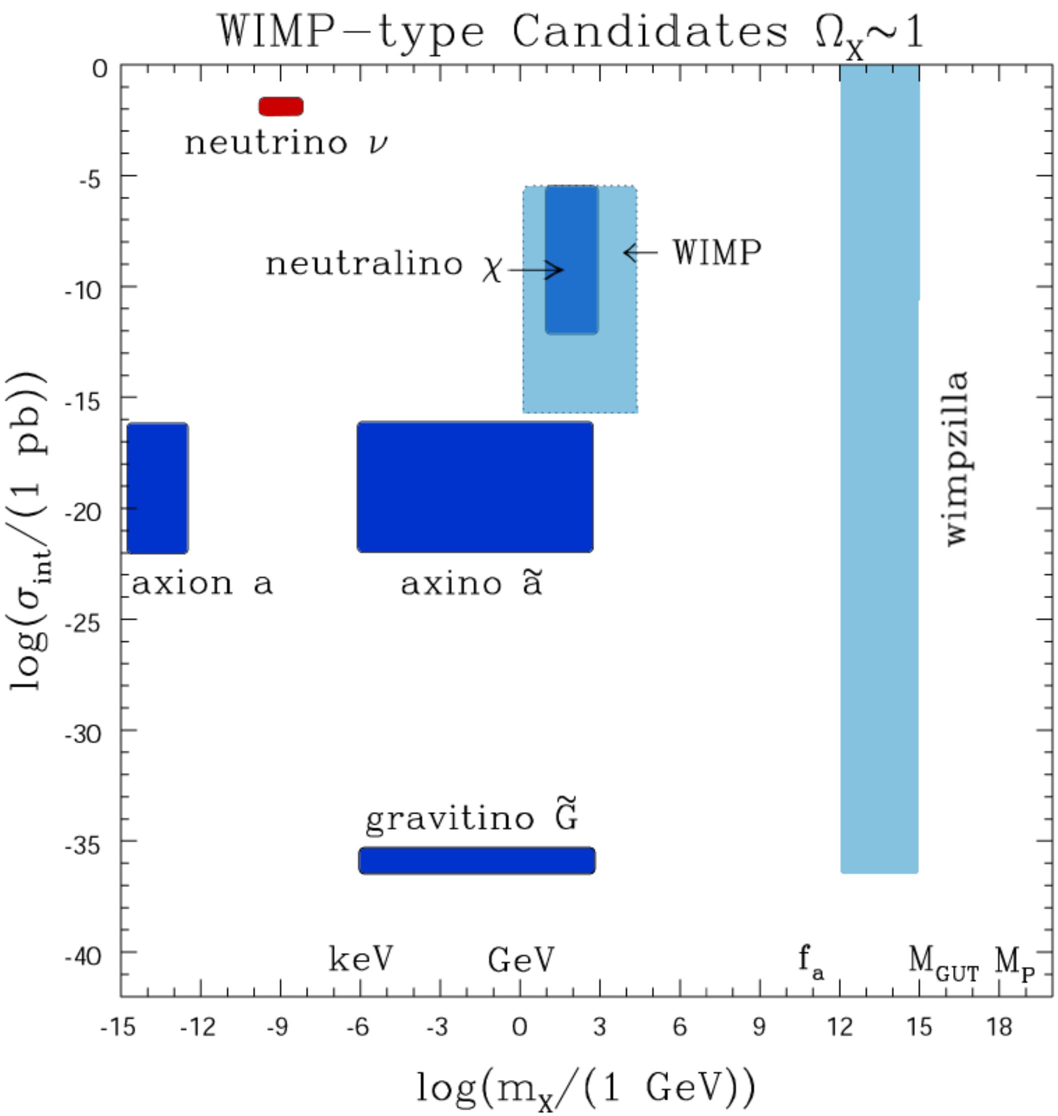
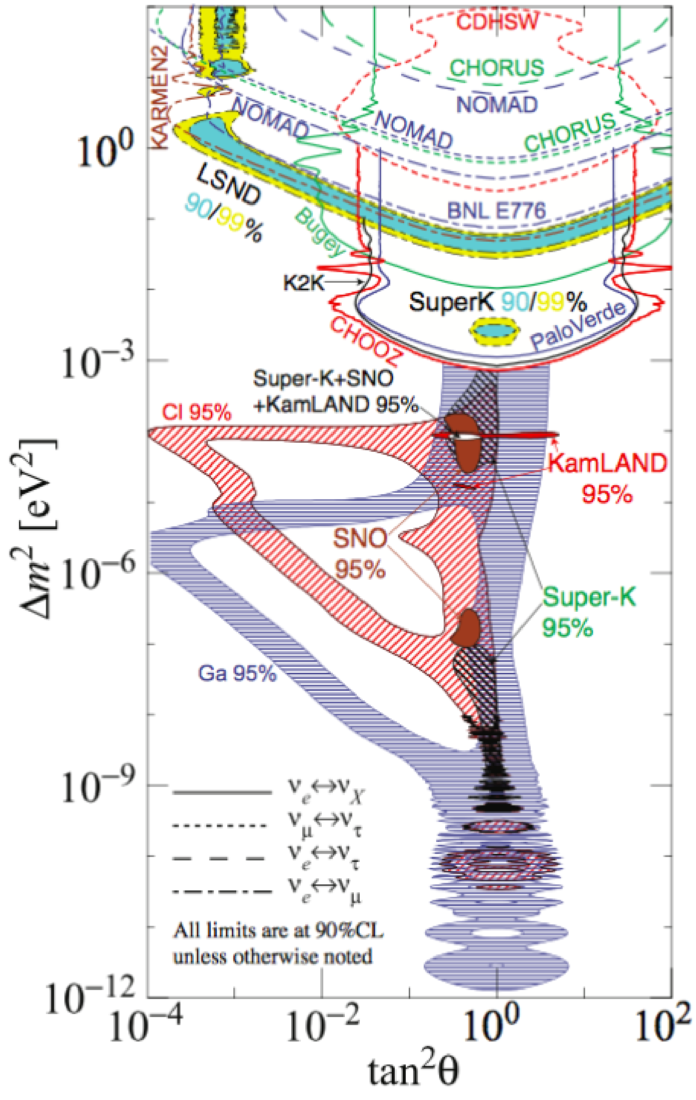
Neutrino & Dark Matter experiments – considerations

Stefan Schönert, TUM

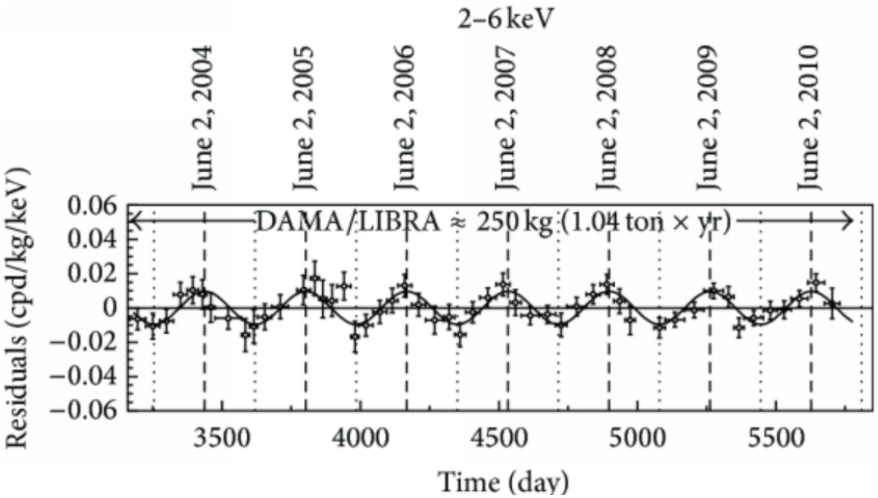
Invisibles17 workshop, June 16, 2017

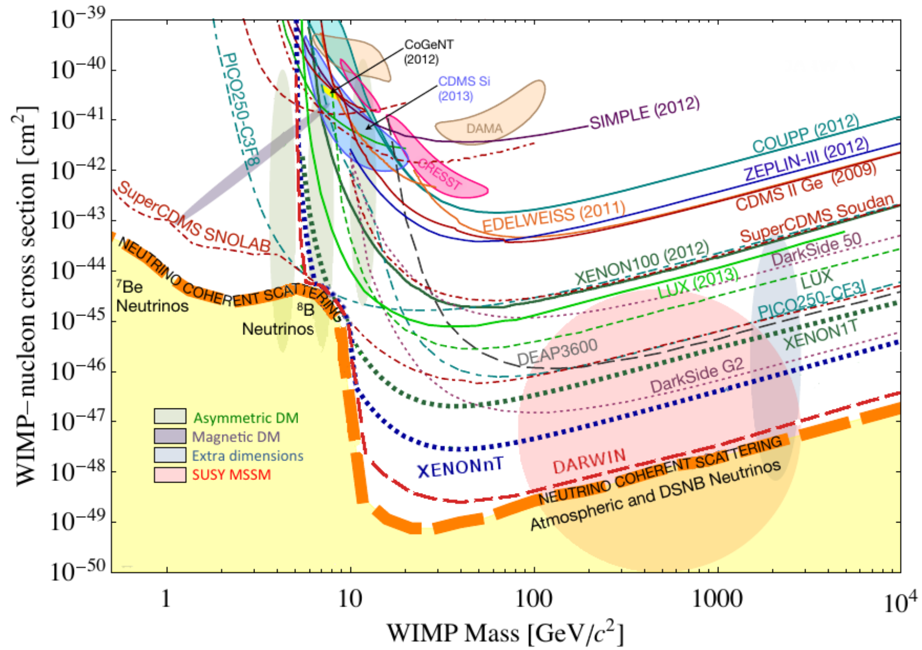
How many orders of magnitudes to explore?





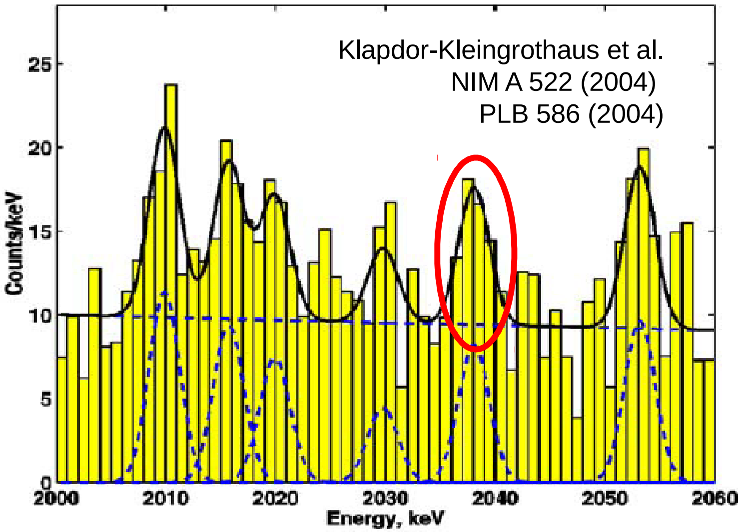
What is a convincing discovery?





- Consistent signal in more than one experiment
- Coherent theoretical description
- Our prior knowledge! ….at the end we all do Bayesian inference!

^{76}Ge 0νββ search: the historic and long-discussed claim



Klapdor-Kleingrothaus et al., NIM A 522 (2004), PLB 586 (2004):

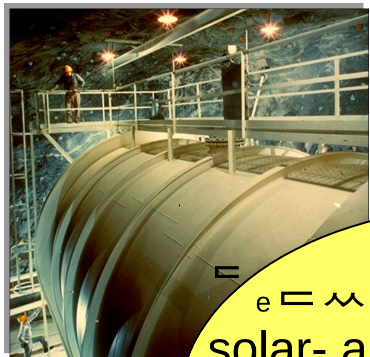
- 71.7 kg year - Bgd 0.17 / (kg yr keV)
- 28.75 ± 6.87 events (bgd:~60)
- Claim: 4.2σ evidence for 0νββ
- reported $T_{1/2}^{0\nu}$ = 1.19 x10^{25} yr

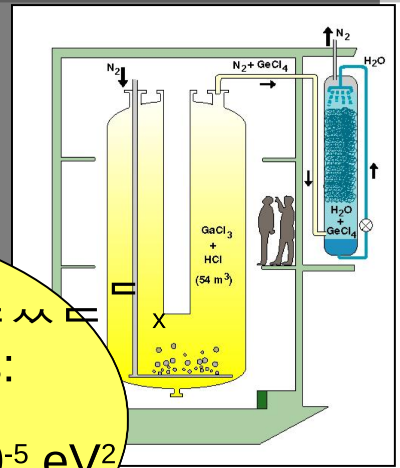
N.B. Half-life $T_{1/2}^{0\nu}$ = 2.23 x10^{25} yr $T_{1/2}$ after PSD analysis (Mod. Phys. Lett. A 21, 1547 (2006).) is not considered because:

- reported half-life can be reconstructed only (Ref. 1) with ε_{psd} = 1 (previous similar analysis $\varepsilon_{psd} \approx 0.6$)
- ε_{fep} = 1 (also in NIM A 522, PLB 586 (2004) (GERDA value for same detectors: ε_{fep} = 0.9)

(1) B. Schwingenheuer in Ann. Phys. 525, 269 (2013):

Non-zero neutrino masses established through ν-oscillation experiments





$\nu_e \leftrightarrow \nu_{\mu,\tau}$; $\bar{\nu}_e \leftrightarrow \bar{\nu}_x$

solar- and reactor-ν's:

$\delta m^2 \approx (7.0 - 8.1)\cdot 10^{-5}\ eV^2$

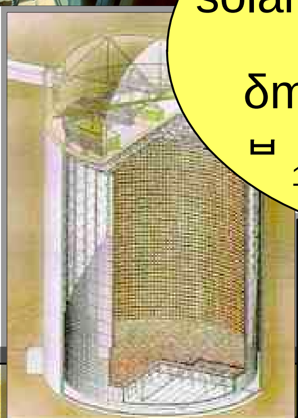
θ_{12}: 31.4°– 36.0°

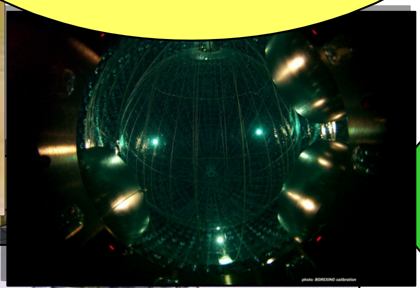
$\nu_\mu \leftrightarrow \nu_\tau$

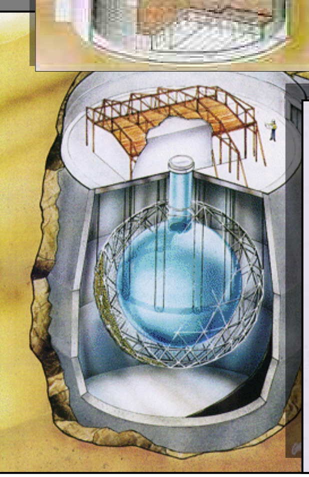
atmospheric- and LBL accelerator-ν's:

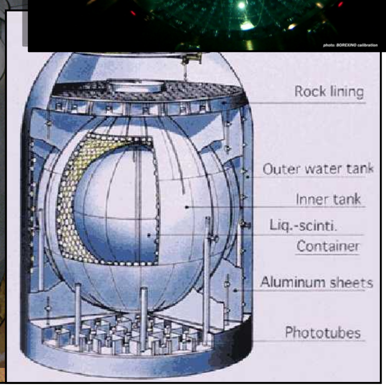
Δm^2: $(2.4 – 2.6)\cdot 10^{-3}\ eV^2$

θ_{23}: 38.5°–53.0°





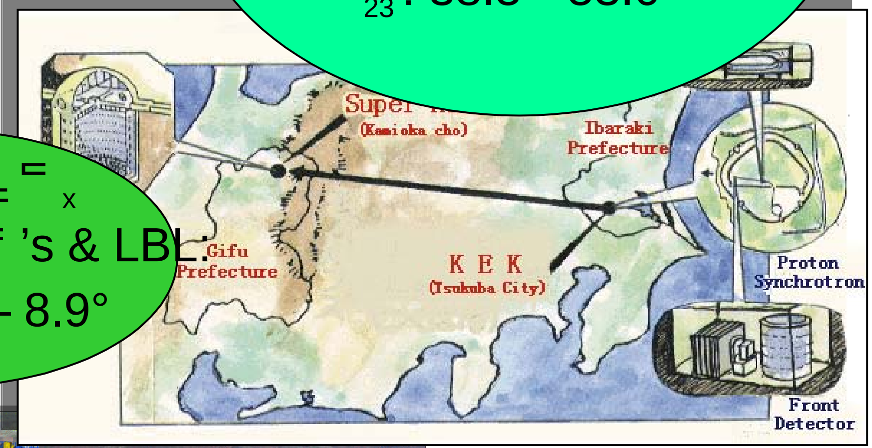


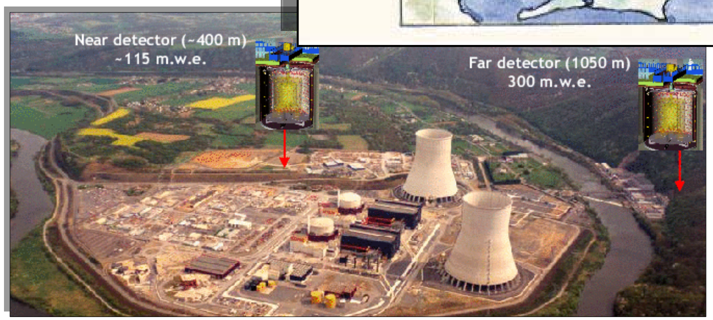


$\bar{\nu}_e \leftrightarrow \bar{\nu}_x$

reactor-ν's & LBL:

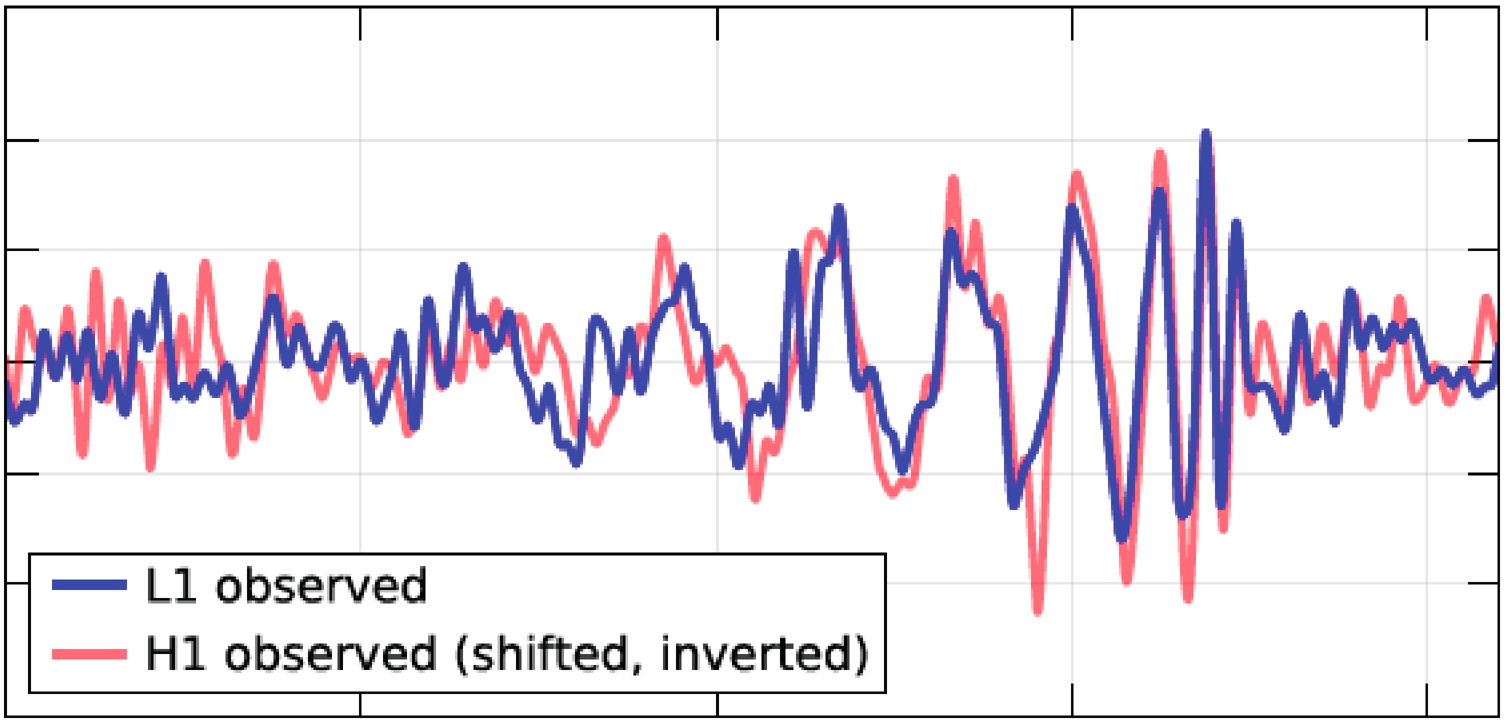
θ_{13}: 8.0°– 8.9°





How many events are needed for a discovery?

This depends on the number of background events!



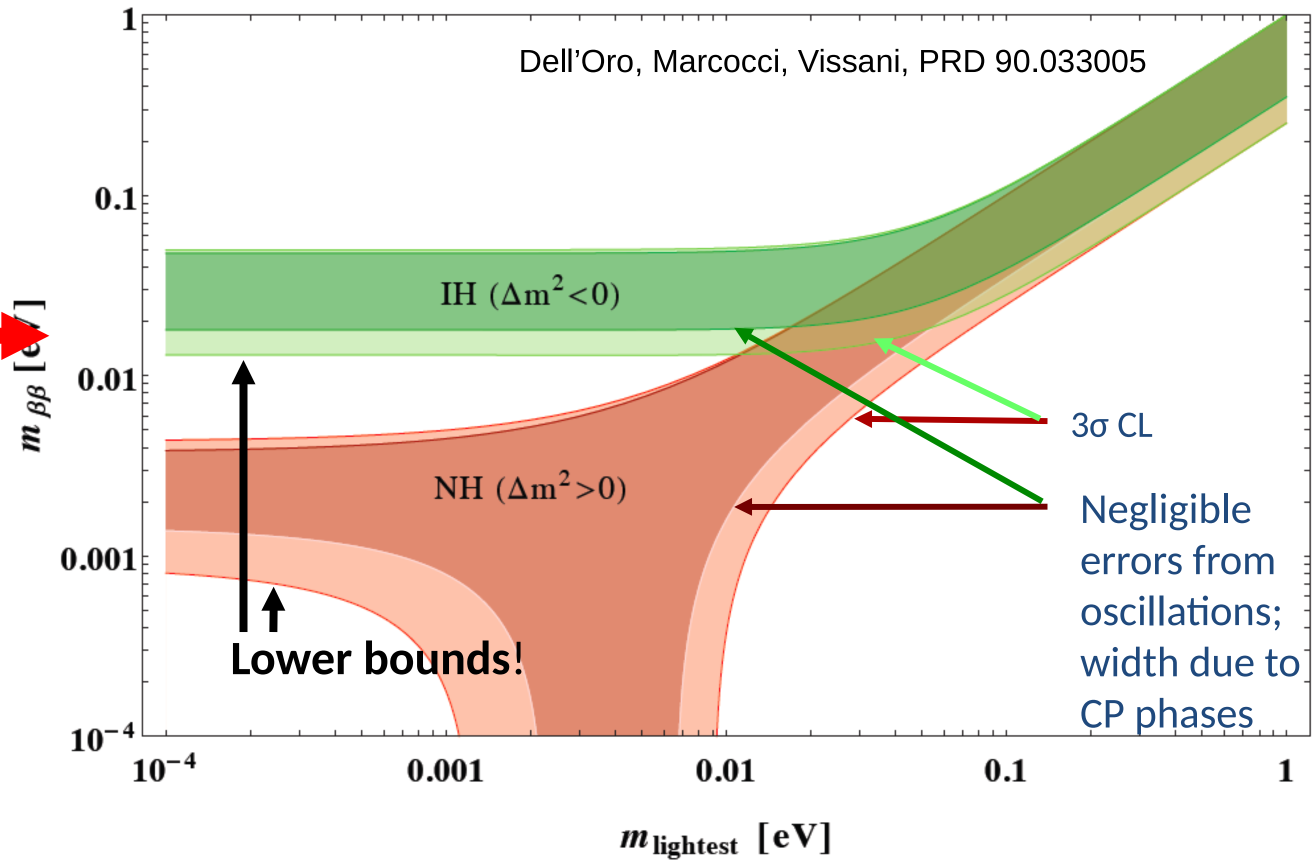
LIGO: discovery potential with single event
Time coincidence between two highly specific signals

0ᄃ ㄴㅈ ㄴㅈ: Range of m_{ee} derived from oscillation experiments

m_{ee} = f(m_1, ㅂ m^2_{sol}, ㅂ m^2_{atm}, ㅜl$_{12}$, ㅜl$_{13}$, ㅈ -ㅊ)

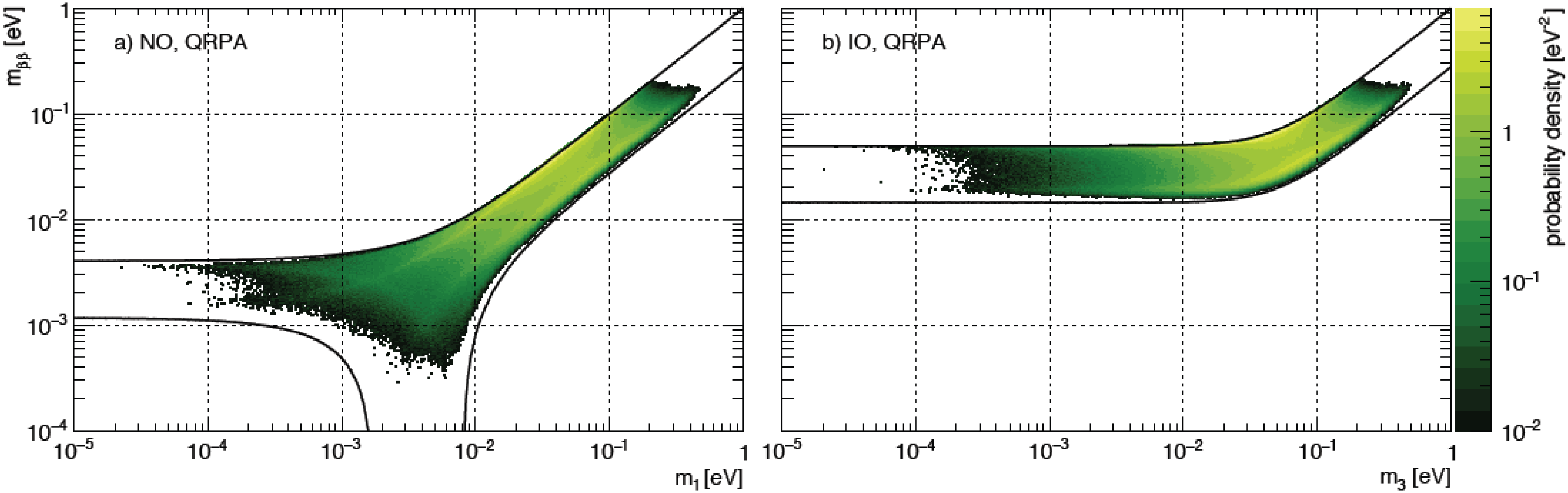
from oscillation experiments

Goal of next generation experiments: ~10 meV



Discovery probabilities

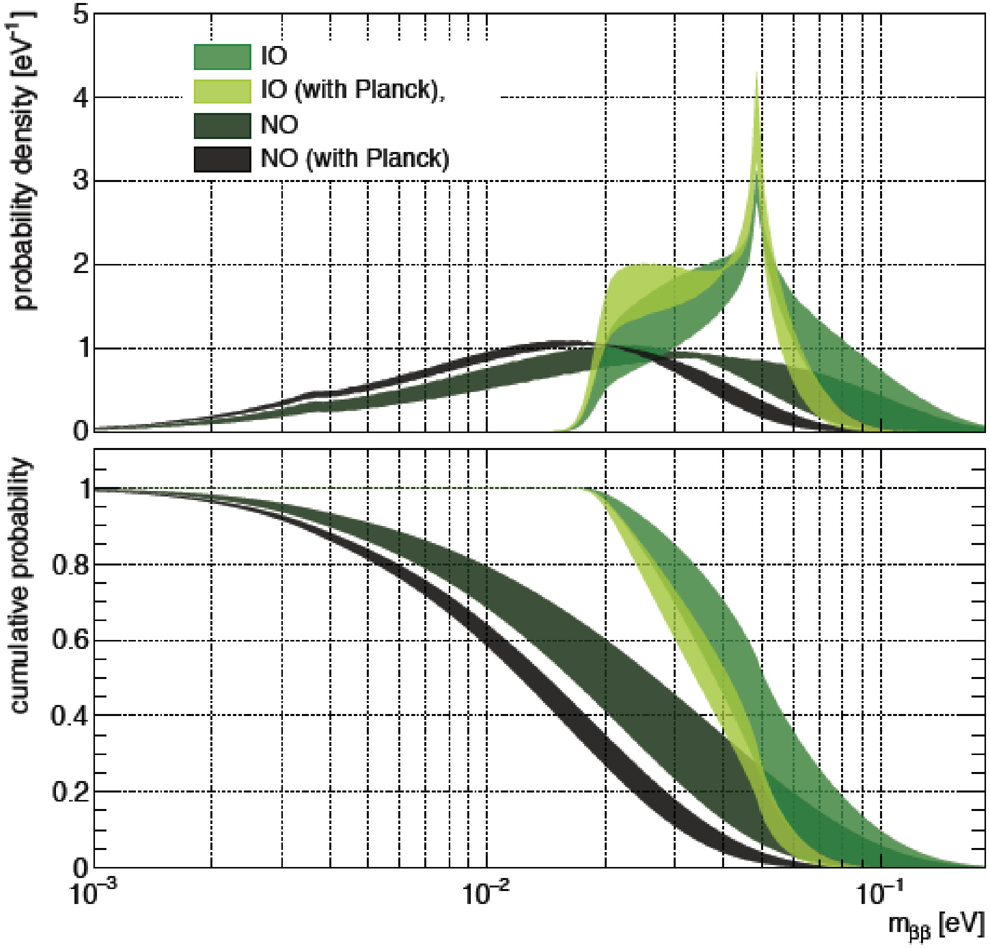
- Global Bayesian analysis including ν-oscillation, m_β $m_{\beta\beta}$, Σ
- Flat prior for Majorana phases
- Scale invariant prior for m_1



M.Agostini, G.Benato and J.Detwiler, arXiv:1705.02996v2

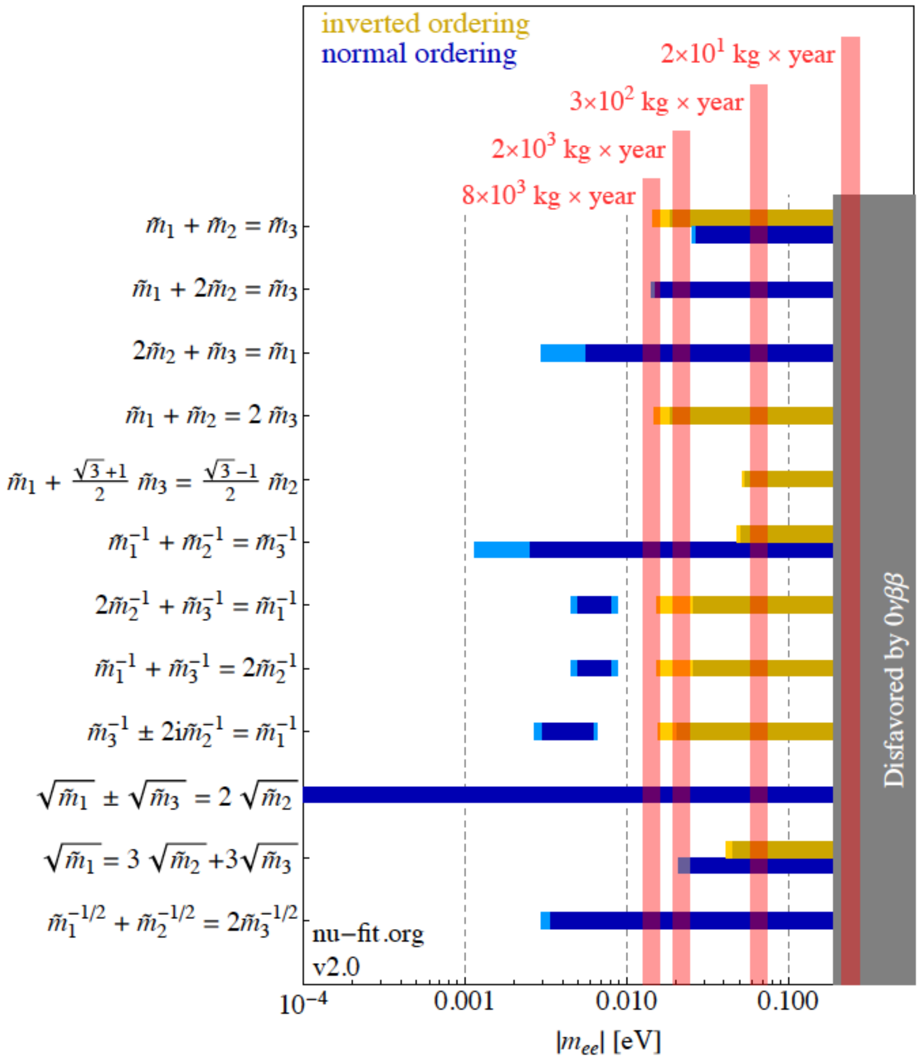
Similar work by
A. Caldwell, A. Merle, O. Schultz and M. Totzauer arXiv:1705.01945

Discovery probabilities



M. Agostini, Benato and Detwiler, arXiv:1705.02996v2 [hep-ex] 11 May 2017

Predictions with informed priors



Range of 0nbb effective mass for different classes of neutrino flavor models

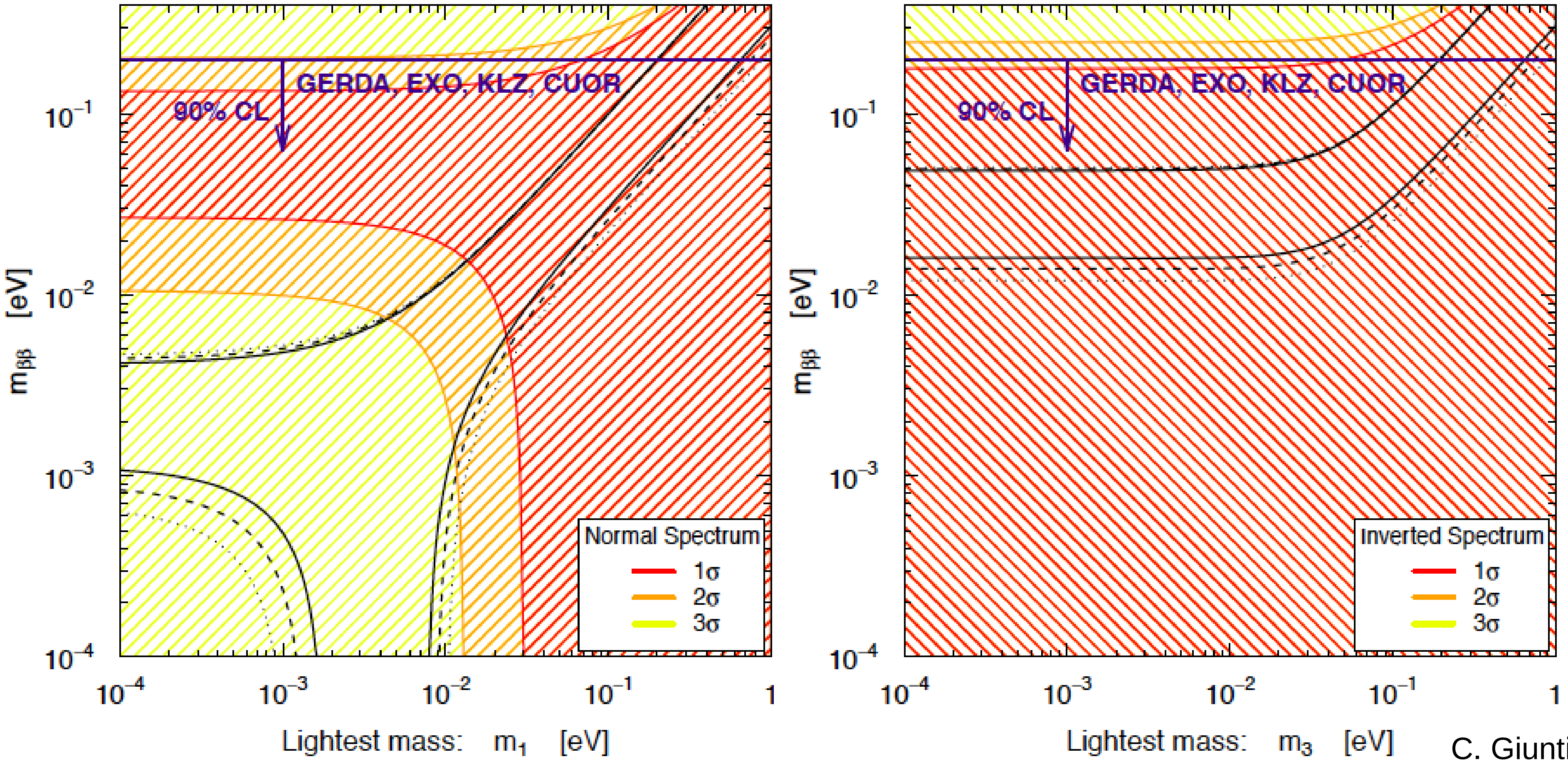
arXiv:: 1506.06133v1
Agostini, Merle, Zuber

Predictions after change of paradigm: eV sterile neutrinos

<u>3ν + light (eV) sterile neutrino</u>

$$m_{\beta\beta}^{(\text{light})} = \left| \sum_{k=1}^{3} U_{ek}^2 \, m_k \right| \qquad m_{\beta\beta}^{(4)} = |U_{e4}|^2 \sqrt{\Delta m_{41}^2}$$

$$m_{\beta\beta} = m_{\beta\beta}^{(\text{light})} + e^{i\alpha_4} m_{\beta\beta}^{(4)} \qquad m_{\beta\beta}^{(4)} \gtrsim 10^{-2}\,\text{eV}$$



C. Giunti

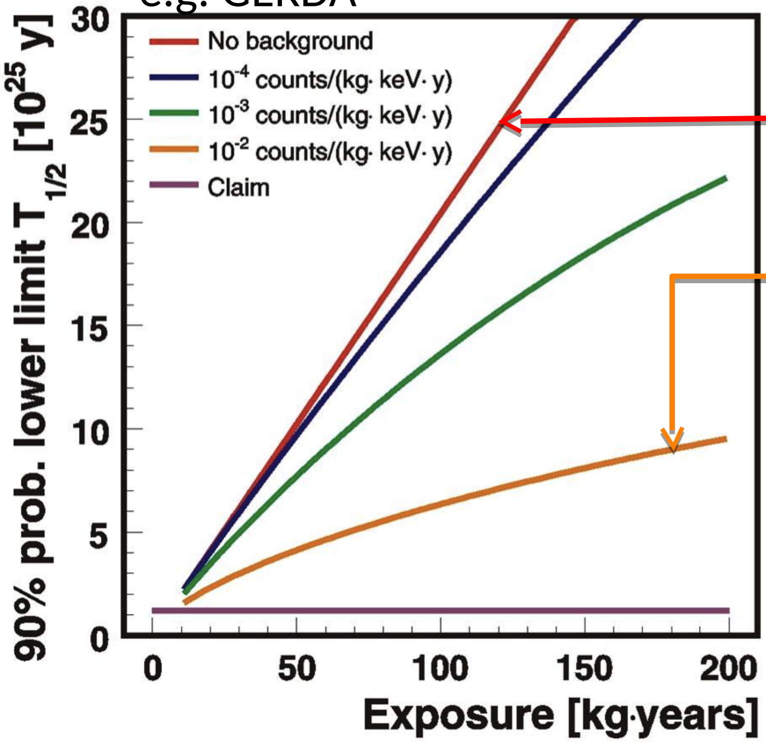
Signal rates & requirements for next generation experiments

Half life [yr]	approx. signal rate [cts/(ton yr)]
10^{25}	500
5×10^{26}	10
5×10^{27}	**1**
$>10^{29}$	<0.05

Present exp. sensitivities → 10^{25}

Goal next generation → 5×10^{26}

e.g. GERDA



$$(T_{1/2}^{0\nu})^{-1} \propto \varepsilon_{eff}\, f_{enr}\, M\, T$$ <u>Background-free</u>

$$(T_{1/2}^{0\nu})^{-1} \propto \varepsilon_{eff}\, f_{enr} \sqrt{\frac{M\,T}{B\,\Delta E}}$$ <u>Background limited</u>

- Large exposure (ε_{eff} f_{enr} MT) of ββ-isotope
- Bgd-free operation in 0νββ peak region
- Best possible energy resolution to discriminate 0νββ from 2νββ
- Several isotopes

comparison experiments

		mass [kg]* (total/FV)	FWHM [keV]	background[&] [cnt/t yr FWHM]	$T_{1/2}$ limit sensitivity [10^{25} yr] after 4 yr	worst m_{ee} limit [meV] (lowest NME, g_A unquenched)	
Gerda II	Ge	35/27	3	5	15	190	running
MajoranaD	Ge	30/24	3	5	15	190	
EXO-200	Xe	170/80	88	220	6	240	
Kamland-Z	Xe	383/88 750/??	250	90 ?	6 50	240 85	design
Cuore	Te	600/206	5	230	9	210	
NEXT-100	Xe	100/80	17	30	6	240	
SNO+	Te	2340/260	190	60	17	160	
nEXO	Xe	5000/4300	58	5	600	24	future
LEGEND-200	Ge	200/155	3	1	100	75	
LEGEND-1000	Ge	1000/780	3	0.2	1000	24	

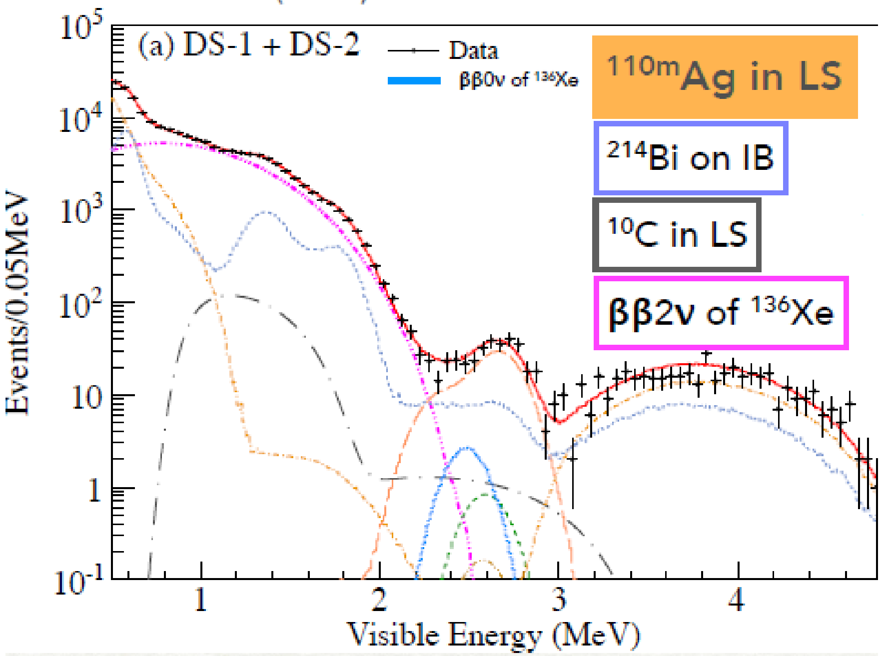
* total= element mass, FV= $0\nu\beta\beta$ isotope mass in fiducial volume (incl enrichment fraction)

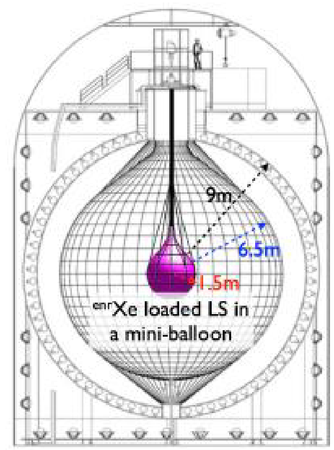
[&] kg of $0\nu\beta\beta$ isotope in active volume and divided by $0\nu\beta\beta$ efficiency

Note: values are design numbers except for GERDA, EXO-200 and Kamland-Zen

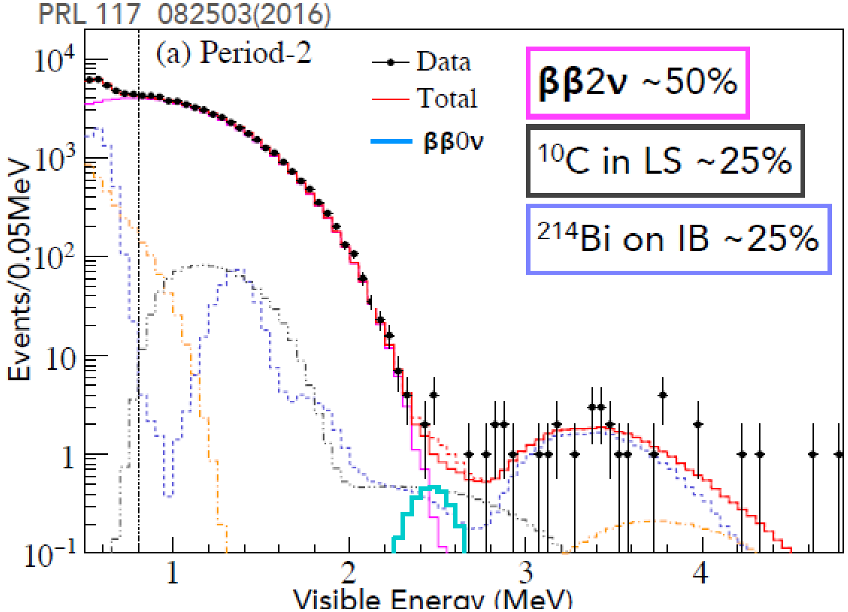
Kamland-Zen

PRL 110 062502(2013)





PRL 117 082503(2016)



Sensitivity:

$T_{1/2} > 5.6 \times 10^{25}$ y (90 % CL)

Limit:

$T_{1/2} > 1.07 \times 10^{26}$ y (90 % CL)

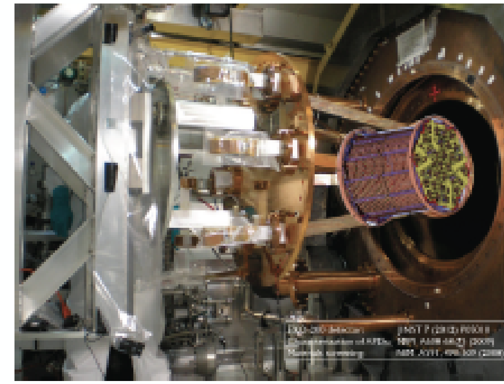
- Limit depends critically on correctness of background model
- … and a discovery even more!

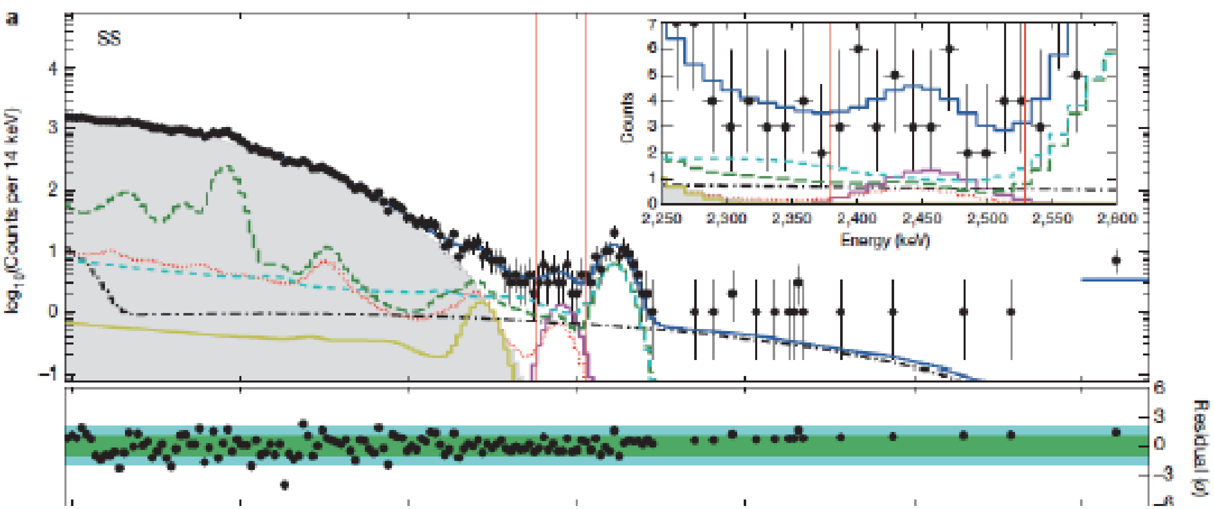
EXO-200 ^{136}Xe (2014)

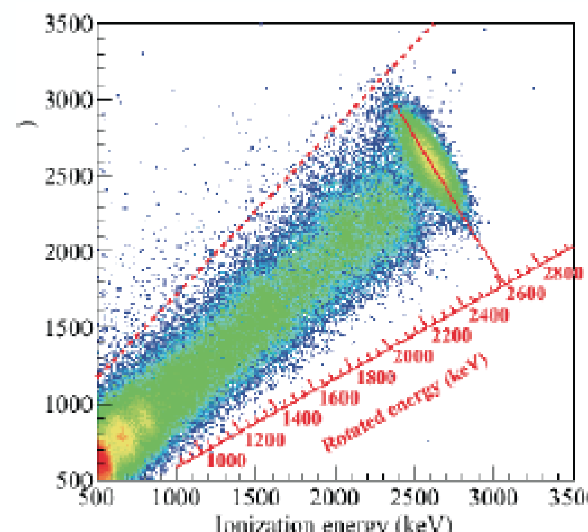
Scintillation - Ionization

- Enriched Liquid Xe in TPC
  - $Q_{\beta\beta}$=2457.8 keV
  - 200 kg of 80.6 % enriched ^{136}Xe
  - 75.6 kg fiducial mass,
  - 100 kg years exposure
  - Combine Scintillation-Ionization signal for improved resolution (88 keV FWHM @ $Q_{\beta\beta}$)
  - Single site - Multisite discrimination

$T_{1/2} > 1.1 \times 10^{25}$ y (90% CL)



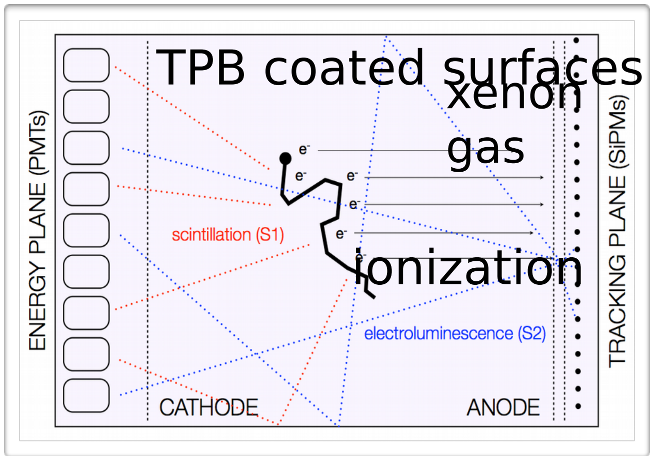




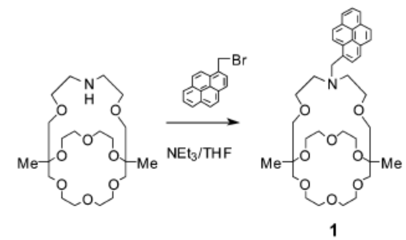
δE/E = 3.6% FWHM

EXO-200 Collaboration, Nature **510** 229 (2014)

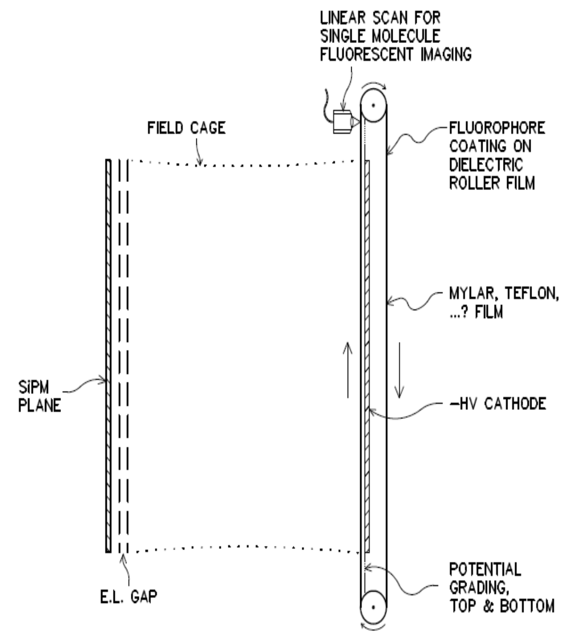
NEXT-XX: A series of photonic TPCs



Fluorescent indicator specific to Ba^{++}



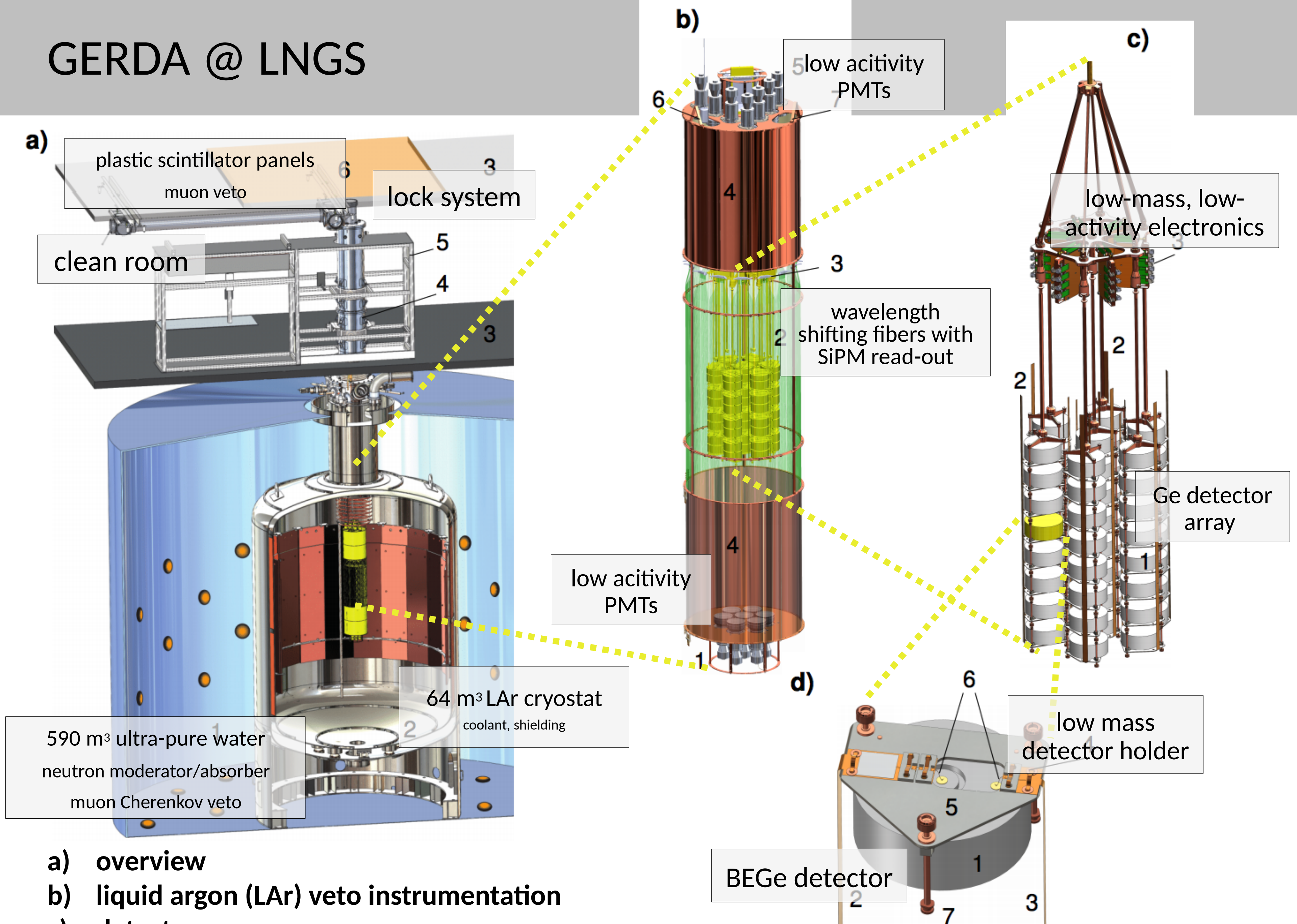
Scheme 1



HIGH PRESSURE XENON GAS ELECTROLUMINESCENT TPC WITH SINGLE MOLECULE FLUORESCENT IMAGING OF BARIUM DAUGHTER

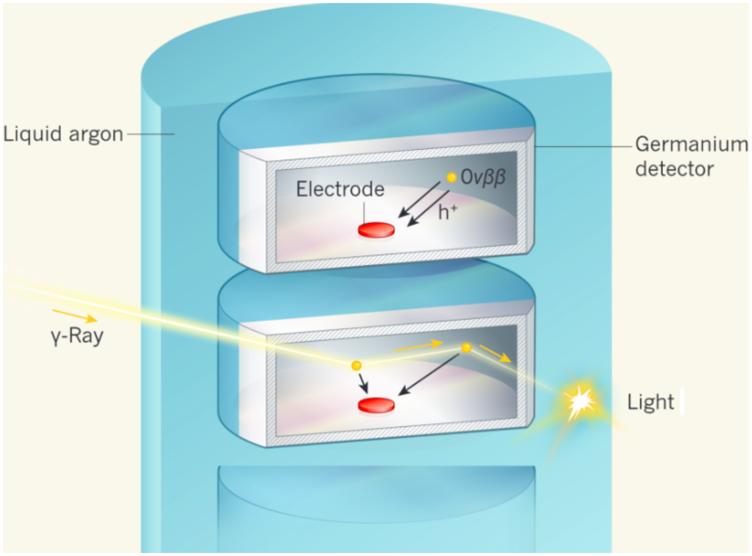
- NEXT: High Pressure Xenon (HPXe) TPC operating in electroluminescent (EL) mode.
- NEXT-100: 100 kg of Xenon enriched at 90% in Xe-136 (in stock) at a pressure of 15 bar.
- Excellent energy resolution in gas phase:
- $\delta E/E = 5 \times 10^{-3}$ FWHM possible
- Topology available for background rejection
- Long-dreamed of Ba tagging ?

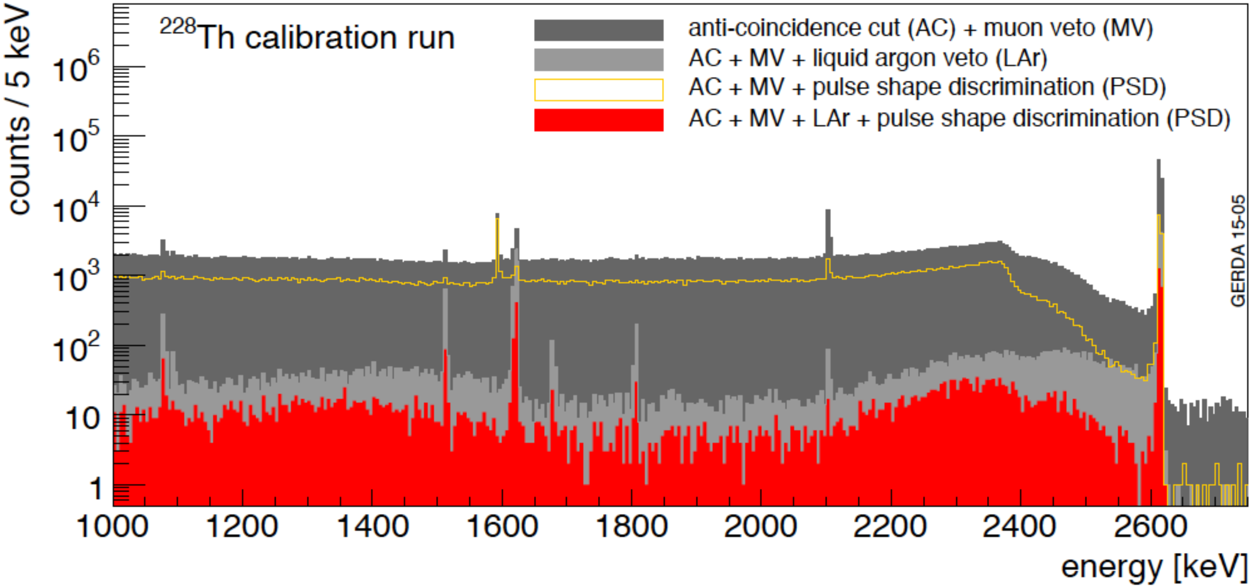
GERDA @ LNGS



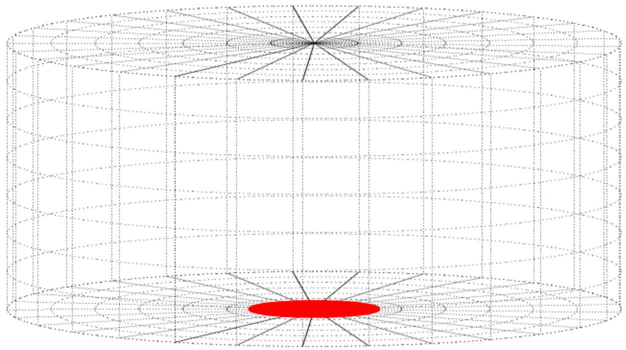
- a) **overview**
- b) **liquid argon (LAr) veto instrumentation**
- c) **detector array**
- d) **detector module**

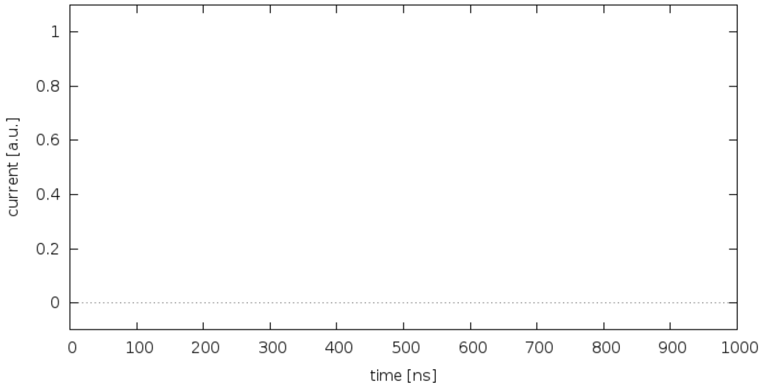
LEGEND: active background suppression



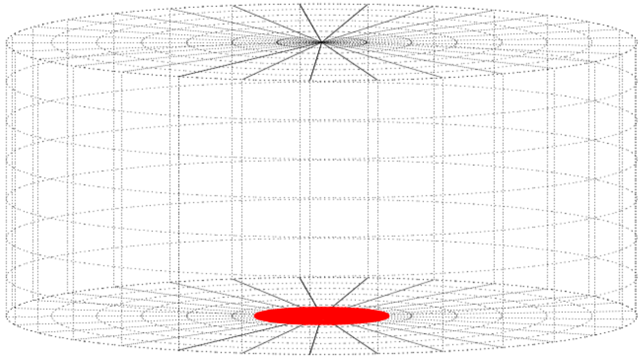


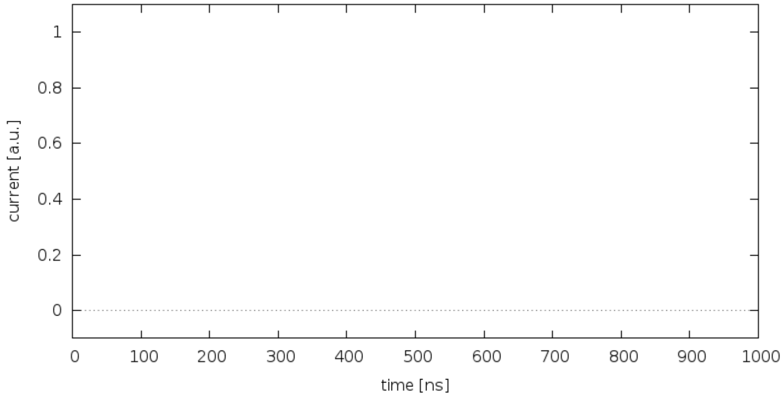
Double beta decay candidate event





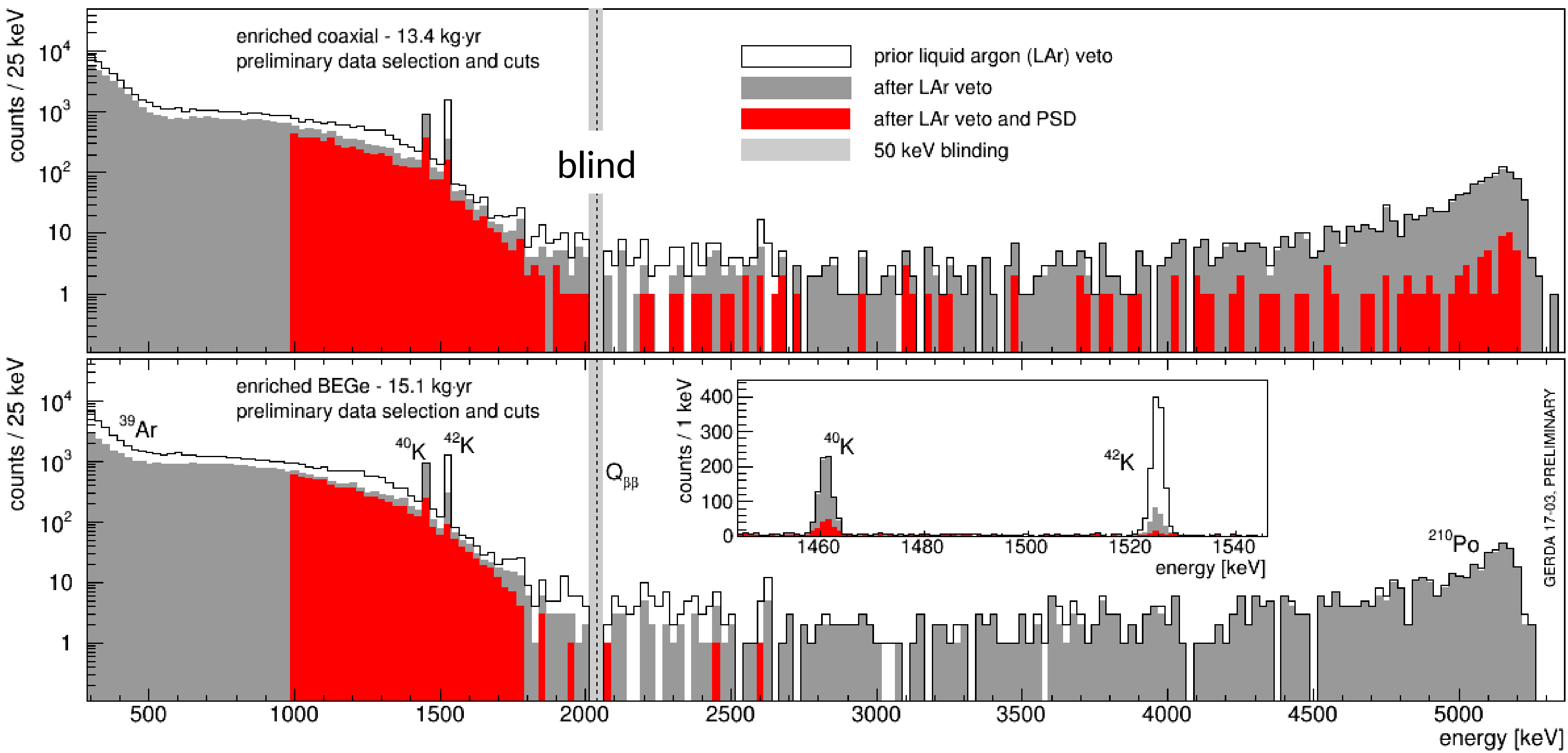
Background candidate event





Energy spectra 28.5 kg yr: before and after LAr veto & PSD

preliminary

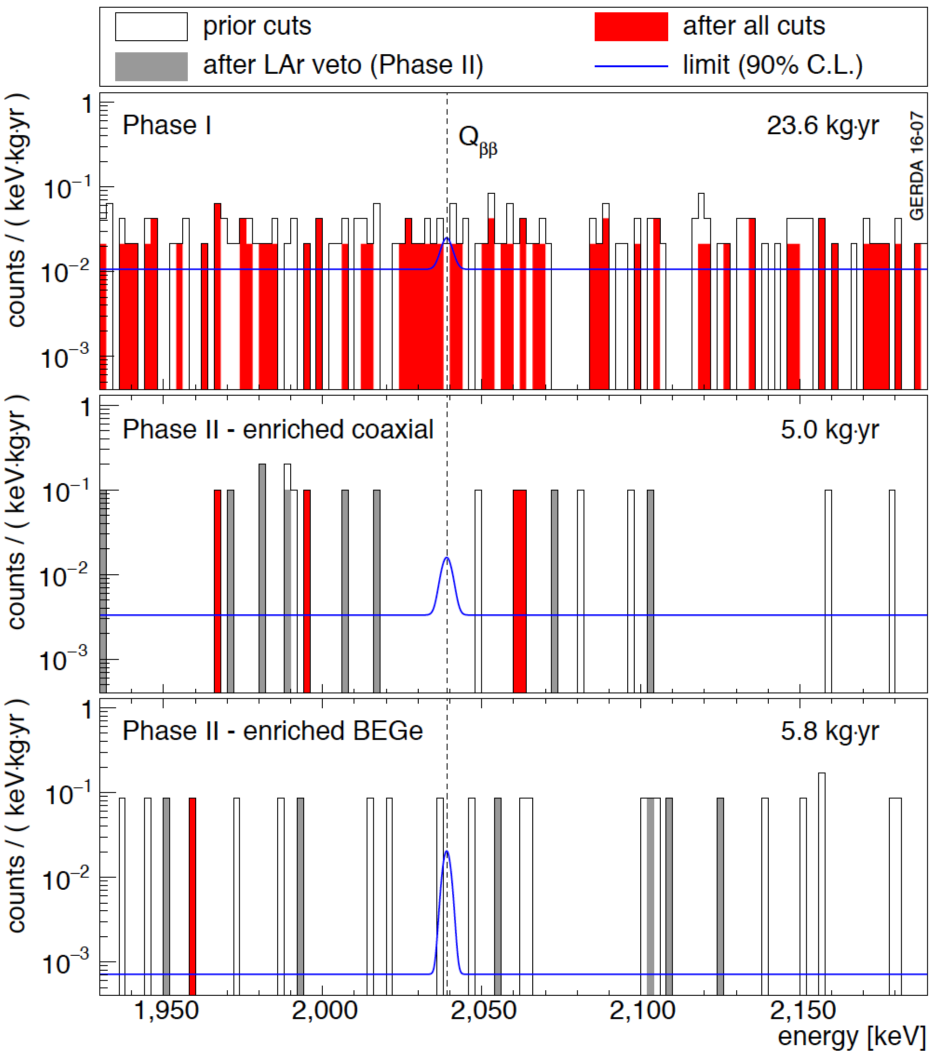


	exposure [kg · yr]	BI* $\left[10^{-3} \cdot \frac{\text{cts}}{\text{keV}\cdot\text{kg}\cdot\text{yr}}\right]$	(cts)	...after LAr veto		...after PSD		...after LAr veto + PSD	
EnrCoax	13.4	$16.7^{+2.7}_{-2.3}$	(46)	$8.0^{+1.9}_{-1.6}$	(22)	$8.0^{+1.9}_{-1.6}$	(22)	$\mathbf{2.2^{+1.1}_{-0.8}}$	(6)
EnrBEGe	15.1	$12.3^{+2.3}_{-1.8}$	(38)	$3.9^{+1.3}_{-1.0}$	(12)	$3.2^{+1.2}_{-0.9}$	(10)	$\mathbf{0.6^{+0.6}_{-0.4}}$	(2)

*background windows weighted by exposure (≈ 205 keV)

Unblinding 10.8 kg yr (PIIa)

arXiv:1703.00570



dataset	exposure [kg · yr]	FWHM [keV]	efficiency*	BI $\left[10^{-3}\frac{\text{cts}}{\text{keV·kg·yr}}\right]$
PI golden	17.9	4.3(1)	0.57(3)	11 ± 2
PI solver	1.3	4.3(1)	0.57(3)	30 ± 10
PI BEGe	2.4	2.7(2)	0.66(2)	5^{+4}_{-3}
PI extra	1.9	4.2(2)	0.58(4)	5^{+4}_{-3}
PIIa coaxial	5.0	4.0(2)	0.53(5)	$3.5^{+2.1}_{-1.5}$
PIIa BEGe	5.8	3.0(2)	0.60(2)	$0.7^{+1.1}_{-0.5}$

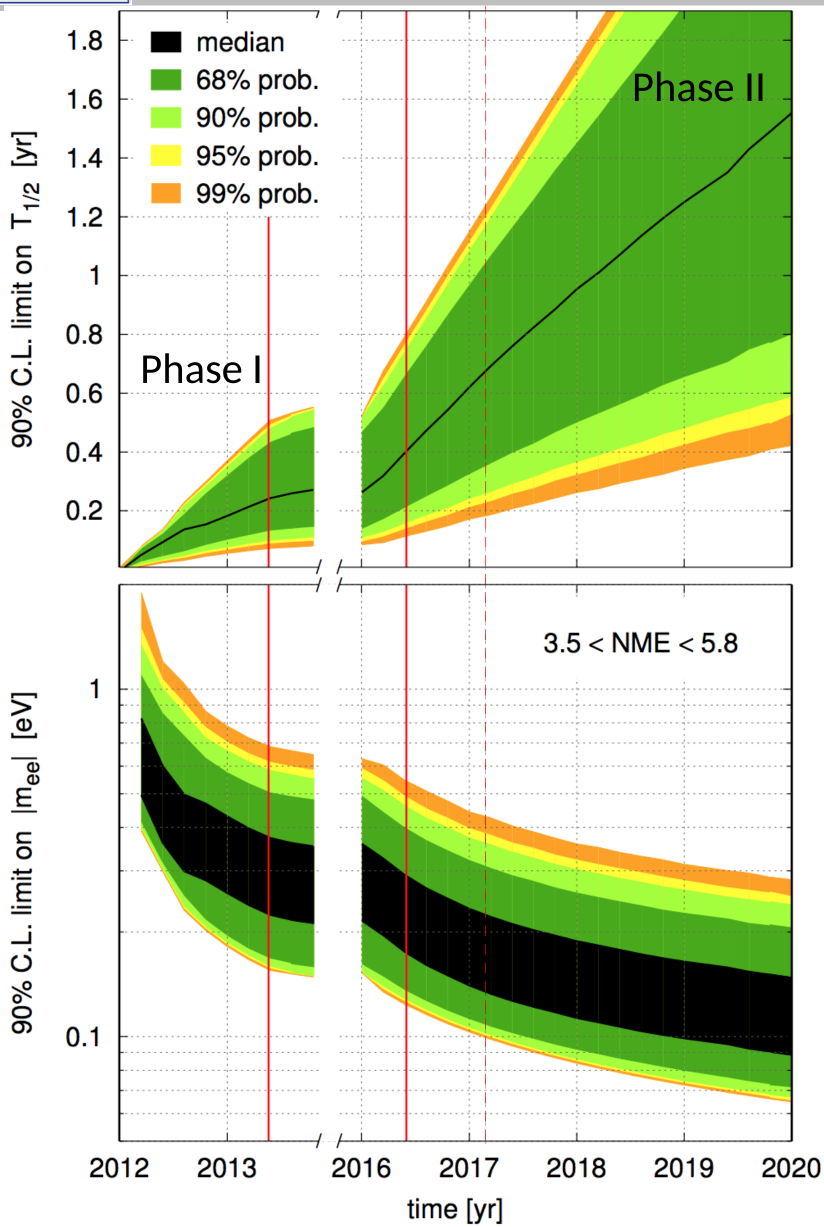
- Phase I: improved energy reconstruction, extra data
- unbinned profile likelihood: flat background, Gaussian signal

	Profile likelihood 2-side-test-stat**	Bayesian flat prior
$0\nu\beta\beta$ best fit value [cts]	0	0
$T^{0\nu}_{1/2}$ lower limit [10^{25} yr]	> 5.3 (90% CL)	> 3.5 (90% CI)
$T^{0\nu}_{1/2}$ median sensitivity [10^{25} yr]	> 4.0 (90% CL)	> 3.1 (90% CI)

*including enrichment, active mass, reconstruction efficiencies, dead times

**frequentist test-statistics and methods [EPJC 71 (2011) 1554]

GERDA Phase II: first **background-free** 0νββ experiment



Phase I achievements

- background
- exposure
- **limit**

Phase I achievements	
background	$\sim 10^{-2}$ cts/(keV · kg · yr)
exposure	21.6 kg · yr
limit	$T^{0\nu}_{1/2} > 2.1 \cdot 10^{25}$ yr (90% CL)

[Phys.Rev.Lett. 111 (2013) 122503]

first Phase II achievements

- background
- exposure
- **limit**

first Phase II achievements	
background	$\sim 10^{-3}$ cts/(keV · kg · yr)
exposure	10.8 kg · yr (34.4 kg · yr)*
limit	$T^{0\nu}_{1/2} > 5.3 \cdot 10^{25}$ yr (90% CL)
	$m_{\beta\beta} < 0.15 - 0.33$ eV (90% CL)

[arXiv:1703.00570; acc. Nature]

Phase II goals

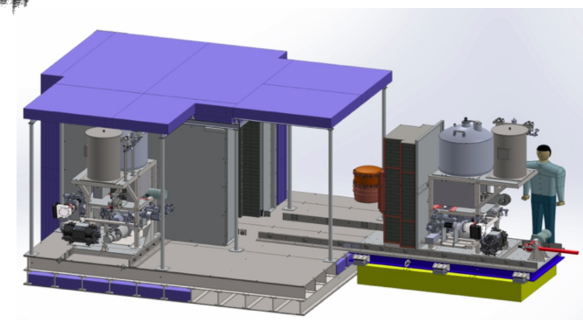
- background
- exposure
- **sensitivity**

Phase II goals	
background	$\sim 10^{-3}$ cts/(keV · kg · yr)
exposure	$\gtrsim 100$ kg · yr
sensitivity	$T^{0\nu}_{1/2} \gtrsim 10^{26}$ yr

*combining Phase I and Phase II data

GERDA

Majorana-Demonstrator (MJD)



- Bare ^{enr}Ge array in liquid argon
- Shield: high-purity liquid Argon / H_2O
- Phase I: 17 kg (HdM/IGEX) - completed
- Phase II: 38 kg enriched in ^{76}Ge

- Array(s) of ^{enr}Ge housed in high-purity electroformed copper cryostat
- Shield: electroformed copper / lead
- 30 kg enriched in ^{76}Ge

Physics goals: degenerate mass range
Technology: study of bgds. and exp. techniques

LoI

- open exchange of knowledge & technologies (e.g. MaGe MC)
- intention to merge for future large scale ^{76}Ge experiment selecting the best technologies tested in GERDA and Majorana

Large Enriched Germaium Experiment for Neutrinoless ββ Decay - LEGEND

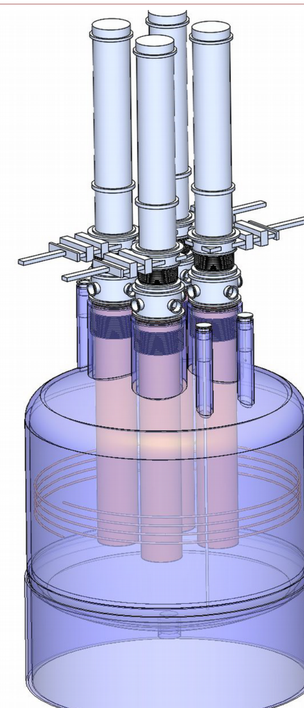
Collaboration forming:

- 1st Munich April 2016
- **2nd** Atlanta October 2016
- 3rd LNGS May 15-17

LEGEND mission: "The collaboration aims to develop a phased, Ge-76 based double-beta decay experimental program with **discovery potential** at a half-life significantly longer than 10^{27} years, using existing resources as appropriate to expedite physics results."

First stage:

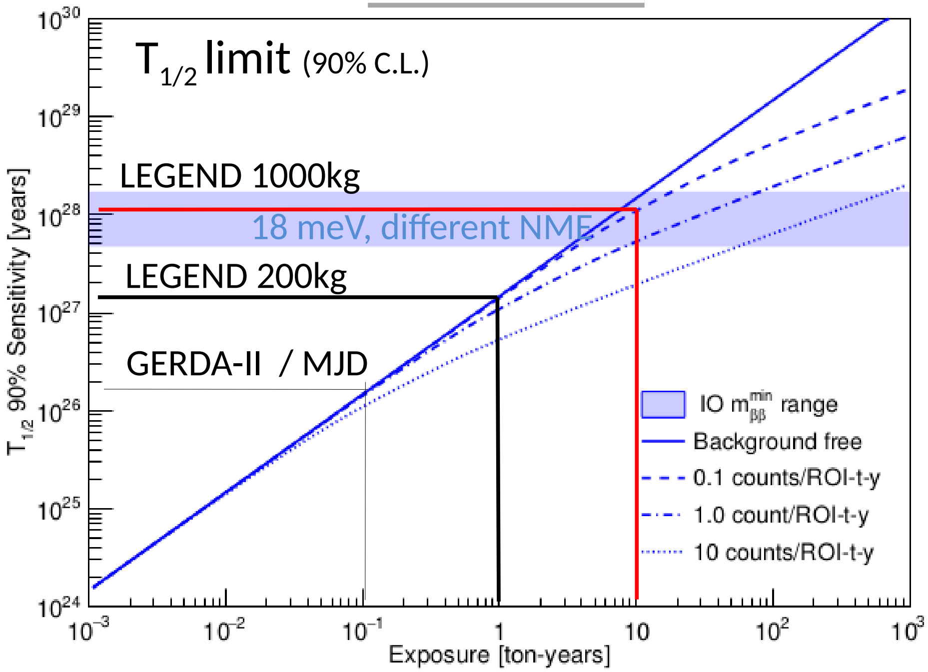
- (up to) 200 kg in upgrade of existing infrastructure at LNGS
- bgd reduction by factor 3-5 w.r.t GERDA

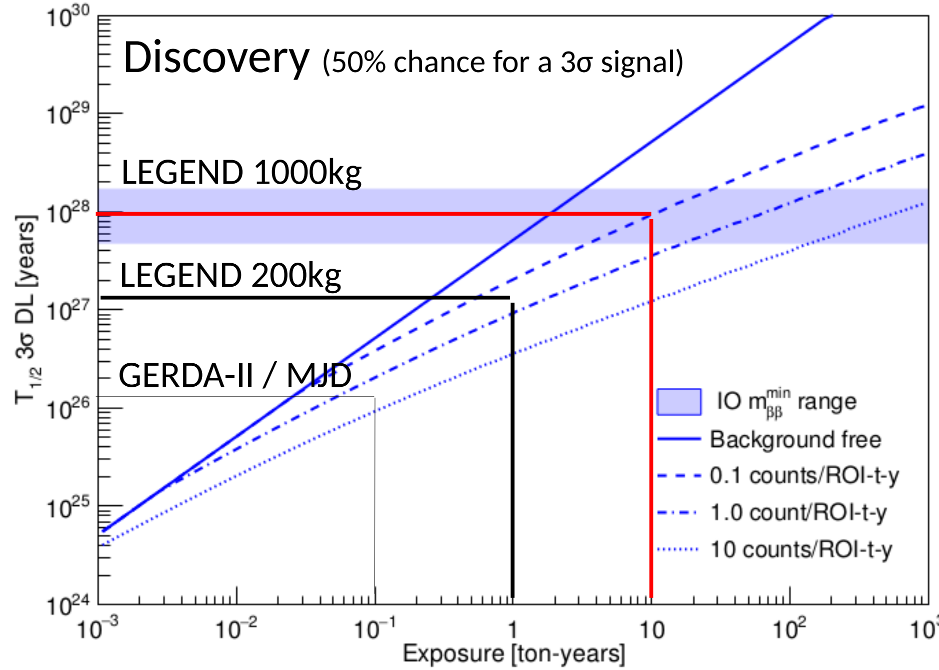


Subsequent stages:

- 1000 kg (staged)
- timeline connected to DOE down select process
- x30 bgd reduction wrt GERDA
- Location tbd
- Required depth (Ge-77m) under investigation

LEGEND: sensitivities for limit setting and discovery





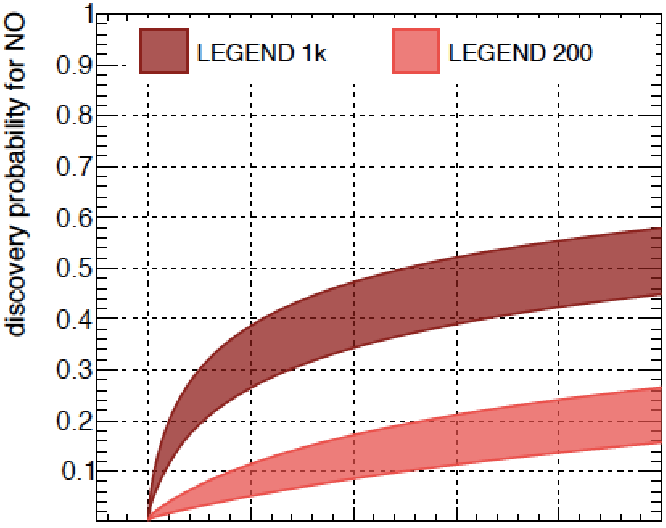
Plot details:

- 60% "efficiency" including isotope fraction, active volume fraction, analysis cuts
- GERDA-II / MJD: 3 counts/(ROI t yr)
- LEGEND-200: 0.6 counts/(ROI t yr)
- LEGEND-1000: 0.1 counts/(ROI t yr)

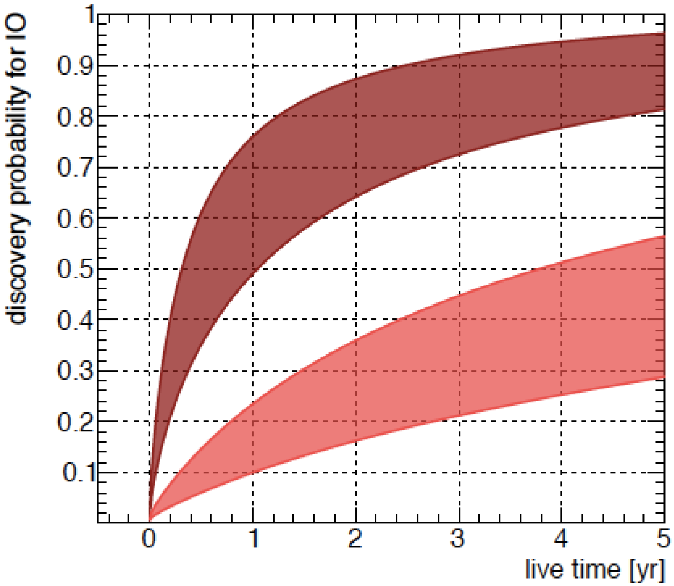
N.B.: background-free operation is a prerequisite for a discovery

Discovery probabilities

Normal Ordering

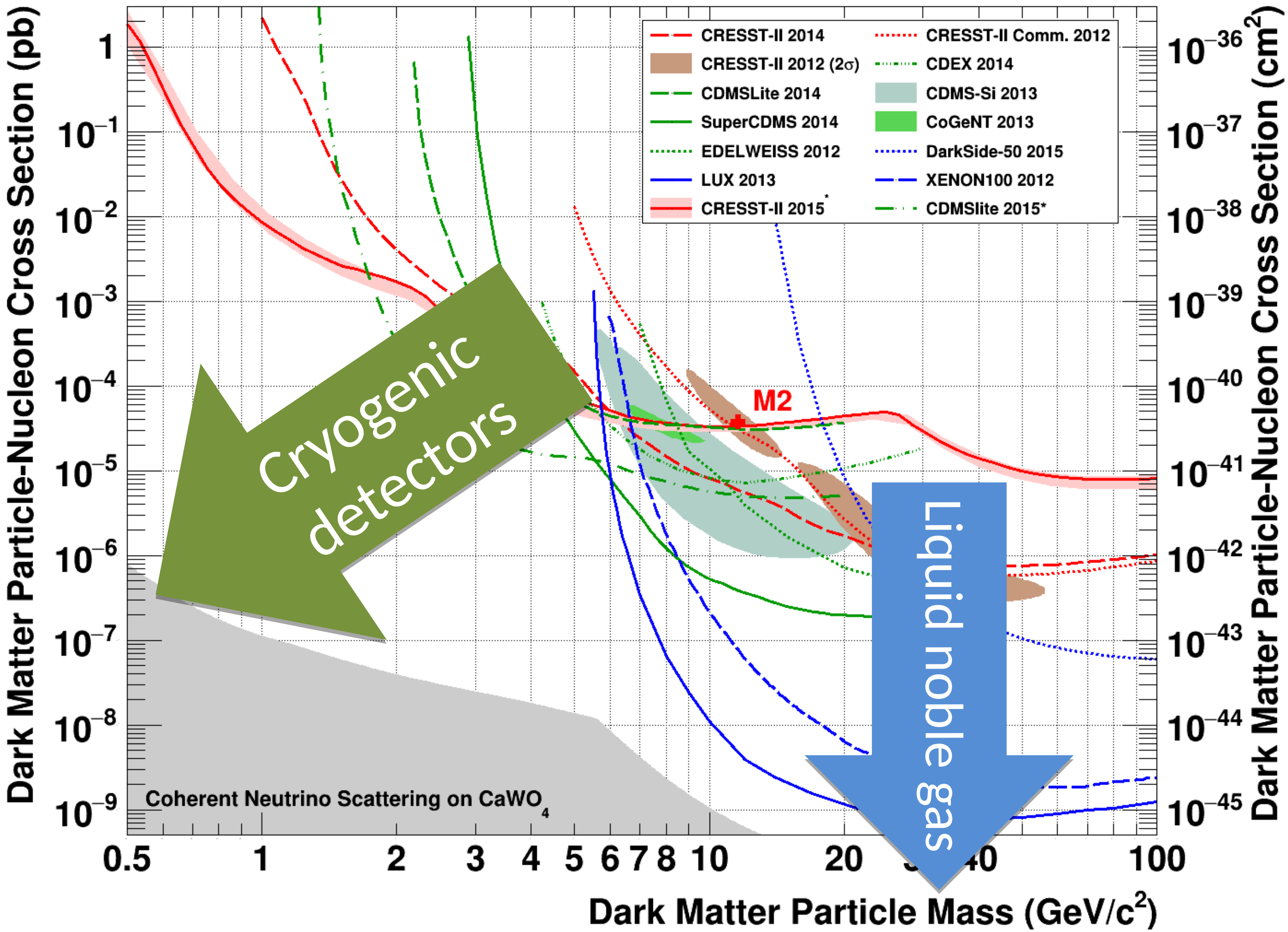


Inverted Ordering



M. Agostini, Benato and Detwiler, arXiv:1705.02996v2 [hep-ex] 11 May 2017

Direct Dark Matter Search experiments

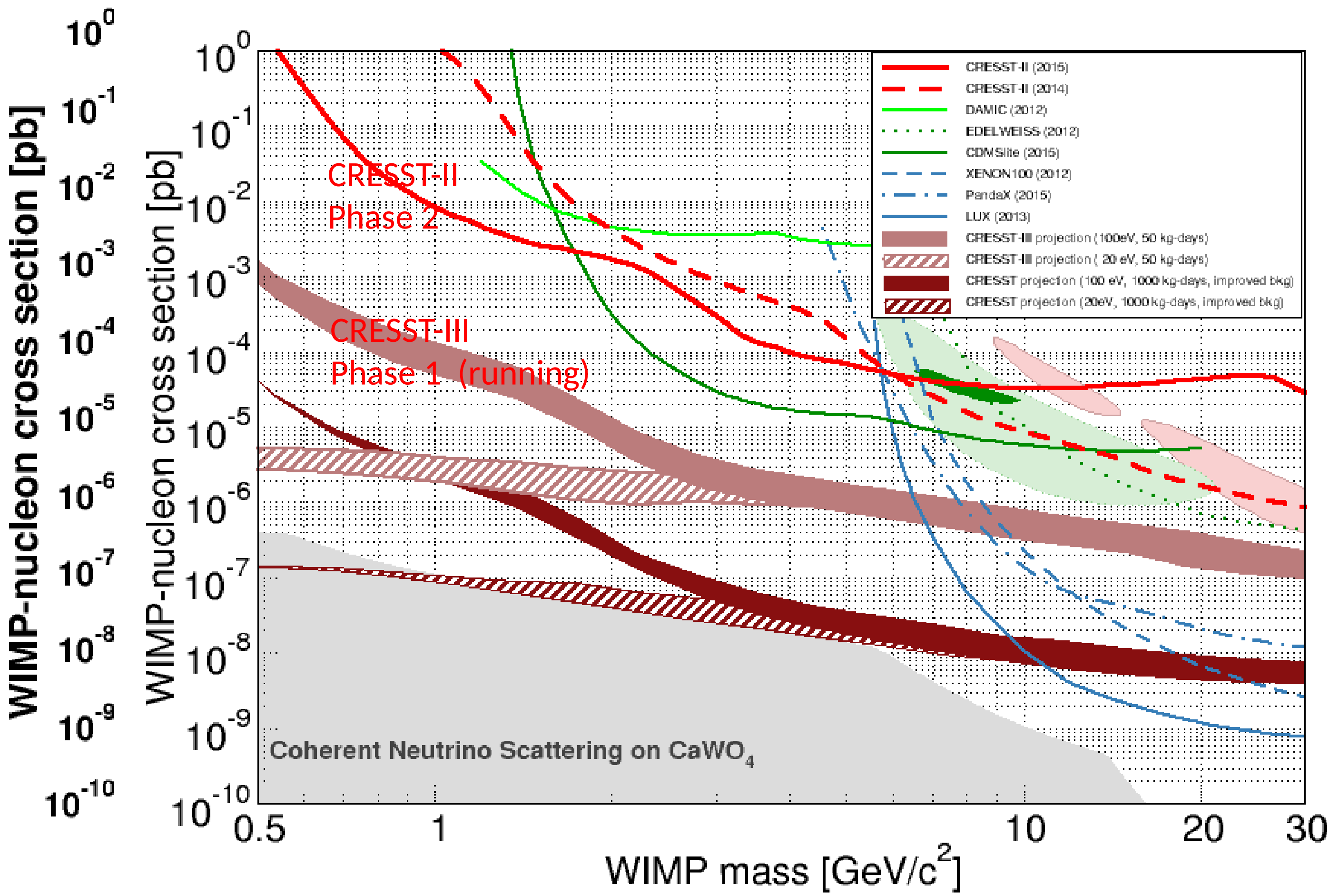


CRESST-III Phases

<u>CRESST-III Phase 1</u>
(assumptions)

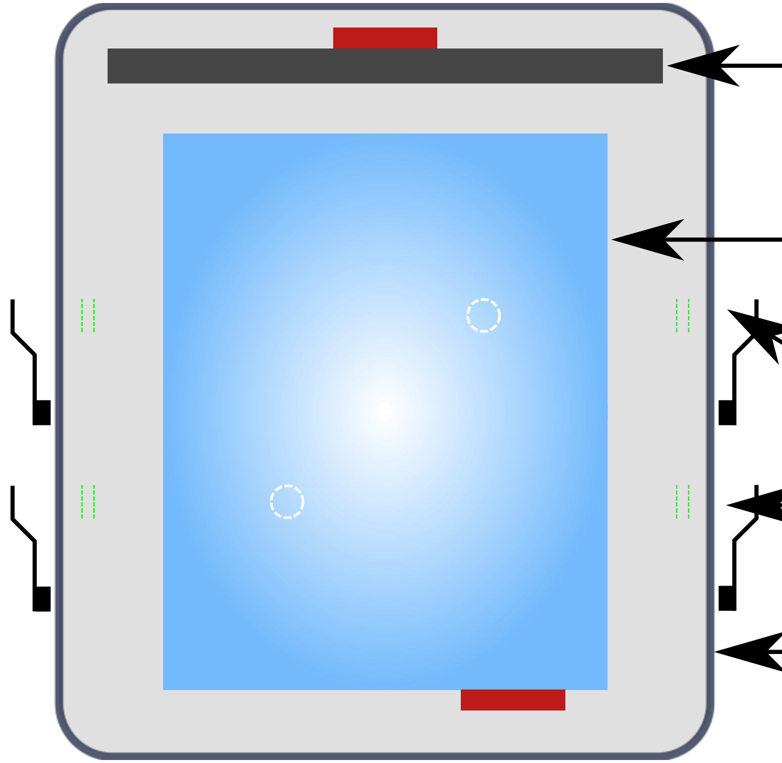
- 24g $CaWO_4$ crystal
- **E_{th} = 100eV**
- Light detector improved by factor 2 (due to smaller volume)
- 2x more detected light: due to thin crystal
- **CRESST-II radiopurity**

CRESST collab. G. Angloher et al. arXiv:1503.08065

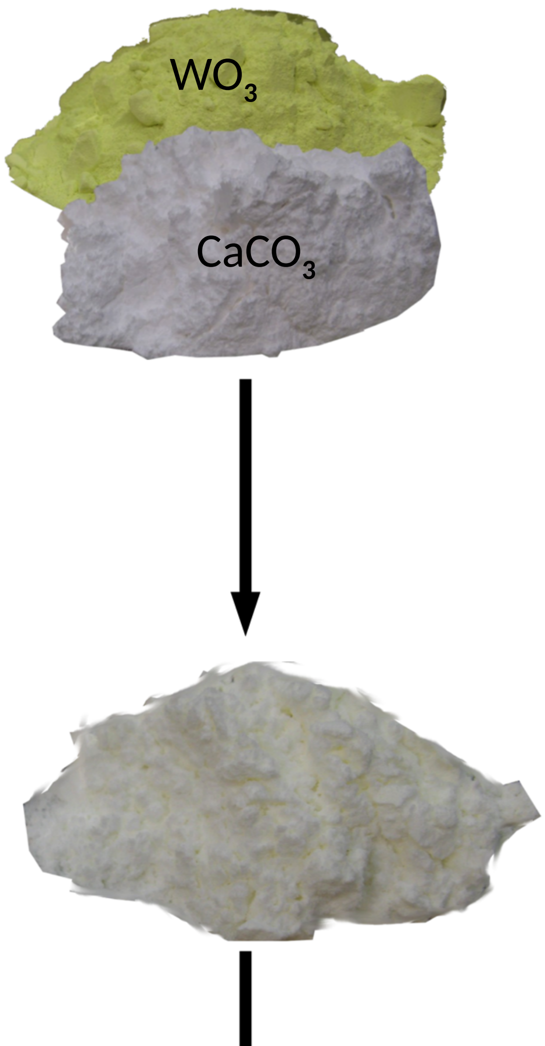


10 x 24g detectors operated for one year ≈ **50 kg-days** (net)

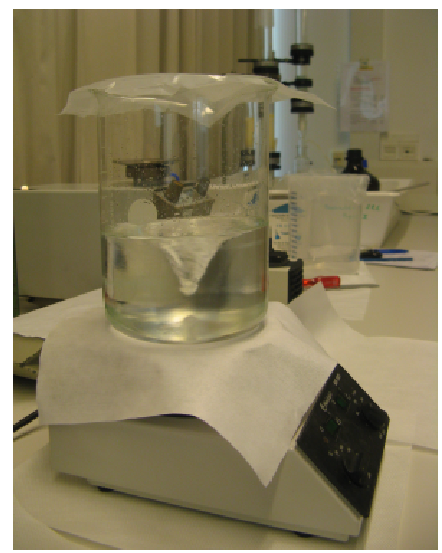
CRESST: phonon and light – fully scintillating design



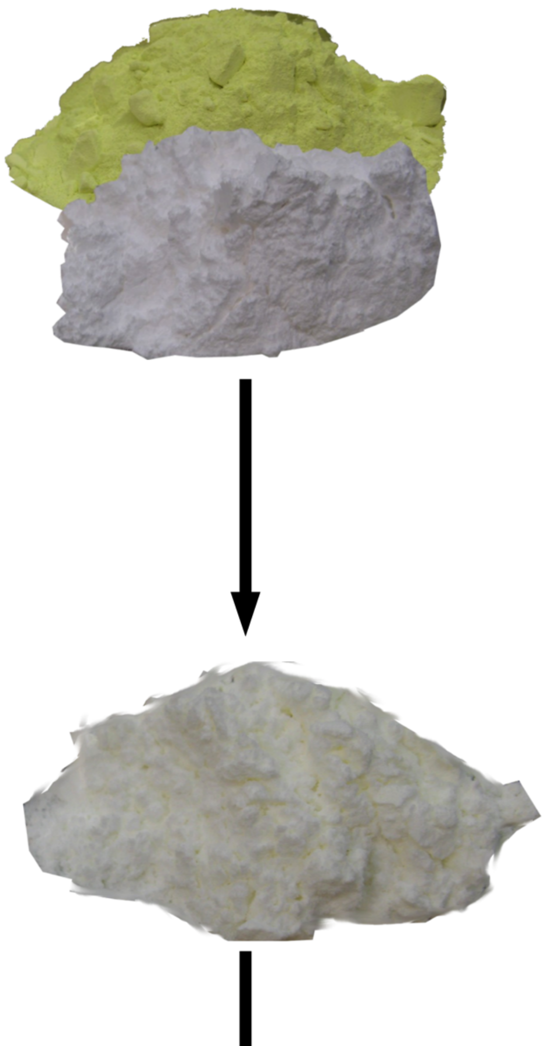
CRESST: phonon and light – from raw materials to final $CaWO_4$ cryogenic detectors



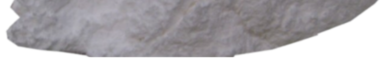
- Shipment of raw material by sea / road transport
- Underground storage to minimize cosmic activation
- Chemical purification of raw material



CRESST: phonon and light – from raw materials to final $CaWO_4$ cryogenic detectors

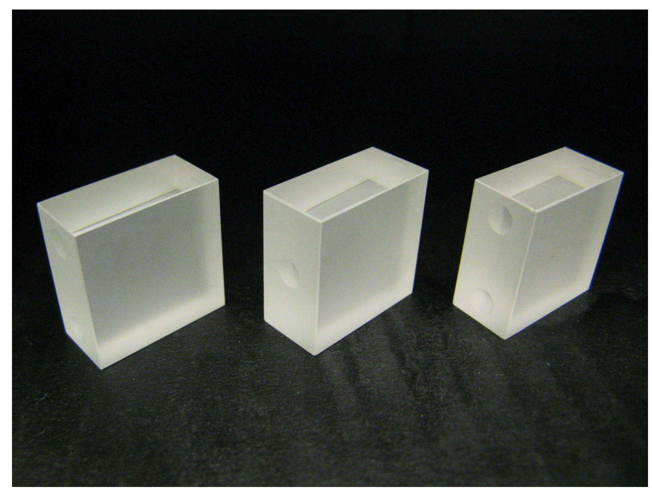


Czochralski crystal pulling at TUM



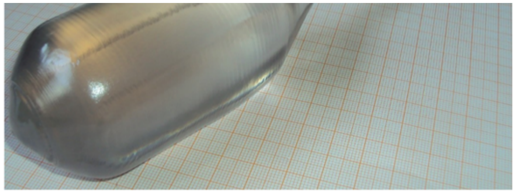
CRESST: phonon and light – from raw materials to final $CaWO_4$ cryogenic detectors

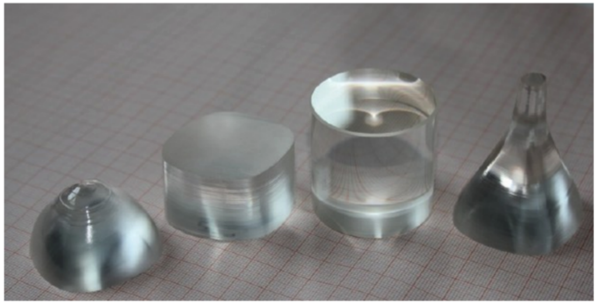
In house crystal cutting, machining and polishing



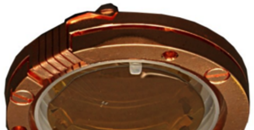
(New crystals for CRESST-III Phase 1)

CRESST: phonon and light – from raw materials to final $CaWO_4$ cryogenic detectors



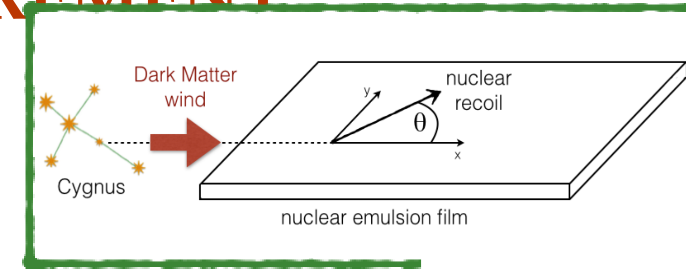


Detector production:
TES evaporation on $CaWO_4$ and on SOS light detector



NUCLEAR EMULSION WIMP SEARCH DIRECTIONAL MEASUREMENT

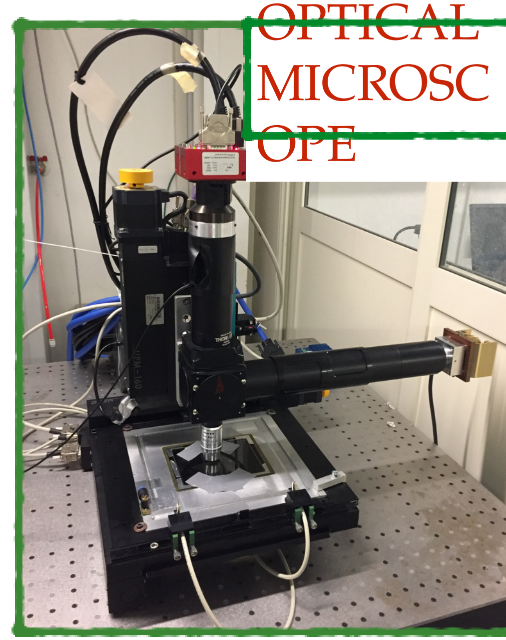
De Lellis



Equatorial Telescope

- **Aim**: detect the direction of **nuclear recoils** produced in WIMP interactions
- **Target**: nanometric nuclear emulsions acting both as target and tracking detector
- **Background reduction:** neutron **shied** surrounding the target
- **Fixed pointing**: target mounted on **equatorial telescope** constantly pointing to the Cygnus Constellation
- **Location**: Underground Gran Sasso Laboratory

OPTICAL MICROSCOPE

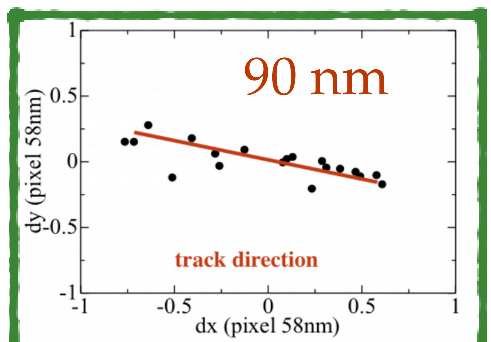


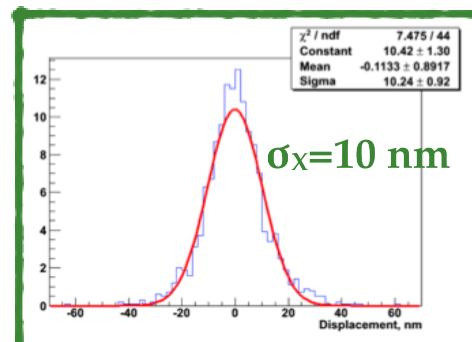
LNGS - Hall B

- Polyethylene/Lead shield against environmental background
- Cooling system to preserve emulsions
- First technical test installed in March 2017

NANOMETRIC TRACK RECONSTRUCTION

- Exploit resonant light scattering
- Measurement of track slope and length beyond optical resolution
- Unprecedented accuracy of **10 nm** achieved on both coordinates





Some concluding remarks

- Optimize experiments and analysis for discovery
- Exploit multitude of signatures & reduce backgrounds
- There is a good chance of discovery already in current experiments
- Stay as close as possible to linear range of sensitivity vs. exposure = best use of costly isotopes / target mass
- Support healthy competition: different targets/isotopes and techniques
- Stay open for new ideas and techniques - scaling in mass is needed, but maybe we have new and better ideas....

And maybe:

invisiblesPlus
neutrinos, dark matter & dark energy physics

elusives
neutrinos, dark matter & dark energy physics

meets

SFB 1258 Neutrinos Dark Matter Messengers

Grad-school in 2018