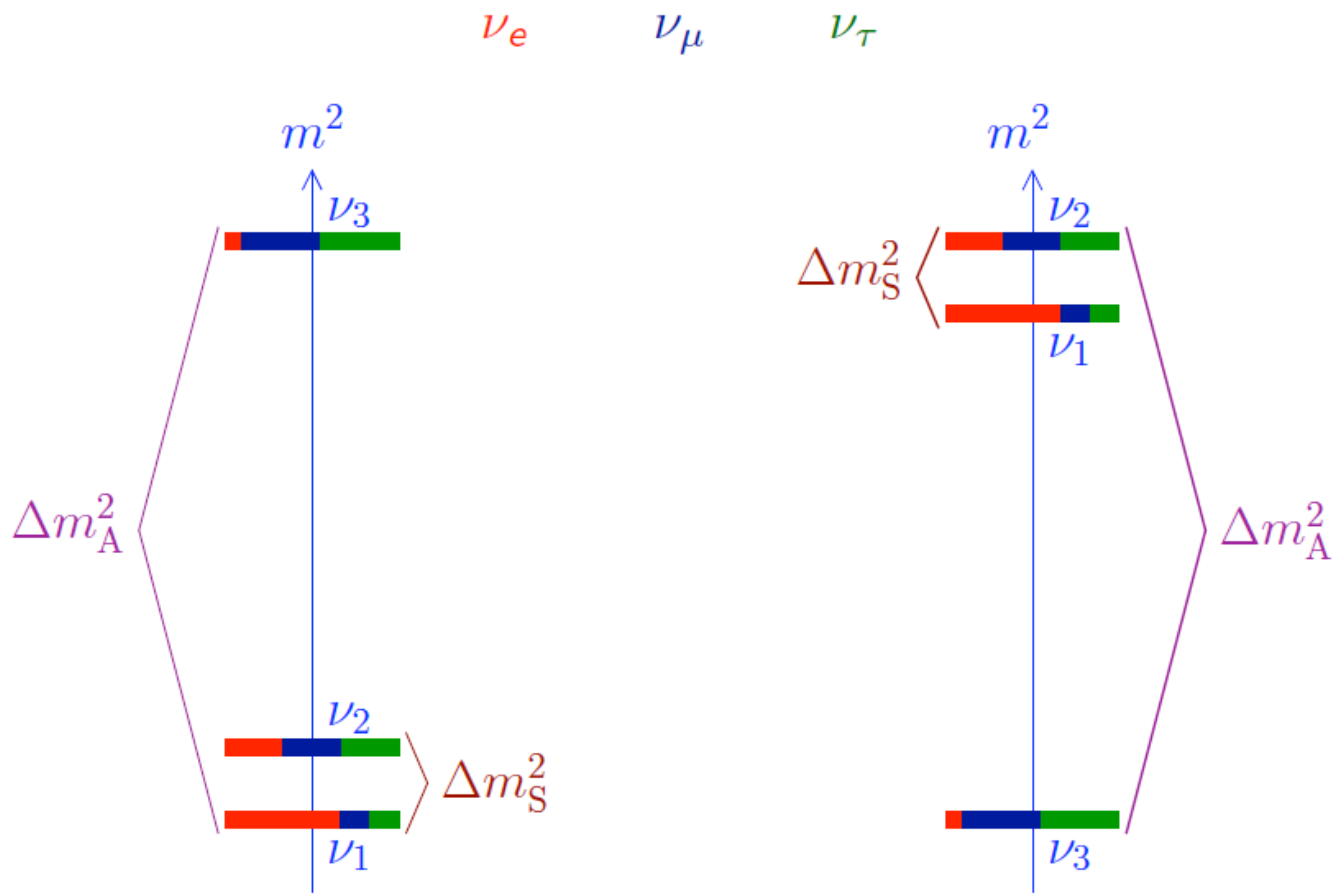
Lecture 1: Direct measurement of neutrino masses

PhD Cycle XXXIII

Three-Neutrino Mixing Paradigm

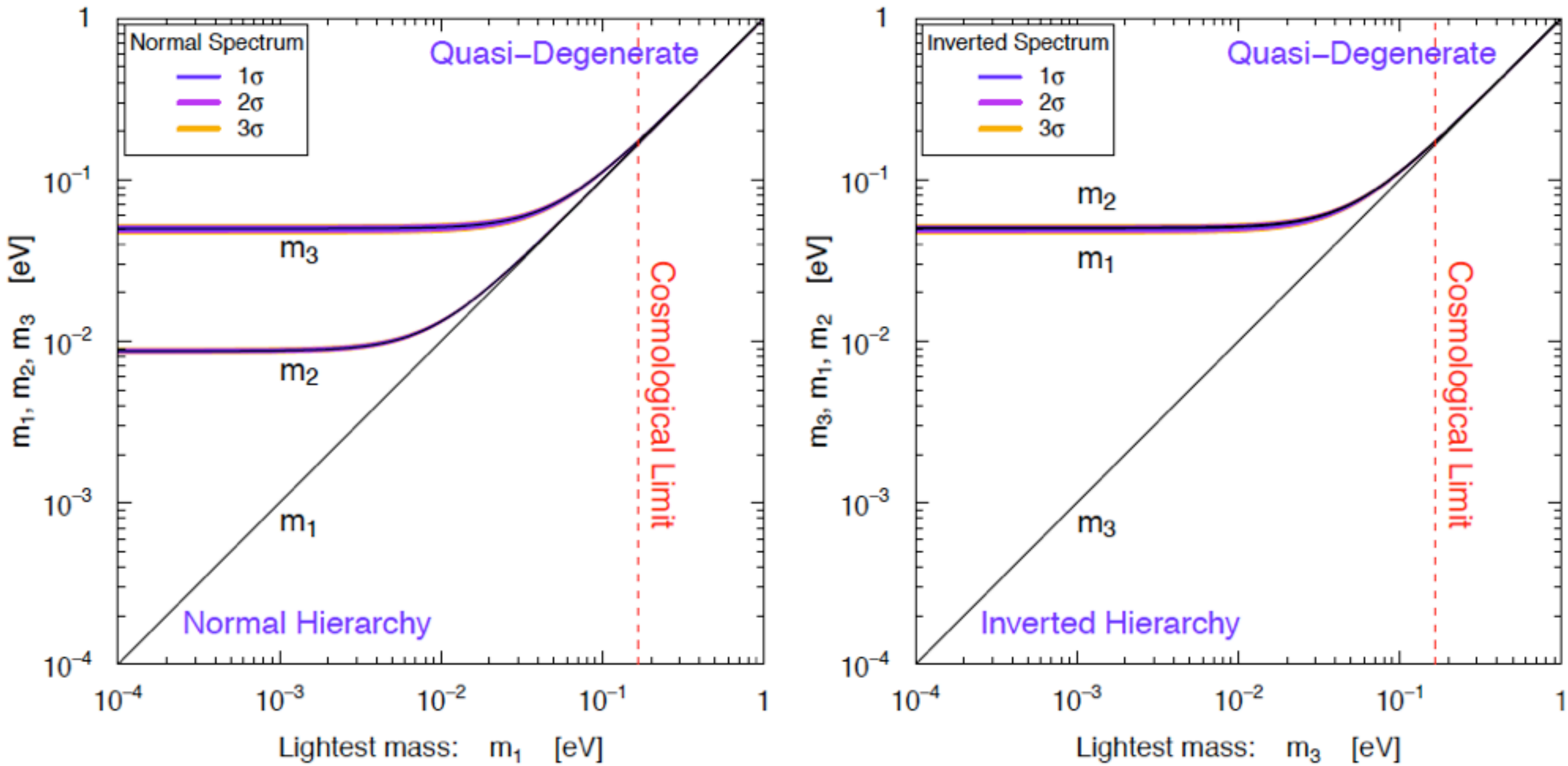


Normal Spectrum

Inverted Spectrum

absolute scale is not determined by neutrino oscillation data

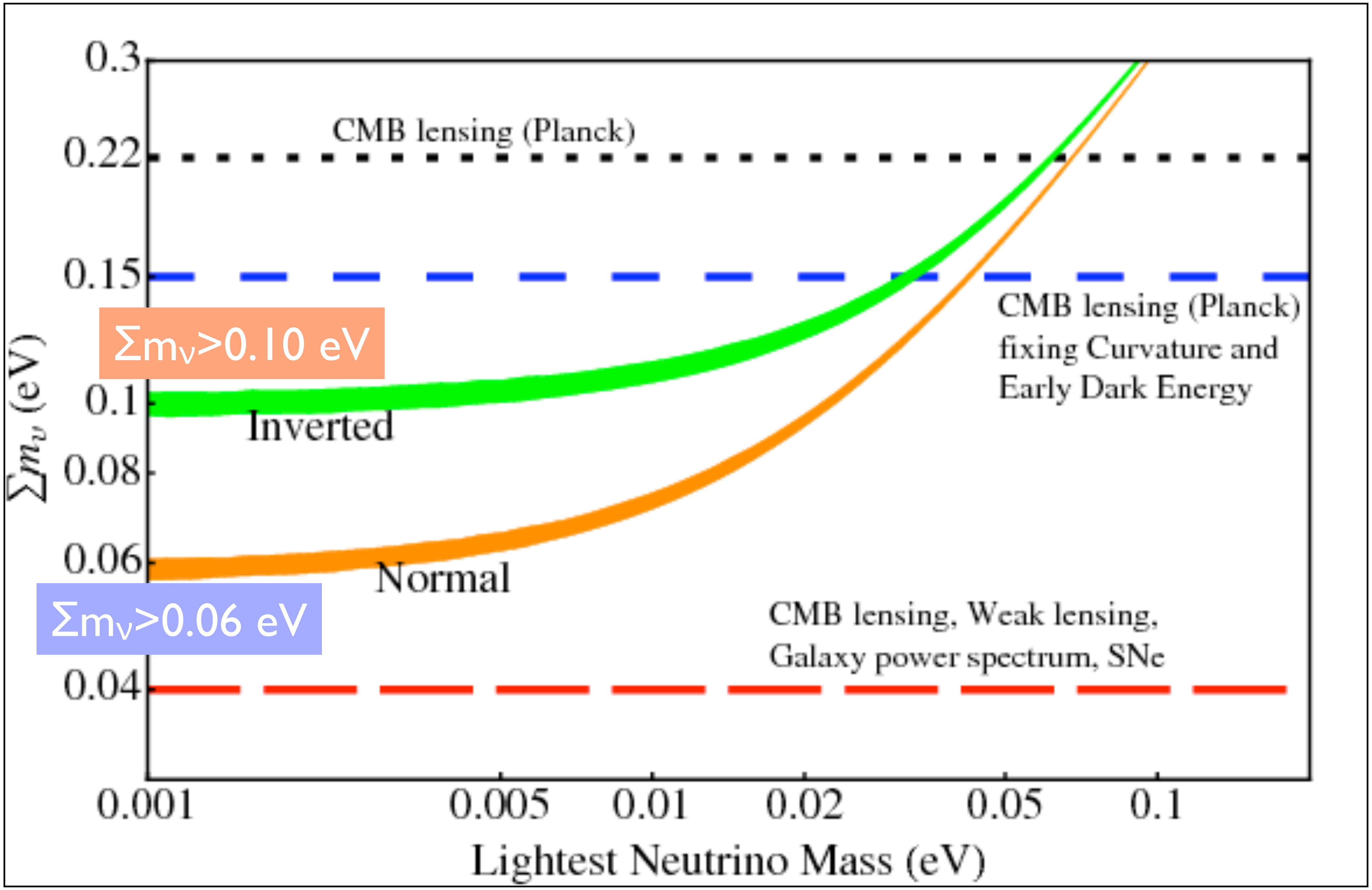
Absolute Values of Neutrino Masses



$$m_2^2 = m_1^2 + \Delta m_{21}^2 = m_1^2 + \Delta m_S^2$$
$$m_3^2 = m_1^2 + \Delta m_{31}^2 = m_1^2 + \Delta m_A^2$$

$$m_1^2 = m_3^2 - \Delta m_{31}^2 = m_3^2 + \Delta m_A^2$$
$$m_2^2 = m_1^2 + \Delta m_{21}^2 \simeq m_3^2 + \Delta m_A^2$$

Quasi-Degenerate for $m_1 \simeq m_2 \simeq m_3 \simeq m_\nu \gg \sqrt{\Delta m_A^2} \simeq 5 \times 10^{-2}\,\text{eV}$



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$$m_2^2 = m_1^2 + \Delta m_{21}^2 \simeq m_3^2 + \Delta m_A^2$$

$\Delta m^2{}_S = (7.6 \pm 0.2) \times 10^{-5}\ eV^2$

$\Delta m^2{}_A = (2.48 \pm 0.06) \times 10^{-3}\ eV^2$

Observables sensitive to m_ν

The absolute mass scale can be measured through:
(numbers on the right are current upper limits)

- tritium beta decay

$$m_\beta \equiv \left[\sum |U_{ei}|^2 m_i^2\right]^{1/2}$$ (2.05 – 2.3 eV @ 95%CL)

- neutrinoless double beta decay

$$m_{\beta\beta} \equiv \left|\sum U_{ei}^2 m_i\right|$$ (0.06 – 0.16 eV @ 90%CL)

- cosmological observations

$$\sum m_\nu \equiv \sum_i m_i$$ (0.2 – 0.7 eV @ 95%CL)

Observables sensitive to m_ν

The absolute mass scale can be measured through:
(numbers on the right are current upper limits)

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TODAY

$$m_\beta \equiv \left[\sum |U_{ei}|^2 m_i^2\right]^{1/2}$$

(2.05 – 2.3 eV @ 95%CL)

- neutrinoless double beta decay

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

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NEXT TIME

Observables sensitive to m_ν

The absolute mass scale can be measured through:
(numbers on the right are current upper limits)

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$$m_{\beta\beta} \equiv \left|\sum U_{ei}^2 m_i\right|$$ (0.06 – 0.16 eV @ 90%CL)

- cosmological observations

LAST LECTURE

$$\sum m_\nu \equiv \sum_i m_i$$ (0.2 – 0.7 eV @ 95%CL)

Direct mass measurements

Beta decay: direct ν_e mass

The most sensitive known method to measure the electron neutrino mass is by observing the electron spectrum in nuclear β-decay

$$\mathcal{N}(A, Z) \to \mathcal{N}(A, Z+1) + e^- + \bar{\nu}_e \,, \tag{14.1}$$

where A and Z are, respectively, the mass and atomic numbers of the parent nucleus.

As we have seen in sections 6.1 and 6.2.1, the electron neutrino, in general, does not have a definite mass, but is a mixture of massive neutrinos. However, following the tradition, in this section we treat the electron neutrino as a mass eigenstate. We will discuss the effects of neutrino mixing in nuclear β-decay in section 14.1.1.

The differential decay rate in allowed[74] β-decays is given by

$$\frac{d\Gamma}{dE_e} = \frac{G_F^2 \, m_e^5}{2\,\pi^3} \cos^2\theta_C \, |\mathcal{M}|^2 \, F(Z, E_e) \, E_e \, p_e \, E_\nu \, p_\nu \,, \tag{14.2}$$

where θ_C is the Cabibbo angle, $\mathcal{M}$ is the nuclear matrix element, E_e (E_ν) and p_e (p_ν) are the electron (neutrino) energy and momentum, and $F(Z, E_e)$ is the Fermi

...

the surrounding electrons). The two factors $E_i \, p_i$ in eqn (14.2), with $i = e, \nu$, come from the phase-space factor of the final state: $d^3 p_i = p_i^2 \, dp_i \, d\cos\theta_i \, d\phi_i = p_i \, E_i \, dE_i \, d\cos\theta_i \, d\phi_i$, where θ_i and ϕ_i are the polar angular coordinates of $\vec{p}_i$.

Fundamentals of Neutrino Physics and Astrophysics

by: Carlo Giunti and Chung W. Kim, Oxford UP 2007

massless. On the other hand, if the electron neutrino has a mass m_{ν_e}, the maximal kinetic energy of the electron is

$$T_{\max} = Q_\beta - m_{\nu_e} \tag{14.5}$$

Since the neutrino momentum is given by

$$p_\nu = \sqrt{E_\nu^2 - m_{\nu_e}^2} = \sqrt{(Q_\beta - T)^2 - m_{\nu_e}^2}\,, \tag{14.6}$$

the differential decay rate in eqn (14.2) can be written, for $T \leq T_{\max}$, as[75]

$$\frac{\mathrm{d}\Gamma}{\mathrm{d}T} = \frac{G_F^2\, m_e^5}{2\,\pi^3} \cos^2\theta_C\, |\mathcal{M}|^2\, F(Z, E_e)\, E_e\, p_e\, (Q_\beta - T) \sqrt{(Q_\beta - T)^2 - m_{\nu_e}^2}\,, \tag{14.8}$$

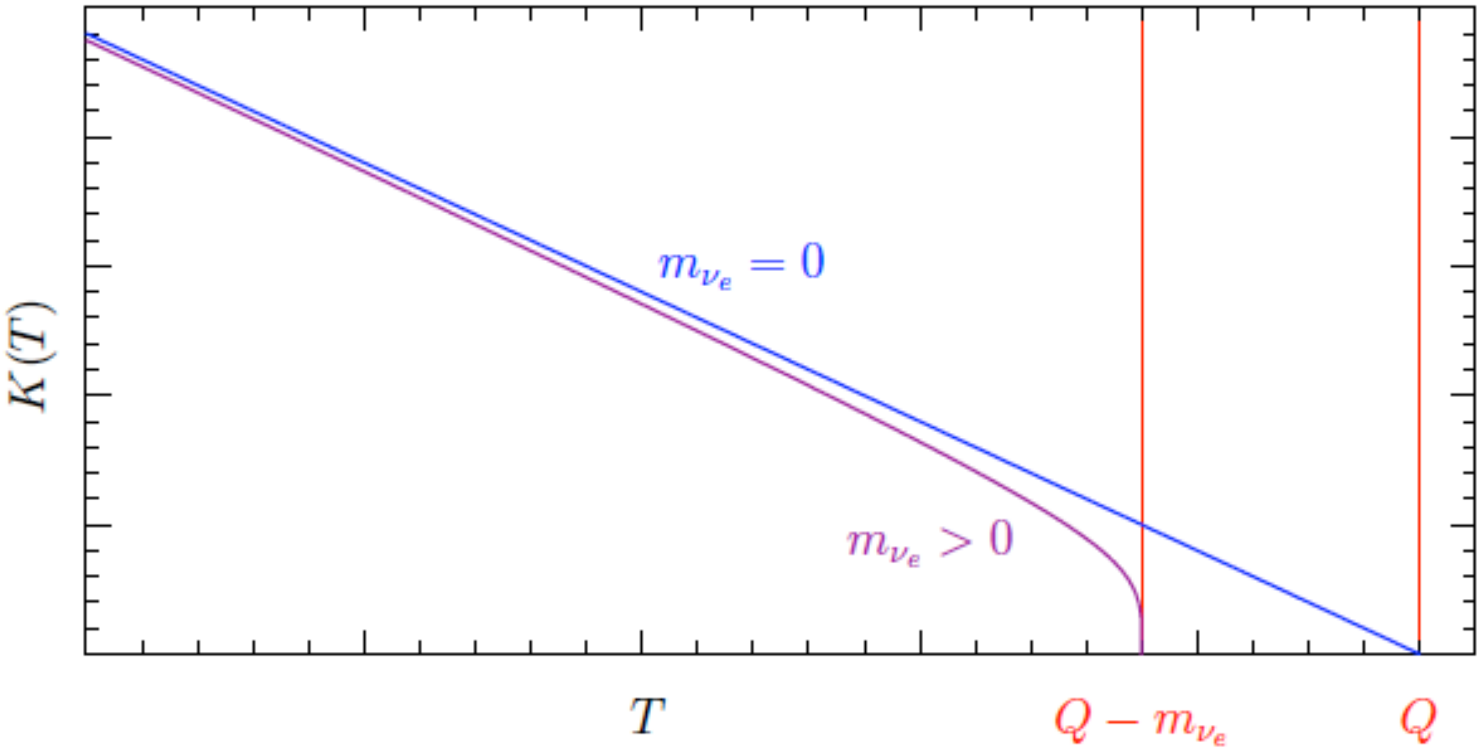
➡ What we measure:

Kurie plot

$$K(T) = \sqrt{\frac{\mathrm{d}\Gamma/\mathrm{d}T}{\frac{(\cos\vartheta_C\, G_F)^2}{2\pi^3}\, |\mathcal{M}|^2\, F(E)\, pE}} = \left[(Q - T)\sqrt{(Q - T)^2 - m_{\nu_e}^2}\right]^{1/2}$$

Kurie plot

$$K(T) = \sqrt{\frac{d\Gamma/dT}{\frac{(\cos\vartheta_C G_F)^2}{2\pi^3} |\mathcal{M}|^2 F(E)\, pE}} = \left[(Q-T)\sqrt{(Q-T)^2 - m_{\nu_e}^2}\right]^{1/2}$$



$m_{\nu_e} < 2.2\,\text{eV}$ (95% C.L.)

Mainz & Troitsk

[Weinheimer, hep-ex/0210050]

future: KATRIN

[www.katrin.kit.edu]

sensitivity: $m_{\nu_e} \simeq 0.2\,\text{eV}$

C. Giunti — Neutrino Mass: Overview of $\beta\beta_{0\nu}$, Cosmology and Direct Measurements — 14 May 2012 — 4/17

The mass is extracted from a fit to the end-point

Pros and cons

- **+** : This method relies **purely** on 3-body kinematics, without any assumption on the nature of the **ν** (e.g. Dirac/Majorana)
- **-** : statistics, especially at the end point:

end-point of the electron spectrum is that very few events occur near the end-point. We can estimate the relative number of events occurring in an interval of energy ΔT below the end-point as follows. Below the end-point we have

$$T \simeq Q_\beta \quad \Longrightarrow \quad \begin{cases} E_e \simeq Q_\beta + m_e \\ p_e = \sqrt{E_e^2 - m_e^2} \simeq \sqrt{Q_\beta\,(Q_\beta + 2\,m_e)}\,. \end{cases} \tag{14.9}$$

Ignoring the neutrino mass and the Fermi function, we have

$$\left.\frac{\mathrm{d}\Gamma}{\mathrm{d}T}\right|_{\substack{T\simeq Q_\beta \\ m_{\nu_e}=0}} \propto (Q_\beta + m_e)\,\sqrt{Q_\beta\,(Q_\beta + 2\,m_e)}\,(Q_\beta - T)^2\,, \tag{14.10}$$

and

$$\int_{Q_\beta-\Delta T}^{Q_\beta} \frac{\mathrm{d}\Gamma}{\mathrm{d}T}\,\mathrm{d}T \propto (Q_\beta + m_e)\,\sqrt{Q_\beta\,(Q_\beta + 2\,m_e)}\,(\Delta T)^3\,. \tag{14.11}$$

The total number of events is proportional to

$$\int_0^{Q_\beta} \frac{\mathrm{d}\Gamma}{\mathrm{d}T}\,\mathrm{d}T \propto \int_0^{Q_\beta} (T + m_e)\,\sqrt{T\,(T + 2m_e)}\,(Q_\beta - T)^2\,\mathrm{d}T\,, \tag{14.12}$$

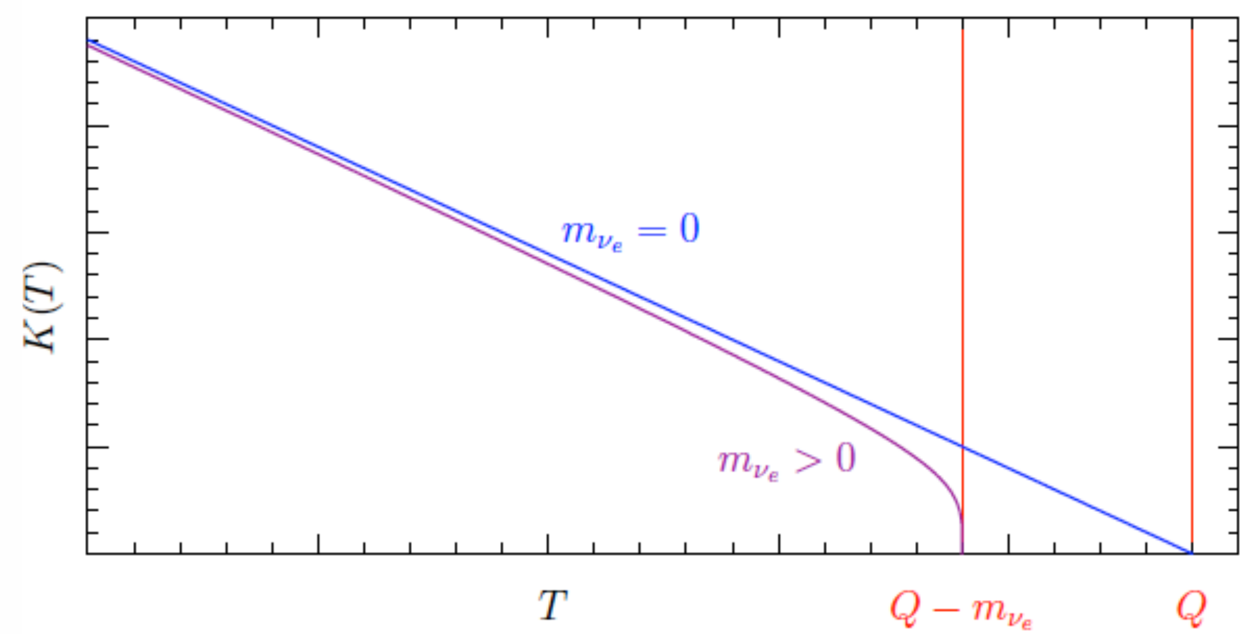
where we have neglected again the Fermi function and the neutrino mass. Since we are interested in an order-of-magnitude estimate, we consider $Q_\beta \gg m_e$, which leads to the approximation

$$\int_0^{Q_\beta} \frac{\mathrm{d}\Gamma}{\mathrm{d}T}\,\mathrm{d}T \propto Q_\beta^5\,. \tag{14.13}$$

Thus, the relative number of events occurring in an interval of energy ΔT below the end-point is given by

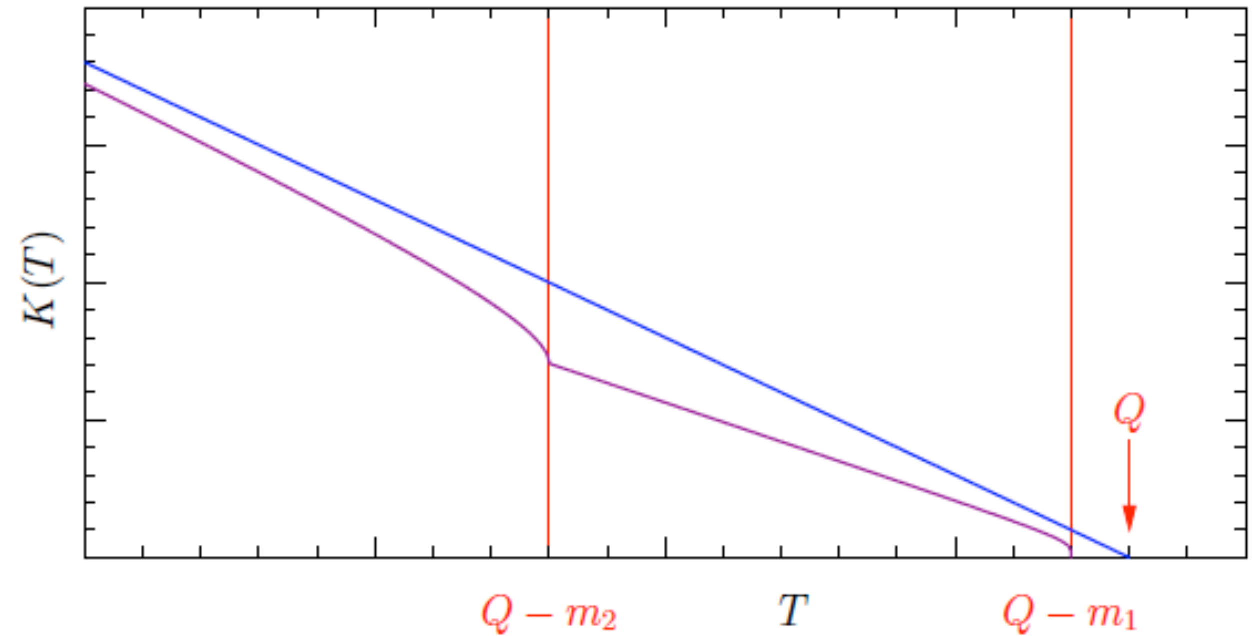
$$\frac{n(\Delta T)}{n} \propto \left(\frac{\Delta T}{Q_\beta}\right)^3\,. \tag{14.14}$$

One can obtain the same result considering $Q_\beta \ll m_e$. From eqn (14.14) it is clear that in order to ...



Added complication: mix

Neutrino Mixing $\Longrightarrow K(T) = \left[(Q-T) \sum_k |U_{ek}|^2 \sqrt{(Q-T)^2 - m_k^2} \right]^{1/2}$



analysis of data is different from the no-mixing case: $2N-1$ parameters $\left(\sum_k |U_{ek}|^2 = 1 \right)$

if experiment is not sensitive to masses $(m_k \ll Q-T)$

effective mass: $$m_\beta^2 = \sum_k |U_{ek}|^2 m_k^2$$

$$K^2 = (Q-T)^2 \sum_k |U_{ek}|^2 \sqrt{1 - \frac{m_k^2}{(Q-T)^2}} \simeq (Q-T)^2 \sum_k |U_{ek}|^2 \left[1 - \frac{1}{2} \frac{m_k^2}{(Q-T)^2} \right]$$

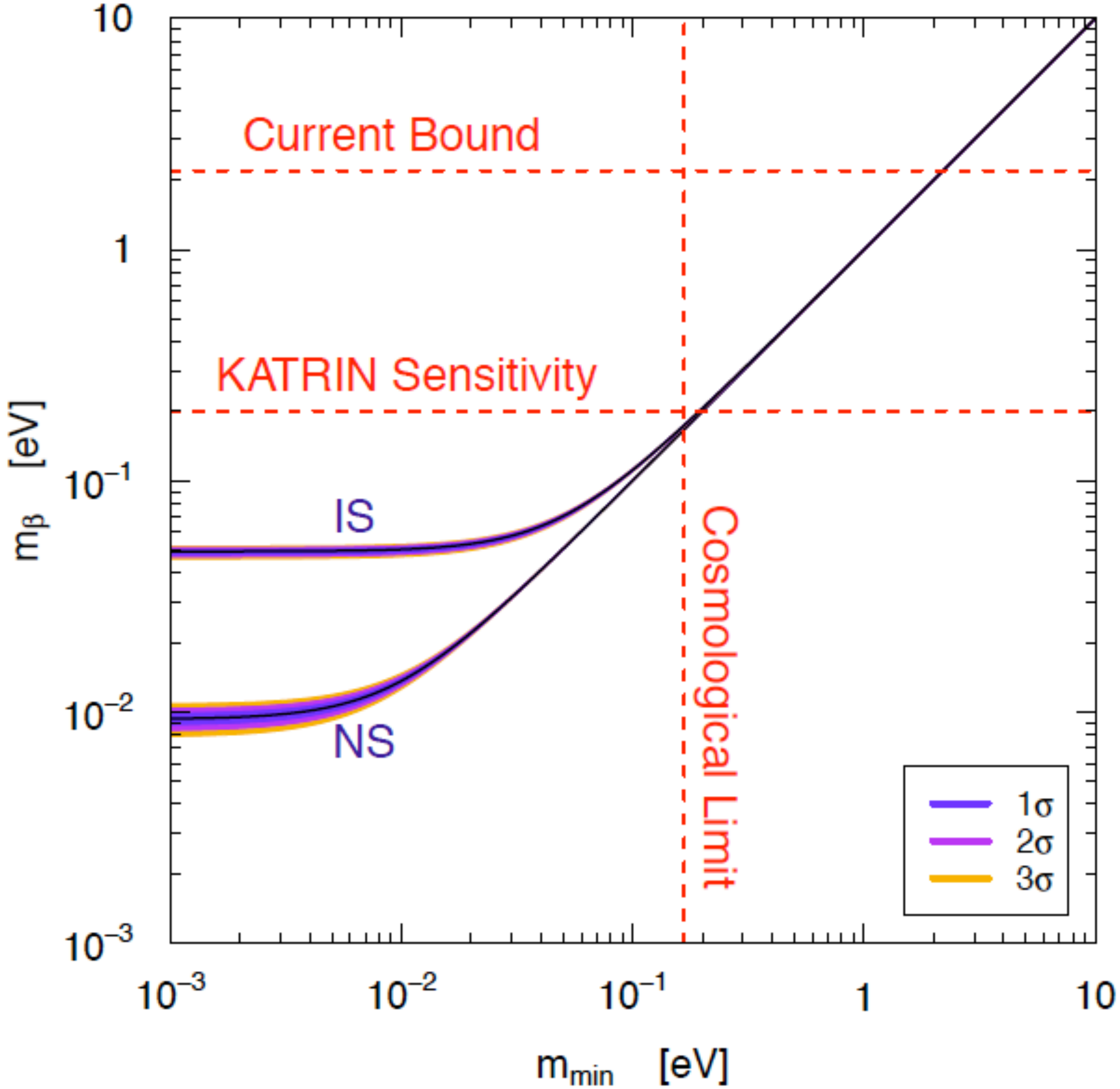
$$= (Q-T)^2 \left[1 - \frac{1}{2} \frac{m_\beta^2}{(Q-T)^2} \right] \simeq (Q-T) \sqrt{(Q-T)^2 - m_\beta^2}$$

Kurie plot

$$K(T) = \sqrt{\frac{d\Gamma/dT}{\frac{(\cos\vartheta_C G_F)^2}{2\pi^3} |\mathcal{M}|^2 F(E)\, pE}} = \left[(Q-T) \sqrt{(Q-T)^2 - m_{\nu_e}^2} \right]^{1/2}$$

Predictions of 3ν-Mixing Paradigm

$$m_\beta^2 = |U_{e1}|^2\, m_1^2 + |U_{e2}|^2\, m_2^2 + |U_{e3}|^2\, m_3^2$$



- **Quasi-Degenerate:**
  $m_\beta^2 \simeq m_\nu^2 \sum_k |U_{ek}|^2 = m_\nu^2$
- **Inverted Hierarchy:**
  $m_\beta^2 \simeq (1 - s_{13}^2)\Delta m_A^2 \simeq \Delta m_A^2$
- **Normal Hierarchy:**
  $m_\beta^2 \simeq s_{12}^2 c_{13}^2 \Delta m_S^2 + s_{13}^2 \Delta m_A^2$
  $\simeq 2 \times 10^{-5} + 6 \times 10^{-5}\,\text{eV}^2$
- If $m_\beta \lesssim 4 \times 10^{-2}\,\text{eV}$
  $\Downarrow$
  Normal Spectrum

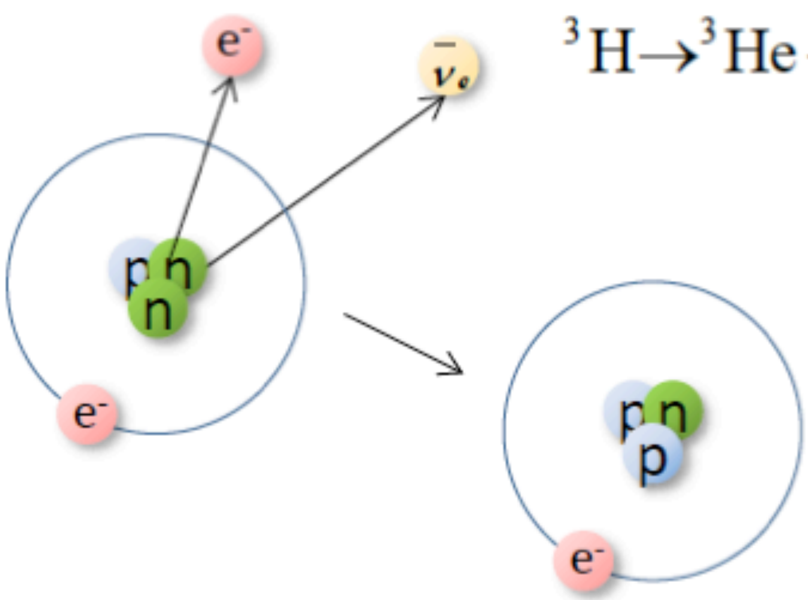
Remember: $\sqrt{\Delta m_A^2} \simeq 5 \times 10^{-2}\,\text{eV}$

Beta decay of ^3H

$$Q = M_{^3\mathrm{H}} - M_{^3\mathrm{He}} - m_e = 18.58\,\mathrm{keV}$$

- $\tau_{1/2} \cong 12.3$ years ($4*10^8$ atoms for 1 Bq)

reasonably short lifetime

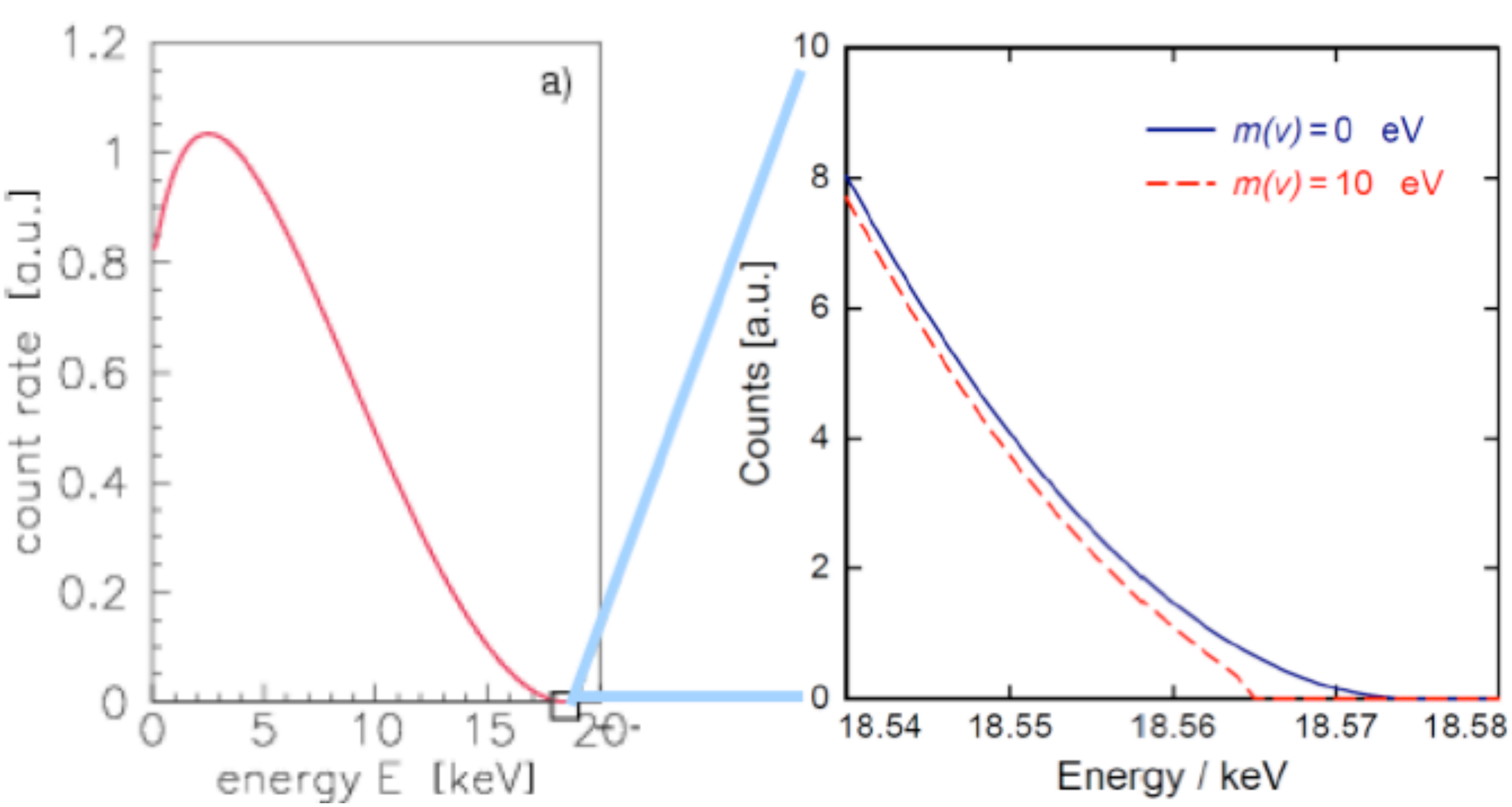


$$^3\mathrm{H} \rightarrow {}^3\mathrm{He} + e^- + \bar{\nu}_e$$

^{3}H: chosen because:

✓ low Q ⇒ enhanced $\frac{n(\Delta T)}{n} \propto \left(\frac{\Delta T}{Q_\beta}\right)^3$

✓ simple atomic structure (small uncertainties on $|\mathcal{M}|^2 F(Z, E_e)$)



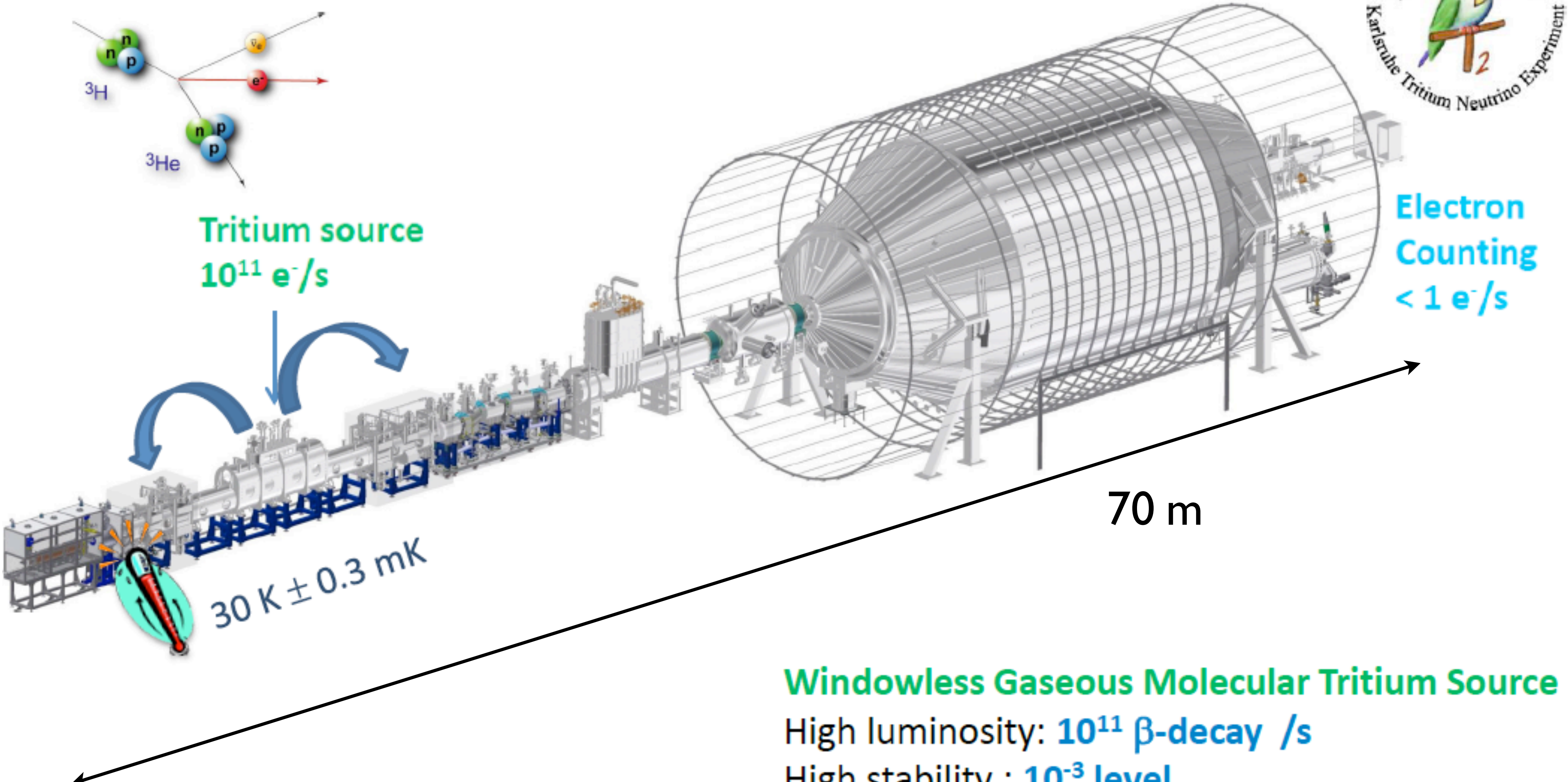
Only a small fraction of events in the last eV below the endpoint: **$2 * 10^{-13}$**

Triutium is present as **bi-atomic molecules**

TRITIUM

The KATRIN experiment

The source should be transparent to the emitted electrons: gas or thin layers



Windowless Gaseous Molecular Tritium Source

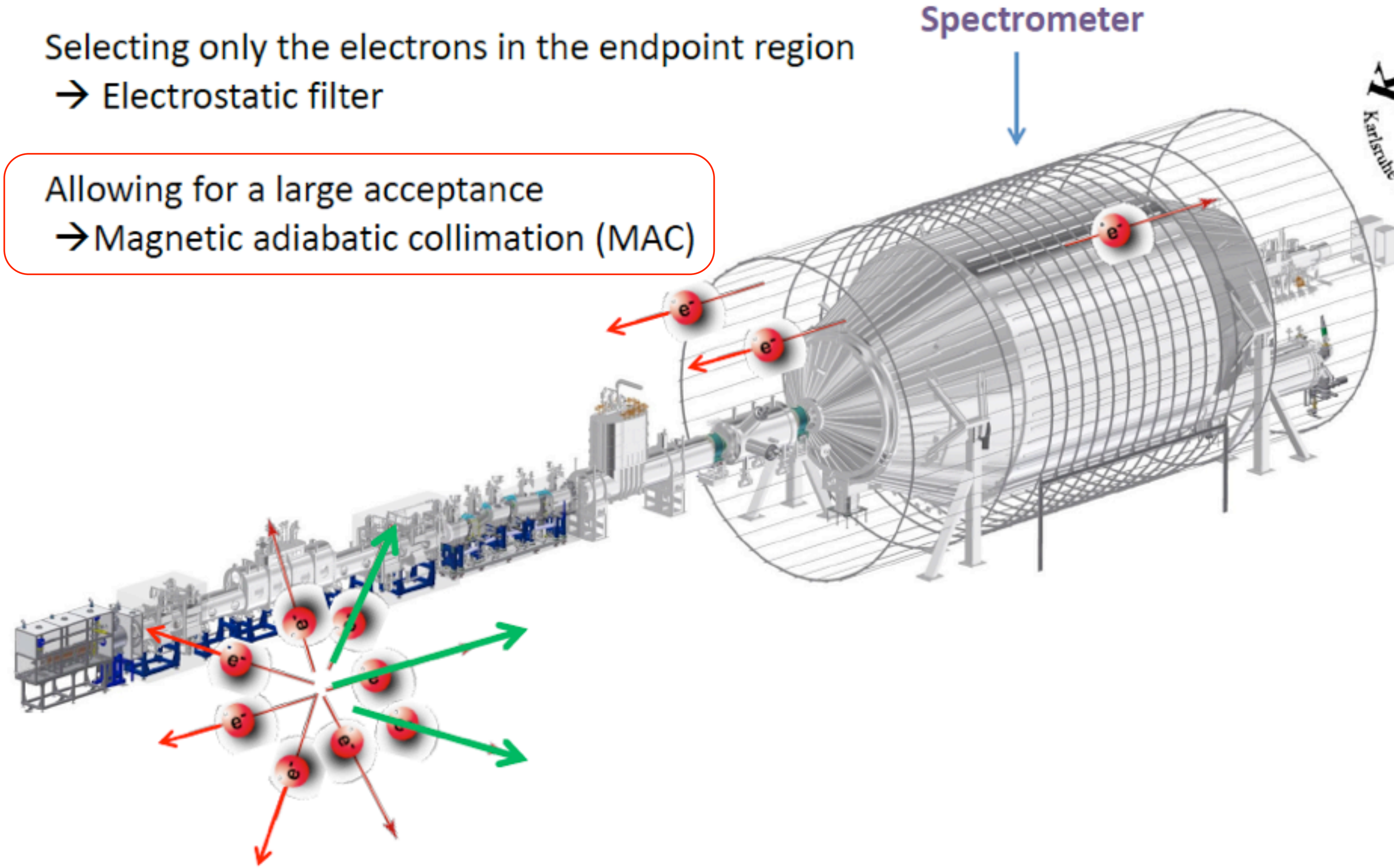
High luminosity: 10^{11} β-decay /s

High stability : 10^{-3} level

The KATRIN experiment

Selecting only the electrons in the endpoint region
→ Electrostatic filter

Allowing for a large acceptance
→ Magnetic adiabatic collimation (MAC)



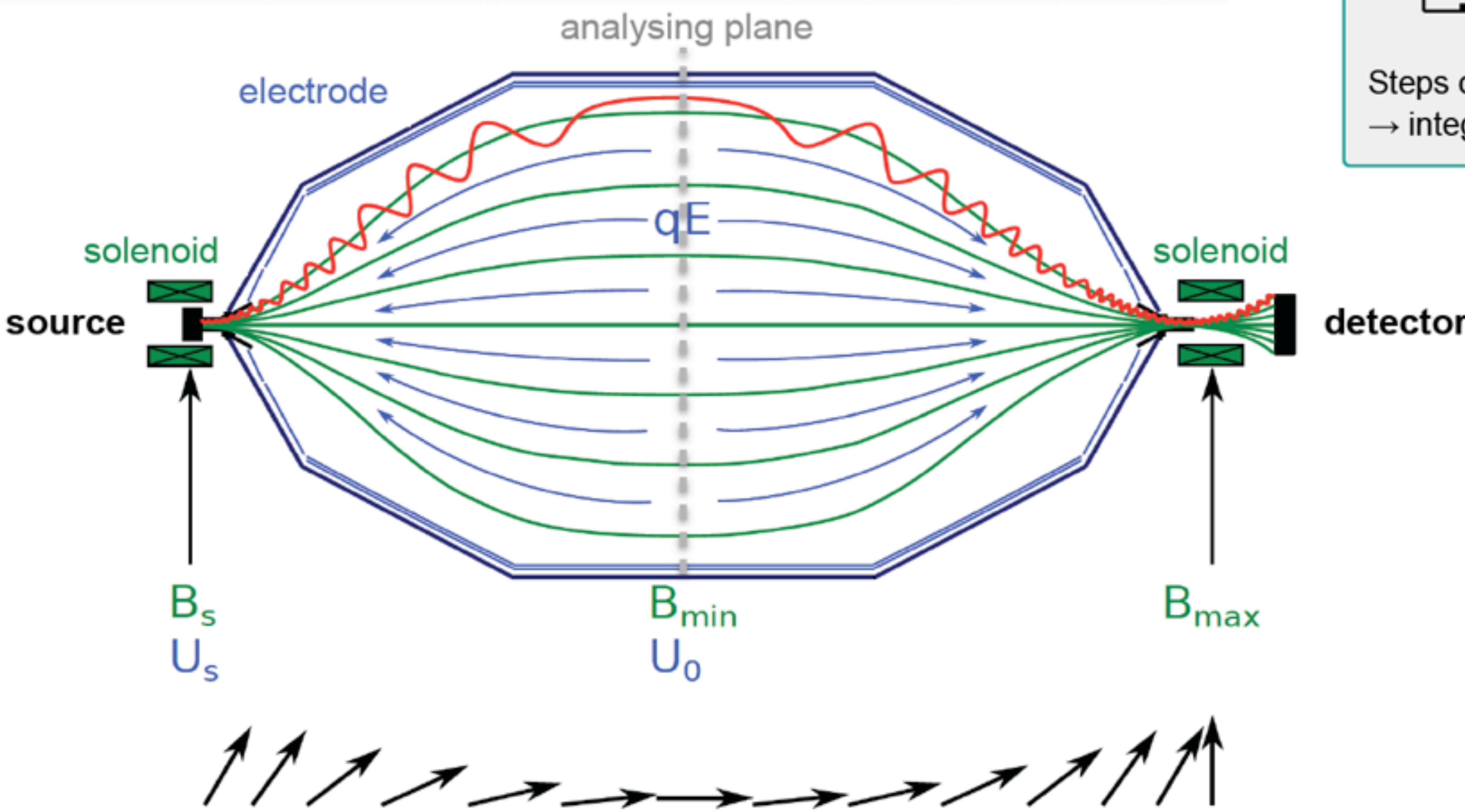
MAC-E filter principle allows for < 1 eV energy cut off

High-resolution β spectrometer

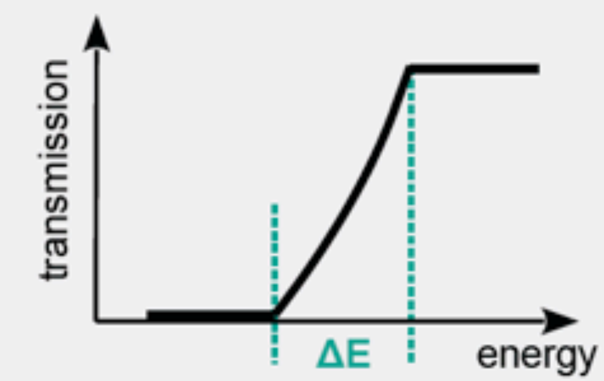
Magnetic Adiabatic Collimation & Electrostatic Filter

- ➜ integrating electrostatic filter ($E_{kin} > eU_0$)
- ➜ "clean" (analytic) response function
- ➜ $\Delta E < 1$ eV at 18.6 keV

$$\frac{\Delta E}{E} = \frac{B_{\mathrm{min}}}{B_{\mathrm{max}}}$$

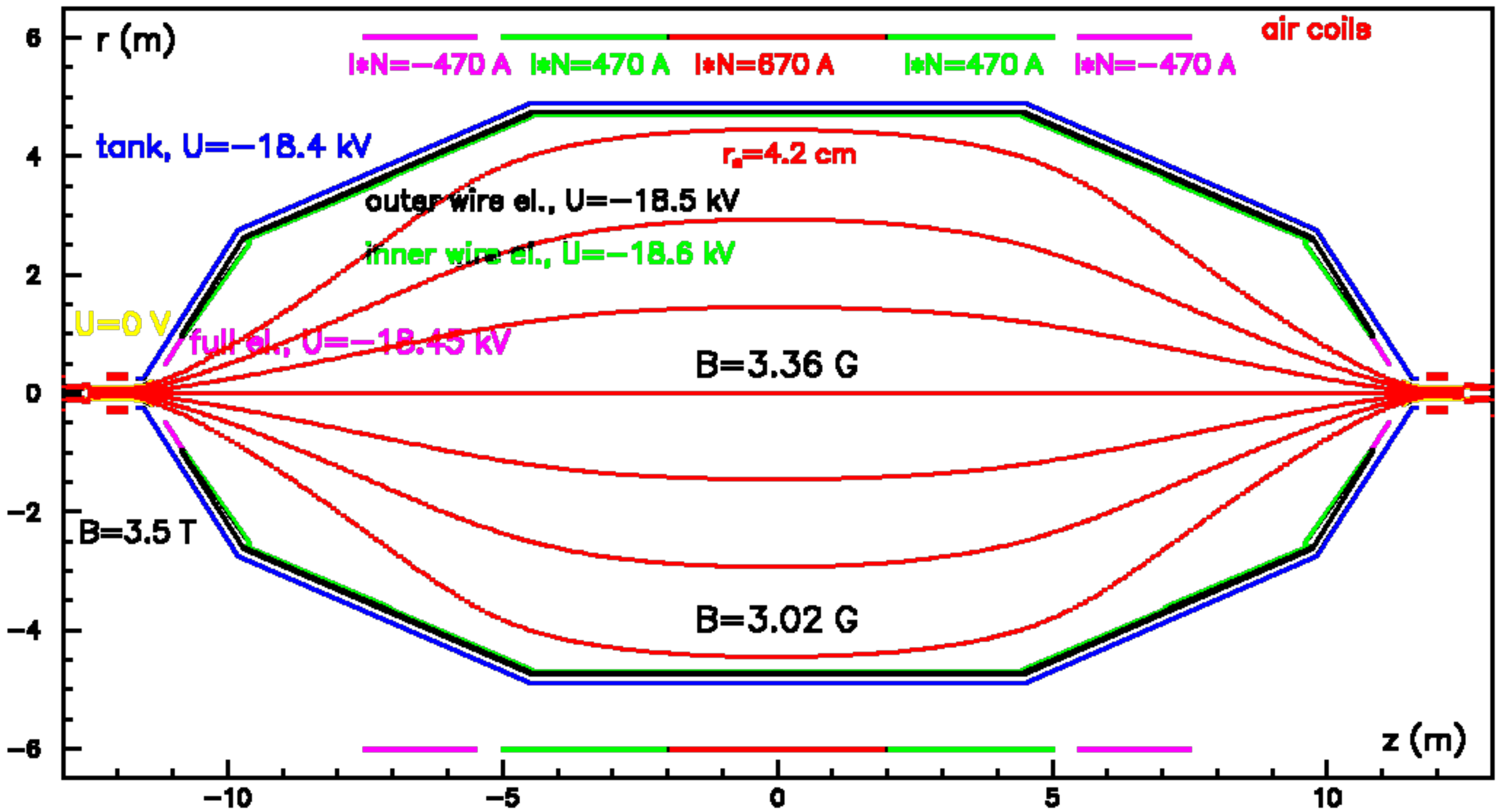


Sharp high-pass filter:

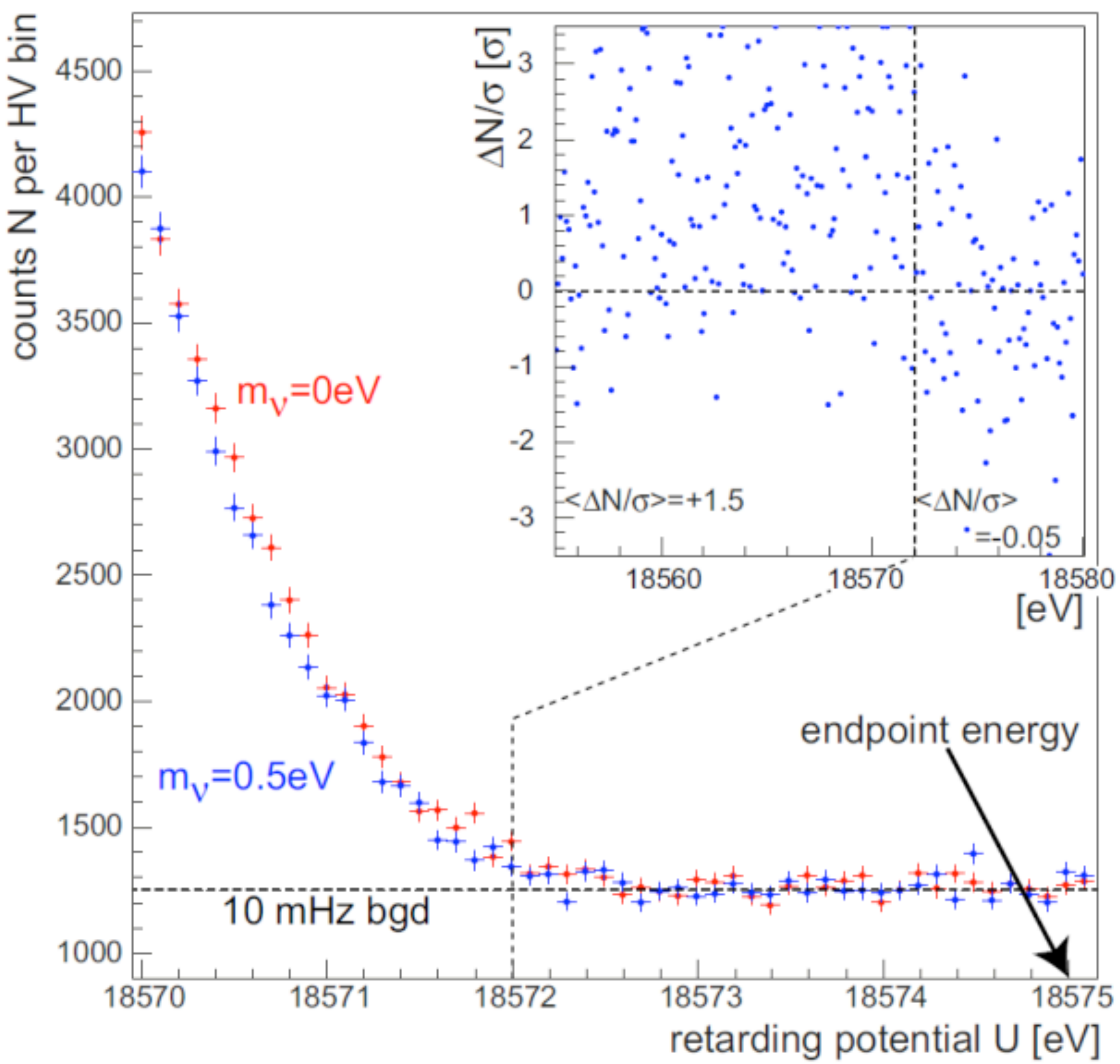


Steps of filter potential
→ integrated β spectrum

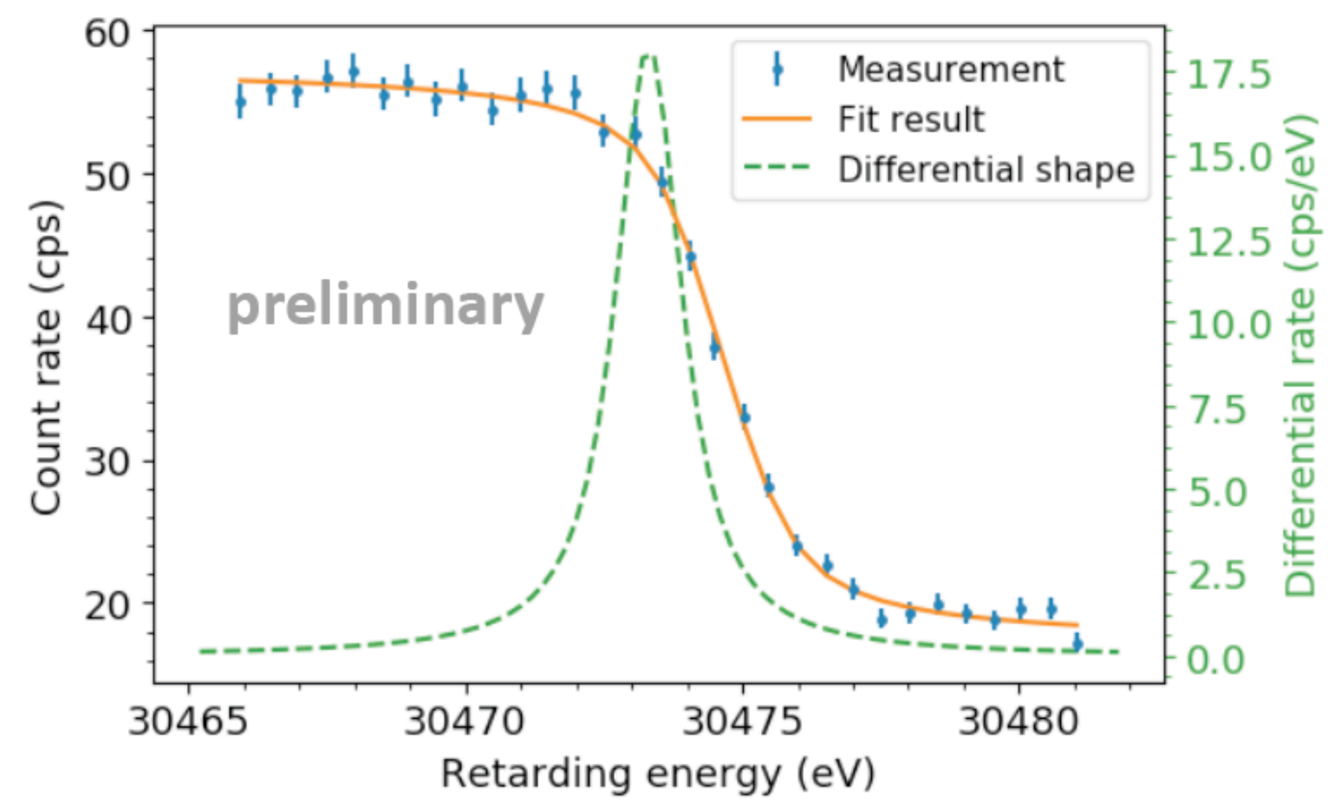
[Beamson et al. 1980; Kruit & Read 1983; **Lobashev 1985; Picard et al. 1992**]



- The larger the spectrometer, the smaller (more "adiabatic") the gradient of the e- momentum
- ~constant along B lines
- spectrometer acts as an **integrating** high-energy pass filter by virtue of E field (threshold effect)



L_3-32 line (30.47 keV, Γ ~1.4 eV)



Example with a real 2017 pre-run with ^{83}Kr de-excitation lines

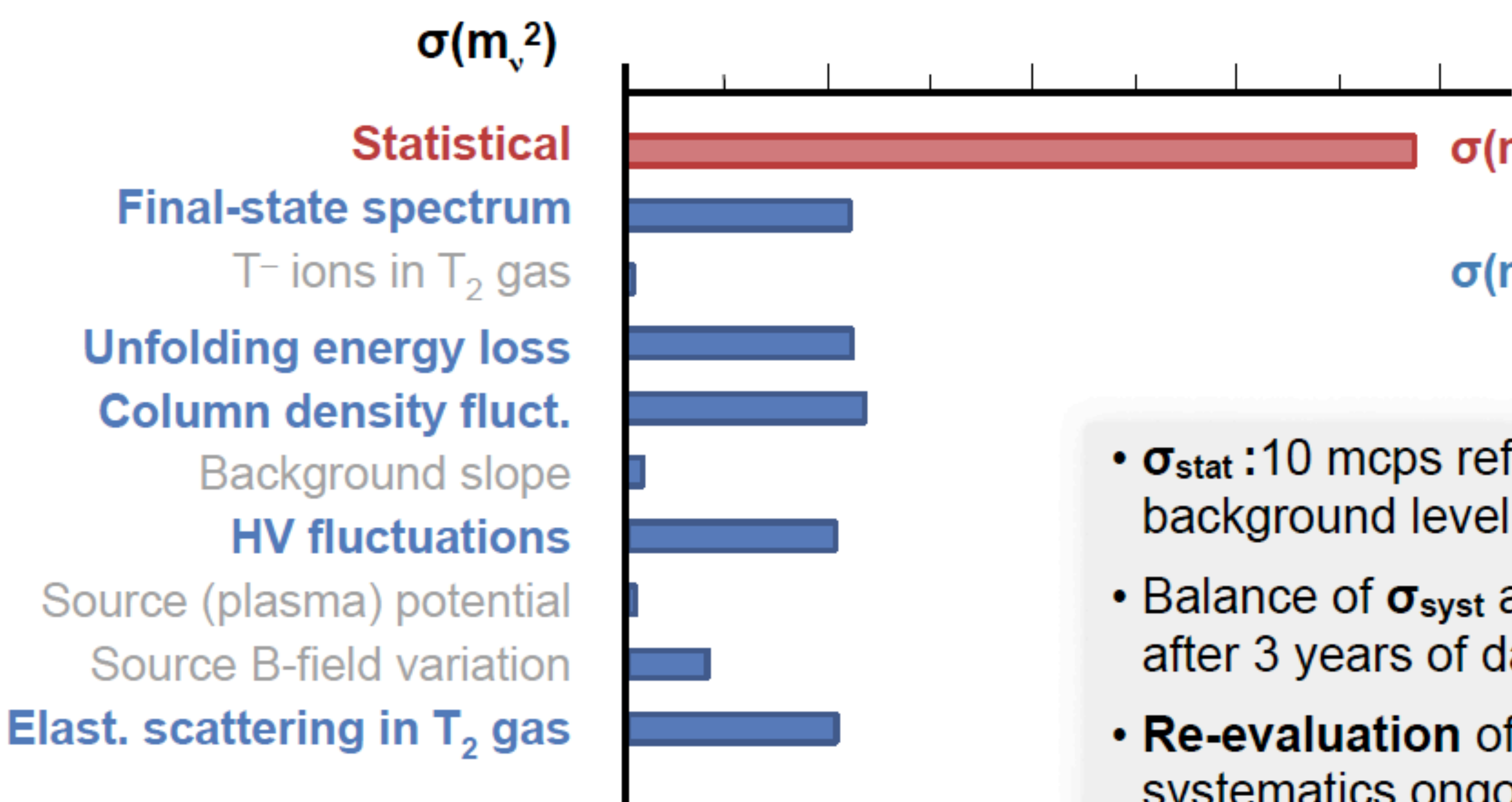
- **Integrated** e- spectrum
- Will measure N(e-) vs electric potential applied
- Measurement up to 30 eV below end-point (Q-value)

Main sources of background:

- electrons produced by ionization in the residual gas: veto system in place
- electrons from interactions of cosmic rays: veto system in place
- γ-rays from natural radioactivity emanating from material surrounding the detector and from the detector itself: this is still open (^{210}Pb on spectrometer walls)

Backgrounds vary over a large range of energies, β-electrons concentrated.
Rely on accurate E determination to separate and reject bkgs

KATRIN's uncertainty budget (design sensitivity, ~2004):



$\sigma(m_\nu^2)_{stat} = 0.018\ eV^2$

$\sigma(m_\nu^2)_{syst} = 0.017\ eV^2$

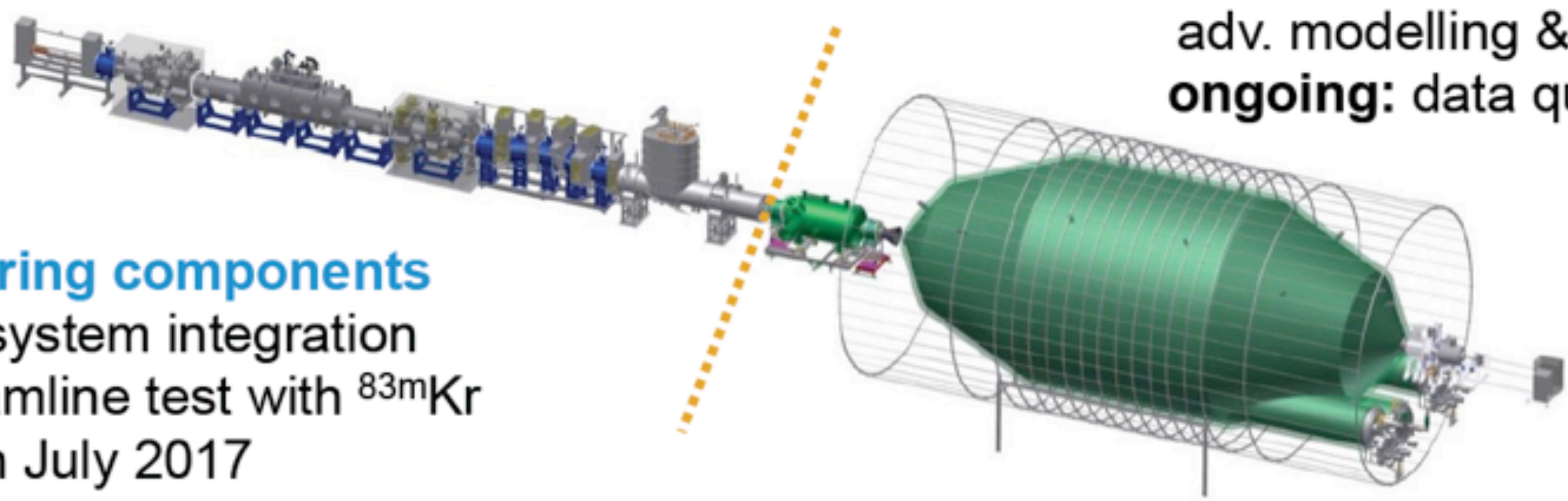
- σ_{stat} : 10 mcps reference background level
- Balance of σ_{syst} and total σ_{stat} after 3 years of data
- **Re-evaluation** of individual systematics ongoing during system characterisation

Summary & outlook

- β decay allows model-independent, **direct** access to neutrino mass scale
- KATRIN will exhaust degenerate mass regime: **200 meV** (90% CL for 5 yrs of running); reaching sub-eV sensitivity with first few weeks of data
- Interesting physics potential beyond m_ν: eV and keV scale sterile ν, RH currents, LIV, …

Preparing KATRIN for neutrino-mass measurements:

Analysis chain
adv. modelling & analysis framework
ongoing: data quality filters, blinding



Tritium-bearing components
- now: final system integration
- overall beamline test with ^{83m}Kr achieved in July 2017
- **next:** inactive commissioning with D_2, then $D_2(T_2)$

Spectrometer & detector section
2 successful commissioning phases already done
ongoing: background investigations

➜ **First tritium runs starting in 2018, inauguration ceremony: 11 June 2018**

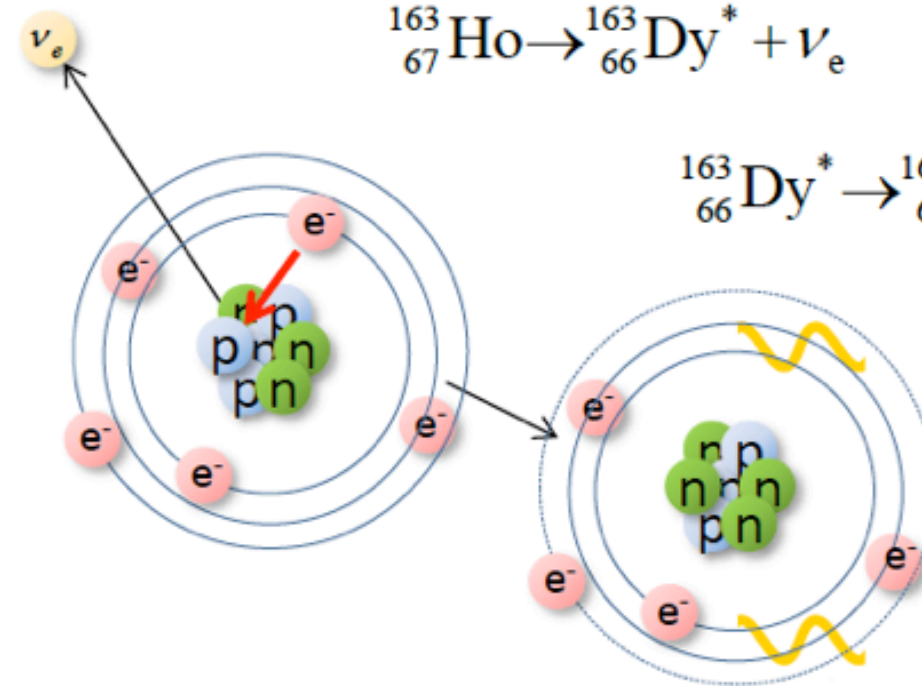
Electron capture in ^{163}Ho

Atomic de-excitation:

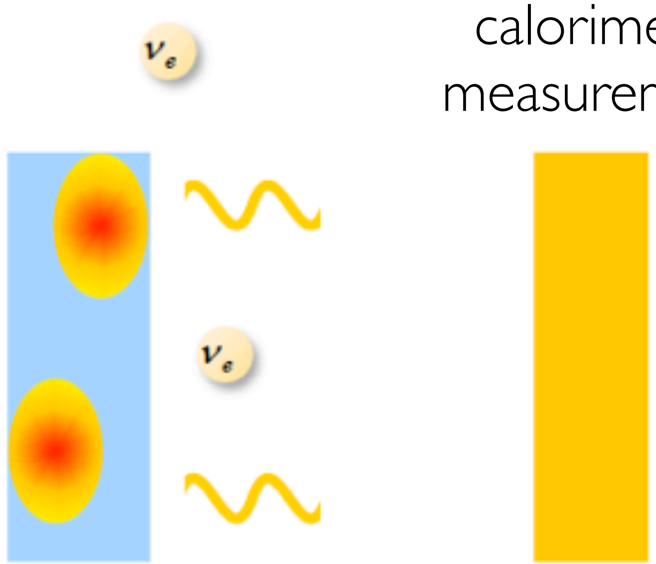
- **X-ray emission**
- Auger electrons
- Coster-Kronig transitions

$$^{163}_{67}\mathrm{Ho} \rightarrow ^{163}_{66}\mathrm{Dy}^* + \nu_e$$

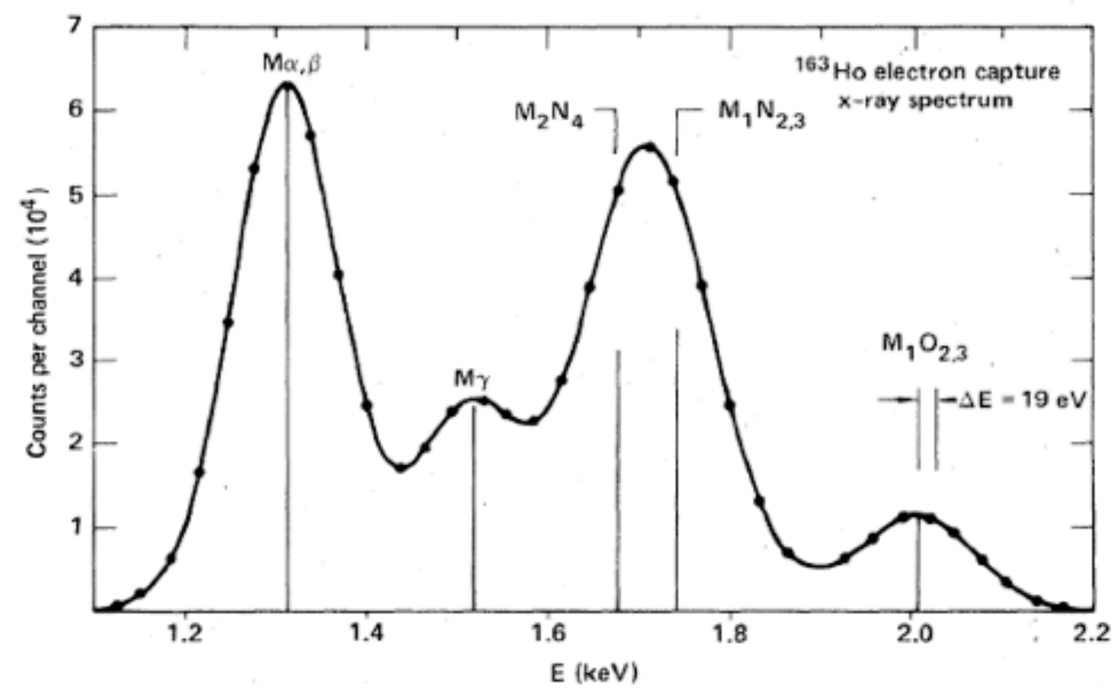
$$^{163}_{66}\mathrm{Dy}^* \rightarrow ^{163}_{66}\mathrm{Dy} + E_C$$



calorimetric measurements



Source ν_e Detector



Volume 118B, number 4, 5, 6 PHYSICS LETTERS 9 December 1982

CALORIMETRIC MEASUREMENTS OF ^{163}HOLMIUM DECAY AS TOOLS TO DETERMINE THE ELECTRON NEUTRINO MASS

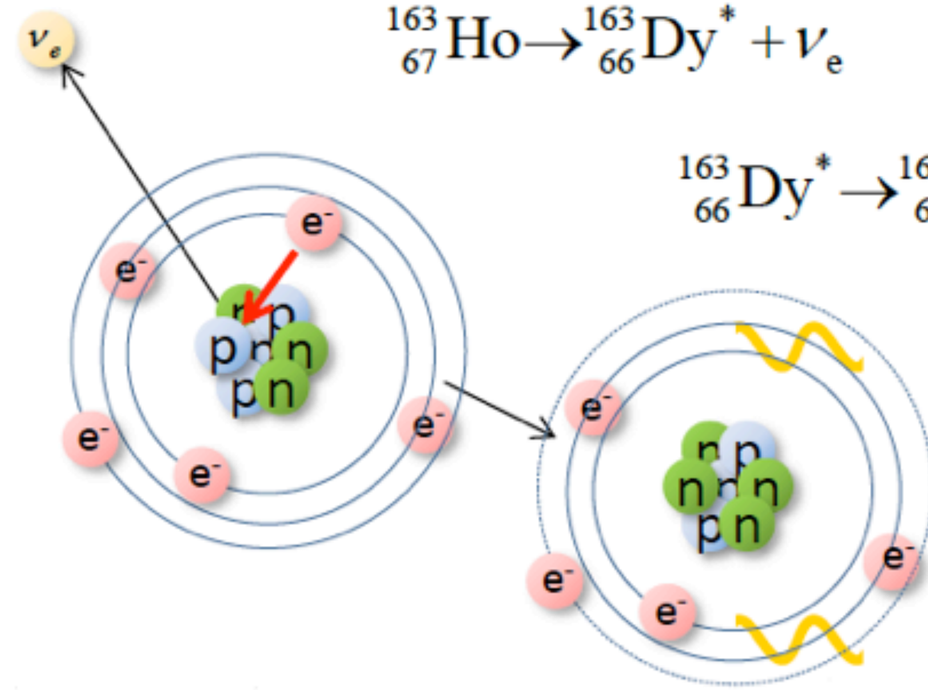
A. DE RÚJULA and M. LUSIGNOLI [1]
CERN, Geneva, Switzerland

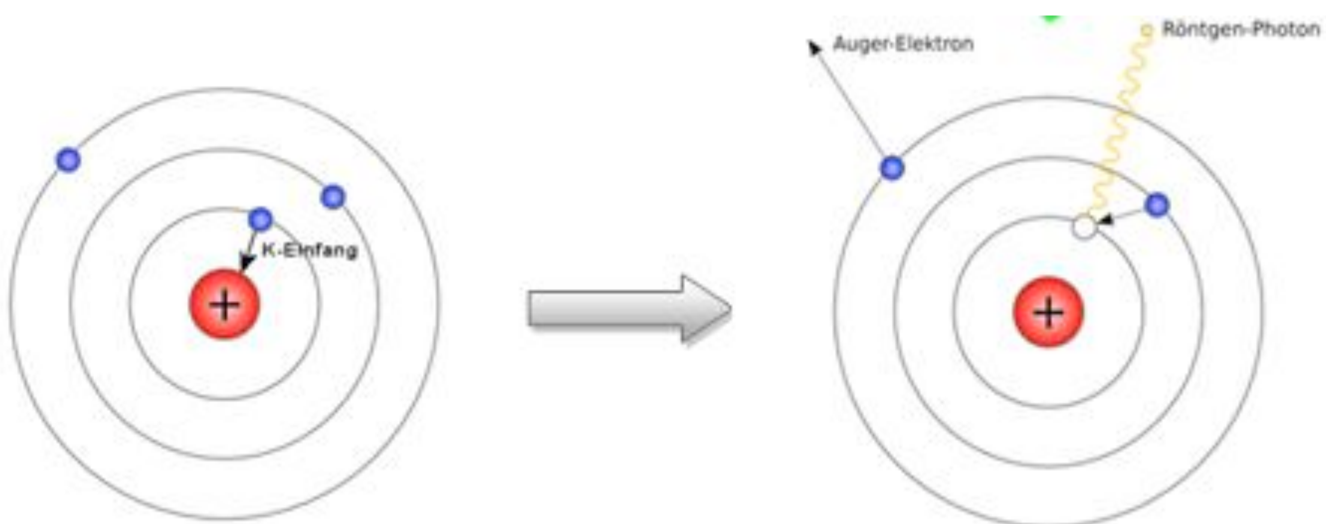
Atomic de-excitation:

- **X-ray emission**
- Auger electrons
- Coster-Kronig transitions

$$^{163}_{67}\mathrm{Ho} \rightarrow ^{163}_{66}\mathrm{Dy}^{*} + \nu_{e}$$

$$^{163}_{66}\mathrm{Dy}^{*} \rightarrow ^{163}_{66}\mathrm{Dy} + E_{C}$$

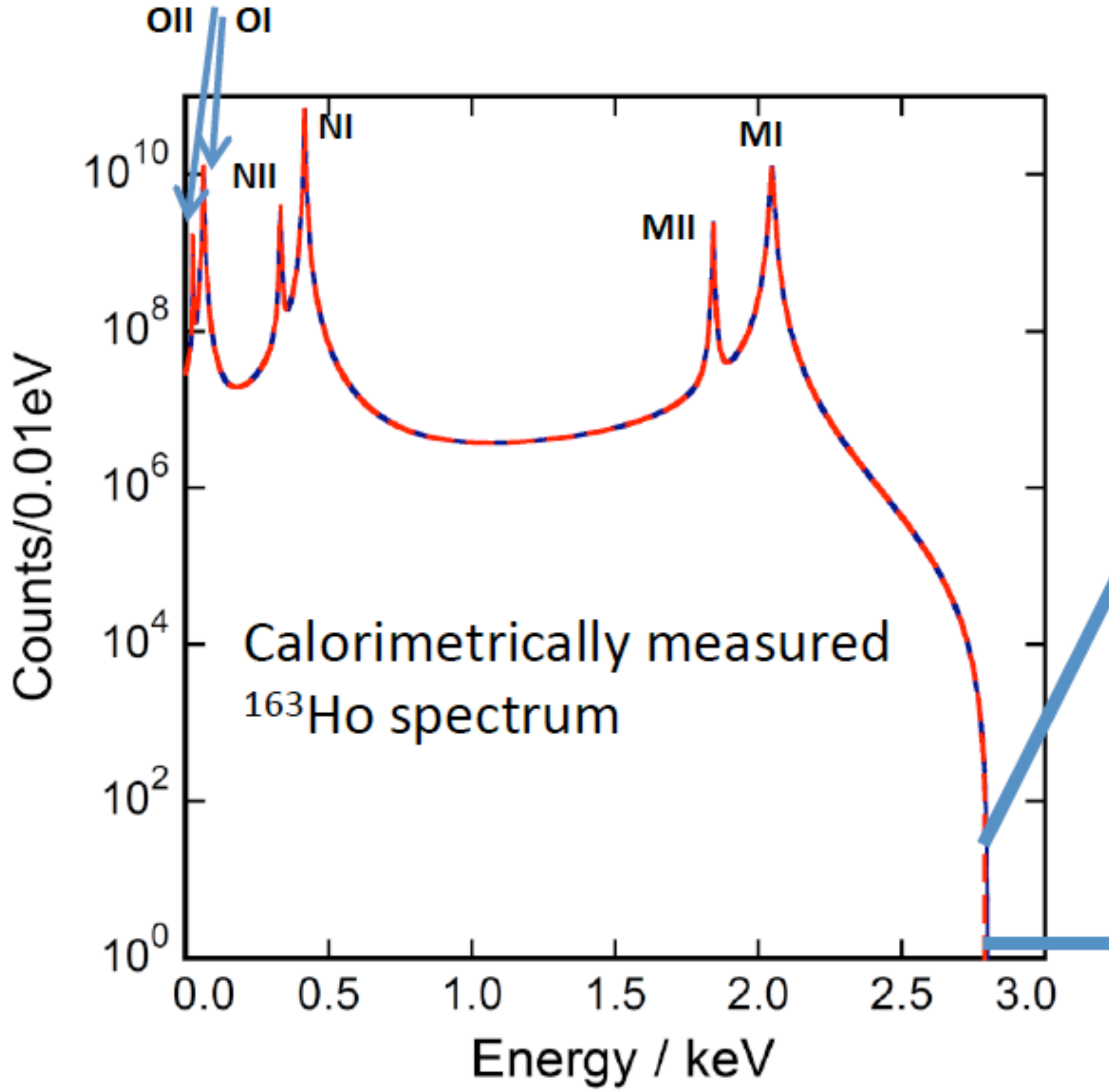


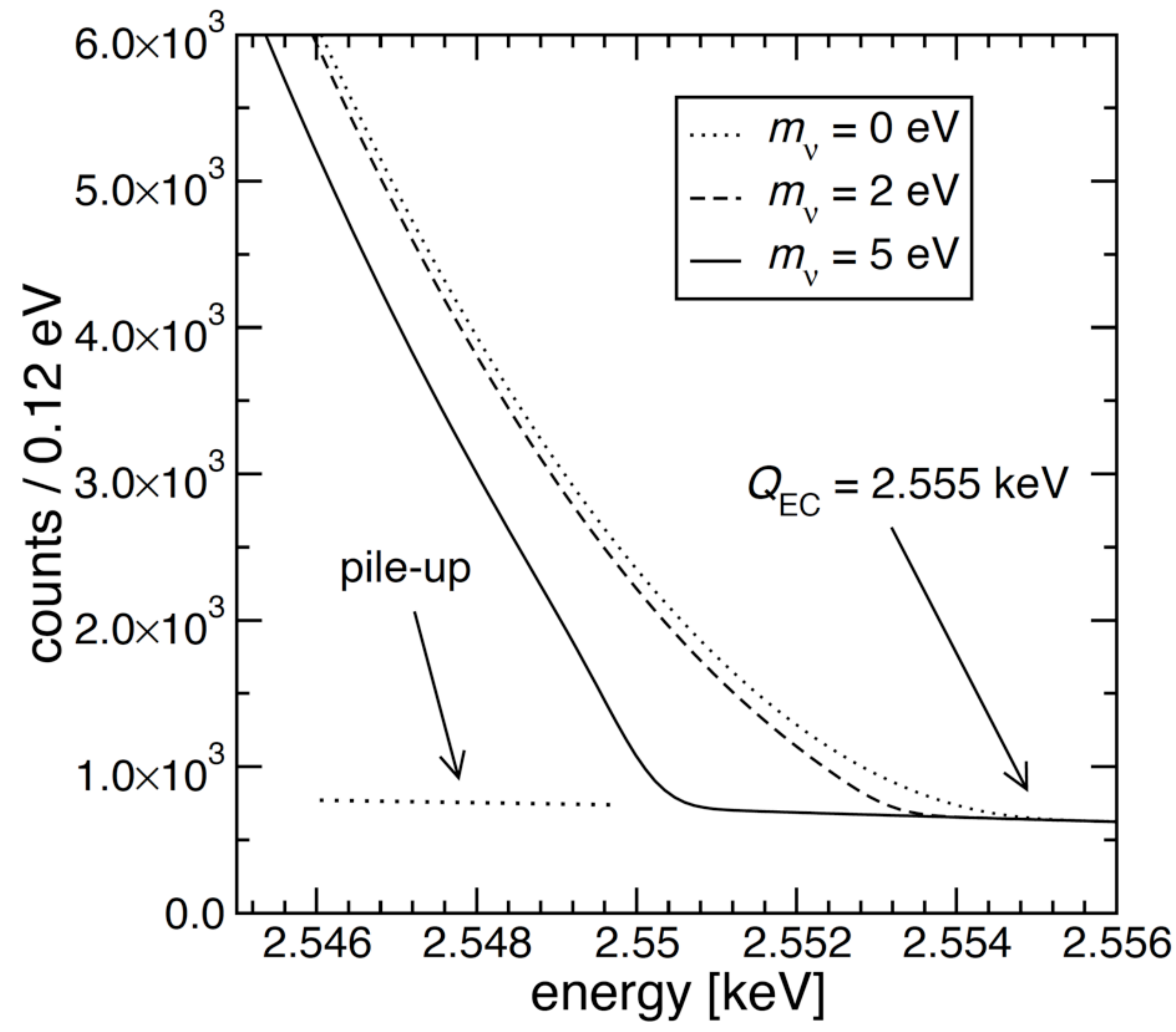


- $\tau_{1/2} \cong 4570$ years (2*10^{11} atoms for 1 Bq)
- Q_{EC} = $(2.833 \pm 0.030^{stat} \pm 0.015^{syst})$ keV

S. Eliseev et al., *Phys. Rev. Lett.* **115** (2015) 062501

- E freed by de-exciting ^{163}Dy has ~lowest known "Q value": 2.8 keV
  - maximize effect of neutrino mass at end-point
- measured inclusively, with source = detector
  - no risk of loss or of mis-modelling energy at source
- *problem*: lifetime! need smart format of detector to maximize statistics



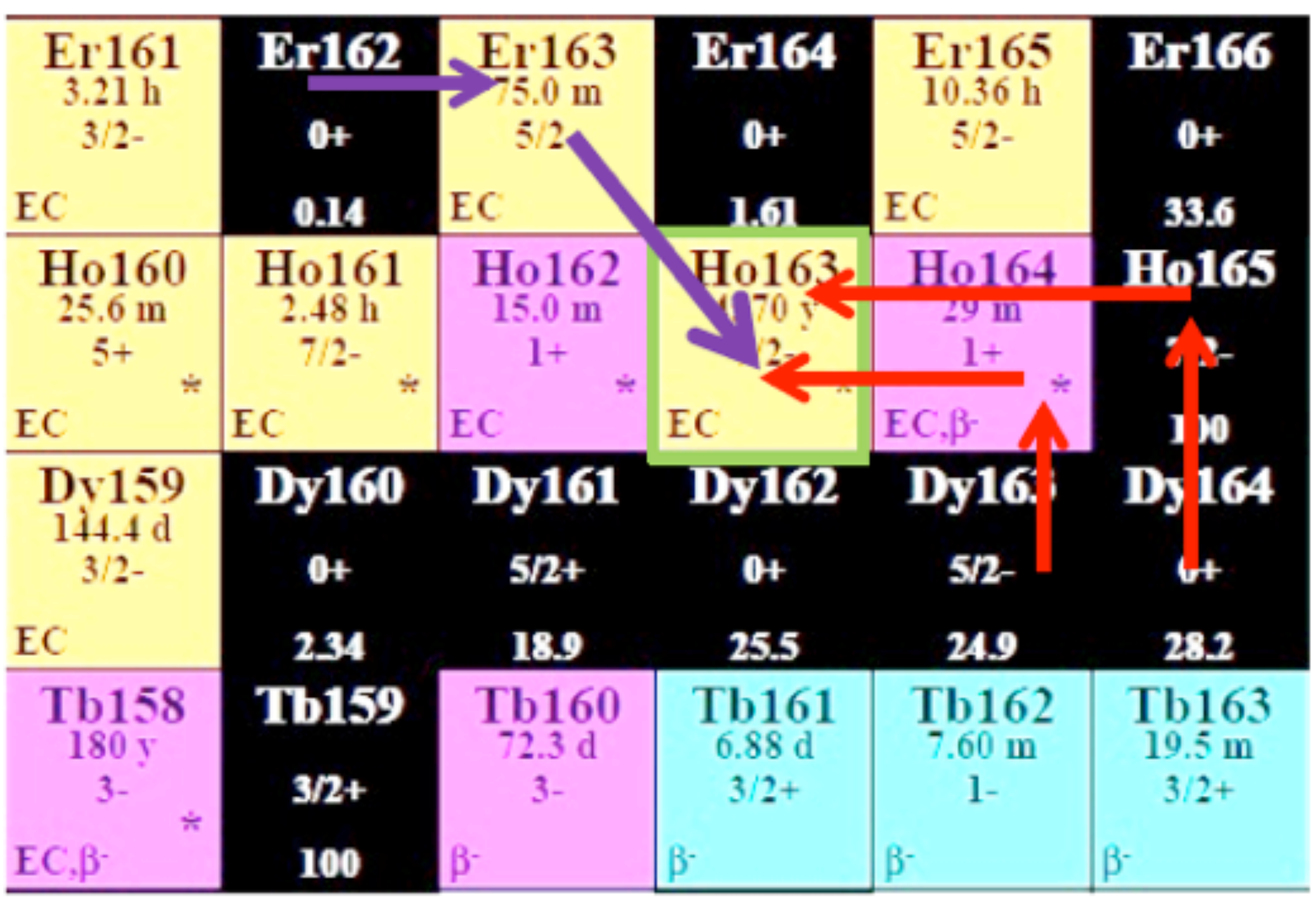


$$\frac{d\lambda_{EC}}{dE_c} = \frac{G_\beta^2}{4\pi^2}(Q - E_c)\sqrt{(Q - E_c)^2 - m_\nu^2} \times \sum_i n_i C_i \beta_i^2 B_i \frac{\Gamma_i}{2\pi} \frac{1}{(E_c - E_i)^2 + \Gamma_i^2/4},$$

Equivalent of beta-decay but with B-W peaks corresponding to energy levels

Main issues

- Measuring the energy with micro-calorimeters with high resolution
- Estimate doubles=overlaps and their bias on Q end-point estimation
- Keep background under control

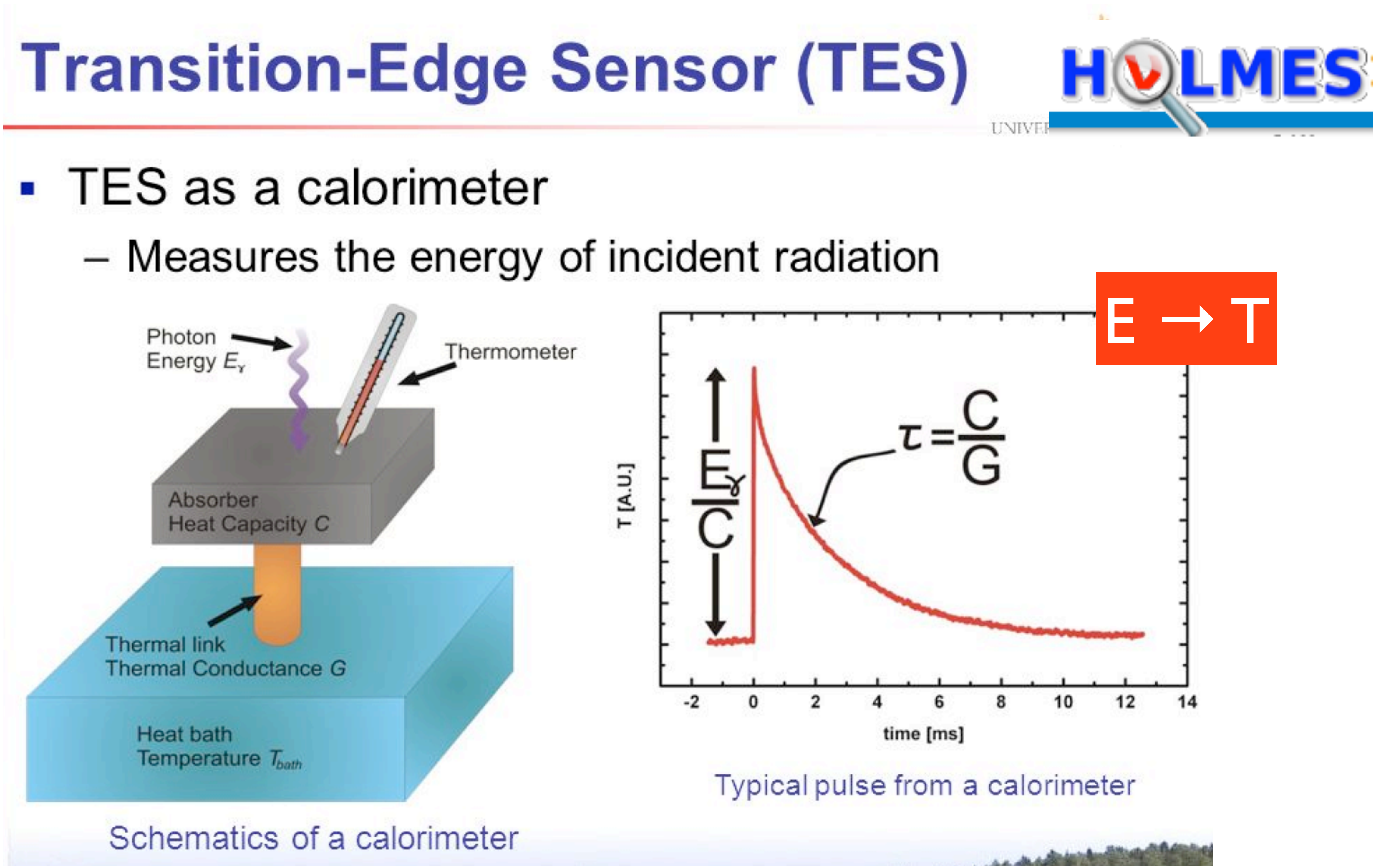


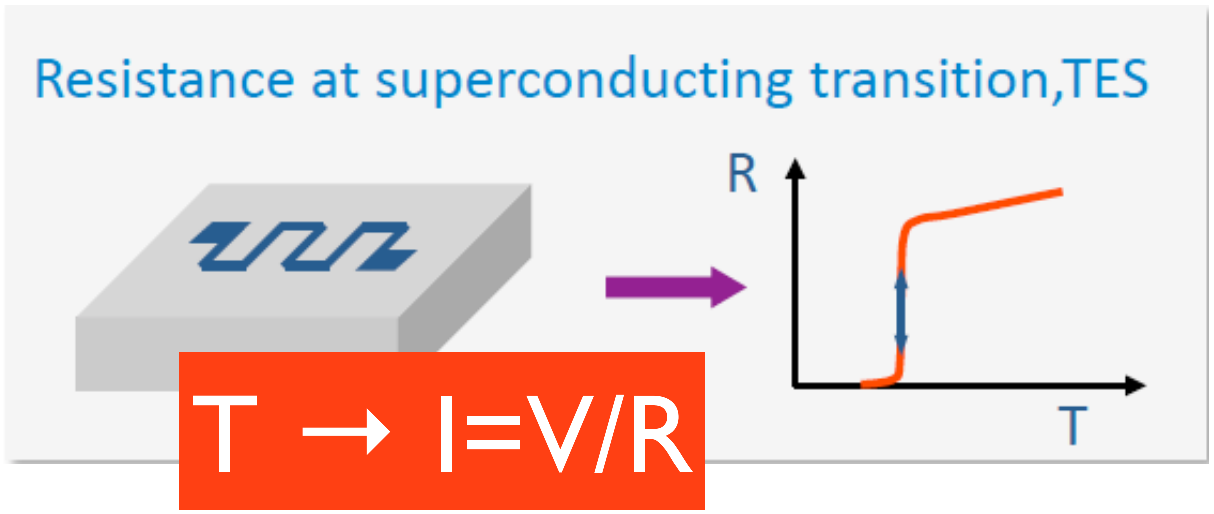
$$^{162}\mathrm{Er}(\mathrm{n},\gamma)^{163}\mathrm{Er} \rightarrow {}^{163}\mathrm{Ho} + \nu_e$$

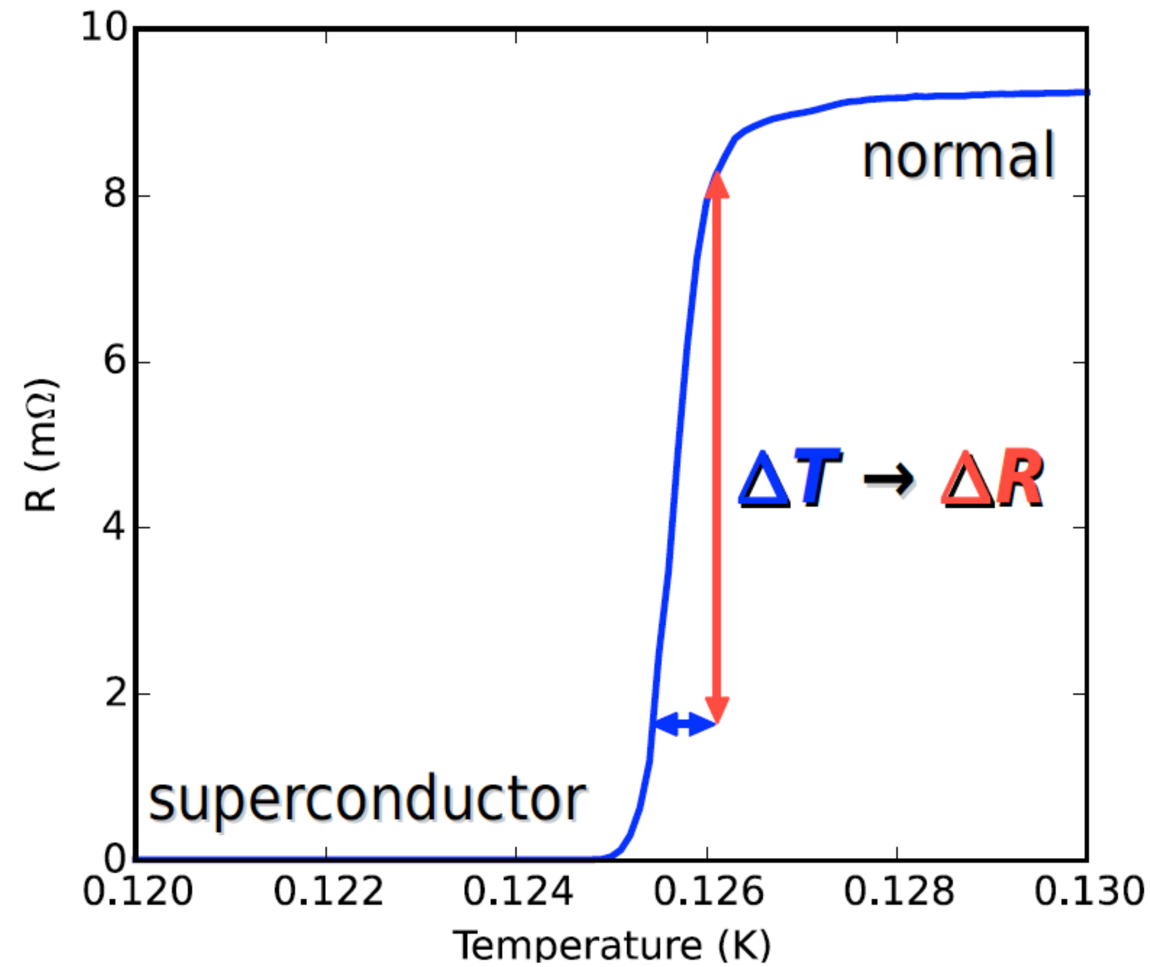
- ^{163}Ho source mostly from neutron irradiation of ^{163}Er
- decays quickly (tau ~75 min) and large x-sec: effective process
- but radioactive impurities from other elements emitting below 5 keV

Microcalorimetry

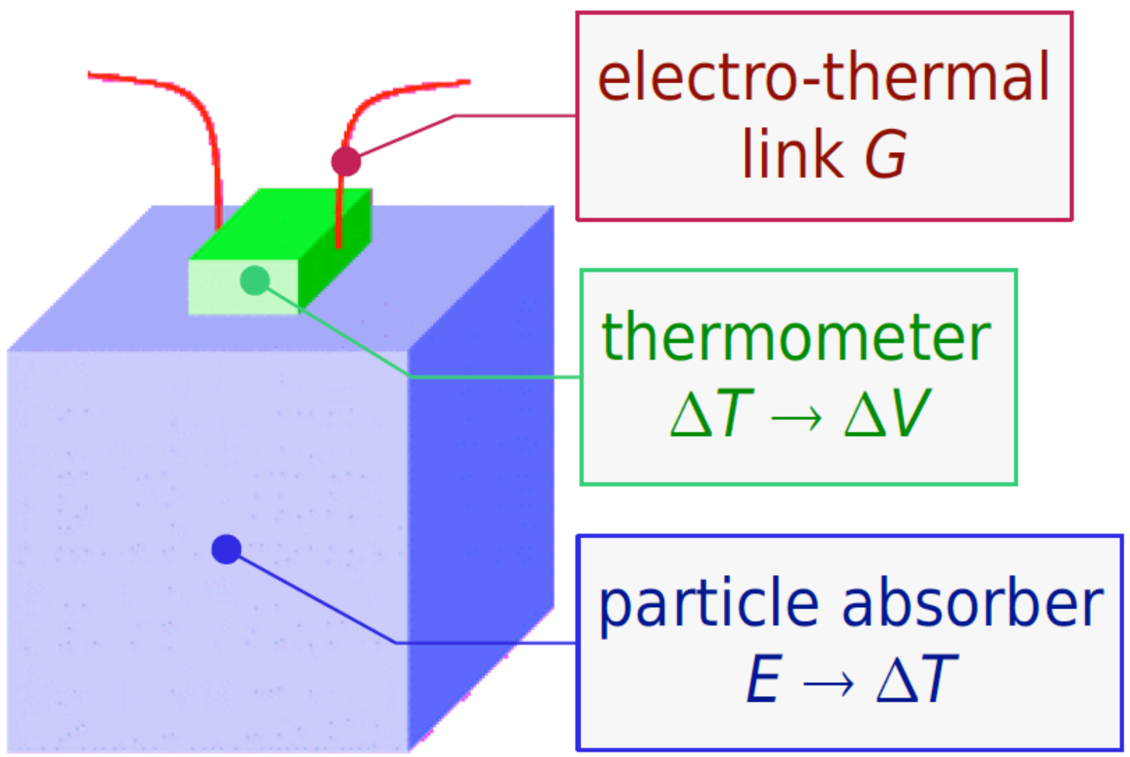
- Small, segmented devices needed for high E resolution (avoid two events overlapping in time in same reading element)







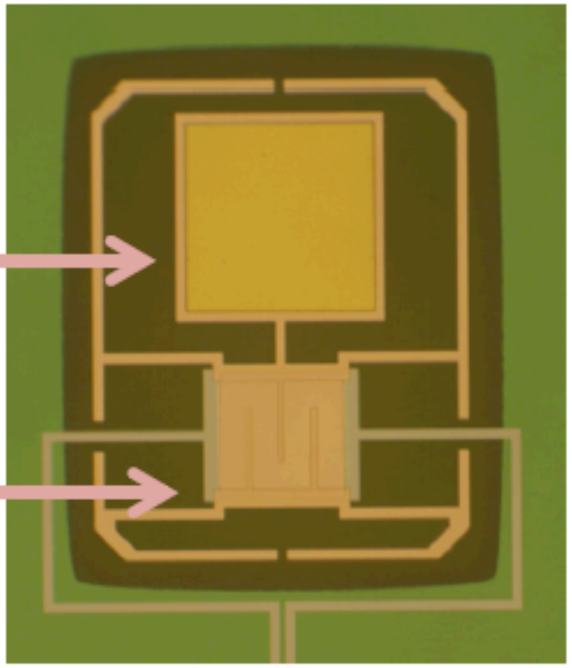
- Exploit super-conducting property to rapidly (but about linearly) change R with T



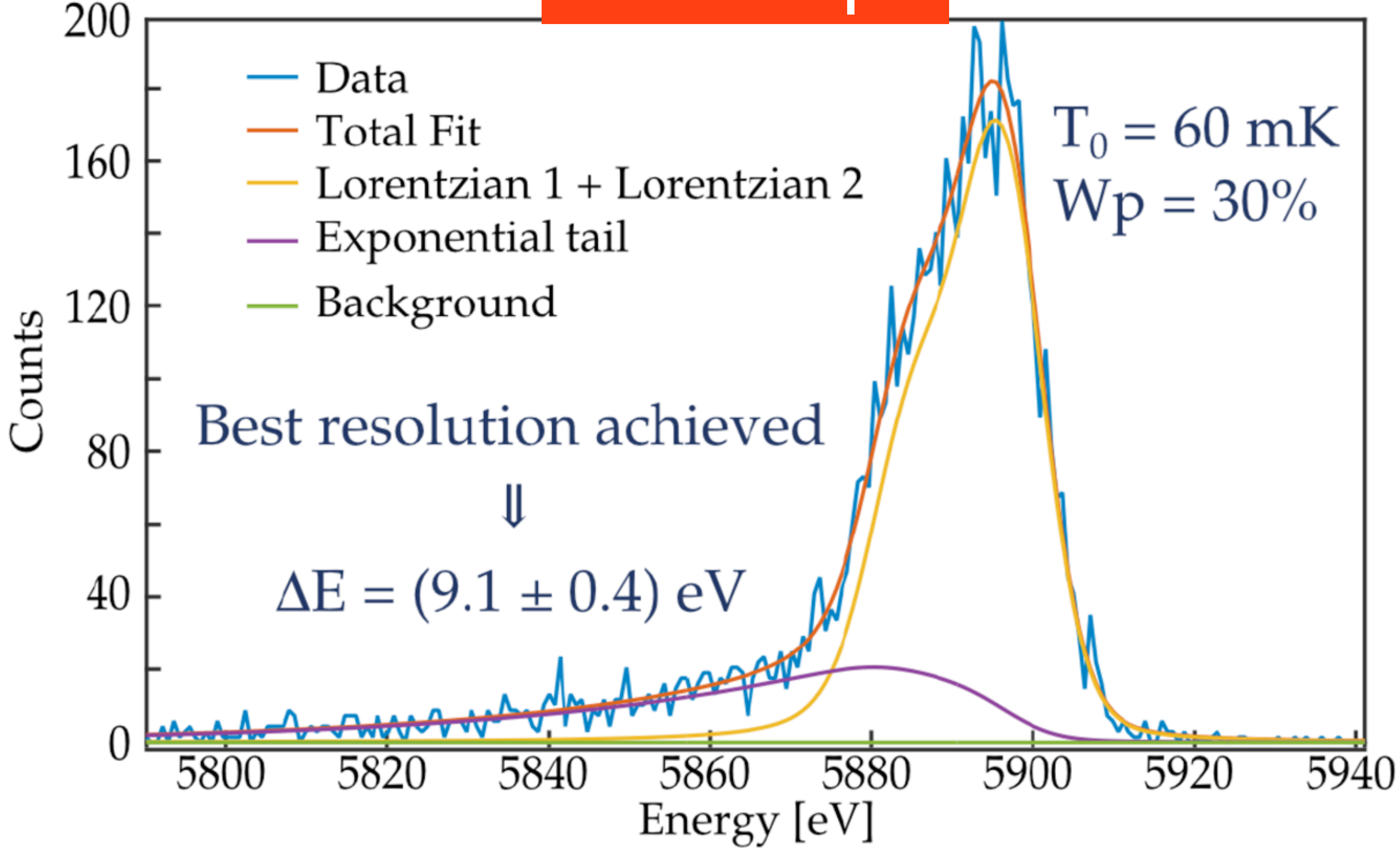
- Use film of material roughly with transition at ^{163}Ho Q (2-3 KeV)
  - linear with Ec <->T
  - generates current read-out
- Electro-thermic feedback compensates increase of I from T, forces TES to stay around linear regime

Absorber: Bi-Au or Au + 6.5x10^{13} ^{163}Ho per detector → **300 dec/sec**
^{163}Ho ion implanted in absorber using dedicated facility at Genoa University

Transition Edge Sensor: MoCu or MoAu superconducting films



An example



$$\Delta E \simeq 2.35\sqrt{4kTE_{max}}$$

- Q = 2.5 keV
- operating at <150 mK heat capacity
- gives ΔE ~ 0.8 eV FWHM

- HOLMES claims ΔE = 1 eV

Pile-up

http://lanl.arxiv.org/pdf/1412.5060v3

- Calorimeters are not fast generally
- TES have a relaxation time of ~several ms
- Two decays can happen within the same TES element close-by and not be discriminated
  - -> bias on the Ec measured by summing two processes

spectrum is given by the two event pile-up probability $f_{pp} = \tau_R A_{EC}$, where τ_R is the time resolution and A_{EC} is the EC activity in each detector. This kind of statis-

tion HOLMES will collect about 3×10^{13} decays with an instrumental energy resolution ΔE of about 1 eV FWHM and a time resolution τ_R of about 1 μs. For 3 years of measuring time t_M, this requires a total ^{163}Ho activity of about 3×10^5 Bq. With an array of 1000 detectors, each pixel must contain an ^{163}Ho activity of about 300 Bq which gives a f_{pp} of about 3×10^{-4}.

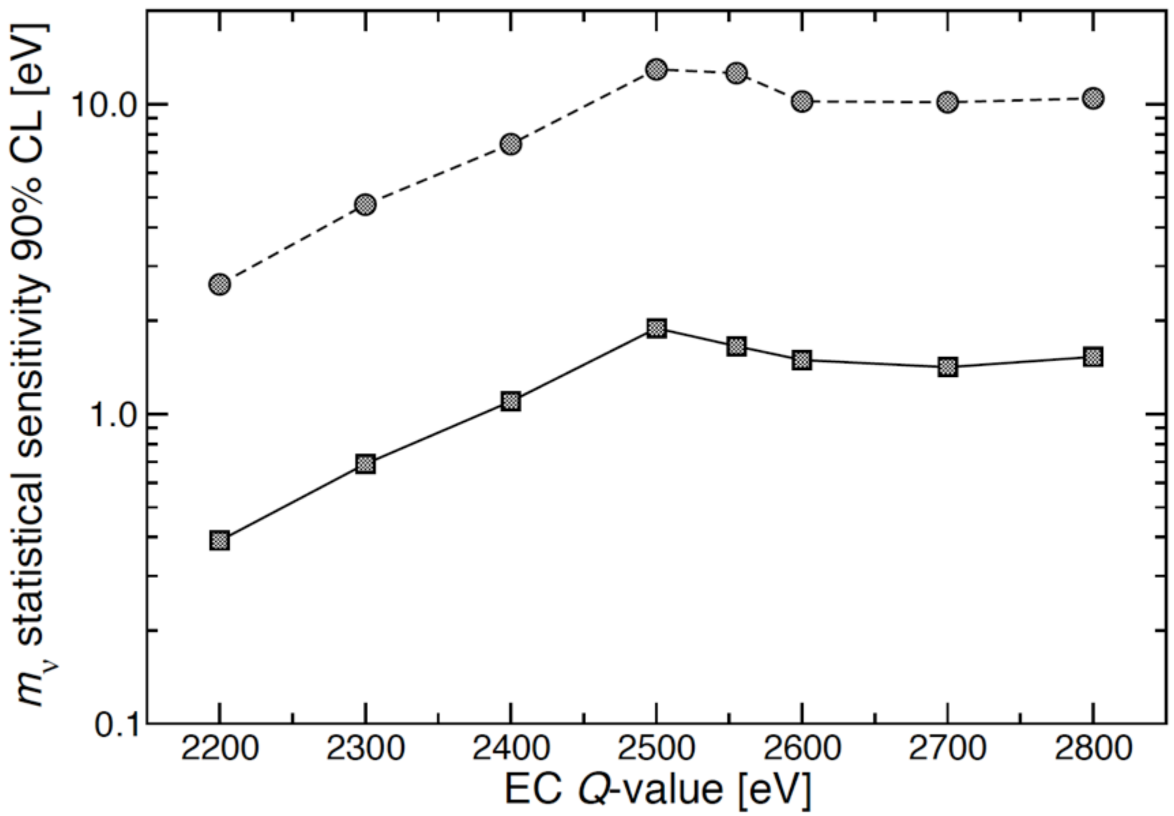


Fig. 4 Monte Carlo estimate of HOLMES neutrino mass statistical sensitivity for $N_{ev} = 3 \times 10^{13}$ (lower curve) or 10^{10} (upper curve) and with $f_{pp} = 3 \times 10^{-4}$, $\Delta E_{\mathrm{FWHM}} = 1\,\mathrm{eV}$, and no background.

Effect of statistics

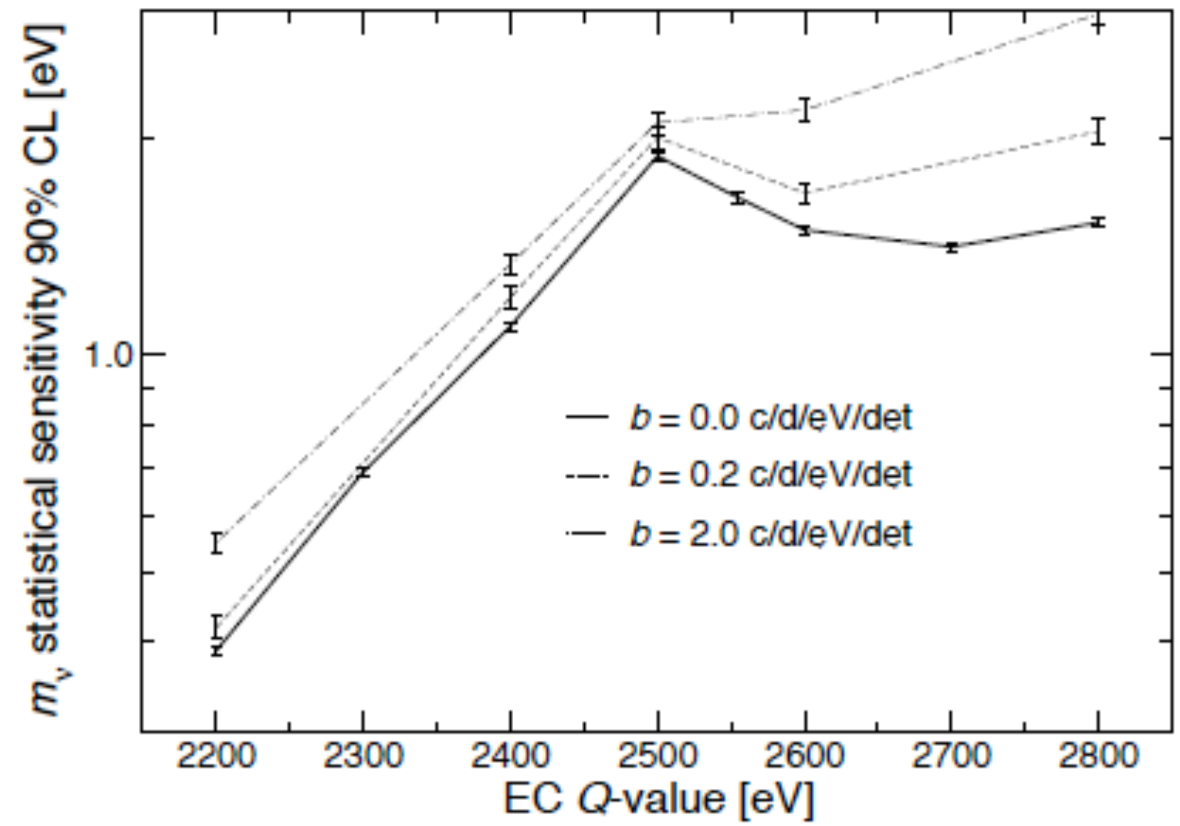
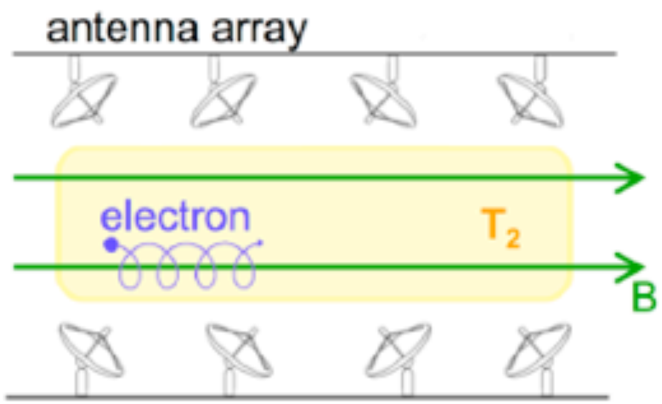


Fig. 9 Monte Carlo estimates of the effect of various background levels on HOLMES baseline statistical sensitivity.

Effect of bkg

Overall this technique expected to currently attain
~0.2-0.4 eV neutrino mass sensitivity
Competitive with spectrometers

PROJECT 8



- Enclosed volume filled with **tritium molecular gas**
- Add a **magnetic field →**
  Decay electrons spiral around field lines
- Add **antennas** to detect the cyclotron radiation

Cyclotron Radiation Emission Spectroscopy (CRES)

- Non-destructive measurement of electron energy

$$\omega_\gamma = \frac{\omega_0}{\gamma} = \frac{eB}{K + m_e}$$

@ 1 Tesla	ω(18 keV) ~ 26 GHz P(18 keV) = 1.2 fW

B. Monreal & J. Formaggio PRD 80 (2009) 051301

PROJECT 8: schedule

Phase I (2010 - 2016)
Demonstration of the CRES method
Conversion electron lines from ^{83m}Kr source ✓

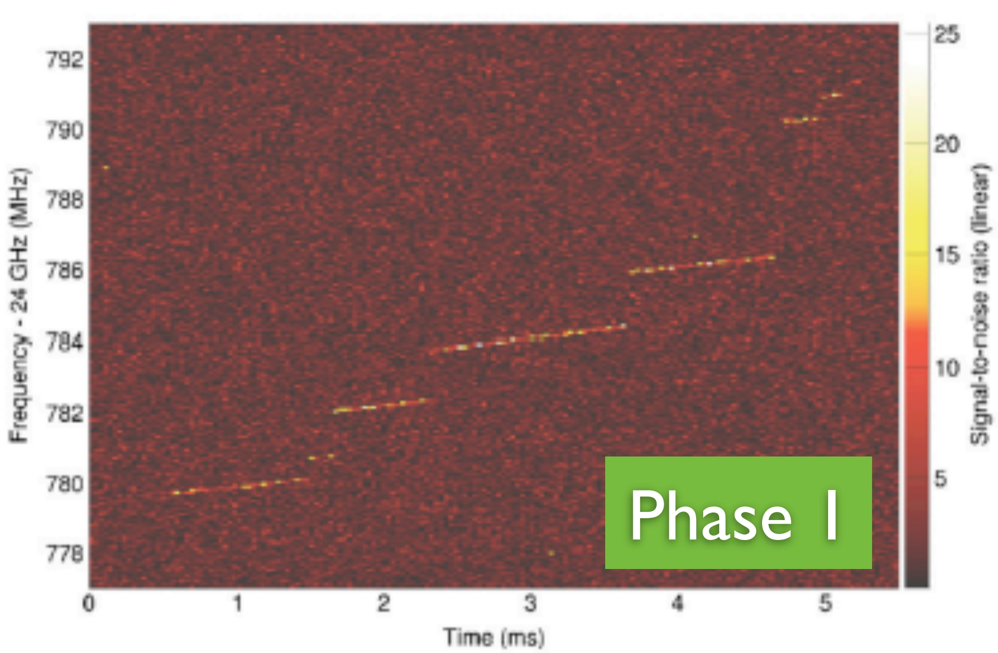
Phase II (2015 - 2017)
Spectroscopy of continuous T_2 spectrum
Study of systematics
improvement of the energy resolution

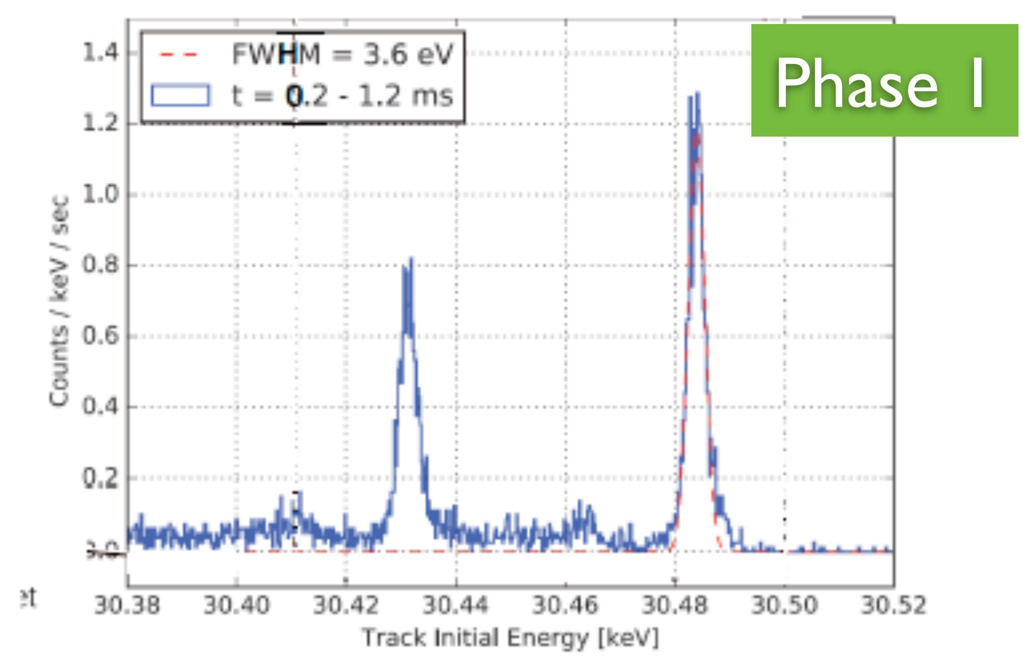
Started

Phase III (2016 - 2020)
10 – 20 cm^3 effective source volume (1 year)
Phased array antenna
Sensitivity goal: $m(\nu_e) < 2$ eV 90% C.L.

Phase IV (2018 +)
Large scale exp. with atomic ^{3}H source for sub-eV sensitivity

First observation of cyclotron radiation from single electrons June 2014



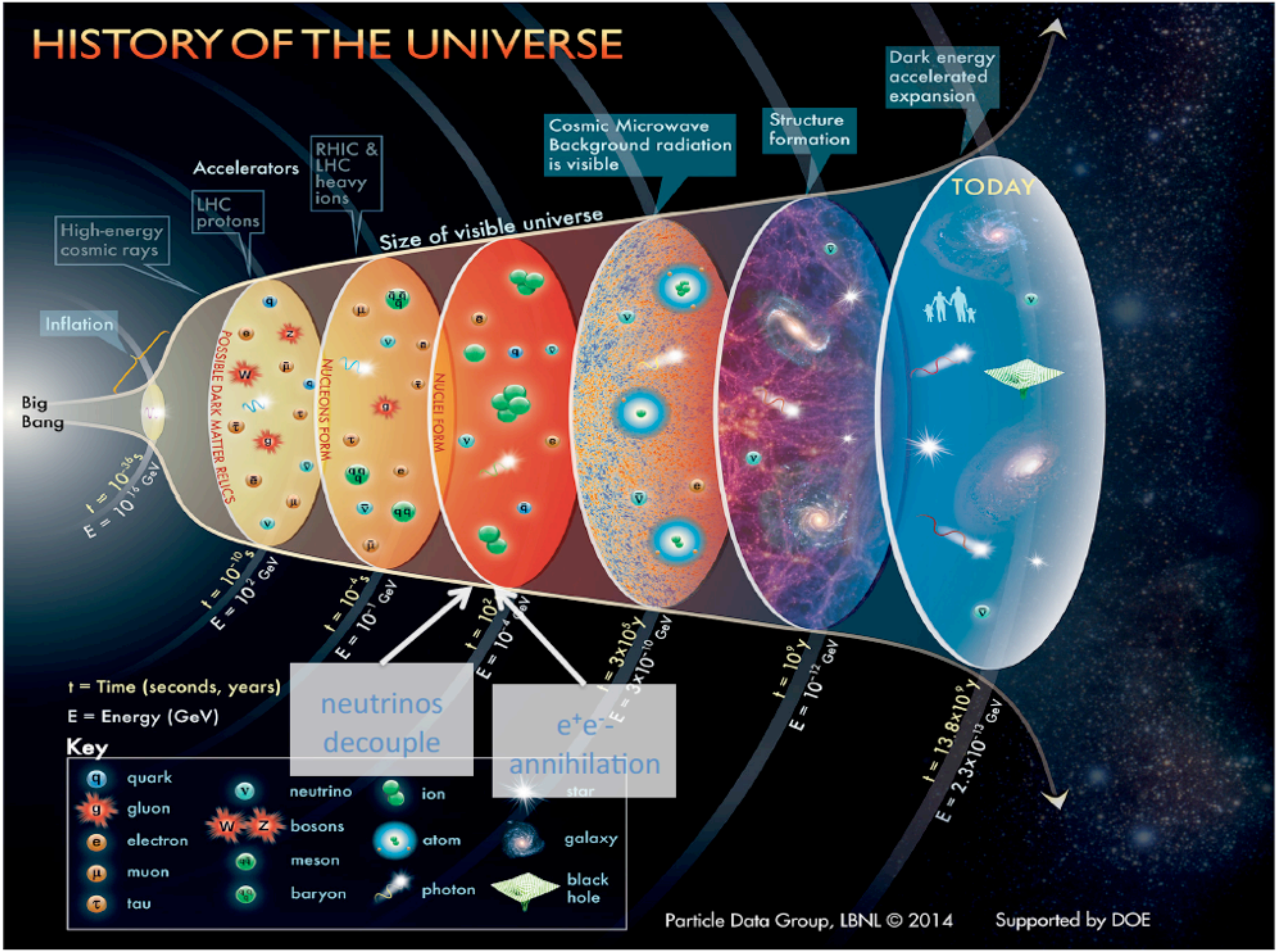


Cosmological constraints

(for more see e.g. seminar by Lattanzi at Roma Tre, 10th Jan 2017)

- cosmological observations

$$\sum m_\nu \equiv \sum_i m_i \qquad (\ 0.2 - 0.7 \text{ eV @ 95\%CL})$$


HISTORY OF THE UNIVERSE
Dark energy accelerated expansion
Cosmic Microwave Background radiation is visible
Structure formation
RHIC & LHC heavy ions
Accelerators
LHC protons
High-energy cosmic rays
Inflation
Size of visible universe
TODAY
Big Bang
POSSIBLE DARK MATTER RELICS
NUCLEONS FORM
NUCLEI FORM
t = 10^-36 s
E = 10^16 GeV
t = 10^-10 s
E = 10^2 GeV
t = 10^-4 s
E = 10^-1 GeV
t = 10^2 s
E = 10^-4 GeV
t = 3x10^5 y
E = 3x10^-10 GeV
t = 10^9 y
E = 10^-12 GeV
t = 13.8x10^9 y
E = 2.3x10^-13 GeV
neutrinos decouple
e+e- annihilation
t = Time (seconds, years)
E = Energy (GeV)
Key
quark
gluon
electron
muon
tau
neutrino
bosons
meson
baryon
ion
atom
photon
star
galaxy
black hole
Particle Data Group, LBNL © 2014
Supported by DOE

The Cosmic Neutrino Background - Properties

At freeze out the neutrinos had a thermal velocity distribution.

Since then the neutrinos have continued to move along geodesics with a velocity which has red-shifted as a result of the expansion of the universe.

This geodesic movement is called *free streaming*.

These free-streaming neutrinos make up the *cosmic neutrino background*.

- Below T ~ 1 MeV, neutrino free stream keeping an equilibrium spectrum:

$$f_\nu(p) = \frac{1}{e^{p/T} + 1}$$

- Today T_ν = 1.9 K and n_ν = 113 part/cm^3 per species

Constraints from the Neutrino Background

In standard cosmologies, the cosmological neutrino background only interacts gravitationally after freeze-out and *all cosmological bounds on neutrino masses arise from gravitational interactions of the cosmic neutrino background.*

The gravitational interaction depends on the sum of the gravity from all of the neutrinos, which is proportional to the sum of the masses once the neutrinos have become nonrelativistic.
This is why cosmology constrains the sum of the masses.

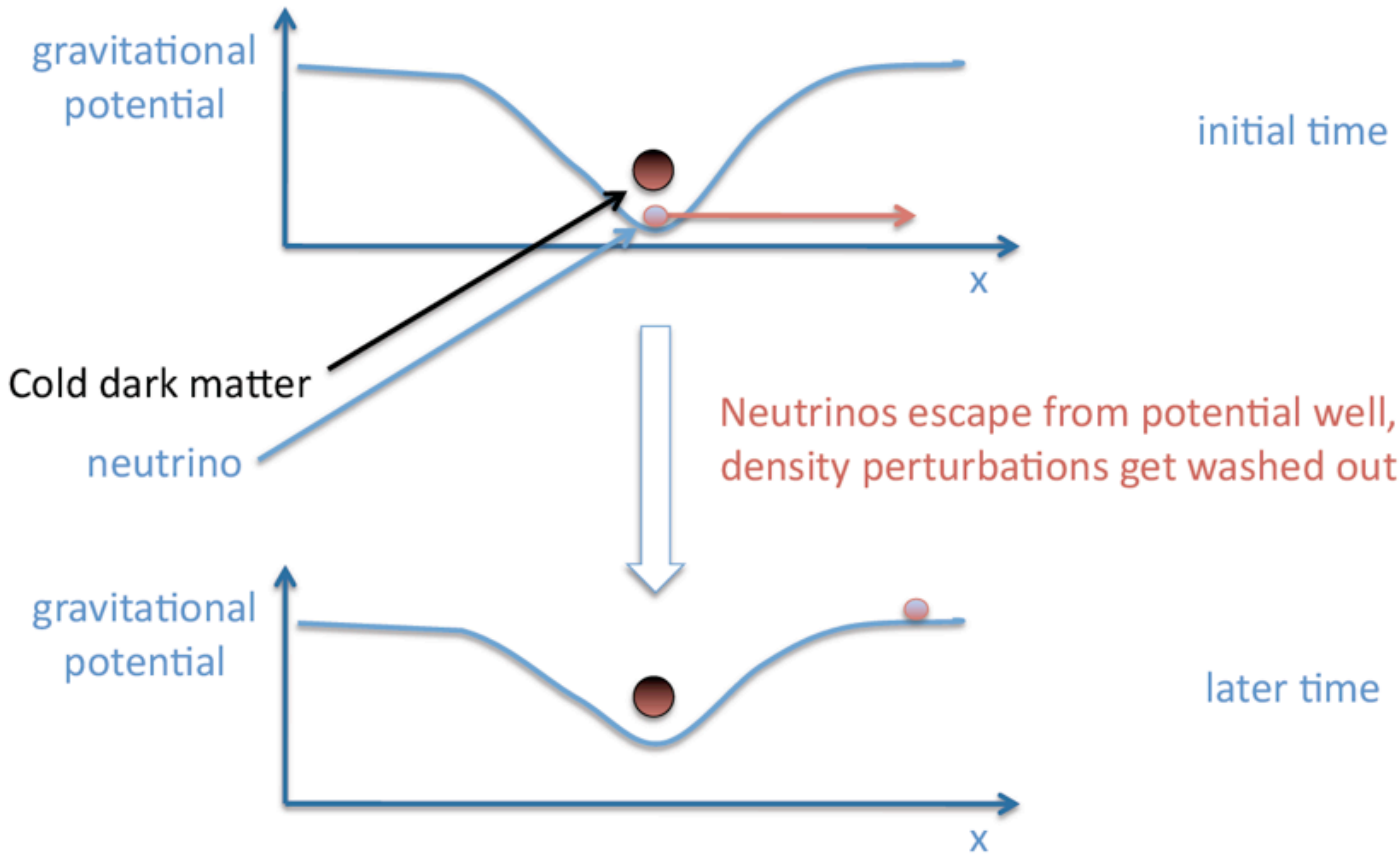
➡ Effects:

I) They contribute to the recent expansion of the universe identically to dark matter.

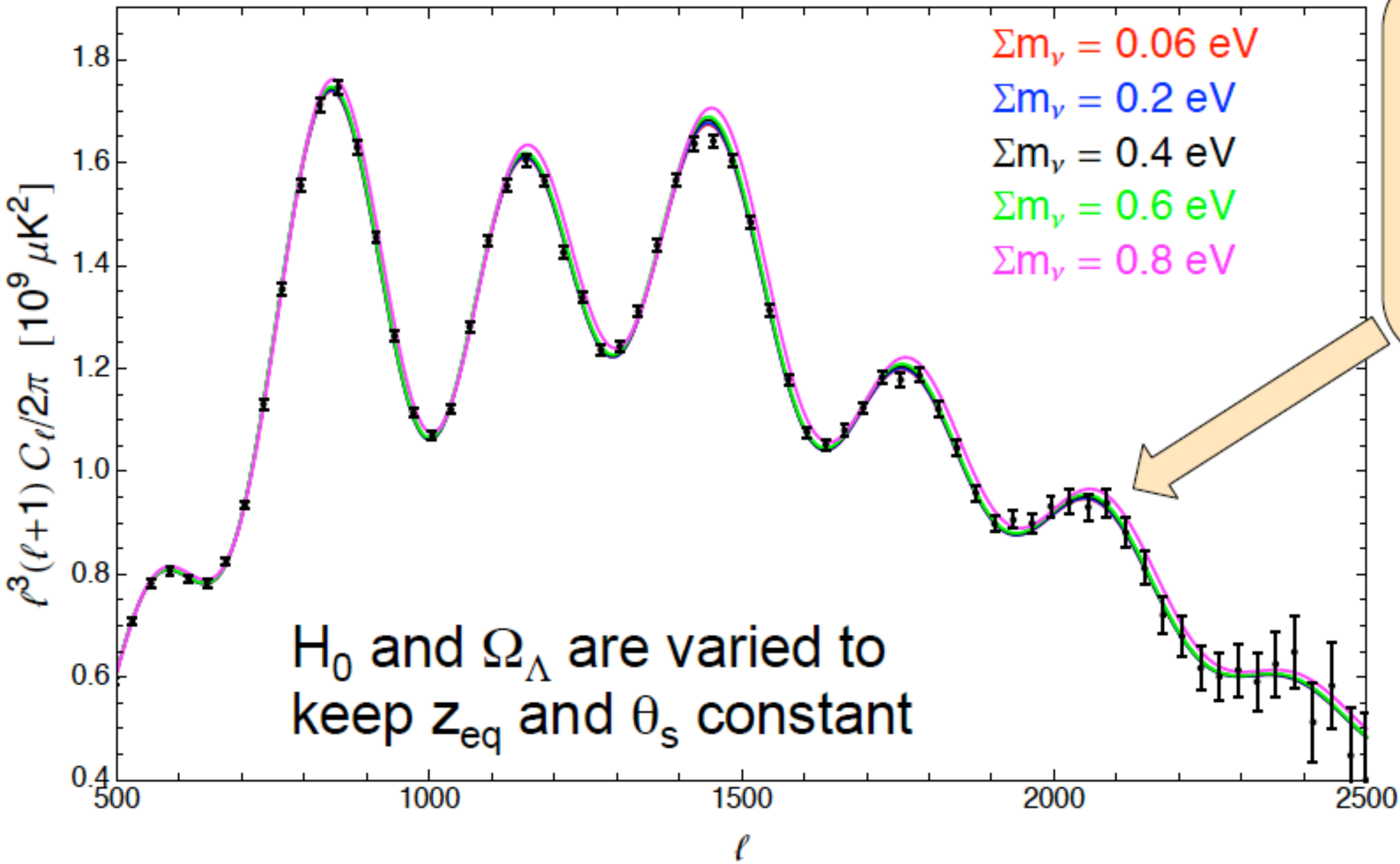
II) Since freeze out they free stream a distance called the *free-streaming length*. This disrupts structure formation on scales below the free-streaming length.

Free streaming

Velocity dispersion large wrt size of potential well



HOW HEAVY?

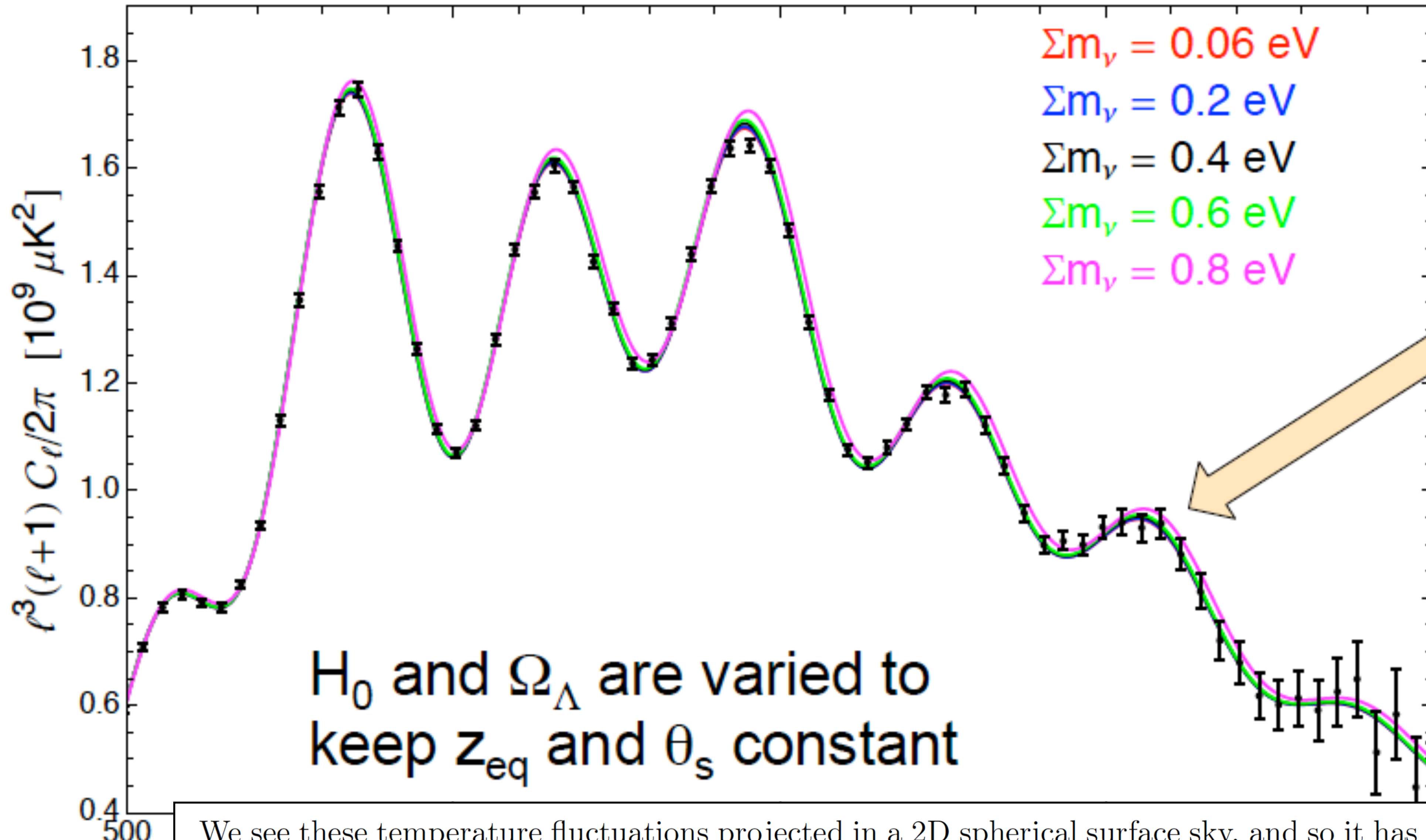


Net effect is to decrease lensing

Perturbations: free streaming, damping of small-scale perturbations
- proportional to the neutrino energy density
- the effect is larger for larger masses

Model-dependent: interplay with Λ_{CDM}, H_0

How heavy?



Net effect is to decrease lensing

P … ons

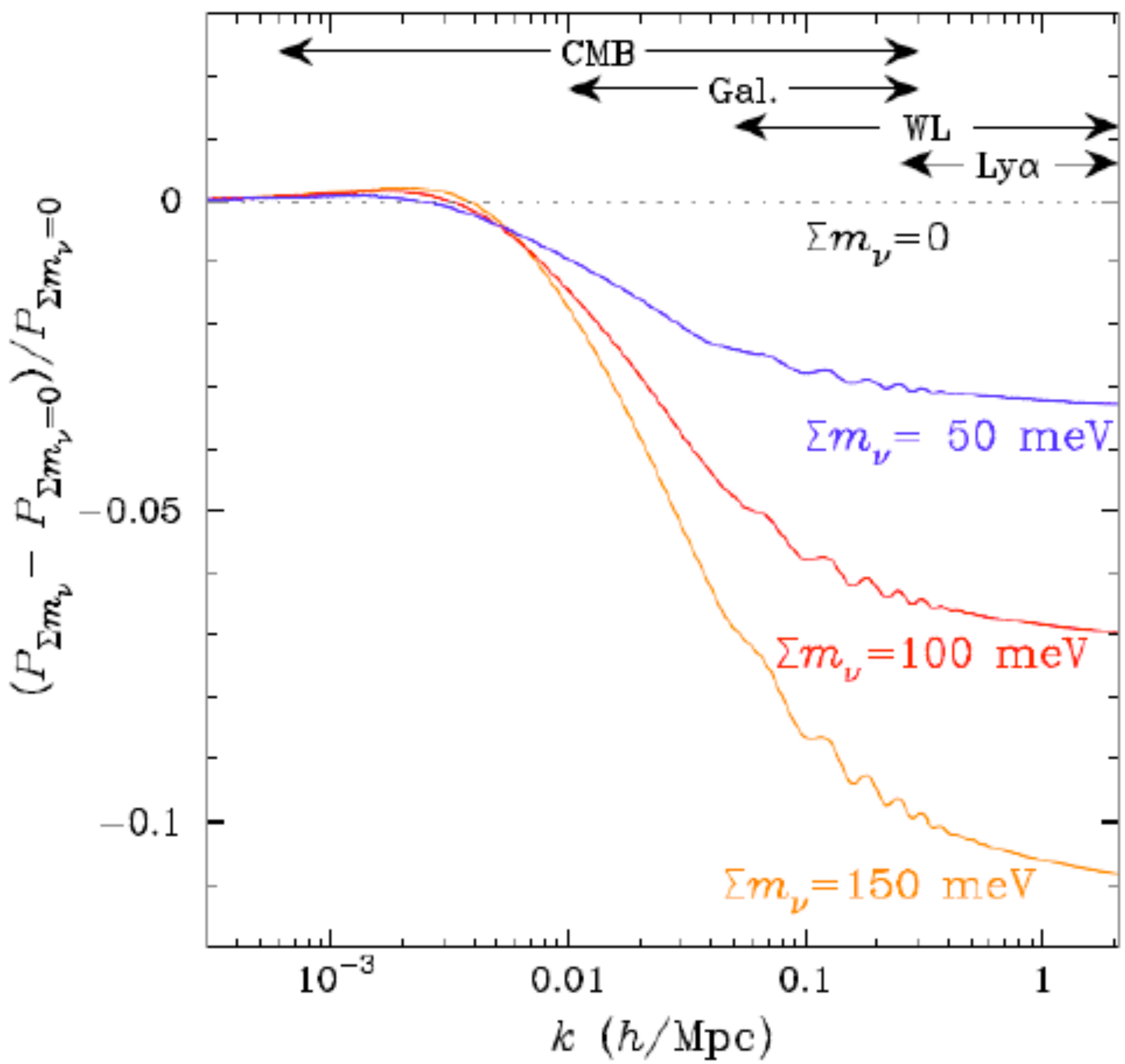
We see these temperature fluctuations projected in a 2D spherical surface sky, and so it has become common in the literature to expand the temperature field using spherical harmonics. The spherical harmonics form a complete orthonormal set on the unit sphere and are defined as

$$Y_{lm} = \sqrt{\frac{2\ell+1}{4\pi}\frac{(\ell-m)!}{(\ell+m)!}}P_\ell^m(cos\theta)e^{im\phi} \quad (2)$$

where the indices $\ell = 0, ..., \infty$ and $-\ell \leq m \leq \ell$ and P_ℓ^m are the Legendre polynomials. ℓ is called the multipole and represents a given angular scale in the sky α, given approximately by $\alpha = \pi/\ell$ (in degrees).

Matter power spectrum with massive neutrinos (at low redshifts)

Suppression of the matter power spectrum wrt massless neutrino case



wavenumber

$$\Delta\mathcal{P}/\mathcal{P} \approx 8\,\frac{\omega_\nu}{\omega_{\rm m}}$$

ratio of density of **ν** to matter (=non-relativistic particles) in the present universe

[Figure from Abazajian+ 2013]

FUTURE PROSPECTS FROM THE LAB

The absolute mass scale can be measured through:
(numbers on the right are forecast for future sensitivities)

- tritium beta decay

$$m_\beta \equiv \left[\sum |U_{ei}|^2 m_i^2\right]^{1/2}$$

(200 meV @ 68%CL)
(Katrin)

- neutrinoless double beta decay

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

(8 – 20 meV @ 90%CL)
(nEXO, 5-year exposure)

- cosmological observations

$$\sum m_\nu \equiv \sum_i m_i$$

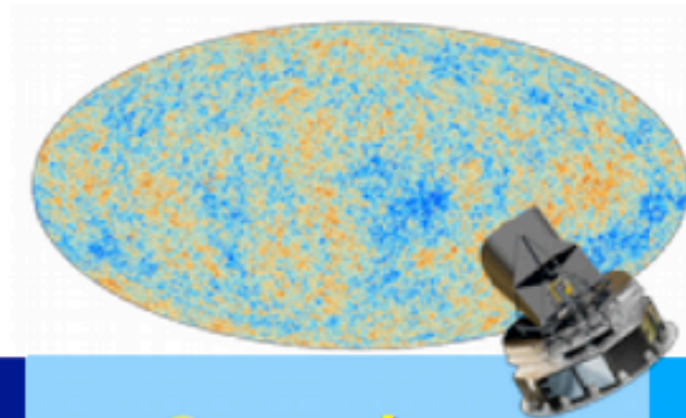
(16 – 45 meV @ 68%CL)
(CORE, CORE+LSS)

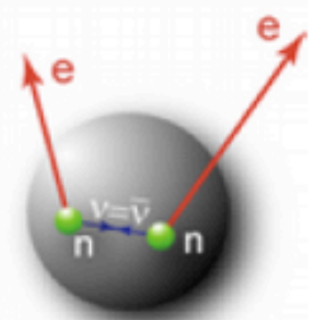
Mass scale: experimental tools / 1

three complementary tools available

→ low temperature detectors play key role

(E. Fiorini and T. Niinikoski, Nucl. Instrum. and Meth. 224, p.83 (1984))

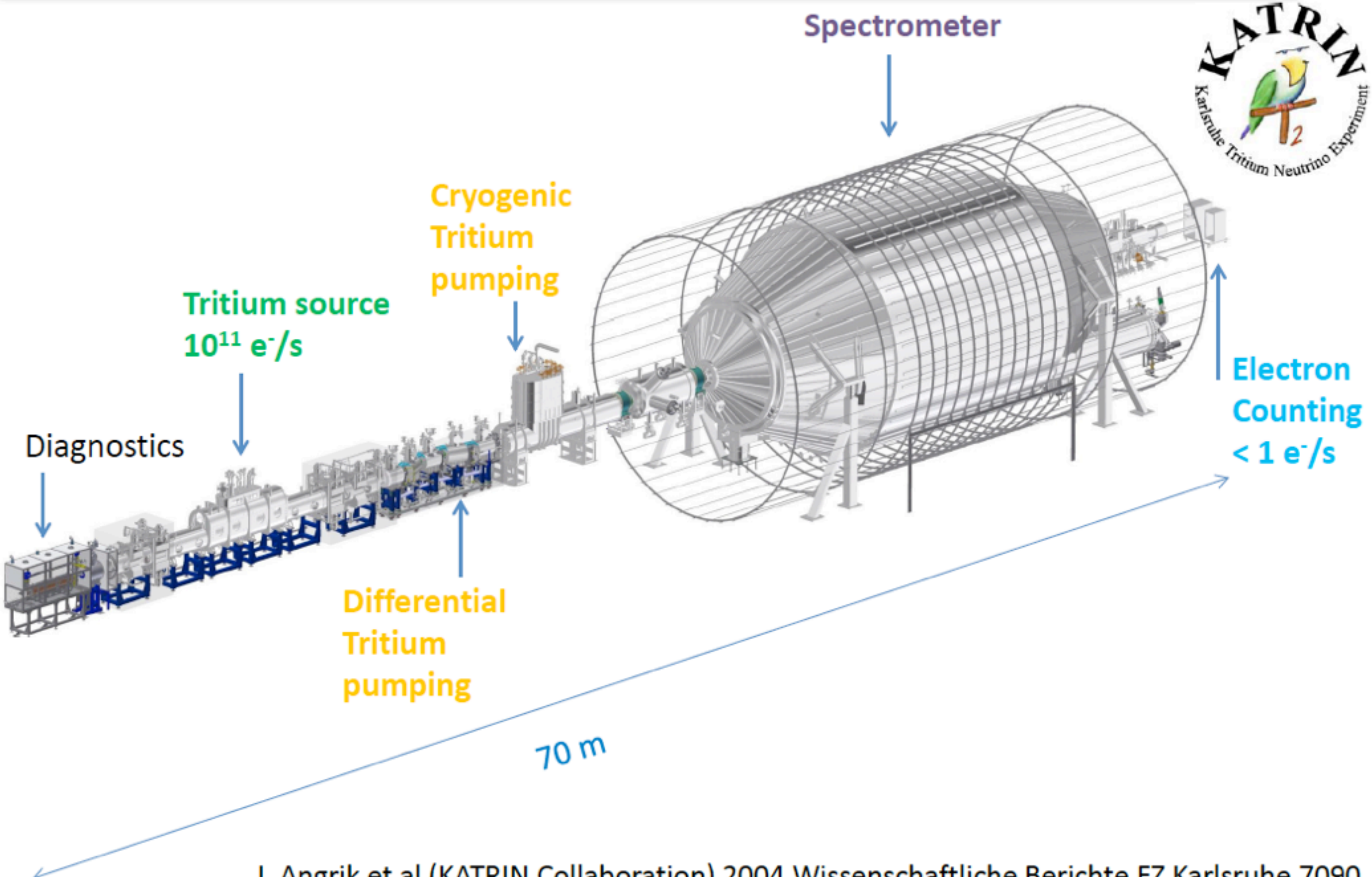




tool	Cosmology CMB+LSS+...	Neutrinoless Double Beta decay	Beta decay end-point
observable	$m_\Sigma=\Sigma_k m_{\nu_k}$	$m_{\beta\beta}=\lvert\Sigma_k m_{\nu_k} U_{ek}^2\rvert$	$m_\beta=(\Sigma_k m_{\nu_k}^2 \lvert U_{ek}\rvert^2)^{1/2}$
present sensitivity	≈0.1 eV	≈0.1 eV	2 eV
future sensitivity	**0.05 eV**	**0.05 eV**	**0.2 eV**
model dependency	yes ☹	yes ☹	no ☺
systematics	large ☹	yes 😐	large ☹

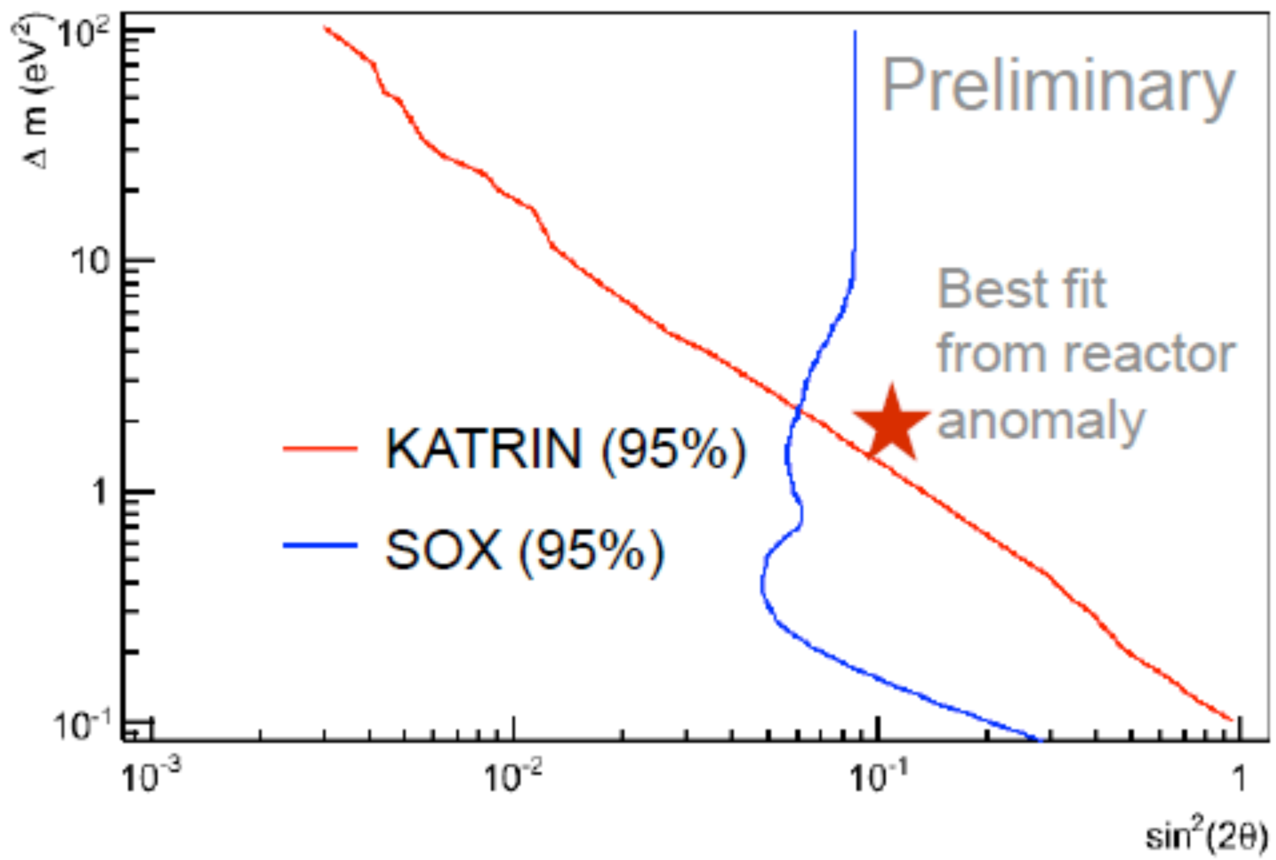
Back up

The KATRIN experiment



J. Angrik et al (KATRIN Collaboration) 2004 Wissenschaftliche Berichte FZ Karlsruhe 7090

eV-scale sterile neutrinos

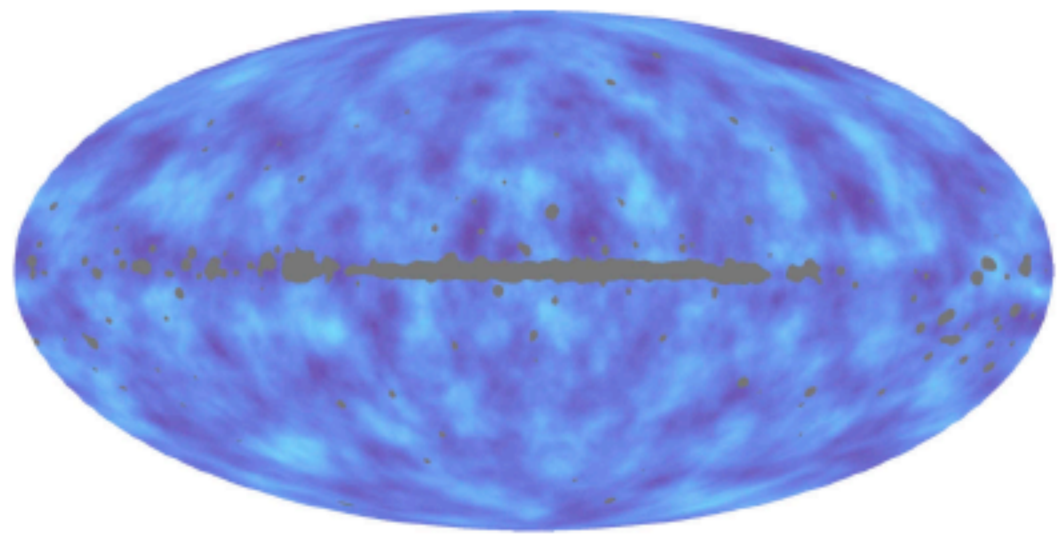


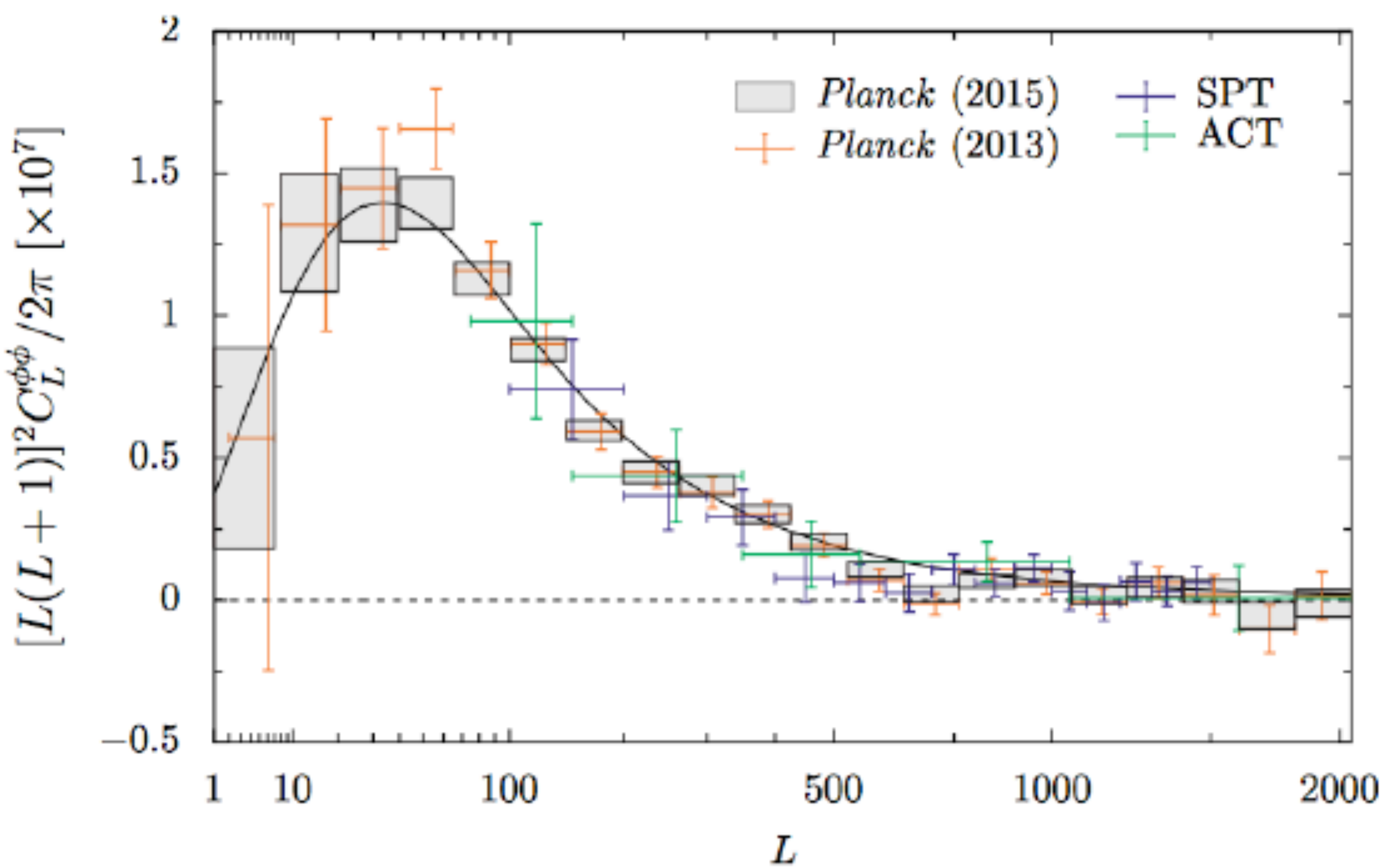
KATRIN **as is** probes the favored parameter space for light sterile neutrinos and is complementary to oscillation experiments

SOX at Borexino

first proposed (AFAIK...):
Phys.Rev. D73 (2006) 045021

CMB lensing potential





LARGE SCALE STRUCTURES

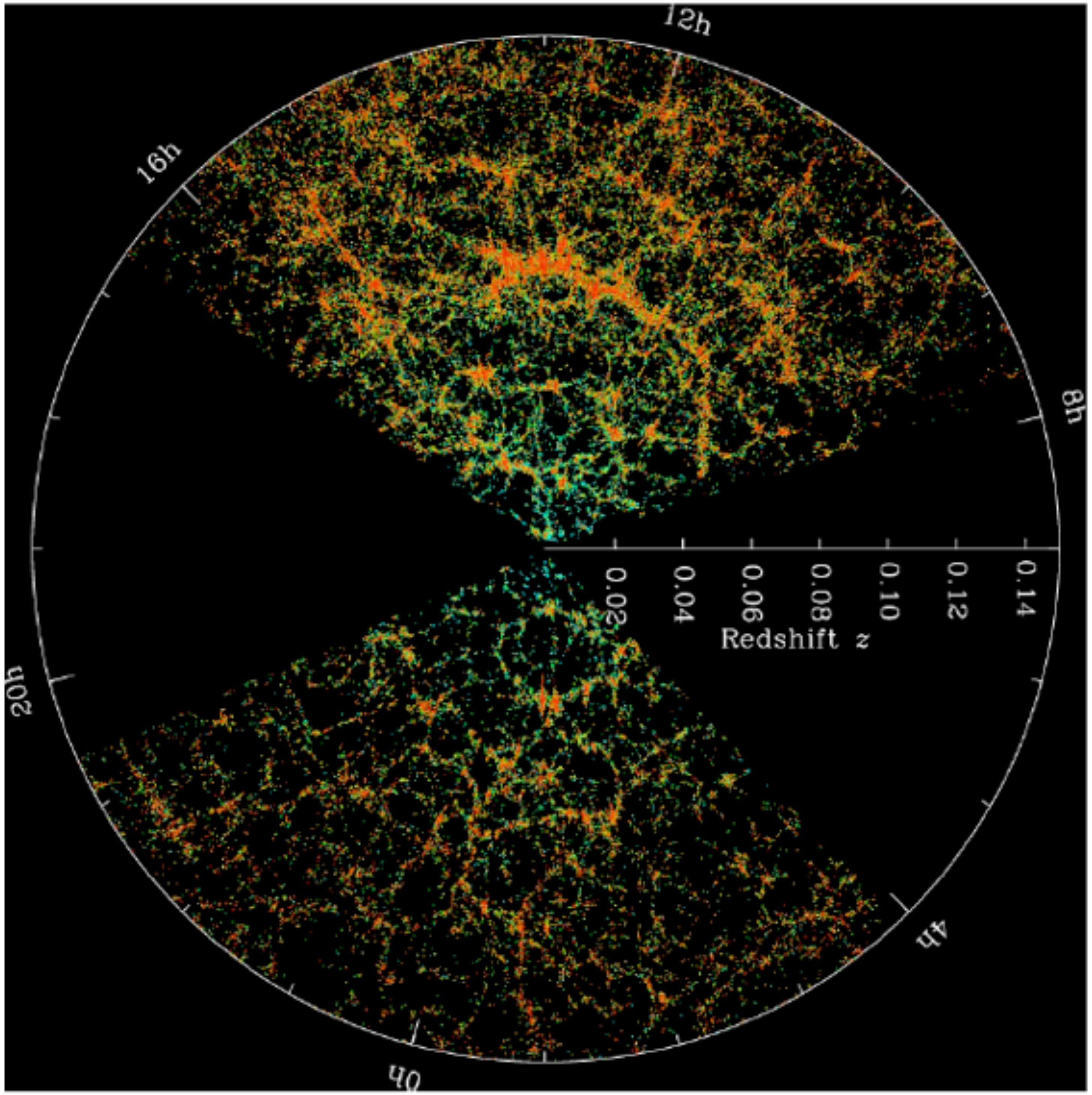
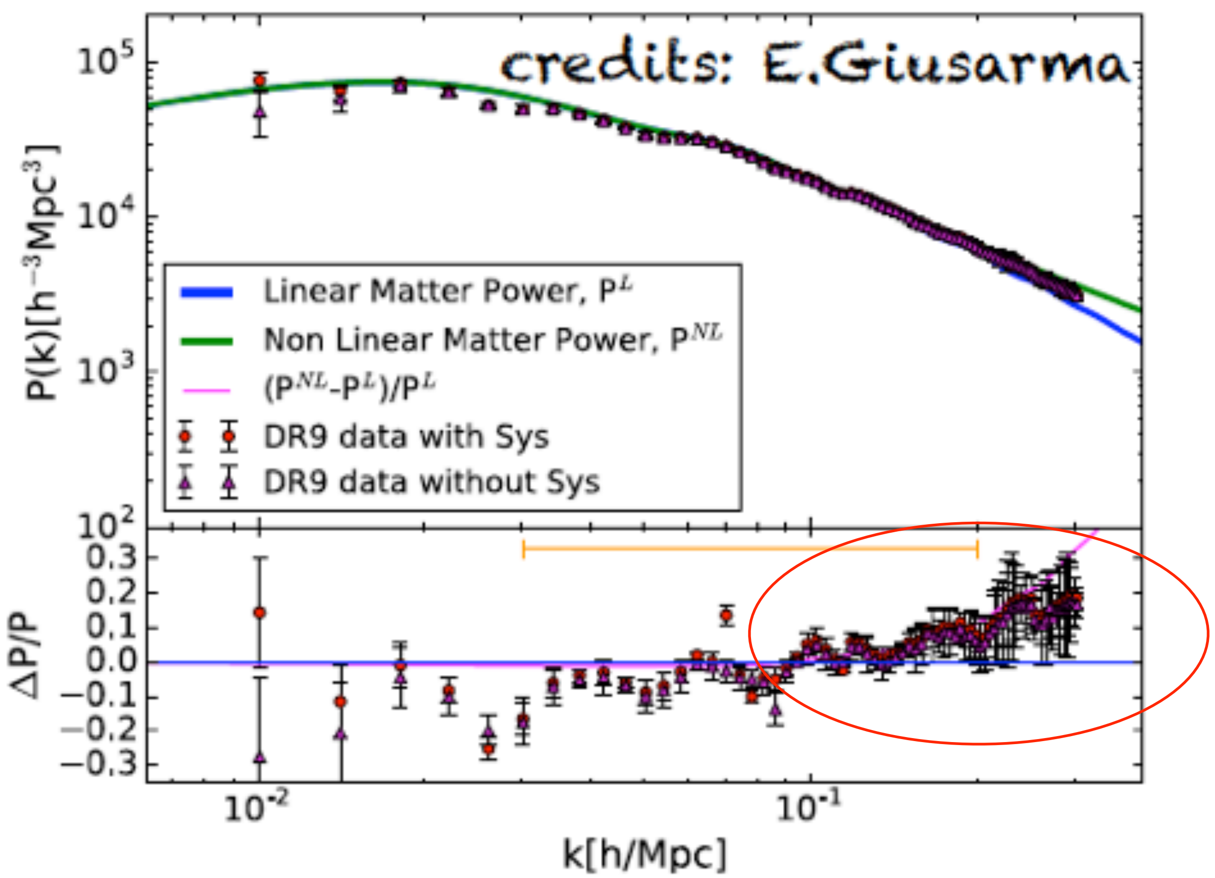
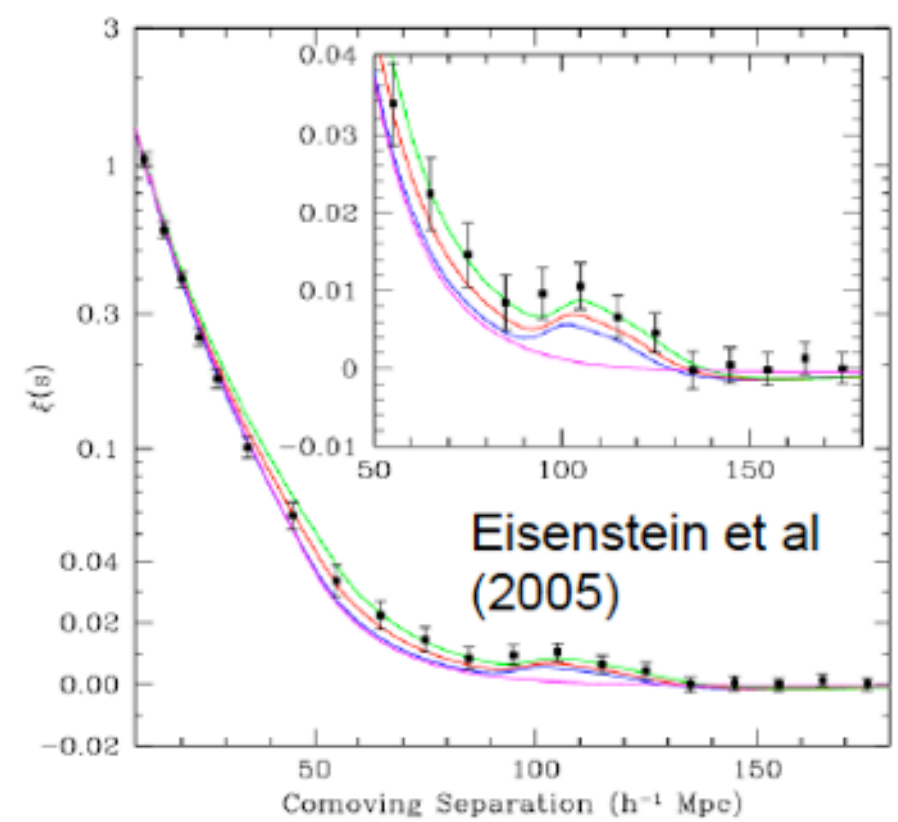


Image Credit: M. Blanton and the Sloan Digital Sky Survey.





95% constraints on total mass	PlanckTT	PlanckTTTEEE
+lowP	<0.72 eV	<0.49 eV
+lowP+lensing	<0.68 eV	<0.59 eV
+lowP+BAO	<0.21 eV	<0.17 eV
+lowP+ext	<0.20 eV	<0.15 eV
+lowP+lensing+ext	<0.23 eV	<0.19 eV

Cosmology constraints can be combined with data from oscillation experiments

$$m_\beta \equiv \left[\sum |U_{ei}|^2\, m_i^2\right]^{1/2}$$

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