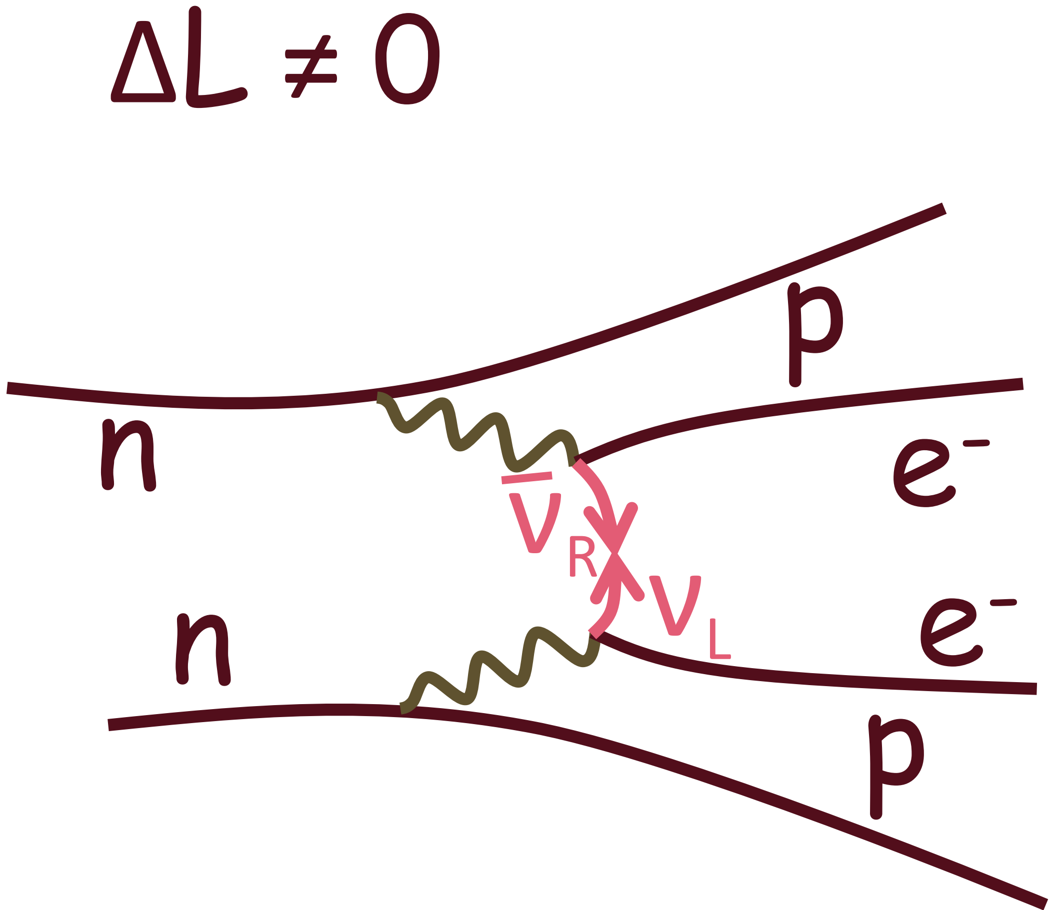
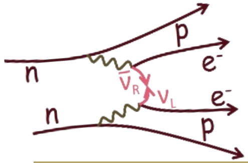
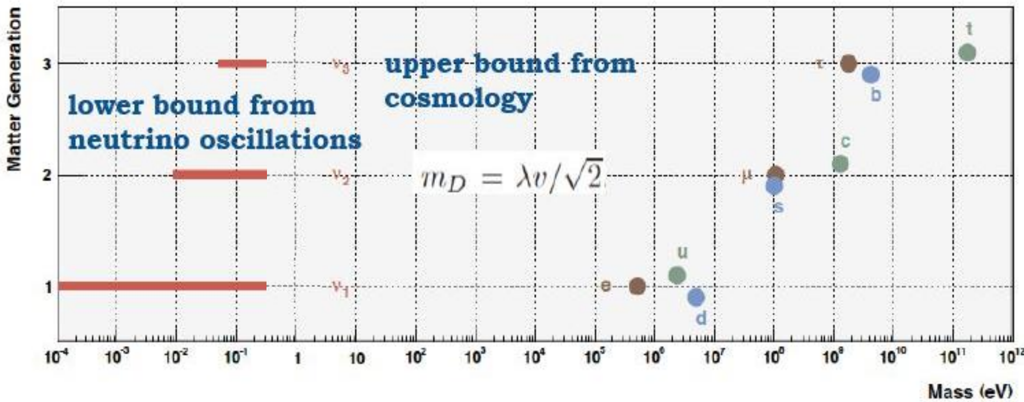
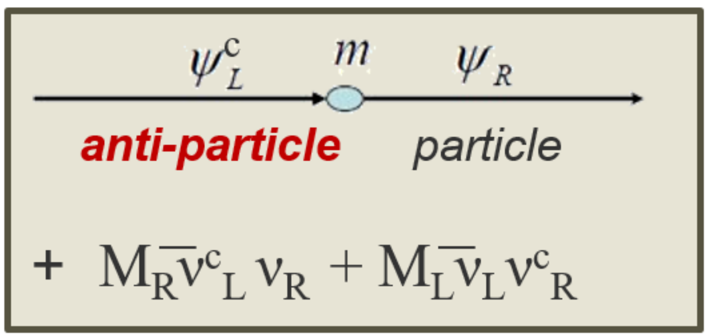
Double Beta Decay and Lepton Number Violation

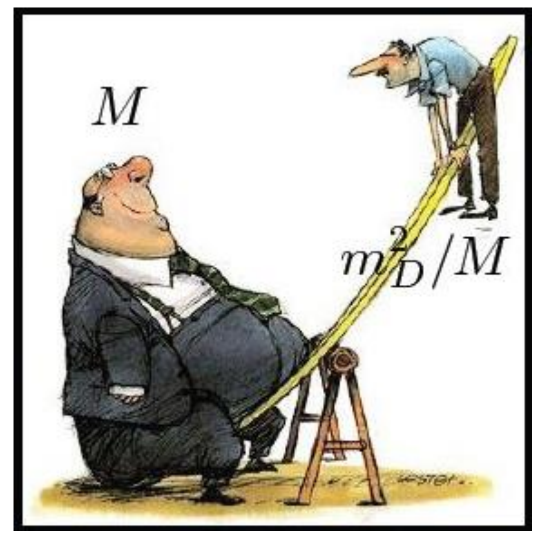




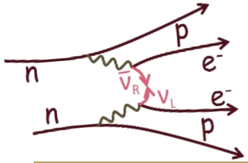
Neutrino Mass – See Saw ?







exeptional small neutrino mass
could be understood by seesaw mechnism
if neutrino is a Majorana particle

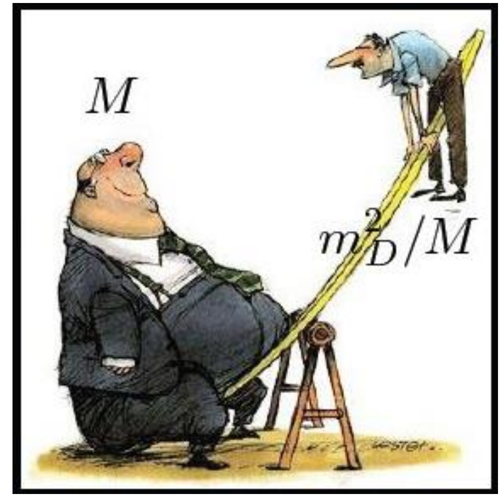


Majorana Neutrino

$$\nu_M = \nu_M^c$$

ν has no charge $\Rightarrow$ can be Majorana-particle
$\Rightarrow$ can explain small ν – mass (even with normal m_D)

and $\Delta L \neq 0$

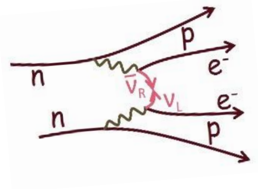


$\Rightarrow$ heavy right handed partner
$\Rightarrow$ decays in early Universe

$\Rightarrow$ could help to explain Matter - Antimatter imbalance

Neutrino is a normal Fermion, it just happend to have no charge

$$\nu_M \overset{?}{=} \nu_M^c$$

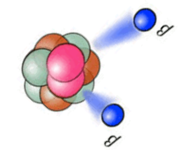


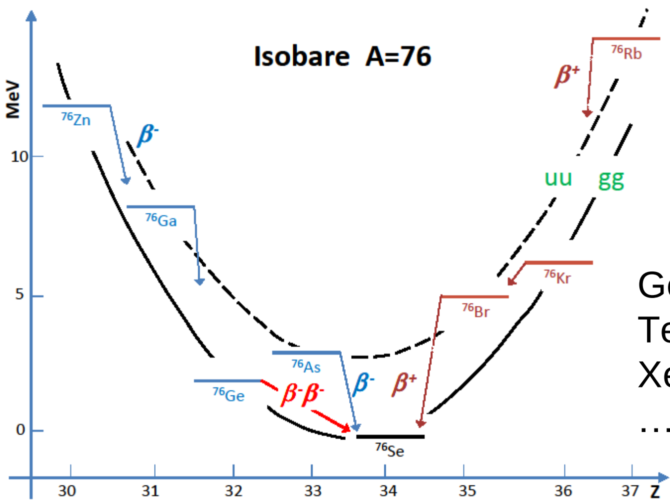
Search for Neutrino-less Double Beta Decay

$\Delta L \neq 0$

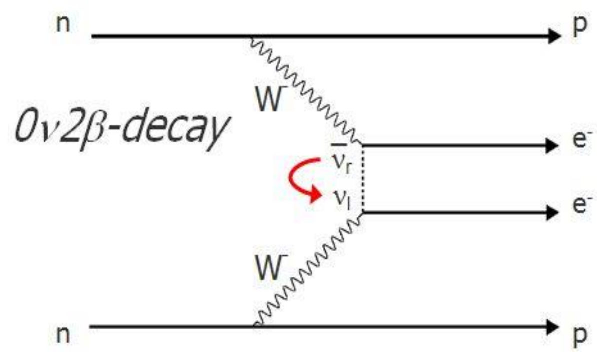
easiest but not easy way to see

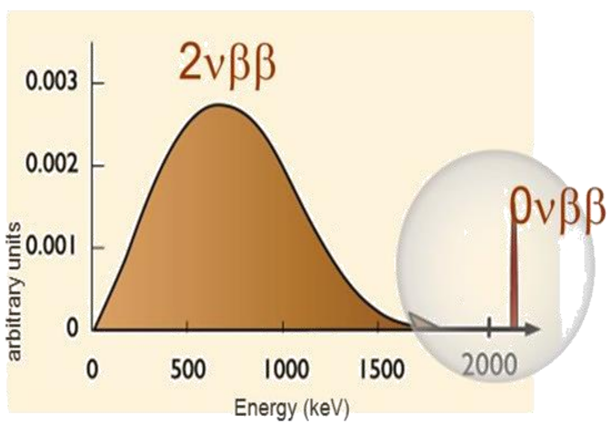
if ν are Majorana-type





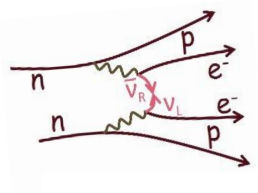
Ge-76
Te-130
Xe-136
....





⇒ checks Majorana character

⇒ very sensitive to m_ν



Sensitivity

$\Delta L \neq 0$

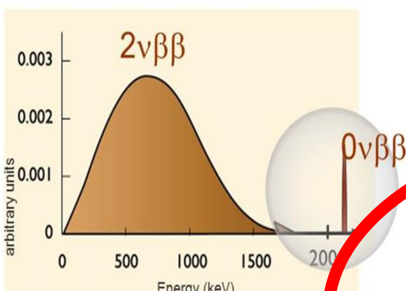
effective neutrino mass

$$1 / T^{0\nu}_{1/2} = G \cdot NME^2 \cdot m^2_{\beta\beta}$$

phase space ~ Q^5 nuclear matrix element

no favored isotope
considering spread of nuclear
matrix elements and Q-values

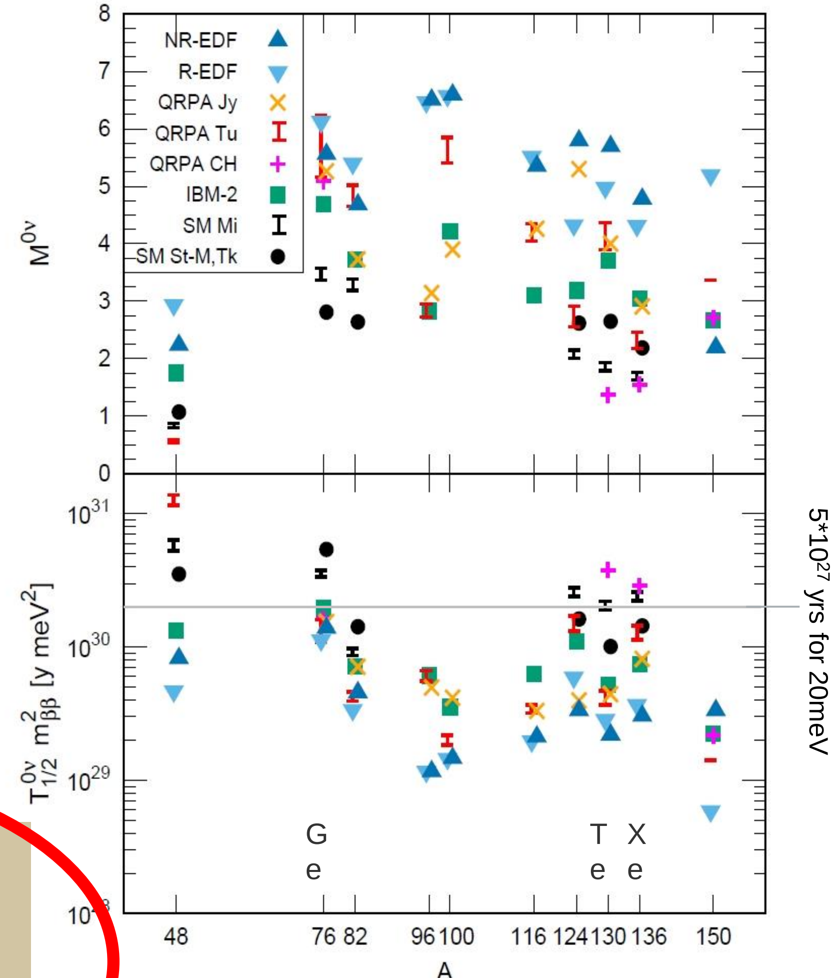
NME extremely important to get $m^2_{\beta\beta}$



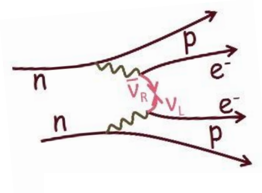
Petr Vogel Friday 11:45h

large mass
[$kg_{isotope}$]

low background in ROI
[cts / FWHM $t_{isotope}$yr]



arXiv:
1610.06548v1



Sensitivity

$\Delta L \neq 0$

effective neutrino mass

$$1 / T^{0\nu}_{1/2} = G \cdot NME^2 \cdot m^2_{\beta\beta}$$

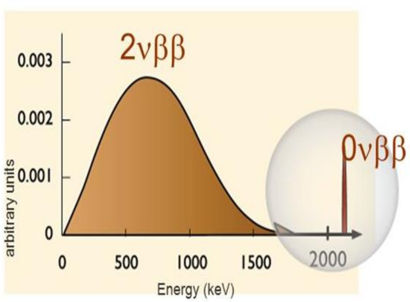
phase space ~ Q^5

nuclear matrix element

sensitivity on $T^{0\nu}_{1/2}$

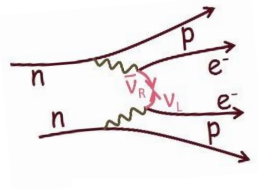
mid term: **a few 10^{26} yrs** ($m_{\beta\beta}$ ~ 40-100 meV)

long term: **a few 10^{27} yrs** ($m_{\beta\beta}$ ~ 10- 20 meV)



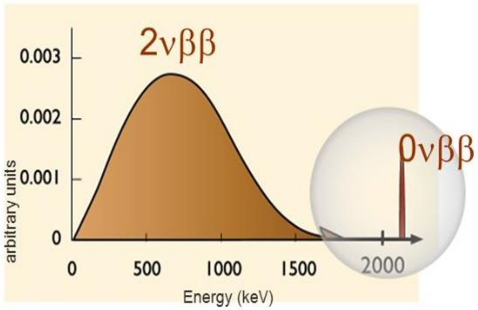
large mass
[$kg_{isotope}$]

low background in ROI
[cts / FWHM $t_{isotope}$yr]



Double Beta Decay and Lepton Number Violation

$\Delta L \neq 0$



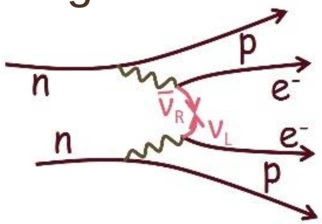
easiest but not easy way to see

if ν are Majorana-type

sensitivity on $T^{0\nu}_{1/2}$

mid term: **a few 10^{26} yrs** ($m_{\beta\beta}$ ~ 40-100 meV)
long term: **a few 10^{27} yrs** ($m_{\beta\beta}$ ~ 10- 20 meV)

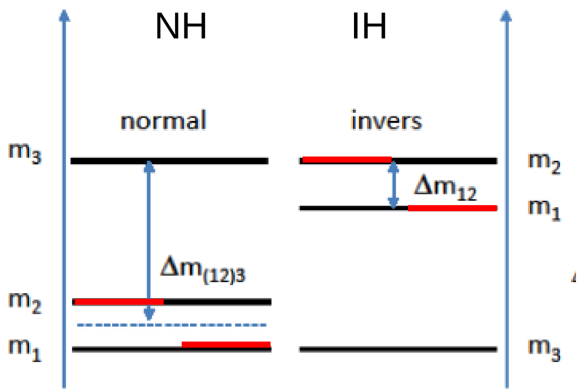
via ν exchange

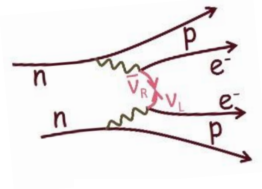


effective neutrino mass

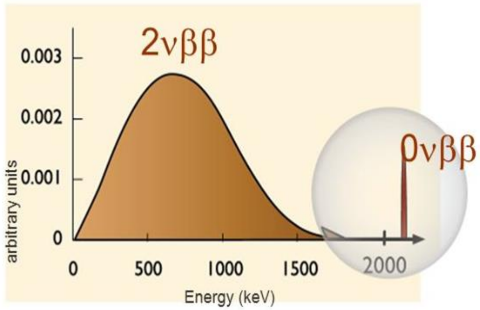
$$1 / T^{0\nu}_{1/2} = G \cdot NME^2 \cdot m^2_{\beta\beta}$$

phase space   nuclear matrix element





Double Beta Decay and Lepton Number Violation $\Delta L \neq 0$



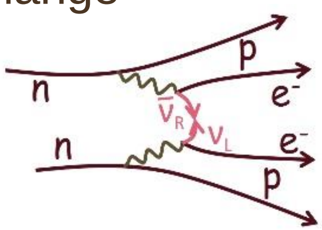
easiest but not easy way to see

if ν are Majorana-type

sensitivity on $T^{0\nu}_{1/2}$

mid term: a few 10^{26} yrs ($m_{\beta\beta}$ ~ 40-100 meV)
long term: a few 10^{27} yrs ($m_{\beta\beta}$ ~ 10- 20 meV)

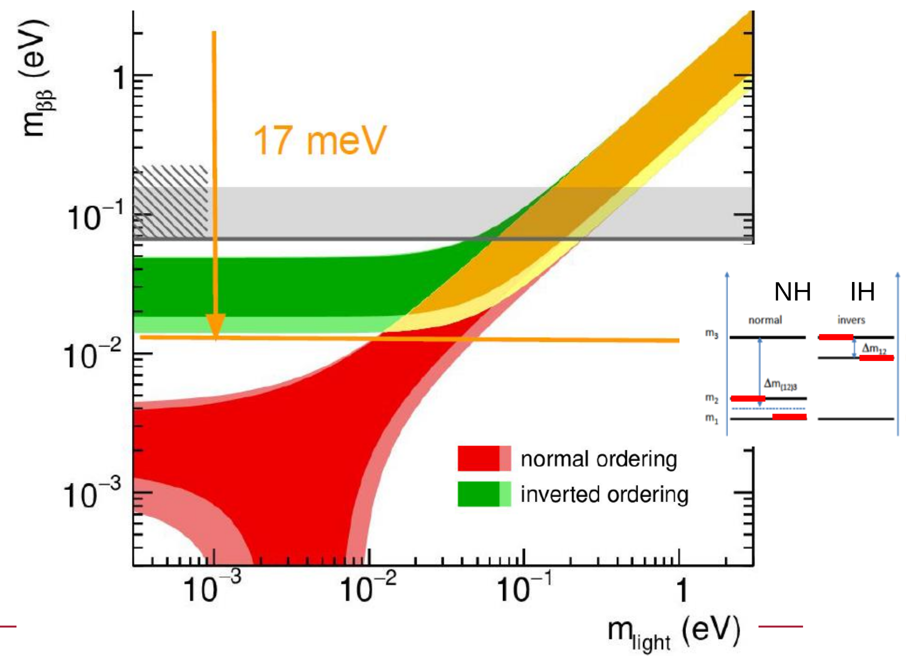
via ν exchange

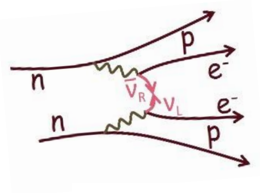


effective neutrino mass

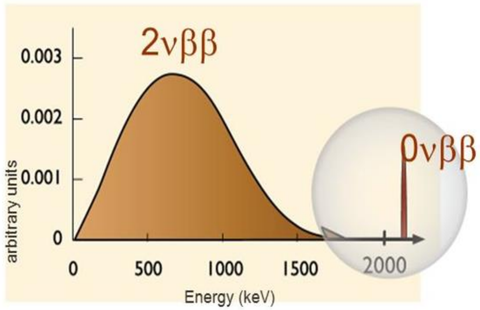
$$1 / T^{0\nu}_{1/2} = G \cdot NME^2 \cdot m^2_{\beta\beta}$$

phase space nuclear matrix element





Double Beta Decay and Lepton Number Violation $\Delta L \neq 0$



easiest but not easy way to see

if ν are Majorana-type

sensitivity on $T^{0\nu}_{1/2}$

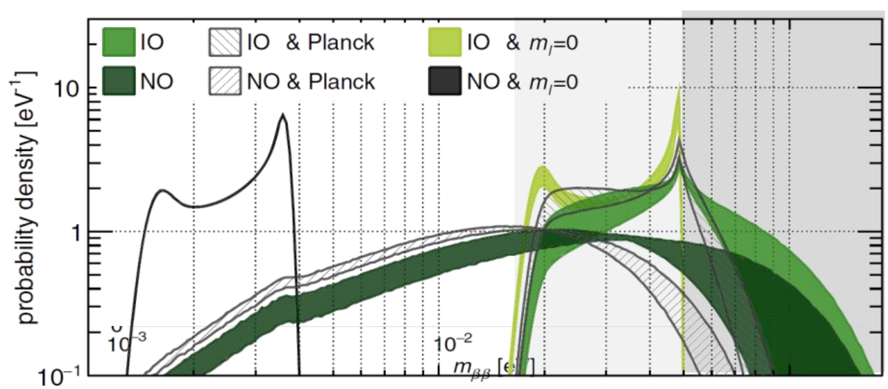
mid term: a few 10^{26} yrs ($m_{\beta\beta}$ ~ 40-100 meV)
long term: a few 10^{27} yrs ($m_{\beta\beta}$ ~ 10- 20 meV)

(Agostini, Benato, Detwiler, PRD 96 (2017) 053001
also A. Caldwell et al., PRD 96 (2017) 073001)

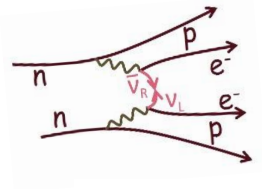
next generation experiments ($m_{\beta\beta}$ ~ 20 meV) have a high discovery potential

cumulative probability for $m_{\beta\beta}$ > 20 meV sensitivity is

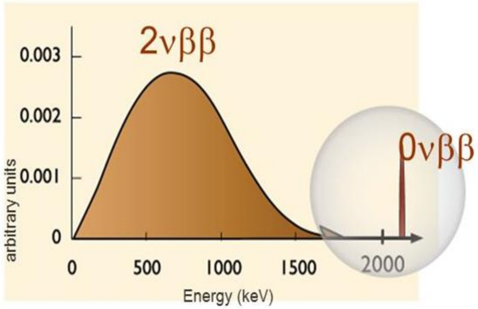
95% inverted
~ 50% normal mass hierarchy



high discovery potential for IH and NH
- not hierarchy, but m_ν is important -



Double Beta Decay and Lepton Number Violation $\Delta L \neq 0$



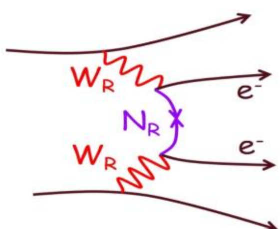
easiest but not easy way to see

if ν are Majorana-type

sensitivity on $T^{0\nu}_{1/2}$

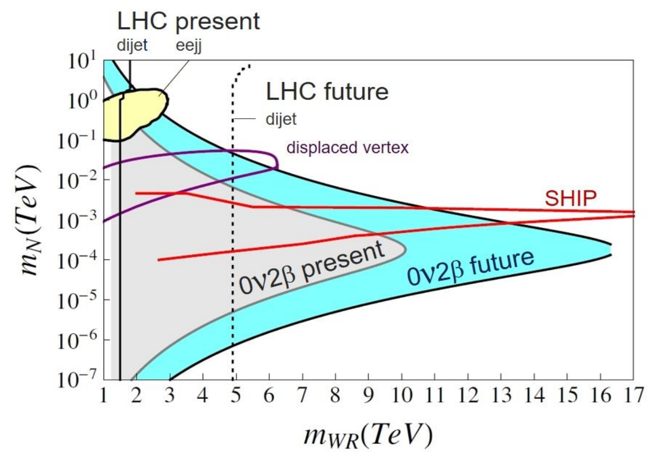
mid term: a few 10^{26} yrs ($m_{\beta\beta}$ ~ 40-100 meV)
long term: a few 10^{27} yrs ($m_{\beta\beta}$ ~ 10- 20 meV)

other $\Delta L \neq 0$ processes



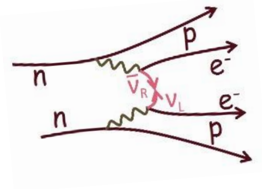
LR symmetry

heavy W_R and N_R exchange



arXiv 1509.00423v1

0νββ searches complementary and competetive
- $\Delta L \neq 0$ is the key, not so much $m_{\beta\beta}$ -

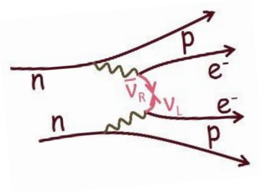


Search for Neutrino-less Double Beta Decay

$\Delta L \neq 0$

Ge detectors	GERDA Majorana LEGEND	very good ΔE (narrow ROI)
liquid noble gas **Xe**	EXO nEXO	large detector masses
loaded liquid scintillator **Xe, Te**	KamLAND-Zen KamLAND2-Zen SNO+	self shielding
gaseous detectors **Xe, Se,Nd,Ca**	SuperNEMO NEXT PANDA - X	tracking
CdZnTe detectors	COBRA	larger variety of isotopes new techniques
cryo bolometers Te	CUORE	
cryo + light Te, Mo	Cupid, AMoRe	

competetive limits — running — in preparation — R&D and future projects



Liquid Noble Gases - EXO 200 / nEXO

$\Delta L \neq 0$

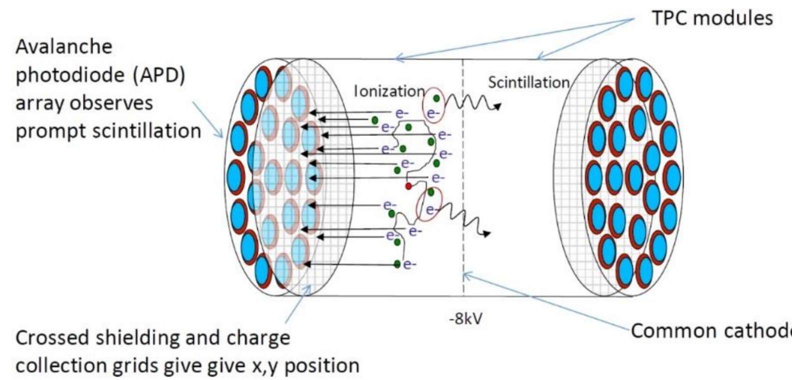
liquid Xenon TPC enriched in ^{136}Xe (80.6 %), charge and light detection

WIPP New Mexico USA

ΔE ~ 70 keV FWHM

self shielding, multi site recognition

EXO 200: 170 $kg_{isotope}$ total / 80 $kg_{isotope}$ active volume



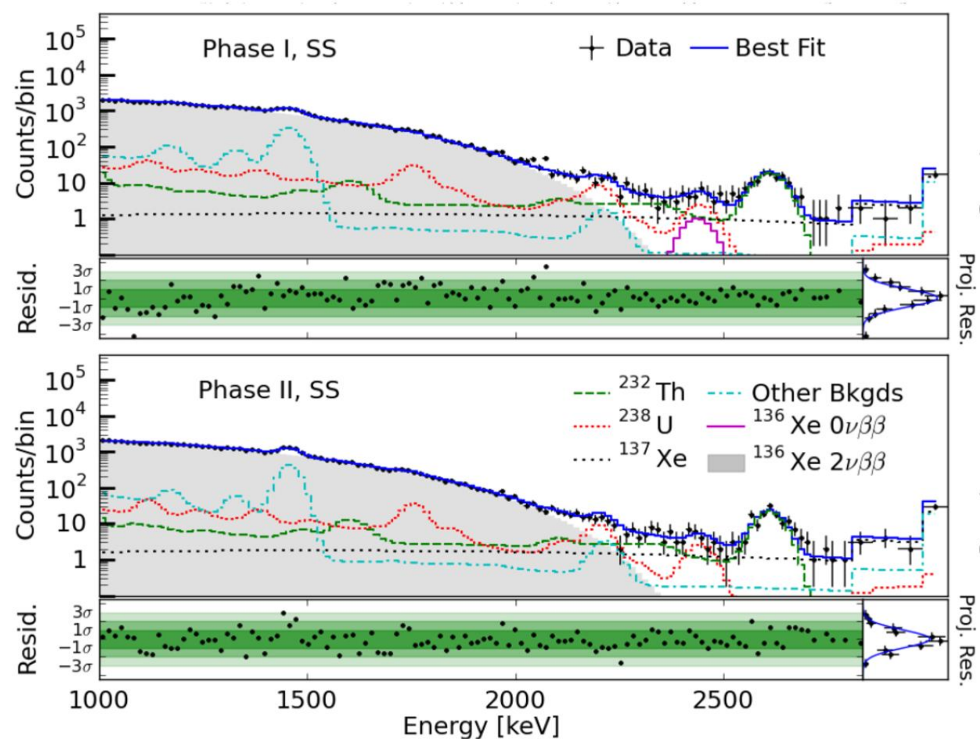
arXiv 1906.02723

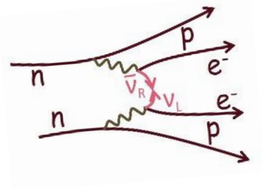
results:
234 kg·yr exposure

sensitivity $5.0\cdot10^{25}$ yr
$T_{1/2}^{0\nu\beta\beta} >$ $3.5\cdot10^{25}$ yr

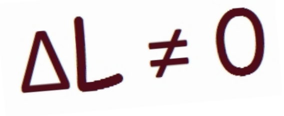
background in ROI
170 / FWHM·$t_{isotope}$·yr

PRL 120 072701 (2018)





Liquid Noble Gases - nEXO



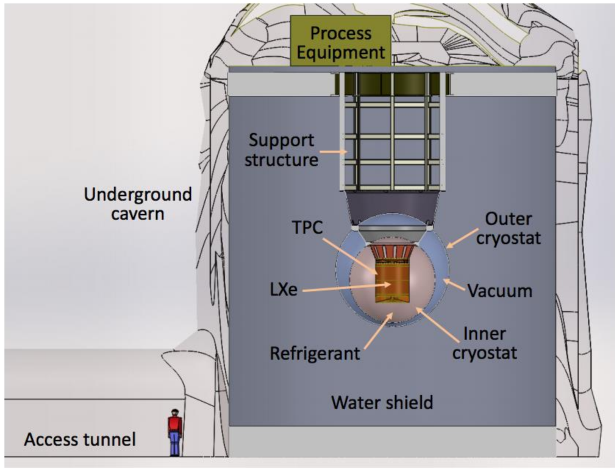
liquid Xenon single TPC

5000 kg enriched lXe

expected to be at **SNOLAB**

improved performance:

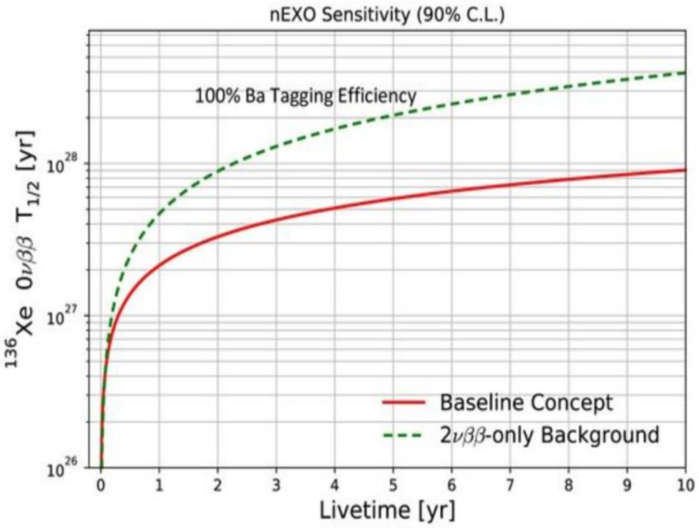
energy and position resolution ….



R&D on Ba-tagging

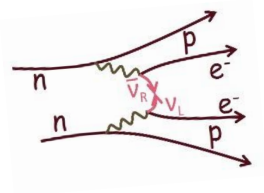
goal $T_{1/2}^{0\nu\beta\beta} > 9{,}2 \cdot 10^{27}$ yr exclusion
$5{,}7 \cdot 10^{27}$ yr discovery

background in ROI
~ 0.6 / FWHM·$t_{isotope}$·yr



arXiv 1710.05075

Andreas Piepke Sunday 9:00h



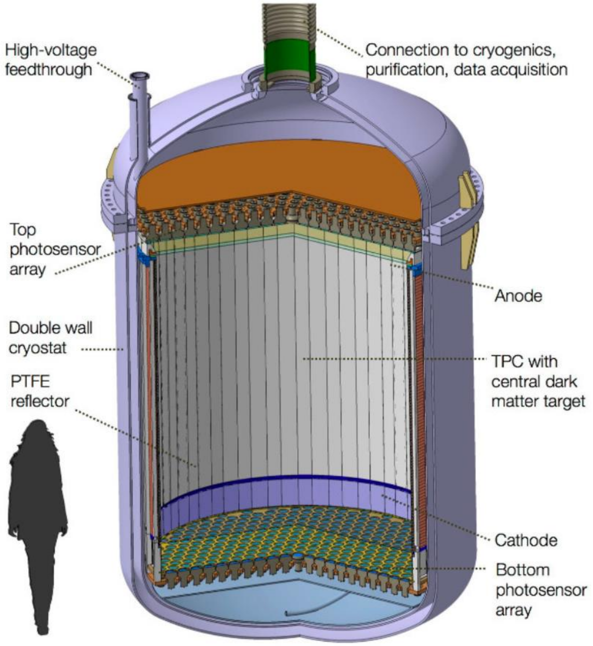
Liquid Noble Gases – Panda X / DARWIN

PANDA-X II at Jjinping / China

sensitivity study for DARWIN

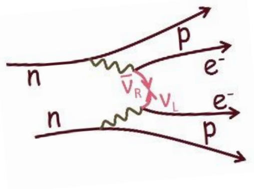
multiton liquid Xenon detector

both so far natural Xenon
mainly direct
WIMP- Dark Matter search

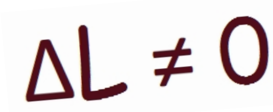


DARWIN Collaboration, JCAP 1611 (2016) 017

Marc Schumann Friday 16:00h

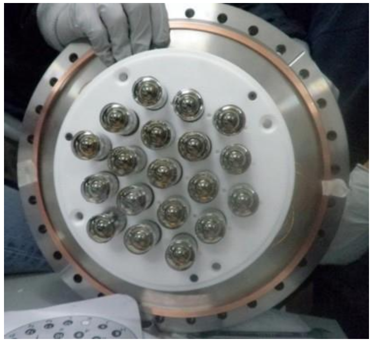


Gas TPC – NEXT



high pressure TPC + scintillation

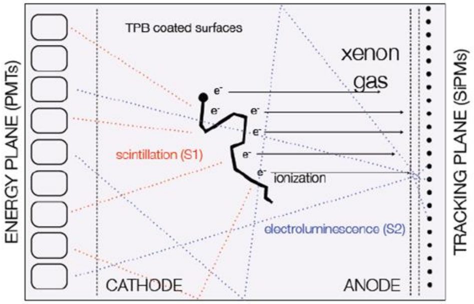
enriched Xe tracking



NEXT at Canfranc / Spain

10 kg prototype nat-Xe running at Canfranc

100kg comissioning in 2019



5 y goal

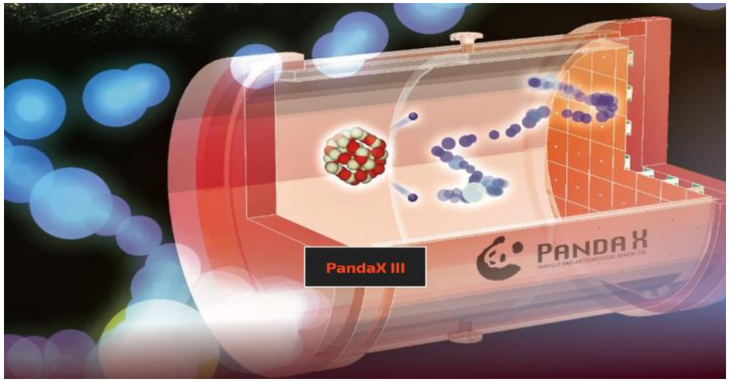
$T_{1/2}^{0\nu\beta\beta} > 9.8 \cdot 10^{25}$ yr

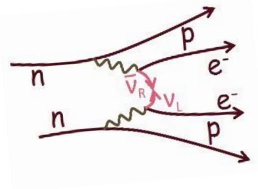
R&D on Ba tagging

ton scale

$T_{1/2}^{0\nu\beta\beta} > 1.5 \cdot 10^{27}$ yr

PANDA X III / China





Liquid Scintillator - KamLAND-Zen

$\Delta L \neq 0$

3 m diam. ballon: **liquid scintillator** loaded with enriched Xenon inserted into KamLAND

$\Delta E \sim 250$ keV FWHM

results: 383 kg Xe / 110 $kg_{isotope}$ in FV

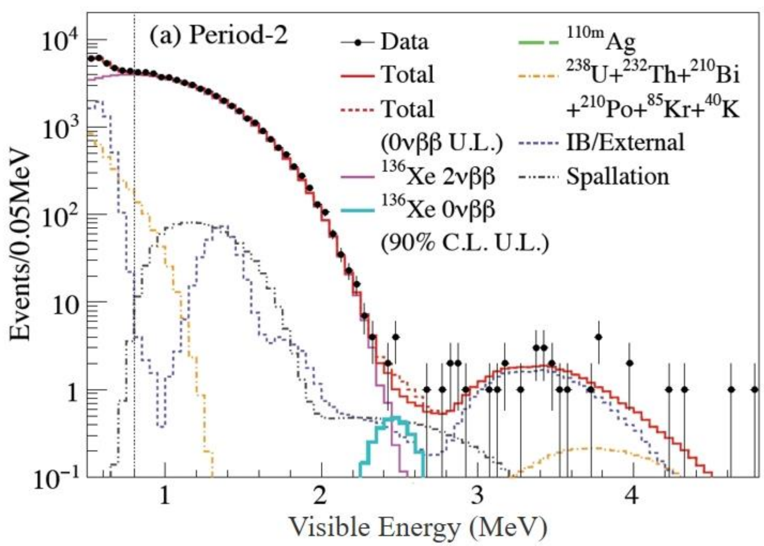
~ 600 kg·yr

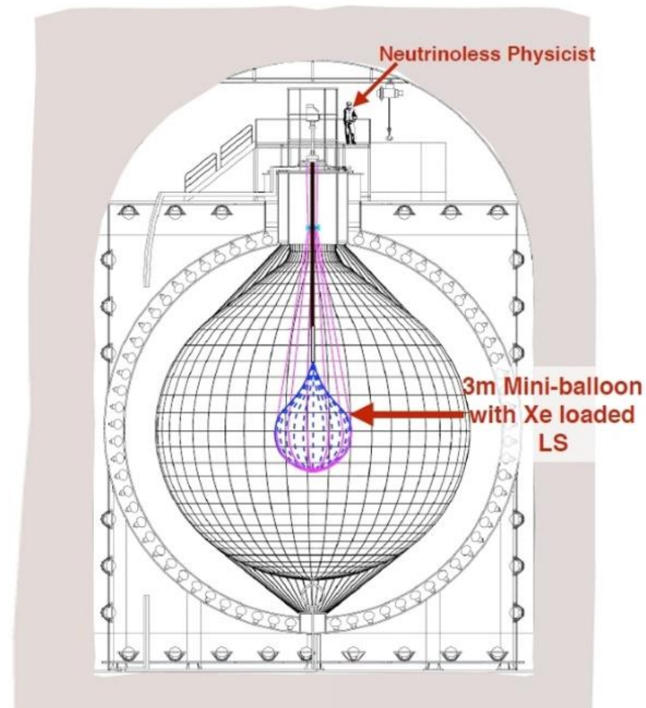
$T_{1/2}^{0\nu\beta\beta}$ > 10.7·10^{25} yr

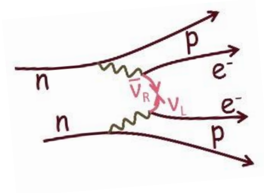
sensitivity 5.6·10^{25} yr

background in ROI ~ 120 / FWHM·$t_{isotope}$·yr

PRL 117 082503 (2016)







Liquid Scintillator - KamLAND-Zen

Update @ TAUP 2019

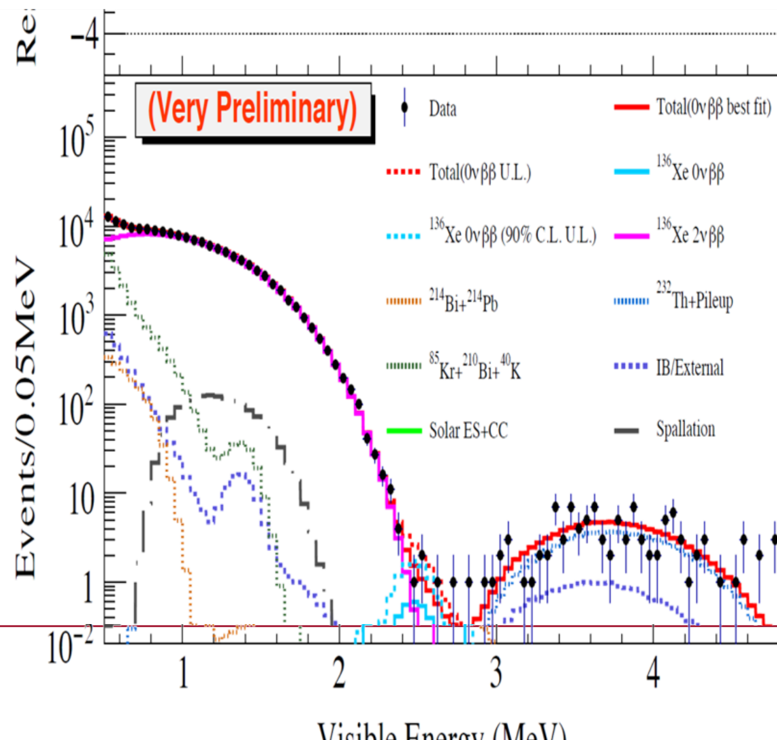
starting: KamLAND Zen 800

750kg Xe larger, cleaner ballon

goal sensitivity

$T_{1/2}^{0\nu\beta\beta}$ > **4.6·10^{26}** yr

background ~ **10 / FWHM·t$_{isotope}$·yr**



running since Jan 2019

prelim.results:

sensitivity

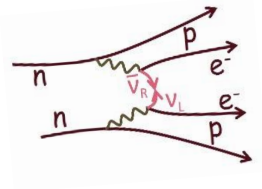
$T_{1/2}^{0\nu\beta\beta}$ > 0,8·10^{26} yr

data

$T_{1/2}^{0\nu\beta\beta}$ > 0,4·10^{26} yr

background ~ 60 / FWHM·t$_{isotope}$·yr

plan: **KamLAND2**: 1000 kg

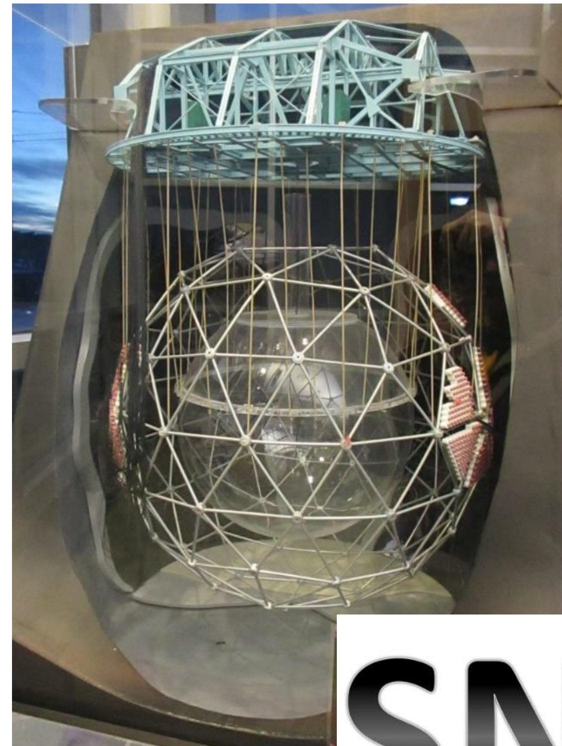


Liquid Scintillator - SNO+

$\Delta L \neq 0$

infrastructure at SNOLAB

Phase I:
acrylic vessel filled with LS
+ 4000 kg of nat-Te
(~30% Te-130)

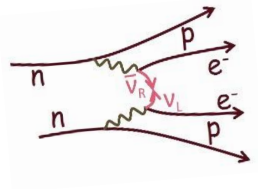


LS filling 2019
Te loading 2020

sensitivity goal $T_{1/2}^{0\nu\beta\beta} > 1.9 \cdot 10^{26}$ yr

Phase II: more Te, better FWHM

THEIA project: 50 kton water-based liquid scintillator
solar-ν will be dominant background



Tracking - SuperNEMO

$\Delta L \neq 0$

tracker calorimeter
at Modane underground lab

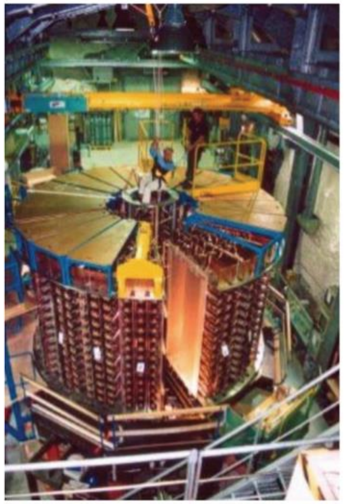
thin foils containing isotope (Se…)
e^- tracking => event topology
- background
- sensitivity to **$0\nu\beta\beta$** mechanism

predecessor NEMO-3 measured limits
for several isotopes: Mo, Nd, Ca, Cd, Te, Zr, Se

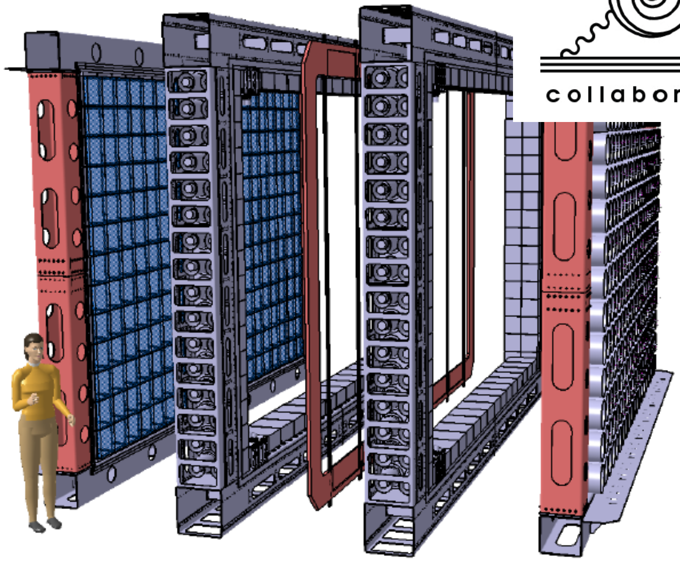
Mo $T_{1/2}^{0\nu\beta\beta} > 1.1 \cdot 10^{24}$ yr   PRL 95 182302

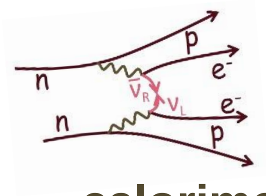
SuperNEMO demsonstrator starting
7kg Se; 2.5 yrs
goal $T_{1/2}^{0\nu\beta\beta} > 6 \cdot 10^{24}$ yr

potential full extension:
20 modules
100 kg Se, 5 yrs:
goal $T_{1/2}^{0\nu\beta\beta} > 10^{26}$ yr



supernemo collaboration





Calorimetry - Cuore @ LNGS

$\Delta L \neq 0$

calorimetry at mK temperature

in natural TeO_2 crystals ^{130}Te (30%)

CUORE 750 kg TeO_2 (206 kg ^{130}Te)
988 crystals

results 2019:

369,9 kg.yr (103 kg·yr ^{130}Te)

ΔE ~ 8 keV FWHM

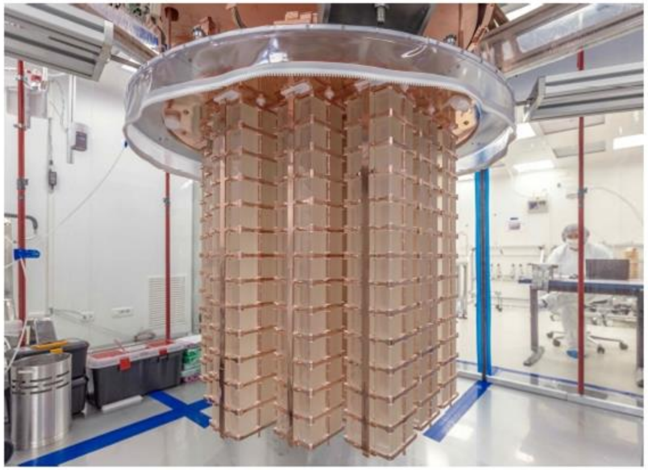
$T_{1/2}^{0\nu\beta\beta} > 2,3 \cdot 10^{25}$ yr

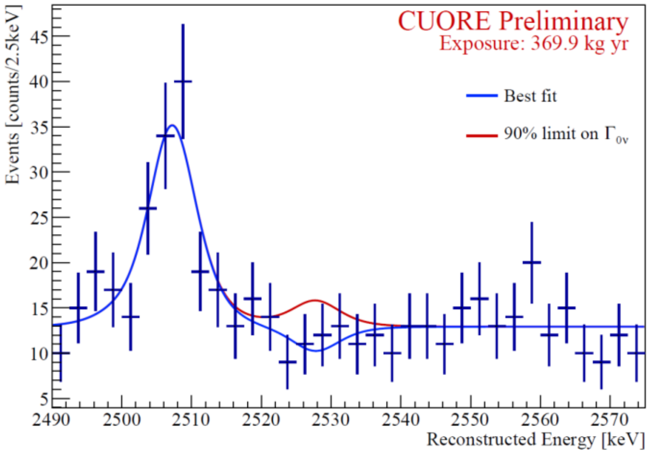
background in ROI
~ 450 / FWHM·$t_{isotope}$·yr

goals:

goal sensitivity
$T_{1/2}^{0\nu\beta\beta} > 9.5 \cdot 10^{25}$ yr

background
~ 180 / FWHM·$t_{isotope}$·yr





Phys.Rev.Lett 120, 132501 (2018)
Update: TAUP 2019 conference

potential upgrade with calorimetry + light

CUORE => CUPID

Giovanni Benato Friday 18:15h

CUPID

CUORE detectors
+ scintillation/cerenkov
read out for α discrimination
possible crystals:
TeO_2, Li_2MoO_4, ZnSe

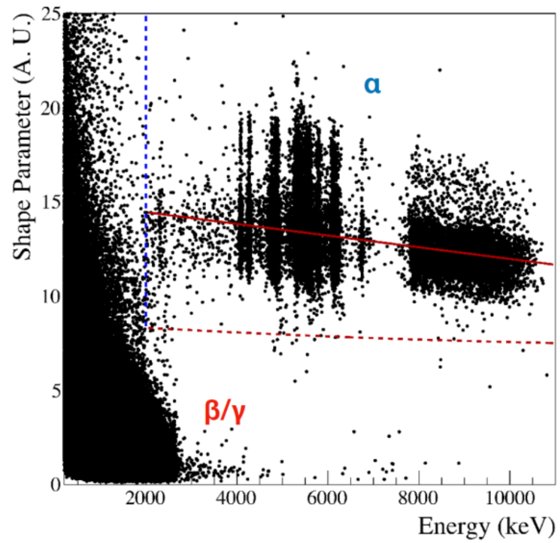
very first results

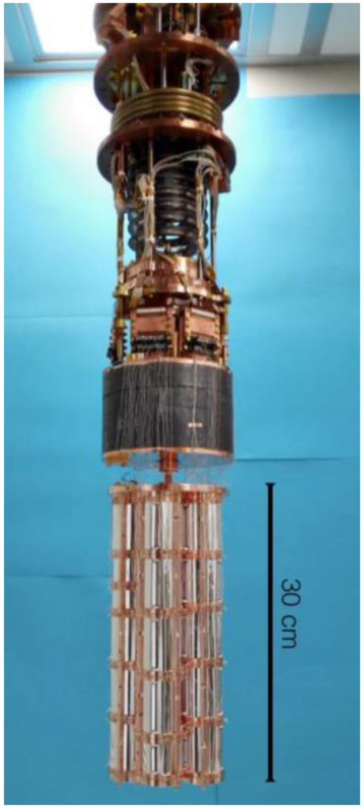
CUPID-0: 9,95 kg·yr with Se,
$T_{1/2}^{0\nu\beta\beta} > 3{,}5 \cdot 10^{24}$ yr

background in ROI
~ 120 / FWHM·$t_{isotope}$·yr

ΔE ~ 20keV FWHM can be improved a lot

arXiv:1802.07791
Update: TAUP 2019

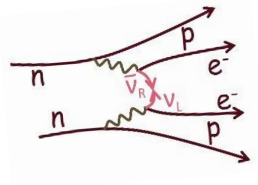




CUPID – 1t goal

sensitivity
$T_{1/2}^{0\nu\beta\beta} > 2.1 \cdot 10^{27}$ yr for Mo
background in ROI
~ 0.1 / FWHM·$t_{isotope}$·yr

Giovanni Benato Friday 18:15h



Scintillating bolometers

$\Delta L \neq 0$

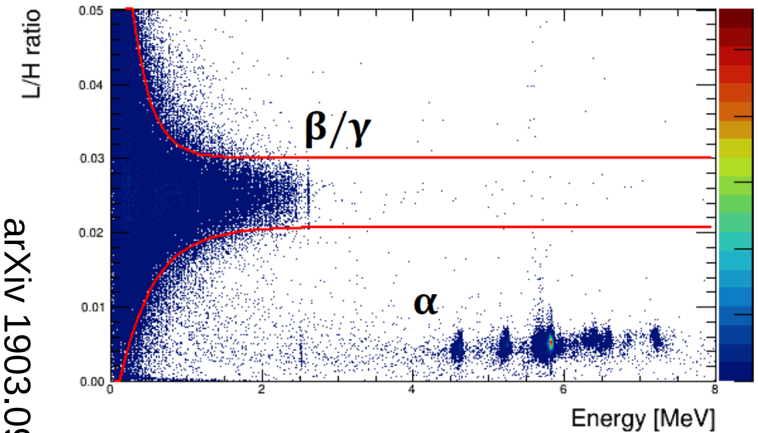
AMORE @ Yangyang UGL Korea

goal

sensitivity $T_{1/2}^{0\nu\beta\beta}$ > $3 \cdot 10^{26}$ yr
for ^{100}Mo 250kg·yr exposure

AMORE-Pilot results
2kg $CaMoO_4$, 0,3 kg*yrs exposure
still very high background
$T_{1/2}^{0\nu\beta\beta}$ > $9{,}5 \cdot 10^{22}$ yr

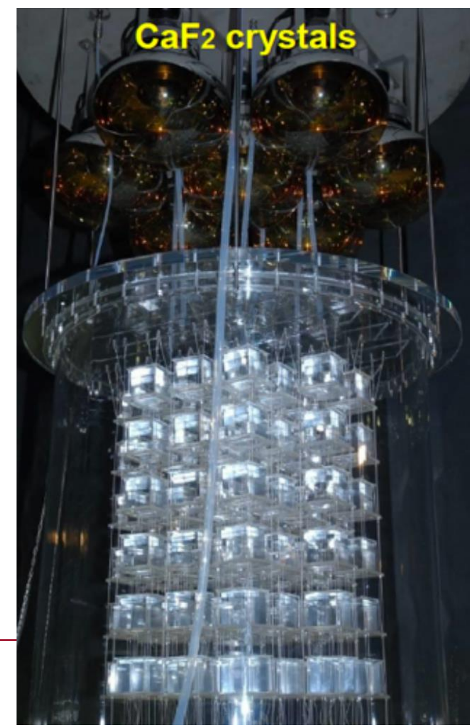
arXiv 1903.09483



CANDLES @ Kamioka / Japan

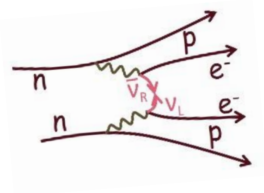
^{48}Ca hightes Q-value 4,27MeV, lowest abundance 0,187%

305 kg CaF scintillator detectors
in liquid scintillator
result from 131 days
$T_{1/2}^{0\nu\beta\beta}$ > $6{,}2 \cdot 10^{22}$ yr



working on scintillating bolometers
first demonstration results

Giovanni Benato Friday 18:15h

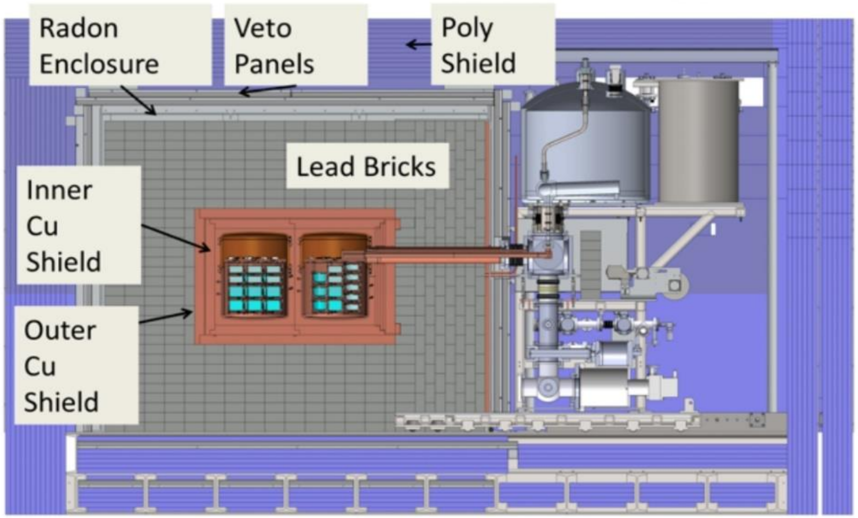


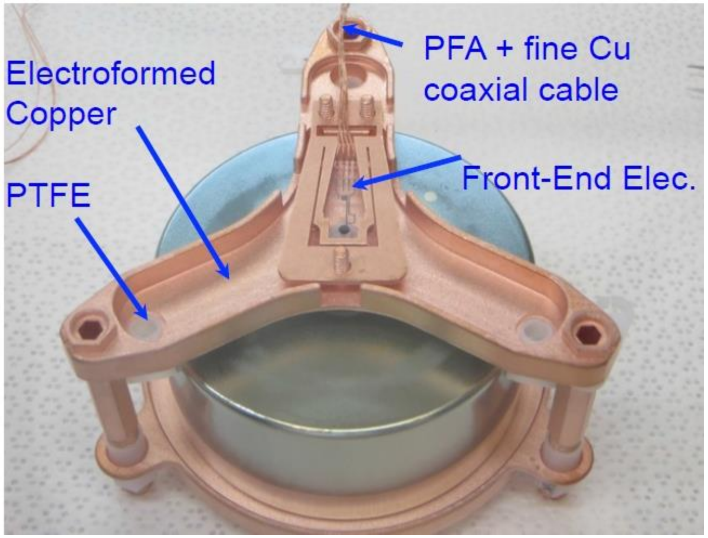
Ge Semiconductor - MAJORANA

$\Delta L \neq 0$

Ge detectors
Cu/Pb shielding

Sanford Lab , USA
44.1 kg ^{76}Ge (88%) running





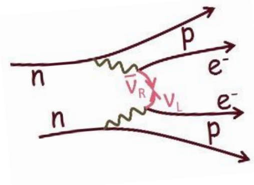
PRC 100 025501 (2019)

results

26 kg·yr

$T_{1/2}^{0\nu\beta\beta} > 2.7\cdot10^{25}$ yr

background in ROI
18 / FWHM·$t_{isotope}$·yr

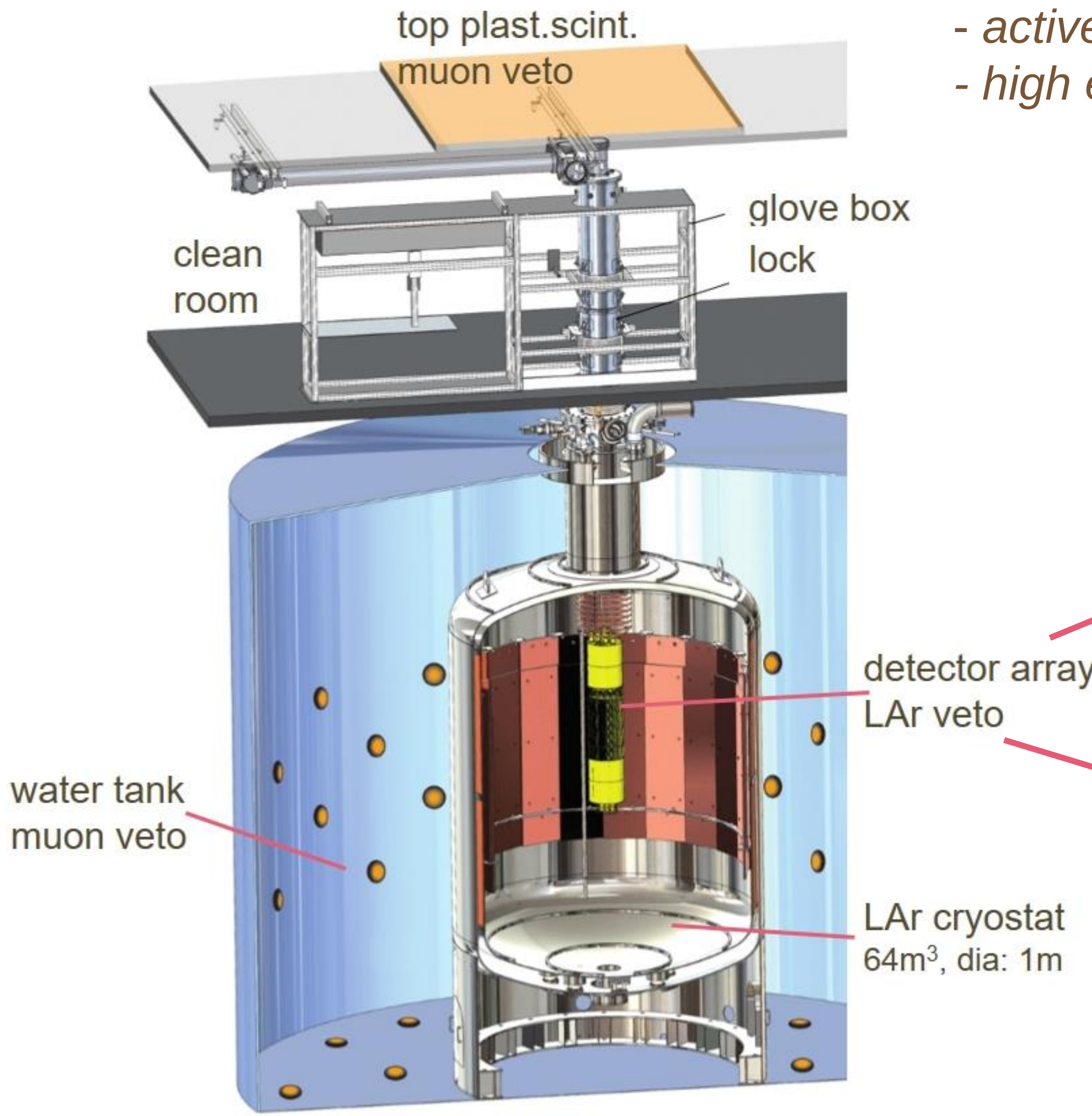


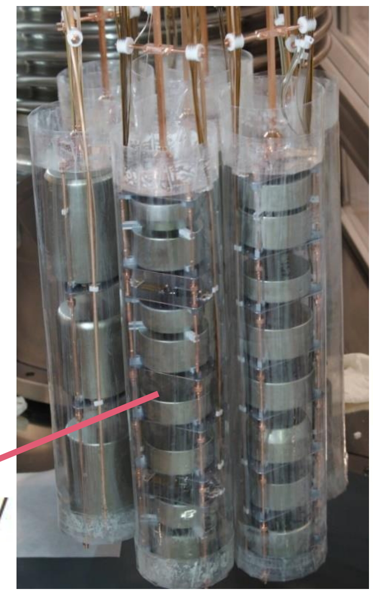
GERDA / LEGEND

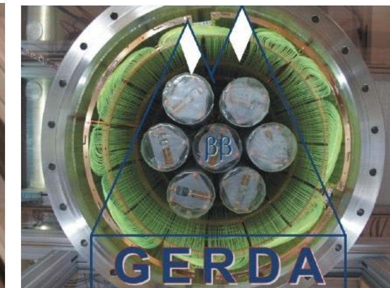
$\Delta L \neq 0$

combines advantages

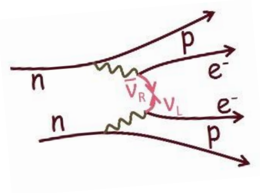
- *active shielding of liquid noble gas*
- *high energy resolution of Ge detectors*







Gran Sasso



GERDA

$\Delta L \neq 0$

LAr veto + pulse shape discrimination
multi site and surface event recognition

GERDA results

82.4 kg·yr total exposure

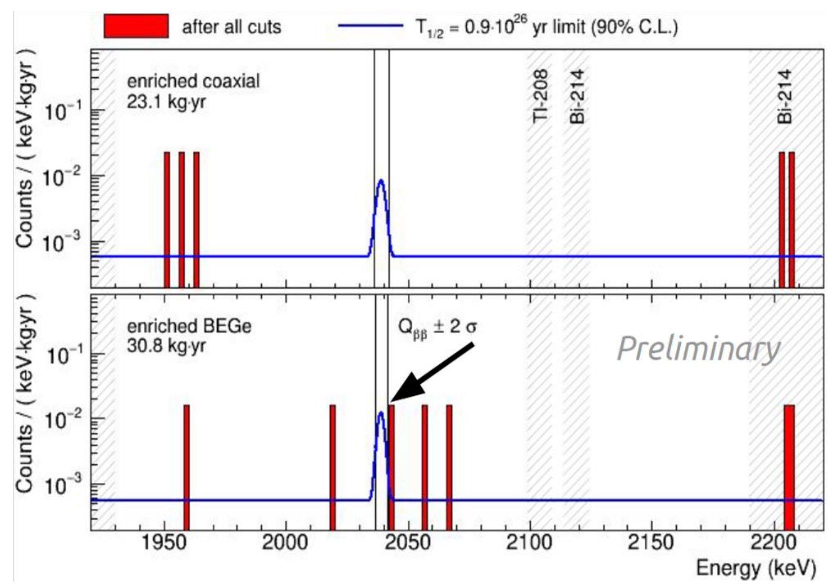
background in ROI
4 / FWHM·$t_{isotope}$·yr

sensitivity $11 \cdot 10^{25}$ yr

$T_{1/2}^{0\nu\beta\beta} > 9 \cdot 10^{25}$ yr

background free 0νββ experiment
→ potential for discovery (up to ~ 10^{26} yr)

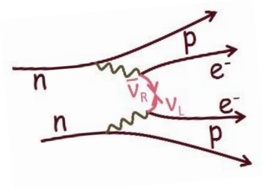
Science 10.112 / science.aav8613 (2019)



background 250 times lower compared to Heidelberg-Moscow Exp. (~10y)

makes sense to grow larger (background goal for LEGEND 200 almost reached)

Bernhard Schwingenheuer Friday 9:00 h

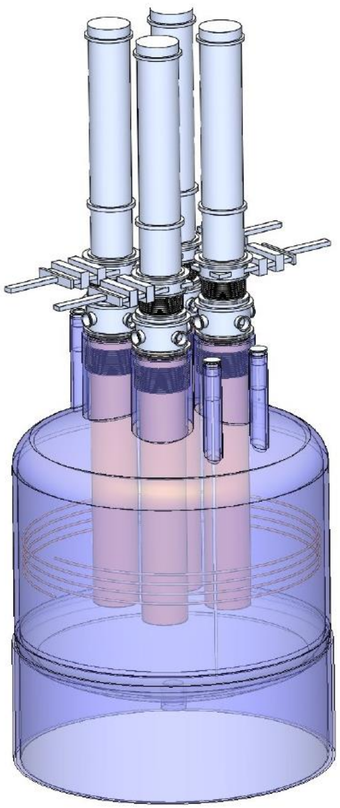


Search for Neutrinoless Double Beta Decay

$\Delta L \neq 0$

new collaboration formed LEGEND
Majorana + GERDA members + others

⇒ one worldwide collaboration on ^{76}Ge



use GERDA concept and
staged approach to 1000kg

LEGEND 200: first 200kg in GERDA setup @ Gran Sasso

- starting 2021
- ^{76}Ge available for 190kg of detectors
- funded by NSF, INFN, MPI, BMBF

sensitivity > 10^{27} yr

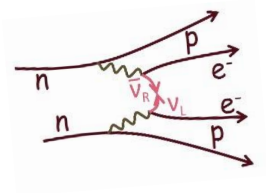
LEGEND

Large Enriched
Germanium Experiment
for Neutrinoless ββ Decay

sensitivity > 10^{28} yr

LEGEND 1000: 1000kg phase depends on US down selection process
same for nEXO

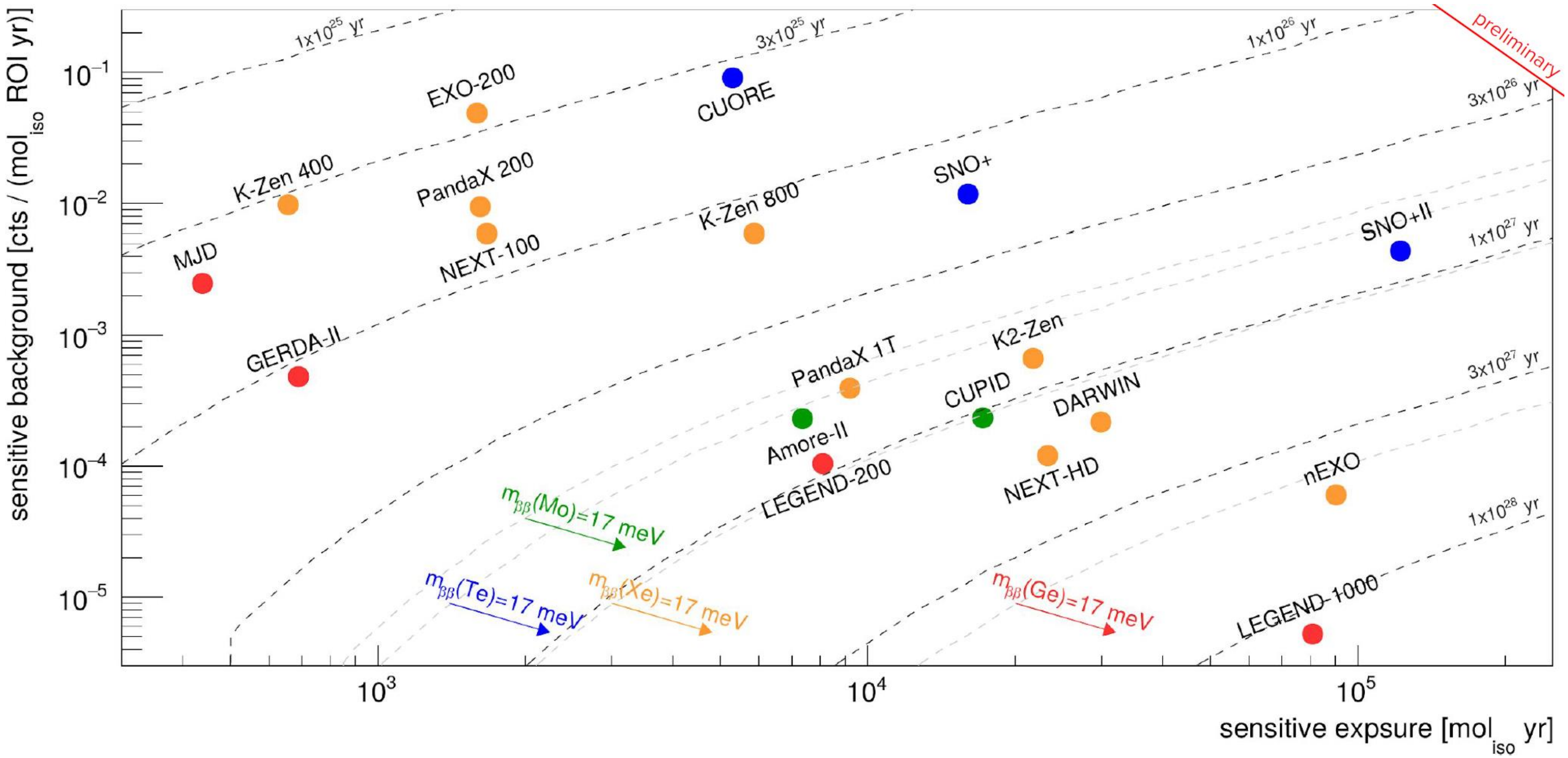
Bernhard Schwingenheuer Friday 9:00 h

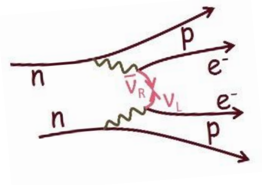


Search for Neutrinoless Double Beta Decay

$\Delta L \neq 0$

taken from M.Agostini @ TAUP 2019





Search for Neutrinoless Double Beta Decay

$\Delta L \neq 0$

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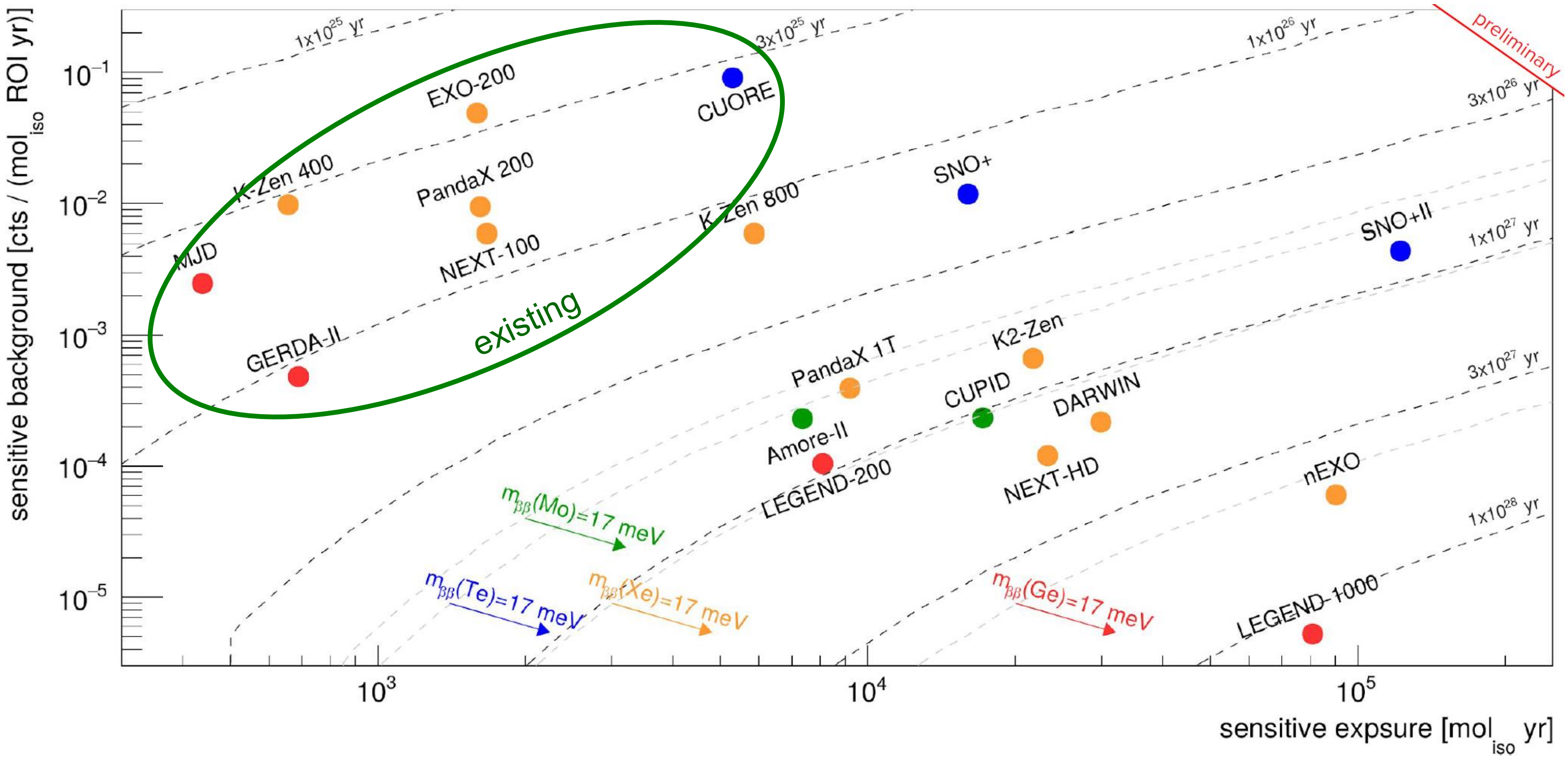

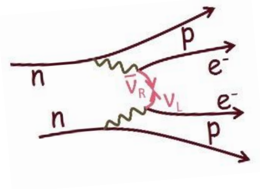

Search for Neutrinoless Double Beta Decay

$\Delta L \neq 0$

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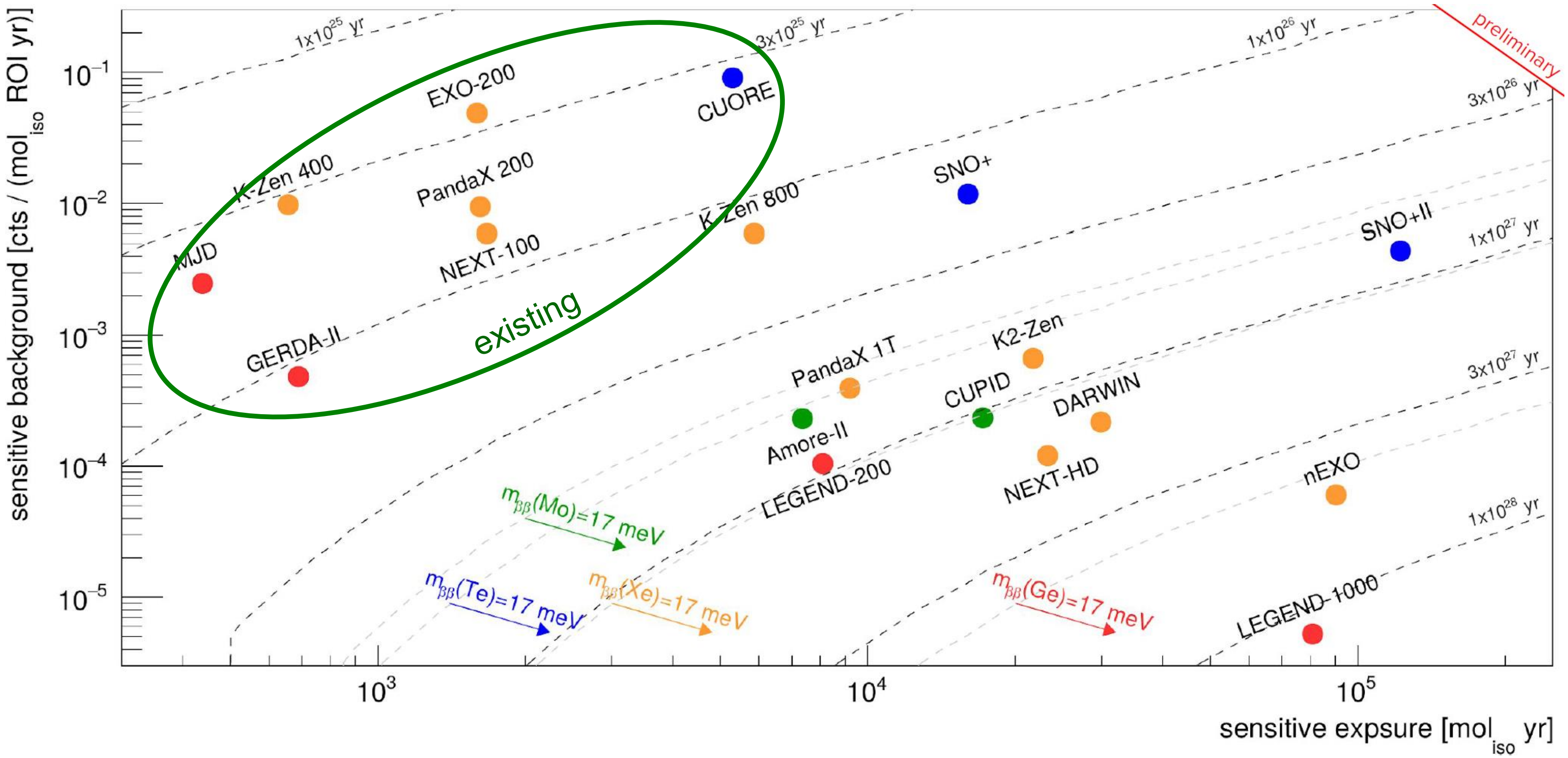
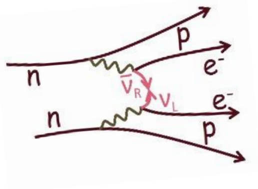


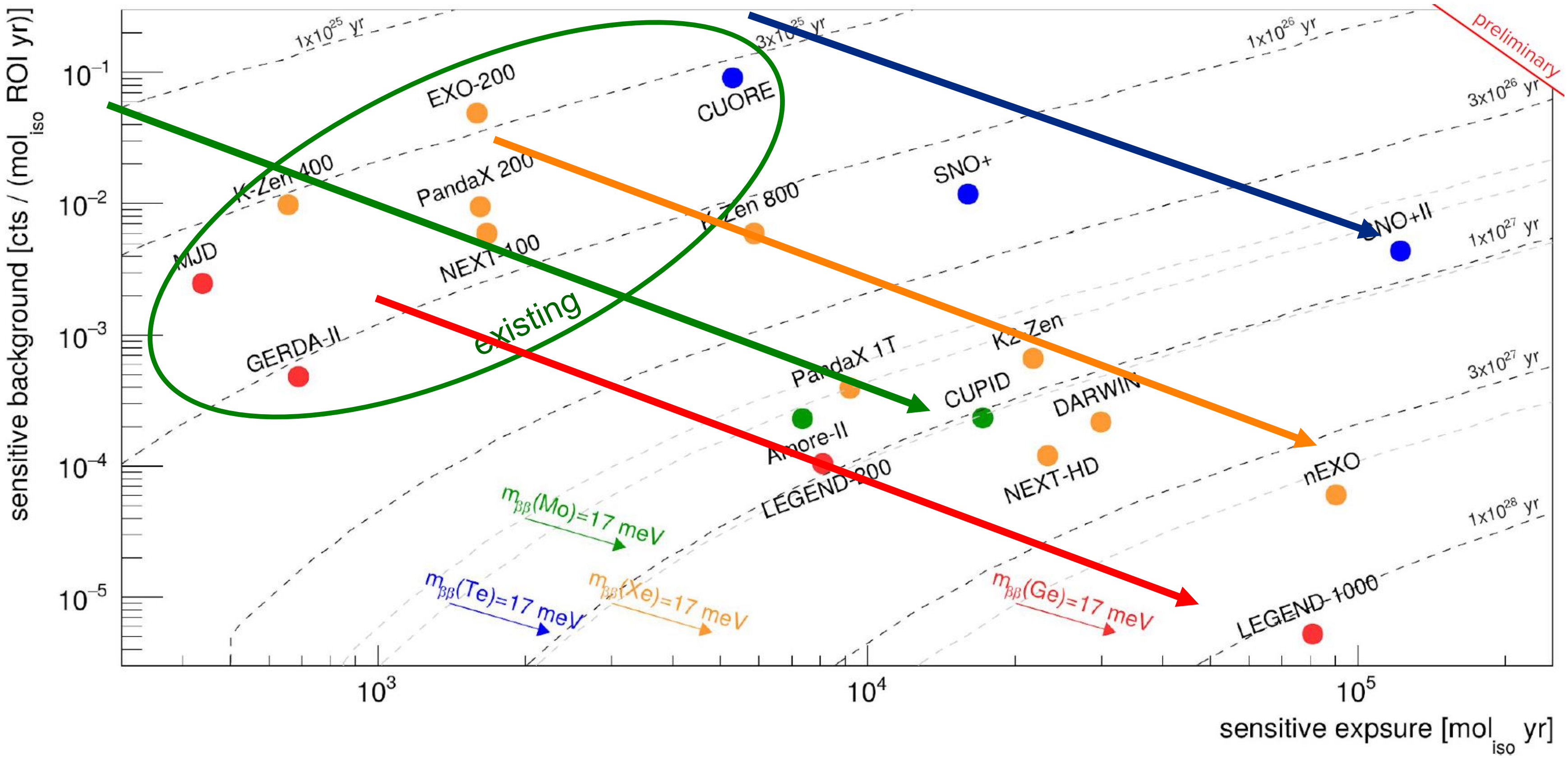
Xe **Te** **Ge** **Mo**



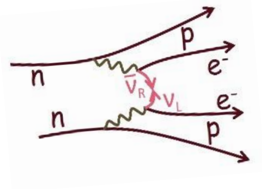
Search for Neutrinoless Double Beta Decay

$\Delta L \neq 0$

taken from M.Agostini @ TAUP 2019



Xe **Te** **Ge** **Mo**

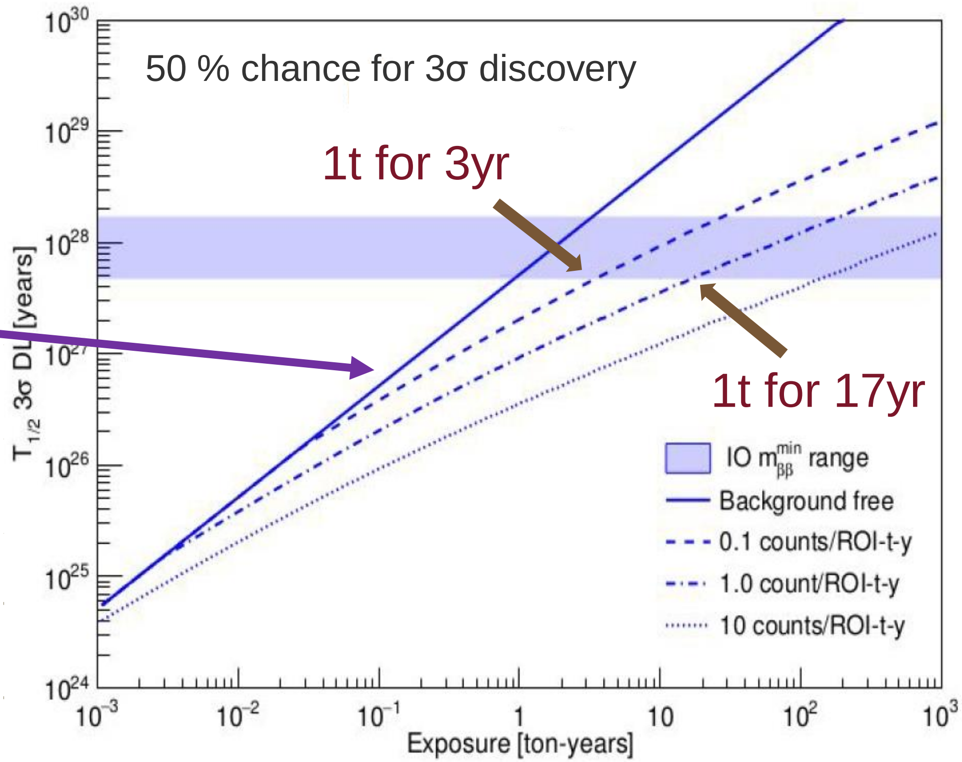


Search for Neutrinoless Double Beta Decay

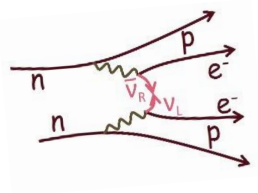
$\Delta L \neq 0$

background
free regime

$T_{1/2}$ ~ exposure

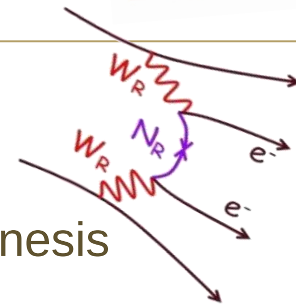


low background essential for discovery potential



Summary

$\Delta L \neq 0$



- search for double beta decay highly motivated:

  $\Delta L \neq 0$, Majorana ν , lightness of ν-mass, Leptogenesis

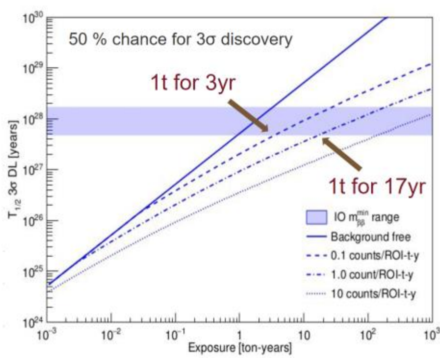
next experiments explore range up to $T_{1/2} < 10^{27}$yr mid term

$T_{1/2} < 10^{28}$yr long term

$\Rightarrow$ chance for discovey of $\Delta L \neq 0$

- field is very active and competitive,

  variety of approaches and technologies



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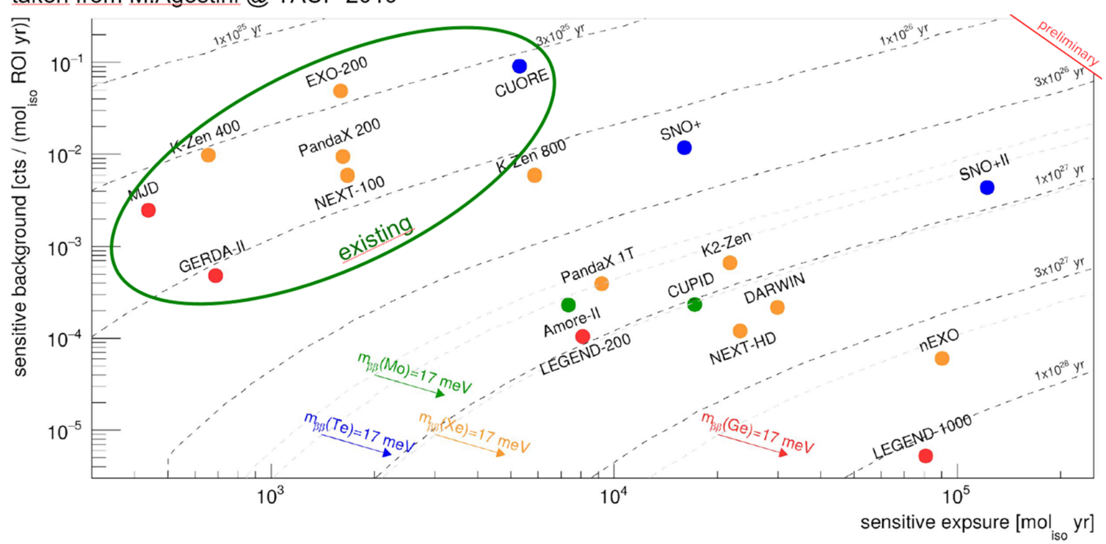

Xe Te Ge Mo

END