Neutrinoless double beta decay and absolute neutrino mass measurements

MAX-PLANCK-INSTITUT
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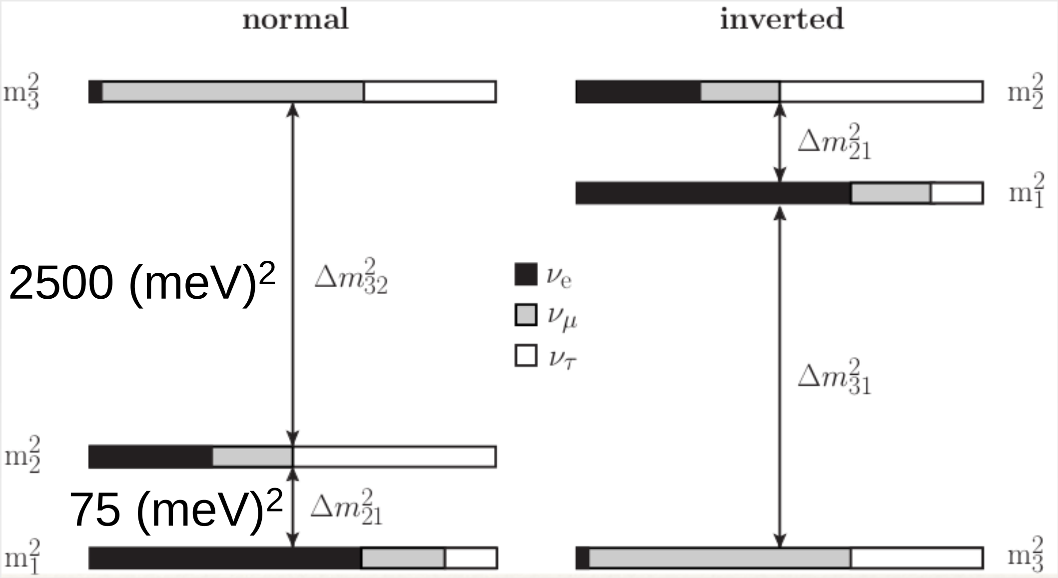
ββ
GERDA

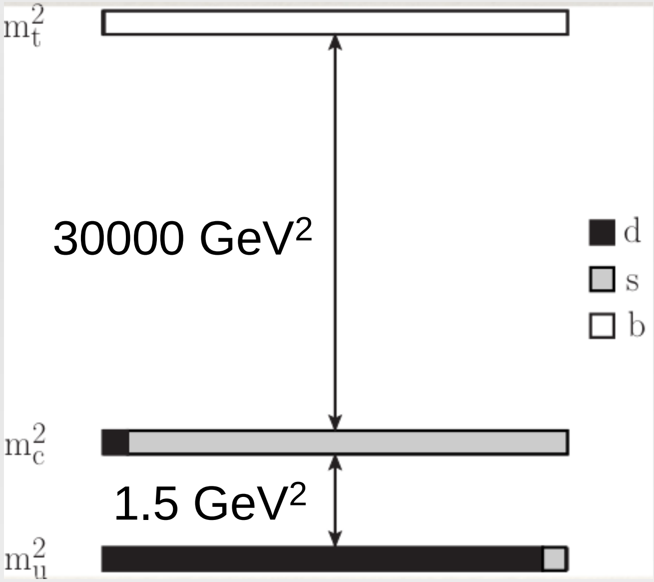
LEPTON PHOTON 2017

Topics in neutrino physics

neutrinos: mass splitting and mixing



quarks



Neutrino flavor physics: underlying symmetry ?

- mixing matrix U and $|\Delta m^2|$, quite well known but: $\theta_{23} = 45^o$ or small deviation from 45^o ?
- sign of Δm_{31}^2 ?
- CP phase = $3\pi/2$? (likely not relevant for leptogenesis)

Neutrino mass: absolute mass scale, origin of neutrino mass: why are masses so small ?

major impact {

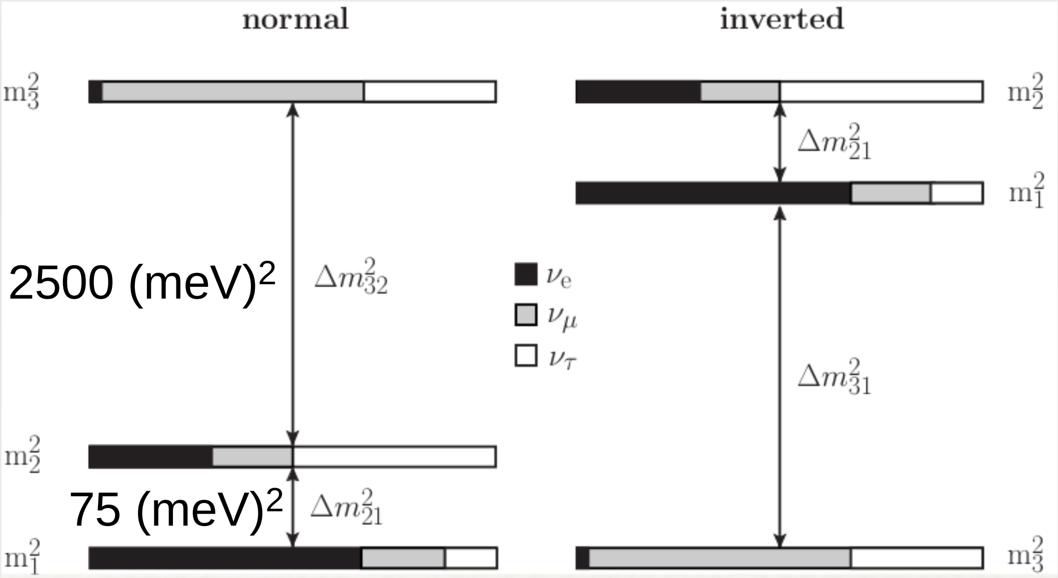
Is mixing matrix unitary (sterile neutrinos, ...)?

Are neutrinos Majorana or Dirac particles (lepton number violation)?

(see talk by W. Rodejohann at TAUP2017)

Topics in neutrino physics

neutrinos: mass splitting and mixing



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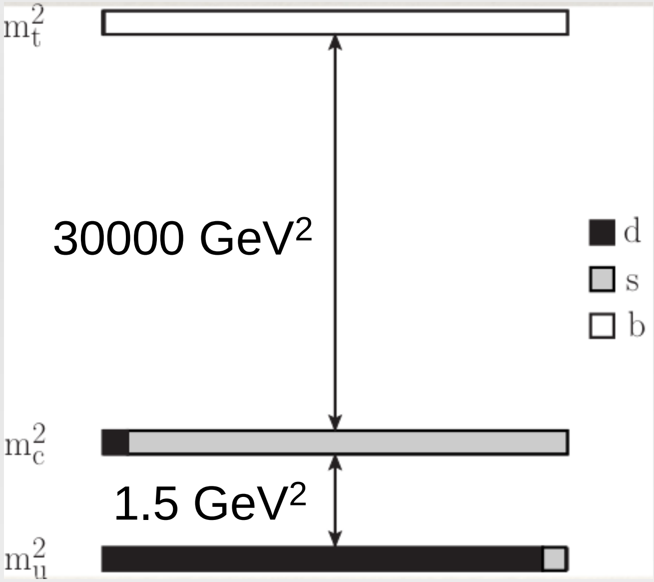

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Neutrino mass: absolute mass scale, origin of neutrino mass: why are masses so small ?

Is mixing matrix unit covered in this talk

major impact

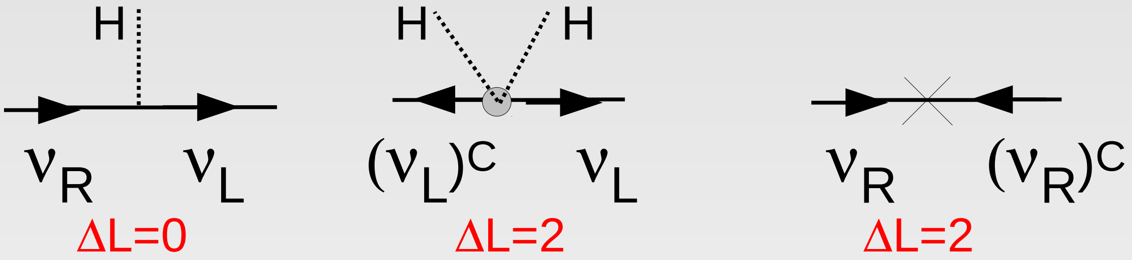
Are neutrinos Majorana or Dirac particles (lepton number violation)?

(see talk by W. Rodejohann at TAUP2017)

Neutrino mass: Lepton number violation?

possible neutrino mass terms (ν has no electric charge)

$$L_{Yuk} = m_D \, \bar{\nu}_L \, \nu_R + m_L \, \bar{\nu}_L \, (\nu_L)^C + m_R \, (\bar{\nu}_R)^C \, \nu_R + h.c.$$



H ν_R ν_L $\Delta L=0$

H H $(\nu_L)^C$ ν_L $\Delta L=2$

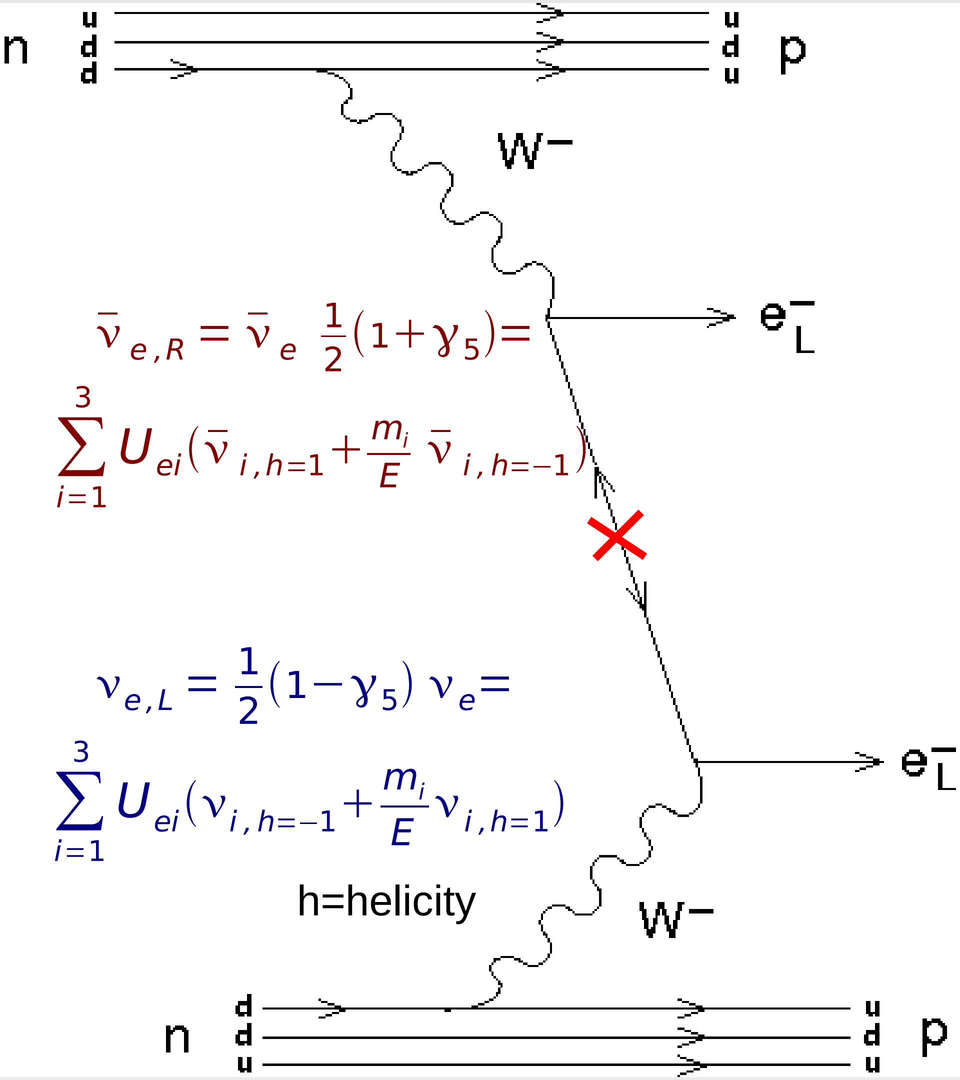
ν_R $(\nu_R)^C$ $\Delta L=2$

eigen vector	$N \sim \nu_R + (\nu_R)^C$	$\nu \sim \nu_L + (\nu_L)^C$	Majorana particles
mass ($m_L \sim 0$)	m_R	m_D^2 / m_R	

in general: expect ν to be Majorana particles → L violation

How to observe ΔL=2: 0νββ

Look for a process which can only occur if neutrino is Majorana particle



$$\bar{\nu}_{e,R} = \bar{\nu}_e\,\frac{1}{2}(1+\gamma_5) = \sum_{i=1}^{3} U_{ei}\left(\bar{\nu}_{i,h=1} + \frac{m_i}{E}\,\bar{\nu}_{i,h=-1}\right)$$

$$\nu_{e,L} = \frac{1}{2}(1-\gamma_5)\,\nu_e = \sum_{i=1}^{3} U_{ei}\left(\nu_{i,h=-1} + \frac{m_i}{E}\,\nu_{i,h=1}\right)$$

h=helicity

coupling strength ~ $m_{\beta\beta} = \sum_{i=1}^{3} U_{ei}^2 m_i$

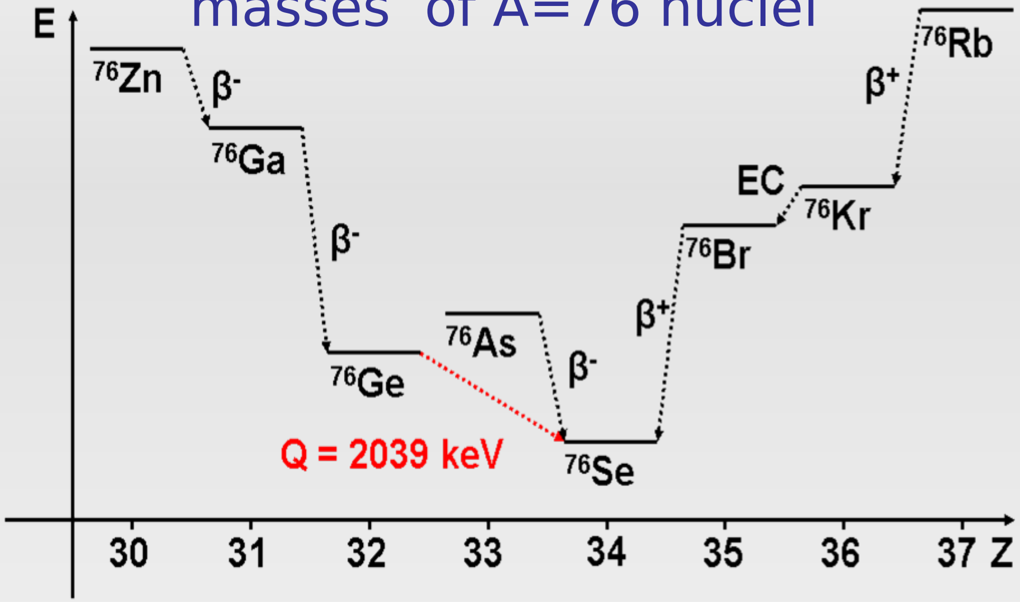
function of
- neutrino mixing parameters
- lightest neutrino mass
- 2 Majorana phases

also possible: heavy N exchange

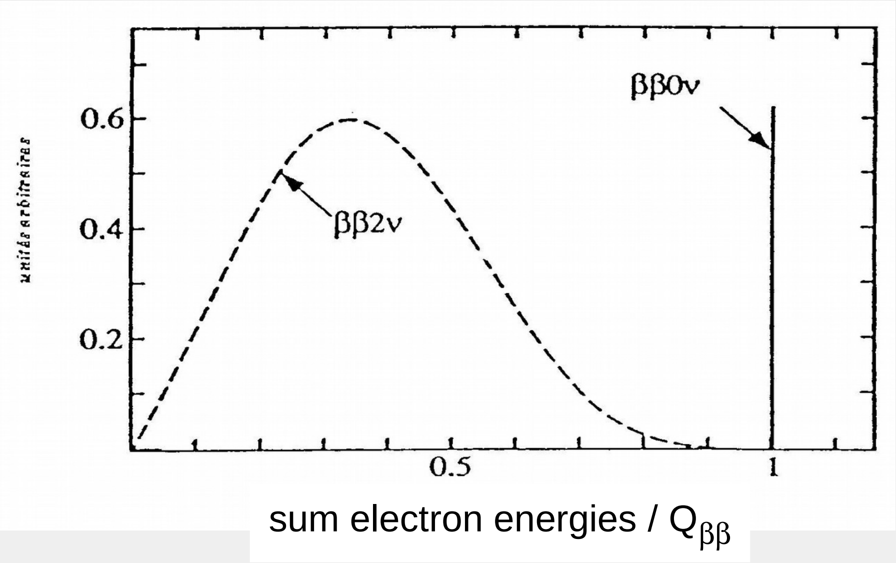
→ coupling strength ~ $\sum_{i=1}^{3} V_{ei}^2 / M_i$

Neutrinoless double beta decay

masses of A=76 nuclei



experimental signature for ββ



”single” beta decay not allowed

$\longrightarrow$ only ”double beta decay”

$$(A,Z) \longrightarrow (A,Z+2) + 2\,e^- + 2\bar{\nu} \qquad \Delta L=0$$

$$(A,Z) \longrightarrow (A,Z+2) + 2\,e^- \qquad \Delta L=2$$

0νββ: search for a line at Q value of decay

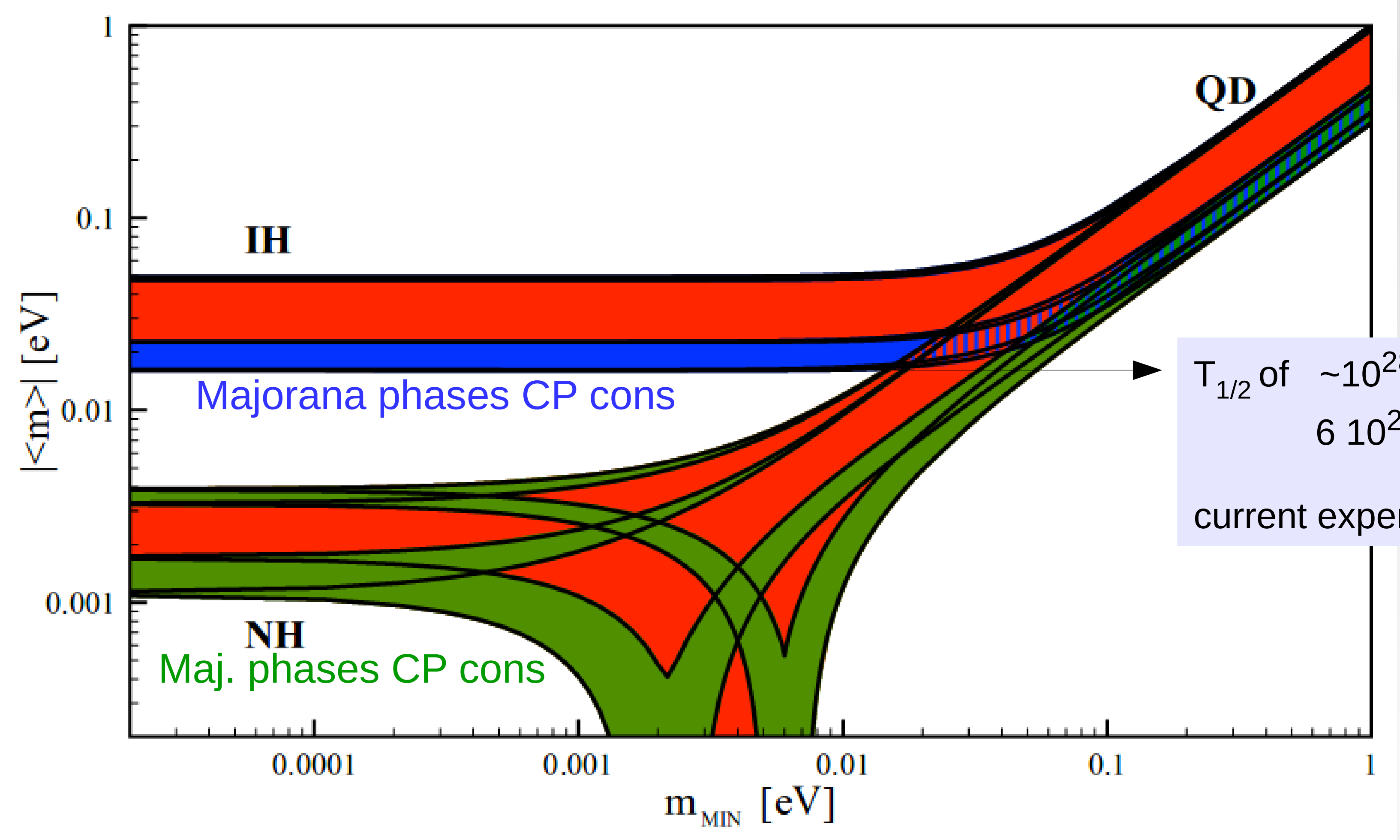
Note: similar process in principle also observable at accelerator or reactor or ... but for light Majorana neutrino:

- background too high
- flux too low compared to Avogadro N_A

Light Majorana neutrino exchange

scan of $m_{\beta\beta}$ (Δm_{atm}^2, Δm_{sol}^2, m_{min}, θ_{atm}, θ_{sol}, θ_{13}, 2 Majorana phases)

according to measurements (2 σ range) or random (2 Maj. phases)



$T_{1/2}$ of ~10^{28} yr for ^{76}Ge

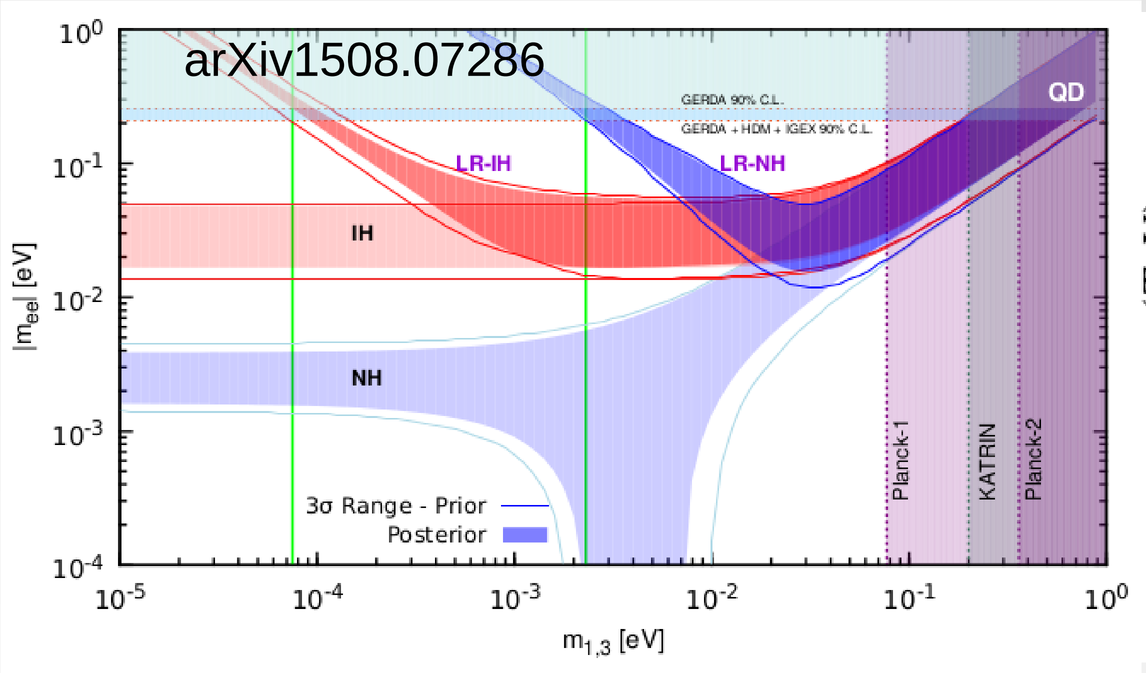
$6\ 10^{27}$ yr for ^{136}Xe

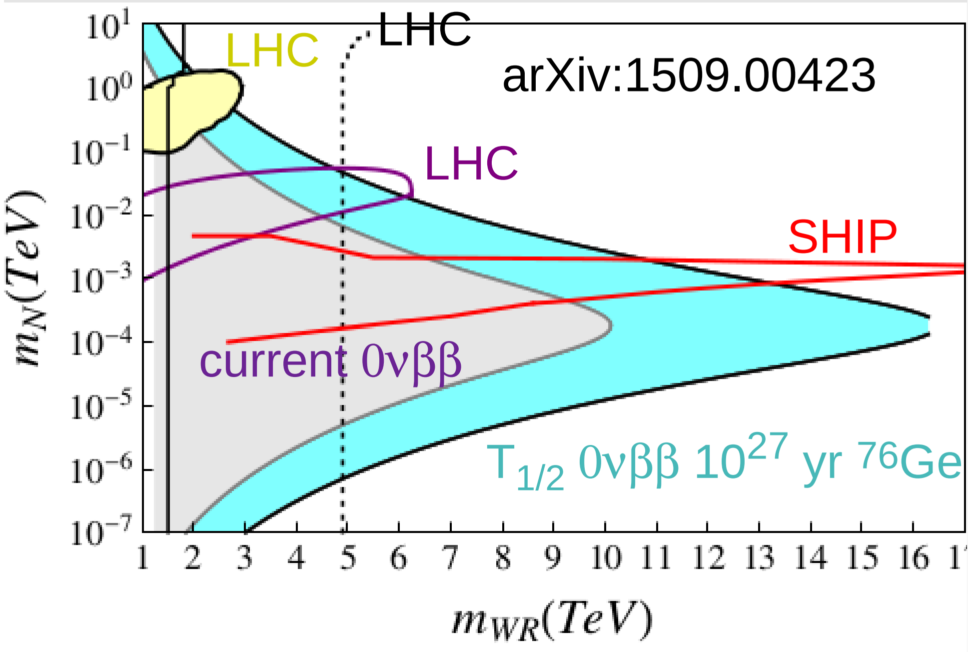
current experiments 10^{25} - 10^{26} yr

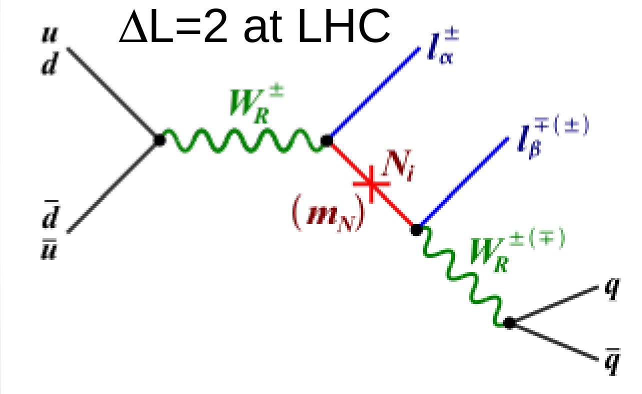
PDG 2016

LHC vs $0\nu\beta\beta$: other mechanisms

extensions of SM → other contributions to $0\nu\beta\beta$ possible, example LRSM
LHC might find W_R and/or $\Delta L=2$ process


arXiv1508.07286


arXiv:1509.00423


$\Delta L=2$ at LHC

best case: find s.th. at LHC and $0\nu\beta\beta$ and lepton flavor violation like $\mu \to e\,\gamma$

From $T_{1/2}$ to $m_{\beta\beta}$

$$\frac{1}{T^{0\nu}_{1/2}} = g_A^4 G^{0\nu} \left|M^{0\nu}\right|^2 \frac{\langle m_{\beta\beta}\rangle^2}{m_e^2}$$

$T^{0\nu}_{1/2}$ = measured experimentally

g_A = axial vector coupl. = 1.27

$G^{0\nu}$ = phase space factor ~ Q^5

$M^{0\nu}$ = nuclear matrix element

m_e = electron mass

need $M^{0\nu}$ to understand physics mechanism

selected $0\nu\beta\beta$ isotopes from PRD 83 (2011) 113010

Isotope	$G^{0\nu}$ [10^{-14}y]	Q[keV]	nat. abund.[%]
^{48}Ca	2.5	4273.7	0.187
^{76}Ge	0.23	2039.1	7.8
^{82}Se	1.0	2995.5	9.2
^{100}Mo	1.6	3035.0	9.6
^{130}Te	1.4	2530.3	34.5
^{136}Xe	1.5	2461.9	8.9
^{150}Nd	6.6	3367.3	5.6

enrichment required except for ^{130}Te,
not (yet) possible for all, costs differ

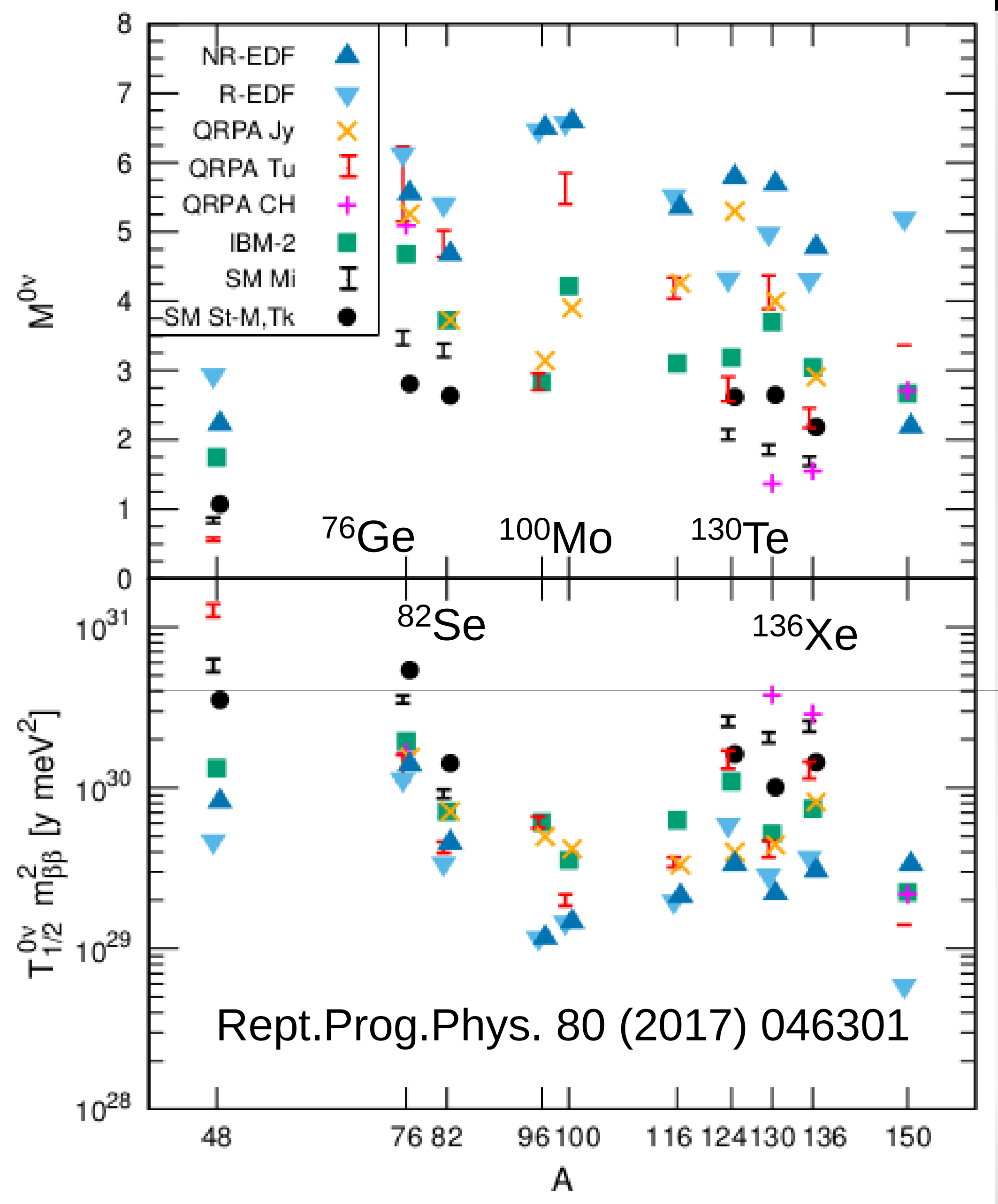
Experiment observes $N^{0\nu} = \ln 2 \frac{N_A}{A} \cdot a \cdot \epsilon \cdot M \cdot t \,/\, T_{1/2}$ and $N^{bkg} = M \cdot t \cdot B \cdot \Delta E$

Experimental sensitivity

$$T_{1/2}(90\%CL) > \begin{cases} \dfrac{\ln 2}{2.3} \dfrac{N_A}{A} a \cdot \epsilon \cdot M \cdot t & \text{for } N^{bkg} = 0 \\[2ex] \dfrac{\ln 2}{1.64} \dfrac{N_A}{A} a \cdot \epsilon \sqrt{\dfrac{M \cdot t}{B \cdot \Delta E}} & \text{for large } N^{bkg} \end{cases}$$

M = mass of detector
t = measurement time
A = isotope mass per mole
N_A= Avogadro constant
a = fraction of $0\nu\beta\beta$ isotope
ε = detection efficiency
B = background index in units cnt/(keV kg y)
ΔE = energy resolution = energy window size

Expected $T_{1/2}$ for different matrix elements



Rept.Prog.Phys. 80 (2017) 046301

10^{28} yr for 20 meV effective mass
0.6 ^{76}Ge decays per t*yr exposure
0.3 ^{136}Xe decays per t*yr exposure
(before enrichment fraction & cuts)
→ background free conditions required

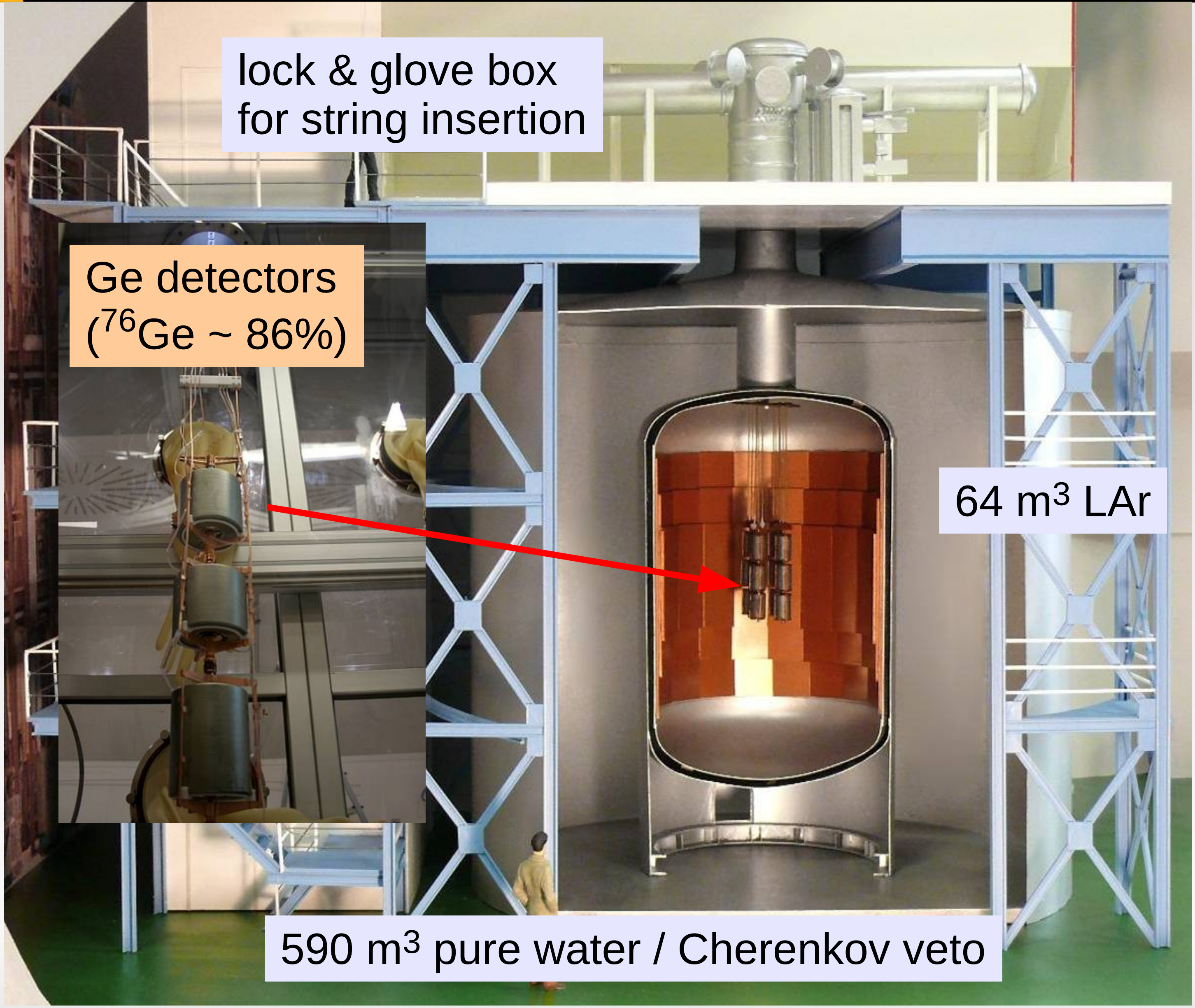
No favored isotope considering spread of nuclear matrix elements

Experiments (status TAUP 2017)

	experiment	form	det.	shielding	bkg reduction	status
Ca	CANDLES	solid	light	Pb+B_4C+org scint	pulse shape	R&D, no enrichm.
Ge	GERDA	solid	ioniz.	water+liquid Ar	pulse s.+LAr veto	running since 2013
	Majorana D.	solid	ioniz.	Cu+Pb+PE	pulse shape	running since 2015
Se	CUPID0	solid	light+heat	Cu+Pb	light/heat	running since 2017
	SuperNemo	solid	track+cal		dE/dx,topology	start end 2017
Mo	AMoRE	solid	light+heat	Pb	light/heat	AMoRE I in 2018
	CUPID-Mo	solid	light+heat		light/heat	R&D
Te	CUORE	solid	heat	Cu+Pb		running since 2016
	SNO+	liquid	light	org. scintillator		start late 2018
Xe	EXO	liquid	light+ioniz	Pb	topology	running since 2011
	KamlandZen	liquid	light	org. scintillator		running since 2011
	NEXT	gas	light+ioniz	Cu+Pb	topology	start end 2018
	PandaX-III	gas	ionization	water	topology	first module in 2019
	AXEL	gas	light+ioniz		topology	R&D

new/first results at TAUP

GERDA: Ge in LAr @ Gran Sasso



lock & glove box for string insertion

Ge detectors (^{76}Ge ~ 86%)

64 m^3 LAr

590 m^3 pure water / Cherenkov veto

EPJ C73 (2013) 2330

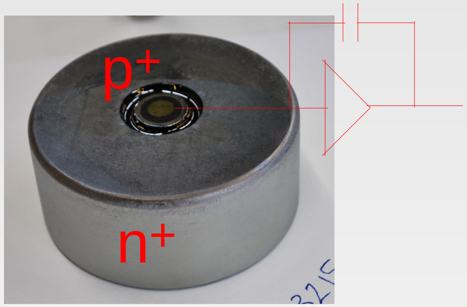
Phase I (2011-13):

$T^{0\nu}_{1/2} > 2.1\cdot10^{25}$ yr (90% C.L.)

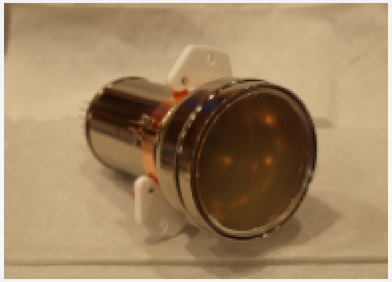
^{76}Ge $0\nu\beta\beta$ decay, PRL 111 122503

Phase II:

2x Ge mass (30 BEGe det.)

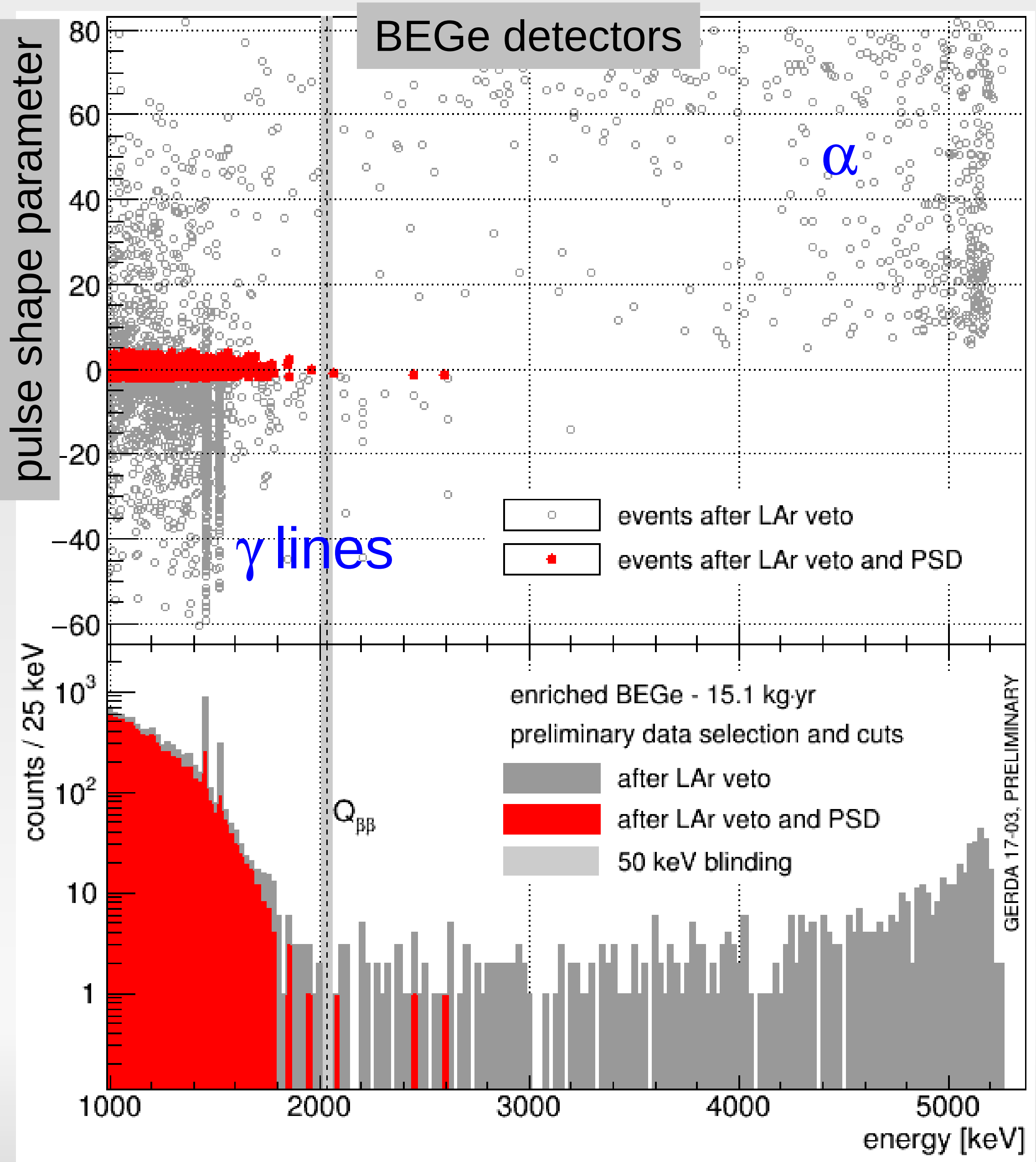


LAr scint. light readout



started end 2015

Background: pulse shape discrimination



use time profile of detector signal to
→ identify signal-like evt, proxies = 2νββ & Double Escape Peak of 2615 keV γ
(γ + A → $e^+ e^-$ with 2x511 keV escape)

all α (surface) events removed
γ lines suppressed by factor ~6

energy resol FWHM ~ 3keV at $Q_{\beta\beta}$
(for MajoranaDemonstrator 2.4 keV)
→ Ge exp have superior resolution

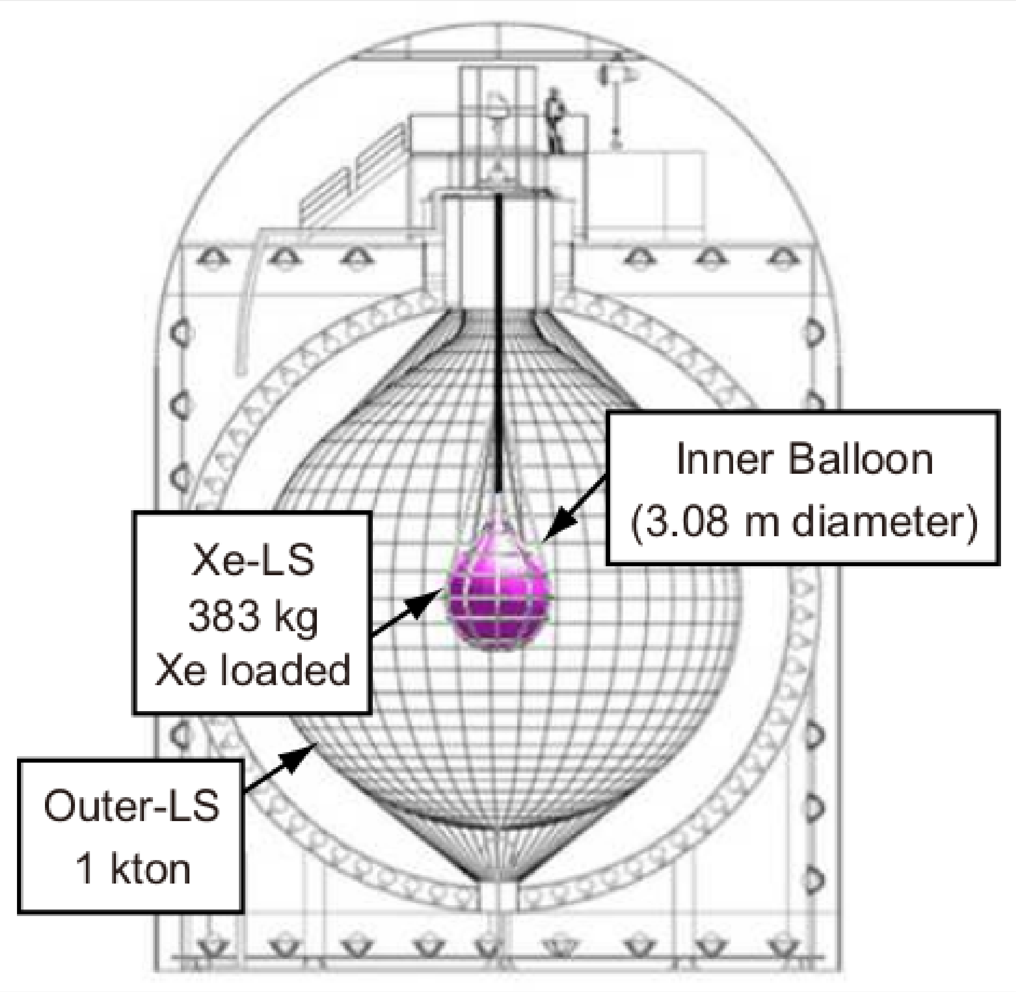
background ~3 cnt/(FWHM t yr)
→ Ge exp. have lowest background

after unblinding: no signal

$$\boxed{T^{0\nu}_{1/2} > 8.0\cdot 10^{25}\ \text{yr (90\% C.L.)}}$$

sensitivity = 5.8 10^{25} y
eventually >1 10^{26} yr

Kamland-Zen



^{136}Xe loaded in liquid scintillator in inner balloon

large mass, poor energy resolution ~250 keV

start 2011 (phase I): fall out of ^{110m}Ag
from Fukushima on inner balloon

2012-13: purification of scintillator and Xe

Dec 2013 – Oct 2015: phase II → ^{110m}Ag bkg
factor 10 reduced, Xe loading 2.44% --> 2.96%

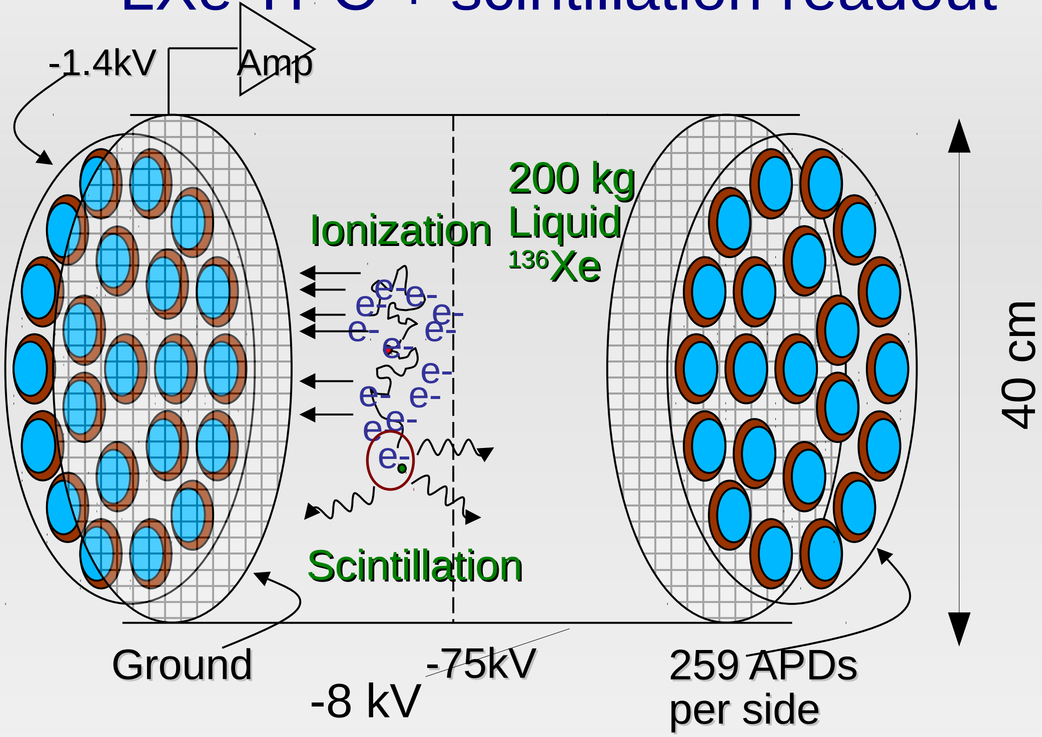
end 2017: larger & cleaner balloon,
loading 380 kg → 750 kg
sensitivity $T_{1/2} > 2\ 10^{26}$ yr

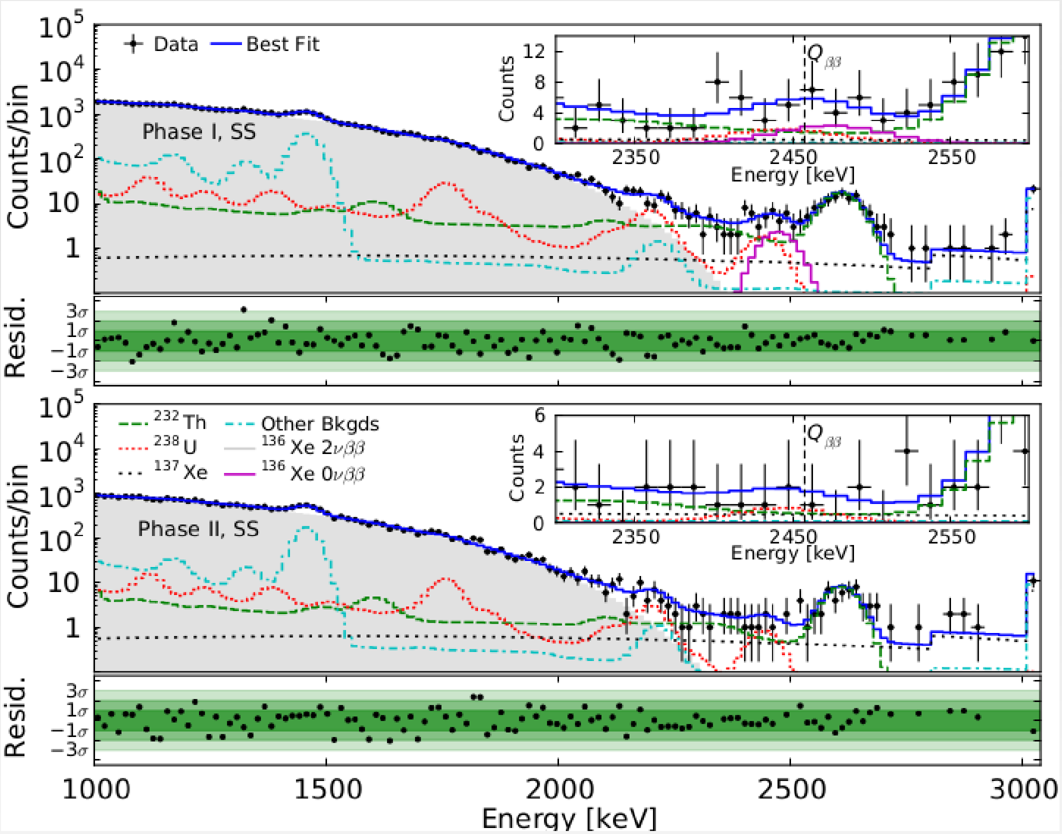
best limit for $0\nu\beta\beta$ of ^{136}Xe: $T^{0\nu}_{1/2} > 10.7 \cdot 10^{25}$ yr (90% C.L.) sensitivity ~5.6 10^{25} yr

PRL 117 (2016) 082503

EXO-200 @ WIPP

LXe TPC + scintillation readout





light+ionization FWHM for $0\nu\beta\beta$ ~70 keV @ $Q_{\beta\beta}$

total/fiducial mass 160/100 kg, ^{136}Xe fraction 80.6%

arXiv:1707.08707

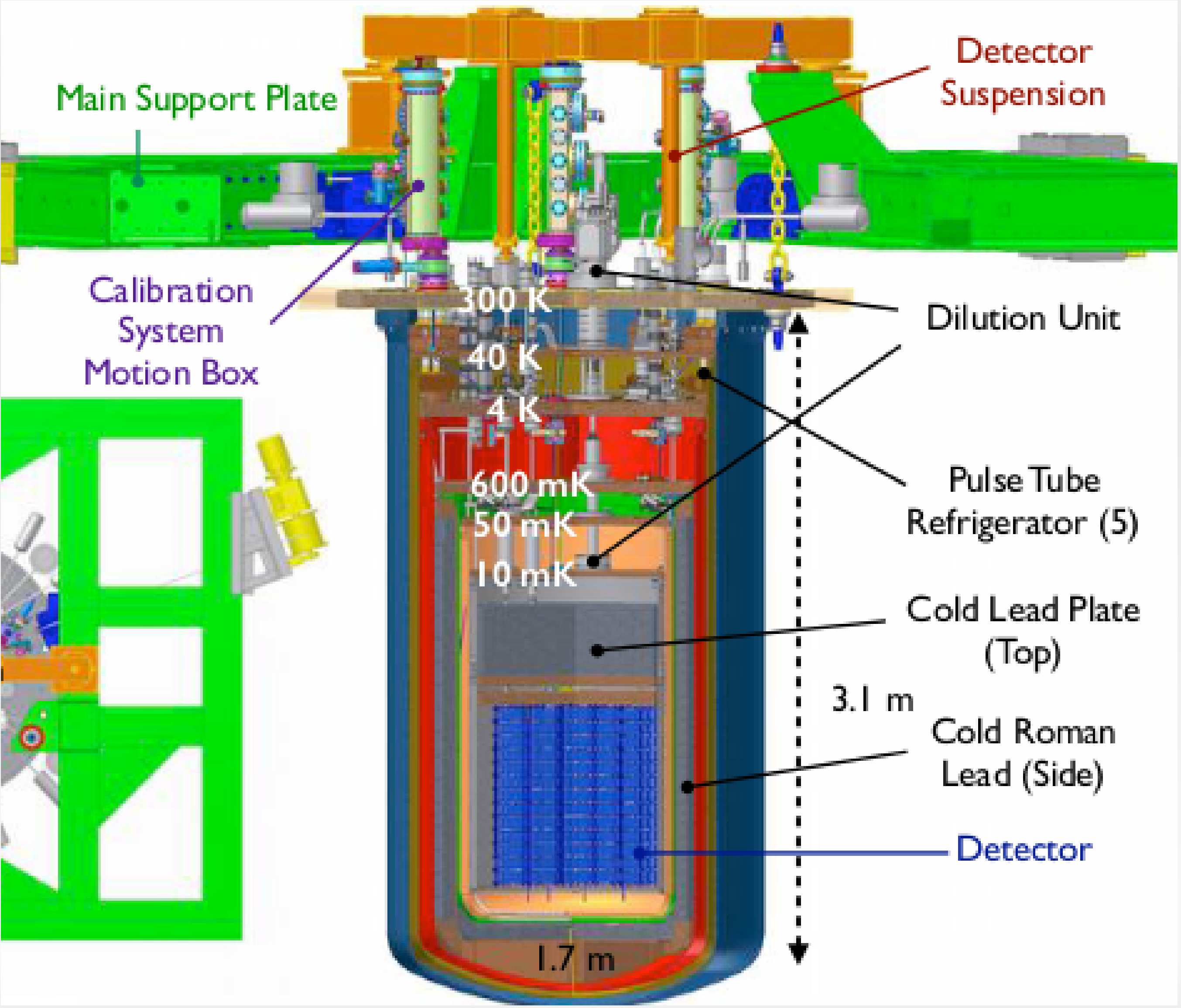
$$\boxed{T^{0\nu}_{1/2} > 1.8\cdot 10^{25}\ yr\,(@\ 90\ C.L.)}$$

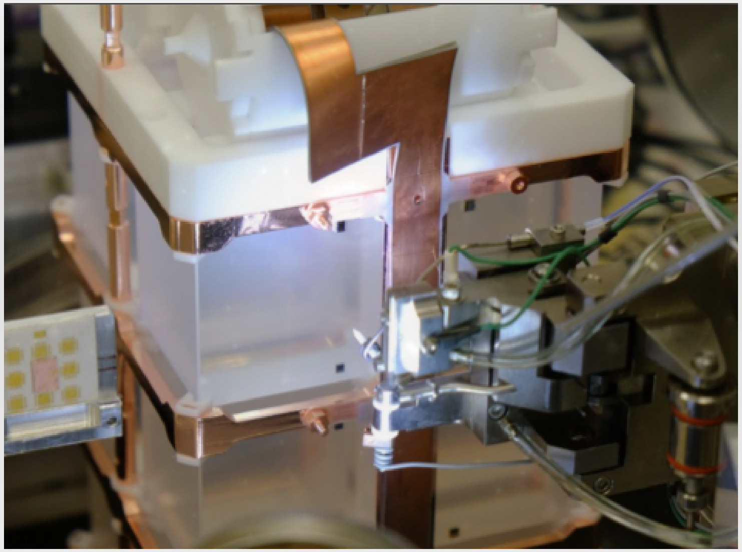
(sensitivity 3.7 10^{25} yr)

start physics data May 2011,
fire & radiation problem at WIPP → interrupt 2014-15

now taking data, σ/Q improved to 1.23%
final sensitivity ~6 10^{25} yr (90% CL)

Cuore: ^{130}Te



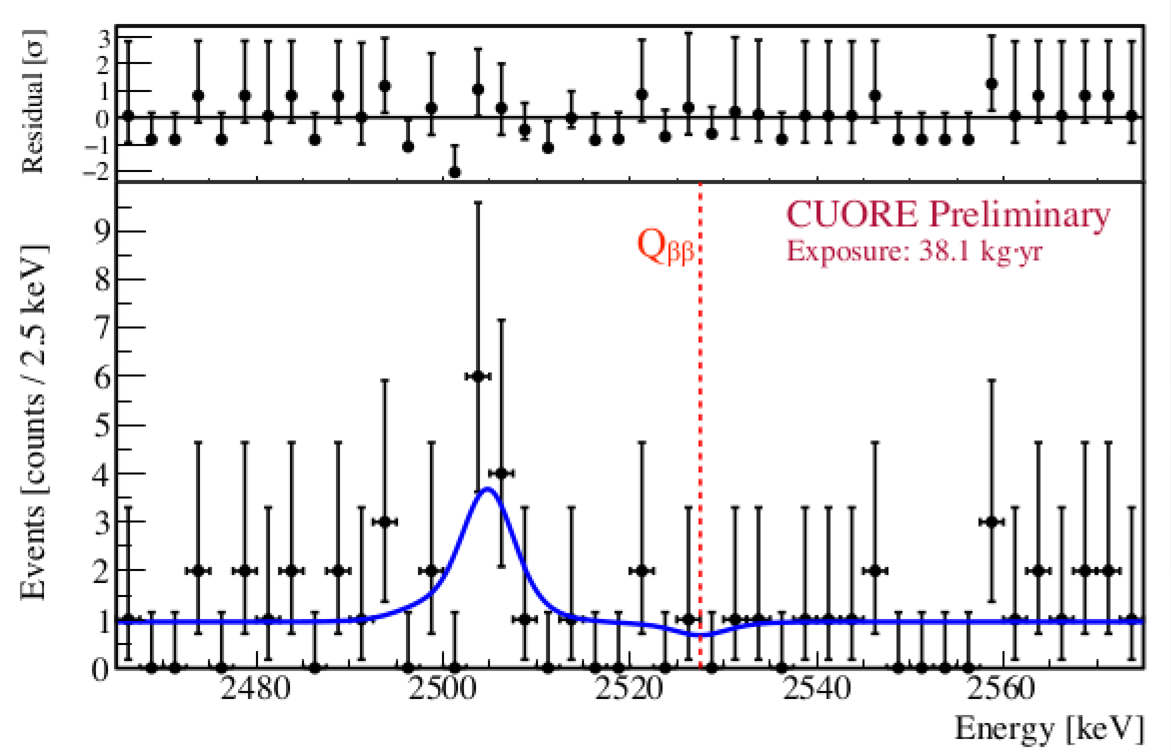


988 $^{nat}TeO_2$ crystals
206 kg ^{130}Te,

calorimeter with Ge NTD readout,
$\Delta T \sim 0.1$ mK / MeV
final resolution ~ 5 keV FWHM

Cuore: ^{130}Te

new cryostat commissioned during last years
all detectors assembled, 984/988 channels working !!!
energy resolution currently ~ 8 keV FWHM at 2615 keV



first result for 2017 physics data:
(blind analysis)

background ~ 0.01 cnt/(keV kg yr)
→ meets design specification
bkg mainly degraded alpha

$$T^{0\nu}_{1/2} > 4.5 \cdot 10^{24}\ yr\,(@\ 90\ C.L.)$$

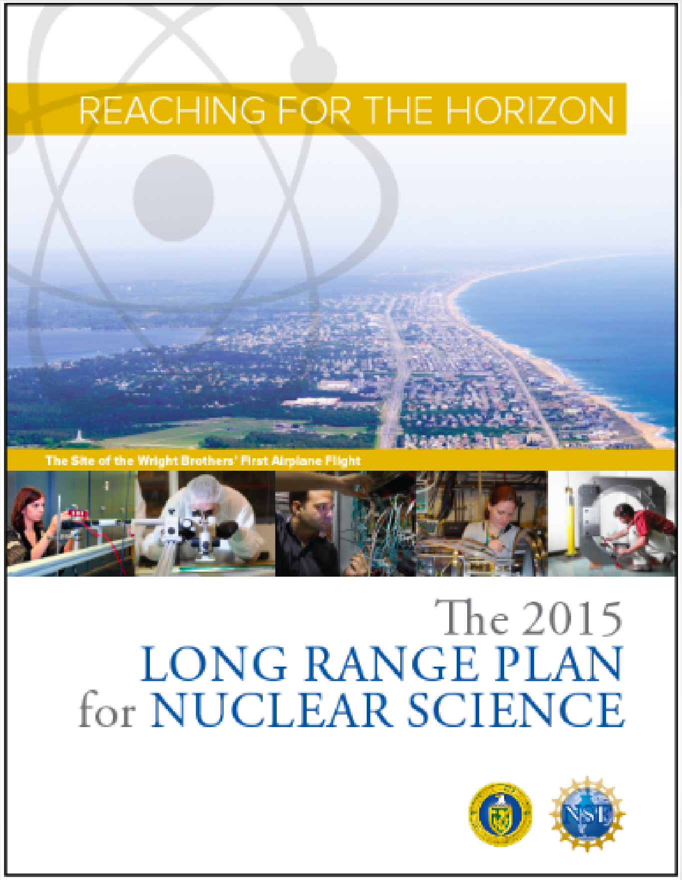
(sensitivity 3.6 10^{24} yr)

final sensitivity 10^{26} yr

future of 0νββ: personal thoughts

many ideas/proposals how to reach 10^{28} yr (discovery) $T_{1/2}$ sensitivity,
each cost 100 M$ (or more)

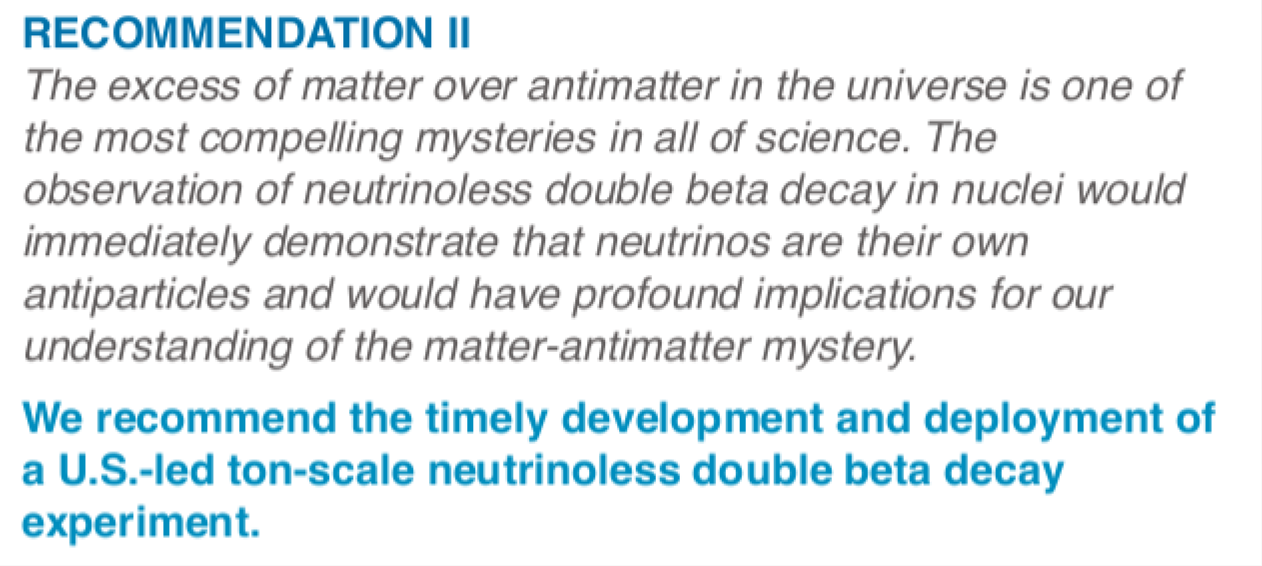
who will fund such experiment(s)?
answer might be here: https://science.energy.gov/np/nsac/



REACHING FOR THE HORIZON

The Site of the Wright Brothers' First Airplane Flight

The 2015
LONG RANGE PLAN
for NUCLEAR SCIENCE



RECOMMENDATION II

The excess of matter over antimatter in the universe is one of the most compelling mysteries in all of science. The observation of neutrinoless double beta decay in nuclei would immediately demonstrate that neutrinos are their own antiparticles and would have profound implications for our understanding of the matter-antimatter mystery.

We recommend the timely development and deployment of a U.S.-led ton-scale neutrinoless double beta decay experiment.

major funding from Europe, China, Japan, Canada, Korea?
US down-select in few years:
nEXO (successor of EXO-200),
LEGEND (successor of MajoranaDemonstrator+GERDA),
+ ?? will apply

comparison (some) 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	2.4	7	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	5000/4000	58	2	600	24	future
LEGEND-200	Ge	200/155	3	1	100	75	
LEGEND-1t	Ge	1000/780	3	0.2	1000	24	

* total= element mass, FV= 0νββ isotope mass in fiducial volume (incl enrichment fraction)

[&] kg of 0νββ isotope in active volume and divided by 0νββ efficiency

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

Absolute neutrino mass

indirect measurements: cosmology, assume ΛCDM? what input measurements?

$$m_{tot} = \sum_{i=1}^{3} m_i$$

0νββ, assume light Majorana neutrino exchange dominates

$$\langle m_{\beta\beta} \rangle = \left| \sum_{i=1}^{3} U_{ei}^2 \cdot m_i \right|$$

direct measurements: kinematic of β decay or electron capture, form of the spectrum

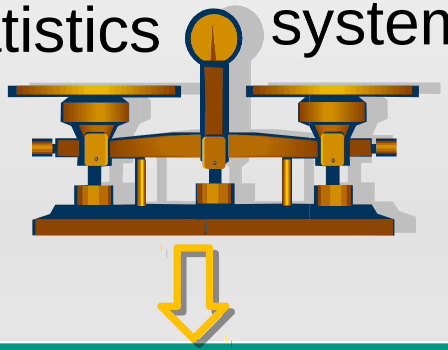
$$m(\nu_e) = \sqrt{\sum_{i=1}^{3} \left| U_{ei} \right|^2 \cdot m_i^2}$$

source requirements:

- low Q value, spectrum close to Q ~ $\sqrt{\left(\left(Q - E_e\right)^2 - m\left(\nu_e\right)^2\right)}$
- low $T_{1/2}$
- simple atom/molecule (distortion of spectrum)
- know the spectral shape (allowed transition)

thanks to G. Drexlin, L. Gastaldo and Ch. Weinheimer for slides

tritium & ^{163}Ho



4×10^{8} atoms
for 1 Bq

$^{3}H \rightarrow {}^{3}He$	
Q	18.6 keV
$T_{1/2}$	**12.3 y**

MAC-E filter

cyclotron radiation

PROJECT 8

ß-source requirements
no source charging (stability)
no isotope exchange
precise description of final state
long-term operation (3-5 y)
minimised atomic/molecular effects

experimental considerations
good energy resolution ~eV
low background at Q
no energy loss of electrons
stability of temperature, B, E field, ...

2×10^{11} atoms
for 1 Bq

$^{163}Ho \rightarrow {}^{163}Dy^{*}$	
Q	2.8 keV
$T_{1/2}$	4570 y

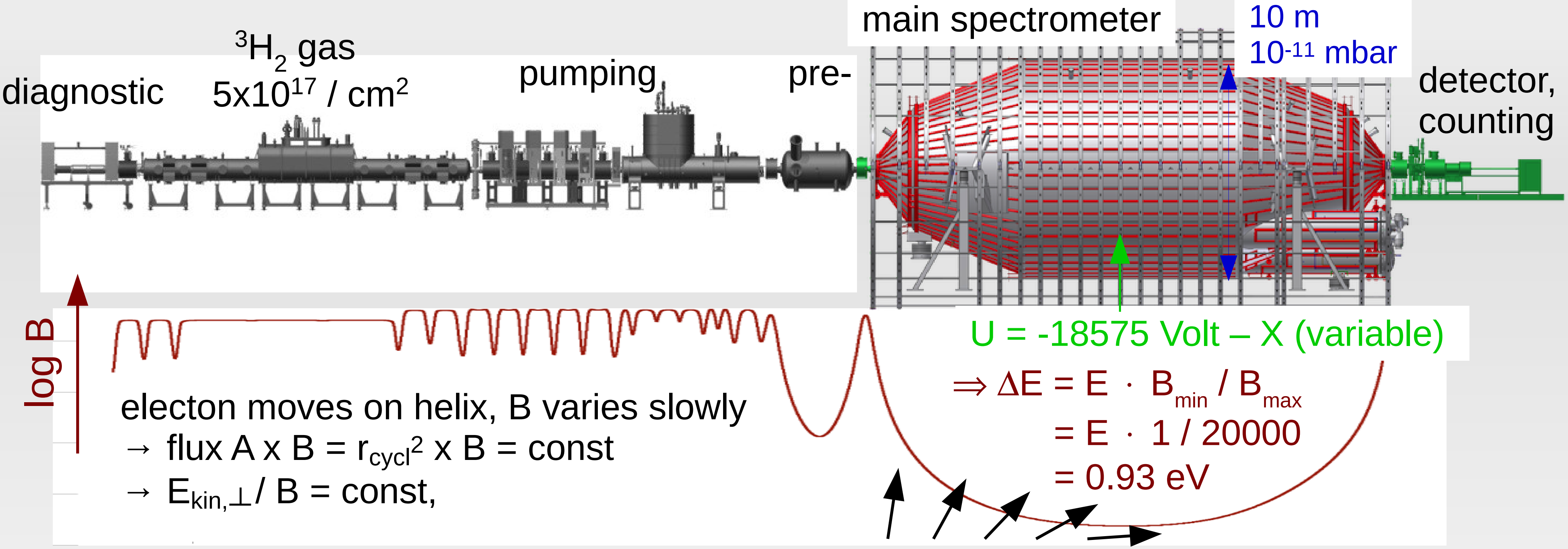
cryogenic calorimeter

ECHo

HOLMES

NuMECS

Katrin @ KIT

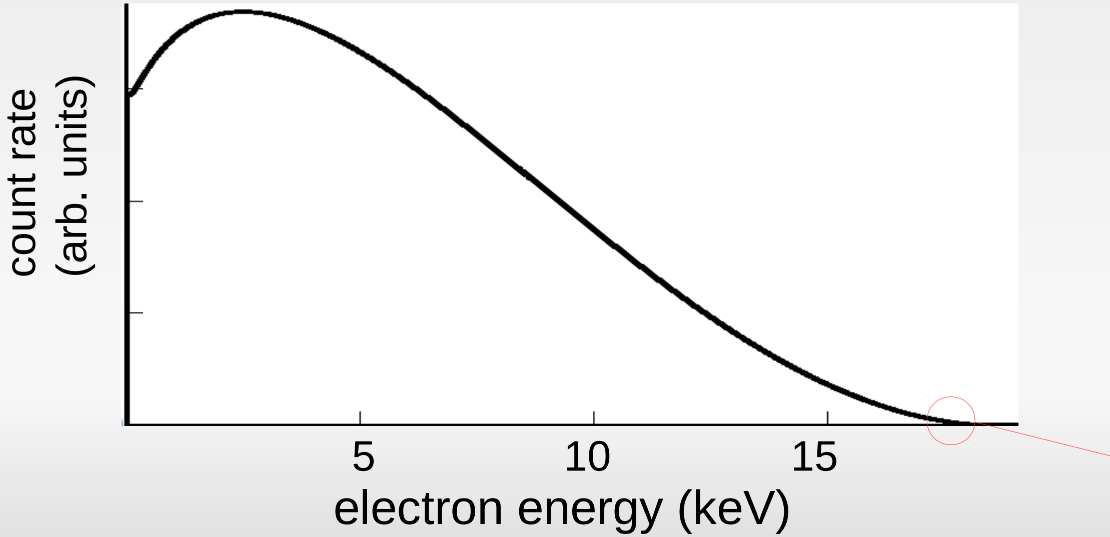


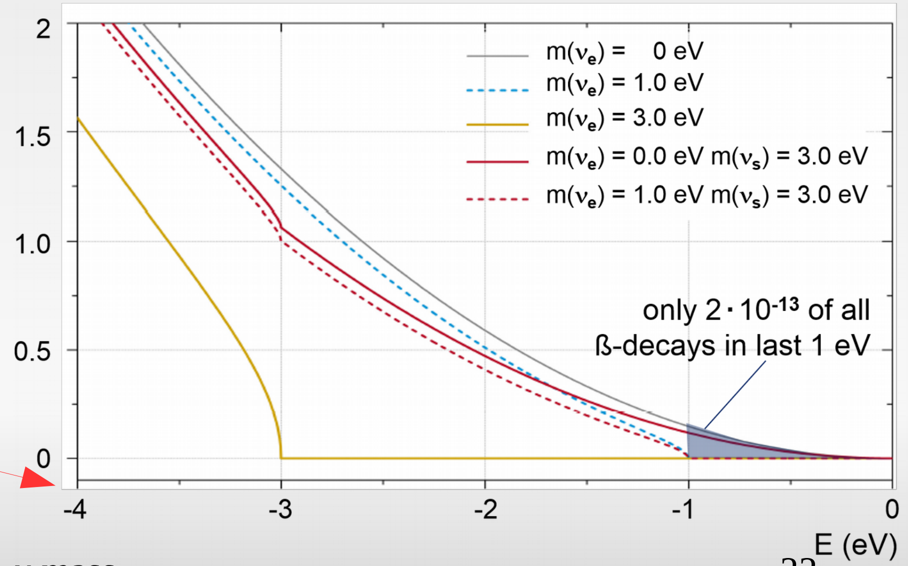
electon moves on helix, B varies slowly

→ flux A x B = r_{cycl}^2 x B = const

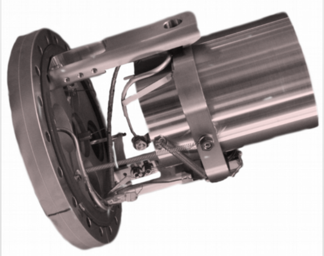
→ $E_{kin,\perp}$ / B = const,

$$\Rightarrow \Delta E = E \cdot B_{min} / B_{max}$$
$$= E \cdot 1 / 20000$$
$$= 0.93 \text{ eV}$$





Katrin: a few of the challenges



e-gun

column density of tritium gas stability at per mill level
(temperature stability measured 5 mK/h)
and β transport: monitor with photo-electron gun in rear section
and 3 ^{85m}Kr sources (σ ~ 200 meV measured)

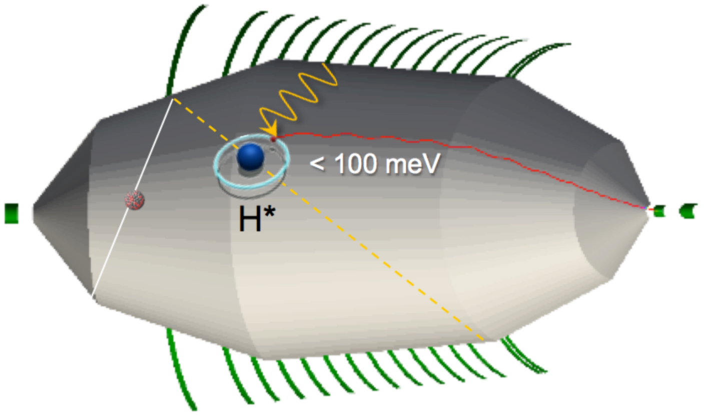
purity of tritium gas: Raman spectroscopy

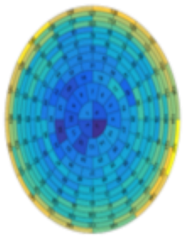
tritium retention > 10^7: cryo-sorption at argon snow at 3-4 K

high voltage stability ~ few ppm, precision voltage divider for regulation,
sub-ppm monitoring with ^{85m}Kr

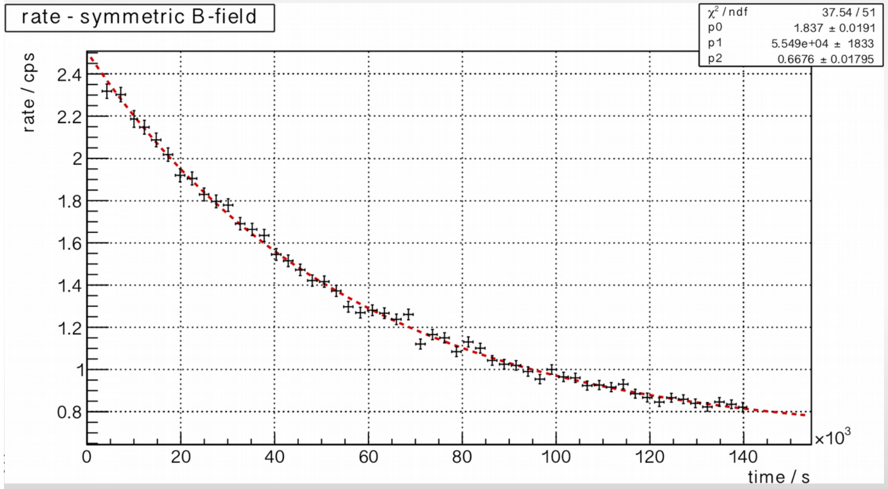
background rate: all sources but one (unexpected) background under control
H* Rydberg atoms sputtered off main spectrometer walls by α/ions,
H* ionized by thermal radiation → meV e$^-$ in main spectrometer

test with short-lived ^{220}Rn daughters





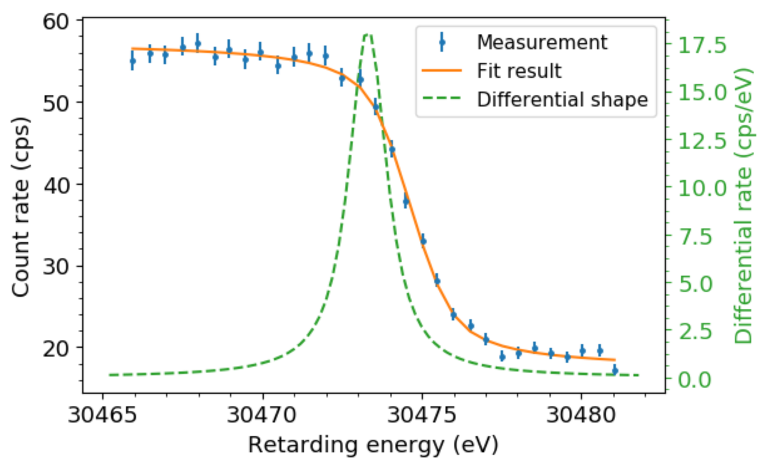
isotropic bg for
longer exposure



Katrin: status

‘first light’ in October 2016

July 2017: ^{83m}Kr calibration(s)



Tritium data taking starts in 2018

beyond:
- search for sterile neutrinos at keV mass range (eV range possible with Katrin)
- instead of integral counting time-of-flight measurement → 100 meV sensitivity

But: energy resolution limited by minimal B field = size of spectrometer
→ no larger spectrometer feasible
→ other technology?

Project 8: cyclotron radiation spectroscopy

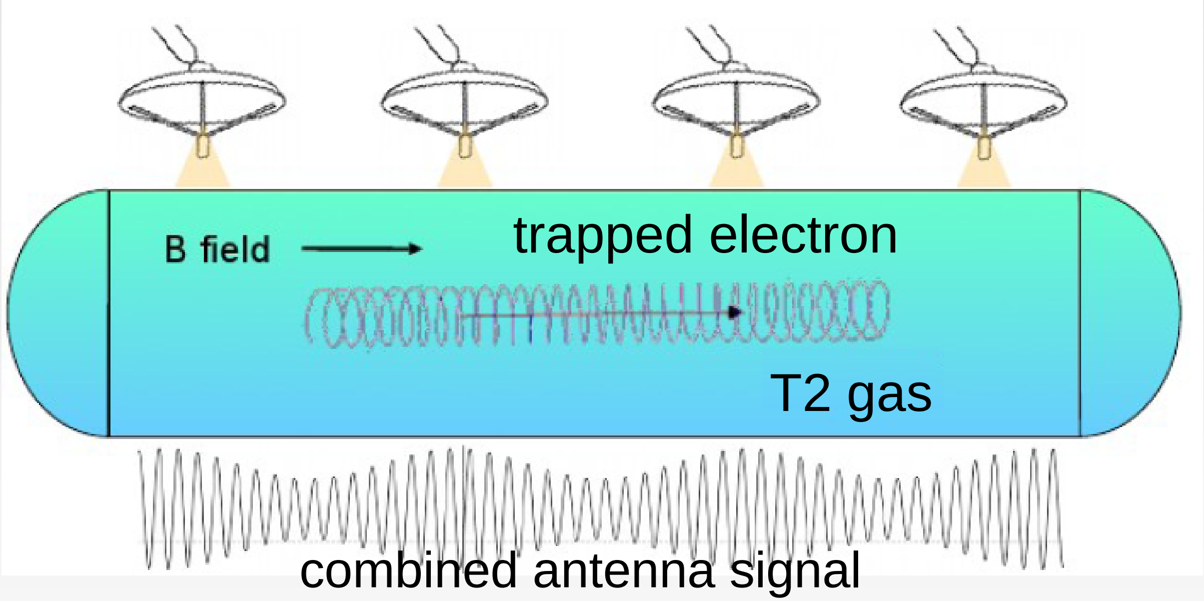
Cyclotron Radiation Emission Spectroscopy (CRES)

$$\omega(\gamma) = \frac{\omega_0}{\gamma} = \frac{e \cdot B}{m_e + E_{e,kin}}$$

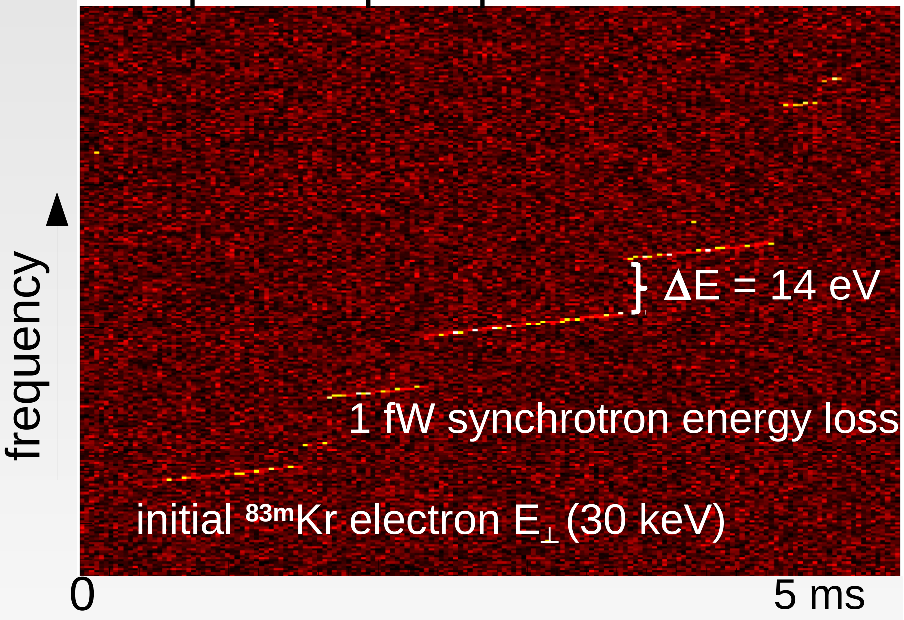
measurement of freq ω
→ energy

$E_{e,kin}$ = 18.575 keV

B = 1 T → 27 GHz



proof of principle with ^{83m}Kr



B. Monreal, J. Formaggio, Phys. Rev. D 80 (2009) 051301(R)

ΔE = 3.6 eV @ 30 keV

Δω ~ 1/t_s sampling time t_s ~ several μs → ΔE = 1 eV

(magnetic bottle)

Asner et al., PRL 114 (2015) 16501

Project 8 status

❶ Phase – I: 2010-2016 – proof-of-principle

test measurements with ^{83m}Kr,

CRES observed for first time

❷ Phase – II: 2015-2017 - tritium demonstrator

commissioning with ^{83m}Kr,

first tritium (T2) data this year

m(ν_e) ~ 10.. 100 eV

❸ Phase – III: 2018-2020 – large volume demonstrator

conceptual design for receiver array

tritium data competitive with m(ν_e) ~ 2 eV

❹ Phase – IV: … - atomic tritium source

conceptual design for very large set-up

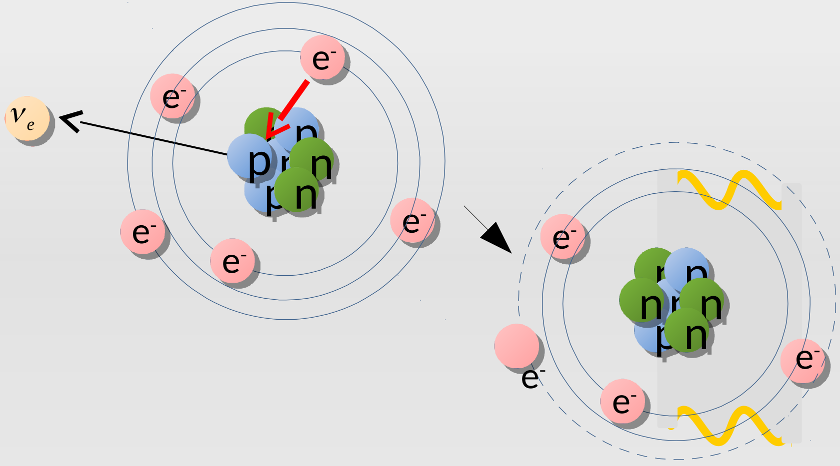
atomic tritium source (Ioffe trap) ?

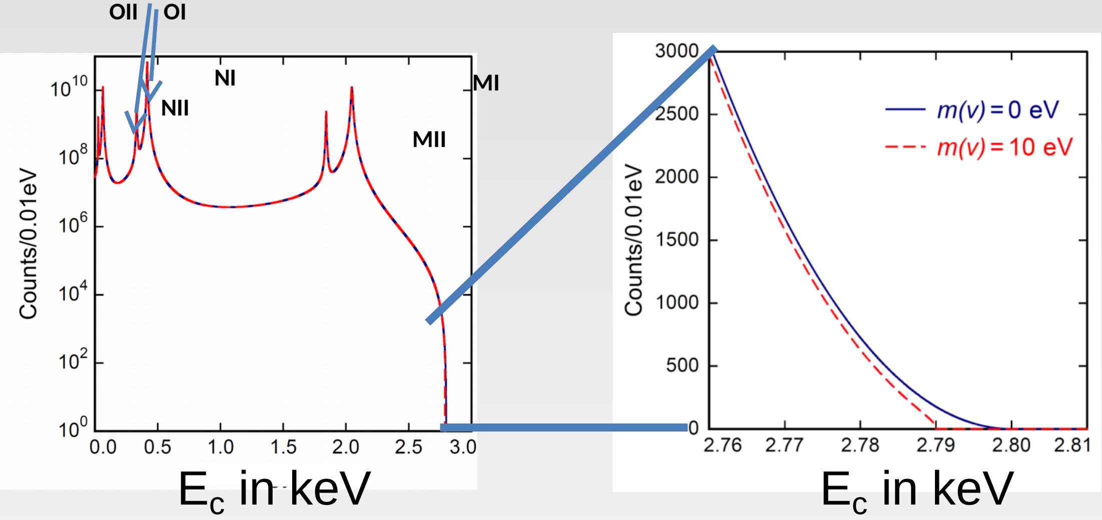
sensitivity to 40 meV ?

^{163}Ho calorimeters

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

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





measure E$_c$ with MMC (metallic magnetic calorimeter) or TES (transition edge sensor)

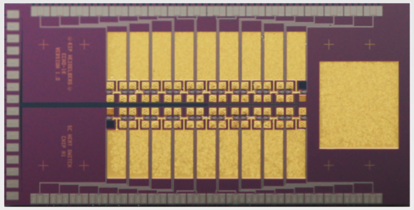
challenges:

- spectrum more complicated, higher order excitations → theory
- pile up fraction <1E-5 → each calorimeter <10 Bq → 100k channels (need 10^{14} decays)
- ^{163}Ho production in reactor + cleaned chemically + mass spectrometry (^{166m}Ho removal) + ^{163}Ho implantation in calorimeter (for example ECHO collab. Eur.Phys.J.ST 226 (2017) 1623)

^{163}Ho experiments

ECHo CERN, India, Slovakia, Russia

- technology: MMC



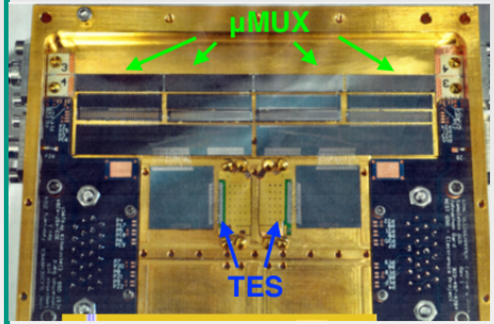
72 MMC px for Echo-1k

high purity ^{163}Ho production
tested Ho implantation
tested MMC array
microwave multiplexing for squid readout
rdy for ECHO-1k (100 px x 10 Bq)
10 eV limit in 2018

future ECHO-1M for <1 eV

HOLMES France, Switzerland

- technology: TES



pixel test

ΔE~7 eV @6keV

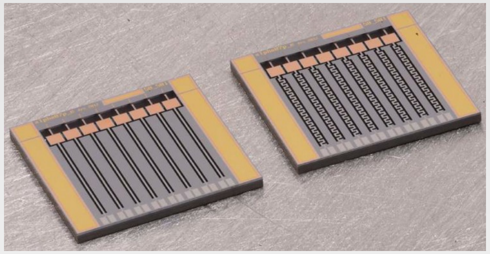
now:

- producing source: radiochemical + mass separation
- TES + source implantation
- 32 px x 300 Bq in 2017
  → 10 eV limit in 1 month

2018: 64 px x 300 Bq x 16 det

NuMECS

- technology: TES



- sensitivity: only R&D

Summary

new (direct) m_ν measurements from KATRIN coming soon
alternative approaches are developing from ‘idea’ to ‘reality’
→ next 10 years will give a lot of new information

(indirect) constraint from cosmology now at $\sum m_i < 0.1x$ eV,
will improved to σ ~ 10-20 meV in next 5-10 yr

(my) strong prejudice: 0νββ exists, ΔL=2 process, possibly our only observable ΔL

$T_{1/2}$ unknown (depending on BSM physics ...), discovery can be 'around the corner'

currently many experiments with $T_{1/2}$ limit sensitivity up to 10^{26} yr,
which technology is good for 10^{28} yr and will be funded?

In US: 0νββ highest priority of any new projects for DOE nuclear physics