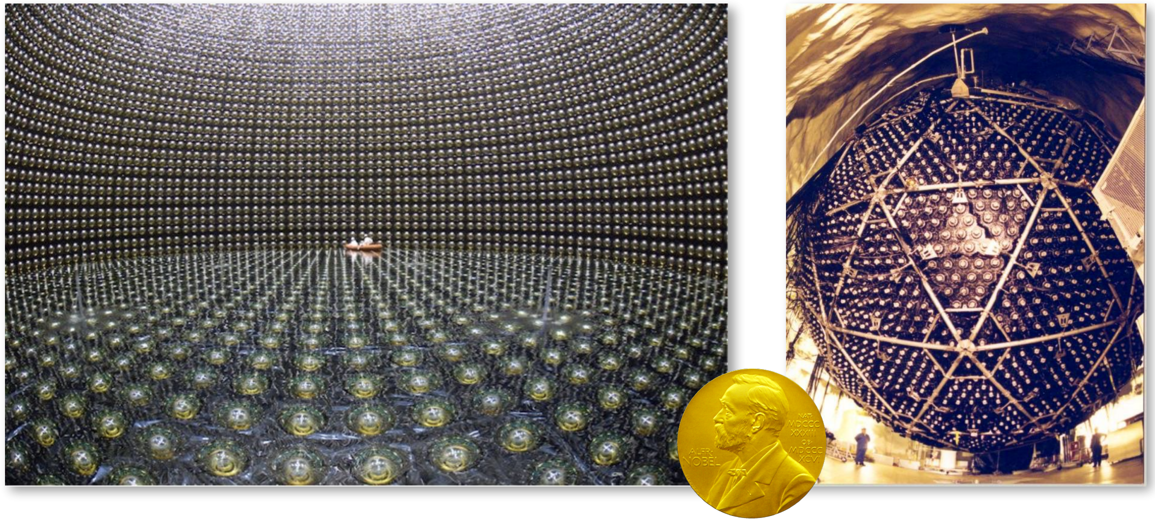
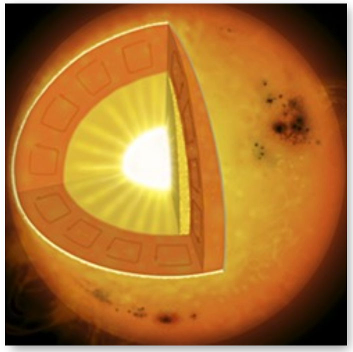
III. Neutrino flavour oscillations

Physics Nobel Prize 2002
to R. Davis Jr., M. Koshiba
“detection of cosmic [solar] neutrinos”

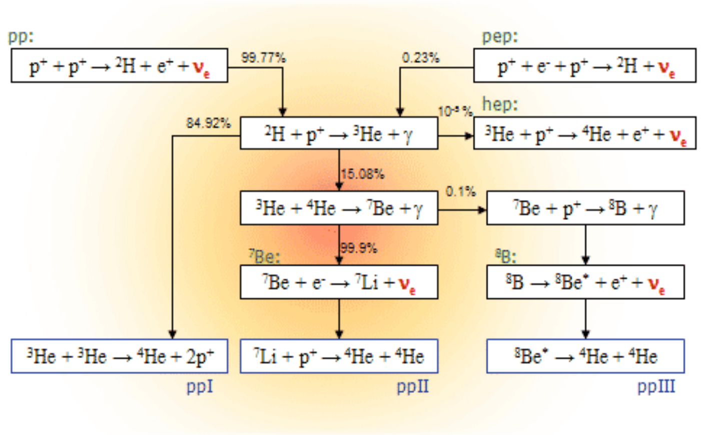


Physics Nobel Prize 2015
to A. B. McDonald and T. Kajita
“discovery of neutrino oscillations
which show that neutrinos have a mass”

Neutrinos from the sun



- Nuclear fusion in the solar core (T ≈ 14.5 × 10^6 K)
- Only electron neutrinos are created
- Integral flux ≈ 66 billion ν /cm^2 / s on Earth



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

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

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

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

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

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

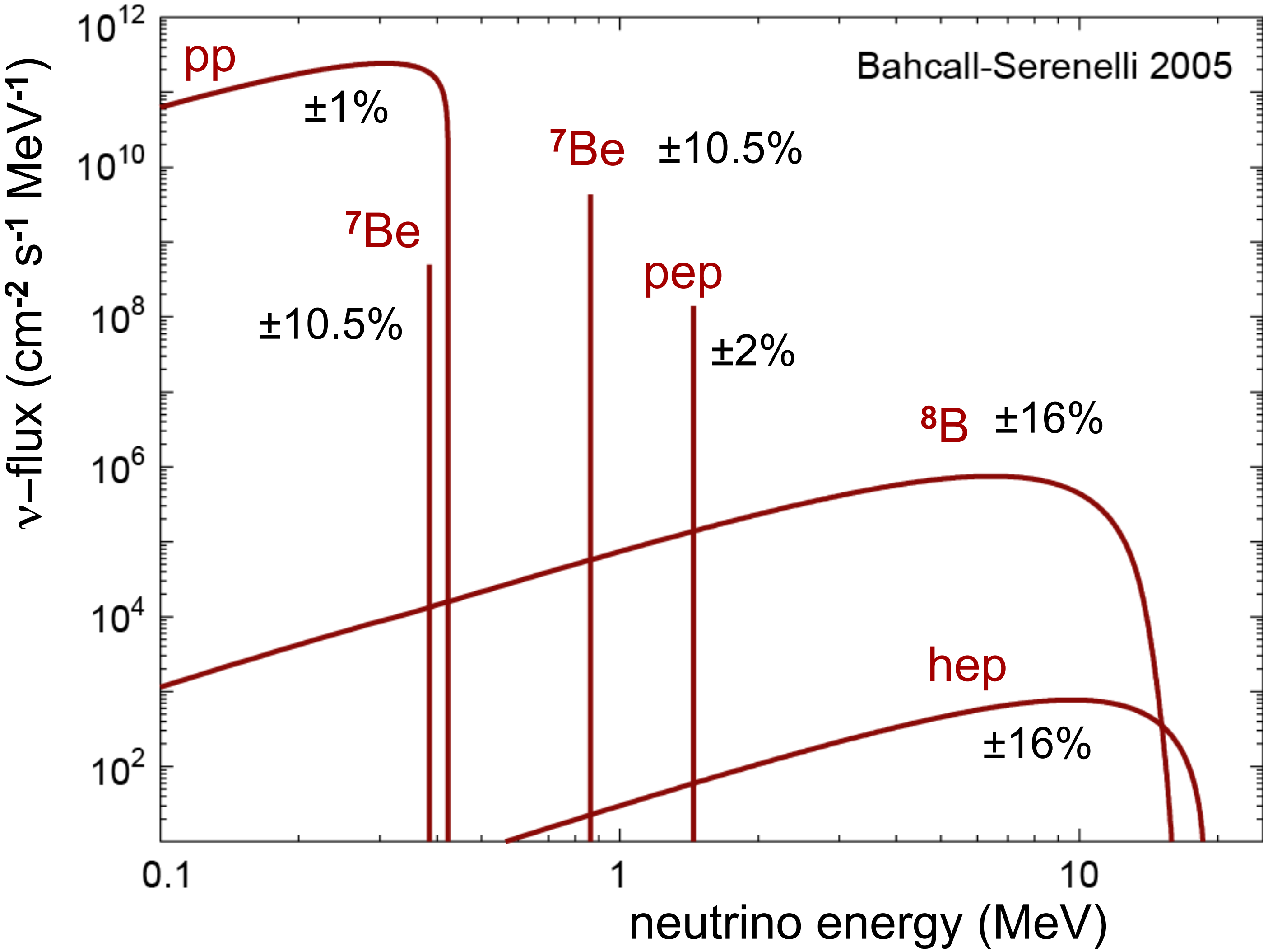
^{7}Be: $^7Be + e^- \rightarrow {}^7Li + \nu_e$

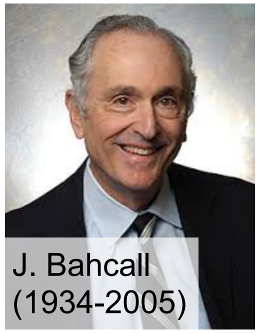
^{8}B: $^8B \rightarrow {}^8Be^* + e^+ + \nu_e$

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

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

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





J. Bahcall
(1934-2005)

Since 1960s:

“Standard Solar Model” with detailed ν flux calculations

Experimental test of the solar model

low-threshold reaction

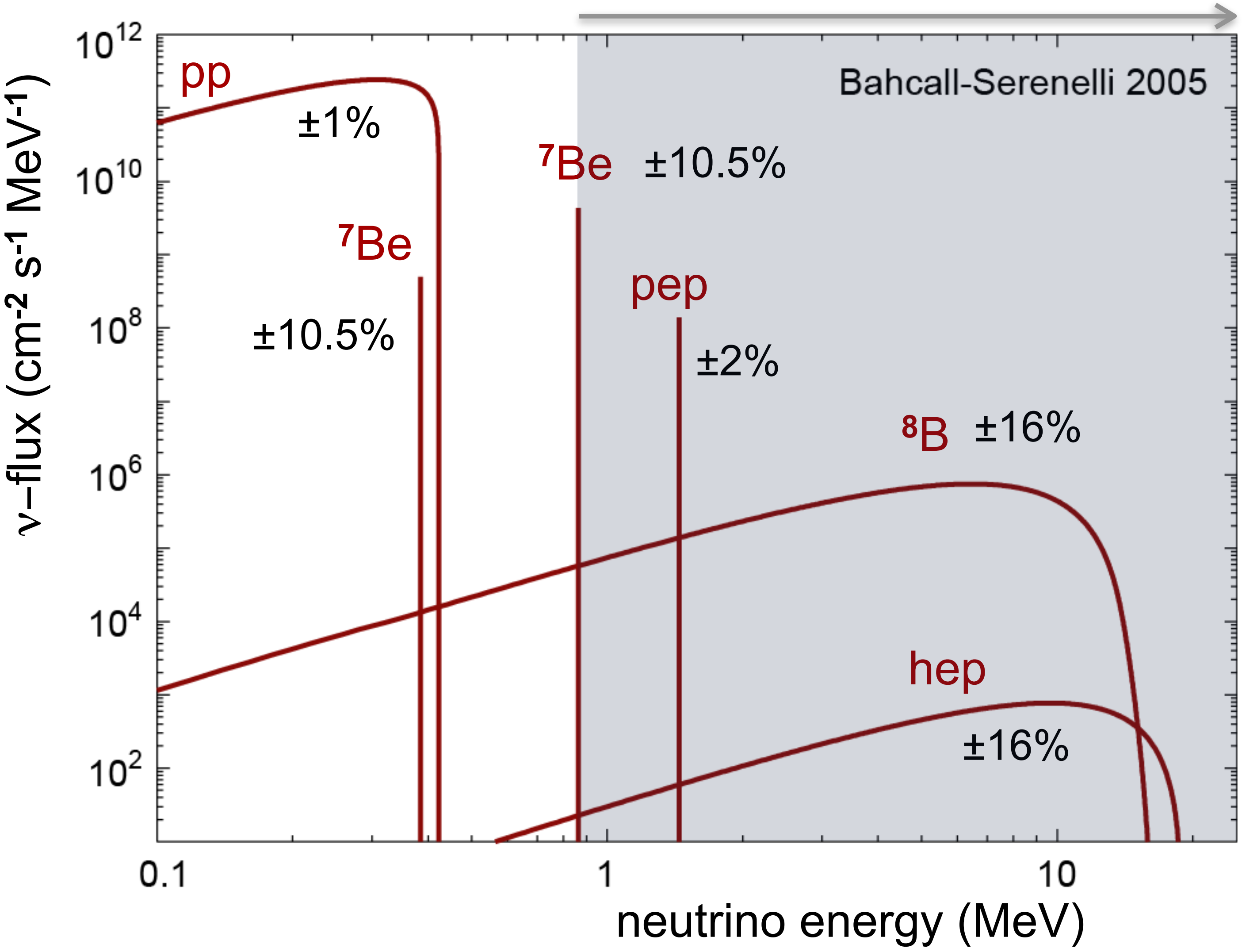
$$\nu_e + {}^{37}\mathrm{Cl} \rightarrow {}^{37}\mathrm{Ar} + e^-$$

“radiochemical method”: extract noble gas argon and detect its decay ($T_{1/2}$ = 35 d)

Ray Davis and John Bahcall at the Homestake mine, ca. 1964

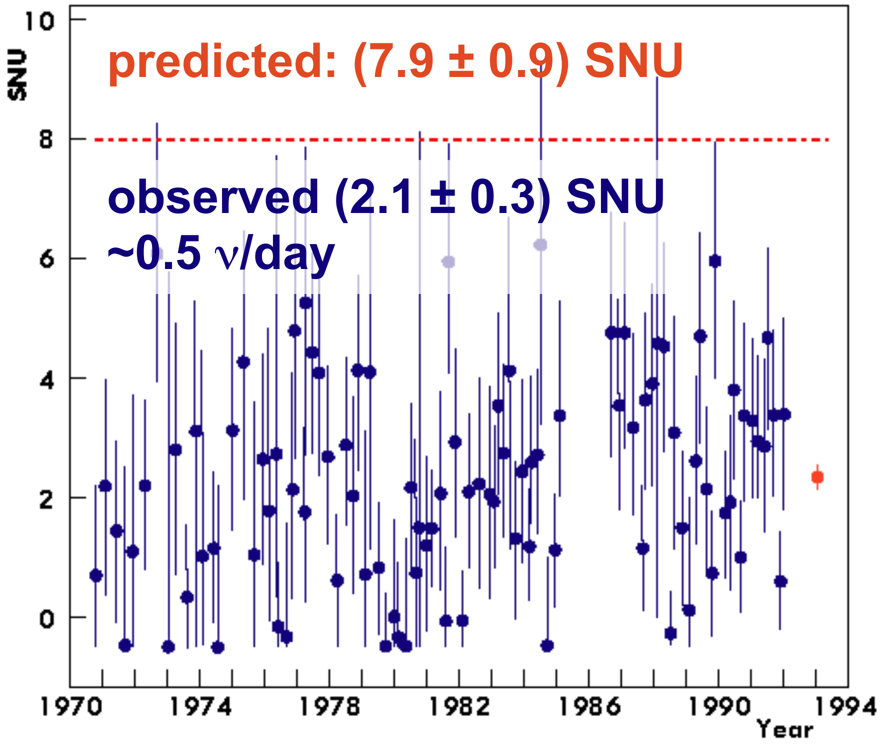
615 tons of perchloroethylene buried in a gold mine

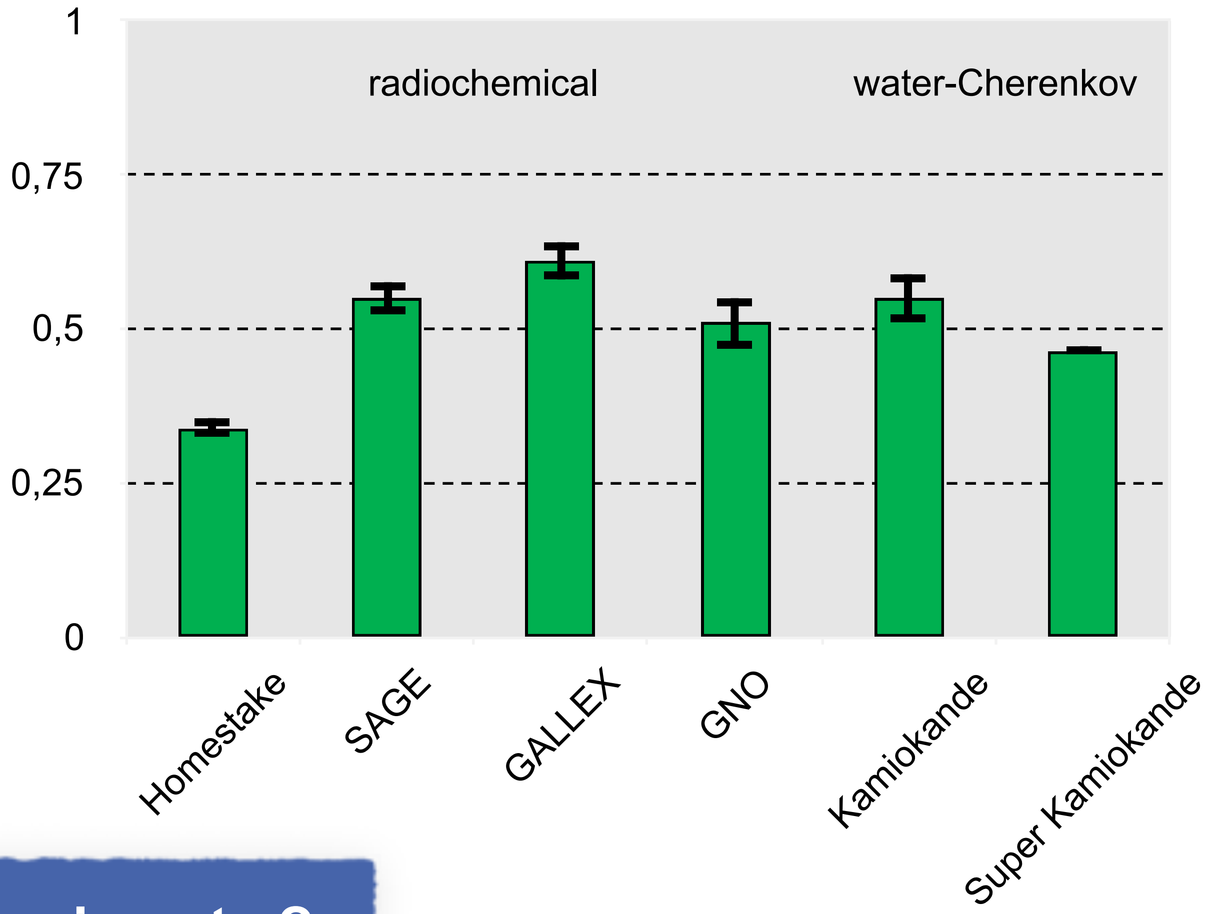
1 neutrino every 2 days



The solar neutrino puzzle

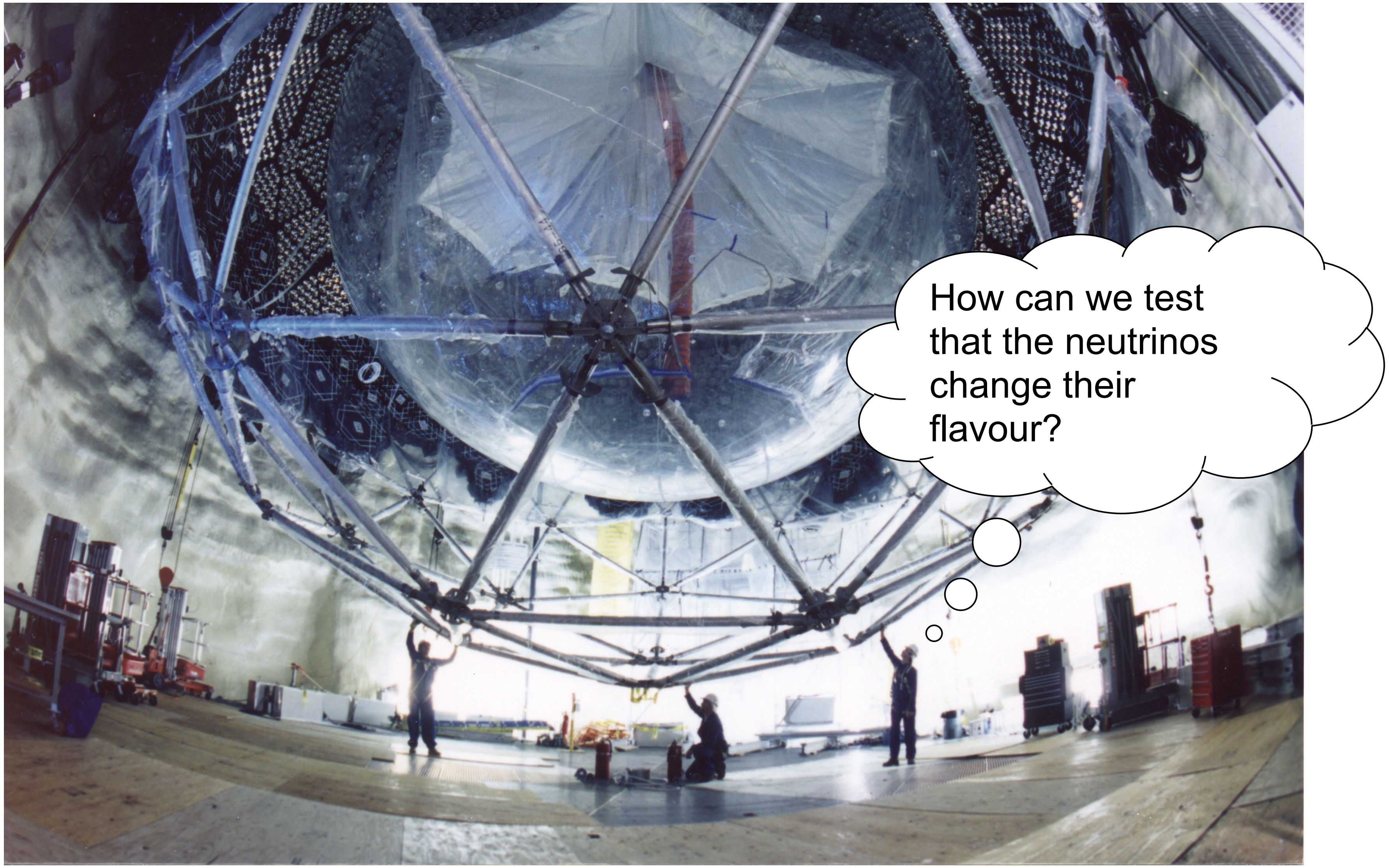
Too few neutrinos detected, consistently!





- Something wrong with all the **experiments ?**
- Something wrong with the **solar model ?**
- Something going on with the **neutrinos ??**

SNO provides the answer to the problem

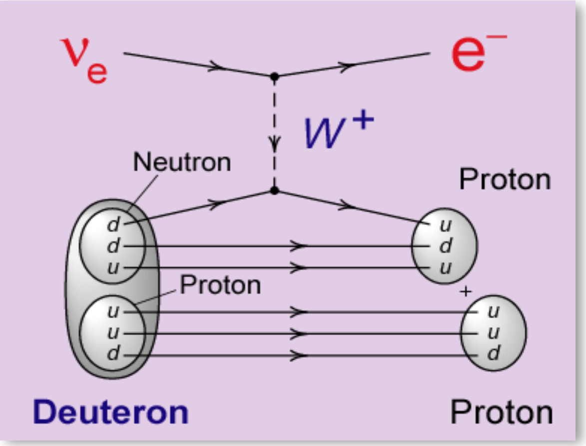


How can we test that the neutrinos change their flavour?

The **Sudbury Neutrino Observatory**, Creighton mine, Ontario/Canada (2100 m deep)
1000 tons of heavy water (D_2O) viewed by 9600 PMTs

The SNO idea

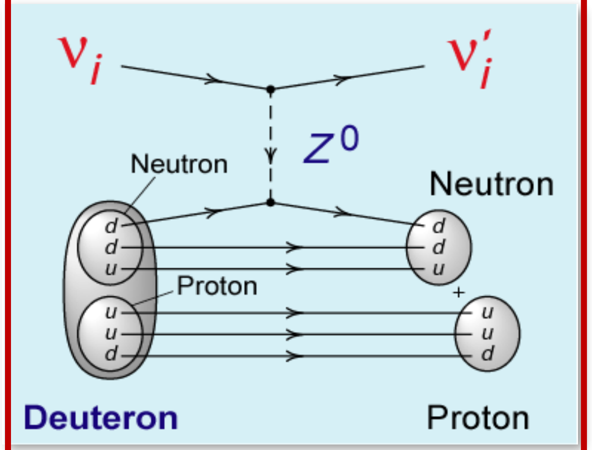
Charged current (CC)



Only ν_e

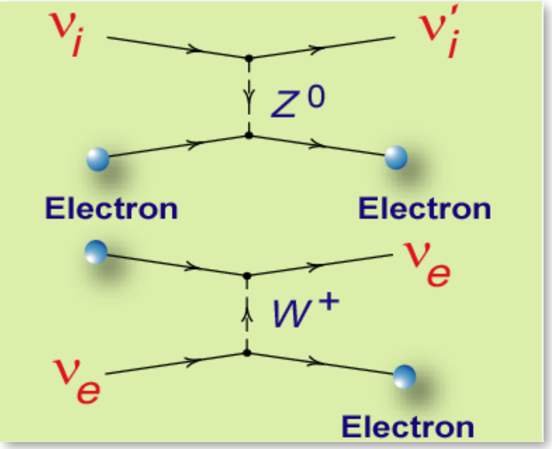
Why is this process not observed with μ^- and τ^- ?

Neutral current (NC)



All flavours

Elastic scattering (ES)

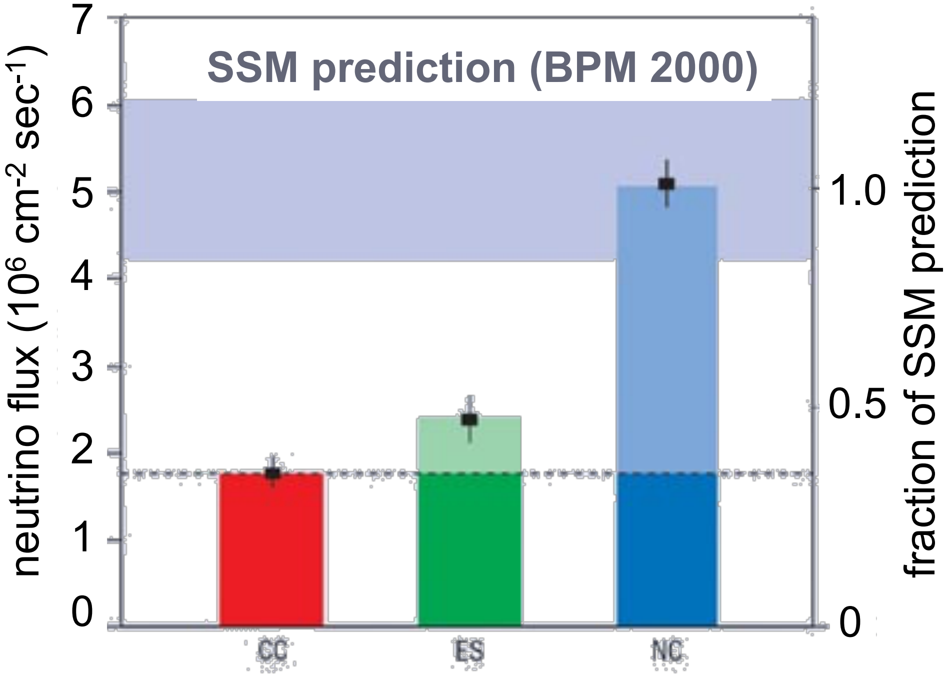


Mostly ν_e

- Scattering via neutral Z-Boson is flavour independent
- This reaction channel measures the entire neutrino flux
- NC detection enhanced by adding ~2 tons of salt (NaCl) to the heavy water (neutron capture on Cl nucleus, emitted gamma leads to detected signal)

SNO results

- Results published in 2001 confirm flavour transformation hypothesis
- Neutral current reaction channel measures full neutrino flux expected in the Standard Solar Model
- Solar neutrino problem finally solved after 30 years!
  (Both Davis' experiment and Bahcall's calculations were right, after all …)



Now that we’re sure we see flavour oscillations: How can we explain them?

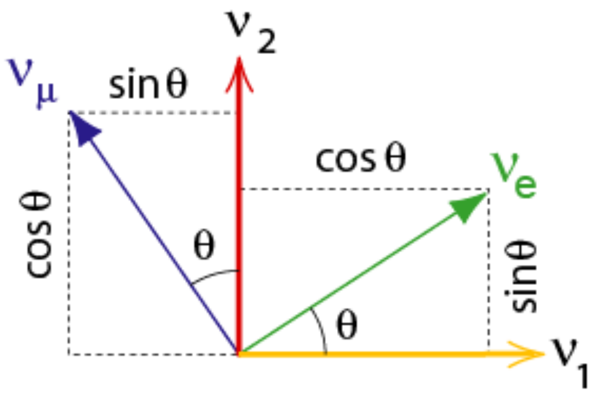
Neutrino oscillations

ν-oscillations are a **quantum mechanical interference phenomenon**

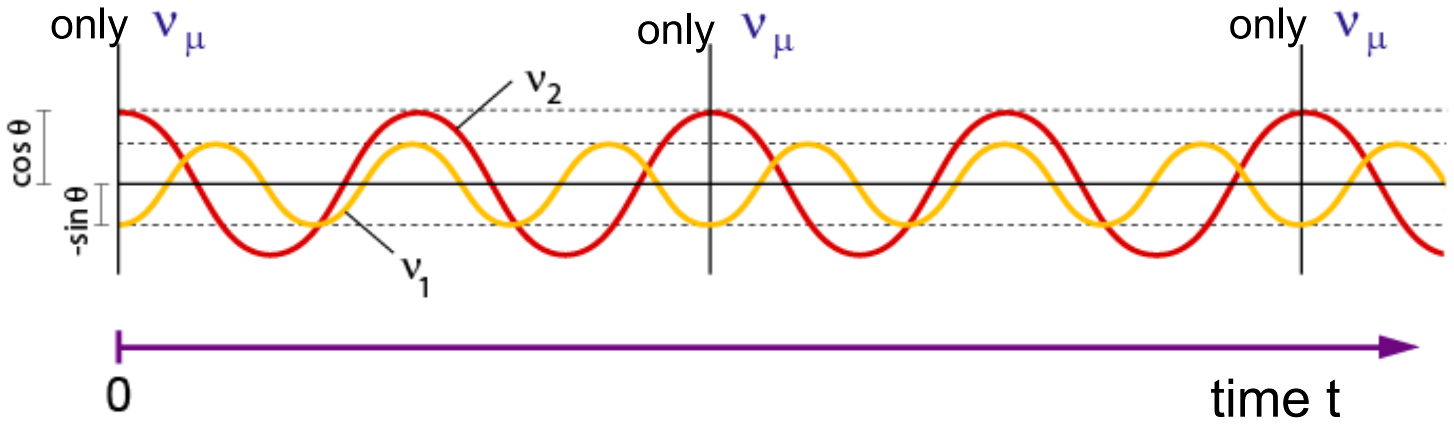
2-flavour mixing:

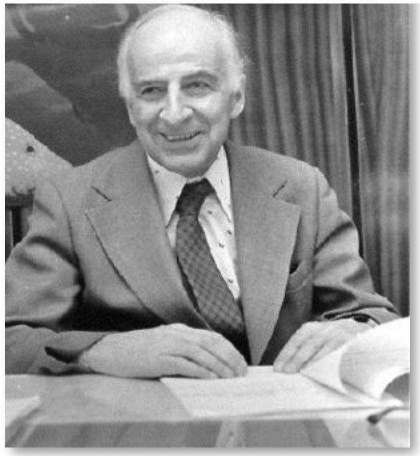
close analogy to
CKM mixing of the
left-handed quarks

mass eigenstates ≠ flavour eigenstates



$$\begin{pmatrix}\nu_e\\ \nu_\mu\end{pmatrix} = \begin{pmatrix}\cos\theta & \sin\theta\\ -\sin\theta & \cos\theta\end{pmatrix}\begin{pmatrix}\nu_1\\ \nu_2\end{pmatrix}$$





Bruno Pontecorvo:
concept of $\nu-\bar{\nu}$ oscillations

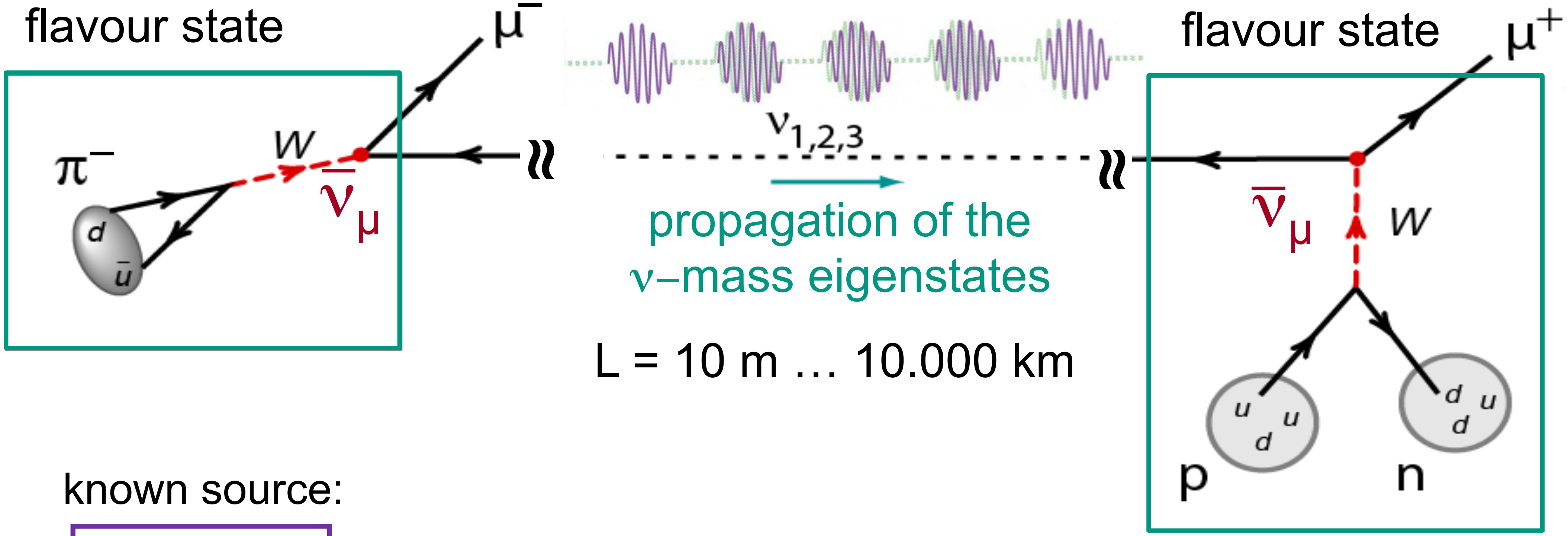
Neutrino oscillations

ν-oscillations result from different **propagation of mass eigenstates**

ν source

ν oscillations

ν detection



flavour state

propagation of the ν–mass eigenstates

L = 10 m … 10.000 km

flavour state

known source:

ν energies
ν fluxes
ν species

detection efficiency
energy resolution

Neutrino oscillations – formalism

Probability P for the **oscillation of a ν_μ into a ν_e** after time t:

$$\boxed{P(\nu_\mu \rightarrow \nu_e) = |\cos\theta \cdot \sin\theta \cdot (1 - e^{i\Delta m^2 t/2E_\nu})|^2}$$

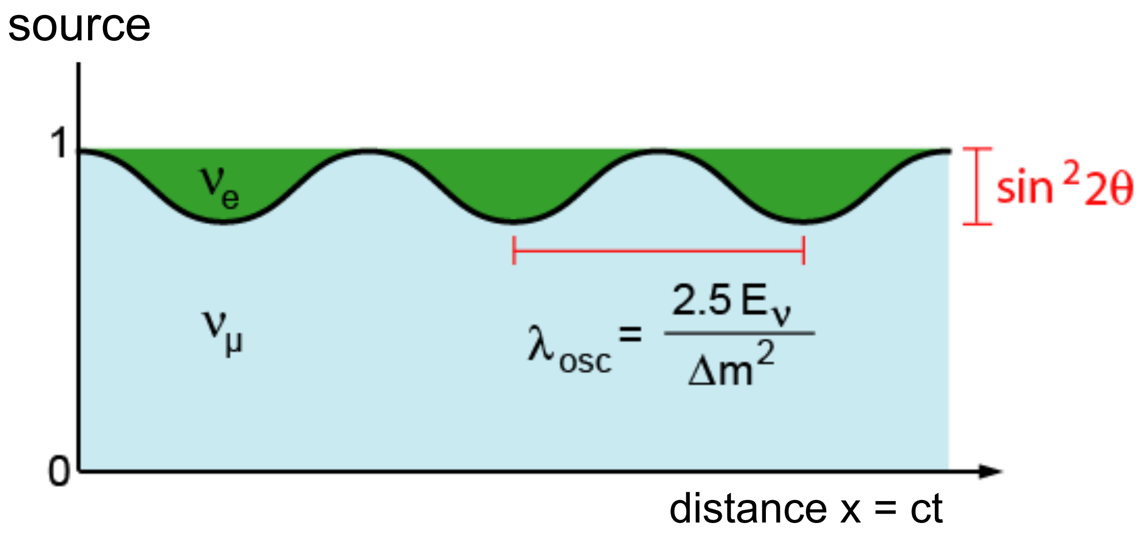
with $P = |\langle\nu_e|\nu_\mu(t)\rangle|^2$

$$\boxed{= \sin^2 2\theta \cdot \sin^2(\Delta m^2 L_\nu / 4E_\nu)}$$

with $\Delta m^2 = |m_1^2 - m_2^2|$

amplitude **frequency**

Oscillations only occur if at least one neutrino has a mass!



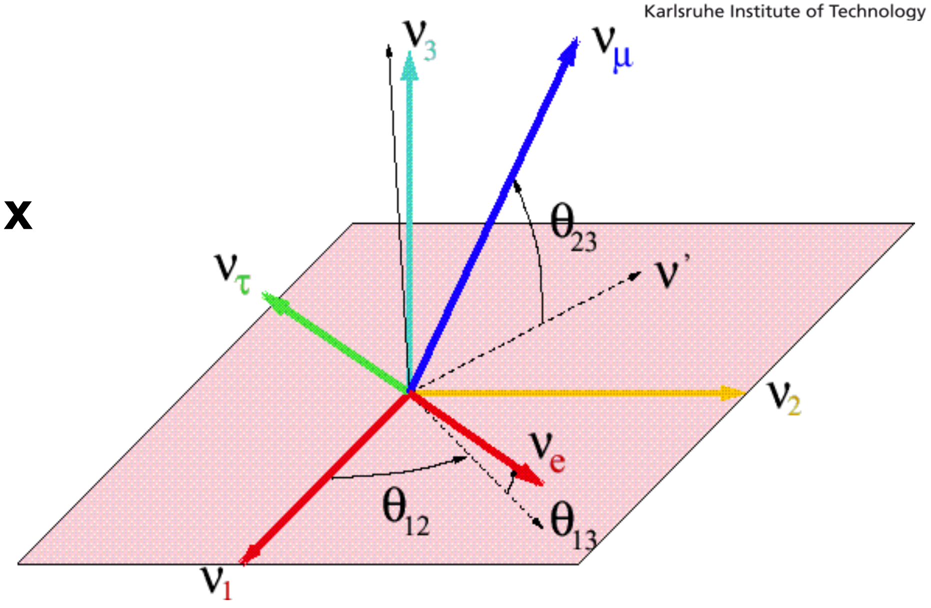
- Periodic decrease/increase of **primary** neutrino flavour state
- Oscillation length $\lambda_{osc} \sim 2.5\ E_\nu / \Delta m^2$
- Choose L and E such that you're sensitive to a given θ and Δm^2 and measure P(L/E)

The full three-flavour picture

3 x 3 unitary mixing matrix analogous to CKM:

"Pontecorvo Maki Nakagawa Sakata"

(PMNS)



- 3 mixing angles: θ_{12}, θ_{23}, θ_{13},
- 1 CP-violating phase: δ
- two independent Δm^2 scales:

$$\boxed{\Delta m_{13}^2 = \Delta m_{12}^2 + \Delta m_{23}^2}$$

$$\boxed{U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_{23} & \sin\theta_{23} \\ 0 & -\sin\theta_{23} & \cos\theta_{23} \end{pmatrix} \cdot \begin{pmatrix} \cos\theta_{13} & 0 & \sin\theta_{13} e^{-i\delta} \\ 0 & 1 & 0 \\ -\sin\theta_{13} e^{-i\delta} & 0 & \cos\theta_{13} \end{pmatrix} \cdot \begin{pmatrix} \cos\theta_{12} & \sin\theta_{12} & 0 \\ -\sin\theta_{12} & \cos\theta_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}}$$

δ: CP-Phase

Three-flavour neutrino mixing — present experimental values

$$U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_{23} & \sin\theta_{23} \\ 0 & -\sin\theta_{23} & \cos\theta_{23} \end{pmatrix} \cdot \begin{pmatrix} \cos\theta_{13} & 0 & \sin\theta_{13} e^{-i\delta} \\ 0 & 1 & 0 \\ -\sin\theta_{13} e^{-i\delta} & 0 & \cos\theta_{13} \end{pmatrix} \cdot \begin{pmatrix} \cos\theta_{12} & \sin\theta_{12} & 0 \\ -\sin\theta_{12} & \cos\theta_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

2. & 3. generation	1. & 3. generation	1. & 2. generation
$\Delta m_{23}^2 = 2.5 \times 10^{-3}$ eV^2	$\Delta m_{13}^2 = 2.5 \times 10^{-3}$ eV^2	$\Delta m_{12}^2 = 7.6 \times 10^{-5}$ eV^2
± 6%	± 6%	± 7%
$\theta_{23} \approx 45°$ (maximal?)	$\theta_{13} \approx 8.5°$ (small)	$\theta_{23} \approx 34°$ (large)
± 16%	± 5%	± 7%

3σ uncertainty,
including ordering

3σ uncertainty,
including ordering

➜ Structure of leptonic mixing matrix very different from CKM matrix:

$$U_{\text{PMNS}} = \begin{pmatrix} 0.800 \to 0.844 & 0.515 \to 0.581 & 0.139 \to 0.155 \\ 0.229 \to 0.516 & 0.438 \to 0.699 & 0.614 \to 0.790 \\ 0.249 \to 0.528 & 0.462 \to 0.715 & 0.595 \to 0.776 \end{pmatrix}$$

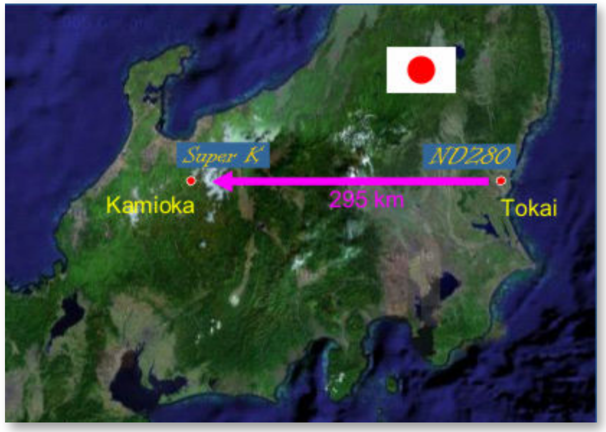
NuFIT 3.0 [Esteban et al., JHEP 01 (2017) 087]

How do we know all this?

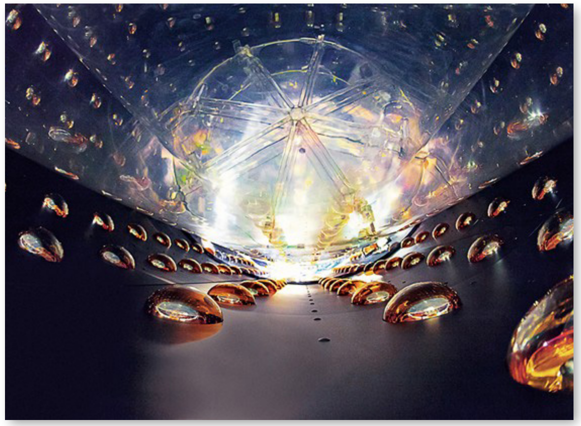
➜ collected “world data” from many different experiments

2. & 3. generation	1. & 3. generation	1. & 2. generation
$\Delta m_{23}^2 = 2.5 \times 10^{-3}$ eV^2	$\Delta m_{13}^2 = 2.5 \times 10^{-3}$ eV^2	$\Delta m_{12}^2 = 7.6 \times 10^{-5}$ eV^2
$\theta_{23} \approx 45°$ *(maximal?)*	$\theta_{13} \approx 8.5°$ *(small)*	$\theta_{23} \approx 34°$ *(large)*

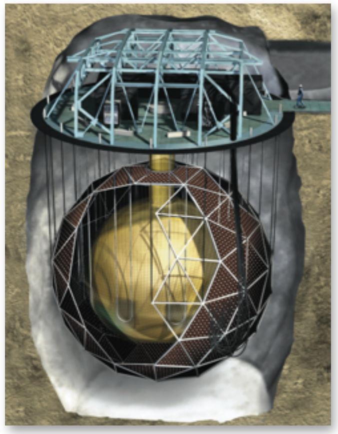
atmospheric & long-baseline accelerator exp.	reactor & long-baseline accelerator exp.	solar & reactor exp.
GeV, ν_μ ($\bar{\nu}_\mu$)	MeV, $\bar{\nu}_e$ GeV, ν_μ ($\bar{\nu}_\mu$)	MeV, ν_e ($\bar{\nu}_e$)



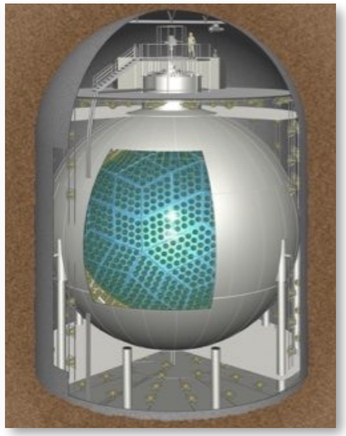
T2K (Tokai-Kamioka)



Daya Bay



SNO



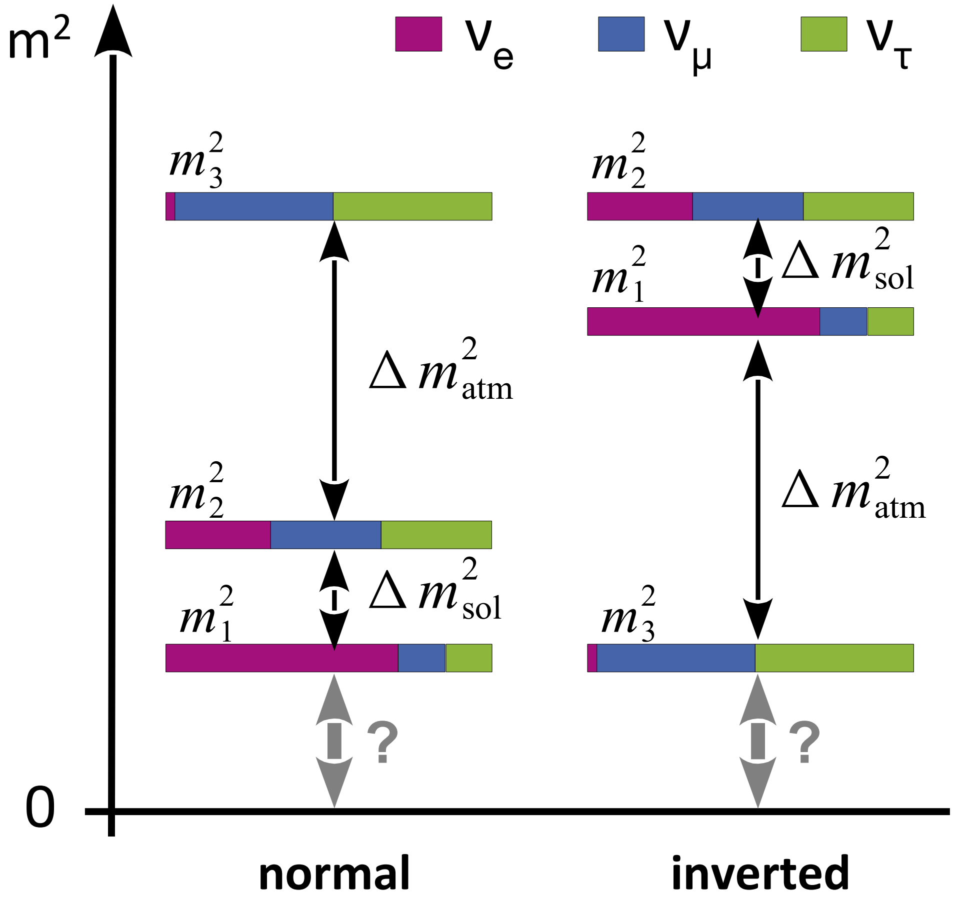
KamLAND

The big picture:
What have we learned from oscillation data?

New!
BSM physics!

- Large neutrino mixing and tiny neutrino masses $m(\nu_i) \neq 0$ established
- Evidence for non-zero θ_{13}
- Hints for non-maximal $\theta_{23} \neq \pi/4$
- Expectation of CP-violating phase δ

- Absolute mass scale cannot be determined from oscillations
- Expect m_ν > 10 meV for normal ordering, m_ν > 50 meV for inverted
- Majorana vs Dirac nature of neutrinos?



IV. How can we measure neutrino masses?

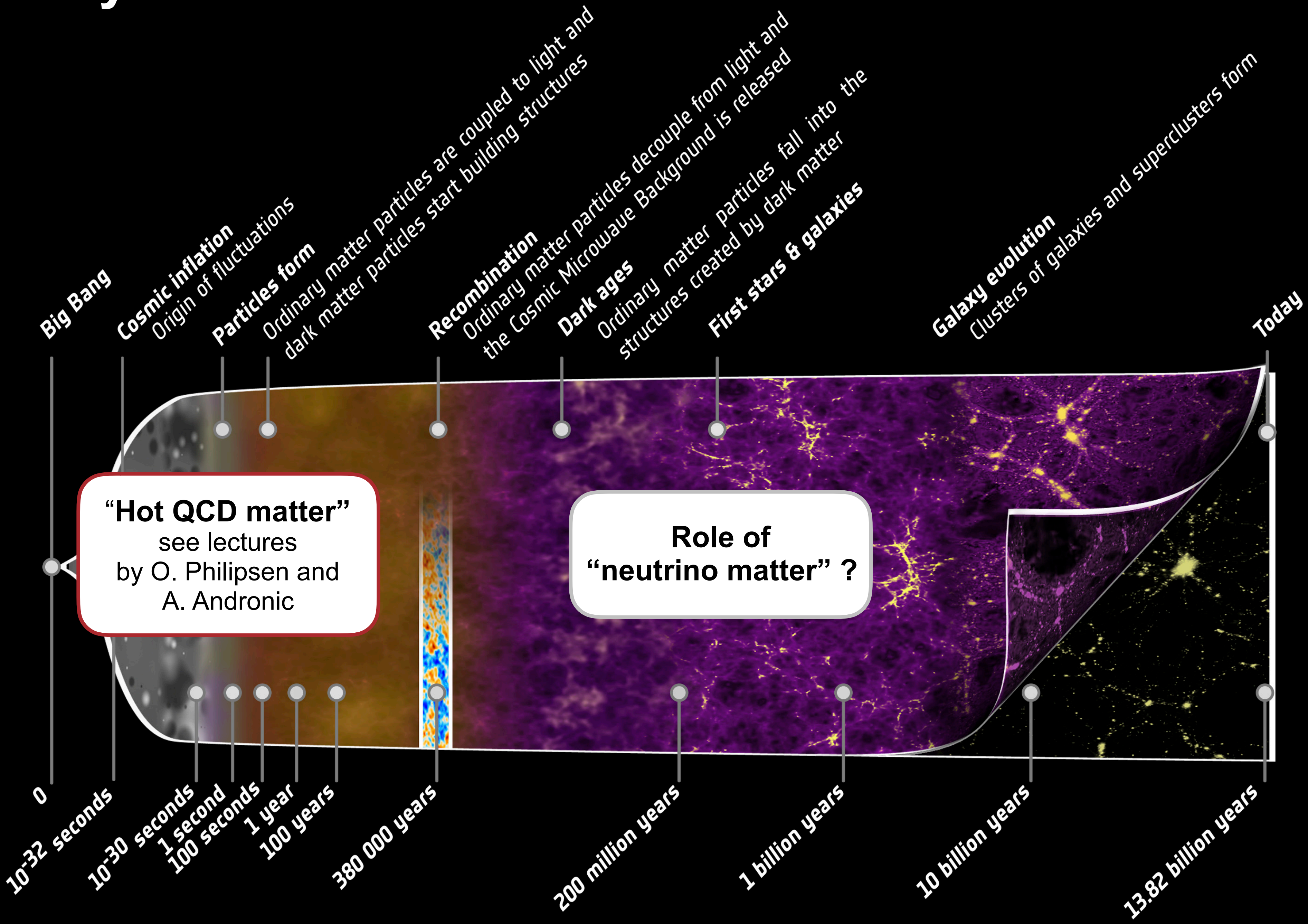
Indirect (model-dependent) probes:

- Observational cosmology
- Search for 0νββ

Direct (model-independent) probes:

- Kinematics of weak decays (^{3}H β-decay, ^{163}Ho EC)

History of the Universe

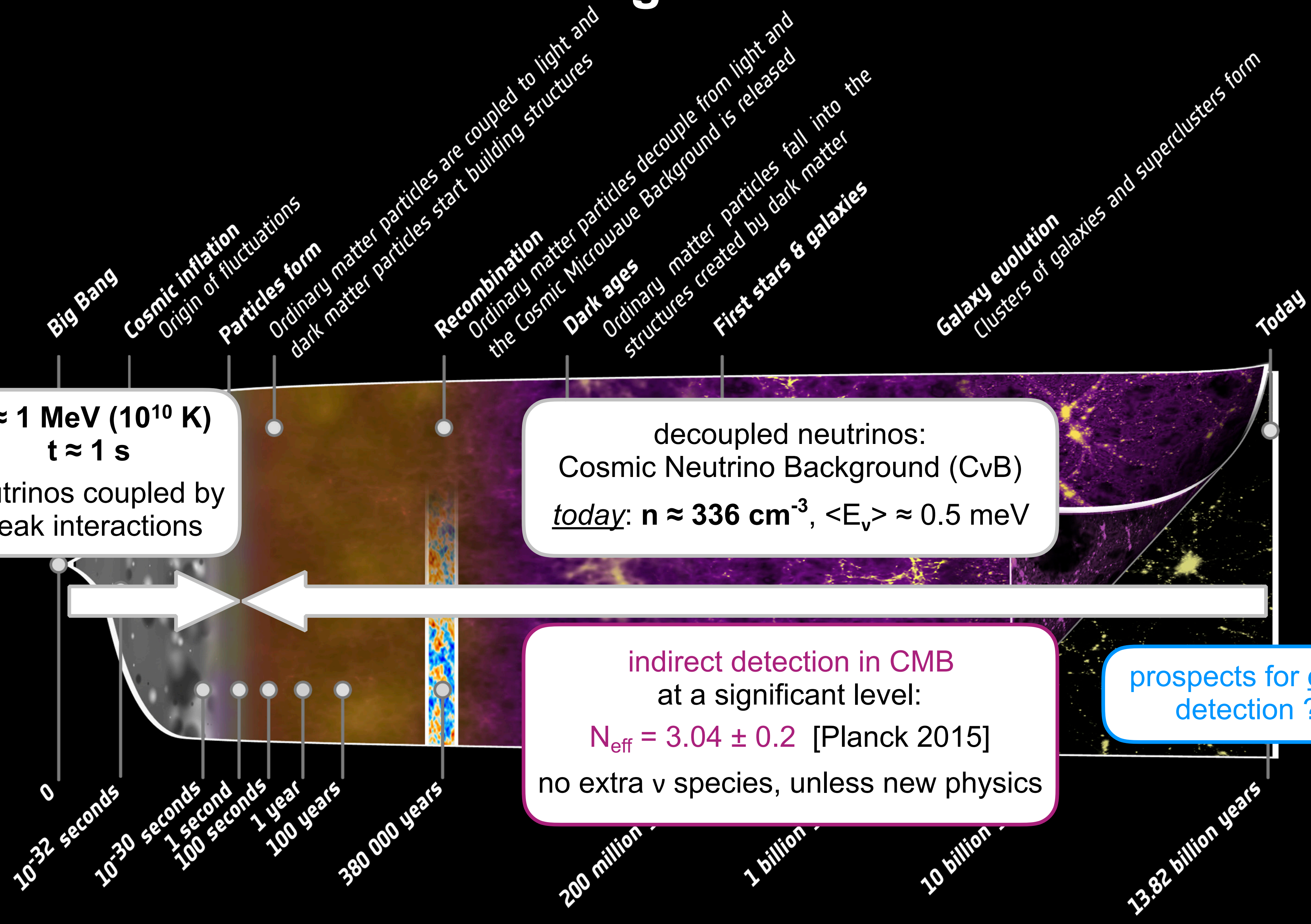


“Hot QCD matter”
see lectures
by O. Philipsen and
A. Andronic

Role of
“neutrino matter” ?

[ESA, Planck]

The Cosmic Neutrino Background



$T \approx 1$ MeV (10^{10} K)
$t \approx 1$ s

neutrinos coupled by weak interactions

decoupled neutrinos:
Cosmic Neutrino Background (CνB)

today: **$n \approx 336\ \mathrm{cm}^{-3}$**, $\langle E_\nu \rangle \approx 0.5$ meV

indirect detection in CMB
at a significant level:

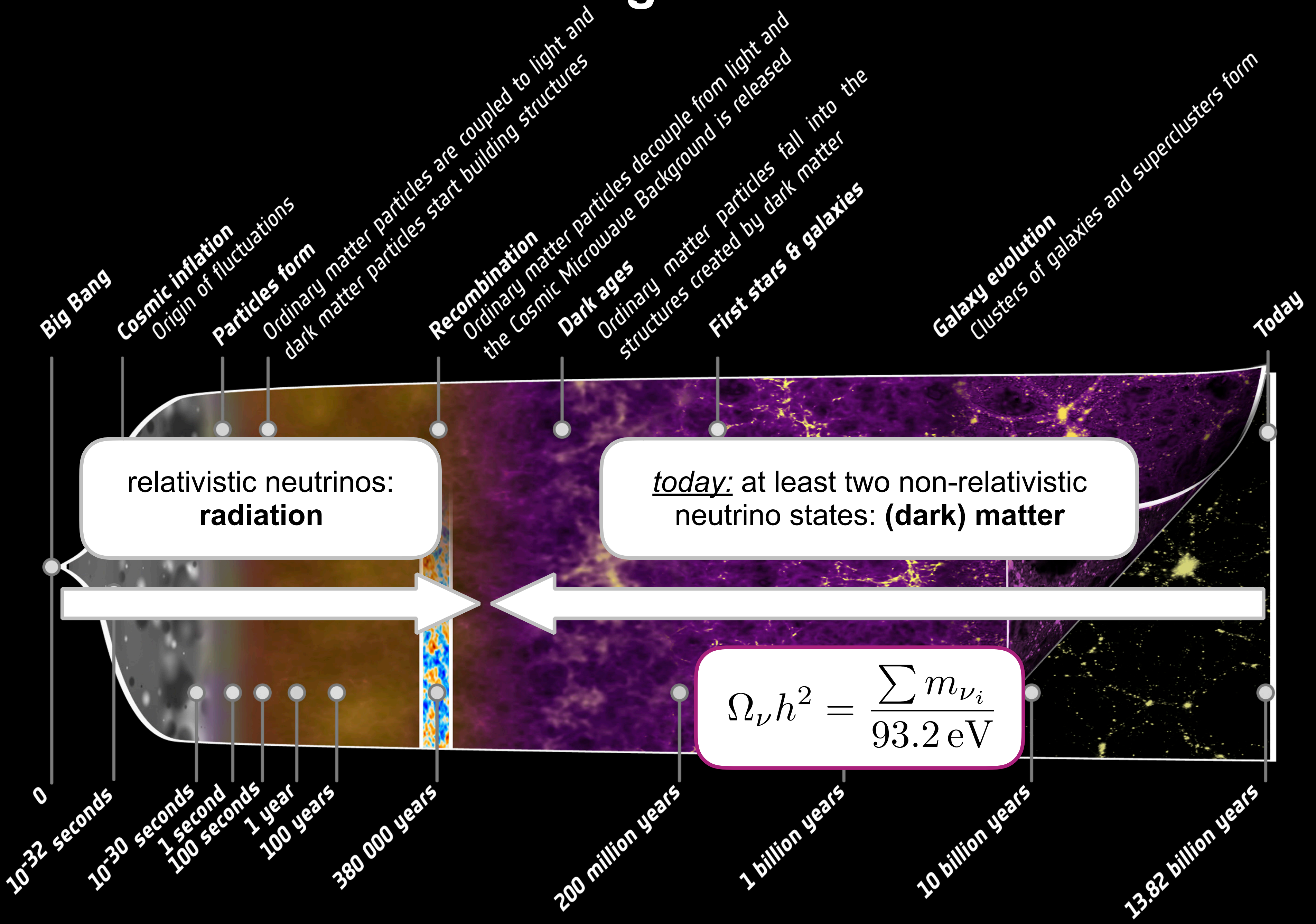
$N_{\mathrm{eff}} = 3.04 \pm 0.2$ [Planck 2015]

no extra ν species, unless new physics

prospects for direct detection ??

[ESA, Planck]

The Cosmic Neutrino Background



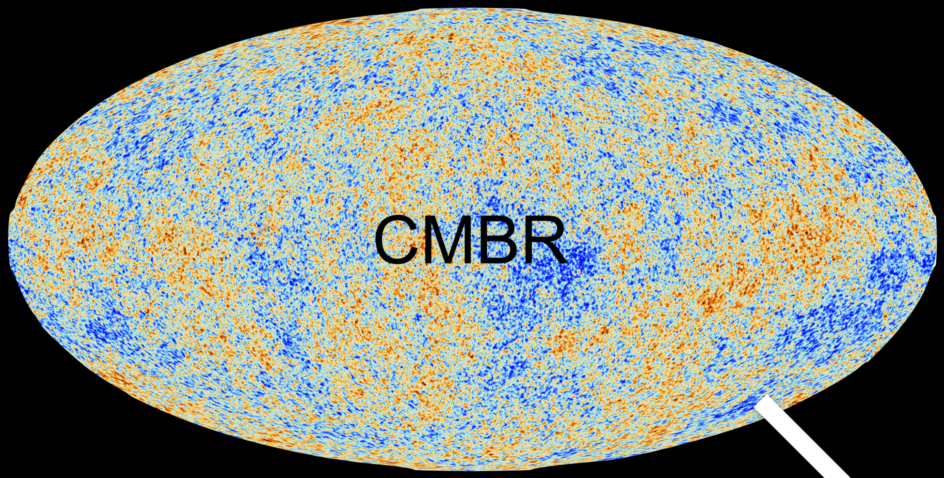
relativistic neutrinos:
radiation

today: at least two non-relativistic neutrino states: **(dark) matter**

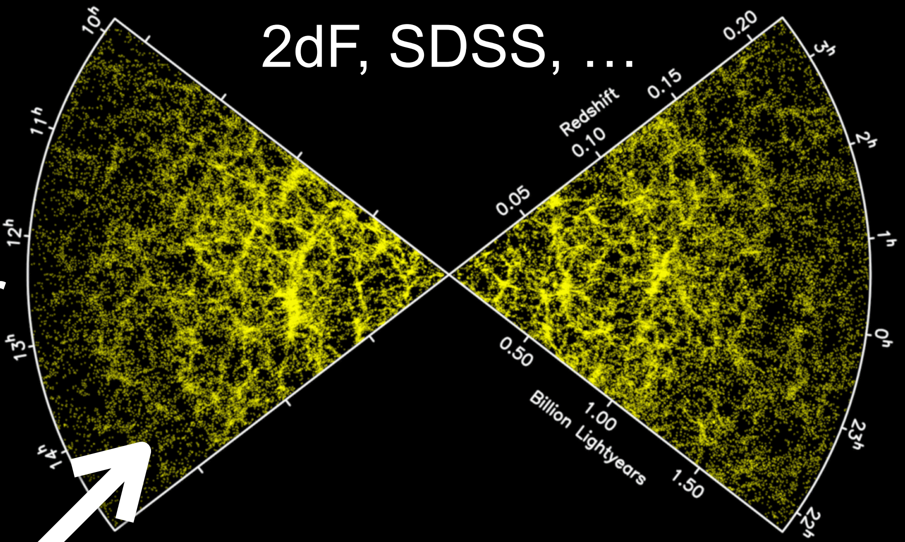
$$\Omega_\nu h^2 = \frac{\sum m_{\nu_i}}{93.2\,\mathrm{eV}}$$

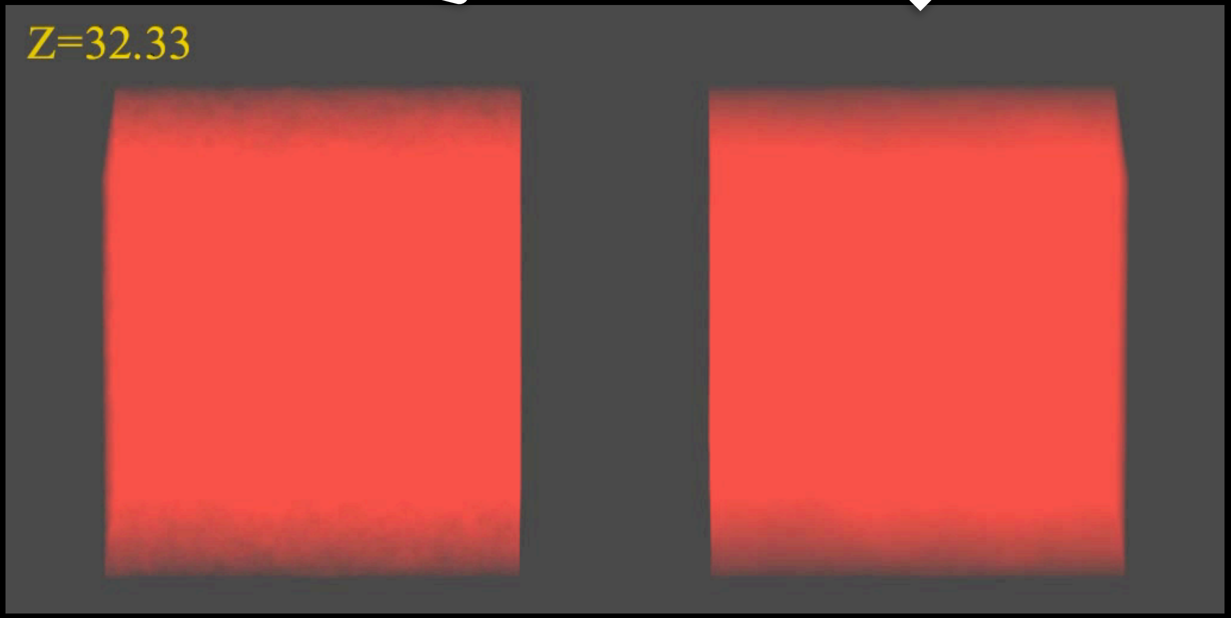
[ESA, Planck]

Neutrino mass: adding information



cold dark matter
+
relic neutrino density:
336 ν /cm^3





m_ν = **0 eV** **2 eV**

[T. Haugbølle, Univ. of Aarhus]

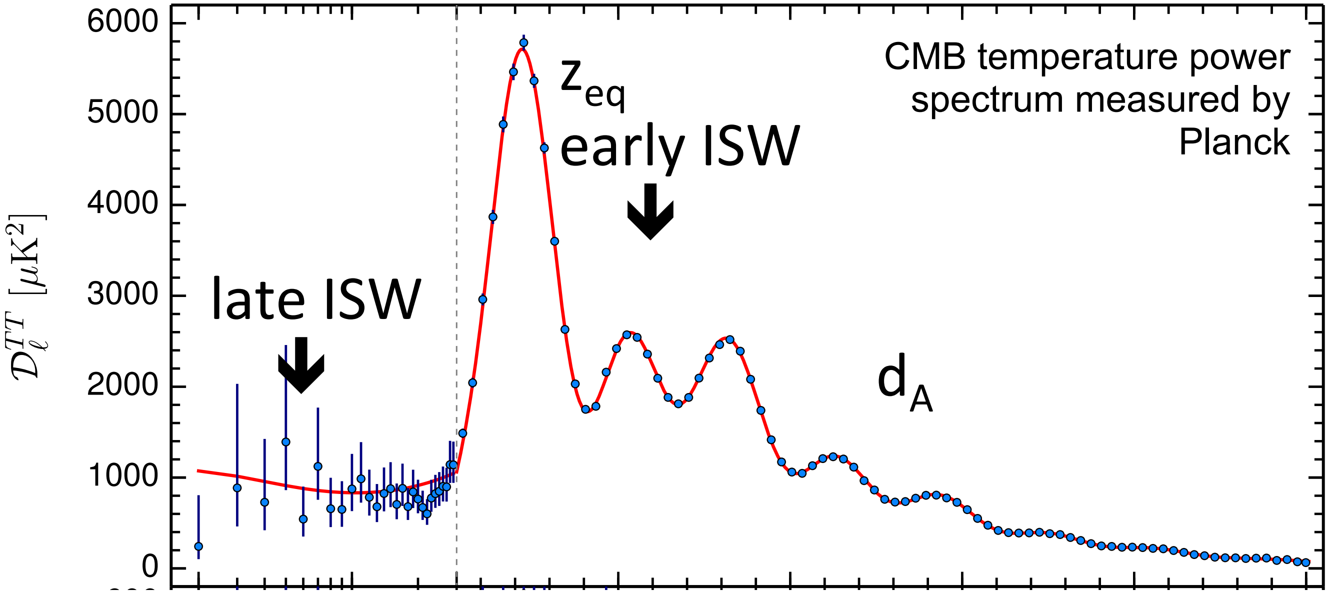
- Massive neutrinos wash out structure at small scales
- Status 2017:

$$\sum m_\nu \lesssim 0.13\,\mathrm{eV}$$

  using CMB + LSS + BAO
- Caveat: degeneracies

Neutrino mass from cosmology

- Current **observational cosmology** offers a wealth of precision data which can be combined to learn about neutrino masses
- Requires interpretation in the framework of the **Standard Model (ΛCDM)** of Cosmology
- CMB measurements only (pre-Planck):
  - probe neutrino mass mainly via Integrated Sachs-Wolfe effect (modified grav. potential seen by photons)
  - neutrinos contribute to radiation density at z_{eq} and to non-rel. matter density today



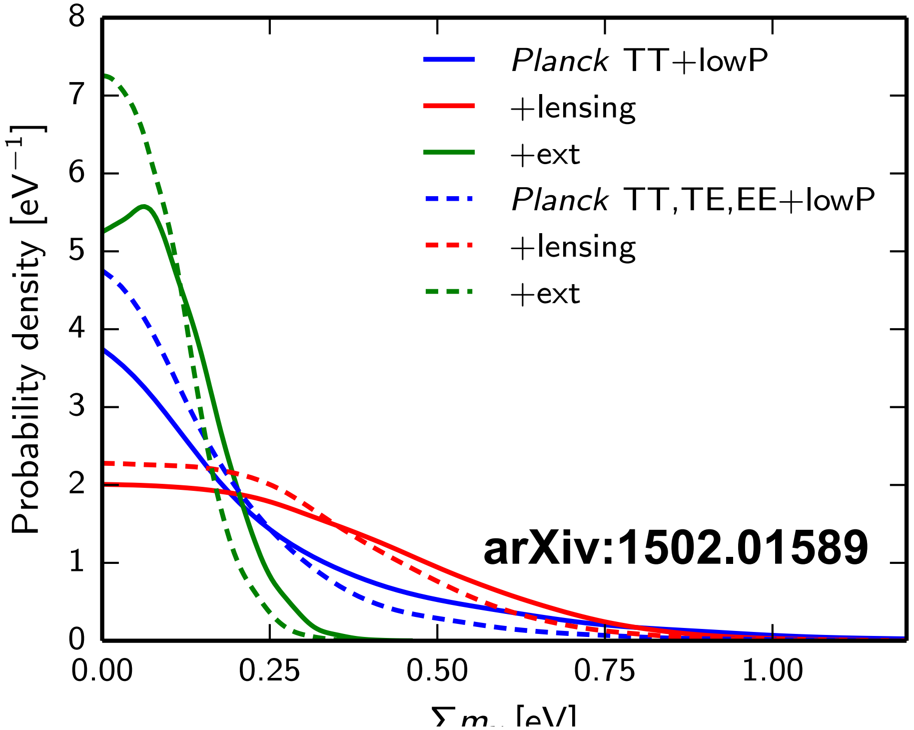
- Post-Planck:
  Weak lensing of CMB gives additional information on Σm_ν
- Status 2017:

$$\sum m_\nu \lesssim 0.6\,\mathrm{eV}$$

using only CMB temperature & polarization data

[from M. Archidiacono]

Neutrino mass from cosmology: other probes



arXiv:1502.01589

$$
\begin{aligned}
\sum m_\nu &< 0.72\ \mathrm{eV} \quad \textit{Planck}\ \mathrm{TT{+}lowP}\,;\\
\sum m_\nu &< 0.21\ \mathrm{eV} \quad \textit{Planck}\ \mathrm{TT{+}lowP{+}BAO}\,;\\
\sum m_\nu &< 0.49\ \mathrm{eV} \quad \textit{Planck}\ \mathrm{TT, TE, EE{+}lowP}\,;\\
\sum m_\nu &< 0.17\ \mathrm{eV} \quad \textit{Planck}\ \mathrm{TT, TE, EE{+}lowP{+}BAO}\,.
\end{aligned}
$$

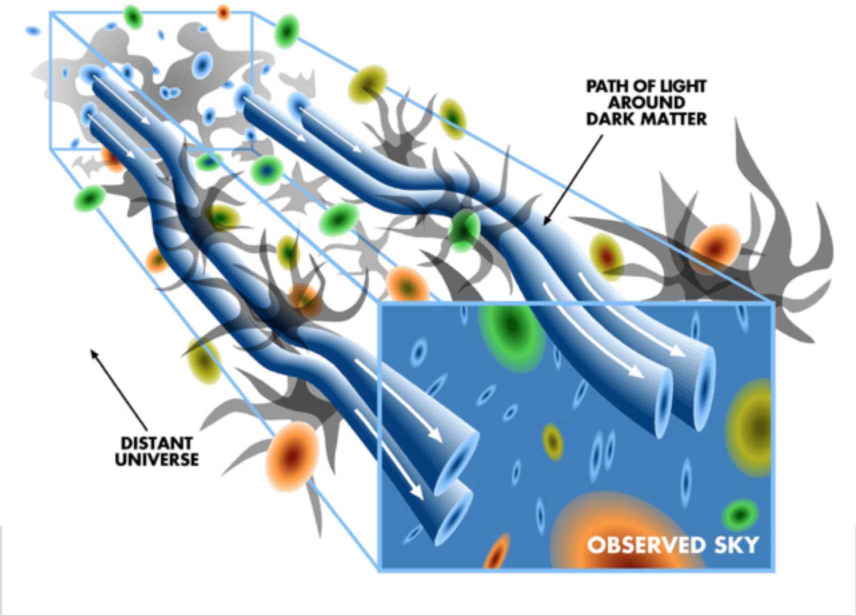
6 + 2 parameter ΛCDM model

reach:
20-50 meV

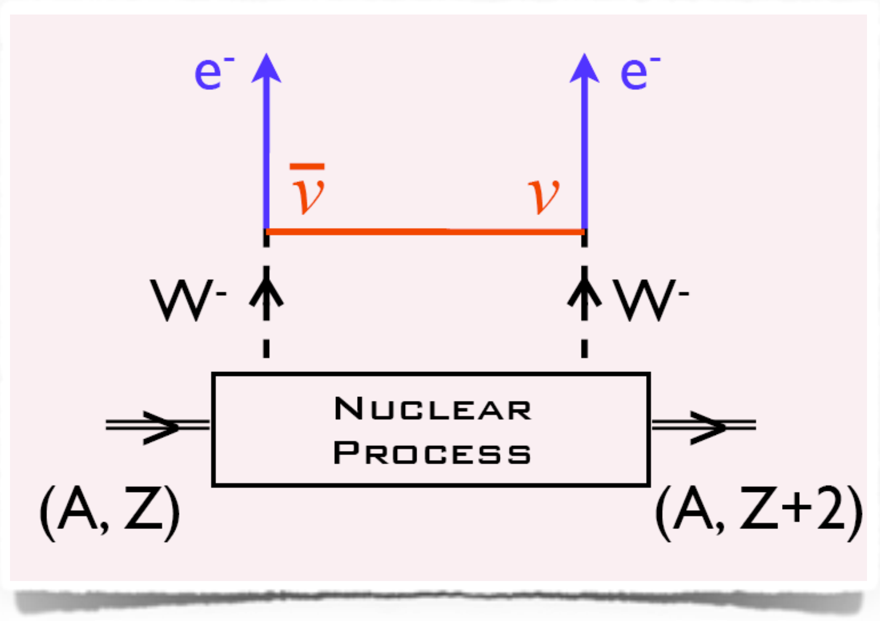
Future EUCLID mission (ESA):
grav. lensing & galactic power spectrum

*“… Euclid will very likely provide a **positive detection** of neutrino mass …,*
the exact nature of the neutrino mass spectrum remains out of its reach …”

[Hamann, Hannestad, & Wong, JCAP 11 (2012) 52]



Search for neutrinoless double beta decay



Are neutrinos Majorana fermions $(\nu = \bar{\nu})$?

Is lepton number violated $(\Delta L = 2)$?

Double β-decay: 2νββ & 0νββ modes

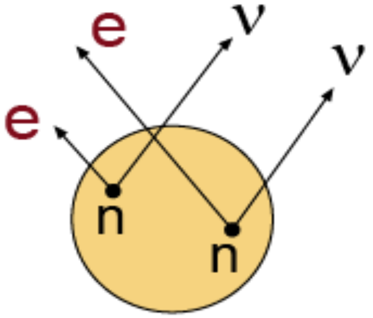
Double beta decay with neutrino emission (2νββ):

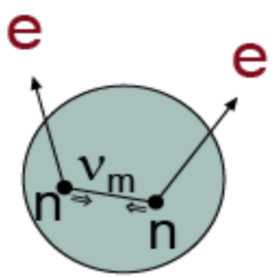
2nd-order weak interaction process

- extremely small transition rates & long half-lives: $T_{1/2} \sim 10^{19} - 10^{21}$ years
- energy E_0 shared by 4 leptons, observed in 12 isotopes so far

2νββ

$$(Z,A) \rightarrow (Z+2,A) + e_1^- + e_2^- + \bar{\nu}_{e,1} + \bar{\nu}_{e,2}$$



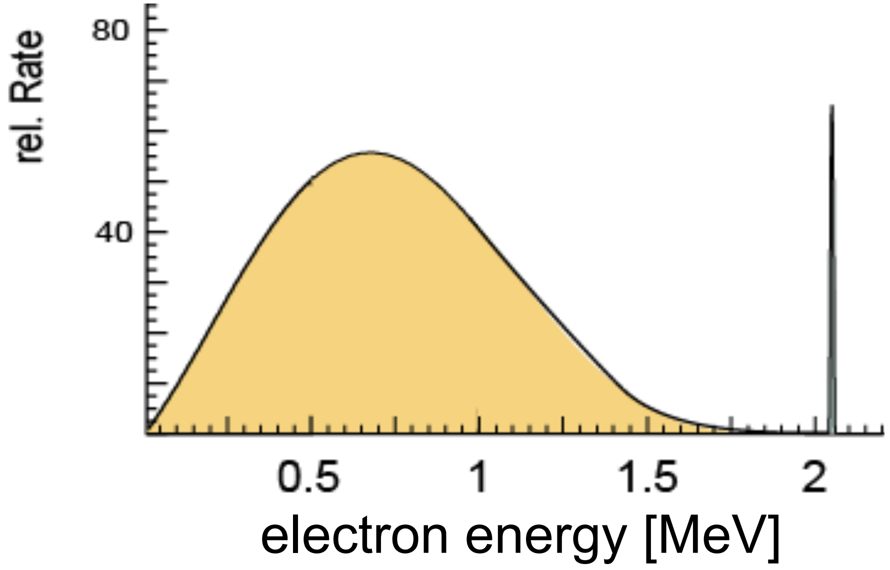


0νββ

$$(Z,A) \rightarrow (Z+2,A) + e_1^- + e_2^-$$

first description:

M. Goeppert-Mayer (1935)



first description:

G. Racah (1937) E. Majorana

Double beta decay: candidate nuclides

35 “energetically” suitable even-even nuclides for double beta decay

Decay rates **~Q^5** ($0\nu\beta\beta$) ➜ find suitable isotope for experiment:

11 nuclei for $2\nu\beta^-\beta^-$ at Q > 2 MeV:

$\beta^-\beta^-$ decay	Q [MeV]	nat. [%]
$^{48}Ca \rightarrow {}^{48}Ti$	4,274	0,187
$^{76}Ge \rightarrow {}^{76}Se$	2,039	7,8
$^{82}Se \rightarrow {}^{82}Kr$	2,995	9,2
$^{96}Zr \rightarrow {}^{96}Mo$	3,348	2,8
$^{100}Mo \rightarrow {}^{100}Ru$	3,034	9,6
$^{110}Pd \rightarrow {}^{110}Cd$	2,004	11,8
$^{116}Cd \rightarrow {}^{116}Sn$	2,809	7,5
$^{124}Sn \rightarrow {}^{124}Te$	2,288	5,64
$^{130}Te \rightarrow {}^{130}Xe$	2,527	34,5
$^{136}Xe \rightarrow {}^{136}Ba$	2,458	8,9
$^{150}Nd \rightarrow {}^{150}Sm$	3,368	5,6

6 nuclei for $2\nu\beta^+\beta^+$/EC at lower Q:

$\beta^+\beta^+$ decay	Q [MeV]	nat. [%]
$^{78}Kr \rightarrow {}^{78}Se$	***0,838***	0,35
$^{96}Ru \rightarrow {}^{96}Mo$	***0,676***	5,5
$^{106}Cd \rightarrow {}^{106}Pd$	***0,738***	1,25
$^{124}Xe \rightarrow {}^{124}Te$	***0,822***	0,10
$^{130}Ba \rightarrow {}^{130}Xe$	***0,534***	0,11
$^{136}Ce \rightarrow {}^{136}Ba$	***0,362***	0,19

Coulomb barrier reduces Q
➜ even longer expected $T_{1/2}$

$T_{½}$ ($\beta^+\beta^+$) ~ 10^{26} a

Double β-decay & Majorana mass $m_{\beta\beta}$

Effective Majorana mass $m_{\beta\beta}$ is **not** identical with $m(\nu_e)$ from β-decay

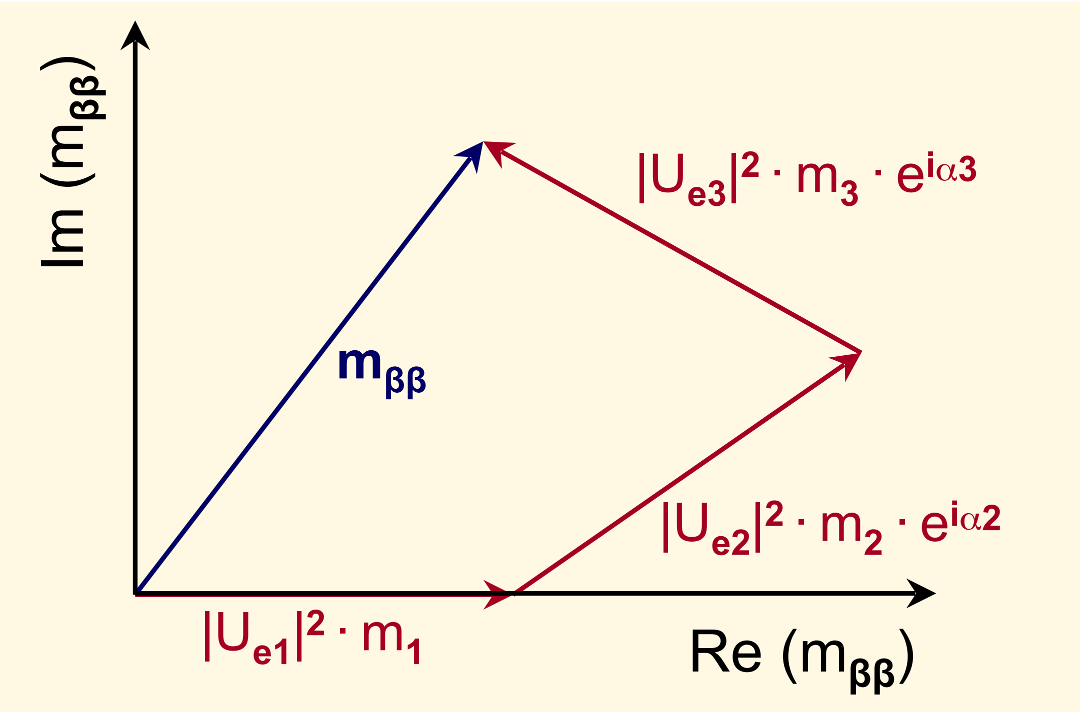
Coherent sum over three ν mass eigenstates m_1, m_2, m_3

$$\boxed{\left\langle m_{\beta\beta} \right\rangle = \left| \sum_{i=1}^{3} \left| U_{e,i} \right|^2 m_i \cdot e^{i\alpha_i} \right|}$$

2 independent Majorana CP-phases α_i

↳ mutual cancellations are possible

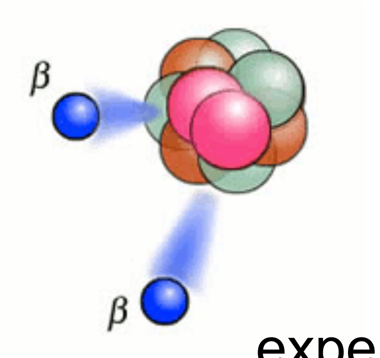
if $\alpha_i \neq n \cdot \pi$ ➜ CP violation



virtual particles interfere!

Double β-decay & Majorana mass $m_{\beta\beta}$

Determination of **effective Majorana mass $m_{\beta\beta}$** from 0νββ half-life $T_{1/2}$



$$\left\langle m_{\beta\beta} \right\rangle^2 = \left(T_{1/2}^{0\nu\beta\beta} \cdot G^{0\nu\beta\beta}(E_0, Z) \cdot \left| M_{GT}^{0\nu\beta\beta} - \frac{g_V^2}{g_A^2} M_F^{0\nu\beta\beta} \right|^2 \right)^{-1}$$

experimental value of
0νββ **half-life**

phase space factor

nuclear matrix element
M_{GT}: Gamov-Teller
M_F: Fermi

- **experimental observable: $T_{1/2}$**
  ➩ 0νββ event number depending on measuring time, number of target nuclei, experimental efficiency, background
- **weak interaction (phase space factor): $G^{0\nu\beta\beta}$**
  ➩ determined by ββ-endpoint energy; strong dependence ~Q^5
- **nuclear physics (matrix elements): $M^{0\nu\beta\beta}$**
  ➩ shell model calculations, large uncertainties O(100%)

Sensitivity drivers

$$T^{0\nu}_{1/2}(\mathrm{FOM}) \propto a \cdot \epsilon \cdot \sqrt{\frac{M \cdot t}{b \cdot \Delta E}}$$

Requirements:

- Large isotopical abundance (***a***)
- High efficiency (***ϵ***)
- Large Mass (***M***)
- Long counting time (***t***)
- Low background (***b***)
- Good energy resolution (***ΔE***)

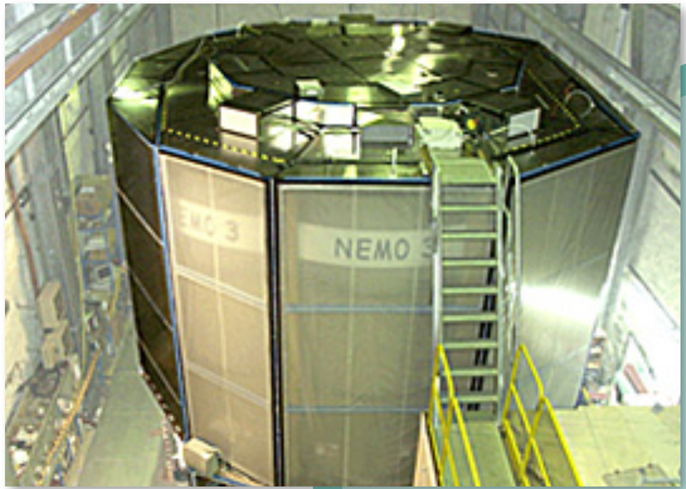
➜ Many suitable combinations for isotope + detector technology

➜ If ROI is background free: linear scaling with ***M*** and ***t*** !

$$T^{0\nu}_{1/2}(\mathrm{FOM}) \propto a \cdot \epsilon \cdot M \cdot t$$

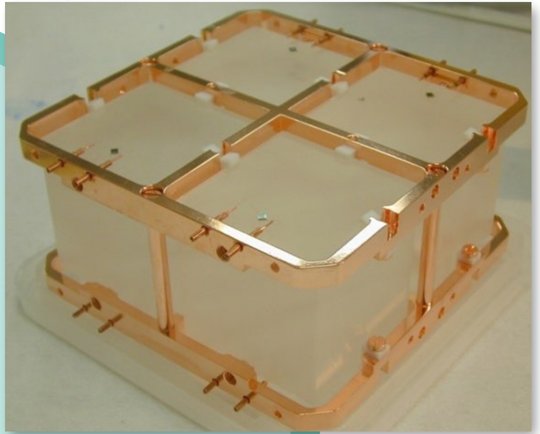
Experimental techniques

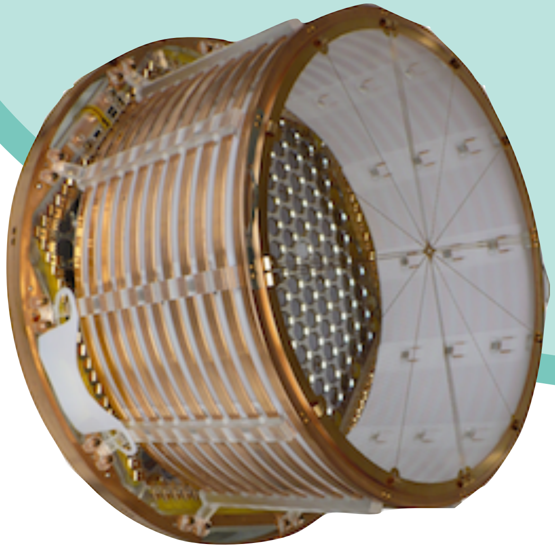
Tracker-calorimeter



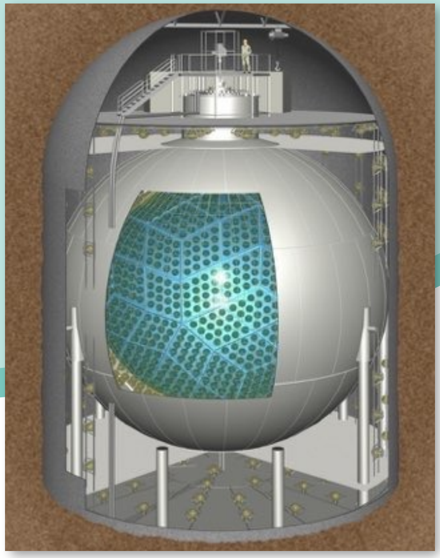
Ge diodes

Cryo-bolometer



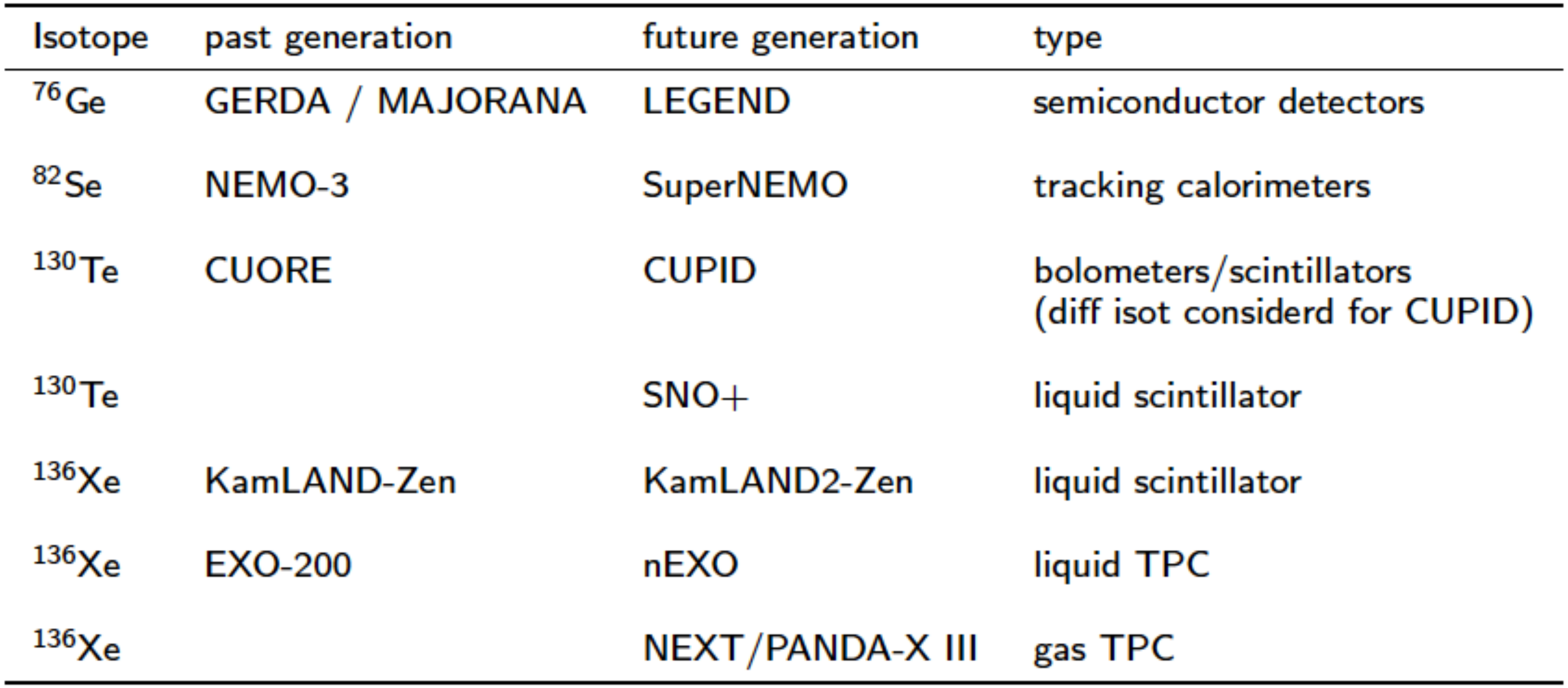


Liquid noble element TPC



Liquid scintillator

Many experimental ideas …

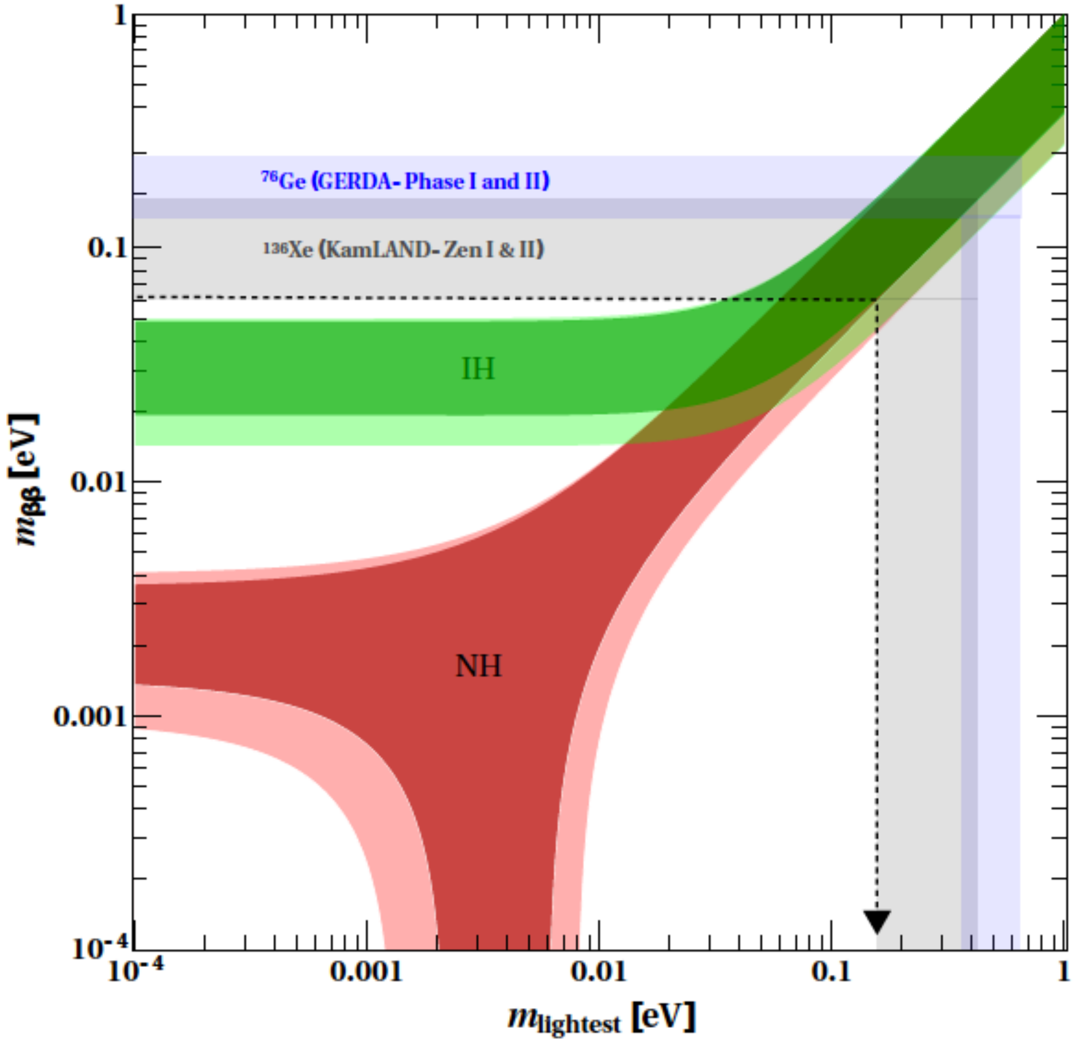


Isotope	past generation	future generation	type
^{76}Ge	GERDA / MAJORANA	LEGEND	semiconductor detectors
^{82}Se	NEMO-3	SuperNEMO	tracking calorimeters
^{130}Te	CUORE	CUPID	bolometers/scintillators (diff isot considerd for CUPID)
^{130}Te		SNO+	liquid scintillator
^{136}Xe	KamLAND-Zen	KamLAND2-Zen	liquid scintillator
^{136}Xe	EXO-200	nEXO	liquid TPC
^{136}Xe		NEXT/PANDA-X III	gas TPC

\+ further projects in R&D phase

[from M. Agostini, Erice 2017]

Current constraints



Most stringent bounds now approaching inverted hierarchy

Next generation has good discovery potential, even for normal hierarchy

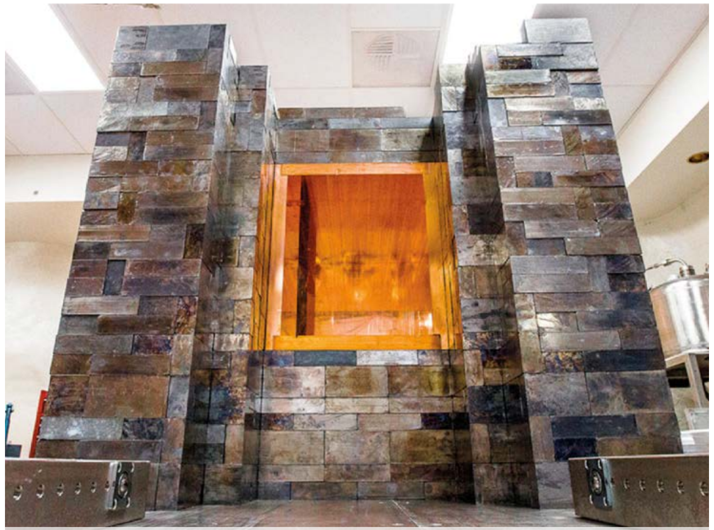
[from M. Agostini, Erice 2017; adapted from Dell'Oro *et al,* Adv. H. Energy Phys. 2016]

Germanium diodes: MAJORANA and GERDA

MAJORANA

Conventional design:

Vacuum cryostats in a *passive graded shield* with *ultra-clean materials*



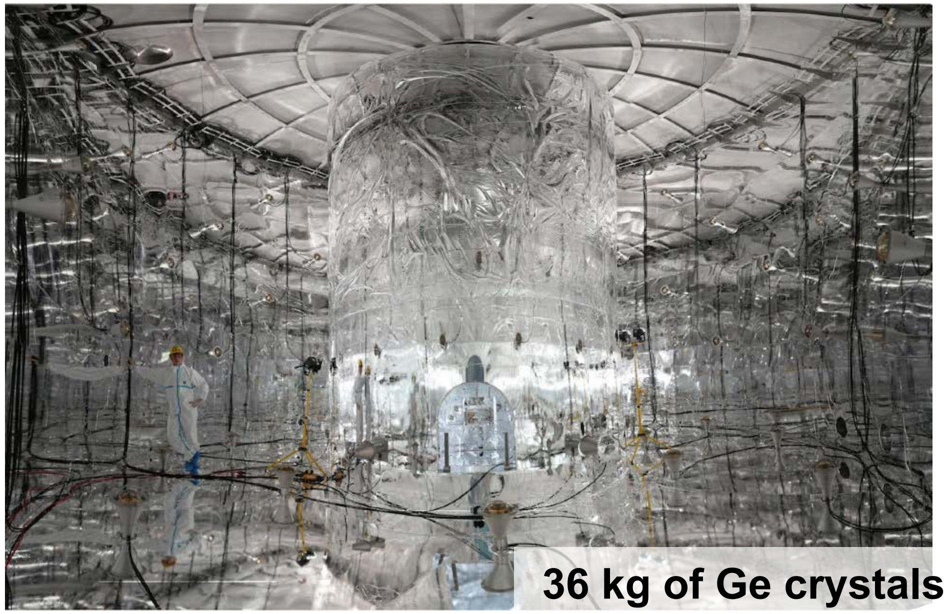
44 kg of Ge crystals (88% ^{76}Ge), ΔE ~0.1%

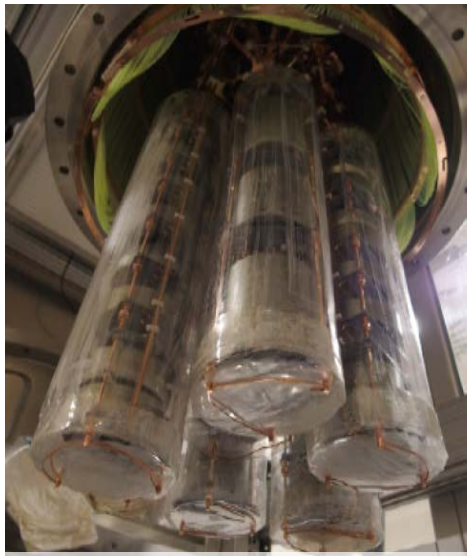
SURF (South Dakota, USA)

GERDA

Novel design:

Direct immersion in *active LAr shield*



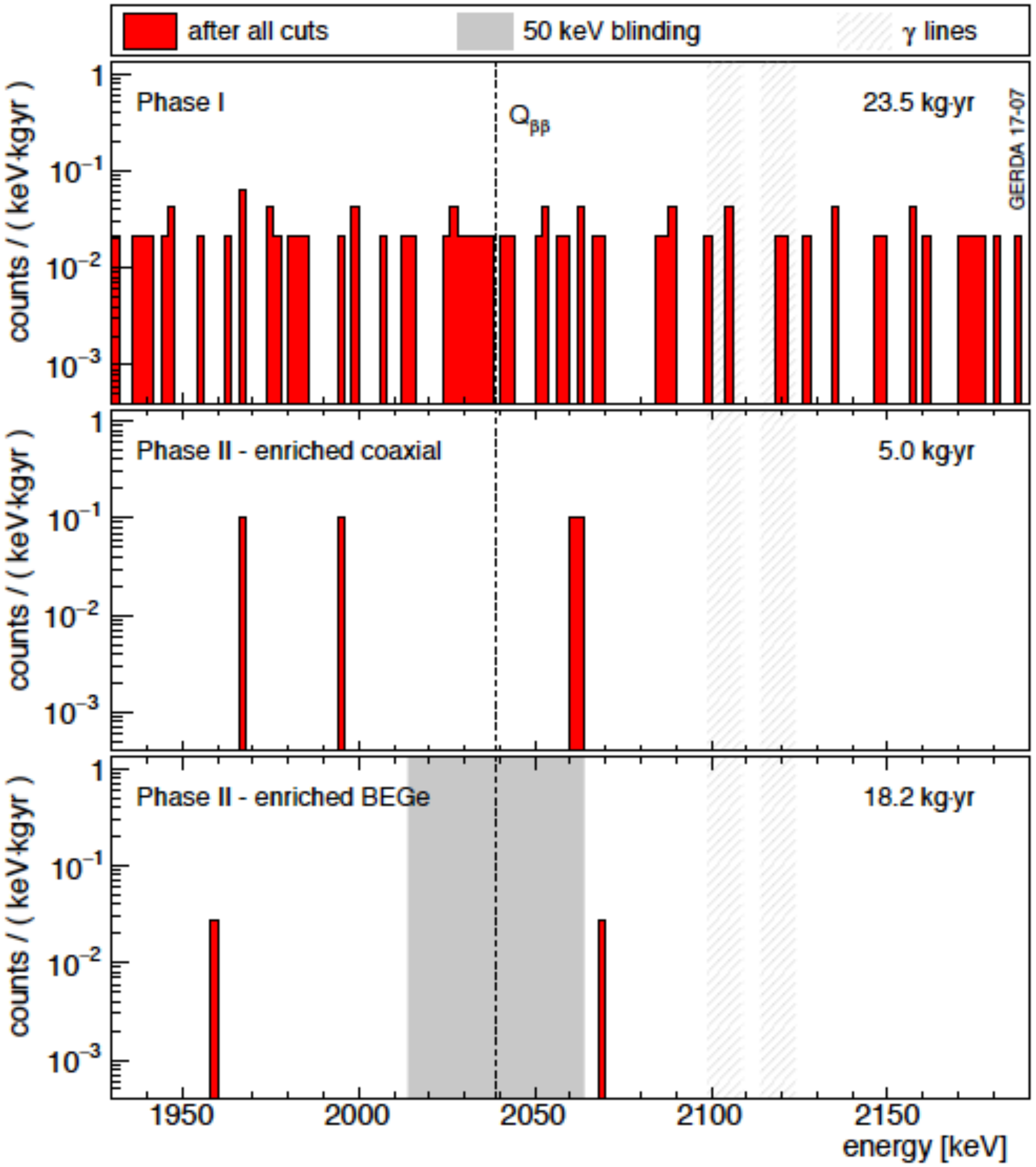


36 kg of Ge crystals (87% ^{76}Ge), ΔE ~0.2%

Gran Sasso (Italy)

Alan Poon (LBNL), Erice 2017

Germanium diodes: results



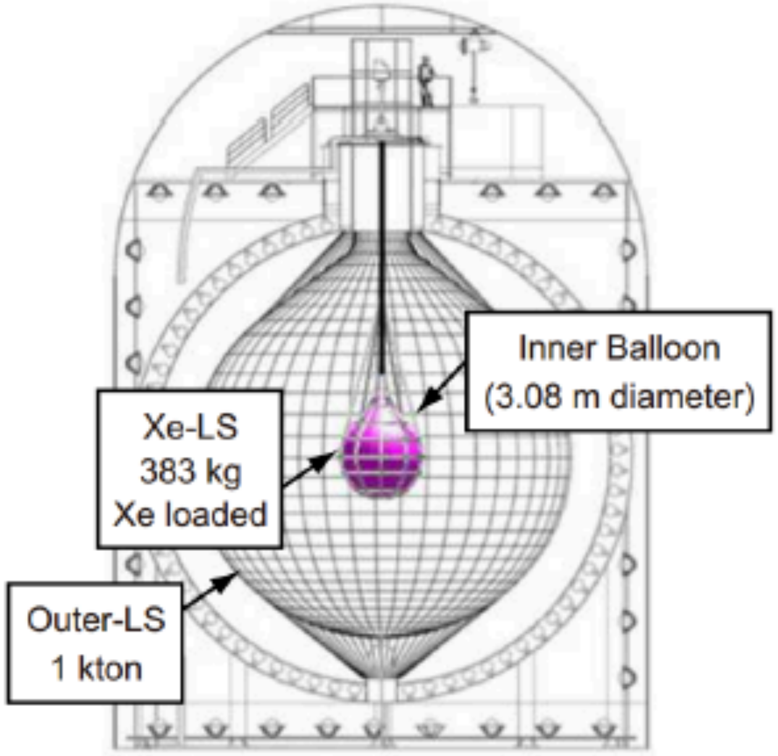
- Combined analysis **GERDA phase I + II**
- “Background-free” running in phase II
  - Two counts after unblinding
  - No count at $Q_{\beta\beta}$
- $T_{1/2} > 8.0 \times 10^{25}$ yr (90% CL)

- Next-generation project: LEGEND “Large Enriched Germanium Experiment for Neutrinoless ββ Decay”
- Staged approach, starting with ~200 kg in existing GERDA cryostat
- Final goal: 1000 kg-scale detector for sensitivity $>10^{27}$ yr
- Background improvement required: x30 (x5 for LEGEND-200)

[Nature 544 (2017) 47 + new data unblinded in August 2017]

Kamland-Zen at Kamioka (Japan)

Isotope:	^{136}Xe ($Q_{\beta\beta}$=2458 keV)
Resolution:	240-270 keV FWHM
Mass:	350 kg
Technology:	Xe-loaded liquid scintillator
Status:	completed/upgrading

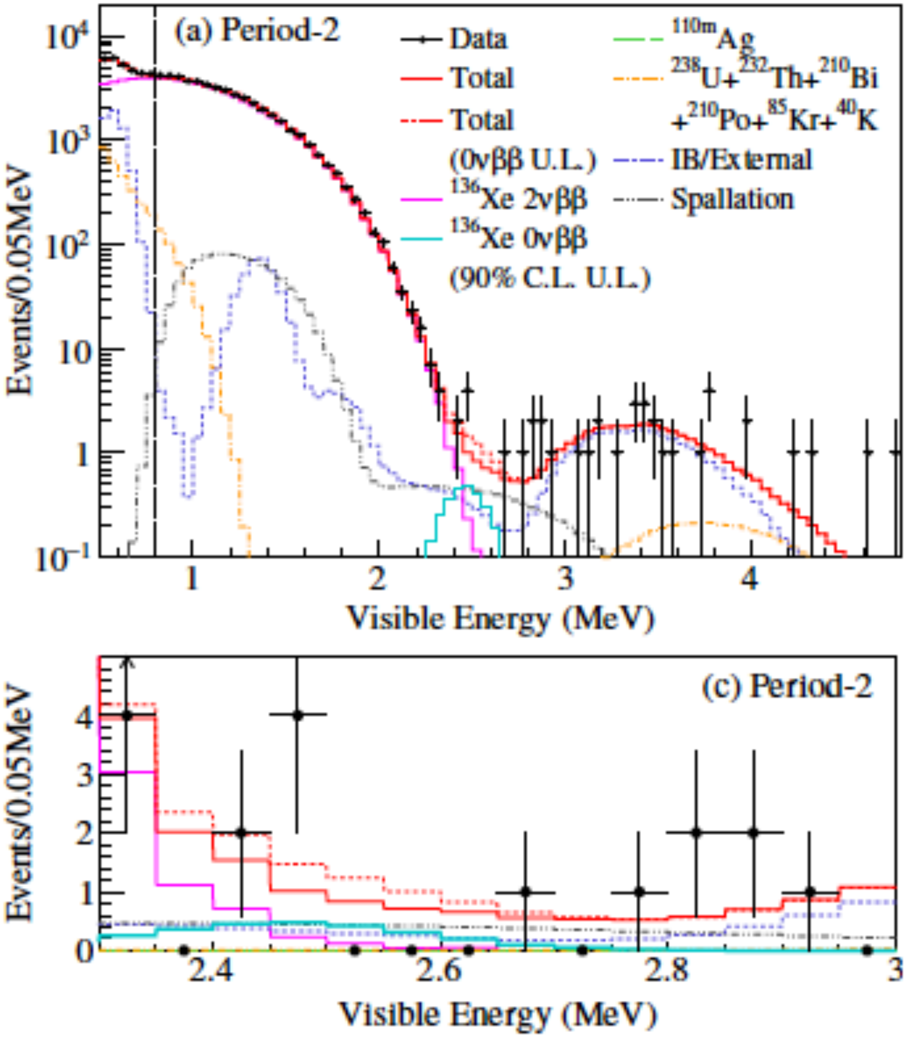


[Phys.Rev.Lett. 117 (2016) no.10, 109903]

Latest result with 504 kg·yr + old data:

$$T^{0\nu}_{1/2} > 10.7 \cdot 10^{25}\,\text{yr (90\% C.L.)}$$

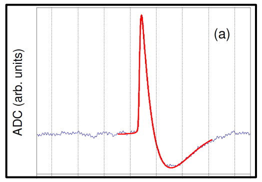
$$T^{0\nu}_{1/2} > 5.6 \cdot 10^{25}\,\text{yr (sensitivity)}$$



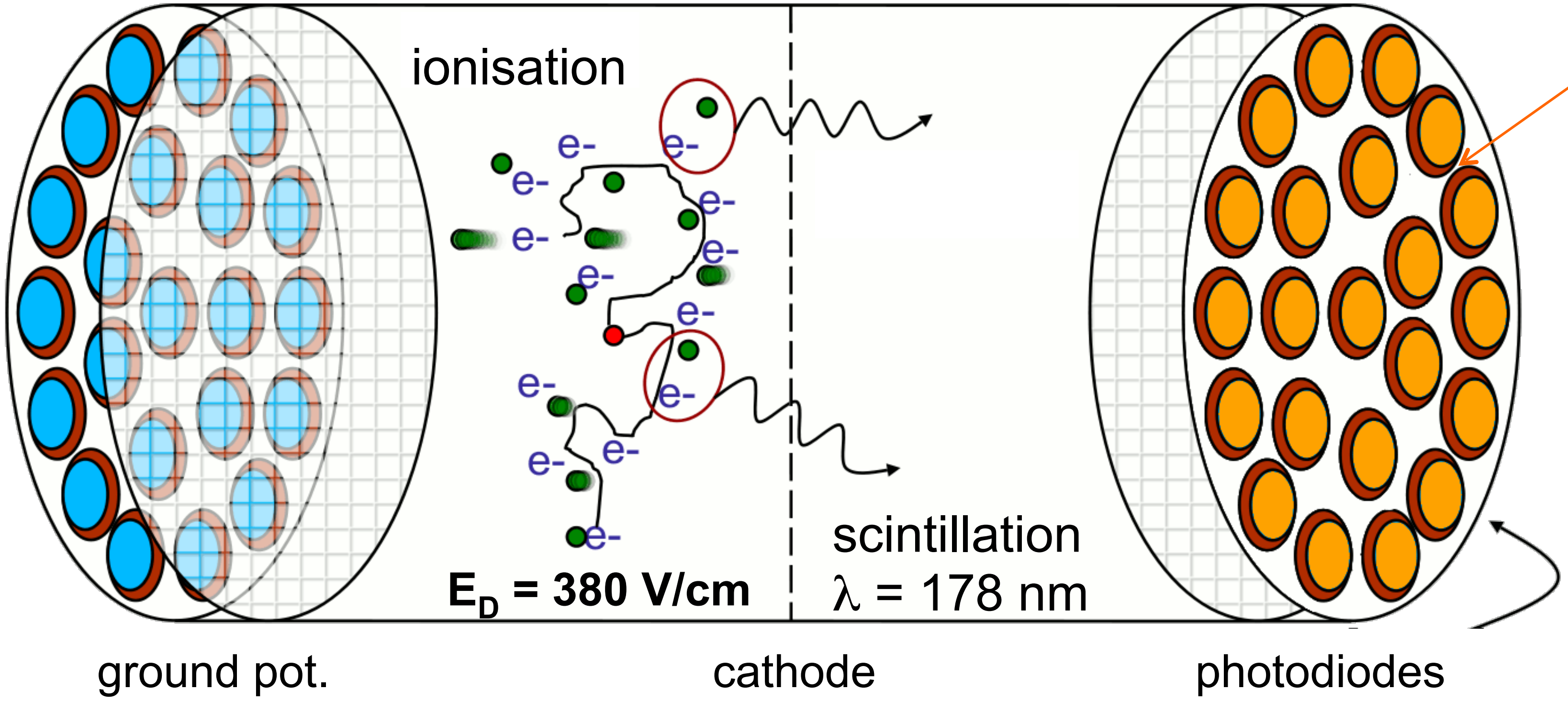
[from M. Agostini, Erice 2017]

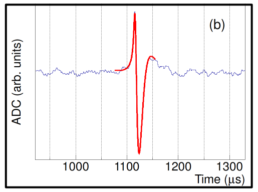
Liquid Xenon TPC: EXO-200

- Enriched Xenon Observatory at WIPP/New Mex., running **~175 kg of LXe** (80.6% ^{136}Xe)
- More than a calorimeter: spatial resolution (x,y,z) and PID allows discrimination of multi-site (bg-like) vs. single-site (0νββ-like) events
- Anticorrelation of charge and light signals (compare DM detectors), tags α events
- Now preparing **nEXO**: 5-ton monolithic detector (~1 t fiducial), 1.3 m electron drift length, ~4 m^2 of SiPM photosensors, option of ^{136}Ba tagging



Collection



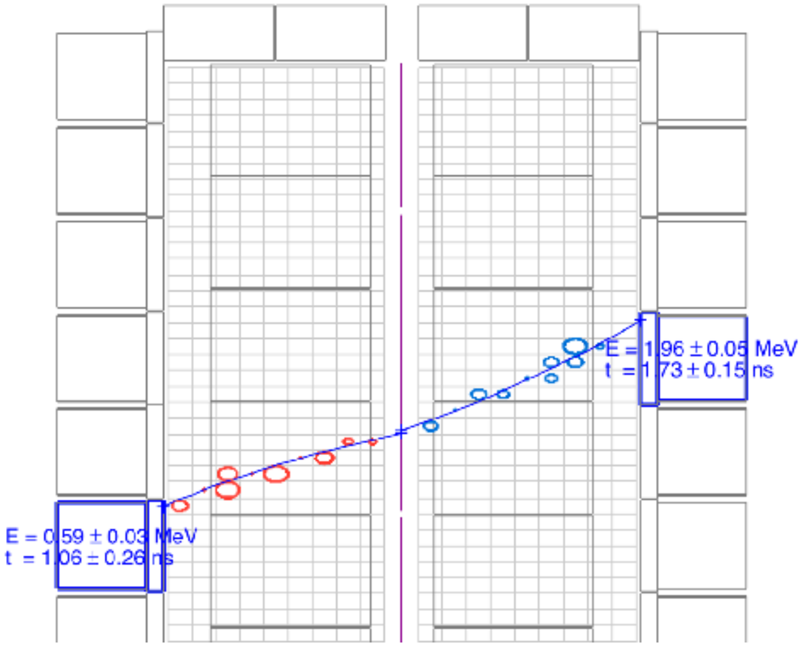


Induction

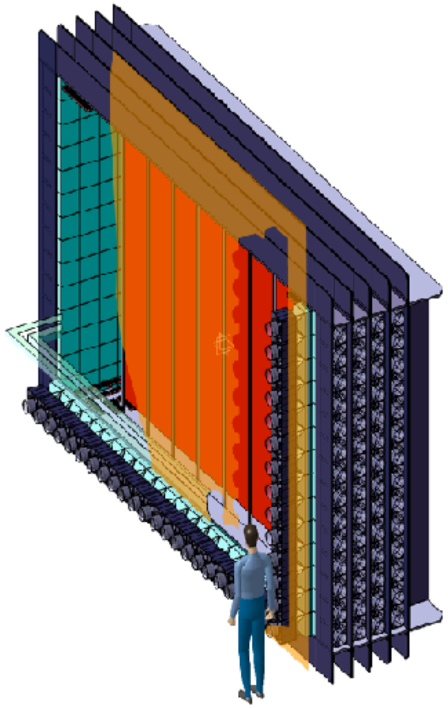
Tracking-Calorimeter: SuperNEMO

- Successor of NEMO-3 at Laboratoire Souterrain de Modane (LSM)
- Baseline isotope: ^{82}Se, foils can be exchanged (high Q-values: ^{150}Nd, ^{48}Ca)
- Unique feature: tracking allows to detect ββ-signature (vertex)
- Demonstrator (= 1st module) currently in commissioning, first data end of 2017
- Design sensitivity: $T_{1/2} > 10^{26}$ a, $m_{\beta\beta}$ ~50-100 meV

$\beta^-\beta^-$ reconstruction

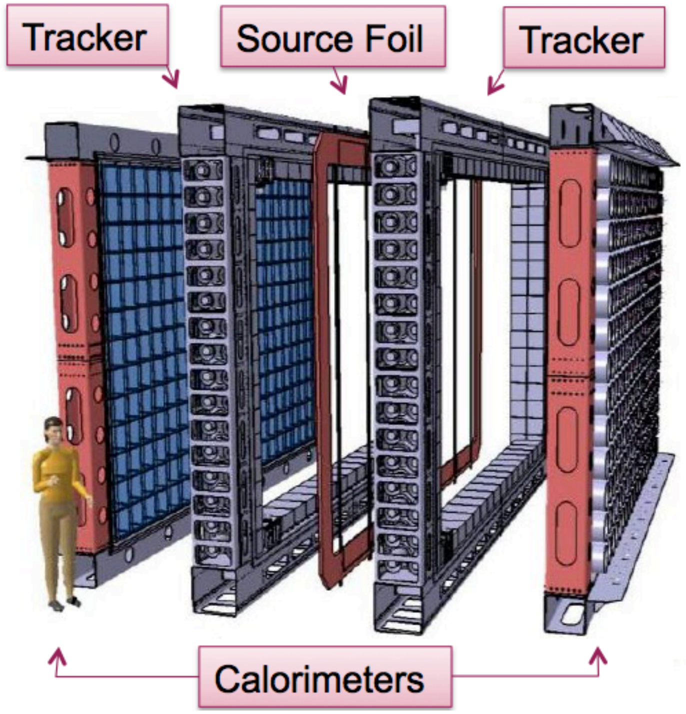


demonstrator module



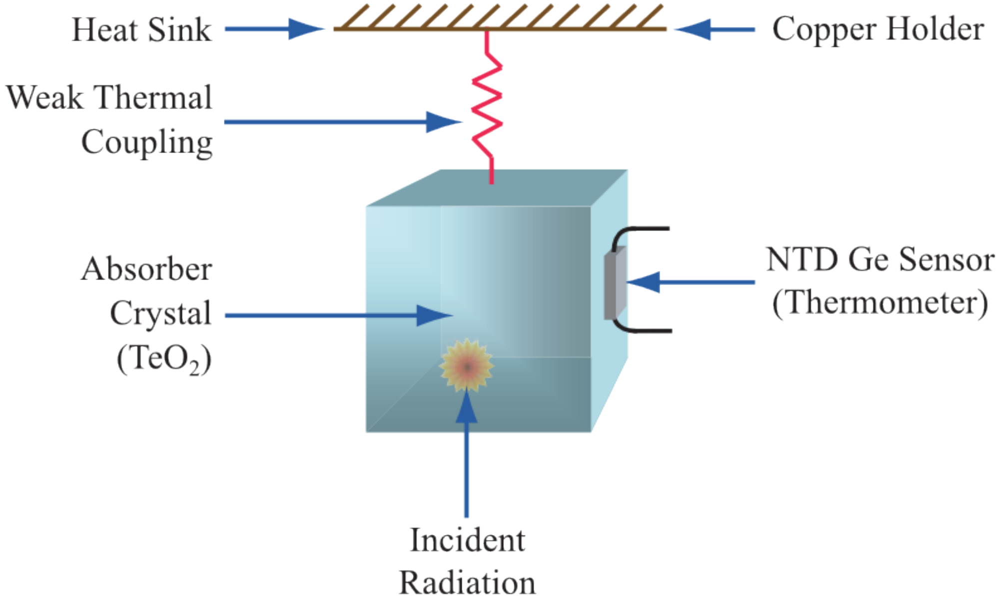
B ~2.5 mT
+ TOF

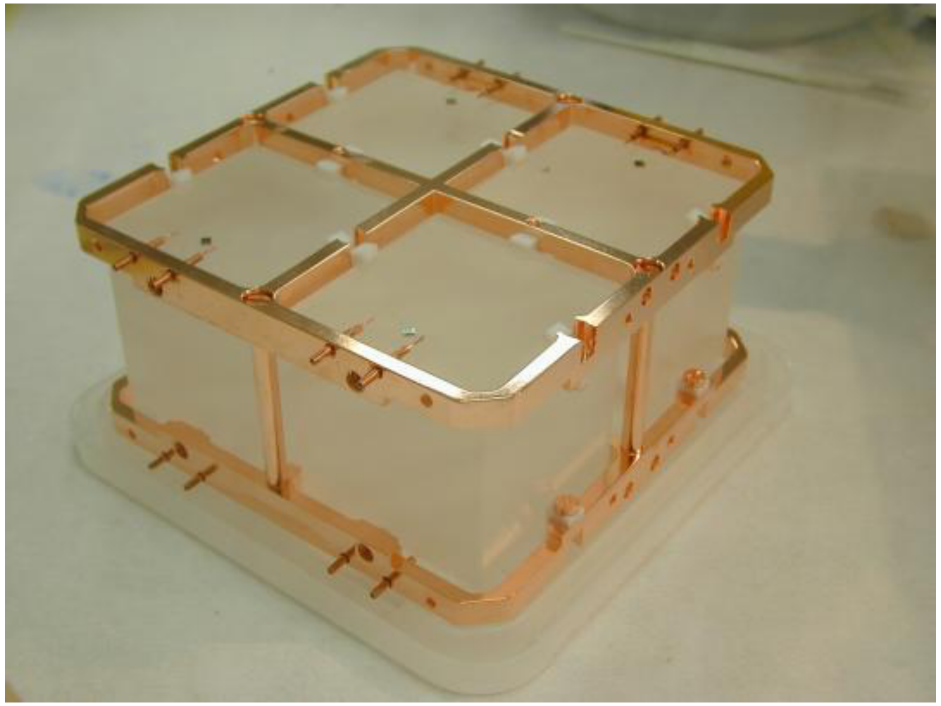
5-7 kg enriched
source material



Cryogenic bolometer technique

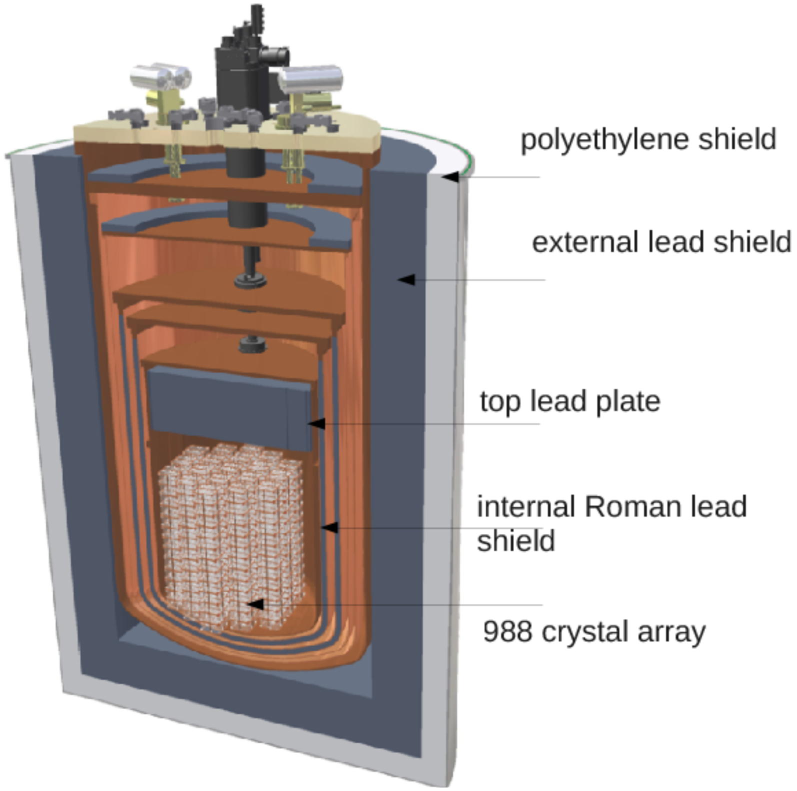
- Electrons create phonons/heat in absorber (e.g., TeO_2 crystal)
- Heat capacity: $\sim(T/T_D)^3$ (Debye Law)
- Example:
  - Operating temperature: 10 mK
  - Temperature change per energy: 10 – 20 μK/MeV
- At $Q_{\beta\beta} = 2.5$ MeV → $\Delta T < 50\ \mu K$



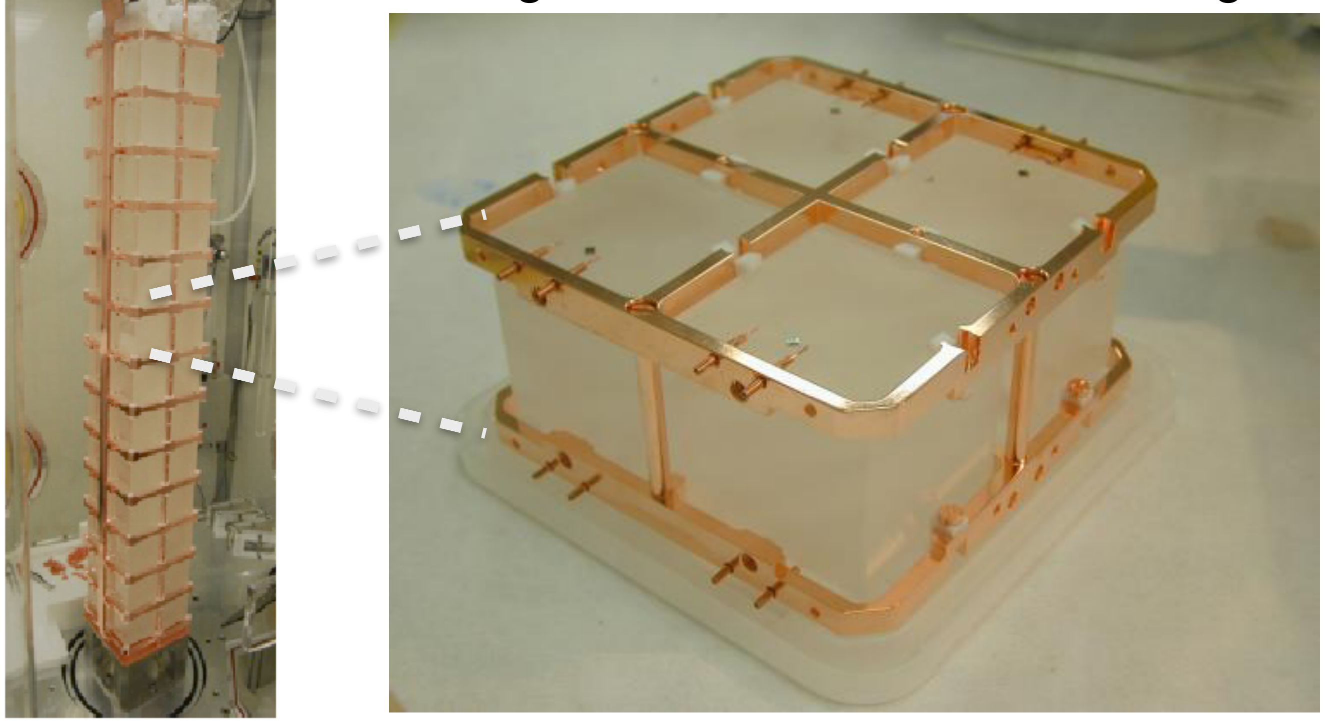


Cryogenic bolometer: CUORE

- First ton-scale $0\nu\beta\beta$ exp. with thermal detectors; at Gran Sasso underground laboratory
- TeO_2 detectors & cryo-technology piloted by Cuoricino & CUORE-0 (~40 kg)
- Since Feb. 2017: operation of **988 detectors** at **T ~7 mK**
- Total mass: 742 kg of TeO_2 ➜ **206 kg of ^{130}Te**



single detector: 5×5×5 cm^3, 750 g



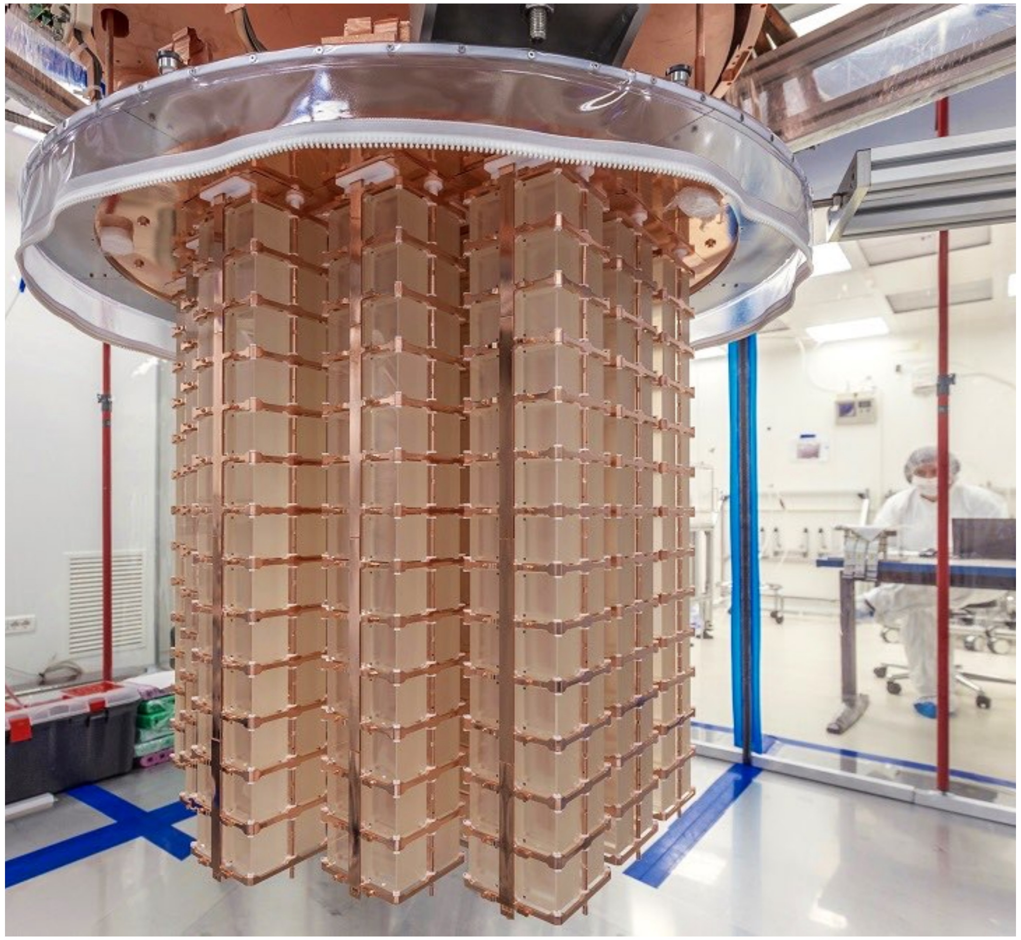
19 towers x 13 planes x 4 crystals = 988 crystals

Cryogenic bolometer: CUORE

The coldest cubic meter in the Universe!

CUORE: at ~10 mK

Cosmic microwave background: 2.7 K



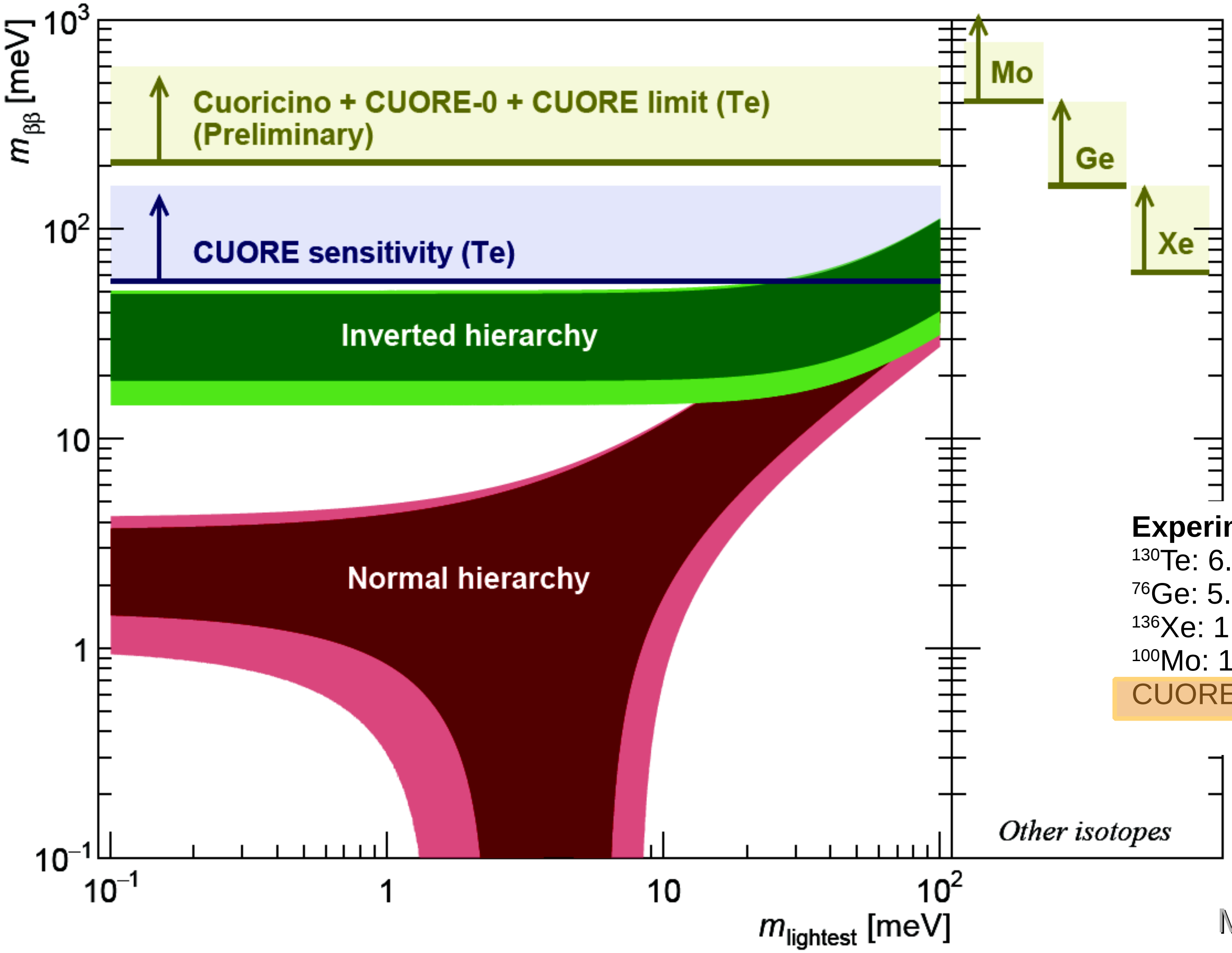
19 towers x 13 planes x 4 crystals = 988 crystals

cryogenic platform with helium dilution cryostat

Cryogenic bolometer: CUORE

First CUORE science run, combined with Cuoricino + CUORE-0:

$\tau_{1/2}^{0\nu} > 6.6 \times 10^{24}$ y (90%C.L.) ↔ $m_{\beta\beta} < 210 - 590$ meV



NME
Phys. Rev. C 91, 034304 (2015)
Phys. Rev. C 87, 045501 (2013)
Phys. Rev. C 91, 024613 (2015)
Nucl. Phys. A 818, 139 (2009)
Phys. Rev. Lett. 105, 252503 (2010)

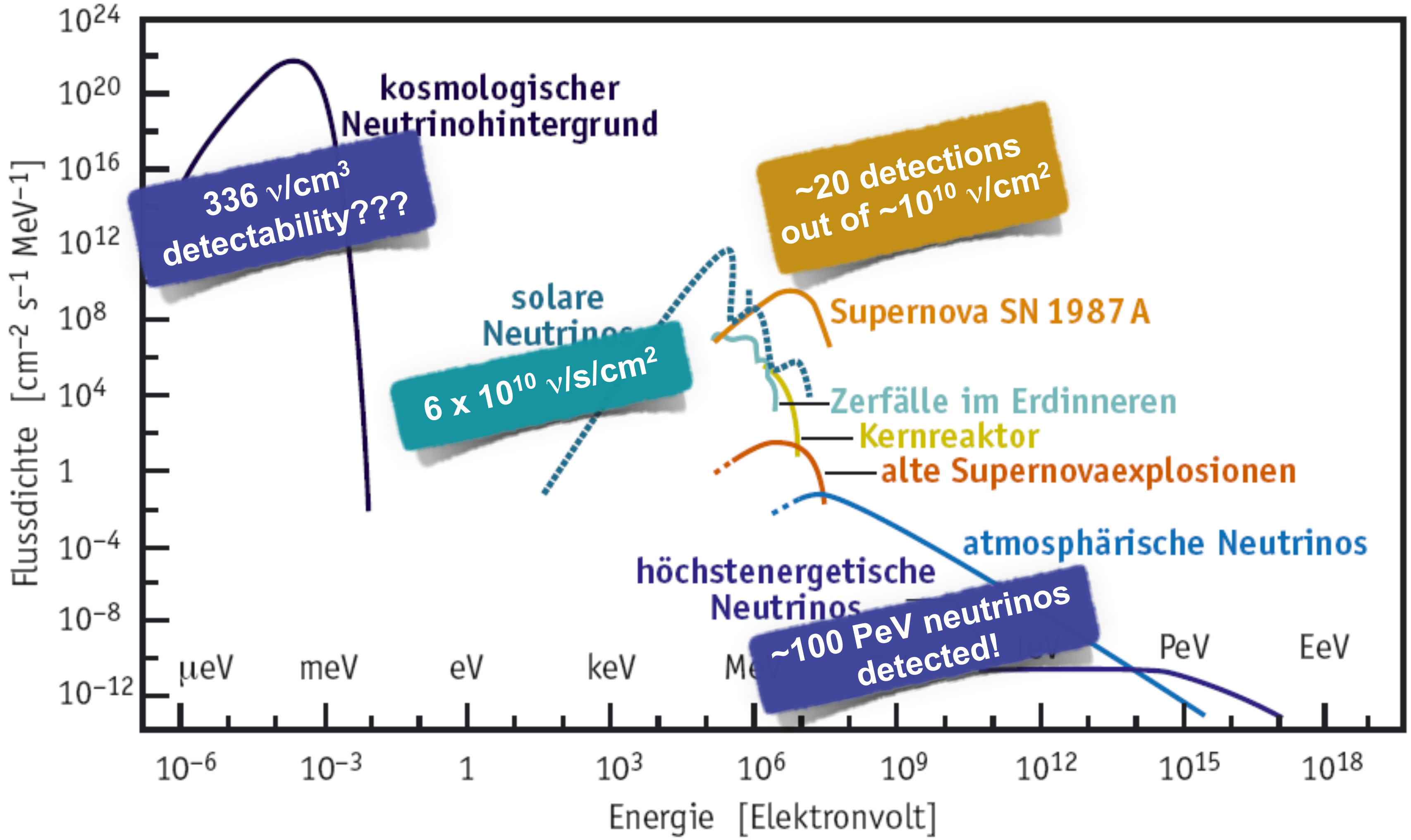
Experiments
^{130}Te: 6.6 × 10^{24} yr from this analysis
^{76}Ge: 5.3 × 10^{25} yr from Nature 544, 47–52 (2017)
^{136}Xe: 1.1 × 10^{26} yr from Phys. Rev. Lett. 117, 082503 (2016)
^{100}Mo: 1.1 × 10^{24} yr from Phys. Rev. D 89, 111101 (2014)
CUORE sensitivity: 9.0 × 10^{25} yr

for 5 years of data

Monica Sisti – Erice, September 18, 2017

Summary / Take-away (part I)

- We learned a lot about neutrinos since their “invention” in 1930
- We exploit a large variety of neutrino sources in our experiments!



336 ν/cm^3 detectability???

~20 detections out of ~10^{10} ν/cm^2

6 x 10^{10} $\nu/\mathrm{s}/\mathrm{cm}^2$

~100 PeV neutrinos detected!

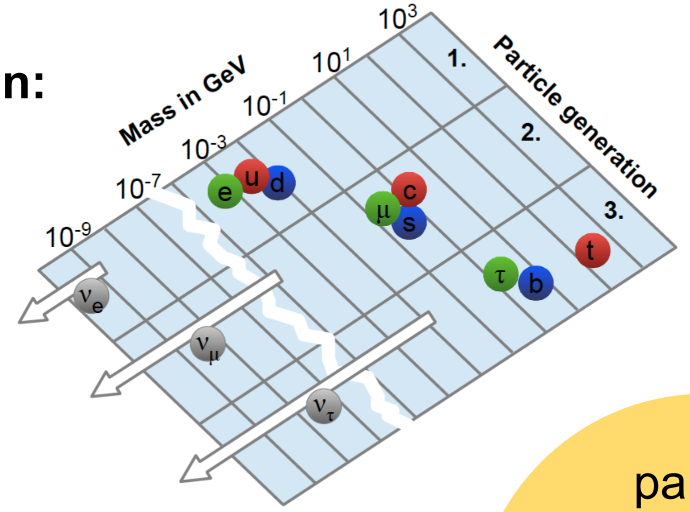
Summary / Take-away (part I)

- Massive neutrinos …
  - are evidence for physics beyond the Standard Model
  - are the only currently known form of Dark Matter
    (their contribution is small, their role not quite fixed yet - what about sterile neutrinos?)
- Neutrinos can point us towards …
  - novel mass-generating concepts in particle physics
    (open question regarding Dirac or Majorana nature of neutrinos)
  - lepton flavour violation (oscillations) and lepton number violation ($0\nu\beta\beta$)
  - leptonic CP violation
- We need to understand the mass pattern of neutrinos
  … and be open for (more) surprises. :)

dedicated experiments
➜ next lecture

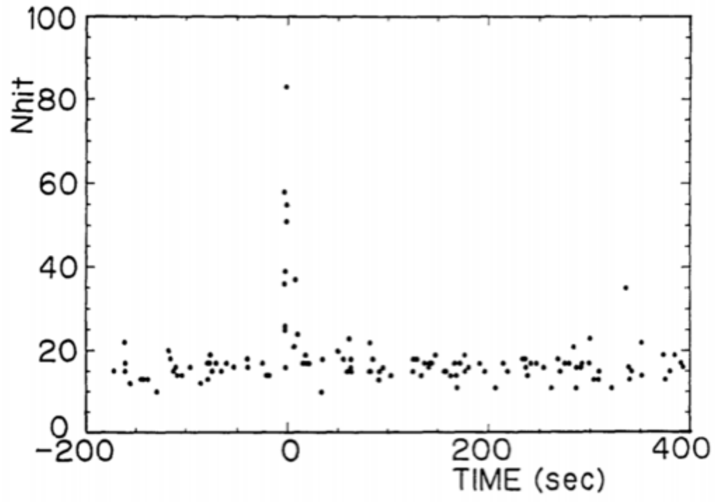
Massive neutrinos: connecting the micro- and the macro-cosmos

mass generation: new concepts

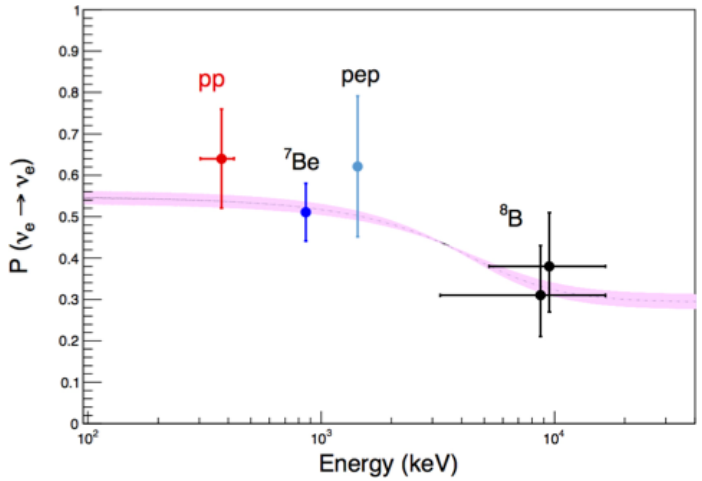


understanding astrophysical processes

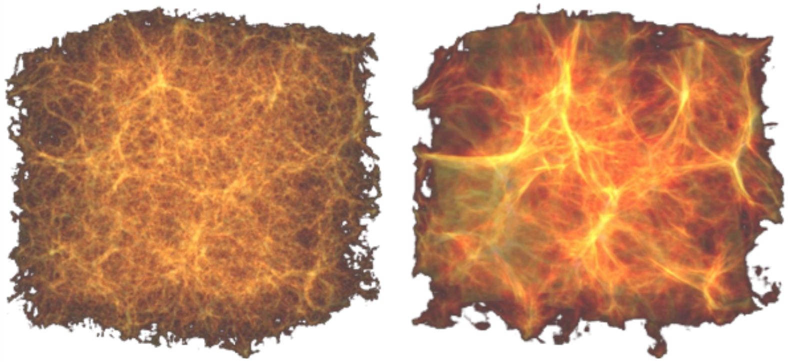
Neutrino burst from SN 1987a



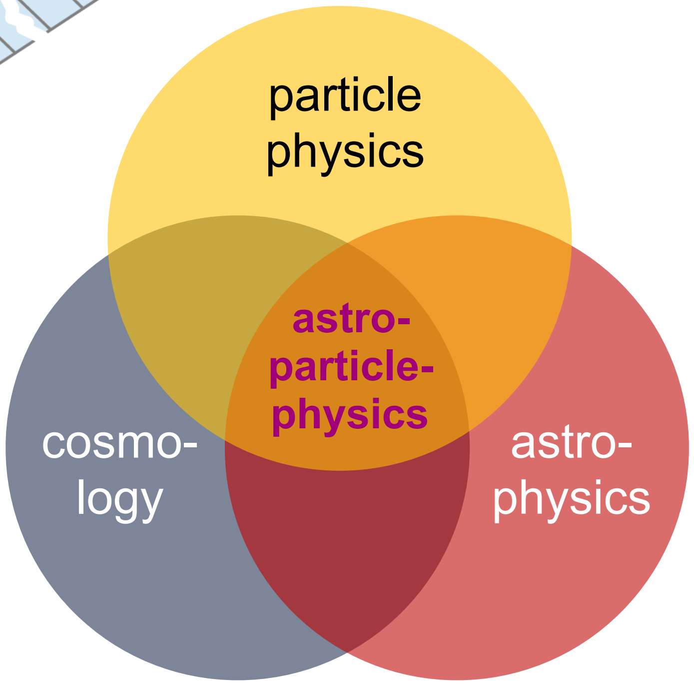
Matter effects in the sun



massive neutrinos as "cosmic architects"



Σm_ν = 0 eV 6.9 eV



particle physics

cosmology

astrophysics

astro-particle-physics