Sterile Neutrinos

Summer School on Neutrino Physics Beyond the Standard Model

Strasbourg, 04/07/2025

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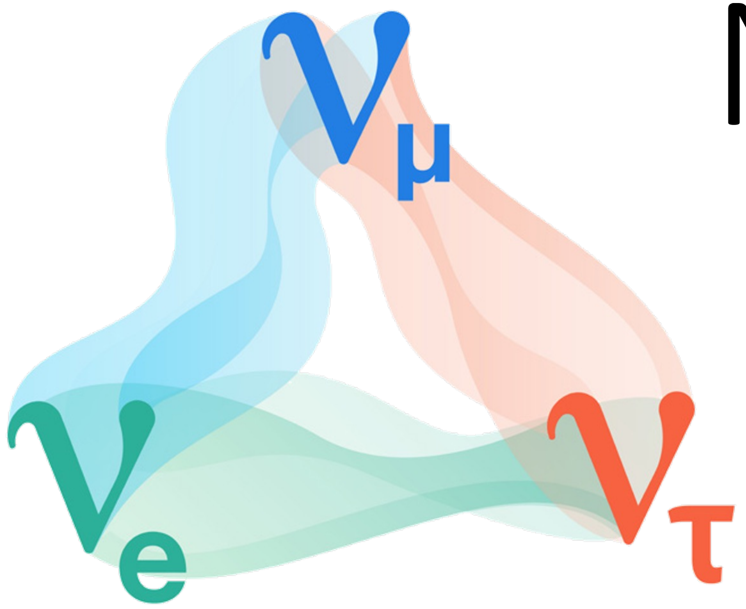
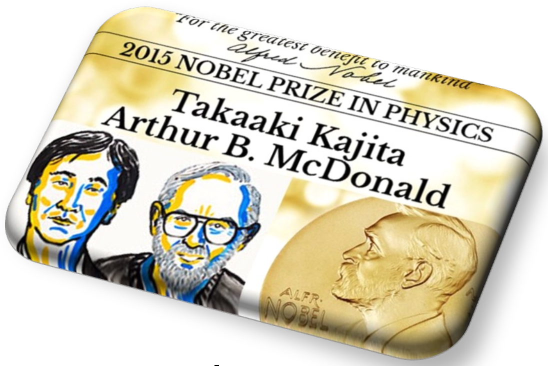
Max-Planck-Institut für Kernphysik

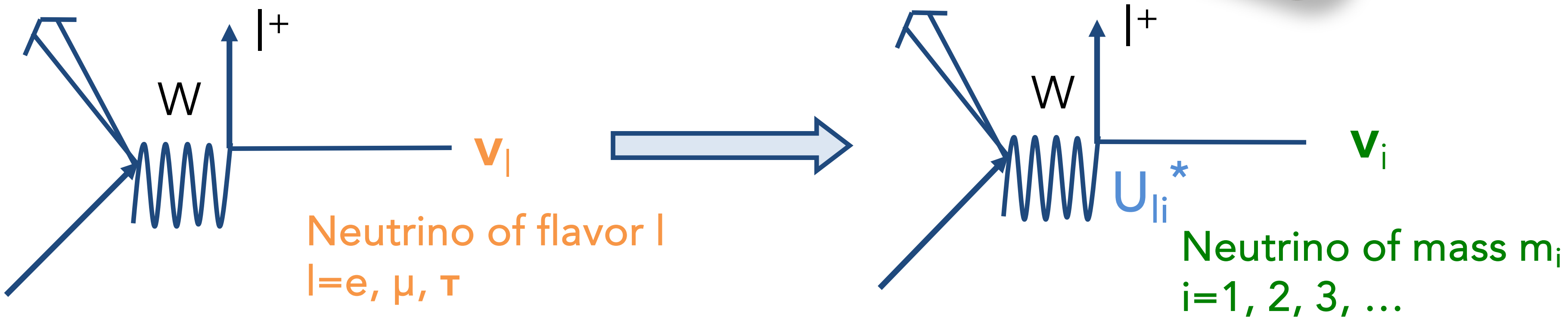
Active Neutrinos



Established Neutrino Physics

- 3 flavor, spin ½, neutral, left handed, **σ**(1 MeV)≈$10^{-44 / -40}$ cm^2
- Tiny masses: 0.03 eV < m_ν < ≈ 0.5 eV
- Mixing: two views on W-decay:





- PMNS mixing matrix U: $|\nu_i\rangle = \Sigma\, U_{\alpha i}\, |\nu_\alpha\rangle$

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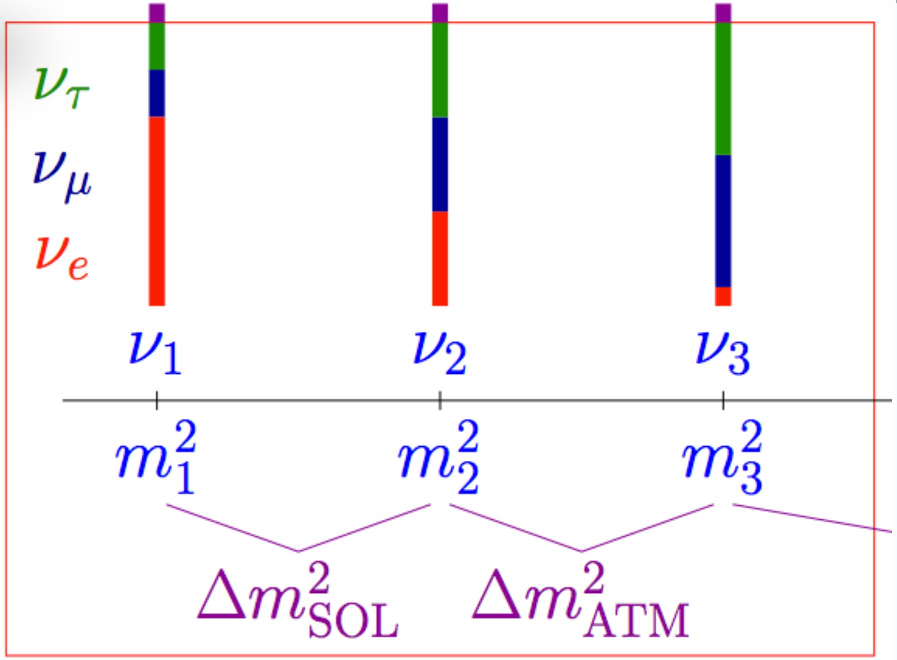
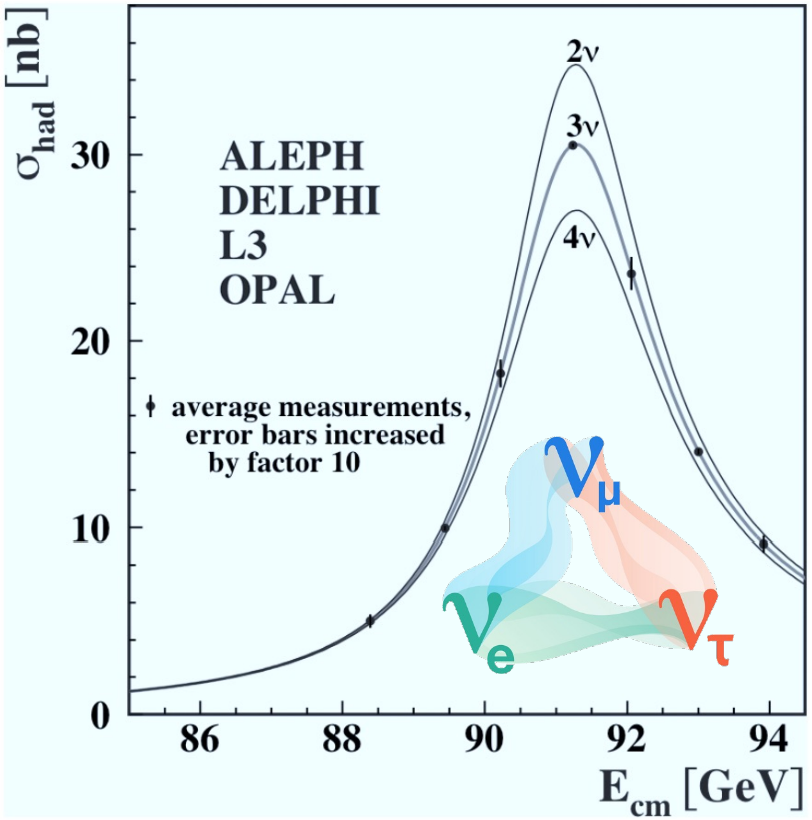
Three known Active Neutrinos

$$\Gamma_Z = \Gamma_{ee} + \Gamma_{\mu\mu} + \Gamma_{\tau\tau} + \Gamma_{had} + N_\nu \Gamma_{\nu\nu},$$

Only 3 light ν's coupling to Z boson
(invisible width of the Z boson)

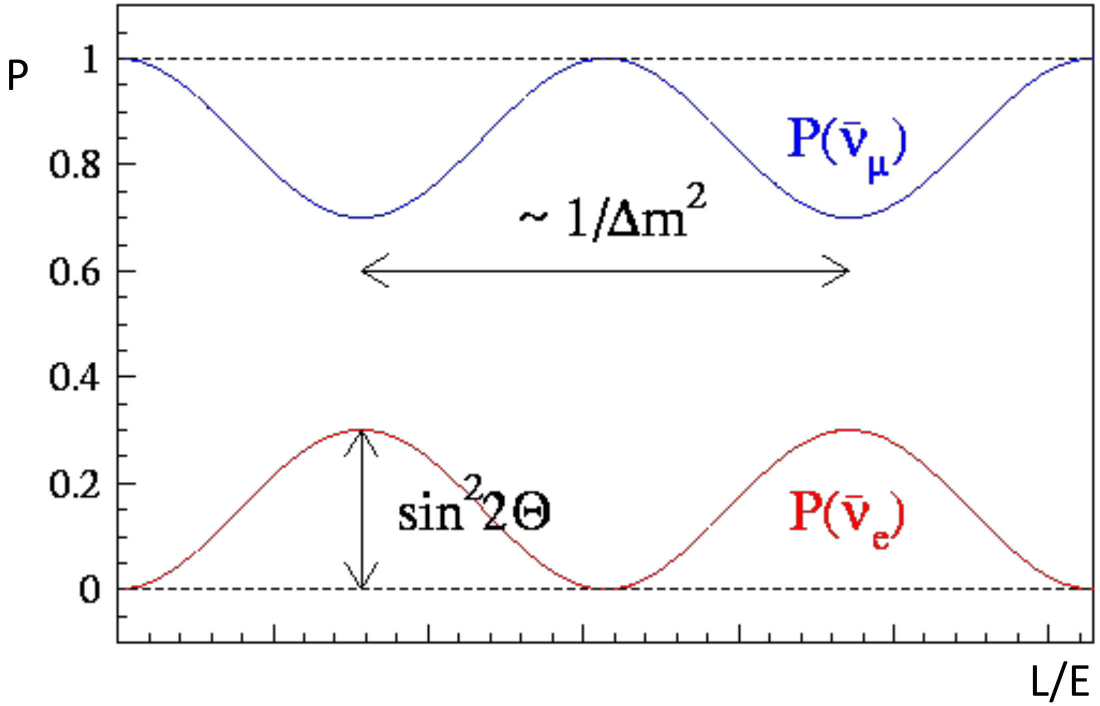


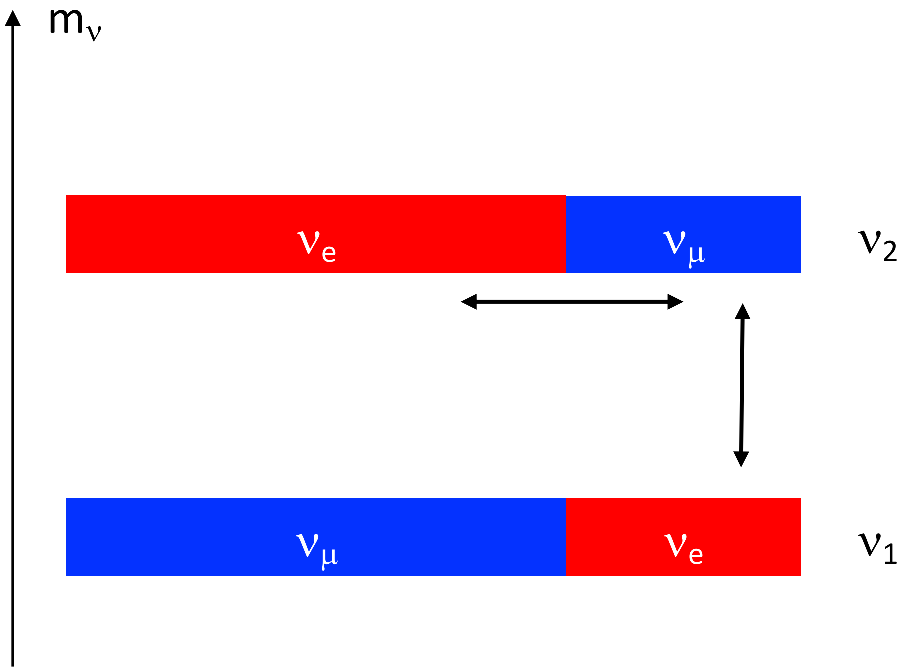
3ν-mixing



https://cds.cern.ch/record/2103251/files/9789814644150_0004.pdf?subformat=pdfa&version=1

Neutrino Oscillations (for 2 Flavour)





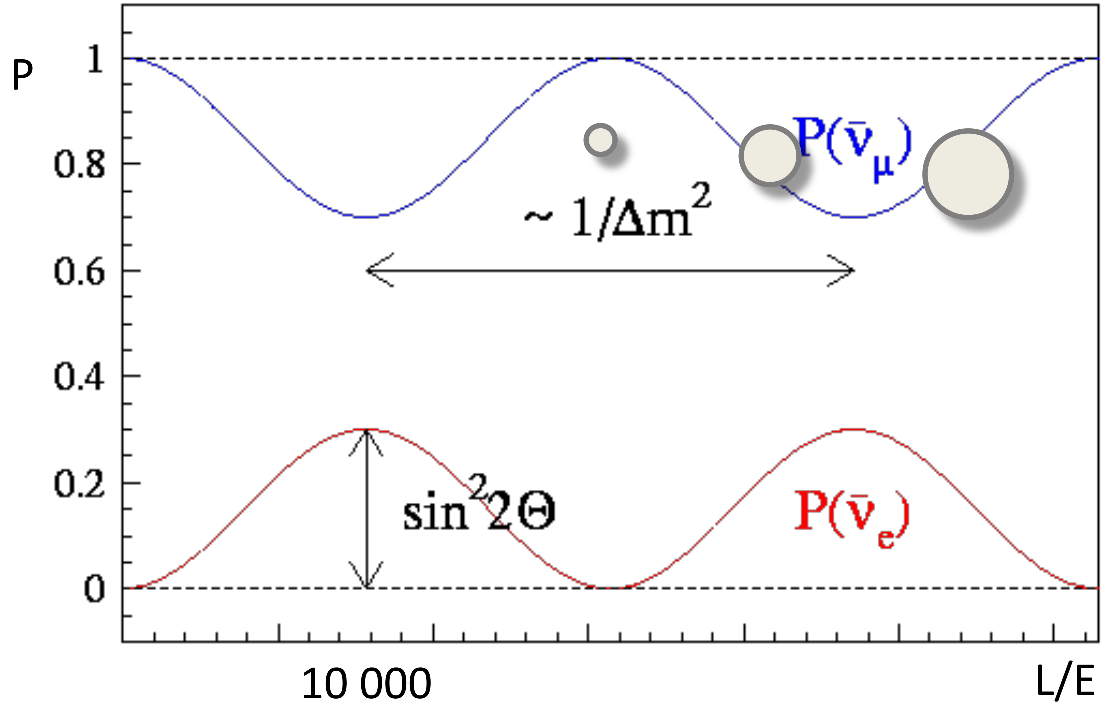
$$P(\nu_\mu \rightarrow \nu_e) = \sin^2 2\theta \, \sin^2(\Delta m^2 \cdot L_\nu / E_\nu)$$

Amplitude

Frequency

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

Neutrino Oscillations (for 2 Flavour)



In numbers (example):

For $\Delta m^2 = 10^{-4}$ eV^2:

$1.27 \times 10^{-4} \times 10\,000 \approx \pi/2$

→ L/E ~ 10 000 m/MeV

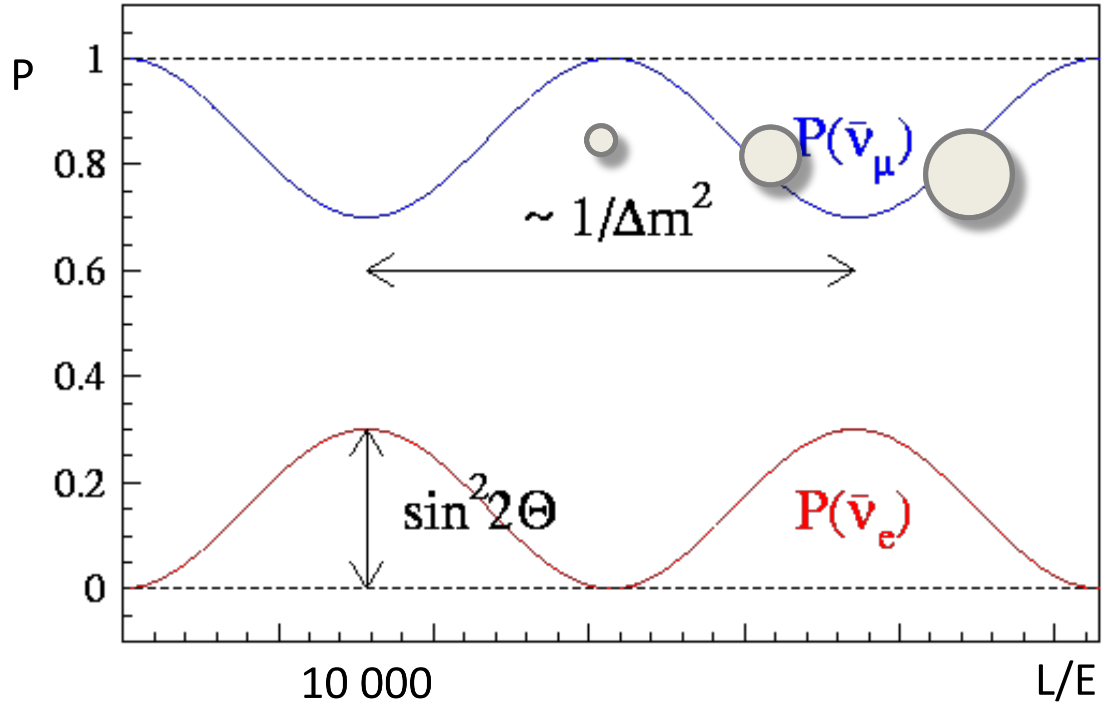
$$P(\nu_\mu \to \nu_e) = \sin^2 2\theta \sin^2(\Delta m^2 \cdot L_\nu / E_\nu)$$

Amplitude　　Frequency

$= \sin^2 2\theta \sin^2(1.27\ \Delta m^2\ L_\nu(\text{km})/E_\nu(\text{GeV}))$

$= \sin^2 2\theta \sin^2(1.27\ \Delta m^2\ L_\nu(\text{m})/E_\nu(\text{MeV}))$

Neutrino Oscillations (for 2 Flavour)



In numbers (example):

For **Δm² = 1 eV²:**

1.27 x 1 x 1 ≈ π/2

→ L/E ~ 1 m/MeV

$$P(\nu_\mu \rightarrow \nu_e) = \sin^2 2\theta \, \sin^2(\Delta m^2 \cdot L_\nu / E_\nu)$$

Amplitude Frequency

= $\sin^2 2\theta \, \sin^2(1.27 \, \Delta m^2 \, L_\nu(\mathrm{km})/E_\nu(\mathrm{GeV}))$

= $\sin^2 2\theta \, \sin^2(1.27 \, \Delta m^2 \, L_\nu(\mathrm{m})/E_\nu(\mathrm{MeV}))$

3ν Oscillation Formalism

Atmospheric | Cross-Mixing | Solar | Majorana CP phases (L violating processes)

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

PMNS mixing matrix

$\theta_{23} \sim 45°$: "atm." angle | $\theta_{13} \sim 9°$ | $\theta_{12} \sim 34°$: "solar" angle

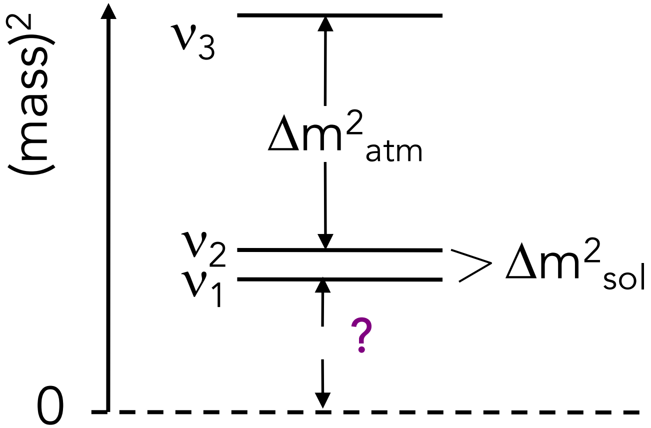
δ dirac CP phase

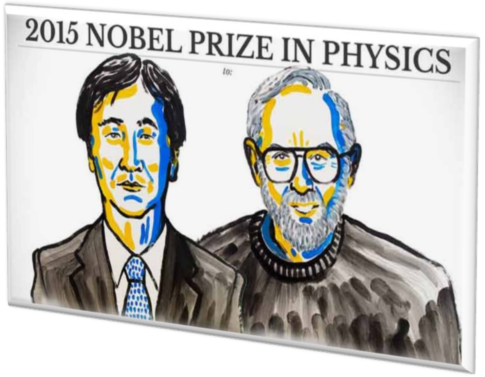
- 3 masses $m_{1,2,3}$: $\Delta m^2_{sol} = m_2^2 - m_1^2 \sim 8\ 10^{-5}\ eV^2$ & $\Delta m^2_{atm} = |m_3^2 - m_1^2| \sim 2\ 10^{-3}\ eV^2$
- Oscillation in vacuum : $P(\nu_x \to \nu_x) \approx 1 - \mathbf{sin^2(2\theta_i)} \times \sin^2\left(1.3 \cdot \boldsymbol{\Delta m_i^2} \cdot \frac{\mathbf{L}}{\mathbf{E}}\right)$

tunable

Facts & open questions

- Masses of the mass eigenstates ν_i?





- Spectral pattern  or  ?

- Lepton Number conservation (Dirac or Majorana) ?

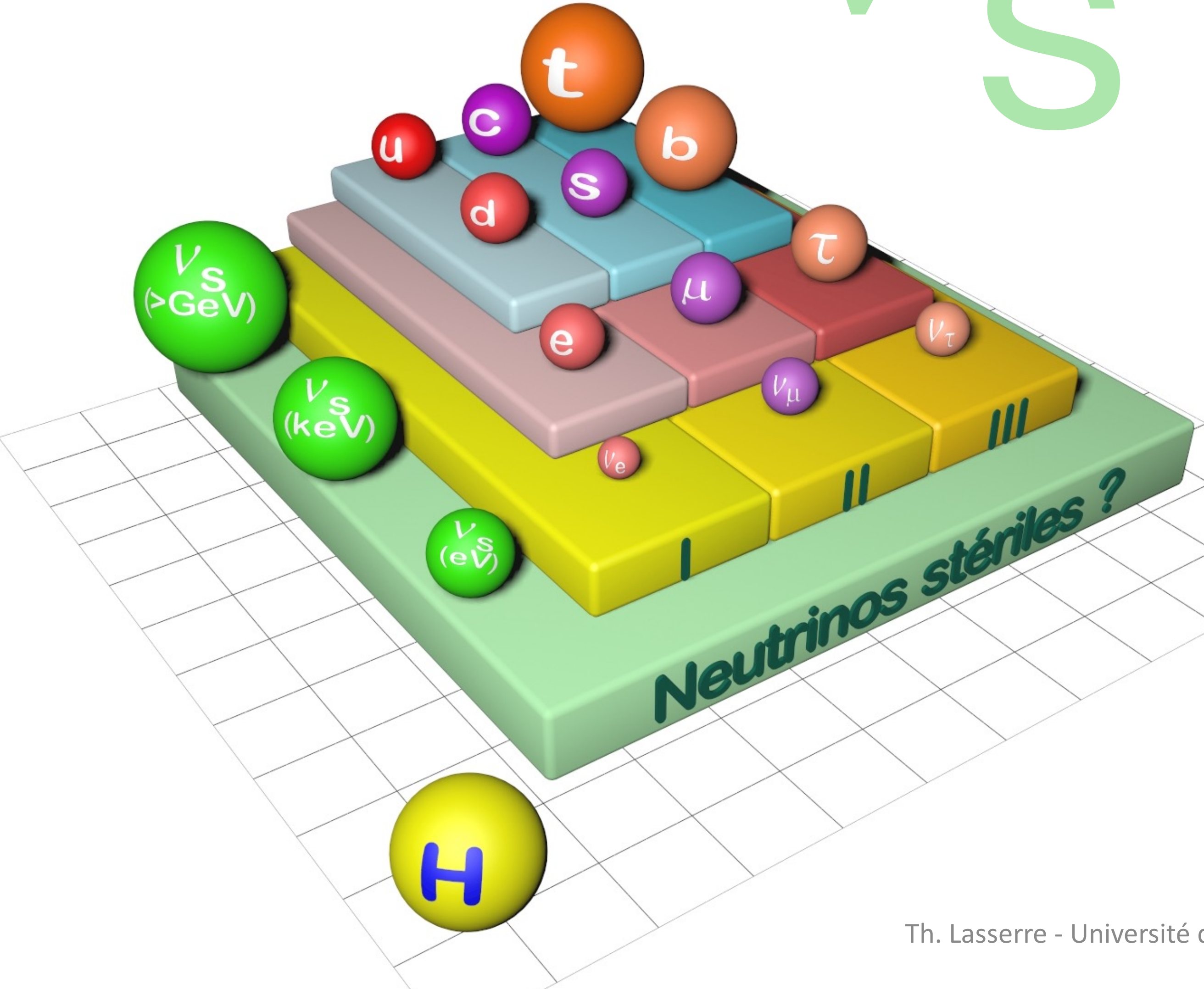
This lecture!

- Precise measurements of PMNS matrix?
- Is CP violated in the neutrino sector?

- **Are there additional (sterile) neutrino states**

Sterile Neutrinos

ν_s



Composition	**Elementary Particle**
Spin	1/2
Electric Charge	0
Strong Charge	0
Interaction	None
Mass	Not yet known
Oscillation	Possible with ν_e , ν_μ , ν_τ
Status	Hypothetic

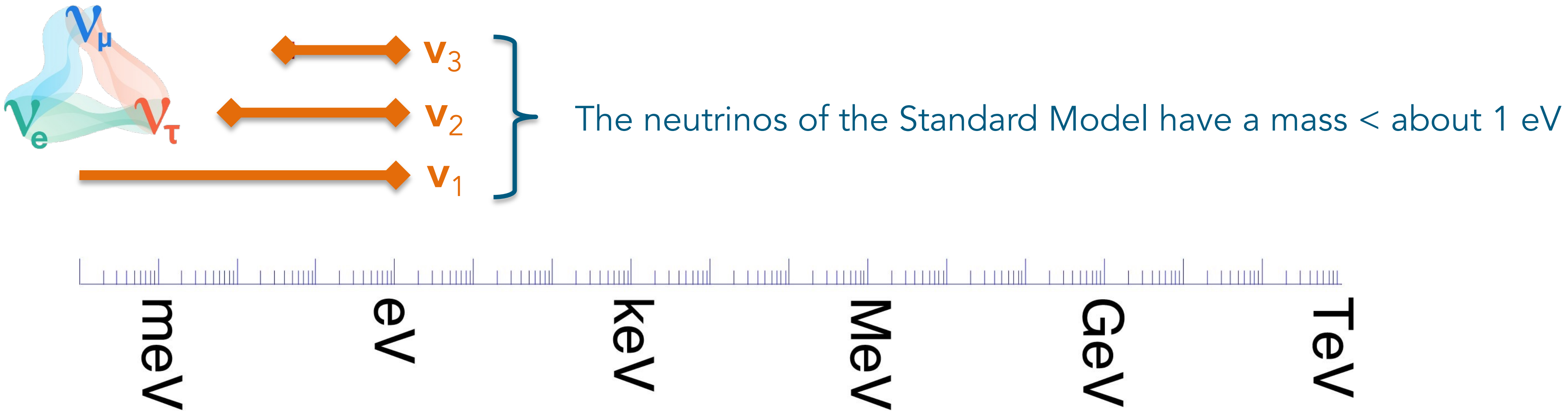
Caveat: ν_4 and ν_s ! ! !

ν_s

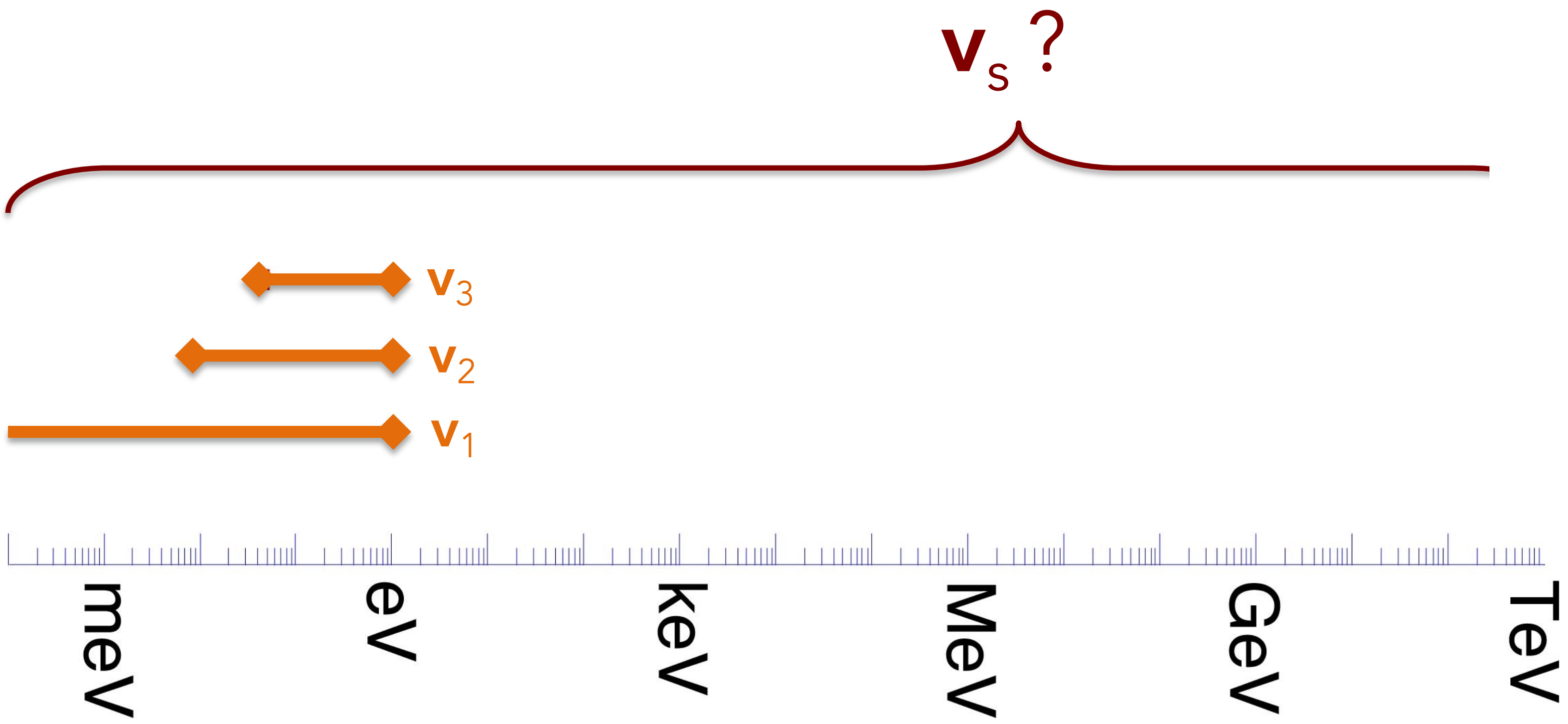
ν_4

This is what we call „sterile" neutrino

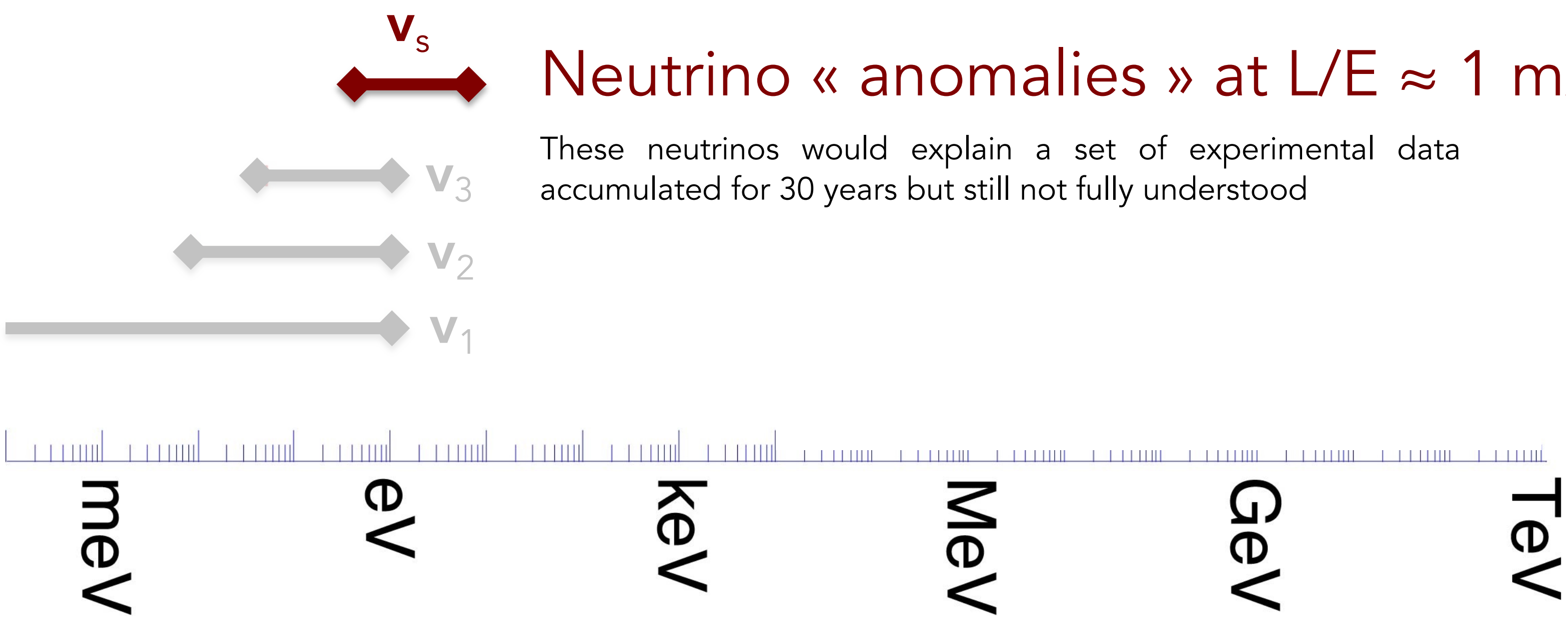
Active Neutrino Mass



Sterile Neutrino Mass



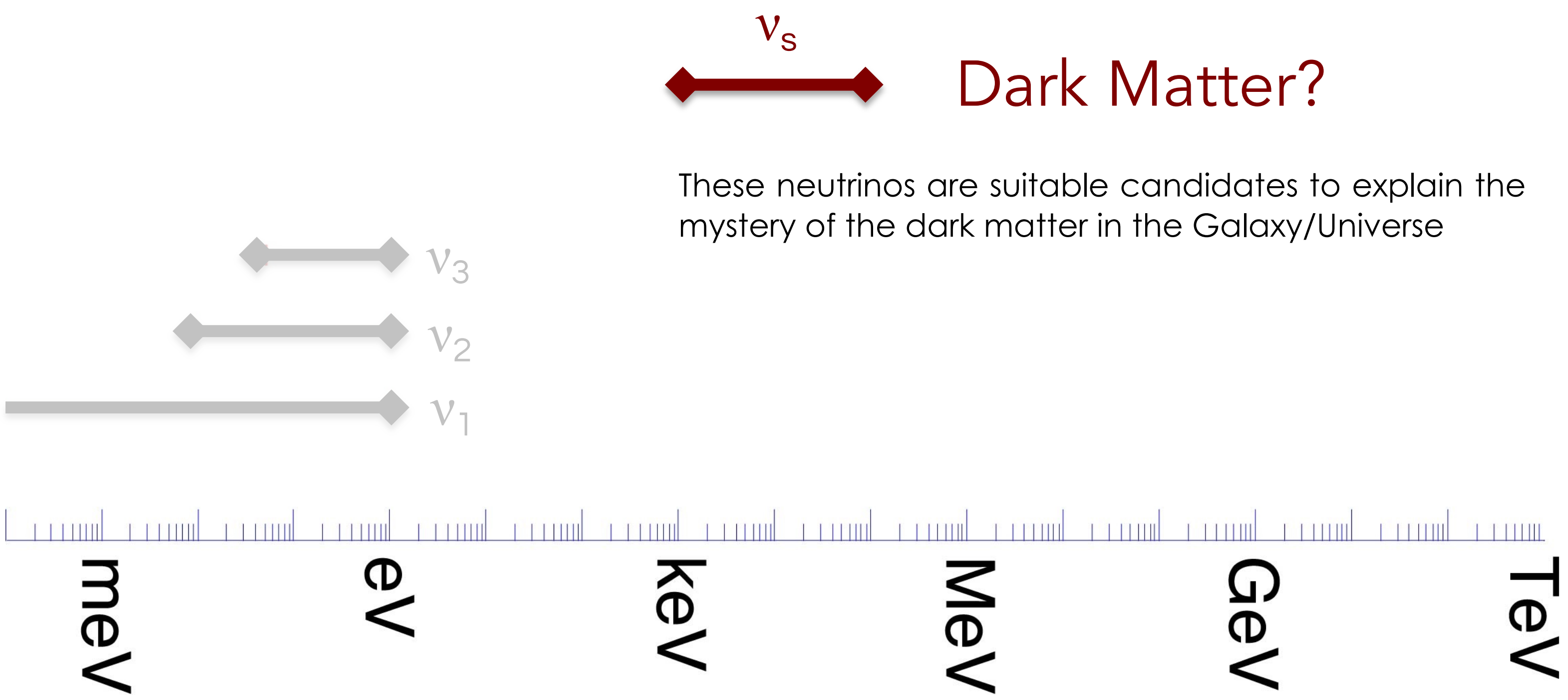
Which Mass: 0.1-1 eV?



Neutrino « anomalies » at L/E ≈ 1 m/MeV ?

These neutrinos would explain a set of experimental data accumulated for 30 years but still not fully understood

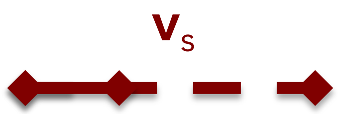
Which Mass: keV?



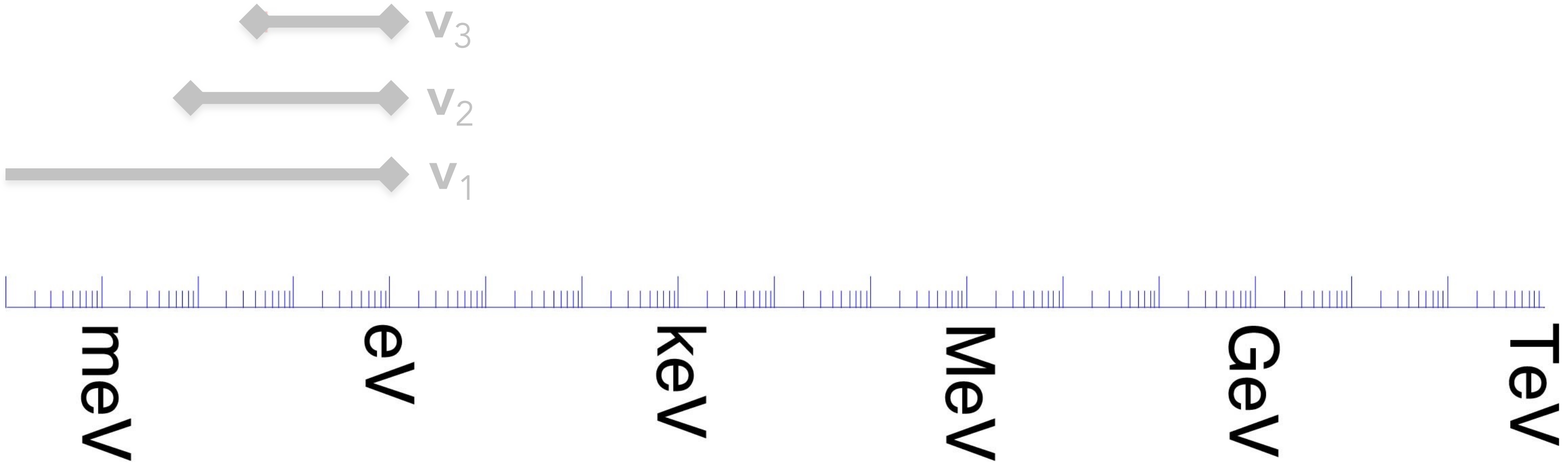
These neutrinos are suitable candidates to explain the mystery of the dark matter in the Galaxy/Universe

Which Mass: GeV?

Matter-antimatter asymmetry ?

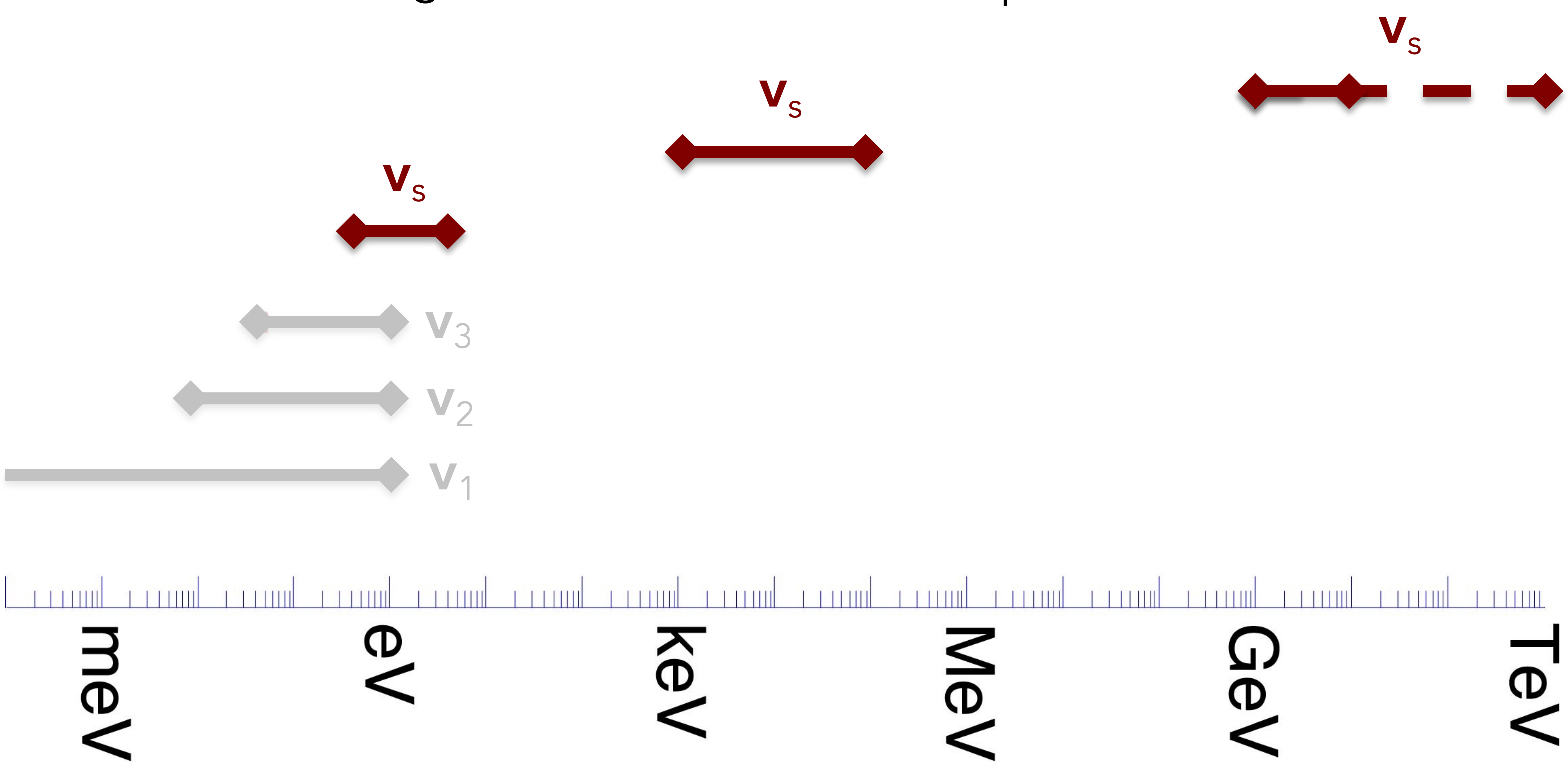


These neutrinos could explain the matter - antimatter asymmetry in the Universe, through a mechanism called the Leptogenesis



New Experiments !

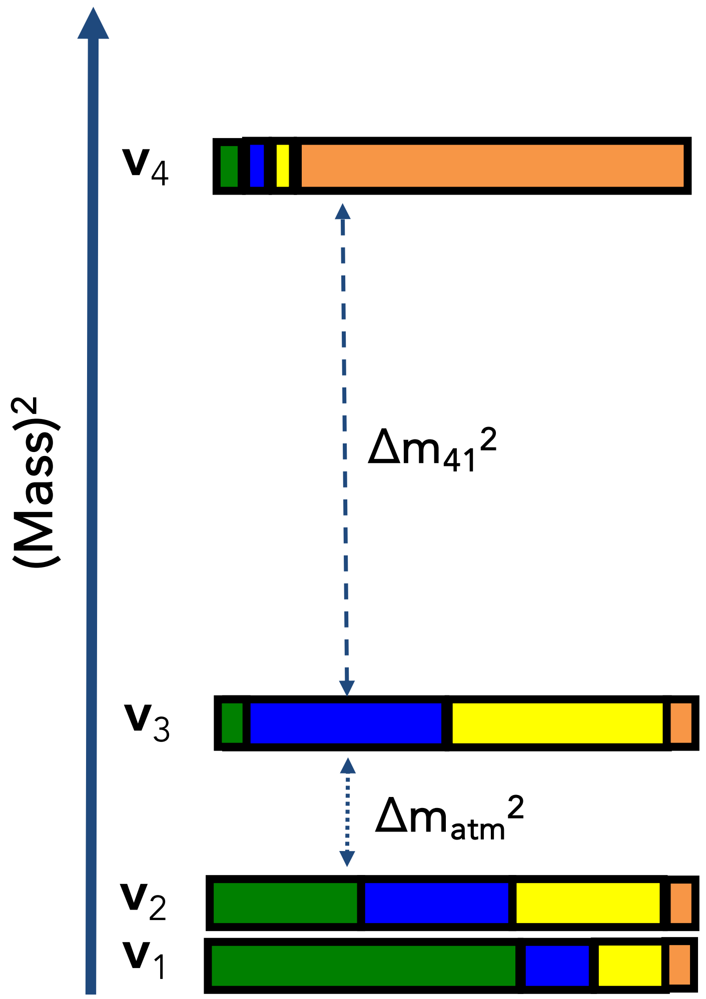
Without new theoretical insights
only new experiments shall bring
light on the sterile neutrino question



How to detect sterile Neutrinos?

… through their Mixing !

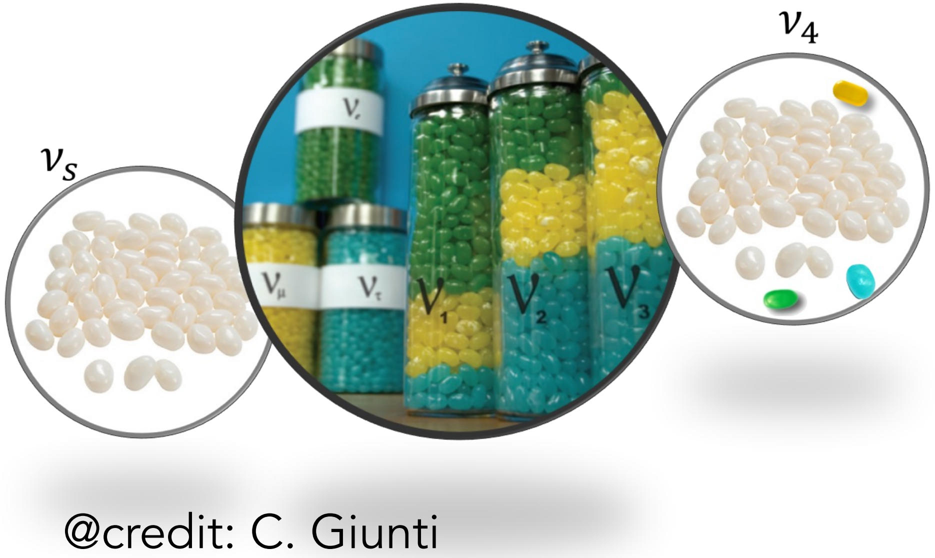
Light sterile neutrino – 3+1 model



$$\frac{L}{E} \sim \frac{\text{meter}}{\text{MeV}}$$ max. oscillation ?

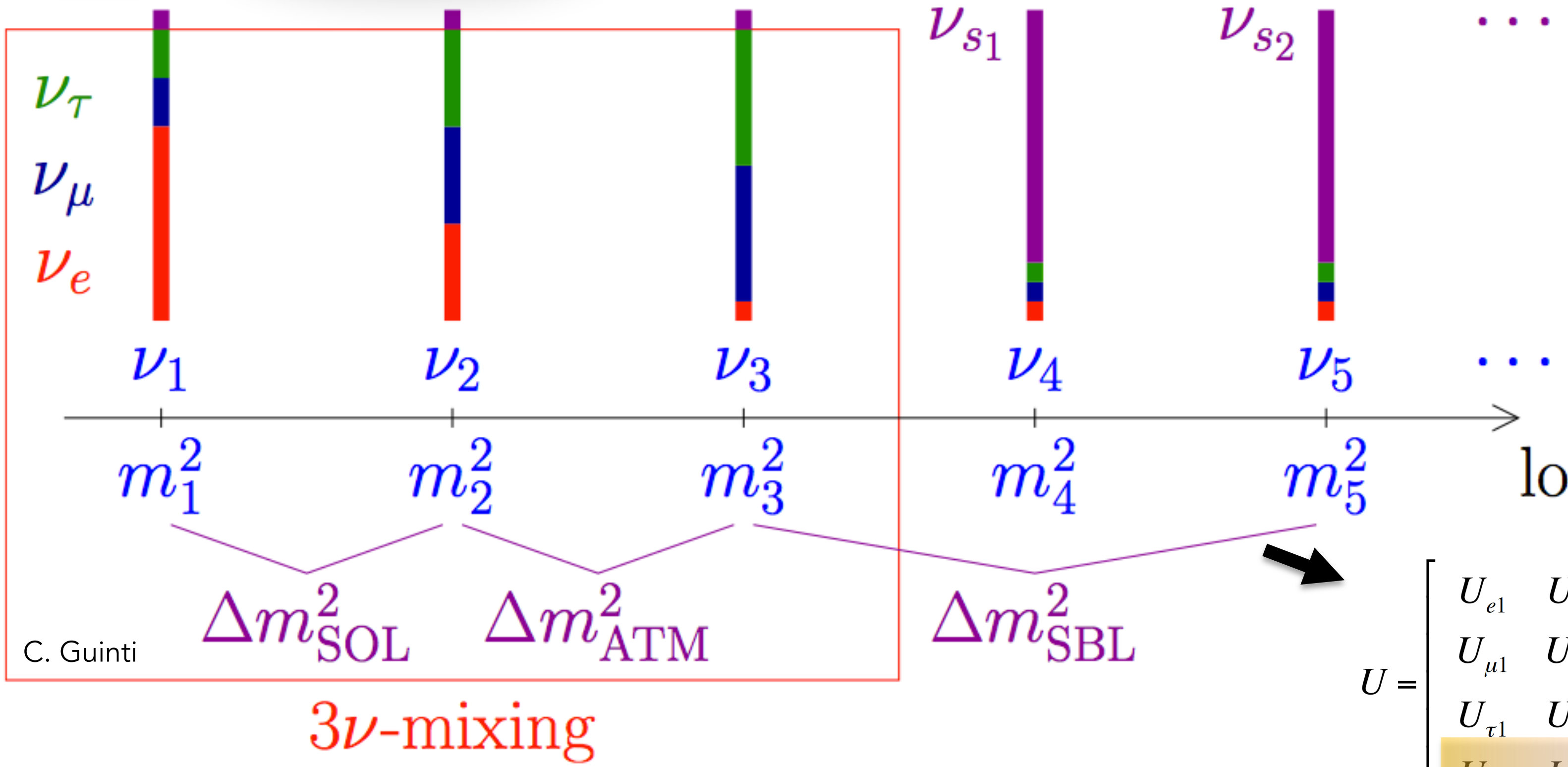
ν_e $|U_{ei}|^2$ ν_μ $|U_{\mu i}|^2$ ν_τ $|U_{\tau i}|^2$ ν_s $|U_{si}|^2$

3+x Model



@credit: C. Giunti

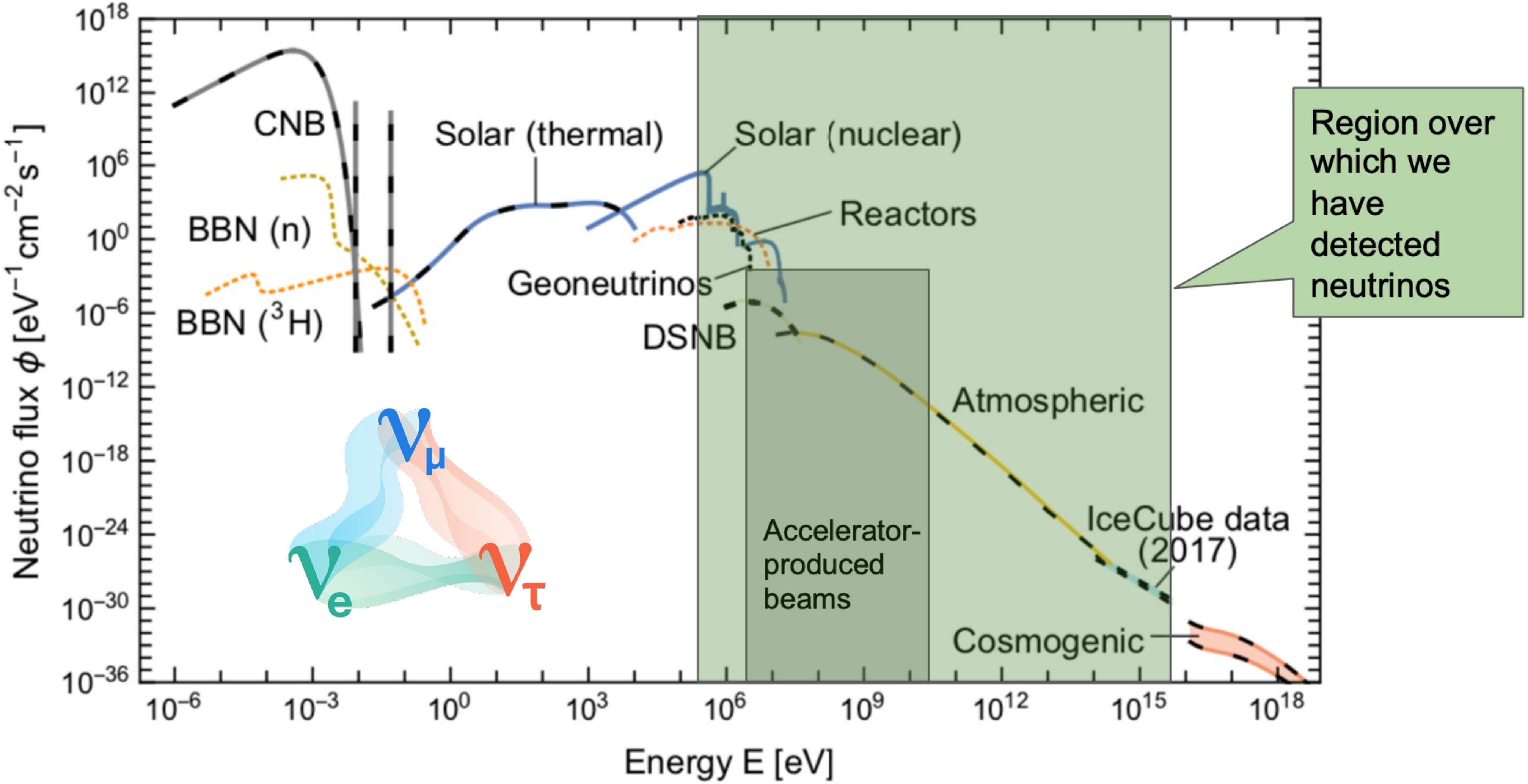
No SM interactions.
But mixing (oscillation) with active ν's



$$U = \begin{bmatrix} U_{e1} & U_{e2} & U_{e3} & U_{e4} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} & U_{\mu 4} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} & U_{\tau 4} \\ U_{s1} & U_{s2} & U_{s3} & U_{s4} \end{bmatrix}$$

Many Neutrino Sources can be used

Grand Unified Neutrino Spectrum at Earth
Edoardo Vitagliano, Irene Tamborra, Georg Raffelt. Oct 25, 2019. 54 pp.
MPP-2019-205
e-Print: arXiv:1910.11878 [astro-ph.HE] | PDF



Sterile- ν Phenomenology (3+1)

- $\overset{(-)}{\nu}_e$ disappearance (Reactor, Gallium, …)
  - $$P_{ee} = 1 - \sin^2 2\theta_{ee} \sin^2 \frac{\Delta m^2_{41}}{4E} \quad \& \quad \sin^2 2\theta_{ee} = |U_{e4}|^2 \left(1 - |U_{e4}|^2\right) \text{ X } 4$$

Sterile- $\boldsymbol{\nu}$ Phenomenology (3+1)

- $\overset{(-)}{\boldsymbol{\nu}}_{\boldsymbol{\mu}}$ disappearance (CDHS, MiniBOONE, Minos, ICE Cube…)
  - $P_{\mu\mu} = 1\text{-}\sin^2 2\theta_{\mu\mu} \sin^2 \frac{\Delta m^2_{41}}{4E}$ & $\sin^2 2\theta_{\mu\mu} = |U_{\mu 4}|^2 \left(1\text{-}|U_{\mu 4}|^2\right)$ X 4

Sterile- ν Phenomenology (3+1)

- $\overset{(-)}{\nu}_e$ appearance (LSND, Karmen, MiniBooNE, Opera, Icarus, JSNS…)
  - $$P_{\mu e} = 4\sin^2 2\theta_{\mu e} \sin^2 \frac{\Delta m^2_{41}}{4E} \quad \& \quad \sin^2 2\theta_{\mu e} \approx \frac{1}{4} \sin^2 2\theta_{ee} \sin^2 2\theta_{\mu\mu}$$

$\nu_\mu \rightarrow \nu_e$ appearance requires ν_μ & ν_e disappearance

Sterile- ν Phenomenology (3+1)

- $\overset{(-)}{\nu}_e$ disappearance (Reactor, Gallium, …)
  - $$P_{ee} = 1 - \sin^2 2\theta_{ee} \sin^2 \frac{\Delta m^2_{41}}{4E} \quad \& \quad \sin^2 2\theta_{ee} = |U_{e4}|^2 \left(1 - |U_{e4}|^2\right) \times 4$$
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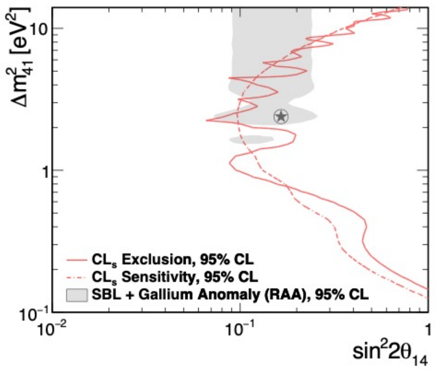
$\nu_\mu \rightarrow \nu_e$ appearance (via ν_s) requires ν_μ & ν_e disappearance

Anomalous findings
&
Sterile Neutrinos

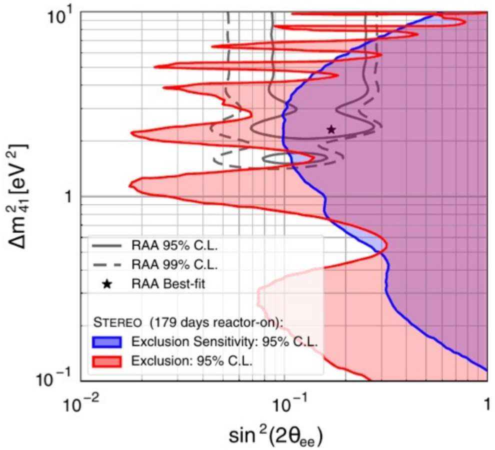
… results against sterile neutrinos !

Short baseline reactor experiments

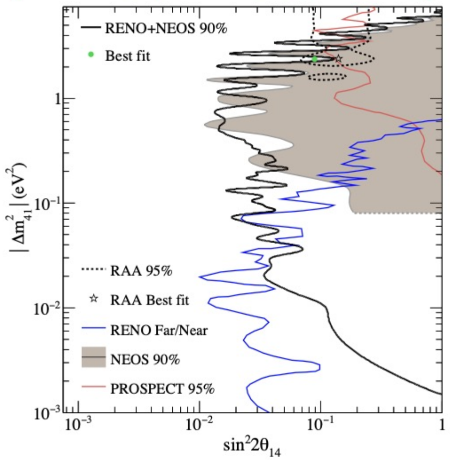
[PROSPECT, PRD 2020]



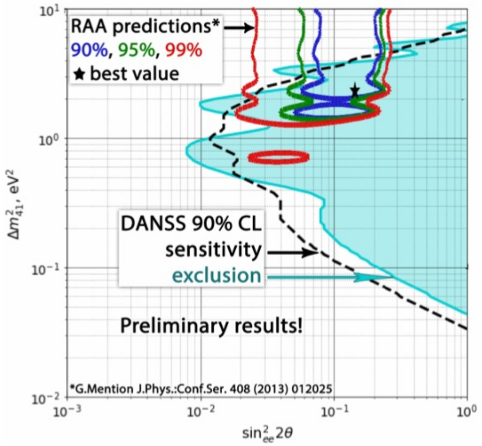
[STEREO, PRD 2020]



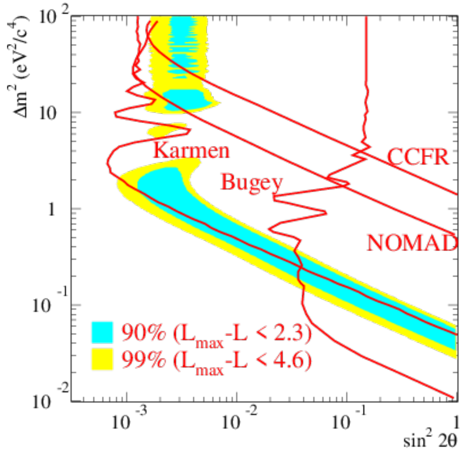
[RENO+NEOS, 2020]



[DANSS, 2020]

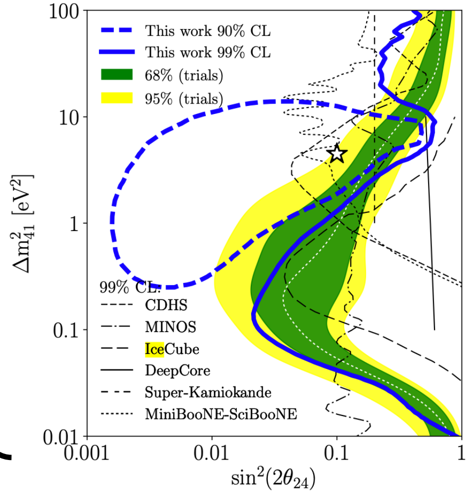


KARMEN

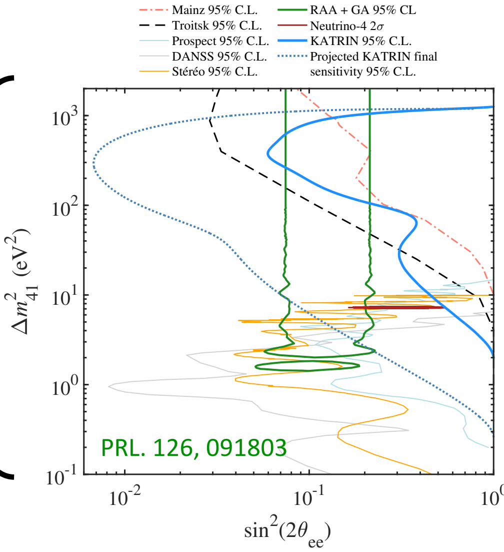


99% ν_μ DIS exclusion

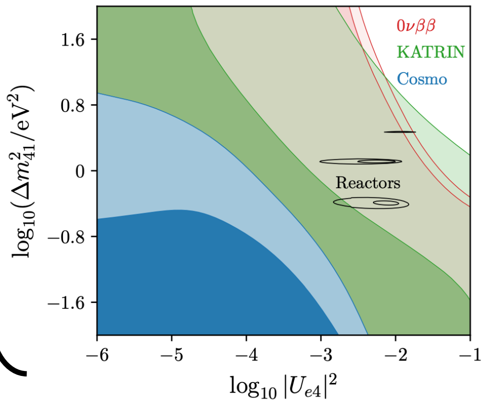
[IceCube, PRL 2020]



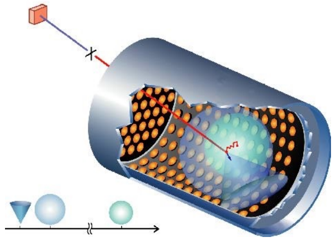
KATRIN



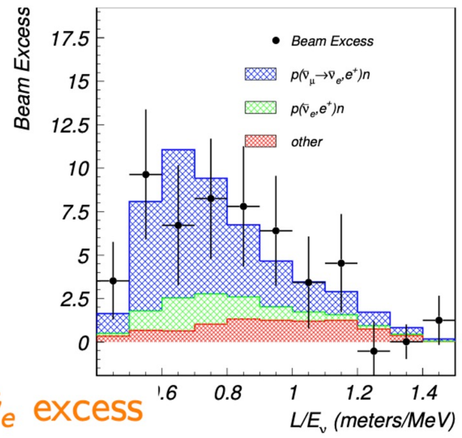
Strong constraints
From cosmology
arXiv:2003.02289



.... anomalies at $\mathbf{L_{[m]}/E_{[MeV]} \sim 1\ m/MeV}$



LSND

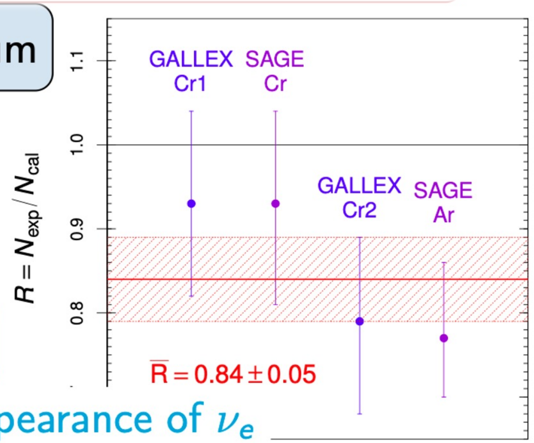


[Aguilar+, 2001]

3.8σ

$\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ excess

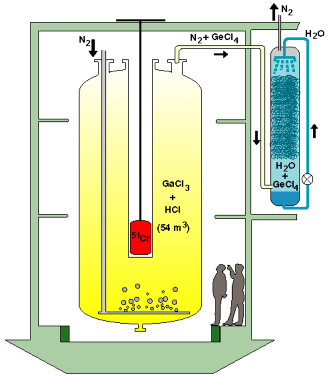
Gallium

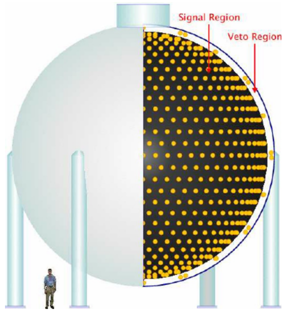


[Giunti, Laveder, 2011]

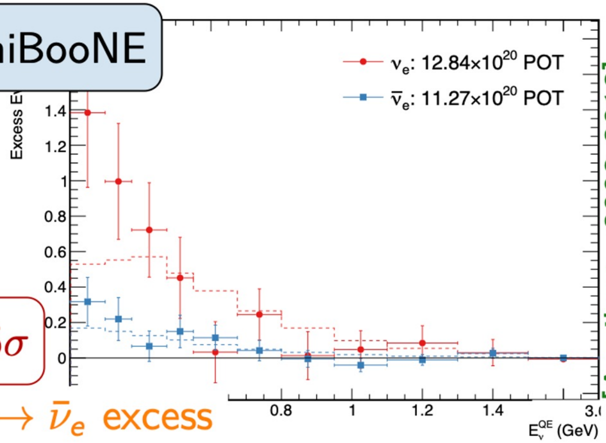
2.7σ

disappearance of ν_e





MiniBooNE



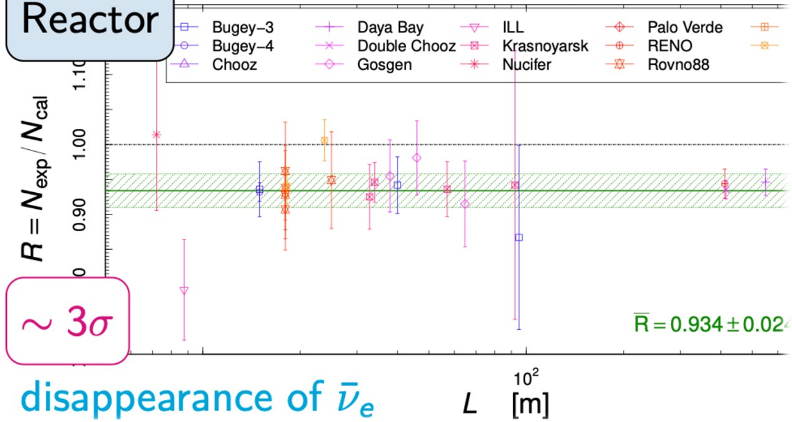
[Aguilar+, 2008-2018]

$\sim 5\sigma$

$\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ excess

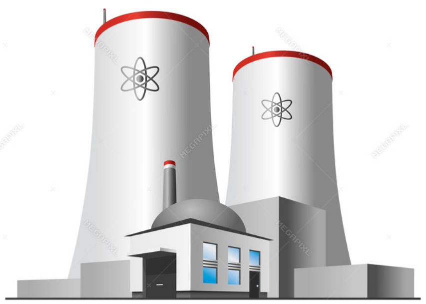
Reactor

[Mention+, 2011] [Azabajian+, 2012]



$\sim 3\sigma$

disappearance of $\bar{\nu}_e$



LSND

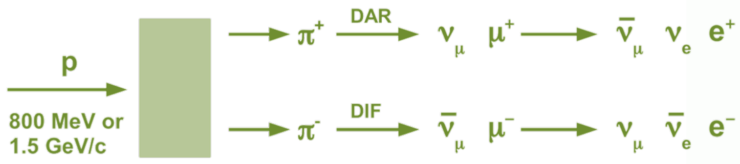
LSND (stopped π^+ beam) – 1990's

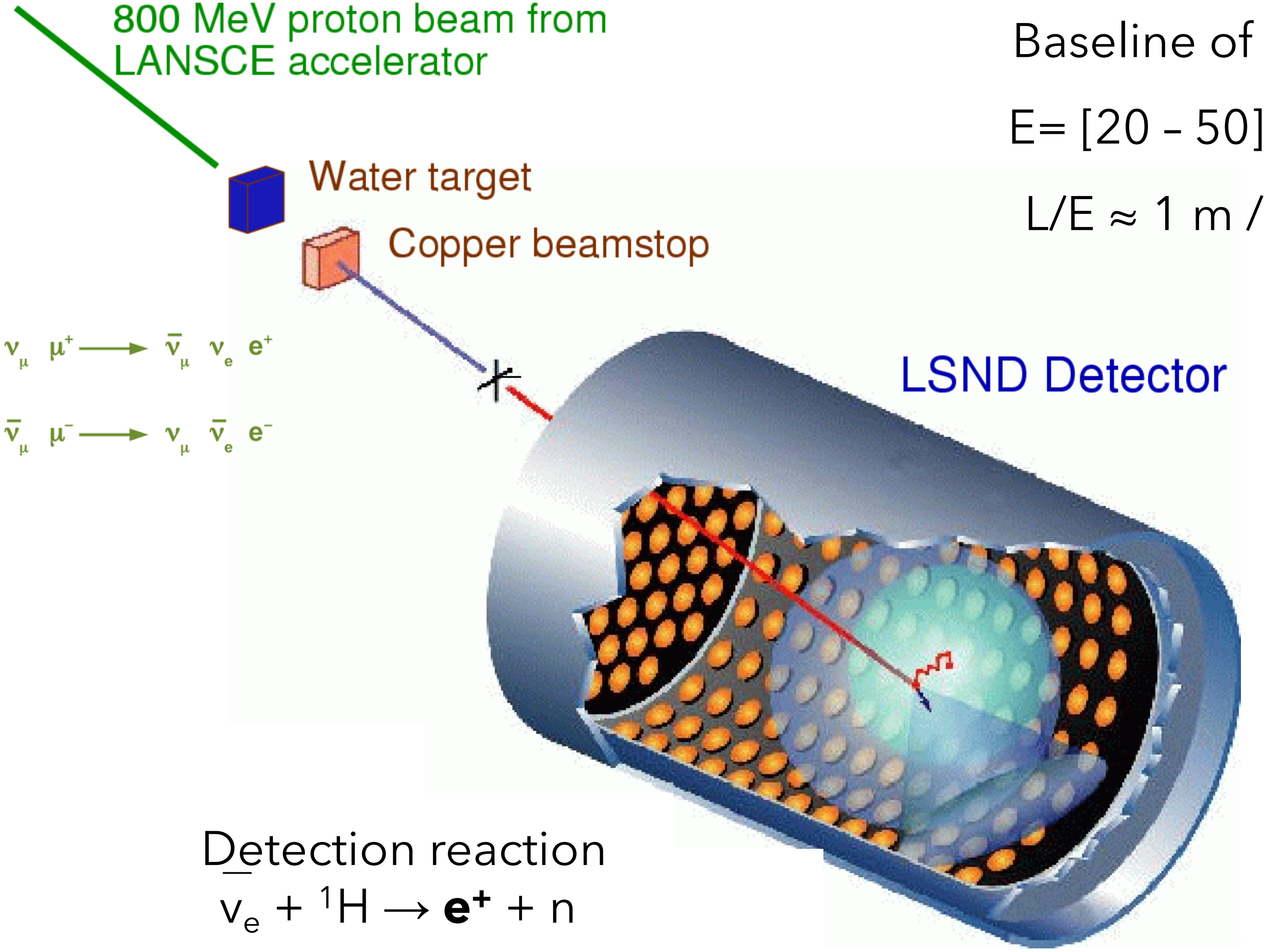
Anomaly on the electron antineutrino interaction rate

Baseline of 30 m

E= [20 – 50] MeV

L/E ≈ 1 m / MeV



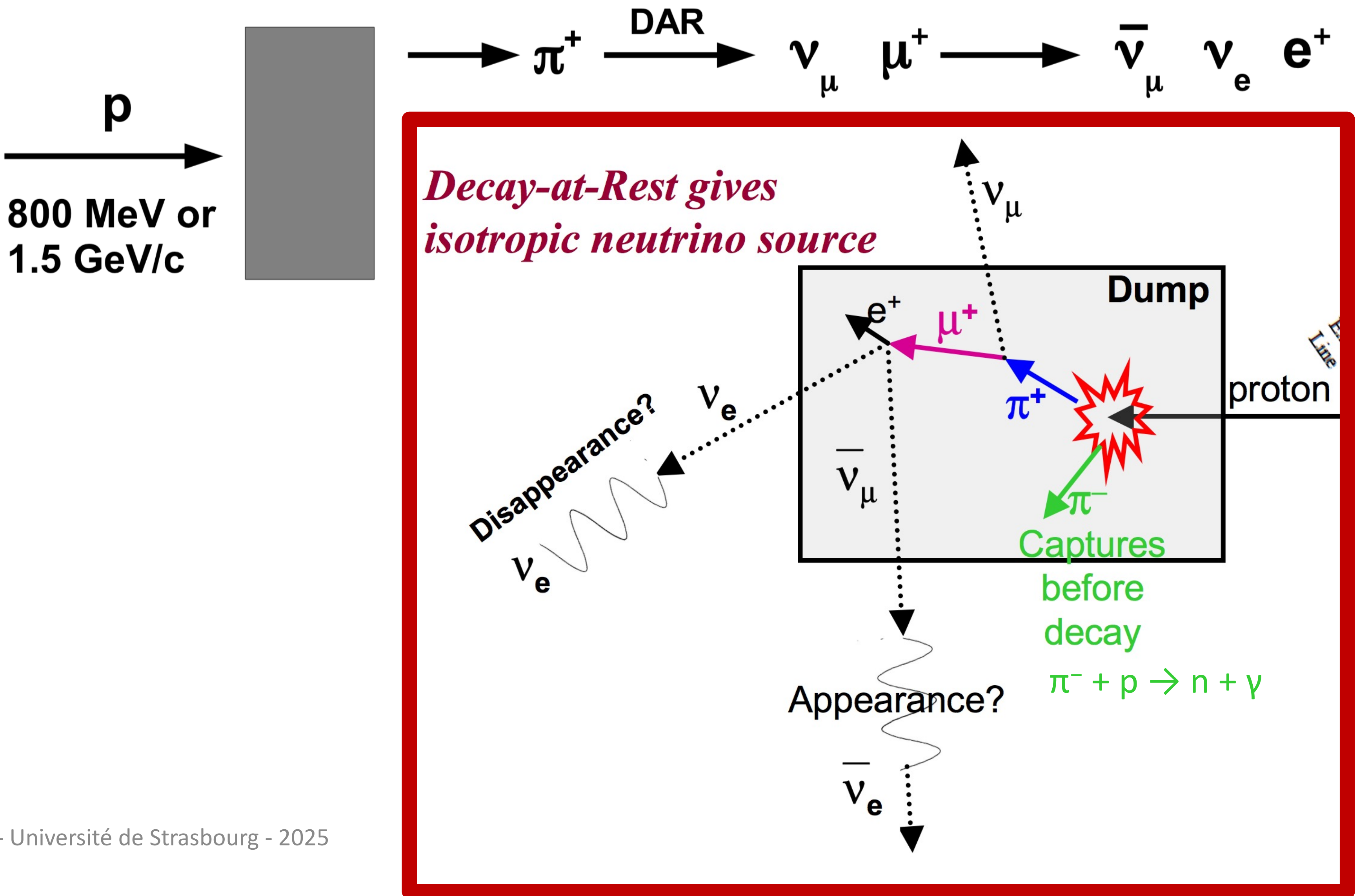


Detection reaction

$\bar{\nu}_e + {}^1H \rightarrow \mathbf{e^+} + n$

Liquid Scintillator Detector Downstream of target

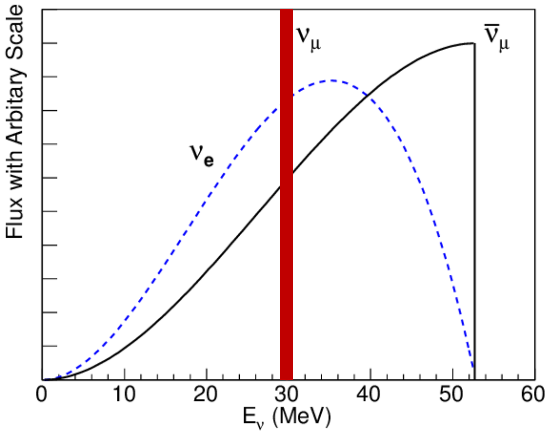
LSND (stopped π^+ beam) – 1990's



By-product charged mesons

- K mesons (493.677 MeV/c²)
  - The energy of the proton beam is too low to create a substantial number of K mesons
- π^- mesons (139.6 MeV/c^2)
  - The great majority (~99%) capture on the target nuclei: $\pi^- + {}^{A}_{Z}\mathrm{X} \rightarrow \mathrm{n} + {}^{A-1}_{Z-1}\mathrm{Y}$
  - Then decay and rarely produce neutrinos
- π^+ mesons (139.6 MeV/c²)
  - Come to rest within the target (less than 1% disintegrate in flight)
  - And then decay at rest

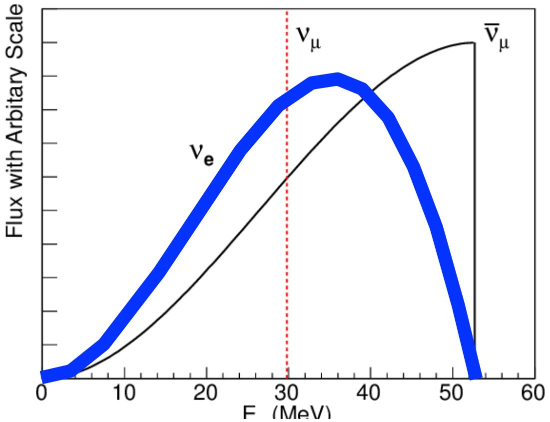
π^+ decay at rest: the « relevant » ν's



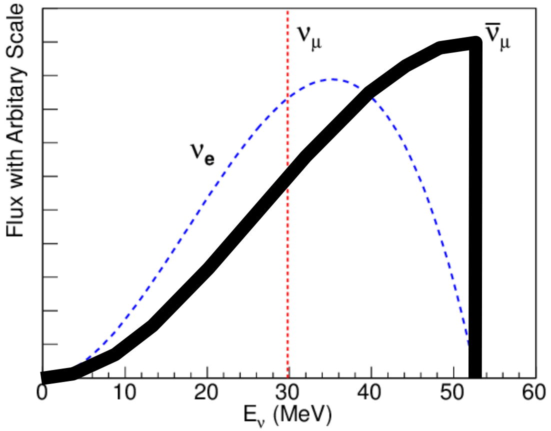
ν_μ

- 1) $\pi^+ \rightarrow \mu^+ + \nu_\mu$
  - Decay At Rest (DAR)
  - Prompt neutrino emission
  - 2 body decay (Q= 33.91 MeV)
    Monoenergetic 29.8 MeV ν_μ emission

ν_e

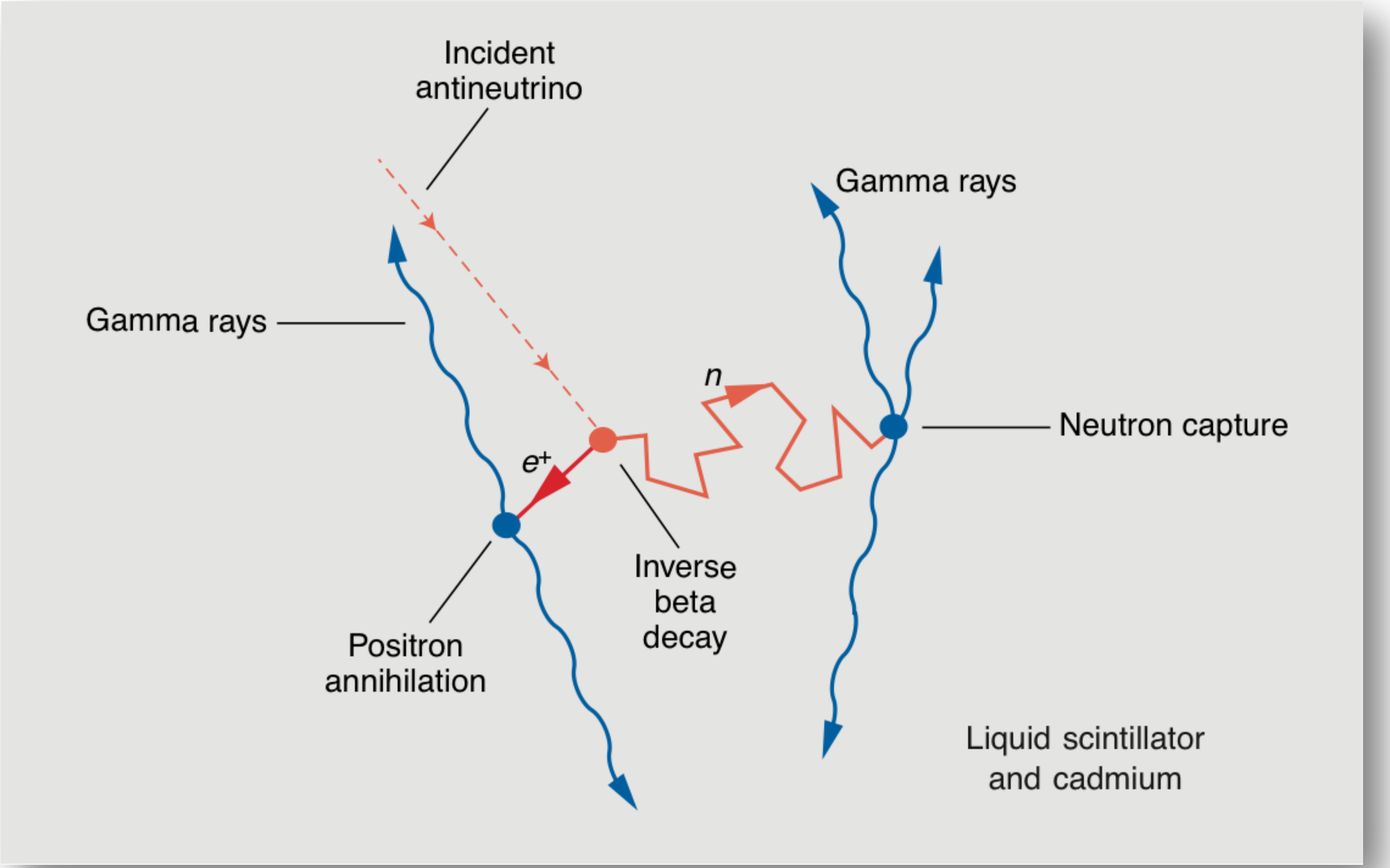


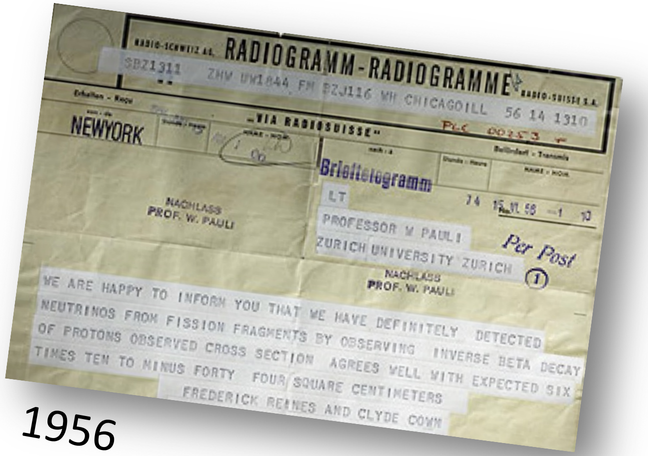
- 2) $\mu^+ \rightarrow e^+ + \nu_e + \overline{\nu_\mu}$
  - Delayed emission (muon decays with a 2.2 μs lifetime)
  - 3 body decay (ν energy between 0 and $m_\mu/2$)
  - ν_e, and $\overline{\nu_\mu}$ have a well-defined « Michel » spectra



$\overline{\nu_\mu}$

LSND Search for $\overline{\nu_e} + p \rightarrow e^+ + n$

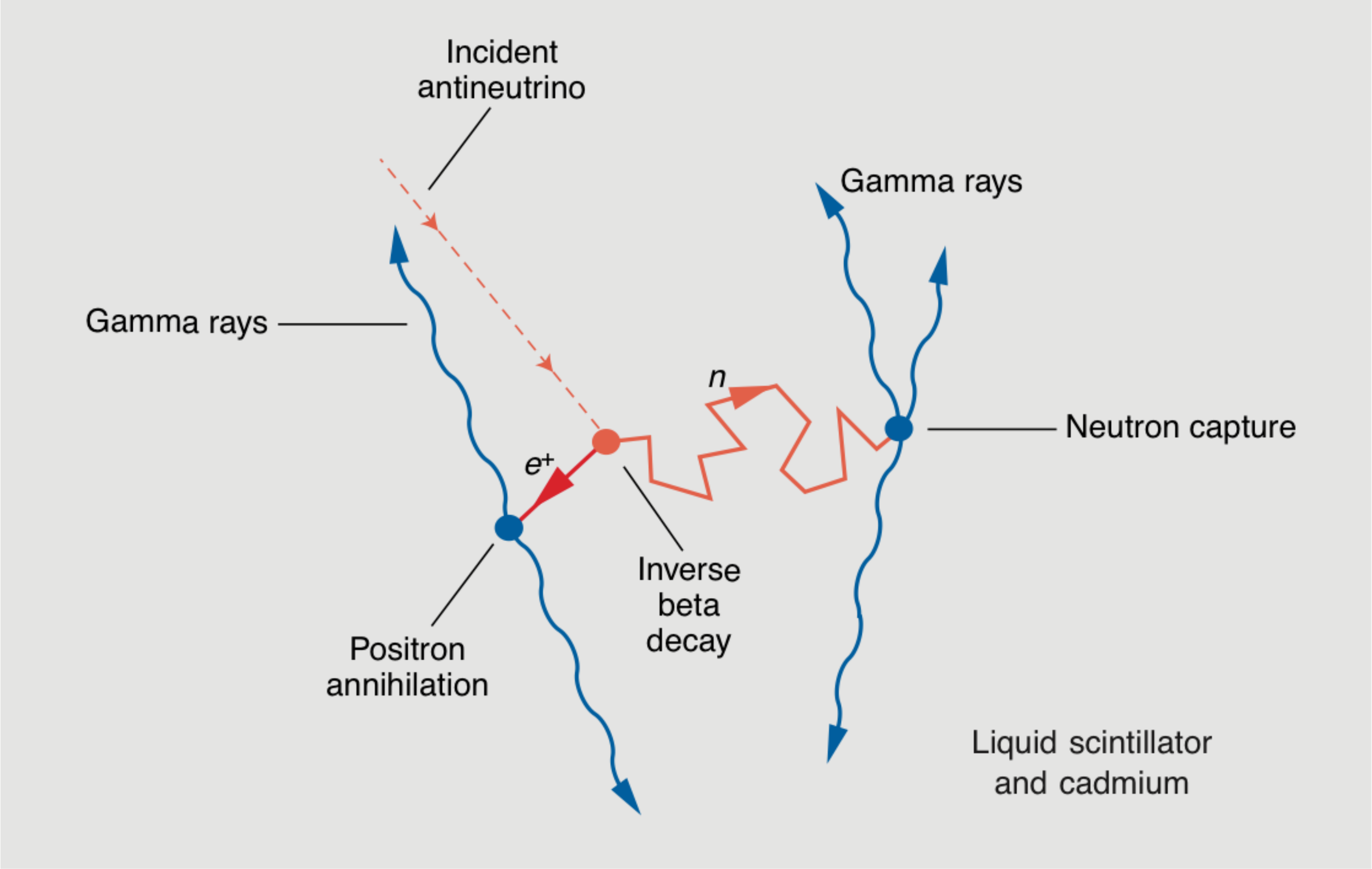



RADIOGRAMM-RADIOGRAMME
SBZ1311 ZHV UW1844 FM BZJ116 WH CHICAGOILL 56 14 1310
NEWYORK
"VIA RADIOSUISSE"
Brieftelogramm
LT
NACHLASS PROF. W. PAULI
PROFESSOR W PAULI
ZURICH UNIVERSITY ZURICH
Per Post
WE ARE HAPPY TO INFORM YOU THAT WE HAVE DEFINITELY DETECTED NEUTRINOS FROM FISSION FRAGMENTS BY OBSERVING INVERSE BETA DECAY OF PROTONS OBSERVED CROSS SECTION AGREES WELL WITH EXPECTED SIX TIMES TEN TO MINUS FORTY FOUR SQUARE CENTIMETERS
FREDERICK REINES AND CLYDE COWN

1956

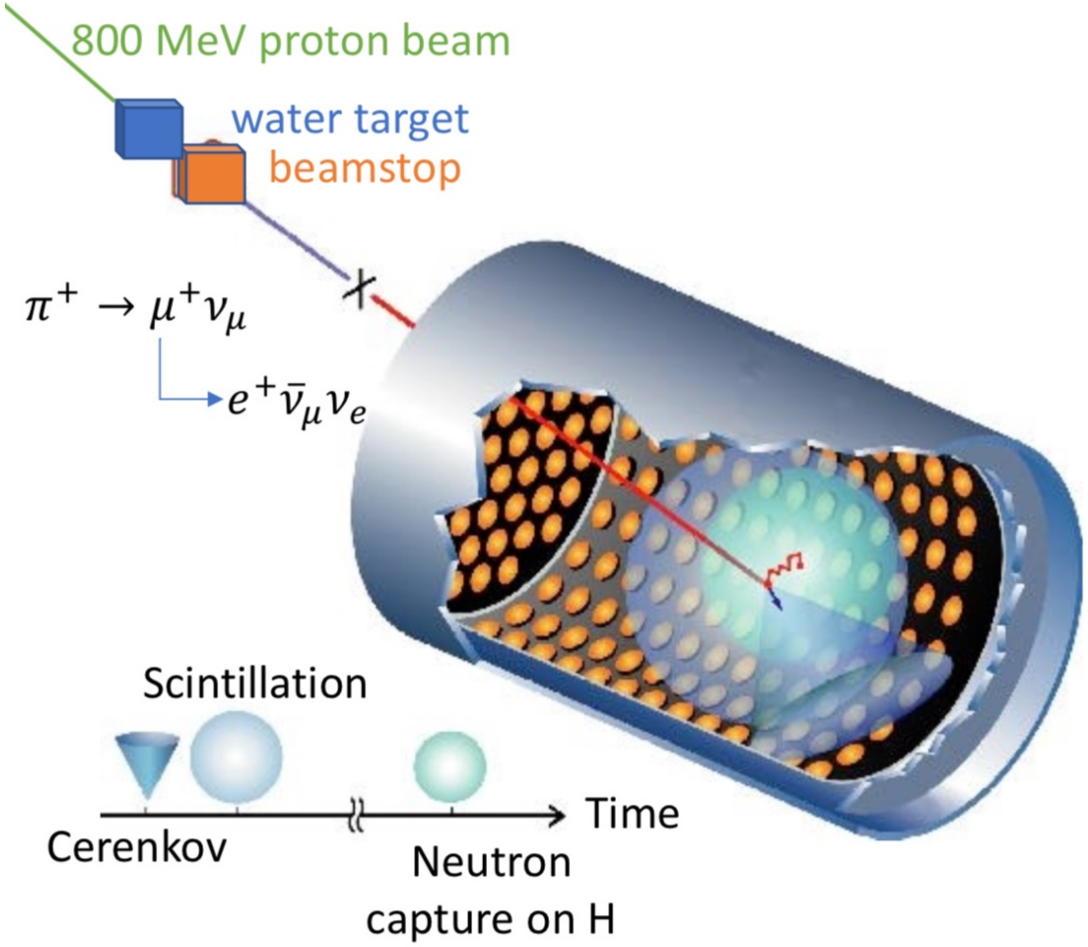
Reines et al. in Physical Review 117 (159) 1960 reported $\sigma = 12^{+7}_{-4}\ 10^{-44}\ \text{cm}^2$

IBD: detecting (e^+,n) in time / space coincidence

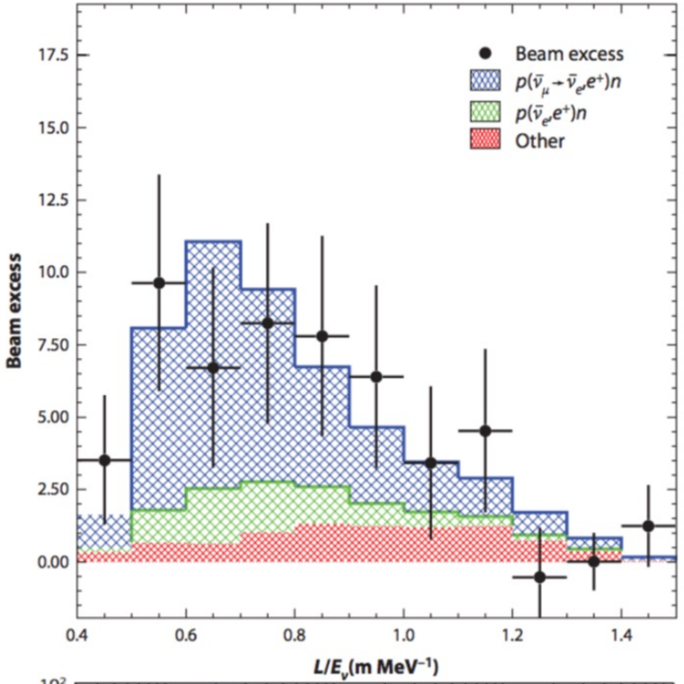


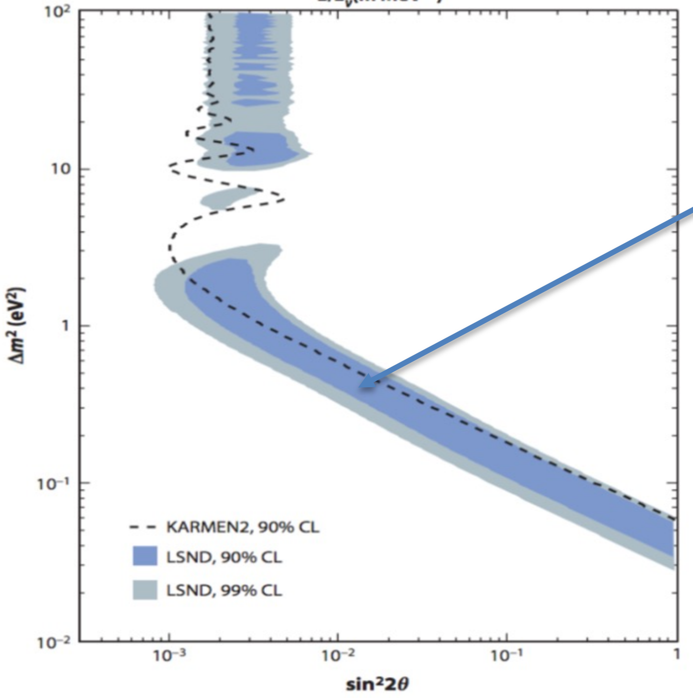
- After the IBD reaction (e+,n) are produced simultaneously
- Step 1)
  e^+ detection
- Step 2)
  neutron detection
- Step 3)
  check that time-difference is less than a few µs

LSND Anomaly



LSND observed a 3.8σ excess





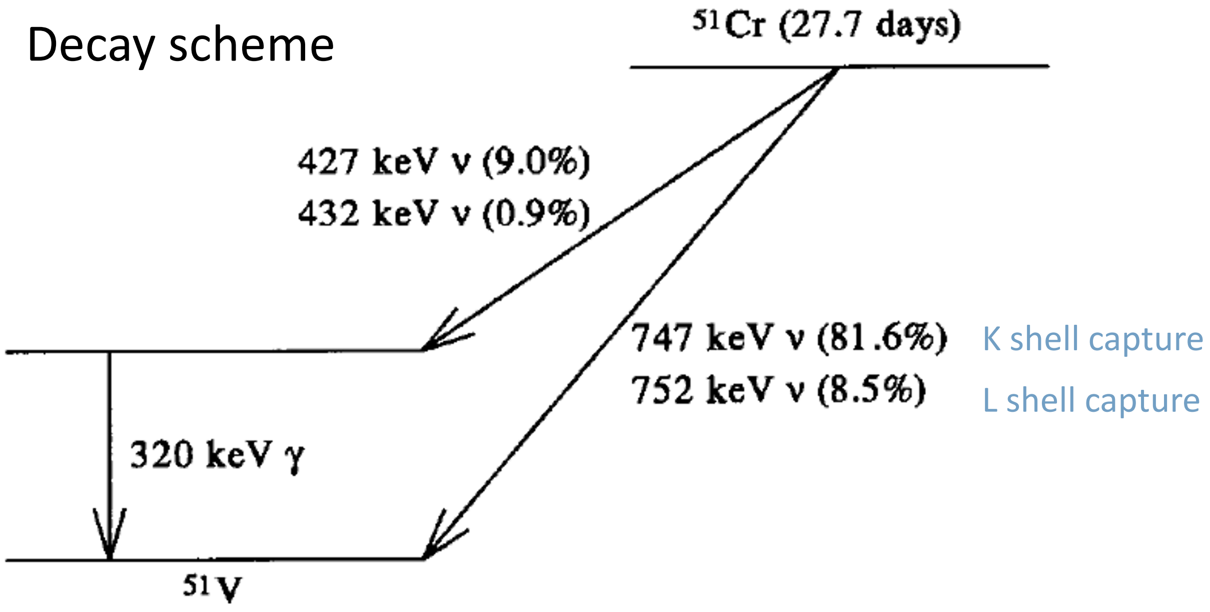
4th (sterile) neutrino mass and mixing explaining the LSND results

Annu. Rev. Nucl. Part. Sci., *63*(1), 45–67.

Gallium Anomaly

^{51}Cr Mono-Energetic Neutrino Source

- Electron capture isotopes decay to two bodies →
  mono-energetic beam of neutrinos at low energies: ^{51}Cr + s-shell e^- → ^{51}V + ν_e (+ X-ray)
- Validated the results of radiochemical solar neutrino experiments (not used for calibration)
- Decay scheme



Decay scheme of ^{51}Cr to ^{51}V through electron capture.

- 90% of the time the capture goes directly to the ground state of ^{51}V and you get a **750 keV neutrino**
- 10% of the time it goes to an excited state of ^{51}V and you get a 320 keV photon plus a 430 keV neutrino

Facts about the ^{51}Cr neutrino generator

- **Can be produced with thermal neutron capture (irradiation)**

  (^{50}Cr has a 17 barn neutron capture cross section)

- Mega-Curie scale sources have been produced by both Gallex, SAGE, and later for BEST

  1 Mega-Curie = 3.7×10^{16} Bq !!!

- Has a long, but not too long, lifetime (39.9 days) → definitively and issue but not a show stopper

- Has one, relatively easy to shield, ***gamma that accompanies 10% of decays.***

  - 5 cm of tungsten reduce 320 keV γ rate from 1 MCi to 1 Hz

Production of ^{51}Cr neutrino generator

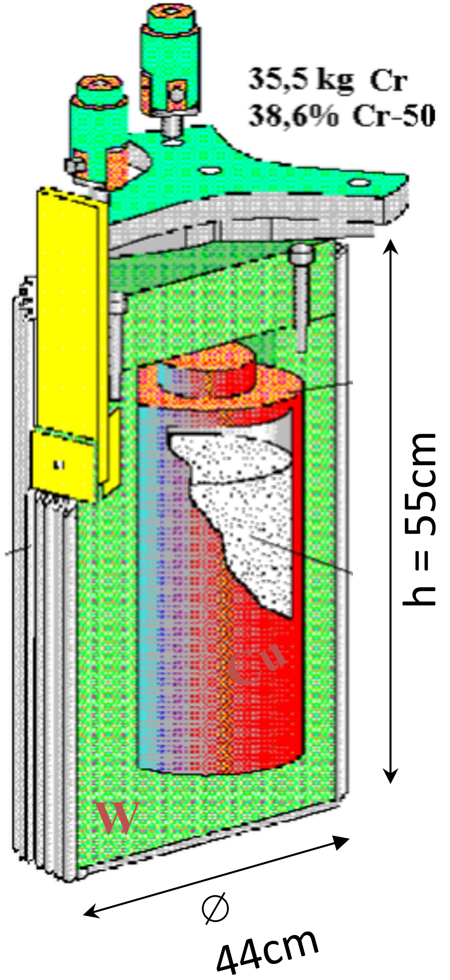
- **First step:**
  - Enrichment of ^{50}Cr by gas centrifugation in form of chromium oxyfluoride $^{50}CrO_2F_2 \rightarrow {}^{50}CrO_3 \rightarrow {}^{50}Cr$ metal

- **Second step:**
  - Irradiation of ^{50}Cr in a nuclear reactor core (slow / thermal neutrons)
  - May need multiple irradiations of a few tens of days

Examples in neutrino physics

GALLEX

(1) 1.17 MCi 1994 –1995
(2) 1.87 MCi 1995 –1996

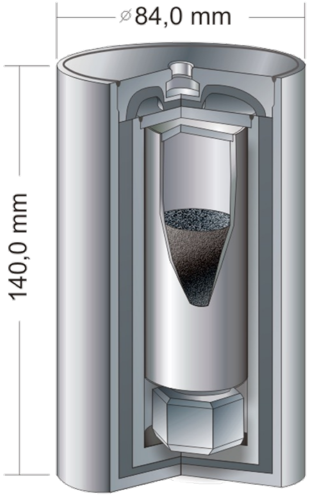


SAGE / BEST

1994 –1995

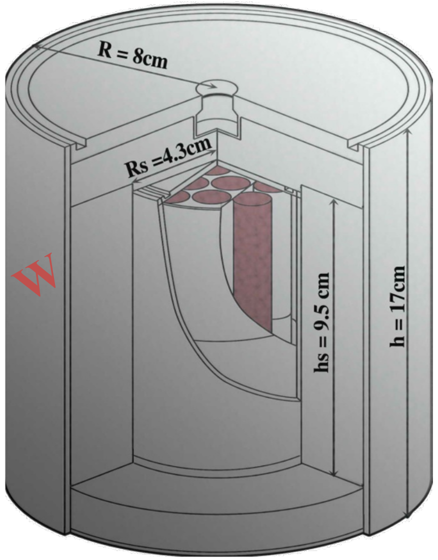
517 kCi ^{51}Cr produced by irradiating 512.7 g of 92.4%-enriched ^{50}Cr in high-flux fast neutron breeder reactor BN-350

2004



409 kCi ^{37}Ar produced by irradiating 330 kg of CaO in the fast neutron breeder reactor BN-600

2020-ish



3 MCi ^{51}Cr produced by rradiating 3 kg of 97%-enriched ^{50}Cr in the research reactor SM-3

The Gallex neutrino generator

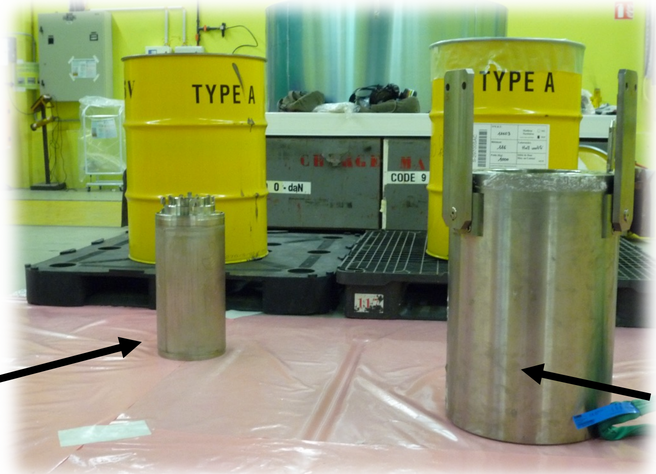
- Made in the Siloé reactor in Gernoble, France (35 MW)

- Two sources produced from the same enriched Cr (38.6% ^{50}Cr)

Characteristics of the production of the two sources in the Siloé reactor.

	First source	Second source
Chromium weight (g)	35 530 ± 10	35 575 ± 10
Duration of the irradiation	23.8 d	26.5 d
Mean neutron flux ($n/cm^2.s$)	5.2×10^{13}	5.6×10^{13}
	1.67 MCi	**1.89 MCi**

- Dismantled in Saclay and sent to INFN in 2017



Transportation of a ^{51}Cr neutrino source

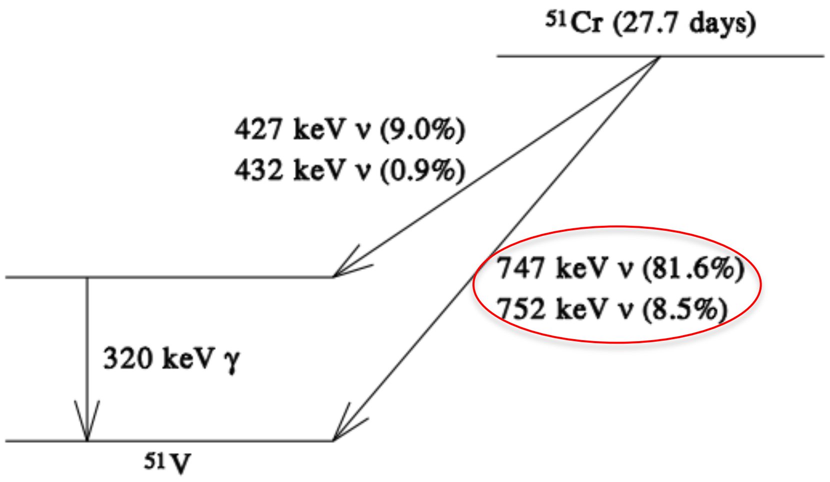
Challenge: ½ of the activity after irradiation is lost every 27 days !!!

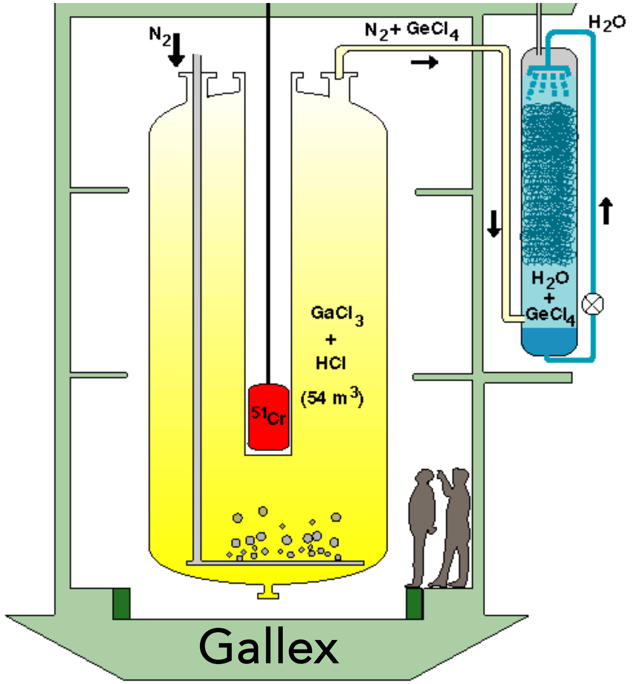
- **Step 1: from production site to airport**
  - By truck / train
- **Step 2: from production airport to detector airport**
  - By plane
  - IAEA Limits ^{51}Cr transport in a type B(U) container by air: 90 PBq (2,4 MCi) per individual package
- **Step 3: from detector airport to detector site**
  - By truck

MAX-PLANCK-INSTITUT FÜR KERNPHYSIK

Gallium Neutrino Anomaly

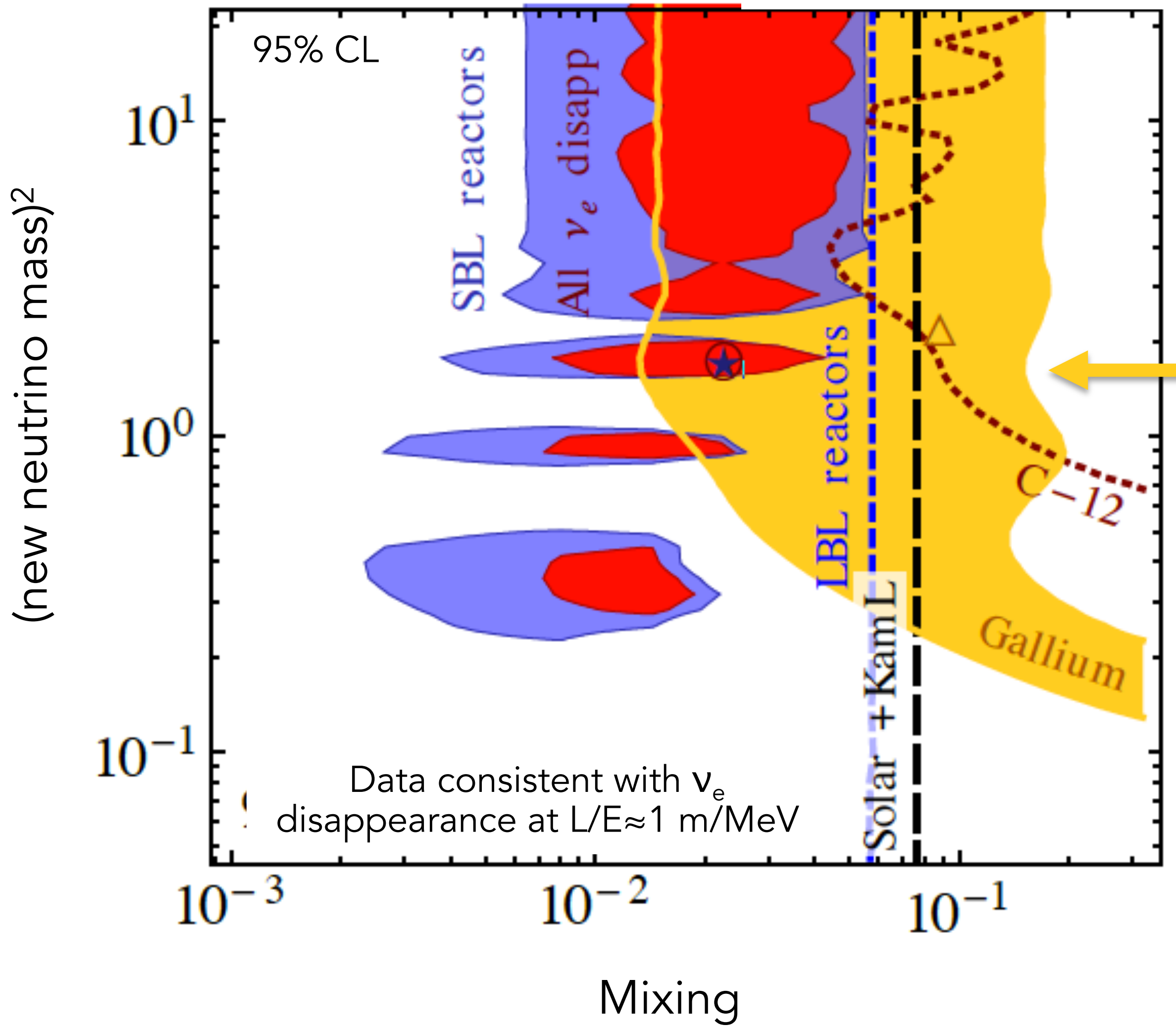
- Test of solar neutrino radiochemical detectors GALLEX and SAGE
  - ^{71}Ga/^{37}Ar + $\boldsymbol{\nu_e} \rightarrow$ ^{71}Ge/^{37}Cl + e^-
- 4 calibration runs with 0.6 - 2 MCi Electron Capture ν_e emitters
  - Gallex, <L>=1.9 m
    - ^{51}Cr, 750 keV
  - Sage, <L>=0.6 m
    - ^{51}Cr & ^{37}Ar (810 keV)
- Deficit observed
  - 3$\boldsymbol{\sigma}$ anomaly
  - Supported by ^{71}Ga(^{3}He,^{3}H)^{71}Ge cross section measurements





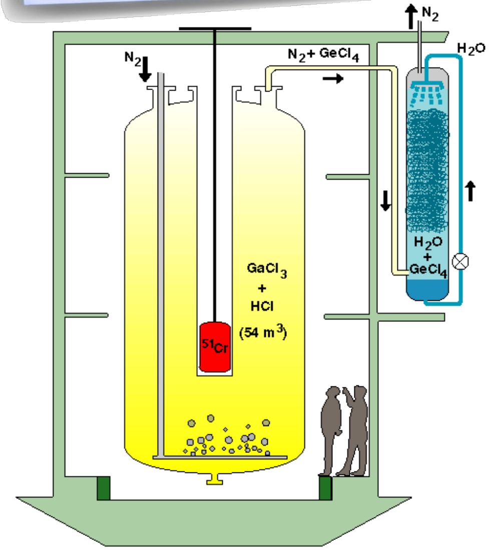
Sterile Neutrino Hypothesis

$$P_{ee} = 1 - \sin^2 2\theta_{ee} \sin^2 \frac{\Delta m^2_{41}}{4E}$$ → new oscillation at $\frac{L}{E} \sim 1 \frac{m}{MeV}$



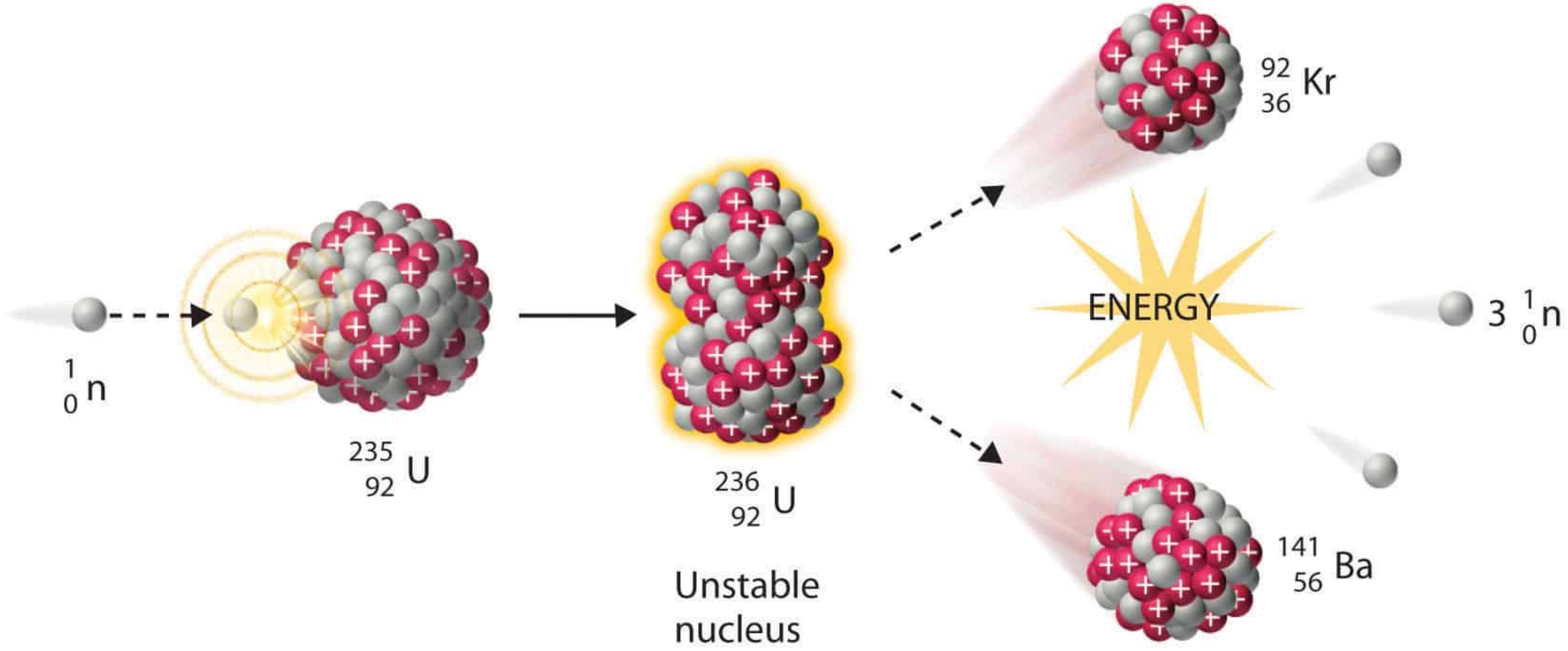
J. Kopp et al., arXiv:1303.3011

ν_s with a mass of ~eV and a mixing angle at >1%

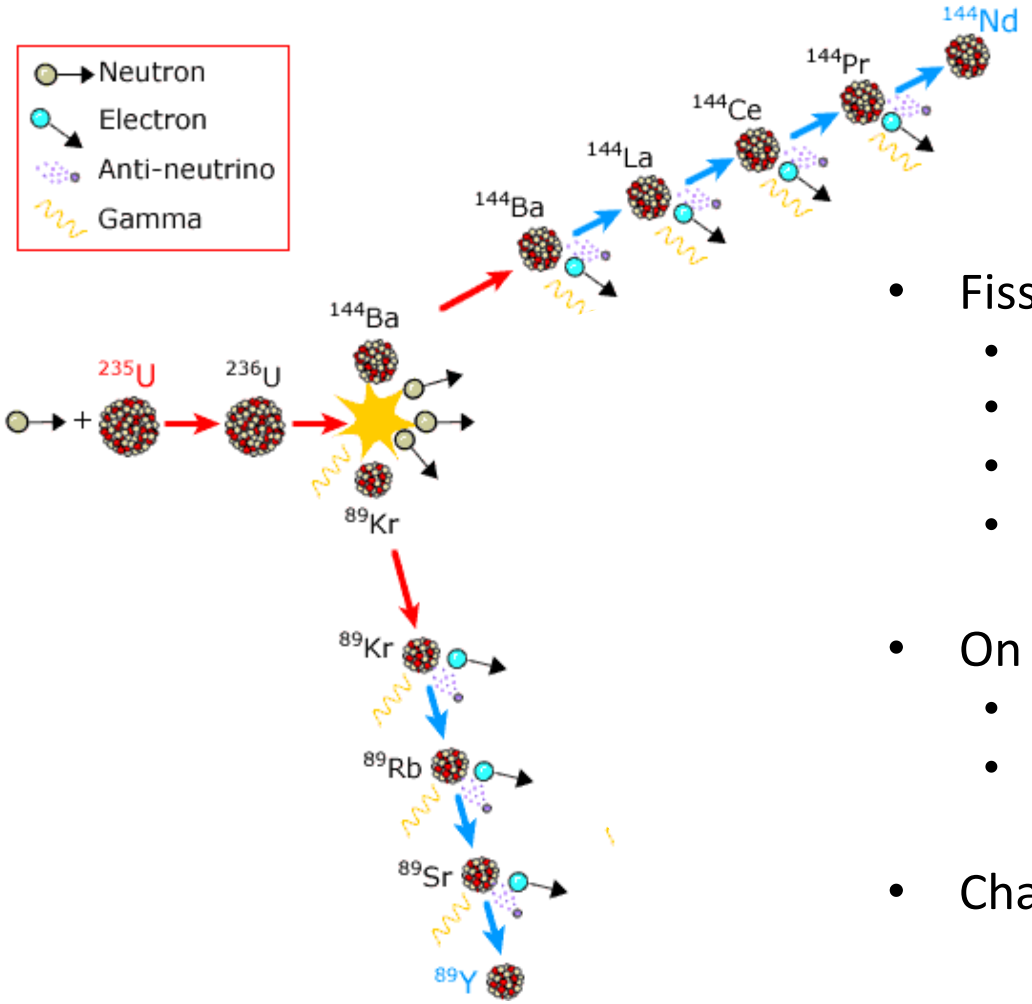


The Reactor Antineutrino Anomaly

Nuclear Fission

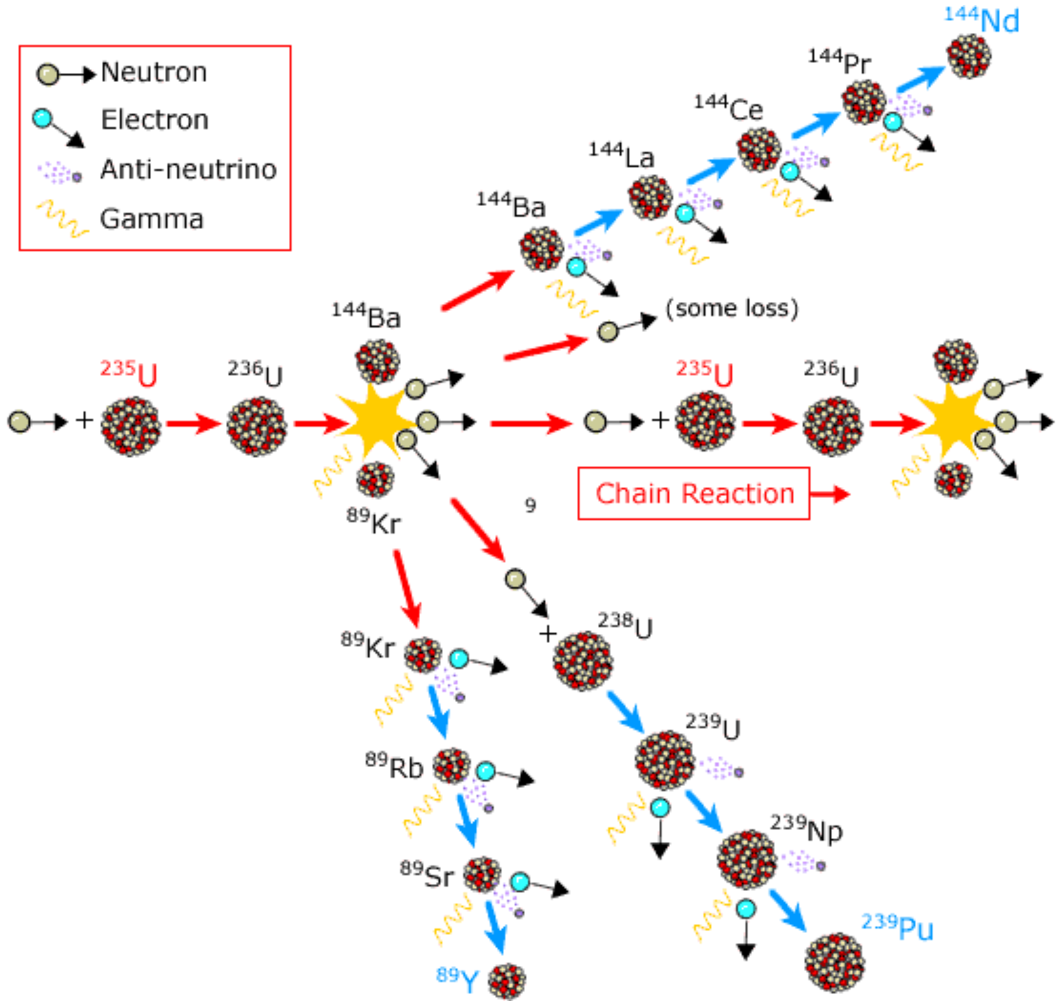


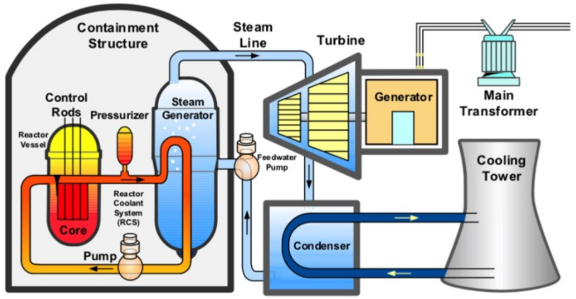
#neutrinos released / fission



- Fission fragments
  - Radioactive too!
  - Too large number of neutrons compared with protons
  - Get rid of their extra neutrons via β^--decays
  - Emission of electron antineutrinos
- On average, for each fission:
  - 200 MeV
  - <u>6 electron antineutrinos emitted</u>
- Chain reaction (1 GW / 200 MeV ~ 10^{19} fissions/s)

#neutrinos released / GW



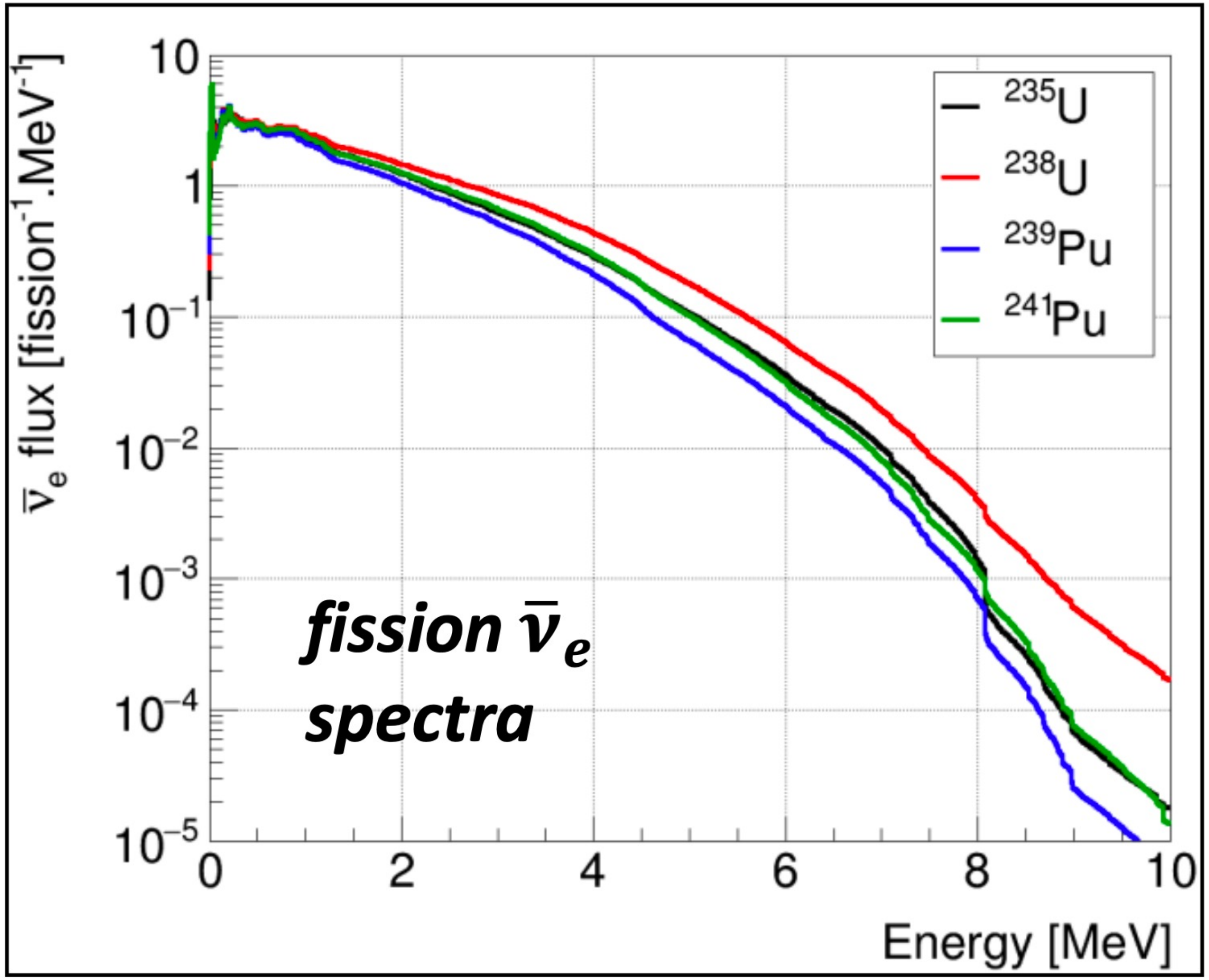


controlled

Continuous neutrino emission
(reactor ON / OFF periods)

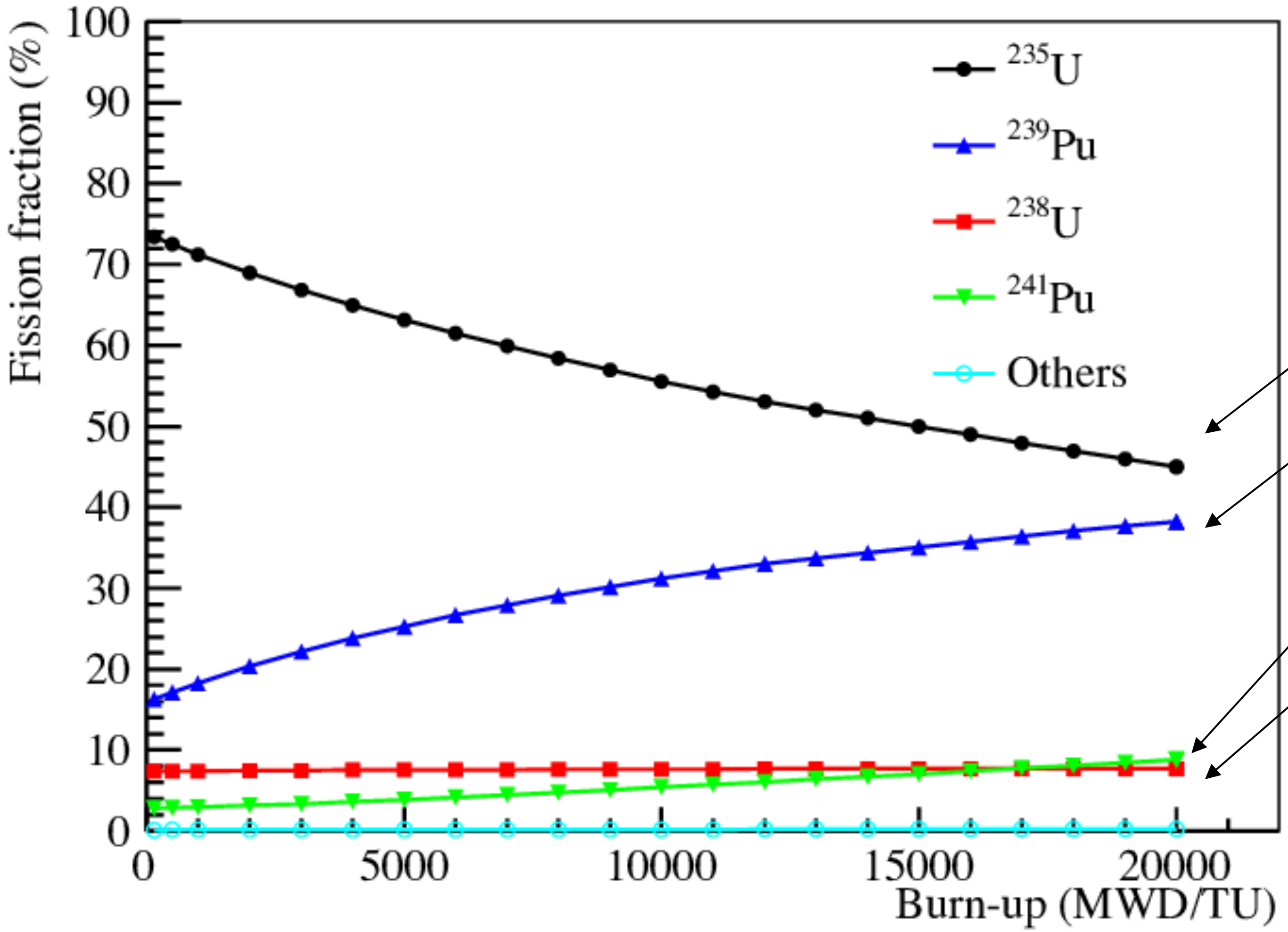
Neutrino flux : 10^{20} ν/GW/s

Overview of reactor neutrino spectra



- Fission-induced neutrino spectra for ^{235}U, ^{238}U, ^{239}Pu, ^{241}Pu
- Spectra between 0 to 10 MeV
- Shape and rate depend on the considered isotope
- Reactor ν spectrum is a mixture of the spectra of the 4 main fissile isotopes, ^{235}U, ^{238}U, ^{239}Pu, ^{241}Pu, weighted by their fission fractions α_{235}, α_{238}, α_{239}, α_{241}

Reactor Fuel evolution (burn-up)



fission fractions: α_{i}

α_{235}

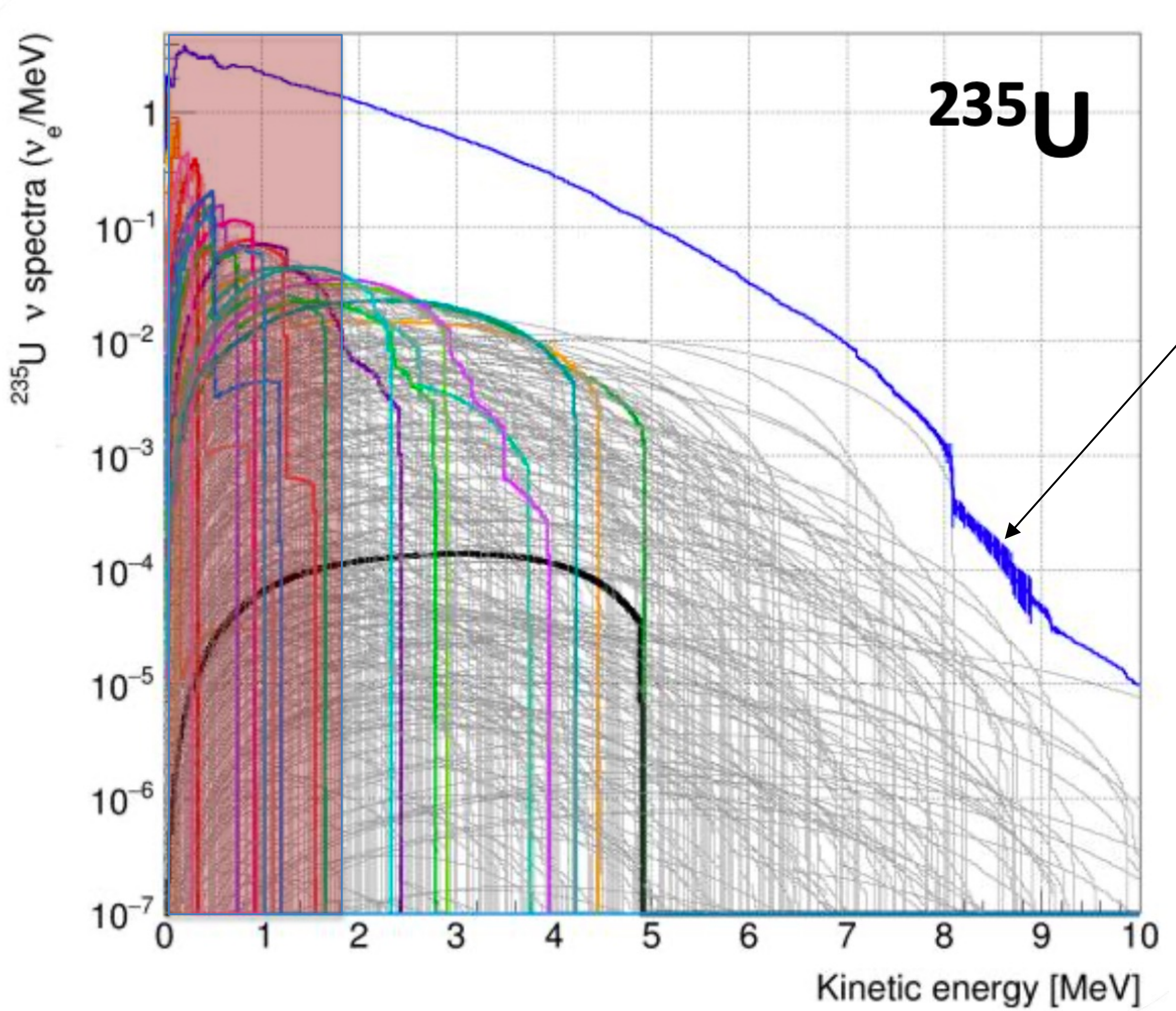
α_{239}

α_{238}

α_{241}

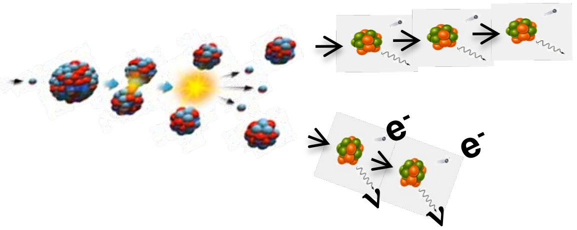
$$\sum_{i=1}^{4} \alpha_i = 1\ (100\%)$$

A closer look at the reactor neutrino spectrum of ^{235}U

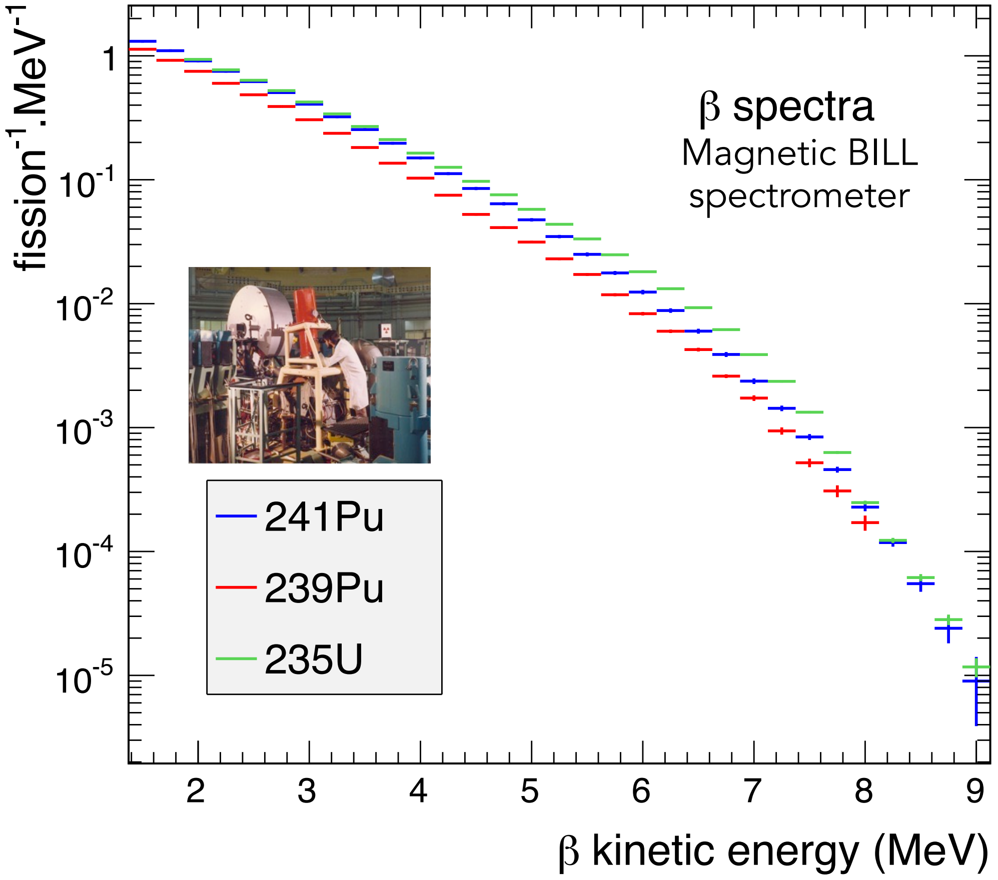


- The neutrino spectrum for a specific isotope is a weighted mixture of the spectra of all fission products involved after the fission
- It is composed of a superimposition of several thousand individual β-decay branches
- It can painfully be calculated (15% uncertainty), or measured by a dedicated experiment (ie. ILL in the 80's, Double Chooz/Daya Bay, few% uncertainty)
- Not (yet) measured below 1.8 MeV IBD ($\overline{\nu}_e p \rightarrow e^+ n$) threshold

Reactor Neutrino Flux Evaluation



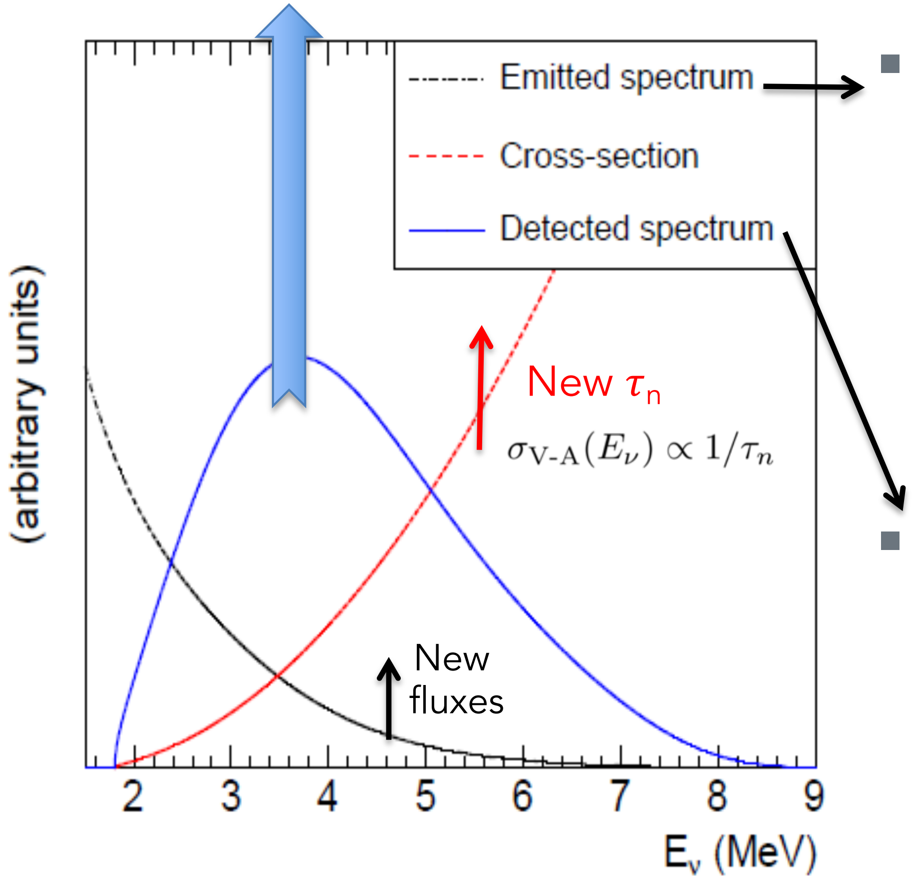
A. A. Hahn, K. Schreckenbach et al., *Phys. Let. B218,365 (1989)*



2011: Reevaluation of the $e - \nu$ conversion procedure

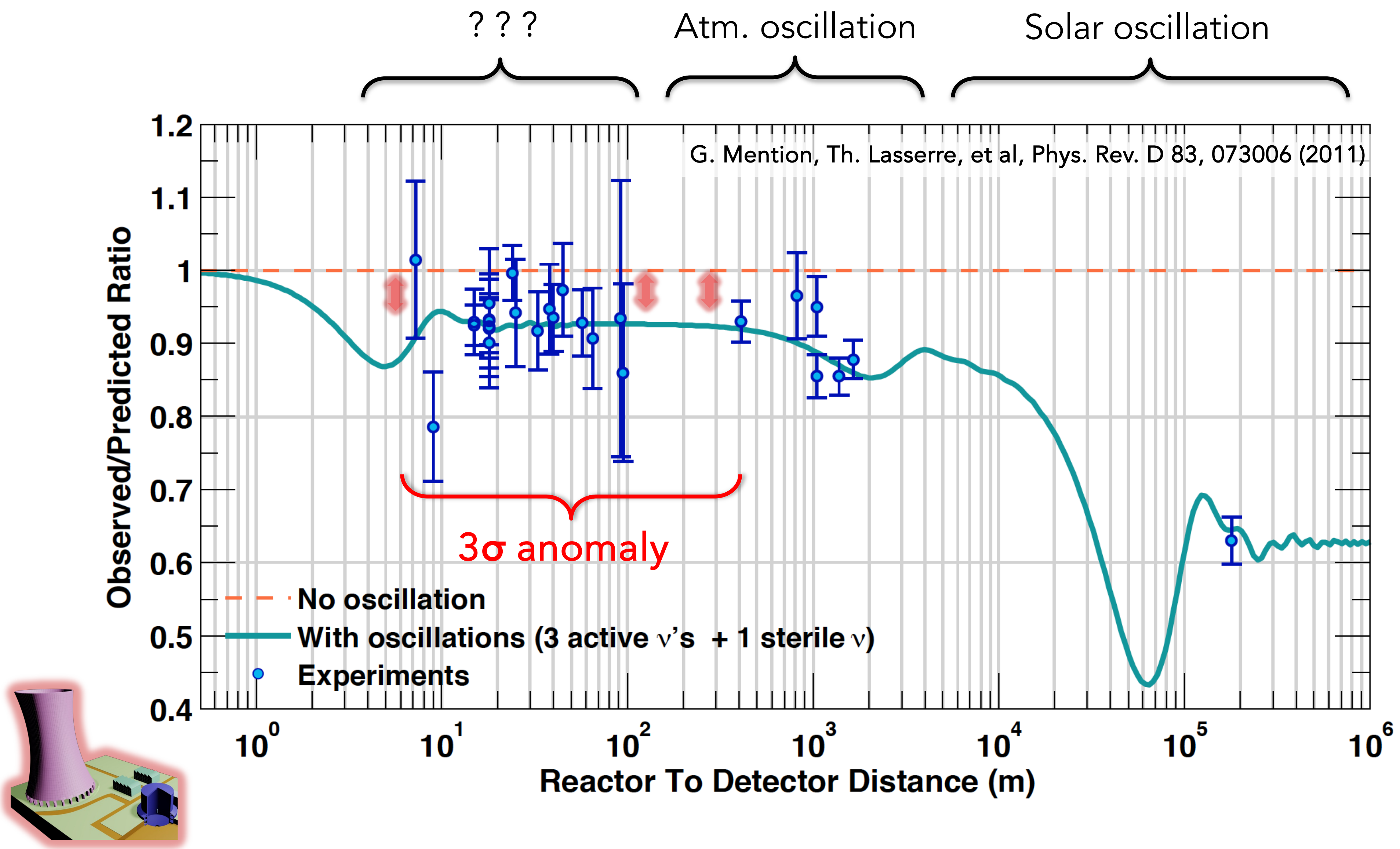
New Reactor ν-Fluxes / IBD - 2011

Increased prediction of detected flux by 6.5%



- **Flux: Neutrino Emission:**
  - Improved reactor neutrino spectra → +3.5%
  - Accounting for long-lived isotopes in reactors → +1%
- **IBD: Neutrino Detection:**
  - Reevaluation of σ_{IBD} → +1.5% (evolution of the neutron life time)
  - Reanalysis of all SBL experiments

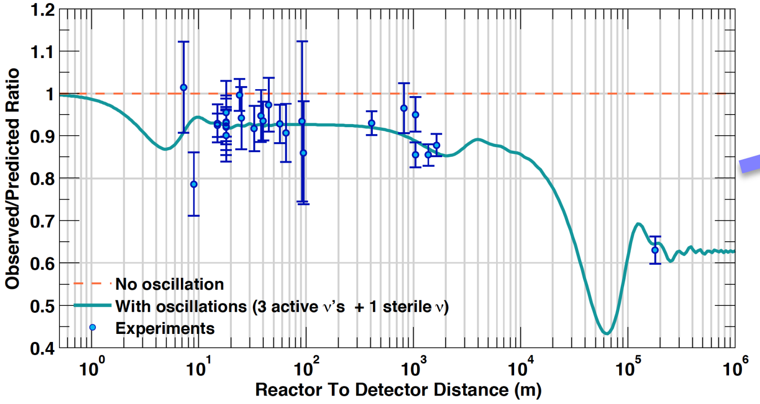
The Reactor Anomaly (2011)



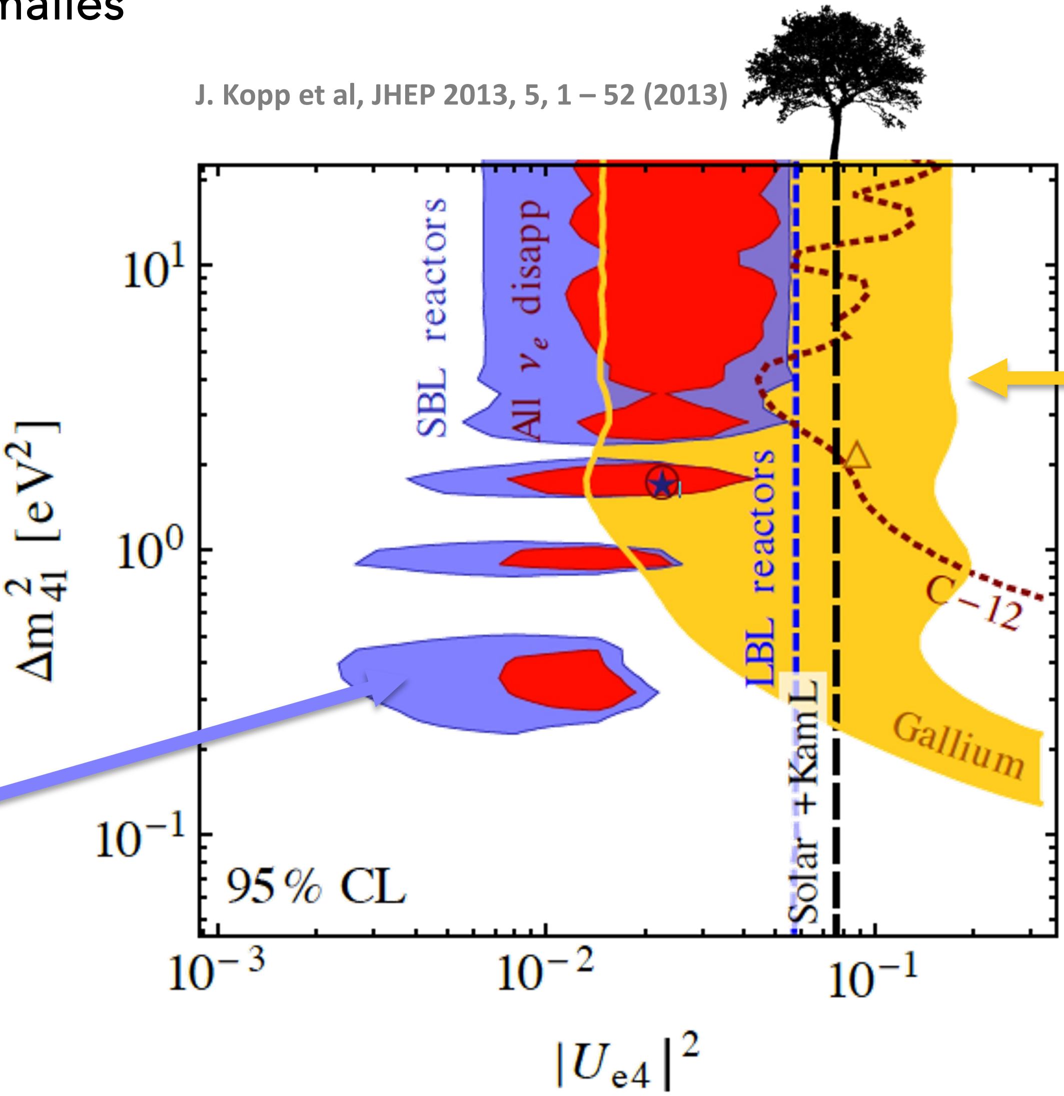
Sterile Neutrino Interpretation

Gallium & Reactor Neutrino Anomalies

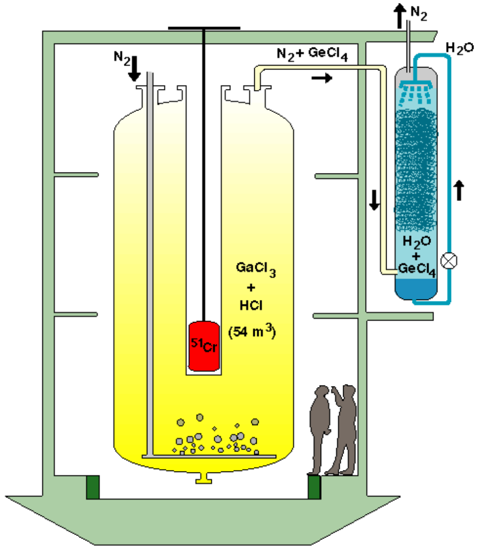
ν_s with a mass of ~eV and a mixing angle at 1-10%



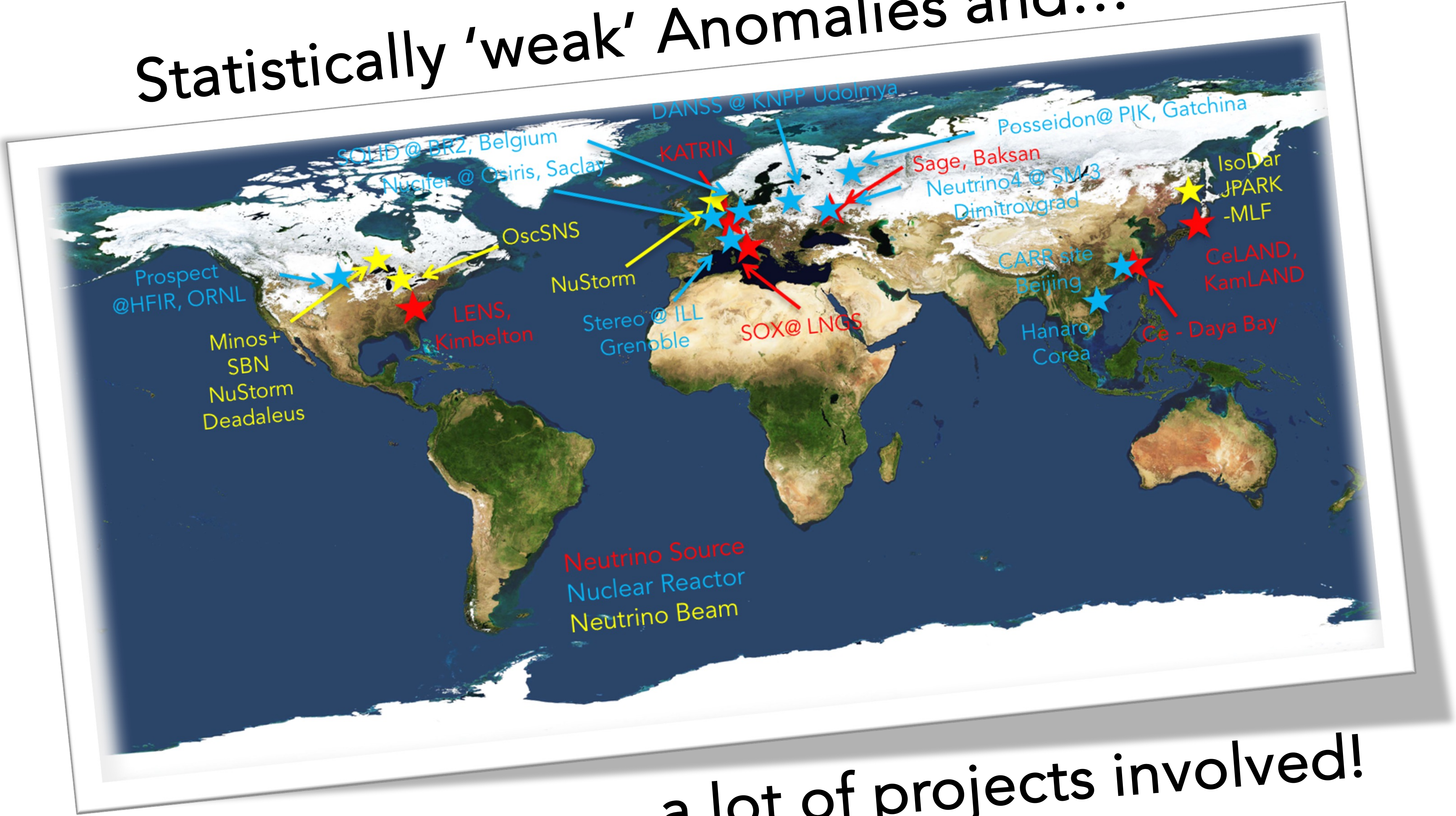
J. Kopp et al, JHEP 2013, 5, 1 – 52 (2013)



ν_s with a mass of ~eV and a mixing angle at >1%



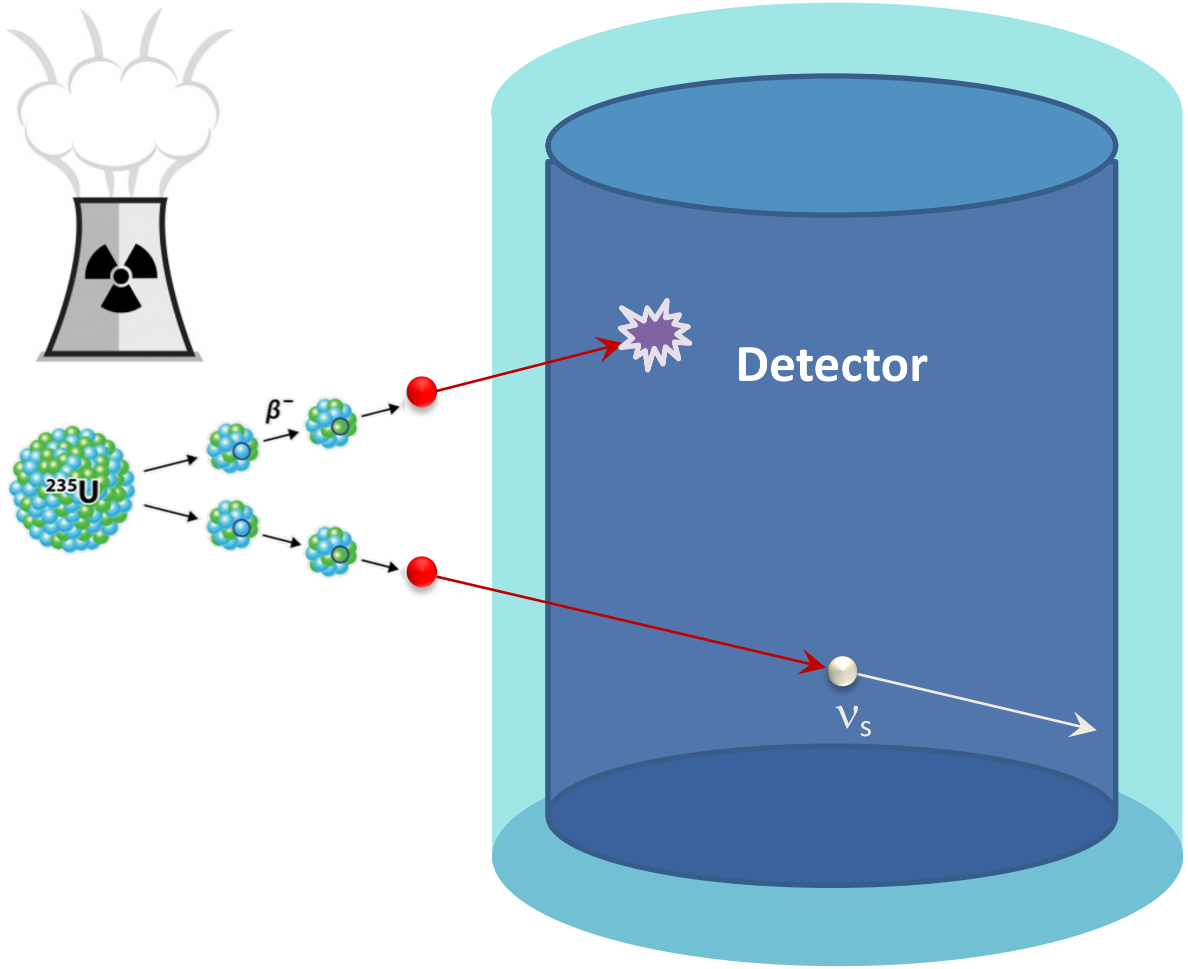
Statistically ‘weak’ Anomalies and…



a lot of projects involved!

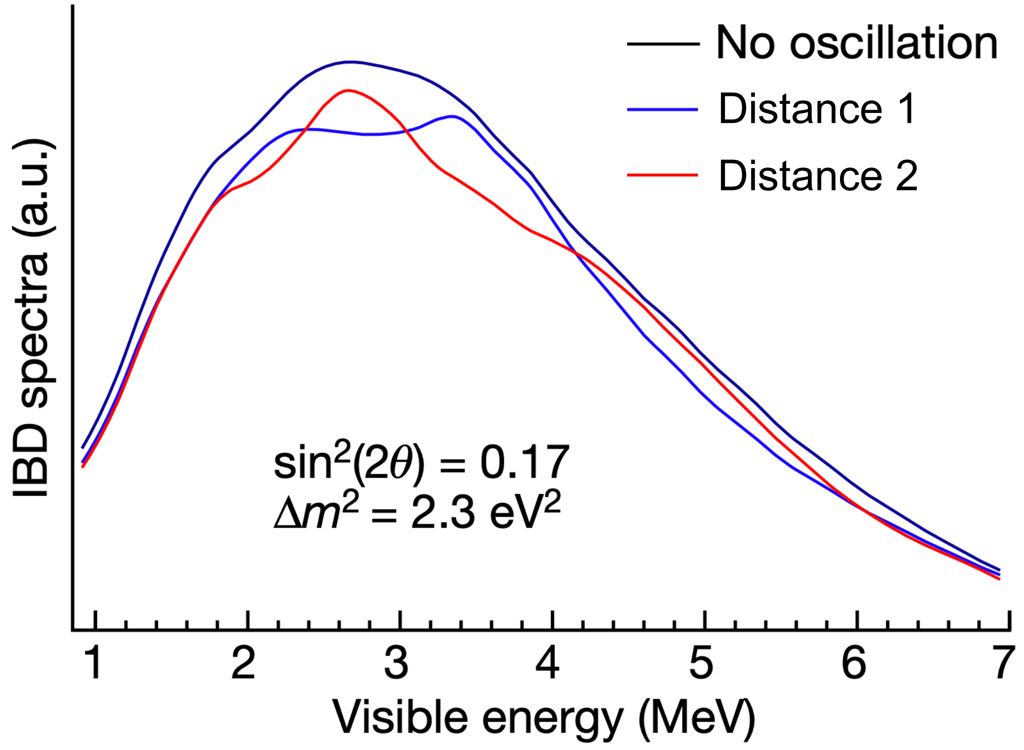
Reactor Experiments dedicated to sterile neutrino search

Searching for sterile ν at reactors



For two flavors:

$$P(\nu_e \longrightarrow \nu_\mu) = \sin^2 2\theta \cdot \sin^2\left(\Delta m^2 \cdot \frac{L}{E_\nu}\right)$$



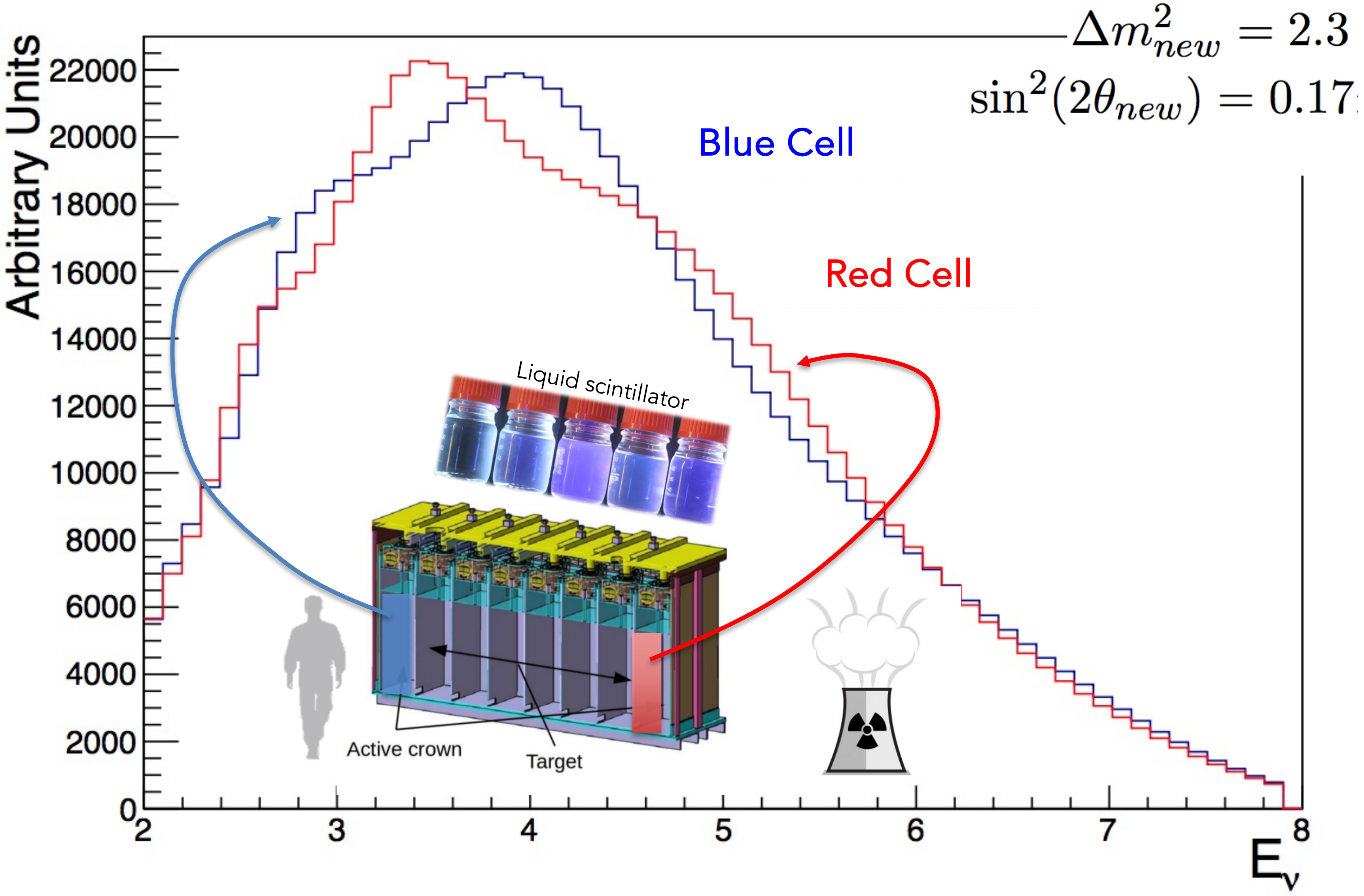
Testing $\overset{(-)}{\nu}_e$ disappearance anomalies

- Input from sterile neutrino fits (anomalies)
  - $\Delta m^2 \approx 0.1\text{-}10\ eV^2 \longrightarrow$ $L_{osc}(m) = 2.5 \frac{E(MeV)}{\Delta m^2 (eV^2)} \approx 2-10\ m$
  - $\sin^2(2\theta_{ee}) \approx 0.01\text{-}0.15$

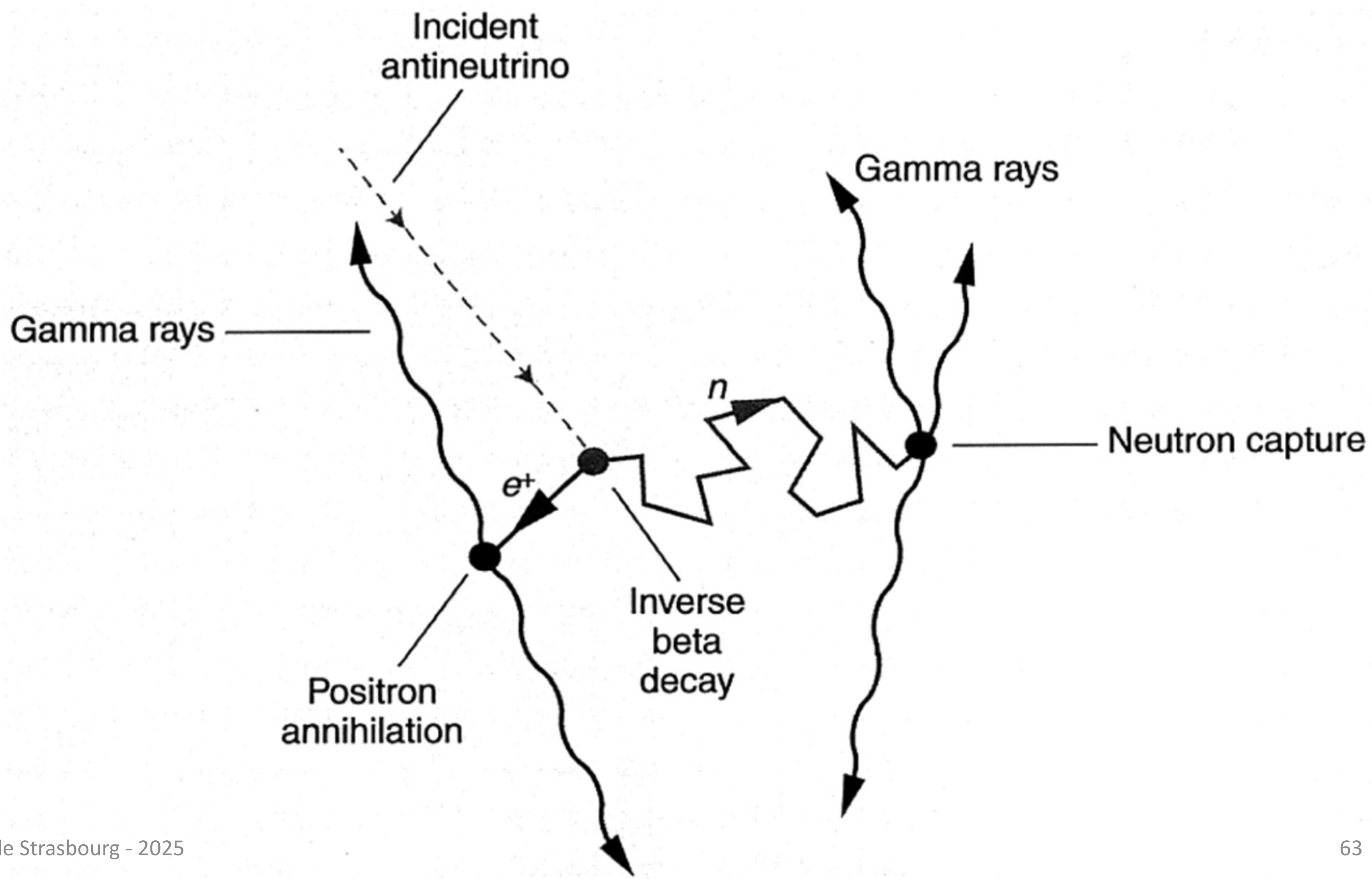
- Experimental specifications
  - Compact neutrino source (<< L_{osc})
  - Good vertex and energy resolutions (<< L_{osc})
  - High statistics (few % stat. uncertainty)
  - Few % syst. uncertainty → Low Backgrounds

- Search for a new oscillation pattern in E & L completed by normalization information

Sterile ν Observable @Reactor



Electron antineutrino Detection (IBD)



Experimental challenges

- Compact reactor core
  - No oscillation smearing

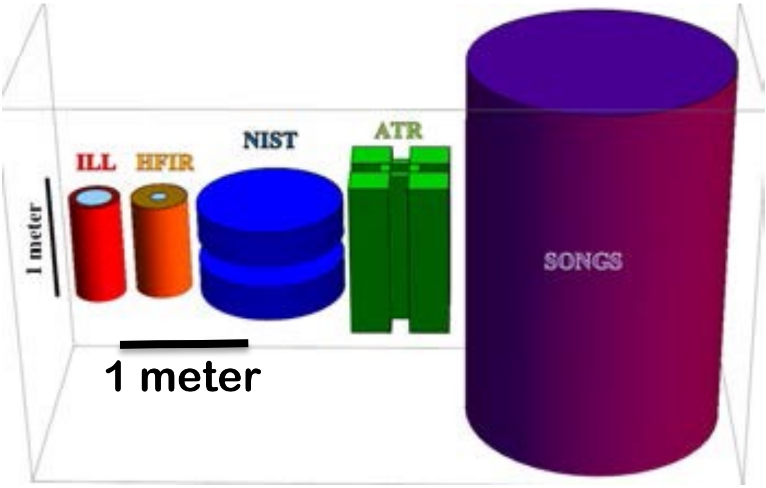
- High statistics (few 100 evts/day/t)
  → High Power (10-3000 MW)
  → Short baselines (5-50 m)

- Highly enriched fuel
  → Well known ^{235}U fission spectrum

- Reactor ON/OFF periods
  → Moderate overburden compensated by accurate measurement of the cosmogenic bkg component (induced by muons)

- But <u>challenging</u> reactor-induced backgrounds (γ and n)
  → Need Particle ID and comprehensive shieldings – S/B around 1!

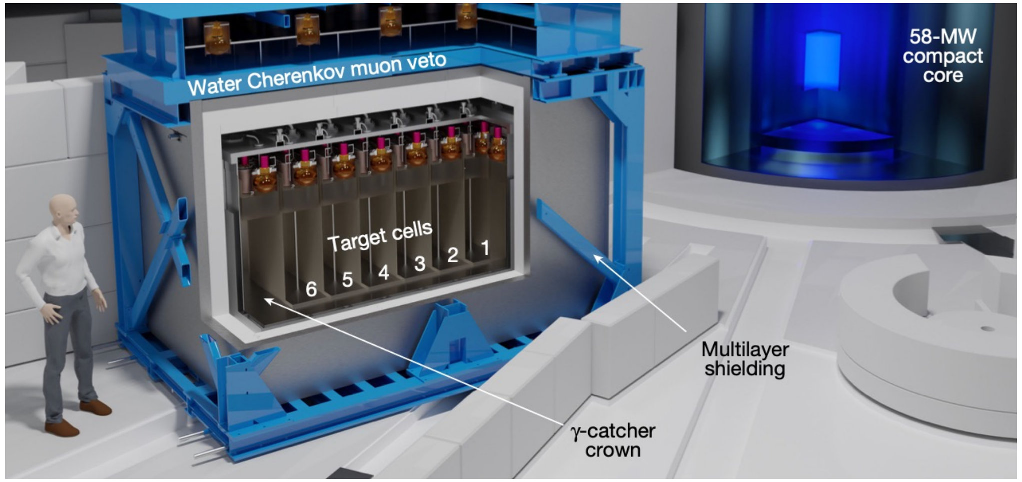
Typical reactor core sizes

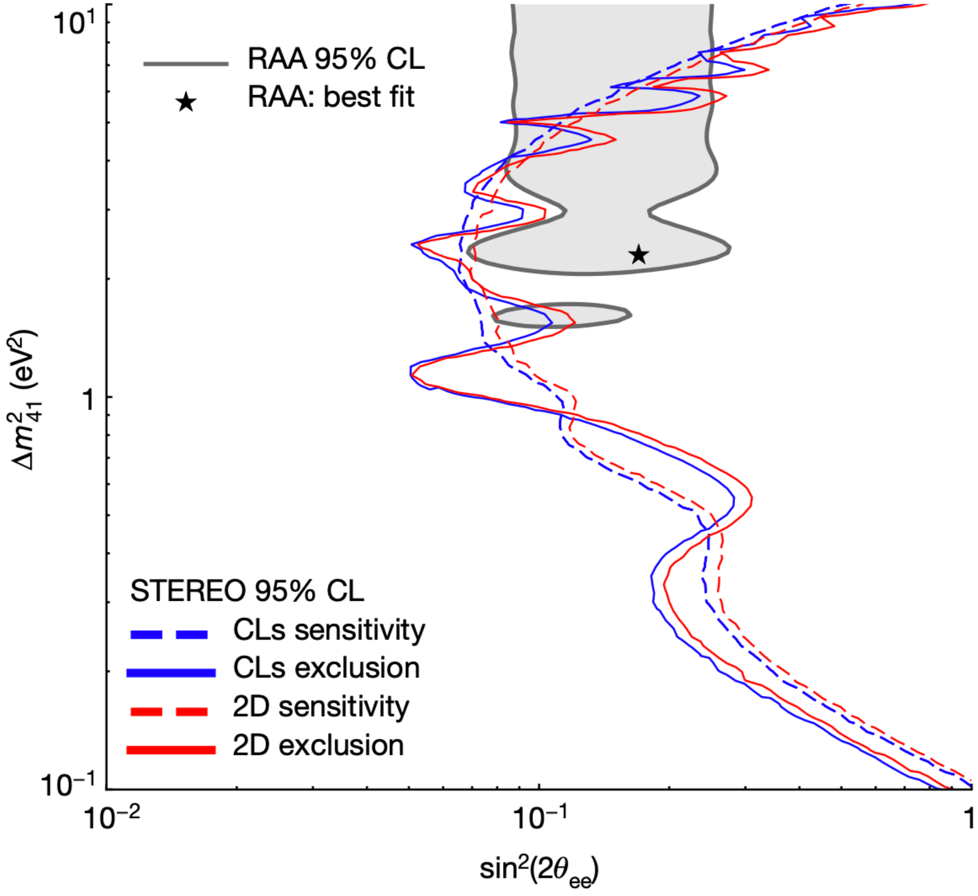


The Stereo Experiment

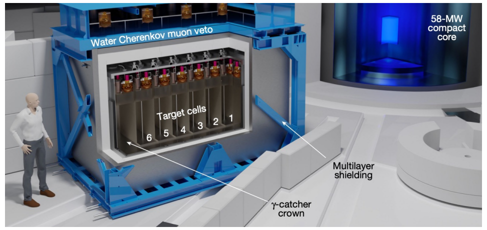
- Source: electron-anti-neutrinos (from reactor)
- Detector: segmented liquid-scintillator
- Detection: inverse beta-decay
- Result: No signature found

Nature volume 613, pages 257–261 (2023)





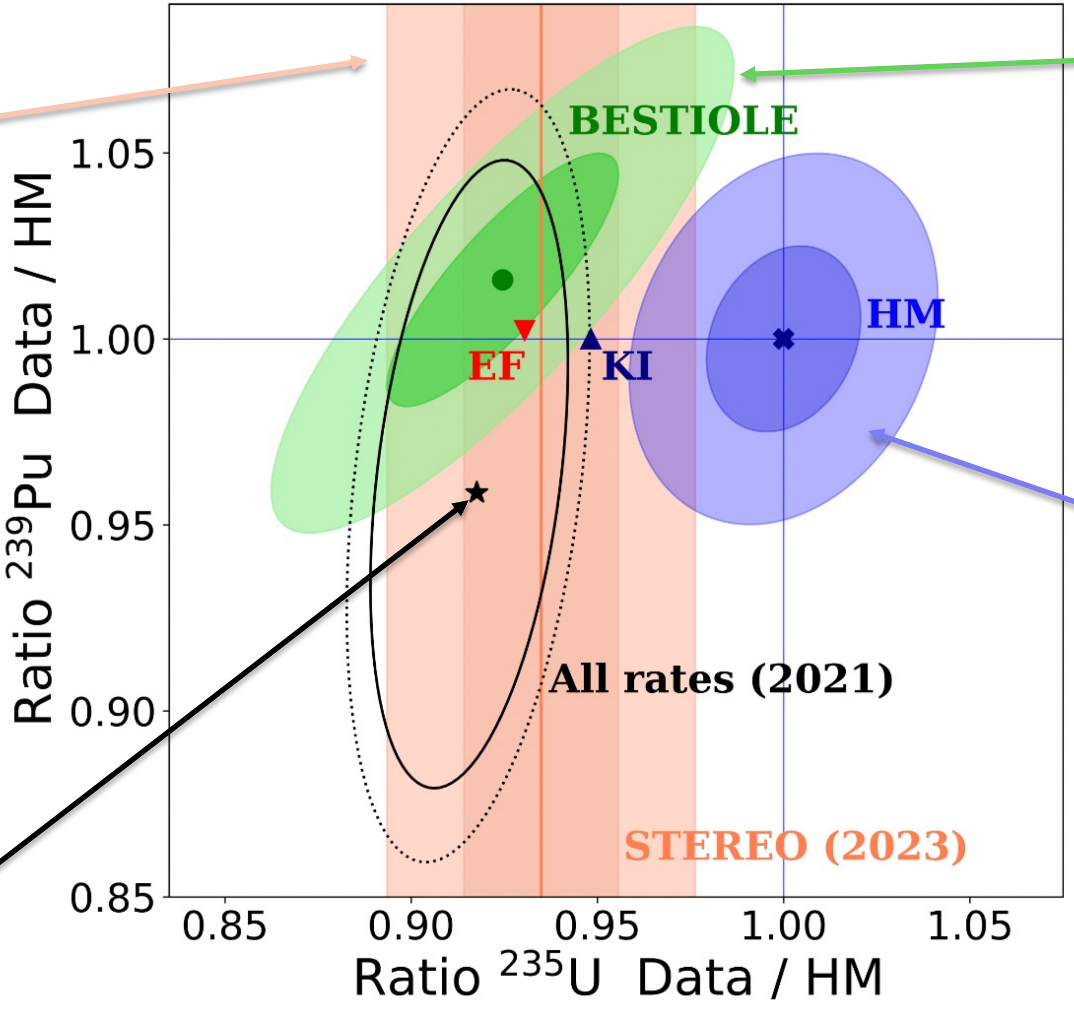
IBD ν fluxes from U-235 and Pu-239



Latest result from STEREO (orange band), which has provided the most accurate measurement of antineutrino flux from U-235 fission to date. Support deficit of U-235 wrt HM, but not with Bestiole

Summary of all rates info
Supports deficit in U-235 (uncertain for Pu-239)
sterile ν: deficit should be the same for all isotopes ⇒ disagrees with these observations.

Phys. Rev. C 108 (2023) 5, 055501



Example of state-of-the-art (2024) neutrino flux summation model
IBD flux from uranium-235 fission by -(7.5 ± 3.9)% compared with the HM model. This shift would significantly reduce the statistical significance of the RAA.

Example of state-of-the-art neutrino flux conversion model. Reference model for the evaluation of the RAA

Reactor anomaly:
sterile ν or biases neutrino fluxes ?

Remark on the ν flux measurement

ЯДЕРНАЯ ФИЗИКА, 2021, том 84, № 1, с. 3–11

ЯДРА

ИЗМЕРЕНИЕ ОТНОШЕНИЯ КУМУЛЯТИВНЫХ СПЕКТРОВ БЕТА-ЧАСТИЦ ОТ ПРОДУКТОВ ДЕЛЕНИЯ ^{235}U И ^{239}Pu ДЛЯ РЕШЕНИЯ ЗАДАЧ ФИЗИКИ РЕАКТОРНЫХ АНТИНЕЙТРИНО

В. И. Копейкин[1)*], Ю. Н. Панин[1)], А. А. Сабельников[1)]

Поступила в редакцию 19.07.2020 г.; после доработки 19.07.2020 г.; принята к публикации 19.07.2020 г.

Выполнен первый цикл измерений отношения кумулятивных спектров β-частиц изотопов ^{235}U и ^{239}Pu, делящихся тепловыми нейтронами. Обнаружено, что кривая отношения спектров β-частиц ^{235}U/^{239}Pu, измеренная в настоящей работе, лежит на 5% ниже такой же кривой, полученной из измерений группы ILL. Проведенный анализ показал, что это связано с ошибочным завышением на 5% измеренного группой ILL спектра β-частиц ^{235}U. Как следствие этого, оказался завышенным на 5% и "спектр $\bar{\nu}_e$ ^{235}U в момент рождения", который восстанавливается из кумулятивного спектра β-частиц ^{235}U. Полученные данные объясняют эффект "реакторной антинейтринной аномалии".

DOI: 10.31857/S0044002721010128

ВВЕДЕНИЕ

Оценки спектра антинейтрино ($\bar{\nu}_e$) ядерного реактора впервые получены Альваресом в 1949 г., см. работу Райнеса и Коуэна [1], в которой по этим данным они рассчитали ожидаемое сечение процесса обратного β-распада

$$\bar{\nu}_e + p \to n + e^+ \qquad (1)$$

в потоке реакторных $\bar{\nu}_e$. С тех пор проводятся исследования спектра $\bar{\nu}_e$, сформировалось и развивается новое направление — спектроскопия реакторных $\bar{\nu}_e$. Знание спектра $\bar{\nu}_e$ необходимо для интерпретации ведущихся и планирования новых нейтринных экспериментов. Особую актуальность изучение спектра $\bar{\nu}_e$ приобрело в последние годы в связи с повышением точности измерений, постановкой ряда крупных экспериментов и развитием нейтринной индустрии на ядерных реакторах.

Спектр $\bar{\nu}_e$ в области энергий, превышающих порог реакции (1) $E_{\rm th} = 1.8$ МэВ, формируется от β-распада продуктов деления изотопов топлива ^{235}U, ^{239}Pu, ^{238}U, ^{241}Pu, где ^{235}U и ^{239}Pu вносят подавляющий вклад. Наиболее тщательное моделирование спектров $\bar{\nu}_e$ изотопов урана и плутония было проведено в 2011 г. [2, 3] по данным измерений кумулятивных спектров β-частиц этих изотопов, выполненных группой института Лауэ–Ланжевена (ILL) [4–7]. Оказалось [8], что измеренный на стандартном удалении ~15–100 м от реактора выход реакции (1) на ~5% меньше, чем ожидаемый выход по данным работ [2, 3]. Обнаруженный 5% дефицит измеренного выхода к ожидаемому ("reactor antineutrino anomaly") обычно связывают с двумя причинами:

– существованием стерильных нейтрино,

– ошибками в измерениях спектров β-частиц ^{235}U и ^{239}Pu группы ILL.

Гипотеза существования стерильных нейтрино проверяется с помощью нескольких детекторов $\bar{\nu}_e$, расположенных на расстояниях менее 15 м от реакторов. Настоящая работа Курчатовского института (KI) нацелена на проверку измерений спектров β-частиц ^{235}U и ^{239}Pu. Статья построена следующим образом. Вначале мы кратко рассмотрим способы определения спектра реакторных $\bar{\nu}_e$ в той части, которая необходима для анализа эксперимента. Далее опишем методику опыта, полученные результаты и проведем их обсуждение. Отметим, что эксперимент в настоящее время продолжается, однако полученный материал уже позволяет сделать определенные выводы.

1. О СПОСОБАХ ИЗУЧЕНИЯ СПЕКТРА РЕАКТОРНЫХ $\bar{\nu}_e$

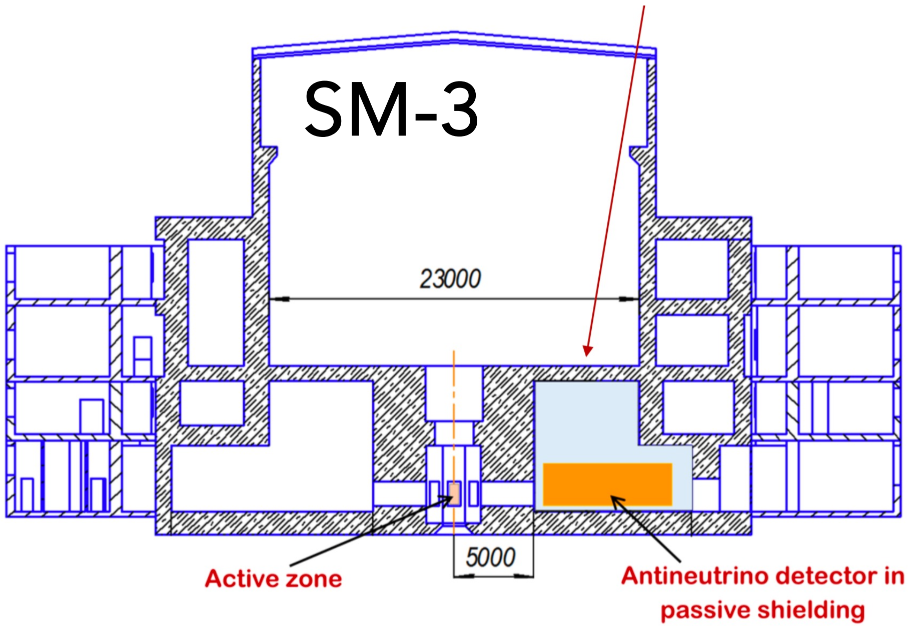
1.1. Расчетный метод

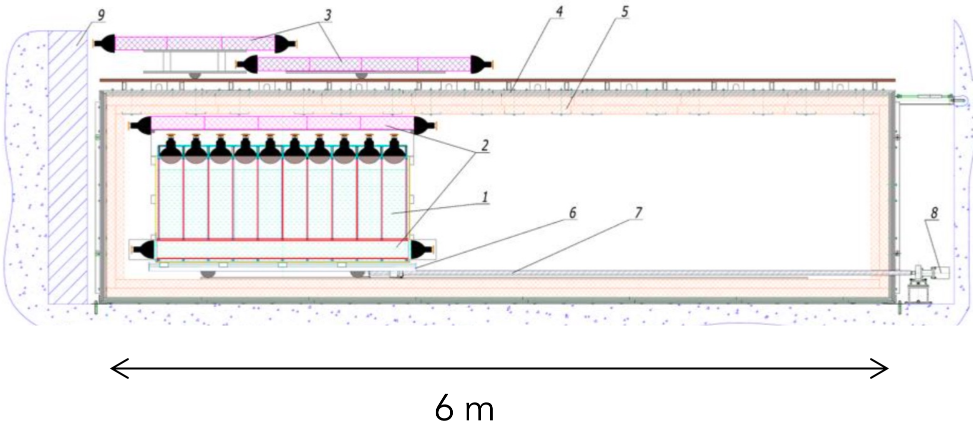
Спектры антинейтрино ρ^i_ν делящихся изотопов i, где индексы $i = 5, 9, 8, 1$ относятся соответственно к изотопам ^{235}U, ^{239}Pu, ^{238}U и ^{241}Pu, получаются путем суммирования вкладов всех β-переходов от всех продуктов деления. На практике спектры

1) Национальный исследовательский центр "Курчатовский институт", Москва, Россия.
* E-mail: kopeikin46@yandex.ru

- New reactor beta spectrum measurements performed at a research reactor in National Research Centre Kurchatov Institute (KI)
- New relative measurements of the ratio between cumulative β spectra from U-235 and Pu-239
- A 5% discrepancy with the β spectra measured at Institut Laue-Langevin (ILL) is observed (normalization)
- Lead to new predictions are consistent with the results of Daya Bay, Double Chooz, RENO, STEREO
- Could be the final explanation for the RAA ☺
- And then lower the interest for light sterile neutrino search (back to the <2011 status-quo)

Neutrino-4 Experiment



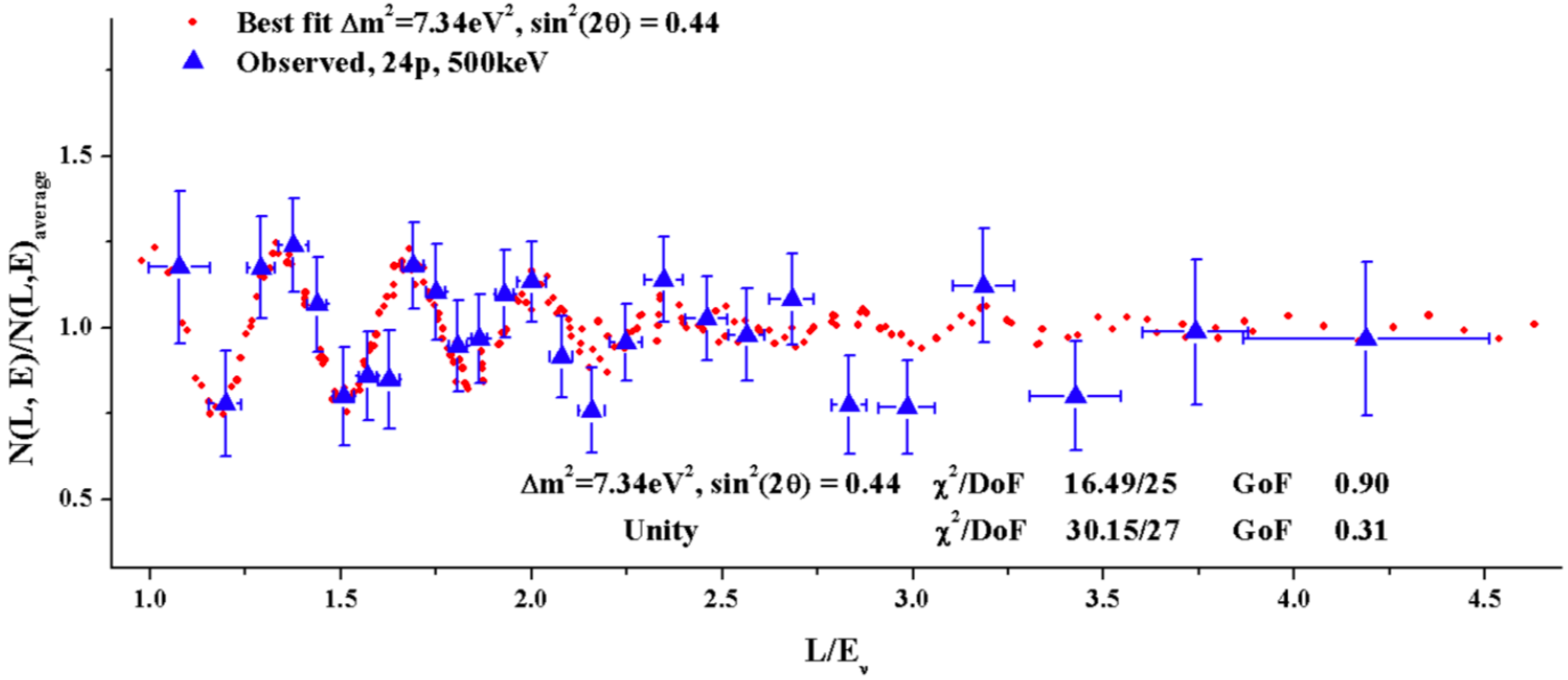


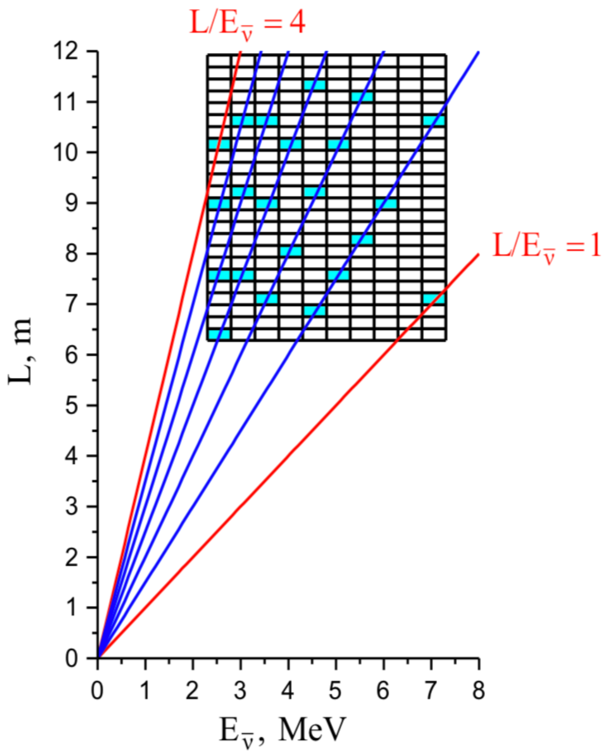
- Overburden: 3-5 mwe
- Baseline: 6-12m
- Pure ^{235}U fission spectrum - compact core
- 5 x 10 identical cells filled with LS-Gd
  Oscillation analysis independent of the prediction
- High external background mitigated by
  - Heavy shielding - PSD capability
- 200 IBD/day – S/B ~ 0.5 - About 500 days of data

Neutrino-4: claim for a « 2-3 σ » signal

- No-oscillation rejected@3σ
  (see arXiv:1809.10561)

- Best fit
  - $\Delta m^2 = 7.3\ eV^2$
  - $\sin^2(2\theta) = 0.44$ (17% deficit)

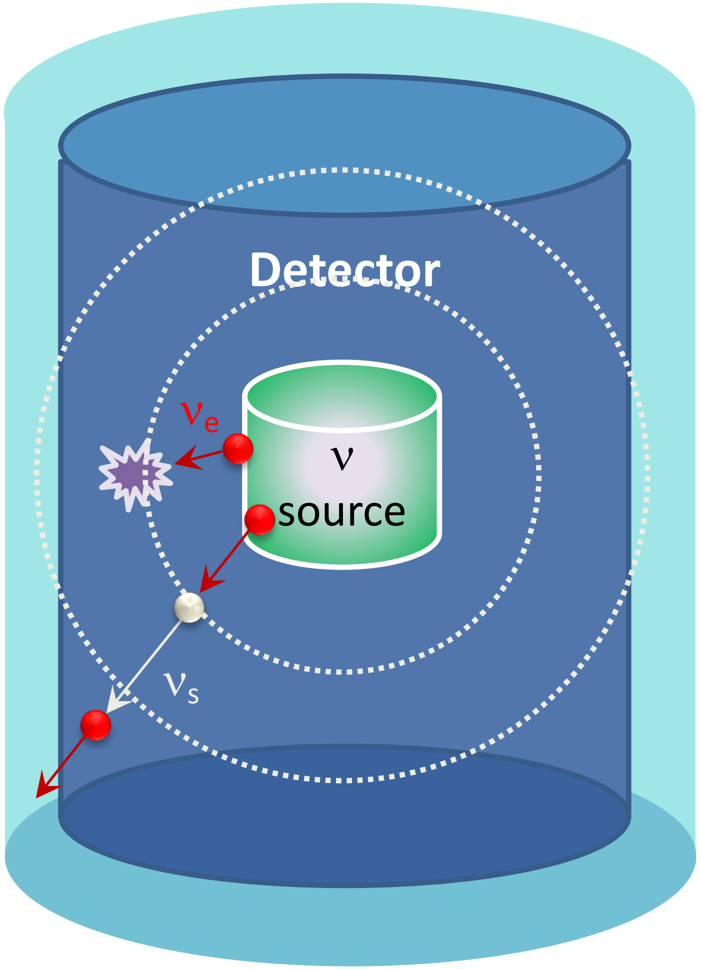




- Large mixing solution!
  - In tension with DC/DB/Reno/Stéréo/Prospect/DANSS and excluded by KATRIN
    …

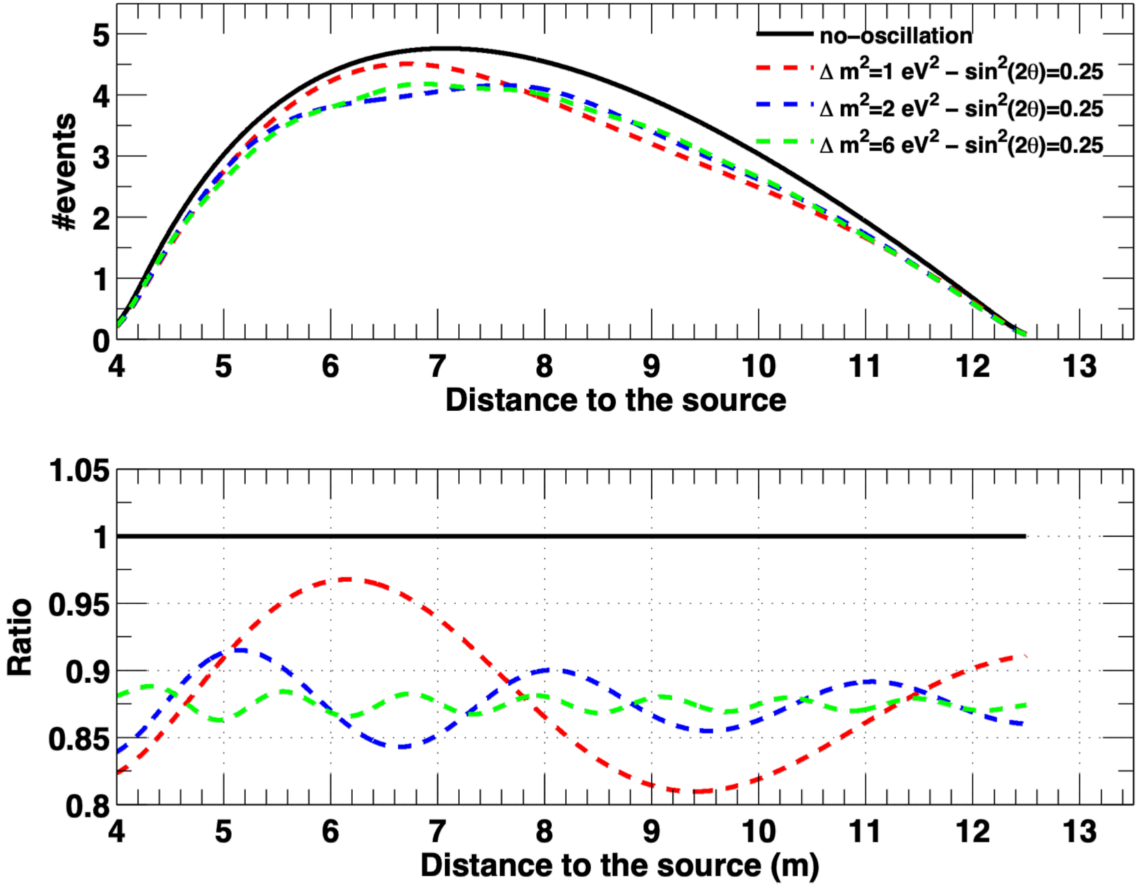
Neutrino Source Experiment dedicated to sterile neutrino search

Neutrino Generator Experiment



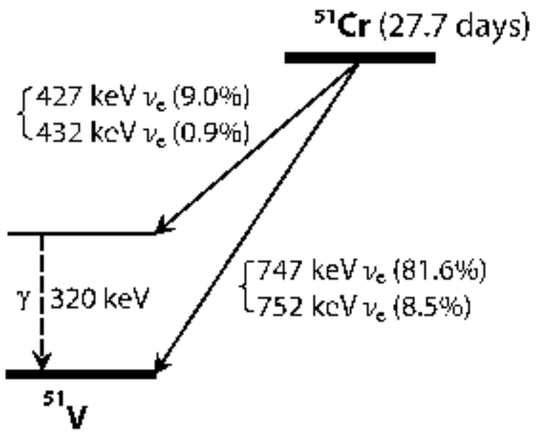
For two flavors:

$$P(\nu_e \longrightarrow \nu_\mu) = sin^2 2\theta \cdot sin^2\left(\Delta m^2 \cdot \frac{L}{E_\nu}\right)$$

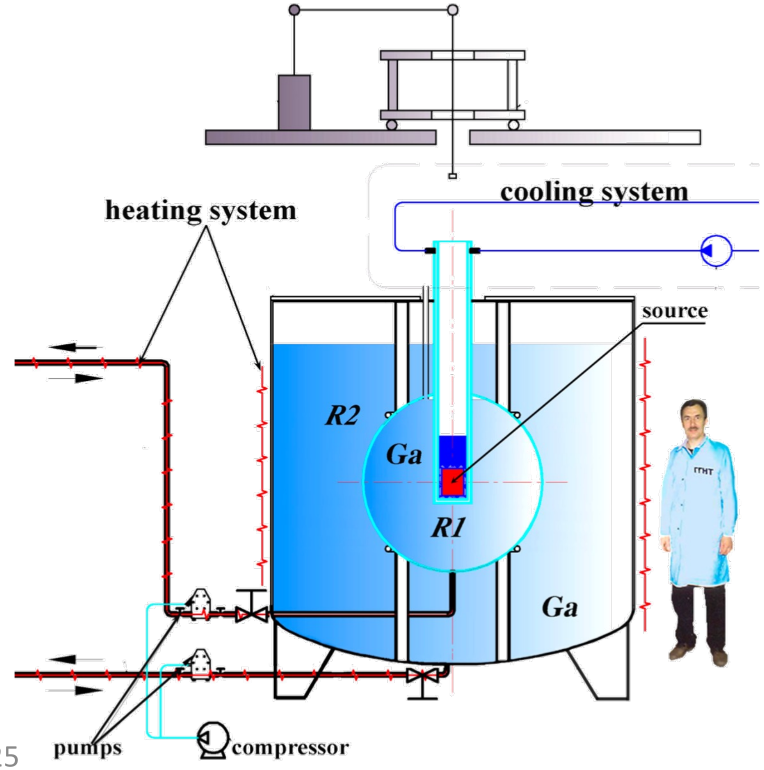


BEST experiment

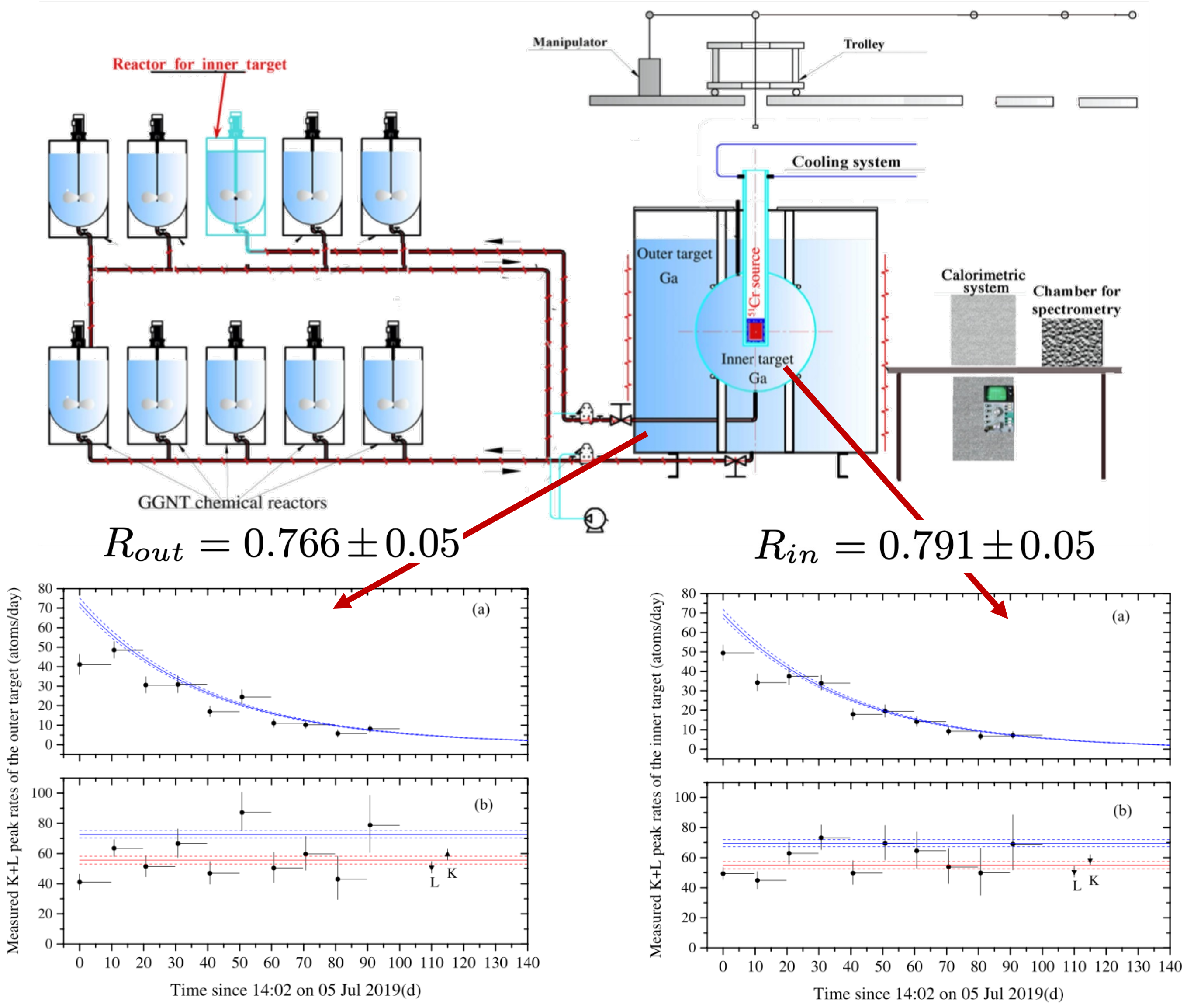
- Source: ^{51}Cr ($t_{1/2}$ = 26 d) → electron neutrinos with 0.75 MeV
- Detector: liquid-metal Ga in 2 zones
- Detection: ν_e capture at two baselines – then count ^{71}Ge atoms



V. V. Barinov *et al.* Phys. Rev. C **105**, 065502, 2022



BEST results – R_{in} , R_{out} , R_{out} / R_{in}

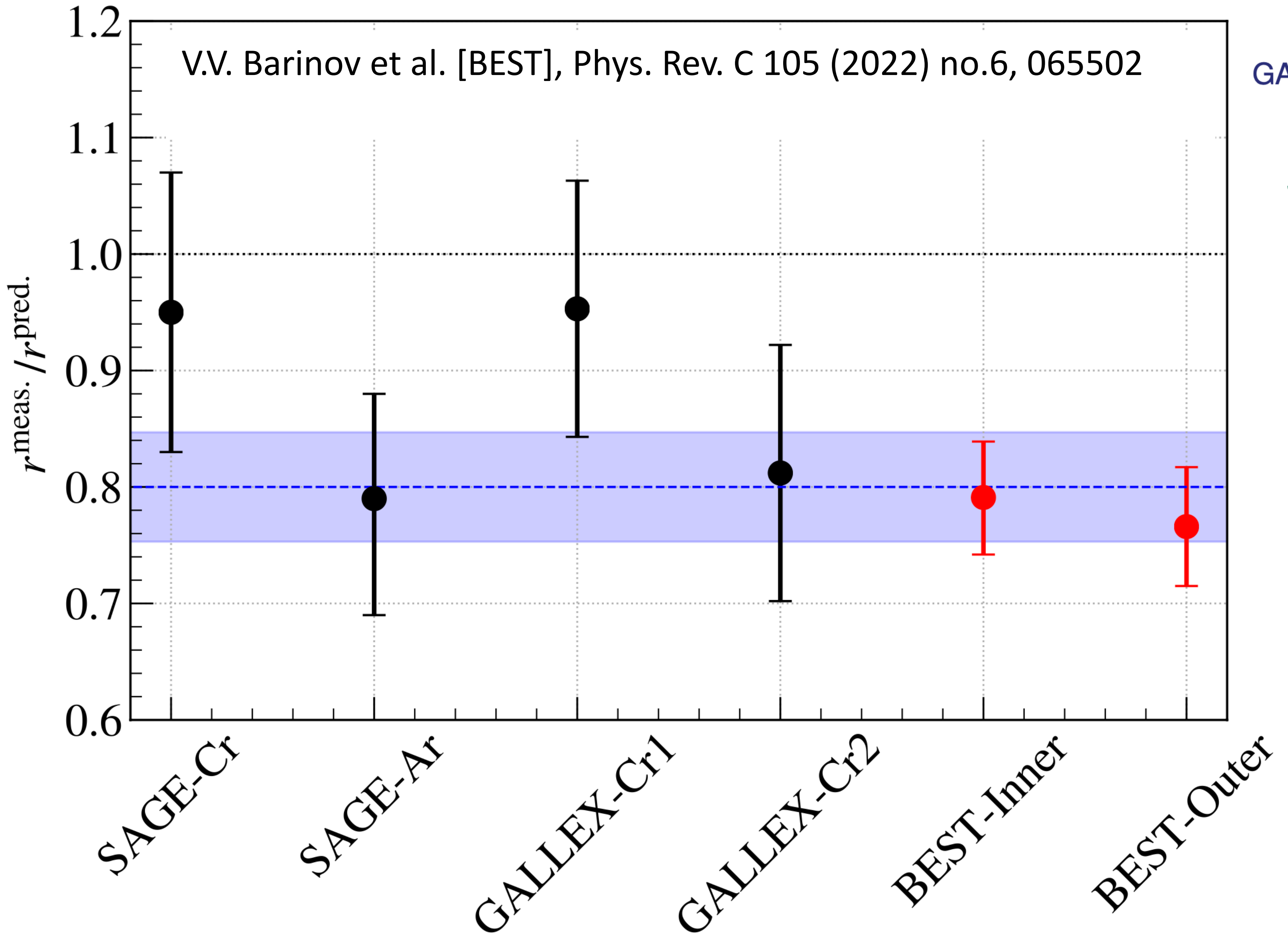


- 3.4-MCi ^{51}Cr source at the center of two nested Ga volumes.
- Production measurements of ^{71}Ge through the CC reaction: ^{71}Ga(ν_e ,e$^-$)^{71}Ge, at two average $L_{in/out}$

- The measured ratio (R) of the measured rate of ^{71}Ge production at each distance to the expected rate from the known cross section are:
  - R_{in} = 0.791±0.05 !
  - R_{out} = 0.766±0.05 !

- The ratio of the outer to the inner result is R_{out} / R_{in} 0.97±0.07

BEST results compared to Gallex / Sage



GALLEX: $\begin{cases} R_1(\mathrm{Cr}) = 0.953 \pm 0.11 \\ R_2(\mathrm{Cr}) = 0.812 \pm 0.11 \end{cases}$

SAGE: $\begin{cases} R_3(\mathrm{Cr}) = 0.95 \pm 0.12 \\ R_4(\mathrm{Ar}) = 0.79 \pm 0.095 \end{cases}$

BEST: $\begin{cases} R_5(\mathrm{I}) = 0.791 \pm 0.05 \\ R_6(\mathrm{O}) = 0.766 \pm 0.05 \end{cases}$

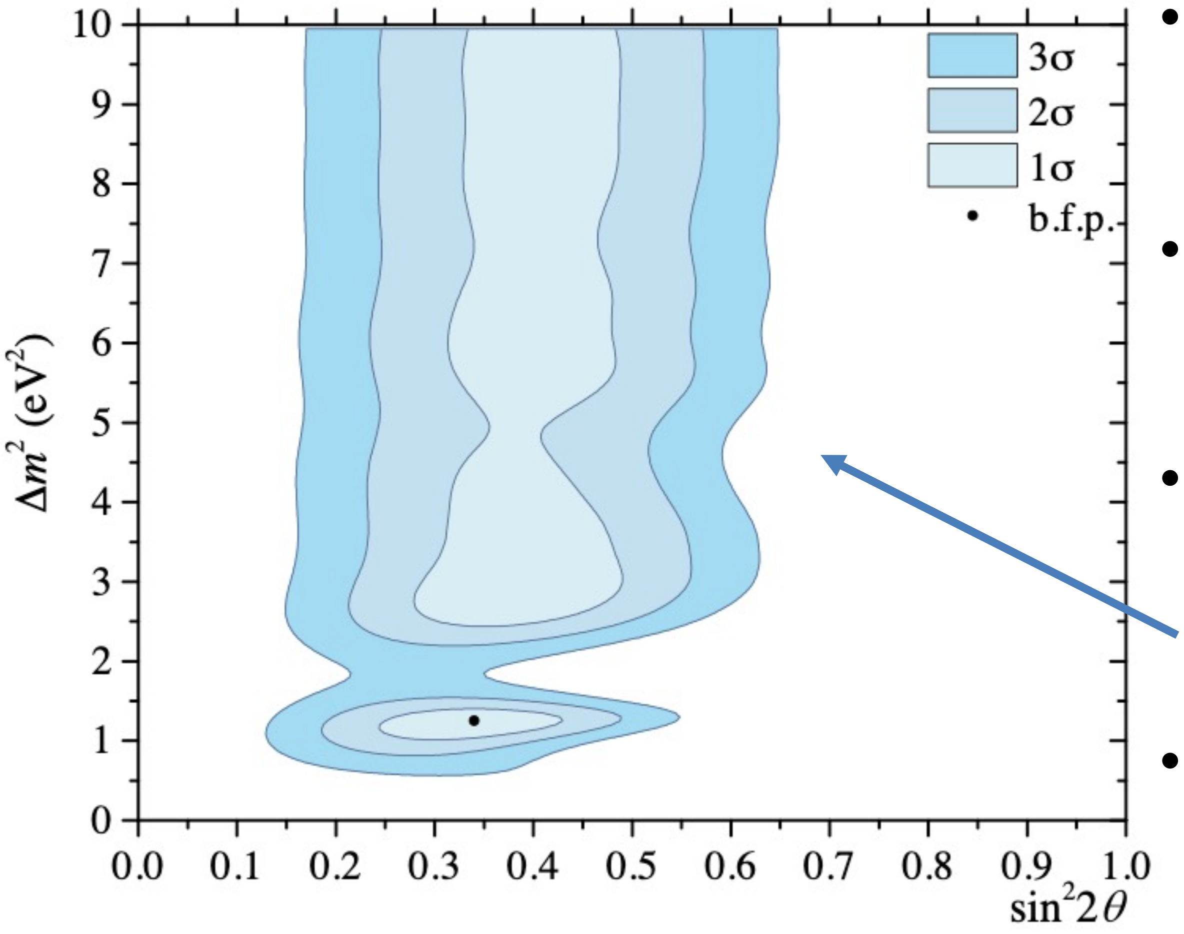
$\Rightarrow$ $\boxed{0.80 \pm 0.047}$

0.80 ± 0.047

> 5 σ deficit !

BEST results are reaffirming the GA

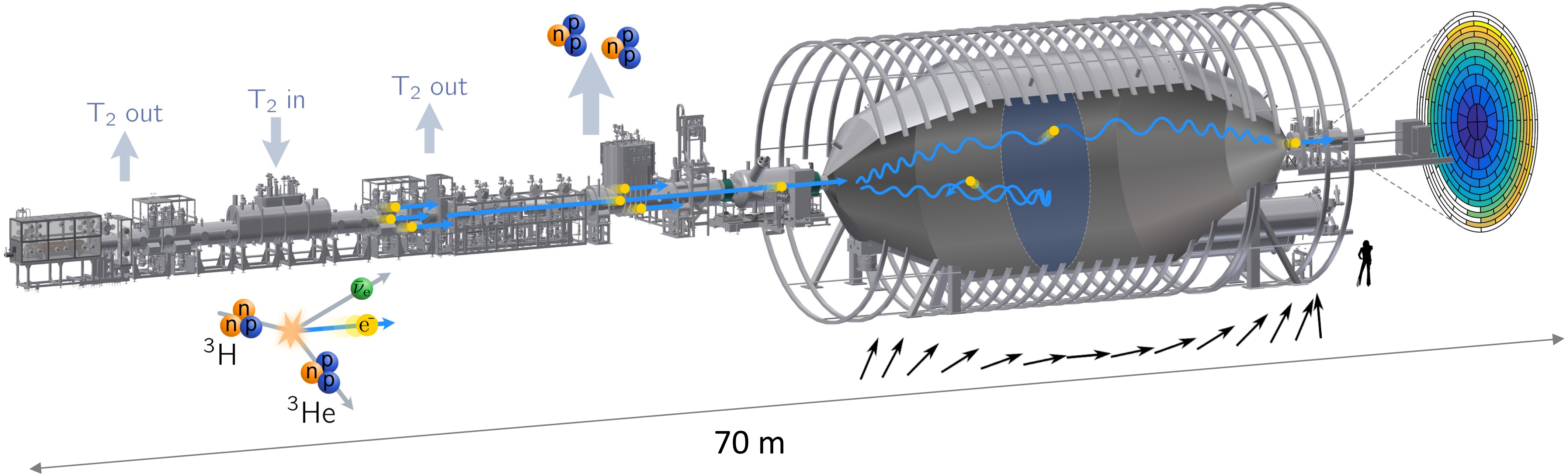
BEST results : sterile neutrino interpretation



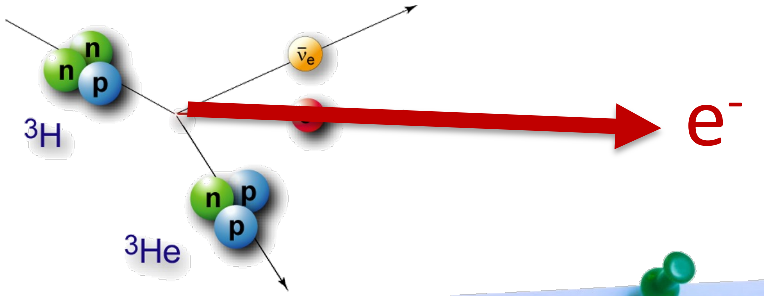
- Proofed technology & methodology.
  BEST results are robust
- R_{in} / R_{out} consistent with 1: No specific sterile neutrino signature
- Results consistent with $\nu_e \rightarrow \nu_s$ oscillations with:
  - Large $\Delta m^2 > 1$ eV^2
  - Large Mixing $\sin^2 2\theta$ (≈0.4)
- Considering the sterile neutrino hypothesis:
  - Large Δm^2 & Large mixing !

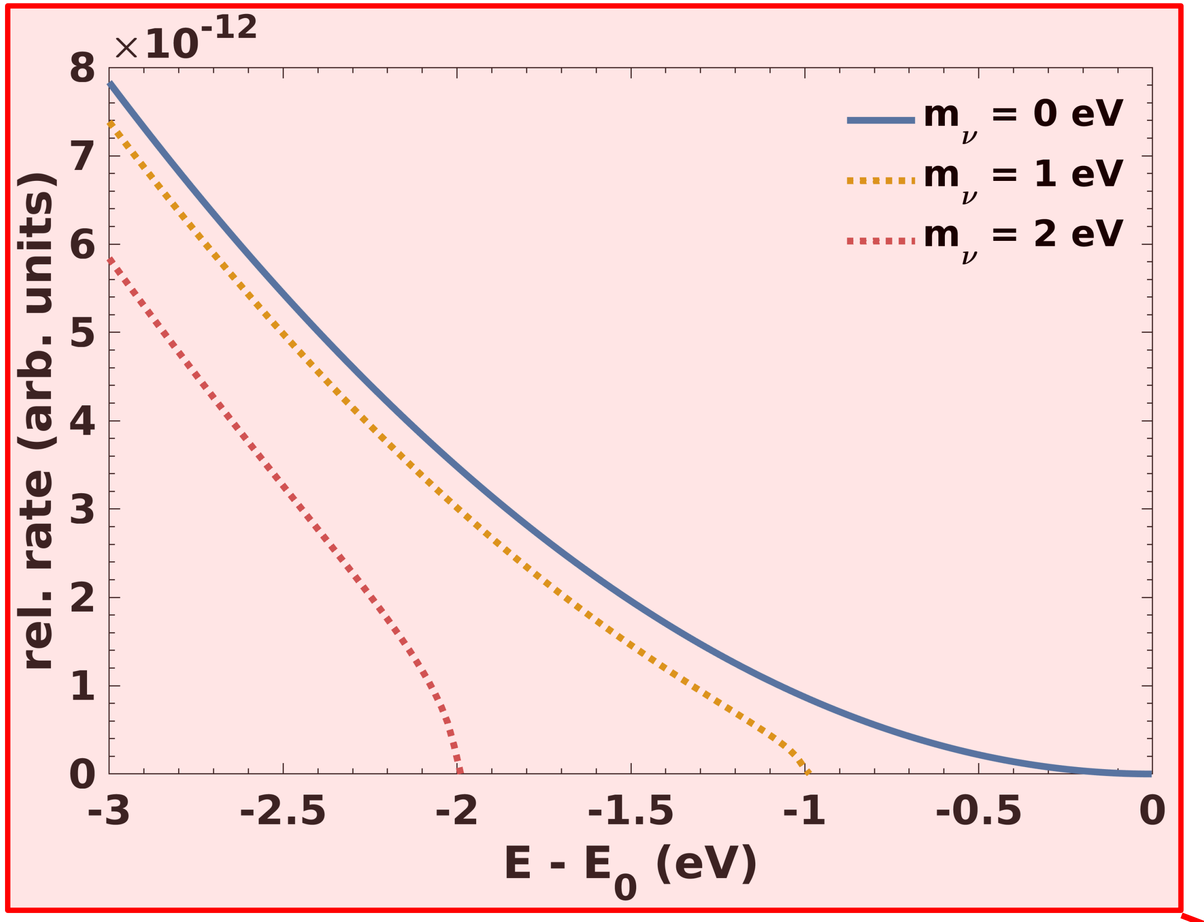
Beta-decay Experiment

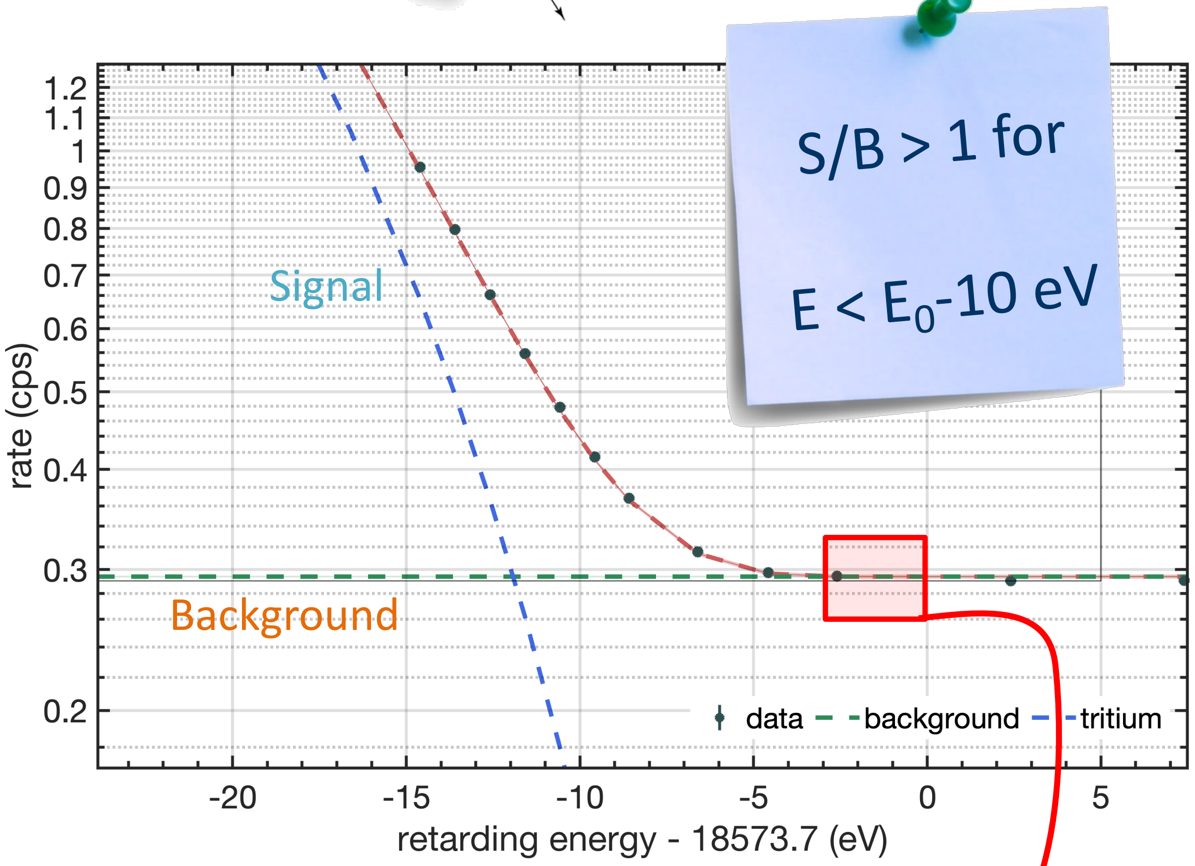
KATRIN experiment



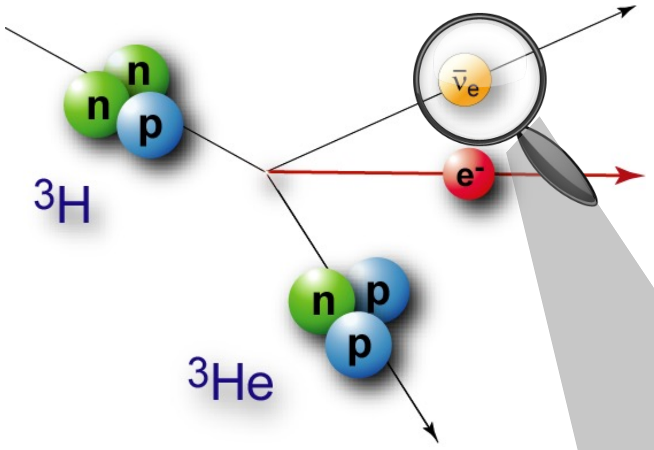
KATRIN Neutrino Mass Imprint

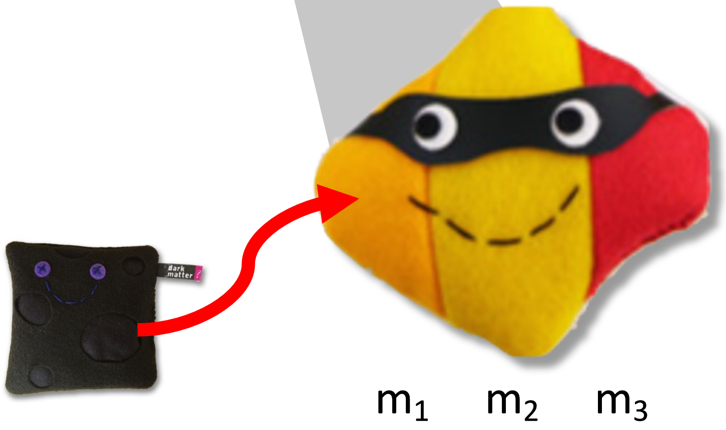




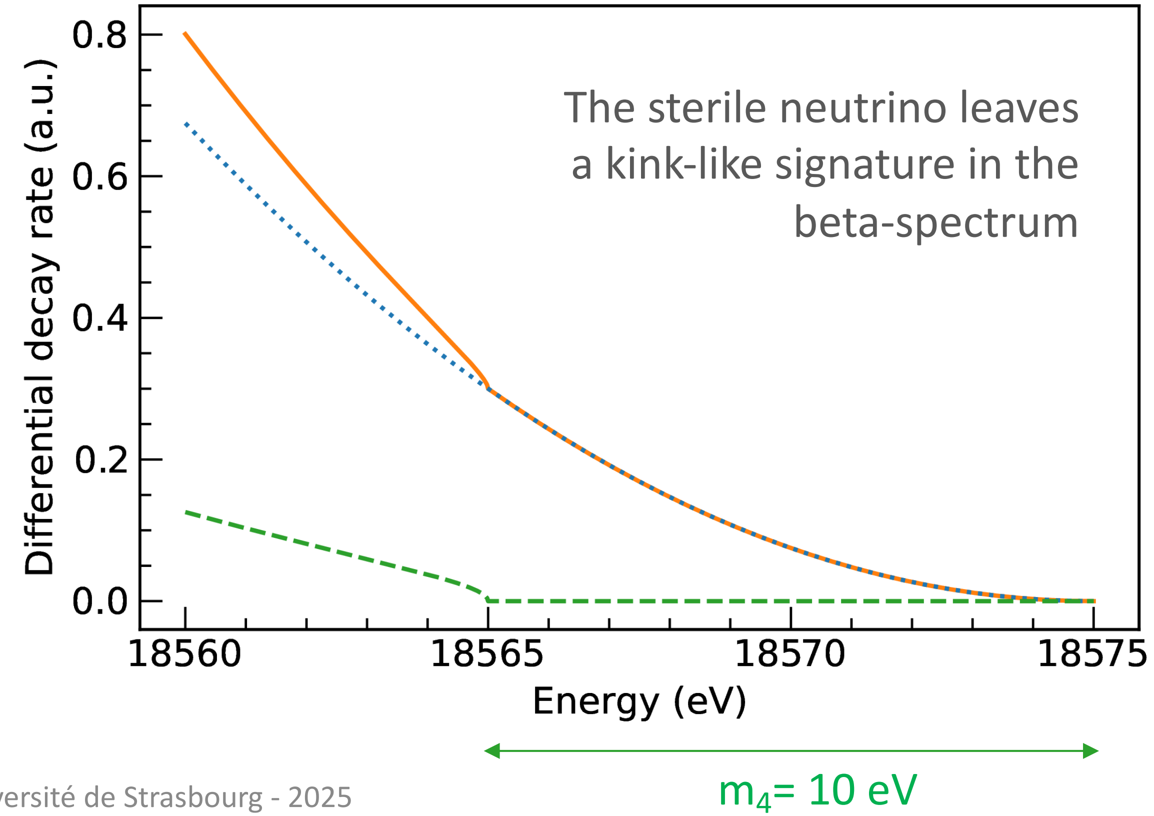


Sterile Neutrino Signature in $\boldsymbol{\beta}$-decay





$$\frac{d\Gamma}{dE} = \cos^2\theta \, \frac{d\Gamma}{dE}(m_\beta) + \sin^2\theta \, \frac{d\Gamma}{dE}(m_4)$$

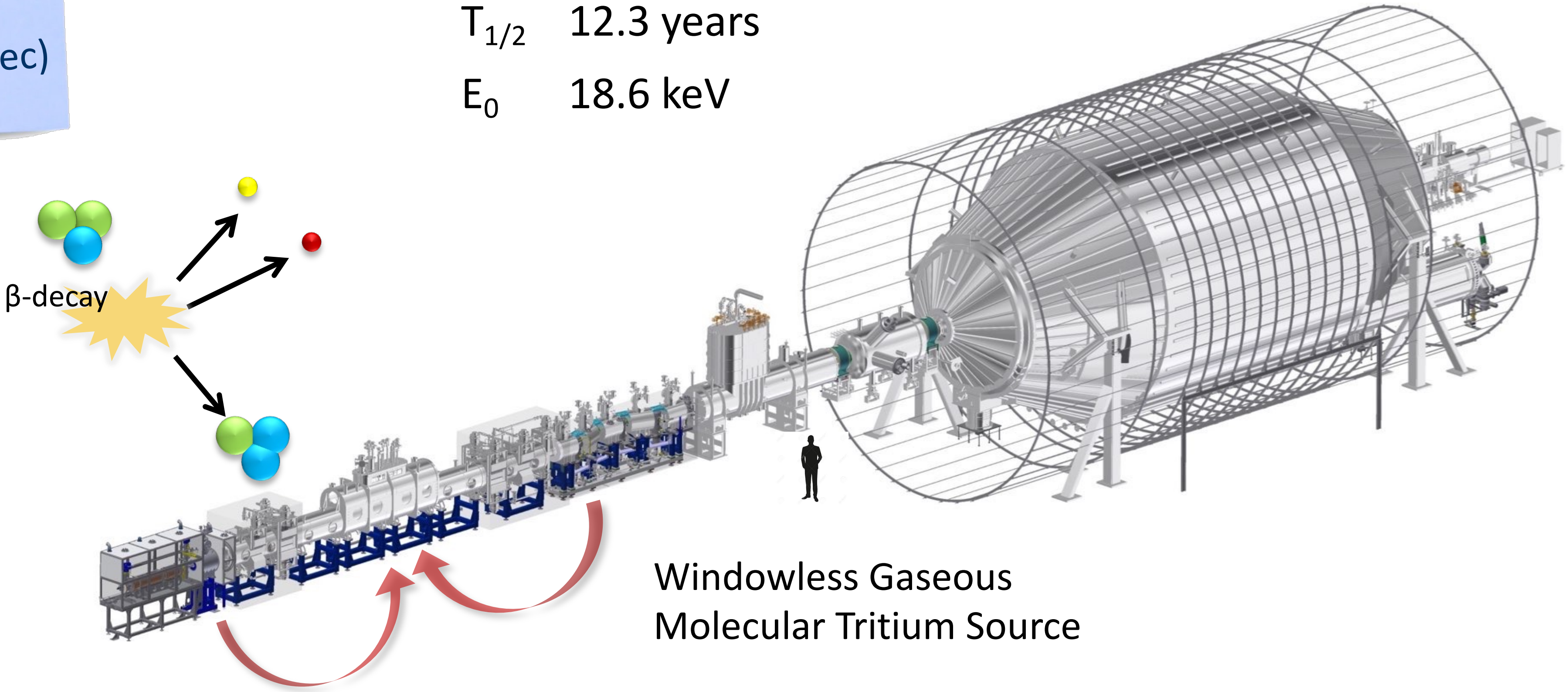


KATRIN Working Principle - recap

high stability
and luminosity

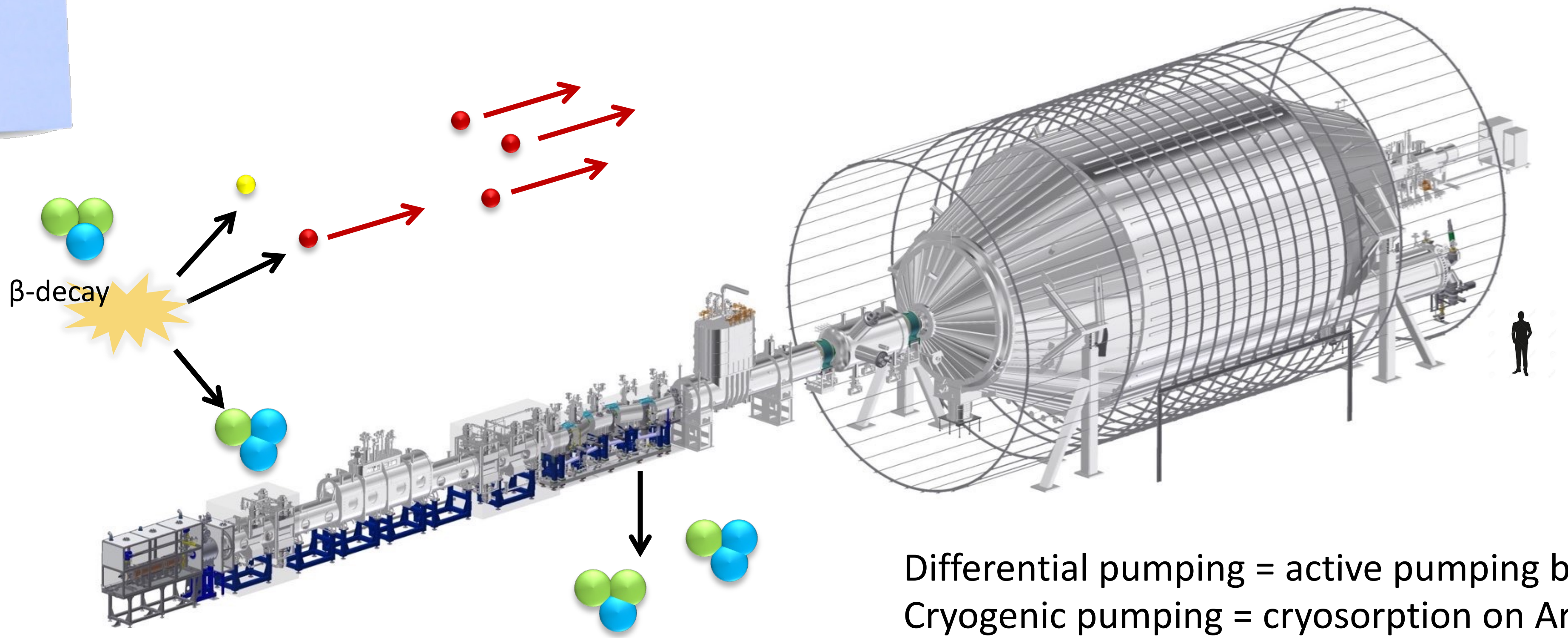
(10^{11} decays/sec)

	^{3}H – Molecular Tritium
	super-allowed β-decay
$T_{1/2}$	12.3 years
E_0	18.6 keV



KATRIN Working Principle - recap

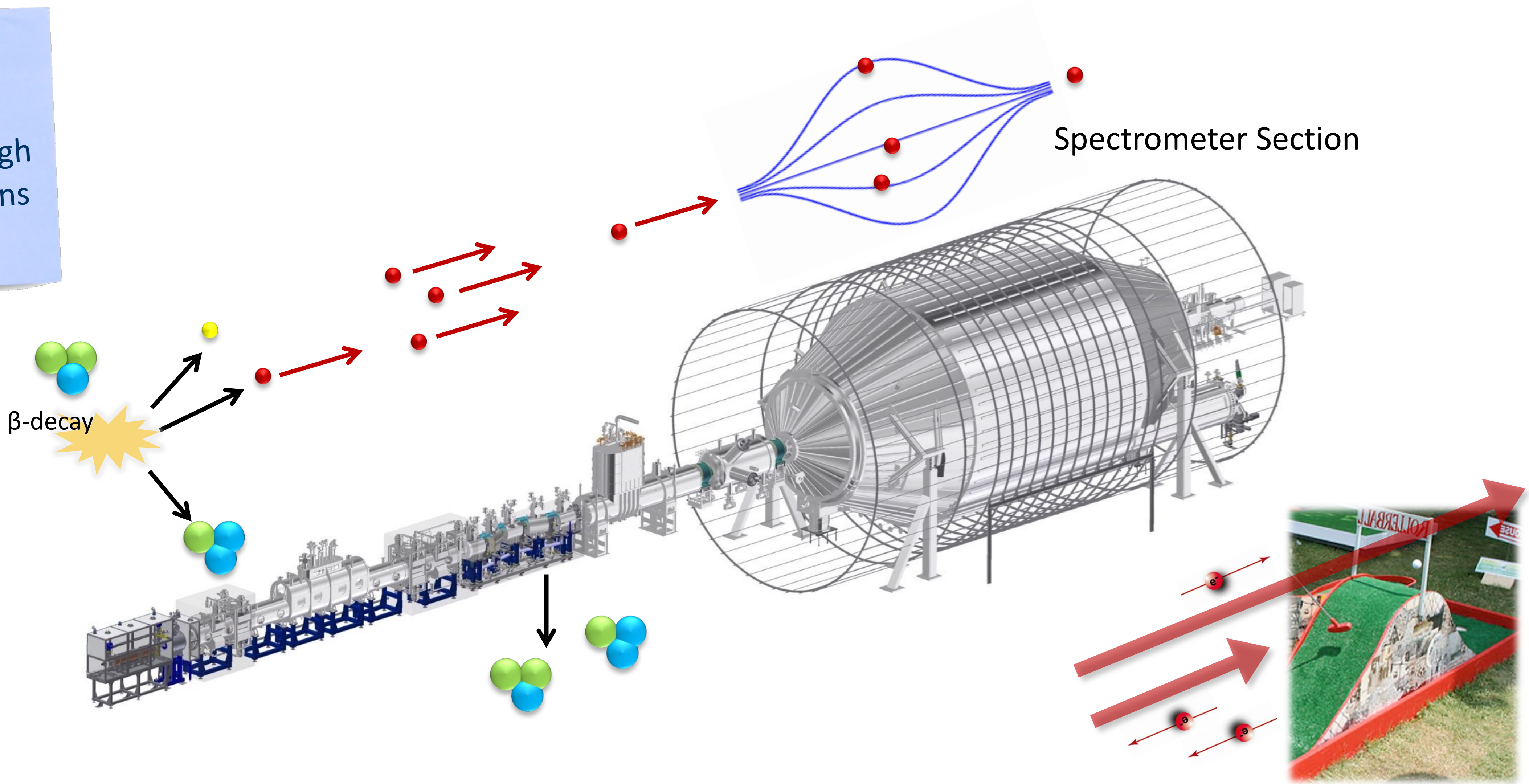
Tritium flow reduction by 14 orders of magnitude



Differential pumping = active pumping by TMPs
Cryogenic pumping = cryosorption on Ar-frost

KATRIN Working Principle - recap

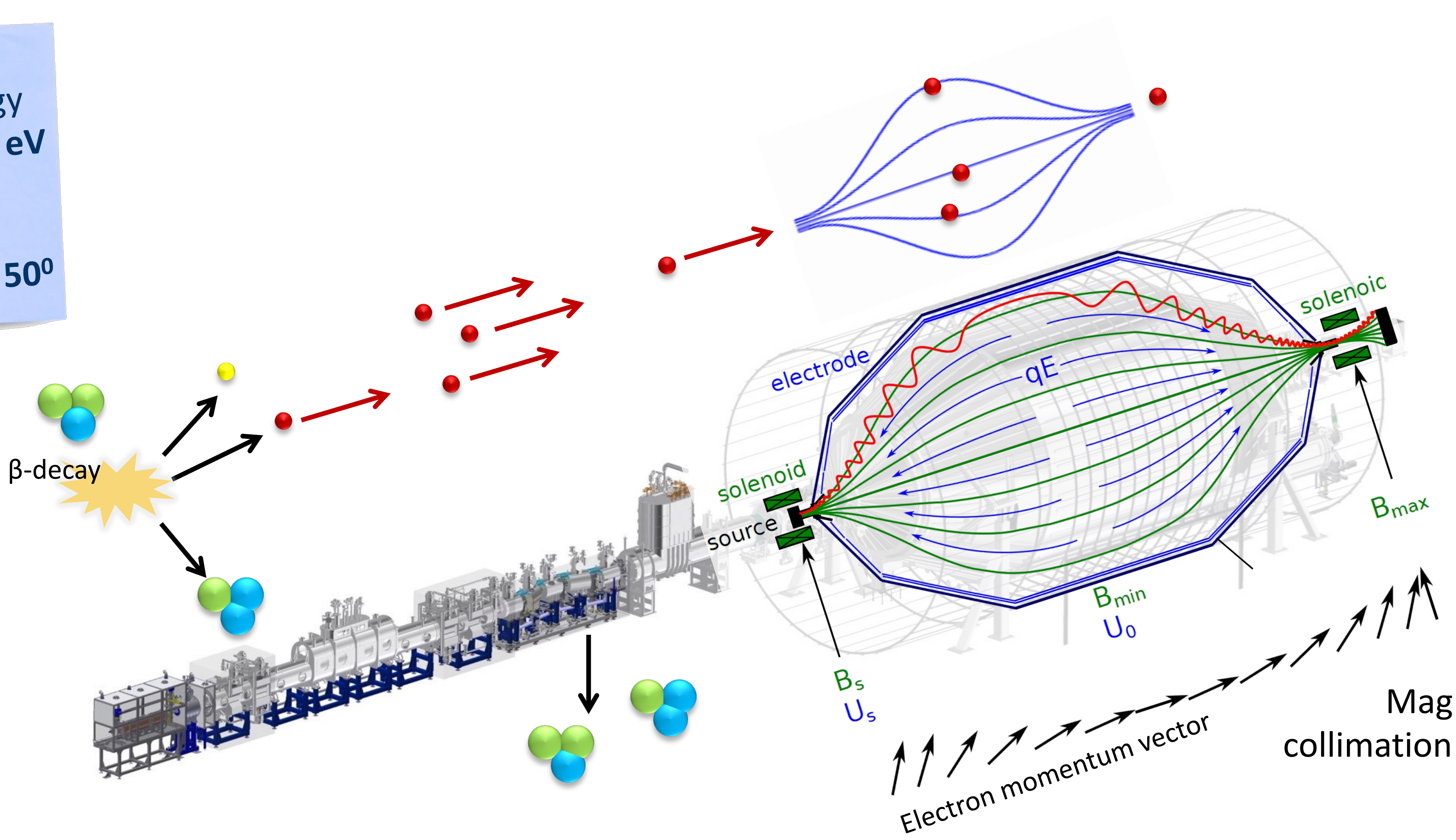
Electrostatic filter selects high energy electrons



KATRIN Working Principle - recap

excellent energy resolution: **~ 3 eV**

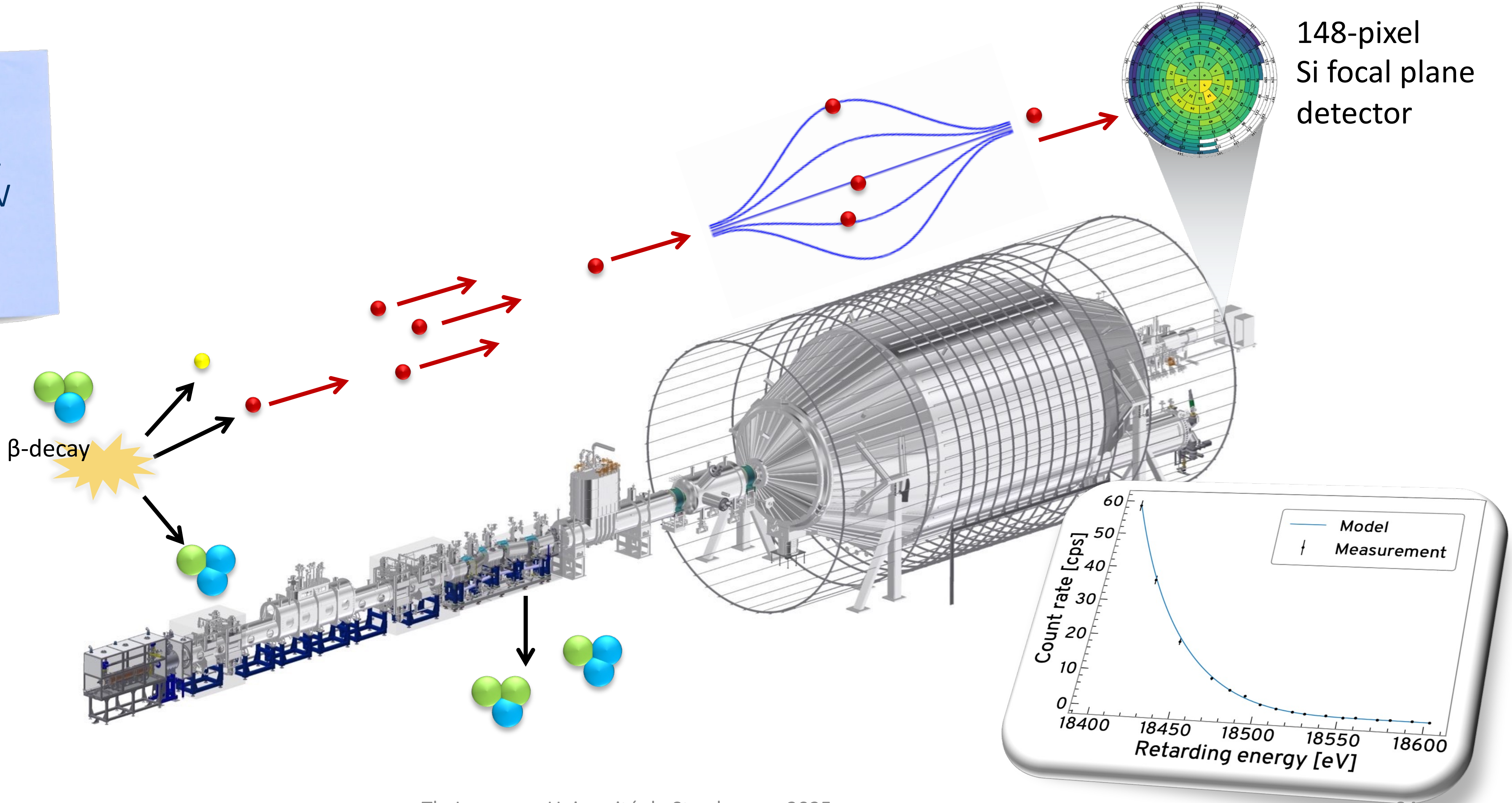
large angle acceptance: **~ 50⁰**



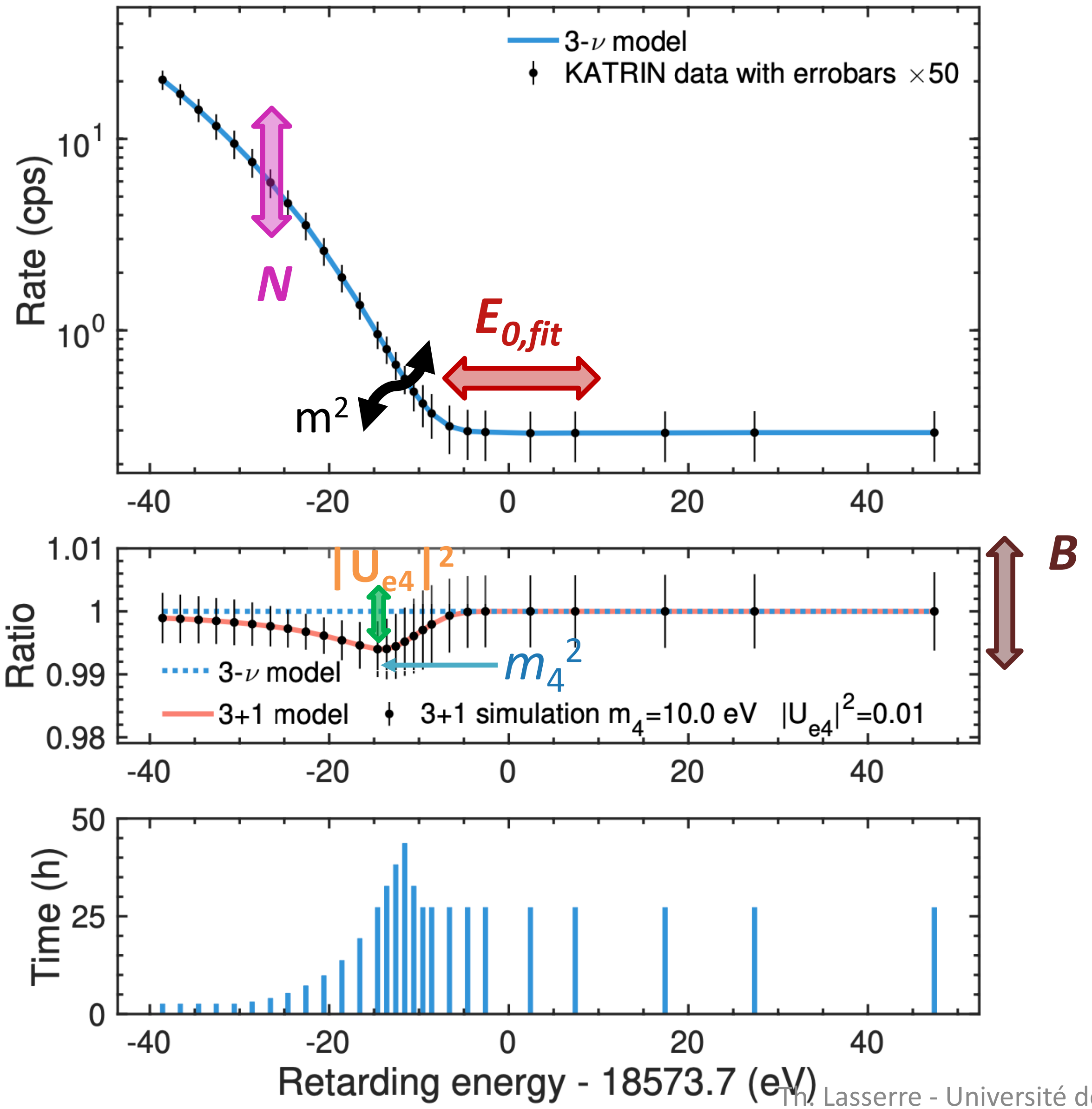
Magnetic adiabatic collimation + electrostatic filter (MAC-E)

KATRIN Working Principle - recap

Integral measurement down to 40 eV below the endpoint



Sterile Neutrino Modeling



$$\frac{d\Gamma}{dE} = \left(1 - |U_{e4}|^2\right) \frac{d\Gamma}{dE}(m_\beta^2) + |U_{e4}|^2 \frac{d\Gamma}{dE}(m_4^2)$$

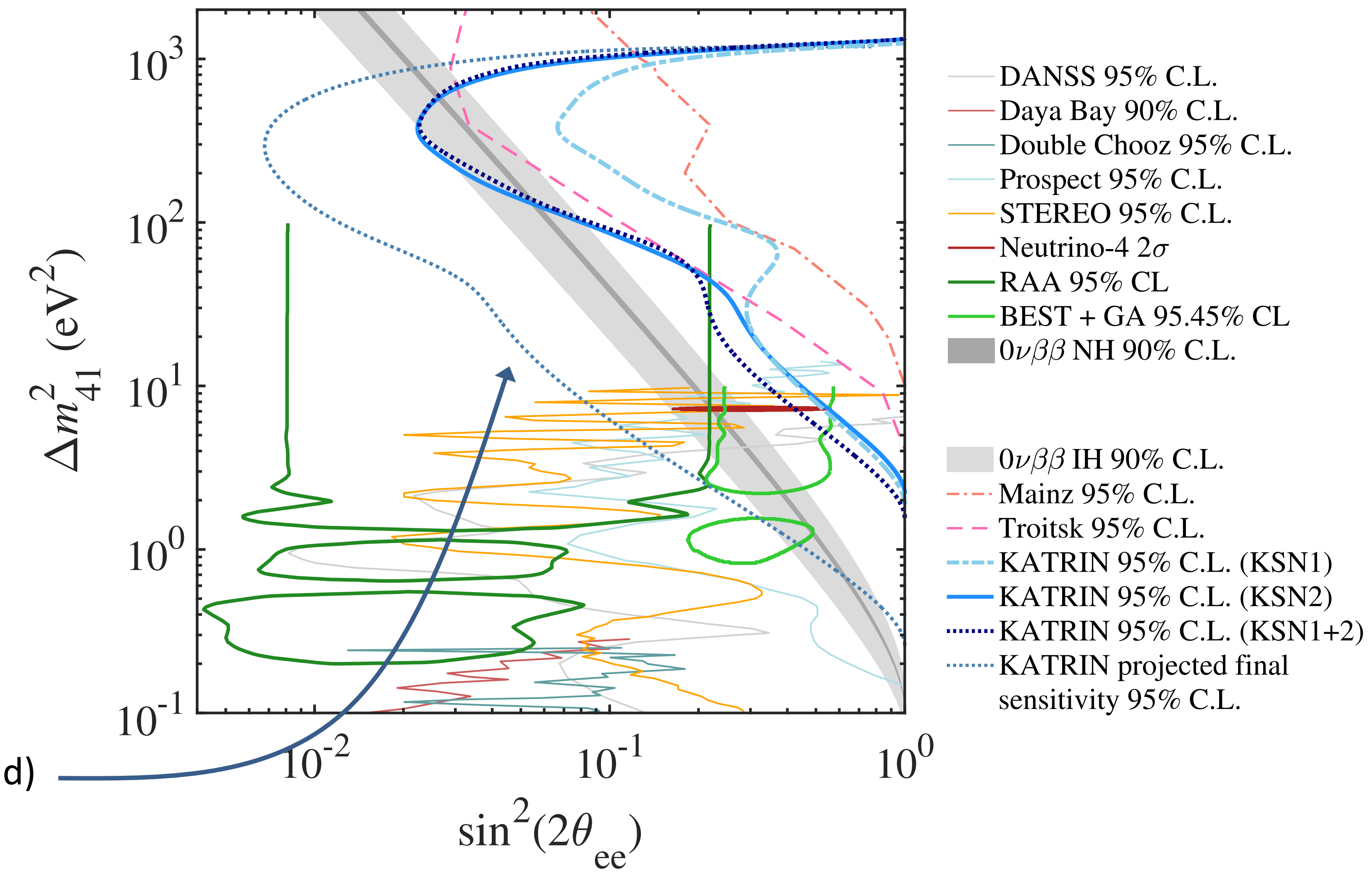
light neutrino — heavy neutrino

Fit Parameters:

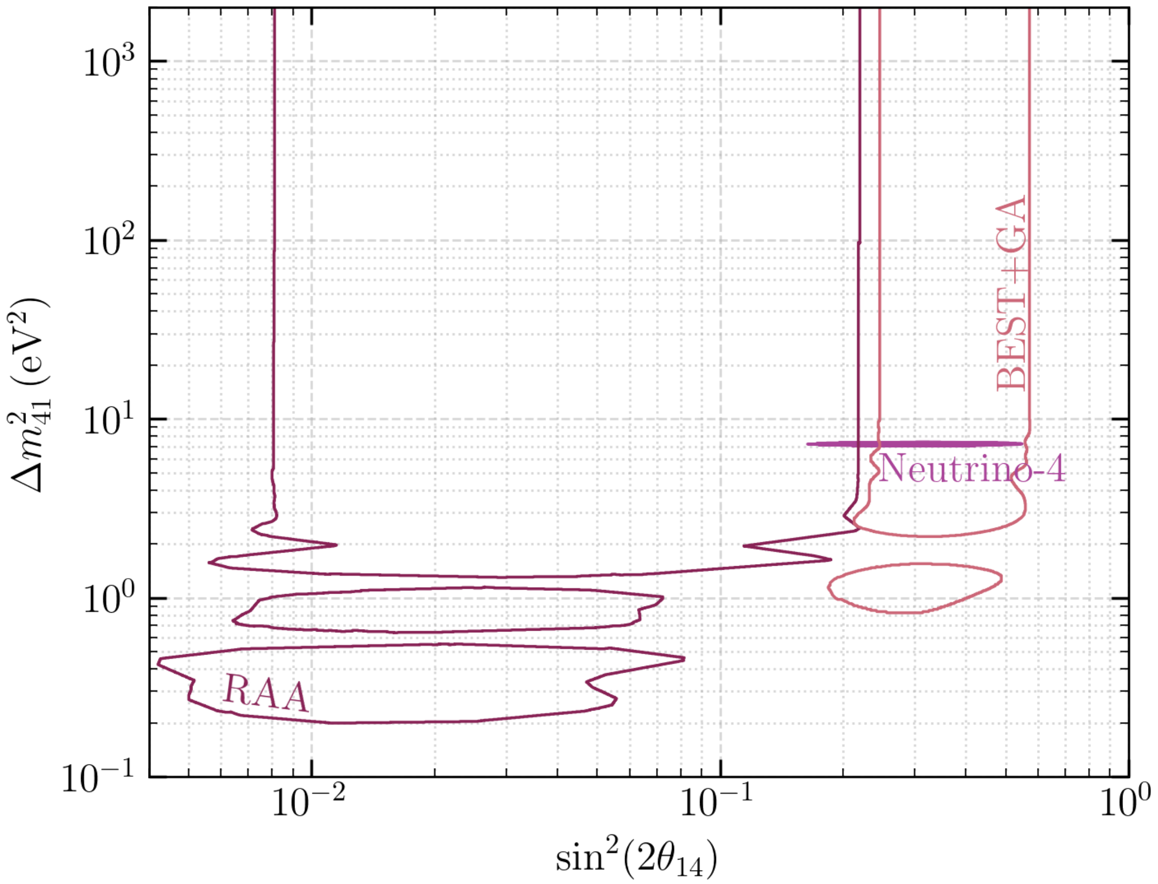
m^2	neutrino mass (fixed/free/constrained)
$E_{0,fit}$	endpoint
N	signal normalization
B	energy-independent background rate
m_4^2	4th neutrino mass
$\lvert U_{e4}\rvert^2$	4th neutrino mixing

Synergy with oscillation experiments

- **Oscillation Electron Disappearance Experiments**
  - $\Delta m_{41}^2 = m_4^2 - m_1^2 \approx \Delta m_{42}^2 \approx \Delta m_{43}^2$
  - $\sin^2 2\Theta = 4|U_{e4}|^2(1-|U_{e4}|^2)$
- **KATRIN**
  - m_β and m_4
  - $\sin^2\Theta = |U_{e4}|^2$
- Conversion KATRIN -to- Oscillation
  - $\Delta m_{41}^2 \simeq m_4^2 - m_\beta^2$
  - $\sin^2 2\Theta = 4 \sin^2\Theta(1- \sin^2\Theta)$
- Projected KATRIN final sensitivity (1000 days of data – reduced background)



KATRIN and the sterile neutrino puzzle



✓ Anomalies observed at reactors and BEST

G. Mention, Phys. Rev. D 83, 073006 (2011)
V. V. Barinov *et al.* Phys. Rev. C **105**, 065502, 2022

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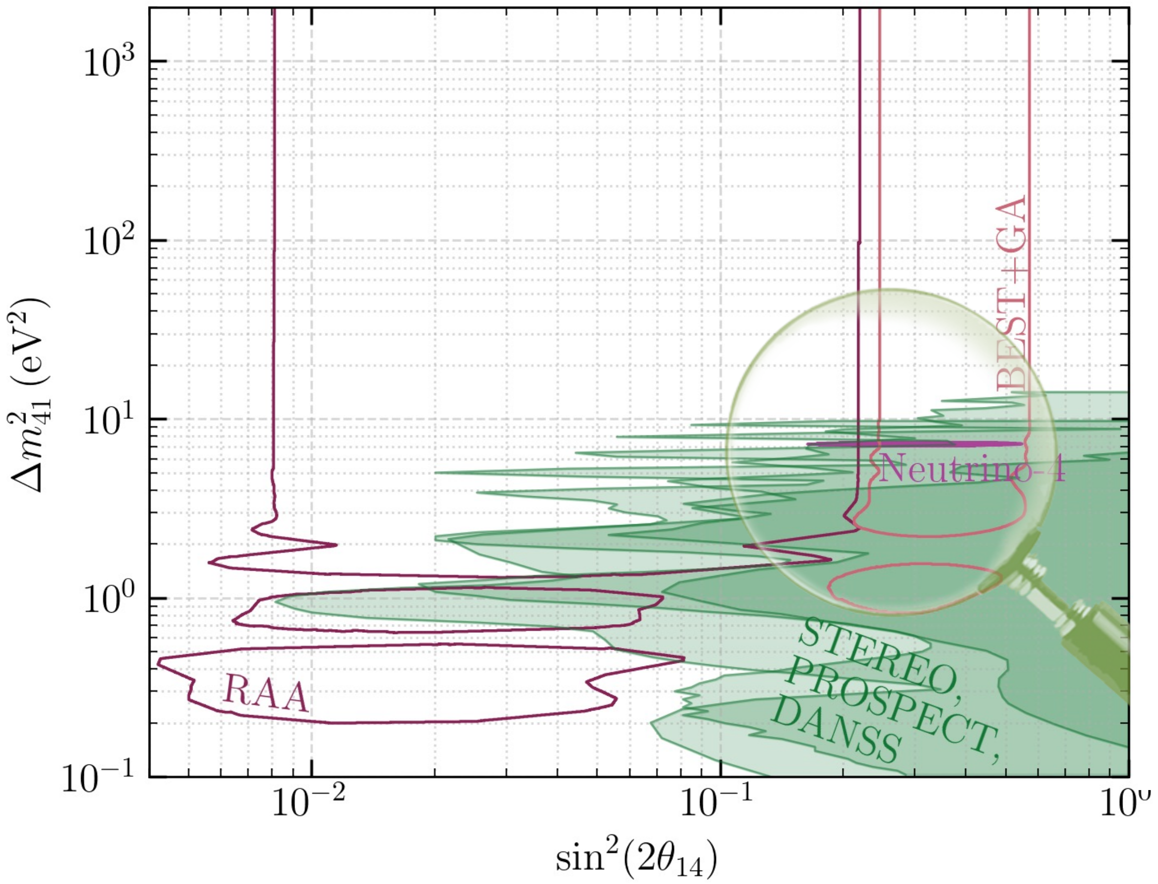

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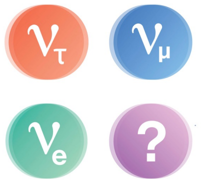
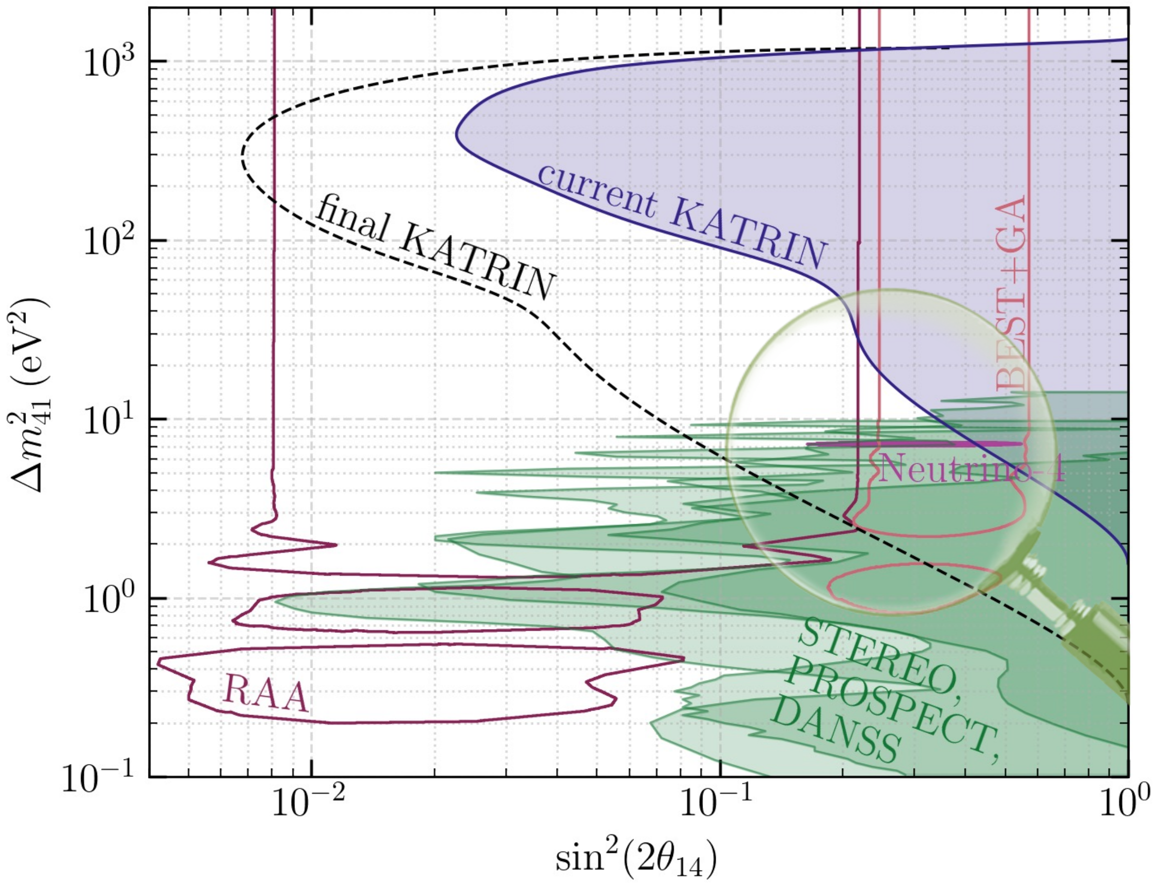
- ✓ Stereo (and similar experiments) do not observe a signal
  DANSS, arXiv:1911.10140 (2019)
  PROSPECT, Phys. Rev. D 103, 032001 (2021) – here new result in 2024
  STEREO, Nature 613, 257–261 (2023)



KATRIN and the sterile neutrino puzzle



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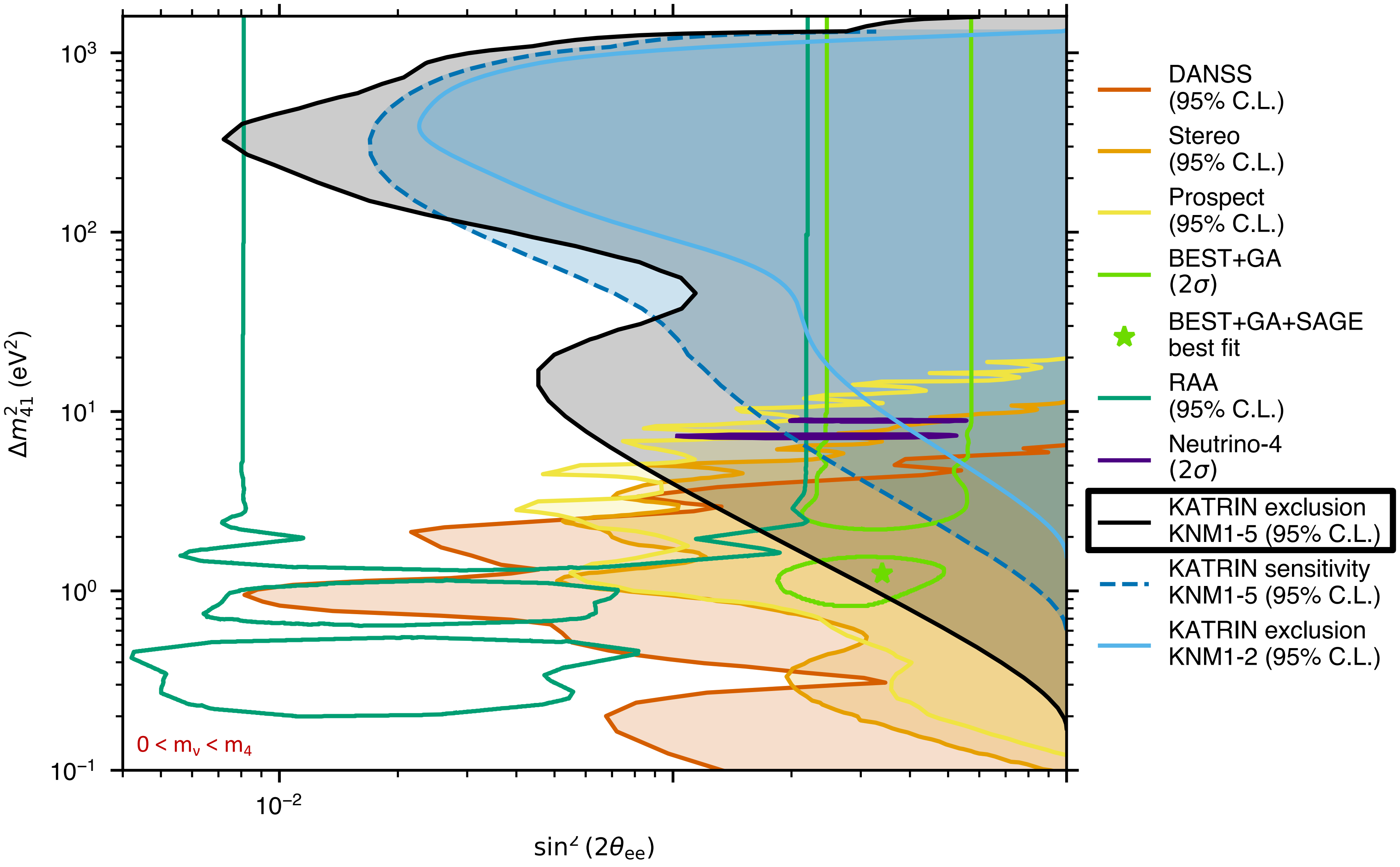
DANSS, arXiv:1911.10140 (2019)
PROSPECT, Phys. Rev. D 103, 032001 (2021)
STEREO, Nature 613, 257–261 (2023)

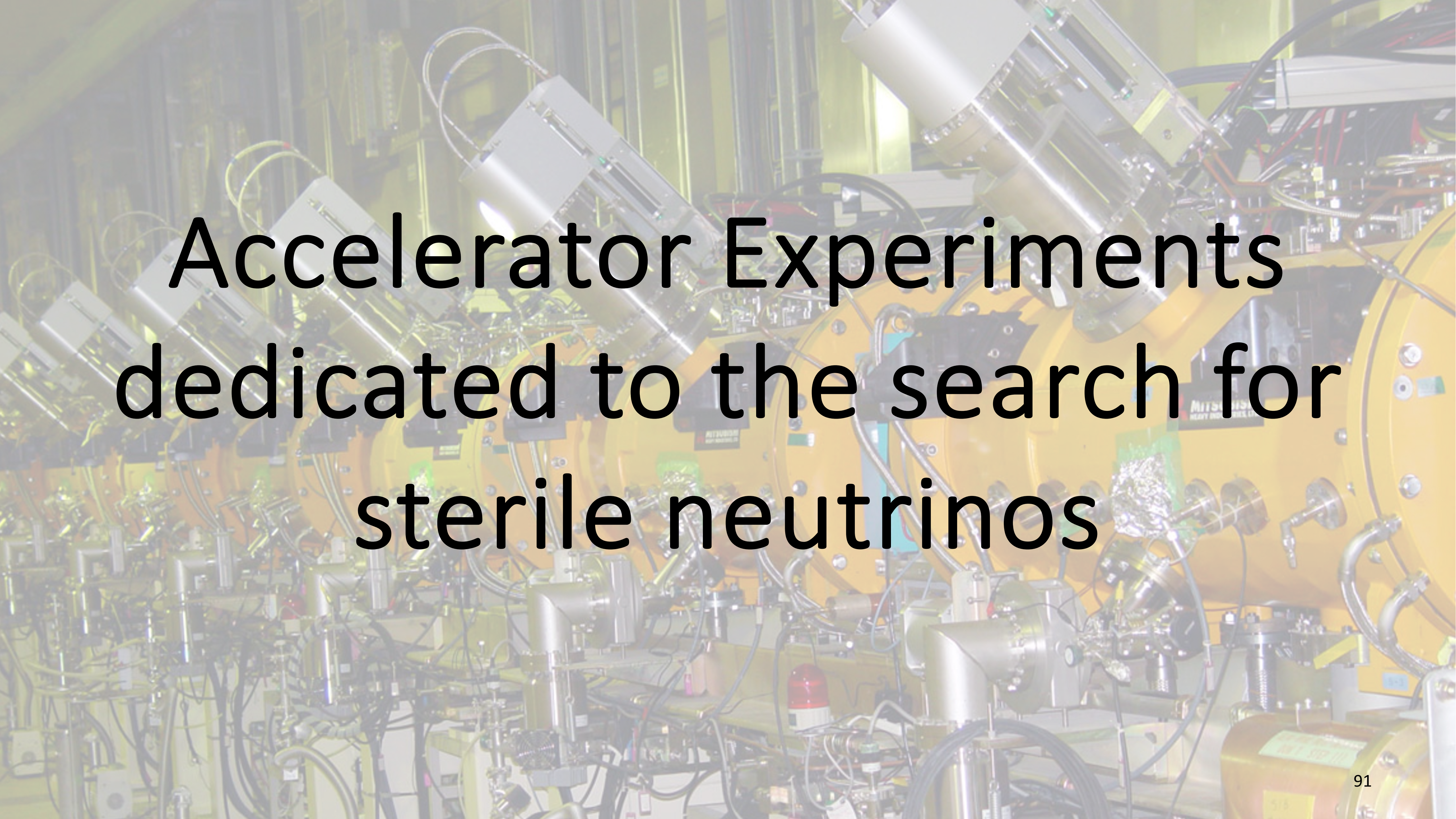
✓ KATRIN is a complementary probe to oscillation-based experiments

KATRIN Collab., PRL. 126, 091803 (2021)
KATRIN Collab. Phys. Rev. D **105**, 072004 (2022)

KATRIN Last Results

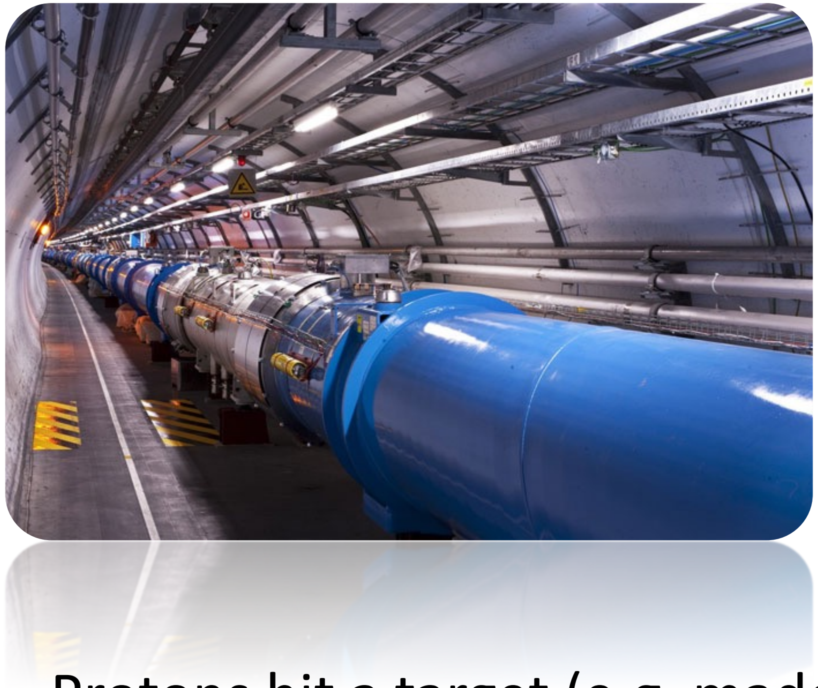
- ✓ **new exclusion limit** NEW!
  http://arxiv.org/abs/2503.18667
- ✓ almost exclude the whole Gallium Anomaly allowed region
- ✓ exclude Neutrino-4
- ✓ synergy with Short Baseline Reactor Experiments
  - Prospect
  - Stereo
  - DANSS …
  - KATRIN provides superior sensitivity for $\Delta m_4^2 > 5eV^2$

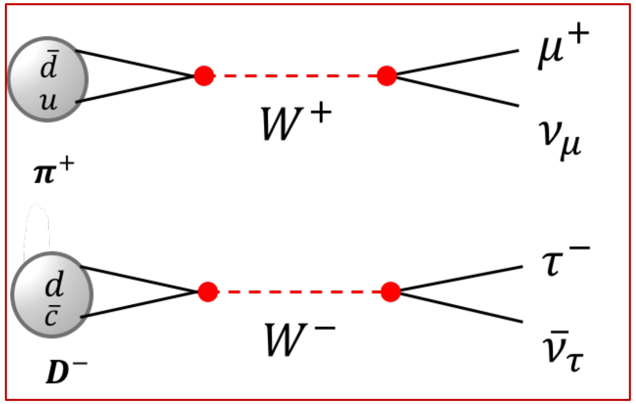


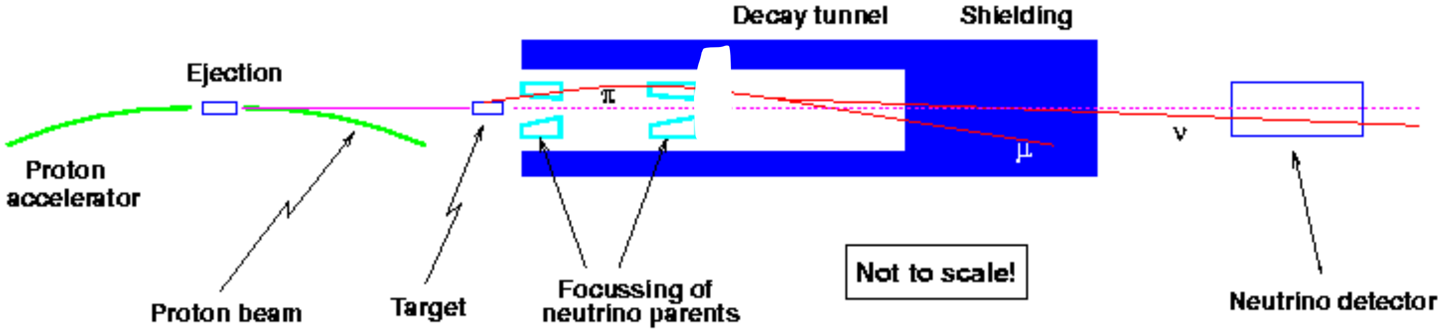


Accelerator Experiments dedicated to the search for sterile neutrinos

Neutrinos from accelerators





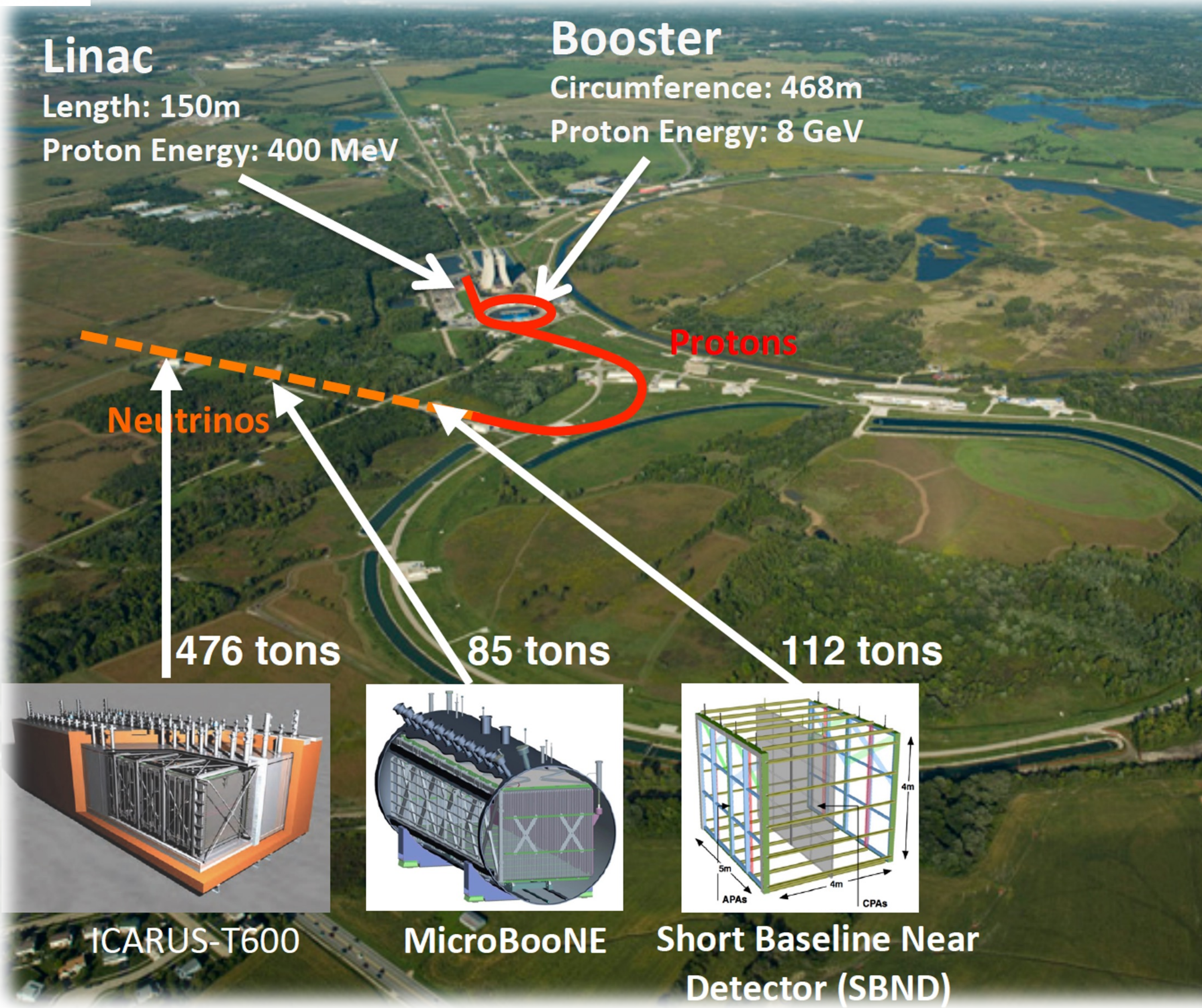


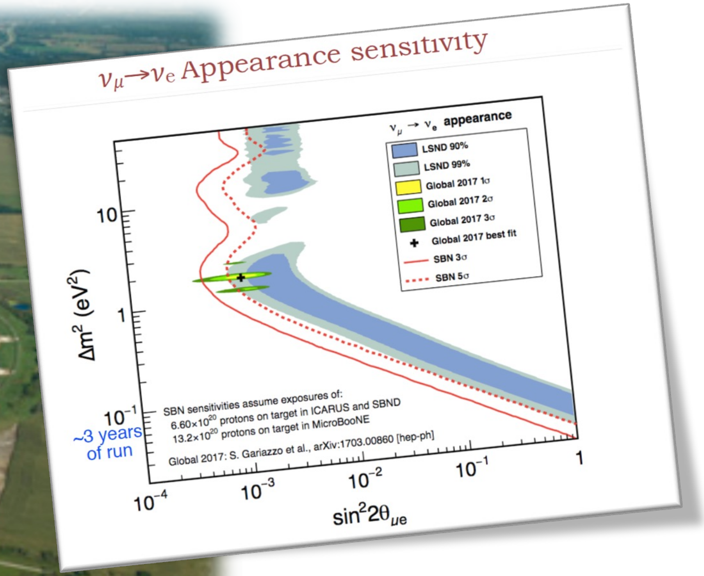
- Protons hit a target (e.g. made of beryllium)
- Generation of pions, kaons, and charmed mesons
- Mesons decay and produce neutrinos

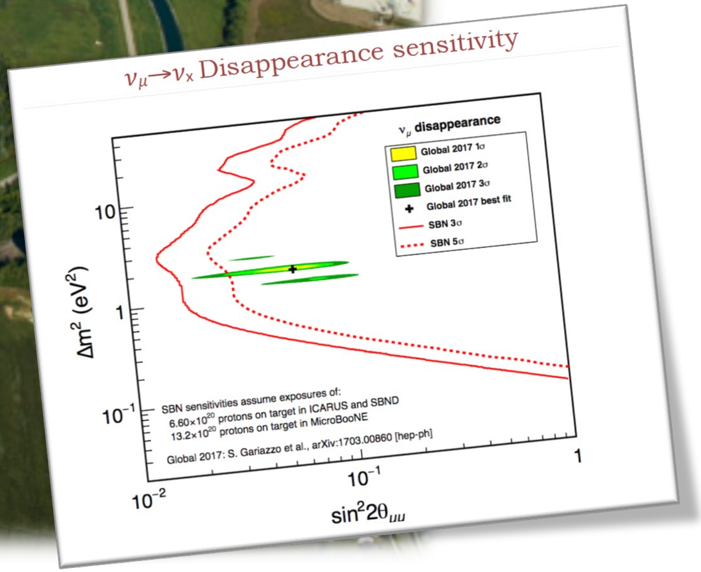
Accelerator ν proposals / projects

Type	Source	App. /Dis.	Oscillation Channels	Projects
Isotope Decay at Rest	$p + {}^{9}Be \rightarrow {}^{8}Li + 2p$ $n + {}^{7}Li \rightarrow {}^{8}Li$ ${}^{8}Li \rightarrow {}^{9}Be + e^{-} + \nu_e$	Dis.	$\nu_e \rightarrow \nu_e$	IsoDAR
Pion (Kaon) Decay at Rest	$\pi^{+} \rightarrow \mu^{+} \nu_\mu$ $\hookrightarrow e^{+} \bar{\nu}_\mu \nu_e$	App. & Dis.	$\nu_\mu \rightarrow \nu_e$ $\nu_e \rightarrow \nu_e$	OscSNS, KDAR, JPARC-MLF
Pion Decay in Flight	$\pi^{+} \rightarrow \mu^{+} \nu_\mu$ $\hookrightarrow e^{+} \bar{\nu}_\mu \nu_e$	App. & Dis.	$\nu_\mu \rightarrow \nu_e$ $\nu_\mu \rightarrow \nu_e$ $\nu_\mu \rightarrow \nu_\mu$ $\nu_e \rightarrow \nu_e$	MINOS+, nuPRISM, **SBN**
Low-E Neutrino Factory	$\mu^{+} \rightarrow e^{+} \bar{\nu}_\mu \nu_e$ $\mu^{-} \rightarrow e^{-} \nu_\mu \bar{\nu}_e$	App. & Dis.	$\nu_e \rightarrow \nu_\mu$ $\nu_e \rightarrow \nu_\mu$ $\nu_\mu \rightarrow \nu_\mu$ $\nu_e \rightarrow \nu_e$	νSTORM

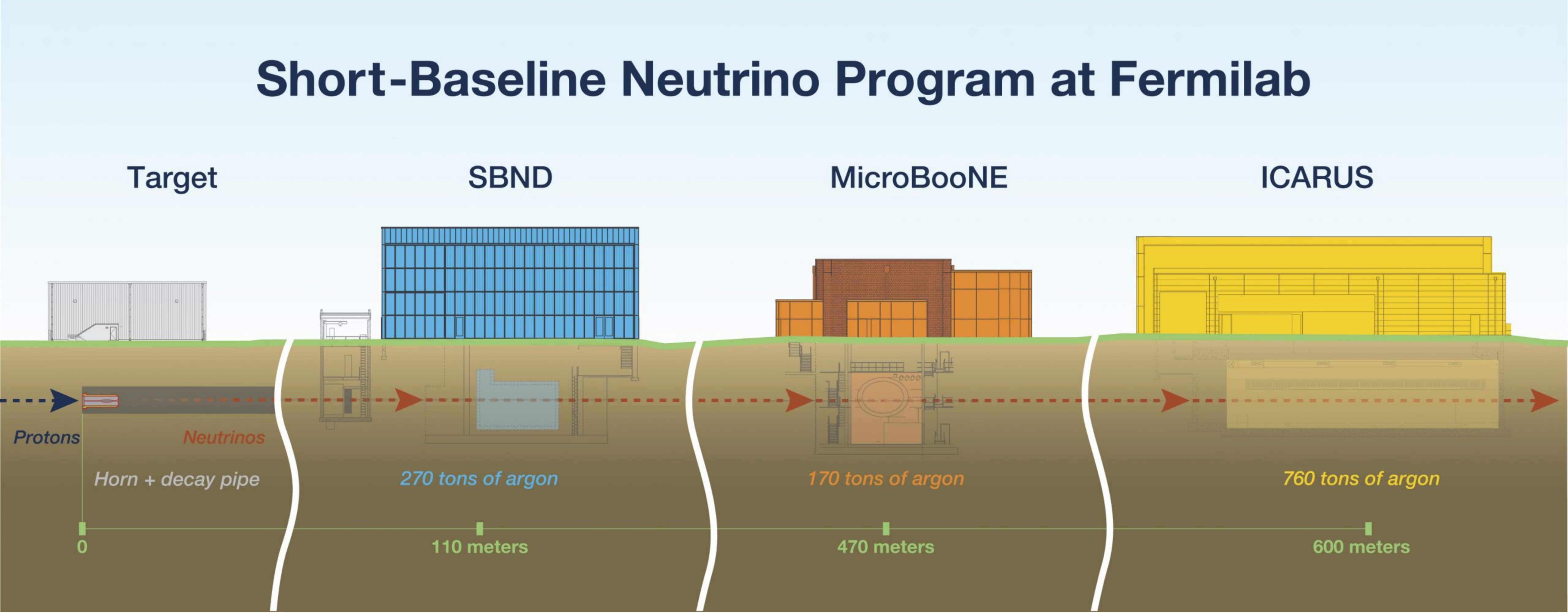
The Fermilab SBN program





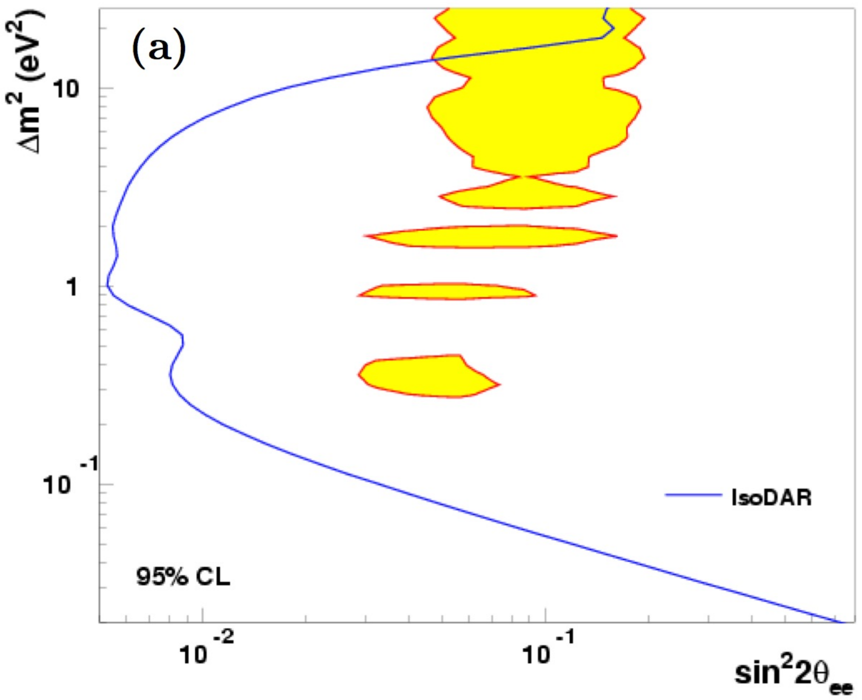


The Fermilab SBN program



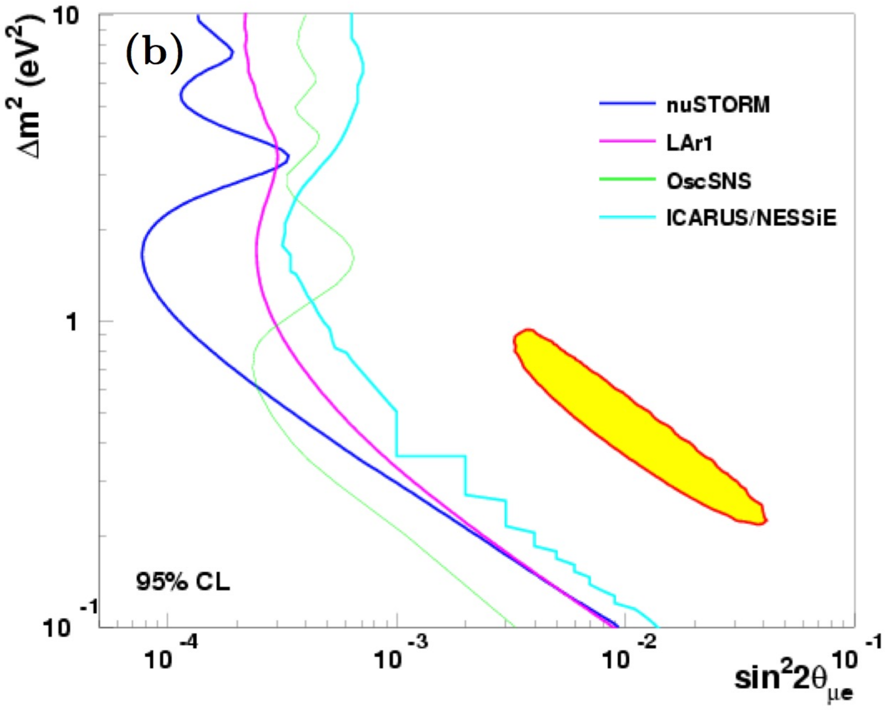
Beam Experiment Sensitivities (example)

Disappearance



Appearance

arXiv:1310.4340



eV sterile ν: Take Away

- 3 σ anomalies calling for clarification

  → $\Delta m^2 \approx eV^2$ Sterile Neutrino? Or Experimental Artifacts?

  - Caveat: tensions in global fits – no global solution
- Reactor Neutrinos – mostly reject the sterile neutrino hypothesis
  - Challenge: background mitigation (S/B close to 1)
- Radioactive Source (^{51}Cr) – confirm the Gallium anomaly
  - Confirm the Gallium anomaly
- KATRIN – a new comer, somehow!
  - Reject the sterile neutrino hypothesis – complementary!
- Neutrino Beams
  - 5-10 years timescale – is going to shed light on the anomalies
  - Added value: allow studying sterile neutrino phenomenology, in case?

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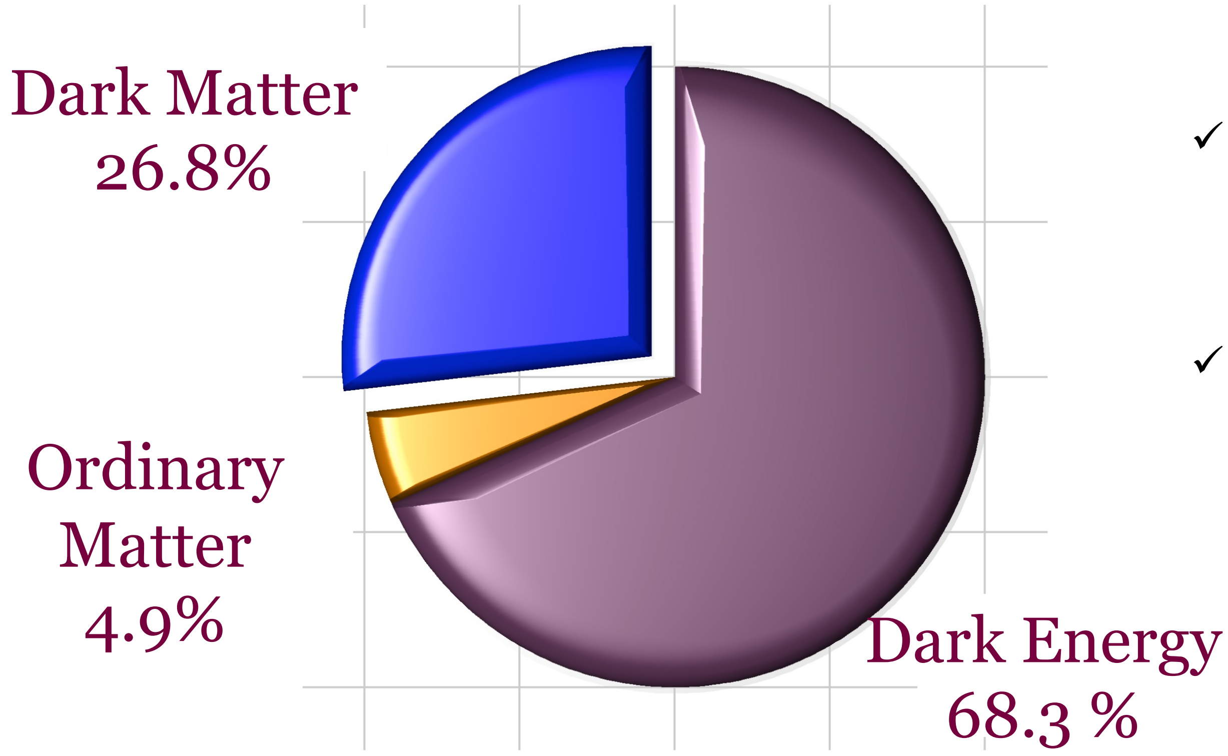
Thanks for your attention

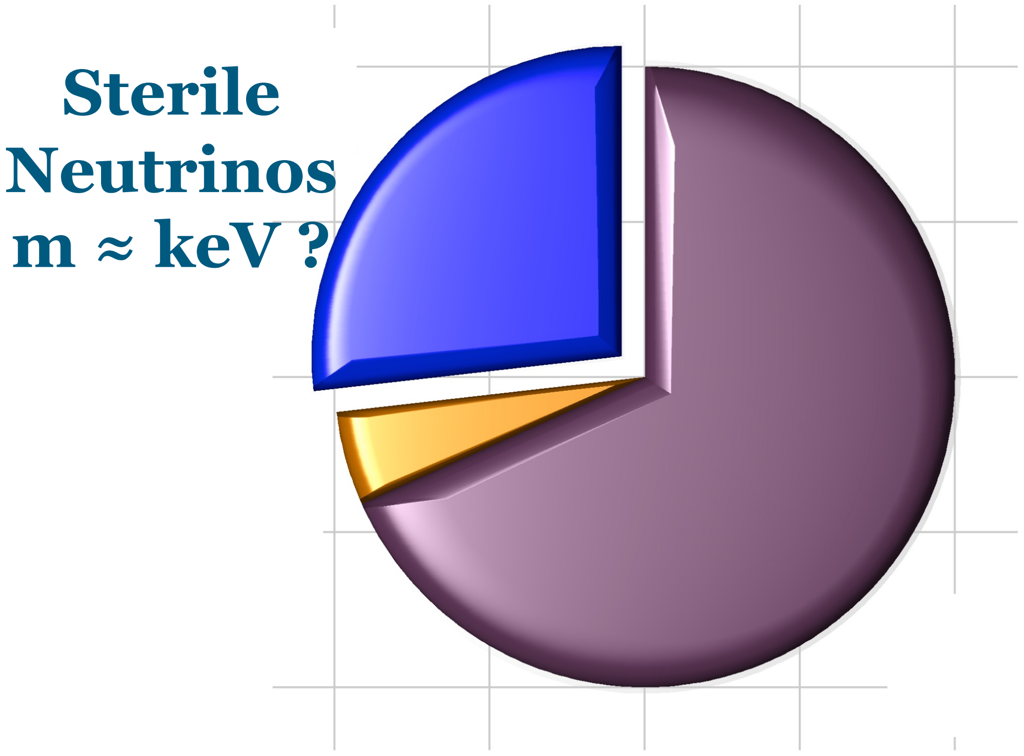
KeV Neutrino Search

keV Sterile Neutrino and Dark Matter



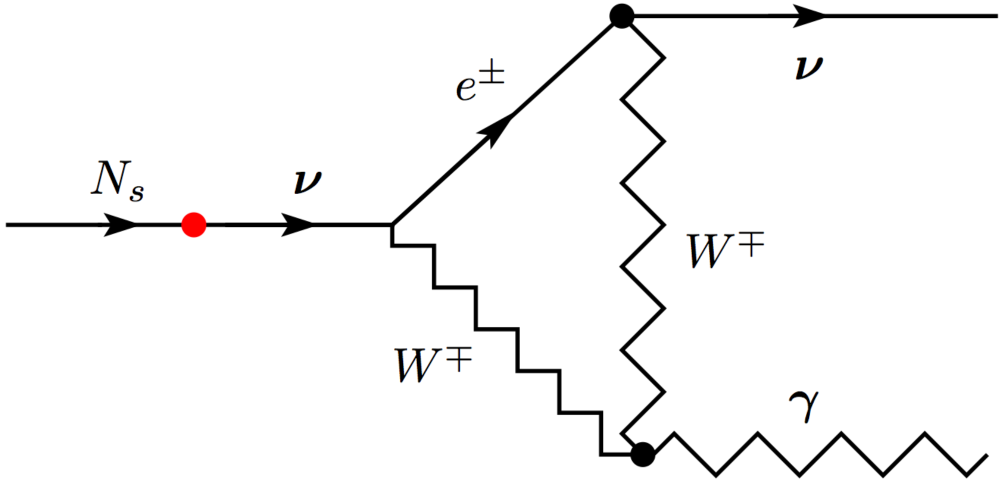
- ✓ Dark matter constitutes 27% of the energy contents of the Universe
- ✓ But no particle of the standard model can explain the Dark Matter

keV Sterile Neutrino and Dark Matter



✓ Sterile neutrinos with a mass of the order of the kilo-electronvolt are viable candidates to explain the observations

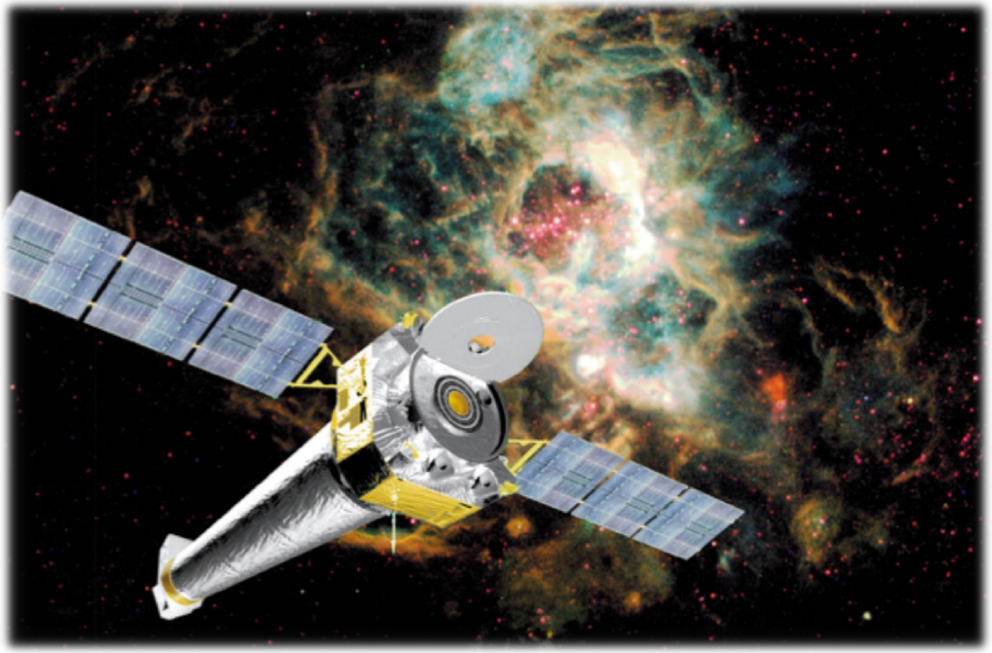
Neutrino Decay



- ✓ If these neutrinos are present in abundance in the galaxies and galaxy clusters
- ✓ They could decay into a neutrino and a photon X, each taking half of the mass-energy of the neutrino constituting the dark matter particle

Astrophysical Searches

Chandra Satellite

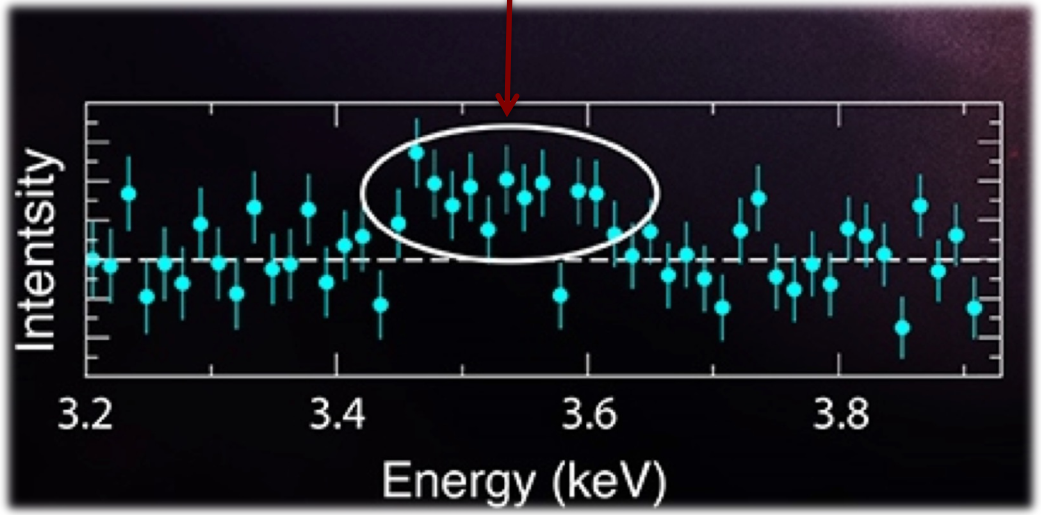


- ✓ These photons are searched for with X-ray satellites such as Chandra or XMM Newton

Is there a 7 keV Neutrino?

X-ray line not yet identified

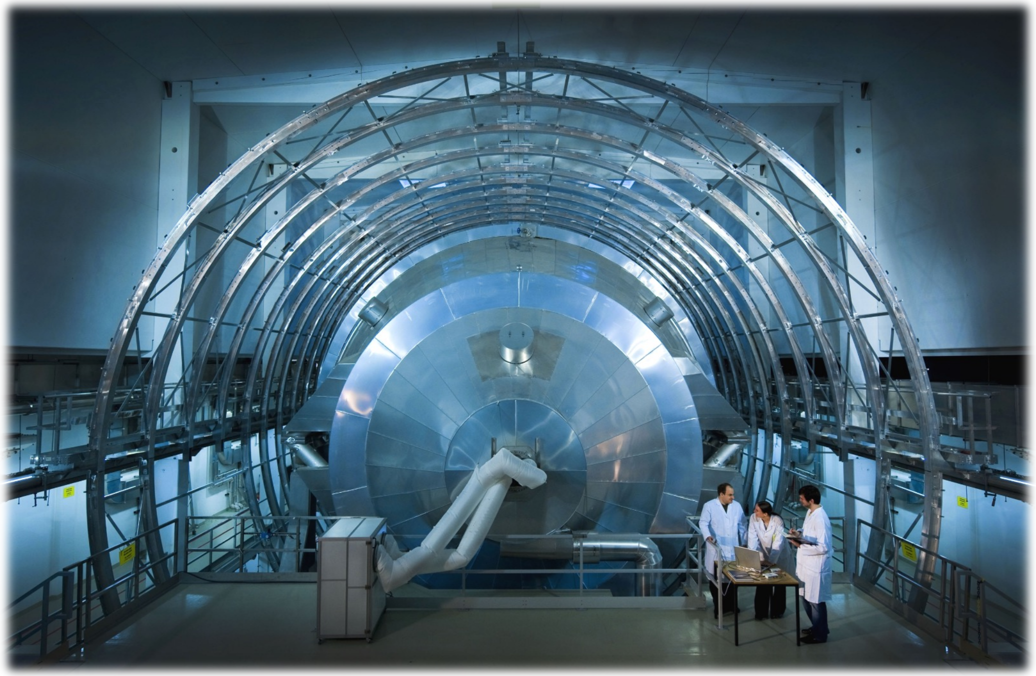
ν_s ?



- ✓ The expected signal is extremely weak and the astrophysical backgrounds are significant
- ✓ Nevertheless two research teams recently discovered a non explained signal that could correspond to 7 keV neutrino
- ✓ This remains obviously to be confirmed

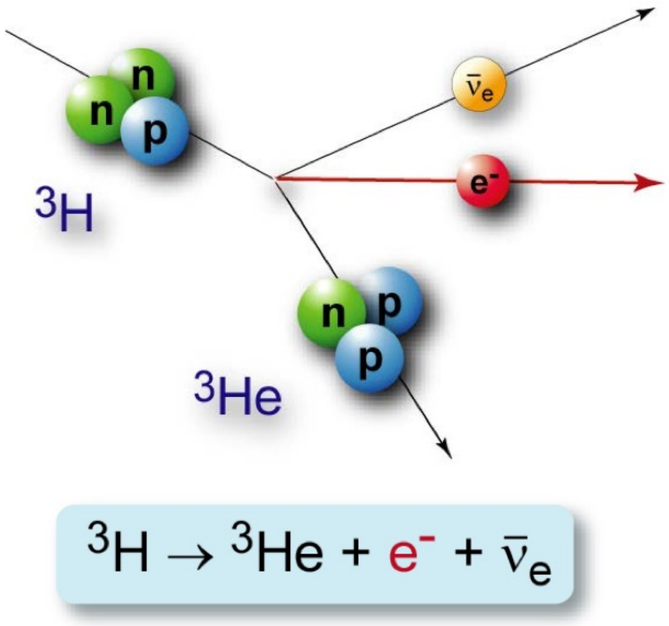
keV Neutrino Search in Laboratory

KATRIN Spectrometer



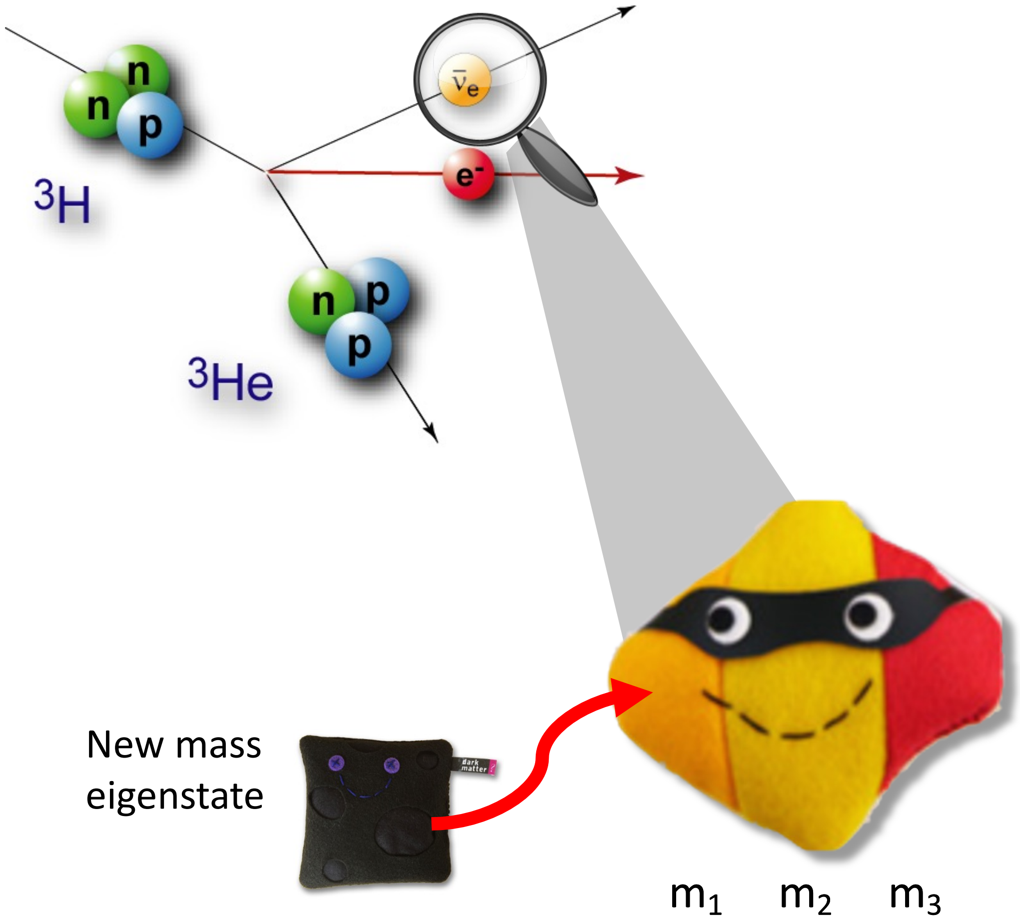
- ✓ It would thus be interesting to test this hypothesis in laboratory
- ✓ It may be possible by modifying the KATRIN experiment currently dedicated to the direct measurement of the Standard Model neutrino mass
- ✓ This experiment, located in Germany, uses the most intense source of Tritium available for the scientific community

Tritium Beta Decay and Sterile Neutrinos

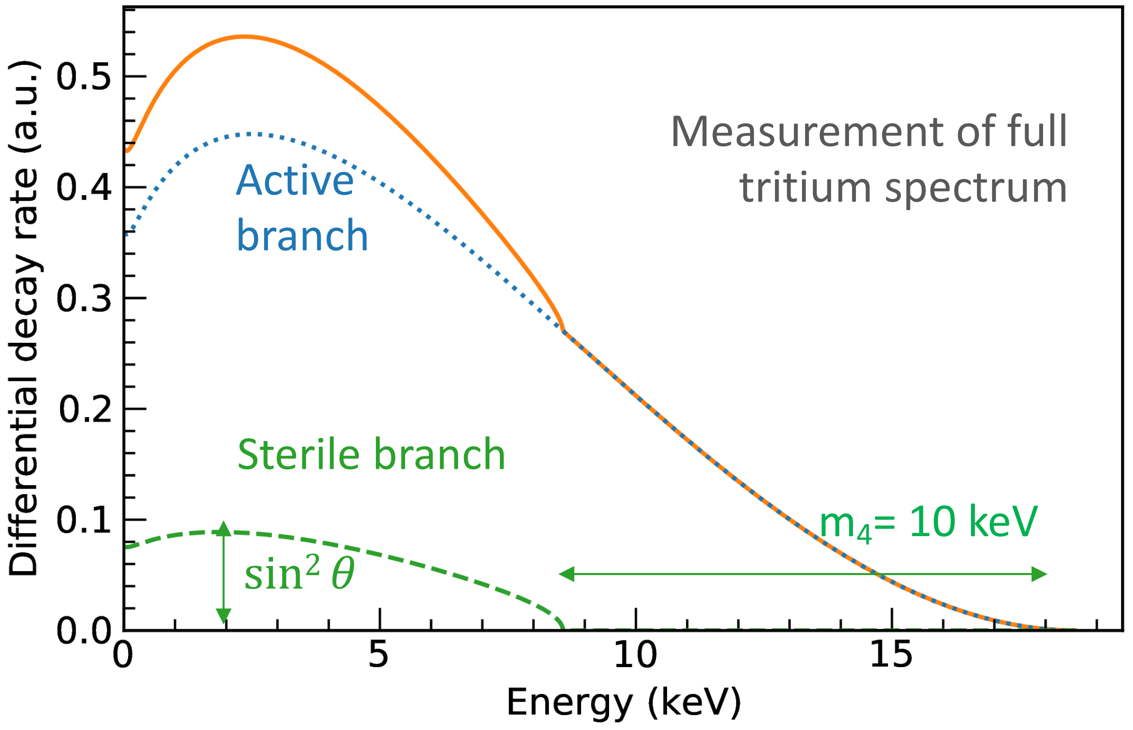


- ✓ Tritium decays into an electron and an electronic antineutrino
- ✓ The precise measurement of the electron energy spectrum allows to search for neutrino in the keV mass range

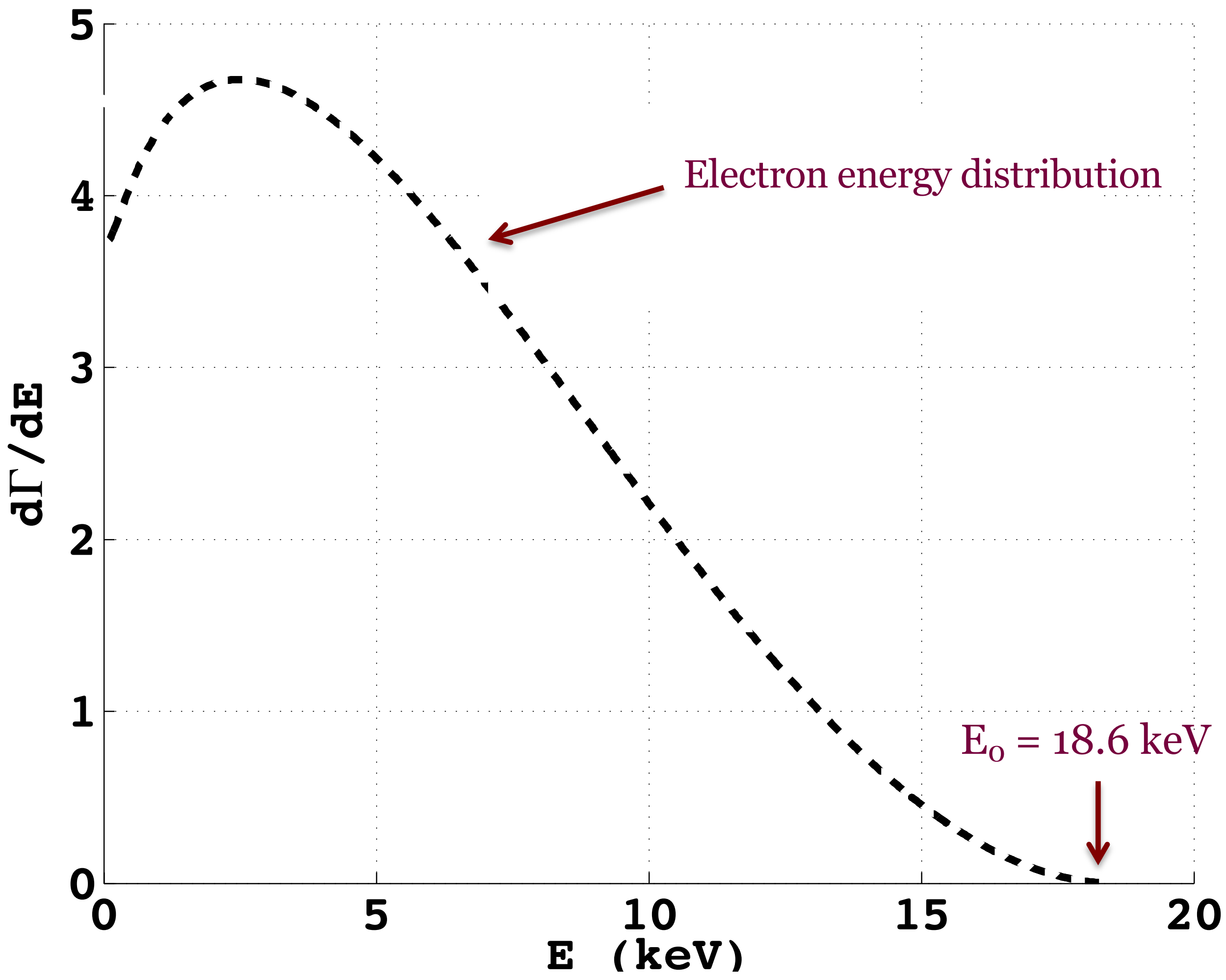
Beta-decay experiments



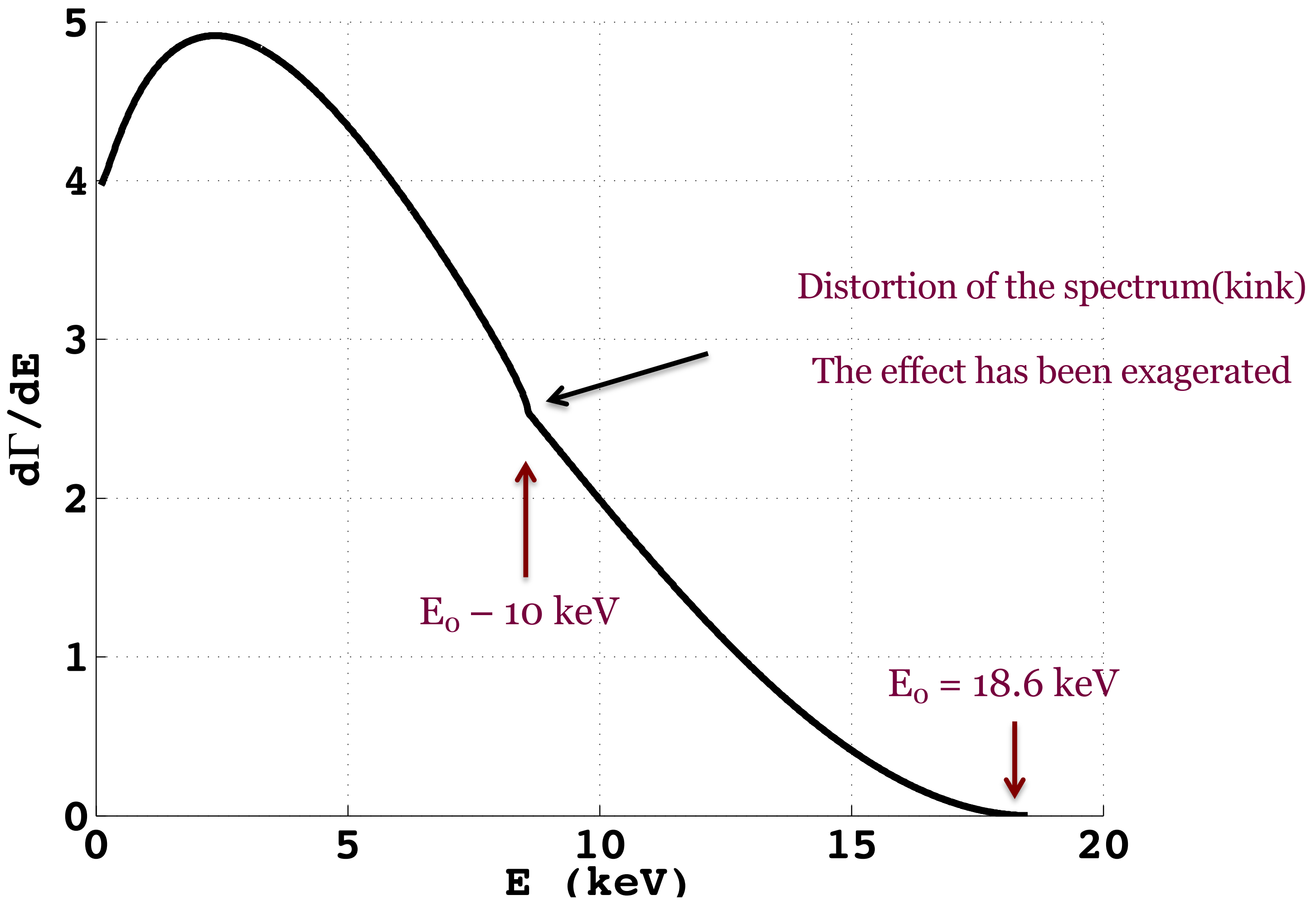
$$\frac{d\Gamma}{dE} = \cos^2\theta \frac{d\Gamma}{dE}(m_\beta) + \sin^2\theta \frac{d\Gamma}{dE}(m_4)$$



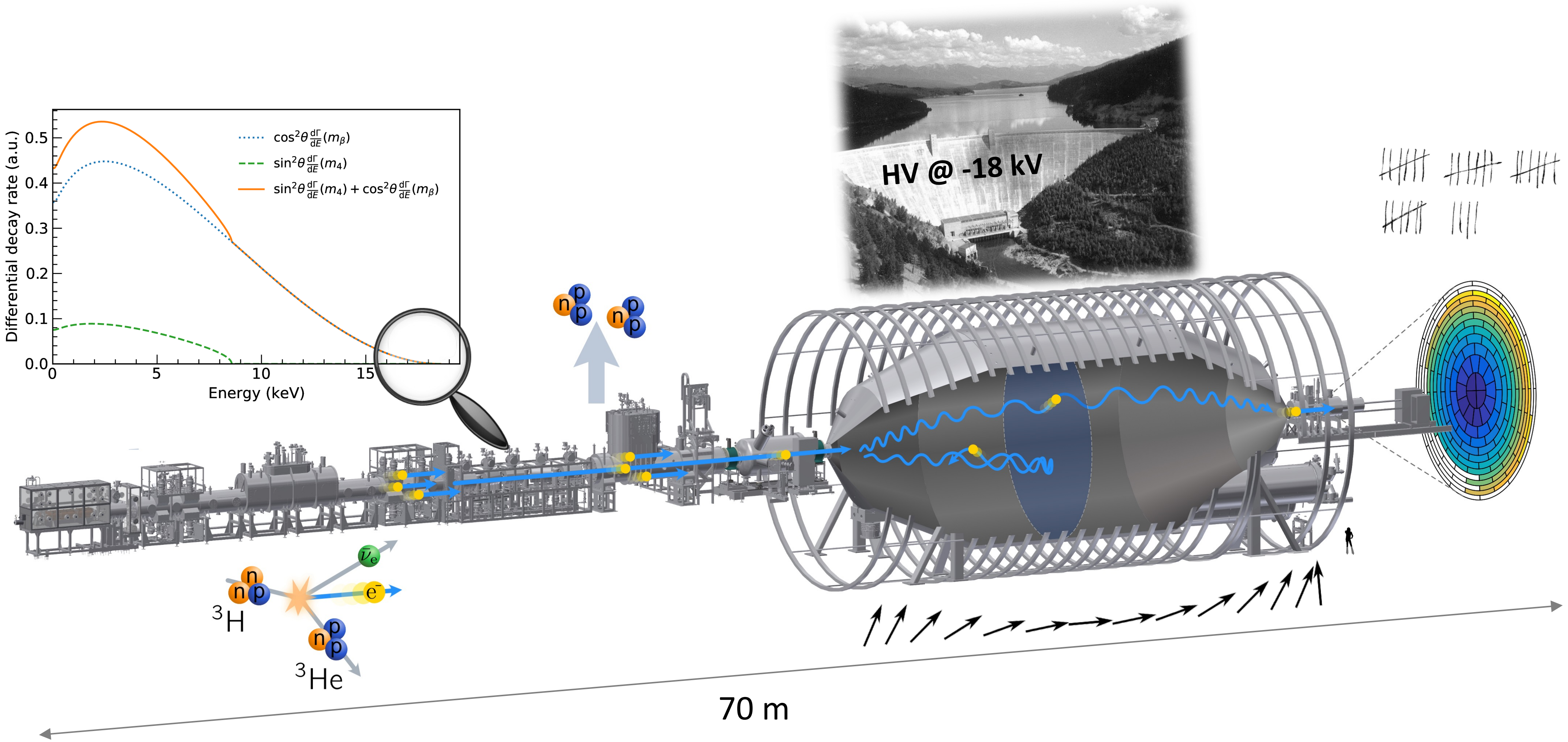
Expected signal without keV neutrino



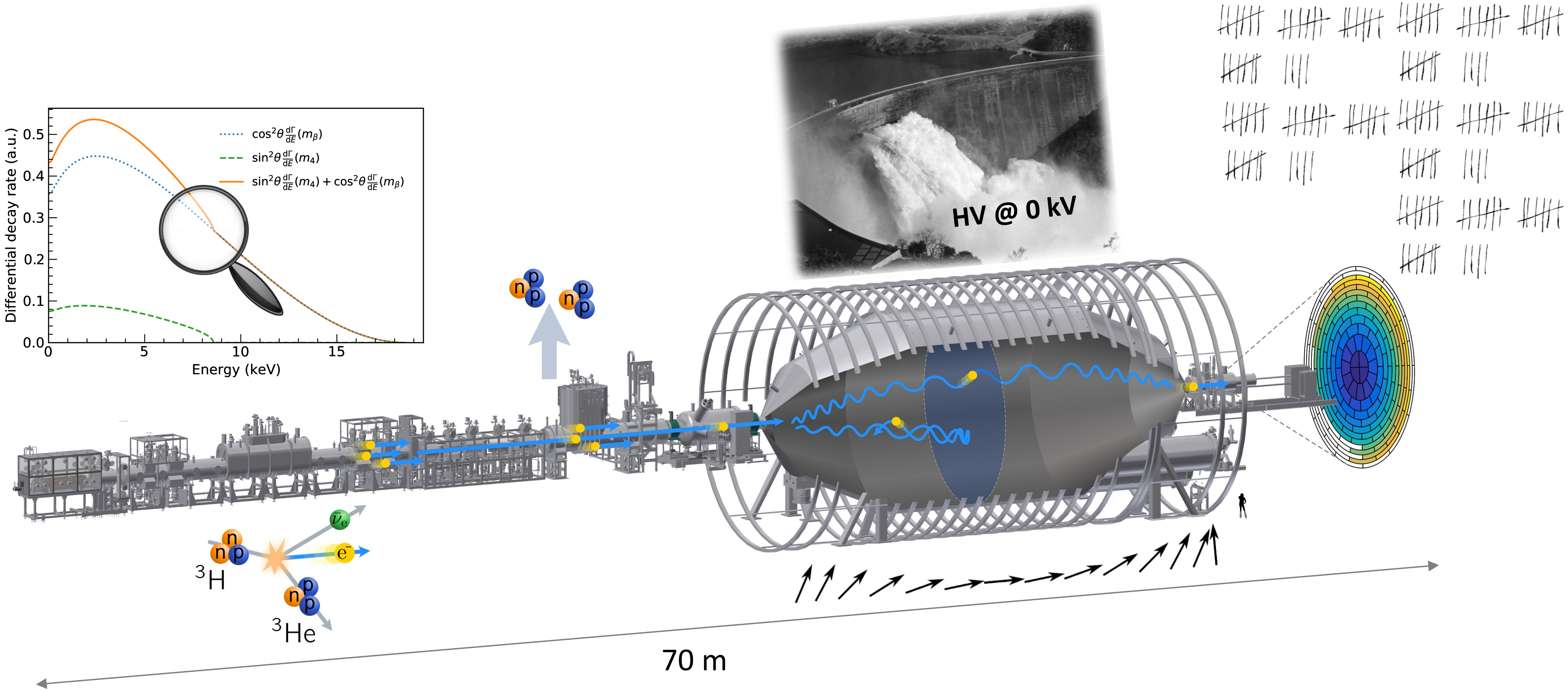
Expected signal with a 10 keV Sterile Neutrino



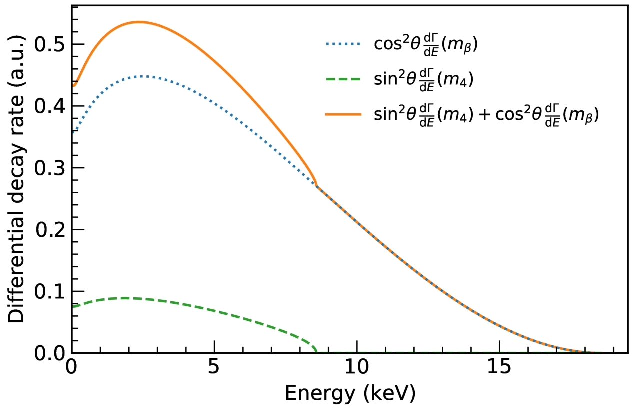
The KATRIN experiment



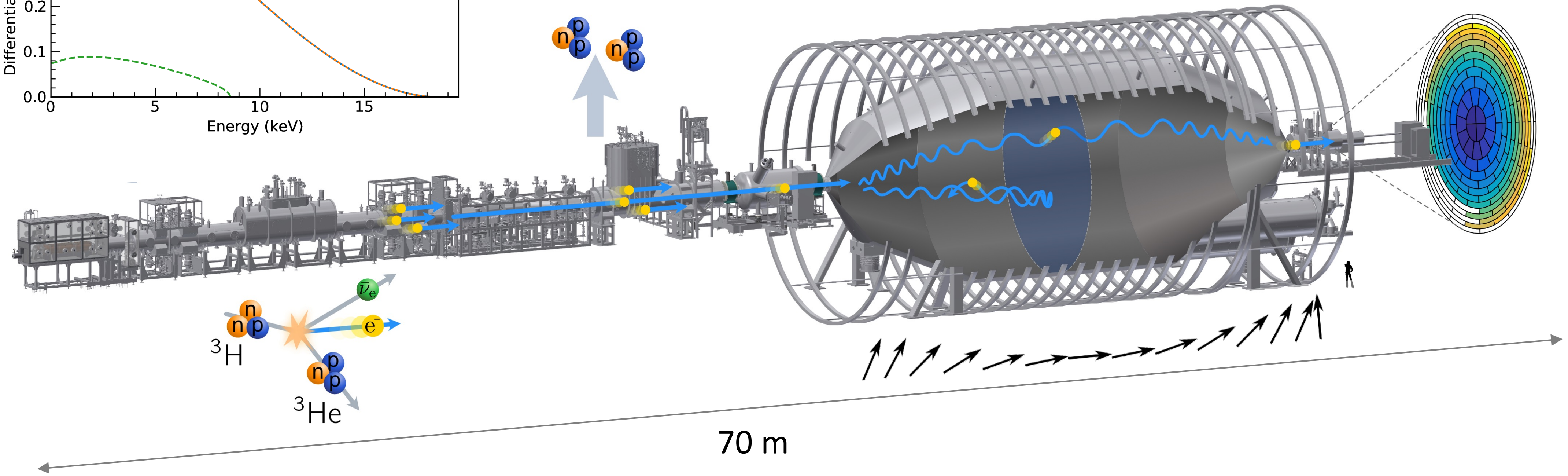
Measurement with KATRIN: the challenge



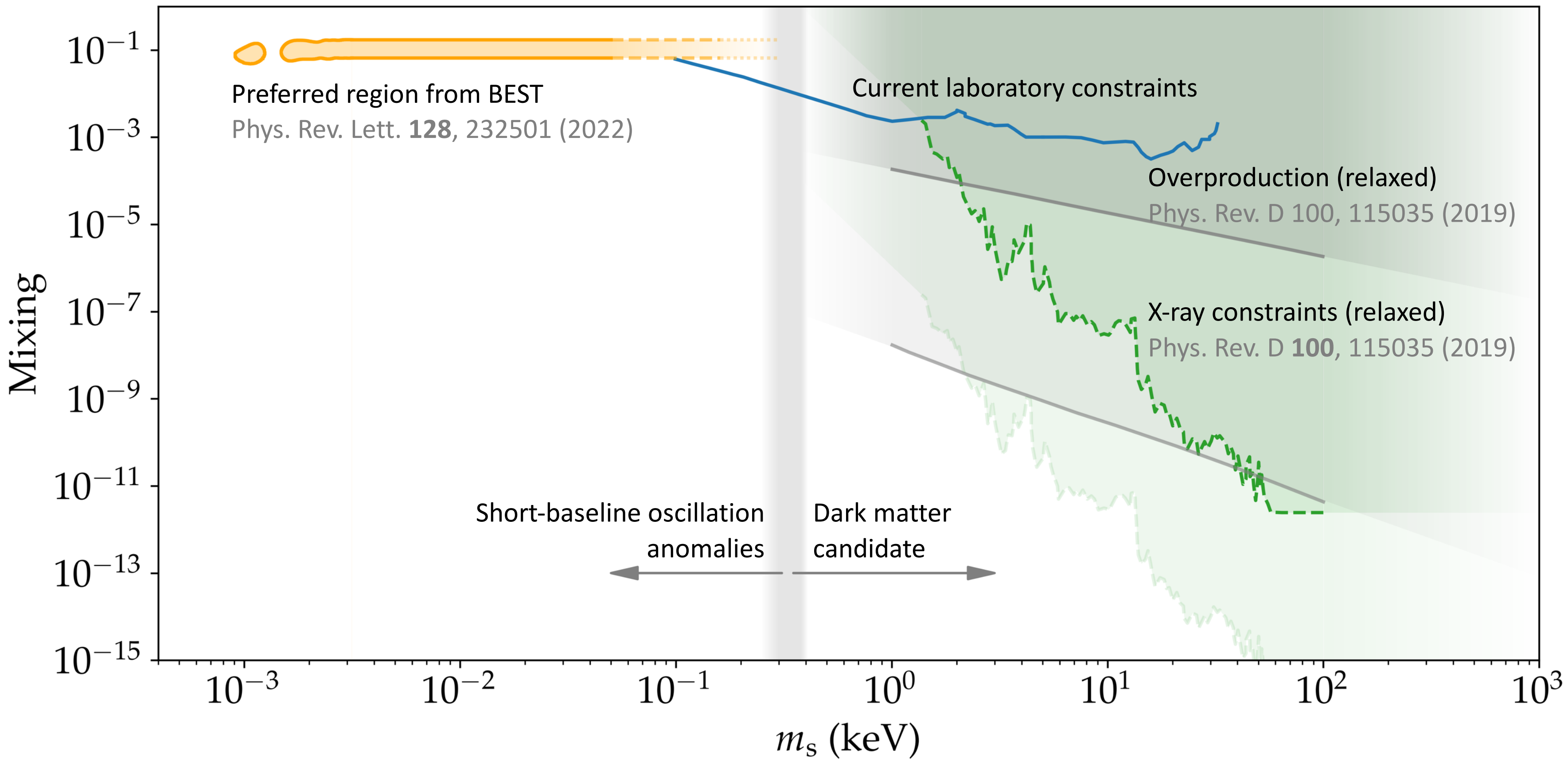
Measurement with KATRIN: the challenge



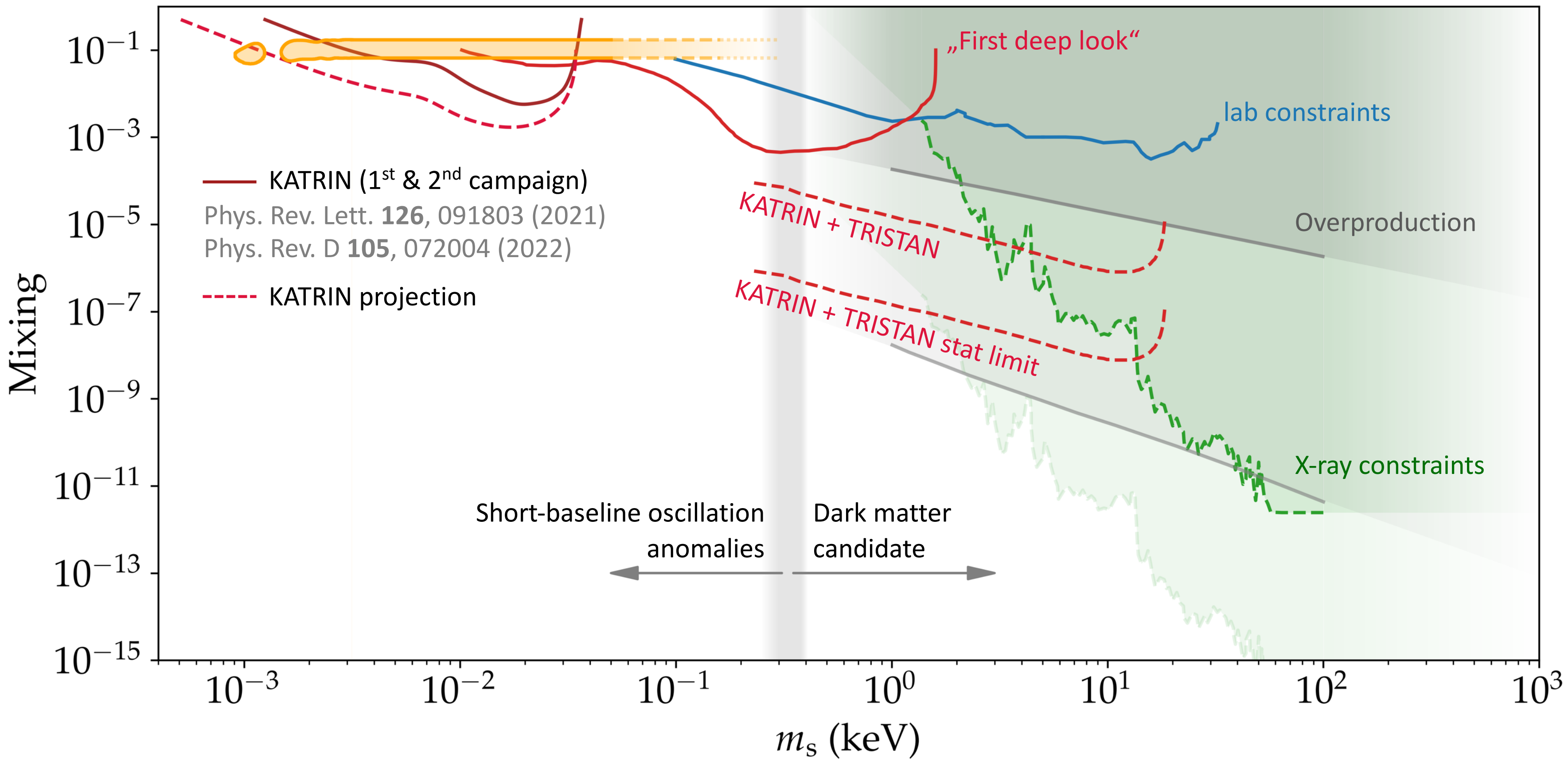
- Less tritium activity
  KATRIN, arxiv 2207.06337 (2022)
- New focal plane detector
  Mertens et al, J. Phys. G46 (2019)



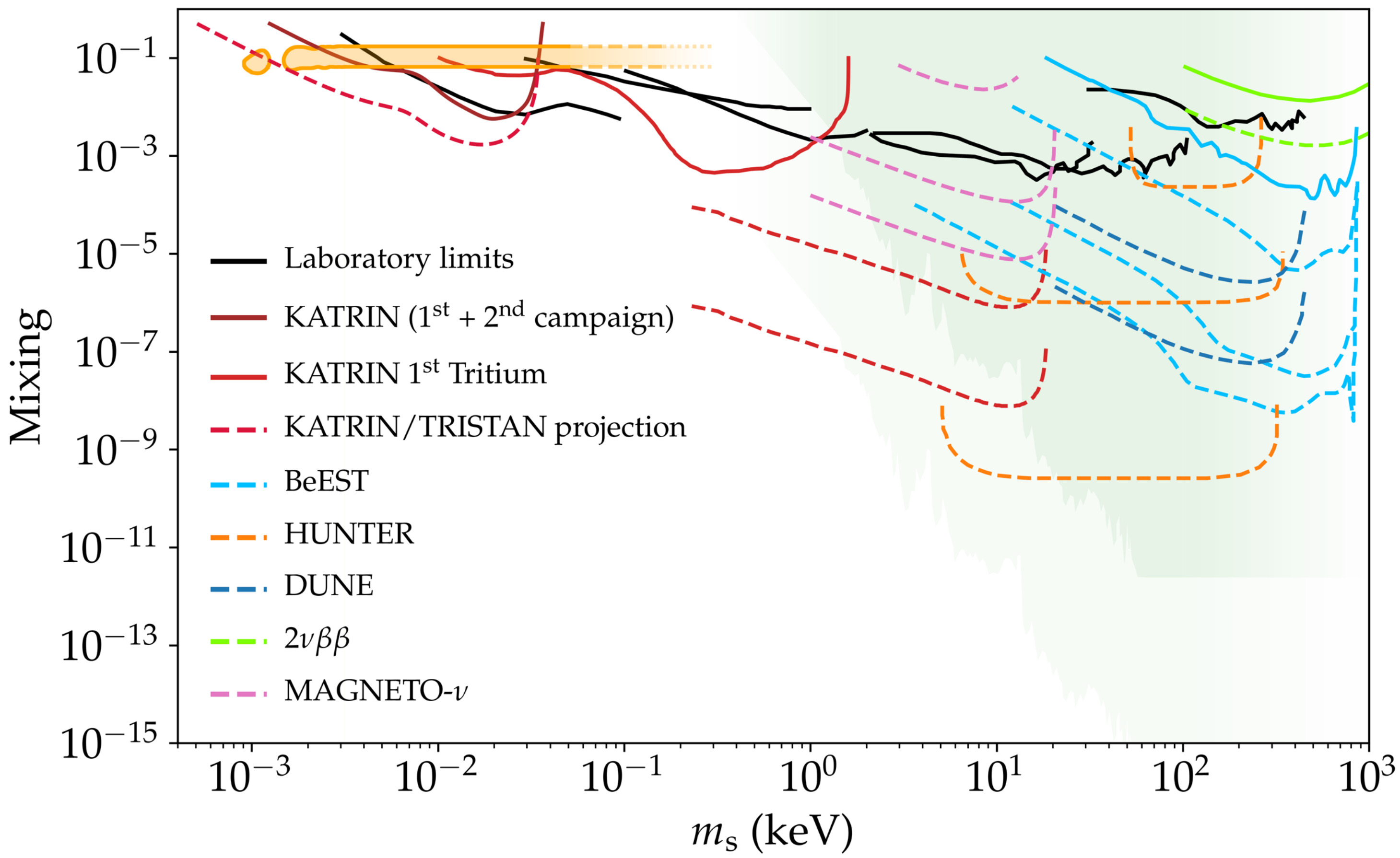
KATRIN/TRISTAN sensitivity to steriles



KATRIN/TRISTAN sensitivity to steriles



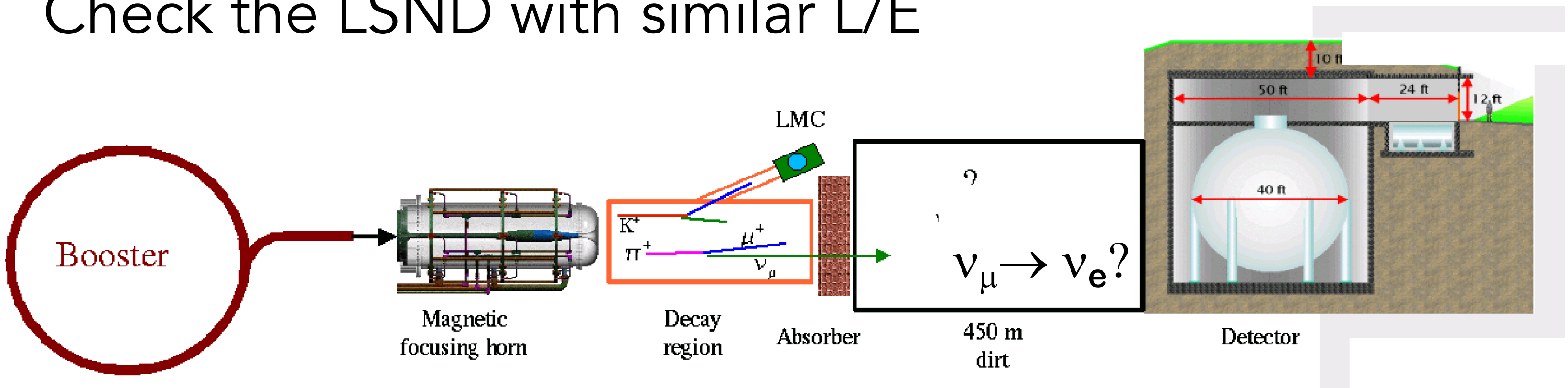
Overview eV-keV-sterile hunt

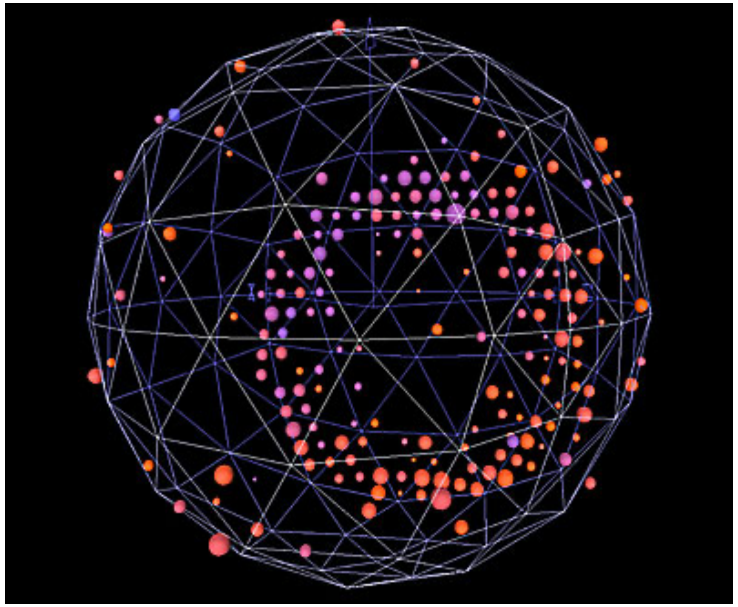


Backup

MiniBooNE (FNAL)

Primary goal: look for $\boldsymbol{\nu}_e$ appearance in a $\boldsymbol{\nu}_\mu$ beam
Check the LSND with similar L/E



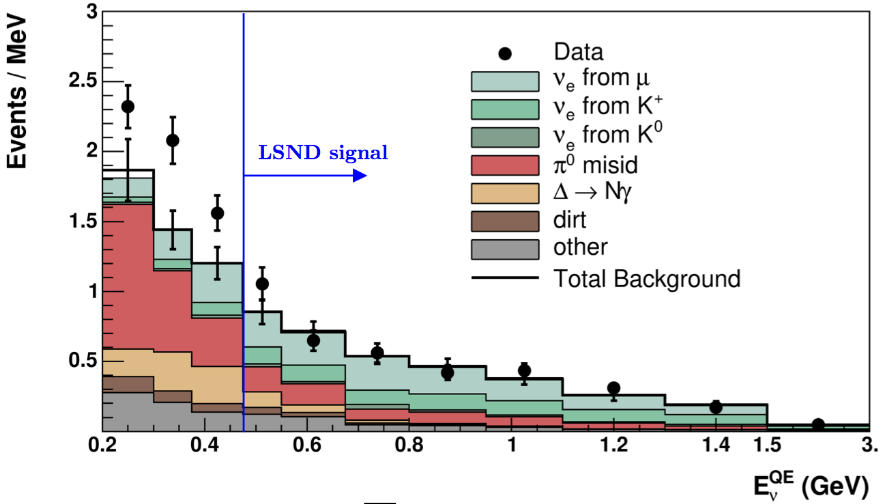


- Beam: π^+ (π^-) decay in flight
- Detection: Cherenkov + scintillation
- L/E ≈ 1 m / MeV
  - Baseline: 541 m
  - 200 < E (MeV) < 3000

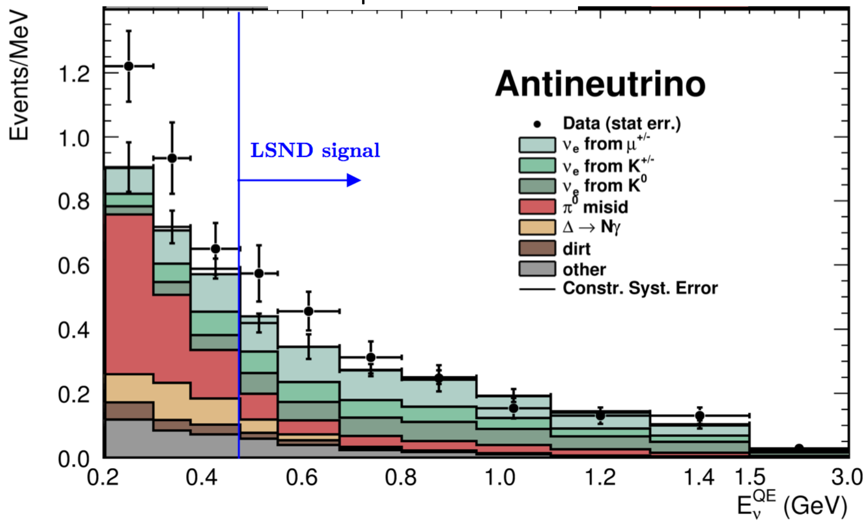
MiniBooNE old-Results

- Results published from 2007-12
- Channel: (anti-)$\nu_\mu \rightarrow$ (anti-) ν_e
- Detection: ν_e (p)n → e p (CCQE)
- Results:
  - An overall 3.8$\boldsymbol{\sigma}$ excess Mostly at low energy
- Backgrounds?
  - But MiniBooNE can't differentiate between electrons and gammas!
- not conclusive…

$\nu_\mu \rightarrow \nu_e$



$\overline{\nu}_\mu \rightarrow \overline{\nu}_e$



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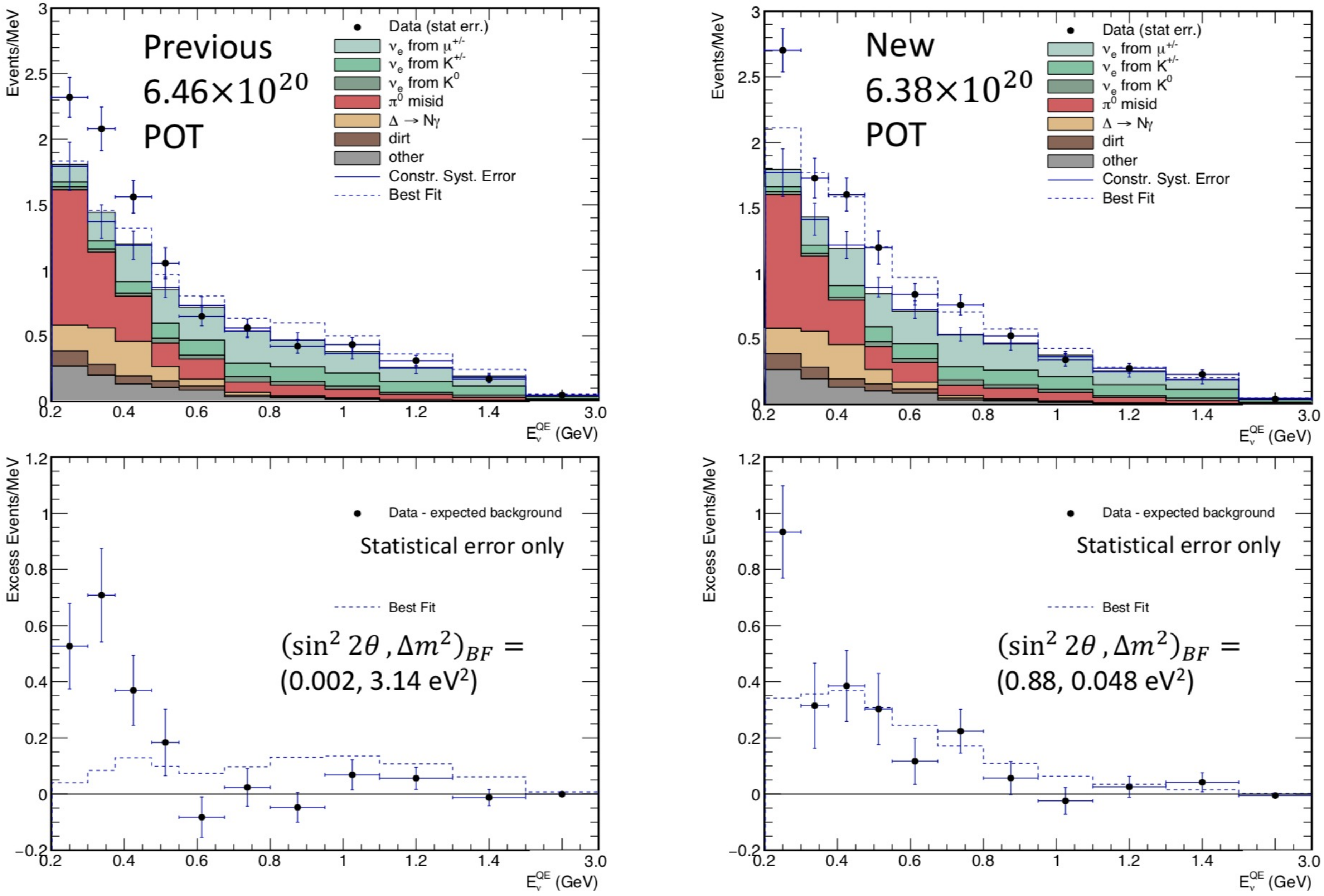
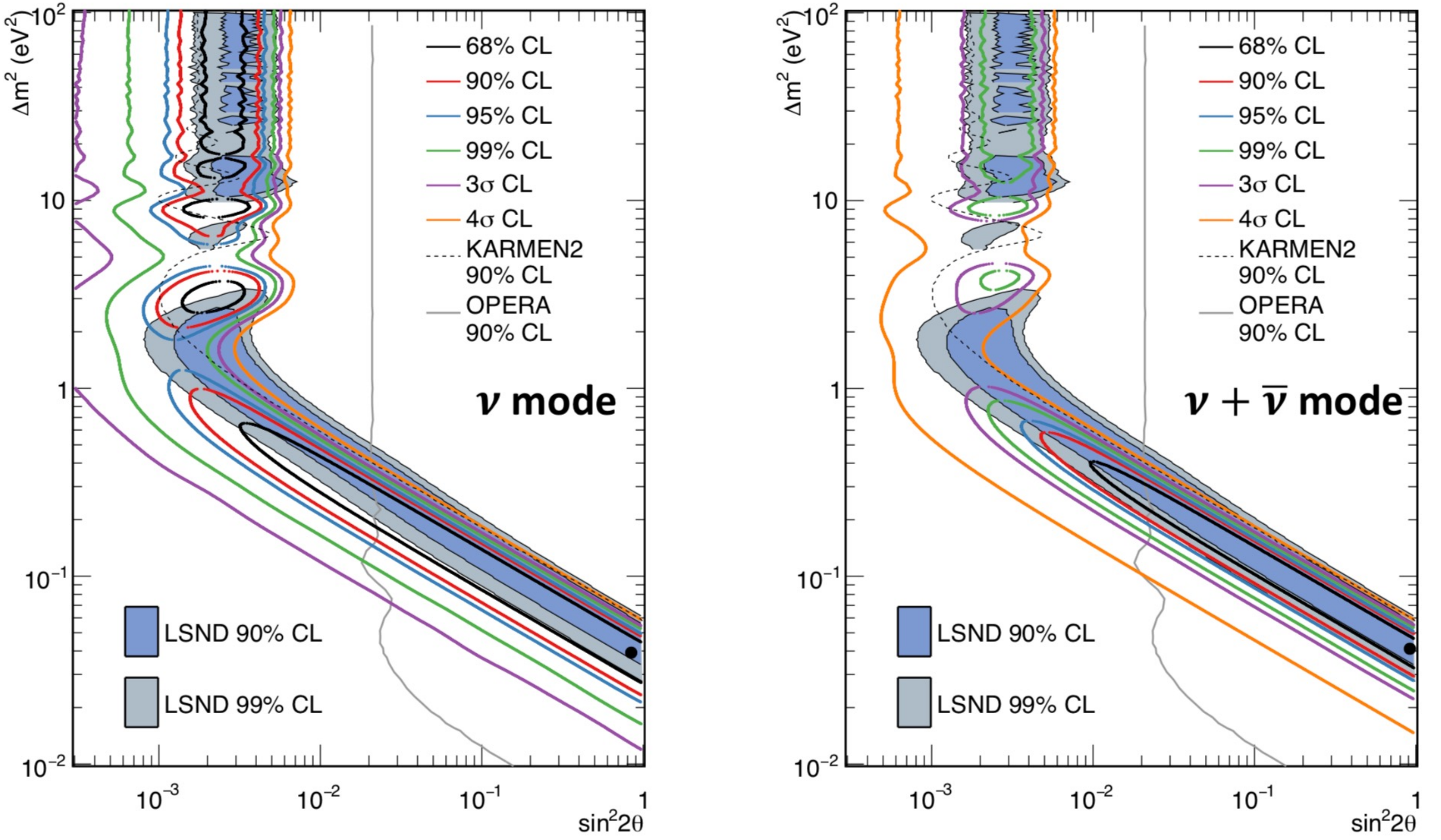
MiniBooNE new-Results in 2018



MiniBooNE allowed regions



$(\Delta m^2, \sin^2 2\theta) = (0.037\ \text{eV}^2, 0.958)$
$\chi^2/ndf = 10.0/6.6$ (prob = 15.4%)

$(\Delta m^2, \sin^2 2\theta) = (0.041\ \text{eV}^2, 0.958)$
$\chi^2/ndf = 19.5/15.4$ (prob = 20.1%)