Direct neutrino mass and neutrinoless double beta decay

Stefan Schönert | TU München

Strategieworkshop Teilchenphysik
Universitätsclub Bonn

3-4 Mai 2018
Bonn

TECHNISCHE UNIVERSITÄT MÜNCHEN

SFB 1258 Neutrinos Dark Matter Messengers

, 3-4.5.

Bundesministerium für Bildung und Forschung

The Quests

What is the neutrino mass scale?

Are neutrinos their own anti-particles?

Is lepton number violated?

Why are neutrinos so much lighter than charged leptons ?
What is the origin of the matter anti-matter asymmetry ?
Neutrinos portal to BSM ?

The Quests

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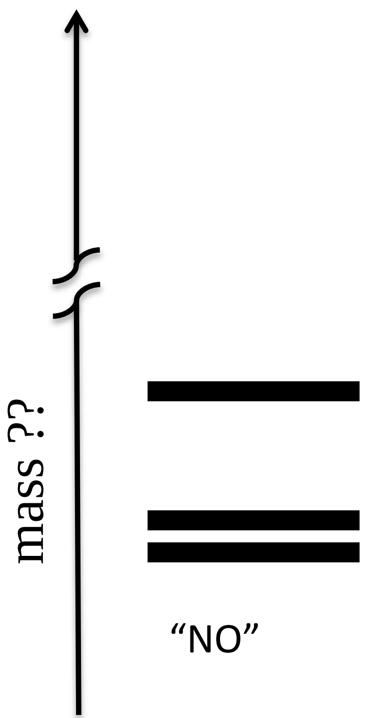

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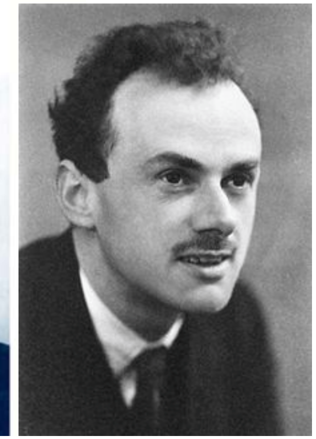

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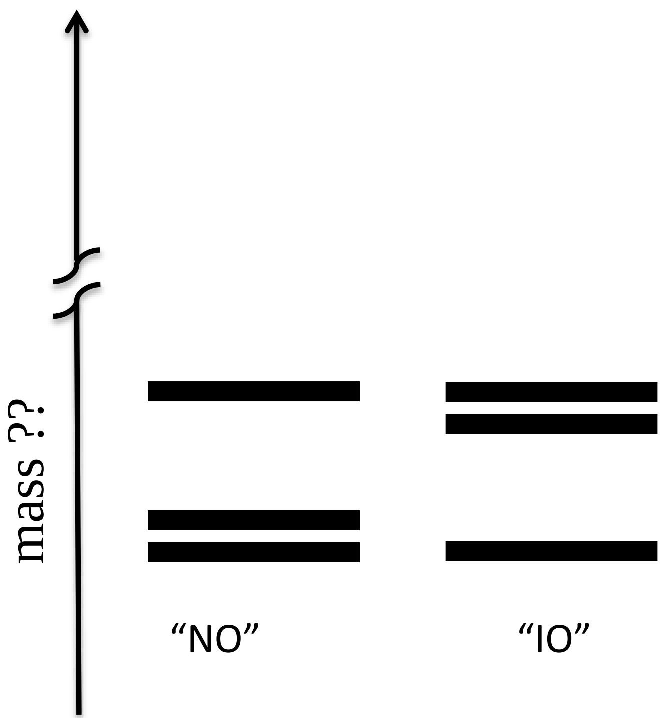

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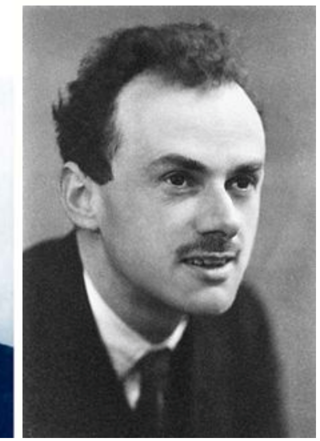

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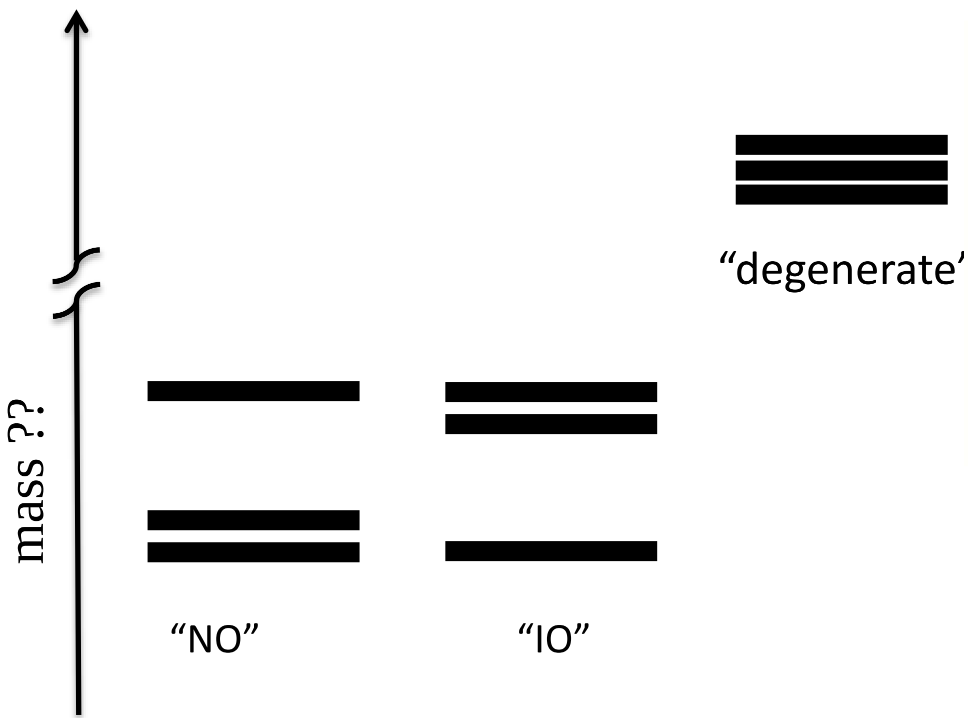

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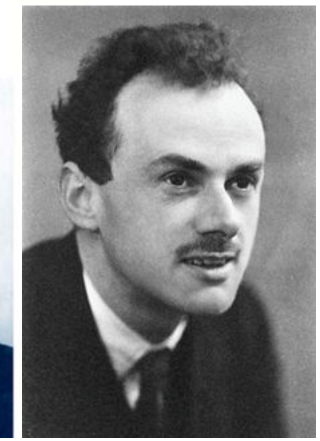

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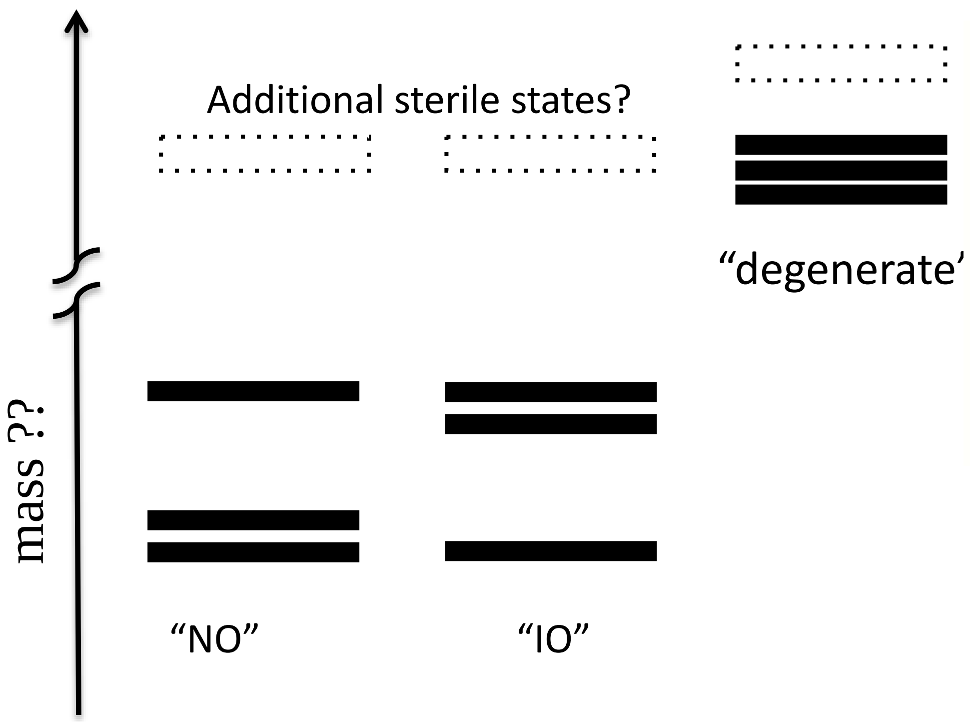

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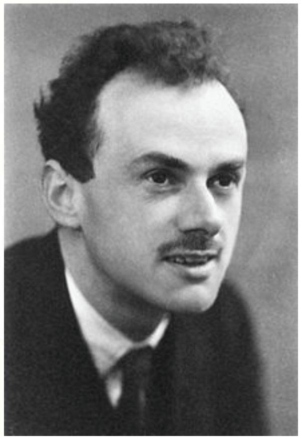

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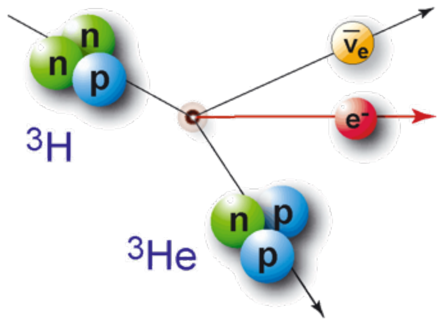
ν-mass observables

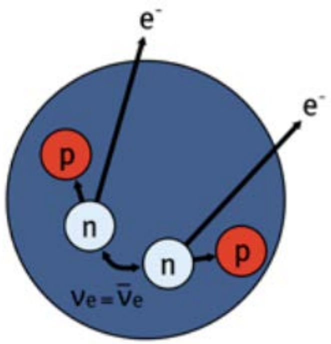
β-decay



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

(Dirac or Majorana)

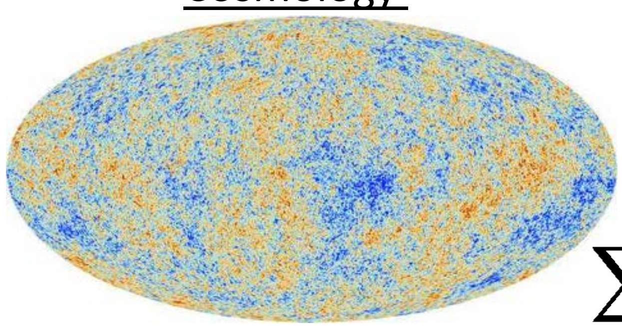
0νββ-decay



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

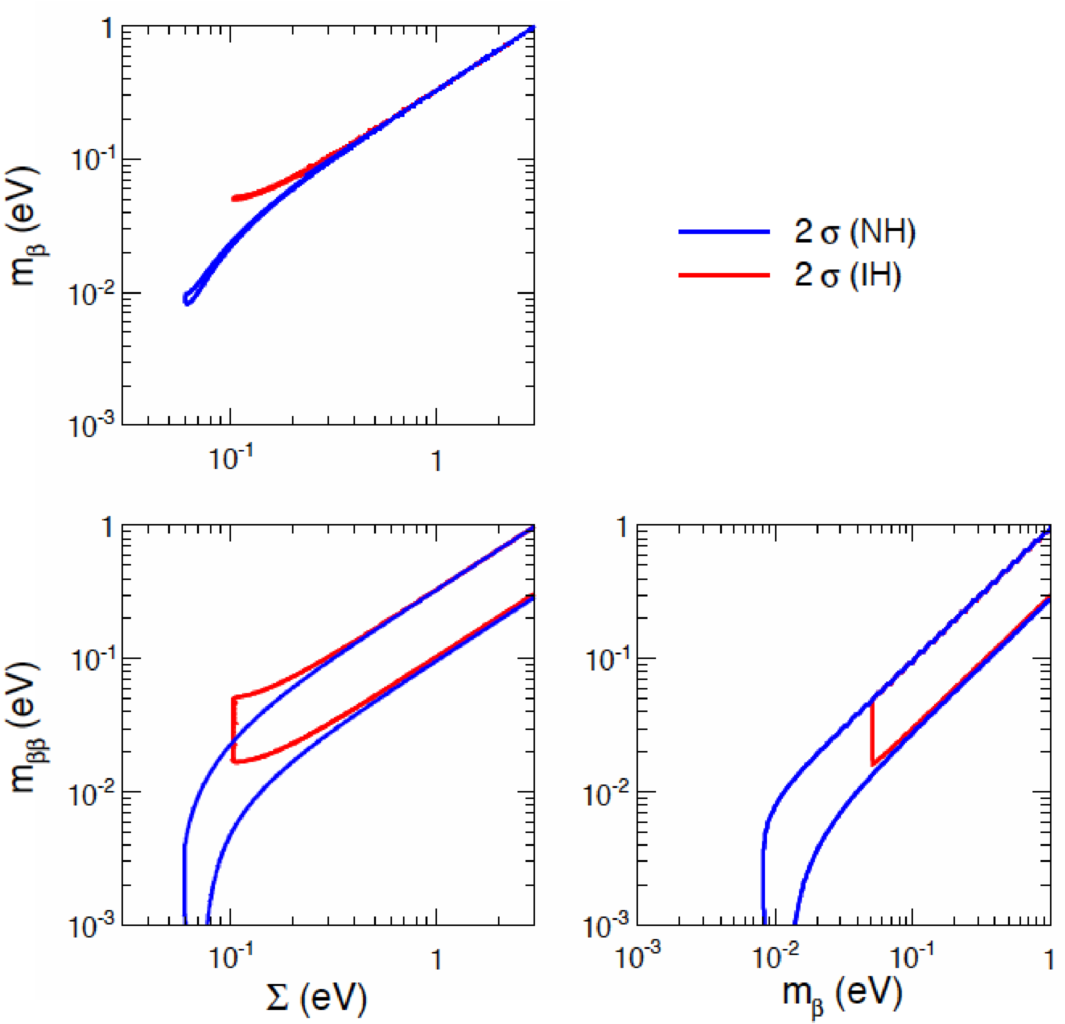
(Majorana)

Cosmology



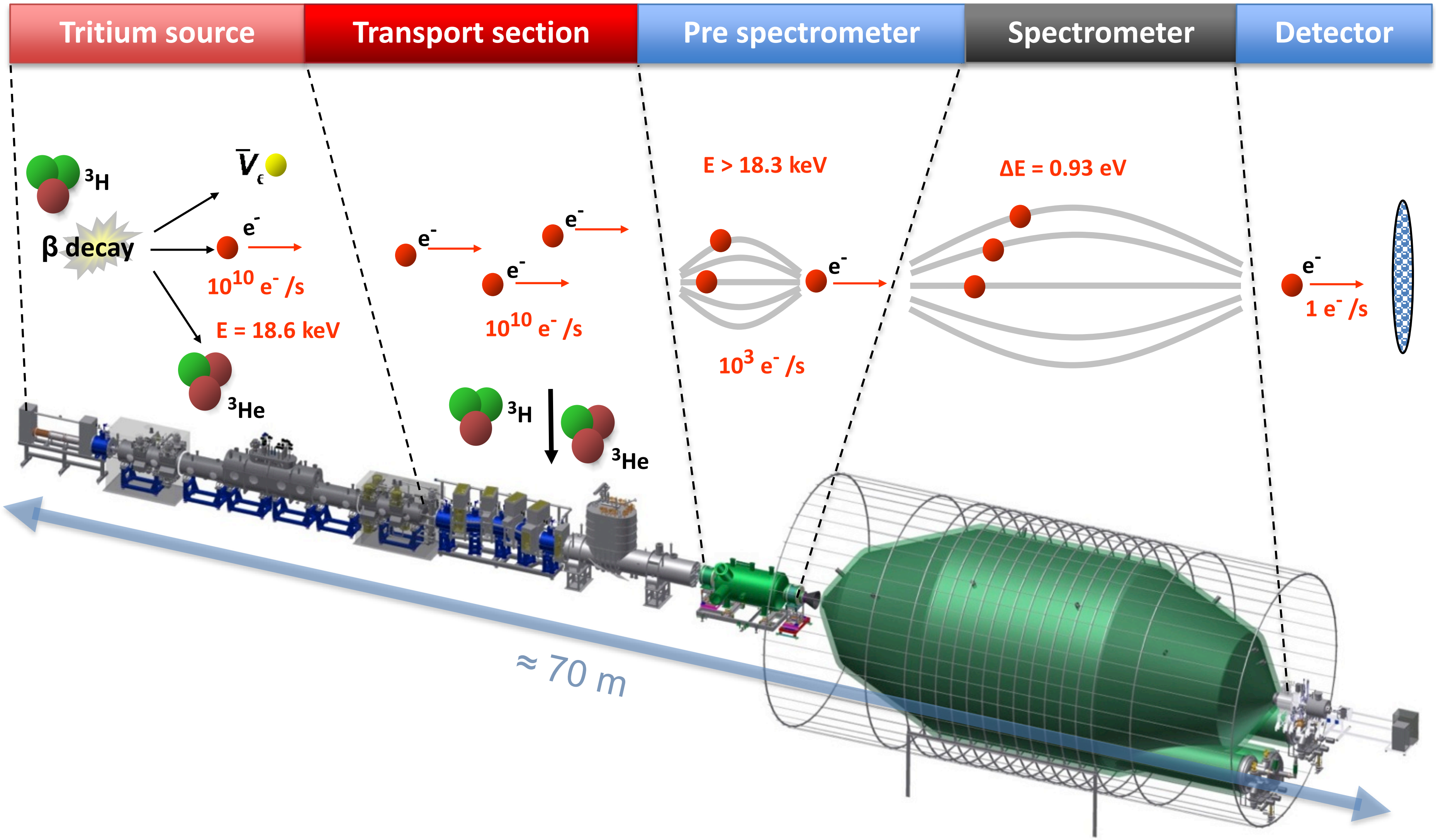
$$\sum_i m_i$$

Predictions from oscillation experiments for mass observables



From E. Lisi et al.

ν-mass from ^3H decay: KATRIN

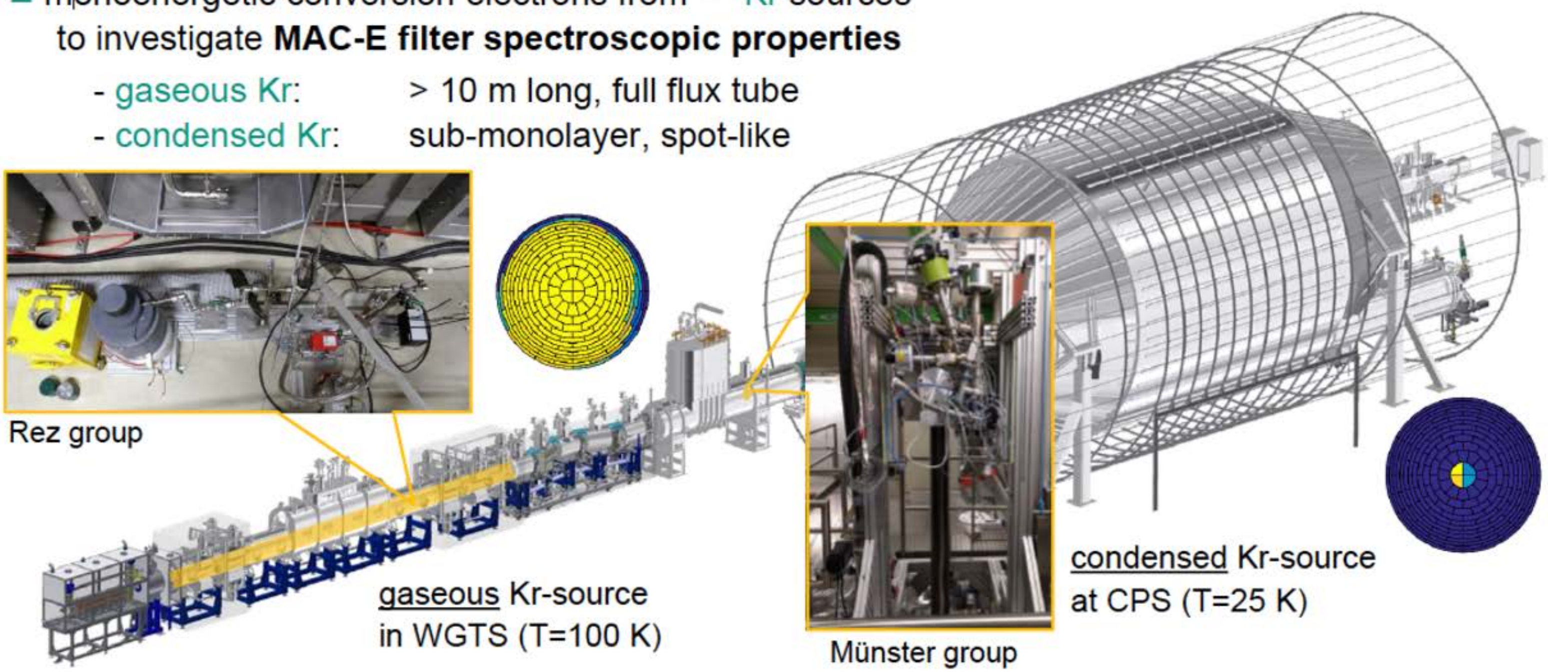


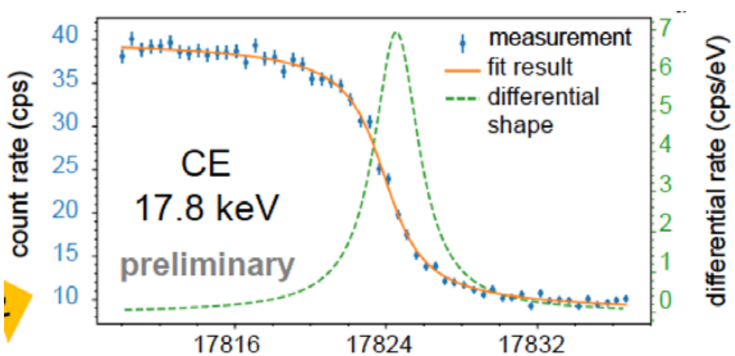
S. Schönert | TUM
Strategieworkshop Teilchenphysik, Bonn, 3-4.5.2018
Neutrinomass & $0\nu\beta\beta$ decay

Courtesy T. Thümmler (Katrin)

KATIN milestone 2017: krypton campaign

- monoenergetic conversion electrons from ^{83m}Kr sources to investigate **MAC-E filter spectroscopic properties**
  - gaseous Kr: > 10 m long, full flux tube
  - condensed Kr: sub-monolayer, spot-like



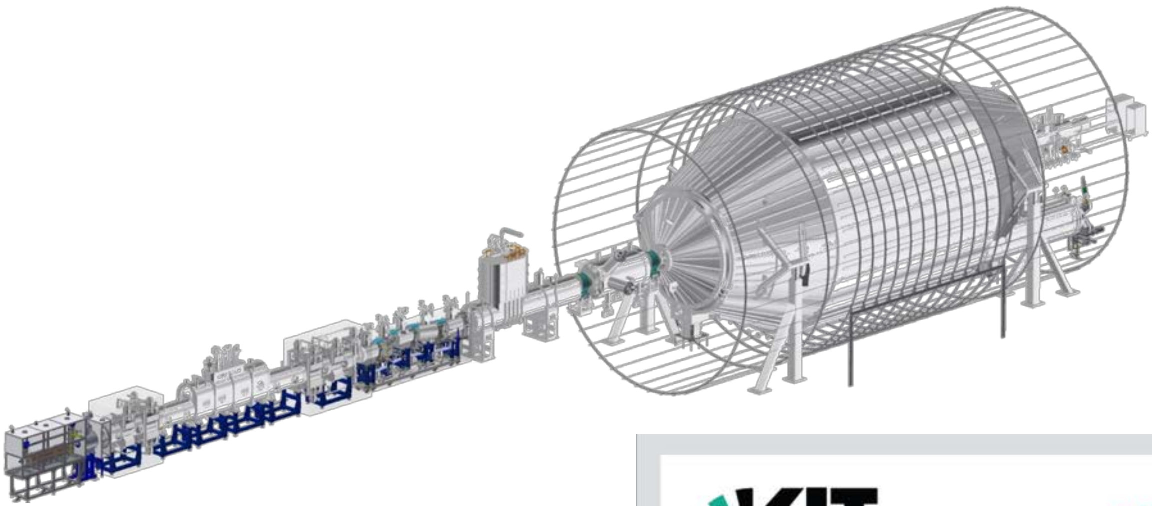


$$\frac{\Delta E}{E} \cong \frac{B_{min}}{B_{max}}$$ (1.15 eV @ 17.83 keV)

Courtesy G. Drexlin

KATRIN milestone 2018: first tritium& inauguration

May/June ´18 –first tritium runs (1%)

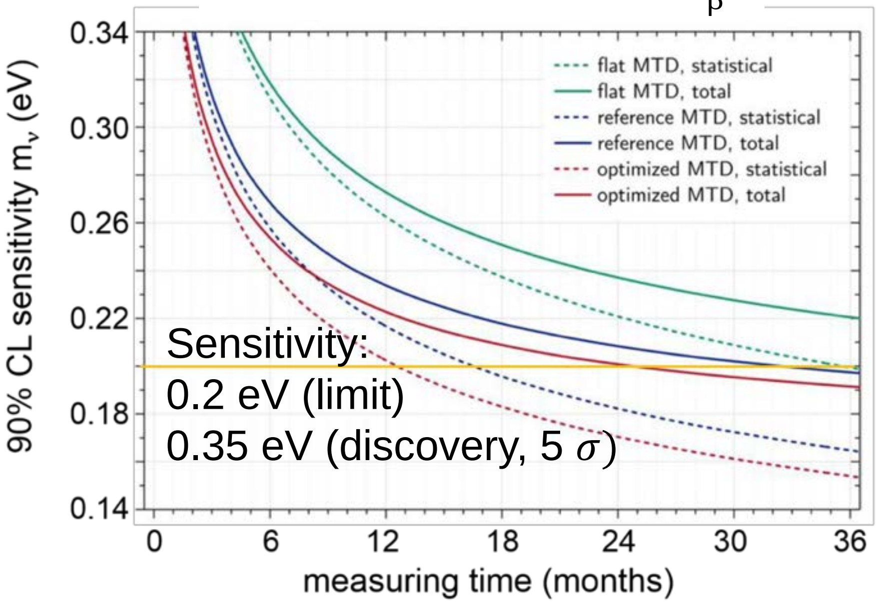


June 11: Inauguration

Courtesy G. Drexlin

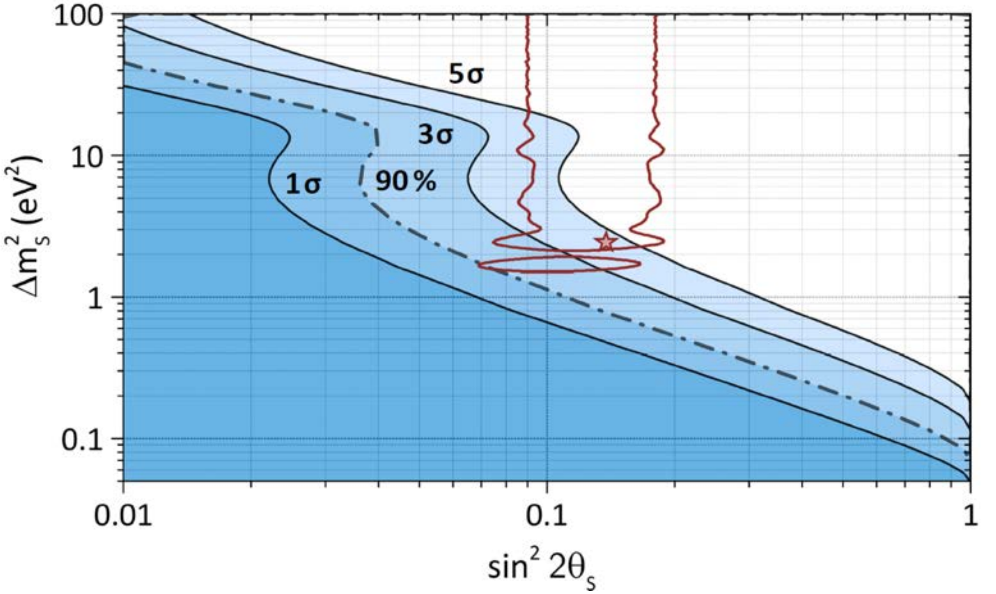
KATRIN: 2019-2023 regular tritium data taking

measure / constrain m_β



Sensitivity:
0.2 eV (limit)
0.35 eV (discovery, 5 σ)

eV-scale sterile neutrinos



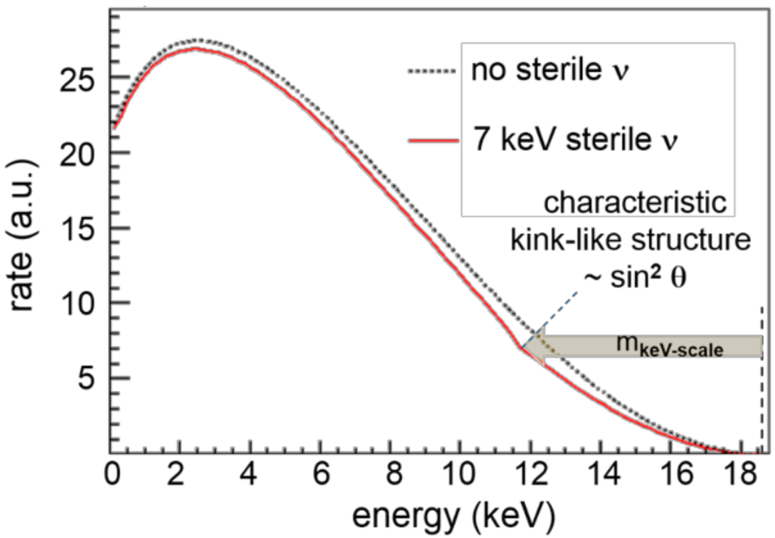
R&D to reach ~0.1 eV:

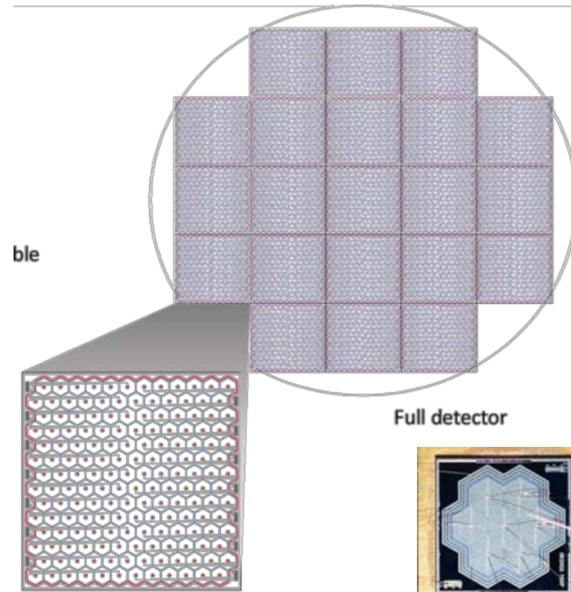
- differential read-out via ToF-technique or cryo-bolometer
- novel source concepts: atomic tritium

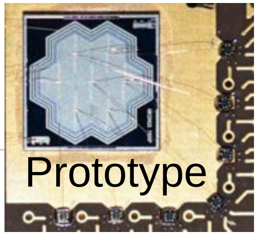
Courtesy G. Drexlin

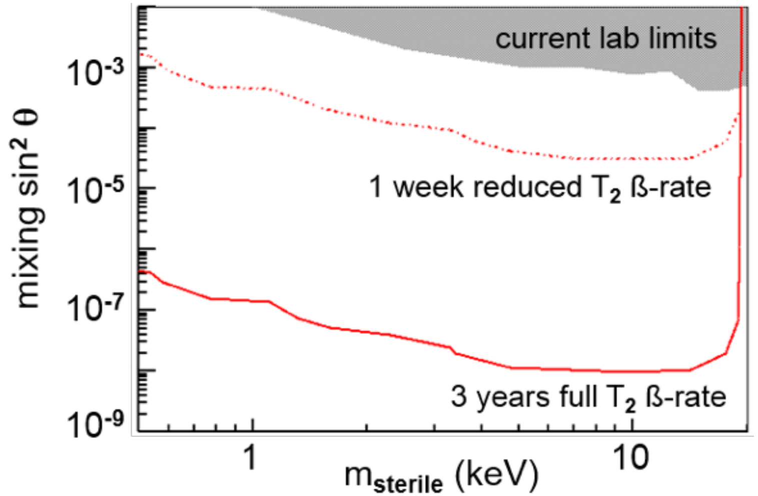
KATRIN future: TRISTAN – search for keV scale ν´s

New Si-array (TRISTAN) to search for kink in ß-spectrum over entire tritium spectrum (0-18.6 keV)







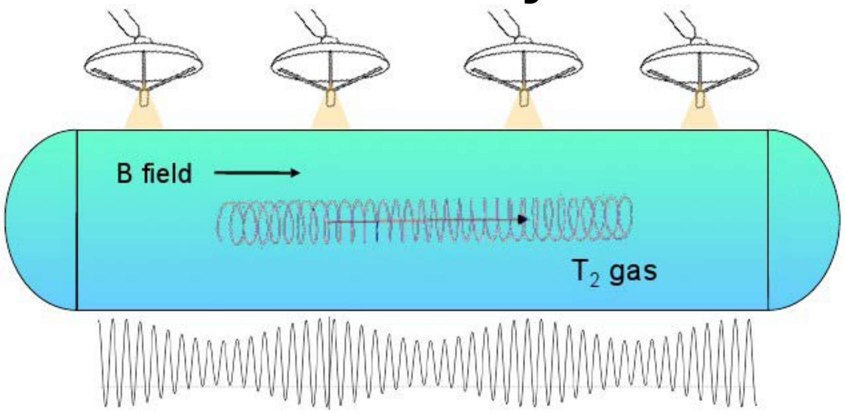


Courtesy G. Drexlin

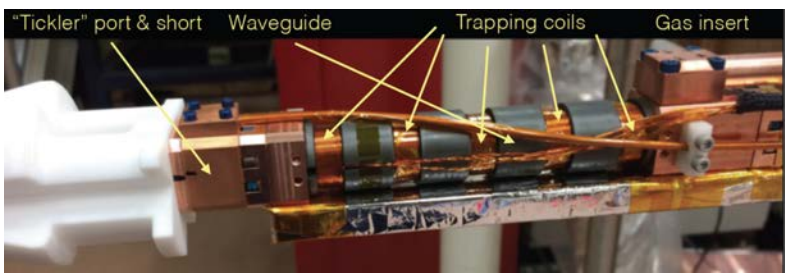
Project 8

Measurement of cyclotron radiation of tritium electrons

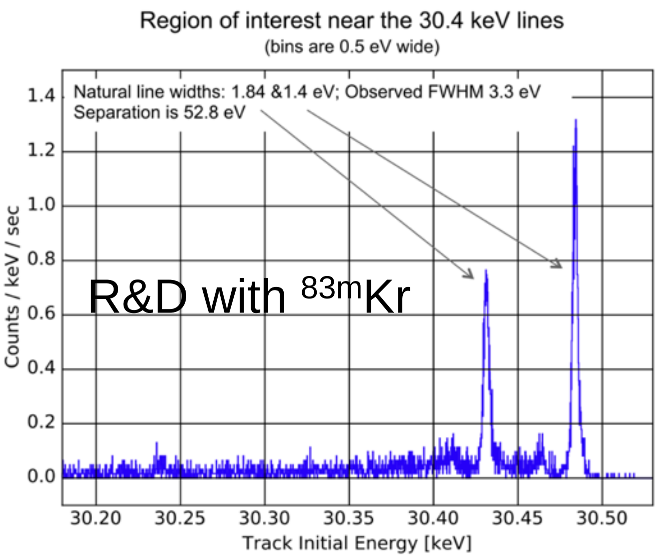
- B-field: 1 Tesla
- ω(18 keV) ~ 26 GHz
- P(18 keV) = 1.2 fW



R&D with tritium



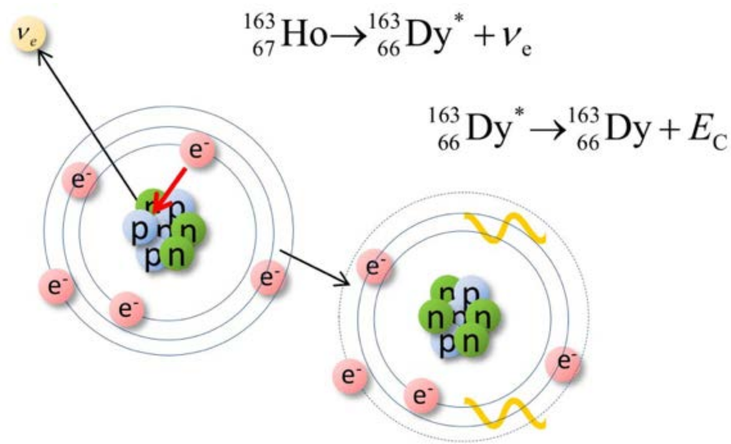
- 10^{11} molecules/cm^3, 10 m^3 ,1 year: optimistically 100 meV
- If 100 m^3 atomic tritium source possible: 40 meV



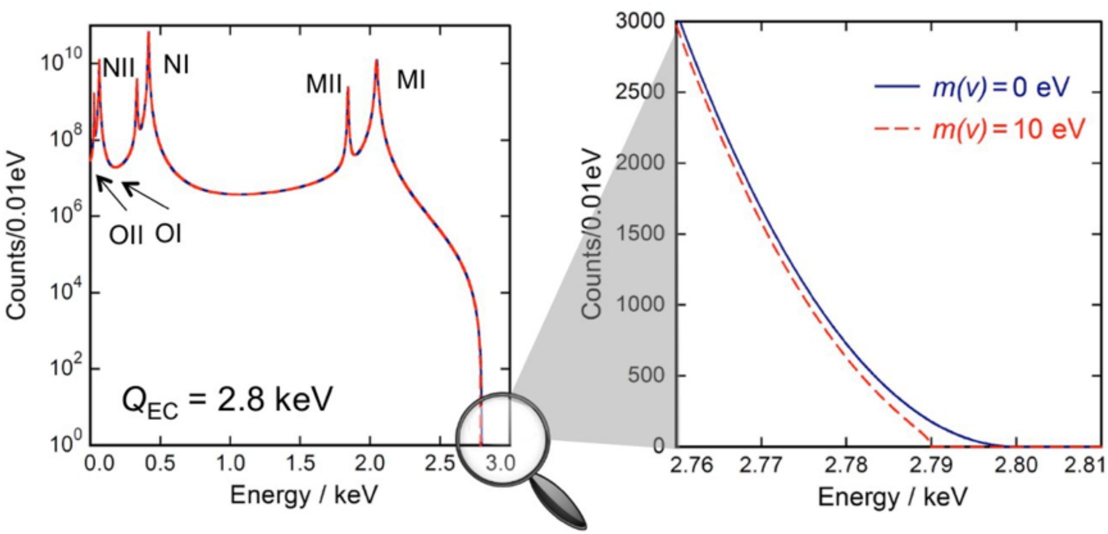
R&D with ^{83m}Kr

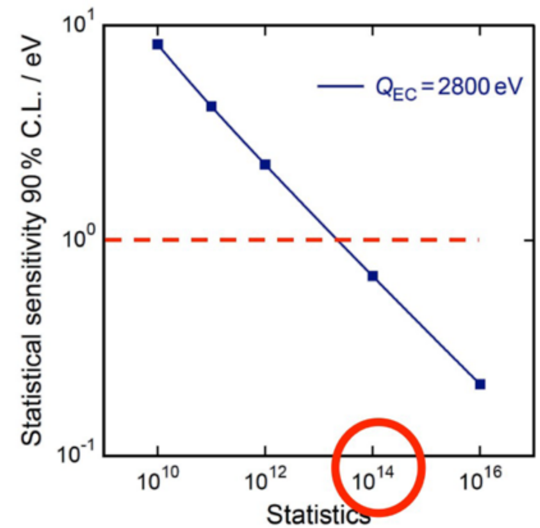
German participation from KIT and Univ. Mainz

ECHo



^{163}Ho decays by electron capture (EC) with $T_{1/2} \approx 4570$ y (2×10^{11} atoms for 1 Bq)

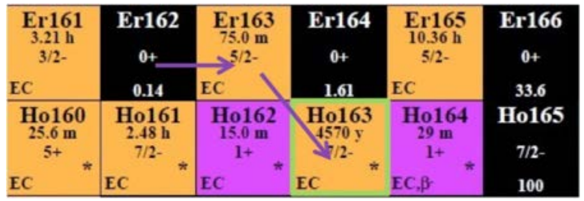


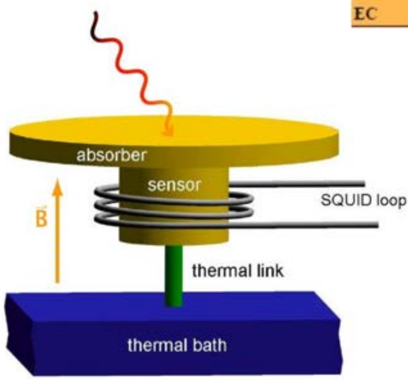


Courtesy L. Gastaldo

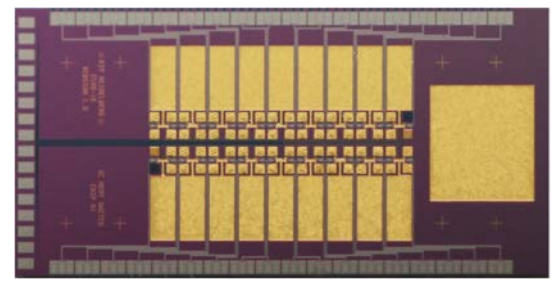
ECHo

@ISOLDE-CERN





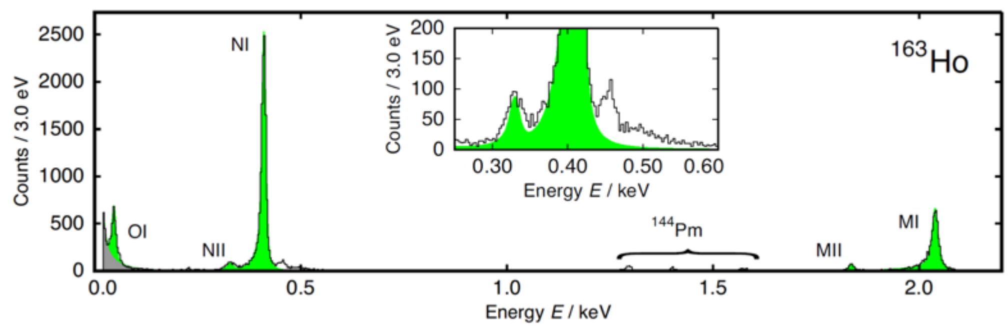
Read out of MMC with microwave SQUID multiplexing



$$\Delta\Phi_S \propto \frac{\partial M}{\partial T}\Delta T \quad \rightarrow \quad \Delta\Phi_S \propto \frac{\partial M}{\partial T}\,\frac{E}{C_{sens}+C_{abs}}$$

Q-value measurement:
Q_{EC} = (2.858 +- 0.010_{stat} +- 0.05_{syst}) keV
Phys. Rev. Lett. 119 (2017) 122501

ECHo-1K (2015-2018): m < 10 eV
Future: ECHo-10M for sub-eV sensitivity



A neutrino mass network: KATRIN + ECHo

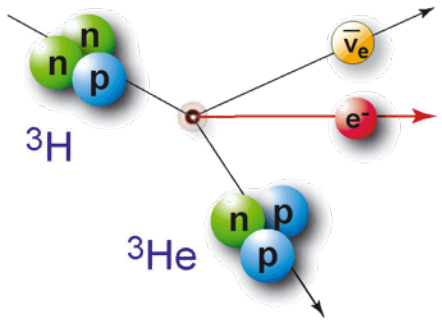
March 2017: MoU on „absolute neutrino mass scale from nuclear ß-decay and electron capture“

Spokespersons: K. Valerius & L. Gastaldo

BiannualTrento meetings of worldwide direct neutrino mass community at ECT*

ν-mass observables

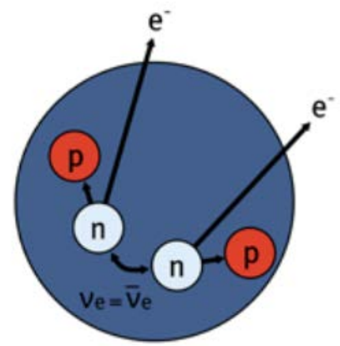
<u>β-decay</u>



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

(Dirac or Majorana)

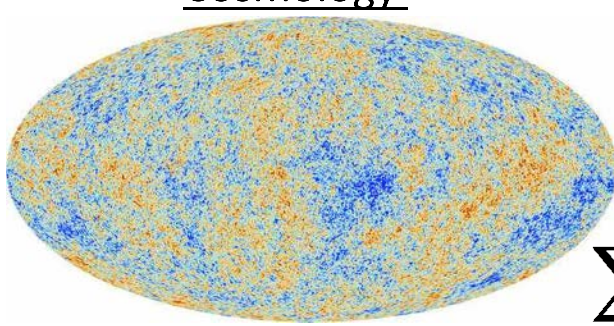
<u>0νββ-decay</u>



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

(Majorana)

<u>Cosmology</u>

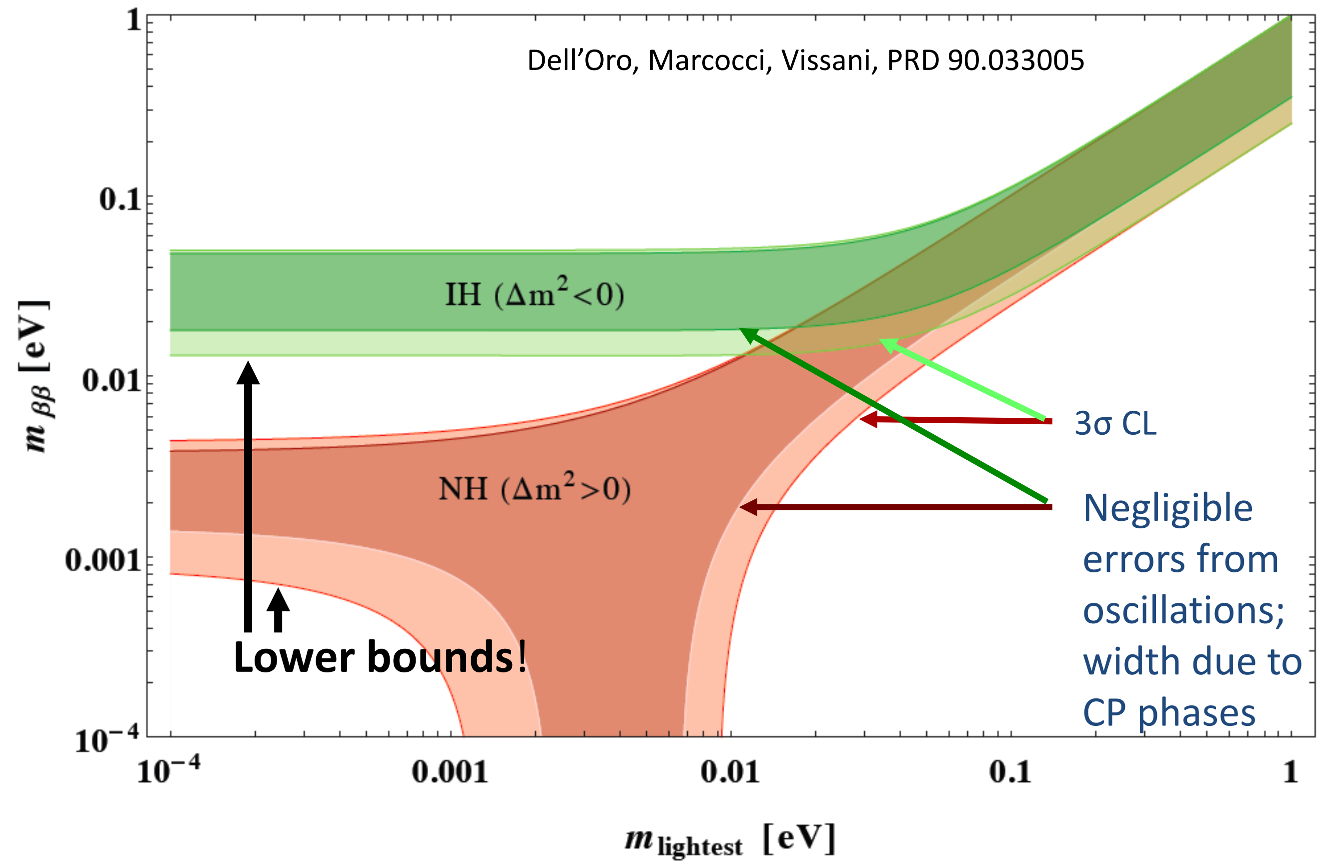


$$\sum_i m_i$$

$0\nu\beta\beta$: Range of m_{ee} from oscillation experiments

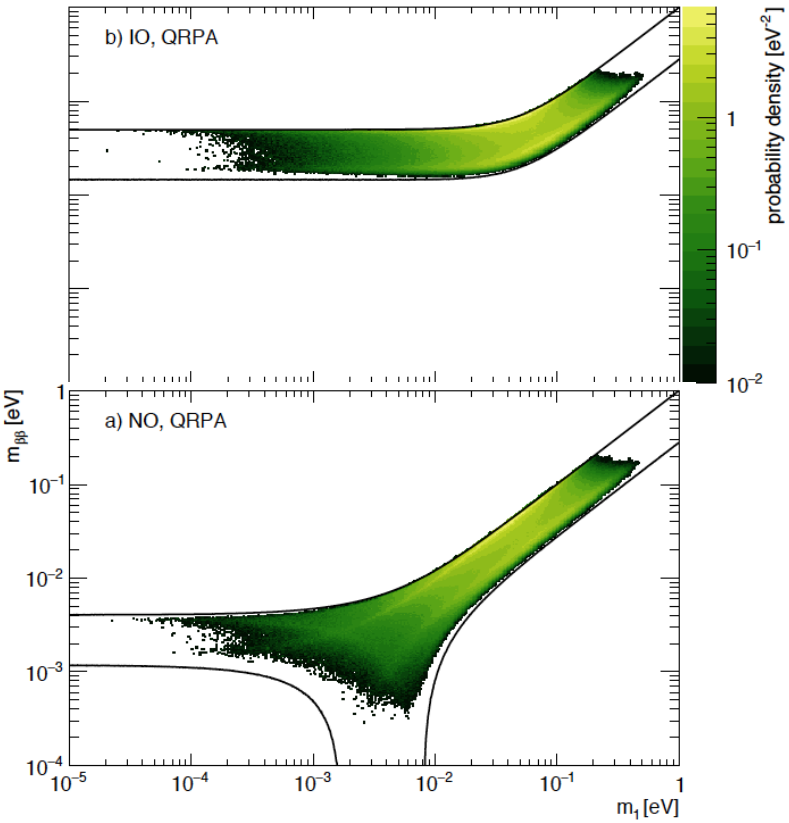
$$m_{ee} = f(m_1, \underbrace{\Delta m^2_{sol}, \Delta m^2_{atm}, \theta_{12}, \theta_{13}}_{\text{from oscillation experiments}}, \alpha\text{-}\beta)$$

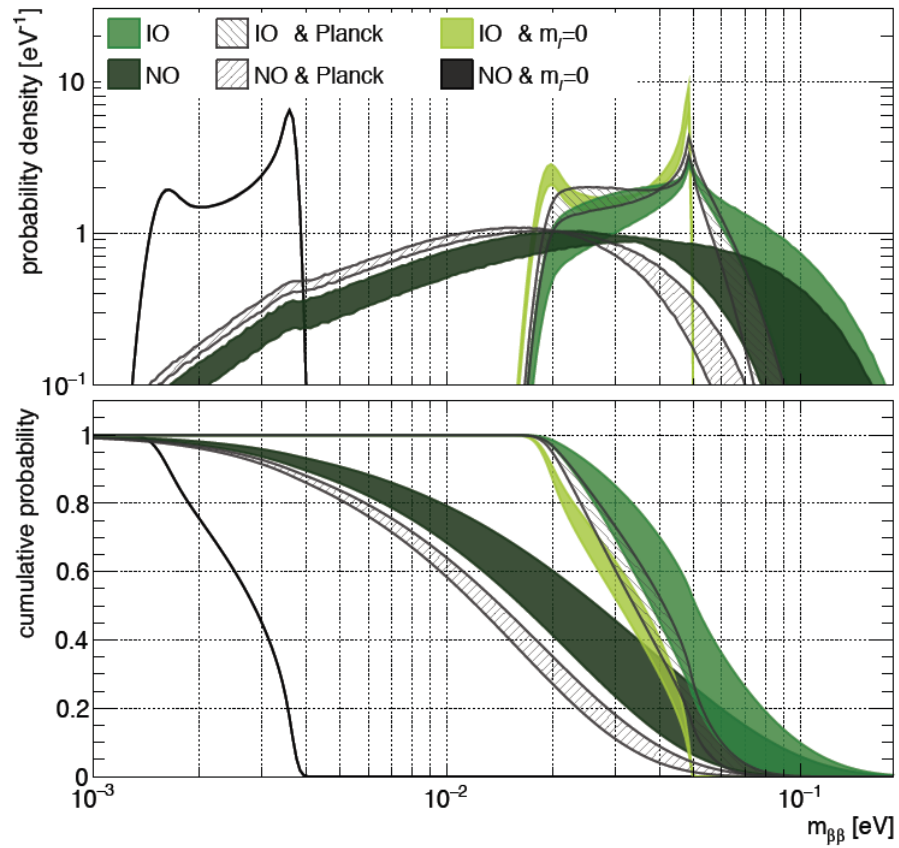
Goal of next generation experiments:



Discovery probabilities

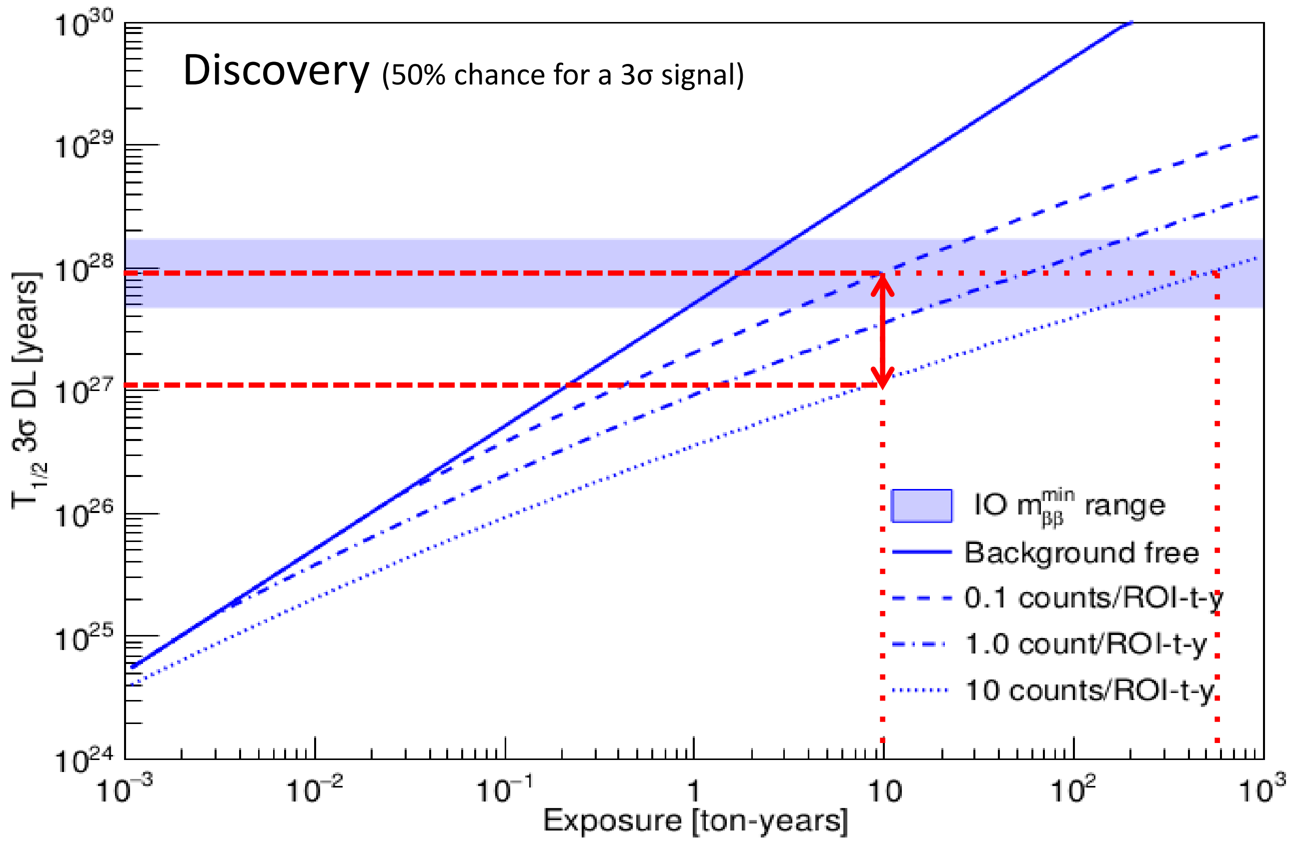
- Global Bayesian analysis including ν-oscillation, m_β $m_{\beta\beta}$, Σ
- Priors:
  - Majorana phases (flat)
  - m_1 (scale invariant)





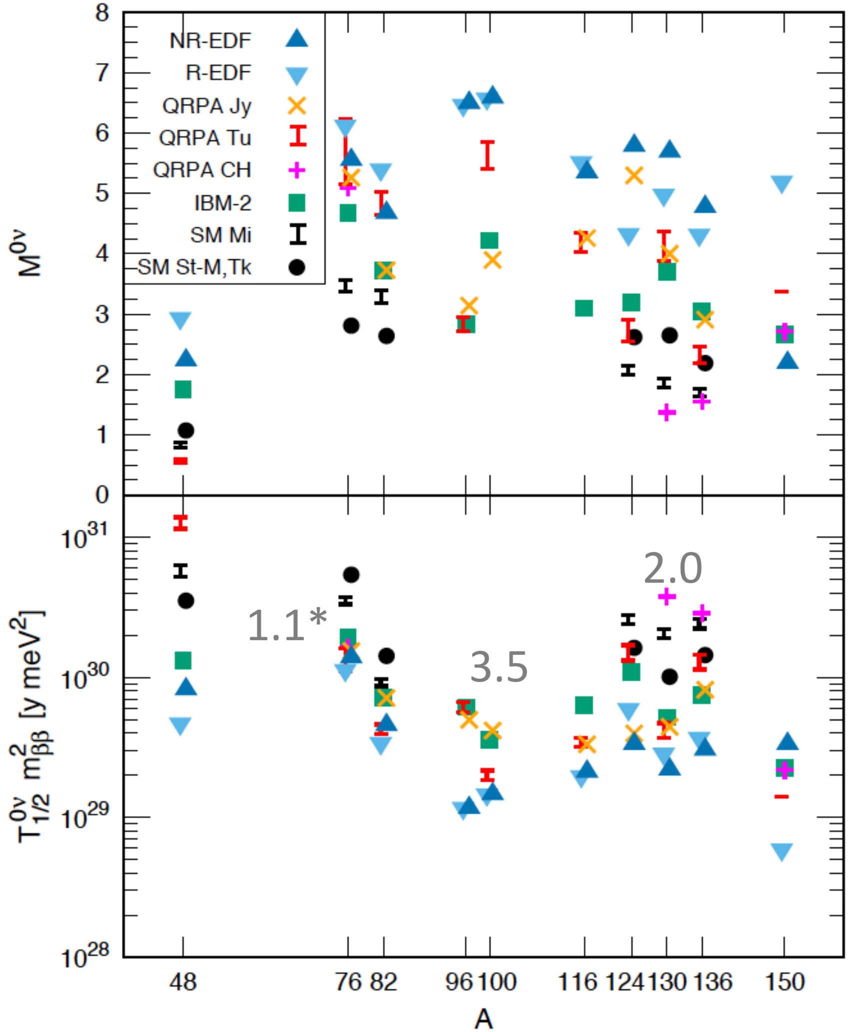
Agostini, Benato, Detwiler arXiv:1705.02996

Discovery sensitivity vs. background



Courtesy J. Detwiler

Nuclear matrix elements



Spread about x2

No isotope significantly preferred when comparing decay rate per mass

Choice mainly driven by experimental considerations

*number = signal rate per 1000 kg yr exposure & for middle of NME values for

For $<m_{ee}>$ = 17.5 meV ('bottom of IH' for g_A=1.25, $\sin^2\theta_{12}$ = 0.318)

Engel & Menédez

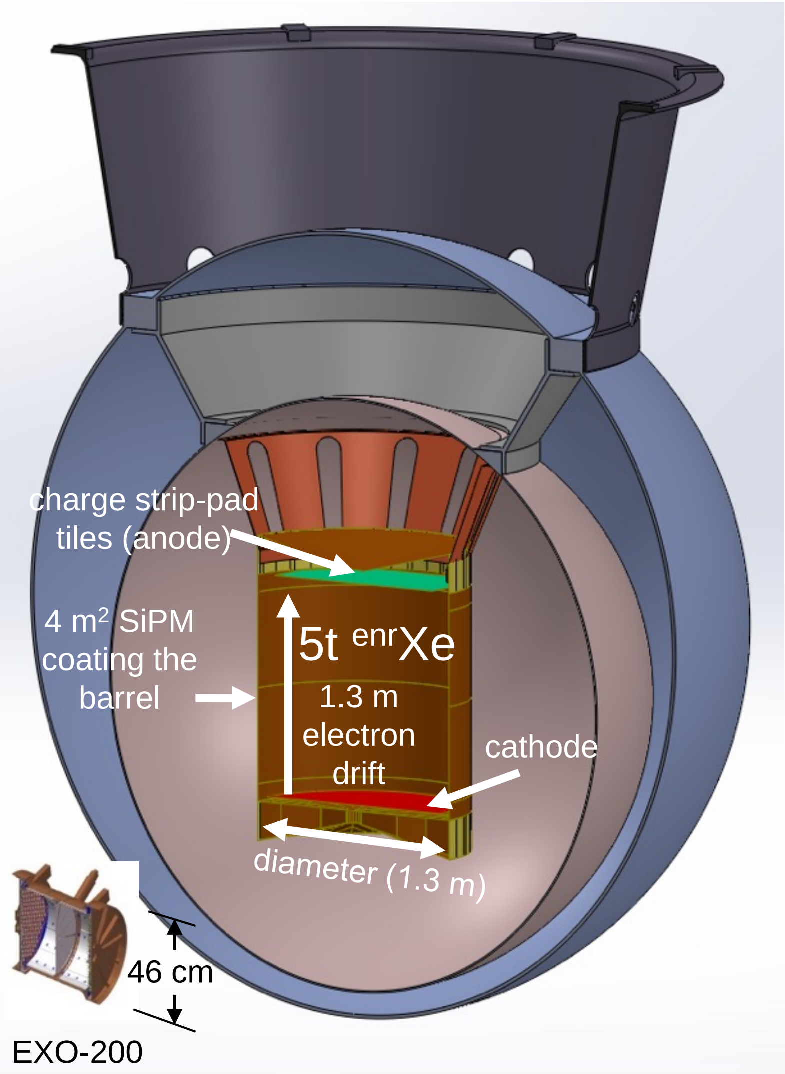
arXiv:1610.06548v2

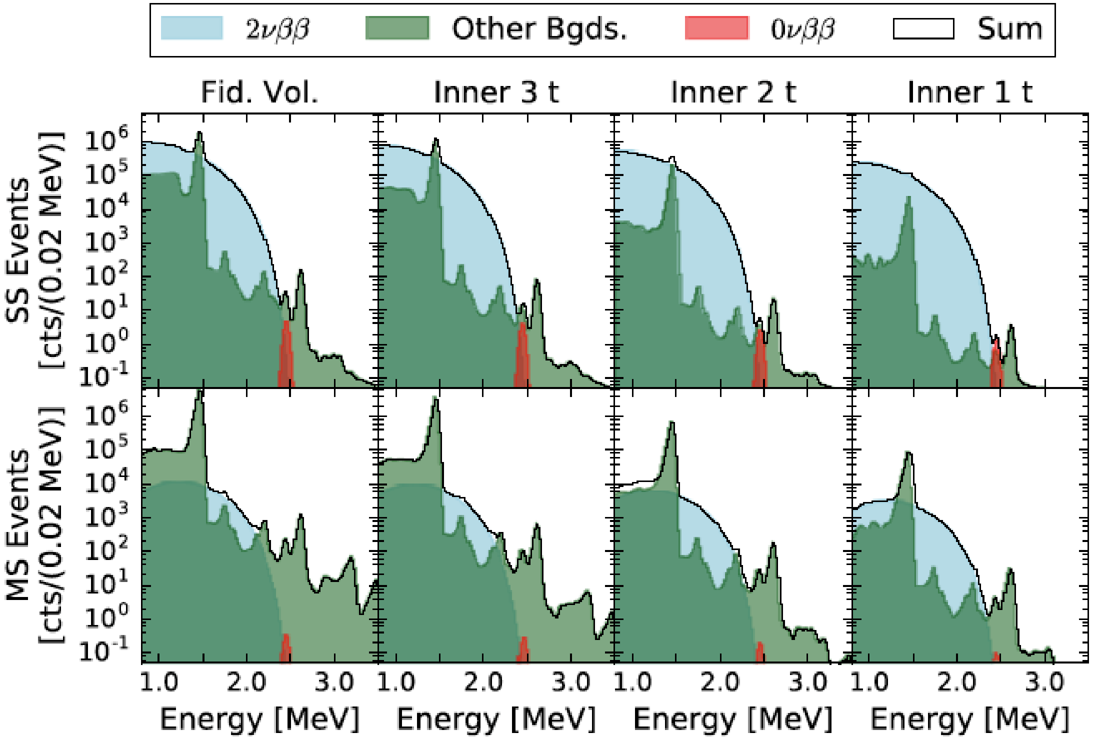
Experimental status: sensitivity & limits on half-life

experiment		isotope	M_i [kg]	NME	sensitivity $T_{1/2}^{0\nu}$ [10^{25} yr]	sensitivity $m_{\beta\beta}$ [eV]	limit $T_{1/2}^{0\nu}$ [10^{25} yr]	limit $m_{\beta\beta}$ [eV]
GERDA		^{76}Ge	31	2.8-6.1	5.8	0.14–0.30	8.0	0.12–0.26
MAJORANA	[13]	^{76}Ge	26	2.8-6.1	2.1	0.23–0.51	1.9	0.24–0.53
KamLAND-Zen	[24]	^{136}Xe	343	1.6-4.8	5.6	0.07–0.22	10.7	0.05–0.16
EXO	[25, 26]	^{136}Xe	161	1.6-4.8	1.9	0.13–0.37	1.1	0.17–0.49
CUORE	[27, 28]	^{130}Te	206	1.4-6.4	0.7	0.16–0.73	1.5	0.11–0.50

PRL 120, 132503, 2018

Xenon Experiments: nEXO





Discovery sensitivity (3σ, 50%) after 10 yr
$T_{1/2}^{0\nu\beta\beta} = 5.5\times10^{27}$ yr

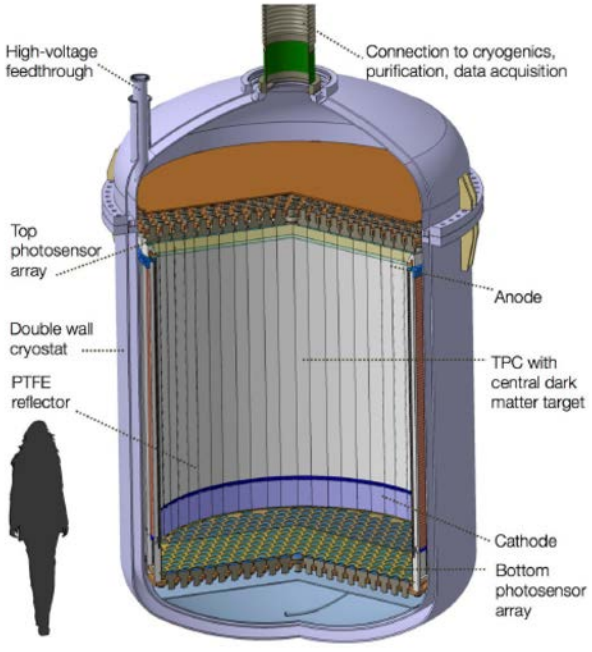
If ^{136}Ba-tagging can be implemented:
$T_{1/2}^{0\nu\beta\beta} = 1.6\times10^{28}$ yr

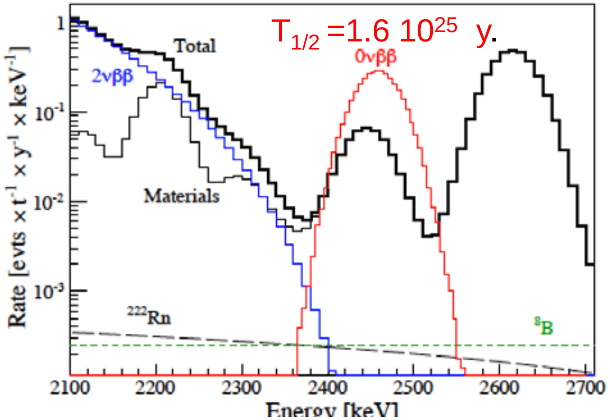
Participation from Germany: Univ. Erlangen

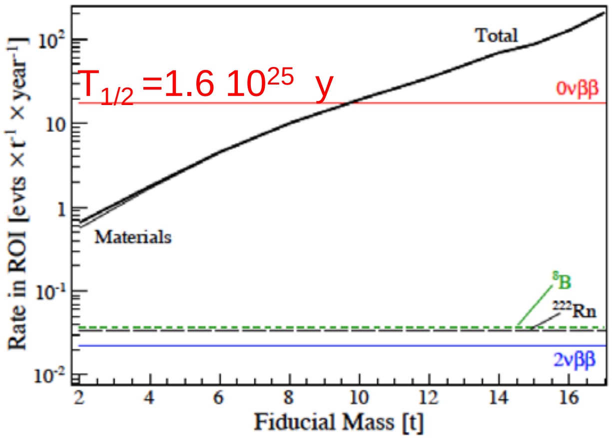
Courtesy G. Gratta

Xenon Experiments: DARWIN

- Primary goal direct dark matter detection



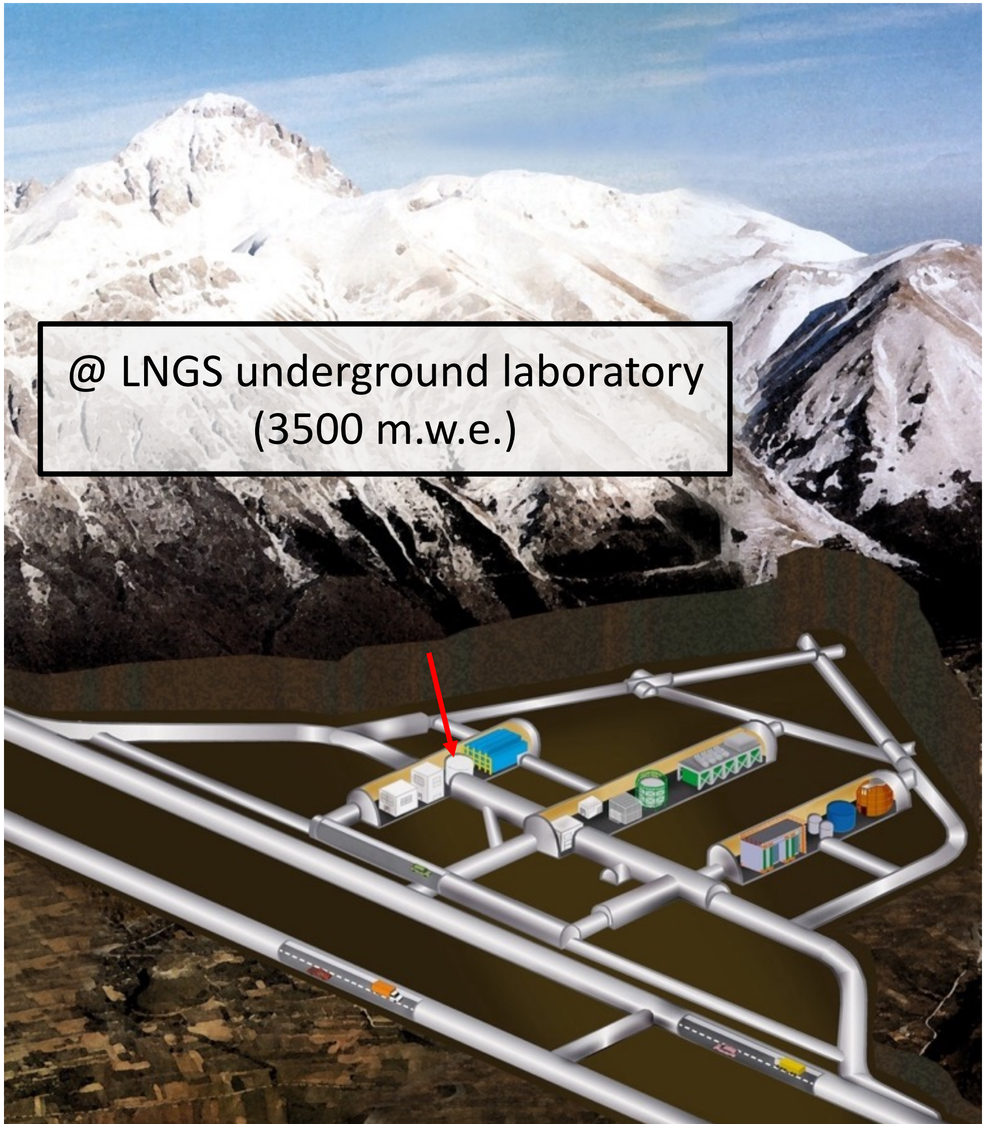


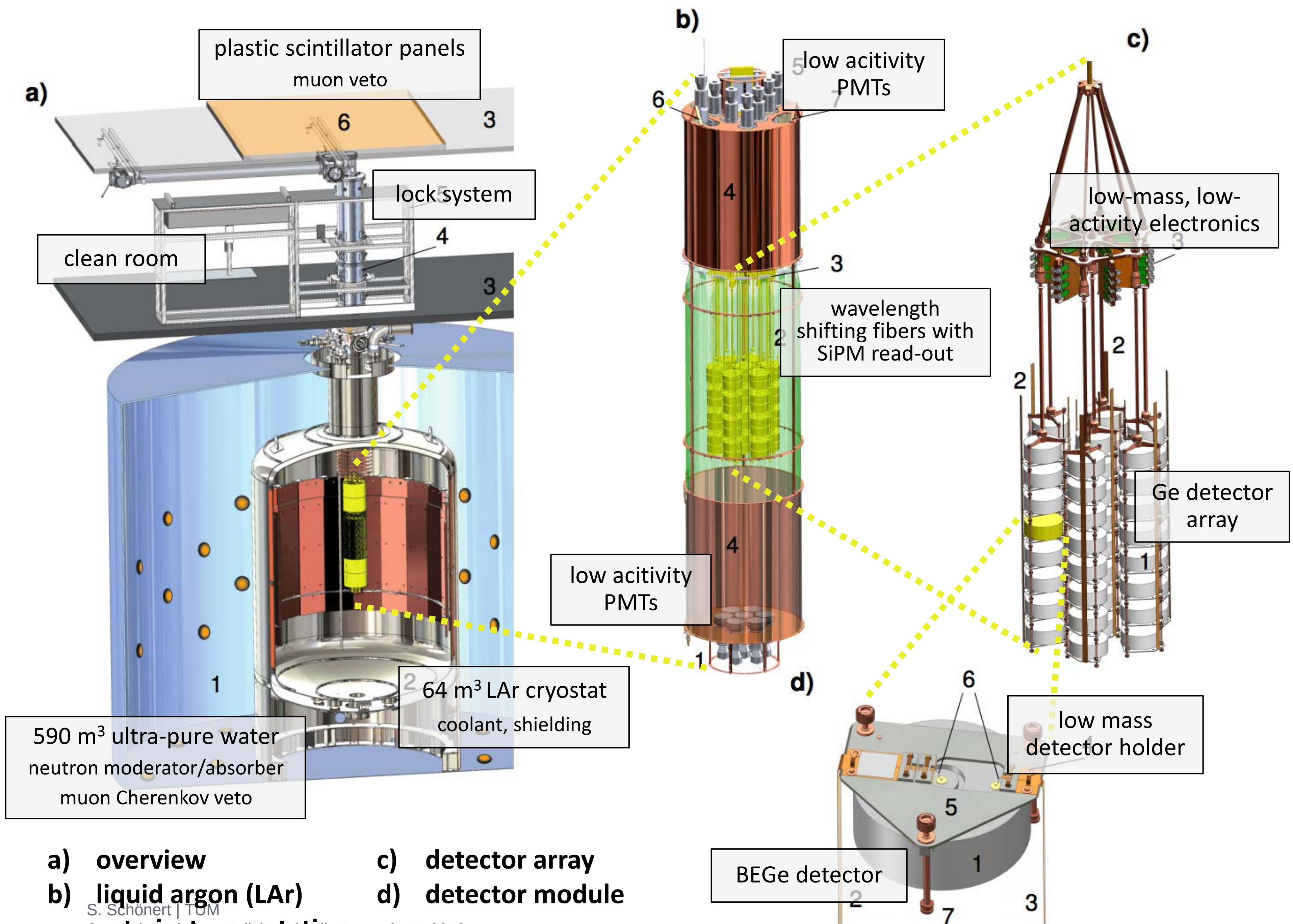


50 t natural Xenon (8.9% Xe-136)
Challenge: keV threshold for DM and $\Delta E/E$ (σ) <1% at $Q_{\beta\beta}$

arXiv:1309.7024v2

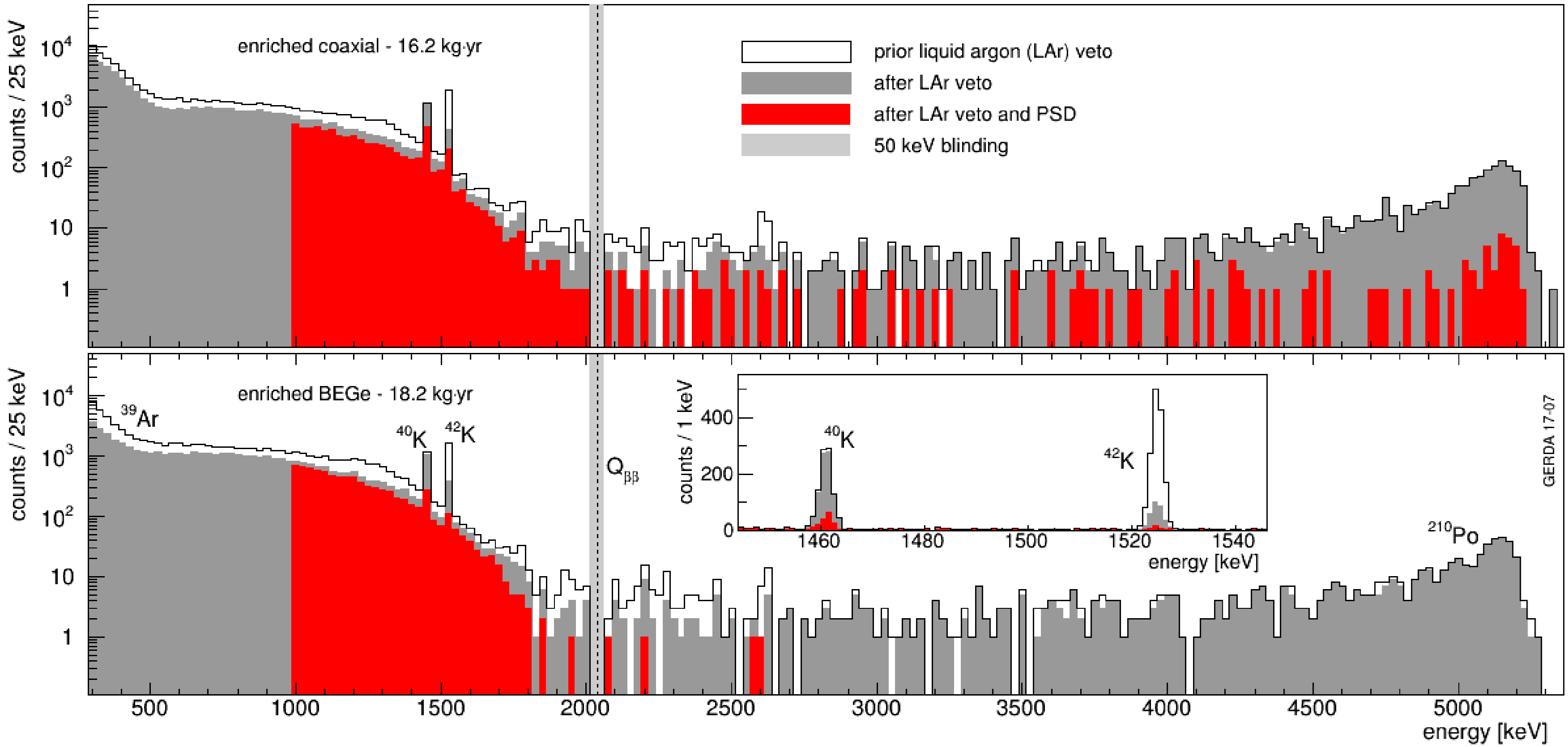
GERDA Phase II experimental setup at LNGS





a) **overview**
b) **liquid argon (LAr) veto instrumentation**
c) **detector array**
d) **detector module**

Spectra / background suppression by LAr & PSD



- **Suppression** by LAr veto
  -> *pure* 2vbb continuum
- LAr veto and PSD **complementary**
- *no* alphas in BEGe's afer PSD

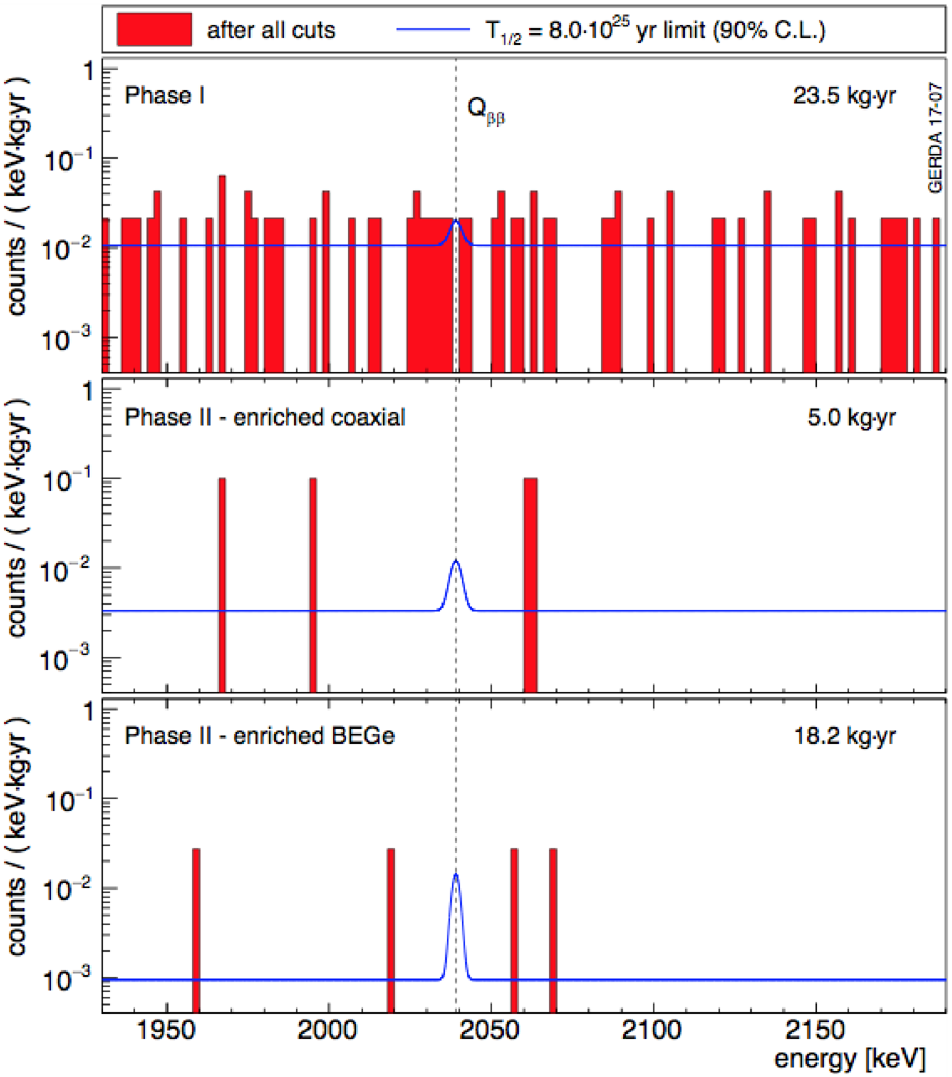
Statistical analysis

- unblinding of **18.2 kg*yr** BEGe data

background index @ Q_{bb}
4 cts -> $1.0^{+0.6}_{-0.4}\ 10^{-3}$ cts/(keV*kg*yr)

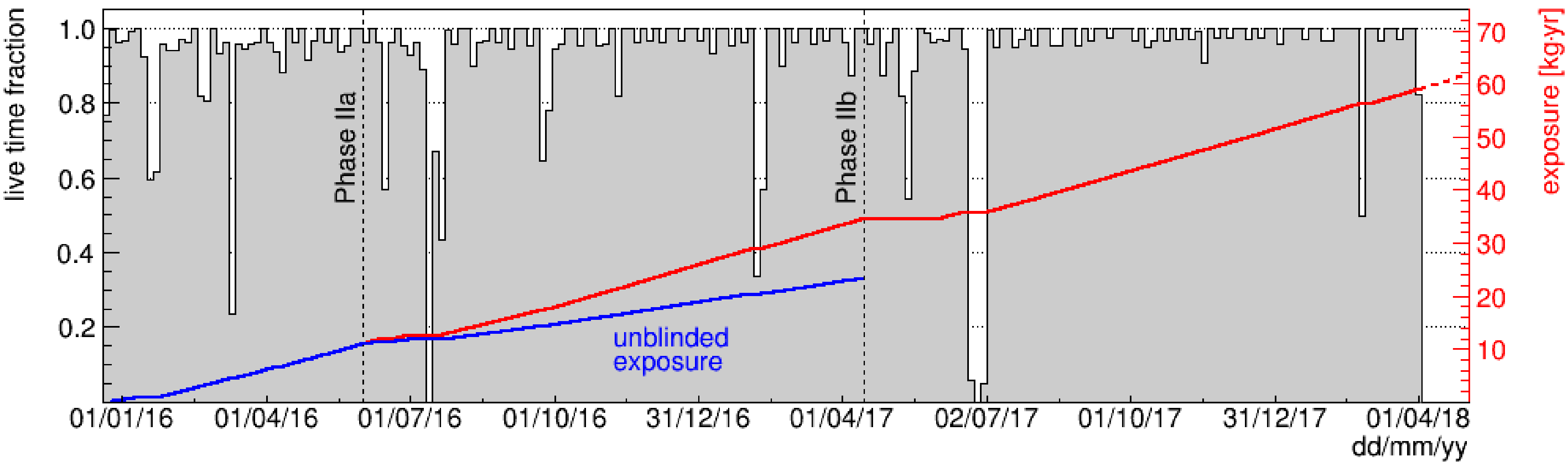
- combined (Phase I, Phase IIa/b) **unbinned maximum likelihood fit**

	Profile likelihood	Bayesian
$T_{1/2}$ lower limit [10^{25} yr]	**8.0** (90% CL)	5.1 (90% CI)
$T_{1/2}$ median sensitivity [10^{25} yr]	**5.8** (90% CL)	4.5 (90% CI)



PRL 120, 132503, March 2018
See also: Nature 544 (2017) 47

GERDA unblinding on Mai 3



significant fraction of fresh data!

(**23.3** (+23.5) **kg*yr** vs. **35.7 kg*yr**)

Sensitivity 10^{26} yr and background goals reached!

New results will be presented at Neutrino 2018

LEGEND the collaboration

Univ. New Mexico
L'Aquila Univ. and INFN
Gran Sasso Science Inst.
Lab. Naz. Gran Sasso
Univ. Texas
Tsinghua Univ.
Lawrence Berkeley Natl. Lab.
Leibniz Inst. Crystal Growth
Comenius Univ.
Lab. Naz. Sud
Univ. of North Carolina
Sichuan Univ.
Univ. of South Carolina
Jagiellonian Univ.
Banaras Hindu Univ.
Univ. of Dortmund
Tech. Univ. – Dresden
Joint Inst. Nucl. Res. Inst.
Nucl. Res. Russian Acad. Sci.
Joint Res. Centre, Geel

47 Institutions
219 scientists

Collaboration formed
1st Munich April 2016
2nd Atlanta October 2016
3rd LNGS May 2017
4th Berkeley Dec 2017

Chalmers Univ. Tech.
Max Planck Inst., Heidelberg
Dokuz Eylul Univ
Queens Univ.

Univ. Tennessee
Argonne Natl. lab.
Univ. Liverpool
Univ. College London

Los Alamos Natl. Lab.
Lund Univ.
INFN Milano Bicocca
Milano Univ. and Milano INFN
Natl. Res. Center Kurchatov Inst.
Lab. for Exper. Nucl. Phy. MEPhI
Max Planck Inst., Munich
Technical Univ. Munich
Oak Ridge Natl. Lab.
Padova Univ. and Padova INFN
Czech Tech. Univ. Prague
Princeton Univ.
North Carolina State Univ.
South Dakota School Mines Tech.
Univ. Washington
Academia Sinica
Univ. Tuebingen
Univ. South Dakota
Univ. Zurich

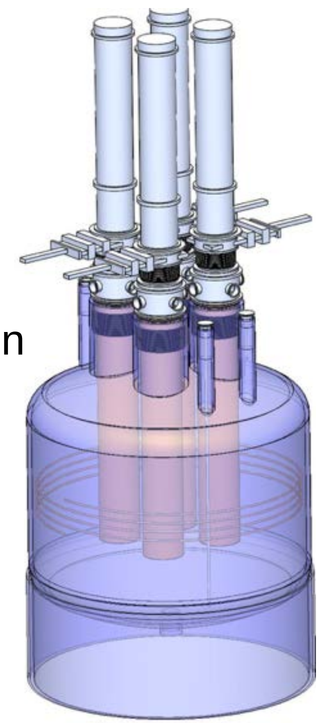
LEGEND program

LEGEND-200 (first phase):

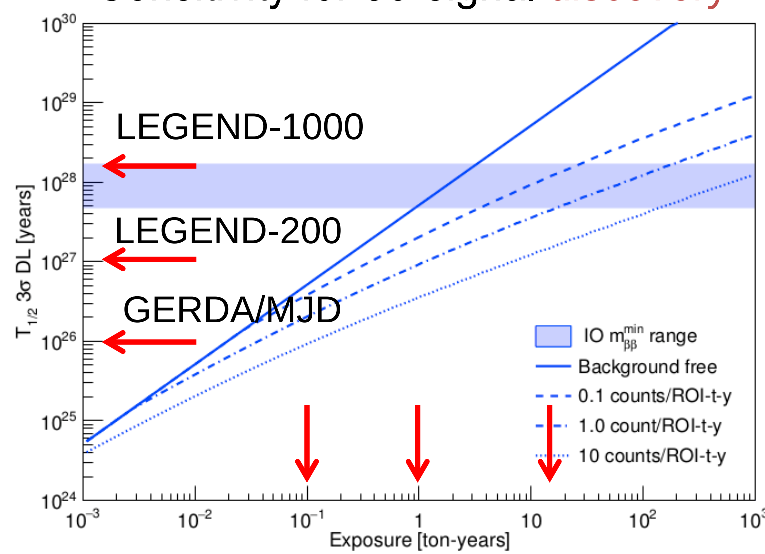
- up to 200 kg of detectors
- BI ~0.6 cts/(FWHM□t□yr)
- upgrade existing GERDA infrastructure at LNGS (2019-2021)
- design exposure: 1 t·yr
- Sensitivity 10^{27} yr

LEGEND-1000 (second phase):

- 1000 kg of detectors (deployed in stages)
- BI <0.1 cts/(FWHM · t · yr)
- Location tbd
- Design exposure 12 t · yr
- $1.2 \cdot 10^{28}$ yr



Sensitivity for 3σ signal discovery



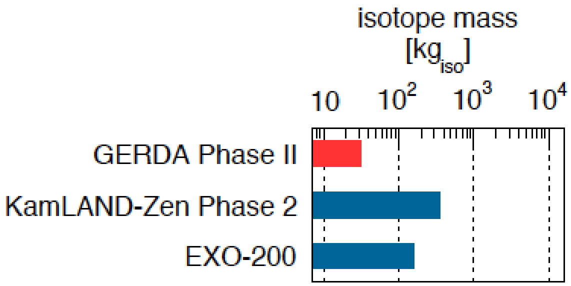
17 meV discovery sensitivity for “worst case” NME of 3.5

Summary & Outlook

- Key results from **KATRIN 2019-2023**: m_β =0.2 eV after 5 yr, eV-sterile, keV-sterile
- **0.1 eV sensitivity** in reach with upgrades (tof, cryogenic detectors)
- ECHo-1k < 10 eV => **ECHo-1M: sub-eV sensitivity**
- **Project 8:** could in principle reach 40 meV sensitivity ($100 m^3$)
- Worldwide **community forming:** KATRIN, ECHo / Holmes, Project 8
- Strong activities world-wide for preparation of **ton-scale $0\nu\beta\beta$** experiments
- **Very high discovery** potential for IO
- **Reasonable high discovery** potential also for NO (assuming absence of mechanism driving $m_{\beta\beta}$ or m_l to zero)
- **Several DBD isotopes** and techniques required, given NME uncertainties and low signal rates
- Formidable **experimental challenges** to acquire ton yr exposure quasi **background free**
- Community now ready to move to **ton-scale experiments** with mostly **reasonable extrapolations** w.r. to detector performance and background reduction
- **Staging** largely adopted to produce physics results & minimize (project) risks
- GERDA has **lowest background** and **highest sensitivity** world-wide
- **GERDA, Majorana** and new groups formed **LEGEND**; LEGEND-200 at LNGS starts **2021**
- Experimental design for **discovery** (not limit setting!)

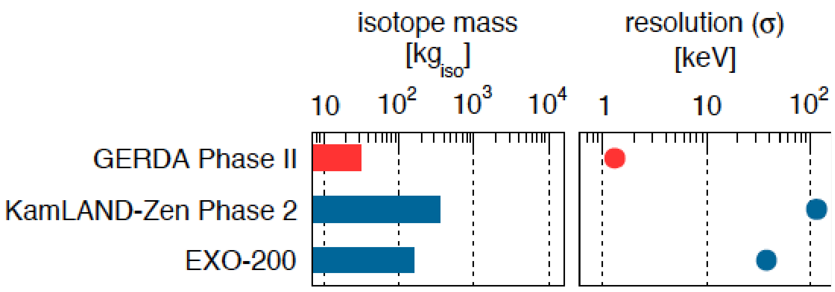
Extra slides

Comparison of Experiments



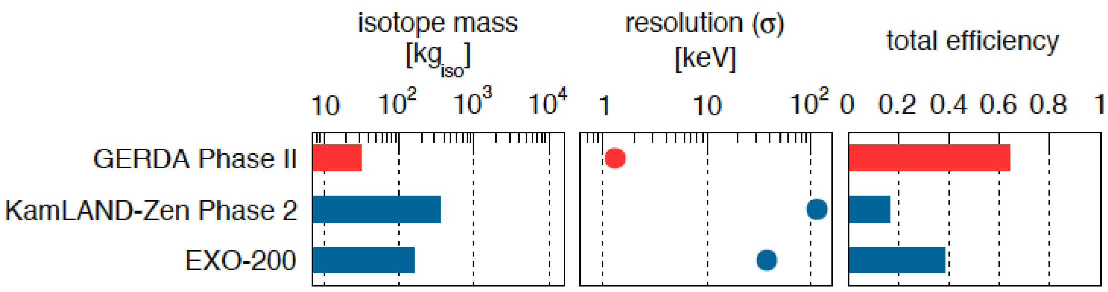
Adopted from Agostini, Benato, Detwiler arXiv:1705.02996

Comparison of Experiments



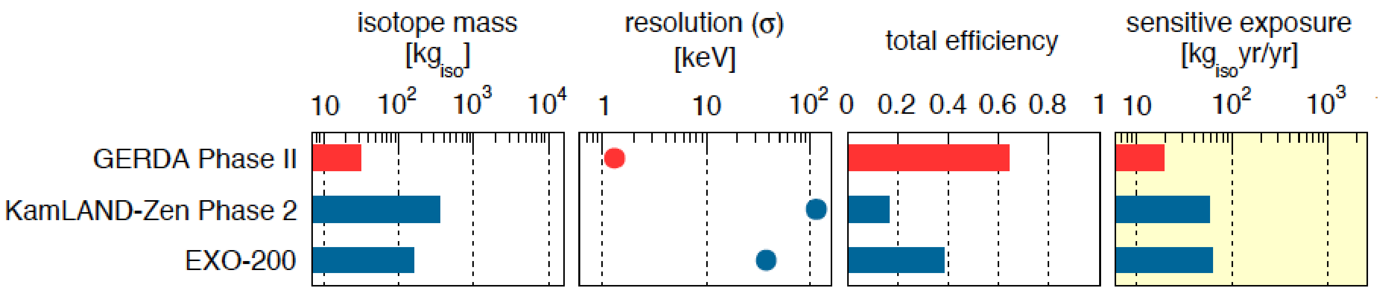
Adopted from Agostini, Benato, Detwiler arXiv:1705.02996

Comparison of Experiments



Adopted from Agostini, Benato, Detwiler arXiv:1705.02996

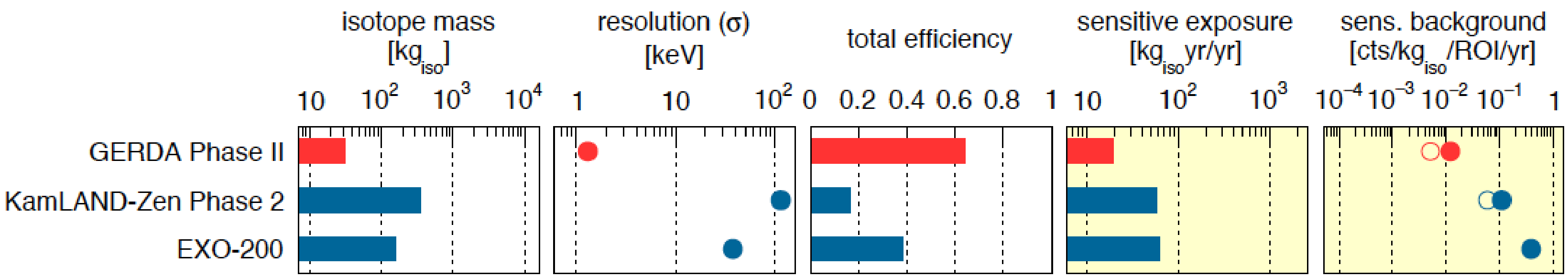
Comparison of Experiments



$M \cdot t \cdot \varepsilon_{tot}$

Adopted from Agostini, Benato, Detwiler arXiv:1705.02996

Comparison of Experiments

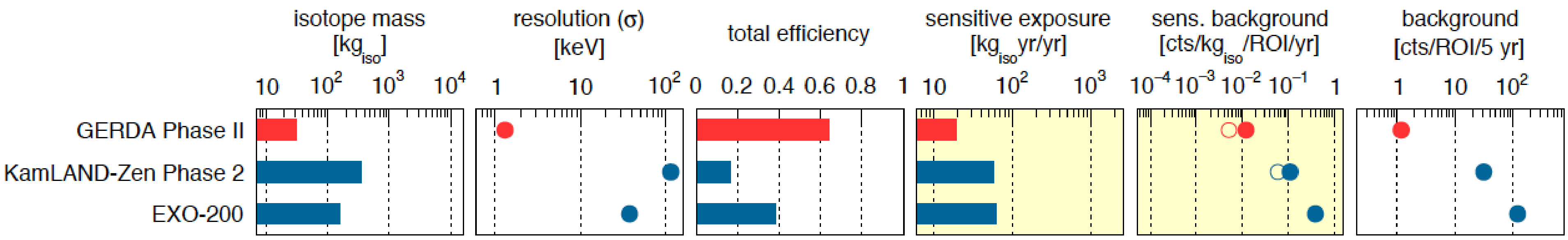


$$M \cdot t \cdot \varepsilon_{tot}$$

$$\frac{n_{bgd}(ROI)}{M \cdot t \cdot \varepsilon_{tot}}$$

Adopted from Agostini, Benato, Detwiler arXiv:1705.02996

Comparison of Experiments



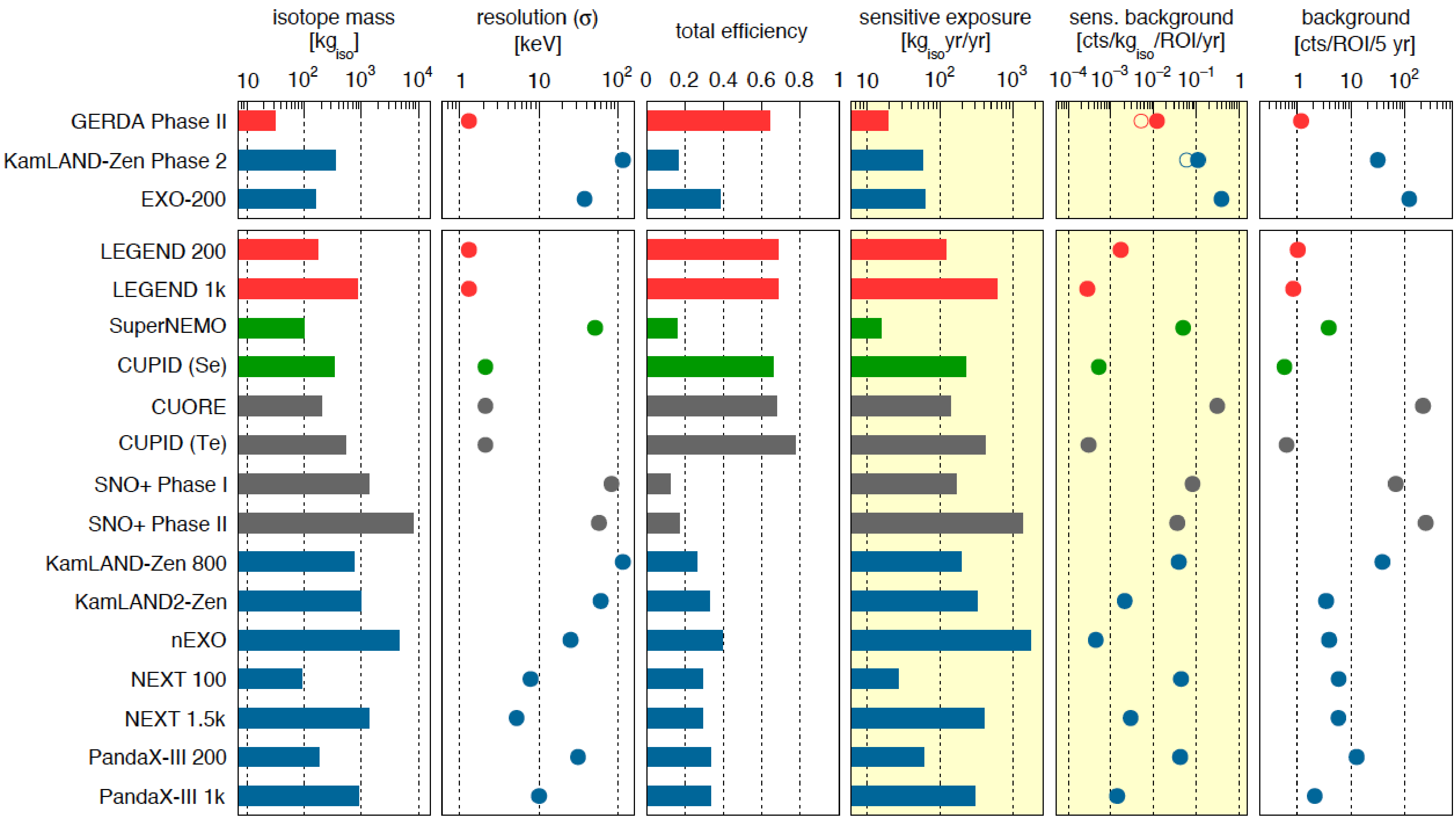
$M \bullet t \bullet \varepsilon_{tot}$

$$\frac{n_{bgd}(ROI)}{M \bullet t \bullet \varepsilon_{tot}}$$

"background free"

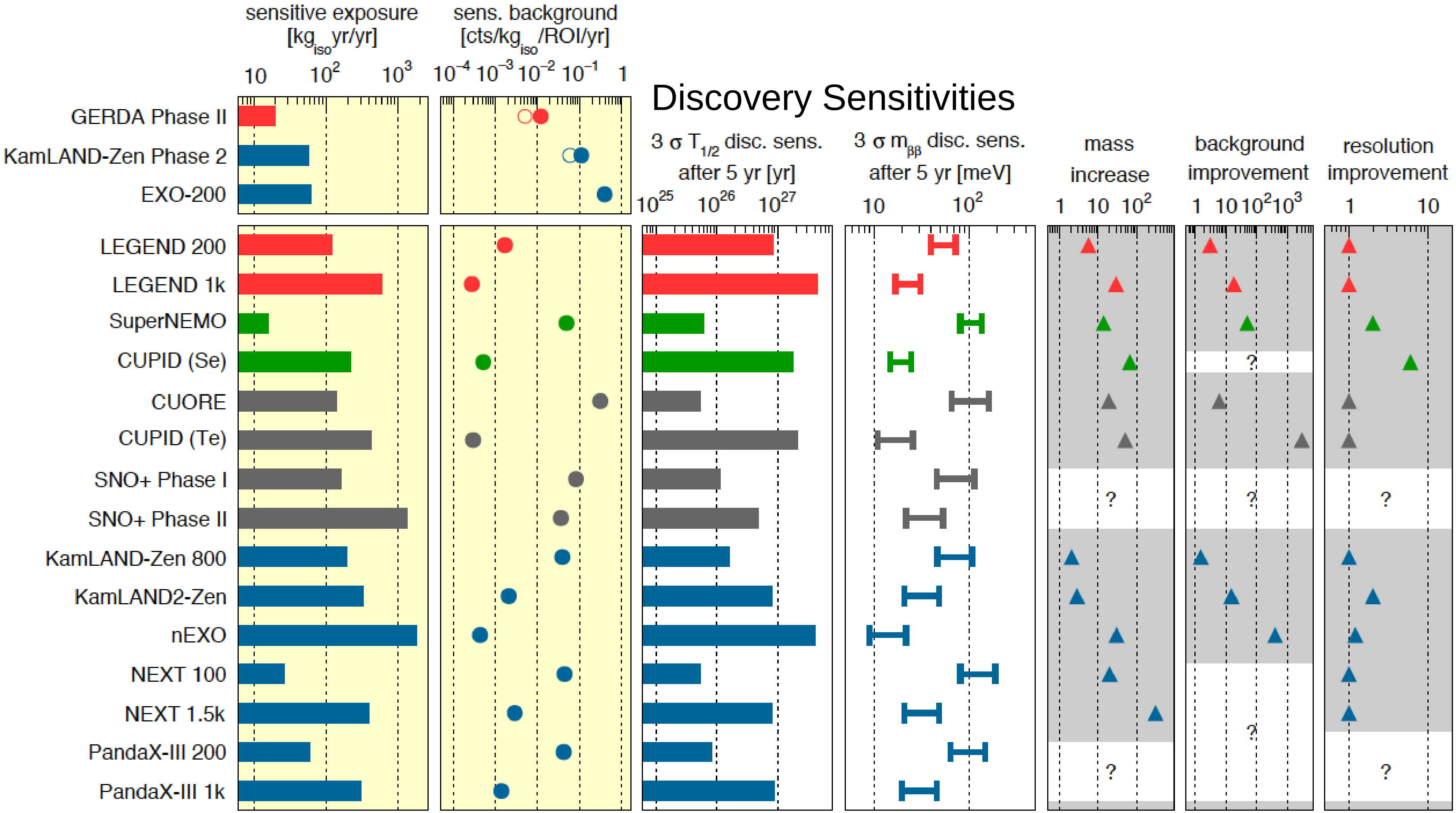
Adopted from Agostini, Benato, Detwiler arXiv:1705.02996

Comparison of Experiments



Adopted from Agostini, Benato, Detwiler arXiv:1705.02996

Comparison of Experiments

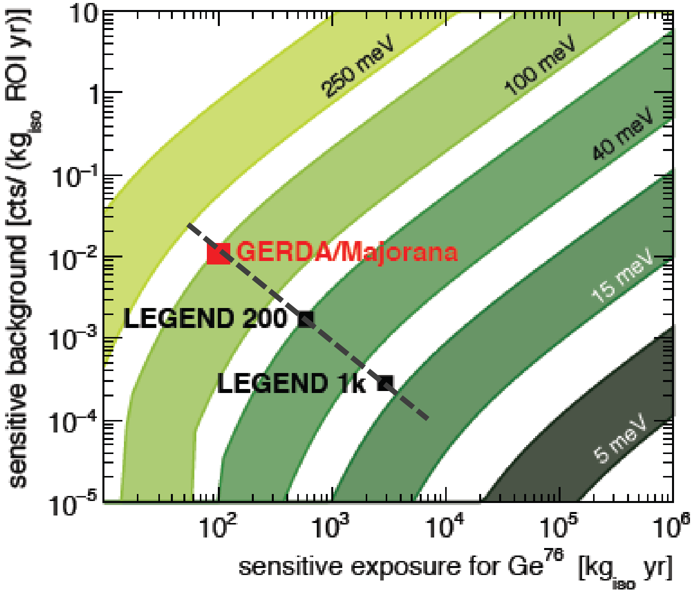


Adopted from Agostini, Benato, Detwiler arXiv:1705.02996

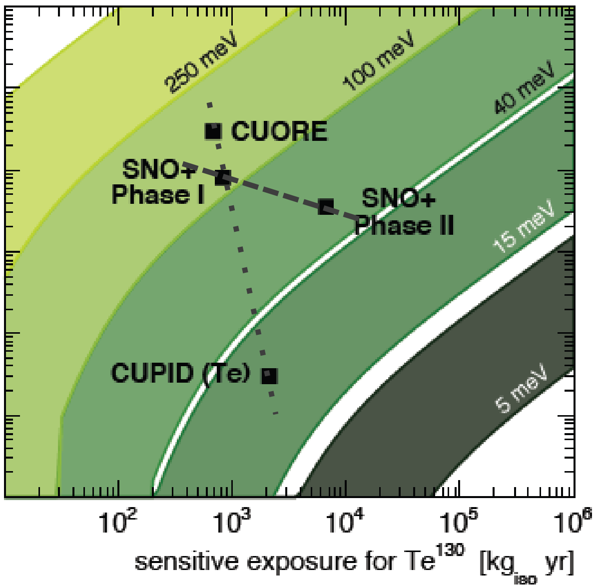
Discovery sensitivities

(5 yr live time)

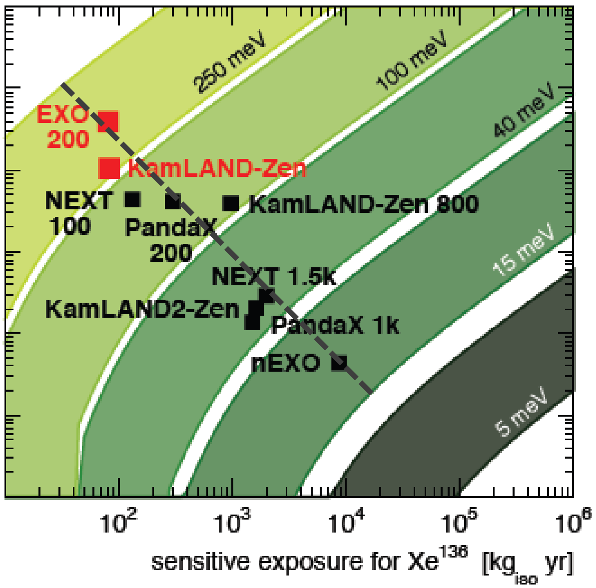
^{76}Ge



^{130}Te



^{136}Xe



Agostini, Benato, Detwiler arXiv:1705.02996