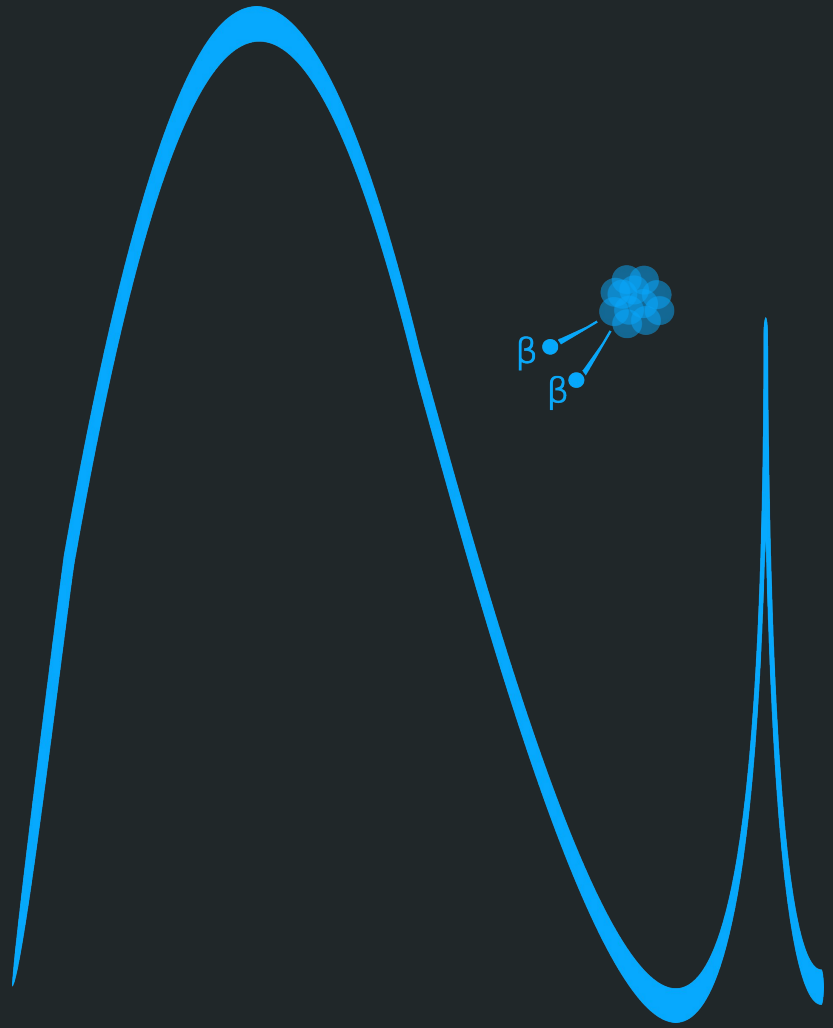


Search for new physics with neutrinoless double-β decay

The ^{76}Ge Experimental Program

Matteo Agostini

Munich Technical University (TUM)

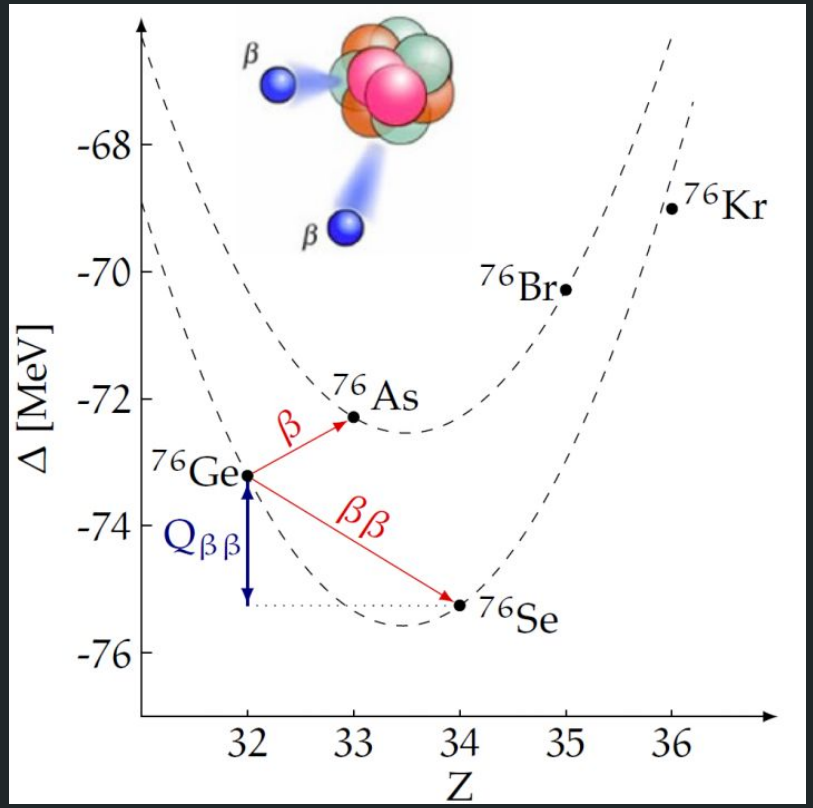
Neutrino Seminar Series, FNAL, Dec 6, 2018

Neutrinoless Double-β Decay ($0\nu\beta\beta$)

From the point of view of Nuclear Physics:

$$(A, Z) \rightarrow (A, Z + 2) + 2e^-$$

- second order nuclear transition
- possible only if single beta decay is forbidden



[Courtesy of G. Benato]

Neutrinoless Double-β Decay ($0\nu\beta\beta$)

From the point of view of Nuclear Physics:

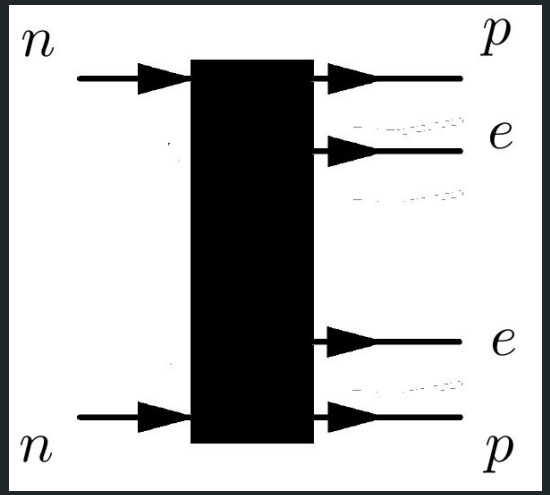
$$(A, Z) \rightarrow (A, Z + 2) + 2e^-$$

- second order nuclear transition
- possible only if single beta decay is forbidden

From the point of view of Particle Physics:

$$2n \rightarrow 2p + 2e^-$$

- 2 leptons produced w/o balancing anti-leptons
- channel depends on new physics



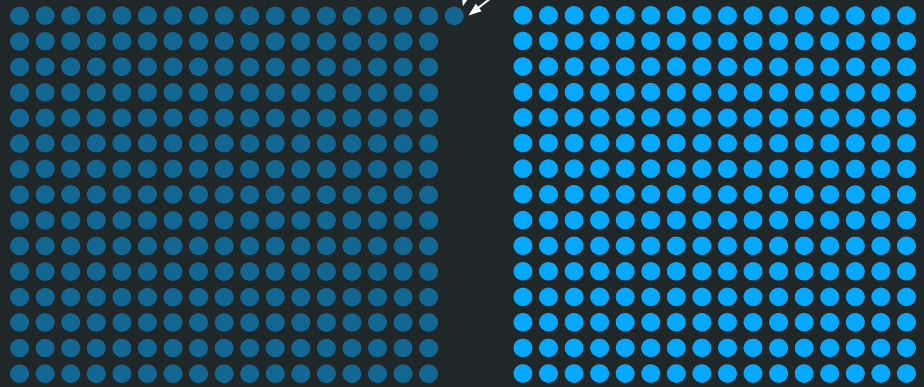
If $0\nu\beta\beta$ decay is discovered:

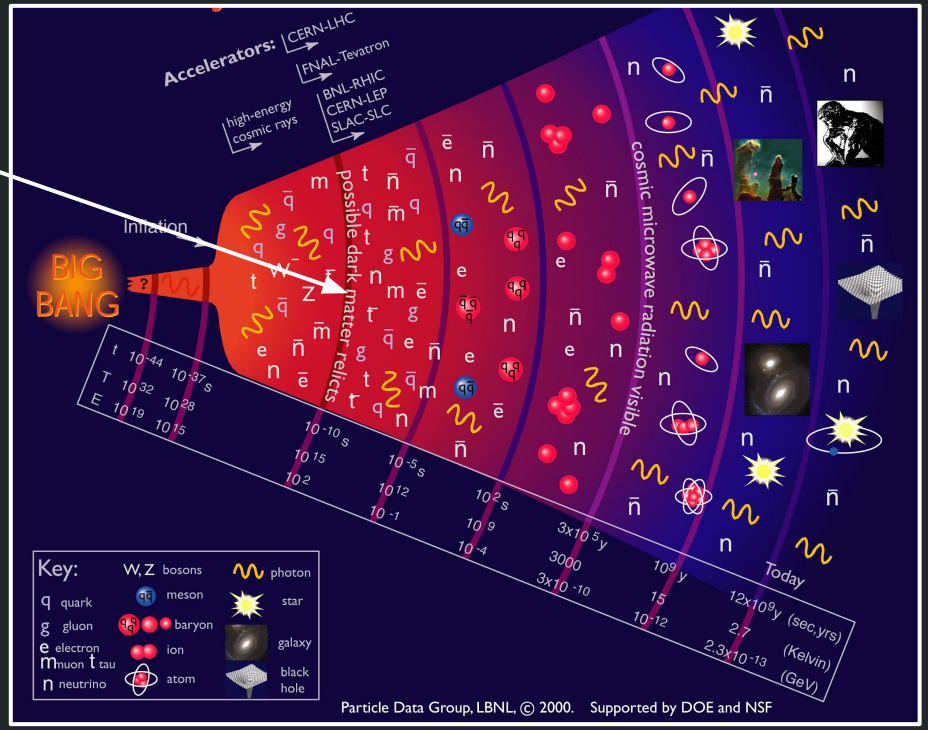
- lepton number is not conserved
- first observation of “matter creation"

$0\nu\beta\beta$ and Leptogenesis

- Tiny asymmetry between the number of particles and antiparticles in the early Universe

$$\frac{1}{1{,}000{,}000{,}000}$$

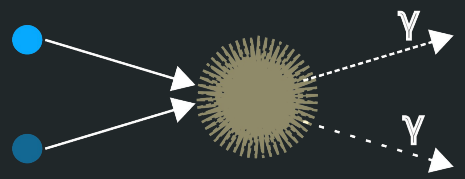


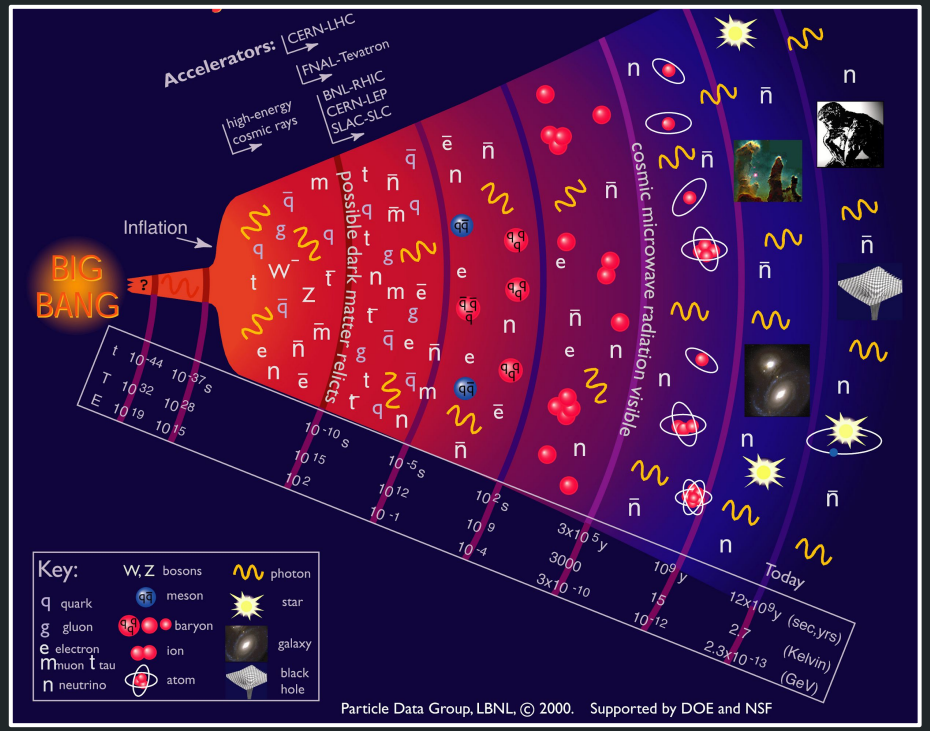


$0\nu\beta\beta$ and Leptogenesis

- Tiny asymmetry between the number of particles and antiparticles in the early Universe
- With the Universe cooling down, only matter remained!

$$\frac{1}{1{,}000{,}000{,}000}$$

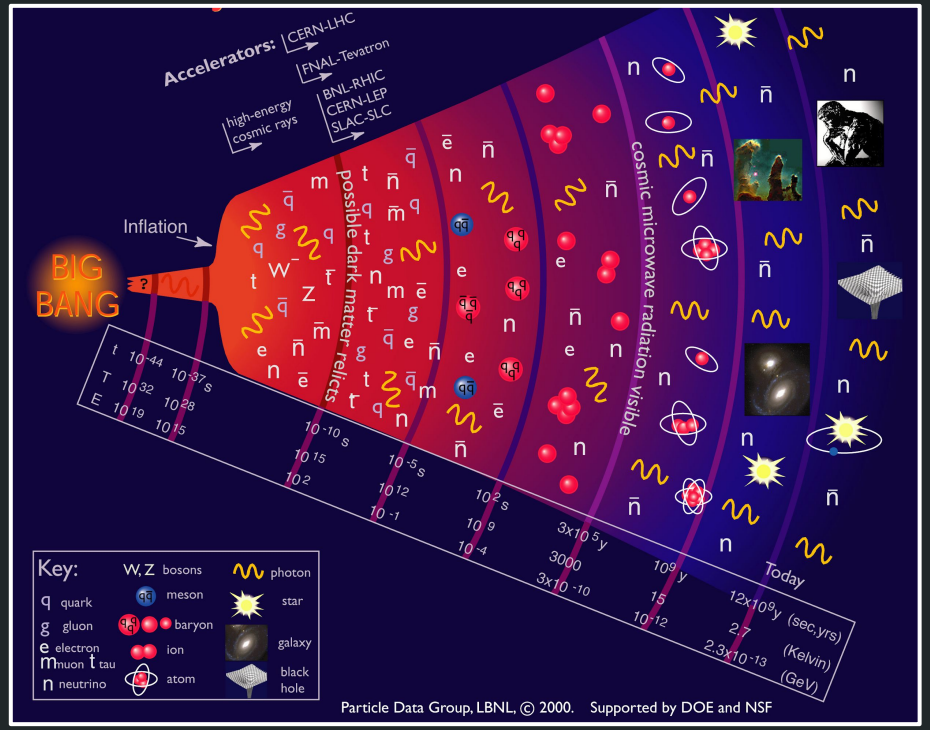




$0\nu\beta\beta$ and Leptogenesis

- Tiny asymmetry between the number of particles and antiparticles in the early Universe
- With the Universe cooling down, only matter remained!
- Current theories require:
  - C and CP violation
  - Out-of-equilibrium condition
  - **violation of Baryon or Lepton number**

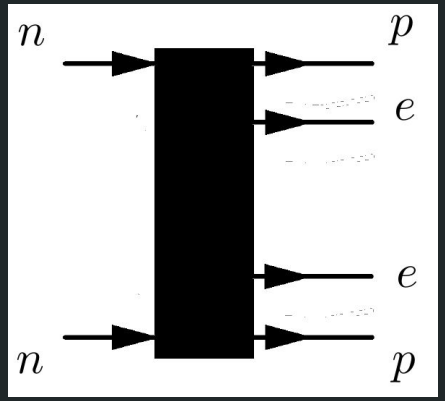
... and predict $0\nu\beta\beta$ decay!



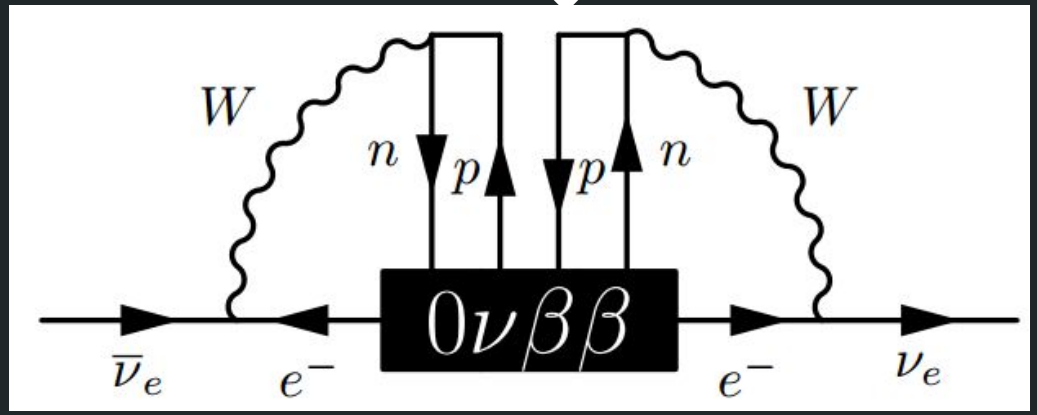
If $0\nu\beta\beta$ decay is discovered:

- strong support to current models
- non-trivial predictions on e.g. RH neutrino masses (see e.g. K.Hamaguchi, K.Shimada)

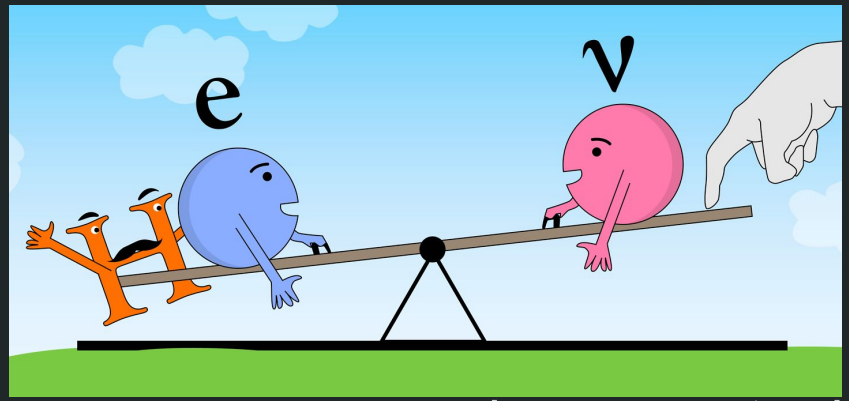
$0\nu\beta\beta$ and ν Mass Origin



Black Box theorem:
$0\nu\beta\beta$ operator can be rearranged into a ν-$\bar{\nu}$ oscillation (i.e. a Majorana mass term)



[Schechter, Valle, PRD 25 (1982) 2951]



[www.symmetrymagazine.org]

If $0\nu\beta\beta$ decay is discovered:

- ➢ neutrinos are Majorana particles
- ➢ neutrino masses can be explained through the see-saw models
- ➢ Note: bulk of neutrino mass not given by $0\nu\beta\beta$ operator [Duerr et al., JHEP 1106 091,2011]

A portal to Physics beyond the Standard Model

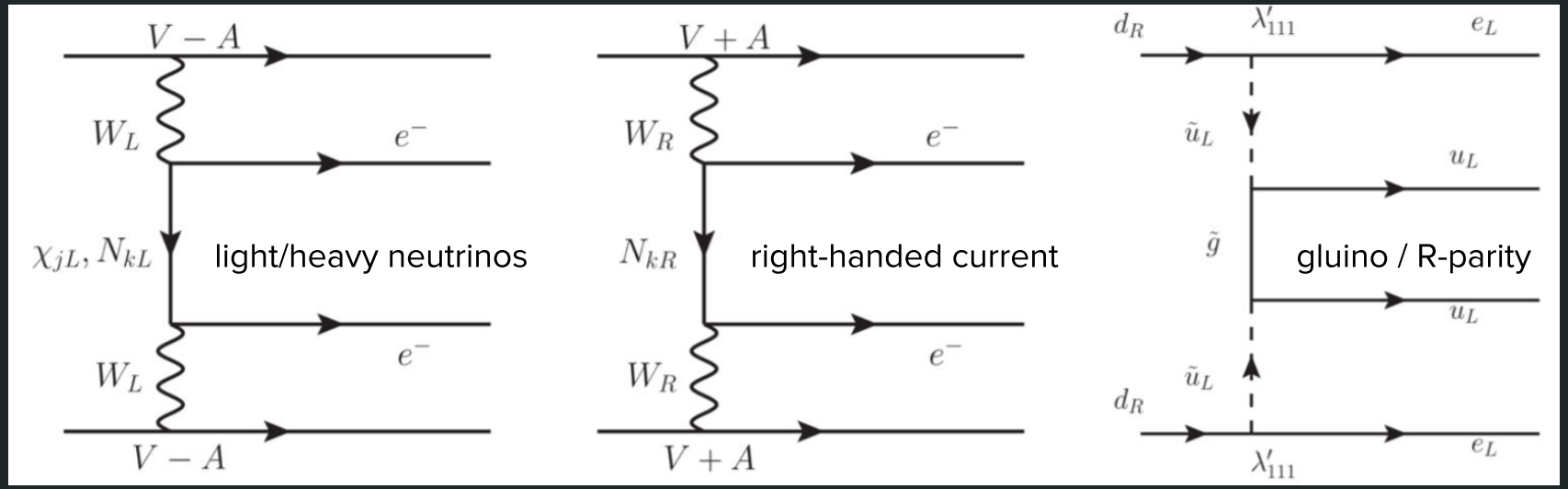
The probability of the process $[T_{1/2}]^{-1}$ is proportional to the coherent sum of all mechanisms involved:

$$\left[T^{0\nu}_{1/2}\right]^{-1} = G^{0\nu}(Q,Z) \cdot \left| \sum_{\text{mech. } i} \mathcal{M}_i \cdot \eta_i \right|^2$$

Phase Space Factor

Nuclear Matrix Element

Propagator



[Faessler et al, PRD, 83, 11 (2011), 113003]

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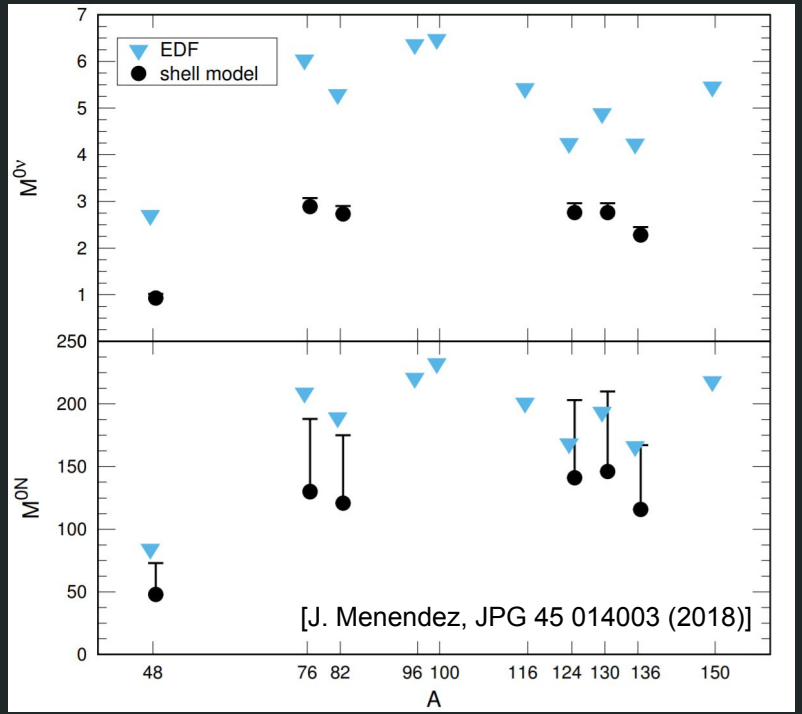


Nuclear Matrix Element:

- depends on channel, in general can be expressed in terms of light and heavy neutrino exchange
- different computations currently within a factor 2-3
- ongoing effort to increase understanding

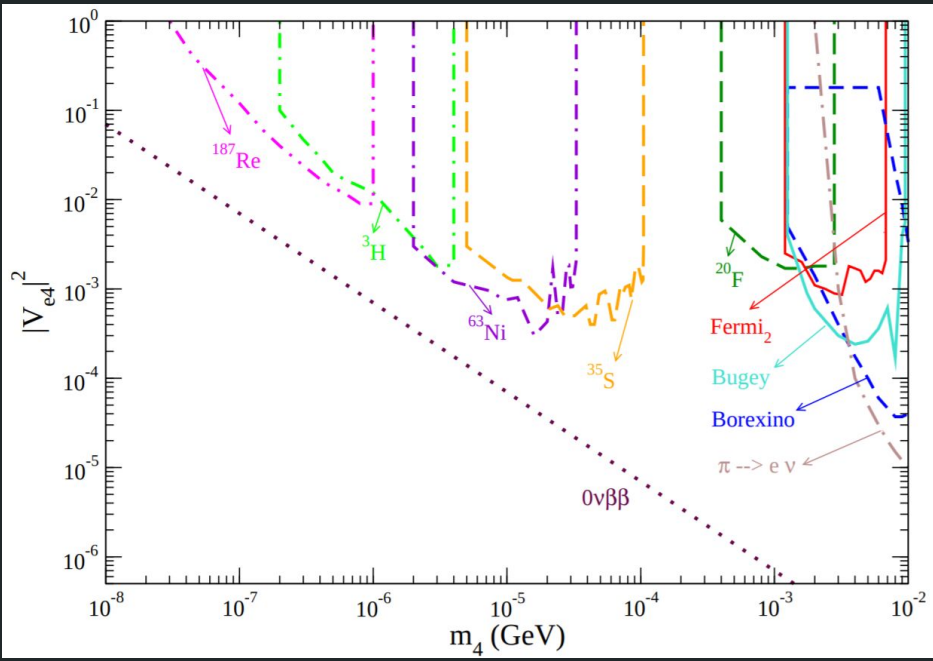
Mechanism:

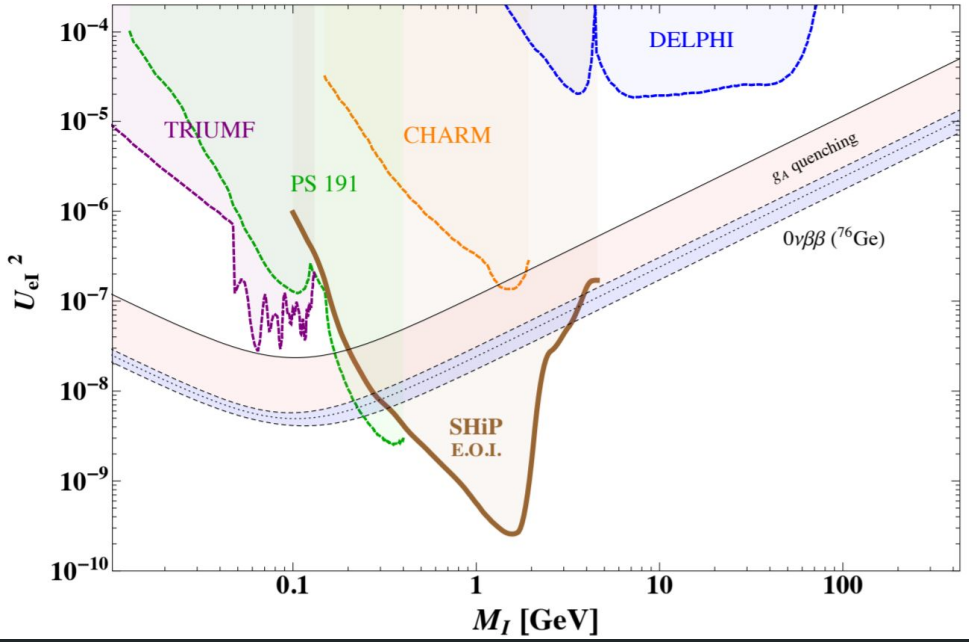
- Scale of new physics connected to the to $[T_{1/2}]^{-1}$
- **$[T_{1/2}]^{-1}$ is for $0\nu\beta\beta$ decay what $\sqrt{s}$ is for LHC**

Exchange of heavy-Majorana neutrinos

[A. Altre et al., JHEP 0905 (2009) 030]

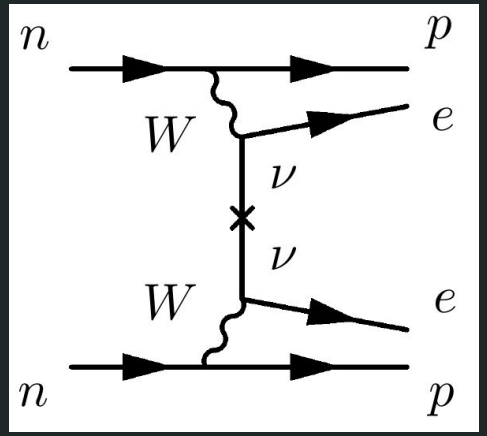
Rep. Prog. Phys. 79 (2016) 124201]





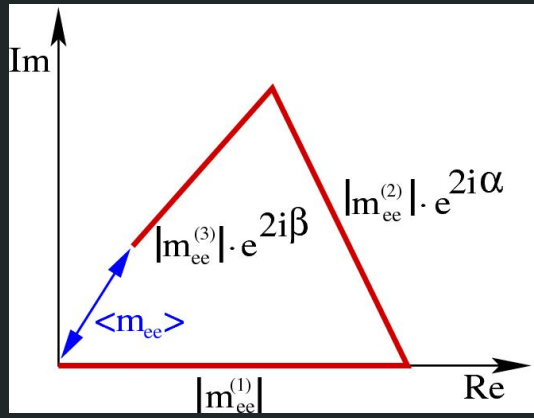
$0\nu\beta\beta$ constraint assuming no cancellation

Exchange of light-Majorana neutrinos



The Vanilla Channel :

- requires minimal extension of the SM
  - neutrinos are massive → already proved
  - neutrinos have a majorana nature
- dominant channel in most of the frameworks



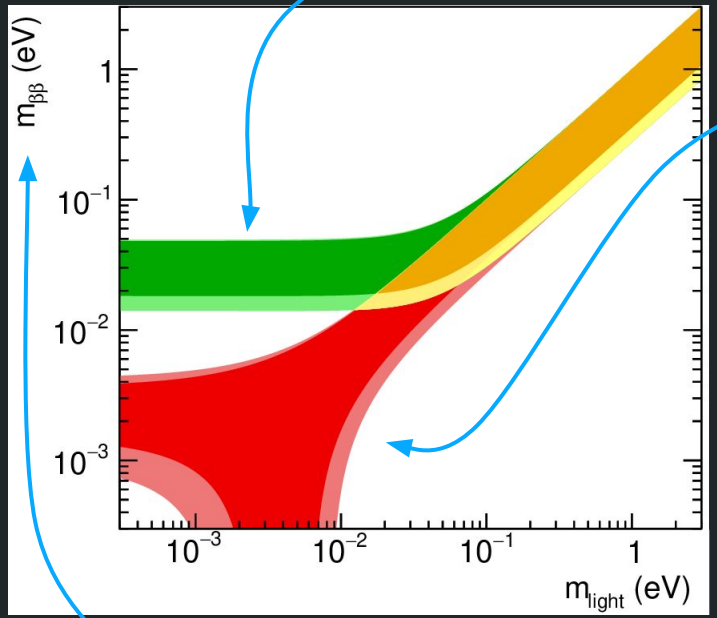
[W. Rodejohann, J.Phys. G39 (2012) 124008]

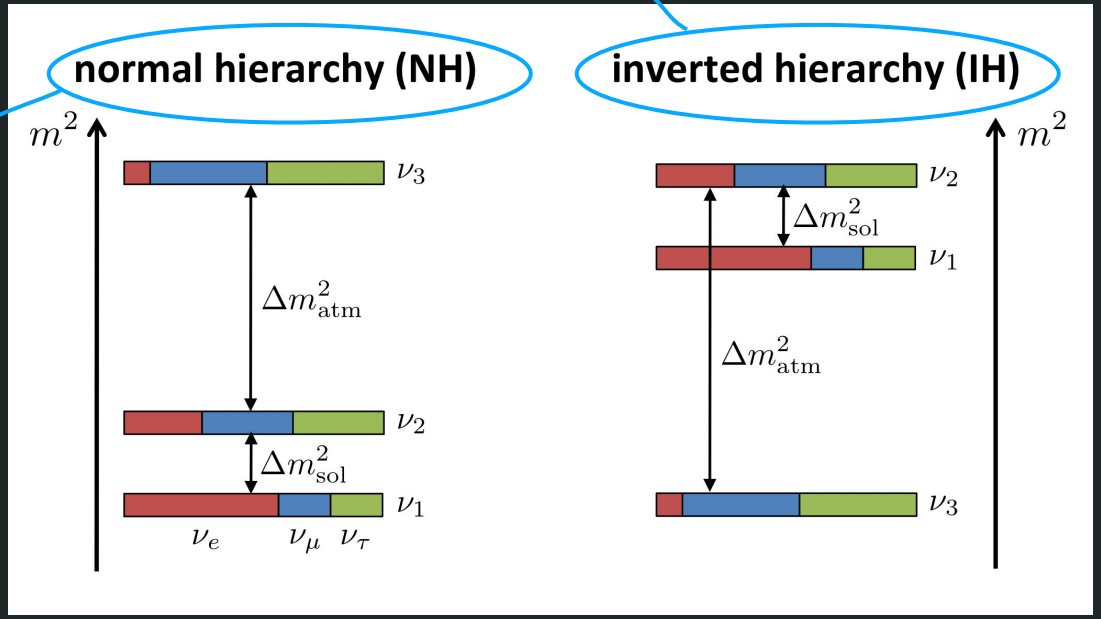
$$[T_{1/2}^{0\nu}]^{-1} = G_{0\nu} \cdot |\mathcal{M}_{0\nu}(A,Z)|^2 \cdot |m_{\beta\beta}|^2$$

Effective Majorana Mass

$$|m_{\beta\beta}| = \left|\cos^2\theta_{12}\,\cos^2\theta_{13}\,m_1 + \sin^2\theta_{12}\,\cos^2\theta_{13}\,m_2\,e^{i2\alpha_1} + \sin^2\theta_{13}\,m_3\,e^{i2\alpha_2}\right|$$

Neutrino Mass Observables





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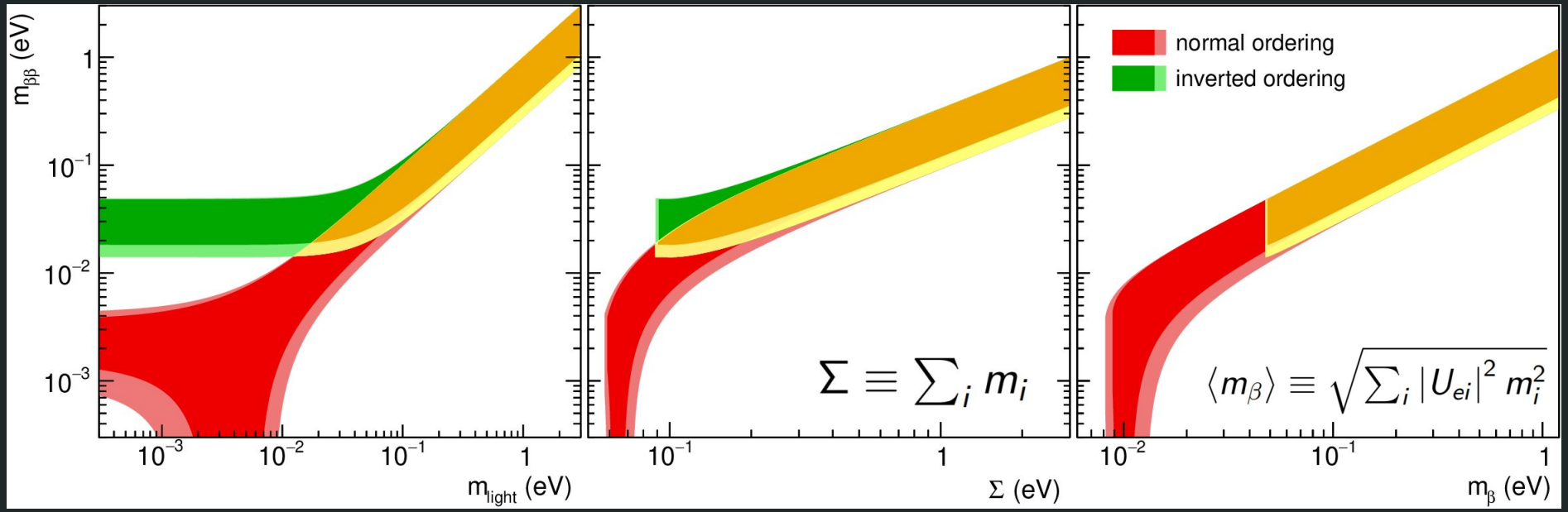
Neutrino Mass Observables

Cosmology (Planck, Euclid)
sum of neutrinos masses

Beta-decay kinematic (KATRIN)
electron neutrino mass



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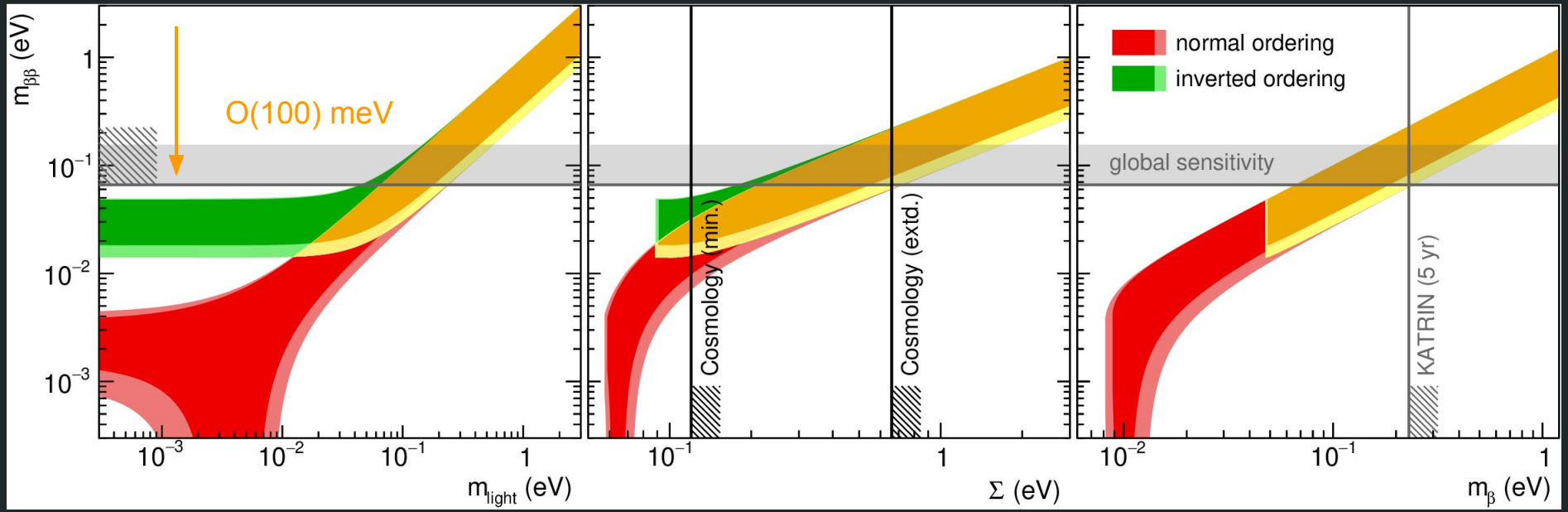

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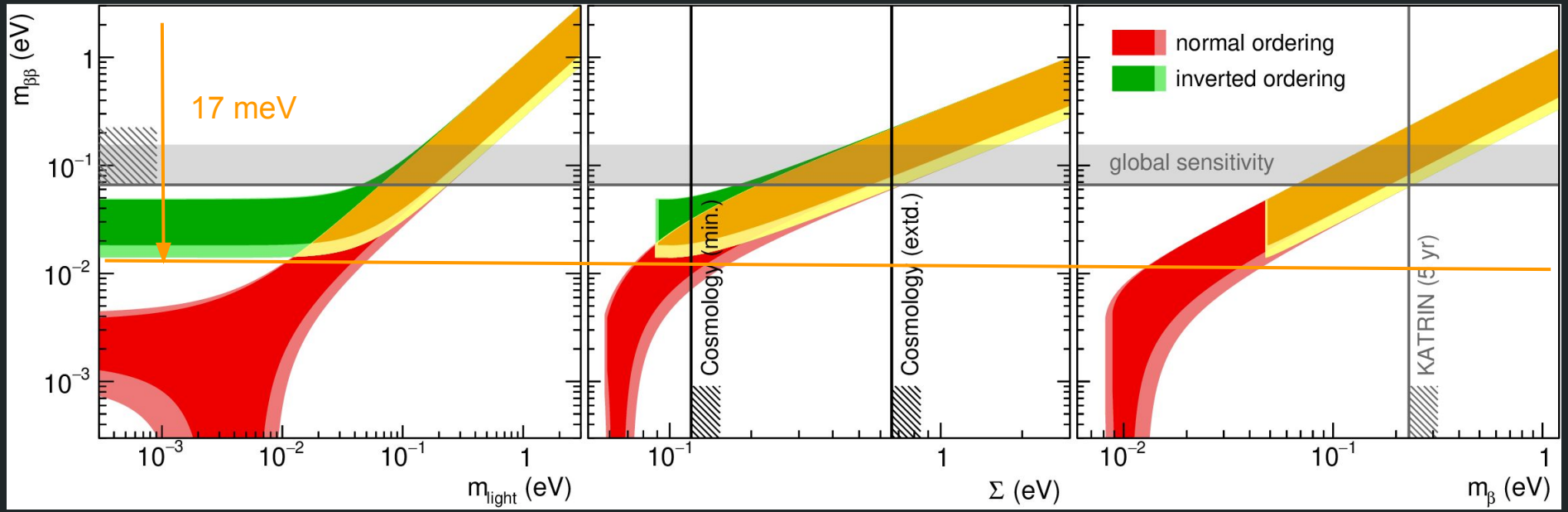
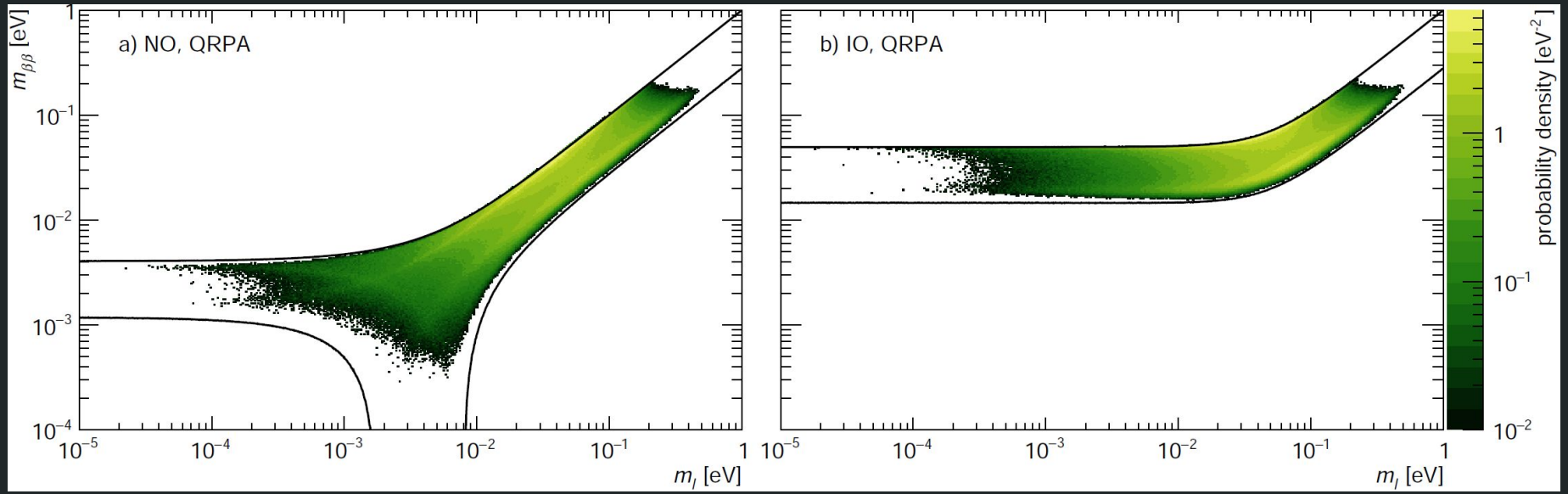


- ➢ Degenerate Majorana masses probed!
- ➢ Next target inverted ordering band
- ➢ $0\nu\beta\beta$ searches, cosmological surveys and direct mass measurements give complementary information!

Probability Density from Global Fits

In absence of neutrino mass mechanisms or flavour symmetries that fix the value of the Majorana phases or drive m_{light} to zero, the probability distribution for $m_{\beta\beta}$ is pushed to large values:



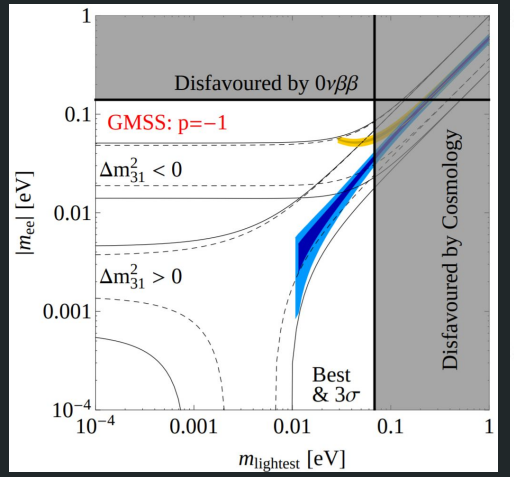
[**M.A.**, G Benato and J A Detwiler, PRD 96, 053001 (2017)]

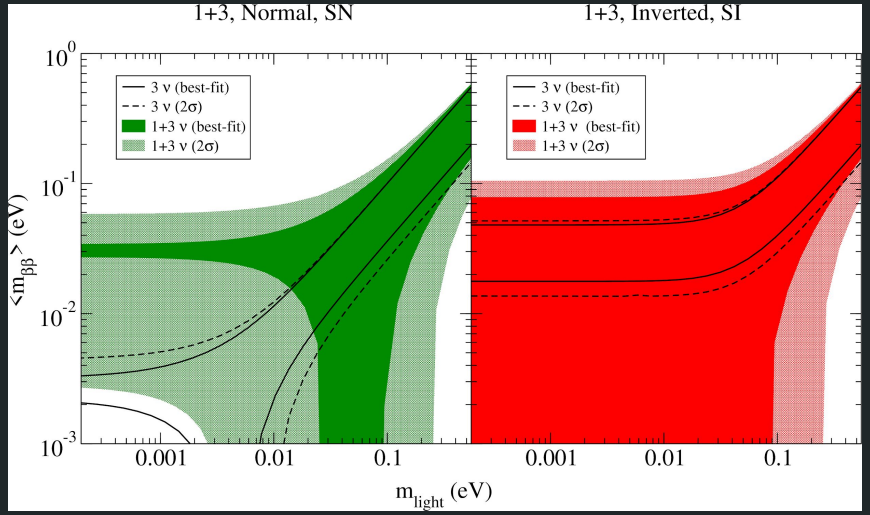
Flat prior for the Majorana phases ➔ small $m_{\beta\beta}$ values require a fine tuning of the parameters

Other Extensions

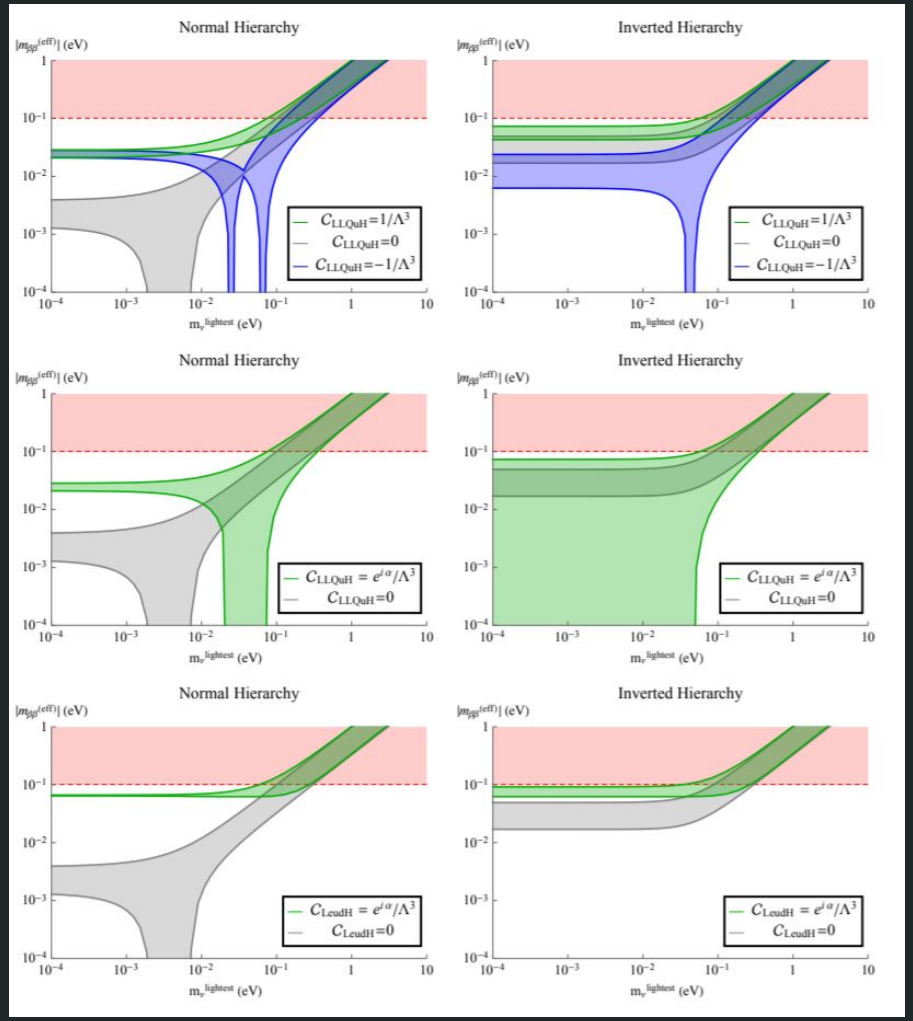
- flavor models
- 3+1 sterile
- dim 7 and 9 operators
- ...

[King, Merle, Stuart, JHEP 1312, 005 (2013)]





[W Rodejohann, Int.J.Mod.Phys. E20(2011)]



[Cirigliano et al. JHEP 12 082 (2017)]

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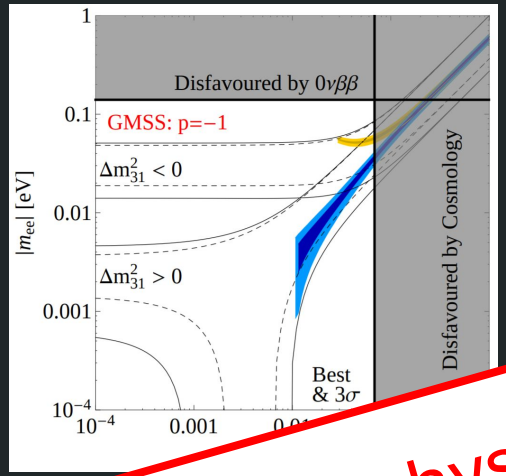
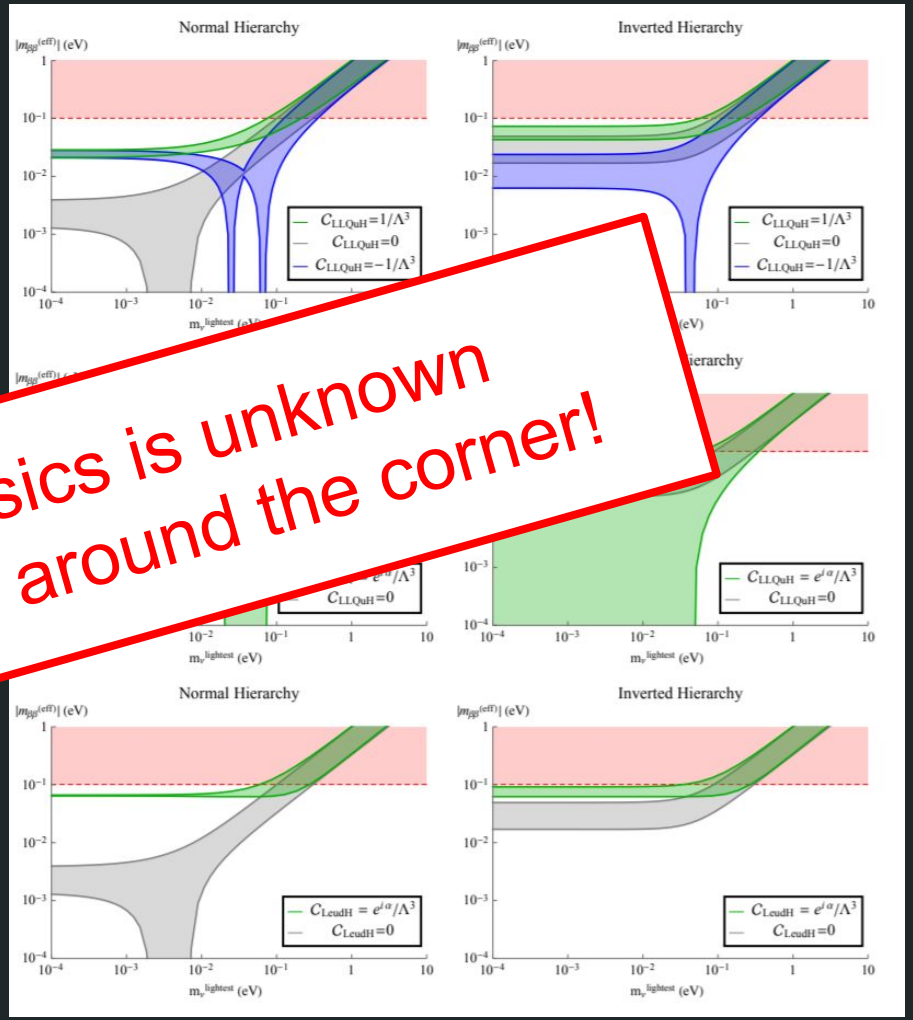
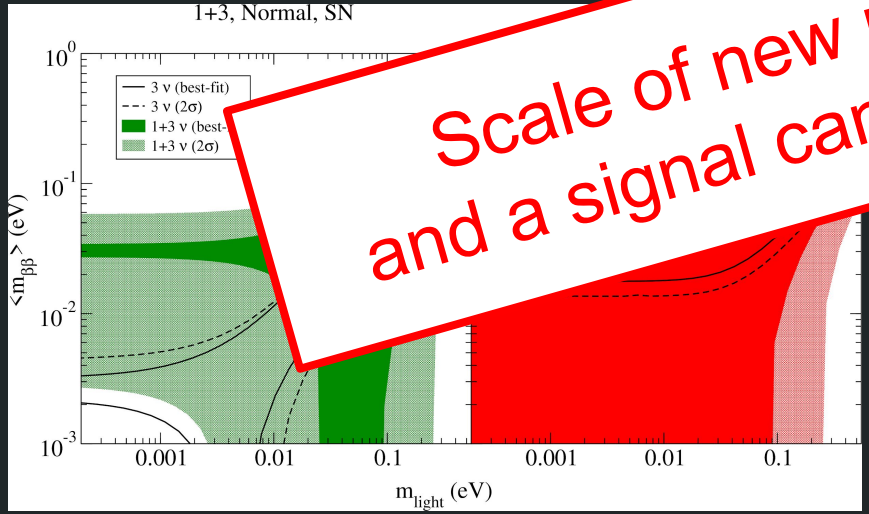
[King, Merle, Stuart, JHEP 1312, 005 (2013)]







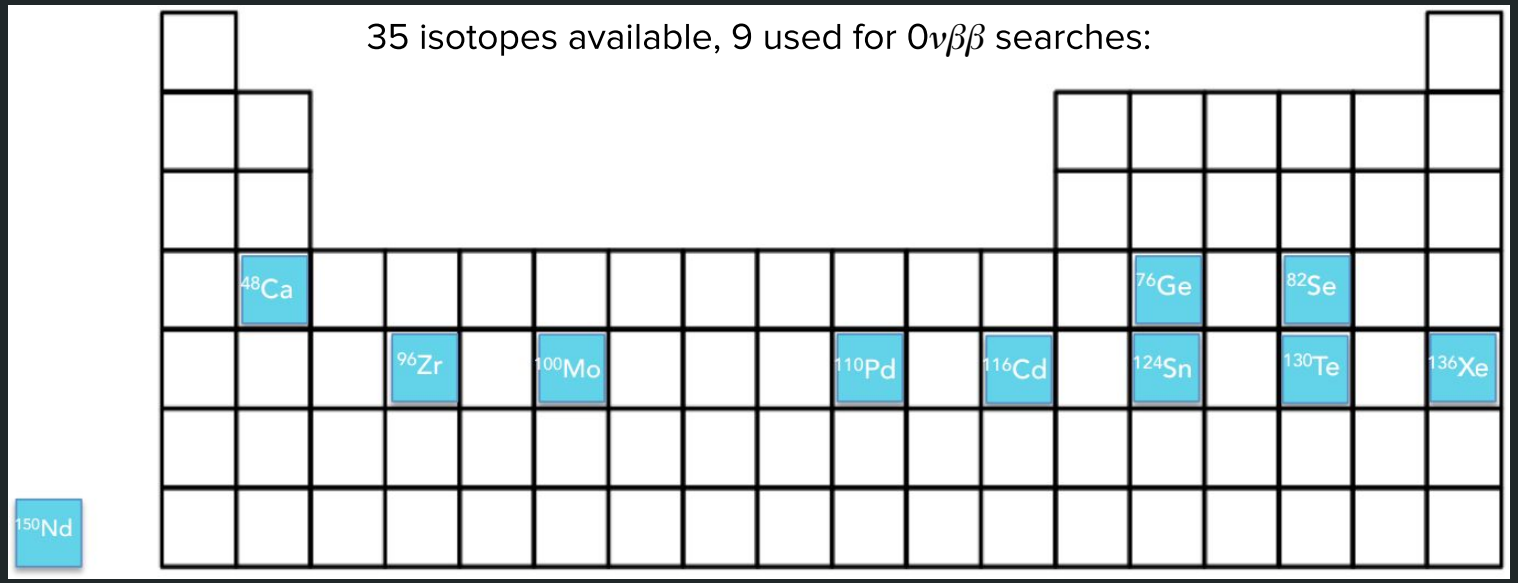
Scale of new physics is unknown and a signal can be around the corner!

[Cirigliano et al. JHEP 12 Int.J.Mod.Phys. E20(2011)]

Experimental Aspects

How to find a process with half-life beyond 10^{26} yr?

Double-β Decaying Isotopes



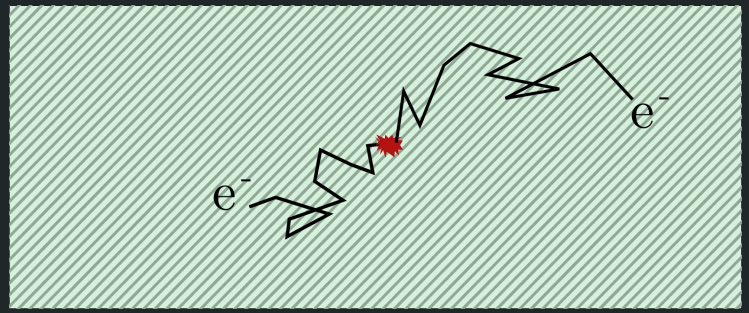
[Courtesy of K. Shaefner]

- cost depends on natural enrichment
- higher Q-value -> higher decay rate + lower background
- NMEs differes up to a factor 3

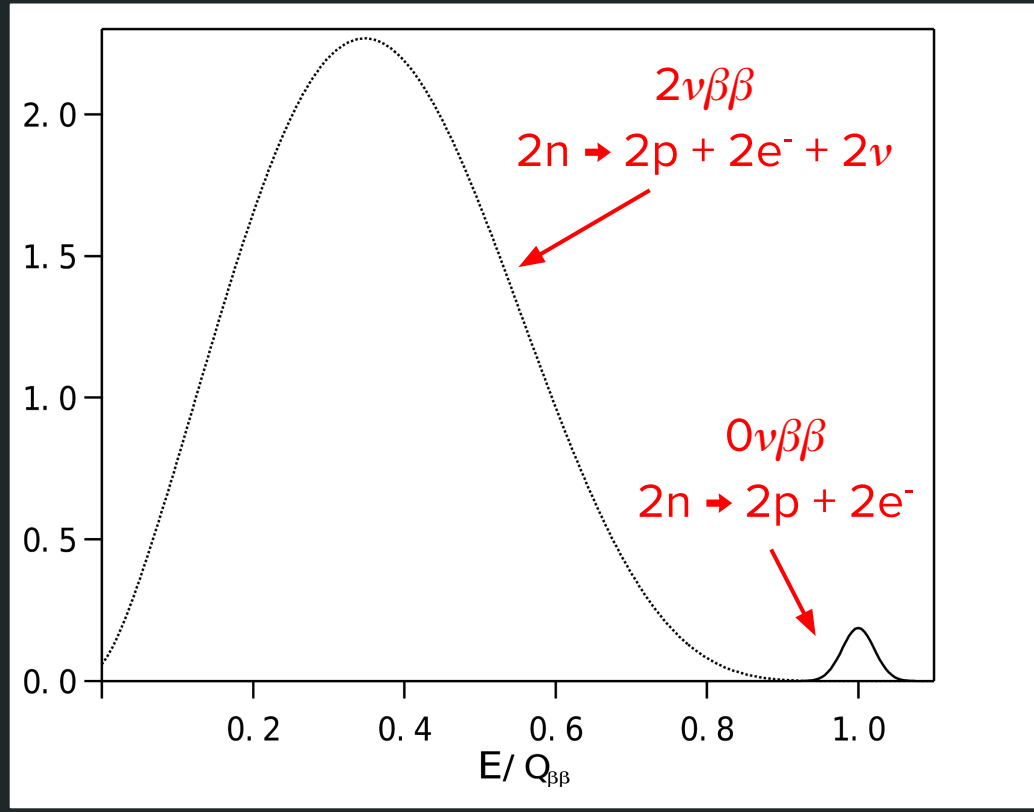
No "best" isotope
The possible detection techniques compensate for unfavorable parameters

Standard Detection Approach

double-β isotope encompassed in the detector active material and behave as calorimeters

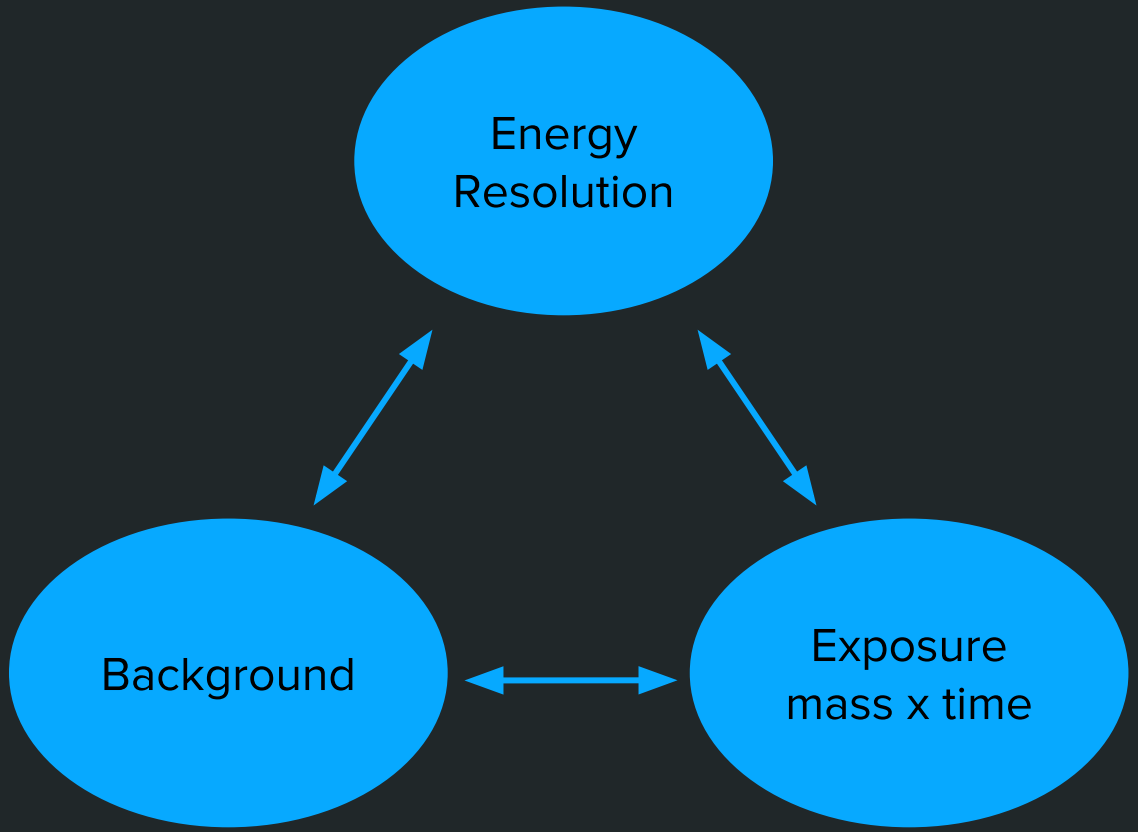


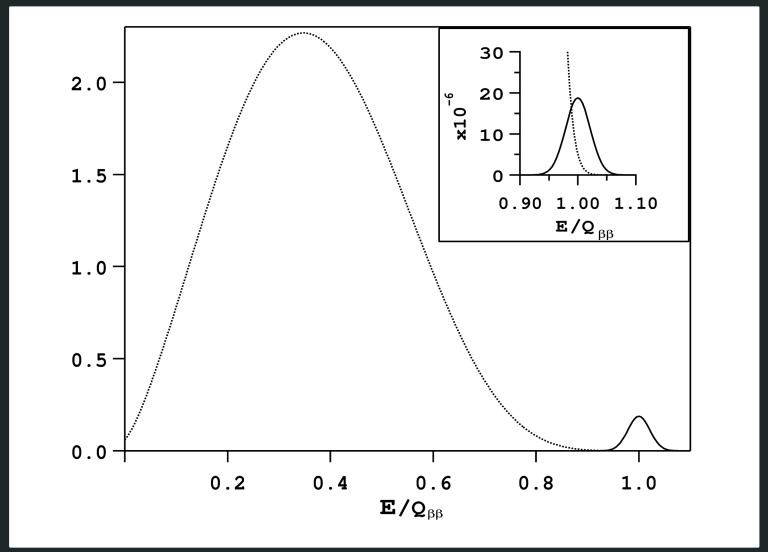
The energy observable is necessary and sufficient for discovery, other observables important for background control.



[S. Elliot et al., Ann.Rev.Nucl.Part.Sci. 52 (2002)]

Experimental Parameters



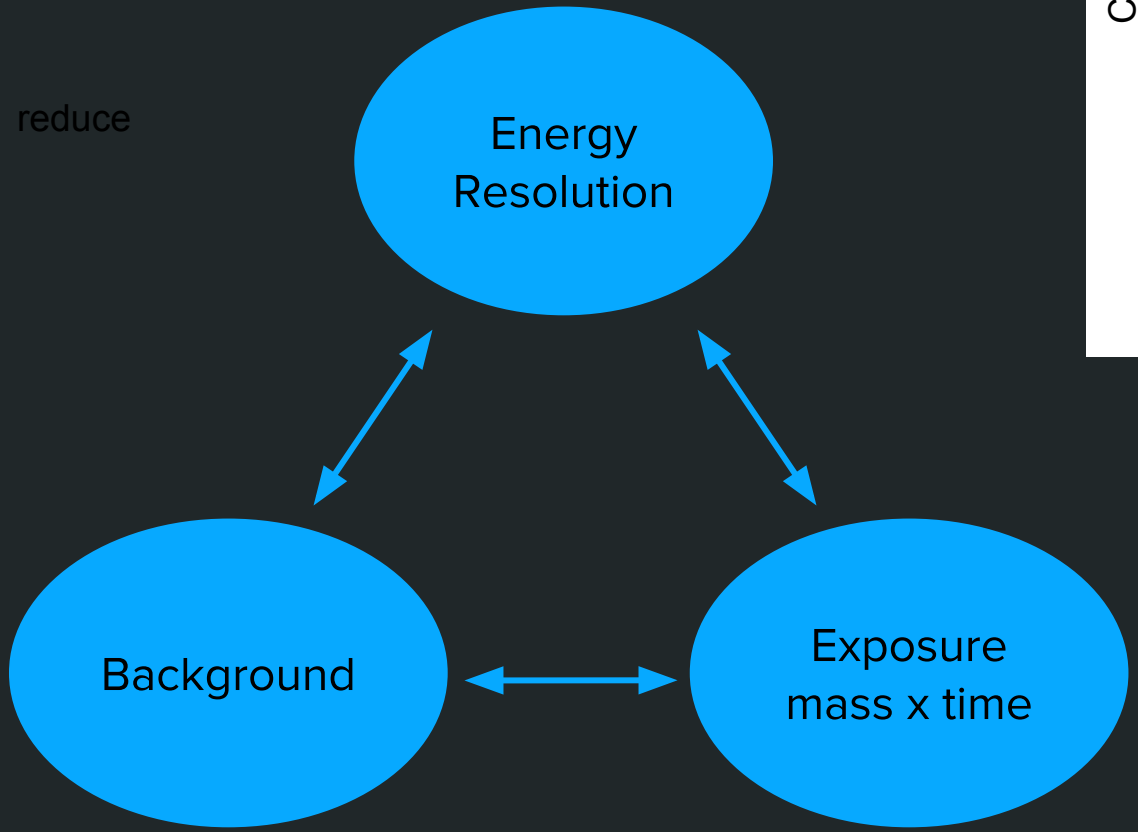


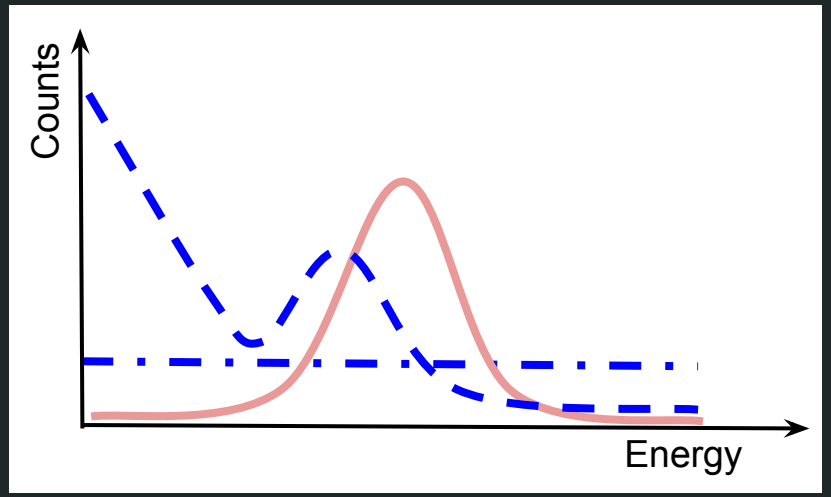
Energy Resolution:

- only way to mitigate the irreducible $2\nu\beta\beta$ decay
- fundamental to discriminate background from signal events

Experimental Parameters

reduce

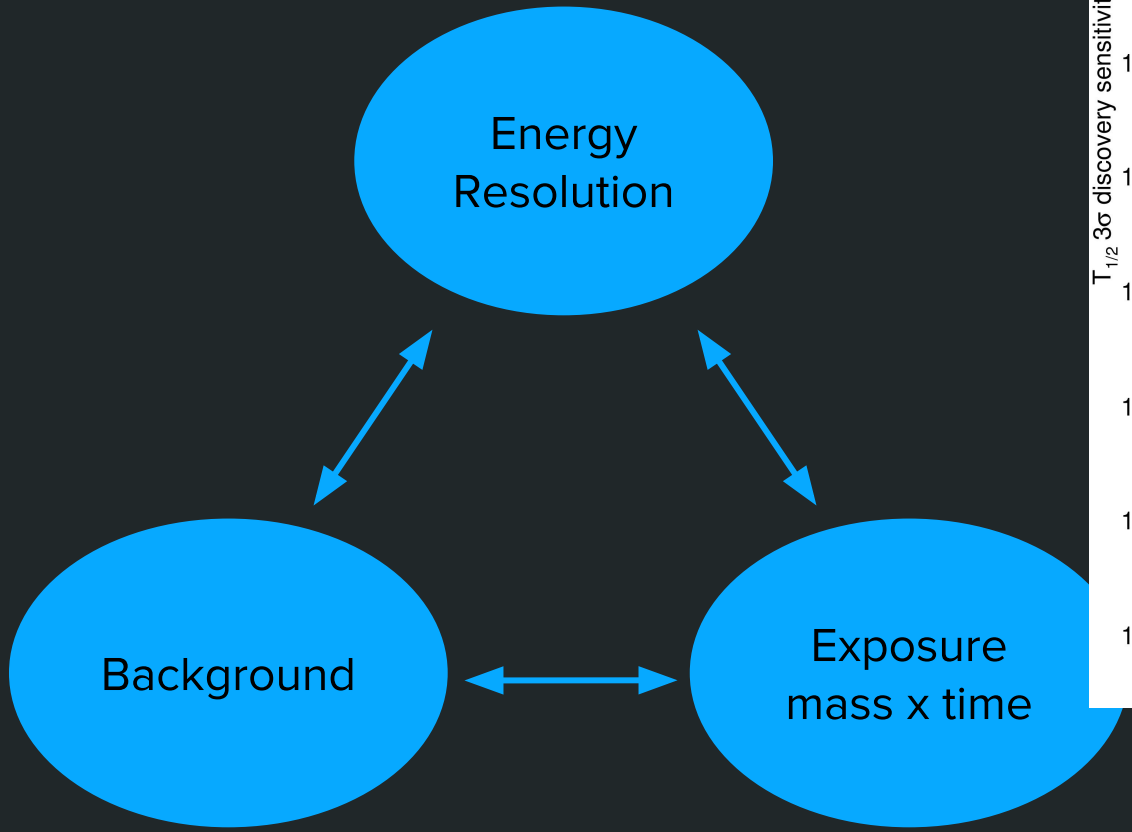


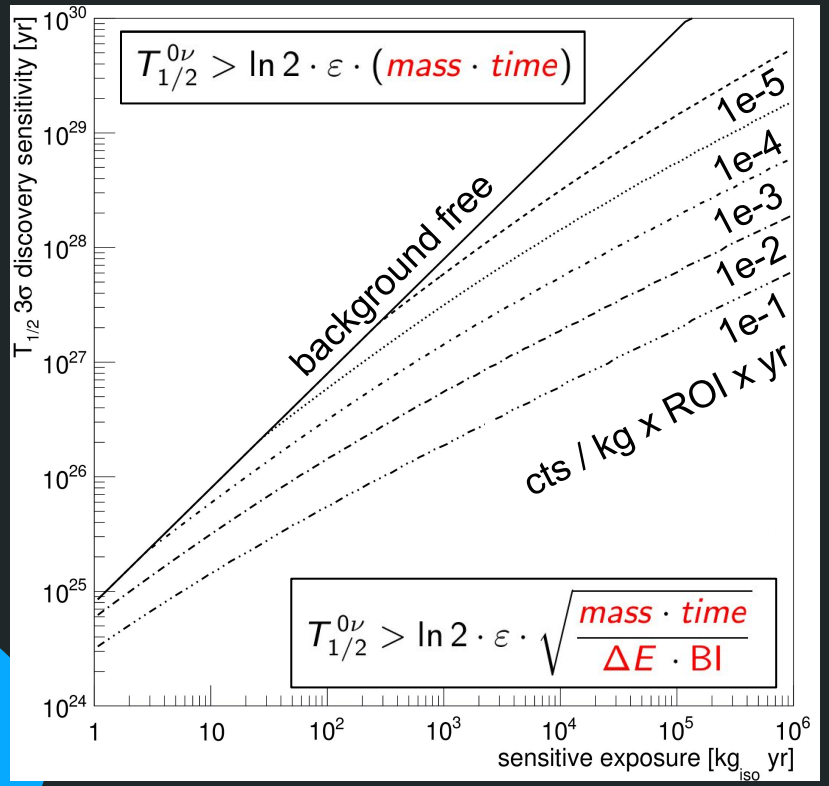


Background:

- ➢ background rate in the region of interest (ROI) determines the signal strength to which an experiment is sensitive
- ➢ complex background shapes create systematic uncertainties

Experimental Parameters

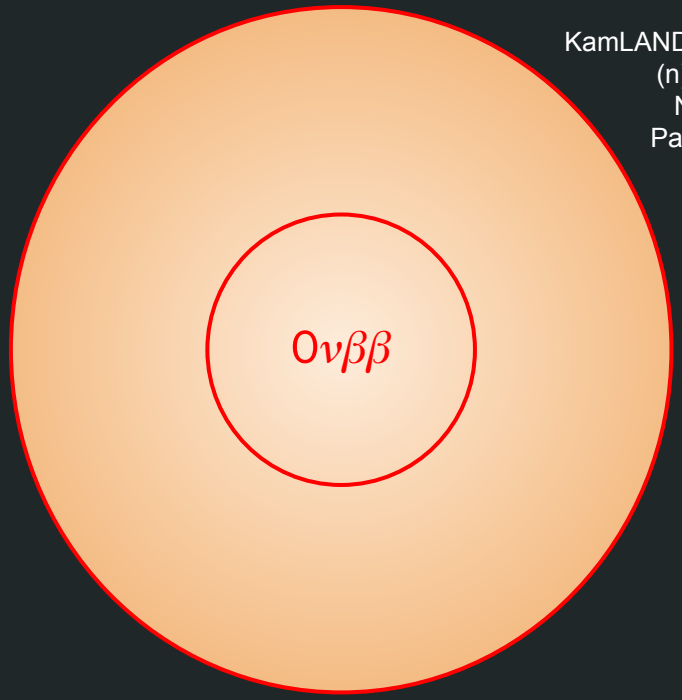




[**M.A.**, G Benato and J A Detwiler, PRD 96, 053001 (2017)]

Liquid/Gas vs Solid Detectors

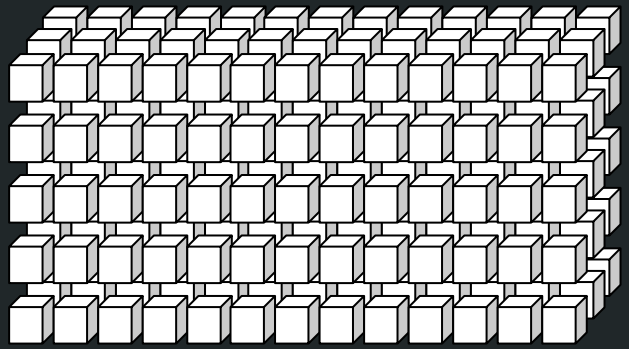
KamLAND-Zen
(n)EXO
NEXT
PandaX



Loaded scintillator detectors or Xe Time Projection Chambers

- $0\nu\beta\beta$ isotope mixed in the liquid/gas material
- self-shielding from external background
- volume fiducialization

CUORE
CUPID
AMORE
Majorana
GERDA



Cryogenic Bolometers or Semiconductor detectors:

- many crystals of isotopically enriched material
- detector granularity
- per mill energy resolution

The ^{76}Ge Experimental Program

GERDA, Majorana and LEGEND

MAJORANA DEMONSTRATOR

LEGEND

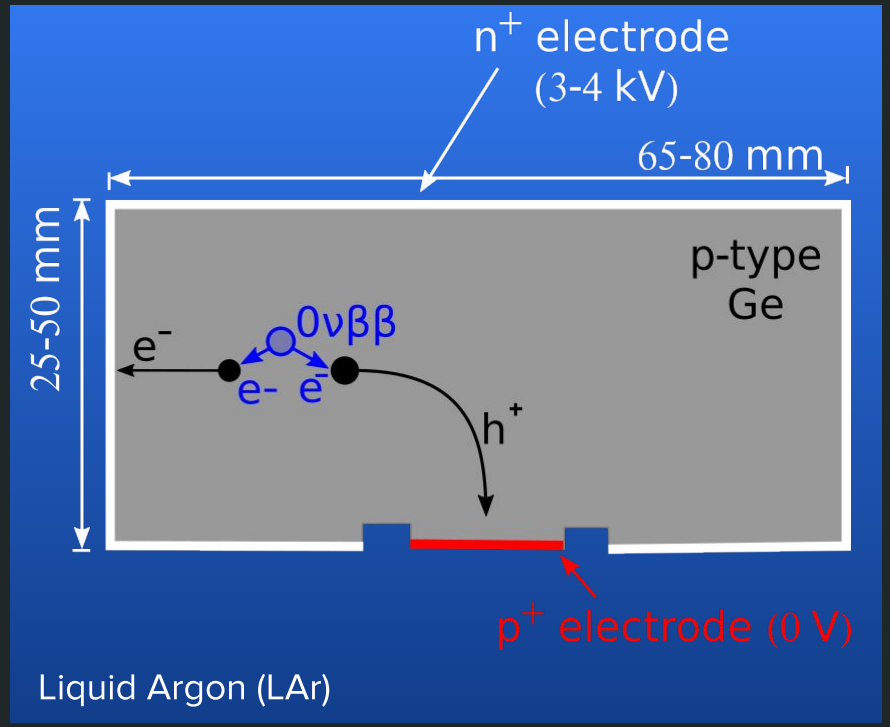
Large Enriched Germanium Experiment for Neutrinoless ββ Decay

GERDA Detection Strategy

Search for 0νββ decay of $^{76}Ge \rightarrow {}^{76}Se + 2e^-$

Semiconductor Ge detectors (87% ^{76}Ge):

- source = detector → high efficiency
- high density → e^- absorbed in ~1 mm
- 0νββ is a point-like event in bulk volume
- operated in ultrapure liquid argon (LAr)



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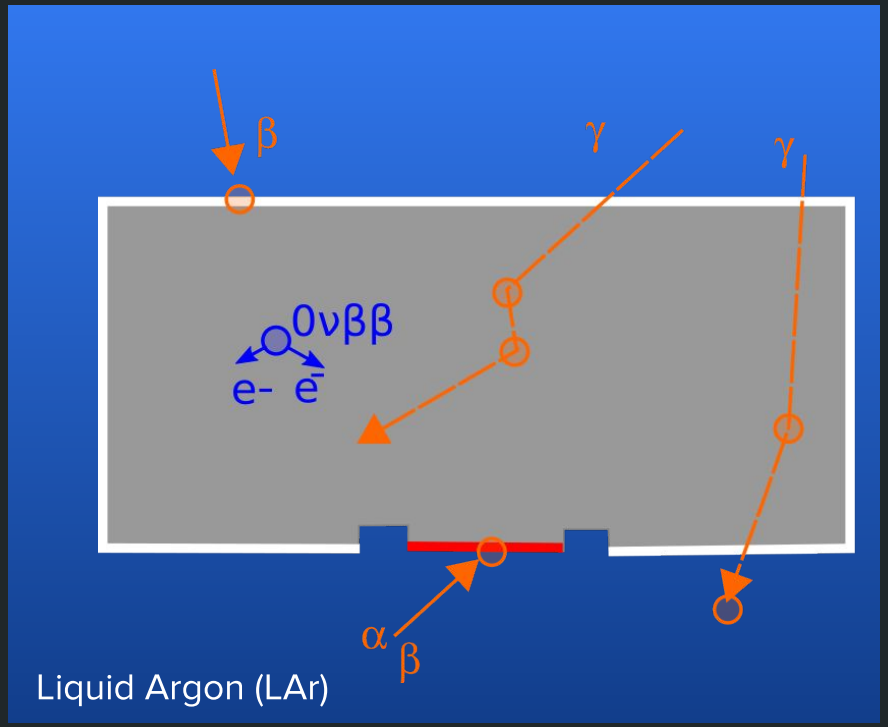
Background sources:

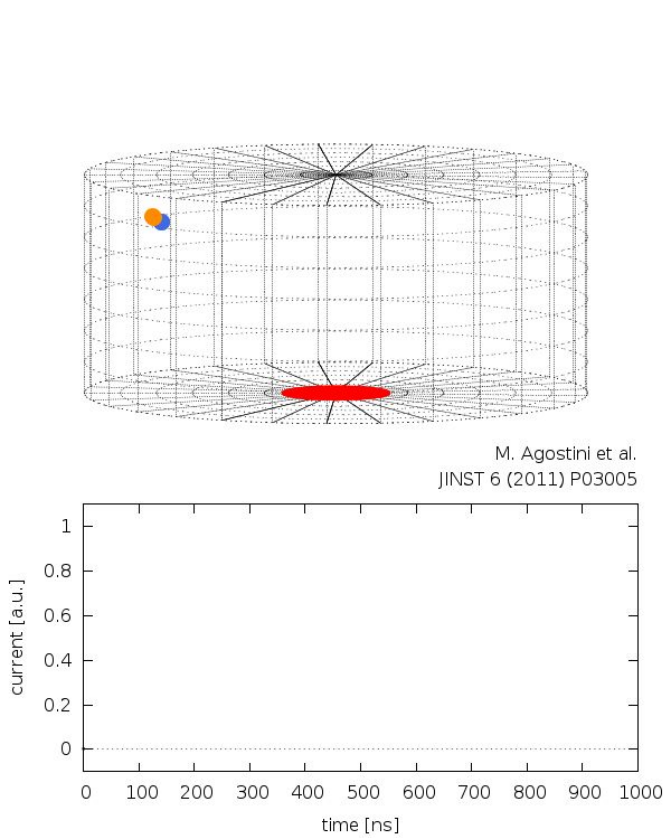
- gammas from material surrounding the detectors
- surface contaminantions (alphas)
- cosmogenic isotopes of Ar



Signal/Background Discrimination

HPGe detector as time-projection chambers:

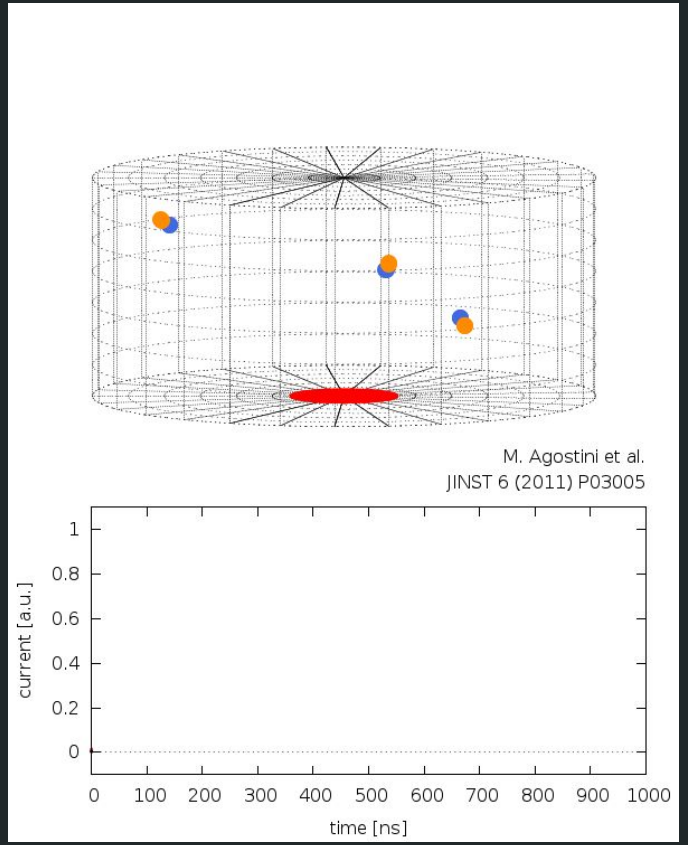
- ➢ 0νββ events ➔ single site interactions in bulk volume



Signal/Background Discrimination

HPGe detector as time-projection chambers:

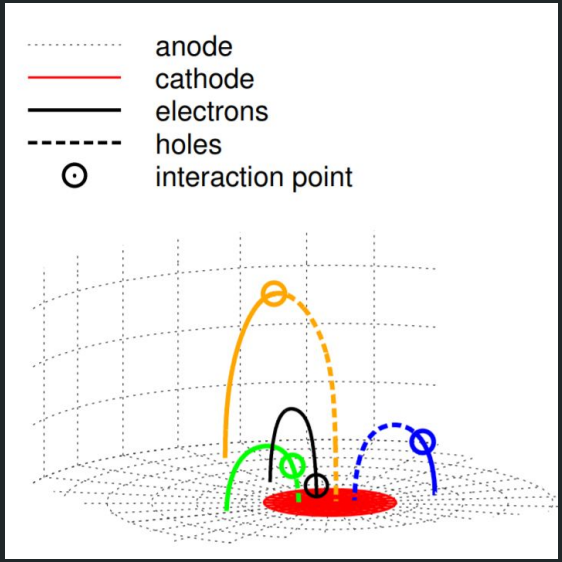
- ➢ 0νββ events ➔ single site interactions in bulk volume
- ➢ γ-rays ➔ multiple Compton scattering

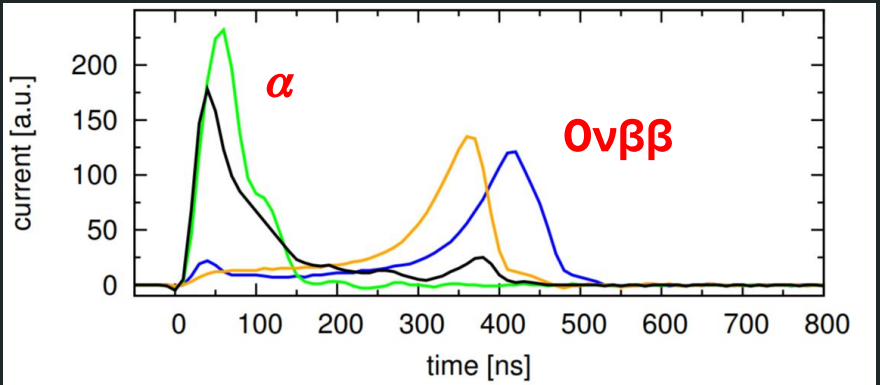


Signal/Background Discrimination

HPGe detector as time-projection chambers:

- 0νββ events → single site interactions in bulk volume
- γ-rays → multiple Compton scattering
- α/β-rays → surface events





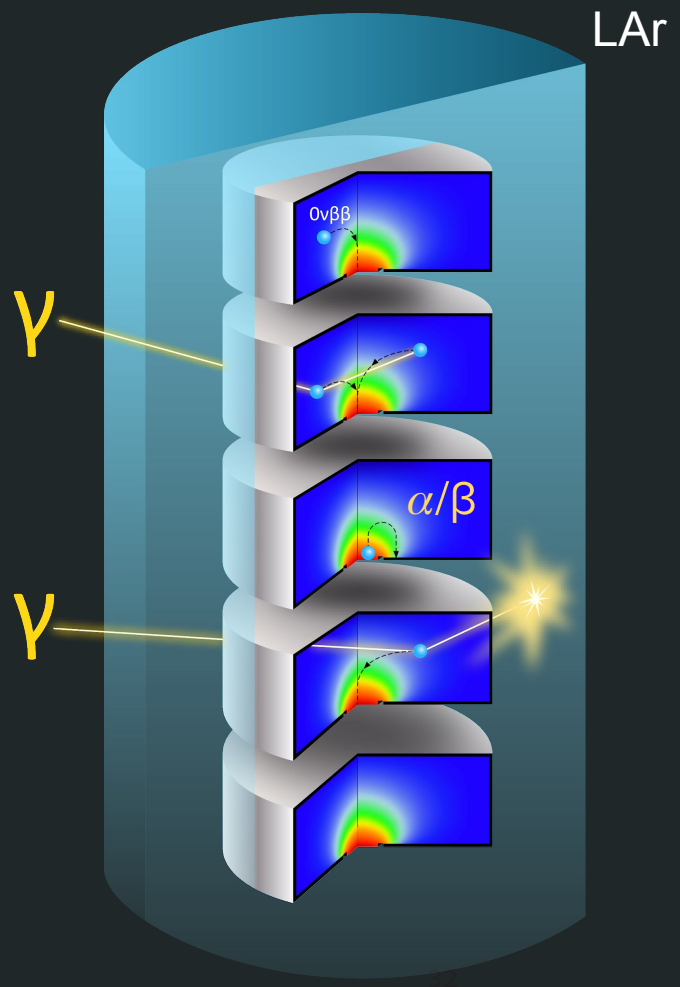
Signal/Background Discrimination

HPGe detector as time-projection chambers:

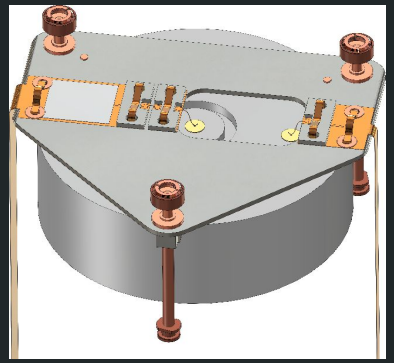
- ➢ 0νββ events → single site interactions in bulk volume
- ➢ γ-rays → multiple Compton scattering
- ➢ α/β-rays → surface events

LAr scintillation as active veto system:

- ➢ γ-rays → single scattering in the Ge detectors



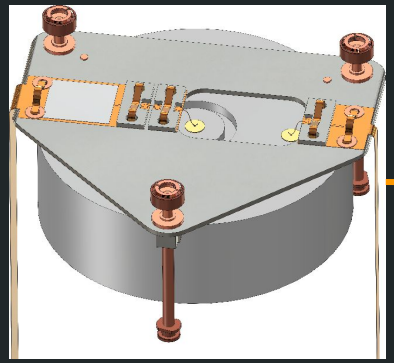
The Setup



Detectors mounting:

- low mass holders
- contacting with wire bonding

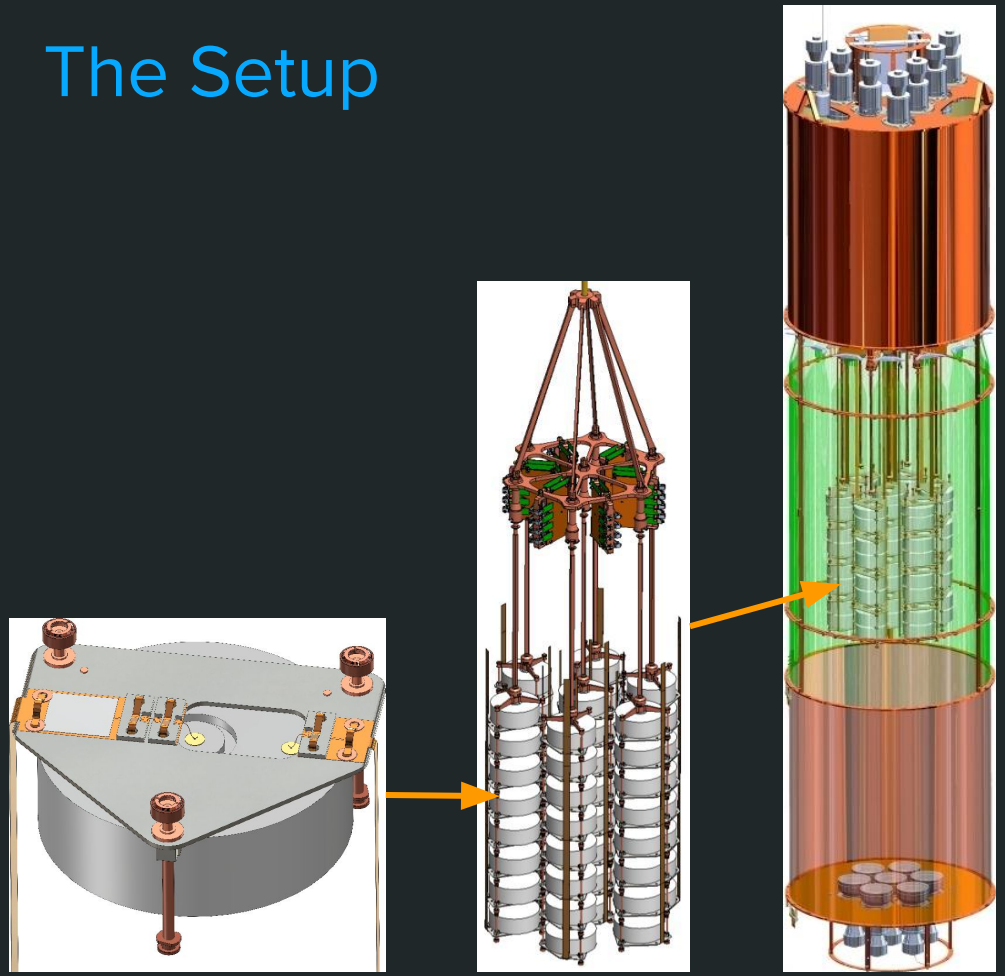
The Setup



Array deployed in Dec 2015:

- 7 strings / 40 detectors
- 30 enriched BEGe (20 kg)
- 7 enriched Coax (15.6 kg)
- 3 natural Coax (7.6 kg)

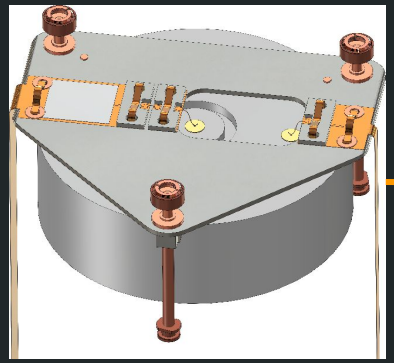
The Setup

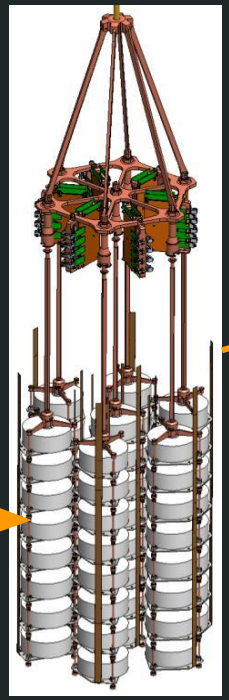


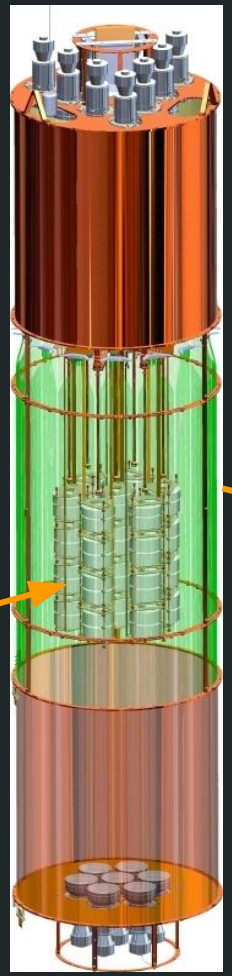
LAr scintillation detection:

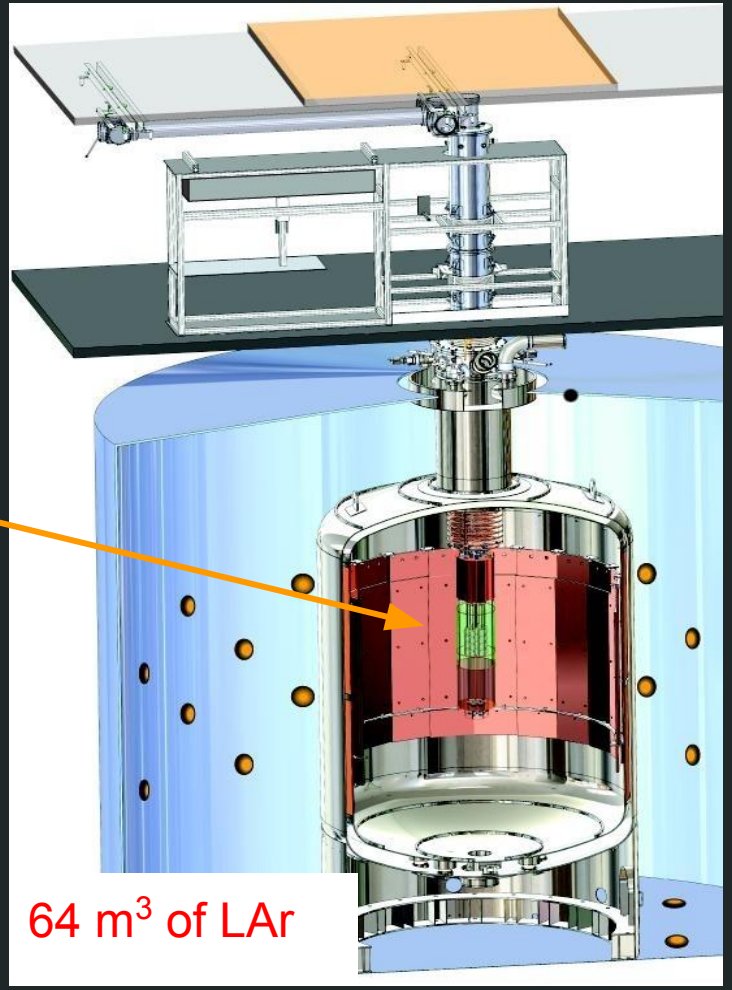
- 16 PMTs (9 top / 7 btm)
- ~1 km fibers with WLS + 90 SiPMs
- nylon mini-shroud around each string coated with WLS

The Setup

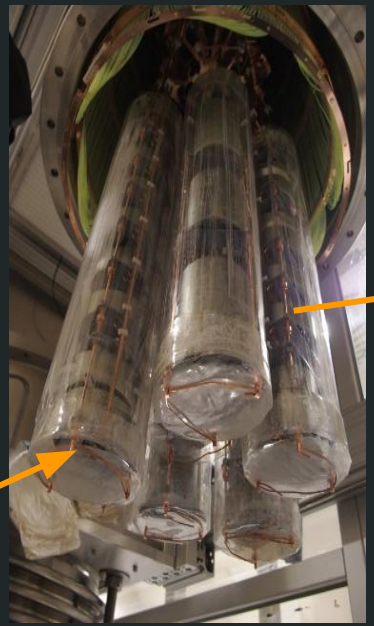


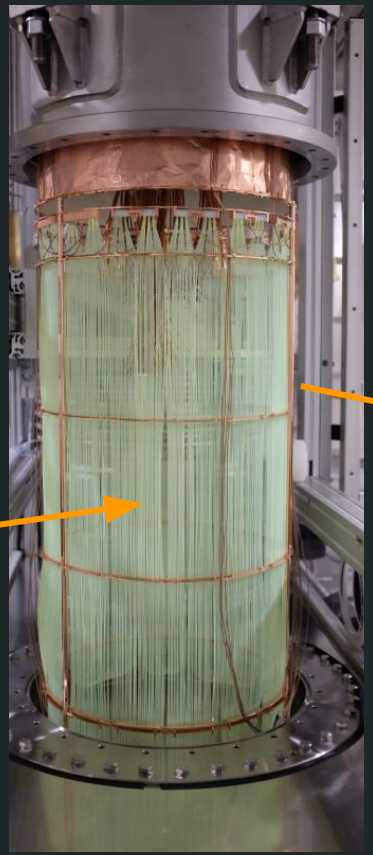






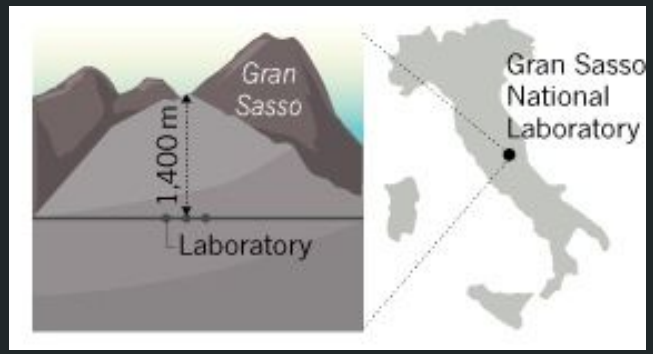
The Setup

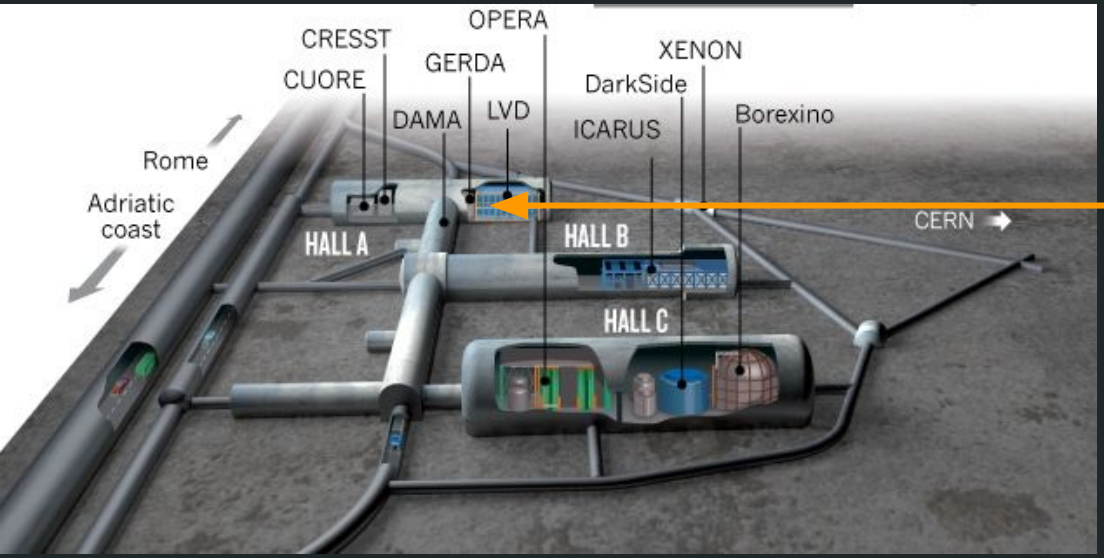




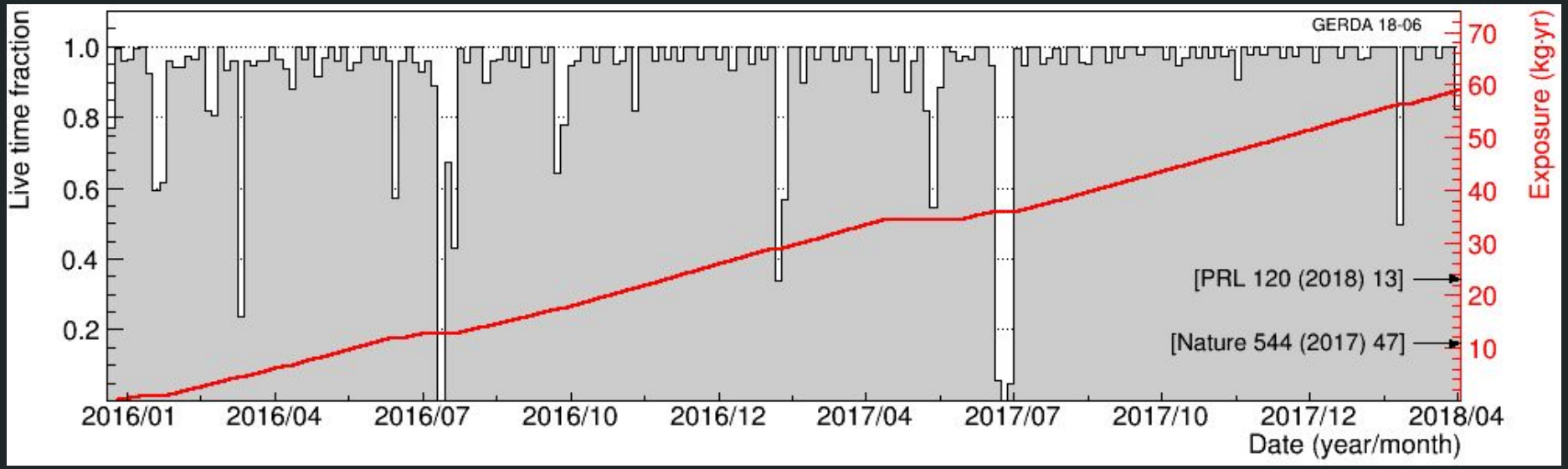
The Setup

LNGS (INFN)
3500 m.w.e.



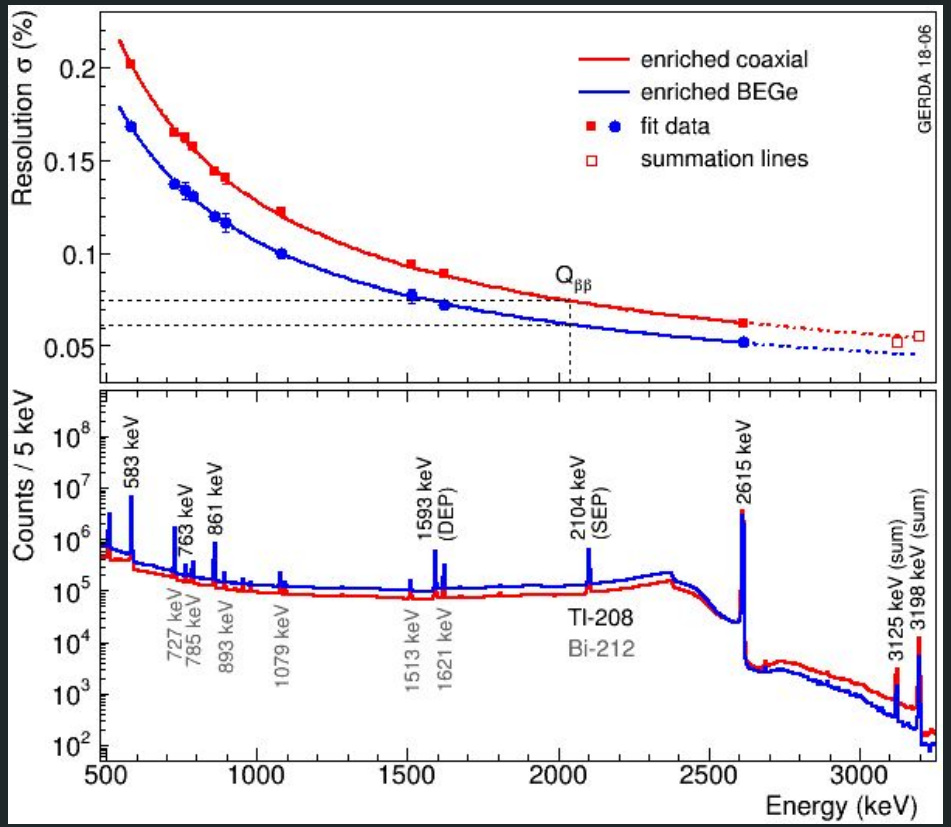


Phase II Data Taking



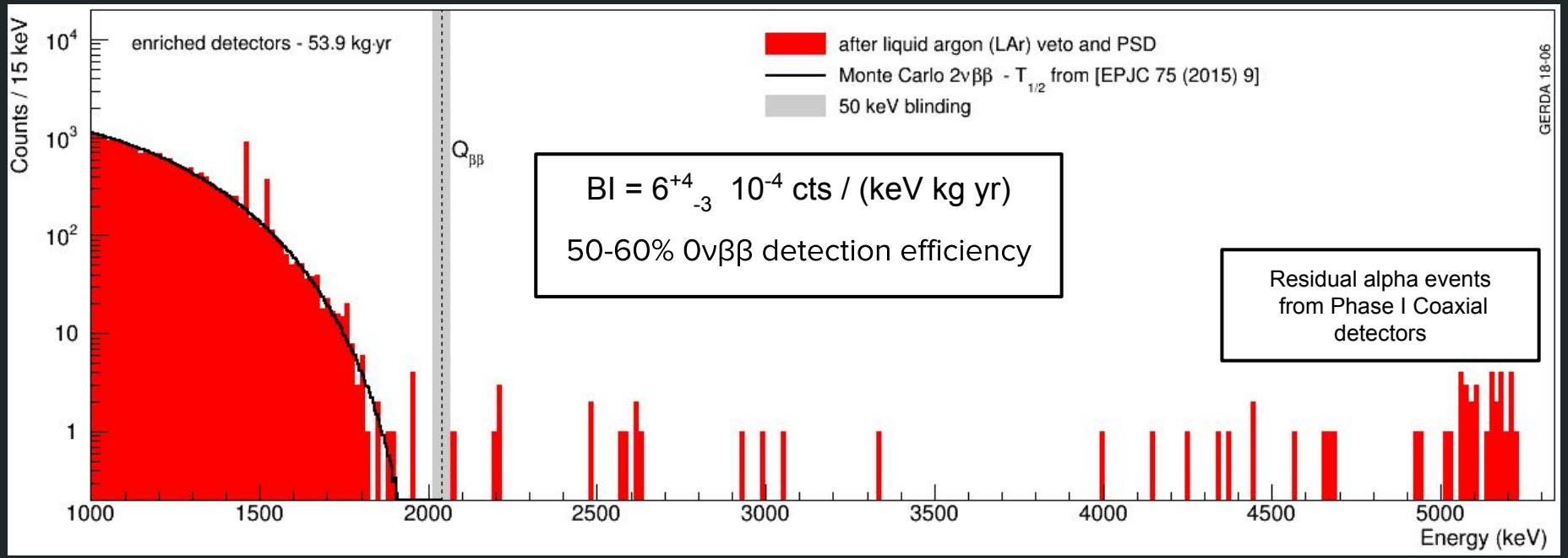
- Dec 2015 → Apr 2018: 835 d live time
- 93% duty cycle
- Phase II Exposure: 59 kg yr
- Phase I + Phase II: 82 kg yr

Energy Scale



- Weekly calibration with Th-228 sources
- Fluctuations between calibrations <1 keV
- Resolution at $Q_{\beta\beta}$ better than 0.1% (3-4 keV FWHM)

Active Background Suppression

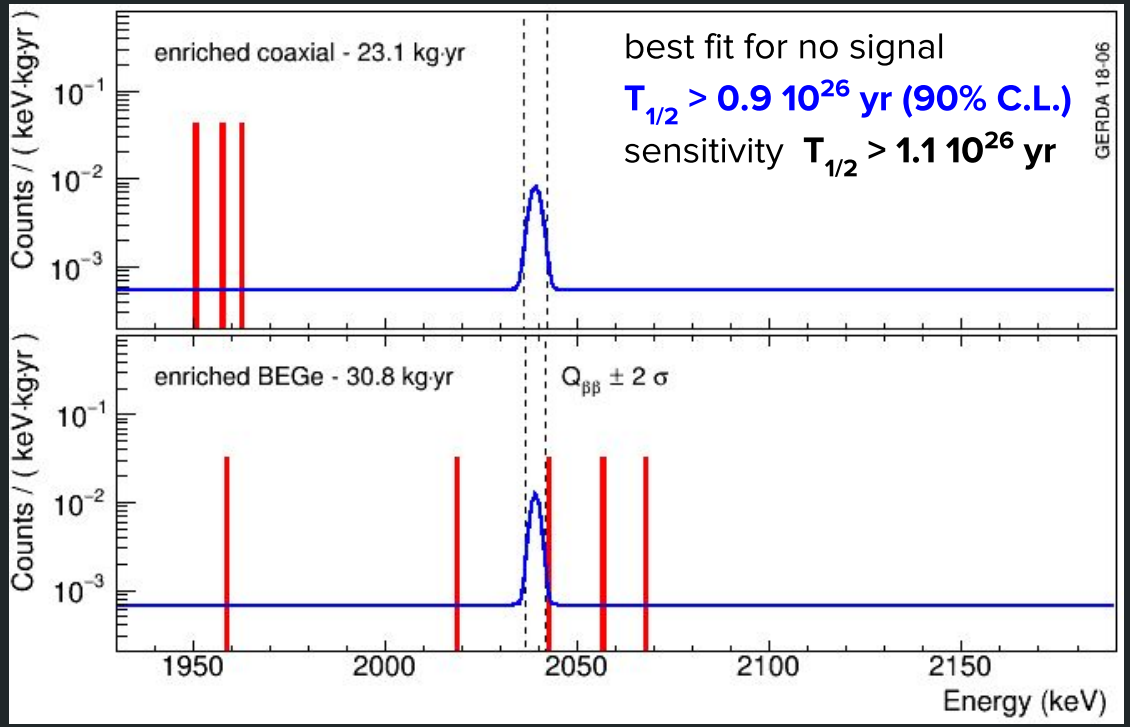


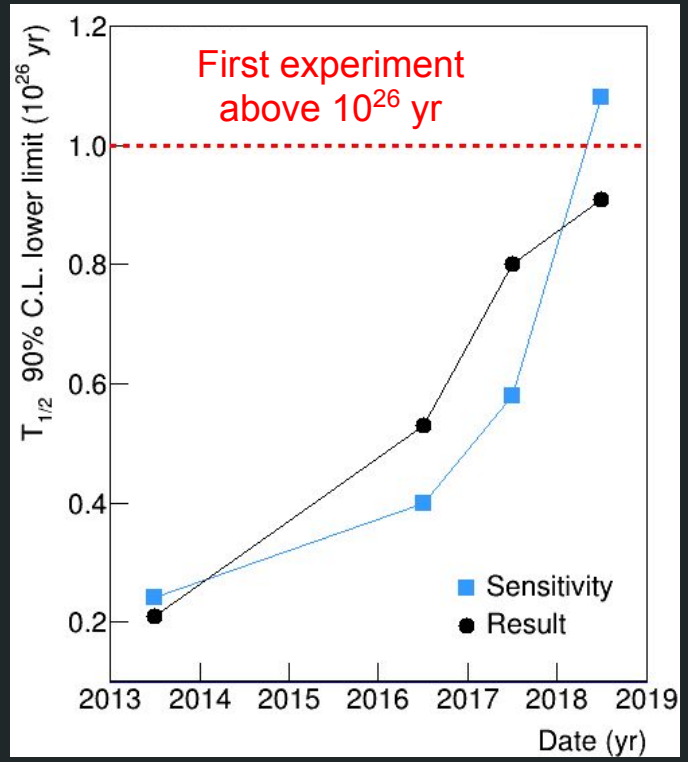
0νββ experiment with the lowest background in the ROI!

Statistical Analysis

High Resolution & Background Free:
1 count at $Q_{\beta\beta}$ → ~2 sigma signal

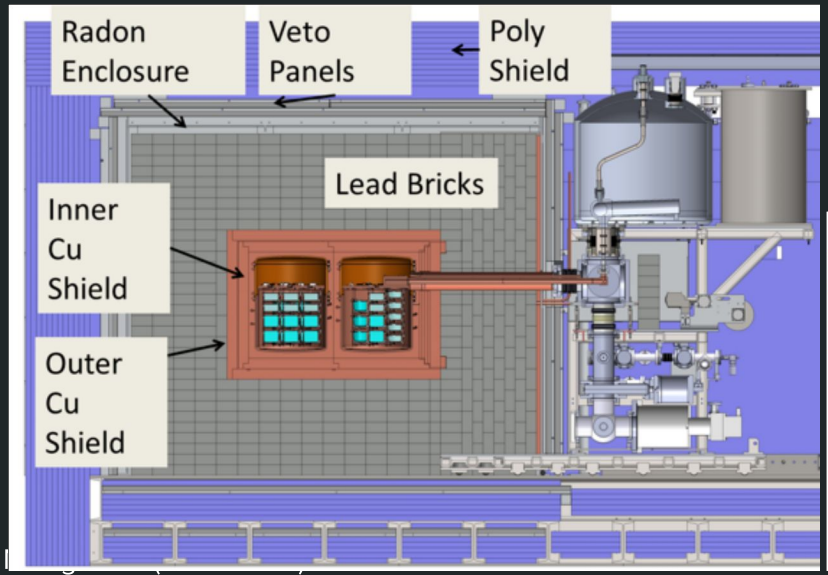
Unbinned profile likelihood of 7 data sets (Phase I + Phase II):

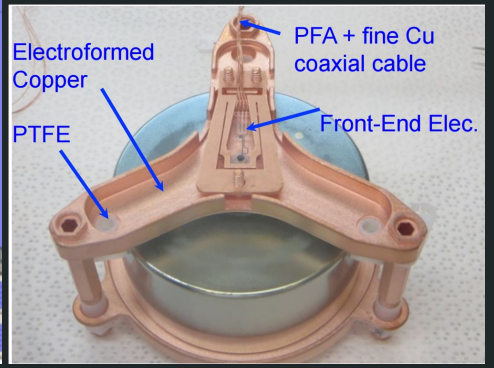


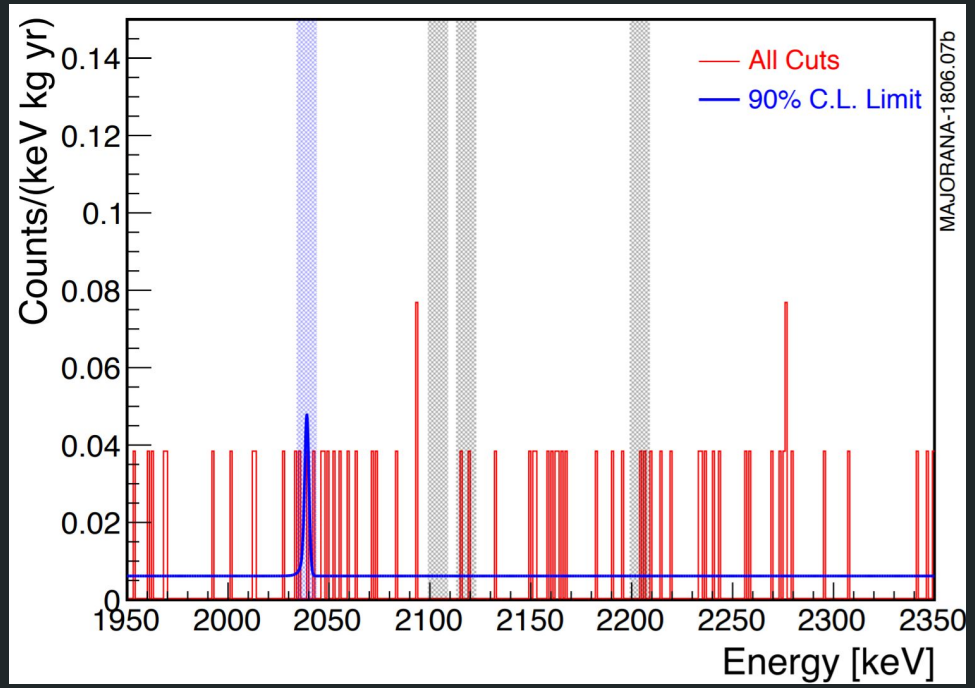


Majorana Demonstrator

- 37 detectors of PPC type
- two independent cryostat
- low-background passive shield (Cu+Pb)
- Cu produced underground to avoid cosmogenic activation







Latest result @ Neutrino18:

- 29 kg-yr exposure
- B = 4.7 ± 0.8 cts/(keV kg yr)
- $T_{1/2} > 2.7\ 10^{25}$ yr (90% C.L.)
- sensitivity **$T_{1/2} > 4.8\ 10^{25}$ yr**

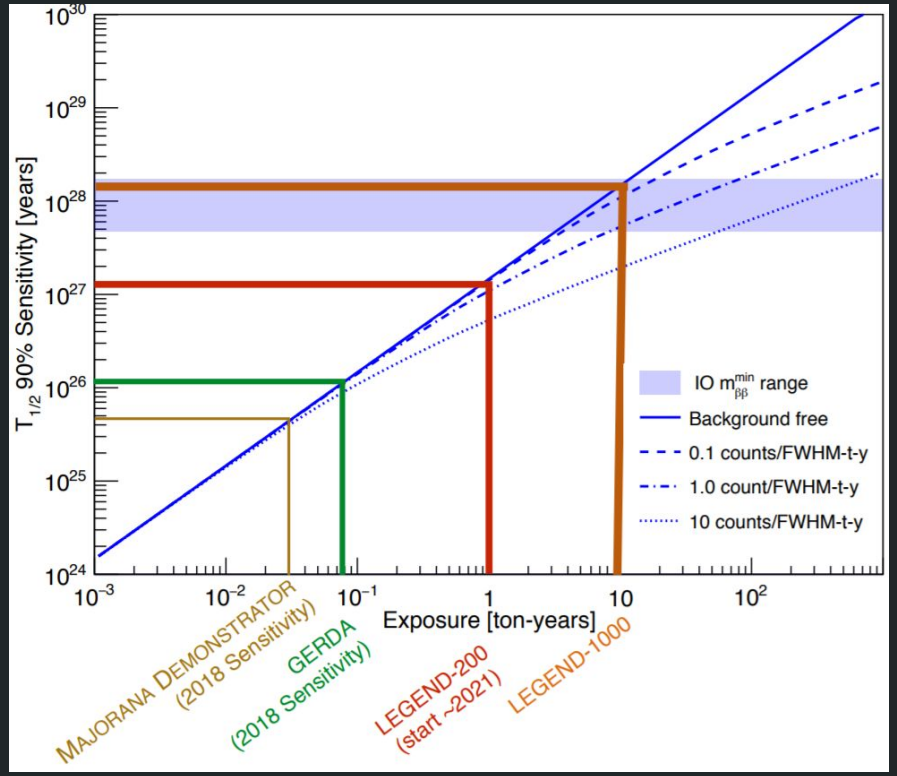
LEGEND

New project built on GERDA and MAJORANA:

- ➢ GERDA → LAr veto system
- ➢ MAJORANA → low background material
  → front-end electronics

Staged approach:

- ➢ L200 → 200 kg mass in GERDA infrastructure
  → background < 2 10^{-4} cts/keV/kg/yr
  → discovery power up to $T_{1/2}$ ~ 10^{27}
- ➢ L1000 → 1000 kg mass in new setup (TBD)
  → discovery power up to $T_{1/2}$ ~ 10^{28}



The future of the ^{76}Ge-based program

Funding for LEGEND-200 largely secured

Completion of MAJORANA Demonstrator

LEGEND-200 first phsyics run

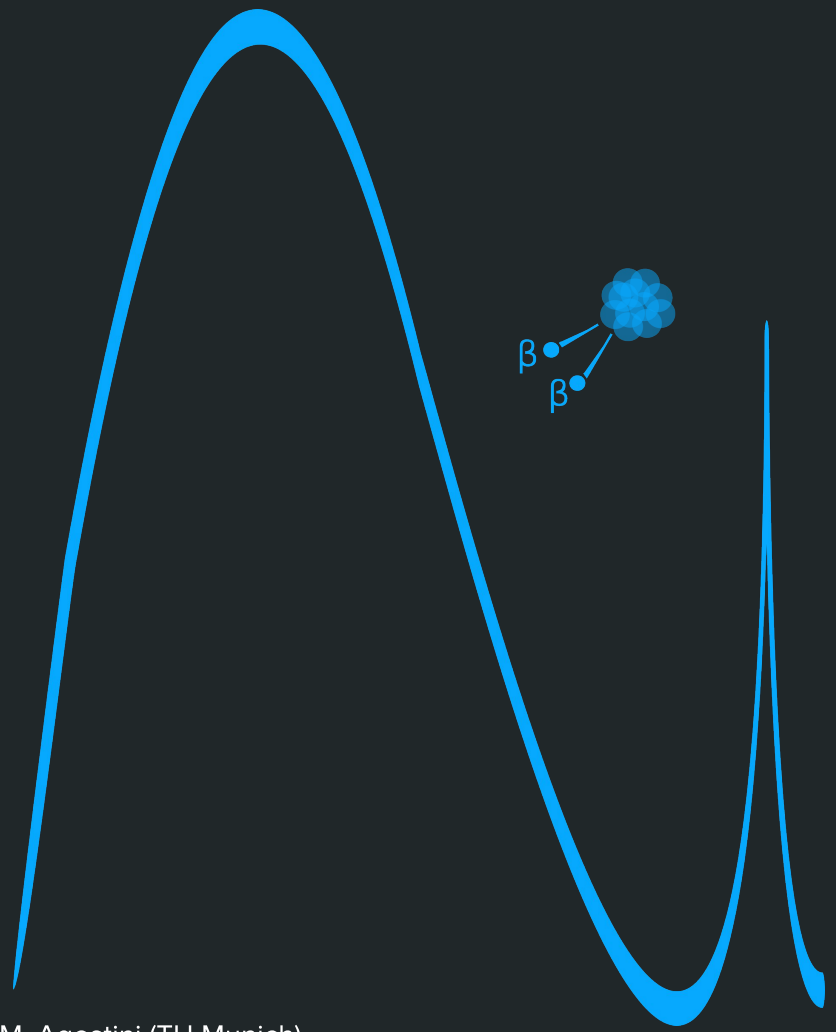
2018 2020 2022 2024 2026

LEGEND 1000

Completion of GERDA

Construction and Commissioning of LEGEND-200

LEGEND-200 achieves a sensitivity of $T_{1/2} \sim 10^{27}$



Outlook

- 0νββ decay is a portal to new physics with strong implications on neutrinos and cosmology
- Experimental search very challenging but a discovery could be around the corner
- GERDA and Majorana proved that a large mass background-free and high-resolution experiment is feasible
- LEGEND is under preparation to boost the $T_{1/2}$ sensitivity of two orders of magnitude