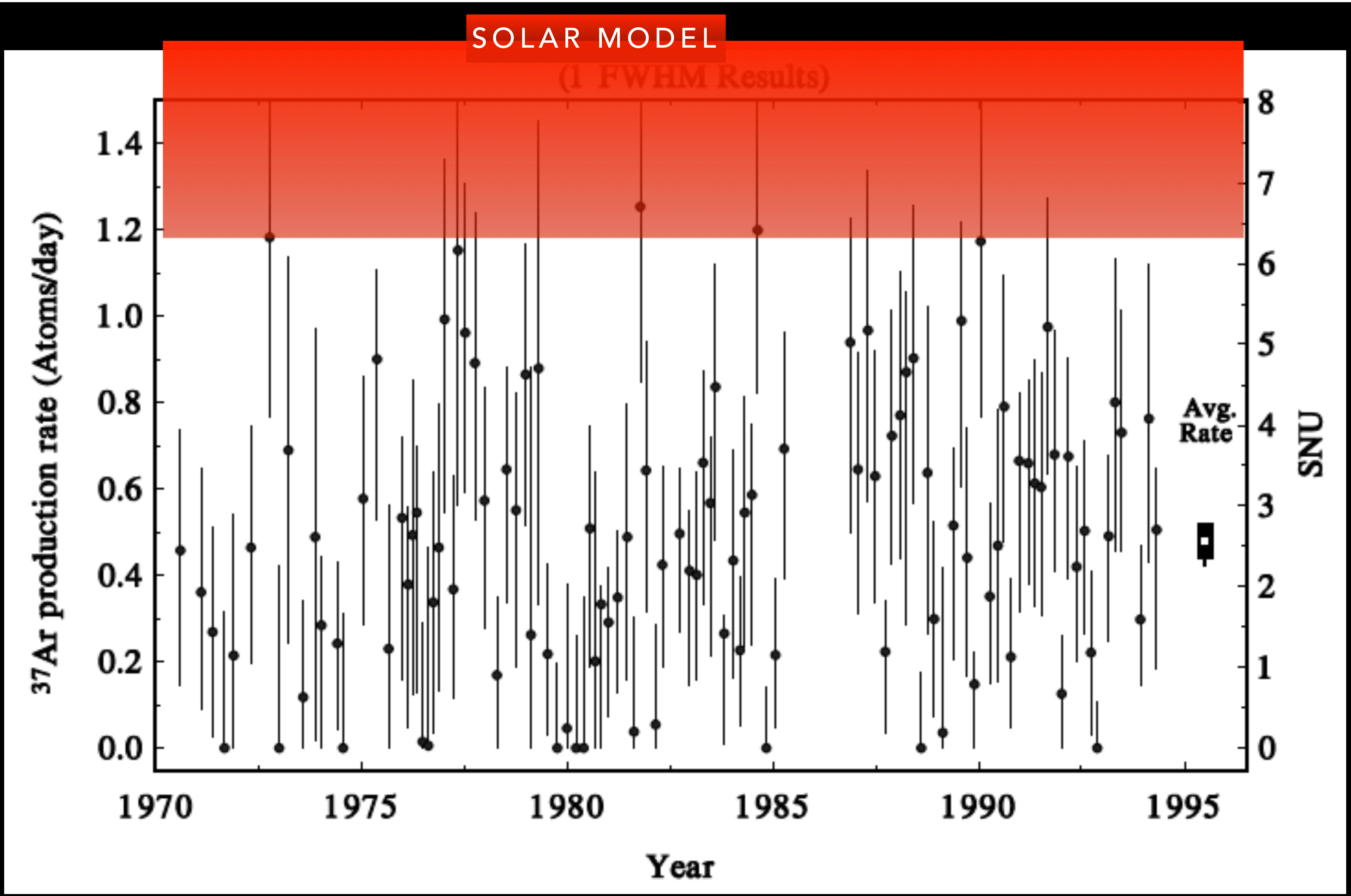
9-1307-66

Solar Neutrinos Are Counted At Brookhaven

Dr. Ray Davis of Chemistry is shown placing a low level counter in a cut-down navy gun barrel which acts as a shield from stray cosmic radiation. This equipment is used in the Brookhaven Solar Neutrino Experiment.

CHLORINE RESULTS



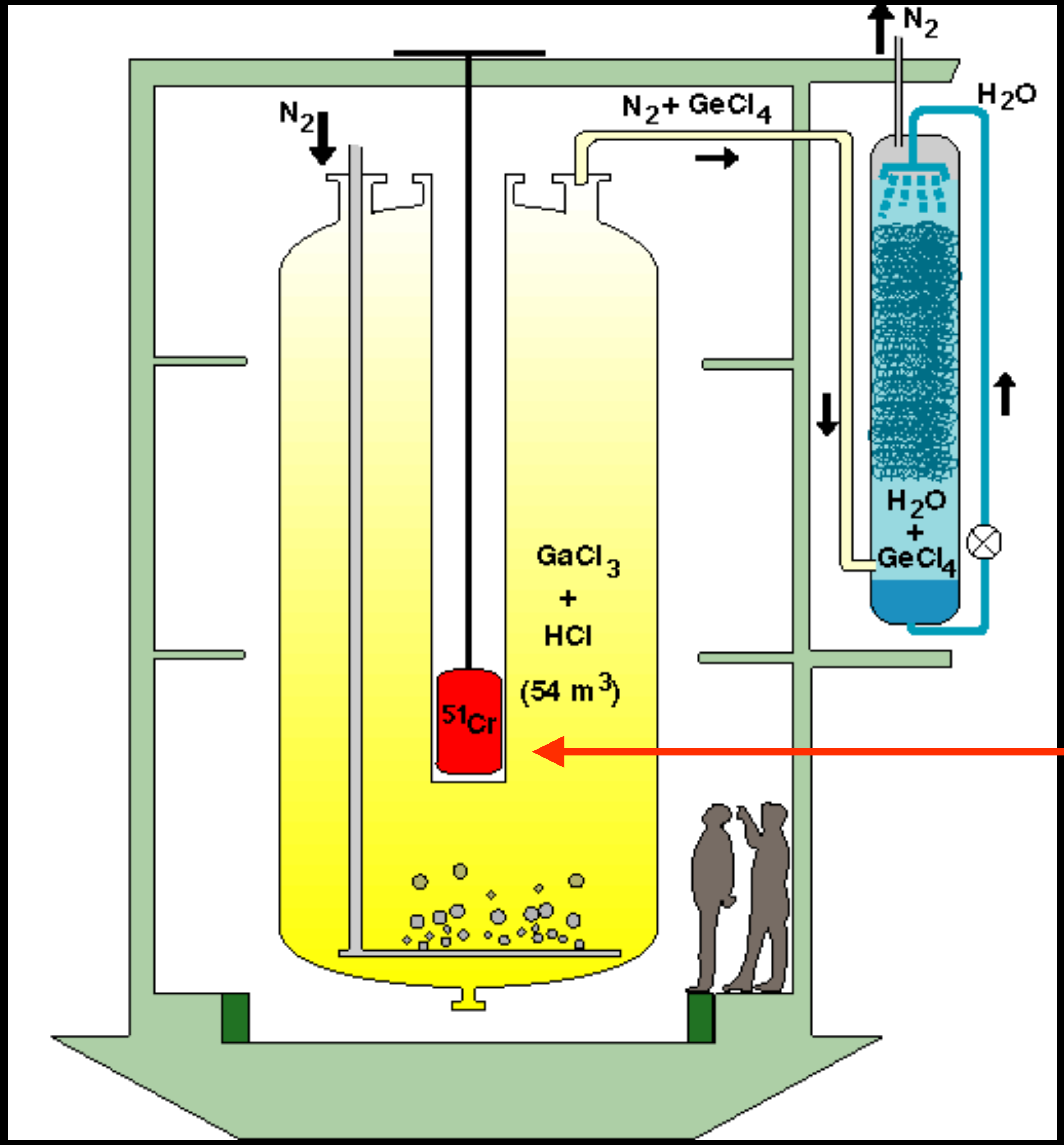
SNU
solar neutrino units
=
interactions per second
per 10^{36} atoms

- 25 year average: **2.56 ±0.16 ±0.16 SNU**
- Solar Model (BP2000): **7.6 ±1.2 SNU**

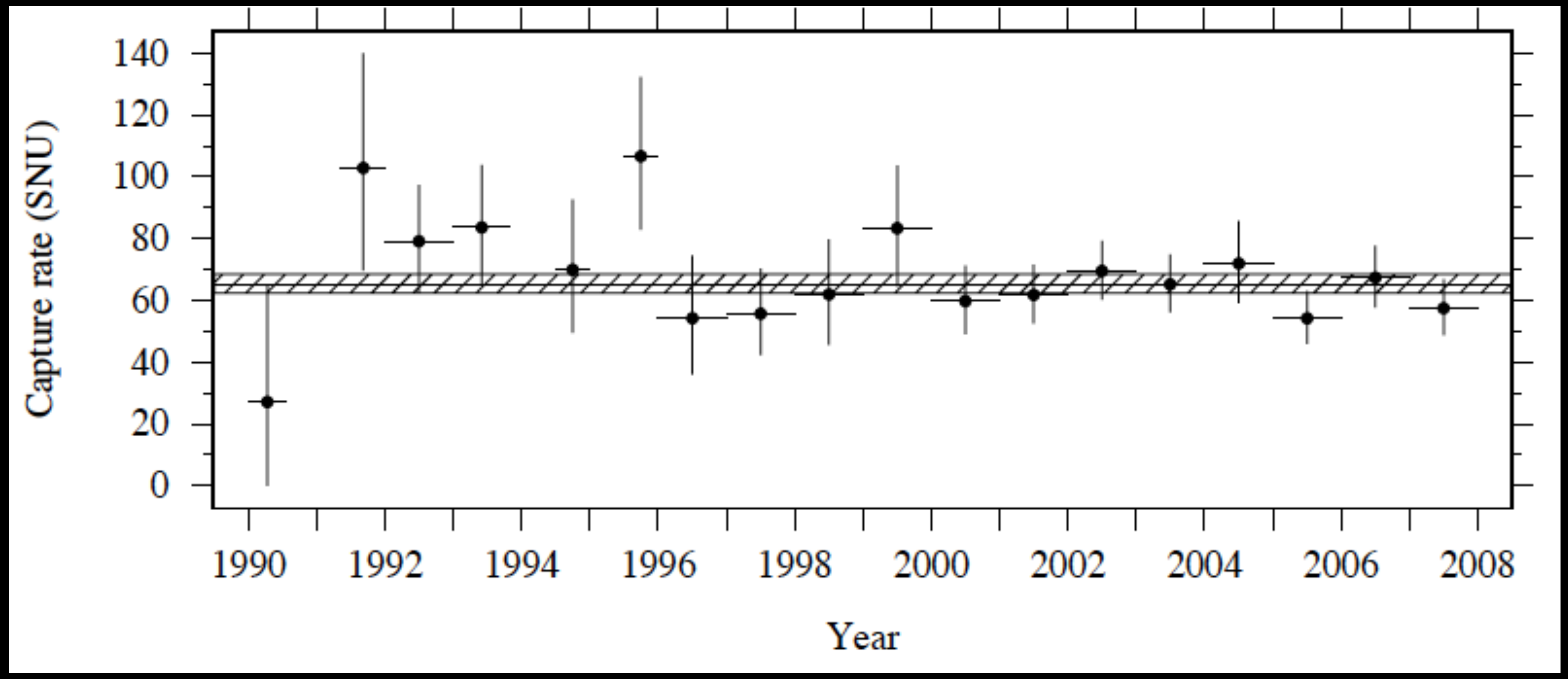
GALLIUM EXPERIMENTS

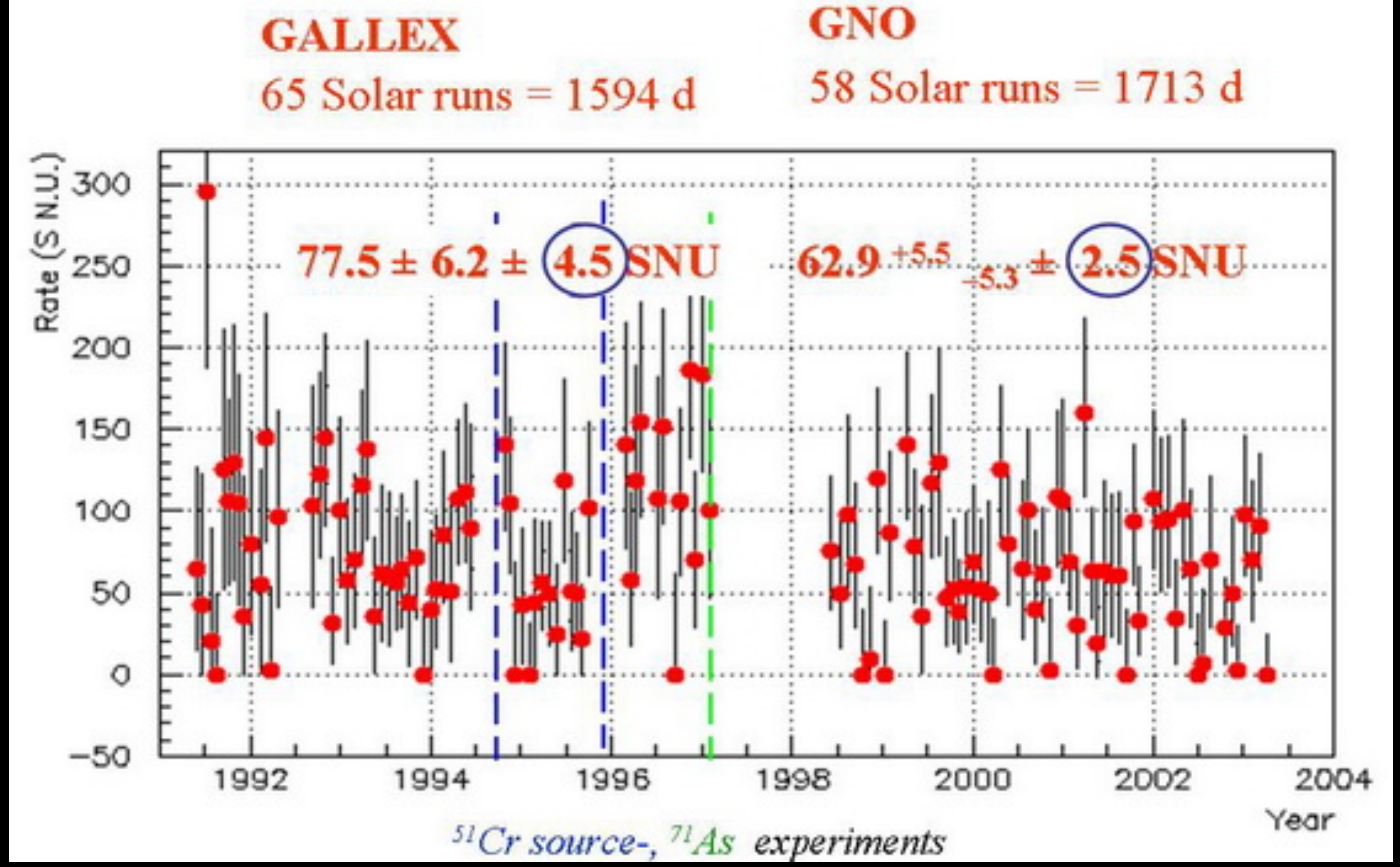
$$^{71}\mathrm{Ga} + \nu_e \rightarrow {}^{71}\mathrm{Ge} + e^-$$

- Also radiochemical method, but with Gallium
- Lower energy threshold (E> 233 keV): sensitive to all solar neutrinos (mostly pp)
- GALLEX/GNO (Gran Sasso, Italy), SAGE (Baksan, Russia)



Intense radioactive source used as neutrino source for calibration

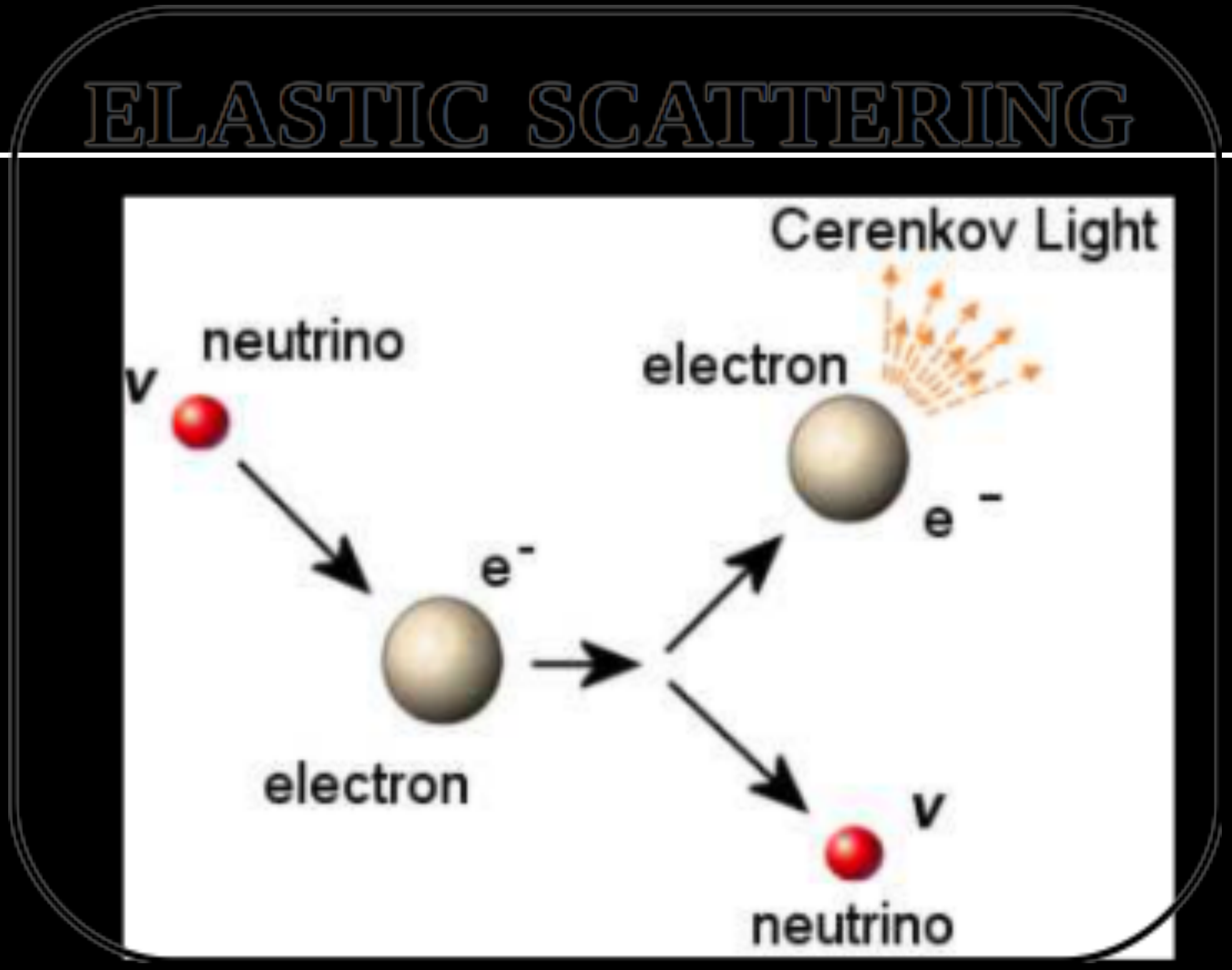




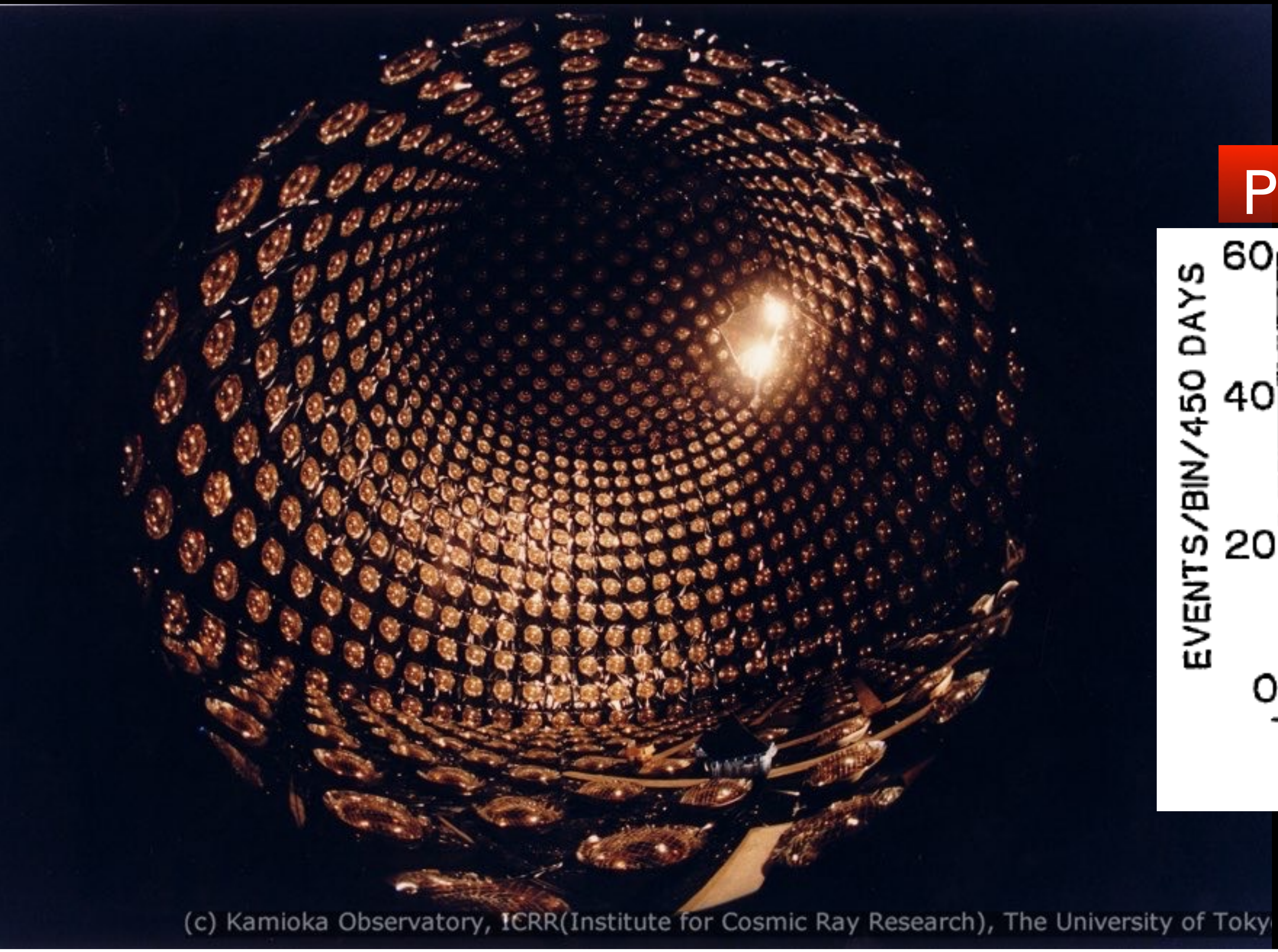
- Average rate: **66 ±3.1 SNU**
- Solar Model: **128 ±8 SNU**

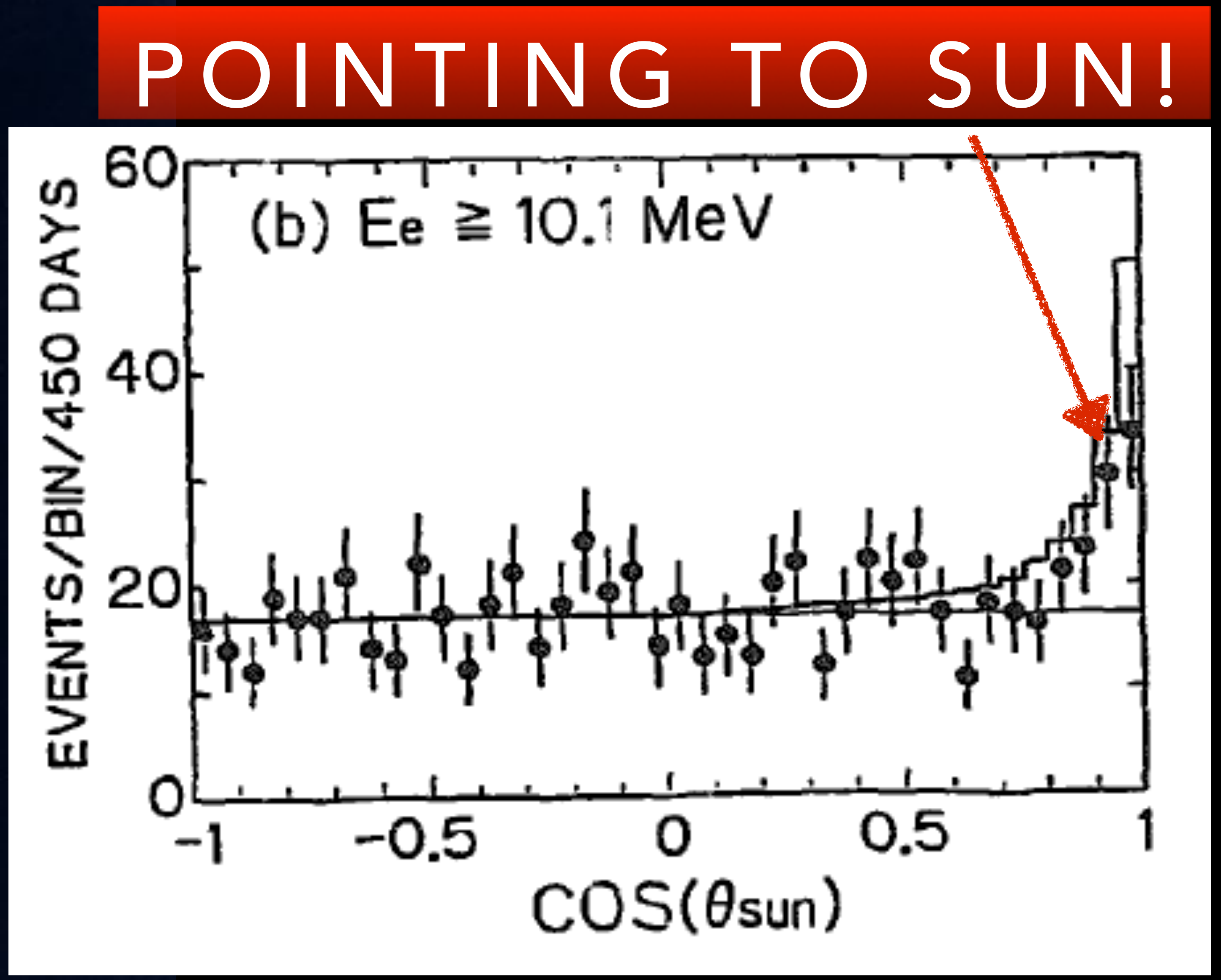
KAMIOKANDE-II

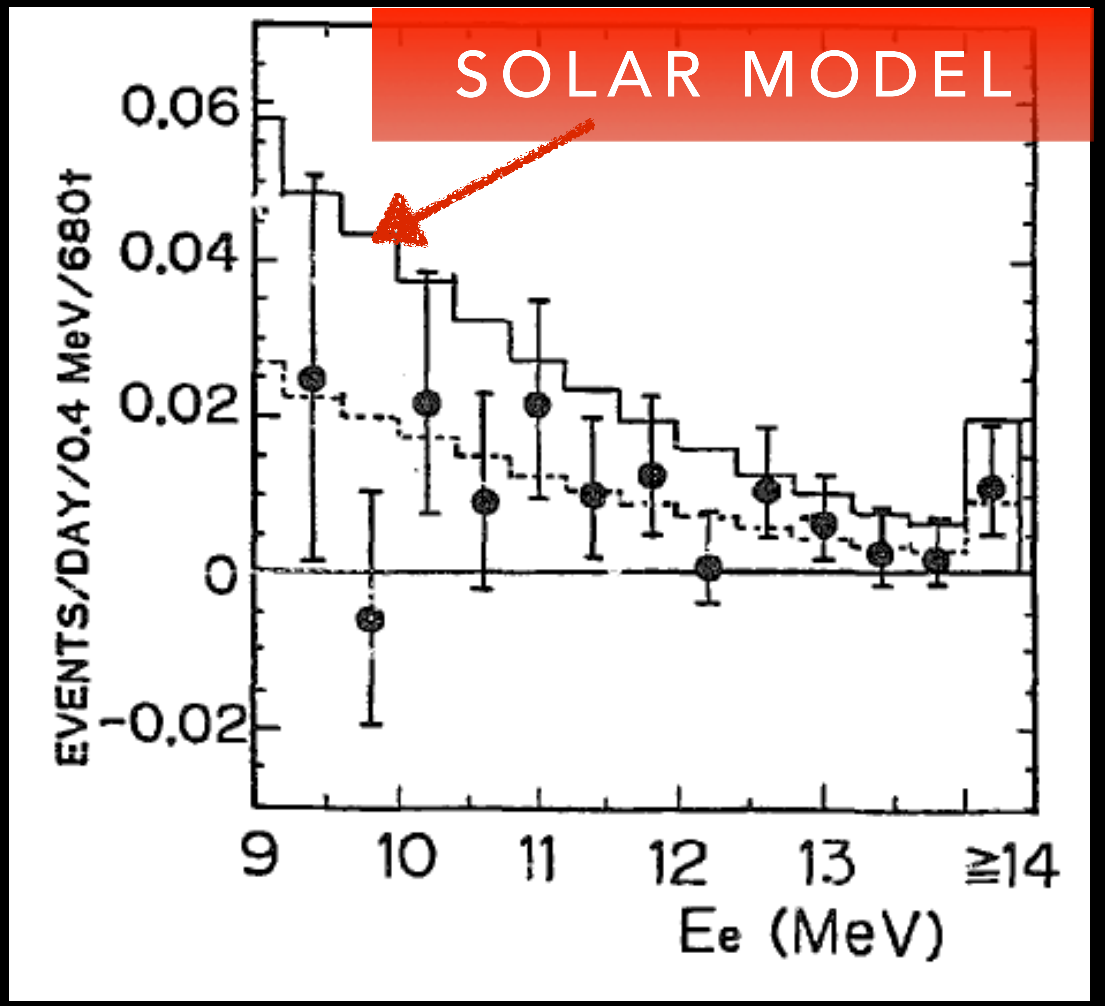
- Water Cherenkov Detector, Kamioka mine
- 2 ktons of water seen by 948 PMTs
- Can measure direction and energy
- High threshold (E> 9 MeV)



Masatoshi Koshiba, Nobel 2002

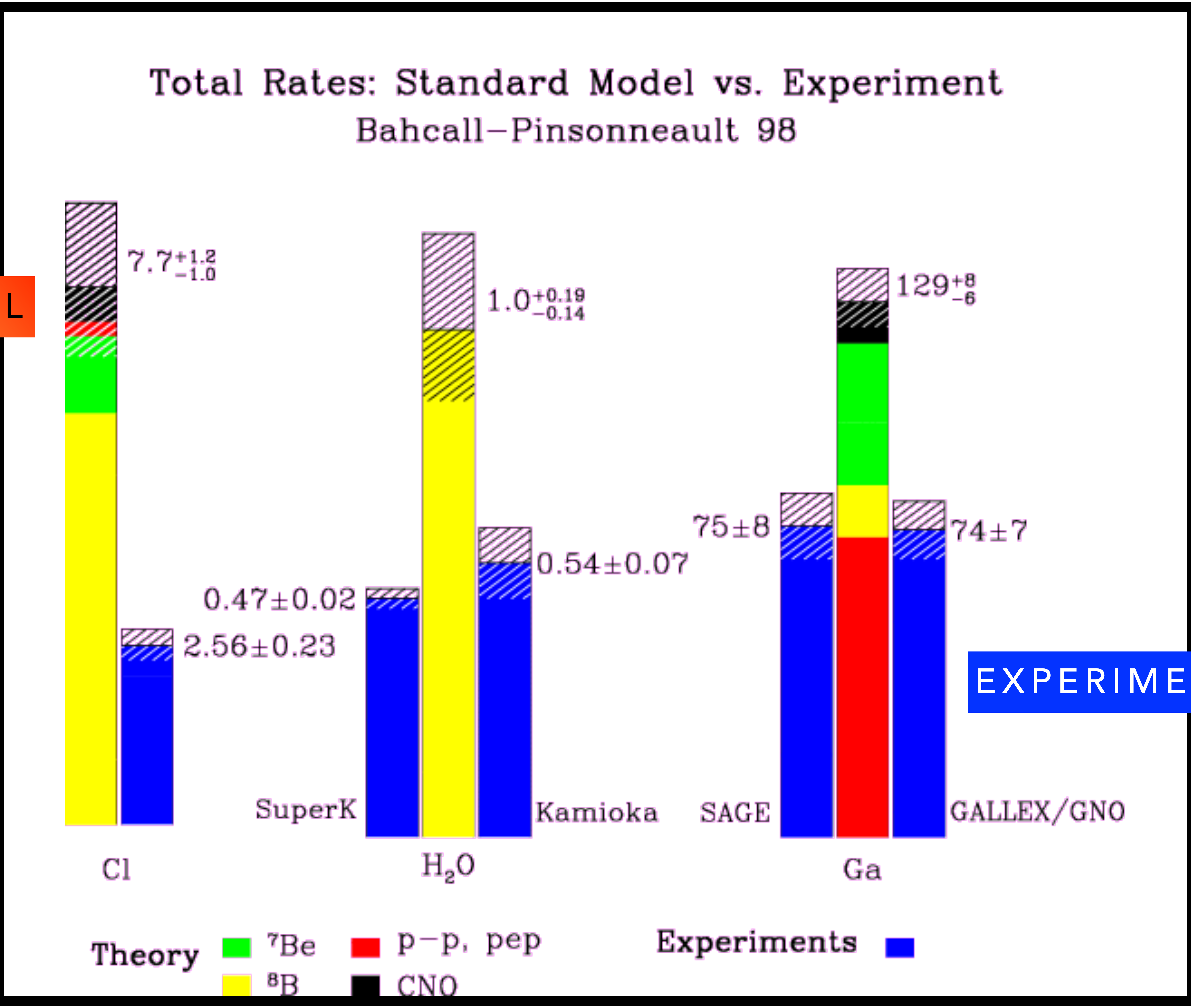

(c) Kamioka Observatory, ICRR(Institute for Cosmic Ray Research), The University of Toky


POINTING TO SUN!


SOLAR MODEL

Also observes suppression

SOLAR NEUTRINO PROBLEM



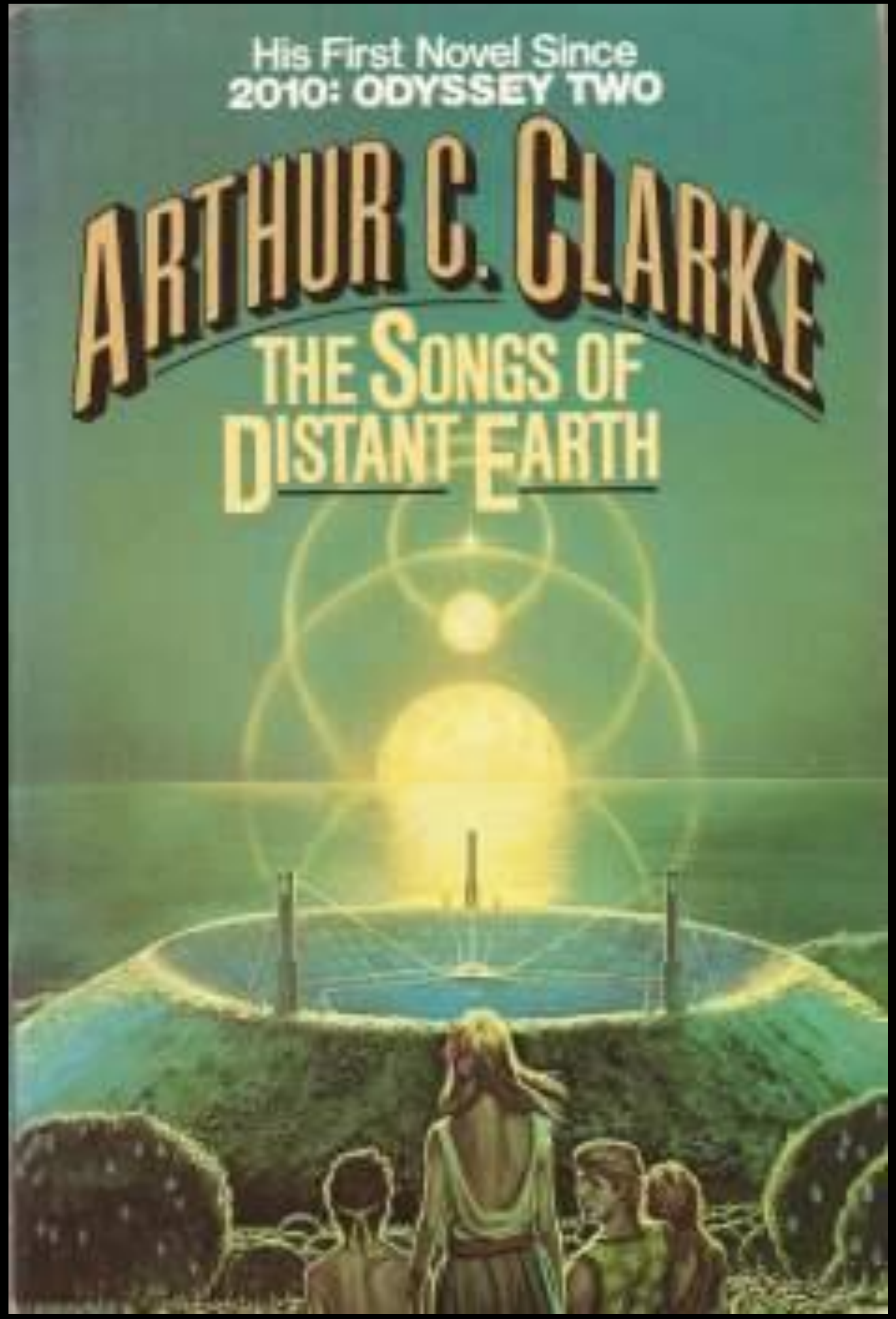
SOLAR MODEL

EXPERIMENTAL RESULTS

PROPHECY OF DOOM?

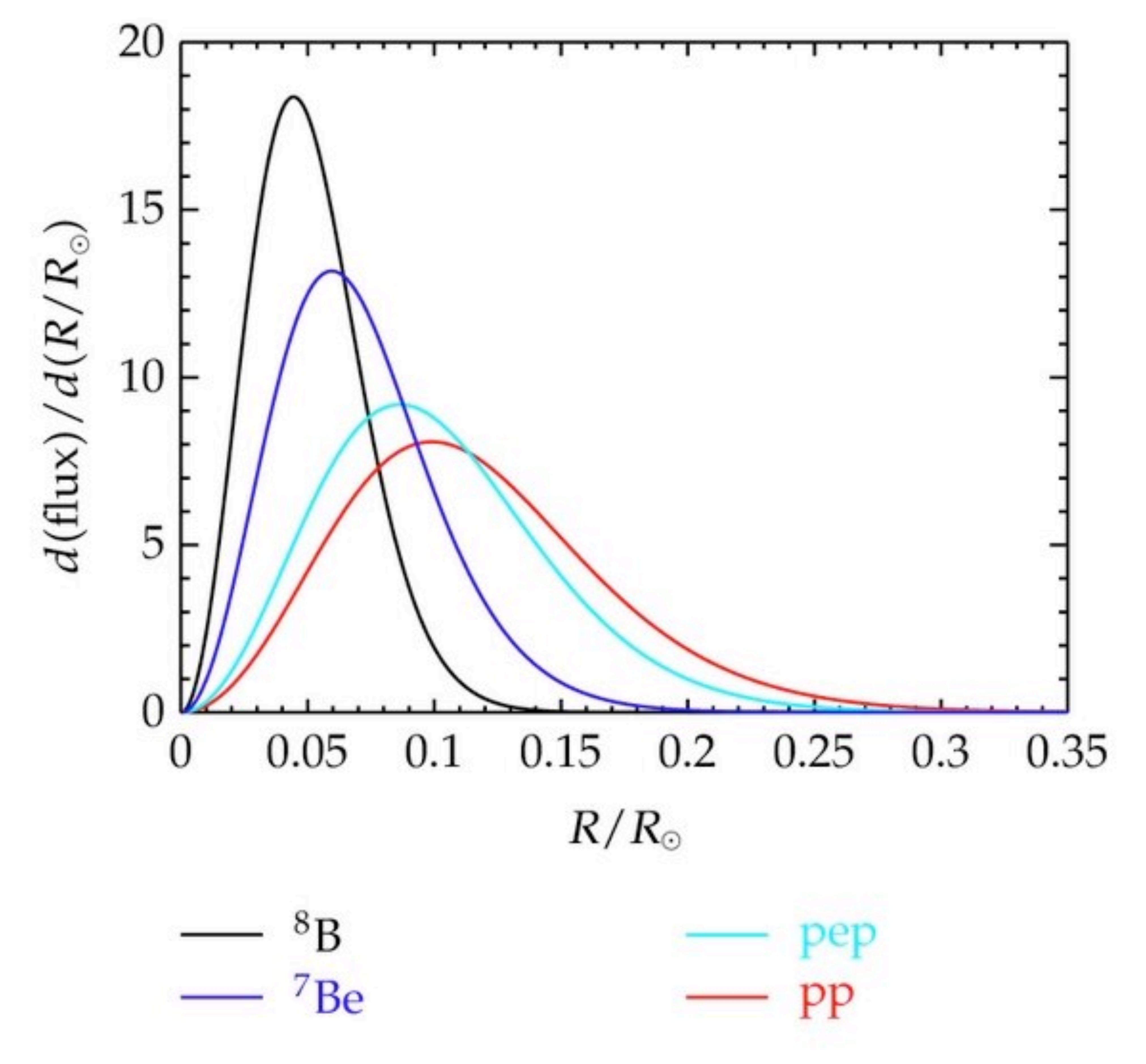
- Earth's funeral bell […] the **neutrino** […] Something so penetrating [...] **could be used to look into the hearts of suns.**[...]
- solar neutrinos were detected. But - **there were far too few of them.** […] nothing wrong with the theory, or with the equipment. **The trouble lay inside the Sun.** [...]
- humanity was under **sentence of death** […] The Sun would not blow up for at least a thousand years; and who could weep for the fortieth generation?

- Arthur C. Clarke, "The Songs of Distant Earth" (1986)



ASTROPHYSICAL SOLUTIONS ?

- Temperature dependence of fluxes
  - $\phi(^8B) \sim T^{25}$ (only in very central region)
  - $\phi(^7Be) \sim T^{11}$ (a bit wider region)
- To explain the results only with astrophysics, the ^{7}Be flux would have to be more suppressed than ^{8}B
- But a T decrease would lower ^{8}B much more than ^{7}Be, so the simple astrophysical solutions didn't work
- Heavy tweaking of input parameters (cross sections) or physics (plasma effects) was necessary, and still the fit was not so good.



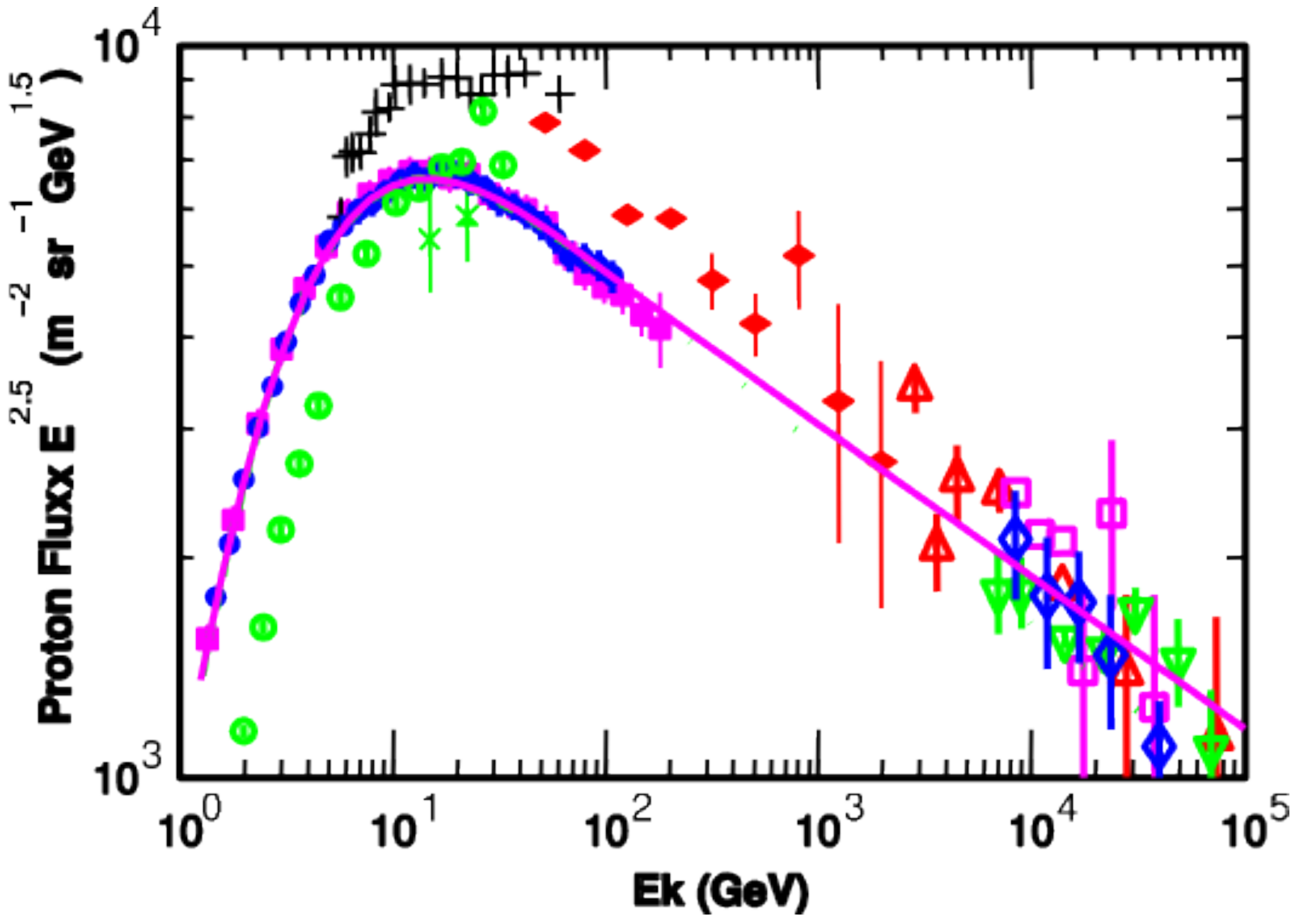
A. DAR, SURVEYS HIGH ENERG. PHYS. 12 (1998)

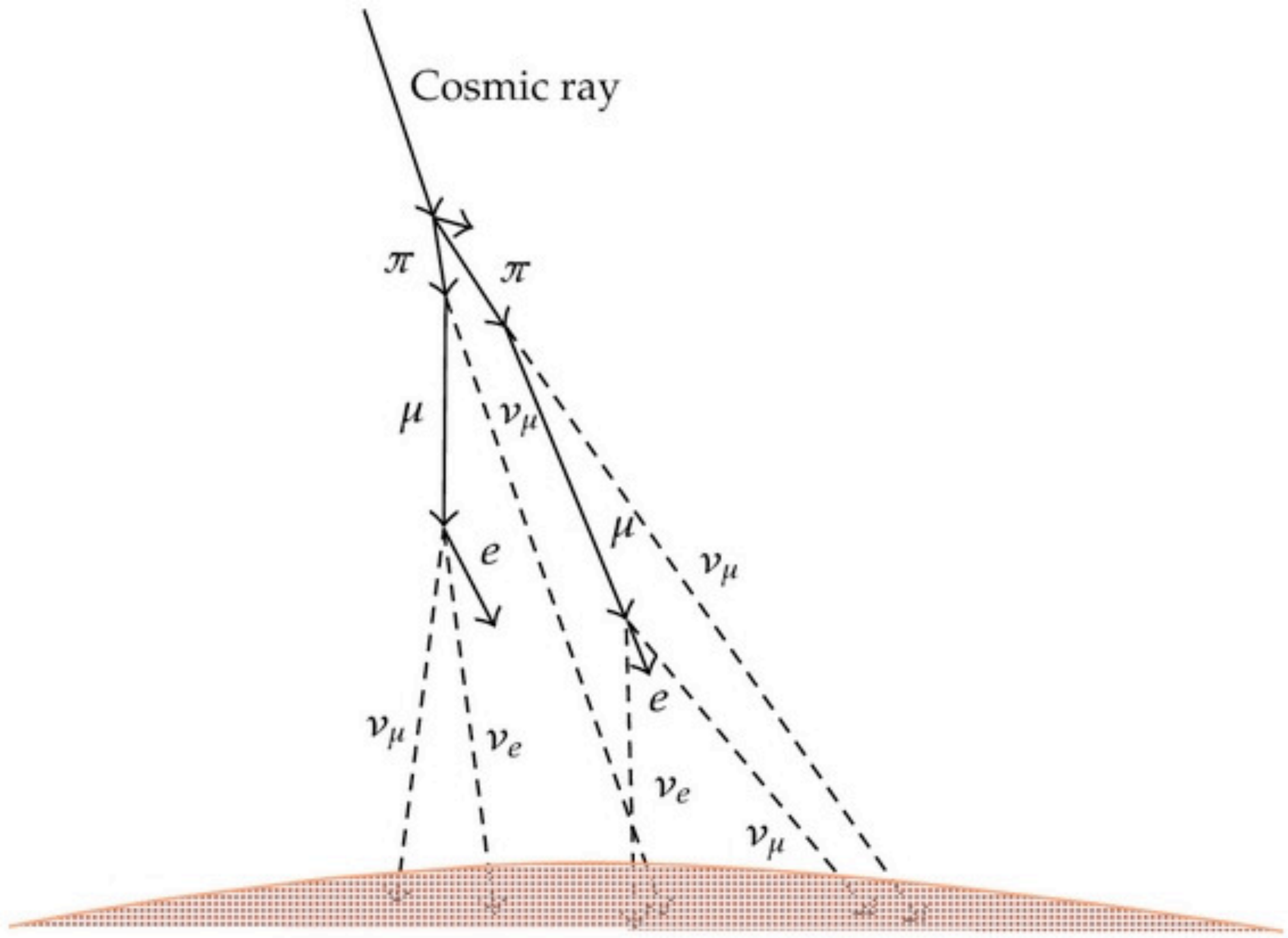
THE ATMOSPHERIC NEUTRINO ANOMALY

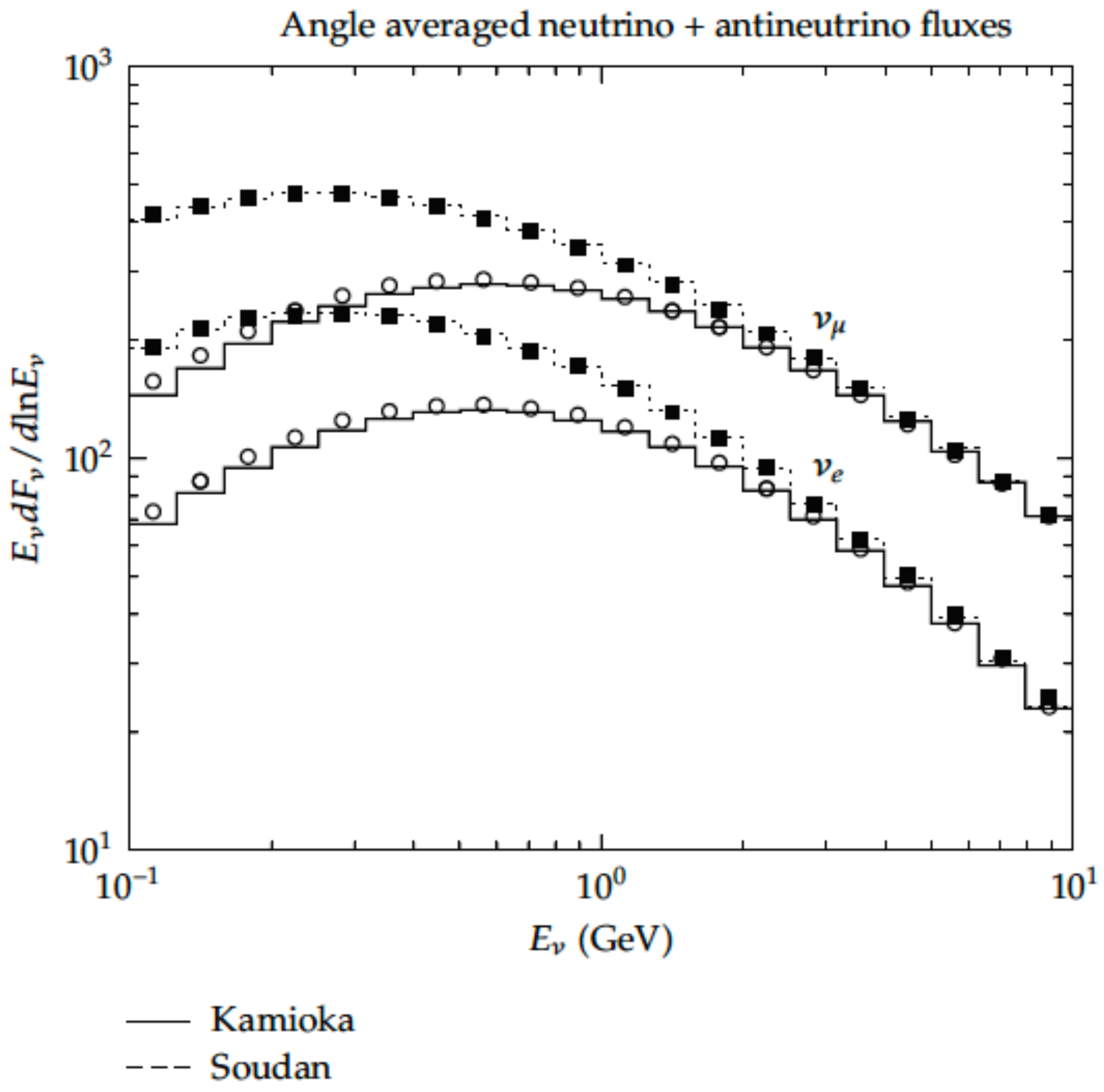
NEUTRINOS FROM COSMIC RAYS

- Interaction of primary cosmic rays (mostly protons) produces many pions, that decay to muons. The decay chain produces a ν_μ, a $\overline{\nu}_\mu$ and a ν_e (or $\overline{\nu}_e$)
- Large uncertainties in primary flux. Also, magnetic field deflects the lower energy CR. So ν flux depends on geomagnetic location

$$\begin{aligned} \pi^{\pm} \rightarrow\ & \mu^{\pm} + \nu_\mu(\overline{\nu}_\mu) \\ & \hookrightarrow e^{\pm} + \nu_e(\overline{\nu}_e) + \overline{\nu}_\mu(\nu_\mu) \end{aligned}$$

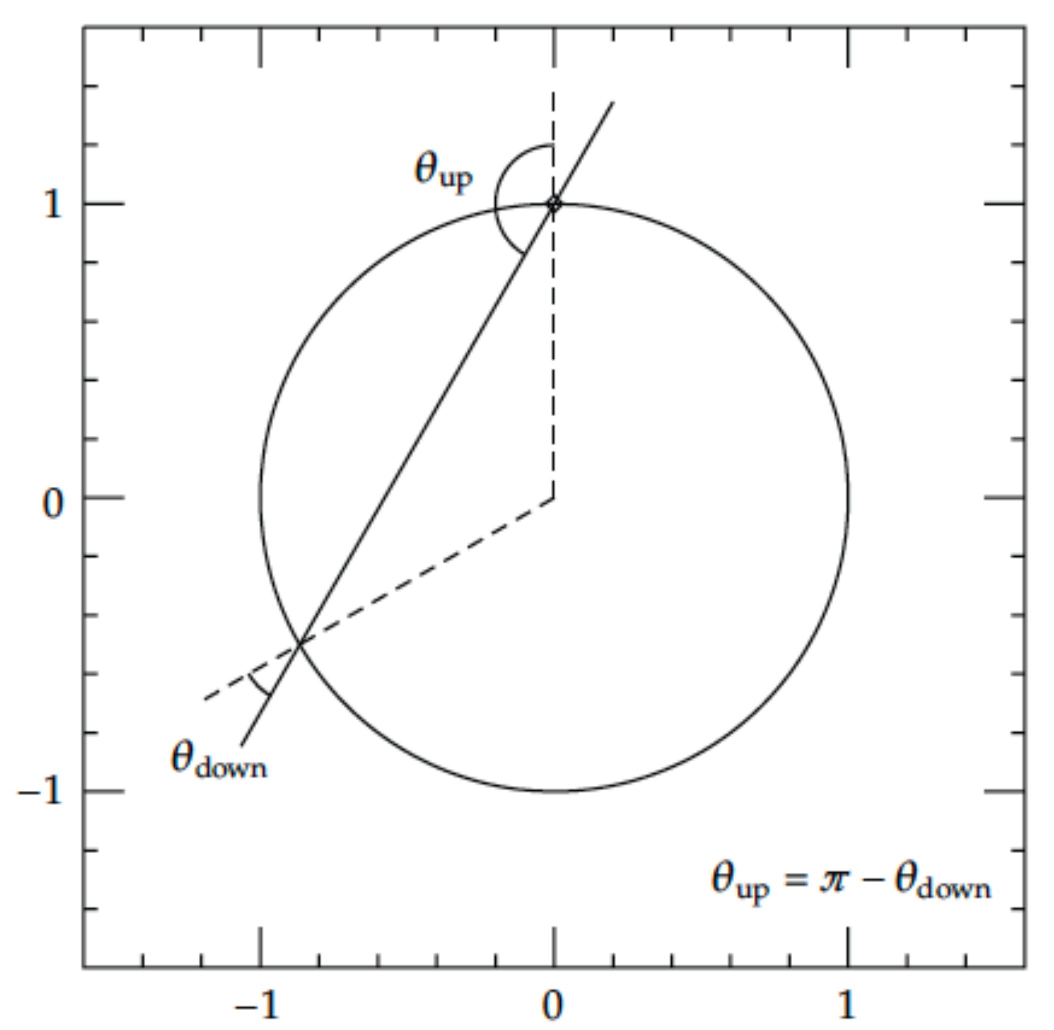




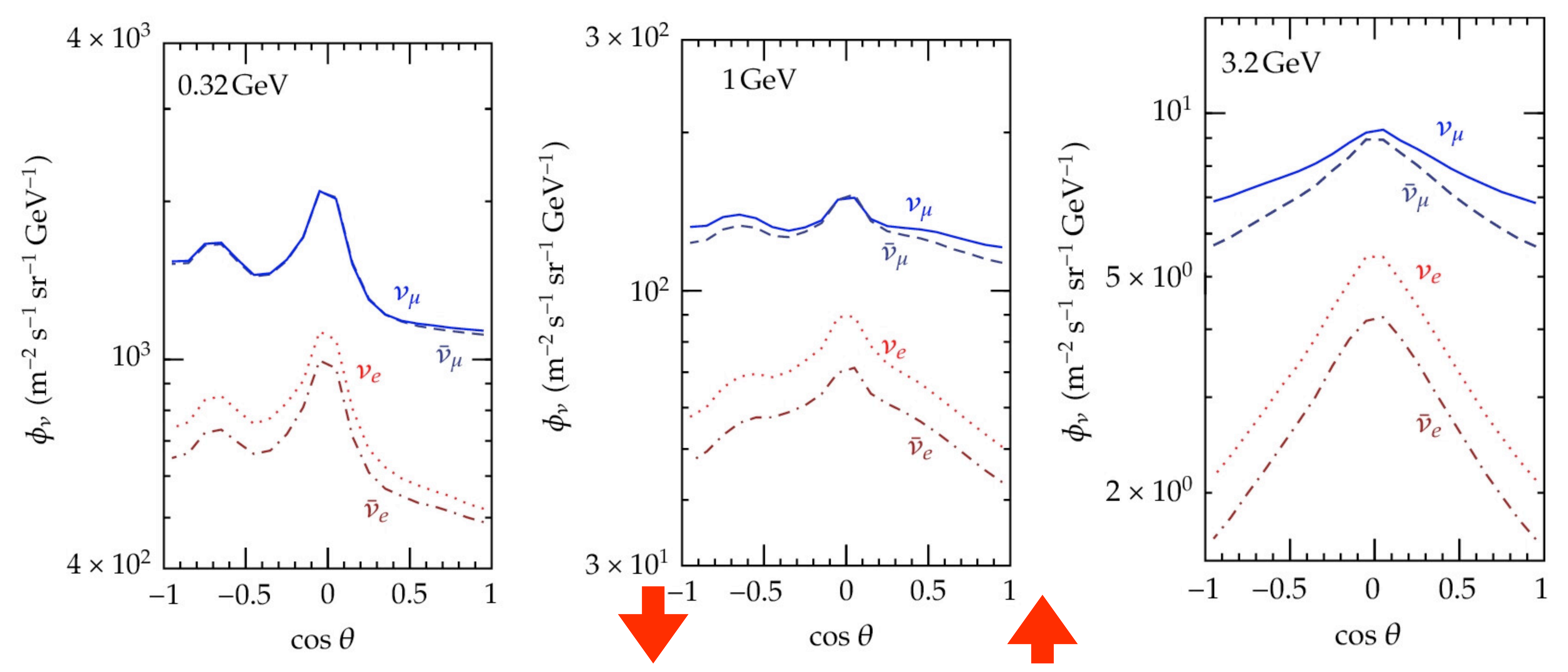


KAJITA, ADV. HEP 2012, 1, 504715

PROPERTIES OF ATMOSPHERIC NEUTRINOS

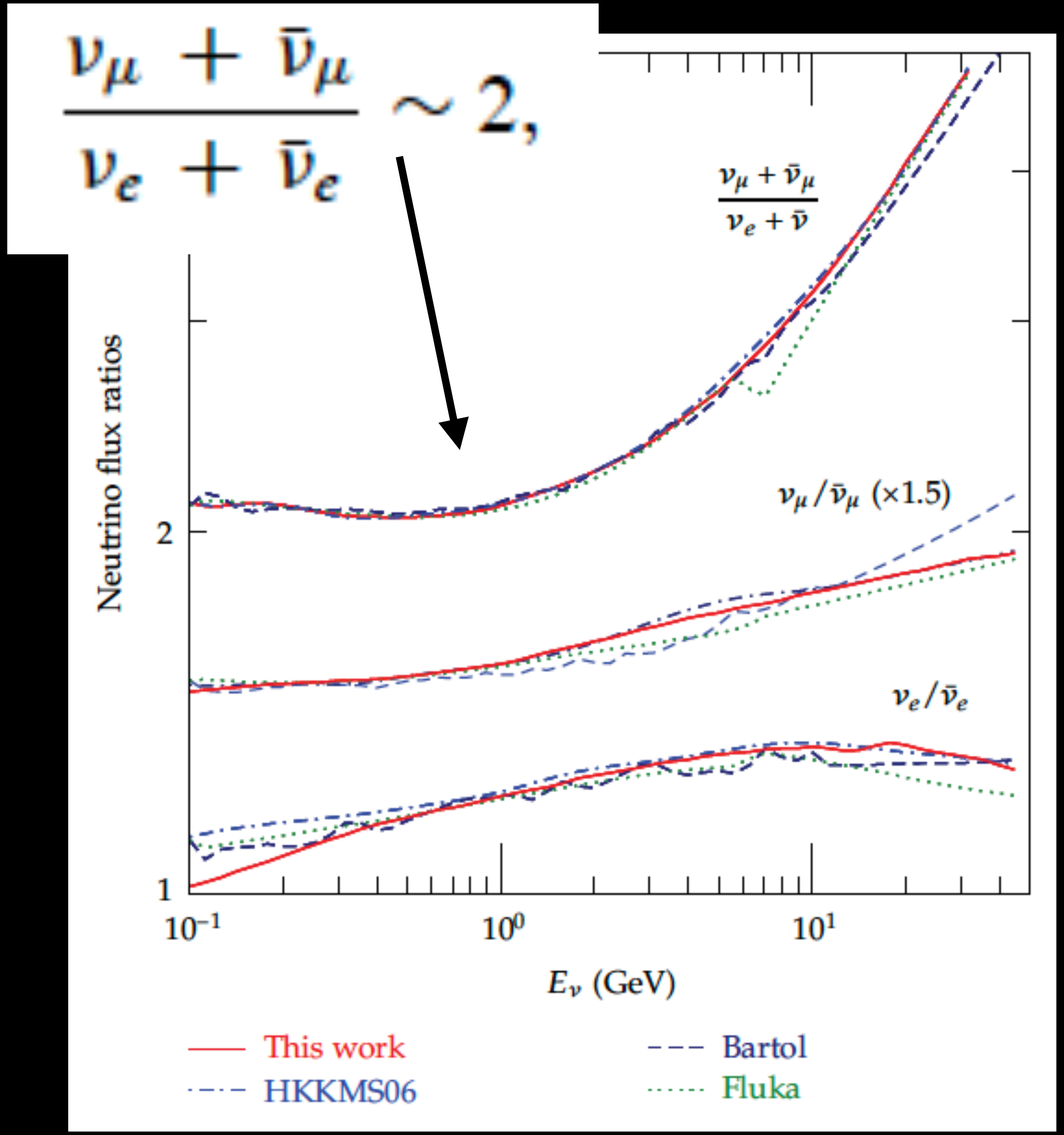


- Upward/downward roughly symmetric (less so at low E)
- Ratio μ/e roughly 2 (higher at high energy)
- Flux much lower than solar neutrinos, sharply decreasing with energy (as for cosmic rays)



downward going

upward going

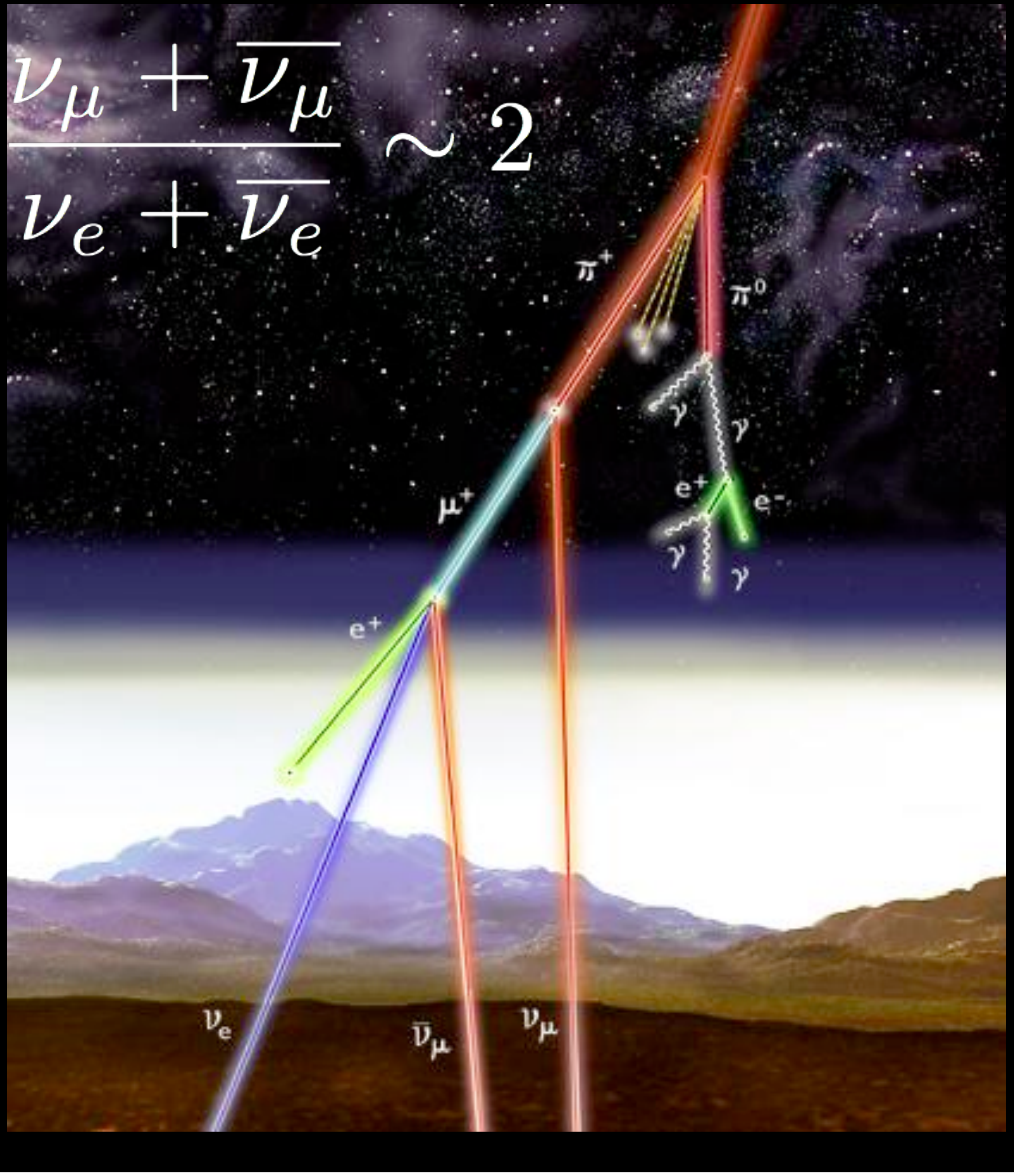

$$\frac{\nu_\mu + \bar{\nu}_\mu}{\nu_e + \bar{\nu}_e} \sim 2,$$

K-II AND IMB

$$p + X \rightarrow \pi^+ + \pi^0 + Y$$

$$\pi^+ \rightarrow \mu^+ + \nu_\mu$$

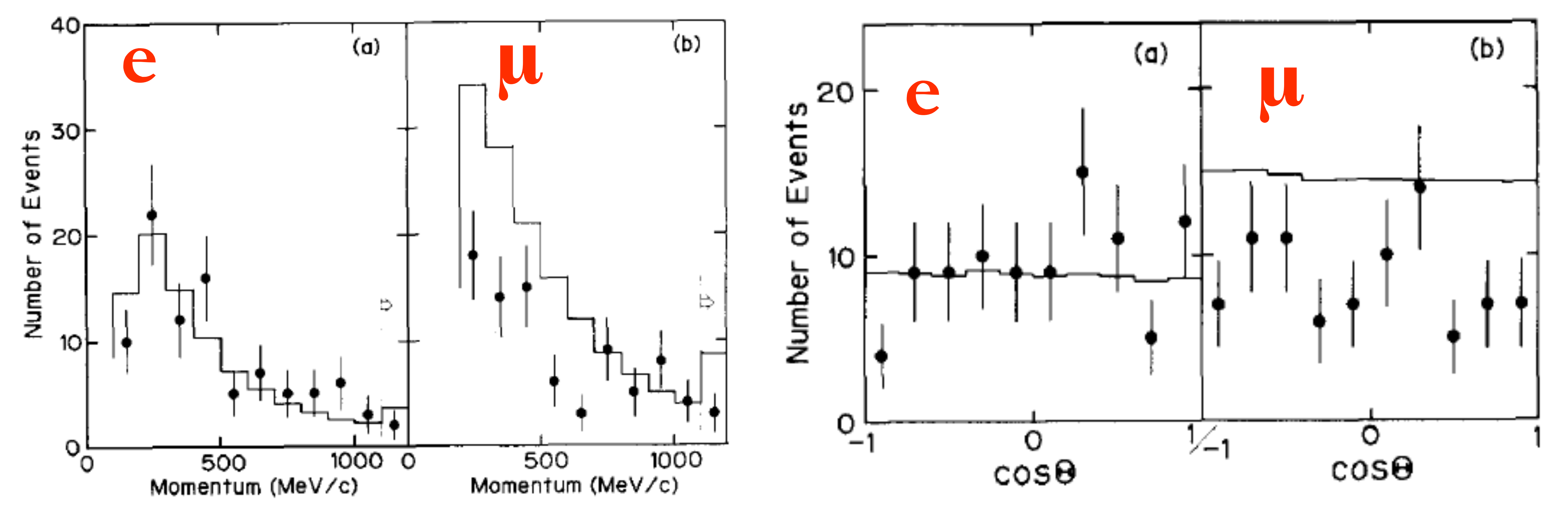
$$\mu^+ \rightarrow e^+ + \overline{\nu_\mu} + \nu_e$$



$$\frac{\nu_\mu + \overline{\nu_\mu}}{\nu_e + \overline{\nu_e}} \sim 2$$

- Kamiokande-II (1988), IMB (1991) detected atmospheric neutrinos, separating ν_e from ν_μ.

K-II



- ν_e flux observed as expected, but ν_μ flux was lower (both experiments)
- Absolute fluxes are very hard to predict, but μ/e ratio is very solid…