Closing Remarks of NuMass 2022

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NuMass 2022
Determination of the Absolute Electron (Anti)-Neutrino Mass
6–10 June 2022

Caveats

- This is a summary of some topics presented and discussed in the workshop.
- The selection of the topics is based on my limited understanding.
- I apologize to the many presenters of wonderful technical achievements that I am not able to report.

The standard 3ν framework: parameters

Mixing matrix: CKM→ PMNS (Pontecorvo-Maki-Nakagawa-Sakata)

$$U_{\alpha i} = \begin{bmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{bmatrix} \begin{bmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{bmatrix} \begin{bmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} 1 & 0 & 0 \\ 0 & e^{i\alpha/2} & 0 \\ 0 & 0 & e^{i\beta/2} \end{bmatrix}$$

2-3 rotation

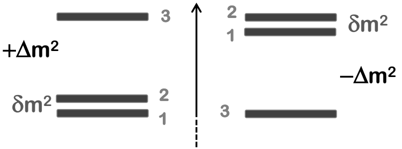
1-3 rotation
+ CPV "Dirac" phase
U(ν) → U*($\overline{\nu}$)

1-2 rotation

Extra CPV phases
[if Majorana]
not tested in oscillat.

Mass [squared] spectrum (E ~ p + m²/2E + "interaction energy")

"Normal"
Ordering
N.O.



"Inverted"
Ordering
I.O.

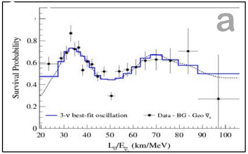
$$\delta m^2 = \Delta m^2_{21}, \quad \Delta m^2 = (\Delta m^2_{32} + \Delta m^2_{31})/2$$

\+ interaction energy in matter → ~ G_F · E · density

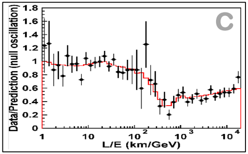
\+ absolute ν mass scale (not tested in oscillations)

Beautiful ν oscillation data have established this 3ν framework…

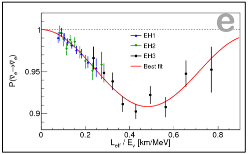
e→e (KamLAND, KL)



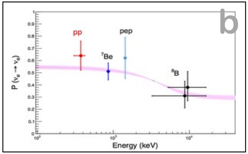
μ→μ (Atmospheric)



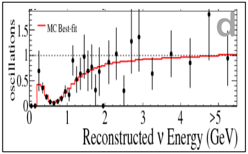
e→e (SBL Reac.)



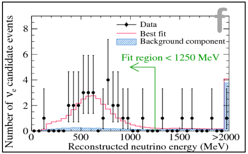
e→e (Solar)



μ→μ (LBL Accel)



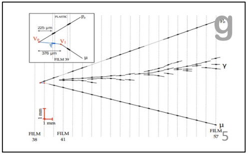
μ→e (LBL Accel)



LBL = Long baseline (few x 100 km); **SBL = short baseline** (~1 km)

(a) KamLAND reactor [plot]; (b) Borexino [plot], Homestake, Super-K, SAGE, GALLEX/GNO, SNO; (c) Super-K atmosph. [plot], DeepCore, MACRO, MINOS etc.; (d) T2K (plot), NOvA, MINOS, K2K LBL accel.; (e) Daya Bay [plot], RENO, Double Chooz SBL reactor; (f) T2K [plot], MINOS, NOvA LBL accel.; (g) OPERA [plot] LBL accel., Super-K and IC-CD atmospheric.

μ→τ (OPERA, SK, DC)



Eligio Lisi: Status of mass-mixing parameters in the three-neutrino framework

Sketchy 3ν picture (1 significant digit)

5 knowns:

δm^2	~ 8×10^{-5} eV^2
Δm^2	~ 2×10^{-3} eV^2
$\sin^2\theta_{12}$	~ 0.3
$\sin^2\theta_{23}$	~ 0.5
$\sin^2\theta_{13}$	~ 0.02

5 unknowns:

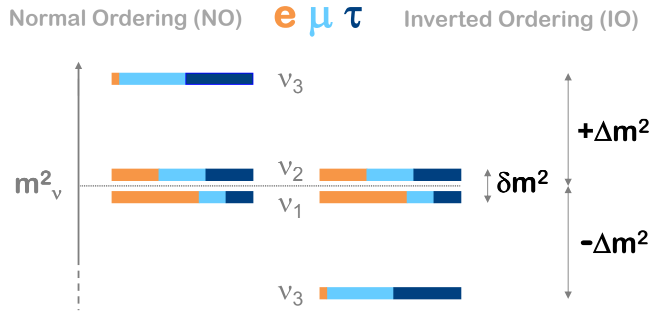
δ **CPV** Dirac phase

sign(Δm^2) → NO/IO

θ_{23} **octant** degeneracy

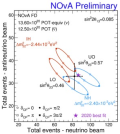
absolute mass scale

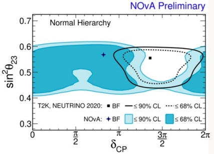
Dirac/Majorana nature

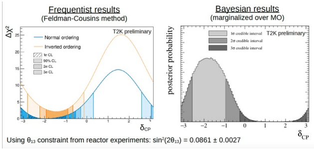


NO/IO and δ_{CP} overview

T2K and NOvA: still in tension; but no joint analysis yet. IC-DC: IO and δ not discussed yet.

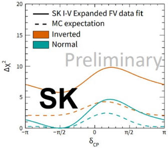


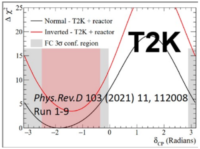




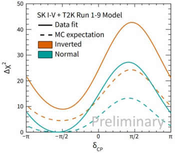
Using θ_{13} constraint from reactor experiments: $\sin^2(2\theta_{13}) = 0.0861 \pm 0.0027$

But SK atm. alone, and SK atm. +T2K → Increased preference for NO and for sinδ < 0





→ SK+T2K



Comment #1: Seperately revised cross sections have not shed light on T2K vs NOvA tension
Comment #2: … but joint T2K+NOvA analysis with common interaction model still lacking
Comment #3: SK and T2K synergy strengthens current hints on NO/IO and δ_{CP}
Comment #4: … but SK speaker admits that *"Results from both experiments exceed sensitivity"*

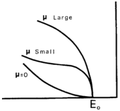
Eligio Lisi: Status of mass-mixing parameters in the three-neutrino framework

Absolute neutrino mass: main focus of NuMass talks!

Including the last 3ν unknowns & their observables (m_β , $m_{\beta\beta}$, Σ)

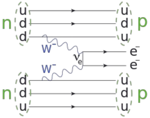
β decay, sensitive to the "effective electron neutrino mass":

$$m_\beta = \left[c_{13}^2 c_{12}^2 m_1^2 + c_{13}^2 s_{12}^2 m_2^2 + s_{13}^2 m_3^2\right]^{\frac{1}{2}}$$



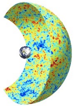
0νββ decay: only if Majorana. "Effective Majorana mass":

$$m_{\beta\beta} = \left|c_{13}^2 c_{12}^2 m_1 + c_{13}^2 s_{12}^2 m_2 e^{i\phi_2} + s_{13}^2 m_3 e^{i\phi_3}\right|$$



Cosmology: Dominantly sensitive to sum of neutrino masses:

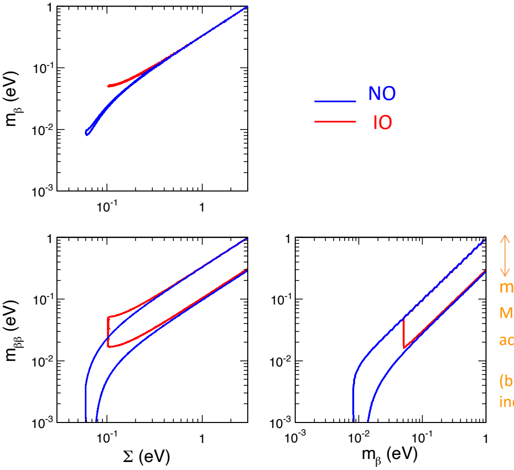
$$\Sigma = m_1 + m_2 + m_3$$



Note 1: These observables may provide handles to distinguish NO/IO.
Note 2: Majorana case gives a new source of CPV (unconstrained)
Note 2: The three observables are correlated by oscillation data→

Eligio Lisi: Status of mass-mixing parameters in the three-neutrino framework

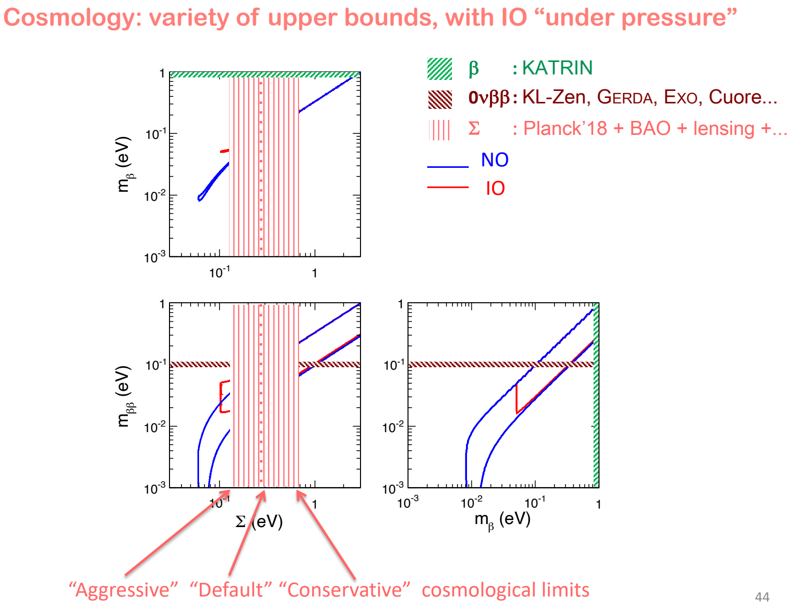
Impact of oscillations on non-oscillation parameter space (2σ)



$m_{\beta\beta}$ spread due to Majorana CP phase(s): accessible in principle

(but: no NME errors included here!)

Eligio Lisi: Status of mass-mixing parameters in the three-neutrino framework



Cosmology: variety of upper bounds, with IO “under pressure”

▨ β : KATRIN

▨ 0νββ : KL-Zen, GERDA, EXO, Cuore...

|||| Σ : Planck’18 + BAO + lensing +...

— NO

— IO

“Aggressive” “Default” “Conservative” cosmological limits

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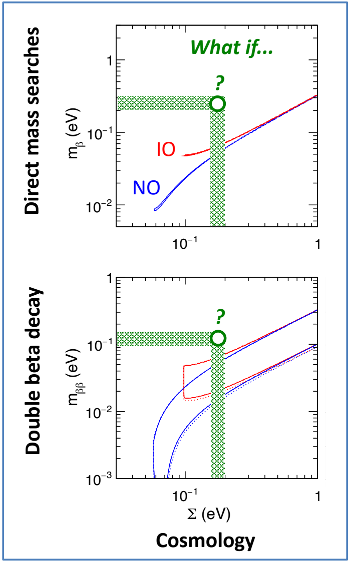
Future data might also bring us beyond 3ν and re-shape the field...



Lack of convergence among data (barring expt mistakes) **might point towards new possibilities:**

- *Cosmology beyond ΛCDM*
- *Alternative DBD mechanisms*
- *New interactions (NSI)*
- *New neutrino states ...*

→ **See talks by: de Gouvea, Tyagi**

Main contender in current ν physics:
Light sterile ν at O(1 eV) scale
but... confusing/unconfirmed hints
→ **See talk by Ternes**

In any case: generic expectations **for new possible ν mass state(s)**

Maria Archidiacono: What cosmology can tell us about neutrinos

Indirect probes of CνB

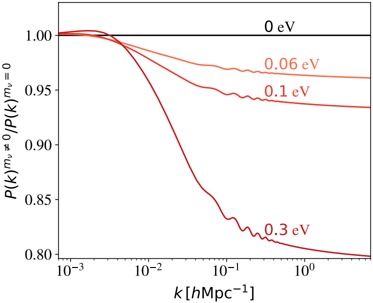
- Impact on power spectrum of matter density fluctuations

$$\delta_{\rm cdm}^{m_\nu=0} \propto a$$

$$\delta_{\rm cdm}^{m_\nu\neq0} \propto a^{1-\frac{3}{5}\frac{\Omega_\nu}{\Omega_m}}$$

Planck TT,TE,EE + low E + lensing + BAO
$\Sigma m_\nu < 0.12$ eV (95%cl)

Planck TT,TE,EE + low E + lensing + BAO
+Lyman-α
$\Sigma m_\nu < 0.09$ (95%cl) [Palanque-Delabrouille et al. 2020]

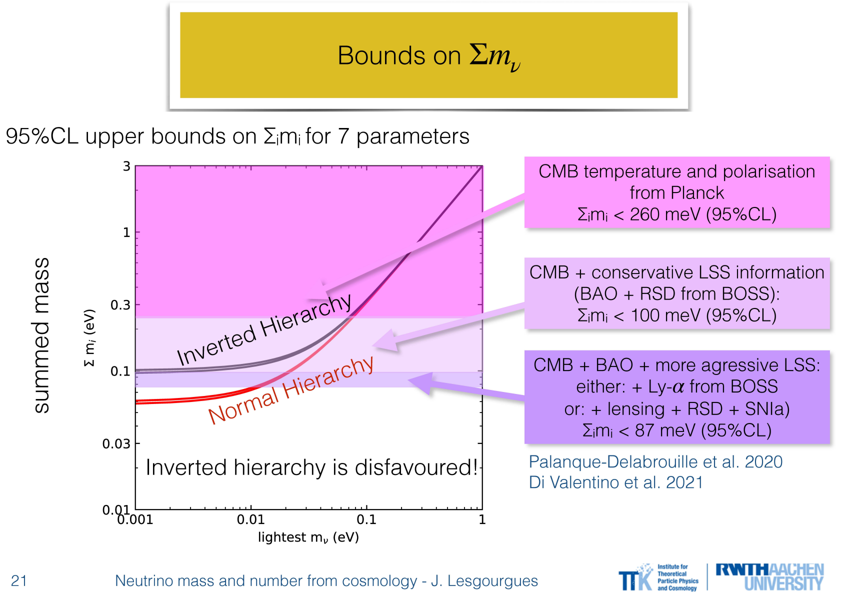


3%

'Ideally' detectable with 1% accuracy

Maria Archidiacono – University of Milan

J. Lesgourgues (Neutrino 2022): Neutrino mass and number from cosmology



Bounds on Σm_ν

95%CL upper bounds on $\Sigma_i m_i$ for 7 parameters

Inverted hierarchy is disfavoured!

CMB temperature and polarisation from Planck
$\Sigma_i m_i < 260$ meV (95%CL)

CMB + conservative LSS information (BAO + RSD from BOSS):
$\Sigma_i m_i < 100$ meV (95%CL)

CMB + BAO + more agressive LSS:
either: + Ly-α from BOSS
or: + lensing + RSD + SNIa)
$\Sigma_i m_i < 87$ meV (95%CL)

Palanque-Delabrouille et al. 2020
Di Valentino et al. 2021

21 Neutrino mass and number from cosmology - J. Lesgourgues

- The bound $\sum_i m_i < 0.09~\text{eV} \quad (95\%~\text{C.L.})$ was obtained assuming $\sum_i m_i > 0$.
- An analysis adopting the oscillation prior $\sum_i m_i \gtrsim 0.05~\text{eV}$ would return a looser bound.
- Thus, inverted hierarchy cannot be considered as disfavored at the 2σ level.

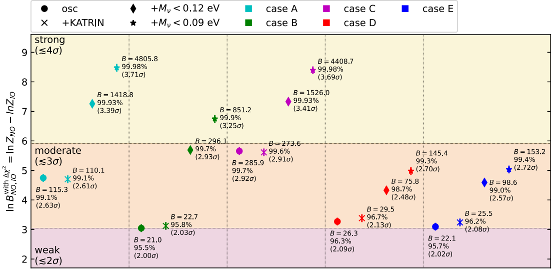
[Palanque-Delabrouille, Yeche, Schoneberg, Lesgourgues, Walther, Chabanier, Armengaud, arXiv:1911.09073]

Maria Archidiacono: What cosmology can tell us about neutrinos

The debate over the hierarchy

Degenerate hierarchy (DH) approximation: $m_1 = m_2 = m_3$

«Moderate evidence, mostly driven by neutrino oscillation data» Gariazzo et al. 2022 (see also Hergt et al. 2021)



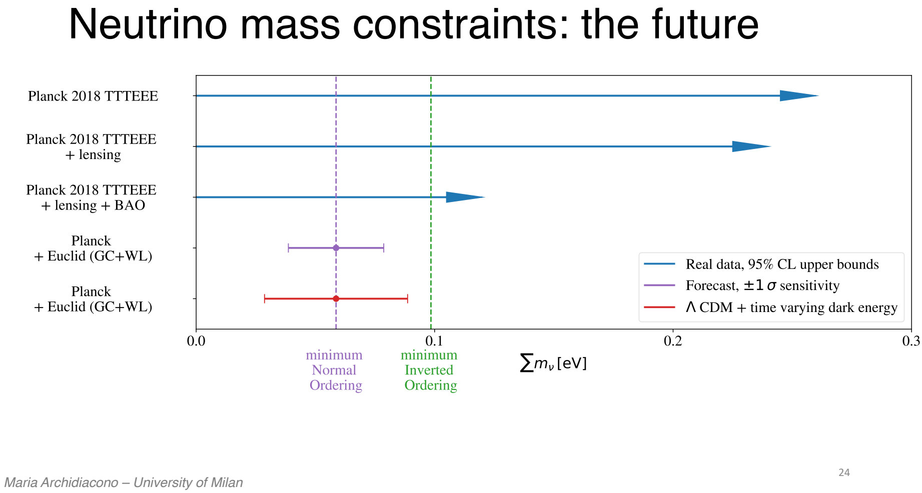
case A is based on Jimenez et al.: a Gaussian prior on the logarithm of the three neutrino mass eigenstates

"The significance of the preference in favor of NO changes significantly when we consider different parameterizations."

For a different approach, Long et al. 2018, and Heavens & Sellentin 2018

Maria Archidiacono – University of Milan

Maria Archidiacono: What cosmology can tell us about neutrinos



Neutrino mass constraints: the future

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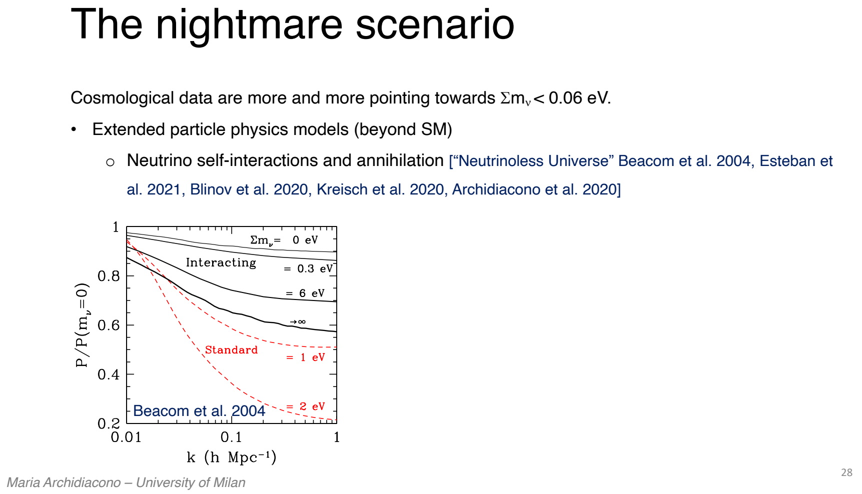
Maria Archidiacono: What cosmology can tell us about neutrinos



The nightmare scenario

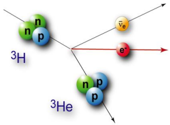
Cosmological data are more and more pointing towards $\Sigma m_\nu < 0.06$ eV.

- Extended particle physics models (beyond SM)
  - Neutrino self-interactions and annihilation ["Neutrinoless Universe" Beacom et al. 2004, Esteban et al. 2021, Blinov et al. 2020, Kreisch et al. 2020, Archidiacono et al. 2020]

The interesting (exciting) scenario!

Direct Neutrino Mass Measurement with Beta Decay

Use Kinematics only, look at the end-point shape



$$\frac{dN}{dE_e} = C \cdot F(E,Z) \cdot P_e \cdot (E_e + m_e c^2) \cdot (E_o - E_e)\sqrt{(E_o - E_e)^2 - m_{\nu_e}^{\ 2}}$$

(some details/corrections not included)

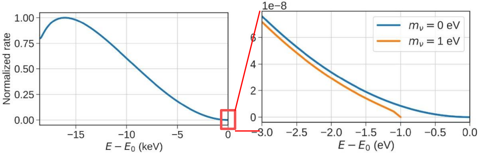
$$\sum_i |U_{ei}|^2 \cdot m_i^{\ 2} \sim m_i^{\ 2}$$

in degenerated region

$$^3\mathrm{H} \rightarrow {}^3\mathrm{He} + \mathrm{e}^- + \bar{\nu}_\mathrm{e}$$

Tritium as beta-source

- low end-point (18.6 keV)
  - → relatively large deformation
  - → electro-statically reachable
- short life (12.3 y):
  - → small source amount
  - → less scattering in source
- super-allowed transition
  - → matrix element reliably calculable
- simplest molecular:
  - → molecular states calculable



only 2×10^{-13} of all beta in last 1 eV

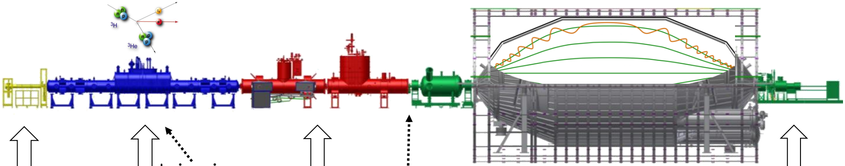
Needs:

- strong stable source
- high precision spectroscopy

KATRIN Experiment (Design)

KArlsruhe TRItium Neutrino Experiment

- located at Karlsruhe Institute of Technology, Karlsruhe, Germany
- design sensitivity: $m(\nu_e) < 0.2$ eV (90%CL, 3 years)



Calibration e-Gun

Injection
1.8 mbar l/s

Tritium Retention
(electrons guided by B)

10^{-14} mbar l/s

10^{-11} mbar

Electron Counter
(~10 mHz)

100 GBq Gaseous Tritium Source
(largest ever tritium throughput, as of 2018)

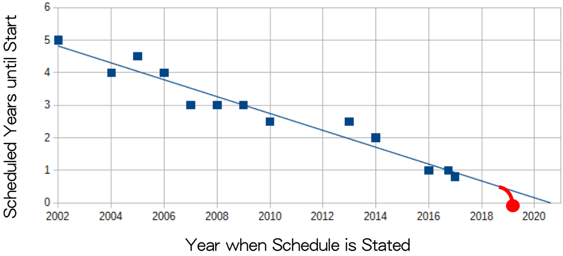
0.9 eV Resolution MAC-E Filter
(largest ever UHV vessel, as of 2013)

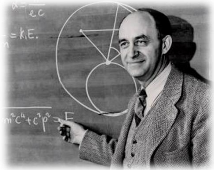
All numbers are from KATRIN Design Report (2004)

Sanshiro Enomoto: KATRIN neutrino mass analysis and results

KATRIN Construction History

- First Collaboration Meeting in 2001
- Design Report in 2004, planned to start in 4 years
- Strat data taking in 2019





Versuch einer Theorie der β-Strahlen. I[1]).

Von **E. Fermi** in Rom.

Mit 3 Abbildungen. (Eingegangen am 16. Januar 1934.)

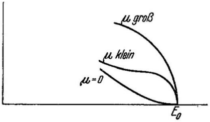


Fig. 1.

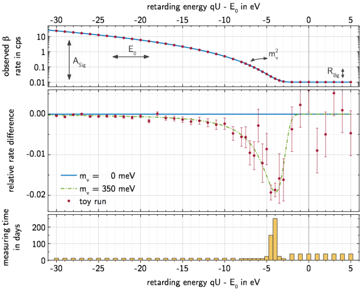
KATRIN has demonstrated end-points are deformed!!

and that there can be one correct red point
in a plot with many wrong blue points

Neutrino Mass Analysis and Results

Spectrum Model and Measurement Strategy

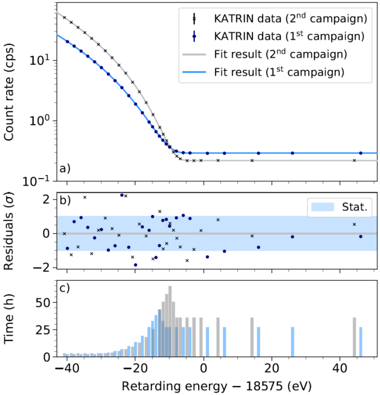
(MC made before measurements)



$$\underbrace{N(qU)}_{\text{retarding energy}} = \underset{\text{activity}}{A} \cdot \underbrace{\int_{qU}^{E_0} \frac{d\Gamma}{dE}(E; m_\nu^2, E_0)}_{\text{beta decay spectrum}} \cdot \underbrace{f(qU,E)}_{\text{apparatus response}}\, dE + \underset{\text{backgrounds}}{B}$$

plus a number of nuisance parameters

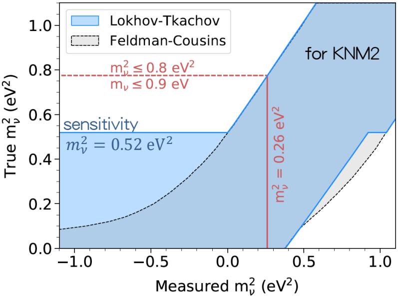
Measured Spectra and Fitting Results



$$\boxed{m_\nu^2 = 0.26 \pm 0.34\ \text{eV}^2}$$

Sanshiro Enomoto: KATRIN neutrino mass analysis and results

Mass Limit Setting



Feldman-Cousins (FC)

- De facto standard
- Provided only for supplementary

Lokhov-Tkachov (LT)

- No “tighter limit” from negative m^2
- For negative m^2, stop at the sensitivity
- Coverage is still correct (no flip-flopping)

A. Lokhov is in this meeting!

KNM 1

$$m_\nu^2 = -1.0^{+0.9}_{-1.1}\ \text{eV}^2$$

$m_\nu < 1.1$ eV (LT 90%CL)

($m_\nu < 0.8$ eV (FC 90%CL))

KNM 2

$$m_\nu^2 = 0.26 \pm 0.34\ \text{eV}^2$$

$m_\nu < 0.9$ eV (90%CL)

KNM 1 & 2 combined

$$m_\nu^2 = 0.1 \pm 0.3\ \text{eV}^2$$

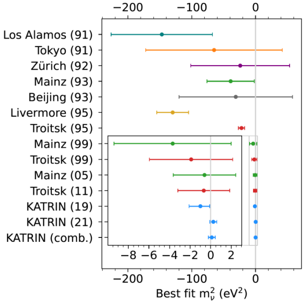
$m_\nu < 0.8$ eV (90%CL)

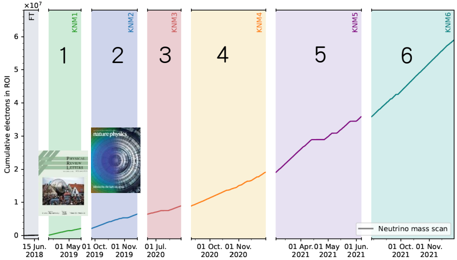
Independent Consistency Check: Beta-decay Q-value

KATRIN:	18575.20 ± 0.60 eV
Δm (^{3}He - ^{3}H):	18575.72 ± 0.07 eV (this information is not used for spectrum fitting)

Conclusions and Outlook

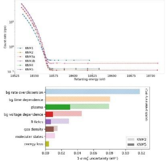
- First sub-eV result: $m_\nu^2 = 0.1 \pm 0.3\ \text{eV}^2,\ m_\nu < 0.8$ eV (90%CL)
- Final design sensitivity 0.2 eV (90%CL) in 5 years





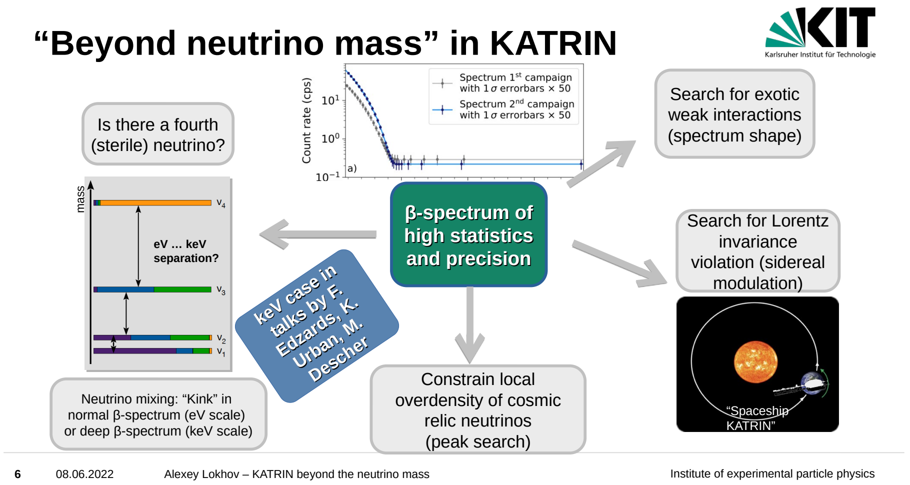
Run 7 is on-going

- Much more data already in hand, being analyzed (still blinded)
- After KNM 2: BG have been significantly reduced
- After KNM 2: Systematics have been significantly reduced



Preliminary estimated sensitivity up to KNM 5: <0.5 eV (90%CL)
Unblinding of KNM 3-5 is planned in this summer

Alexey Lokhov: KATRIN beyond the neutrino mass measurements



“Beyond neutrino mass” in KATRIN

Is there a fourth (sterile) neutrino?

β-spectrum of high statistics and precision

Search for exotic weak interactions (spectrum shape)

Search for Lorentz invariance violation (sidereal modulation)

Constrain local overdensity of cosmic relic neutrinos (peak search)

Neutrino mixing: “Kink” in normal β-spectrum (eV scale) or deep β-spectrum (keV scale)

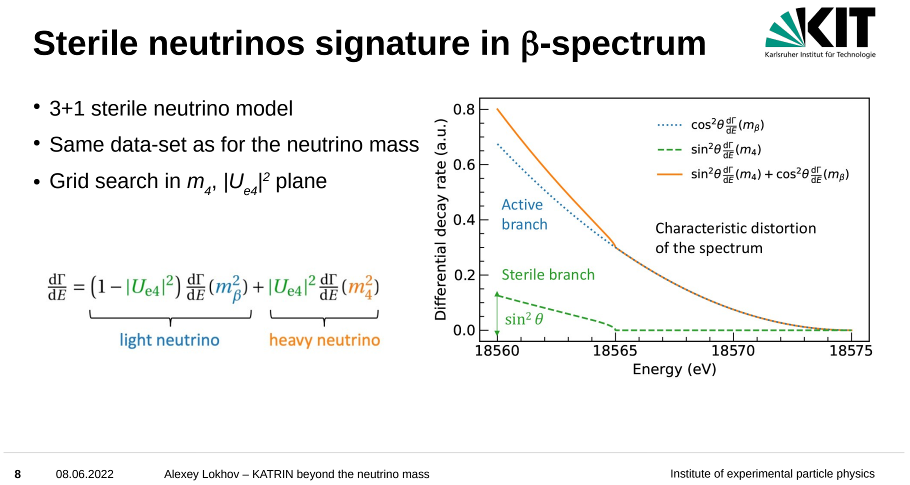
keV case in talks by F. Edzards, K. Urban, M. Descher

Christoph Ternes: Current status of 3+1 neutrino mixing

Conclusions

- RAA mostly resolved for some flux models
- The Gallium anomaly is in strong tension with the analysis of reactor rate data
- No indication from ratio analyses, Neutrino-4 result doubtful
- First MicroBooNE data do not confirm the MiniBooNE excess (but can not rule it out either)
- No (significant) signal in atmospheric or accelerator experiments
- A global 3+1 fit is statistically not acceptable
- More data is needed to clarify open issues
- Anomalous AND also Null results have to be checked

Alexey Lokhov: KATRIN beyond the neutrino mass measurements



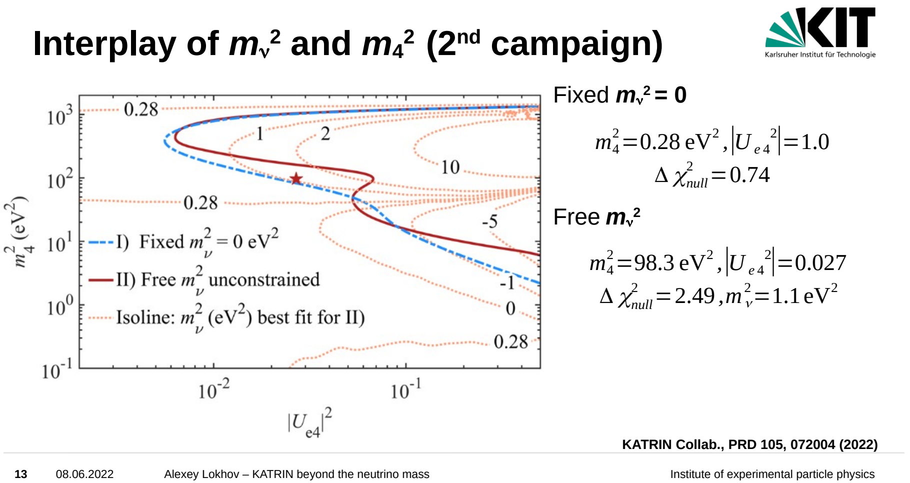
Sterile neutrinos signature in β-spectrum

- 3+1 sterile neutrino model
- Same data-set as for the neutrino mass
- Grid search in m_4, $|U_{e4}|^2$ plane

$$\frac{d\Gamma}{dE} = \underbrace{\left(1-|U_{e4}|^2\right)\frac{d\Gamma}{dE}(m_\beta^2)}_{\text{light neutrino}} + \underbrace{|U_{e4}|^2\,\frac{d\Gamma}{dE}(m_4^2)}_{\text{heavy neutrino}}$$

8 08.06.2022 Alexey Lokhov – KATRIN beyond the neutrino mass Institute of experimental particle physics

Alexey Lokhov: KATRIN beyond the neutrino mass measurements



Interplay of m_ν^2 and m_4^2 (2nd campaign)

Fixed $m_\nu^2 = 0$

$$m_4^2 = 0.28\ \mathrm{eV}^2, |U_{e4}^2| = 1.0$$
$$\Delta\chi^2_{null} = 0.74$$

Free m_ν^2

$$m_4^2 = 98.3\ \mathrm{eV}^2, |U_{e4}^2| = 0.027$$
$$\Delta\chi^2_{null} = 2.49, m_\nu^2 = 1.1\ \mathrm{eV}^2$$

KATRIN Collab., PRD 105, 072004 (2022)

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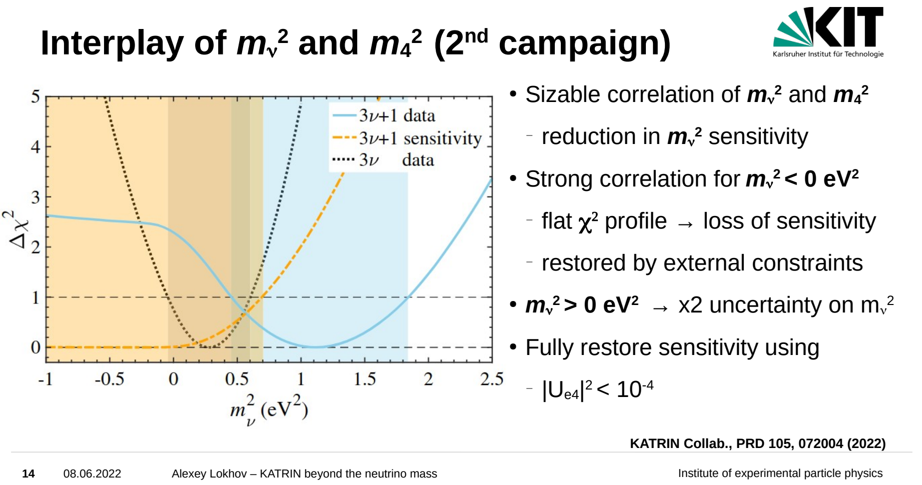
Please try to find the bound for free m_ν:

- In the $|U_{e4}|^2$–$\Delta m^2_{\mathrm{SBL}}$ plane, with $\Delta m^2_{\mathrm{SBL}} = m_4^2 - m_\nu^2$ and $m_4^2 > m_\nu^2$.
- Considering only positive m_ν^2.

Alexey Lokhov: KATRIN beyond the neutrino mass measurements



Interplay of m_ν^2 and m_4^2 (2nd campaign)

- Sizable correlation of m_ν^2 and m_4^2
  - reduction in m_ν^2 sensitivity
- Strong correlation for $m_\nu^2 < 0$ eV²
  - flat χ^2 profile → loss of sensitivity
  - restored by external constraints
- $m_\nu^2 > 0$ eV² → x2 uncertainty on m_ν^2
- Fully restore sensitivity using
  - $|U_{e4}|^2 < 10^{-4}$

KATRIN Collab., PRD 105, 072004 (2022)

14 08.06.2022 Alexey Lokhov – KATRIN beyond the neutrino mass Institute of experimental particle physics

$$m_\nu \lesssim \sqrt{2.3\ \text{eV}^2} \simeq 1.5\ \text{eV} \quad (90\%\ \text{C.L.}) \quad \text{in } 3\nu{+}1$$

about 1.7 times larger than $m_\nu \lesssim \sqrt{0.8\ \text{eV}^2} \simeq 0.9\ \text{eV} \quad (90\%\ \text{C.L.})$ in 3ν !

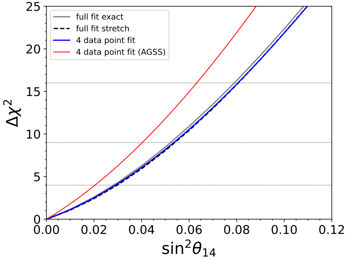
- I think that the interpretation depends on the values of $|U_{e4}|^2$ corresponding to the marginalized $\Delta\chi^2$ curve.
- The sensitivity to m_ν obviously decreases for increasing $|U_{e4}|^2$, because

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

- A reliable bound on $|U_{e4}|^2$ is the solar neutrino limit:

[Goldhagen, Maltoni, Reichard, Schwetz, arXiv:2109.14898]

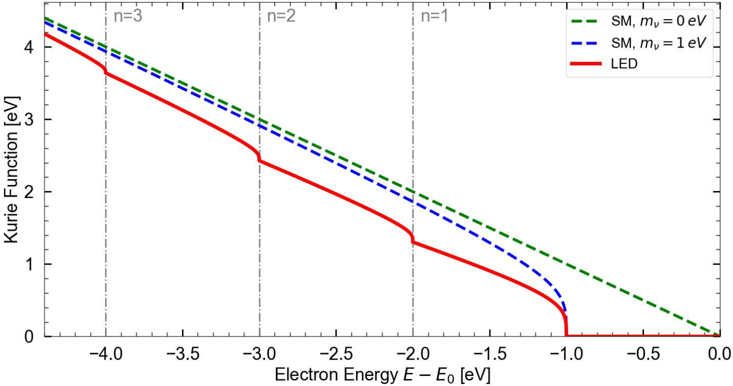
$$\sin^2\theta_{14} = |U_{e4}|^2$$



- I think that it would be useful to see:
  - The $\Delta\chi^2$ contours in the m_ν–$|U_{e4}|^2$ plane.
  - The $\Delta\chi^2$ for m_ν with a solar $\Delta\chi^2$ pull term.

Oddharak Tyagi: Constraining Large Extra Dimensions with Neutrino Experiments

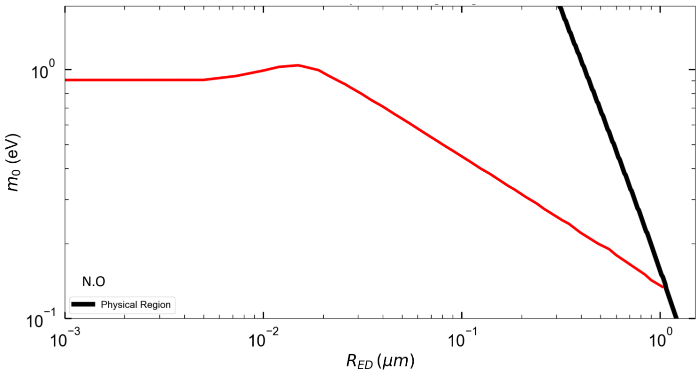
Beta-decay Experiments



10 June 2022 NuMass 2022 Milano 11

Oddharak Tyagi: Constraining Large Extra Dimensions with Neutrino Experiments

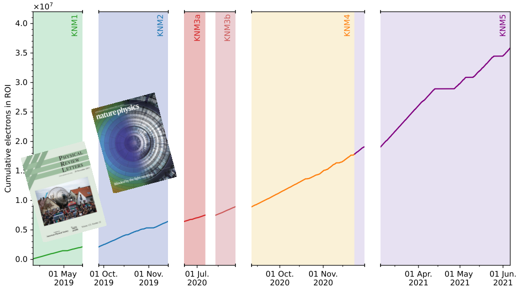
Bound



10 June 2022 NuMass 2022 Milano 20

Leonard Köllenberger: (KATRIN) Details on the ν mass analysis

Measurement campaigns

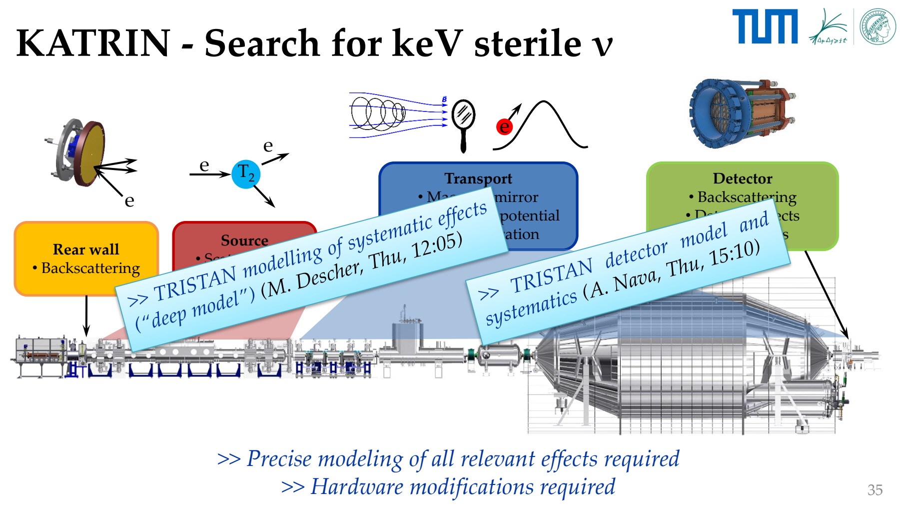


KATRIN **N**eutrino mass **M**easurements

	Time (hrs)	$\boldsymbol{\rho d\sigma}$ **(m^{-2})**	**Bg (mcps)**
KNM1	522	1.11×10^{21}	370
KNM2	294	4.23×10^{21}	278
KNM3a	220	2.08×10^{21}	137
KNM3b	224	3.75×10^{21}	258
KNM4	1267	3.77×10^{21}	150
KNM5	1232	3.78×10^{21}	160

- Published results: KNM1 and KNM2
  Phys. Rev. Lett. 123, 221802
  Nat. Phys. 18, 160–166 (2022)
- Current analysis: KNM1 – KNM5
- Data-taking: KNM6, KNM7, ...

Frank Edzards: keV-scale sterile neutrino search with KATRIN



KATRIN - Search for keV sterile ν

Rear wall
- Backscattering

Source
- Sc

Transport
- Ma mirror
- potential
- ation

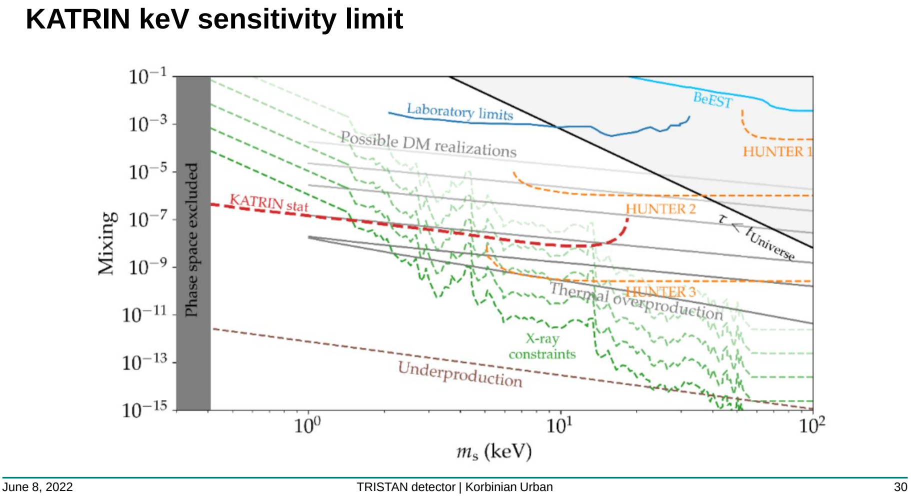
Detector
- Backscattering
- D cts
- s

>> TRISTAN modelling of systematic effects (“deep model”) (M. Descher, Thu, 12:05)

>> TRISTAN detector model and systematics (A. Nava, Thu, 15:10)

>> Precise modeling of all relevant effects required
>> Hardware modifications required

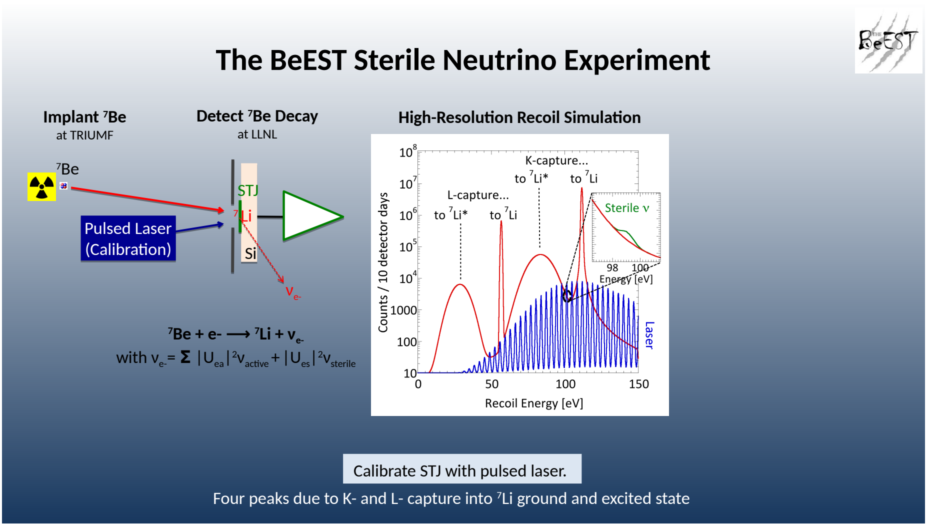
35



KATRIN keV sensitivity limit

June 8, 2022 TRISTAN detector | Korbinian Urban 30

Stephan Friedrich: BeEST



The BeEST Sterile Neutrino Experiment

Implant ^{7}Be at TRIUMF

Detect ^{7}Be Decay at LLNL

High-Resolution Recoil Simulation

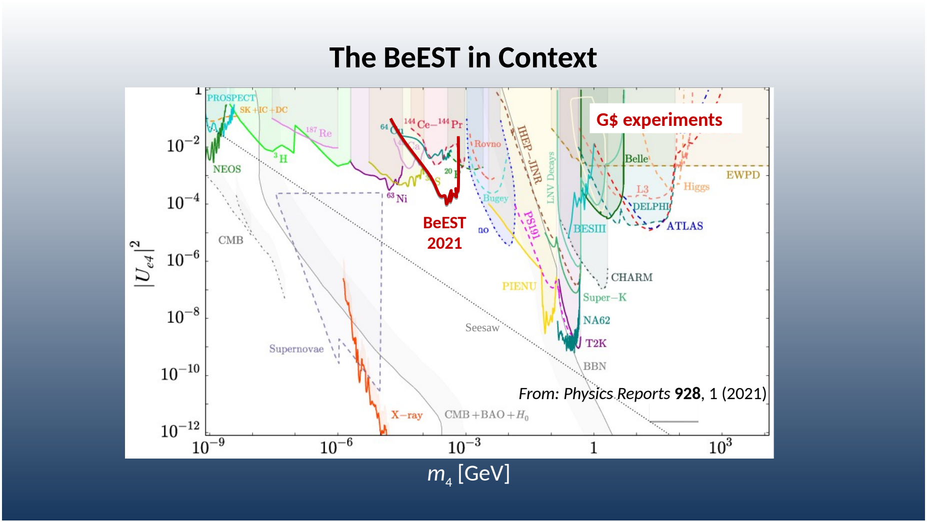
^{7}Be + e- ⟶ ^{7}Li + ν_{e-}

with $\nu_{e-} = \Sigma\ |U_{ea}|^2 \nu_{active} + |U_{es}|^2 \nu_{sterile}$

Calibrate STJ with pulsed laser.

Four peaks due to K- and L- capture into ^{7}Li ground and excited state

Stephan Friedrich: BeEST



The BeEST in Context

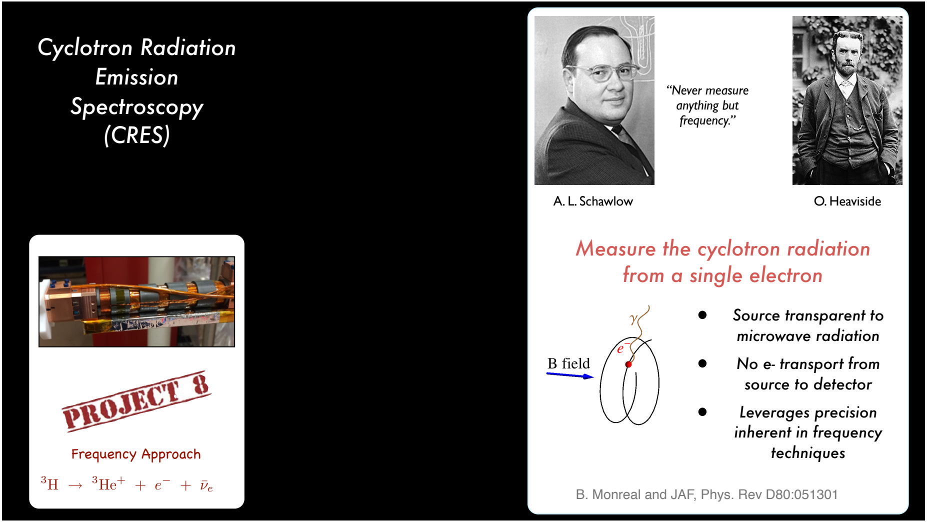
G$ experiments

BeEST 2021

From: Physics Reports **928**, 1 (2021)

m_4 [GeV]

Joseph A. Formaggio: Project 8, CRES and Neutrino Mass Measurements



Cyclotron Radiation Emission Spectroscopy (CRES)

PROJECT 8

Frequency Approach

$^{3}\mathrm{H} \to {}^{3}\mathrm{He}^{+} + e^{-} + \bar{\nu}_e$

"Never measure anything but frequency."

A. L. Schawlow

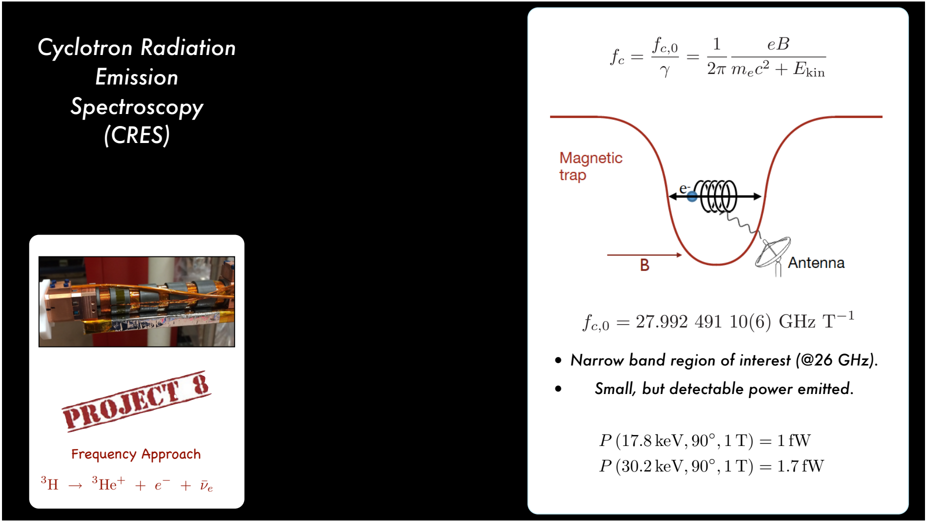
O. Heaviside

Measure the cyclotron radiation from a single electron

- *Source transparent to microwave radiation*
- *No e- transport from source to detector*
- *Leverages precision inherent in frequency techniques*

B. Monreal and JAF, Phys. Rev D80:051301

Joseph A. Formaggio: Project 8, CRES and Neutrino Mass Measurements



Cyclotron Radiation Emission Spectroscopy (CRES)

PROJECT 8

Frequency Approach

$^3\mathrm{H} \to {}^3\mathrm{He}^+ + e^- + \bar{\nu}_e$

$$f_c = \frac{f_{c,0}}{\gamma} = \frac{1}{2\pi}\frac{eB}{m_e c^2 + E_{\mathrm{kin}}}$$

$$f_{c,0} = 27.992\ 491\ 10(6)\ \mathrm{GHz\ T^{-1}}$$

- *Narrow band region of interest (@26 GHz).*
- *Small, but detectable power emitted.*

$$P\,(17.8\,\mathrm{keV}, 90^\circ, 1\,\mathrm{T}) = 1\,\mathrm{fW}$$
$$P\,(30.2\,\mathrm{keV}, 90^\circ, 1\,\mathrm{T}) = 1.7\,\mathrm{fW}$$

Joseph A. Formaggio: Project 8, CRES and Neutrino Mass Measurements

Phase II Results

Phase II CRES instrument provides 1mm³ volume inside waveguide. Total of 3770 events observed over 3 months of data taking.

First endpoint CRES measurement conducted with no observed background in 81 days of data taking.

T_2 endpoint

Frequentist: $E_0 = (18550^{+22}_{-18})$ eV (1σ)

Bayesian: $E_0 = (18553^{+17}_{-17})$ eV (1σ)

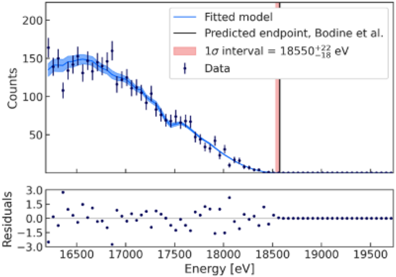
Neutrino mass

Frequentist: $\lesssim 178$ eV/c² (90% C.L.)

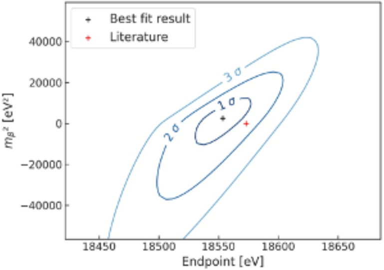
Bayesian: $\lesssim 169$ eV/c² (90% C.L.)

Background rate

$\lesssim 3\times10^{-10}$ eV^{-1}s^{-1} (90% C.I.)



First CRES Mass Limit

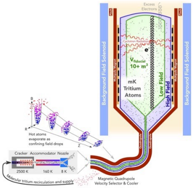


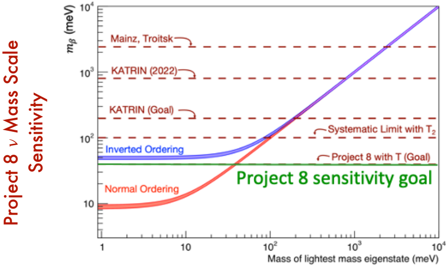
Joseph A. Formaggio: Project 8, CRES and Neutrino Mass Measurements

The two R&D efforts will combine into a demonstrator atomic cavity experiment at the end of Phase III, with a projected sensitivity of 400 meV/c².

A pathfinder for the final experimental goal of 40 meV/c².

CRES Phase III Pathfinder Experiment





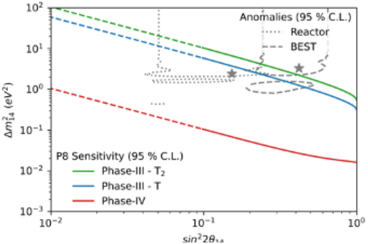
Joseph A. Formaggio: Project 8, CRES and Neutrino Mass Measurements

A low background, high resolution tritium experiment can help resolve "kinks" in the spectrum.

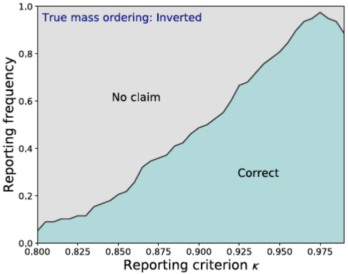
Potentially sensitive to mass splittings or low mass sterile neutrinos.

PHYSICAL REVIEW C 103, 065501 (2021)
arXiv:2203.07349v1

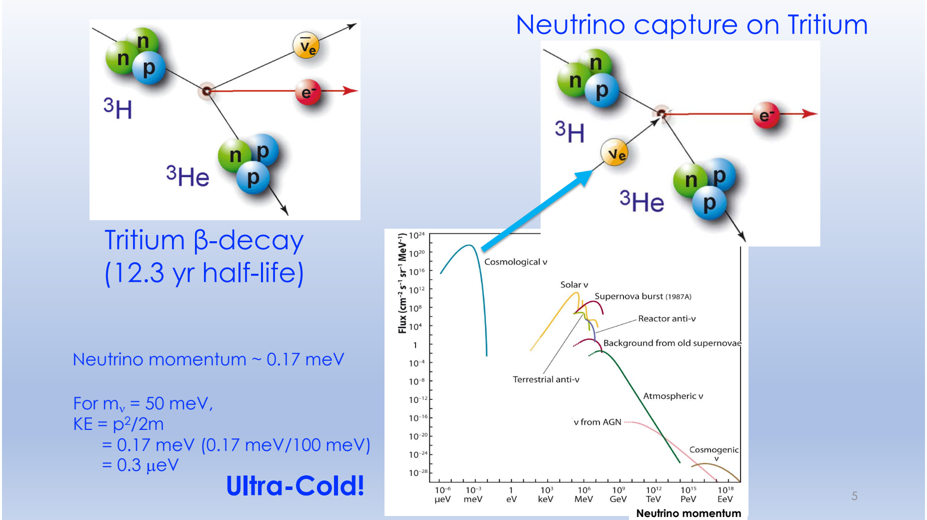
Project 8 Sterile Neutrino Sensitivity



Sensitivity to Neutrino Mass Ordering



Chris Tully: Status of PTOLEMY



Neutrino capture on Tritium

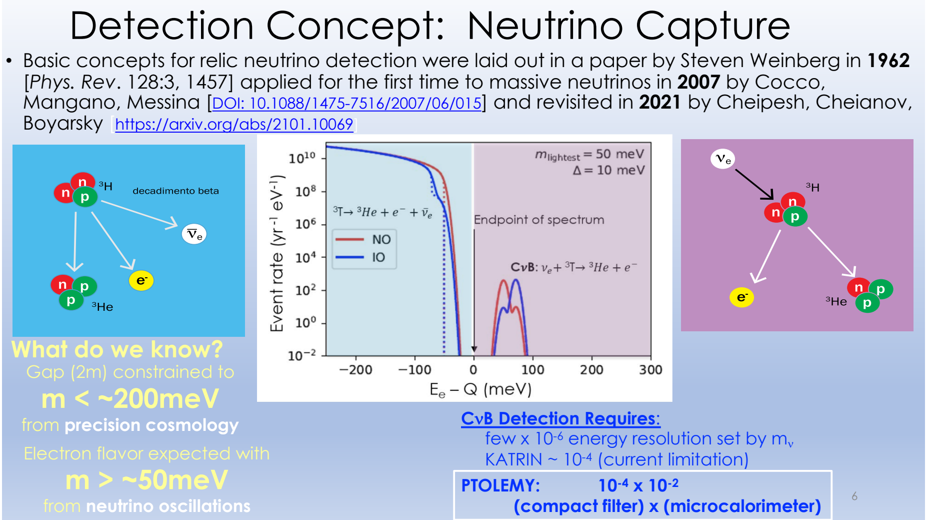
Tritium β-decay
(12.3 yr half-life)

Neutrino momentum ~ 0.17 meV

For m_ν = 50 meV,
KE = $p^2/2m$
= 0.17 meV (0.17 meV/100 meV)
= 0.3 μeV

Ultra-Cold!

Chris Tully: Status of PTOLEMY



Detection Concept: Neutrino Capture

- Basic concepts for relic neutrino detection were laid out in a paper by Steven Weinberg in **1962** [*Phys. Rev.* 128:3, 1457] applied for the first time to massive neutrinos in **2007** by Cocco, Mangano, Messina [DOI: 10.1088/1475-7516/2007/06/015] and revisited in **2021** by Cheipesh, Cheianov, Boyarsky https://arxiv.org/abs/2101.10069

What do we know?

Gap (2m) constrained to

m < ~200meV

from **precision cosmology**

Electron flavor expected with

m > ~50meV

from **neutrino oscillations**

CνB Detection Requires:

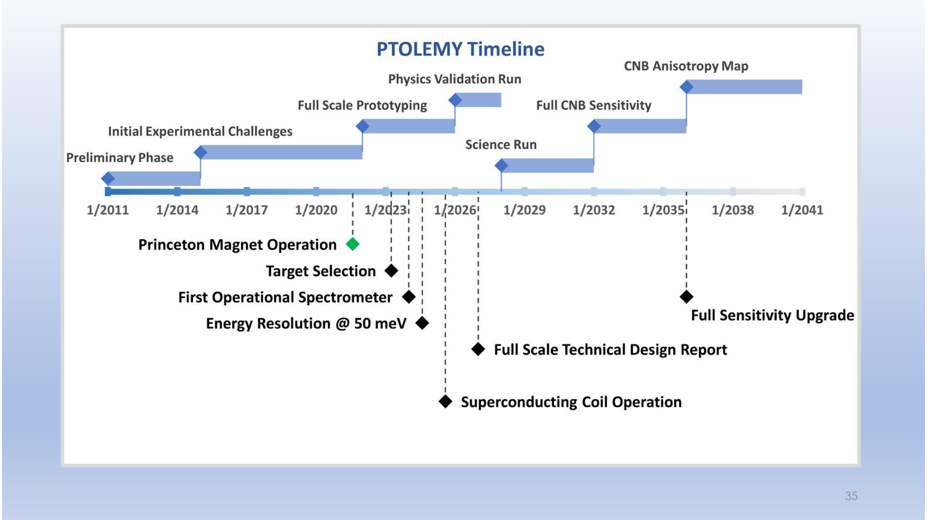
few x 10^{-6} energy resolution set by m_ν

KATRIN ~ 10^{-4} (current limitation)

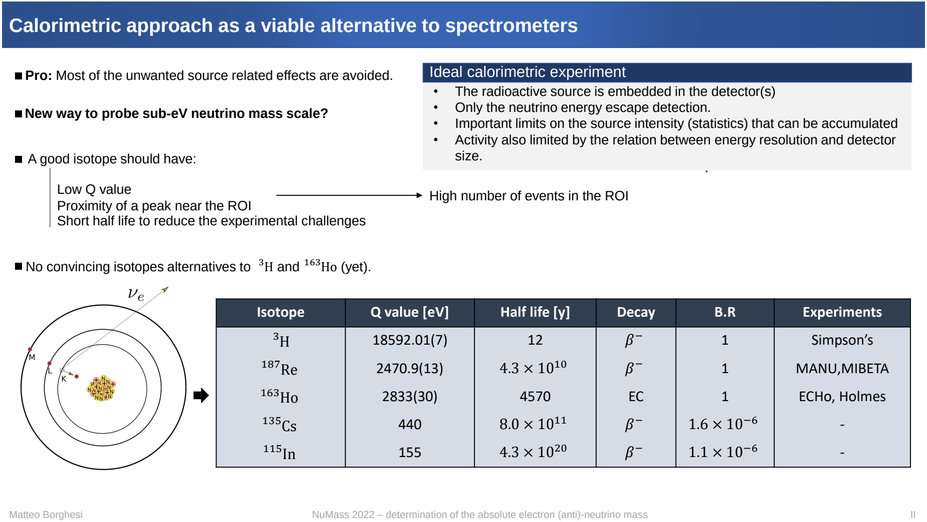
PTOLEMY: 10^{-4} x 10^{-2}

(compact filter) x (microcalorimeter)

Chris Tully: Status of PTOLEMY



Matteo Borghesi: An updated overview of the HOLMES status



Calorimetric approach as a viable alternative to spectrometers

- **Pro:** Most of the unwanted source related effects are avoided.
- **New way to probe sub-eV neutrino mass scale?**
- A good isotope should have:

  Low Q value
  Proximity of a peak near the ROI
  Short half life to reduce the experimental challenges

  → High number of events in the ROI

Ideal calorimetric experiment

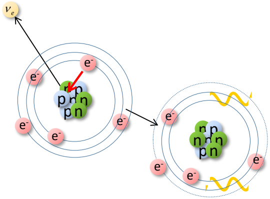
- The radioactive source is embedded in the detector(s)
- Only the neutrino energy escape detection.
- Important limits on the source intensity (statistics) that can be accumulated
- Activity also limited by the relation between energy resolution and detector size.

- No convincing isotopes alternatives to $^{3}\mathrm{H}$ and $^{163}\mathrm{Ho}$ (yet).

Isotope	Q value [eV]	Half life [y]	Decay	B.R	Experiments
$^{3}\mathrm{H}$	18592.01(7)	12	β^-	1	Simpson's
$^{187}\mathrm{Re}$	2470.9(13)	4.3×10^{10}	β^-	1	MANU,MIBETA
$^{163}\mathrm{Ho}$	2833(30)	4570	EC	1	ECHo, Holmes
$^{135}\mathrm{Cs}$	440	8.0×10^{11}	β^-	1.6×10^{-6}	-
$^{115}\mathrm{In}$	155	4.3×10^{20}	β^-	1.1×10^{-6}	-

Loredana Gastaldo: Report on ECHo activities and results

Electron Capture in ^{163}Ho

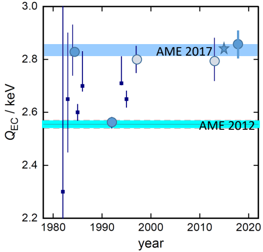


$$^{163}_{67}\mathrm{Ho} \rightarrow ^{163}_{66}\mathrm{Dy}^* + \nu_e$$

$$^{163}_{66}\mathrm{Dy}^* \rightarrow ^{163}_{66}\mathrm{Dy} + E_C$$

- $\tau_{1/2} \cong 4570$ years (2*10^{11} atoms for 1 Bq)
- $\boldsymbol{Q_{EC} = (2.833 \pm 0.030^{stat} \pm 0.015^{syst})}$ **keV**

S. Eliseev et al., *Phys. Rev. Lett.* **115** (2015) 062501



$$Q_{EC} = m(^{163}\mathrm{Ho}) - m(^{163}\mathrm{Dy})$$

Penning Trap Mass Spectroscopy

@TRIGA TRAP (Uni-Mainz) (♦)

@SHIPTRAP (GSI – Darmstadt) (♦♦)

Future goal: 1 eV precision:

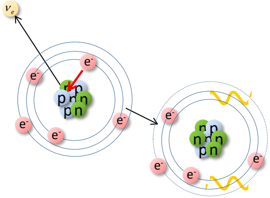
PENTATRAP @MPIK, Heidelberg (*)

(♦) F. Schneider et al., Eur. Phys. J. A **51** (2015) 89

(♦♦) S. Eliseev et al., *Phys. Rev. Lett.* **115** (2015) 062501

(*) J. Repp et al., Appl. Phys. B **107** (2012) 983, C. Roux et al., Appl. Phys. B **107** (2012) 997

Electron Capture in ^{163}Ho – Spectrum



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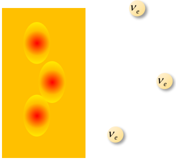
S. Eliseev et al., *Phys. Rev. Lett.* **115** (2015) 062501



Source = Detector

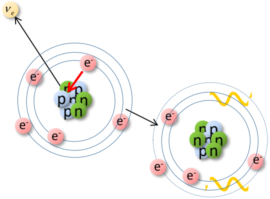
Advantages:	Measured neutrino complementary spectrum No final state problems
Disadvantages:	Unresolved pile-up

Calorimetric measurement

A. De Rujula and M. Lusignoli, *Phys. Lett.* **118B** (1982)

Source inside

Electron Capture in ^{163}Ho – Spectrum



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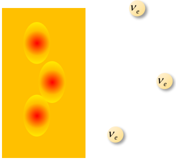
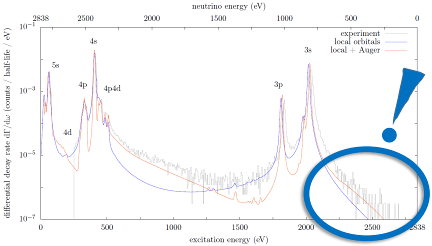
S. Eliseev et al., *Phys. Rev. Lett.* **115** (2015) 062501



Source = Detector

Calorimetric measurement

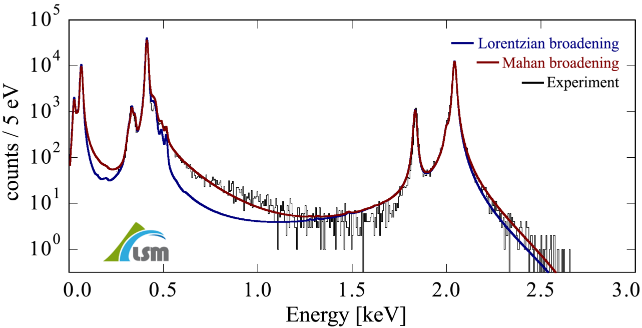
A. De Rujula and M. Lusignoli, *Phys. Lett.* **118B** (1982)



M. Braß and M. W. Haverkort, *New J. Phys.* **22** (2020) 093018

Loredana Gastaldo: Report on ECHo activities and results

Proof of concept



C. Velte et al., EPJC **79** (2019) 1026

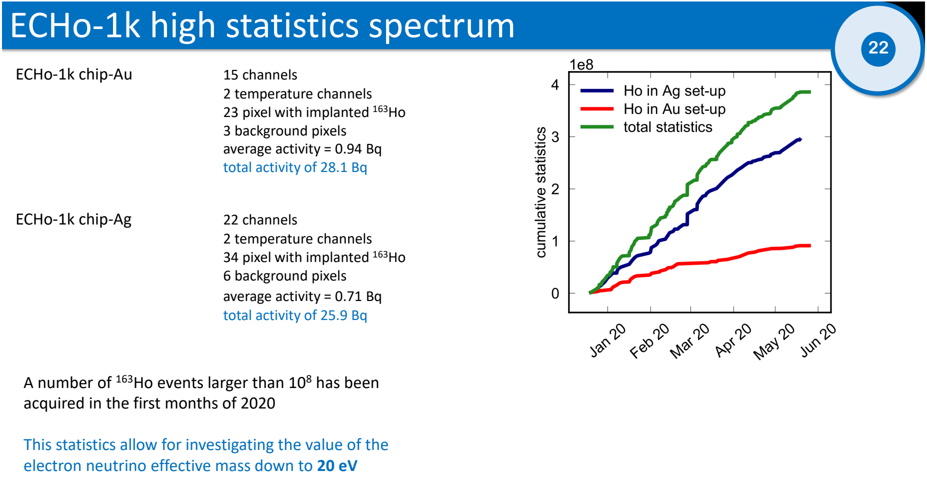
Energy resolution
$\Delta E_{\mathrm{FWHM}} = 9.2$ eV

Background level
b < 1.6×10^{-4} events/eV/pixel/day

4 day measurement with 4 pixels loaded with ~0.2 Bq ^{163}Ho
- measurement performed underground
- test for data reduction and spectral shape analysis

- $Q_{\mathrm{EC}} = (2838 \pm 14)$ eV
- $m(\nu_e) < 150$ eV (95% C.L.)

Loredana Gastaldo: Report on ECHo activities and results



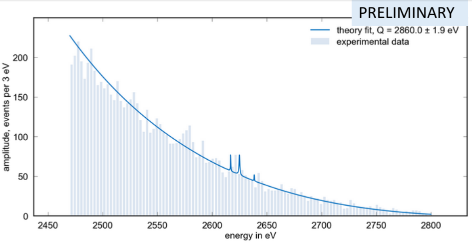
ECHo-1k high statistics spectrum

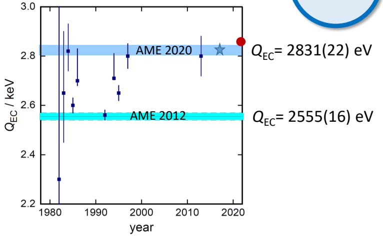
ECHo-1k chip-Au	15 channels 2 temperature channels 23 pixel with implanted ^{163}Ho 3 background pixels average activity = 0.94 Bq total activity of 28.1 Bq
ECHo-1k chip-Ag	22 channels 2 temperature channels 34 pixel with implanted ^{163}Ho 6 background pixels average activity = 0.71 Bq total activity of 25.9 Bq

A number of ^{163}Ho events larger than 10^8 has been acquired in the first months of 2020

This statistics allow for investigating the value of the electron neutrino effective mass down to **20 eV**

2.5 keV < E < 2.8 keV





Determination of Q_{EC} by fitting the spectrum using:

- Brass & Haverkort theory
- Flat background

$$Q_{EC} = (2860 \pm 2_{stat} \pm 5_{syst})\ \text{eV}$$

Systematic uncertainties related to theoretical spectral shape

…still too large for analysis of smaller endpoint region

★ $Q_{EC} = (2.833 \pm 0.030^{stat} \pm 0.015^{syst})$ keV

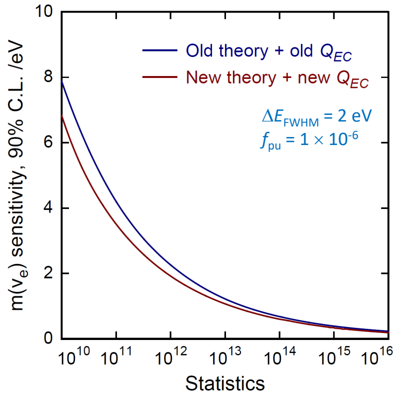
S. Eliseev et al., *Phys. Rev. Lett.* **115** (2015) 062501

Waiting for new PENTATRAP* results

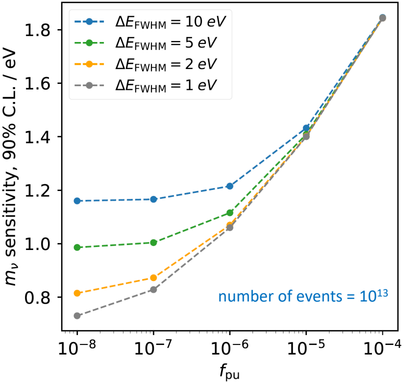
(*) J. Repp et al., Appl. Phys. B **107** (2012) 983
C. Roux et al., Appl. Phys. B **107** (2012) 997

Updated sensitivity

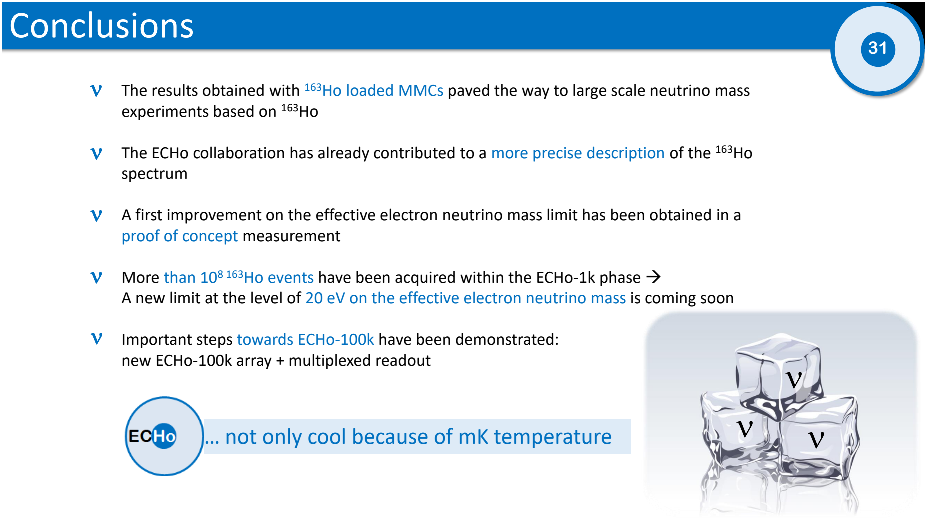
Brass & Haverkort theoretical model + new Q_{EC}-value



Sensitivity for the coming phase of ECHo



Loredana Gastaldo: Report on ECHo activities and results

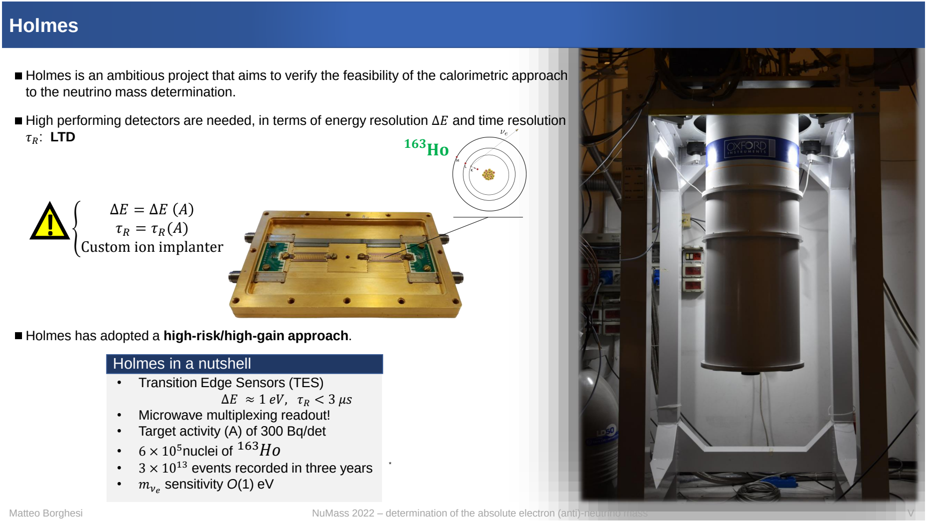


Conclusions

- The results obtained with ^{163}Ho loaded MMCs paved the way to large scale neutrino mass experiments based on ^{163}Ho
- The ECHo collaboration has already contributed to a more precise description of the ^{163}Ho spectrum
- A first improvement on the effective electron neutrino mass limit has been obtained in a proof of concept measurement
- More than 10^8 ^{163}Ho events have been acquired within the ECHo-1k phase →
  A new limit at the level of 20 eV on the effective electron neutrino mass is coming soon
- Important steps towards ECHo-100k have been demonstrated:
  new ECHo-100k array + multiplexed readout

ECHo … not only cool because of mK temperature

Matteo Borghesi: An updated overview of the HOLMES status



Holmes

- Holmes is an ambitious project that aims to verify the feasibility of the calorimetric approach to the neutrino mass determination.
- High performing detectors are needed, in terms of energy resolution ΔE and time resolution τ_R: **LTD**

$$\begin{cases} \Delta E = \Delta E\,(A) \\ \tau_R = \tau_R(A) \\ \text{Custom ion implanter} \end{cases}$$

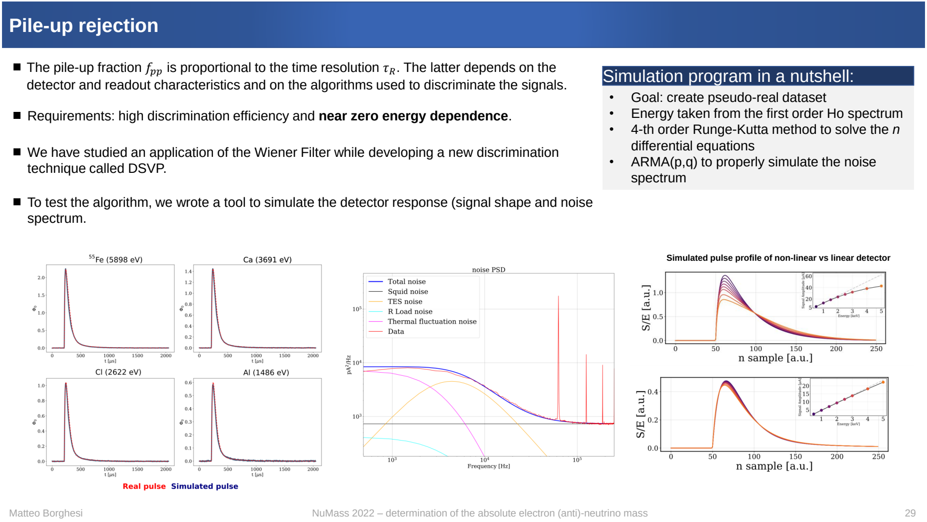
- Holmes has adopted a **high-risk/high-gain approach**.

Holmes in a nutshell

- Transition Edge Sensors (TES)
  $\Delta E \approx 1\,eV,\ \tau_R < 3\,\mu s$
- Microwave multiplexing readout!
- Target activity (A) of 300 Bq/det
- 6×10^5nuclei of ^{163}Ho
- 3×10^{13} events recorded in three years
- m_{ν_e} sensitivity $O(1)$ eV

Matteo Borghesi NuMass 2022 – determination of the absolute electron (anti)-neutrino mass

Matteo Borghesi: An updated overview of the HOLMES status



Pile-up rejection

- The pile-up fraction f_{pp} is proportional to the time resolution τ_R. The latter depends on the detector and readout characteristics and on the algorithms used to discriminate the signals.
- Requirements: high discrimination efficiency and **near zero energy dependence**.
- We have studied an application of the Wiener Filter while developing a new discrimination technique called DSVP.
- To test the algorithm, we wrote a tool to simulate the detector response (signal shape and noise spectrum).

Simulation program in a nutshell:

- Goal: create pseudo-real dataset
- Energy taken from the first order Ho spectrum
- 4-th order Runge-Kutta method to solve the *n* differential equations
- ARMA(p,q) to properly simulate the noise spectrum

Real pulse **Simulated pulse**

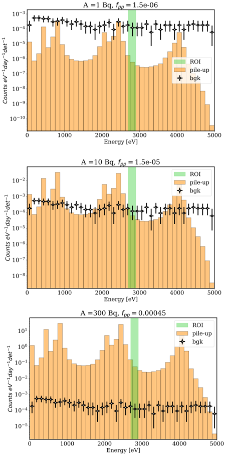
Simulated pulse profile of non-linear vs linear detector

Matteo Borghesi NuMass 2022 – determination of the absolute electron (anti)-neutrino mass 29

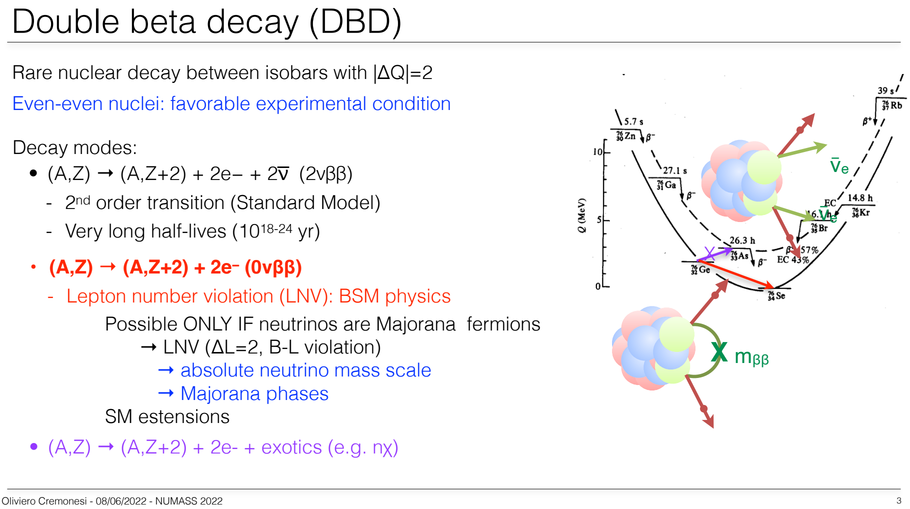
Matteo Borghesi: An updated overview of the HOLMES status

Conclusions

- Tested and tuned the final array fabrication processes.
  - These did not spoil the detectors' performances.
- The software for analysis and signal processing of microcalorimeters events is up and running!
- The expected background contributions were assessed, both with simulations and dedicate measurements.
  - A further reduction of a factor roughly 25% could be achieved with a similar setup studied in this work (muon veto).
  - Pile-up reduction results equivalent to increase the measurement time by a factor 4: from 3 to 12 years.
- Ion implanter is working as expected. The production of a proper sputter target is almost ready!
- The first phase of the HOLMES experiment is expected on the last quarter of 2022: a low dose implantation of a 2 × 32 pixel array.
  - Influence of the Ho on the detector response will be assessed
  - A high resolution Ho calorimetric spectrum will help to discriminate between the different theoretical models
  - A first limit on the neutrino mass $O(10)$ eV will be reached
- These results will contribute to clarify if the calorimetric approach can still be considered a feasible way to reach the required sub-eV sensitivity on the neutrino mass.



Oliviero Cremonesi: Review on neutrino-less double beta decay



Double beta decay (DBD)

Rare nuclear decay between isobars with $|\Delta Q|=2$

Even-even nuclei: favorable experimental condition

Decay modes:

- $(A,Z) \rightarrow (A,Z+2) + 2e^- + 2\bar{\nu}$ $(2\nu\beta\beta)$
  - 2^{nd} order transition (Standard Model)
  - Very long half-lives ($10^{18\text{-}24}$ yr)
- **$(A,Z) \rightarrow (A,Z+2) + 2e^-$ $(0\nu\beta\beta)$**
  - Lepton number violation (LNV): BSM physics

    Possible ONLY IF neutrinos are Majorana fermions

    → LNV ($\Delta L=2$, B-L violation)

    → absolute neutrino mass scale

    → Majorana phases

    SM estensions
- $(A,Z) \rightarrow (A,Z+2) + 2e^- +$ exotics (e.g. $n\chi$)

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Oliviero Cremonesi: Review on neutrino-less double beta decay

Double beta decay (DBD)

Rare nuclear decay between isobars with |ΔQ|=2

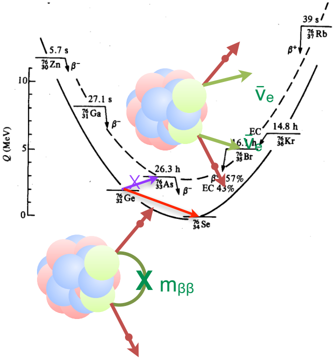
Even-even nuclei: favorable experimental condition

Decay modes:

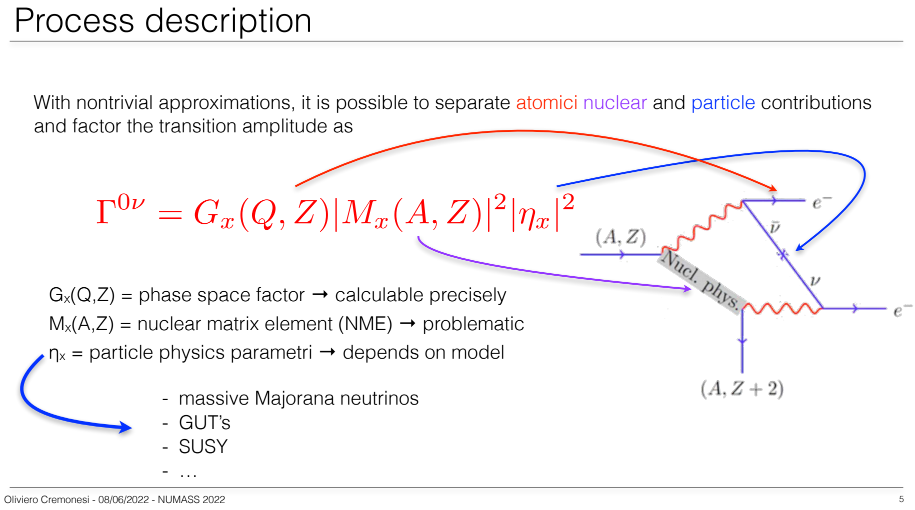
- (A,Z) → (A,Z+2) + 2e− + 2$\overline{\nu}$ (2νββ)
  - 2nd order transition (Standard Model)
  - Very long half-lives ($10^{18\text{-}24}$ yr)
- **(A,Z) → (A,Z+2) + 2e⁻ (0νββ)**
  - Lepton number violation (LNV): BSM physics

Possible ONLY IF neutrinos are Majorana fermions
→ LNV (ΔL=2, B-L violation)
→ absolute neutrino mass scale
→ Majorana phases
SM estensions

- (A,Z) → (A,Z+2) + 2e- + exotics (e.g. nχ)



Oliviero Cremonesi: Review on neutrino-less double beta decay



Process description

With nontrivial approximations, it is possible to separate atomici nuclear and particle contributions and factor the transition amplitude as

$$\Gamma^{0\nu} = G_x(Q,Z)|M_x(A,Z)|^2|\eta_x|^2$$

$G_x(Q,Z)$ = phase space factor → calculable precisely

$M_x(A,Z)$ = nuclear matrix element (NME) → problematic

η_x = particle physics parametri → depends on model

- massive Majorana neutrinos
- GUT's
- SUSY
- …

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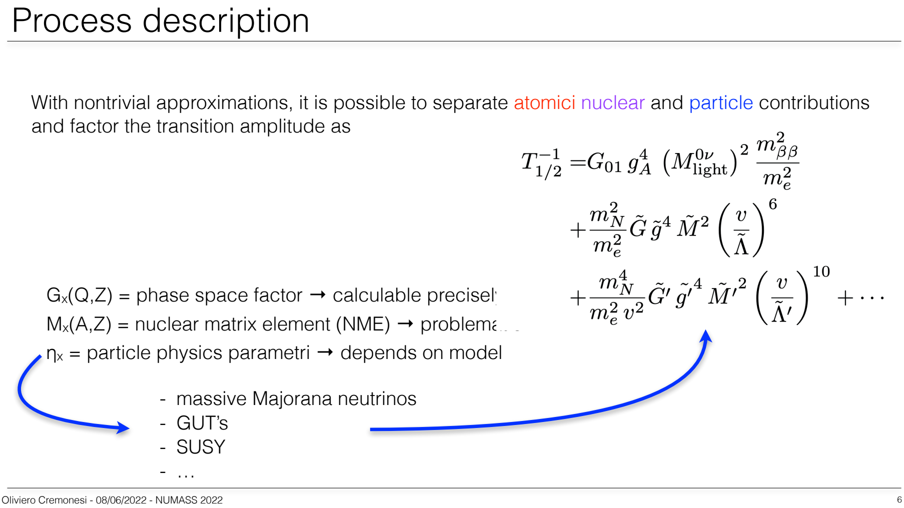
Oliviero Cremonesi: Review on neutrino-less double beta decay



Process description

With nontrivial approximations, it is possible to separate atomici nuclear and particle contributions and factor the transition amplitude as

$$
\begin{aligned}
T_{1/2}^{-1} = & G_{01}\, g_A^4 \,\left(M^{0\nu}_{\text{light}}\right)^2 \frac{m_{\beta\beta}^2}{m_e^2} \\
& + \frac{m_N^2}{m_e^2} \tilde{G}\, \tilde{g}^4\, \tilde{M}^2 \left(\frac{v}{\tilde{\Lambda}}\right)^6 \\
& + \frac{m_N^4}{m_e^2\, v^2} \tilde{G}'\, \tilde{g}'^4\, \tilde{M}'^2 \left(\frac{v}{\tilde{\Lambda}'}\right)^{10} + \cdots
\end{aligned}
$$

$G_x(Q,Z)$ = phase space factor → calculable precisel

$M_x(A,Z)$ = nuclear matrix element (NME) → problema

η_x = particle physics parametri → depends on model

- massive Majorana neutrinos
- GUT's
- SUSY
- …

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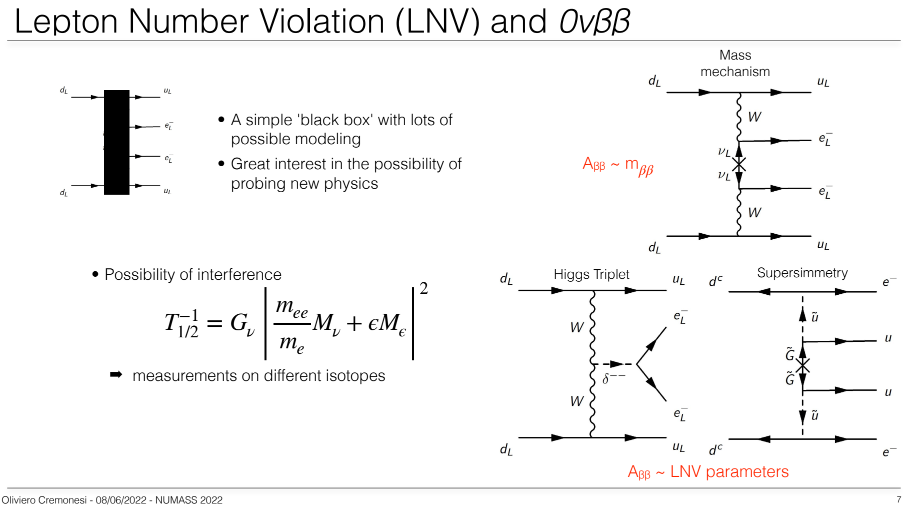
Oliviero Cremonesi: Review on neutrino-less double beta decay



Lepton Number Violation (LNV) and 0νββ

- A simple 'black box' with lots of possible modeling
- Great interest in the possibility of probing new physics

- Possibility of interference

$$T_{1/2}^{-1} = G_\nu \left| \frac{m_{ee}}{m_e} M_\nu + \epsilon M_\epsilon \right|^2$$

➡ measurements on different isotopes

$A_{\beta\beta} \sim m_{\beta\beta}$

$A_{\beta\beta} \sim$ LNV parameters

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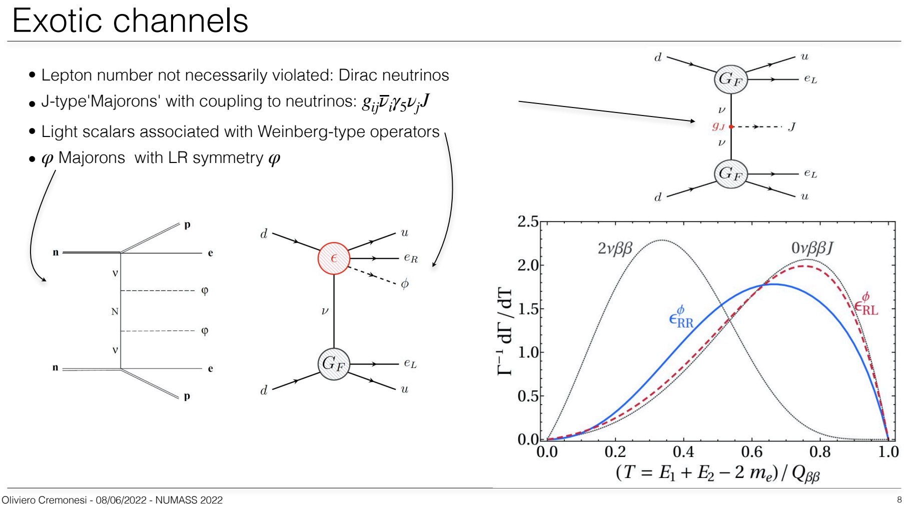
Oliviero Cremonesi: Review on neutrino-less double beta decay



Exotic channels

- Lepton number not necessarily violated: Dirac neutrinos
- J-type'Majorons' with coupling to neutrinos: $g_{ij}\overline{\nu}_i\gamma_5\nu_j J$
- Light scalars associated with Weinberg-type operators
- φ Majorons with LR symmetry φ

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Oliviero Cremonesi: Review on neutrino-less double beta decay

The standard interpretation: light Majorana neutrino

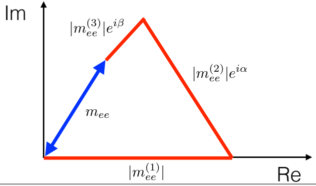
- ββ0ν is assumed to be mediated by the exchange of light Majorana neutrinos and all other mechanisms make zero or negligible contributions

- $m_{\beta\beta}$ depends on a total of seven parameters (θ_{12}, θ_{13} thrre masses and two Majorana phases)
- neutrino oscillation experiments are sensitive only to the two mixing angles, two neutrino mass squared differences, and the mass ordering $\Longrightarrow$ only four out of seven degrees of freedom, can be bounded

$$\eta_x = < m_{ee} > = \sum_k U_{ek}^2 m_k$$

$$= c_{12}^2 c_{13}^2 \enclose{circle}{m_1} + s_{12}^2 c_{13}^2 \enclose{circle}{e^{i\alpha}} m_2 + s_{13}^2 \enclose{circle}{e^{i\beta}} m_3$$

- Transition amplitude is proportional to the coherent sum of neutrino masses
- Majorana phases play a crucial role: possible cancellations



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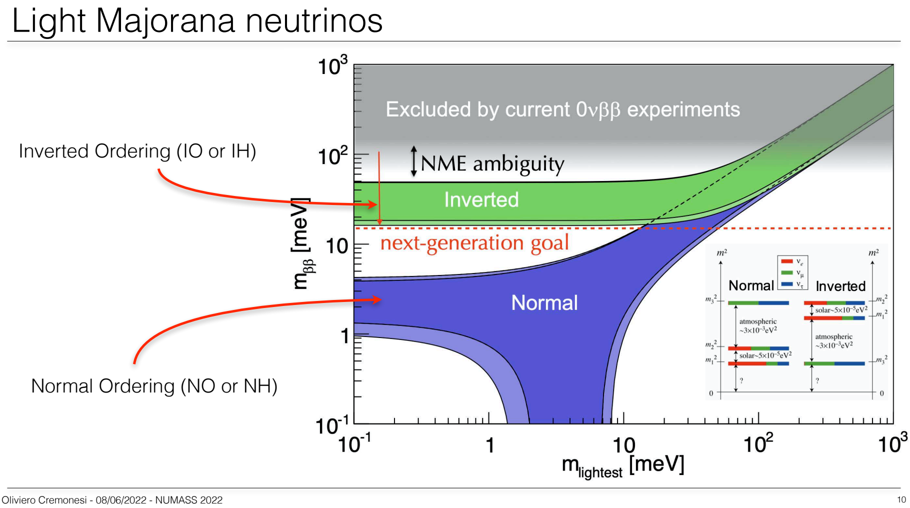

Light Majorana neutrinos

Inverted Ordering (IO or IH)

Normal Ordering (NO or NH)

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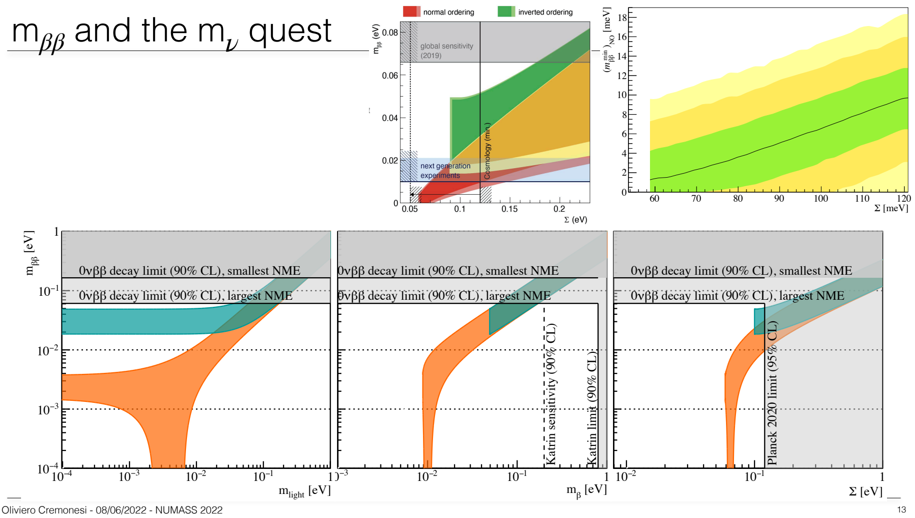
Oliviero Cremonesi: Review on neutrino-less double beta decay



$m_{\beta\beta}$ and the m_ν quest

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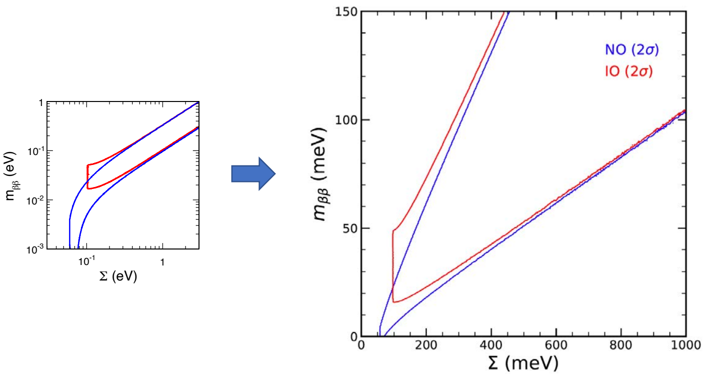
Eligio Lisi: Round Table: Discussion on Future

(1) Time to shift from log to linear scales!

$$m_{\beta\beta} = |U_{e1}^2 m_1 + U_{e2}^2 m_2 + U_{e3}^2 m_3|$$

vs

$$\Sigma = m_1 + m_2 + m_3$$



Regions allowed by current oscillation data for NO and IO separately.

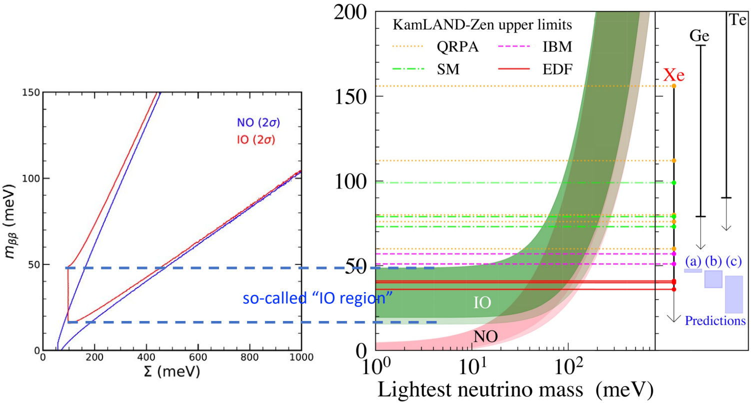
[Width of regions dominated by unknown Majorana phases]

Similarly for m_β vs Σ, without Majorana phase uncertainties

Eligio Lisi: Round Table: Discussion on Future

(2) Language bonus: avoid log-inspired misleading jargon

The (improperly named) "IO region" is compatible with NO as well…

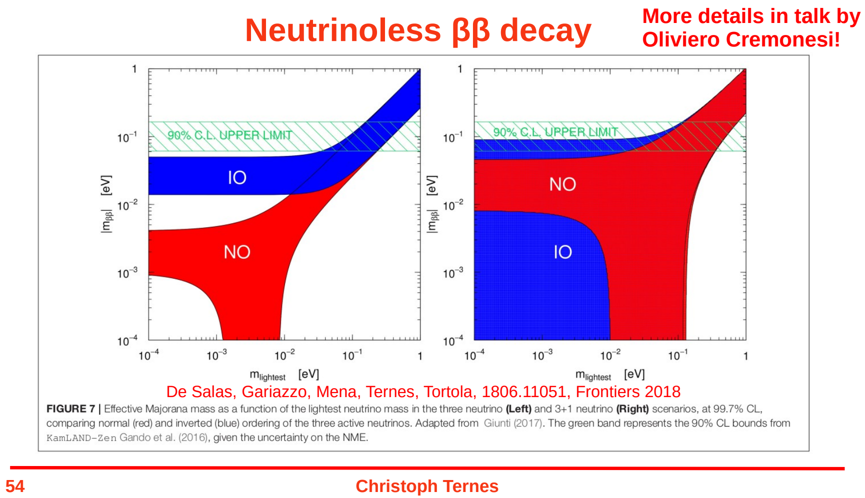


Important to note that Σ is observable while m_{lightest} is not.

Elongated stripes in $\log(m_{\text{lightest}})$ have no real significance.

Stat. bonus: If Bayesian results depend sensitively on log vs linear priors etc. → unreliable, IMHO

Christoph Ternes: Current status of 3+1 neutrino mixing



Neutrinoless ββ decay

More details in talk by Oliviero Cremonesi!

De Salas, Gariazzo, Mena, Ternes, Tortola, 1806.11051, Frontiers 2018

FIGURE 7 | Effective Majorana mass as a function of the lightest neutrino mass in the three neutrino **(Left)** and 3+1 neutrino **(Right)** scenarios, at 99.7% CL, comparing normal (red) and inverted (blue) ordering of the three active neutrinos. Adapted from Giunti (2017). The green band represents the 90% CL bounds from `KamLAND-Zen` Gando et al. (2016), given the uncertainty on the NME.

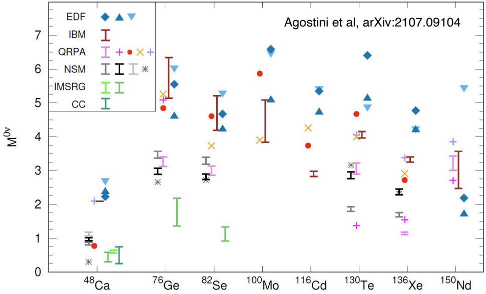
Oliviero Cremonesi: Review on neutrino-less double beta decay

$m_{\beta\beta}$ extraction from data: a hard task

$M^{0\nu}$ values estimated from different calculation methods

$$\Gamma^{0\nu} = G_{0\nu}(Q,Z)|M_{0\nu}(A,Z)|^2|m_{ee}|^2$$

- Factor 2-3 “uncertainty” among nuclear models.
- 'Ab initio' calculations for lighter isotopes give lower values



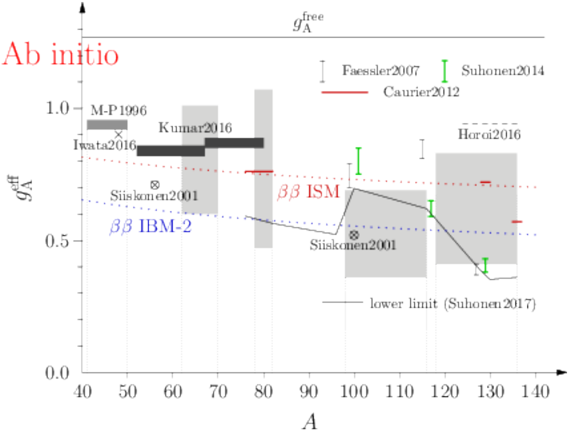
NME calculations:
- EDF: large
- QRPA: larger spread
- NSM: small
- IMSRG ^{48}Ca ab initio: very small

Much more problematic: nuclear matrix elements

- Significant differences
- Results inaccuracy

g_A quenching?

Results extracted from the GT $\beta^{\pm}$/EC and $2\nu\beta\beta$ calculations

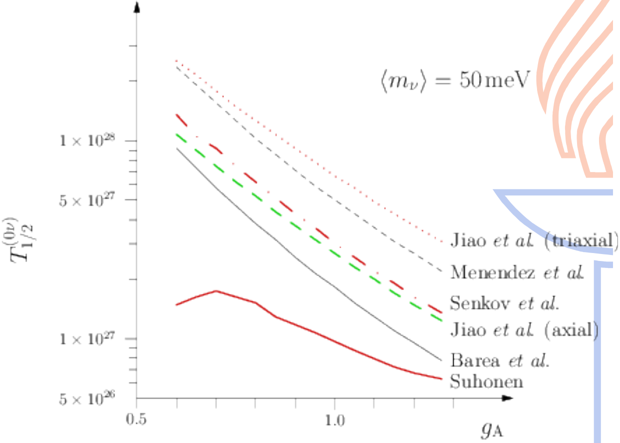


Ab initio: P. Gysbers *et al.*, Nature Physics 15 (2019) 428

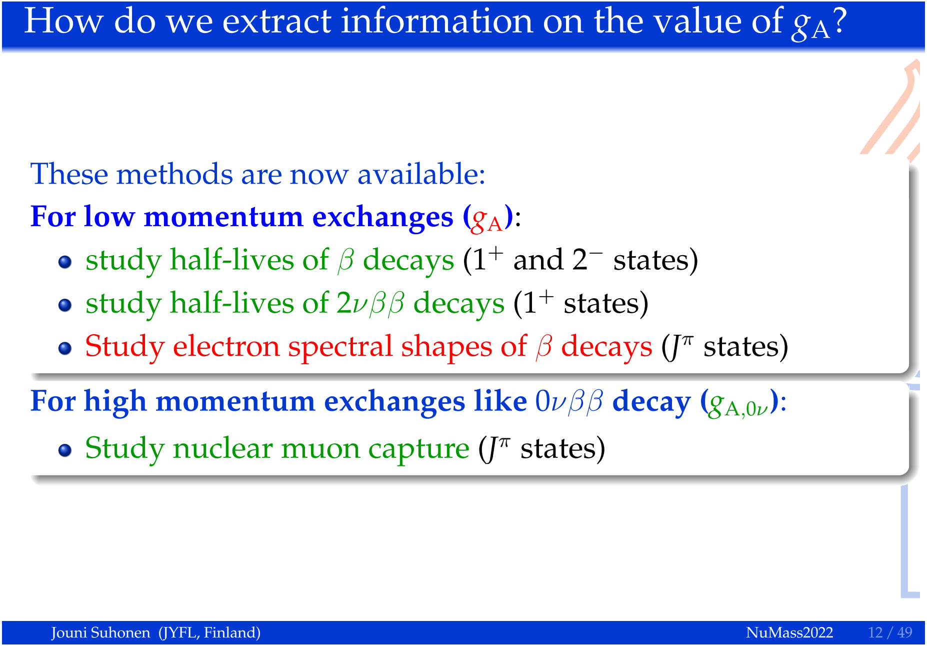
- Faessler2007: pnQRPA A. Faessler *et al.*, arXiv 0711.3996v1 [Nucl-th]
- Suhonen2014: pnQRPA J. Suhonen *et al.*, Nucl. Phys. A 924 (2014) 1
- Suhonen2017: pnQRPA J. Suhonen, Phys. Rev. C 96 (2017) 055501
- Caurier2012: ISM E. Caurier *et al.*, Phys. Lett. B 711 (2012) 62
- Horoi2016: ISM M. Horoi *et al.*, Phys. Rev. C 93 (2016) 024308
- M-P1996: ISM G. Martínez-Pinedo *et al.*, Phys. Rev. C 53 (1996) R2602
- Iwata2016: ISM Y. Iwata *et al.*, Phys. Rev. Lett. 116 (2016) 112502
- Kumar2016: ISM V. Kumar *et al.*, J. Phys. G 43 (2016) 105104 Phys. Lett. B 711 (2012) 62
- Siiskonen2001: ISM T. Siiskonen *et al.*, Phys. Rev. C 63 (2001) 055501
- $\beta\beta$ ISM and IBM-2: J. Barea *et al.*, Phys. Rev. C 87 (2013) 014315
- Light hatched regions: pnQRPA H. Ejiri *et al.*, J. Phys. G 42 (2015) 055201 ; P. Pirinen *et al.*, Phys. Rev. C 91 (2015) 054309 ; F. Deppisch *et al.*, Phys. Rev. C 94 (2016) 055501

Example: $0\nu\beta\beta$ NMEs of ^{76}Ge, effect on the half-life

- Jiao *et al.*: Phys. Rev. C 96 (2017) 054310 (GCM+ISM)
- Menendez *et al.*: Nucl. Phys. A 818 (2009) 139 (ISM)
- Senkov *et al.*: Phys. Rev. C 93 (2016) 044334 (ISM)
- Barea *et al.*: Phys. Rev. C 91 (2015) 034304 (IBM-2)
- Suhonen: Phys. Rev. C 96 (2017) 055501 (pnQRPA + $g_{\rm pp}$ + isospin restoration + data on $2\nu\beta\beta$)



Jouni Suhonen: Beta-electron spectral shapes and the effective value of g_A



How do we extract information on the value of g_{A}?

These methods are now available:

For low momentum exchanges (g_{A}):

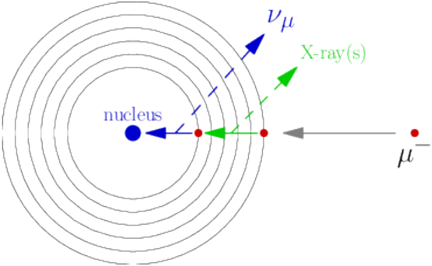
- study half-lives of β decays (1^+ and 2^- states)
- study half-lives of $2\nu\beta\beta$ decays (1^+ states)
- Study electron spectral shapes of β decays (J^π states)

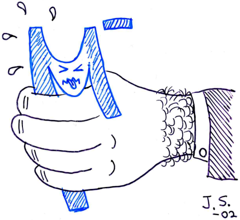
For high momentum exchanges like $0\nu\beta\beta$ decay ($g_{\mathrm{A},0\nu}$):

- Study nuclear muon capture (J^π states)

Jouni Suhonen: Beta-electron spectral shapes and the effective value of g_A

Ordinary Muon Capture (OMC)





Nuclear muon capture:

OMC: ${}^{A}_{Z}\mathrm{X} + \mu^- \to {}_{Z-1}^{\quad A}\mathrm{Y} + \nu_\mu$

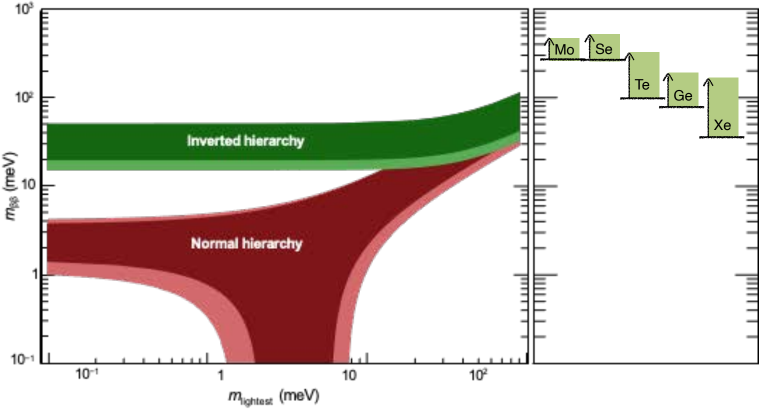
Also:

Muon decay: $\mu^- \to e^- + \bar{\nu}_e + \nu_\mu$ ($\tau = 2.2\mu$s)

OMC probability $\sim Z^4$
(in Fe 91% are captured,
breakeven at $Z \sim 11$)

Current results: $m_{\beta\beta}$

no g_A quenching



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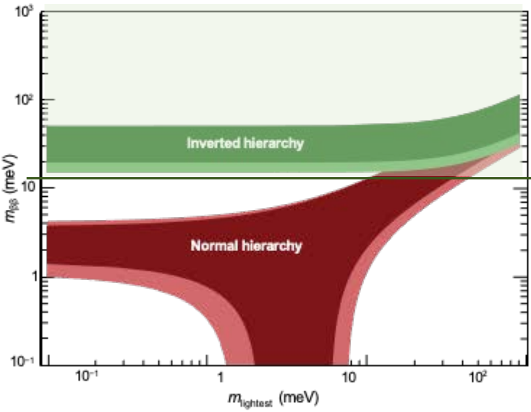
Future sensitivities

no g_A quenching



CUPID, LEGEND,KamLAND-ZEN,nEXO,...

$\tau_{0\nu} > 10^{27}\text{-}10^{28}$ y

Conclusions

- The future is bright for:
  - Neutrino Physics.
  - The Determination of the Absolute Electron (Anti)-Neutrino Mass.
  - The Detection of the Cosmic Neutrino Background.
  - Finding Lepton Number Violation and Majorana Neutrino Masses.
  - The NuMass Workshop Series.
- Thanks to Angelo and all the local organizers for the perfect organization!
- See you at NuMass 2024!