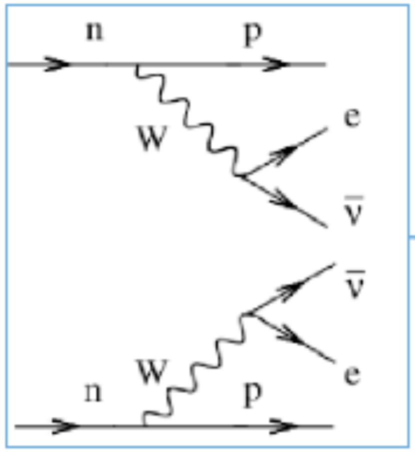
Investigation of neutrino nature with LEGEND

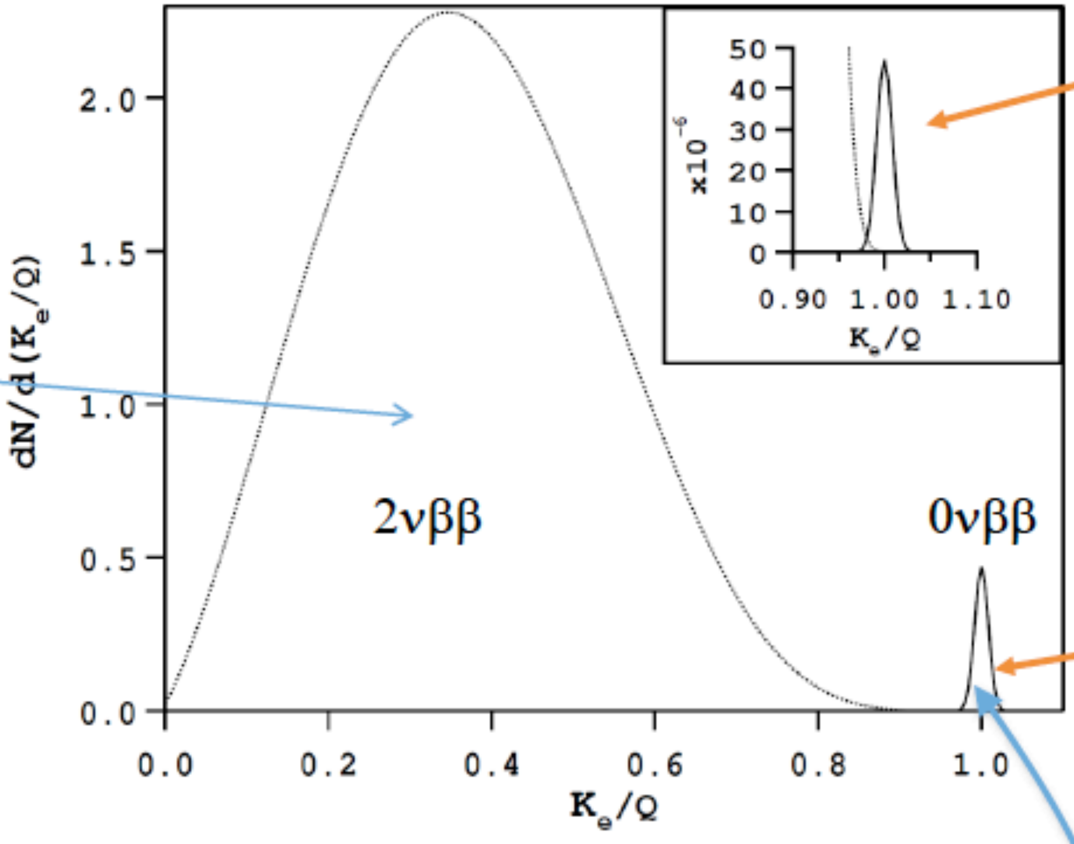
G.Salamanna

$0\nu2\beta$ decays

ΔL=2

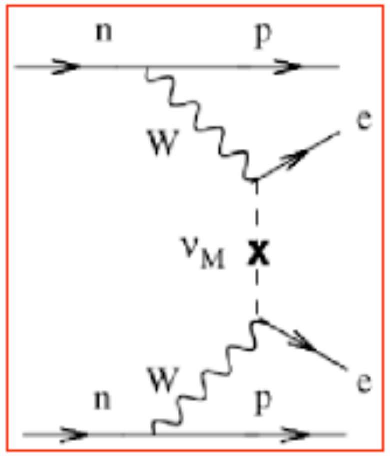


[arXiv:hep-ph/0611243]



0νββ peak (normalized to 10^{-6})

0νββ peak (normalized to 10^{-2})



- Two beta decays at the same time
- Only a few isotopes able to undergo 2β
  - among which **Ge76**

$0\nu\beta\beta : (A, Z) \rightarrow (A, Z{+}2) + 2e^-$

new physics, $T_{1/2} > 10^{25}$ yrs

Only feasible way at present to determine ν nature:

$\nu = \bar{\nu} \Rightarrow$ ***Majorana particle***

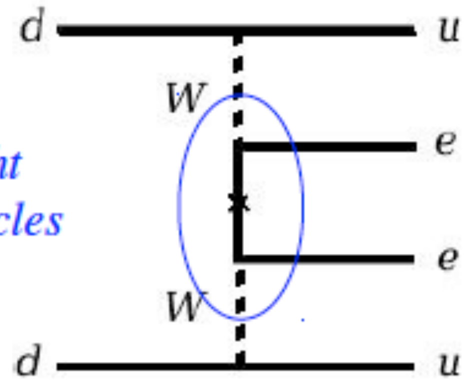
$$\left(T^{0\nu}_{1/2}\right)^{-1} = G^{0\nu}(Q_{\beta\beta}, Z)\,\left|M^{0\nu}\right|^2 \left(\frac{\langle m_{ee}\rangle}{m_e}\right)^2 \qquad \langle m_{ee}\rangle = \left|\sum_i U^2_{ei} m_i\right|$$

phase space factor

nuclear matrix element

effective Majorana neutrino mass

exchange of light Majorana particles



- Has also important cosmological repercussions

Challenges of double-β decay experiments

Sensitivity on $T_{1/2} \propto \varepsilon \cdot A \cdot \sqrt{\frac{M \cdot T}{b \cdot \Delta E}}$

ε	detection efficiency
A	isotopic abundance
M	active mass
T	exposure
b	background rate
ΔE	energy resolution

$T_{1/2}^{0\nu} > 10^{25}$ years !!
→Need:
- ○ high target mass
- ○ high exposure
- ○ low background rate
- ○ good energy resolution

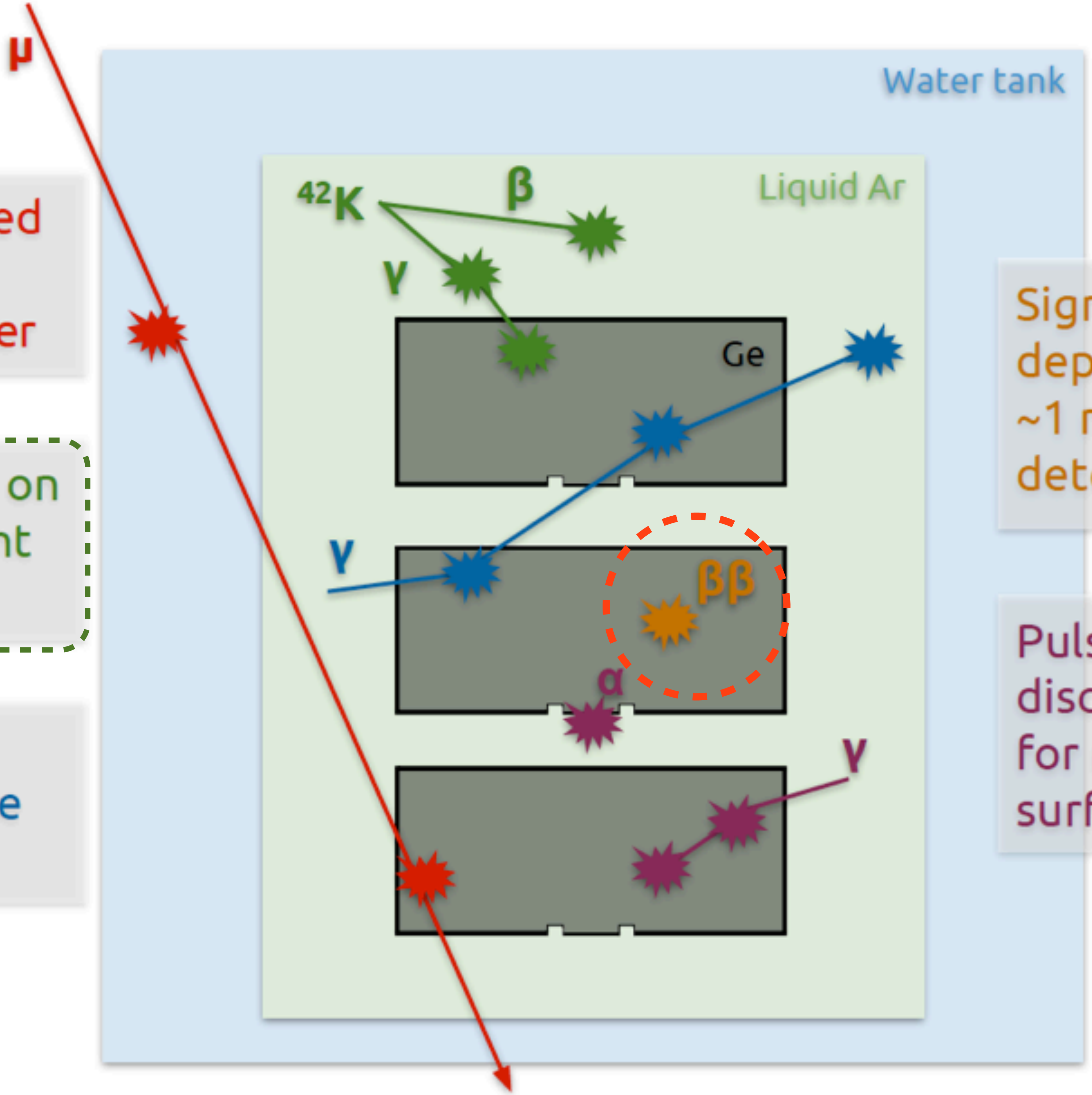
Possible **backgrounds** from:

External:
- γ from Th and U chain
- neutrons
- μ from cosmic rays (prompt and delayed)

Internal:
- cosmogenic ^{60}Co ($T_{1/2}$=5.3 yr)
- cosmogenic ^{68}Ge ($T_{1/2}$=271 d)
- Radioactive surface contaminations

+ **Ge**: source + detector: high **ε**
+ has best **Δ**E on the market
- expensive to get to high A for Ge76
- many bkgs around Q(bb, Ge)

BACKGROUND REDUCTION CONCEPT



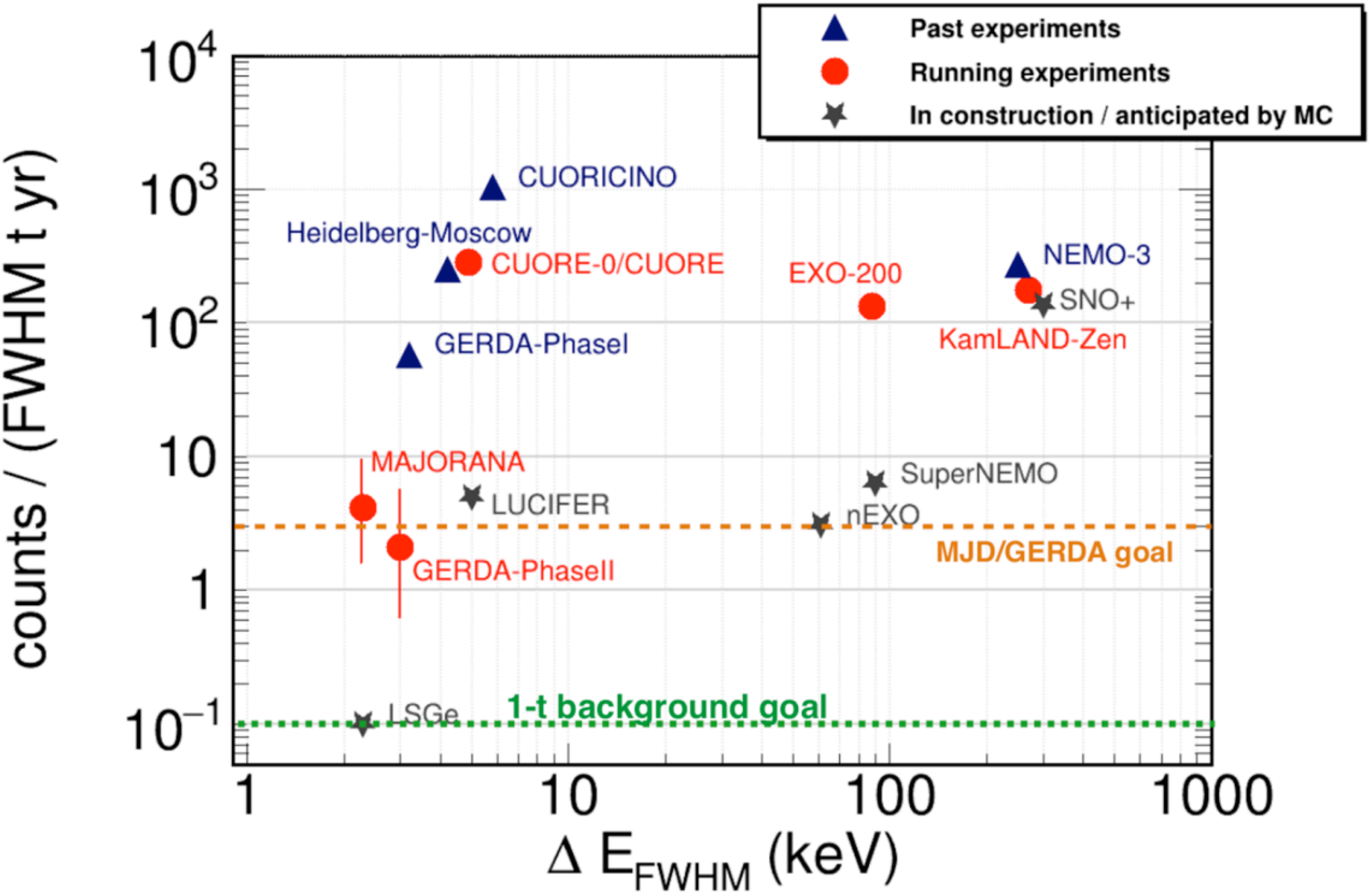
Muon veto based on Cherenkov photons in water

LAr veto based on scintillation light from γs and βs

Detector anti-coincidence of the array

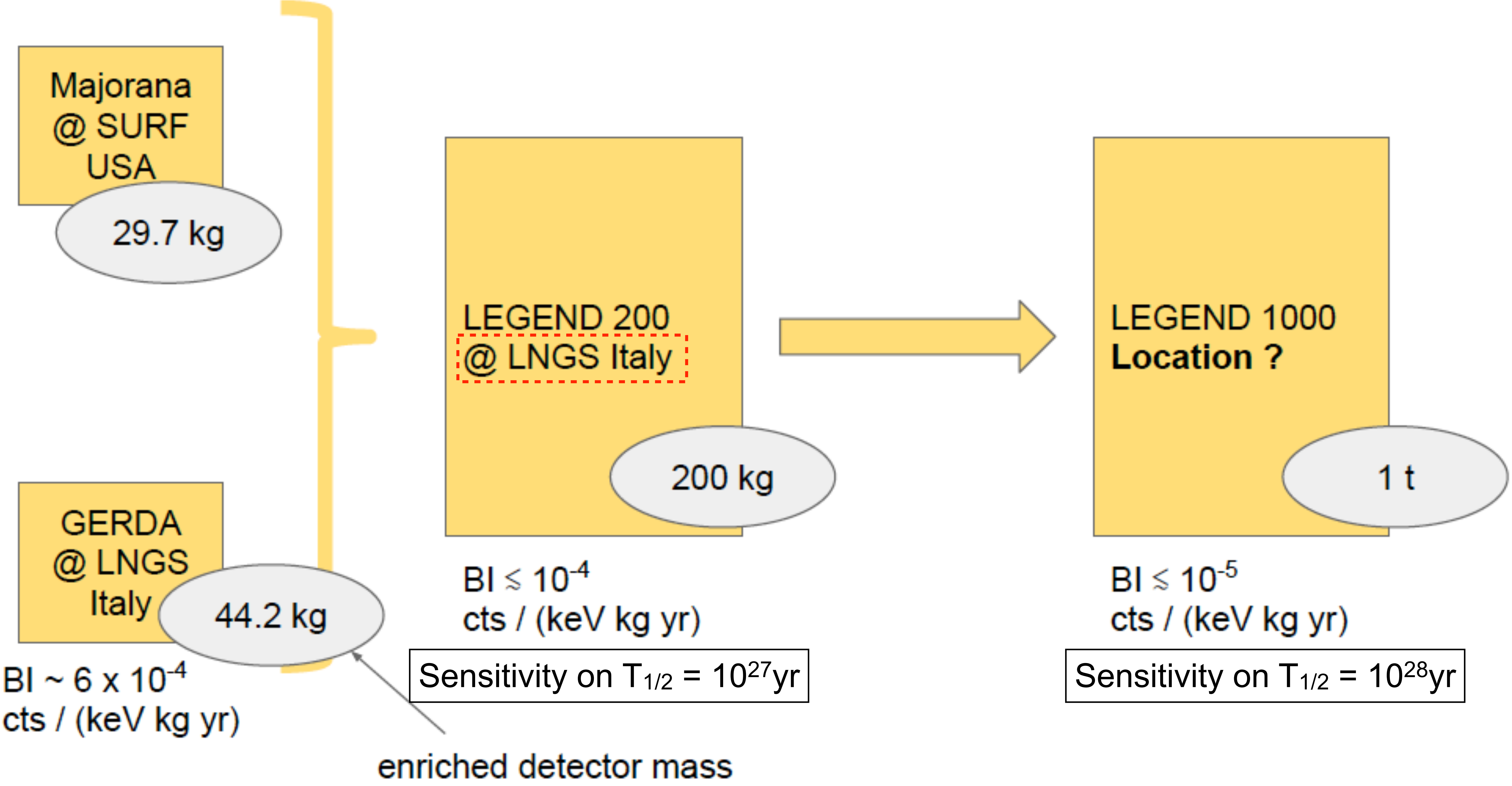
Signal: single energy deposition within ~1 mm^3 of the detector volume

Pulse shape discrimination (PSD) for multi-site and surface events



Ge76 experiments aggressive in keeping background low

The Large Enriched Germanium Experiment for Neutrinoless ββ decay - LEGEND



Majorana
@ SURF
USA

29.7 kg

GERDA
@ LNGS
Italy

44.2 kg

BI ~ 6 x 10^{-4}
cts / (keV kg yr)

enriched detector mass

LEGEND 200
@ LNGS Italy

200 kg

BI $\lesssim 10^{-4}$
cts / (keV kg yr)

Sensitivity on $T_{1/2} = 10^{27}$yr

LEGEND 1000
Location ?

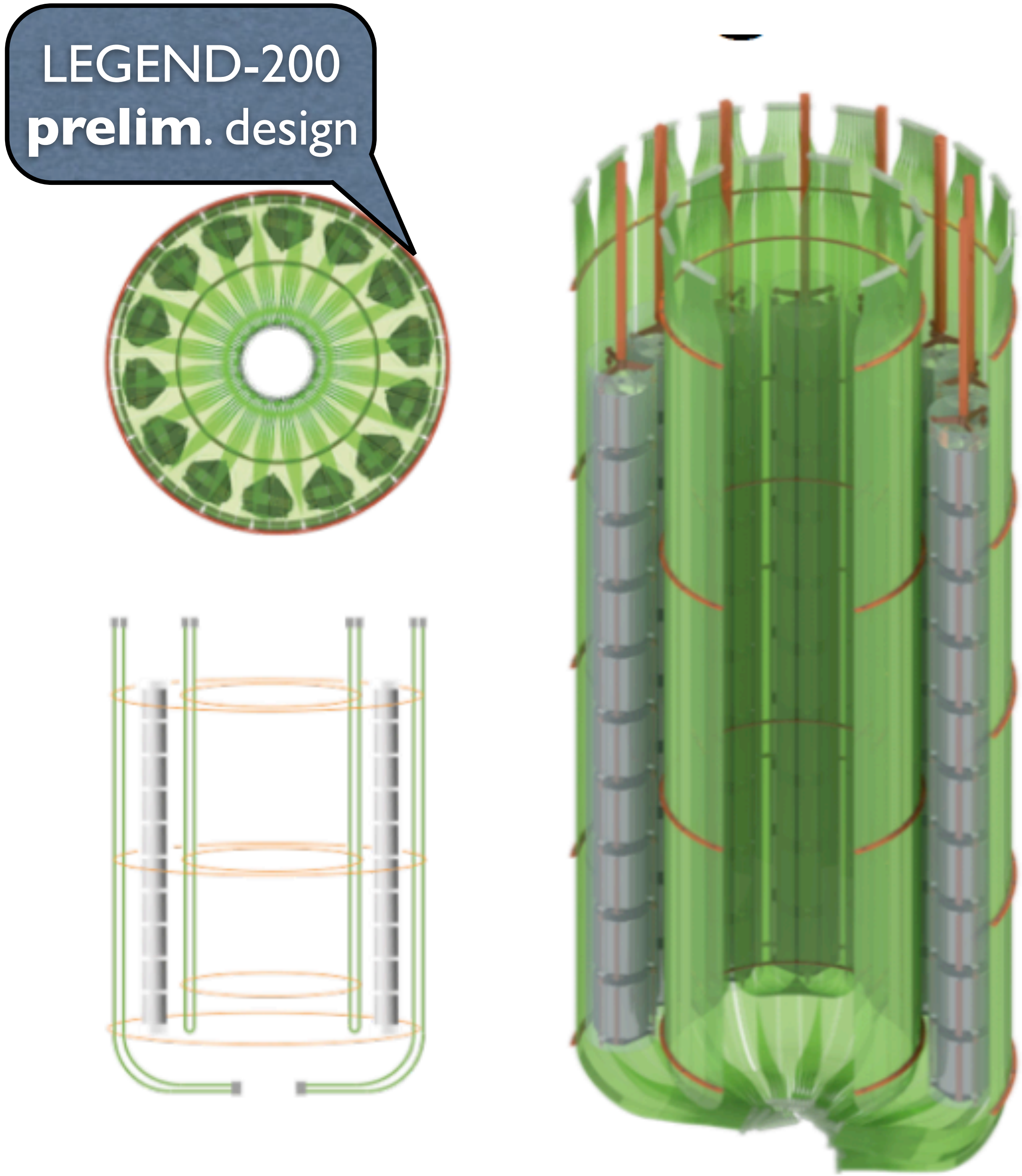
1 t

BI $\lesssim 10^{-5}$
cts / (keV kg yr)

Sensitivity on $T_{1/2} = 10^{28}$yr

Planned local activities on LEGEND LAr veto

LEGEND-200 LAr veto



SiPM top & bottom readout for outer curtain
Removable segments to install central strings

- An active veto is one of main resources to reach such low bkg
- LAr veto improved in coverage and read-out wrt Gerda
- Veto efficiency is then introduced in simulations to estimate expected BI close to signal region
- important to response know well:
  - attenuation length at desired purity
  - light yield
  - fast vs slow component
  - reflectivity of immersed materials

- room in LEGEND-1000 for R&D to improve veto capability

LEGEND-200: Activities/ I

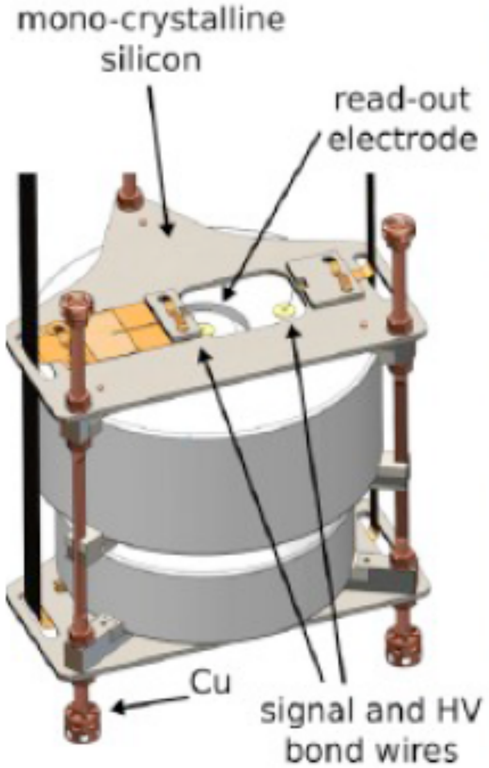
- Study optical properties of pure samples of LAr for LEGEND-200
    - cryogenic conditions: Ar is liquid at T=87 K
    - expected λ_{att} ~50-100 cm, but large discrepancies in available measurements such that more studies are necessary

✓ coherent with local activities on liquid scintillators (e.g. JUNO) and should be able to profit from dedicated cryo equipment

- ◉ + integrations to keep cold and monitor larger volumes: seeking advise of cryo experts at LNGS on set-up design
- ◉ + best set-up: there are various ways to make a λ_{att} measurement; we need to consider systematic light collection effects and space/funds constraints
- People: Diego T and Giuseppe S + LNGS LEGEND people

- Tune Geant-4 LAr optical response (+smart speed optimization on specific bkg processes?) to model full LAr veto
    - People: Andrea A

LEGEND-200: Activities/2



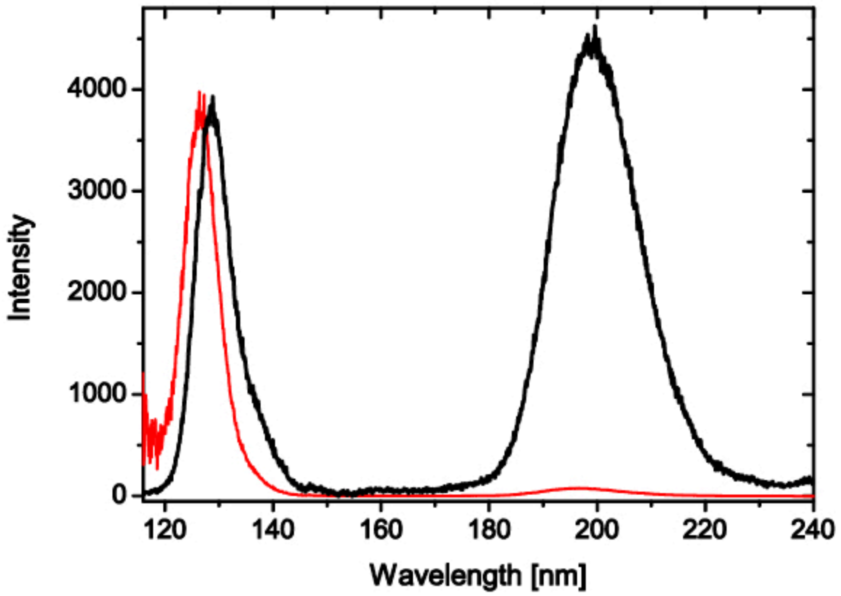
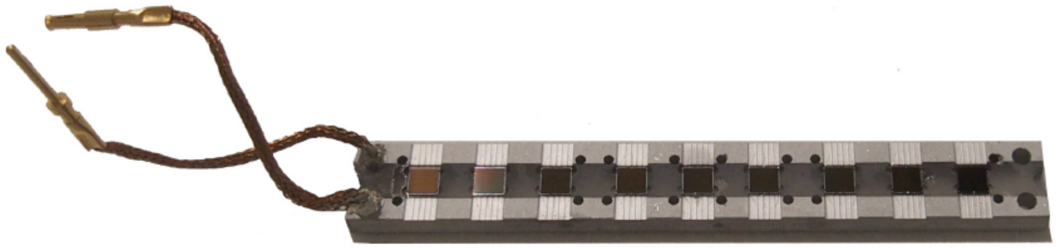


Fig. 5. *Emission spectrum of unpurified liquid argon (85K) with (thin line) and without (thick line) sensitivity correction of our setup. The broad emission structure around 197 nm may be attributed to an oxygen impurity [12, 24].*

- Materials immersed in LAr (detectors, support structures) reflect scintillation photons
  - need to know reflectivity down to VUV (λ_{LAr}=128 nm) to model overall light collection in veto
  - many old measurements of reflectivity, but it heavily depends on surface
    - e.g. polishing of Ge detectors + incident angle will change reflectivity
  - Scouting to do campaign of dedicated measurements with vacuum optical set-up; e.g. at synchrotron radiation from 128 to ~500 nm with Ge, Si, Cu samples
  - People: Enrico B, Giuseppe S

Activities/3

Electronics + anti-muon trigger

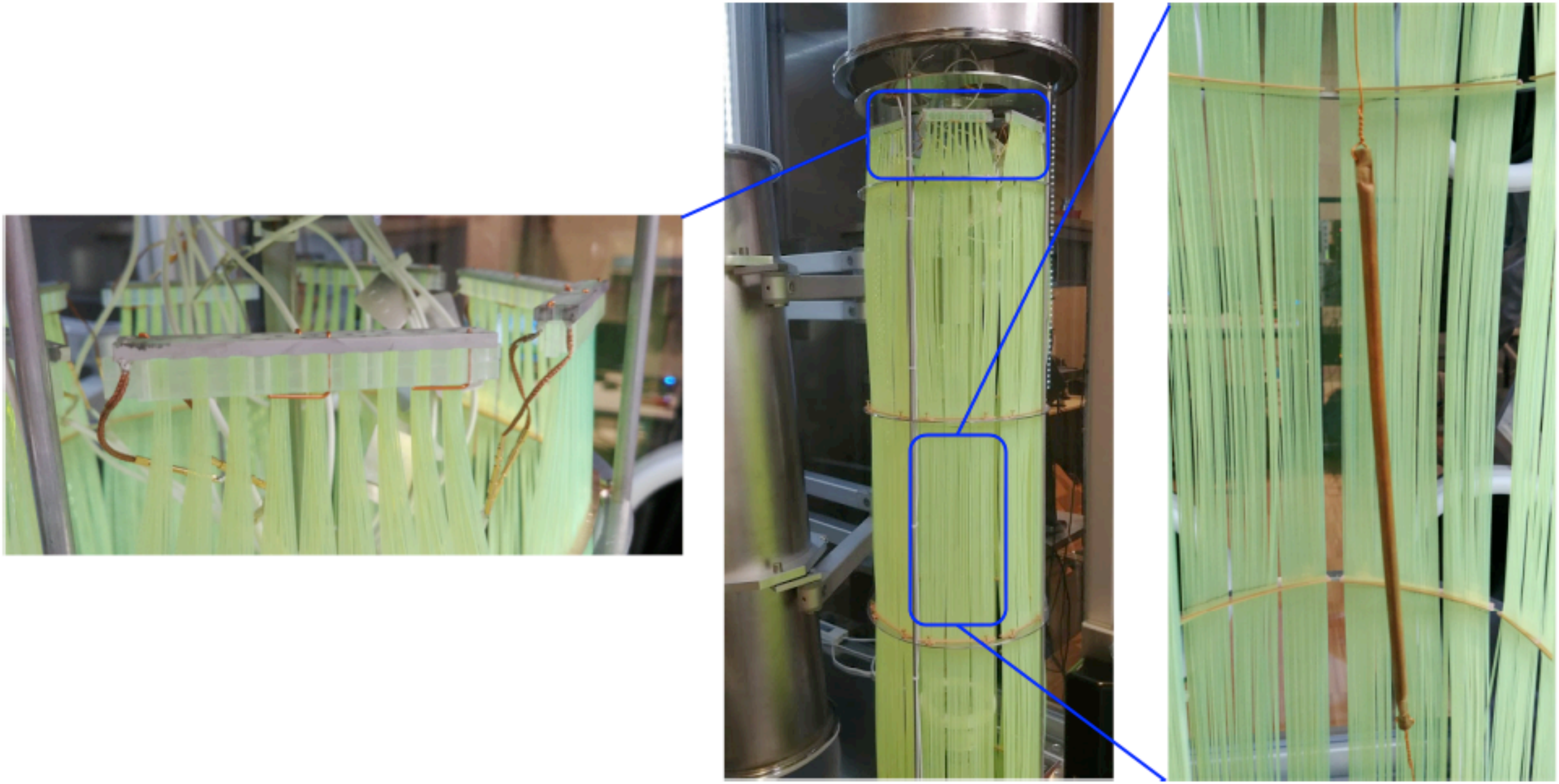


- 9 SiPM = 81 fiber signals in parallel are collected and amplified by Cremat CR-112
  - Overall 52 channels plugged to 8-channel NIM boards for FE (FADC for digitization) together with Ge detectors

a. Can "packaging" be improved (change card output to board and group more effectively)?

b. Study possibility to introduce "fast-trigger" directly on analog signals using topology to veto *Ar40* + *n* → *Ar41* + γ (n from cosmogenic muons close to Ge detectors)

- People: Diego + Giuseppe + TUMunich people for simulations



LEGEND-1000

- This opens door to LEGEND-1000
- In R&D phase, with chance to study solutions to attain VERY challenging background levels (really the issue!)
- Identifying some ideas that can be pursued:
    - Screen off incoming radioactivity in double way: "mechanically" with low-rad plastic shrouds + "electrically" against K42 ions that are created close to, and get drifted towards, Ge p-n junction
    - better light yield, ΔE and PSD by doping Ar with materials like Xe *in the right concentrations*
        - shifts wavelength efficiently, suppresses slow and fast component differently + has different peaks with changing intensity based on bkg particle mass
        - small needed concentrations of Xe (10 to 1000 ppm) at 87K a challenge

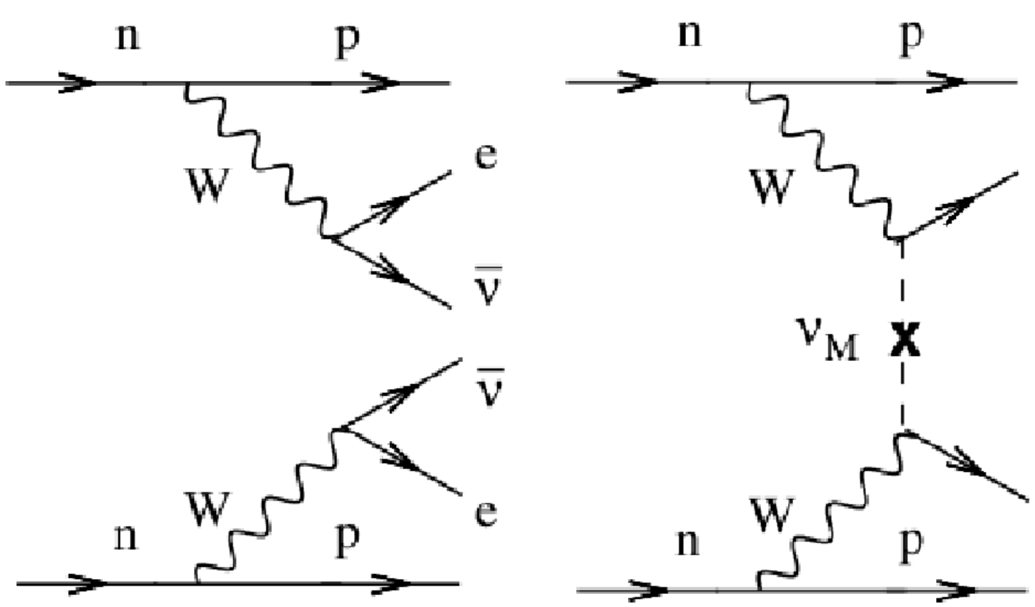
C G Wahl *et al* 2014 *JINST* **9** P06013

arXiv:1511.07723, 1906.00836

Back up

0ν2β decays

ΔL=2



- Two beta decays at the same time
- Only a few isotopes able to undergo 2β
  - those with peculiar energy level arrangements such that the emission is more convenient than the unstable isotope

$$0\nu\beta\beta : (A, Z) \rightarrow (A, Z+2) + 2e^-$$

new physics, $T_{1/2} > 10^{25}$ yrs

$$2\nu\beta\beta : (A, Z) \rightarrow (A, Z+2) + 2e^- + 2\nu_e$$

2^{nd} order process, observed, $T_{1/2}$ ~ 10^{19}-10^{24} yrs

^{76}Ge: $T_{1/2}$ ~ 10^{21} yrs

$$\left(T^{0\nu}_{1/2}\right)^{-1} = G^{0\nu}(Q_{\beta\beta}, Z)\ \left|M^{0\nu}\right|^2 \left(\frac{\langle m_{ee}\rangle}{m_e}\right)^2 \qquad \langle m_{ee}\rangle = \left|\sum_i U^2_{ei} m_i\right|$$

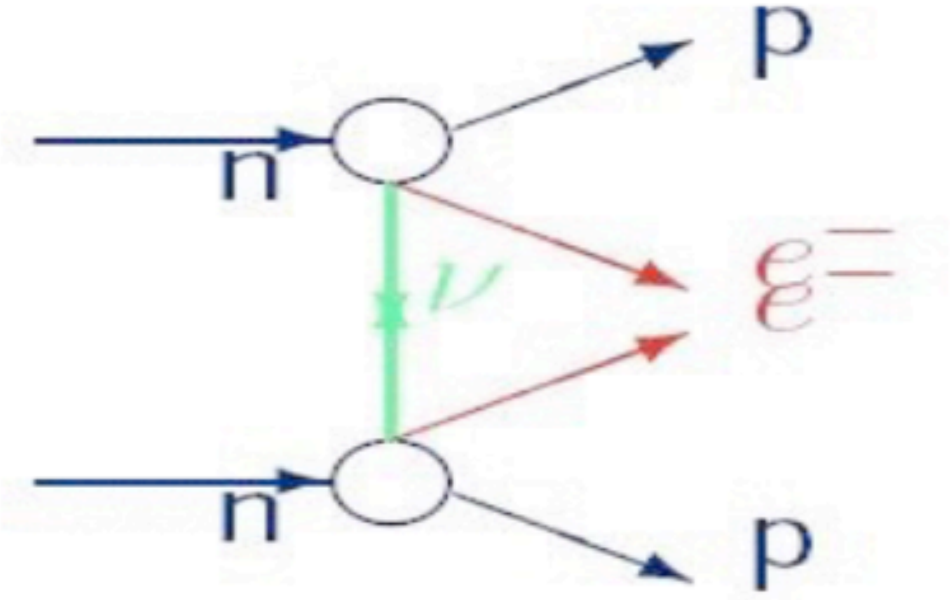
nuclear matrix element

phase space factor

effective Majorana neutrino mass

Neutrinoless double beta decay

Neutrinoless double beta decay, (A, Z) → (A, Z+2) + 2 e, tests the nature of neutrinos. It violates L by 2 units.



The half-life time depends on neutrino properties

$$\left[T^{1/2}_{0\nu}(0^+ \to 0^+)\right]^{-1} \propto |M_F - g_A^2 M_{GT}|^2 \, |<m>|^2$$

$$\boxed{|<m>| \equiv |\, m_1|U_{e1}|^2 + m_2|U_{e2}|^2 e^{i\alpha_{21}} + m_3|U_{e3}|^2 e^{i\alpha_{31}} \,|\,,}$$

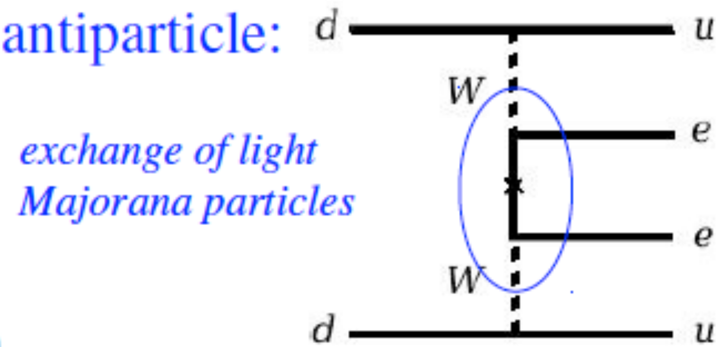
Mixing angles (known)

CPV phases (unknown)

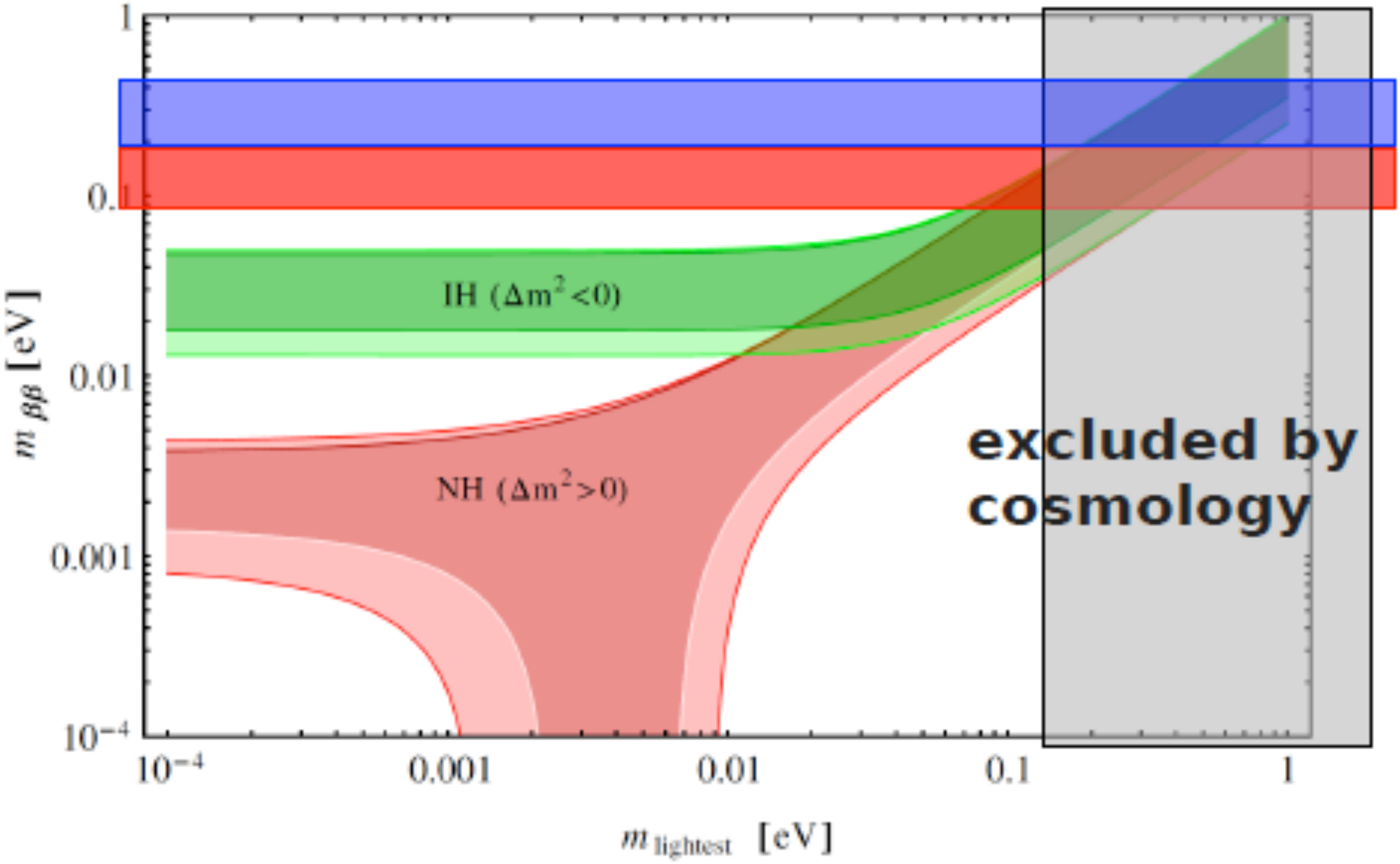
Why look for it...

◆ Only way to determine if neutrino is its own antiparticle:

$\nu = \bar{\nu}$ ⇒ ***Majorana particle***



S. Dell'Oro, S. Marcocci, F. Vissani, PRD 90 (2014)



$$\left(T^{0\nu}_{1/2}\right)^{-1} = G^{0\nu}(Q_{\beta\beta}, Z)\ \left|M^{0\nu}\right|^2 \left(\frac{\langle m_{ee}\rangle}{m_e}\right)^2 \qquad \langle m_{ee}\rangle = \left|\sum_i U^2_{ei} m_i\right|$$

phase space factor

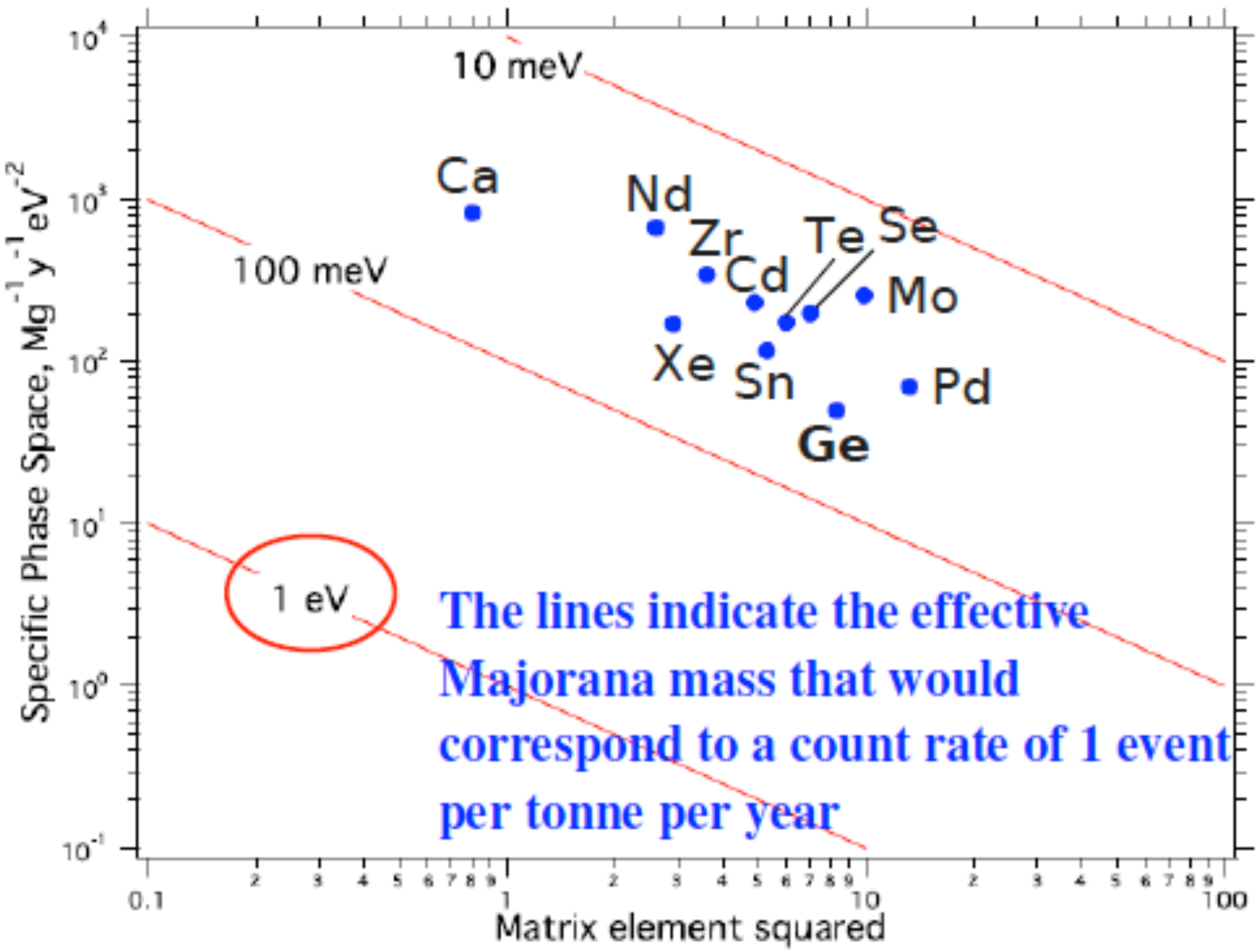
nuclear matrix element

effective Majorana neutrino mass

- A weighted average of neutrino masses enters the decay rate (decay half life)
- **NB: experiments measure $T^{0nu}_{1/2}$**
- Limits on m_{ee} from above, can also exclude IH
  - because one is still looking only at electron flavour, therefore a mix of mass eigenstates, with their MH arrangement in $<m_{ee}>$
  - <u>nuclear matrix element uncertainties are the biggest spoiler in the conversion</u>

Comparing different isotopes

R.G.H. Robertson arXiv:1301.1323



The lines indicate the effective Majorana mass that would correspond to a count rate of 1 event per tonne per year

$$\left(T_{1/2}^{0\nu}\right)^{-1} = G^{0\nu}(Q_{\beta\beta}, Z)\ \left|M^{0\nu}\right|^2 \left(\frac{\langle m_{ee}\rangle}{m_e}\right)^2 \qquad \langle m_{ee}\rangle = \left|\sum_i U_{ei}^2 m_i\right|$$

phase space factor

nuclear matrix element

effective Majorana neutrino mass

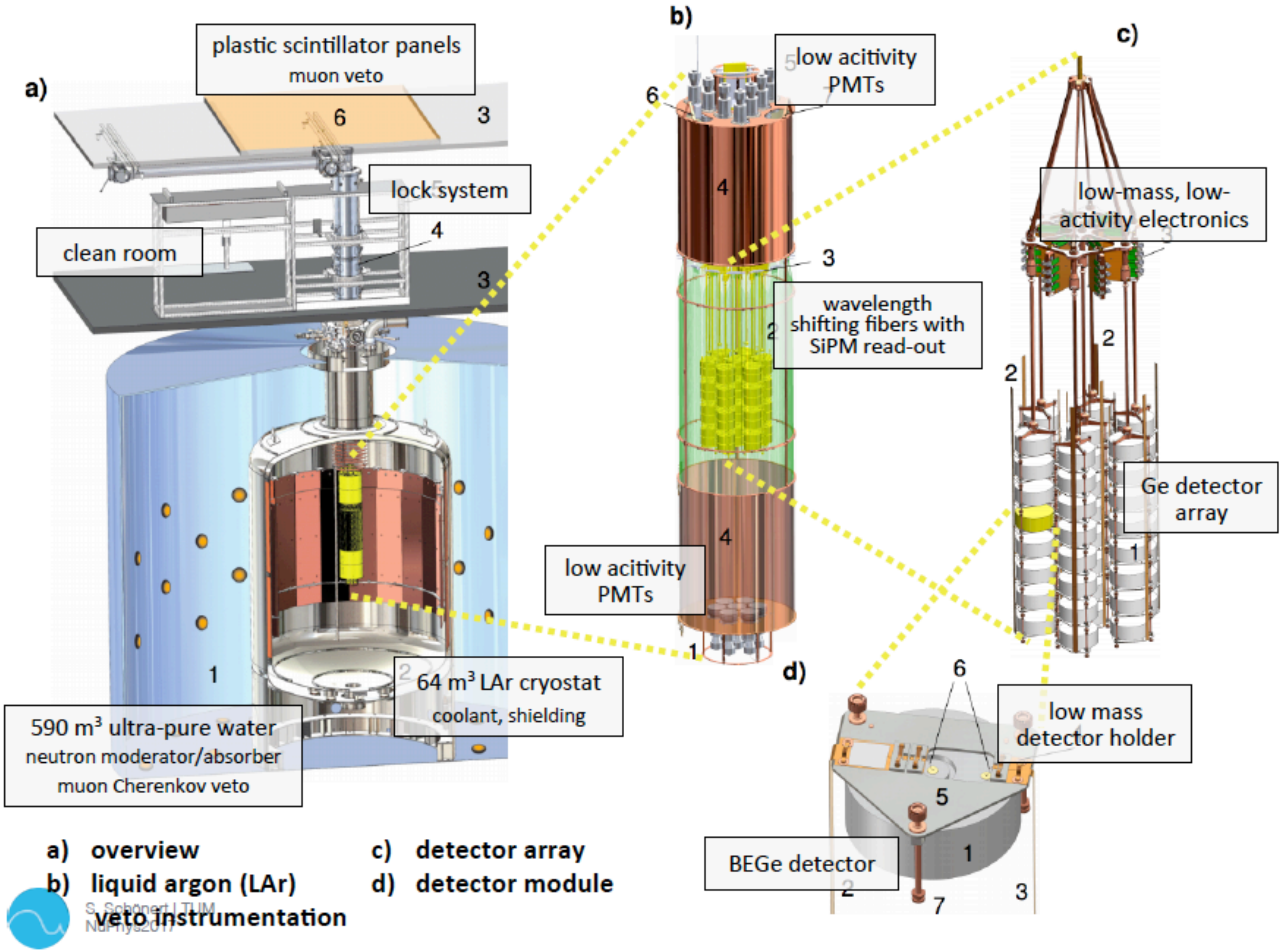
No theoretical preference

- Phase Space and NME inversely correlated. Tend to compensate.
- Theoretical uncertainties very large

Experimental/practical criteria

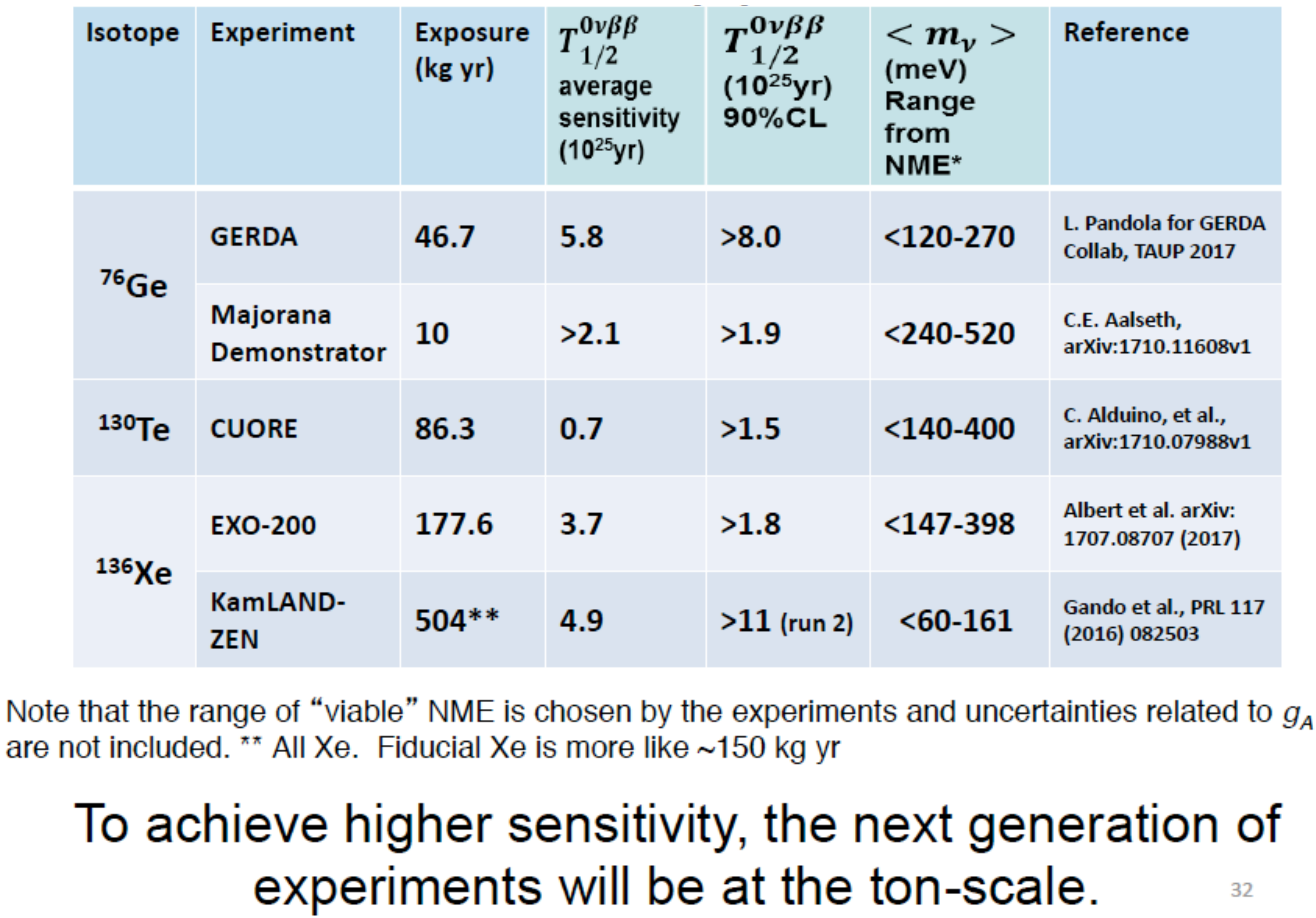
- Enrichment cost
- Energy resolution
    - Narrow peak for discovery
- Background index
    - Ultraclean components
    - Avoid surfaces
        - Especially in a vacuum
- Scalability
    - Liquids, gases, large crystals

Gerda/LEGEND



- high-purity germanium (HPGe) detectors enriched in ^{76}Ge to (86–88)%: source + detector
- detectors mounted in low-mass holders (to minimize radioactive bkg)
- **embedded in liquid argon (LAr): cryogenic coolant and absorber against external radiation**
- ultrapure water tank: buffer around cryostat as additional absorber + Cherenkov mu veto

Synoptic comparison (*not most up to date*)



Isotope	Experiment	Exposure (kg yr)	$T^{0\nu\beta\beta}_{1/2}$ average sensitivity (10^{25}yr)	$T^{0\nu\beta\beta}_{1/2}$ (10^{25}yr) 90%CL	$< m_\nu >$ (meV) Range from NME*	Reference
^{76}Ge	GERDA	46.7	5.8	>8.0	<120-270	L. Pandola for GERDA Collab, TAUP 2017
	Majorana Demonstrator	10	>2.1	>1.9	<240-520	C.E. Aalseth, arXiv:1710.11608v1
^{130}Te	CUORE	86.3	0.7	>1.5	<140-400	C. Alduino, et al., arXiv:1710.07988v1
^{136}Xe	EXO-200	177.6	3.7	>1.8	<147-398	Albert et al. arXiv: 1707.08707 (2017)
	KamLAND-ZEN	504**	4.9	>11 (run 2)	<60-161	Gando et al., PRL 117 (2016) 082503

Note that the range of "viable" NME is chosen by the experiments and uncertainties related to g_A are not included. ** All Xe. Fiducial Xe is more like ~150 kg yr

To achieve higher sensitivity, the next generation of experiments will be at the ton-scale.

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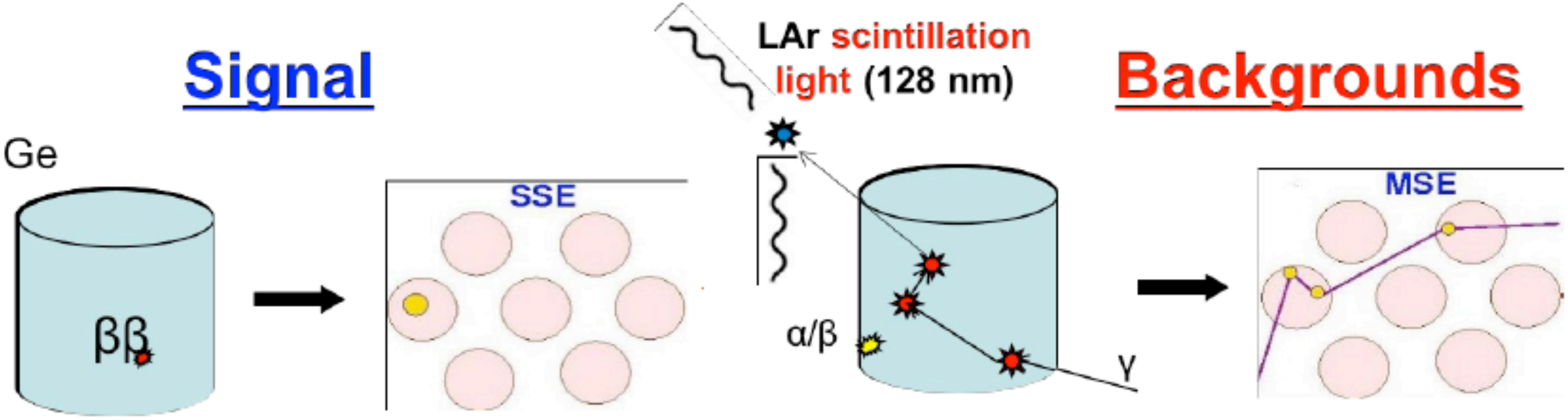
https://indico.ph.qmul.ac.uk/indico/getFile.py/access?contribId=36&resId=1&materialId=slides&confId=170

Active background reduction tools



Point-like (single-site) energy deposition inside one HP-Ge diode

Multi-site energy deposition inside HP-Ge diode (Compton scattering), or **surface** events

- **Anti-coincidence** with the **muon veto** (MV)
- Anti-coincidence **between detectors** (cuts multi-site) (AC)
- **Active veto** using LAr scintillation (LAr Veto)
- **Pulse shape** discrimination (PSD)

https://arxiv.org/pdf/1205.5608.pdf

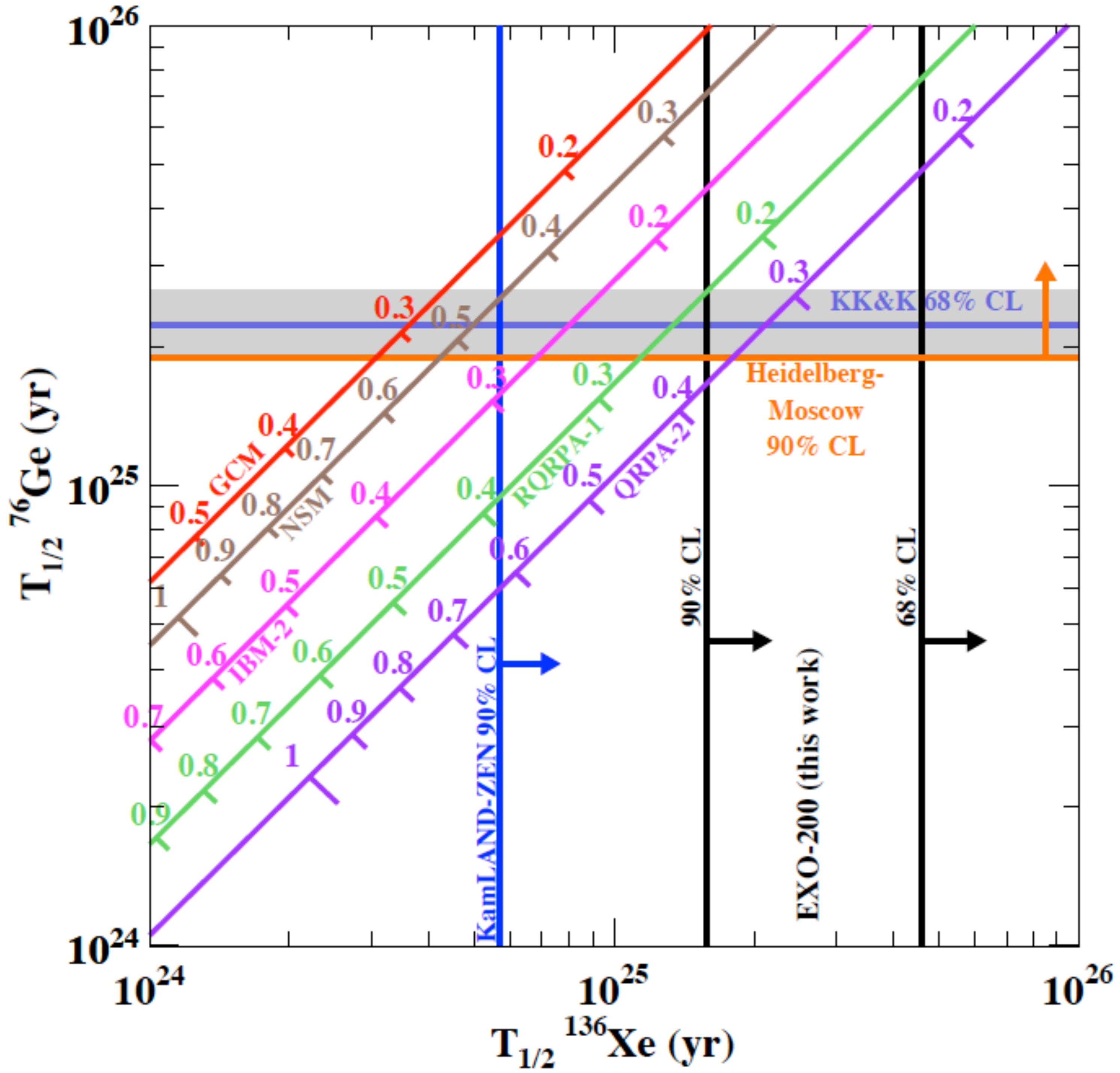
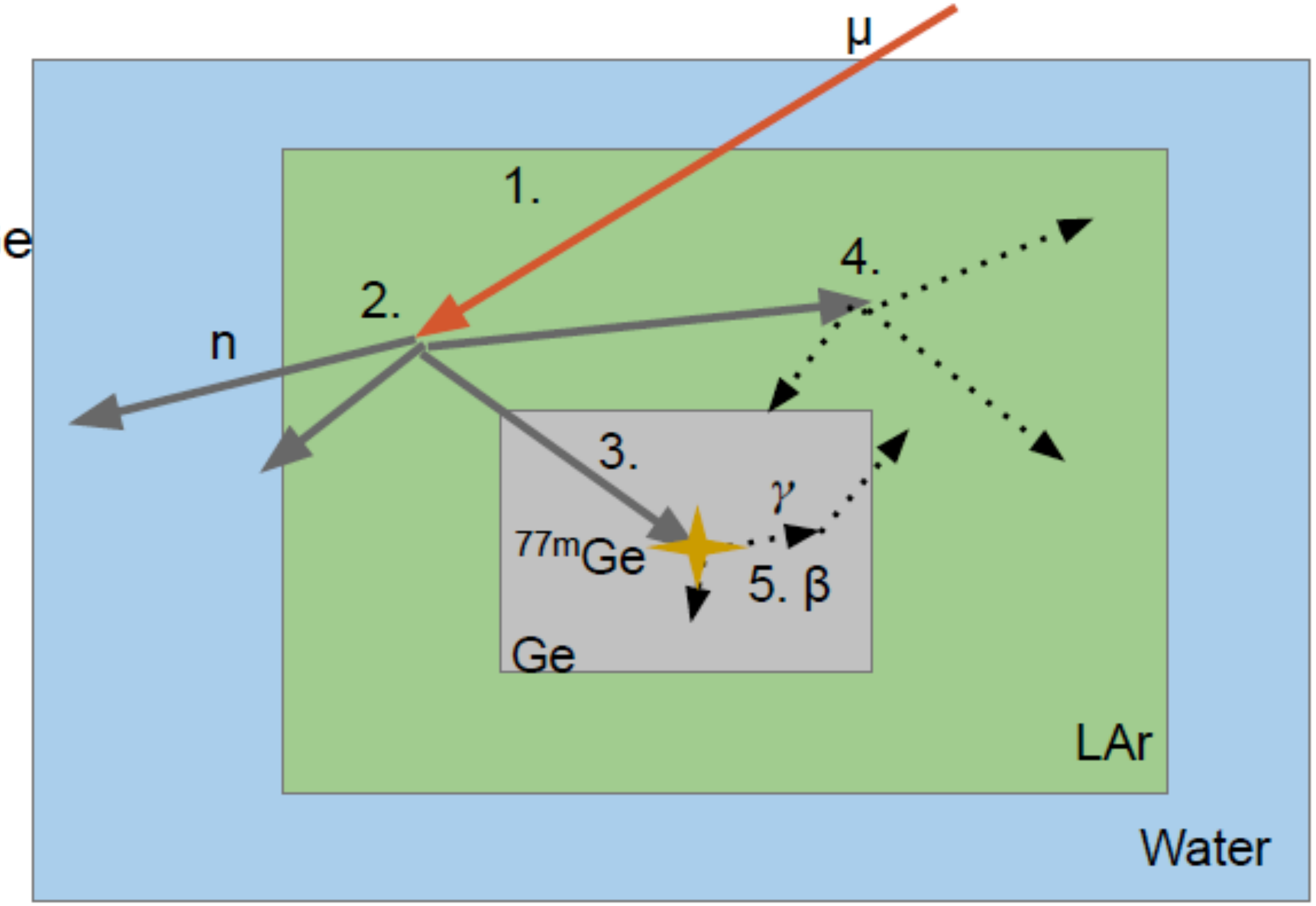


FIG. 6: Relation between the $T_{1/2}^{0\nu\beta\beta}$ in ^{76}Ge and ^{136}Xe for different matrix element calculations (GCM [20], NSM [21], IBM-2 [22], RQRPA-1 [23] and QRPA-2 [5]). For each matrix element $\langle m\rangle_{\beta\beta}$ is also shown (eV). The claim [4] is represented by the grey band, along with the best limit for ^{76}Ge [19]. The result reported here is shown along with that from [7].

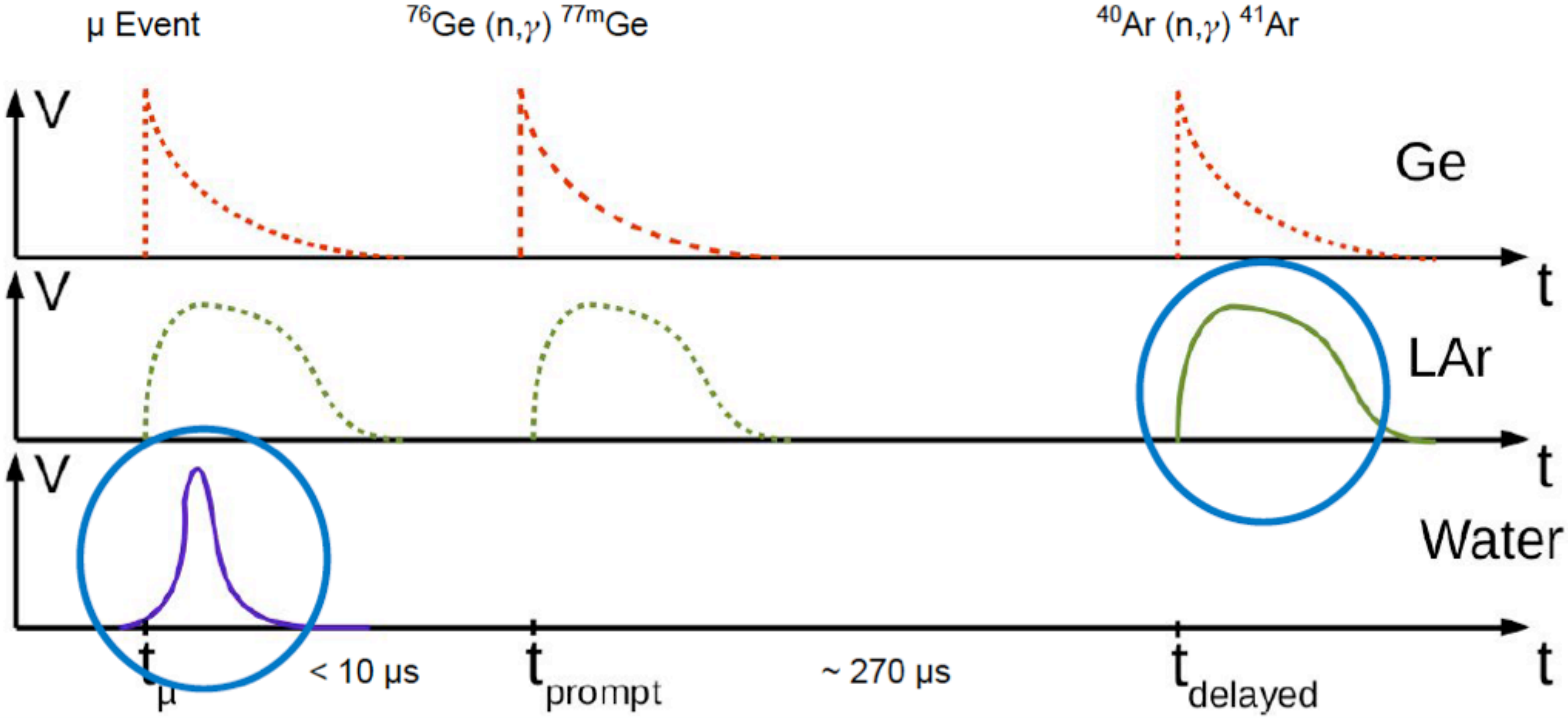
Topology of μ induced events with ^{77m}Ge production

1. A cosmic muon passes through the setup creating signals in water and LAr channels
2. Neutrons are produced; usually n > 1
3. Neutron capture on ^{76}Ge producing ^{77m}Ge & prompt gammas
4. Neutrons of step 2. can be captured on ^{40}Ar, producing gammas, τ ~ 271 μs
5. β decay of ^{77m}Ge: $T_{1/2}$~ 53 s



Signal structure of ^{77m}Ge production events

- Possible to tag ^{77m}Ge production by muon veto and delayed LAr signals only
- Delayed signals can reduce dead time compared to prompt signals



LEGEND program

LEGEND-200 (first phase):

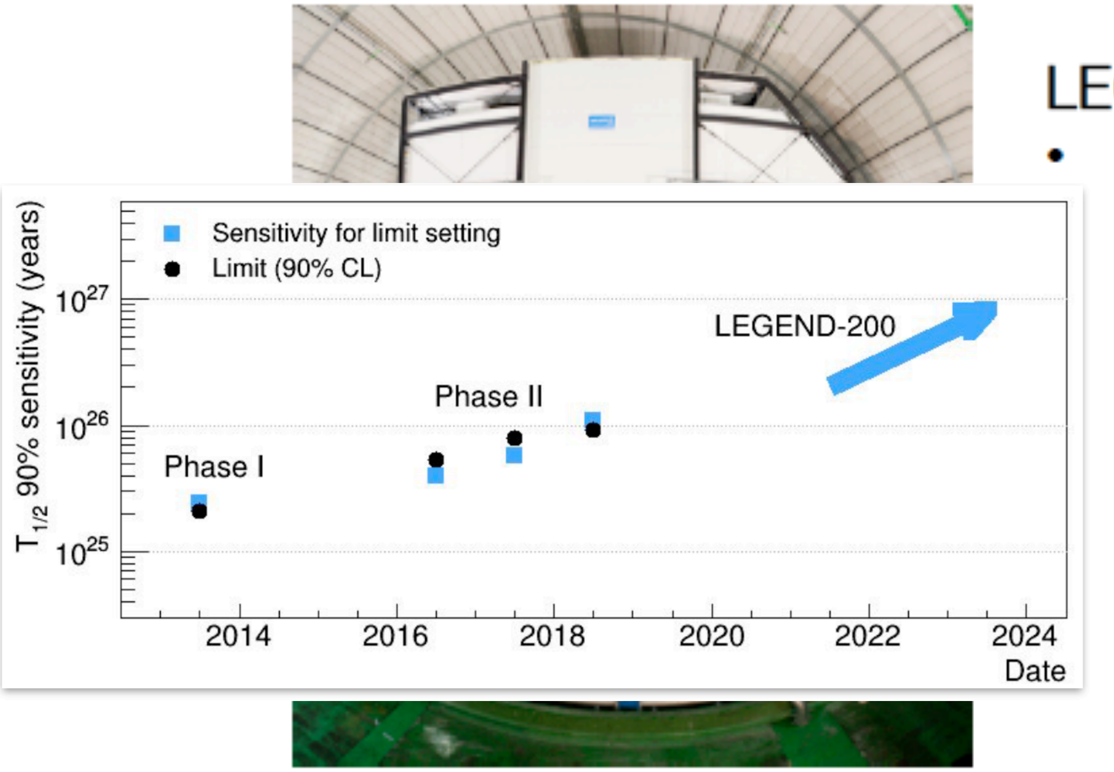
- up to 200 kg of detectors

BI ~0.6 cts/(FWHM·t·yr) → ~1/5 of Gerda!

use existing GERDA infrastructure at LNGS

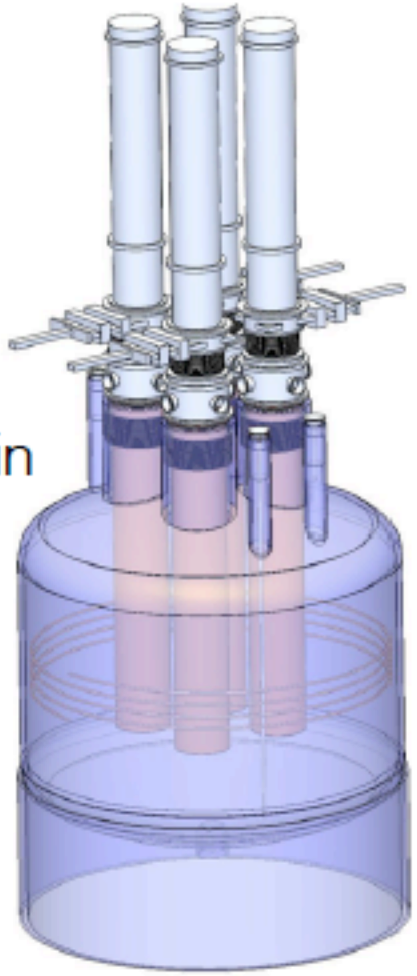
design exposure: 1 t·yr

Sensitivity 10^{27} yr

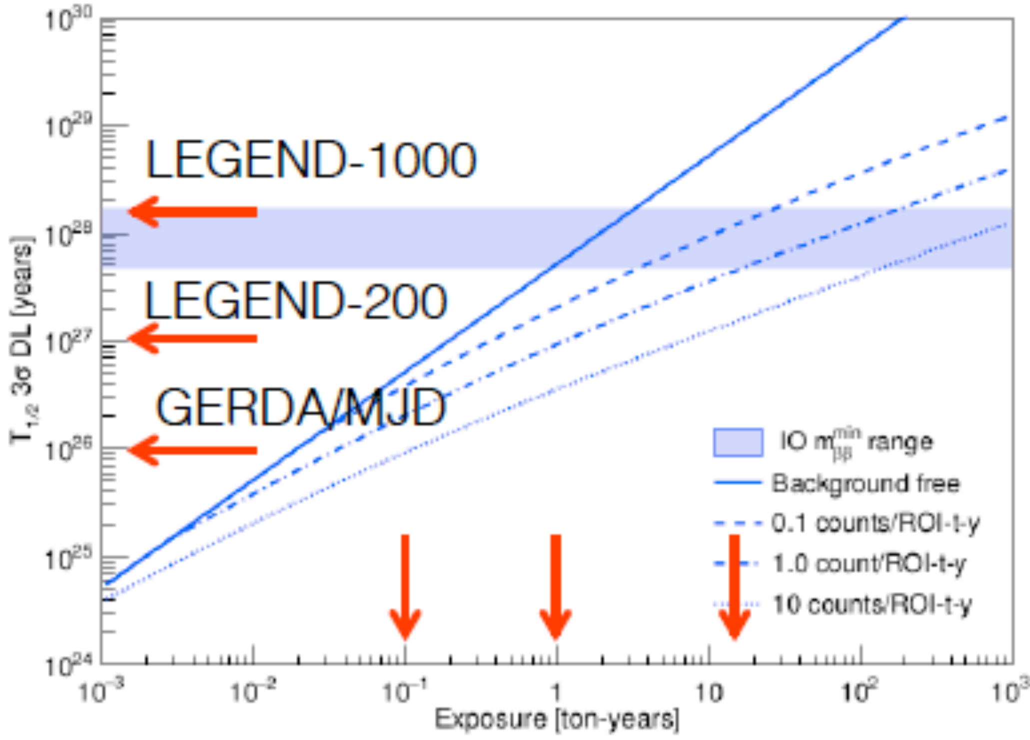


LEGEND-1000 (second phase):

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

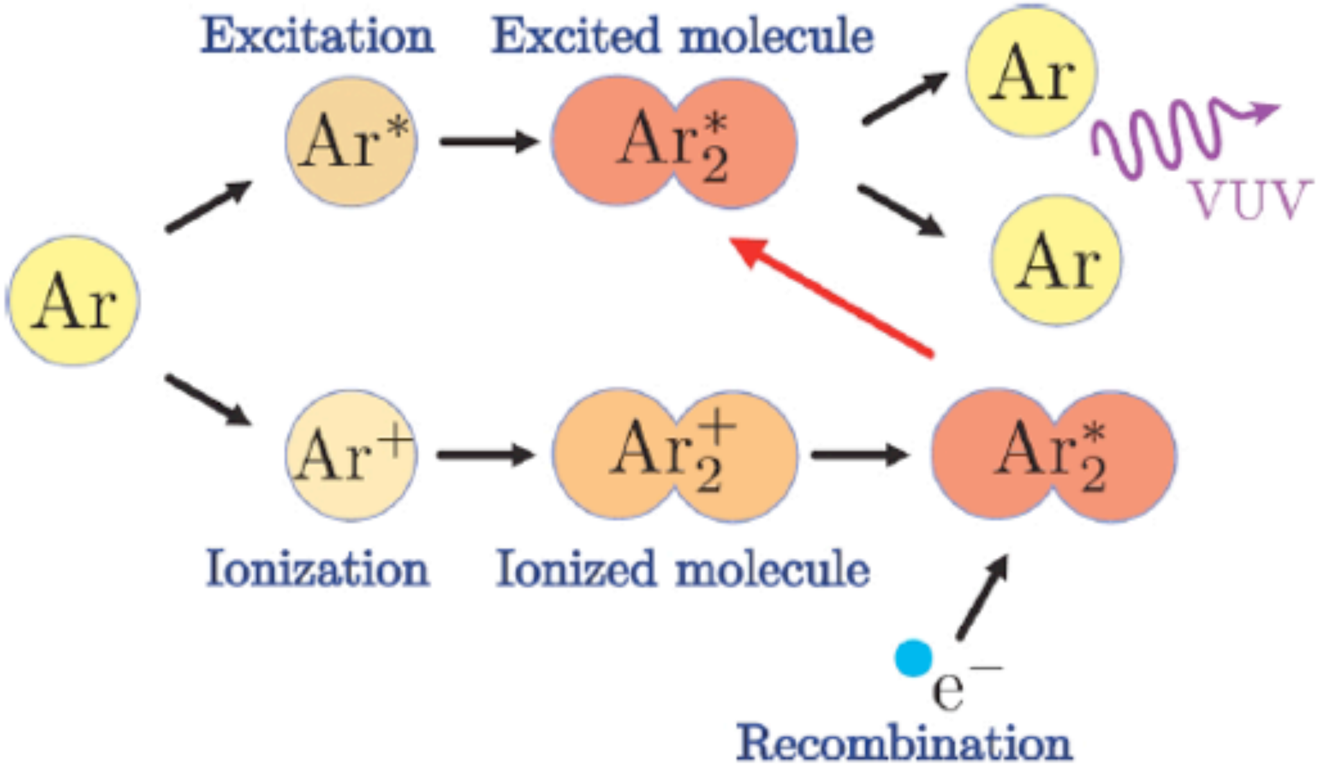


Sensitivity for 3σ signal discovery



17 meV discovery sensitivity for "worst case" NME of 3.5

Argon scintillation mechanism



[arXiv:0708.2621v1]

- Ionizing radiation leads to excited or ionized argon atoms
  → Forming molecules with ground state argon atoms
- Ar_2^+ recombine with free electrons into excited states
- Excited states are created in:
  - singlets (allowed, $\tau \sim 4 - 7\,\text{ns}$)
  - triplets (forbidden, $\tau \sim 1.0 - 1.7\,\mu\text{s}$)
  - singlet to triplet production ratio is 0.3 for electrons

  → decay by emission of photons, $\lambda = 128\,\text{nm}$
- Contaminations lead to reduction of triplet lifetime and extinction of scintillation light

Consequences of impurities in LAr

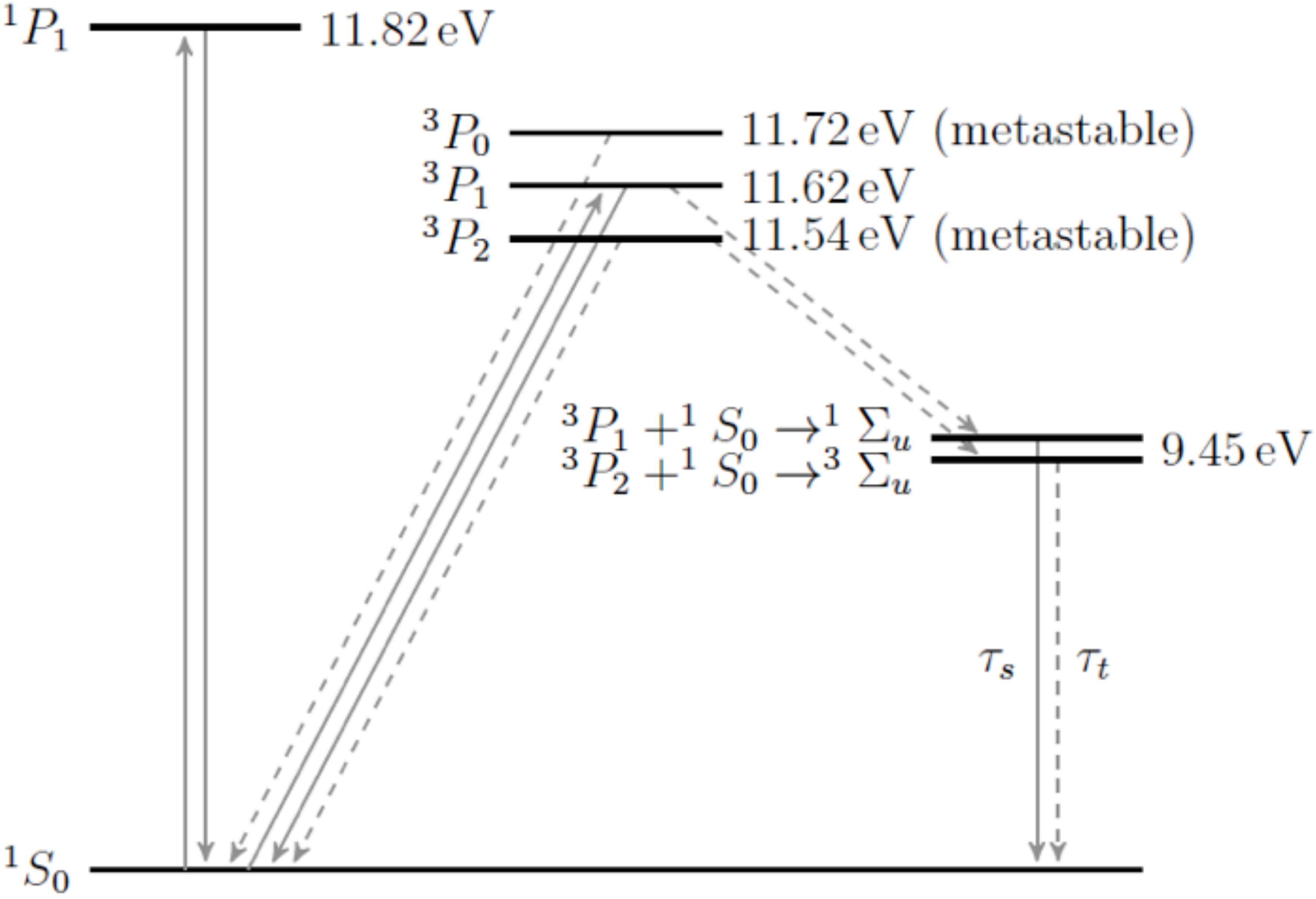
O_2 : Free electrons are bound by Oxygen molecules $e^- + O_2 \rightarrow O_2^-$
Non-radiative collision $Ar_2^* + O_2 \rightarrow 2Ar + O_2$
Absorption of scintillation photons, emission of Oxygen resonance line at 557 nm

N_2 : Non-radiative collision $Ar_2^* + N_2 \rightarrow 2Ar + N_2$

Xe : Emission of the Xenon resonance line around 149 nm,
emission of Xenon excimer at 175 nm

α_{att}	Impurity	concentration	Reference
50 cm	O_2, H_2O, CH_4	100 ppb	arXiv:1611.02481
	Xe, Kr	1 ppb	
	Hg	10 ppb	
	N_2	1 ppm	
110 cm	Xe	0.1 ppm	arXiv:1511.07725
66 ± 3 cm			interpreted as scattering
118 ± 10 cm	Xe	3%	NIMPRS A: V. 384, 380-386
1790 ± 160 (m?)	N_2	37 ppb	arXiv:1306.4605
30 ± 3 m	N_2	2 ppb	

Argon scintillation mechanism



- Electron configuration of argon: [Ne]$(3s)^2(3p)^6 \longrightarrow$ [Ne]$(3s)^2(3p)^5(4s)$
- Radiation from $^1P_1$ and $^3P_1$ to $^1S_0$ ground state reabsorbed in argon
- Atom in $^3P_1$ and $^3P_2$ state can form molecule with $^1S_0$ argon atom
- γ's from Ar_2^* have not enough energy to be absorbed by $^1S_0$ argon atoms
- Peaks from singlet and triplet excimer decay are not resolved