The search for neutrinoless double beta decay

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Colloquium
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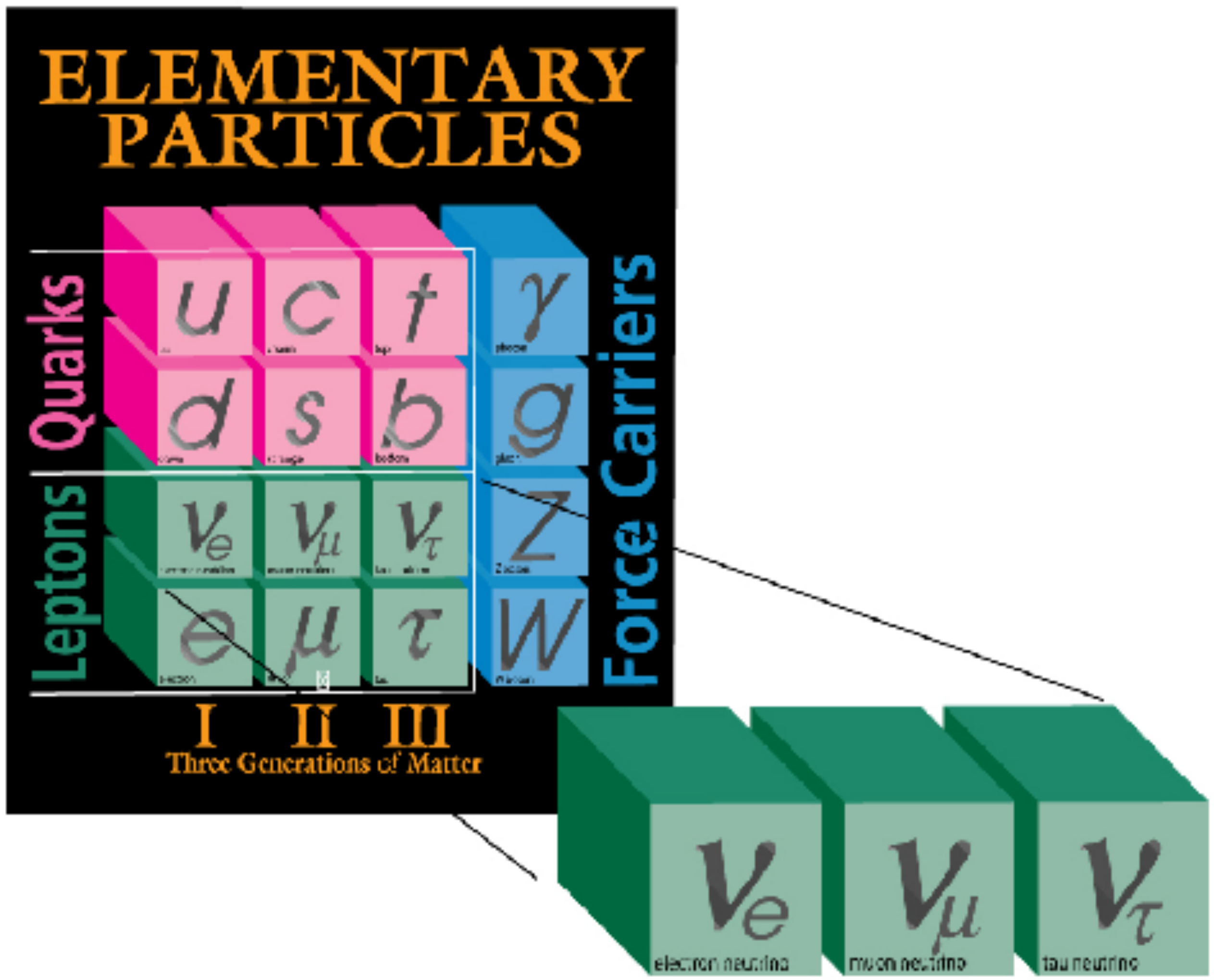
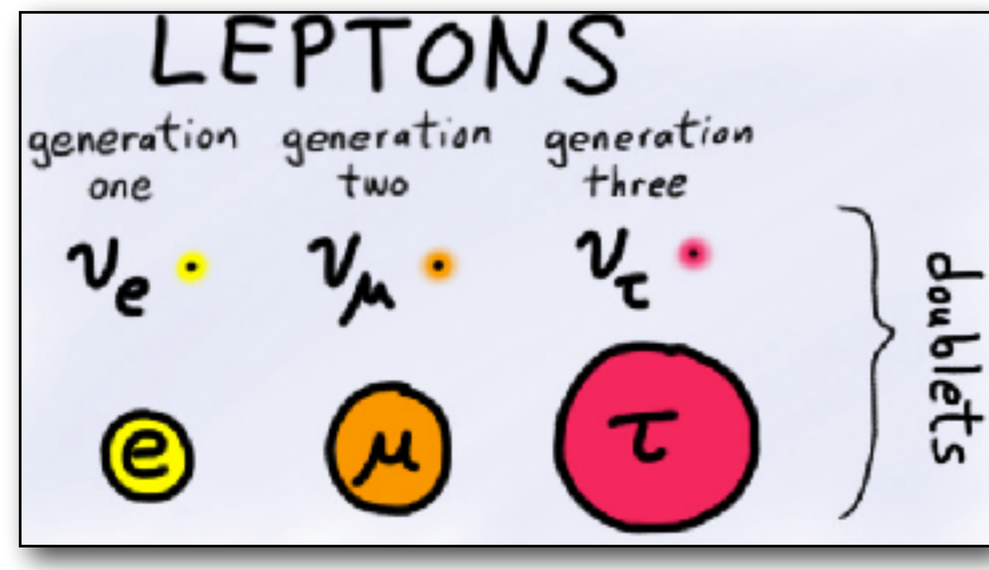
Chapter 1:

Neutrinos and the flavour puzzle

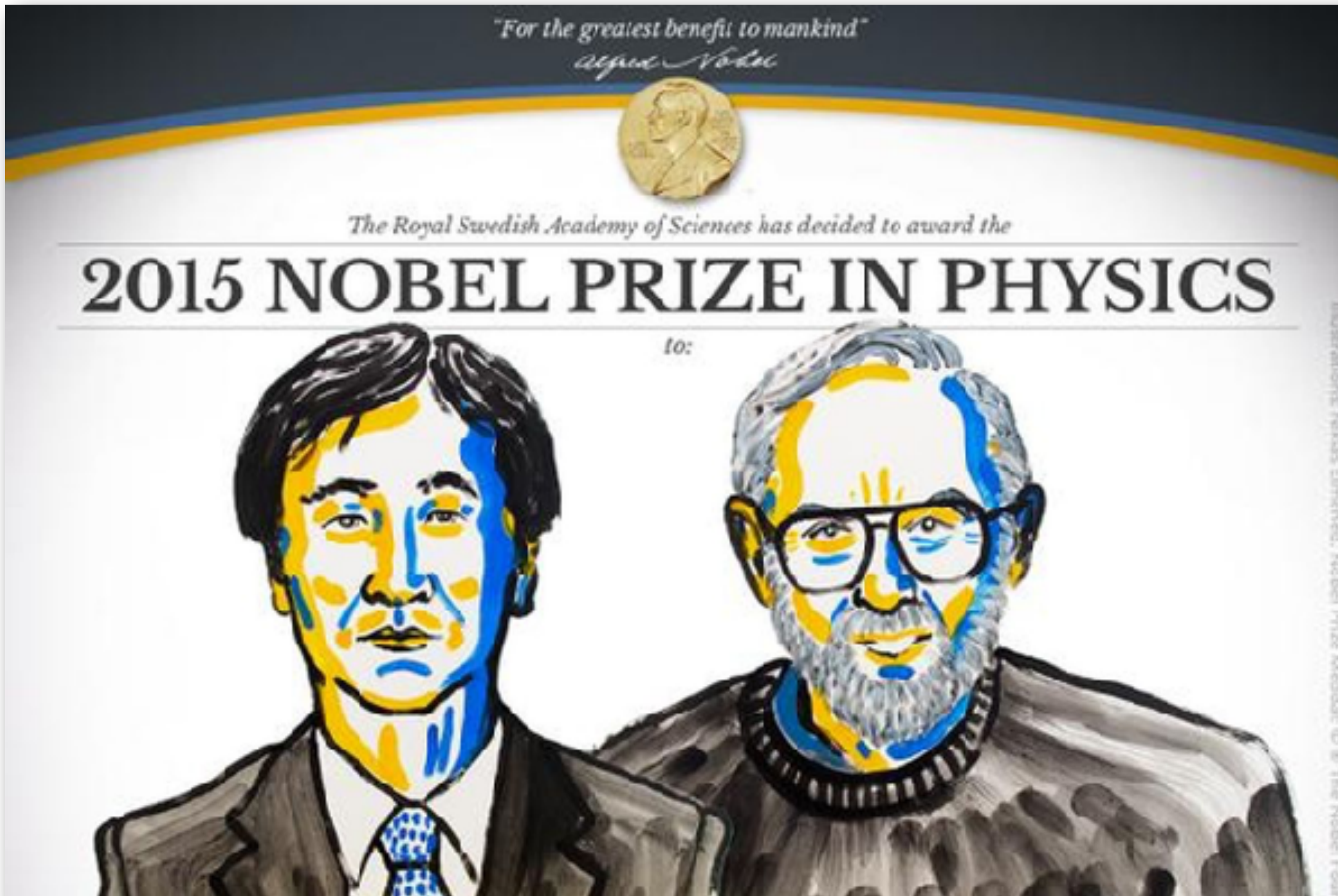
Neutrinos in the Standard Model





- **Standard Model neutrinos:** 3 types, only weakly interacting, massless

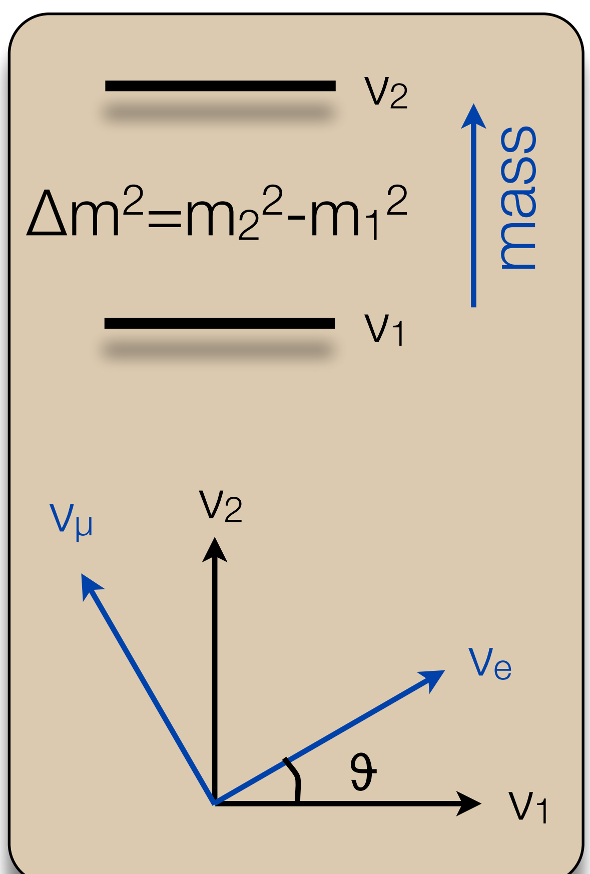
Late '90s: cracks in the Standard Model

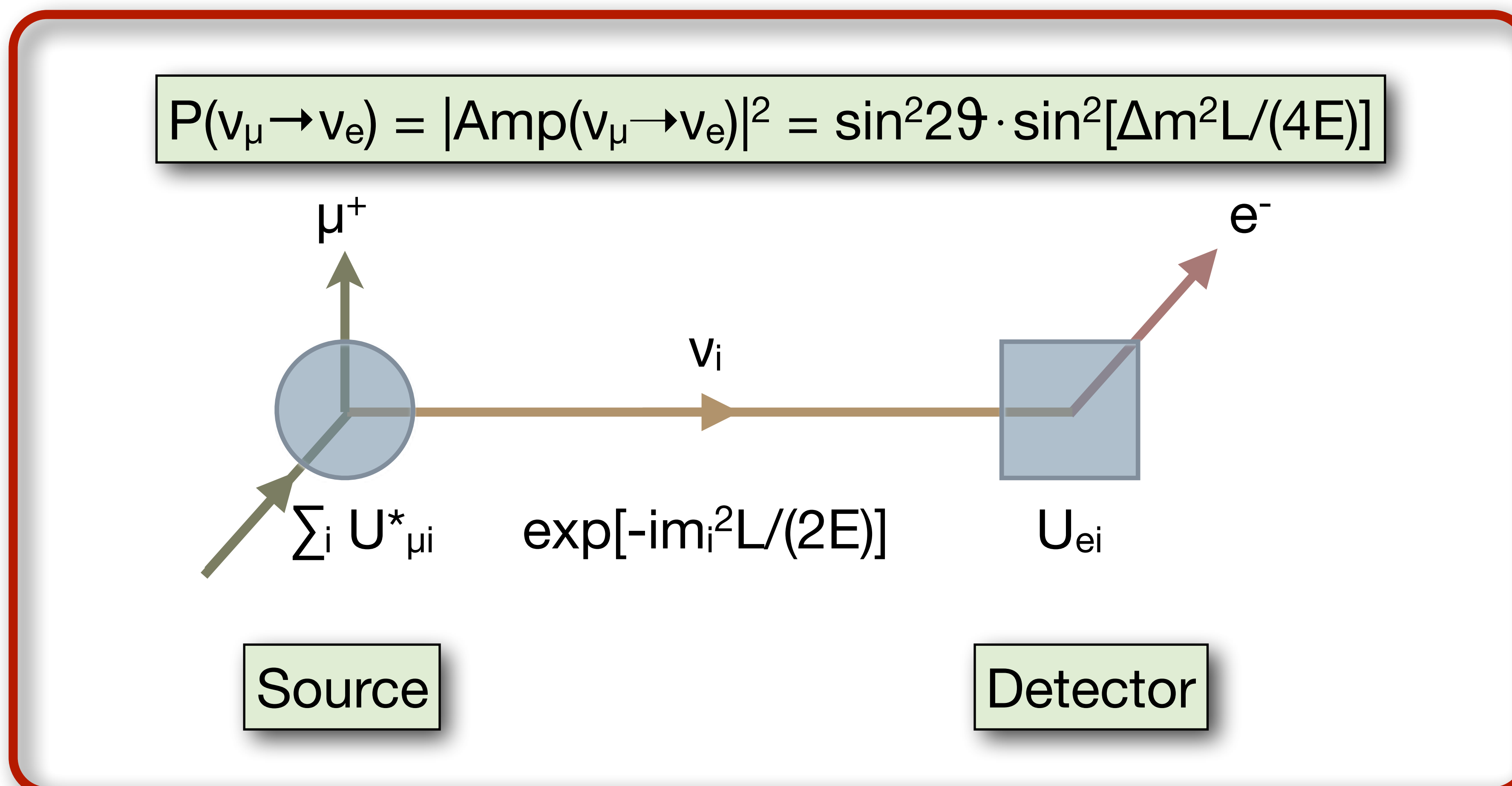


Nobel Prize in Physics 2015:
to Takaaki Kajita (Super-Kamiokande) and Arthur B. McDonald (SNO)
"for the discovery of neutrino oscillations, which shows that neutrinos have mass"

Neutrino oscillations

- Neutrinos change flavour as they propagate following oscillatory pattern
- Neutrino oscillation implies massive neutrinos and neutrino mixing





2-neutrino mixing example, for ν_μ beam with energy E

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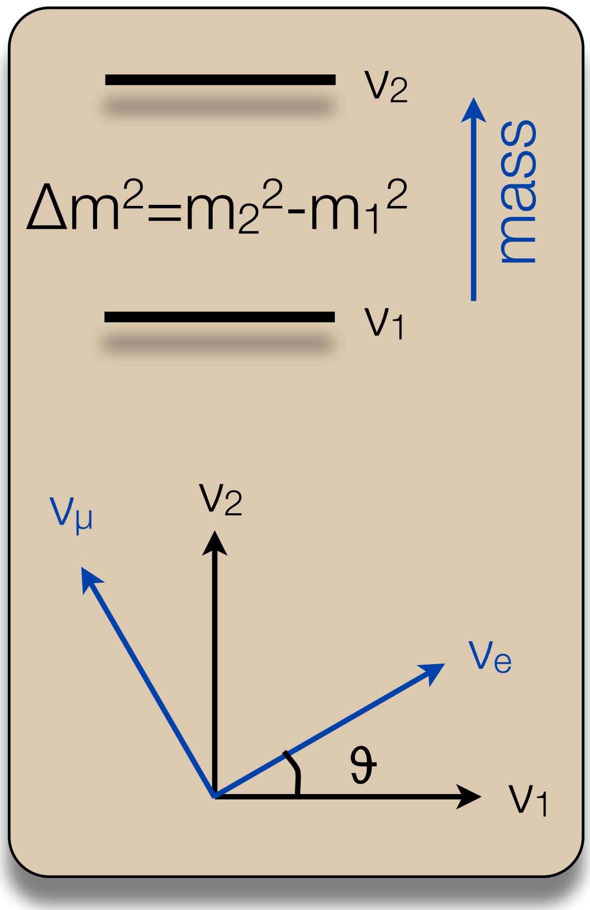

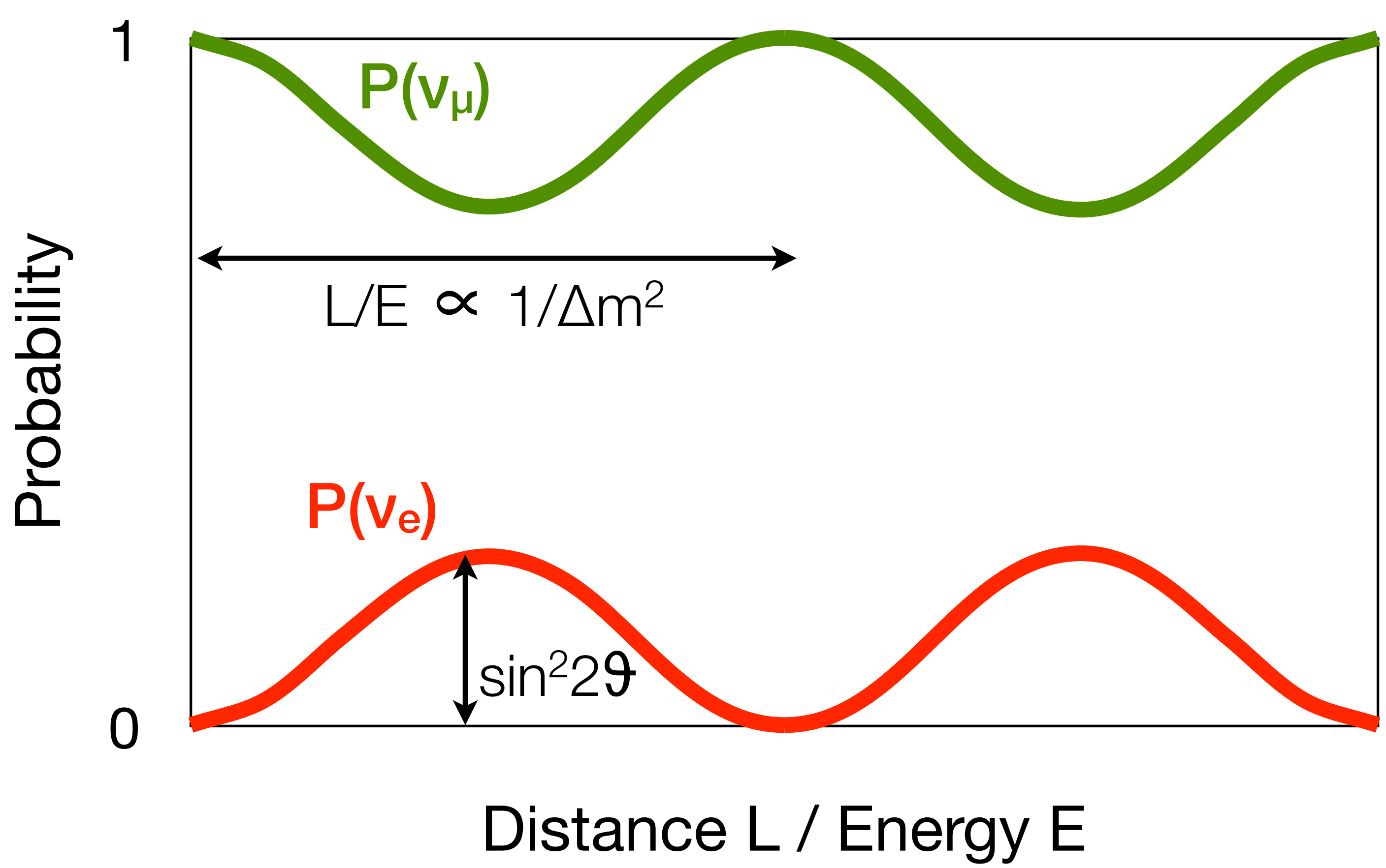

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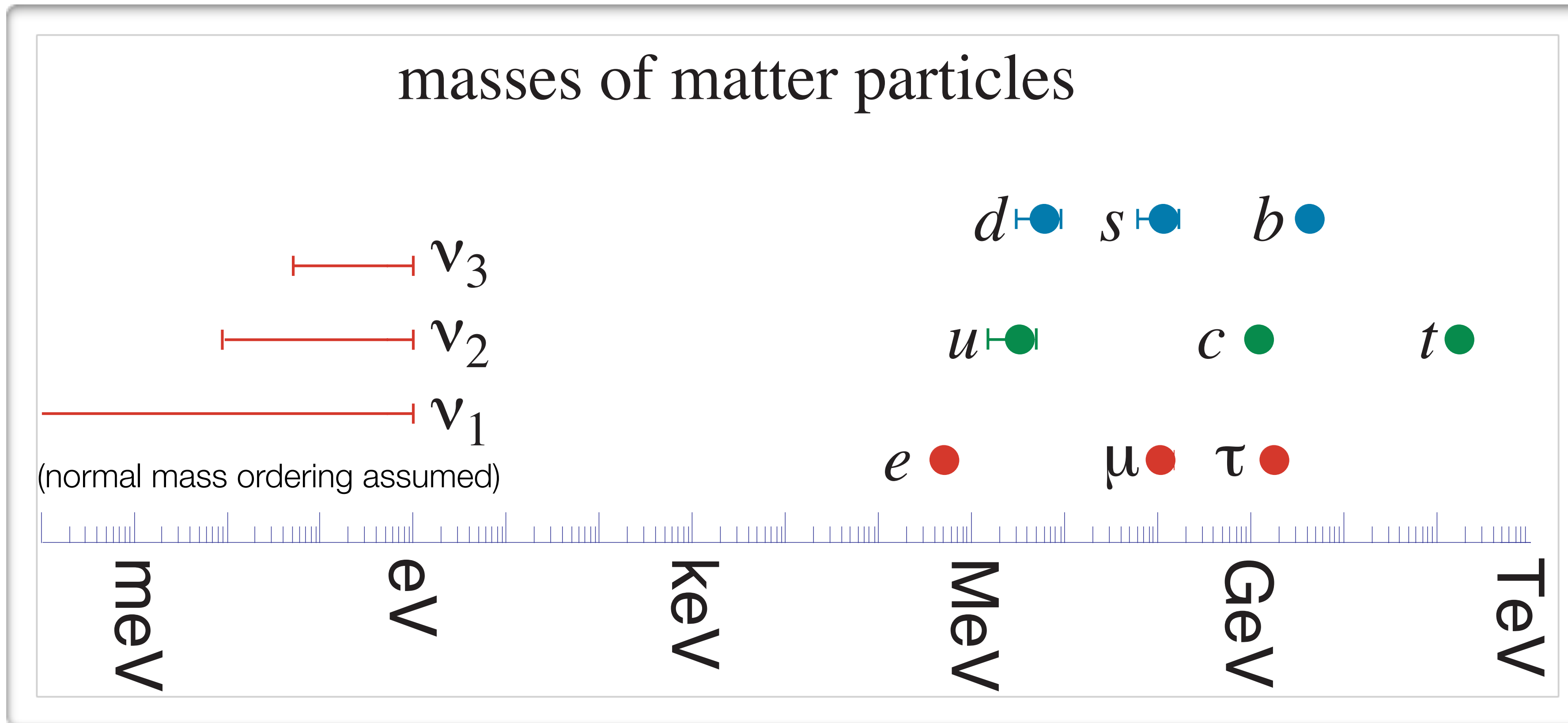
Neutrinos and the flavour puzzle

- **Neutrino mass:** non-zero and <u>small</u>
- **3ν flavour mixing:** large

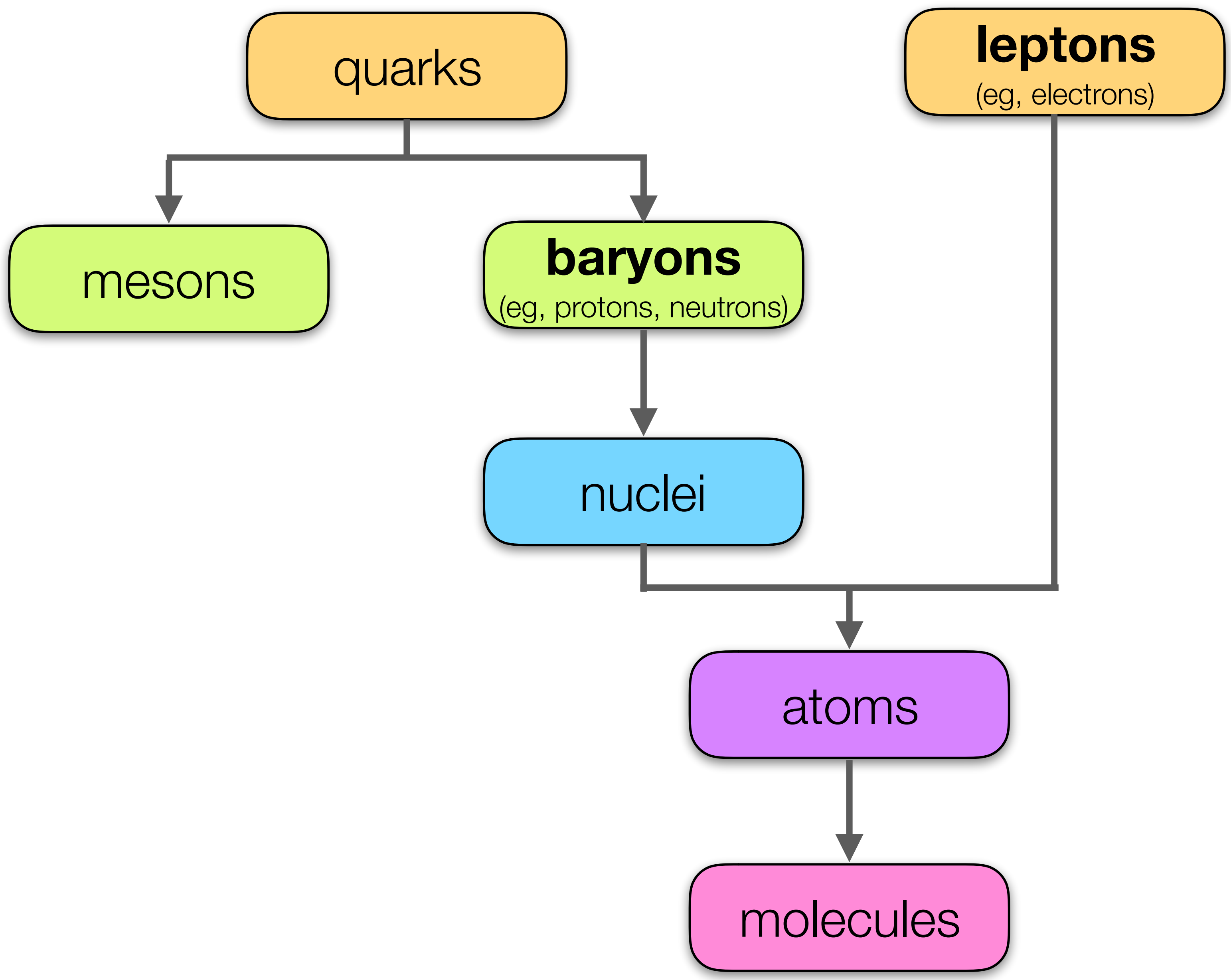


- **Flavour puzzle:**
  - Why three generations?
  - Why hierarchical masses?
  - Origin of mixing pattern?

Chapter 2:

The baryogenesis puzzle

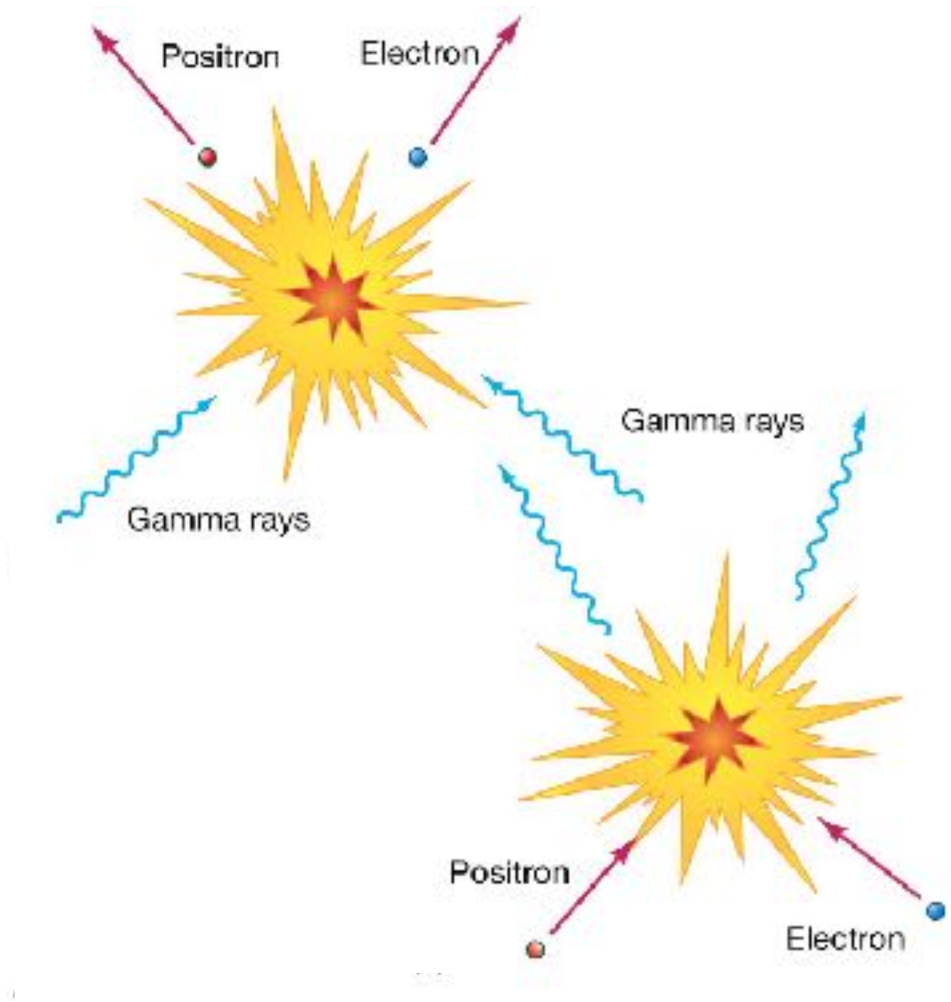
The building blocks of matter



- Ordinary matter requires both baryons and leptons

The first matter in the Universe

- Early Universe dominated by high-energy radiation
- Photons with enough energy to produce particle-antiparticle pairs
- Matter and antimatter thought to be equally abundant at first



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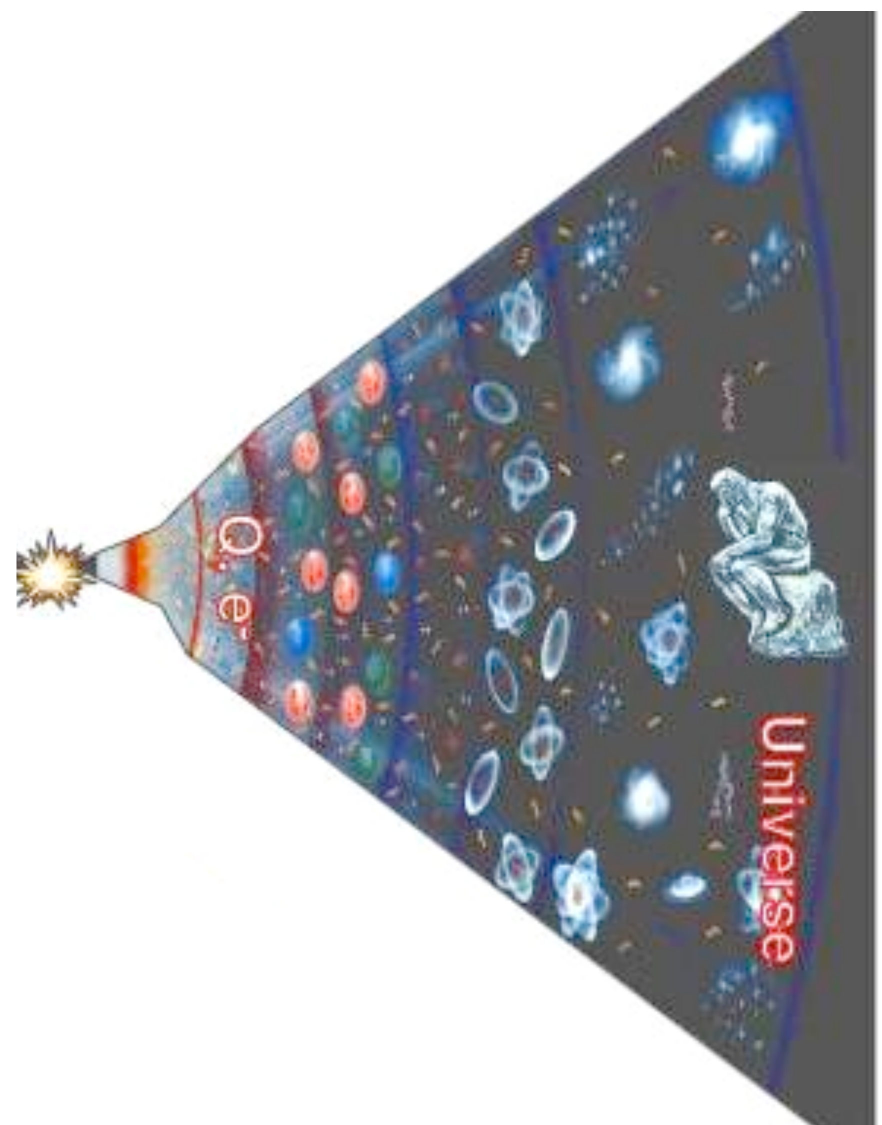
The current matter in the Universe

- No convincing evidence to date for complex antimatter in space
- Search for anti-nuclei with AMS experiment: **Anti-He / He** ≲ **10^{-8}**



In fact, why do we see matter at all?

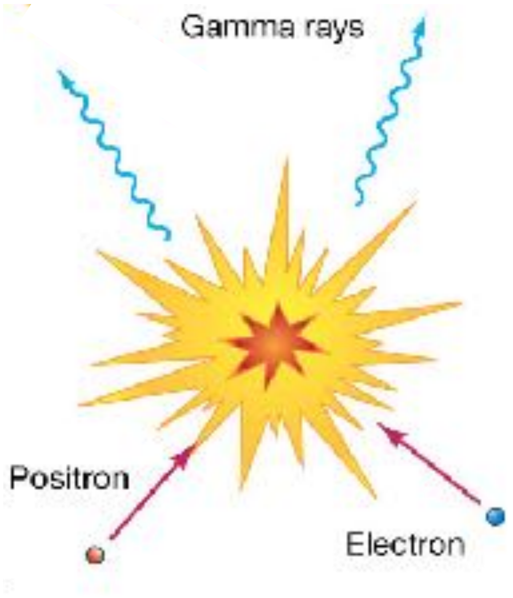
Baryon symmetry

1,000,000,000 | 1,000,000,000
MATTER | ANTIMATTER

ANNIHILATION

No Baryogenesis

MATTER | ANTIMATTER



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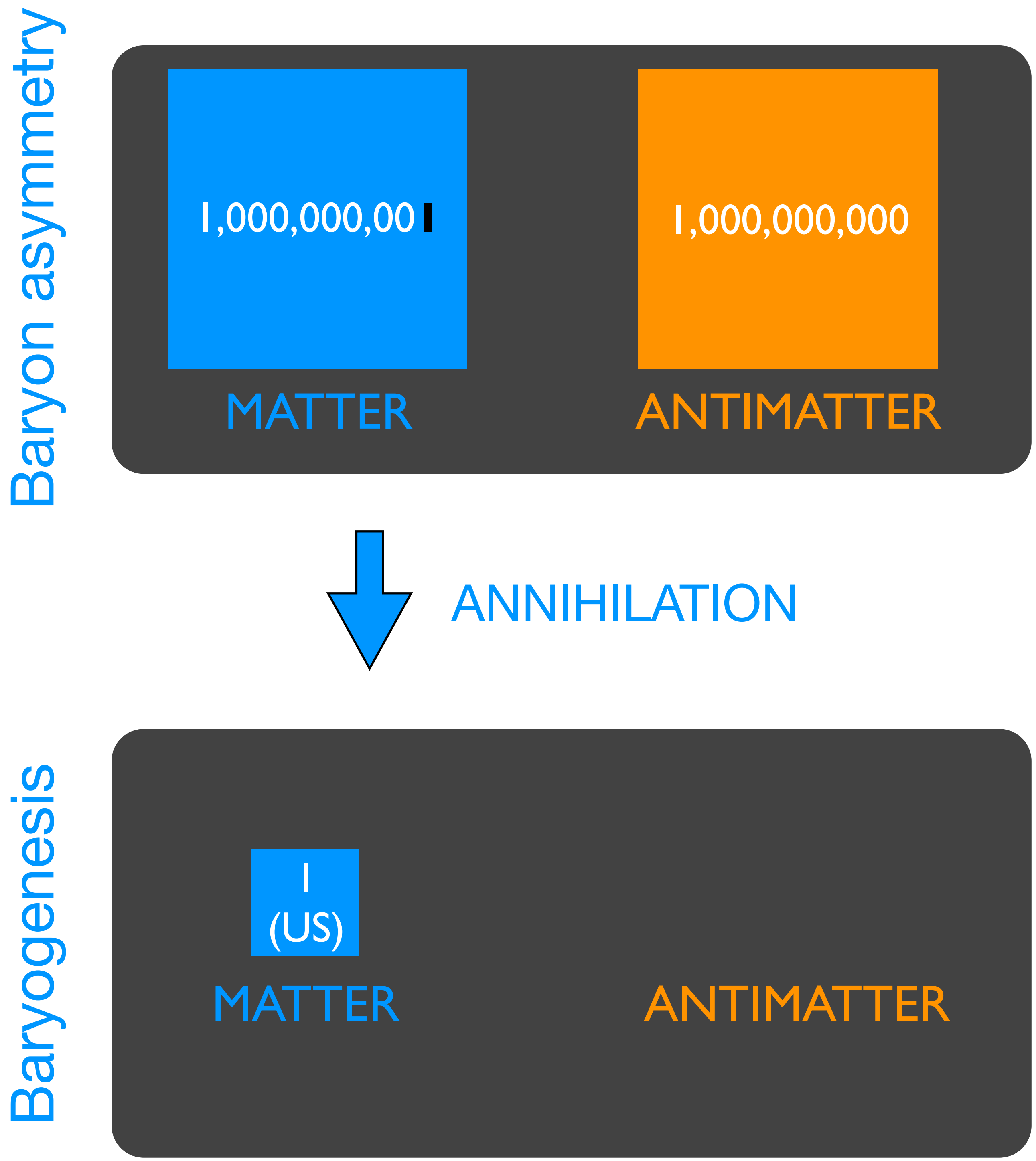


- Some physics process slightly changed matter/antimatter equilibrium in favor of matter, shortly after Big Bang
- All antimatter annihilated with matter, leaving only matter: **birth of baryons**

Baryon asymmetry in the early Universe

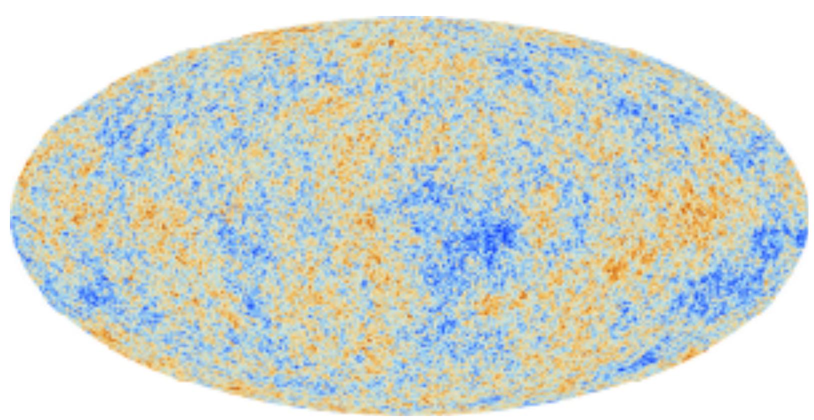
Experimental evidence

- The baryon asymmetry per unit volume, normalised to the photon number density, has not changed since a few secs after Big Bang
- It has been accurately measured via multiple probes:

BBN ($t \simeq$ min):

$$(n_B - n_{\bar{B}})/n_\gamma = 6\times10^{-10}$$

CMB ($t \simeq$ Myr):



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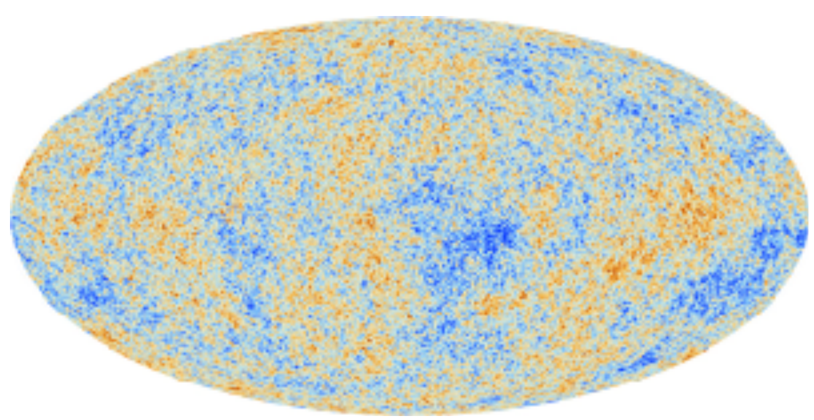


What process caused this baryon/antibaryon asymmetry?

Chapter 3:

Majorana neutrinos to the rescue

Is a neutrino its own antiparticle?

YES

Majorana Neutrino

NO

Dirac Neutrino

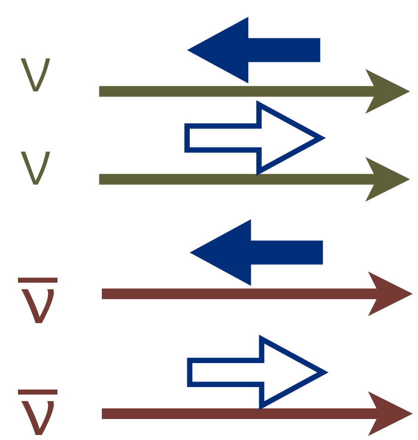
- Both possibilities exist for the neutrino
- A Majorana neutrino would be unlike any other fundamental fermion: **a new form of matter**

Difference between Dirac and Majorana neutrinos

Idealised neutrino scattering experiment

Dirac:

- 4 states
- $\nu \neq \bar{\nu}$



Helicity	Conserved Lepton Number	Lepton production rate	Anti-lepton production rate
-1/2	+1	1	0
+1/2	+1	$(m/E)^2 << 1$	0
-1/2	-1	0	$(m/E)^2 << 1$
+1/2	-1	0	1

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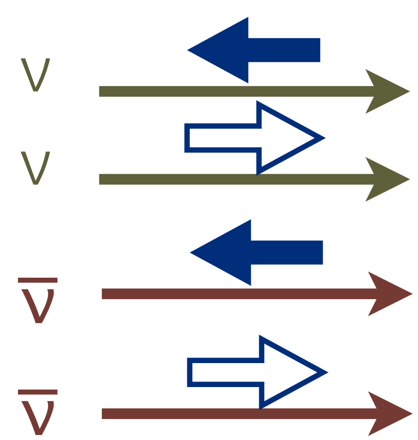

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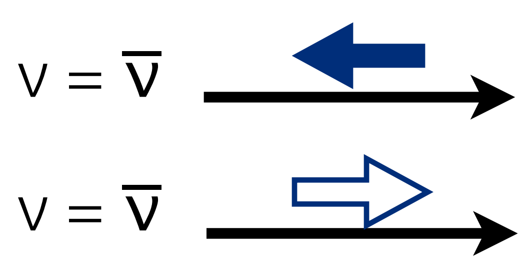
Majorana:

- 2 states
- $\nu = \bar{\nu}$

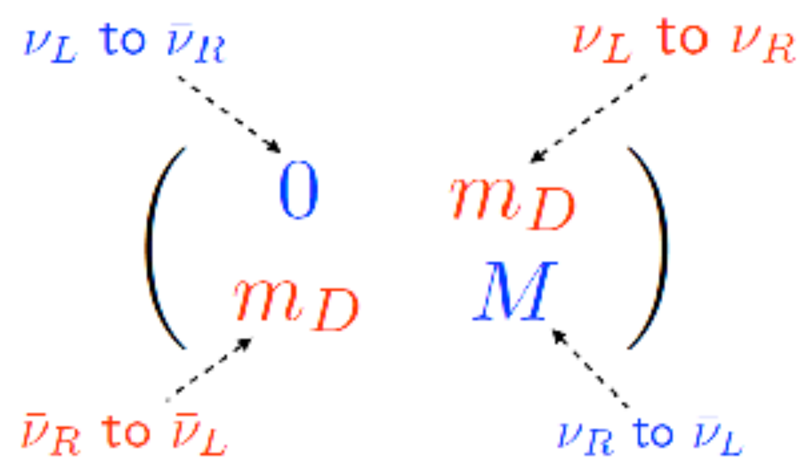


Helicity	Conserved Lepton Number	Lepton production rate	Anti-lepton production rate
-1/2	none	1	$(m/E)^2 << 1$
+1/2	none	$(m/E)^2 << 1$	1

A prime candidate for small neutrino mass

The see-saw mechanism

- Neutrino mass matrix, with both Majorana (M) and Dirac (m_D) terms:



- Majorana terms induce **| ΔL | = 2** lepton number violating processes and imply ν = $\bar{\nu}$
- M: **a new physics scale**

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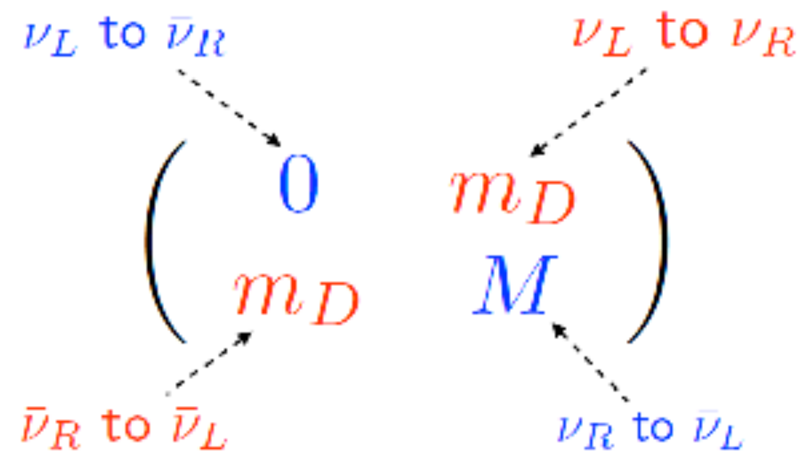
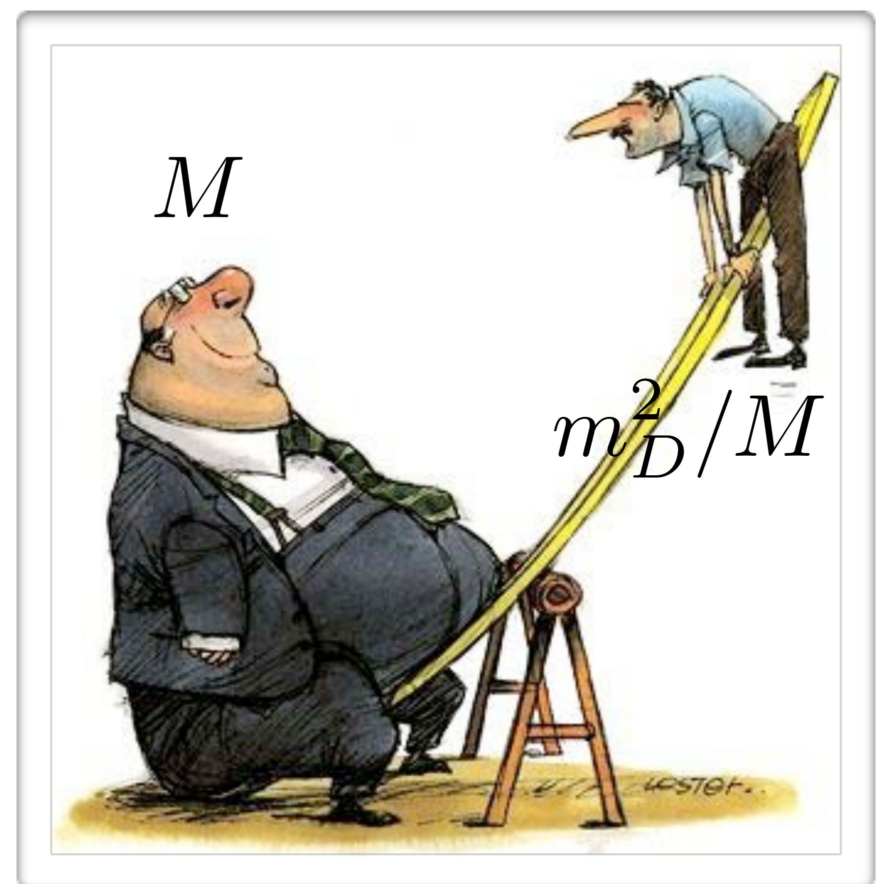
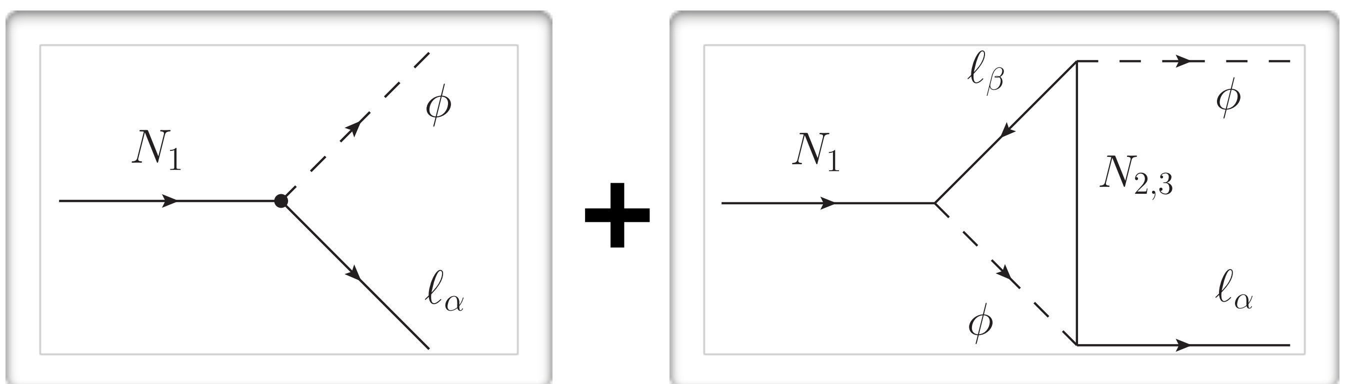


- Majorana terms induce **| ΔL | = 2** lepton number violating processes and imply ν = $\bar{\nu}$
- M: **a new physics scale**
- ”See-saw” limit **m_D << M** explains small neutrino masses, which indirectly probe new physics scale



A prime candidate for the baryon asymmetry

- Baryon asymmetry possibly induced by a lepton asymmetry: *leptogenesis*
- *Decay of heavy Majorana neutrinos* ideal for leptogenesis, if CP is violated



$$\text{Rate}(N_1 \rightarrow l_\alpha\, \phi) \neq \text{Rate}(N_1 \rightarrow \bar{l}_\alpha\, \bar{\phi})$$

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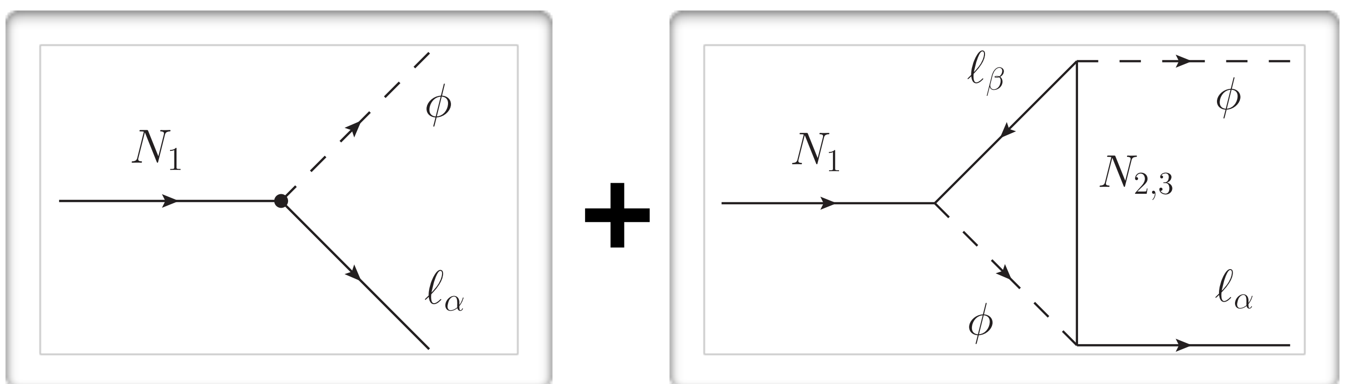


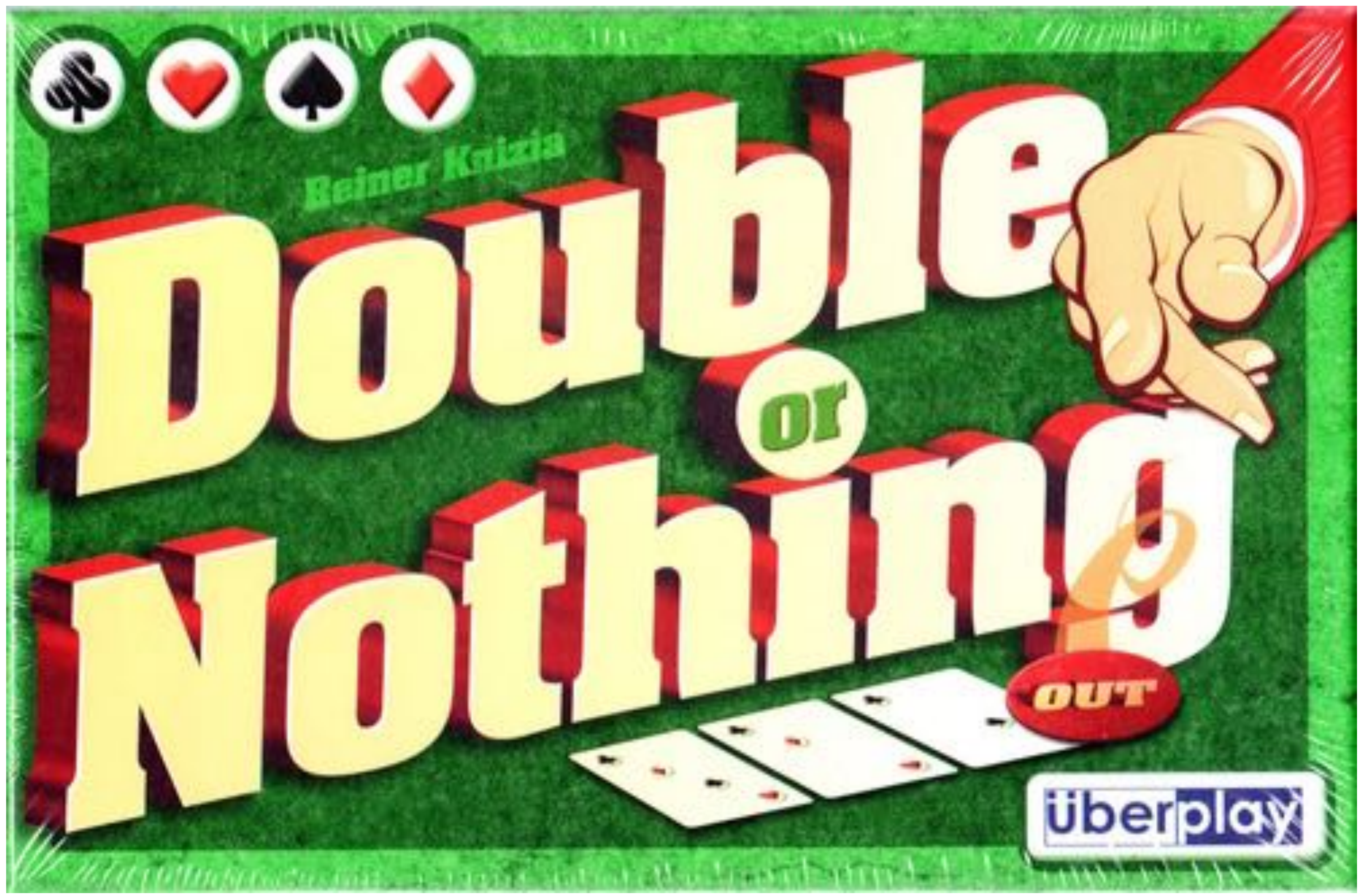
$$\text{Rate}(N_1 \to l_\alpha\, \phi) \neq \text{Rate}(N_1 \to \bar{l}_\alpha\, \bar{\phi})$$

- Unequal number of leptons and antileptons is later transferred to baryons:

baryon asymmetry

How to find out if neutrinos are Majorana?

Play…



Chapter 4:

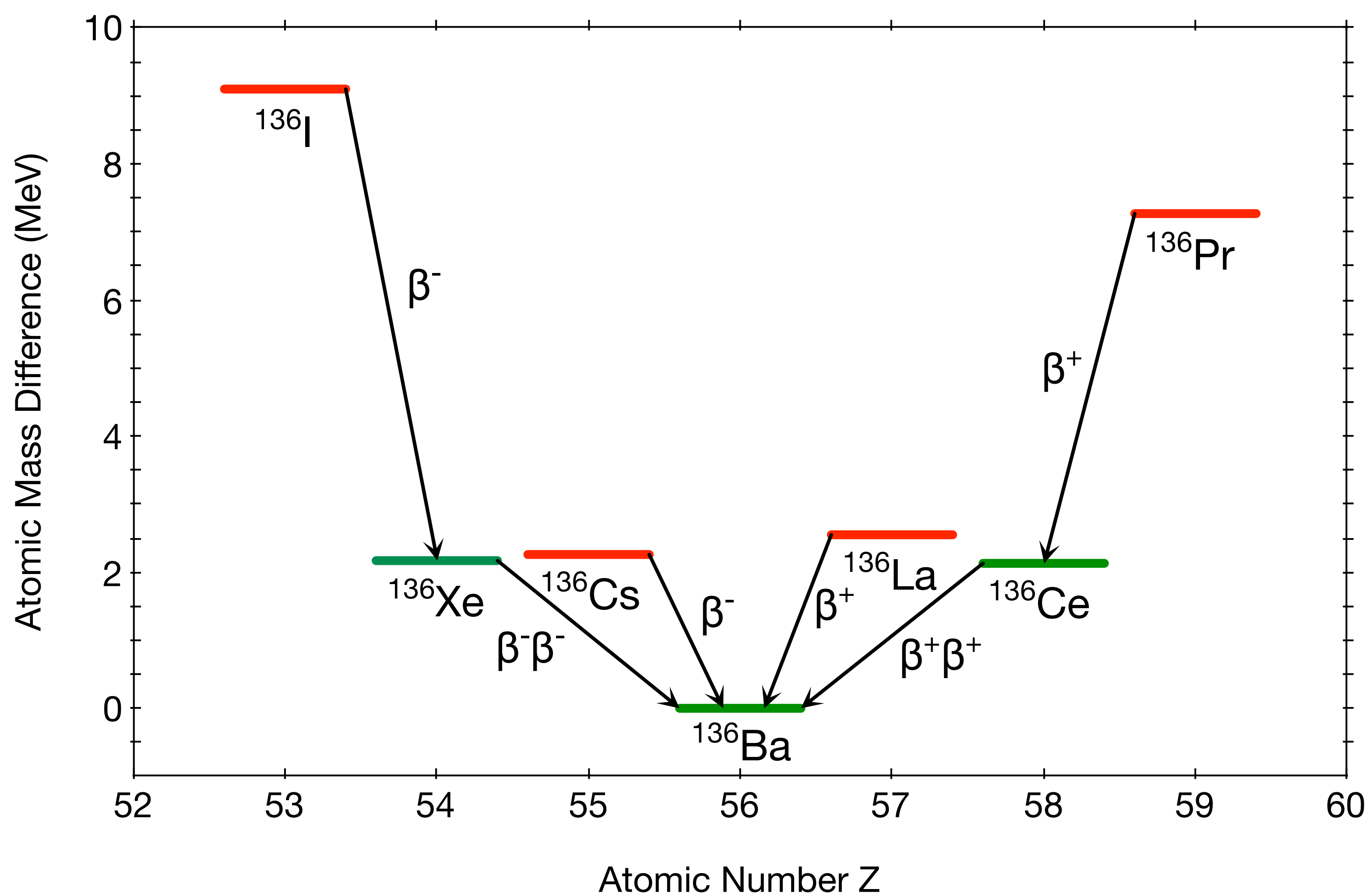
Searching for Majorana neutrinos with ββ0ν

Nuclear double beta decay

- Nuclear **(Z,A)→(Z+2,A)** transition with emission of two electrons. Second order process mediated by the weak interaction

- This process exists in 35 nuclides due to nuclear pairing interaction

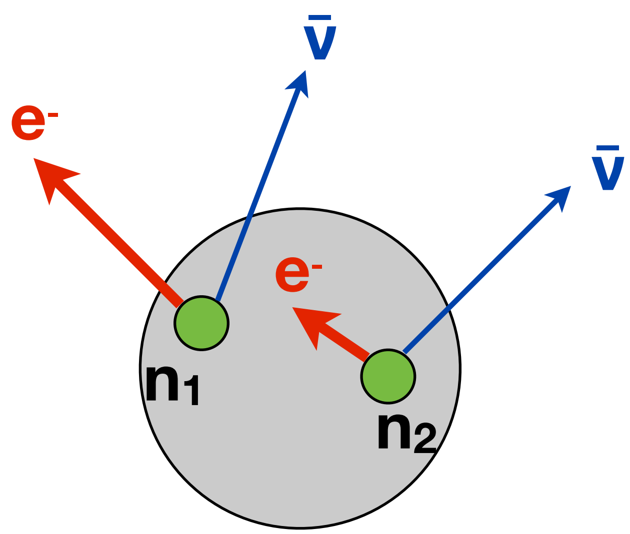
  → favours energetically the even-even isobars over the odd-odd ones.



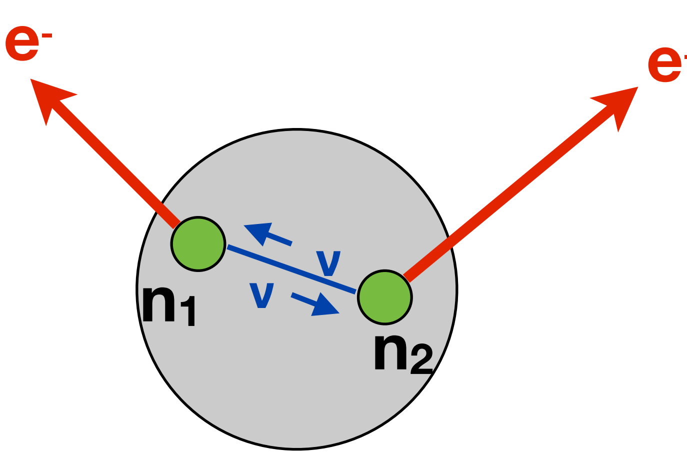
Double beta decay modes

- Two basic decay modes:

ββ2ν



ββ0ν



Two neutrino mode

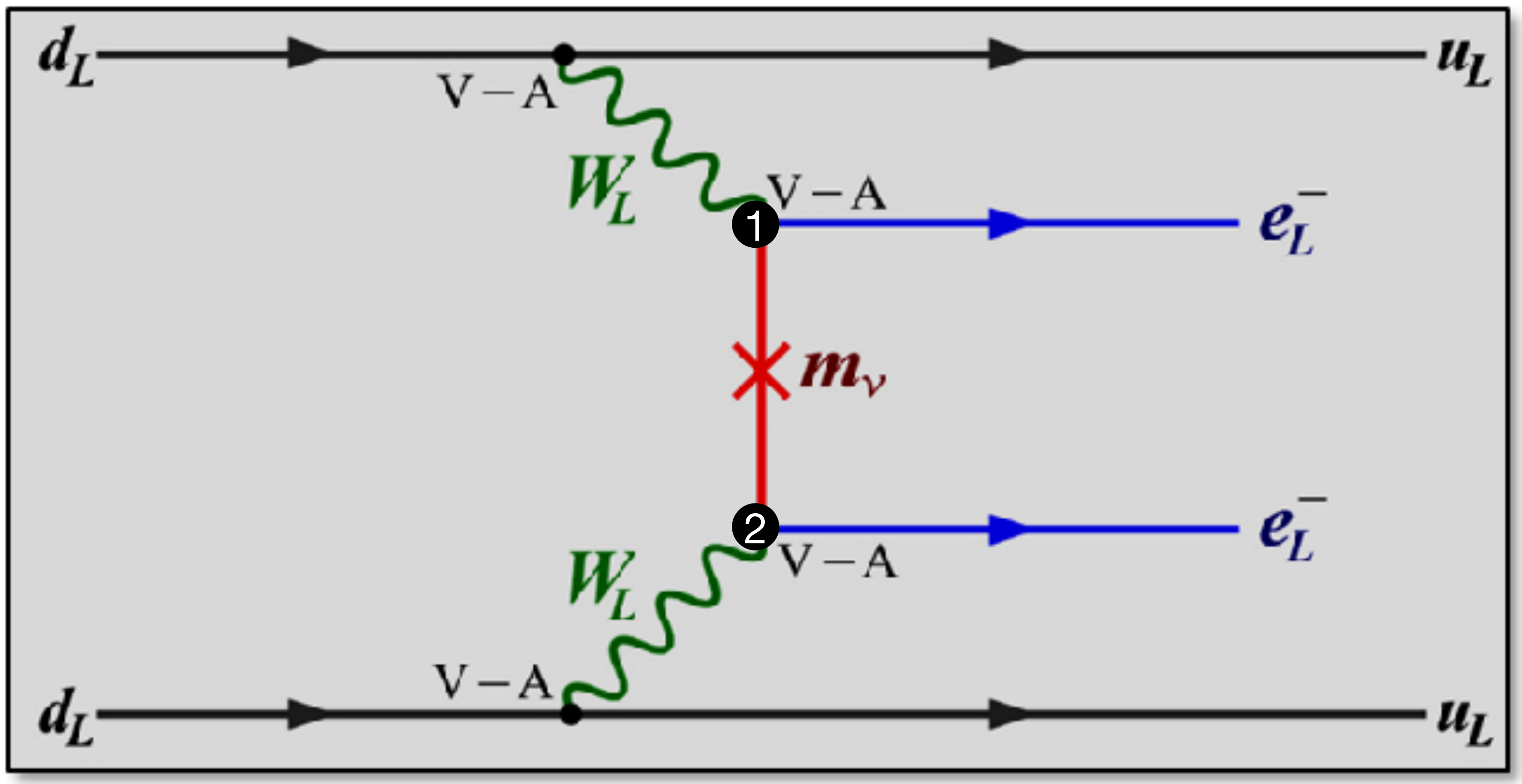
- Observed in several nuclei
- 10^{19}-10^{21} yr half-lives
- Standard Model allowed
- Conserves lepton number

Neutrinoless mode

- Not observed yet in Nature
- $>10^{26}$ yr half-lives
- Would signal BSM physics
- Violates **L** by two units

ββ0ν and Majorana neutrinos

- ββ0ν evidence would imply that neutrinos are massive, Majorana, particles



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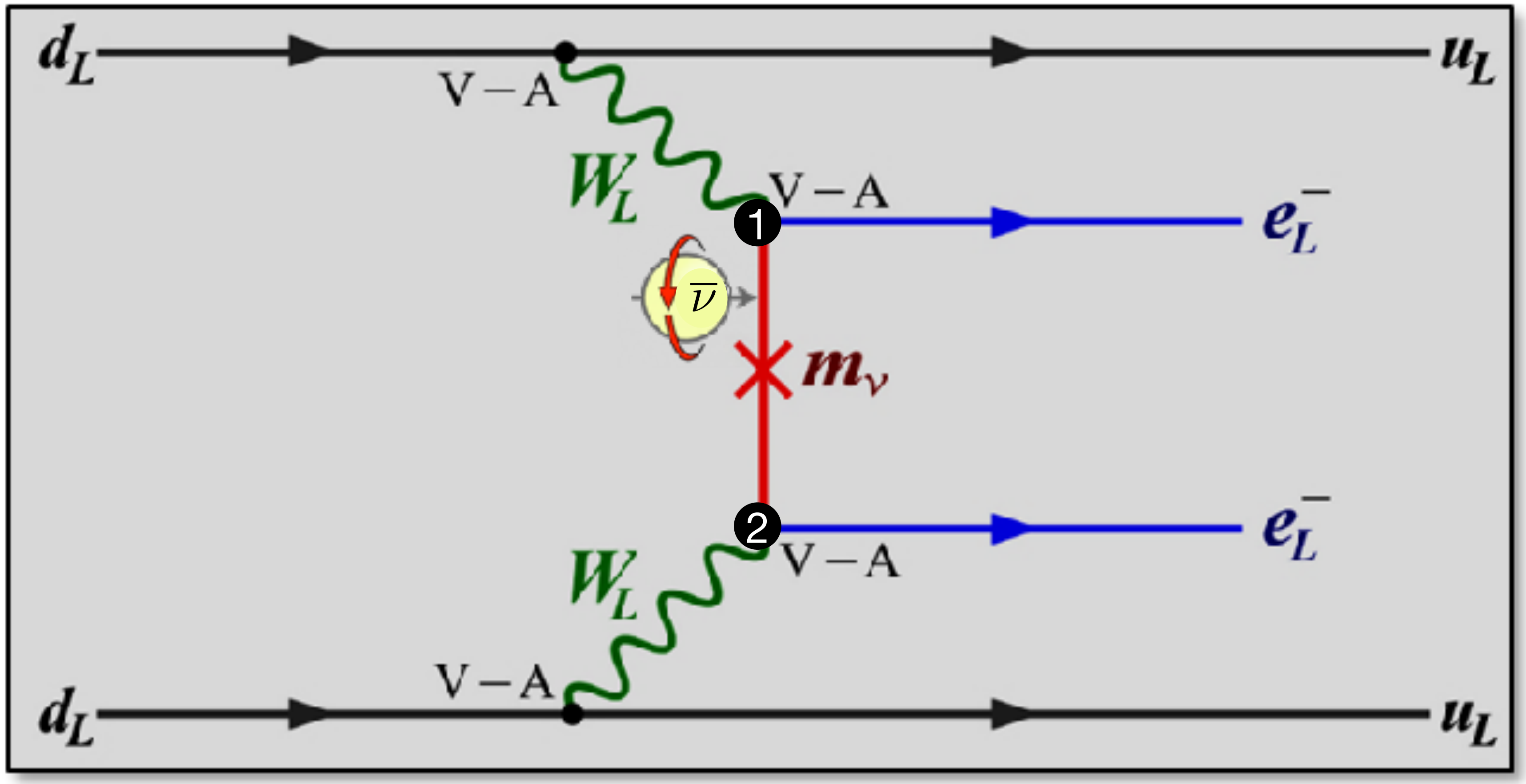

Emitted in ❶, in association with electron, with almost total positive helicity

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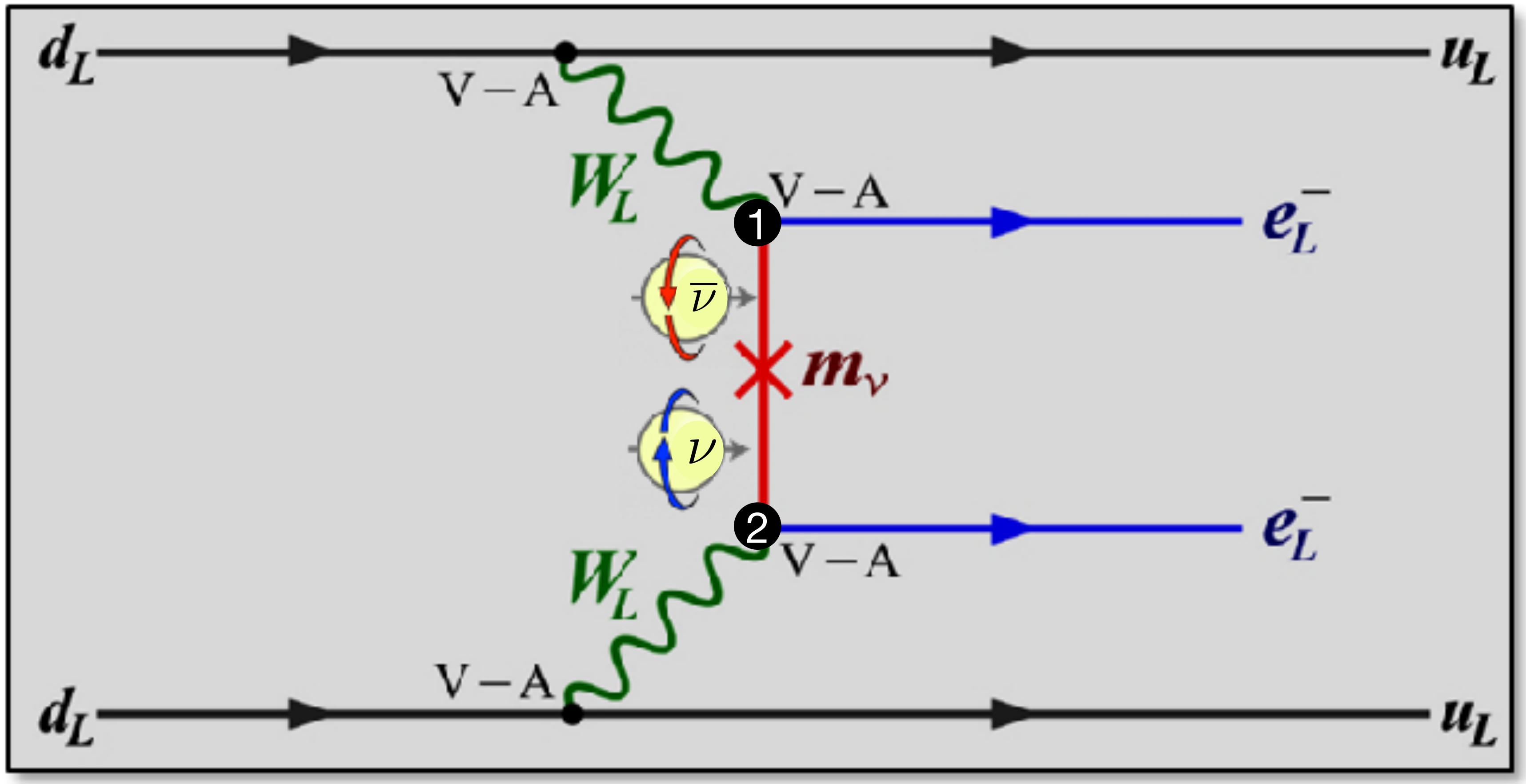


Emitted in ❶, in association with electron, with almost total positive helicity

Only its small, $\mathcal{O}$(m/E), negative helicity component absorbed in ❷, producing another electron

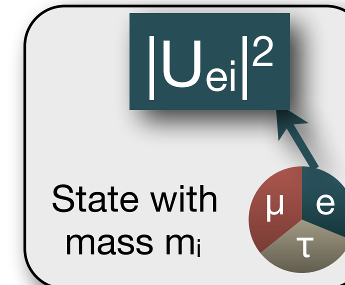
ββ0ν and neutrino mass

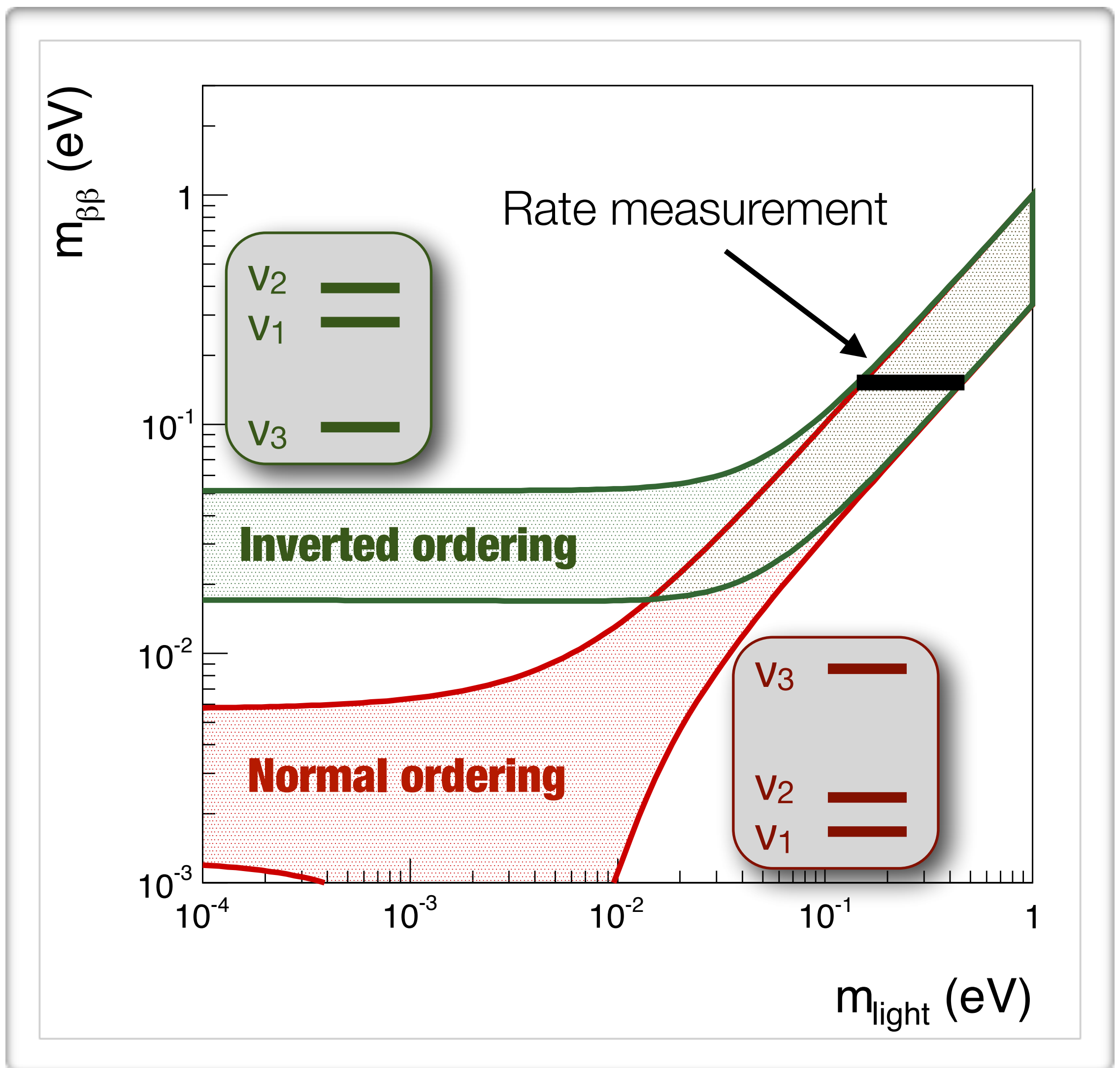
- ββ0ν rate constrains neutrino mass:

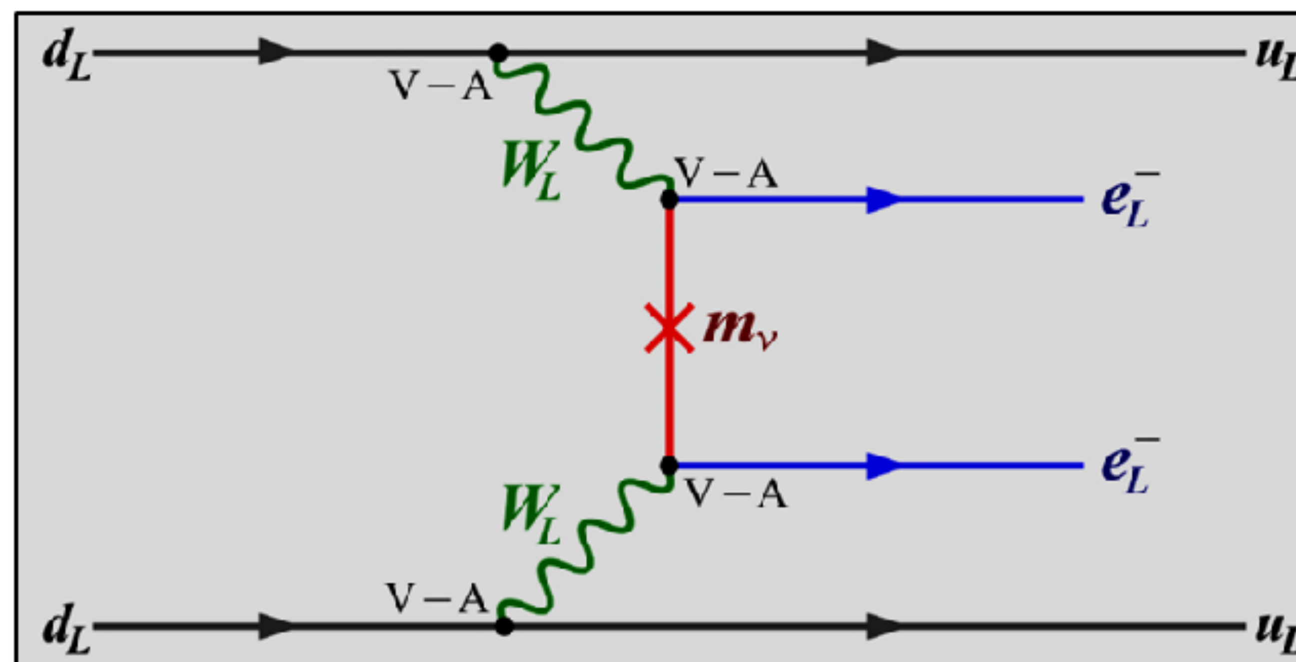
$$(\text{Rate})_{\beta\beta 0\nu} \propto m_{\beta\beta}^{\mathbf{2}}$$

Majorana ν mass:

$$m_{\beta\beta} \equiv \left| \sum_i m_i U_{ei}^2 \right|$$







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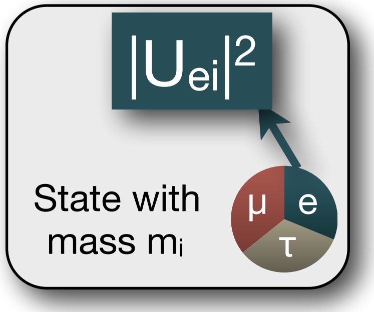

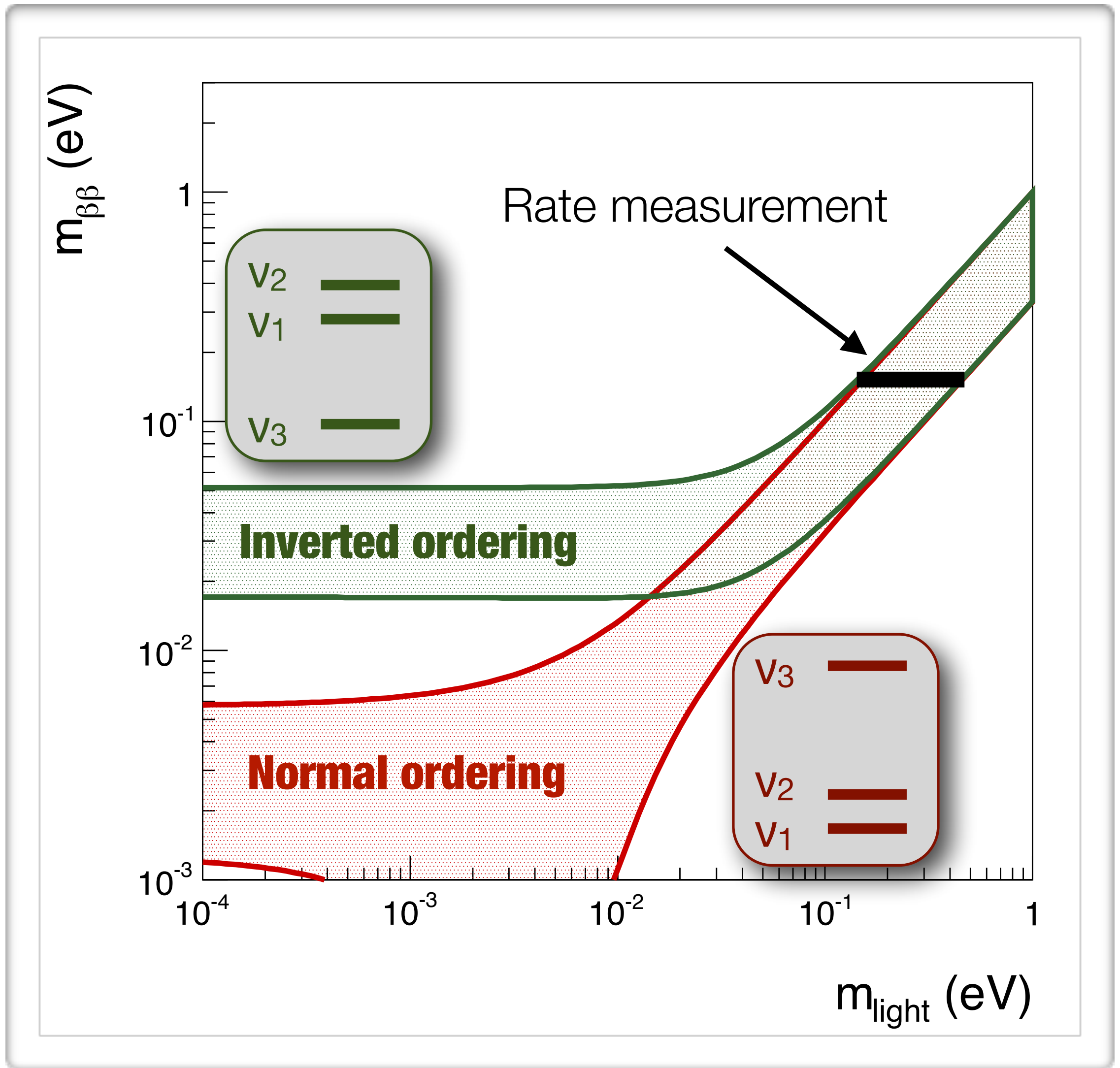

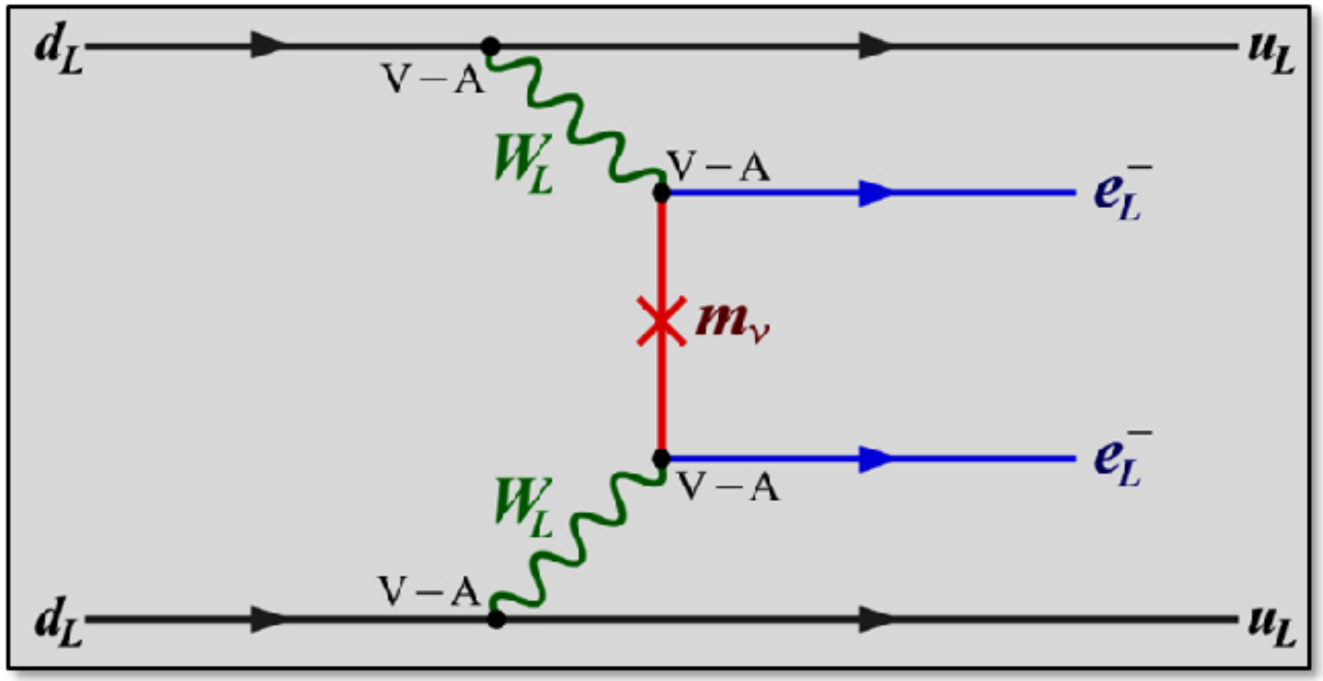

ββ0ν: most sensitive probe for Majorana neutrinos → low $m_{\beta\beta}$ reach!

Chapter 5:

Experimental challenges in ββ0ν searches

Facts of life of the double beta decay experimentalist

- Total number of ββ0ν decays that can be observed in a detector is:

$$N_{\beta\beta 0\nu} = \log 2 \cdot \frac{M_{\beta\beta} \cdot N_A}{W_{\beta\beta}} \cdot \varepsilon \cdot \frac{t}{T^{0\nu}_{1/2}}$$

mass of ββ isotope
Avogadro's constant
Exposure time
ββ0ν half-life
Molar mass of ββ isotope
Efficiency

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Exposure time

ββ0ν half-life

Molar mass of ββ isotope

Efficiency

- For ^{136}Xe experiment with 100% efficiency and 1 year exposure time, what is the mass $M_{\beta\beta}$ required to observe <u>only one</u> ββ0ν decay?

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- If ^{136}Xe ββ0ν half-life is $T_{1/2} = 10^{27}$ years, get: **$M_{\beta\beta}$ = 326 kg!**

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mass of ββ isotope — Avogadro's constant — Exposure time

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ββ0ν half-life — Molar mass of ββ isotope — Efficiency

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- Life is harder than this: non-perfect efficiencies and <u>backgrounds</u>

Experimental sensitivity to ββ0ν

- Experiment with no background:

detector efficiency

$$T^{0\nu}_{1/2} \propto \varepsilon \cdot M_{\beta\beta} \cdot t$$

exposure
(mass×time)

Experimental sensitivity to ββ0ν

- Experiment with no background:

detector efficiency

$$T^{0\nu}_{1/2} \propto \varepsilon \cdot M_{\beta\beta} \cdot t$$

exposure (mass×time)

- Experiment with background:

detector efficiency

$$T^{0\nu}_{1/2} \propto \varepsilon \cdot \sqrt{\frac{M_{\beta\beta} \cdot t}{c \cdot \Delta E}}$$

exposure (mass×time)

energy resolution

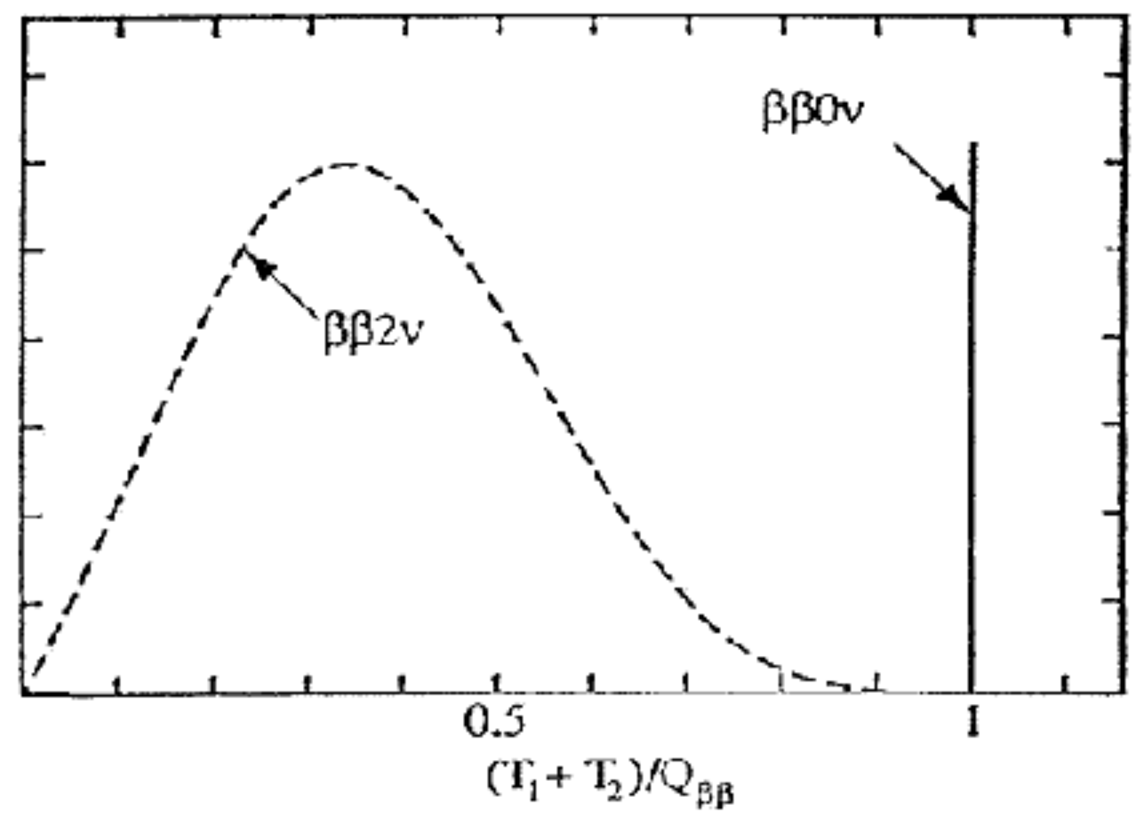
background rate (per unit energy, mass and time)

ββ0ν experimental signature

Rare process to be isolated in radio-pure detector underground

1.Calorimetry *(A MUST)*:

- *2ν mode:* continuous spectrum for sum electron kinetic energy T_1+T_2
- *0ν mode:* mono-energetic line at $Q_{\beta\beta}$ for T_1+T_2 spectrum



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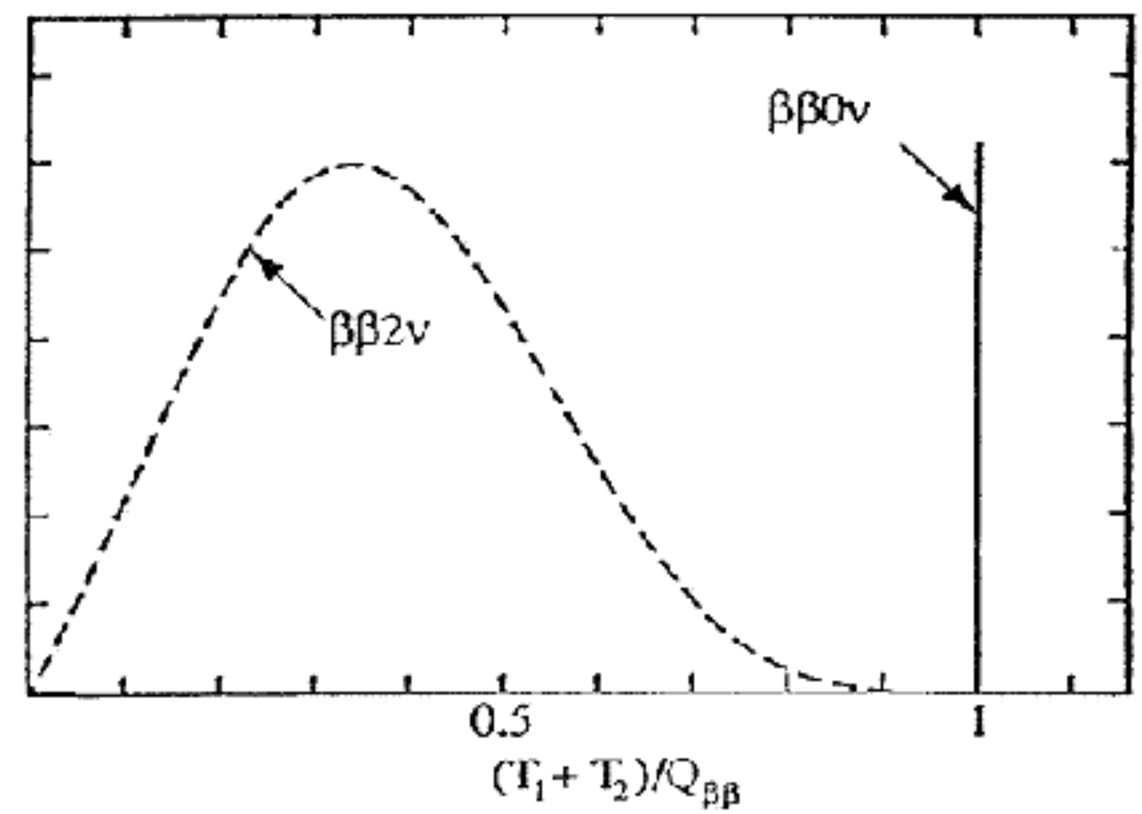
2.Topology of decay electrons *(AN ADDITIONAL HANDLE)*:

- Two electrons from common vertex



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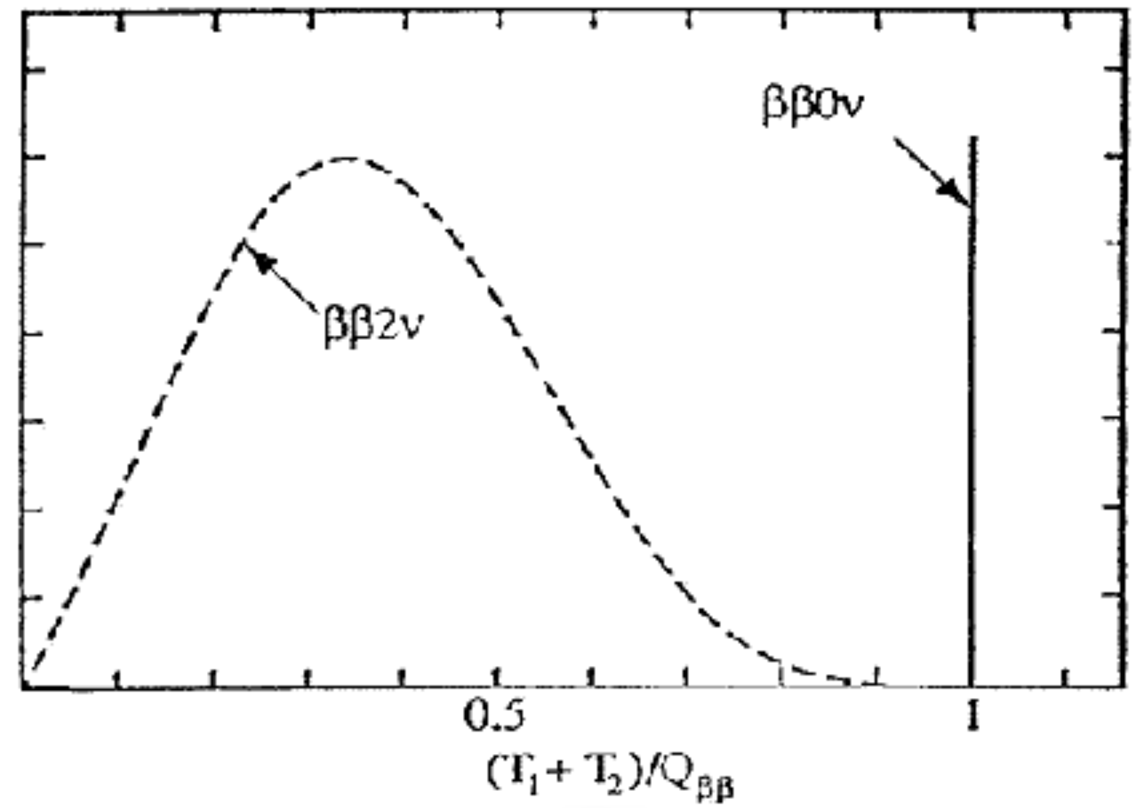


2.Topology of decay electrons *(AN ADDITIONAL HANDLE)*:

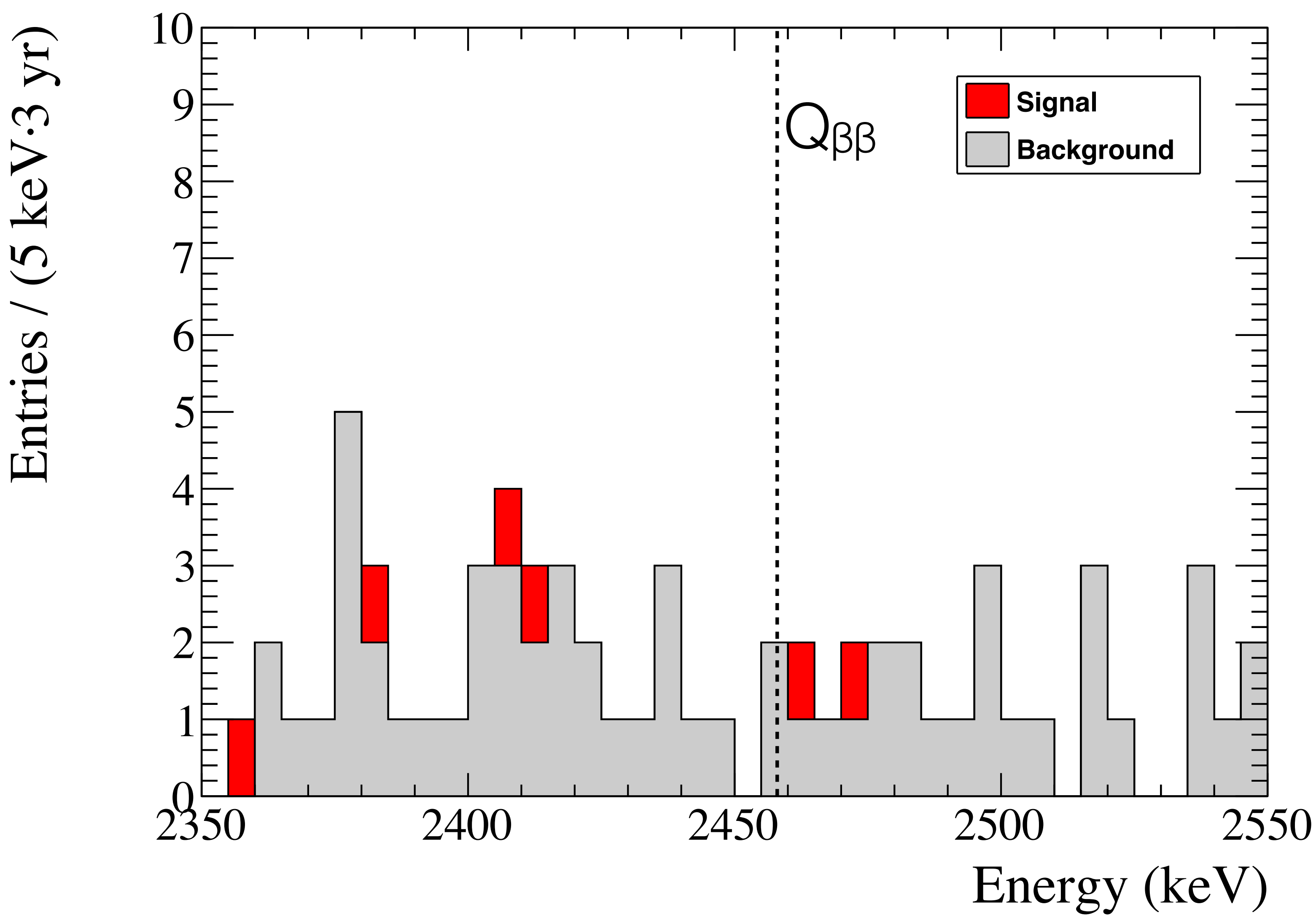
- Two electrons from common vertex

3.Daughter ion tagging *(A DREAM)*:

- Observe ion produced in the decay

How can we uncover the $Q_{\beta\beta}$ peak in the energy spectrum?

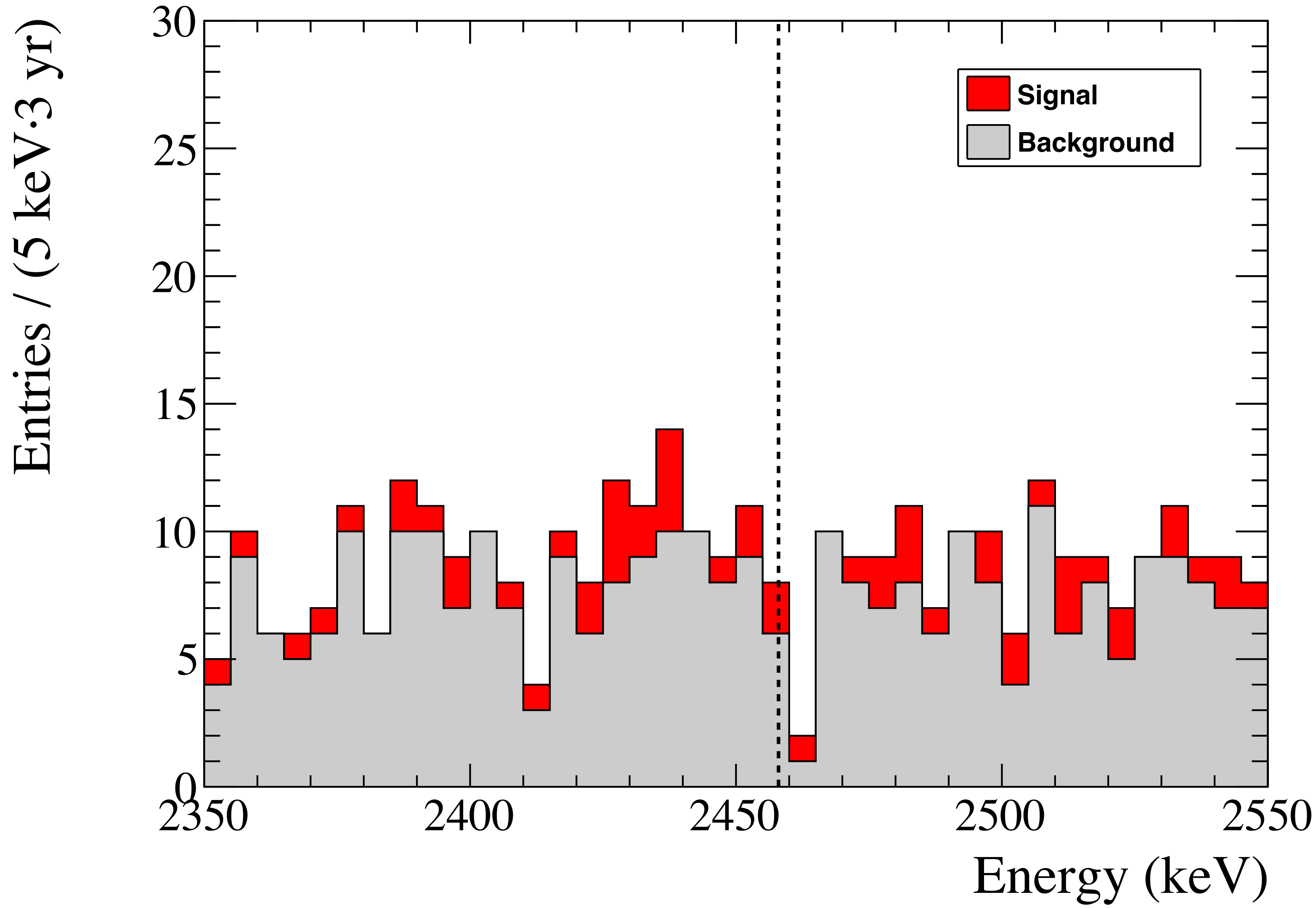
- Typical situation for current-generation detector performance, assuming $T_{1/2}^{0\nu} = 10^{26}$ yr:



- M = 100 kg
- t = 3 yr
- $T_{1/2} = 10^{26}$ yr
- ε = 100%
- ΔE = 10% FWHM
- $c = 10^{-3}$ /(keV·kg*yr)

Improvement no.1:
larger detector

$$T^{0\nu}_{1/2} \propto \varepsilon \sqrt{\frac{Mt}{c\,\Delta E}}$$



- **M = 1,000 kg**
- t = 3 yr
- $T_{1/2} = 10^{26}$ yr
- ε = 100%
- ΔE = 10% FWHM
- **c = $5 \cdot 10^{-4}$ /(keV·kg*yr)**

- More events! Also: signal ∝ volume, background ∝ surface → S/B ↗
- Mass scalability depends on chosen ββ isotope

Comparison of ββ isotopes

- ββ isotope choice also affects relationship (ββ0ν rate ↔ Majorana mass):

atomic, nuclear, particle physics

$$1/T_{1/2}^{0\nu} = G^{0\nu} \cdot |M^{0\nu}|^2 \cdot m_{\beta\beta}^2$$

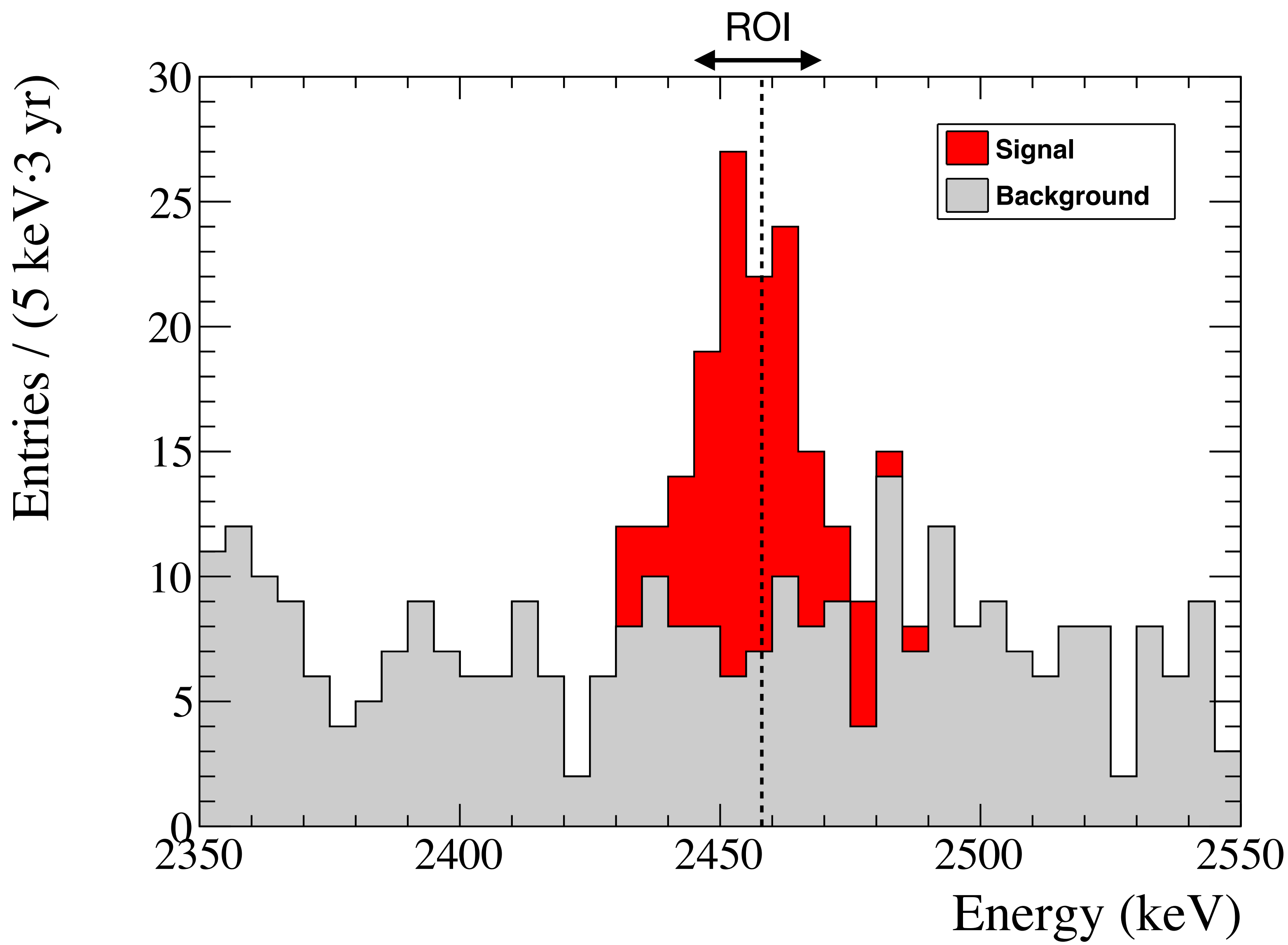
Isotope	Q-value (MeV)	Phase space $G^{0\nu}$ (yr^{-1} eV^{-2})	Matrix element $\|M^{0\nu}\|$	Isotopic abundance (%)	Cost (normalized to ^{76}Ge)	Current experiments
^{76}Ge	2.04	3.0×10^{-26}	≈4.1	7.8	1	GERDA, Majorana
^{130}Te	2.53	2.1×10^{-25}	≈3.6	33.8	0.2	CUORE, SNO+
^{136}Xe	2.46	2.3×10^{-25}	≈2.8	8.9	0.1	EXO, KamLAND-Zen, NEXT

The higher, the better

The lower, the better

Improvement no.2:
better energy resolution

$$T^{0\nu}_{1/2} \propto \varepsilon \sqrt{\frac{Mt}{c\,\Delta E}}$$



- M = 1,000 kg
- t = 3 yr
- $T_{1/2} = 10^{26}$ yr
- ε = 100%
- **ΔE = 1% FWHM**
- $c = 5 \cdot 10^{-4}$ /(keV·kg*yr)

- Experiments define energy **R**egion **O**f **I**nterest near $Q_{\beta\beta}$. ROI width depends on energy resolution (1 FWHM typical)
- The better the resolution, the lower the background within the ROI!

Energy resolution versus background type

ββ0ν backgrounds unrelated to ββ source: contamination of detector components, cosmogenics, etc.

- Can be eliminated in experiment with average energy resolution, provided perfect shielding (c~0) available

Energy resolution versus background type

ββ0ν backgrounds unrelated to ββ source: contamination of detector components, cosmogenics, etc.

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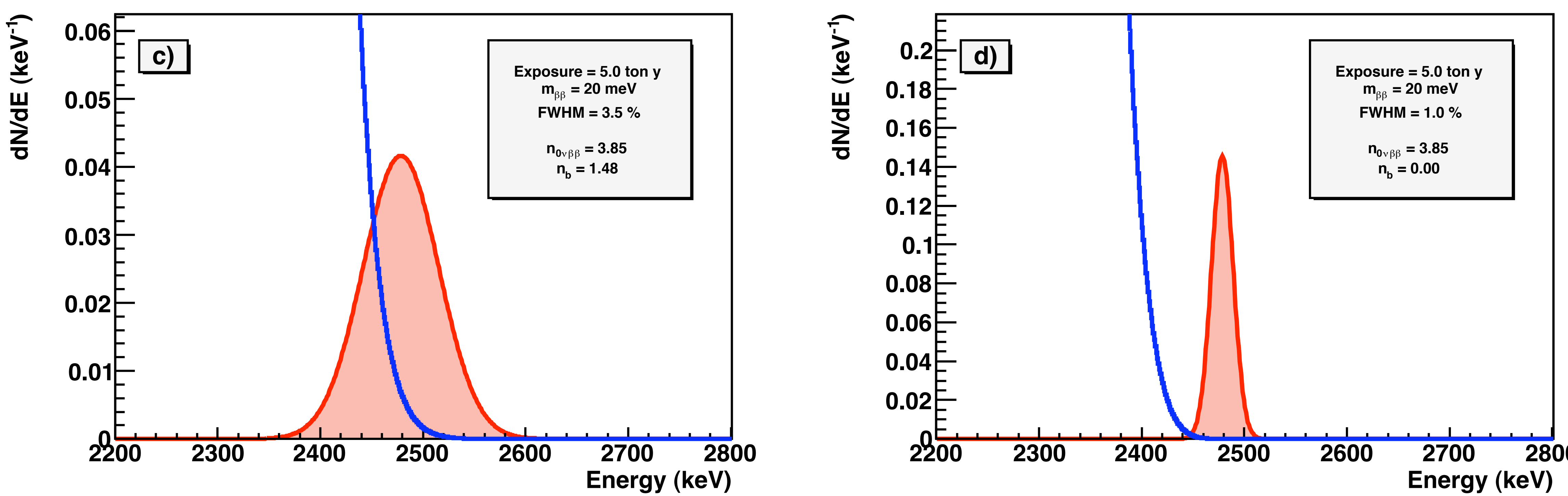
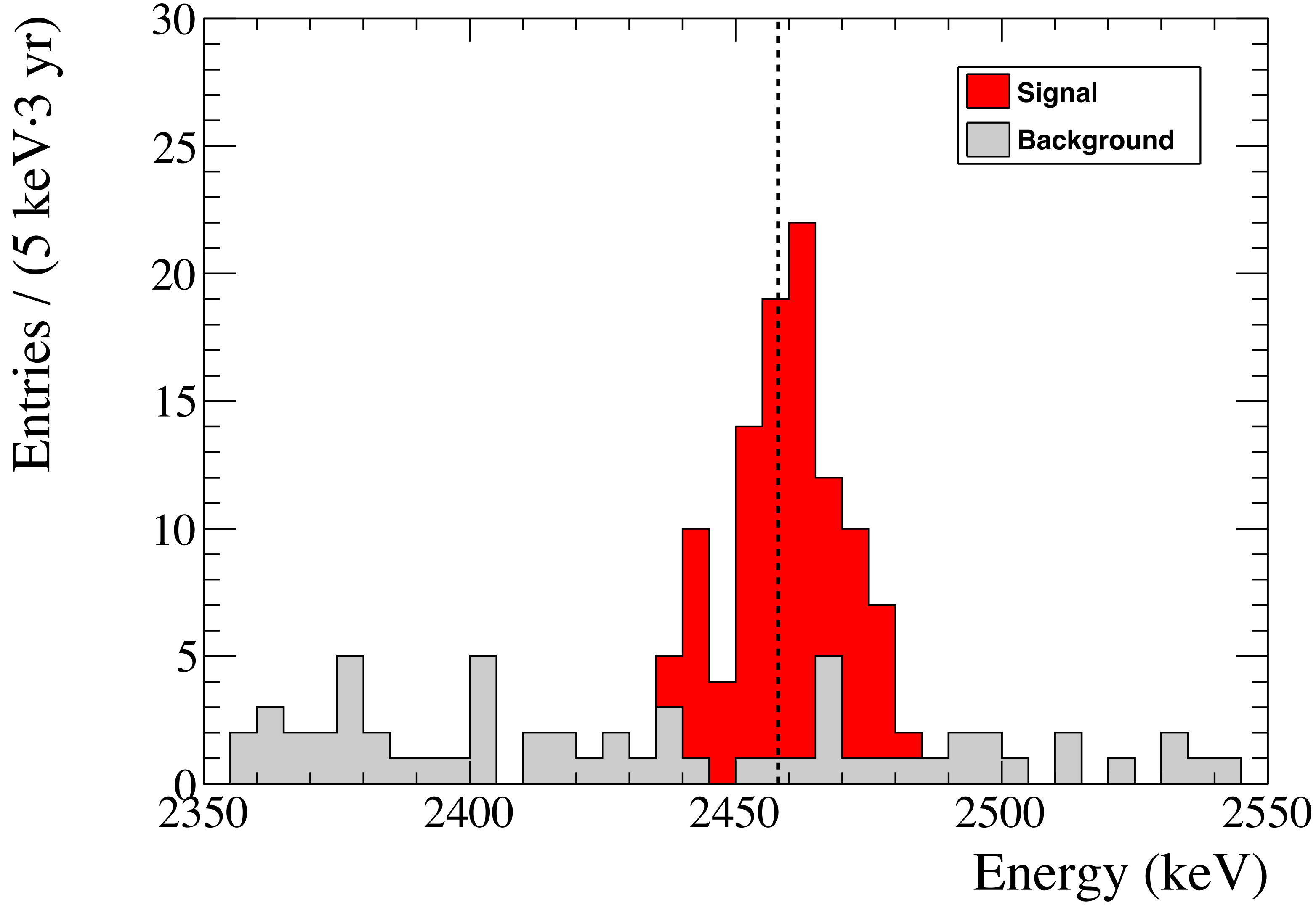
ββ0ν backgrounds related to ββ source: ββ2ν!

- Irreducible background unless resolution is excellent



Improvement no.3:
lower background rate

$$T^{0\nu}_{1/2} \propto \varepsilon \sqrt{\frac{Mt}{c\,\Delta E}}$$

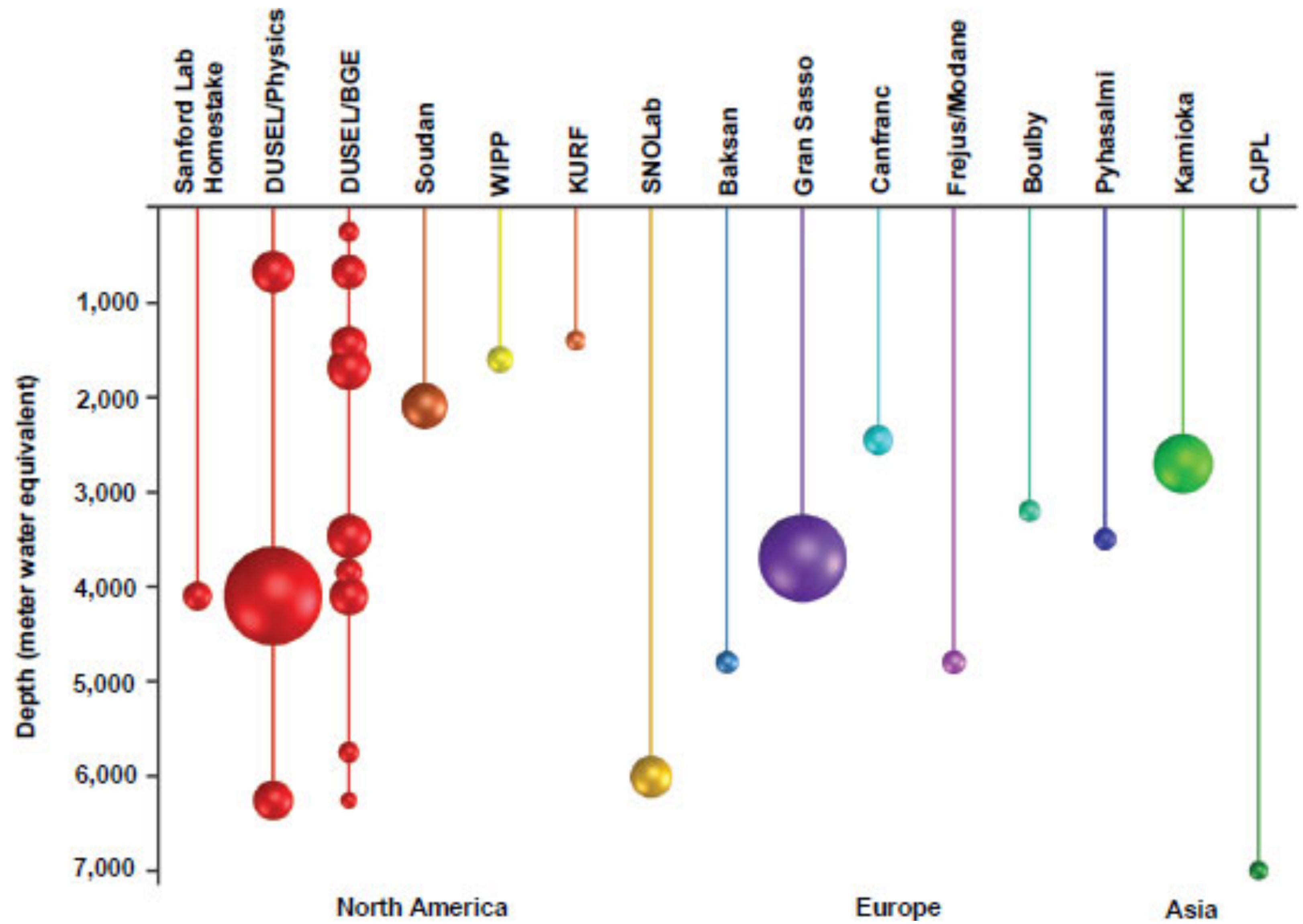


- M = 1,000 kg
- t = 3 yr
- $T_{1/2} = 10^{26}$ yr
- ε = 100%
- ΔE = 1% FWHM
- **c = 10^{-3} /(keV·kg*yr)**

How to lower background rate?

- Go underground and radiopure
- Electron tracking
- Daughter ion tagging?

Underground detectors

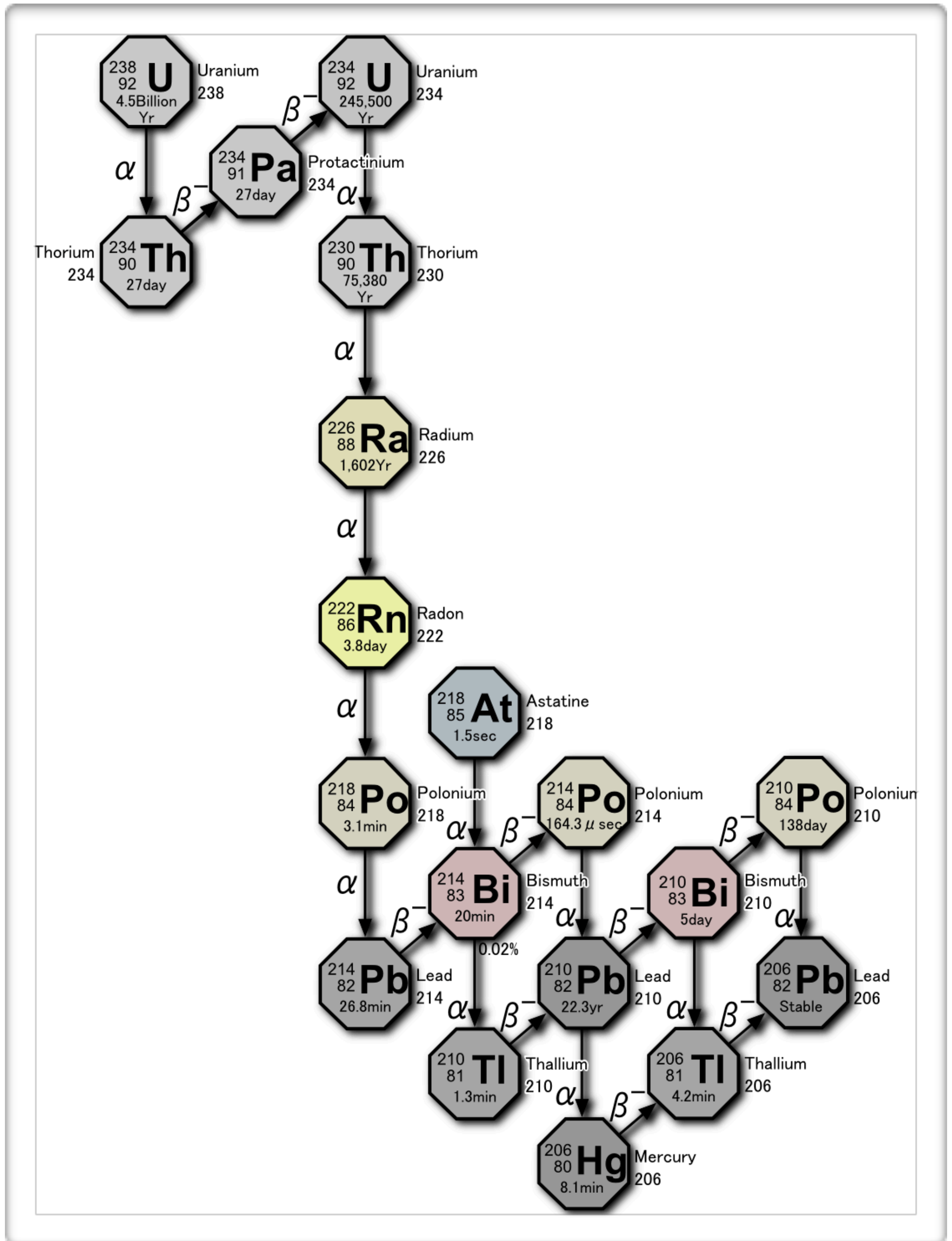


- Some backgrounds originated outside detector by cosmic-ray interactions
- All ββ0ν experiments located deep underground, using rock as shield


Laboratori Nazionali del Gran Sasso

Radiopure detectors

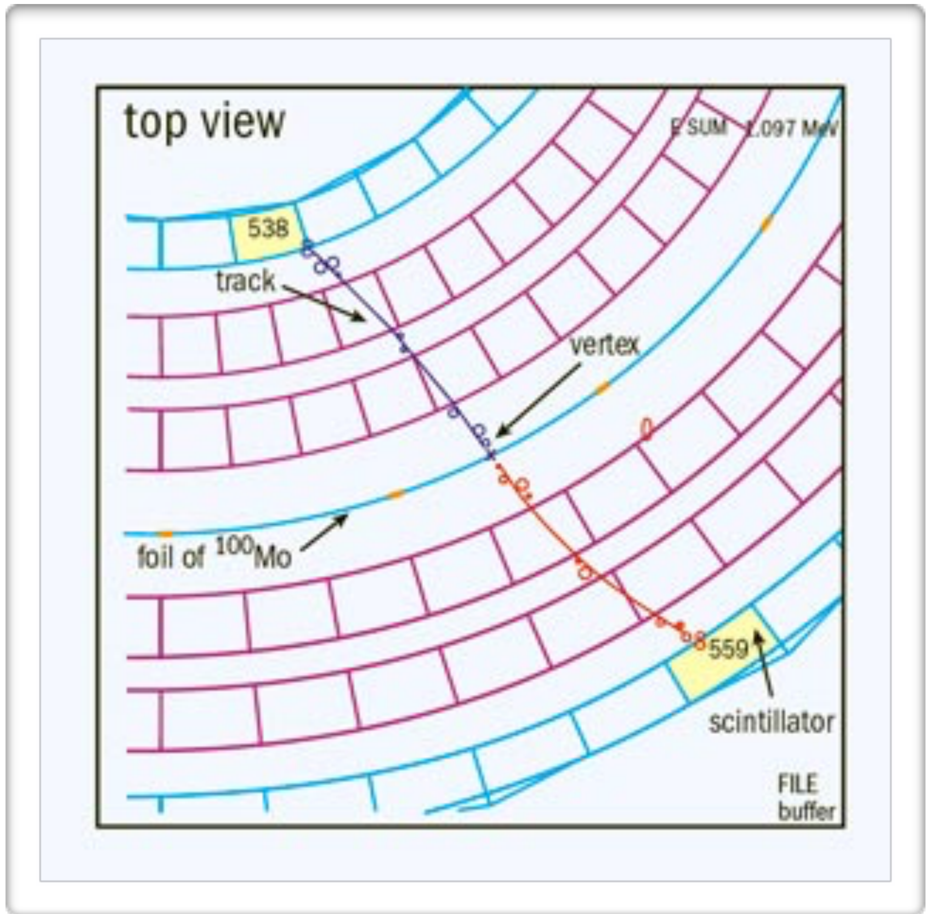
- Minimise contamination from natural radioactivity in all detector components



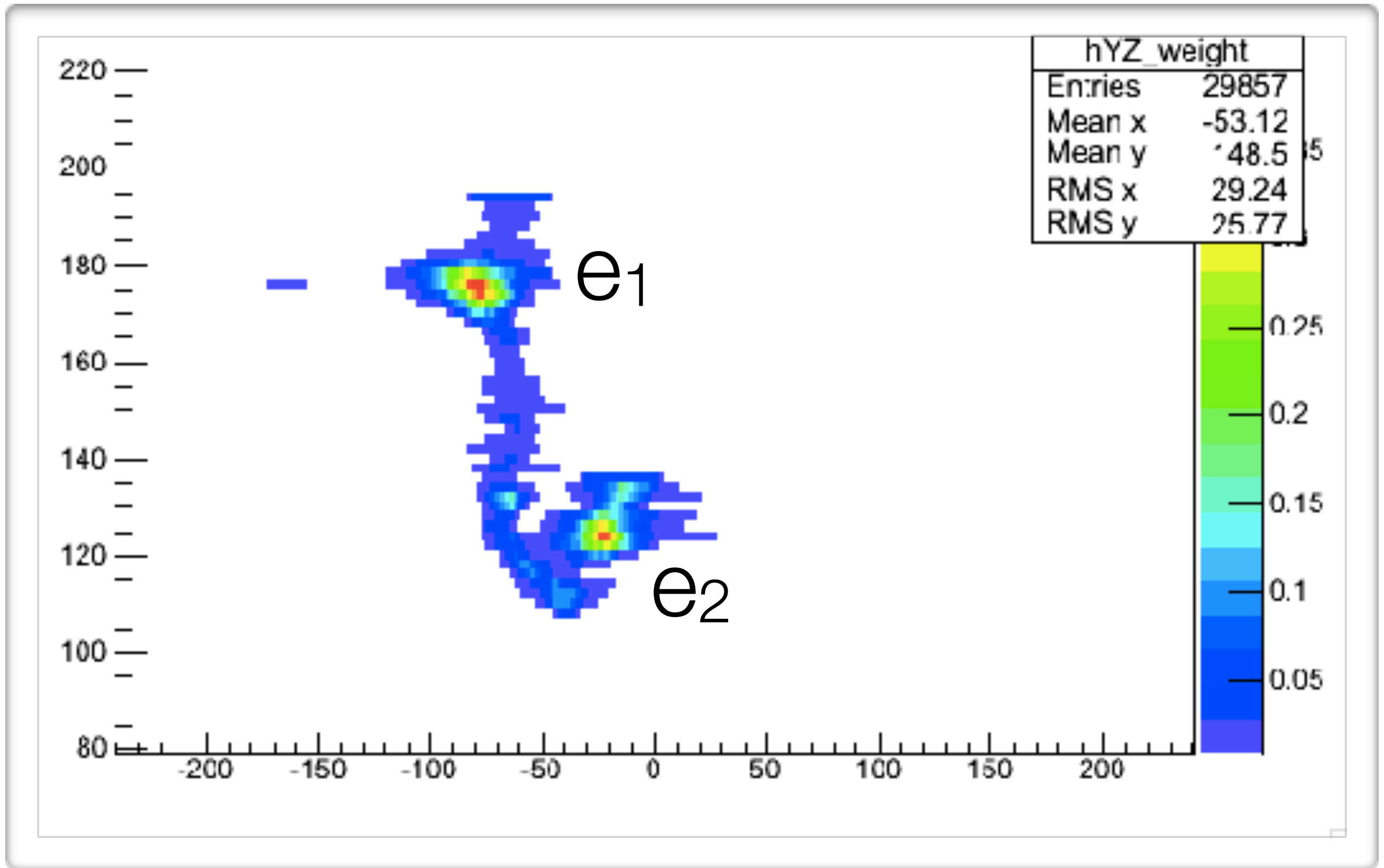
Tracking detectors

- Observe the two stopping electron tracks emitted from common vertex!

NEMO3 experiment
(drift Geiger cells, He gas at 1 bar)

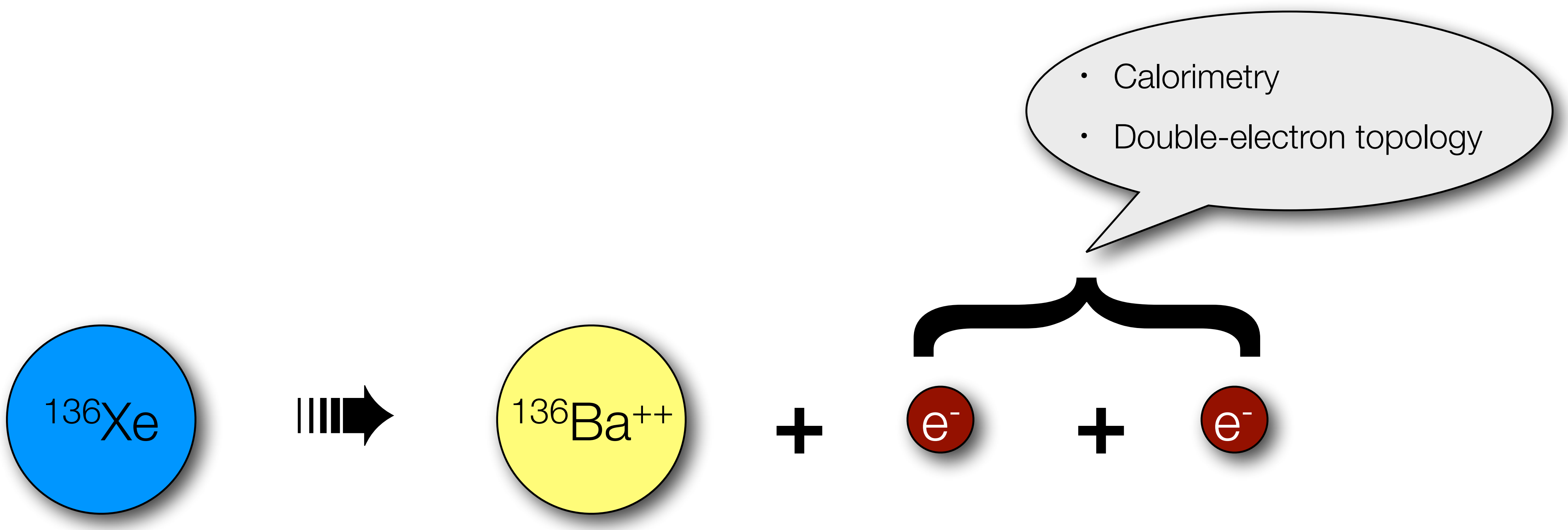


NEXT experiment
(time projection chamber, Xe gas at 7-15 bar)



Is daughter ion tagging possible?

- Active R&D in ^{136}Xe experiments (liquid and gas) to detect $^{136}Ba^{++}$ ion:



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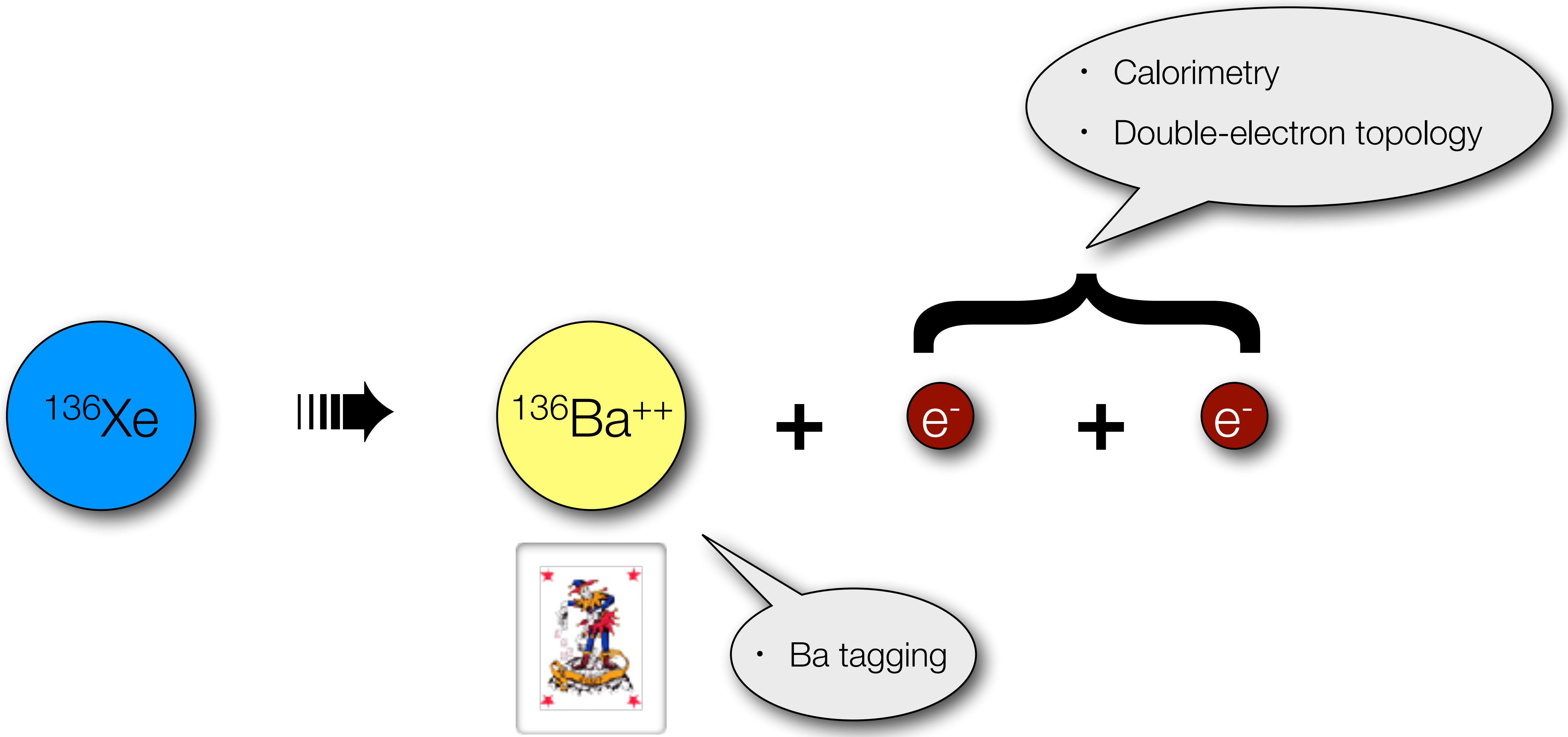
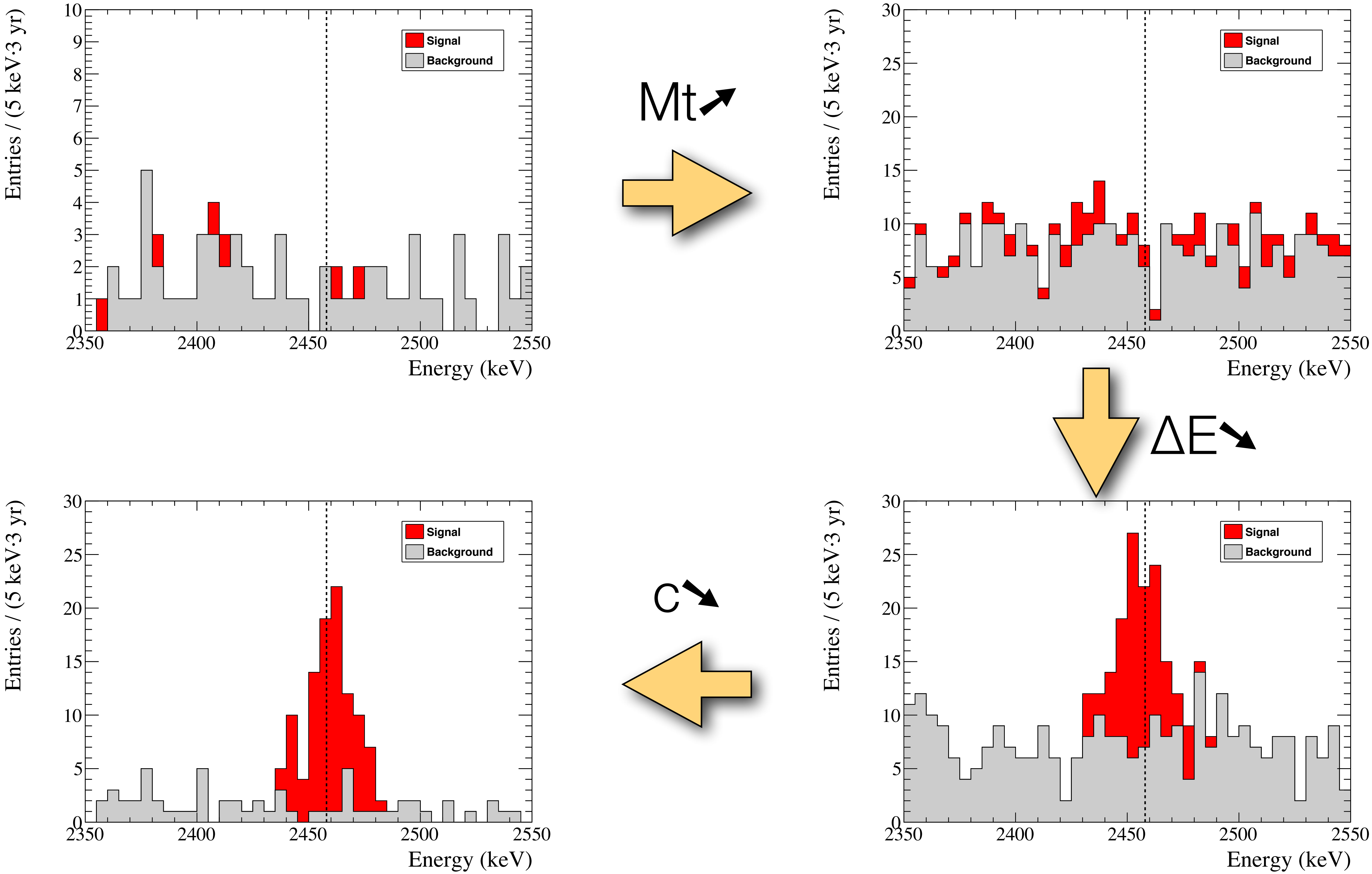


- If successful, one would be left with ββ2v background only!

Putting it all together: $Q_{\beta\beta}$ peak uncovered!

$$T^{0\nu}_{1/2} \propto \varepsilon \sqrt{\frac{Mt}{c\,\Delta E}}$$



Chapter 6:

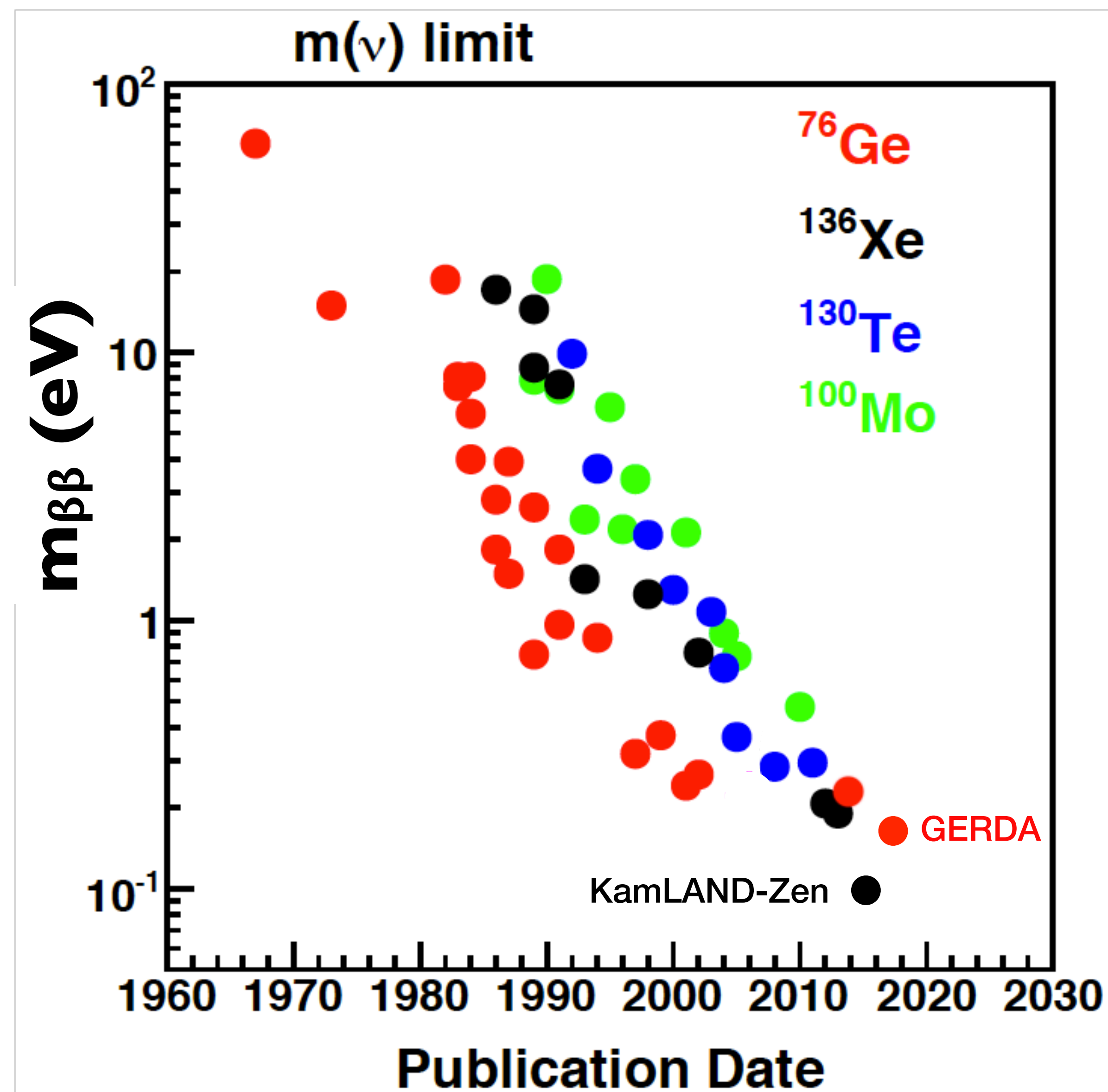
The present of ββ0ν searches

ββ0ν experimental status

Main experiments, current generation:

- No convincing evidence for ββ0ν
- Best limits:

Experiment	$T_{1/2}^{0\nu}$ limit (yr)	$m_{\beta\beta}$ limit (meV)
KamLAND-Zen	> 1.07×10^{26}	< 61-165
GERDA	> 5.3×10^{25}	< 150-330



GERDA experiment

- High-purity germanium diodes enriched in ^{76}Ge immersed in LAr
- **Advantages**: energy resolution, radiopurity → background-free!

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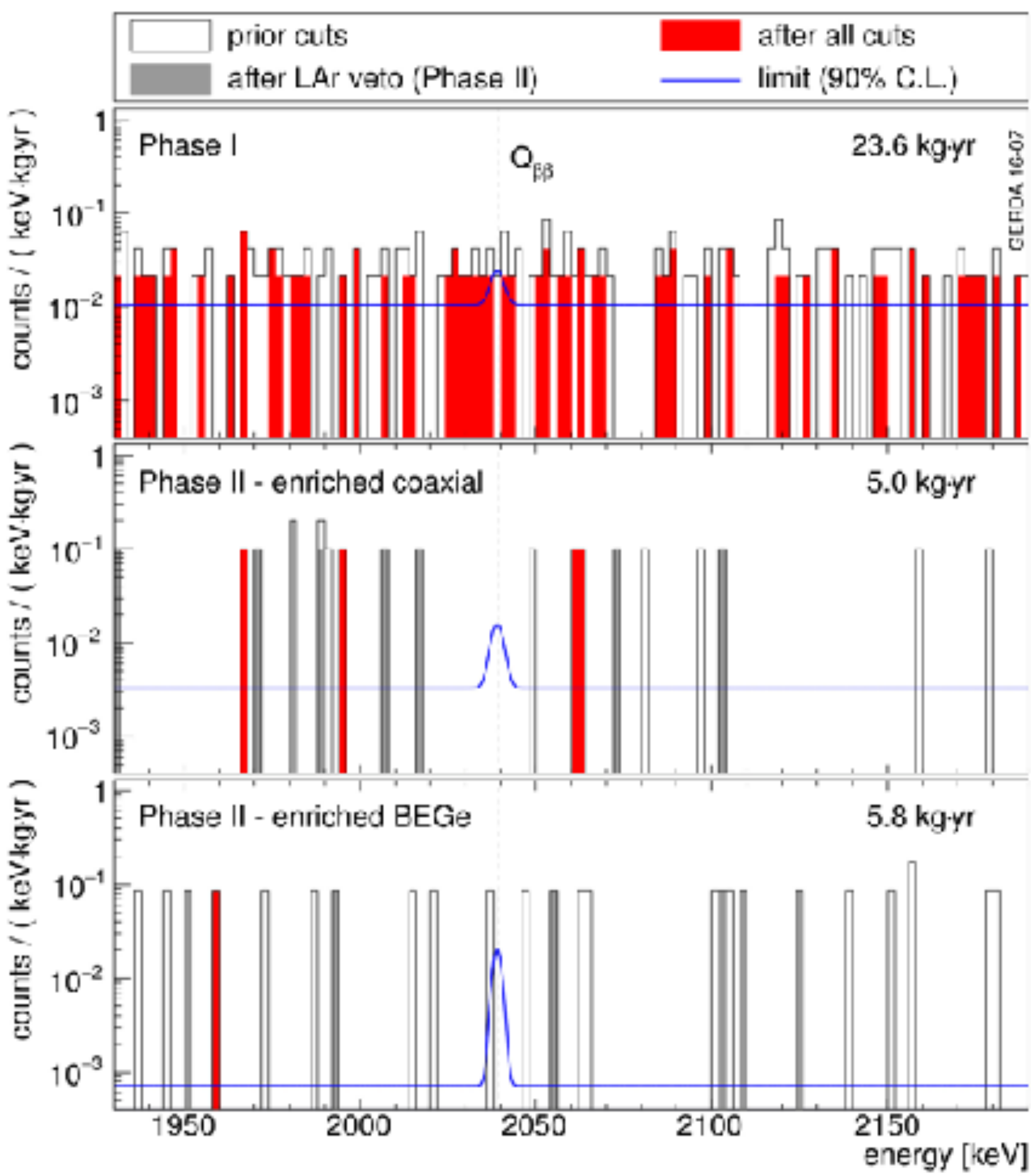
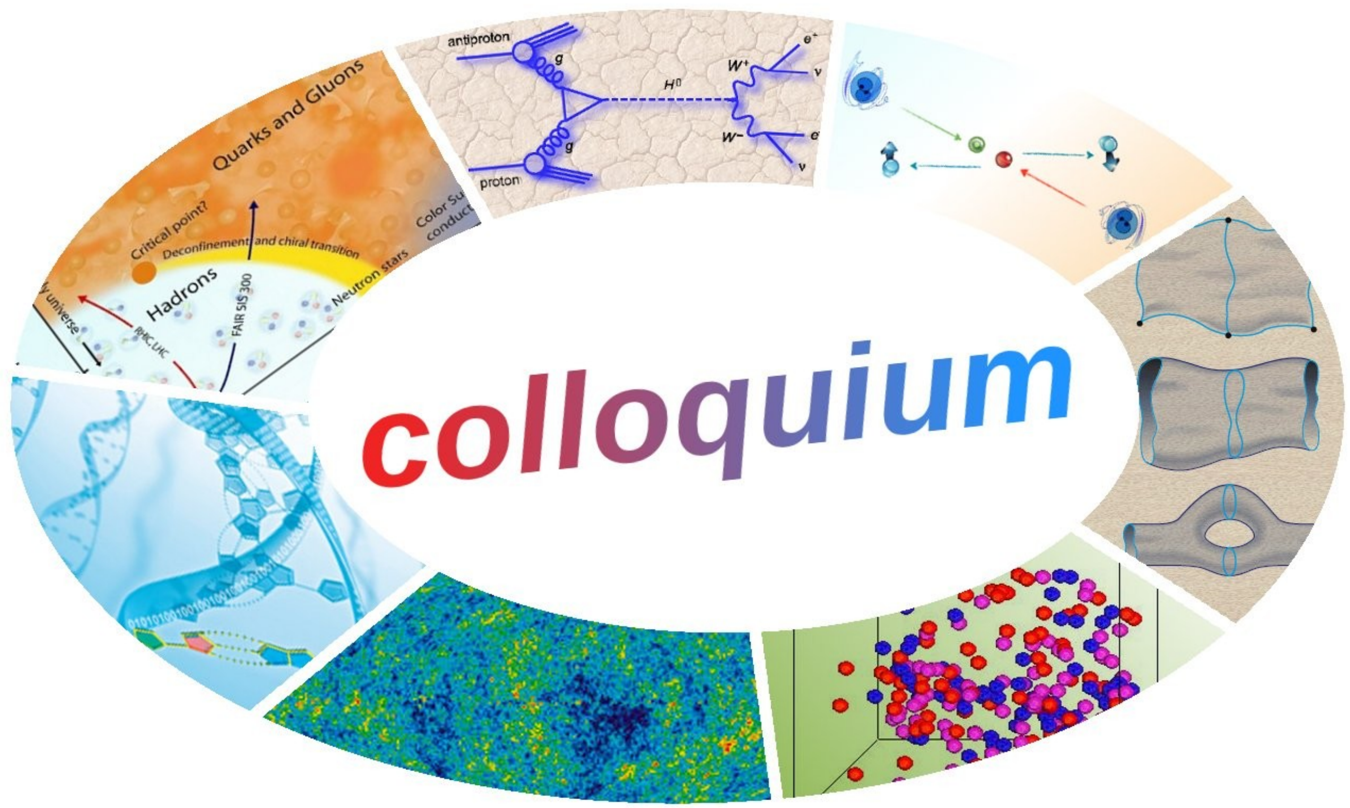


GERDA experiment

Dipartimento di Fisica e Sezione INFN di Torino

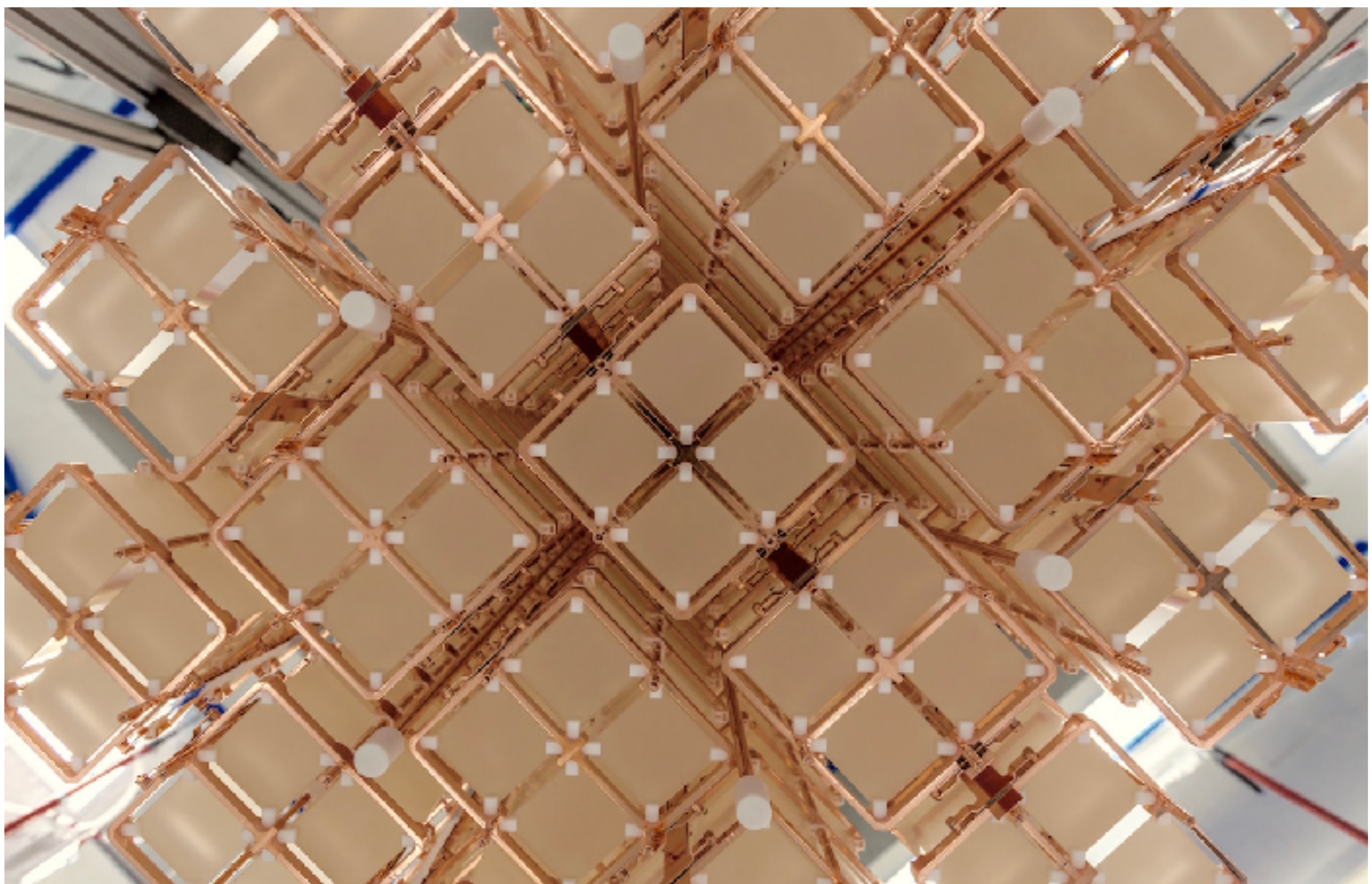


Giovedì 1 Giugno 2017, ore 14:30, Sala Wataghin
Riccardo Brugnera
(Università di Padova)

Neutrinoless double-beta decay searches with ^{76}Ge

CUORE experiment

- Towers of TeO_2 crystals. ββ energy measured as temperature increase
- **Advantages**: energy resolution, mass scalability



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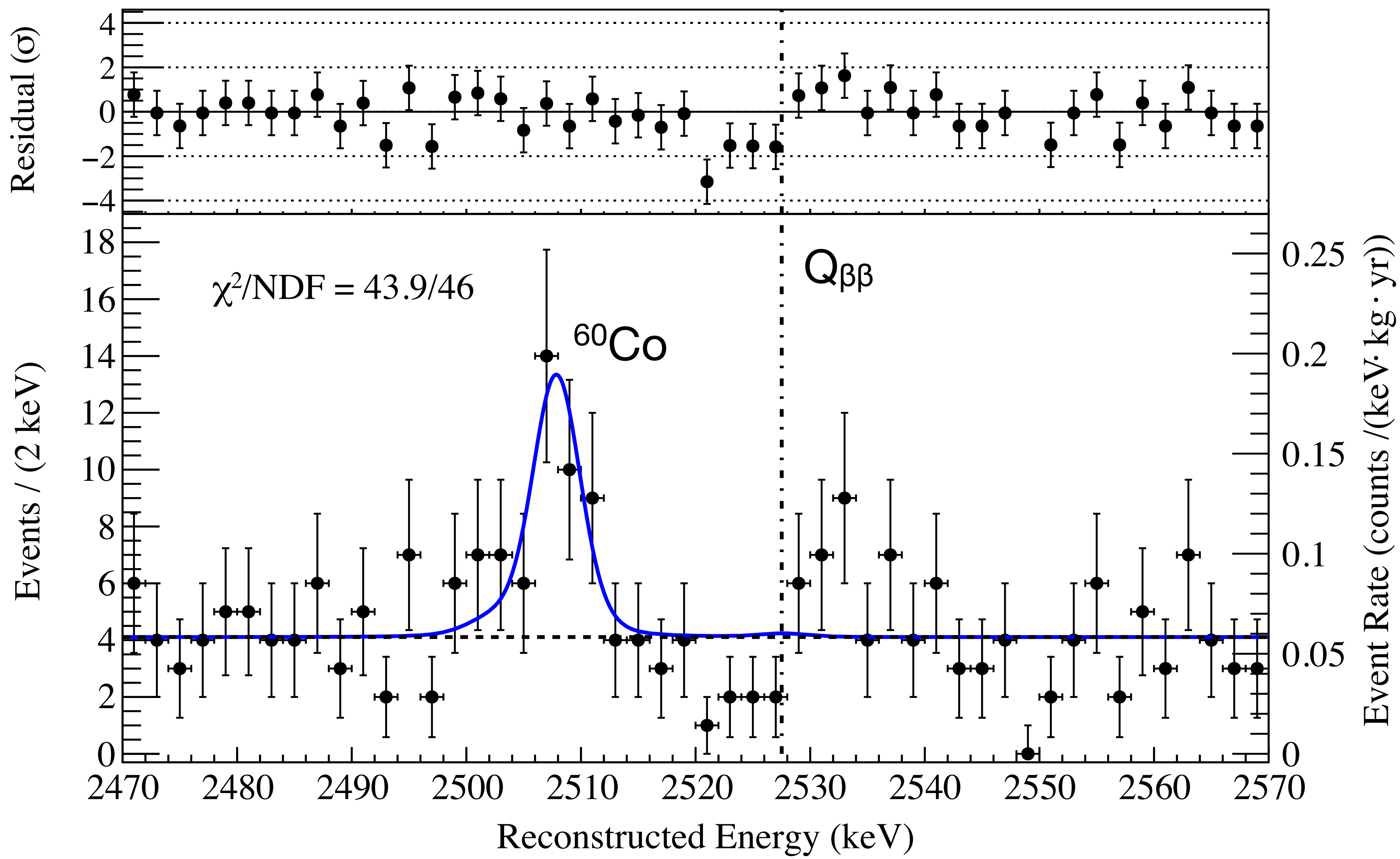
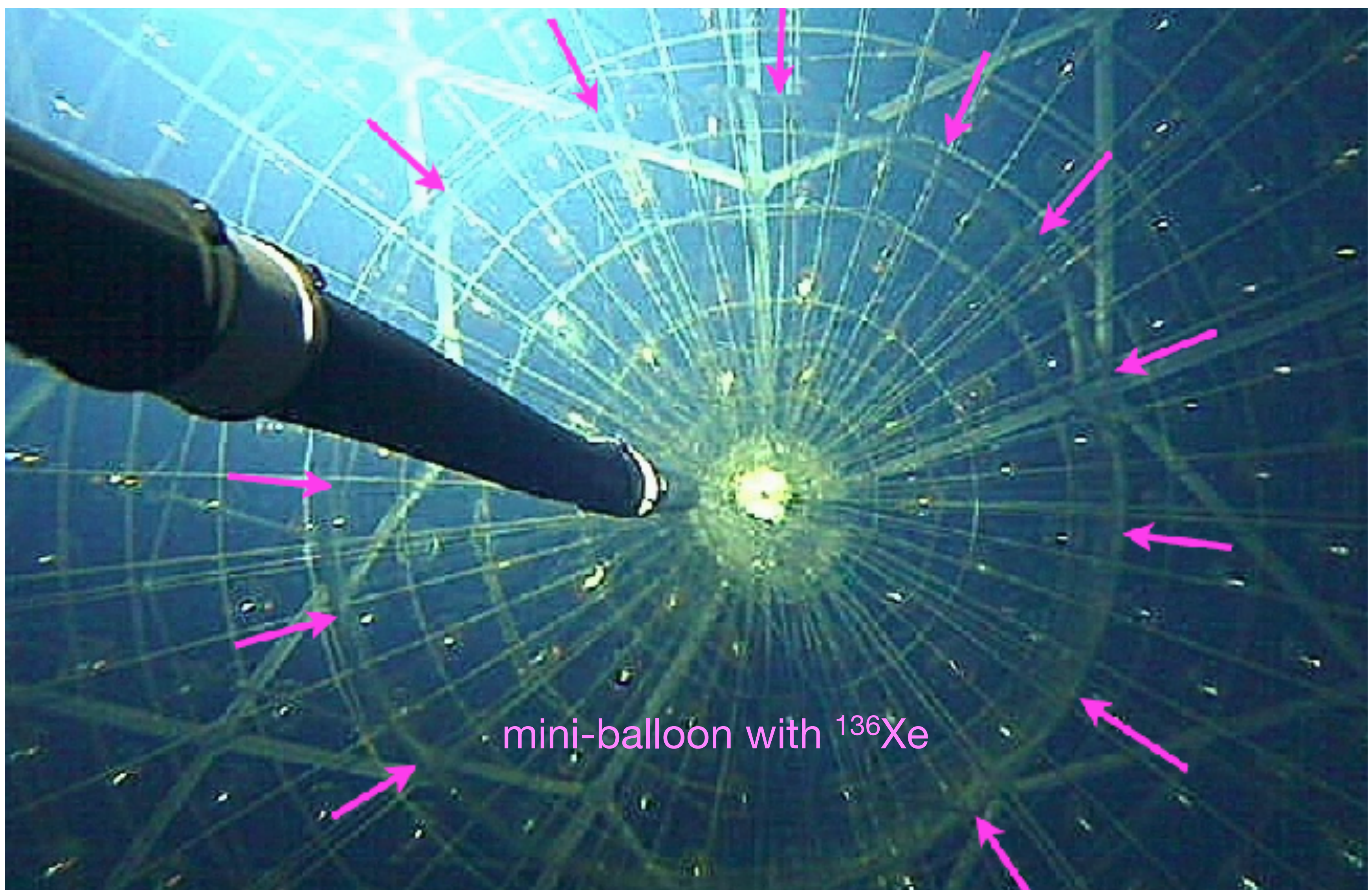


KamLAND-Zen experiment

- Liquid scintillator with 300-750 kg of ^{136}Xe gas dissolved in it
- **Advantages**: mass scalability, radiopure, veto region → leading the field



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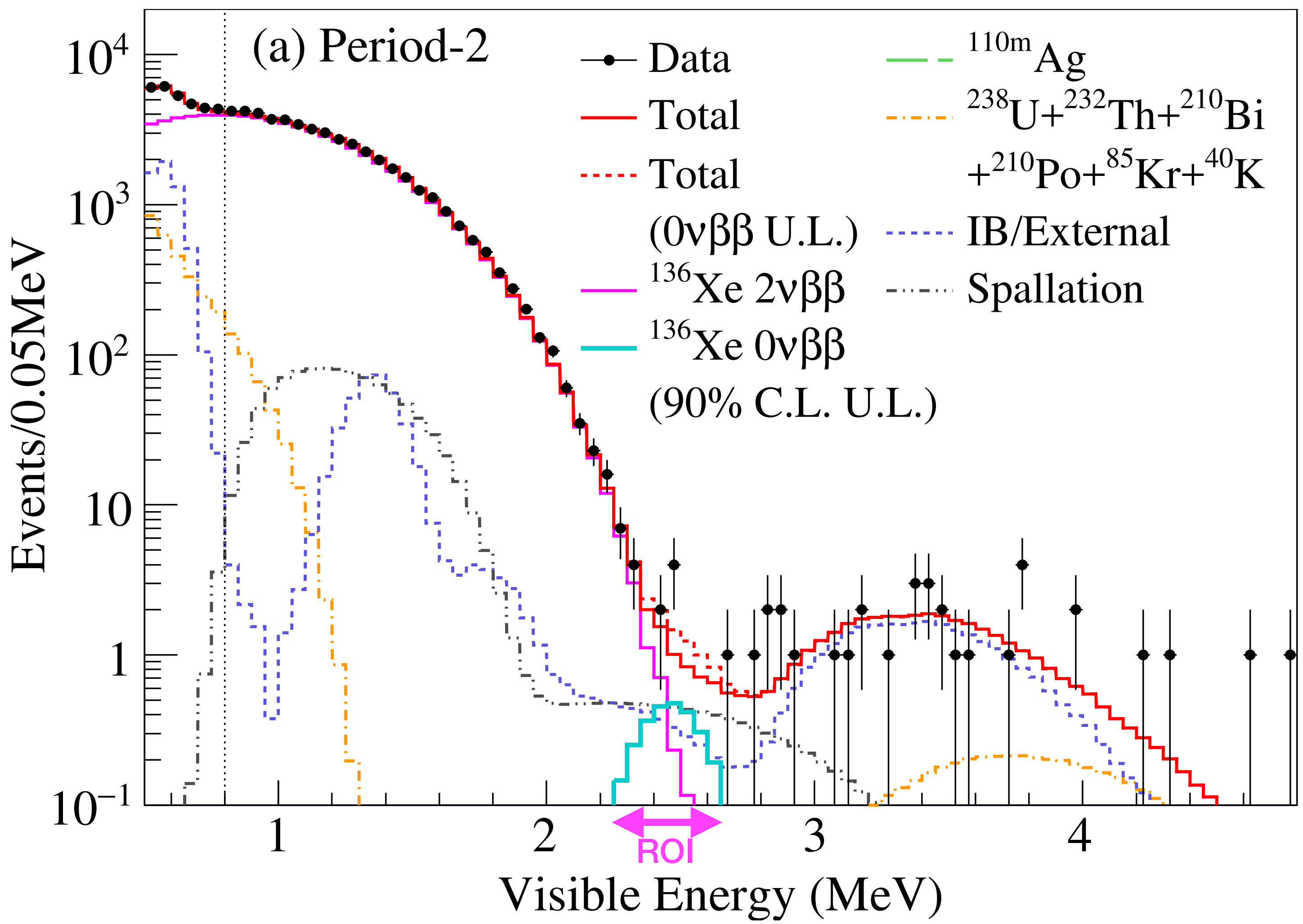
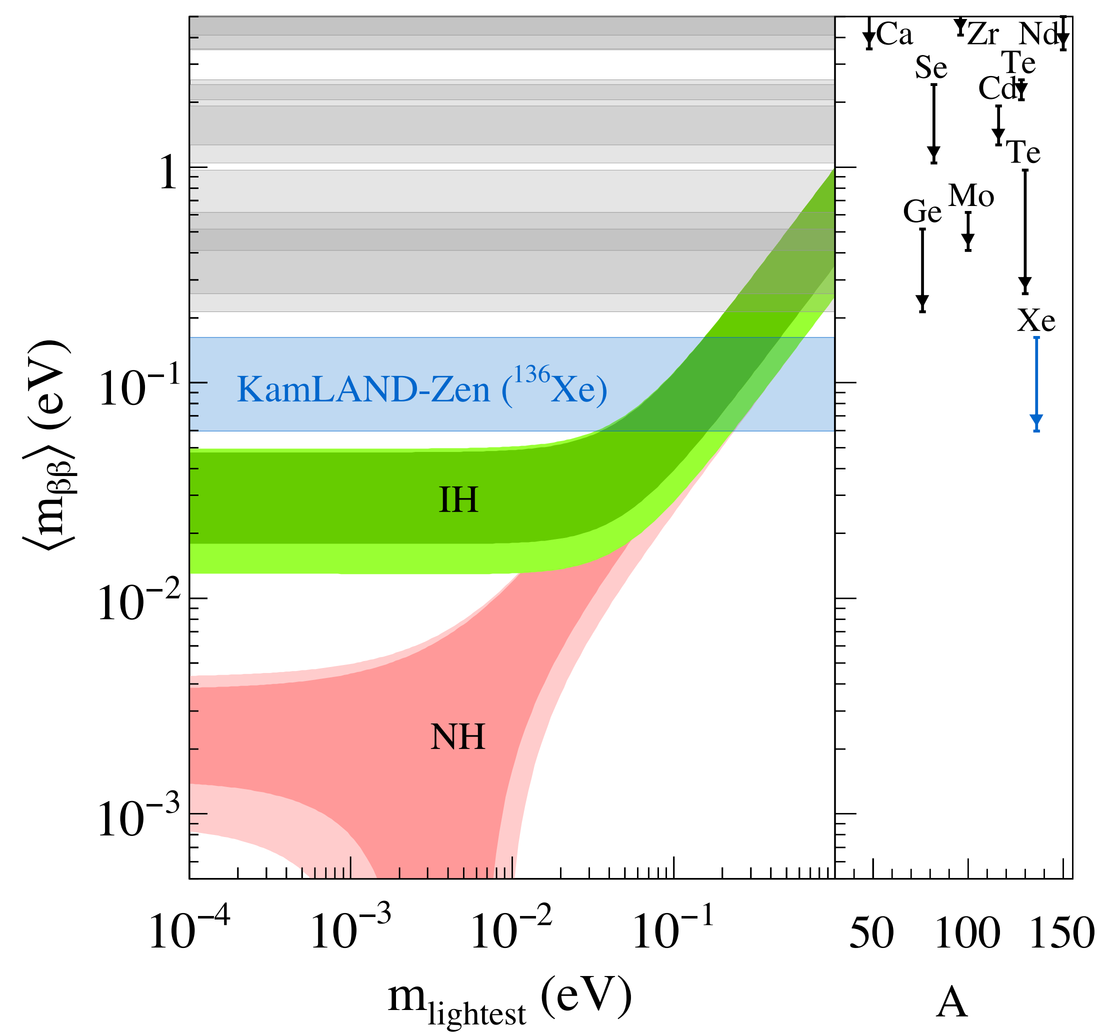
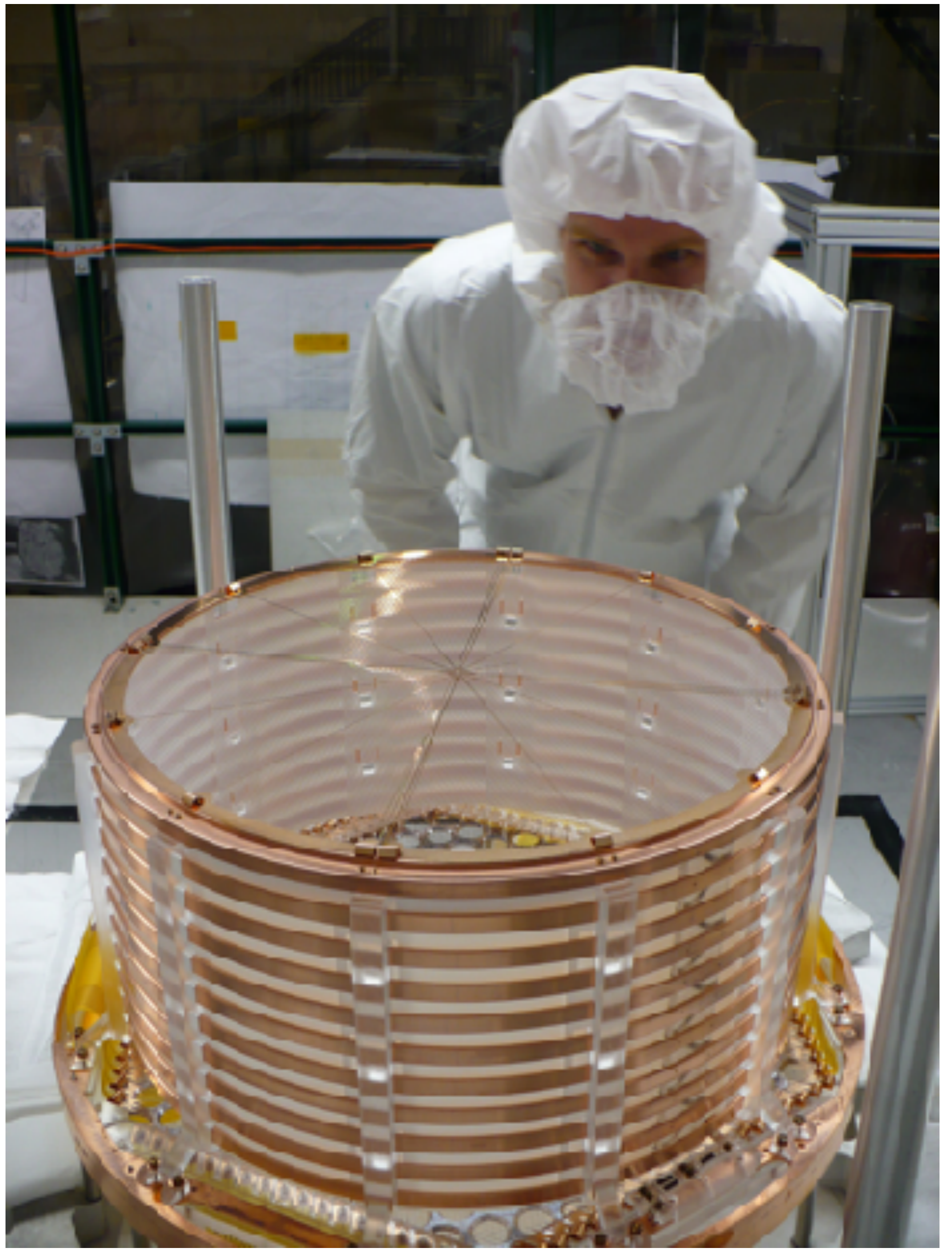




EXO experiment

- Cryogenic time projection chamber filled with 80 kg (fiducial) liquid xenon
- **Advantages**: mass scalability, some electron topology



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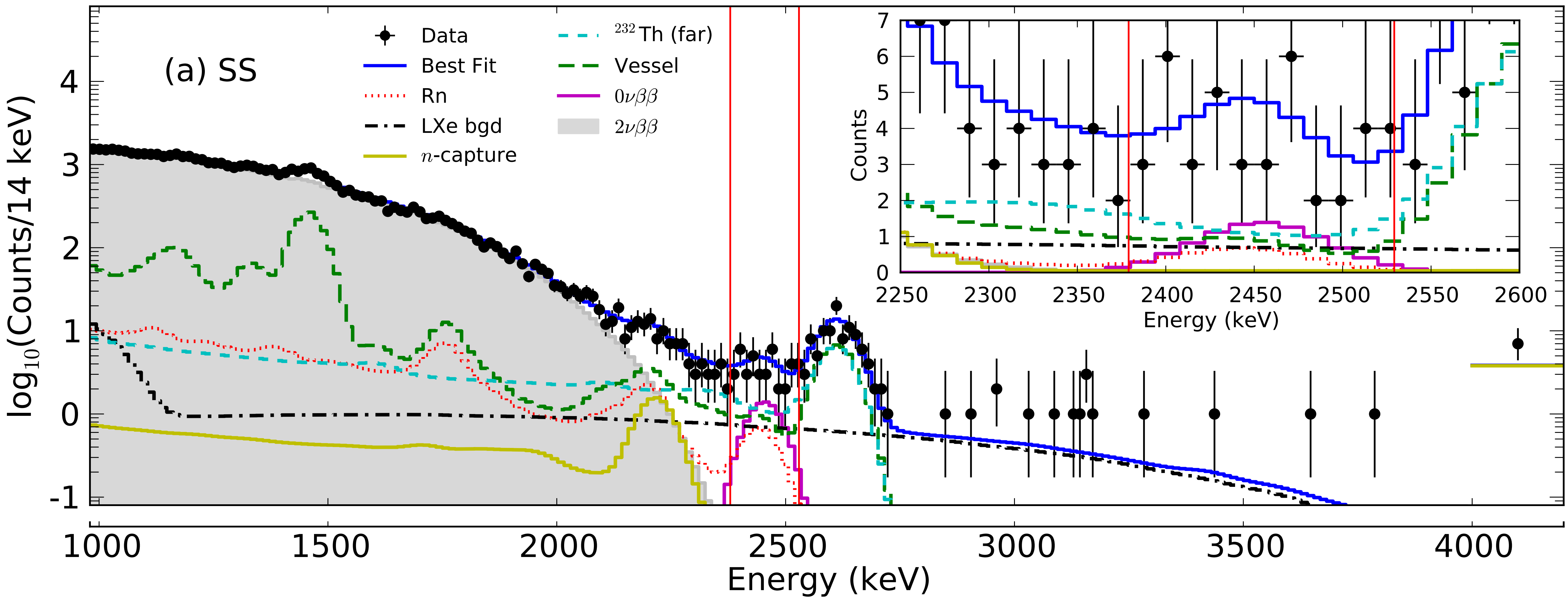
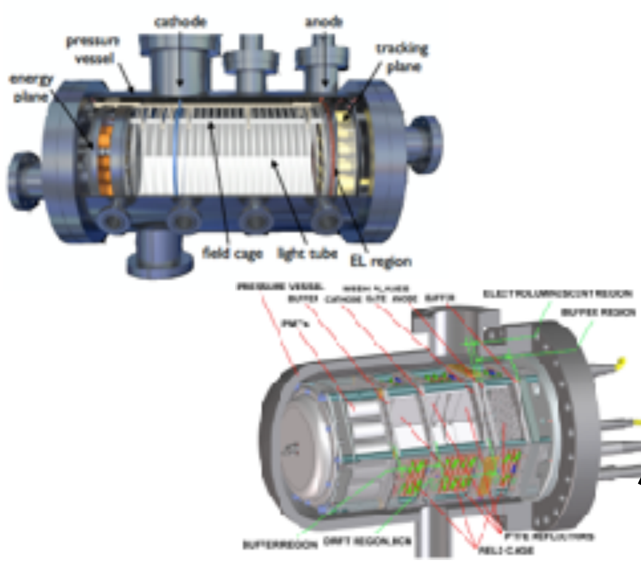


NEXT experiment

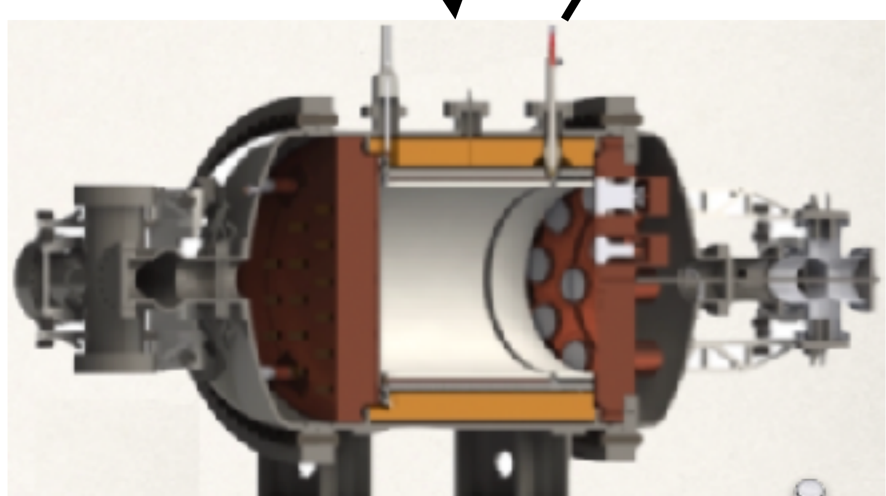
- Time projection chamber filled with high-pressure (10-15 bar) ^{136}Xe gas
- **Advantages**: energy resolution, image electron tracks

NEXT phases



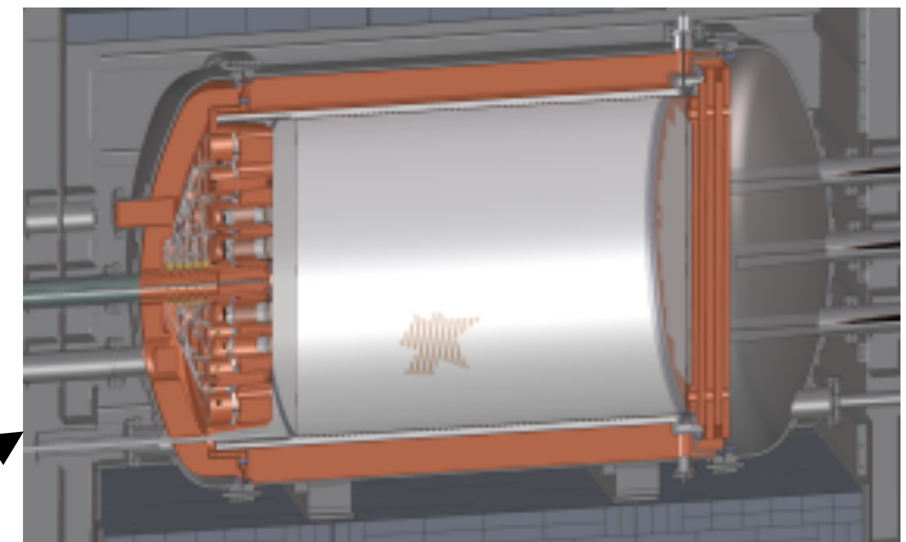
Prototypes (~1 kg)
[2009 - 2014]

Demonstration of detector concept



NEXT-NEW (~5 kg)
[2015 - 2018]

Underground and radio-pure operations, background, ββ2v

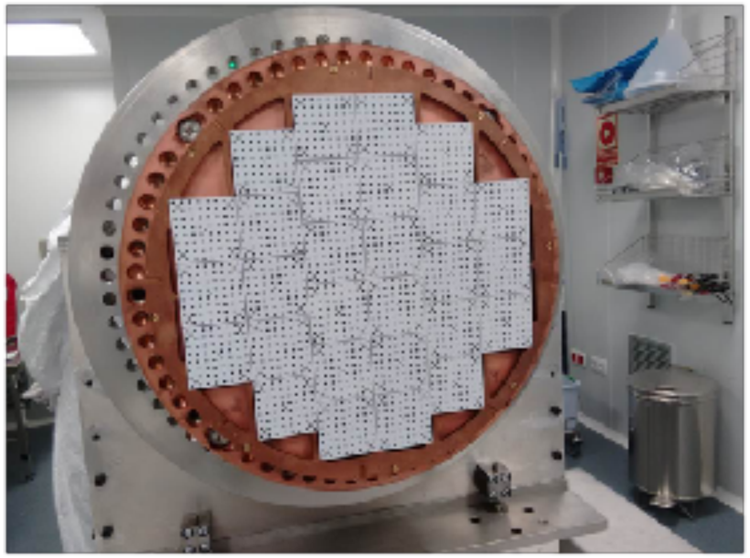


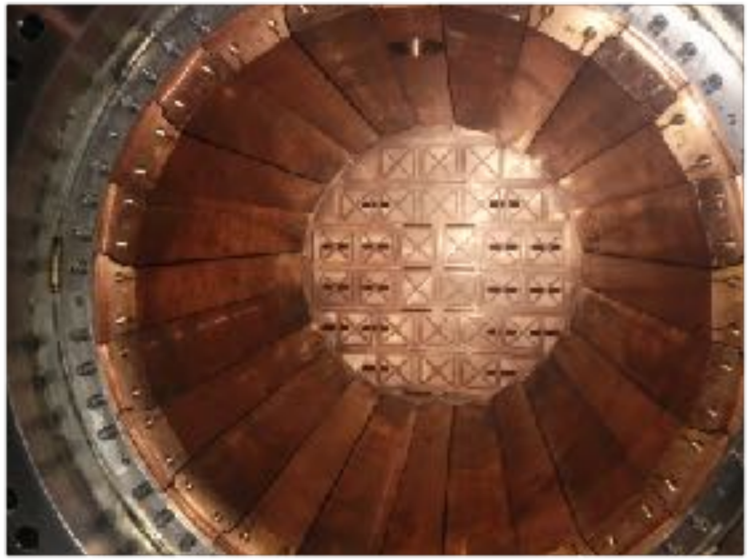
NEXT-100 (~100 kg)
[2018 - 2020's]

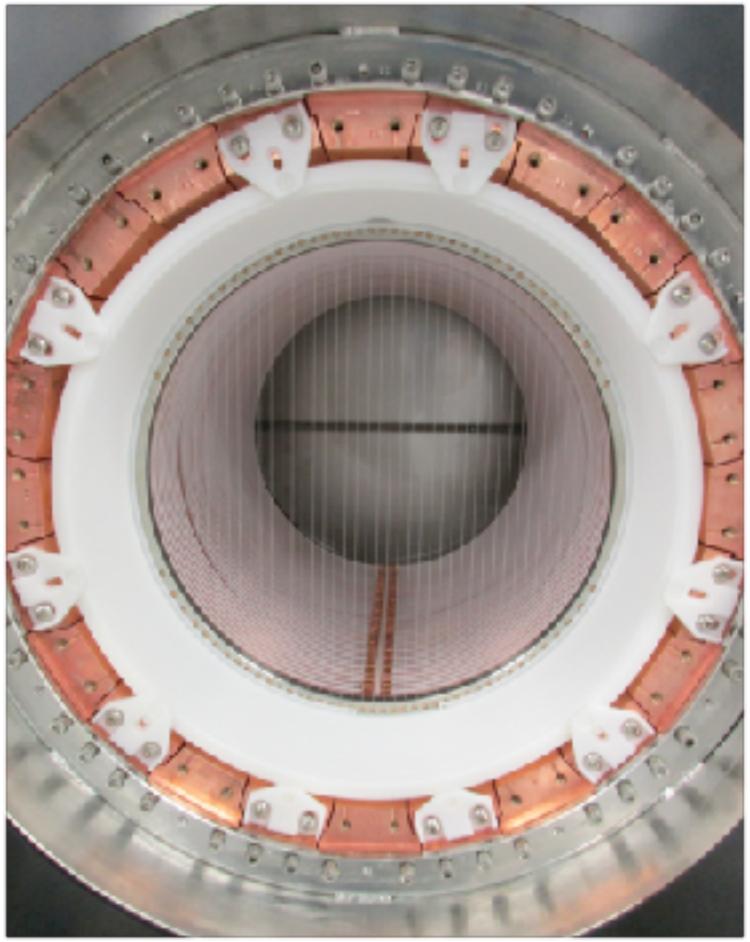
Neutrinoless double beta decay search

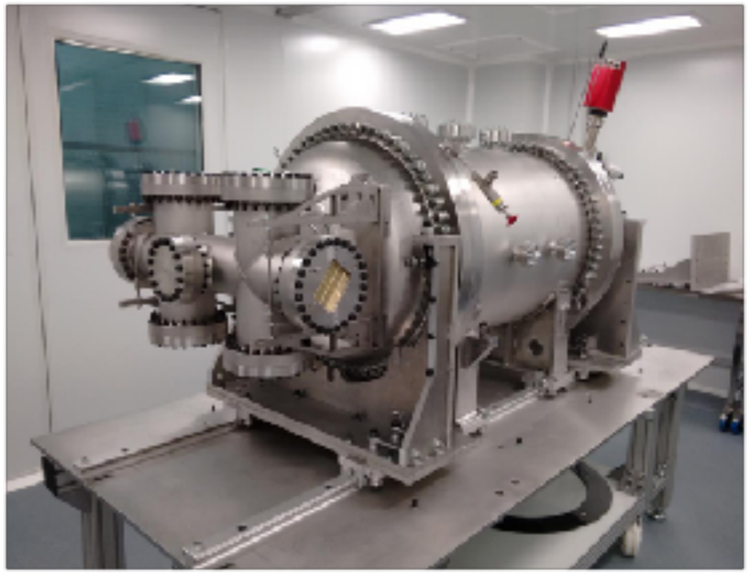
NEXT-tonne (~1000 kg)
[future generation]

NEXT-NEW construction

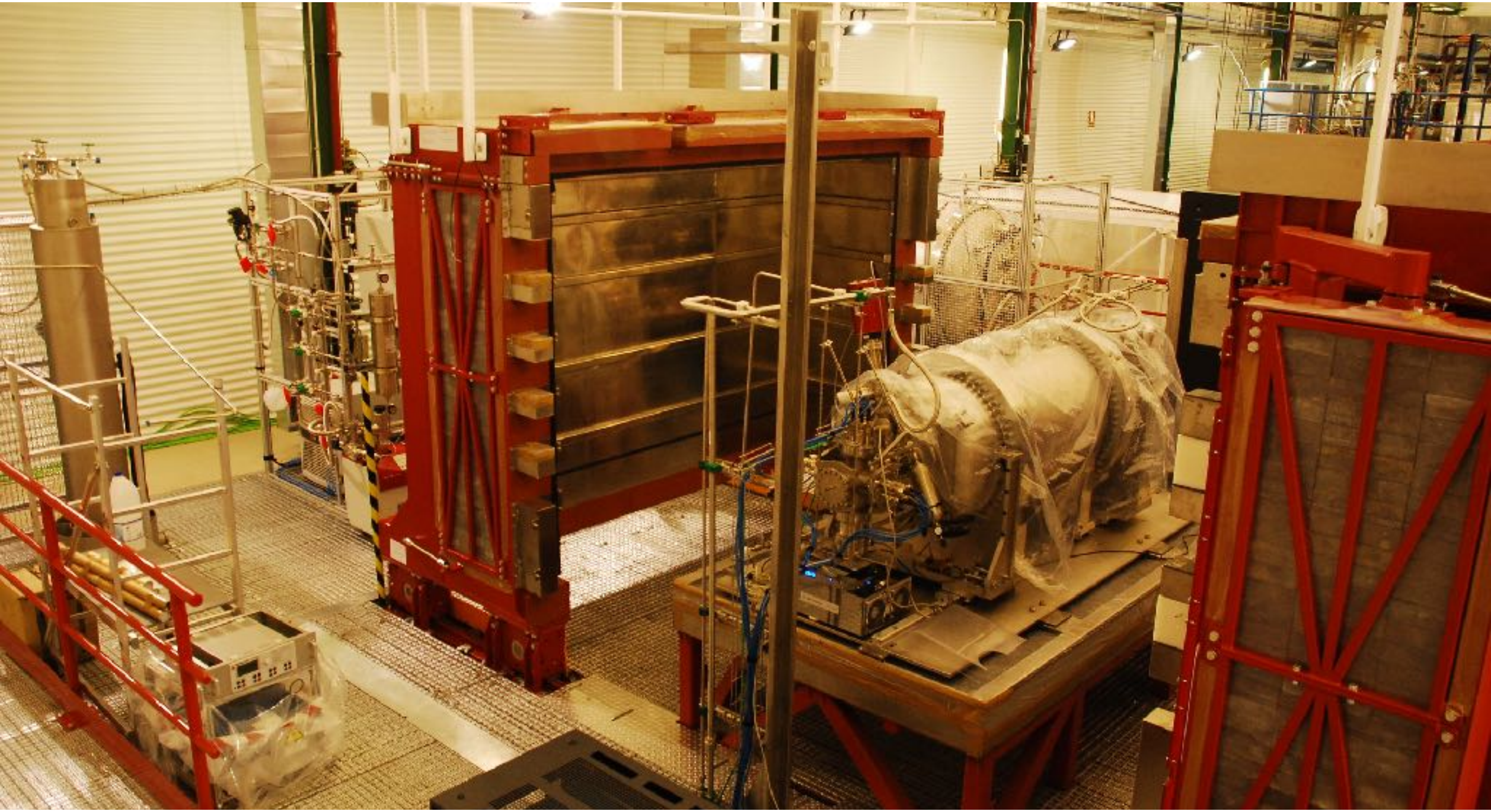






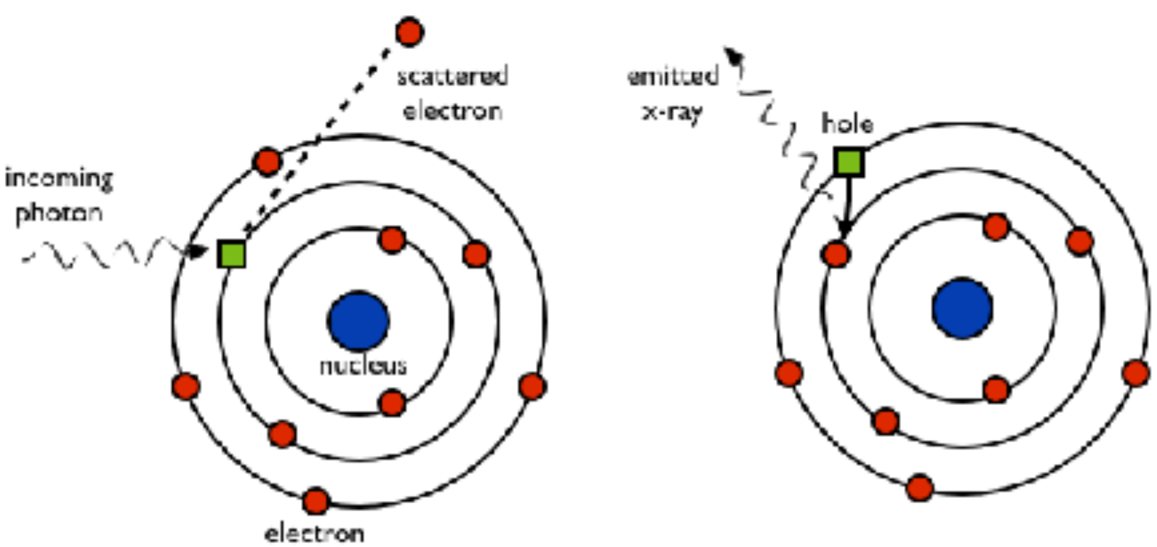


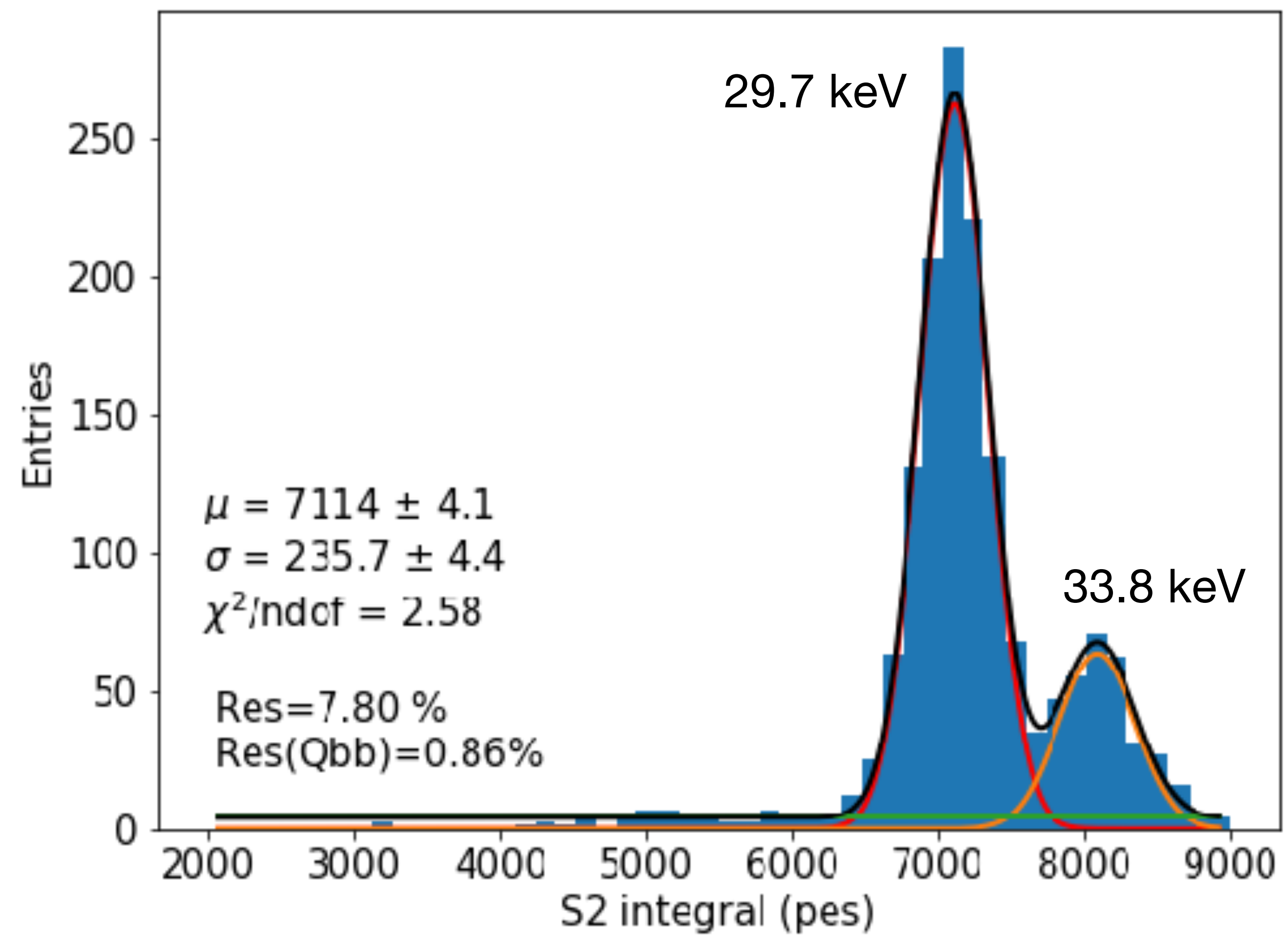
NEXT-NEW installation at the LSC



NEXT-NEW first results

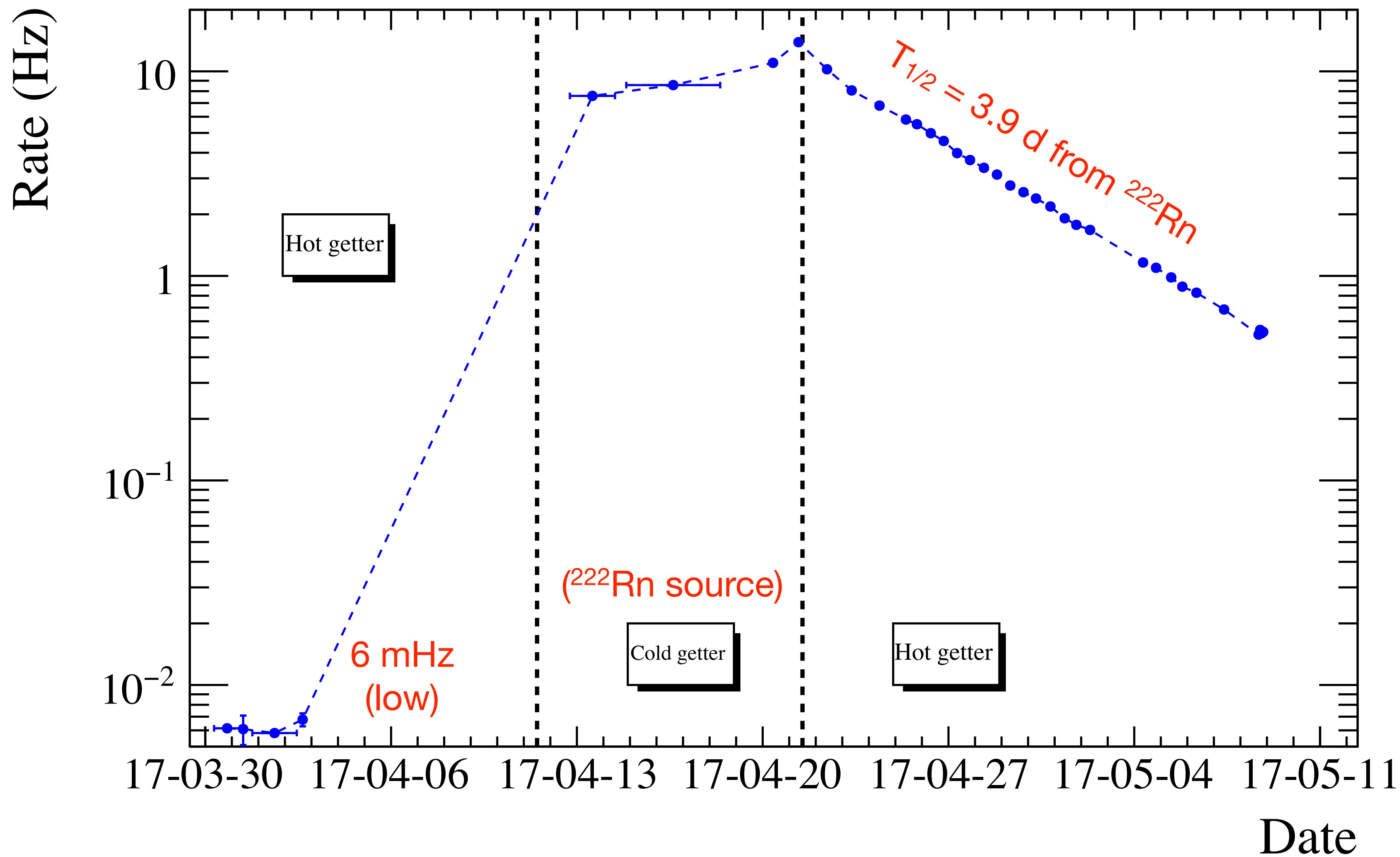
- Energy resolution from low-energy xenon X-rays:





NEXT-NEW first results

- Alpha production rate from radon (→ ββ0ν background!):



Chapter 7:

The future of ββ0ν searches

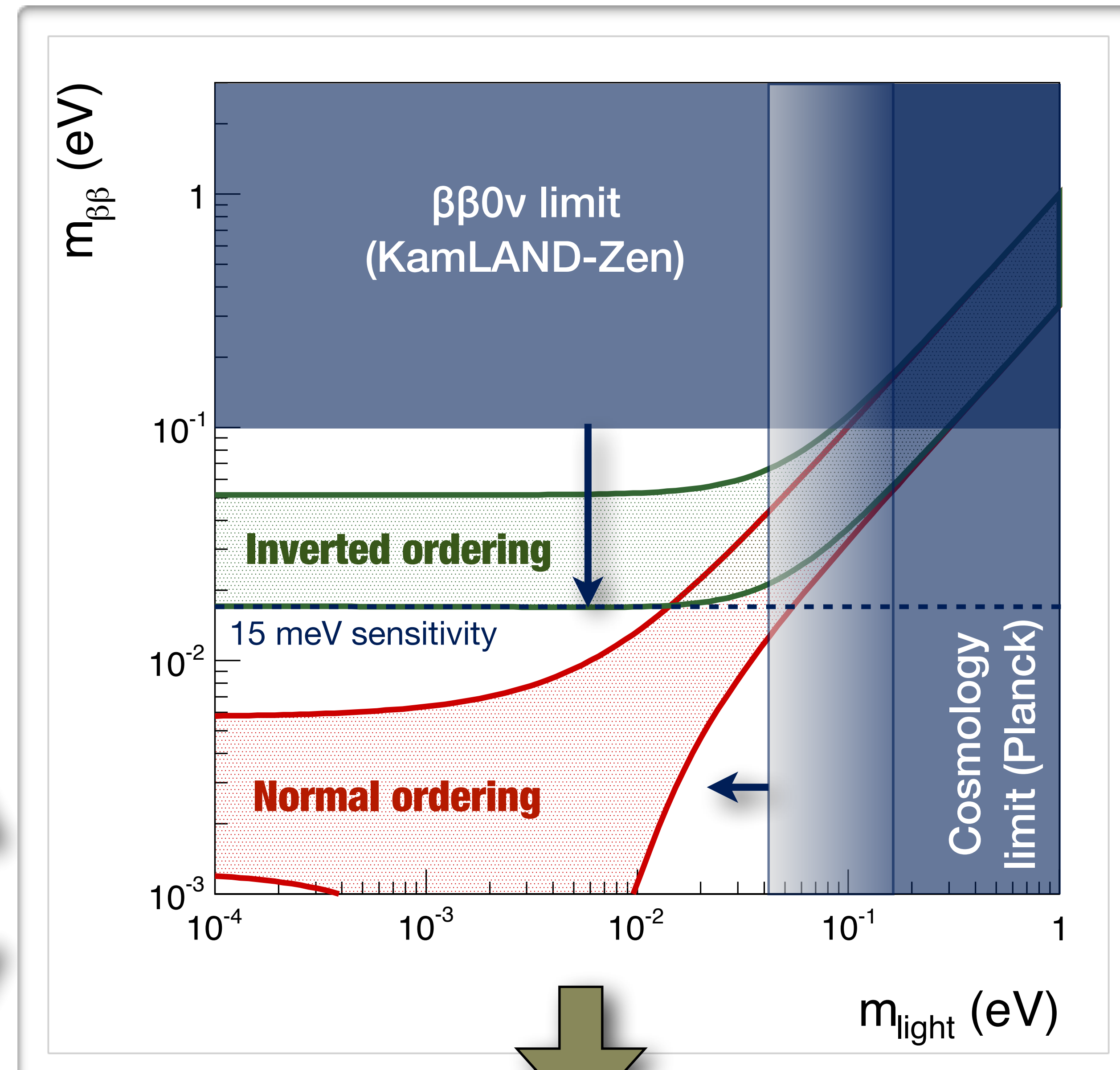
How to move forward?

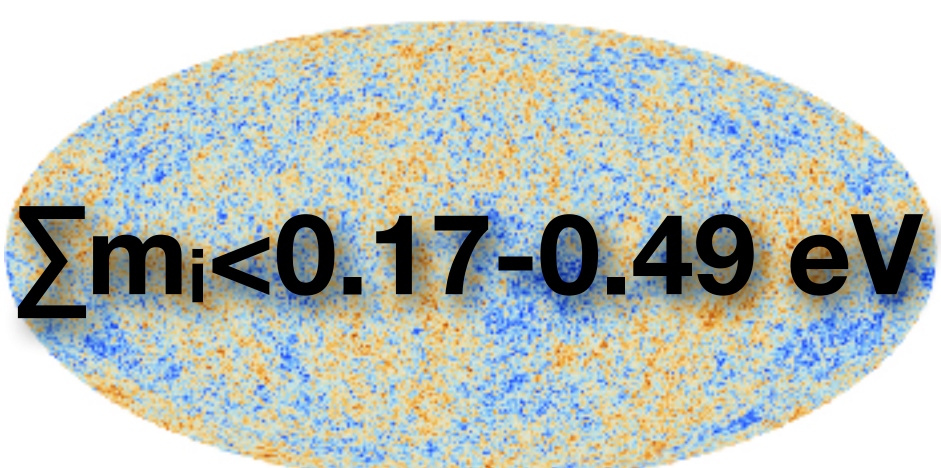
- Strong support to build 2-3 next-generation experiments. Which ones?

Goal for next-generation experiments

15 meV Majorana neutrino mass sensitivity

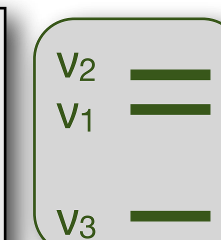
$m_{\beta\beta}$<0.06-0.16 eV





$\sum m_i$<0.17-0.49 eV

Guaranteed ββ0ν discovery if neutrinos are Majorana and have "inverted" mass ordering



Recipe for next-generation experiments

Favour ββ isotopes that can be extrapolated to large masses (~ton)

+

Favour low background rate experimental techniques

The problem of backgrounds

$$T^{0\nu}_{1/2} \propto \varepsilon \sqrt{\frac{Mt}{c\,\Delta E}}$$

ΔE → energy resolution

c → background rate (per unit energy, mass and time)

Current-generation detector performance:

Experiment	c (counts / (keV·kg·yr))	ΔE (keV)	Notes
GERDA	$(0.7\text{-}3.5)\times10^{-3}$	3.5	Measured
CUORE	6×10^{-2}	5	CUORE-0
KamLAND-Zen	1.6×10^{-4}	250	Measured
EXO	1.7×10^{-3}	75	Measured
NEXT	4×10^{-4}	17.5	Prediction

→

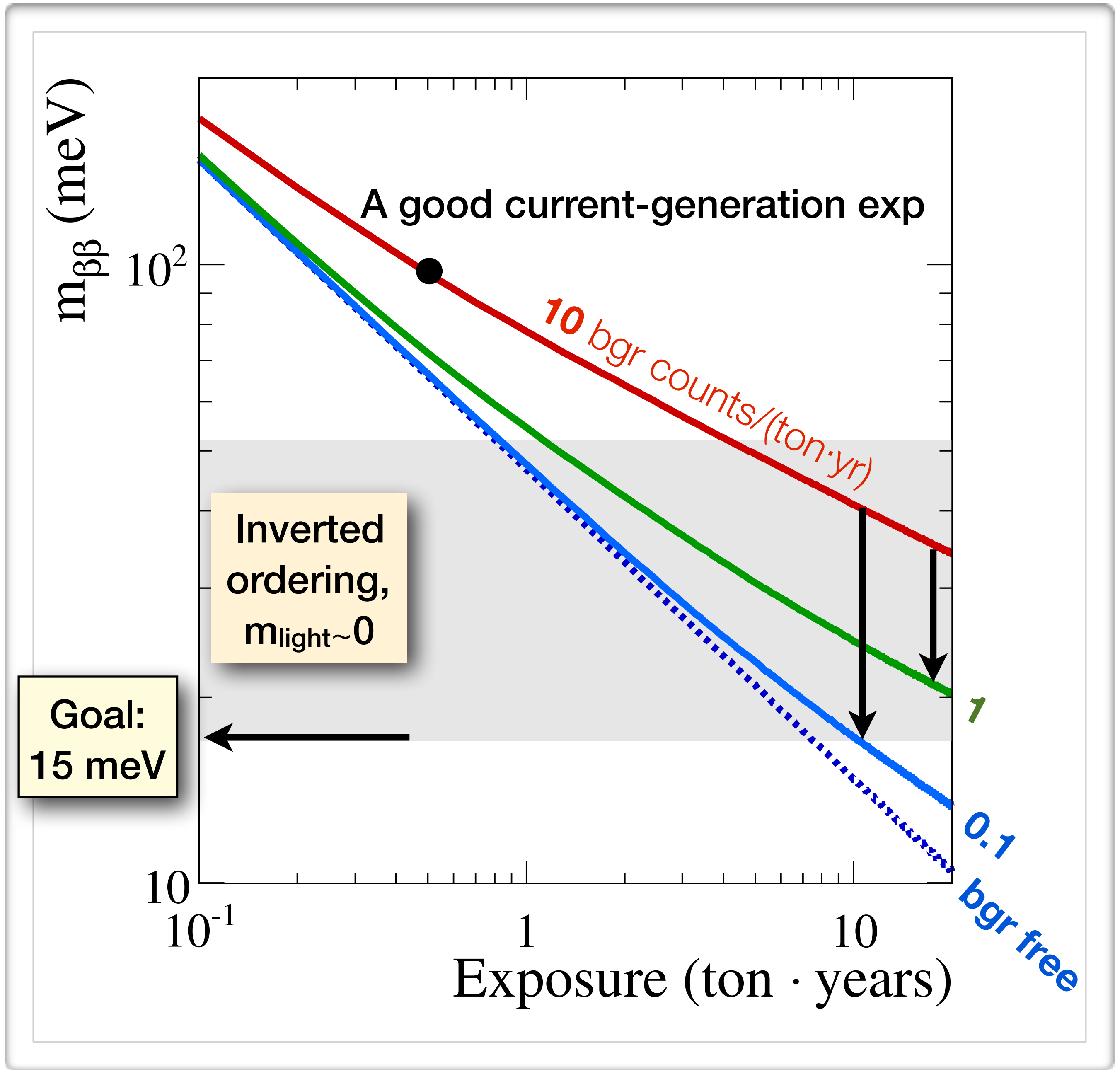
Ton-scale extrapolation:

Background (counts / (ton·yr))
2-12
300
40
130
7

- Today, no technique extrapolates to background-free regime at ton-scale

Ton-scale detector and need for background R&D

- Ton-scale detector necessary but not sufficient requirement
- Need at least 1-2 orders of magnitude background reduction with respect to current-generation
- R&D on active background reduction techniques



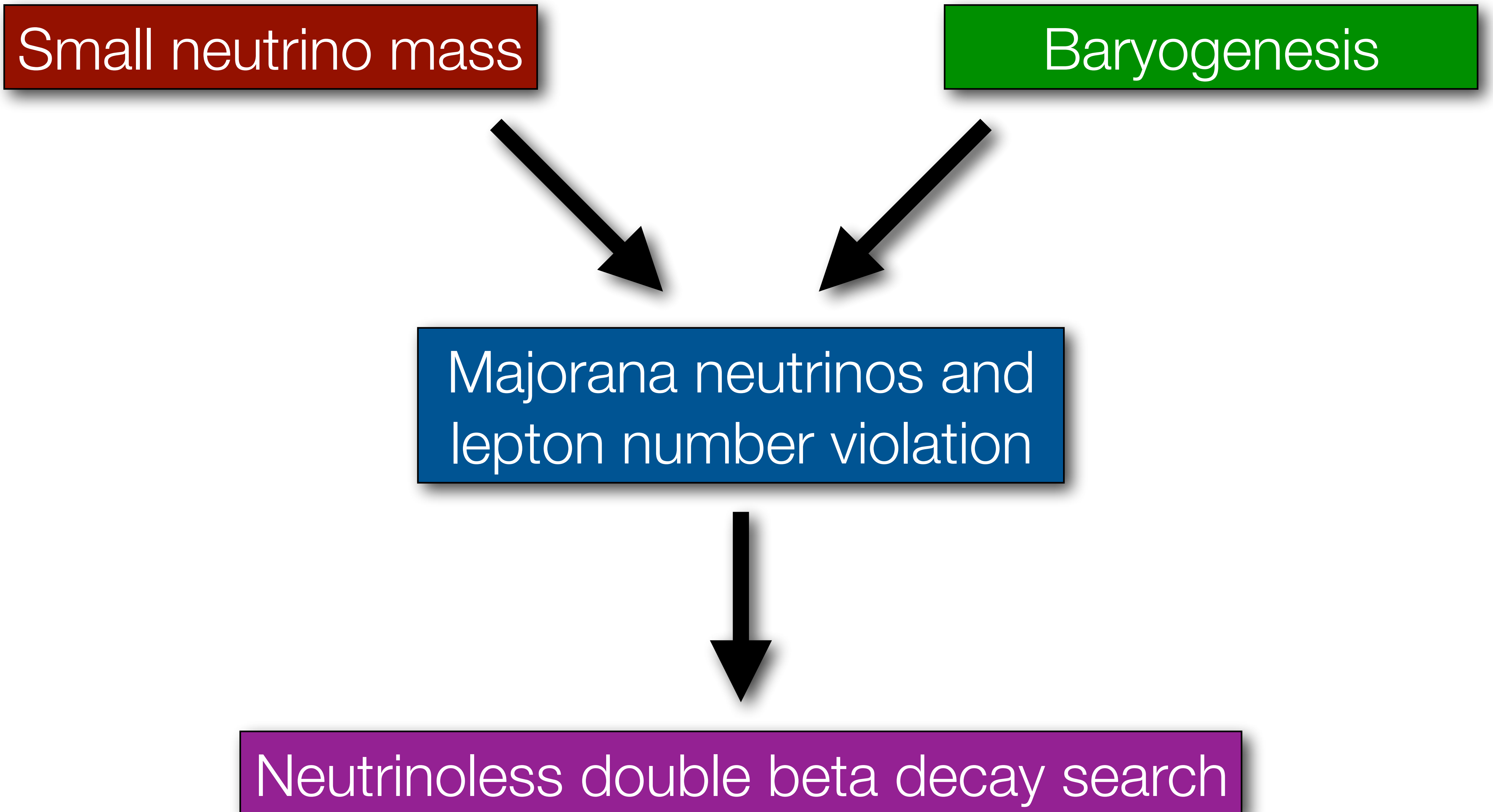
Background reduction R&D

Technology	R&D	Current experiments	Ton-scale proposal
Ge detectors	Larger Ge detectors, improved LAr scint. detection	GERDA, MAJORANA	LEGEND (200 kg)
Bolometers	Scintillating bolometers, isotopic enrichment	CUORE	CUPID
Liquid scintillators	High yield LS, light concentrators, high QE PMTs, enrichment	KamLAND-Zen, SNO+	KamLAND2-Zen
LXe-TPCs	Xe scint. readout with SiPMs, cold electronics, Ba tagging	EXO-200	nEXO
HPXe-TPCs	Low diffusion gas mixtures, finer tracking readout, Ba tagging	NEXT-NEW	NEXT-ton

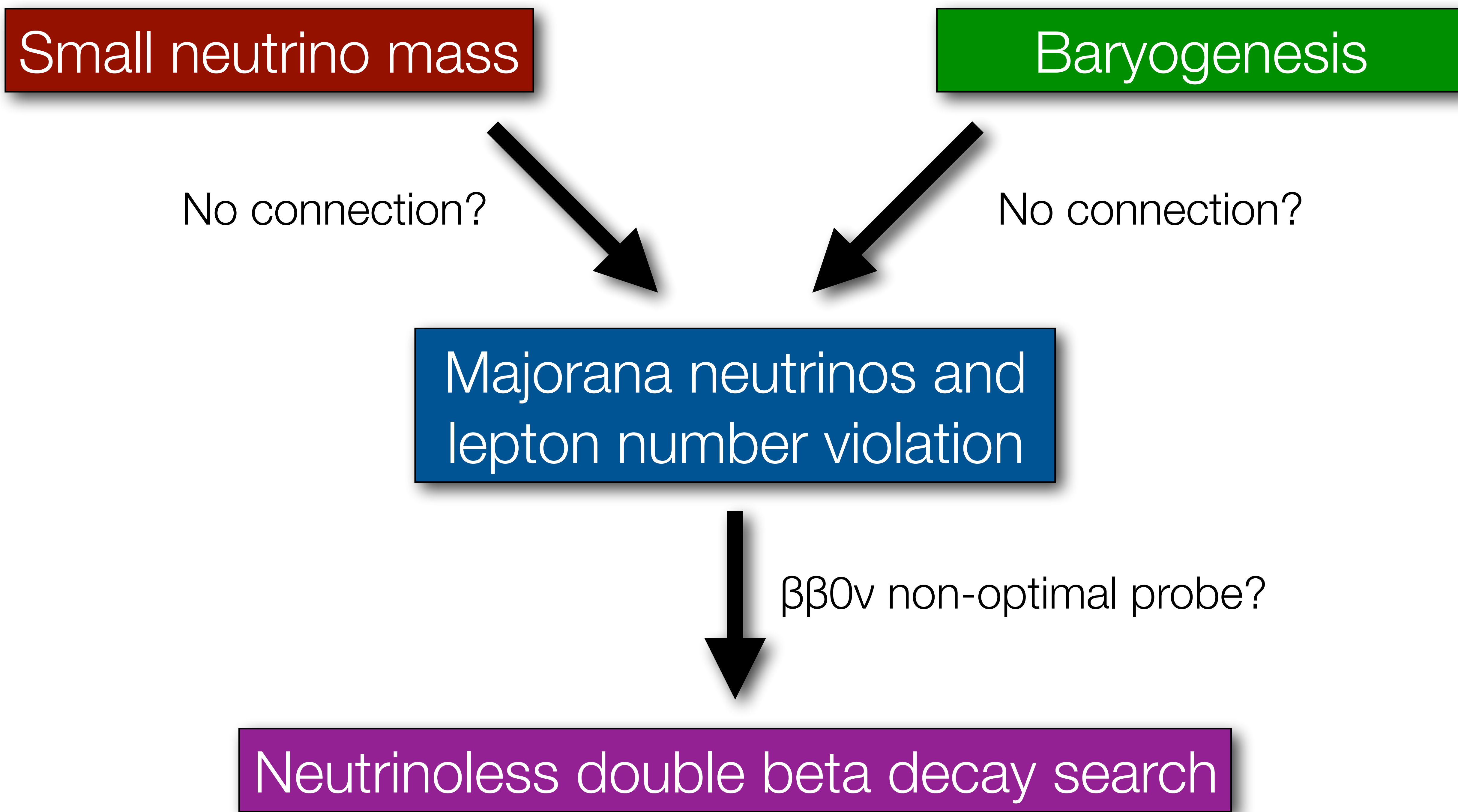
Appendices:

Thinking outside the box

The standard story I just told you



Possible variations



Other lepton number violating processes?

- $|\Delta L| = 2$ process mediated by: $W^- W^- \to l_\alpha^- l_\beta^-$, $\alpha,\beta = e,\mu,\tau$

➔ can probe different neutrino mass matrix elements $\mathbf{m_{\alpha\beta}}$

Other lepton number violating processes?

- $|\Delta L| = 2$ process mediated by: $W^- W^- \rightarrow l_\alpha^- l_\beta^-$, $\alpha,\beta = e,\mu,\tau$

➔ can probe different neutrino mass matrix elements $\mathbf{m_{\alpha\beta}}$

Flavors	Exp. technique	Mass bound (eV)
(e,e)	ββ0ν	$m_{ee} < 1\times10^{-1}$
(e,μ)	$\mu^- \rightarrow e^+$ conversion	$m_{e\mu} < 2\times10^{7}$
(e,τ)	Rare τ^- decays	$m_{e\tau} < 3\times10^{12}$
(μ,μ)	Rare K^+ decays	$m_{\mu\mu} < 3\times10^{8}$
(μ,τ)	Rare τ^- decays	$m_{\mu\tau} < 2\times10^{12}$
(τ,τ)	None	None

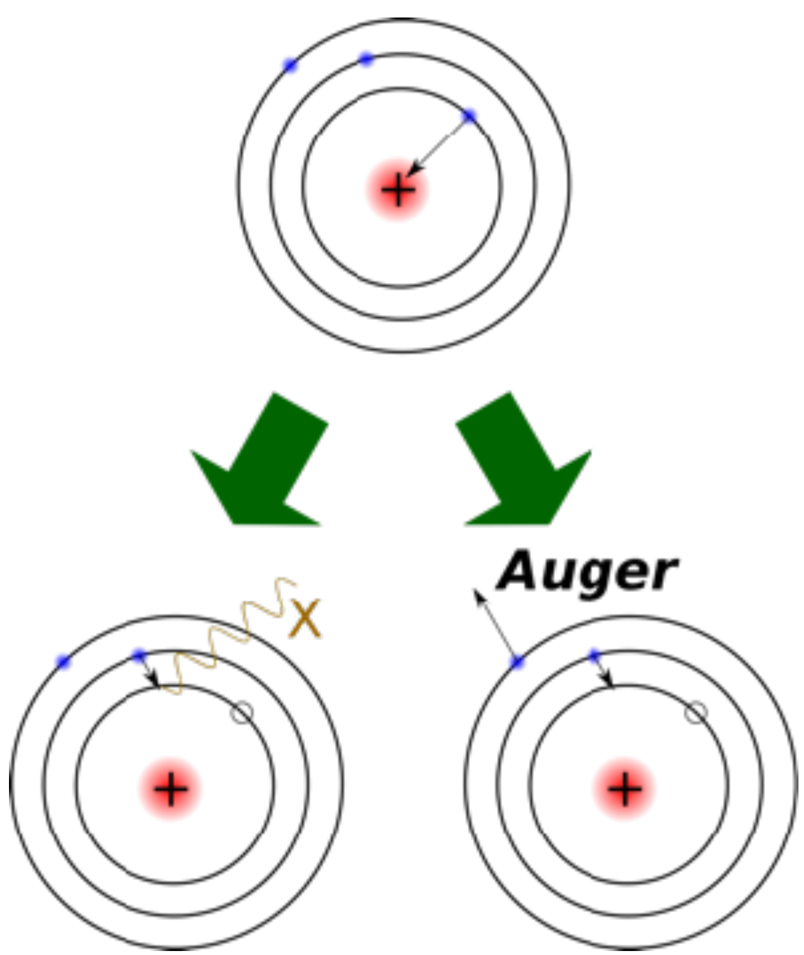
➔ best constraint by far on **(e,e)** element and from **ββ0ν**, currently

Example: neutrinoless double **E**lectron **C**apture

Inverse of neutrinoless double beta decay!

$\beta\beta_{0\nu}$: $^{136}Xe \rightarrow {}^{136}Ba + e^- + e^-$

$ECEC_{0\nu}$: $^{124}Xe + e^- + e^- \rightarrow {}^{124}Te$



Observables:

- Two X-rays
- Gamma-rays

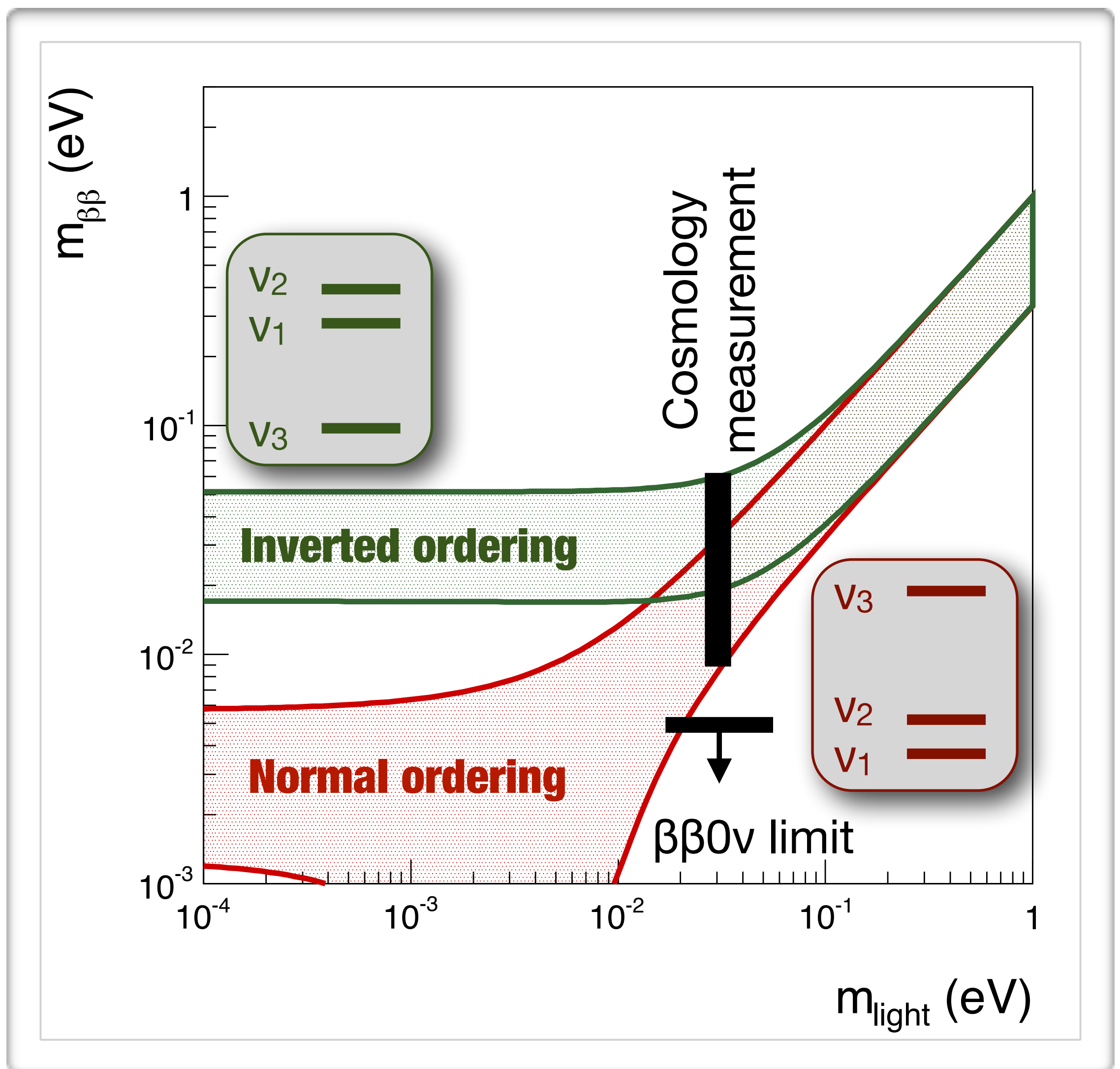
What if ν mass is not connected to Majorana neutrinos?

- **Possible**: Dirac neutrinos!

What if ν mass is not connected to Majorana neutrinos?

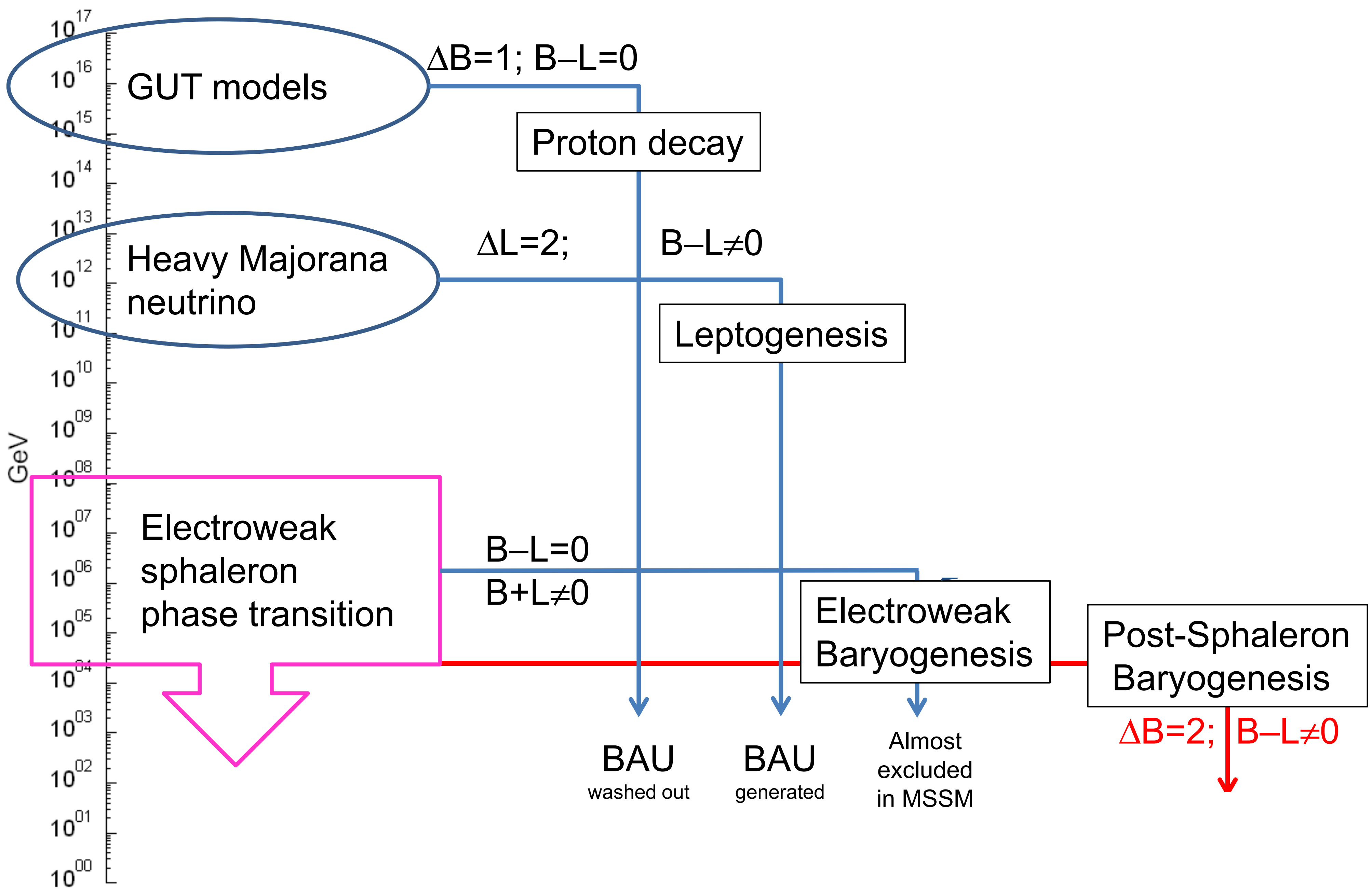
- **Possible**: Dirac neutrinos!

- How can we **prove** that neutrinos are Dirac particles? Difficult!
- **Best bet**: neutrino mass measured with cosmology, not in ββ0ν



What if baryogenesis is not connected to Majorana neutrinos?

- **Possible**: alternatives to leptogenesis-induced baryogenesis!

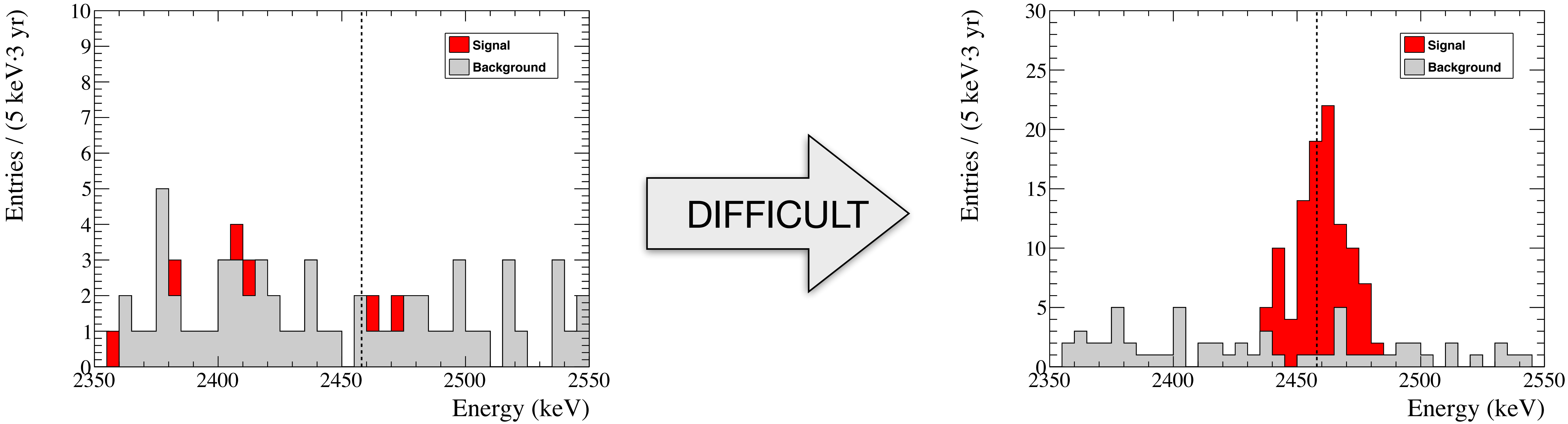


Epilogue:

Final thoughts

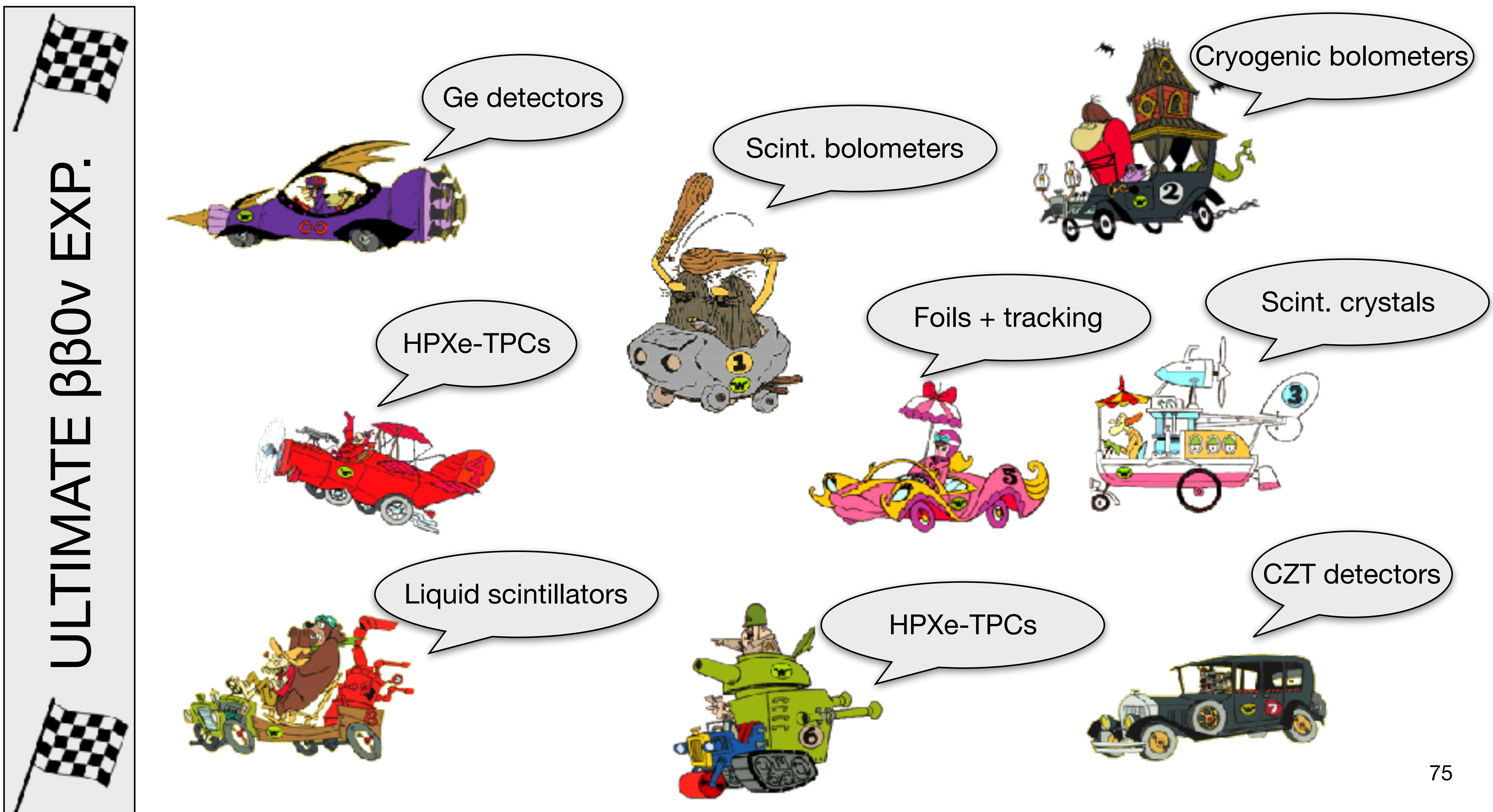
Double beta decay experiments are challenging

$$T^{0\nu}_{1/2} \propto \varepsilon \sqrt{\frac{Mt}{c\,\Delta E}}$$

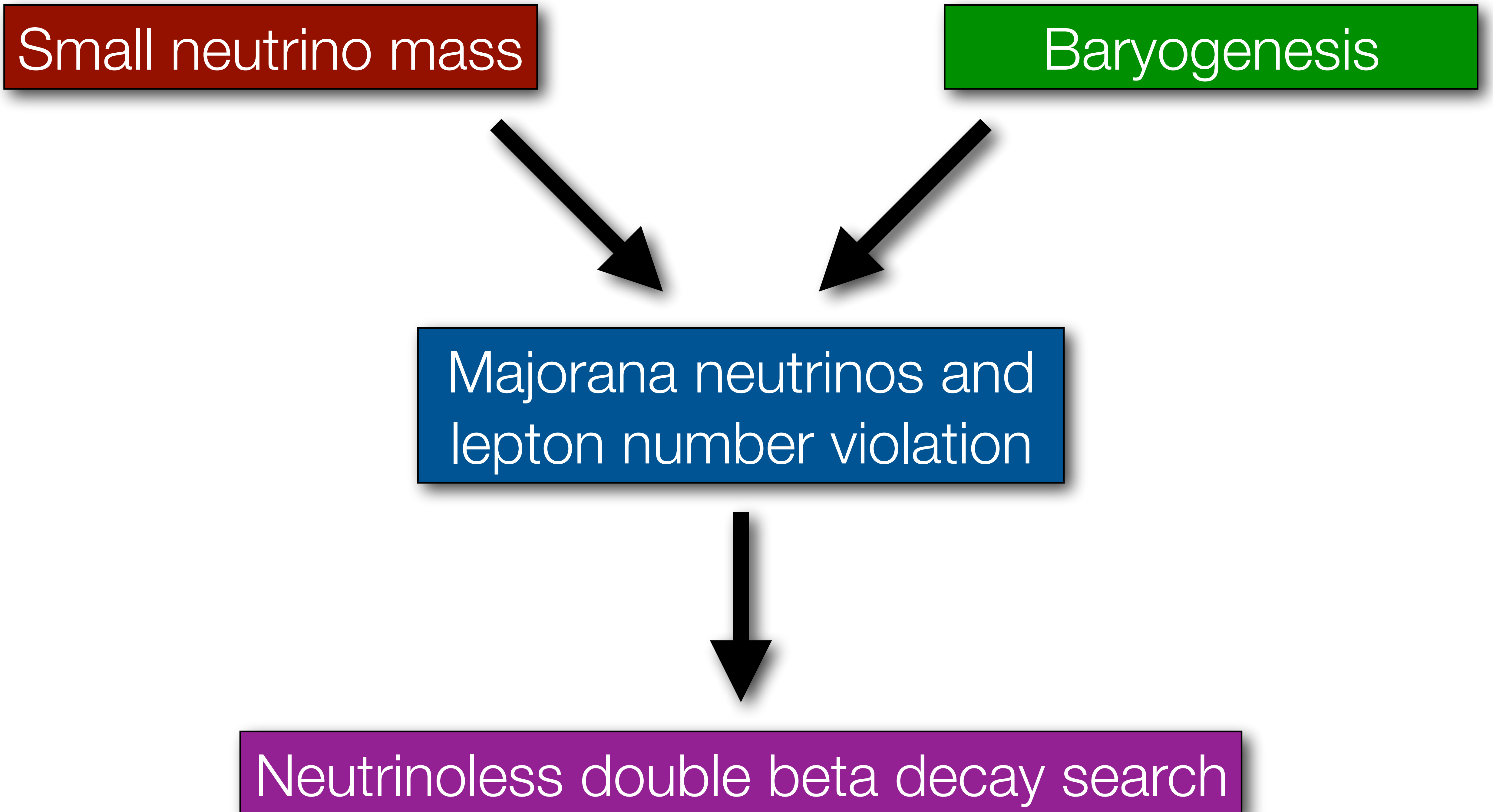


A variety of double beta decay experiments

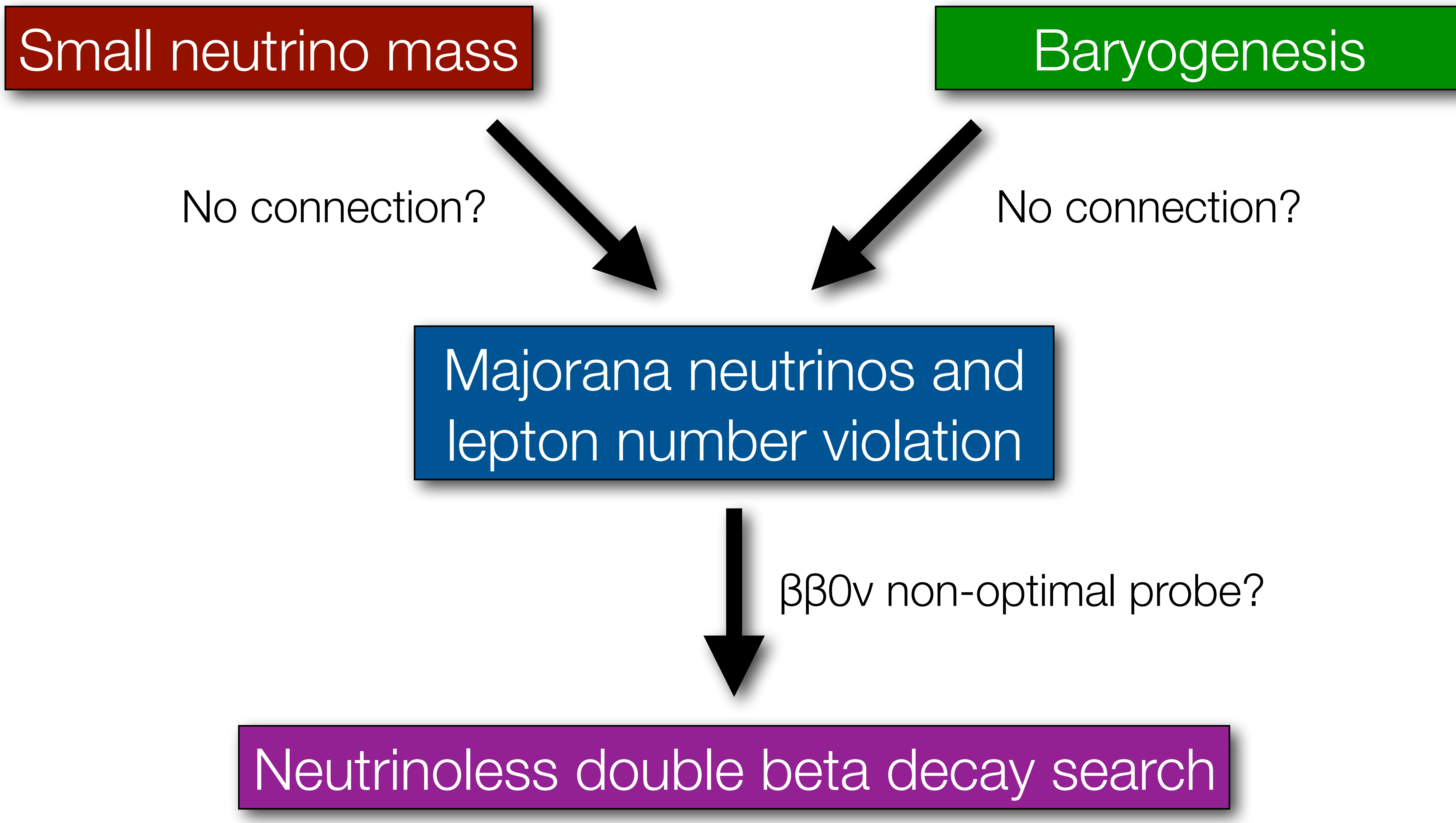
- Non-trivial detector optimisation process, relatively inexpensive → diversity



The theory-experiment connection is essential



Think outside the box!



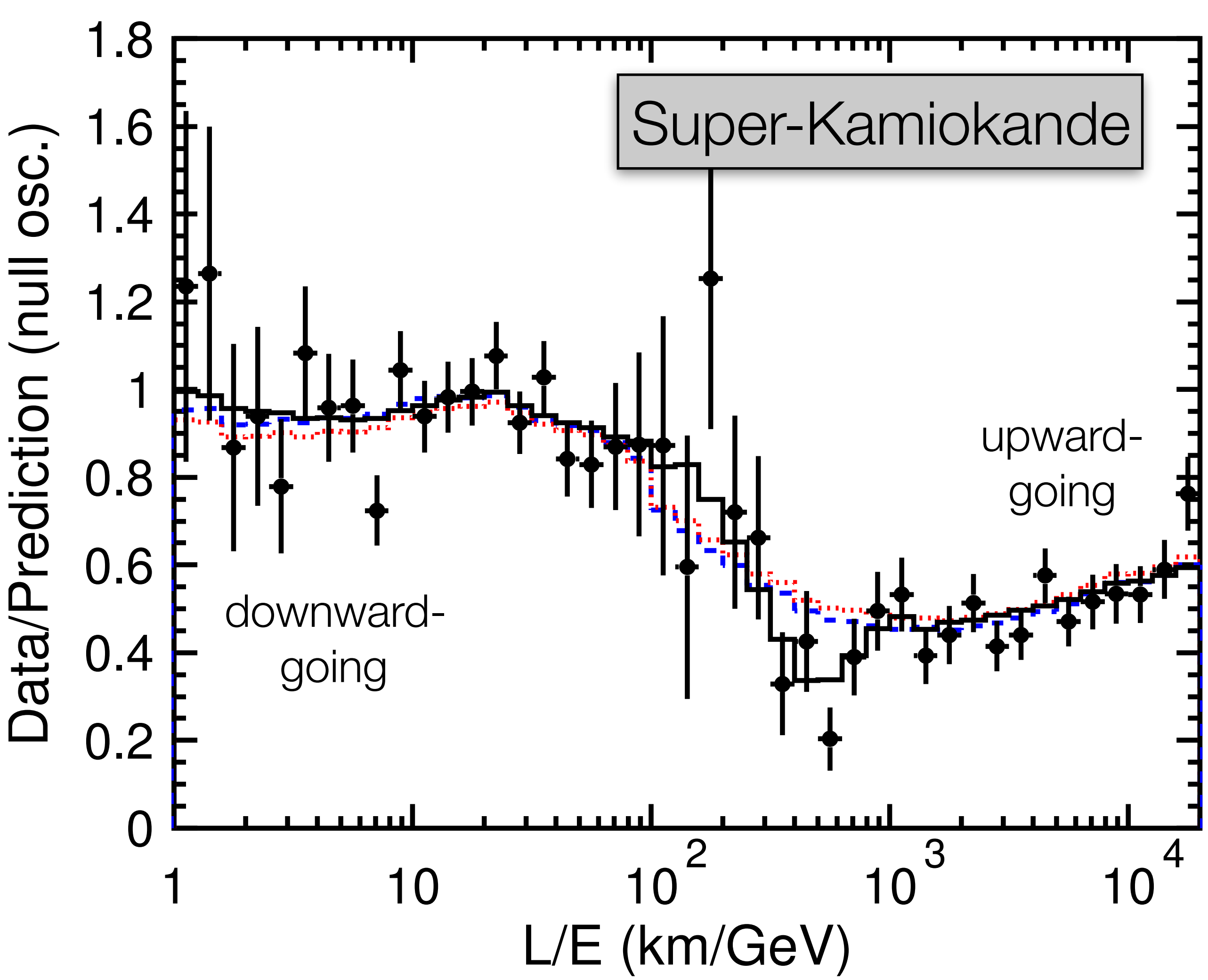
The End.

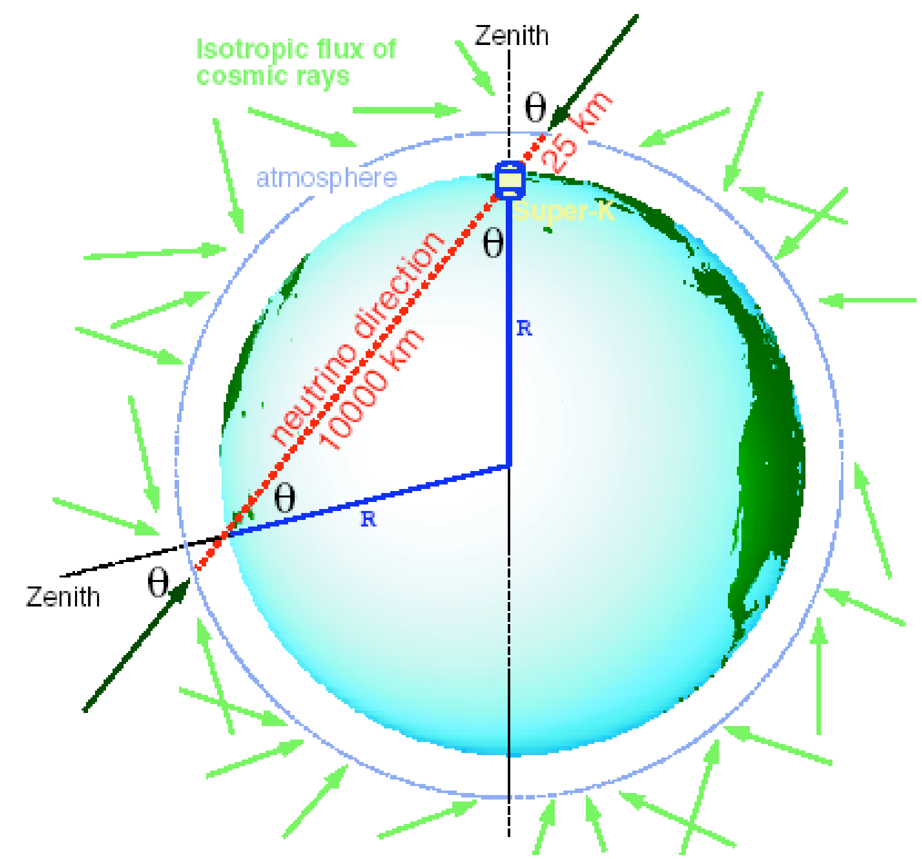
Backups

The discovery of neutrino oscillations

With atmospheric neutrinos

- Disappearance of atmospheric ν_μ's and $\bar{\nu}_\mu$'s
- First conclusive evidence for oscillations: zenith angle-dependent deficit

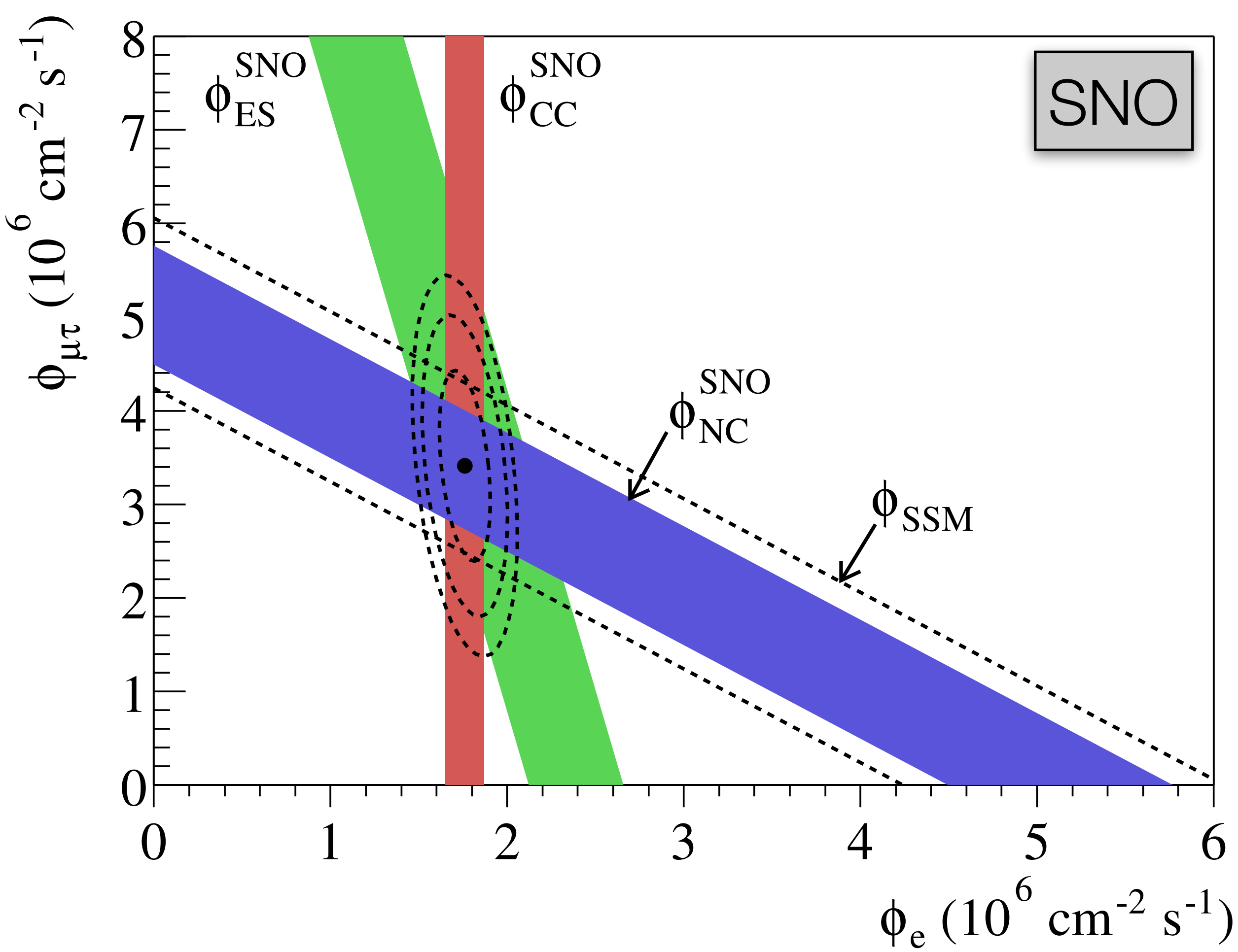


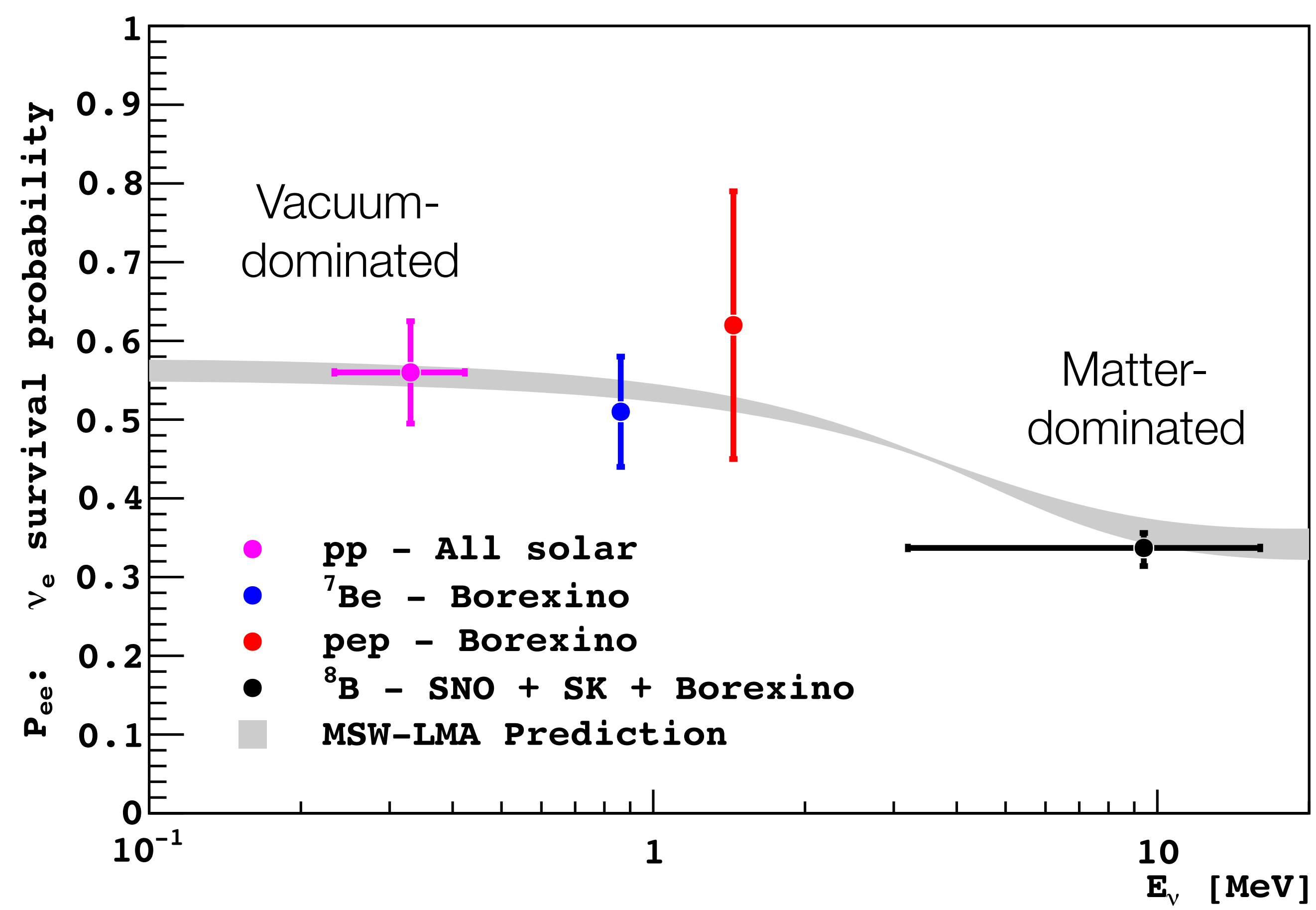


The discovery of neutrino oscillations

With solar neutrinos

- Disappearance of solar ν_e's, appearance into other "active" flavours (μ, τ)
- Energy dependence of ν_e suppression also measured

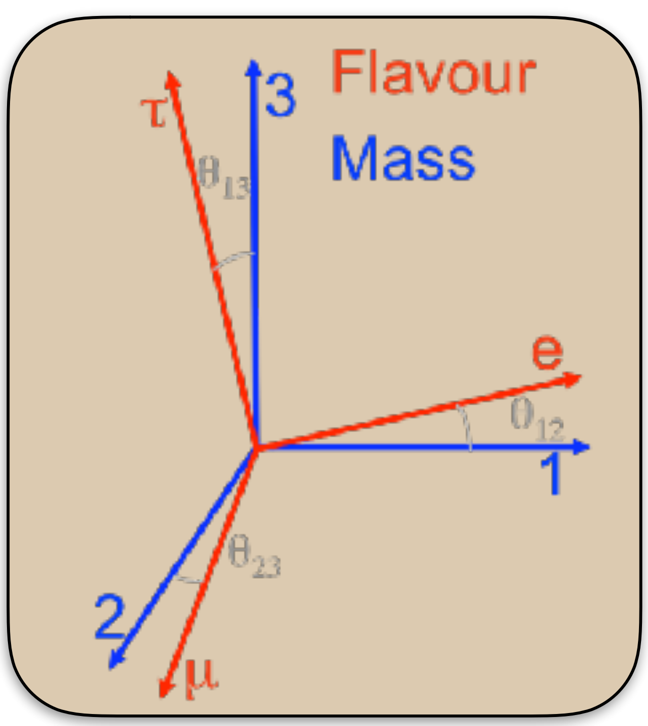




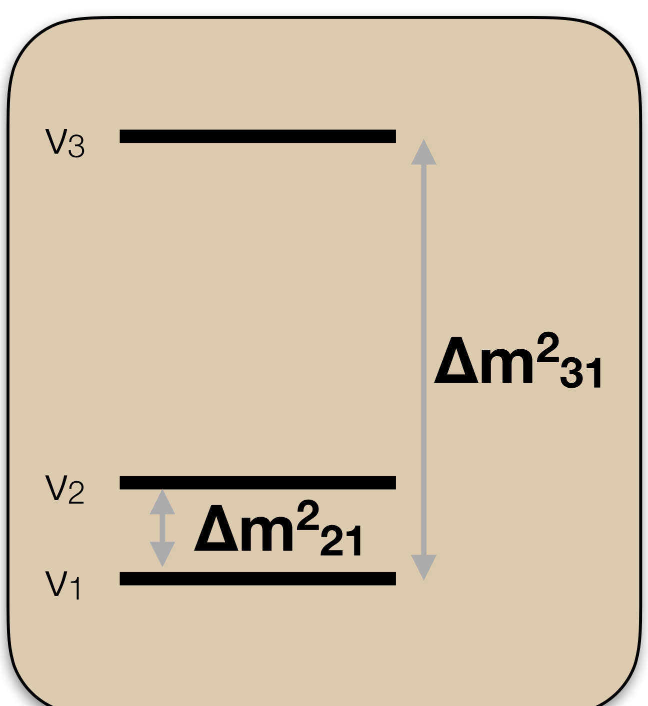
3-Neutrino mixing parametrisation

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \underbrace{\begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix}}_{\text{Atmospheric Oscillations}} \underbrace{\begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix}}_{\text{Interference}} \underbrace{\begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}}_{\text{Solar Oscillations}} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

$$c_{23} = \cos\theta_{23} \text{ etc...}$$



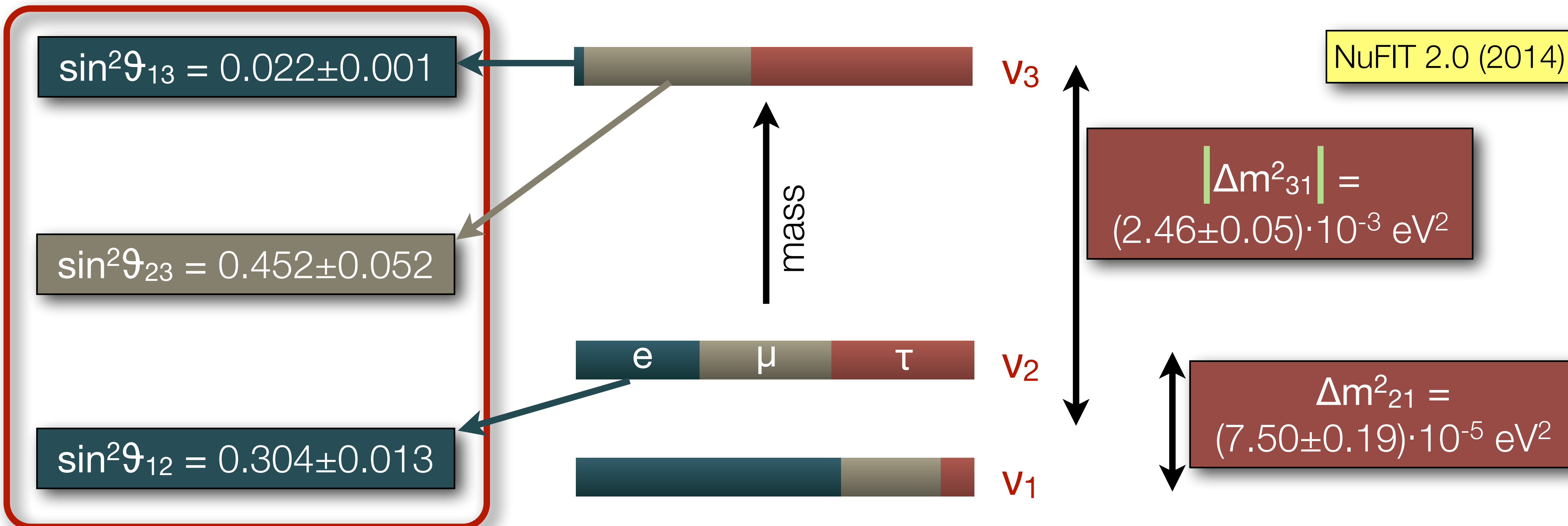
- 2 mass splittings, 3 mixing angles,1 CPV phase
- Describe all convincing evidence for neutrino oscillations



Neutrino oscillation experimental status

3-neutrino mixing parametrisation

Mass splittings and mixing angles measured with 10% precision or better



- θ_{12} and Δm^2_{21}: solar and reactor experiments
- θ_{23} and $|\Delta m^2_{31}|$: atmospheric and accelerator experiments
- θ_{13}: reactor and accelerator experiments
- δ_{CP} phase compatible with any value at 3σ, sgn(Δm^2_{31}) unknown

Ingredients for ββ0ν experiments

Current-generation

Ingredients for ββ0ν experiments

Current-generation

- Isotope with large $Q_{\beta\beta}$ value ································· >2 MeV
  - Larger phase space and less backgrounds

Typical

Ingredients for ββ0ν experiments

Current-generation

- Isotope with large $Q_{\beta\beta}$ value ·························· >2 MeV
  - Larger phase space and less backgrounds
- High detection efficiency ·························· >0.25

Typical

Ingredients for ββ0ν experiments

Current-generation

- Isotope with large $Q_{\beta\beta}$ value ································ >2 MeV
  - Larger phase space and less backgrounds
- High detection efficiency ································ >0.25
- Large ββ isotope mass ································ 100 kg
  - Only way to probe 10^{26} yr half-lives!

Typical (>2 MeV, >0.25)

Current goal (100 kg)

Ingredients for ββ0ν experiments

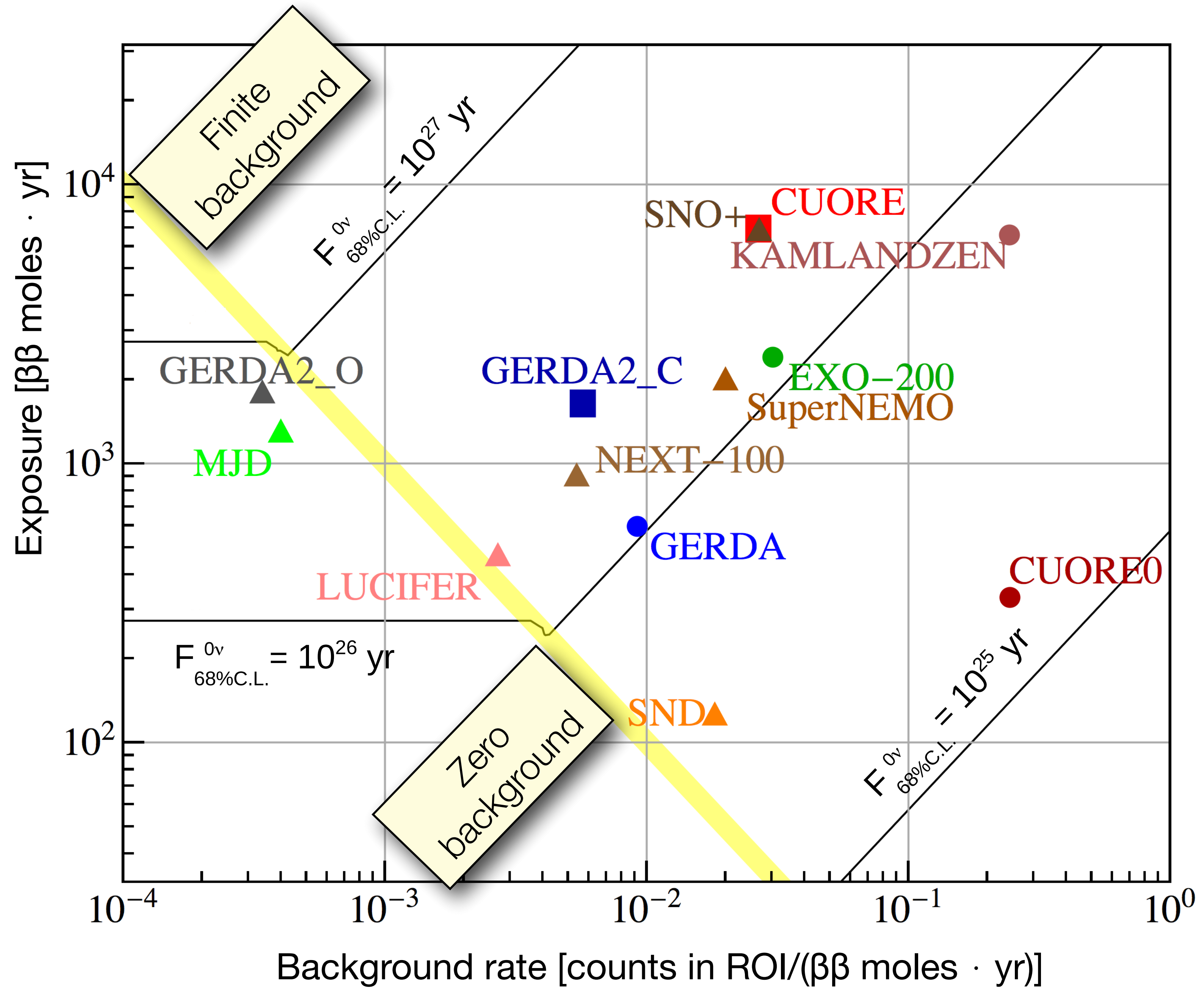
Current-generation

- Isotope with large $Q_{\beta\beta}$ value ································ >2 MeV
  - Larger phase space and less backgrounds
- High detection efficiency ································ >0.25
- Large ββ isotope mass ································ 100 kg
  - Only way to probe 10^{26} yr half-lives!
- Low backgrounds in energy region of interest ······················ 1 cts/(100 kg·yr)
  - Excellent energy resolution and/or very low background rates (per unit energy) near $Q_{\beta\beta}$

Typical

Current goal

ββ0ν experiments comparison: mass, background



[From O. Cremonesi, M. Pavan, arXiv:1310.4692]