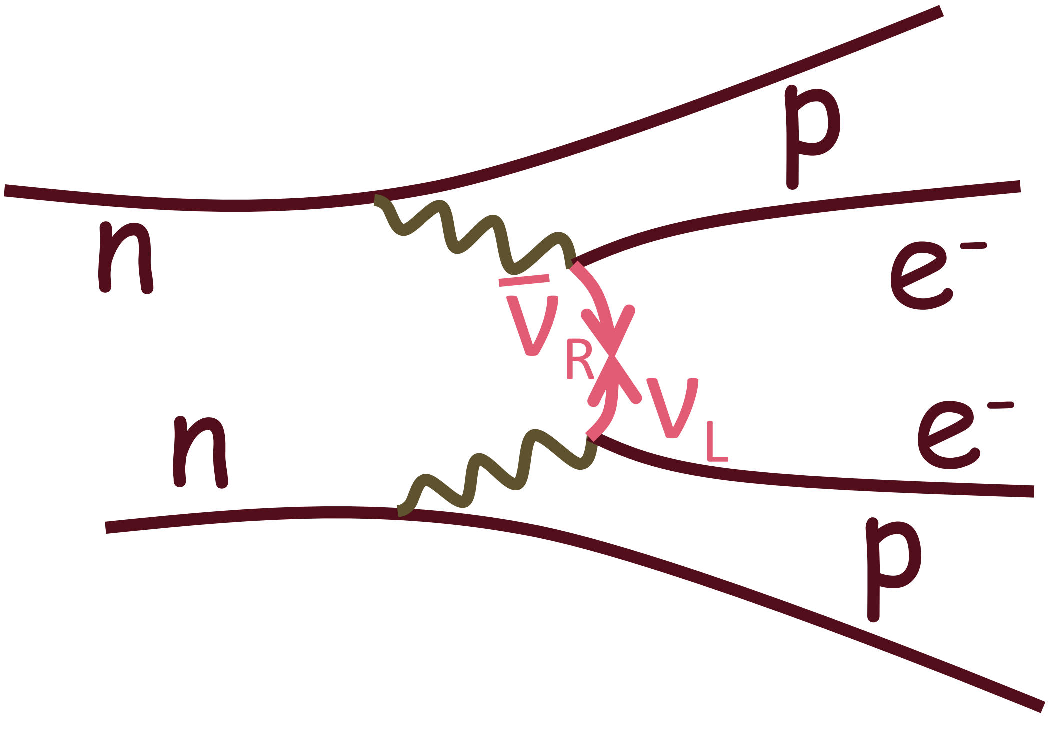
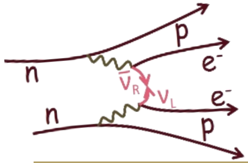
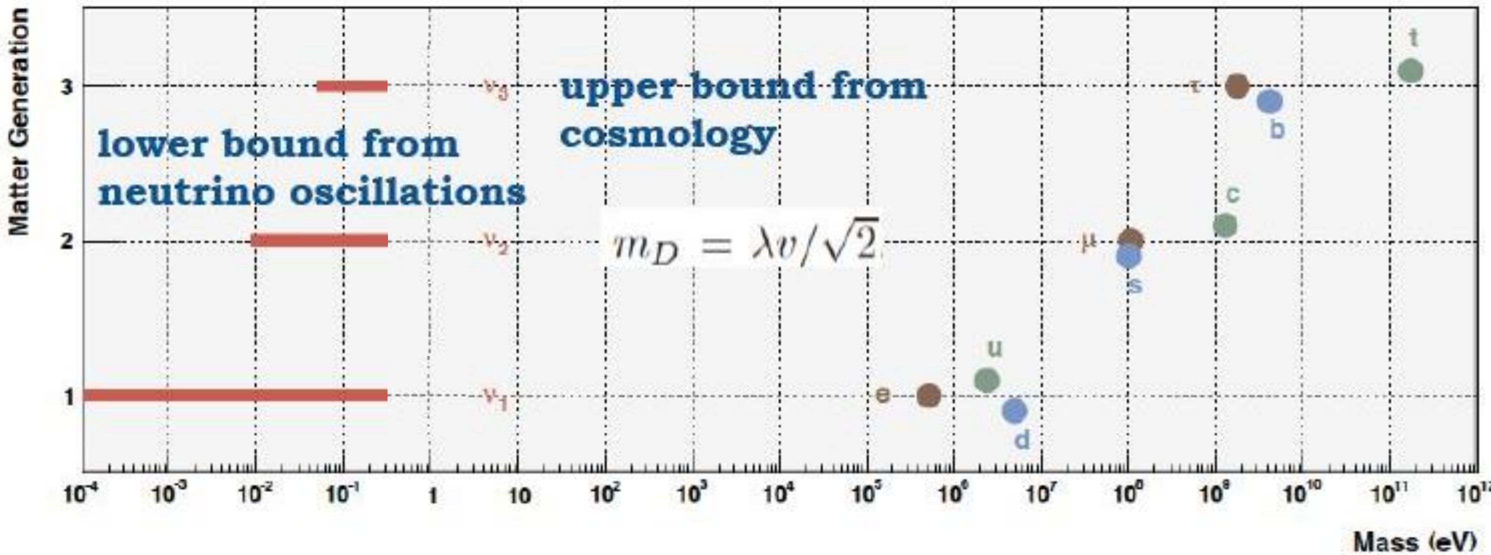
Double Beta Decay and Lepton Number Violation

$\Delta L \neq 0$

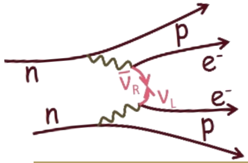




Why are Neutrino Masses so small ?

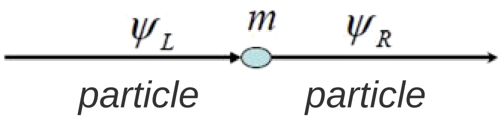


if neutrinos acquire their mass by coupling to the Higgs,
in the same way as the charged leptons,
why should the coupling be so different ?



Neutrino Mass

SM massterms: $m\,(\,\overline{e_L}\,e_R + \overline{e^c{}_R}\,e^c{}_L\,)$



no ν_R or $\nu^c{}_L$ in standard model

⇒ no ν-massterm

⇒ add ν_R , $\nu^C{}_L$

$$m_D\overline{\nu_L}\,\nu_R + m_D\overline{\nu^c{}_L}\,\nu^c{}_R$$

$$= \overline{N_L}\begin{pmatrix} 0 & m_D \\ m_D & 0 \end{pmatrix} N_R$$

$$N_L = \begin{pmatrix} \nu_L \\ \nu^C{}_L \end{pmatrix} \qquad N_R = \begin{pmatrix} \nu^C{}_R \\ \nu_R \end{pmatrix} \qquad \begin{pmatrix} \text{active} \\ \text{sterile} \end{pmatrix}$$

two degenerate mass-eigenvalues m_D

Dirac

ν_L $\quad$ $\nu^c{}_L$

$\nu^c{}_R$ $\quad$ ν_R

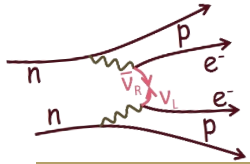
$$\nu_D \neq \nu_D{}^c$$

Majorana

$\nu_{M,L} = \nu_L + \nu^c{}_L$

$\nu_{M,R} = \nu^c{}_R + \nu_R$

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



Majorana Neutrino

$$\nu_M = \nu_M^c$$

particle *particle*

$$m_D \overline{\nu}_L \nu_R + m_D \overline{\nu^c}_L \nu^c_R$$

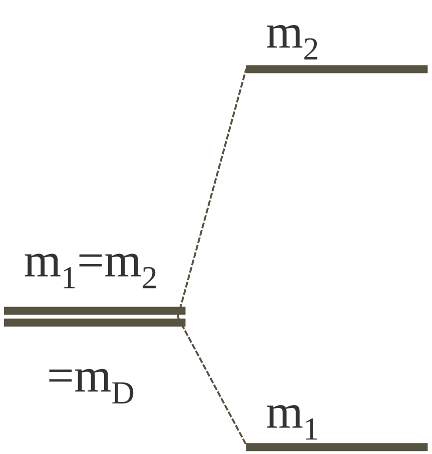
anti-particle *particle*

$$+ \ M_R \overline{\nu^c}_L \nu_R + M_L \overline{\nu}_L \nu^c_R$$

$$= \overline{N}_L \begin{pmatrix} M_L & m_D \\ m_D & M_R \end{pmatrix} N_R$$

$$N_L = \begin{pmatrix} \nu_L \\ \nu^C_L \end{pmatrix}$$

$$N_R = \begin{pmatrix} \nu^C_R \\ \nu_R \end{pmatrix}$$



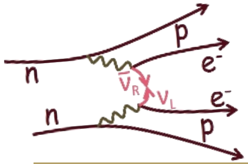
mass-eigenvalues split

Majorana

$$\nu_{M,L} = \nu_L + \nu^c_L$$

$$\nu_{M,R} = \nu^c_R + \nu_R$$

$$\nu_M = \nu_M^c$$



Majorana Neutrino

$\nu_M = \nu_M{}^c$

$$\begin{pmatrix} 0 & m_D \\ m_D & M_R \end{pmatrix}$$

m_D normal Fermion-mass
M_R ~ higher scale (GUT ?)

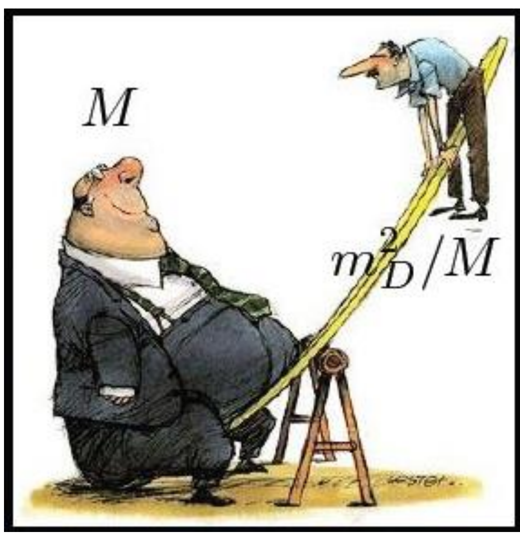
$m_1 = m_D{}^2 / M_R$

mostly left-handed, active

=> ν we know

$m_2 = M_R$

mostly right-handed, sterile



to get
$m_1 \sim$ meV

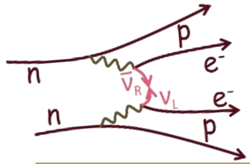
$M_R \sim 10^{15}$ eV

Majorana

$\nu_{M,L} = \nu_L + \nu^c{}_L$

$\nu_{M,R} = \nu^c{}_R + \nu_R$

$\nu_M = \nu_M{}^c$



Majorana Neutrino

$$\nu_M = \nu_M^{\,c}$$

ν has no charge $\Rightarrow$ can be Majorana-particle

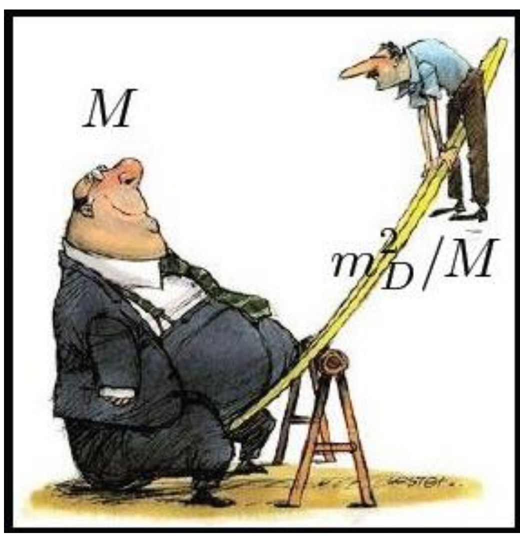
$\Rightarrow$ can explain small ν – mass (even with normal m_D)

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

$\Rightarrow$ heavy right handed partner

$\Rightarrow$ decays in early Universe $\Delta L \neq 0$

$\Rightarrow$ creates Matter - Antimatter imbalance



to get
$m_1 \sim \text{meV}$

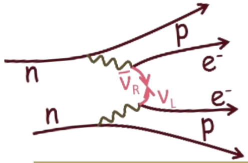
$M_R \sim 10^{15}\,\text{eV}$

Majorana

$\nu_{M,L} = \nu_L + \nu^c{}_L$

$\nu_{M,R} = \nu^c{}_R + \nu_R$

$$\nu_M = \nu_M^{\,c}$$



Majorana Neutrino

$\nu_M = \nu_M^c$

ν has no charge ⇒ can be Majorana-particle

⇒ can explain small ν – mass (even with normal m_D)

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

⇒ heavy right handed partner

⇒ decays in early Universe $\Delta L \neq 0$

⇒ creates Matter - Antimatter imbalance

$\nu_M = \nu_M^c$

$\Delta L \neq 0$

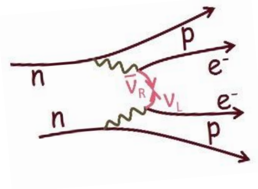
\+

CP violation in ν-sector

⇒

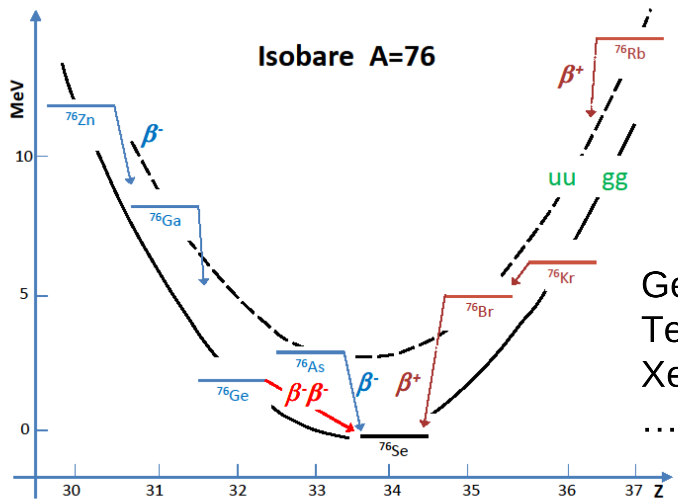
Us !

Matter in the Universe



Search for Neutrino-less Double Beta Decay

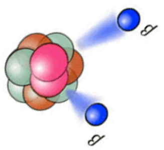
$\Delta L \neq 0$

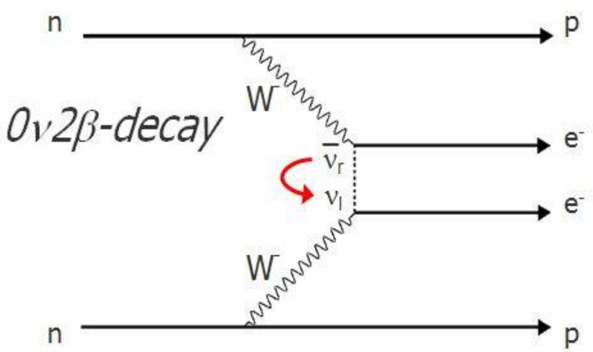


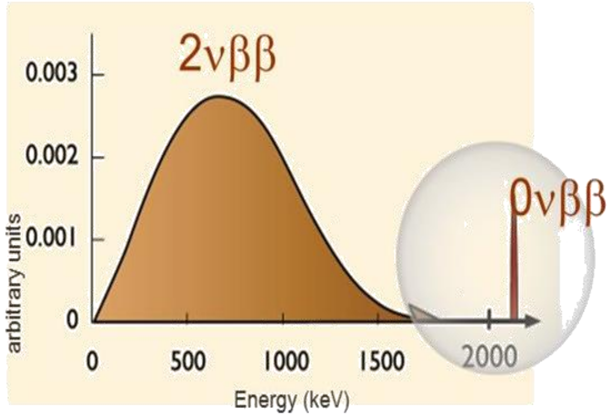
Ge-76
Te-130
Xe-136
….

easiest but not easy way to see

if ν are Majorana-type

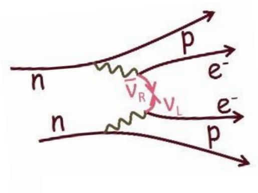






$\Rightarrow$ checks Majorana character

$\Rightarrow$ very sensitive to m_ν



Sensitivity

$\Delta L \neq 0$

effective neutrino mass

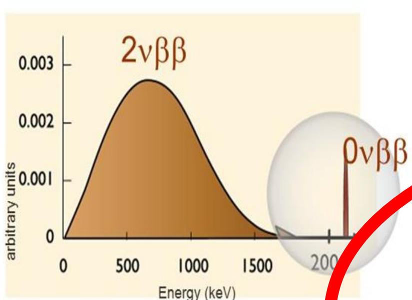
$$1 / T^{0\nu}_{1/2} = G \cdot NME^2 \cdot m^2_{\beta\beta}$$

phase space ~ Q^5

nuclear matrix element

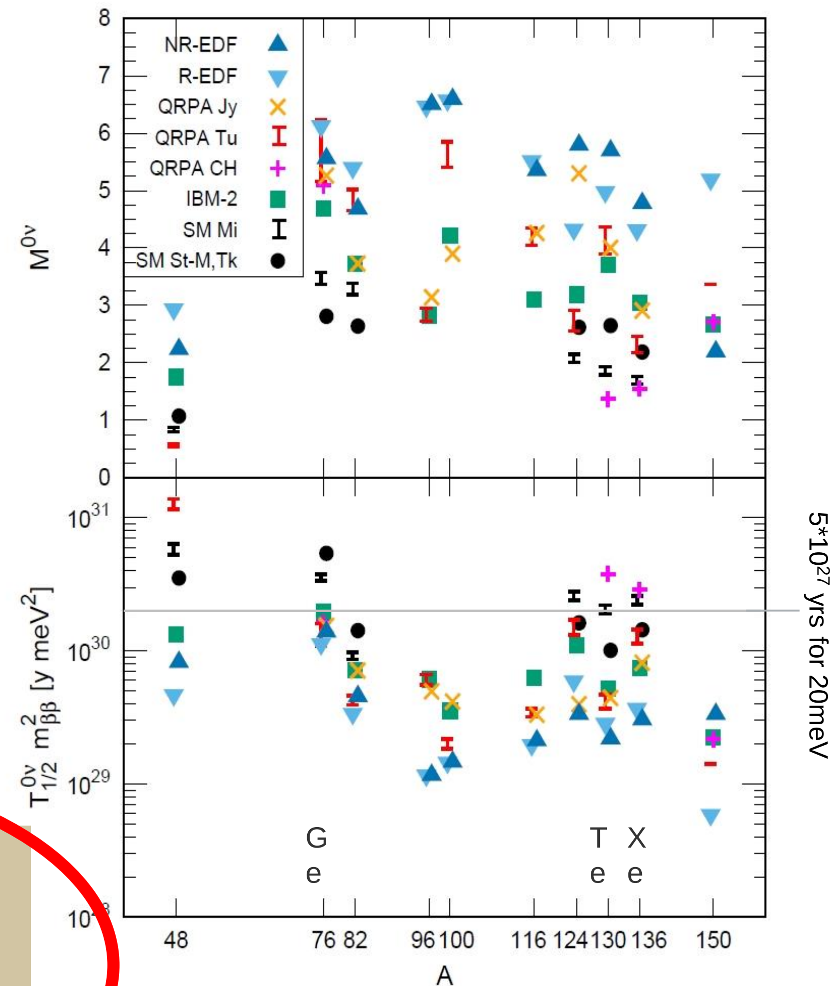
no favored isotope
considering spread of nuclear matrix elements and Q-values

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

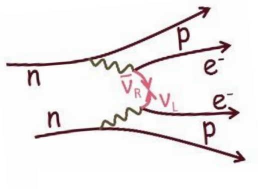


large mass
[$kg_{isotope}$]

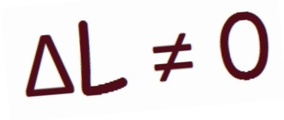
low background in ROI
[cts / FWHM $t_{isotope}$yr]



arXiv:
1610.06548v1



Sensitivity



effective neutrino mass

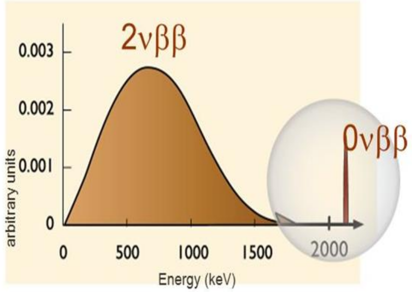
$$1 / T^{0\nu}_{1/2} = G \cdot NME^2 \cdot m^2_{\beta\beta}$$

phase space $\sim Q^5$ — nuclear matrix element

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

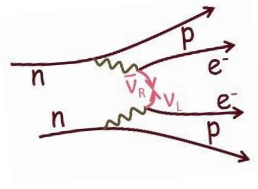
mid term: **a few 10^{26} yrs** ($m_{\beta\beta}$ ~ 40-100 meV)

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

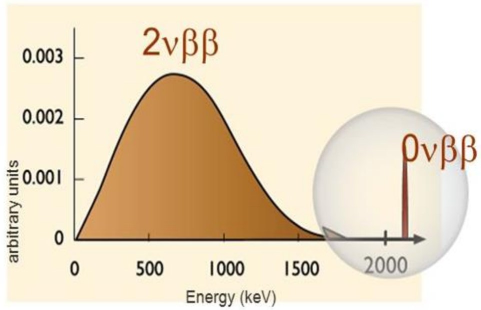


large mass
[$kg_{isotope}$]

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



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



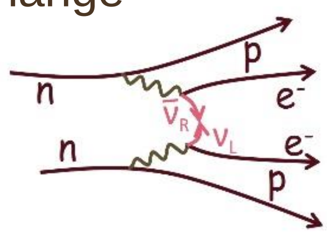
easiest but not easy way to see

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)

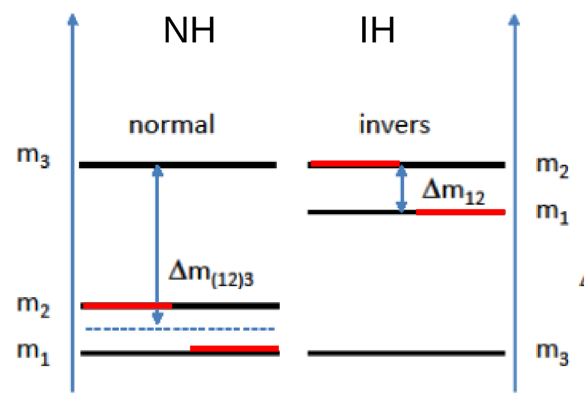
via ν exchange

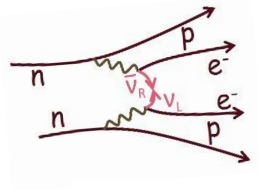


effective neutrino mass

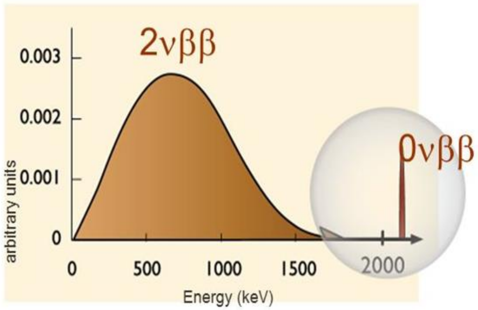
$$1 / T^{0\nu}_{1/2} = G \cdot NME^2 \cdot m^2_{\beta\beta}$$

phase space nuclear matrix element





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



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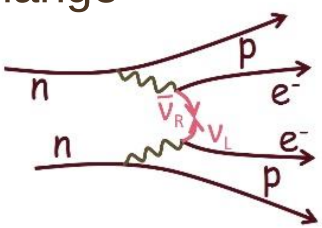
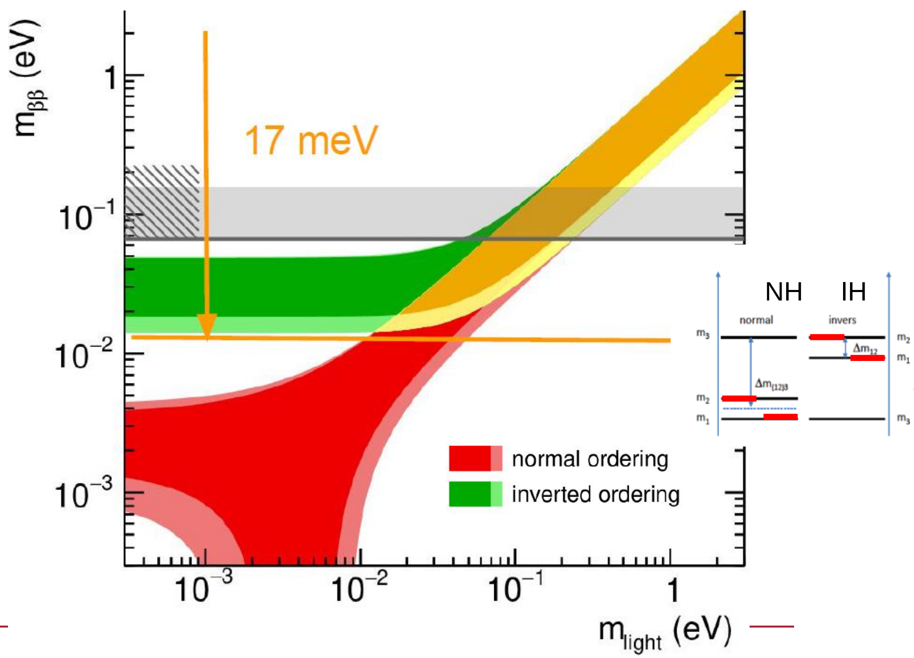
via ν exchange

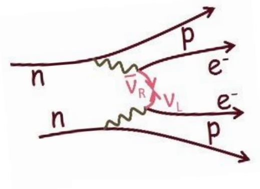


effective neutrino mass

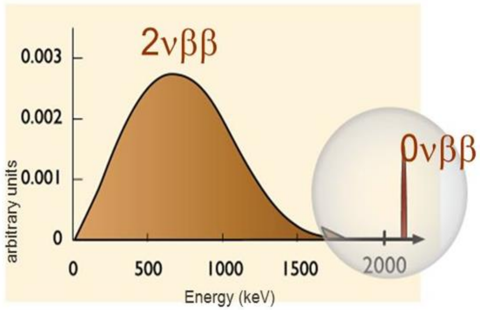
$$1 / T^{0\nu}_{1/2} = G \cdot NME^2 \cdot m^2_{\beta\beta}$$

phase space nuclear matrix element





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



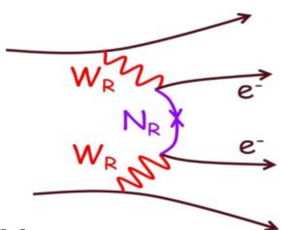
easiest but not easy way to see

if ν are Majorana-type

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

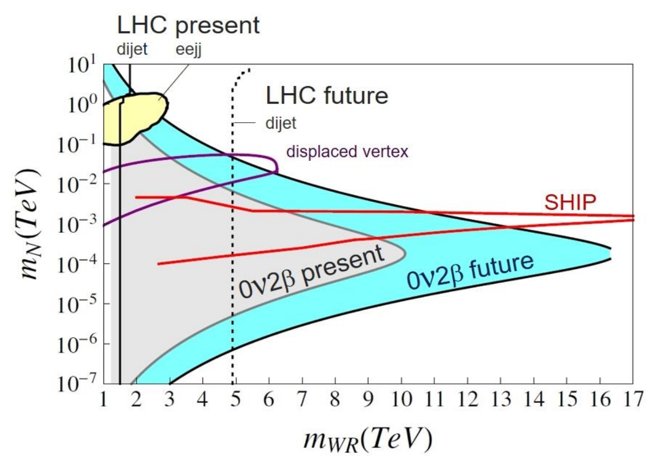
mid term: a few 10^{26} yrs ($m_{\beta\beta}$ ~ 40-100 meV)
long term: a few 10^{27} yrs ($m_{\beta\beta}$ ~ 10- 20 meV)

other $\Delta L \neq 0$ processes



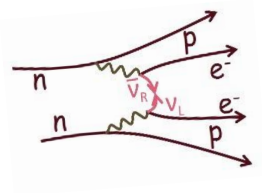
LR symmetry

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 $m_{\beta\beta}$ -

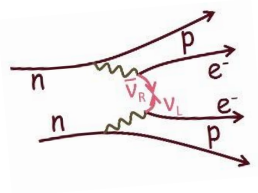


Search for Neutrino-less Double Beta Decay

$\Delta L \neq 0$

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

$\Delta L \neq 0$

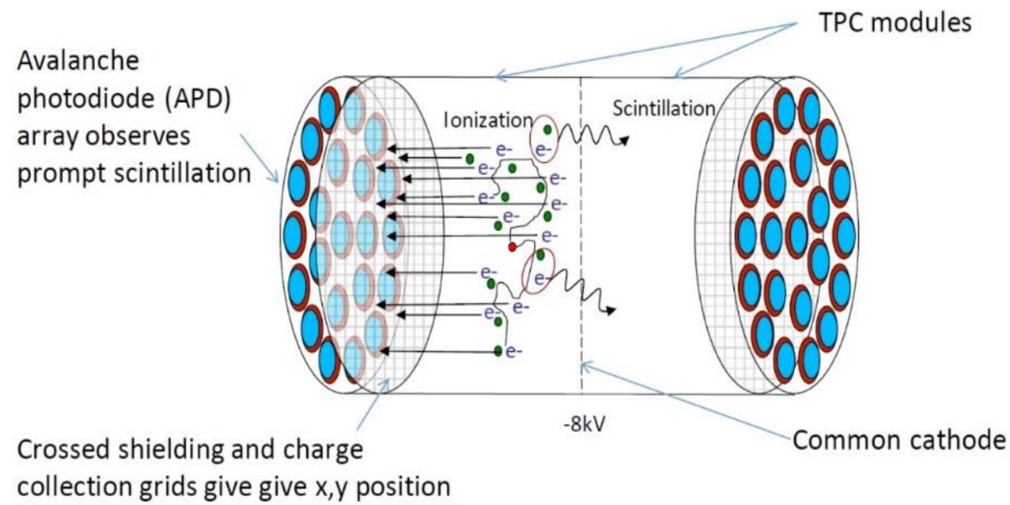
liquid Xenon TPC enriched in ^{136}Xe (80.6 %), charge and light detection

WIPP New Mexico USA

ΔE ~ 70 keV FWHM

self shielding, multi site recognition

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



results:

234 kg·yr exposure

sensitivity 5.0·10^25 yr

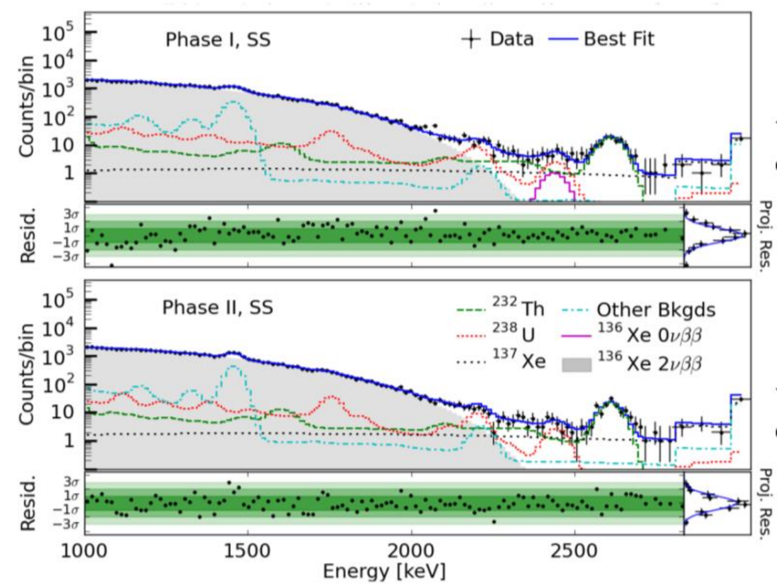
$T_{1/2}^{0\nu\beta\beta} >$ 3.5·10^25 yr

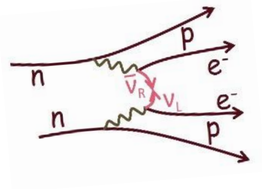
background in ROI

170 / $FWHM \cdot t_{isotope} \cdot yr$

PRL 120 072701 (2018)

arXiv 1906.02723





Liquid Noble Gases - nEXO

$\Delta L \neq 0$

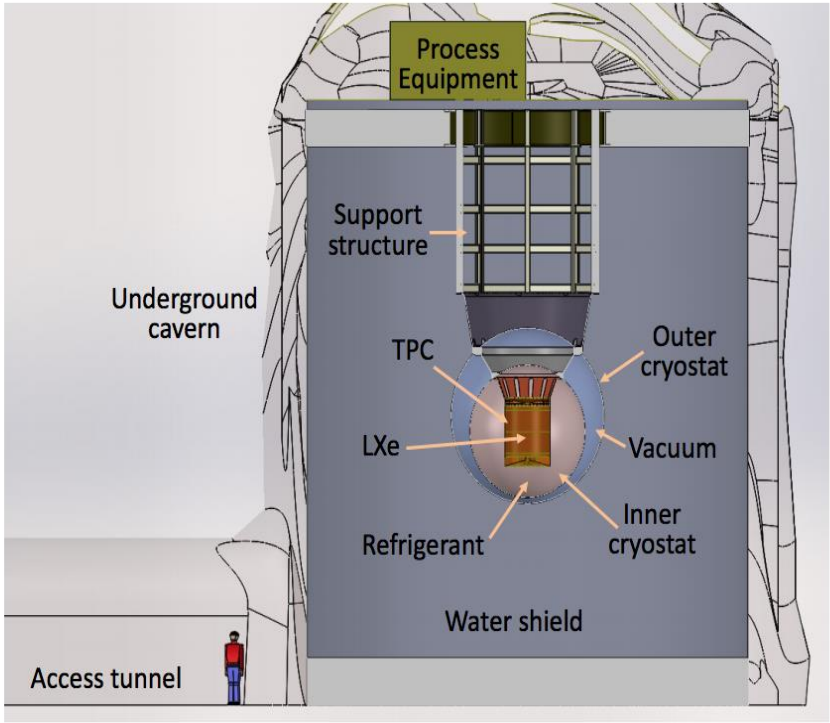
liquid Xenon single TPC

5000 kg enriched lXe

expected to be at **SNOLAB**

improved performance:

energy and position resolution ….

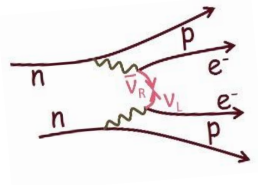


R&D on Ba-tagging

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$\cdot t_{isotope} \cdot$yr

arXiv 1710.05075



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

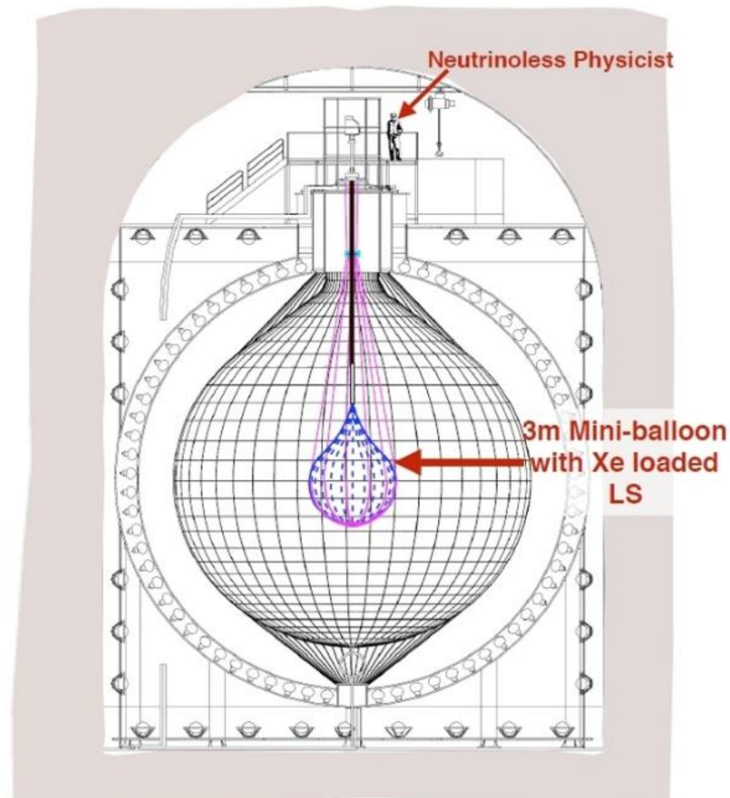
results: 383 kg Xe / 110 $kg_{isotope}$ in FV

~ 600 kg·yr

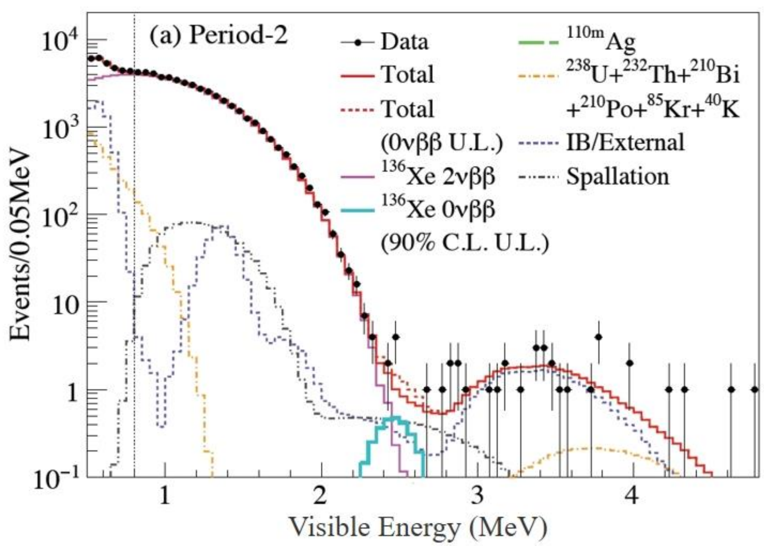
$T_{1/2}^{0\nu\beta\beta}$ > 10.7·10^{25} yr

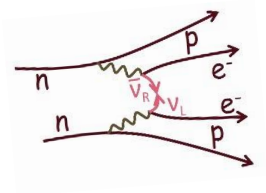
sensitivity 5.6·10^{25} yr

background in ROI ~ 60 / FWHM·$t_{isotope}$·yr



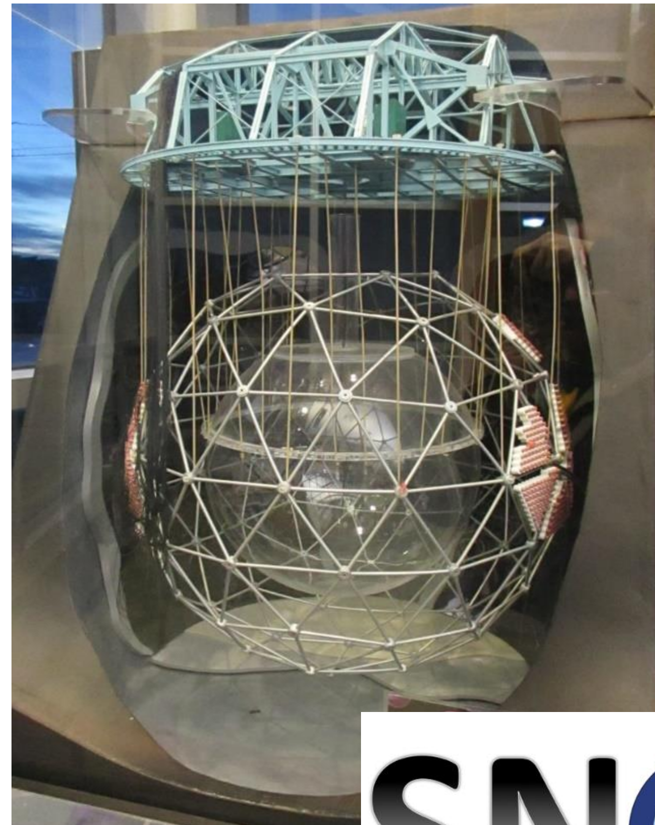
PRL 117 082503 (2016)





Liquid Scintillator - SNO+

$\Delta L \neq 0$



infrastructure at SNOLAB

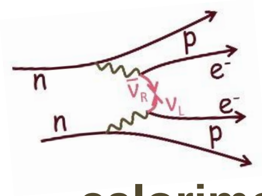
Phase I:
acrylic vessel filled with LS
+ 4000 kg of nat-Te
(~30% Te-130)

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

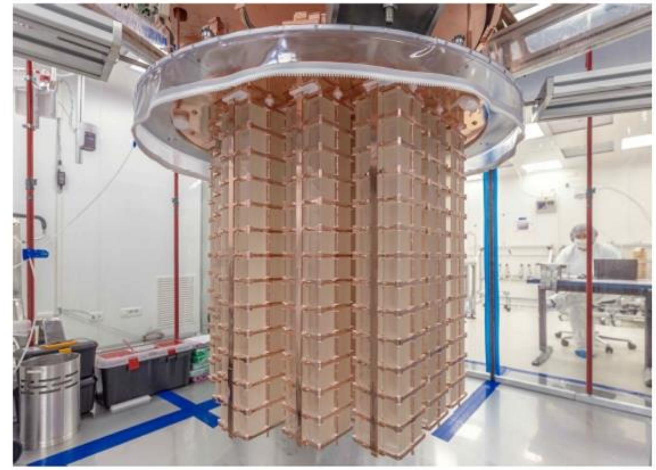
THEIA project: 50 kton water-based liquid scintillator
solar-ν will be dominant background



Calorimetry - Cuore @ LNGS

$\Delta L \neq 0$

calorimetry at mK temperature
in natural TeO_2 crystals ^{130}Te (30%)



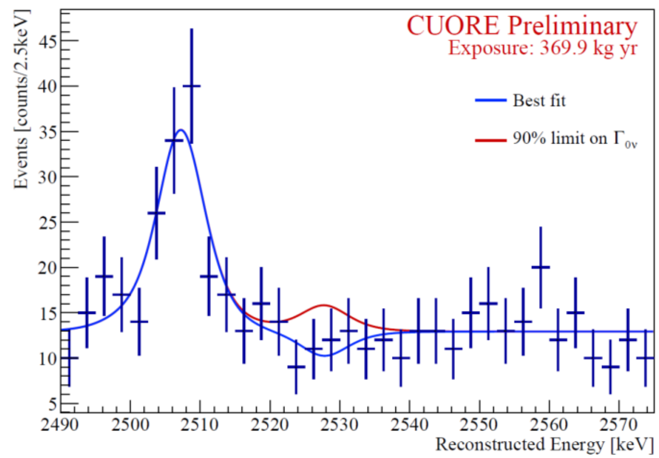
CUORE 750 kg TeO_2 (206 kg ^{130}Te)
988 crystals

results 2019:
369,9 kg.yr (103 kg·yr ^{130}Te)

ΔE ~ 8 keV FWHM

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

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

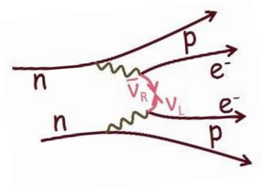


Phys.Rev.Lett 120, 132501 (2018)
Update: TAUP 2019 conference

goals:
goal sensitivity
$T_{1/2}^{0\nu\beta\beta}$ > 9.5·10^{25} yr
background
~ 180 / FWHM·$t_{isotope}$·yr

potential upgrade with calorimetry + light

CUORE => CUPID



Scintillating bolometers

$\Delta L \neq 0$

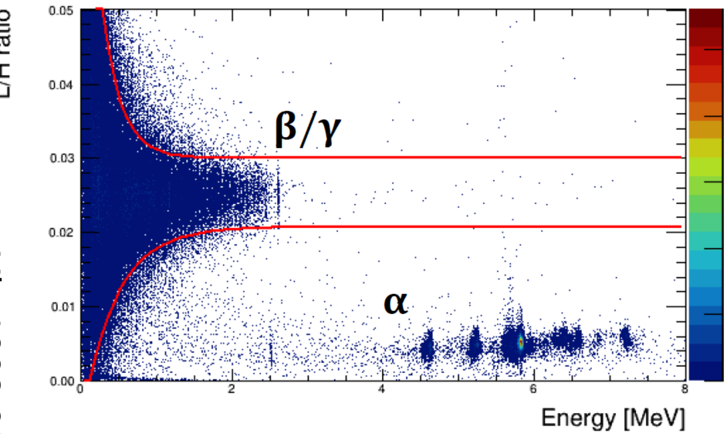
AMORE @ Yangyang UGL Korea

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

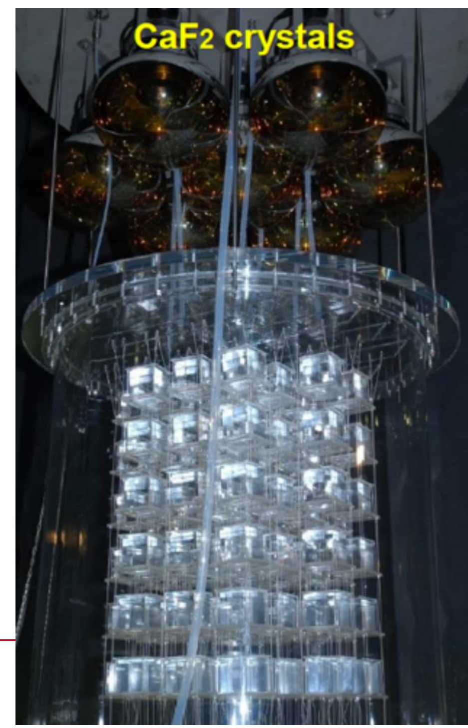
arXiv 1903.09483



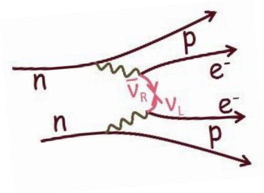
CANDLES @ Kamioka / Japan

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

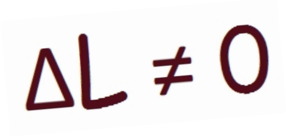
305 kg CaF scintillator detectors
in liquid scintillator
result from 131 days
$T_{1/2}^{0\nu\beta\beta}$ > $6{,}2 \cdot 10^{22}$ yr



working on scintillating bolometers
first demonstration results

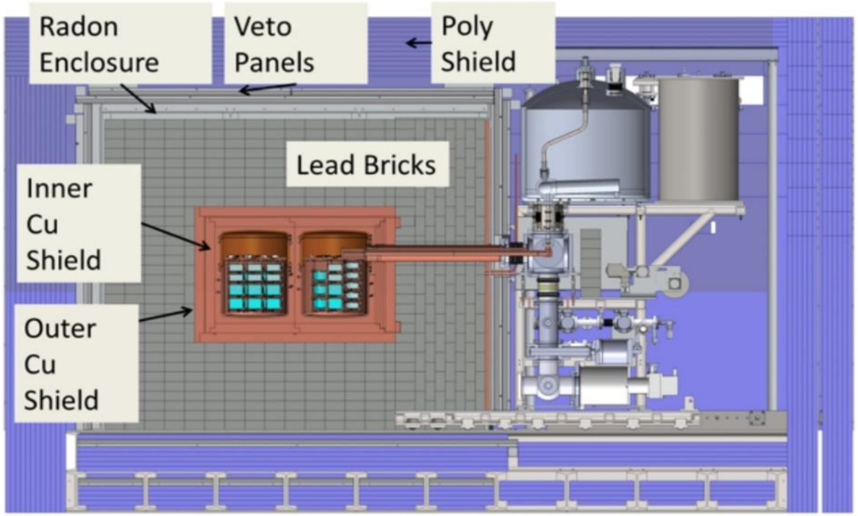


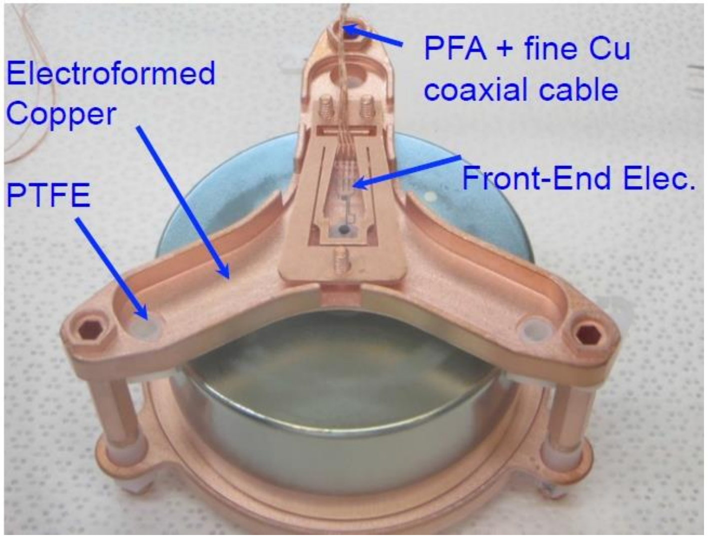
Ge Semiconductor - MAJORANA



Ge detectors
Cu/Pb shielding

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





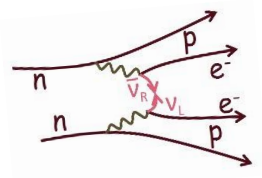
PRC 100 025501 (2019)

results

26 kg·yr

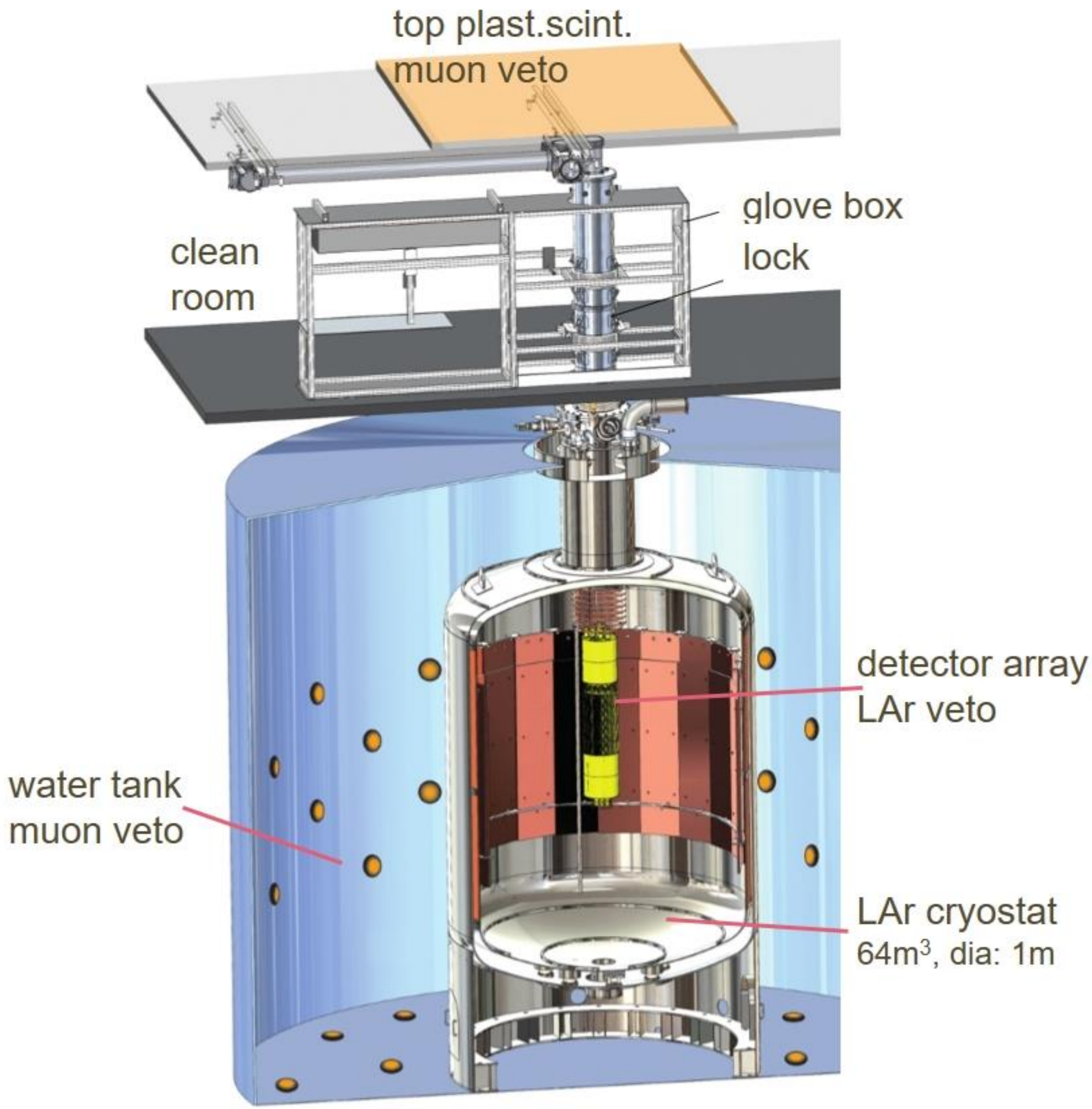
$T_{1/2}^{0\nu\beta\beta} > 2.7 \cdot 10^{25}$ yr

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



GERDA

ΔL ≠ 0



ΔE ~ 3keV FWHM

LAr veto

combines

- selfshielding / veto of liquid noble gas
- high resolution of Ge detectors

pulse shape discrimination

multi site and surface event recognition

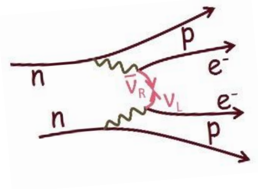
GERDA Phase II

started Dec 2015

35,6 kg enr. Ge (86%)

goals:

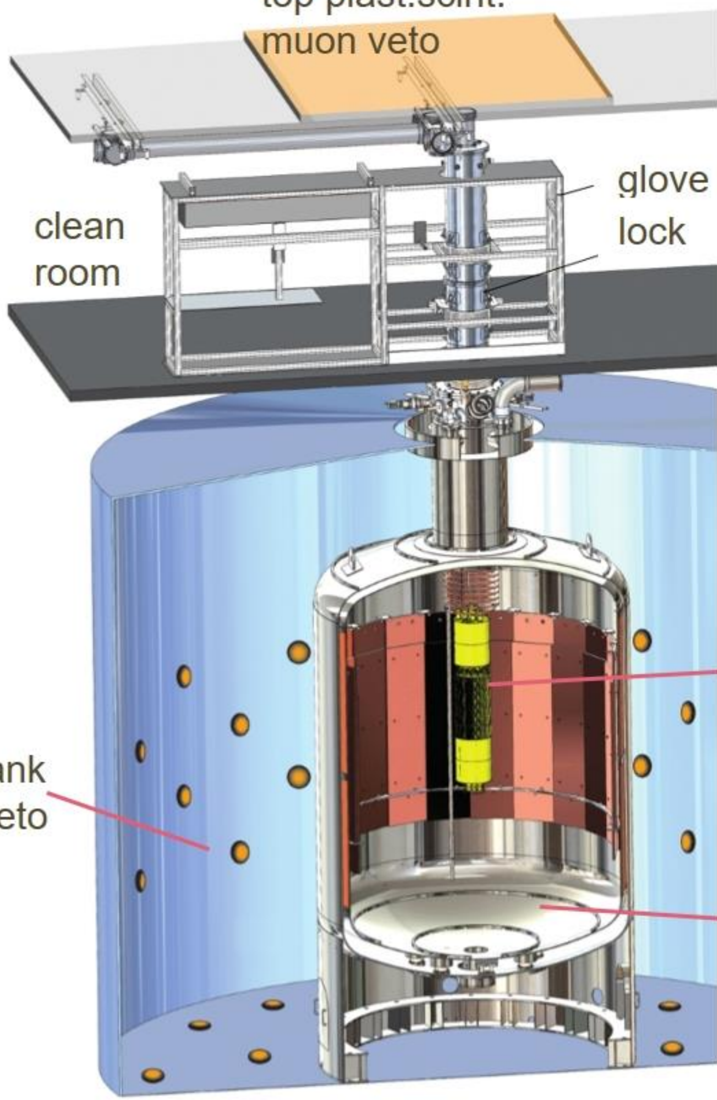
- 100 kgyr
- sensitivity > 10^{26} yr
- bkg 3 / FWHM t yr

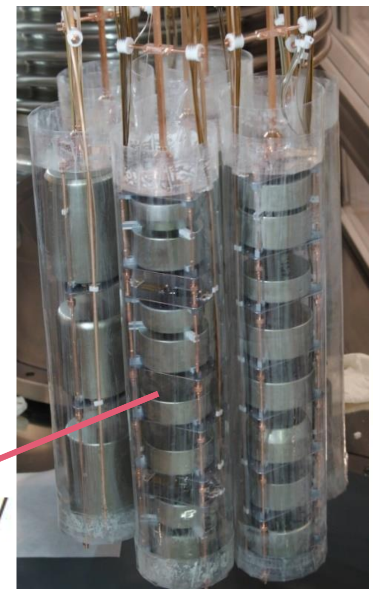


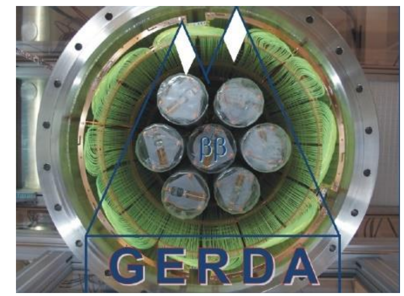
GERDA

$\Delta L \neq 0$

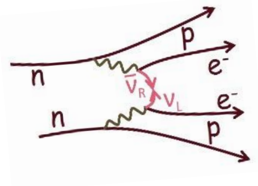
combines advantages
- *active shielding of liquid noble gas*
- *high energy resolution of Ge detectors*





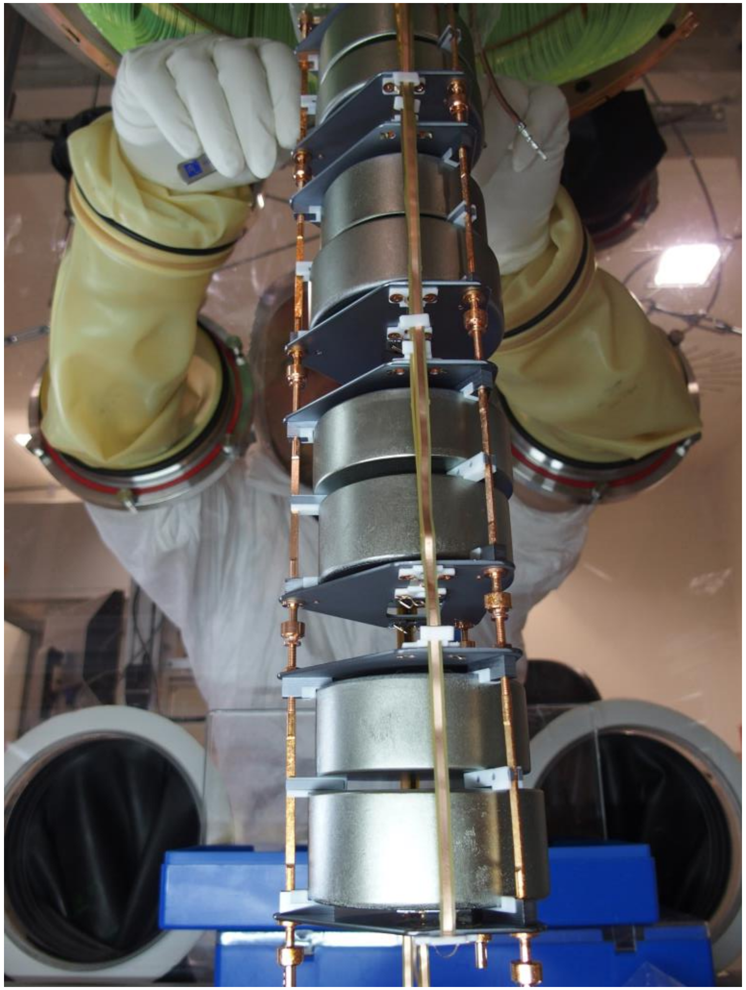


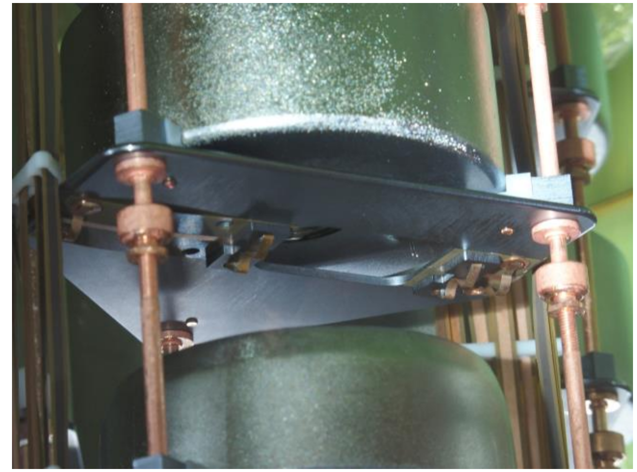
Gran Sasso

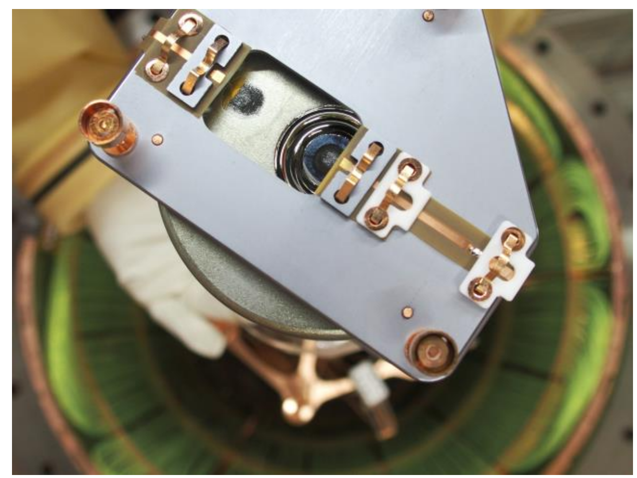


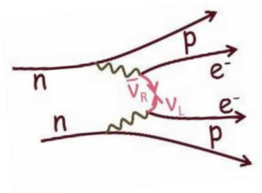
GERDA

$\Delta L \neq 0$



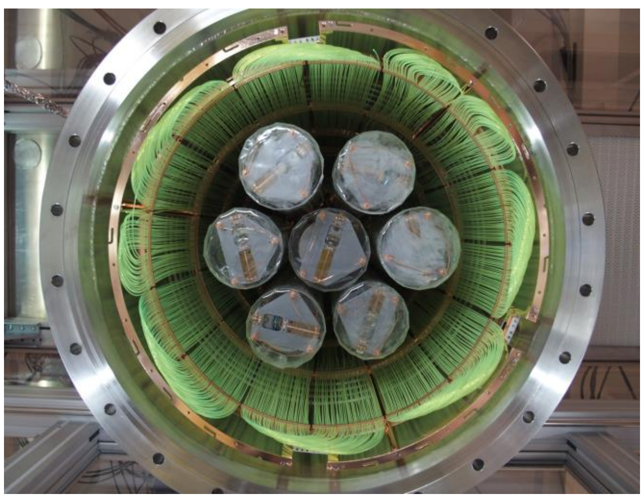


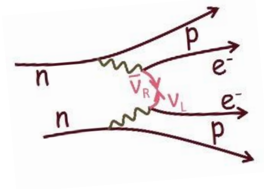




GERDA

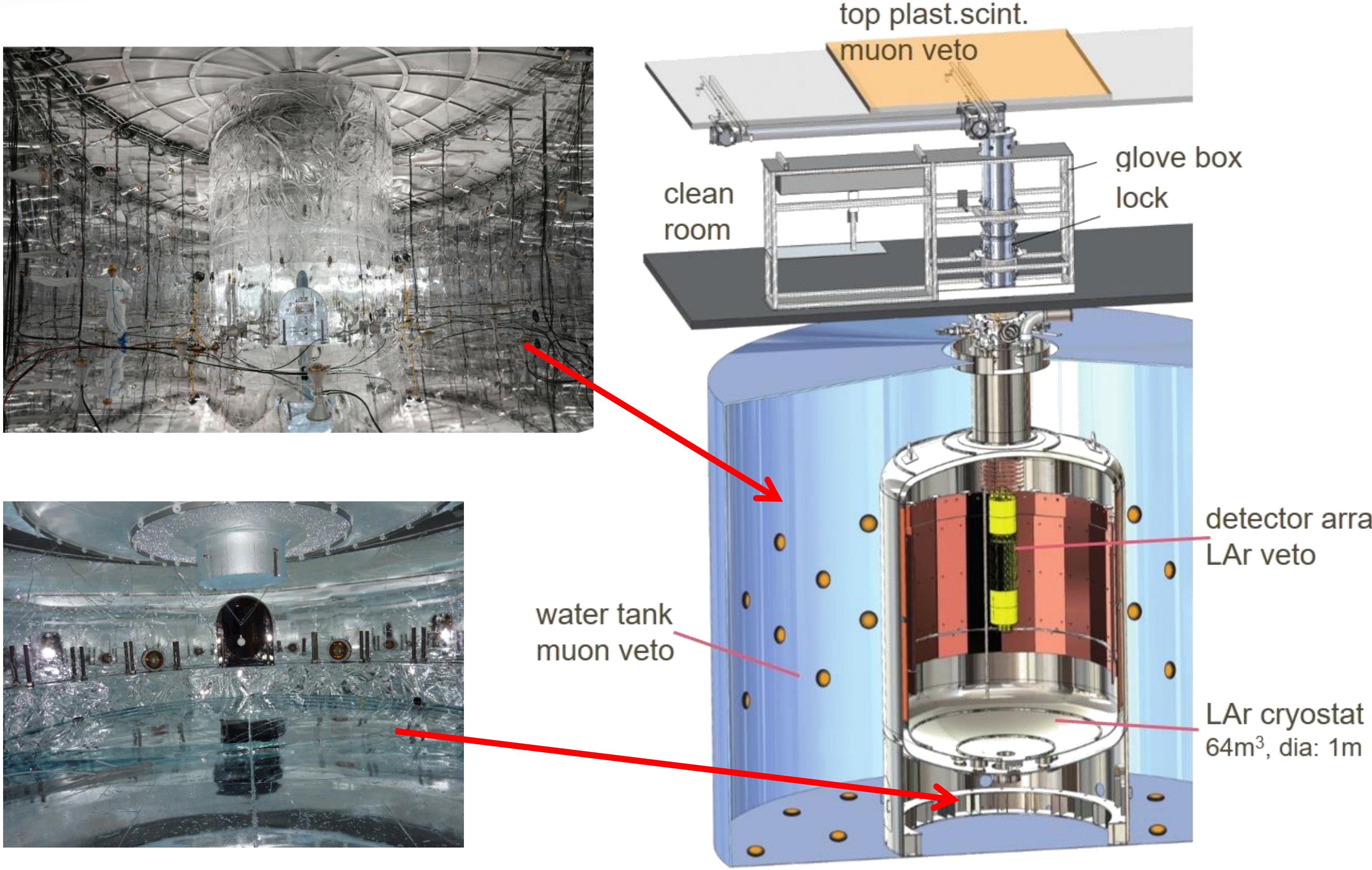
$\Delta L \neq 0$

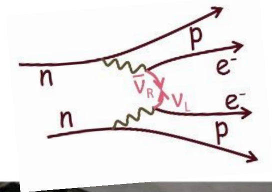




GERDA

$\Delta L \neq 0$



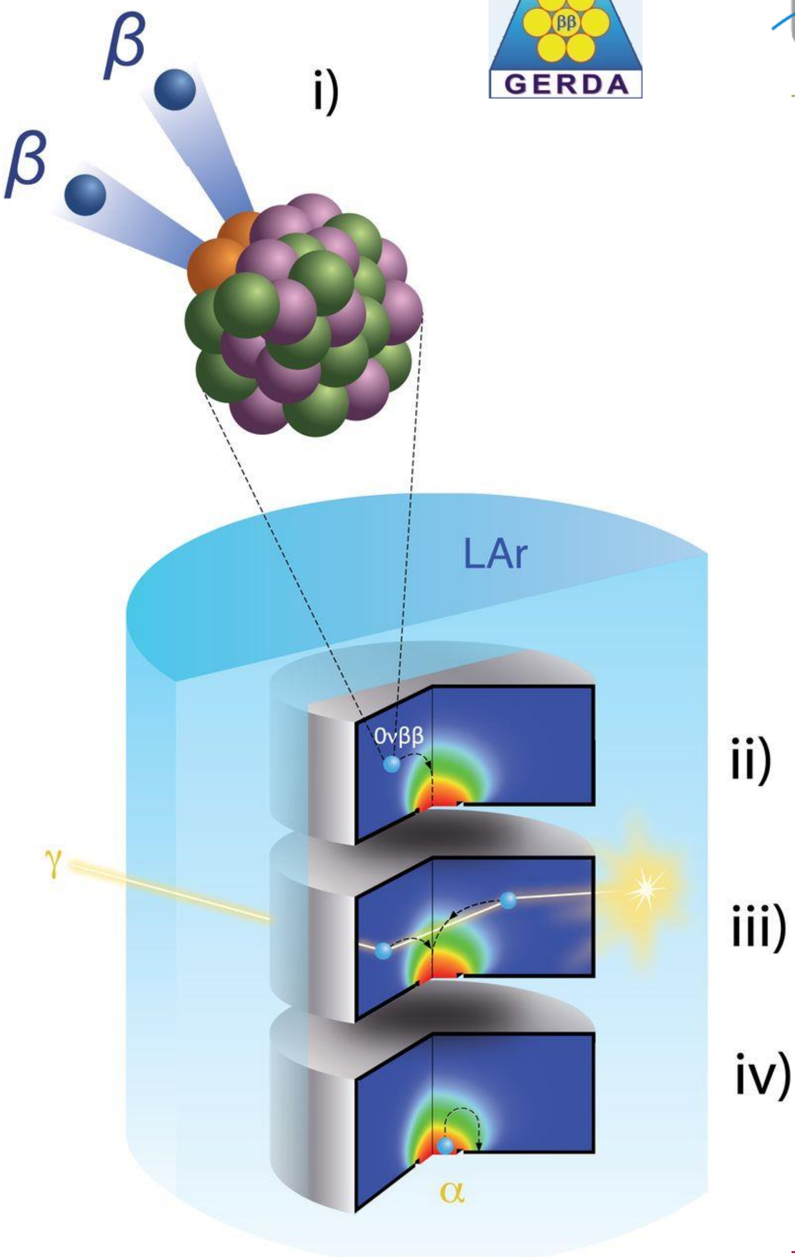


GERDA

$\Delta L \neq 0$

Large Enriched Germanium Experiment for Neutrinoless ββ Decay

$\Delta L \neq 0$



pulse shape discrimination

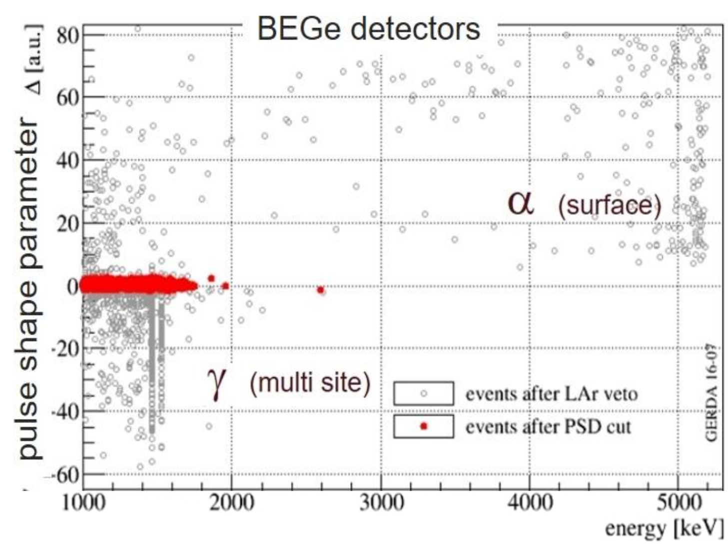
multi site and surface event recognition

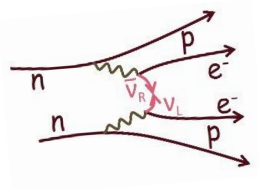
i) ββ decay is localized (pointlike) – single site event

ii) signal generation mostly when charges reach region close to small electrode

iii) different drift times for multi site events => slower signal rise

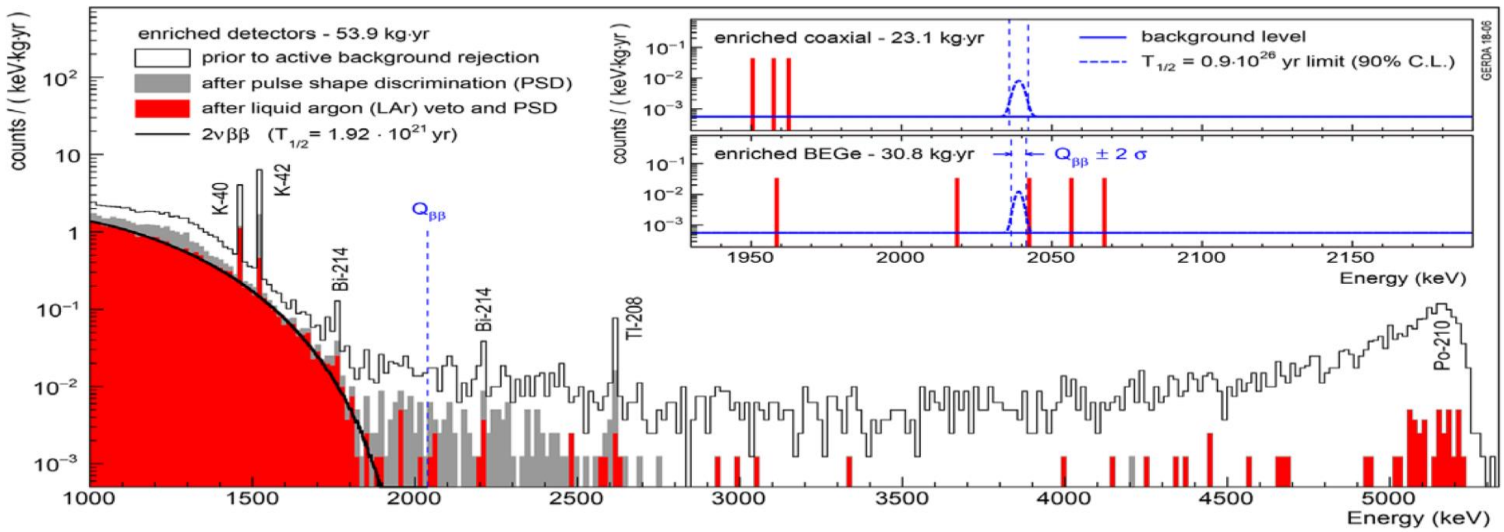
iv) α decays at unprotected contact surface show very fast rise



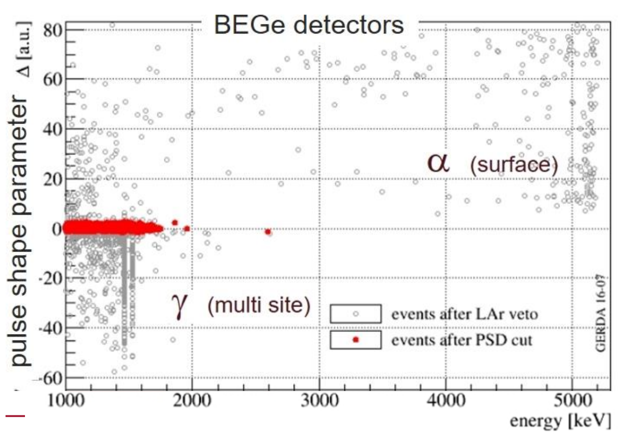


GERDA

$\Delta L \neq 0$

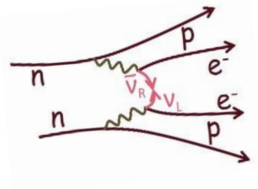


- 97% of events between 600-1300keV are $2\nu\beta\beta$
- Background 250 times lower compared to Heidelberg-Moscow Exp. (~10y)



pulse shape discrimination

- single site / multi site
⇒ γ lines supressed by ~ 6
- surface / bulk
⇒ all α (surface) events removed



GERDA

ΔL ≠ 0

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

GERDA results

82.4 kg·yr total exposure

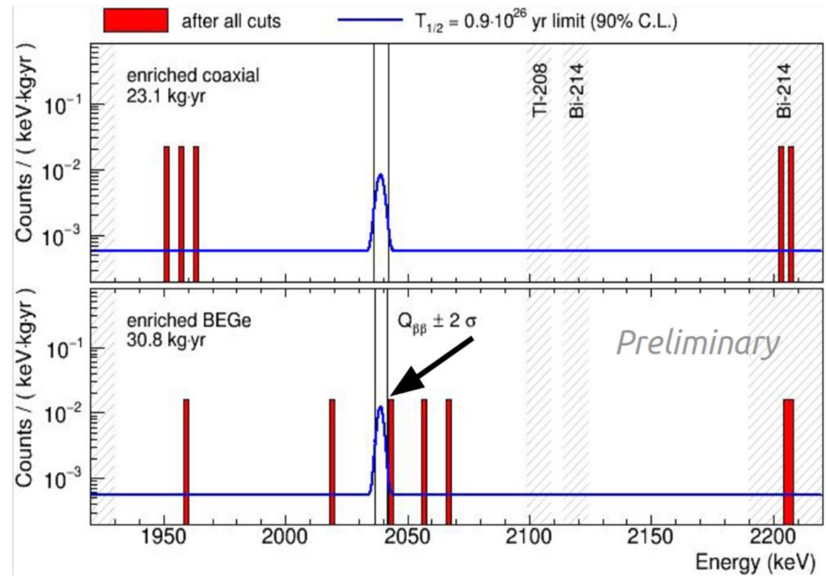
background in ROI
4 / FWHM·$t_{isotope}$·yr

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

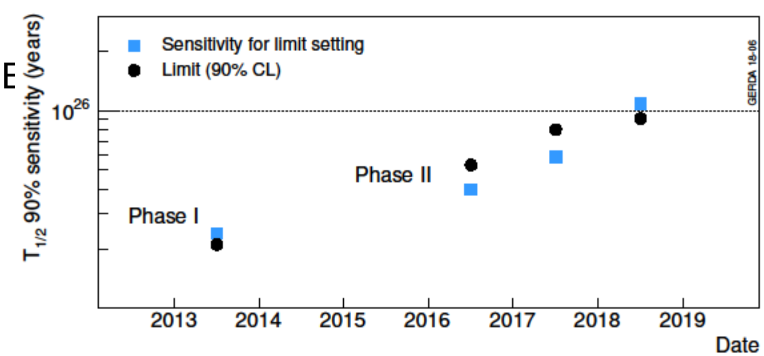
$T_{1/2}^{0\nu\beta\beta}$ > $9 \cdot 10^{25}$ yr

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

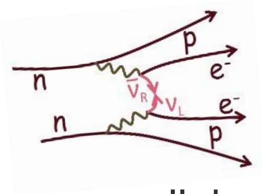
Science 10.112 / science.aav8613 (2019)



background 250 times lower compared to Heidelberg-Moscow E



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



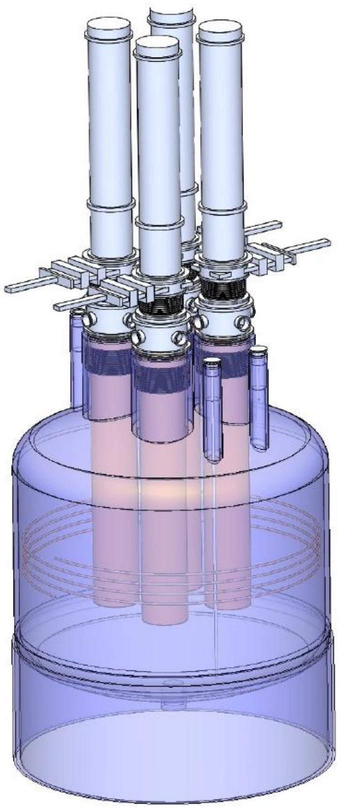
Search for Neutrinoless Double Beta Decay

$\Delta L \neq 0$

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

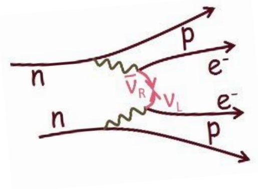
sensitivity > 10^{27} yr

LEGEND

Large Enriched Germanium Experiment for Neutrinoless ββ Decay

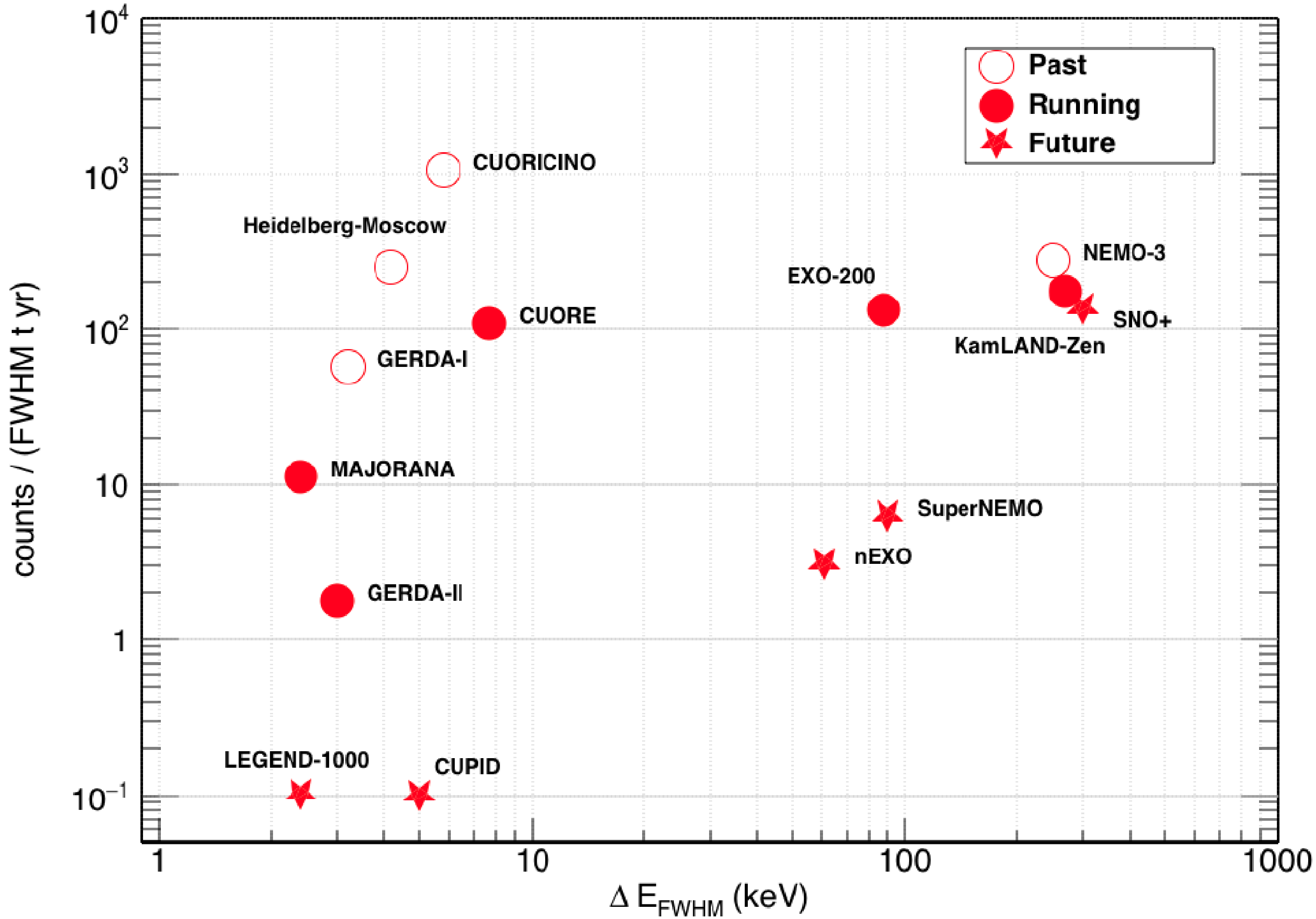
sensitivity > 10^{28} yr

LEGEND 1000: 1000kg phase depends on US down selection process

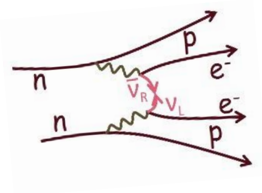


Search for Neutrinoless Double Beta Decay

$\Delta L \neq 0$



M.J.Dolinski, A.W.P.Poon, W.Rodejohann „Neutrinoless Double-Beta Decay: Status and Prospects“; arXiv:1902.04097

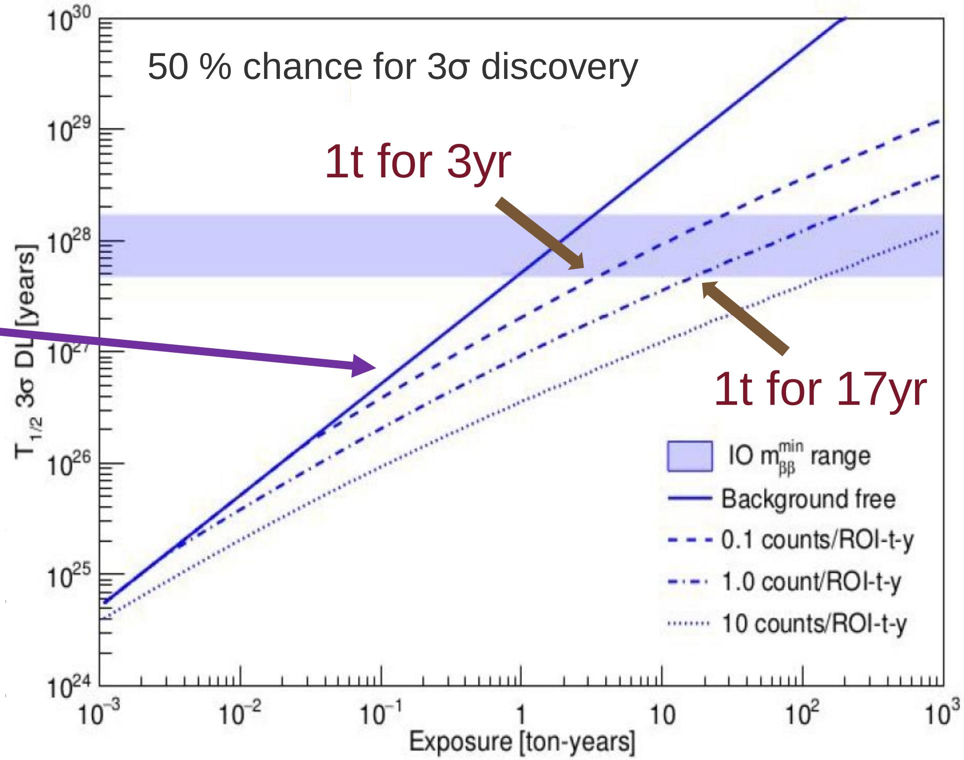


Search for Neutrinoless Double Beta Decay

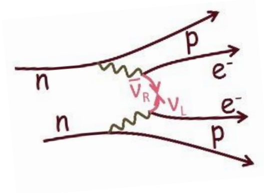
$\Delta L \neq 0$

background free regime

$T_{1/2}$ ~ exposure

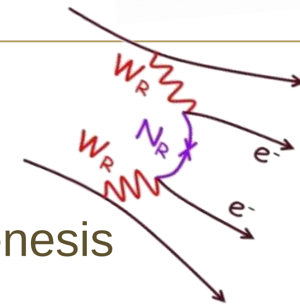


low background essential for discovery potential



Summary

$\Delta L \neq 0$



- search for double beta decay highly motivated:

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

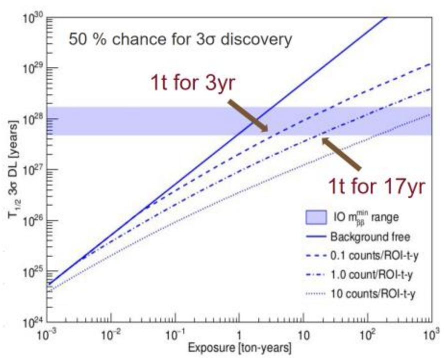
next experiments explore range up to $T_{1/2} < 10^{27}$yr mid term

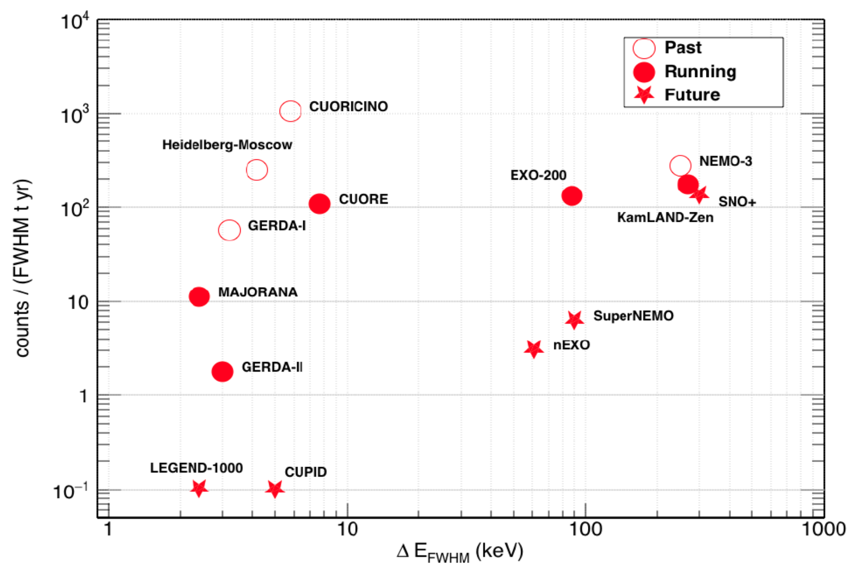
$T_{1/2} < 10^{28}$yr long term

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

- field is very active and competitive,

  variety of approaches and technologies





1902.04097

low background essential for discovery potential

END