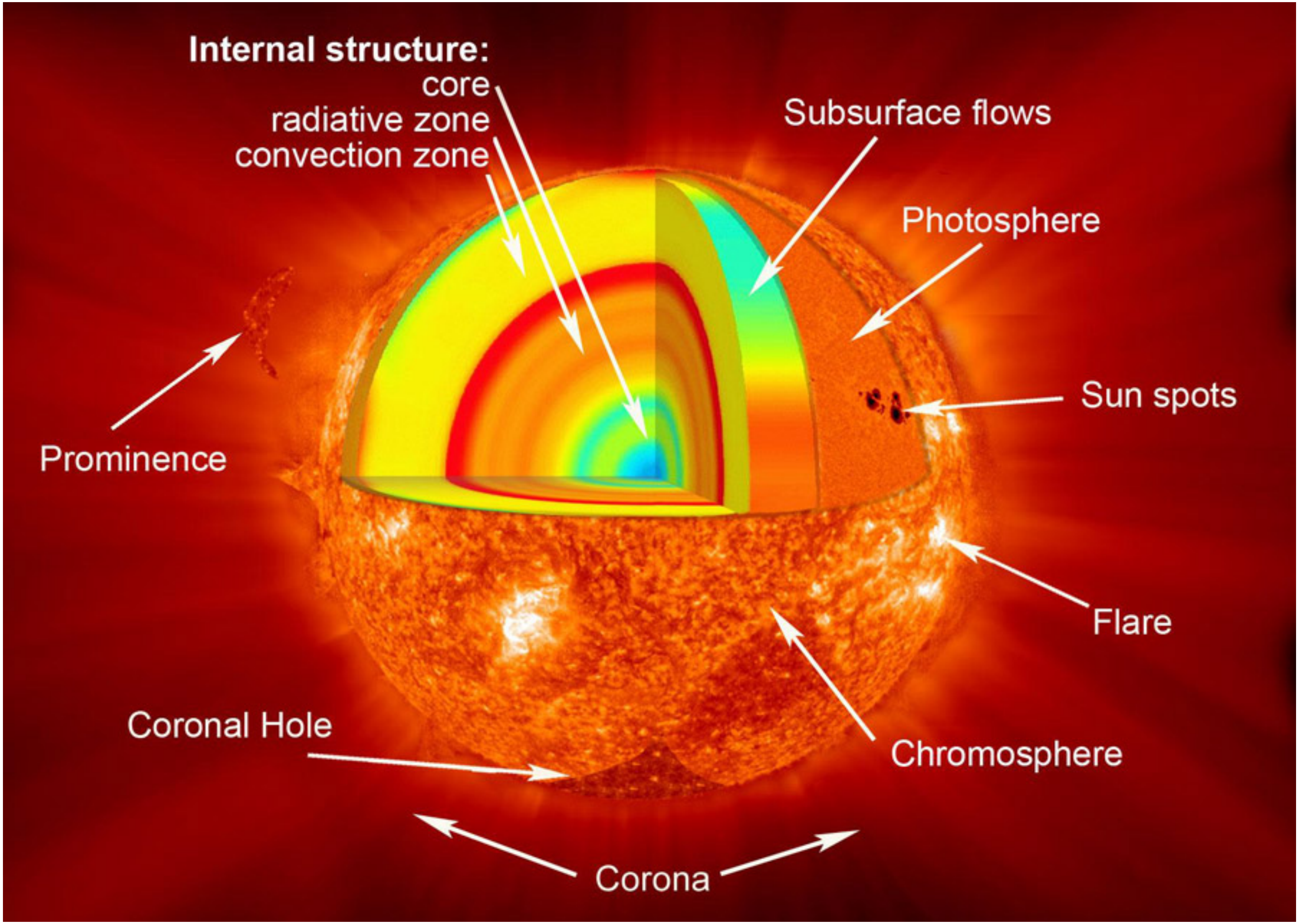
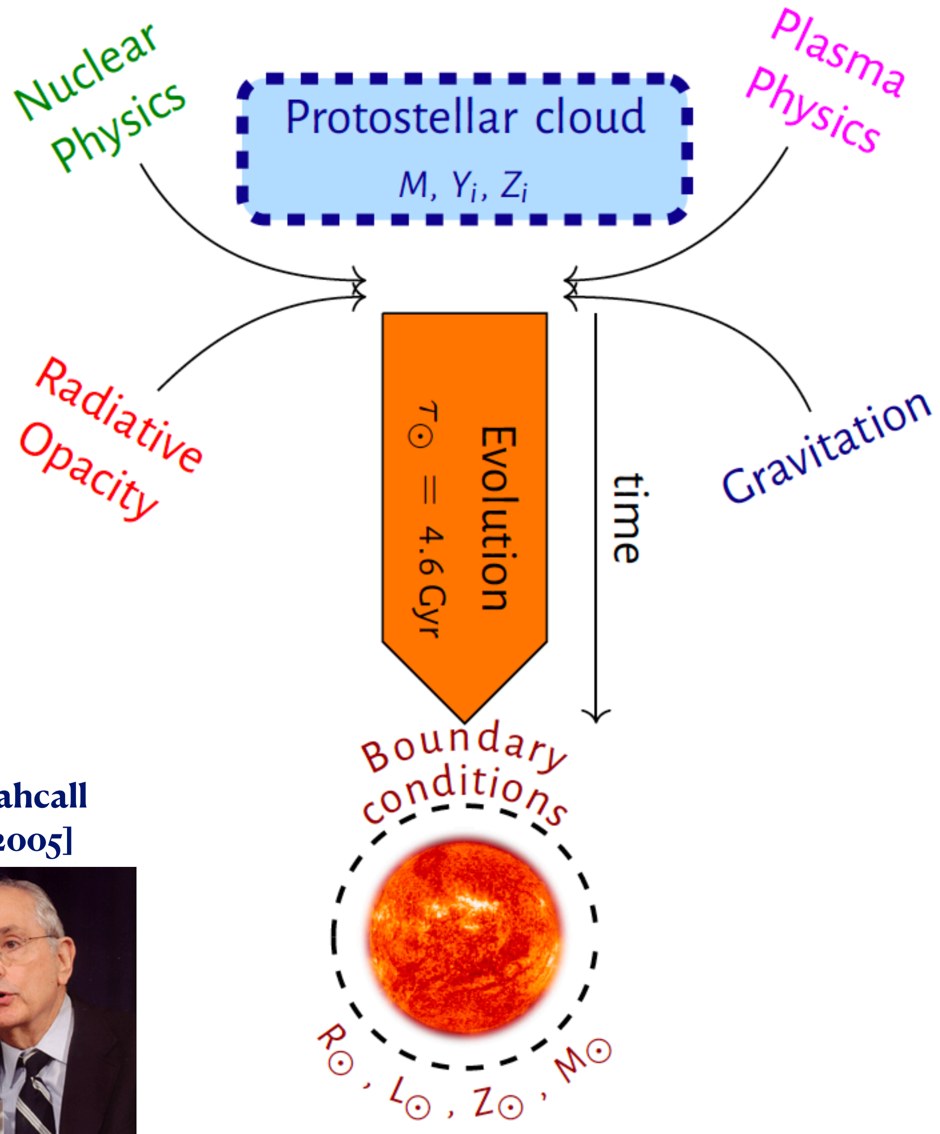
The structure of the Sun

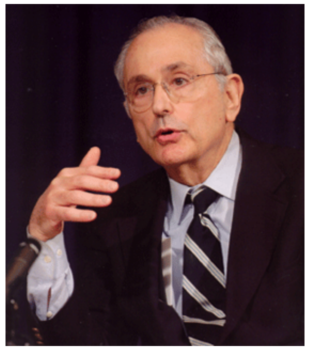


The Standard Solar Model

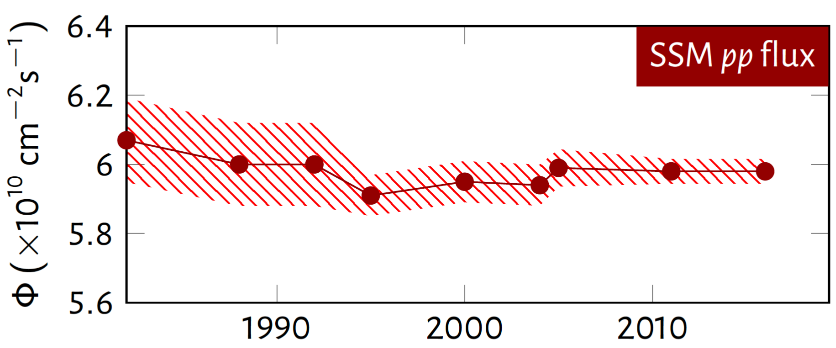
- **The observable is the Sun we see now,** which depends on a **complex evolution process**
  - Gravity
  - **Composition**: X (hydrogen), Y (helium), , Z ("metals")
  - Radiative **opacity** and plasma physics
  - Temperature and density profiles
  - Energy transport: radiative until 0.71 $R_\odot$, then convective
- Todays conditions act as boundary conditions
  - Two crucial **observables:**
    - Elio-seismology
    - **Solar neutrinos**

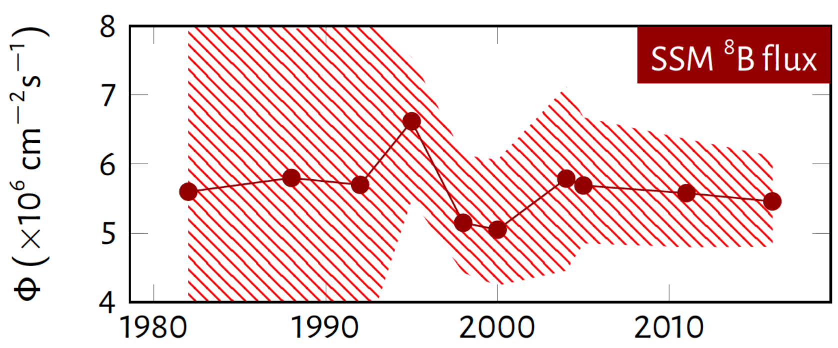


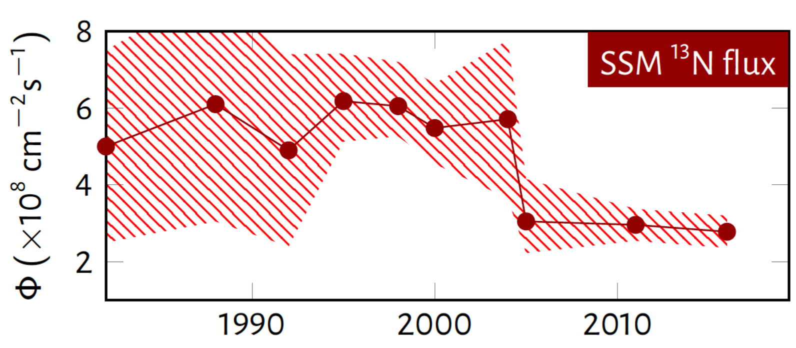
John Bahcall
[1934-2005]



- The model as well has evolved (better cross sections, opacity and diffusion models)







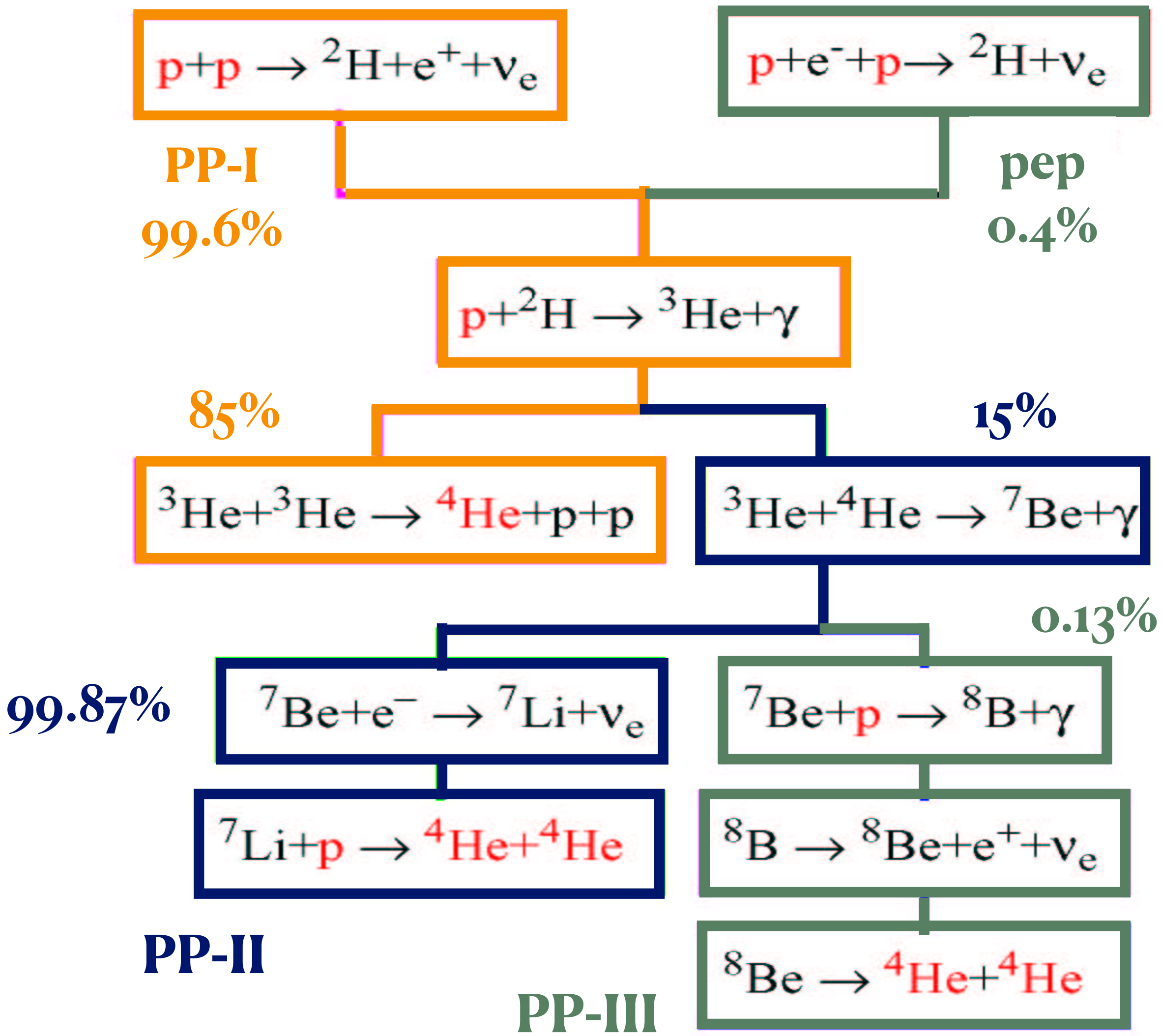
Solar neutrinos from hydrogen burning

A.S. Eddington Observatory 43 (1920), Nature (1920)

Bethe & Critchfield 1938

pp chain

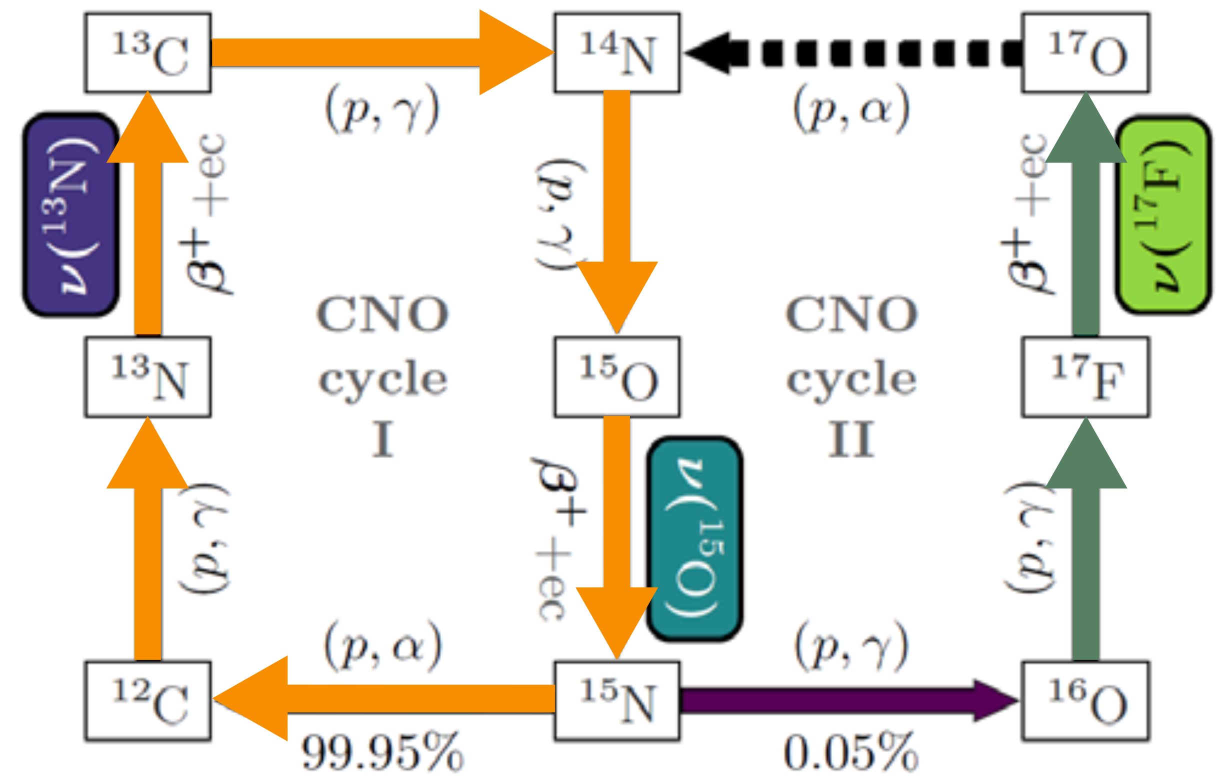
(99% energy)



CNO cycle

(~ 1% energy)

Weizsäcker (1937, 1938), Bethe (1939)



^{12}C is the main catalyst
CNO-II is suppressed in the Sun

REACTION

$$4p \rightarrow {}^4He + 2e^+ + 2\nu_e$$

ENERGY YIELD

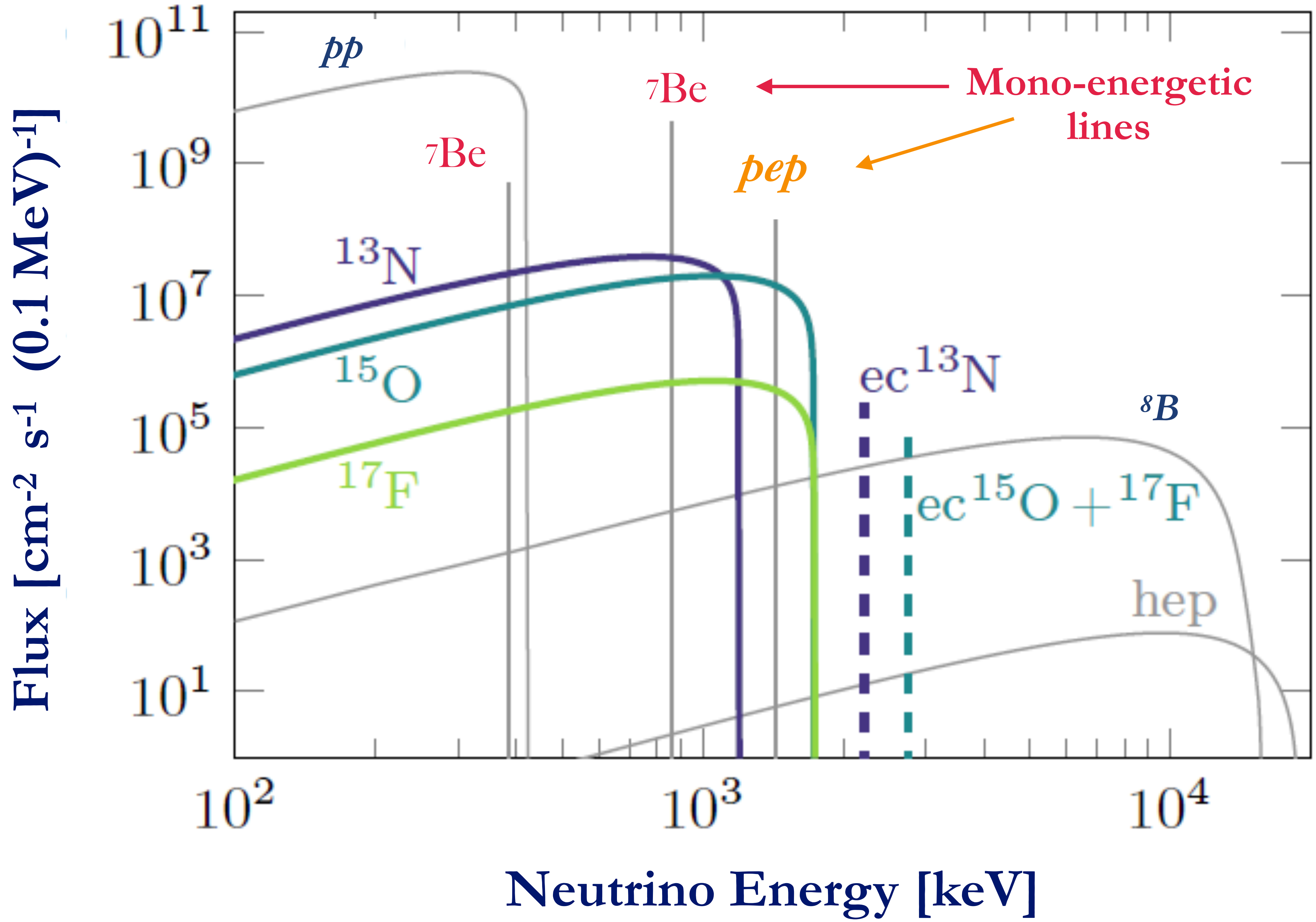
$$24.7\ MeV + 2m_ec^2$$

2% of E in NEUTRINOS

$$< E_\nu >= 0.53\ MeV$$

Neutrino spectrum from the SSM

$L_\odot = 3.846 \pm 0.015\ 10^{26}$ W



N. Vinyoles et al., The Astrophysical Journal (2017), 835:202 Feb. 1st. doi:10.3847/1538-4357/835/2/202

History: counting an atom a day at Homestake

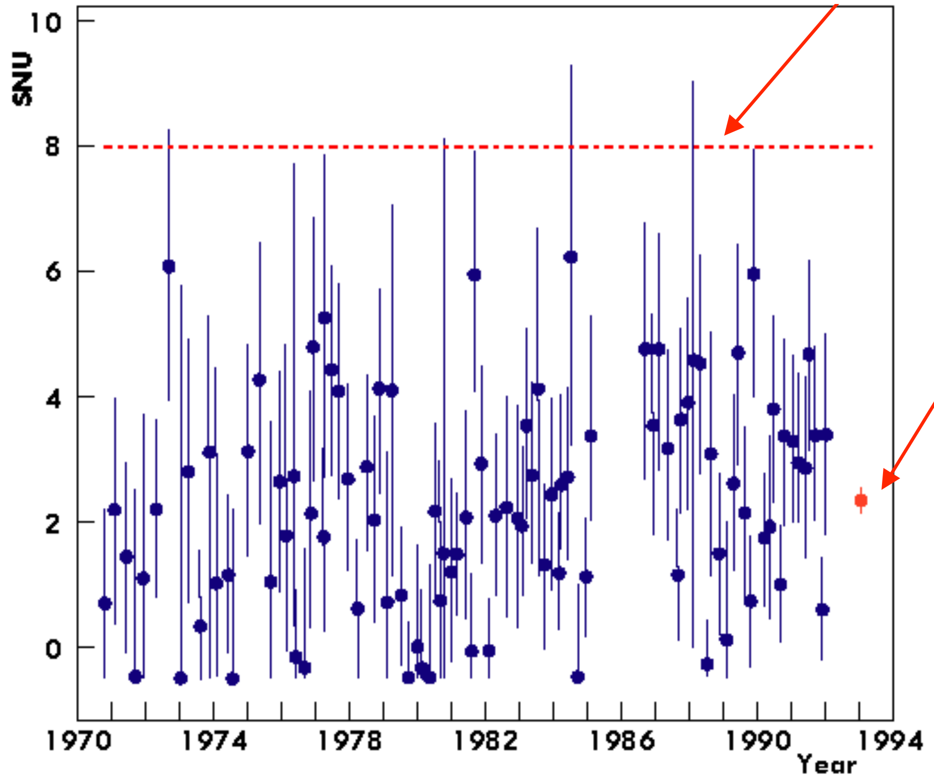
- Extract a single atom out of ~ 10^{31}

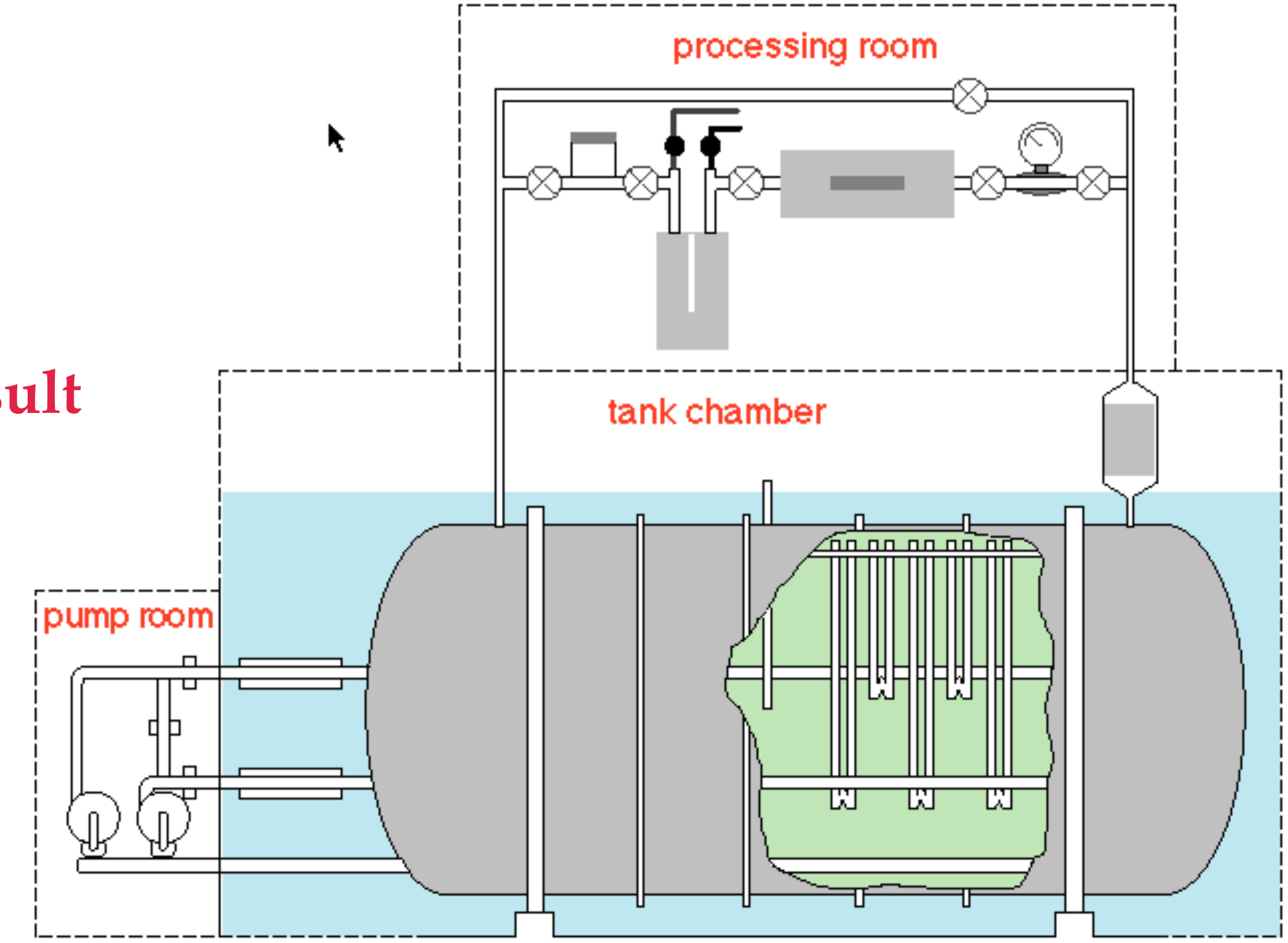
$$\nu_e + {}^{37}Cl \longrightarrow {}^{37}Ar + e^-$$

  - Target: **614 t of liquid soap**
  - ^{37}Ar atoms extraction with charcoal filters (every ~ months)
  - Very low background proportional counters to count **^{37}Ar** atoms (which decays by **e^- capture** with $\tau_{1/2}$ **~ 35 d**)

Solar model

Final result





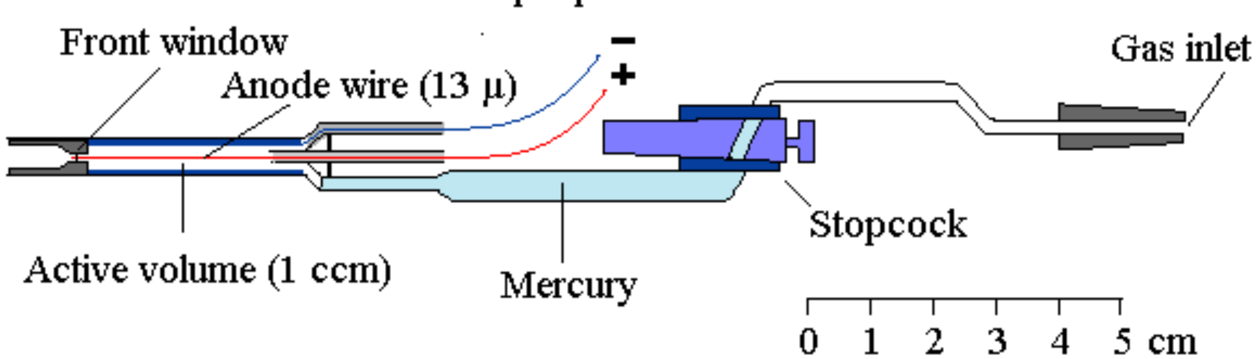
History: Gallex/GNO @ LNGS

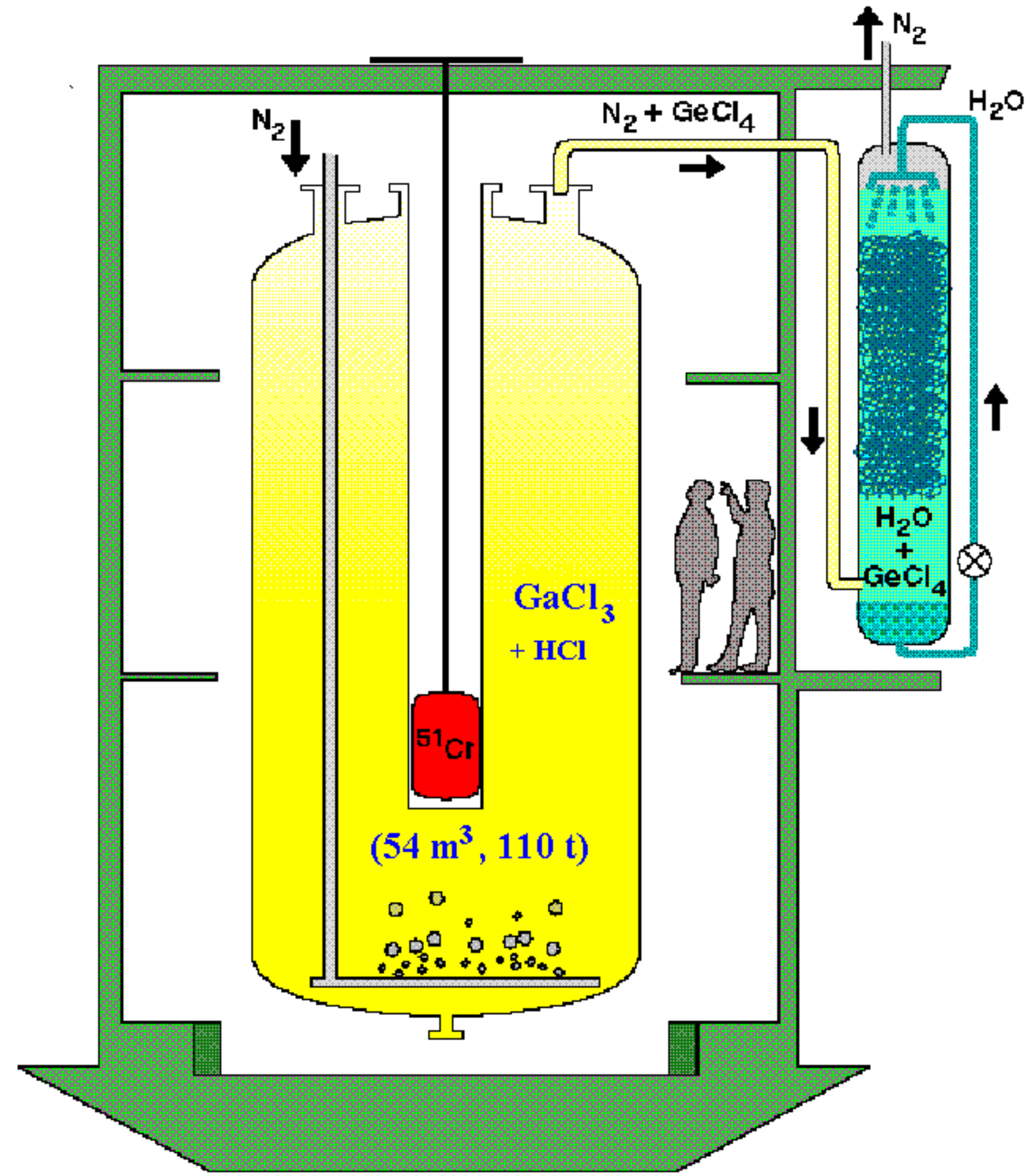
- **A key radio-chemical experiment** for solar neutrino physics
  - **The first sensitive to all solar neutrino components** (through an **integrated,** energy-weighted spectrum)
  - 30.3 ton of Ga in $GaCl_3 -$ HCl solution.

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

  - **Threshold: 233 keV**
  - Extraction every ~ 3 weeks
  - The volatile $GeCl_4$ is extracted using N_2 flow and then inserted into proportional counters [^{71}Ge **e^- capture $\tau_{1/2}$ ~ 11.43 d**]

HD-II proportional counter

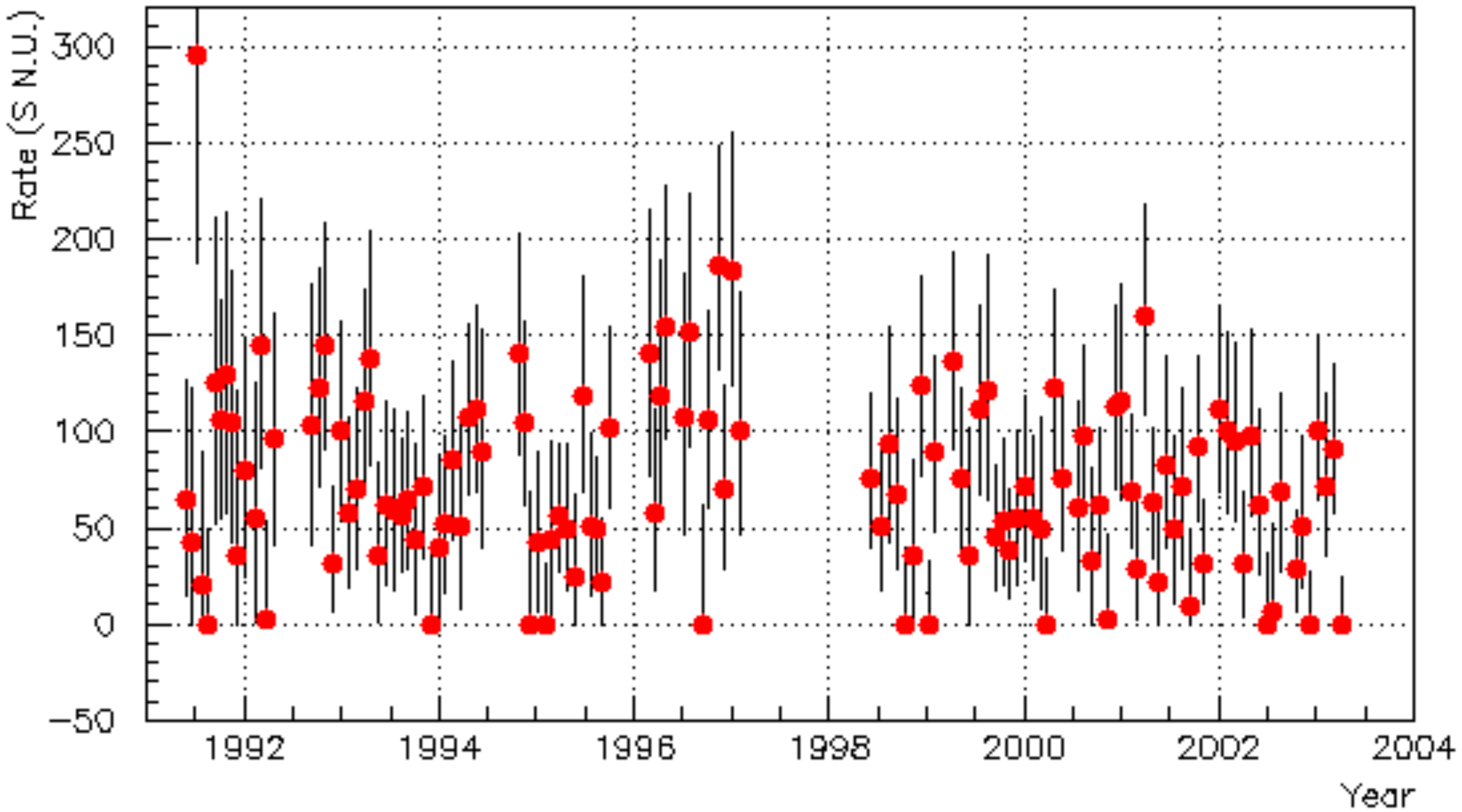




Gallex/GNO results [1990-2004]

- Extraction efficiency checked with:
  - 1.6 MCi (!) ν_e source [based on ^{51}Cr e-capture decay, obtained from irradiated ^{50}Cr in reactor]
    - Initial ν_e flux 5 times the Sun
    - ε=95±3 %
    - Mono-chromatic ν_e flux, E_ν=0.75 MeV
  - At the end only, insertion of ^{71}As
    - $^{71}As \rightarrow {}^{71}Ge + e^- + \nu_e$
    - [$\tau_{1/2}$ =2.72 d];
    - ε=100±1 %

GALLEX/GNO results



Experiment	Runs	Result
GALLEX	65	77.5 ± 6.2 (stat) ± 6.2 (sys) SNU
GNO	58	62.9 ± 5.4 (stat) ± 2.5 (sys) SNU
GALLEX+GNO	123	69.3 ± 4.1 (stat) ± 3.6 (sys) SNU

STANDARD SOLAR MODEL prediction: 129 ± 7 SNU

Neutrino detection in water/ice: Cherenkov light

In a medium with refractive index n the light speed is c/n. When a charged particle travel in the medium with a speed higher than light speed, it emits Cerenkov light. The minimum energy to emit Cerenkov light is:

Particle	Cerenkov threshold (Energy (MeV))
e	0.768
μ	158.7
π	209.7

Cerenkov light is emitted in a cone with a θ opening in the track direction:

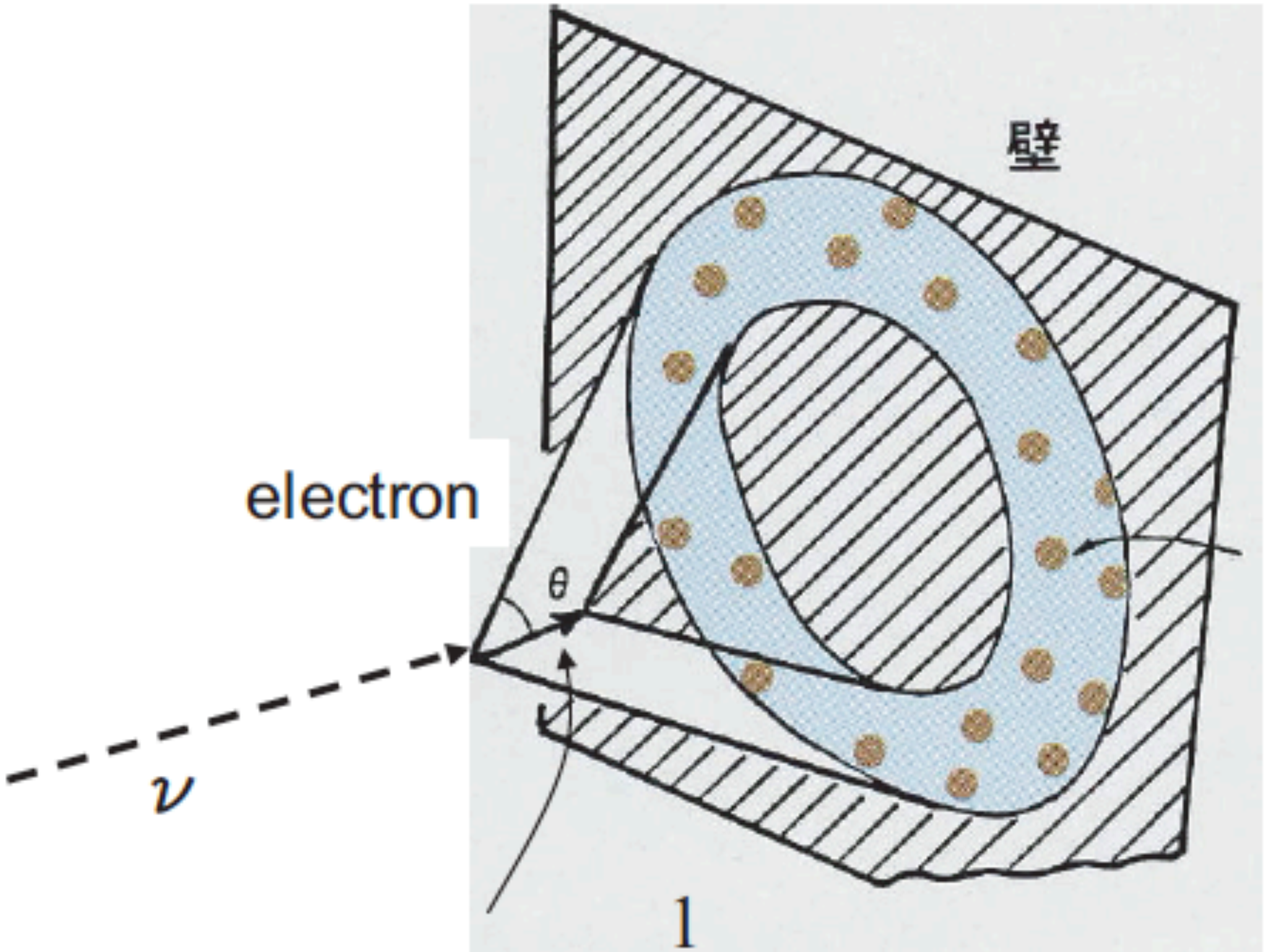
$$cos\theta = \frac{1}{n\beta}$$

$\theta = 42°$ for $\beta = 1.0$ in water.
Cerenkov light spectrum as function of wavelength λ:

$$\frac{dN}{d\lambda} = \frac{2\pi\alpha l}{c}\left(1 - \frac{n^2}{beta^2}\right)\frac{1}{\lambda^2}$$

where α is the fine structure constant and l is the track length.
A charged particle emits about 390 photons for 1cm track length in water with $300\,\mathrm{nm} < \lambda < 700\mathrm{nm}$.

Detection of light in water



$\cos\theta = \frac{1}{n}$

n (refractive index)=1.34 in water

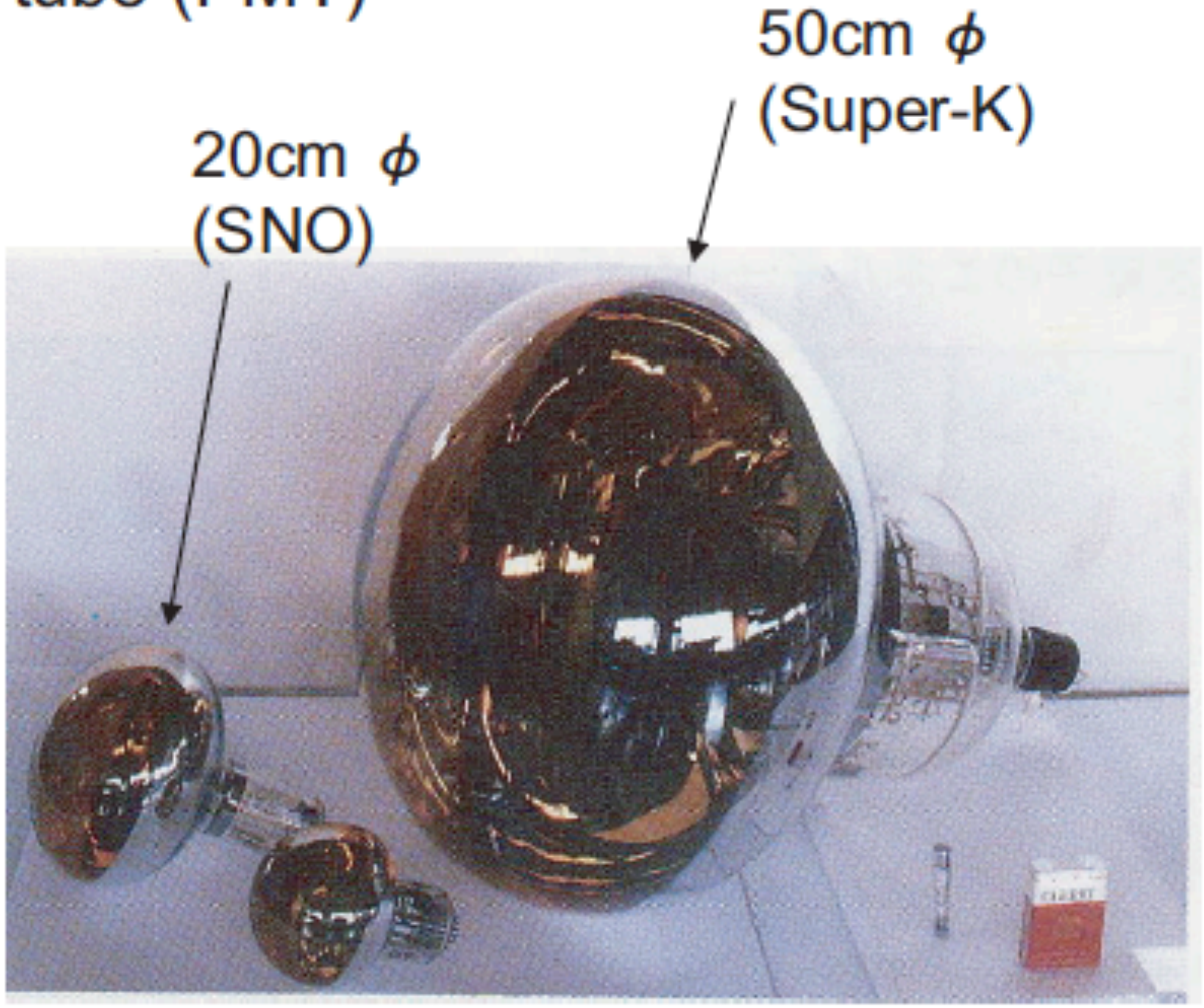
⇨ θ =42deg. for β =1

Number of Ch. photons with λ =300-600 nm emitted by a relativistic particle per cm = 340.

⇩

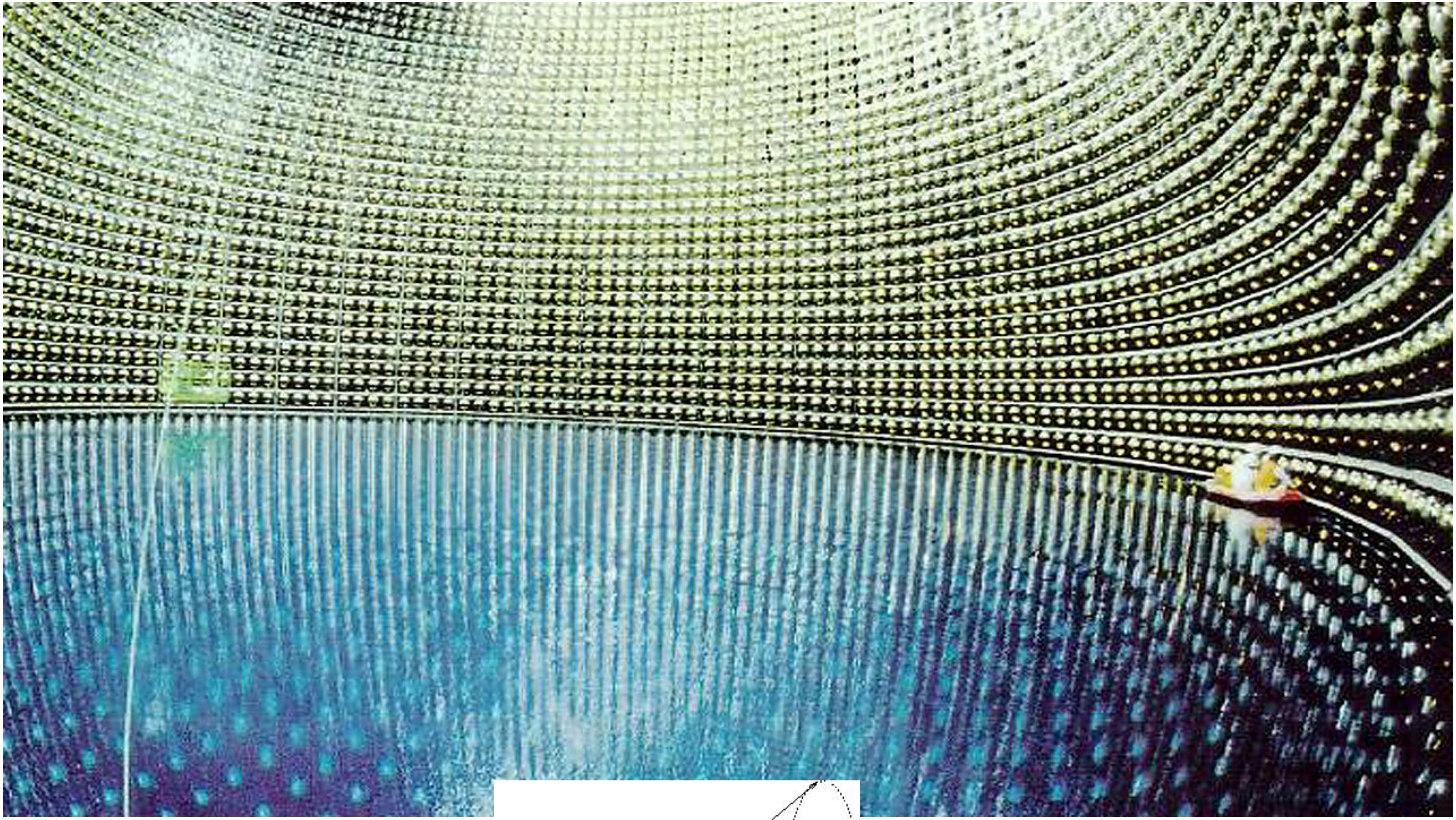
Need an efficient detection of the photons. ⇨ Large PMTs

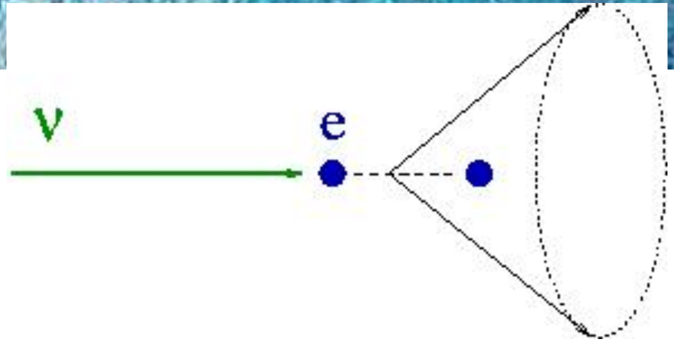
Photomultiplier tube (PMT)



T. Kajita - Nufact 05 School

SK experiment

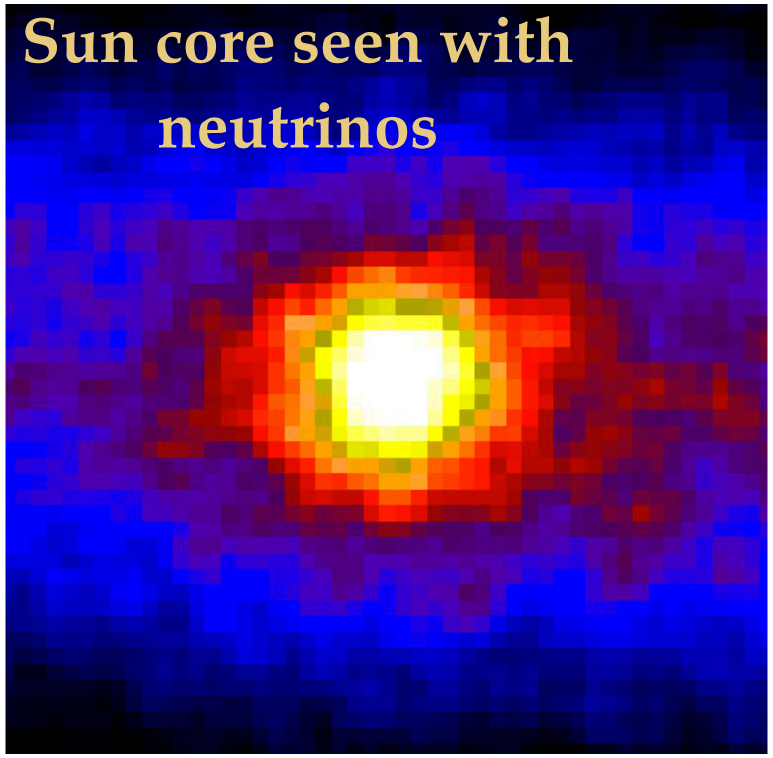


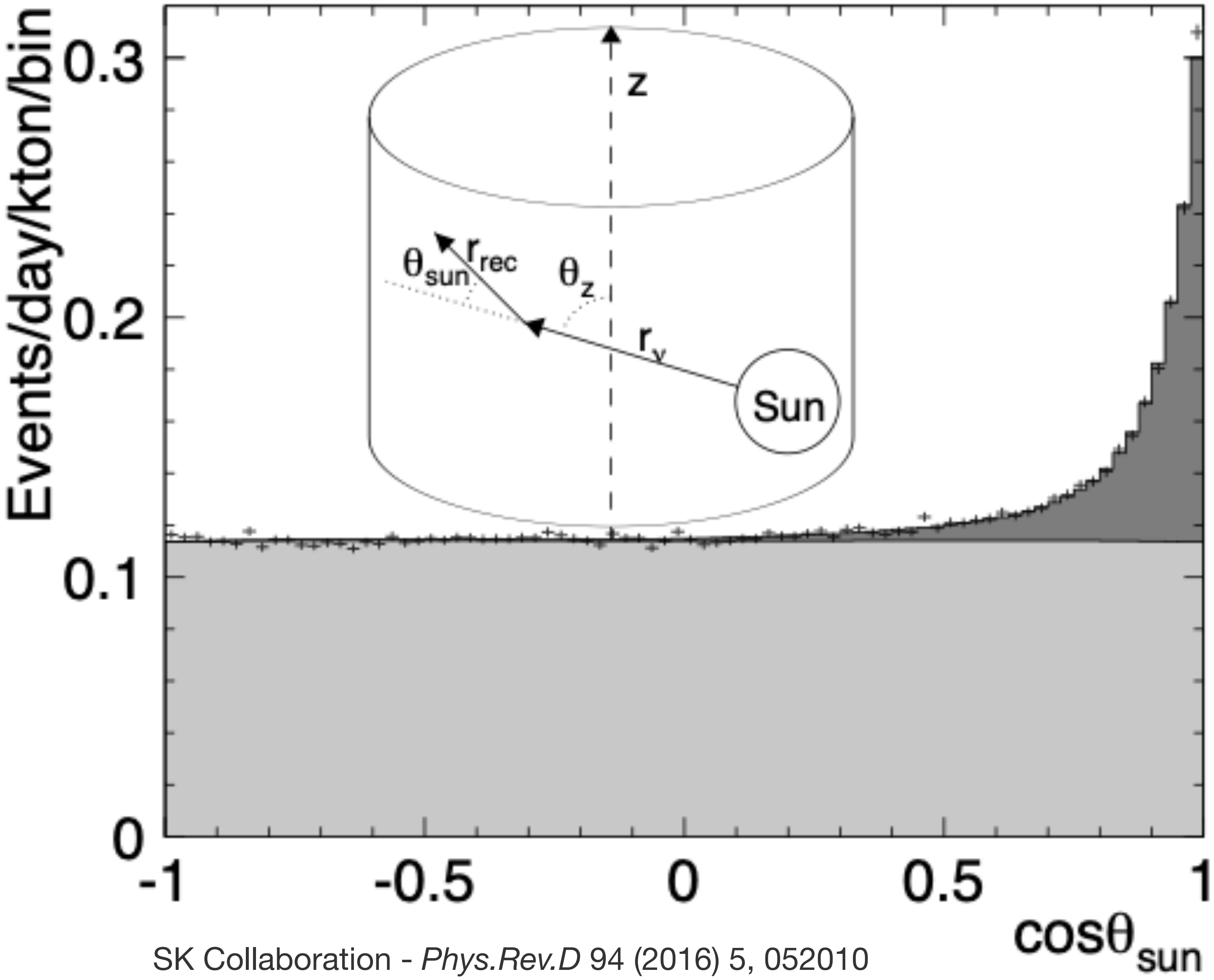


Cherenkov detector for solar, accelerator and atmospheric neutrinos

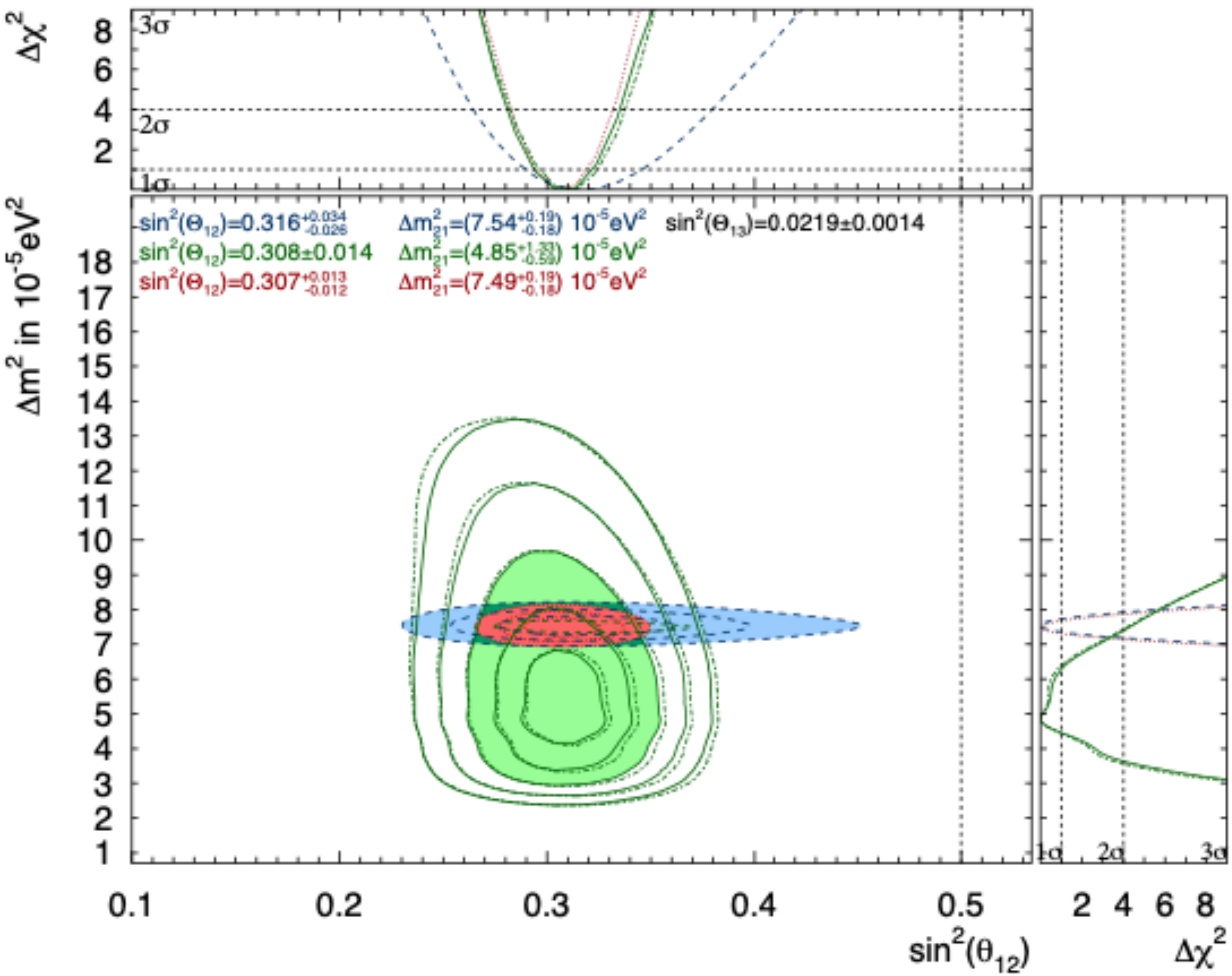
Solar neutrinos at SK

- Detection technique: elastic scattering on electrons
  - Cherenkov light gives direction of incoming neutrino
  - Threshold ~ 3.5 - 5 MeV (depending on period)



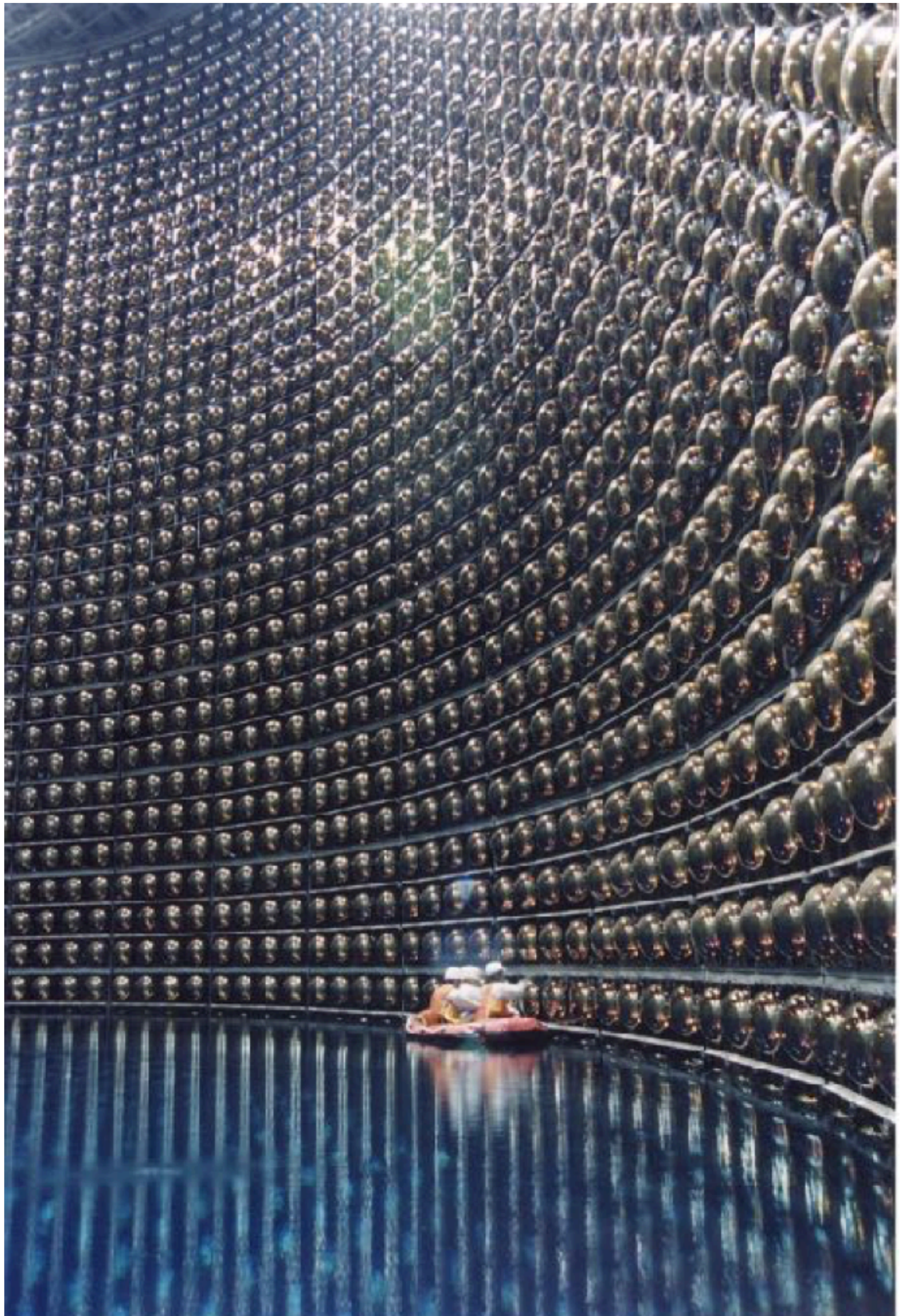


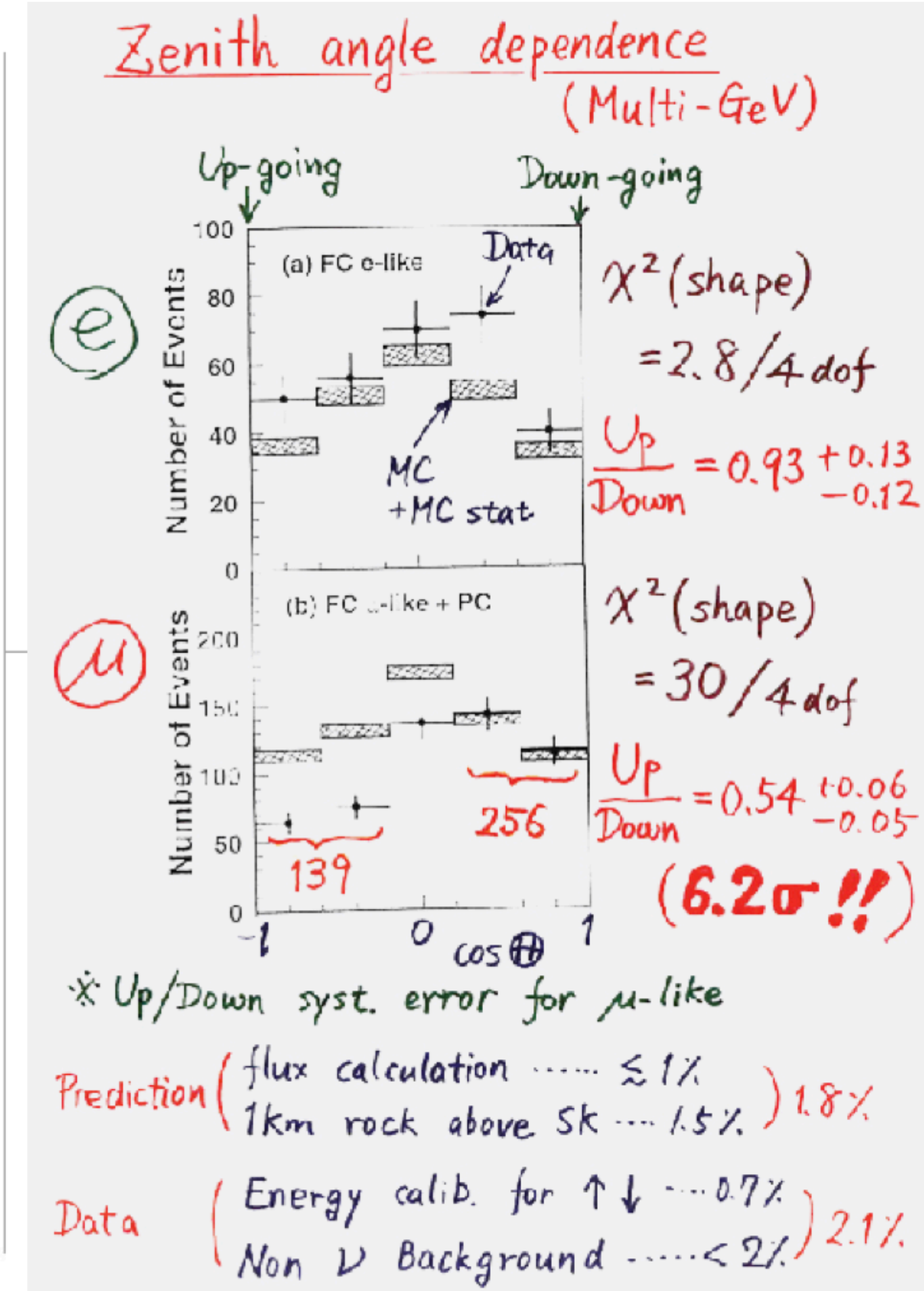
SK Collaboration - *Phys.Rev.D* 94 (2016) 5, 052010

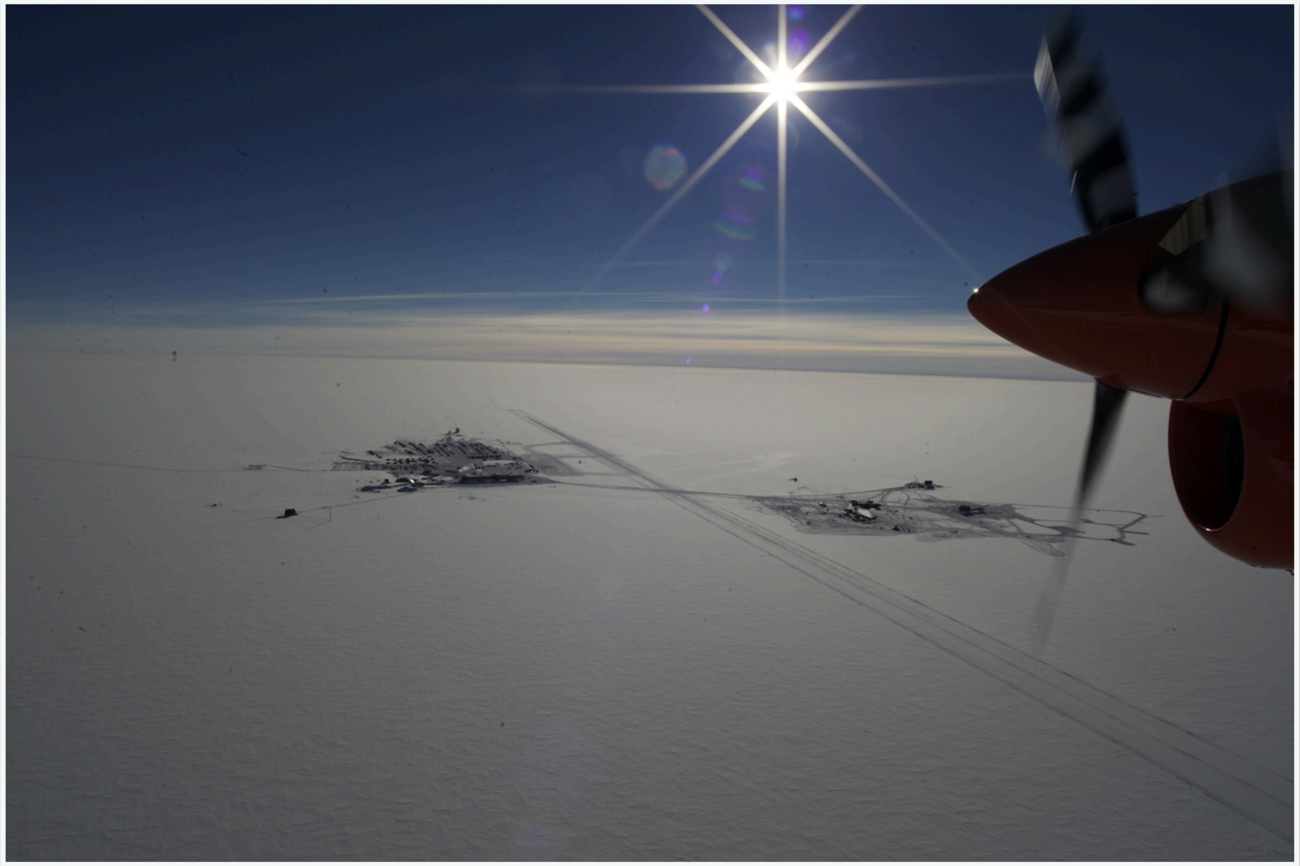


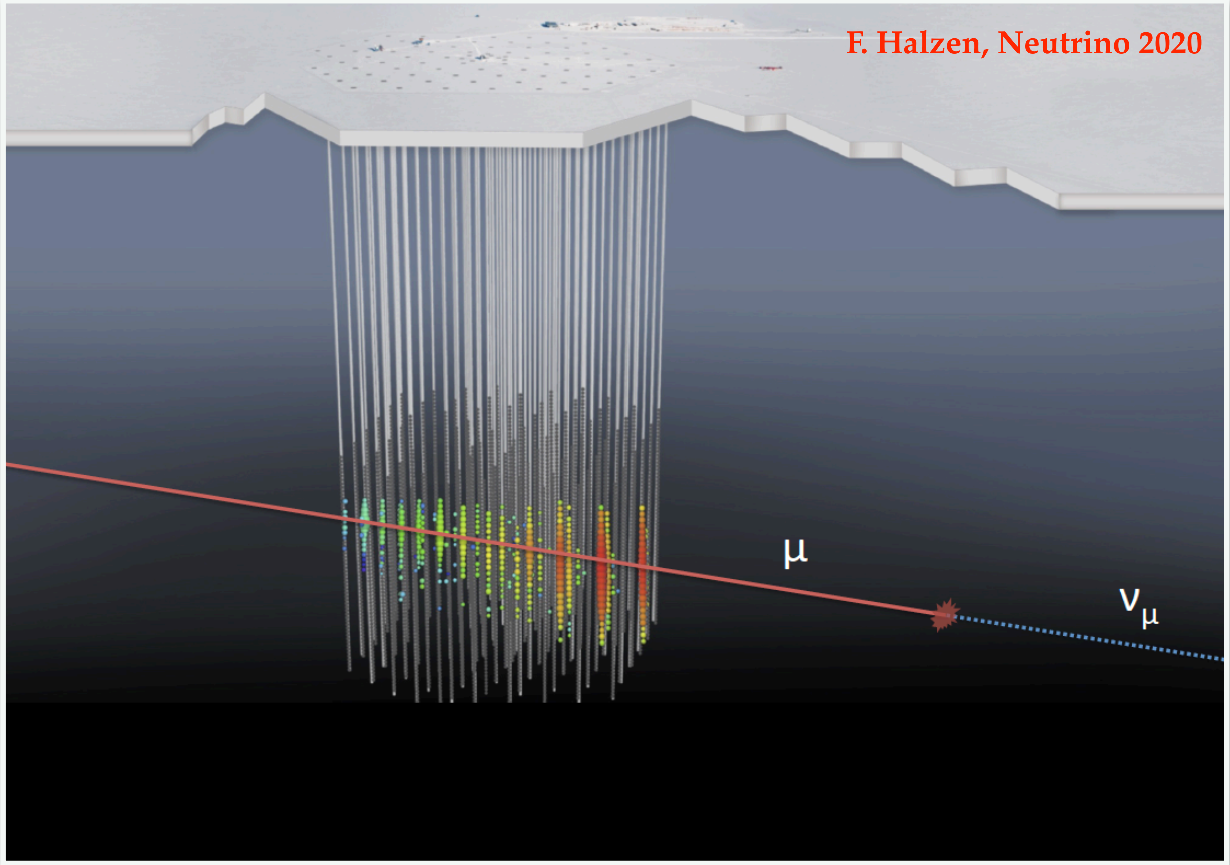
SK Collaboration - *Phys.Rev.D* 94 (2016) 5, 052010

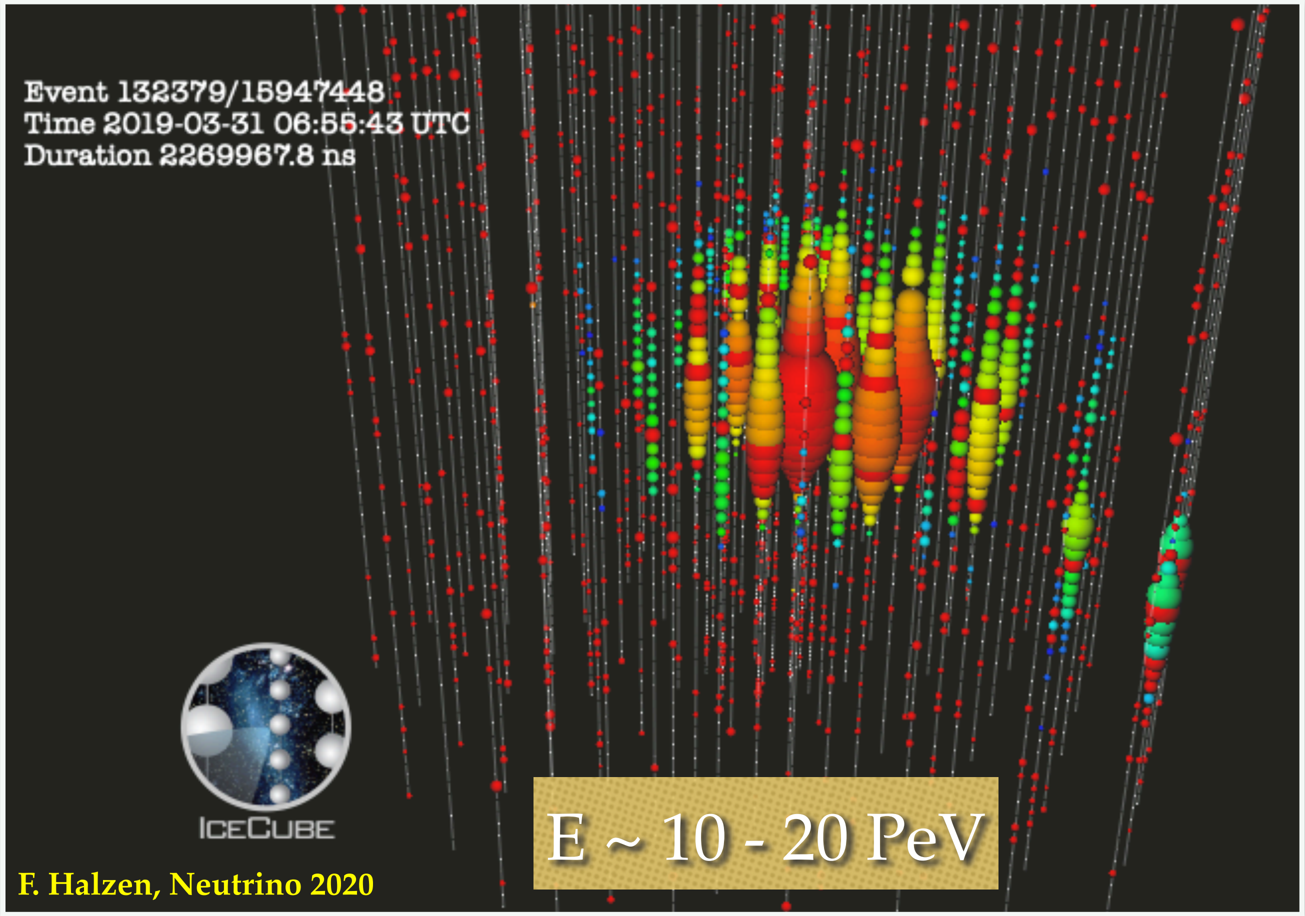
Discovery of atmospheric neutrinos at SK: 1998

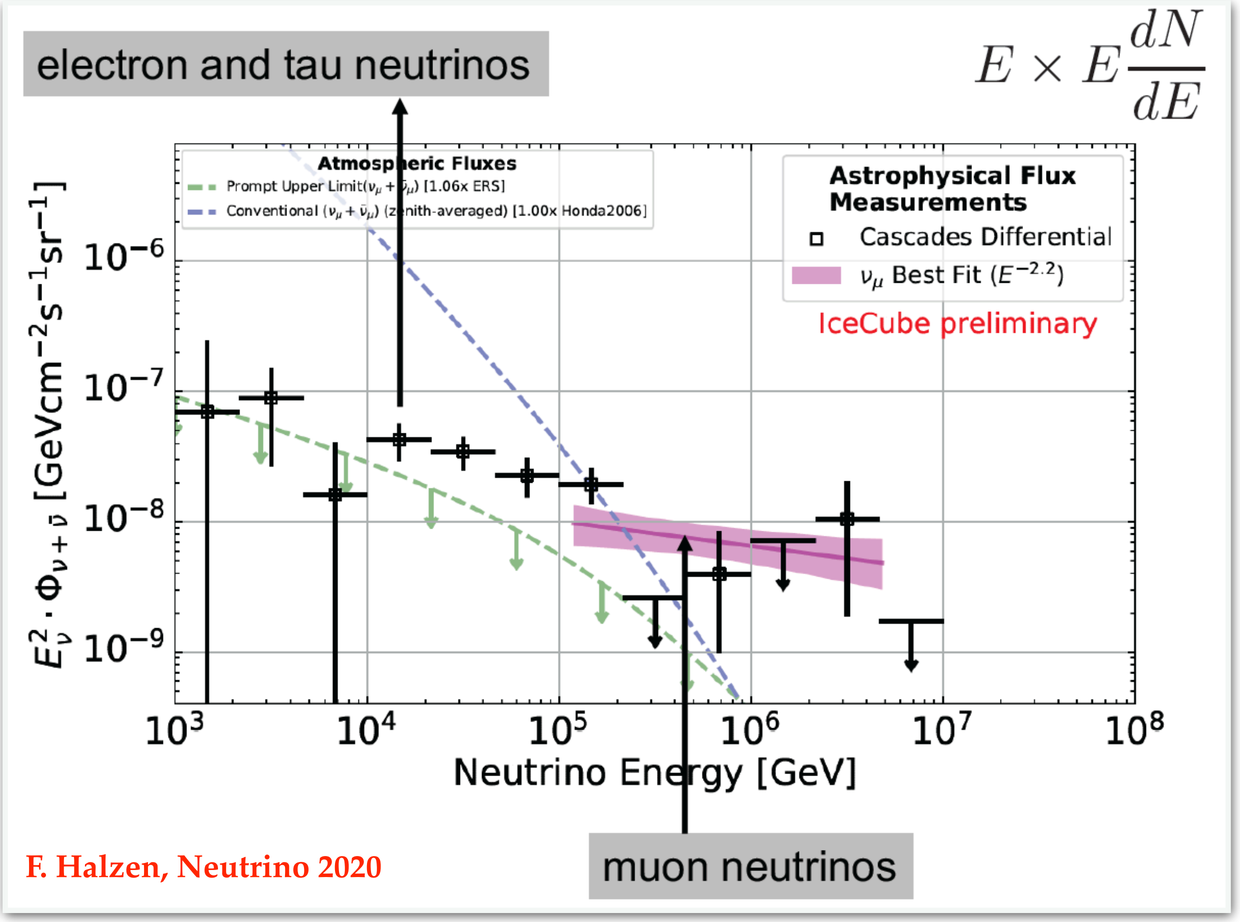







F. Halzen, Neutrino 2020
μ
ν_μ


Event 132379/15947448
Time 2019-03-31 06:55:43 UTC
Duration 2269967.8 ns
ICECUBE
E ~ 10 - 20 PeV
F. Halzen, Neutrino 2020


electron and tau neutrinos
$E \times E\frac{dN}{dE}$
Atmospheric Fluxes
Prompt Upper Limit [1.06x ERS]
Conventional (zenith-averaged) [1.00x Honda2006]
Astrophysical Flux Measurements
Cascades Differential
ν_μ Best Fit ($E^{-2.2}$)
IceCube preliminary
$E^2_\nu \cdot \Phi_{\nu+\bar\nu}$ [GeVcm^{-2}s^{-1}sr^{-1}]
Neutrino Energy [GeV]
F. Halzen, Neutrino 2020
muon neutrinos

Solution of Solar Neutrino Problem: SNO

- **S**udbury **N**eutrino **O**bservatory
  - Key feature: 1 kt D_2O
    - Ability to identify electron type neutrinos, and measurethe others

- Three key reactions:
  - **CC:** ν_e only

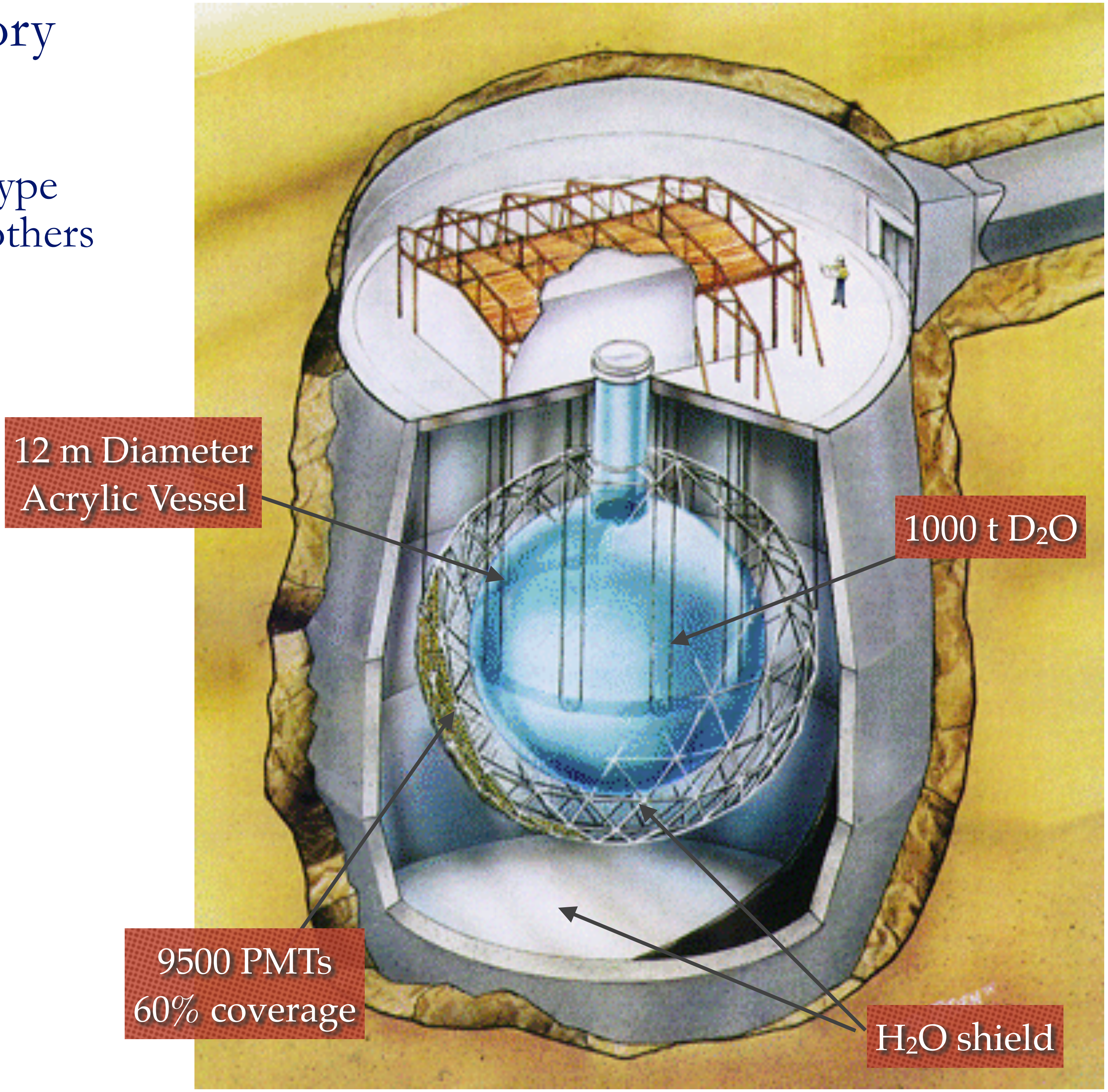
$$\nu_e + d \rightarrow p + p + e^+$$

  - **NC:** All types, equal

$$\nu_x + d \rightarrow \nu_x + p + n$$

  - **ES:** All types, un-equal

$$\nu_x + e^- \rightarrow \nu_x + e^-$$

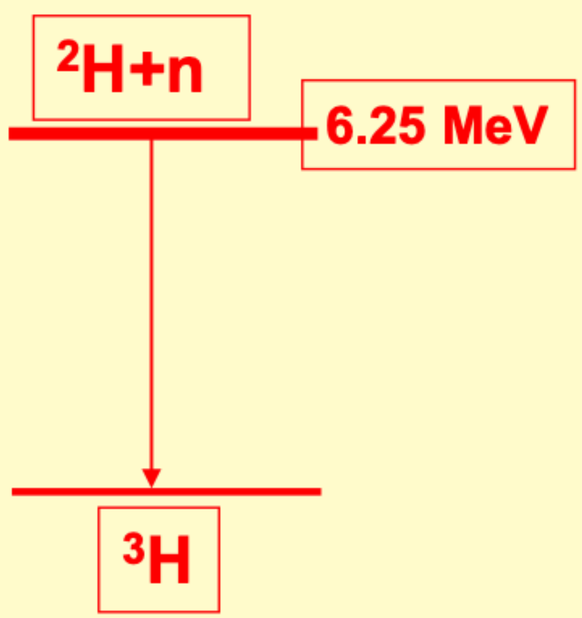


SNO neutron measurements

3 neutron (NC) detection methods (systematically different)

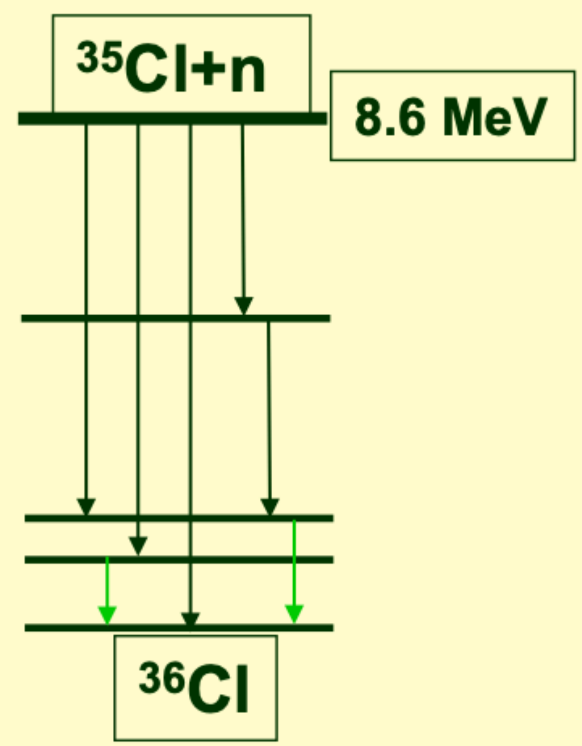
Phase I (D_2O)
Nov. 99 - May 01

n captures on
$^2H(n, \gamma)^3H$
Effc. ~14.4%
NC and CC separation by energy, radial, and directional distributions



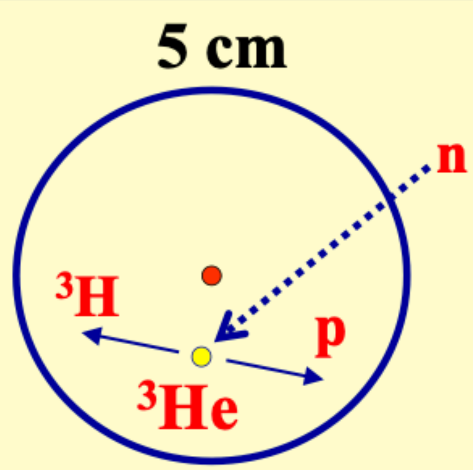
Phase II (salt)
July 01 - Sep. 03

2 tonnes of NaCl
n captures on
$^{35}Cl(n, \gamma)^{36}Cl$
Effc. ~40%
NC and CC separation by event isotropy



Phase III (^3He)
Nov. 04-Dec. 06

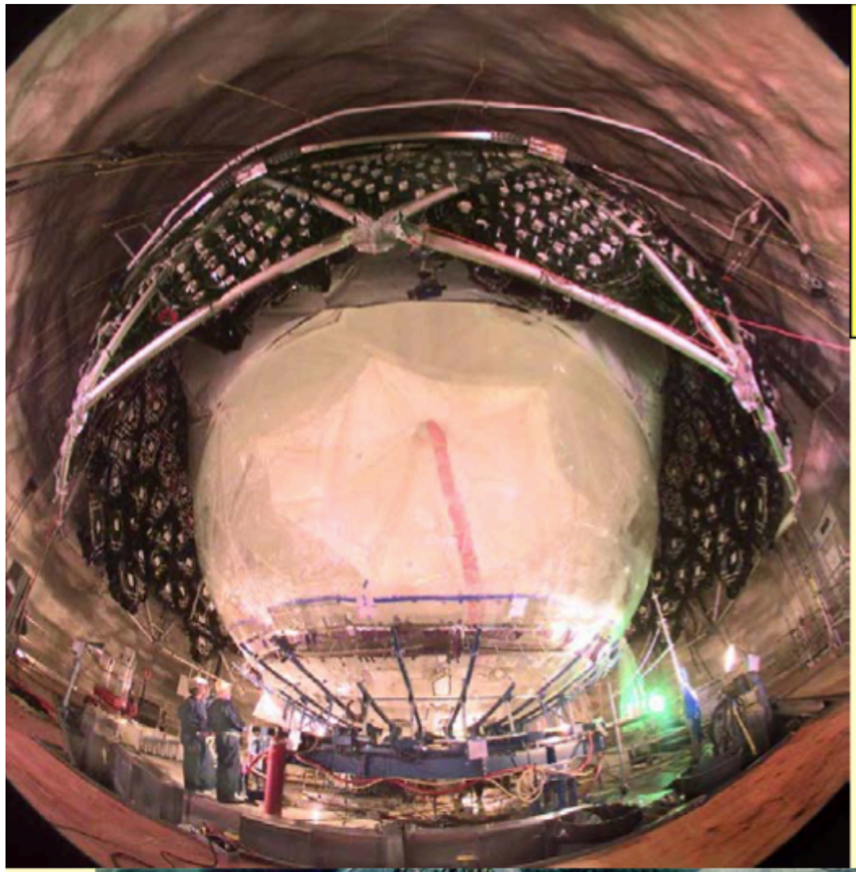
400 m of proportional counters
$^3He(n, p)^3H$
Effc. ~ 30% capture
Measure NC rate with entirely seperate detection system.



$$n + {}^3He \rightarrow p + {}^3H$$

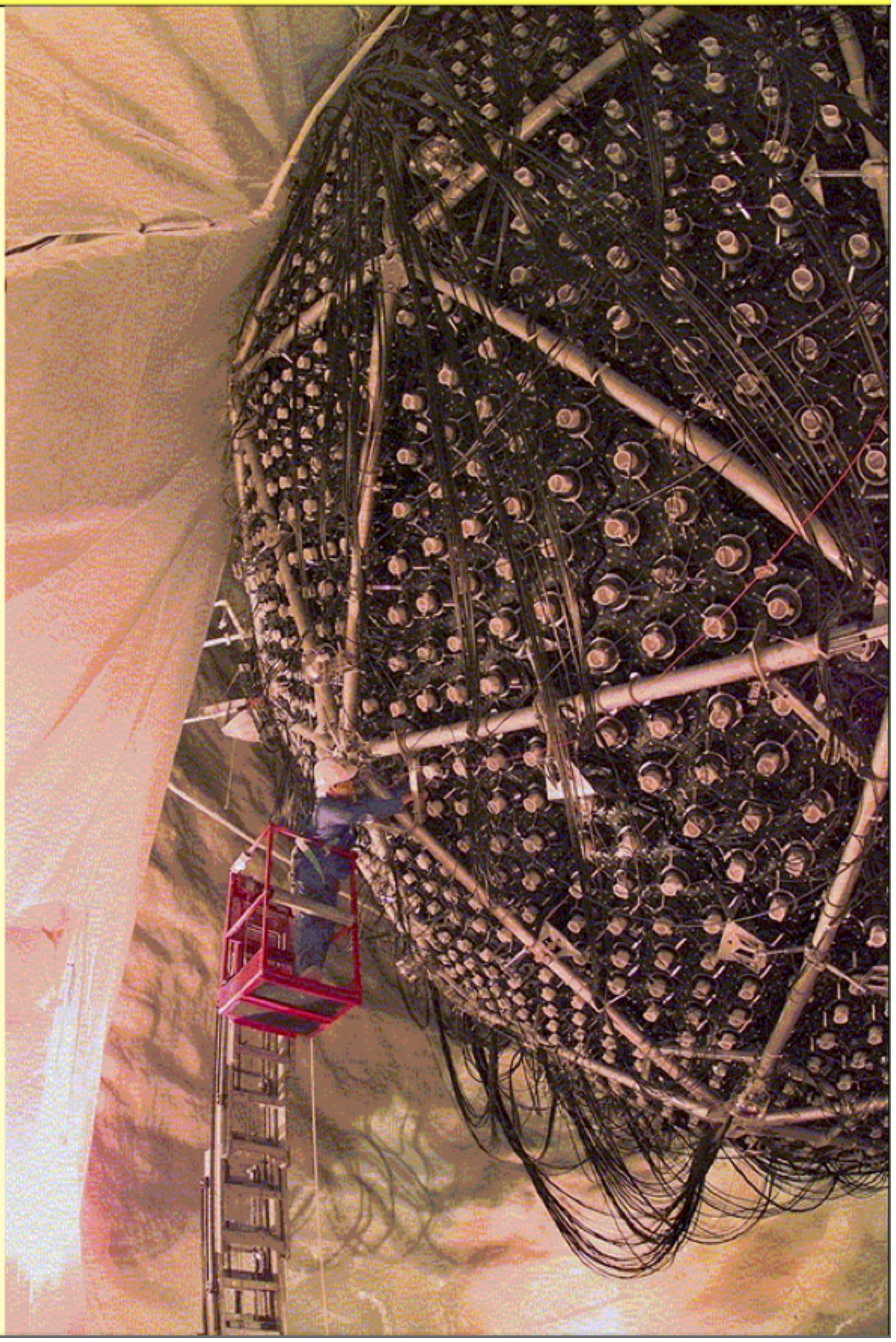
Art McDonald: Neutrino 2016

SNO picture gallery



SNO: One million pieces transported down in the 3 m x 3 m x 4 m mine cage and re-assembled under ultra-clean conditions. Every worker takes a shower and wears clean, lint-free clothing.

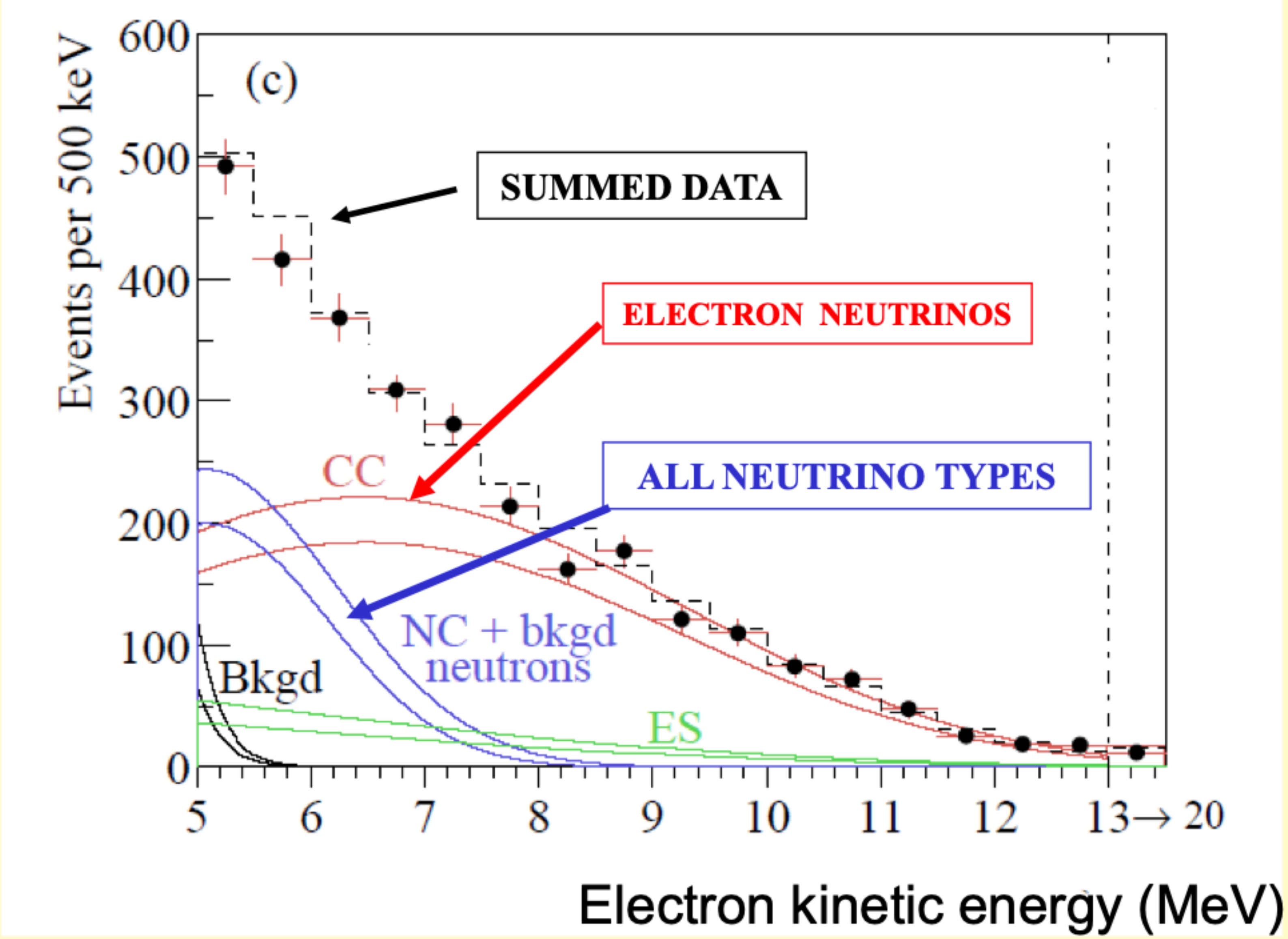
70,000 showers during the course of the SNO project



Art McDonald: Neutrino 2016

SNO spectrum

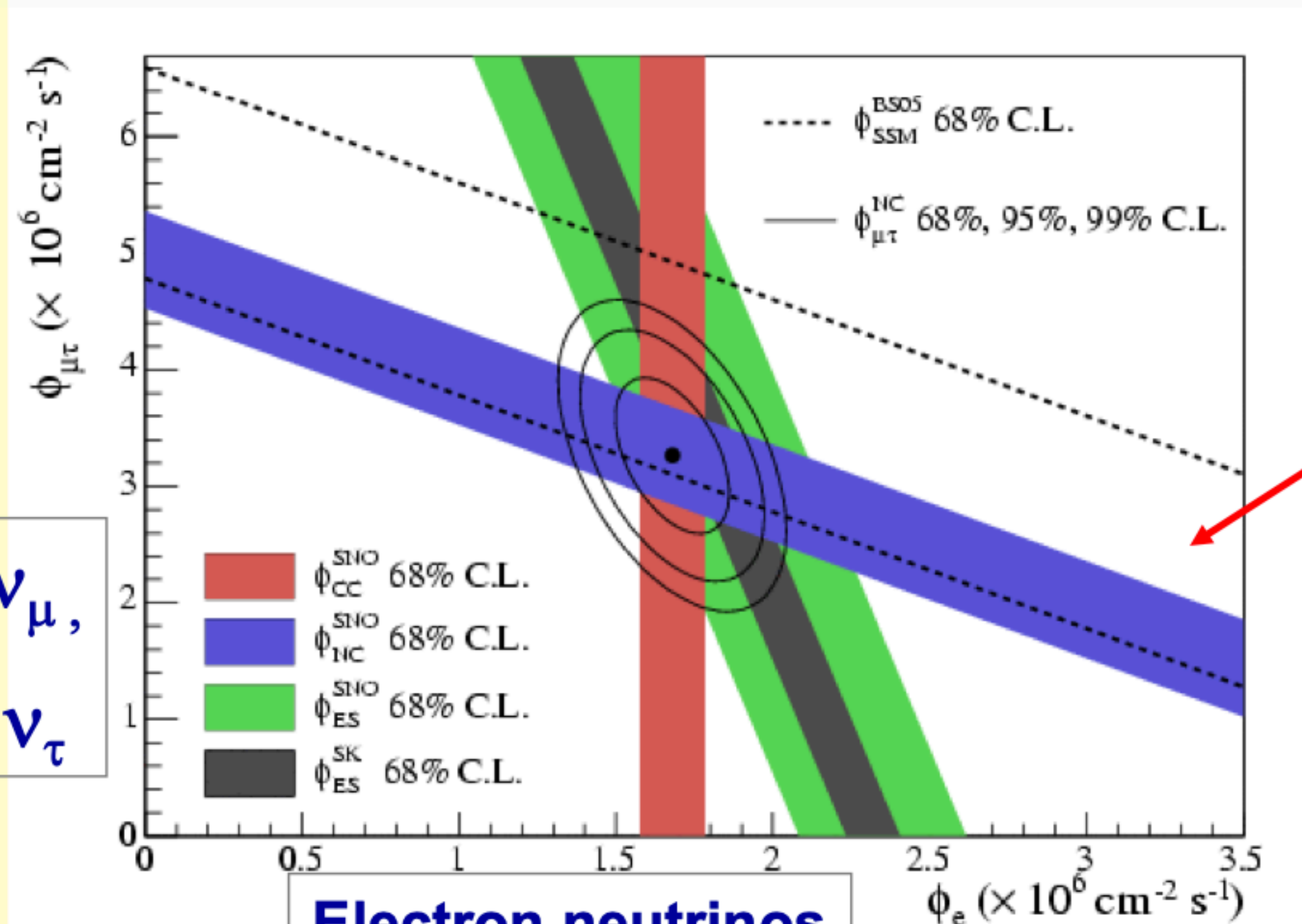
WE OBSERVED NEUTRINOS FROM THE SUN WITH ALMOST NO RADIOACTIVE BACKGROUND



**After Calibration:
ELECTRON NEUTRINOS AT EARTH ARE ONLY 1/3 OF ALL NEUTRINOS**

Data from Pure Heavy Water Phase in 2002

Art McDonald: Neutrino 2016



ν_μ, ν_τ

Electron neutrinos

SNO Results for Salt Phase

Flavor change determined by > 7 σ.

New physics beyond The Standard Model of Elementary Particles!

$$\phi_{CC} = 1.68 \ ^{+0.06}_{-0.06}(\text{stat.})^{+0.08}_{-0.09}(\text{syst.})$$

$$\phi_{NC} = 4.94 \ ^{+0.21}_{-0.21}(\text{stat.})^{+0.38}_{-0.34}(\text{syst.})$$

$$\phi_{ES} = 2.35 \ ^{+0.22}_{-0.22}(\text{stat.})^{+0.15}_{-0.15}(\text{syst.})$$

(In units of $10^6 \text{cm}^{-2}\text{s}^{-1}$)

$$\frac{\phi_{CC}}{\phi_{NC}} = 0.34 \pm 0.023(\text{stat.})^{+0.029}_{-0.031}$$

The Total Flux of Active Neutrinos is measured independently (NC) and agrees well with solar model Calculations:

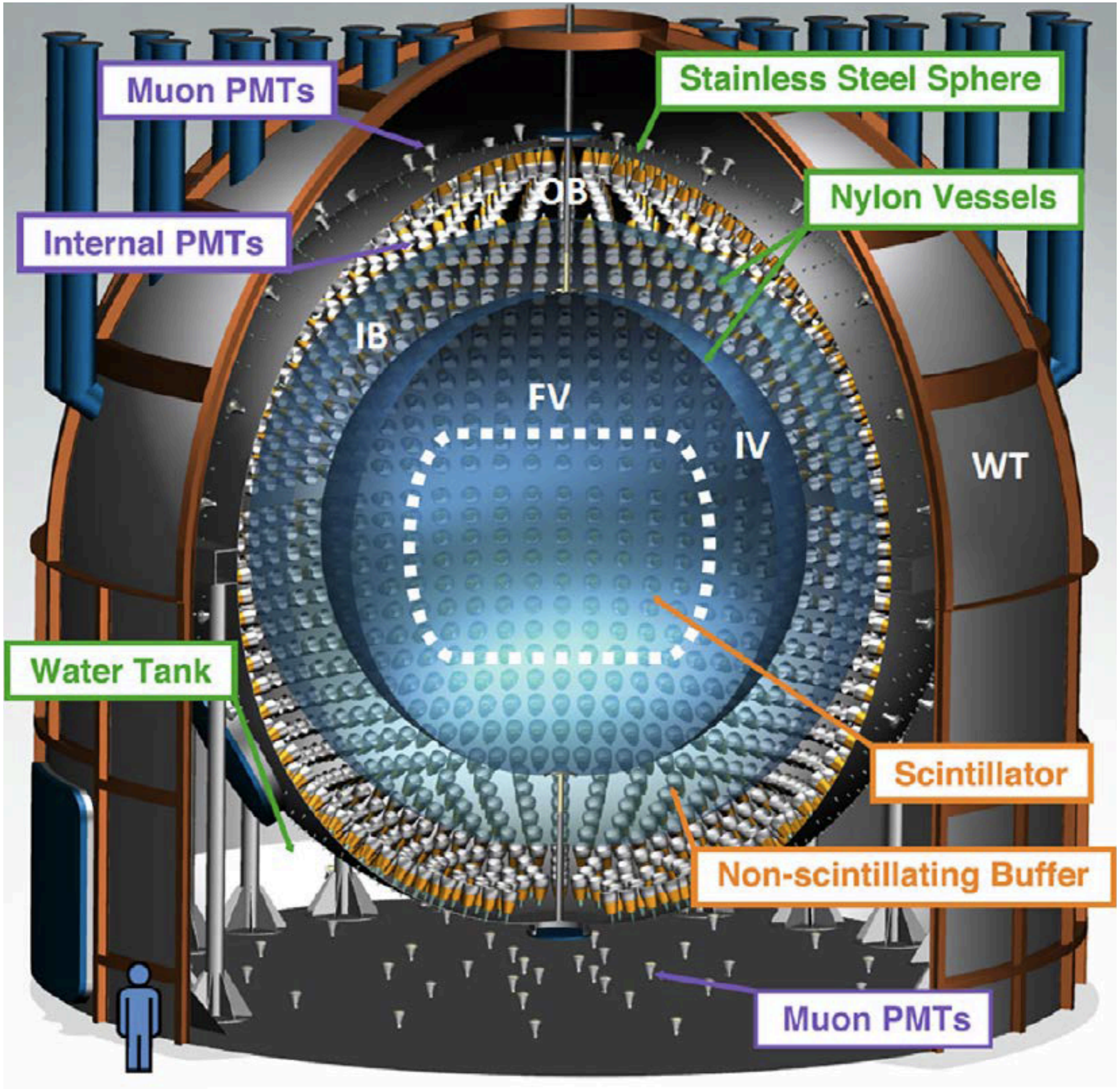
5.82 +- 1.3 (Bahcall et al),

5.31 +- 0.6 (Turck-Chieze et al)

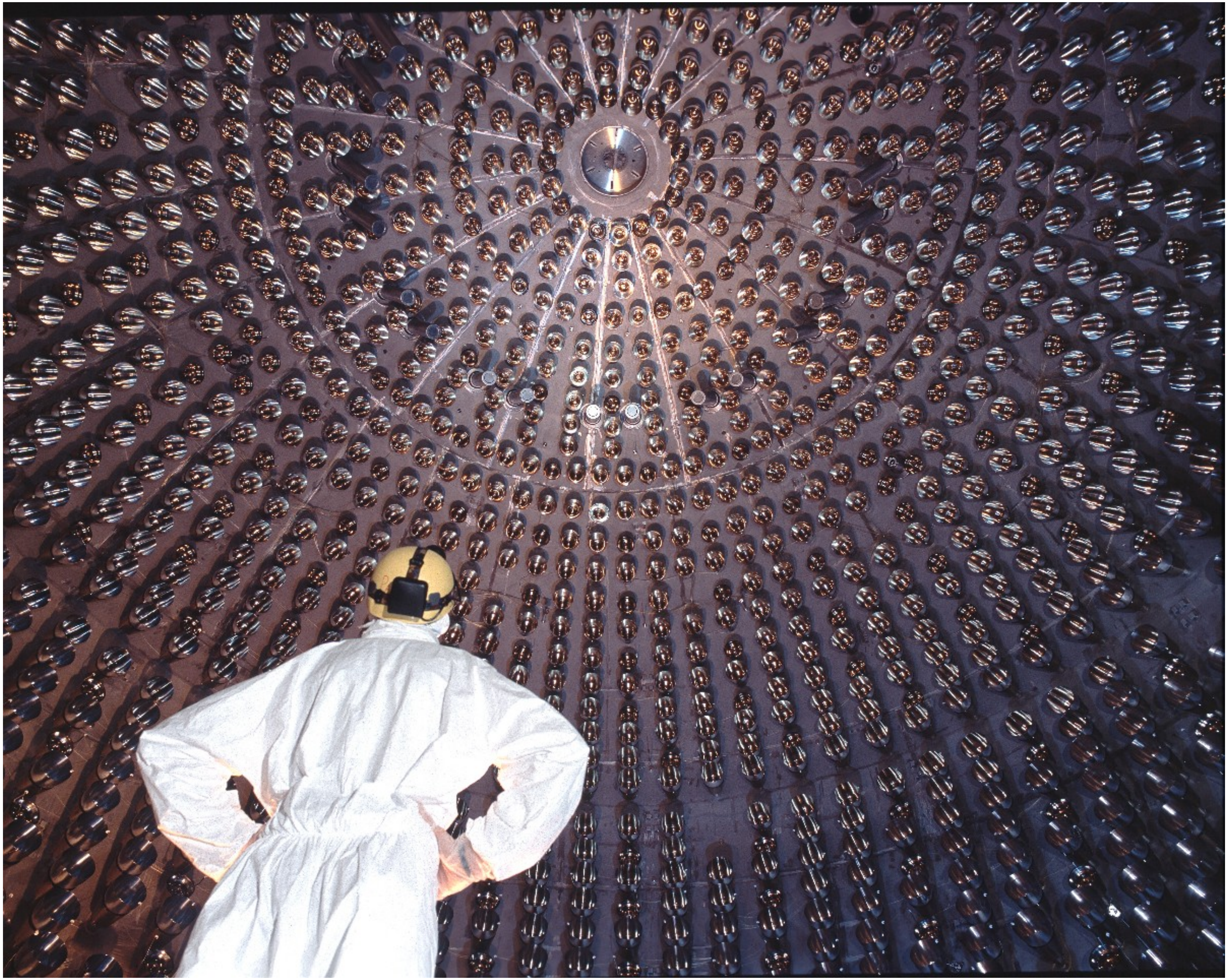
Electron Neutrinos are only 1/3 of Total

Art McDonald: Neutrino 2016

The Borexino detector

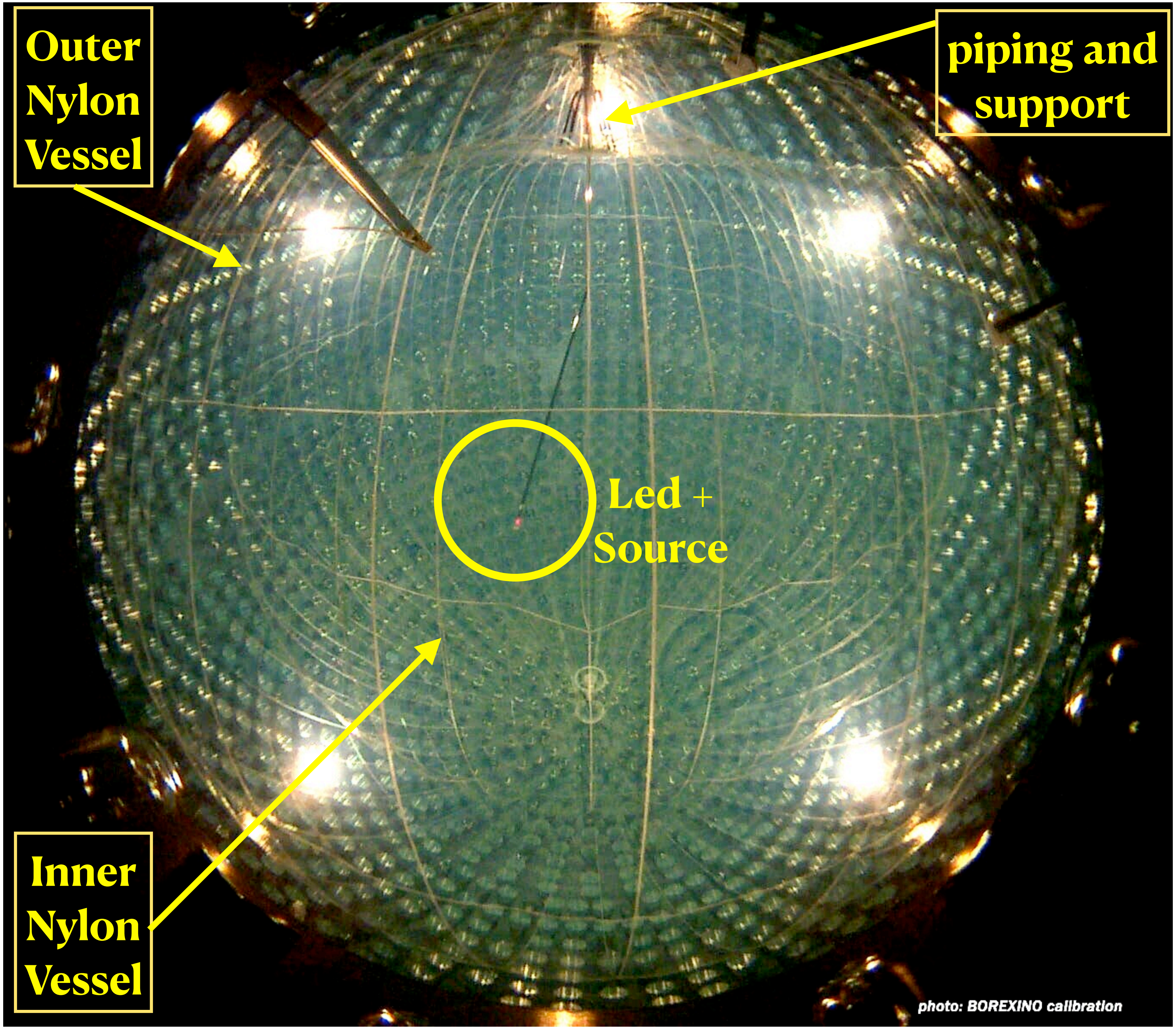


Internal view, empty

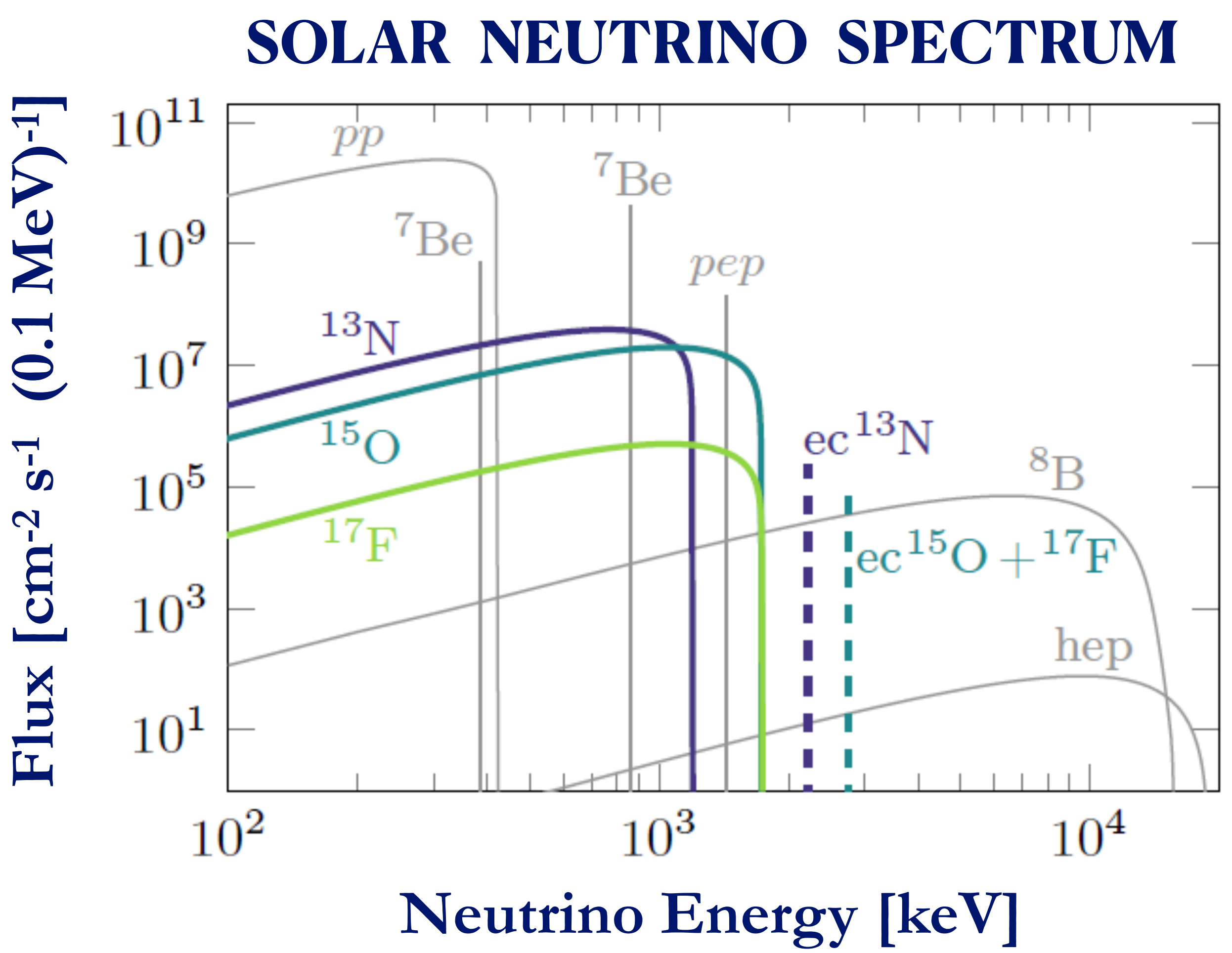


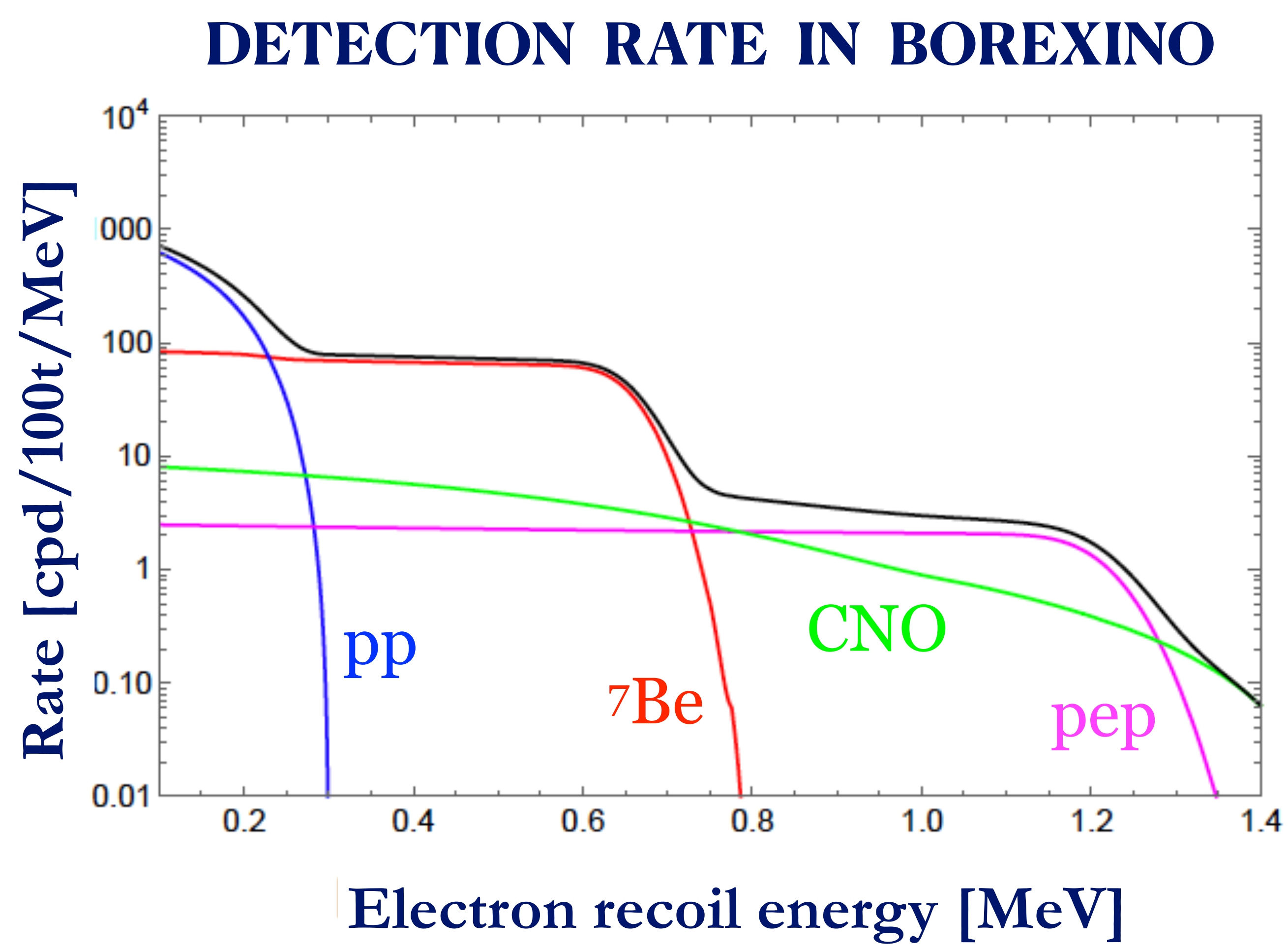
Internal view: inflated vessels (with N_2)

Internal view, filled, during calibration in 2009



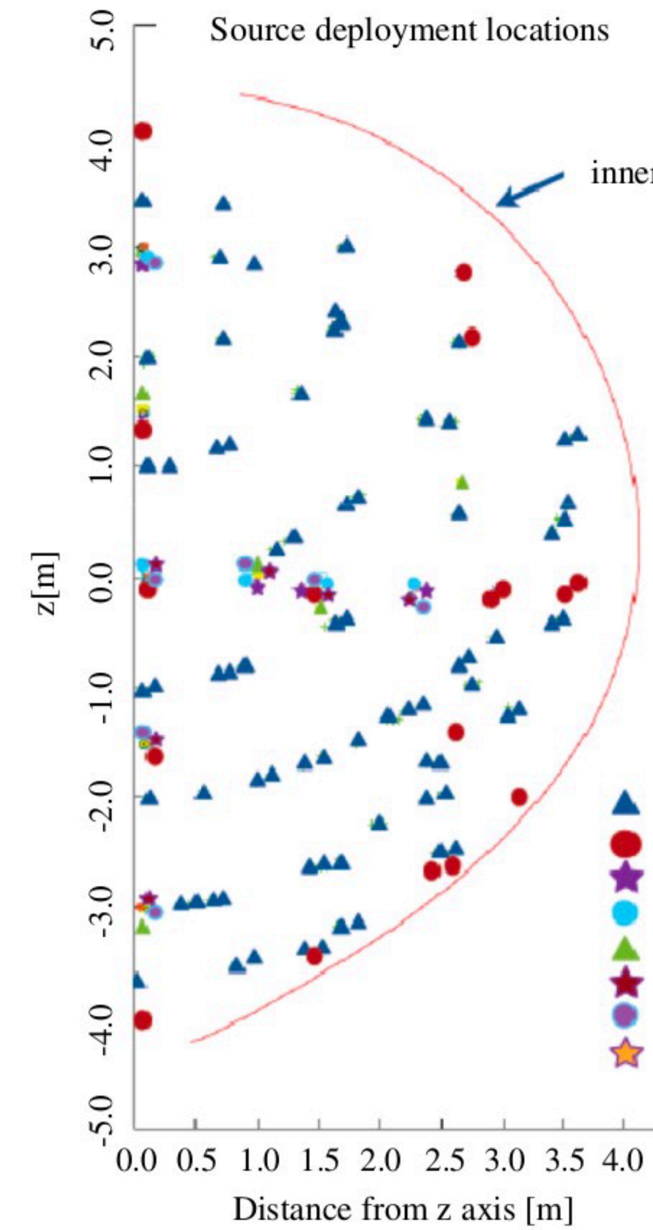
Neutrino detection in Borexino





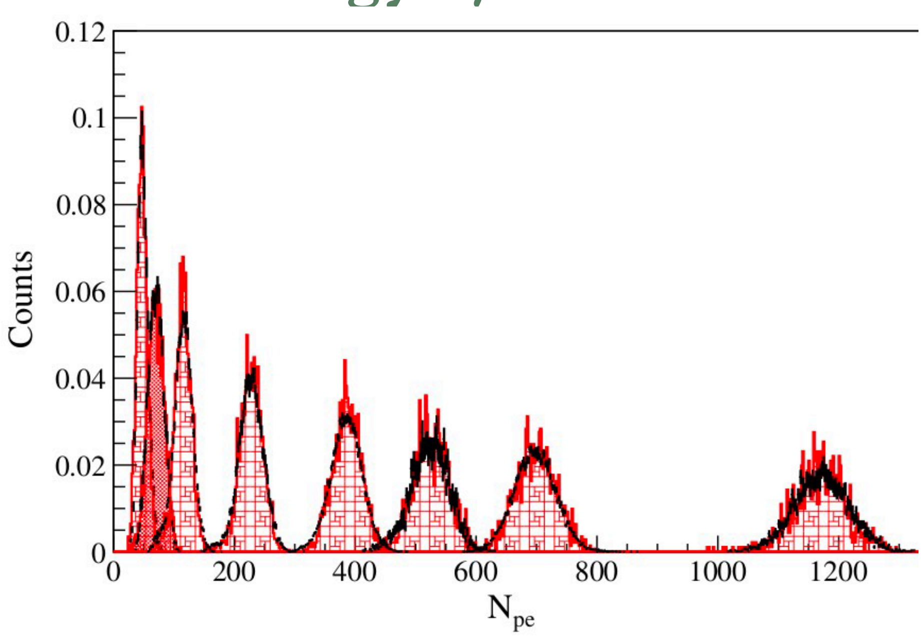
Detector response

- Large liquid scintillator signal yields:
  - # photo-electrons:
    - **energy: 6% @ 1 MeV**
  - time-of-flight:
    - **position: ~11 cm @ 1 MeV**
  - pulse shape:
    - very good α/β and (weak) β^+/β^- **discrimination**

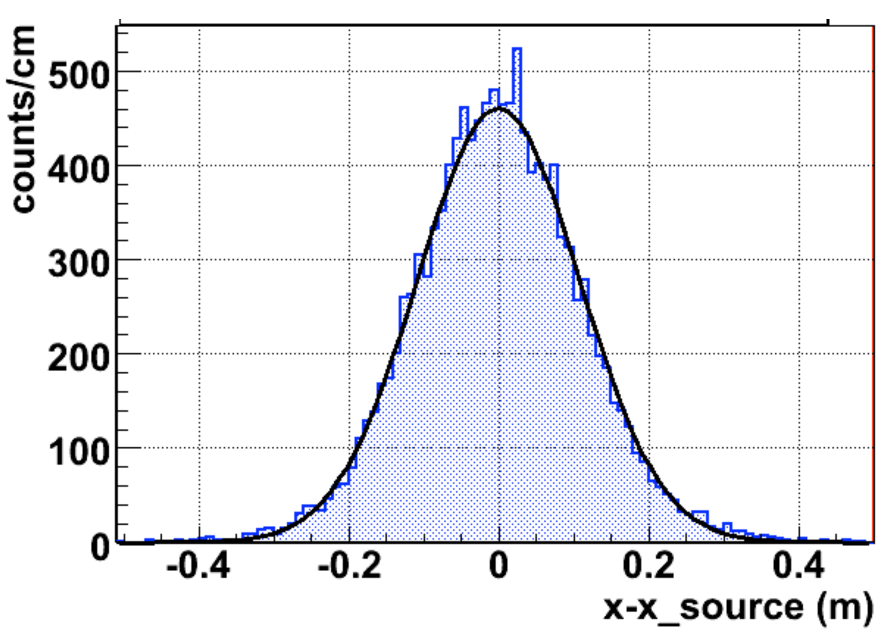


Internal source calibration campaign in 2009

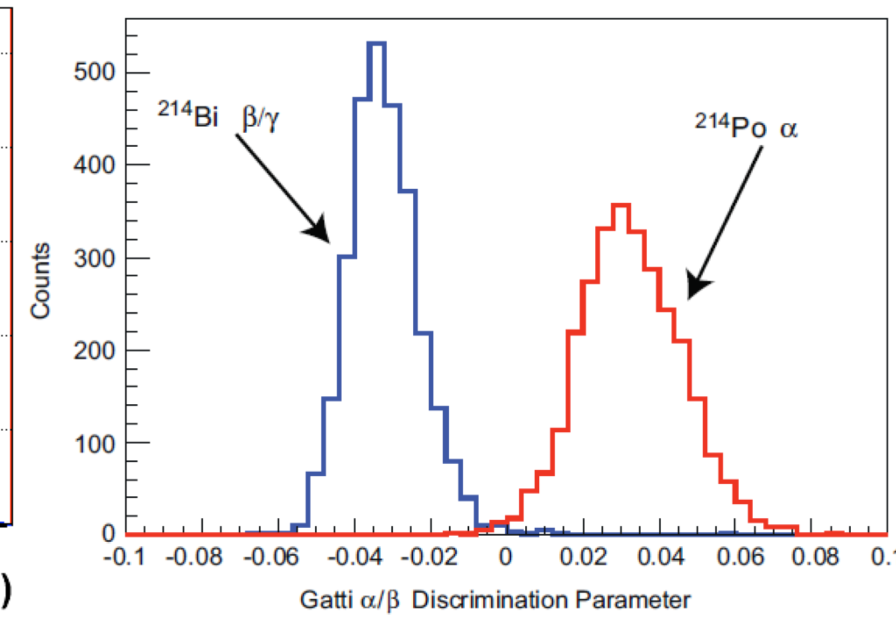
Energy: γ sources



Position: ^{214}Po



α/β: ^{214}Bi - ^{214}Po



Fighting backgrounds

- Quasi-point-like energy deposits mimic neutrino events

EXTERNAL

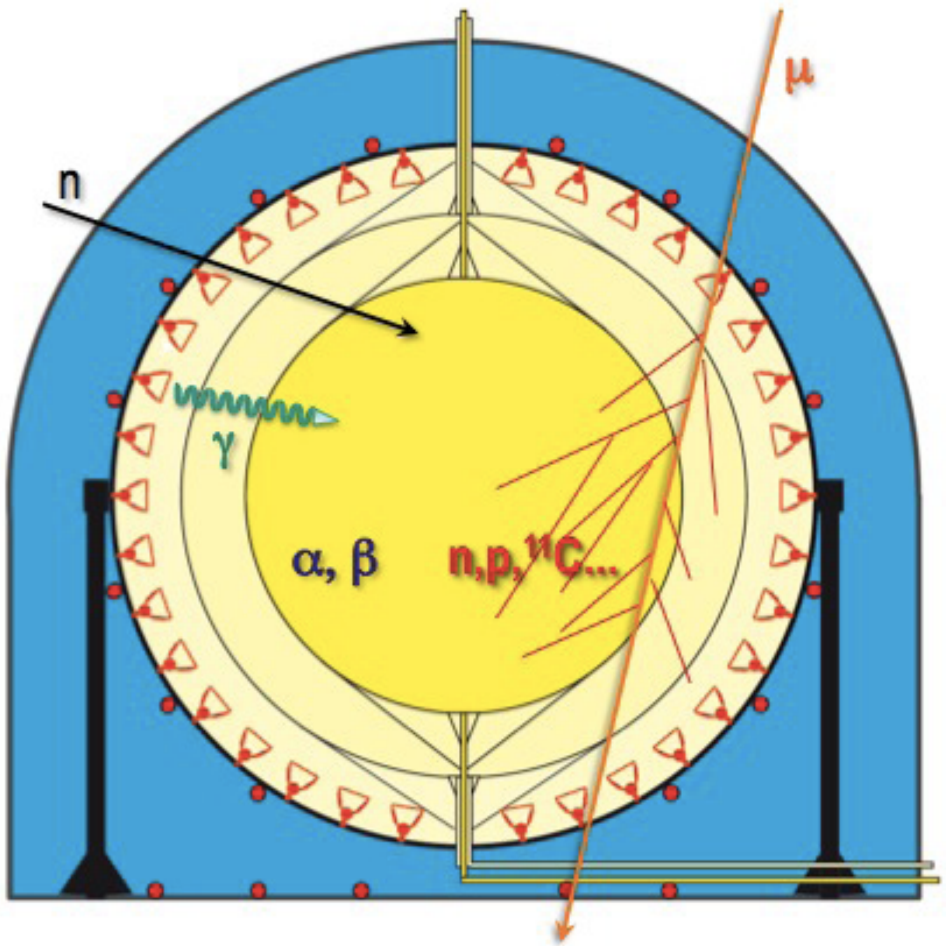
- γs (and n) from environment and detector materials (PMTs and SSS, mostly)

A tiny amount reaches FV

INTERNAL

- α and β emitters dissolved in the scintillator

^{14}C, ^{238}U, ^{232}Th, ^{40}K, ^{39}Ar, ^{7}Be, …
^{85}Kr, ^{210}Pb, ^{210}Po



COSMOGENIC

- Residual muons produce long living isotopes (μs to days range)

^{11}C, ^{8}He, ^{9}C, ^{9}Li, ….

MIGRATING

- Detaching from Nylon Vessel and transported by convection into the FV

^{210}Po, ^{222}Rn

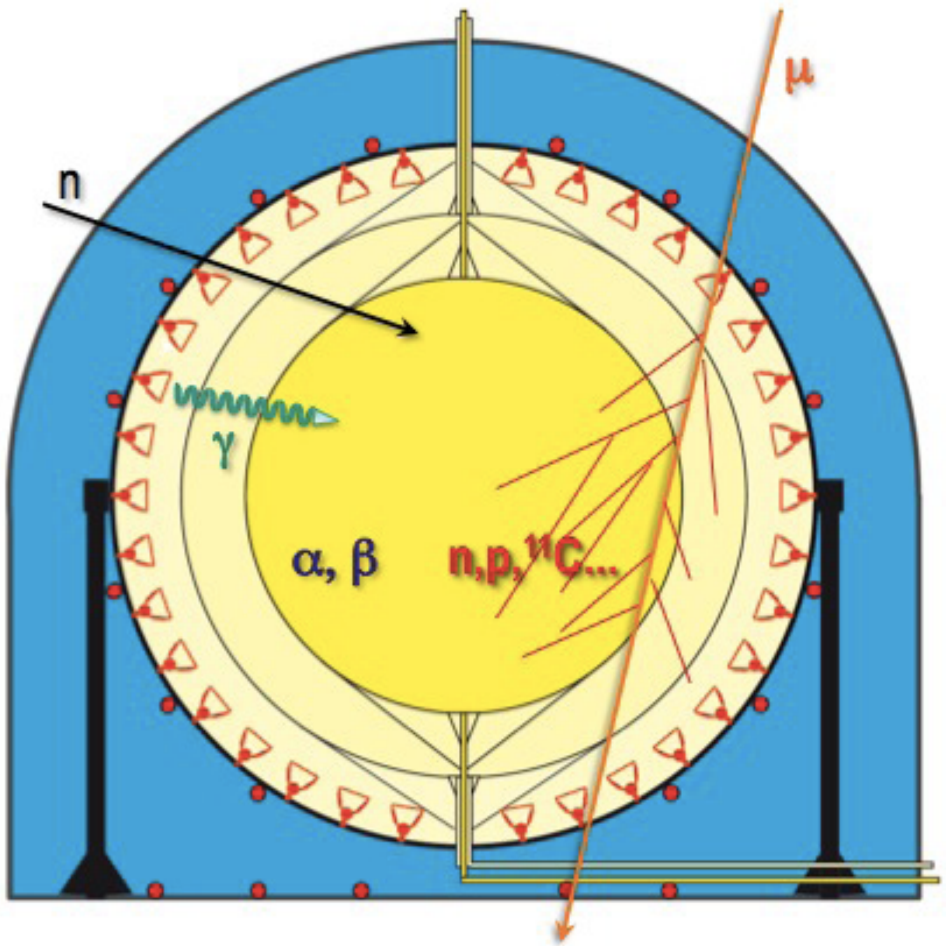
Fighting backgrounds

- **Quasi-point-like energy deposits mimic neutrino events**

EXTERNAL

- γs (and n) from environment and detector materials (PMTs and SSS, mostly)

A tiny amount reaches FV



COSMOGENIC

- Residual muons produce long living isotopes (μs to days range)

^{11}C, ^{8}He, ^{9}C, ^{9}Li, ….

INTERNAL

- α and β emitters dissolved in the scintillator

^{14}C, ^{238}U, ^{232}Th, ^{40}K, ^{39}Ar, ^{7}Be, … ^{85}Kr, ^{210}Pb, ^{210}Po

MIGRATING

- Detaching from Nylon Vessel and transported by convection into the FV

^{210}Po, ^{222}Rn

FIGHTING STRATEGY

- Shielding, muon tagging and tracking
- Material selection (steel, PMTs, nylon)
- Nylon vessel (material selection, clean construction, no air exposure)

Fighting backgrounds

- **Quasi-point-like energy deposits mimic neutrino events**

EXTERNAL

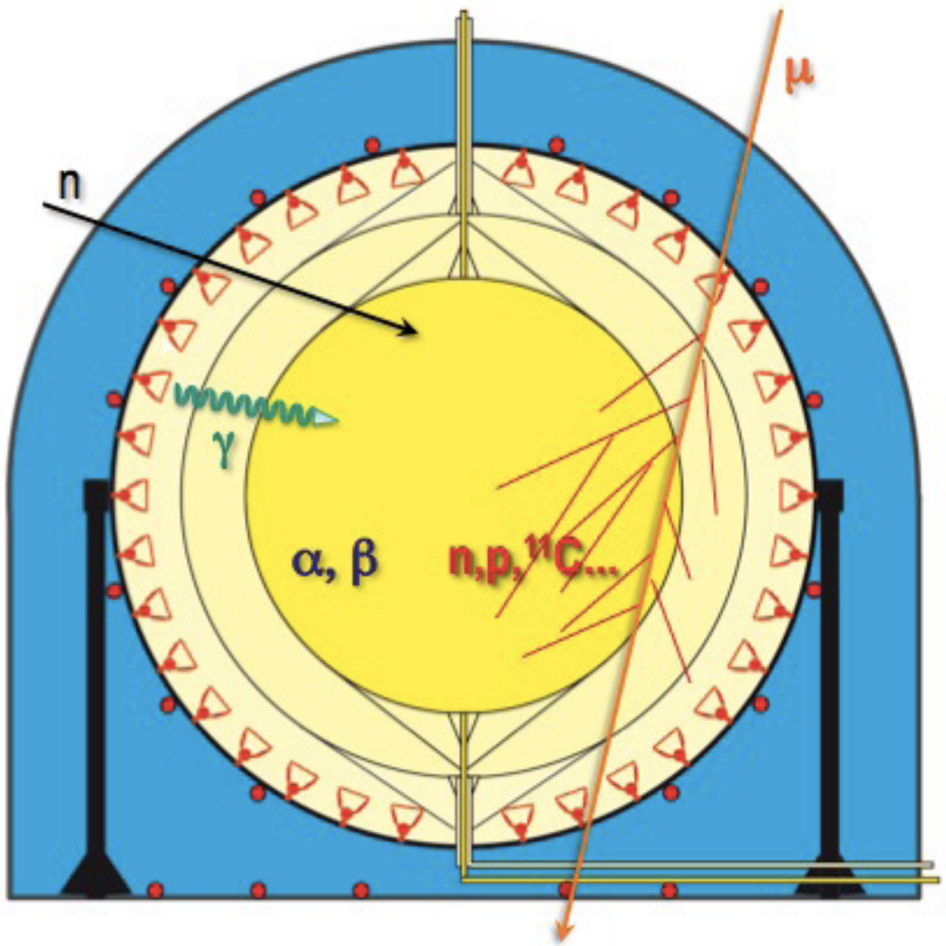
- γs (and n) from environment and detector materials (PMTs and SSS, mostly)

A tiny amount reaches FV

INTERNAL

- α and β emitters dissolved in the scintillator

^{14}C, ^{238}U, ^{232}Th, ^{40}K, ^{39}Ar, ^{7}Be, …
^{85}Kr, ^{210}Pb, ^{210}Po



COSMOGENIC

- Residual muons produce long living isotopes (μs to days range)

^{11}C, ^{8}He, ^{9}C, ^{9}Li, ….

MIGRATING

- Detaching from Nylon Vessel and transported by convection into the FV

^{210}Po, ^{222}Rn

FIGHTING STRATEGY

- Selection of PC vendor for low ^{14}C, dedicated plant, and custom transportation
- **Distillation** of PC, **Water Extraction** of PC+PPO solution
- Development of **low Ar and Kr N_2** to remove dissolved contaminants
- Extreme cleanliness of plants, carefully designed filling procedures

A long story made short!

- **Quasi-point-like energy deposits mimic neutrino events**

EXTERNAL

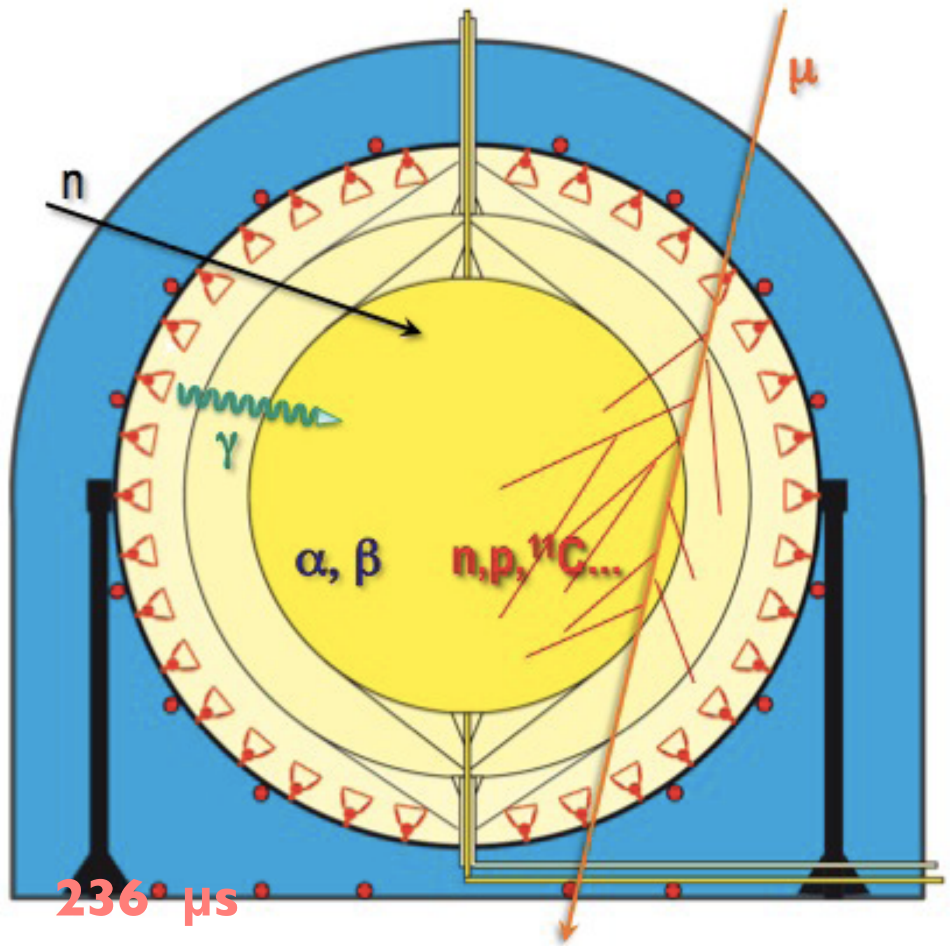
- γs (and n) from environment and detector materials (PMTs and SSS, mostly)

  A tiny amount reaches FV

INTERNAL

- α and β emitters dissolved in the scintillator

^{14}C, ^{238}U, ^{232}Th, ^{40}K, ^{39}Ar, ^{7}Be, …
^{85}Kr, ^{210}Pb, ^{210}Po



COSMOGENIC

- Residual muons produce long living isotopes (μs to days range)

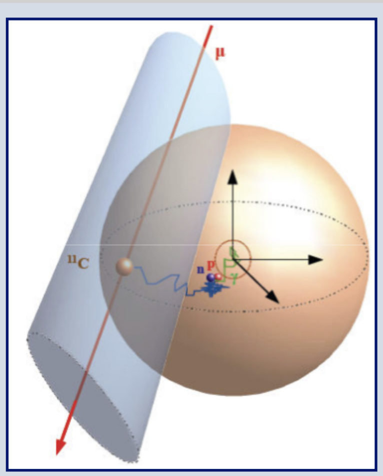
^{11}C, ^{8}He, ^{9}C, ^{9}Li, ….

MIGRATING

- Detaching from Nylon Vessel and transported by convection into the FV

^{210}Po, ^{222}Rn

FIGHTING STRATEGY



$$\mu + {}^{12}C \rightarrow n + {}^{11}C + \mu$$

29.4 min

$${}^{11}C \rightarrow {}^{11}B + e^+ + \nu_e$$

$$n + p \rightarrow D + \gamma \text{ (2.2 MeV)}$$

236 μs

Other isotopes: removed by "after muon" veto cuts

Fighting backgrounds

- **Quasi-point-like energy deposits mimic neutrino events**

EXTERNAL

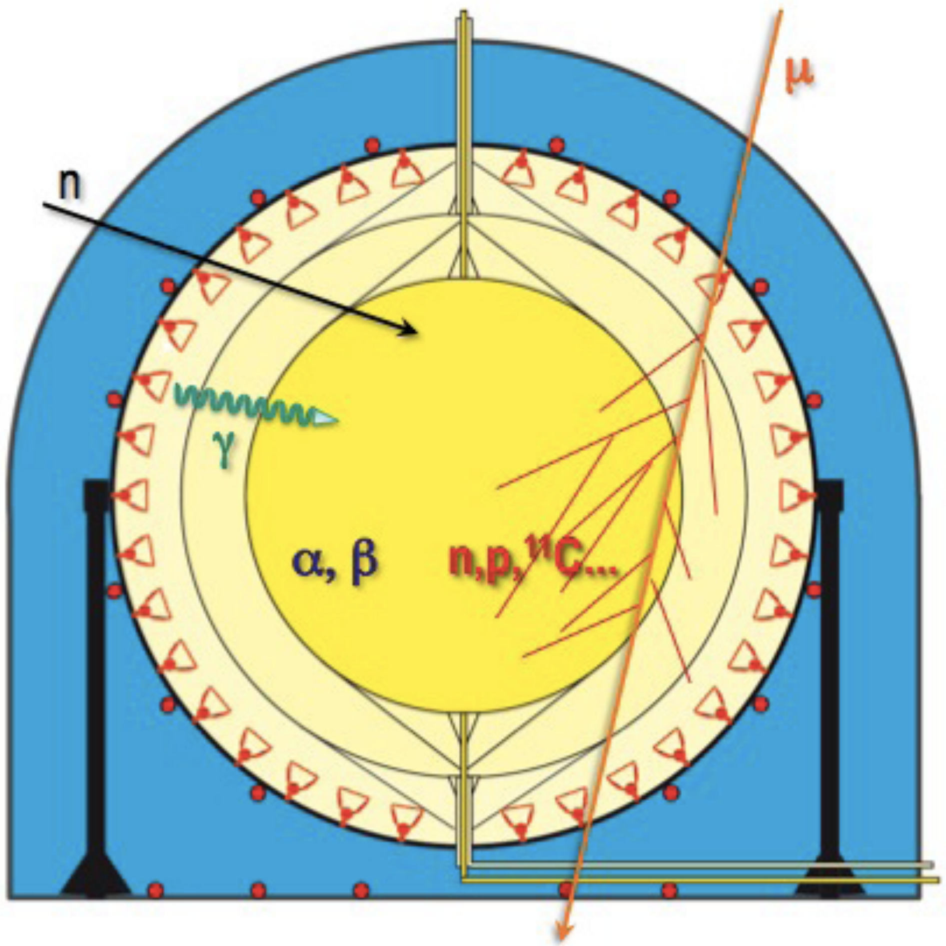
- γs (and n) from environment and detector materials (PMTs and SSS, mostly)

A tiny amount reaches FV

INTERNAL

- α and β emitters dissolved in the scintillator

^{14}C, ^{238}U, ^{232}Th, ^{40}K, ^{39}Ar, ^{7}Be, … ^{85}Kr, ^{210}Pb, ^{210}Po



COSMOGENIC

- Residual muons produce long living isotopes (μs to days range)

^{11}C, ^{8}He, ^{9}C, ^{9}Li, ….

MIGRATING

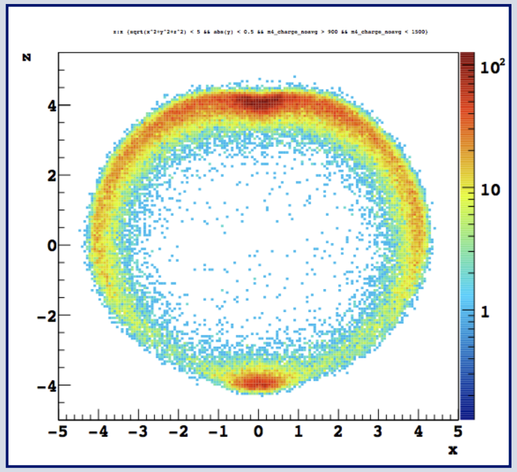
- Detaching from Nylon Vessel and transported by convection into the FV

^{210}Po, ^{222}Rn

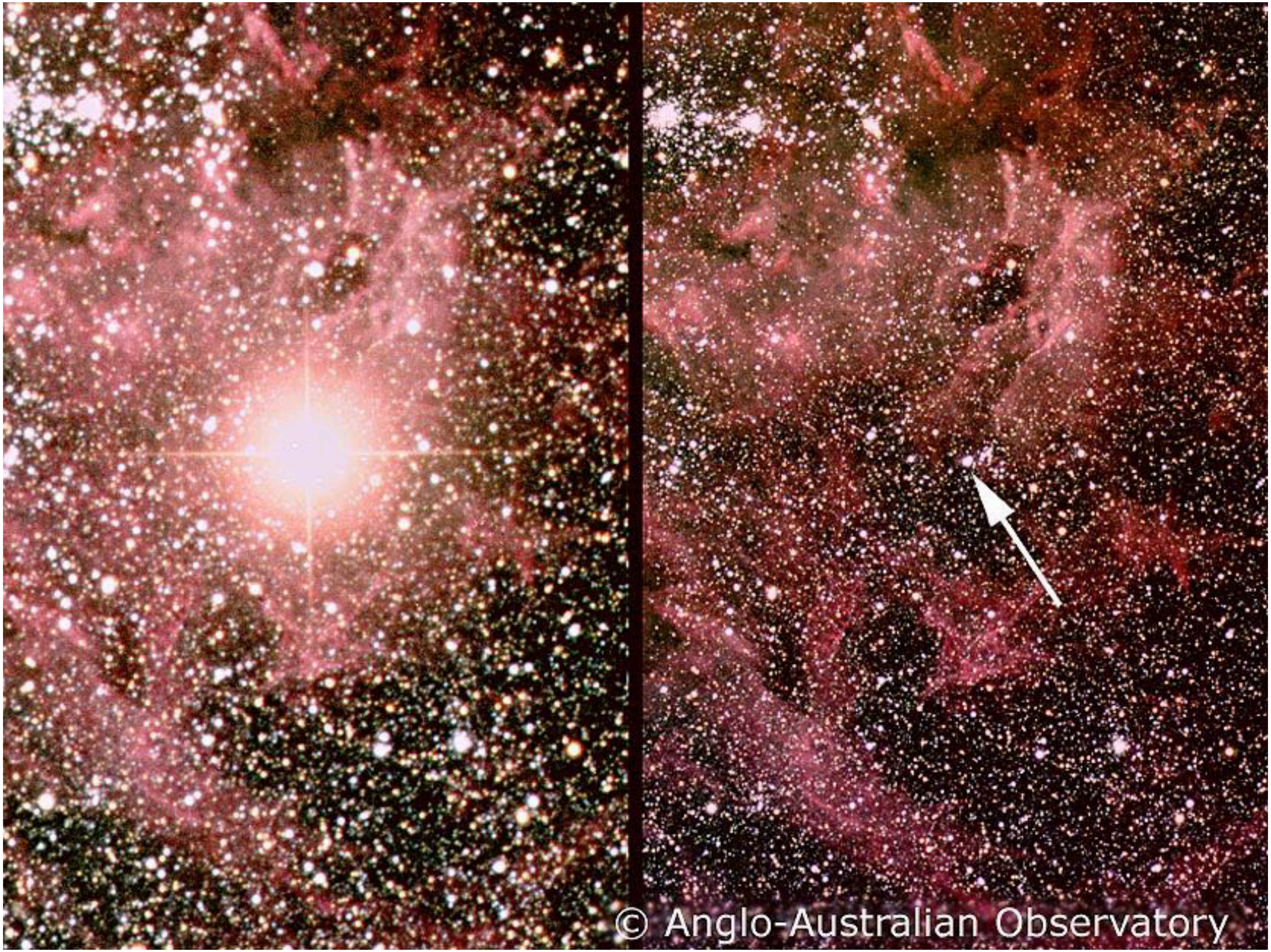
FIGHTING STRATEGY

- Isotopes detaching from IV may reach the FV
  - ^{210}Po (chiefly) and ^{222}Rn daughters
- Leaching rate (chemistry) and speed (convection currents)
  - Only if they live long enough!

See later



SN1987a: optical image before and after



SN1987a

- The first (and so far unique) neutrino detection for a star other than our Sun

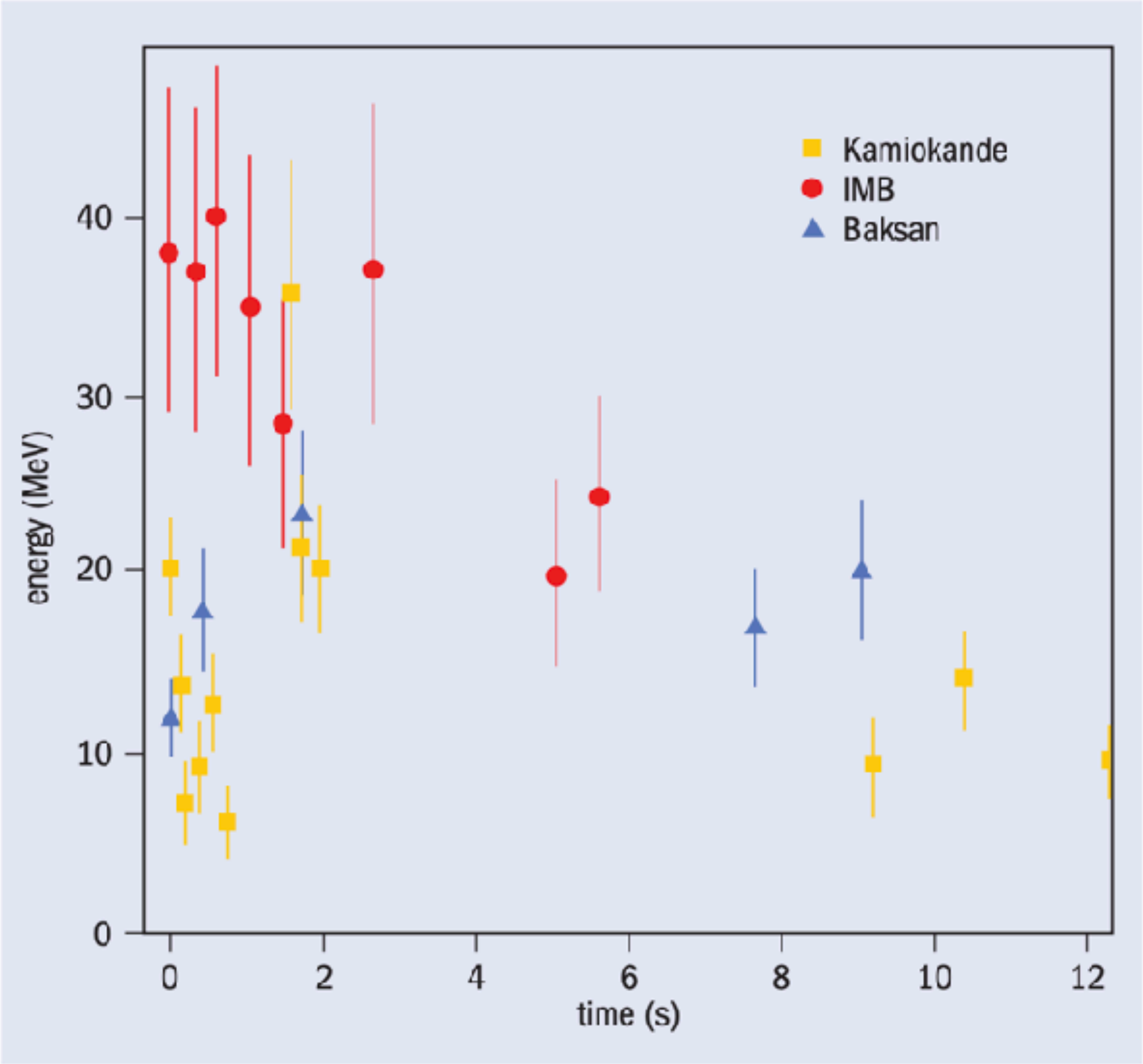


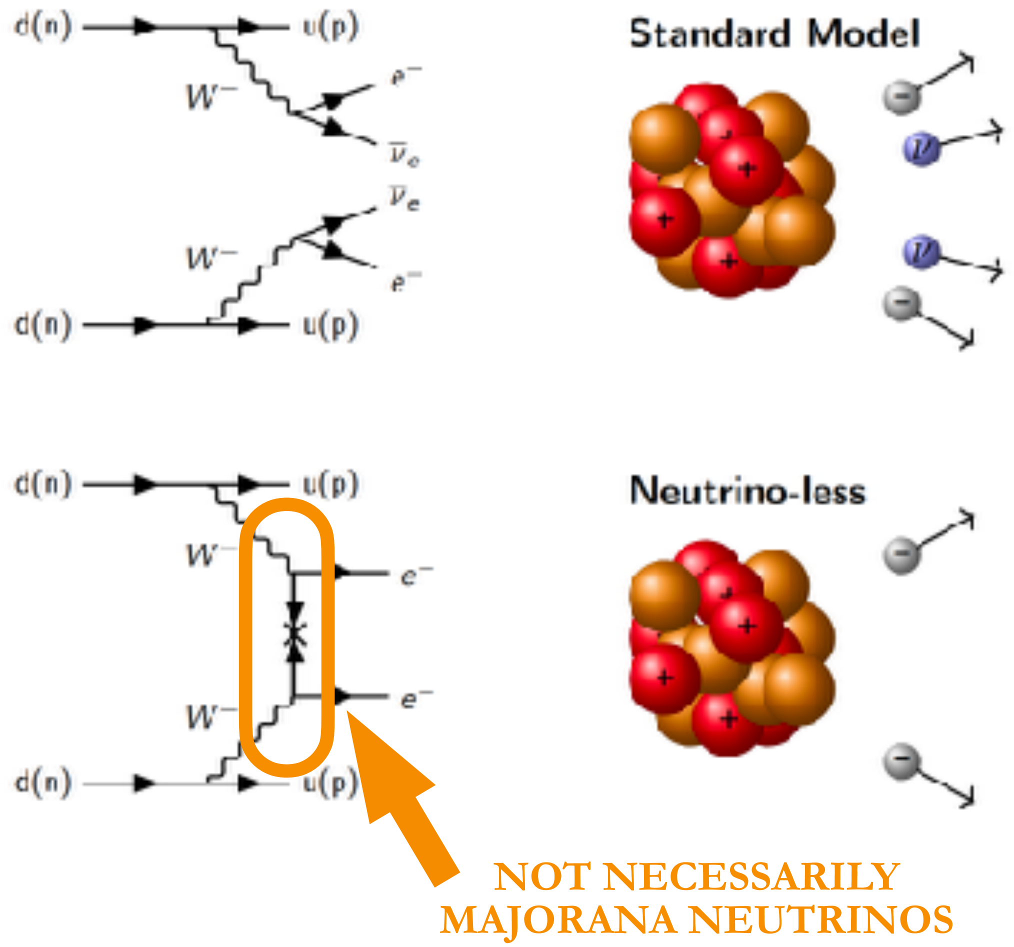
Fig. 3. SN1987A neutrino events observed by Kamiokande, IMB and Baksan showed that the neutrino burst lasted about 13 s.

Open problems

- **Neutrino mass type**
  - Majorana vs Dirac
    - **NEUTRINOLESS DOUBLE BETA DECAY**
- **Neutrino mass scale**
  - What is the value of m_1 ?
    - **DIRECT NEUTRINO MEASUREMENTS** (not covered)
- **Neutrino mass ordering**
  - $m_3>m_1$ or $m_3<m_1$?
    - JUNO, ORCA, DUNE
- **CP violation in lepton sector ?**
  - What is the value of δ_{CP} ?
    - T2K and Nova, then (>2028) DUNE and T2HK

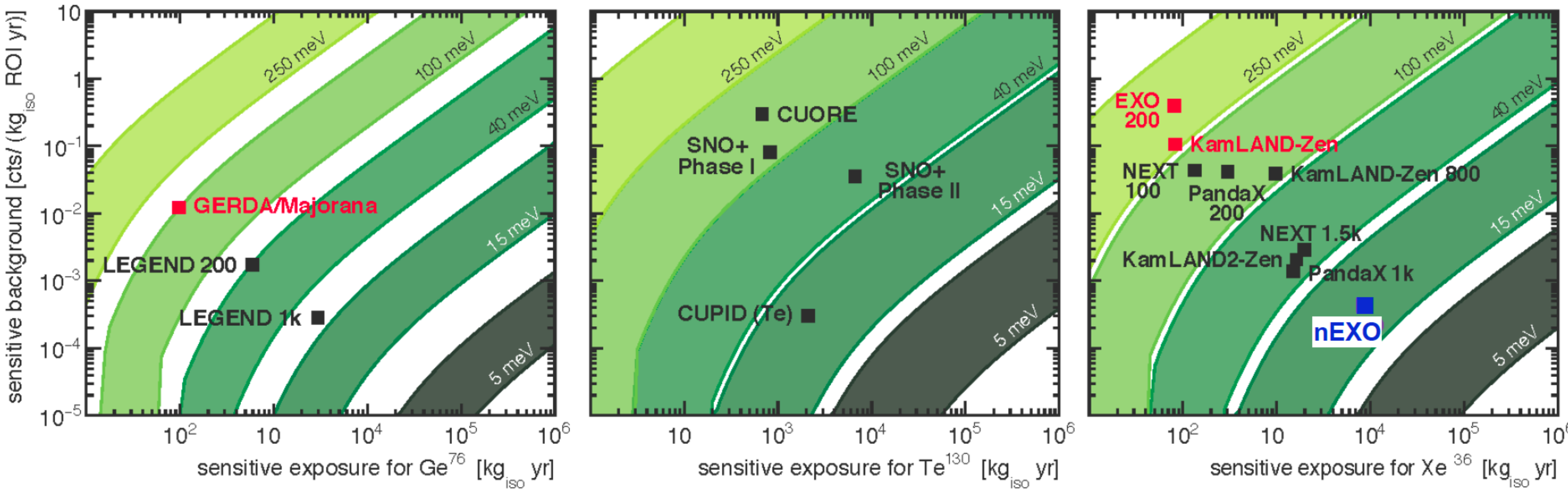
Why $0\nu\beta\beta$ is important ?

- The only know process that can **distinguish** between **Majorana and Dirac mass terms**
  - i.e. $0\nu\beta\beta$ can happen only if neutrinos are their own anti-particle (truly neutral)
  - i.e. lepton number is violated
  - **In all scenarios $0\nu\beta\beta$ implies new physics**

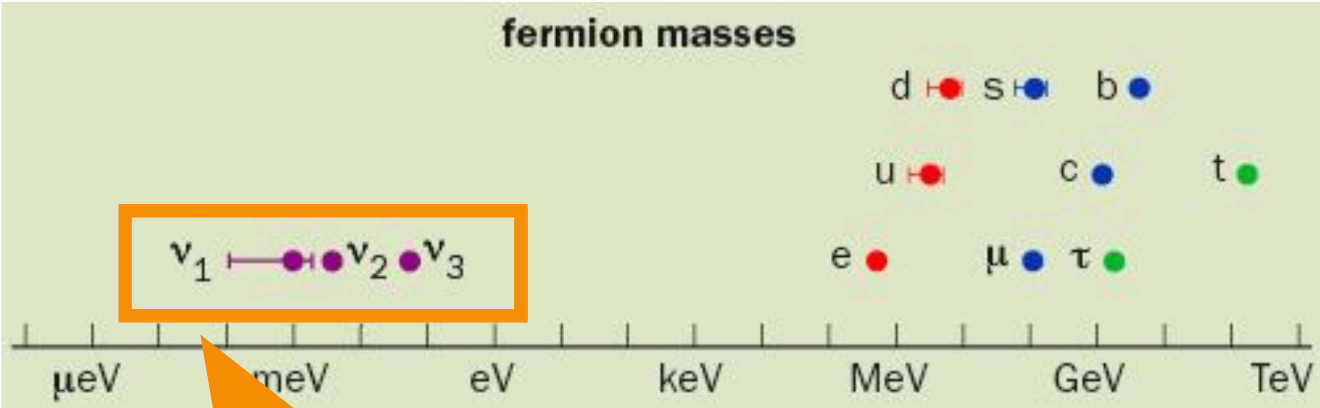


SENSITIVITY OF NEXT GENERATION EXPERIMENTS

PRD 96 (2017) 053001
PRD 96 (2017) 073001)



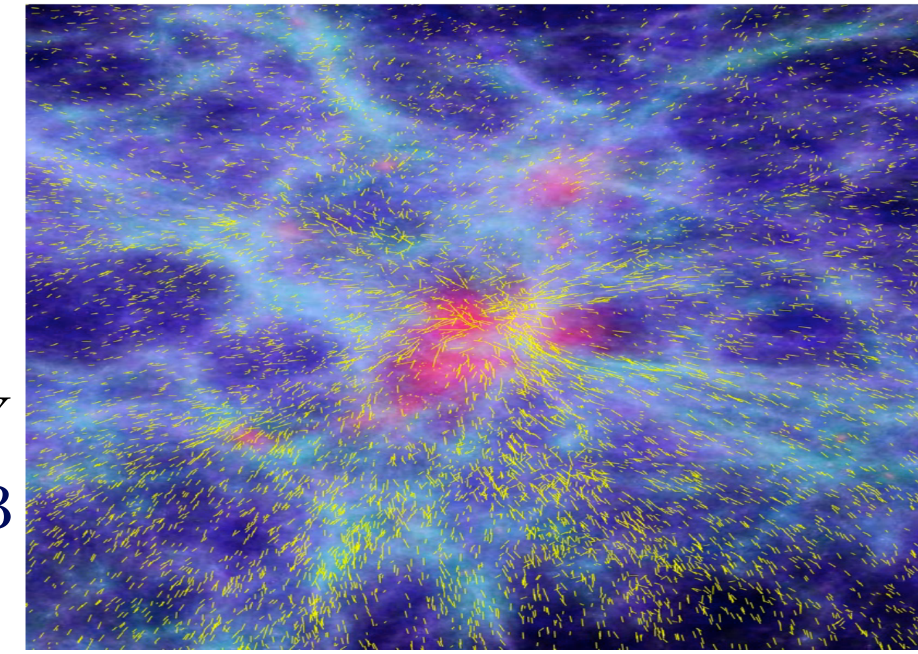
Why mass is important: three ways, three “masses” !



NEUTRINOS ARE DIFFERENT ?

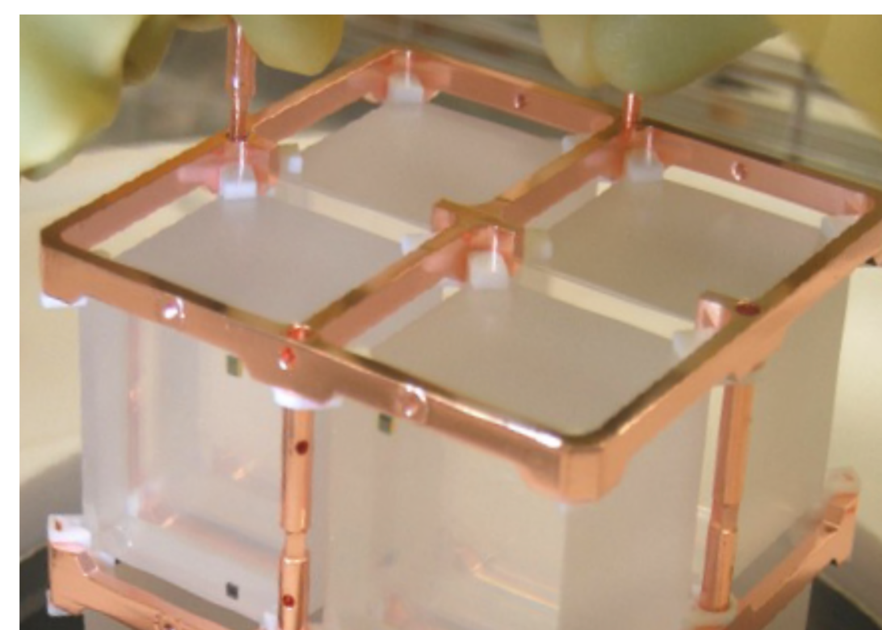
GRAVITY

$$\Sigma_\nu = m_1 + m_2 + m_3$$



β **DECAY KINEMATICS**

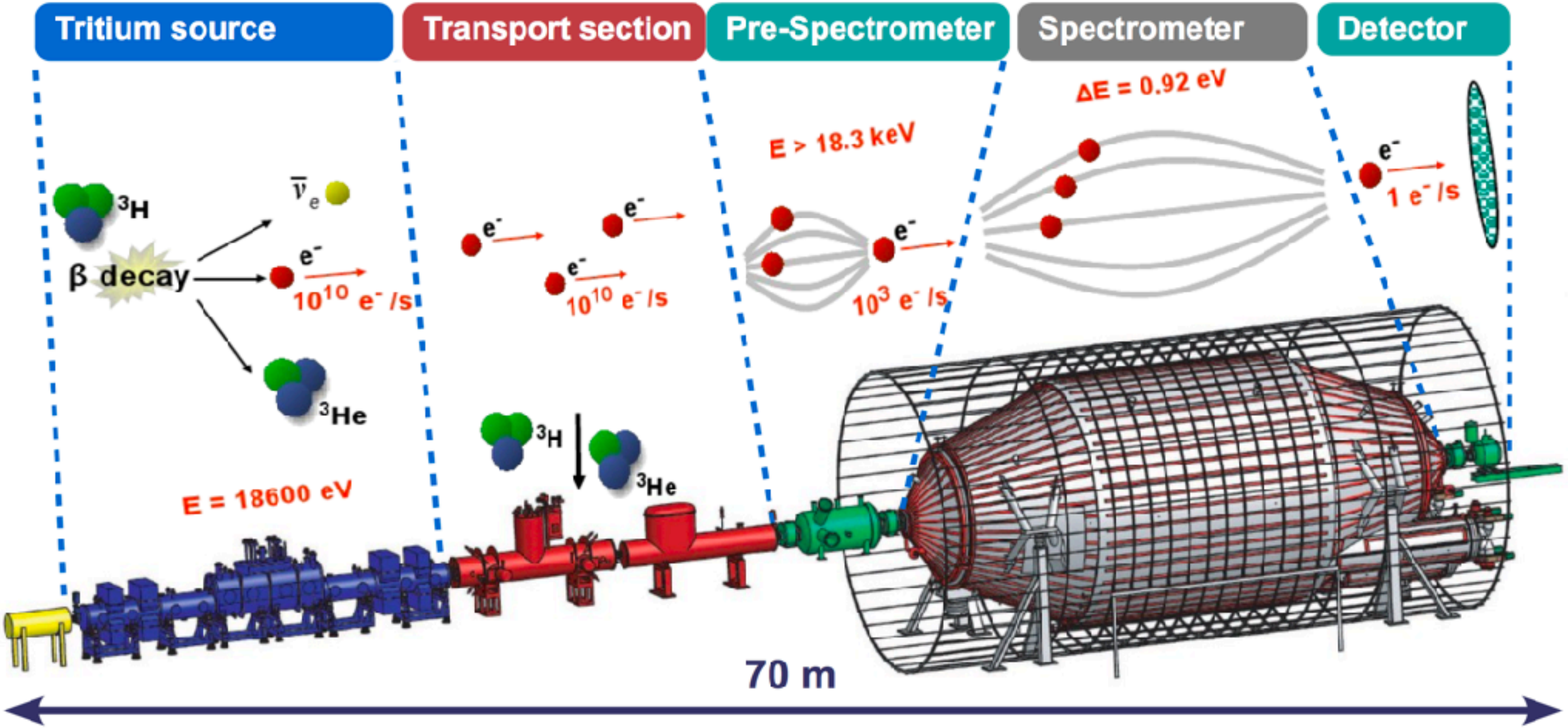
$$m_\beta = \sqrt{|U_{e1}|^2\, m_1^2 + |U_{e2}|^2\, m_2^2 + |U_{e3}|^2\, m_3^2}$$



LEPTON NUMBER VIOLATION ($0\nu\beta\beta$ DECAY)

$$m_{\beta\beta} = \left| U_{e1}^2\, m_1 + U_{e2}^2\, m_2 + U_{e3}^2\, m_3 \right|$$

Katrin



Potential sensitivity: 0.35 eV (discovery at 5 σ, 0.2 upper limit)

Why measuring δ_{CP} is important ?

- We do not understand the **origin of matter-antimatter asymmetry in the Universe**
  - To get it you need CP violation (and baryon number violation)
  - Is the CP violation required explained by Standard Model + PMNS ?

- CP violation is proportional to so called Jarlskog invariant

$$J = \sin\vartheta_{12}\cos\vartheta_{12}\sin\vartheta_{23}\cos\vartheta_{23}\sin\vartheta_{13}\cos^2\vartheta_{13}\sin\delta_{CP} = J_{max}\sin\delta_{CP}$$

$$J_{max}^{quarks} = (3.18 \pm 0.15)\cdot 10^{-5}$$

$$J_{max}^{leptons} = (3.3 \pm 0.06)\cdot 10^{-2}$$

  - Quarks are ruled out
  - Leptons, not necessarily. They may play a role, possibly not unique.

- **Be aware:** you need, anyway, a **baryon number violation mechanism,** which cannot be related to SM

Thank you