Sterile Neutrinos at the eV and keV Scales

KAVLI INSTITUTE FOR THEORETICAL PHYSICS
Symmetry Tests in Nuclei and Atoms
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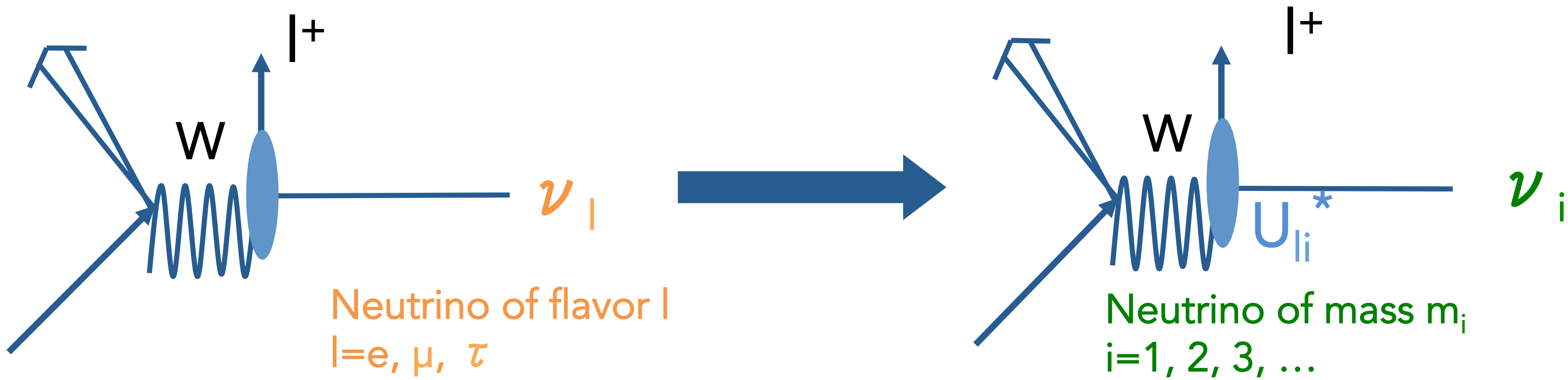
Established Neutrino Physics

- 3 types, spin ½, neutral, left handed, $\sigma(1\ \text{MeV}) \approx 10^{-45-43}\ \text{cm}^2$
- Neutrinos have tiny masses and mix: $0.04\ \text{eV} < m_\nu < \approx 1\ \text{eV}$
- Two views on W decay:



- PMNS matrix U relates mass & flavor: $|\nu_i\rangle = \Sigma\, U_{\alpha i}\, |\nu_\alpha\rangle$

$$P(\bar{\nu}_x \rightarrow \bar{\nu}_x) = 1 - \sin^2(2\theta_i)\sin\left(1.27\frac{\Delta m_i^2\ (\text{eV}^2) L\ (\text{m})}{E\ (\text{MeV})}\right)$$

3 ν Oscillation Formalism

PMNS mixing matrix

Atmospheric | Cross-Mixing | Solar | Majorana ~~CP~~ phases

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

q_{23} : "atm." mixing angle | θ_{13} | q_{12} : "solar" mixing angle

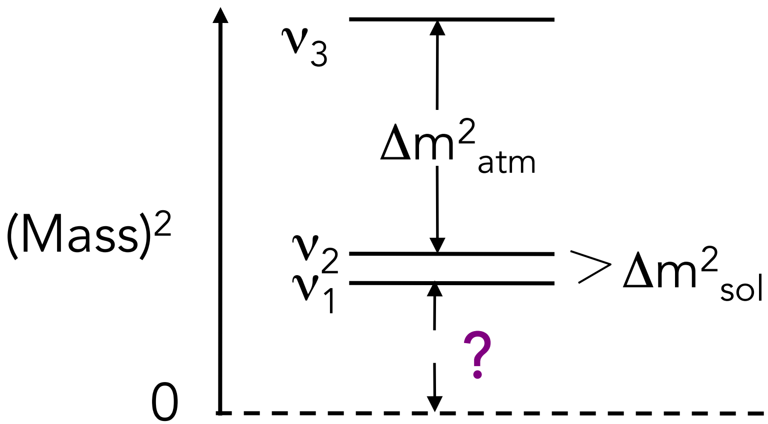
δ Dirac CP violating phase

2 Majorana phases
(L violating processes)

- 3 masses m_1, m_2, m_3 : $\Delta m^2_{sol} = m_2^2 - m_1^2$ & $\Delta m^2_{atm} = |m_3^2 - m_1^2|$
- 3-flavour effects are suppressed since: $\Delta m^2_{sol} << \Delta m^2_{atm}$ $(1/30)$ & $\theta_{13} << 1$

Open Questions

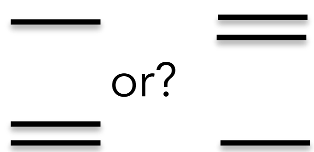
- What are the masses of the mass eigenstates ν_i?



} ν flavor change

} β decay, $\beta\beta 0\nu$ decay, cosmology

- Is the spectral pattern



$\overset{(-)}{\nu}$ behavior in matter, $\beta\beta 0\nu$

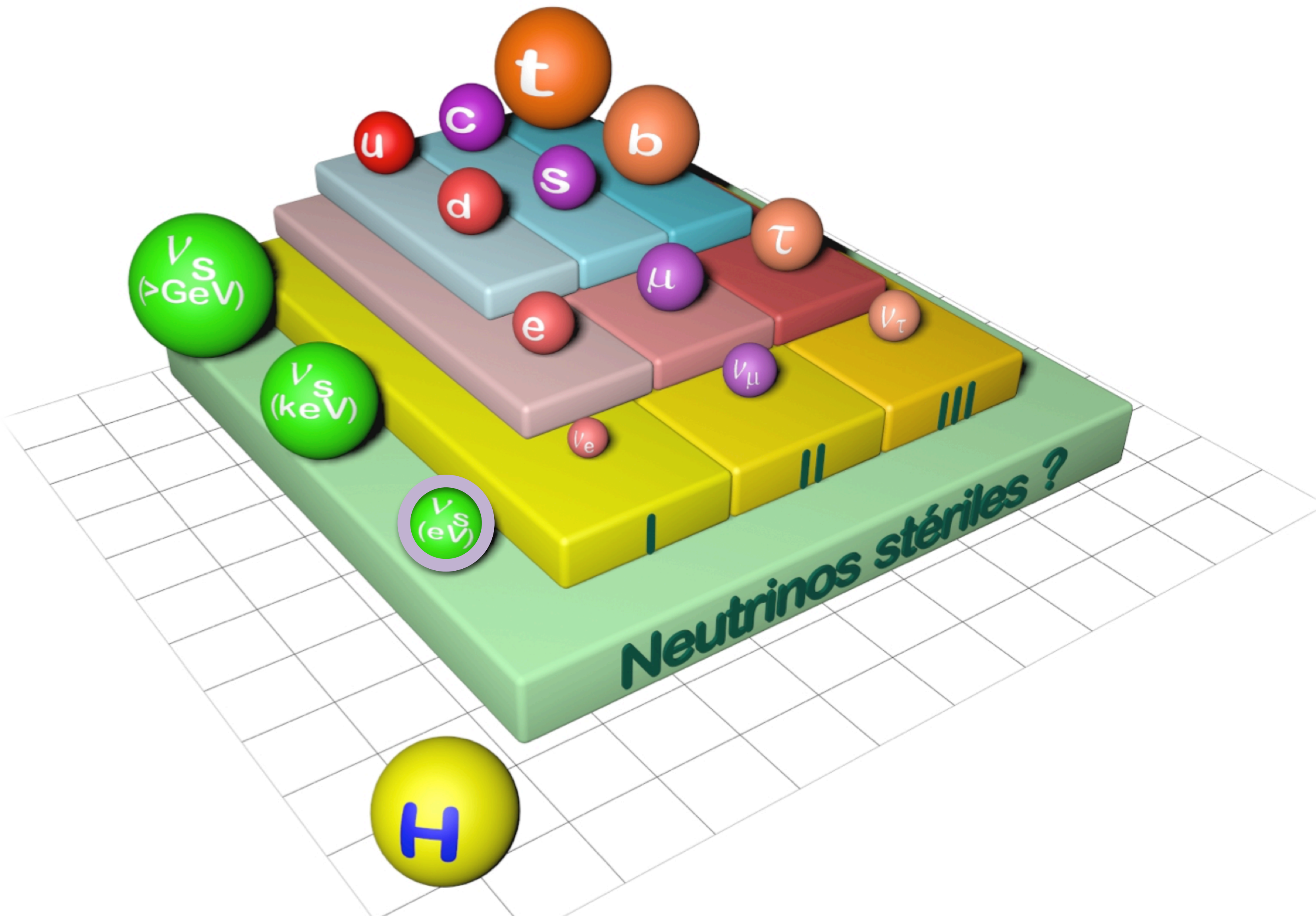
- Is there any conserved Lepton Number (Dirac or Majorana neutrino) ? $\beta\beta 0\nu$

- Precise measurements of the leptonic mixing matrix?
- Do the behavior of ν violate CP?
- Is leptonic ~~CP~~ responsible for the matter-antimatter asymmetry?

} ν flavor change

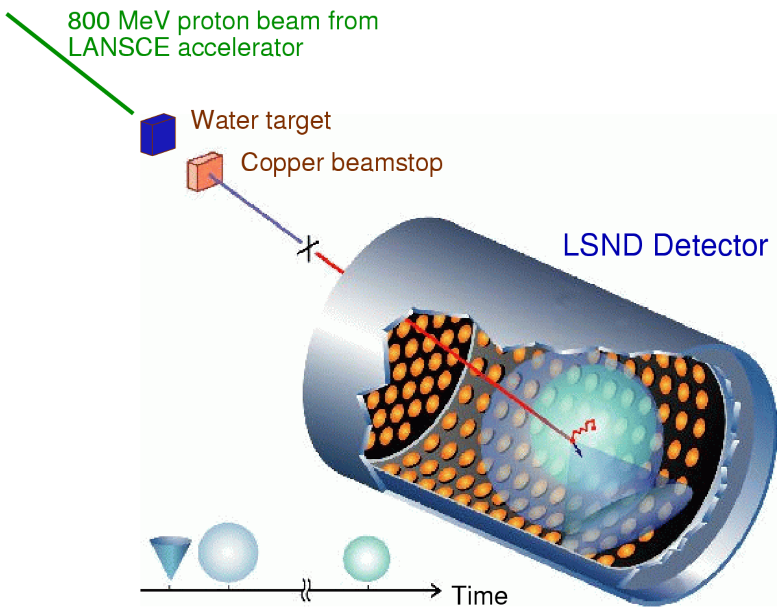
- Are there additional (sterile) neutrino states ν flavor change, Cosmology

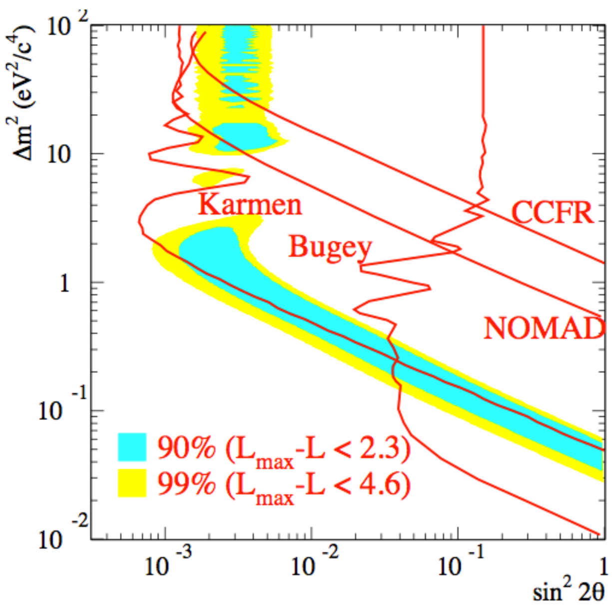
Sterile Neutrinos at the eV-scale



LSND Anomaly (stopped π^+ beam)

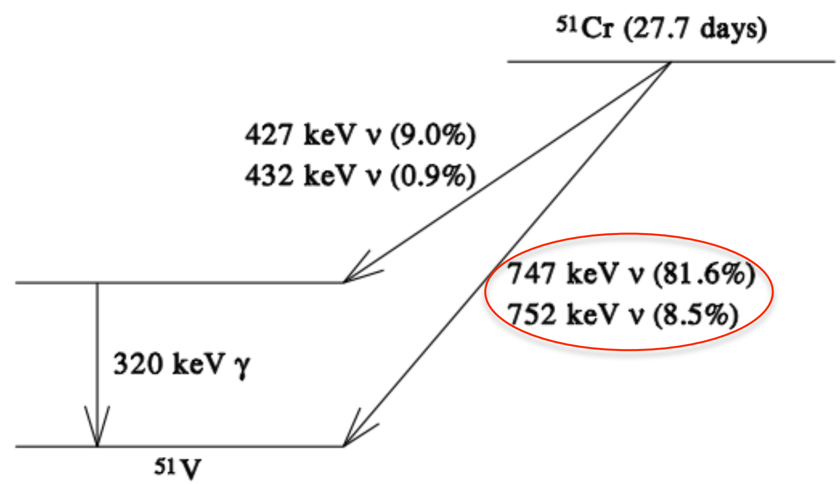
- 1^{st} results in 1995
- Channel: anti-ν_μ → anti-ν_e
- Detection : anti-ν_e + ^1H → e^+ + n
- Baseline: 30 m
- Energy: 20 < E (MeV) < 50
- Status:
  - anti-ν_e excess observed
    → 32.2 ± 9.4 ± 2.3 (3.8σ)
  - not confirmed by Karmen
  - confirmed by MiniBooNE
- ν-Oscillation interpretation:
  - $\Delta m^2 > 0.1\ eV^2 >> \Delta m_{atm}^2$



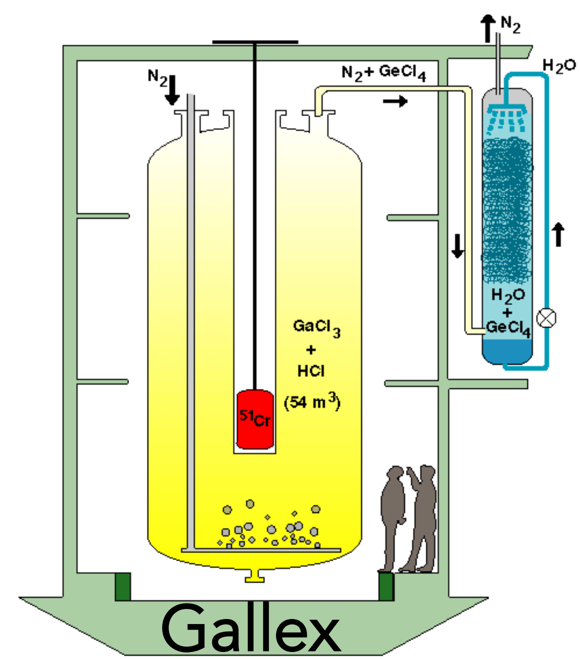


The Gallium Anomaly (GA)

- Test of solar neutrino radiochemical detectors GALLEX and SAGE
  - $^{71}Ga + \nu_e \rightarrow {}^{71}Ge + e^-$



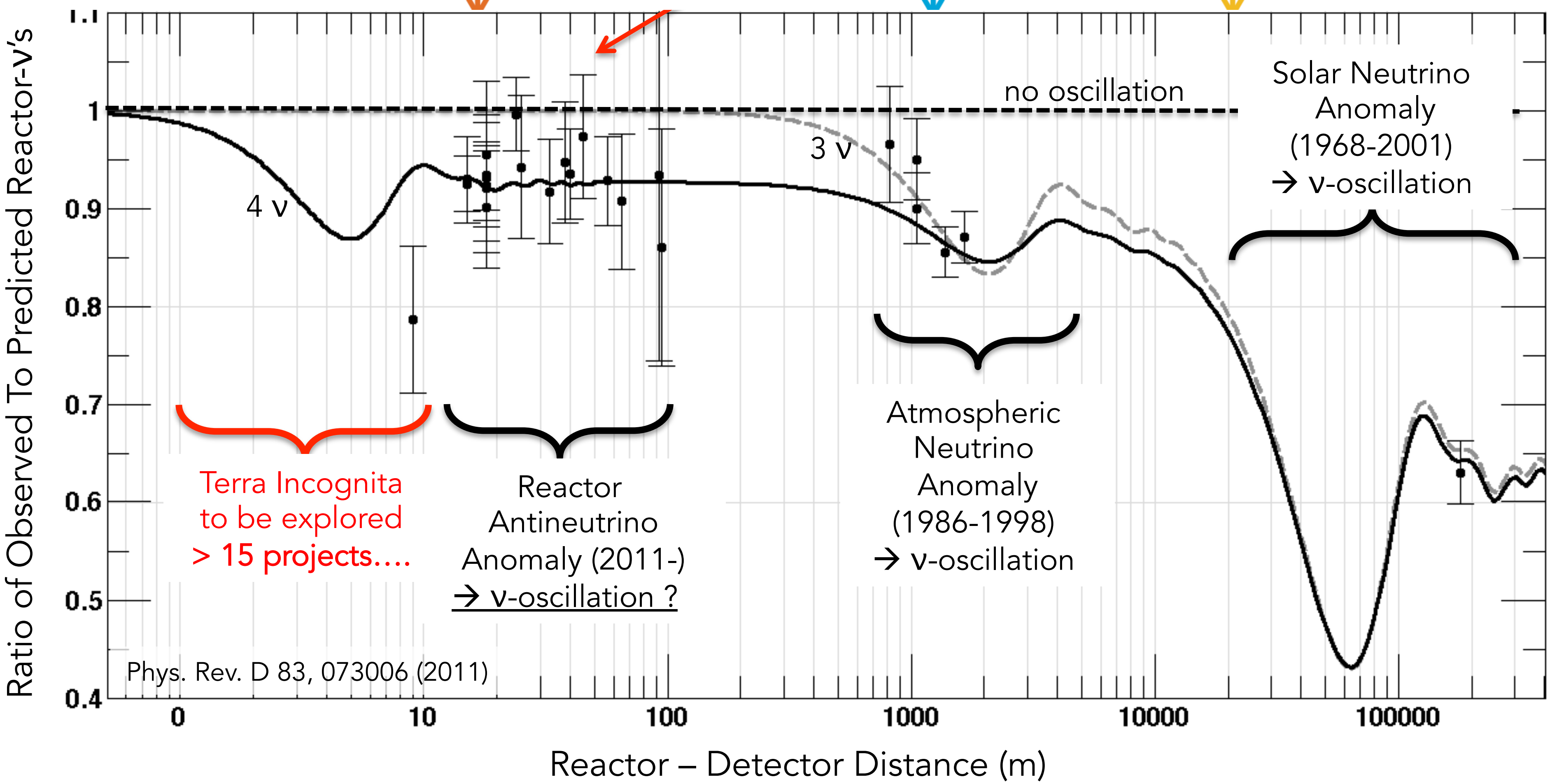
- 4 calibration runs with 20-60 PBq Electron Capture ν_e emitters
  - Gallex, <L>=1.9 m
    - ^{51}Cr, 750 keV
  - Sage, <L>=0.6 m
    - ^{51}Cr & ^{37}Ar (810 keV)



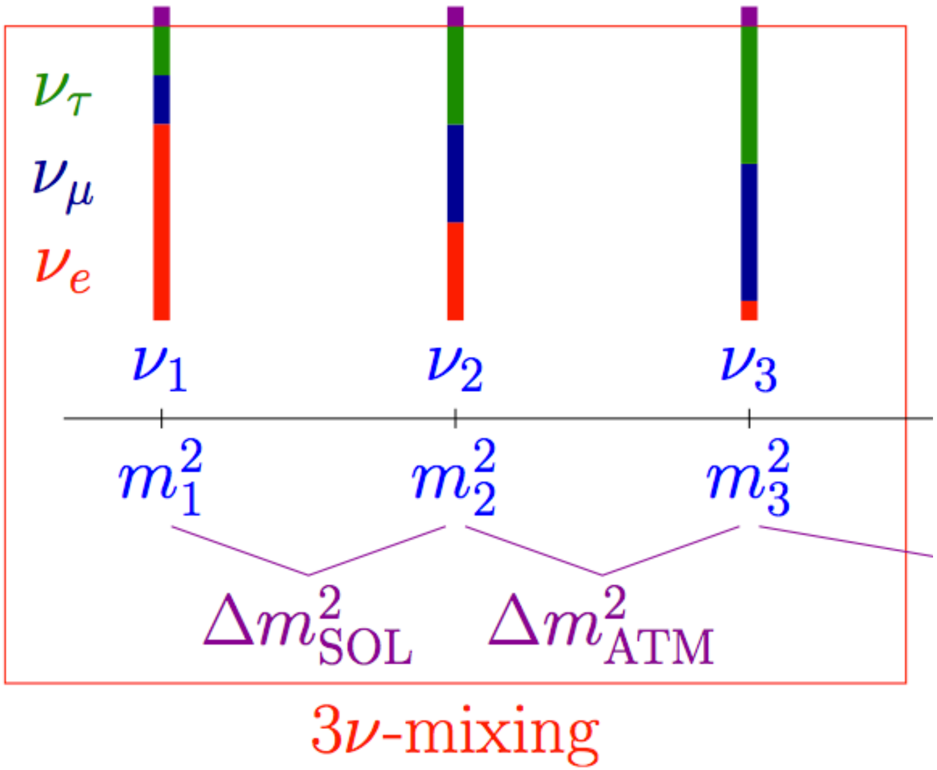
- Deficit observed
  - 3σ anomaly

The Reactor Anomaly (RAA)

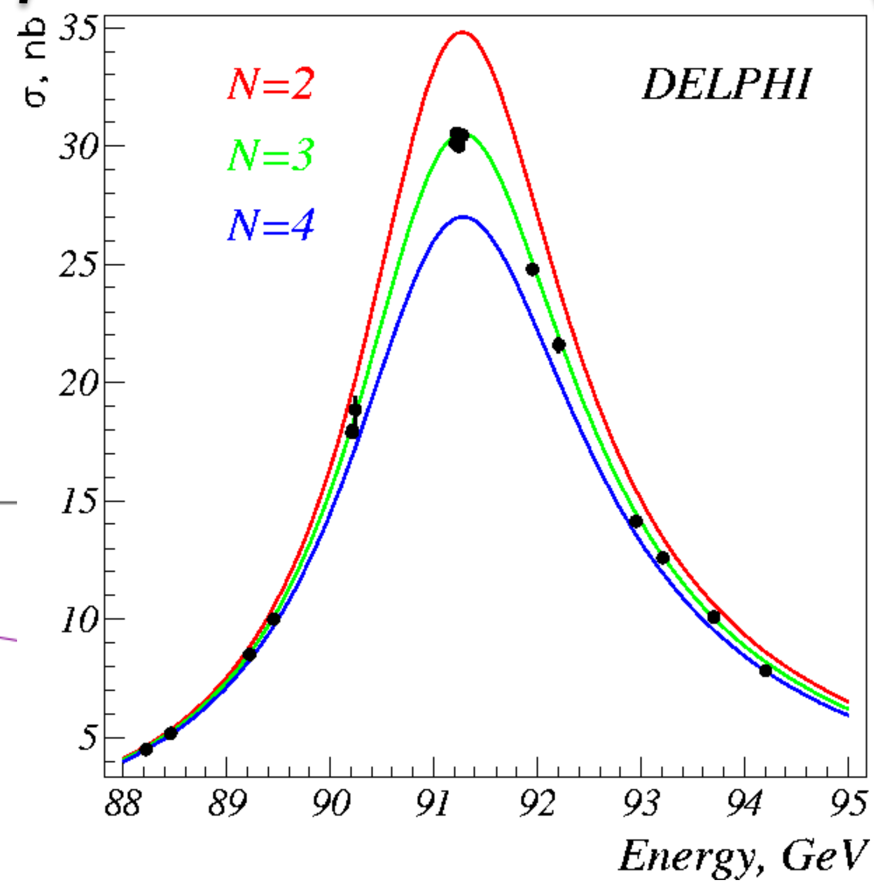
$$P_{\bar{\nu}_e \to \bar{\nu}_e} = 1 - \sin^2 2\Theta_{14} \sin^2(1.27\Delta m^2_{41} \frac{L}{E}) - c^4_{14} \sin^2 2\Theta_{13} \sin^2(1.27\Delta m^2_{31} \frac{L}{E}) - c^4_{14} c^4_{13} \sin^2 2\Theta_{12} \sin^2(1.27\Delta m^2_{21} \frac{L}{E})$$



Three Active Neutrinos



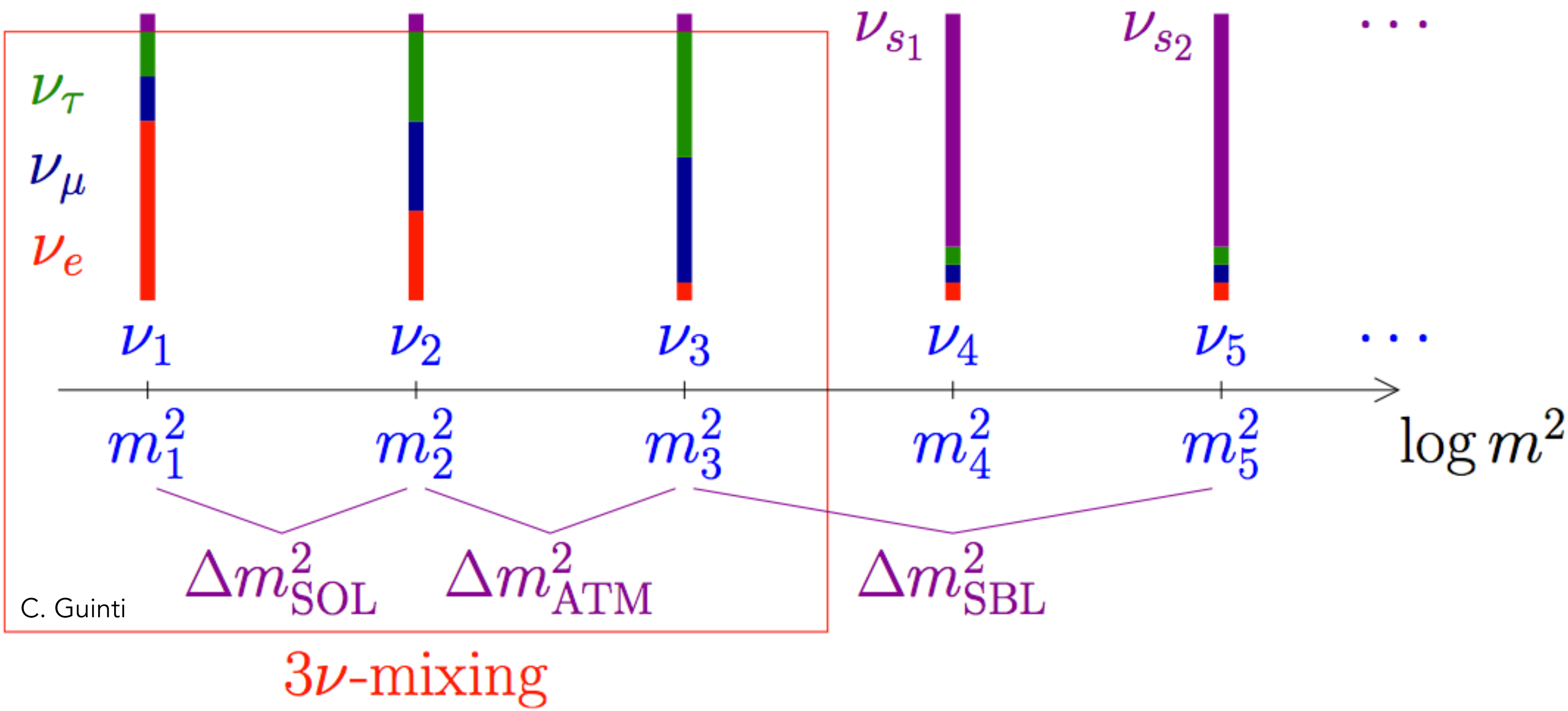
Only 3 light ν's coupling to Z boson



Adding Sterile Neutrinos

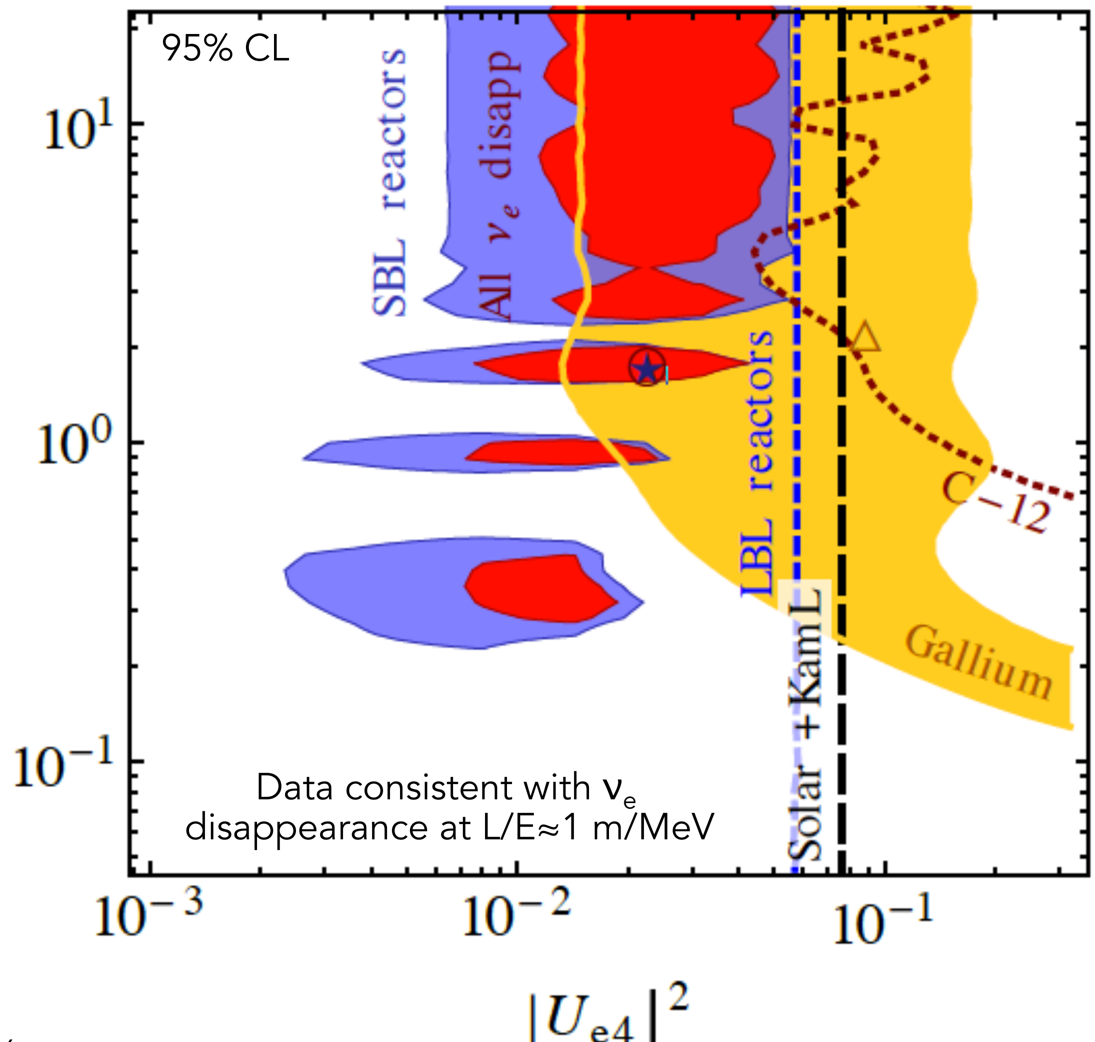
No SM interactions.
Mixing with active ν's

@credit: C. Giunti



$\overset{(-)}{\nu}_e$ disappearance (3+1)

$$P_{ee} = 1 - \sin^2 2\theta_{ee} \sin^2 \frac{\Delta m^2_{41}}{4E} \quad \& \quad \sin^2 2\theta_{ee} = |U_{e4}|^2 \left(1 - |U_{e4}|^2\right)$$



J. Kopp et al., arXiv:1303.3011

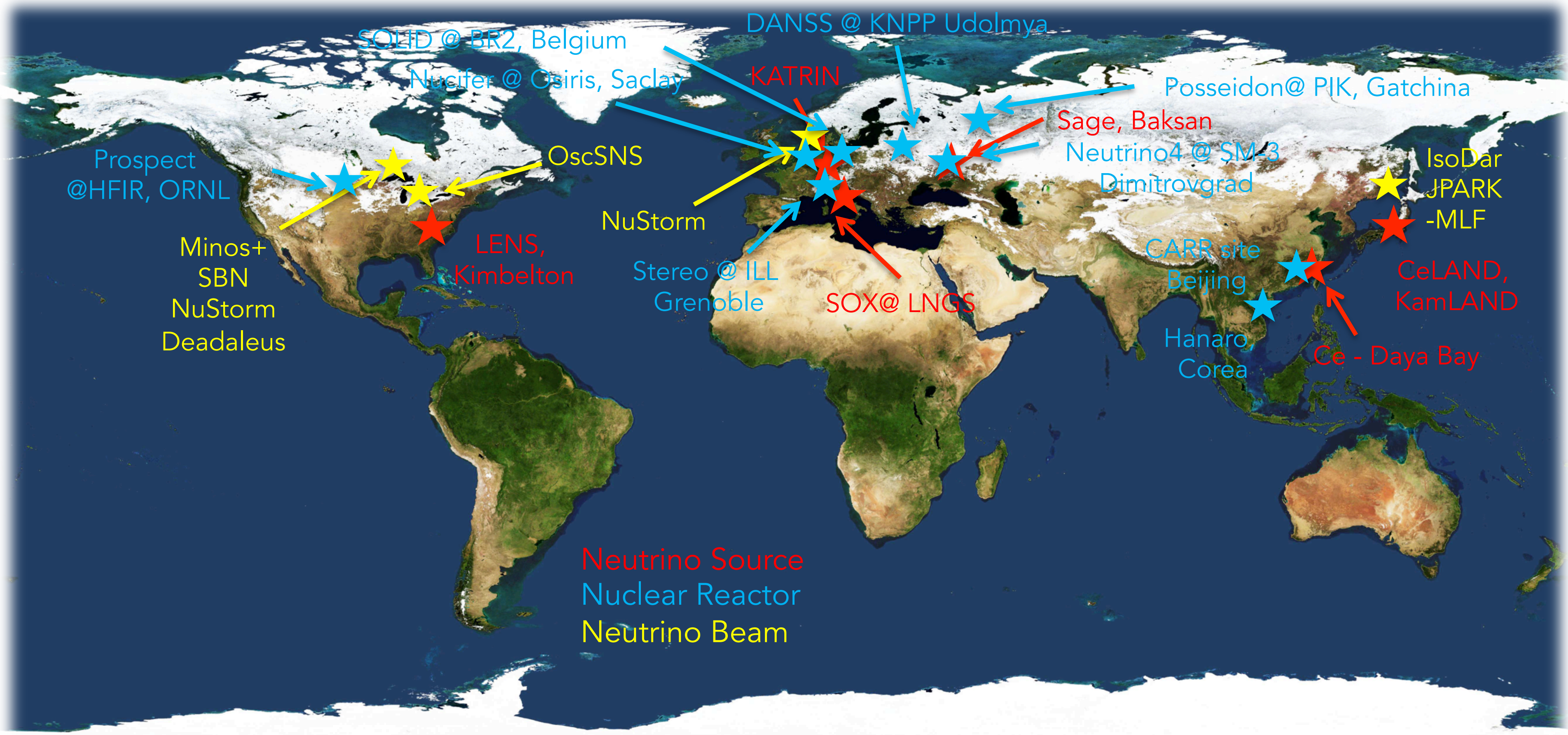
Testing $\overset{(-)}{\nu}_e$ the Anomalies

- GA & RAA : comparison between data and interaction rate prediction
  - Search for L, E, L/E pattern (shape only)
  - Complement with a rate analysis – need for an absolute calibration

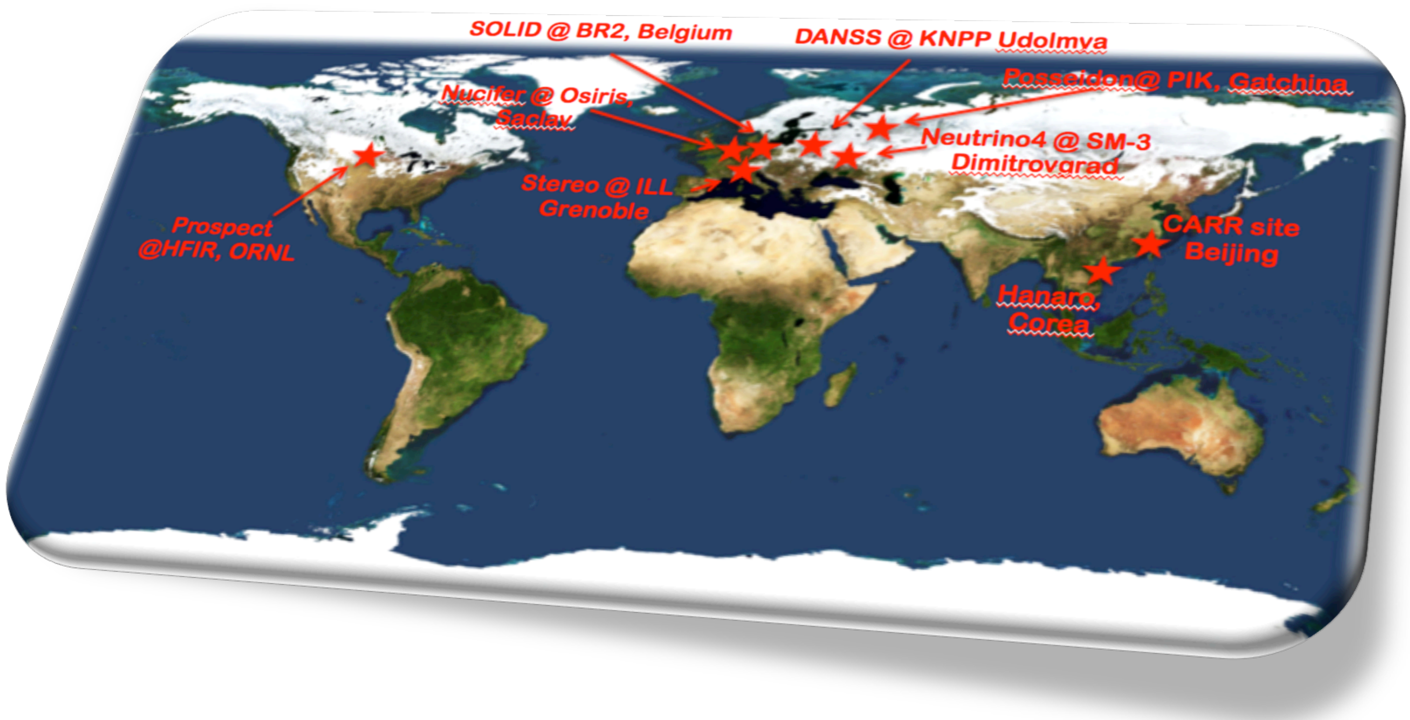
- Input from sterile neutrino global fits
  - $\Delta m_{new}^2 \approx 0.1\text{-}10\ eV^2 \rightarrow L_{osc}(m) = 2.5 \frac{E(MeV)}{\Delta m^2(eV^2)} \approx 1-10\ m$
  - $\sin^2(2\theta_{new}) \approx 0.01 - 0.2$

- Experimental requirements
  - $\Delta m_{new}^2 \approx eV^2$: compact source < 1m & vertex resolution << 1m
  - $\sin^2(2\theta_{new})$: experiment with few % stat. & syst. uncertainties

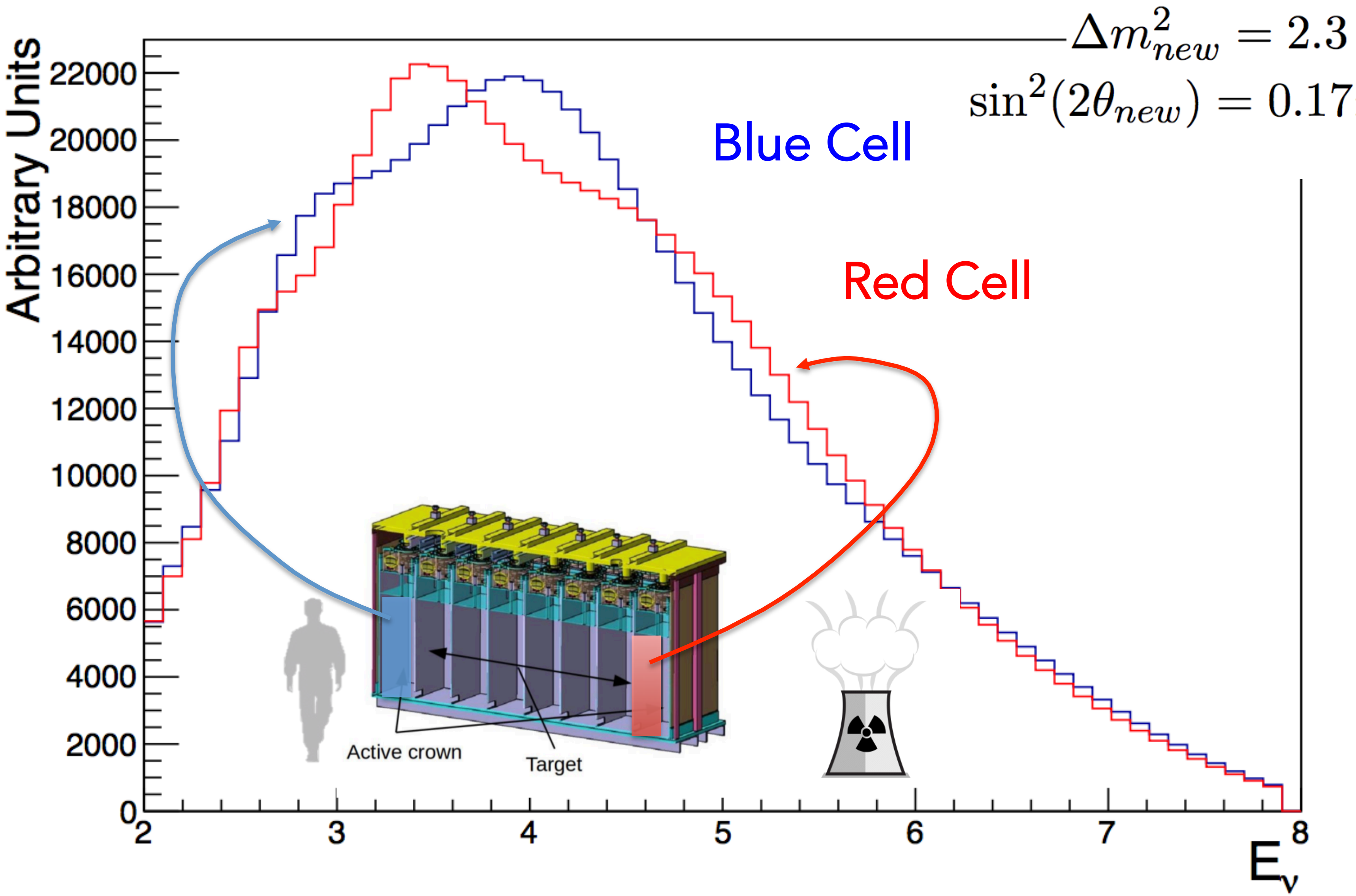
Searches for eV Sterile-ν



eV Sterile-ν Search at Reactors



Principle of the Measurement



cea

A selection of Ongoing Efforts

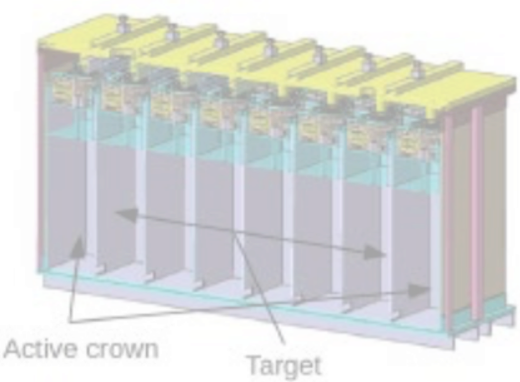
IAS TUM Institute for Advanced Study

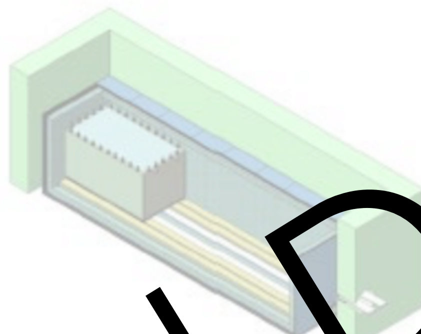
STEREO: **Gd-LS detector** at 10m from ILL , France

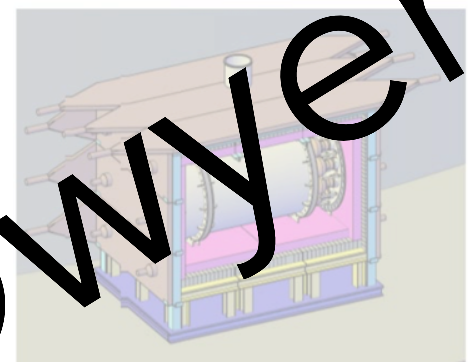
Neutrino-4: **Gd-LS detector** at 6-12m from SM-3, Russia

NEOS: **Gd-LS detector** at ~30m from Hanbit, Korea

NuLAT: Li-loaded plastic scintillator cubes



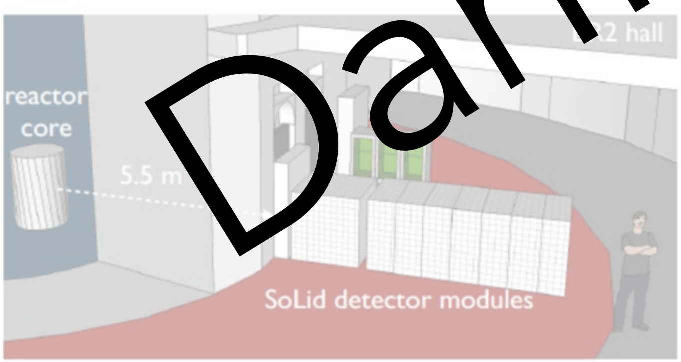


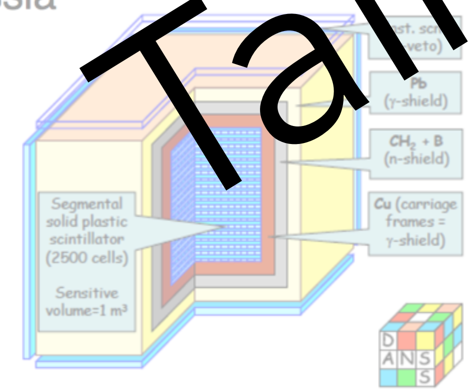


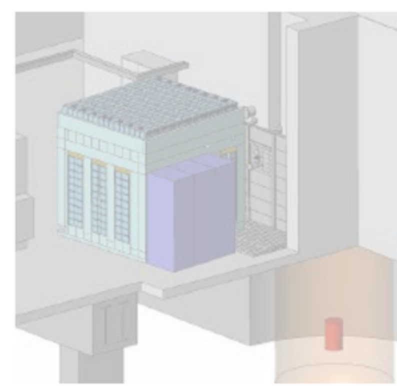
SoLid/CHANDLER: segmented composite scintillator cubes at 5.5m from BR2, Belgium

DANSS: Segmented plastic scintillator at ~10m from KNPP, Russia

PROSPECT: **Segmented ^{6}Li liquid** scintillator at 7-12m from HFIR, US







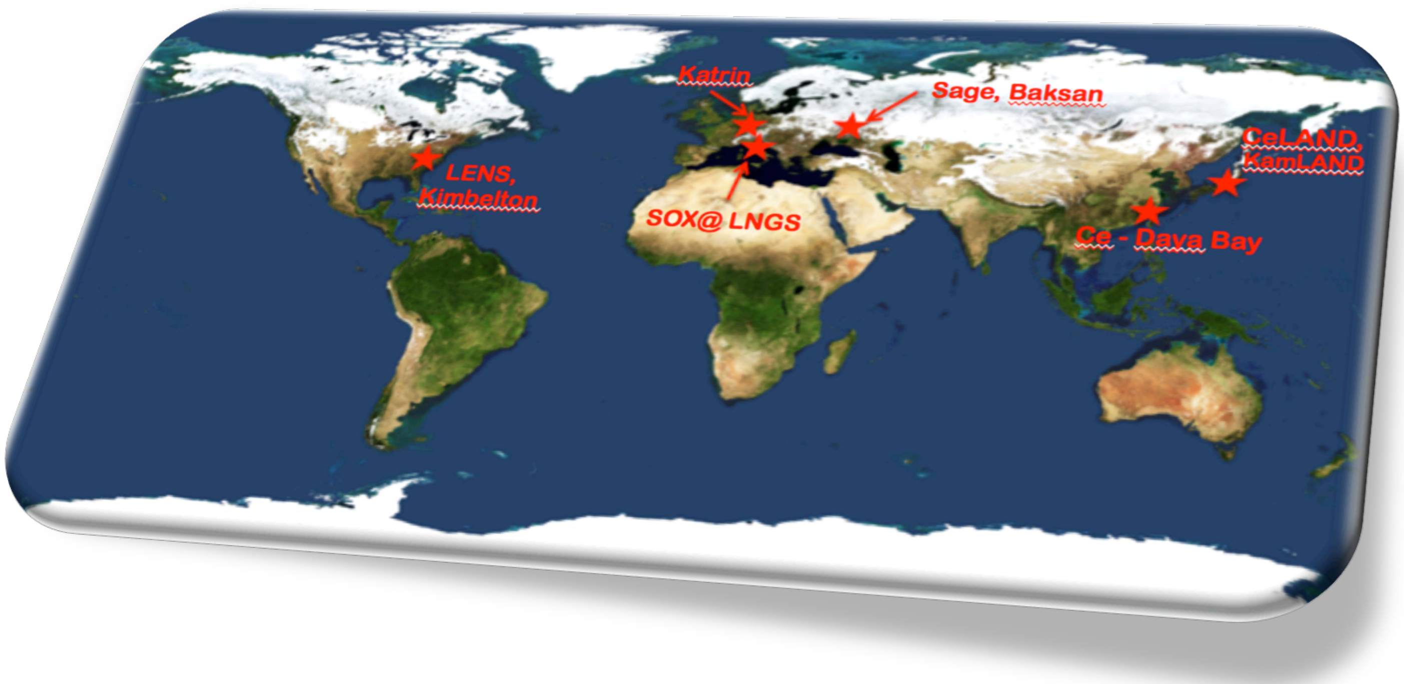
Daniel Dwyer's Talk

@Credit: K. Heeger

ν Generator Proposals

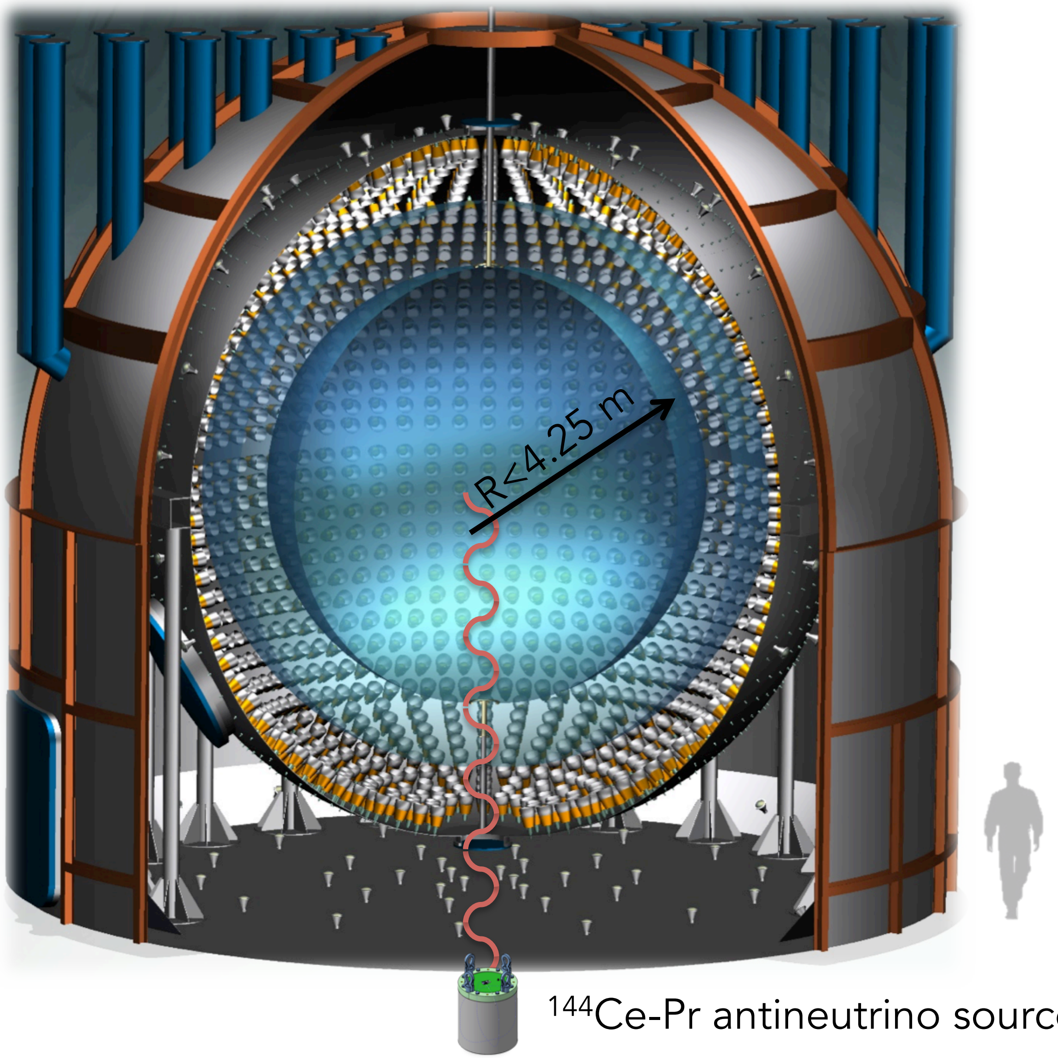
Type	Detection	Background	Isotope	Production	Activity	Projects
ν_e	$\nu_e e \rightarrow \nu_e e$ 5% E_{res} 15cm R_{res} or Radio-chemical	Detector Radioactivity Solar ν (irreducible) ν generator impurities	^{51}Cr 0.75 MeV $t_{1/2}$=26d	n_{th} irradiation in Reactor	>110 PBq	Sage LENS
					>370 PBq	SOX-Cr (SNO+)
			^{37}Ar 0.8 MeV $t_{1/2}$=35d	n_{fast} irradiation in Reactor (breeder)	>37 PBq	-
					185 PBq	Ricochet
$\bar{\nu}_e$	$\bar{\nu}_e p \rightarrow e^+ n$ E_{th}=1.8 MeV (e^+,n) 5% E_{res} 15cm R_{res}	reactor ν, geo ν, n generator impurities	^{144}Ce E<3MeV $t_{1/2}$=285d	spent nuclear fuel reprocessing + REE extraction	3.7 PBq	CeLAND Ce-SOX
					18.5 PBq	Daya-Bay
			^{90}Sr ^{106}Rh		-	-
	$^3H \rightarrow He\ e^-\ \bar{n}_e$ EC/b-decay	Kink search	^3H E<18 keV	Irradiation in reactors	110 GBq	KATRIN (Mare/Echo)

Sterile-ν Search with a ^{144}Ce source: CeSOX



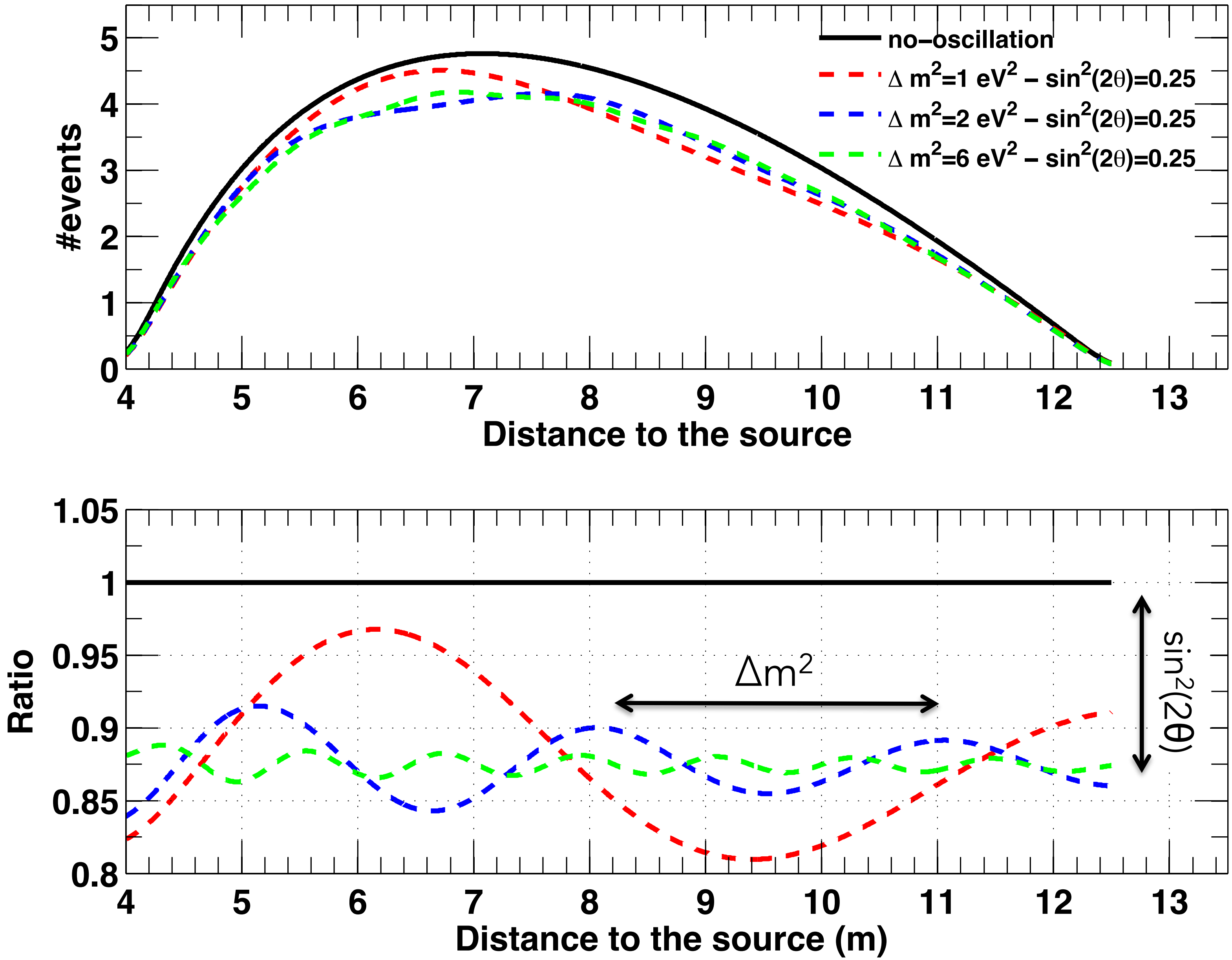
Concept of CeSOX

Shape only: Search for a neutrino oscillation pattern
Rate+Shape: Include ratio of observed to expected ν rate



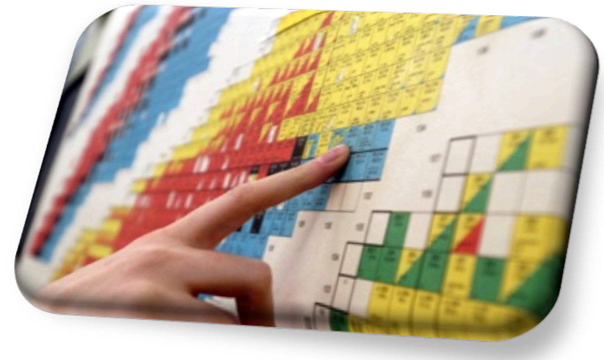
^{144}Ce-Pr antineutrino source

Oscillometry inside BOREXINO



Antineutrino Emitter

(ITEP N°90 1994, PRL 107, 201801, 2011)



- $\bar{\nu}_e$ detection: $\bar{\nu}_e + p \rightarrow e^+ + n$
  - large IBD cross section → 5 PBq
  - (e^+,n) coincidence → mitigate backgrounds

- ???
  - Abundant fission product
  - : long-lived & low-Q_β
    time to produce, transport, use
  - : short-lived & high-Q_β
    $\bar{\nu}_e$-emitter above IBD threshold

Antineutrino Emitter: ^{144}Ce-^{144}Pr

(ITEP N°90 1994, PRL 107, 201801, 2011)

- $\bar{\nu}_e$ detection: $\bar{\nu}_e + p \rightarrow e^+ + n$
  - large IBD cross section → 5 PBq
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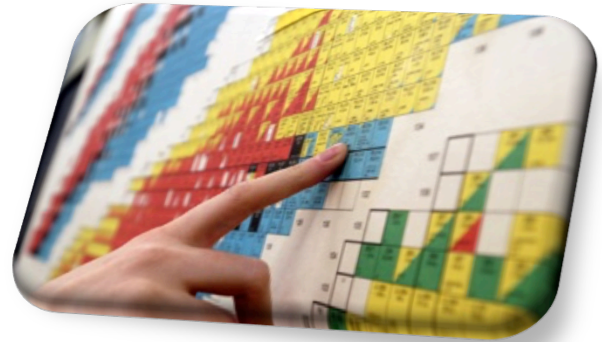
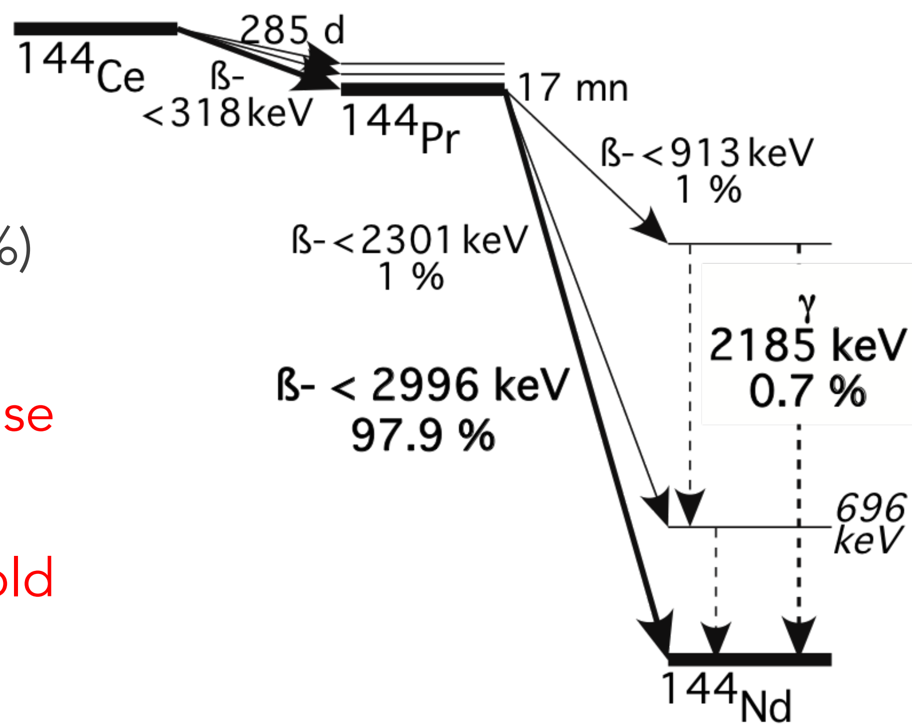
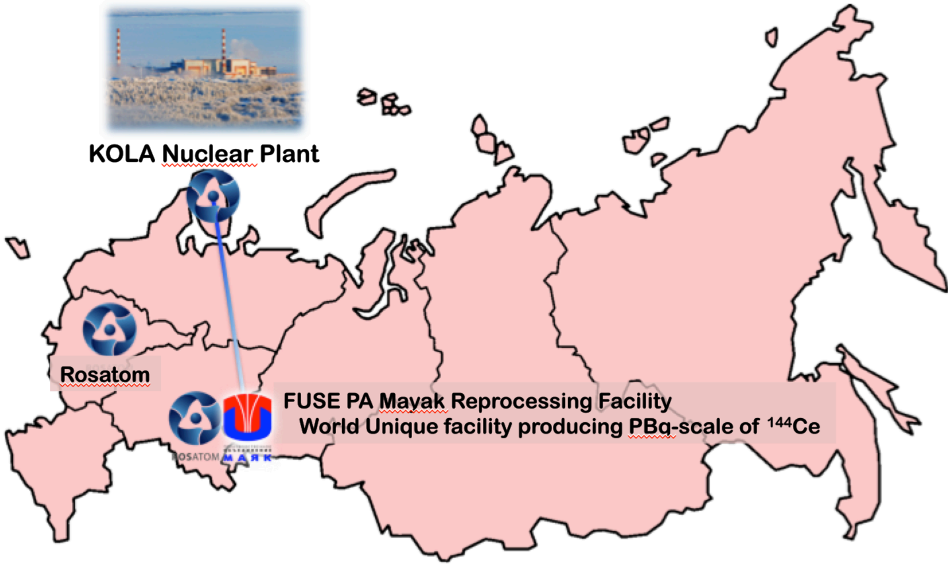


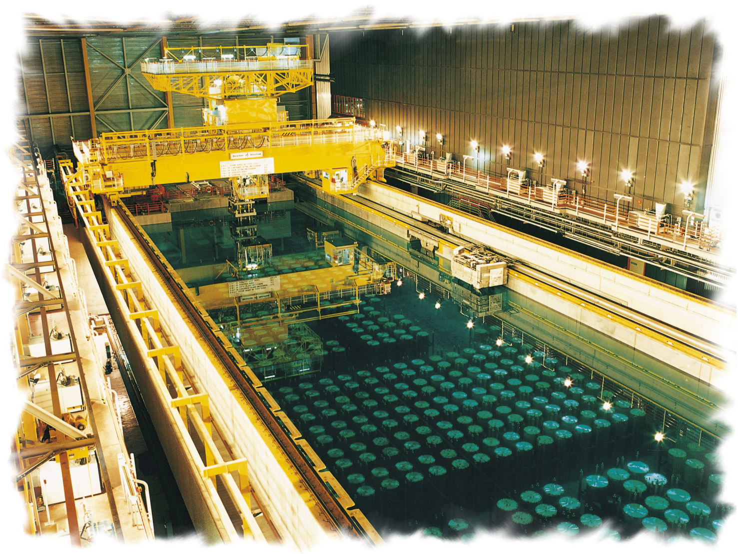
- ^{144}Ce-^{144}Pr
  - Abundant fission product (5%)
  - ^{144}Ce: long-lived & low-Q_β
    time to produce, transport, use
  - ^{144}Pr: short-lived & high-Q_β
    $\bar{\nu}_e$-emitter above IBD threshold



CeANG Production Overview

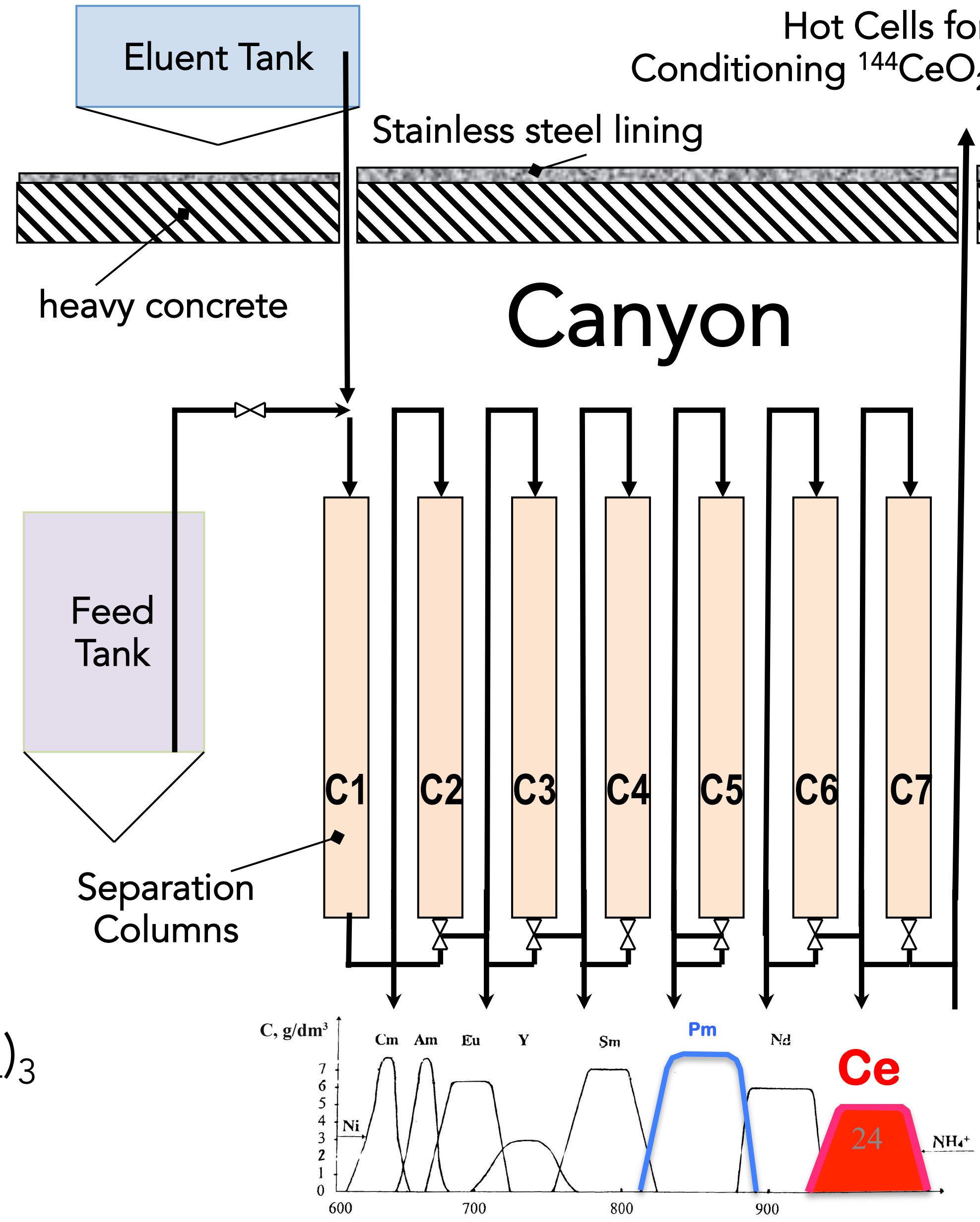
- Start from 2y old spent nuclear fuel
- Radiochemical Plant
  - U and Pu recovered by reprocessing of SNF (Purex®)
  - Removal of ^{137}Cs, ^{90}Sr, ^{106}Ru
  - Extraction of Cerium
  - Primary encapsulation
  - Activity measurement (≈5%)
- Radioisotope Plant
  - Source (CeANG) manufacture
  - Certification SFRM / ISO 9978
  - Loading into tungsten shield
  - Loading into TN-MTR cask
- 2012-15: R&D. 2017: production





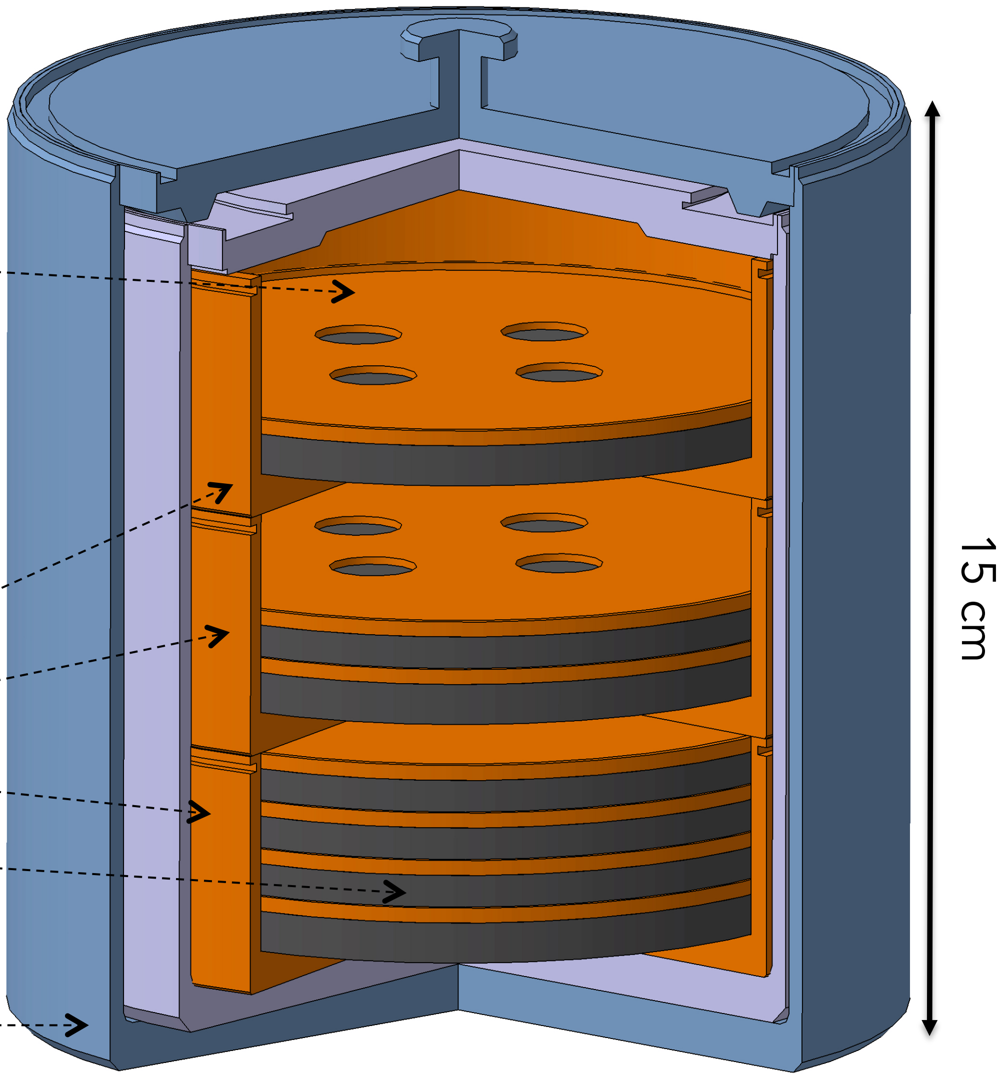
Cerium Extraction

- Complexing agent displacement chromatography
- Separation of Cerium
  - From Lanthanum
  - From Praseodymium
  - From other radio-impurities
- Extra-purification for ^{244}Cm
  - Neutron emitter
- Control of radio-impurities
  - ϒ and α spectroscopy
  - ICP-MS
- Precipitation in oxalate $Ce_2(C_2O_4)_3$



Special Form Radioactive Material

- 3.7 – 5.5 PBq – 1200 W
- Free volume: 25%
- Sketch of CeO_2 inside SFRM capsule
  - CeO_2 pellets 2.5 g/cm^3
  - Cu-disk radiators
  - 3 Cu-capsule
  - T(CeO_2) < 600 °C
  - T(Out Cap) < 500 °C



ISO 9978:1992(E) – ISO 2919

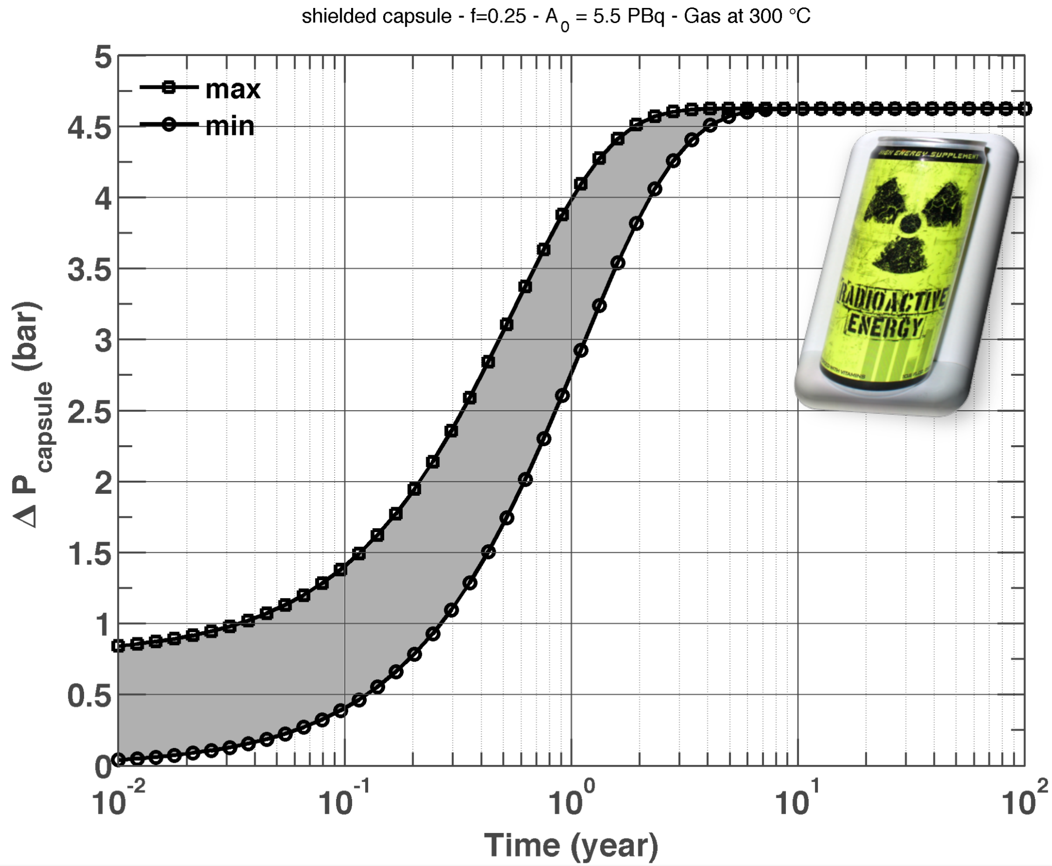
Inner Capsule Pressure

- The radioactive decay of ^{144}Ce in the form of CeO_2 releases O_2

$$2CeO_2 \xrightarrow{^{144}\text{Ce } \beta\text{-decay}} Pr_2O_3 + \frac{1}{2}O_2$$

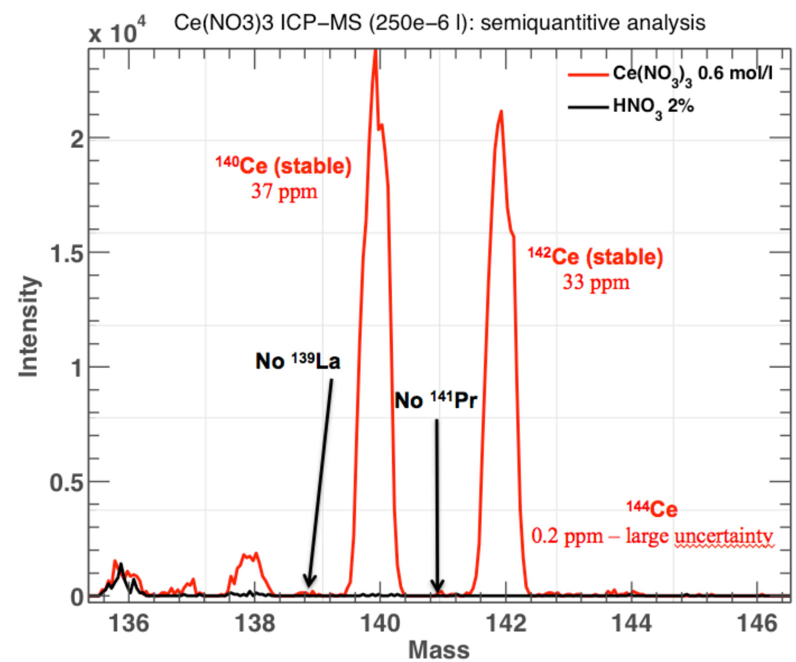
- CeO_2: Cerium oxidation state = +IV
- Pr_2O_3: Praseodymium oxidation state = +III

- Pressure evolution
  - Increase due to the production of O_2
  - Decrease due to the CeANG cooling as ^{144}Ce decays
  - Maximum pressure reached after 3 years at $\Delta P < 5$ bar

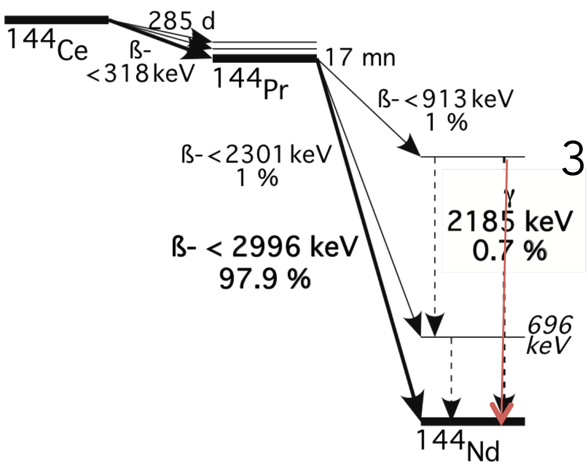


^{144}Ce samples (Mayak)

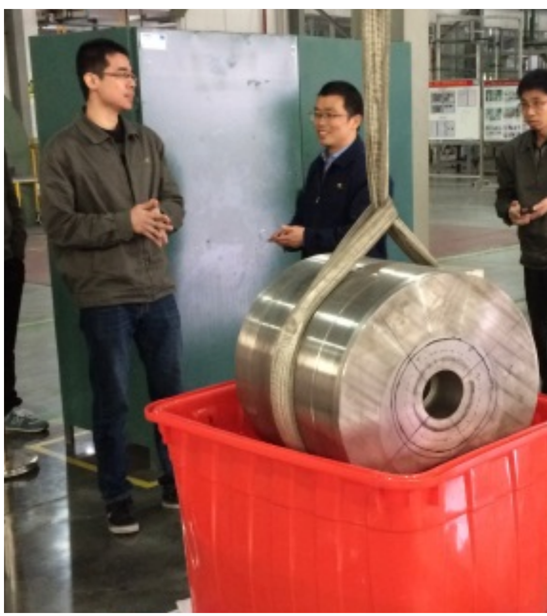
- Pilot production in Mayak (2013)
  - PBq-scale – 6 y old fuel
  - 30 cm^3 $Ce(NO_3)_3$
    60 kBq of ^{144}Ce
- ICP-MS and α-spectroscopy
  - Cerium extraction process
  - Neutron emitter impurities
- γ-spectroscopy
  - β / γ impurities
- β-spectroscopy
  - ^{144}Ce & ^{144}Pr β-spectra (W/Bq)
  - ^{144}Pr β-spectrum: expected ν-rate

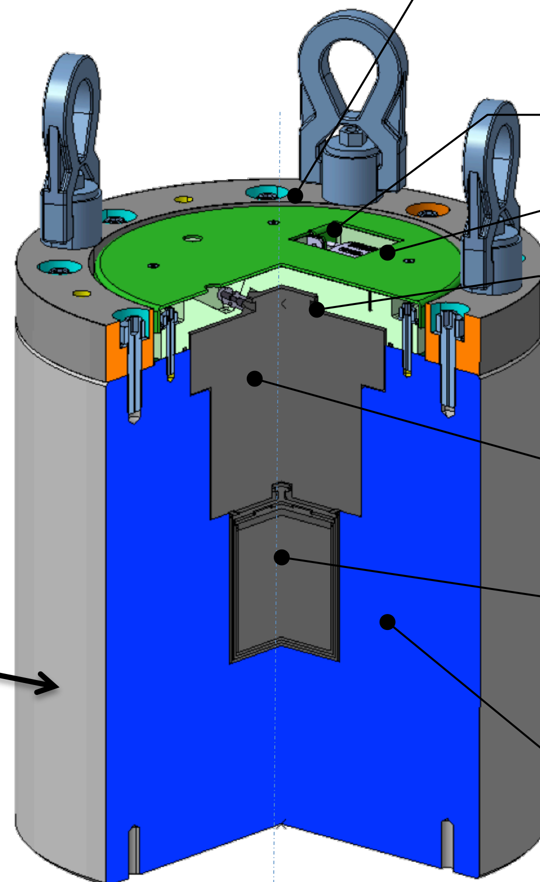


High Density Tungsten Shield



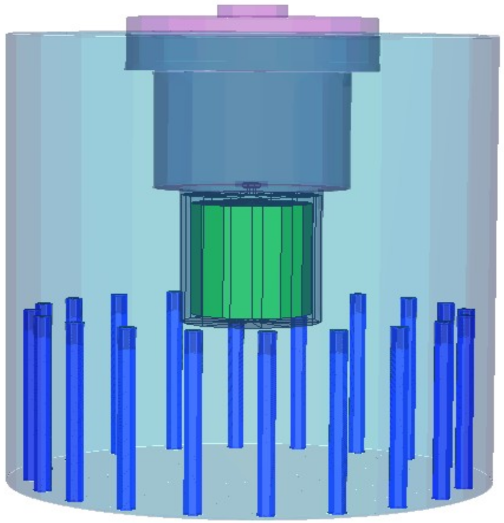
3 10^{10} γ /sec





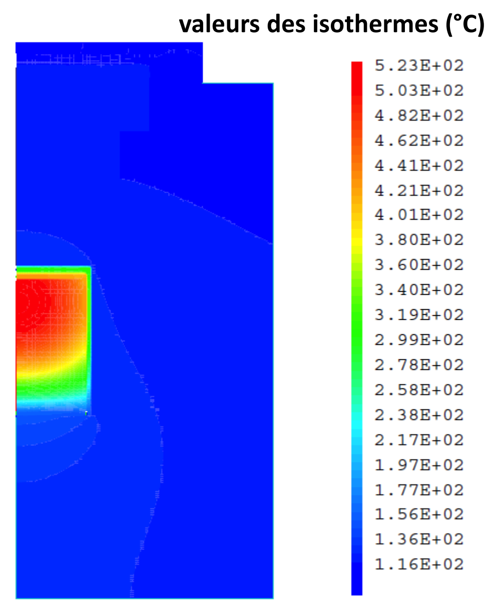
2.3 tons

Radiation Dose / Thermal Features

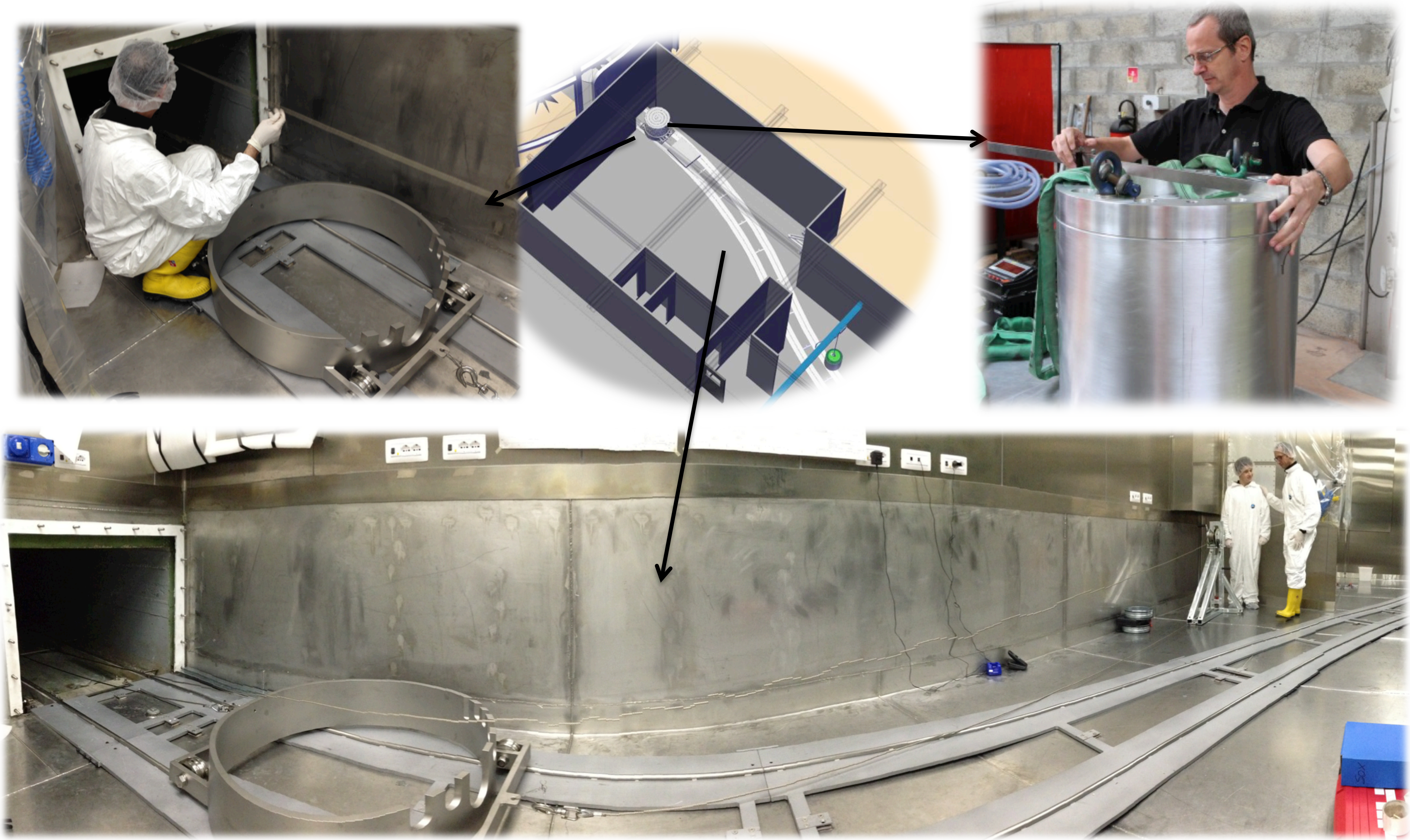


- Radiation Dose
  - 5.5 PBq in ^{144}Ce
  - Gamma dose
    - at 1 m < 8 μSv/h
    - origin: ^{144}Pr de-excitation
  - Neutron dose
    - at 1 m < 5 nSv/h
    - origin: ^{244}Cm SF (<10^5 n/s)

- Thermal Features
  - 5.5 PBq in ^{144}Ce
  - Cerium
    - T < 550 °C
  - Capsule
    - T < 400 °C
  - Shielding
    - T < 80 °C



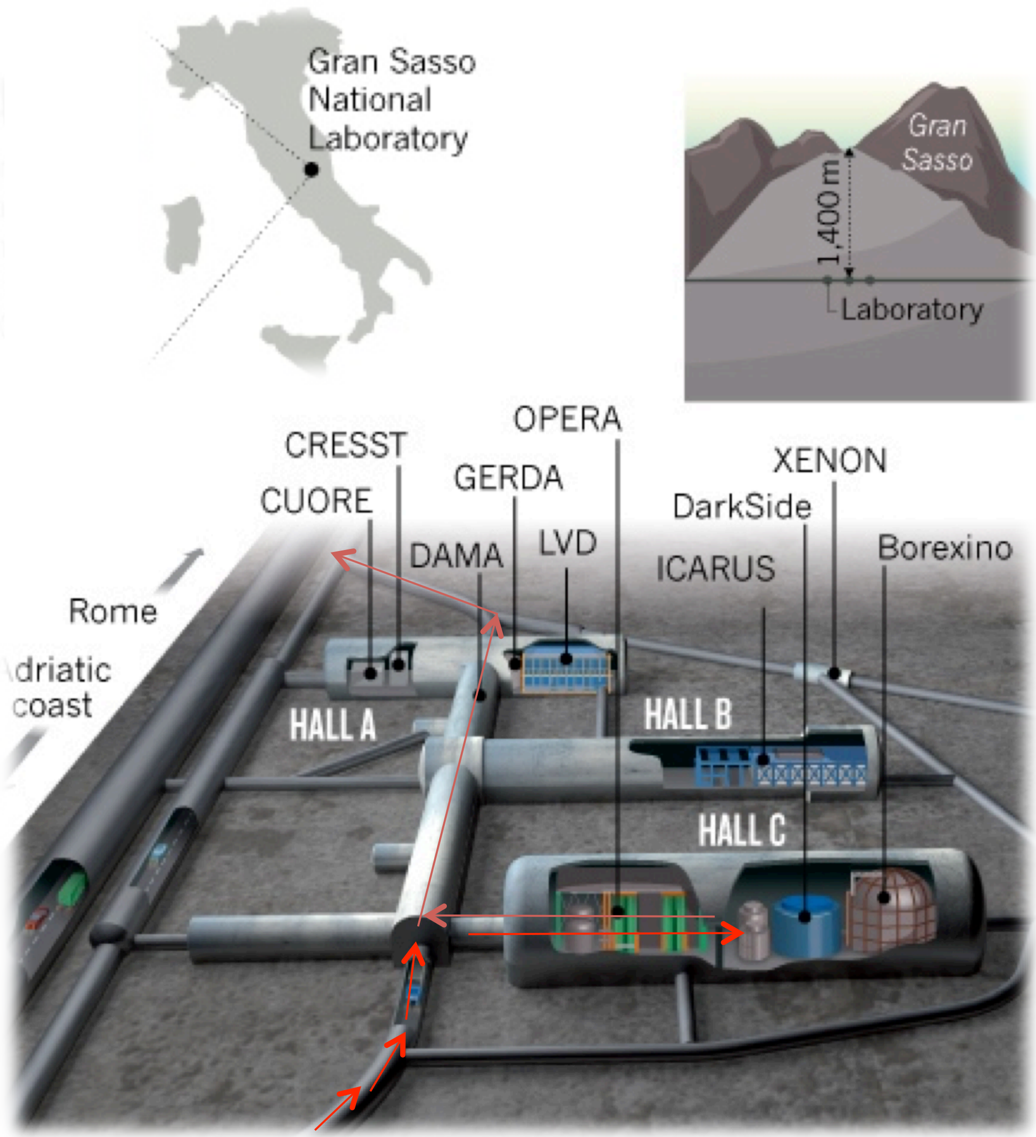
Installation Status



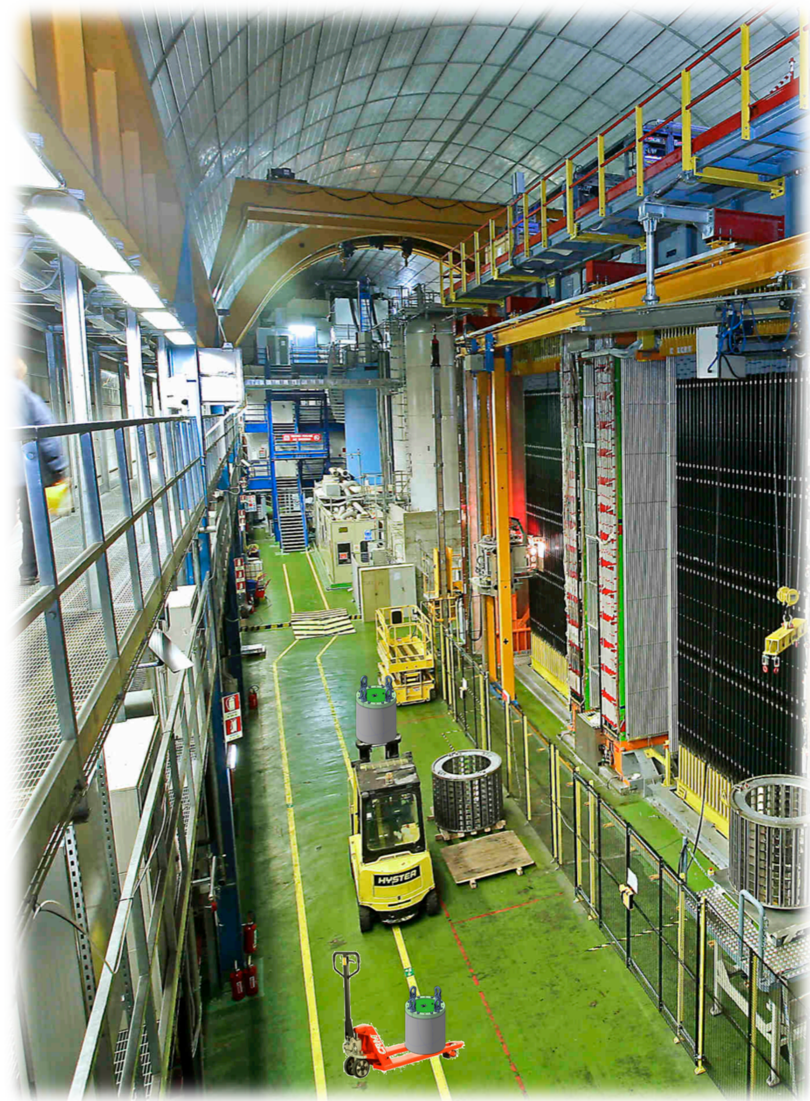
Transport & Logistics

- IAEA Regulations for the Safe Transport of Radioactive Material
- Train / Dedicated Boat/ Truck: 3 weeks (5% activity loss)

Arrival at LNGS

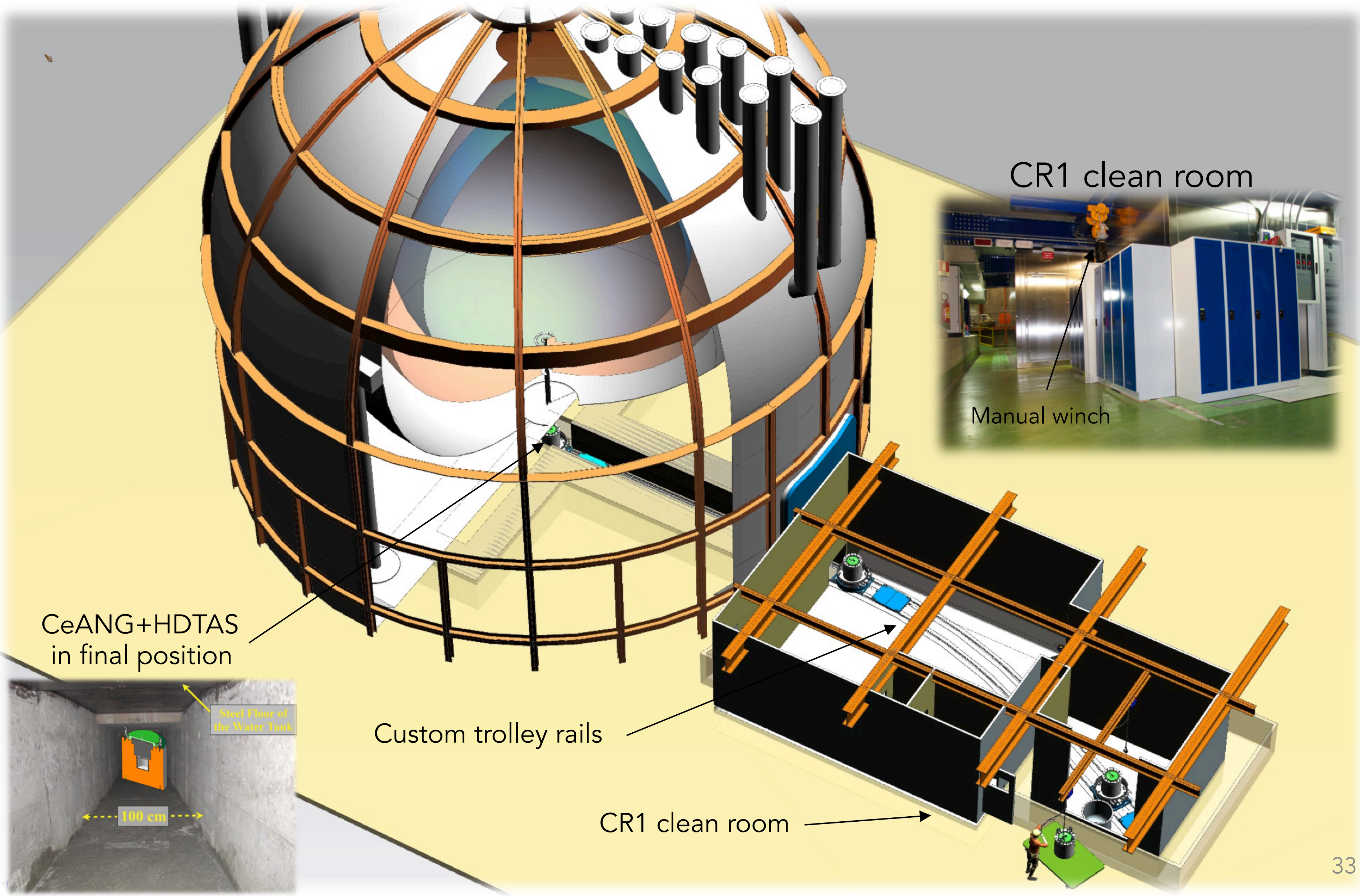


Gran Sasso National Laboratory



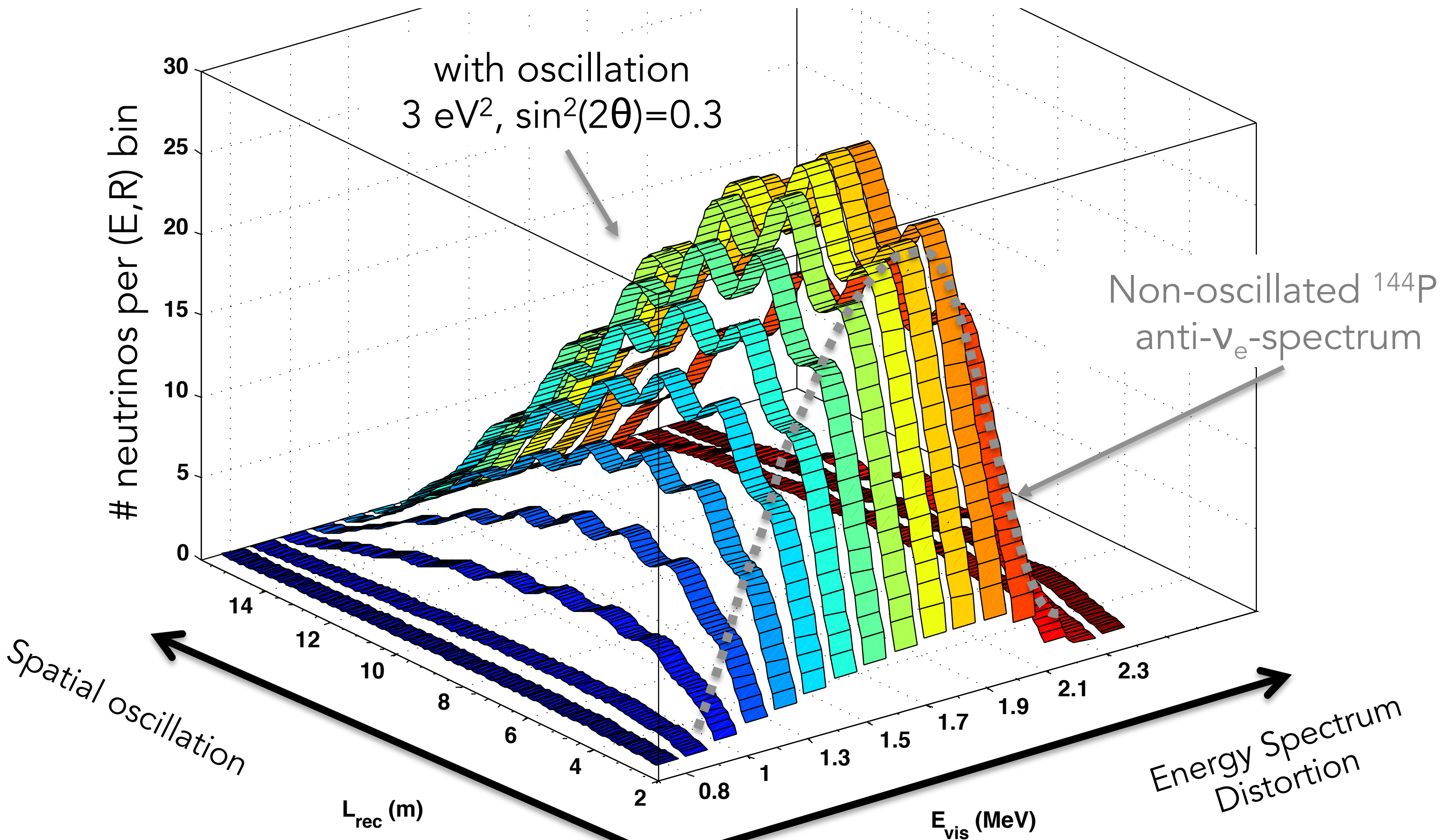
Hall C (Opera / Borexino)

Deployement



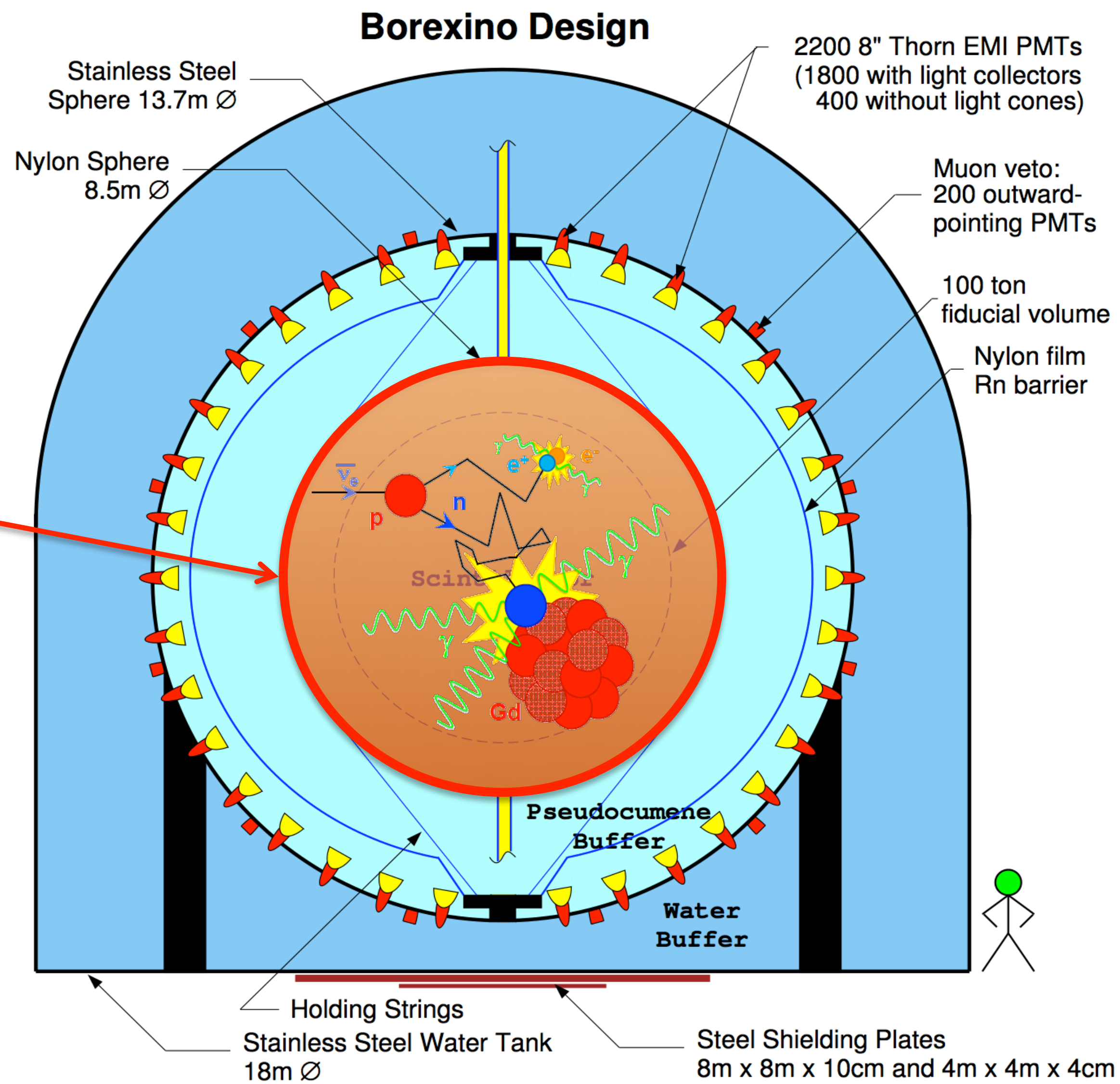
Expected Signal: 30/d (3.7 PBq)

$$\frac{\mathrm{d}^5 N_{\bar{\nu}_e}}{\mathrm{d}t\,\mathrm{d}E\,\mathrm{d}^3\mathscr{V}_{\mathrm{det}}} = \mathcal{A}_0\, e^{-t\,\lambda_{\mathrm{Ce}}}\, \eta_p\, \varepsilon\, \frac{1}{4\pi L^2}\, \sigma_{\mathrm{IBD}}(E)\, S_{\mathrm{Ce}}(E) \times \mathcal{P}(L,E)$$



Borexino

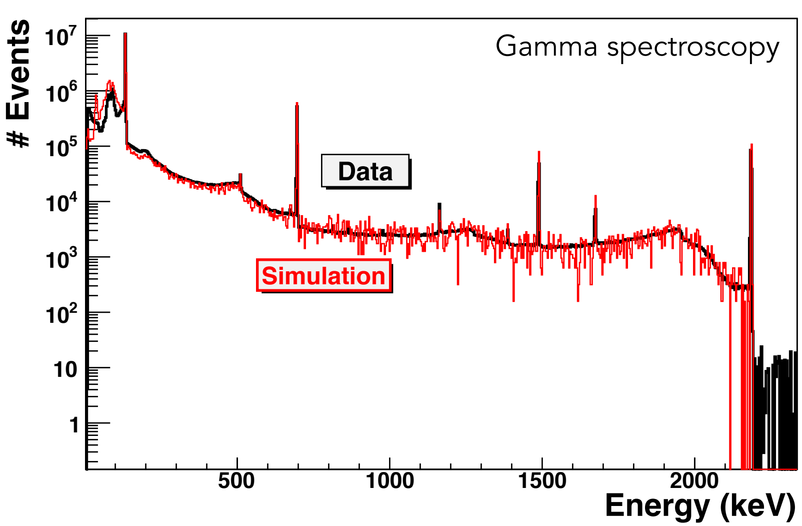
CeSOX target
- R < 4.25 m
- 280 tons
- C_6H_{12}
- #H: $1.7\ 10^{31}$



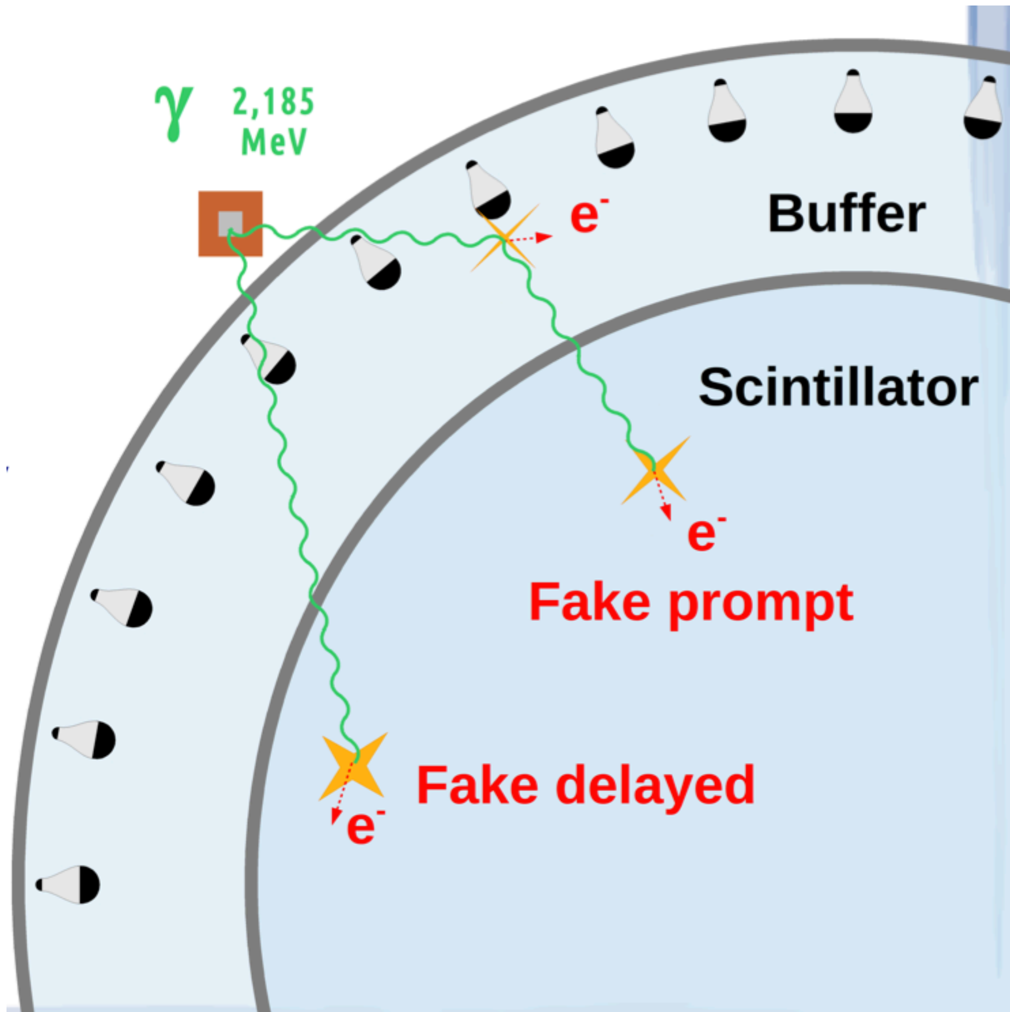
Gamma Induced Background

- Random coincidence between two γ's from the ^{144}Ce source

- ^{144}Ce sample: no γ contamination @10^{-4} Bq / Bq of ^{144}Ce

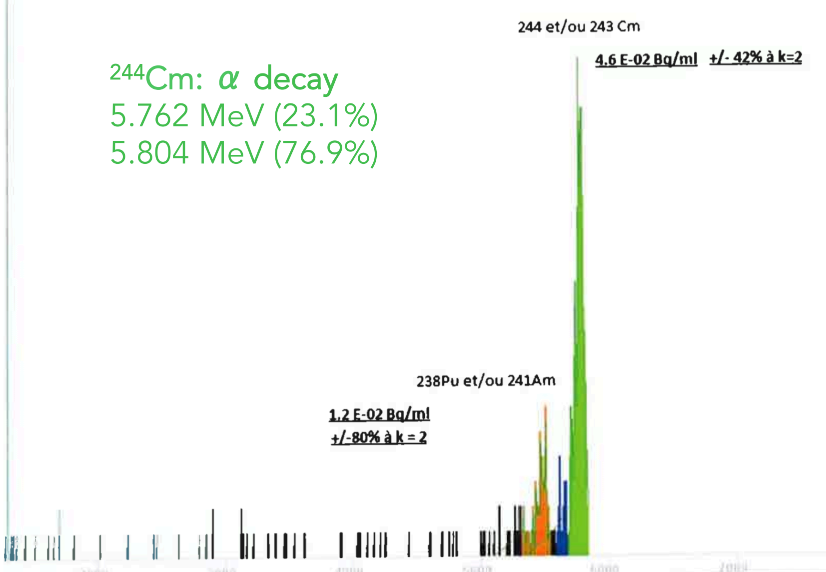


- Strict control of impurities
  → shall be negligible

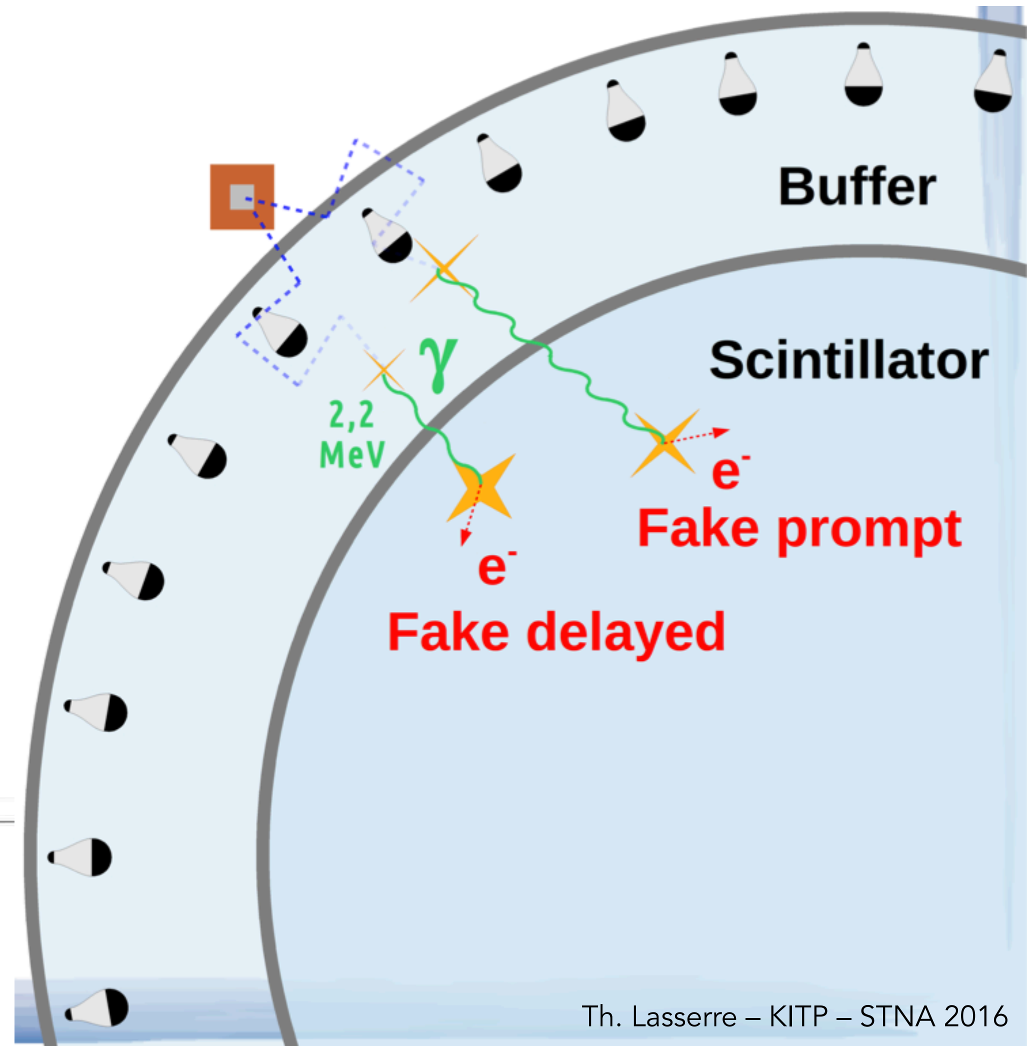


Neutron Induced Background

- 2 neutrons from spontaneous fission → 2 neutron captures → 2 γ's
- CeANG test production:
- 10^{-5} Bq ^{244}Cm / Bq ^{144}Ce



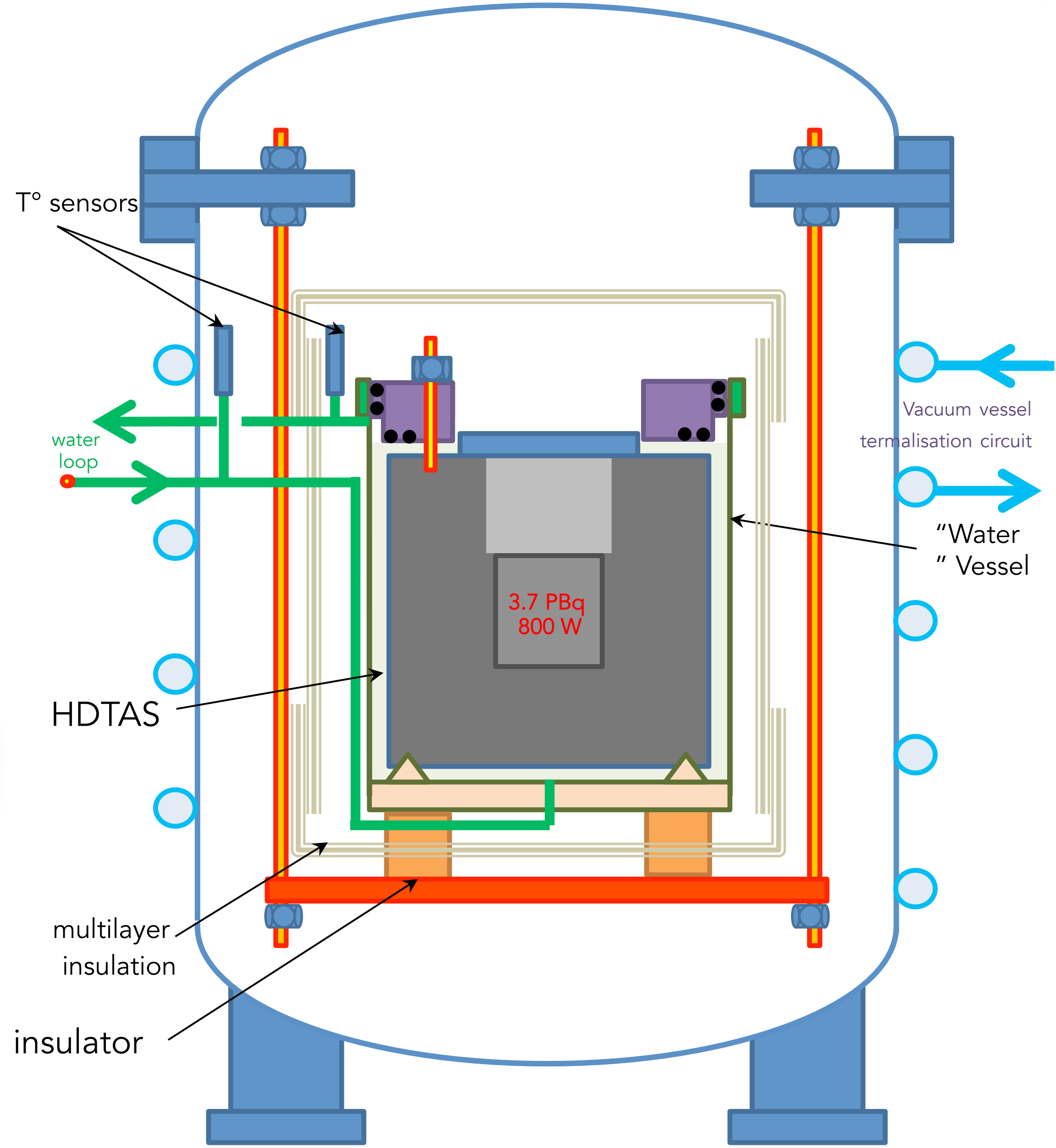
- Strict control of radioimpurities → shall be negligible



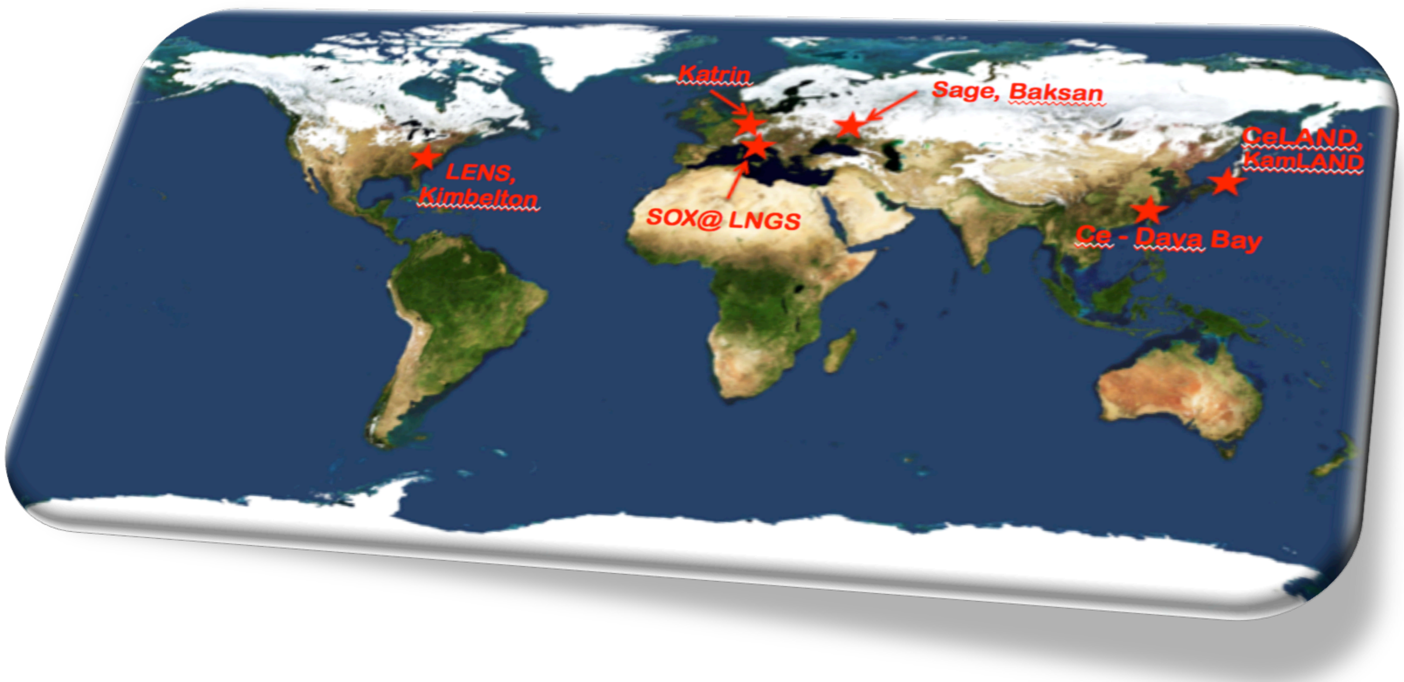
CeANG Activity: Calorimeter(s)

$$A\ (\mathrm{Bq}) = \frac{\text{CeANG Heat (W)}}{\left\langle E_{\text{per decay of } ^{144}\text{Ce-}^{144}\text{Pr}} \right\rangle}$$

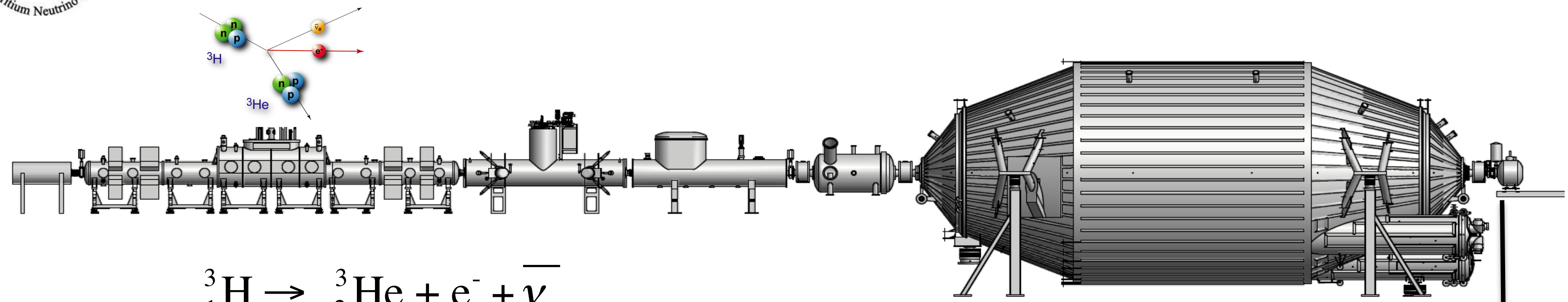
- Mesure water flow and T° at in/outlets: $\dot{Q} = \dot{m}C\left(T_{in} - T_{out}\right)$
  - ≈1.5% precision
  - Minimizing heat leaks
  - Calibration with a dummy electrical source



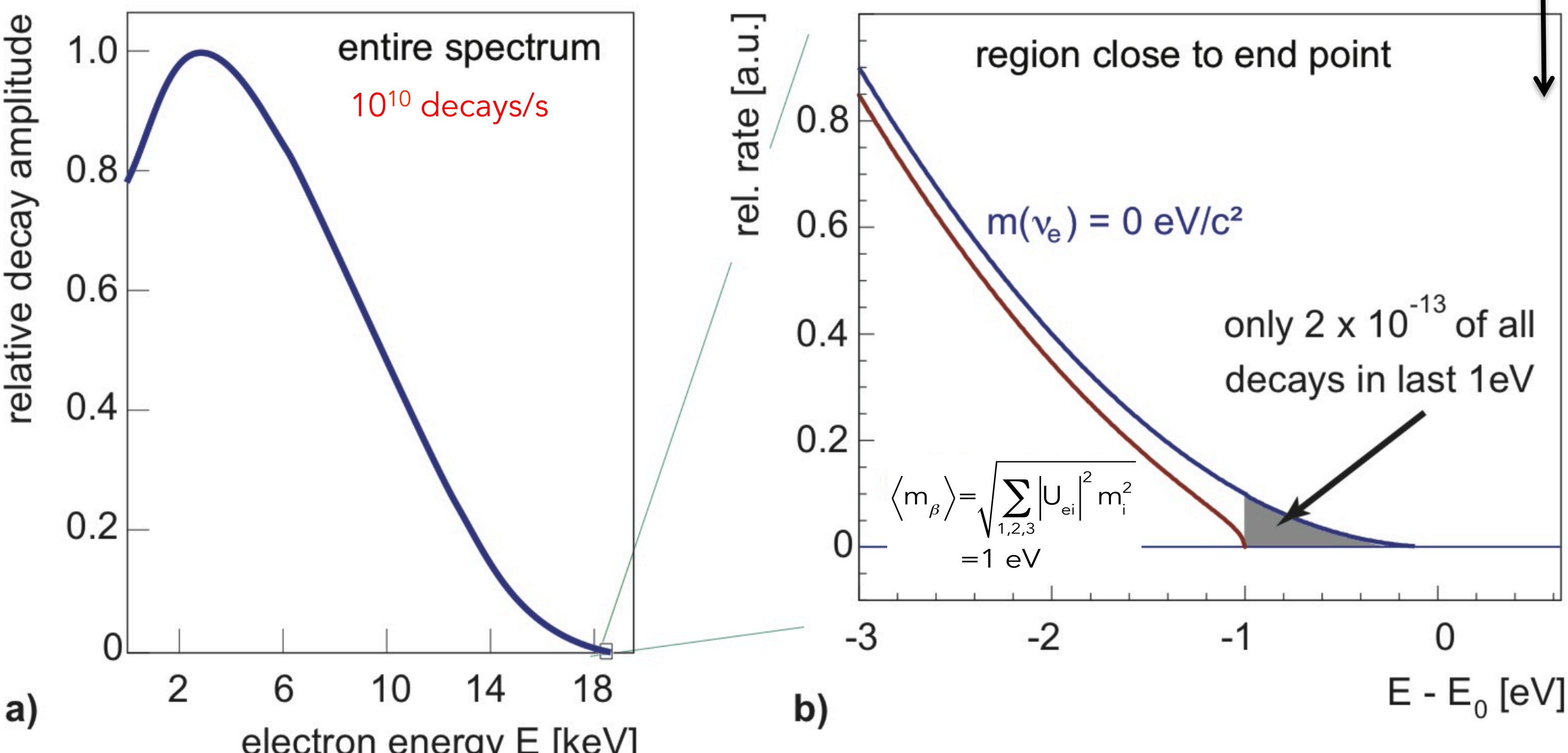
eV Sterile-ν Search with a Tritium Source: KATRIN



Active ν Mass with KATRIN



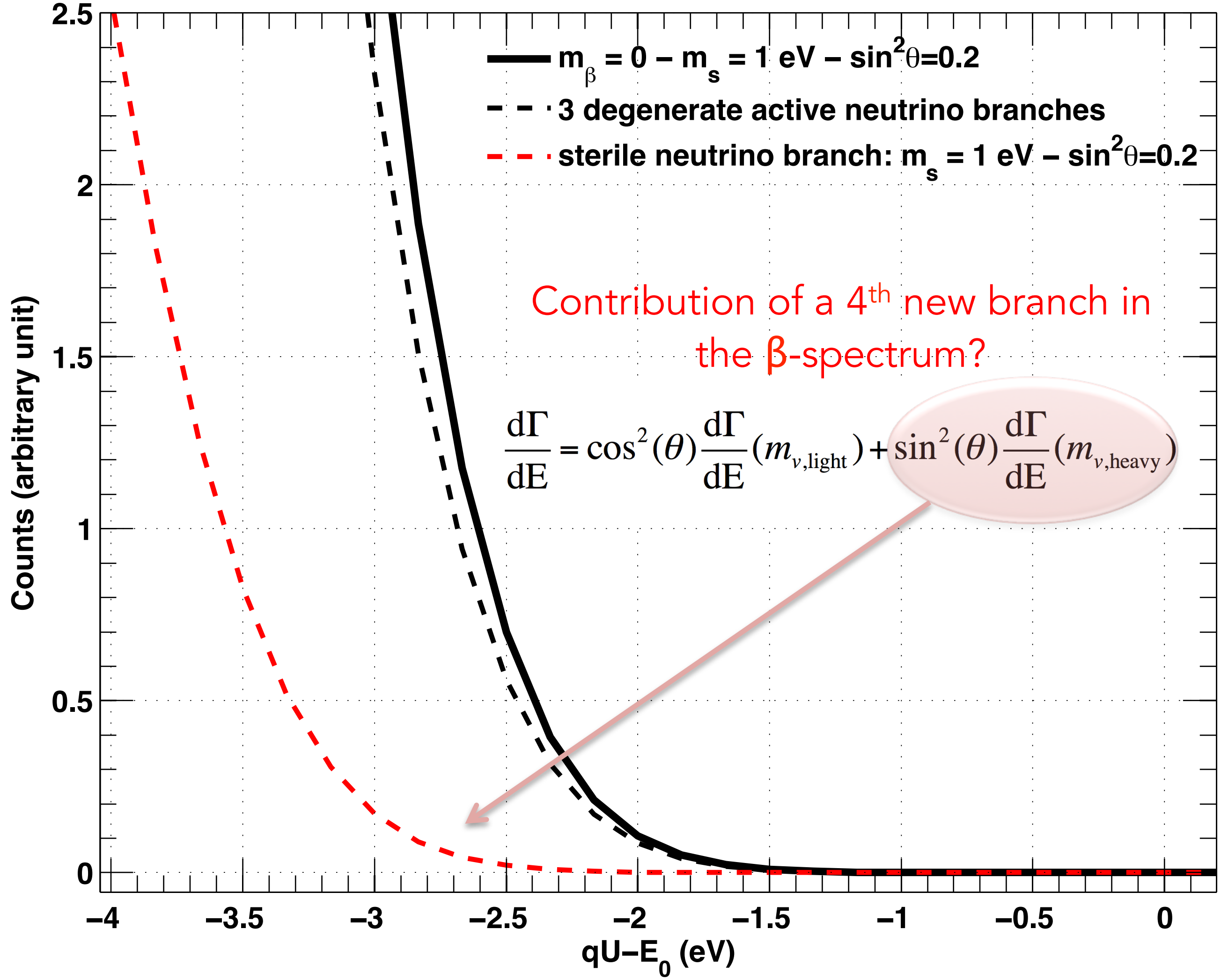
$$ {}^3_1H \rightarrow {}^3_2He + e^- + \overline{\nu}_e $$



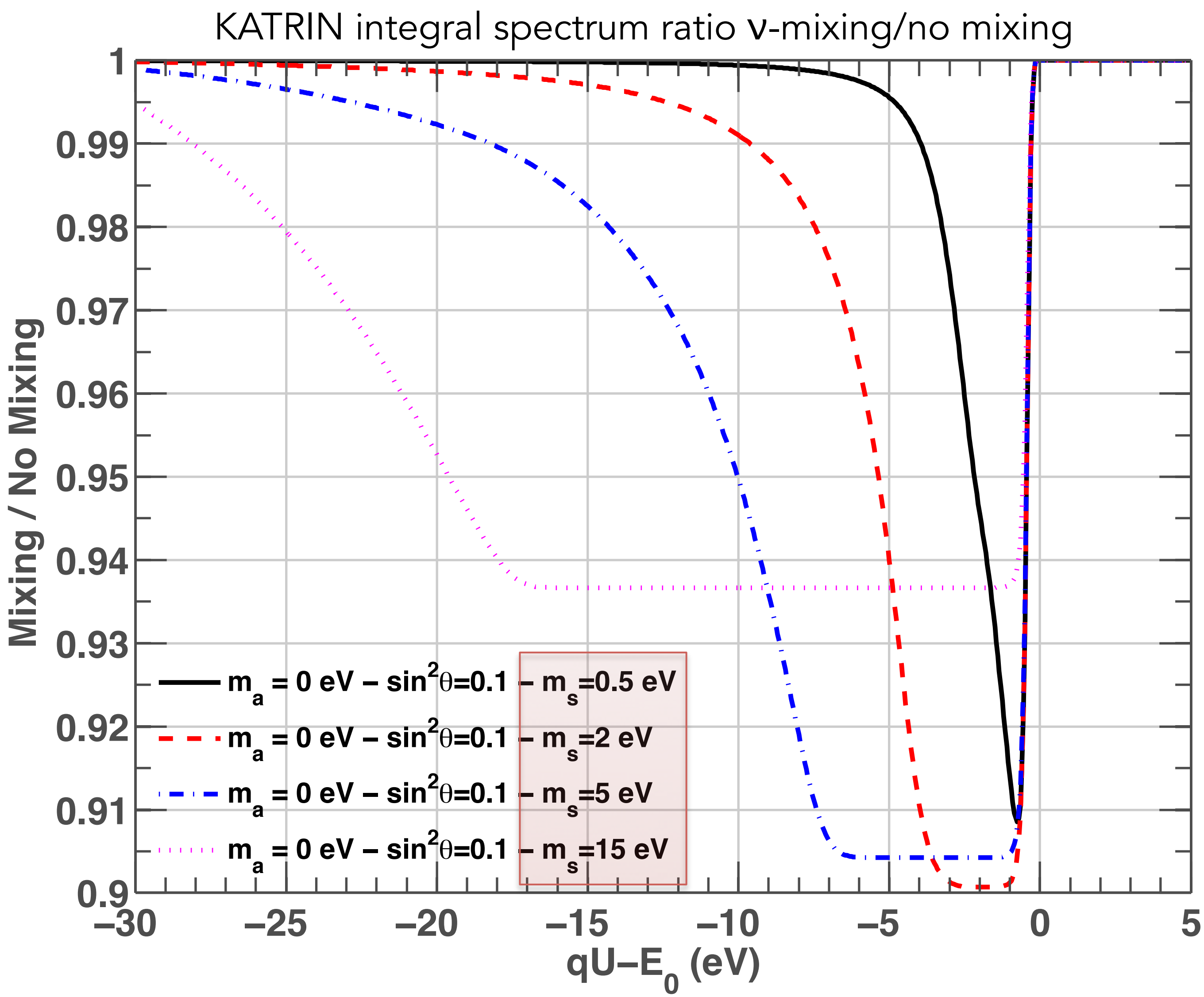
Th. Lasserre – KITP – STNA 2016

Light Sterile Neutrino in KATRIN

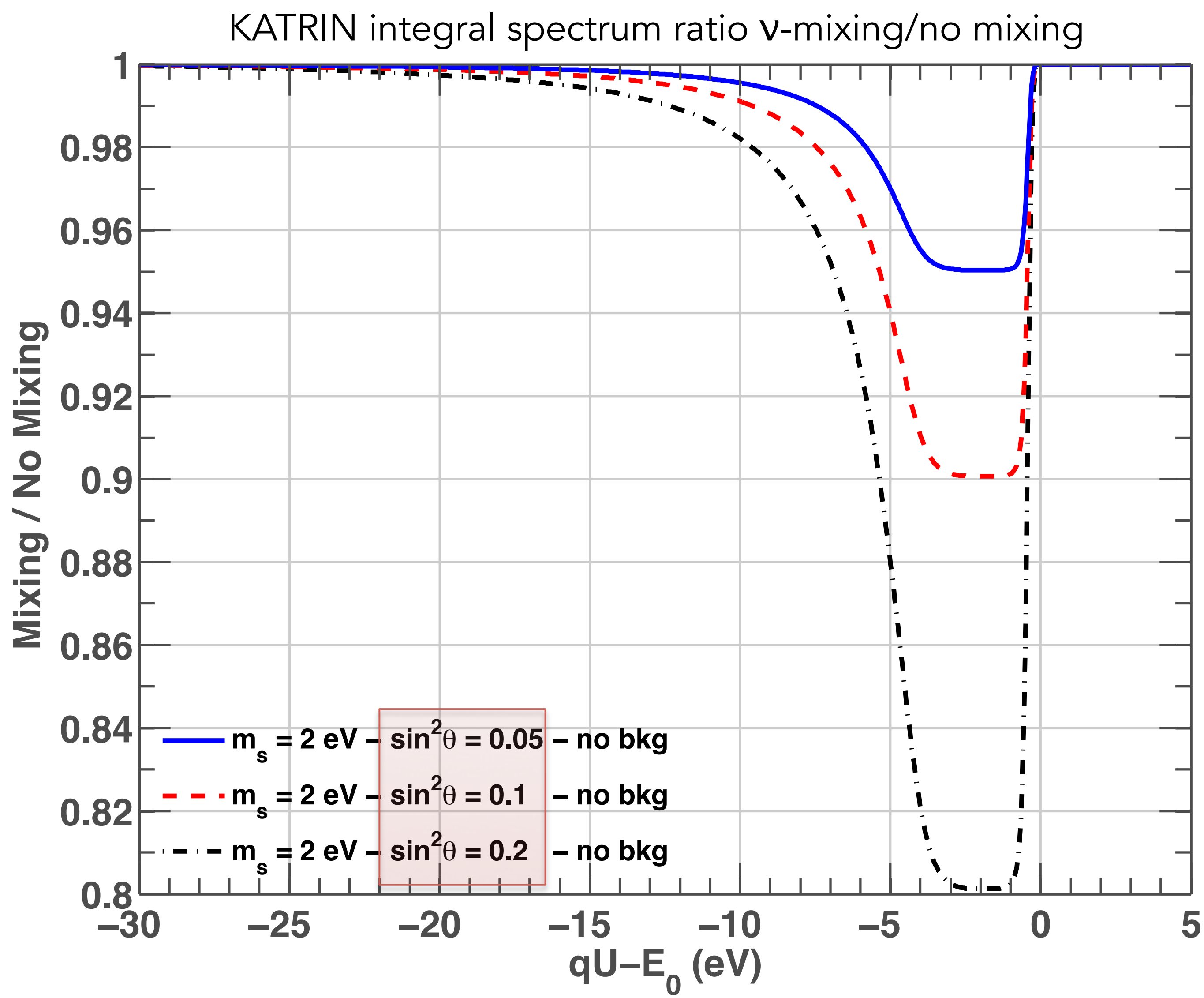
Integral Tritium β-decay spectrum near endpoint E_0=18.575 keV



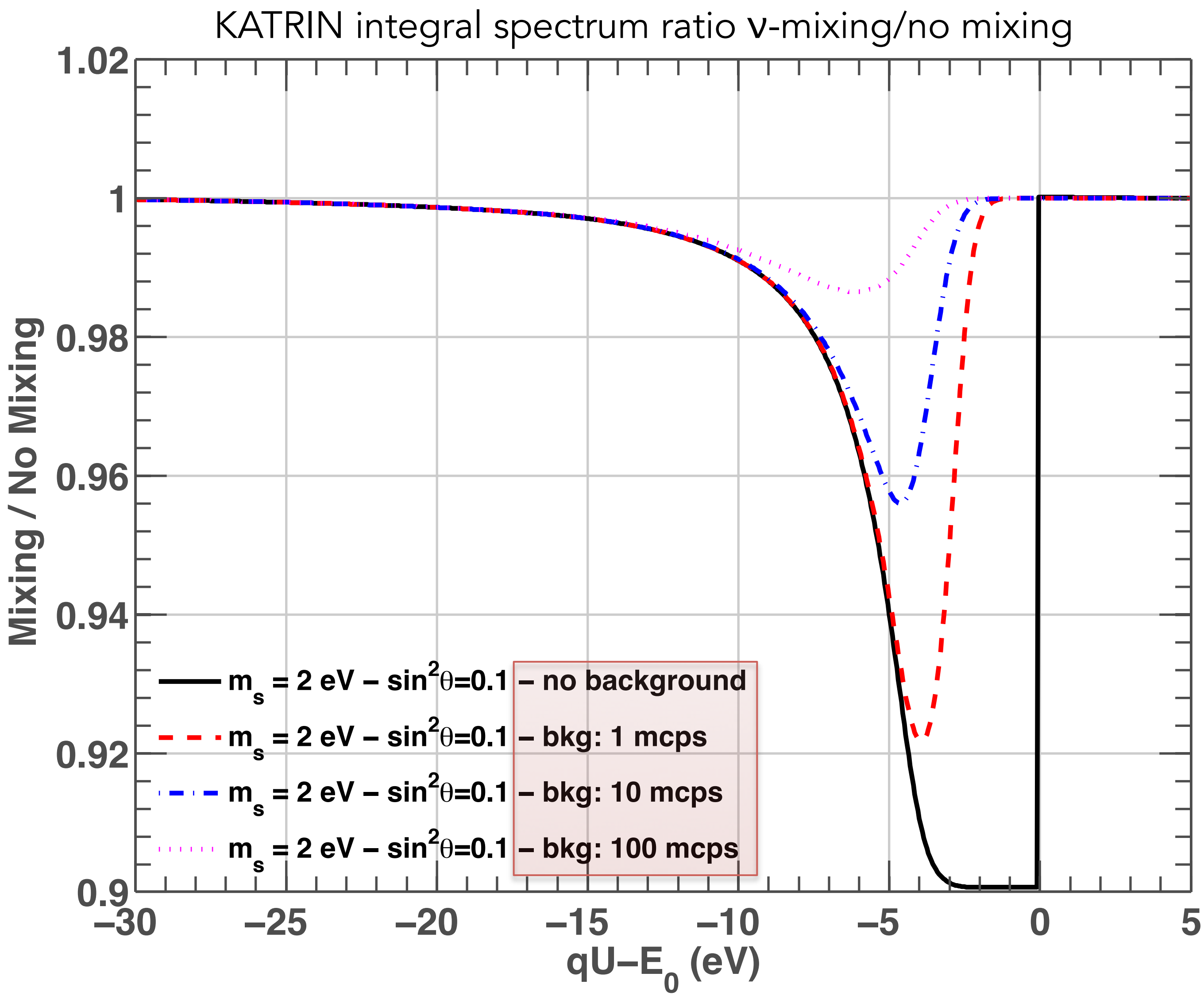
Impact of the sterile ν mass



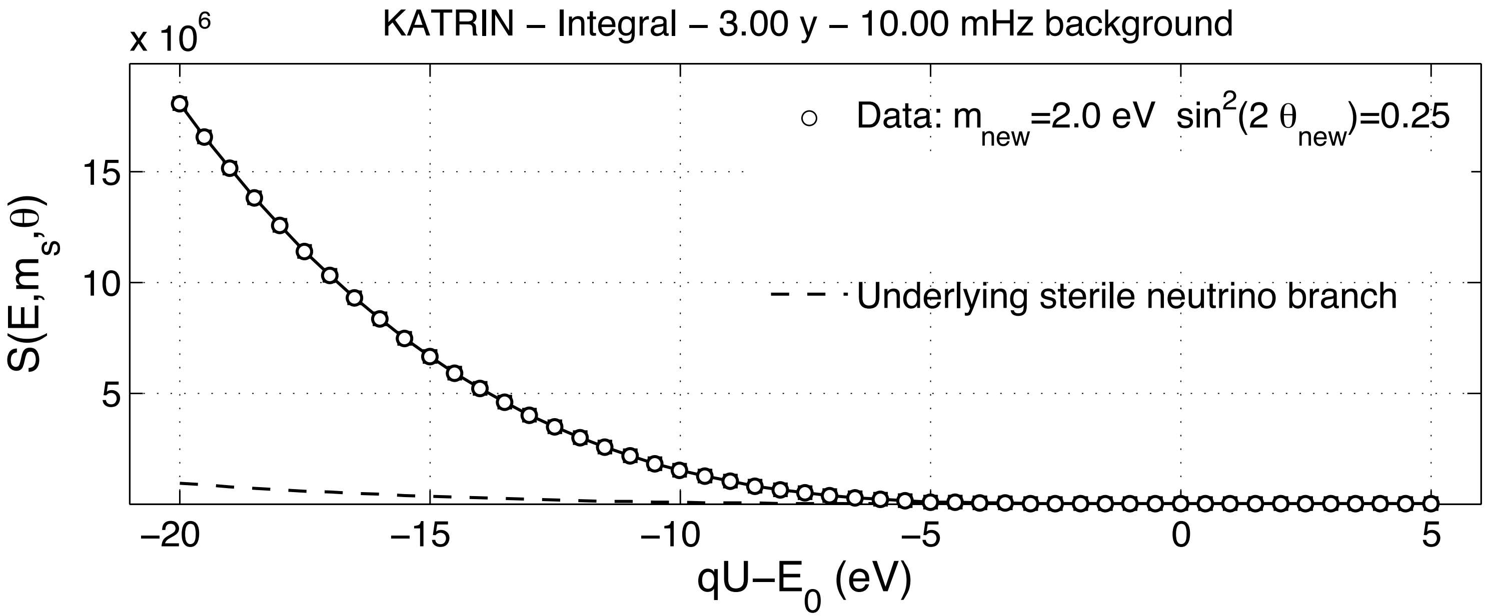
Impact of the sterile ν mixing

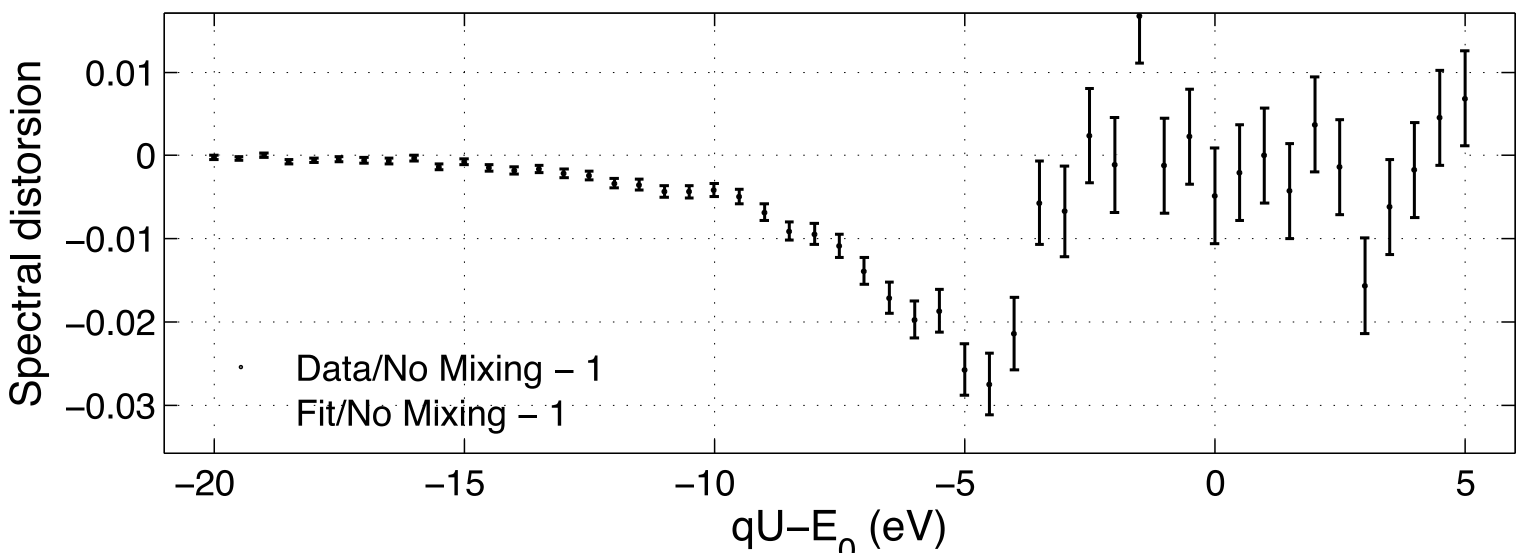


Impact of backgrounds

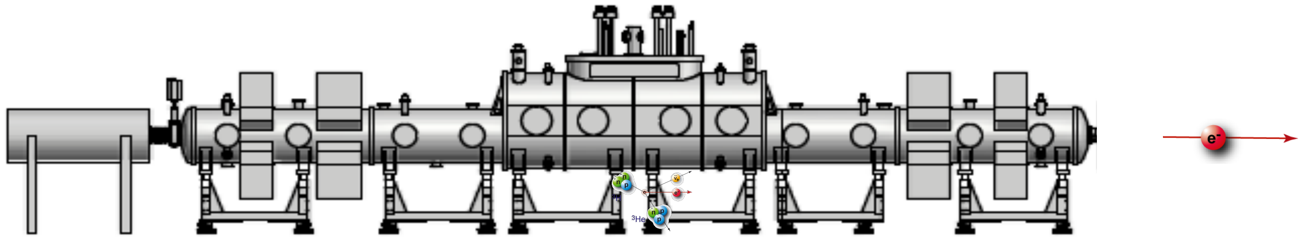


Signal & Statistical Uncertainty



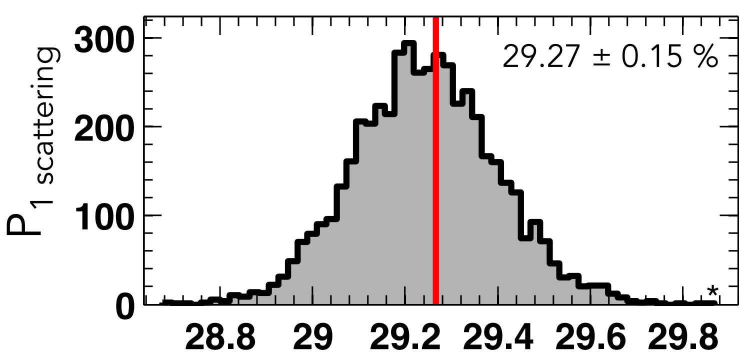


Tritium Source Induced Systematics

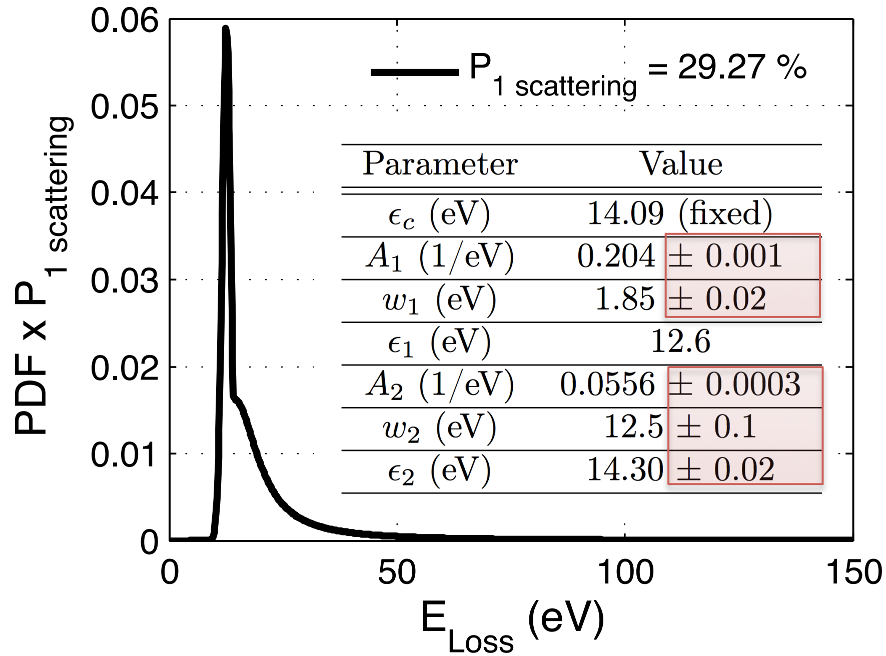


Systematics: Electron-T_2 scattering

- Scattering probabilities (correlated)
  - B_s ±0.5%
  - B_{max} ±0.5%
  - ρd ±0.5%
  - σ_{IS} ±1%

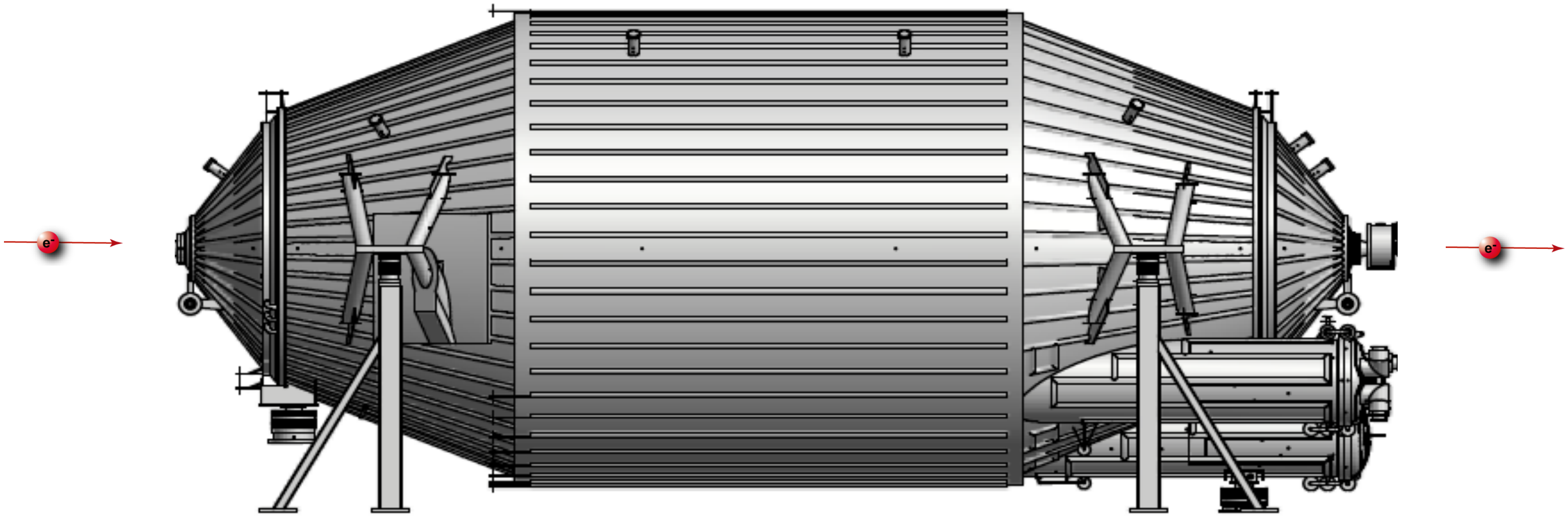


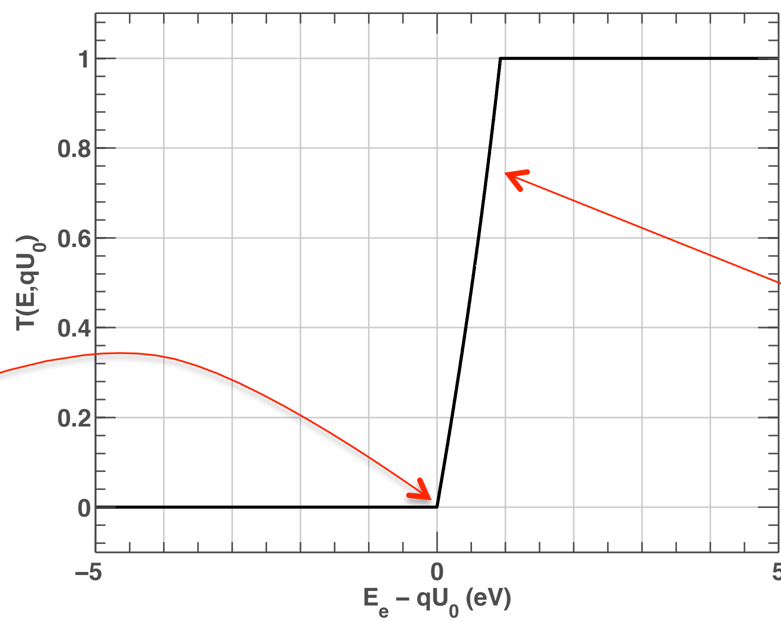
- Energy Loss (uncorrelated)



Parameter	Value
ϵ_c (eV)	14.09 (fixed)
A_1 (1/eV)	0.204 ± 0.001
w_1 (eV)	1.85 ± 0.02
ϵ_1 (eV)	12.6
A_2 (1/eV)	0.0556 ± 0.0003
w_2 (eV)	12.5 ± 0.1
ϵ_2 (eV)	14.30 ± 0.02

Spectrometer Induced Systematics





qU setting
Known within 2 ppm

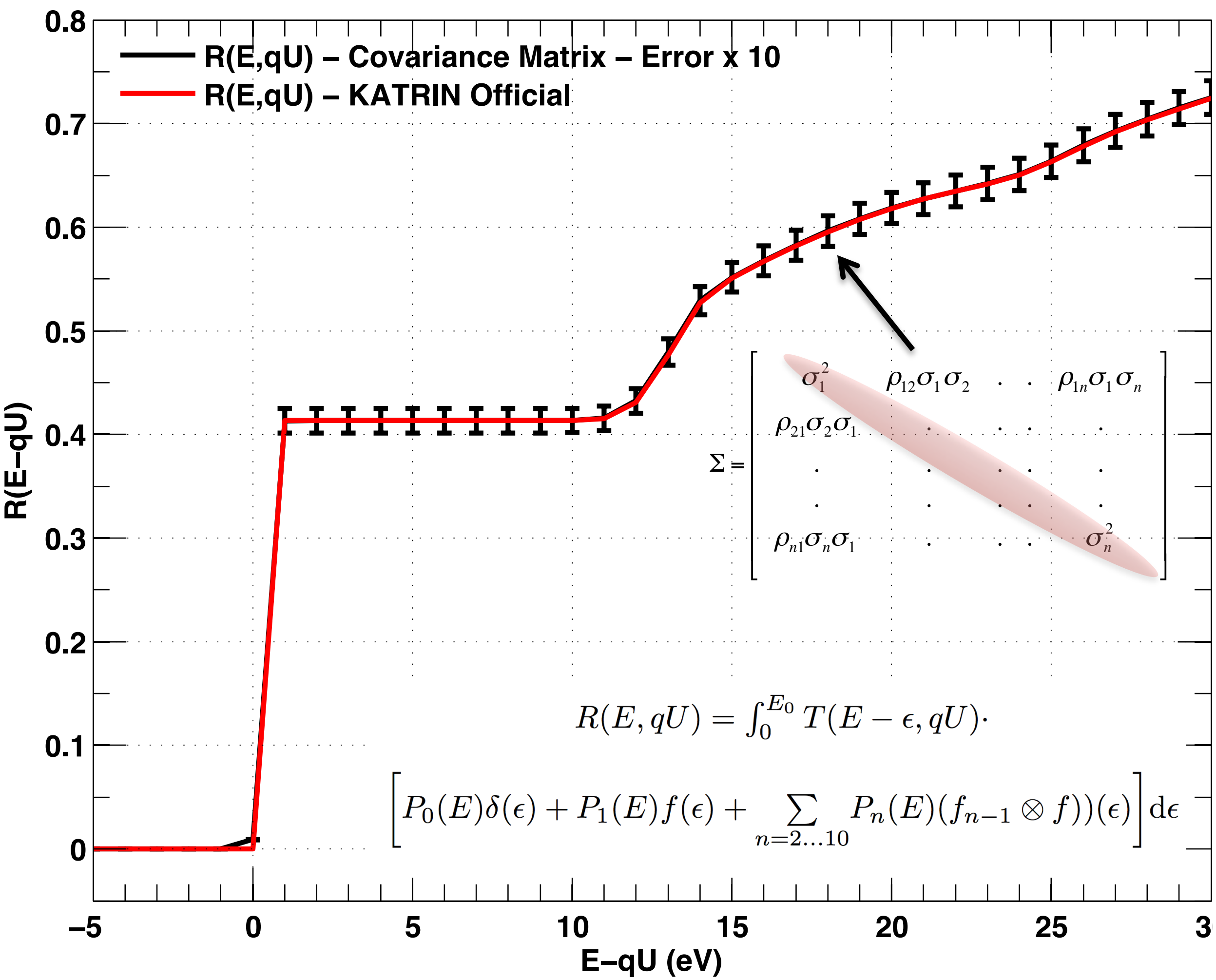
Energy Resolution

$$\Delta E_e / E_e = B_A / B_{\max}$$

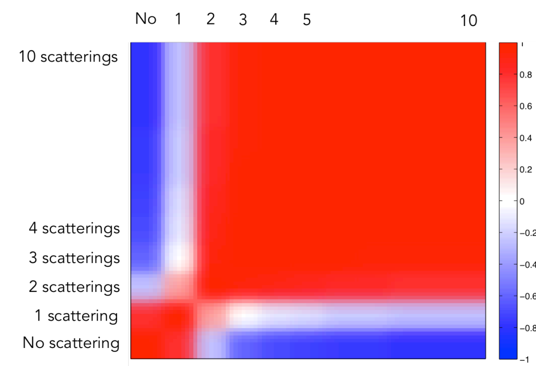
Known within ±1%

Response Function with Uncertainties

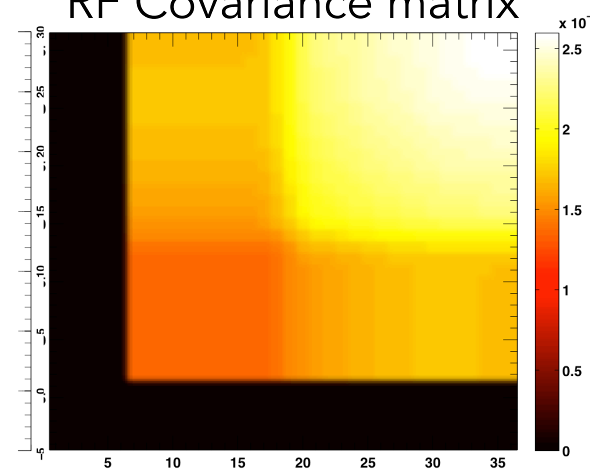
5000 KATRINs simulated varying Source + Spectrometers parameters



IS probabilities correlation

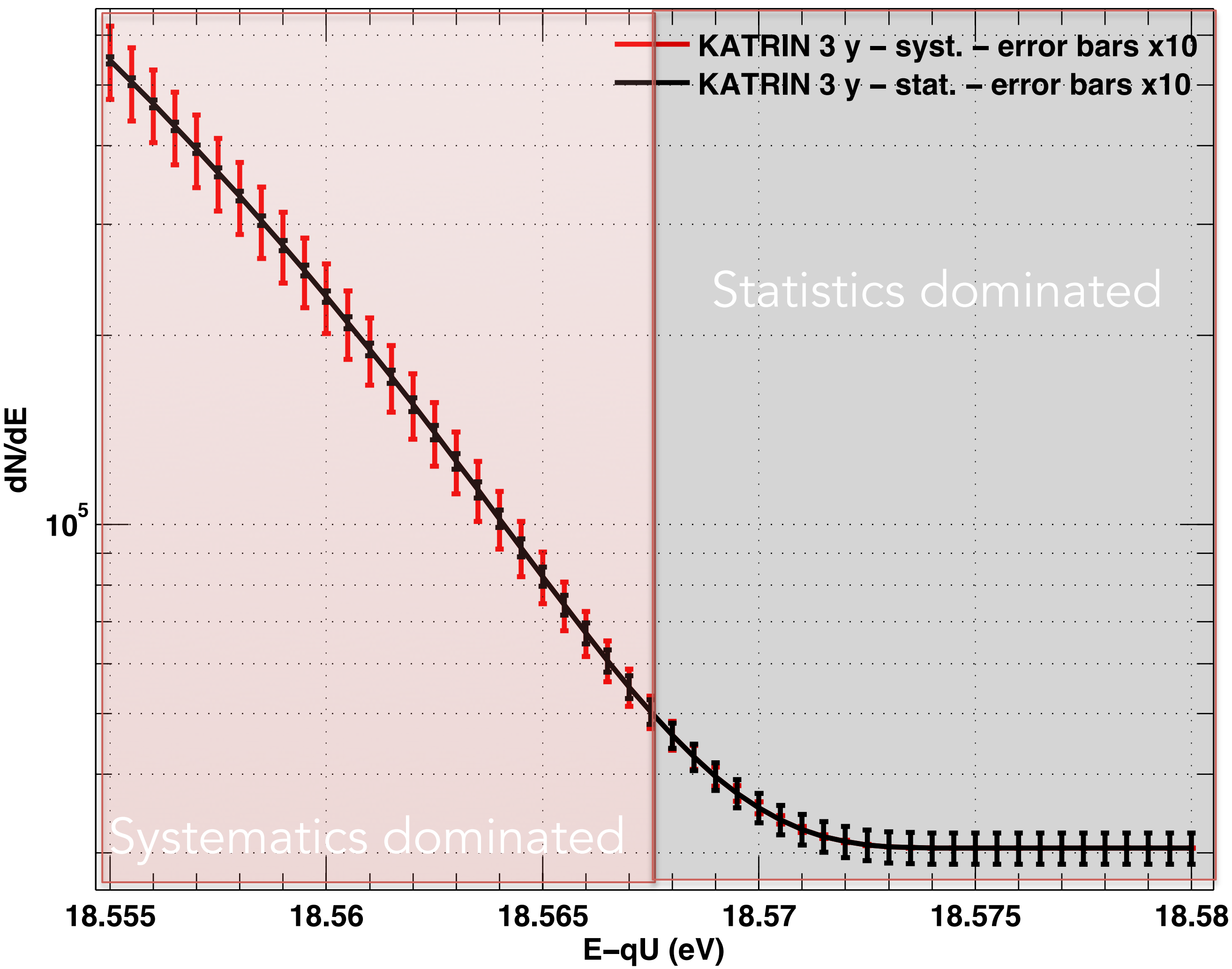


RF Covariance matrix

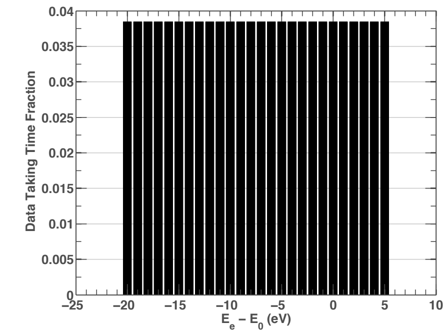


Integral Spectrum With Uncertainties

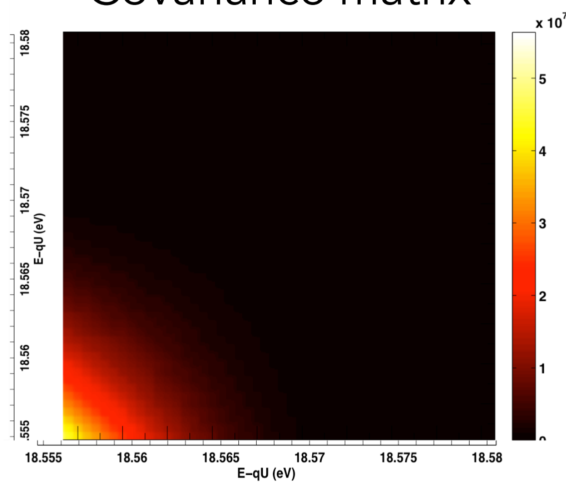
3 years - 10 mcps background - uncorrelated



Scanning time distribution



Covariance matrix

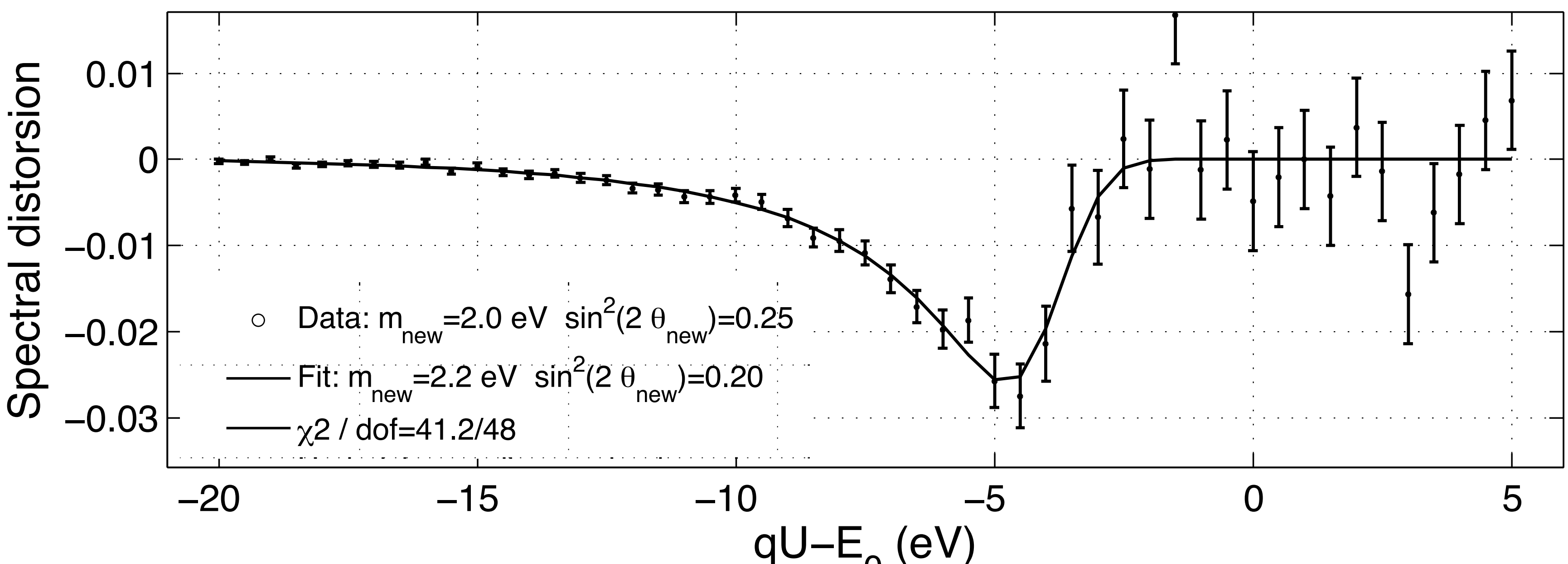


Fit of the Sterile Neutrino Signal

$$\chi^2 = \sum_{i=1}^{N} \sum_{j=1}^{N} (y_i - f(x_i|\alpha))(y_i - f(x_j|\alpha))(V^{-1})_{ij}$$

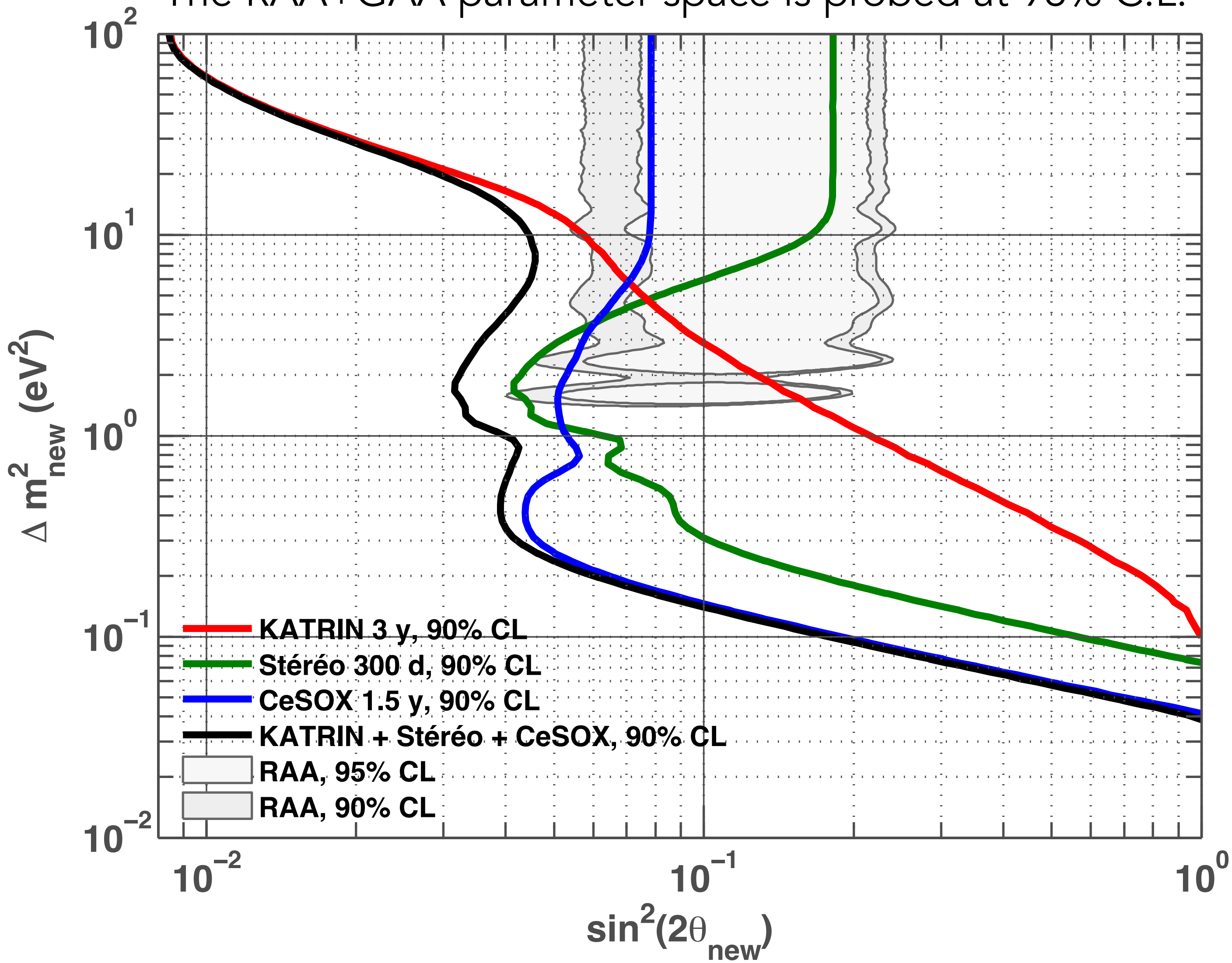
Covariance matrix
$V = V_{stat} + V_{RF} + \ldots$

- Normalization - Free parameter
- $\sin^2(\Theta)$ - Free parameter
- Sterile mass (eV) - Free parameter
- Endpoint/Q-value shift - Free parameter + Pulls term with $\sigma = 1$ eV
- Background rate - Free parameter + Pulls term with $\sigma = 10\%$



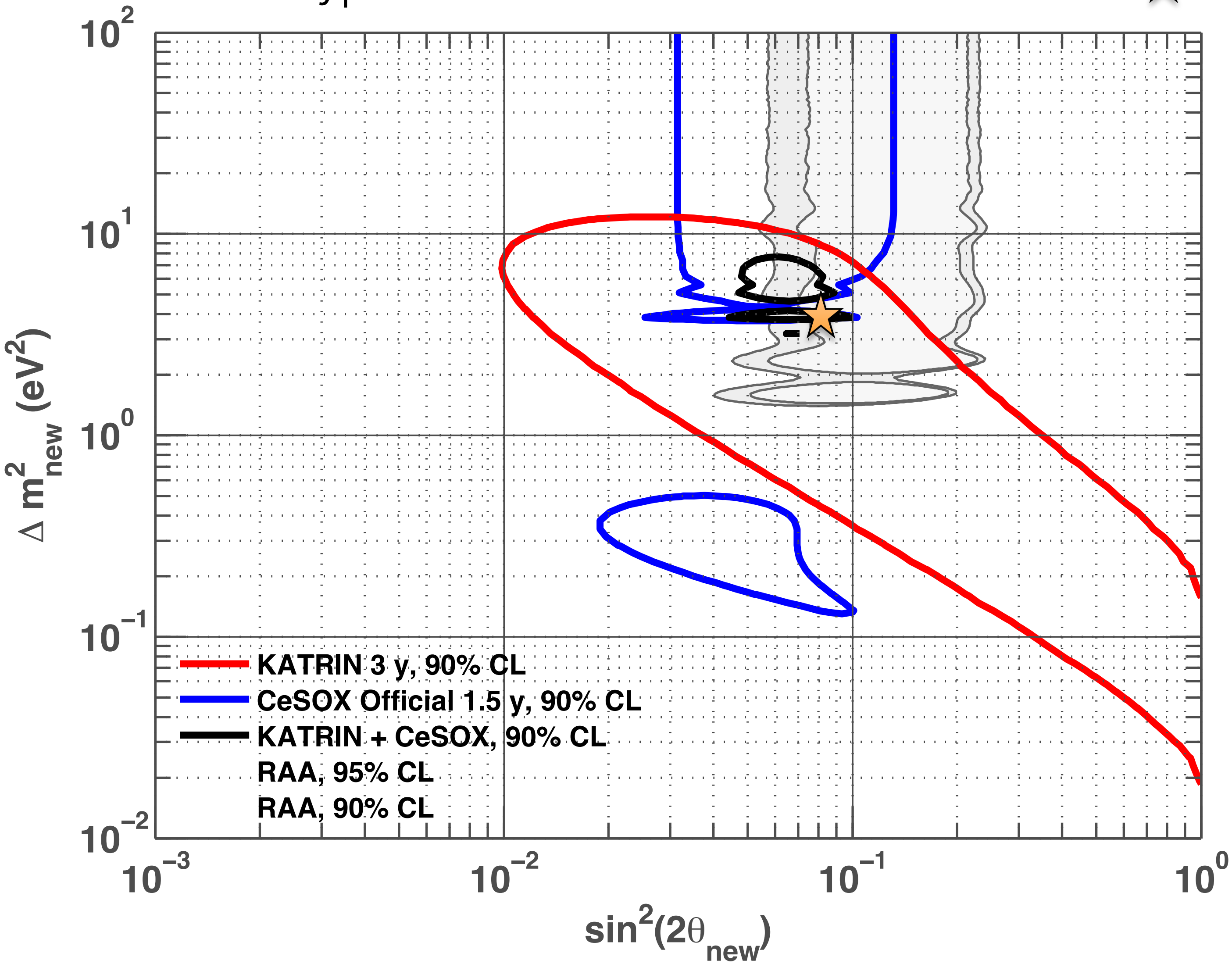
KATRIN + Stéréo + CeSOX

The RAA+GAA parameter space is probed at 98% C.L.

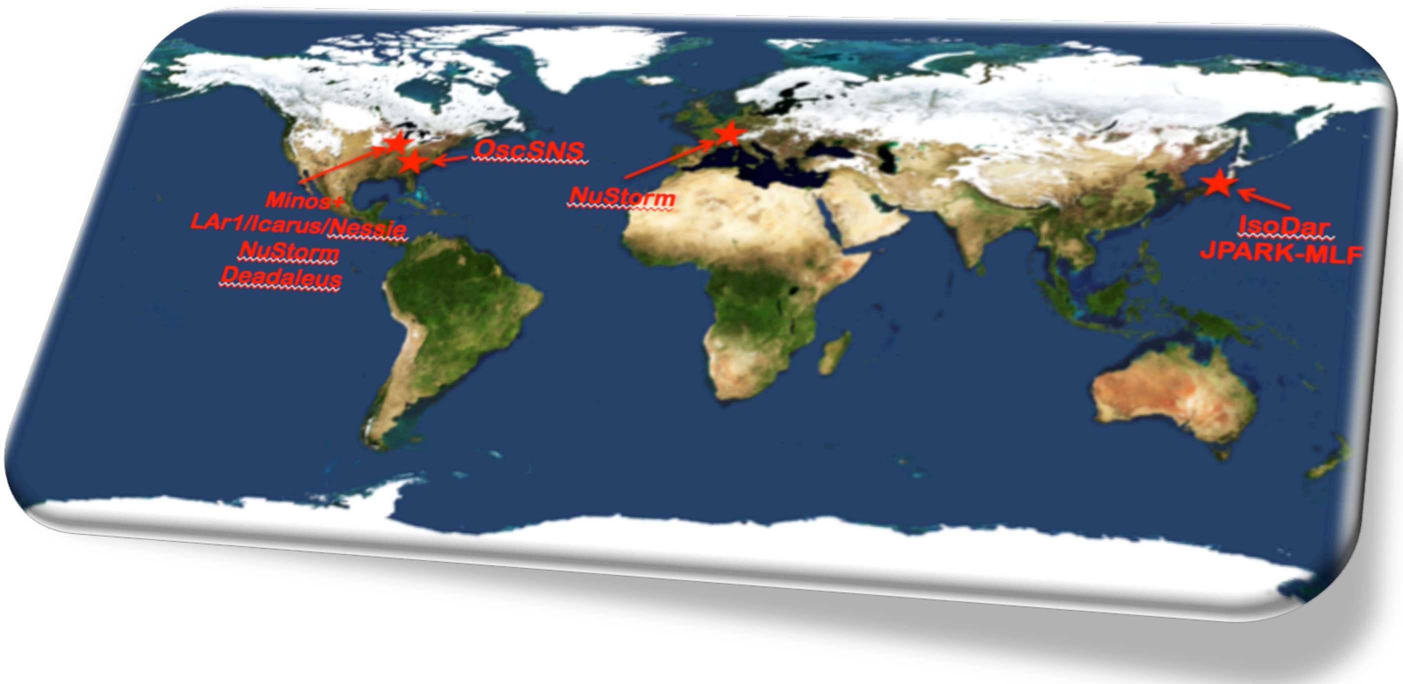


CeSOX+ KATRIN Interplay

True hypothesis: m=2000 meV – $\sin^2 2\theta$=0.08 ☆



eV Sterile-ν Search with Beams: SNB

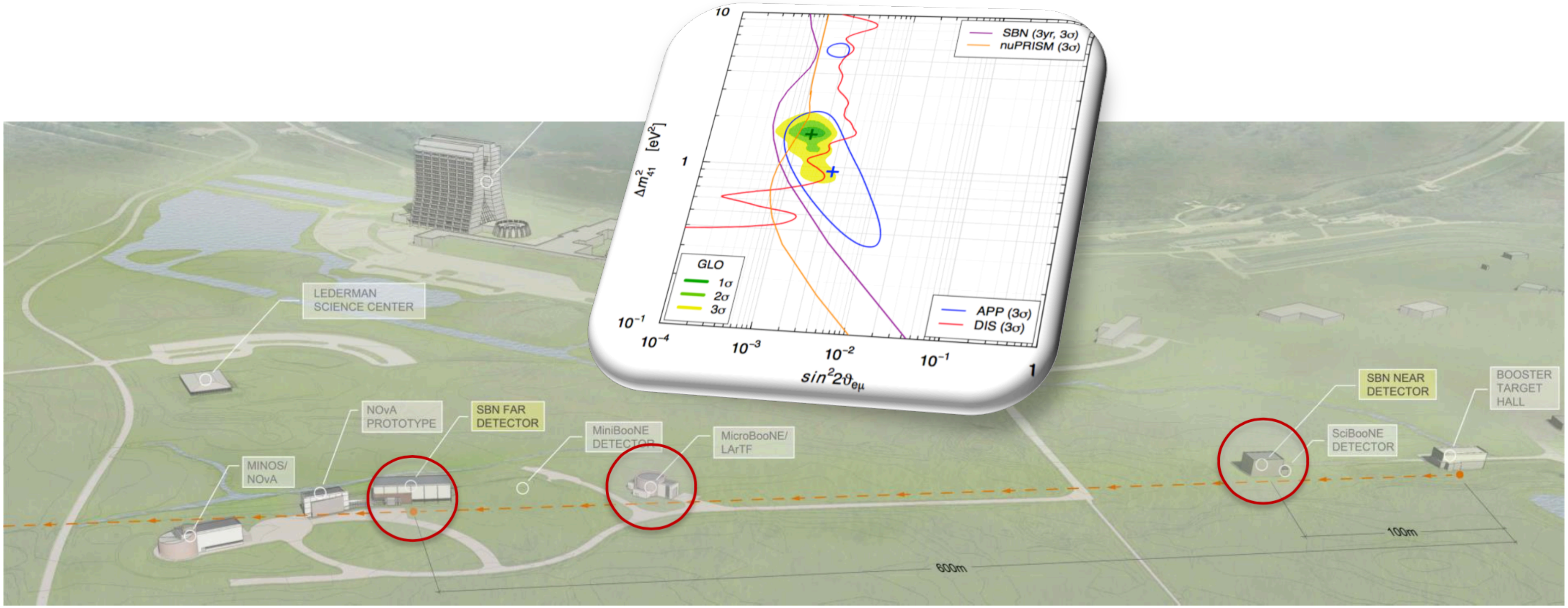


ν beam proposals

Type	Source	App. /Dis.	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	$\pi^+ \rightarrow \mu^+ \nu_\mu$ $\hookrightarrow e^+ \bar{\nu}_\mu \nu_e$	App. & Dis.	$\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ $\nu_e \rightarrow \nu_e$	OscSNS, KDAR, JPARC-MLF
Pion Decay in Flight	$\pi^+ \rightarrow \mu^+ \nu_\mu$ $\hookrightarrow e^+ \bar{\nu}_\mu \nu_e$	App. & Dis.	$\nu_\mu \rightarrow \nu_e$ $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ $\nu_\mu \rightarrow \nu_\mu$ $\nu_e \rightarrow \nu_e$	MINOS+, nuPRISM, SBN 2018
Low-E Neutrino Factory	$\mu^+ \rightarrow e^+ \bar{\nu}_\mu \nu_e$ $\mu^- \rightarrow e^- \nu_\mu \bar{\nu}_e$	App. & Dis.	$\nu_e \rightarrow \nu_\mu$ $\bar{\nu}_e \rightarrow \bar{\nu}_\mu$ $\nu_\mu \rightarrow \nu_\mu$ $\bar{\nu}_e \rightarrow \bar{\nu}_e$	ν STORM

Start SNB Neutrino Program with Icarus in 2018/19

The Fermilab SBN program



ICARUS	MicroBooNE	SBND	Produce
Fewer ν_μ ?	Fewer ν_μ ?	ν_μ	ν_μ
More ν_e?	More ν_e?	~1% ν_e	~1% ν_e

110m

470m

600m

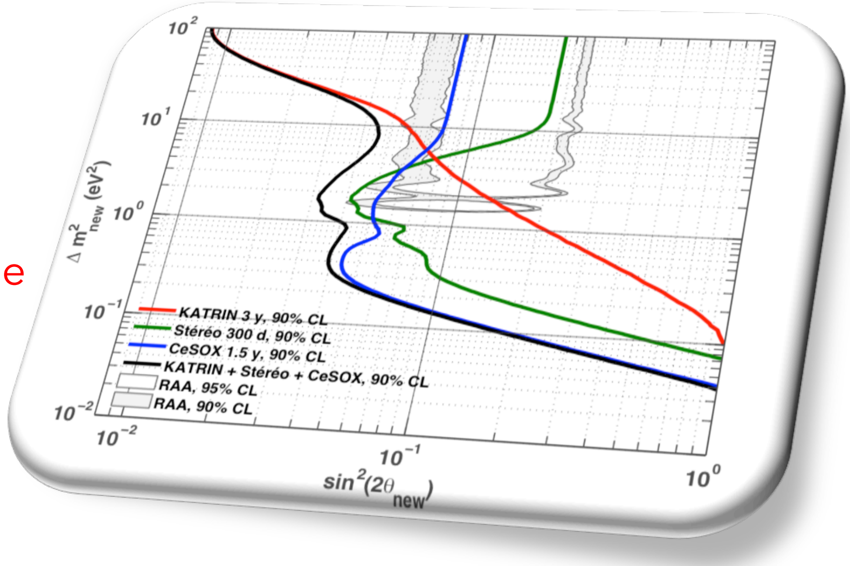
SBN Fermilab

eV-scale: Conclusions and Outlook

- 3 σ anomalies calling for clarification

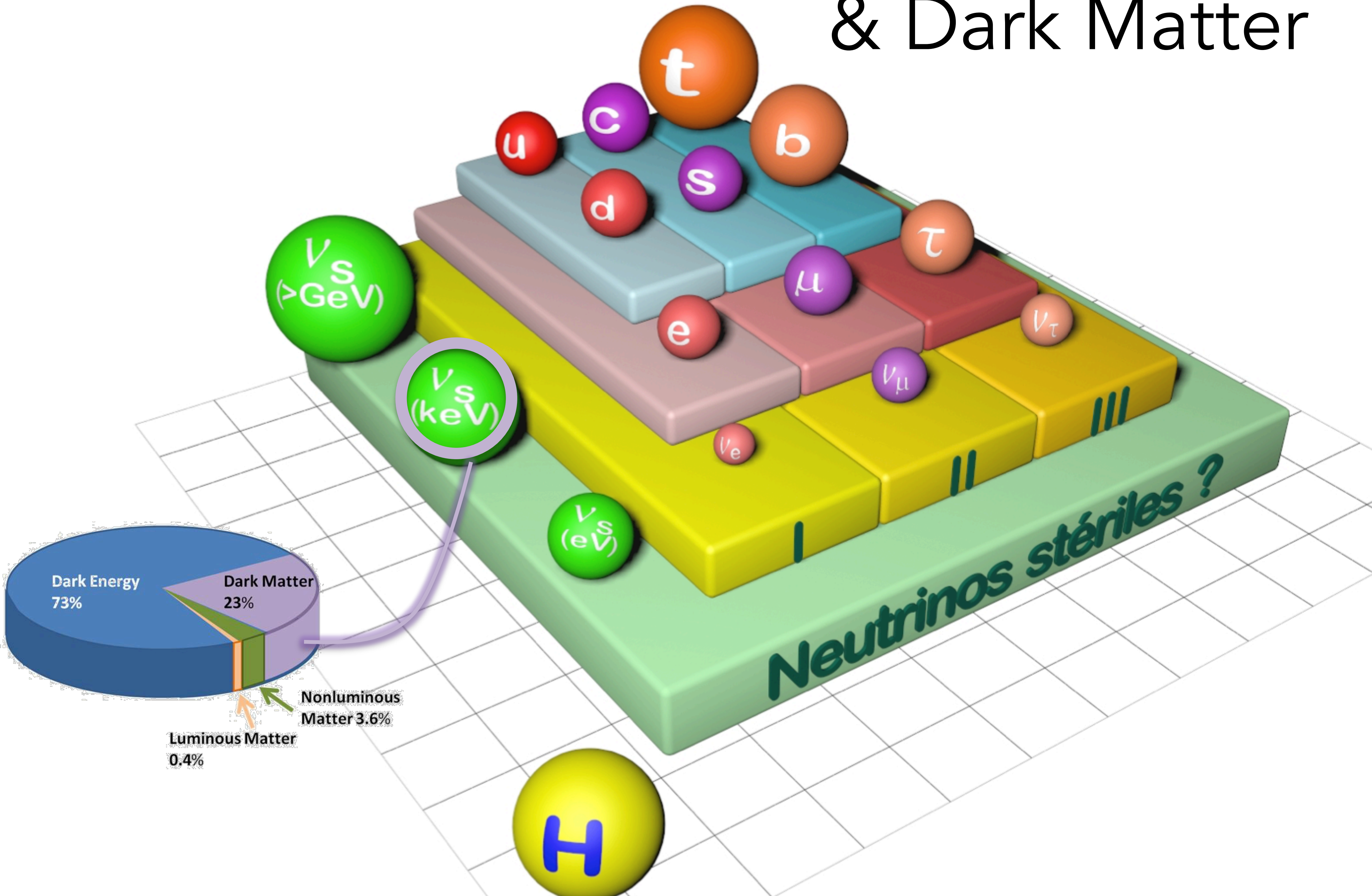
  → $\Delta m^2 \approx eV^2$ Sterile Neutrino? Or Experimental Artifacts?

  - Caveat: tensions in global fits



- Reactor Neutrinos – 3 years timescale
  - Challenge: background mitigation
- Radioactive Sources – 3 years timescale
  - KATRIN
    - Challenge: backgrounds
  - CeSOX
    - Challenges: isotope production, transportation, authorizations
- Neutrino Beams – 5-10 years timescale
  - Added value: allow studying sterile neutrino phenomenology, in case?
- Other tests with $(\beta\beta)0\nu$-decay, cosmological data

Sterile Neutrinos at the keV-scale & Dark Matter



keV-ν Dark Matter (CMνB)

- Right-handed ν 's
  - A 'natural' extension of the SM
  - Possibility for a new – arbitrary – mass Eigenstate in the keV-range
  - Mix (oscillate) with active ν 's

    $\sin^2\theta_{e4} < 10^{-6}$ … challenging for all experiments!

- keV Sterile ν are suitable DM candidates :
  - Can be produced in the Early Universe
  - Abundance depends on production mechanism (thermal or not)
  - Cosmological life-time
  - Can suppress galactic-scale structures in the Universe

White Paper - arXiv:1602.04816

A White Paper on keV Sterile Neutrino Dark Matter

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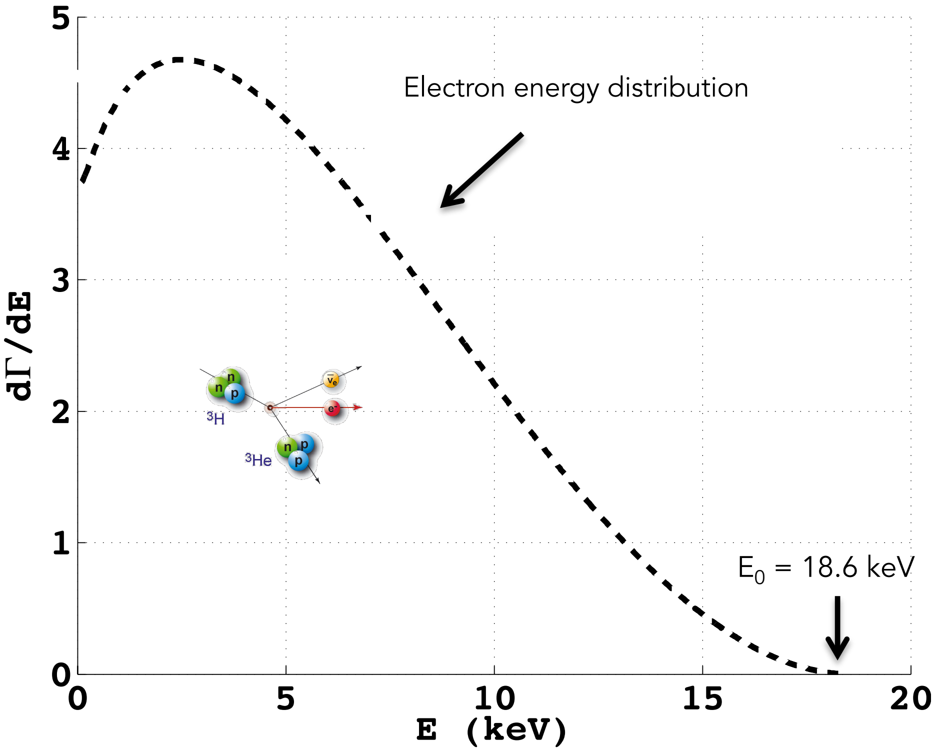
- Interdisciplinary review of the physics case, constraints, and perspectives
- 140 authors from 91 institutions – Submitted to JCAP

Search for keV Neutrino with KATRIN/TRISTAN

TRItium β-decay to Search for STerile Neutrino

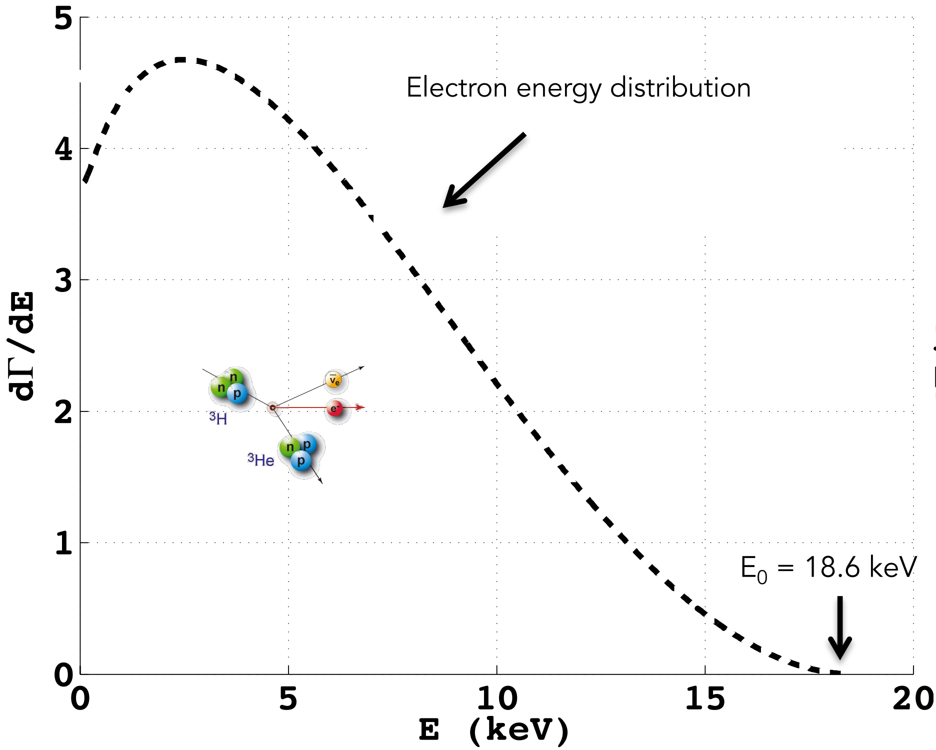
keV neutrino signal in ^3H β-decay

No Sterile Neutrino

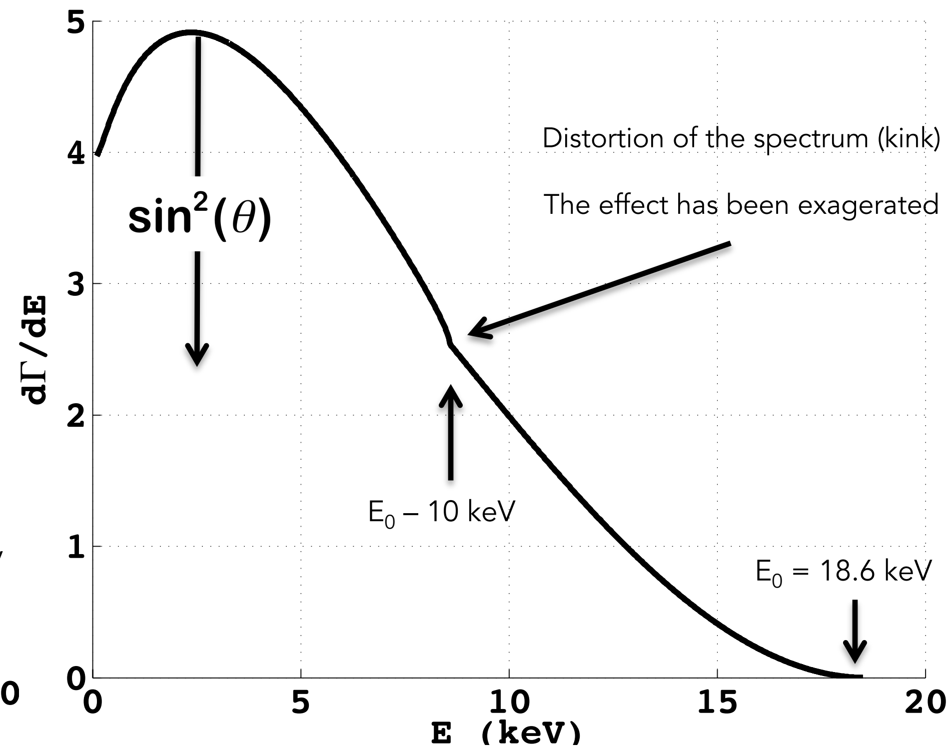


keV neutrino signal in ^3H β-decay

No Sterile Neutrino

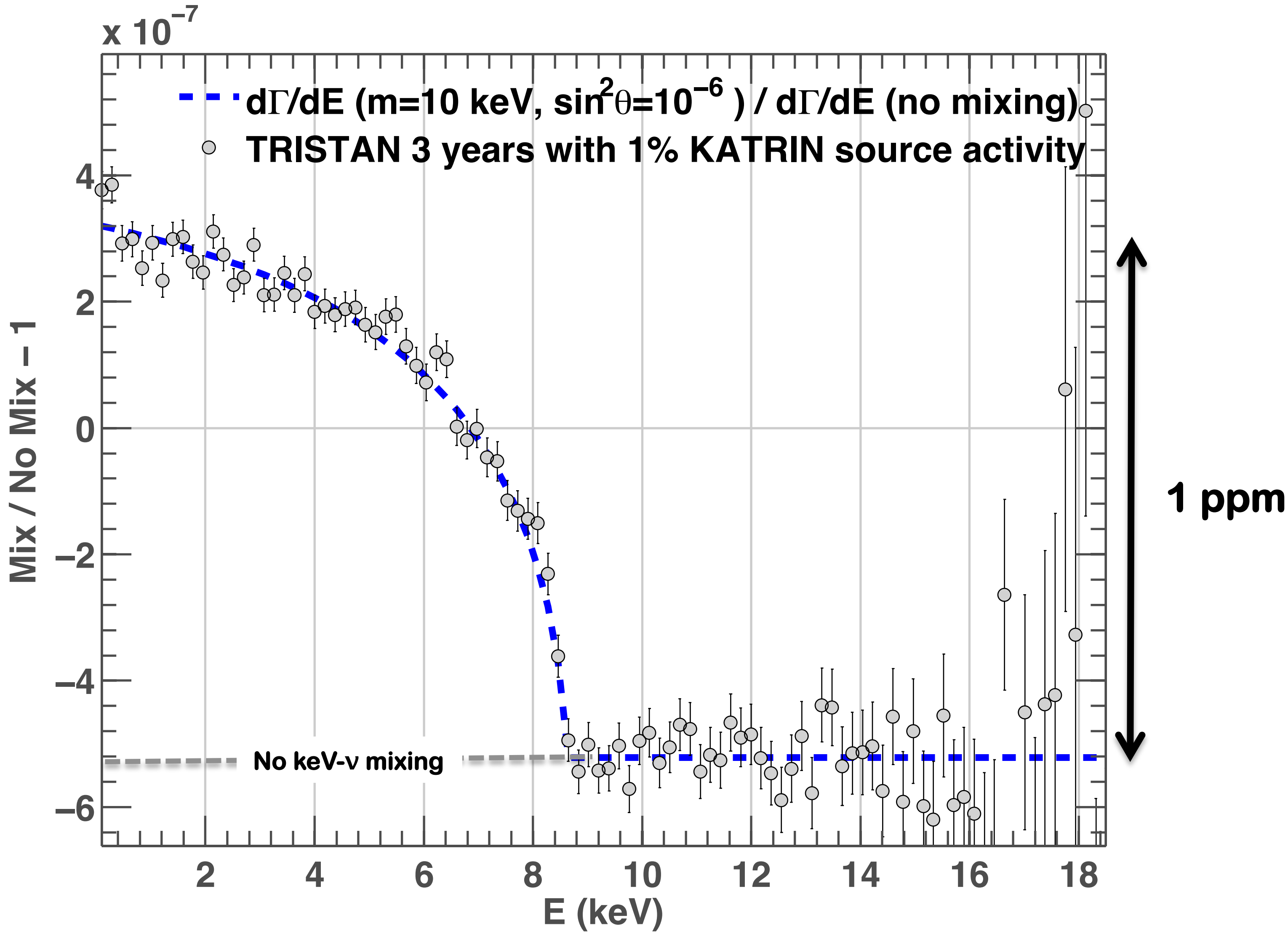


10 keV Sterile Neutrino



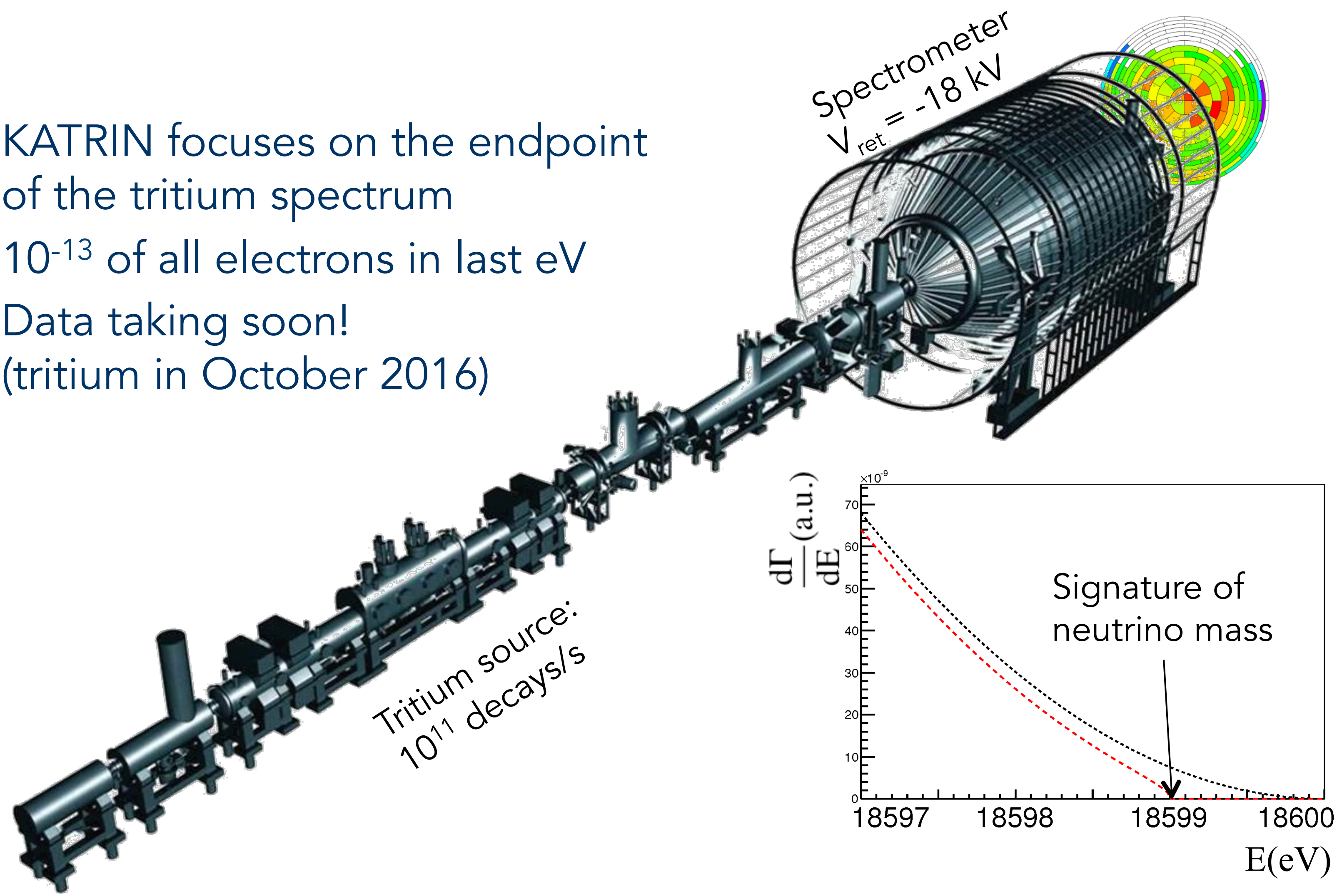
$$\frac{d\Gamma}{dE} = \cos^2(\theta)\frac{d\Gamma}{dE}(m_{\nu,\text{light}}) + \sin^2(\theta)\frac{d\Gamma}{dE}(m_{\nu,\text{heavy}})$$

Dark Matter calls for a tiny mixing…

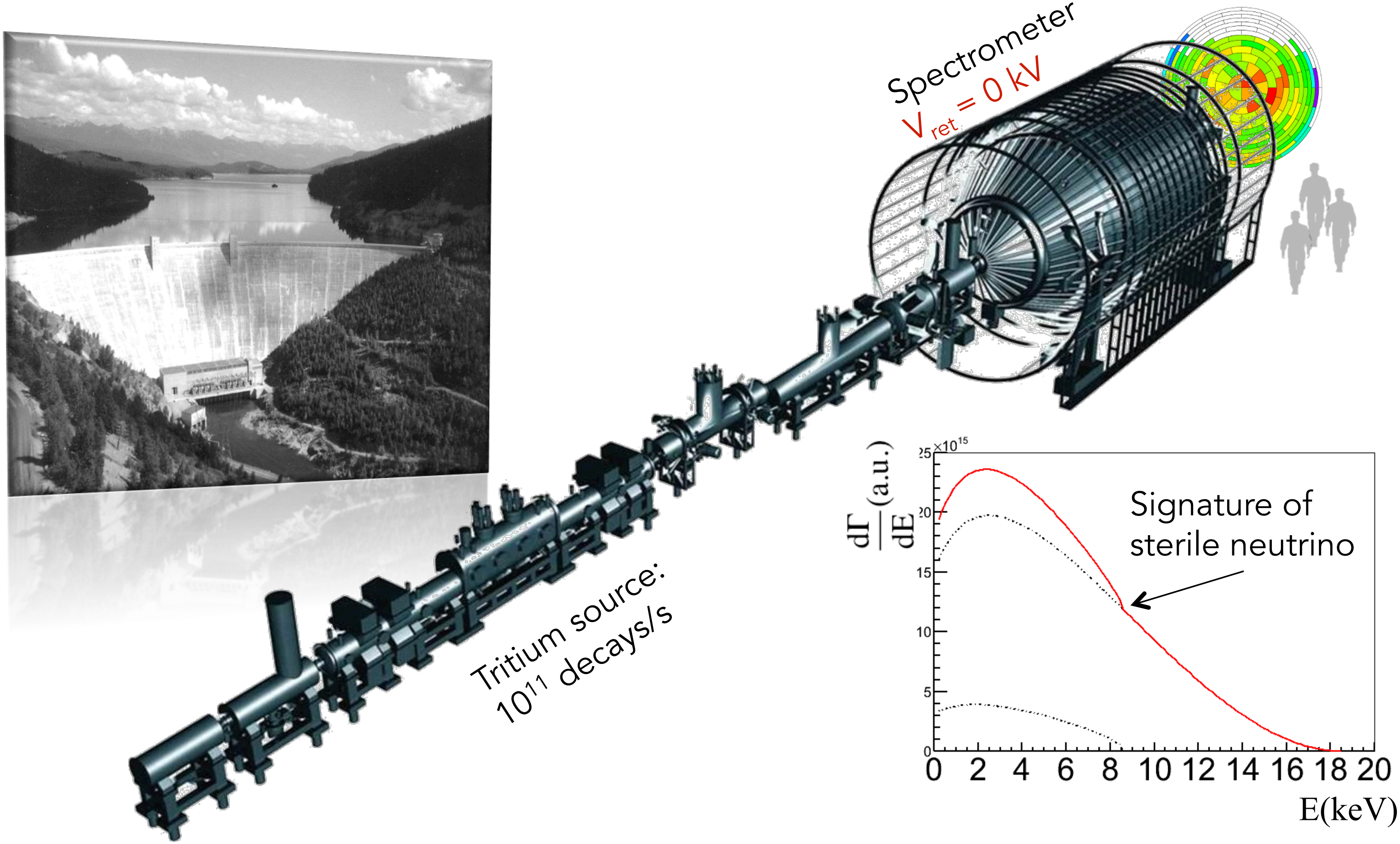


Can we use KATRIN?

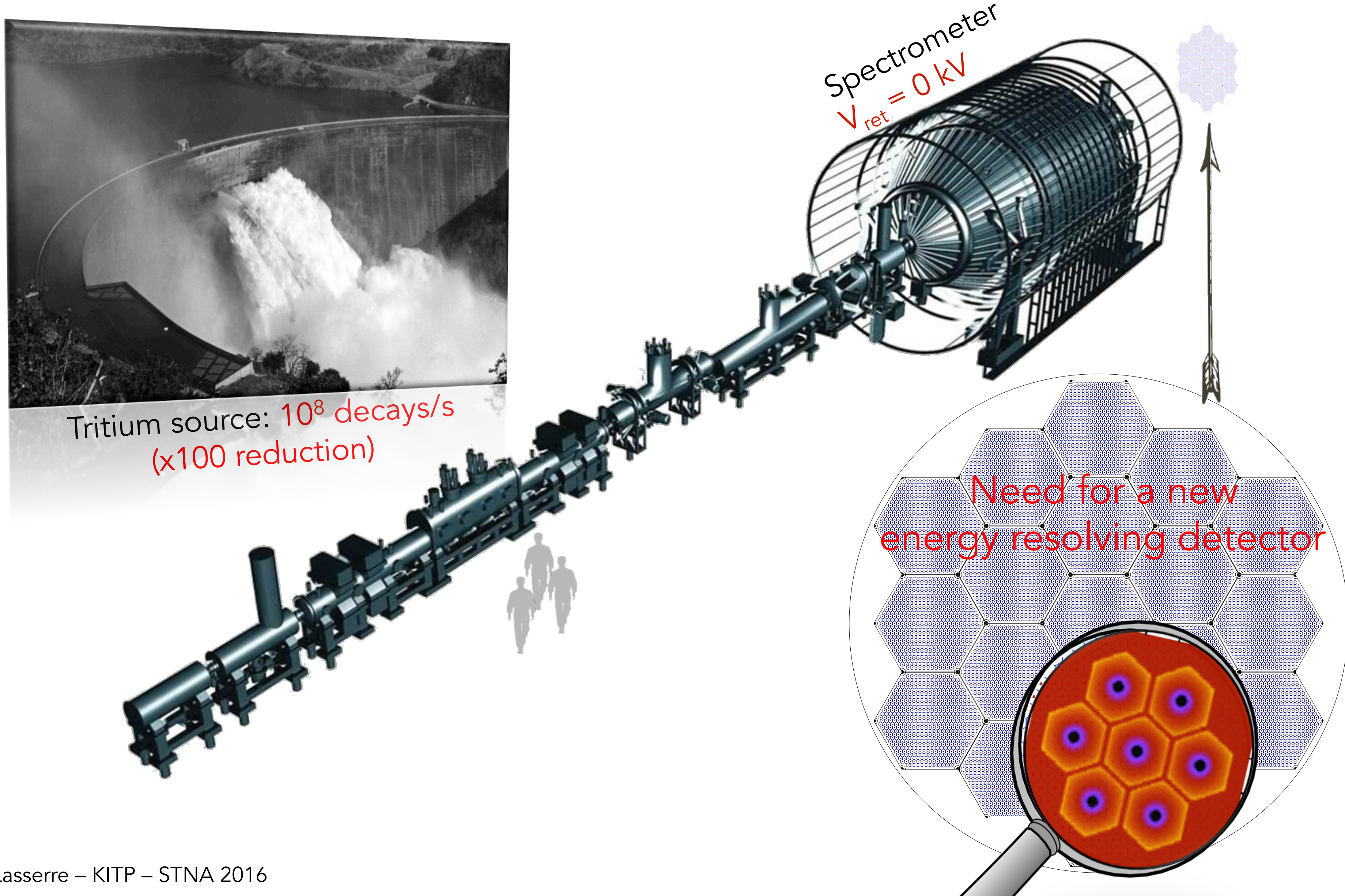
- KATRIN focuses on the endpoint of the tritium spectrum
- 10^{-13} of all electrons in last eV
- Data taking soon! (tritium in October 2016)



An Upgrade: KATRIN/TRISTAN

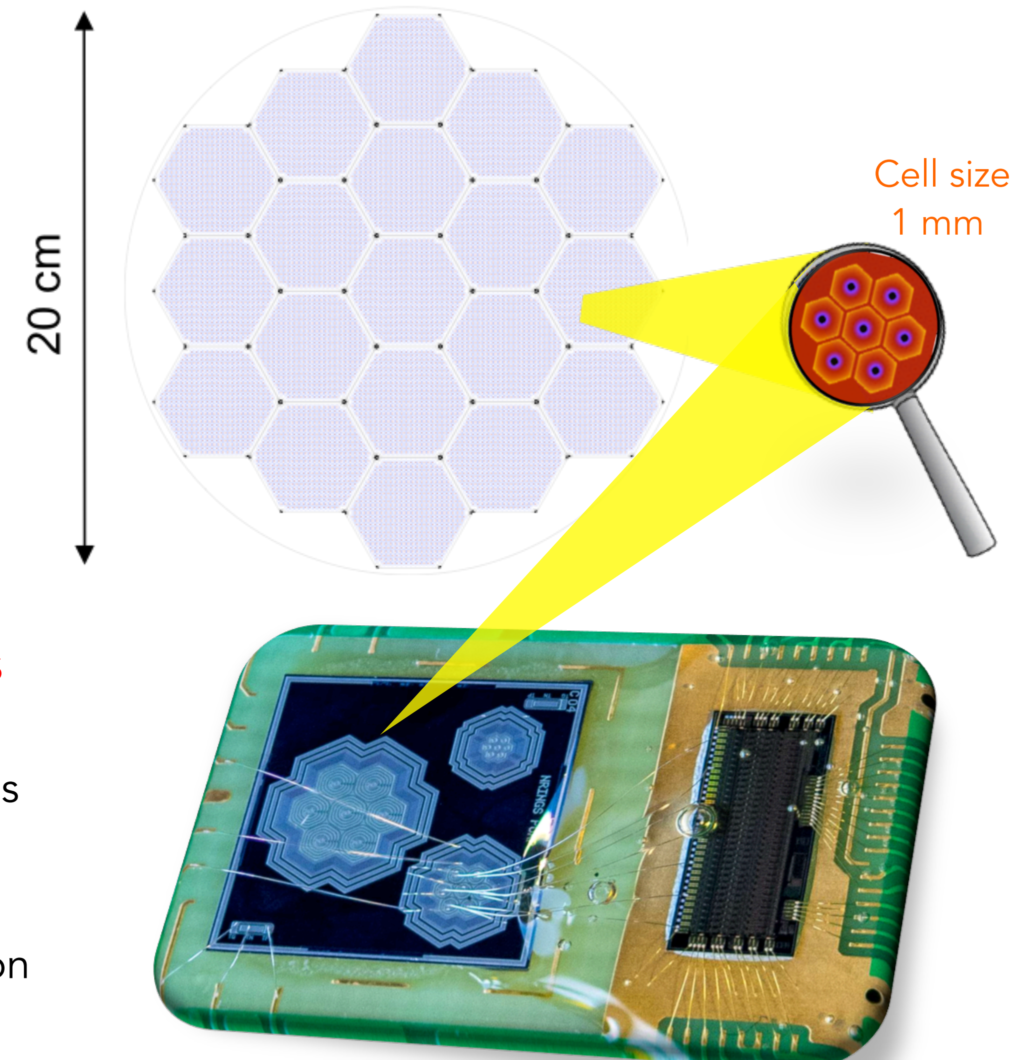


The TRISTAN project



KATRIN Upgrade: New detector

- Measure ultra-accurately the entire tritium β-decay spectrum
  - Minimize pile-up
  - 10 000 to 100 000 pixels
- Energy resolving silicon detector
  - Low threshold:
    - 10 nm dead layer
  - Energy resolution
    - ≈ 300 eV @20 keV
  - Minimize charge sharing between pixels
- Minimize and control systematics
  - Backscattering of e^- on silicon
    - Optimize geometry and B-fields
    - Active veto?
  - Sophisticated readout system
    - Low noise – accurate digitization



Tritium β-decay Modeling

$$\frac{d\Gamma}{dE_e}(m_{\nu_i}) = C \cdot p_e E_e \cdot \sqrt{(E_e - E_0)^2 - m_{\nu_i}^2} \cdot (E_e - E_0) \cdot F(E_e, Z)$$

Tritium Activity

Phase space factor

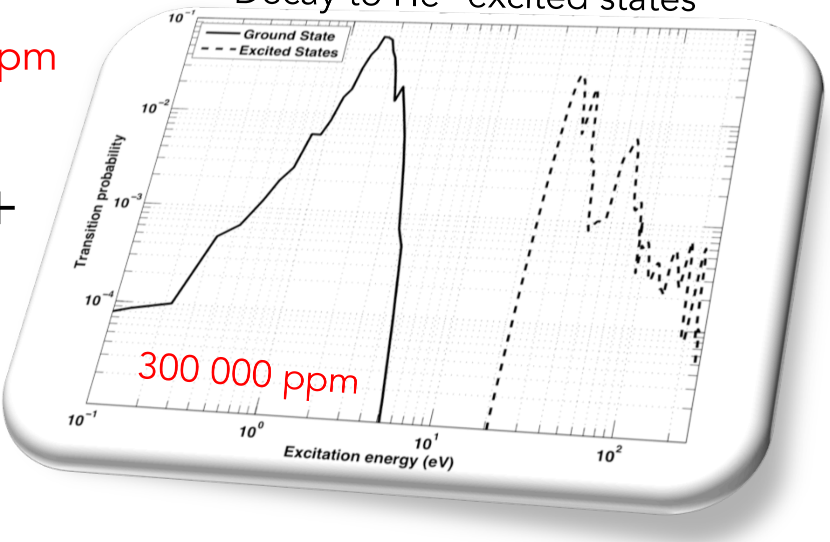
Relativistic Fermi function – O(1) effect

$$\left(\frac{d\Gamma}{dE_e}\right)^{corr} = \frac{d\Gamma}{dE_e} \cdot \left[\prod_{\Psi = L_0, S, E, Q, R, G} \Psi(E_e, Z) \right]$$

- Screening Correction (S) – 1000 ppm
- β−electron to orbital electron exchange (E) - 1000 ppm
- He recoil corrections ® - 50 ppm
  - 3 body decay
  - weak magnetism
  - V-A correction
- Recoiling Coulomb field (Q) – 100 ppm
- Finite extension of the nucleus
  - Coulomb field
  - weak interaction (L_0, C)
- Radiative corrections (G) – 1000 ppm

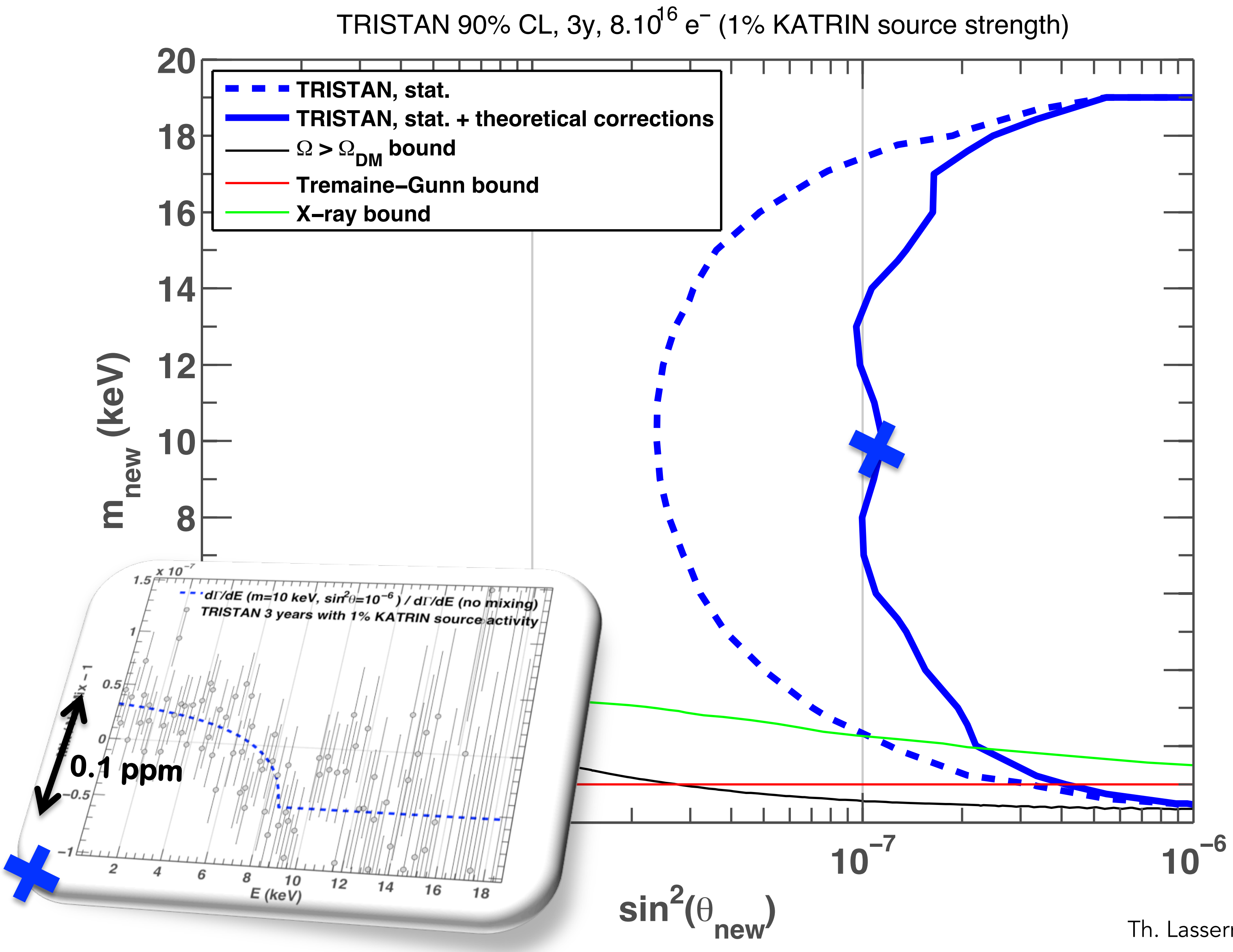
\+

Decay to He^+ excited states

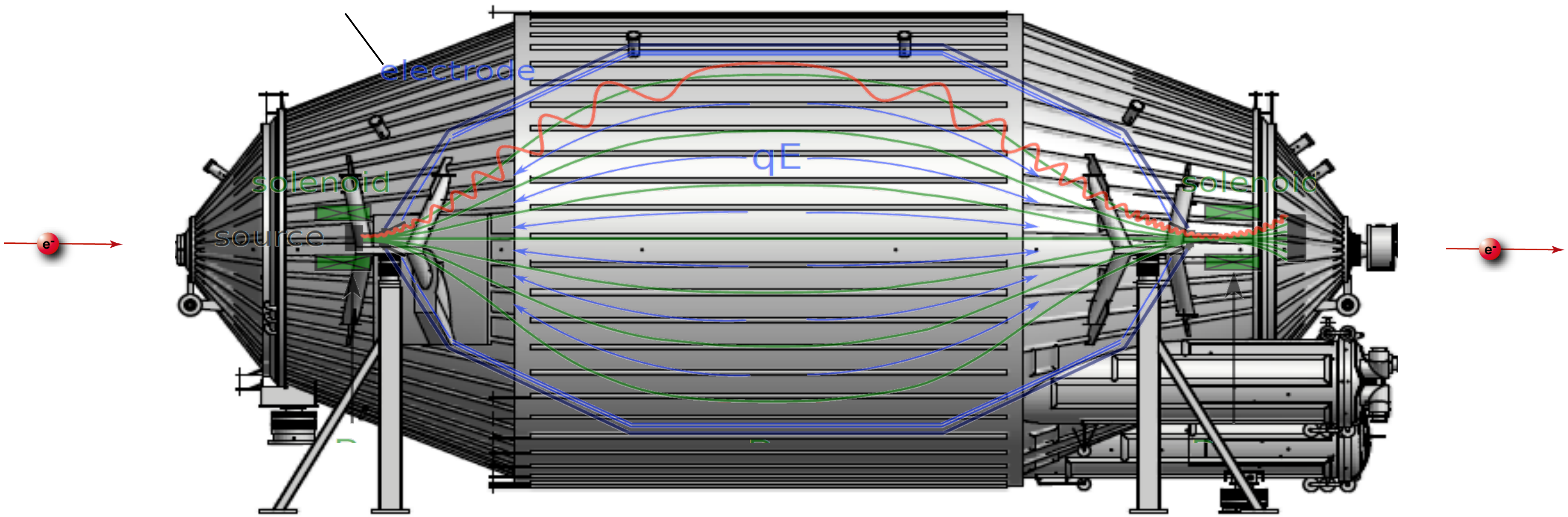


KATRIN/TRISTAN Statistical Sensitivity

S. Mertens, T. L. *et al.* JCAP 1502 (2015) 02, 020



KATRIN Upgrade: Spectrometer

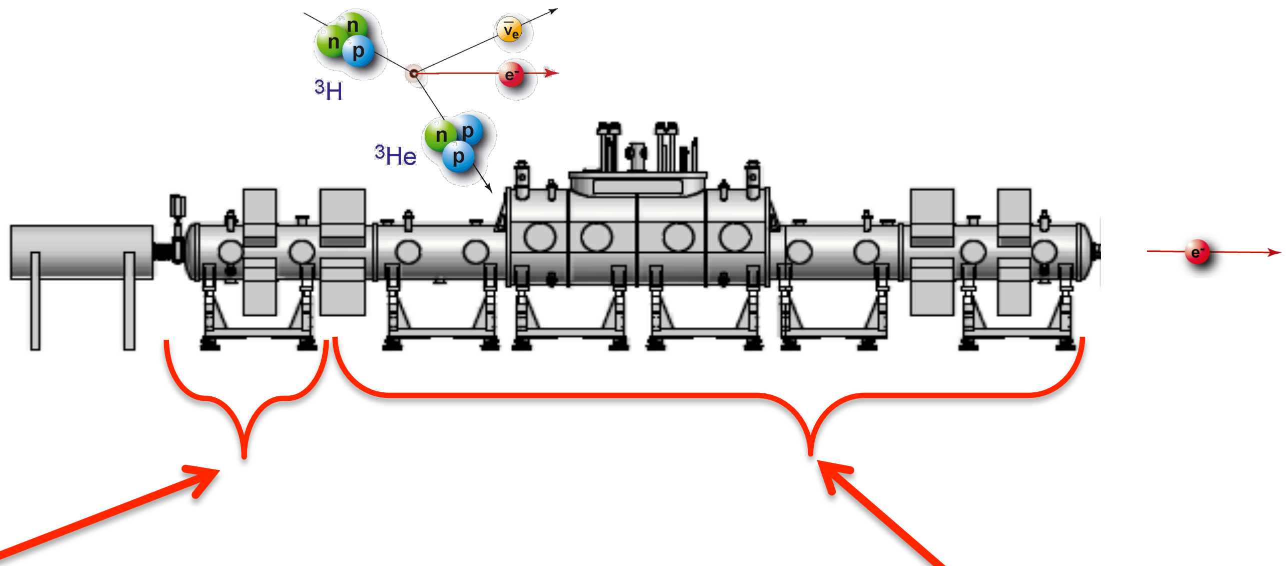


- Differential measurement
  - Retarding potential qU ≈ 0 keV eq. to no use of spectrometer
- Integral measurement
  - Retarding potential qU scan from 1 to 19 keV

Magnetic field settings to be optimized

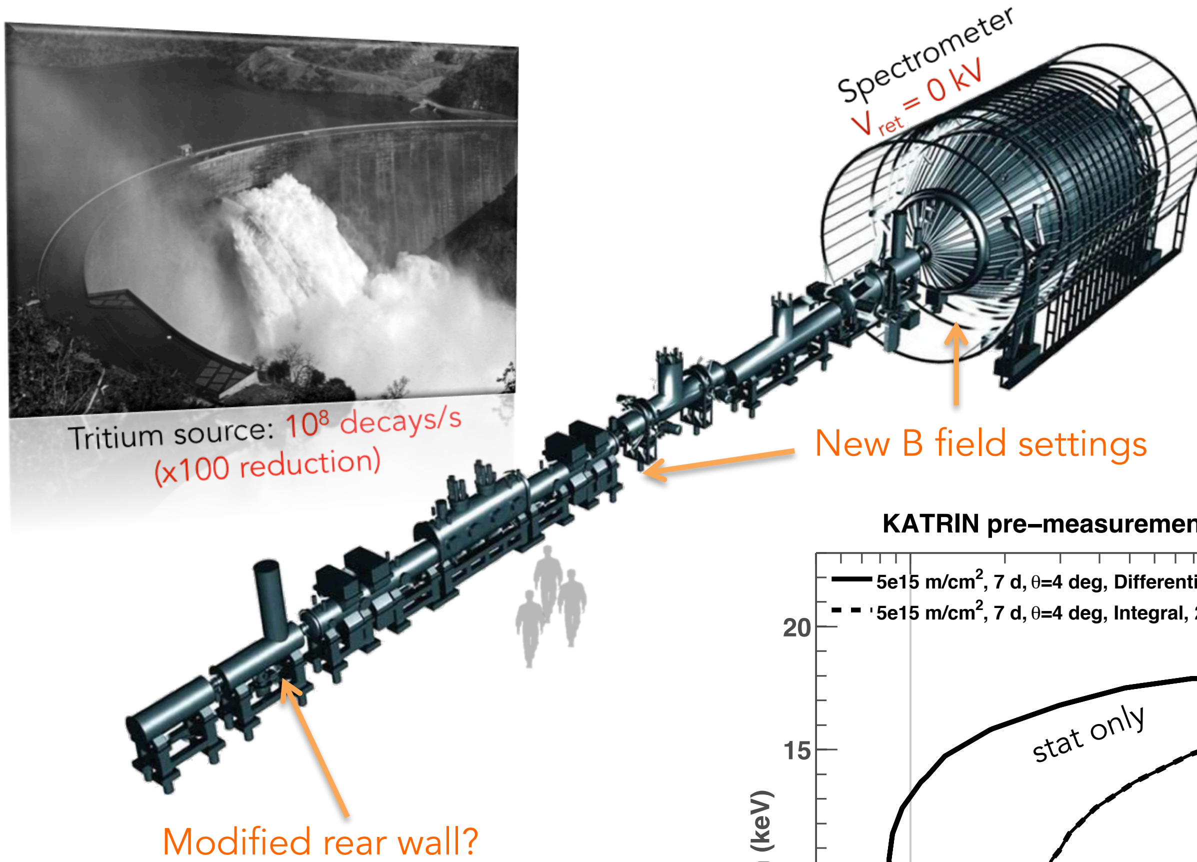
Differential / Integral can be combined to minimize systematics

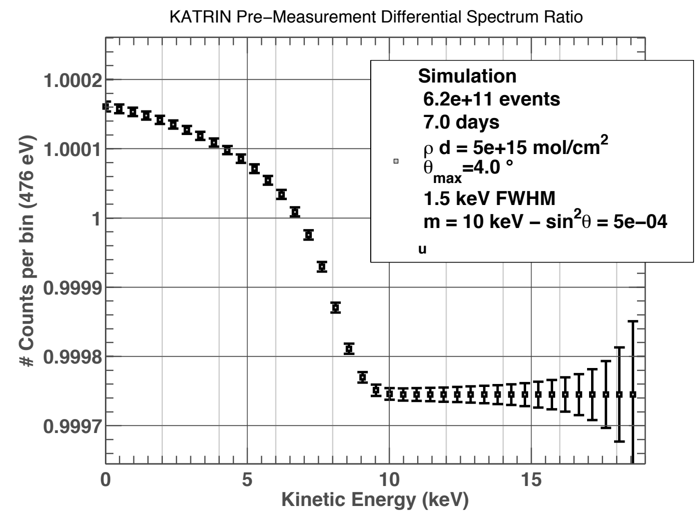
KATRIN Upgrade: Tritium Source

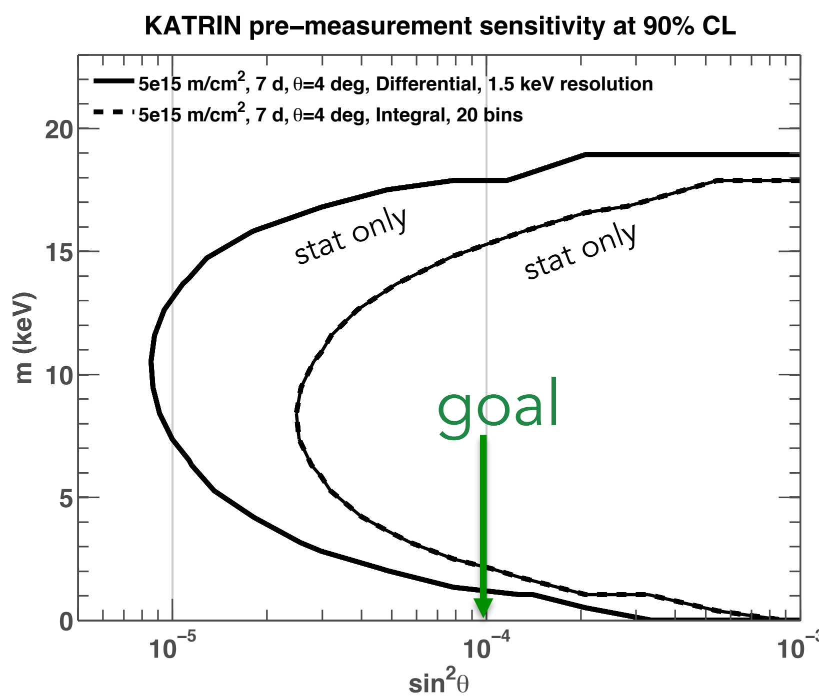


- Rear wall – defines 0-potential
  - To be modified to mitigate
    - backscattering of electrons
    - emission of auger electrons
  - KATRIN: gold, 20 cm
  - Upgrade: Berylium >> 20 cm
- Windowless molecular tritium Source (WGTS)
  - X 100 reduction → 10^8 decays/sec
    - Reduction of e-scattering
    - Mitigate e-rate on detector
  - Reduce activity fluctuations < 10^{-3}

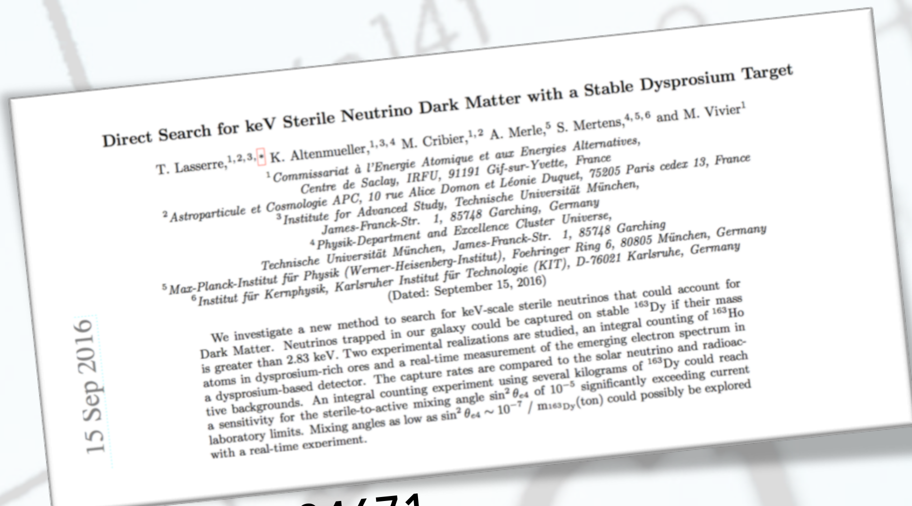
Feasibility Run with KATRIN - 2017







Direct Search for Sterile Neutrino Dark Matter with a Stable Dysprosium 163 Target


Direct Search for keV Sterile Neutrino Dark Matter with a Stable Dysprosium Target

T. Lasserre,[1,2,3,*] K. Altenmueller,[1,3,4] M. Cribier,[1,2] A. Merle,[5] S. Mertens,[4,5,6] and M. Vivier[1]

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[6] *Institut für Kernphysik, Karlsruher Institut für Technologie (KIT), D-76021 Karlsruhe, Germany*

(Dated: September 15, 2016)

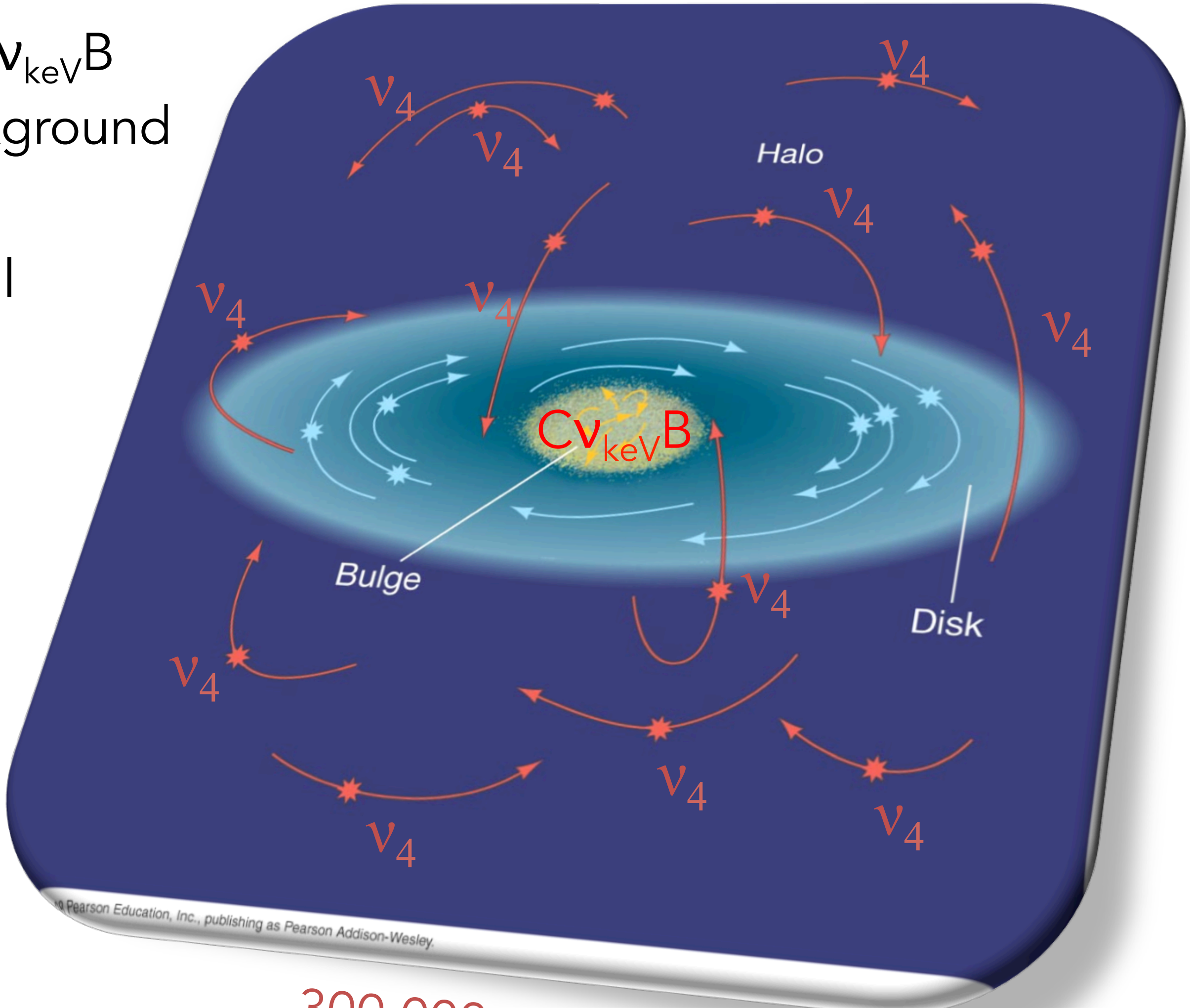
We investigate a new method to search for keV-scale sterile neutrinos that could account for Dark Matter. Neutrinos trapped in our galaxy could be captured on stable ^{163}Dy if their mass is greater than 2.83 keV. Two experimental realizations are studied, an integral counting of ^{163}Ho atoms in dysprosium-rich ores and a real-time measurement of the emerging electron spectrum in a dysprosium-based detector. The capture rates are compared to the solar neutrino and radioactive backgrounds. An integral counting experiment using several kilograms of ^{163}Dy could reach a sensitivity for the sterile-to-active mixing angle $\sin^2\theta_{e4}$ of 10^{-5} significantly exceeding current laboratory limits. Mixing angles as low as $\sin^2\theta_{e4} \sim 10^{-7}$ / $m_{^{163}Dy}$(ton) could possibly be explored with a real-time experiment.

15 Sep 2016

arXiv:1609.04671

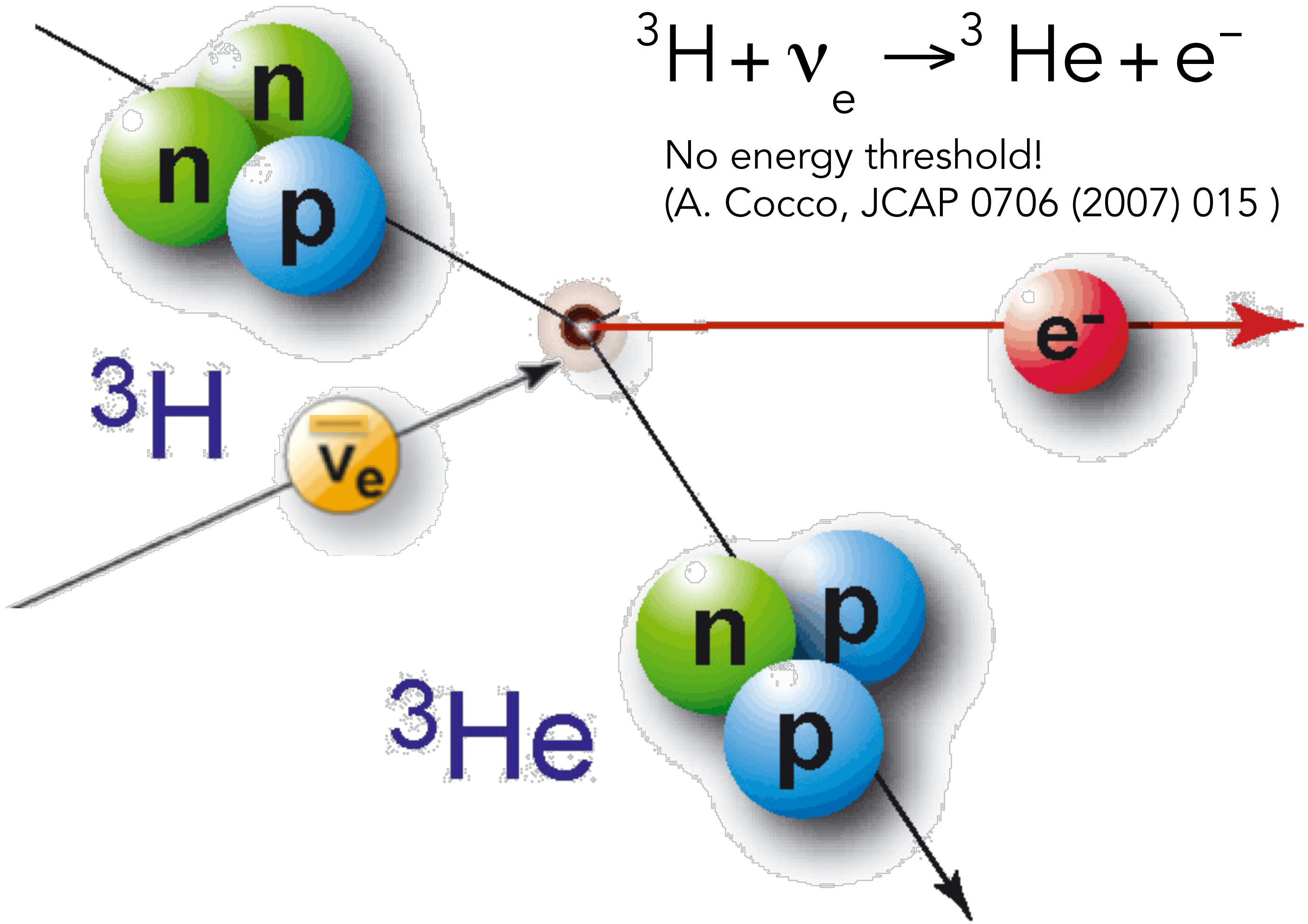
Relic keV Neutrinos in Galactic Halo

- keV relic neutrinos = $C\nu_{keV}B$ Cosmic Massive ν Background
- Cluster in potential well of Galaxies
- **$n_{\nu 4} \approx 3\ 10^5$ / m_4 (keV) per cm^3**
- X 1000 more than active C ν B !
- Velocity: 220 km/s



300 000 ν_4/cm^3

ν-Capture on Radioactive Nuclei

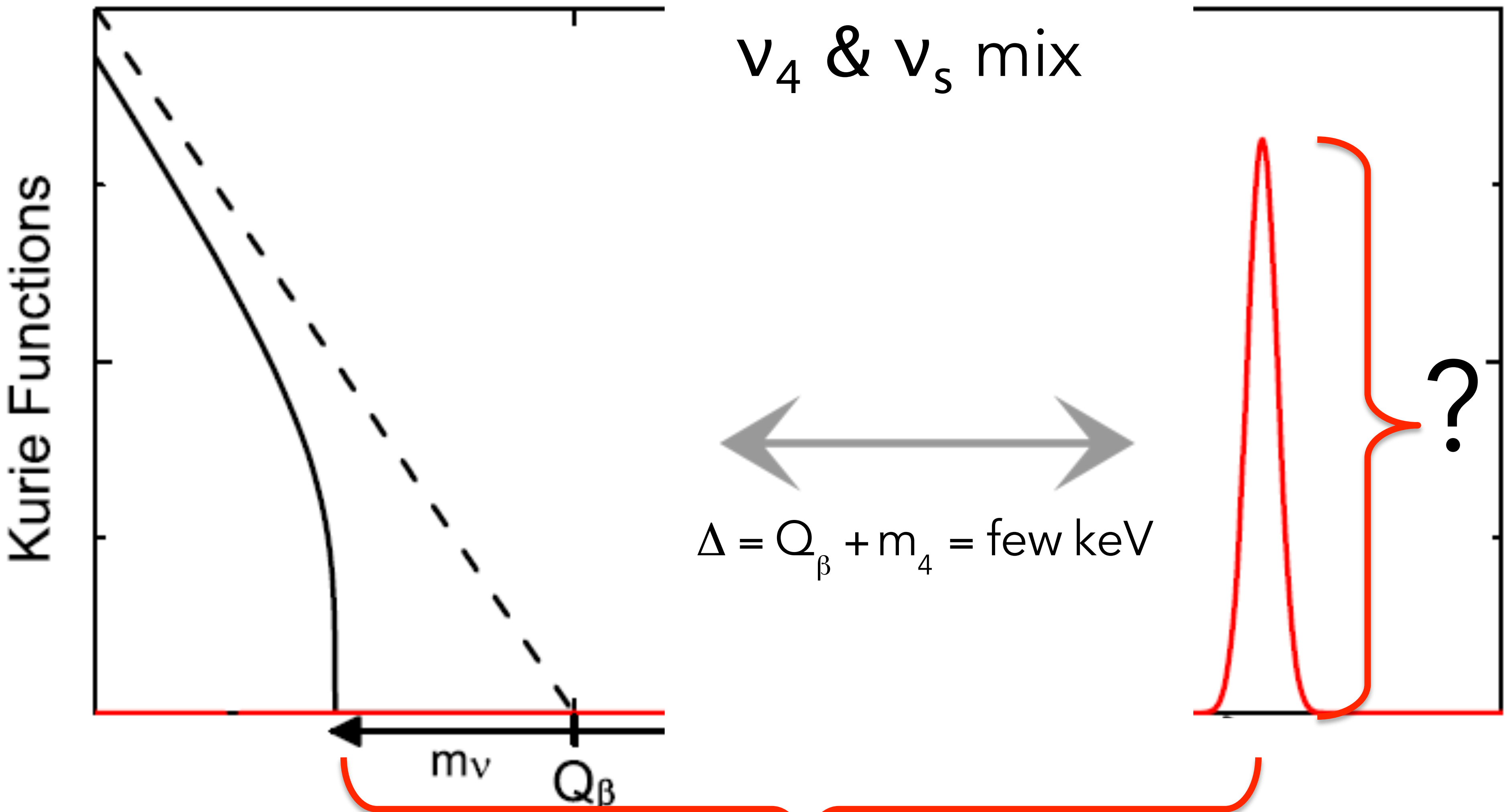


$$^3H + \nu_e \rightarrow ^3He + e^-$$

No energy threshold!
(A. Cocco, JCAP 0706 (2007) 015)

Suitable for Cosmic active/sterile ν Background detection

(Sterile) keV Neutrino Capture: Signal

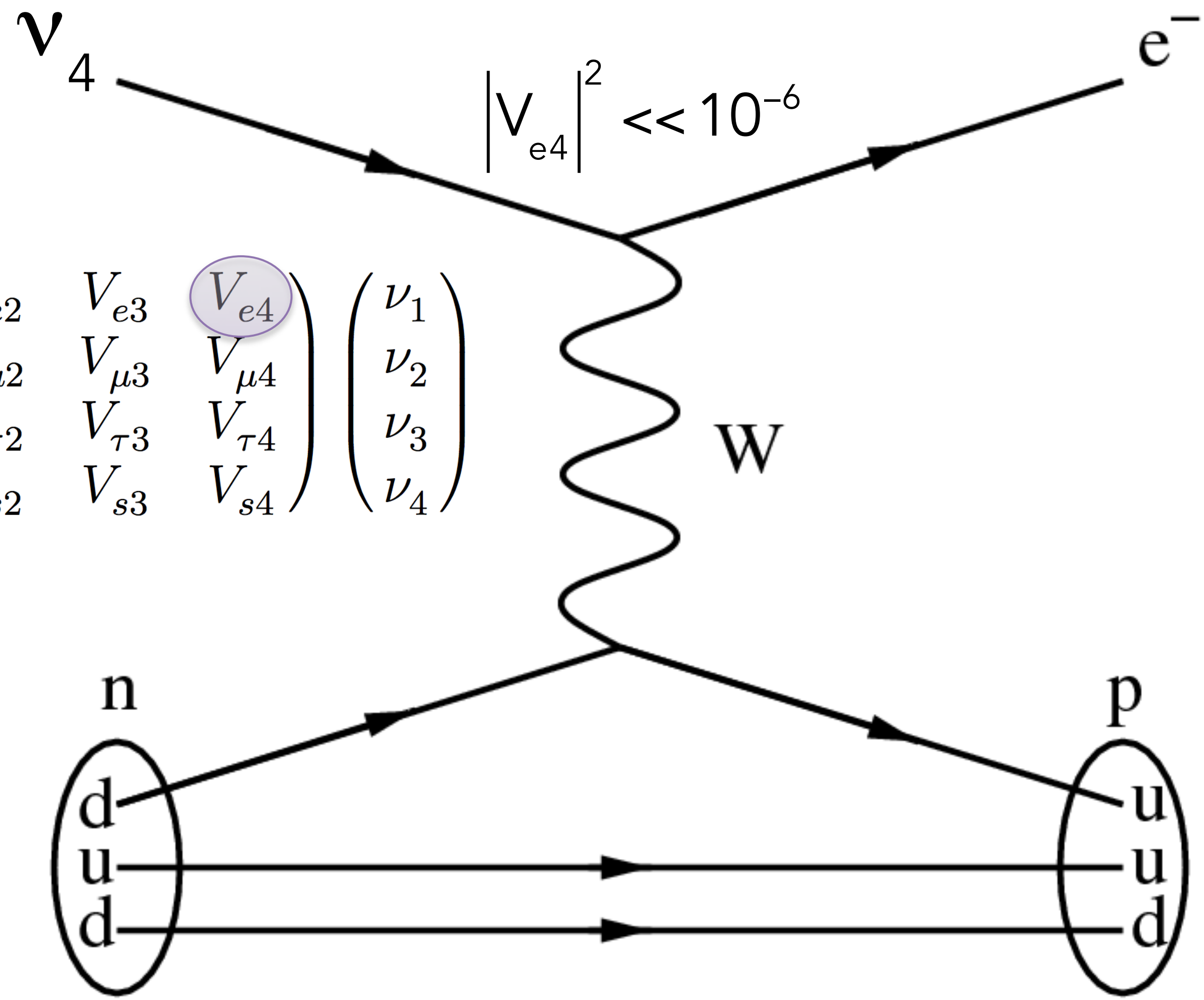


Energy resolution achievable
with standard technologies

keV Sterile Neutrino Capture: Rate

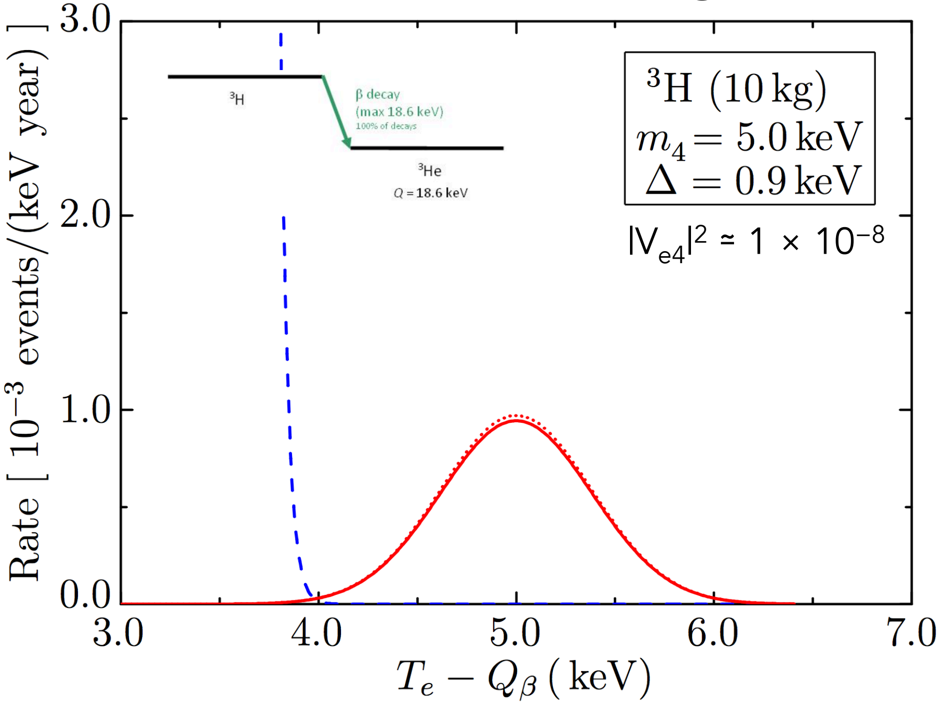
Process suppressed by the ν_e to ν_4 mixing

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \\ \nu_s \end{pmatrix} = \begin{pmatrix} V_{e1} & V_{e2} & V_{e3} & V_{e4} \\ V_{\mu 1} & V_{\mu 2} & V_{\mu 3} & V_{\mu 4} \\ V_{\tau 1} & V_{\tau 2} & V_{\tau 3} & V_{\tau 4} \\ V_{s1} & V_{s2} & V_{s3} & V_{s4} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \\ \nu_4 \end{pmatrix}$$

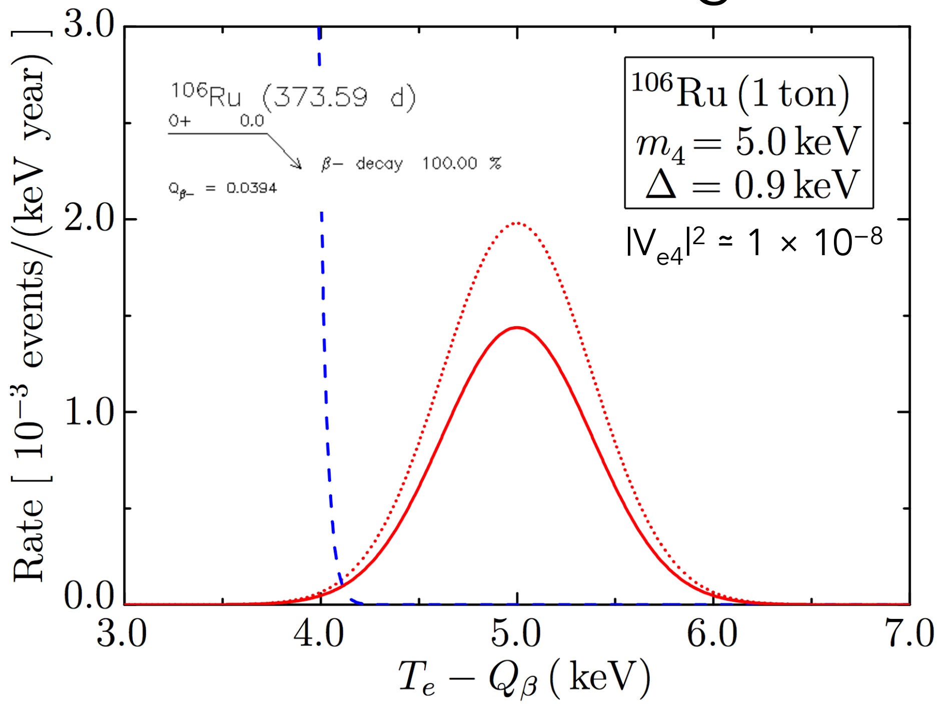


Towards $\sin^2\Theta=10^{-8}$ with $^3H/^{106}Ru$

Tritium – 10 kg

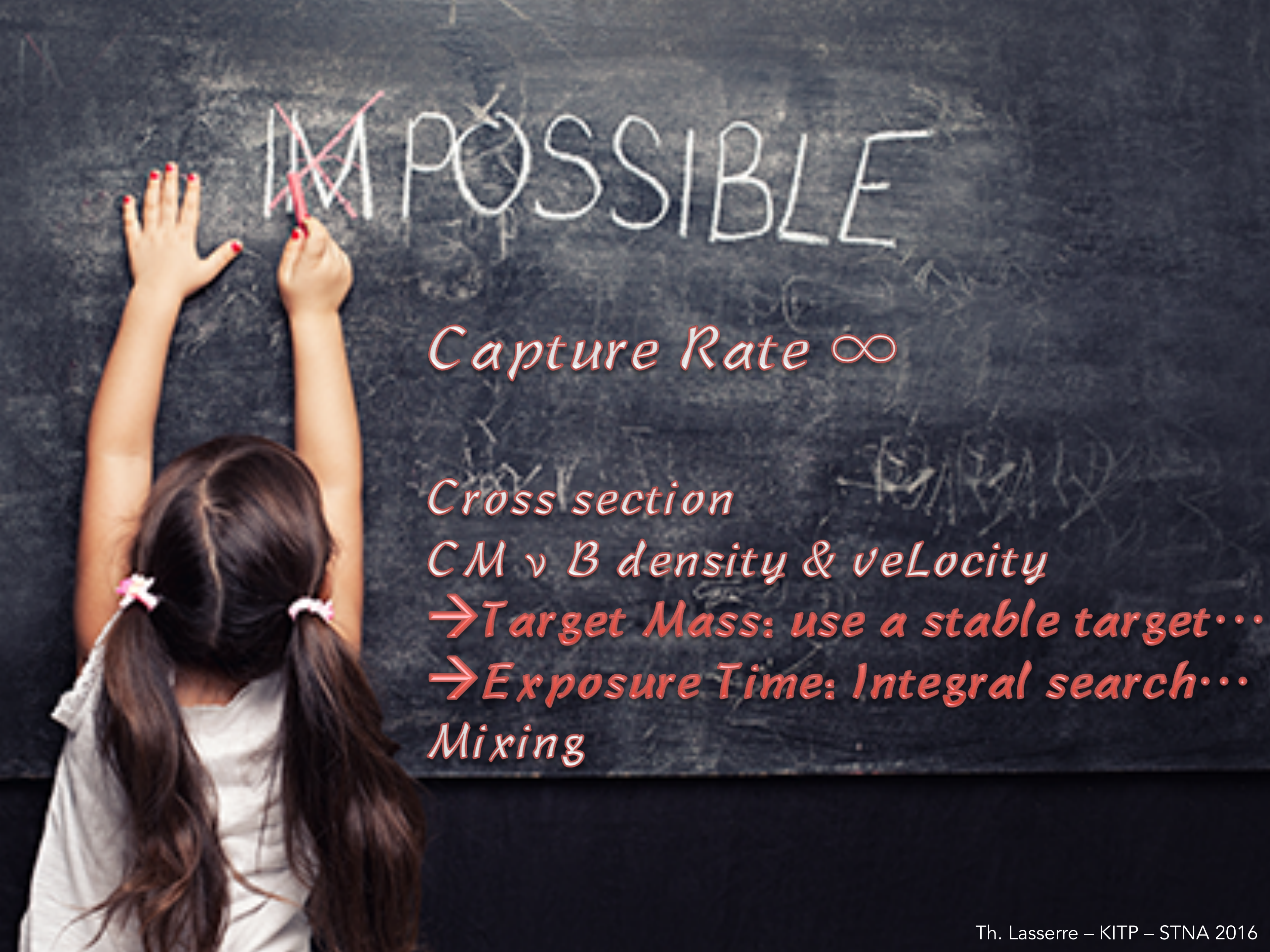


^{106}Ru – 1000 kg



- Tritium: 50 µg in KATRIN, ITER total inventory is 2 kg…
- ^{106}Ru: radioactive sources produced at the level of a few g…

→ beyond reasonable technological reach (major safety issues too)



Capture Rate ∞

Cross section

CM ν B density & veLocity

→Target Mass: use a stable target…

→Exposure Time: Integral search…

Mixing

keV ν-capture on a stable target

$$\nu +_{Z} S \rightarrow _{Z+1} D + e^{-}$$

- Amount of energy available

$$Q_{\nu_e-capture} = M_n(S) - M_n(D) - m_e + m_\nu = Q_{\beta^-}^{tab} + m_\nu$$

- CνB – capture process forbidden if $Q_{\beta^-}^{tab} < 0$
  ($m_\nu < 1$ eV and tiny kinetic energy)

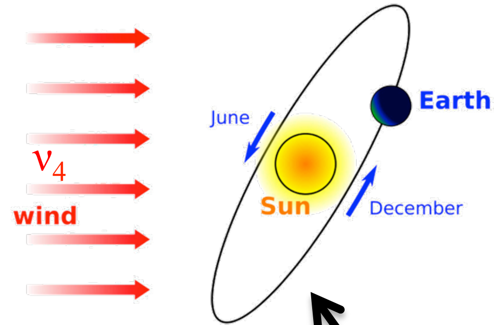
- $C\nu_{keV}B$ – allowed for massive neutrinos $-m_{\nu_4} < Q_{\beta^-}^{tab} \leq 0$
  (reaction stimulated by keV neutrino mass)

New Target Candidate: ^{163}Dy

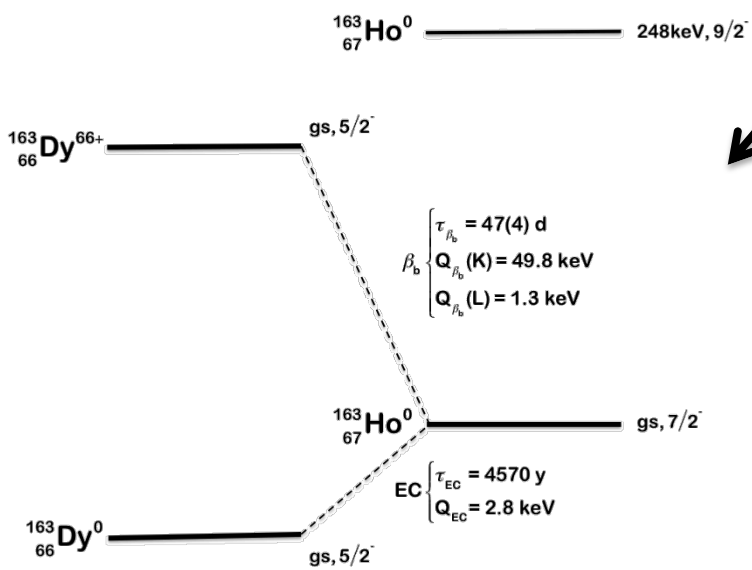
$$^{163}\mathrm{Dy}(\mathrm{gs}, I^{\pi} = 5/2^{-}) + \nu_4(m_4 > 2.83\ \mathrm{keV}, \sin^2\theta)$$
$$\rightarrow {}^{163}\mathrm{Ho}(\mathrm{gs}, I'^{\pi'} = 7/2^{-}) + e^{-}$$

^{163}Dy – 25% natural abundance

Prompt Capture Rate



$$R_{^{163}Ho} = N_{^{163}Dy} \cdot < \sigma_C v_{\nu_4} > \cdot n_{\nu_4} \cdot \sin^2\theta$$



$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \\ \nu_s \end{pmatrix} = \begin{pmatrix} V_{e1} & V_{e2} & V_{e3} & V_{e4} \\ V_{\mu1} & V_{\mu2} & V_{\mu3} & V_{\mu4} \\ V_{\tau1} & V_{\tau2} & V_{\tau3} & V_{\tau4} \\ V_{s1} & V_{s2} & V_{s3} & V_{s4} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \\ \nu_4 \end{pmatrix}$$

Prompt Capture Rate

1 ton

220km/s

$n_{\nu 4} = 3.10^5 \frac{1\text{keV}}{m_4} \text{cm}^{-3}$

$$R_{^{163}\text{Ho}} = N_{^{163}\text{Dy}} \cdot < \sigma_C v_{\nu 4} > \cdot n_{\nu 4} \cdot \sin^2 \theta$$

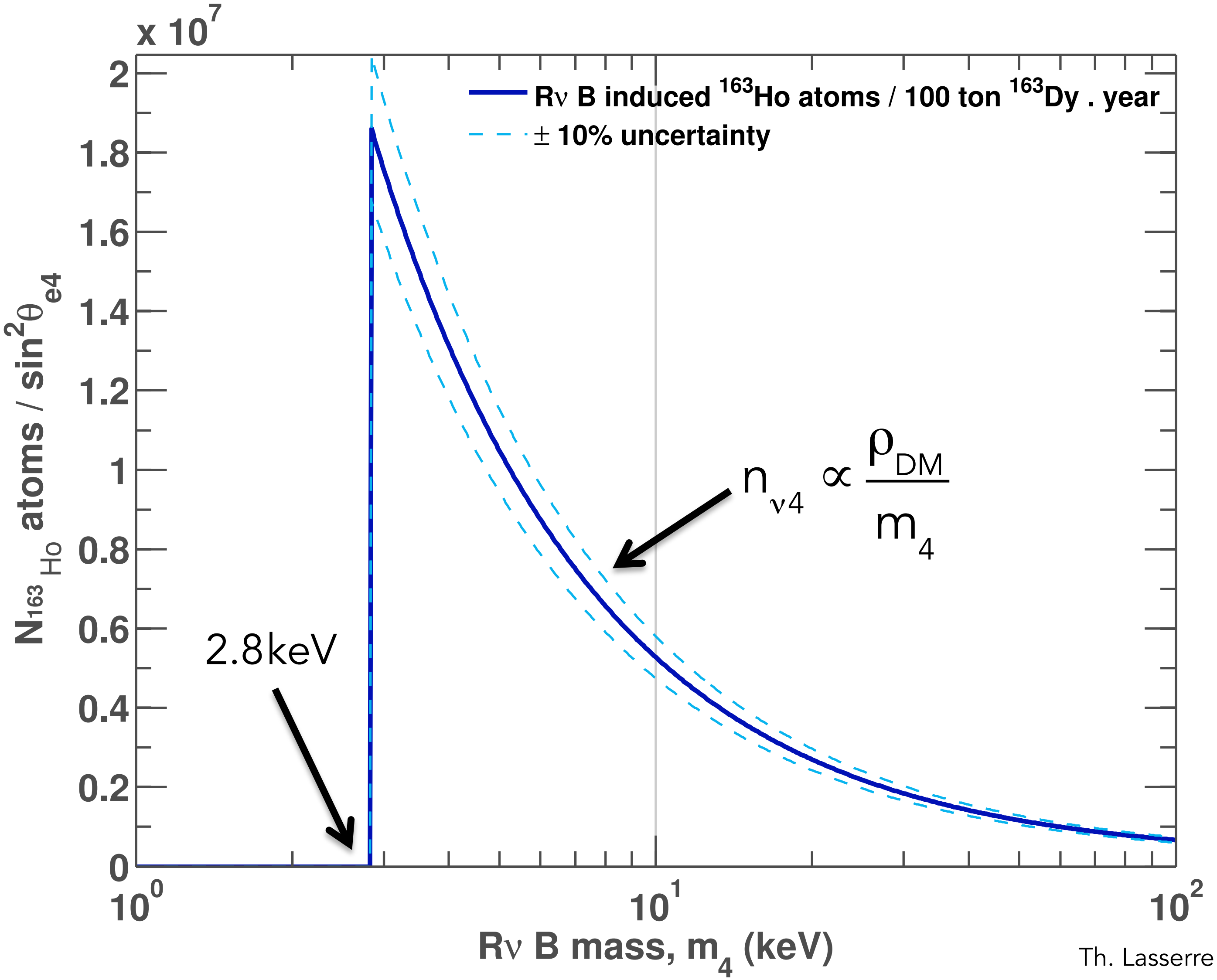
$<< 10^{-3}$

$$\sigma = G_F^2 \cdot cos^2\theta_C/\pi \cdot |\mathcal{M}_{nucl}|^2 \cdot \frac{2I^{'}+1}{2I+1}$$

$$< \frac{c}{v_{\nu 4}} \cdot E_e \cdot p_e \cdot F(E_e) > \text{ cm}^2$$

Prompt Capture Rate

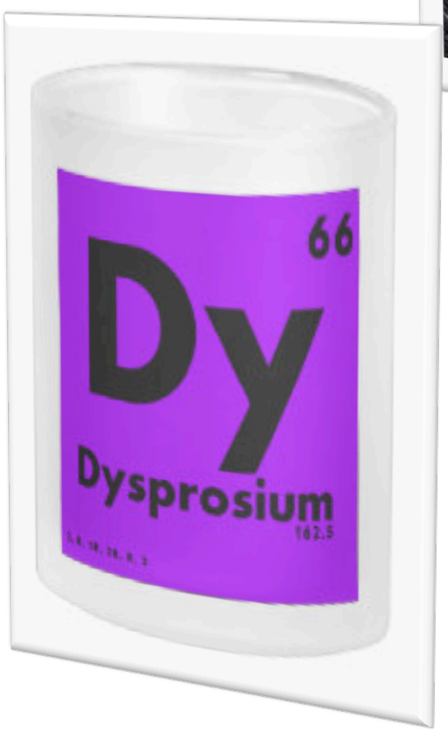
m_4=5 keV : $10^6 \times \sin^2\theta_{e4}$ ^{163}Ho atoms produced in 1 ton of ^{163}Dy exposed for 10 y



Two Measurement Approaches

- **Integral:**
  #^{163}Ho atom counting

- **Real-time:**
  $R\nu_{keV}B$
  e^--spectroscopy



Integral: #^{163}Ho counting

- Extract ^{163}Dy from ore and count ^{163}Ho atoms induced by Cν_{keV}B

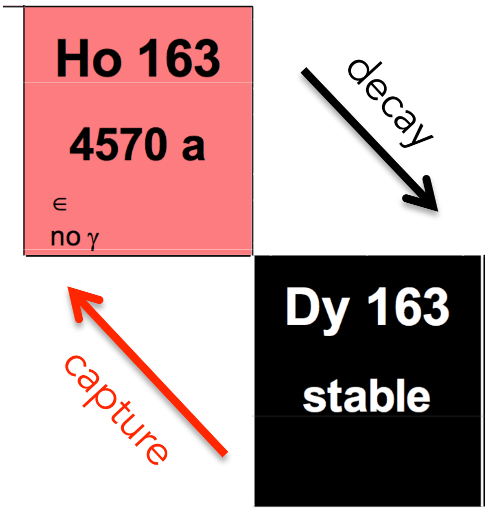
- Two main advantages:
  - ^{163}Dy can be handled in large quantity without radiation hazard
  - ^{163}Dy ore is being exposed for geological times, enhancing the number of captures (x1000)

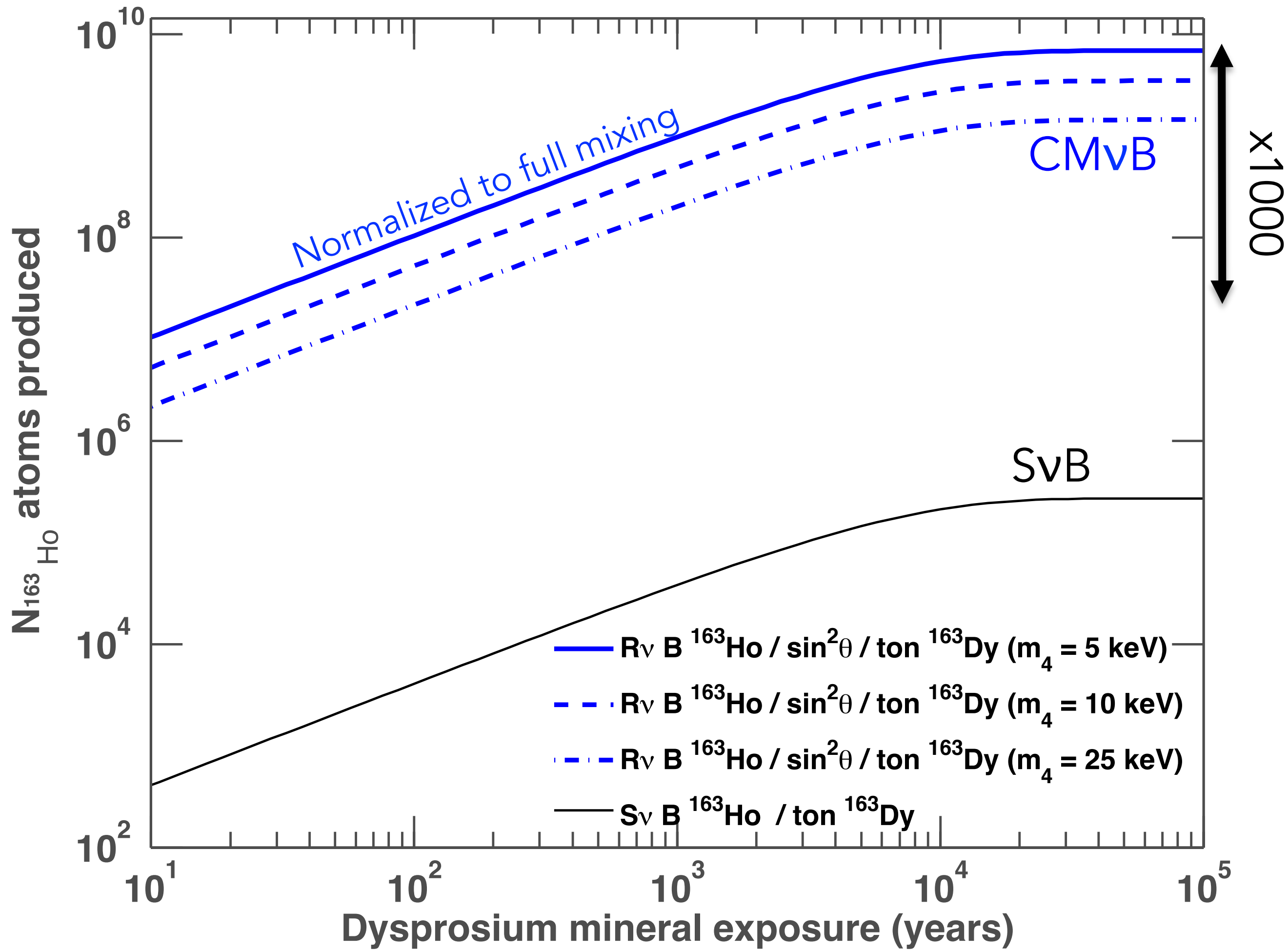
- Challenges:
  - Isolate and count low number of ^{163}Ho atoms with high efficiency
  - Background: solar neutrinos, natural cosmogenic production, …

^{163}Ho: Integral Production

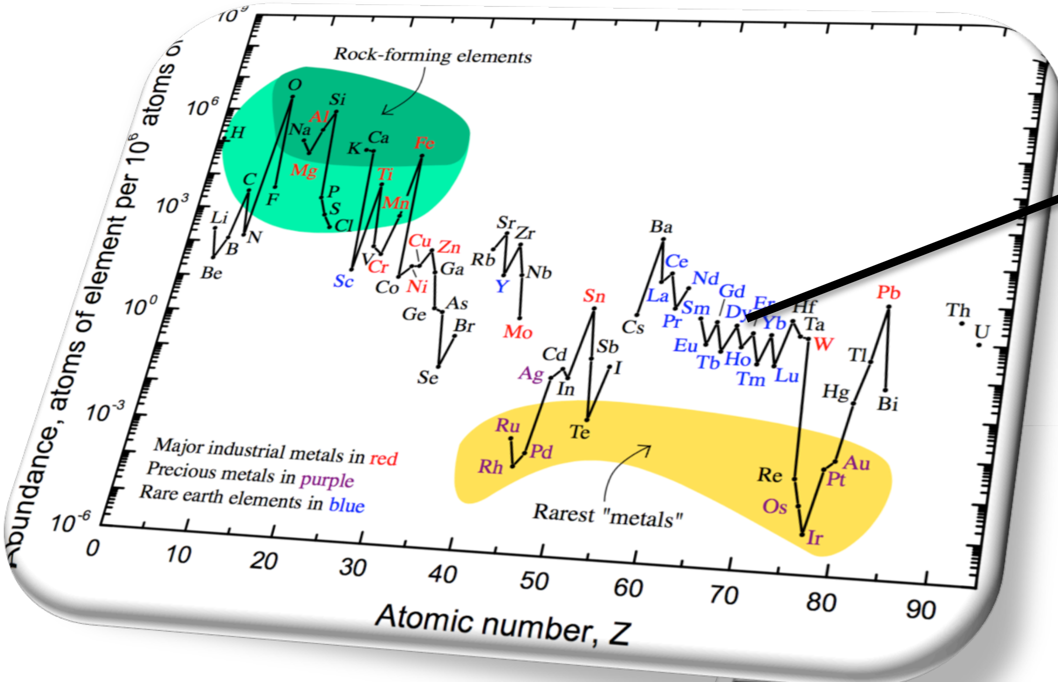
Accumulation of ν-capture on ^{163}Dy in the last 30 000 years

m_4 =5 keV: $7 \cdot 10^9 \cdot \sin^2\theta_{e4}$ ^{163}Ho in 1 ton of ^{163}Dy

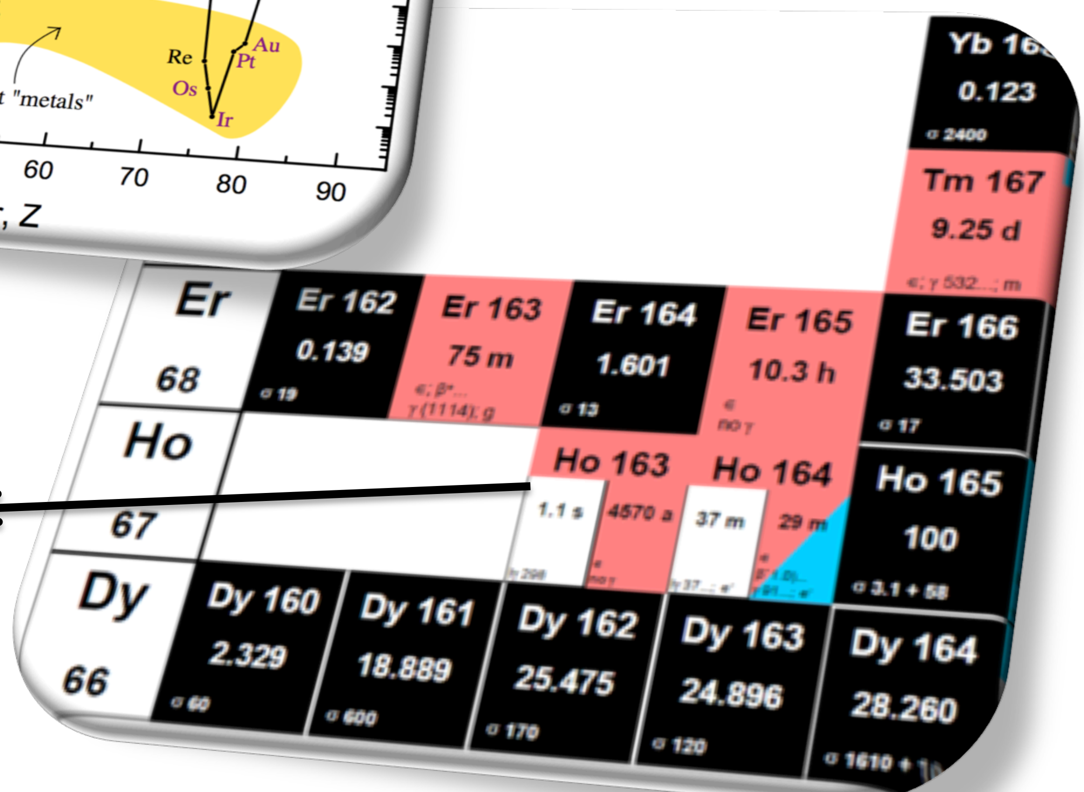




Abundance of ^{163}Dy and ^{163}Ho



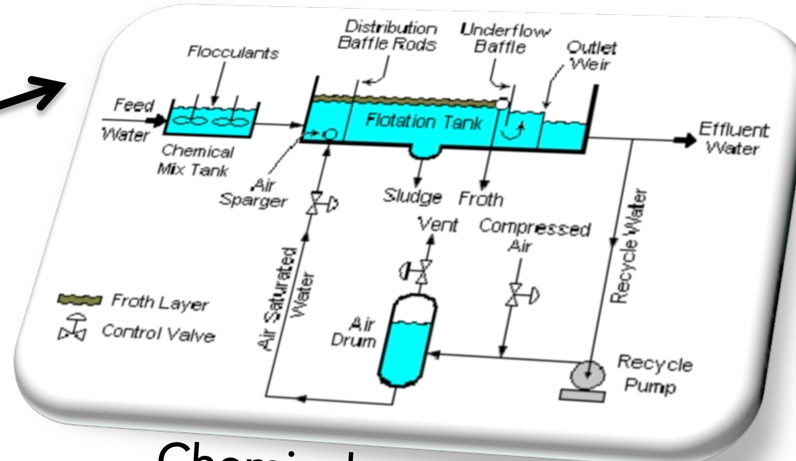
Abundant Target:
^{163}Dy = 25% of Dy



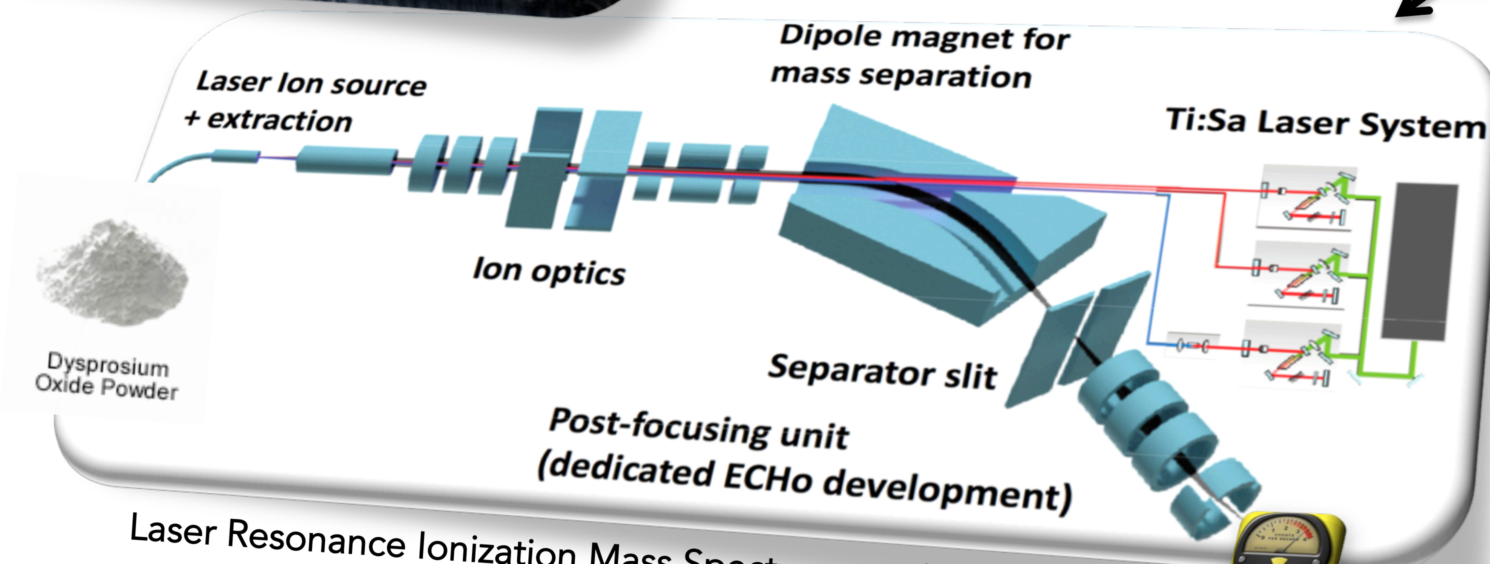
Zero natural abundance of ^{163}Ho reported in the literature…

Challenge: counting ^{163}Ho Atoms

Ore extraction (underground)



Chemical treatment

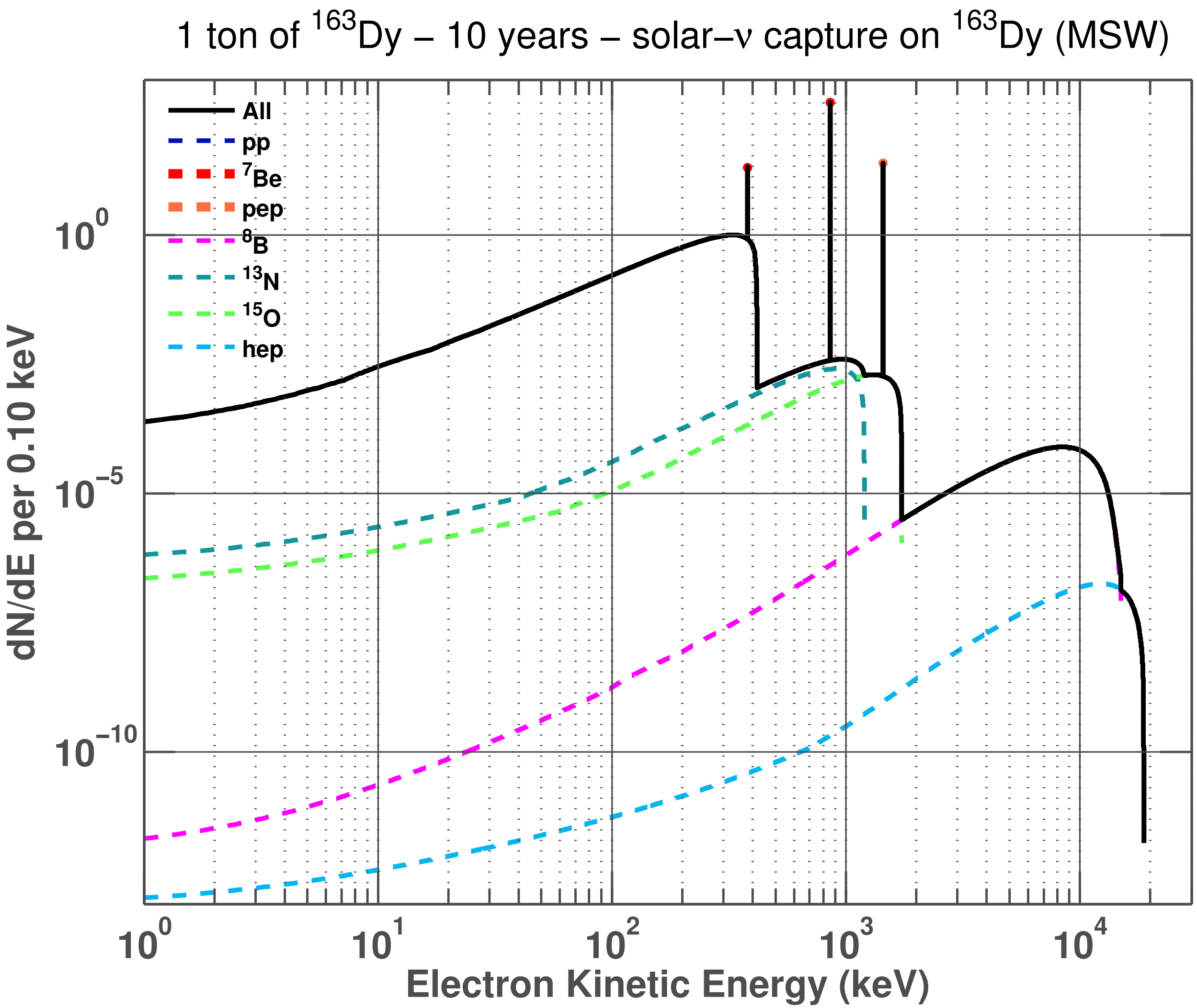


Laser Resonance Ionization Mass Spectroscopy (Risiko)

Holmiumeter-163

Solar Neutrino Background (SνB)

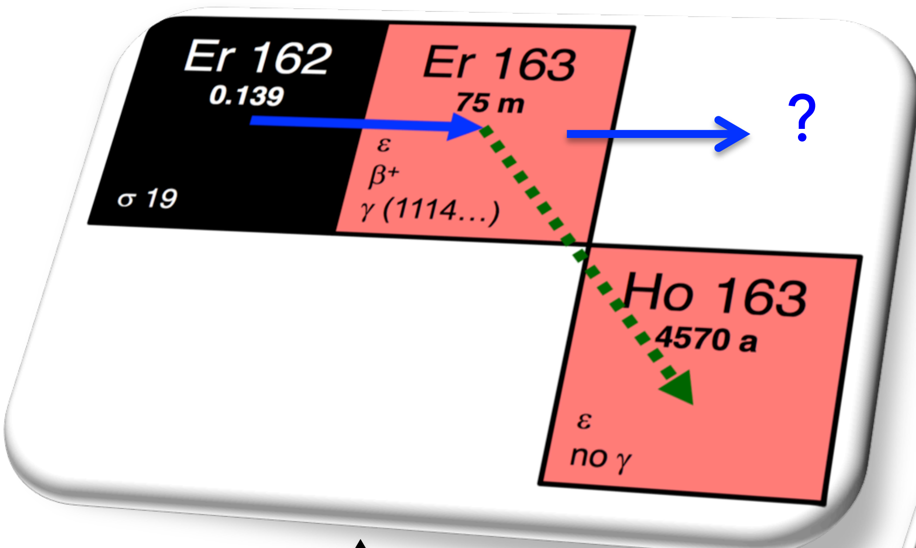
Solar ν are captured too: $3 \cdot 10^5$ ^{163}Ho atoms per ton of ^{163}Dy



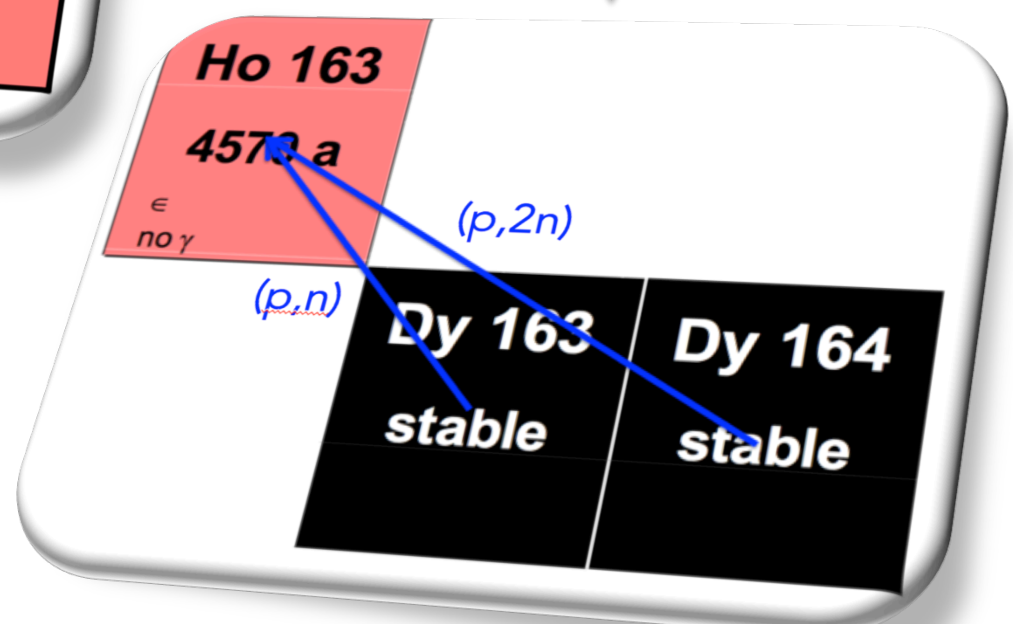
C. Bennett, Phys. Rev. C36, 1522 (1987)

Cosmogenic ^{163}Ho Production

< 1000 ^{163}Ho atoms per 1 ton ^{163}Dy – Less than SνB/GνB

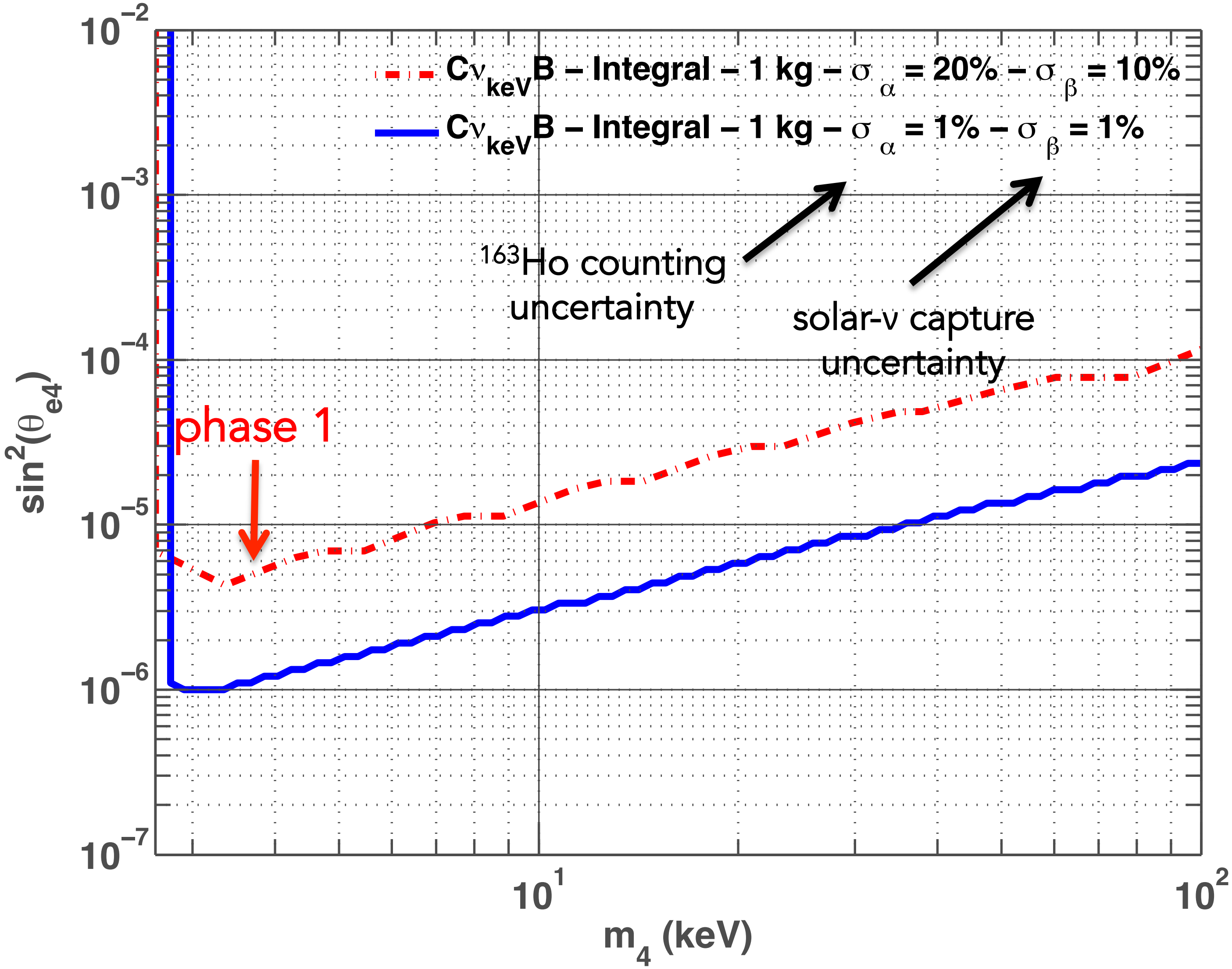


(fast, > 10 MeV)
Proton irradiation
Cosmic rays

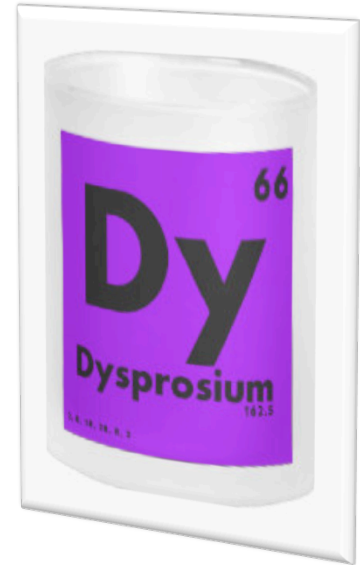


(slow, 0.025 eV)
Neutron irradiation
^{238}U fission

Integral Sensitivity (preliminary)



Real-Time Approach: Concept

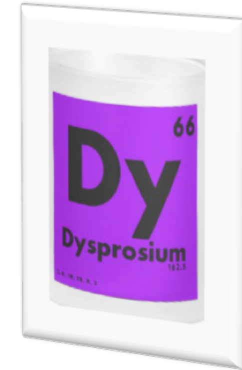


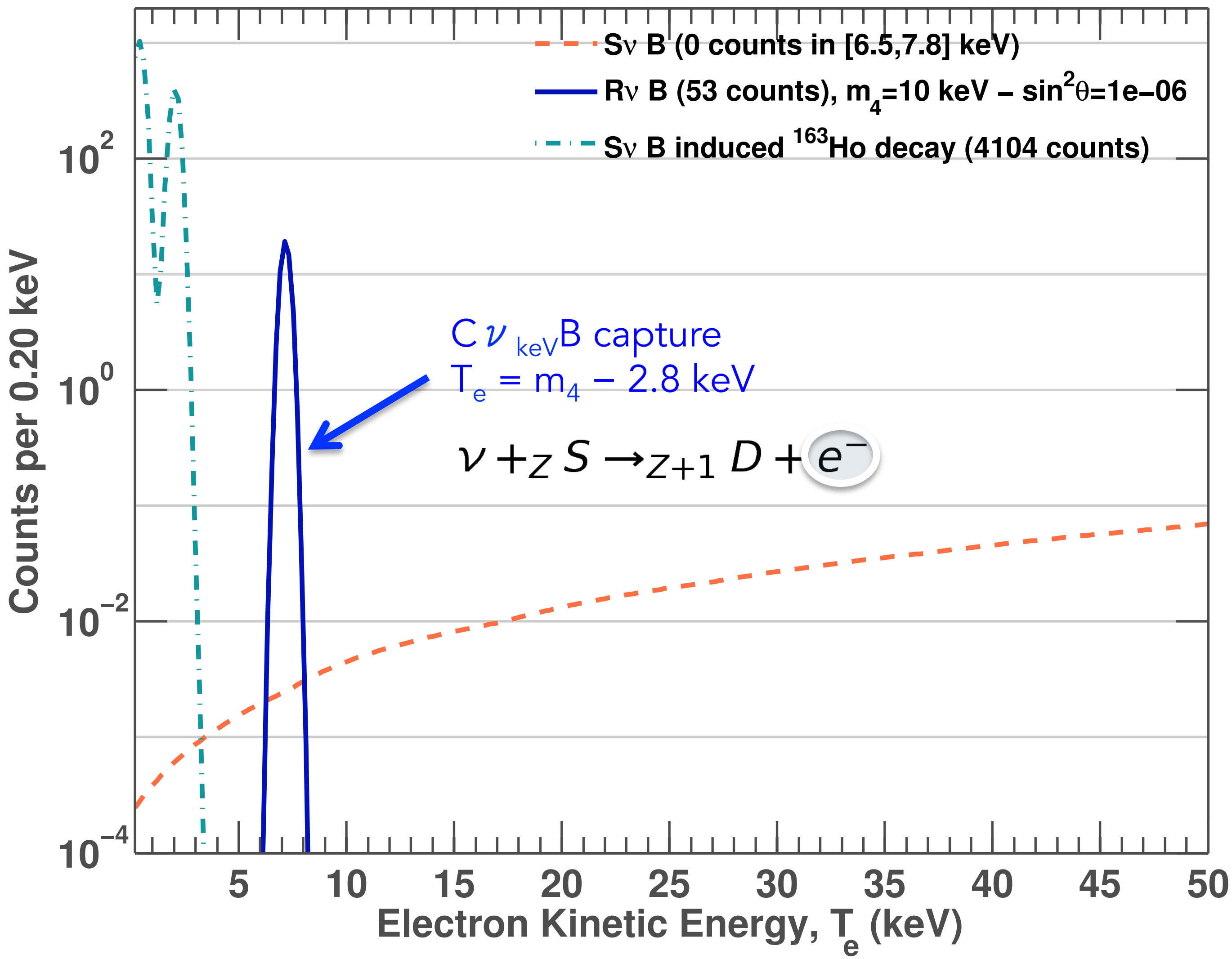
- Search for an electron peak induced by $C\nu_{keV}B$ capture on ^{163}Dy in an active Dy-based detector
  - Signature similar to $0\nu\beta\beta$ decay
  - Energy-scale similar to Dark Matter WIMP search

- Two main advantages:
  - $S\nu B$ becomes negligible in the region of interest
  - Constrain both the sterile neutrino mass and mixing

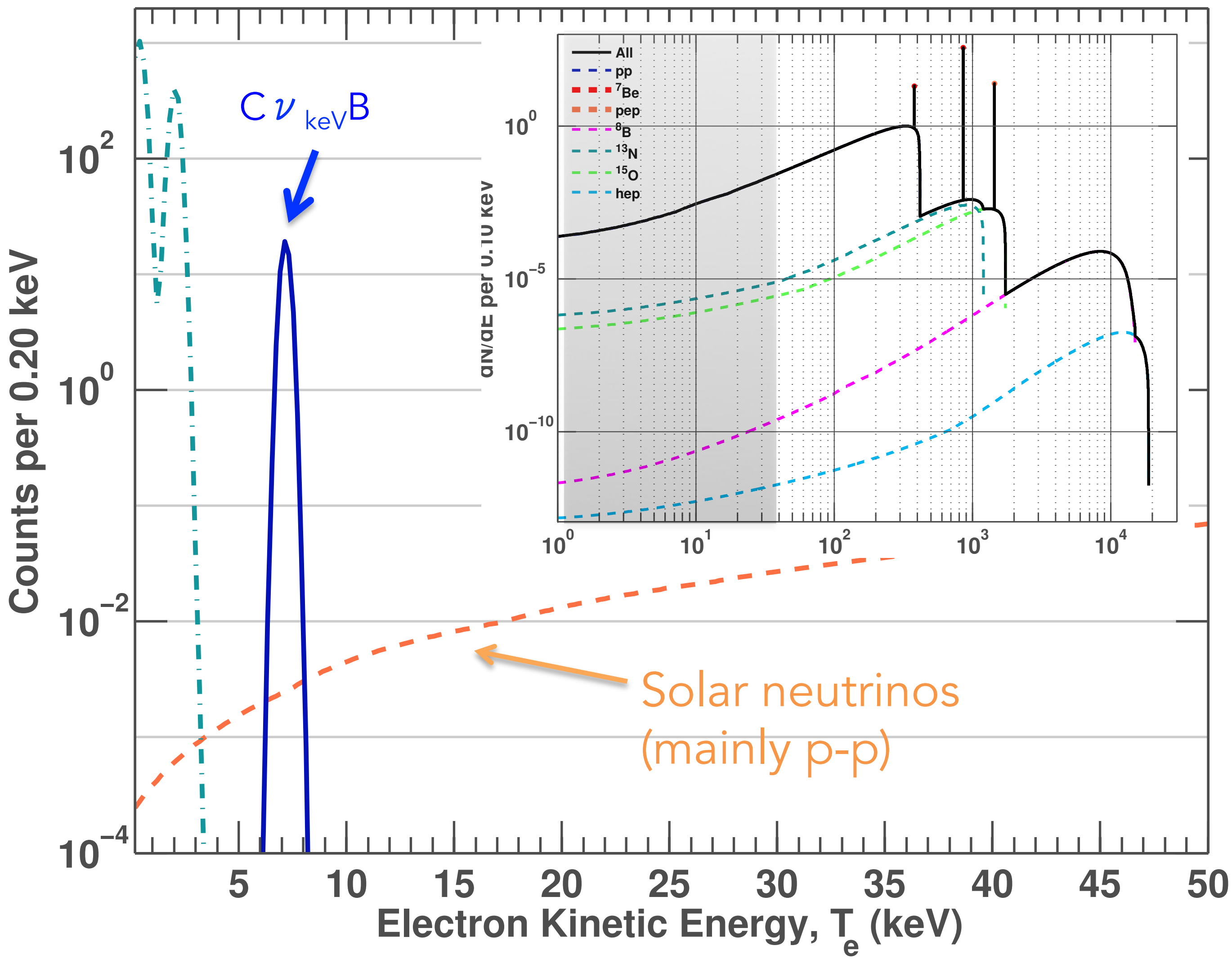
- Challenges
  - Detector design, R&D, and realization
  - Backgrounds

Signal for $\sin^2\Theta=10^{-6}$

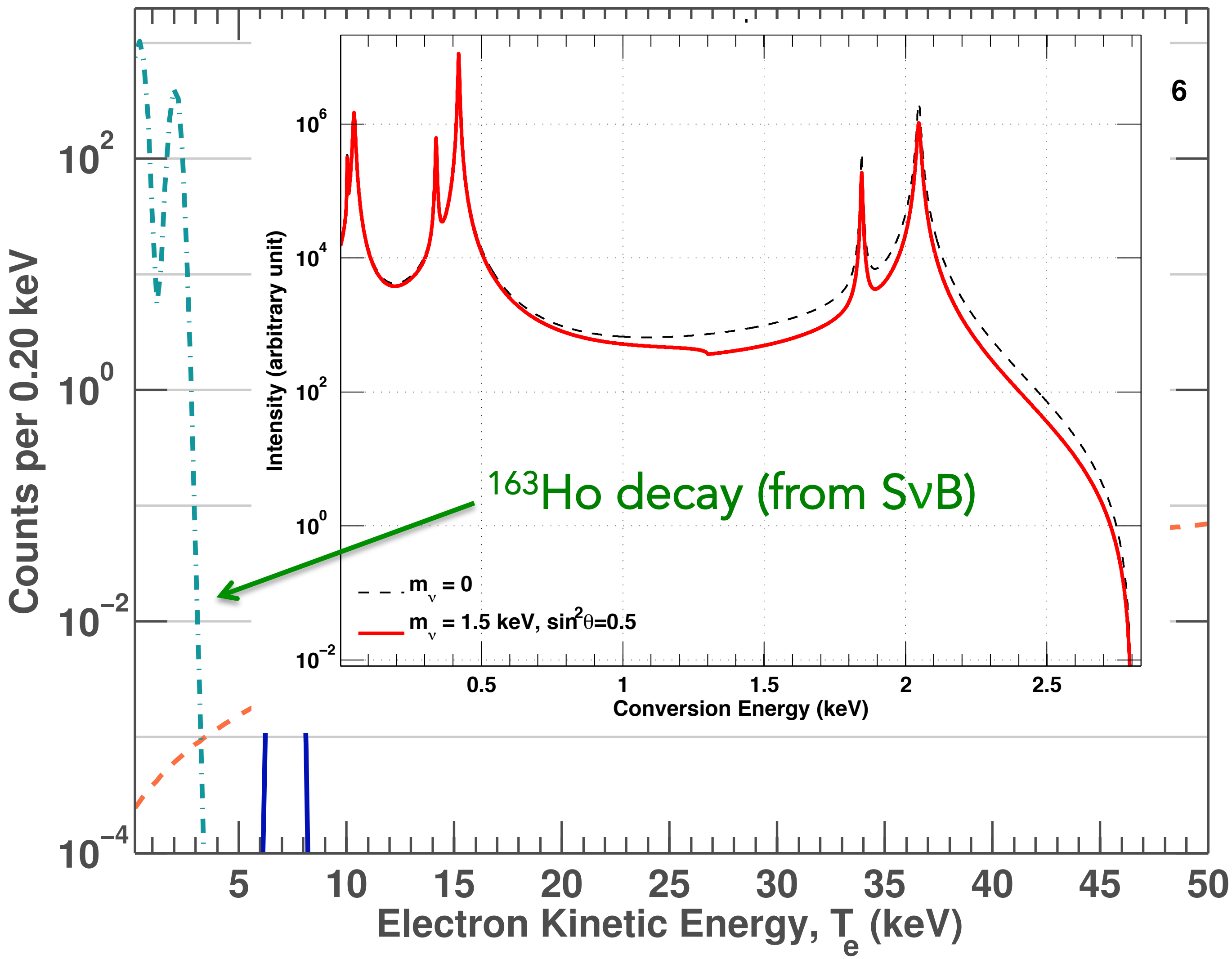




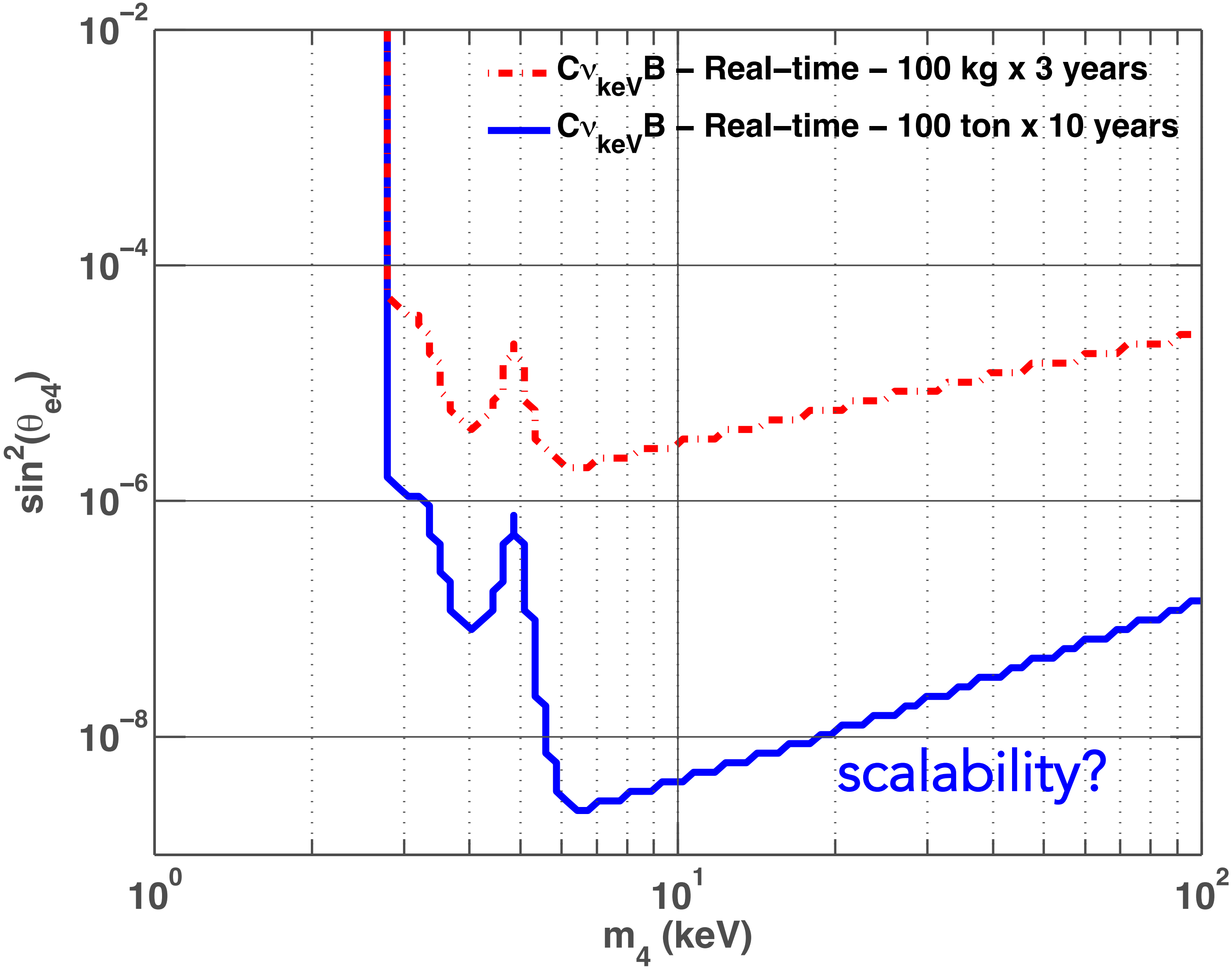
Solar Neutrino Background



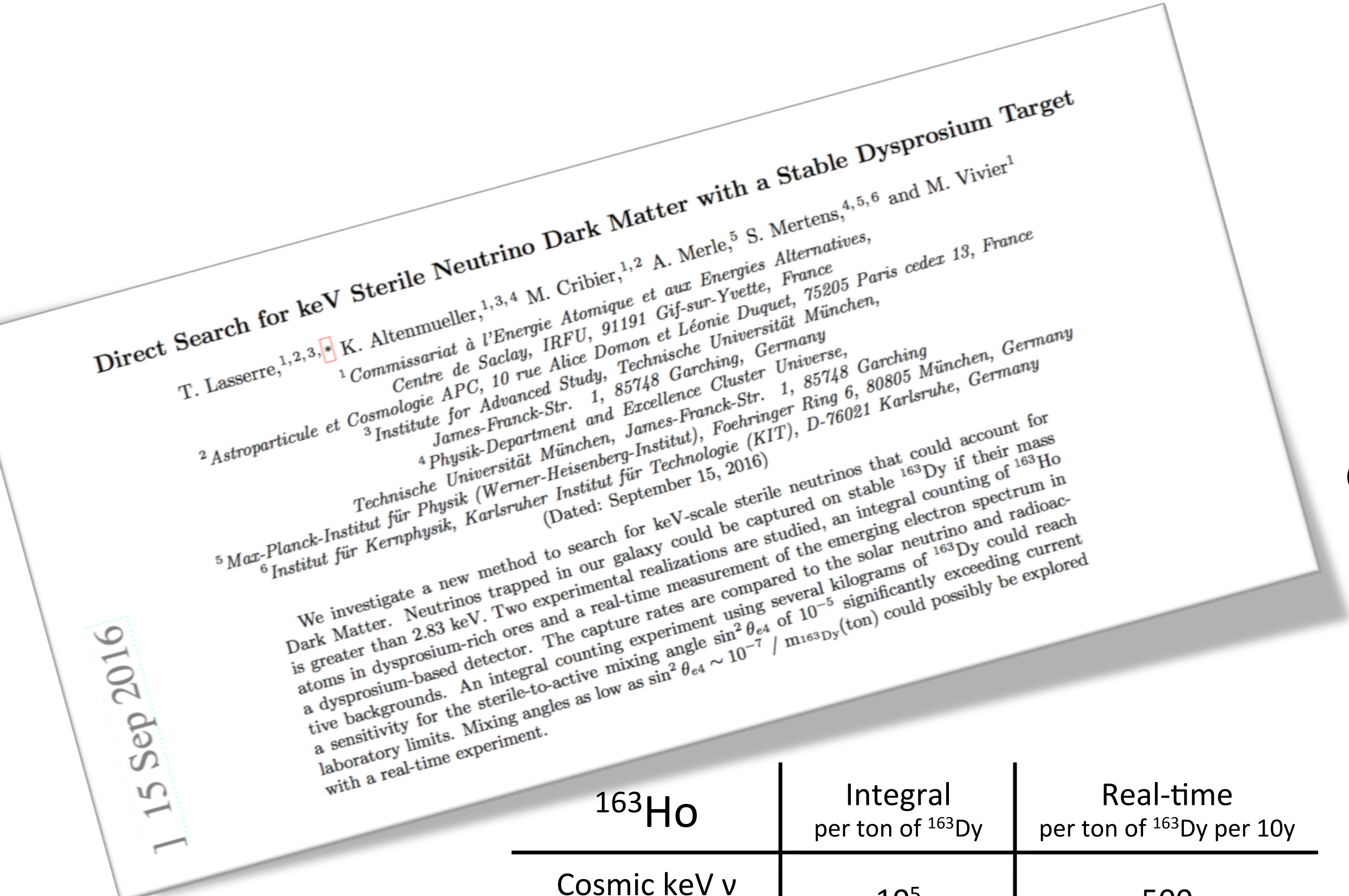
^{163}Ho Decays at low energy



Direct Sensitivity (preliminary)



keV-scale: Conclusions and Outlook



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[1] Commissariat à l'Energie Atomique et aux Energies Alternatives, Centre de Saclay, IRFU, 91191 Gif-sur-Yvette, France
[2] Astroparticule et Cosmologie APC, 10 rue Alice Domon et Léonie Duquet, 75205 Paris cedex 13, France
[3] Institute for Advanced Study, Technische Universität München, James-Franck-Str. 1, 85748 Garching, Germany
[4] Physik-Department and Excellence Cluster Universe, Technische Universität München, James-Franck-Str. 1, 85748 Garching
[5] Max-Planck-Institut für Physik (Werner-Heisenberg-Institut), Foehringer Ring 6, 80805 München, Germany
[6] Institut für Kernphysik, Karlsruher Institut für Technologie (KIT), D-76021 Karlsruhe, Germany

(Dated: September 15, 2016)

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1 15 Sep 2016

dyo$\nu_s$os

^{163}Ho	Integral per ton of ^{163}Dy	Real-time per ton of ^{163}Dy per 10y
Cosmic keV ν $\sin^2\theta=10^{-5}$	10^5	500
Solar ν	10^5	<1
Geo-ν	<1	<<1
^{163}Ho$_{nat}$	<1000	---