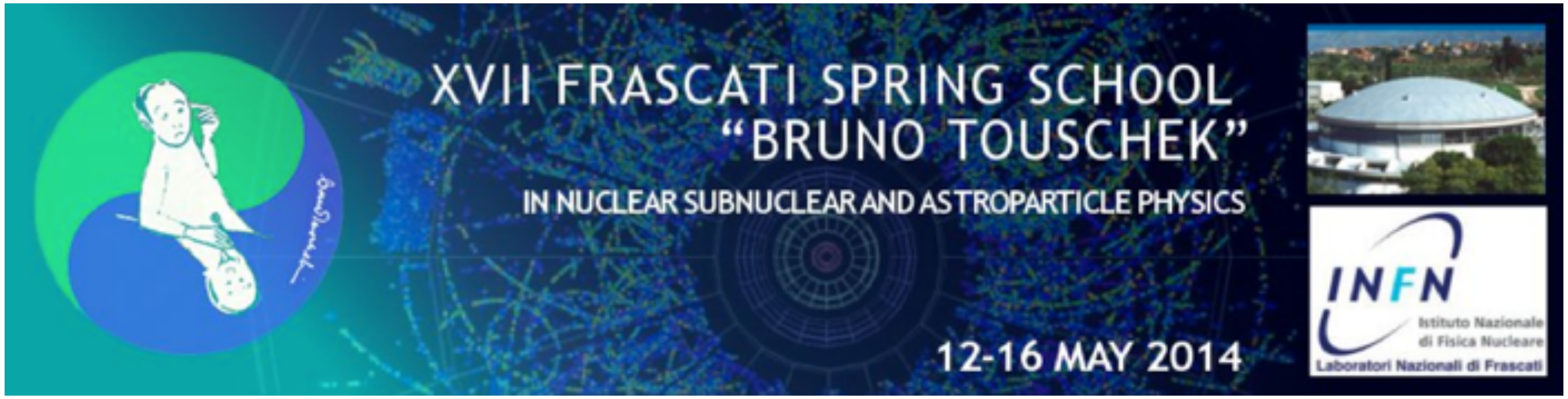
Neutrino Experiments

Lecture 2

M. Sorel (IFIC - CSIC & U. de Valencia)



Plan for these lectures

- Yesterday: neutrino oscillation experiments
  - How to measure neutrino oscillation parameters
  - Neutrino sources
  - Neutrino interactions with matter
  - Neutrino detector technologies
  - A selection of current and future experiments

- Today: other neutrino experiments
  - Neutrinoless double beta decay experiments
  - Direct neutrino mass measurements
  - Neutrino cosmology

How to experimentally address neutrino questions

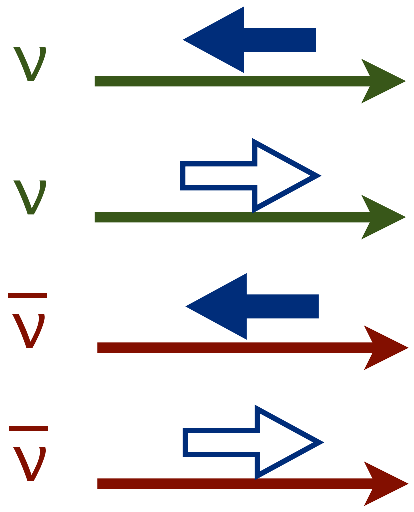
Identity	Neutrinoless double beta decay
Mass scale	Direct neutrino mass measurements, neutrino cosmology, neutrinoless double beta decay
Mass ordering	Neutrino oscillations, neutrino cosmology
Mixing	Neutrino oscillations
Species	Neutrino oscillations, neutrino cosmology

Neutrino question 1: *Identity*

Dirac or Majorana fermion?

Dirac:

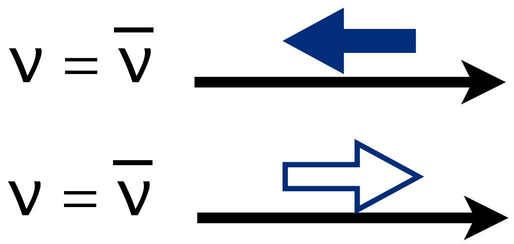
- 4 states
- $\nu \neq \bar{\nu}$



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

Majorana:

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



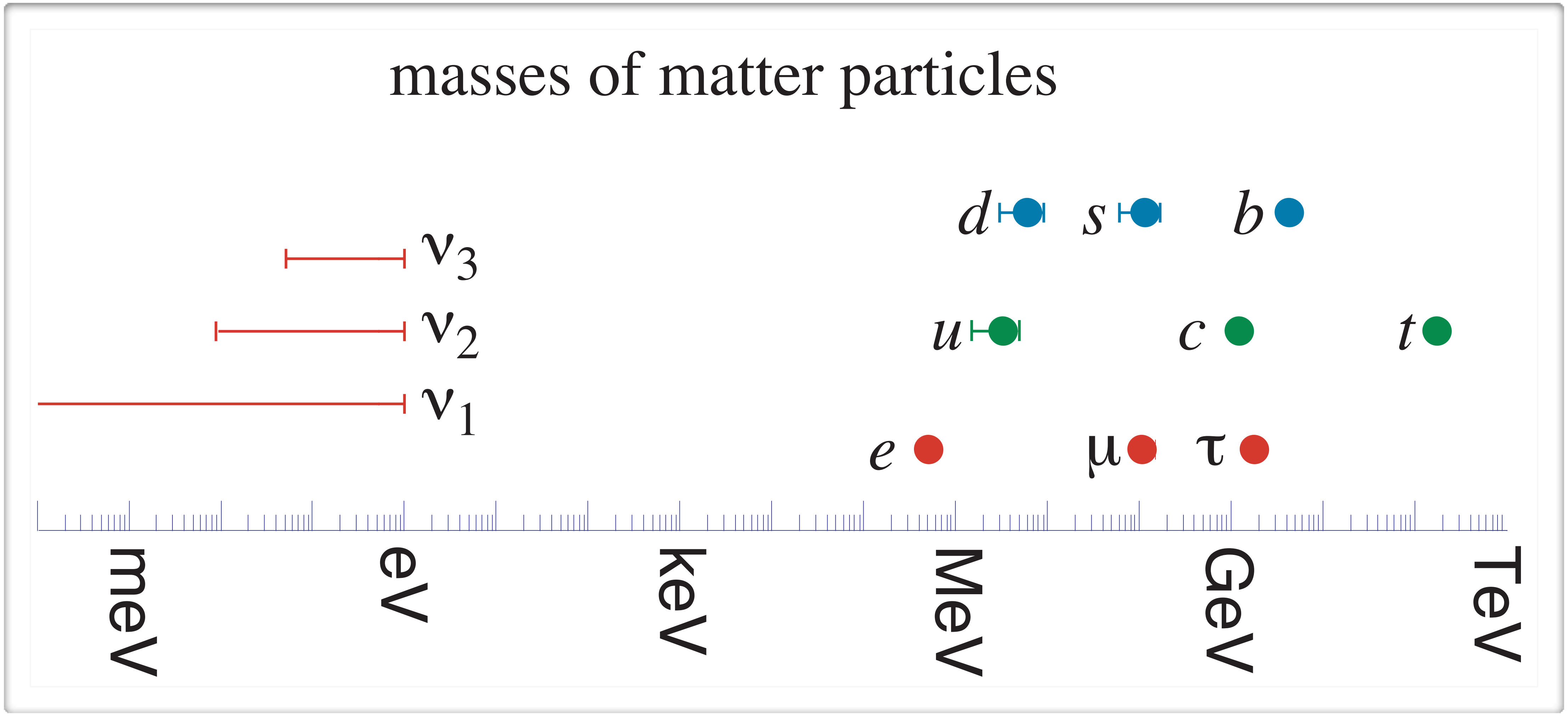
Helicity	Conserved Lepton Number	Lepton production rate	Anti-lepton production rate
-1/2	**none**	1	0
+1/2	**none**	0	1

Neutrino question 2: Mass scale

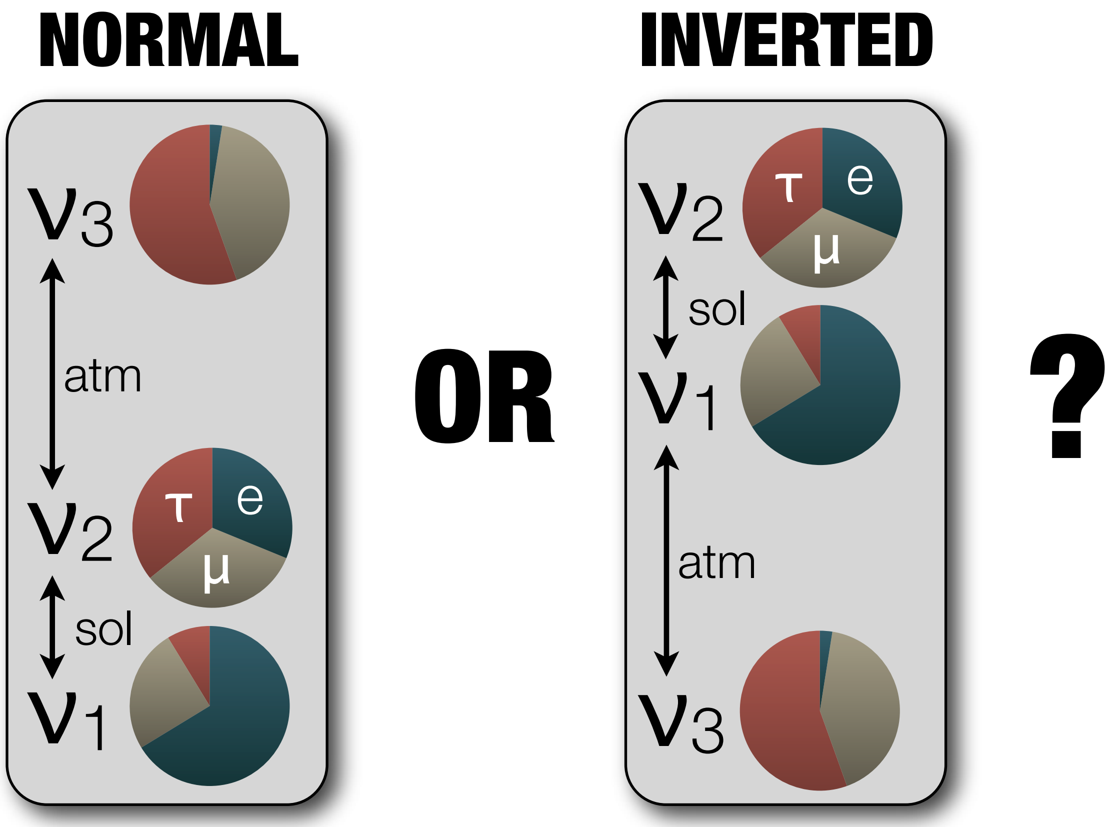
We know it is non-zero, but... What is the neutrino mass value?

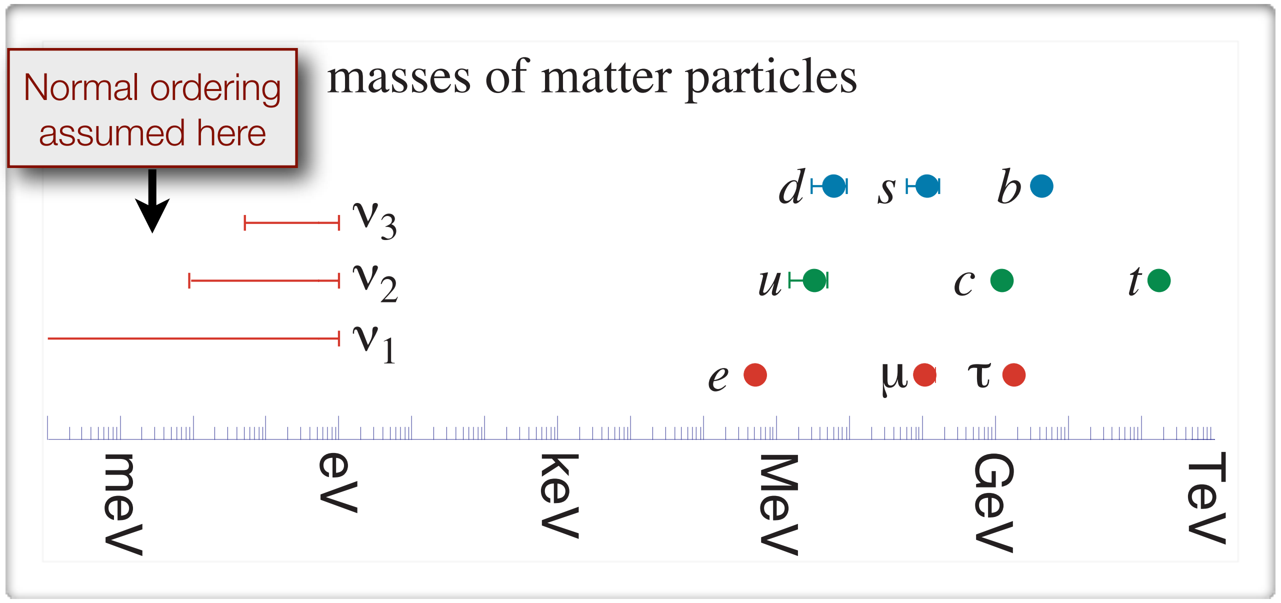
- Neutrino mass could be anywhere between 0 and ~1 eV

⇨ how different from quarks and charged leptons?


masses of matter particles

Neutrino question 3: Mass ordering





- If ν_1 taken as most electron-rich state, $m_1 < m_2$ from solar neutrinos
- **Normal** mass ordering: $m_{light} = m_1$ ➪ similar to quarks and charged leptons
- **Inverted** mass ordering: $m_{light} = m_3$ ➪ “opposite” to quarks and charged leptons

Neutrino question 4: Mixing

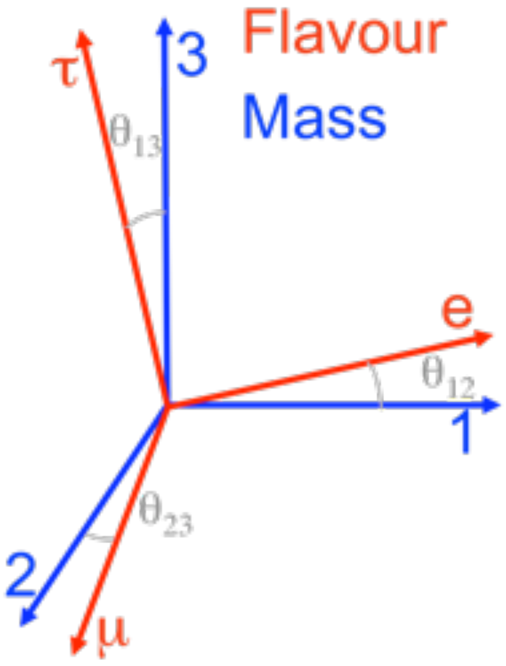
$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \overbrace{\begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix}}^{\text{Atmospheric Oscillations}} \underset{\text{Interference}}{\begin{pmatrix} c_{13} & 0 & \boxed{s_{13}e^{-i\delta}} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta}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

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

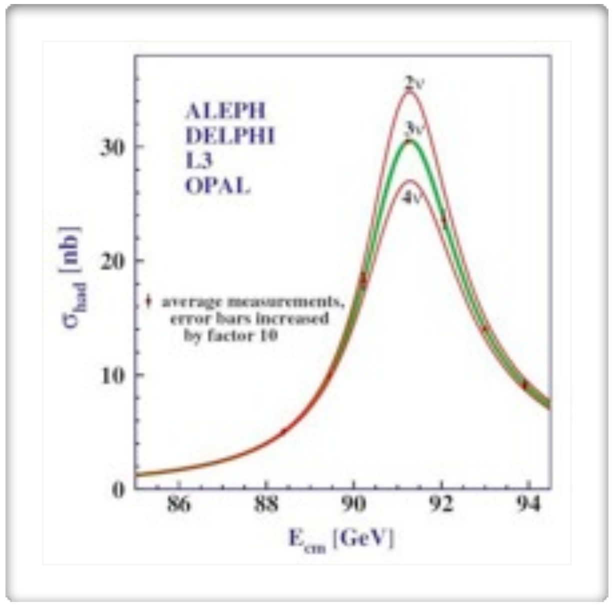
Is CP symmetry violated in the neutrino sector?

Possible source of CP violation in neutrino sector that can be measured with oscillations: Dirac CP-odd phase δ

δ ≠ 0, π ⇔ oscillation probabilities violate CP invariance: different probabilities for neutrinos and antineutrinos!



Neutrino question 5: Species

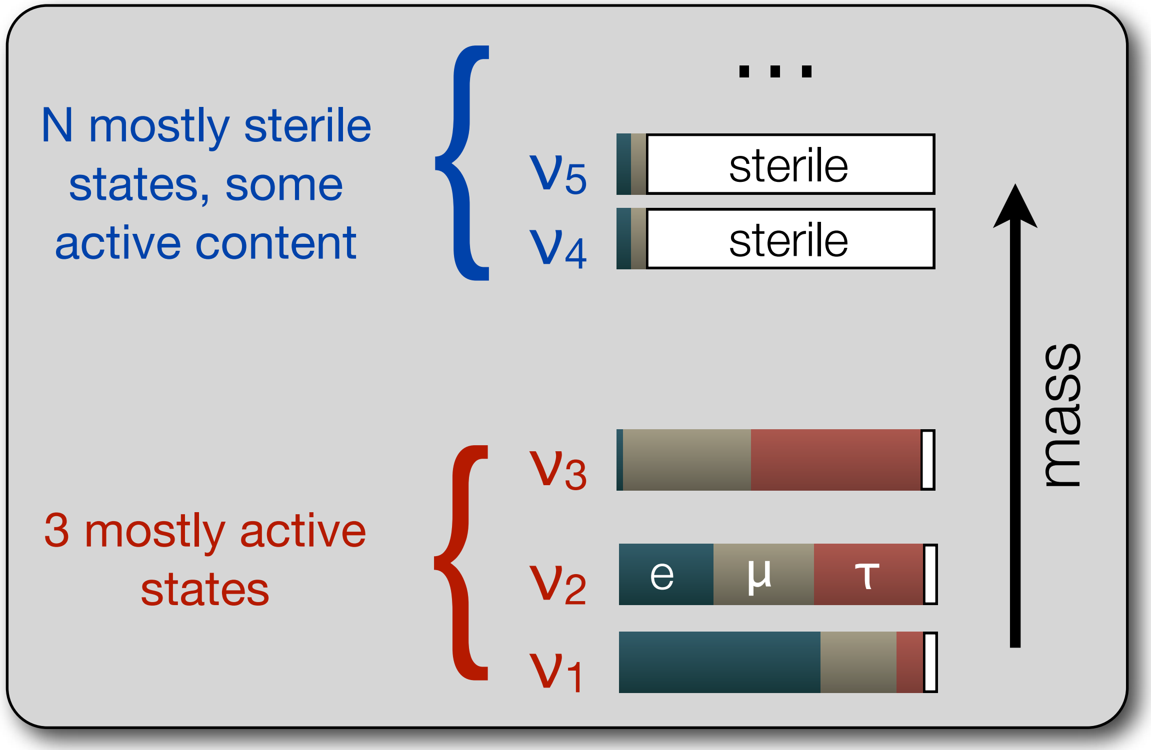


- LEP: three neutrino flavors participating in the weak interactions and with mass $<m_Z/2$. But...

...are there light "sterile" neutrino states, in addition to the three "active" ones?

- Hinted by anomalous results at short baselines:

Anomaly	Baseline (m)	Energy (MeV)	Oscillation interpretation	Significance (σ)
LSND	30	50	$\bar{\nu}_\mu \to \bar{\nu}_e$	3.8
MiniBooNE ν	500	600	$\nu_\mu \to \nu_e$	3.4
MiniBooNE $\bar{\nu}$	500	600	$\bar{\nu}_\mu \to \bar{\nu}_e$	2.8
Gallium	2	1	$\nu_e \to \nu_s$	2.8
Reactor	20	5	$\bar{\nu}_e \to \bar{\nu}_s$	2.9



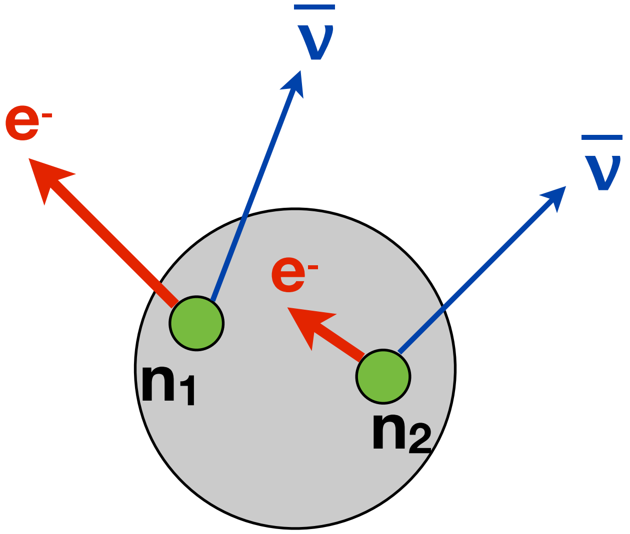
Neutrinoless double beta decay

Generalities

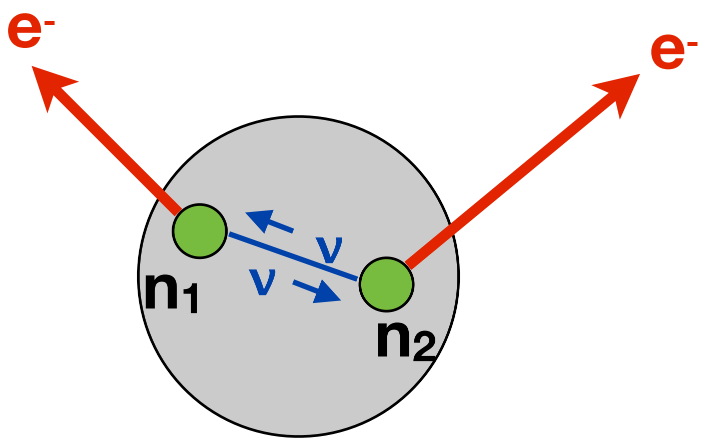
Double beta decay

- Rare (Z,A)→(Z+2,A) nuclear transition, with emission of two electrons
- Two basic decay modes

$\beta\beta 2\nu$



$\beta\beta 0\nu$



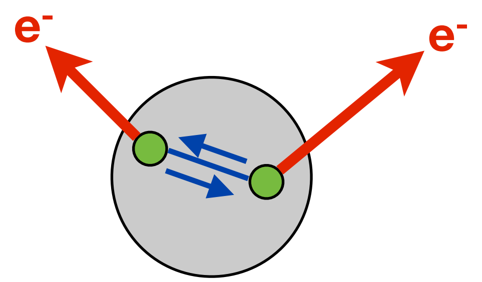
Two neutrino mode

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

Neutrinoless mode

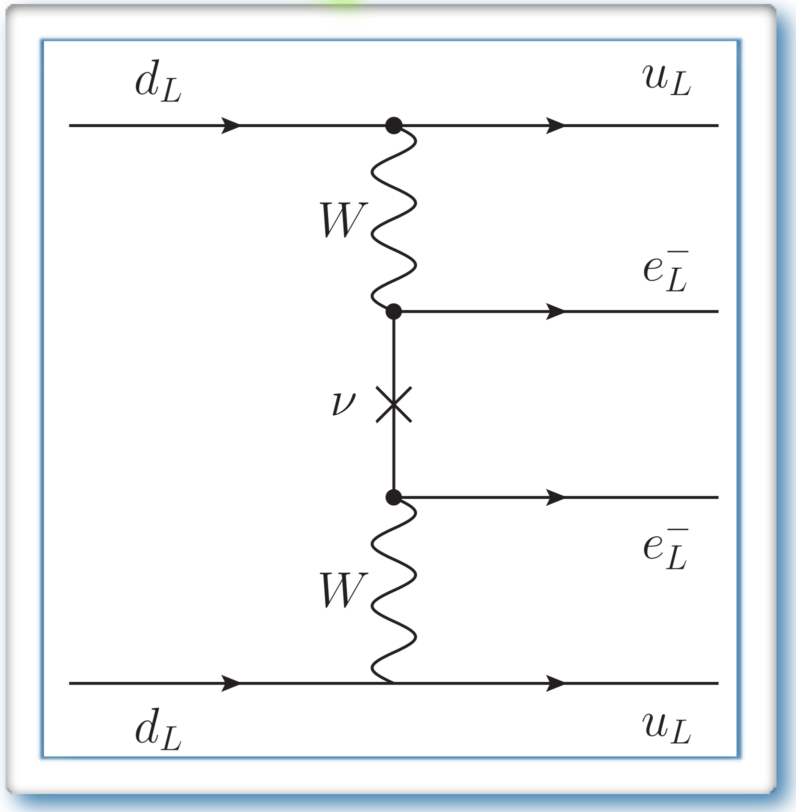
- Not observed yet in Nature
- $>10^{25}$ yr half-lives
- Would signal Beyond-SM physics

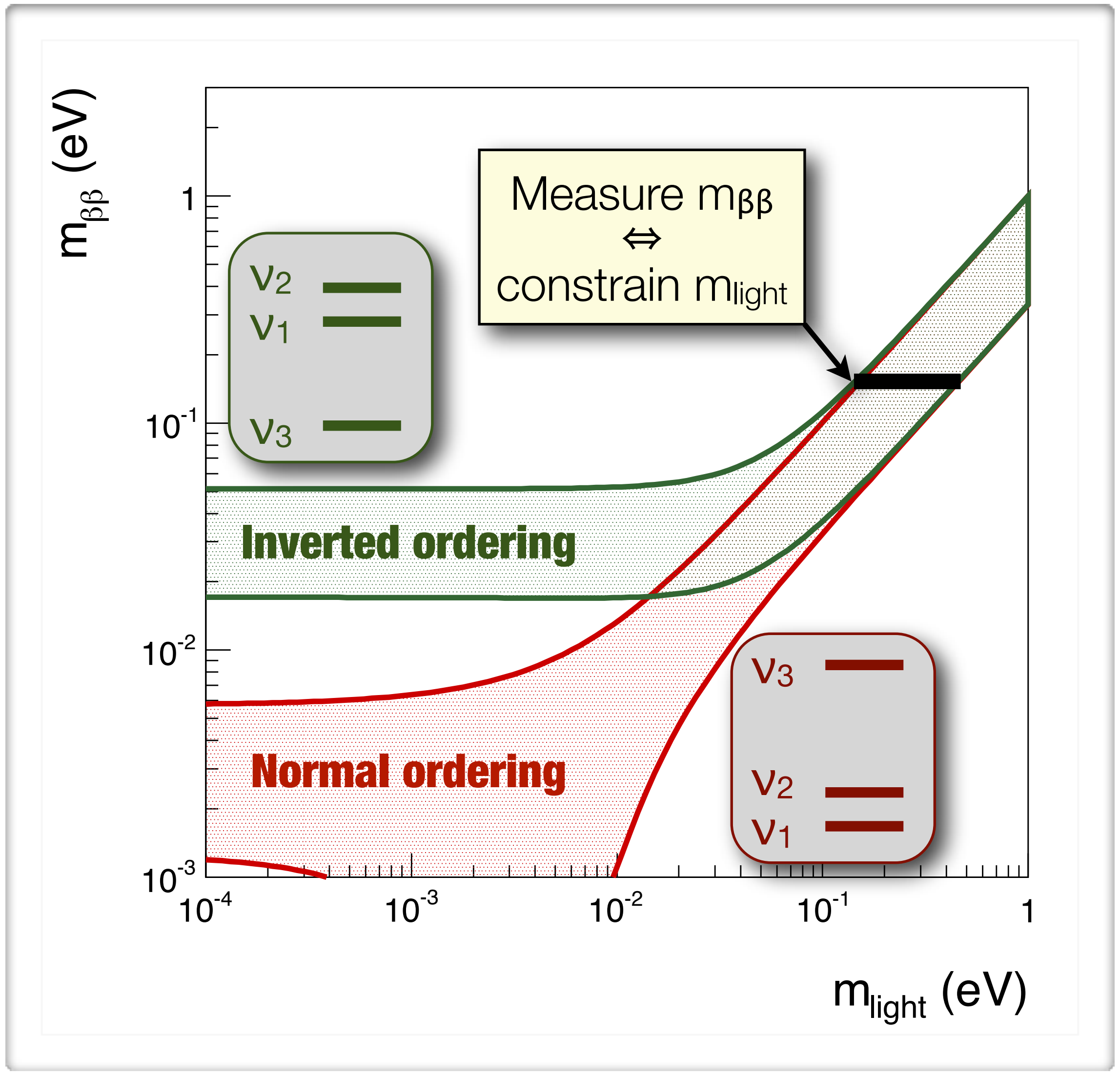
Neutrinoless double beta decay and the neutrino questions



Lepton number violating process
implying massive Majorana neutrinos

- Identity
- Mass scale
- Mass ordering
- Mixing
- Species

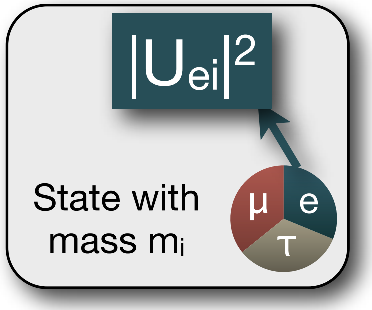




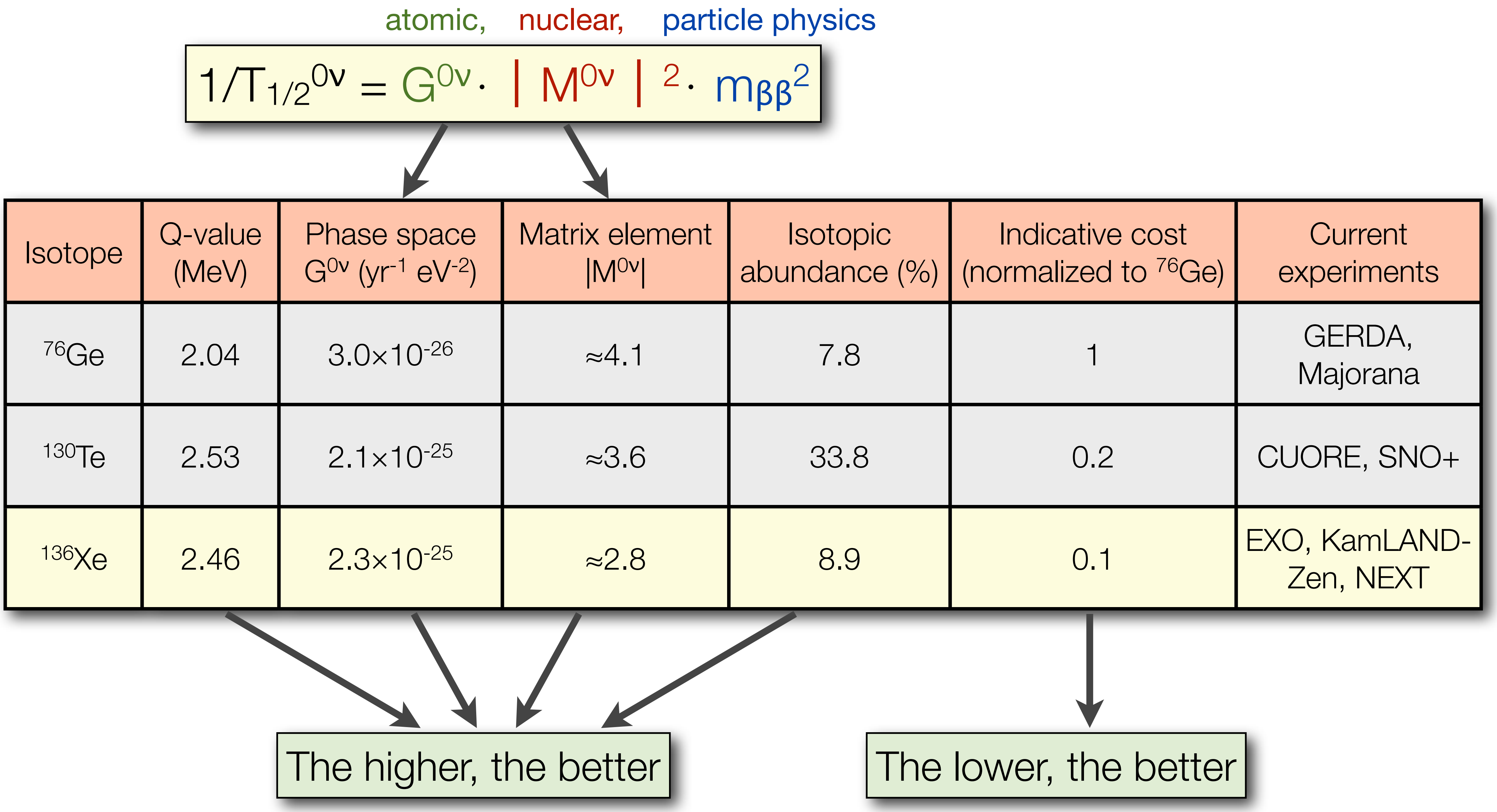
Measure $m_{\beta\beta}$ ⇔ constrain m_{light}

$$(\text{Rate})_{\beta\beta0\nu} = 1/T_{1/2} = G^{0\nu}\cdot|M^{0\nu}|^2\cdot m_{\beta\beta}^2$$

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



Comparison of ββ isotopes



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 $\lvert M^{0\nu}\rvert$	Isotopic abundance (%)	Indicative 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

Facts life of the double beta decay experimentalist

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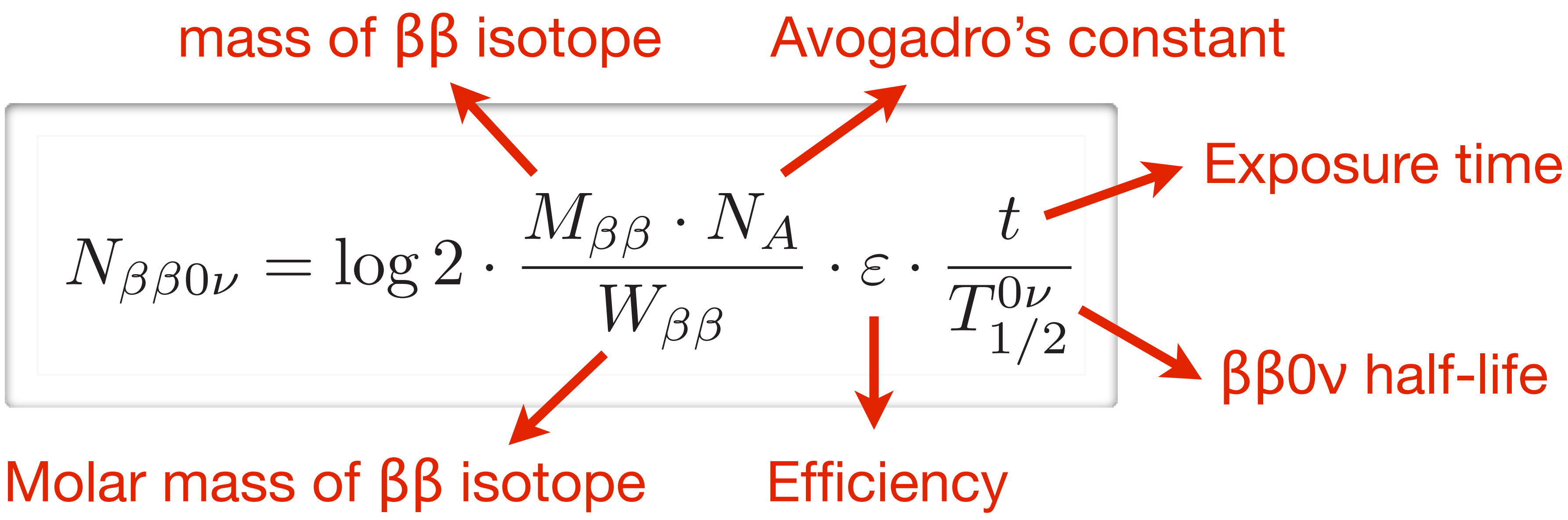
- Total number of **ββ0ν** decays that can be observed in a detector is (exercise: derive!)



$$N_{\beta\beta0\nu} = \log 2 \cdot \frac{M_{\beta\beta} \cdot N_A}{W_{\beta\beta}} \cdot \varepsilon \cdot \frac{t}{T^{0\nu}_{1/2}}$$

mass of ββ isotope

Avogadro's constant

Exposure time

ββ0ν half-life

Molar mass of ββ isotope

Efficiency

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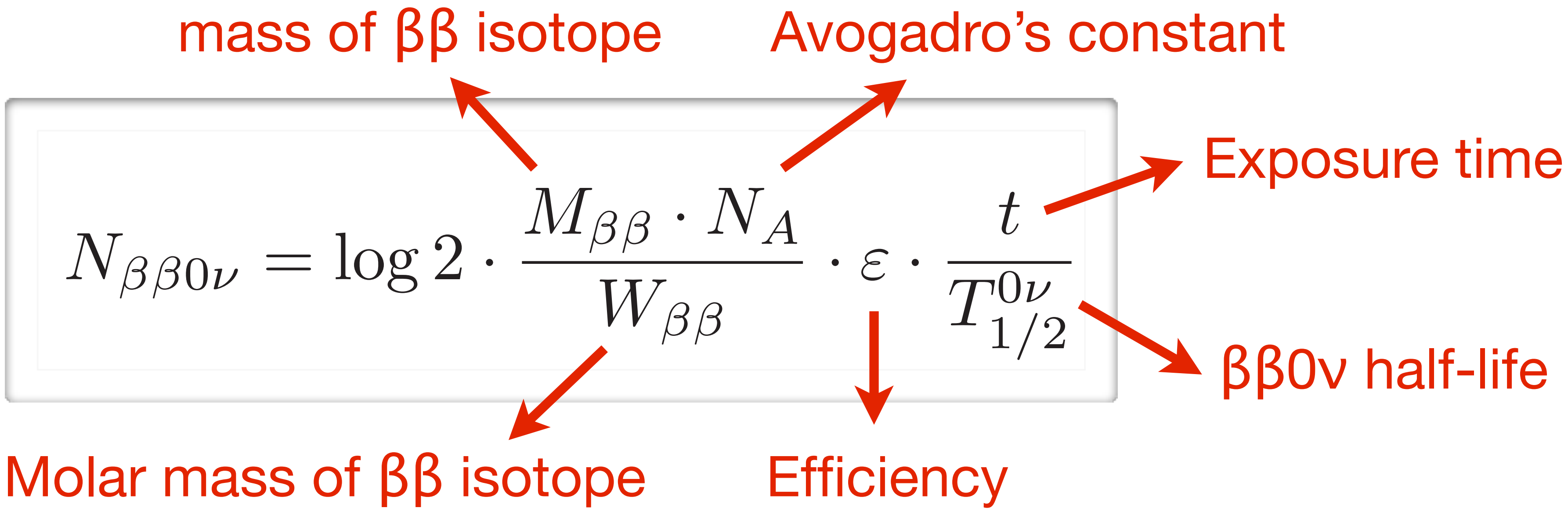

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ββ0ν half-life

Molar mass of ββ isotope

Efficiency

- Question: for a ^{136}Xe experiment with 100% efficiency and 1 year exposure time, what is the mass $M_{\beta\beta}$ required to observe only one **ββ**0ν decay?

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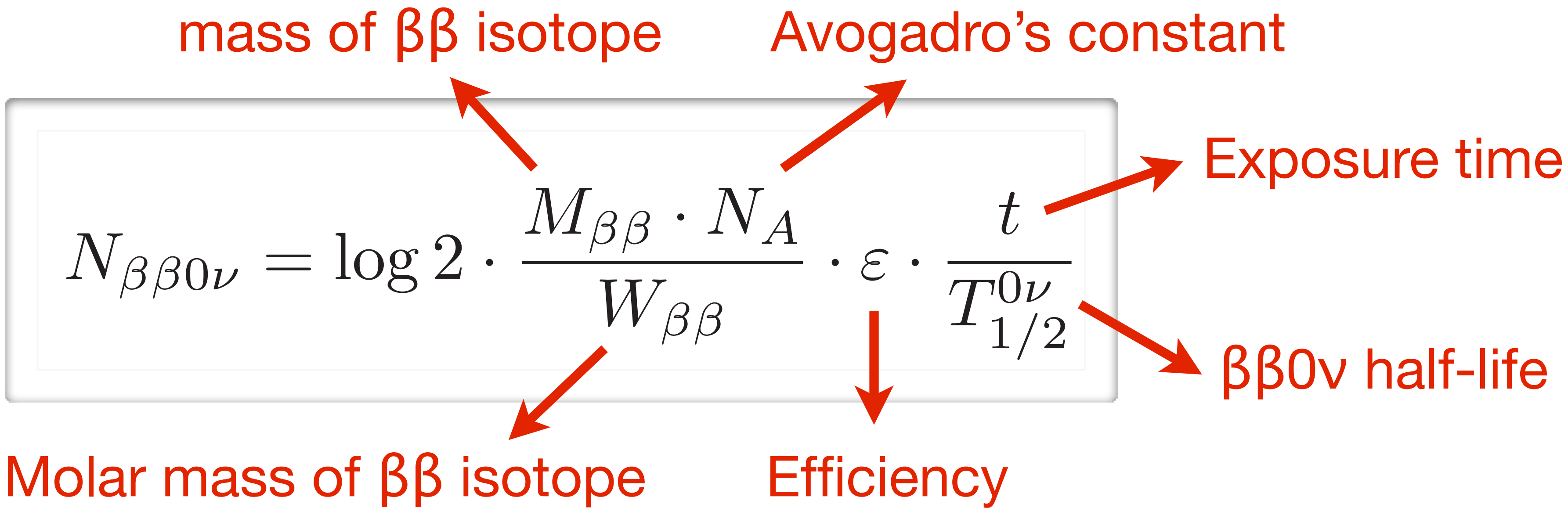

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- Assuming that the (unknown) **ββ**0ν half-life of ^{136}Xe is $T_{1/2}$ = 10^{27} years, get:

$M_{\beta\beta}$ = 326 kg!

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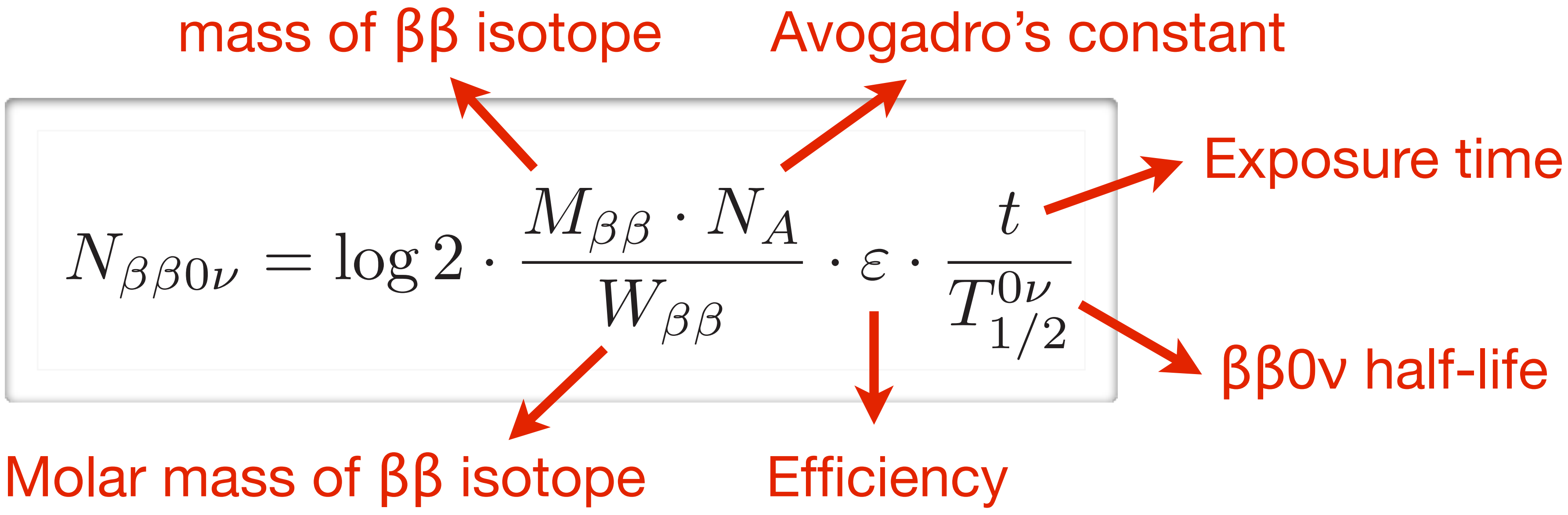

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$$\boxed{M_{\beta\beta} = 326 \text{ kg!}}$$

- Life is harder than this: non-perfect efficiencies and especially backgrounds

Experimental signature

Rare signature to be isolated in radio-pure detector underground:

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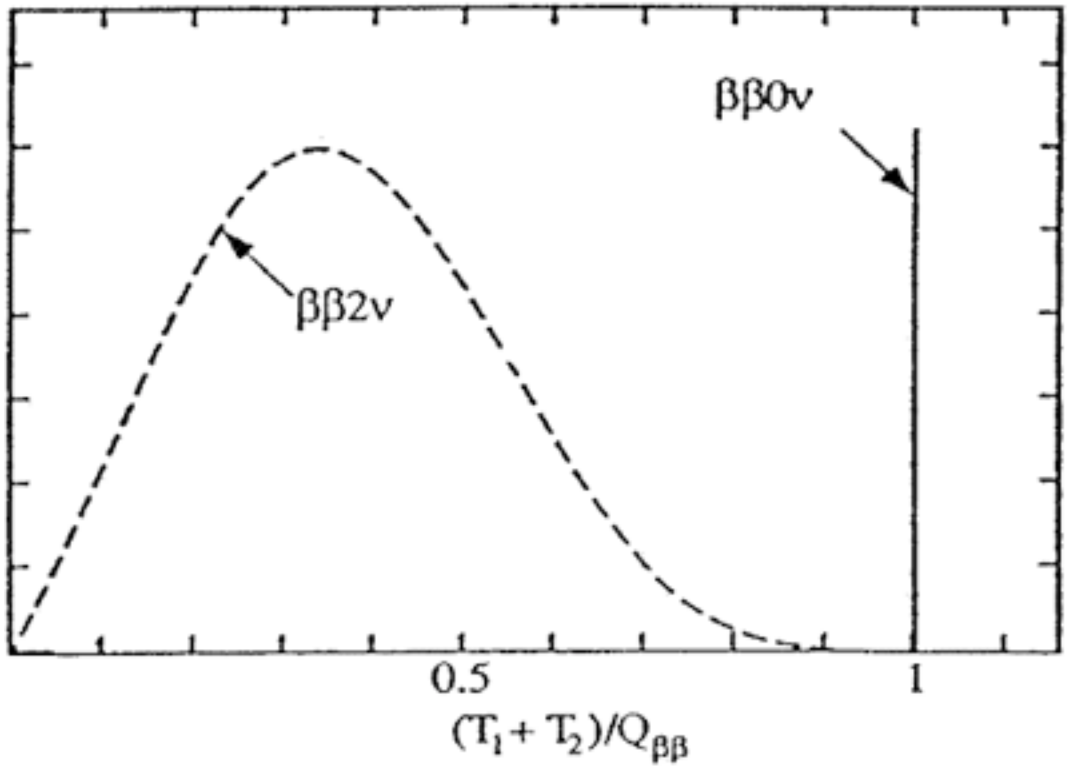
1.Calorimetry *(A MUST)*:

- 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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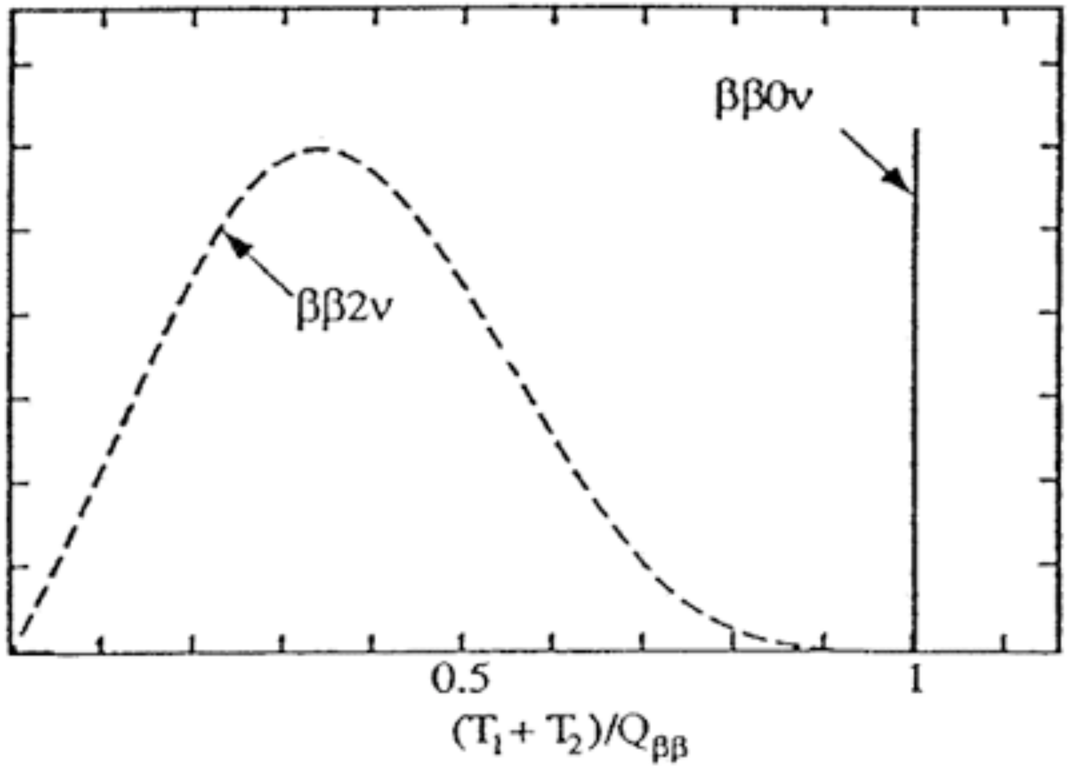

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- Observe two electrons emitted from a common vertex
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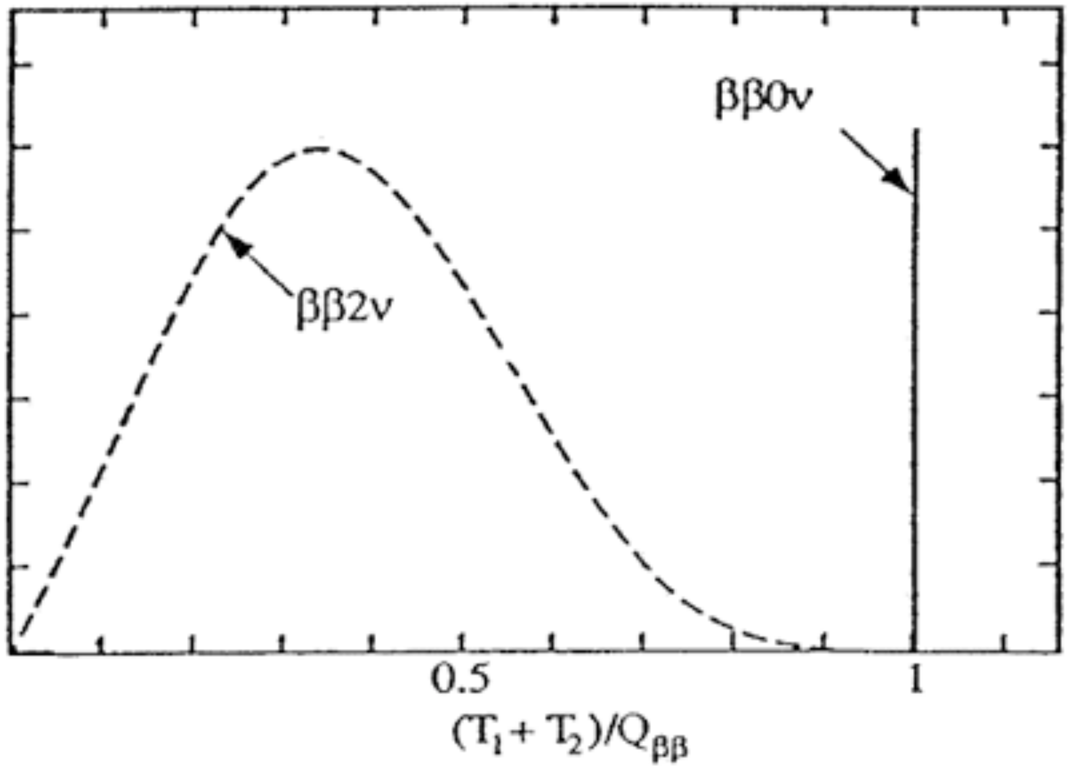

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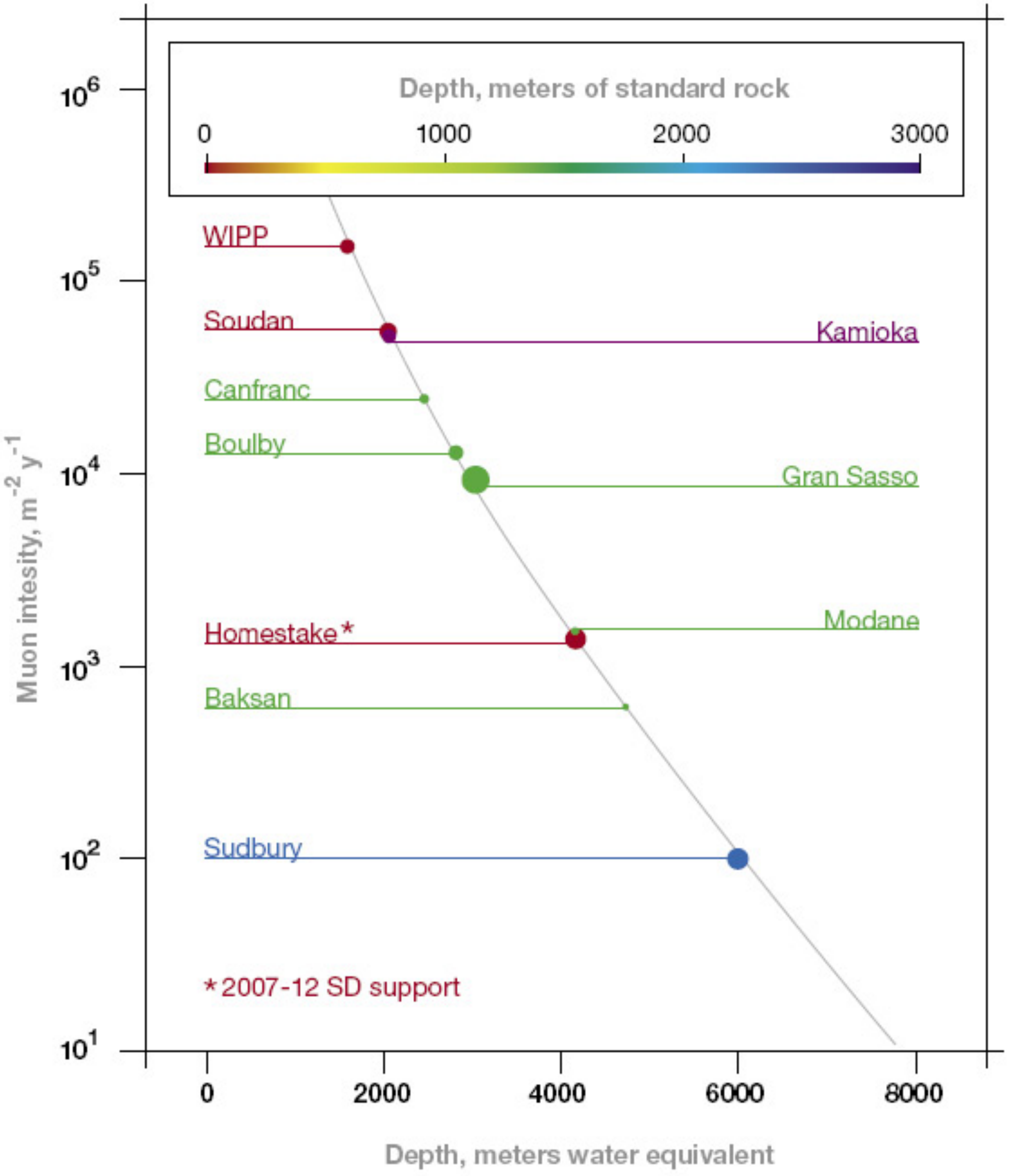
- Observe two electrons emitted from a common vertex
- Nothing else

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

- Observe nucleus produced in the decay

Underground physics



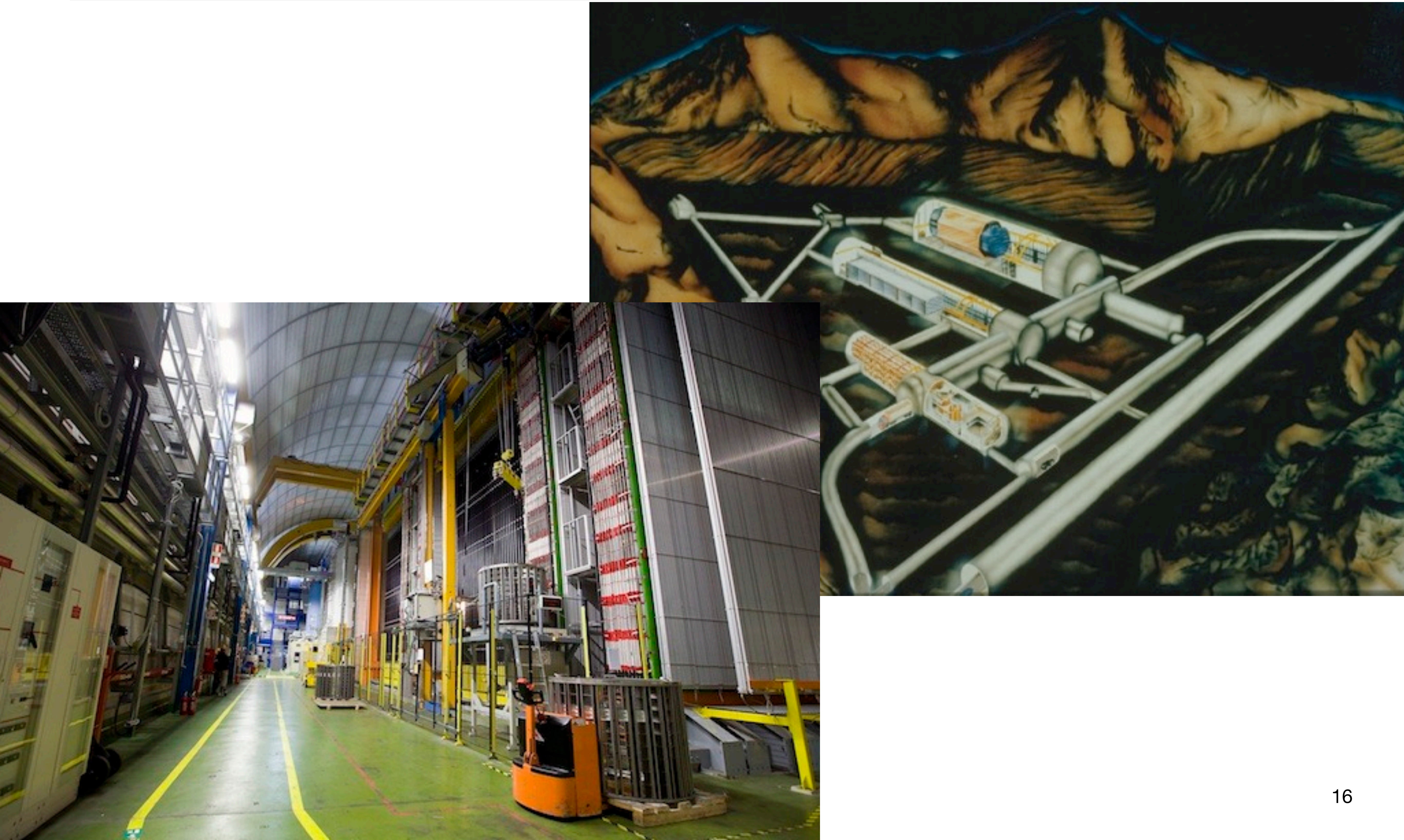
- Not only internal backgrounds from radioactive impurities in detector components

- Also external backgrounds originated outside detector by cosmic ray interactions

- All $\beta\beta0\nu$ experiments located underground, using rock as shield against cosmics

- Share infrastructures with direct dark matter detection experiments

INFN Gran Sasso National Laboratory



Ingredients for ββ0ν experiments

Current-generation

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

Typical

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- Large $\beta\beta$ isotope mass ································· 100 kg
  - Only way to probe 10^{26} yr half-lives!

Typical

Current goal

Ingredients for $\beta\beta0\nu$ experiments

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- Large $\beta\beta$ isotope mass ································ 100 kg
  - Only way to probe 10^{26} yr half-lives!

Current goal

- 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 $Q_{\beta\beta}$

Existing experimental results on ββ0ν searches

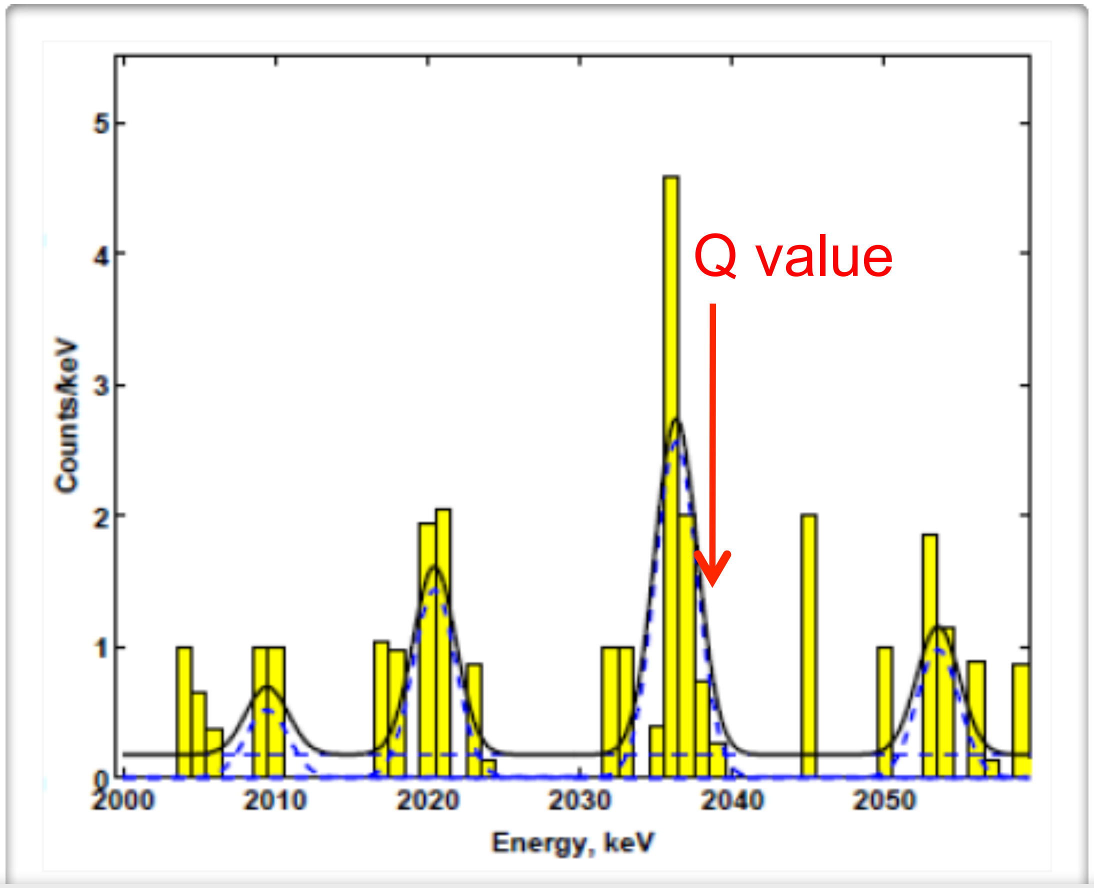
No convincing evidence to date

Positive result

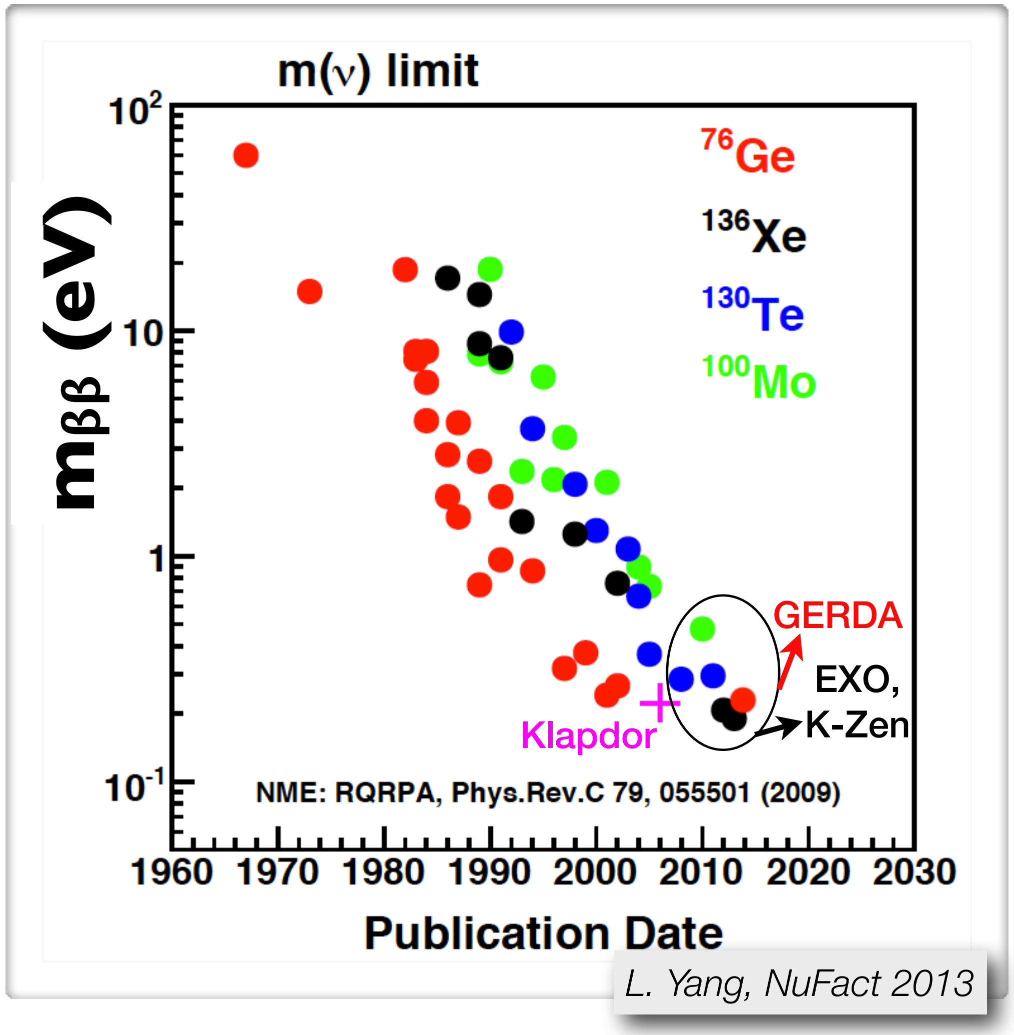
- Controversial claim by part of Heidelberg-Moscow Collaboration
  - $T_{1/2}(^{76}Ge) = (2.23^{+0.44}_{-0.31}) \cdot 10^{25}$ yr
- Large tension with null results

Null results

- Best constraints: **$m_{\beta\beta}$~200 meV**
  - *^{136}Xe: EXO, KamLAND-Zen*
  - *^{76}Ge: GERDA-1*



H.V. Klapdor-Kleingrothaus, I.V. Krivosheina, Mod.Phys.Lett. A21 (2006)



L. Yang, NuFact 2013

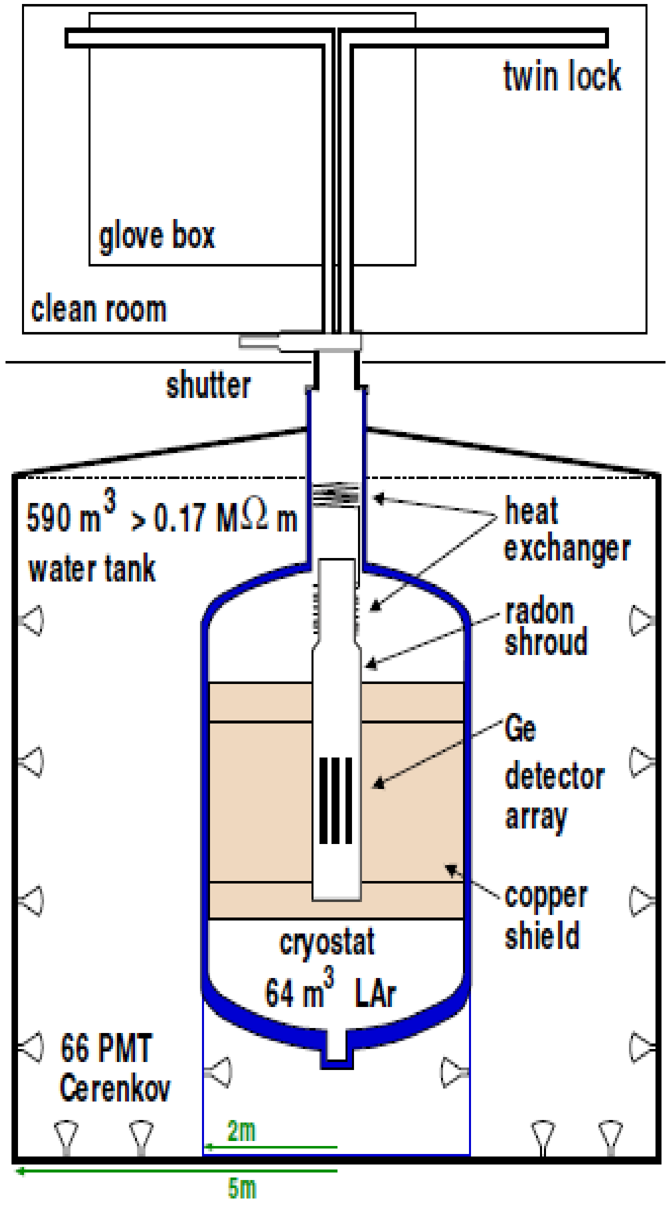
Neutrinoless double beta decay

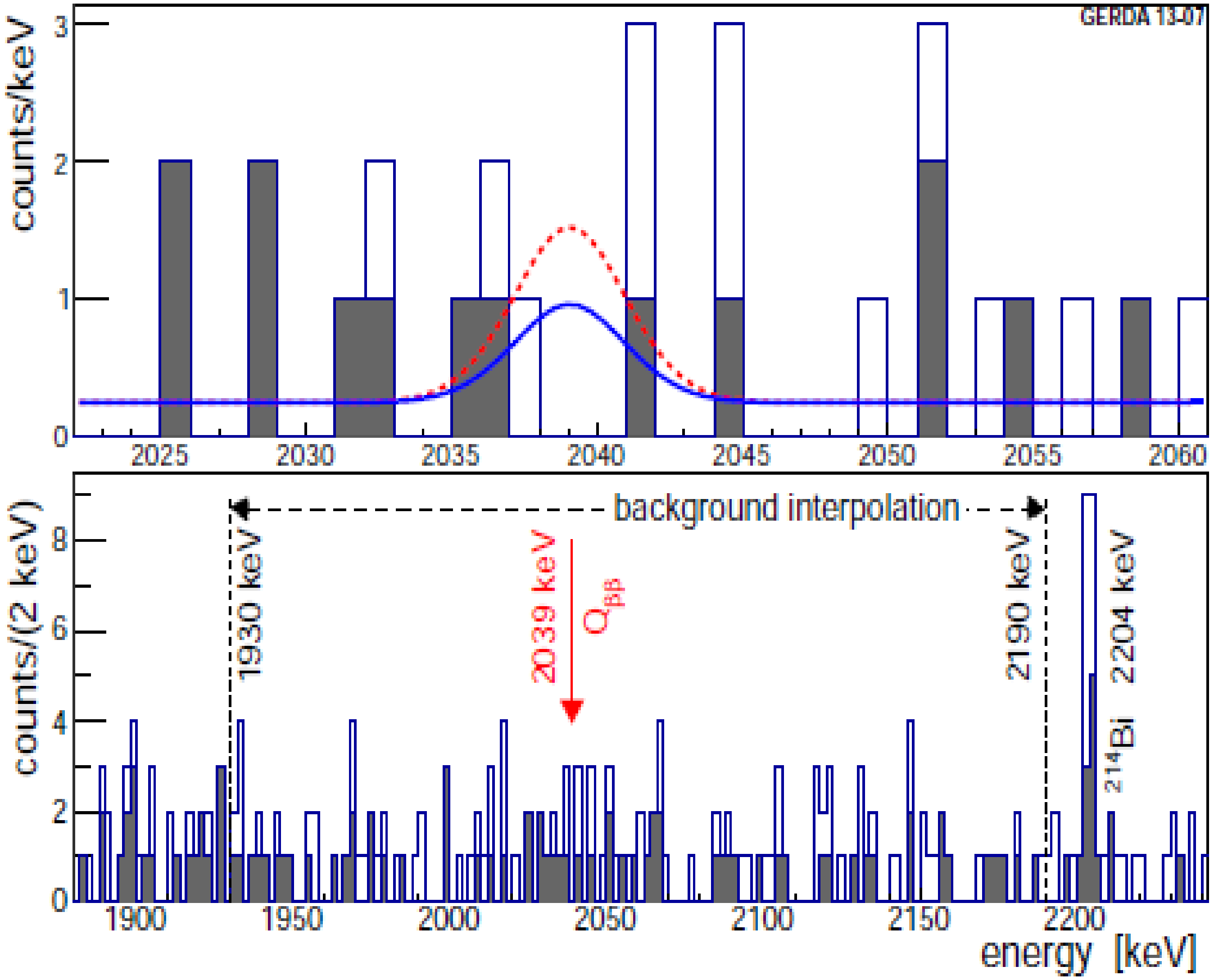
A selection of experiments

GERDA experiment

Started in 2011

- High-purity germanium diodes enriched in ^{76}Ge immersed in LAr
- Advantages: energy resolution, radiopurity
- No evidence for ββ0ν of ^{76}Ge. Next step: pulse shape discrimination (GERDA-2)

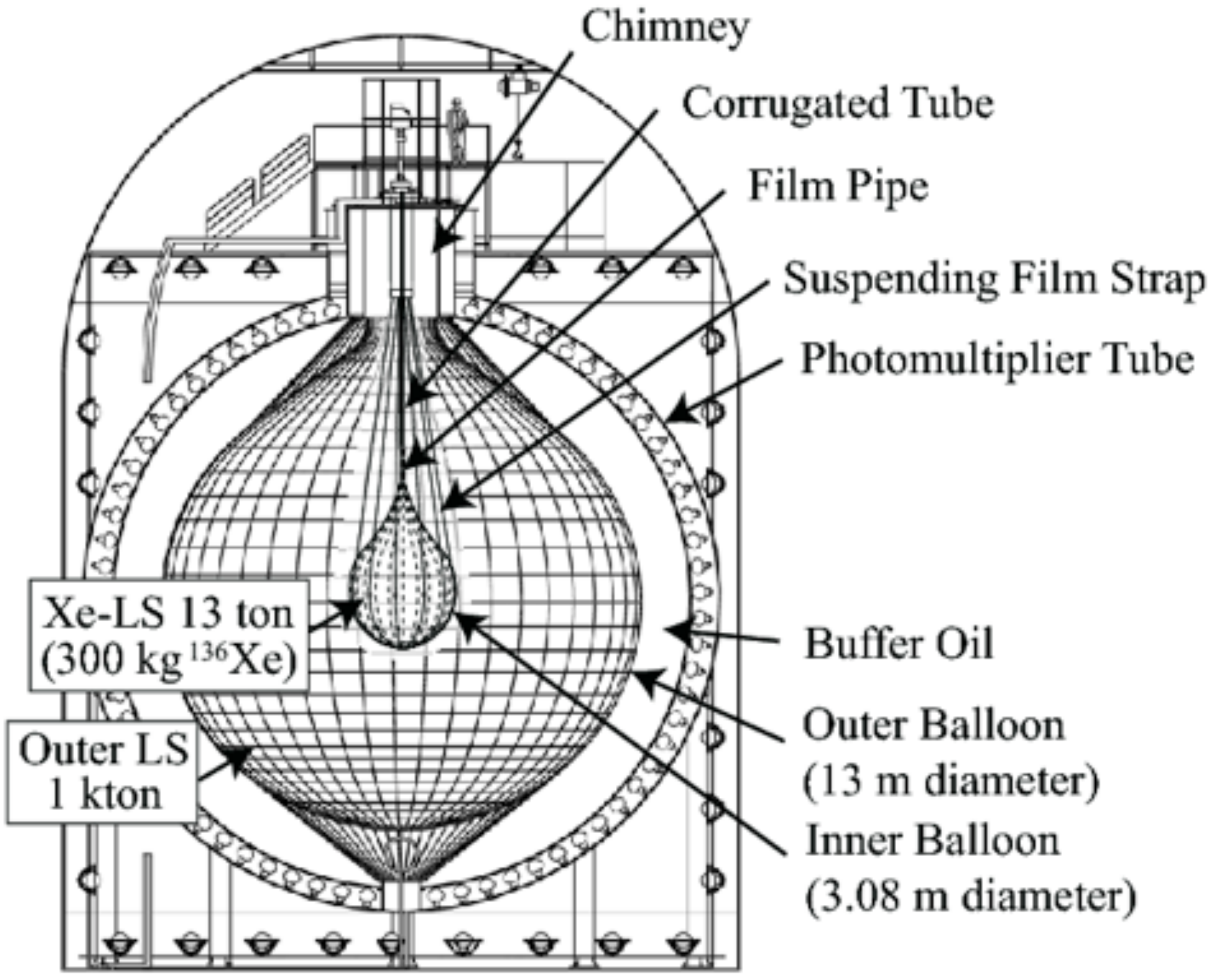


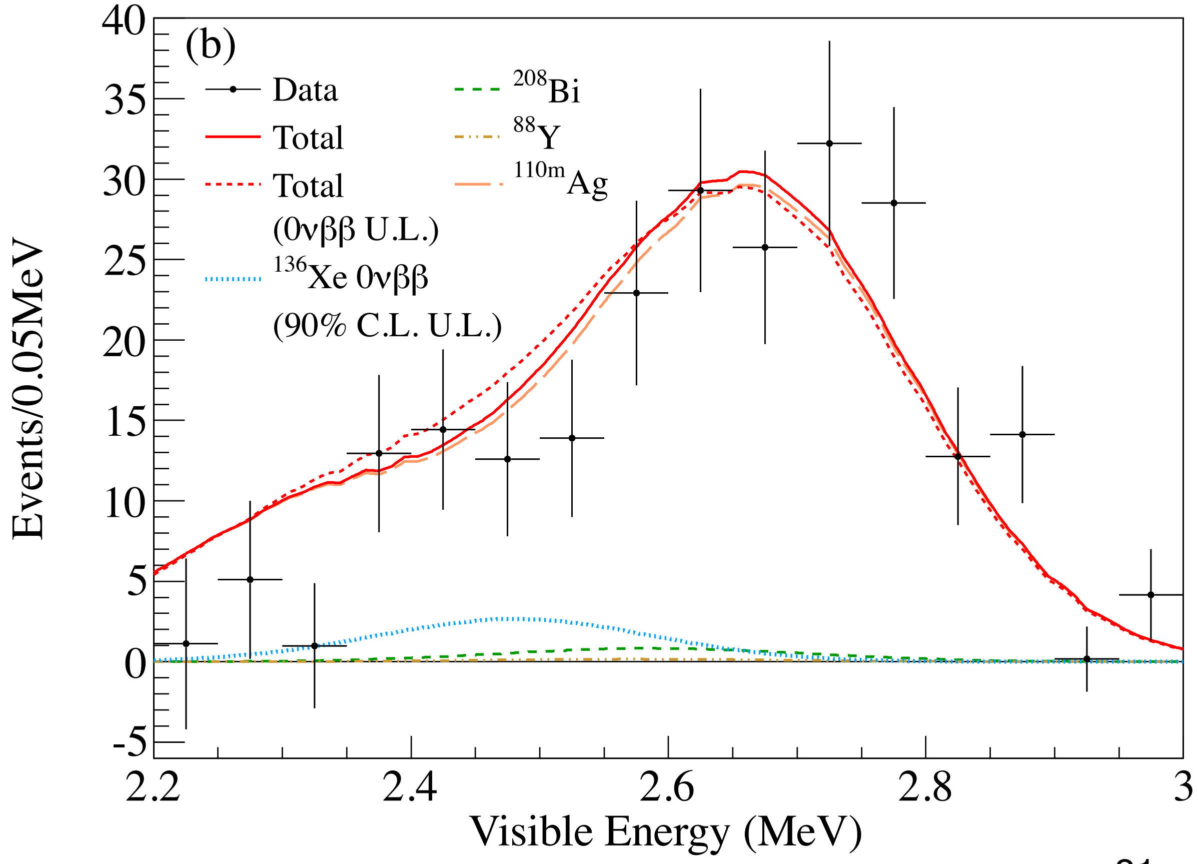


KamLAND-Zen experiment

Started in 2011

- Liquid scintillator with 300 kg of ^{136}Xe gas dissolved in it
- Advantages: mass scalability, buffer region
- No evidence for **ββ0ν** of ^{136}Xe
- Next steps: purification campaign, more xenon mass, better energy resolution

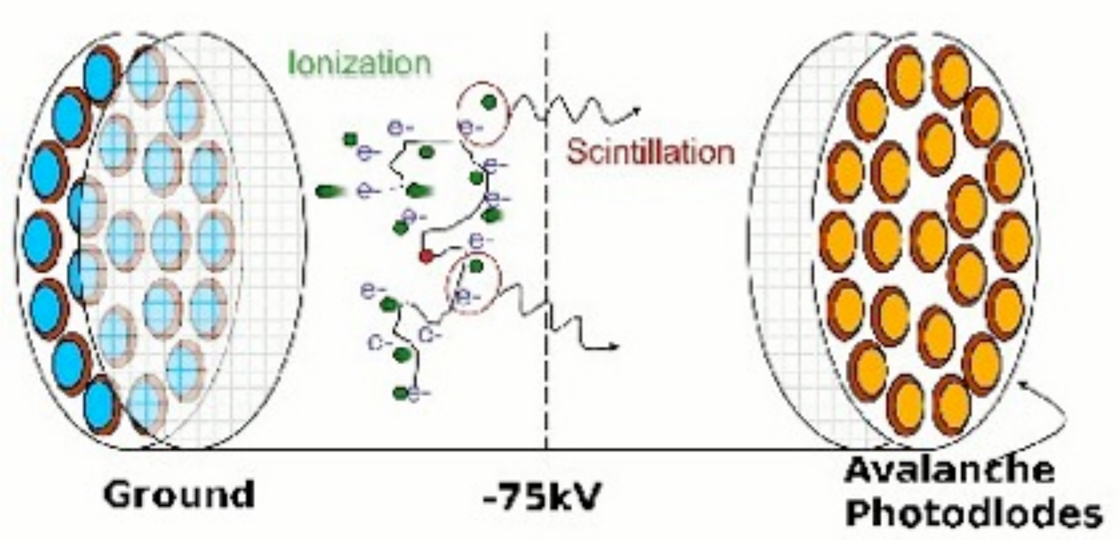


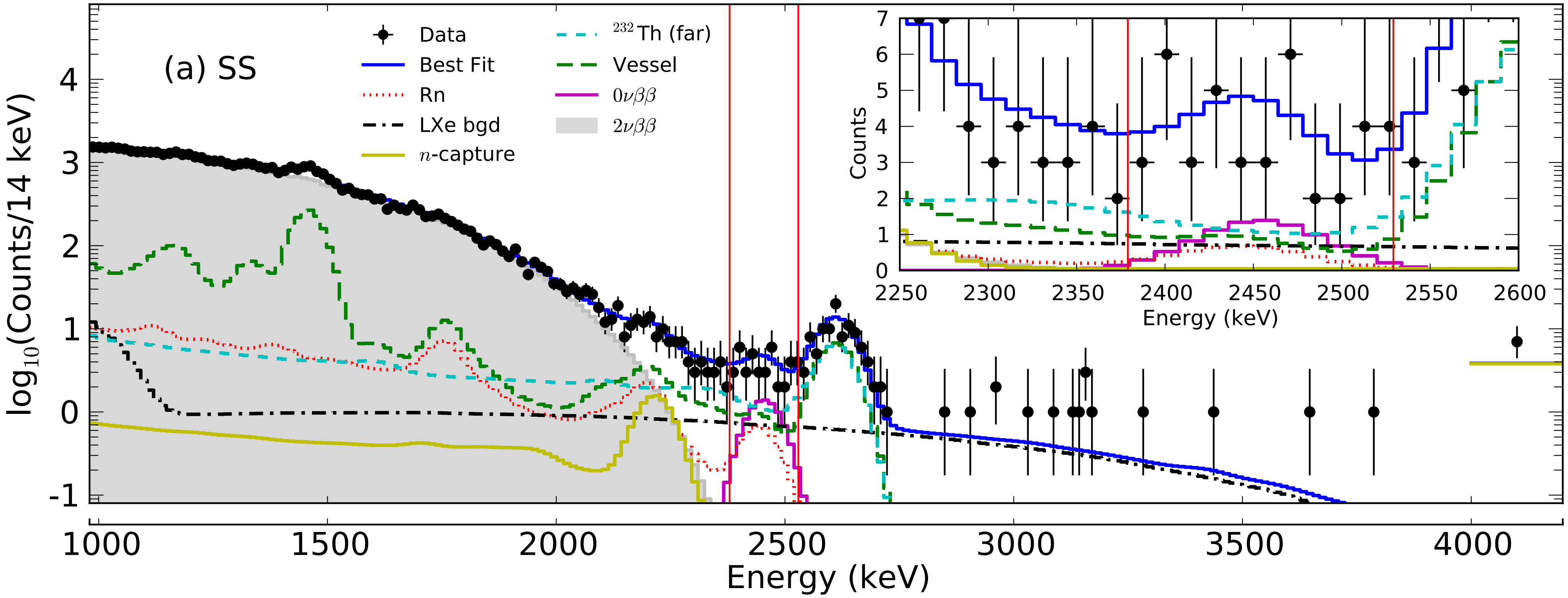


EXO experiment

Started in 2011

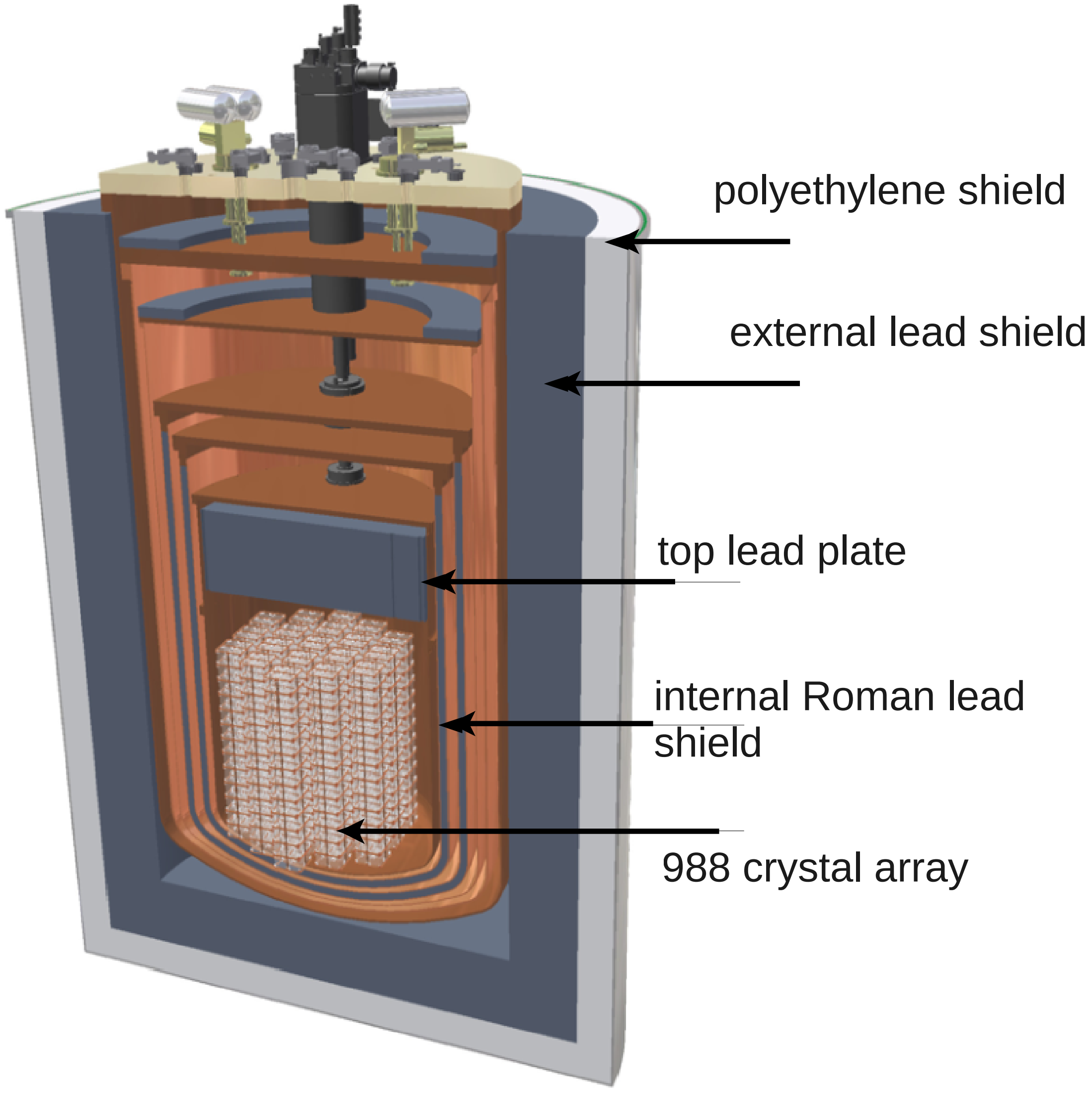
- Cryogenic TPC filled with 80 kg (fiducial) liquid xenon
- Advantages: mass scalability, some topology
- No evidence for ββ0ν of ^{136}Xe
- Next: nEXO (5 tons!) and tagging of barium daughters?

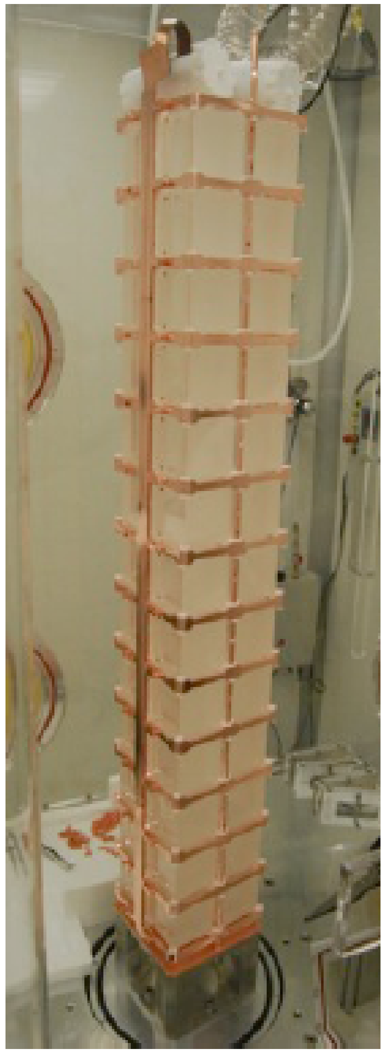




CUORE experiment

Started in 2013

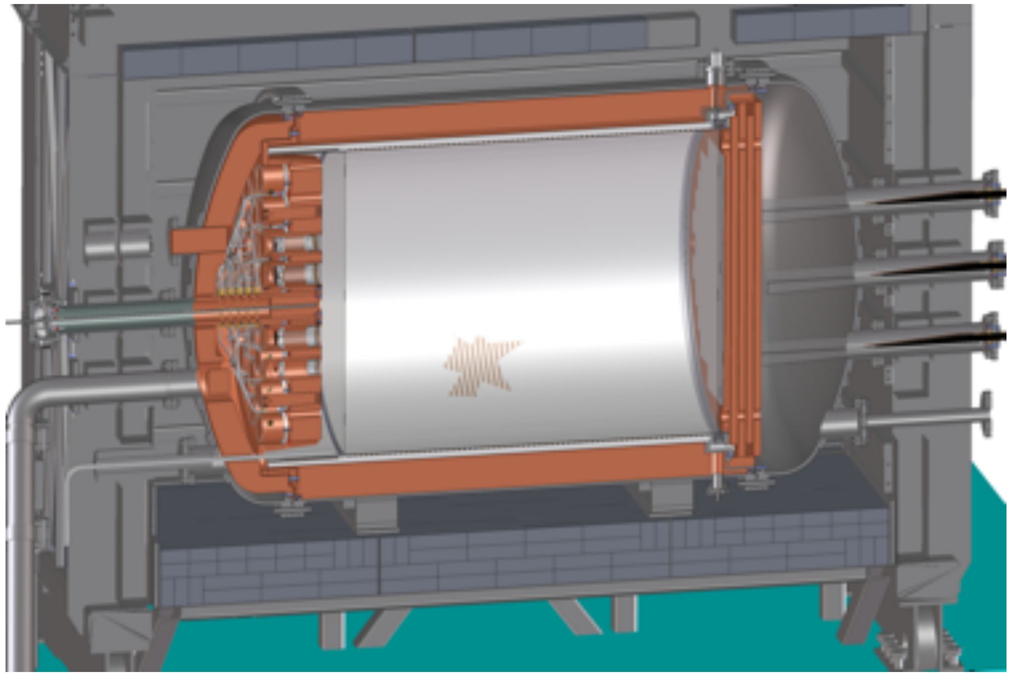


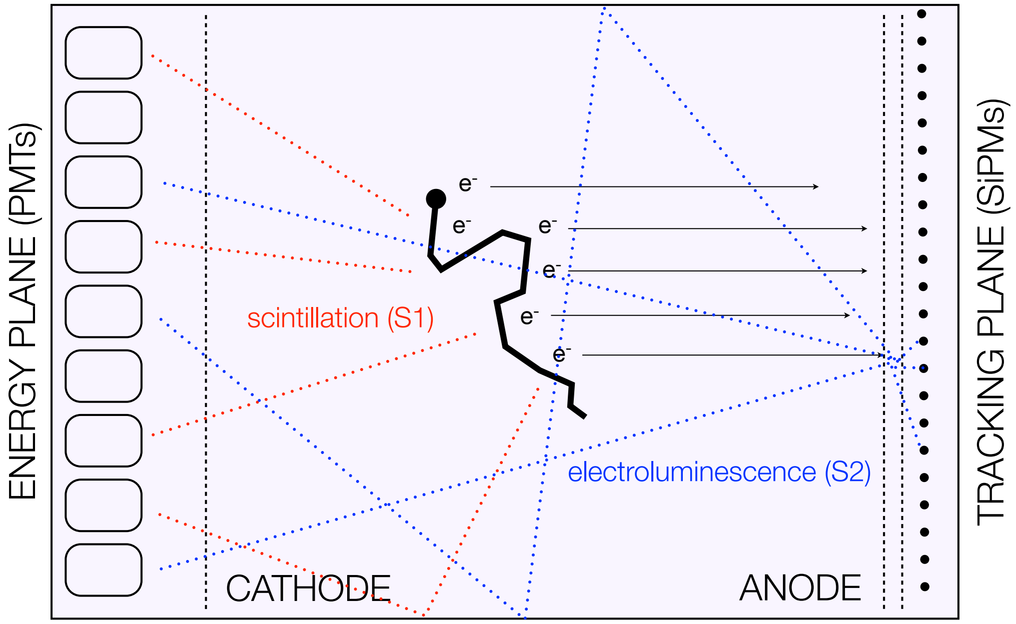


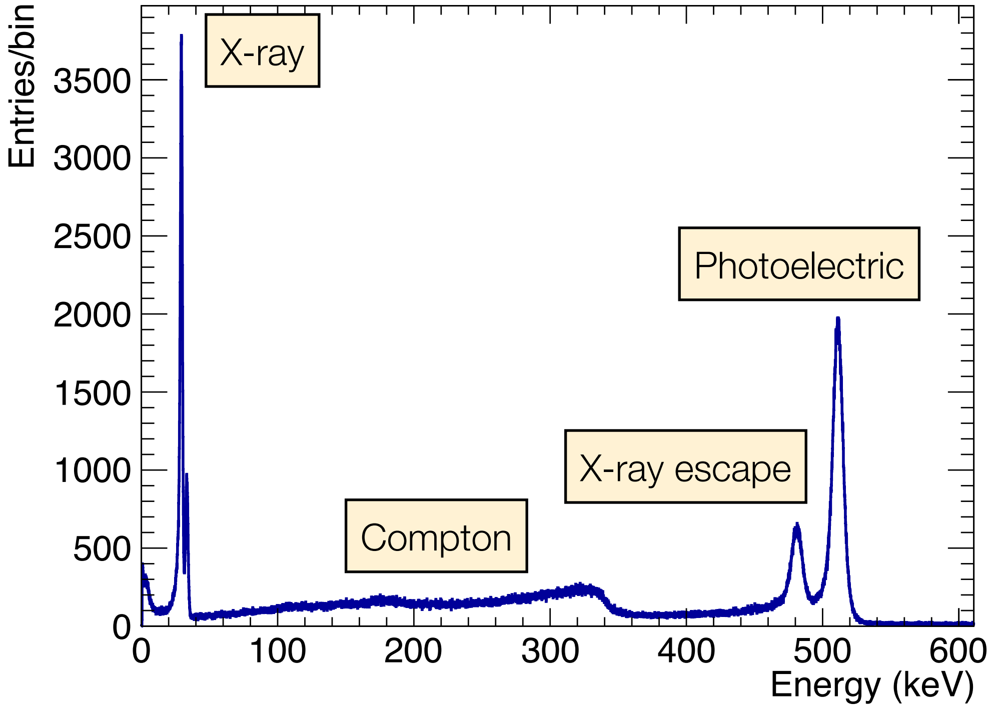
- Towers of $Te0_2$ crystals. ββ decay energy measurable as temperature increase
- Advantages: energy resolution, mass scalability
- CUORE-0 results expected soon
- Next step: full CUORE, scintillating bolometers (heat plus scintillation readout)

NEXT experiment

Starting in 2015

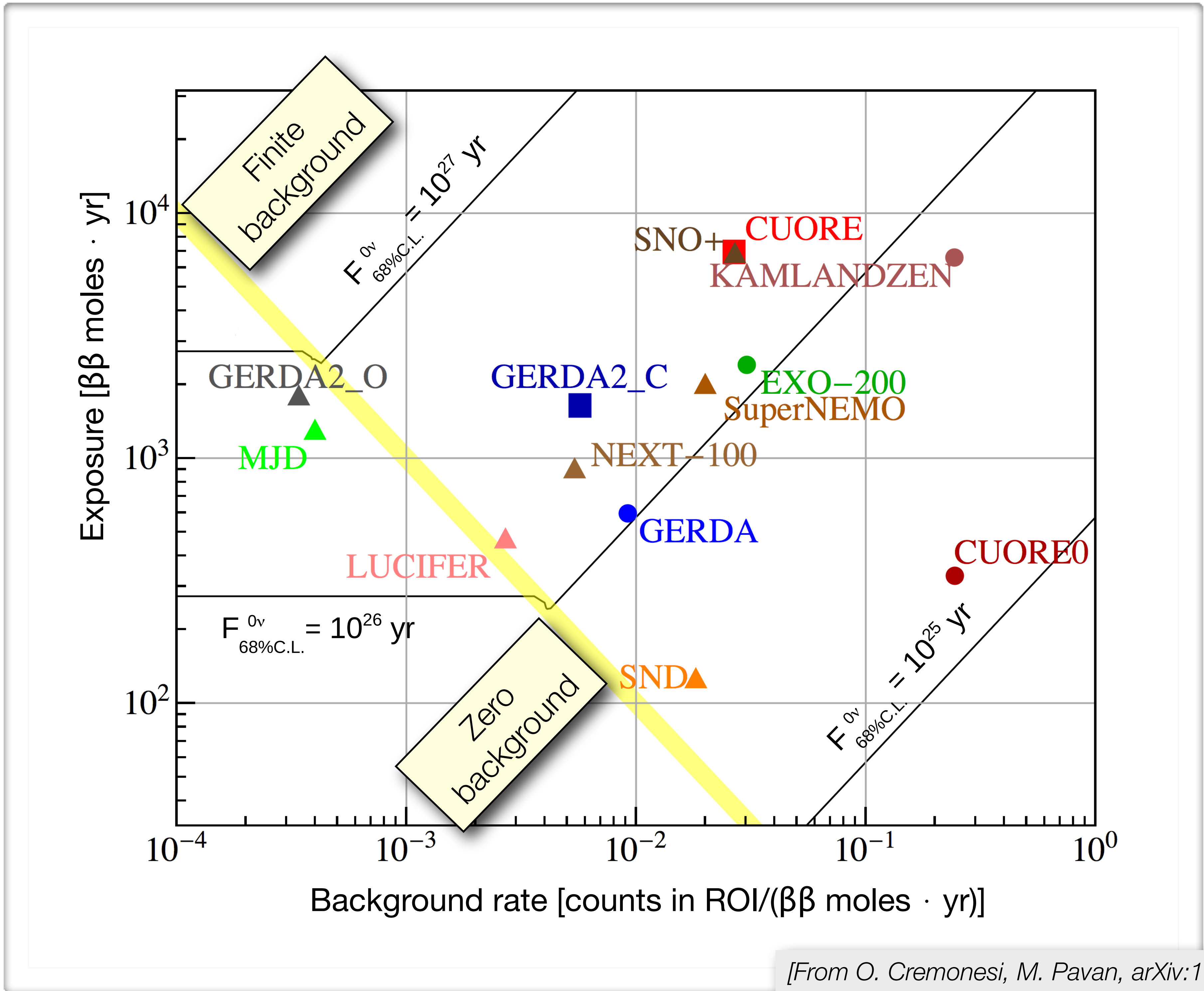






- Electroluminescent TPC with 100 kg of high-pressure ^{136}Xe gas
- Advantages: energy resolution, image electron tracks
- **2008-2013**: R&D phase with 1 kg-scale prototypes
- **2014-2016**: 10 kg detector at LSC
- **2016-2020**: full 100 kg detector at LSC

ββ0ν experiments comparison: mass, background



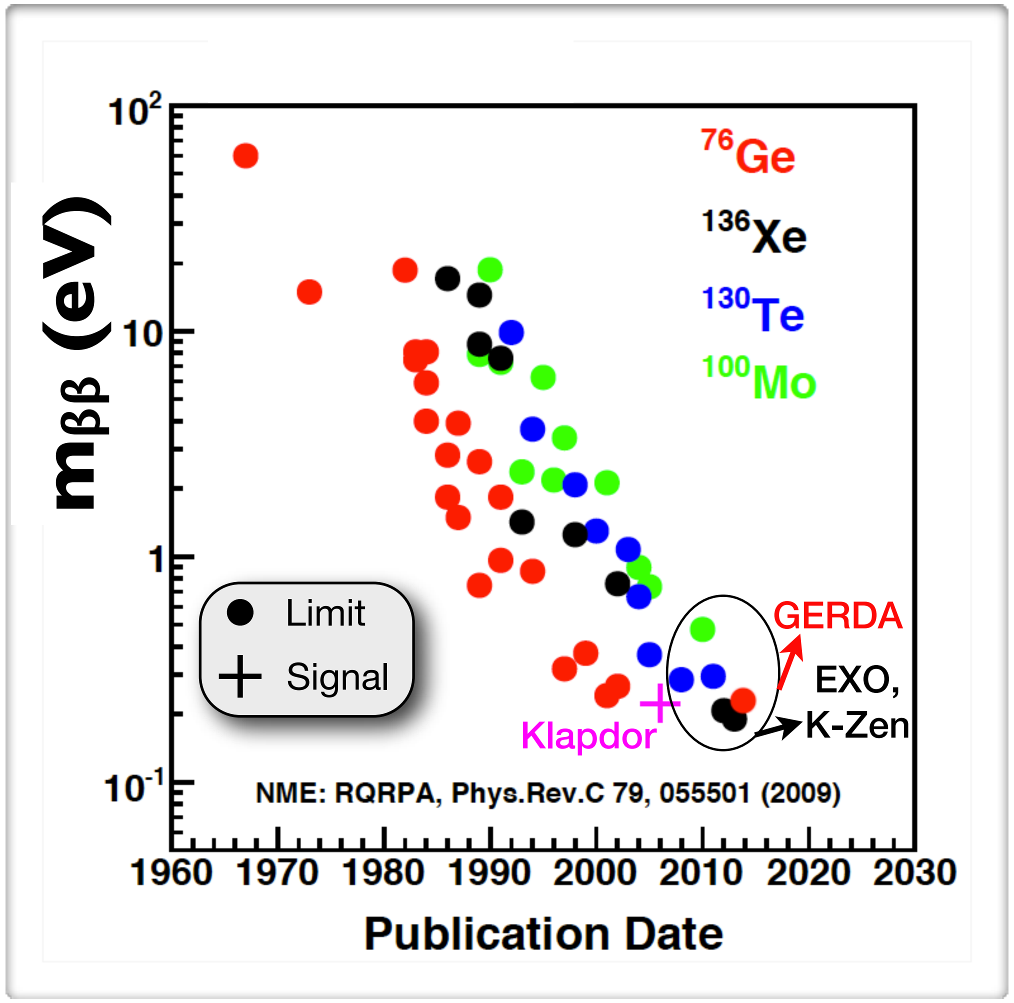
[From O. Cremonesi, M. Pavan, arXiv:1310.4692]

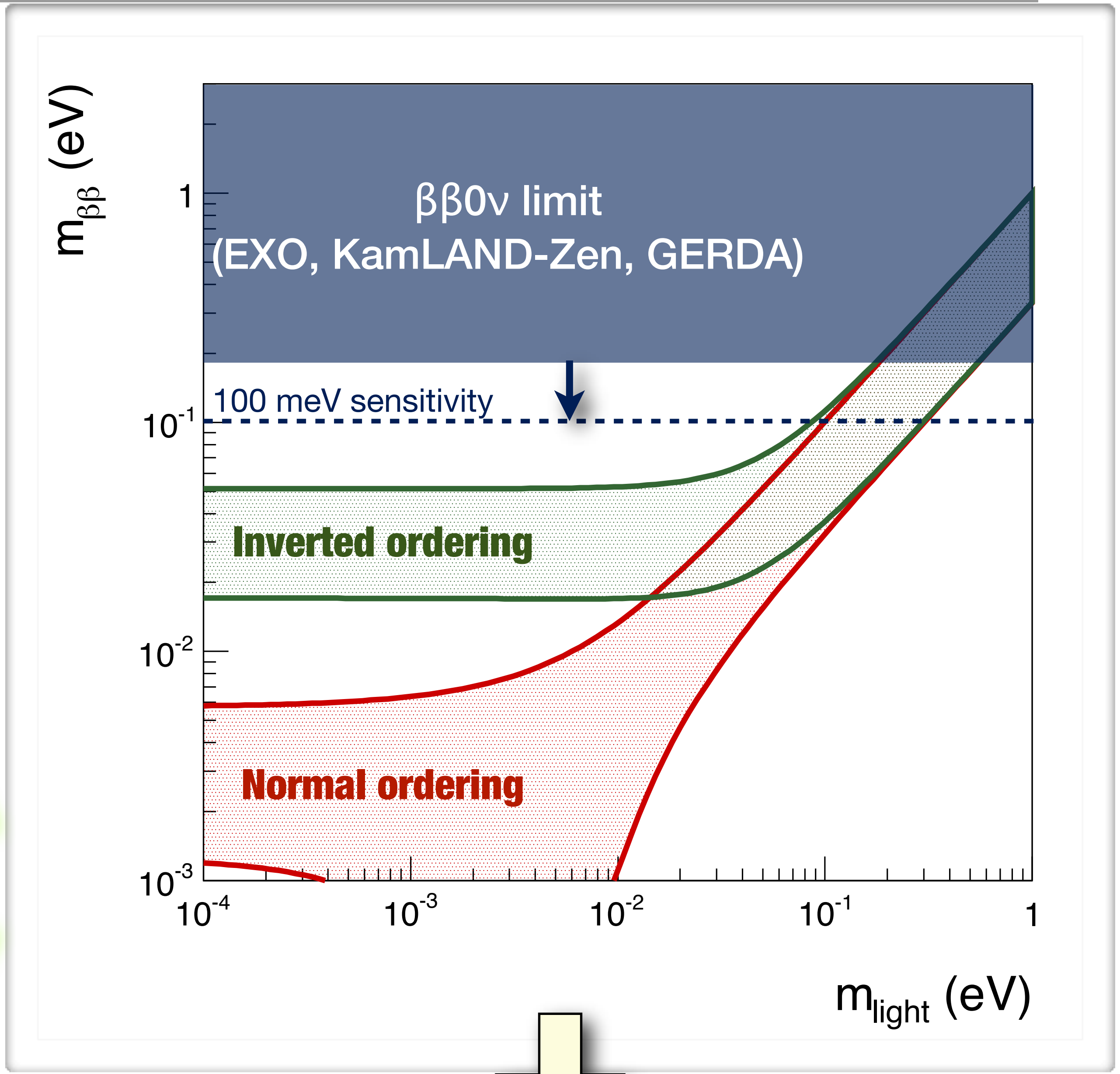
ββ0ν experiments comparison: sensitivity

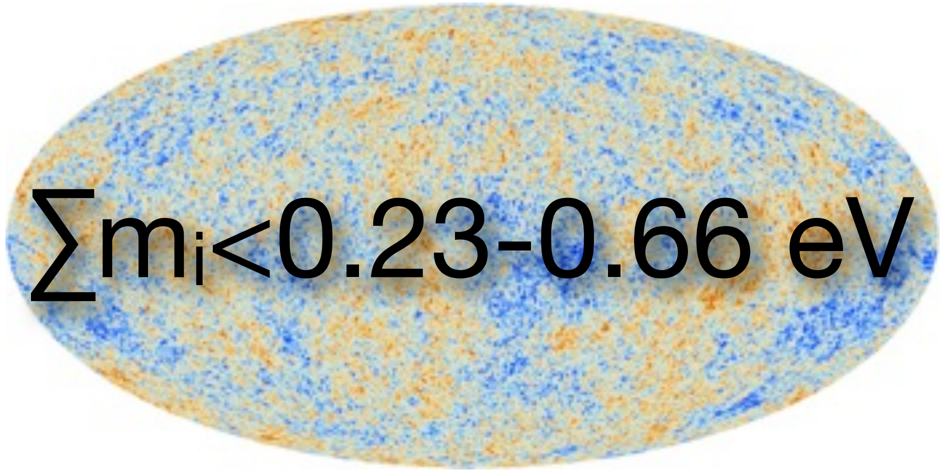
Current-generation experiments should reach $m_{\beta\beta}$ *~100 meV*

[From J.J. Gomez-Cadenas et al., Riv.Nuovo Cim. 35 (2012)]

Discovery potential





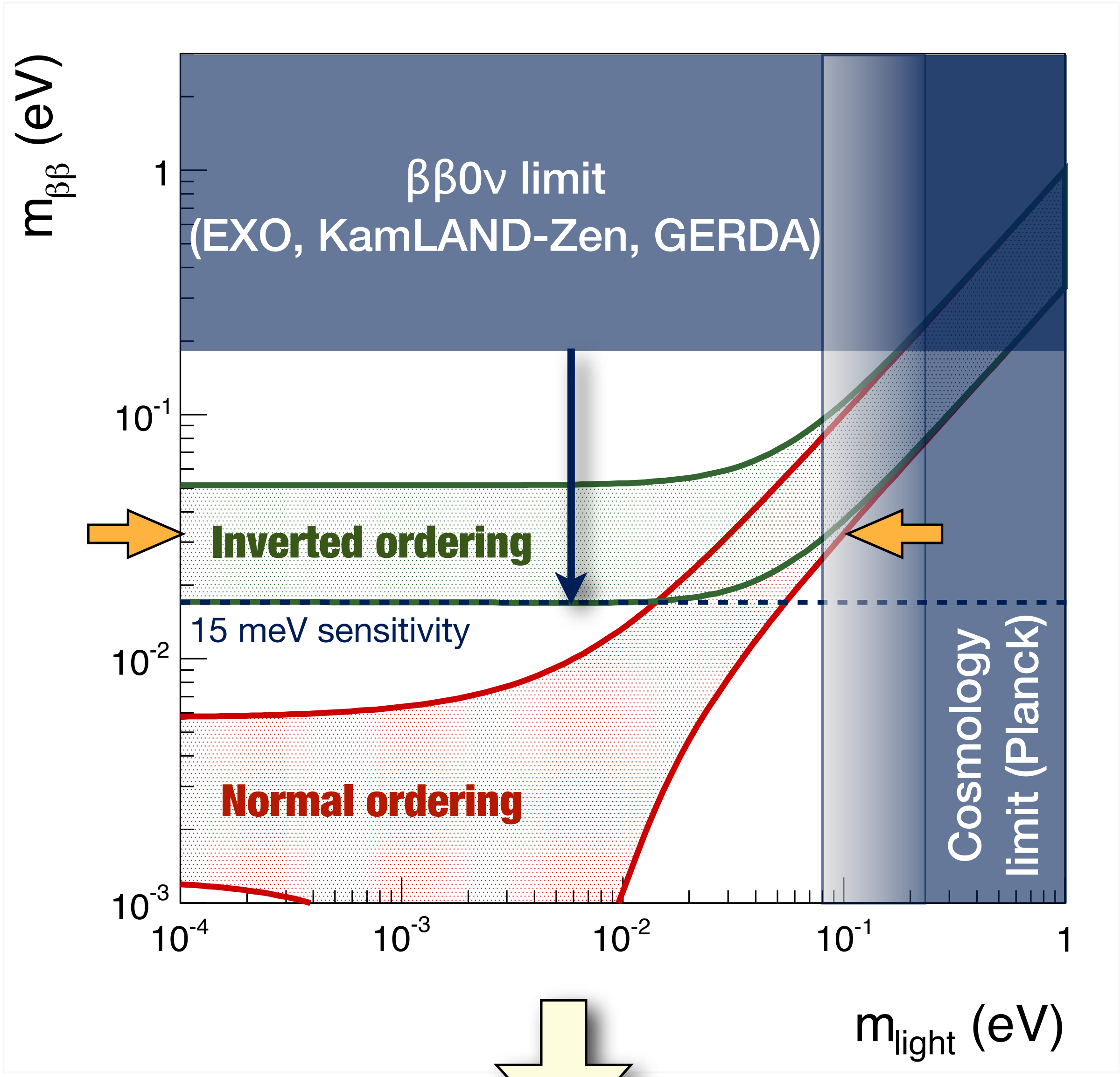


$\sum m_i < 0.23\text{-}0.66$ eV

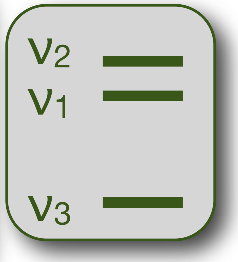
Possible, but unlikely, that current-generation experiments will discover ββ0ν

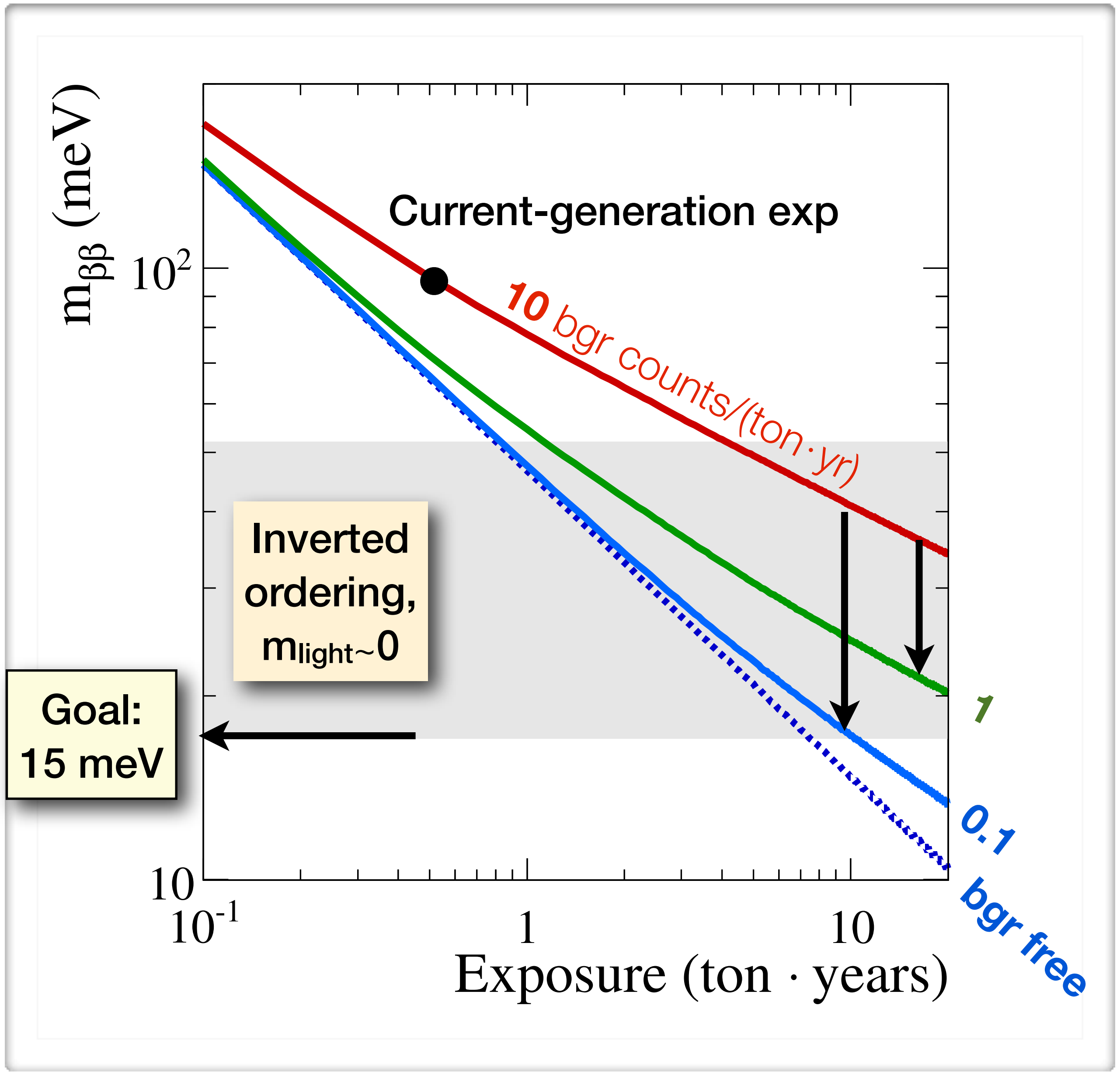
Goal for next-generation (2020+) experiments

15 meV Majorana neutrino mass sensitivity



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





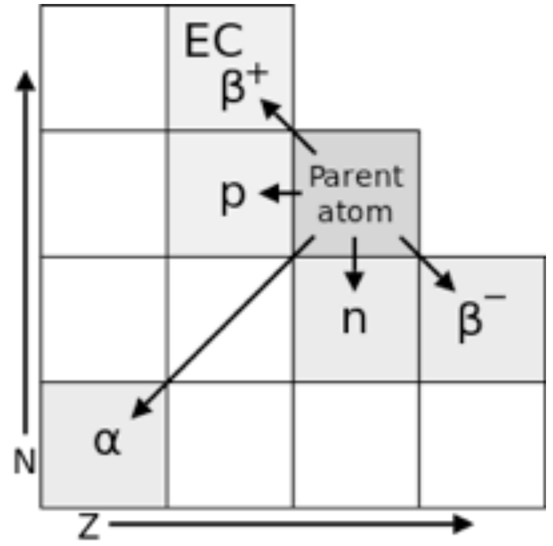
- Ton-scale detector necessary but not sufficient requirement to reach 15 meV → R&D

Direct neutrino mass measurements

Radioactive decays

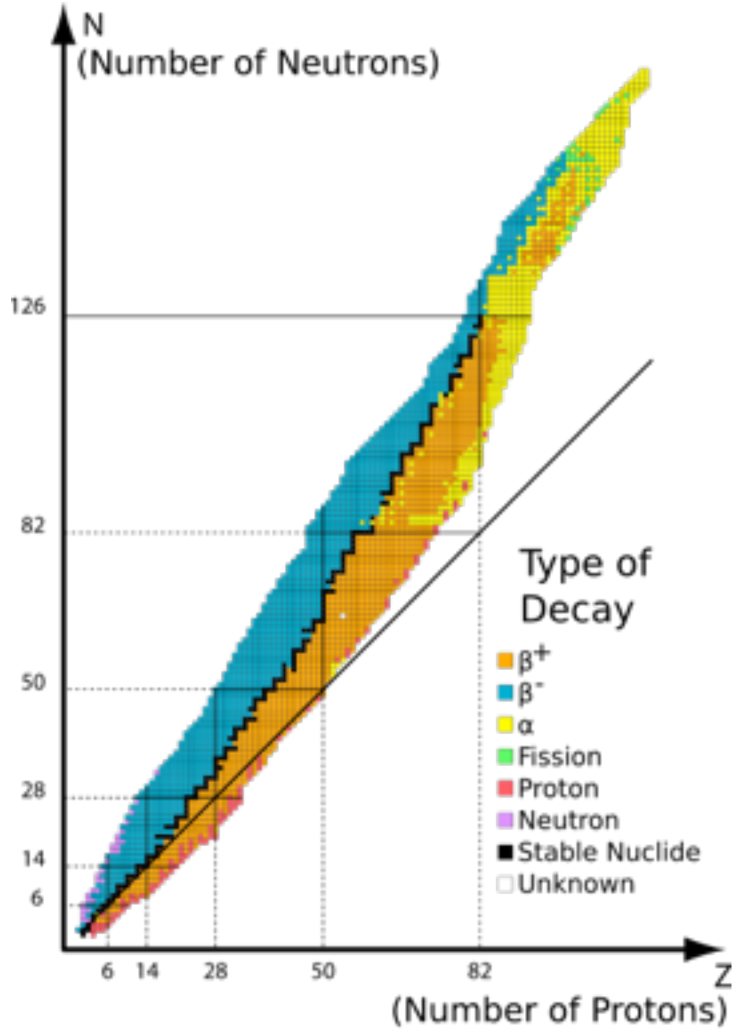
A reminder

- Three types of (1st order) nuclear transitions producing neutrinos or antineutrinos:

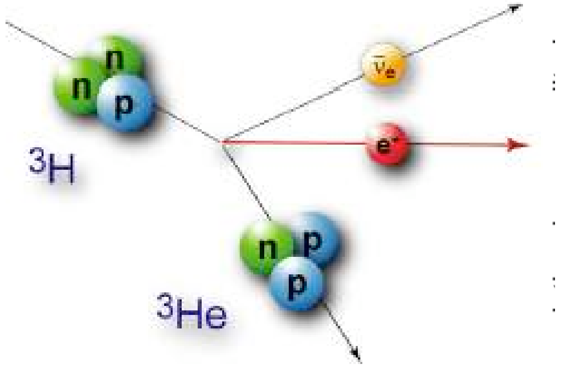


- β^- decay: $(Z,A) \rightarrow (Z+1,A) + e^- + \bar{\nu}_e$
- β^+ decay: $(Z,A) \rightarrow (Z-1,A) + e^+ + \nu_e$
- Electron Capture (EC): $(Z,A) + e^- \rightarrow (Z-1,A)^* + \nu_e \rightarrow (Z-1,A) + \gamma/e^- + \nu_e$

- Information on neutrino mass from kinematics of emitted electrons (and photons)



Beta-decay energy spectrum



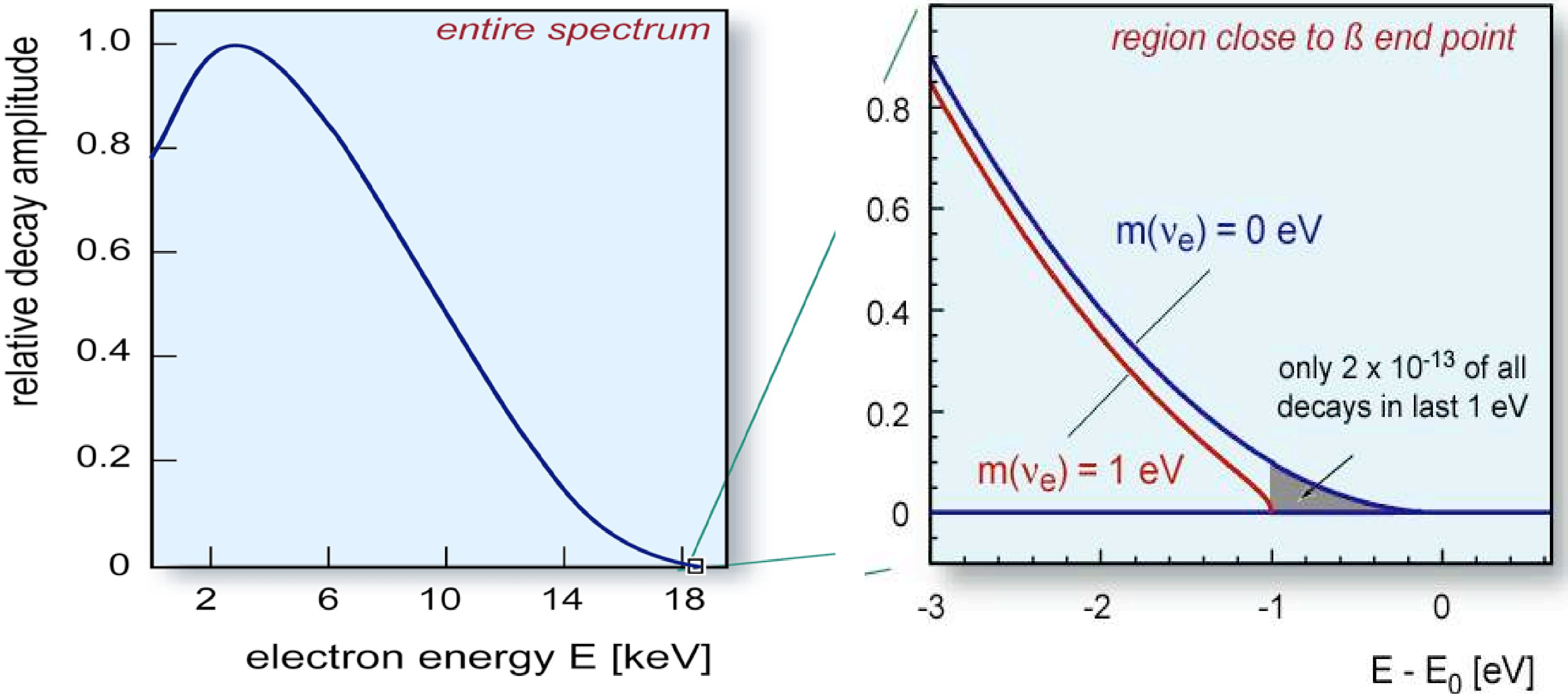
- Phase space determines electron energy spectrum
- Massive neutrinos distort the end-point spectrum:

$$dN/dK_e \propto F(K_e,Z) \cdot p_e \cdot (K_e+m_e) \cdot (E_0-K_e) \cdot [(E_0-K_e)^2-m_\beta^2]^{1/2}$$

Endpoint energy (Q-value): $E_0 = K_e + E_\nu$

Observable: β decay neutrino mass

$$m_\beta = (\sum_i |U_{ei}^2| \cdot m_i^2)^{1/2}$$



Experimental requirements

$$dN/dK_e \propto F(K_e,Z) \cdot p_e \cdot (K_e+m_e) \cdot (E_0-K_e) \cdot [(E_0-K_e)^2-m_\beta^2]^{1/2}$$

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- Low endpoint energy E_0 → ^{3}H, ^{187}Re, ^{163}Ho

Isotope	Q_β-value (keV)
^{3}H	18.6
^{163}Ho	2.3-2.8
^{187}Re	2.5

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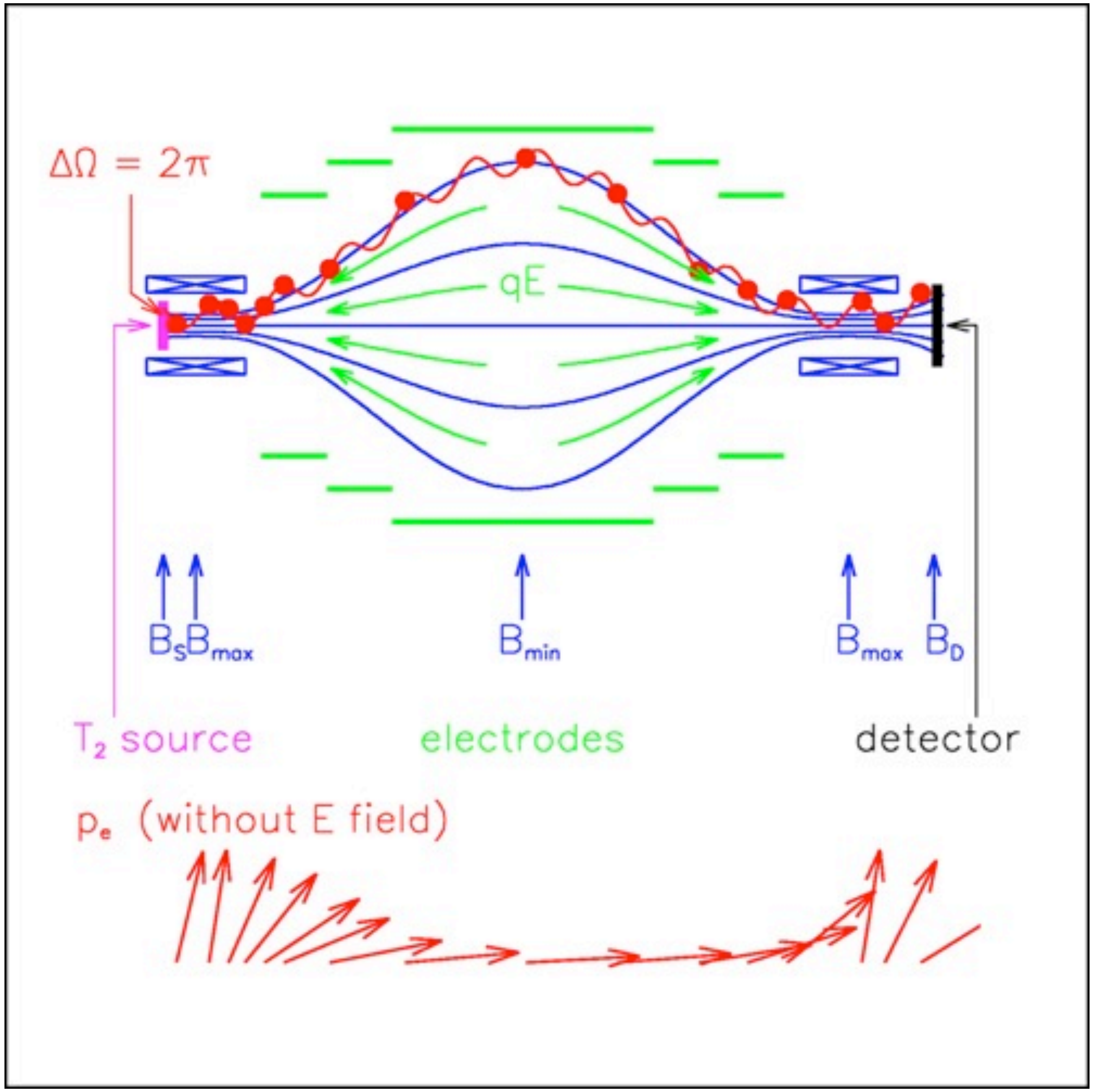
- High energy resolution
- High luminosity
- Low background

} → MAC-E-Filters or Bolometers

MAC-E-Filter technique

***M**agnetic **A**diabatic **C**ollimation combined with an **E**lectrostatic Filter*



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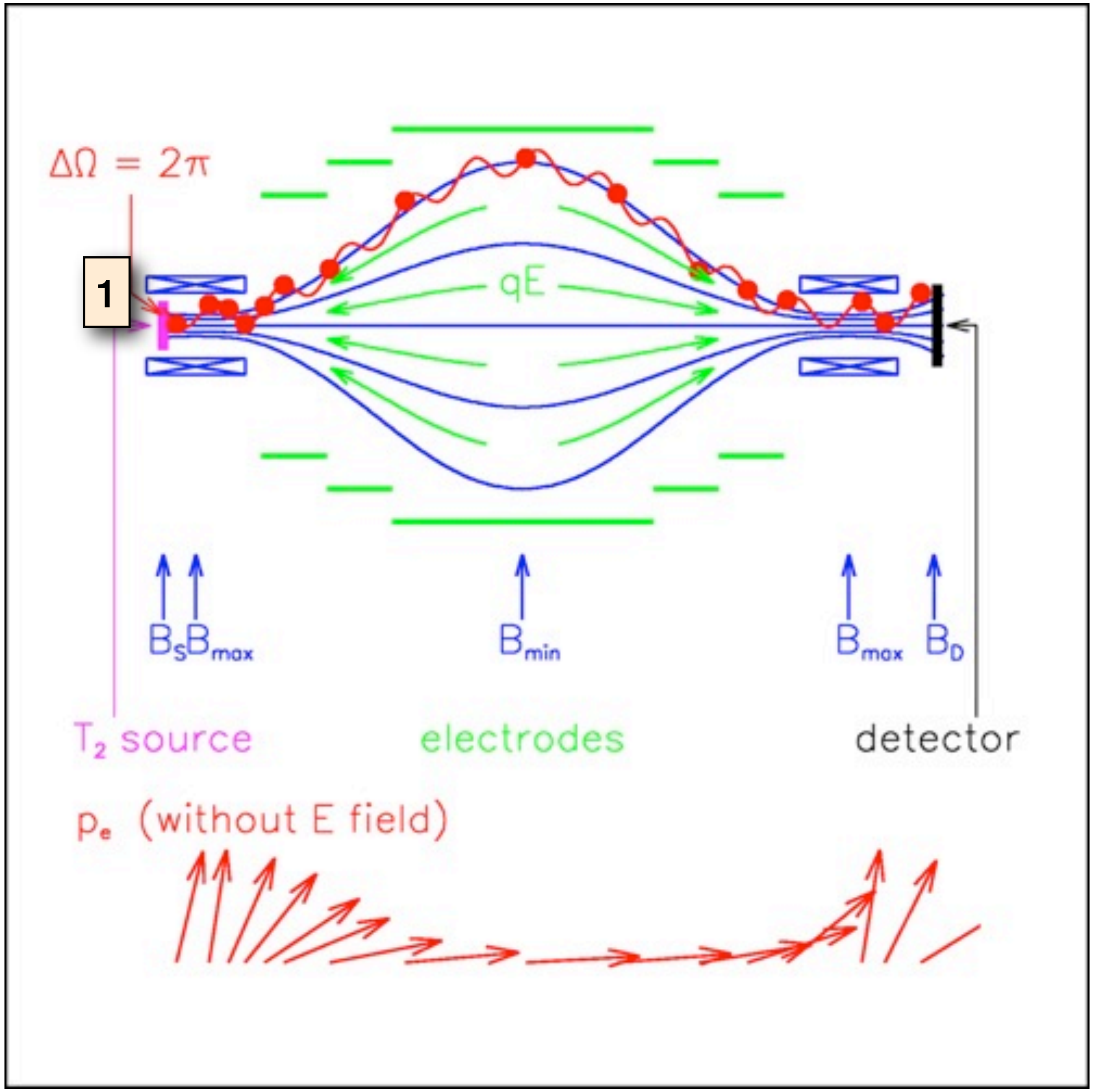

1. Electrons emitted isotropically at T_2 source

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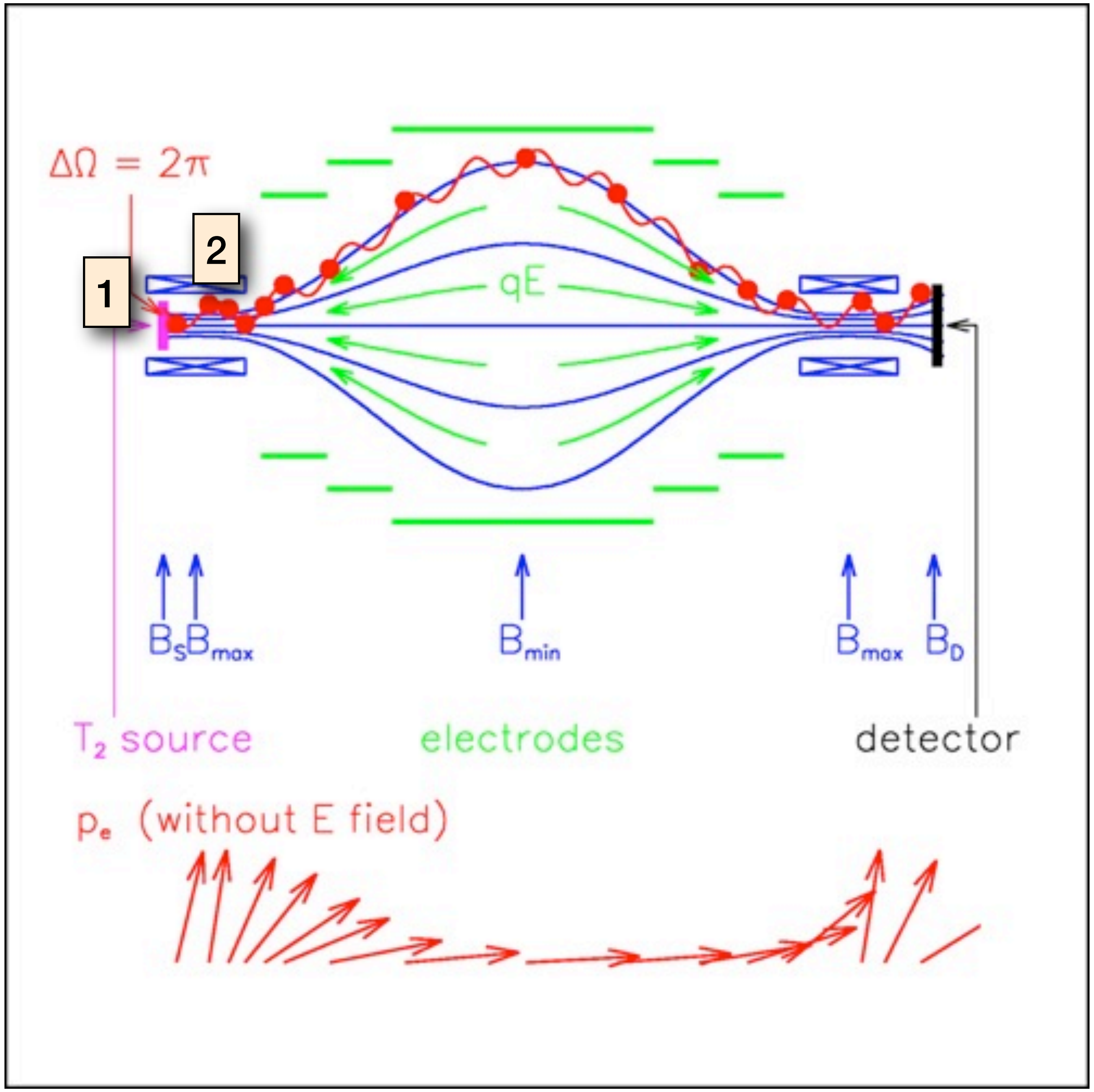

1. Electrons emitted isotropically at T_2 source
2. Guided magnetically on a cyclotron motion

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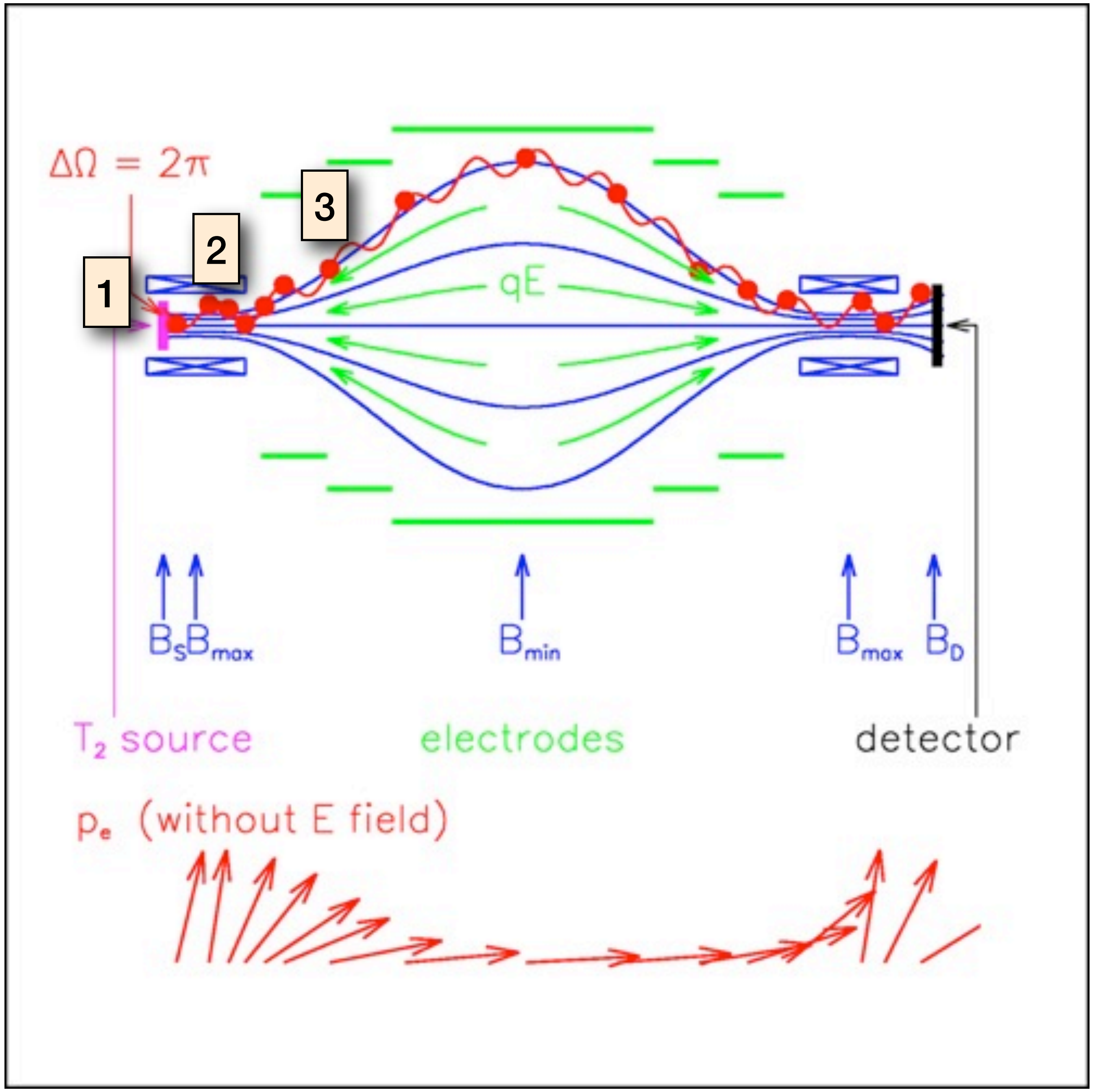

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3. Adiabatic transformation of cyclotron motion into longitudinal motion
→ <u>Broad beam almost parallel to B field lines</u>

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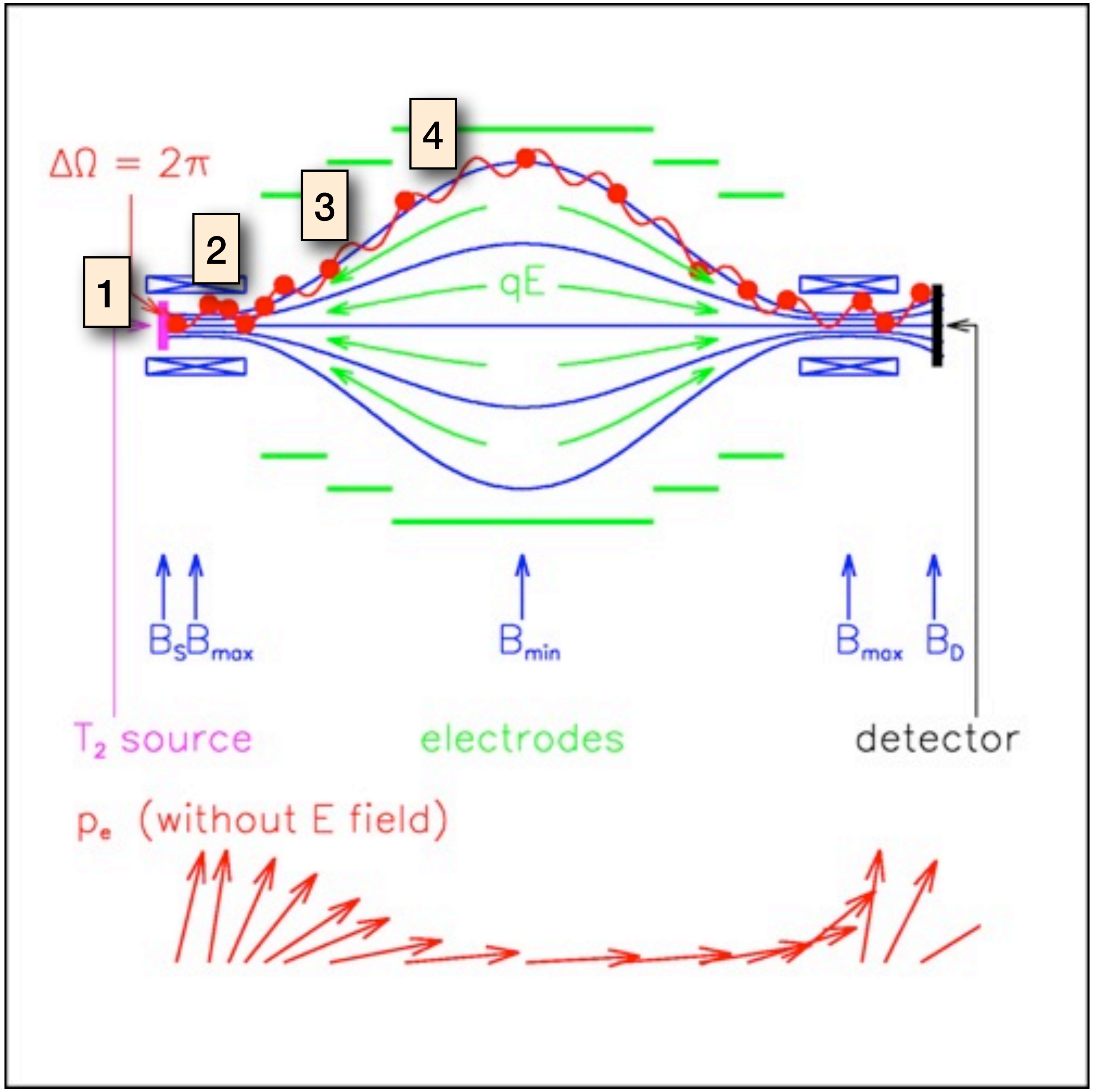

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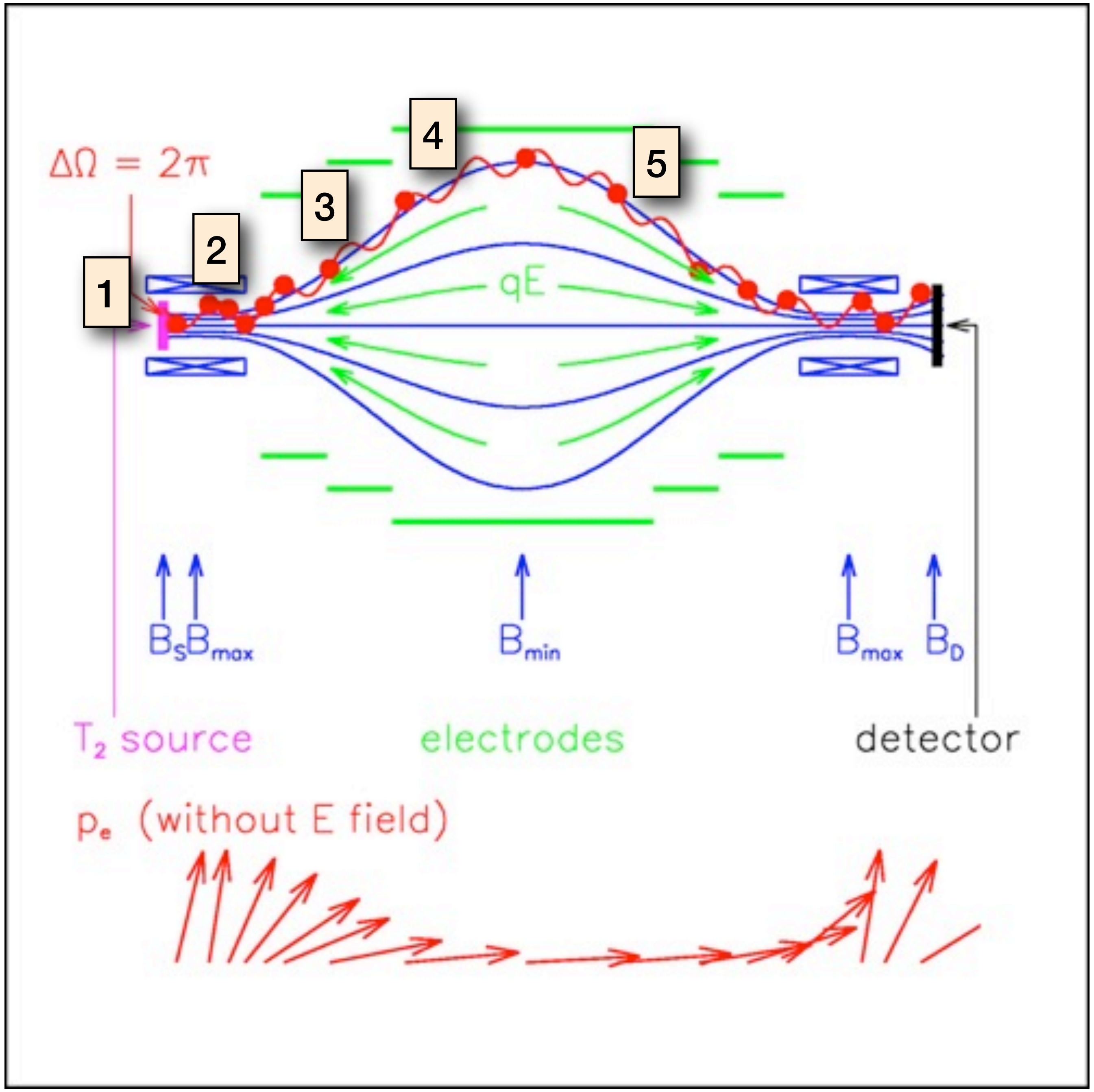

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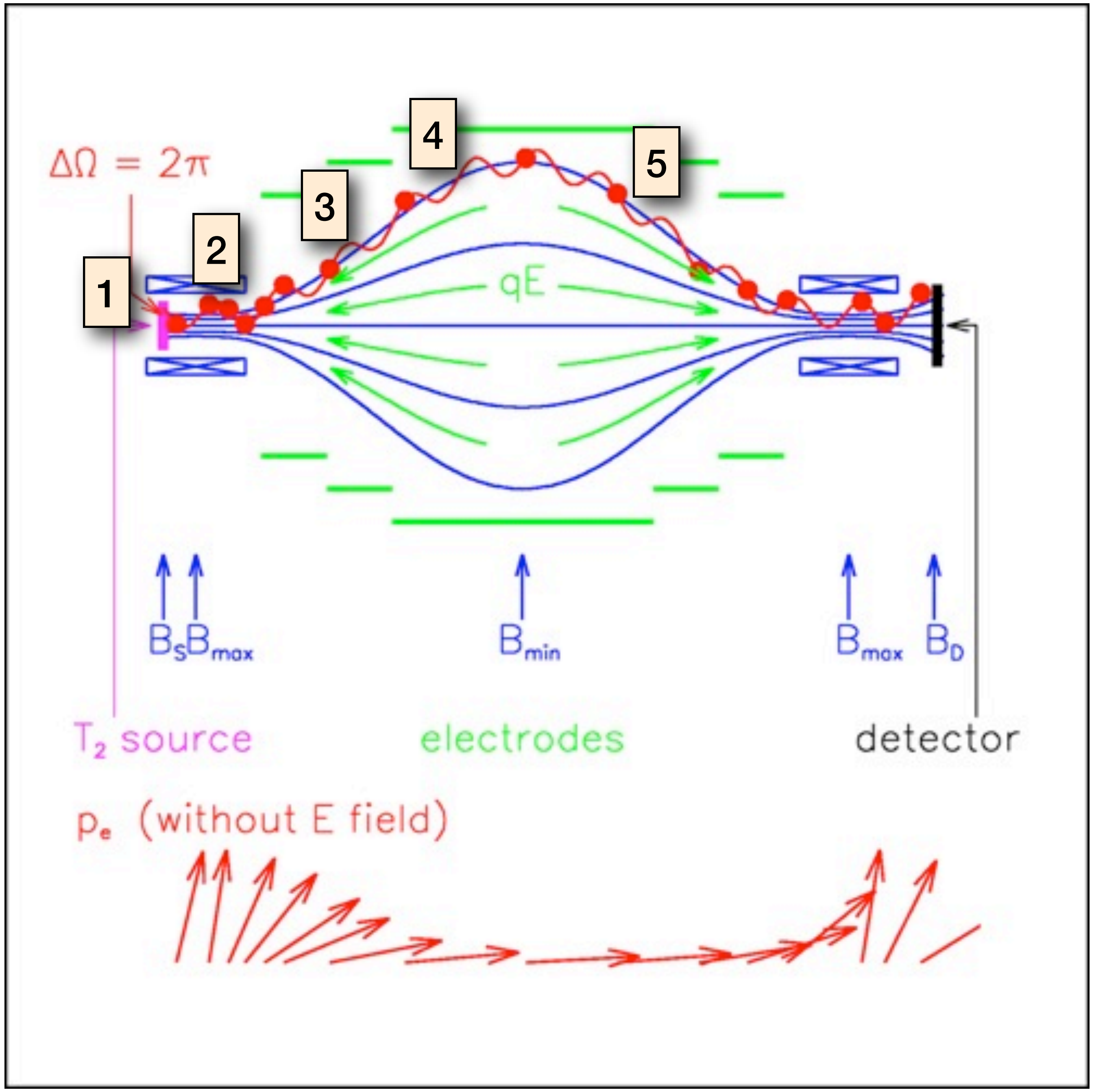

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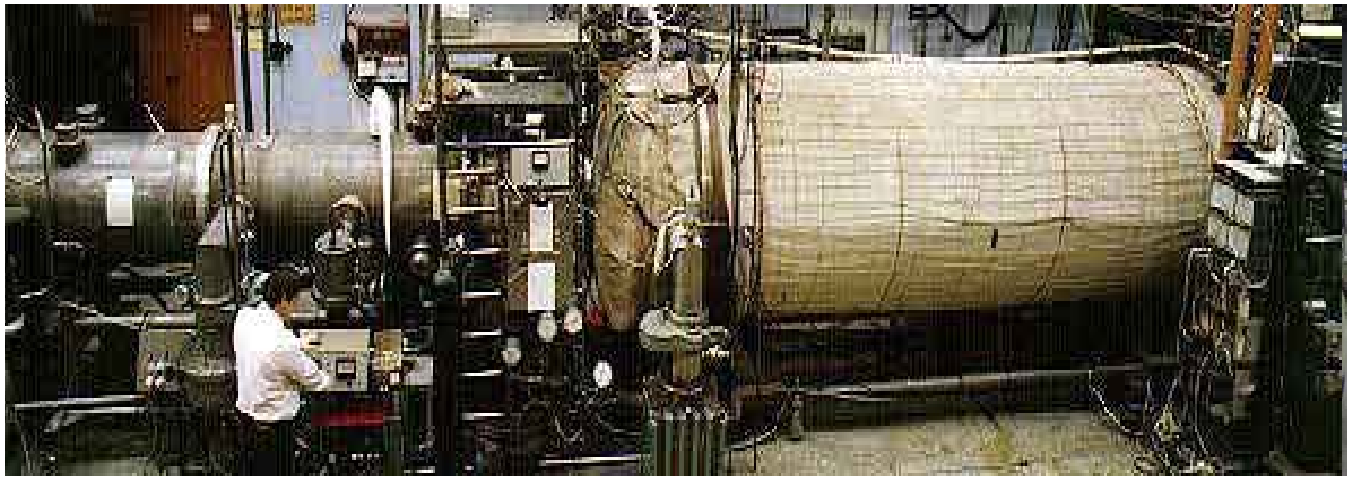
Measure β spectrum endpoint by varying electrostatic potential close to Q-value

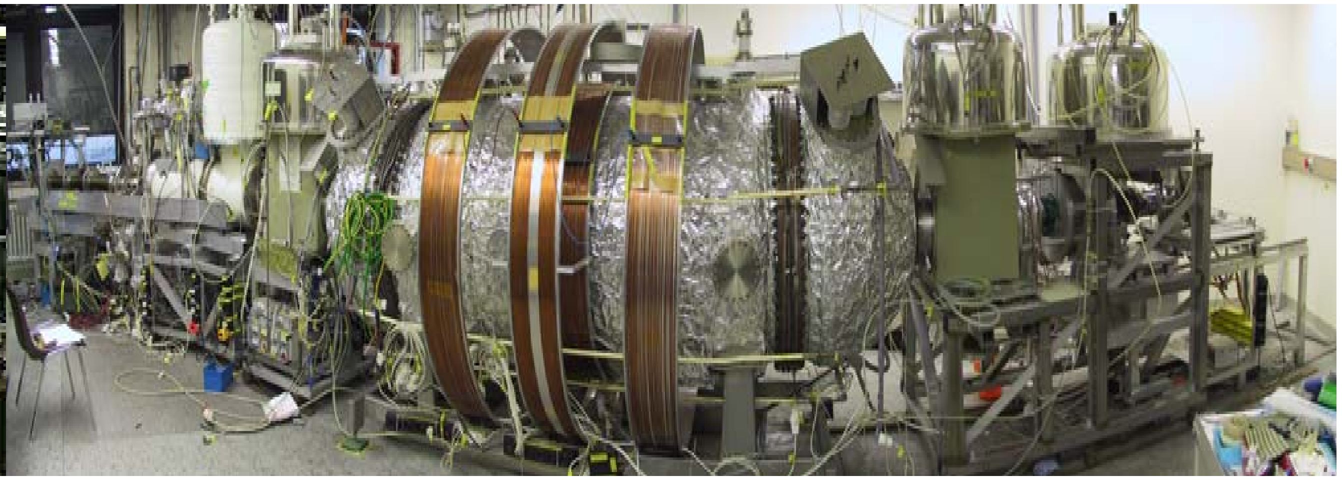
Mainz and Troitsk experiments

No evidence for non-zero neutrino mass from β decay experiments

Troitsk



Mainz



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$m_\beta^2 = -2.3 \pm 2.5 \pm 2.0\ eV^2$

$m_\beta < 2.1$ eV (95% CL)

$m_\beta^2 = -0.6 \pm 2.2 \pm 2.1\ eV^2$

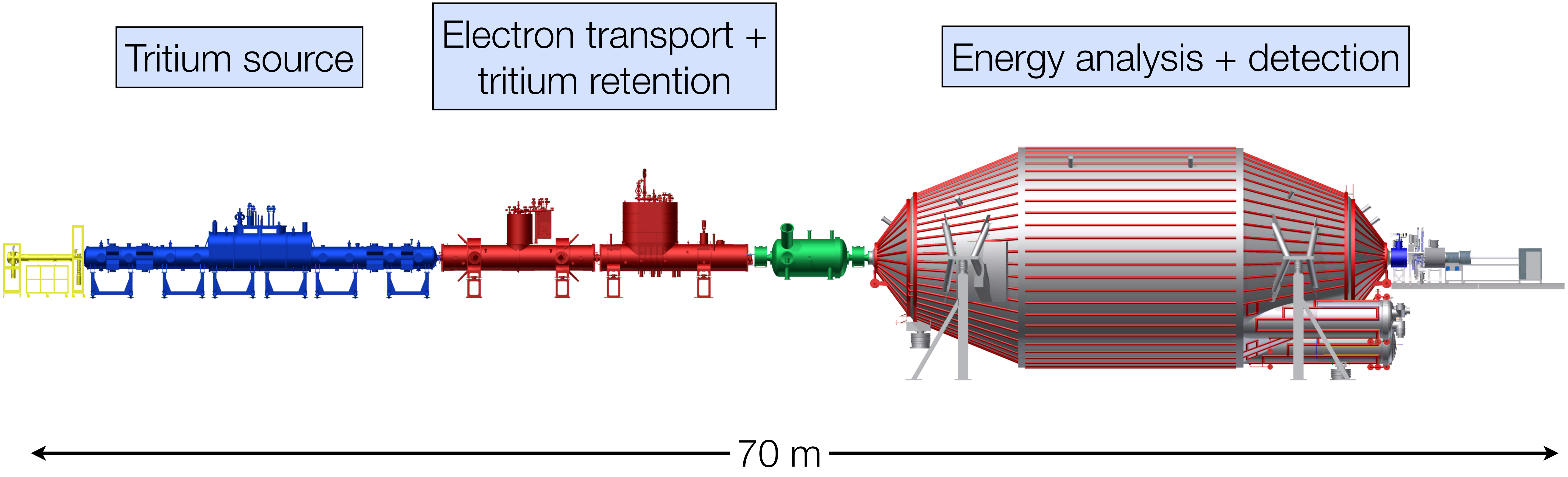
$m_\beta < 2.3$ eV (95% CL)

KATRIN experiment

Starting in 2017?

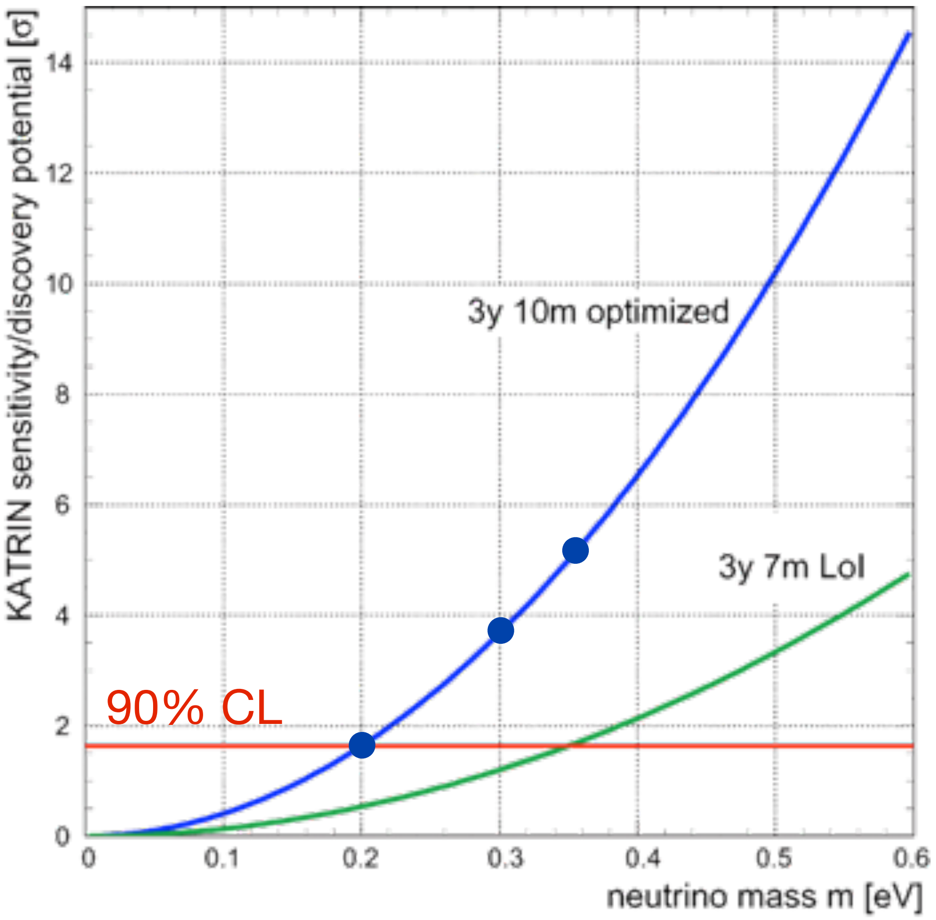
- Tritium source
  - Low end-point (18.6 keV), intense (10^{11} β decays/sec))

- Electron energy analysis + detection
  - MAC-E-Filter technique with largest spectrometer to date!



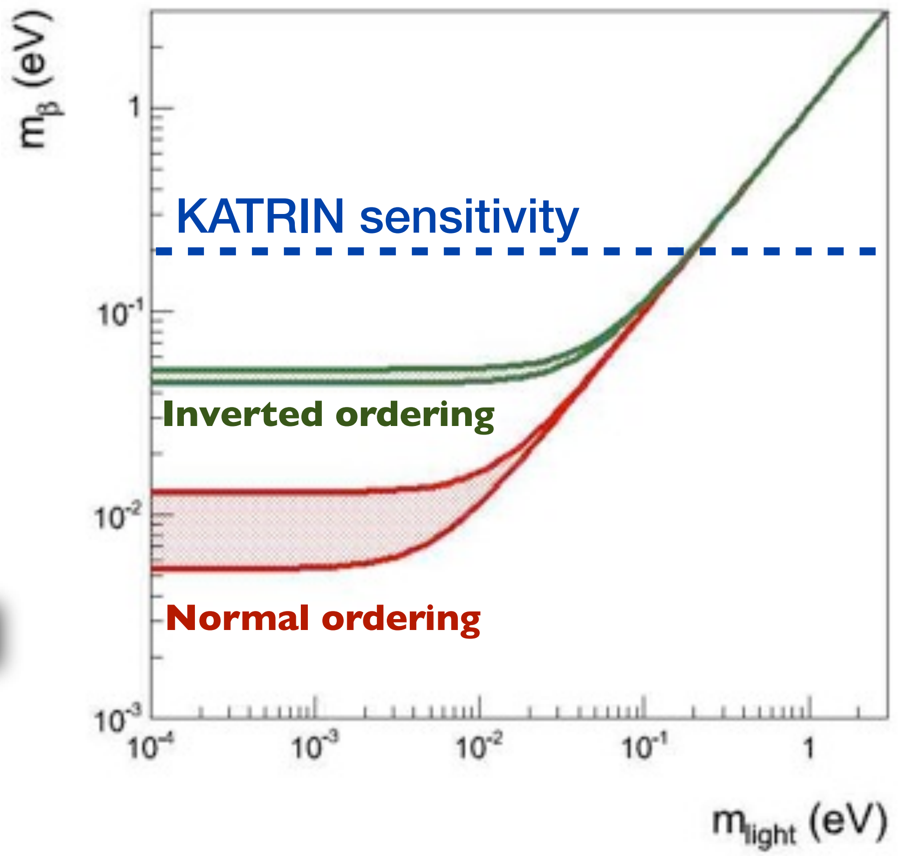
KATRIN design sensitivity

Assuming 3 years exposure



- Sensitivity down to m_β = 0.2 eV at 90% CL
  - One order of magnitude improvement over Mainz and Troitsk

- Discovery potential:
  - 3.5σ if m_β = 0.3 eV
  - 5σ if m_β = 0.35 eV



- Sensitive to ~ mass-degenerate neutrinos only (no sensitivity to mass ordering)

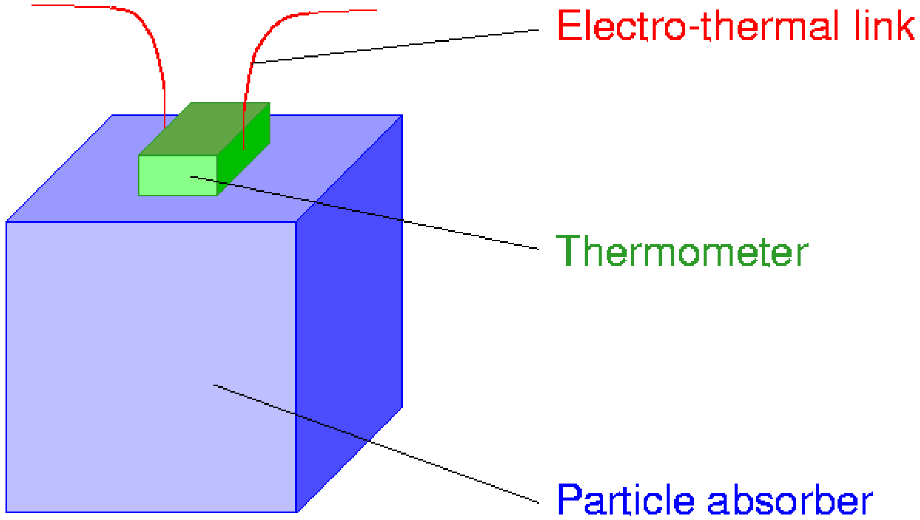
Cryogenic bolometers

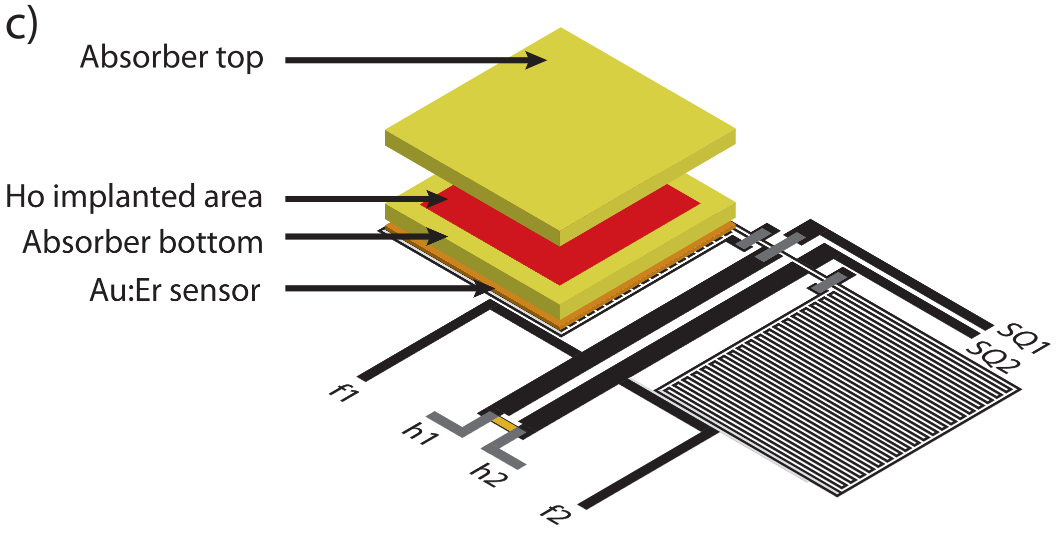
Electron capture of ^{163}Ho or β decay of ^{187}Re: ECHo, HOLMES, MARE

●Detectors with small heat capacity C_{tot}
→ operate at ultra-low temperatures: $T < 100$ mK

●Small deposited energy ΔE results in large temperature increase: $\Delta T = \Delta E / C_{tot}$

●Only detectors capable of measuring <3 keV energy with high precision





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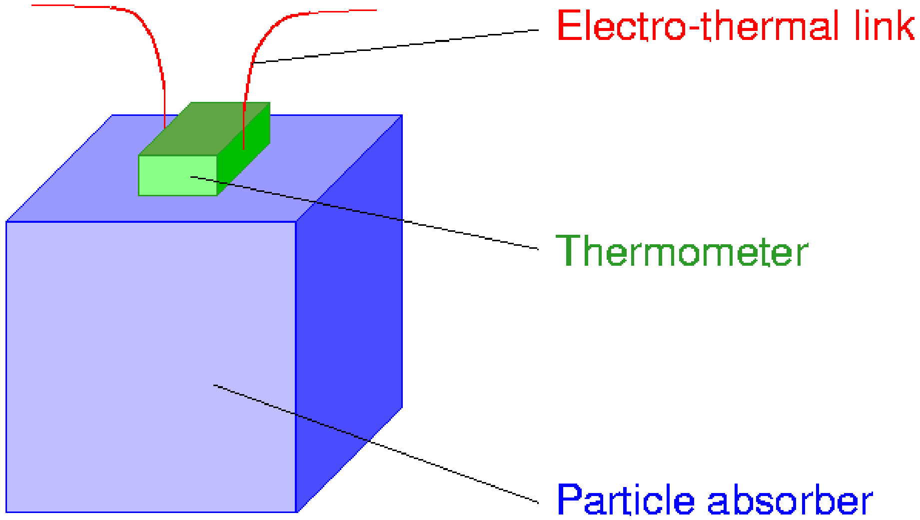
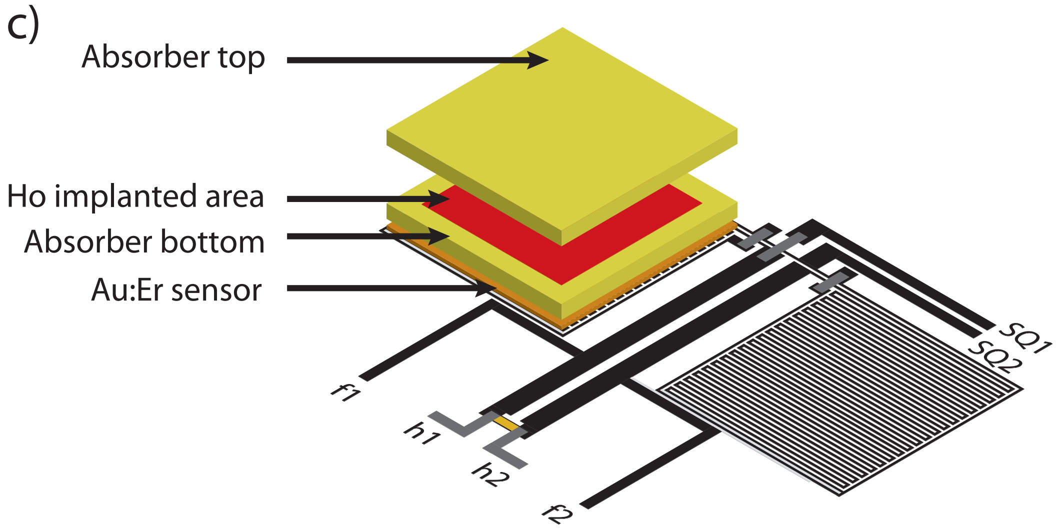


Advantage:

- Measures all released energy except that of the neutrino, no final atomic/molecular states involved



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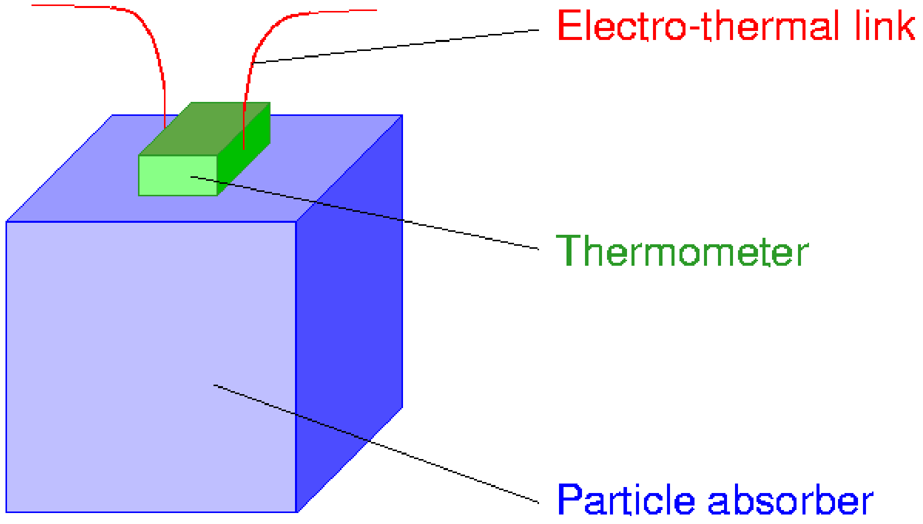

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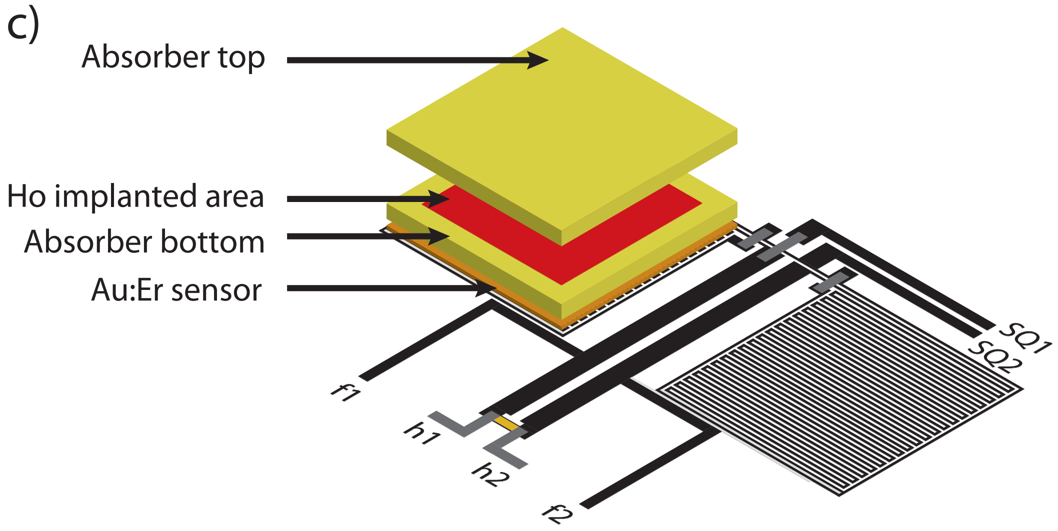
- Relatively low time response → measured energy spectrum suffers from pile-up → segment detector into many pixels → hard to scale to large masses!



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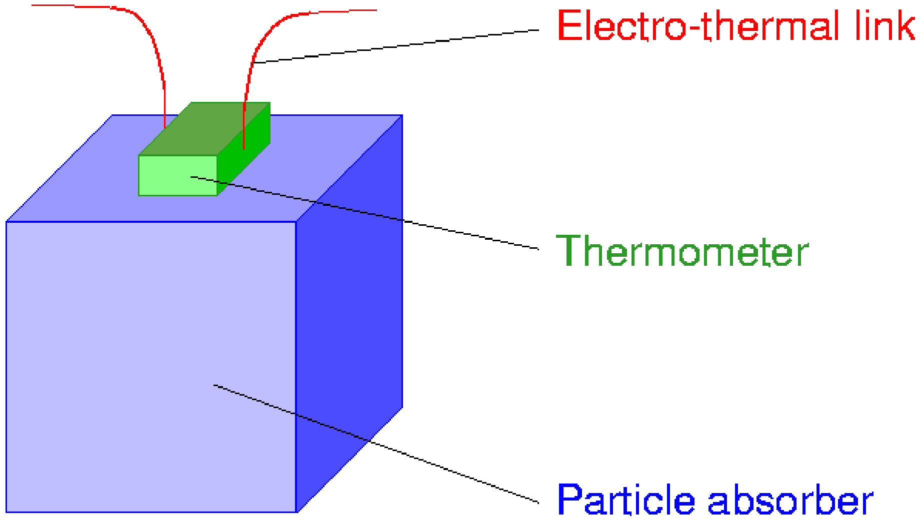

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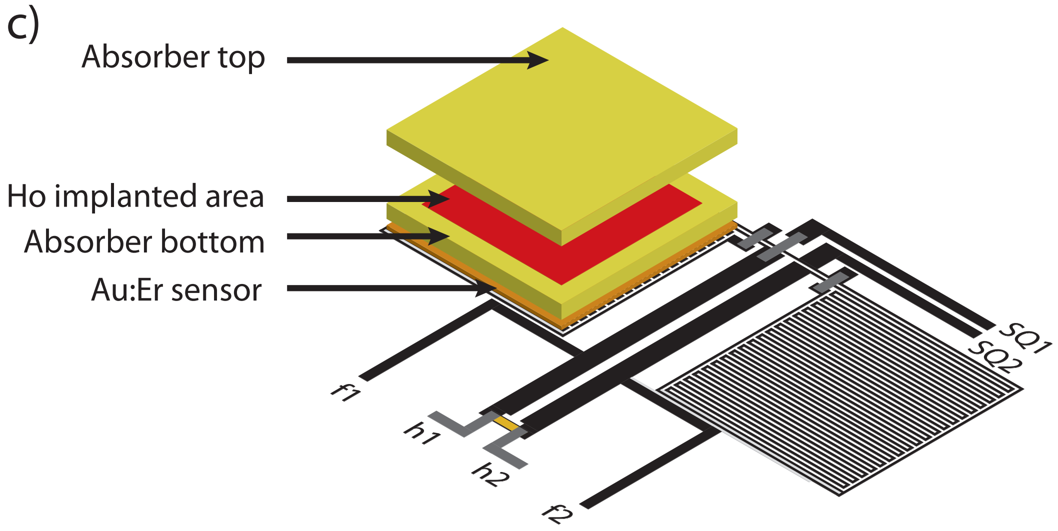
- Sub-eV neutrino mass sensitivity within reach?



Neutrino cosmology

Constraints on neutrino mass

Neutrinos from the Big Bang

See W. Percival's lectures

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- As the Universe expands (cools), neutrinos transition from a state where they are in thermal equilibrium with electrons, to one where they are decoupled from them

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- Neutrino decoupling occurs when

$\nu+\bar{\nu}$ annihilation rate:

$$\Gamma = n_\nu \, \sigma_\nu \, v \propto T^5$$

=

Expansion rate:

$$H(t) \propto T^2$$

$$\Rightarrow$$

$$T \approx 1 \text{ MeV}$$

Neutrinos from the Big Bang

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$H(t) \propto T^2$

→

$T \approx 1$ MeV

- Neutrino decoupling occurs just <u>before</u> e^+e^- annihilations, so they take no share of released energy in this process and they are <u>colder</u> than CMB photons:

$$T_{\nu 0} = \left(\frac{4}{11}\right)^{1/3} T_0 = 1.945 \text{ K} \rightsquigarrow 1.697 \times 10^{-4} \text{ eV}$$

$$n_{\nu_i}(T_{\nu 0}) \approx 56 \text{ cm}^{-3}$$

- $T_{\nu 0}$: temperature of neutrinos today
- T_0: temperature of photons today

Massive neutrinos from the Big Bang

See W. Percival's lectures

- What is the contribution of massive neutrinos to the energy density today?

Massive neutrinos from the Big Bang

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- Since $m_\nu >> T_{\nu 0}$, neutrinos are non-relativistic and contribute to the matter density today:

$$\boxed{\rho_\nu = m_\nu n_\nu \qquad \Omega_\nu h^2 = \frac{\sum m_\nu}{93 \text{ eV}}}$$

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- Neutrino dark matter is hot, with a large velocity dispersion:

$$\boxed{\langle v_{\mathrm{thermal}} \rangle \simeq 81(1+z)\left(\frac{\mathrm{eV}}{m_\nu}\right)\ \mathrm{km\ s}^{-1}}$$

  - Galaxy velocity dispersions ≈ 100 km/s or less
  - Sub-eV neutrinos have too much thermal energy to be packed into galaxy-sized self-gravitating systems
  - Neutrinos cannot be the dominant galactic dark matter

Sub-eV massive neutrinos cosmological signatures

On Cosmic Microwave Background (CMB)

Sub-eV massive neutrinos cosmological signatures

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Early Integrated Sachs Wolfe (ISW) effect:

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→effect imprinted in CMB anisotropies, especially around the first peak of the CMB temperature power spectrum

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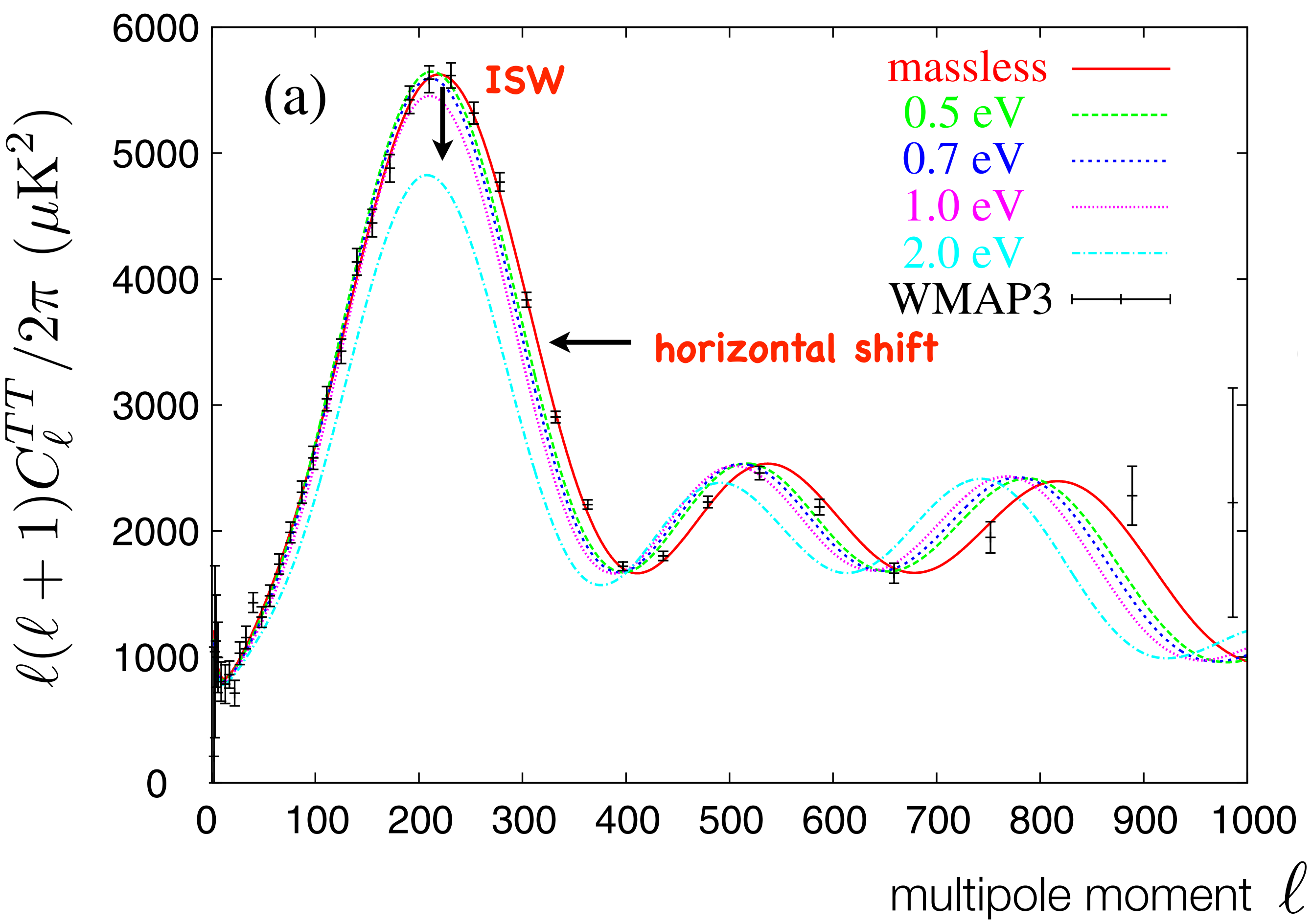
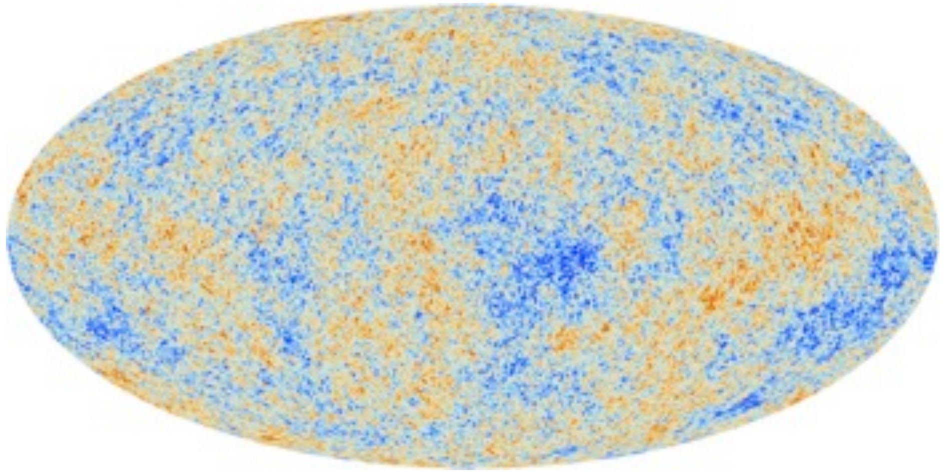


- Sensitive to <u>sum</u> of neutrino masses



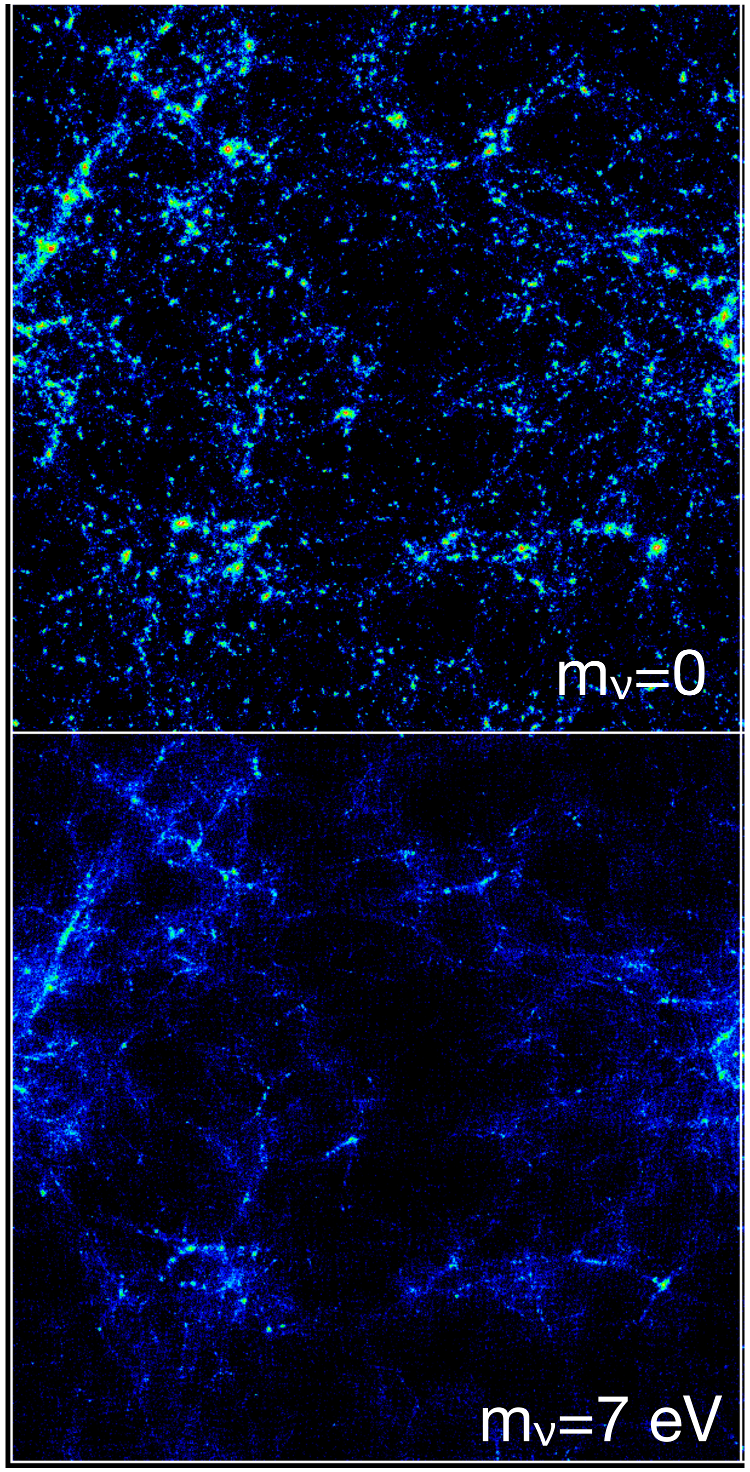
Sub-eV massive neutrinos cosmological signatures

On Large Scale Structure (LSS)

Sub-eV massive neutrinos cosmological signatures

On Large Scale Structure (LSS)

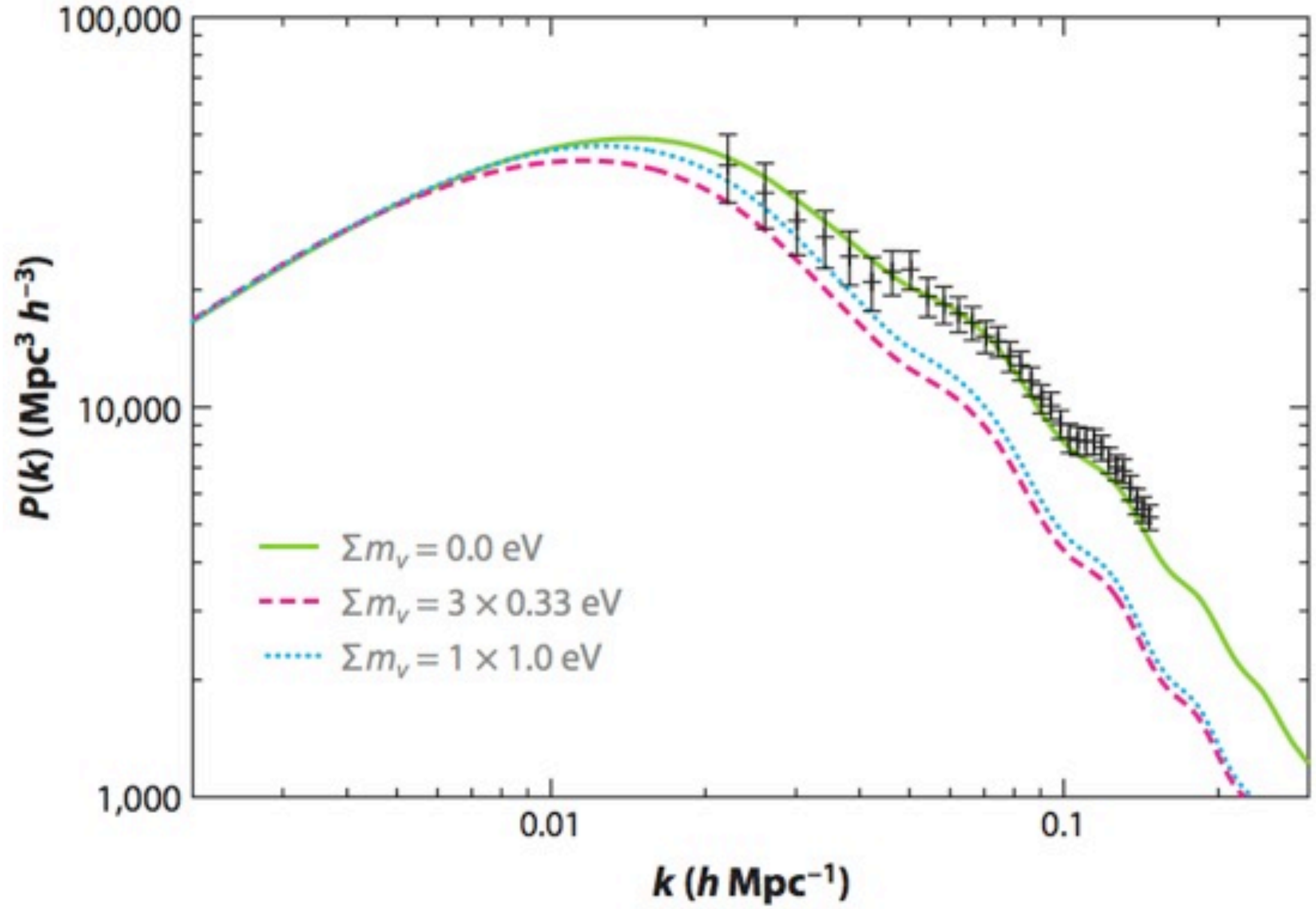
- Suppression of structure formation on scales smaller than free streaming scale when neutrinos turn non-relativistic

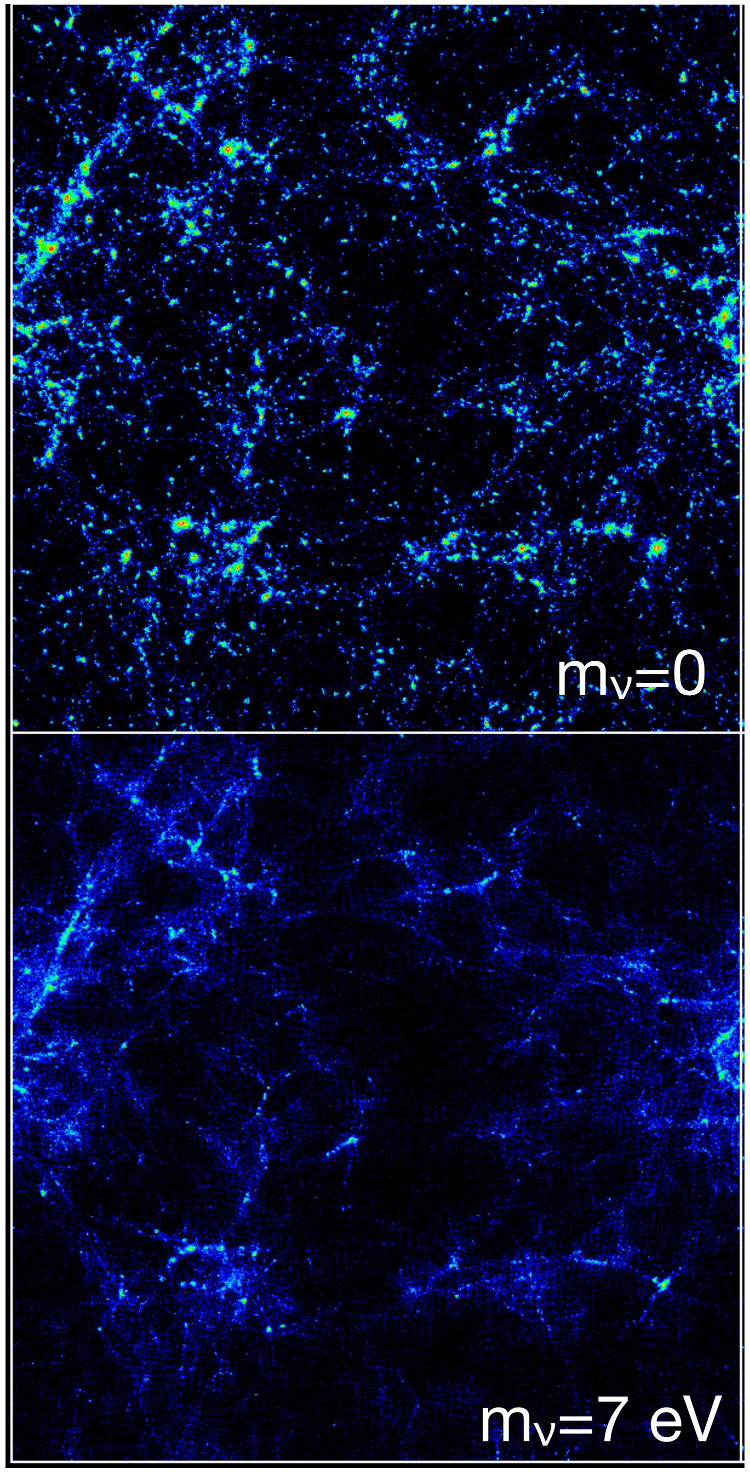


Sub-eV massive neutrinos cosmological signatures

On Large Scale Structure (LSS)

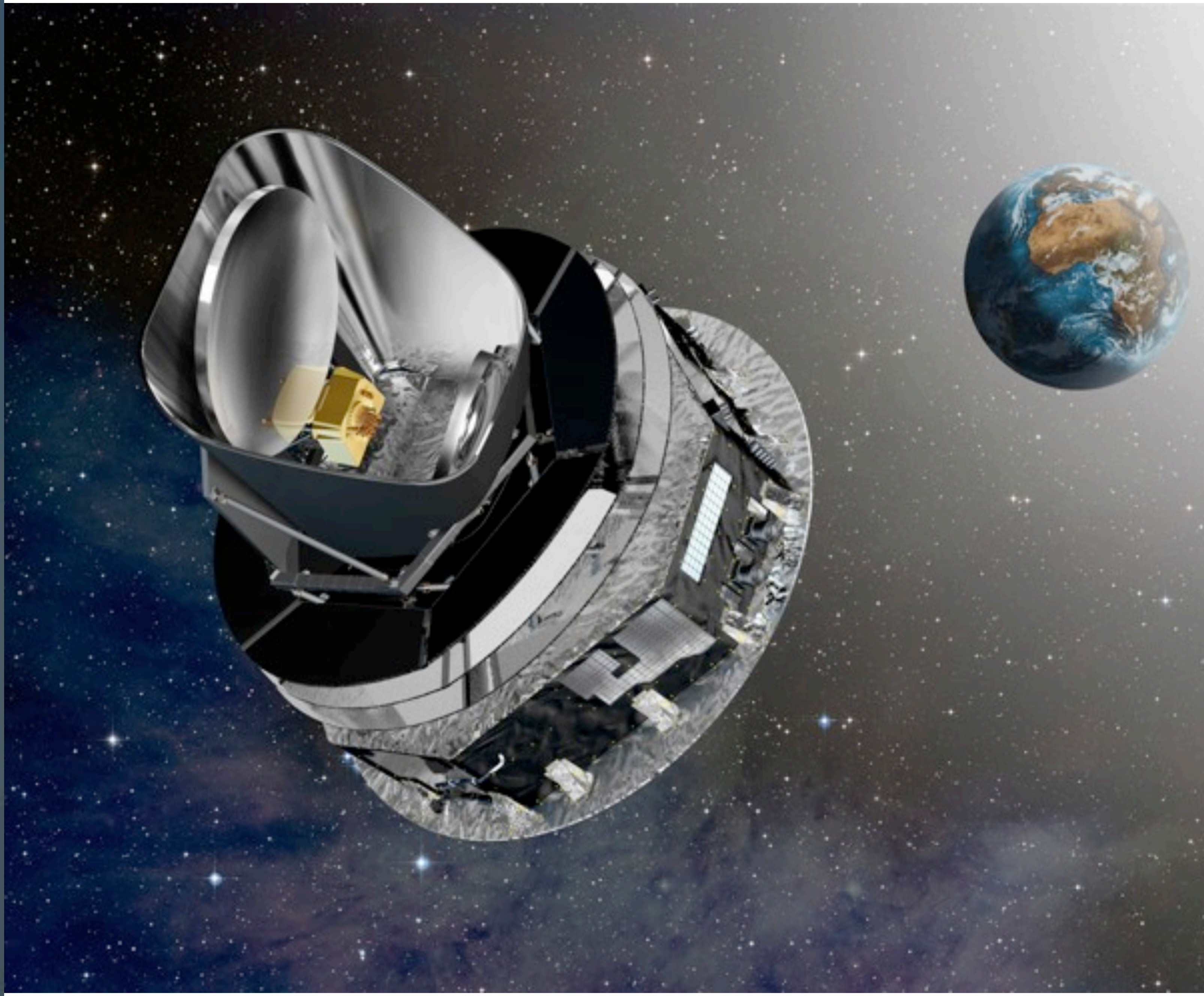
- Suppression of structure formation on scales smaller than free streaming scale when neutrinos turn non-relativistic
- Imprint on galaxy clustering observables: suppression of power at small scales (large k) in matter power spectrum
- Also sensitive to <u>sum</u> of neutrino masses





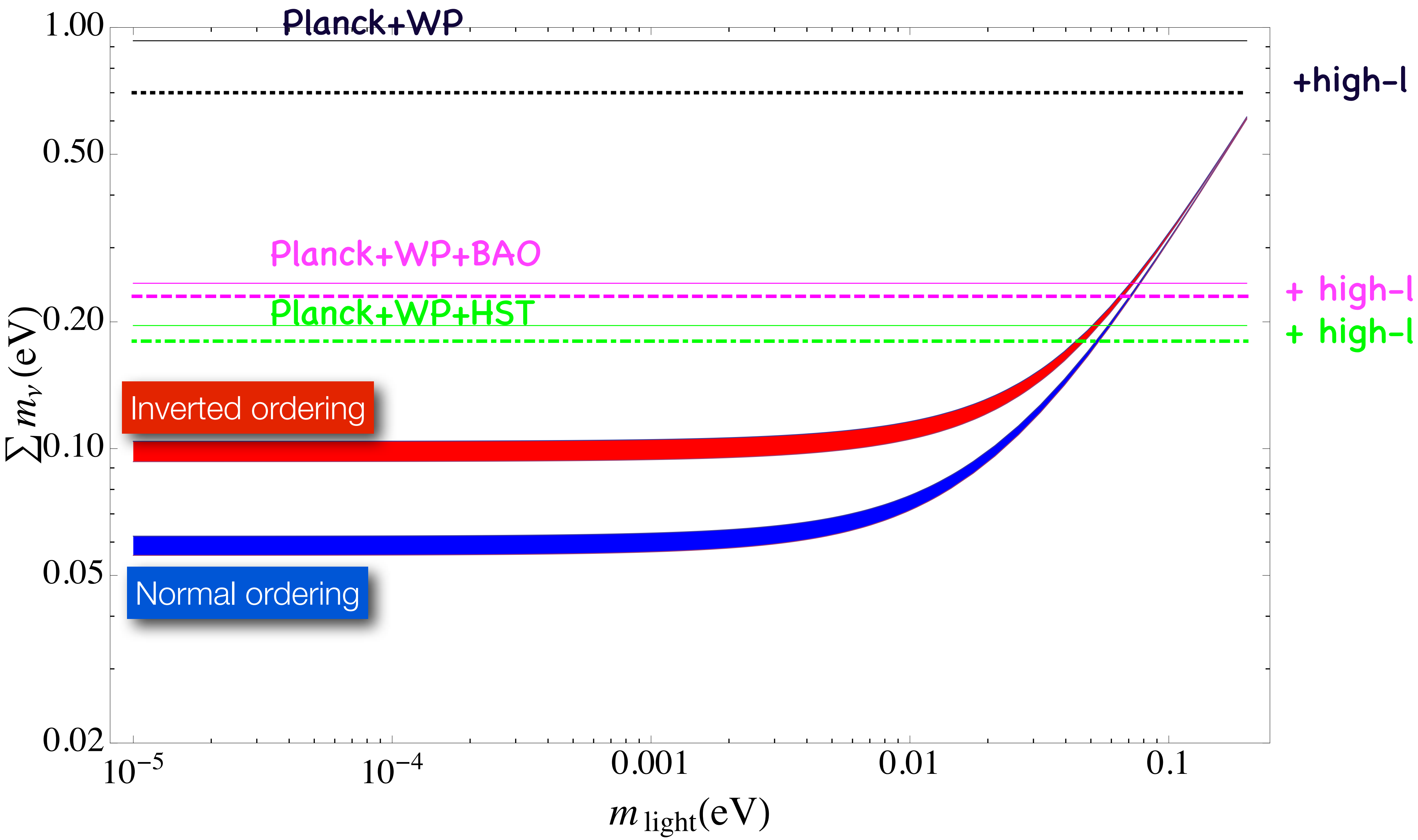
Planck satellite

Launched in 2009



Post-Planck state-of-the-art on neutrino mass

- No cosmological evidence for neutrino mass
- 95% CL upper limits for several dataset combinations:



Neutrino mass scale summary

What is the best experimental strategy?

β decay

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

ββ0ν decay

$m_{\beta\beta} \equiv \; | \sum_i m_i \, U_{ei}^2 \, |$

Cosmology

$m_{cosmo} \equiv \sum_i m_i$

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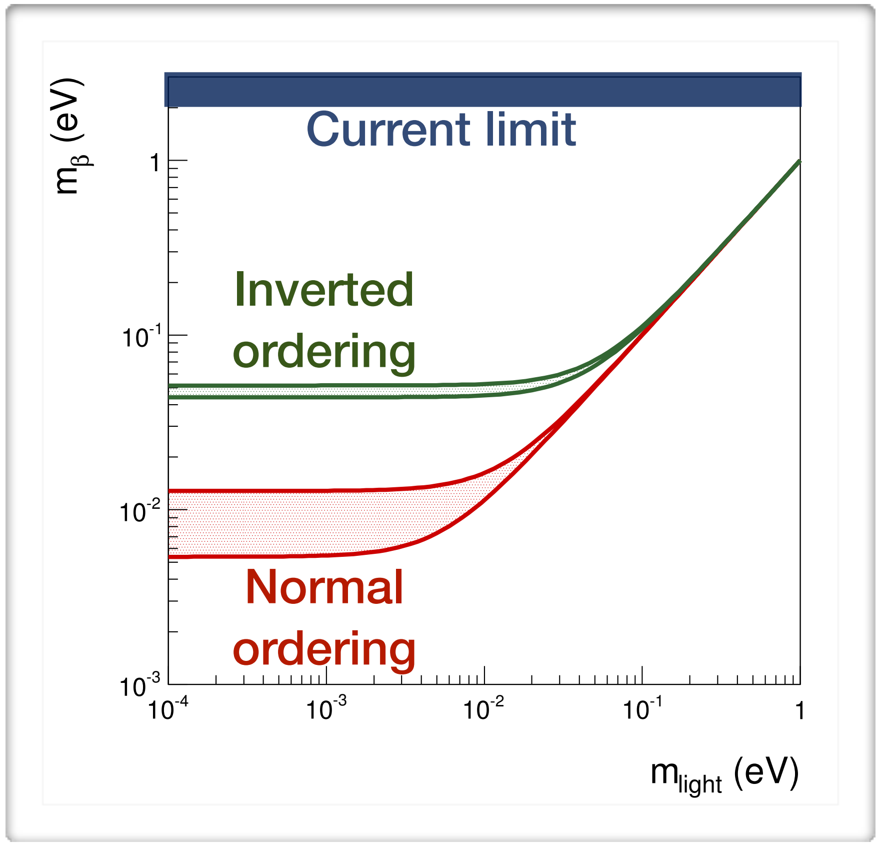
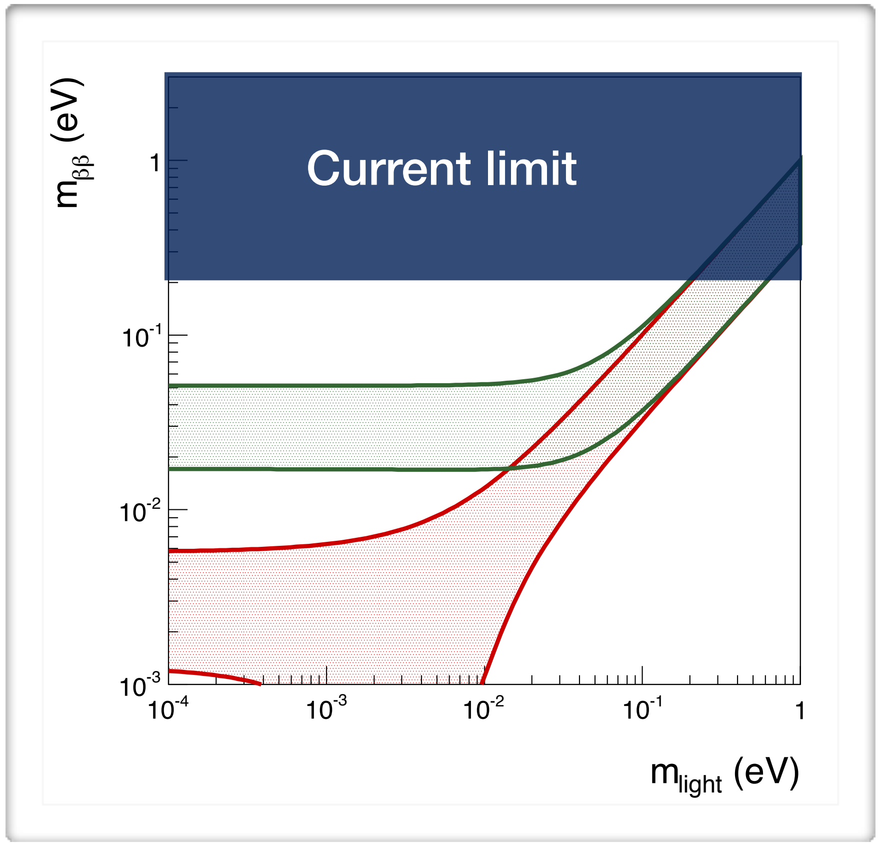
β decay

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



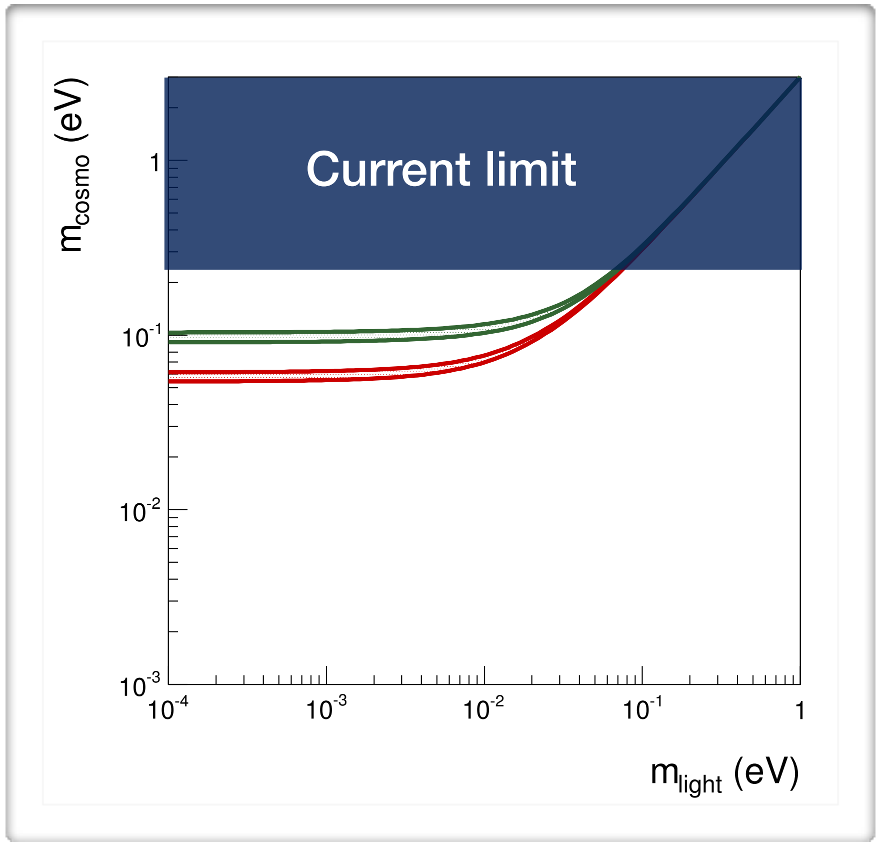
ββ0ν decay

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



Cosmology

$m_{cosmo} \equiv \sum_i m_i$



Less stringent, but less model-dependent

More stringent, but more model-dependent

Neutrino cosmology

Constraints on N_{eff}

Number of effective neutrino species

aka N_{eff}

- Number of relativistic species in thermal equilibrium is usually parametrized in terms of N_{eff}, the number of effective neutrino species (at early times, when neutrinos contributed to radiation):

$$\boxed{\Omega_r h^2 = \left(1 + \tfrac{7}{8}\left(\tfrac{4}{11}\right)^{4/3} N_{\mathrm{eff}}\right)\Omega_\gamma h^2}$$

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Three possibilities:

- **$N_{\text{eff}} = 3.046$ - standard scenario:** three neutrino species (deviation from 3 accounting for small corrections)

- **$N_{\text{eff}} < 3.046$ - less neutrinos:** non-standard neutrino couplings, neutrino decays, extremely low reheating temperature models

- **$N_{\text{eff}} > 3.046$ - more neutrinos:** sterile neutrino species, other radiation-like degrees of freedom

N_{eff} cosmological signatures

On Big Bang Nucleosynthesis (BBN)

- BBN theory predicts primordial abundances of D, ^{3}He, ^{4}He and ^{7}Li, fixed by t ~ 180 s
- Chemical abundances inferred at late times from spectroscopic methods
→ Best to study low metallicity sites with little evolution
- N_{eff} has an impact on the freeze out temperature of weak interactions, set by:

$$\boxed{\Gamma_{n \leftrightarrow p} \sim H}$$

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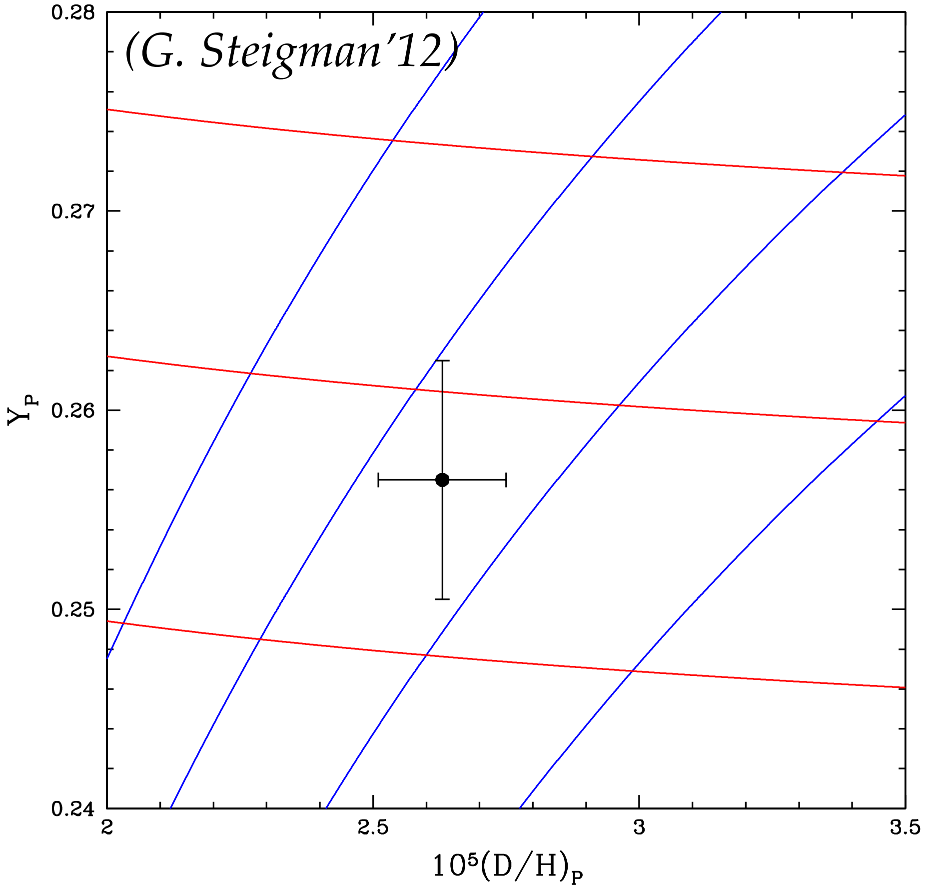
N_{eff} ↗ → expansion rate H ↗ → freeze out temperature T_{freeze} ↗ → ^{4}He fraction Y_p ↗

$$n/p \simeq e^{-\frac{m_n - m_p}{T_{freeze}}} \qquad Y_p = \frac{2(n/p)}{1+n/p}$$

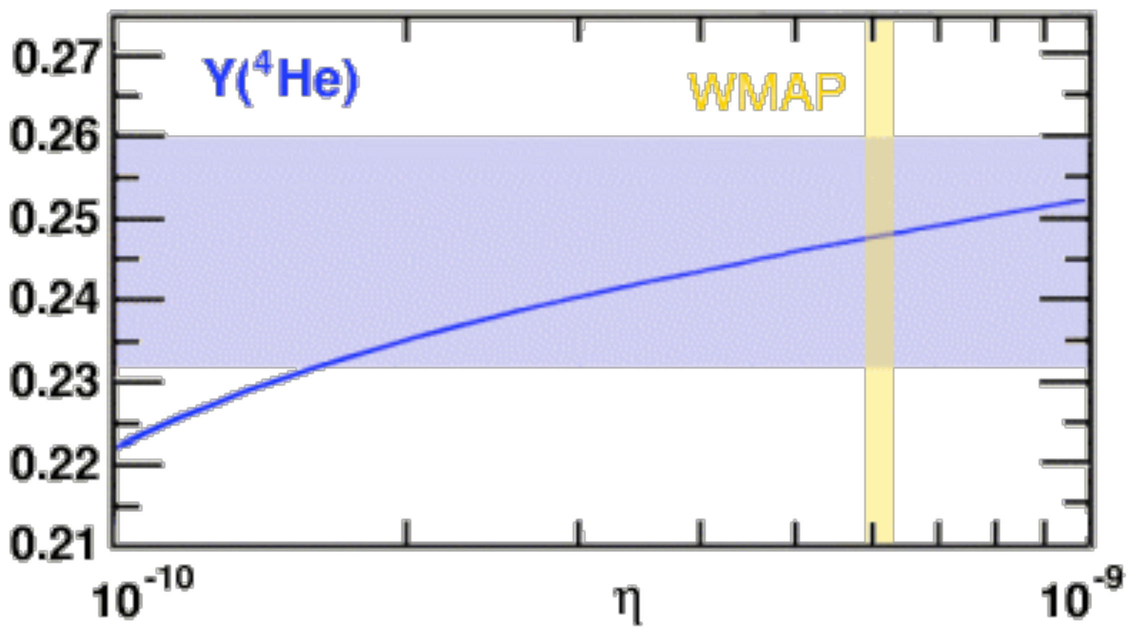
N_{eff} cosmological signatures

On Big Bang Nucleosynthesis (BBN)

- Recent BBN observations point to high Y_p values, marginally preferring more neutrinos ($\Delta N_{eff} > 0$) than standard value of 3.046:



$$\Delta N_{\rm eff} = 0, 1, 2$$



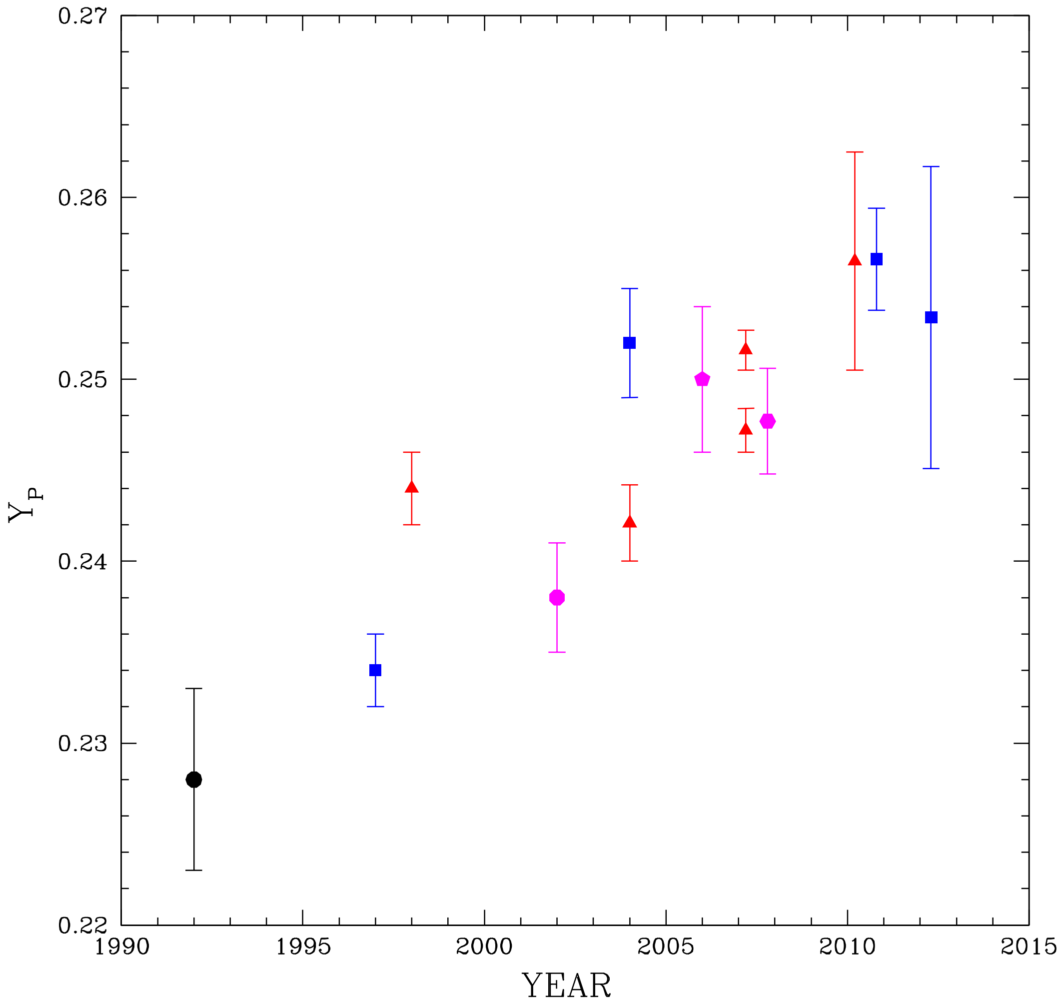
$$\eta_{10} = 7.0, 6.5, 6.0, 5, 5$$

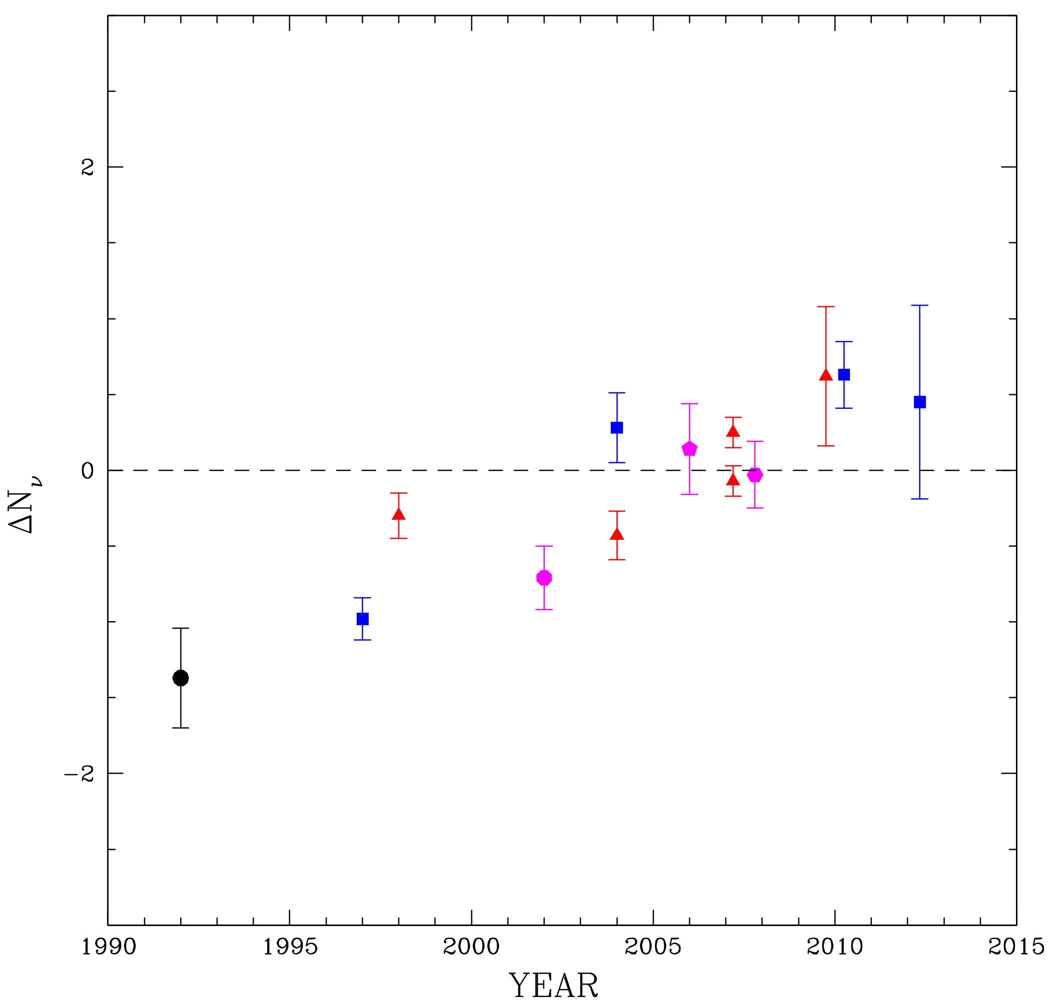
Baryon-to-photon ratio (10^{-10})

N_{eff} cosmological signatures

On Big Bang Nucleosynthesis (BBN)

- This has not always been the case...
- Reported Y_p values have increased over time! (syst. uncertainties affecting measurements)
- Extracted BBN value for ΔN_{eff} mirrors this increase in Y_p



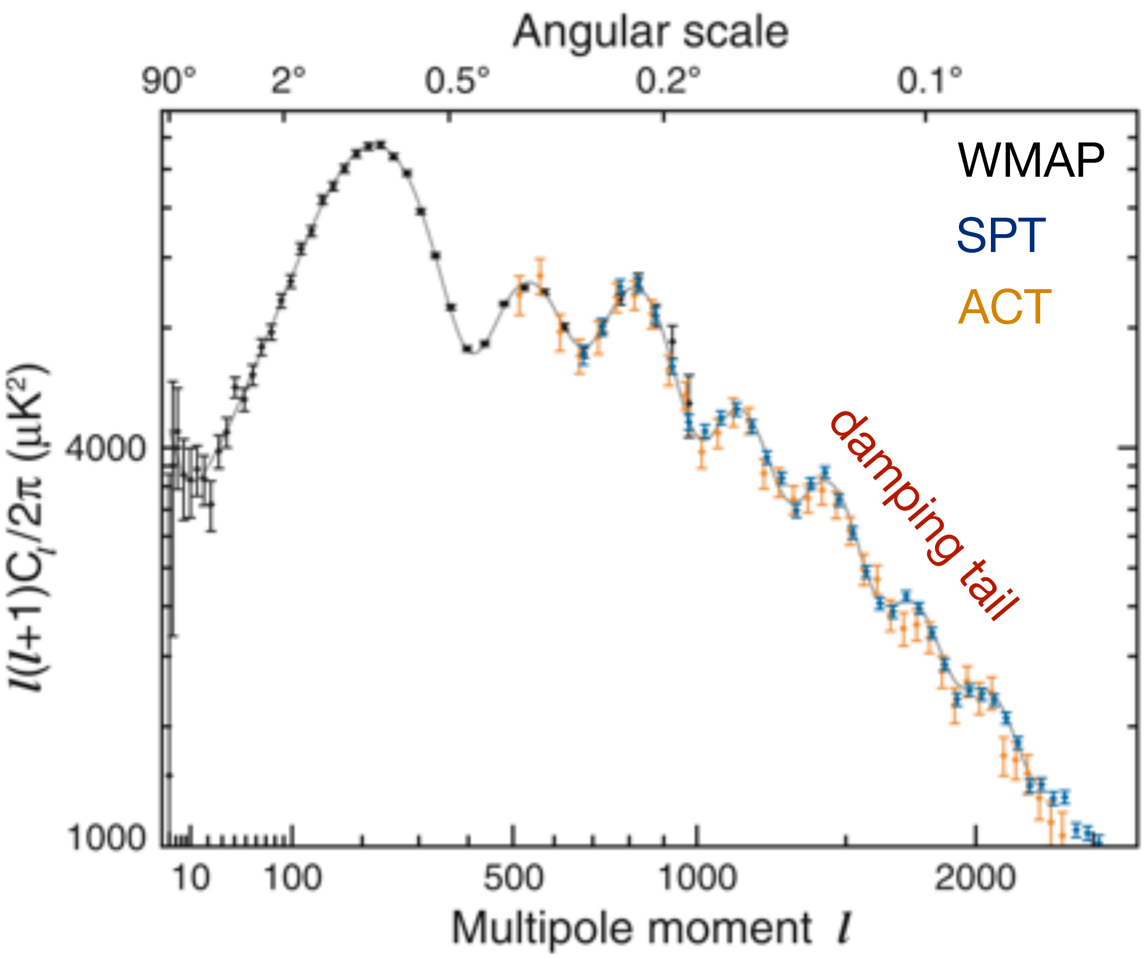


N_{eff} cosmological signatures

On Cosmic Microwave Background (CMB)

Diffusion damping:

- Photons diffuse from hot to cold regions, damping temperature anisotropies at high multipoles



N_{eff} cosmological signatures

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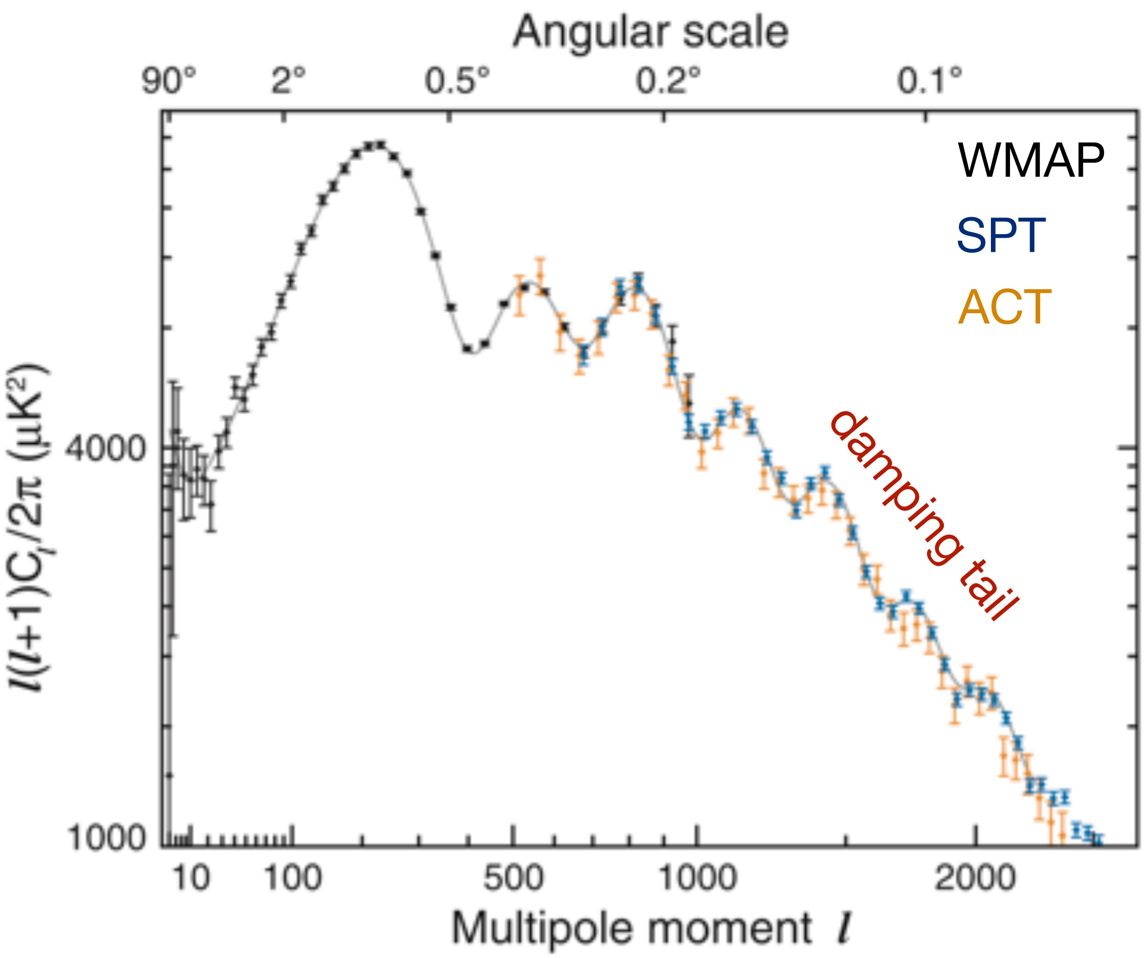

N_{eff} cosmological signatures

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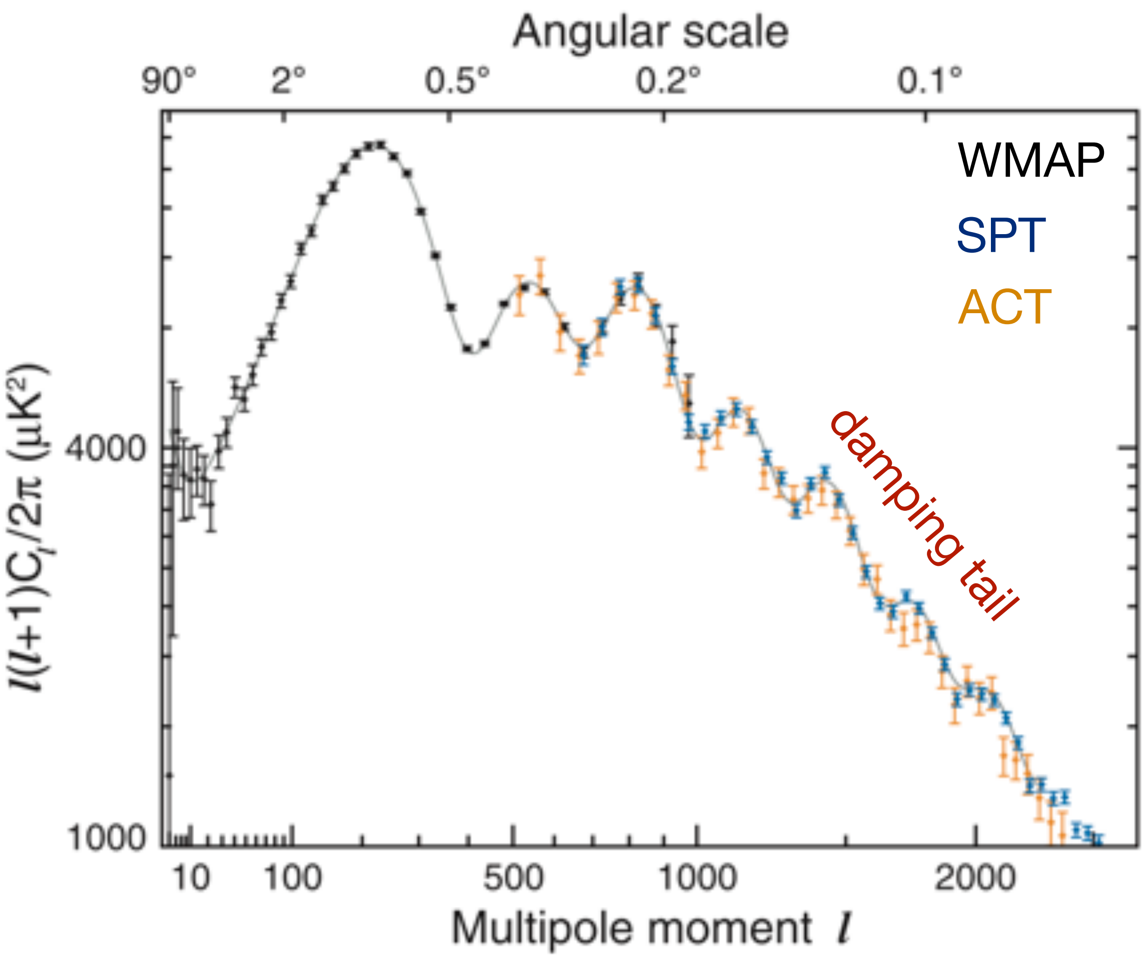

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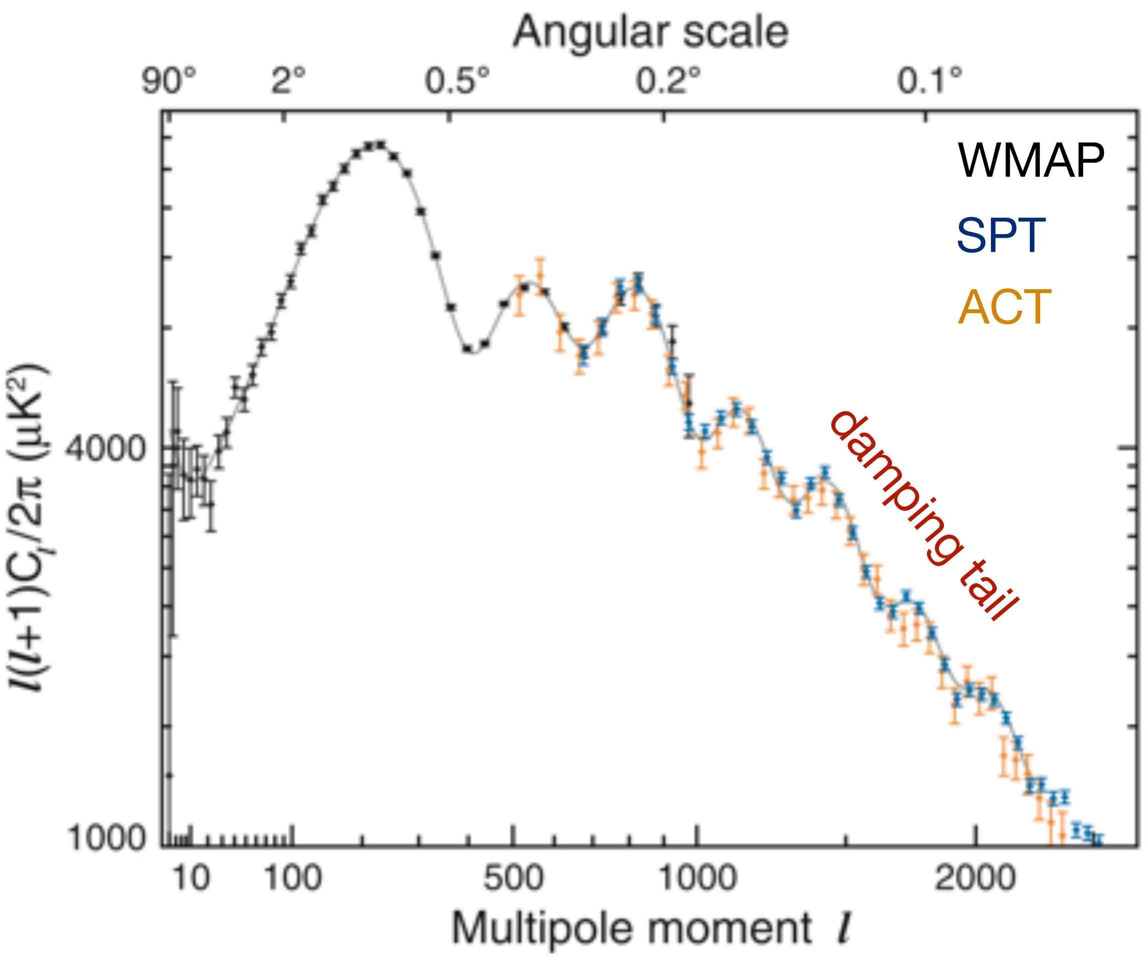


- Amount of damping depends on expansion rate H

- Since H ~ N_{eff}, damping sensitive to N_{eff}

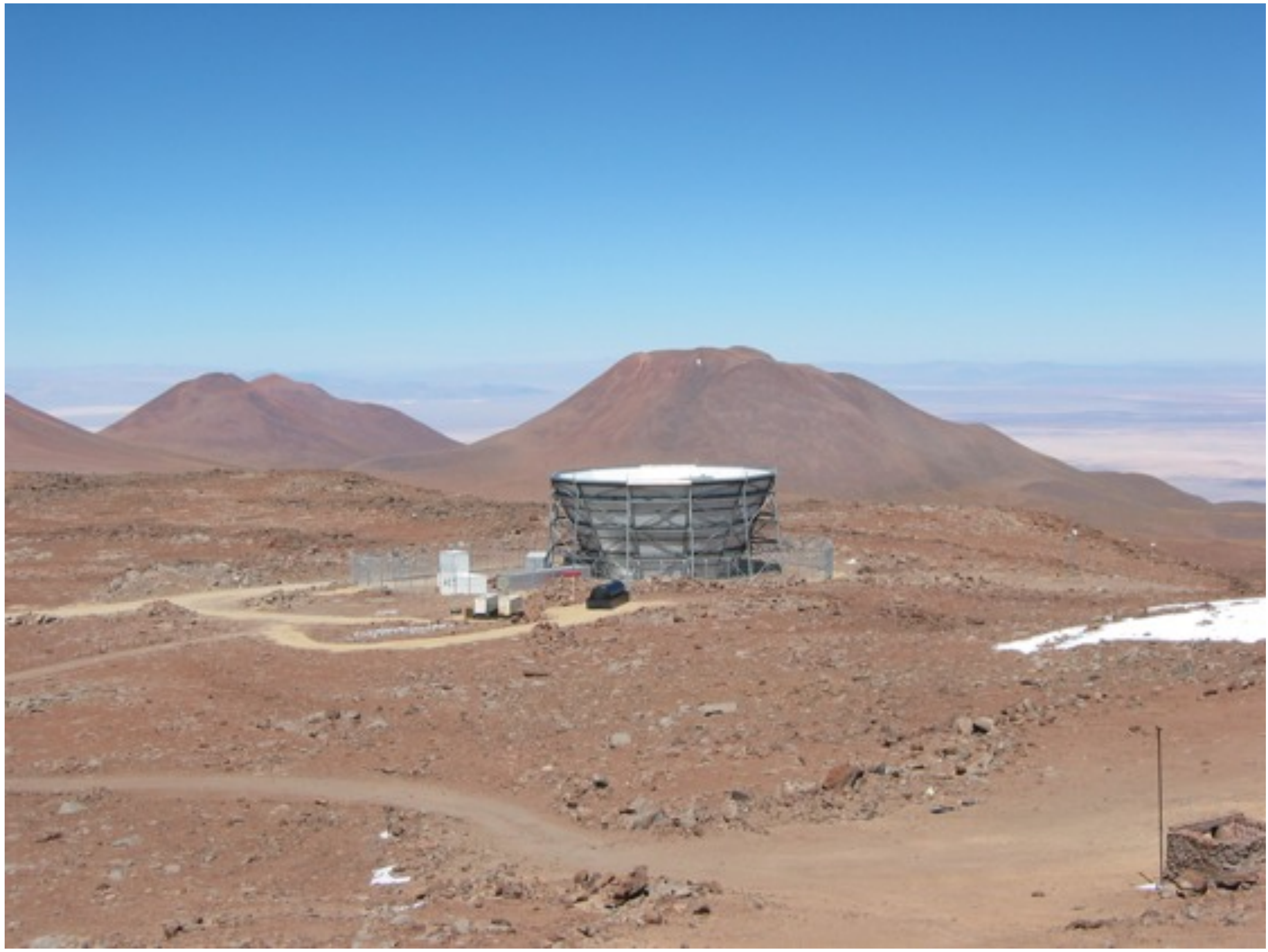
- Since helium recombines with free eletrons, effect degenerate with helium fraction Y_p:

Y_p ↗ → free electrons ↘ → photon diffusion ↗ → damping ↗

High-resolution, microwave-wavelength telescopes

South Pole Telescope (SPT)

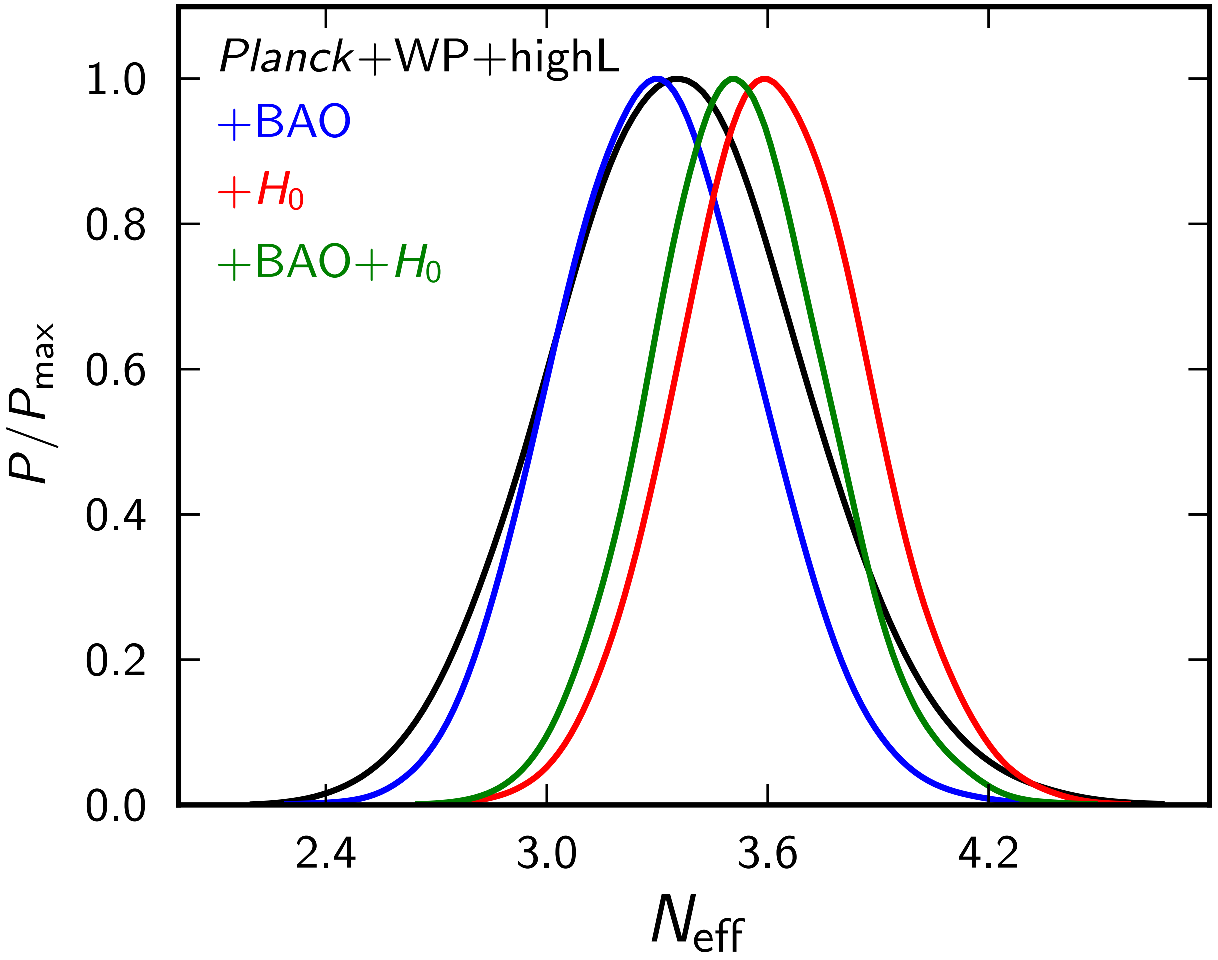
Atacama Cosmology Telescope (ACT)



N_{eff} cosmological signatures

On Cosmic Microwave Background (CMB)

- Post-Planck results:



95%CL

$$N_{\mathbf{eff}} = 3.62^{+0.50}_{-0.48}$$

$$N_{\mathbf{eff}} = 3.52^{+0.48}_{-0.45}$$

$$N_{\mathbf{eff}} = 3.36^{+0.68}_{-0.64}$$

$$N_{\mathbf{eff}} = 3.30^{+0.54}_{-0.51}$$

- Interestingly, $N_{\mathrm{eff}} > 3.046$ alleviates 2.5σ tension between **Planck** and **HST** H_0 values:

$$H_0 = 68.6^{+2.3}_{-2.1} \qquad H_{0,N_{\mathbf{eff}}} = 72.1 \pm 3.7 \qquad H_0 = 73.8 \pm 2.4$$

- Sterile neutrinos?

Concluding remarks

A wealth of neutrino experiments!

Abstracts about neutrino experiments submitted to ICHEP 2014 Conference

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ZICOS
NEMO-3
KATRIN NEXT
SOX HOLMES SoLid
INO-ICAL
nEXO CANDLES OPERA Majorana LUNA
AMoRE Daya-Bay Double-Chooz NESSIE
IsoDAR LAGUNA/LBNO MiniTimeCube
MicroBooNE Hyper-Kamiokande LAr1-ND
T2K SuperNEMO LUMINEU GADZOOKS NOvA
MINERvA Super-Kamiokande Borexino ORCA
LUCIFER NA61/SHINE nuSTORM ICARUS
Daedalus KamLAND-Zen EXO-200 SNO+
COBRA GERDA JUNO LBNE
ESS ECHo CUORE
PINGU

Concluding remarks

The life of a neutrino experimentalist

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- Build powerful neutrino sources...

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- Build powerful neutrino sources...

- and massive neutrino detectors...

Concluding remarks

The life of a neutrino experimentalist

- Build powerful neutrino sources...
- and massive neutrino detectors...
- in a low-background environment...

Concluding remarks

The life of a neutrino experimentalist

- Build powerful neutrino sources...
- and massive neutrino detectors...
- in a low-background environment...
- to answer known neutrino questions and be prepared for the unexpected!

Identity

Mixing

Mass ordering

?

Mass scale

Species