Selected topics in nuclear and particle physics

(Chapitres choisis de physique nucléaire et corpusculaire)

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https://moodle.epfl.ch/course/view.php?id=2861

Spring semester 2025

PART I

Neutrino Physics

Neutrinos: Historical Introduction

1910's: the β decay spectrum is continuous

- 1914: J. Chadwick observes that the electron spectrum is continuous in nuclear β decays $A \rightarrow B + e^-$

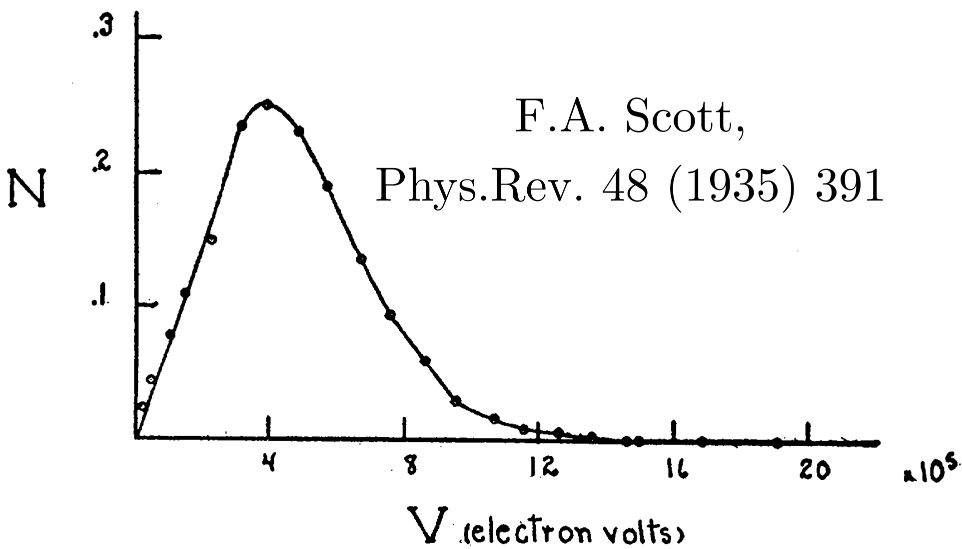


FIG. 5. Energy distribution curve of the beta-rays.

Electron energy in two-body decays:

$$E(e) = \frac{m_A^2 - m_B^2 + m_e^2}{2m_A} c^2$$

  - this result is in contradiction with the hypothesis of energy conservation in two-body decays
  - this remained a mystery for more than 15 years!

1930's: the neutrino hypothesis

- 1930 : Wolfgang Pauli postulates the existence of a new **light**, **neutral**, **spin 1/2**, and **non-interacting** particle, which he calls "neutron"
  - such a particle would explain the observed continuous spectrum
  - it is a very hypothetical idea... ... but which will prove to be correct!

W. Pauli, Lecture in Copenhagen, 1929
CERN PAULI-ARCHIVE-PHO-021-1

- 1932 : James Chadwick discovers a neutral particle, with a mass similar to the proton mass: the "neutron" (n)

J. Chadwick, Proc. R. Soc. Lond. A136 (1932) 692

  - Fermi renames "neutrino" (ν) Pauli's neutral particle

1930's: Fermi's theory

- 1934: Enrico Fermi gives the first theoretical description for nuclear β decays
  - the electron and the neutrino are not pre-existing components of the nucleus: a neutron decays into a proton, an electron, and a (anti-)neutrino

E.Fermi
(Los Alamos ID card)

$$(A, Z) \to (A, Z+1) + e^- + \bar{\nu}_e$$

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

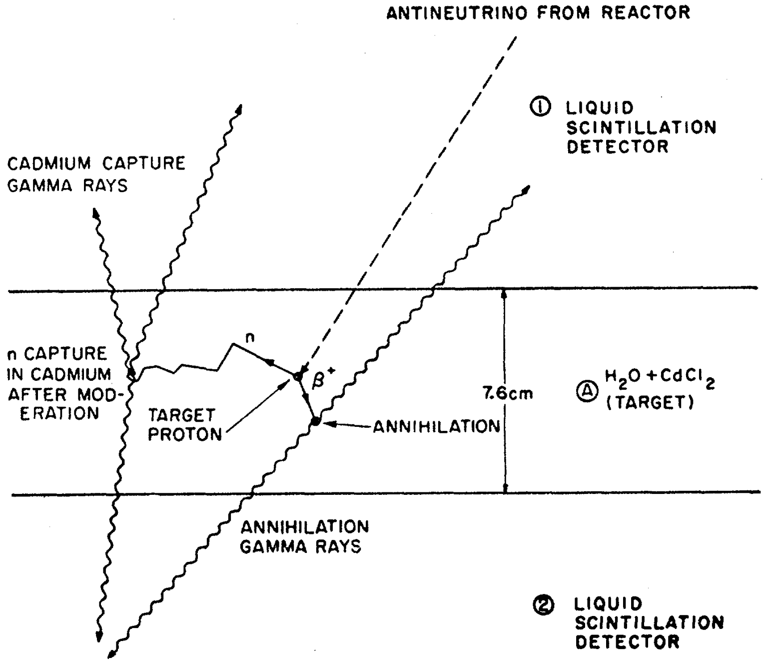
  - Fermi describes the transition probability in terms of hadronic and leptonic currents (similarly to quantum electrodynamics)

1950's: observation of the neutrino (I)

- 1956: Reines and Cowan observe the neutrino in inverse β decays (Savannah River experiment)

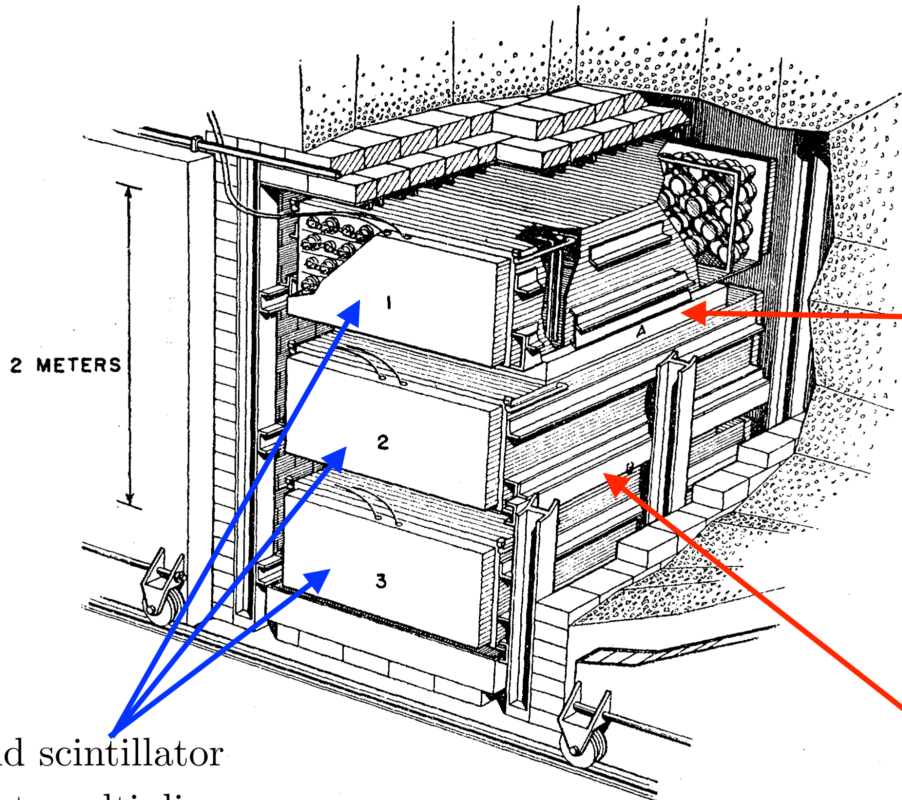
$$\bar{\nu}_e + p \to n + e^+$$

  - anti-neutrinos are produced in a nuclear reactor
  - e^+ annihilation with e^- gives two 511 keV photons in coincidence
  - a neutron captured by Cd gives several delayed photons (depends on Cd concentration ⇒ calibration)

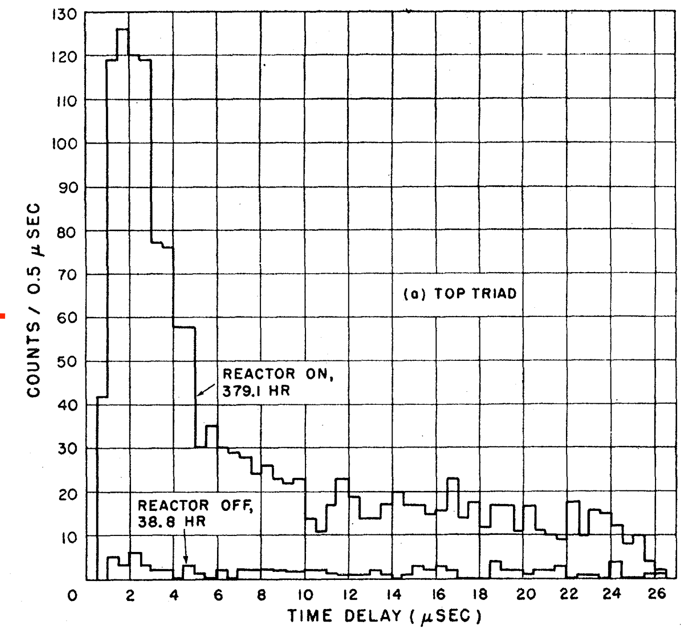


Reines et.al., Phys. Rev. 117 (1960) 159

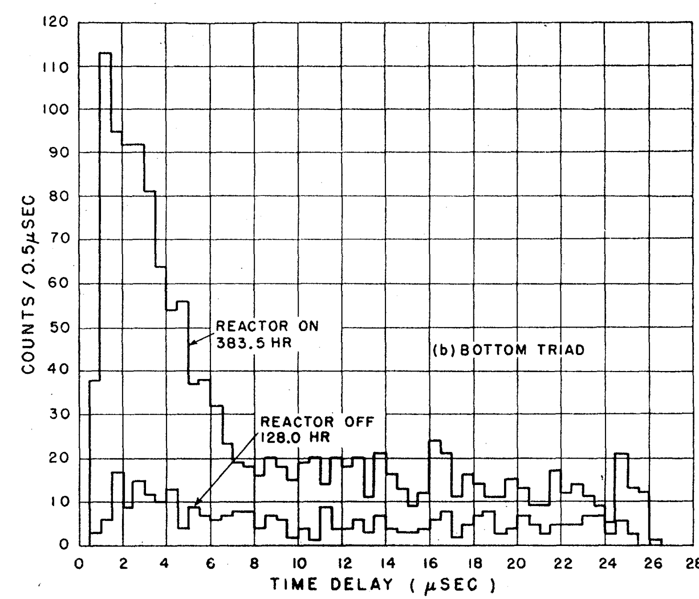
1950's: observation of the neutrino (II)



Liquid scintillator
+ photomultipliers



(a)



- Unambiguous observation of a signal associated to the reactor activity

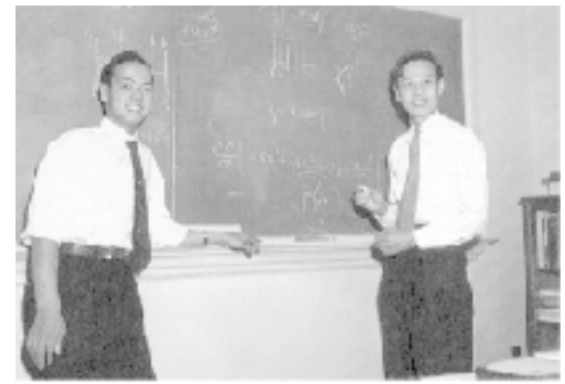
$\Rightarrow$ confirms the existence of the neutrino

Reines et.al., Phys. Rev. 117 (1960) 159

1950-1960's: the neutrino "flavour"

- 1958: Parity violation
  - neutrinos are "left handed" (left polarisation), while anti-neutrinos are "right handed" ⇒ description of the neutrino with spinors

- 1960: $\mu^{\pm} \rightarrow e^{\pm} + \gamma$ is not observed
  ⇒ forbidden decay
  - T.D.Lee and C.N.Yang conclude that $\nu_e \neq \nu_\mu$
    ⇒ need a distinct lepton number
    for each lepton family

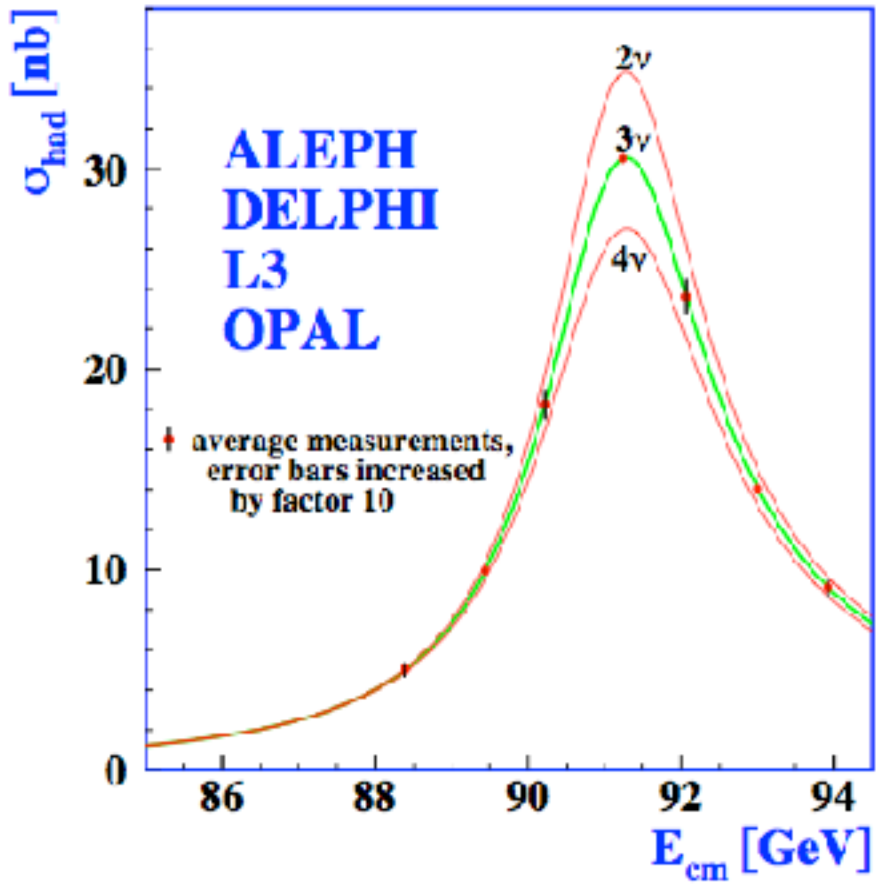


T. D. Lee   C. N. Yang

- 1962: Schwartz, Lederman and Steinberger observe the muon neutrino ν_μ
  in the decay $\pi^+ \rightarrow \mu^+ + \nu_\mu$

1980's: number of neutrino families

- 1989: the LEP experiments (CERN) show that there are exactly 3 types of light neutrinos coupling to SM particles

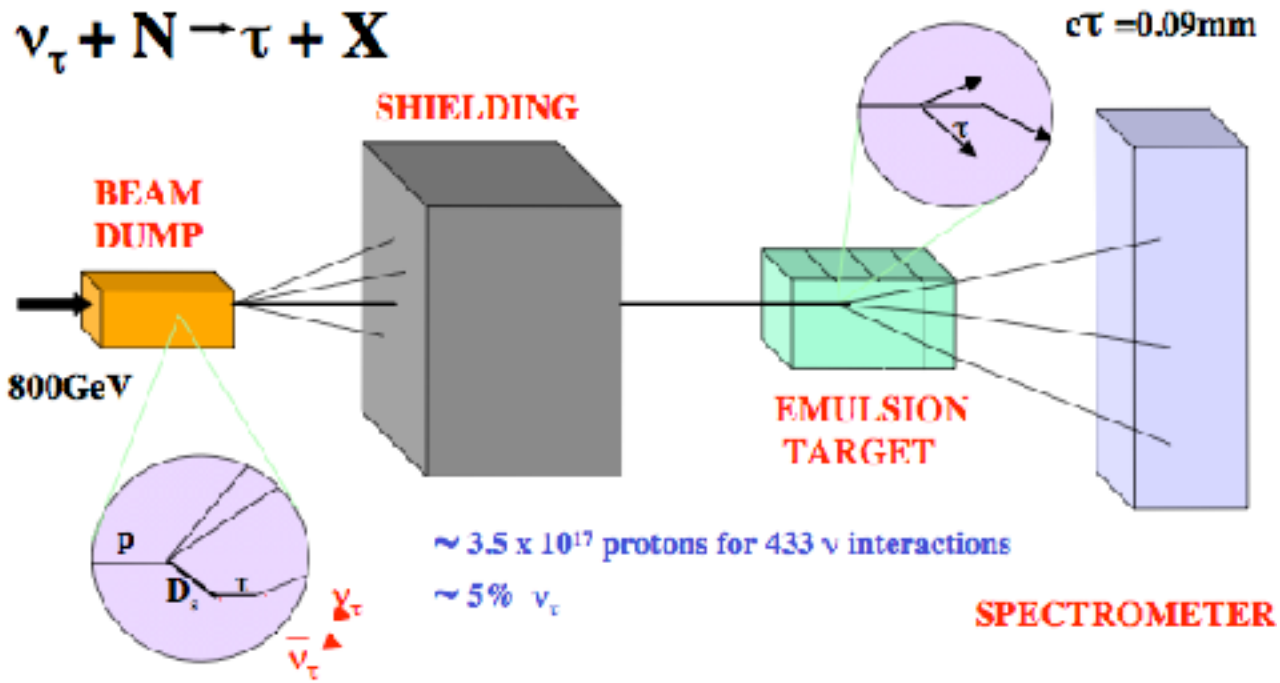


ALEPH, DELPHI, L3, OPAL
Phys. Lett. B276 (1992) 247

⇒ this result predicted the existence of the τ neutrino (ν_τ), although it had not been observed yet

2000: observation of the τ neutrino (ν_τ)

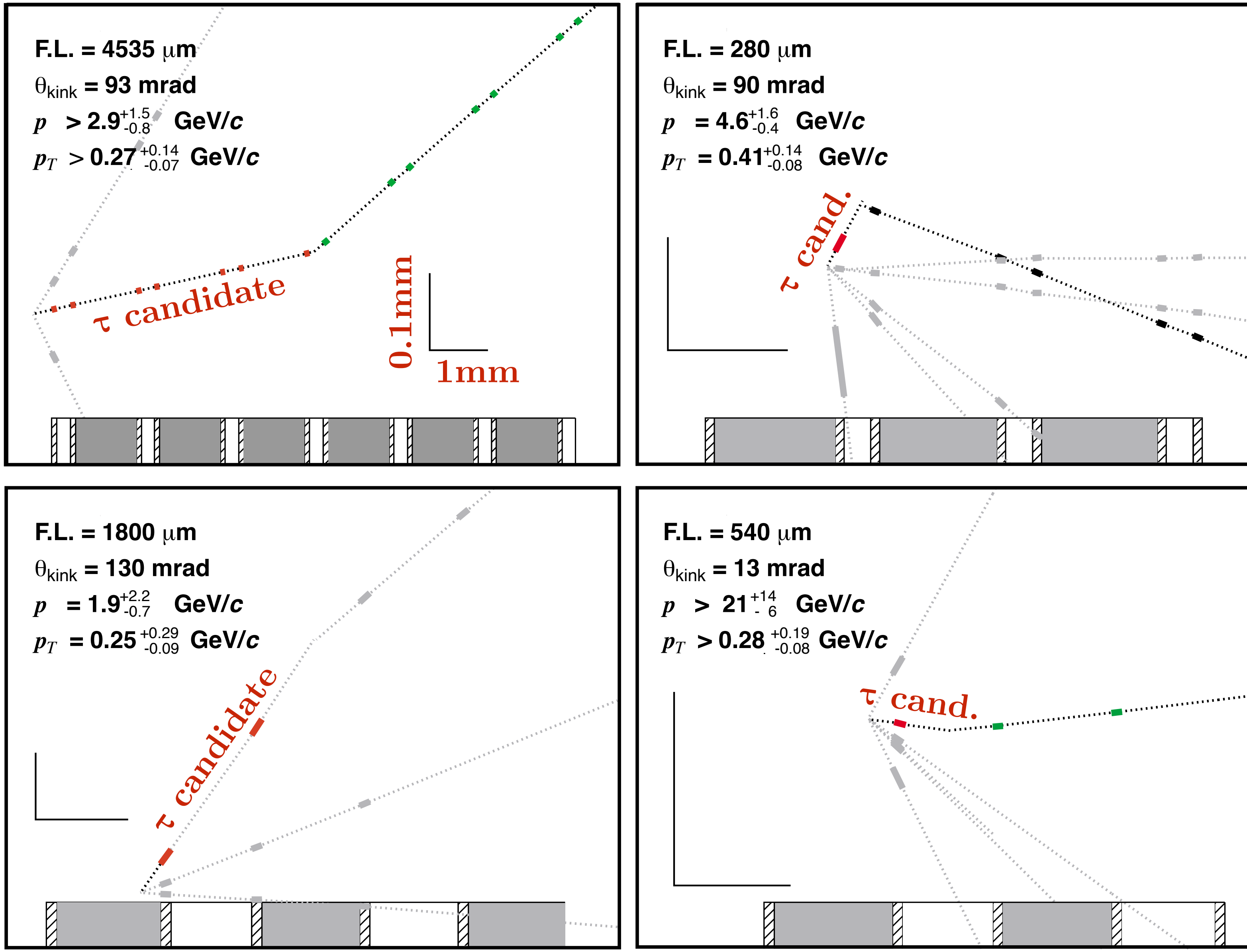
- 2000: the DONuT experiment (at Fermilab) observes ν_τ interactions with matter ⇒ first direct observation



- neutrinos (of all flavours) are produced with 800 GeV protons on a Tungsten fixed target
- neutrinos are filtered (shielding) and detected in an emulsion target

$$\bar{\nu}_\tau + N \to \tau^+ + X$$
$$\nu_\tau + N \to \tau^- + X$$

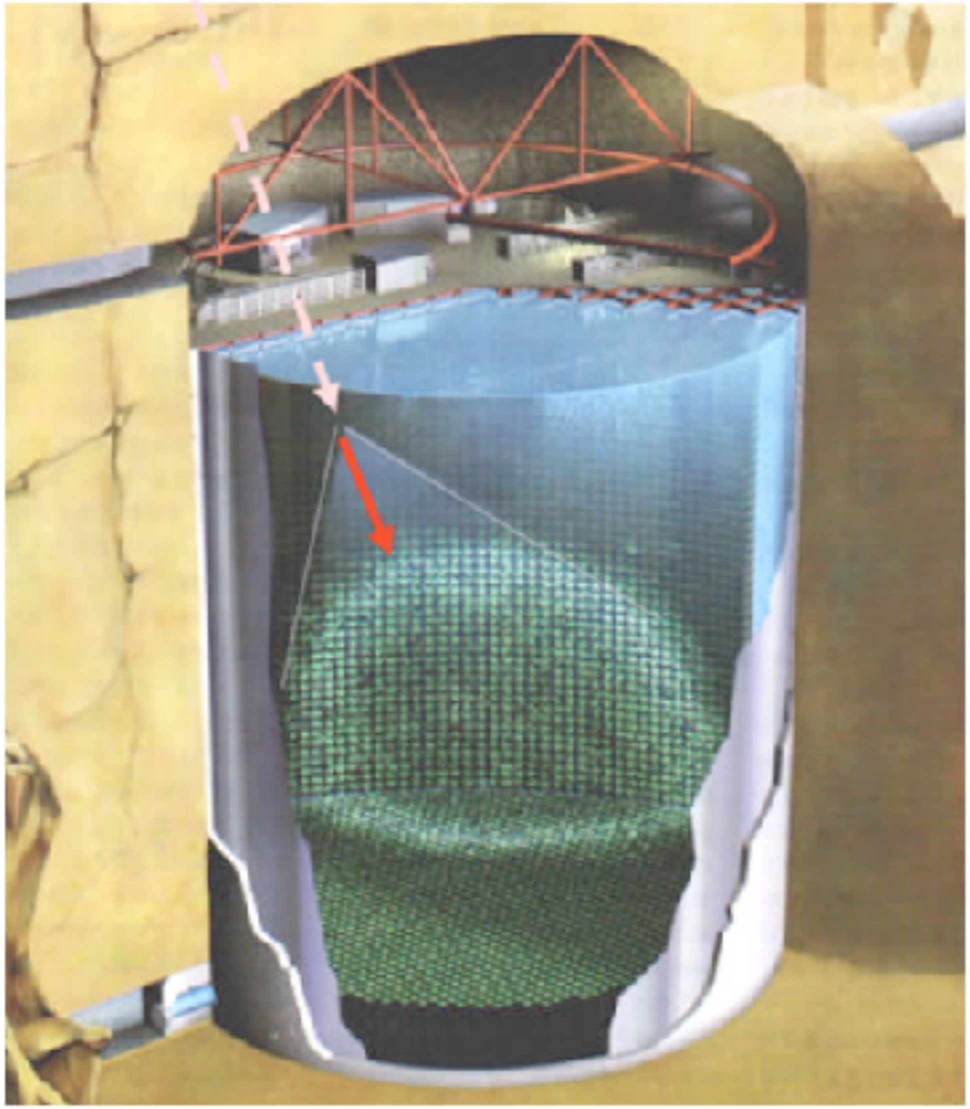
ν_τ signal candidates (DONuT)



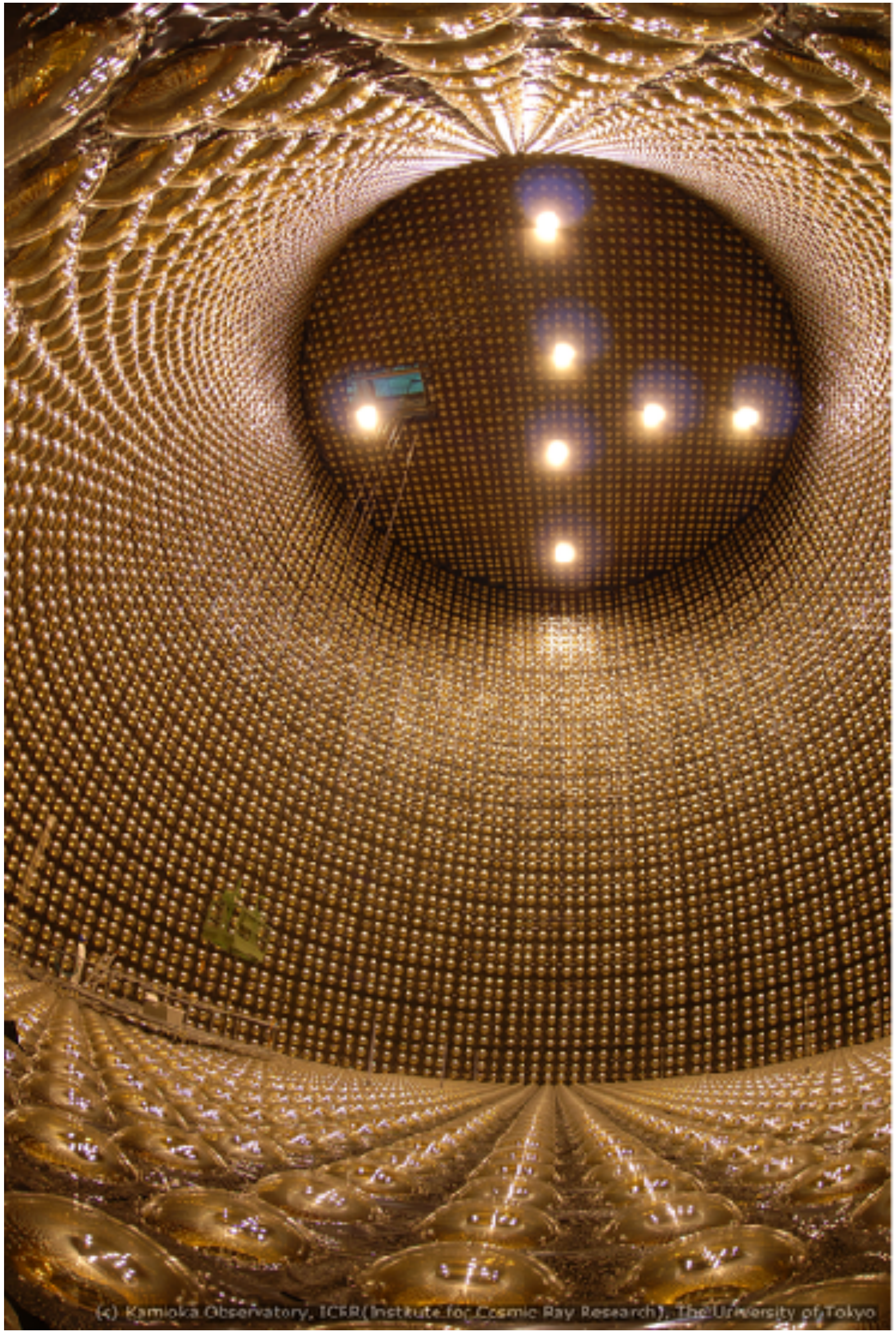
arXiv:hep-ex/0012035

1998: observation of neutrino oscillations

- 1998: Observation of neutrino oscillations at Super-Kamiokande
  - Cherenkov detector
    - 50'000 tons of pure water
    - 39m diameter
    - 41m high
  - >11'000 photo-multiplier tubes

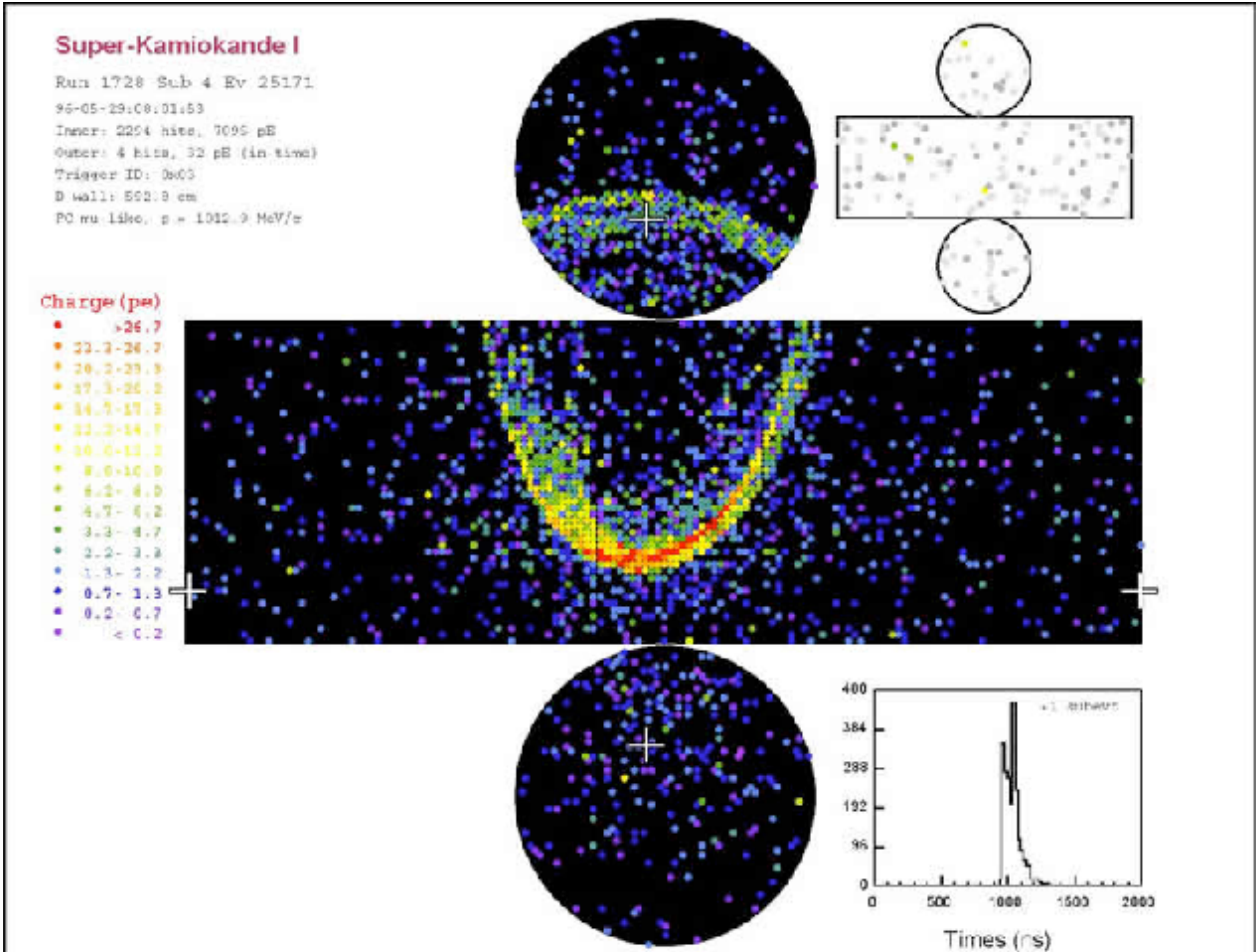


Super-Kamiokande detector



View of the photo-multipliers in the empty volume

Super-K: event display

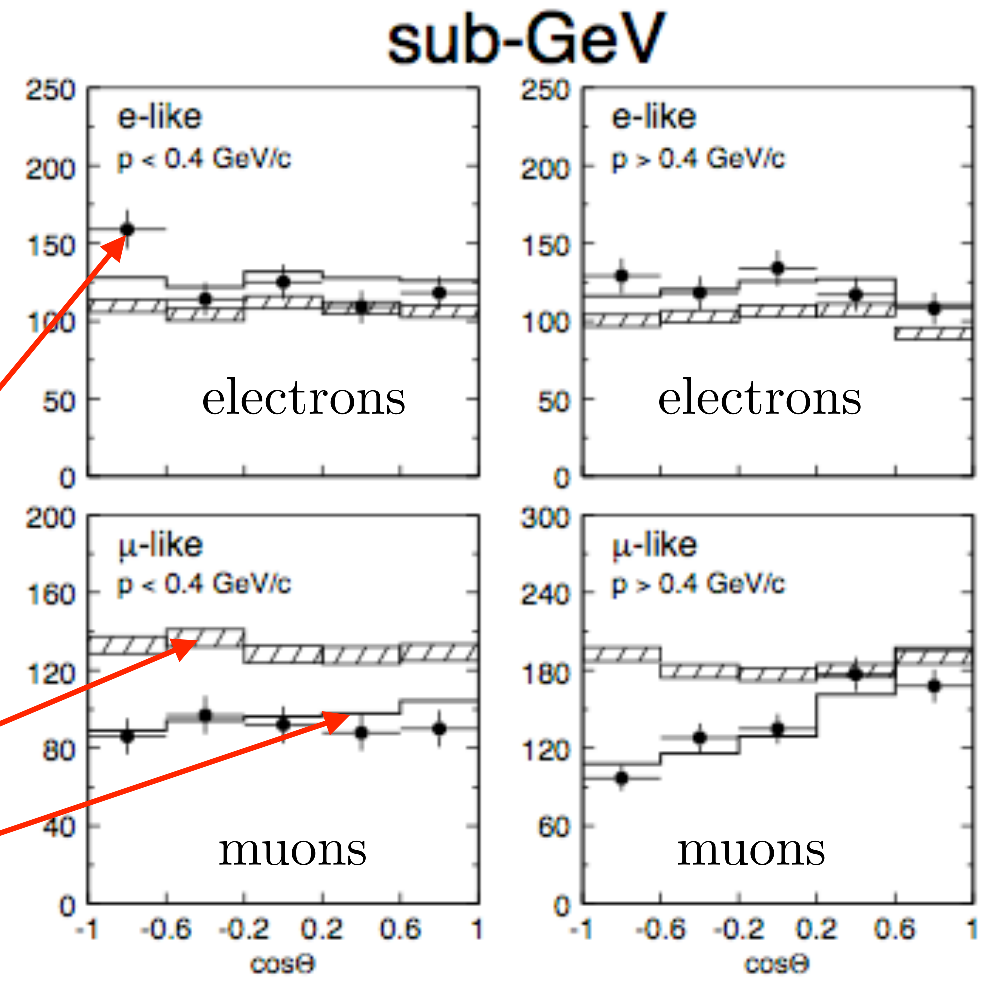


Observation of neutrino oscillations

- Measure the expected rate of atmospheric ν_e ...

  ...but observe a significant deficit of ν_μ !

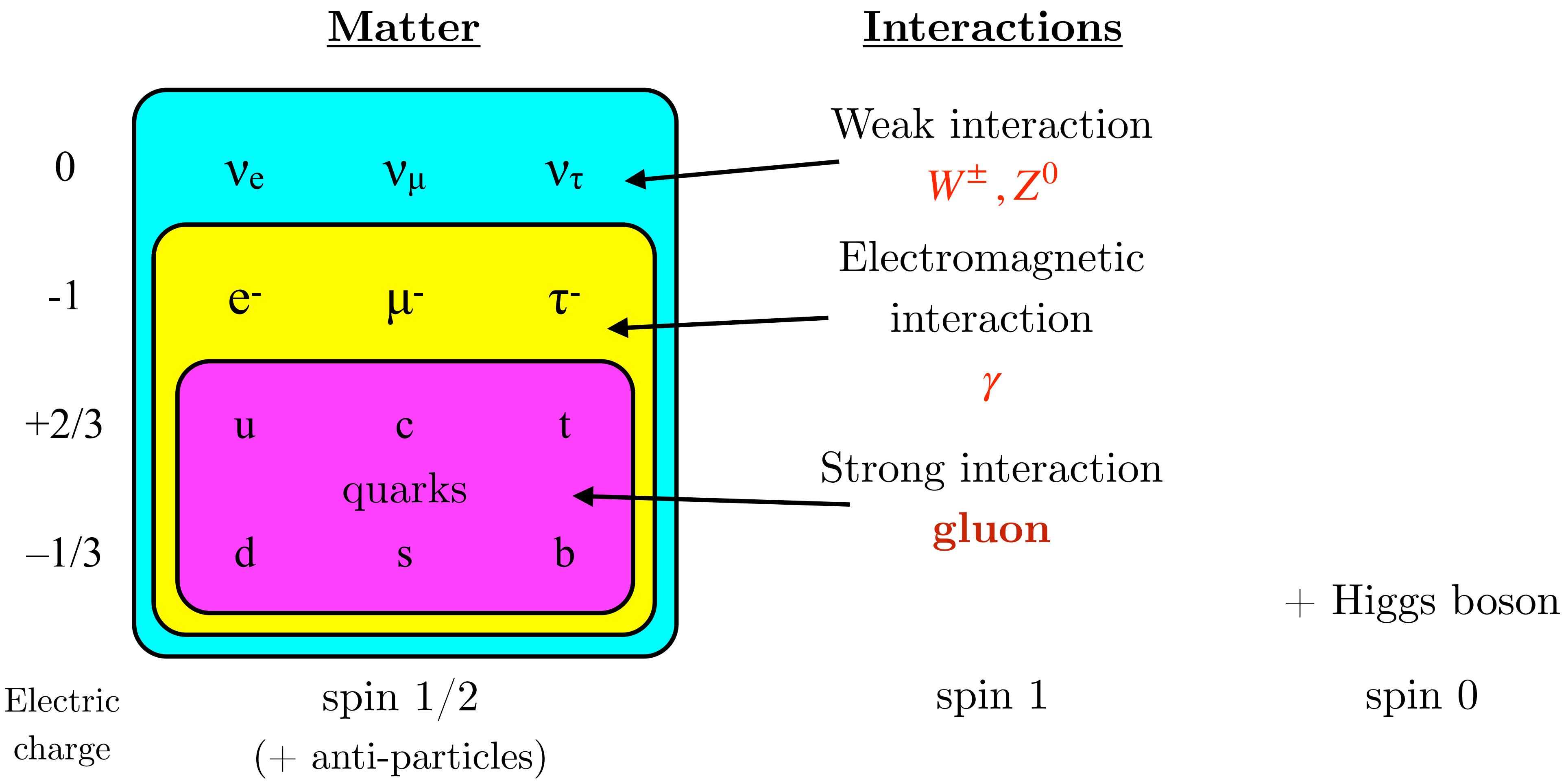
    - Real data: points with error bars
    - Simulation:
      1. without oscillations: hashed area
      2. with oscillations: continuous line



- this observation is compatible with a $\nu_\mu \leftrightarrow \nu_\tau$ oscillations
- allowed range of squared-mass difference (Δm^2) :
  $5 \times 10^{-4} < \Delta m^2 < 6 \times 10^{-3}\,\mathrm{eV}^2$ (@90% C.L.)

The neutrino in the Standard Model
&
Neutrino mass measurements in nuclear β decays

Neutrinos in the standard model (SM)

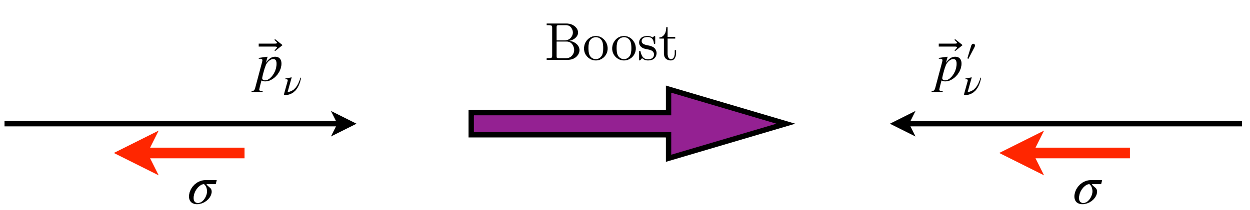


- Neutrinos only interact weakly $\Rightarrow$ small cross-section with matter

  $\Rightarrow$ difficult to observe

The problem of the neutrino mass

- The quark and charged lepton masses are known to be non-zero, but not those of the neutrinos are set to zero in the Standard Model
- The unique polarisation of the neutrinos suggests that these particles are massless



For massless particles ($\Rightarrow$ velocity $= c$), one cannot find a boost that inverts the polarisation

- But the observation of oscillations between the three flavours of neutrinos implies neutrinos have a non-zero mass
- Questions:
  $\Rightarrow$ what is the mass of the neutrinos?
  $\Rightarrow$ can we observe right-handed neutrinos (or left-handed anti-neutrinos)?
  $\Rightarrow$ is the neutrino a Majorana fermion (i.e. the neutrino is its own anti-particle)?

The measurement of the neutrino masses

- Multiple physics processes provide information on the neutrino masses:

- β decays

- direct mass measurement

- double β decay (with 2 neutrinos, $\beta\beta$–2ν or "neutrinoless", $\beta\beta$–0ν)

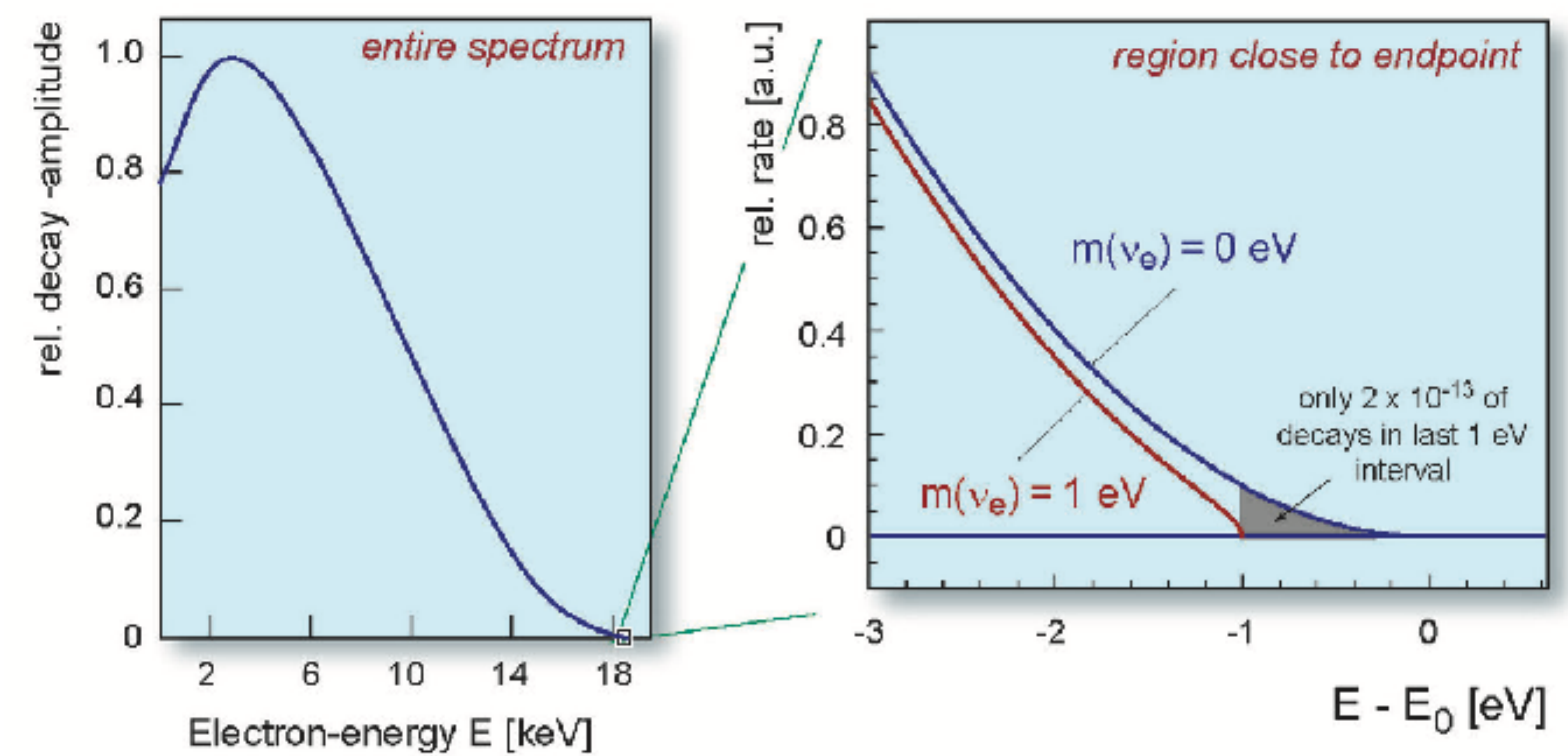
- mass measurement
- allows the distinction between Dirac et Majorana neutrinos

- neutrino oscillations

- measurement of the mass-squared differences: $\Delta m^2_{12} \equiv (m_1)^2 - (m_2)^2$

Measurement of m_ν : β decays (I)

- Principle: determine the neutrino mass from the measured highest value ("endpoint") of the electron energy spectrum (T_{max}) in β decays



source: katrin.kit.edu

Measurement of m_ν : β decays (II)

- Electron energy spectrum close to the endpoint:

$$\frac{\mathrm{d}N}{\mathrm{d}E} \propto (Q-T)\sqrt{(Q-T)^2 - m_\nu^2}$$

$T =$ kinetic energy of the electron

$Q =$ maximum possible value for T if $m_\nu = 0$

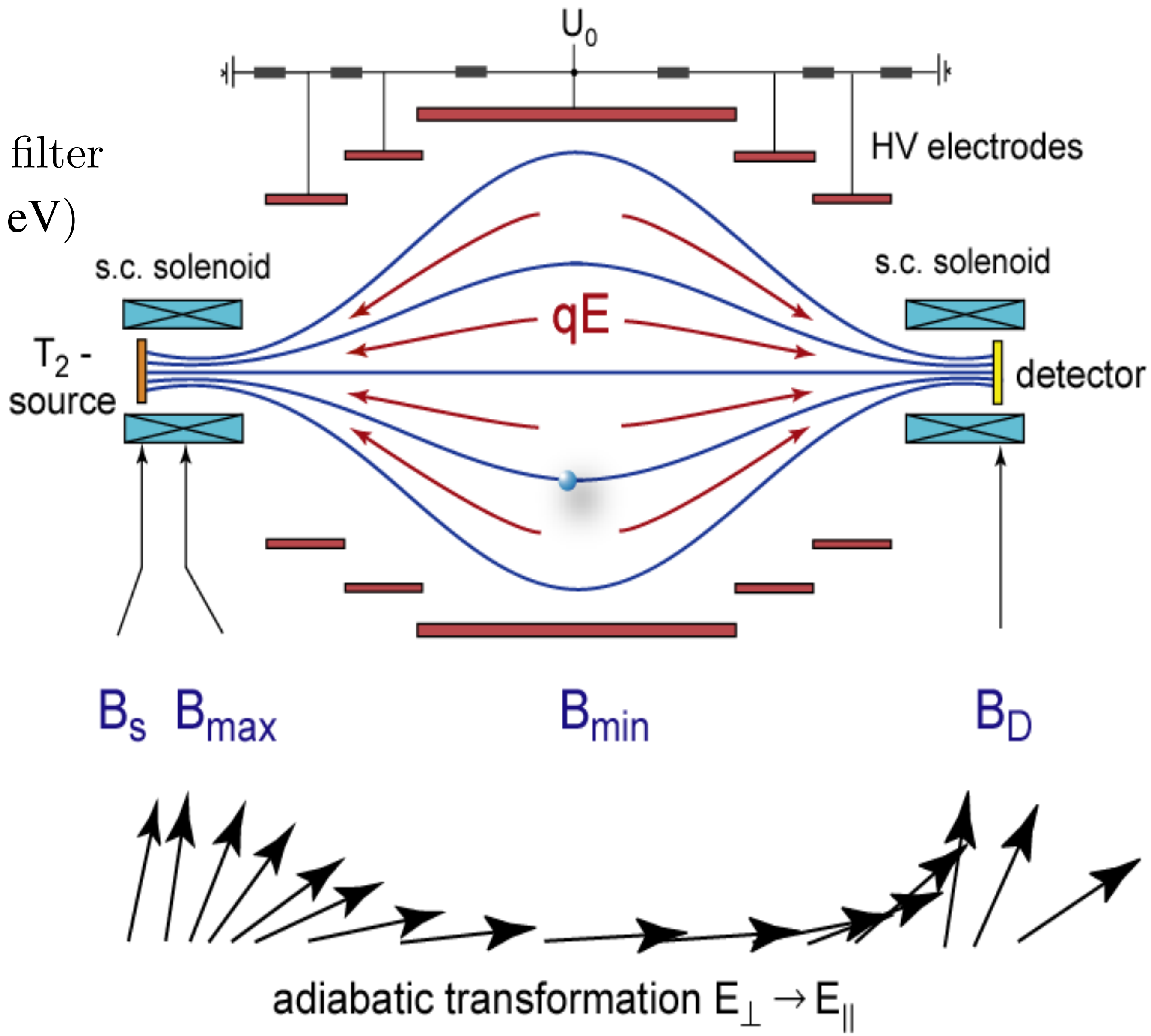
- Experimentally, one measures: $m_\nu = Q - T_{\mathrm{max}}$
- The fraction of electrons in the interval ΔT near endpoint is proportional to $(\Delta T/Q)^3$
  - maximal sensitivity to m_ν if Q is small

    ⇒ choice of tritium (^{3}H) β decay

$$^3\mathrm{H} \to {}^3\mathrm{He} + e^- + \bar{\nu}_e \qquad Q = 18.6\,\mathrm{keV}\ (\ll m_e)$$

Spectrometer: Magnetic bottle

- Principle:
  - ^{3}H source
  - electrostatic energy filter $E_e > E_{\min}$ $(\Delta E = 4.8\,\mathrm{eV})$
  - electron detector

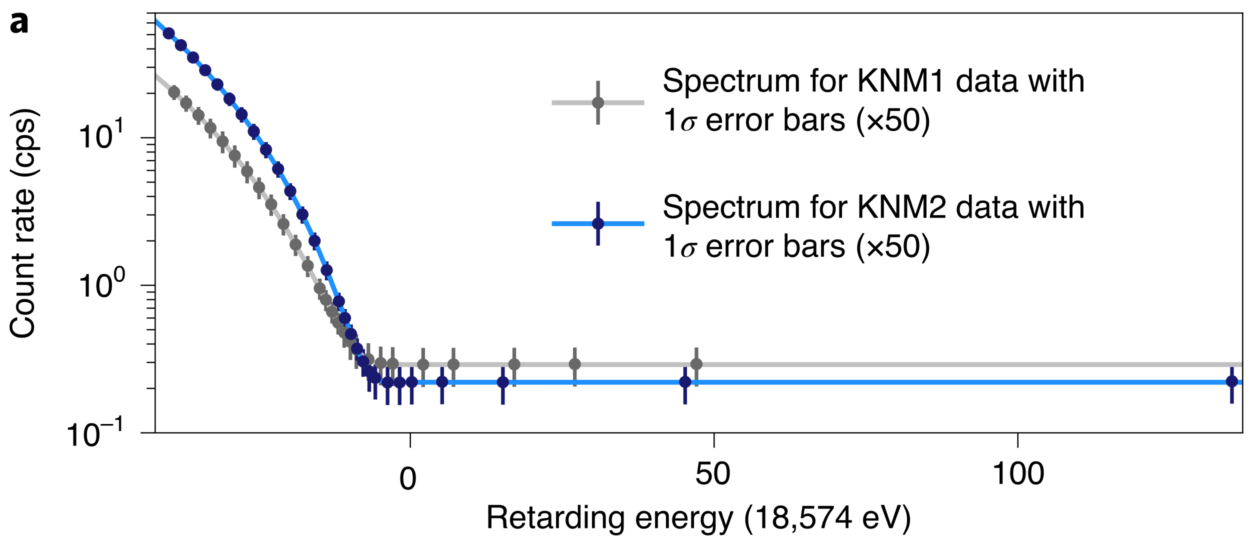


KATRIN

- KA(rlsruhe) TRI(thium) N(eutrino)
- Measurement of $m(\nu_e)$ with sensitivity <0.2eV
  - large geometric coverage ($\Rightarrow$ size)
  - high tritium activity (10^{11} Bq) ; low background rate (<0.1 cps)
- Construction and calibration until 2018
- Two data taking campaigns since 2019

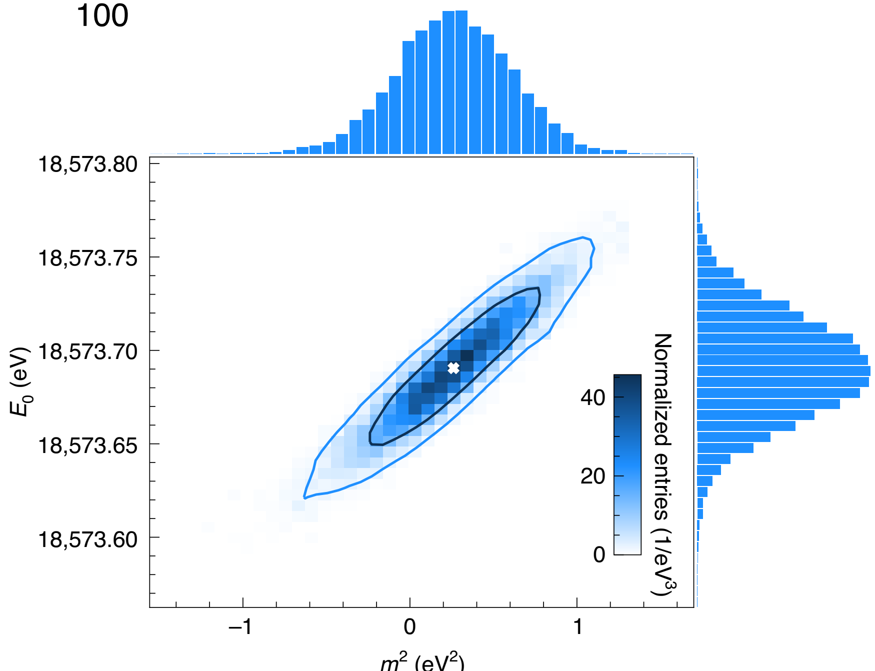
KATRIN

- Electron based neutrino mass limit (Feb 2022)
- Energy scan near the end-point: $-40 < E - E_0 < 135\,\text{eV}$



- Fit the end-point spectrum to measure the end-point energy, E_0, and m_ν
  $\Rightarrow m_\nu^2 = 0.26 \pm 0.34\,\text{eV}^2$
- Limit on m_ν (electron based):

  $m_\nu < 0.8\,\text{eV}$ **@90% C.L.**



Nature Phys. 18 (2022) 160

Neutrino masses: direct measurements

- electron neutrino based
  - KATRIN experiment: $m(\nu_e) < 0.8\,\text{eV}/c^2$

$m(\nu_e) < 0.8\,\text{eV}$

$m(\nu_\mu) < 170\,\text{keV}$

$m(\nu\tau) < 18.2\,\text{MeV}$

- muon neutrino based
  - measured in pion decay at rest $\pi^+ \to \mu^+ \nu_\mu$
  - depends on knowledge of pion and muon masses
  - limit: $m(\nu_\mu) < 0.17\,\text{MeV}/c^2$

    Assamagan et.al., Phys. Rev. D 53 (1996) 6065
    (experiment at PSI)

- tau neutrino based
  - measured in tau hadronic decays
  - limit: $m(\nu_\tau) < 18.2\,\text{MeV}/c^2$

    ALEPH experiment, Eur. Phys. J. C 2 (1998) 395

Neutrino mass measurements in neutrinoless double β decays

Absolute mass scale: double-β decay

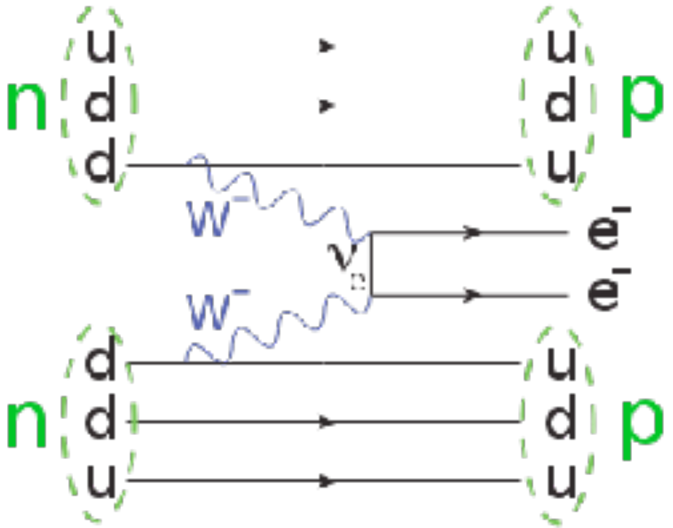
- Rare decays allowed in the standard model ($\beta\beta$-2ν):

$$(A, Z) \rightarrow (A, Z+2) + 2e^- + 2\bar{\nu}_e$$

- If the neutrino is a Majorana fermion, the annihilation of neutrinos is possible ($\beta\beta$-0ν):

$$(A, Z) \rightarrow (A, Z+2) + 2e^-$$

  - Leptonic number violation $\Delta L = 2$



- Decay rate

$$(\tau_{1/2}^{0\nu})^{-1} = F_{\rm N} \frac{|m_{2\beta}|^2}{m_e^2}$$

  - $F_{\rm N}$: nuclear factor (poorly known)
  - $m_{2\beta}$: effective Majorana mass

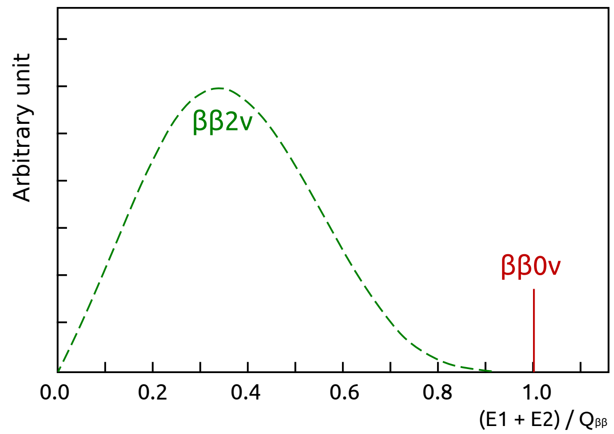
$$m_{2\beta} = \sum_{j=1}^{3} U_{ej}^2 m_{\nu_j}$$

$\beta\beta$ decay experimental principle

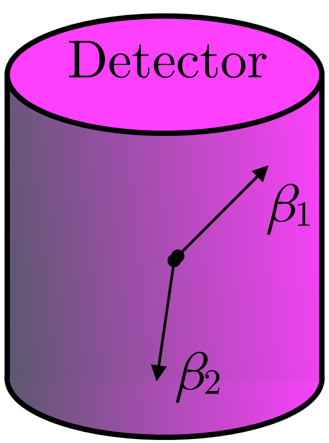
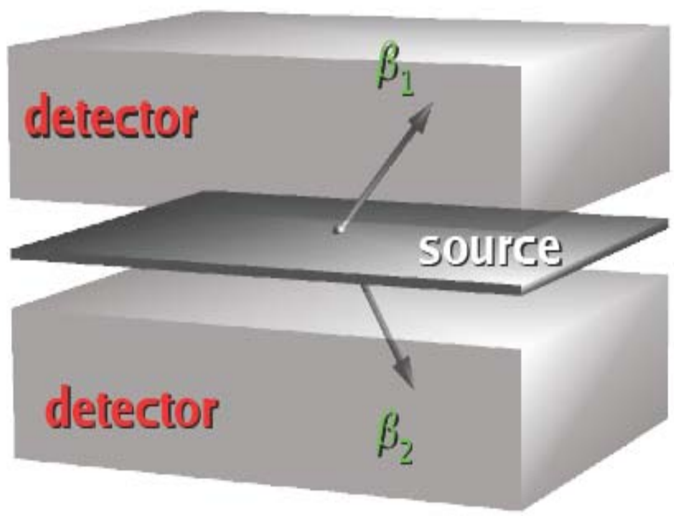
- All the energy is carried by the electrons

$$\Rightarrow E(e_1^-) + E(e_2^-) = Q_{\beta\beta}$$

$\Rightarrow$ count number of $\beta\beta$ events with total energy $Q_{\beta\beta}$ after subtracting background



- Two complementary techniques:

Source = Detector (Calorimetry) high efficiency	Source ≠ Detector (Event reconstruction) good background rejection
	

$\beta\beta$ decay: experimental determination

- Measured lifetime:

$$\tau_{1/2}^{0\nu} = \ln 2 \cdot \frac{\epsilon \cdot N_{\text{nuclei}} \cdot t_{\text{meas}}}{N_{\beta\beta}}$$

- $N_{\text{nuclei}} =$ number of nuclei in the source

- $t_{\text{meas}} =$ measurement duration

- $N_{\beta\beta} =$ number of observed $\beta\beta$ decays

- $\epsilon =$ efficiency factor

$\beta\beta$-0ν decay experiments

	Exposure (kg × yr)	**Sensitivity** ($\times 10^{25}$ yr)	$T_{1/2}^{0\nu}$ ($\times 10^{25}$ yr)	$m_{\beta\beta}$ (eV)	**Experiment**
^{48}Ca	13.5	1.8×10^{-3}	$> 5.8 \times 10^{-3}$	$< 3.5 - 22$	ELEGANT VI [360]
^{76}Ge	127.2	18	> 18	$< 0.08 - 0.18$	GERDA [355]
	26.0	4.8	> 2.7	$< 0.20 - 0.43$	Majorana Demonstrator [361]
^{82}Se	5.29	5.0×10^{-1}	$> 3.5 \times 10^{-1}$	$< 0.31 - 0.64$	CUPID-0 [362]
^{96}Zr	(–)	(–)	$> 9.2 \times 10^{-4}$	$< 7.2 - 19.5$	NEMO-3 [363]
^{100}Mo	1.17	(–)	$> 1.5 \times 10^{-1}$	$< 0.31 - 0.54$	CUPID-Mo [364]
^{116}Cd	(–)	(–)	$> 2.2 \times 10^{-2}$	$< 1.0 - 1.7$	Aurora [365]
^{128}Te	(–)	(–)	$> 1.1 \times 10^{-2}$	(–)	Arnaboldi et al. [366]
^{130}Te	$1038.4^{\diamond}$	2.8	> 2.2	$< 0.09 - 0.31$	CUORE [367]
^{136}Xe	$504^{\dagger}$	5.6	> 10.7	$< 0.06 - 0.17$	KamLAND-Zen [303]
	234.1	5.0	> 3.5	$< 0.09 - 0.29$	EXO-200 [368]
^{150}Nd	0.19	(–)	$> 2.0 \times 10^{-3}$	$< 1.6 - 5.3$	NEMO-3 [369]
^{3}H	β-endpoint measurement			$m_\beta < 0.8$	KATRIN [304]

M. Sajjad Athar, et.al., "Status and perspectives of neutrino physics", arXiv:2111.07586

- One experiment claims observation: Heidelberg/Moscow
- NEMO-3 and Cuoricino: had the best limits for many years

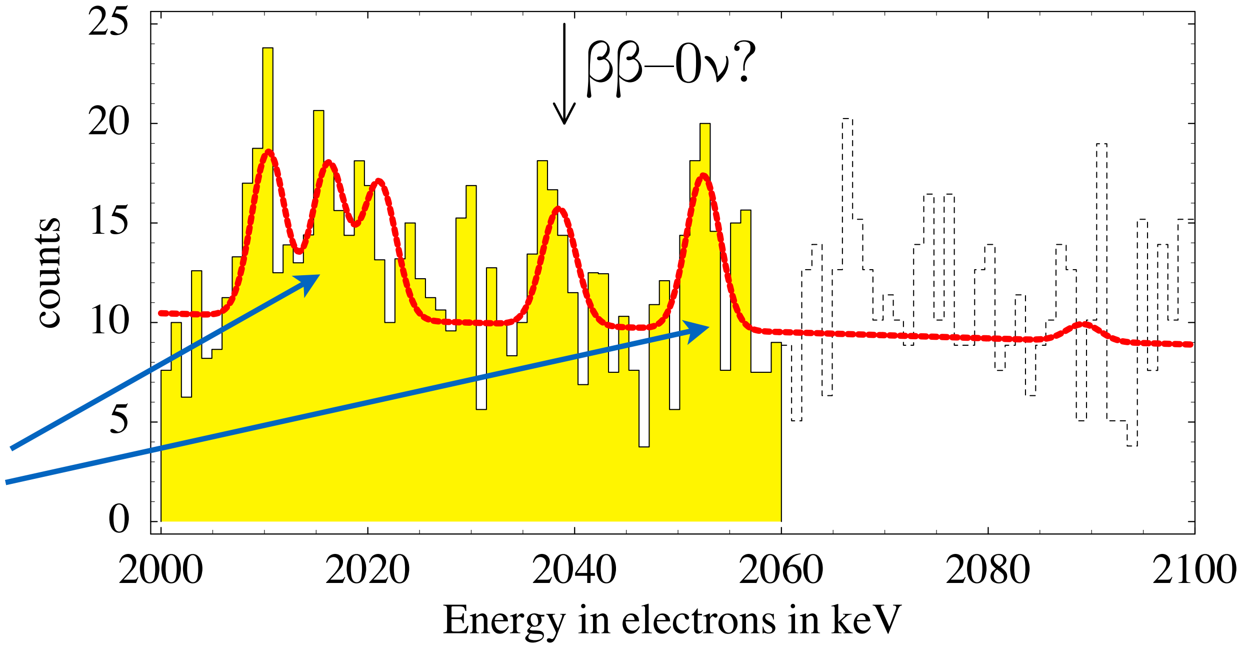
[⇒ find most recent results in PDG (http://pdg.lbl.gov)]

Heidelberg-Moscow: $2\beta - 0\nu$ results

- Data taking:
  - 1990–2003 at Gran Sasso, Italy
- 5 high-purity Germanium crystals
  - enriched in ^{76}Ge at 87%
  - 10.96 kg of active mass
  - $Q_{\beta\beta} = 2039\,\text{keV}$
- Calorimetric technique
  - good energy resolution
  - poor background rejection

- HM claims 4.2σ evidence for $\beta\beta$-0ν
  - $\tau_{1/2} = (68 - 418) \times 10^{23}\,\text{yr}$ @ 99.73% C.L.
  - $m_\nu = (0.24 - 0.58)\,\text{eV}$ @ 99.73% C.L.

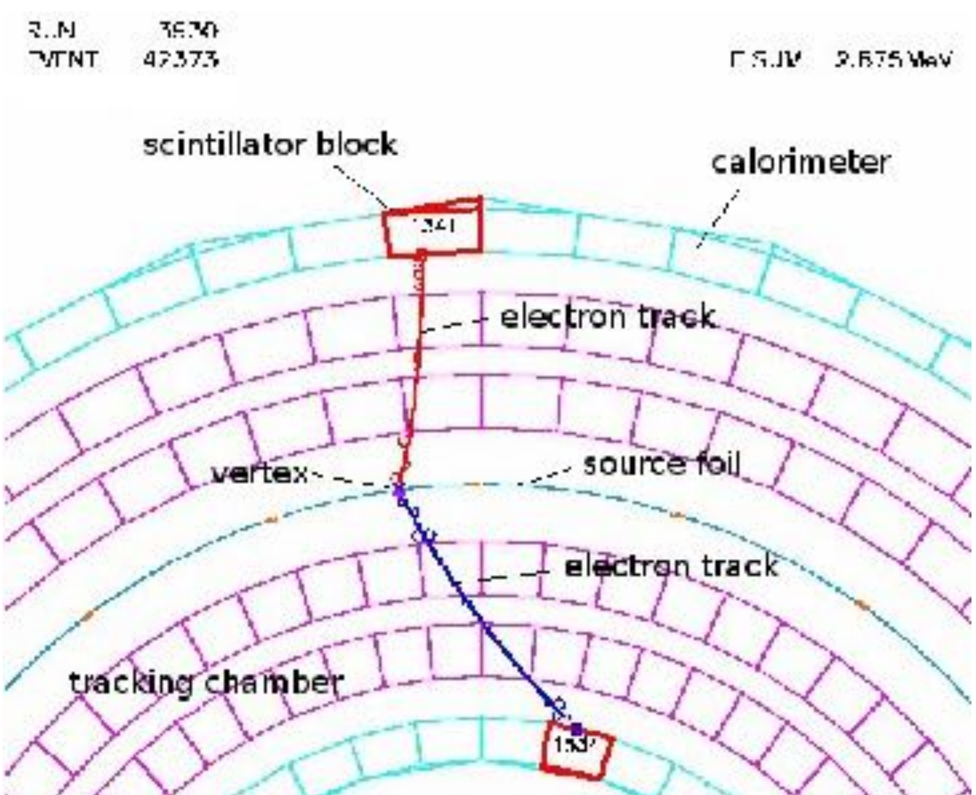
Are these backgrounds understood?

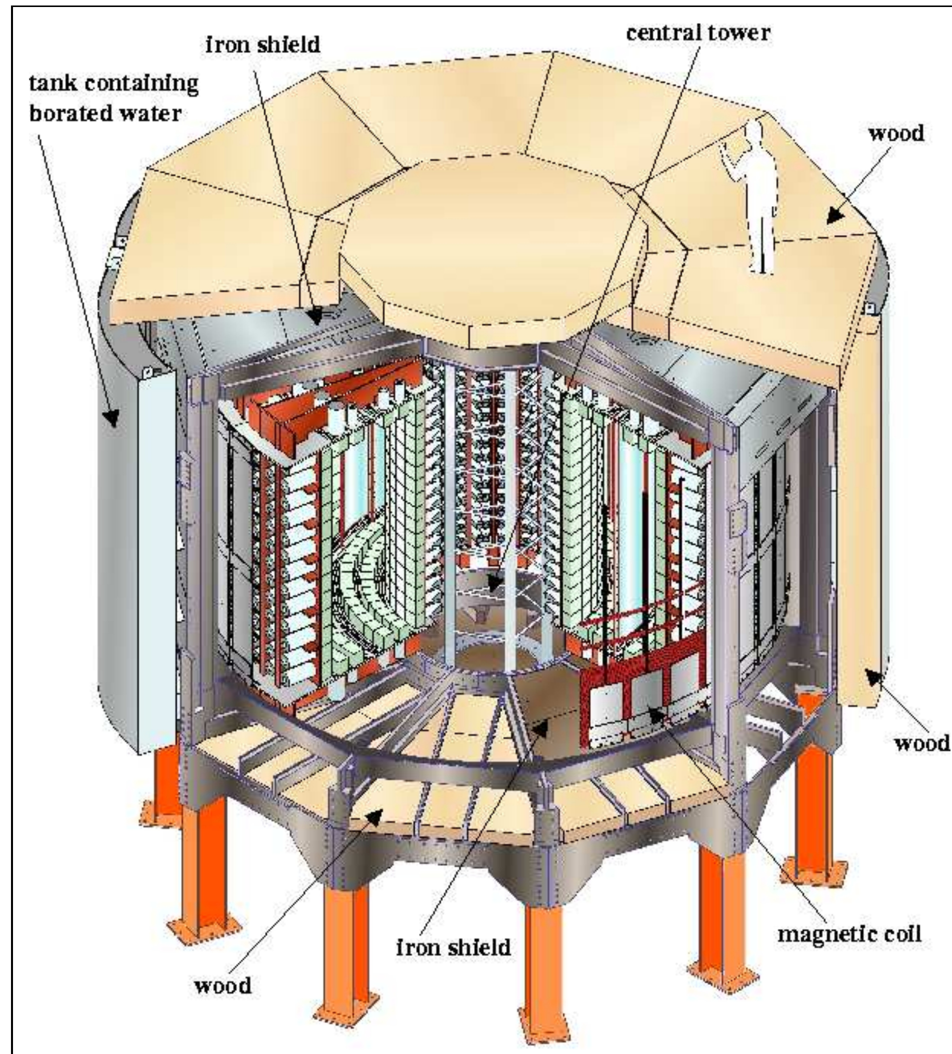


- Controversial result...

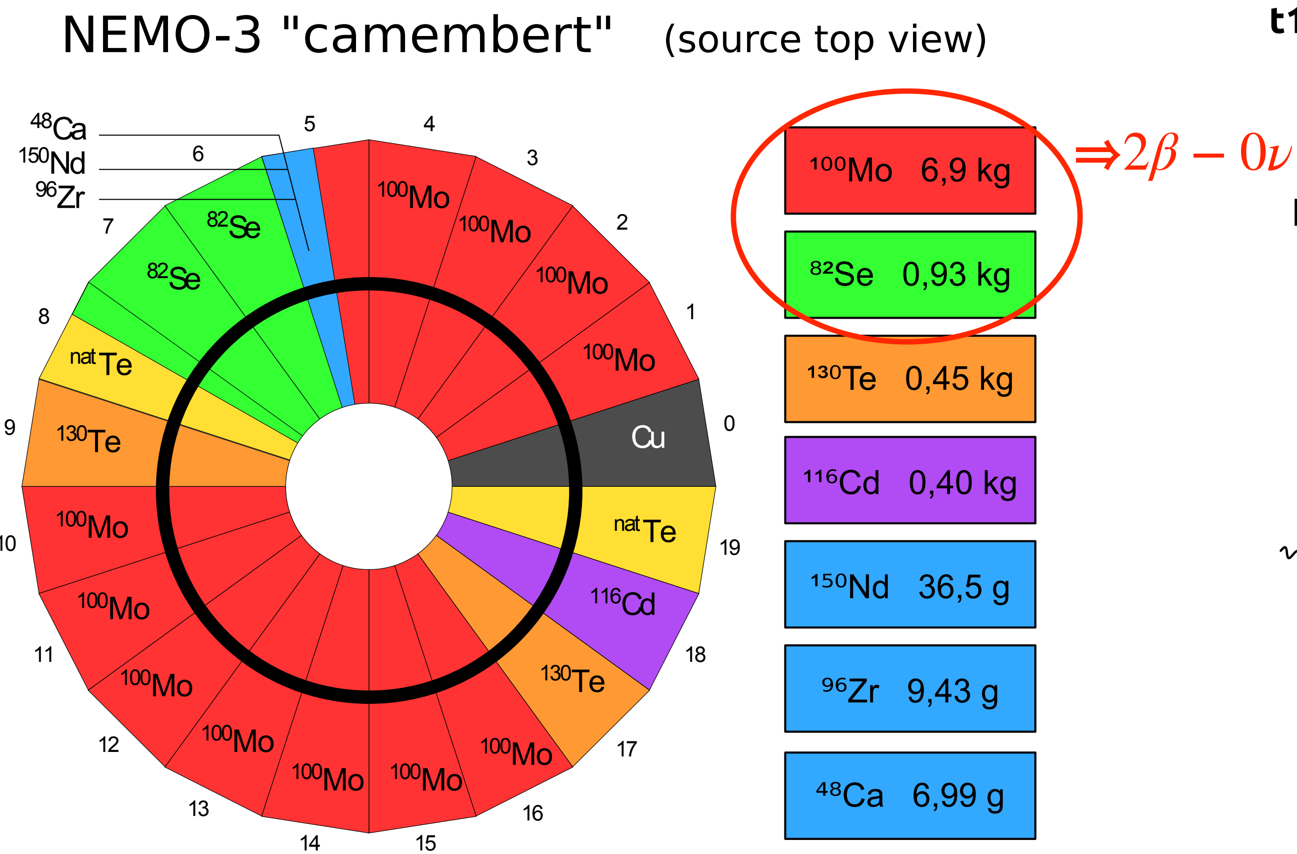
2β decay: NEMO3

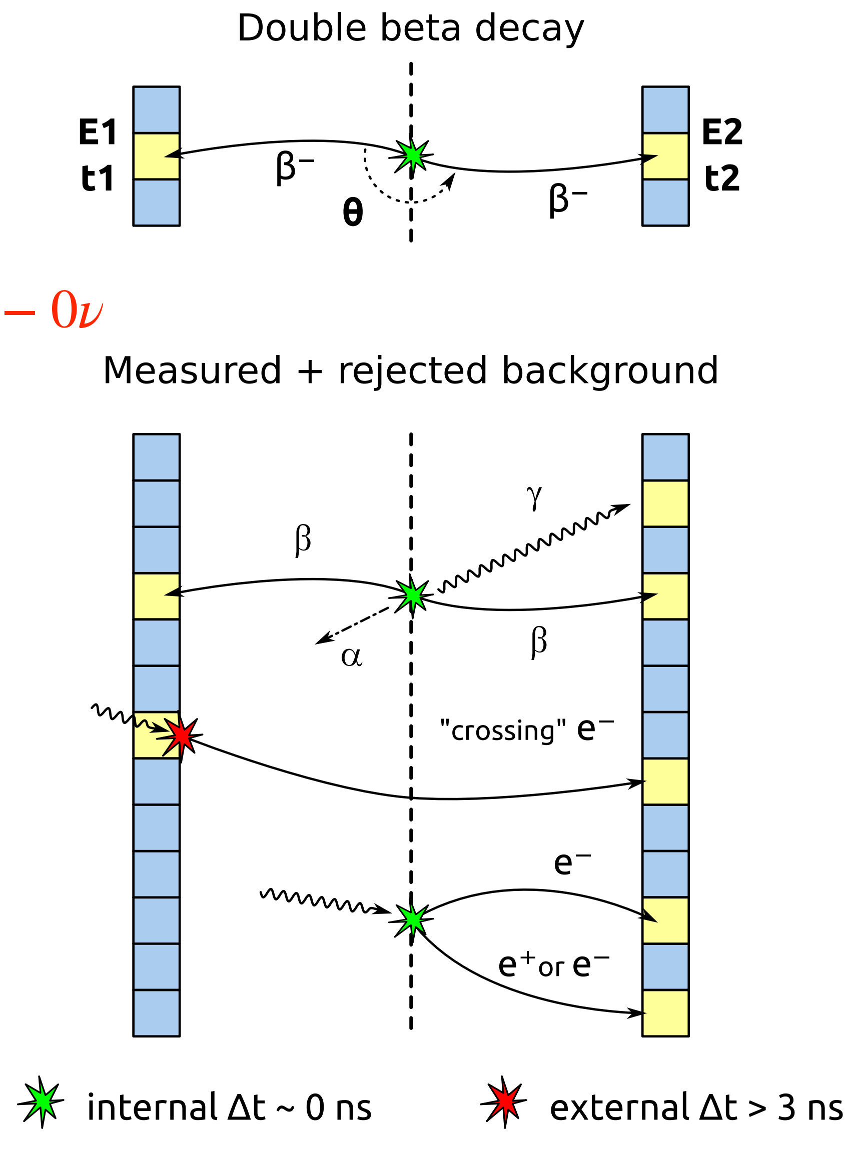
- Taking data 2003–2011 in Modane (France)
- Source separate from tracking and calorimeter detectors
  - good background rejection
  - limited efficiency and energy resolution





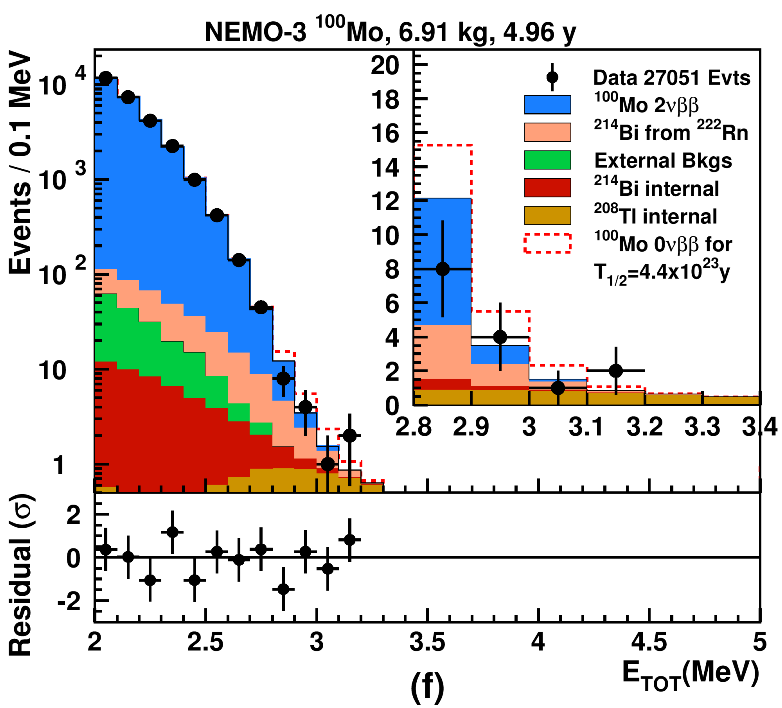
NEMO3 detector

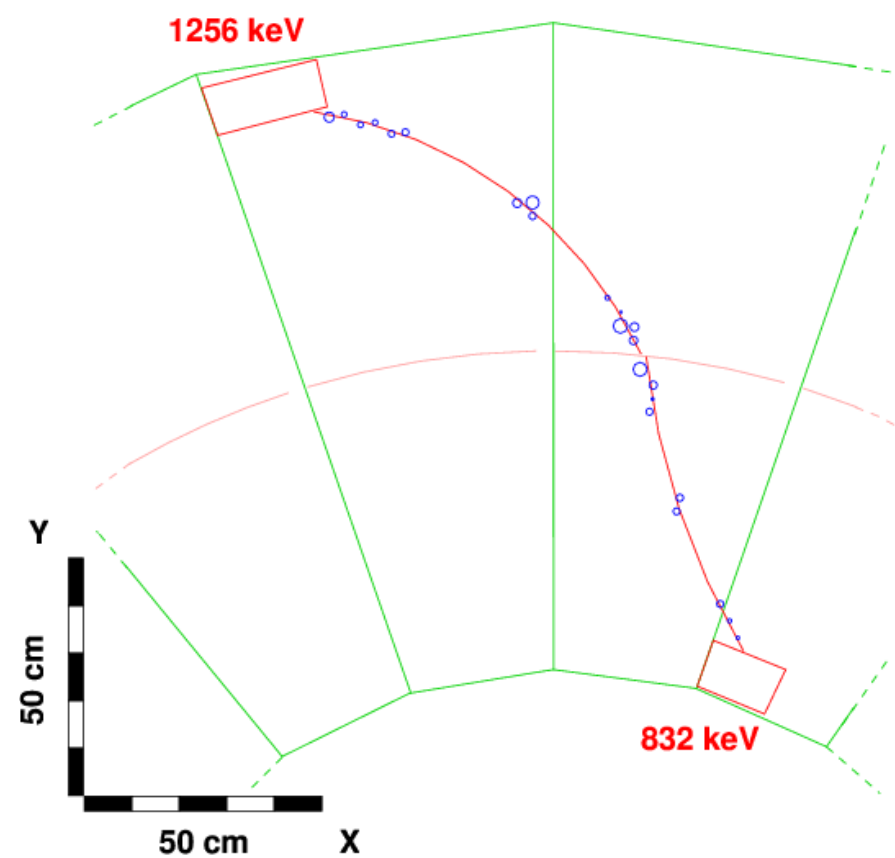




NEMO3: $\beta\beta$–0ν results

- ^{100}Mo ($Q_{\beta\beta} = 3034\,$keV)
  - 15 events observed
  - 18.0±0.6 background events expected
  - efficiency = 4.7%
  - exposure = 34.3 kg·yr



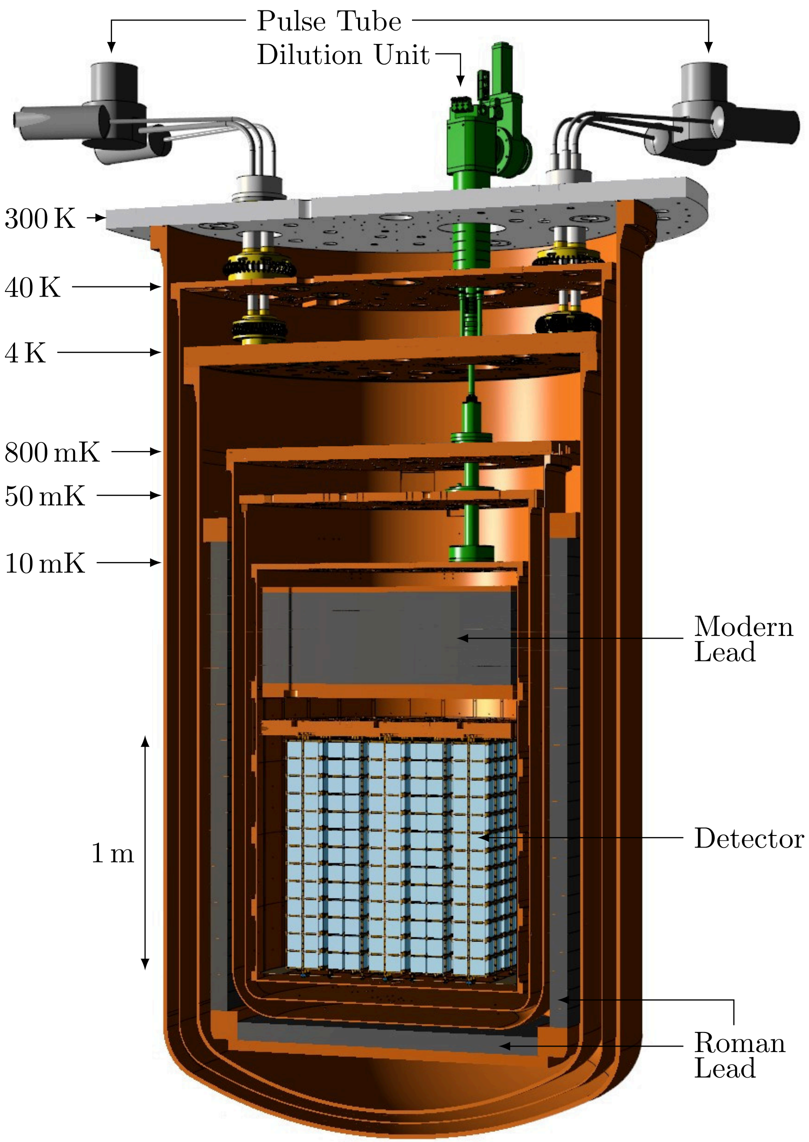


- $\tau_{1/2} > 1.1 \times 10^{24}\,$yr @ 90% C.L.
- $m_\nu < (0.33 - 0.62)\,$eV

[Phys. Rev. D 92, 072011 (2015)]

$\beta\beta$ decay: CUORE

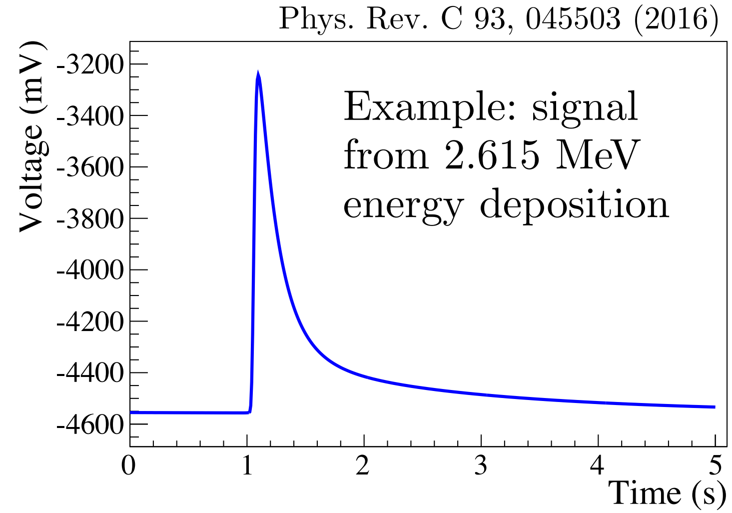
- Data taking since 2017 in Gran Sasso
- TeO_2 crystals
- Active isotope: ^{130}Te
  - abundance = 27.8%
  - $Q_{\beta\beta} = 2528\,\mathrm{keV}$
- Calorimetric technique (source = detector)
  - bolometric technique: measure energy as temperature variation in the medium
    - $\Delta T/\Delta E \approx 10 - 20\,\mu\mathrm{K/MeV}$
  - good energy resolution ($\approx$ 5 keV)
  - no electron identification

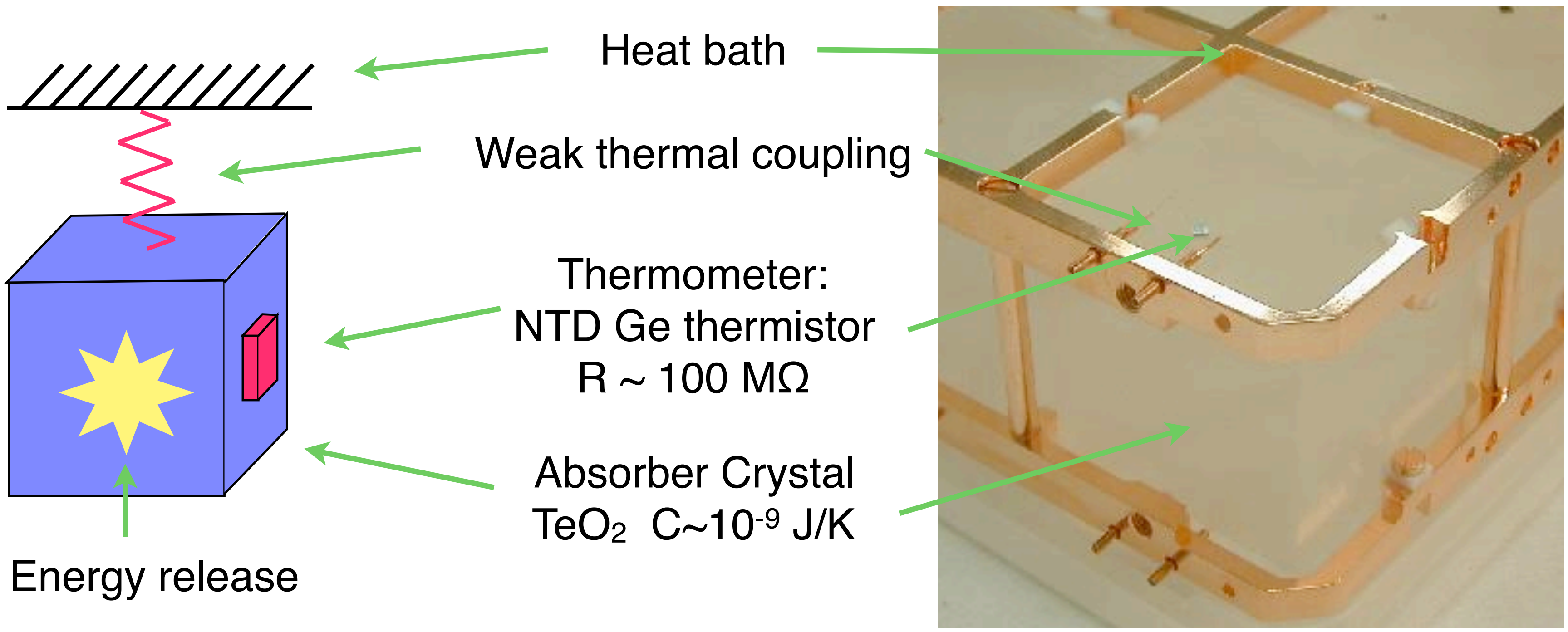


CUORE detector
= 19 crystal towers

CUORE detector

- TeO_2 crystals (742 kg)
- 206 kg active mass
- Cooled to approximately 10 mK





CUORE: ββ-0ν results

- TeO_2 exposure = 1038.4 kg·yr ; ^{130}Te exposure = 288.8 kg·yr
- Results (limit @90% C.L.): $\tau^{0\nu}_{1/2} > 2.2 \times 10^{25}$ yr, $m_{\beta\beta} < (0.090 - 0.350)$ eV

Nature 604, 53-58 (2022)

arXiv:2104.0690

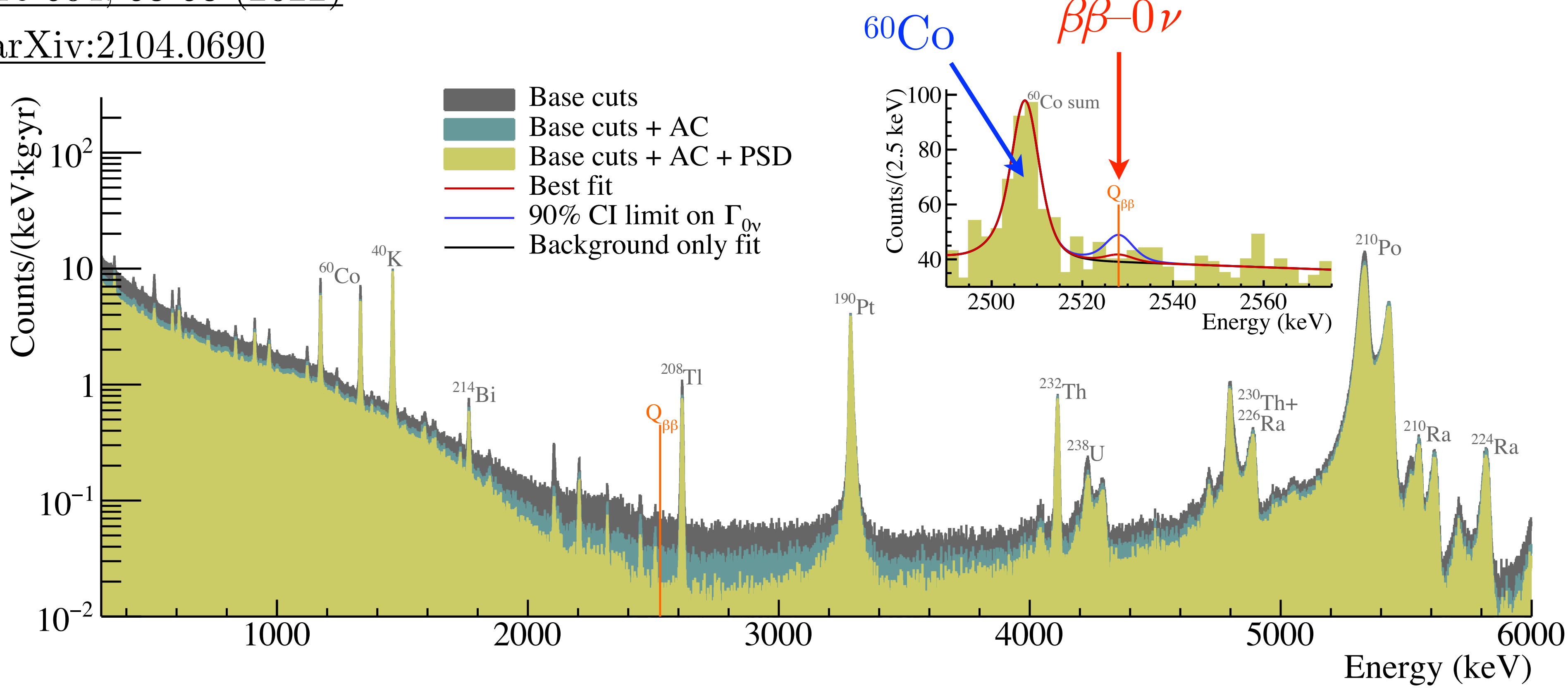


Figure 4. Physics spectrum for 1038.4 kg·yr of TeO_2 exposure. We separately show the effects of the base cuts, the anti-coincidence (AC) cut, and the pulse shape discrimination (PSD). The most prominent background peaks in the spectrum are highlighted. Top right inset: the ROI after all selection cuts, with the best-fit curve (solid red), the best-fit curve with the $0\nu\beta\beta$ rate fixed to the 90% CI limit (blue), and background-only fit (black) superimposed.

2β decay: future experiments

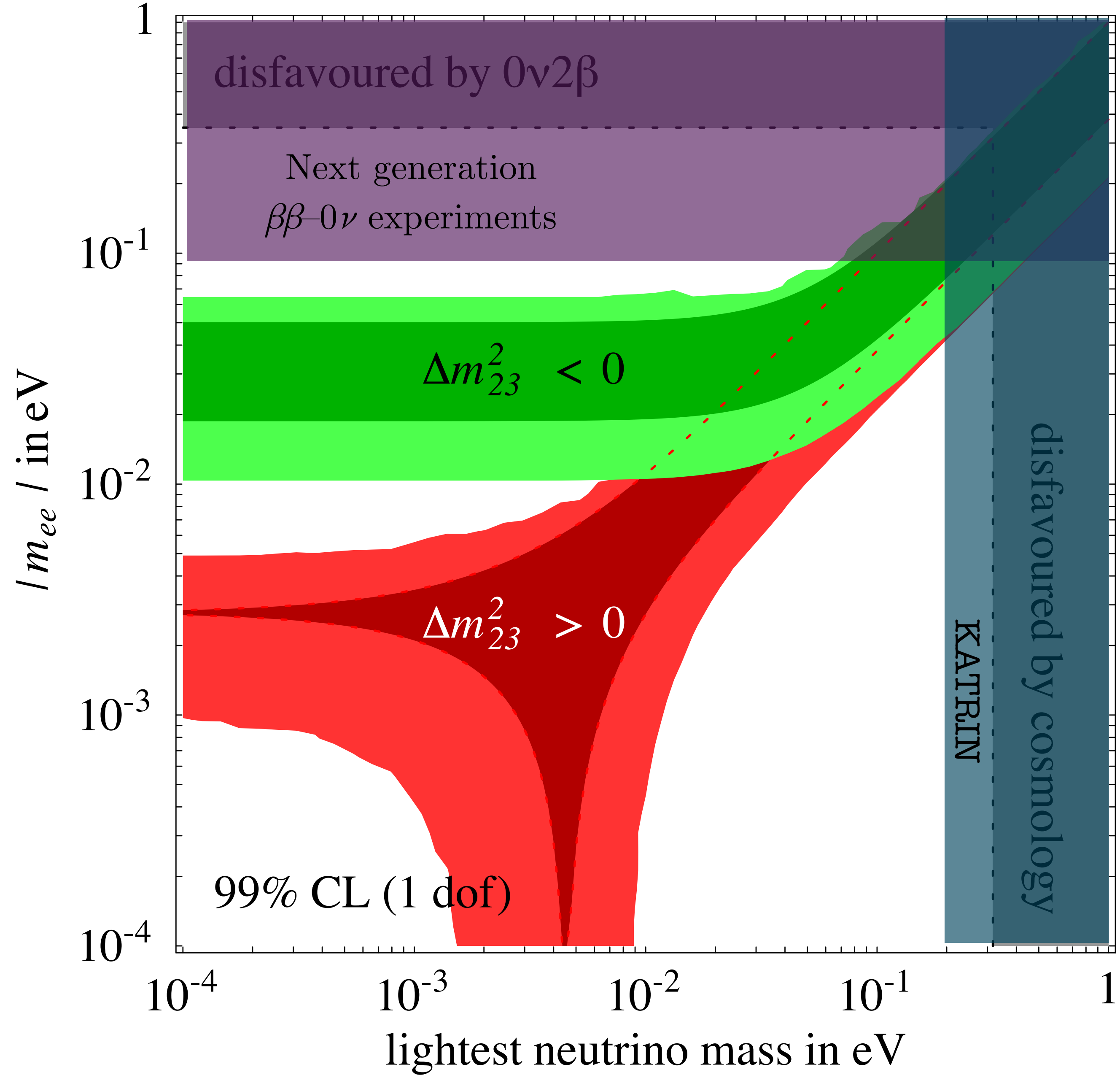
Table 2. High-sensitivity DBD experiments in futures. A:natural abundance. $Q_{\beta\beta}$: Q value for the $0^+ \rightarrow 0^+$ and low BG ground state transition. $G^{0\nu}$: kinematic (phase space volume) factor ($g_A = 1.25$ and R = 1.2 fm $A^{1/3}$).

isotope	A [%]	$Q_{\beta\beta}$ [MeV]	$G^{0\nu}$ [10^{-15} y^{-1}]	Future experiments experiments
^{76}Ge	7.8	2.039	2.36	GERDA, Majorana Demonstrator
^{82}Se	9.2	2.992	10.2	SuperNEMO, MOON
^{100}Mo	9.6	3.034	15.9	AMoRE, LUMINEU, CUPID, MOON
^{116}Cd	7.5	2.804	16.7	AURORA COBRA
^{130}Te	34.5	2.529	14.2	CUORE
^{136}Xe	8.9	2.467	14.6	EXO, KamLAND-Zen, NEXT, Panda X-III
^{150}Nd	5.6	3.368	63.0	SuperNEMO, SON+, DCBA

J.D. Vergados, H. Ejiri, F. Simkovic, "Neutrinoless double beta decay and neutrino mass", arXiv:1612.02924

- Plans to achieve $\tau_{1/2} \gtrsim 10^{28}$ yr
  ... and $m_\nu \lesssim 0.01$ eV

Neutrino mass bounds



Neutrino mass generation in the Standard Model

Status and Questions

- Known facts:
  - neutrinos oscillate
  - (at least 2) neutrinos have masses
  - neutrino masses are tiny relative to other standard model fermions ($m_\nu < 1 eV$)

- Questions:
  - how is the neutrino mass generated?
  - how can we explain it is so small?

  } → seesaw mechanism

  - is the neutrino mass hierarchy normal or inverted?

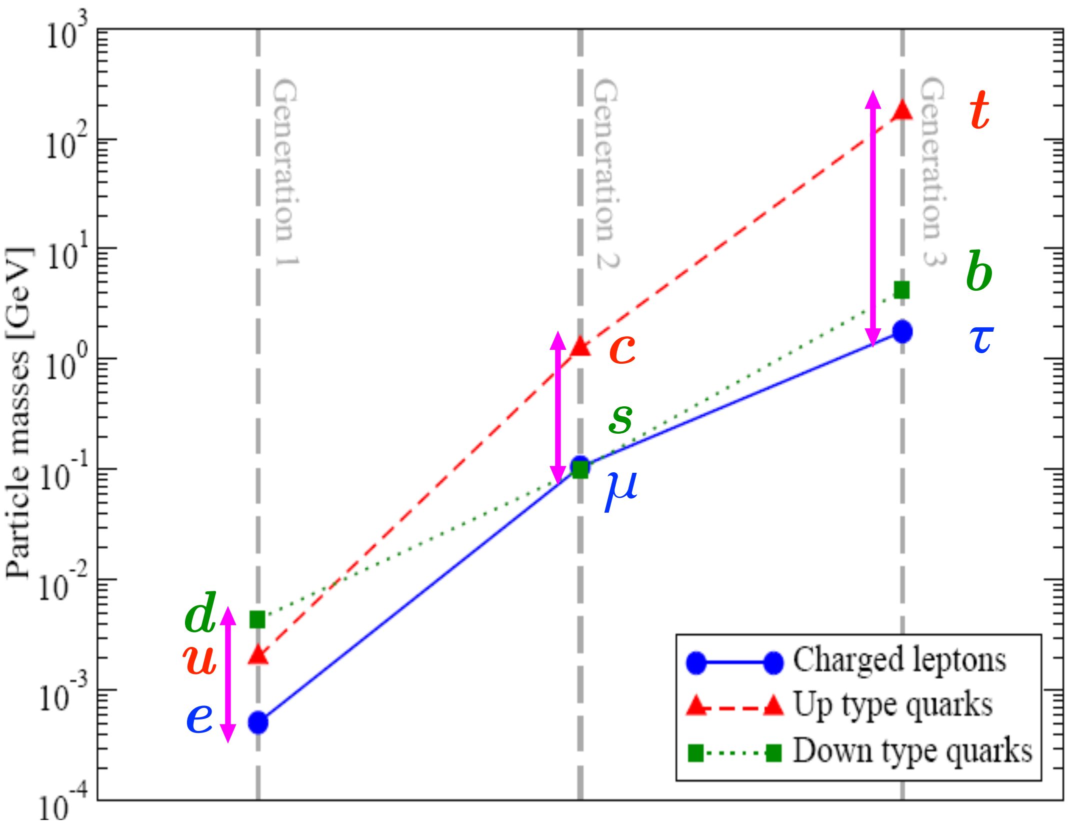
  → current + future experiments

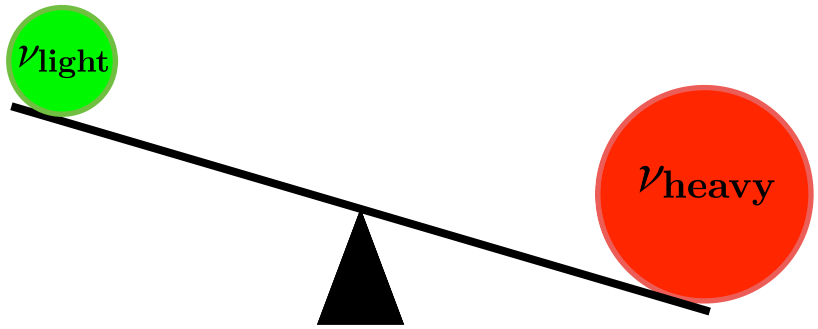
  - is CP conserved in the neutrino sector?

  → next generation experiments

Generation of mass: seesaw mechanism

- Within each family, the masses differ by 10^2 or less
- Neutrinos ($m < 10^{-9}\,\mathrm{GeV}$) increase the differences by several orders of magnitude
- A natural explanation for the light neutrino mass is provided by the seesaw mechanism





Masses in the standard model

- The SM lagrangian satisfies the SU(3)×SU(2)$_L$×U(1) symmetry

- But mass terms break the SU(2)$_L$×U(1) symmetry

$$-\bar{\psi}\psi = -m(\bar{\psi}_R\psi_L + \bar{\psi}_L\psi_R)$$

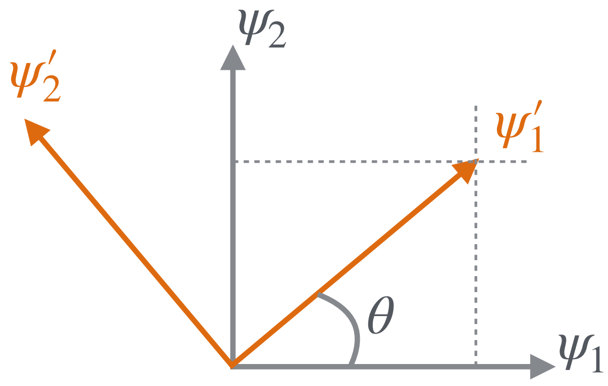
- Generate mass with the Higgs mechanism

  - introduce a doublet scalar Higgs field Φ
  - couple to fermions with $-y\bar{\psi}\phi\psi$
  - the potential is minimum at $\phi = v \neq 0$
  - the Yukawa term becomes $-yv\bar{\psi}\psi$
  - and we identify the mass of the fermion field as $m \sim yv$

Consequences of the Higgs mechanism

- Physical states are mass eigenstates ψ'
- Interactions act on flavour eigenstates $\psi \neq \psi'$

⇒ mass eigenstates are superpositions of flavour states



⇒ this offers a possibility for “mixing” between flavour eigenstates

- Mixing observed in neutral mesons:

$$K^0 \Leftrightarrow \bar{K}^0 \ , \ D^0 \Leftrightarrow \bar{D}^0 \ , \ B^0 \Leftrightarrow \bar{B}^0$$

... and among neutrinos

⇒ therefore neutrinos must be massive to allow mixing!

Introducing a ν mass

- Option 1: (if ν is a Dirac particle)
  - introduce a right-handed neutrino ν_R and define the mass like for the other fermions (e.g. quarks) : $-m\bar{\nu}\nu$
  - problems:
    - ν_R must be "sterile", i.e. it does not interact, to be consistent with experiments ⇒ no theoretical motivation
    - the mass is set by hand to a value un-natural (⇒ fine tuning) to the other members of the corresponding family

- Option 2: (if ν is a Majorana particle; $\nu_R = \nu^c_L$)
  - mass term in the Lagrangian : $-\dfrac{m_L}{2}(\bar{\nu}^c_L \nu_L + \bar{\nu}_L \nu^c_L)$
  - consequences:
    - a sterile neutrino is not necessary
    - the problem of mass hierarchy is still present

Dirac-Majorana mass term

- Option 3:
  - combine Dirac and Majorana mass terms

$$\underbrace{-m_D(\bar{\nu}_R\nu_L + \bar{\nu}_L\nu_R)}_{\text{Dirac term}} \underbrace{- \frac{m_L}{2}(\bar{\nu}_L^c\nu_L + \bar{\nu}_L\nu_L^c)}_{\text{Majorana Left term}} \underbrace{- \frac{m_R}{2}(\bar{\nu}_R^c\nu_R + \bar{\nu}_R\nu_R^c)}_{\text{Majorana Right term}}$$

  - Dirac mass from Higgs mechanism $\Rightarrow m_D \sim v \sim 100\,\mathrm{GeV}$
  - $m_L = 0$ in the SM, but could be set to $m_L \ll m_D$
  - no constraint on m_R from SM
    - can be set to GUT scale: $m_R \sim 10^{14} - 10^{16}\,\mathrm{GeV}$
  - Remark: can be generalised to multiple families $\Rightarrow m_{ij}$

Dirac-Majorana mass term

Seesaw mechanism

- Lagrangian mass term can be rewritten as:

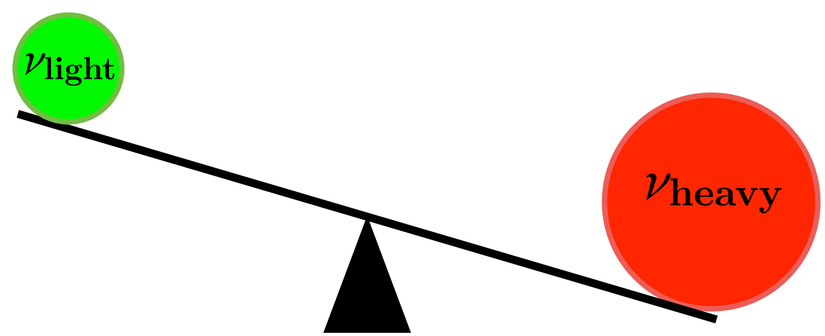
$$-\frac{1}{2}\begin{pmatrix} \bar{\nu}_L^c & \bar{\nu}_R \end{pmatrix}\begin{pmatrix} m_L & m_D \\ m_D & m_R \end{pmatrix}\begin{pmatrix} \nu_L \\ \nu_R^c \end{pmatrix} + h.c.$$

- Diagonalisation (with $m_L=0$; $m_D \ll m_R$) gives

$$-\frac{1}{2}\begin{pmatrix} \bar{\nu} & \bar{N}_R \end{pmatrix}\begin{pmatrix} (-)\frac{m_D^2}{m_R} & 0 \\ 0 & m_R \end{pmatrix}\begin{pmatrix} \nu \\ N \end{pmatrix} + h.c.$$

- Consequences:
  - $m_\nu \approx 10^4/10^{14} = 0.1\,\mathrm{eV}$

    $\Rightarrow$ small ν mass is generated naturally
  - ν is an effective Majorana particle
  - hierarchy problem is solved!
  - (quasi-) Lepton number conserved at low energies



Neutrino mass: summary

- We started with:
  - $m_\nu = 0$; ν_L only; Lepton number conserved

- We now have a better description of experimental data with:
  - $m_\nu > 0$; ν_L and ν_R;
  - lepton number violation (but near conservation at low energy)

- Our understanding suggests that the small ν mass is a consequence of physics at very high energy (seesaw mechanism)

- Better understanding will come from experiments:
  - oscillations; CP violation?; Majorana vs. Dirac; $\Delta L \neq 0$ processes
  - cosmic neutrinos...

Cosmic neutrinos

Cosmic neutrinos

- Atmospheric neutrinos
- Solar neutrinos
- Neutrinos from SuperNovae (SN)
- Ultra-high-energy (UHE) neutrinos

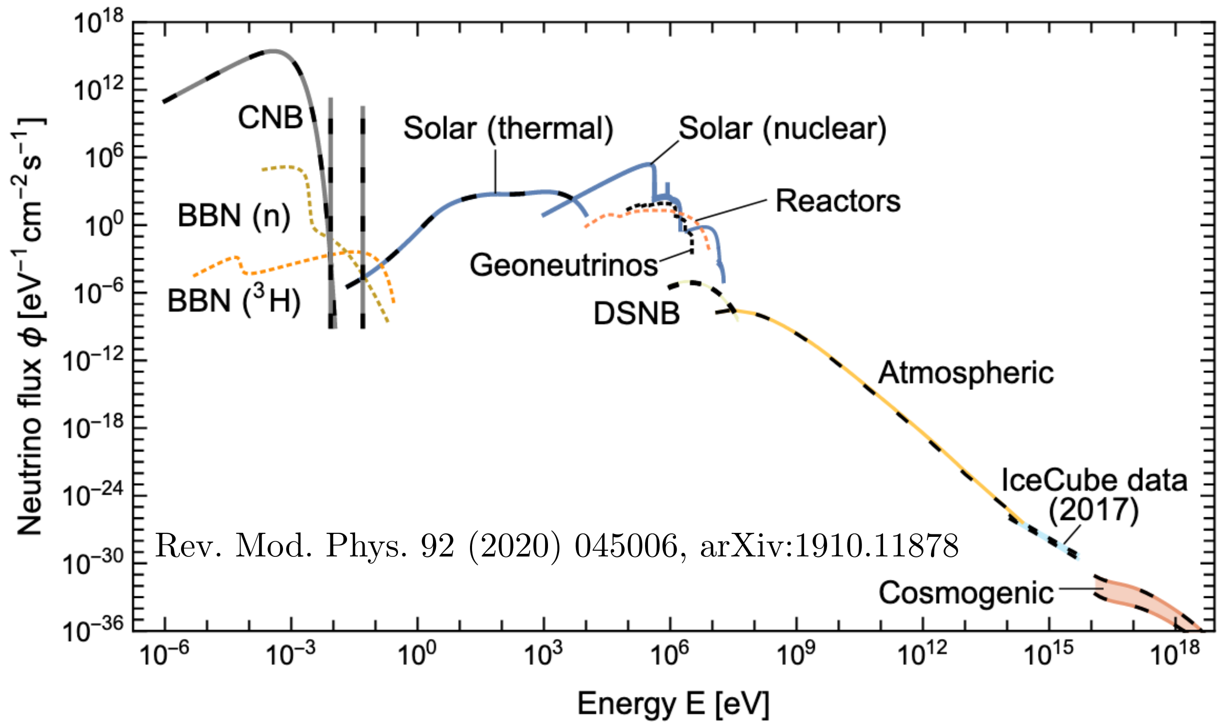
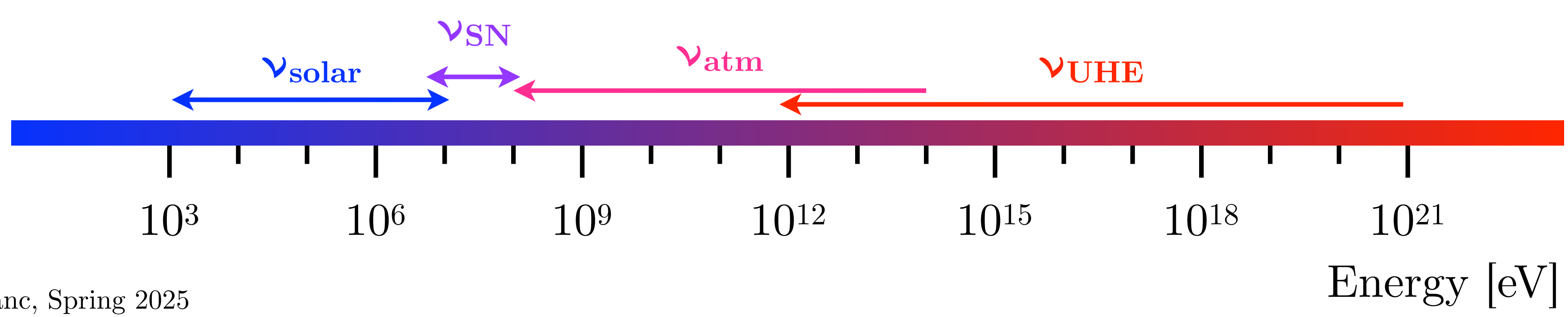


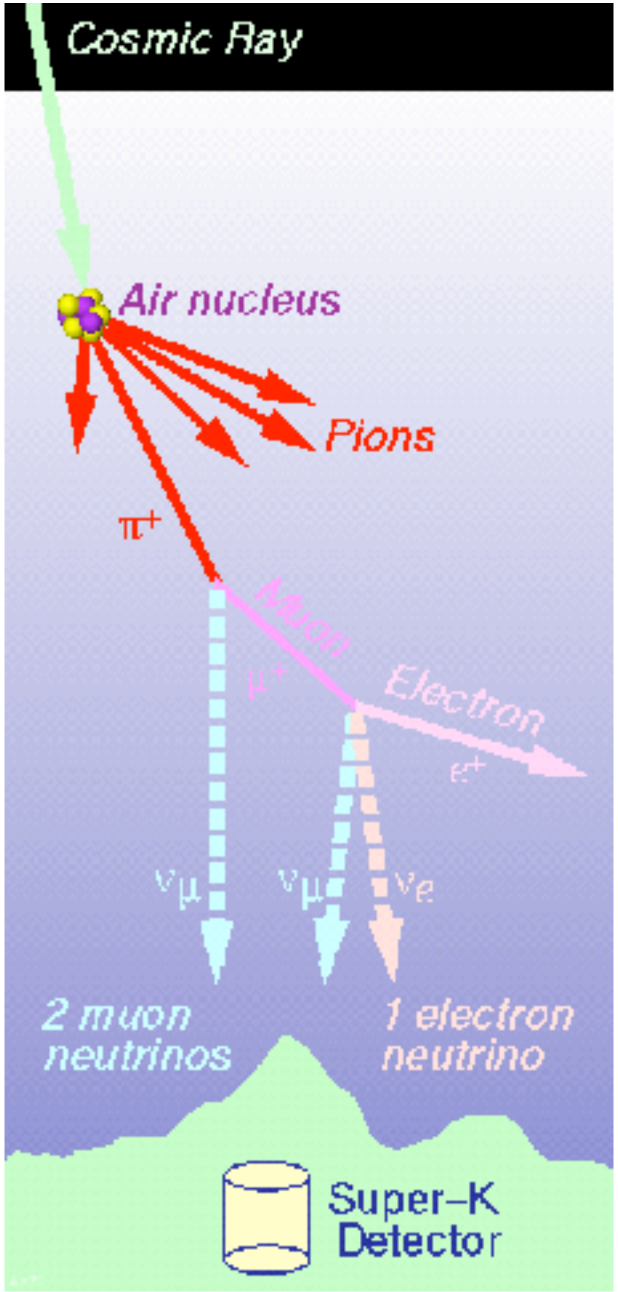
Figure 1: Neutrino sources and corresponding energies and fluxes on Earth, taken from Ref. [1]. The abbreviations are Big Bang Nucleosynthesis (BBN), Cosmic Neutrino Background (CNB) and DSNB (Diffuse Supernova Neutrino Background). Nuclear solar neutrinos are produced by *pp* and CNO cycles, thermal solar neutrinos are produced from processes like bremsstrahlung or plasmon decay. See later sections for more on the various neutrino sources.

arXiv: 2111.07586



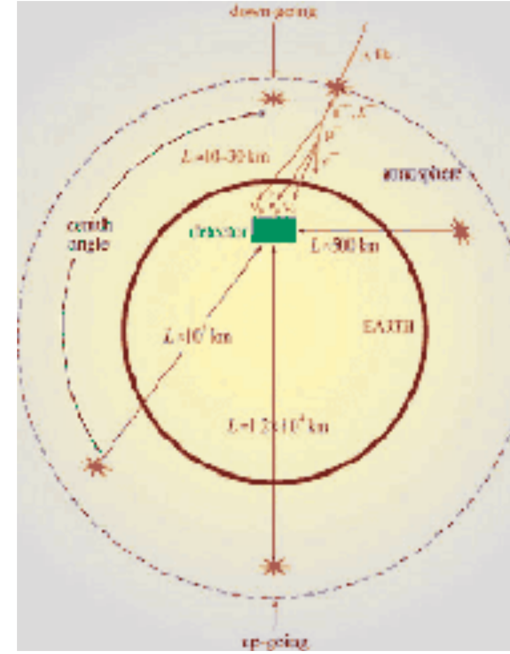
1. Atmospheric neutrinos

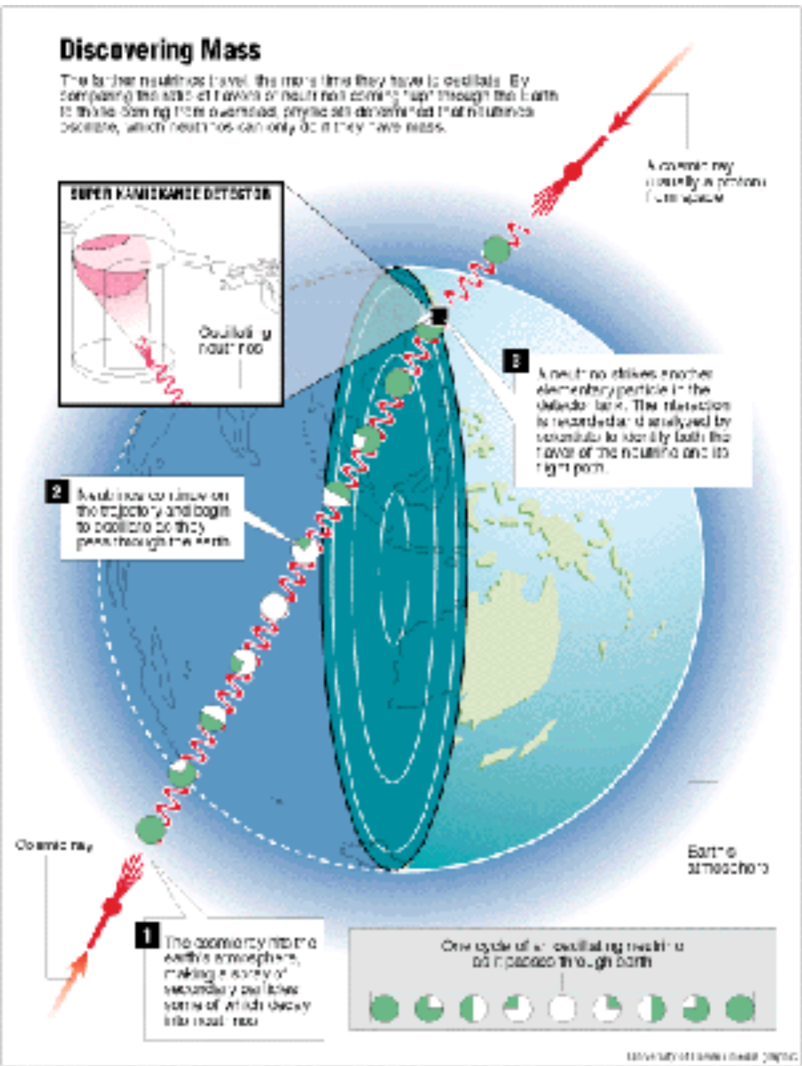
- Cosmic rays interact in the high atmosphere and produce neutrinos
  - ν_e and ν_μ in ratio 1:2
- Useful for neutrino oscillation measurements
- Observed in all neutrino experiments
- Background to UHE neutrino studies

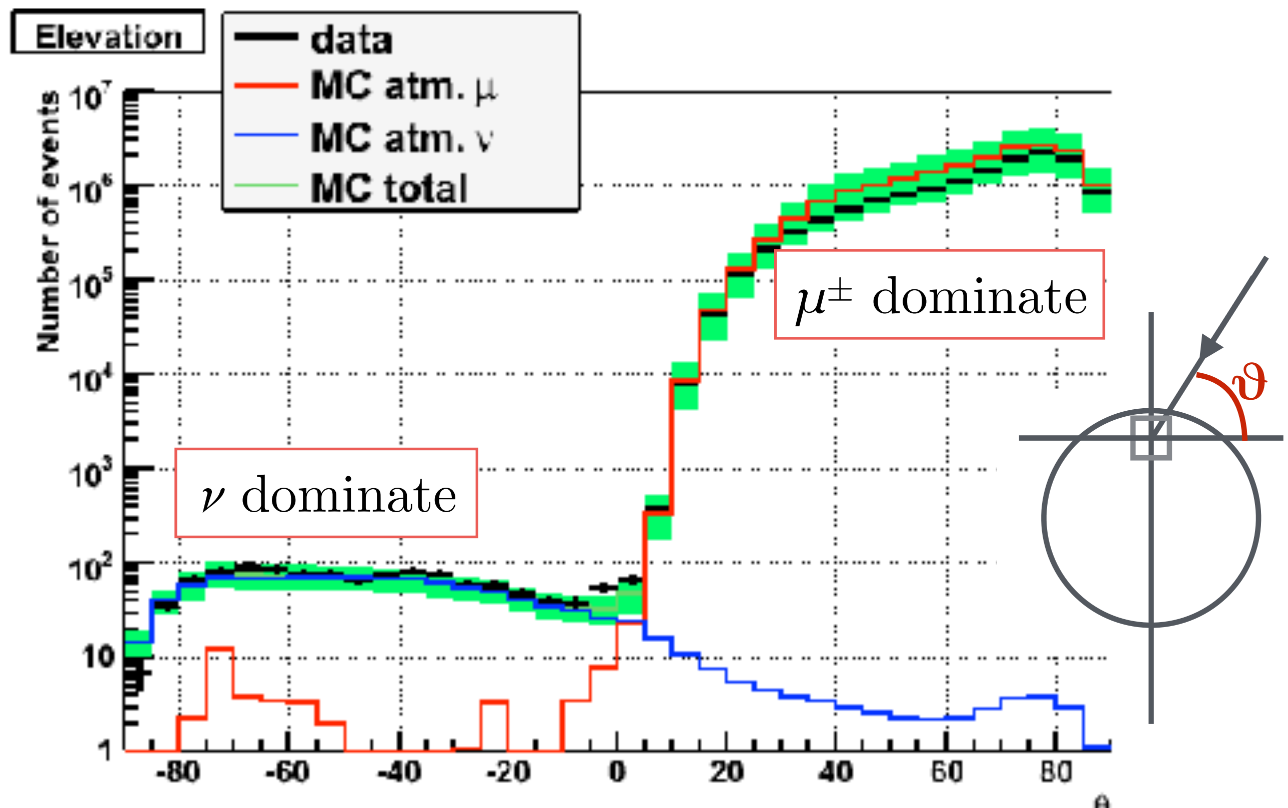


Upward vs. downward

- Upward "beam" is a clean neutrino source
- Downward beam is polluted with muons



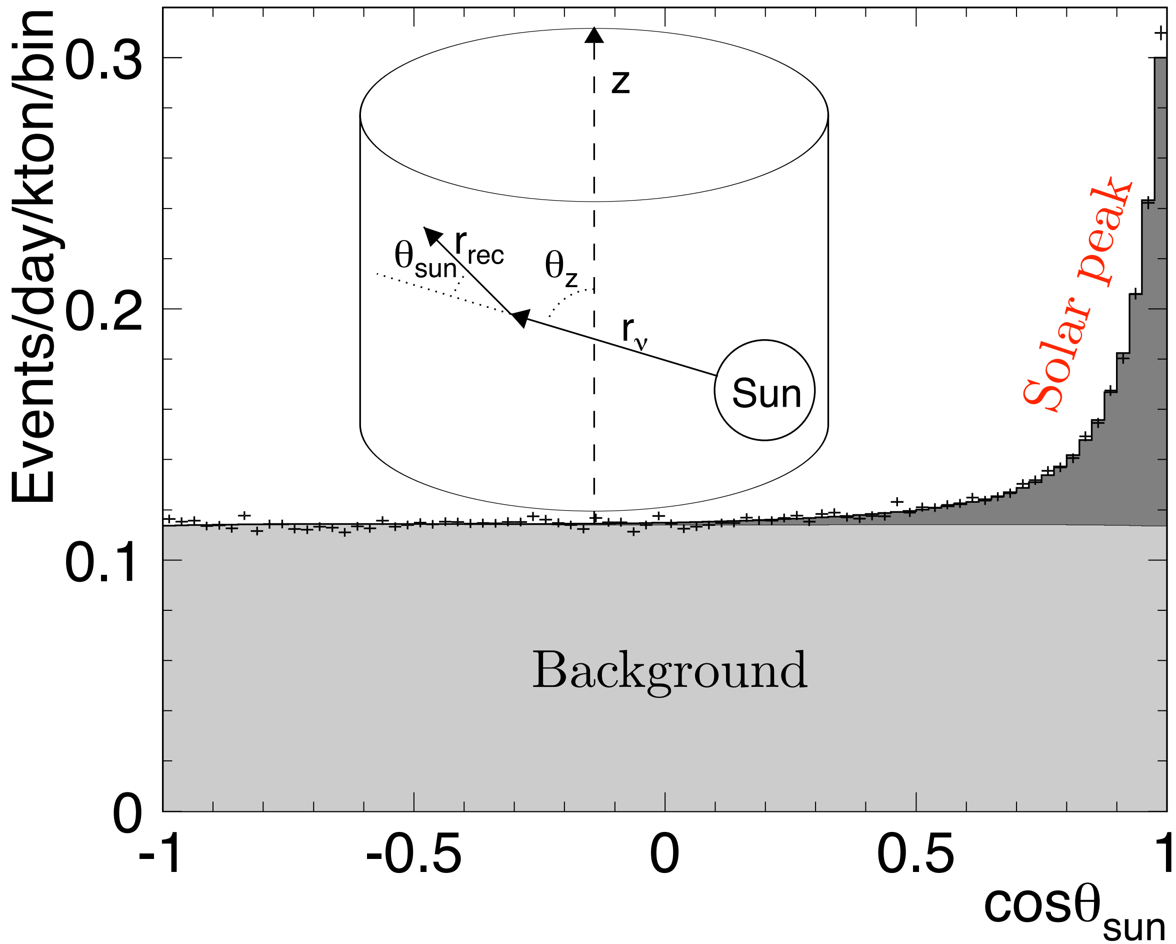




From below http://antares.in2p3.fr **From above**

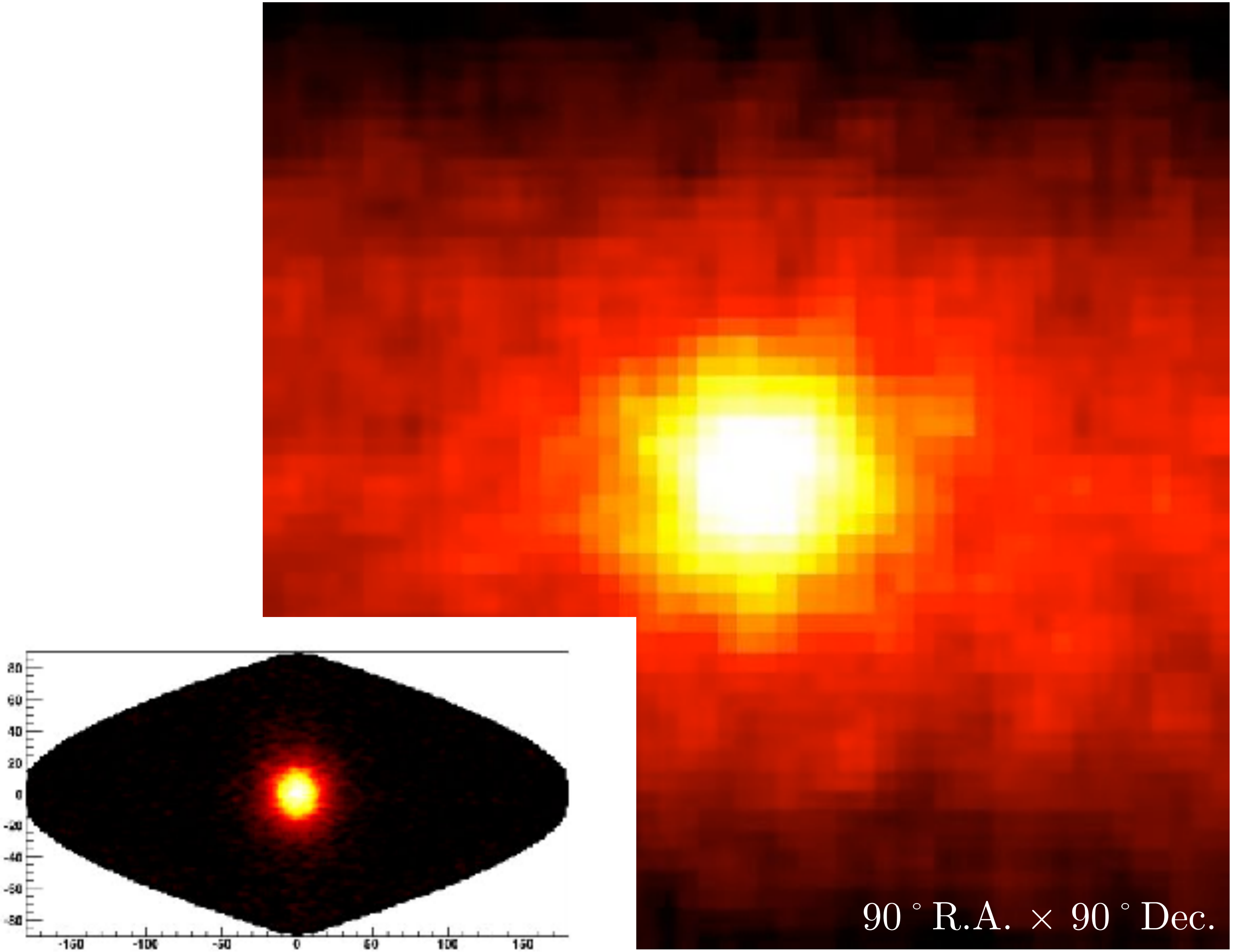
2. Solar neutrinos

- Neutrinos of a few MeV are produced in fusion processes inside stars
  - neutrino production dominated by the *pp* chain (see next slides)
- Neutrinos emitted by the Sun are clearly visible in earth-bound detectors
- Neutrino small cross-section
  ⇒ probe the Sun's inner structure



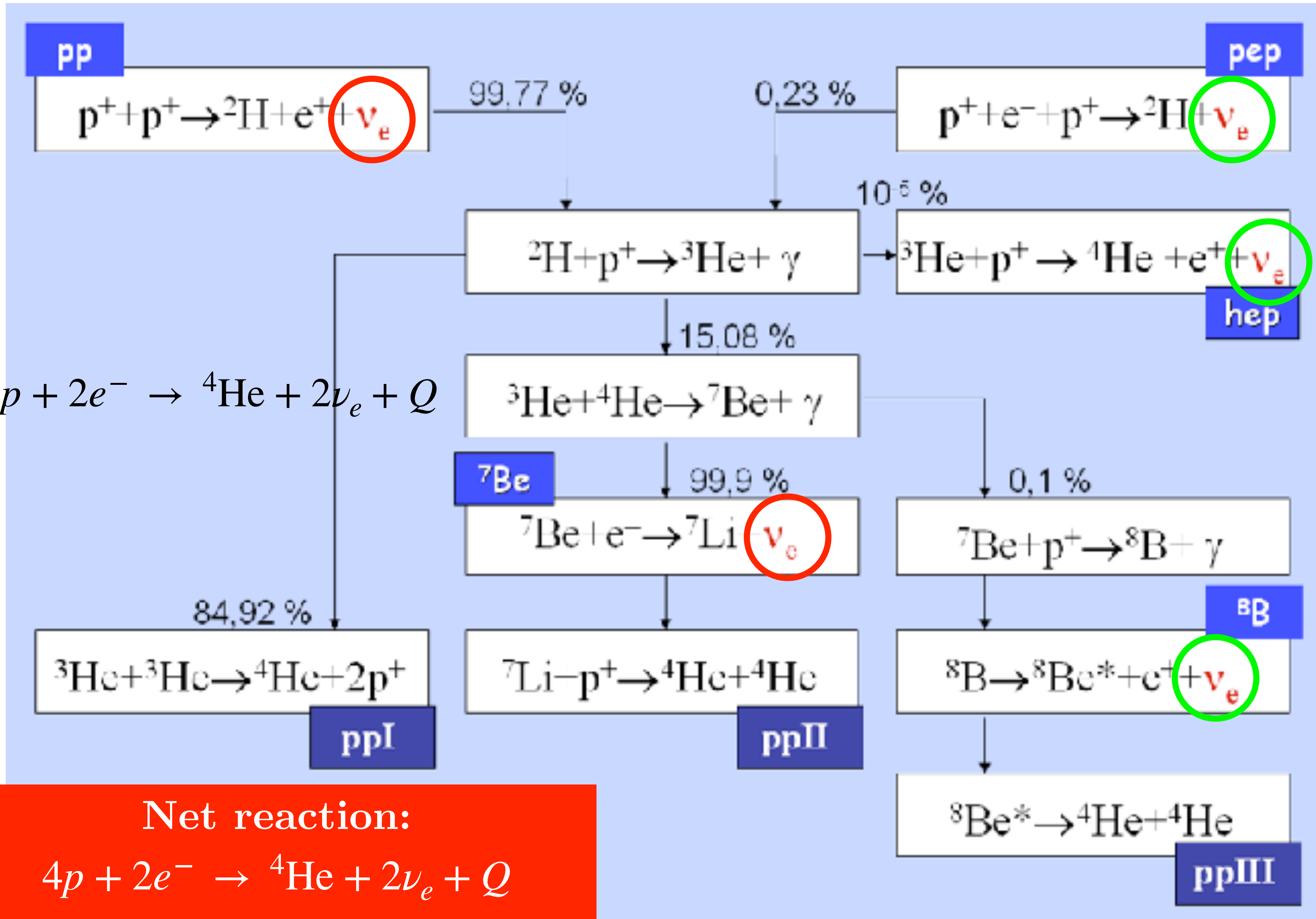
Super-Kamiokande
Phys. Rev. D94 (2016) 052010

Neutrino picture of the Sun



Super-Kamiokande
http://apod.nasa.gov/apod/ap980605.html

Solar neutrinos: *pp* chain



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

Net reaction:

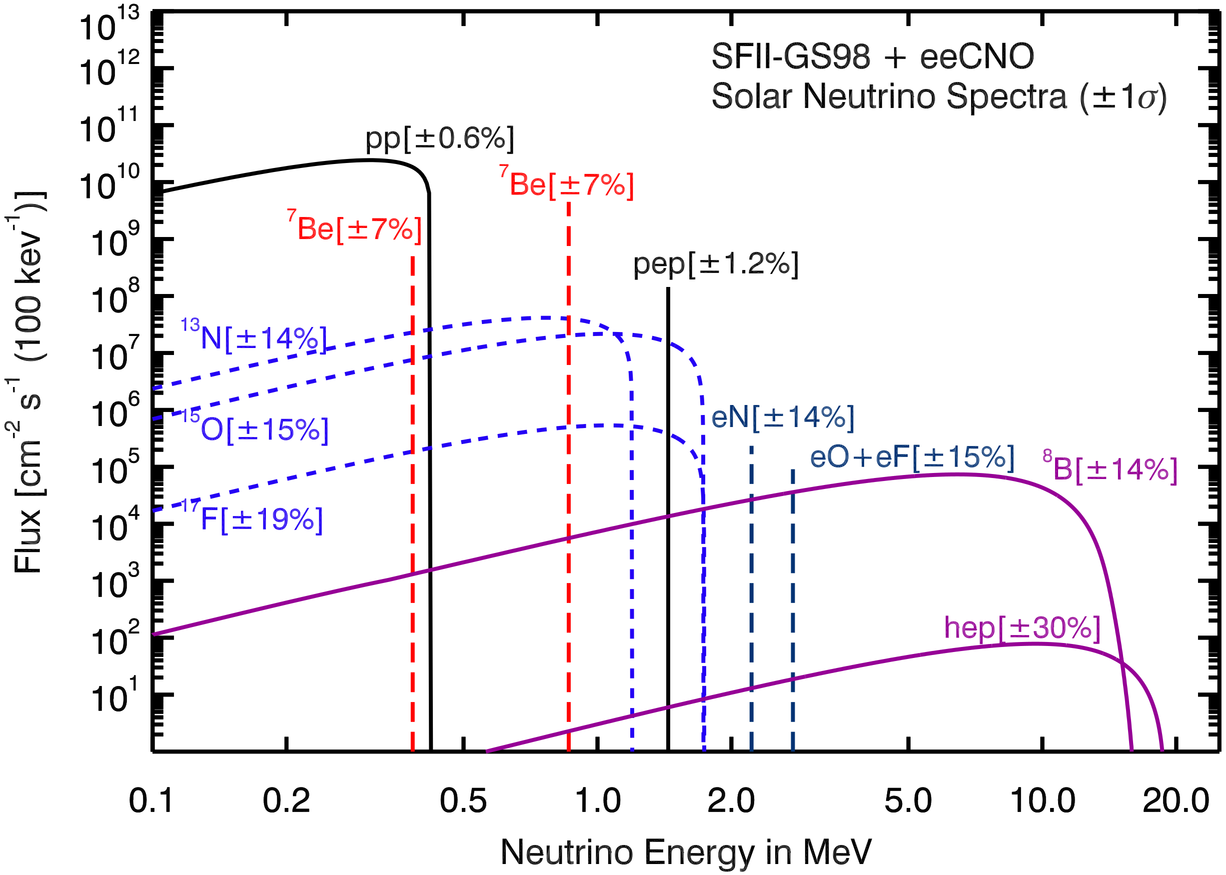
$$4p + 2e^- \rightarrow {}^4\text{He} + 2\nu_e + Q$$

$$Q = 26.7\,\text{MeV}$$

Solar neutrino energy spectrum

- ν flux dominated by *pp* chain:
  - Flux on Earth $\approx 6 \times 10^{10}\,\mathrm{cm^{-2}\,s^{-1}}$
- Deficit of neutrinos detected relative to prediction of the Solar Standard Model (SSM)
  - Understood now as being due to ν oscillations
- Confront SSM with:
  - neutrino flux
  - helio-seismology

  $\Rightarrow$ strong constraints on Sun inner structure



Source: RPP 2017

Solar neutrino experiments (I)

A. Chlorine

- Principle: $$\nu_e + {}^{37}\mathrm{Cl} \rightarrow {}^{37}\mathrm{Ar} + e^-$$
  - $E_{\text{threshold}} = 0.814\text{MeV}$ (⇒ sensitive to ^{8}B)
  - ^{37}Ar detected by "radiochemical" methods: proportional chambers count Auger e^- produced in e^--capture process (τ=35day)
- Homestake (1970-1994): 1st observation of Solar neutrinos, with 1/3 of the expected rate...

B. Gallium

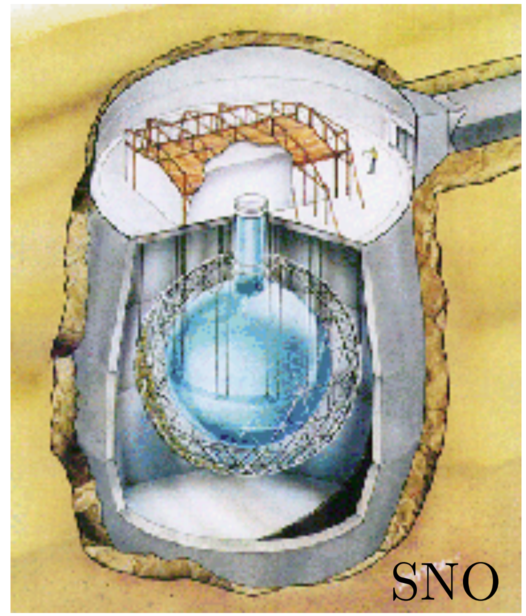
- Principle: $$\nu_e + {}^{71}\mathrm{Ga} \rightarrow {}^{71}\mathrm{Ge} + e^-$$
  - $E_{\text{threshold}} = 0.233\text{MeV}$ (⇒ sensitive to all sources)
  - ^{71}Ge extracted chemically, and decay to ^{71}Ga measured
- Gallex/GNO (1991-1997), SAGE (1990-)

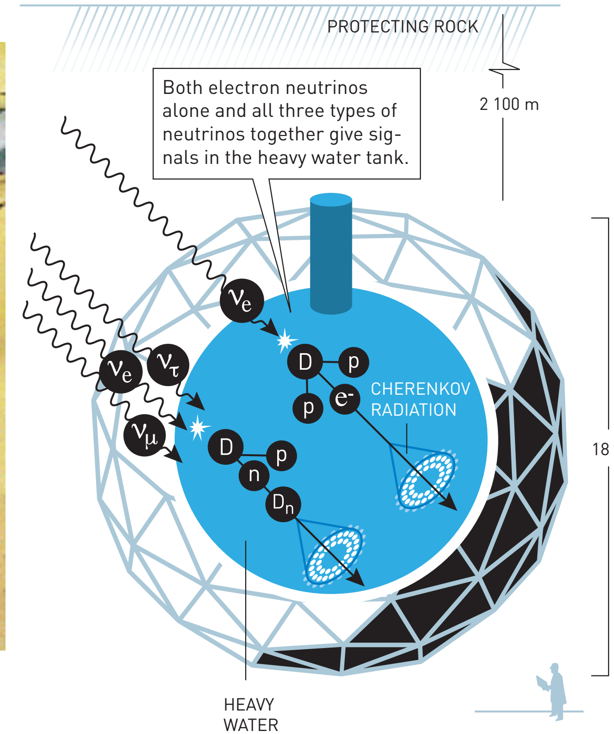
- **All observed a deficit of Solar neutrinos (30% – 80% of expectation)**

Solar neutrino experiments (II)

C. Water Cherenkov detectors:

- (Super-)Kamiokande
  - $E_{\text{threshold}} = 4.7\,\text{MeV}$
- SNO:
  - 99.92% pure D_2O
  - reactions:





CC: $$\nu_e + d \to p + p + e^-$$

NC: $$\nu_\alpha + d \to p + n + \nu_\alpha \quad , \quad \alpha = e, \mu, \tau$$

NC equally sensitive to all ν flavours

  - gamma detected in $$n + d \to {}^3\text{H} + \gamma(6.25\,\text{MeV})$$
  - $E_{\text{threshold}} = 2.2\,\text{MeV}$
  - **deficit seen in CC processes, but no deficit seen in NC processes**
    $\Rightarrow$ consistent with $\nu_e \to \nu_\mu, \nu_\tau$ oscillations!

3. SuperNovae neutrinos

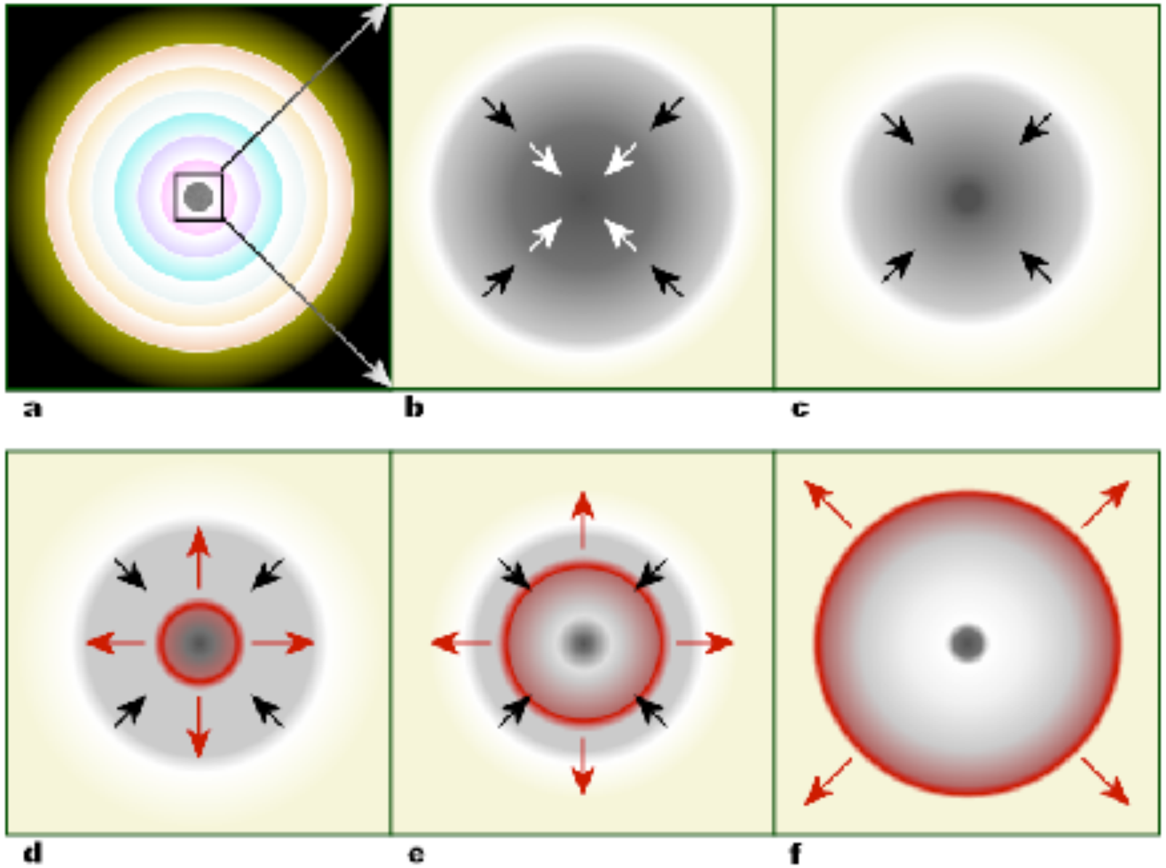
- ν produced and ejected in star's core collapse
  - e.g. SN type II (8-60 solar masses):

(a) (b) (c) ≈ 1s

- Iron core of star (a) reaches Chandrasekhar mass and collapses (b)
- Inner part compresses into a degenerate neutron (fermionic) gas through e^- capture (c), on which the in-falling material bounce (d)

(d) (e) ≈ 50ms

- A shock wave is generated, in which neutrinos are produced (e)



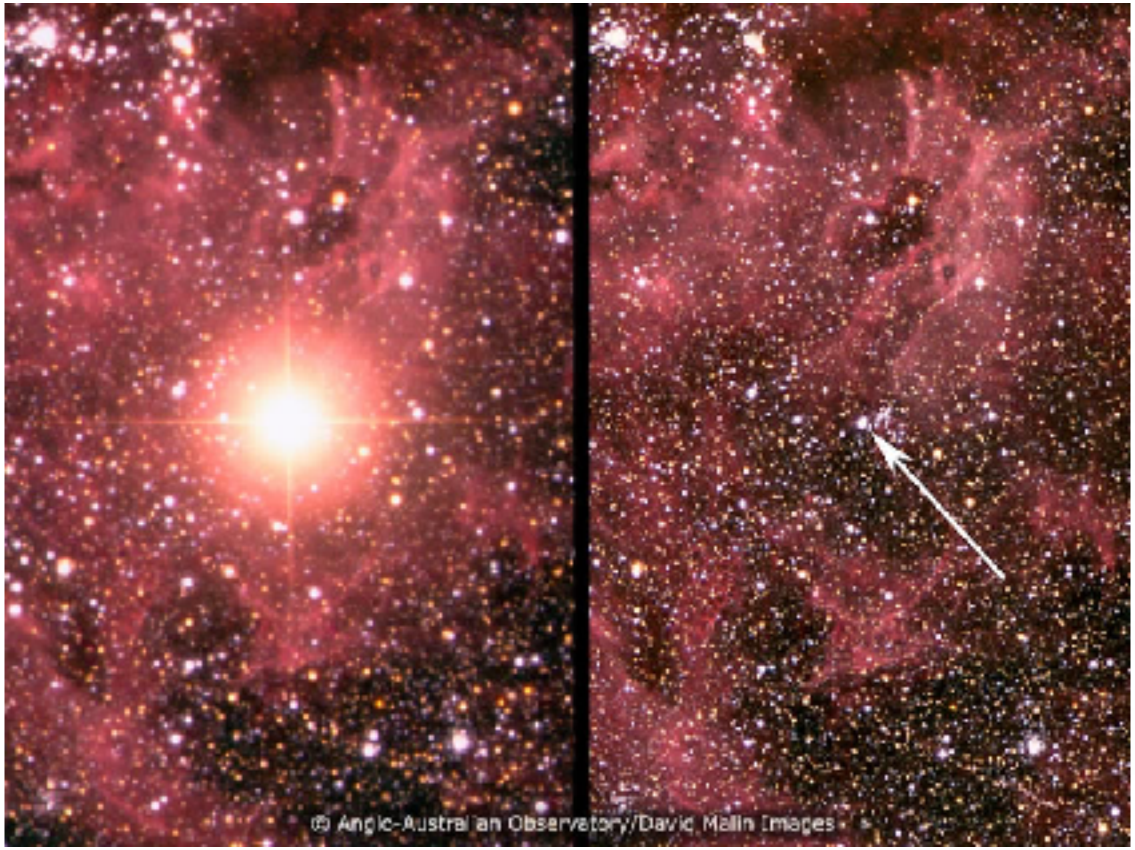
- Neutrinos produced in following cycle during collapse:

$$(p + e^- \to n + \nu_e) \leftrightarrow (n \to p + e^- + \bar{\nu}_e)$$

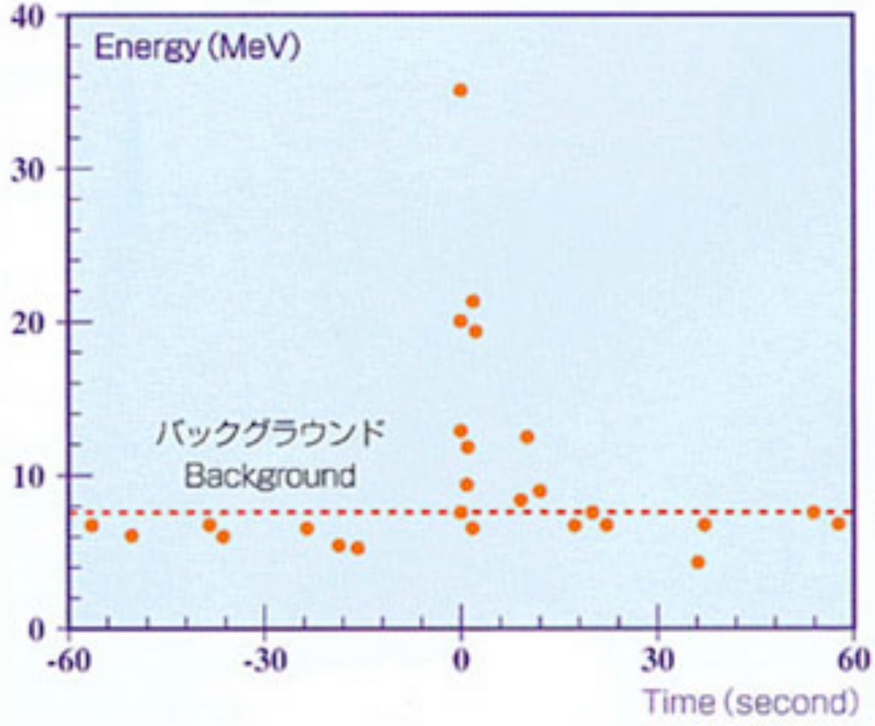
$$E_\nu \approx 10 - 40\text{MeV}$$

SuperNovae SN1987A

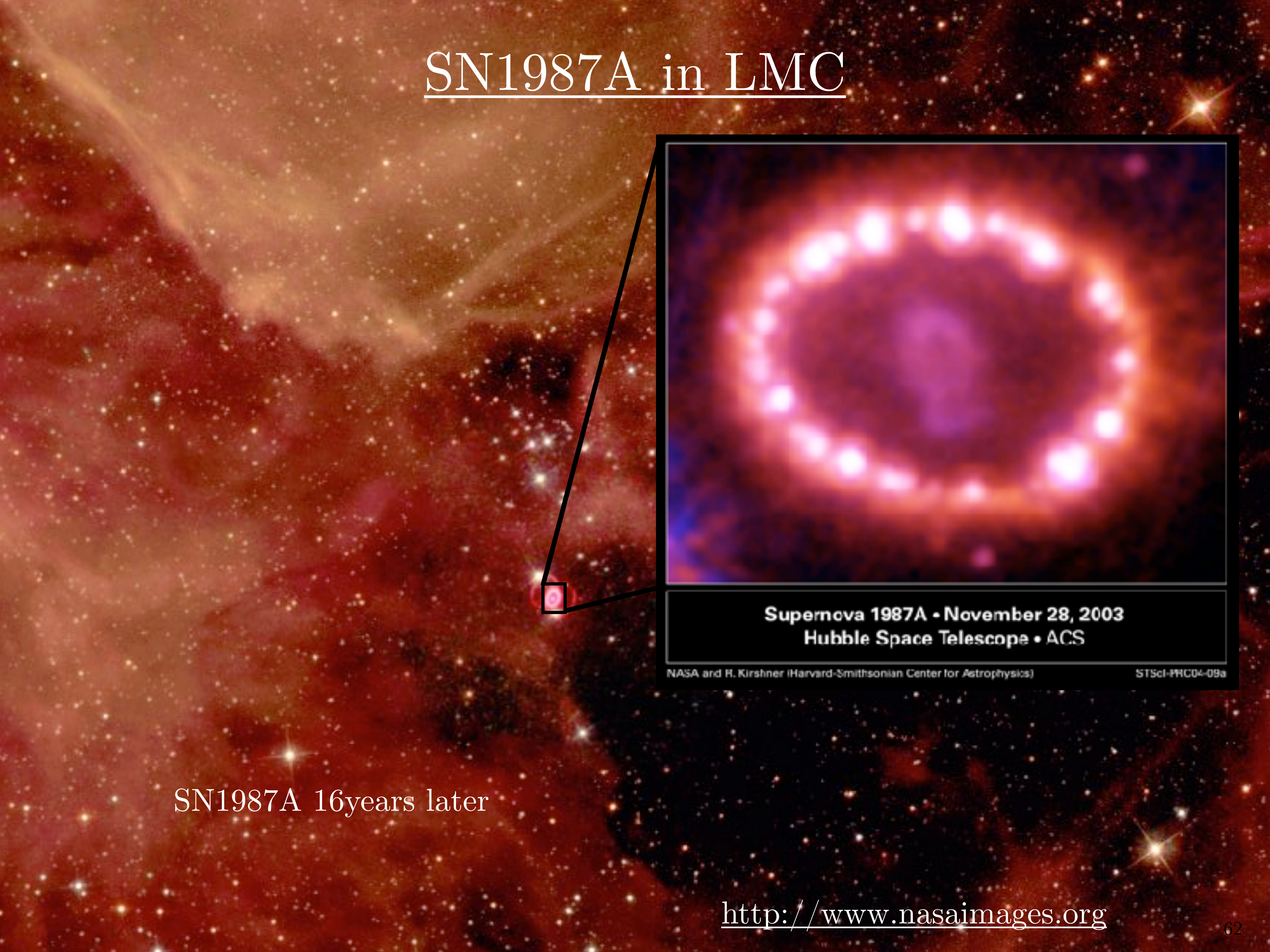
- 24 February 1987, in the Large Magellanic Cloud (≈50 kpc)
- Observed in 3 neutrino detectors:
  - Kamiokande (Japan)
  - IMB (USA)
  - Baksan (Russia)



Energy and arrival time evolution at Kamiokande



SN1987A in LMC

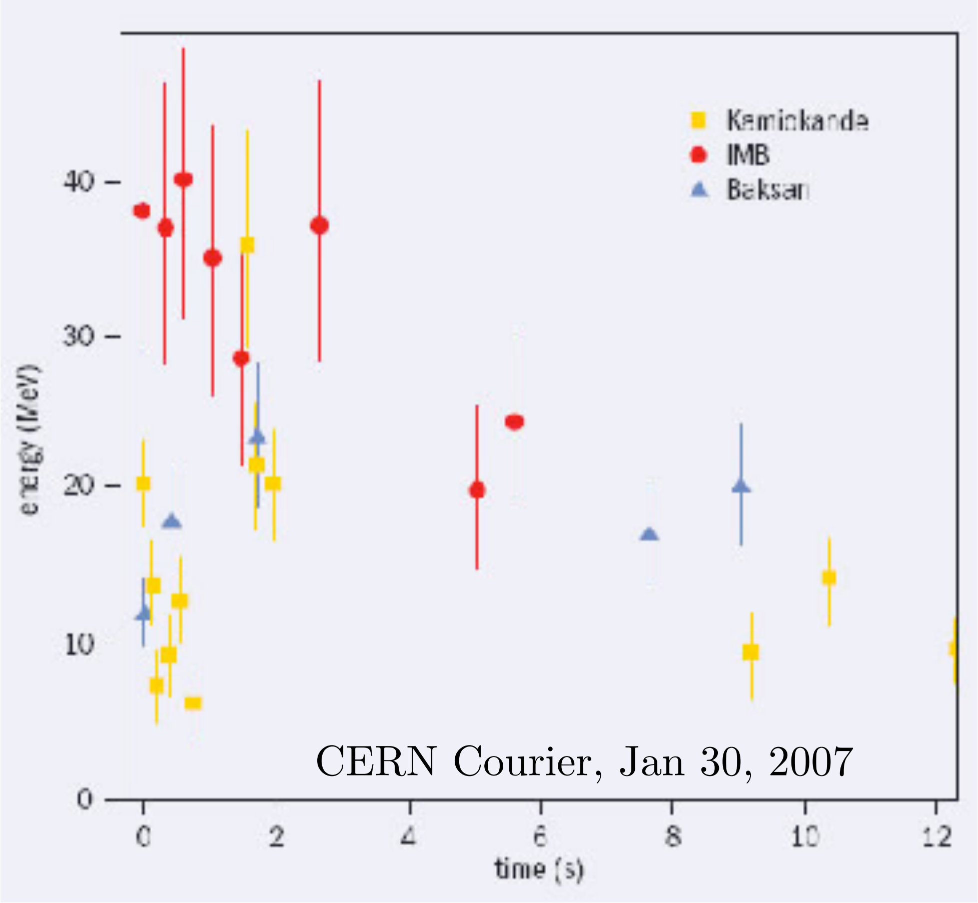


SN1987A 16years later

http://www.nasaimages.org

SN1987A: constraints on neutrino physics

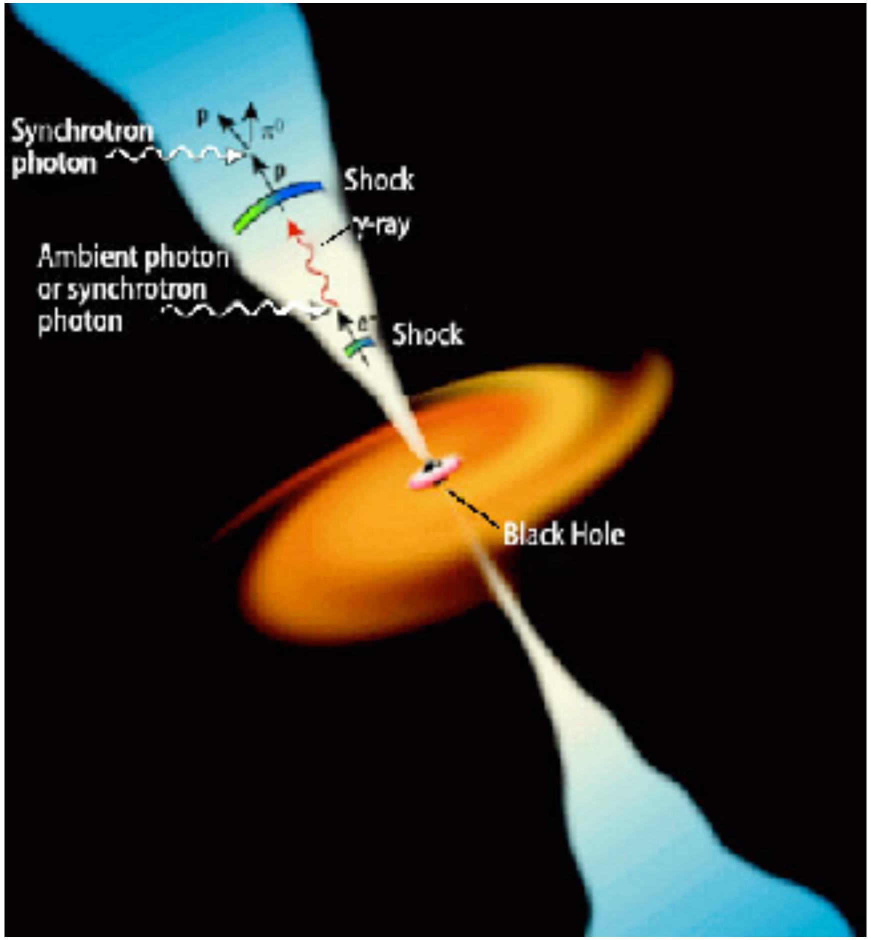
- Mass:
  - Model-independent limit $m(\nu_e) < 30\,\mathrm{eV}$
  - Model-dependent limit: $m(\nu_e) < 5.7\,\mathrm{eV}$ [Phys. Rev. D 65 (2002) 063002]
    - mixing $\Rightarrow$ valid for all ν species
- Lifetime:
  no decay over 50 kpc
  $\Rightarrow \tau(\nu_e) > 1.6 \times 10^5 (m_\nu / E_\nu)\,\mathrm{yr}$
- Electric charge:
  - the galactic magnetic field increases the path length of charged particles $\Rightarrow$ higher time spread due to E spectrum
    $\Rightarrow q(\nu_e) < 10^{-17}\,\mathrm{e}$

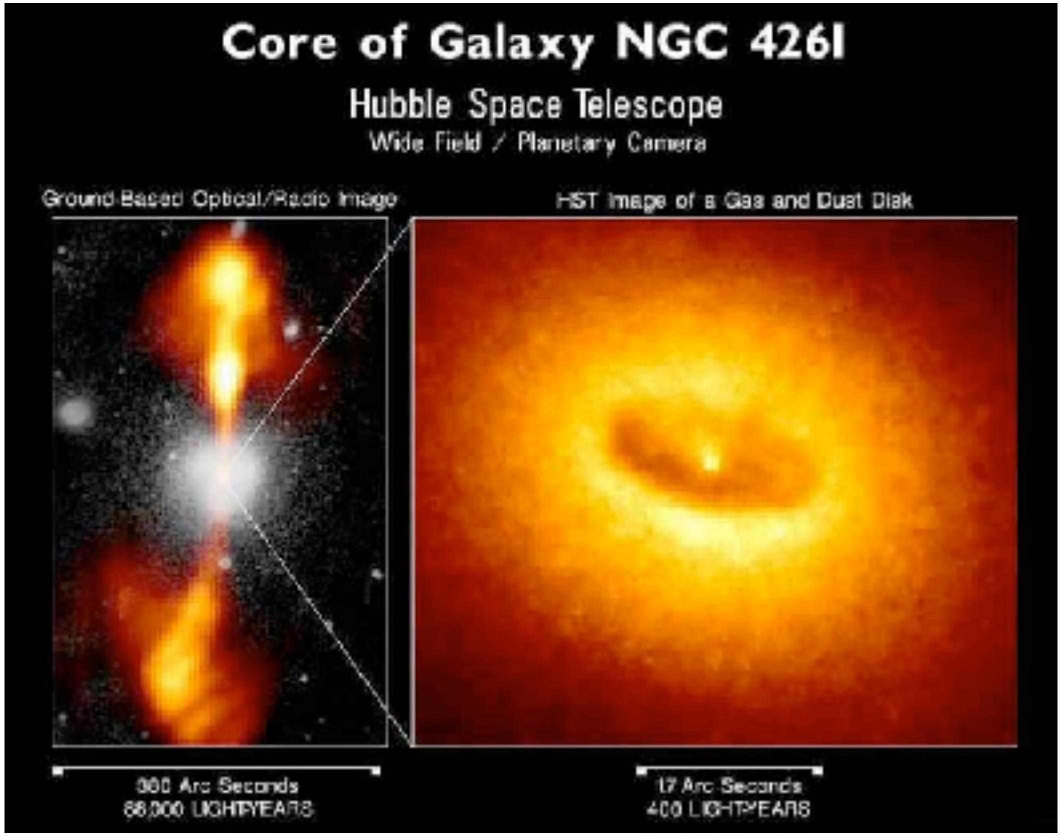


CERN Courier, Jan 30, 2007

4. High-energy astroparticles

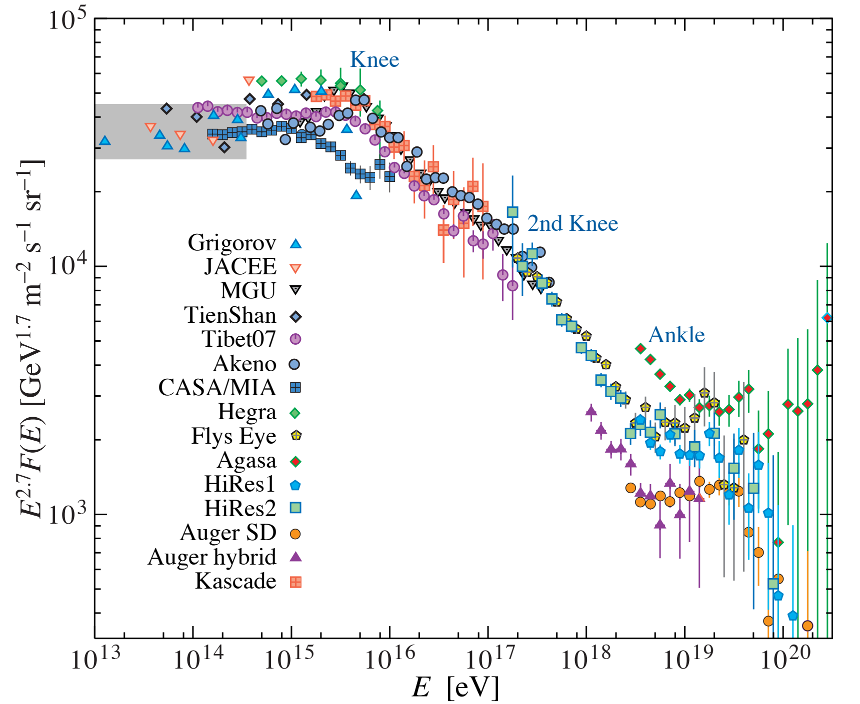
- In general, violent events are source of high-energy particles:
  - Active Galactic Nuclei (AGN)
  - Associated to Gamma Ray Bursts
  - Intergalactic shock waves





Ultra High Energy neutrinos

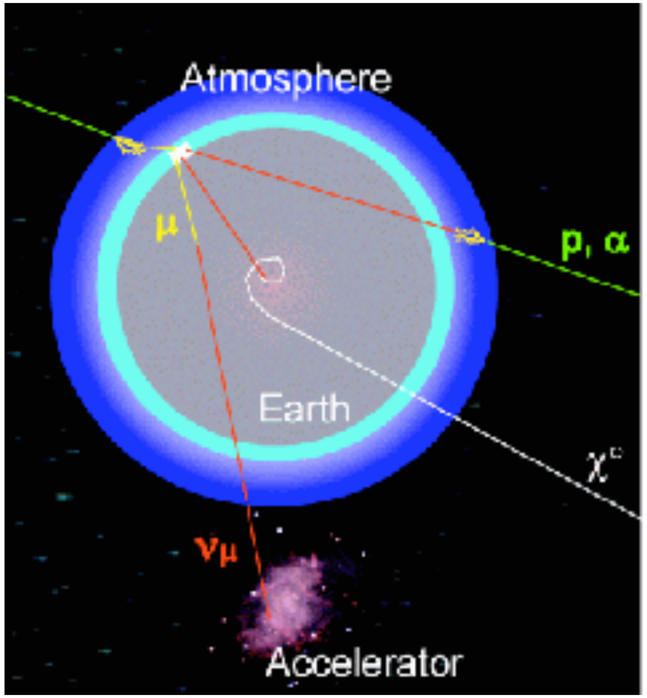
- Astroparticle energy spectrum $\approx E^{-2.7}$
- At $E < 10^{19}$ eV, protons bend in the galactic magnetic field and loose memory of direction
- "GZK" cutoff when charged particles interact with Cosmic Microwave Background (CMB)



$$p + \gamma_{\mathrm{CMB}} \rightarrow \Delta^{+} \rightarrow n + \pi^{+}$$

$$\pi^{+} \rightarrow \mu^{+} + \nu_{\mu} \rightarrow (e^{+} + \nu_{e} + \bar{\nu}_{\mu}) + \nu_{\mu}$$

$\rightarrow$ production of "GZK neutrinos" at energies $\approx 10^{18} - 10^{20}$ eV



- UHE neutrinos:
  - oscillations ⇒ all flavours reach Earth
  - not affected by GZK cutoff
  - point to source

Neutrino telescopes

- Principle:
  - detect Cherenkov light emitted by $\mu^{\pm}$ and $e^{\pm}$ produced in neutrino interactions with matter
  - placed in deep water or deep ice

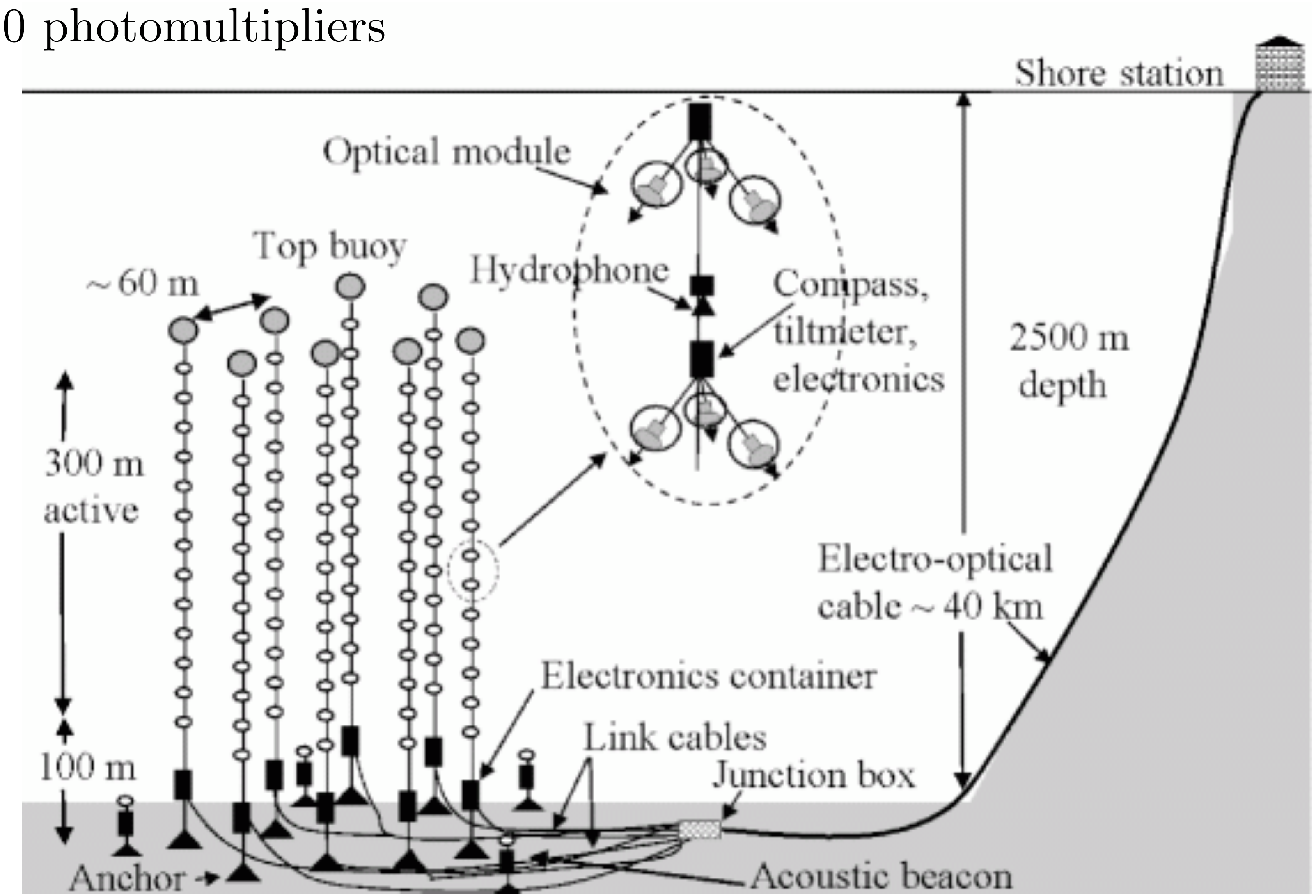
detector properties	ν_e	ν_μ
direction	poor	good
energy	good	poor

- Past, current and future experiments:
  - AMANDA (1997-2003), at South Pole
  - Baïkal/NT200, Russia
  - ANTARES, Mediterranean Sea
  - IceCube, South Pole
  - [KM2NET (ANTARES+NESTOR+NEMO)]

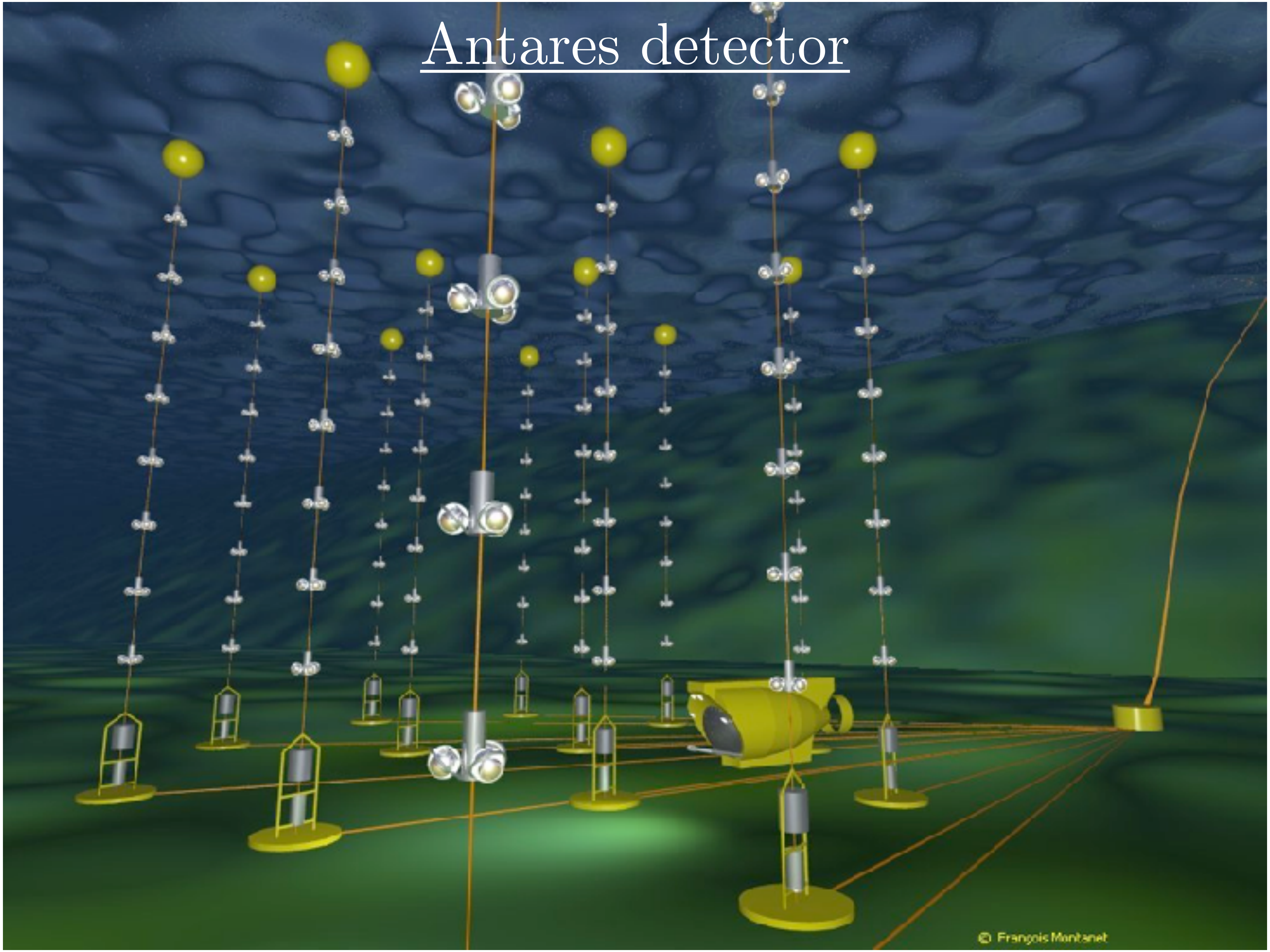
http://antares.in2p3.fr/

Antares

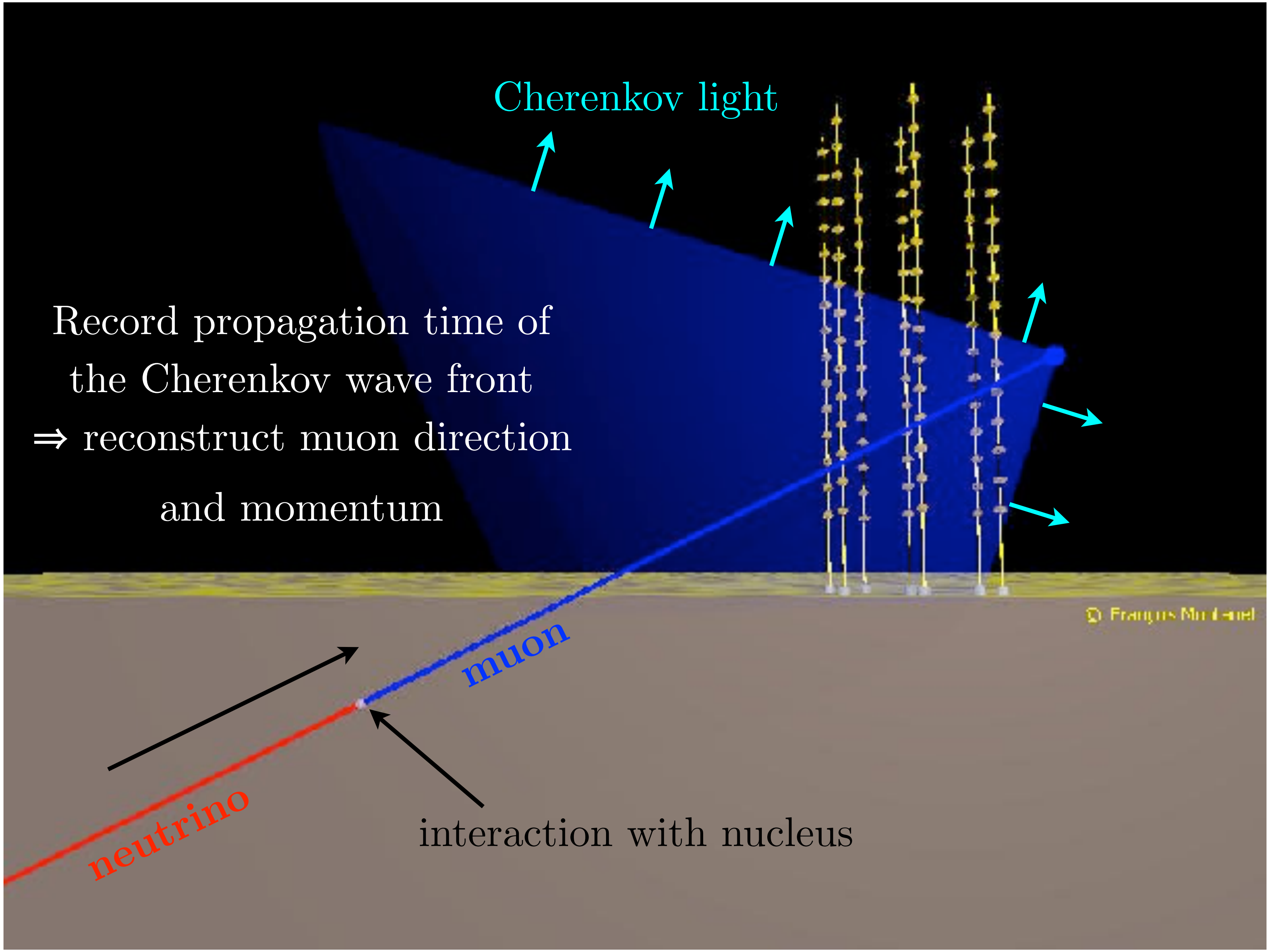
- Located 2400m deep, near Toulon, France
- 12 cables × 25 optical modules
- 900 photomultipliers

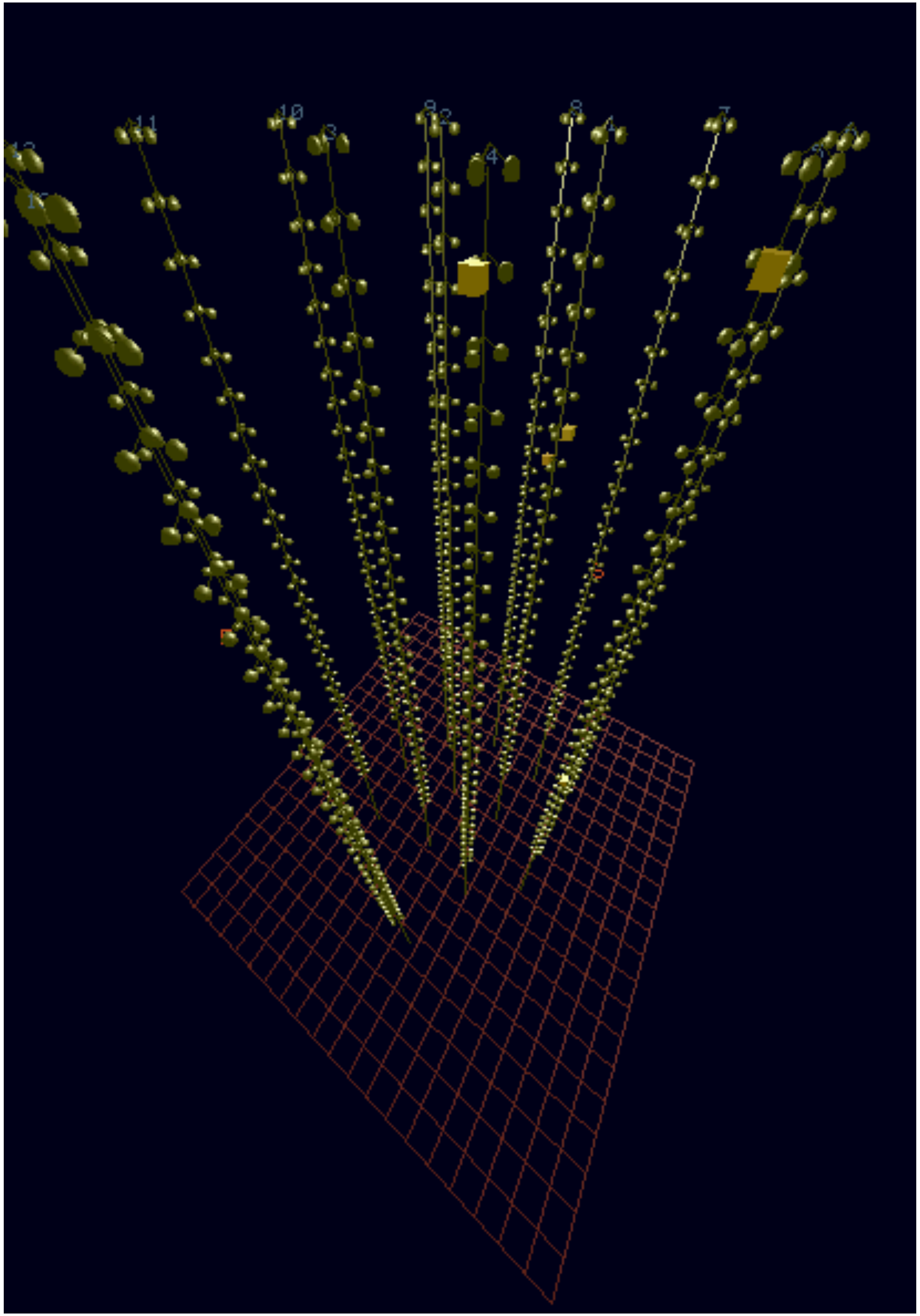


Antares detector



Event propagation





Observations of highest energy neutrino

- On 12 February 2025, the KM3NeT collaboration announced the observation of a neutrino of energy $2.2^{+5.7}_{-1.1} \times 10^{17}\,\mathrm{eV}$

Article

Observation of an ultra-high-energy cosmic neutrino with KM3NeT

Nature 638, 376-382 (2025)

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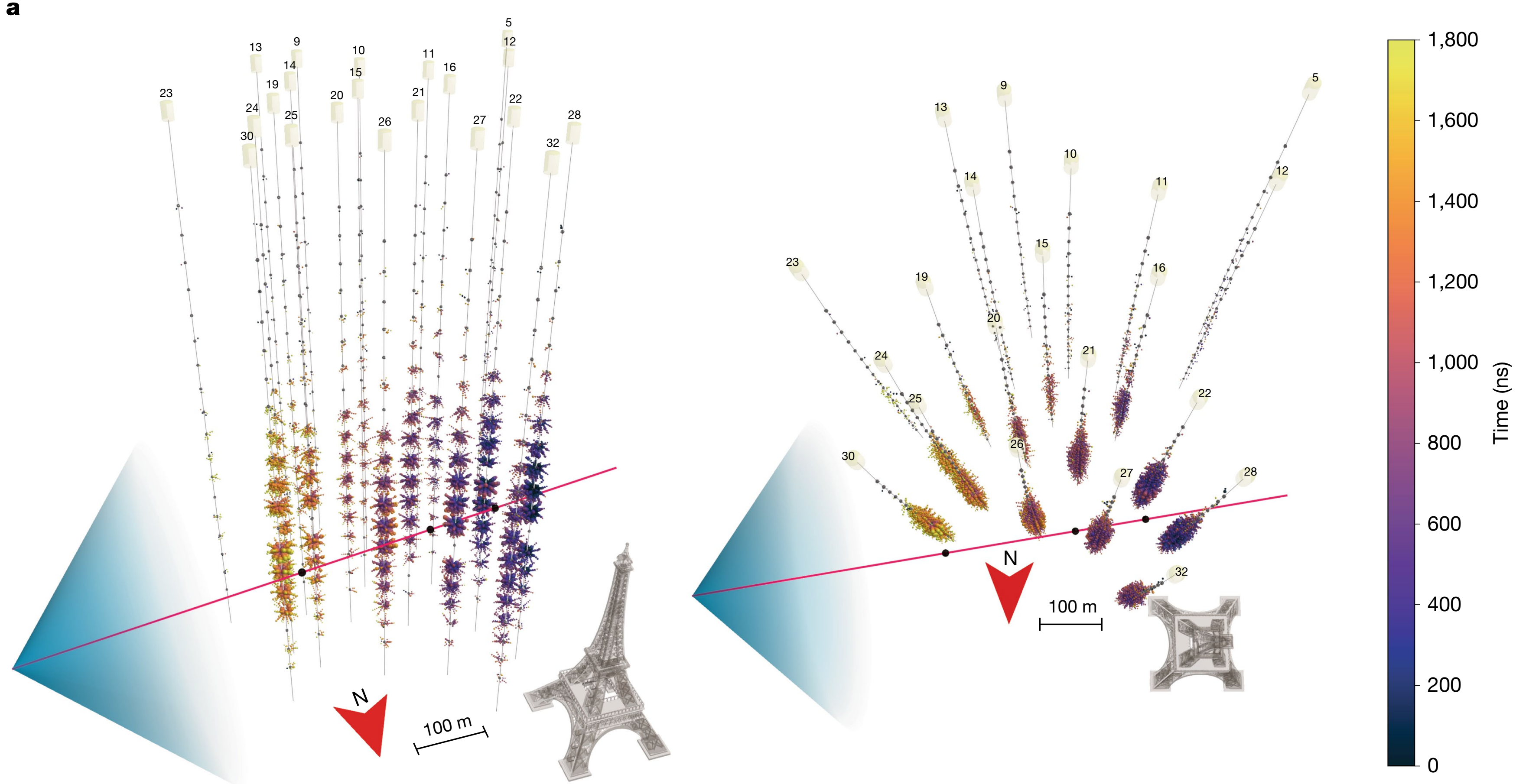
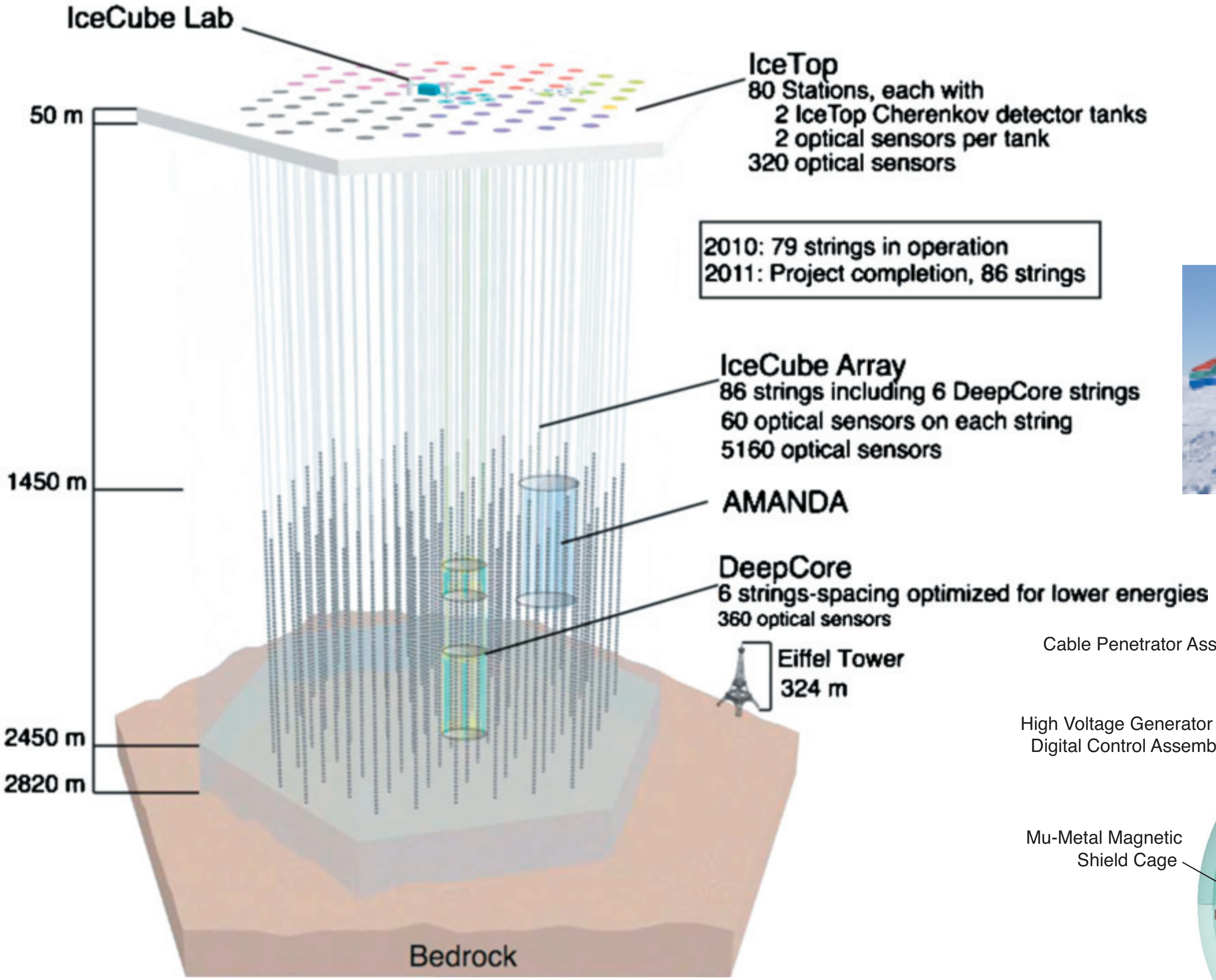
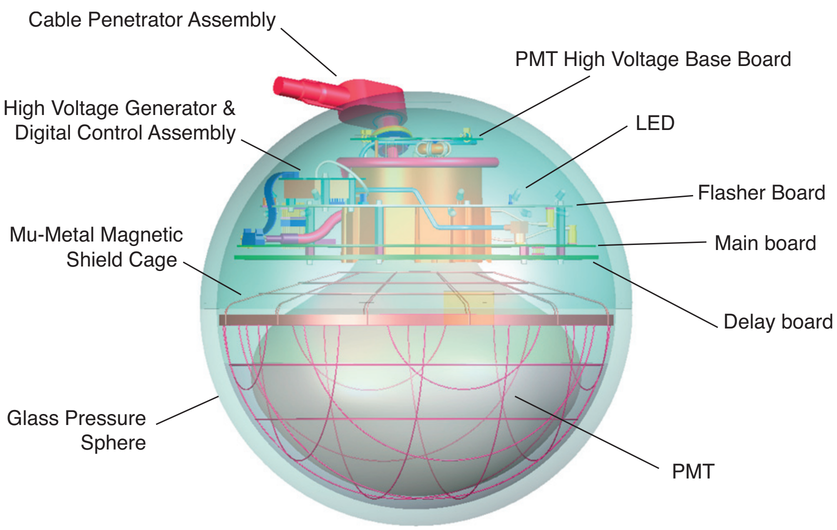


Ice Cube

Marc Jacquart
EPFL Master 2022
Antartica 2022-2023





http://www.icecube.wisc.edu

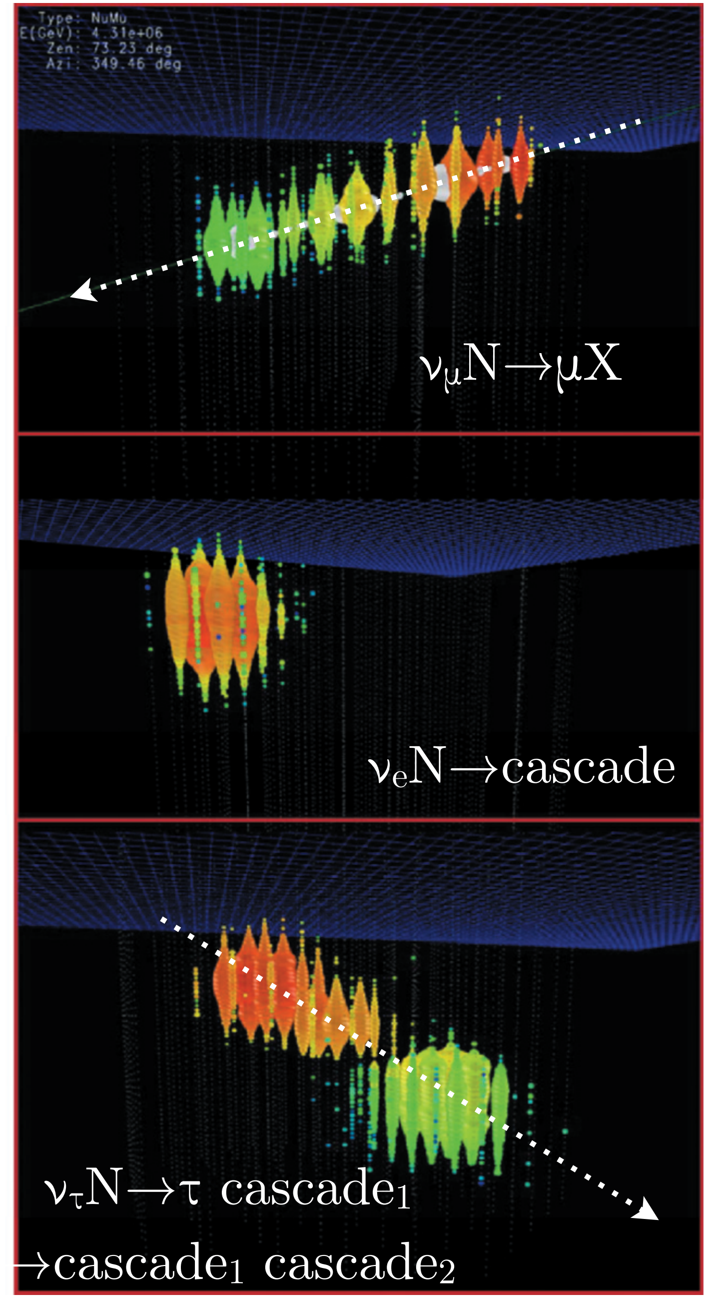
IceCube

- 4200 optical modules on 86 “strings”

- 2450m long strings, separated by 125m
  - optical modules at depths 1450 – 2450m (“InIce”)

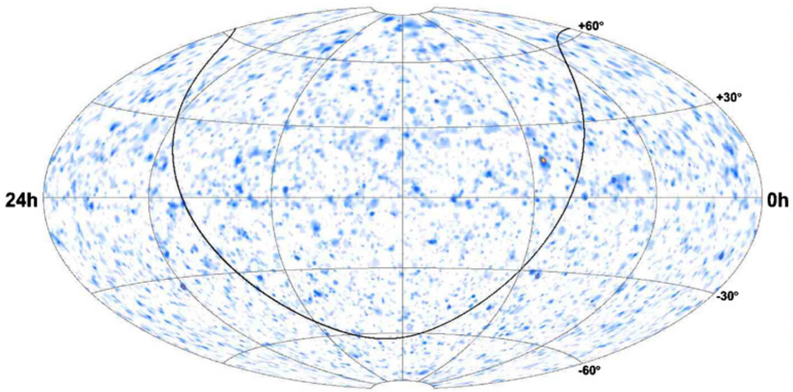
- 320 surface (“IceTop”) optical module to identify air showers

- data taken with 22 (IC-22), 40 (IC-40), and 79 (IC-79) strings



IceCube sky survey

arXiv: 2111.07586



No significant clustering

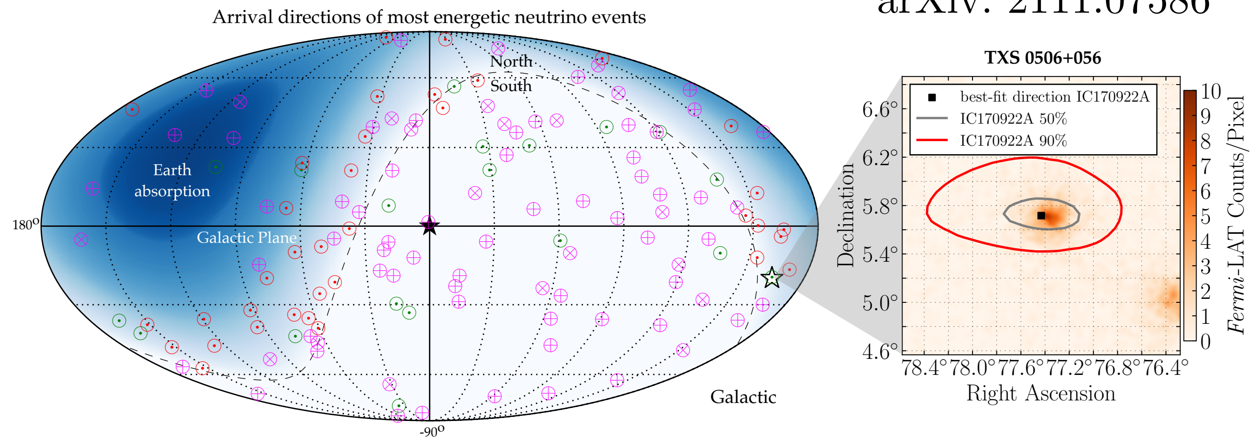


Figure 14: The current sky map of highly energetic neutrino events detected by IceCube. Shown are upgoing track events [130,187], the high-energy starting events (HESE) and cascades [161,188,189], and additional track events published as public alerts [190]. The distribution of the events is largely isotropic. The location of the first compelling neutrino source, blazar TXS 0506+056, is marked with a star. Shown in the inset are the related *Fermi Large Area Telescope* (LAT) measurements of the region centred on TXS 0506+056 from September 2017 [148]. The uncertainty ellipses of the IceCube neutrino event IC-170922A are shown for reference.

- Analysis of extra-terrestrial neutrinos
  - reject atmospheric neutrinos and search for point sources
- A few candidate clusters to be associated with known sources
  - but no statistically significant cluster
  - a transient source has been observed (in conjunction with γ-ray flare from a Blazar) [Science 361 (2018) 147]

IceCube search for GZK neutrinos