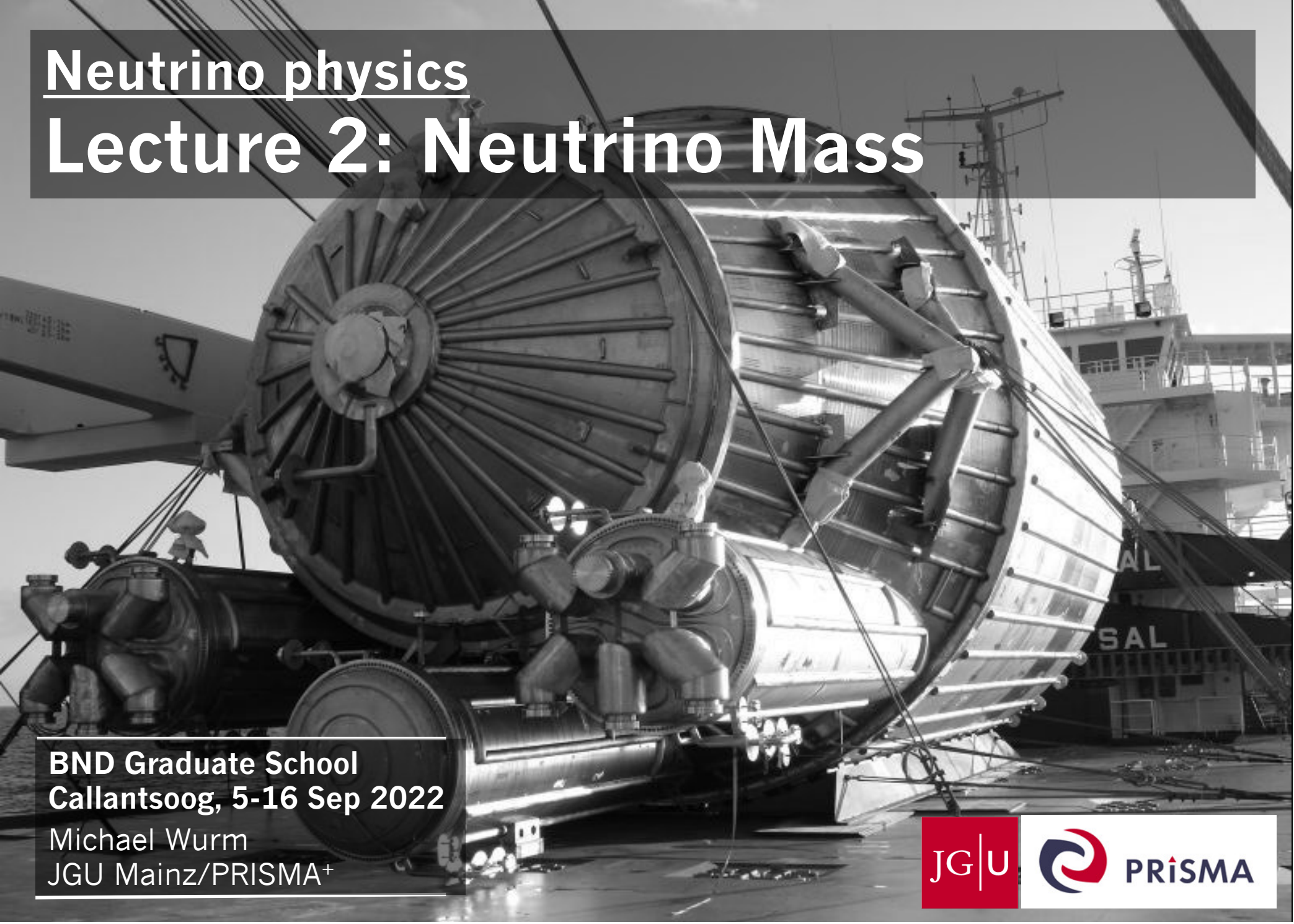


Neutrino physics
Lecture 2: Neutrino Mass

BND Graduate School
Callantsoog, 5-16 Sep 2022

Michael Wurm
JGU Mainz/PRISMA+

LECTURE QUIZ

Question 4

In three-flavor oscillations, what minimum number of neutrinos is required to have mass?

D : 1

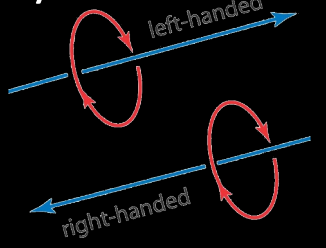
E : 2

F : 3

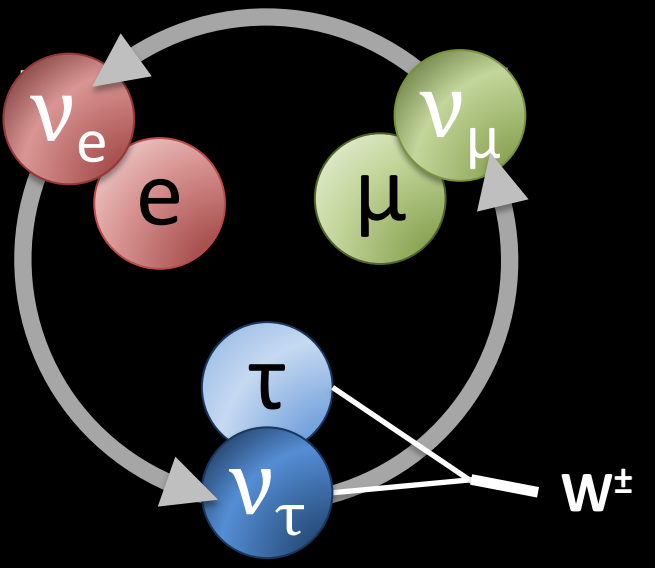
Note down the **fifth letter** of the solution word.

Neutrinos in a nut-shell

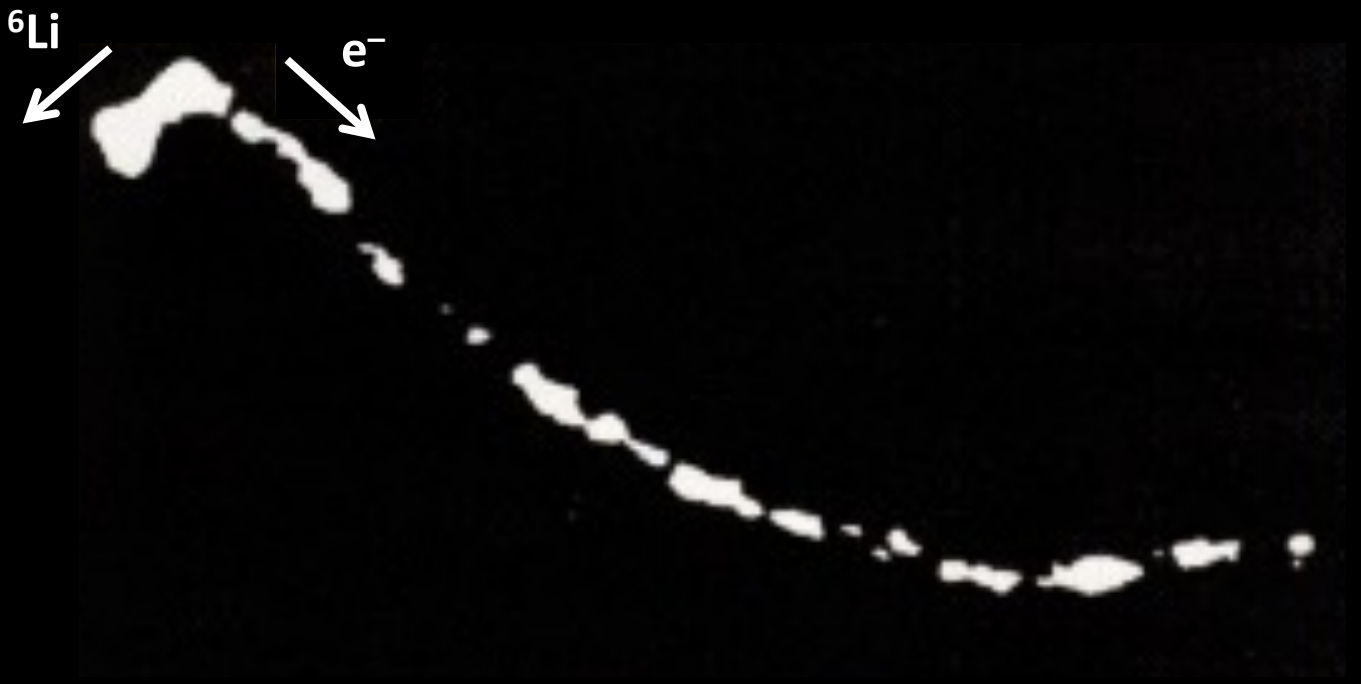
- Neutrinos are fermions.
- no electric or color charge
- **but:** weak charge
- virtually but not completely massless
  [$\Sigma m_\nu < 0.23\text{eV} \approx 5\text{x}10^{-7}\ m_e$]
- **three kinds (flavors) of neutrinos**
  are produced/absorbed in weak
  interactions along with e^-, μ^-, τ^-
- **each neutrino has (is?) its antiparticle:**
  same properties but different chirality
  - neutrinos = left-handed
  - antineutrinos = right-handed



- **flavor and mass eigenstates are different**
  → neutrino oscillations

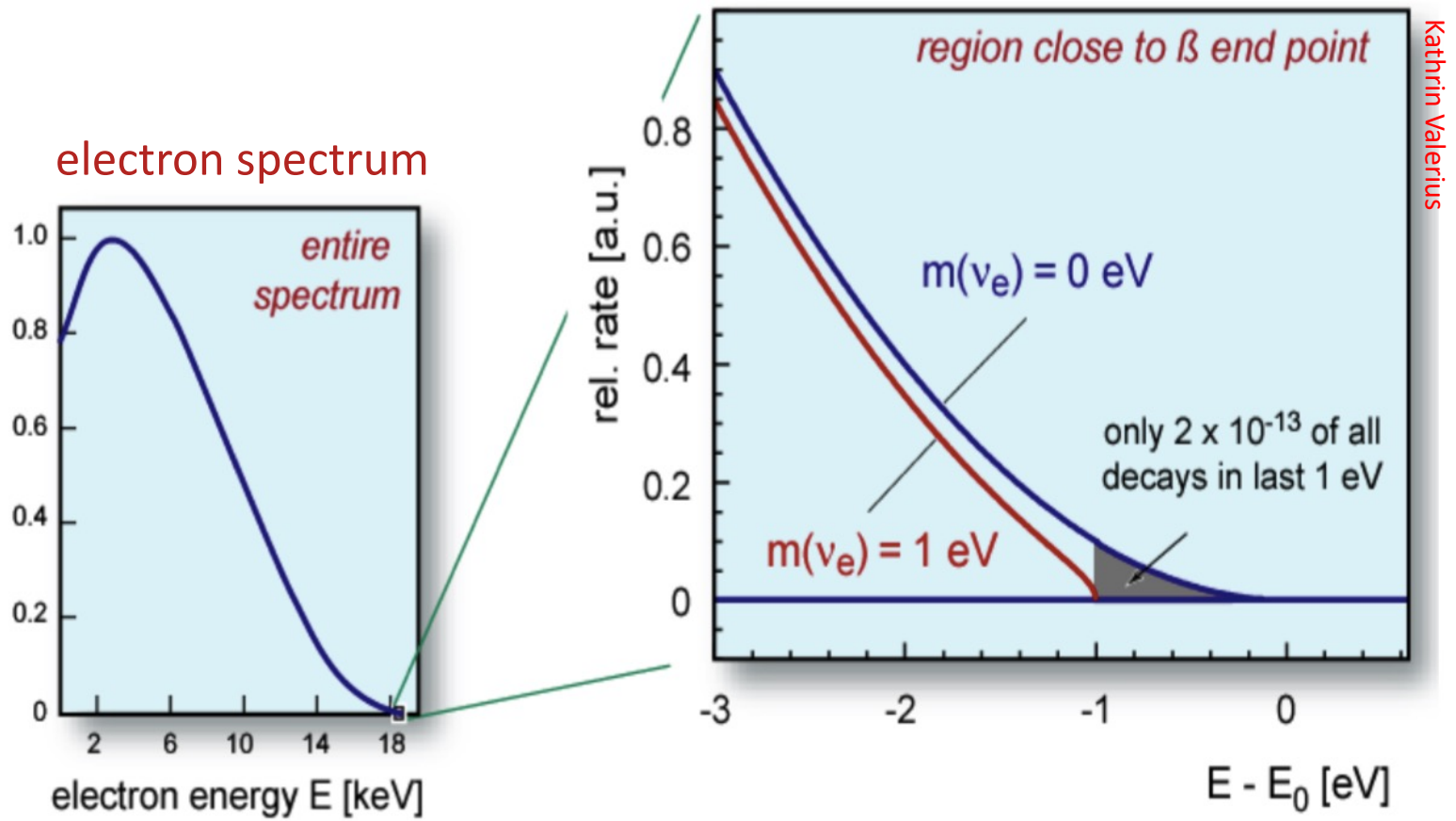


Direct neutrino mass measurement



Direct neutrino mass measurement

- Investigate energy distribution of weak decays.
- Mass differences Δm^2_{ji} known → ν_e mass measurement sufficient

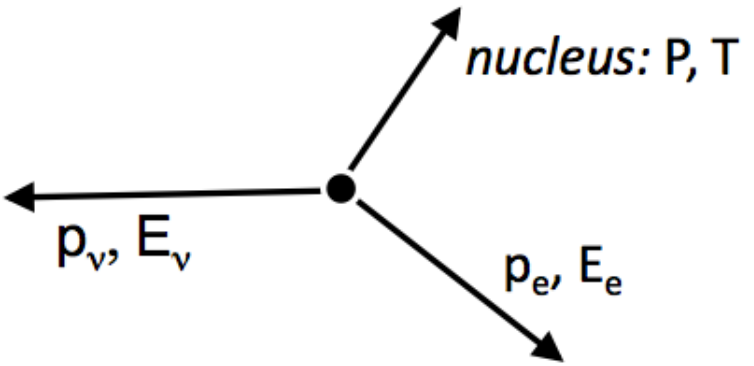


→ Finite neutrino mass will change both **β-endpoint** energy and shape

Fermi theory and shape of β spectrum

- **Fermi's Golden Rule:**

$$\frac{\mathrm{d}^2 N}{\mathrm{d}t\mathrm{d}E} = \frac{2\pi}{\hbar}\left|\langle f|H|i\rangle\right|^2 \cdot \rho(E) \cdot F(Z,E)$$



- In lowest order approximation, spectral shape depends only on **phase space factor**

$$\rho(E) = \frac{32\pi^2 V^2}{h^6} p_e (E + m_e)(E_0 - E)^2$$

→ neutrino phase space, depends on m_ν

E	kinetic energy of the electron
E_e	total energy of the electron, $E_e = m_e + E$
$\langle f\|H\|i\rangle$	transition matrix element
H	weak Hamilton operator
$\rho(E)$	density of final states
$F(Z,E)$	Fermi function (corrects for Coulomb effects of nucleus on $e^\pm$

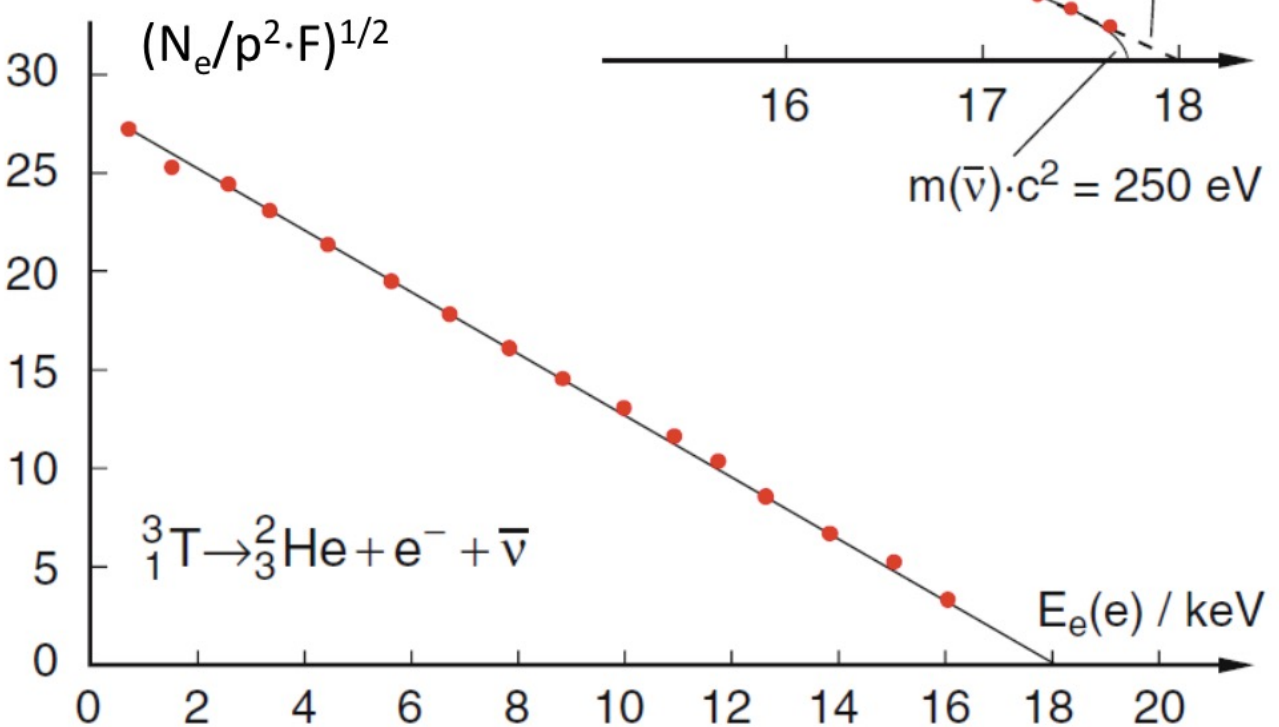
Source: β-Emitter

Source requirements

- Low spectral end-point
  → low background rate
  → good energy resolution
- Short half-life
  → high decay rate

→ best candidates:
tritium T=^{3}H (1p2n)
rhenium ^{187}Re

Kurie plot for T: $\sqrt{\frac{N_e(E)}{p_e^2 \cdot F(E)}}$



Detector: β-Spectrometer

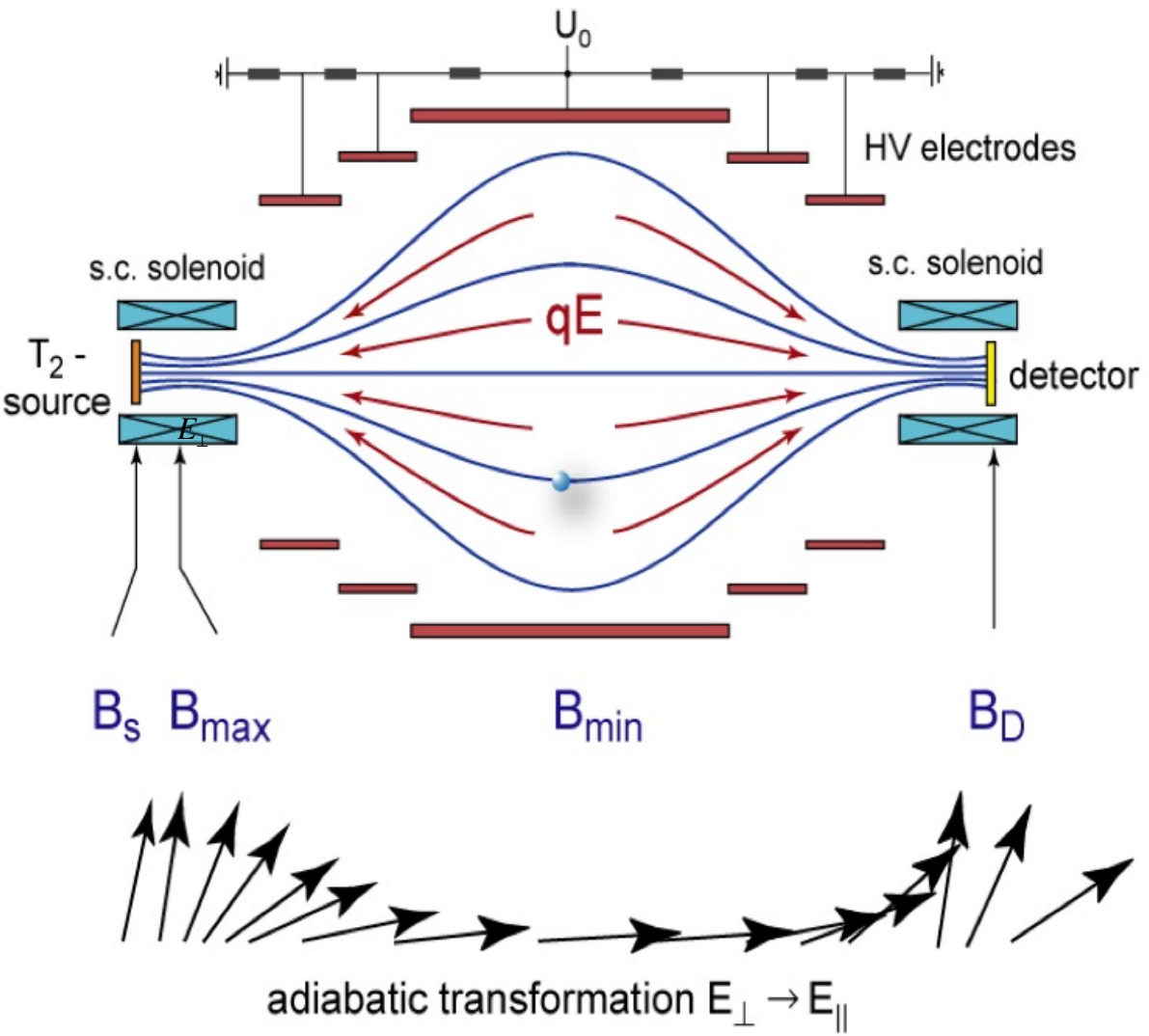
accurate measurement
of spectral endpoint

→ **energy resolution**

MAC-E filter

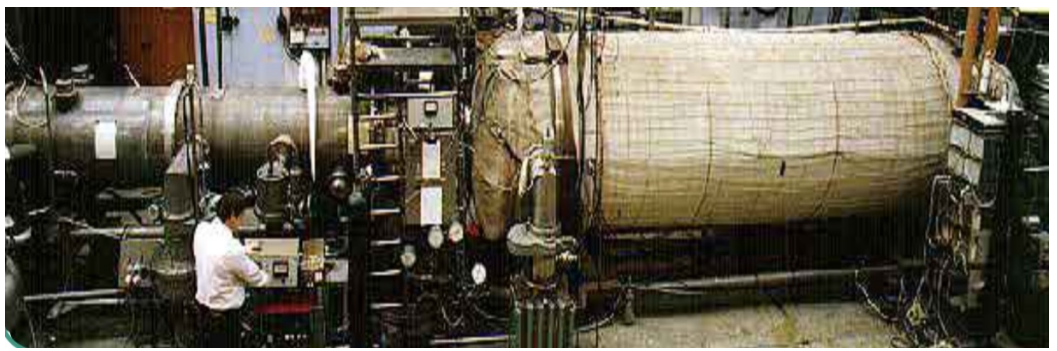
- negative **electric field E** acts as filter for electrons with decay energy E_{kin}<qE
- **magnetic field B** transforms all perpendicular energy $E_\perp$ to parallel component $E_\parallel$
- **resolution** depends on

$$\frac{\Delta E_{\mathrm{kin}}}{E_{\mathrm{kin}}} = \frac{B_{\mathrm{min}}}{B_{\mathrm{max}}}$$

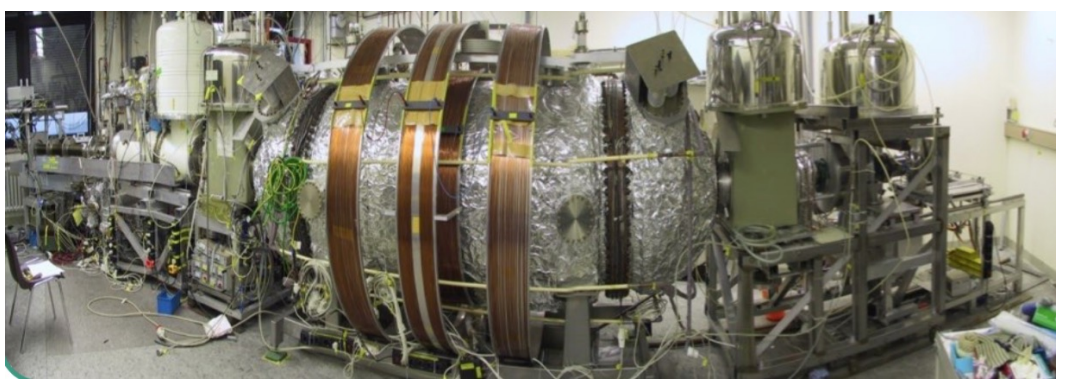


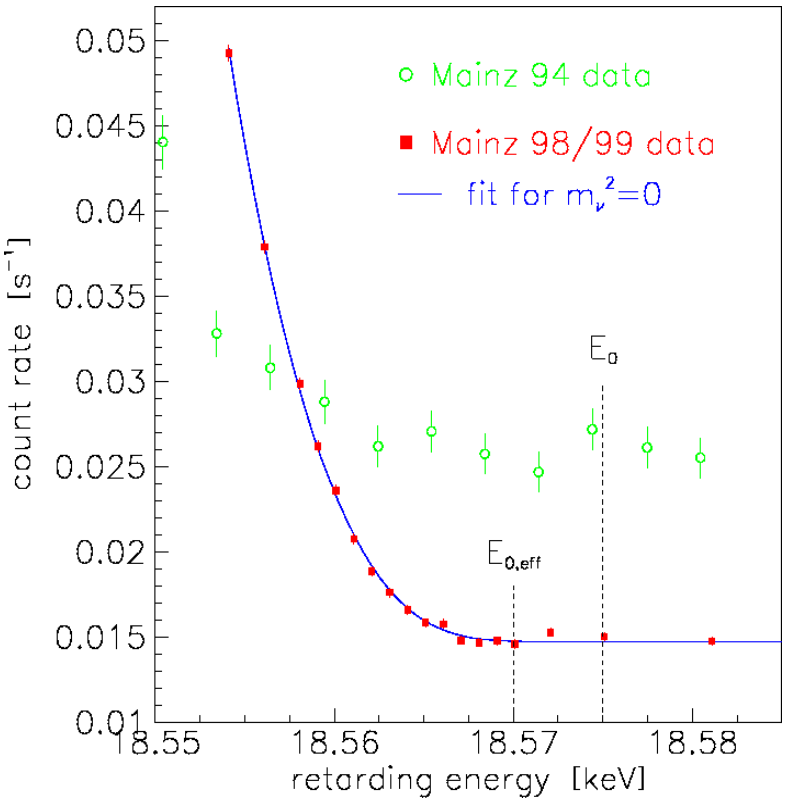
Mainz & Troitsk experiments

Troitsk: windowless gaseous T source



Mainz: quench condensed T source

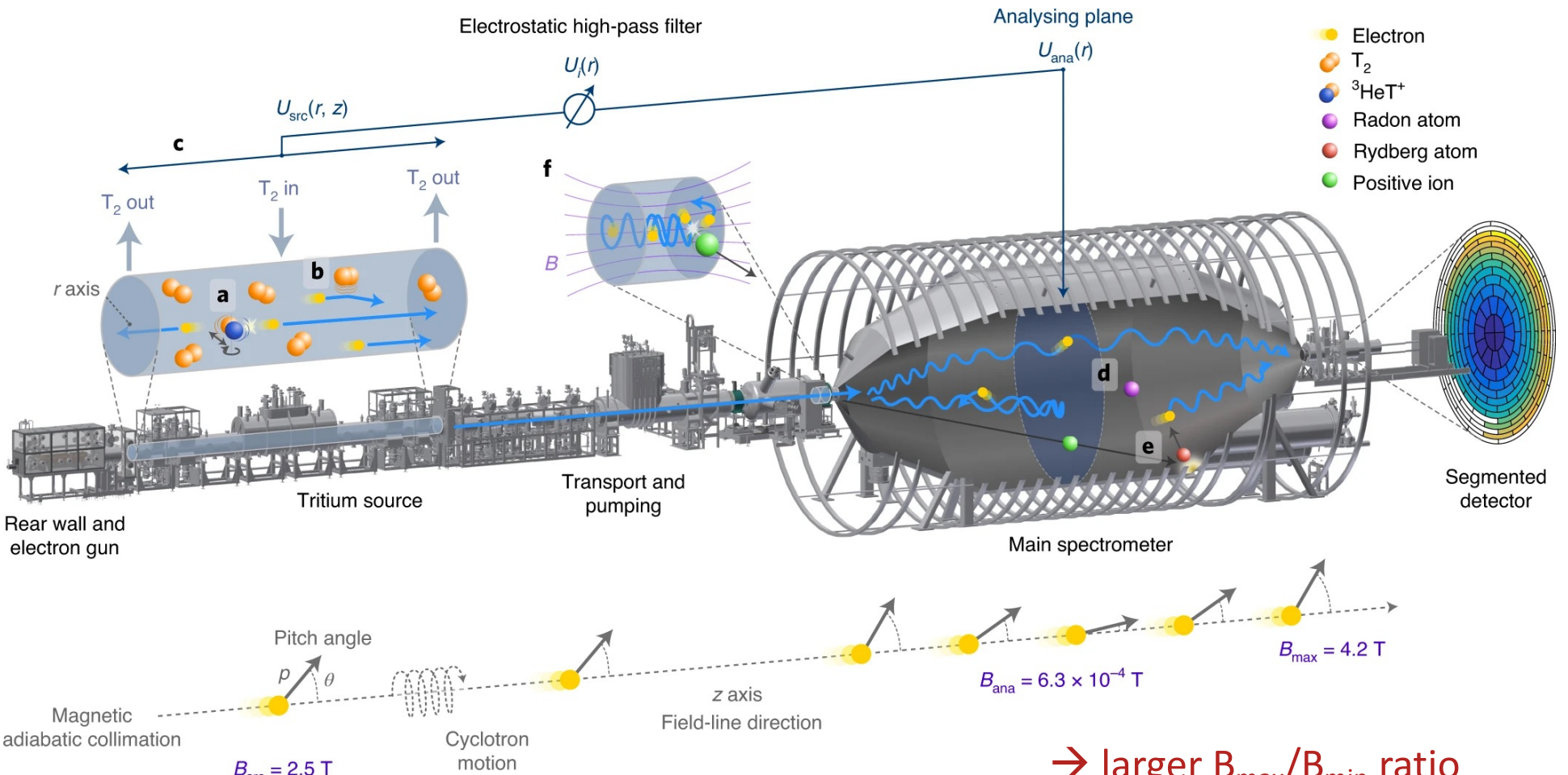




→ until 2019: best lab limits on neutrino mass: **$m(\nu_e) < 2.05$ eV** (95% C.L.)

KATRIN experiment in Karlsruhe

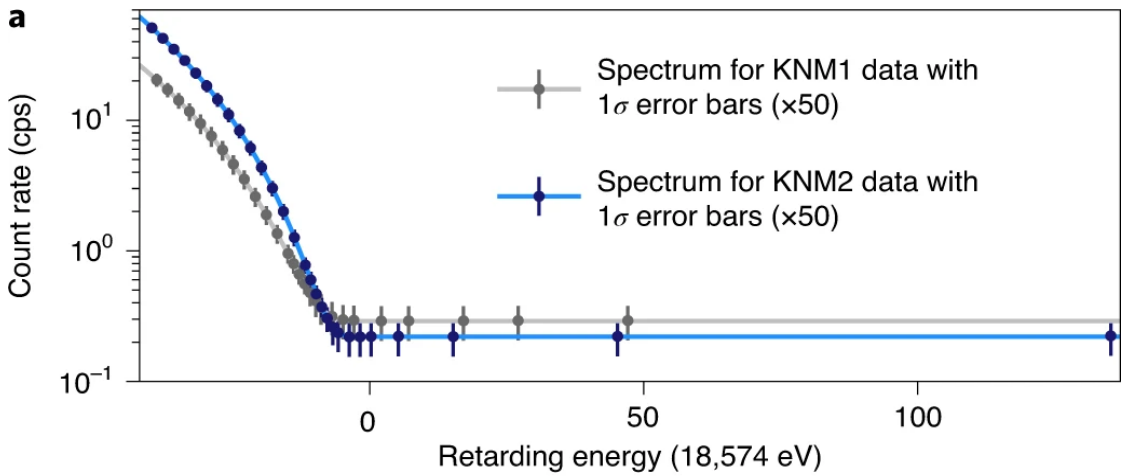
Further improvement: 100x higher rate
100x lower systematics
} sensitivity: 2eV → 0.2eV

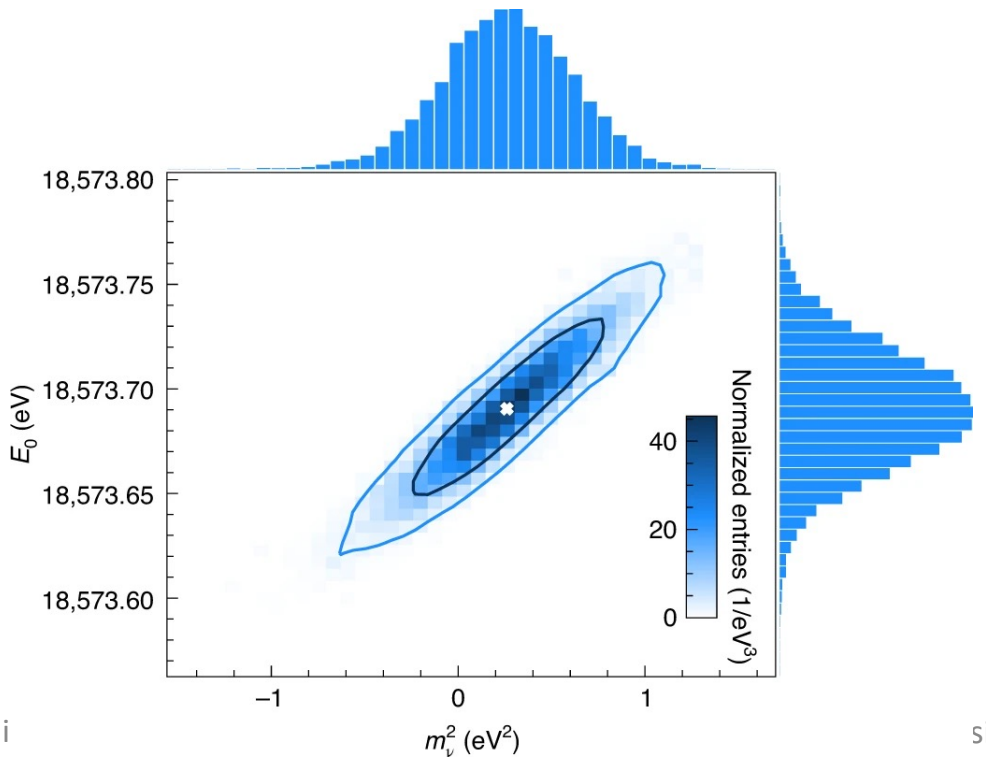


→ larger B_{max}/B_{min} ratio
→ larger filter diameter …

KATRIN Main Spectrometer on the road

Current sensitivity of KATRIN





latest result from early 2022
(common fit of endpoint energy & spectral deformation)

m_ν < 0.85 eV (90% C.L)

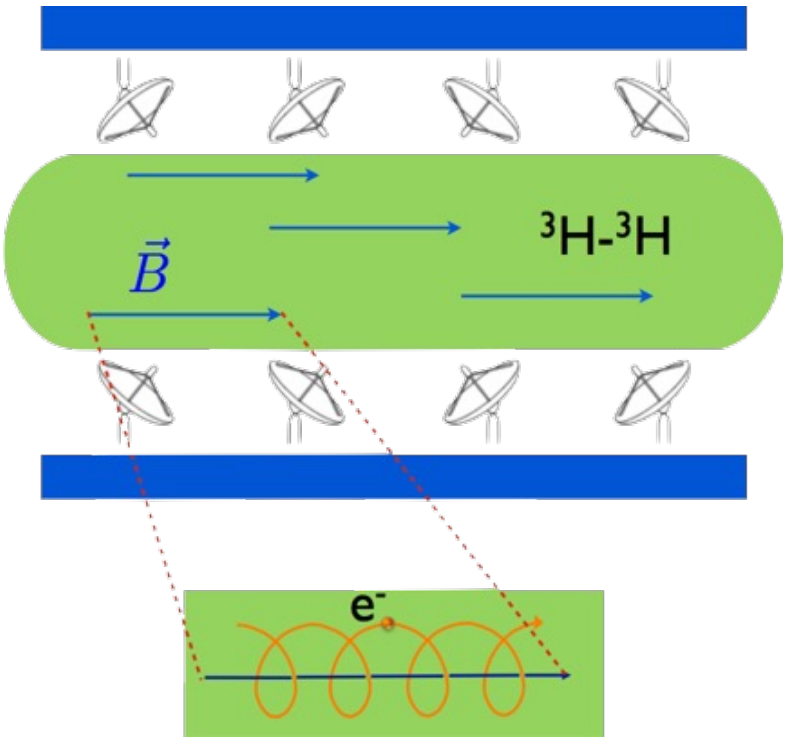
Alternatives: Project-8

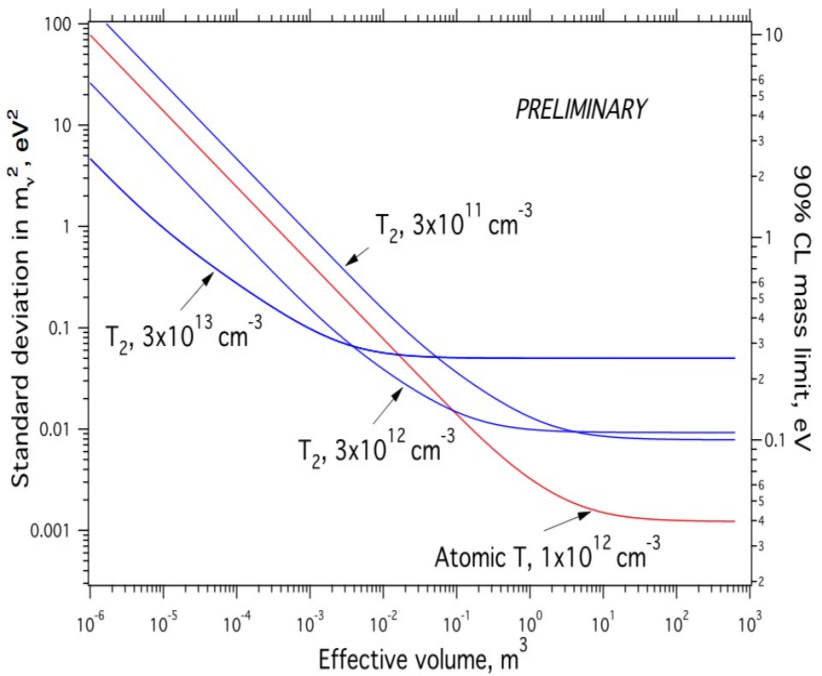
Novel concept based on gaseous tritium

- $T_{(2)}$ gas decays in strong magnetic field
- gyrating electrons emit synchrotron radiation
- β energy measured by radio-detection of synchrotron frequency:

$$f_\gamma = \frac{f_c}{\gamma} = \frac{1}{2\pi} \frac{eB_\perp}{m_e + E_{\mathrm{kin}}}$$

→ very accurate β-endpoint measurement



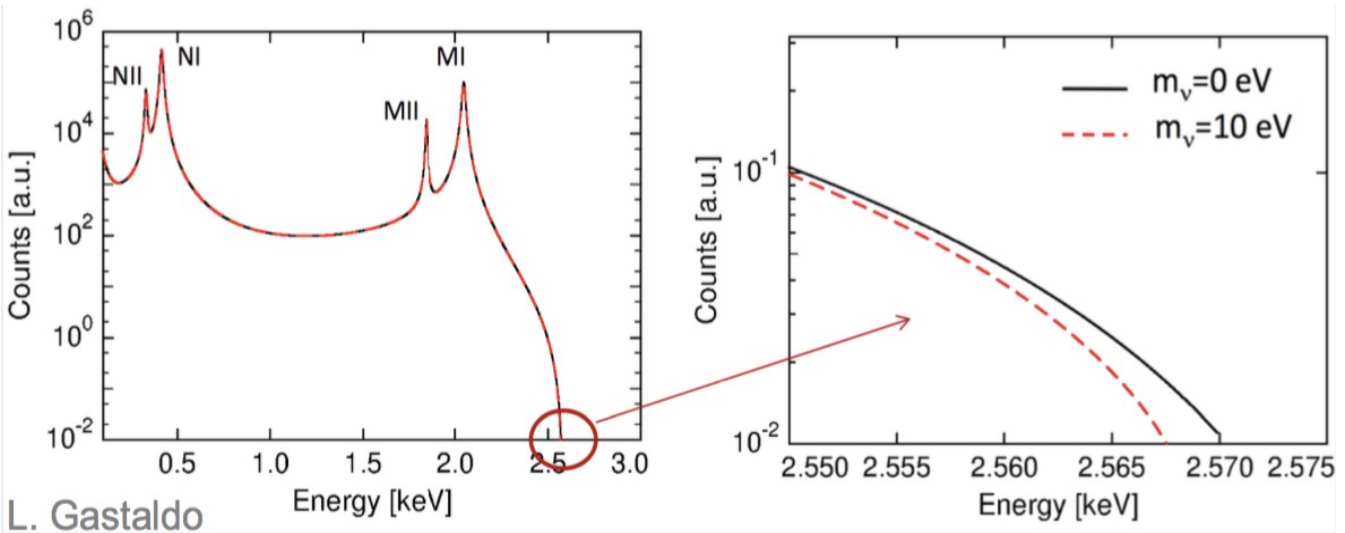


→ **Projected sensitivity**

- up to now: proof of principle
- with molecular T_2: $m(\nu_e) < 0.1$eV
- with atomar T: $m(\nu_e) < 0.04$eV

Alternatives: ECHO, ^{163}Ho

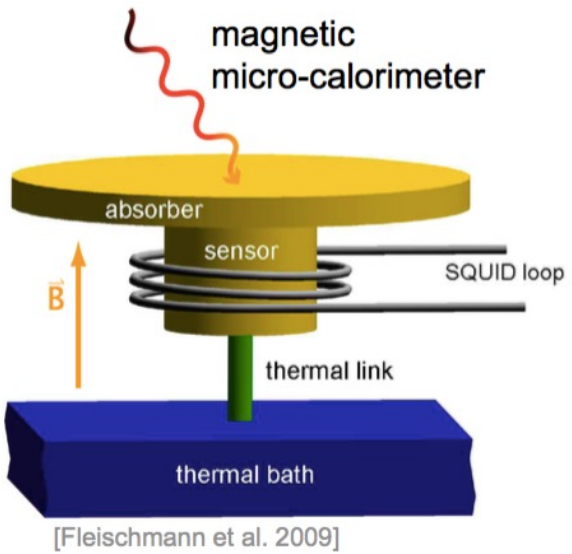
^{163}Ho (EC) ^{163}Dy*: Electron shell de-excitation spectrum



^{163}Ho EC

$Q_{EC} \approx 2.5$keV

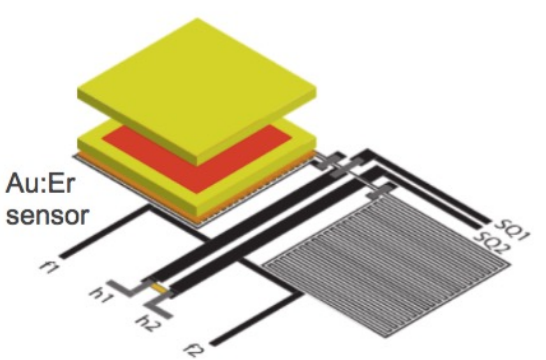
$T_{1/2} = 4570$a



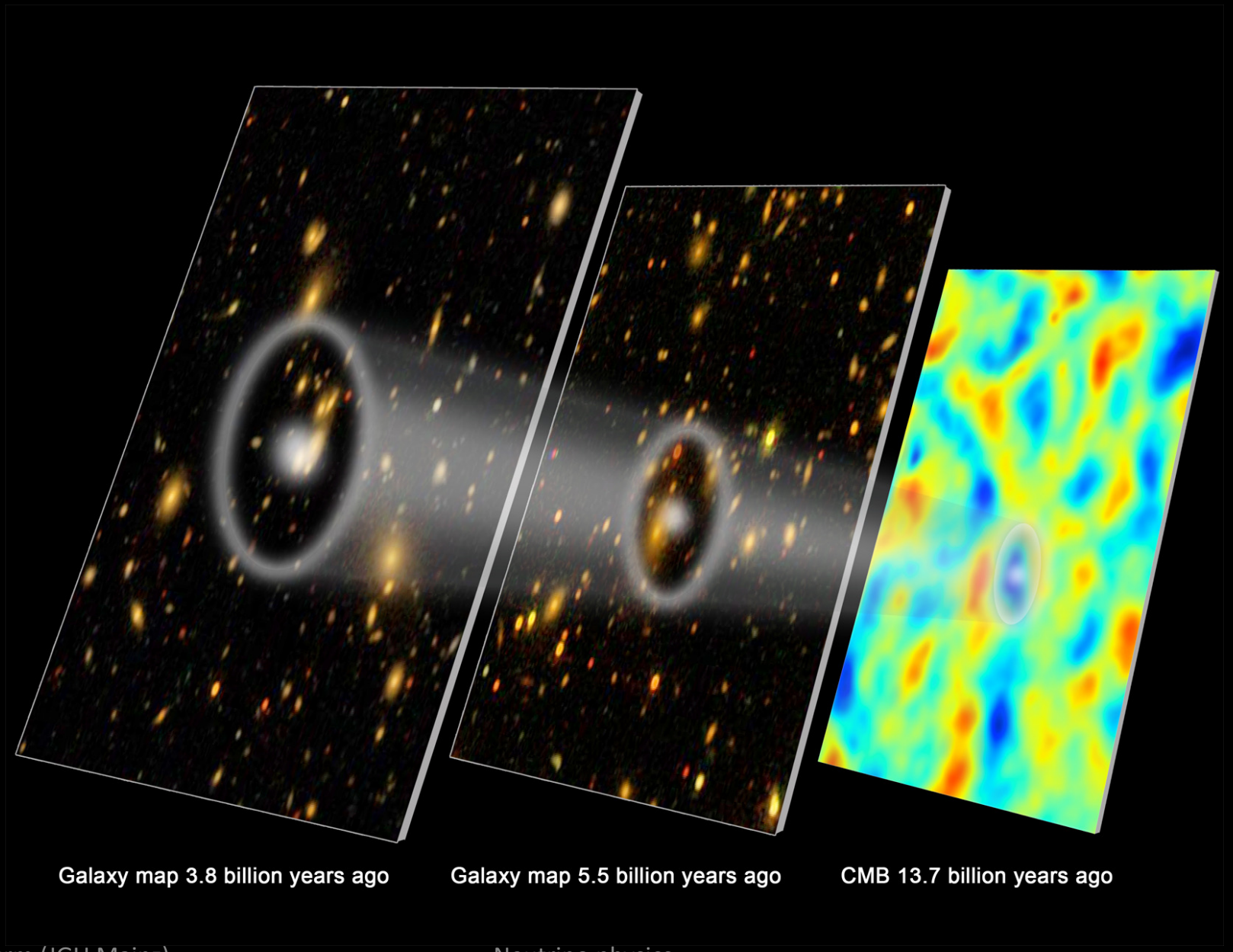
[Fleischmann et al. 2009]

- neutrino mass has impact on **spectral endpoint**
- ^{163}Ho atoms implemented in cryogenic Au:Er sensor
  → precise measurement of decay spectrum

- currently: best limit on $m(\nu_e) < 3xx$ eV
- next phase: 10^3 Bq, 1 yr → $m(\nu_e) < 10$ eV
- long-term: 10^6 Bq, 3 yrs → sub-eV limit



Neutrino limits from cosmology

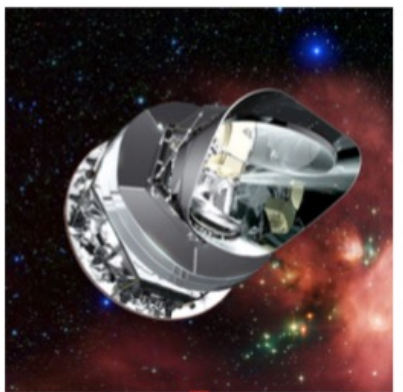


Cosmology and limits on neutrinos

The most popular ingredients

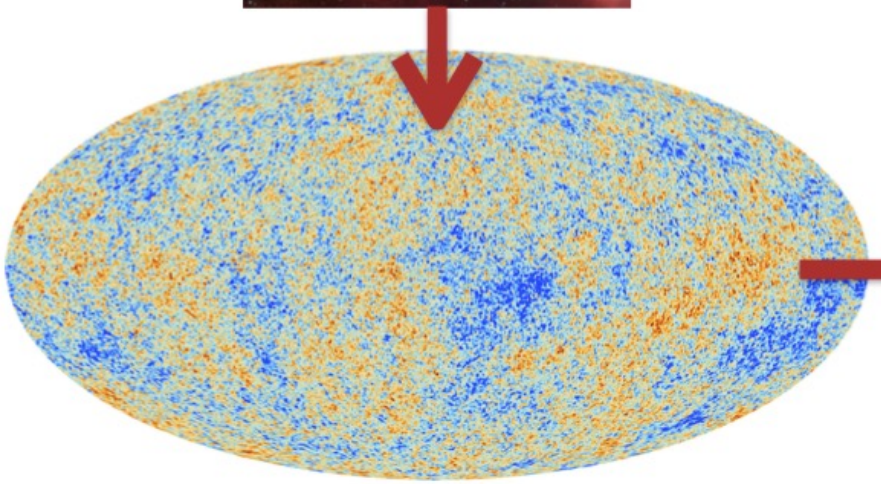
- Cosmic microwave background

- sum of neutrino masses Σm_ν
- relativistic neutrino flavors N_{eff}

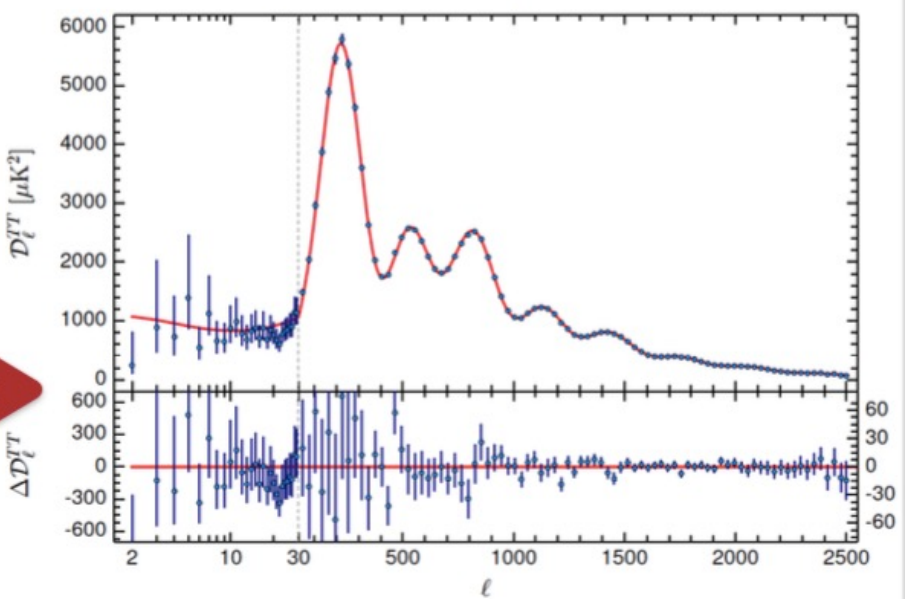


PLANCK satellite mission

→ angular correlation between CMB temperature/polarization variations



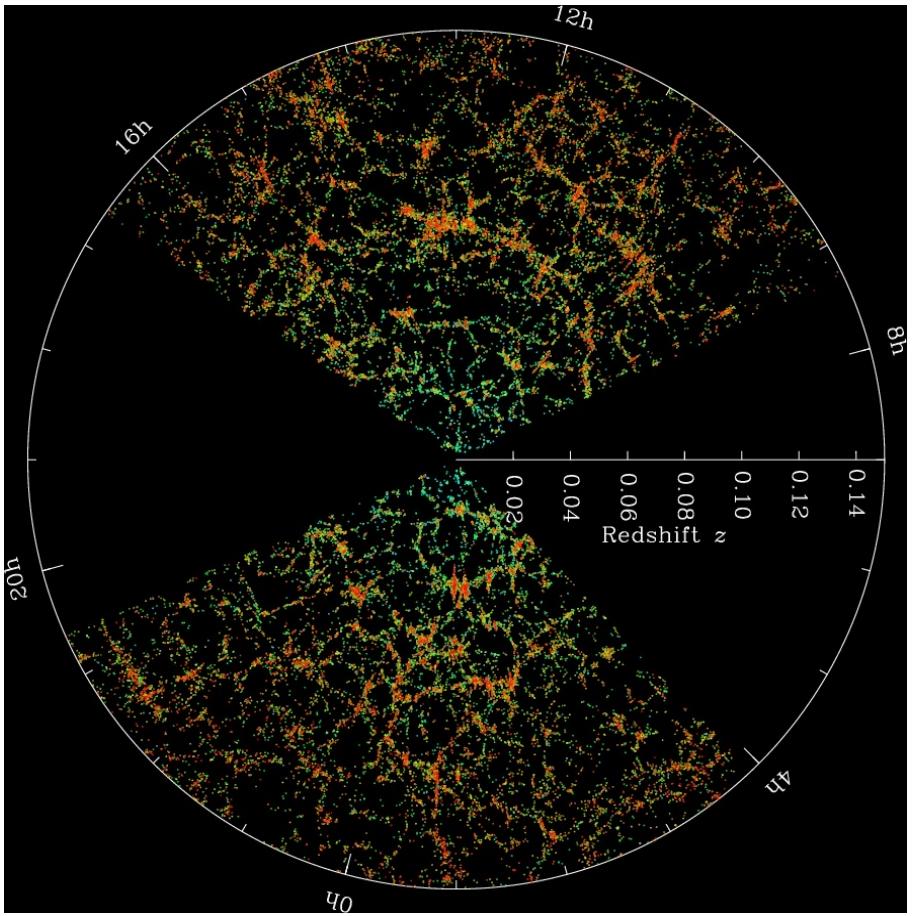
Ade et al. (Planck Coll.), arXiv:1502.01589



Cosmology and limits on neutrinos

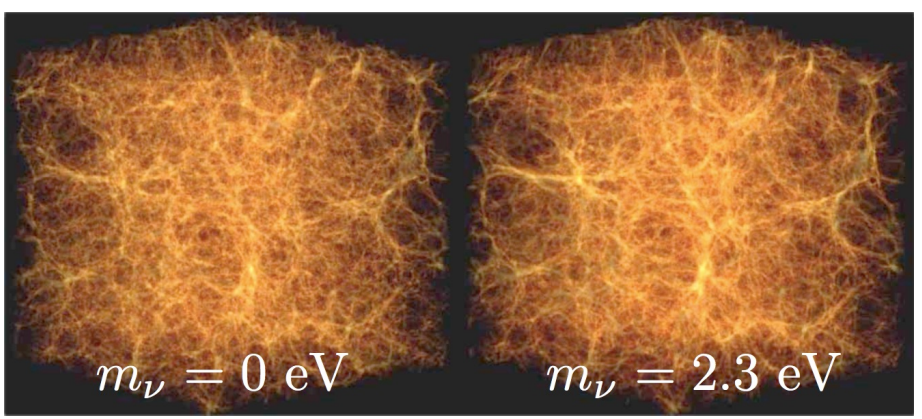
The most popular ingredients

- Cosmic microwave background (CMB)
- Baryon acoustic oscillations (BAO)



Sloan Digital Sky Survey (SDSS)

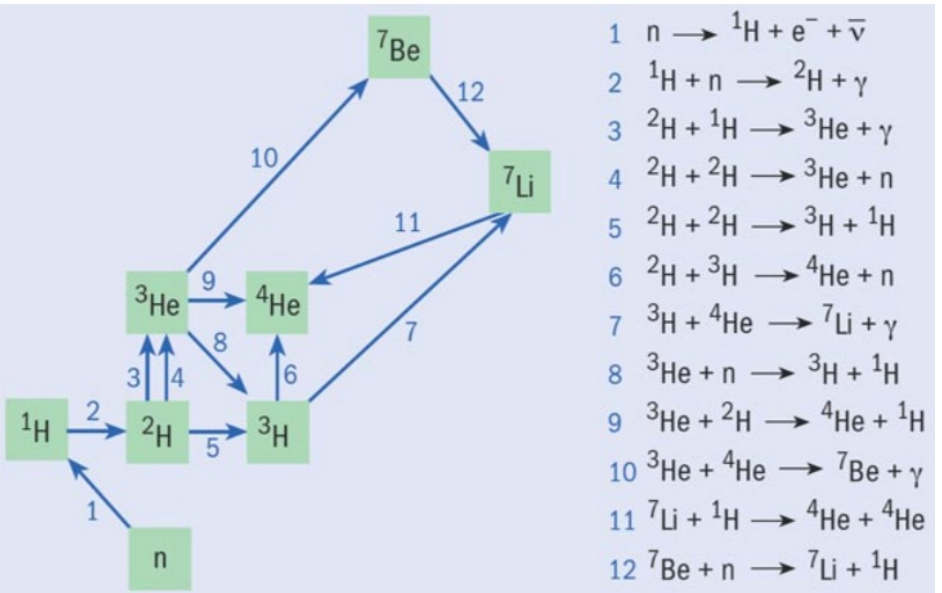
- mapping of galaxy positions out to high redshifts (z=0.15)
- galaxy cluster formation depends on neutrino free streaming

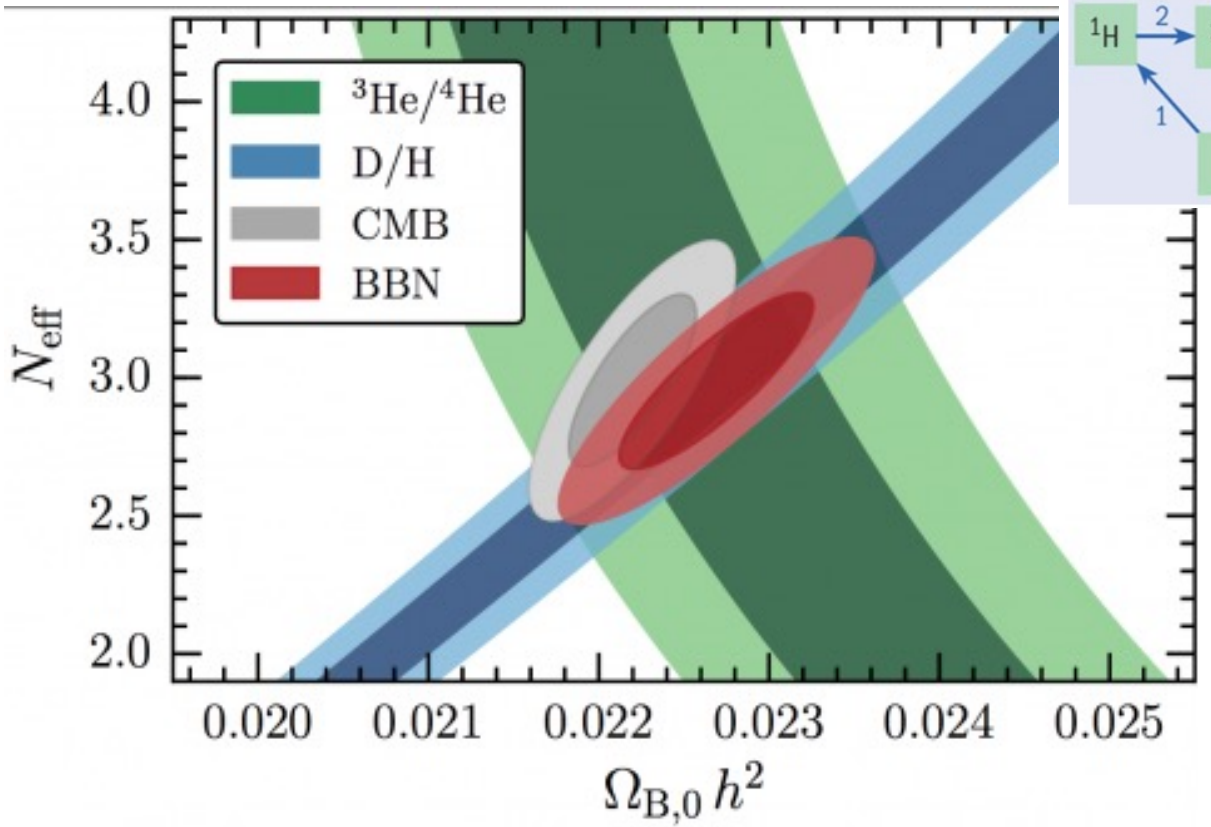


Cosmology and limits on neutrinos

The most popular ingredients

- Cosmic microwave background (CMB)
- Baryon acoustic oscillations (BAO)
- Big bang nucleosynthesis (BBN)

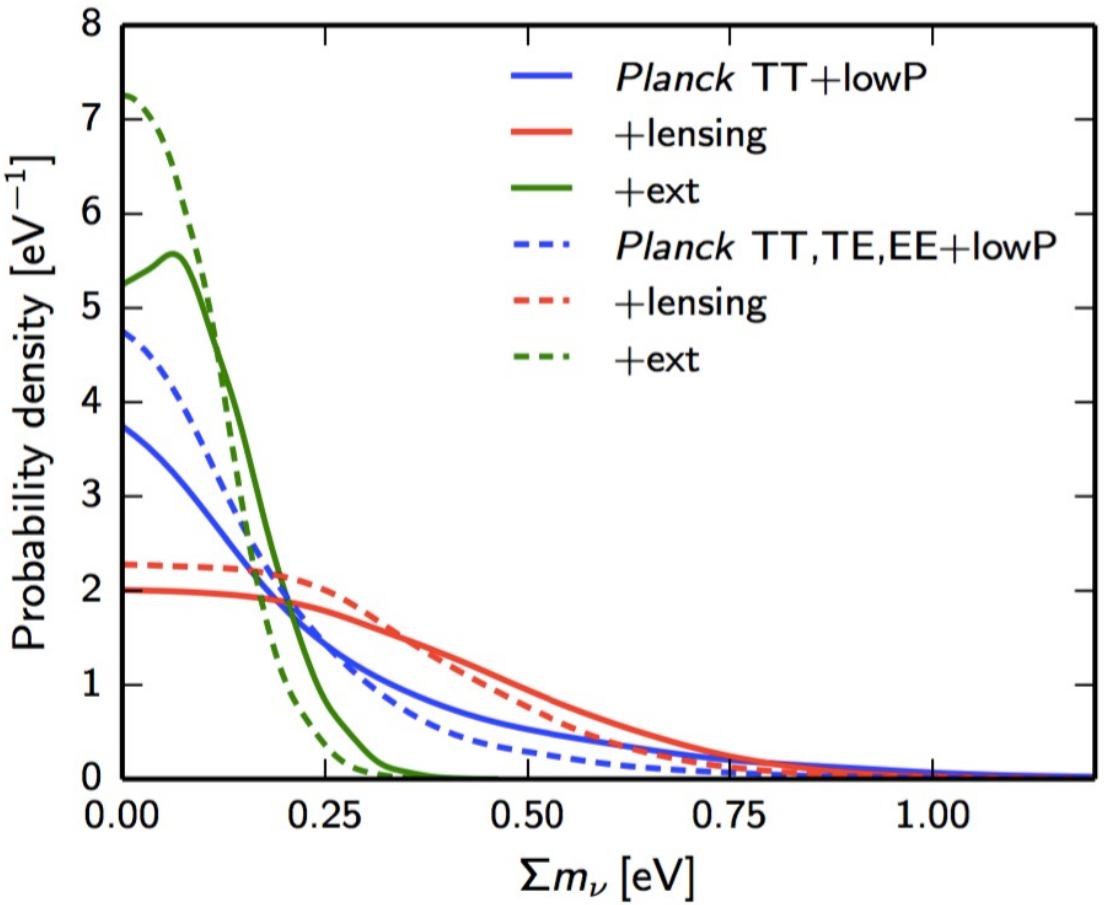




Abundances of D, ^{3}He, ^{4}He

- N_{eff} adds relativistic degrees of freedom to radiation density
  → expansion rate in early universe
- light elemental abundances depend on start of D formation by p+n→^{2}H

Cosmological limits on m_ν and N_{eff}



Planck temperature data + low-Z Hubble parameter

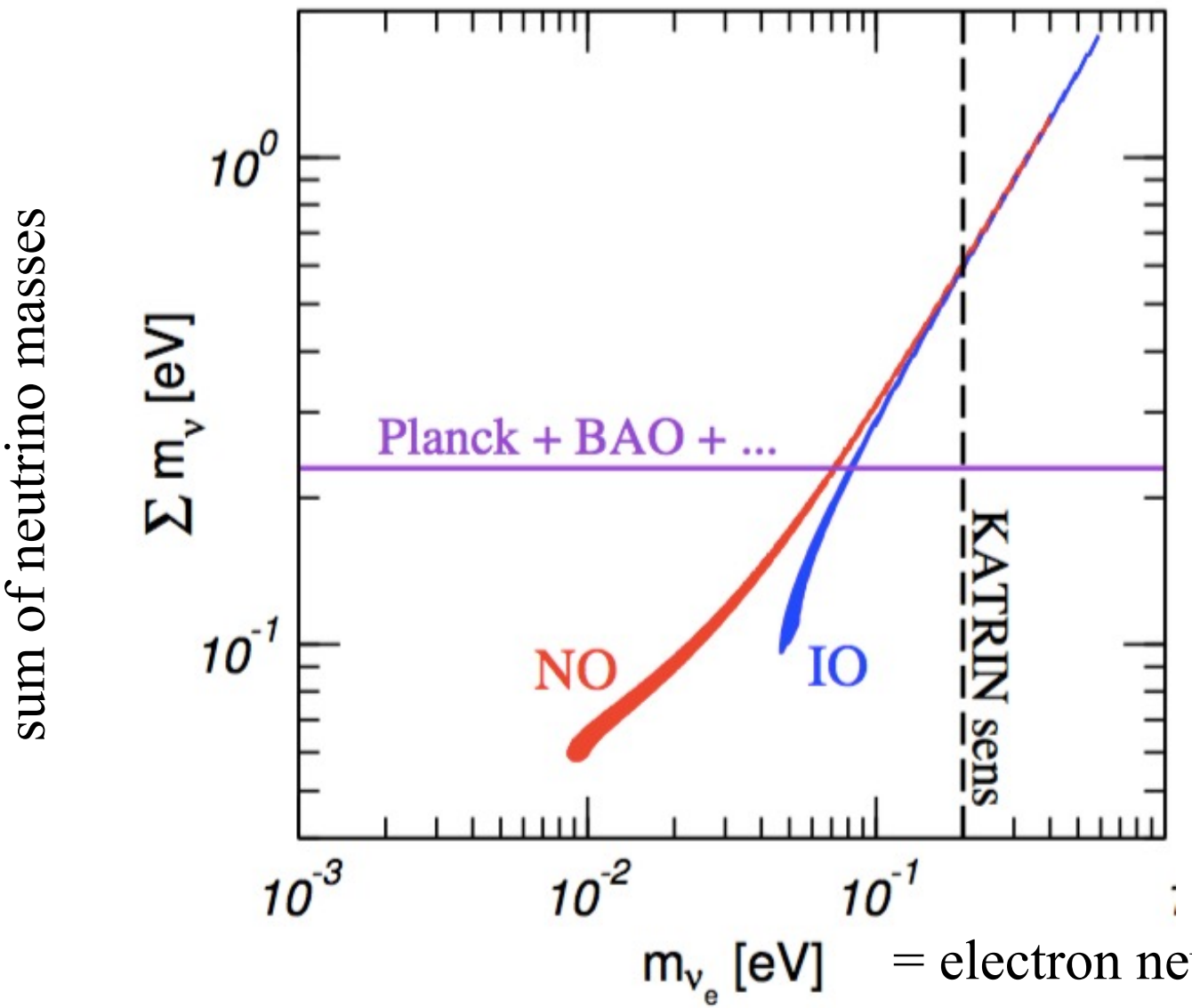
+ gravitational lensing

+ ext

Planck polarization data

→ range for upper limits: $\sum m_\nu < 0.17 - 0.72$ eV

Limits on the neutrino mass



LECTURE QUIZ

Question 5

Can the three mass eigenstates be resolved in a tritium decay experiment?

R : in principle yes

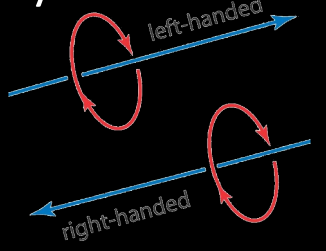
S : in principle no

T : depends on the mass ordering

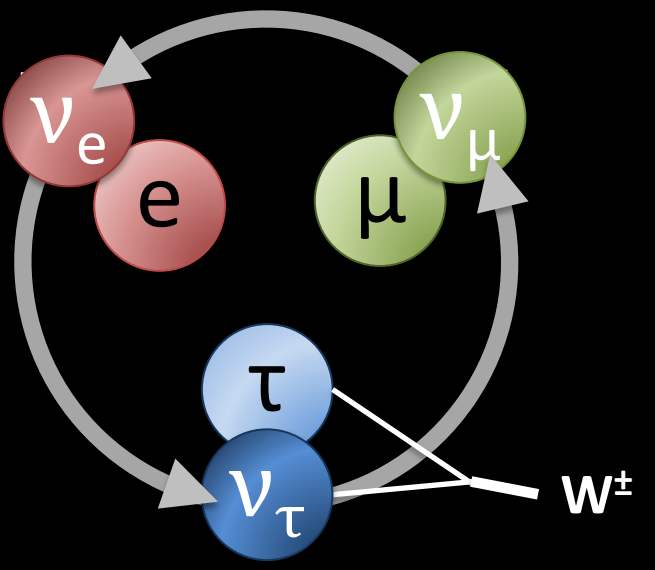
Note down the **11th letter** of the solution word.

Neutrinos in a nut-shell

- Neutrinos are fermions.
- no electric or color charge
- **but:** weak charge
- virtually but not completely massless
  [$\Sigma m_\nu < 0.23\text{eV} \approx 5\text{x}10^{-7}\ m_e$]
- **three kinds (flavors) of neutrinos**
  are produced/absorbed in weak interactions along with e^-, μ^-, τ^-
- **each neutrino has (is?) its antiparticle:**
  same properties but different chirality
  - neutrinos = left-handed
  - antineutrinos = right-handed



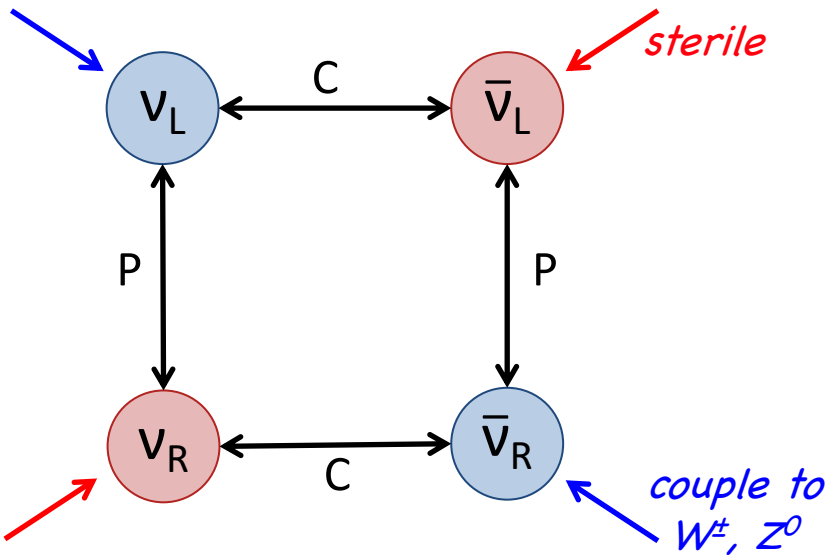
- **flavor and mass eigenstates are different**
  → neutrino oscillations

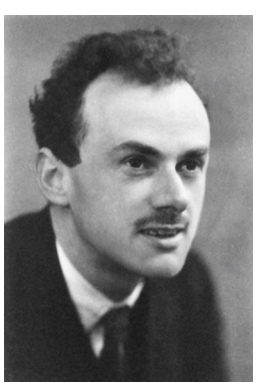


Dirac or Majorana neutrinos?

Two possibilities to generate neutrino masses:

DIRAC: $m_\nu \psi_R \psi_L$

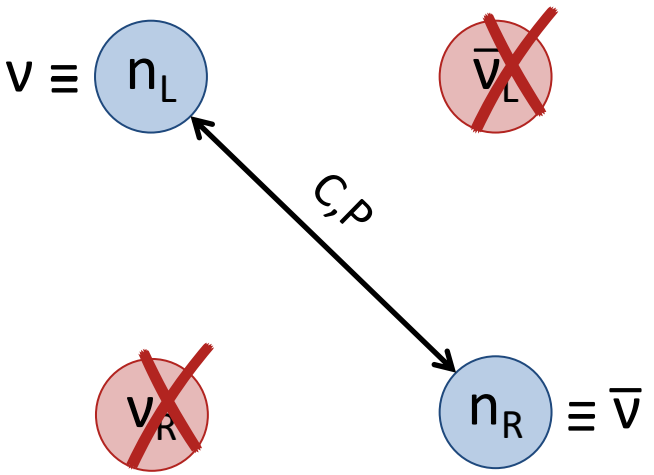




Paul Dirac

- SM Higgs mechanism
- active LH neutrinos and RH antineutrinos
- surplus RH neutrino and LH antineutrino (no weak coupling)

MAJORANA: $m_n \psi_L \psi_L^C$

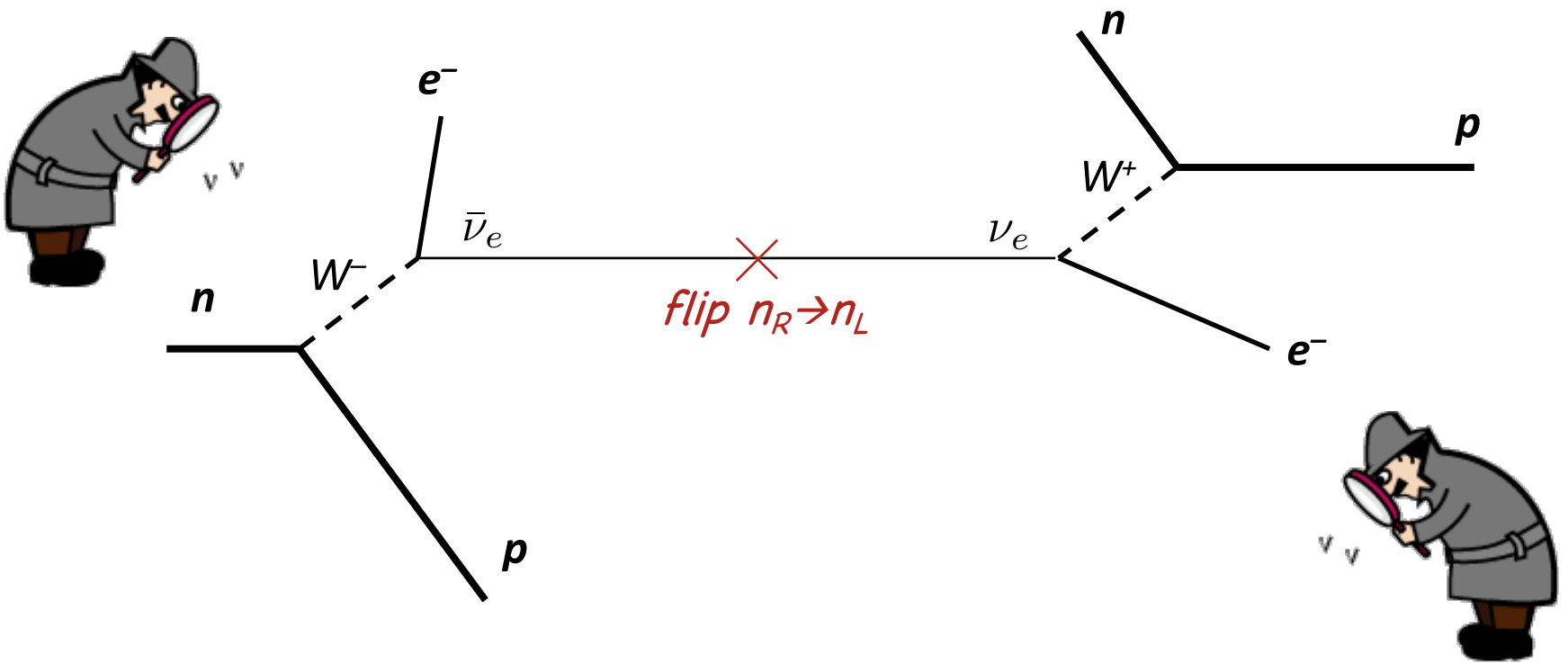


- only for **neutral** particles
- single particle n, acts as neutrino if LH, as antineutrino if RH
- surplus neutrino states not needed

Ettore Majorana

Experimental signature

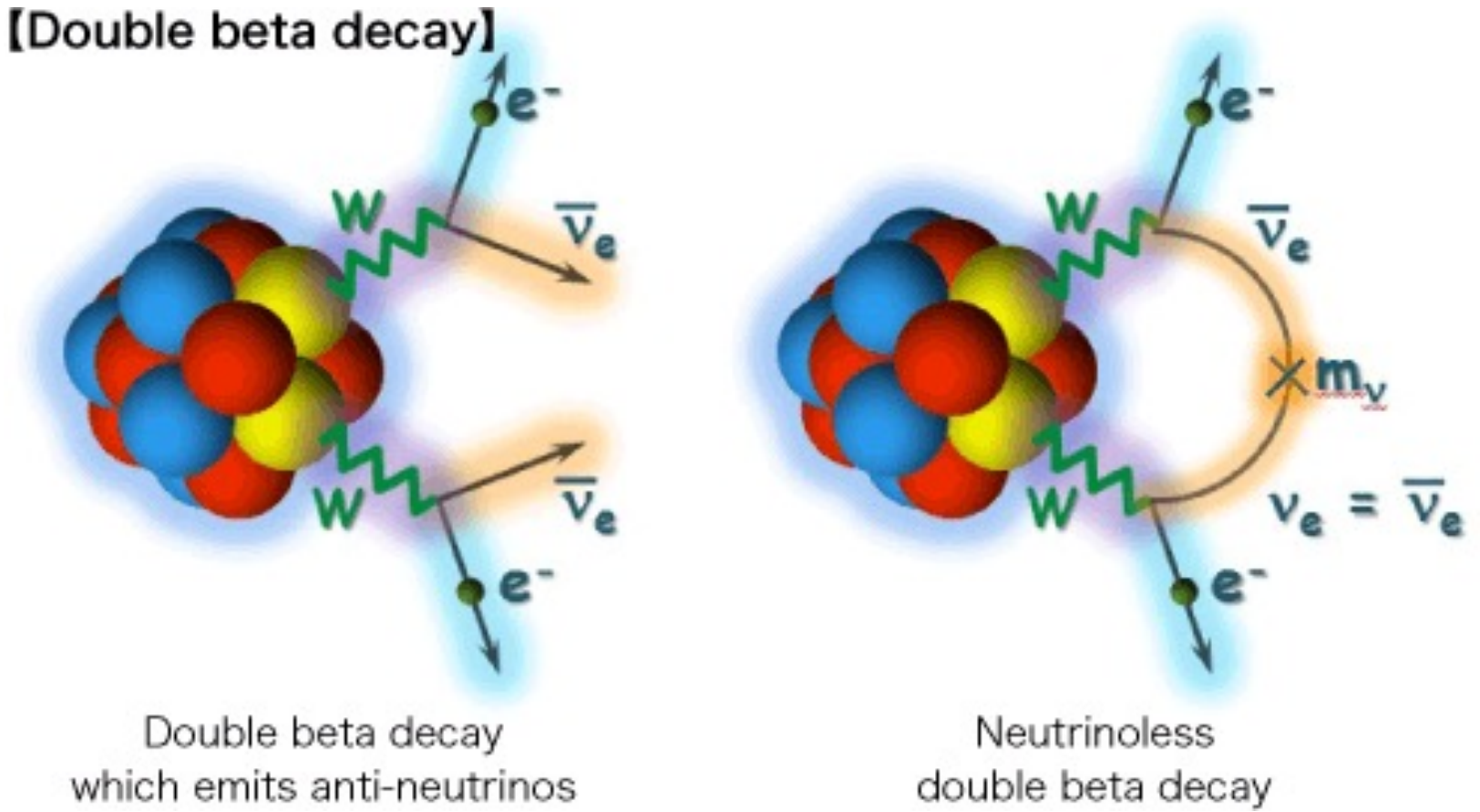
In principle: Easy. **This** (or similar) processes work only if $\nu = \nu_L \rightarrow \nu_R = \nu$
if it is observed → Majorana neutrinos



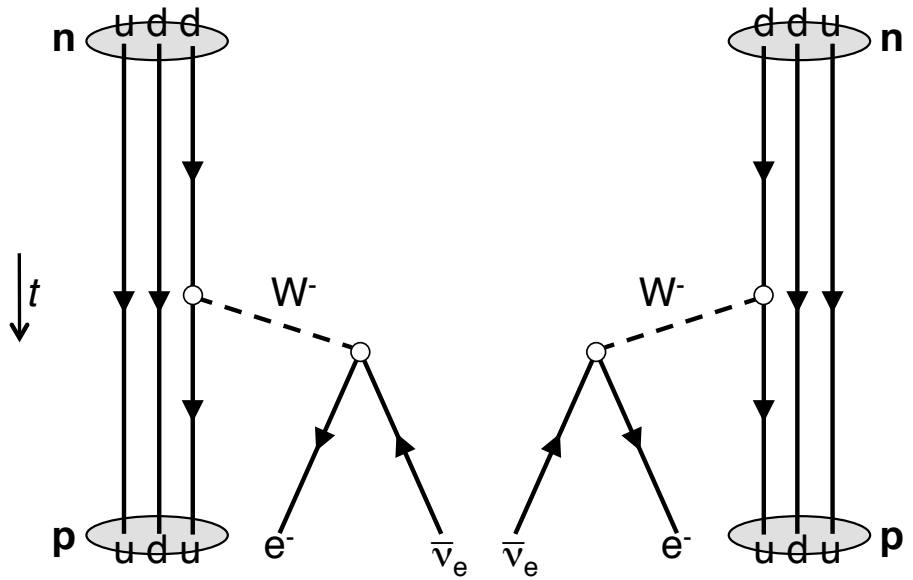
In practice: Very hard.
Neutrino mass is tiny: $P(n_R \rightarrow n_L) = ½ (1-v/c) \rightarrow 0$ for $v \rightarrow c$

→ best/only experimental approach: neutrino-less double-beta decay

Neutrinoless double beta decay



Double-beta decay

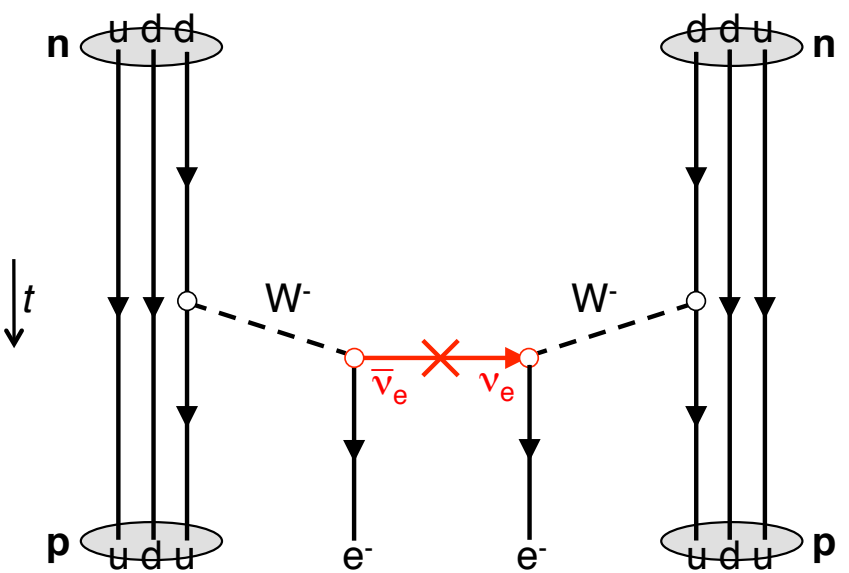


$2\nu\beta\beta$

- allowed in the Standard Model
- observed by many experiments:
  $T_{½} \geq 10^{20}$ yrs

- only for Majorana neutrinos
- not found yet

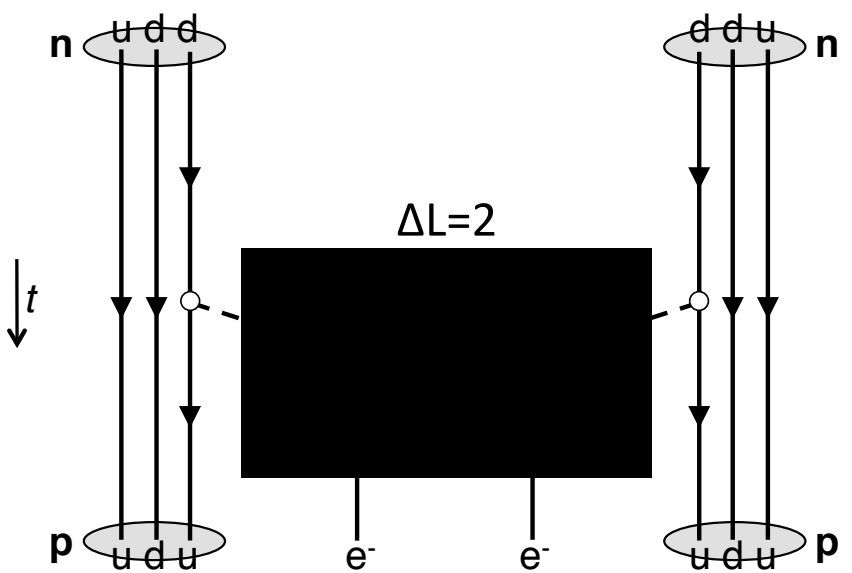
$0\nu\beta\beta$



What about alternative processes?

- only for Majorana neutrinos
- not found yet

$0\nu\beta\beta$



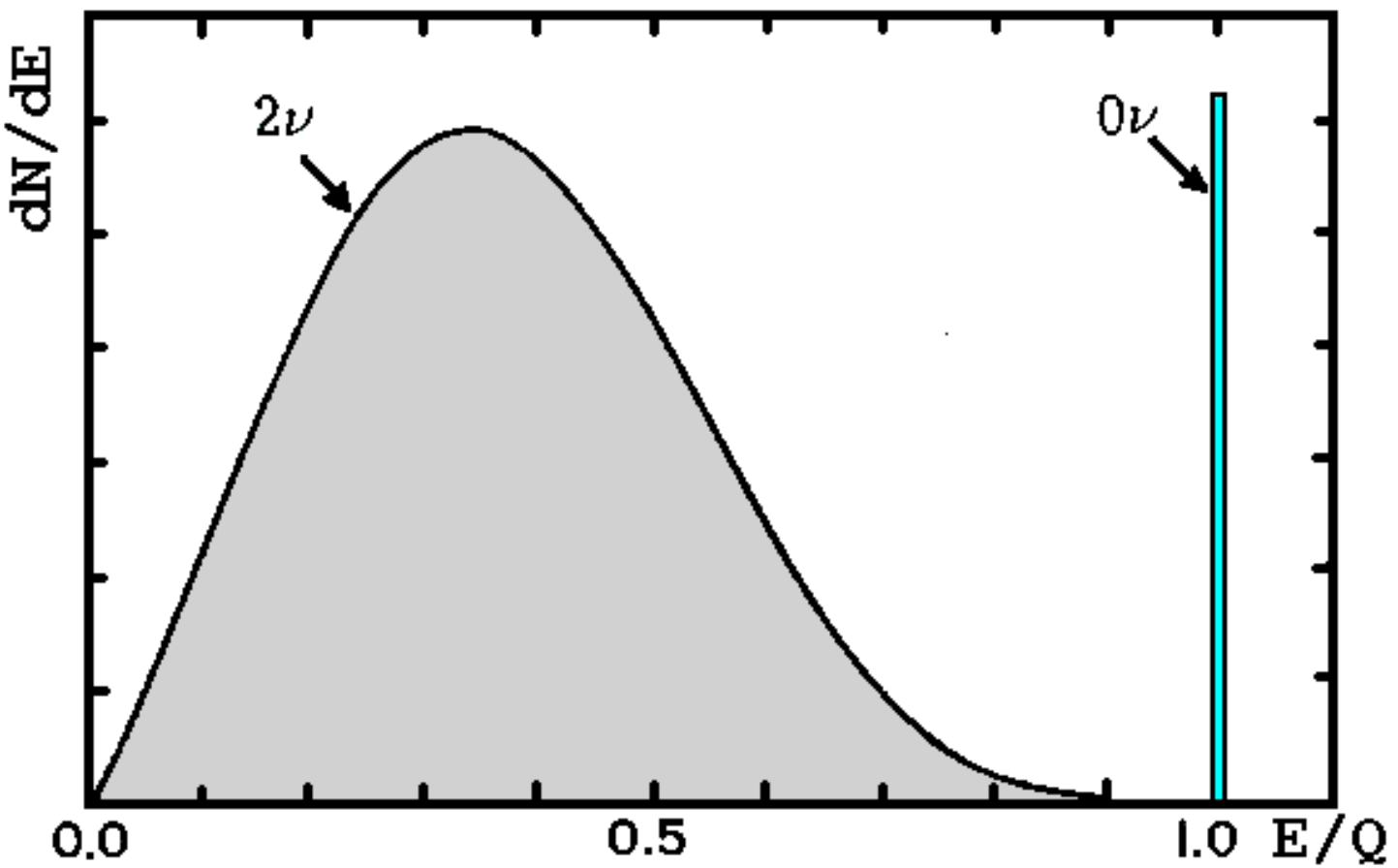
Is this the only mechanism for 0νββ?

No. But IF you observe it:

- ΔL=2 → lepton number violated
- neutrino is Majorana
  + some new BSM process
    (e.g. RH weak currents)

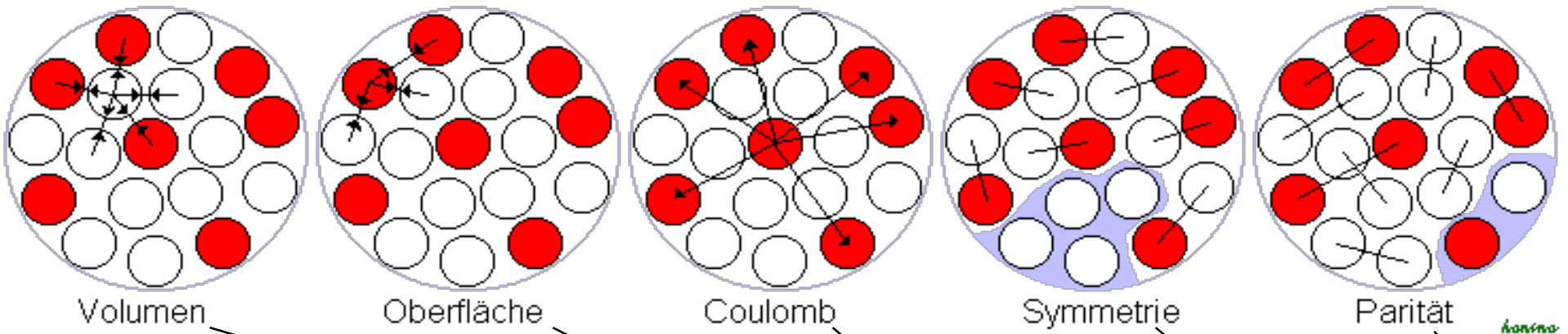
Signature of neutrinoless ββ-decay

Sum energy of the two electrons



Nuclear binding energy

Weizsäcker mass formula

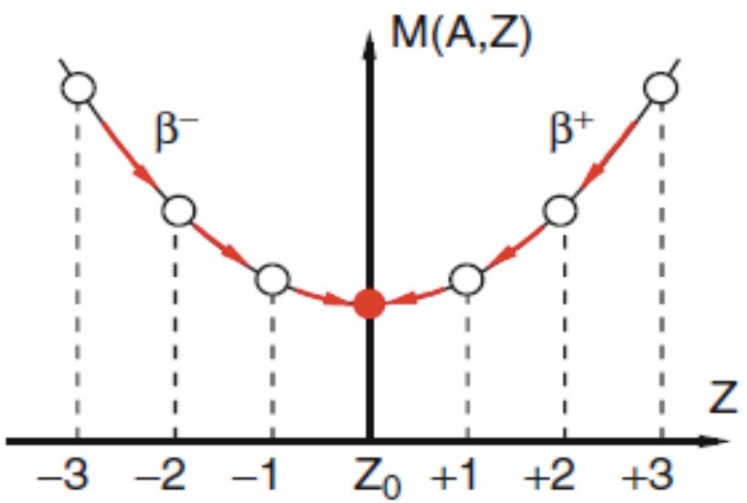


$$m(Z,A) = Zm_p + (A-Z)m_n - a_V A + a_S A^{2/3} + a_C Z^2 A^{-1/3} + a_A \frac{(2Z-A)^2}{A} + \delta_P$$

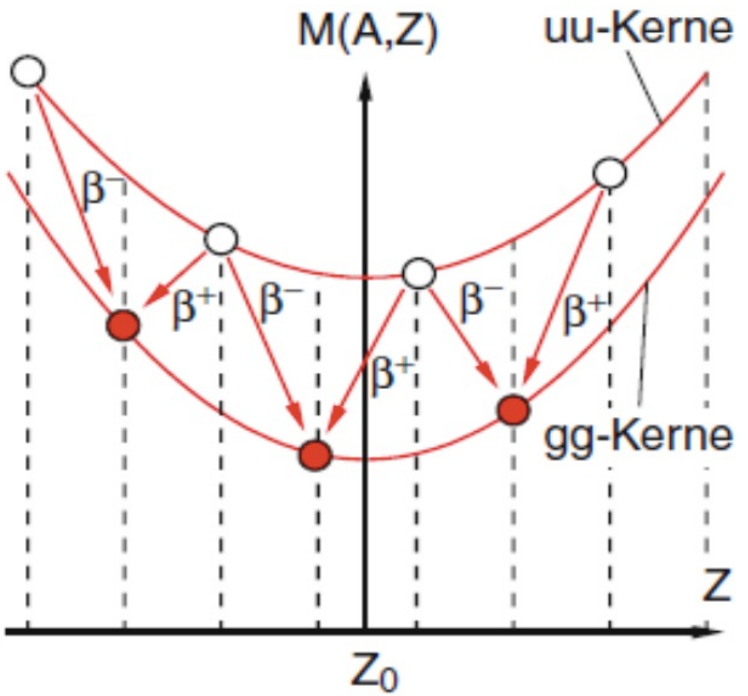
$$\text{pairing term}: \quad \delta_P \begin{cases} -a_P A^{-1/2} & \text{even-even nuclei} \quad (Z = \text{even}, N = \text{even}) \\ 0 & \text{even-odd nuclei} \\ +a_P A^{-1/2} & \text{odd-odd nuclei} \end{cases}$$

Nuclear mass of isobars (A=const.)

A odd

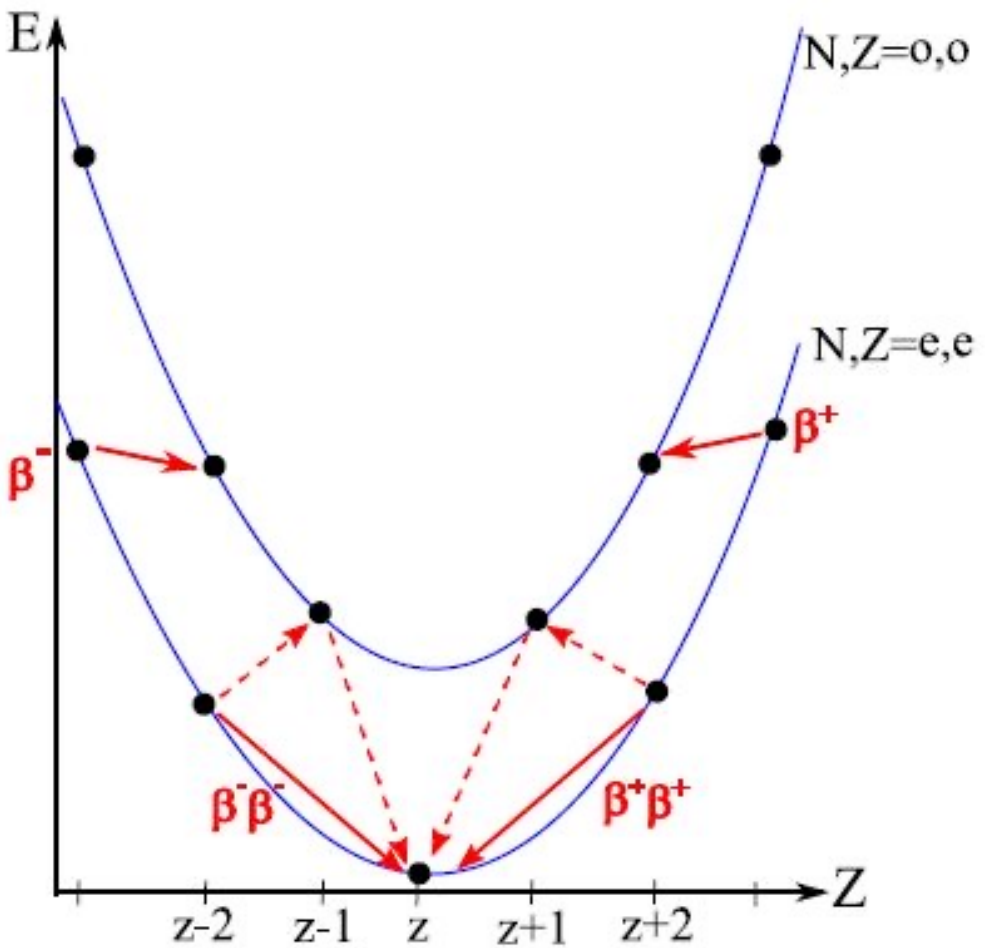


A even



Candidate nuclei

Mass parabula for isobars



Quite a few candidate isotopes:

- ^{48}Ca
- ^{76}Ge
- ^{82}Se
- ^{100}Mo
- ^{116}Cd
- ^{130}Te
- ^{136}Xe
- ^{150}Nd
- ...

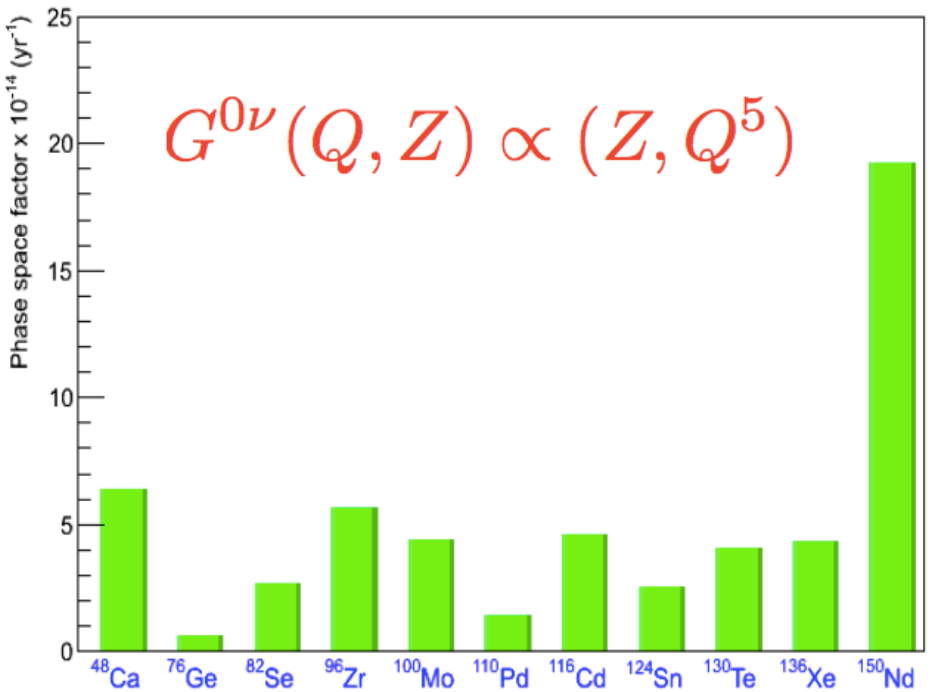
→ *ideal candidate?*

What makes a good 0νββ candidate?

Decay rate: $\Gamma^{0\nu} = \frac{1}{T^{0\nu}_{1/2}} = G^{0\nu}(Q,Z)\,|M^{0\nu}|^2\,\frac{|m_{\beta\beta}|^2}{m_e^2}$

nuclear matrix element — *phase space factor* — *probability of changing helicity*

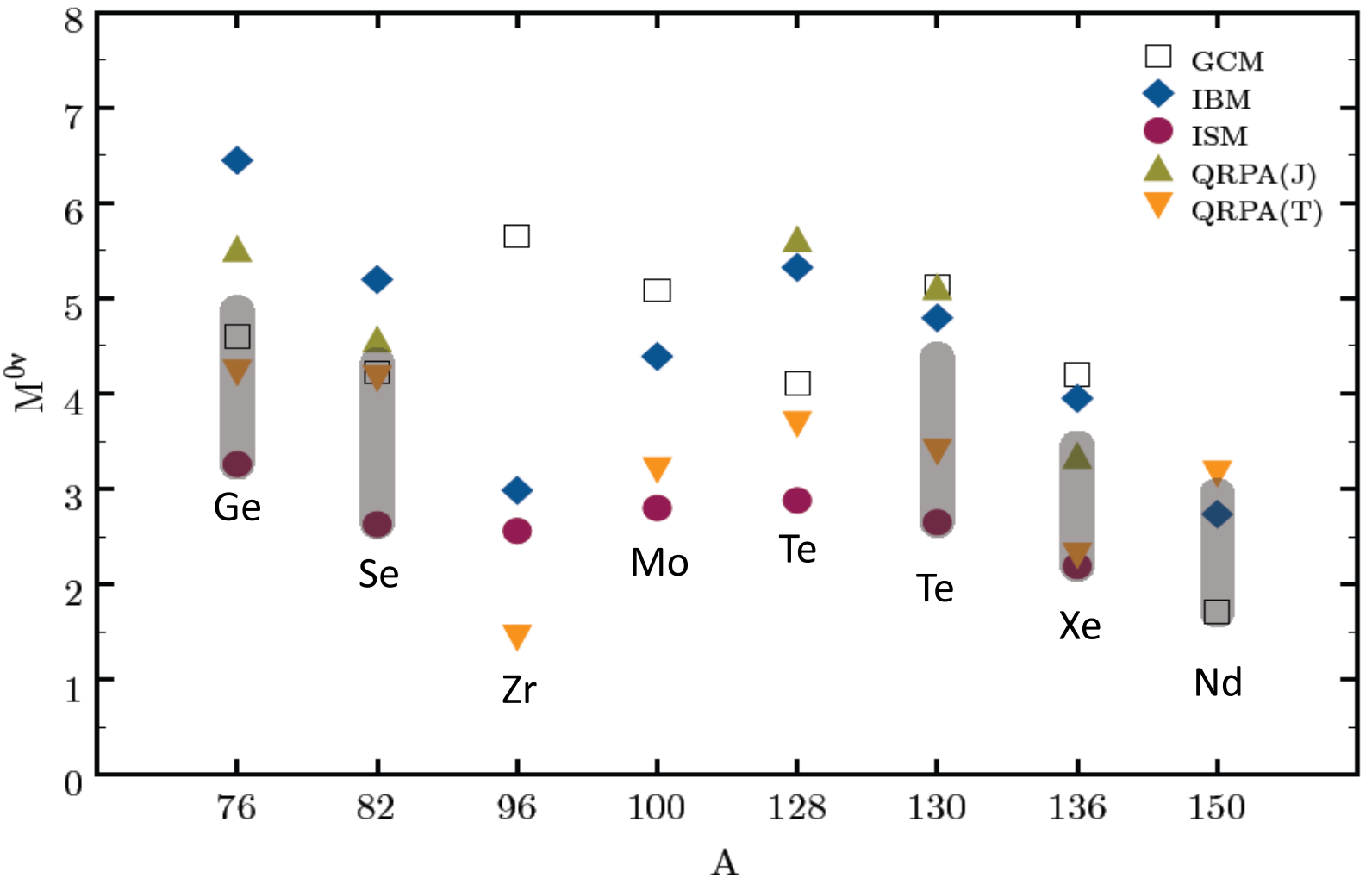
- Large phase space factor $G^{0\nu}$ → high count rate!



Transition	G [10^{-14} yr^{-1}]	Q [keV]
$^{48}Ca \rightarrow ^{48}Ti$	☺ 6.35	4373.7
$^{76}Ge \rightarrow ^{76}Se$	☹ 0.63	2039.1
$^{82}Se \rightarrow ^{82}Kr$	2.70	2995.5
$^{100}Mo \rightarrow ^{100}Ru$	4.36	3035
$^{116}Cd \rightarrow ^{116}Sn$	4.62	2809
$^{130}Te \rightarrow ^{130}Xe$	4.09	2530.3
$^{136}Xe \rightarrow ^{136}Ba$	4.31	2461.9
$^{150}Nd \rightarrow ^{150}Sm$	☺ 19.2	3367.3

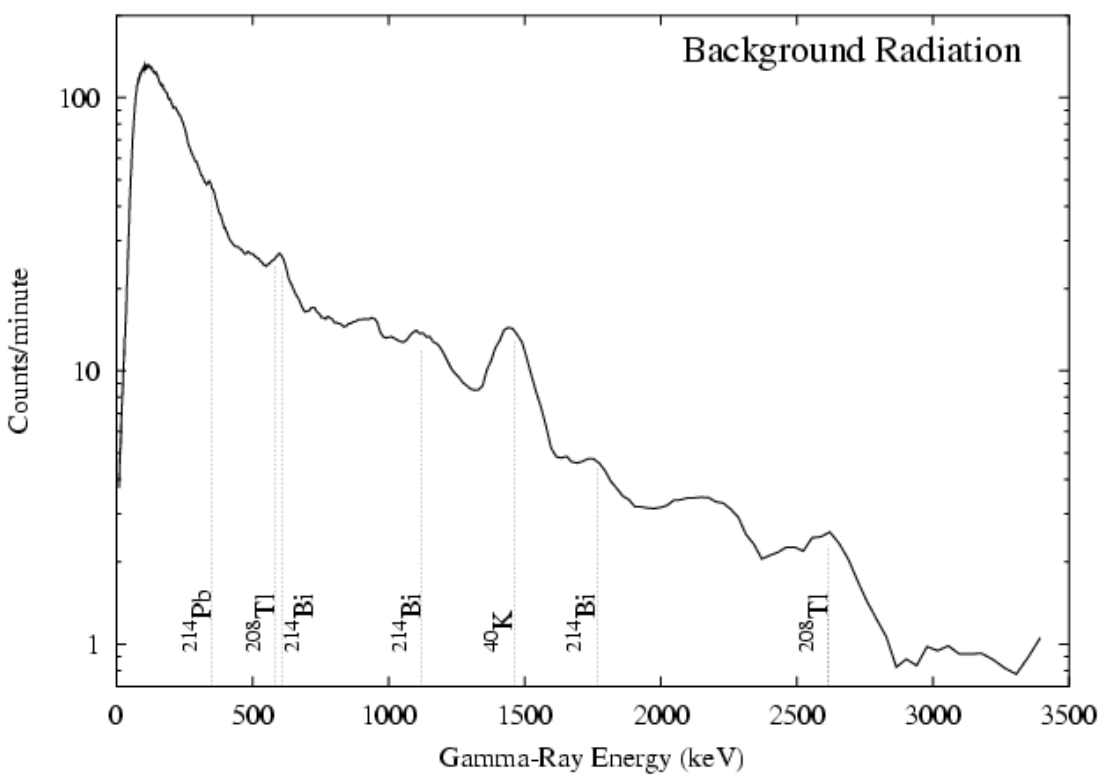
What makes a good candidate? (cont.)

- Large phase space factor $G^{0\nu}$
- Nuclear matrix element $|M^{0\nu}|^2$ → relatively large uncertainties



What makes a good candidate? (cont.)

- Large phase space factor $G^{0\nu}$
- Nuclear matrix element $|M^{0\nu}|^2$
- High value of $Q_{\beta\beta}$ → above natural background level (^{208}Tl γ-line)



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^{48}Ca → ^{48}Ti	☺ 6.35	☺ 4373.7
^{76}Ge → ^{76}Se	☹ 0.63	☹ 2039.1
^{82}Se → ^{82}Kr	2.70	☺ 2995.5
^{100}Mo → ^{100}Ru	4.36	☺ 3035
^{116}Cd → ^{116}Sn	4.62	☺ 2809
^{130}Te → ^{130}Xe	4.09	☹ 2530.3
^{136}Xe → ^{136}Ba	4.31	☹ 2461.9
^{150}Nd → ^{150}Sm	☺ 19.2	☺ 3367.3

What makes a good candidate? (cont.)

- Large phase space factor $G^{0\nu}$
- Nuclear matrix element $|M^{0\nu}|^2$
- High Q-value $Q_{\beta\beta}$
- High natural abundance a → high number of nuclei→ no isotope enrichment

Transition	G [10^{-14} yr^{-1}]	Q [keV]	a [%]
$^{48}Ca \rightarrow ^{48}Ti$	☺ 6.35	☺ 4373.7	☹ 0.2
$^{76}Ge \rightarrow ^{76}Se$	☹ 0.63	☹ 2039.1	7.8
$^{82}Se \rightarrow ^{82}Kr$	2.70	☺ 2995.5	8.7
$^{100}Mo \rightarrow ^{100}Ru$	4.36	☺ 3035	9.6
$^{116}Cd \rightarrow ^{116}Sn$	4.62	☺ 2809	7.5
$^{130}Te \rightarrow ^{130}Xe$	4.09	☹ 2530.3	☺ 34
$^{136}Xe \rightarrow ^{136}Ba$	4.31	☹ 2461.9	8.9
$^{150}Nd \rightarrow ^{150}Sm$	☺ 19.2	☺ 3367.3	5.6

What makes a good candidate? (cont.)

- Large phase space factor $G^{0\nu}$
- Nuclear matrix element $|M^{0\nu}|^2$
- High Q-value $Q_{\beta\beta}$
- High natural abundance a → effective ways for enrichment

Transition	G [10^{-14} yr^{-1}]	Q [keV]	a [%]	enrichment
$^{48}Ca \rightarrow ^{48}Ti$	6.35	4373.7	0.2	
$^{76}Ge \rightarrow ^{76}Se$	0.63	2039.1	7.8	
$^{82}Se \rightarrow ^{82}Kr$	2.70	2995.5	8.7	
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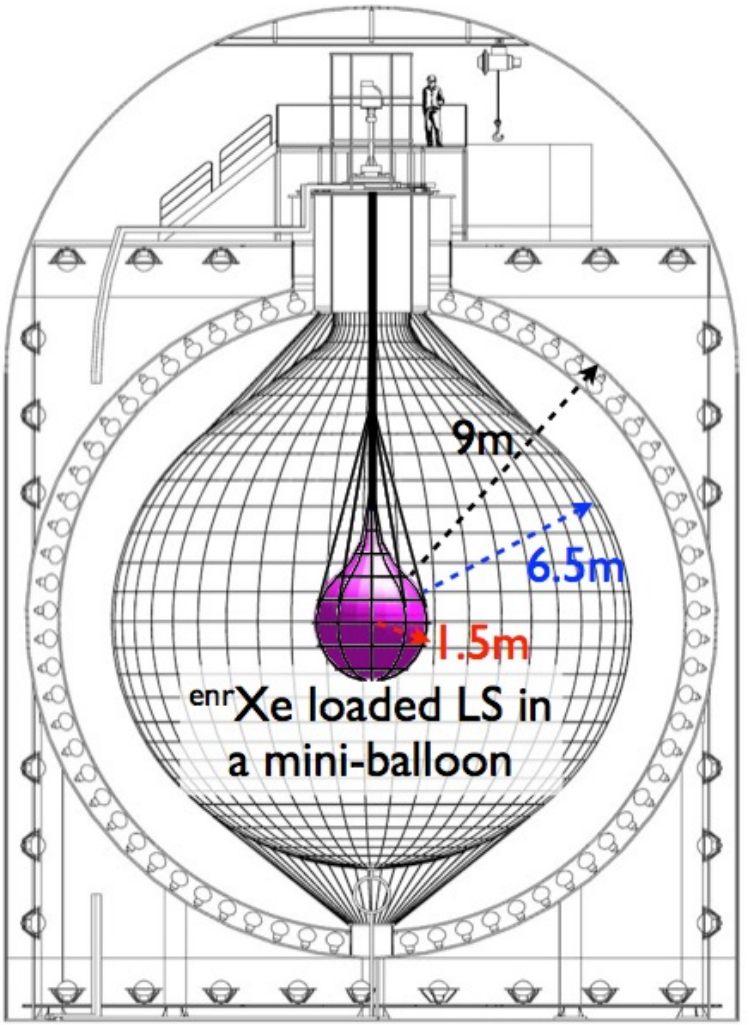
$^{150}Nd \rightarrow ^{150}Sm$	19.2	3367.3	5.6	

0ν2β experiments

Two state-of-the-art examples, but there are **many** more ...

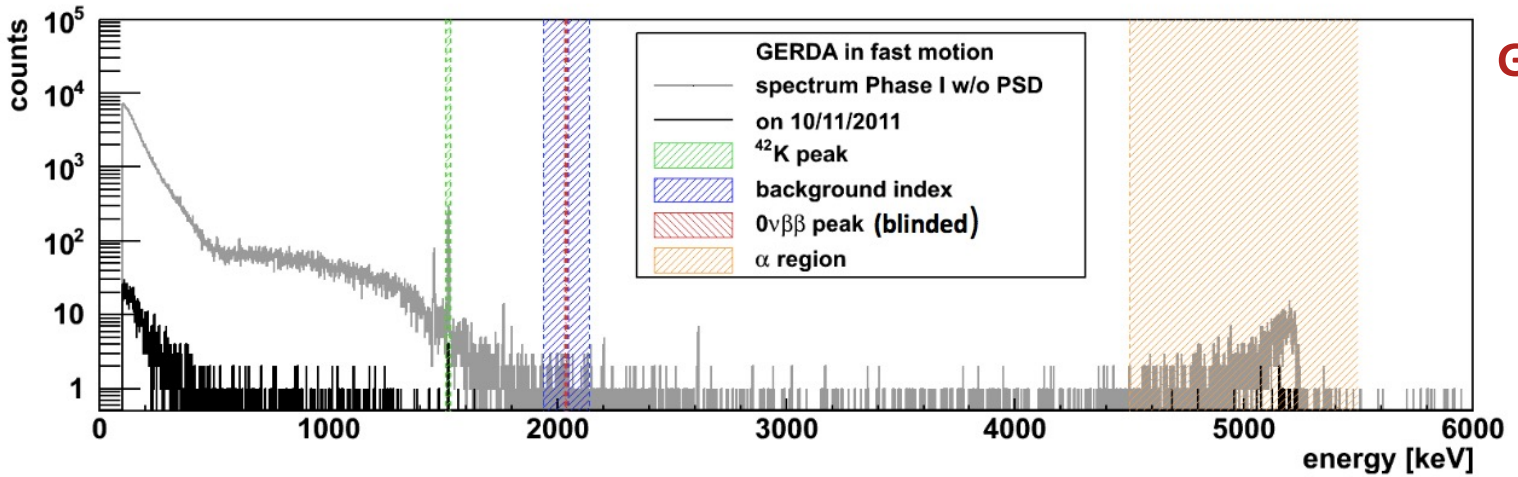
GERDA-Phase II: 43kg ^{76}Ge



KamLAND-ZEN 800: 800kg ^{136}Xe

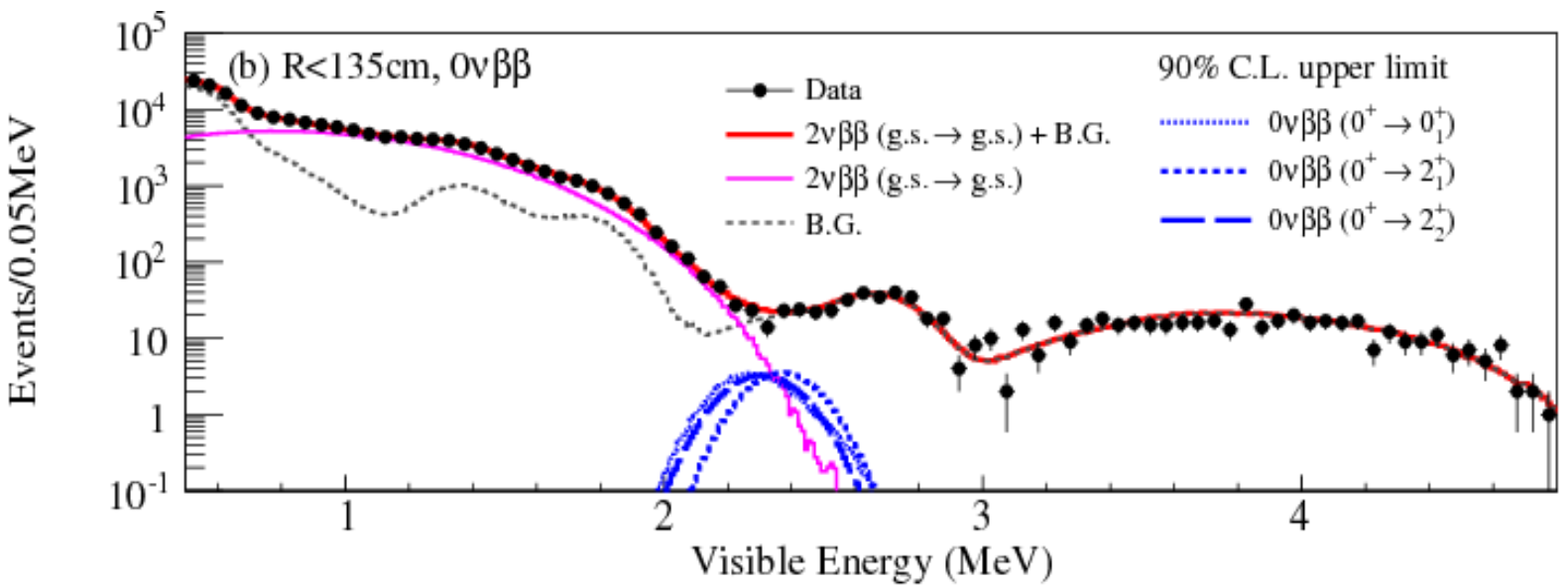
Energy spectra of 0ν2β experiments

- Detector properties: Energy resolution, particle identification



GERDA

- ^{76}Ge
- Q = 2039 keV
- ΔE/E ~ 0.1%
- PSD

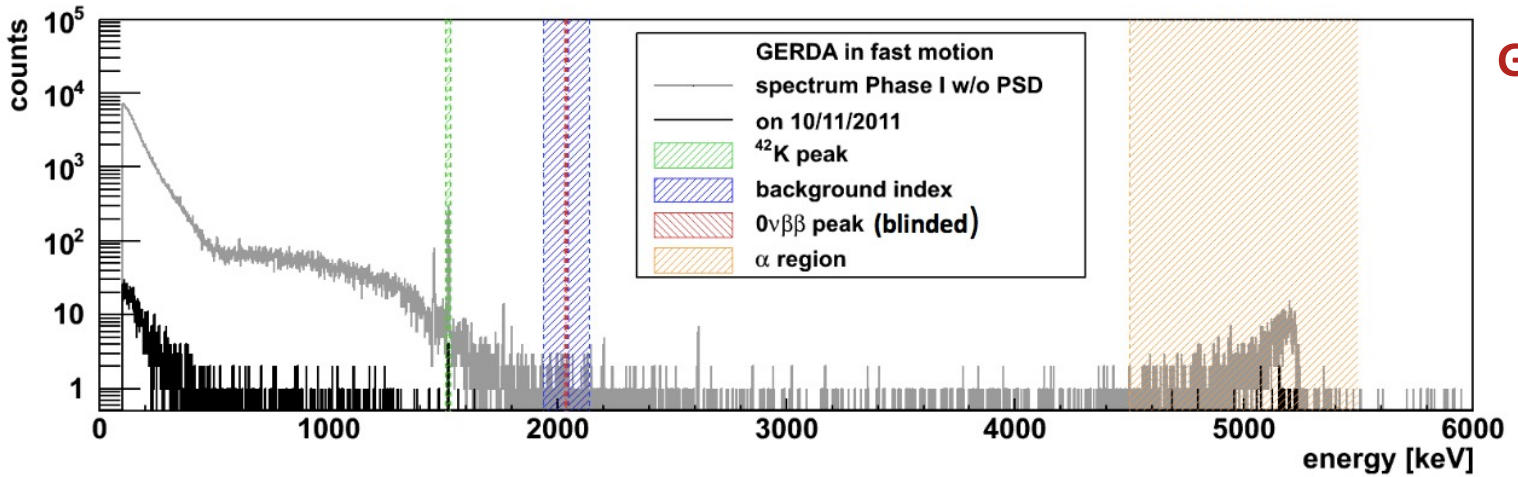


KamLAND-ZEN

- ^{136}Xe
- Q = 2462 keV
- ΔE/E ~ 4.2%
  → 2νββ BG

Energy spectra of 0ν2β experiments

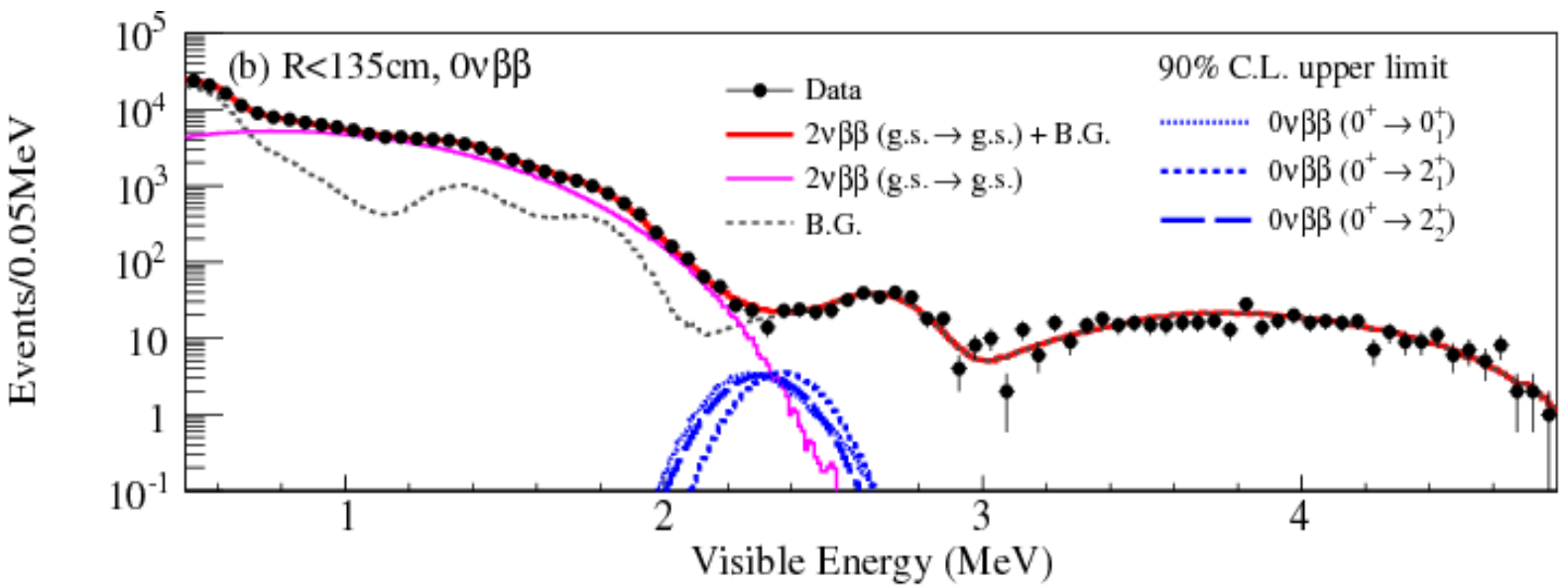
- Detector properties: Energy resolution, particle identification



GERDA

- ^{76}Ge
- Q = 2039 keV
- ΔE/E ~ 0.1%
- PSD

→ $T_{½} > 1.8 \times 10^{26}$ yrs



KamLAND-ZEN

- ^{136}Xe
- Q = 2462 keV
- ΔE/E ~ 4.2%
  → 2νββ BG

→ $T_{½} > 1.07 \times 10^{26}$ yrs

Expected 0νββ-decay rate

Decay rate: $\Gamma^{0\nu} = \frac{1}{T^{0\nu}_{1/2}} = G^{0\nu}(Q,Z)\,|M^{0\nu}|^2\,\frac{|m_{\beta\beta}|^2}{m_e^2}$

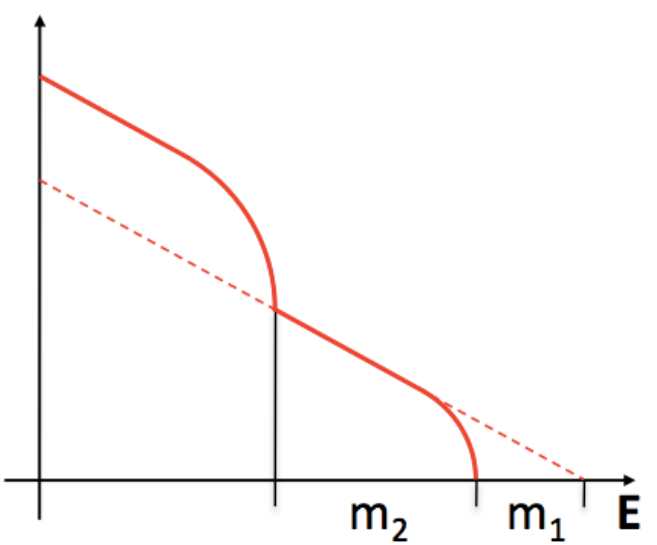
nuclear matrix element — *phase space factor* — *probability of changing helicity*

- Helicity change depends on effective ββ neutrino mass:

$$m_{\beta\beta} = \left|\sum_i U_{ei}^2 m_i\right| \quad \rightarrow \text{coherent sum}$$

- for comparison: β-endpoint measurements look for

$$m_\beta^2 = \sum_i |U_{ei}^2| m_i^2 \quad \rightarrow \text{incoherent sum} \quad \rightarrow$$



Majorana CP phases

Extended PMNS matrix for Majorana neutrinos

$$U = \begin{bmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{bmatrix}$$

standard neutrino oscillations: Dirac CPV via δ

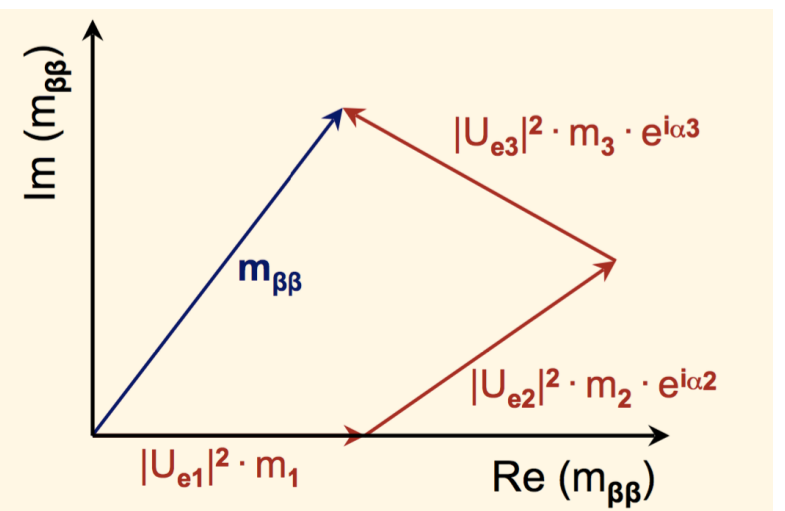
only for Majorana neutrinos! → no effect on oscillations

$$= \begin{bmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{bmatrix} \begin{bmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{bmatrix} \begin{bmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} 1 & 0 & 0 \\ 0 & e^{i\alpha_1/2} & 0 \\ 0 & 0 & e^{i\alpha_2/2} \end{bmatrix}$$

0νββ is **coherent sum**:

$$m_{\beta\beta} = \left| \sum_i U_{ei}^2 m_i \right|$$

→ complex phases have to be considered:

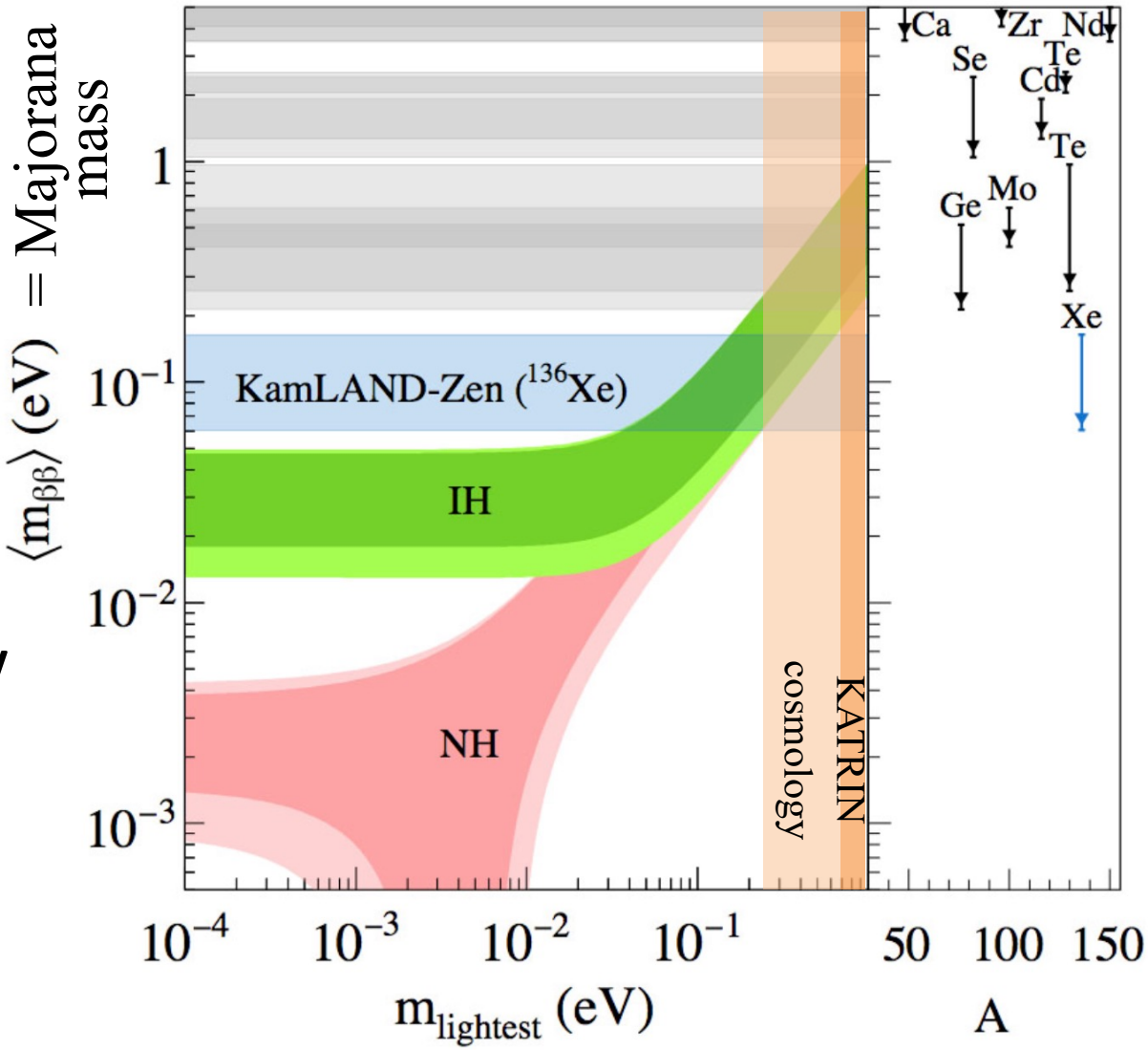


0νββ: CP phases and mass hierarchy

- **CP phases** define effective Majorana neutrino mass m_{ee}

$$m_{\beta\beta} = \left| \sum_i U_{ei}^2 m_i \right|$$

- width of the bands reflects influence of Majorana phases
- **Mass ordering/hierarchy** determines minimum value of Majorana mass (if there is)



= lightest neutrino mass

LECTURE QUIZ

Question 6

What properties of isotopes makes them a good double-beta candidate?

M : even proton and neutron numbers

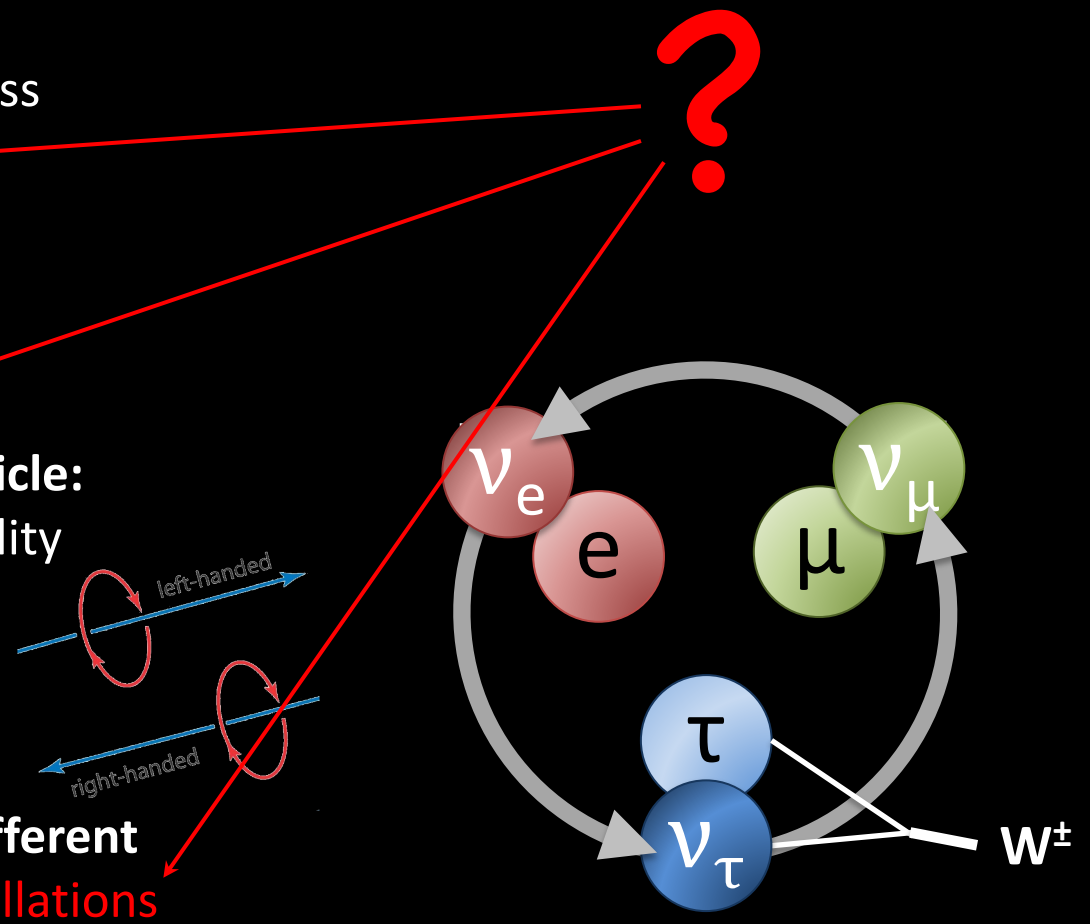
N : large phase space factor

O : low endpoint energy

Note down the **4th letter** of the solution word.

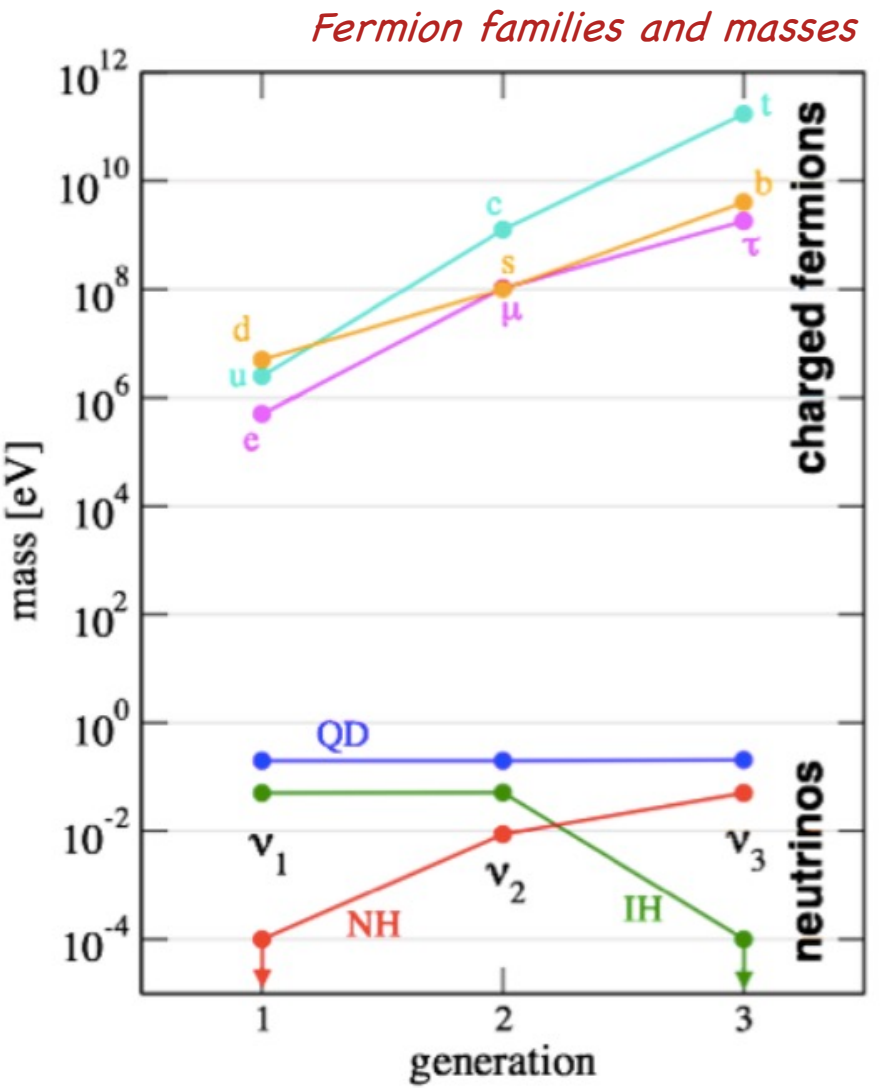
Neutrinos in a nut-shell

- Neutrinos are fermions.
- no electric or color charge
- **but:** weak charge
- virtually but not completely massless
  [$\Sigma m_\nu < 0.23\text{eV} \approx 5\text{x}10^{-7}\ m_e$]
- **three kinds (flavors) of neutrinos**
  are produced/absorbed in weak interactions along with e^-, μ^-, τ^-
- **each neutrino has (is?) its antiparticle:**
  same properties but different chirality
  - neutrinos = left-handed
  - antineutrinos = right-handed
- **flavor and mass eigenstates are different**
  → neutrino oscillations



Neutrino Mass Ordering/Hierarchy

- **Arrangement** of the neutrino masses
  - as in quark sector: $m_1 < m_2 < m_3$
    → normal ordering (NMO)
  - opposed to it: $m_3 < m_1 < m_2$
    → inverted ordering (IMO)
  - w/o clear ordering: $m_1 \approx m_2 \approx m_3$
    → quasi-degenerate (QD)



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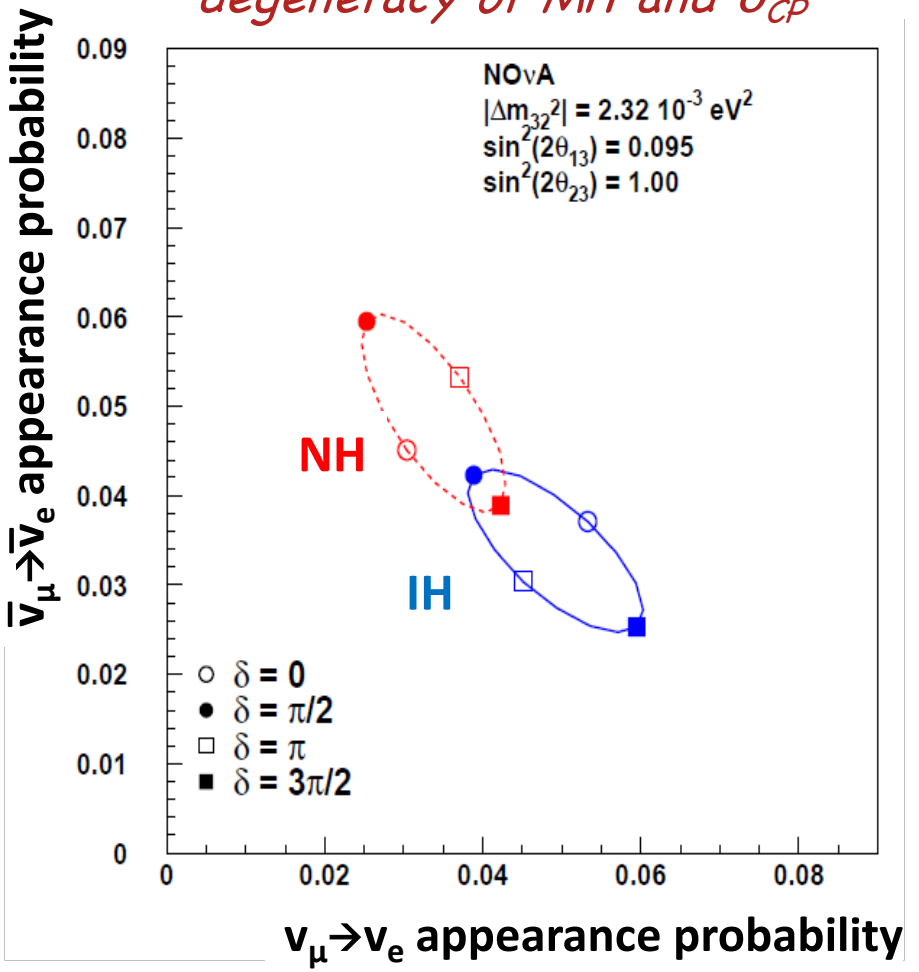
- resolving the **degeneracy in** the interpretation of **δ_{CP} measurements**

long baseline experiments: degeneracy of MH and δ_{CP}



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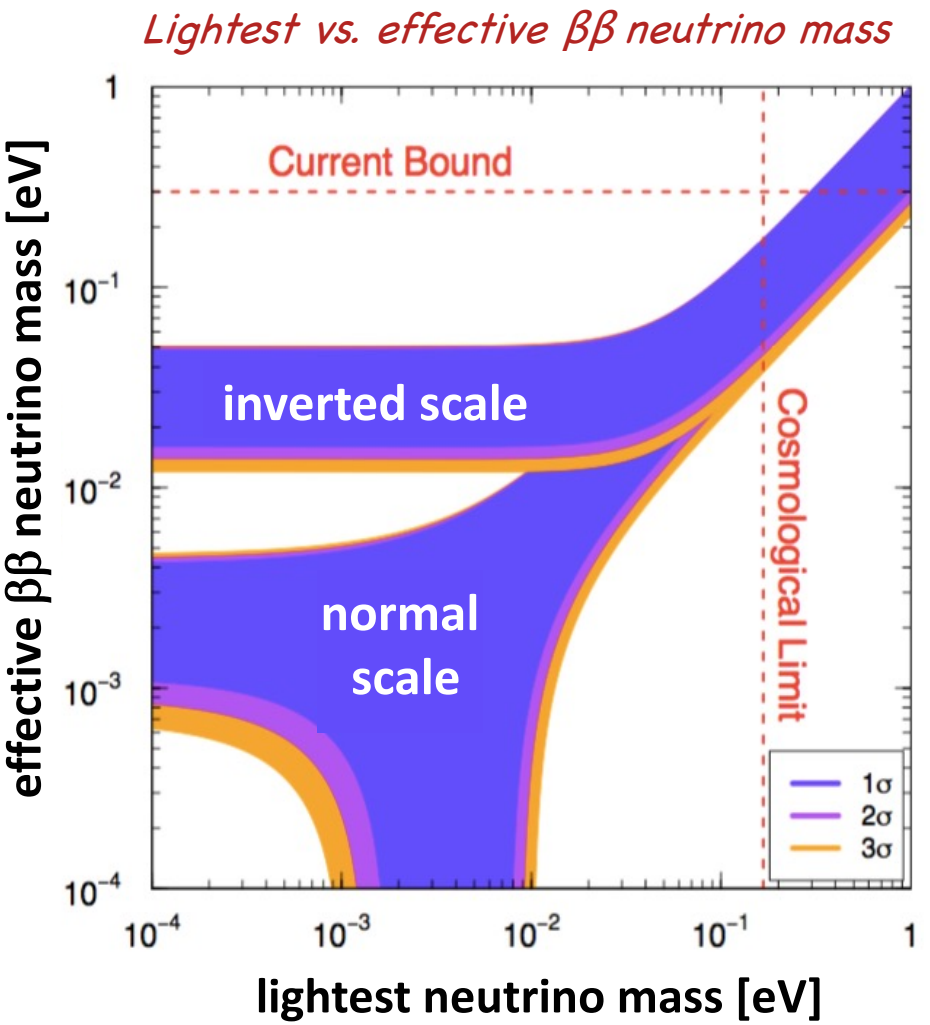
- resolving the **degeneracy in** the interpretation of δ_{CP} **measurements**
- target range for **sensitivity** of **0νββ decay** experiments



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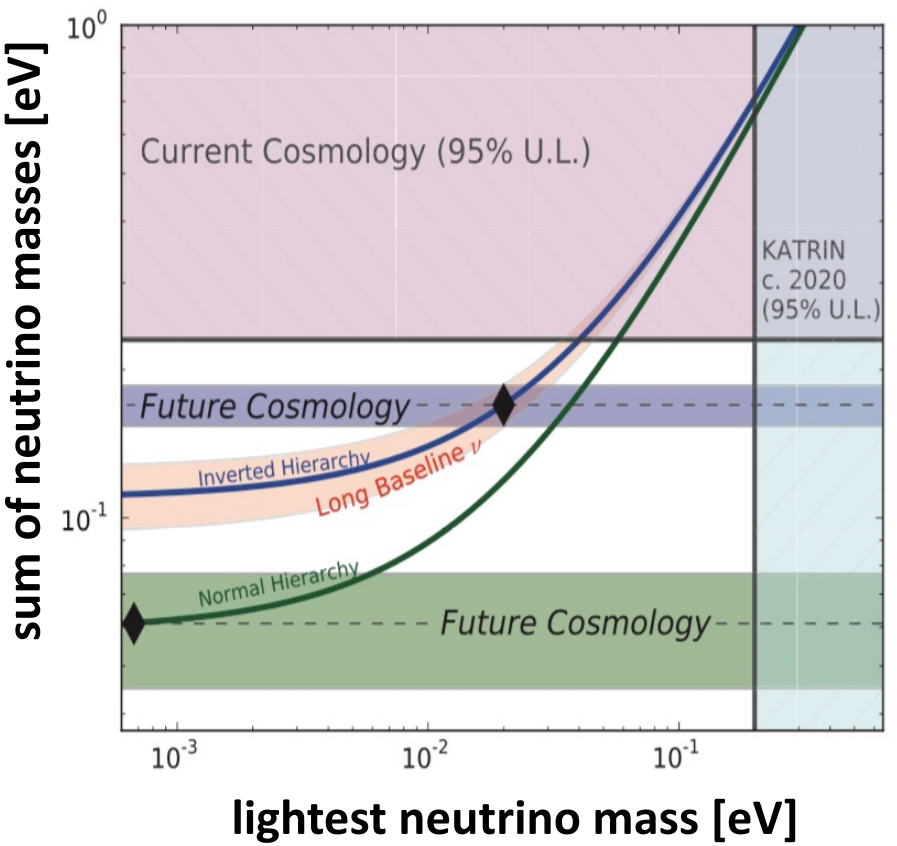
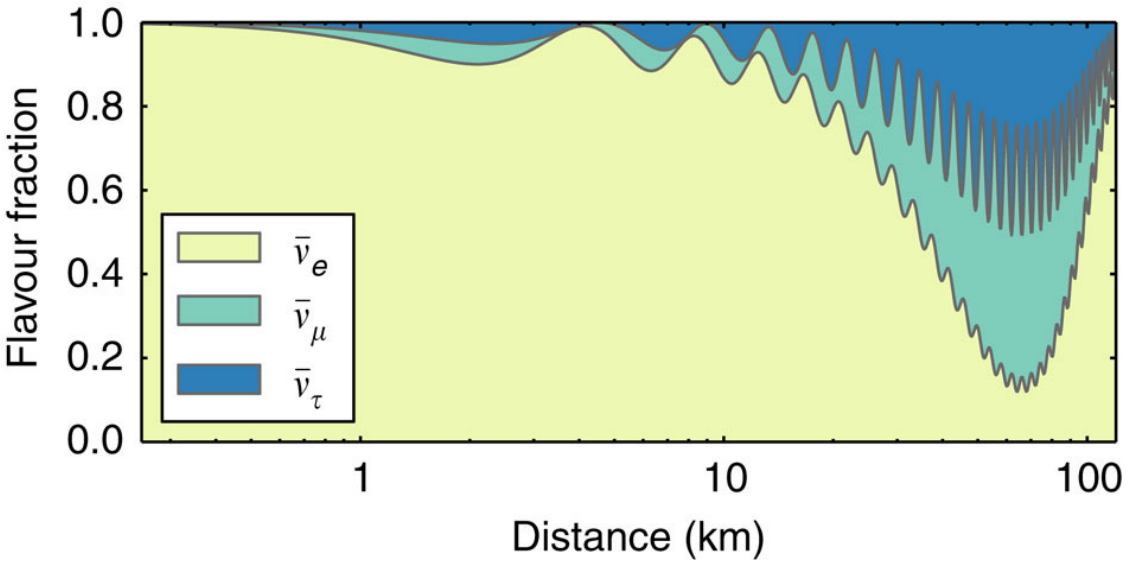
  - w/o clear ordering
    → quasi-degenerate (QD)
- resolving the **degeneracy in** the interpretation of δ_{CP} **measurements**
- target range for **sensitivity** of **0νββ decay** experiments
- combination with **cosmology** to find **lightest neutrino mass**

Cosmological neutrino mass vs. MH



Standard oscillations and Δm^2_{ij} values



- **Reminder:** Most oscillations experiments are well described by effective oscillation probabilities, e.g.

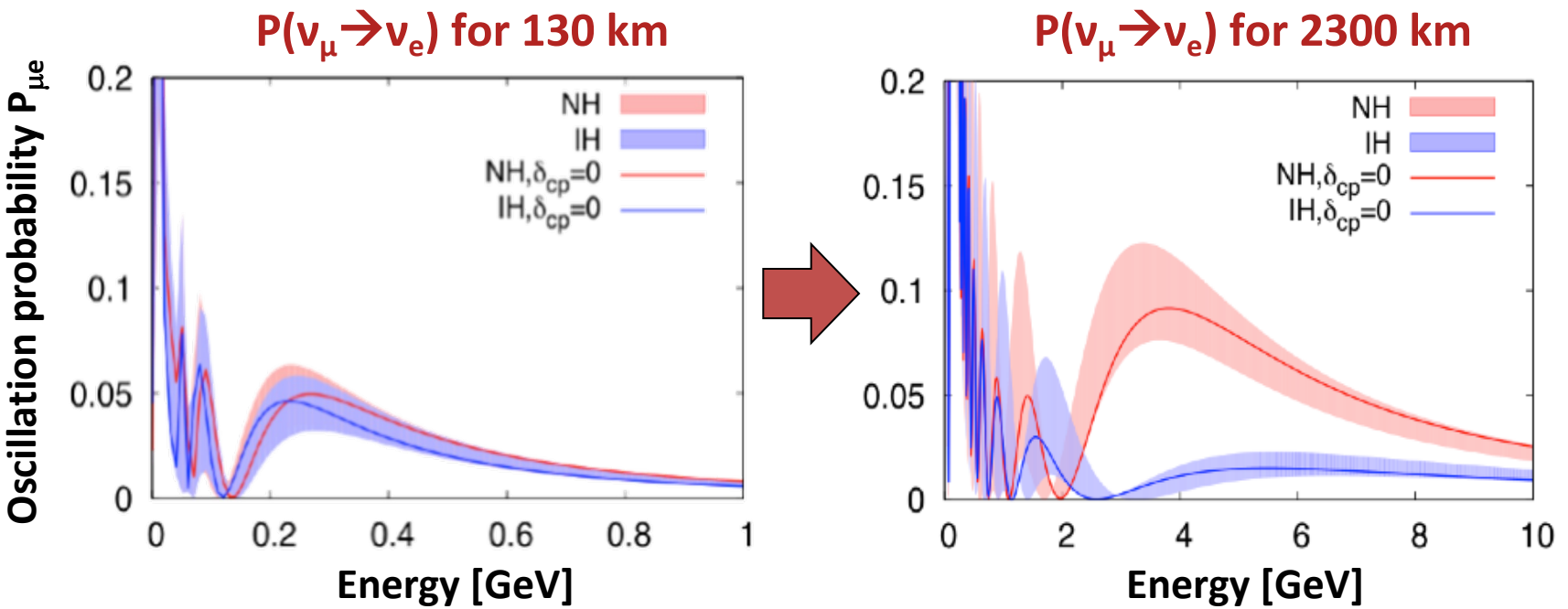
$$P_{\bar{e}\bar{e}} = 1 - \sin^2(2\theta_{13}) \sin^2\left(\frac{\Delta m^2_{31} L}{4E}\right) - \sin^2(2\theta_{12}) \sin^2\left(\frac{\Delta m^2_{21} L}{4E}\right)$$

→ those are independent of the sign of Δm^2!
and thus cannot tell which mass state is the heavier

- how to break this degeneracy?

Matter effects in long-baseline oscillations

- **Oscillation probabilities** differ for $\nu_\mu \rightarrow \nu_e$ vs. $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$
- Enhanced electron-flavor appearance for: neutrinos → normal hierarchy; antineutrinos → inverted

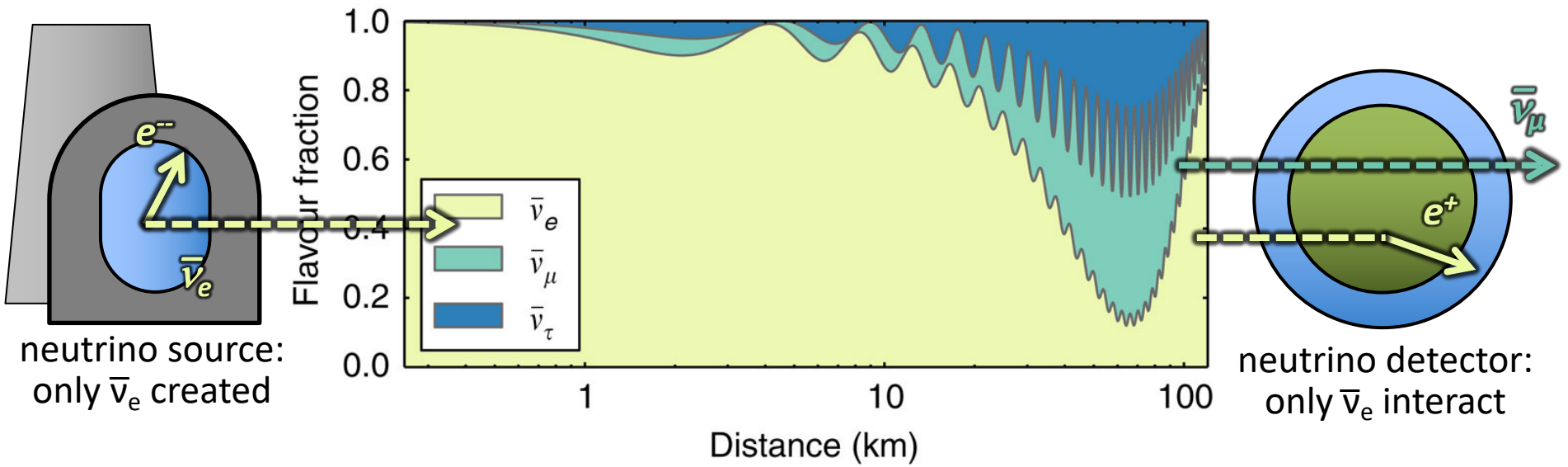


- **Far detector** at first atmospheric oscillation maximum: longer baseline → larger energy → larger matter effect!
- suitable experiments: **long-baseline beams (NOvA, DUNE)** and **atmospheric neutrinos (IceCube-Upgrade, ORCA)**

Reactor neutrino oscillations in 3 flavors

Common three-flavor reactor electron-antineutrino survival probability:

$$P_{ee} = 1 - \sin^2(2\theta_{13}) \sin^2\left(\frac{\Delta m^2_{31}}{4E}\right) - \sin^2(2\theta_{12}) \sin^2\left(\frac{\Delta m^2_{21}}{4E}\right)$$



→ oscillation parameters are extracted from $\bar{\nu}_e$ **disappearance pattern**

→ however, the formula above implicitly assumes $\Delta m^2_{31} = \Delta m^2_{32}$

MH from reactor $\bar{\nu}_e$ disappearance

Petcov, Piai, hep-ph/0112074

Survival probability

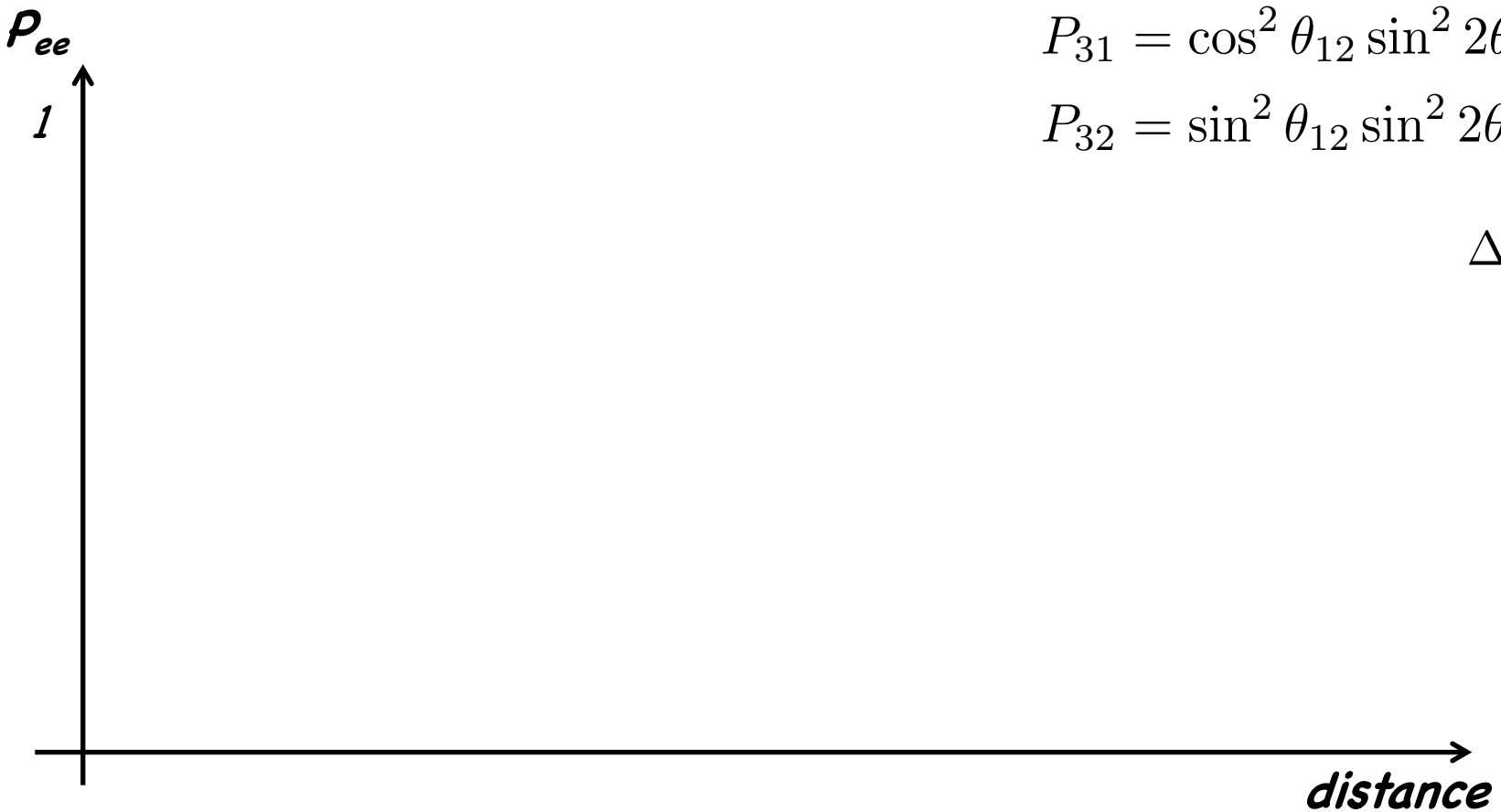
$$P_{\bar{e}\bar{e}} = 1 - P_{21} - P_{31} - P_{32}$$

$$P_{21} = \cos^4\theta_{13}\sin^2 2\theta_{12}\sin^2\Delta_{21}$$

$$P_{31} = \cos^2\theta_{12}\sin^2 2\theta_{13}\sin^2\Delta_{31}$$

$$P_{32} = \sin^2\theta_{12}\sin^2 2\theta_{13}\sin^2\Delta_{32}$$

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



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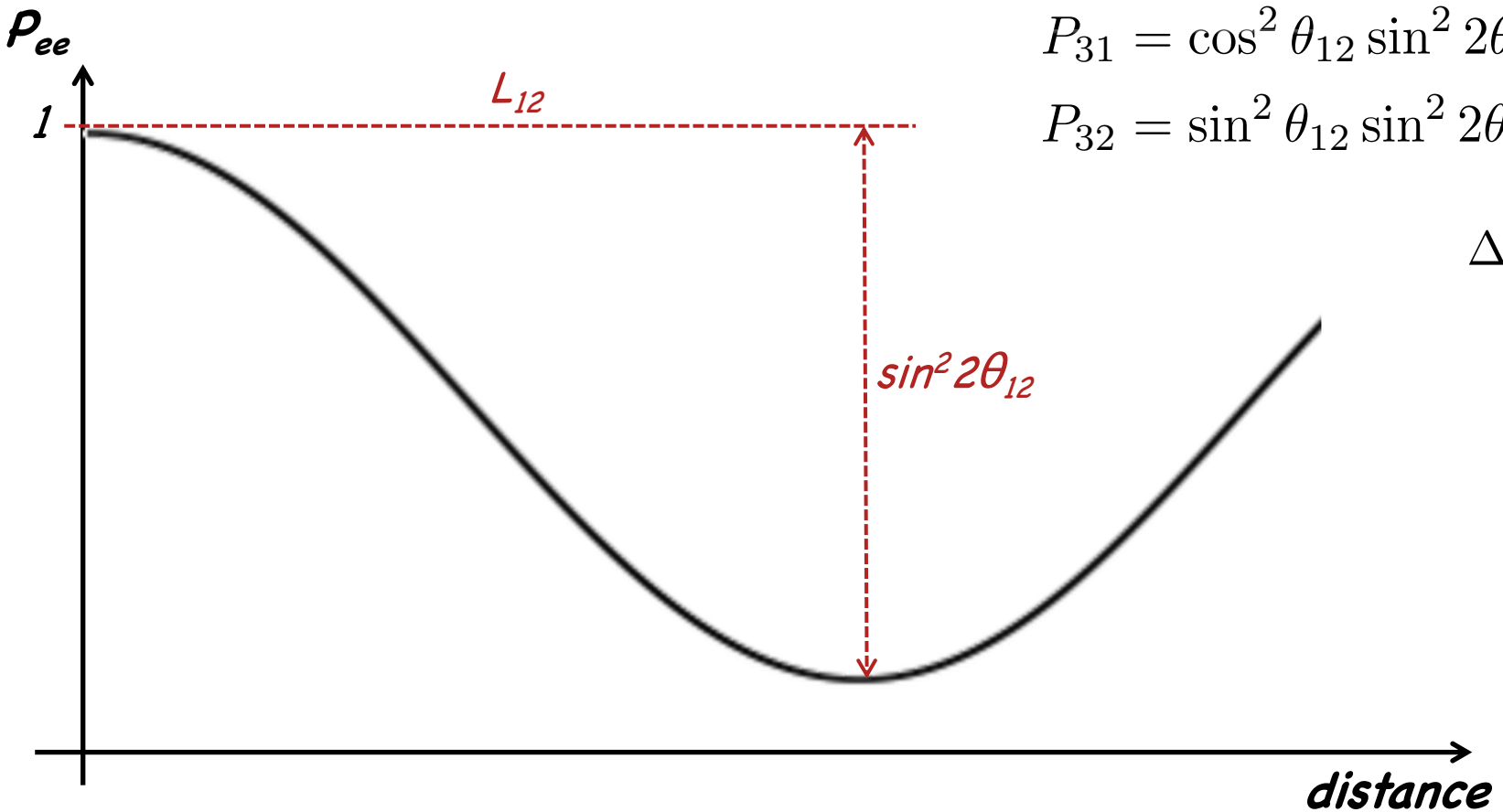


MH from reactor $\bar{\nu}_e$ disappearance

Petcov, Piai, hep-ph/0112074

→ subdominant oscillation pattern depends on phase terms of P_{31}/P_{32}

→ depends on **relative sizes** of Δm^2_{32} and Δm^2_{31}

Survival probability

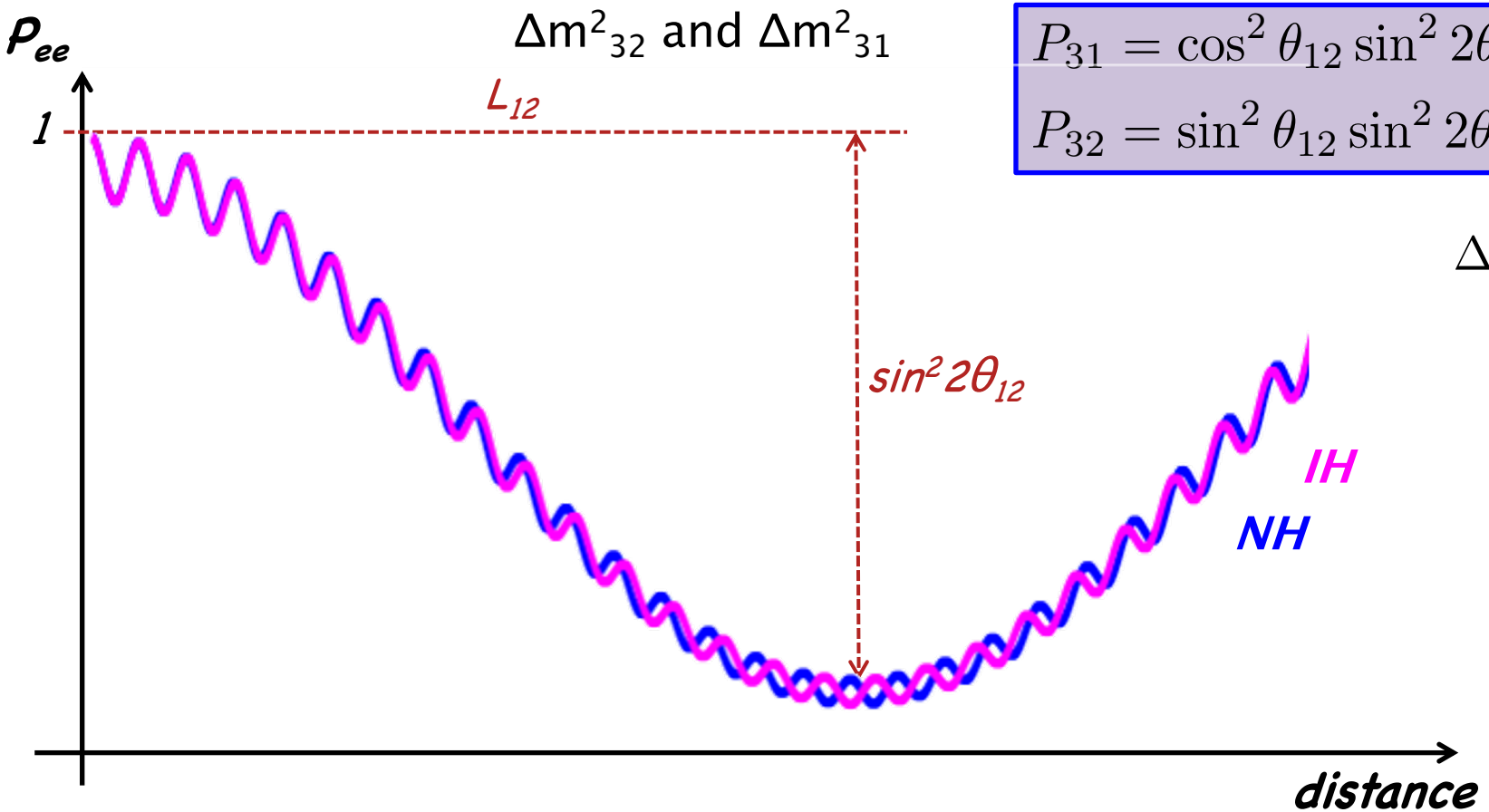
$$P_{\bar{e}\bar{e}} = 1 - P_{21} - P_{31} - P_{32}$$

$$P_{21} = \cos^4\theta_{13}\sin^2 2\theta_{12}\sin^2\Delta_{21}$$

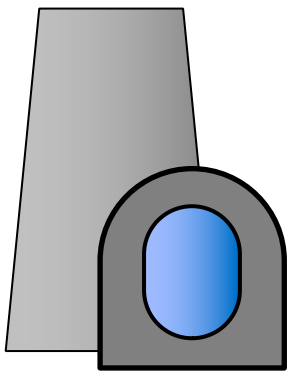
$$P_{31} = \cos^2\theta_{12}\sin^2 2\theta_{13}\sin^2\Delta_{31}$$

$$P_{32} = \sin^2\theta_{12}\sin^2 2\theta_{13}\sin^2\Delta_{32}$$

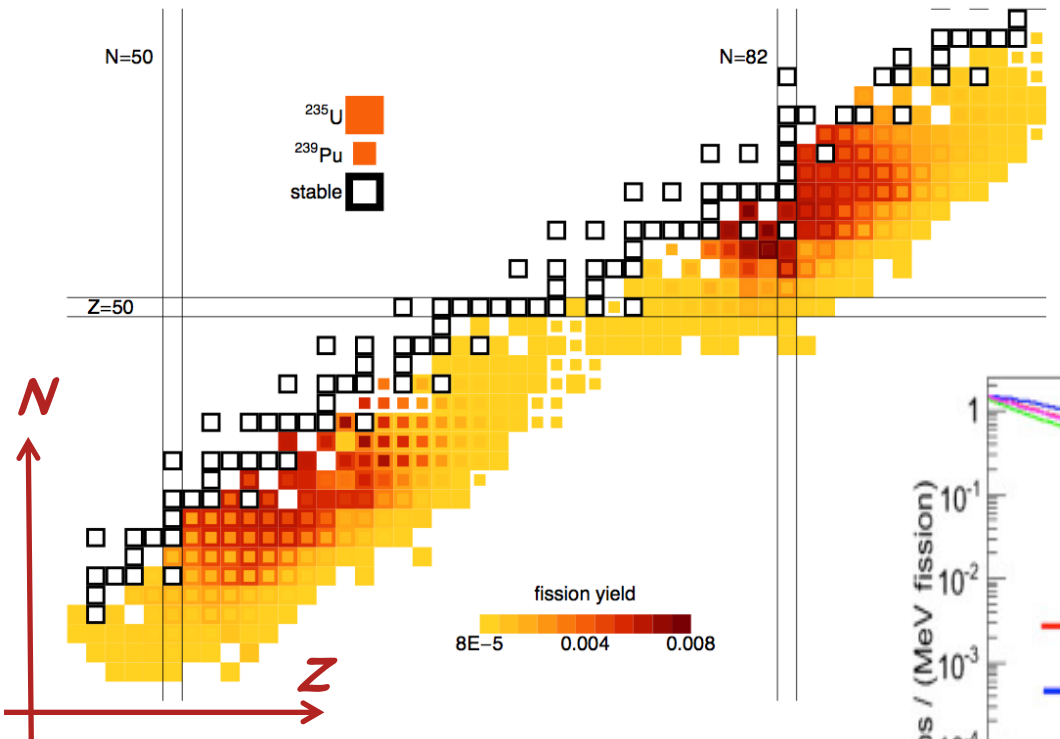
$$\Delta_{ij} = \frac{\Delta m^2_{ij} L}{4E}$$

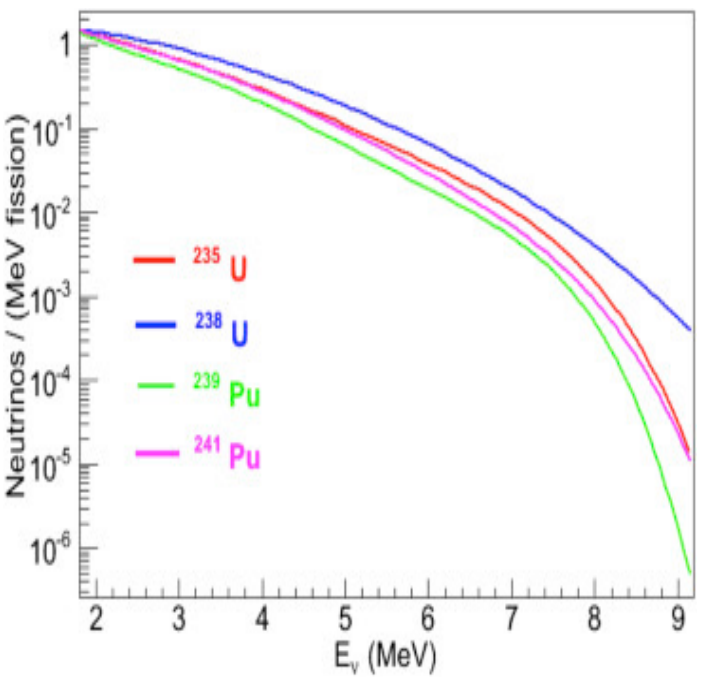


Nuclear reactors as a neutrino source



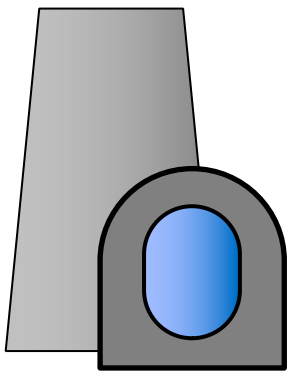
$$n + {}^{235}\mathrm{U} \rightarrow {}^{A}(Z) + {}^{233-A}(92-Z) + 3n + 200\,\mathrm{MeV}$$

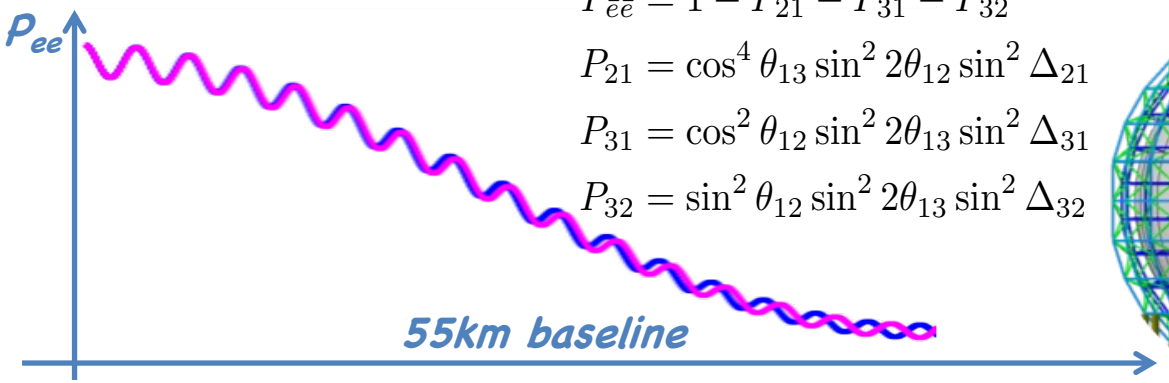




- ν's from β^--decays of neutron-rich fission products
- ~6 $\bar{\nu}_e$'s per fission (200MeV) → **intense! ~10^{20} $\bar{\nu}$/GW$_{th}$**
- **energy spectra:** up to ~8 MeV

Mid-distance reactor $\bar{\nu}_e$ oscillations





$$P_{\bar{e}\bar{e}} = 1 - P_{21} - P_{31} - P_{32}$$
$$P_{21} = \cos^4\theta_{13}\sin^2 2\theta_{12}\sin^2\Delta_{21}$$
$$P_{31} = \cos^2\theta_{12}\sin^2 2\theta_{13}\sin^2\Delta_{31}$$
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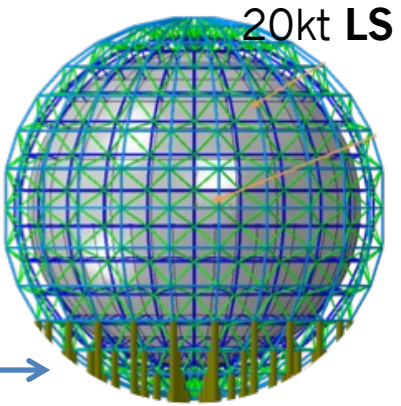
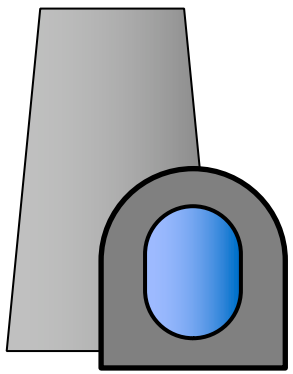
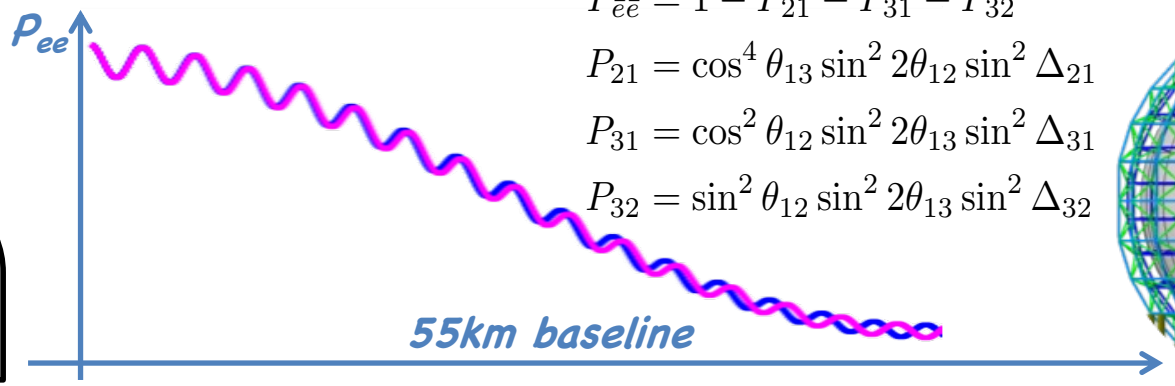


Nuclear reactor(s)
ΣP~30GW

Mid-distance reactor $\bar{\nu}_e$ oscillations





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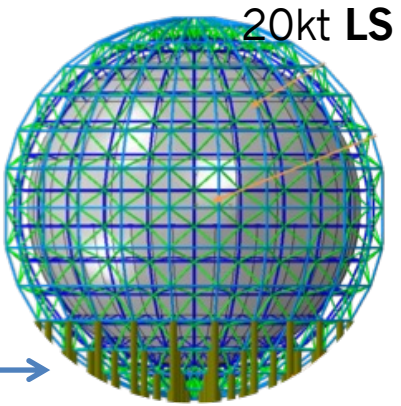
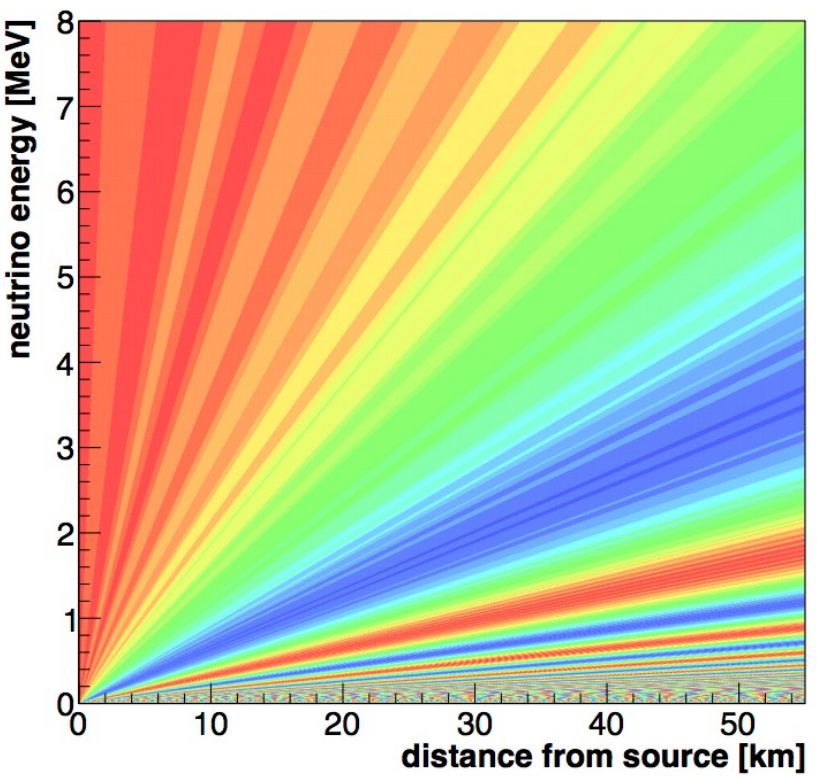
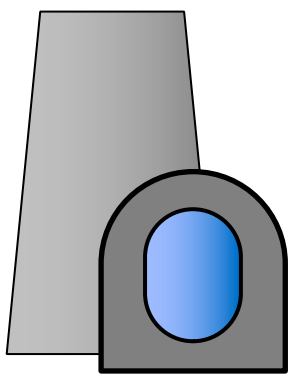


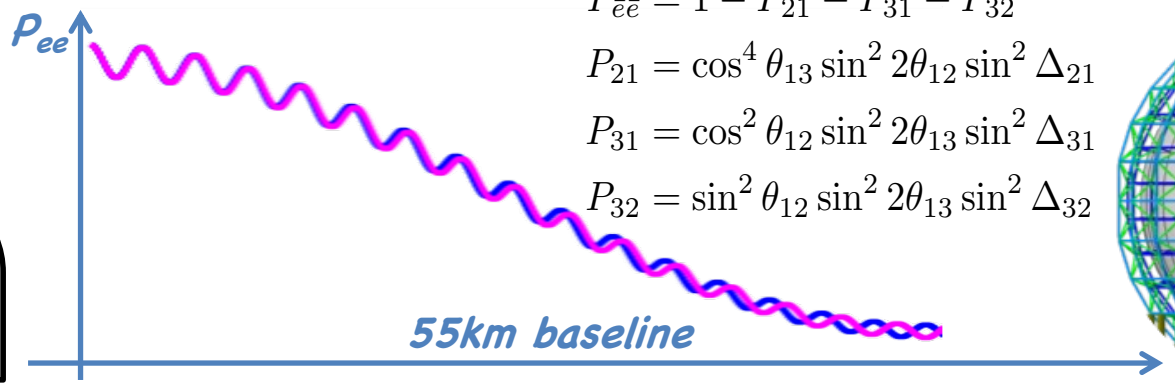
Nuclear reactor(s)
ΣP~30GW

energy range of reactor spectrum



Mid-distance reactor $\bar{\nu}_e$ oscillations





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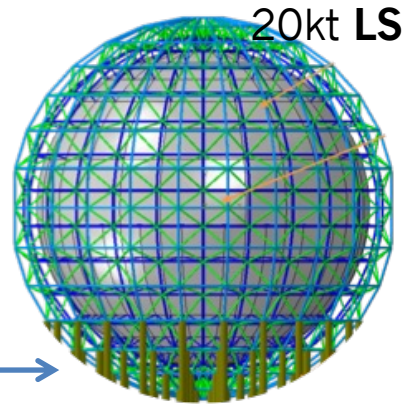
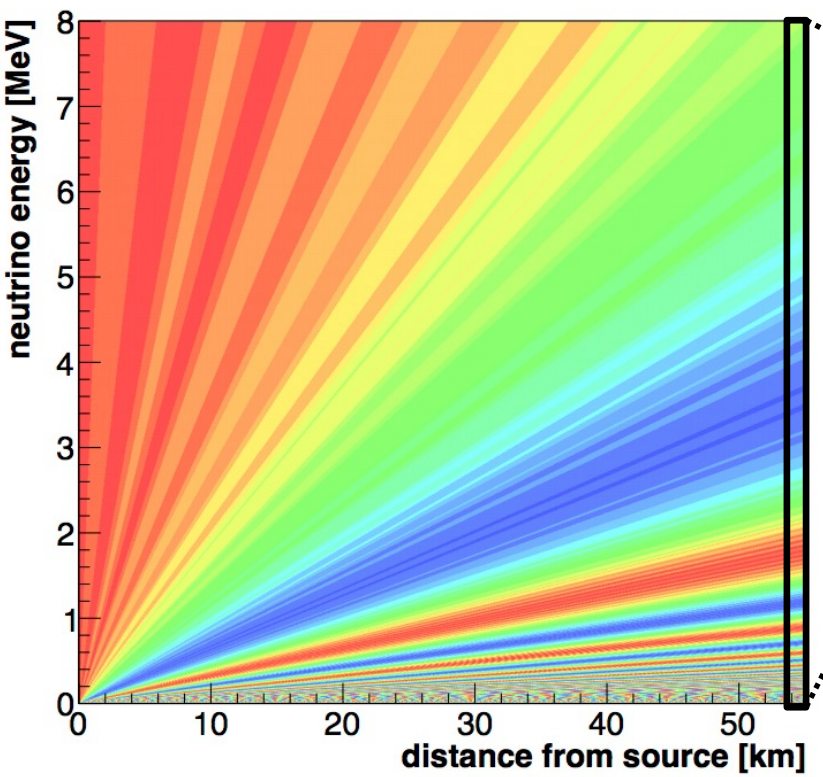
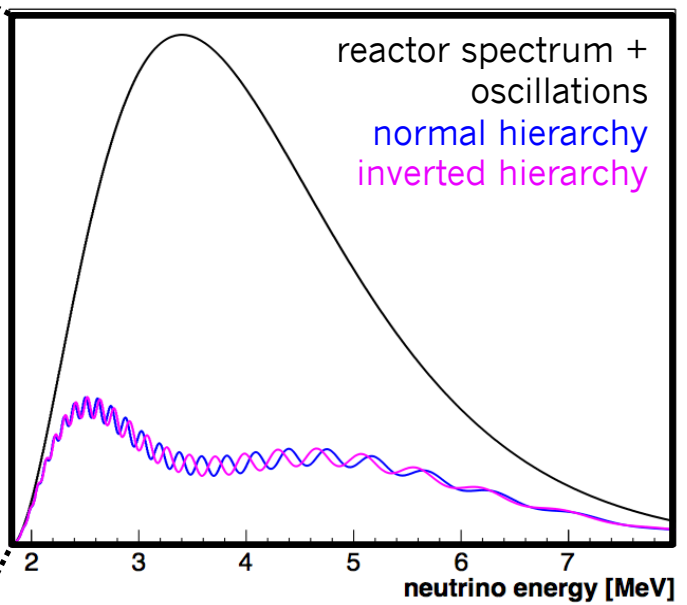


Nuclear reactor(s)
ΣP~30GW

energy range of reactor spectrum





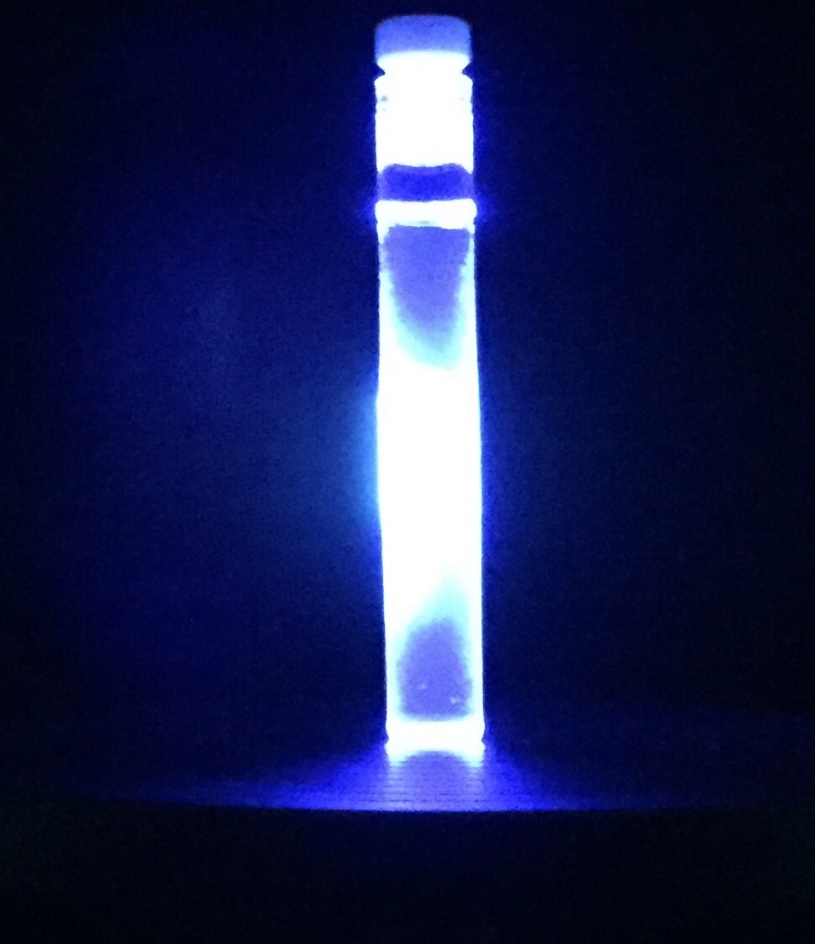
→ ***MH from position of spectral wiggles!***

Basic detector requirements for JUNO

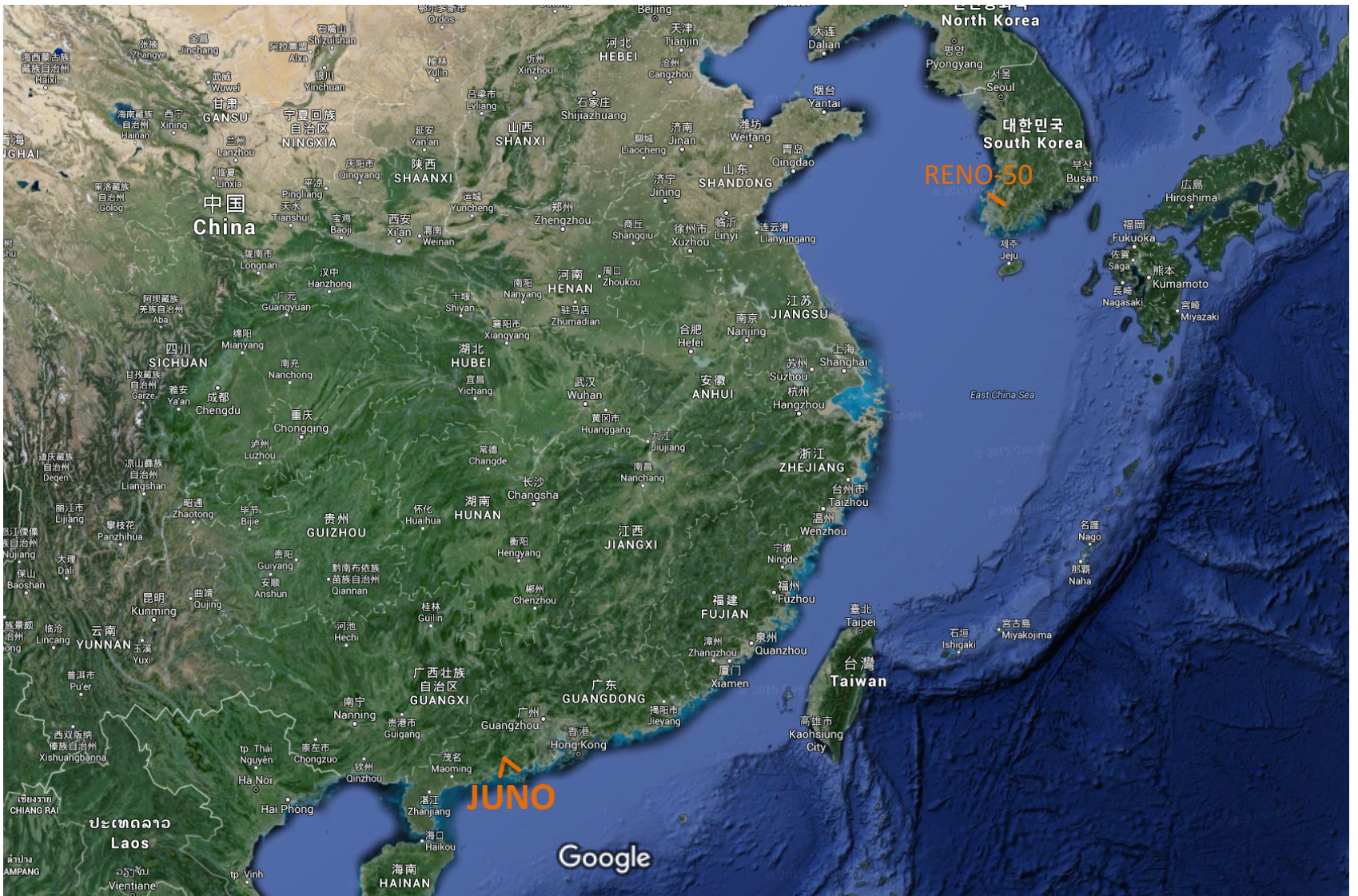
- reactor antineutrinos at MeV energies
  → **Liquid-scintillator detector**
  → Detection by inverse beta decay

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

- signature in position of spectral wiggles
  → **~3% energy resolution** at 1 MeV
  → photoelectron yield: **~1,100 pe/MeV**
- large distance to source and high-statistics measurement
  → large target mass: **20 kilotons of LAB**
- cosmogenic background
  → rock overburden of **~700 m**

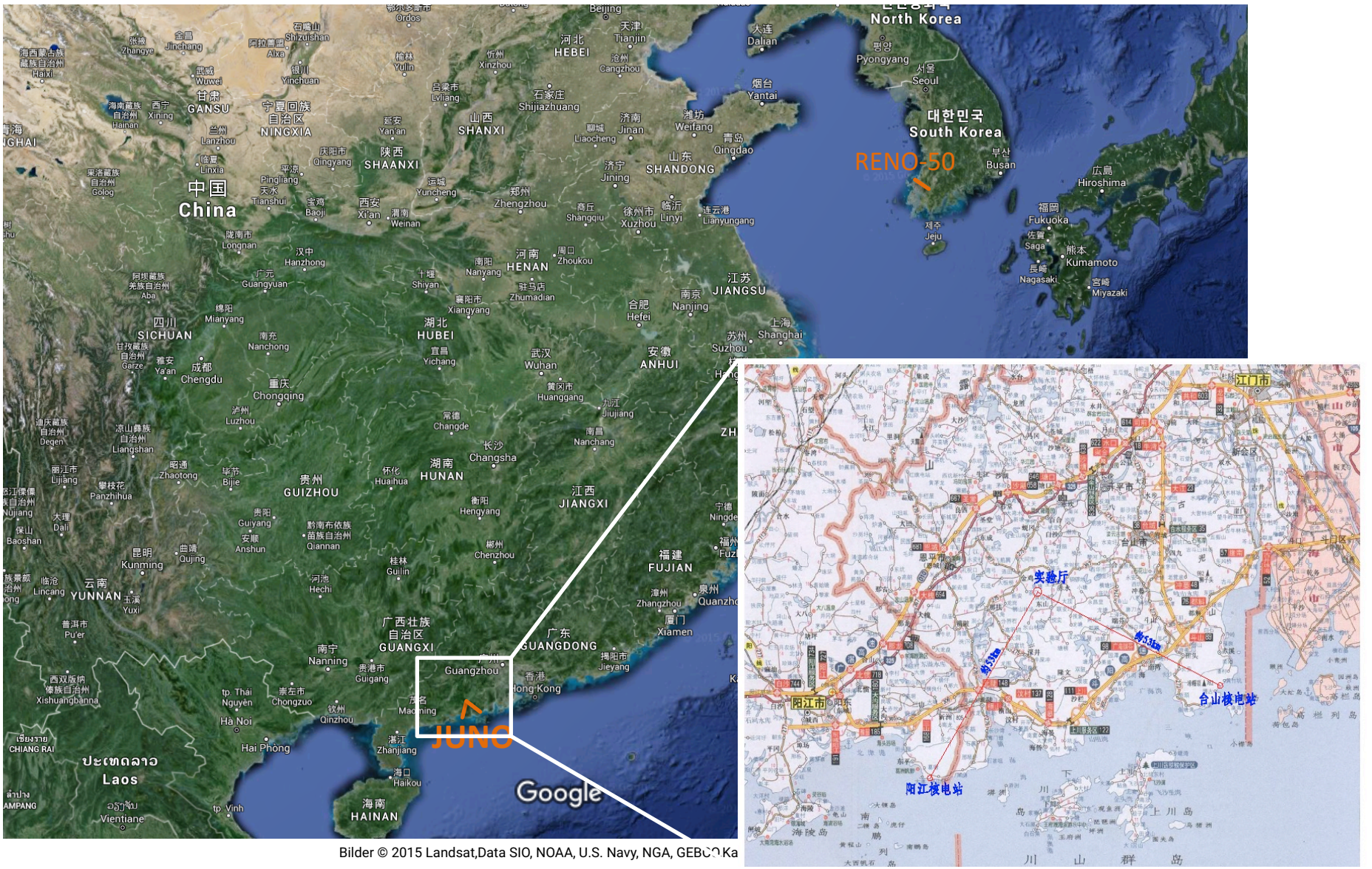


Mid-distance reactor experiments

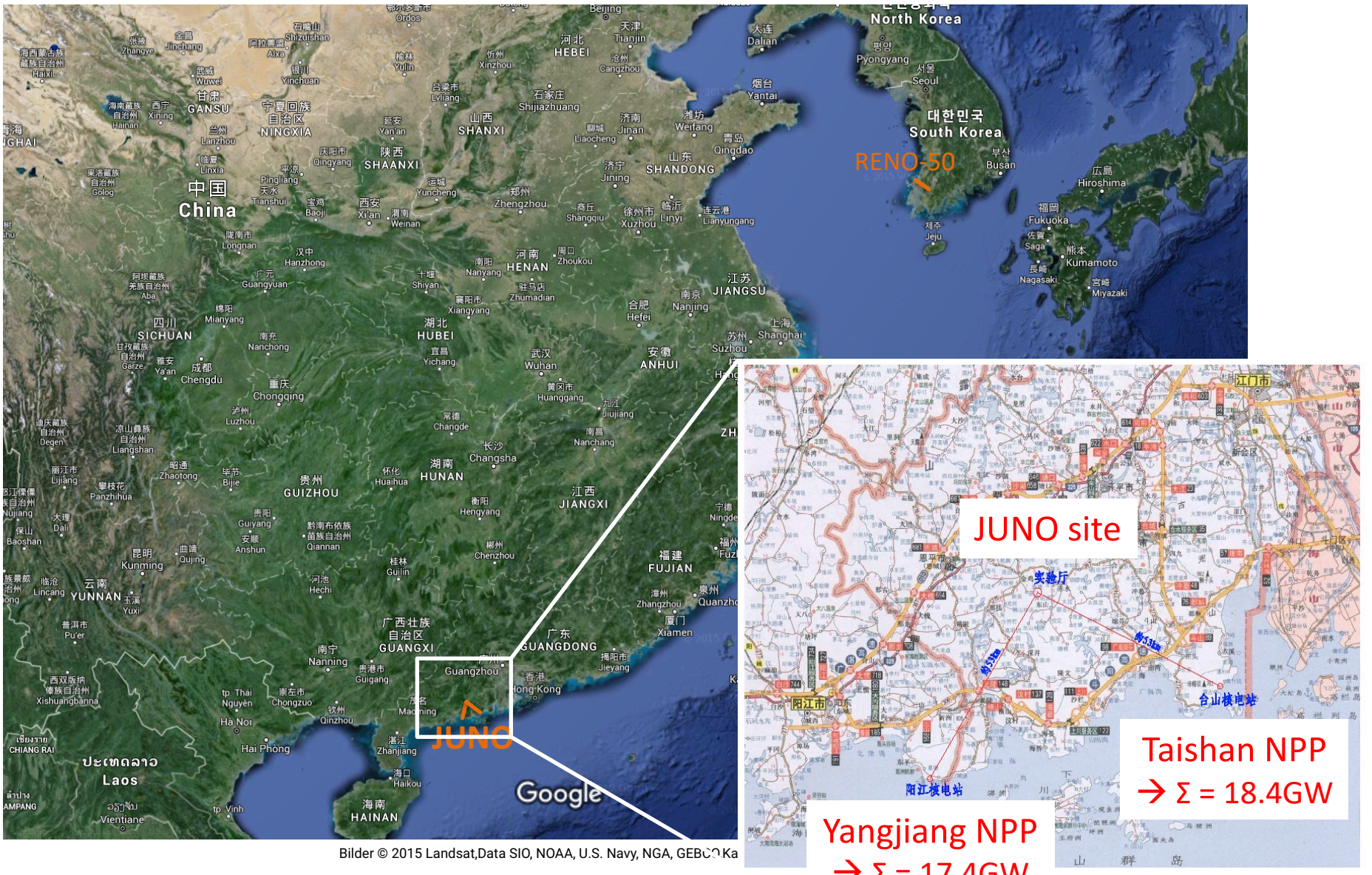


Bilder © 2015 Landsat,Data SIO, NOAA, U.S. Navy, NGA, GEBCO,Kartendaten © 2015 Google,SK planet,ZENRIN 200 mi

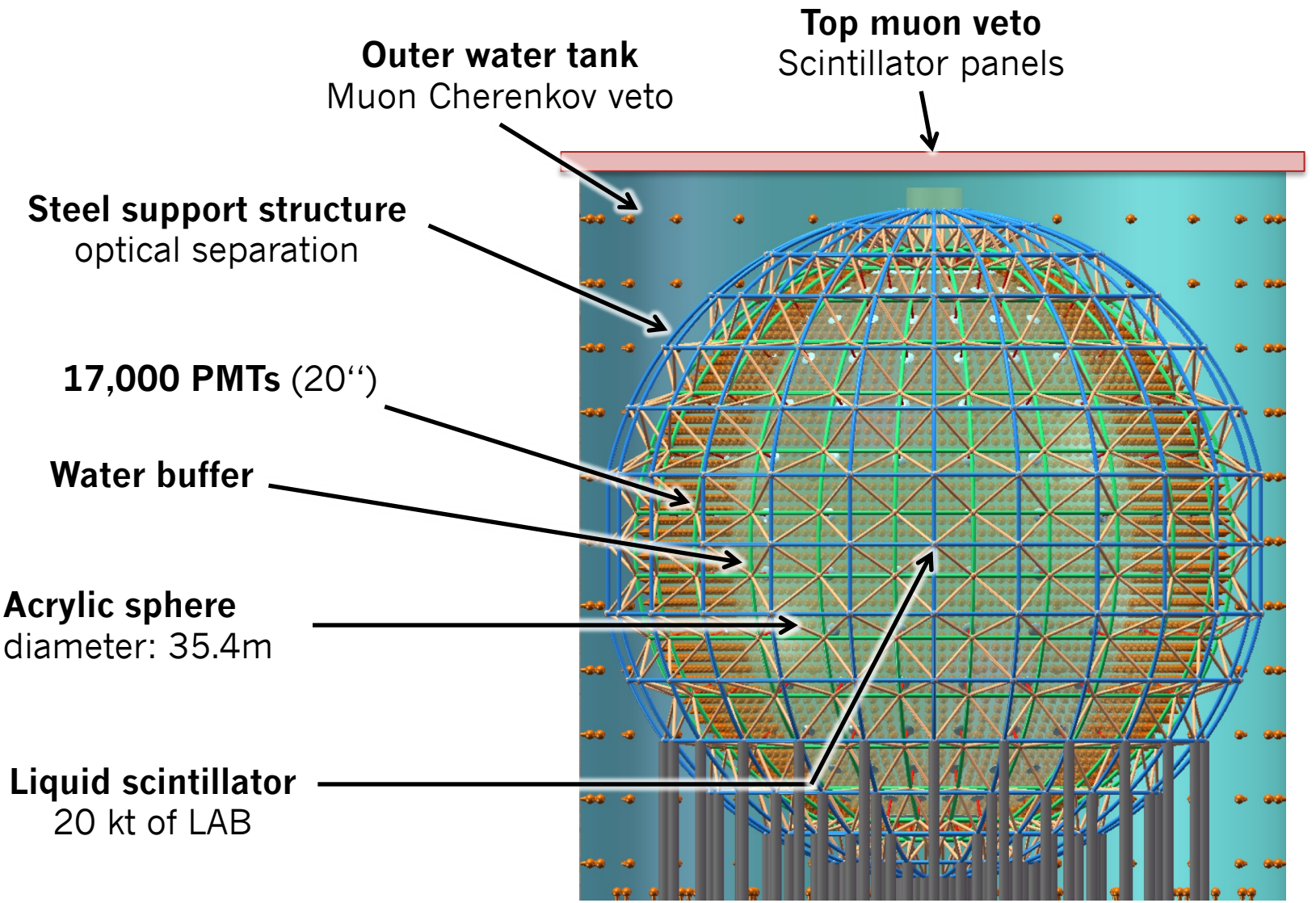
Mid-distance reactor experiments



Mid-distance reactor experiments



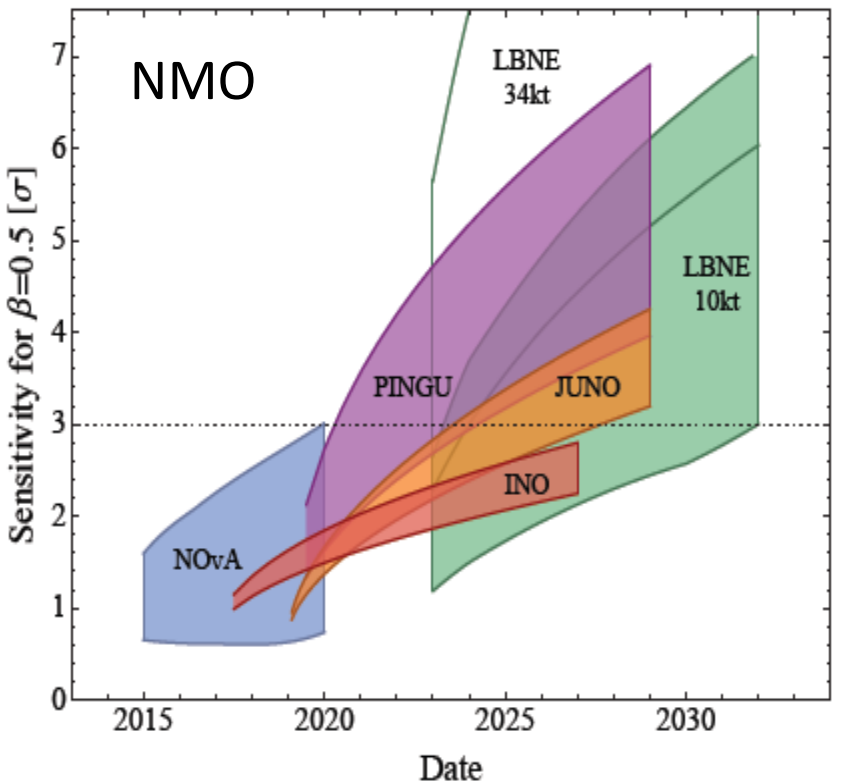
JUNO Detector Layout

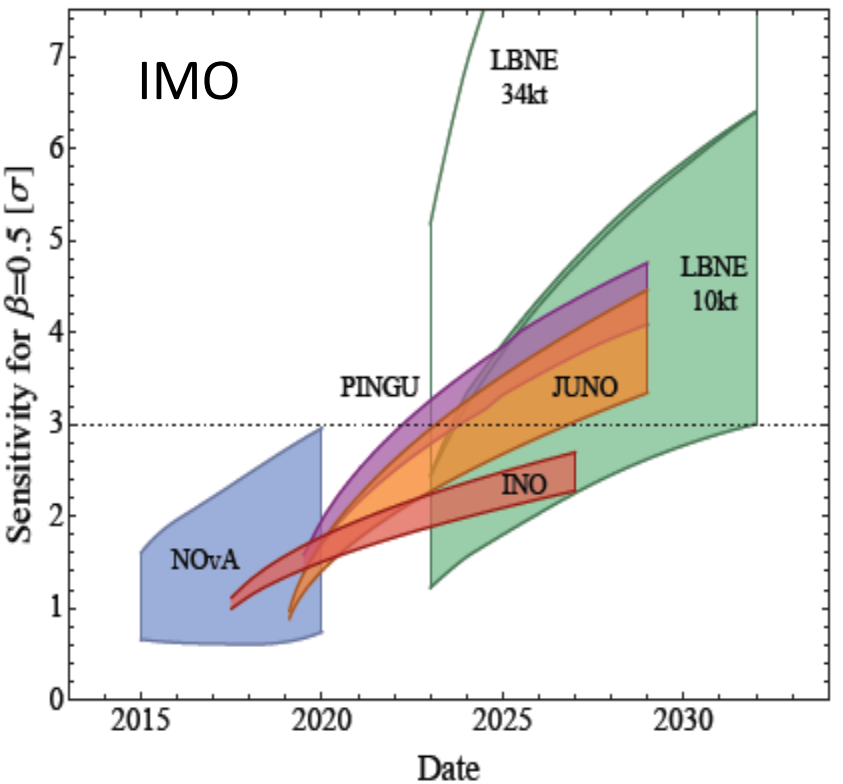


JUNO: Current Status

Experimental sensitivity for Mass Ordering

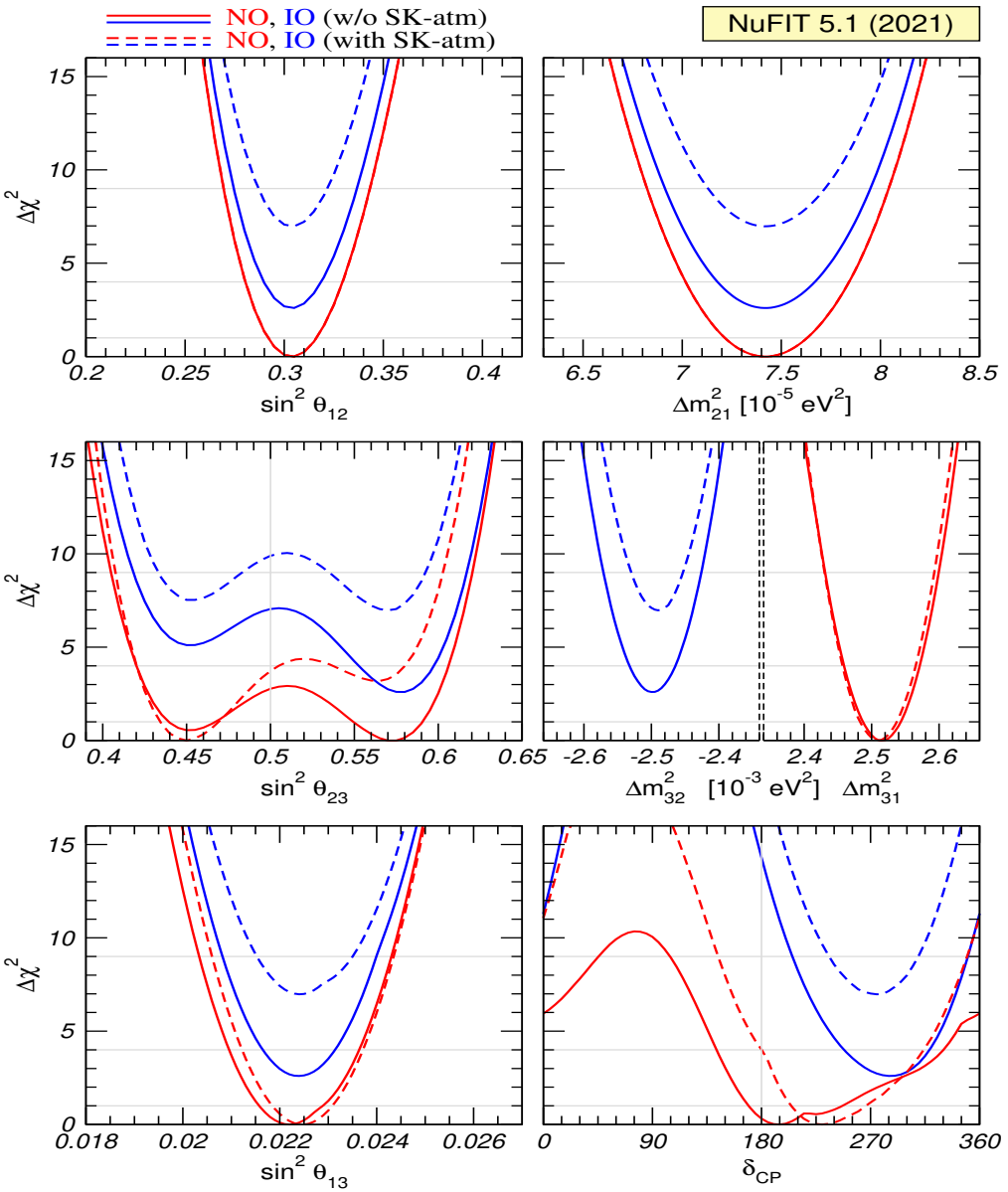
Blennow, Schwetz, arXiv:1311.1822





Experimental technique	**Mode**	**Dominant factor**
▪ long-baseline beams: NOvA, DUNE ...	$\nu_\mu \rightarrow \nu_e$	value of δ_{CP}
▪ atmospheric ν's: INO, IC-Upgrade, ORCA, HK ...	$\nu_\mu \rightarrow \nu_\mu$	value of θ_{23}=40-50°
▪ reactor neutrinos: JUNO	$\bar{\nu}_e \rightarrow \bar{\nu}_e$	energy res. (3-3.5%)

Global oscillation fits and Mass Ordering



Color scheme

- Normal Ordering (NO)
- Inverted Ordering (IO)

→ normal ordering is preferred (~2σ)

some controversy about most recent atmospheric data from Super-K (inclusion increases significance)

LECTURE QUIZ

Question 7

What arrangement of neutrino masses is described by the inverted ordering?

R : $m_2 < m_3 < m_1$

S : $m_1 < m_3 < m_2$

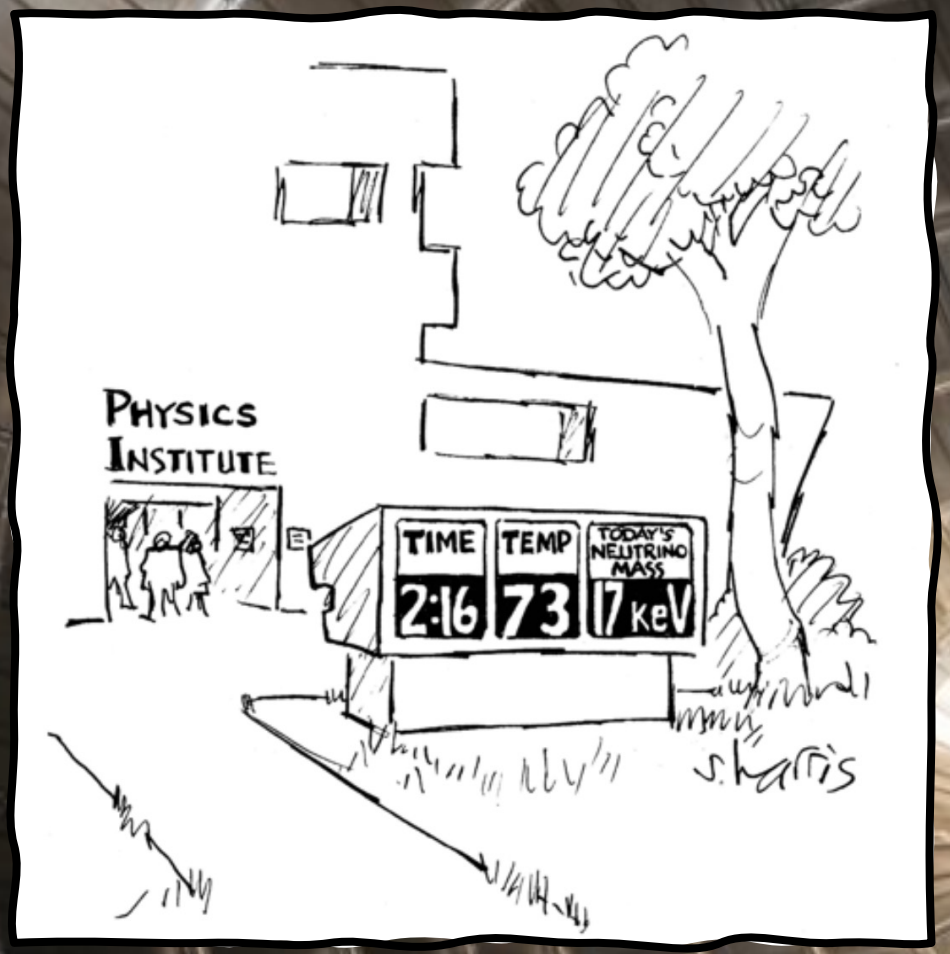
T : $m_3 < m_1 < m_2$

Note down the **9th letter** of the solution word.

Summary of Lecture 2

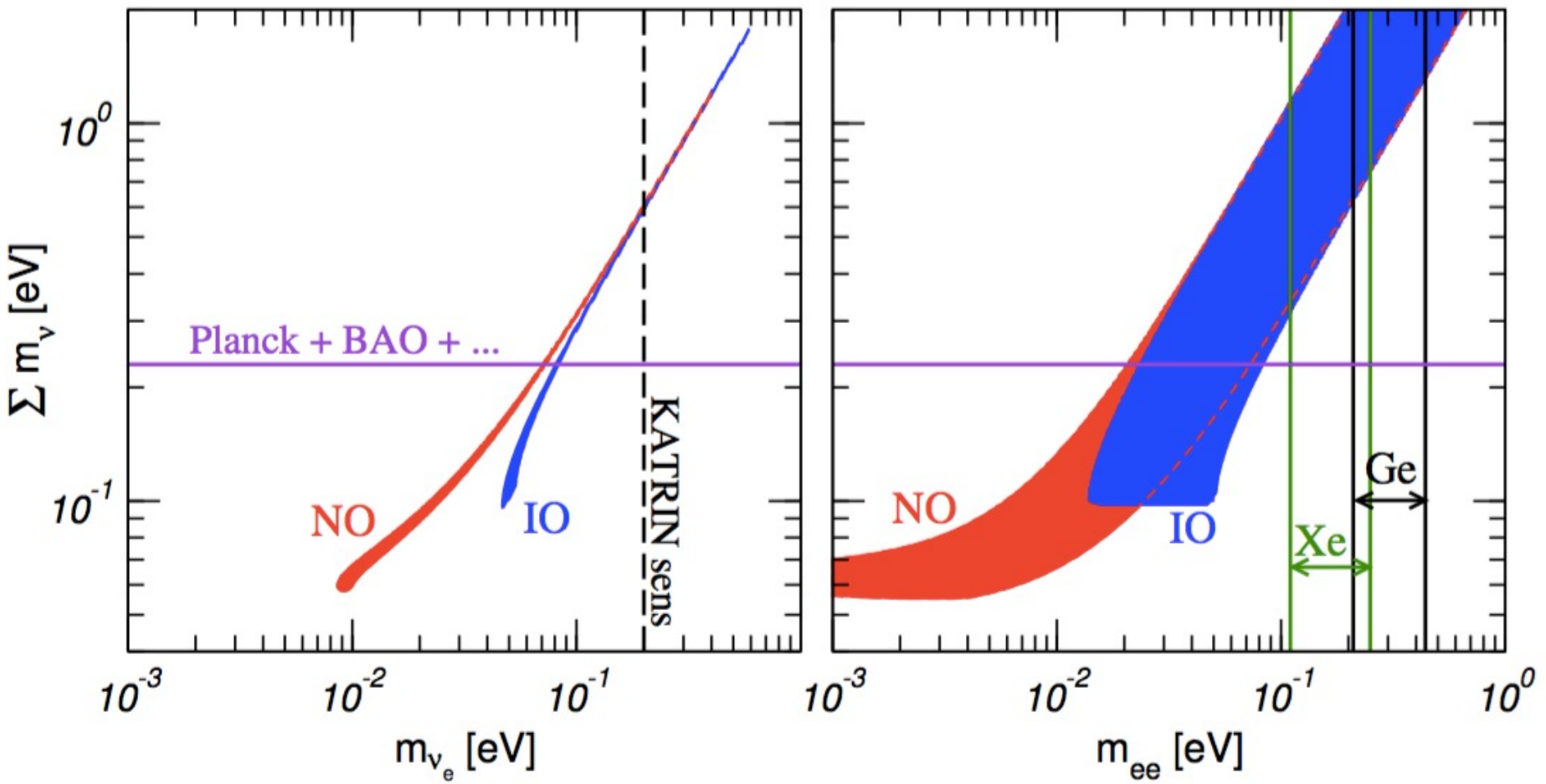
- Presence of **neutrino oscillations** proves that **neutrinos are massive** but up to now only upper limits.
- **Absolute neutrino mass** is constrained by **tritium decay experiments** (~0.8eV) and **cosmological observations** (~0.2 eV) → better limits to come
- Nature of neutrino mass (**Dirac/Majorana**) as well as the effective $<m_{\beta\beta}>$ mass is constrained by **neutrinoless double-beta decay (0νββ) experiments**.
- Additional information from **oscillation experiments** on the **neutrino mass ordering**, normal or inverted ($m_3<m_1<m_2$).

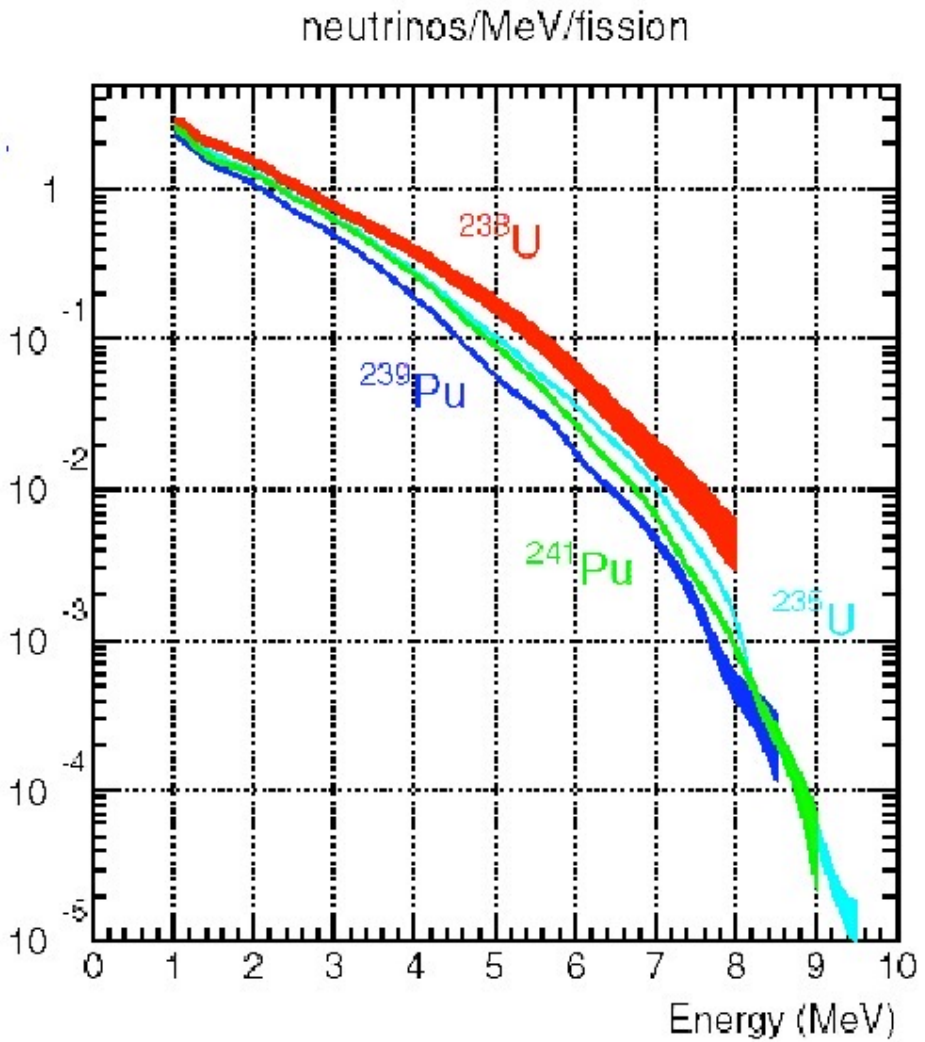
Thanks for your attention!



Questions?

Limits on the neutrino mass (2)



Reactor antineutrino spectrum

- Four relevant fission elements
  - ^{235}U, ^{238}U, ^{239}Pu, ^{241}Pu
  - variable with fuel burn-up
- Effective spectrum from overlaying β-spectra of many fission products
- ν-spectra from spectral inversion of β-decay electron spectra
  - BILL measurements at ILL commonly used reference [arXiv:1405.3501]
- ab-initio calculations of neutrino spectrum very challenging
  fission yields → decay chains → spectra