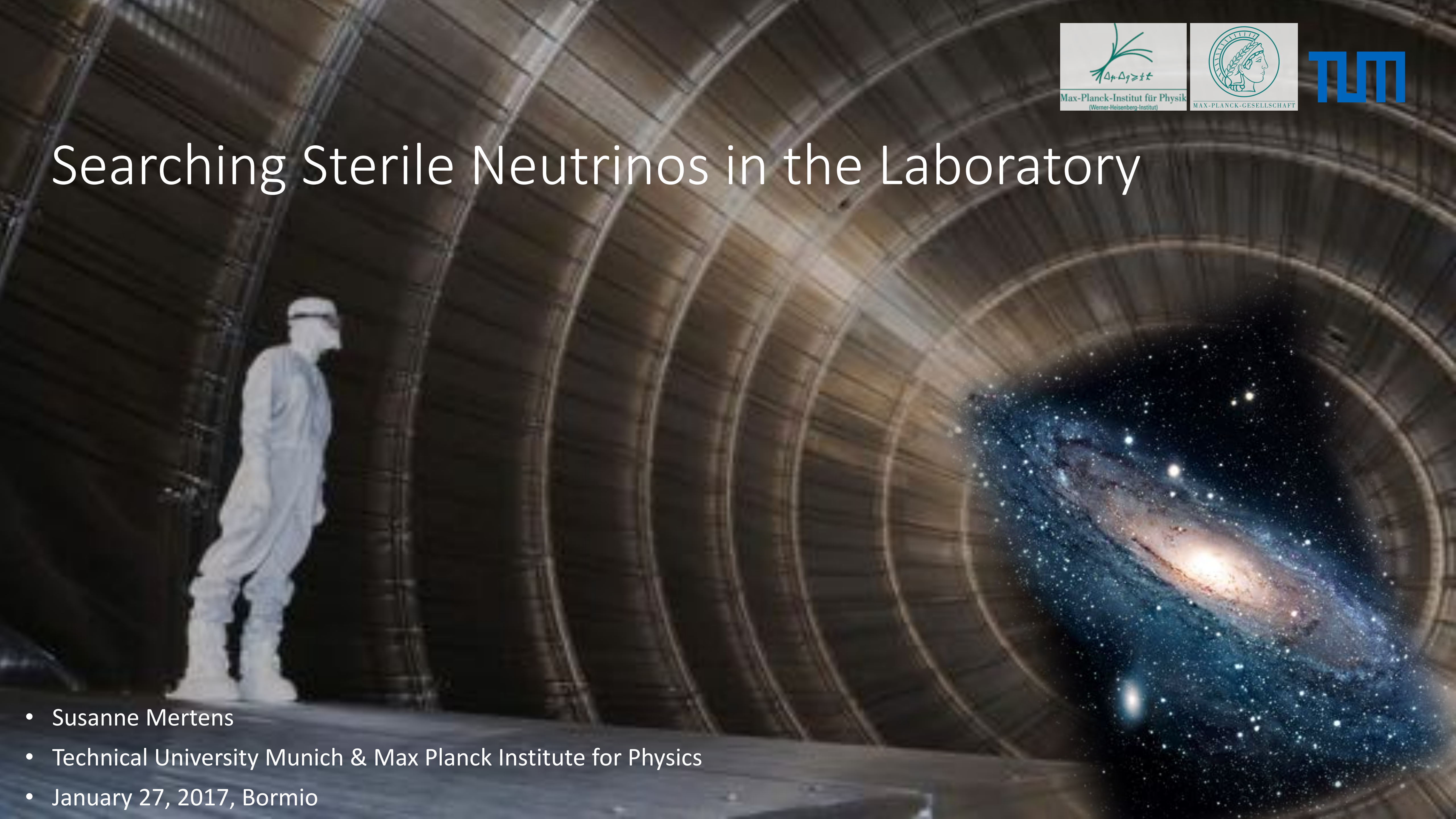


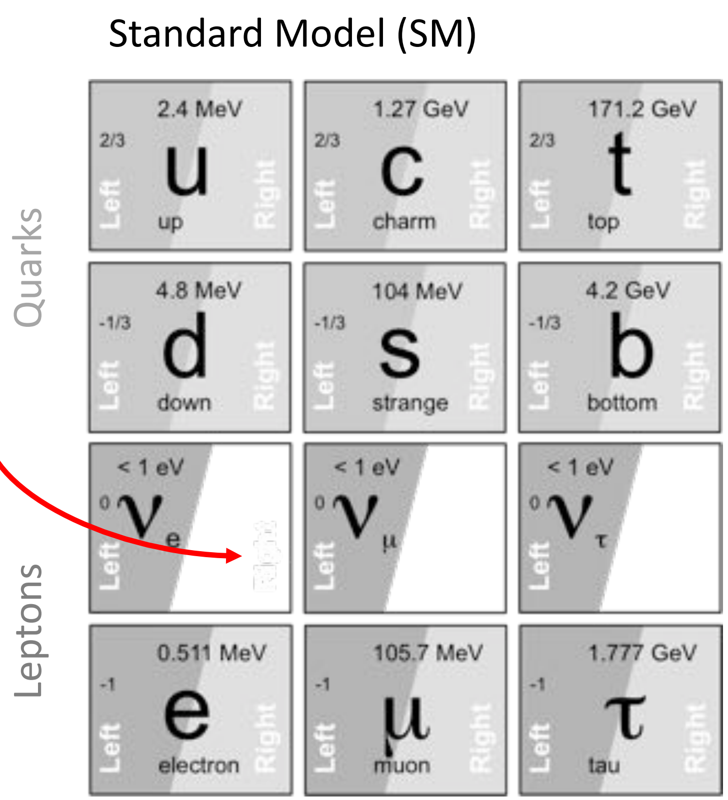
Searching Sterile Neutrinos in the Laboratory

- Susanne Mertens
- Technical University Munich & Max Planck Institute for Physics

- January 27, 2017, Bormio

Sterile Neutrinos

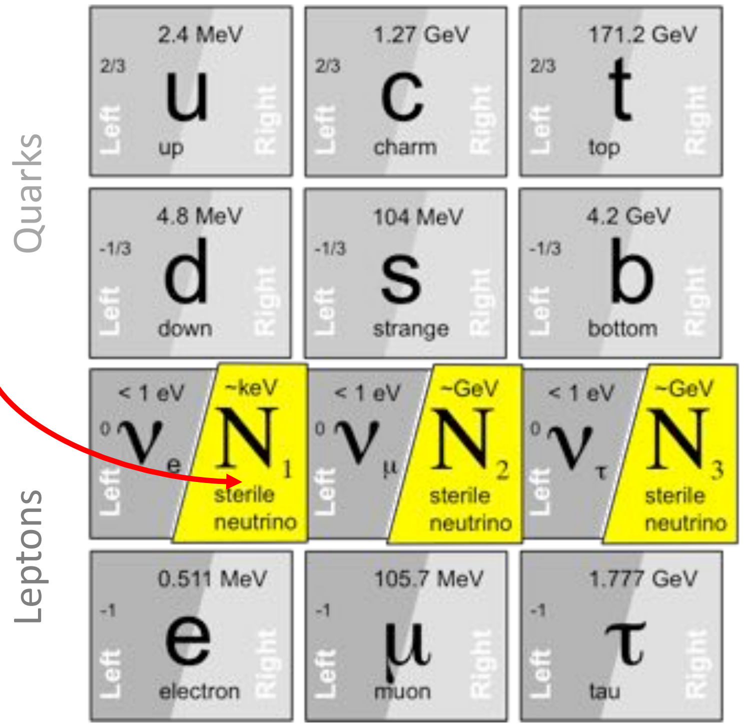
Something is missing



Sterile Neutrinos

Standard Model (SM)

Sterile neutrino



Sterile Neutrinos

Active and sterile neutrinos mix

- 4th neutrino mass eigenstate: mostly (but not totally) sterile

Sterile Neutrinos

Heavy sterile neutrinos (~ GeV)

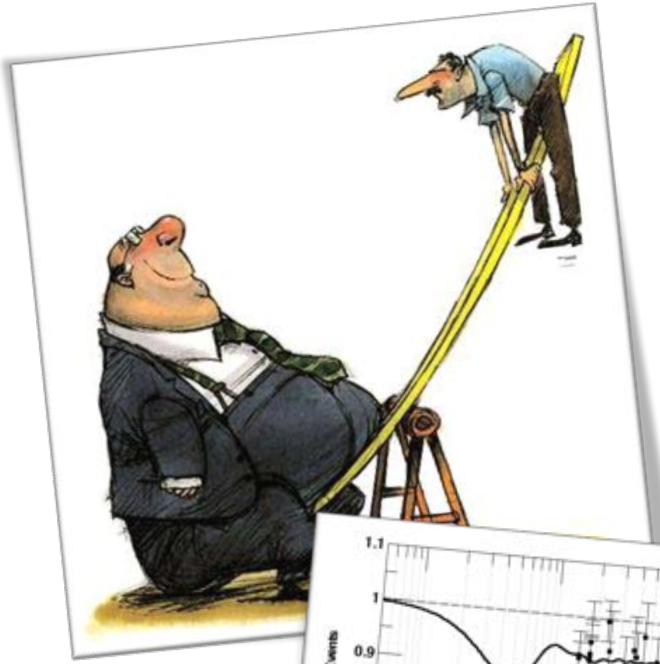
- Lightness of neutrinos via
  See-saw mechanism

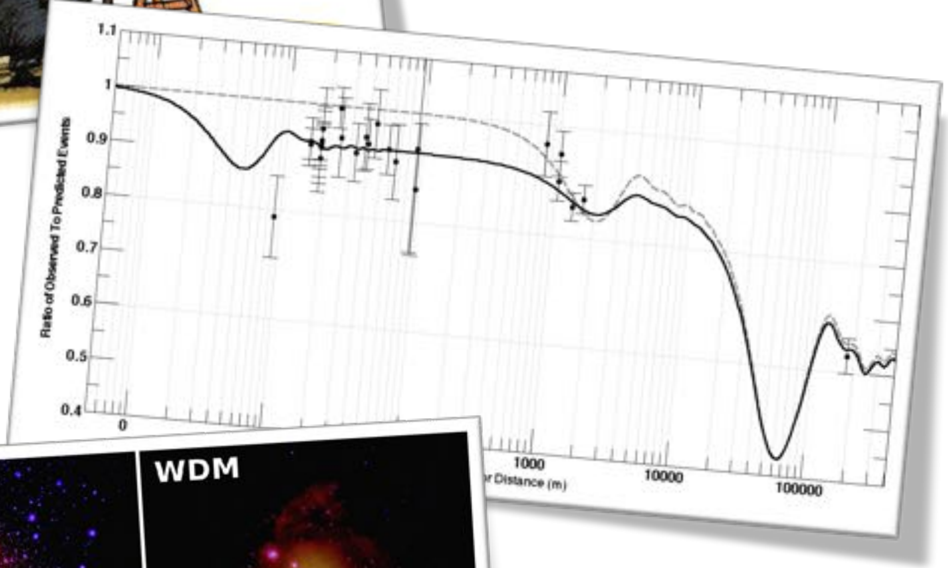
Light sterile neutrinos (~1 eV)

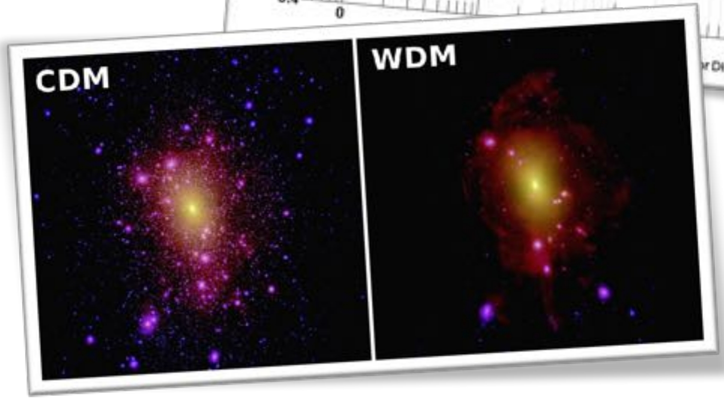
- Reactor anomaly, Gallium anomaly, Short baseline accelerator results

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

- Warm and cold dark matter candidates







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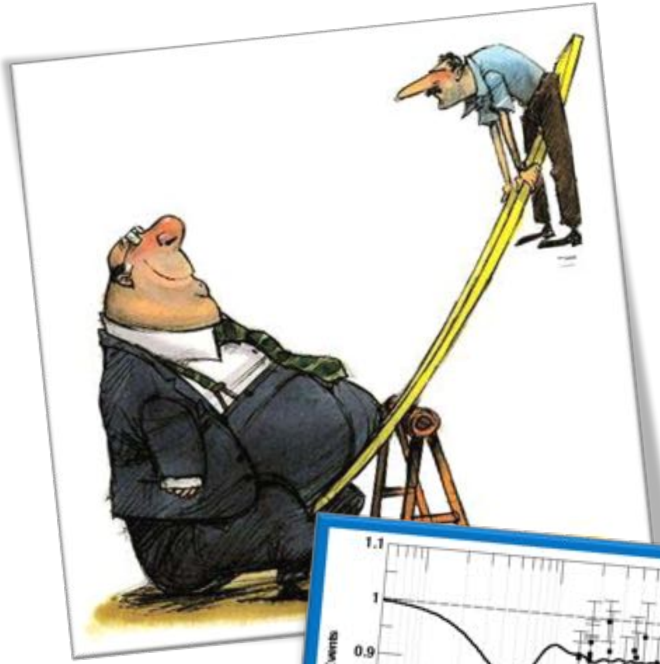
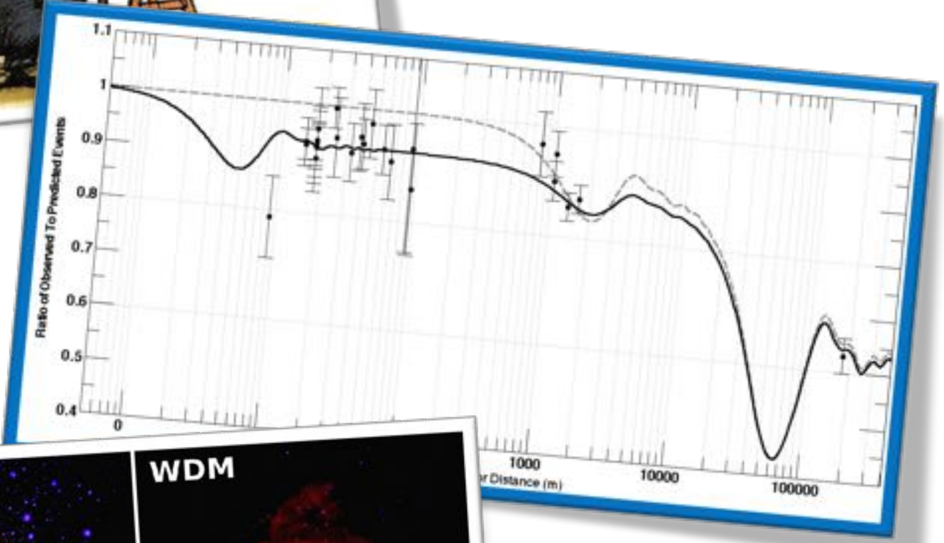
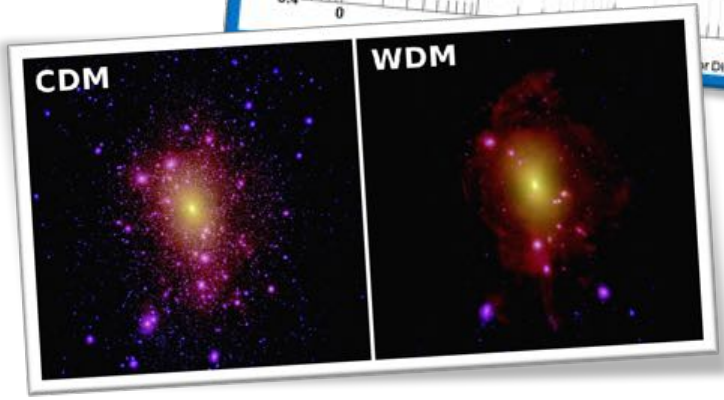
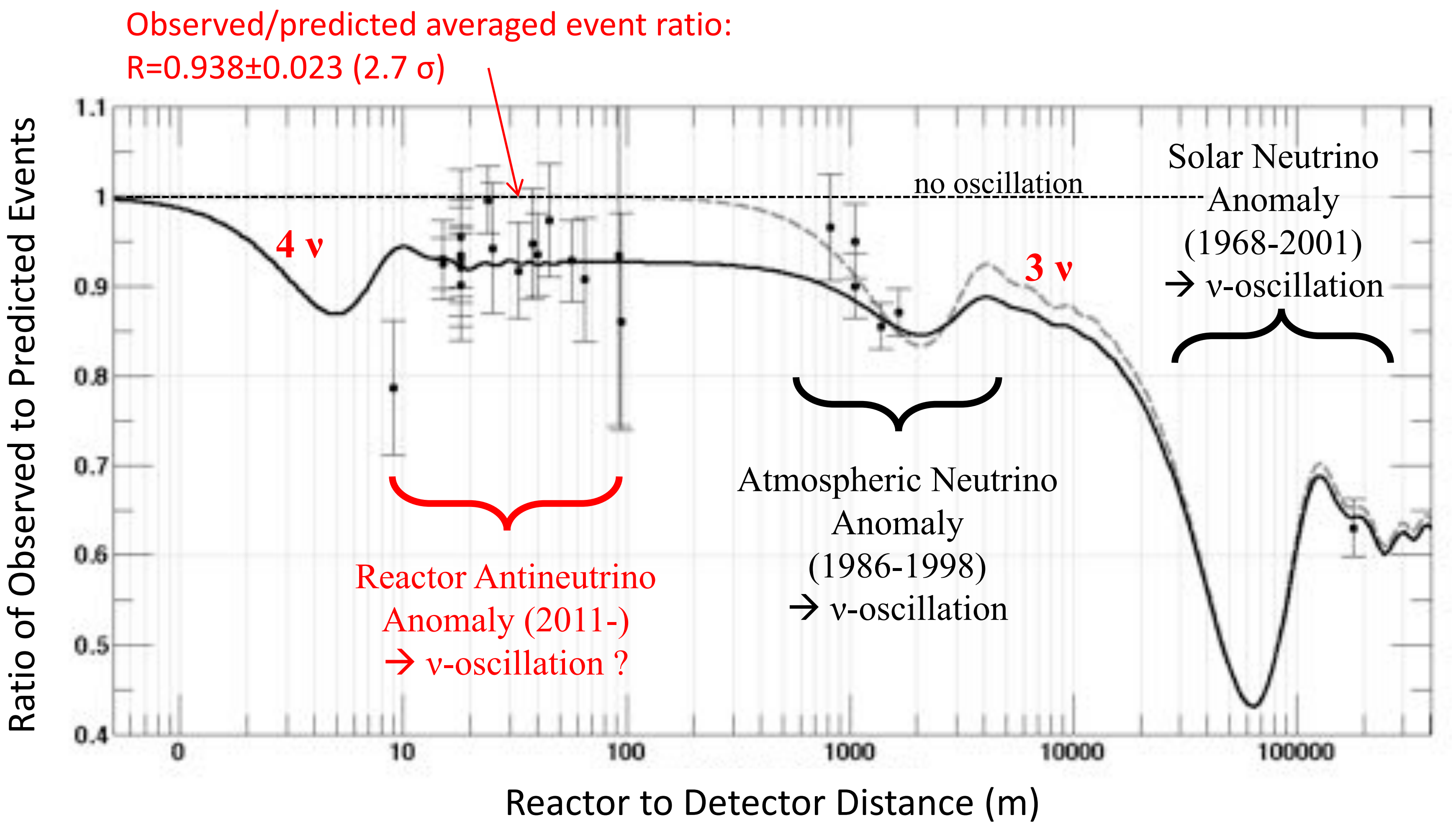






The Reactor Anomaly

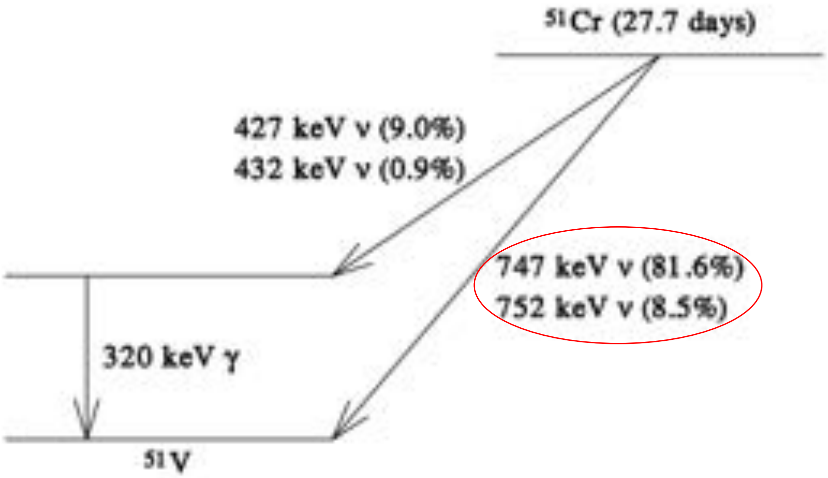


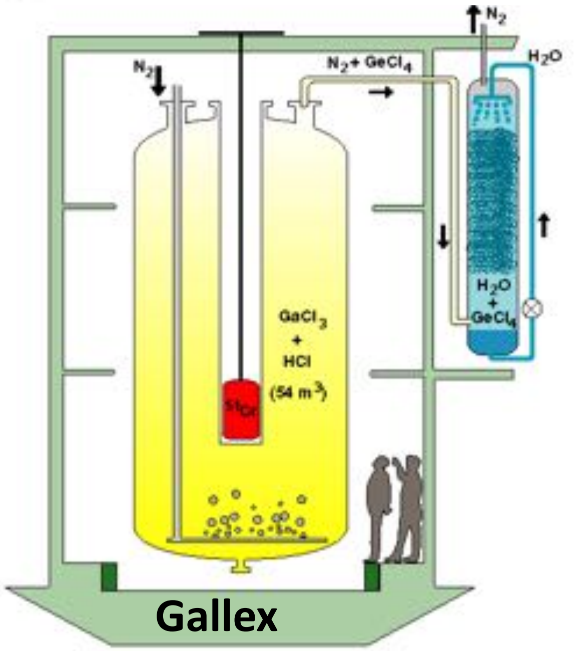
G. Mention, Phys. Rev. D 83, 073006 (2011)

The Gallium Anomaly

- Test of solar neutrino radiochemical detectors GALLEX and SAGE
  - $^{71}Ga + \nu_e \rightarrow {}^{71}Ge + e^-$
- 4 calibration runs with 20-60 PBq Electron Capture ν_e emitters
  - **GALLEX:**
    $\langle L \rangle = 1.9\ \mathrm{m}$
    $E_\nu = 750\ \mathrm{keV}\ ({}^{51}\mathrm{Cr})$
  - **SAGE:**
    $\langle L \rangle = 0.6\ \mathrm{m}$
    $E_\nu = 810\ \mathrm{keV}\ ({}^{51}\mathrm{Cr},\ {}^{37}\mathrm{Ar})$

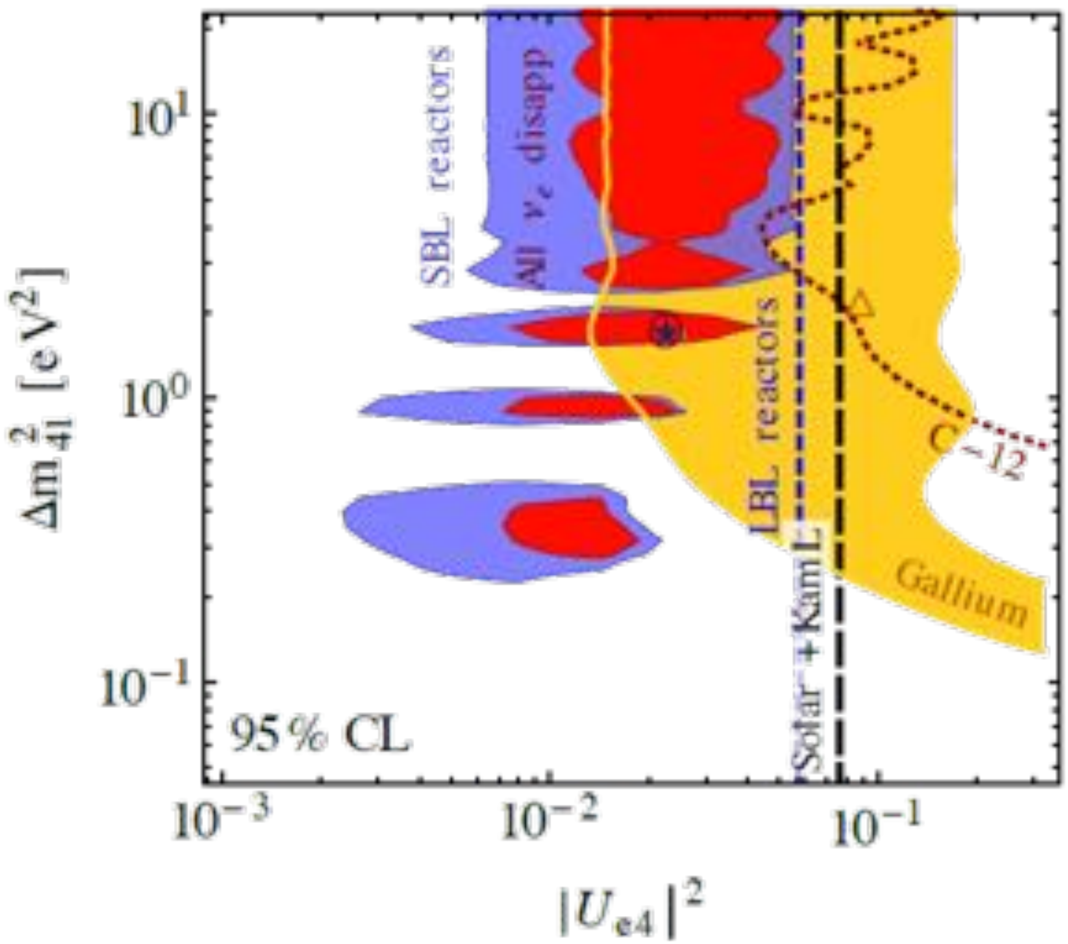
➢ 3σ deficit observed





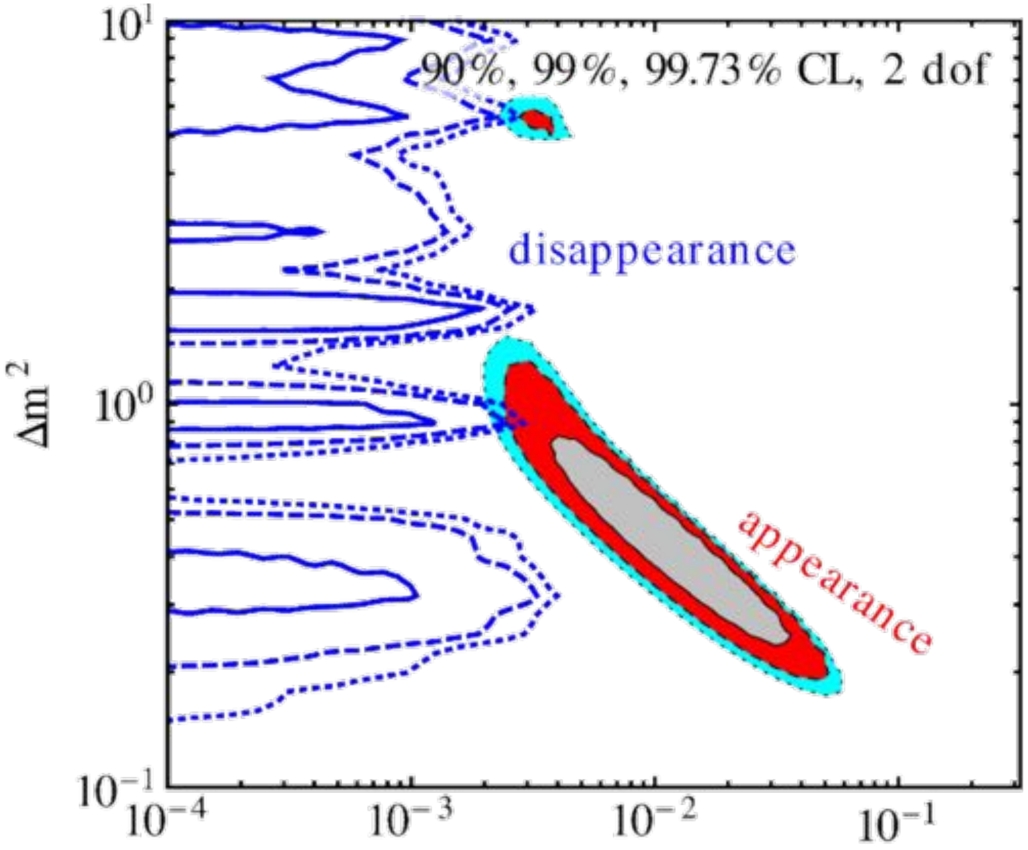
ν_e disappearance (3+1)

Data consistent with ν_e disappearance at L/E≈1 m/MeV



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

ν_e appearance vs disappearance (3+1)



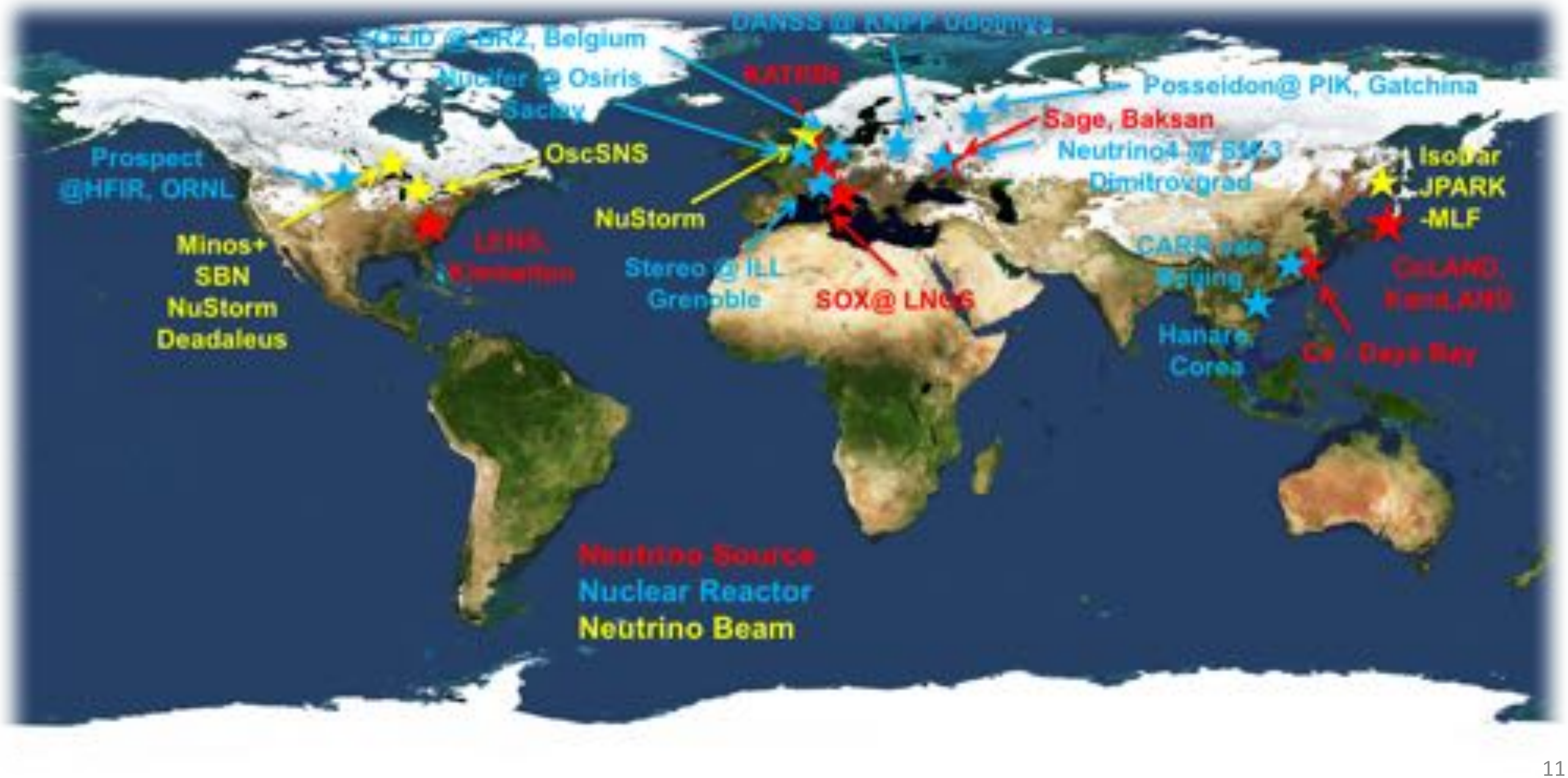
$\sin^2(2\theta_{\mu e})$

ν_e – disappearance
→ observed

ν_μ – disappearance
→ not observed

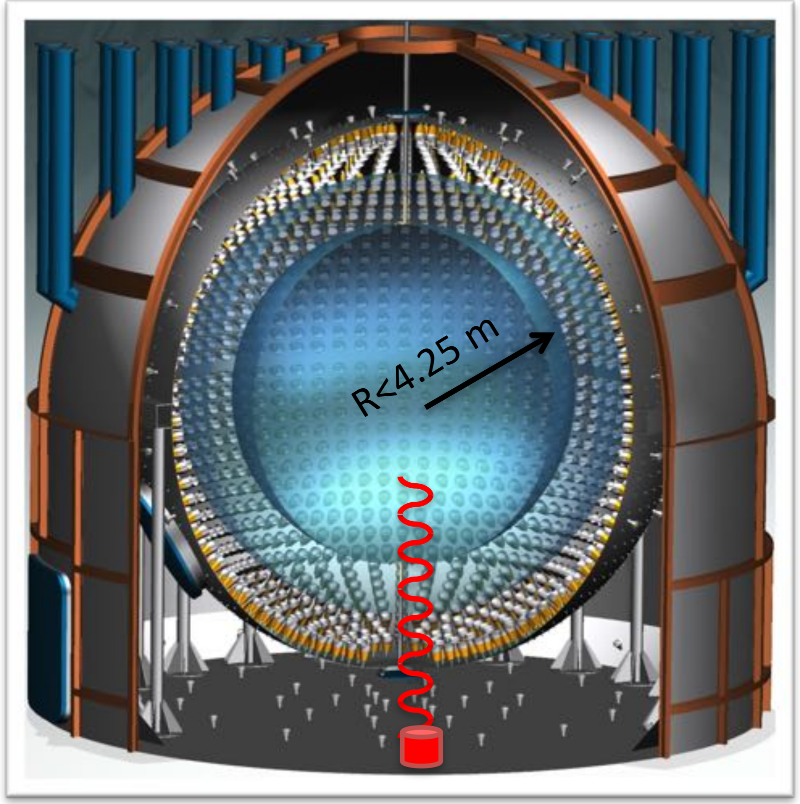
$= \sin^2(2\theta_{\mu\mu}) \sin^2(2\theta_{ee})$

World-wide Hunt for Steriles

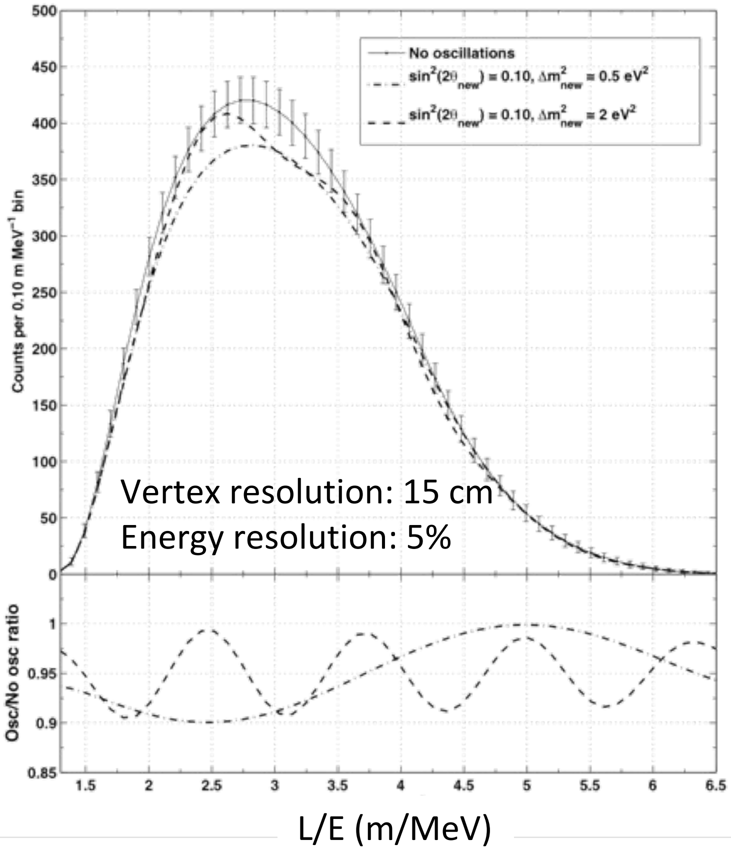


The Ce-SOX Experiment

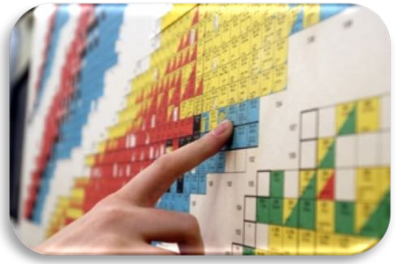
Deploying a neutrino source at the Borexino detector at Gran Sasso

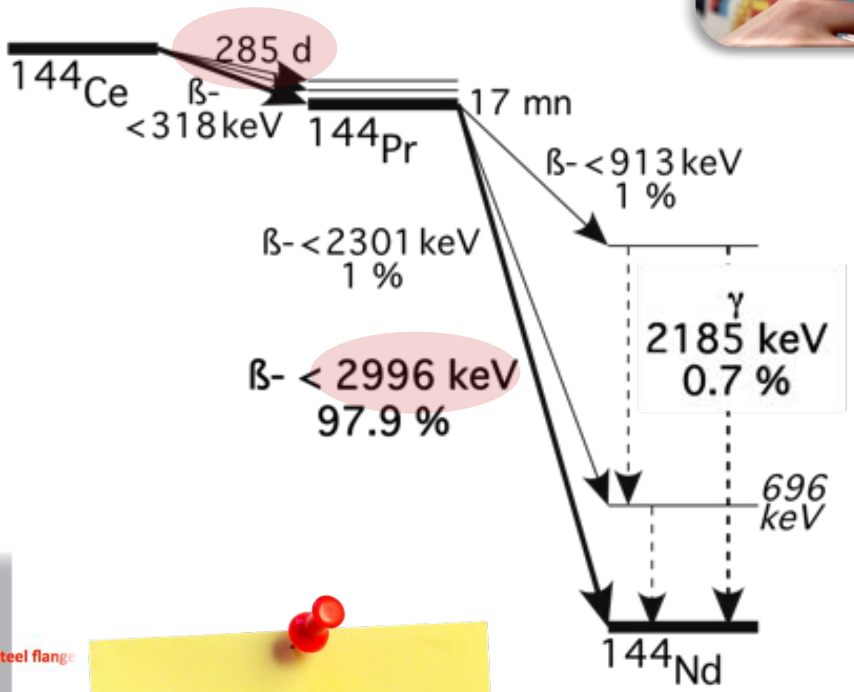


Observe oscillation signature inside the detector volume



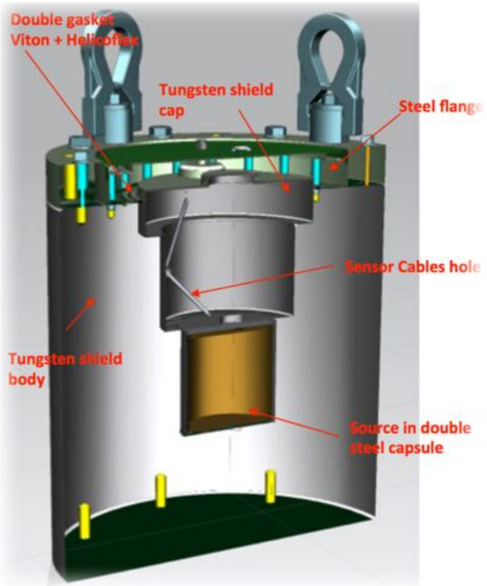
The Ce-SOX Source





- Anti-neutrino source: $\bar{\nu}_e + p \rightarrow e^+ + n$
  - ➢ coincidence signal
  - ➢ background discrimination

- ^{144}Ce abundant fission product,
  long-lived enough,
  endpoint above threshold



500^0 C inside the capsule
19 cm tungsten shielding

- 3.7-5.5 PBq (10^{15} Bq) of ^{144}Ce

- Source production started this year!

A challenging Journey

Start data taking in 2018

Other Challenging Journeys…

Other Challenging Journeys…

KATRIN can also look for sterile ν

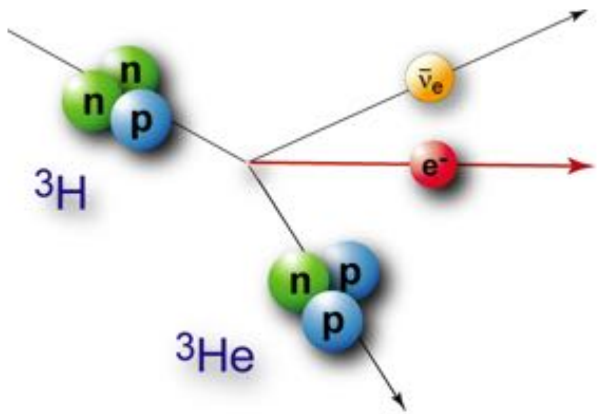
The KATRIN Experiment

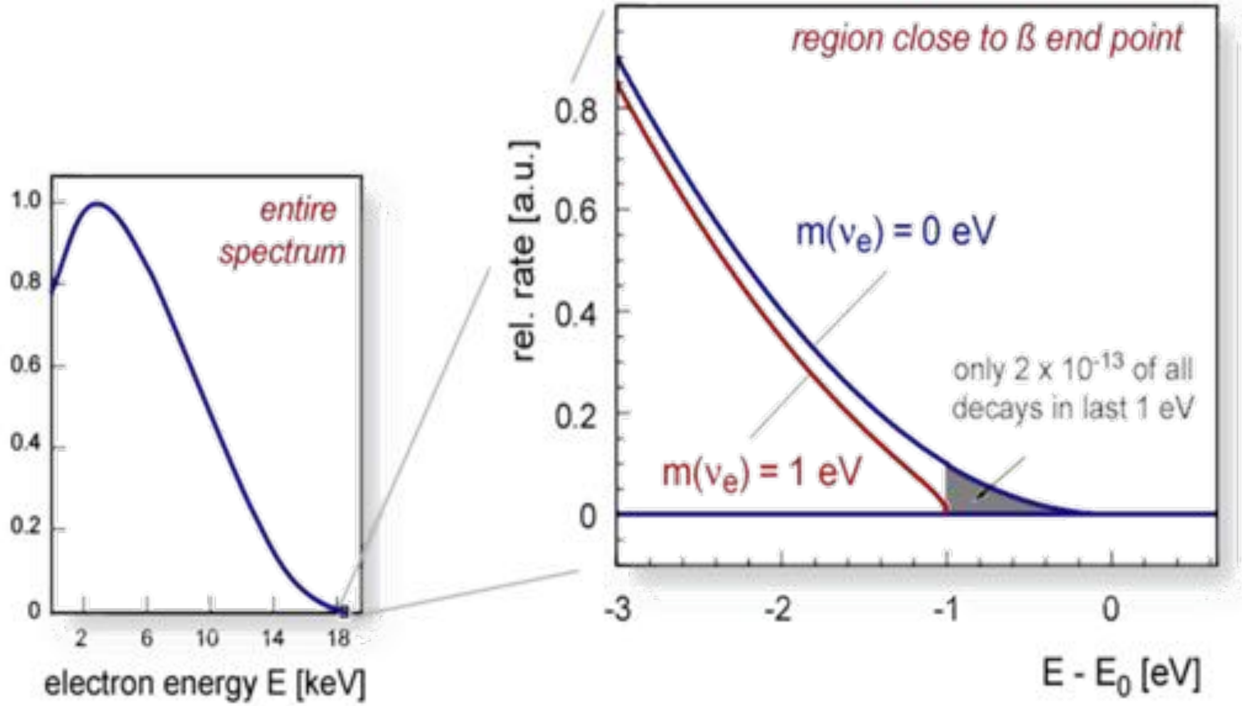
Goal:
Probing the effective electron anti-neutrino mass

200 meV sensitivity @90%CL (3 years)

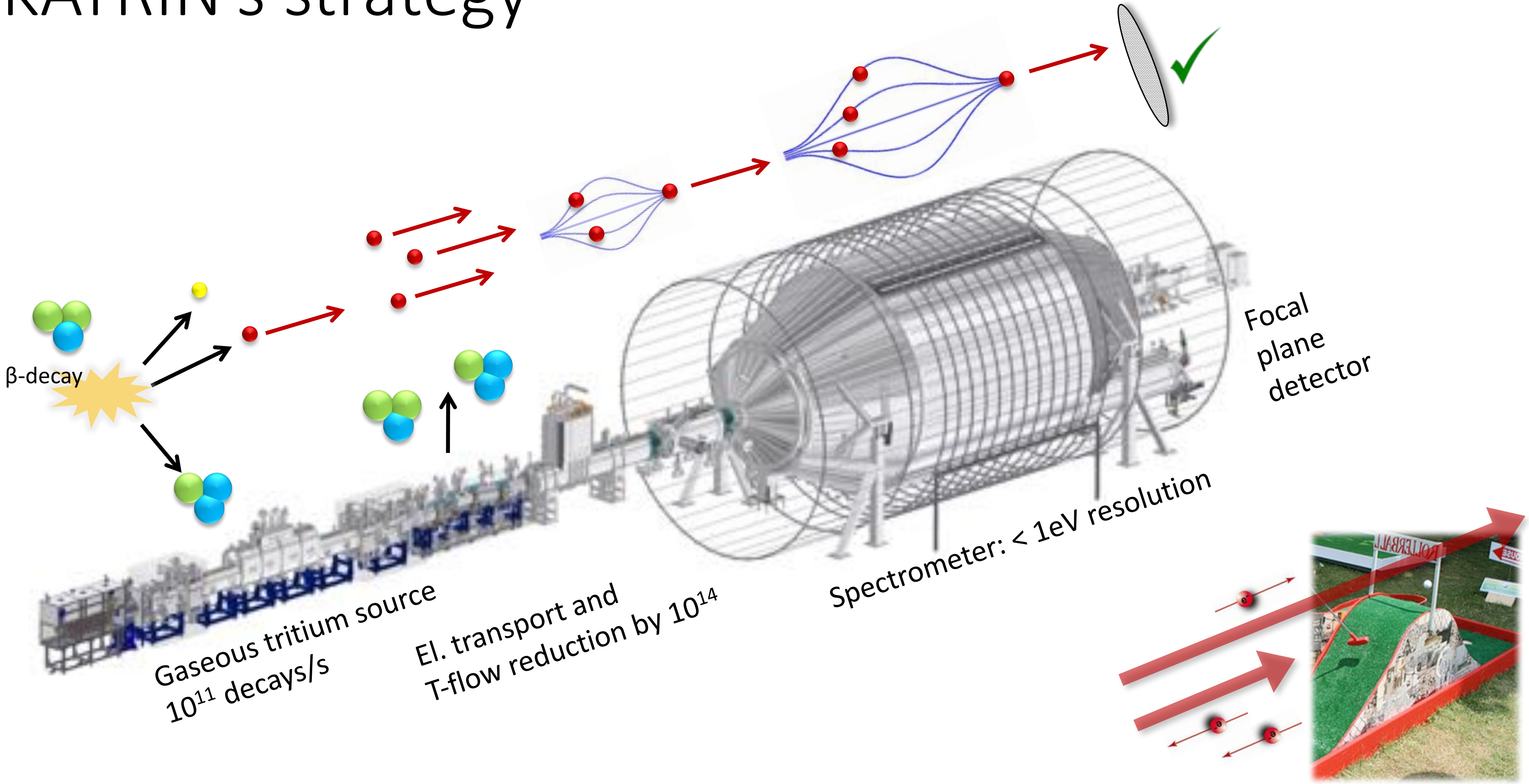
The KATRIN Experiment

- Kinematic determination of the neutrino mass
- Non-zero neutrino mass reduces the endpoint and distorts the spectrum



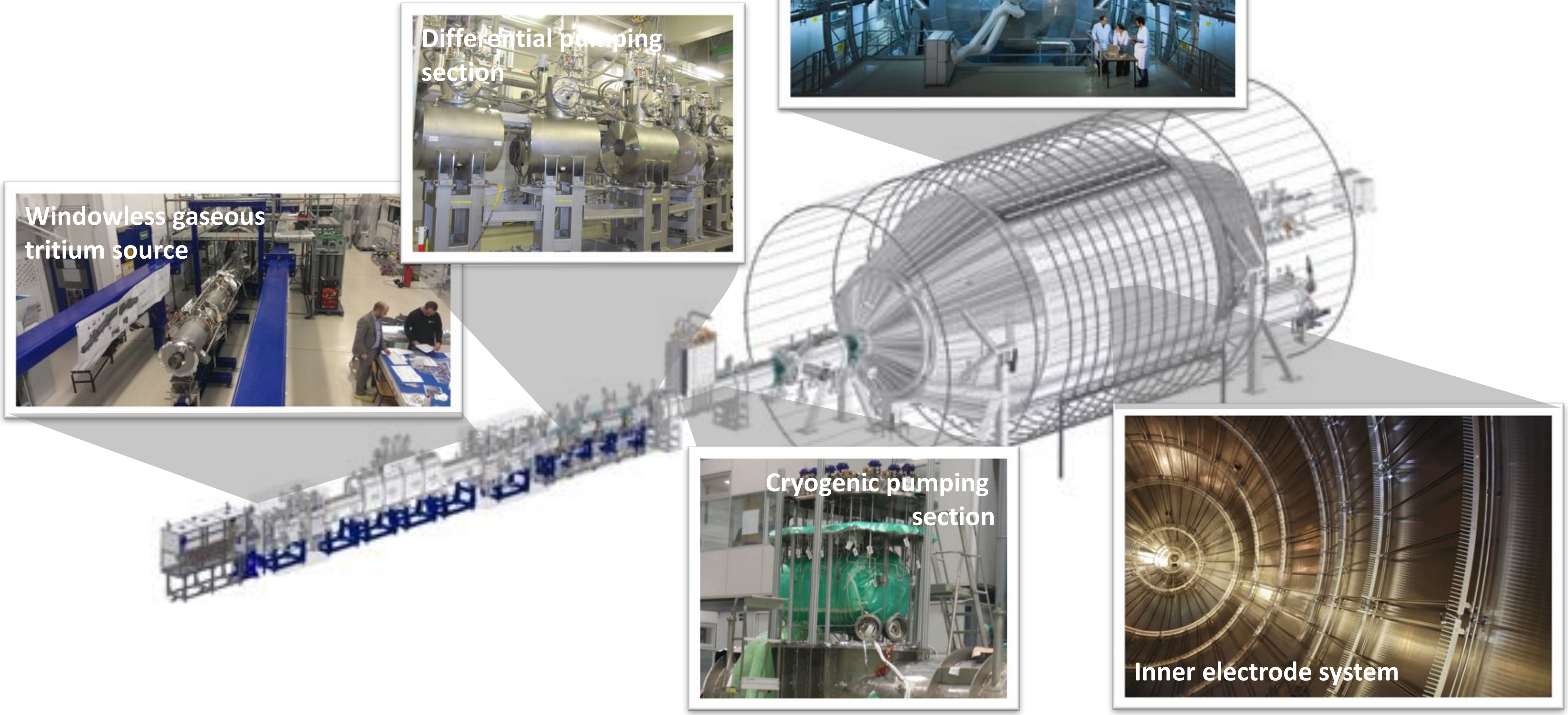


KATRIN’s strategy



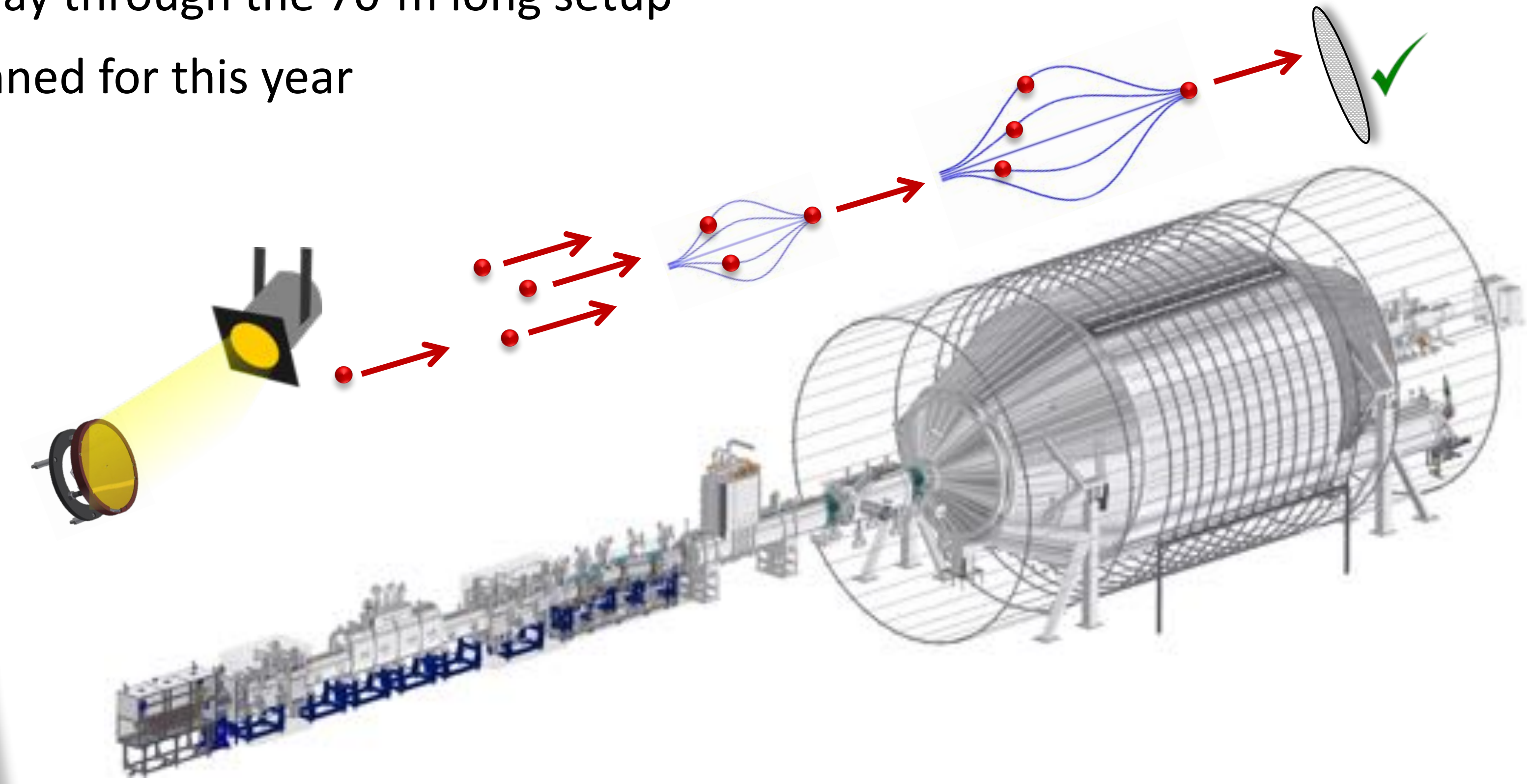
KATRIN Status

All components are at KIT

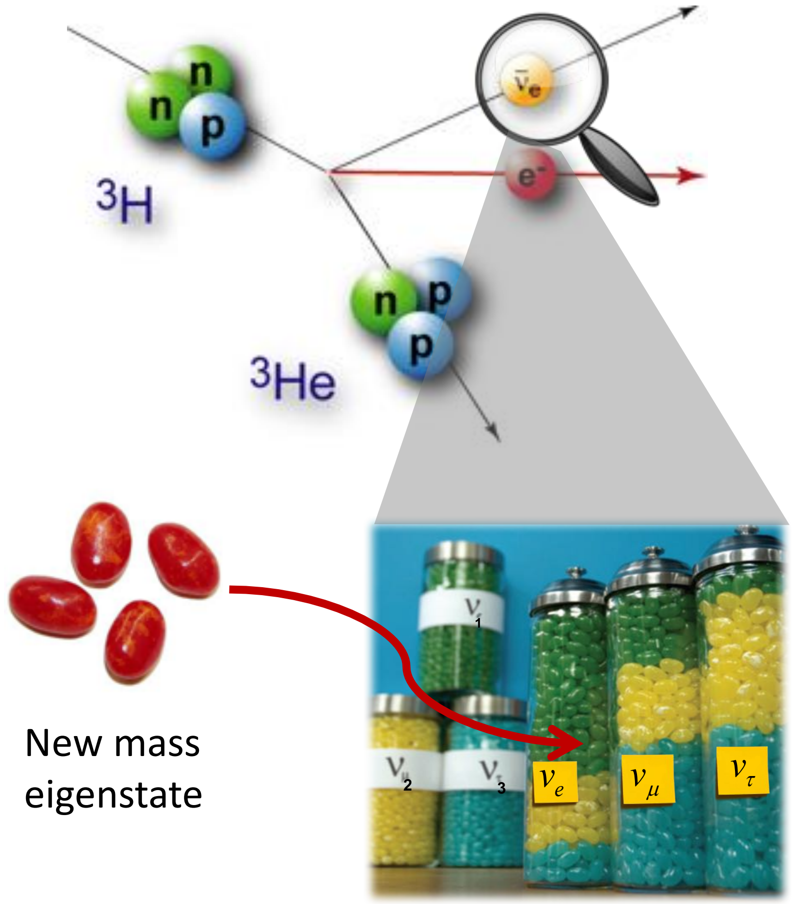


KATRIN’s first light: October 14, 2016

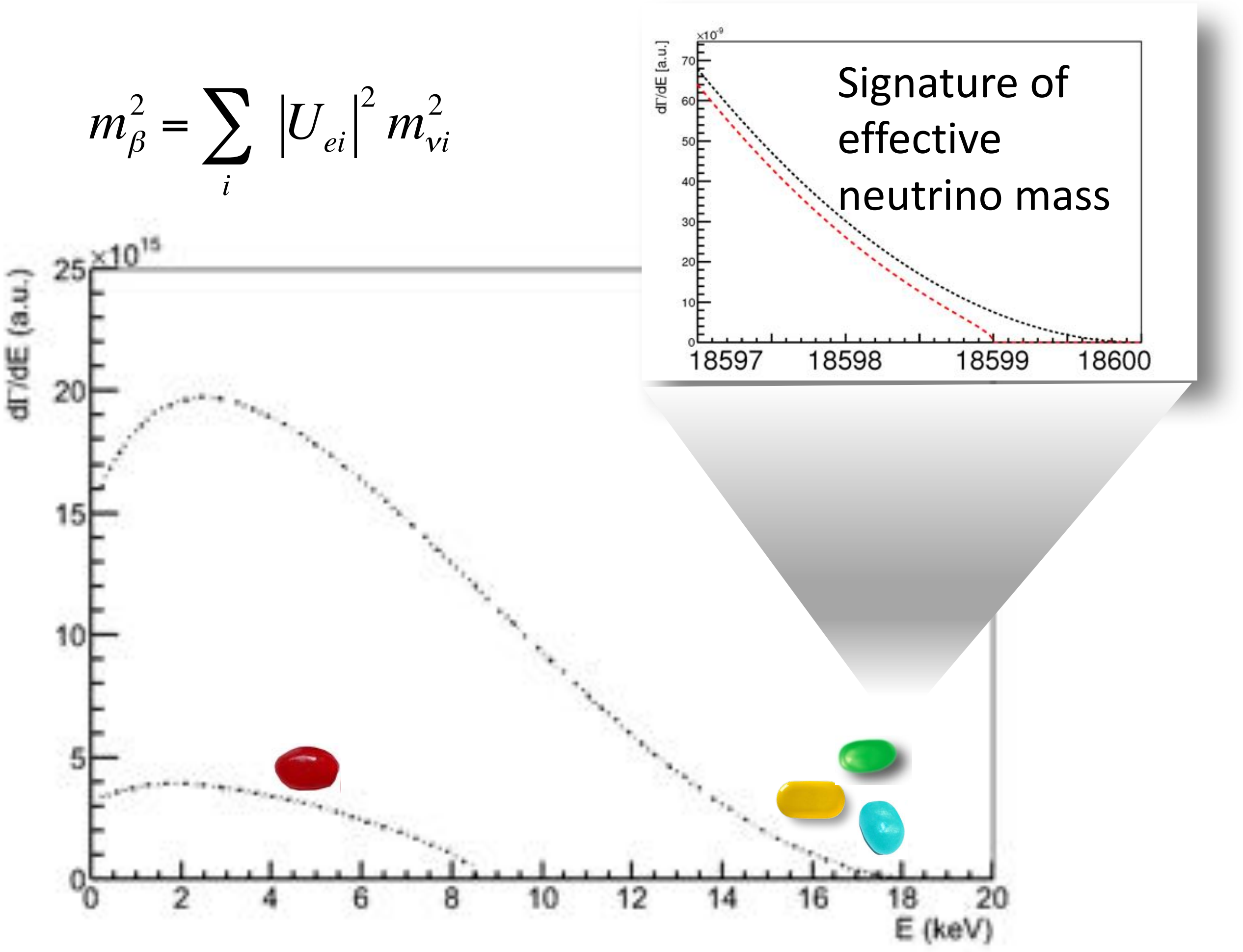
- The first electrons found their way through the 70-m long setup
- First tritium measurements planned for this year



Imprint of sterile ν‘s on ß-spectrum



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



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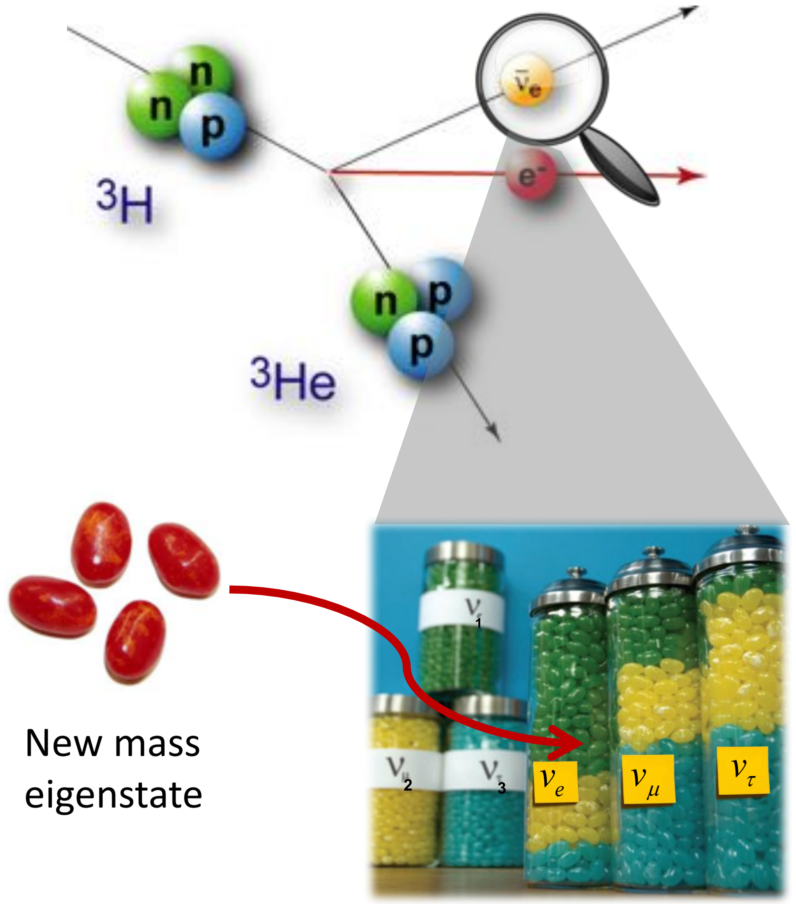
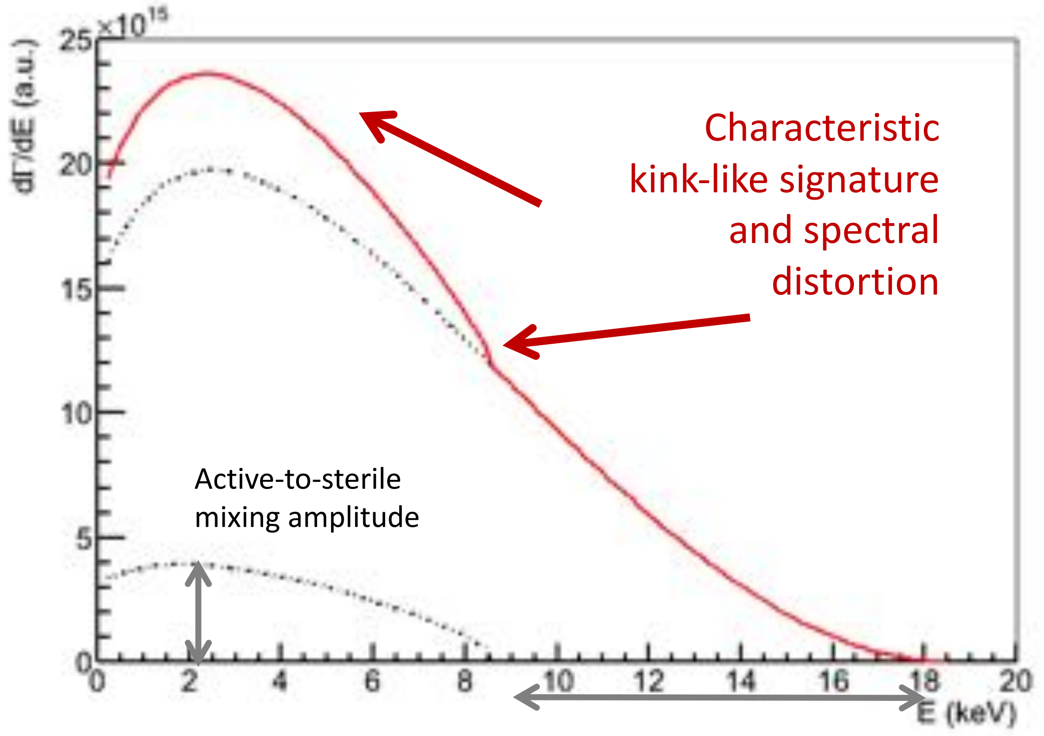


New mass eigenstate

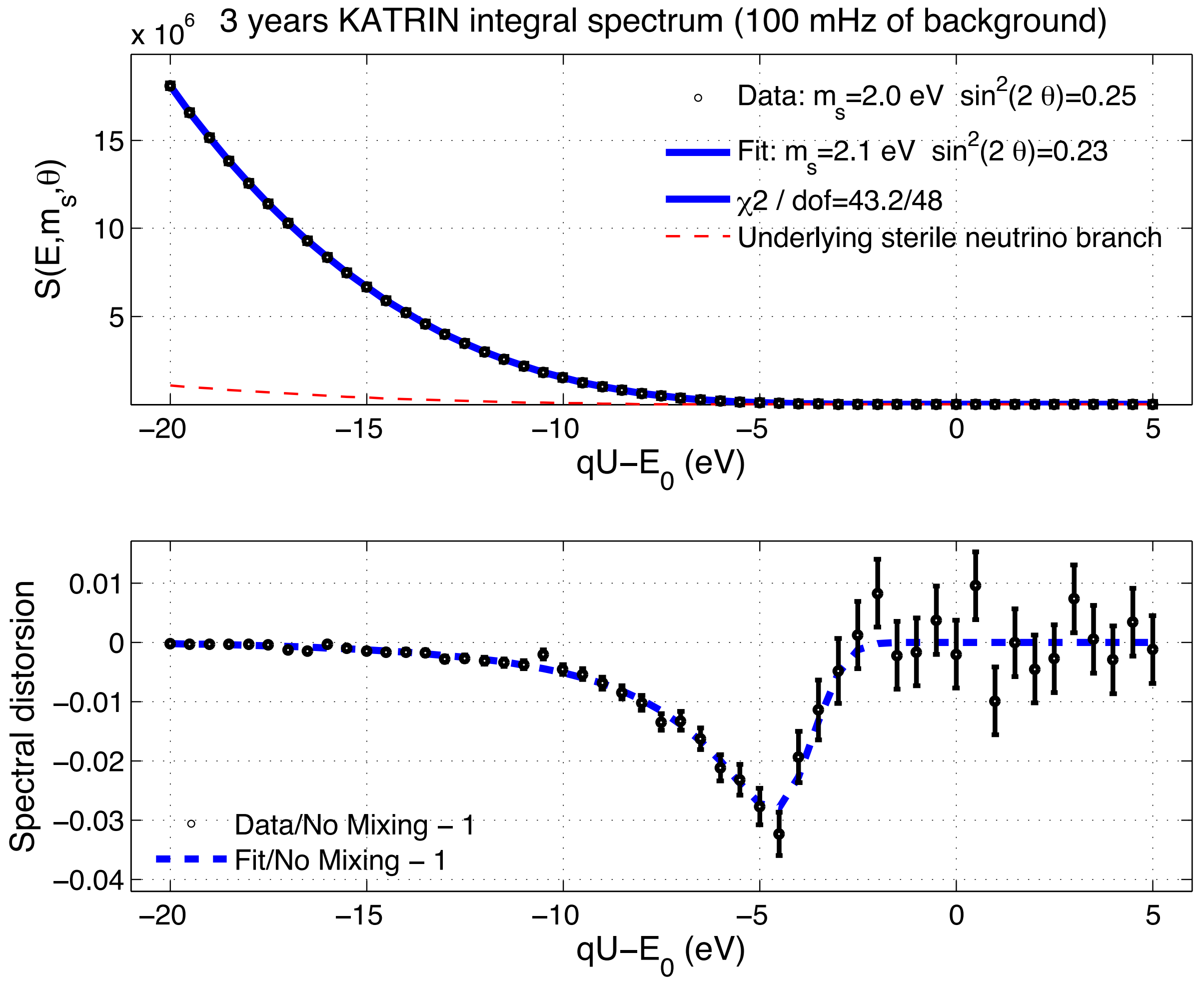
$$\frac{d\Gamma}{dE} = \cos^2\theta\,\frac{d\Gamma}{dE}(m_\beta) + \sin^2\theta\,\frac{d\Gamma}{dE}(m_s)$$



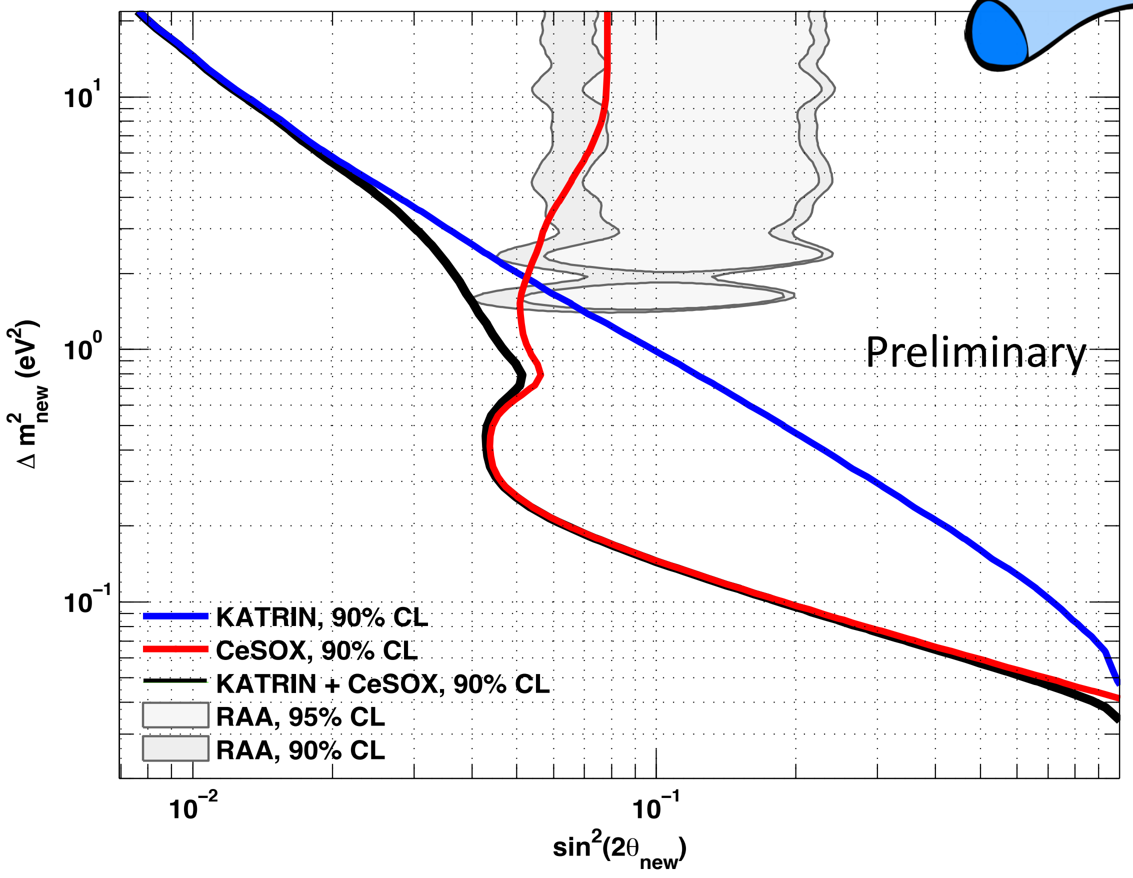
Characteristic kink-like signature and spectral distortion

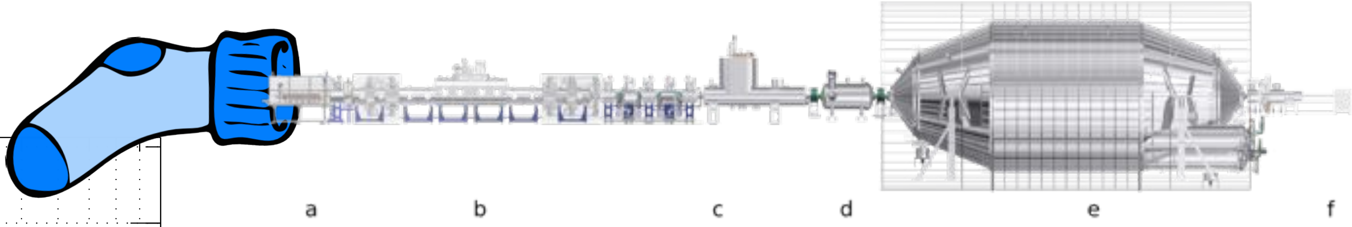
Mass of the sterile neutrino

The signature eV sterile ν's in KATRIN



KATRIN + SOX combined sensitivity





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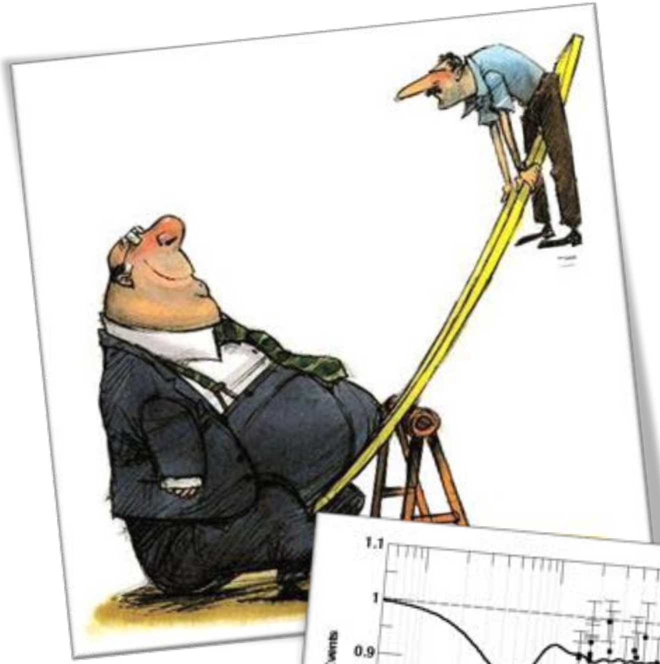
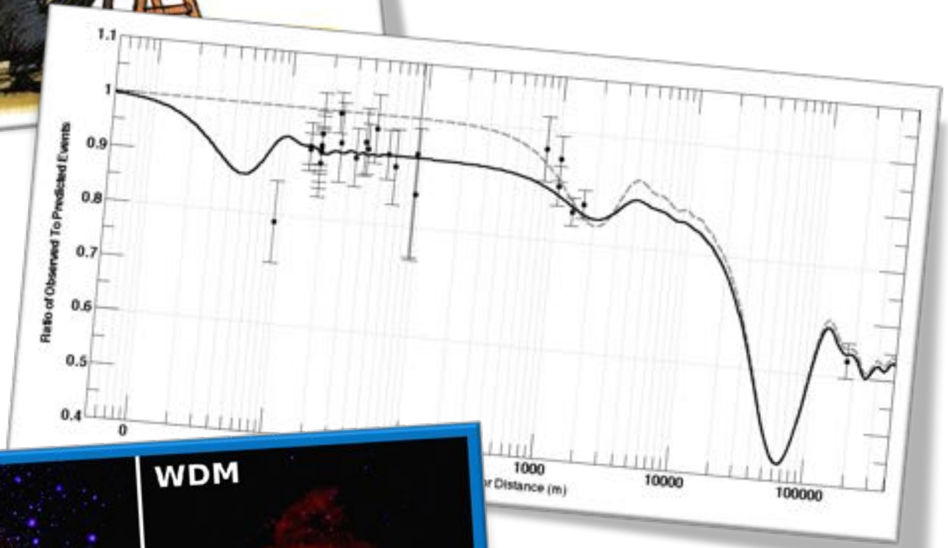
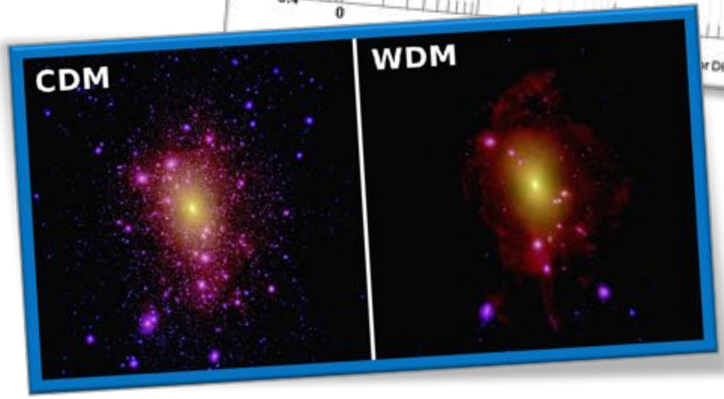
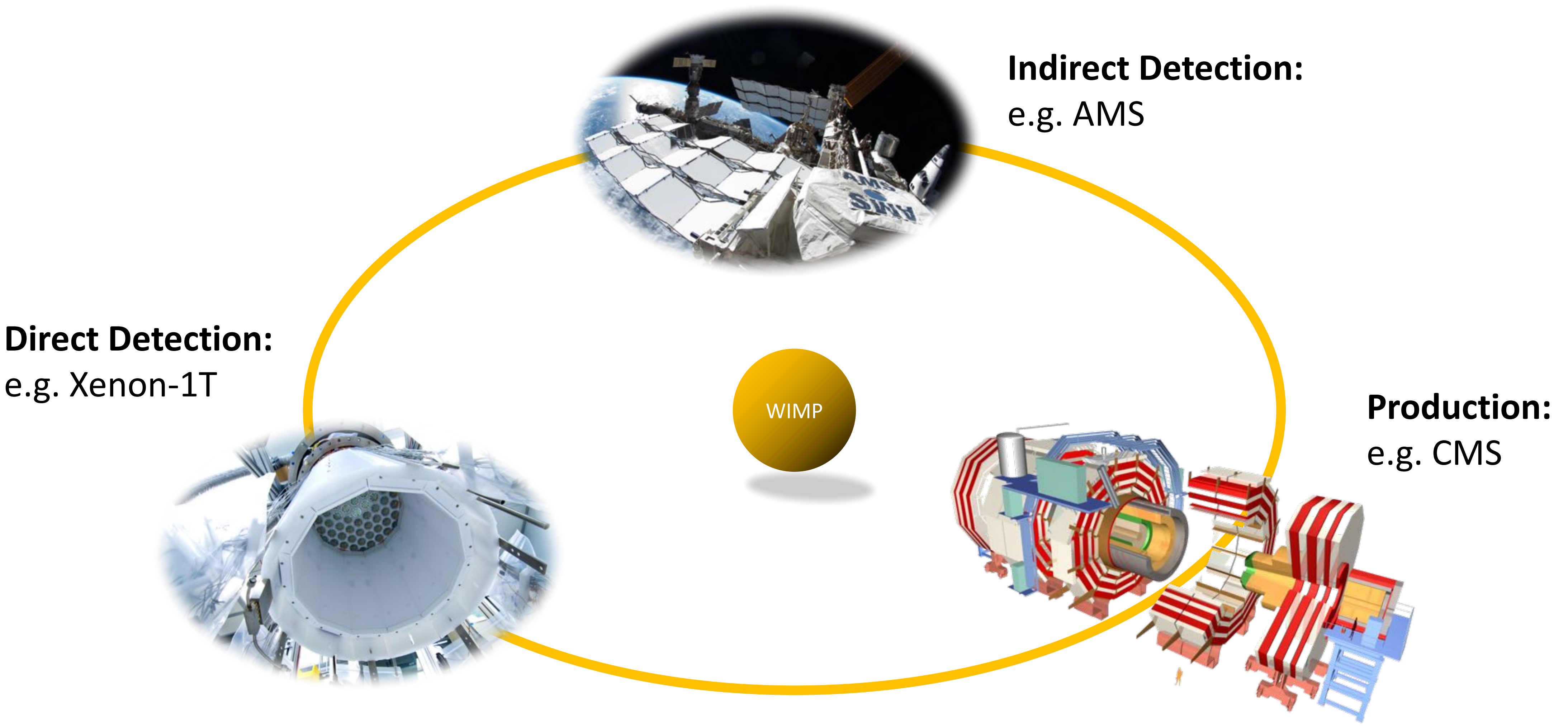


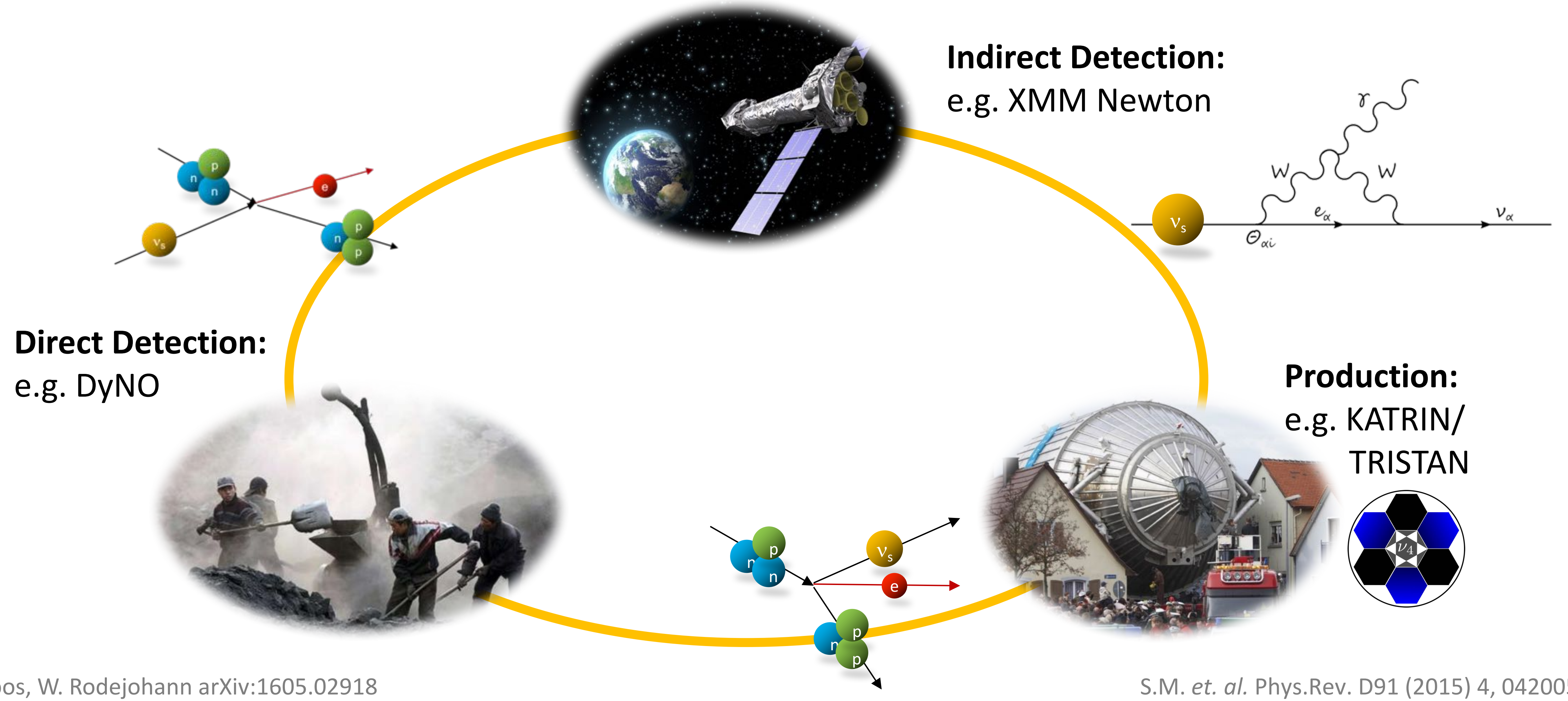




Experimental searches …reminder WIMPS



Experimental searches ...keV-scale sterile ν

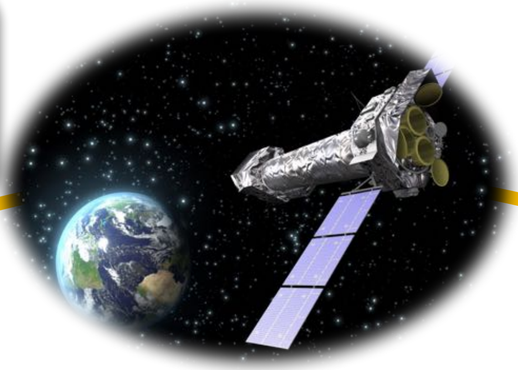


M. D. Campos, W. Rodejohann arXiv:1605.02918
T. Lasserre, K. Altenmueller, M. Cribier, A. Merle, S. M., M. Vivier arXiv:1609.04671

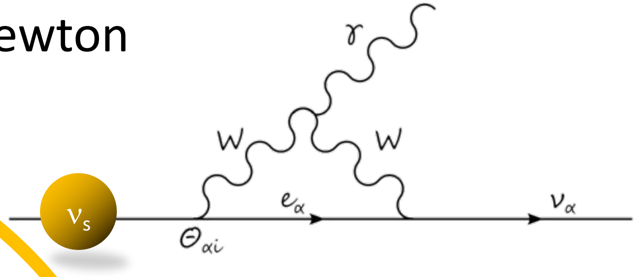
S.M. *et. al.* Phys.Rev. D91 (2015) 4, 042005
S.M. *et al.* JCAP 1502 (2015) 02, 020

Experimental searches - the challenge

Strong constraint:
Mixing to active neutrinos
$\sin^2\theta < 10^{-6}$



Indirect Detection:
e.g. XMM Newton



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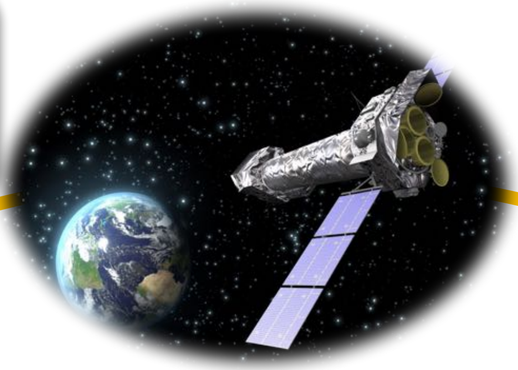
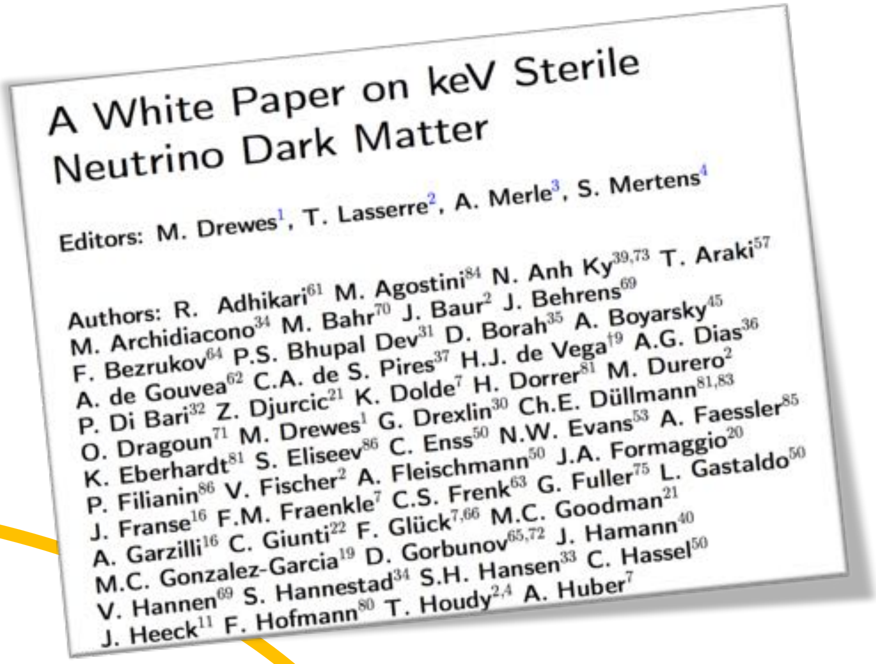


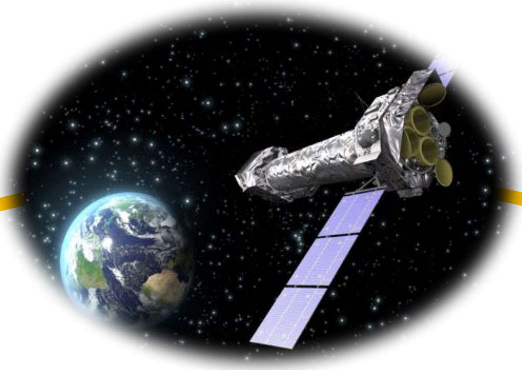

A White Paper on keV Sterile Neutrino Dark Matter

Editors: M. Drewes[1], T. Lasserre[2], A. Merle[3], S. Mertens[4]

Authors: R. Adhikari[61] M. Agostini[84] N. Anh Ky[39,73] T. Araki[57] M. Archidiacono[34] M. Bahr[70] J. Baur[2] J. Behrens[69] F. Bezrukov[64] P.S. Bhupal Dev[31] D. Borah[35] A. Boyarsky[45] A. de Gouvea[62] C.A. de S. Pires[37] H.J. de Vega[†9] A.G. Dias[36] P. Di Bari[32] Z. Djurcic[21] K. Dolde[7] H. Dorrer[81] M. Durero[2] O. Dragoun[71] M. Drewes[1] G. Drexlin[30] Ch.E. Düllmann[81,83] K. Eberhardt[81] S. Eliseev[86] C. Enss[50] N.W. Evans[53] A. Faessler[85] P. Filianin[86] V. Fischer[2] A. Fleischmann[50] J.A. Formaggio[20] J. Franse[16] F.M. Fraenkle[7] C.S. Frenk[63] G. Fuller[75] L. Gastaldo[50] A. Garzilli[16] C. Giunti[22] F. Glück[7,66] M.C. Goodman[21] M.C. Gonzalez-Garcia[19] D. Gorbunov[65,72] J. Hamann[40] V. Hannen[69] S. Hannestad[34] S.H. Hansen[33] C. Hassel[50] J. Heeck[11] F. Hofmann[80] T. Houdy[2,4] A. Huber[7]

arXiv:1602.04816

Experimental searches



Indirect Detection:
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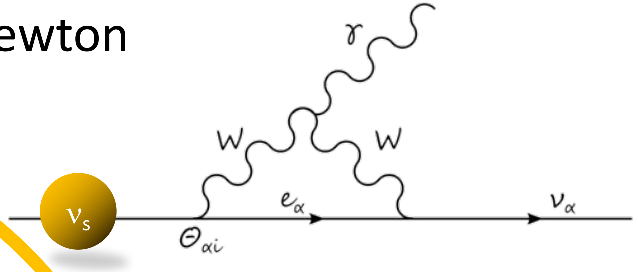
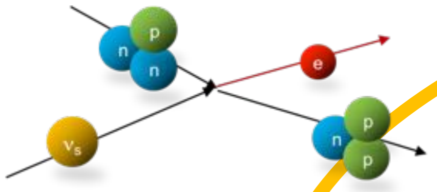
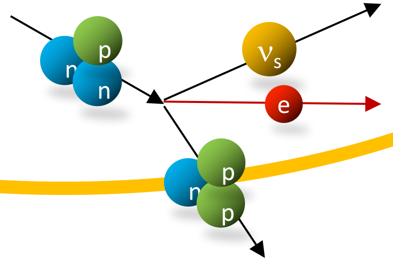
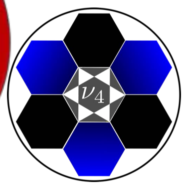




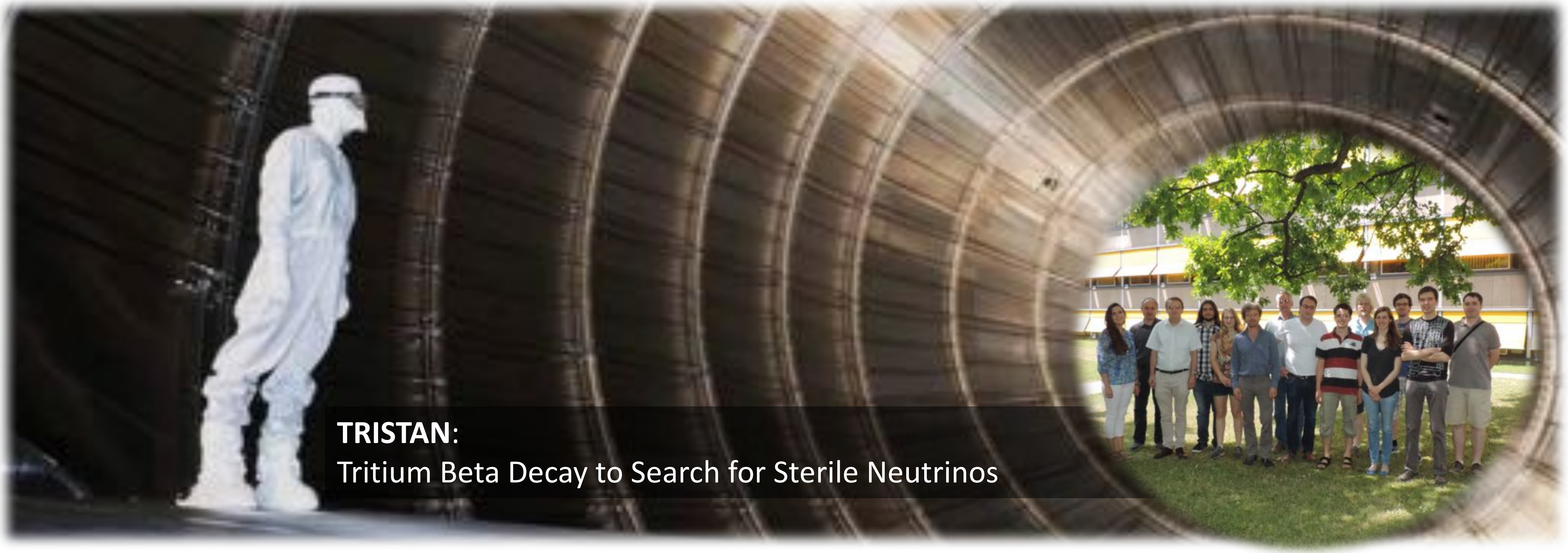
Direct Detection:
e.g. DyNO



Production:
e.g. KATRIN/
TRISTAN

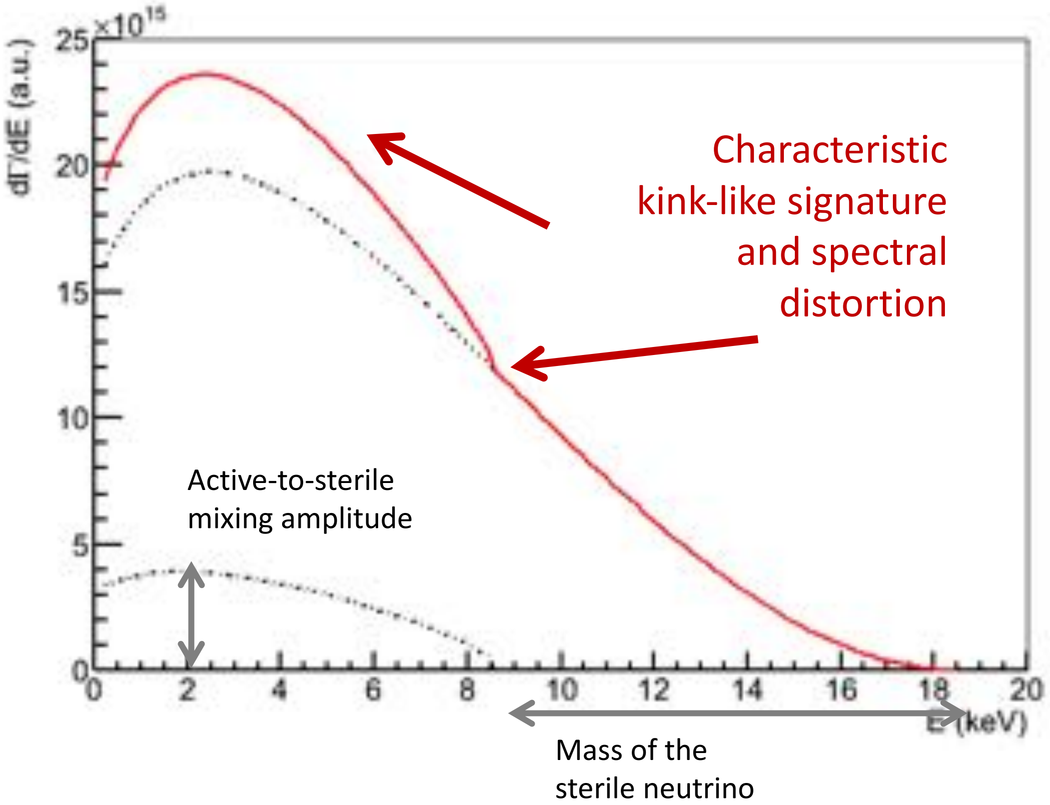


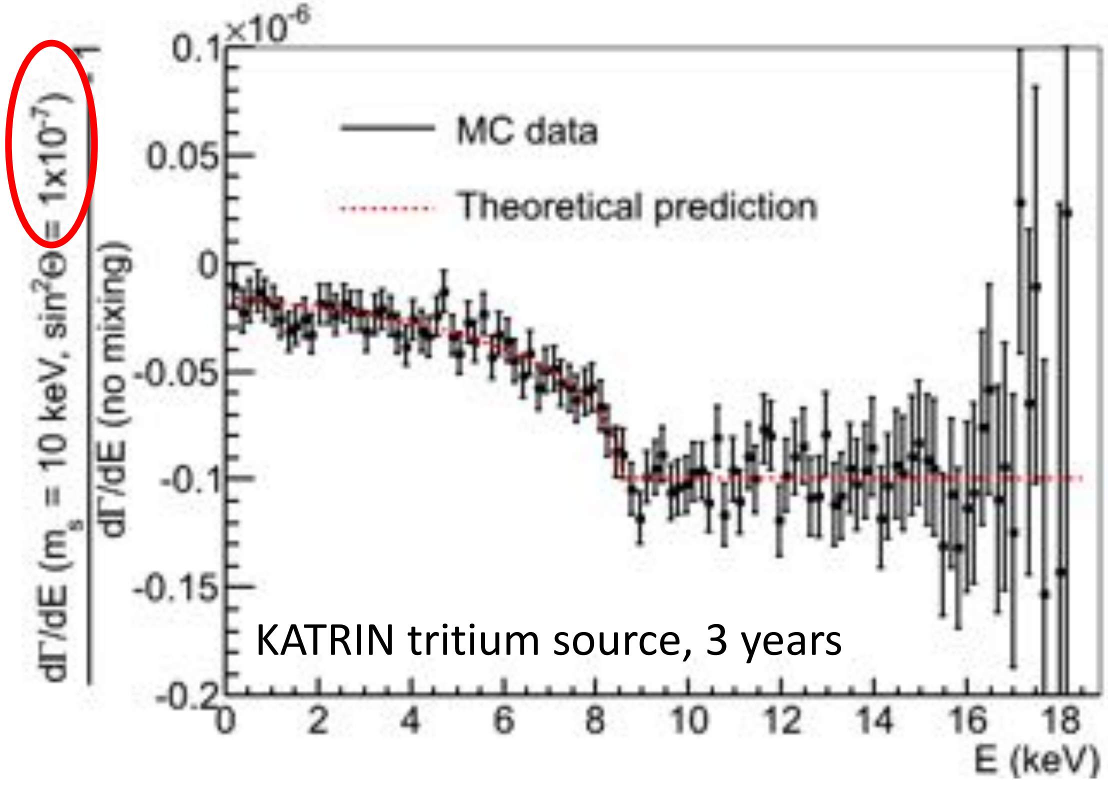
New Project: TRISTAN



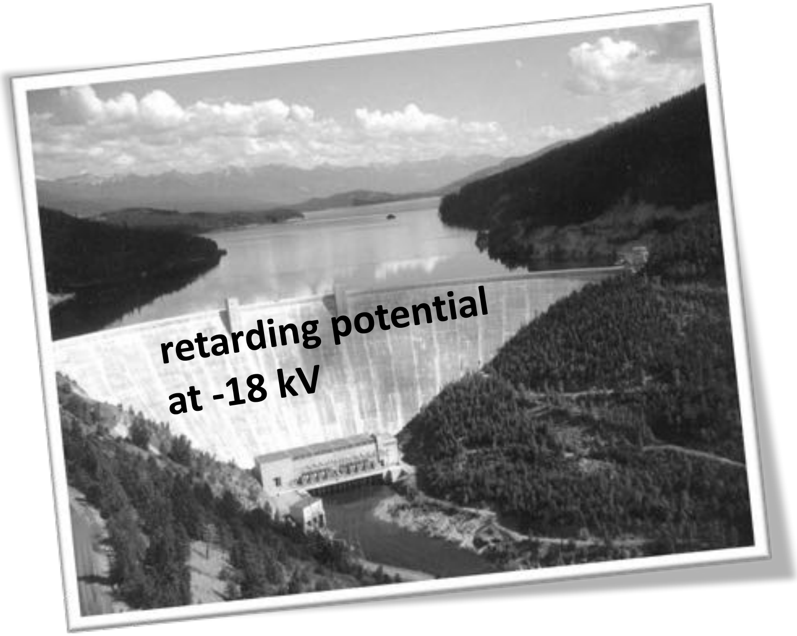
Imprint of sterile ν's on ß-spectrum

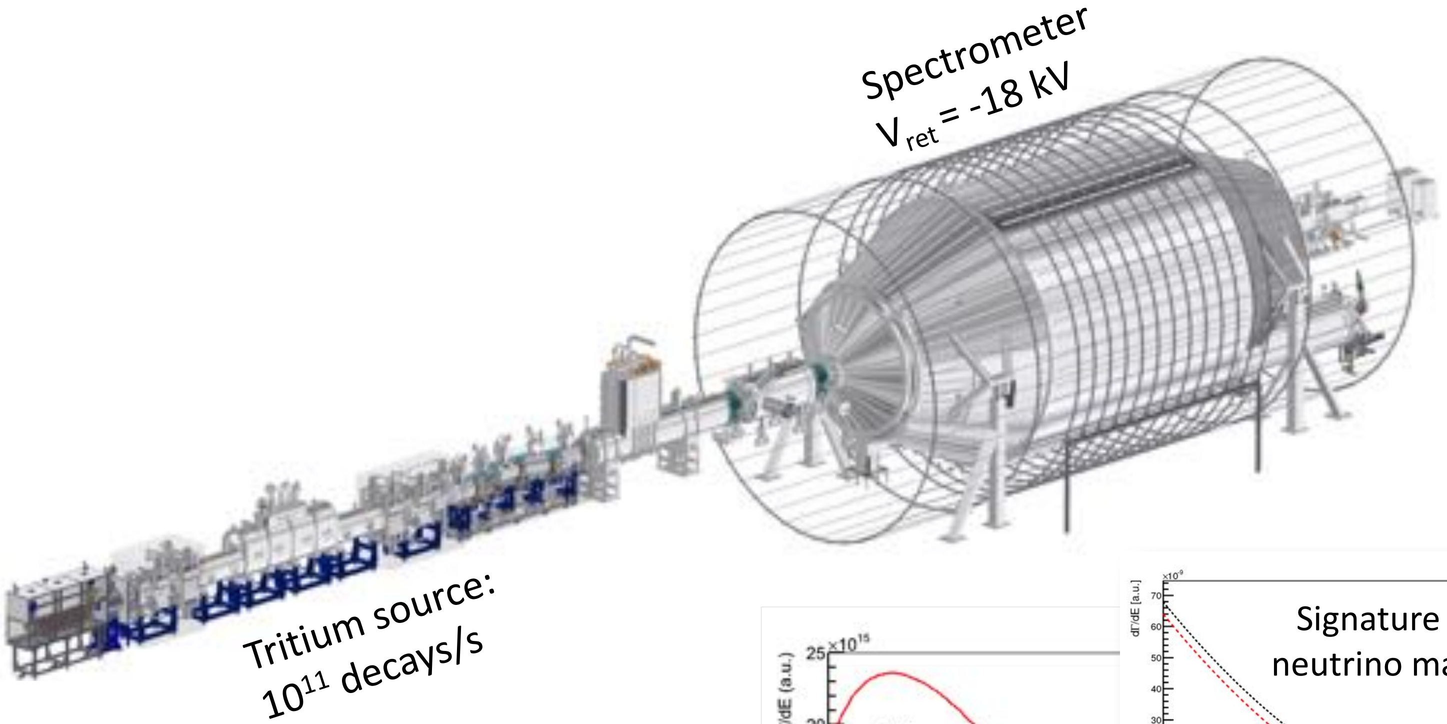
$$\frac{d\Gamma}{dE} = \cos^2\theta \frac{d\Gamma}{dE}(m_\beta) + \sin^2\theta \frac{d\Gamma}{dE}(m_s)$$

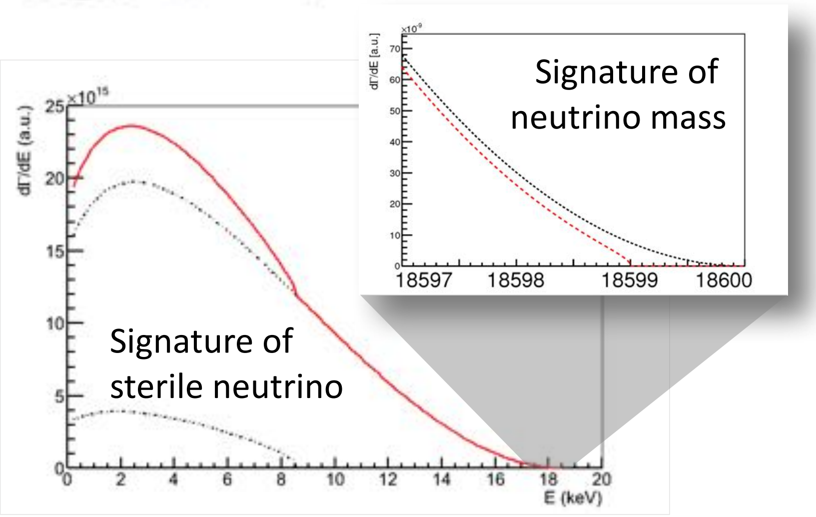




How to use KATRIN







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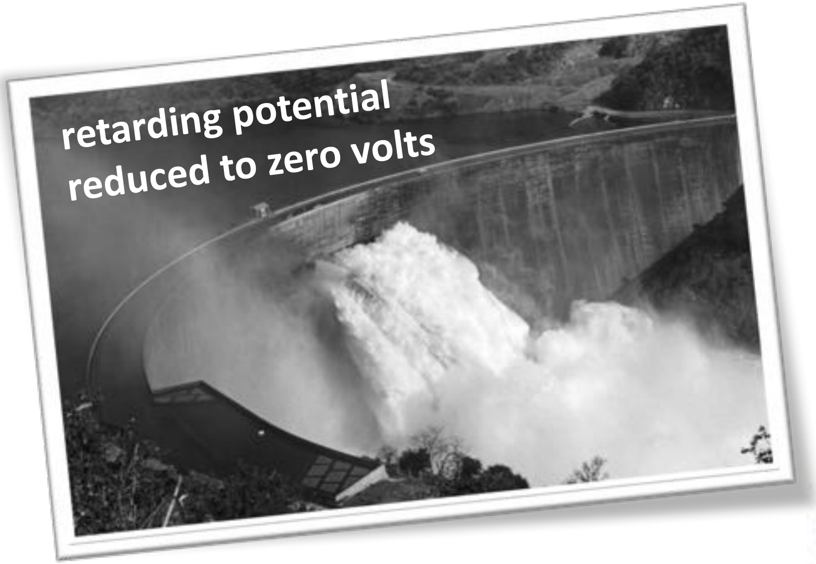
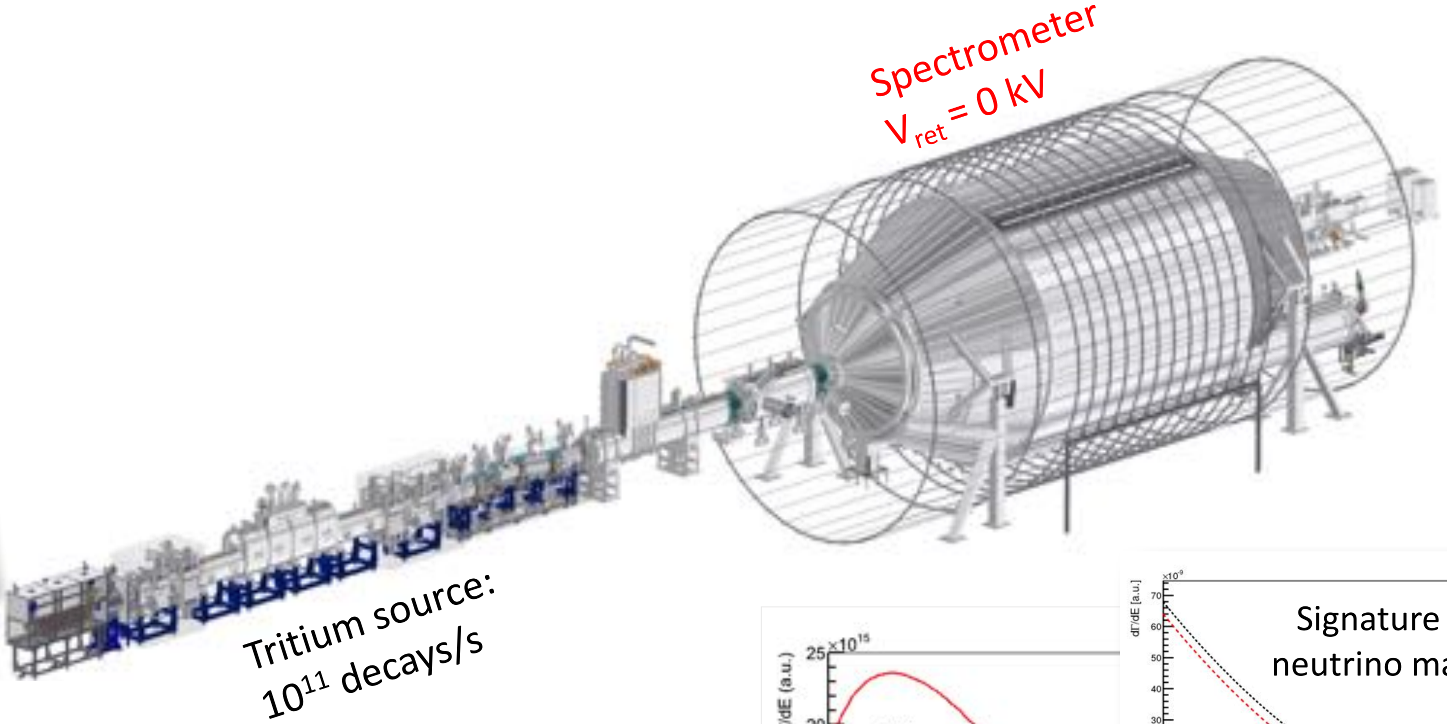
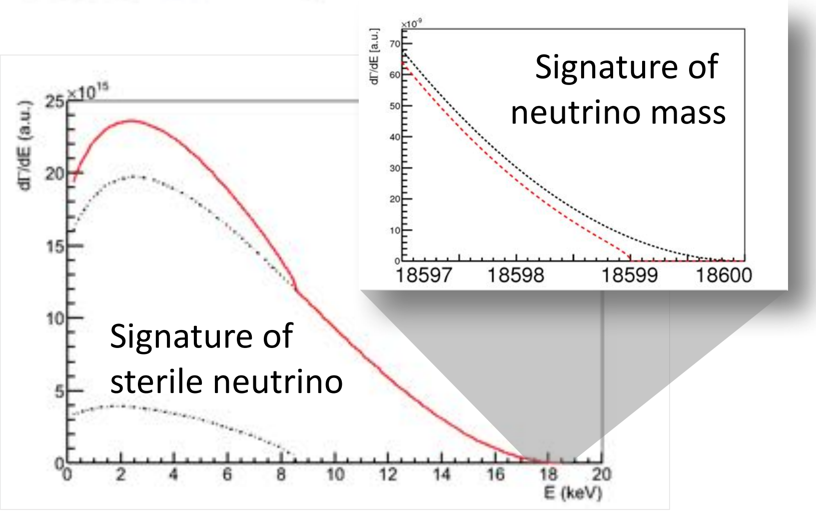
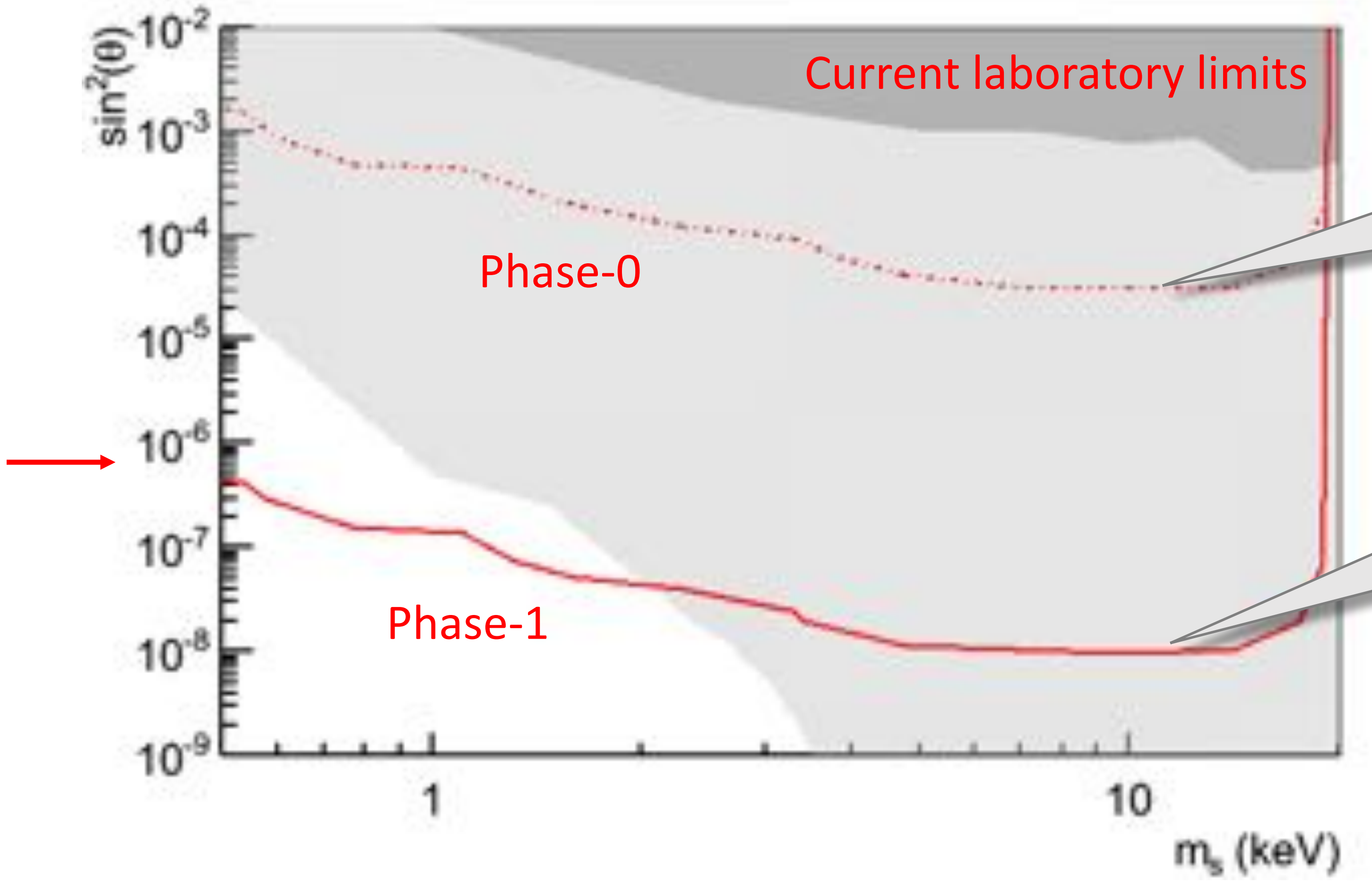






- ➢ Reduce the count rate (Phase – 0)
- ➢ Develop a new detector (Phase – 1)

Staged Approach

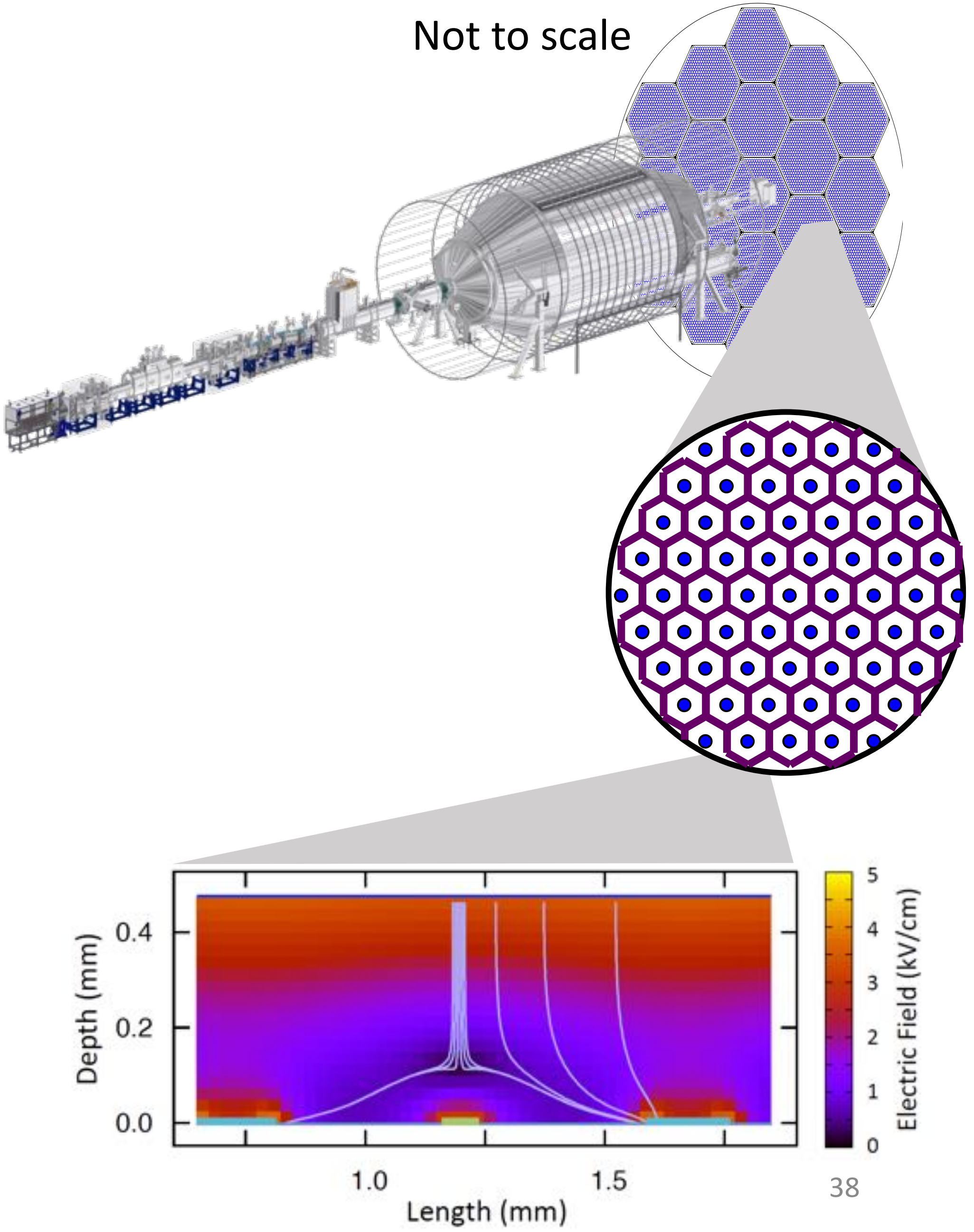


10^{11} electrons:
Reduced source strength and
7 days of measurement time
With KATRIN "as is"

10^{18} electrons:
Full source strength and
3 years of measurement time
With TRISTAN

TRISTAN detector R&D

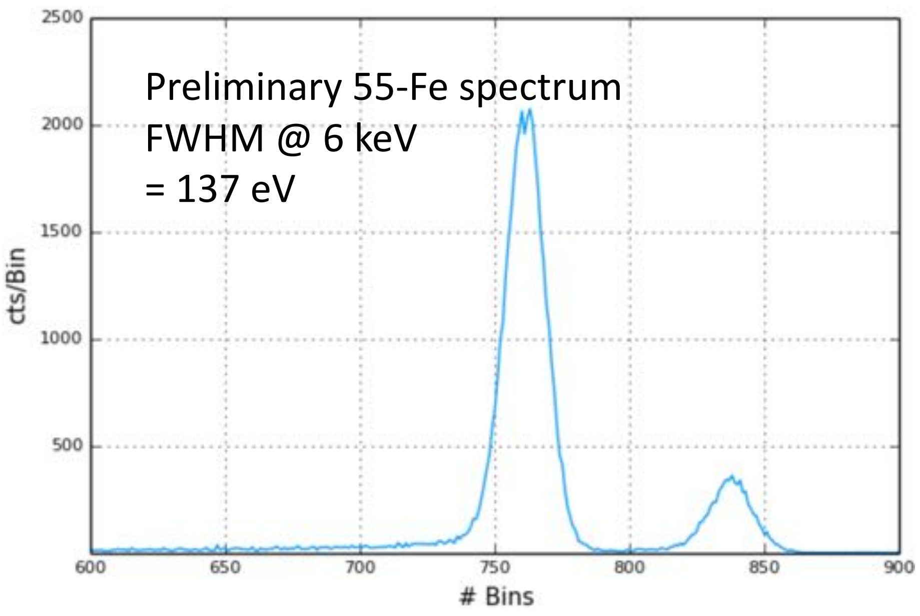
- Capability of handling high rates (10^8 cps)
  - O(10 000) pixel
- Excellent energy resolution (300eV@20keV) Low energy threshold (1 keV)
  - Thin deadlayer (~10 nm)
- Large pixels (low noise at high rate) (cell size ~ 2mm)
  - Silicon Drift Detector design, capacity < 0.05 pF

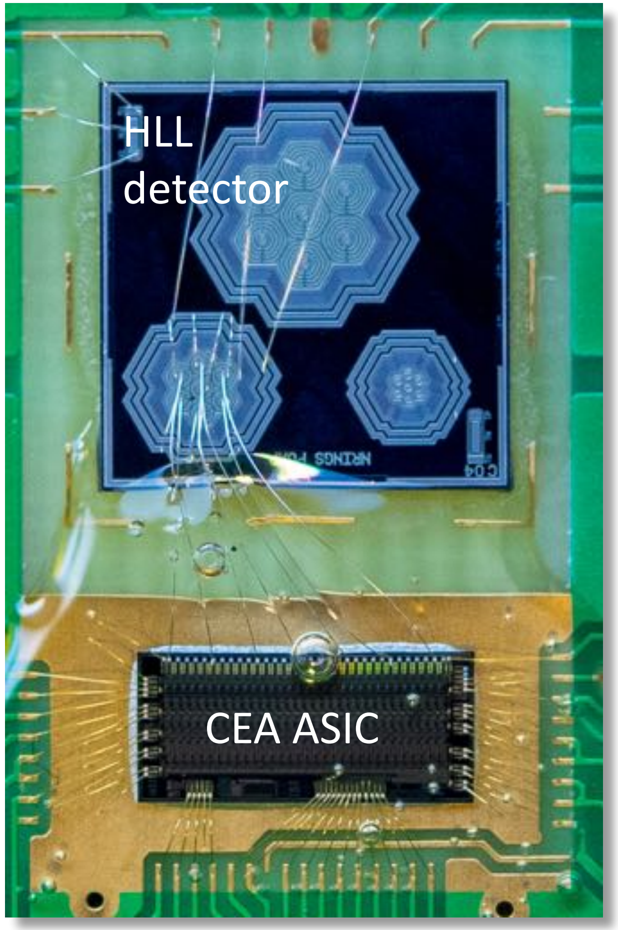


K. Dolde, S. M., D. Radford *et. al.* accepted for publication in NIM-A (arXiv:1608.03158)

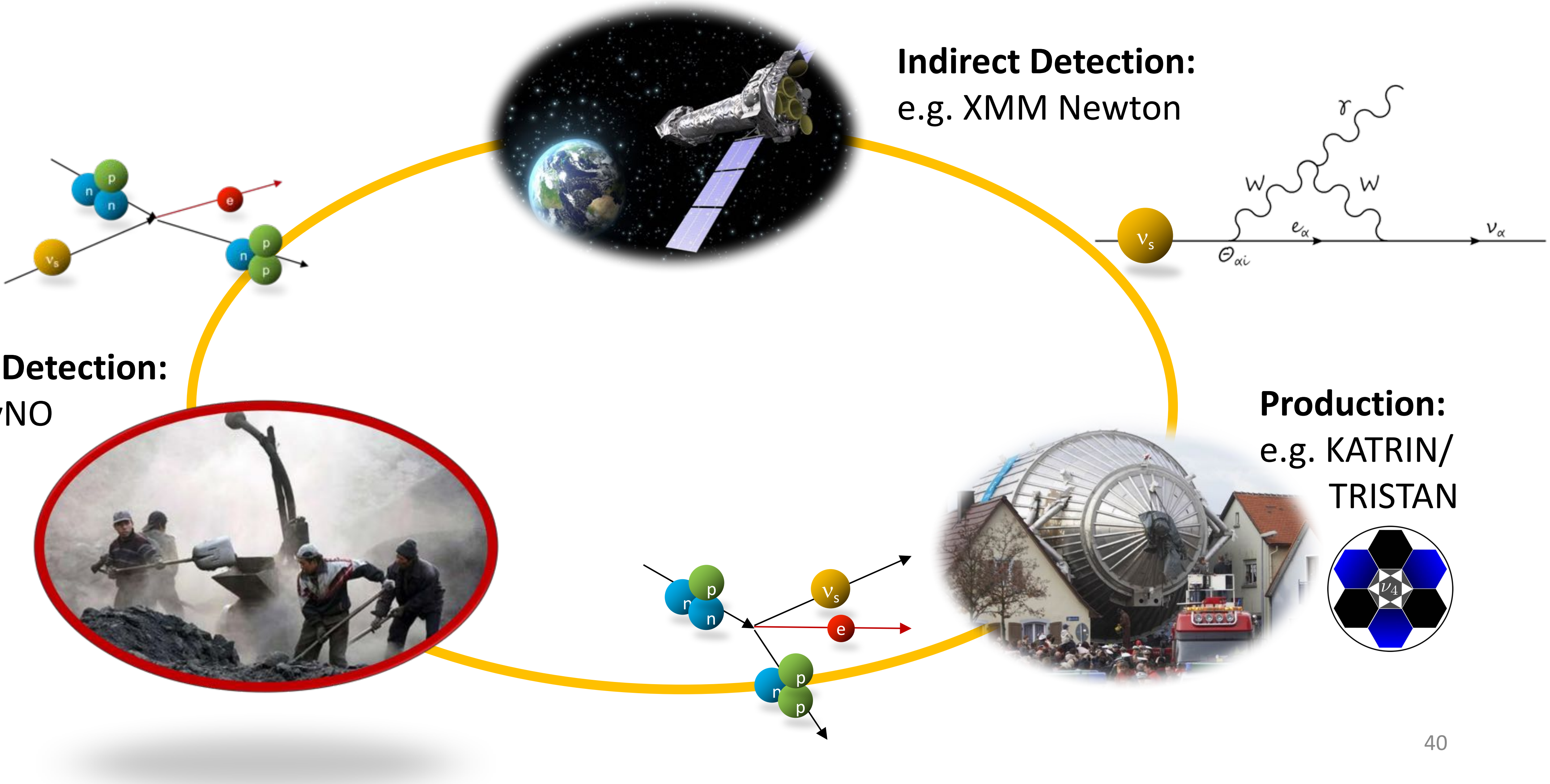
TRISTAN Prototypes

- Prototypes produced by Halbleiterlabor of the Max Planck Society and Lawrence Berkeley National Laboratory
- First promising results





Experimental searches



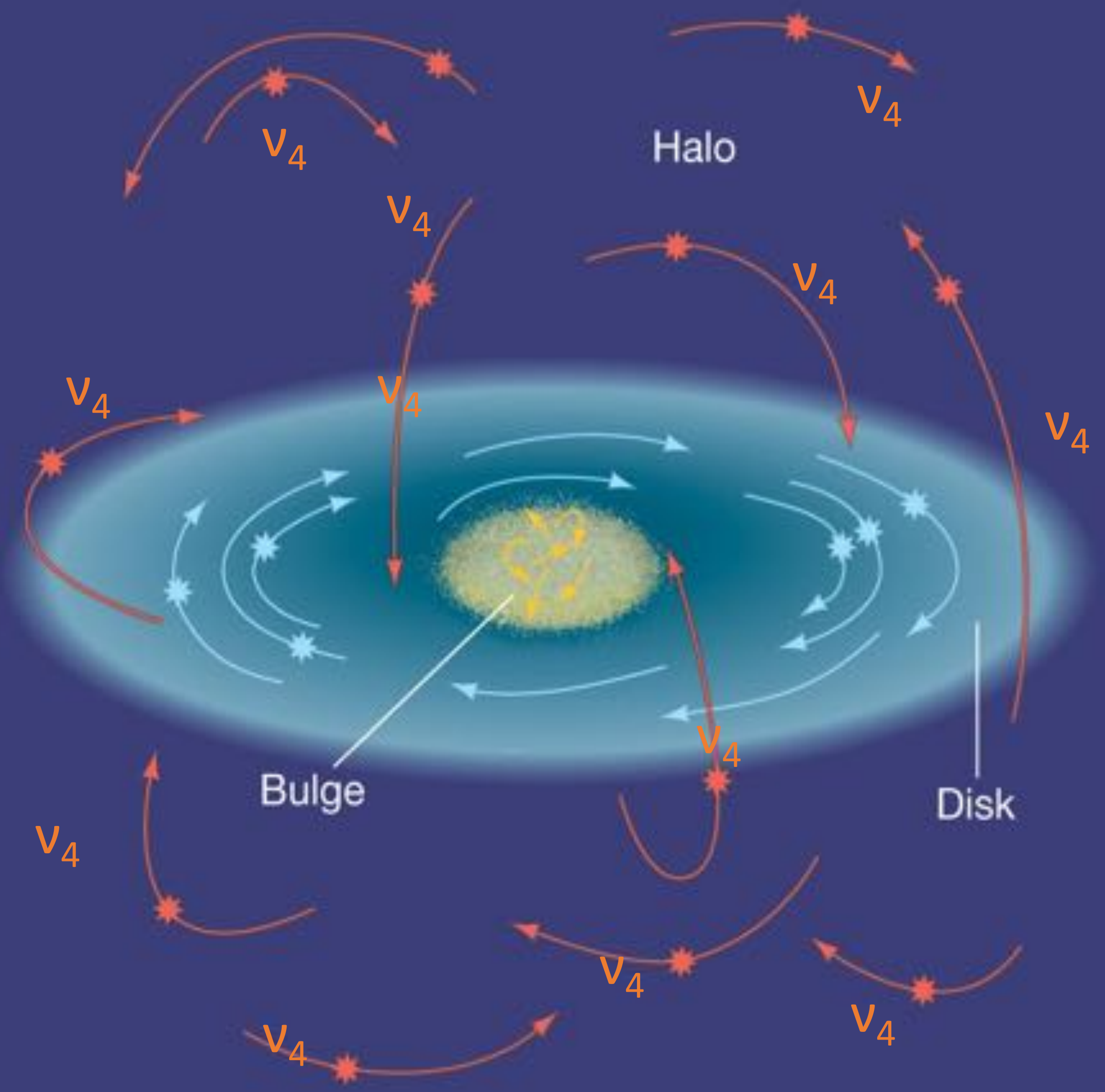
Indirect Detection:
e.g. XMM Newton

Direct Detection:
e.g. DyNO

Production:
e.g. KATRIN/
TRISTAN

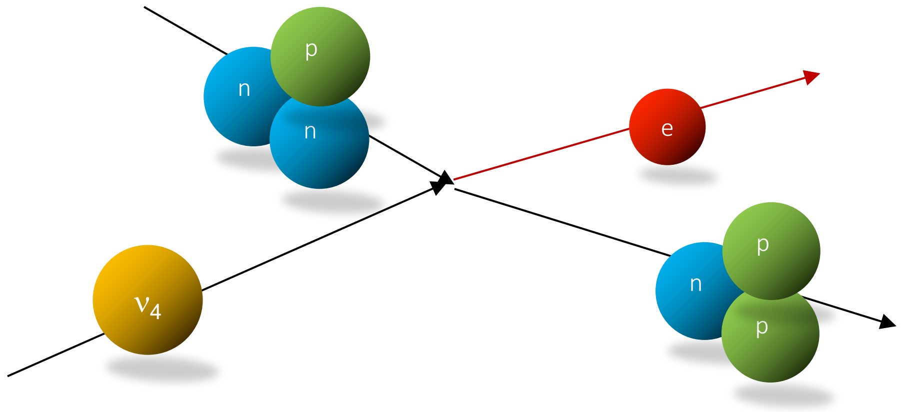
Direct detection

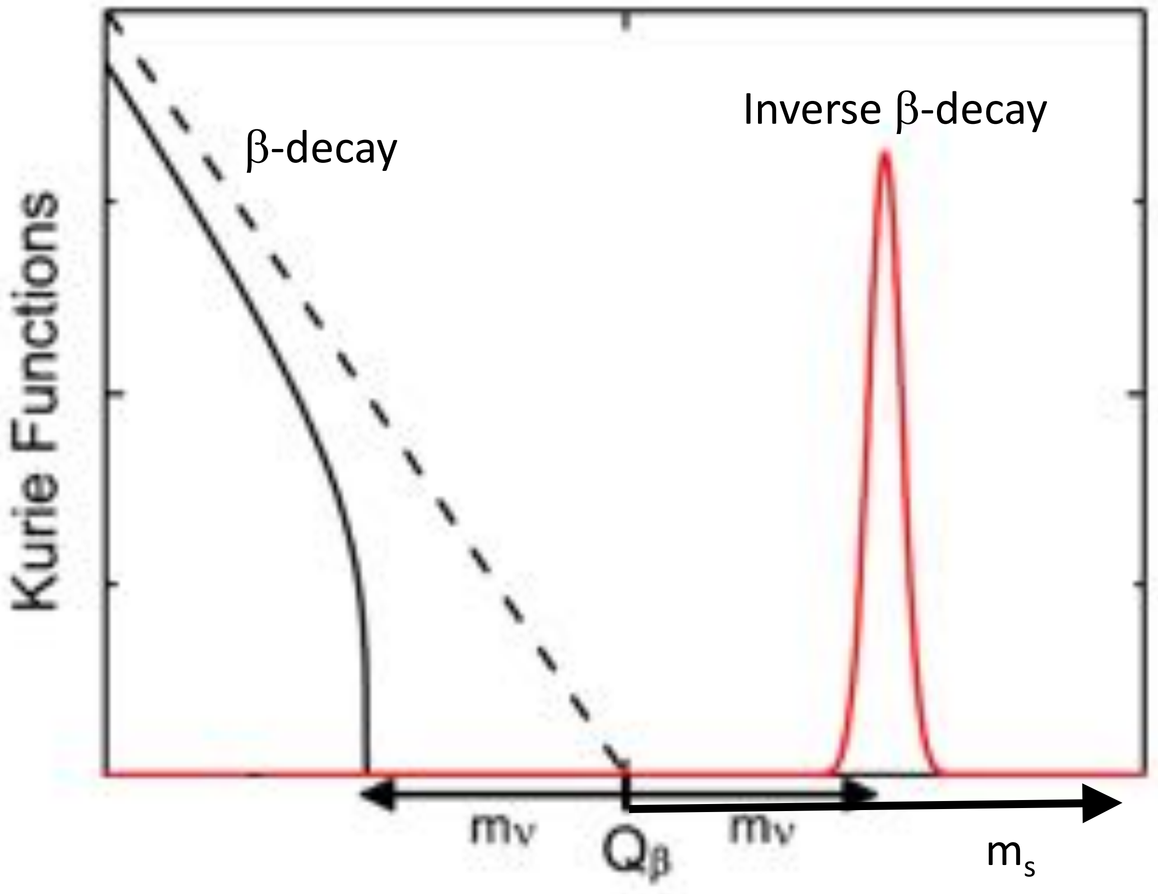
- The “classical” idea:
  - ➢Capture on decaying target



Capture on radioactive isotope

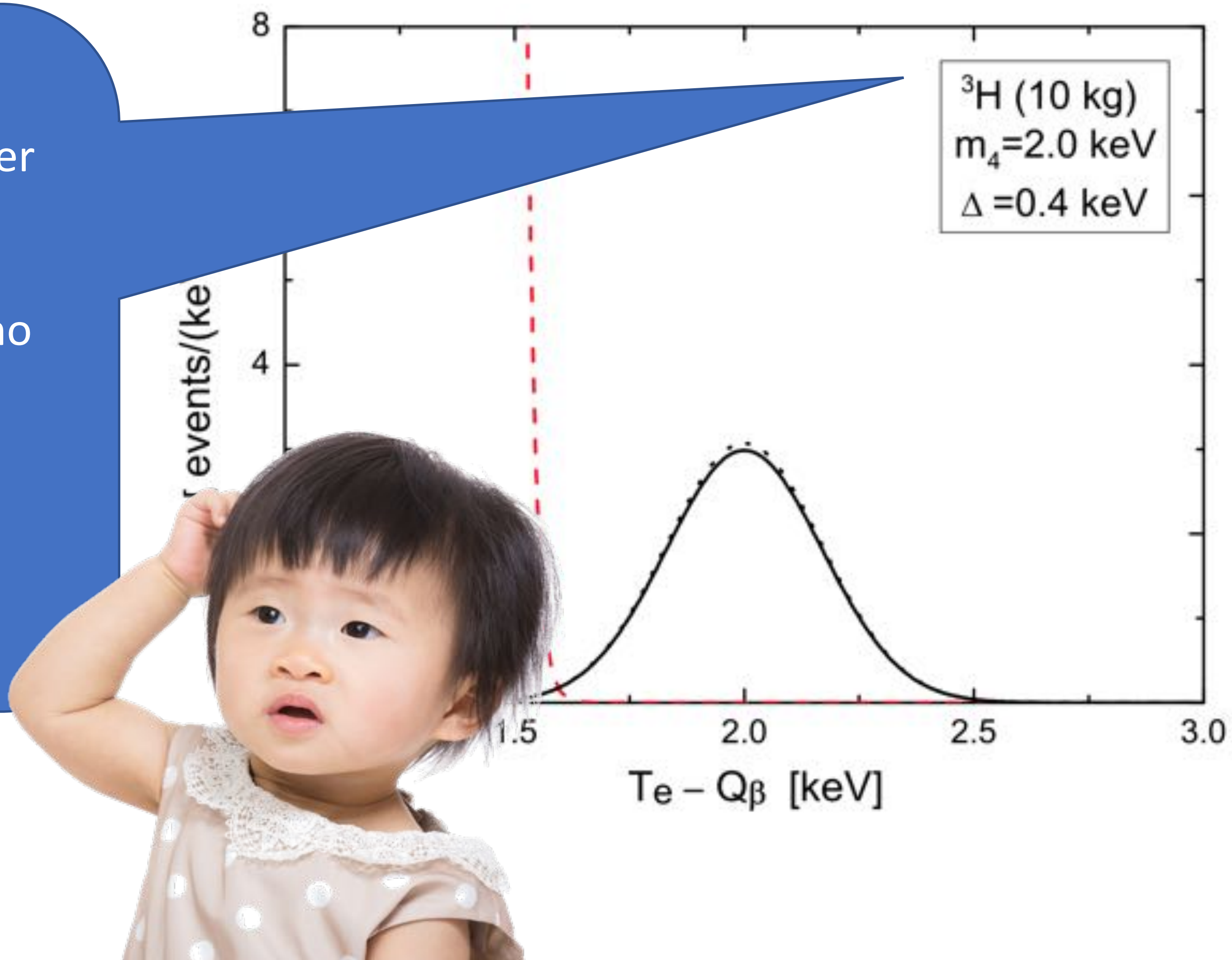
- Inverse beta decay
- No energy threshold
- Peak at m_s above endpoint
- Possible source: tritium





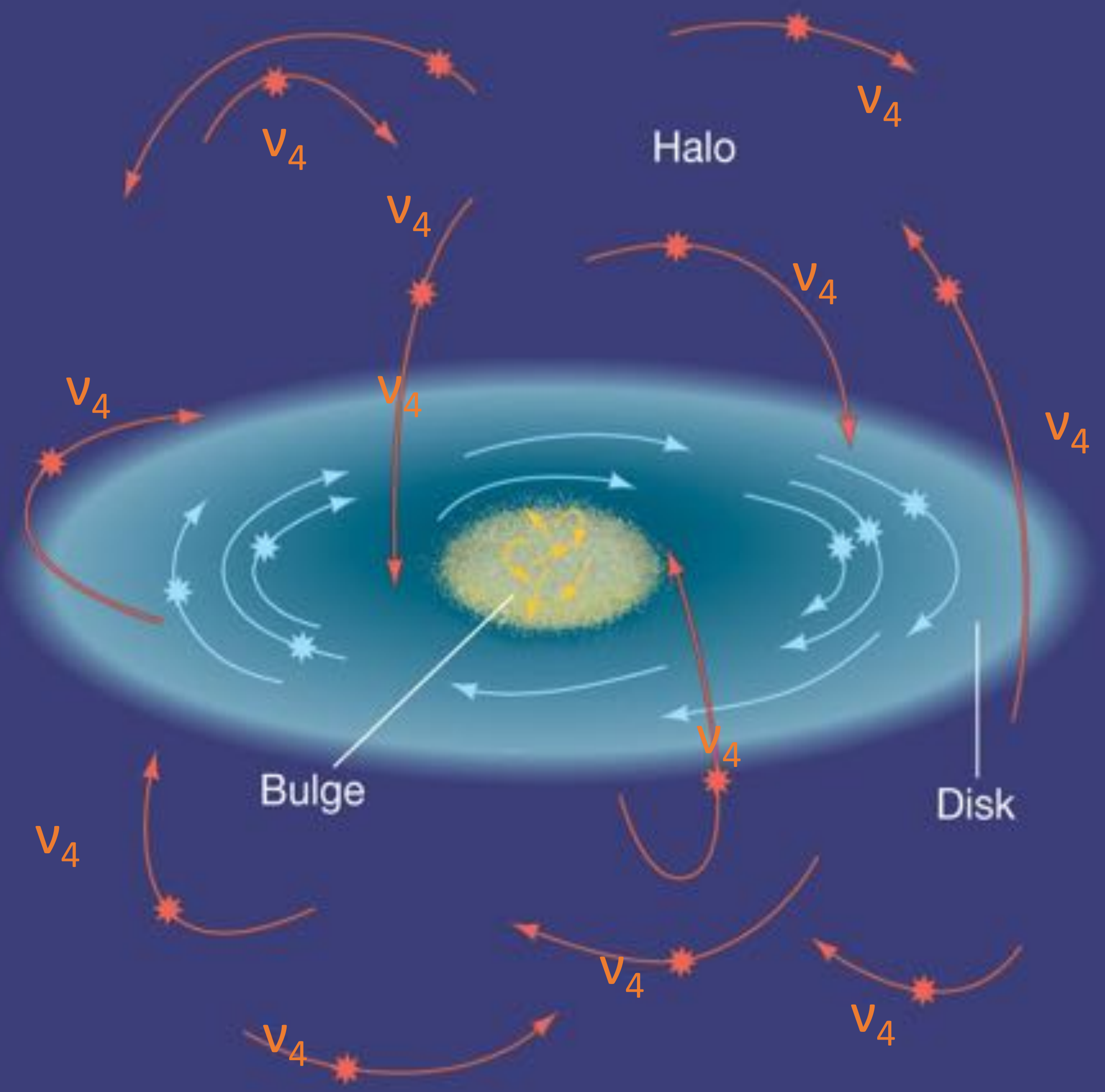
The challenge !

- 10 kg of tritium for ~1 capture per year (if $\sin^2\theta \sim 10^{-6}$)
- **Compare**: for relic active neutrino background 100 g are needed
- **Compare**: KATRIN operates effectively 30μg of tritium



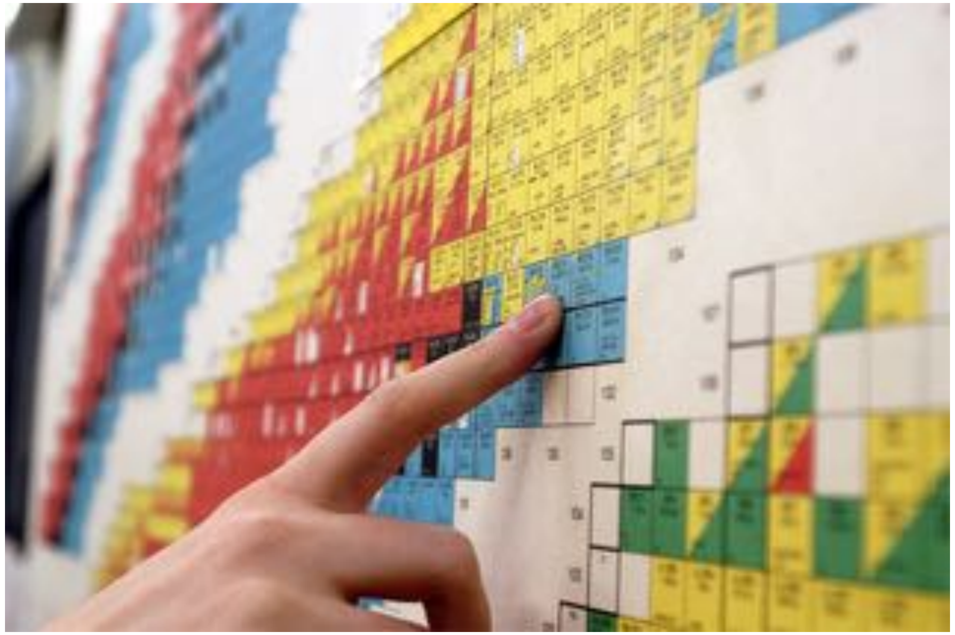
Direct detection

- The "classical" idea:
  - ➢Capture on decaying target
- The new idea:
  - ➢Capture on stable target

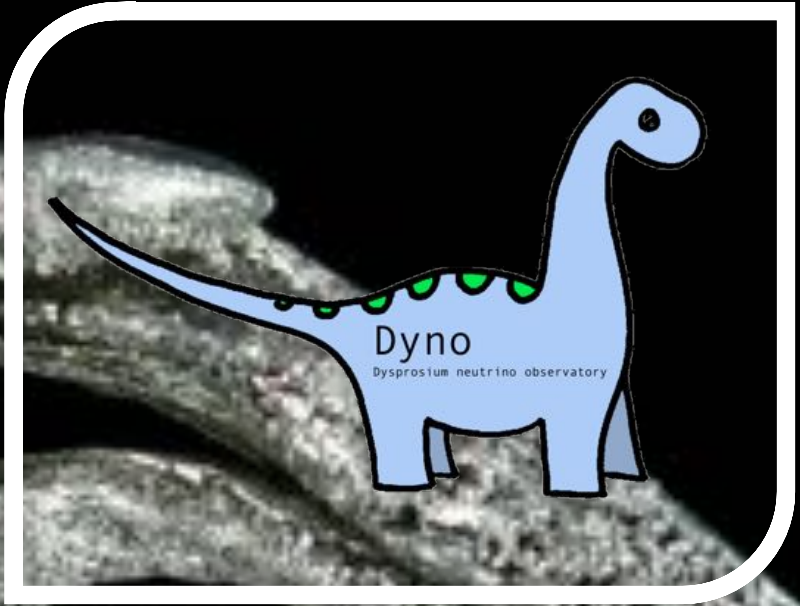


Capture on stable isotope

- $\nu_4 + M \rightarrow D + e$
- Energy balance: $M_M + m_\nu - M_D - m_e > 0$
- Almost beta decaying isotope
- Sterile neutrino mass breaks the camels back…



Dysprosium -163

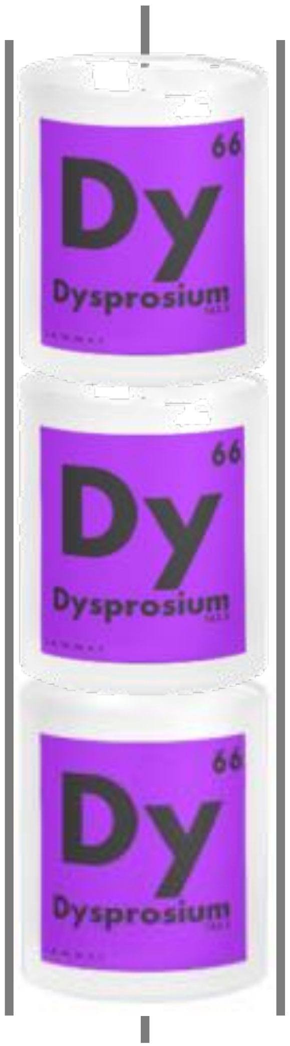


- $^{163}\mathrm{Dy} + \nu_4 \rightarrow {}^{163}\mathrm{Ho} + e$ (holmium half life: 4500 years)
- $^{163}\mathrm{Dy}$ – 25% of natural dysprosium
- Zero natural abundance of ^{163}Ho reported in the literature…

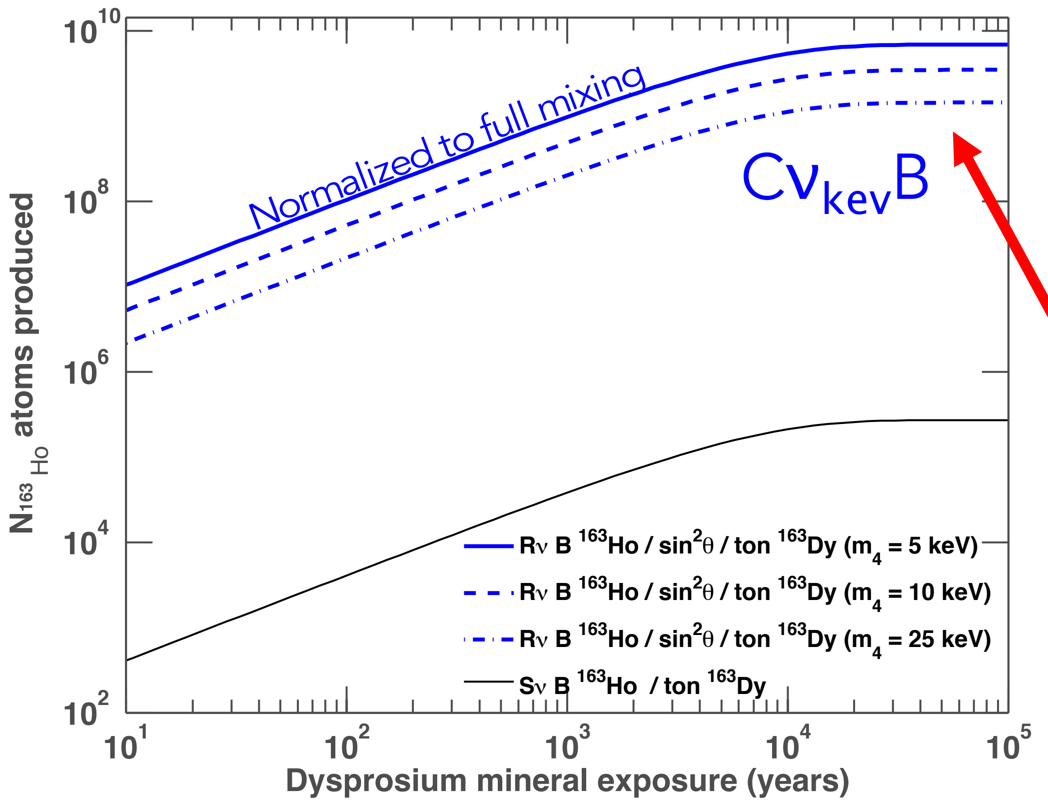
T. Lasserre, K. Altenmueller, M. Cribier, A. Merle, S. M., M. Vivier arXiv:1609.04671

Two Options $^{163}\mathrm{Dy} + \nu_4 \rightarrow {}^{163}\mathrm{Ho} + e$

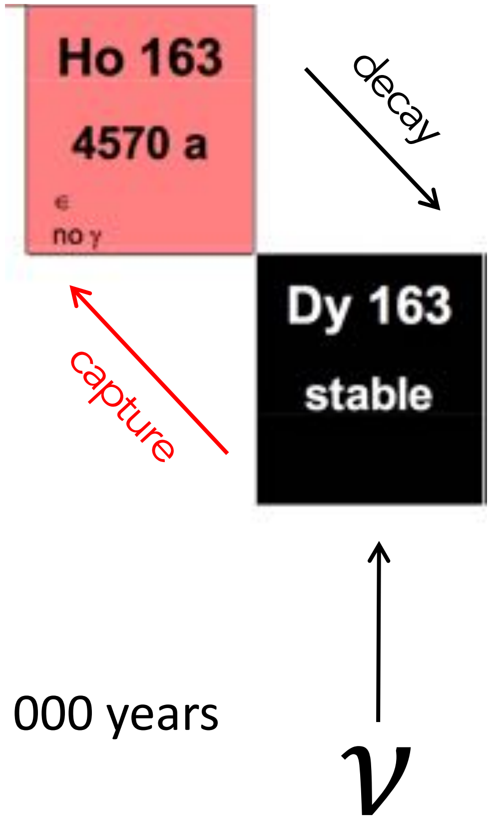
1. Built a large detector out of dysprosium
   … and measure the energy of the emitted electron
2. Use the natural abundance of dysprosium
   … and search for holmium atoms



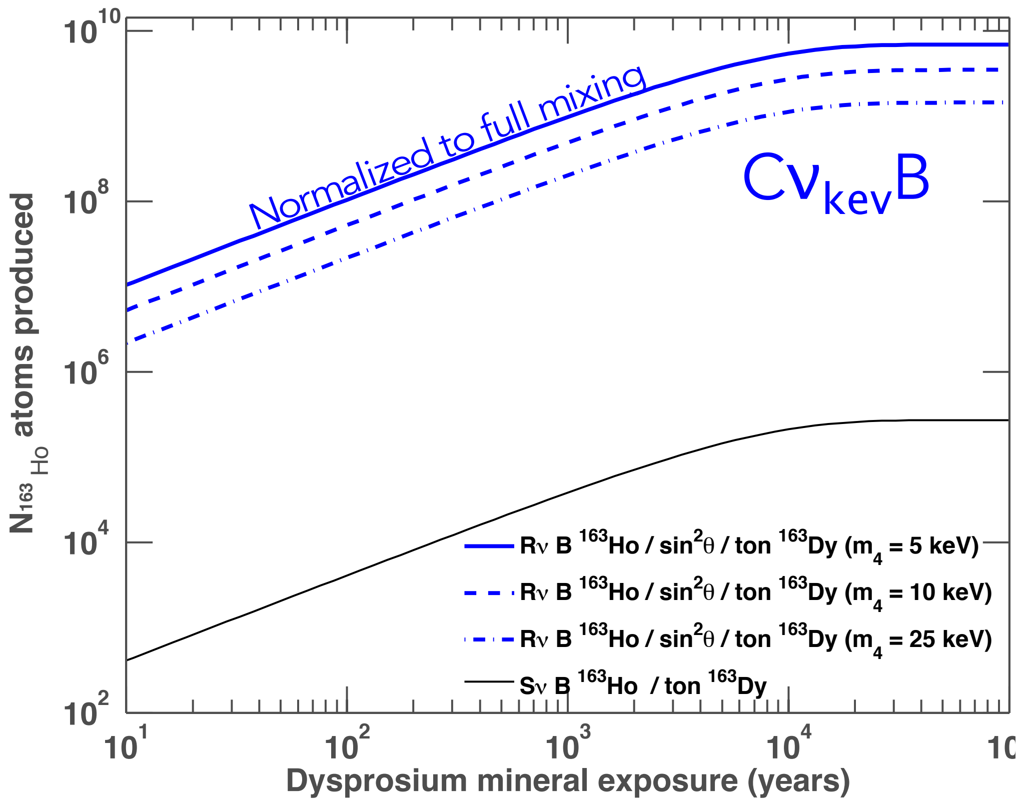
Number of ^{163}Ho atoms

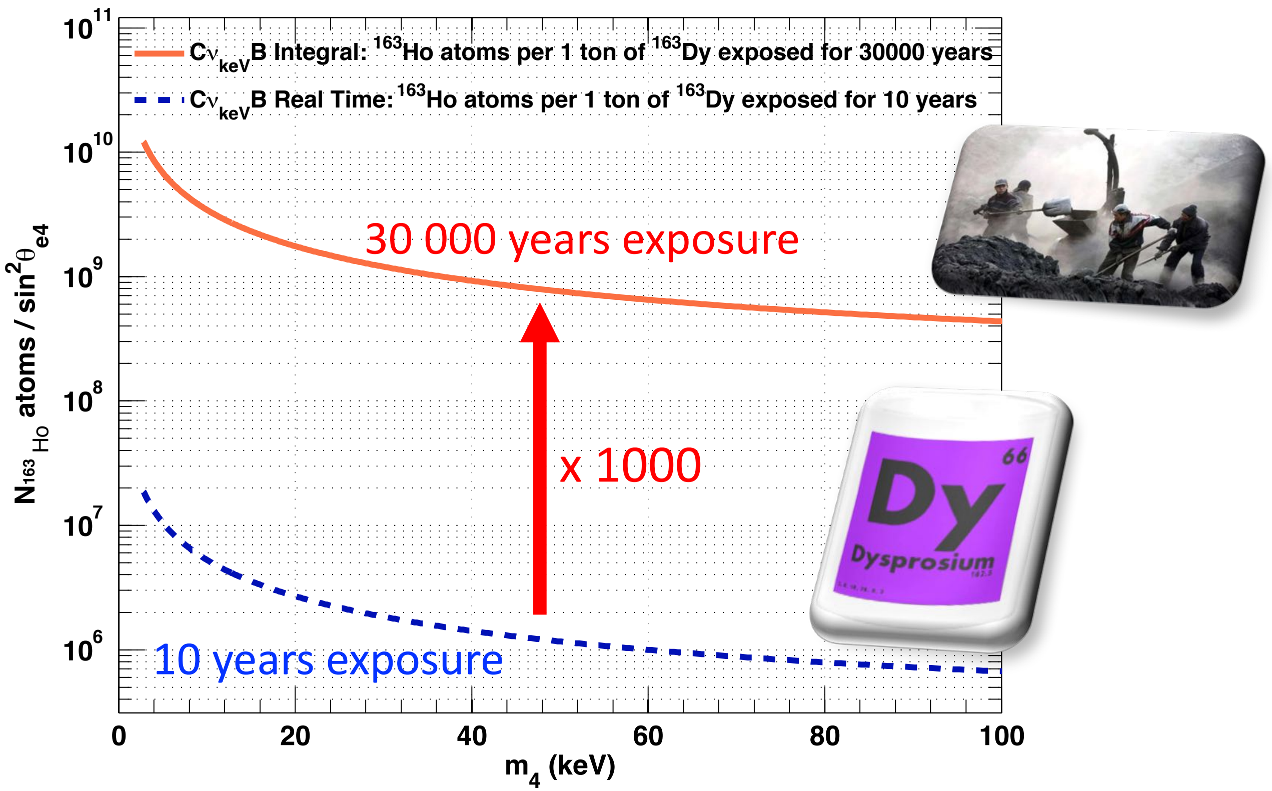


Equilibrium after 30 000 years

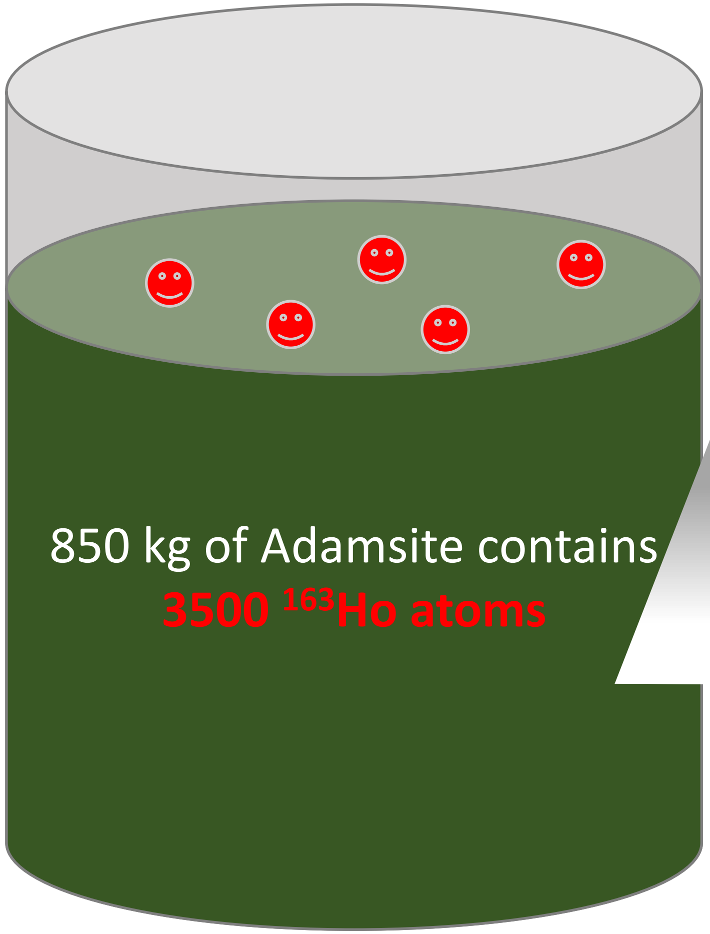


Number of ^{163}Ho atoms





Technical realization



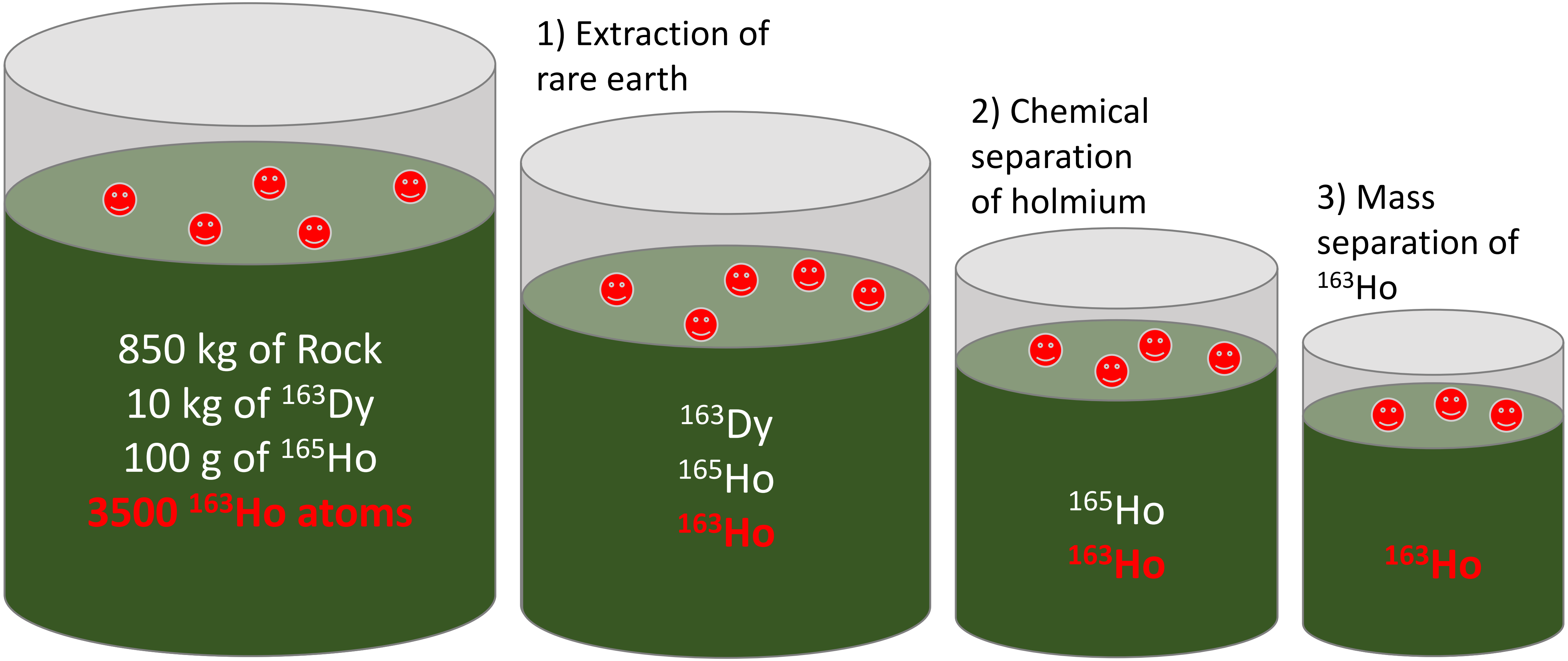
Adamsite Rock

- Na $Y_{0.7}$ $Dy_{0.1}$ $Er_{0.05}$ $Gd_{0.04}$ $(CO_3)_2$ $6(H_2O)$
- 5% of natural dysprosium
- 25% of ^{163}Dy in natural dysprosium

- Contains Gd (neutron capture)
- Low U, Th content

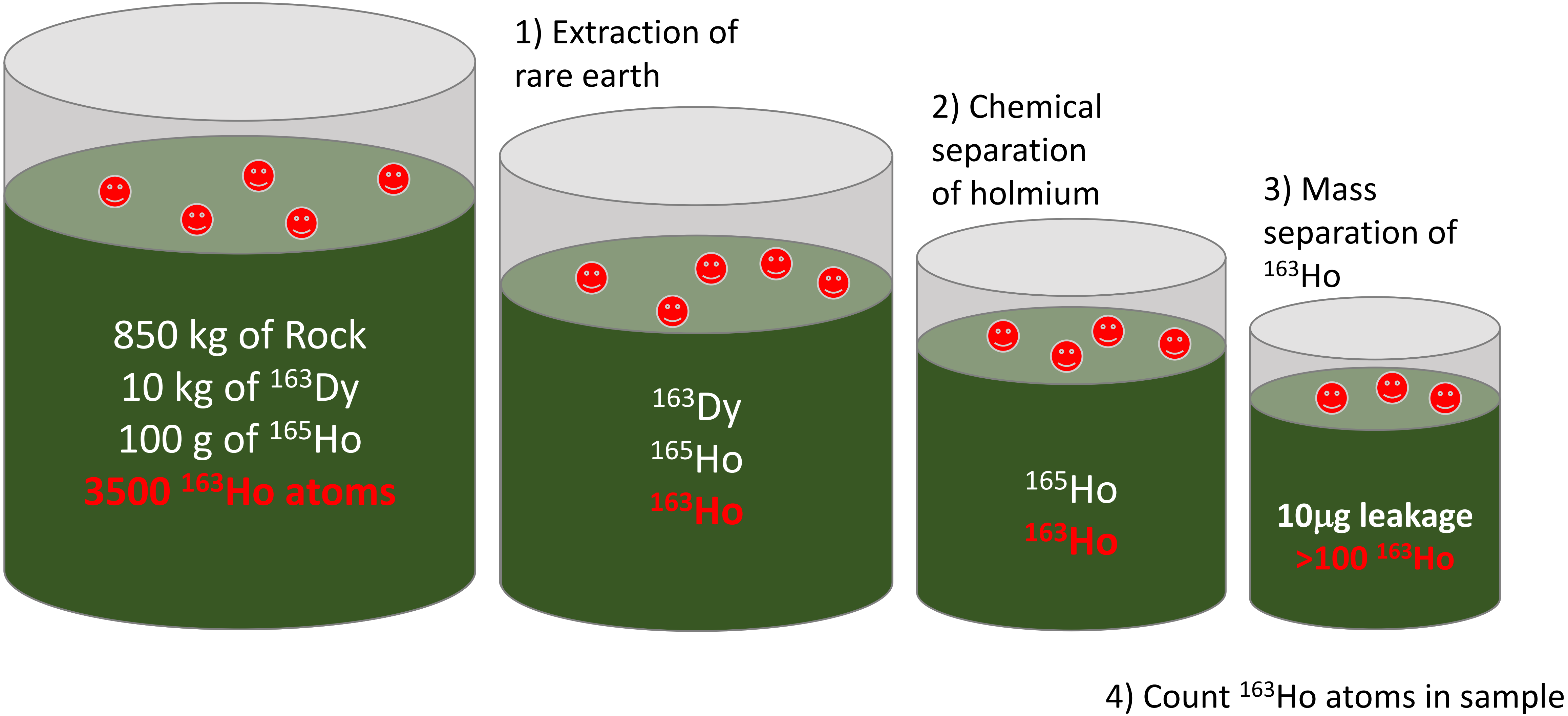
➢ Minimize cosmogenic activation of ^{163}Ho to negligible level

Technical realization (simplified)

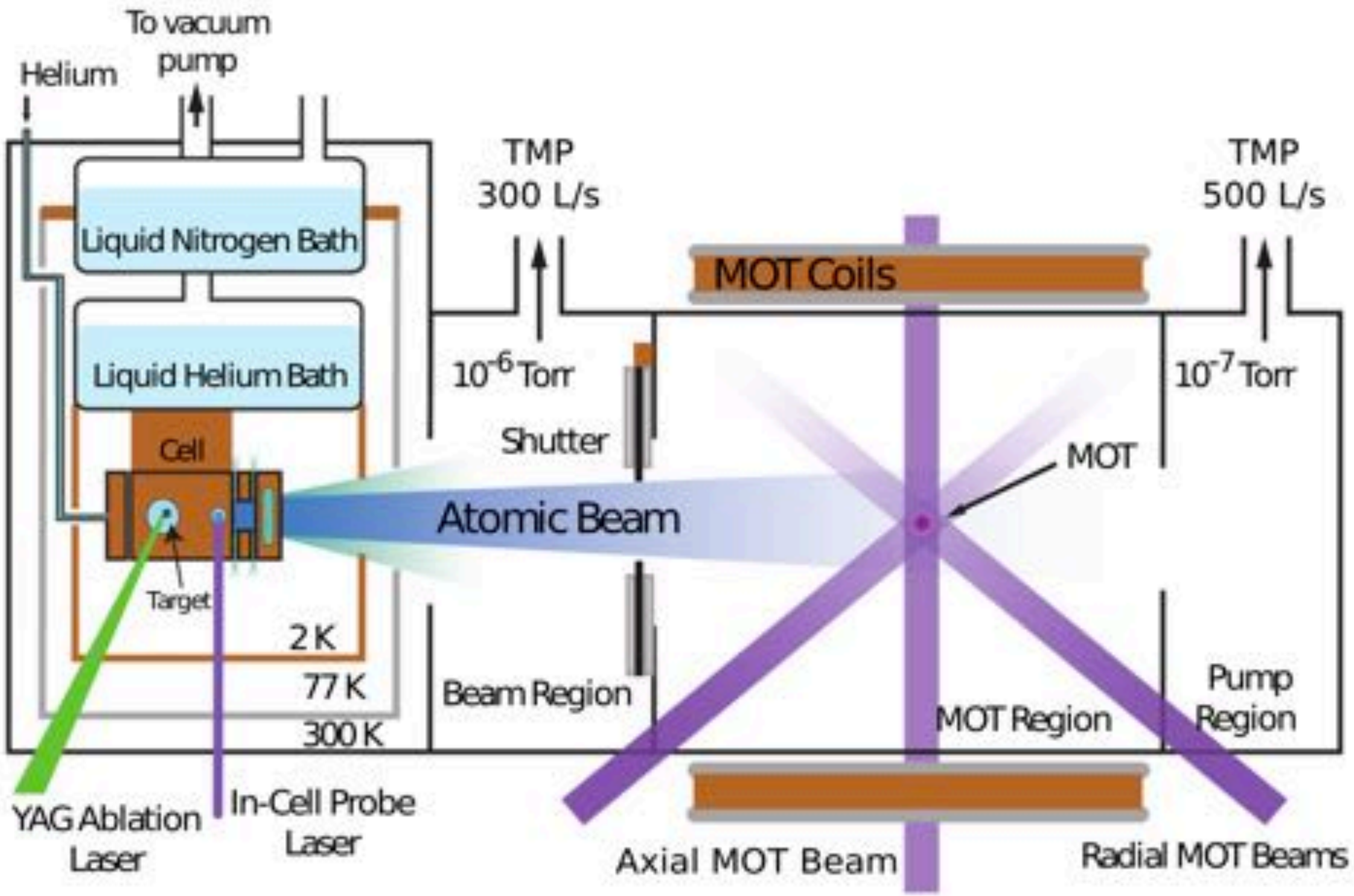


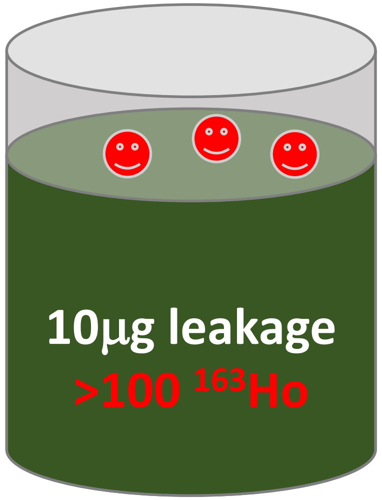
4) Count ^{163}Ho atoms in sample

Technical realization (goal)



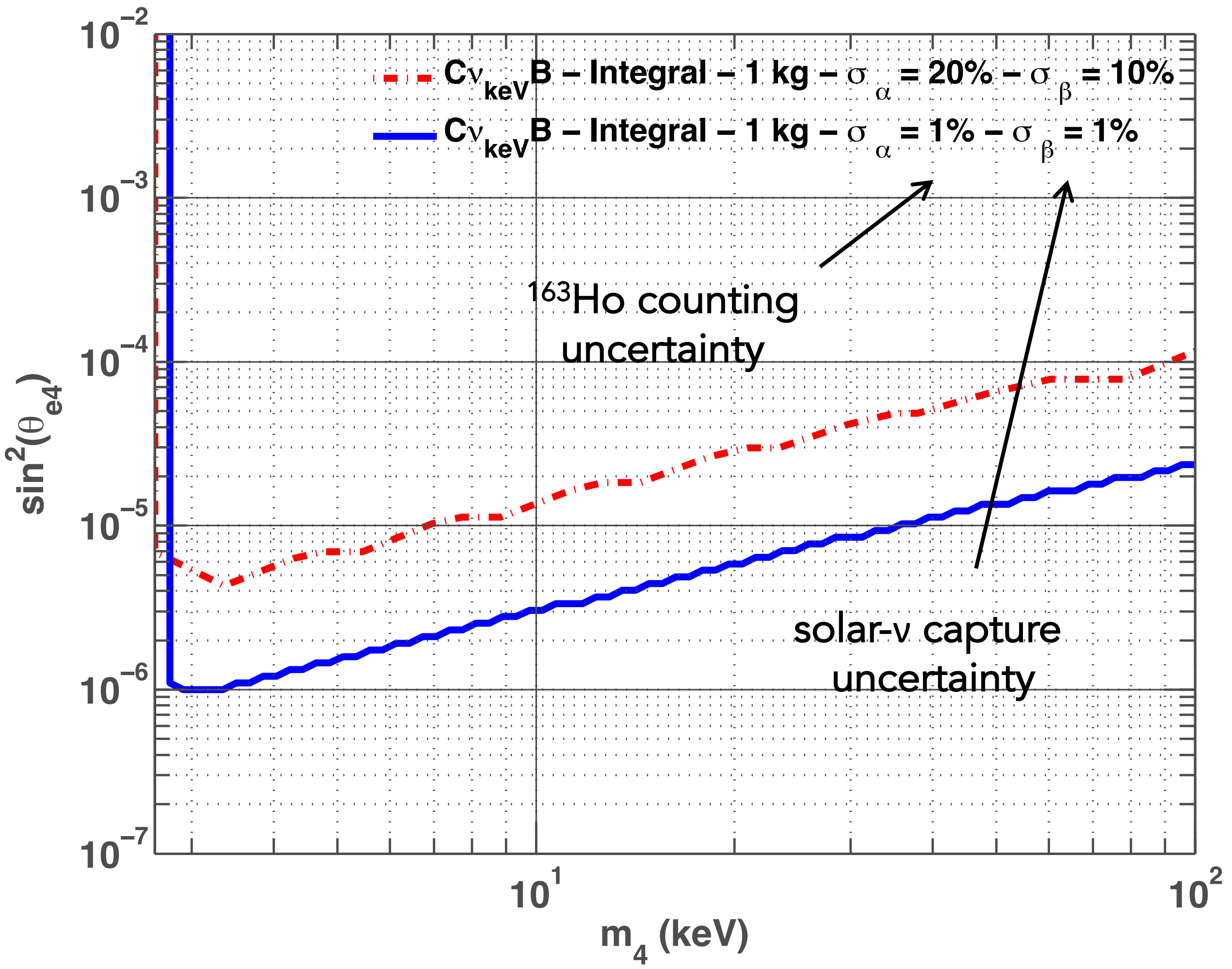
Counting ^{163}Ho in Magneto-Optical-Trap





4) Count ^{163}Ho atoms in sample

Expected Sensitivity



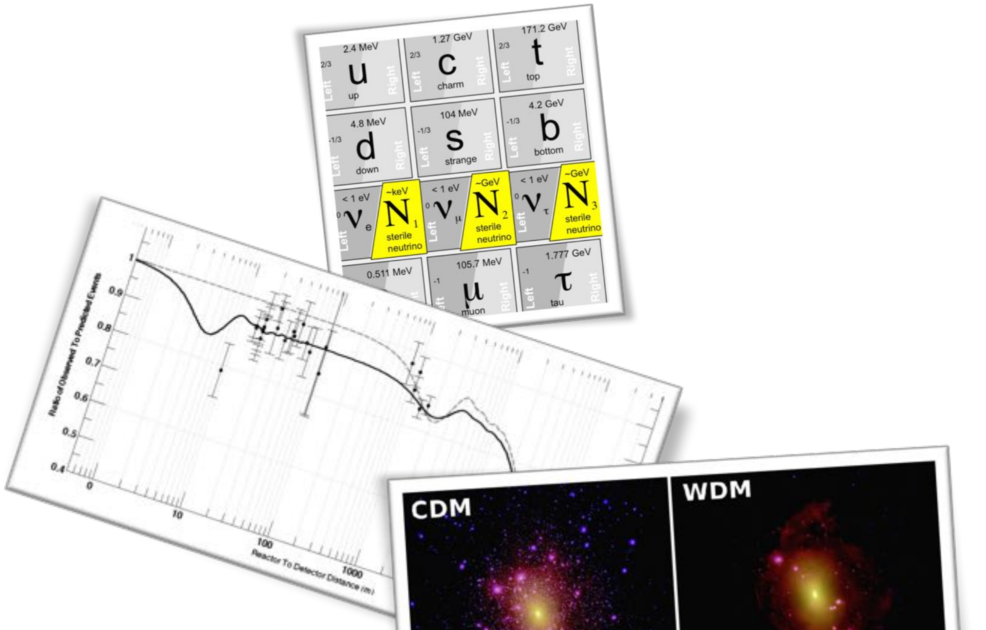
- Interesting parameter space in reach
- Limiting factor: production of ^{163}Ho via solar neutrinos
- Technical feasibility under investigation, seems not impossible…

Summary

Sterile neutrinos are a natural extension of the SM

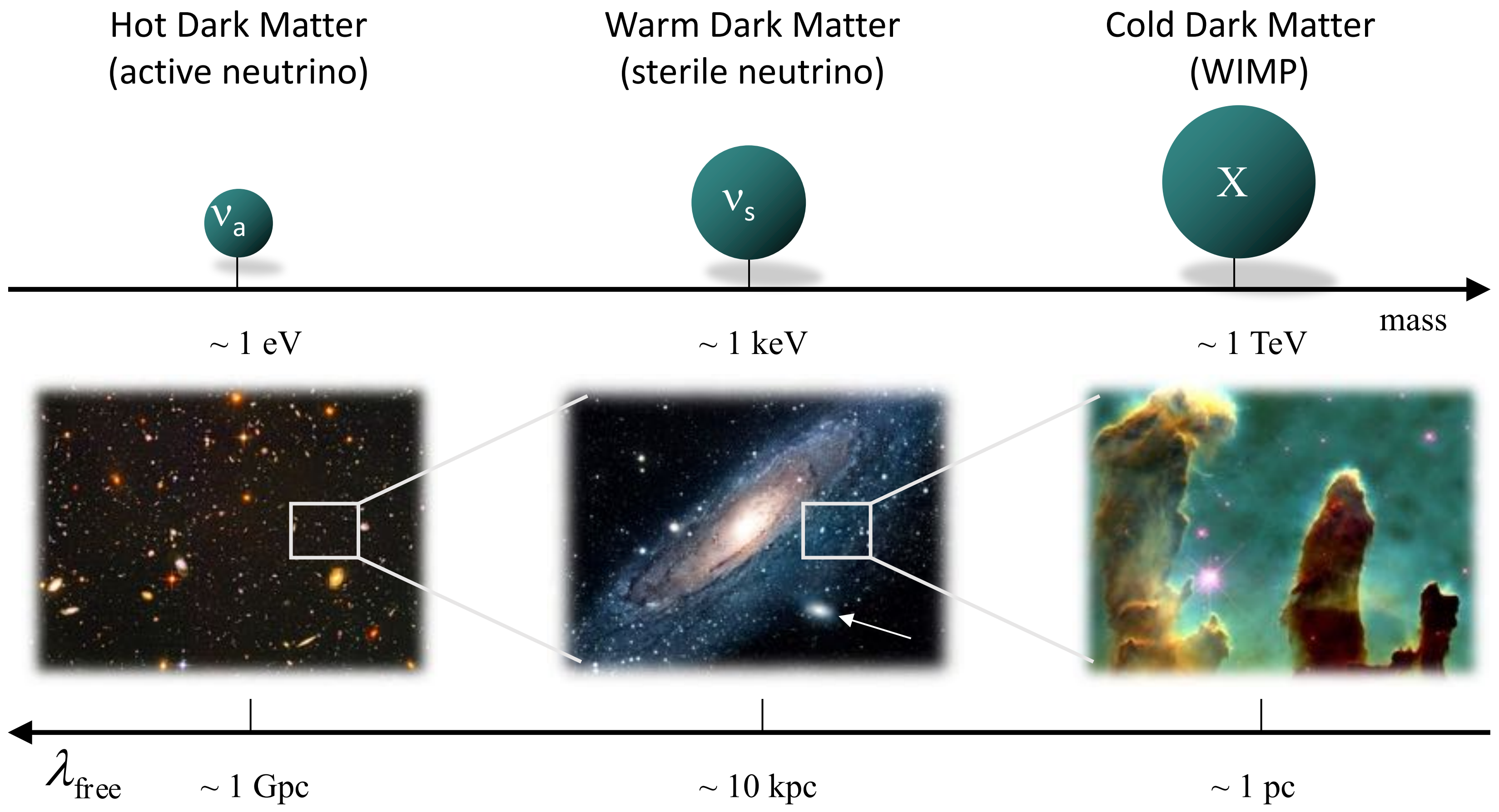
- **eV-scale sterile neutrinos:**
  - 3 σ anomalies call for clarification
  - World-wide effort is ongoing
  - KATRIN and SOX will be among the first (~2 years) to provide results

- **keV-scale sterile neutrinos:**
  - Alternative dark matter candidate
  - Strong indirect limits from X-ray observation
  - New ideas are being explored to catch up with laboratory searches TRISTAN + DyNO

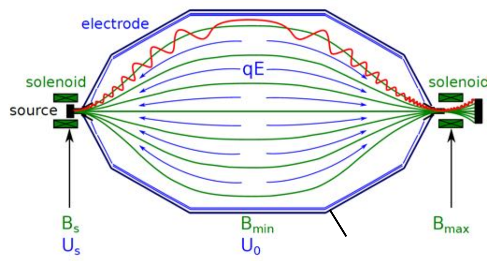



Thanks for your attention
Max-Planck-Institut für Physik
(Werner-Heisenberg-Institut)
MAX-PLANCK-GESELLSCHAFT

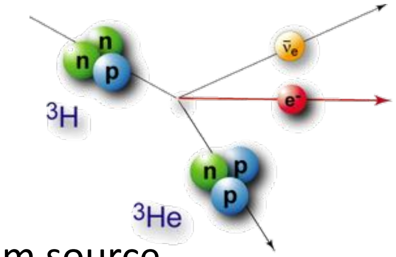
Why keV-scale sterile neutrinos?



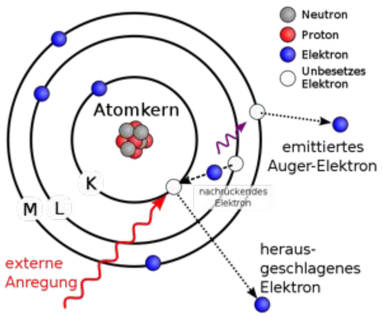
Other Challenges



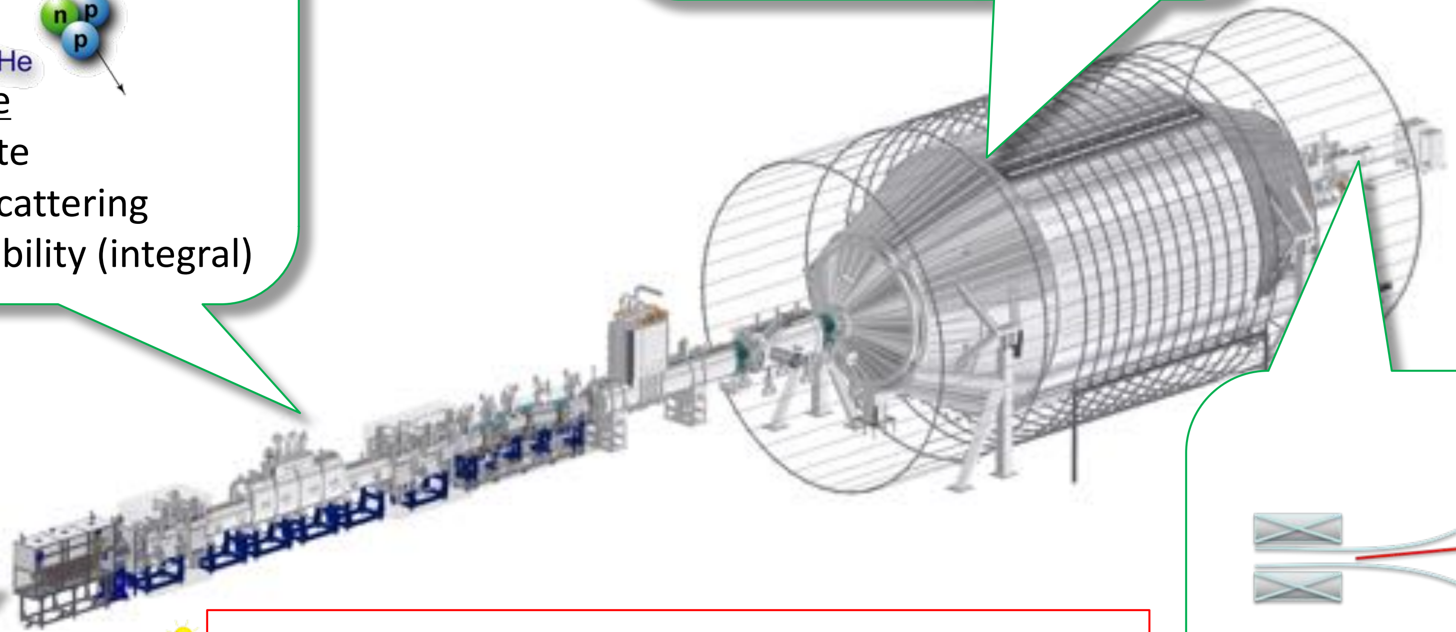
<u>Spectrometer</u>
- Adiabatic transport



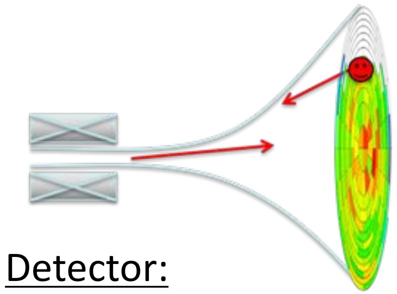
<u>Tritium source</u>
- Reduce rate
- Multiple scattering
- Source stability (integral)



<u>Gold Rear Wall</u>
- Auger e emission
- Backscattering

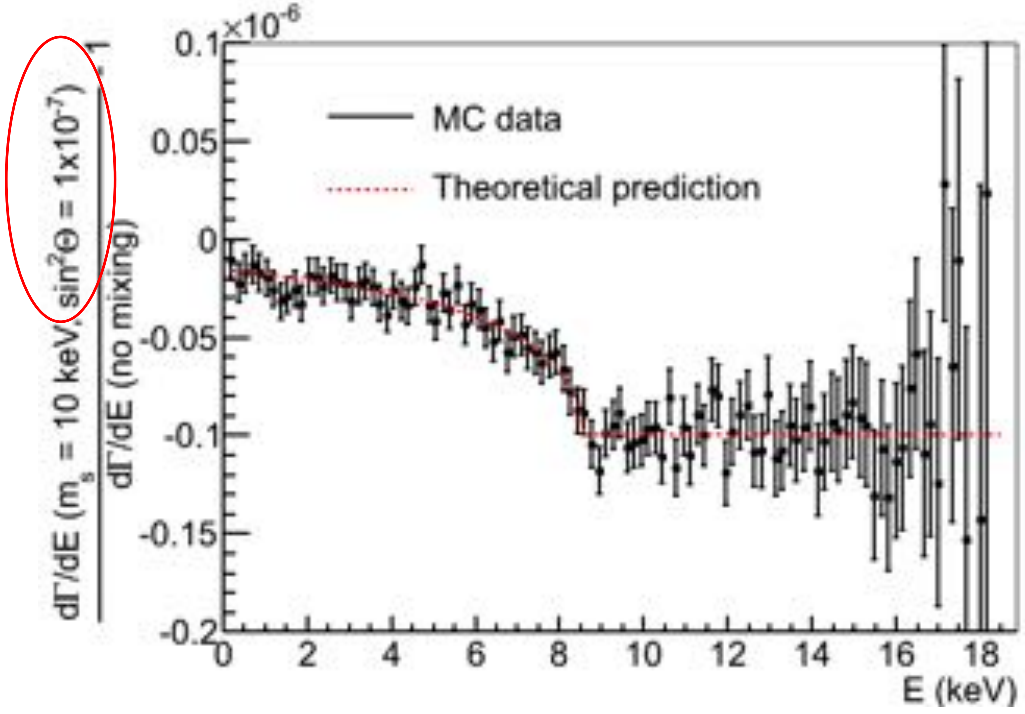


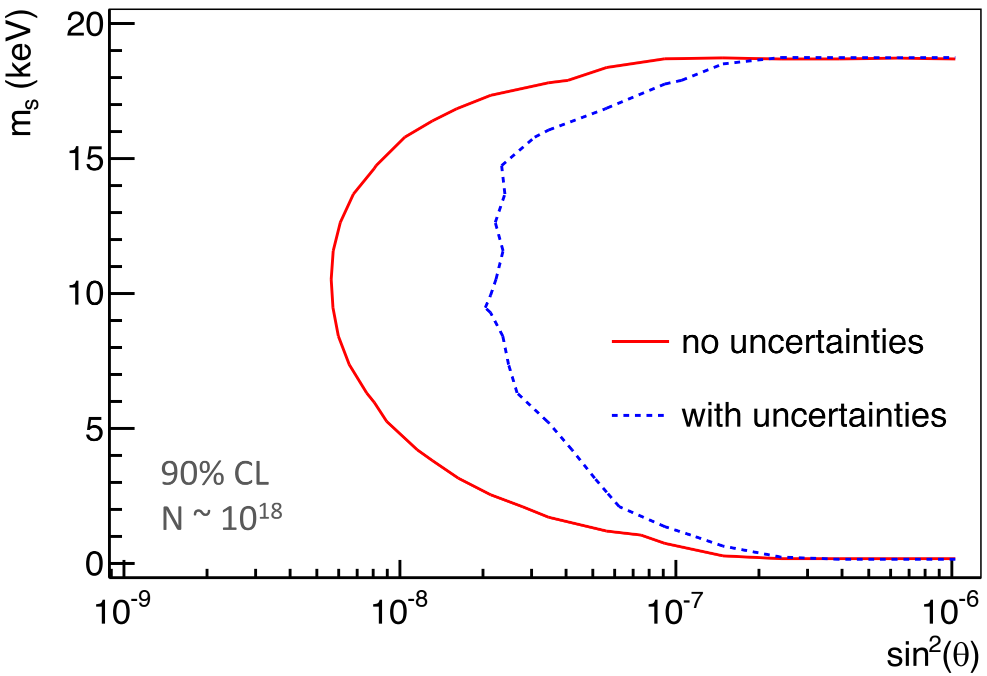
Optimized magnetic field layout
Improved modelling
Combination of integral and differential mode



<u>Detector:</u>
- Backscattering
- Energy response (differential)

Sensitivity

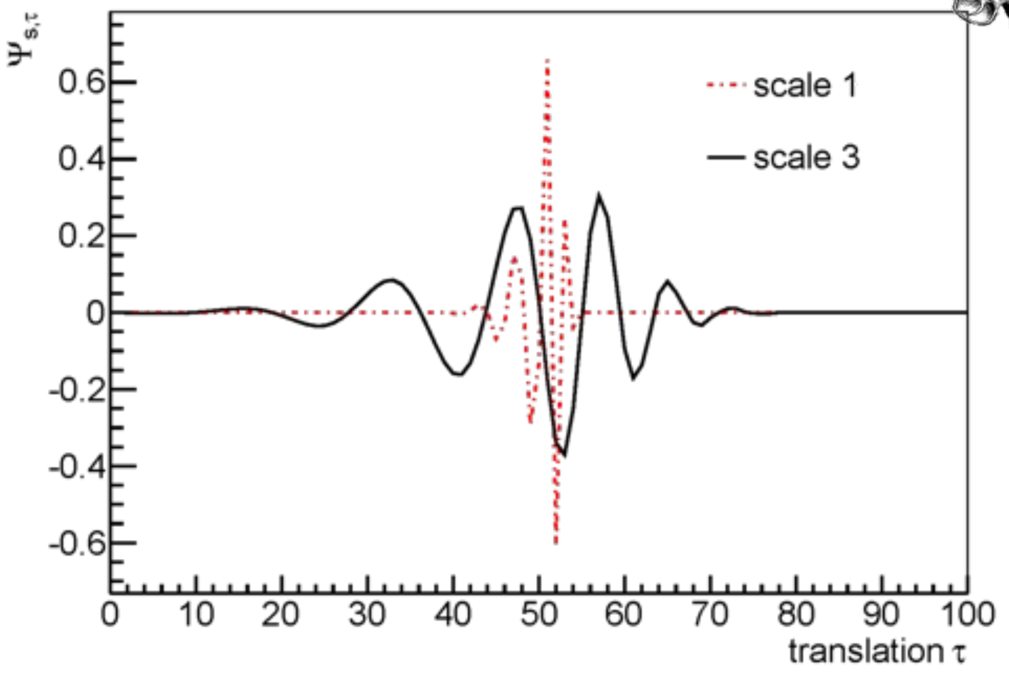


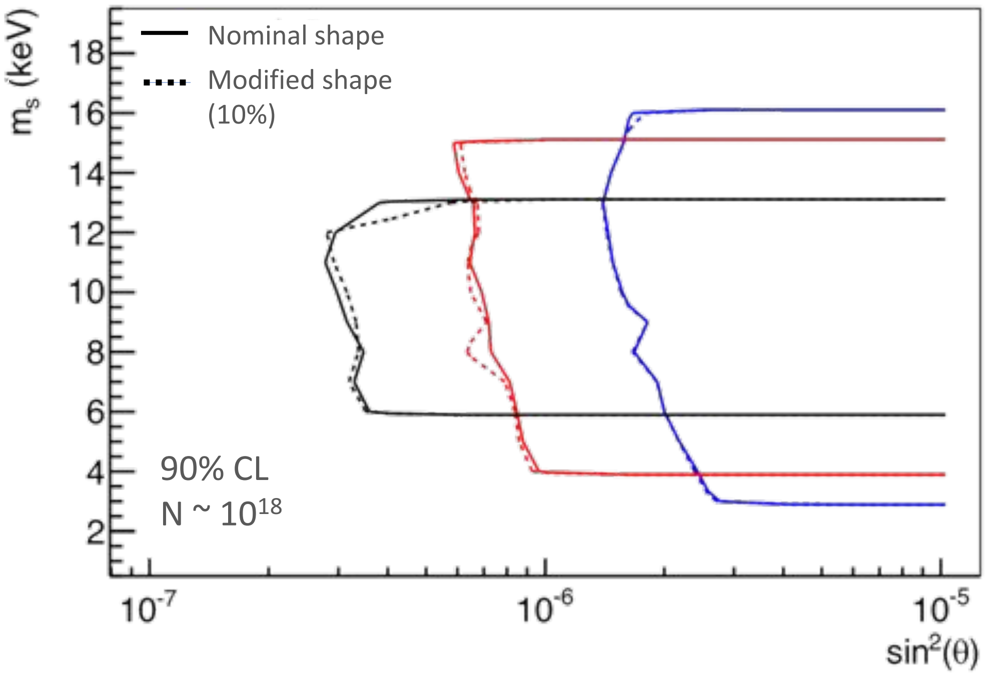


- Expected signal after 3-years with full KATRIN source strength
- Theoretical uncertainties do not destroy the sensitivity

S.M. *et. al.* Phys.Rev. D91 (2015) 4, 042005
S.M. *et al.* JCAP 1502 (2015) 02, 020

Sensitivity





- Wavelet transformation to detect characteristic kink-like signature

- Result largely independent of exact shape
- But good energy resolution required (200 eV)

S.M. *et. al.* Phys.Rev. D91 (2015) 4, 042005
S.M. *et al.* JCAP 1502 (2015) 02, 020

Backgrounds: Solar neutrinos

5 keV sterile ν capture on 1 ton ^{163}Dy:

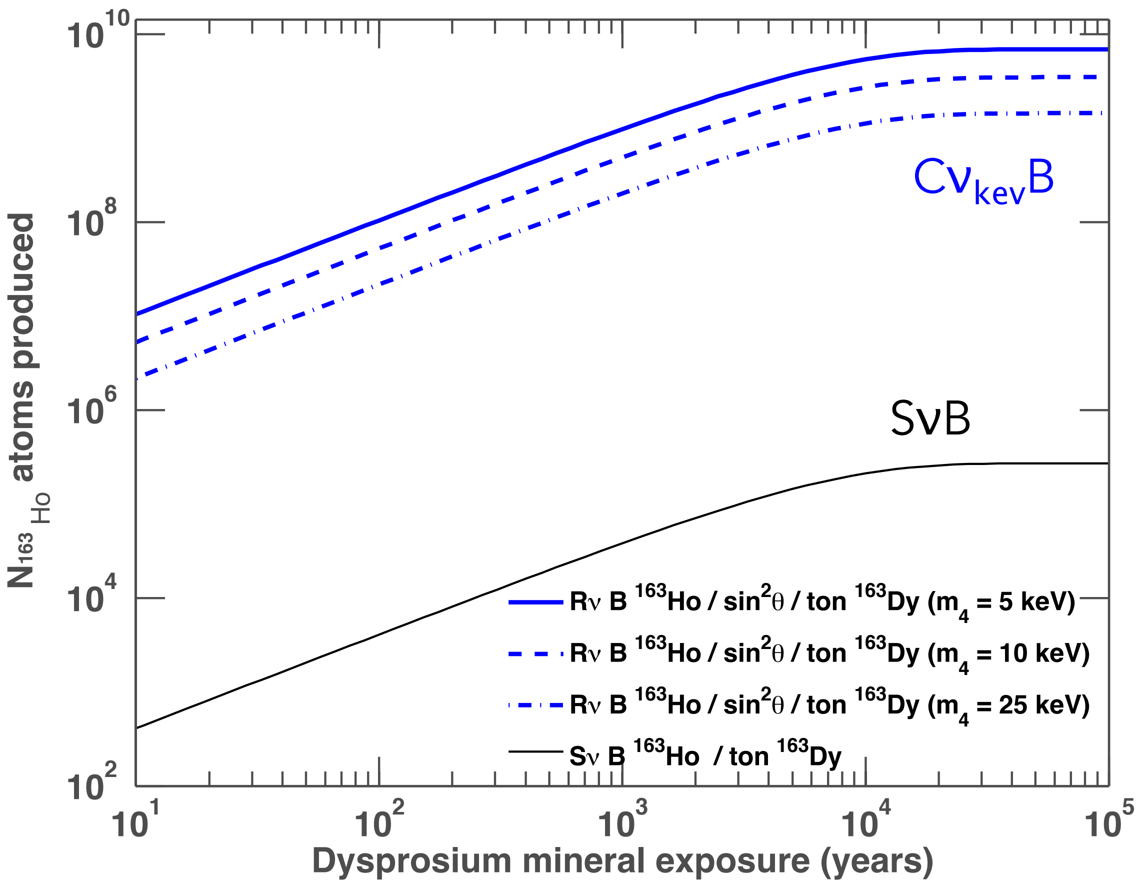
- $7 \cdot 10^9 \cdot \sin^2\theta_{e4}$ atoms of ^{163}Ho

Solar ν capture on 1 ton ^{163}Dy:

- $3 \cdot 10^5$ atoms of ^{163}Ho

Geo ν capture on 1 ton ^{163}Dy:

- negligible



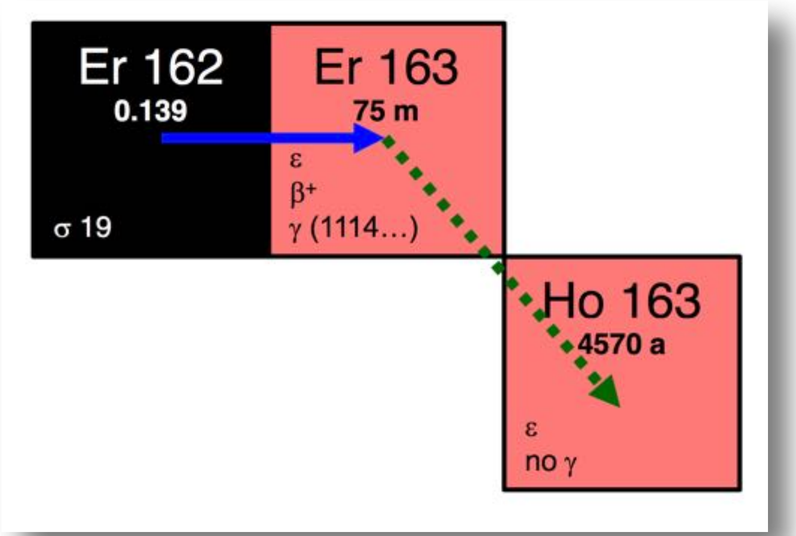
Backgrounds: Cosmogenic activation

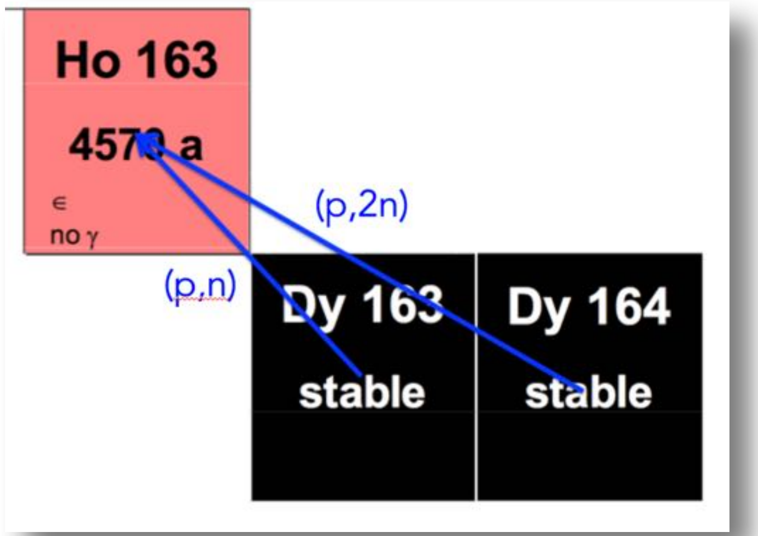
Neutron irradiation

- Slow n: 0.025 eV via ^{238}U fission
- n self-shielding by gadolinium present in rock
- ➢ Probably negligible

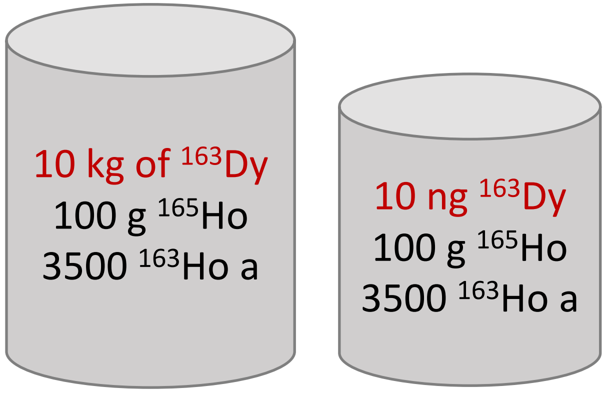
Proton irradiation

- Fast p: > 10 MeV via cosmic rays
- Shielded by earth
- ➢ negligible

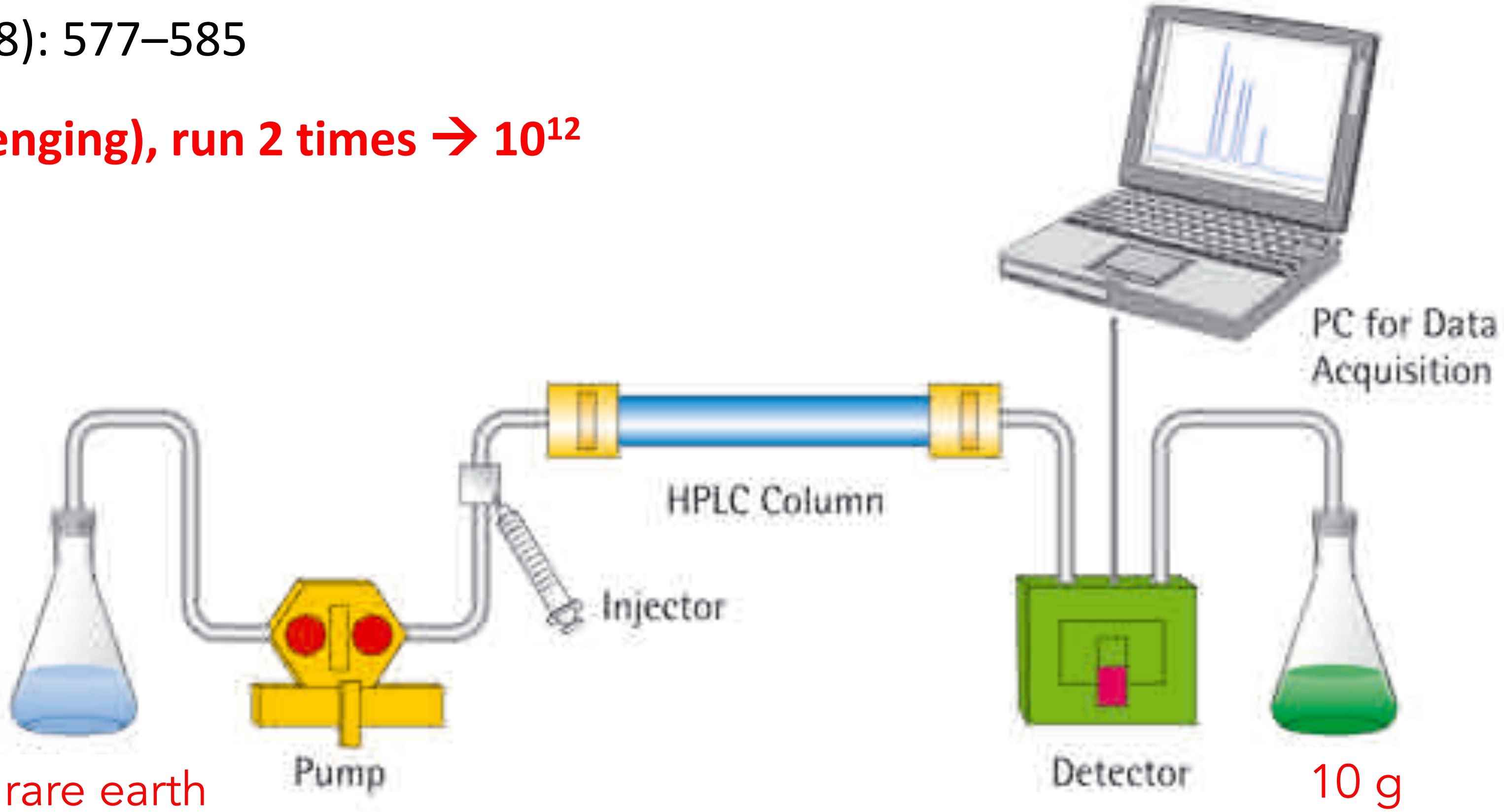




Chemical separation of holmium



- E.g. High Performance Liquid Chromatography (HPLC)
- Radiochim. Acta 2015; 103(8): 577–585
- **Reduction of Dy: 10^6 (challenging), run 2 times → 10^{12}**
- **Retention of Ho: 95 %**



few kg rare earth

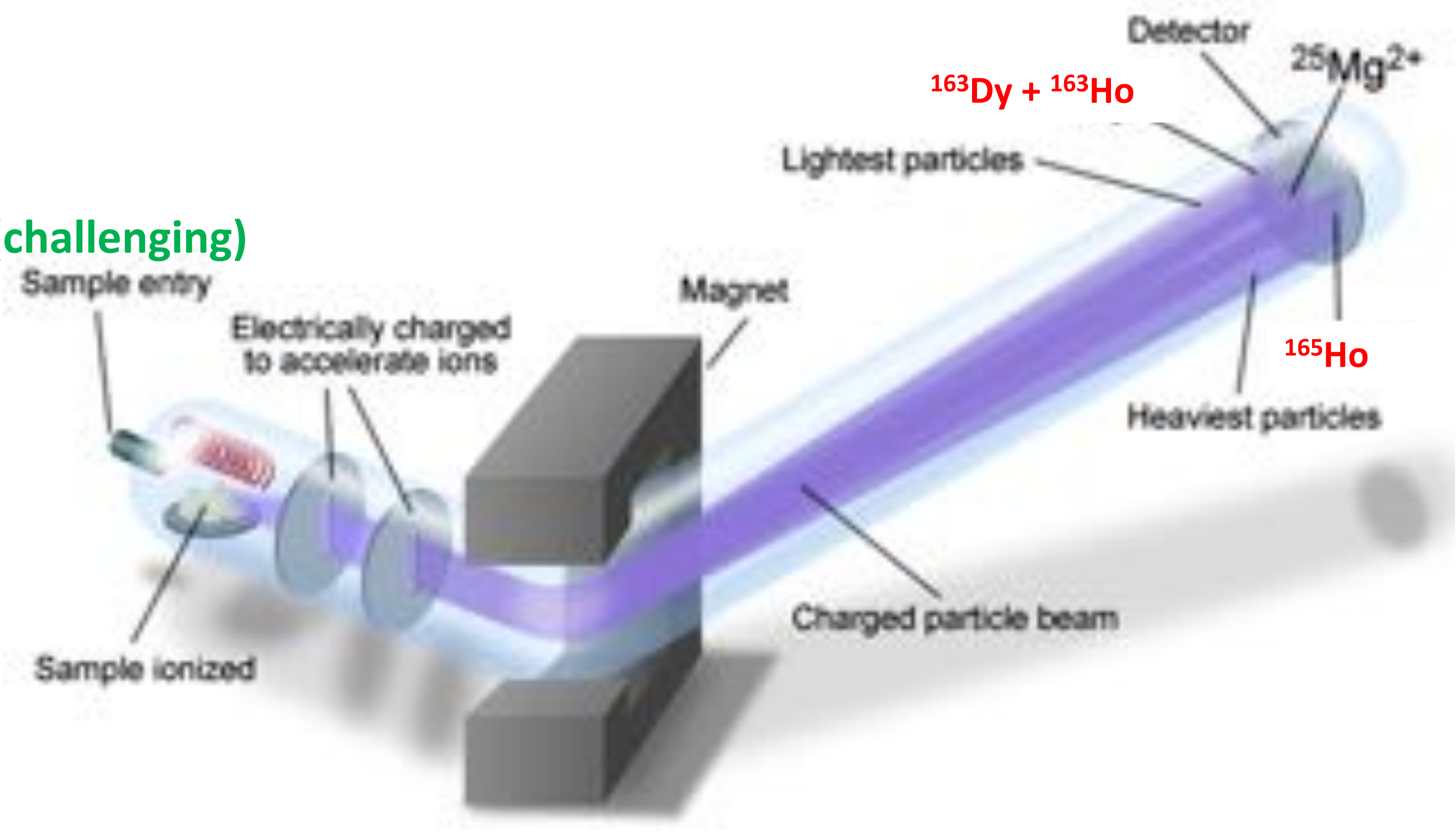
10 g Holmium

Mass separation (a)

10 ng of ^{163}Dy
100 g ^{165}Ho
3500 ^{163}Ho a

5 ng ^{163}Dy
10 mg ^{165}Ho
700 ^{163}Ho a

- E.g. @SIDONE / CSNSM Orsay
- Can handle > 1 g ?
- **Reduction of ^{165}Ho: 10^4**
- **Retention of ^{163}Ho: 20% (challenging)**

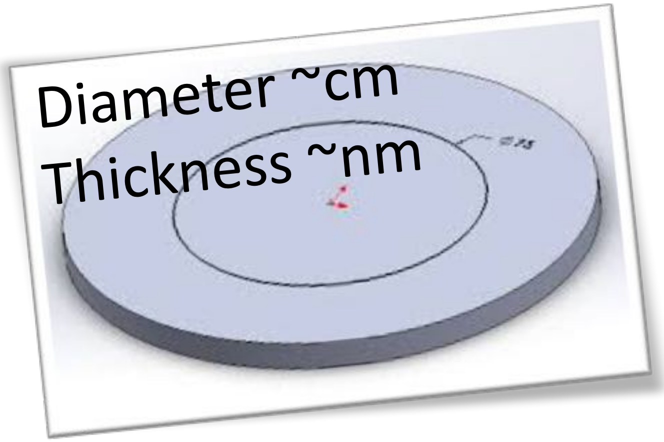


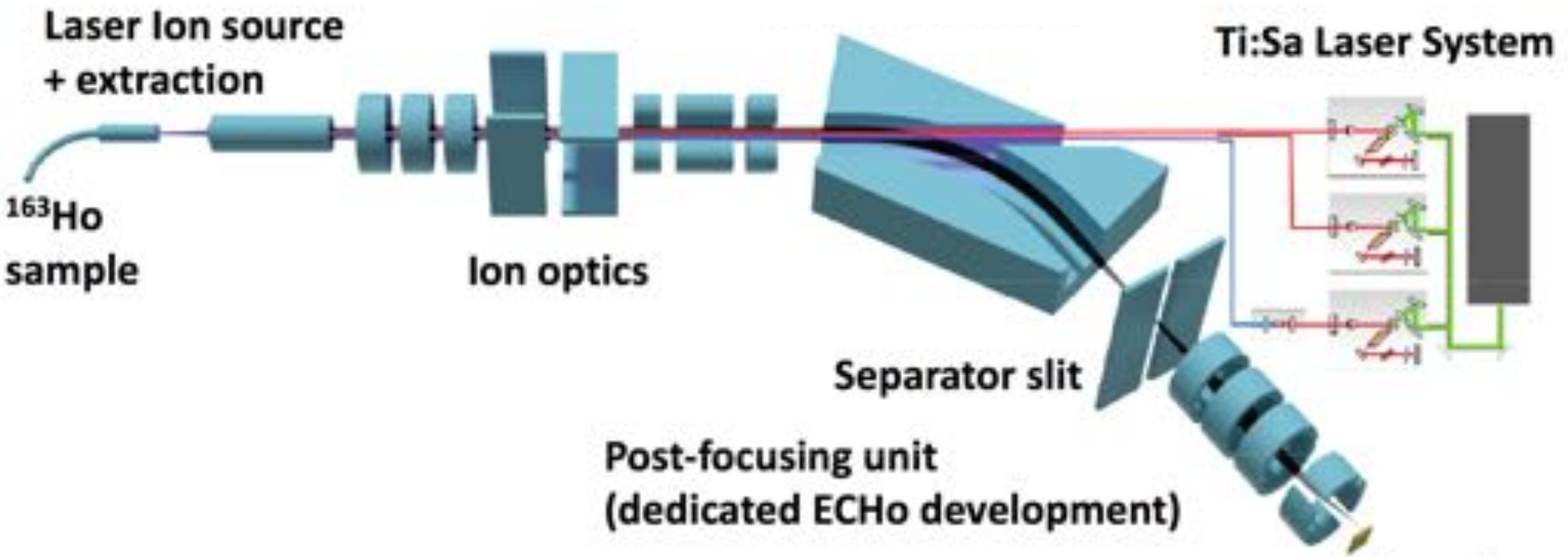
Mass separation (b)

5 ng of ^{163}Dy
10 mg ^{165}Ho
700^{163}Ho a

2 ng ^{163}Dy
1 μg ^{165}Ho
140^{163}Ho a

- E.g. RISIKO / Mainz
- Can handle < 1 g ?
- **Reduction of ^{165}Ho : 10^4 (together with (a): 10^8)**
- **Retention of ^{163}Ho : 20% (challenging)**





Calibration of efficiencies