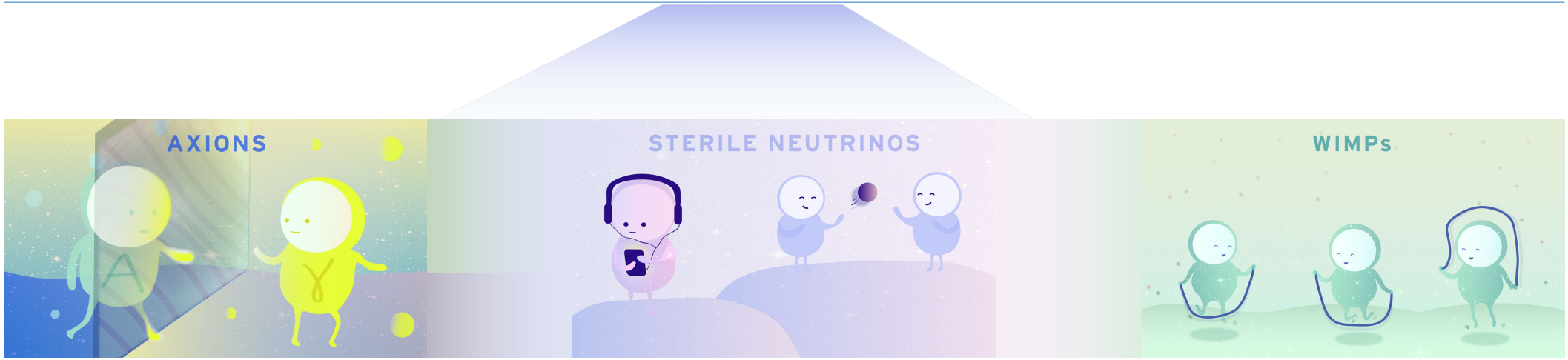
Sterile neutrinos as Dark Matter

Susanne Mertens
Technical University Munich

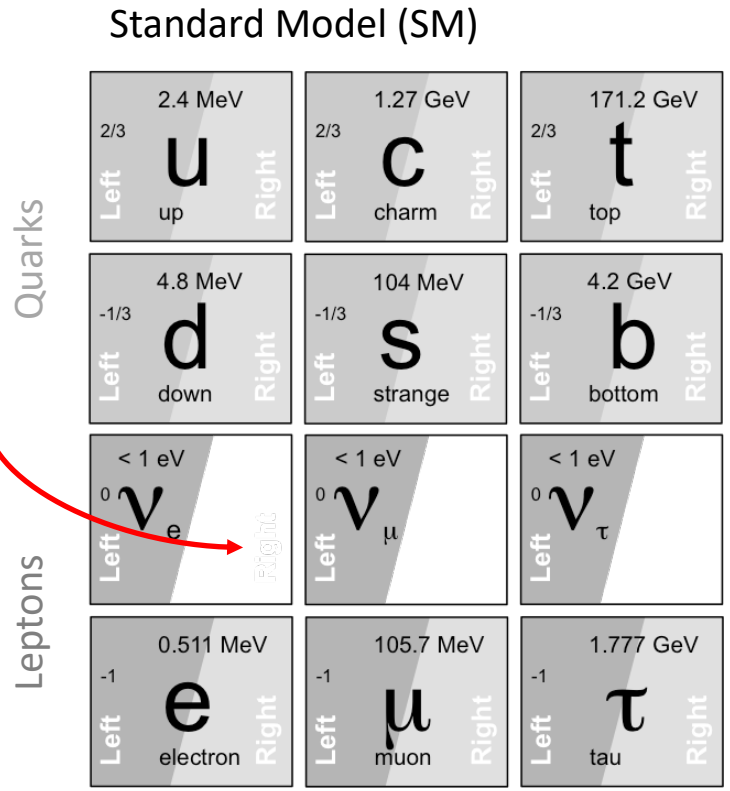
Dark Matter Candidates

μeV meV eV keV MeV GeV TeV



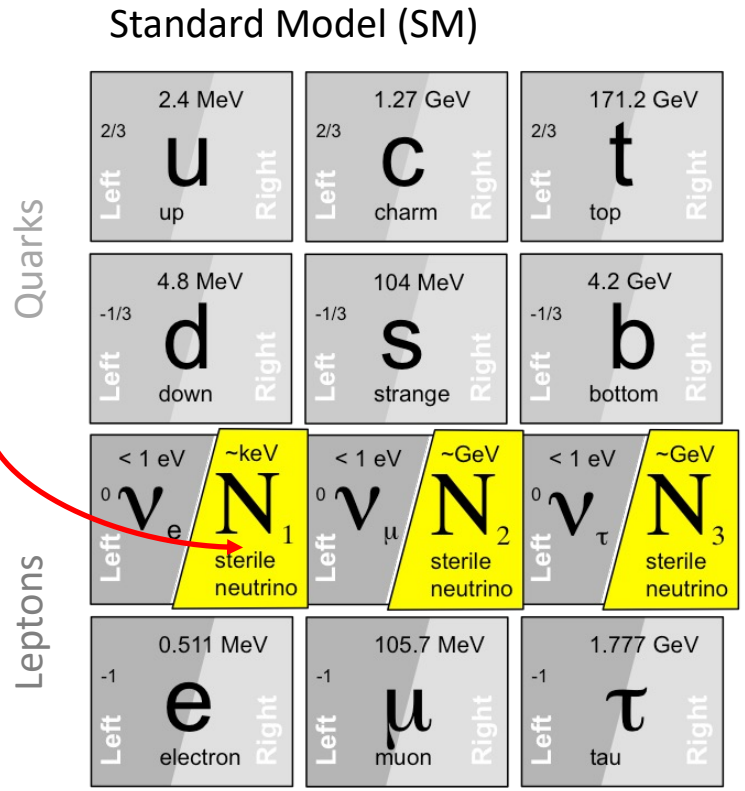
Sterile Neutrinos

No right-handed neutrino in the SM



Sterile Neutrinos

New neutrino mass eigenstates



L. Canetti, M. Drewes, and M. Shaposhnikov, PRL **110** 061801 (2013)

Sterile Neutrinos

Heavy sterile neutrinos (>> GeV)

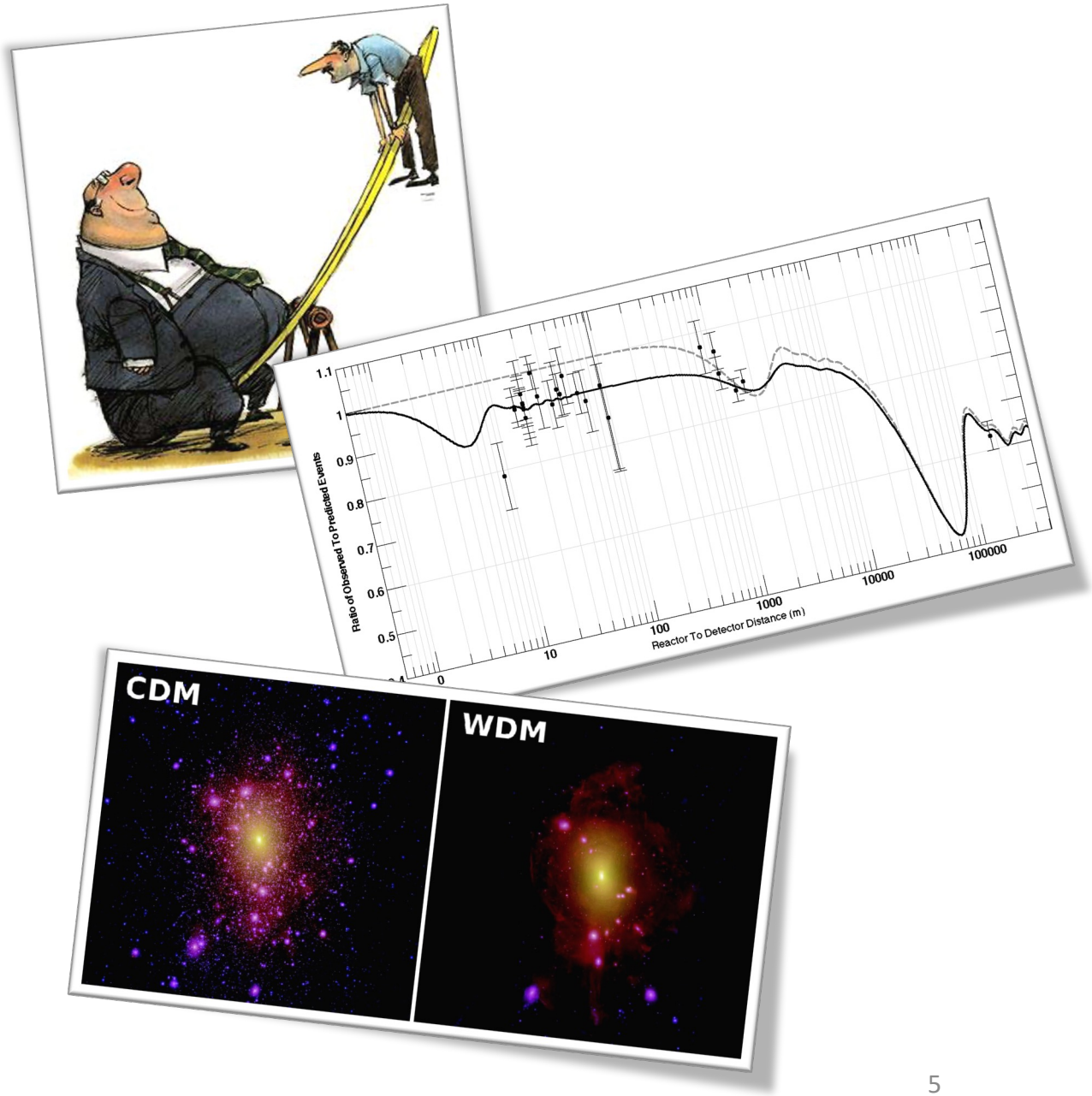
- Lightness of neutrinos
  + Matter/Anti-matter asymmetry

Light sterile neutrinos (~1 eV)

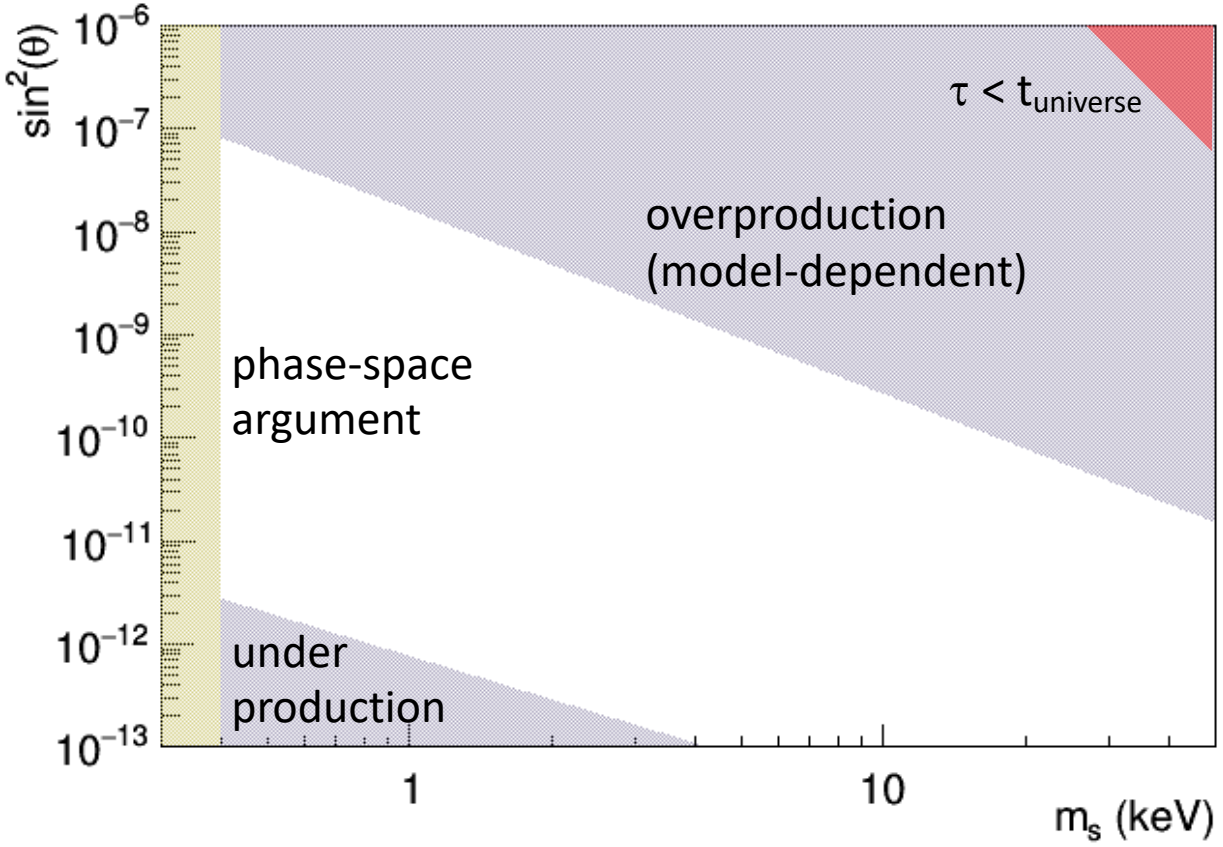
- Short-baseline neutrino oscillation anomalies

KeV-scale sterile neutrinos (~ 1 - 50 keV)

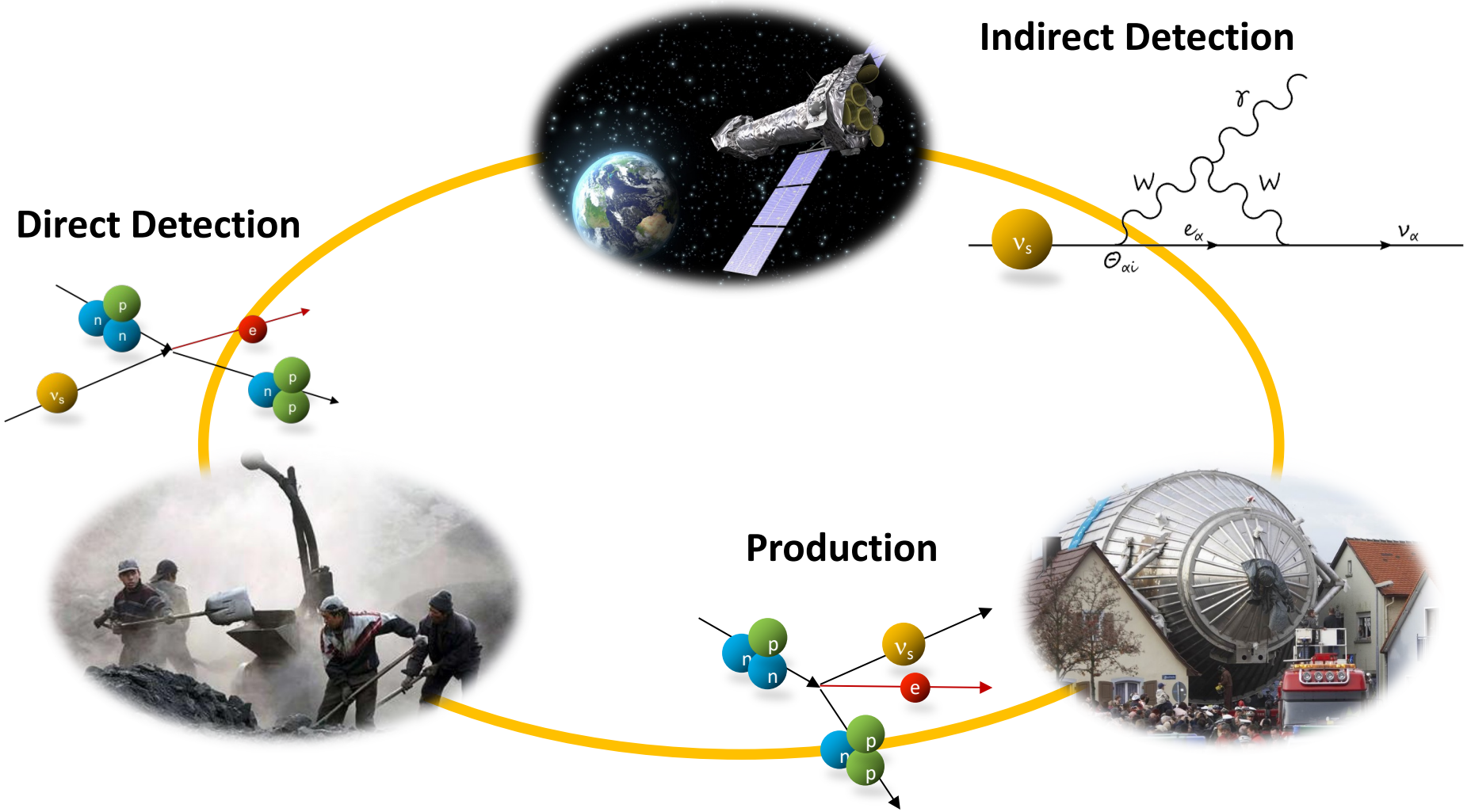
- Dark matter candidate



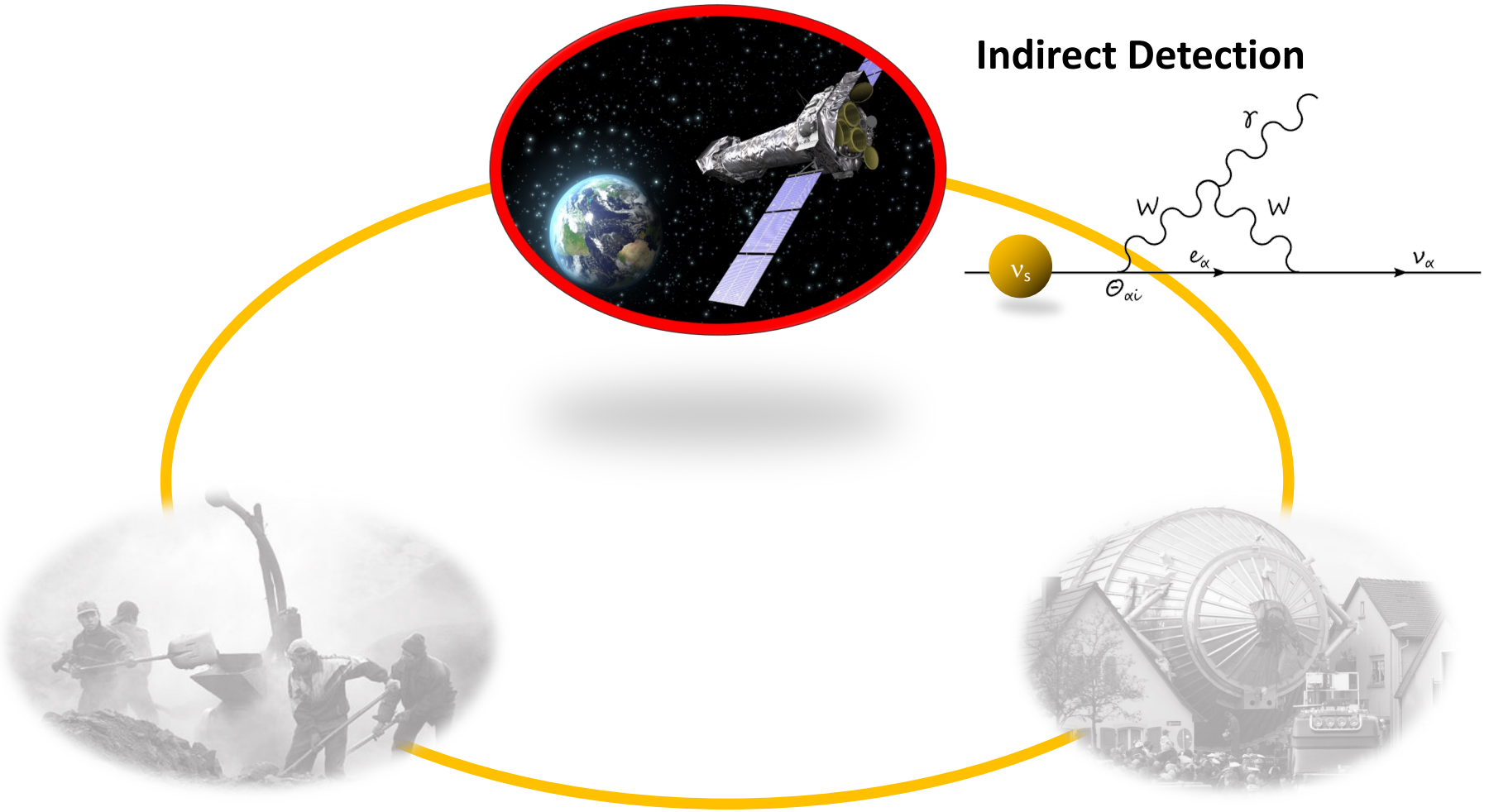
Cosmological constrains



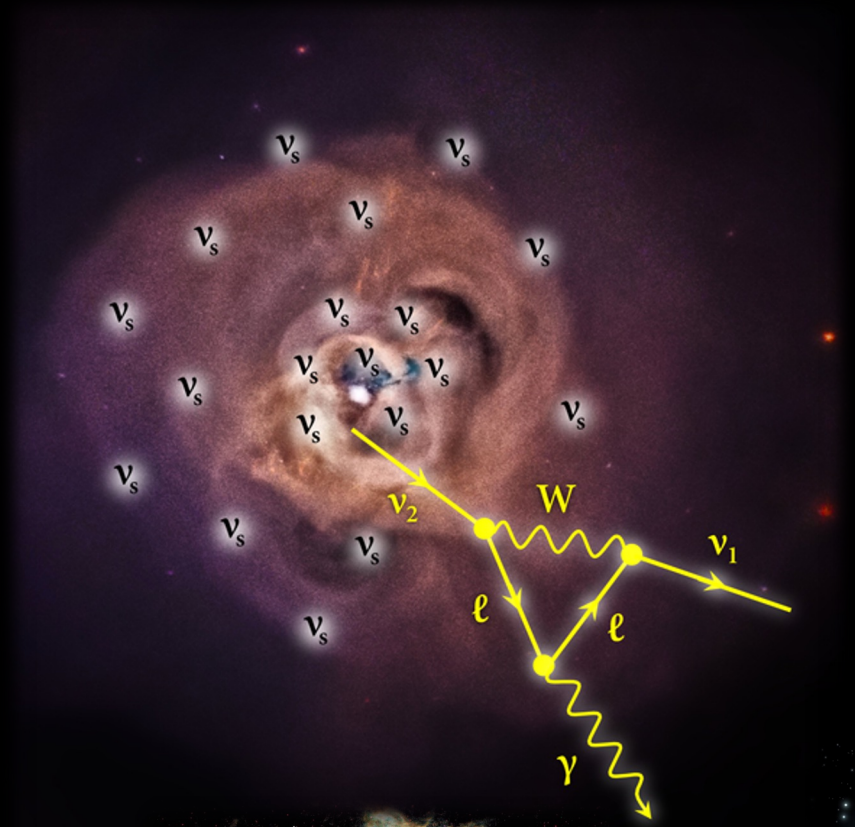
Experimental searches



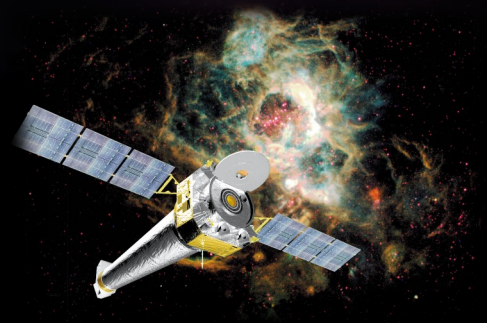
Experimental searches

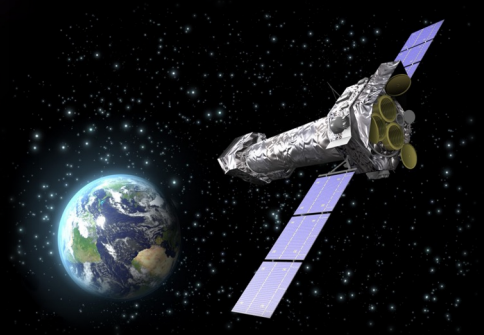


Indirect Searches

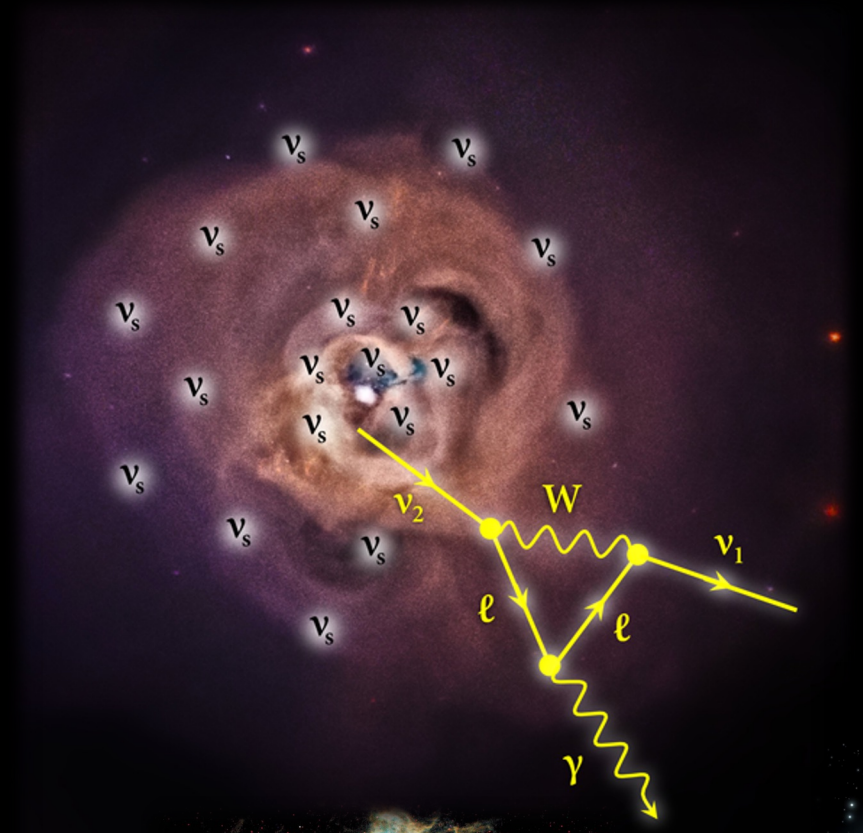


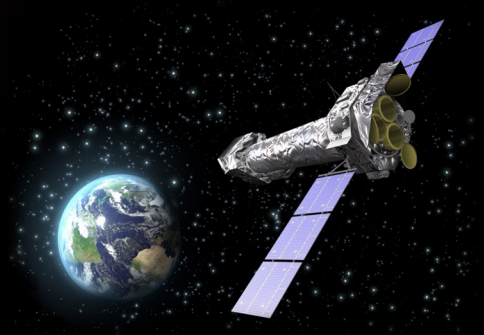
- Idea: Search for mono-energetic X-ray line





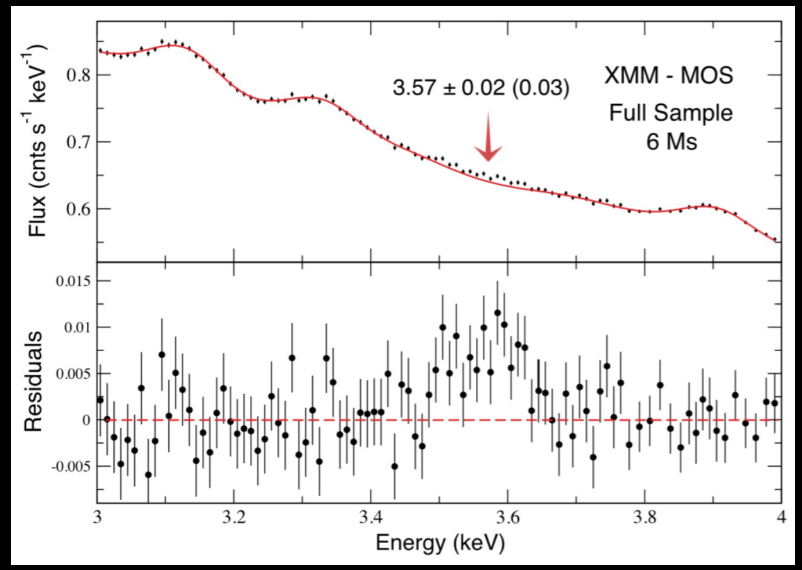
Indirect Searches



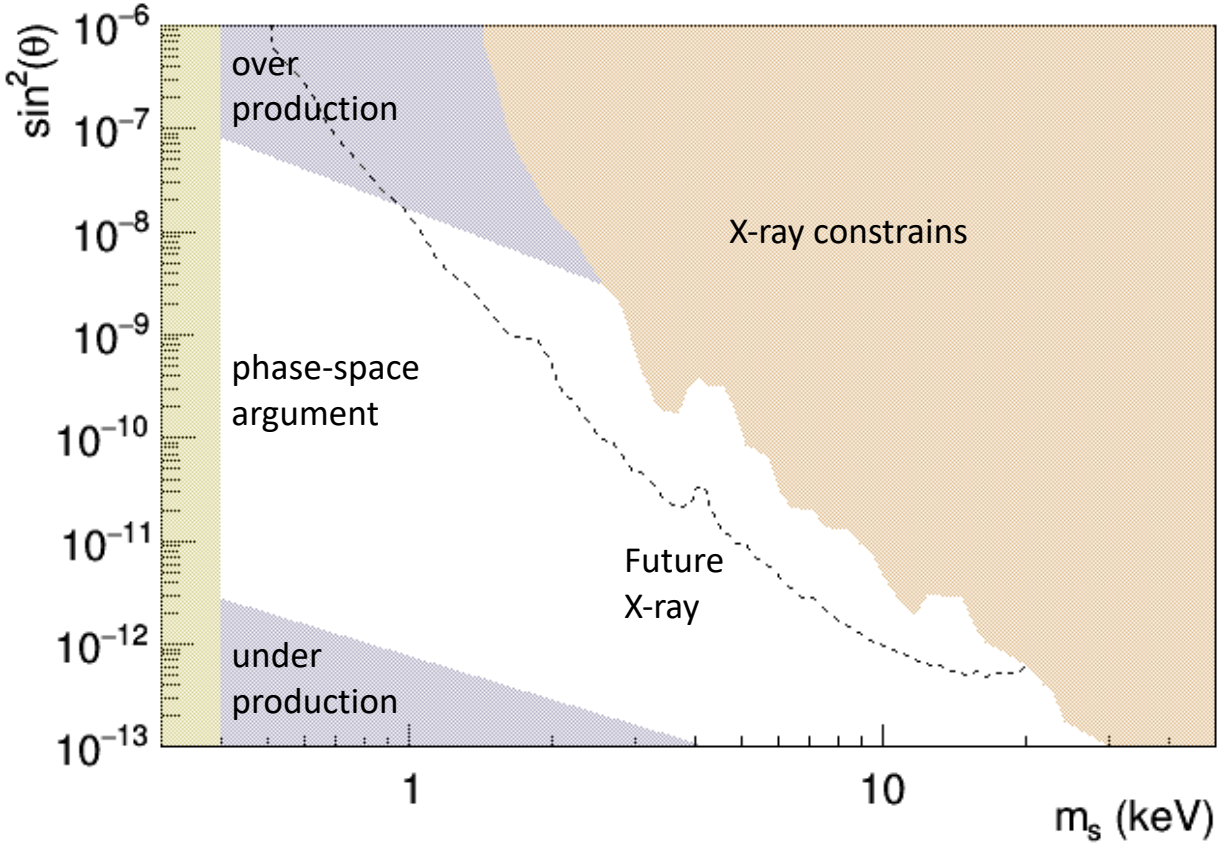


- Idea: Search for mono-energetic X-ray line
- Line observed by: XMM Newton, Chandra, NuStar, Suzaku
- No line seen by Hitomi (Astro-H), but only short observation time…

➢ Interpretation remains inconclusive



Constrains from indirect searches



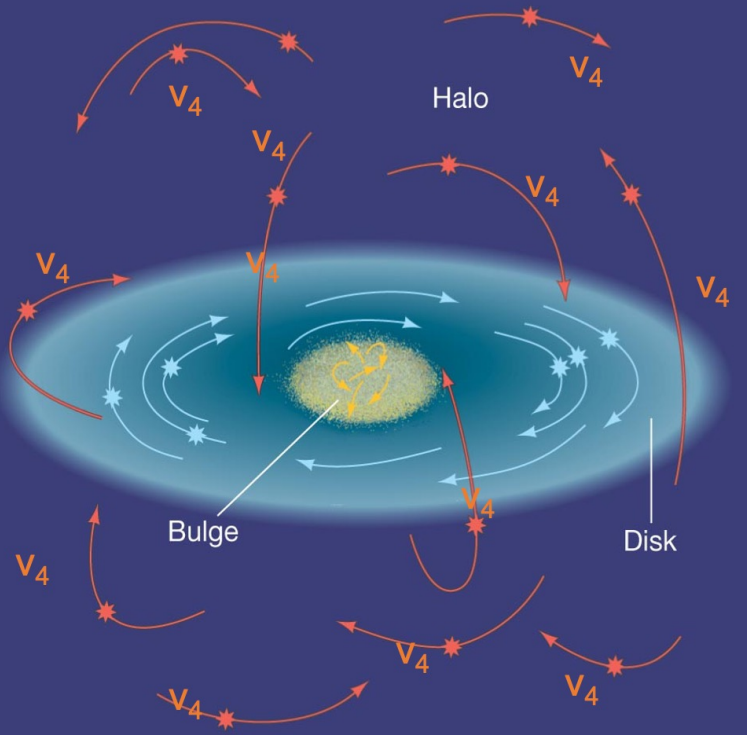
Experimental searches

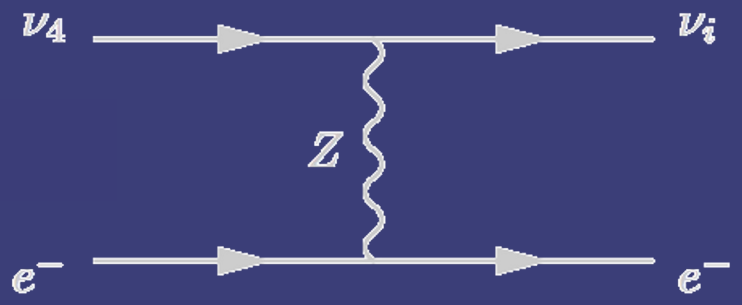
Direct detection

Elastic scattering

- Detect electronic recoil in large DM experiment (e.g. DARWIN)
- Challenge: background…
- Sensitivity down to $\sin^2\theta < 10^{-6}$

  Phys. Rev. D 94, 095010 (2016)

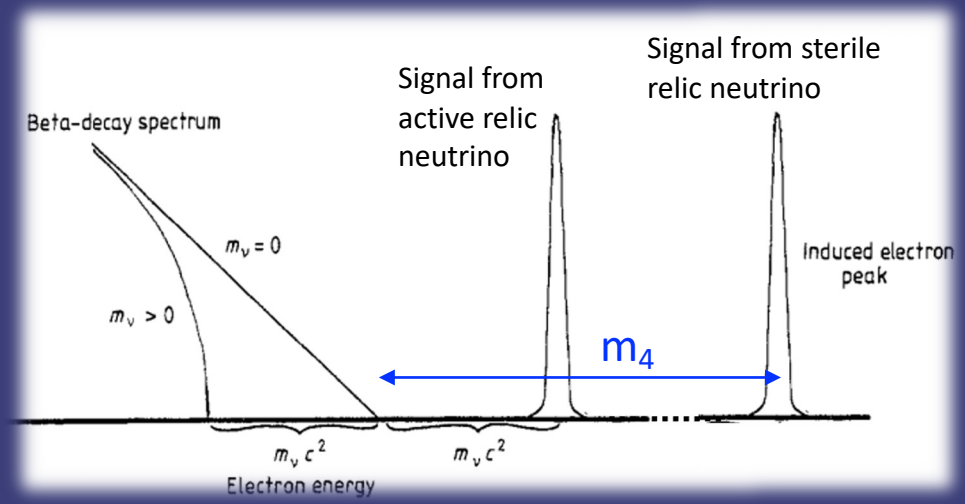


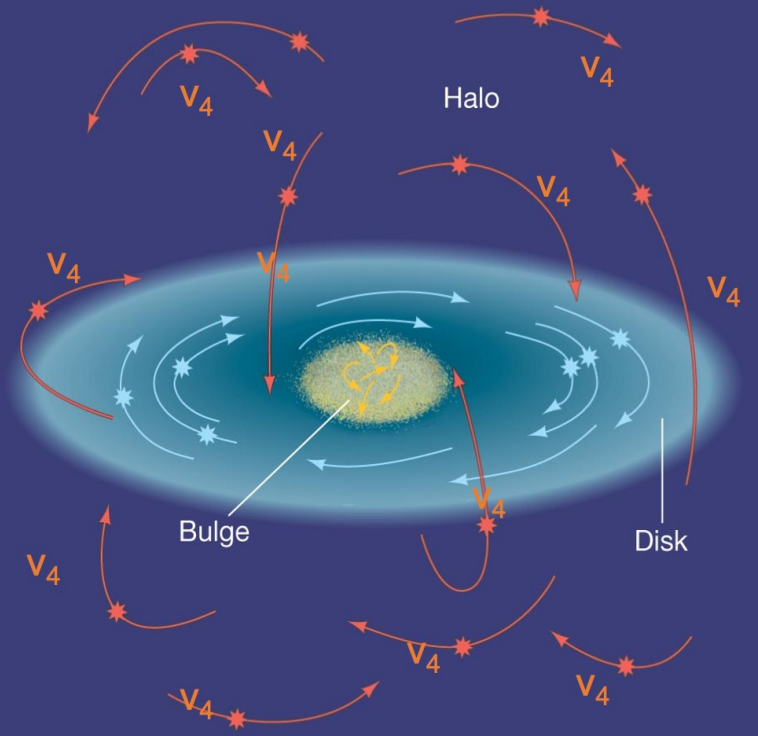


Direct detection

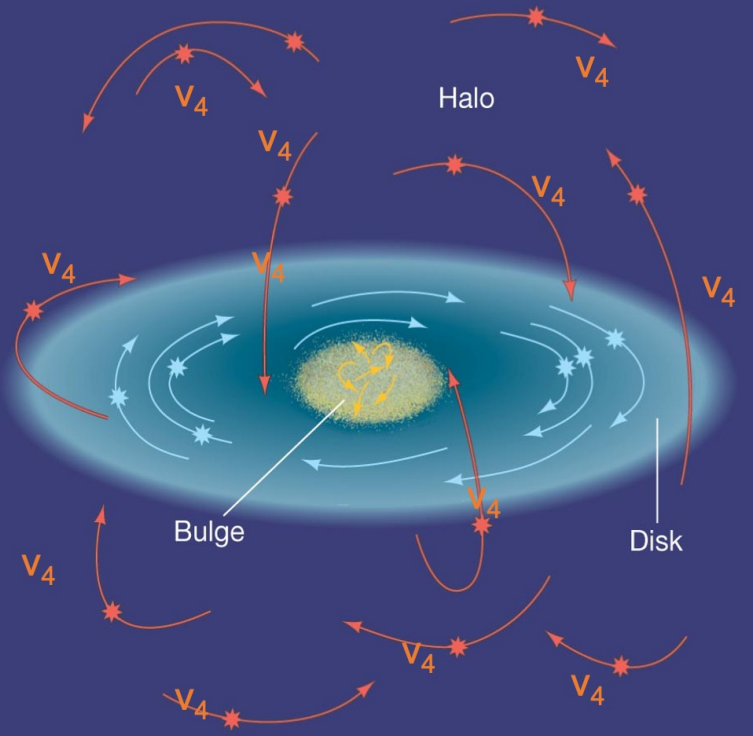
Capture on target

- Decaying target (e.g. tritium)
  - no energy threshold
  - search for peak above the spectrum
  - challenge: 10 kg of T for 1 capture/year for $\sin^2\theta = 10^{-6}$ ☹





Direct detection

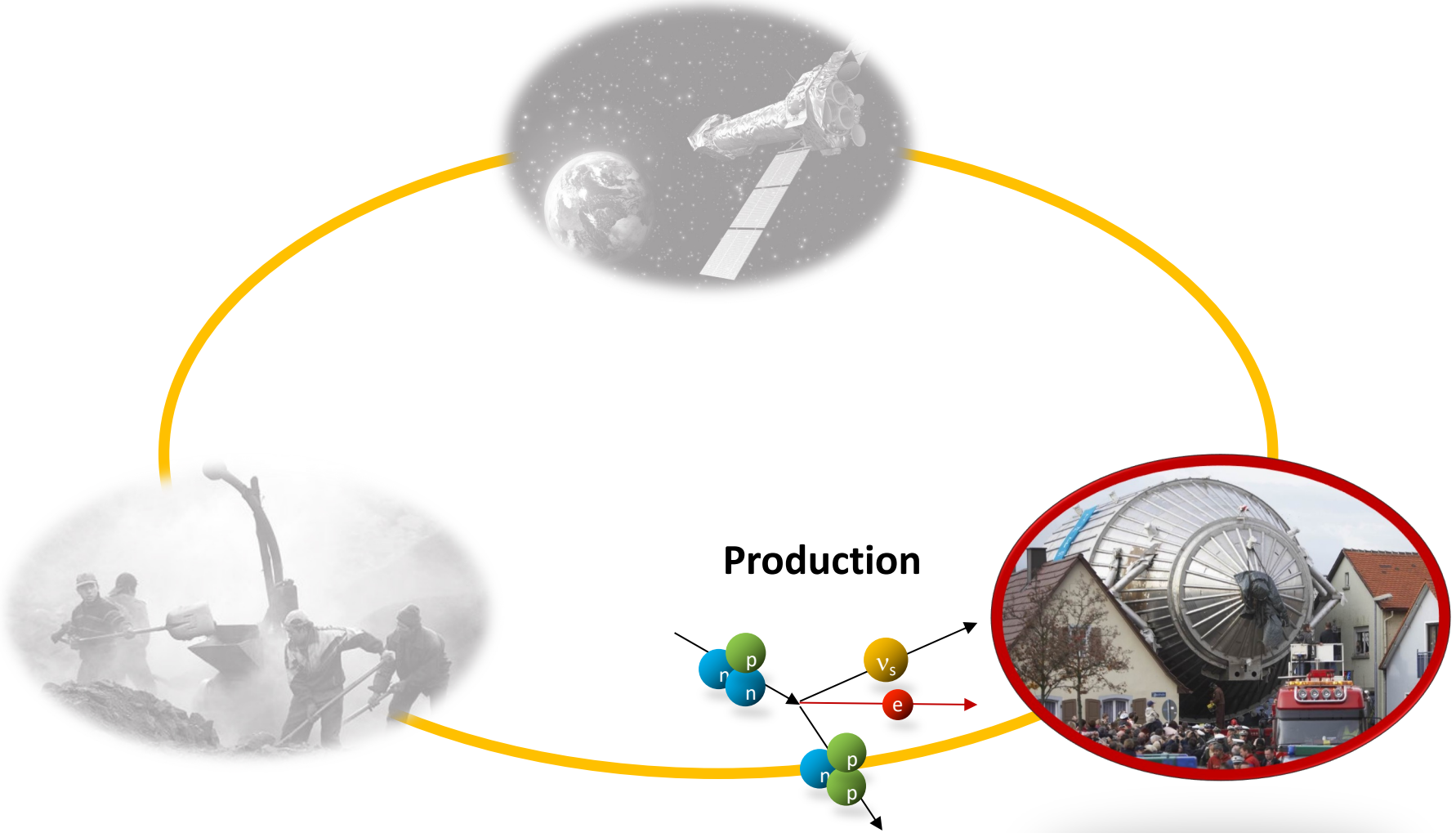


Capture on target

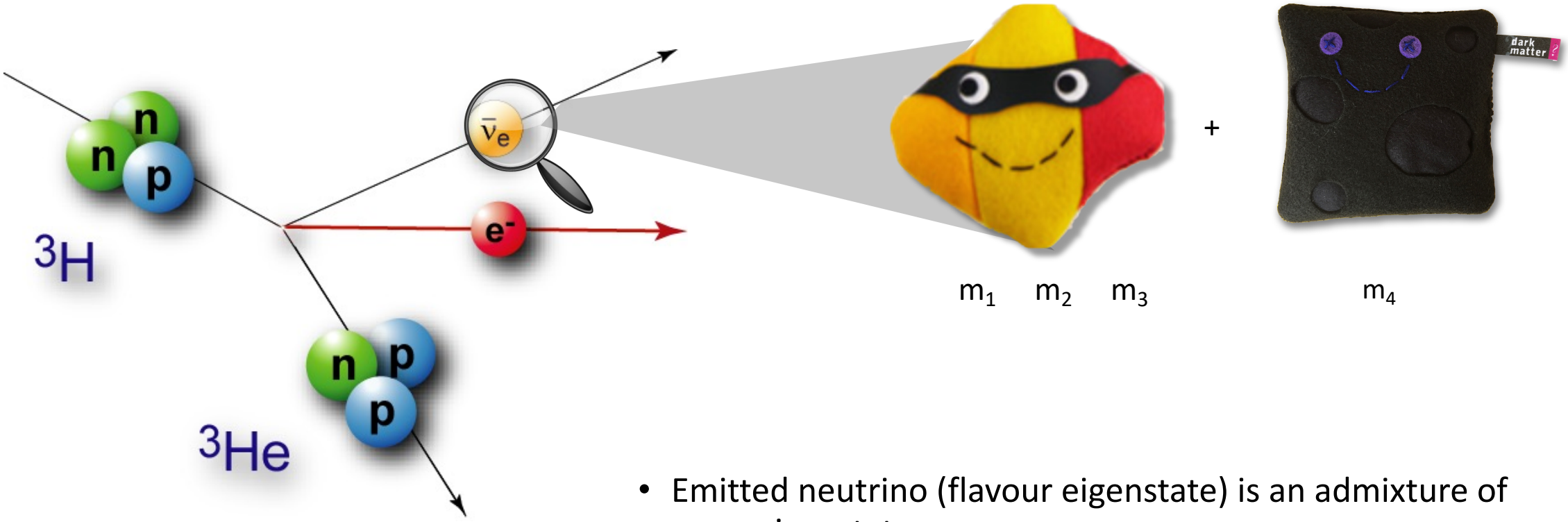
- Decaying target (e.g. tritium)
  - no energy threshold
  - search for peak above the spectrum
  - challenge: 10 kg of T for 1 capture/year for $\sin^2\theta = 10^{-6}$ ☹

- Alternative idea: capture on a almost-decaying target
  T. Lasserre et.al. arXiv:1609.04671 (2016)
  - $^{163}\mathrm{Dy} + \nu_4 \rightarrow {}^{163}\mathrm{Ho} + e$
  - Dy-detector, or search for Ho in the rocks….

Experimental searches

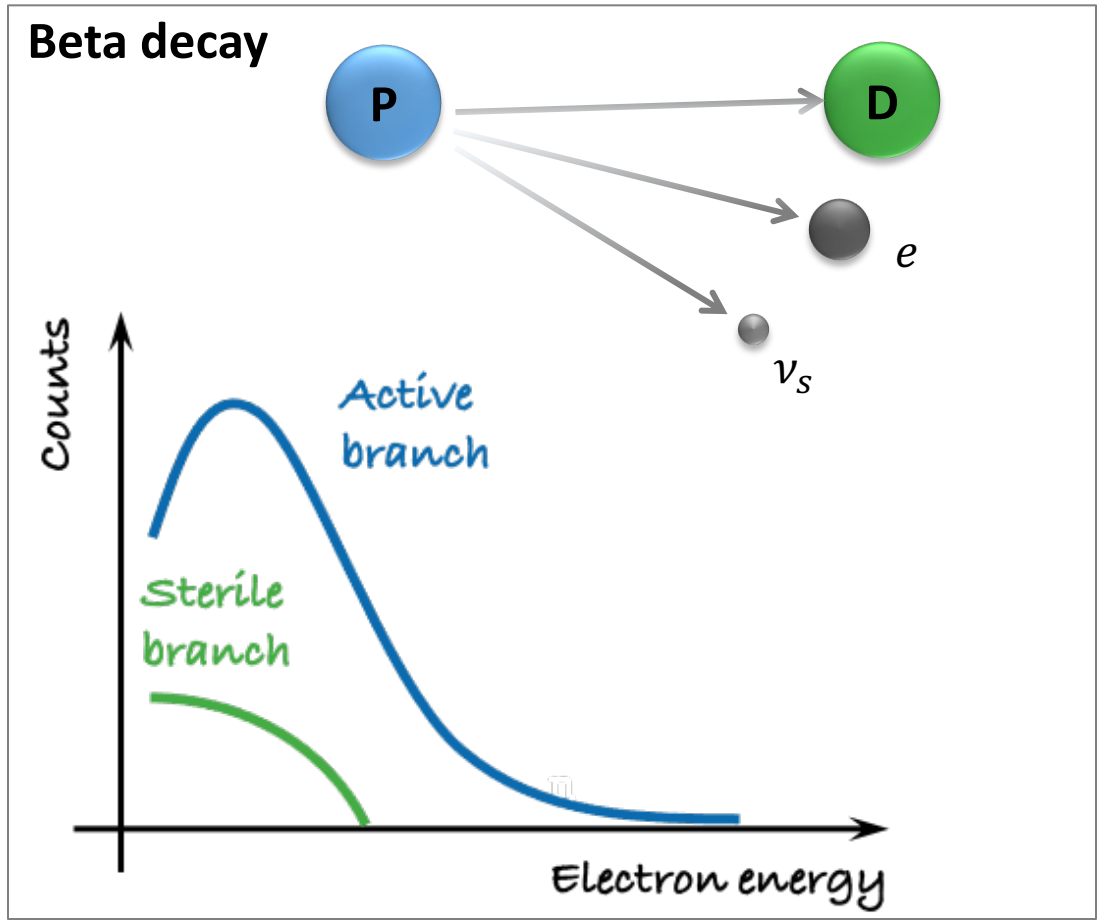


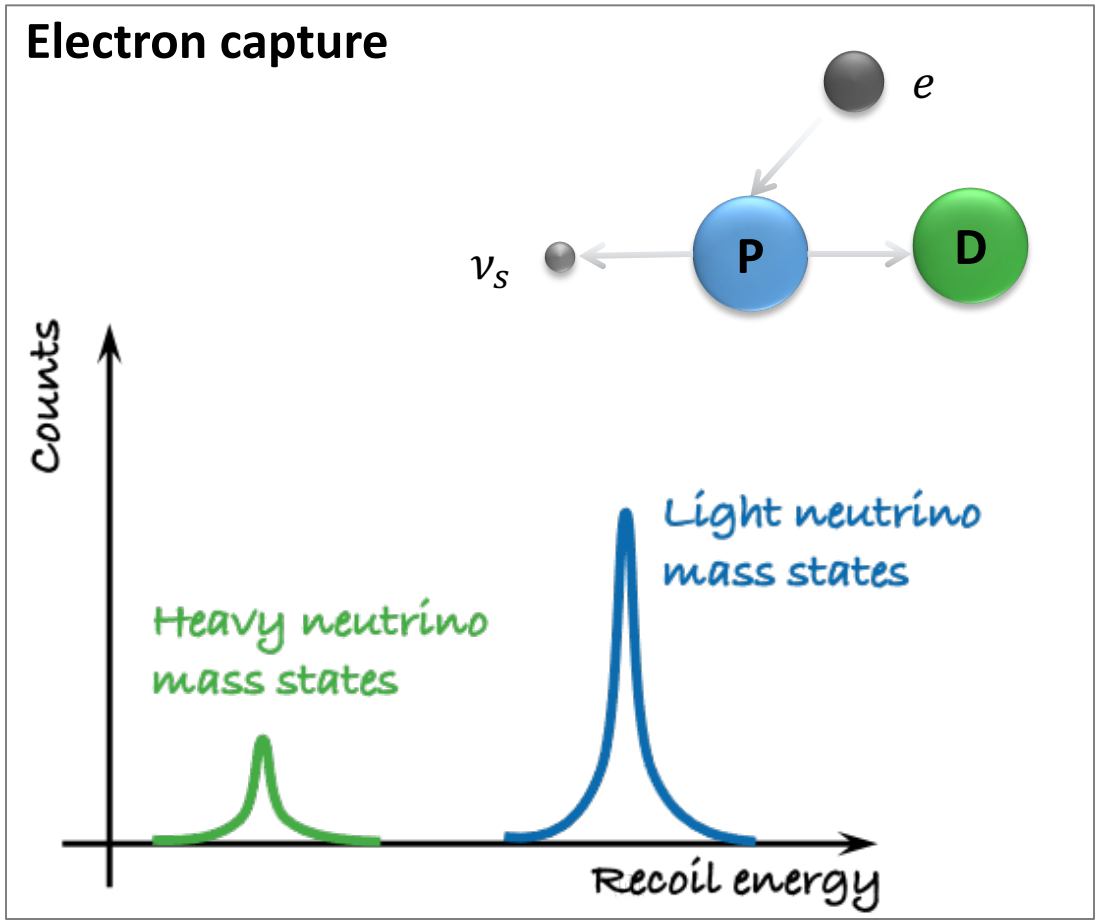
Production in beta decays



- Emitted neutrino (flavour eigenstate) is an admixture of mass eigenstates
- Emission of keV-scale mass eigenstate changes the kinematic of the decay

Production in beta decays



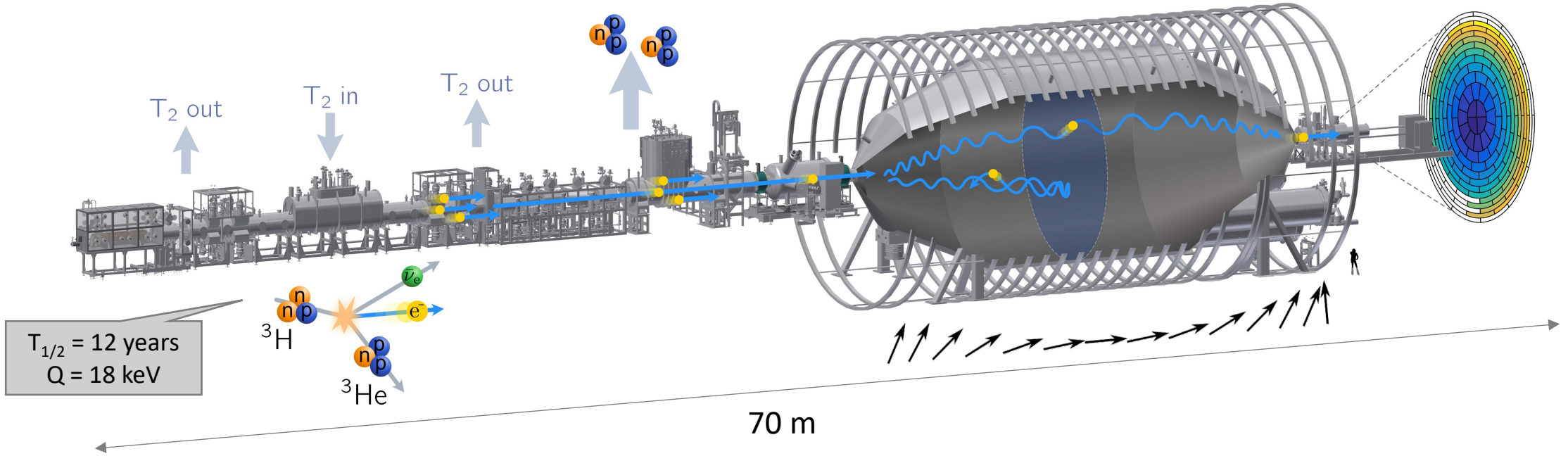


The KATRIN experiment

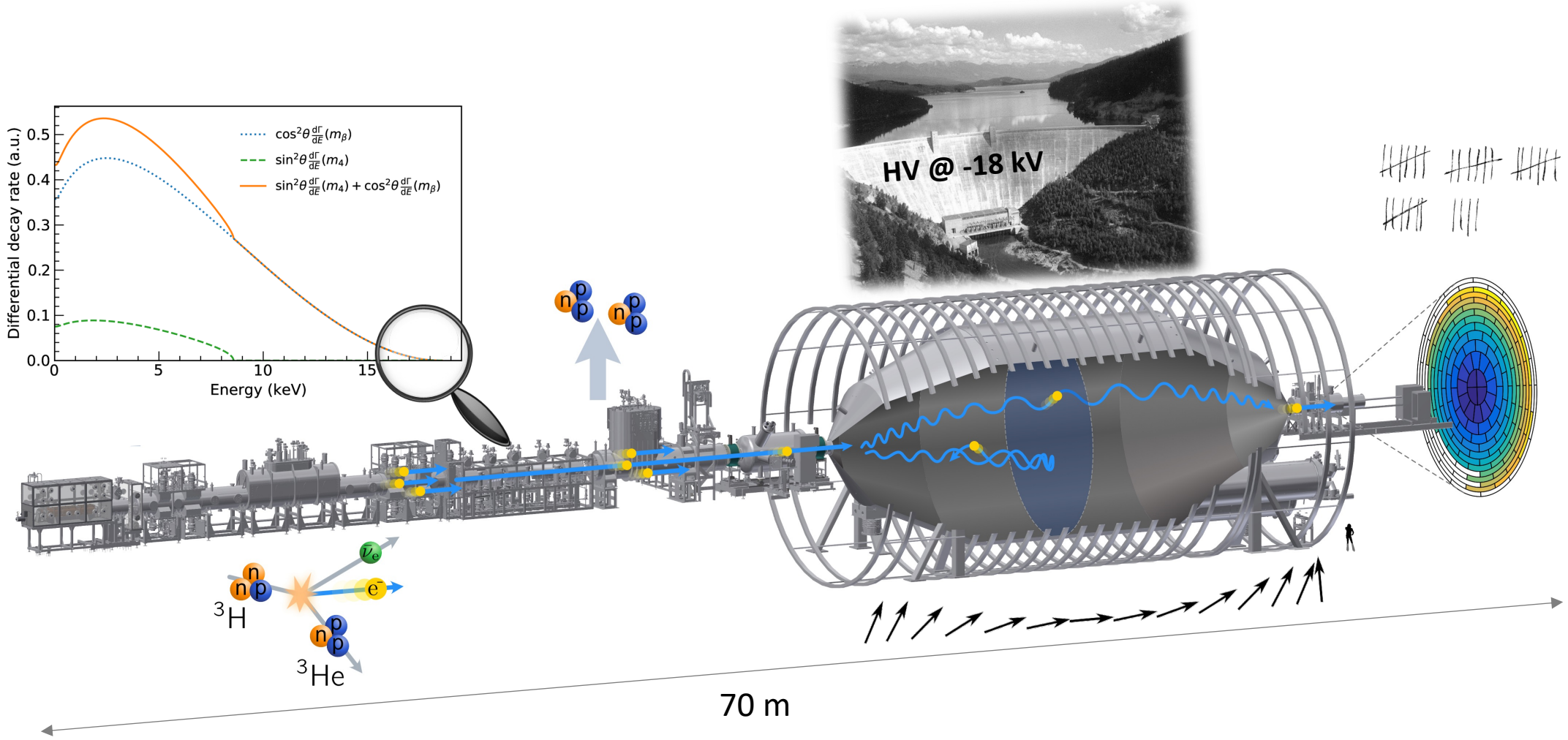
Tritium source
- 30 μg of gaseous T_2
- 10^{11} T_2 decays/s

Spectrometer
- Electrostatic filter
- MAC-E filter principle

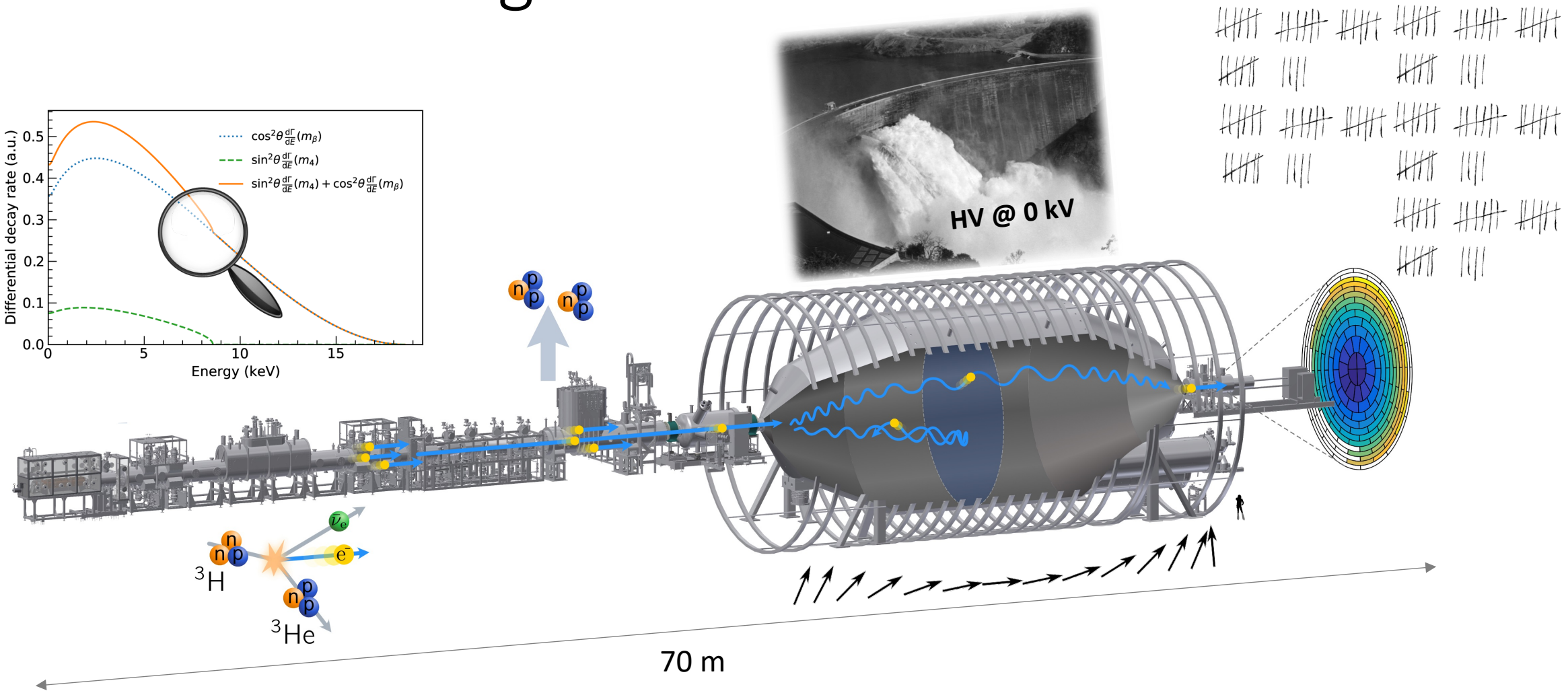
Detector
- Counts electrons
- Rate vs HV



The KATRIN experiment



KATRIN: challenge



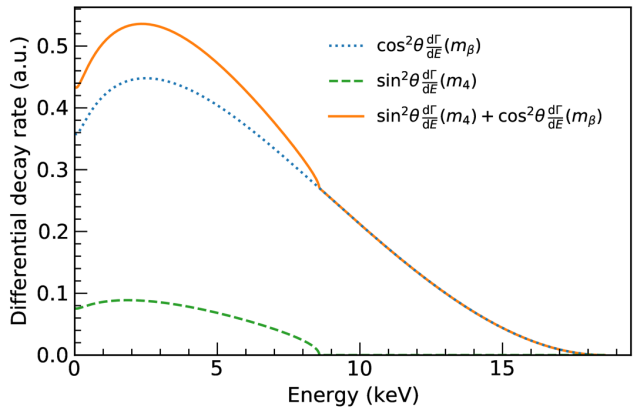
KATRIN: challenge

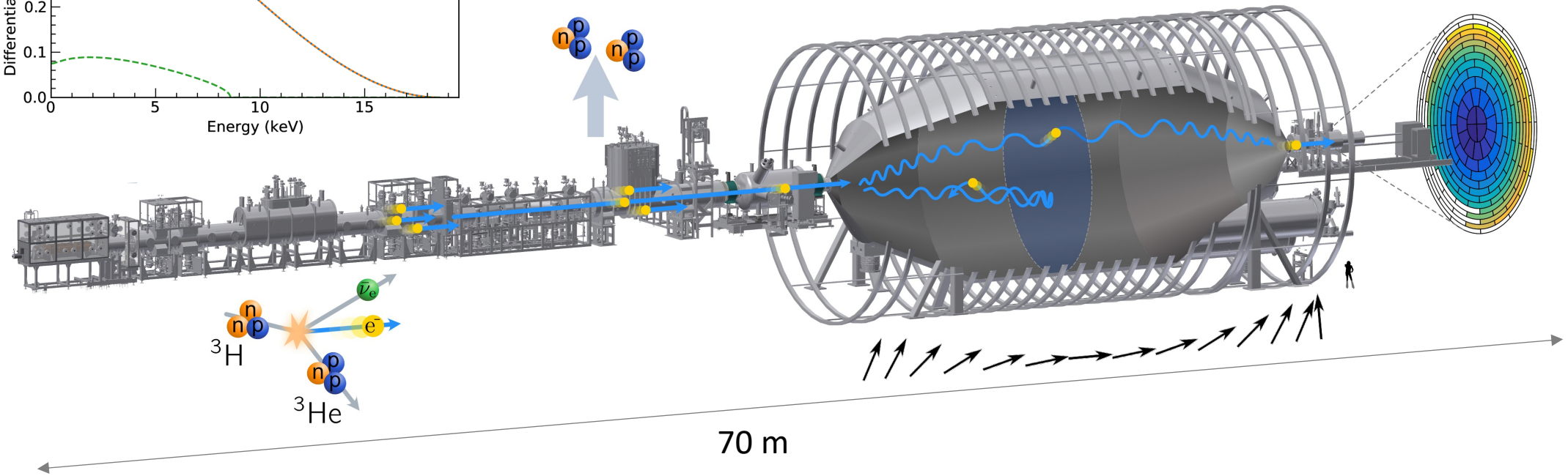
High rates

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

Full spectrum

- New model
  Mertens et al, Phys.Rev. D91 (2015)
- New analysis tools
  Mertens et al, JCAP 1502 (2015)



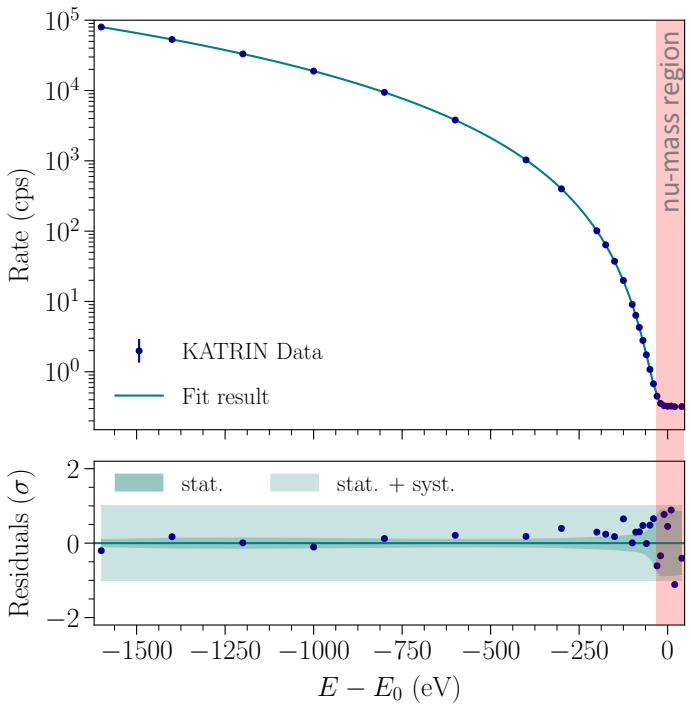


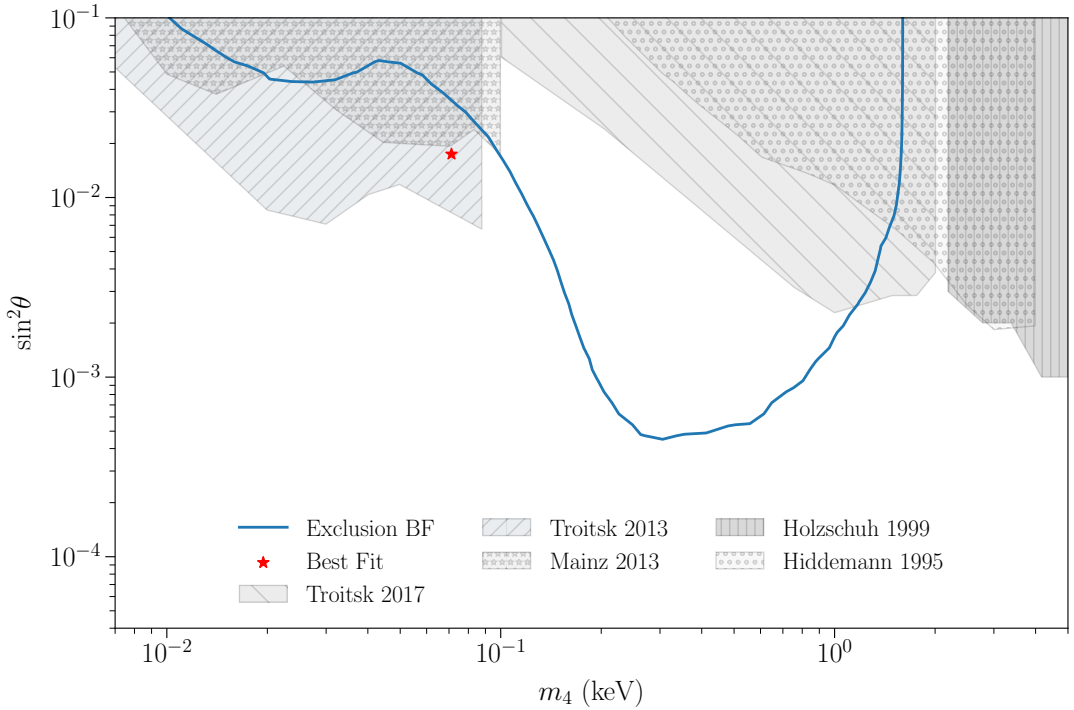
KATRIN with less tritium activity

Low-activity (0.5% of nominal) KATRIN run, down to 1.6 keV below E_0 with (10^9 electrons)

✓ excellent agreement of model and data (p-value = 0.6)

✓ improved sensitivity to $\sin^2\theta < 10^{-3}$ @ $m_4 = 0.4$ keV (arxiv 2207.06337 (2022))

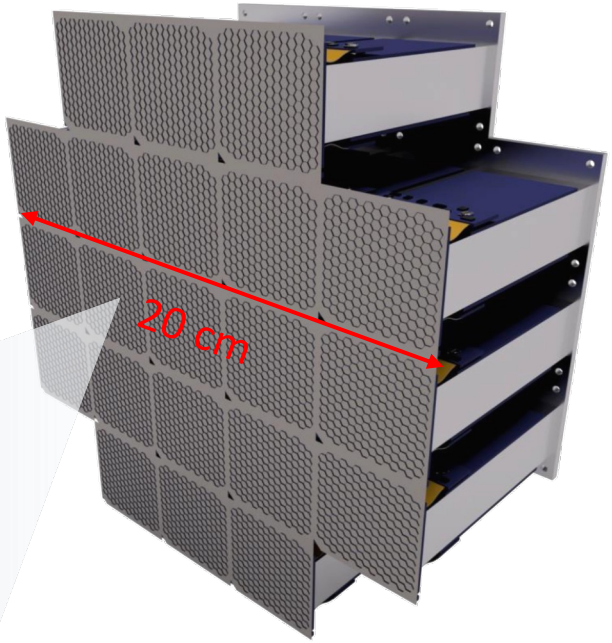


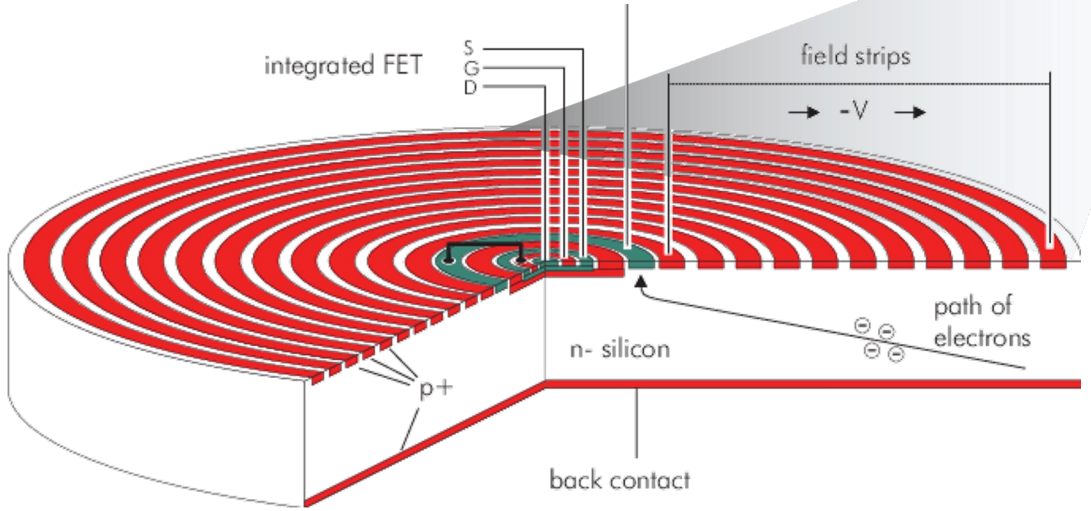


KATRIN with new detector (TRISTAN)

Silicon drift detector (SDD) with > 1000 pixels

- ✓ Capability of handling high rates (100 kcps/pixel)
- ✓ Excellent energy resolution (300 eV @ 20 keV) → diff. measurement
- ✓ Integrated read-out → focal plane design

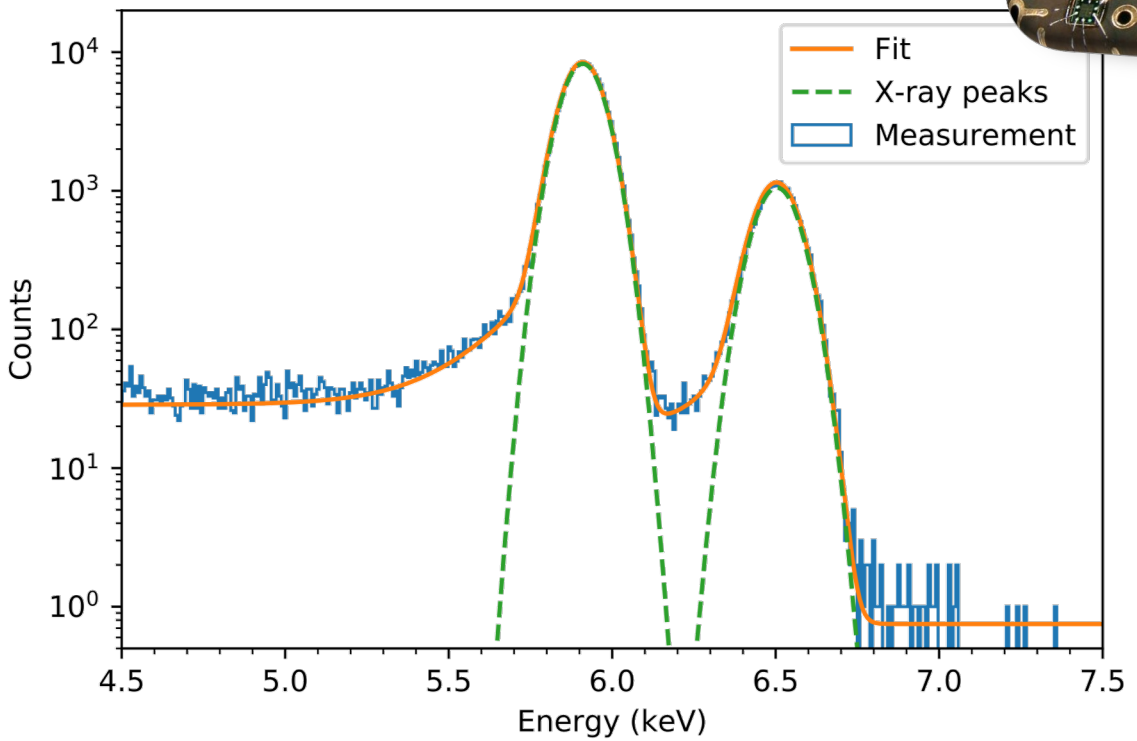


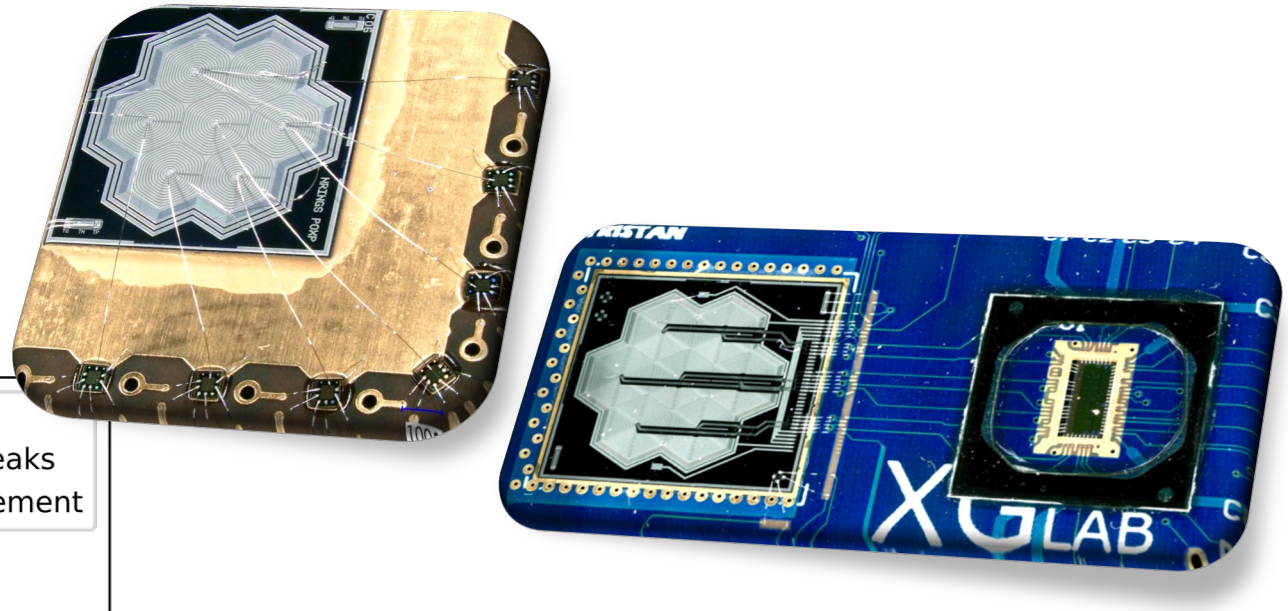


3 mm, 220 fF

TRISTAN detector

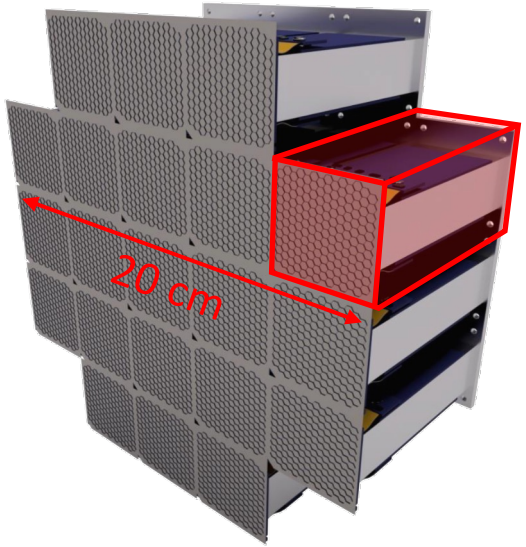
130 eV (FWHM) @ 6 keV @ 1 μs shaping

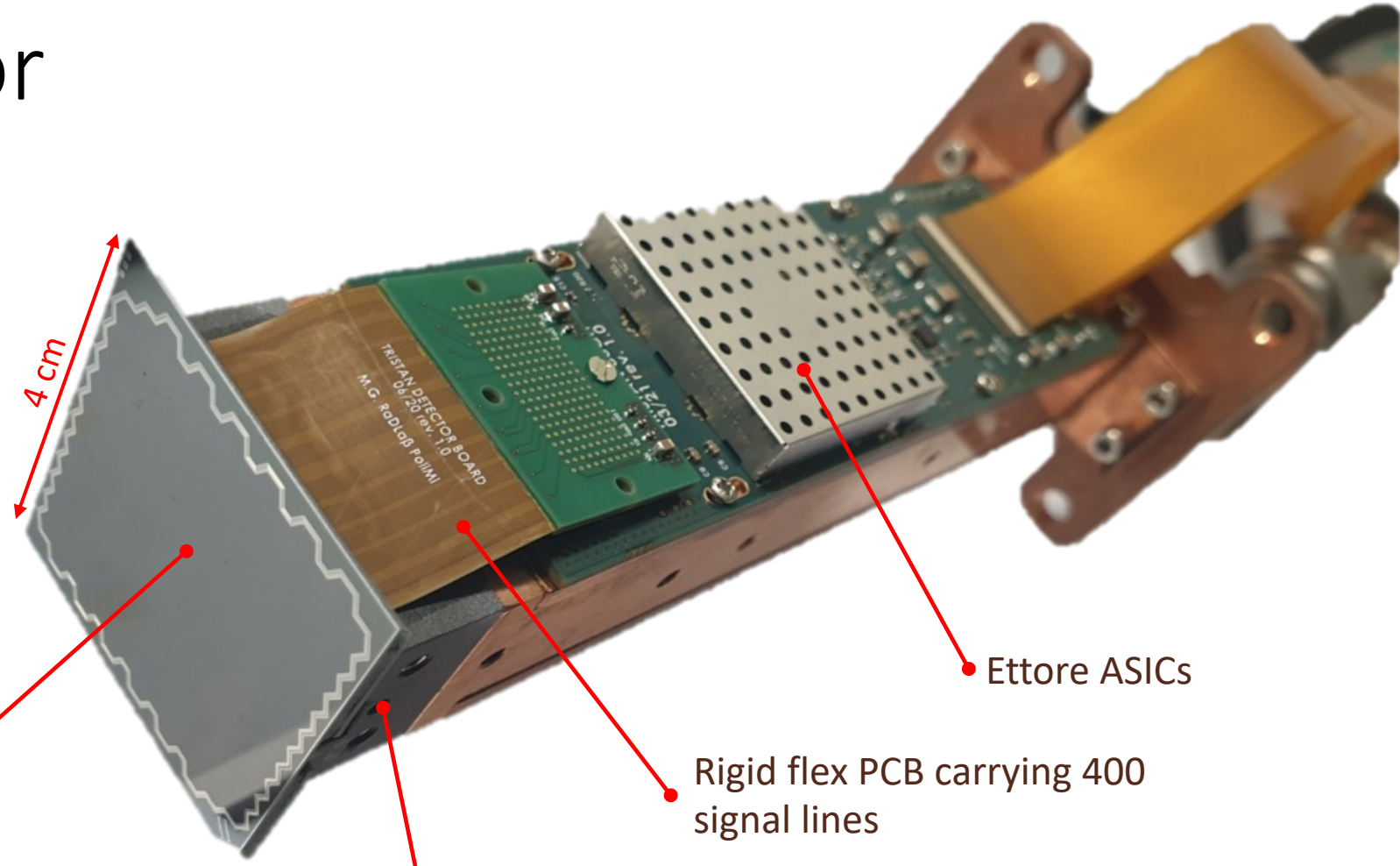




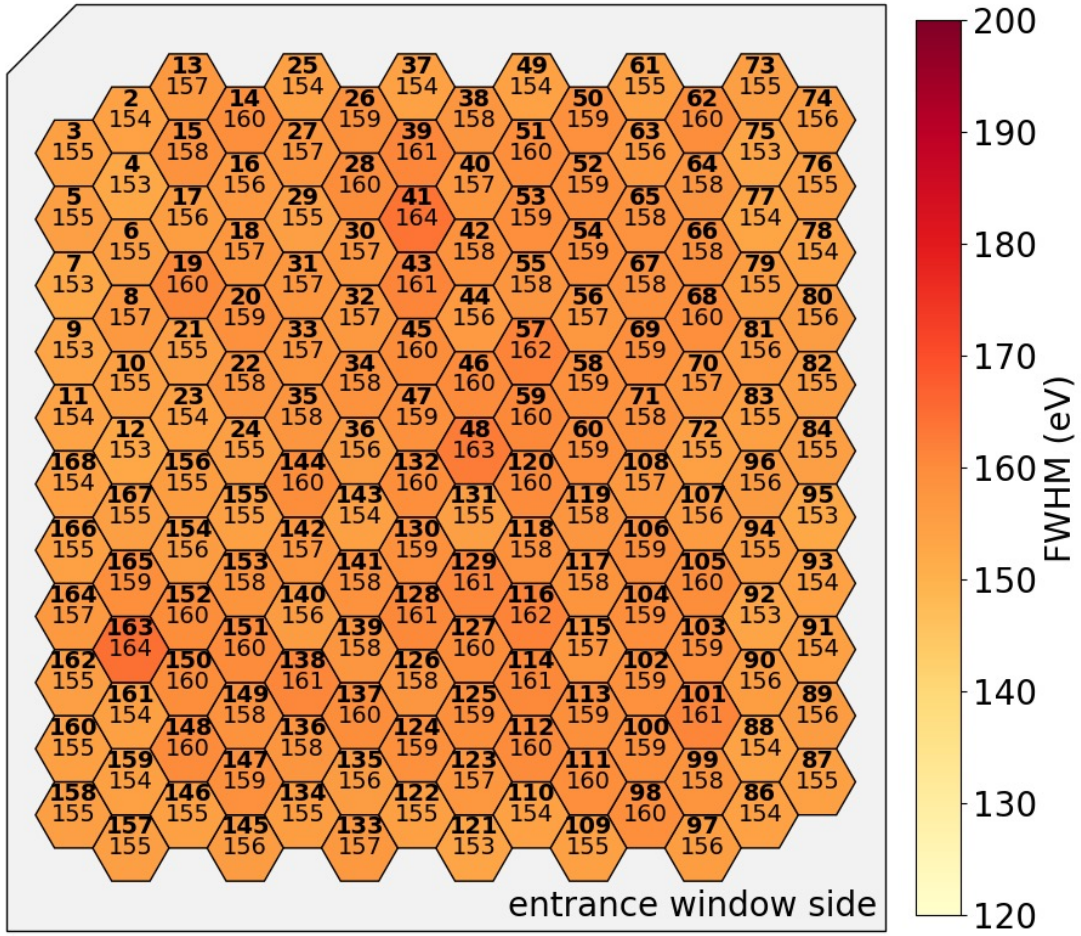
- ✓ Test of multiple prototype designs
- ✓ Excellent energy resolution for x-rays (140 eV @ 6 keV)
  S. Mertens et al, J. Phys. G46 (2019)
- ✓ Detailed characterization with electron
  S. Mertens et al, J. Phys. G48 (2020)

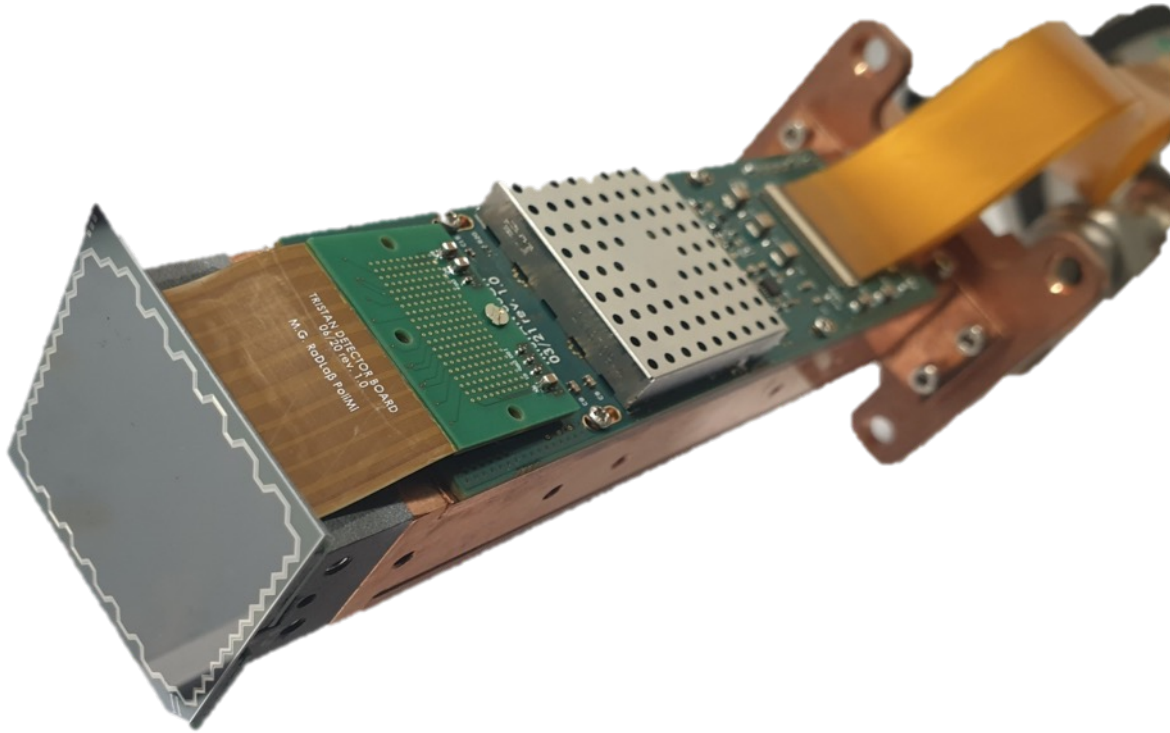
TRISTAN detector





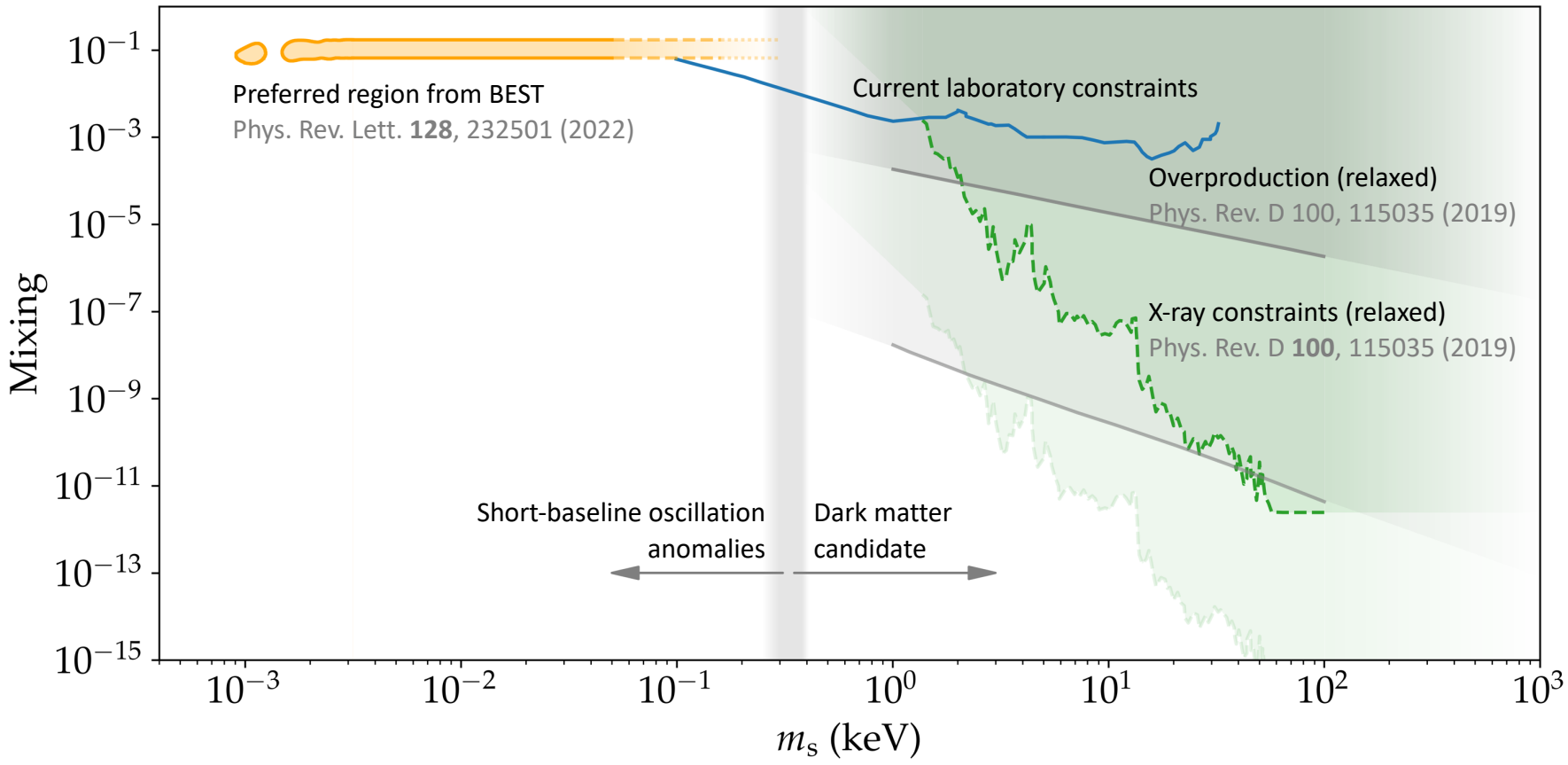
TRISTAN detector



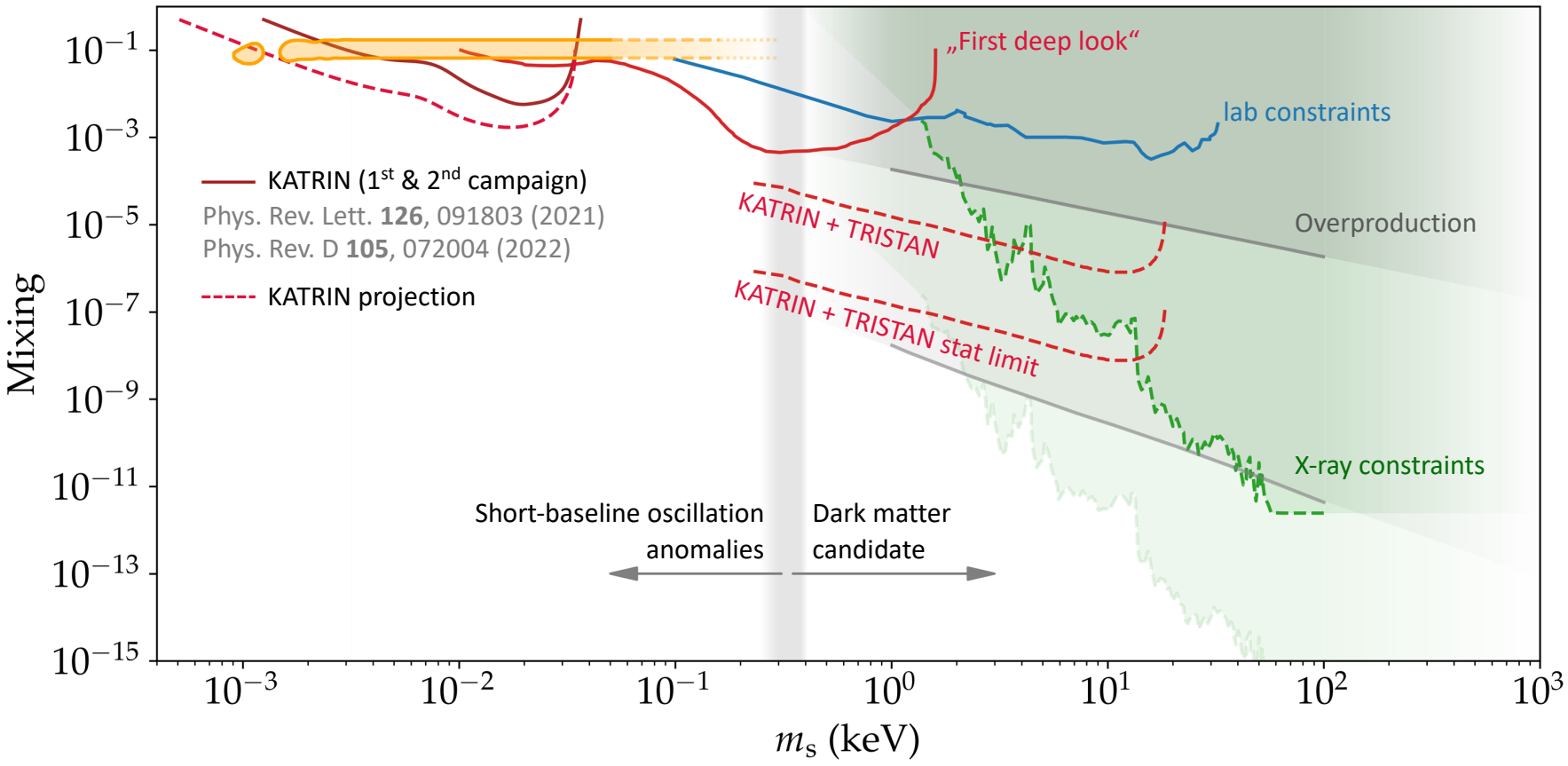


- ✓ Largest monolithic SDD ever operated ☺
- ✓ All pixels working
- ✓ Average resolution of 160 eV (FWHM) at 6 keV
- ✓ Homogeneous performance
- ✓ Integration of 9 modules in KATRIN in 2025

KATRIN/TRISTAN sensitivity to steriles

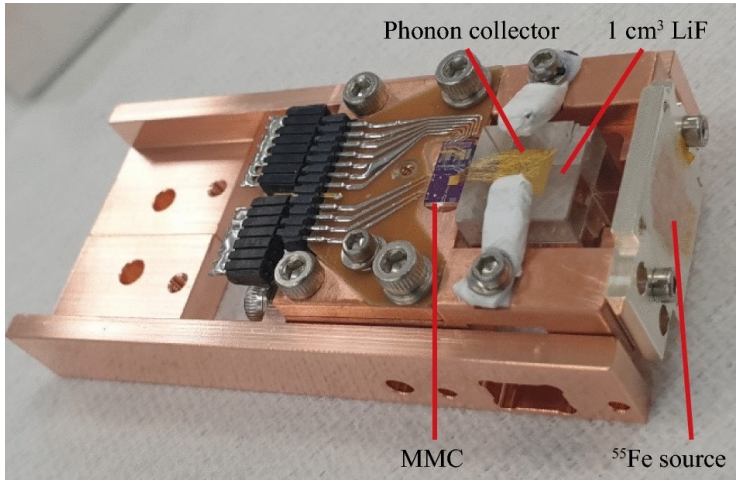


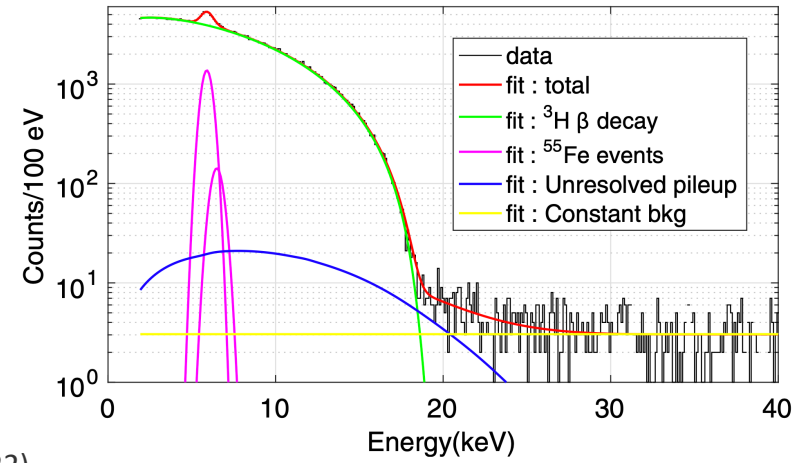
KATRIN+TRISTAN sensitivity to steriles

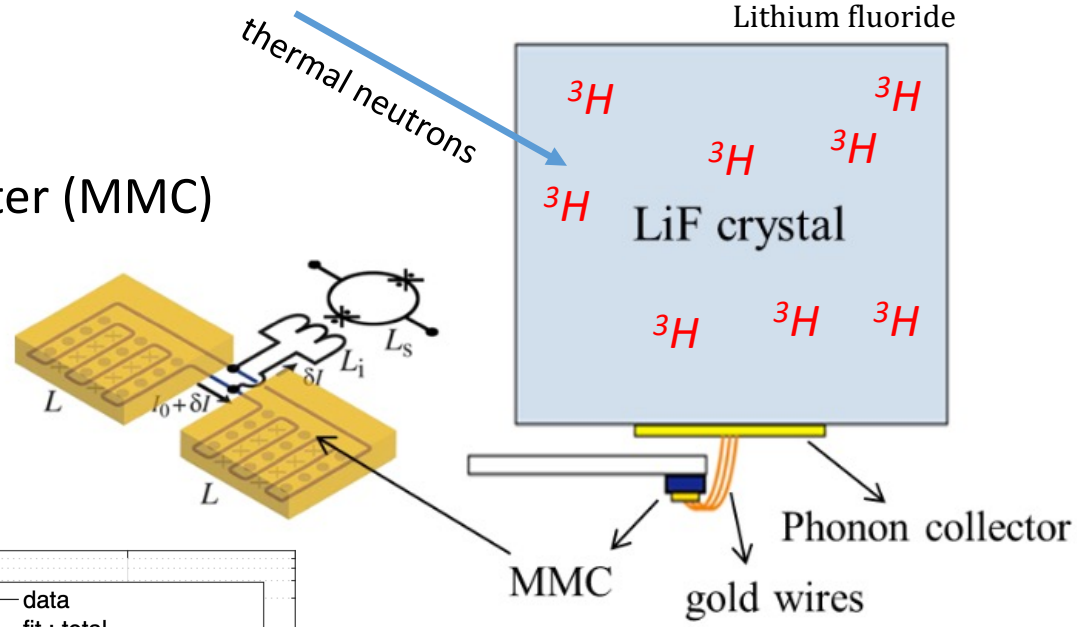


Other approaches: CUP

- Produce tritium in LiF crystal via ^{6}Li (n, α) ^{3}H reaction
- Measure decay energy with metallic magnetic calorimeter (MMC)
- Sensitivity target $\sin^2 \theta < 10^{-5}$
  (100 detectors × 100 Bq × 3 year)





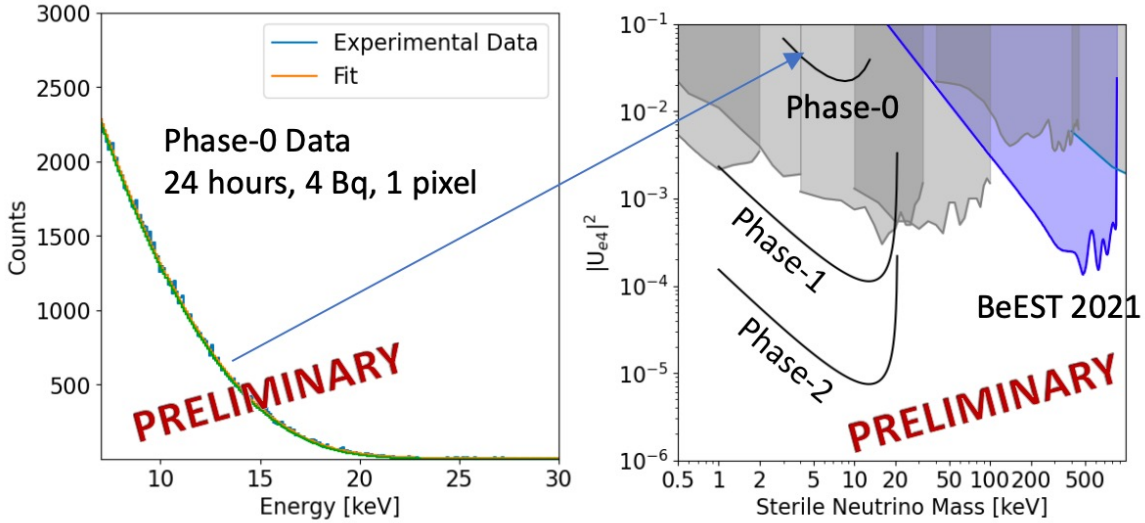


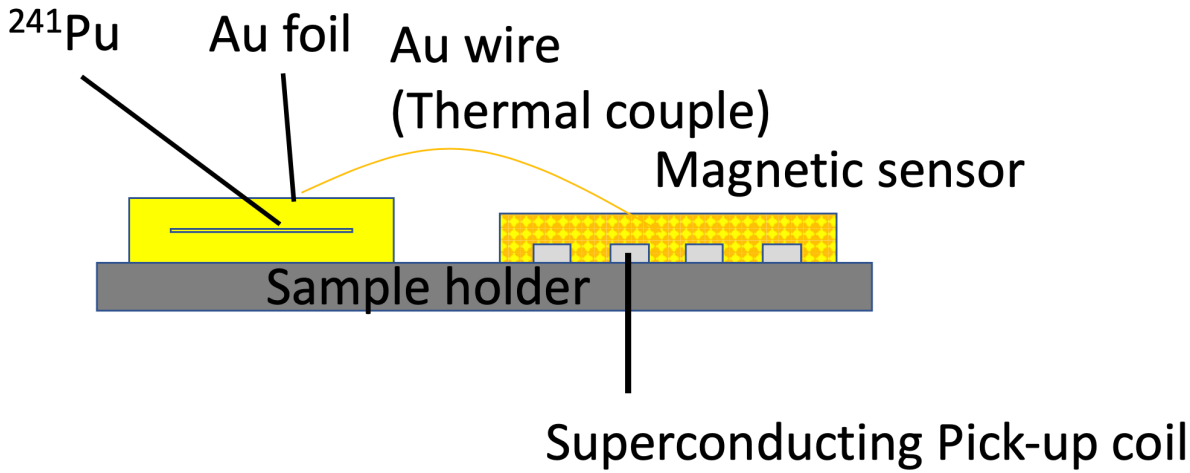
Lee, Y.C., Kim, H.B., Kim, H.L. *et al.* . *J Low Temp Phys* (2022)

Other approaches: Magneto-ν

- Plutonium-241 in gold foil
- Measure decay energy with metallic magnetic calorimeter (MMC)
- Sensitivity target $\sin^2\theta < 10^{-5}$

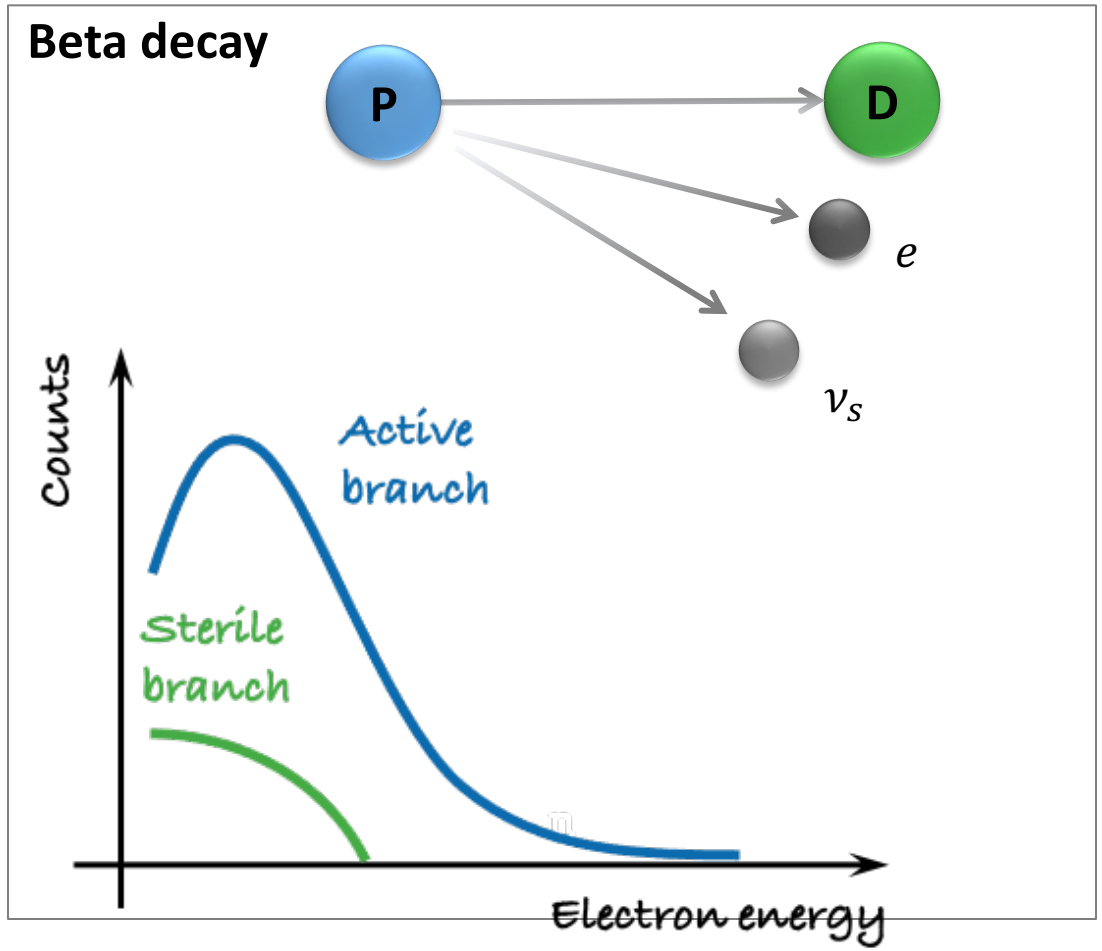
$T_{1/2}$ = 14 years
Q = 21 keV
First-forbidden

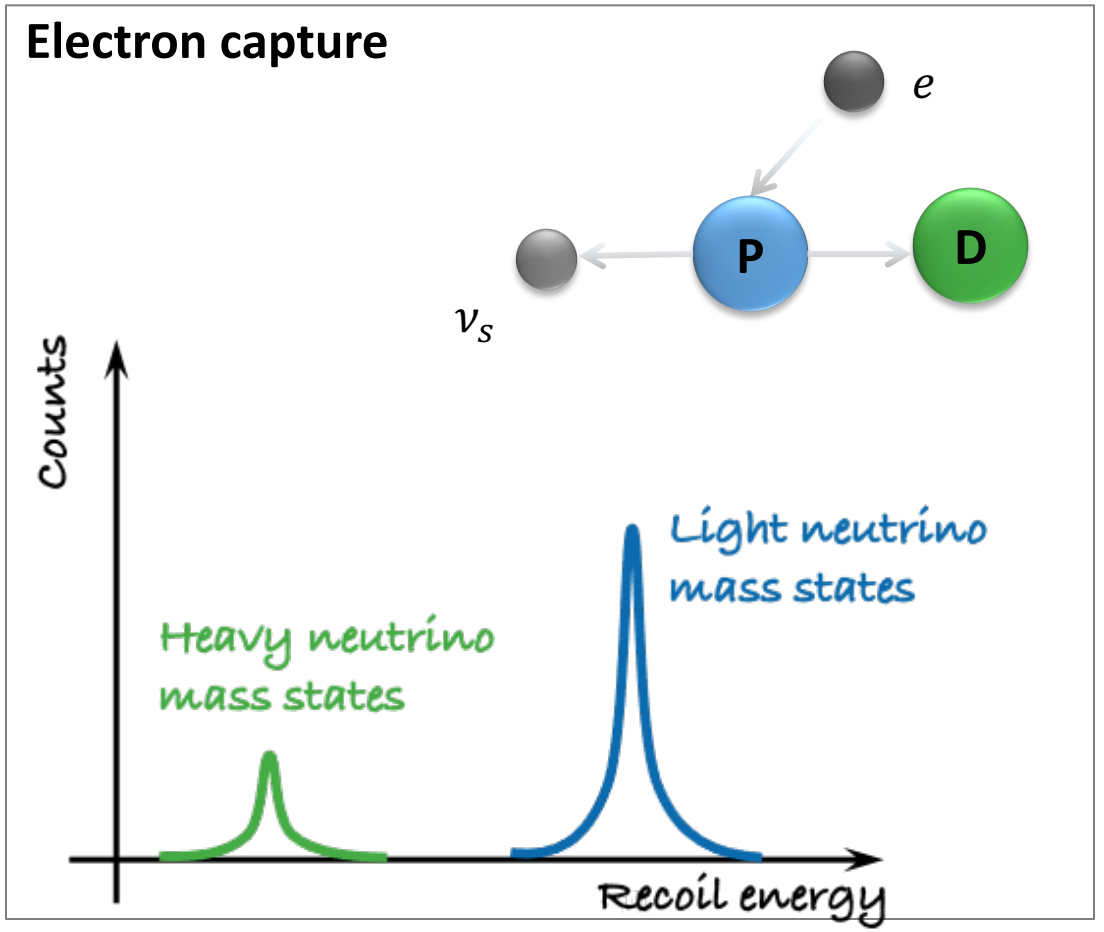




https://doi.org/10.5281/zenodo.6805550

Production in beta decays

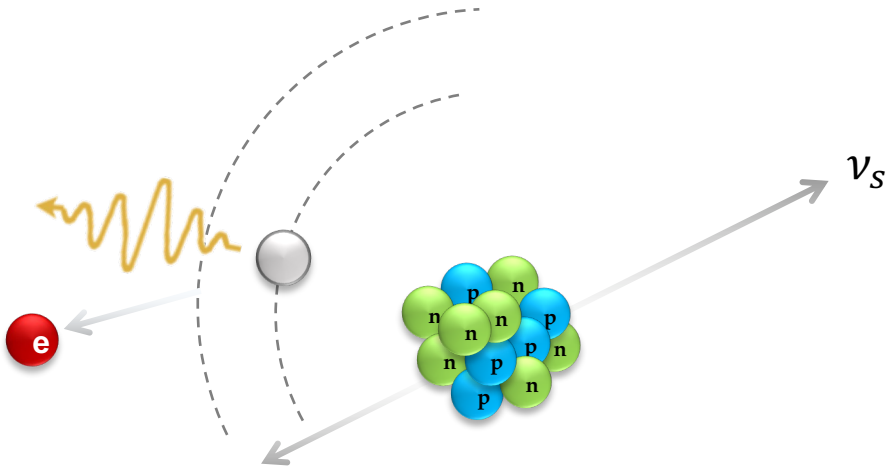




HUNTER

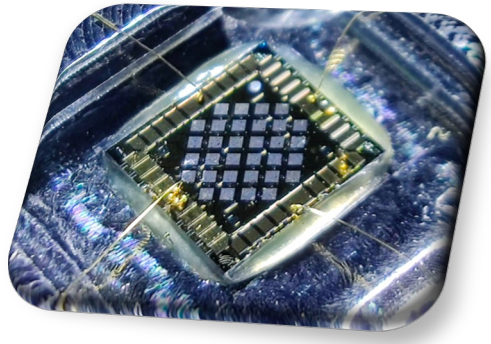
$T_{1/2}$ = 9 days
Q = 352 keV

- Electron capture decay: $e + {}^{131}Cs \rightarrow \nu_s + {}^{131}Xe$
- Atoms stored with Magneto-Optical-Trap (MOT)
- Detect recoiling Xe, but also x-rays and Auger electrons
- Sensitivity target $\sin^2\theta < 10^{-10}$ (10 – 300 keV)
  arXiv:1607.06876



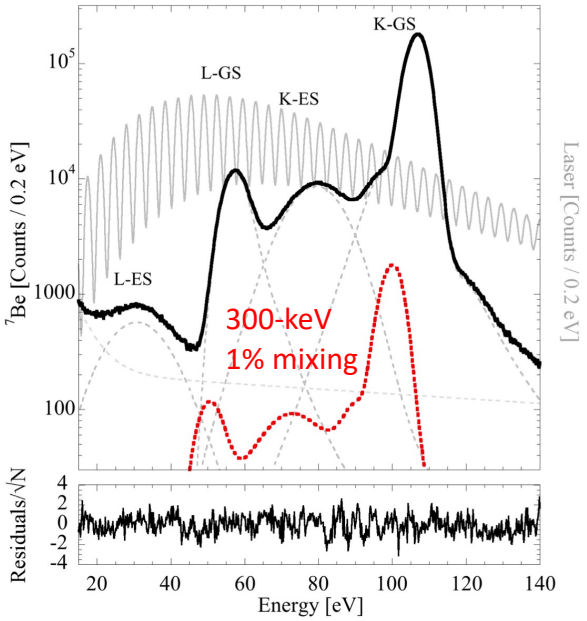
BeEST

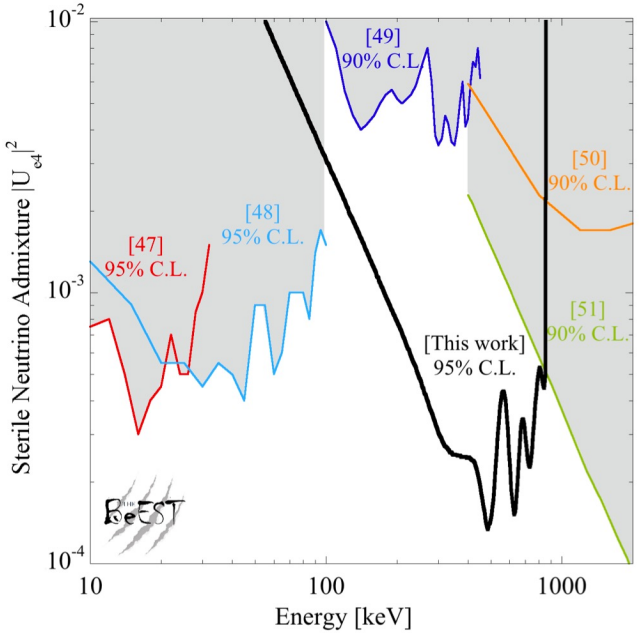
$T_{1/2}$ = 53 days
Q = 862 keV

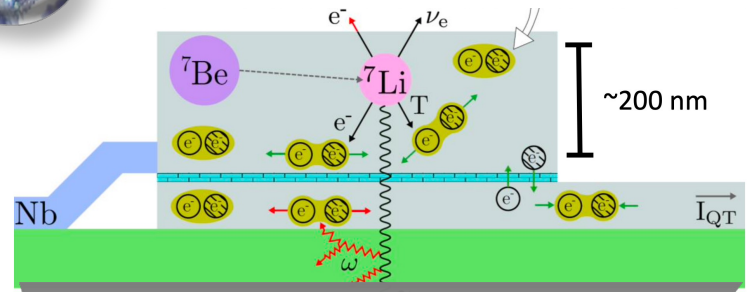


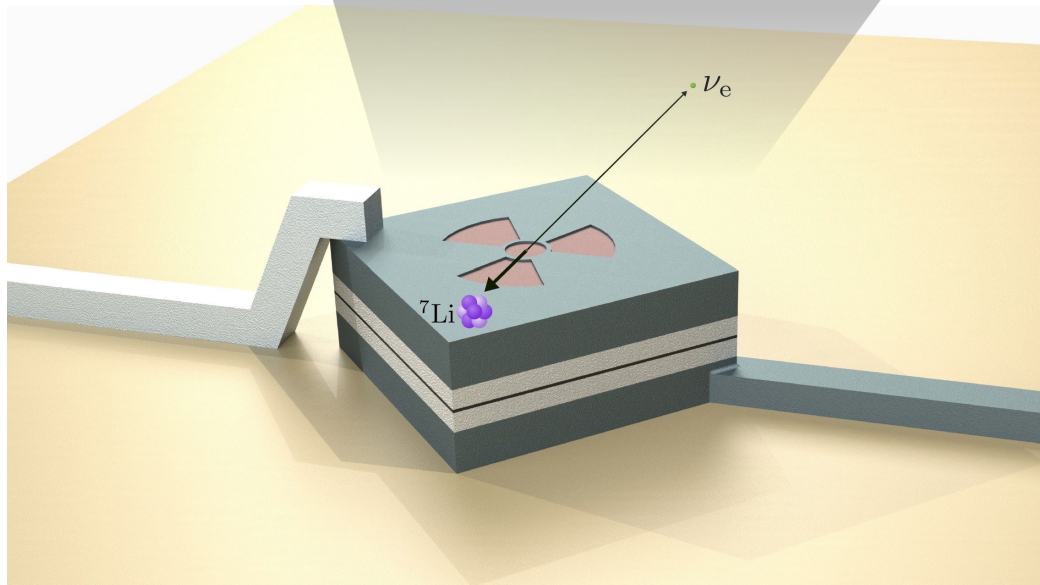
- Electron capture decay: $e + {}^{7}Be \rightarrow \nu_s + {}^{7}Li$
- High-resolution superconducting tunnel junction (STJ) detector
- First results published

  S. Fretwell *et al.*, Phys. Rev. Lett. **125**, 032701 (2020)
  S. Friedrich *et al.*, Phys. Rev. Lett. **126**, 021803 (2021)







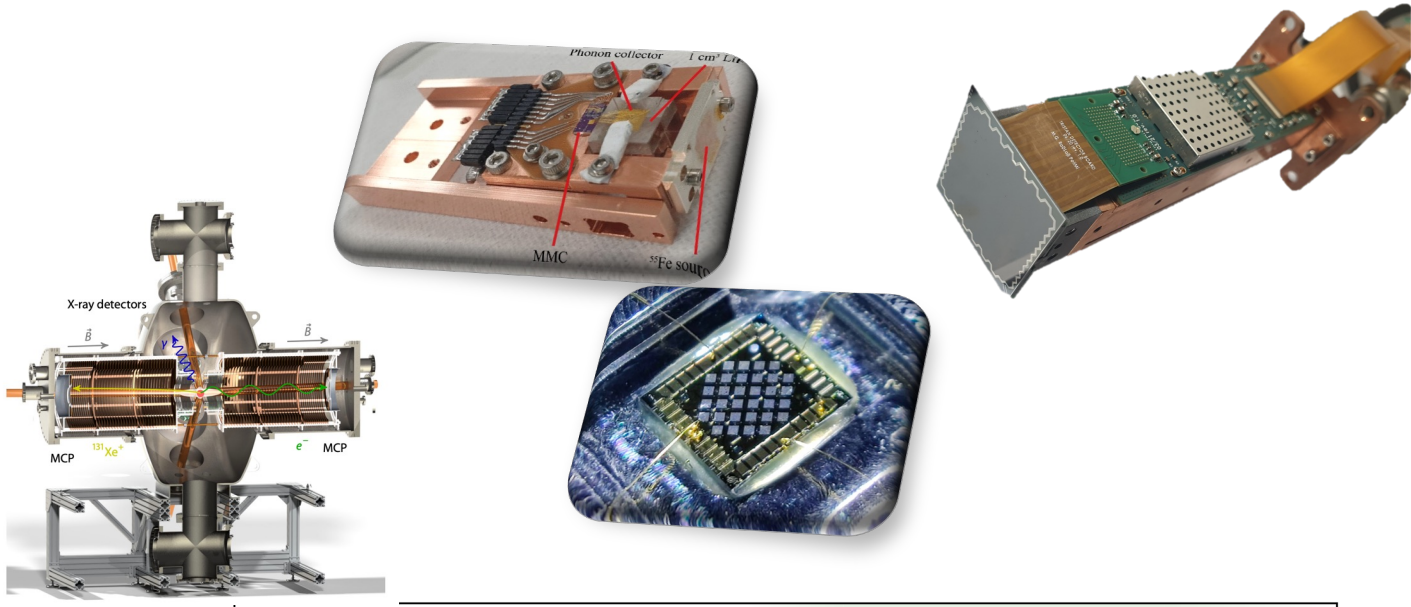


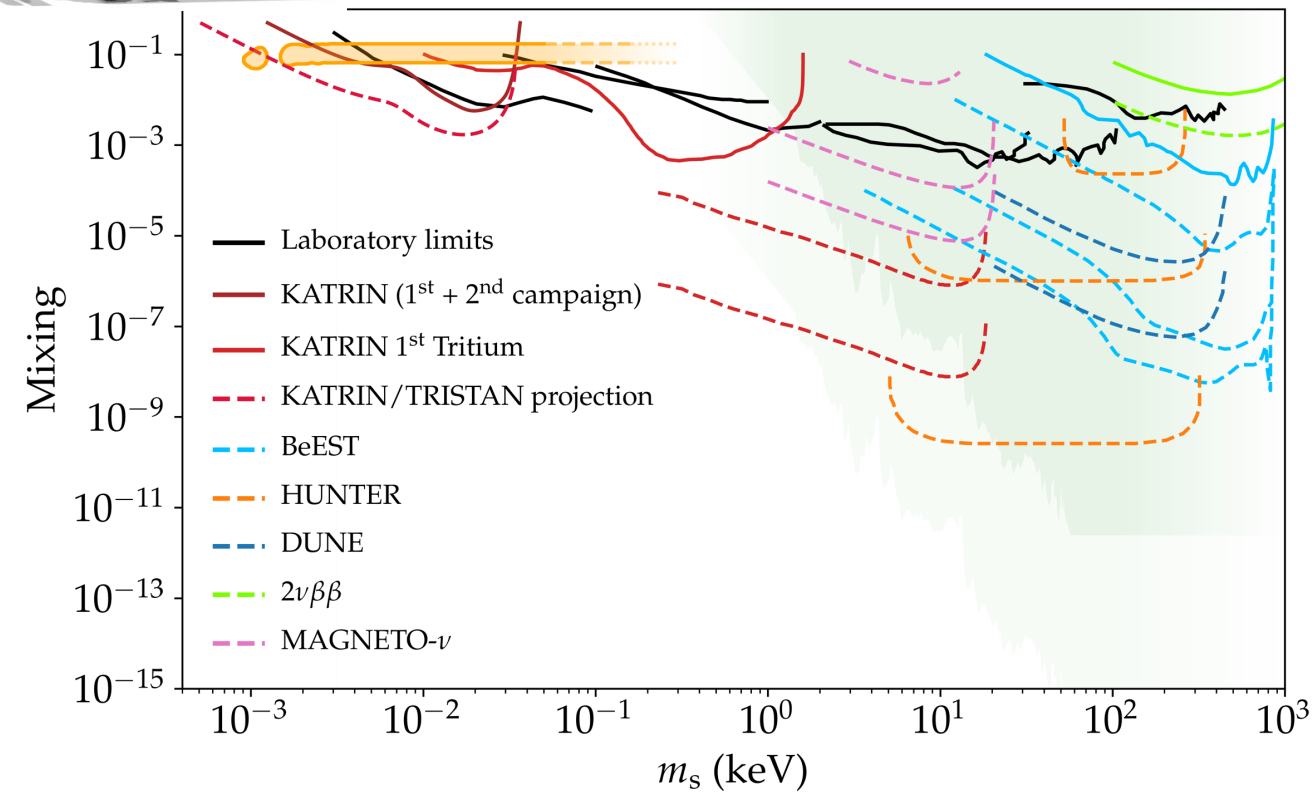
Summary

- keV-sterile neutrinos are a viable dark matter candidate
- Strong cosmological and indirect limits (but model-dependent)
- No dedicated direct search experiment

➢ **Searches via β-decays and electron capture**

- First results from KATRIN and BeEST
- Many promising R&D efforts
- Target sensitivity at 10^{-6} (or below)

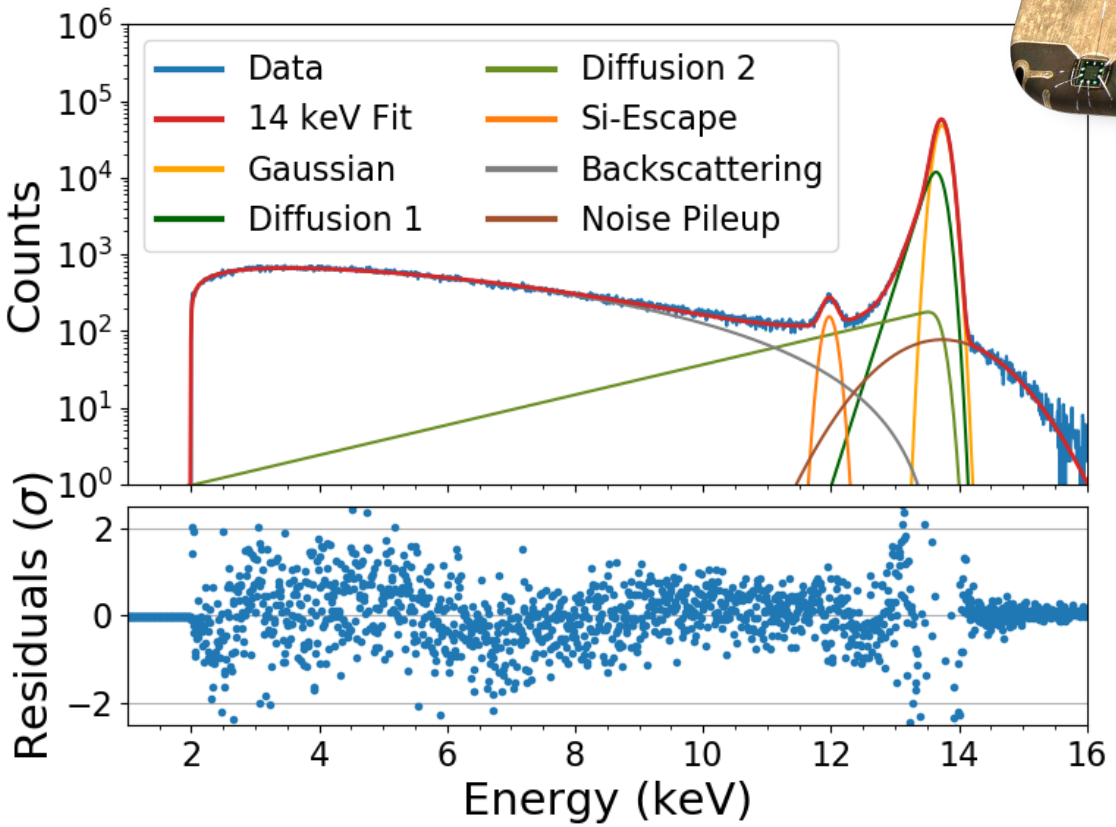


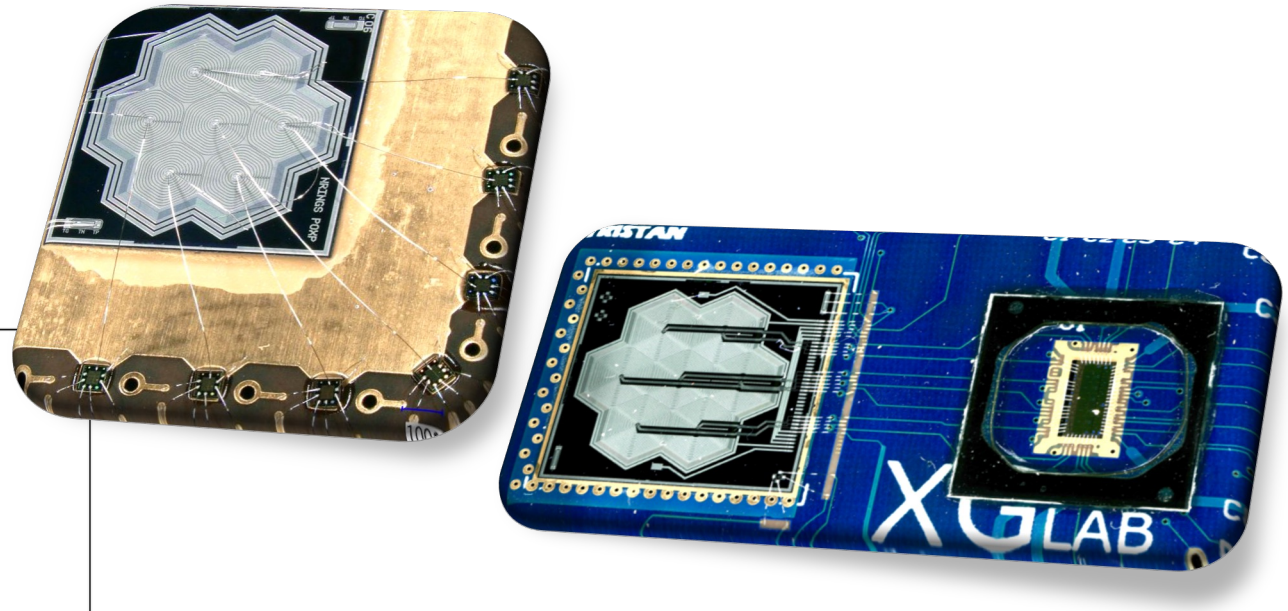


Thanks for your attention

Susanne Mertens
Technical University Munich

TRISTAN detector

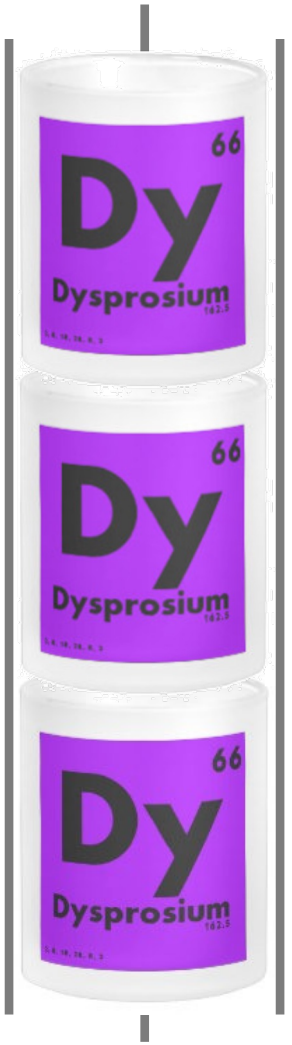


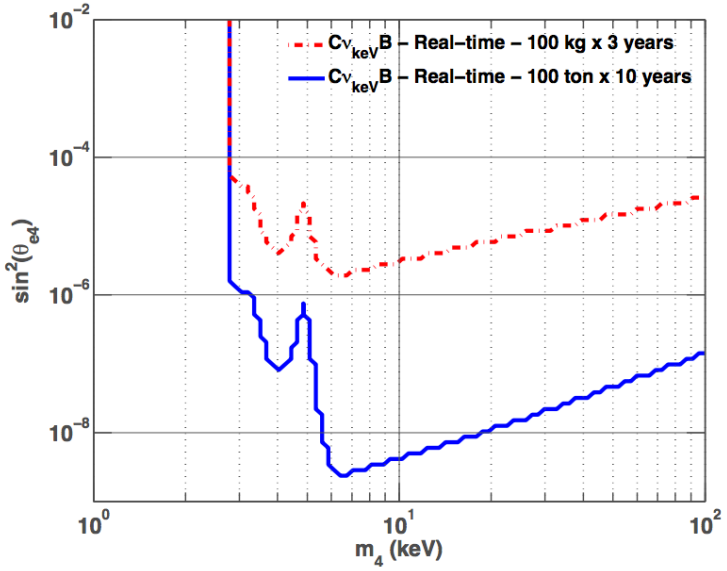


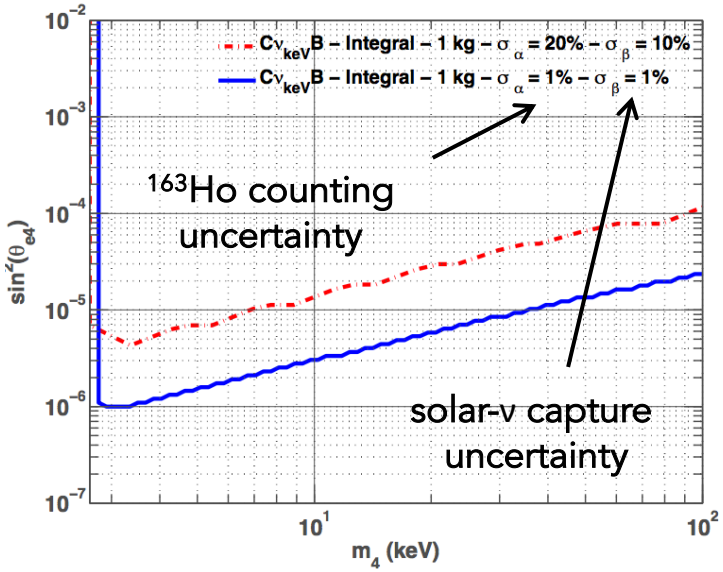
- ✓ Test of multiple prototype designs
- ✓ Excellent energy resolution for x-rays (140 eV @ 6 keV)
  S. Mertens et al, J. Phys. G46 (2019)
- ✓ Detailed characterization with electron
  S. Mertens et al, J. Phys. G48 (2020)

Dysprosium: $^{163}\mathrm{Dy} + \nu_4 \rightarrow {}^{163}\mathrm{Ho} + e$

1. Built a large detector out of dysprosium
   … and measure the energy of the emitted electron
   … extremely challenging background requirements
2. Use the natural abundance of dysprosium
   … and search for holmium atoms







T. Lasserre, K. Altenmueller, M. Cribier, A. Merle, S. Mertens, M. Vivier arXiv:1609.04671 (2016)