Sterile neutrinos and experimental searches for their existence

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International Workshop on “Double Beta Decay and Underground Science”

November 2016, Osaka, Japan

$\Delta p \cdot \Delta q \geq \frac{1}{2}\hbar$

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Outline

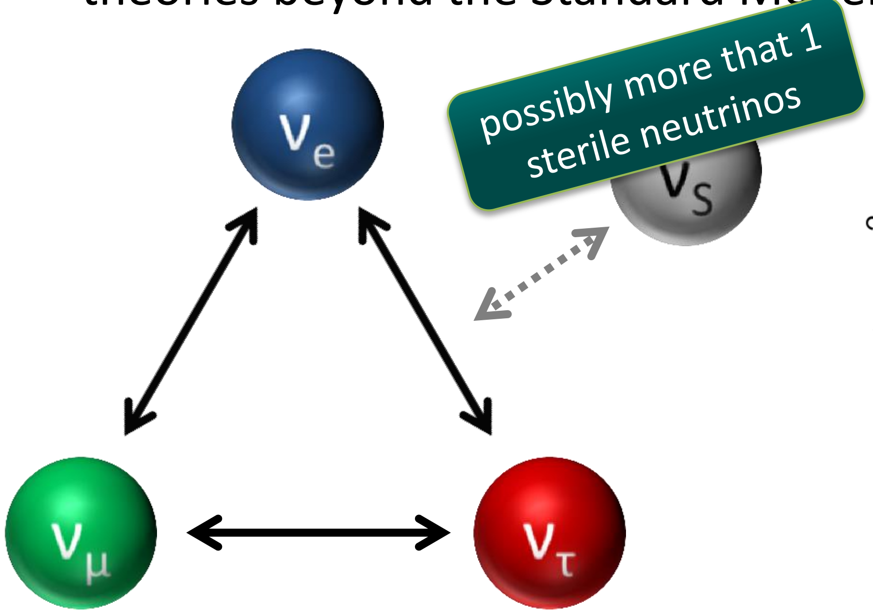
- what is a sterile neutrino?

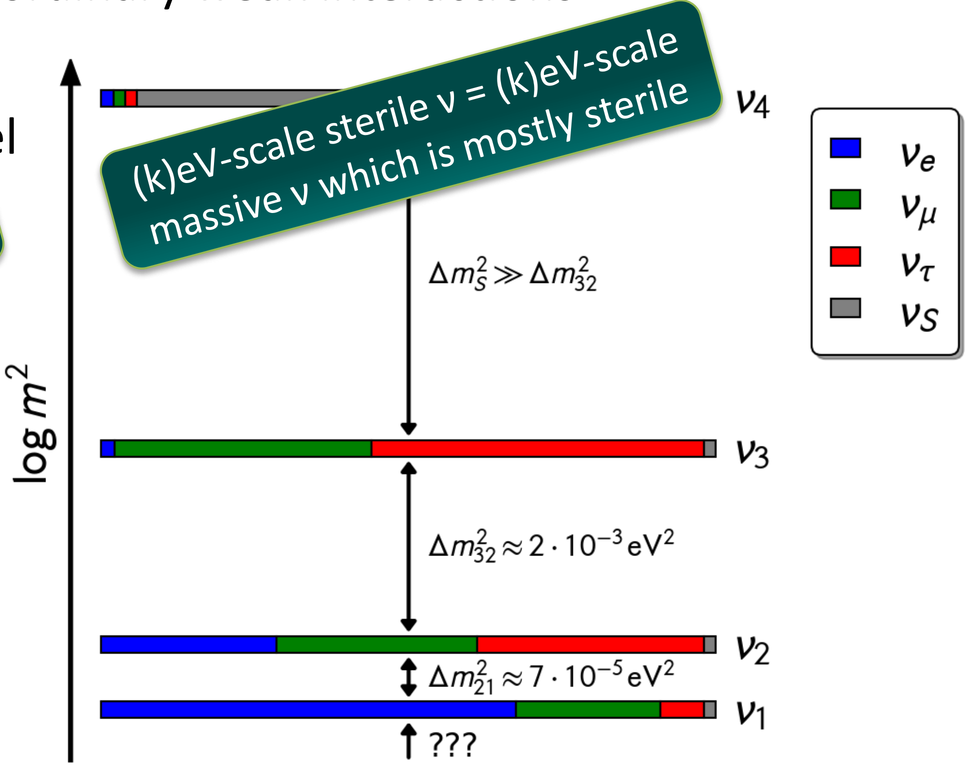
- motivation for possible **eV**- and **keV-**scale sterile neutrinos
- experimental searches for sterile ν

- conclusion and outlook

What is a sterile neutrino?

- hypothetical neutral lepton with no ordinary weak interactions
- can mix with active neutrinos
- theories beyond the Standard Model





Sterile neutrinos at the eV-scale

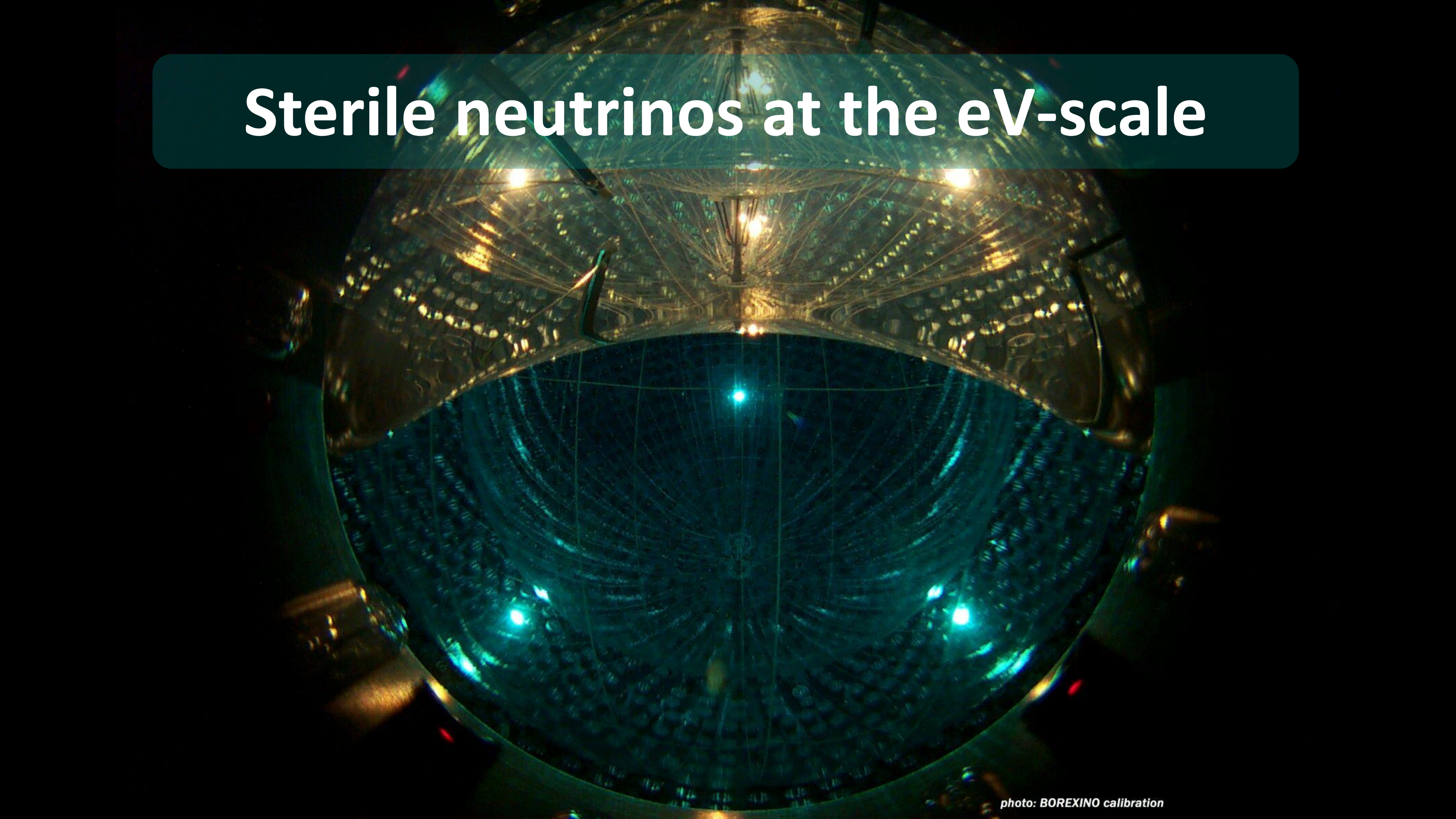


photo: BOREXINO calibration

Motivation for eV-scale sterile neutrinos

- eV-scale sterile neutrinos as possible explanation for several experimental “anomalies“ = observations not compatible with the 3-flavor ν mixing

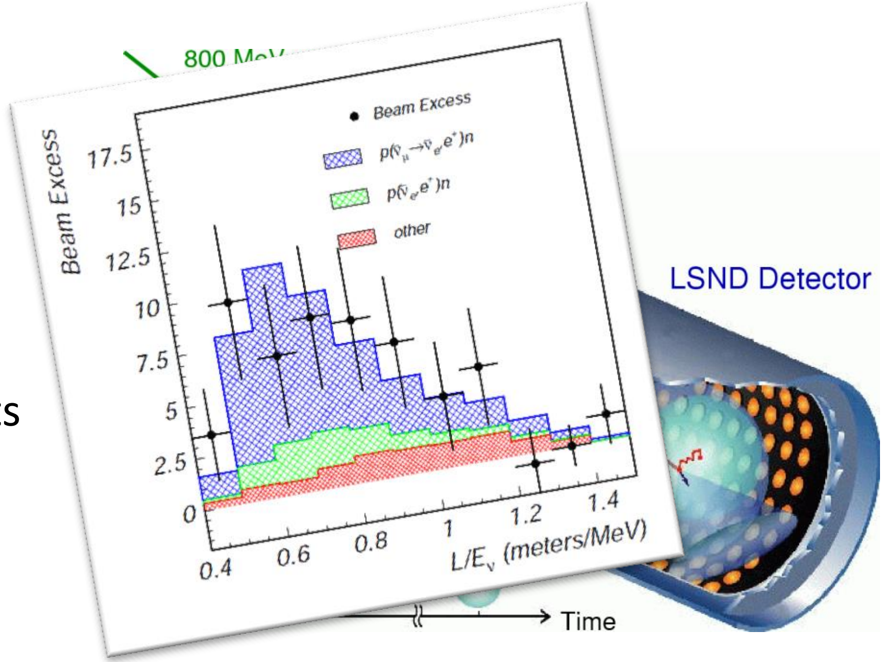
short-baseline
accelerator experiments

LSND: $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$

- pion beam dump, 30 m baseline
- excess of events above expectation
- not clarified by other similar experiments

- possible interpretation: ν oscillation

$$\Delta m_S^2 \gtrsim 0.2 \text{ eV}^2 \gg m_{\text{atm}}^2$$



Motivation for eV-scale sterile neutrinos

- eV-scale sterile neutrinos as possible explanation for several experimental “anomalies“ = observations not compatible with the 3-flavor ν mixing

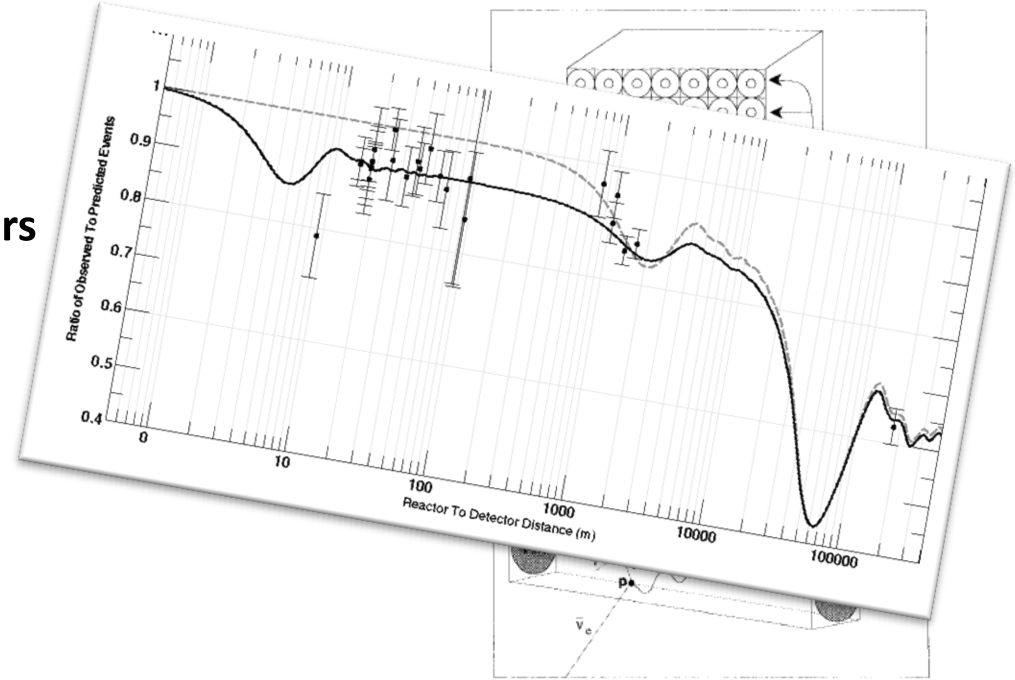
short-baseline
reactor experiments

disappearance of $\bar{\nu}_e$ from nuclear reactors

- rate theoretically, baseline < 100 m
- deficit of observed events
- realiability of calculation?

- possible interpretation: ν oscillation

$$\Delta m_S^2 \gtrsim 0.5\ \mathrm{eV}^2 \gg m_{\mathrm{atm}}^2$$



Motivation for eV-scale sterile neutrinos

- eV-scale sterile neutrinos as possible explanation for several experimental “anomalies“ = observations not compatible with the 3-flavor ν mixing

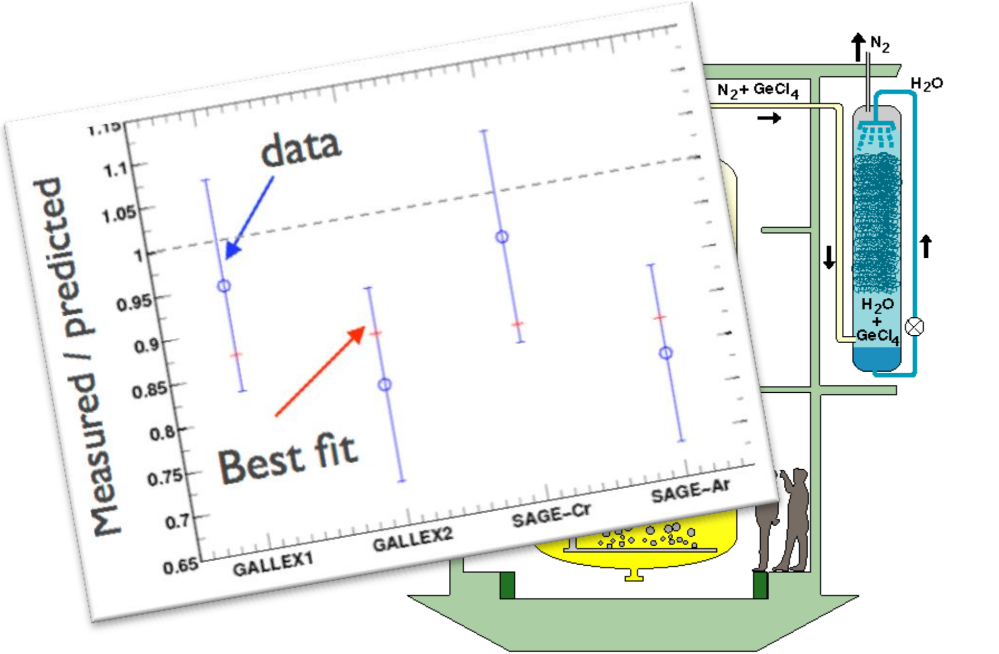
radiochemical experiments

calibrations of solar ν_e detectors

- mono-energetic ν_e from ^{51}Cr, ^{37}Ar
- smaller number of measured events
- uncertainties in cross-sections?

- possible interpretation: ν oscillation

$$\Delta m_S^2 \gtrsim 1\ \text{eV}^2 \gg m_{\text{atm}}^2$$



Resolving the anomalies

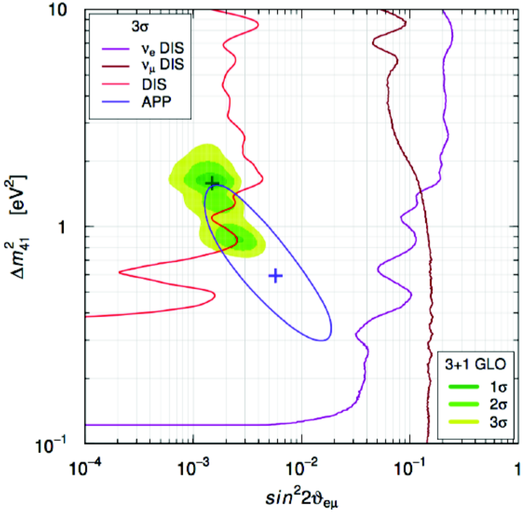
short-baseline accelerator experiments

short-baseline reactor experiments

radiochemical experiments

$\Delta m_S^2 \sim 1\ \mathrm{eV}^2$
$\sin^2 2\theta_S \sim 0.01$

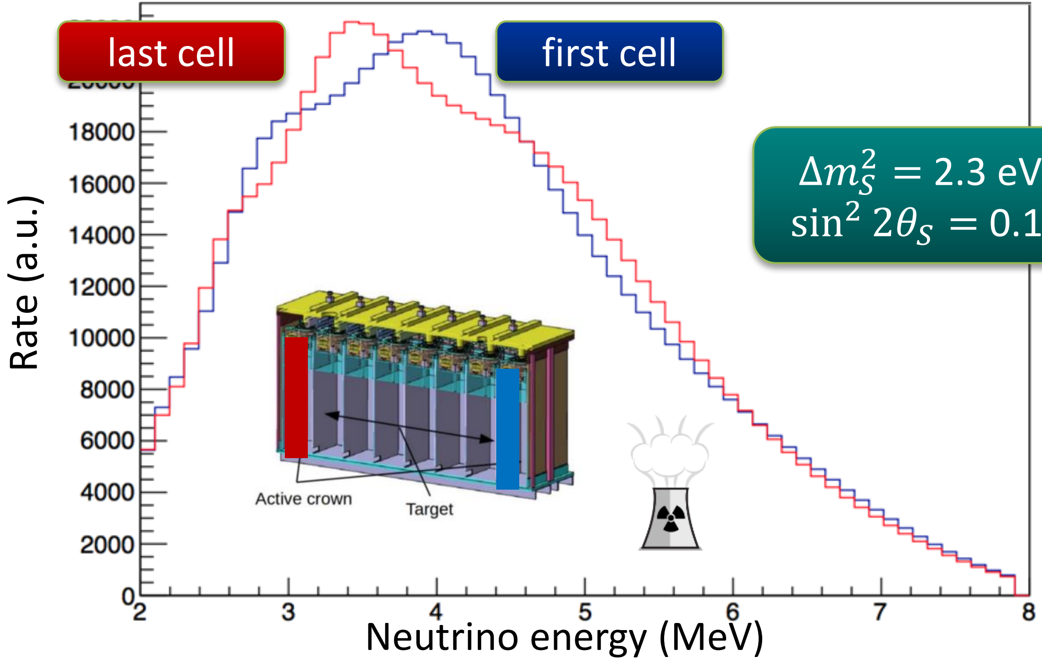
- tension with limits derived from other app. or disapp. searches → need more data!
- search for L/E oscillation pattern, complement with integral rate measurement
- compact source < 1 m, vertex resolution << 1 m
- few % statistical & systematic uncertainties



Search for eV-scale sterile ν at reactors

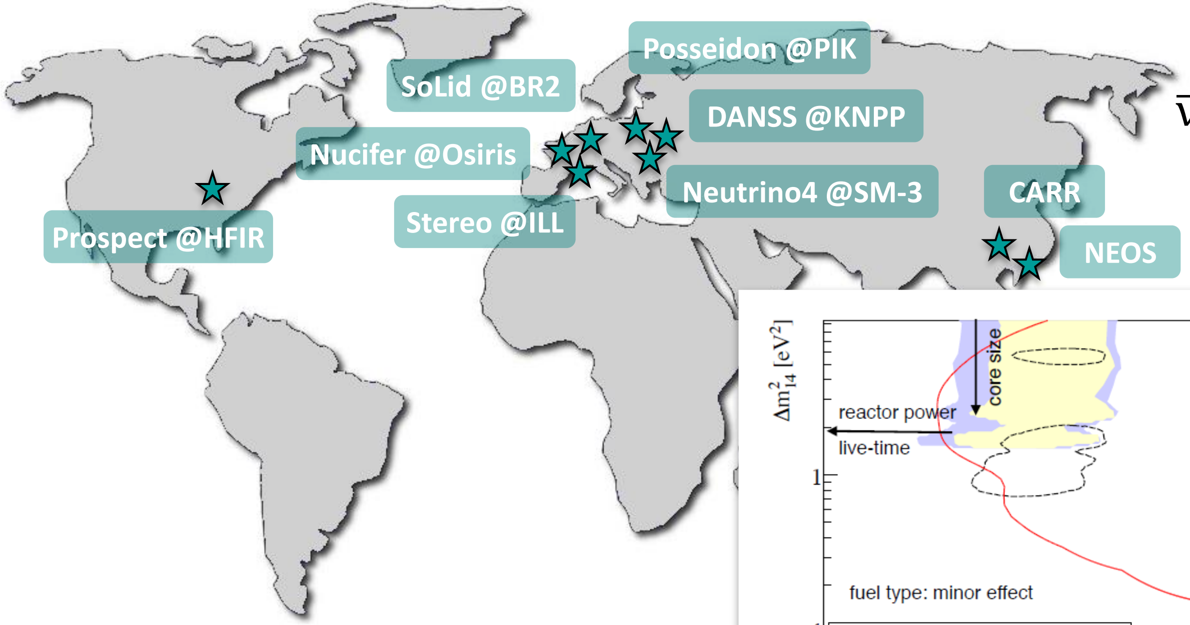
- for $\Delta m_S^2 \sim 1$ eV² and $E \sim 1$ to 8 MeV → $L < 10$ m → very short baselines

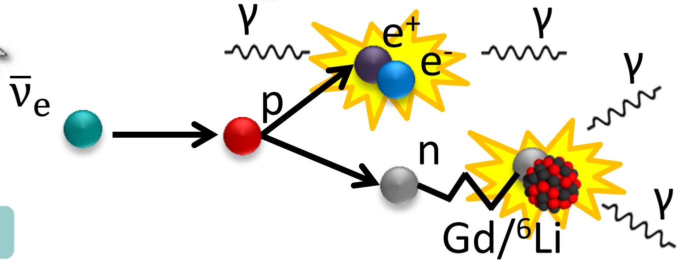
- measurement of relative reactor flux and spectrum at different baselines
- ➢ independent of reactor models/predictions
- compact core: research reactors
- background:
  - shallow overburden
  - fast neutrons, high-energy gammas

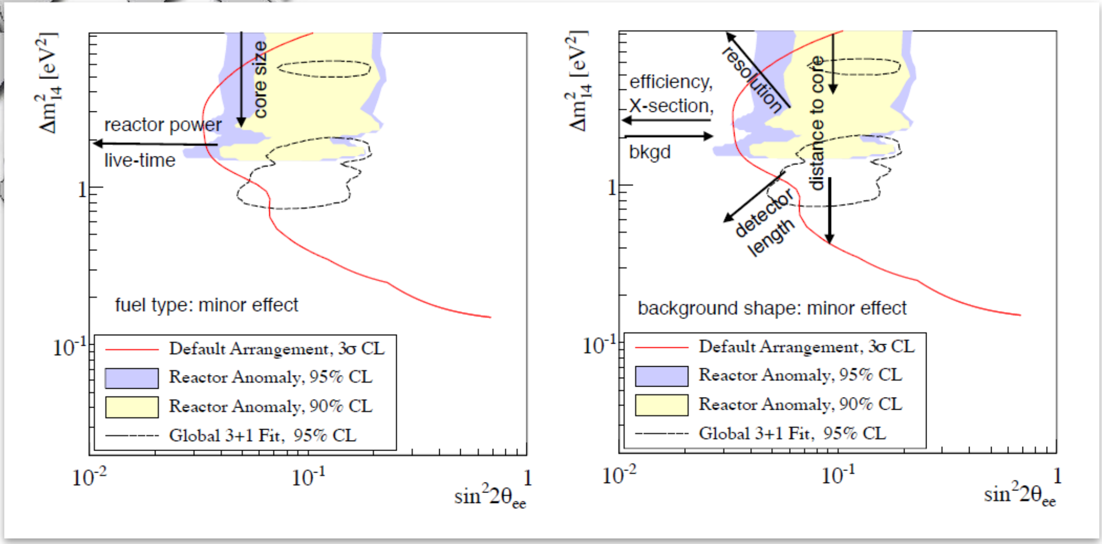


$\Delta m_S^2 = 2.3$ eV²
$\sin^2 2\theta_S = 0.17$

Search for eV-scale sterile ν at reactors





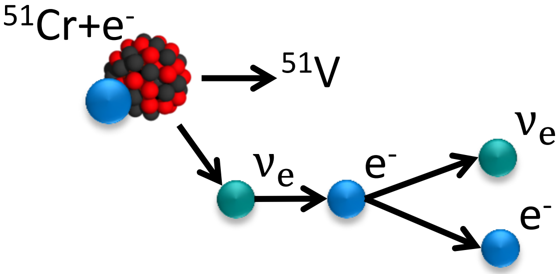


experiments being set up or running → timescale 3 years

Search for eV-scale sterile ν with RA sources

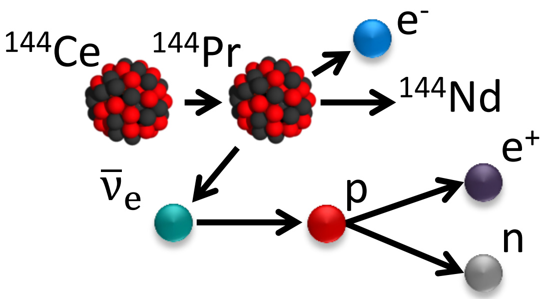
- utilize intense RA sources with detectors capable of resolving L/E pattern

electron capture → monoenergetic ν_e



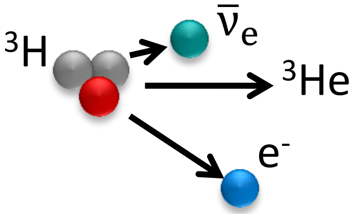
- low cross section, sensitive to background
- irradiation in reactor
- ^{51}Cr: SOX-Cr, BEST
- ^{37}Ar: RICOCHET

β$^-$-decay → continuous energy $\bar{\nu}_e$



- higher cross section, effective tagging
- abundant fission product
- CeLAND, CeSOX

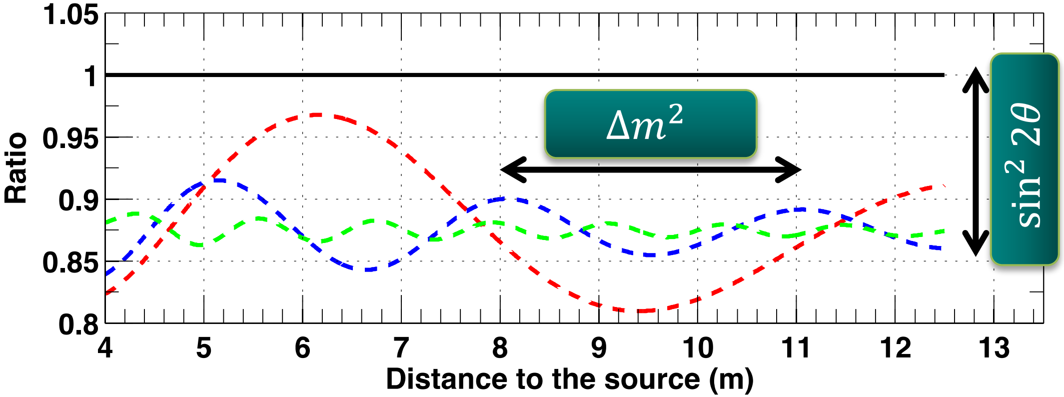
tritium decay → imprint on electron spectrum

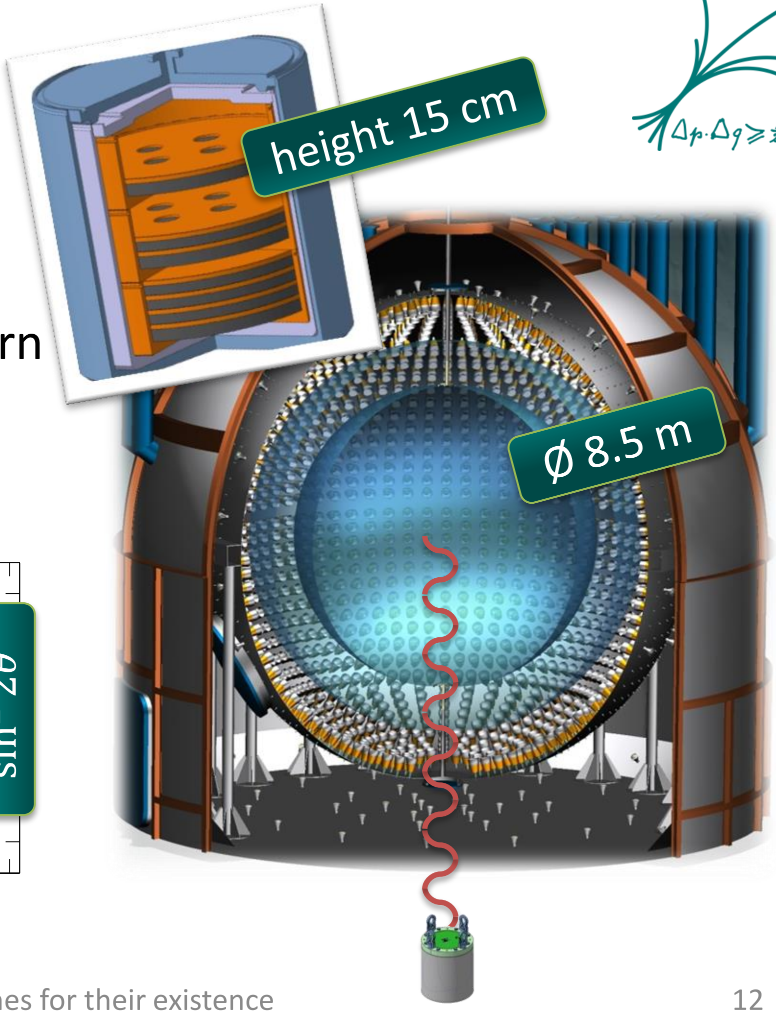


- super-allowed transition, low Q-value
- good spectrum description
- KATRIN, PROJECT 8

Concept of CeSOX

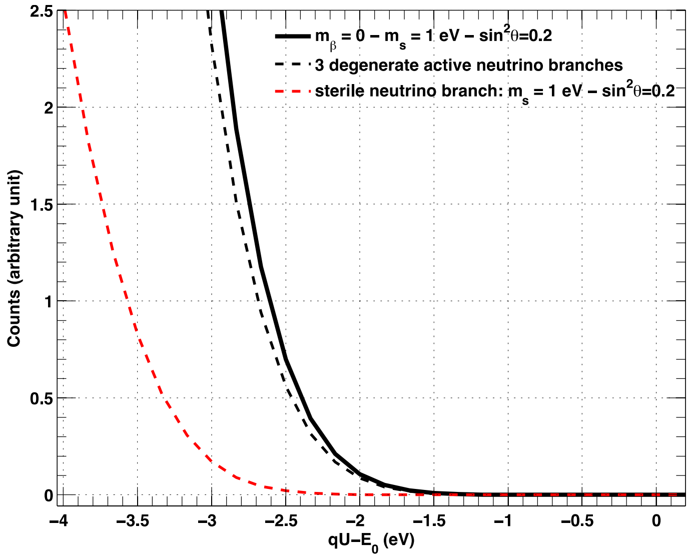
- Borexino detector + ^{144}Ce-^{144}Pr source
- 5 PBq in a special capsule
- ➢ shape: search for a neutrino oscillation pattern
- ➢ rate+shape: include ratio of observed to expected rate

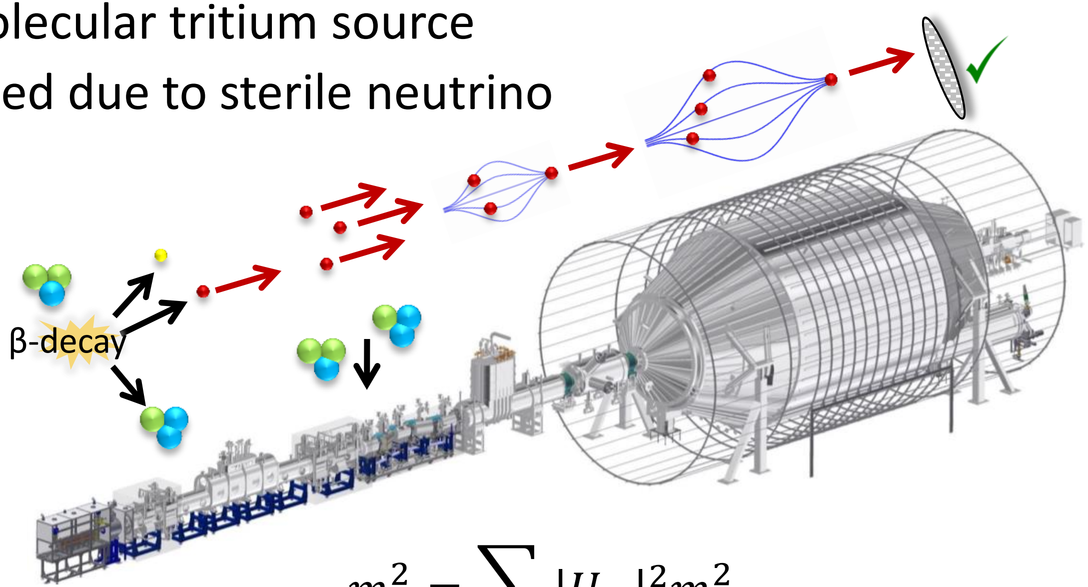




Concept of KATRIN

- precision measurement of tritium β-decay electron spectrum shape
- intense windowless gaseous molecular tritium source
- close to endpoint: shape modified due to sterile neutrino





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

$$\approx \cos^2(\theta)\, m_{\text{light}}^2 + \sin^2(\theta)\, m_{\text{heavy}}^2$$

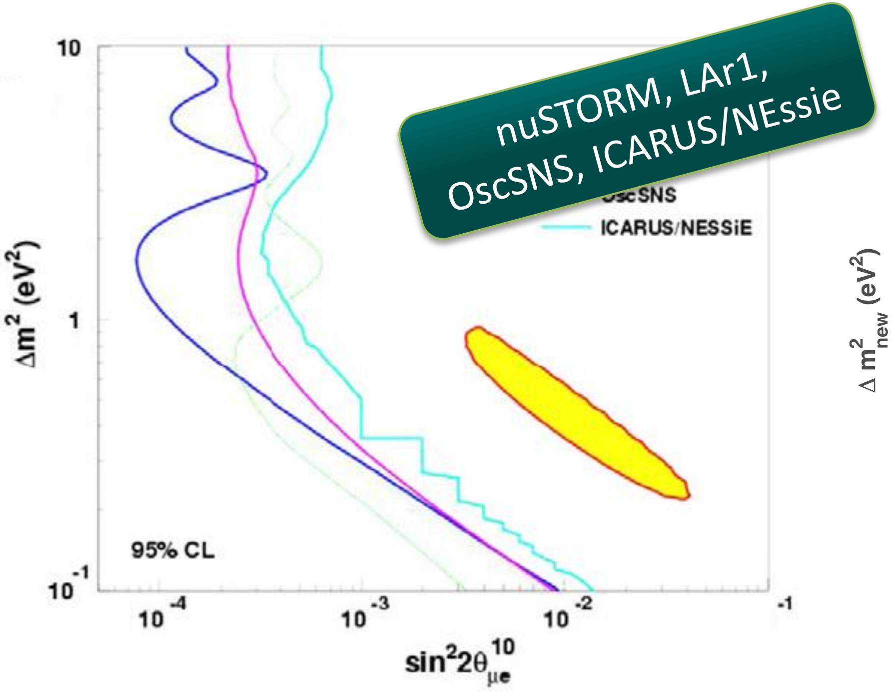
Search for eV-scale sterile ν using accelerators

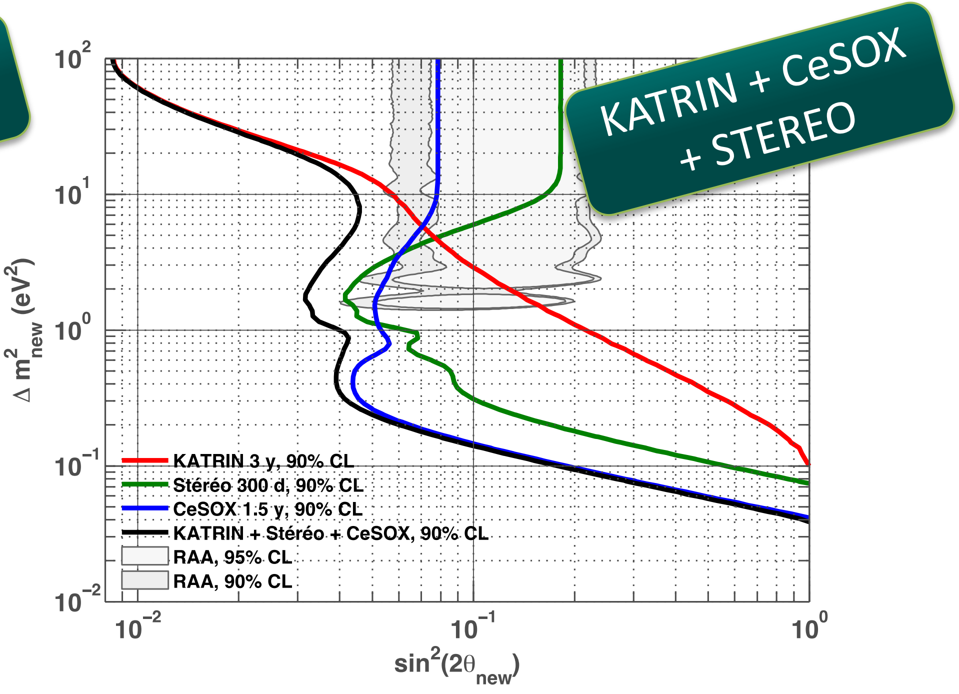
- for $\Delta m_S^2 \sim 1\ \mathrm{eV}^2$ and $E \sim$ GeV → $L < 10$ km → short baseline

type	source	appearance / disappearance	oscillation channels	projects
isotope decay at rest	$p + {}^9Be \rightarrow {}^8Li + 2p$ $n + {}^7Li \rightarrow {}^8Li$ ${}^8Li \rightarrow {}^9Be + e^- + \bar{\nu}_e$	dis.	$\bar{\nu}_e \rightarrow \bar{\nu}_e$	IsoDAR
pion (kaon) decay at rest	$\pi^+ \rightarrow \mu^+\nu_\mu$ $\rightarrow e^+\bar{\nu}_\mu\nu_e$	app. & dis.	$\bar{\nu}_\mu \rightarrow \bar{\nu}_e, \nu_e \rightarrow \nu_e$	OscSNS, KDAR, JPARC-MLF
pion decay in flight	$\pi^+ \rightarrow \mu^+\nu_\mu$ $\rightarrow e^+\bar{\nu}_\mu\nu_e$	app. & dis.	$\nu_\mu \rightarrow \nu_e, \bar{\nu}_\mu \rightarrow \bar{\nu}_e$ $\nu_\mu \rightarrow \nu_\mu, \nu_e \rightarrow \nu_e$	nuPRISM, SBN
low-energy neutrino factory	$\mu^+ \rightarrow e^+\bar{\nu}_\mu\nu_e$ $\mu^- \rightarrow e^-\nu_\mu\bar{\nu}_e$	app. & dis.	$\nu_e \rightarrow \nu_\mu, \bar{\nu}_e \rightarrow \bar{\nu}_\mu$ $\nu_\mu \rightarrow \nu_\mu, \bar{\nu}_e \rightarrow \bar{\nu}_e$	νSTORM

Interplay of different experiments

- ~~competitive~~ **complementary** ways to confirm / rule out eV-scale sterile ν



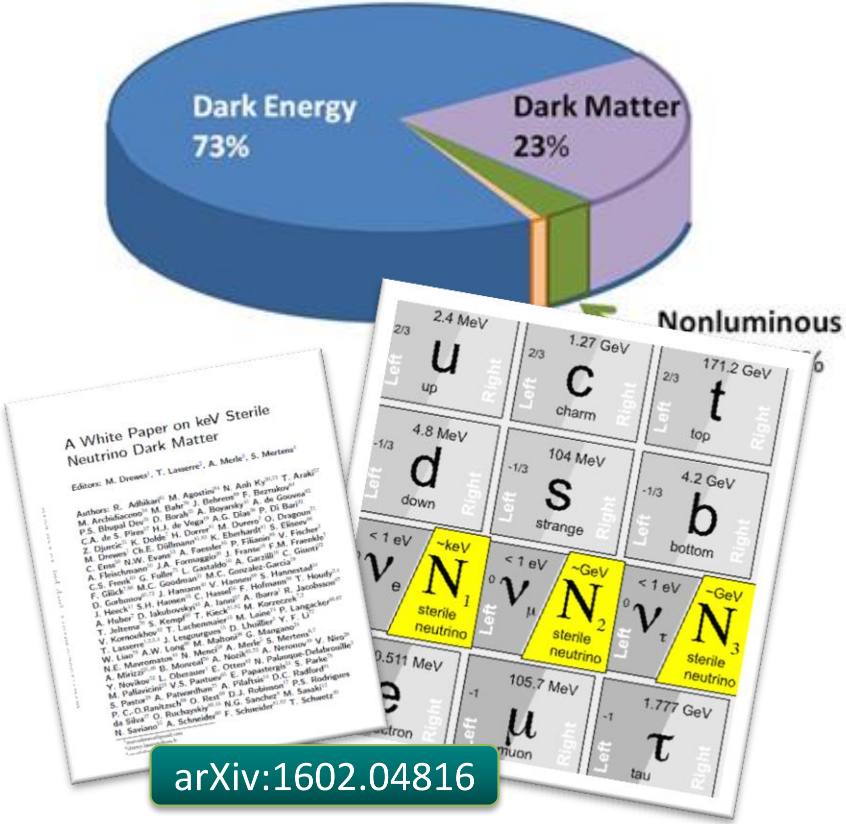


Sterile neutrinos at the keV-scale

Motivation for keV-scale sterile neutrinos

Energy content of the Universe

- need of non-baryonic dark matter
- active neutrinos only < few %
- 95 % of the Universe‘s content not understood



arXiv:1602.04816

Physics beyond the Standard Model

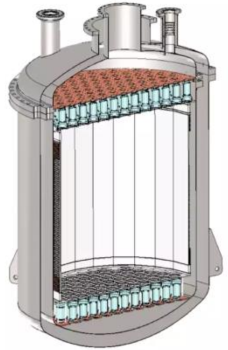
- ν-minimal SM: minimal extension to solve a maximal number of open questions
- N_1 in keV region: dark matter
- N_2, N_3 in GeV region: give masses to νs and produce baryon asymmetry of the Universe

Search for keV-scale sterile ν

x-ray spectra of astrophysical objects

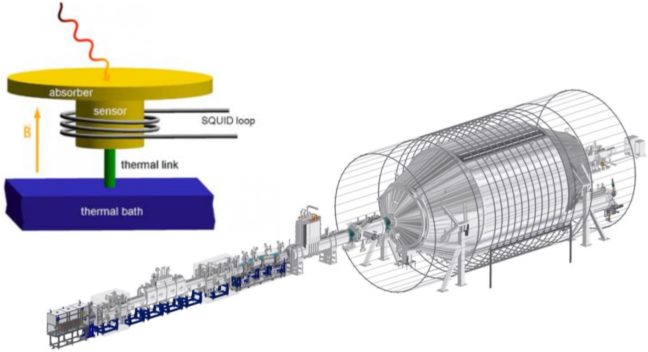
- $N \rightarrow \gamma + \nu$
- cosmological lifetime
- weak atomic and instrumental lines
- Micro-X, eROSITA, ASTRO-H2?

direct detection using large-scale detectors



- $\nu_S + e^- \rightarrow \nu_i + e^-$
- $\nu_S + N(A, Z)$
  $\rightarrow N(A, Z+1) + e^-$
- signal rates ~1/year (!)
- source scattering

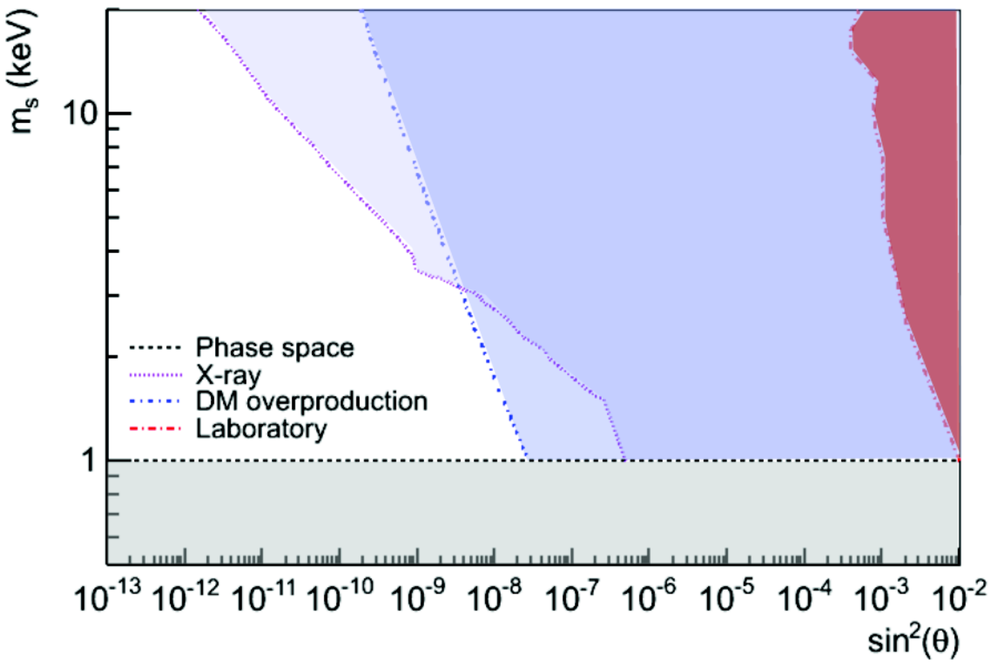
kinematics of β-decay



- $^3H \rightarrow {}^3He + e^- + \bar{\nu}_e$
- $^{163}Ho + e^- \rightarrow {}^{163}Dy^* + \nu_e$
  $\Rightarrow {}^{163}Dy^* \rightarrow {}^{163}Dy + \gamma/e^-$
- R&D needed for large rates
- Troitsk nu-mass, KATRIN, ECHo

Current constraints on keV-scale sterile ν

- phase-space density constraints
- x-ray constraints
- dark matter overproduction
- **laboratory experiments**



- ➢ need laboratory input
- ➢ very small mixing angle: $\sin^2\theta < 10^{-6}$ (!)

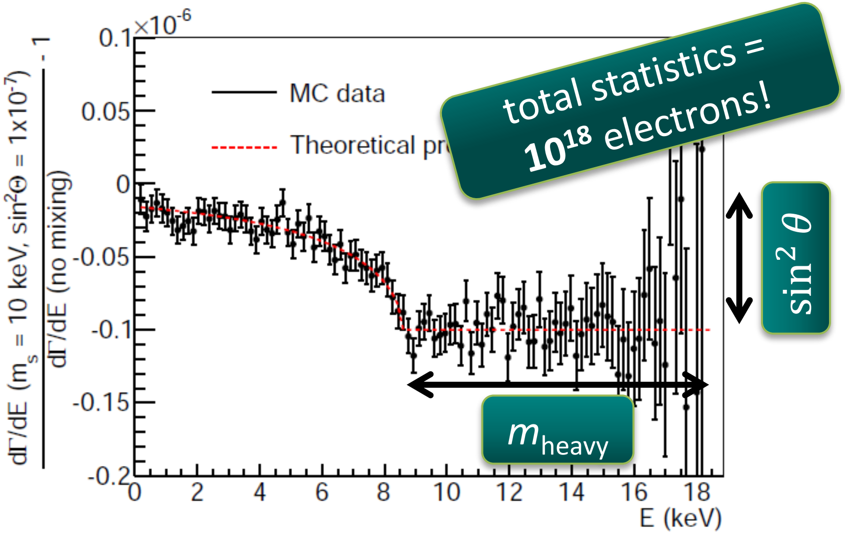
How do we get to 10^{-6} with laboratory experiments?

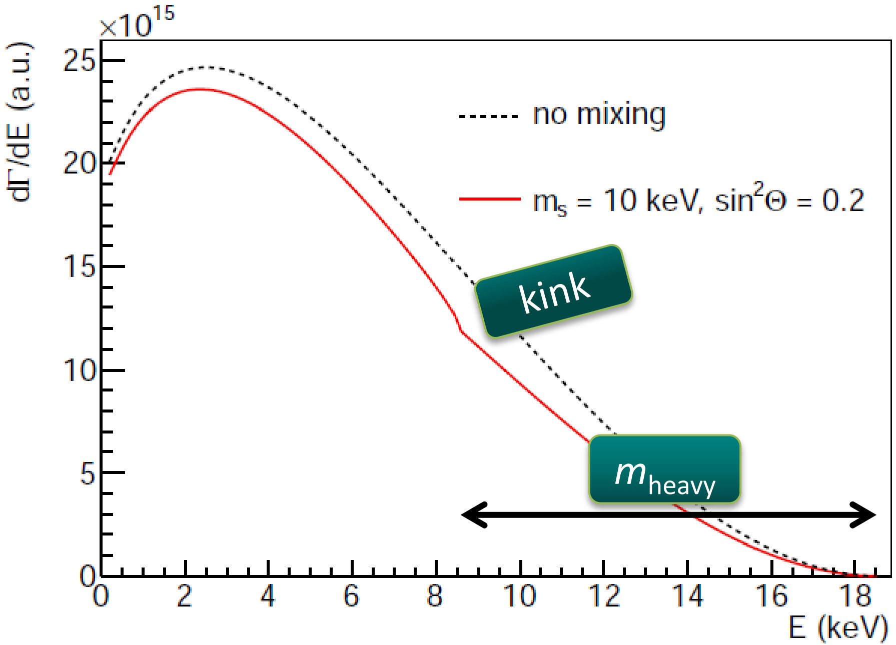
Tritium β-spectrum revisited

- differential β-spectrum: $\frac{\mathrm{d}\Gamma}{\mathrm{d}E} = \cos^2\theta \frac{\mathrm{d}\Gamma}{\mathrm{d}E}(m_{\mathrm{light}}) + \sin^2\theta \frac{\mathrm{d}\Gamma}{\mathrm{d}E}(m_{\mathrm{heavy}})$

➢ need high statistics

➢ extremely low systematic uncertainties





KATRIN/TRISTAN project

- KATRIN provides high-luminosity tritium source: $1.5 \cdot 10^{10}$ e^-/s → 2-3 years
- current detector system capable of "only" 10^6 e^-/s

feasibility run with KATRIN - 2017

100x reduction of tritium density

new B-field settings

systematic effects and analysis strategies under study

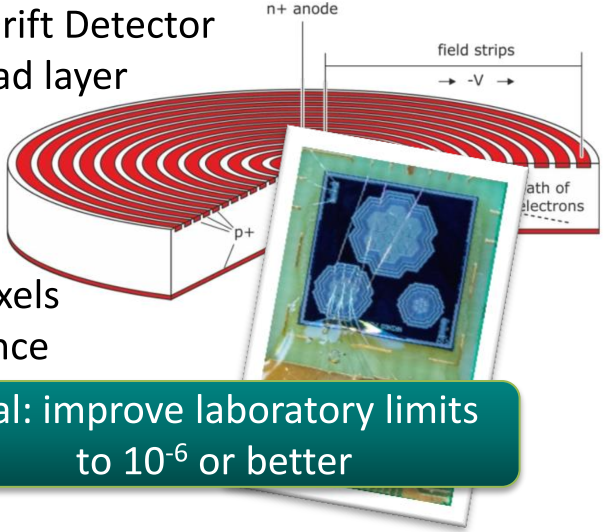
goal: improve laboratory limits by 1-2 orders of magnitude

new detector R&D

combine Silicon Drift Detector with thin dead layer

high E resolution (300 eV @ 20 keV)

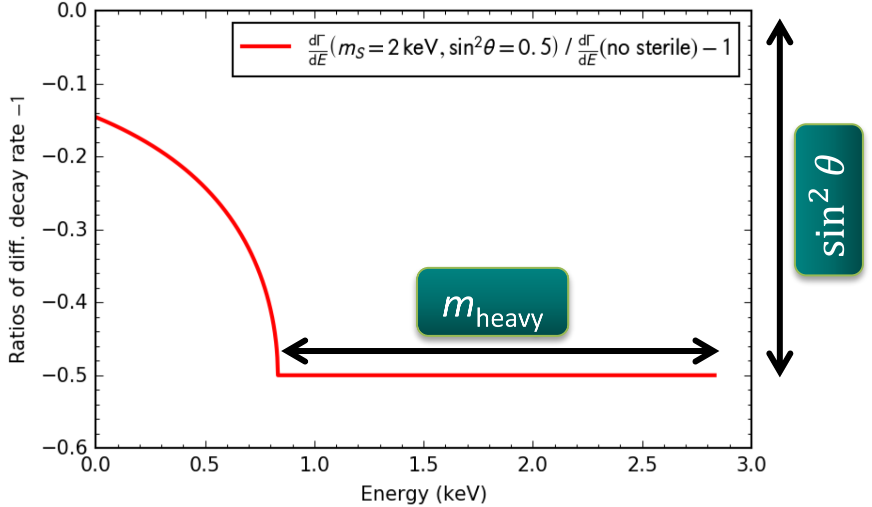
10^3-10^4 mm-sized pixels with small capacitance

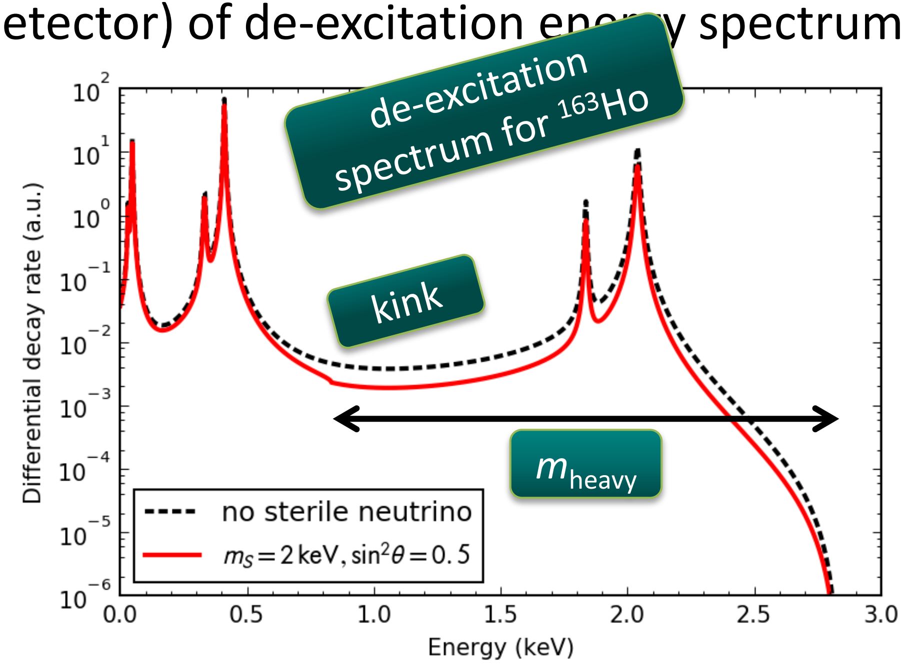


goal: improve laboratory limits to 10^{-6} or better

Electron capture experiments

- calorimetric measurement (source ⊂ detector) of de-excitation energy spectrum
- whole spectrum measured at once
  - ➢ high statistics needed as well
  - ➢ systematic effects under study





potential: < 10^{-6} for masses between 1 and 2 keV

eV-scale sterile ν: conclusion

- accelerator, reactor and gallium anomalies calling for clarification
  - $\Delta m^2 \approx eV^2$ sterile neutrino or experimental artifacts?
- reactor antineutrinos - 3 years timescale
- radioactive sources - 3 years timescale (KATRIN, CeSOX)
- neutrino beams - 5–10 years timescale

Within a few years the anomalies will be resolved!

keV-scale sterile ν: conclusion

- keV-ish neutrinos are dark matter candidates
- stringent limits from astrophysical observations
  - need input from laboratory experiments
- white paper (accepted for publication)

- approaches to search for keV-ν in laboratory
  - TRISTAN @ KATRIN (tritium β-spectroscopy)
  - electron capture experiments
- more ideas?

Thank you for your attention!