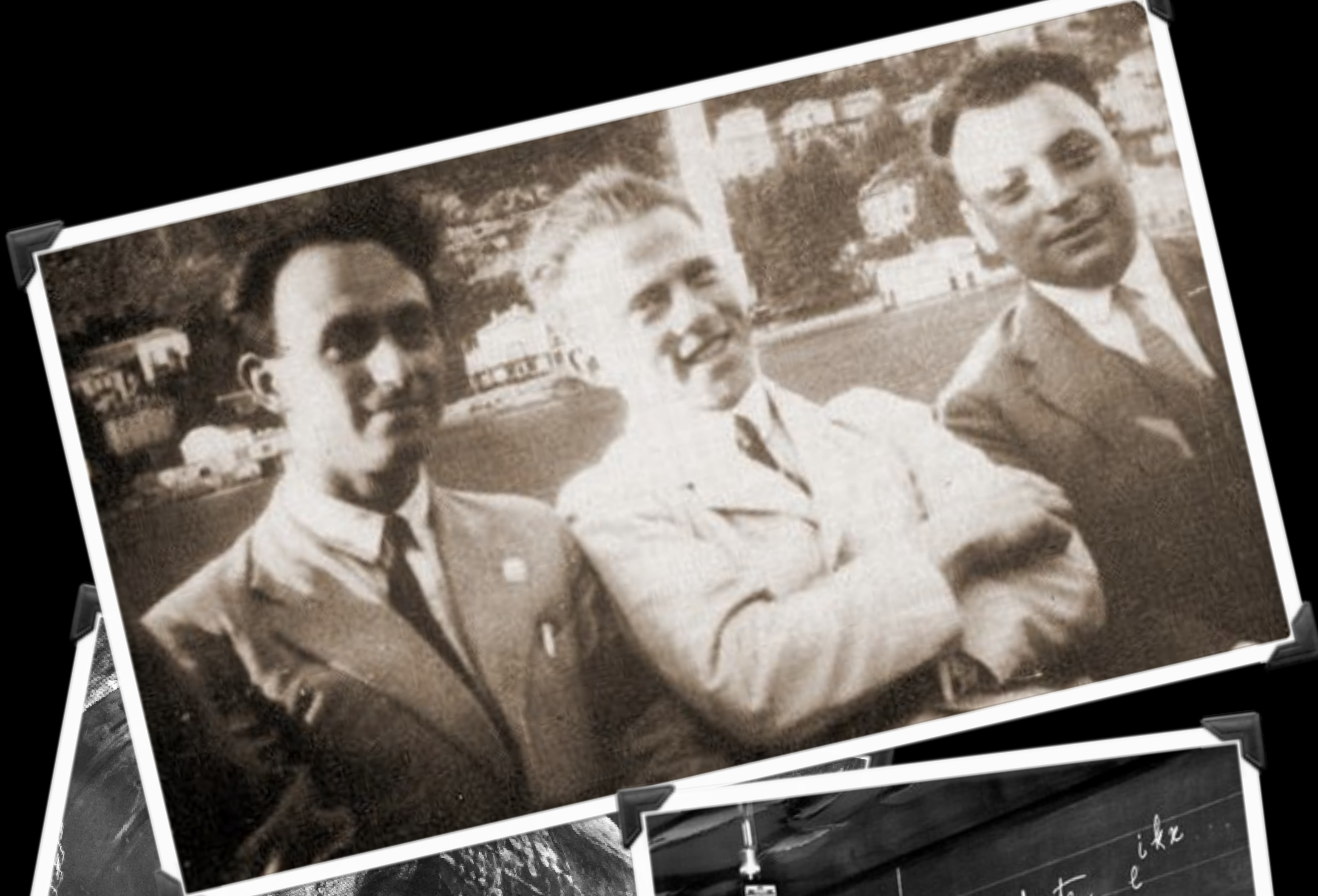
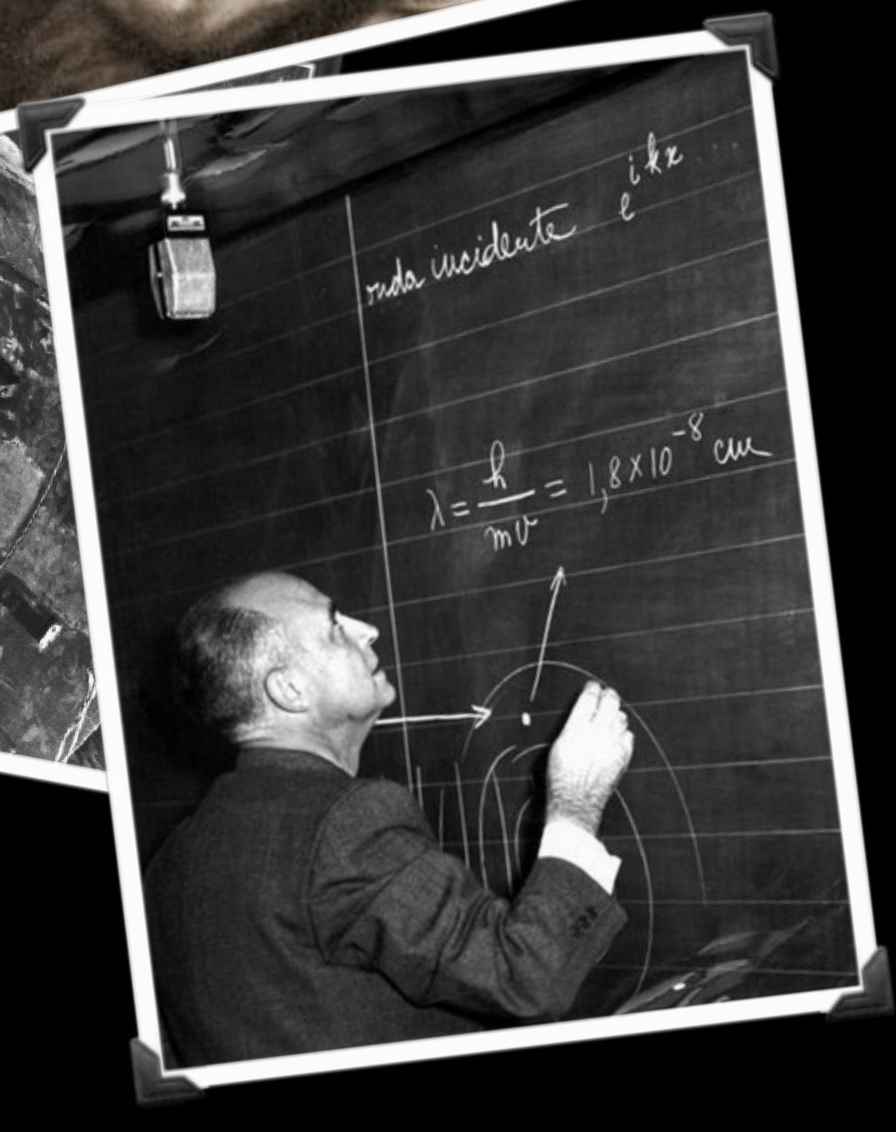


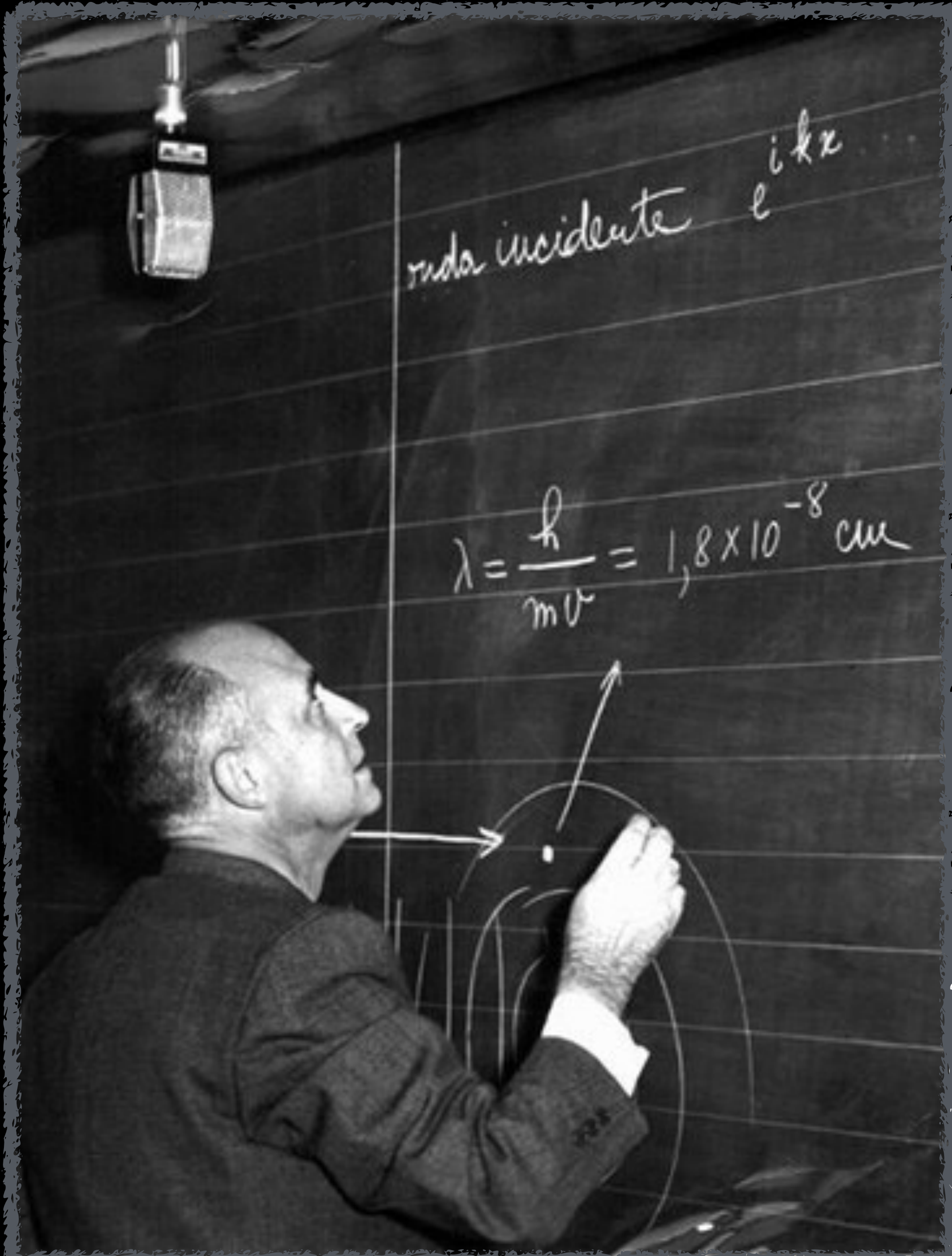

onda incidente e^{ikx}
$\lambda = \frac{h}{mv} = 1,8 \times 10^{-8}$ cm

Weighting Neutrinos

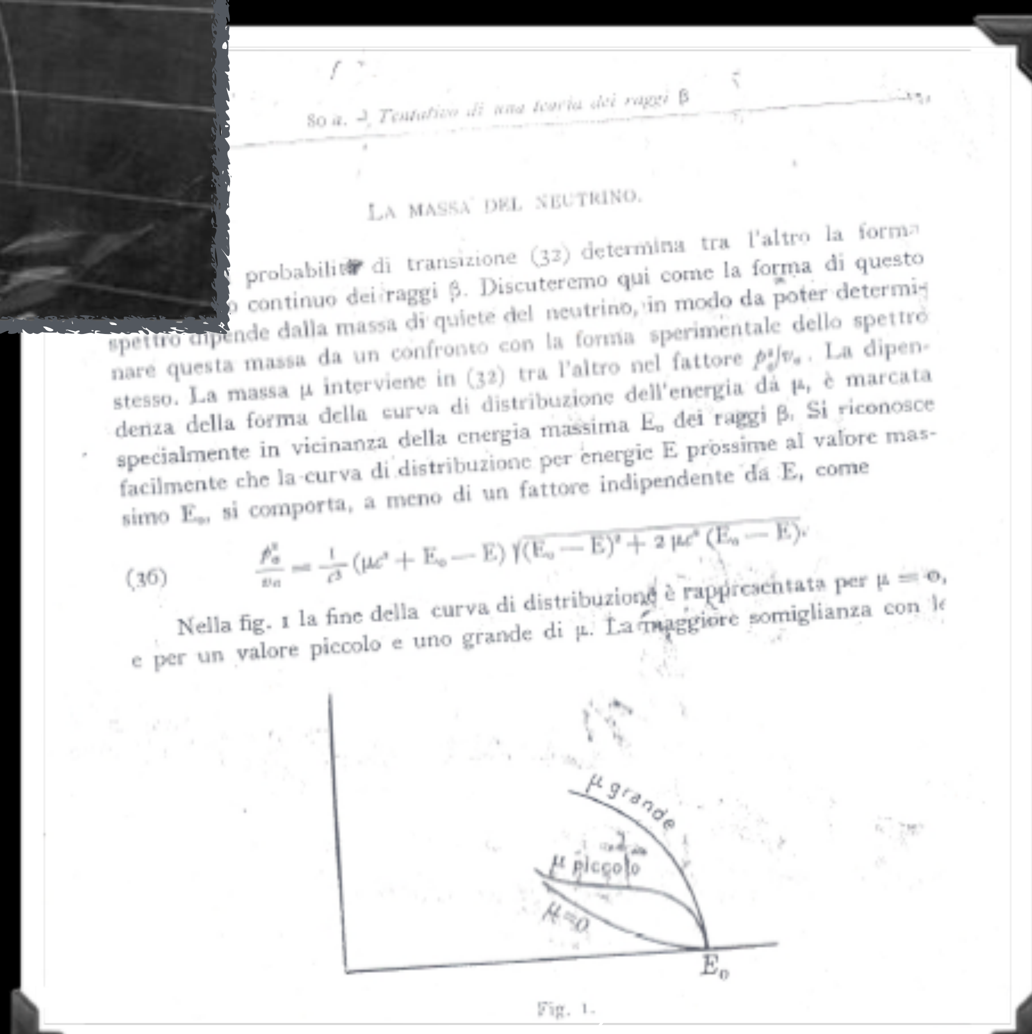
National Nuclear Physics Summer School

July 29th 2016

Joseph A. Formaggio
MIT



Neutrino mass measurements have a long history in physics, predating the Standard Model itself.



80 a. - Tentativo di una teoria dei raggi β

LA MASSA DEL NEUTRINO.

... probabilità di transizione (32) determina tra l'altro la forma ... continuo dei raggi β. Discuteremo qui come la forma di questo spettro dipende dalla massa di quiete del neutrino, in modo da poter determinare questa massa da un confronto con la forma sperimentale dello spettro stesso. La massa μ interviene in (32) tra l'altro nel fattore p_σ^2/v_σ. La dipendenza della forma della curva di distribuzione dell'energia da μ, è marcata specialmente in vicinanza della energia massima E_0 dei raggi β. Si riconosce facilmente che la curva di distribuzione per energie E prossime al valore massimo E_0, si comporta, a meno di un fattore indipendente da E, come

$$\frac{p_\sigma^2}{v_\sigma} = \frac{1}{c^3}(\mu c^2 + E_0 - E)\sqrt{(E_0 - E)^2 + 2\mu c^2 (E_0 - E)}. \quad (36)$$

Nella fig. 1 la fine della curva di distribuzione è rappresentata per μ = 0, e per un valore piccolo e uno grande di μ. La maggiore somiglianza con le

Fig. 1.

$$\frac{1}{c^3}(\mu c^2 + E_0 - E)\sqrt{(E_0 - E)^2 + 2\mu c^2 (E_0 - E)}.$$

a fine della curva di distribuzione è rappresentata per $\mu = 0$, piccolo e uno grande di μ. La maggiore somiglianza con le

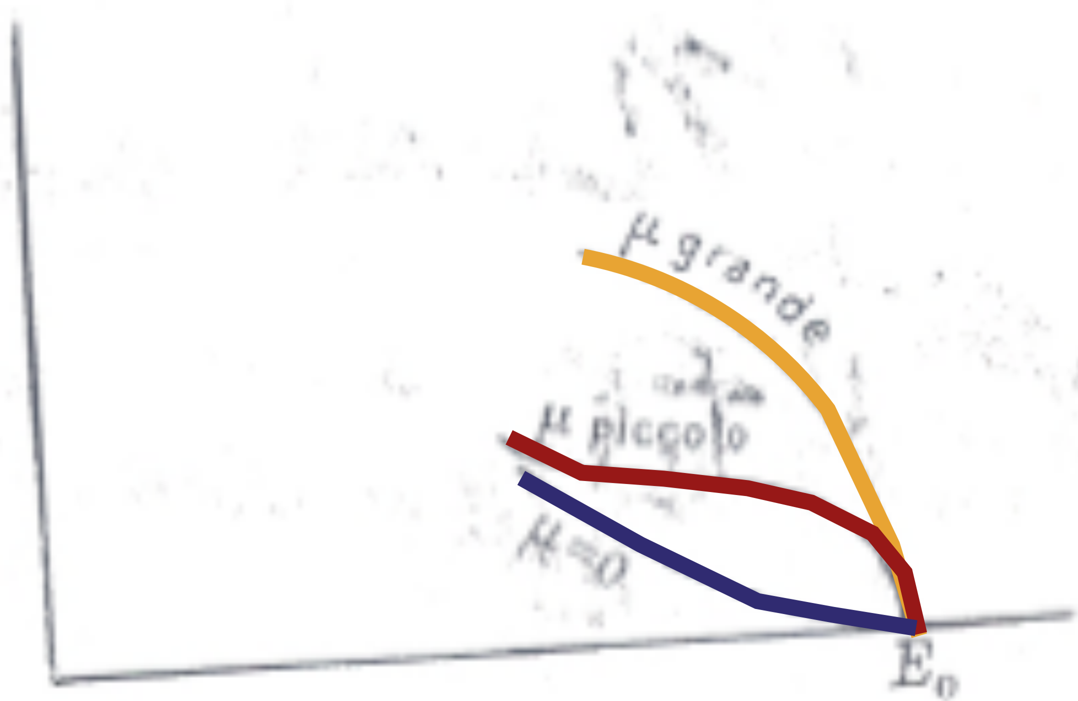


Fig. 1.

We have learned one thing in this time.

"Grande" is ruled out.

And now, so is "Zero".

$$\frac{1}{c^3}(\mu c^2 + E_0 - E)\sqrt{(E_0 - E)^2 + 2\mu c^2 (E_0 - E)}.$$

a fine della curva di distribuzione è rappresentata per $\mu = 0$,
piccolo e uno grande di μ. La maggiore somiglianza con le

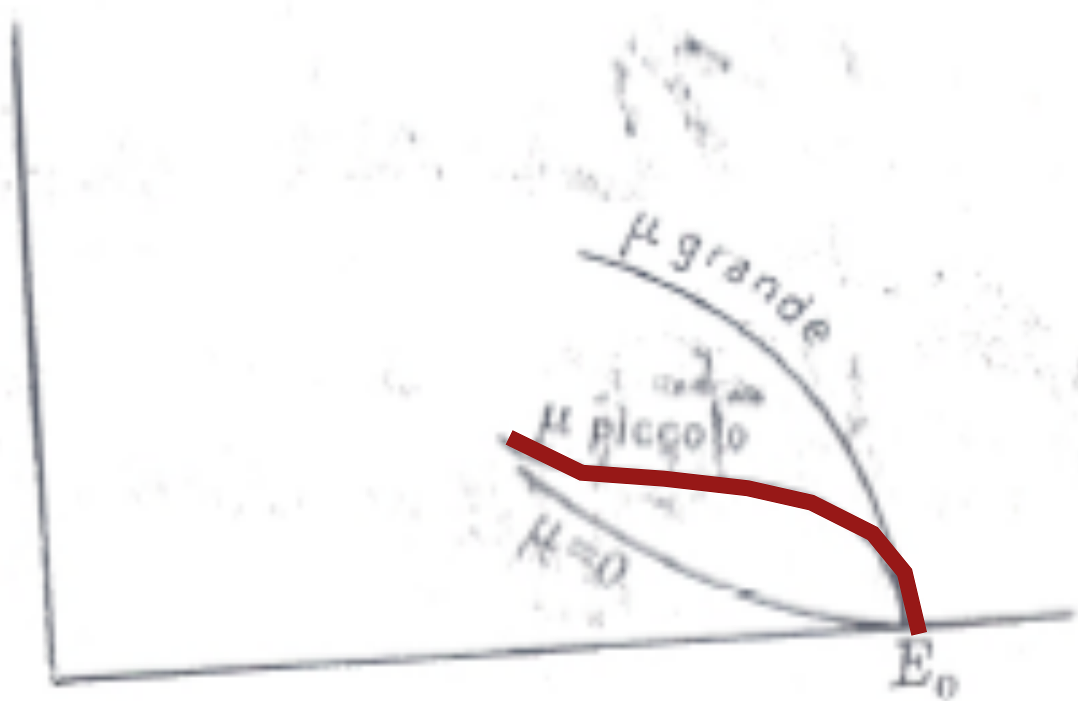


Fig. 1.

We have learned one thing in this time.

"Grande" is ruled out.

And now, so is "Zero".

First Evidence

A Crack in the Standard Model

Neutrino Oscillations

- From Monday's lecture you learned that oscillations are described by a 3 x 3 matrix(the Maki-Nakagawa-Sakata-Pontecorvo, or MNSP mixing matrix):

- However, the picture simplifies if one of the mixing angles is small...

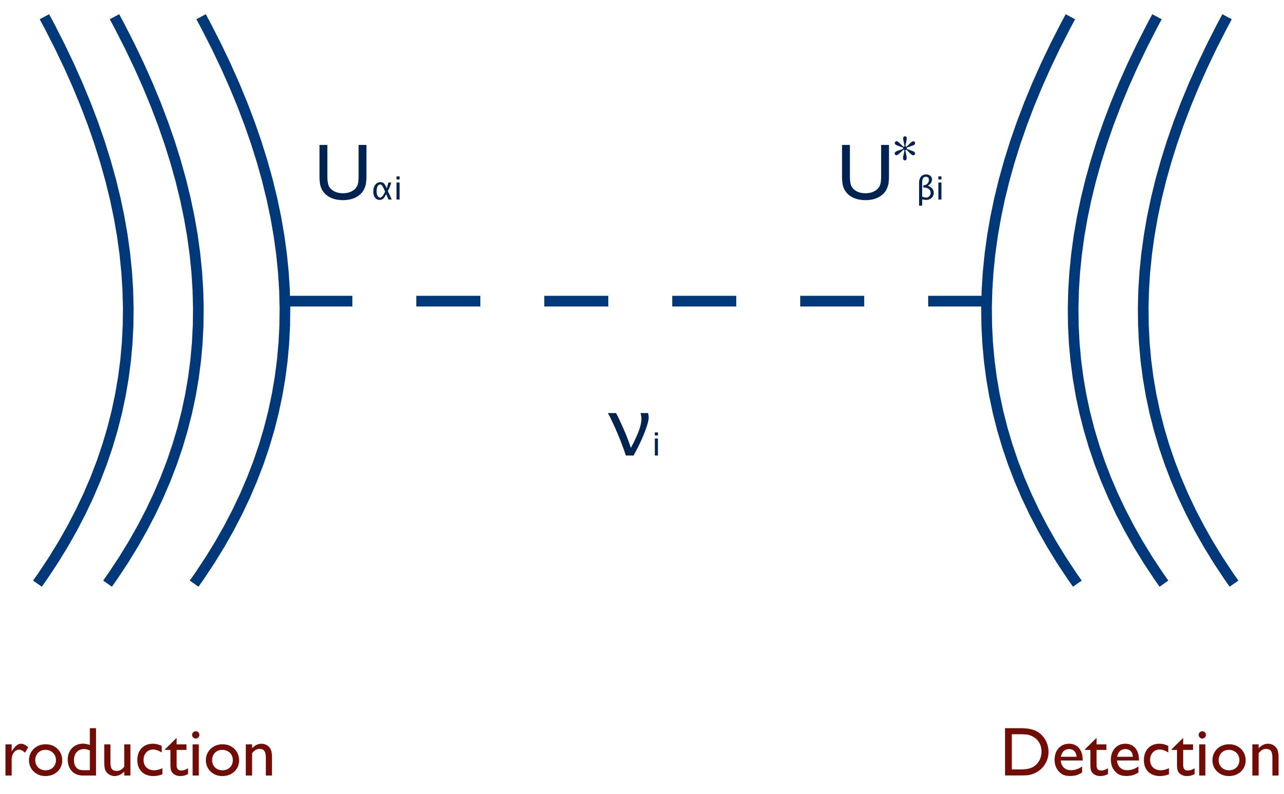
Bruno Pontecorvo

$$= \underbrace{\begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_{23} & \sin\theta_{23} \\ 0 & -\sin\theta_{23} & \cos\theta_{23} \end{pmatrix}}_{\text{atmospheric, long baseline}} \times \underbrace{\begin{pmatrix} \cos\theta_{13} & 0 & e^{-i\delta_{CP}}\sin\theta_{13} \\ 0 & 1 & 0 \\ -e^{i\delta_{CP}}\sin\theta_{13} & 0 & \cos\theta_{13} \end{pmatrix}}_{\text{reactor, accelerator}} \times \underbrace{\begin{pmatrix} \cos\theta_{12} & \sin\theta_{12} & 0 \\ -\sin\theta_{12} & \cos\theta_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}}_{\text{solar, KamLAND}} \times \underbrace{\begin{pmatrix} 1 & 0 & 0 \\ 0 & e^{i\alpha/2} & 0 \\ 0 & 0 & e^{i\alpha/2+i\beta} \end{pmatrix}}_{0\nu\beta\beta}$$

- Depends only on two fundamental parameter and two experimental parameters (for a given neutrino species).

$$\mathcal{P}_{\rm surv} = 1 - \sin^2 2\theta \sin^2 (\frac{\Delta m^2}{4E_\nu} L)$$

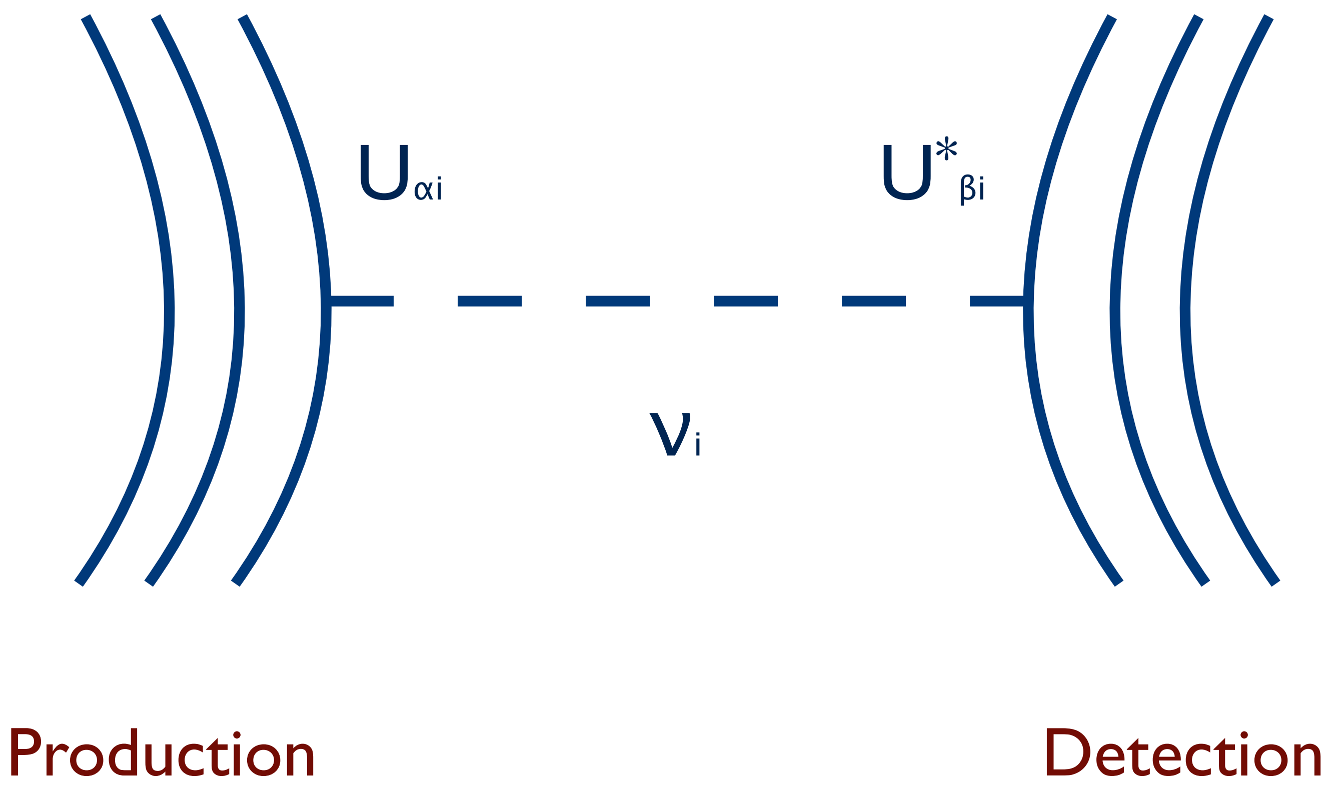
How to Think About Oscillations?



Oscillations are fundamentally a QUANTUM phenomena.

It is useful to cast it in such a framework. For example, one could cast it in the language of Quantum Field Theory

How to Think About Oscillations?



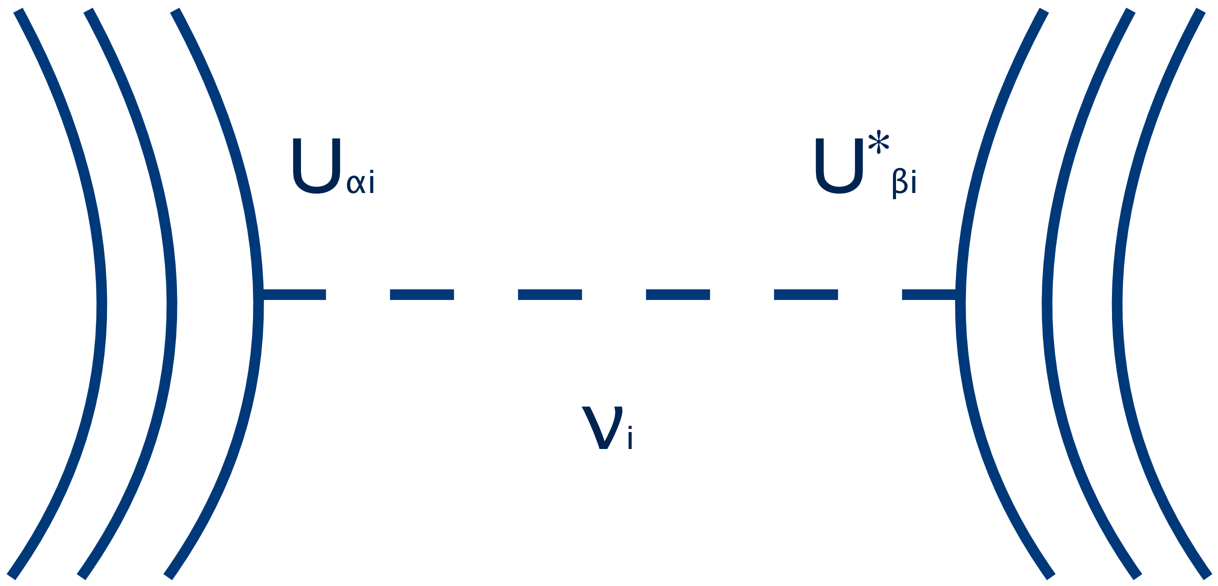
We can treat the neutrino as a propagating fermion...

See J. Kopp, arXiv:0904.4346

Oscillations are fundamentally a QUANTUM phenomena.

It is useful to cast it in such a framework. For example, one could cast it in the language of Quantum Field Theory

How to Think About Oscillations?

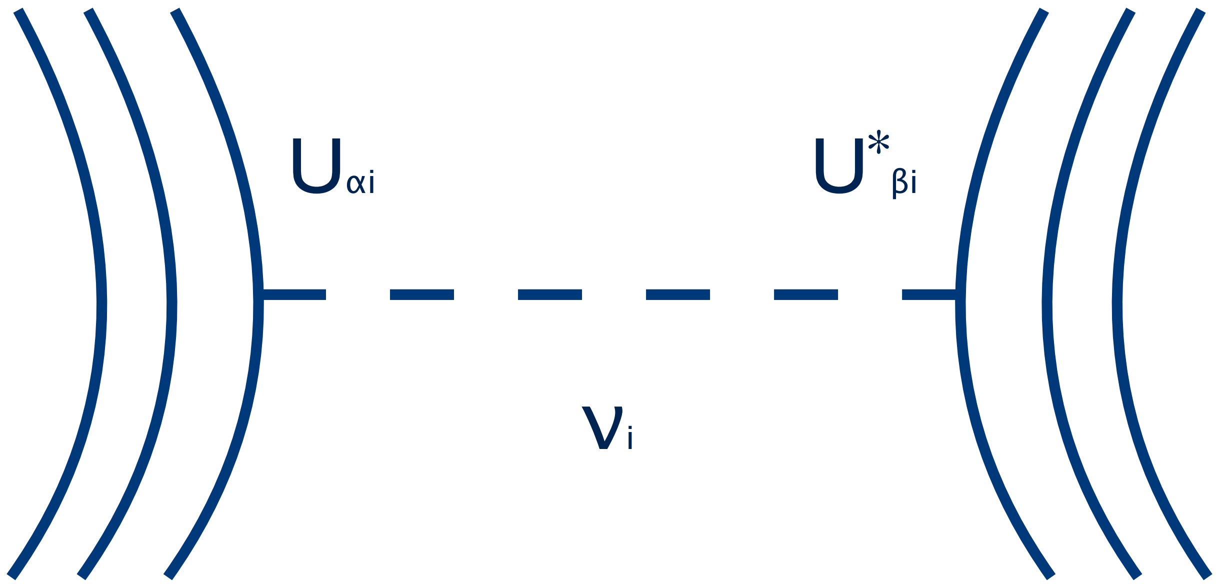


$$i\mathcal{M} \propto$$

Matrix element

Thus the matrix element picks up a propagating term that depends on the neutrino mass and coupling

How to Think About Oscillations?



Thus the matrix element picks up a propagating term that depends on the neutrino mass and coupling

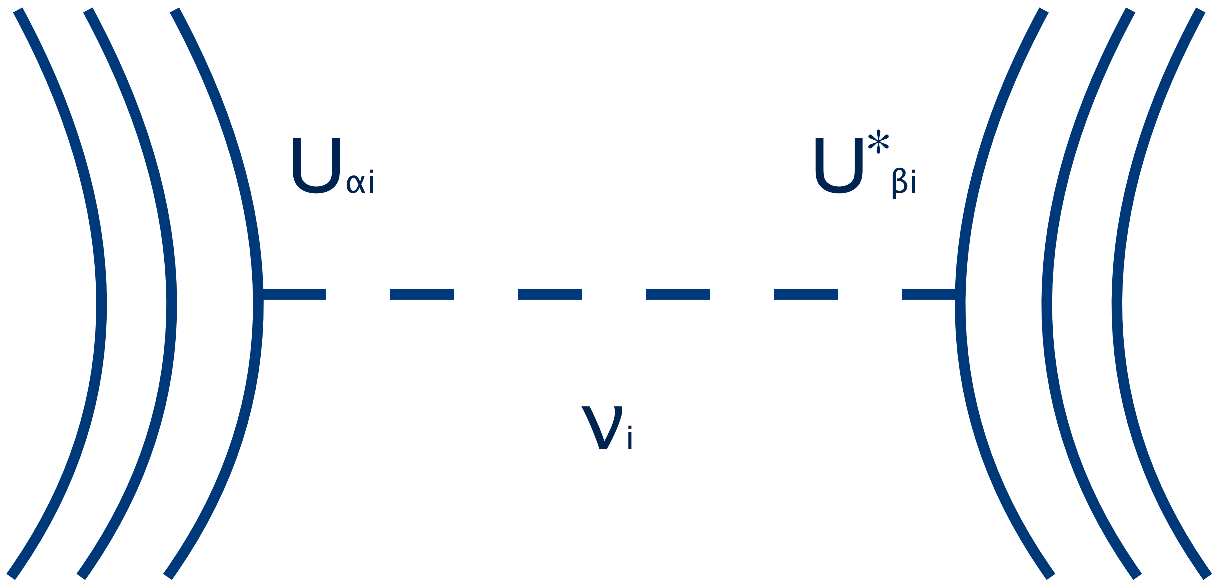
$$i\mathcal{M} \propto$$

Matrix element

$$\int \frac{d^4p}{(2\pi)^4} e^{ip_0(t_D - t_P) + i\vec{p}\cdot(\vec{x}_D - \vec{x}_P)}$$

Energy conservation

How to Think About Oscillations?



Thus the matrix element picks up a propagating term that depends on the neutrino mass and coupling

$$i\mathcal{M} \propto$$ Matrix element

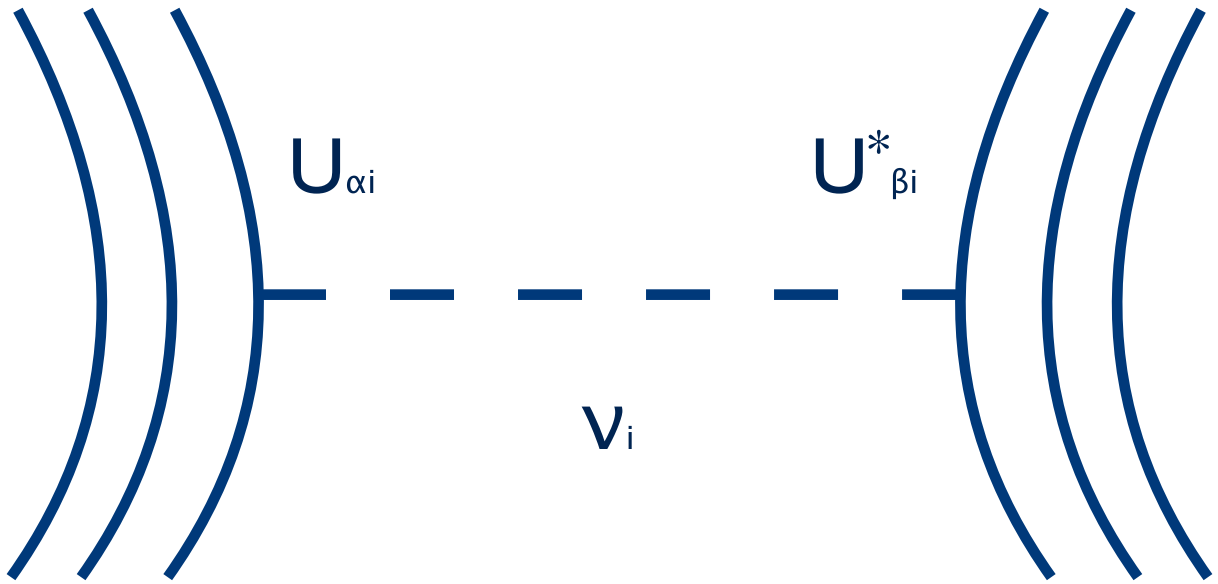
$$\int \frac{d^4p}{(2\pi)^4} e^{ip_0(t_D - t_P) + i\vec{p}\cdot(\vec{x}_D - \vec{x}_P)}$$ Energy conservation

$$U_{\alpha,i} U^*_{\beta,i} \bar{u}_{\alpha,P} \gamma_\mu (1 - \gamma^5)$$ Couplings, production wave function

$$\frac{i(\not{p} + m_i)}{p_0^2 - \vec{p}^2 - m_i^2 + i\epsilon}$$ Fermion propagator

$$(1 + \gamma^5)\gamma_\nu u_{\alpha,D}$$ Detection wave function

How to Think About Oscillations?

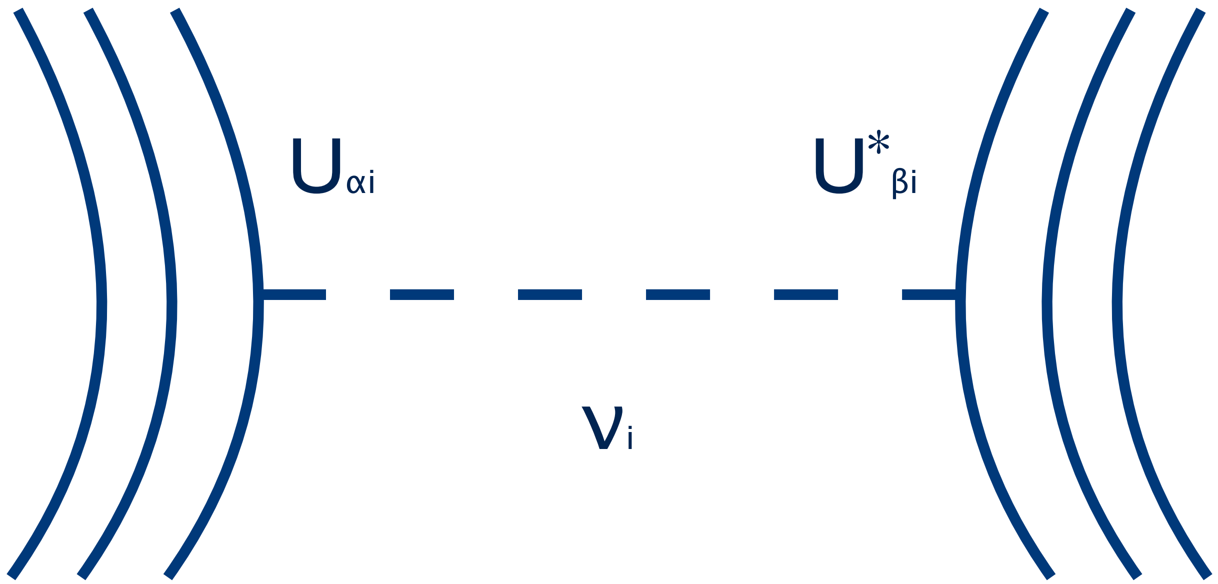


Use the Grimus-Stockinger theorem to simplify the propagator term...

Let $\psi(\vec{p})$ be a three times continuously differentiable function on $\mathbb{R}^3$, such that ψ itself and all its first and second derivatives decrease at least like $1/|\vec{p}|^2$ for $|\vec{p}| \to \infty$. Then, for any real number $A > 0$,

$$\int d^3p \, \frac{\psi(\vec{p}) \, e^{i\vec{p}\vec{L}}}{A - \vec{p}^2 + i\epsilon} \xrightarrow{|\vec{L}|\to\infty} -\frac{2\pi^2}{L}\psi(\sqrt{A}\tfrac{\vec{L}}{L})e^{i\sqrt{A}L} + \mathcal{O}(L^{-\frac{3}{2}}).$$

How to Think About Oscillations?



Sum over all contributing terms (i.e. all mass states!)

Result takes on the more familiar form...

$$i\mathcal{M} \propto \sum_i U_{\alpha i} U^*_{\beta i} e^{i\sqrt{E^2 - m_i^2}L}$$

Phase shift due to masses

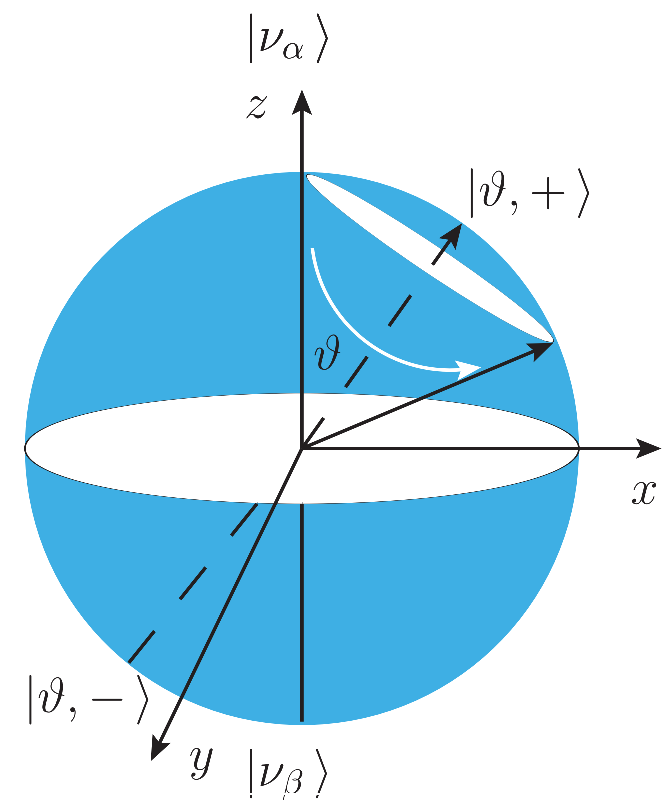
$$|\mathcal{M}|^2 \propto \sum_{i,j} U_{\alpha i} U^*_{\beta j} U^*_{\alpha i} U_{\beta j} e^{i(\sqrt{E^2 - m_i^2} - \sqrt{E^2 - m_j^2})L}$$

Oscillation probability

How to Think About Oscillations?

Poincare Sphere

See P. Mehta, arXiv:0901.0790



$$\mathcal{H} = \left(p + \frac{m_1^2 + m_2^2}{4p} + \frac{V_C}{2} + V_N\right)\mathcal{I} + \frac{1}{2}\begin{pmatrix} V_C - \omega\cos 2\theta & \omega\sin 2\theta \\ \omega\sin 2\theta & \omega\cos 2\theta - V_C \end{pmatrix}$$

OR... you can cast things in terms of Pauli matrices (equivalent to quantum optics)

How to Think About Oscillations?

$$\mathcal{H} = \left(p + \frac{m_1^2 + m_2^2}{4p} + \frac{V_C}{2} + V_N\right)\mathcal{I} + \frac{1}{2}\begin{pmatrix} V_C - \omega\cos 2\theta & \omega\sin 2\theta \\ \omega\sin 2\theta & \omega\cos 2\theta - V_C \end{pmatrix}$$

$$\omega \equiv (m_2^2 - m_1^2)/2p$$

$$\mathbb{H} = \mathcal{A}\sigma_x + \mathcal{B}\sigma_y + \mathcal{C}\sigma_z + \mathcal{D}\mathbb{I} = r_0\mathcal{I} + \frac{\vec{r}\cdot\vec{\sigma}}{2}$$

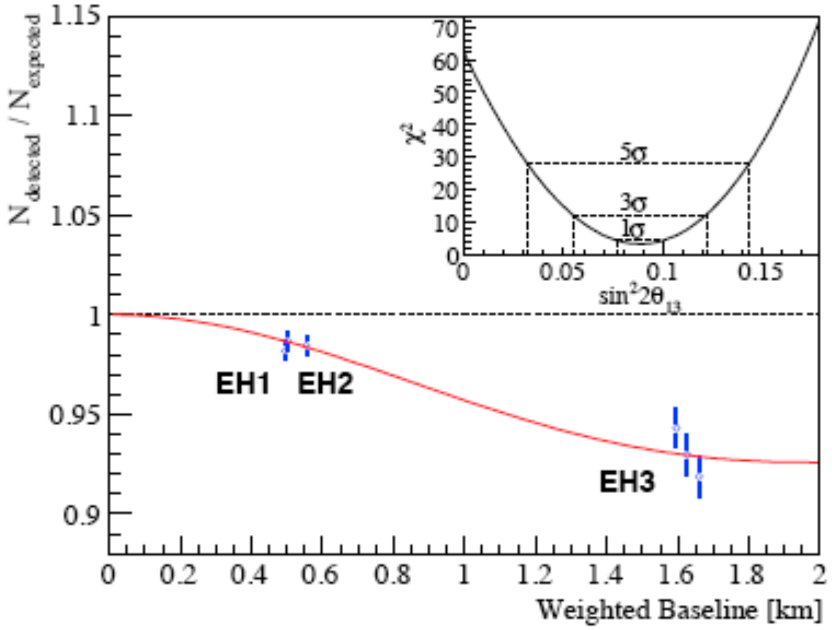
Here, σ represents the Pauli matrices and r is a vector that points along a Poincare sphere

OR... you can cast things in terms of Pauli matrices (equivalent to quantum optics)

Oscillations then cast as a property that Pauli matrices do not commute

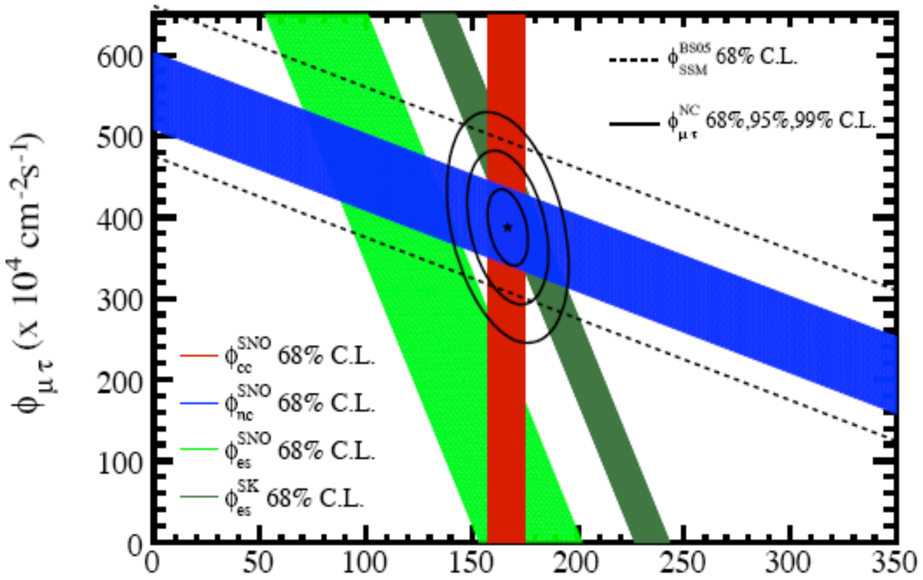
With oscillations firmly in place, we at least understand that the neutrino has a mass

As such, oscillation measurements place a lower limit on the neutrino mass scale.



$$\sin^2(2\theta_{13}) = 0.093 \pm 0.008$$

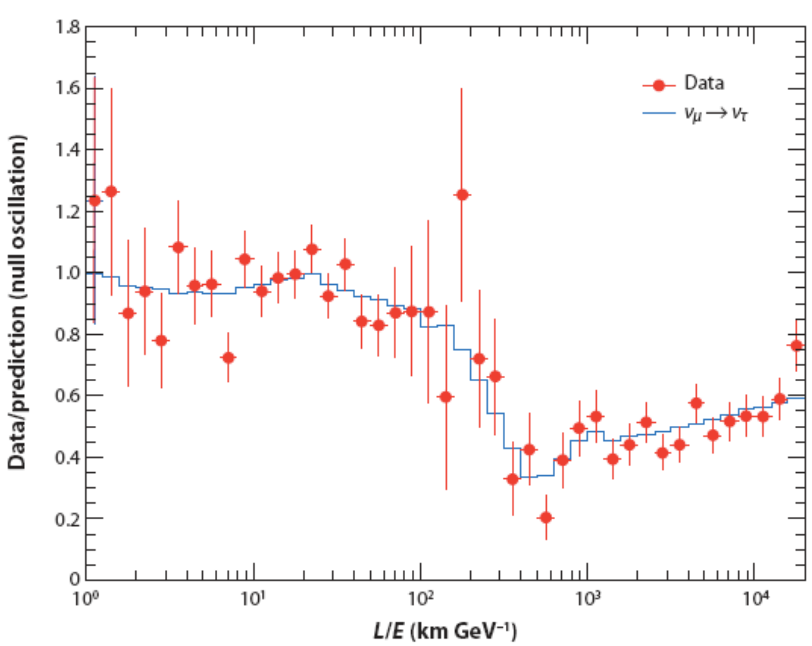
Reproducing Reactor & Long Baseline



$$\sin^2(2\theta_{12}) = 0.846 \pm 0.021$$

$$\Delta m^2_{21} = (7.53 \pm 0.18) \times 10^{-5} \text{ eV}^2$$

Solar



$$\sin^2(2\theta_{23}) = 0.999^{+0.001}_{-0.018}$$

$$\Delta m^2_{32} = 0.00244 \pm 0.00006 \text{ eV}^2$$

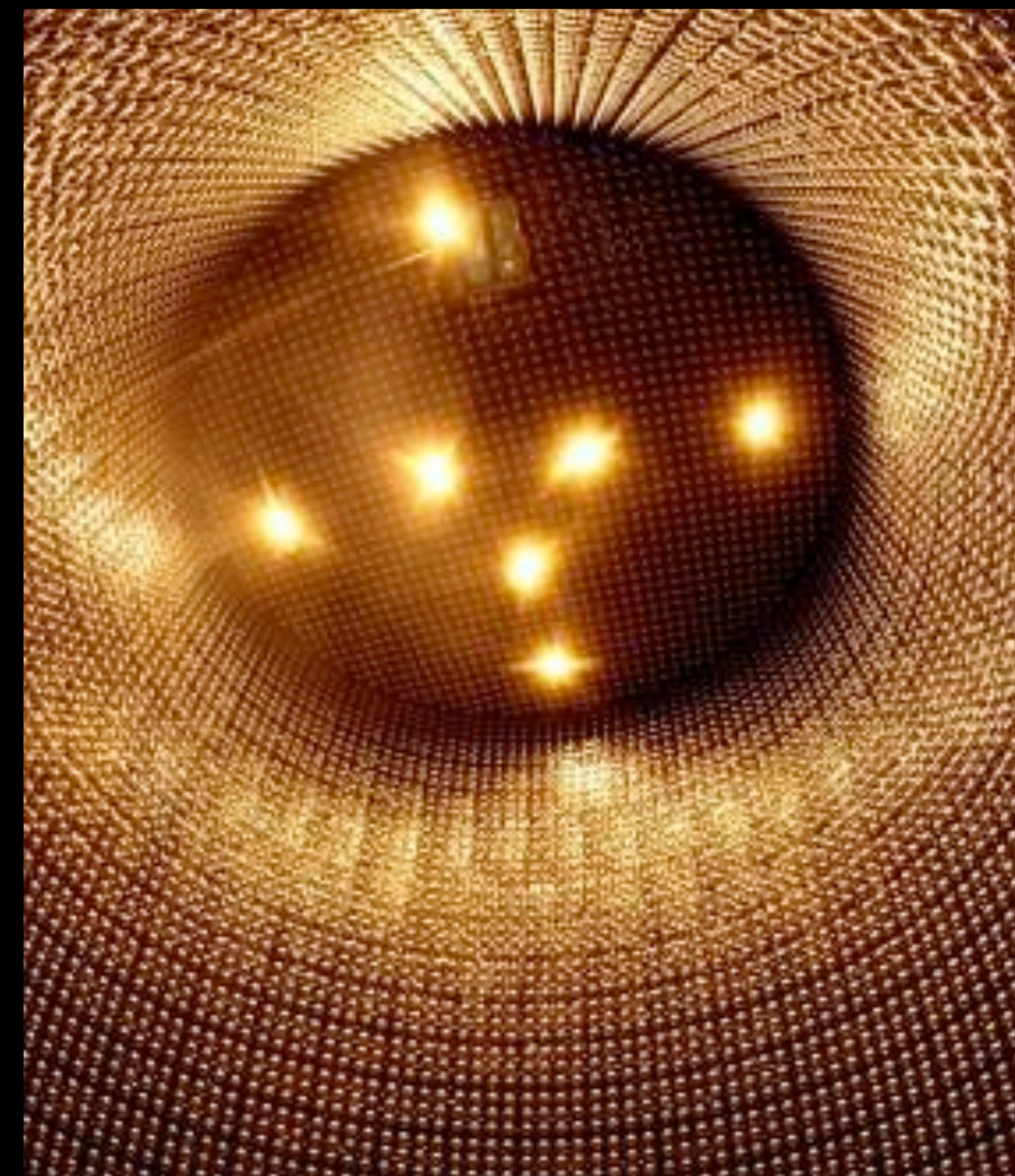
Atmospheric

Camilieri, Lisi, Wilkerson Ann. Rev. 57 (2008).
Fogli et al, arXiv:1205.5254 (hep-ph)

With oscillations firmly in place, we at least understand that the neutrino has a mass

As such, oscillation measurements place a lower limit on the neutrino mass scale.

2015 Nobel Prize in Physics

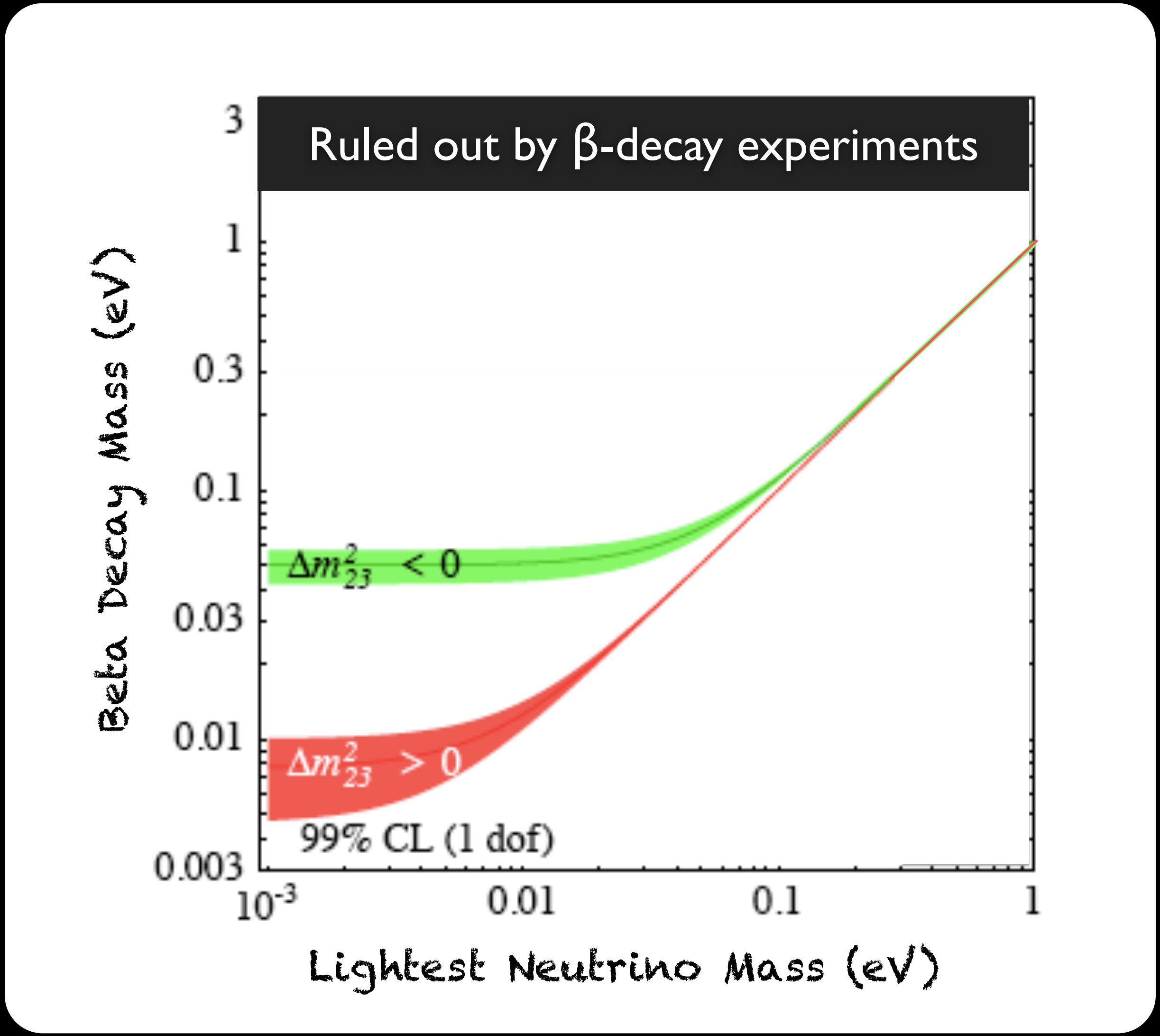


Arthur B. McDonald
(Sudbury Neutrino Observatory)

Takaaki Kajita
(Super-Kamiokande)

Measuring Neutrino Masses

Oscillations now make a prediction upon other measurements.



$$M = \sum_i^{n_\nu} m_{\nu,i}$$

Cosmological Measurements

$$\langle m^2_{\beta\beta} \rangle = \left| \sum_i^{n_\nu} U^2_{ei} m_{\nu,i} \right|^2$$

0νββ Measurements

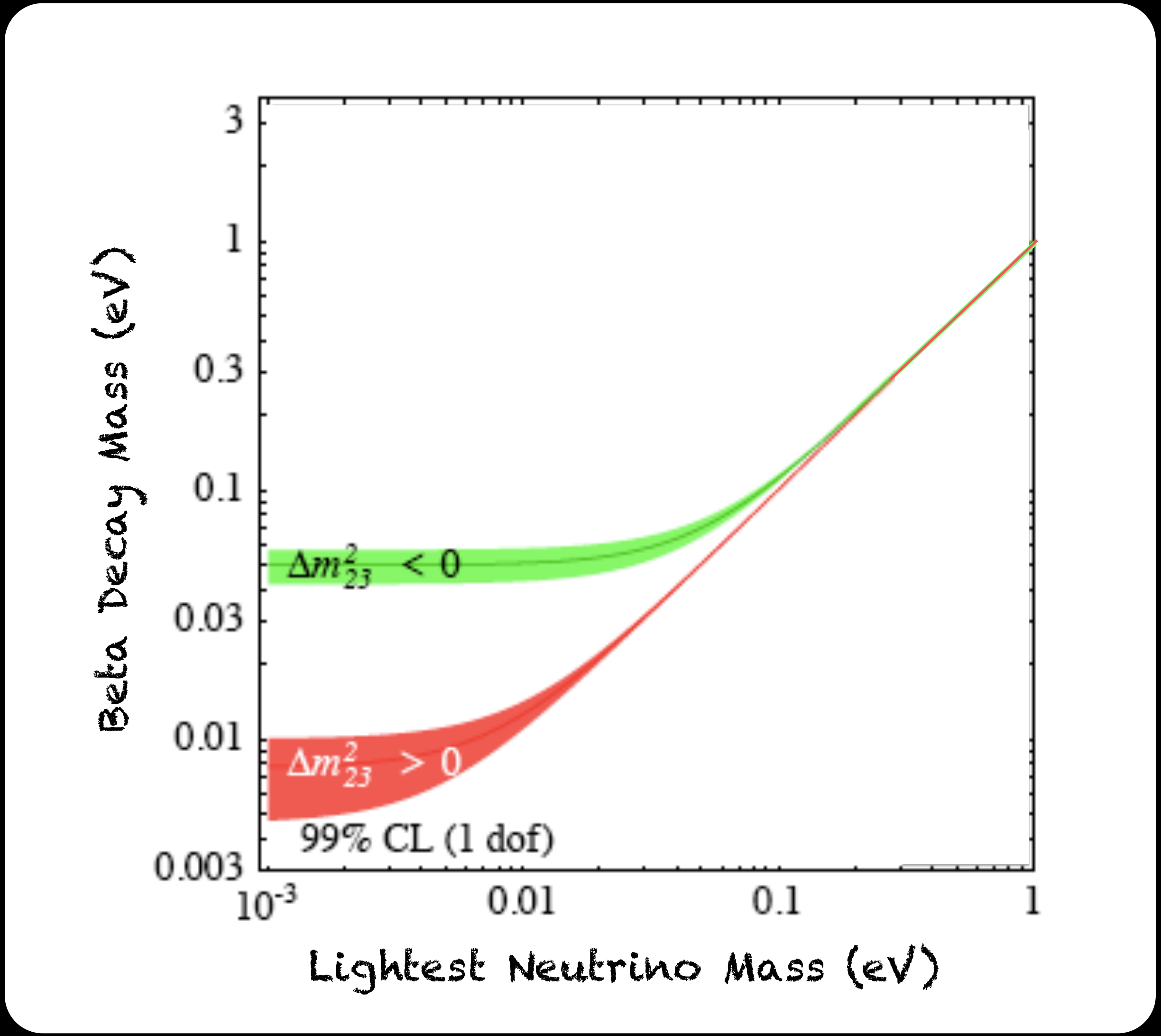
$$\langle m_\beta \rangle^2 = \sum_i^{n_\nu} | U_{ei} |^2 \, m^2_{\nu,i}$$

Beta Decay Measurements

The Neutrino Mass Scale

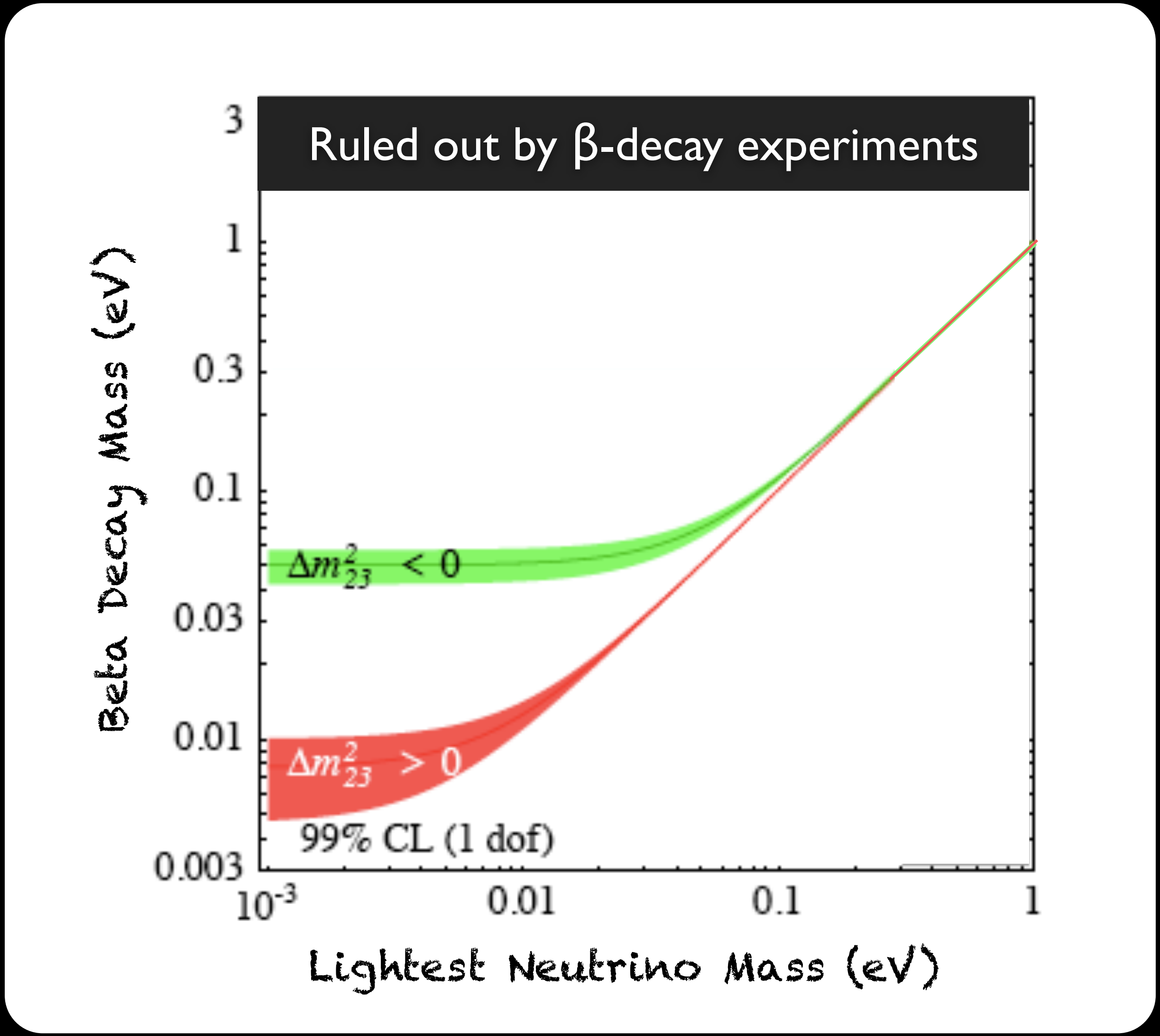
- The neutrino mass scale remains one of the essential "unknowns" of the Standard Model.

- Knowledge of neutrino masses can have a significant impact on many different arenas, including cosmology, the mass hierarchy, sterile neutrinos, and even relic neutrino detection.



The Neutrino Mass Scale

- The neutrino mass scale remains one of the essential "unknowns" of the Standard Model.
- Knowledge of neutrino masses can have a significant impact on many different arenas, including cosmology, the mass hierarchy, sterile neutrinos, and even relic neutrino detection.

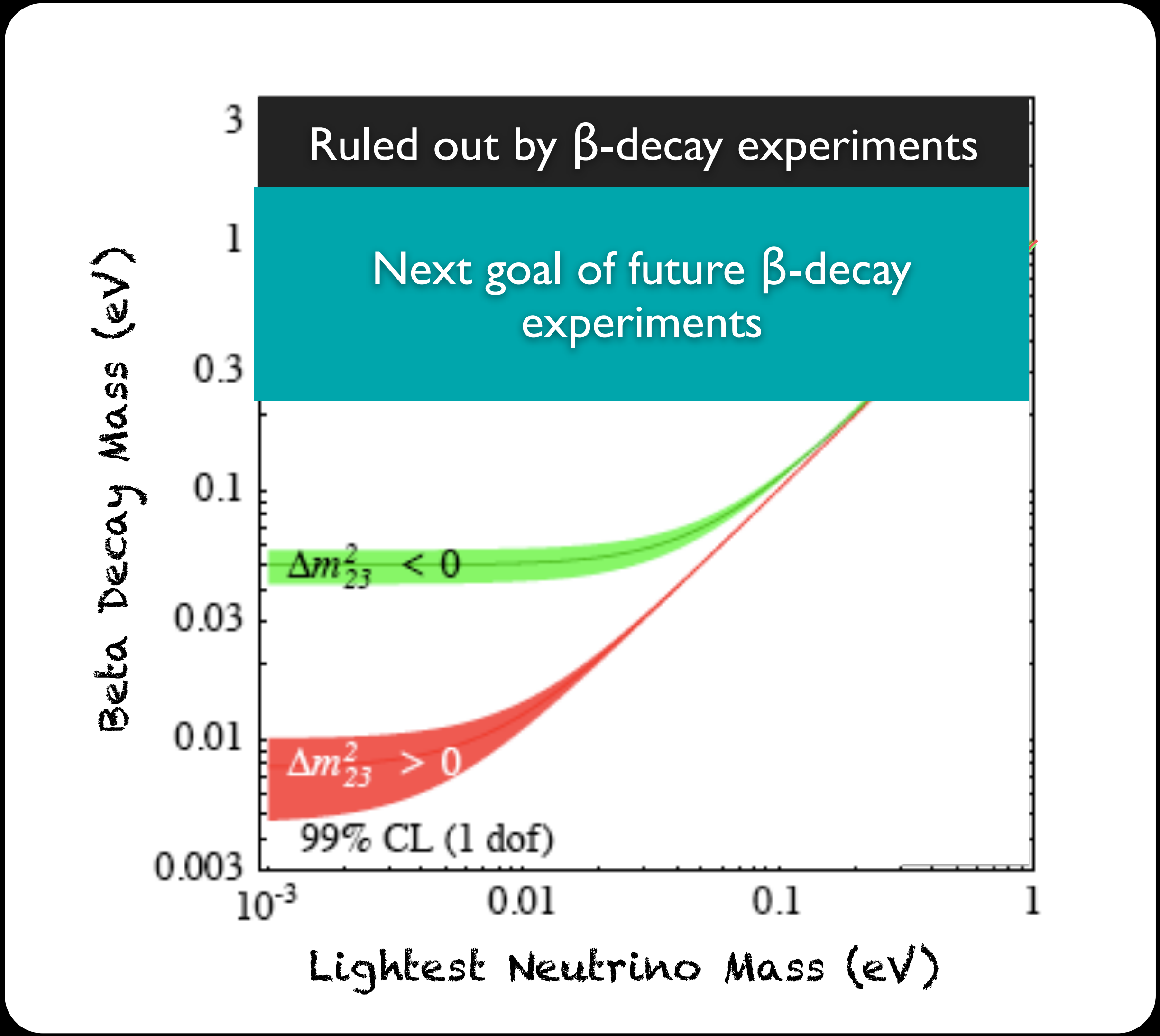


<u>m_ν > 2 eV (eV scale, current)</u>

Neutrinos ruled out as dark matter

The Neutrino Mass Scale

- The neutrino mass scale remains one of the essential "unknowns" of the Standard Model.
- Knowledge of neutrino masses can have a significant impact on many different arenas, including cosmology, the mass hierarchy, sterile neutrinos, and even relic neutrino detection.



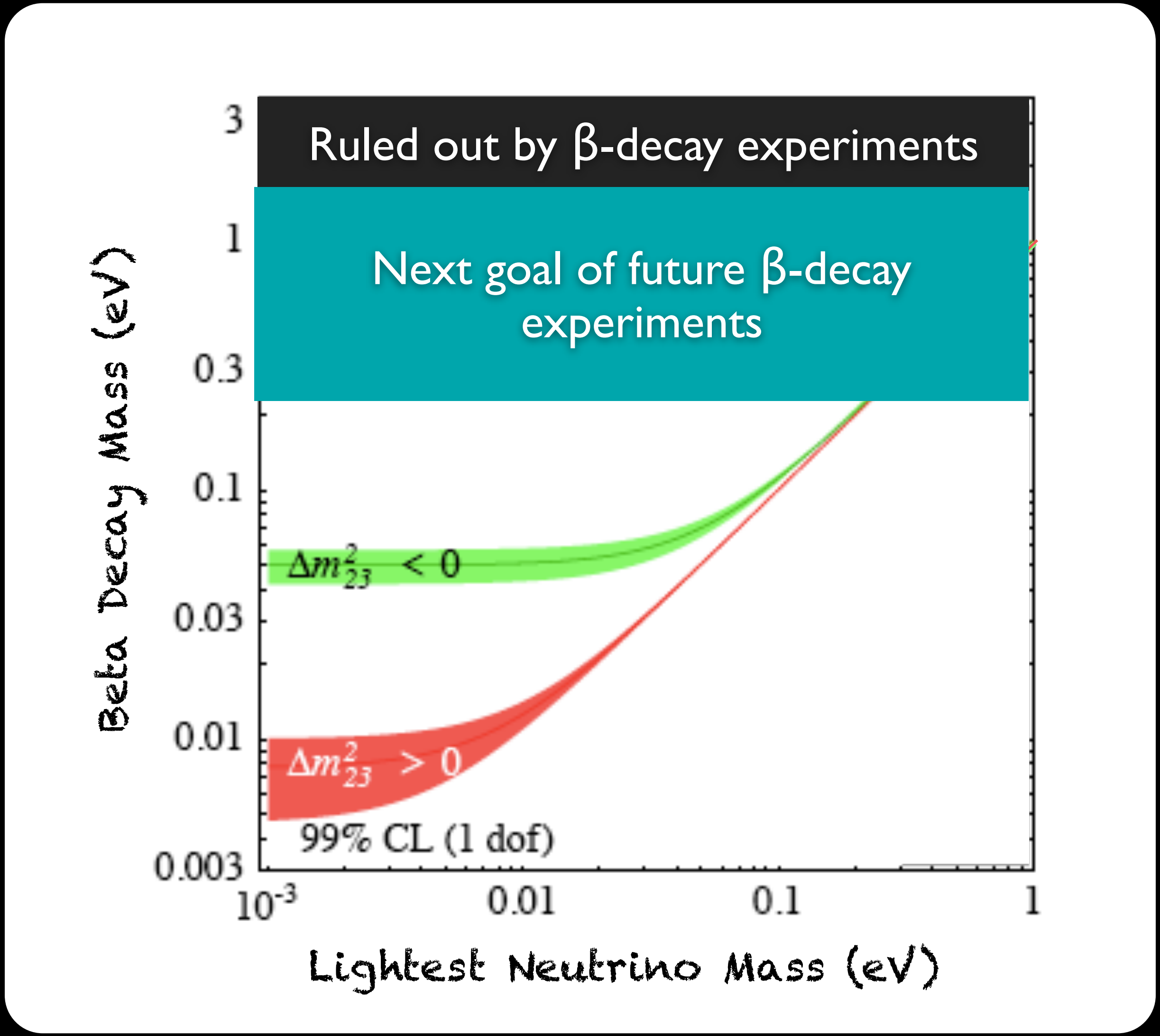
$m_\nu > 2$ eV (eV scale, current)
Neutrinos ruled out as dark matter

$m_\nu > 0.2$ eV (degeneracy scale)
Impact on cosmology and $0\nu\beta\beta$ reach

The Neutrino Mass Scale

- The neutrino mass scale remains one of the essential "unknowns" of the Standard Model.

- Knowledge of neutrino masses can have a significant impact on many different arenas, including cosmology, the mass hierarchy, sterile neutrinos, and even relic neutrino detection.



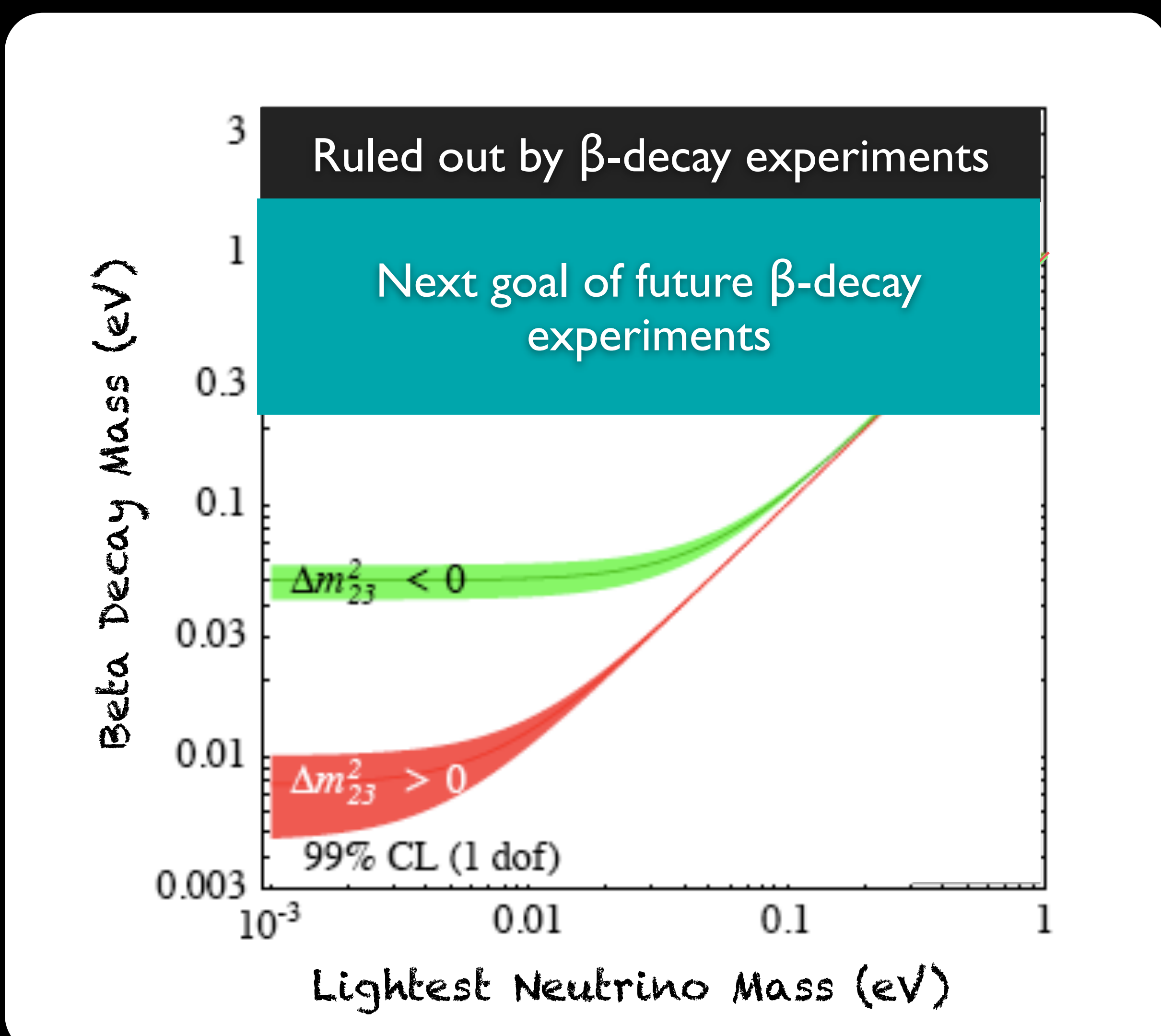
$m_\nu > 2$ eV (eV scale, current)
Neutrinos ruled out as dark matter

$m_\nu > 0.2$ eV (degeneracy scale)
Impact on cosmology and $0\nu\beta\beta$ reach

$m_\nu > 0.05$ eV (inverted hierarchy)
Resolve hierarchy if null result

The Neutrino Mass Scale

- The neutrino mass scale remains one of the essential "unknowns" of the Standard Model.
- Knowledge of neutrino masses can have a significant impact on many different arenas, including cosmology, the mass hierarchy, sterile neutrinos, and even relic neutrino detection.



<u>$m_\nu > 2$ eV (eV scale, current)</u>
Neutrinos ruled out as dark matter

<u>$m_\nu > 0.2$ eV (degeneracy scale)</u>
Impact on cosmology and $0\nu\beta\beta$ reach

<u>$m_\nu > 0.05$ eV (inverted hierarchy)</u>
Resolve hierarchy if null result

<u>$m_\nu > 0.01$ eV (normal hierarchy)</u>
Oscillation limit; possible $C\nu B$ detection

Wilson & Penzias

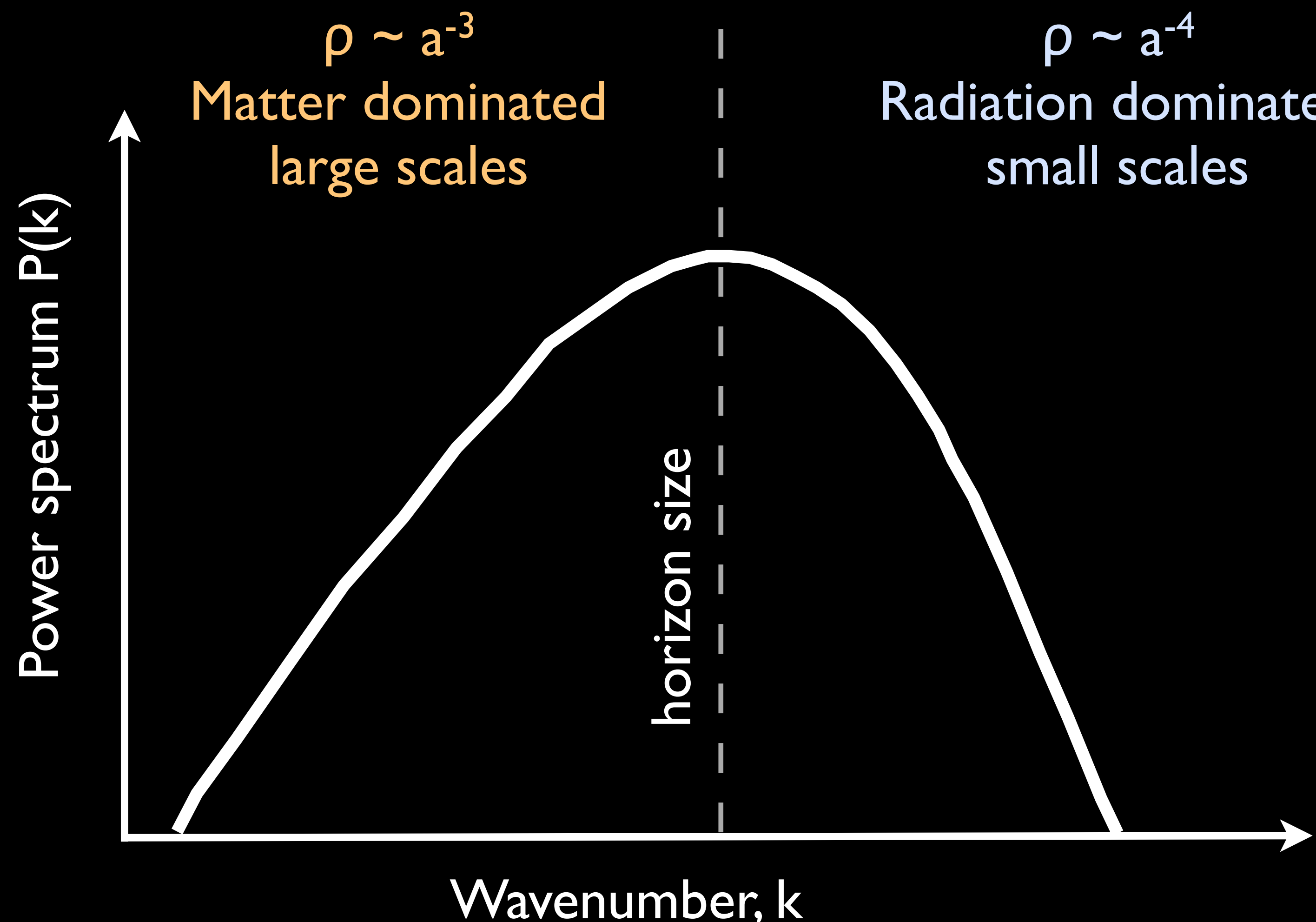
$$M = \sum_{i}^{n_\nu} m_{\nu,i}$$

Cosmological Measurements

The Era of Precision Cosmology

Cosmology has had a similar trajectory as neutrino physics, from inception to present day

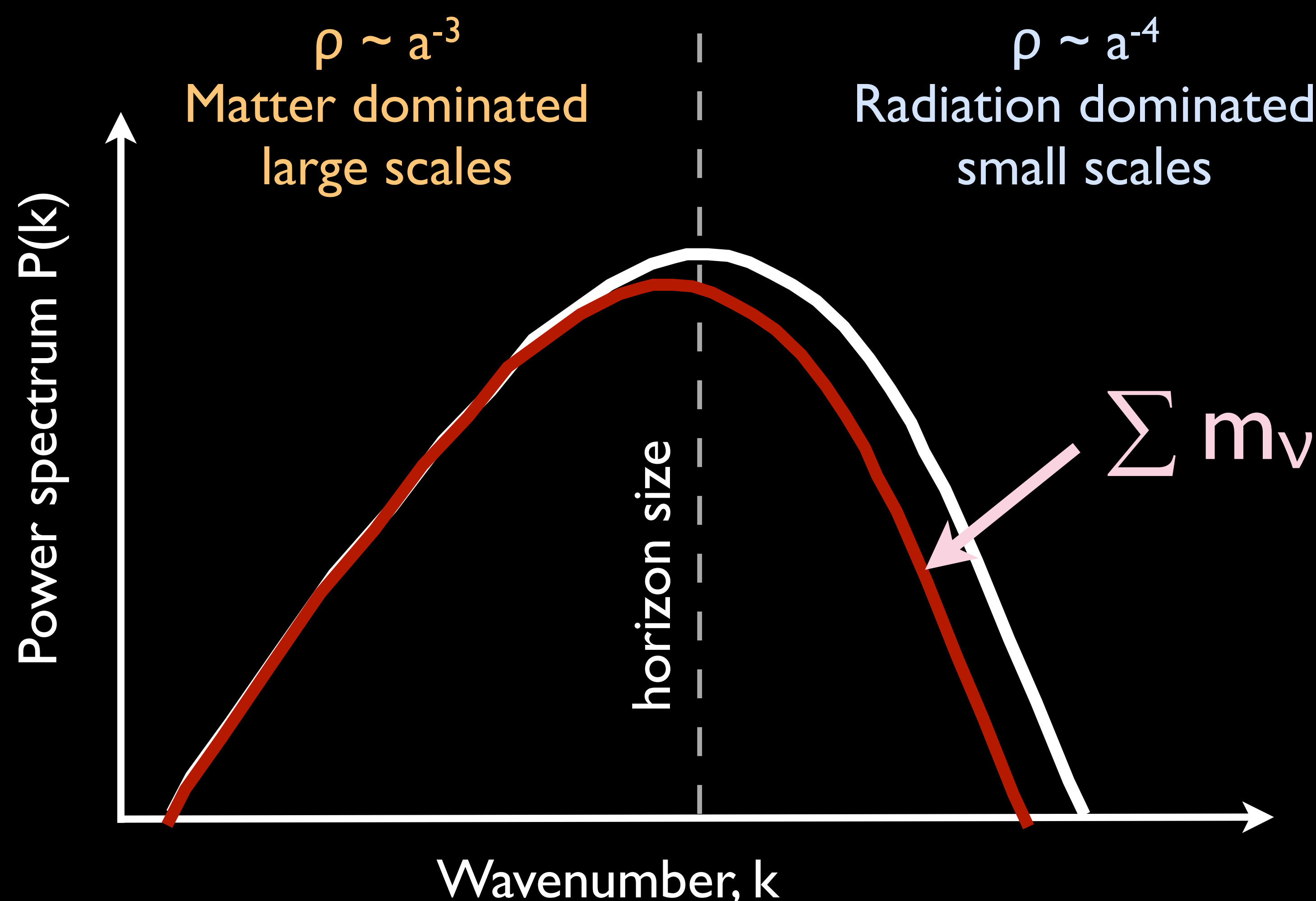
The Strategy
(a naive view)



$$\delta(x) = (\rho(x) - \bar{\rho})/\bar{\rho}$$

$$P(k) = \left\langle |\delta(k)|^2 \right\rangle$$

The Strategy
(a naive view)

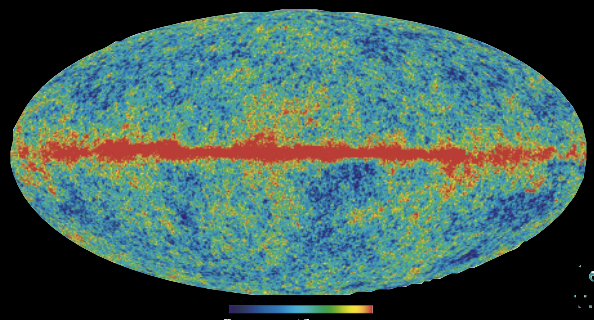


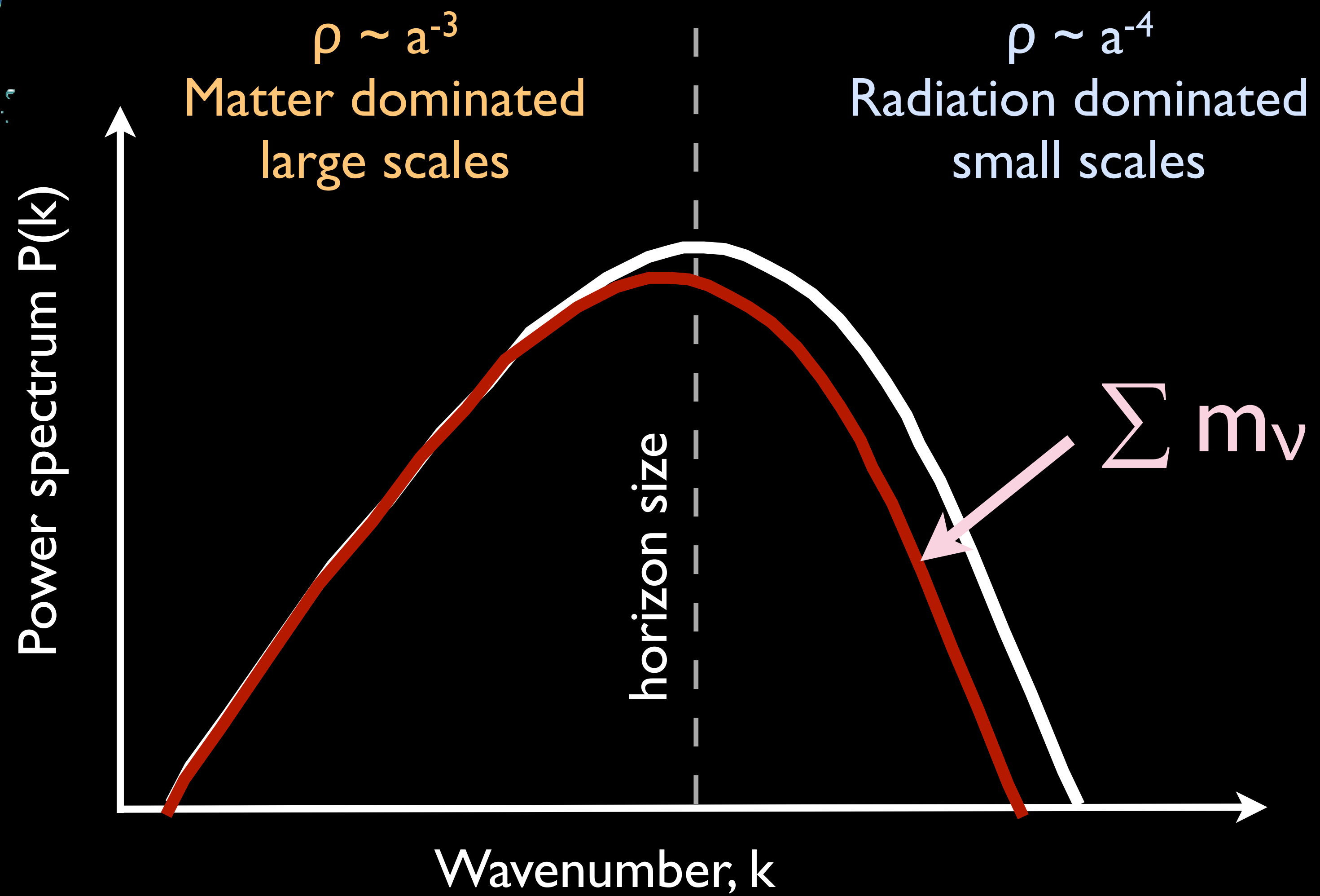
Neutrinos come to affect the power spectrum,

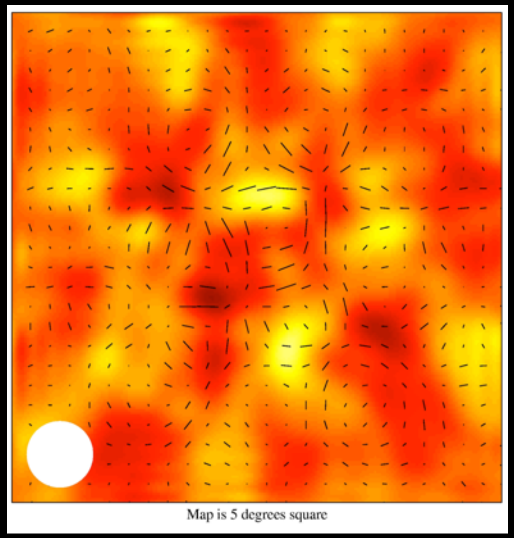
particularly at small distance scales

The Strategy
(a naive view)

WMAP Temperature Map







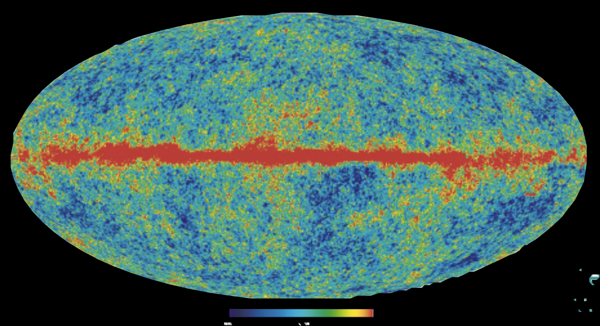
CMB Polarization

Neutrinos come to affect the power spectrum,

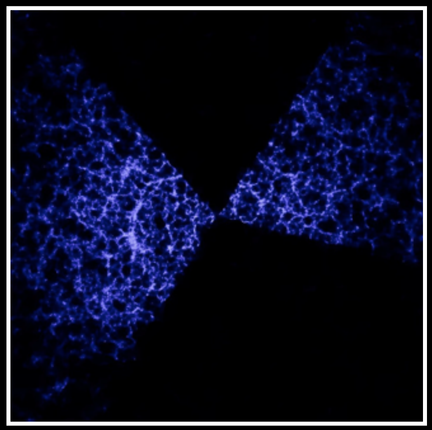
particularly at small distance scales

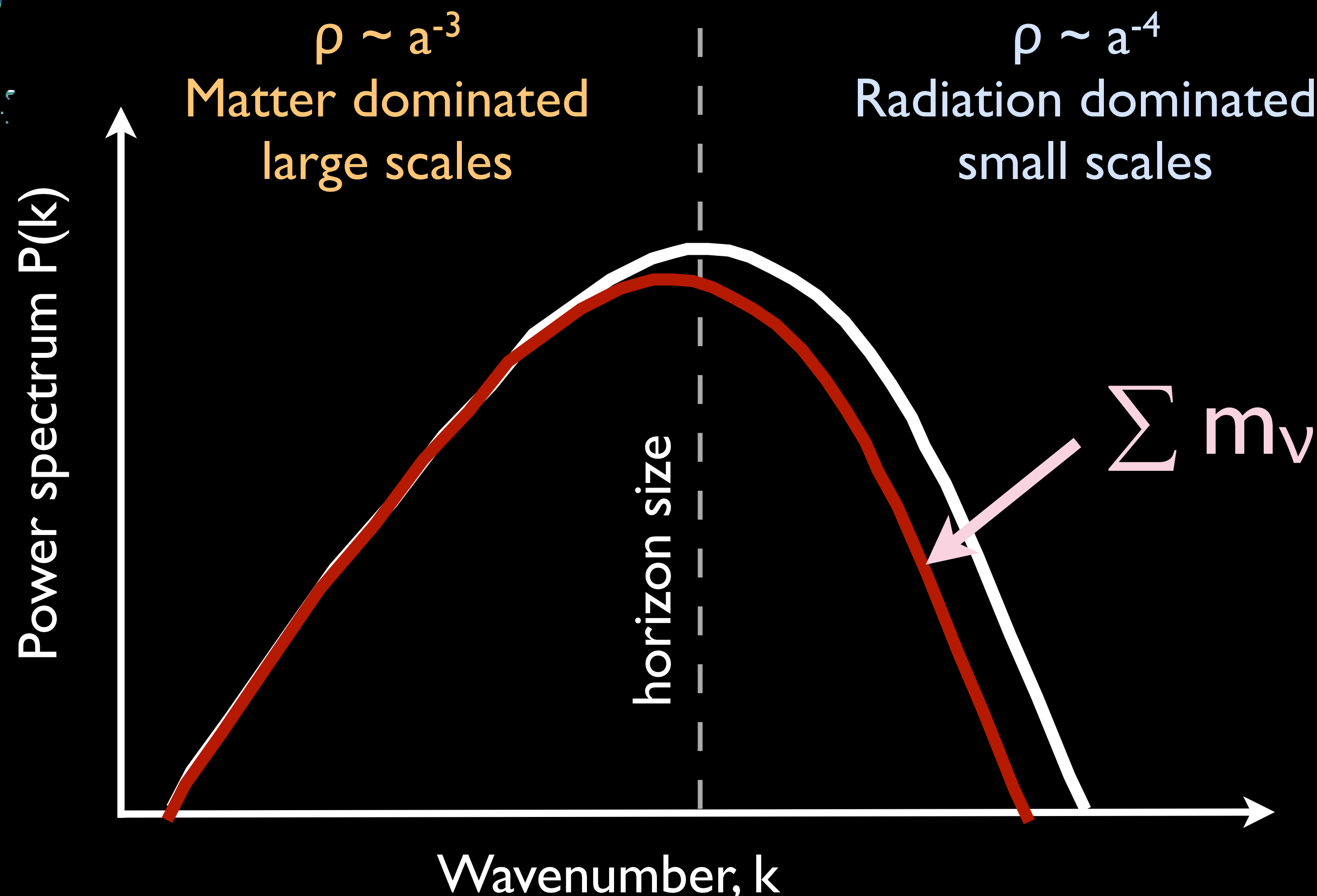
The Strategy
(a naive view)

WMAP Temperature Map

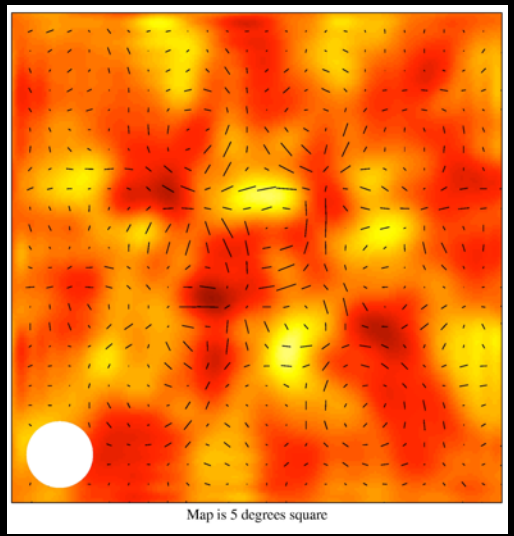


Galaxy Surveys

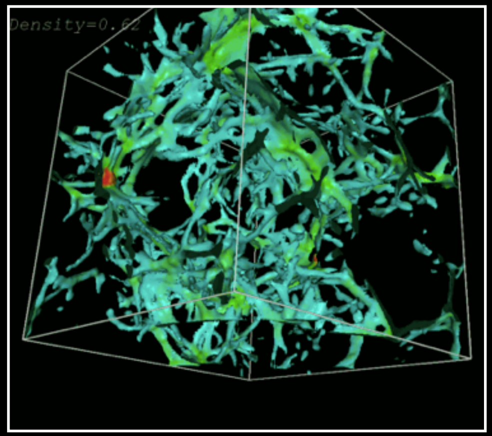




Weak lensing



CMB Polarization

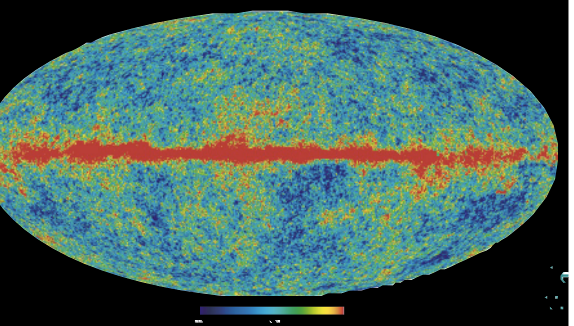


Lyman α

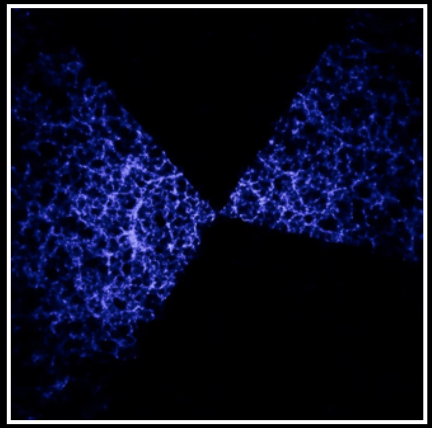
Neutrinos come to affect the power spectrum,

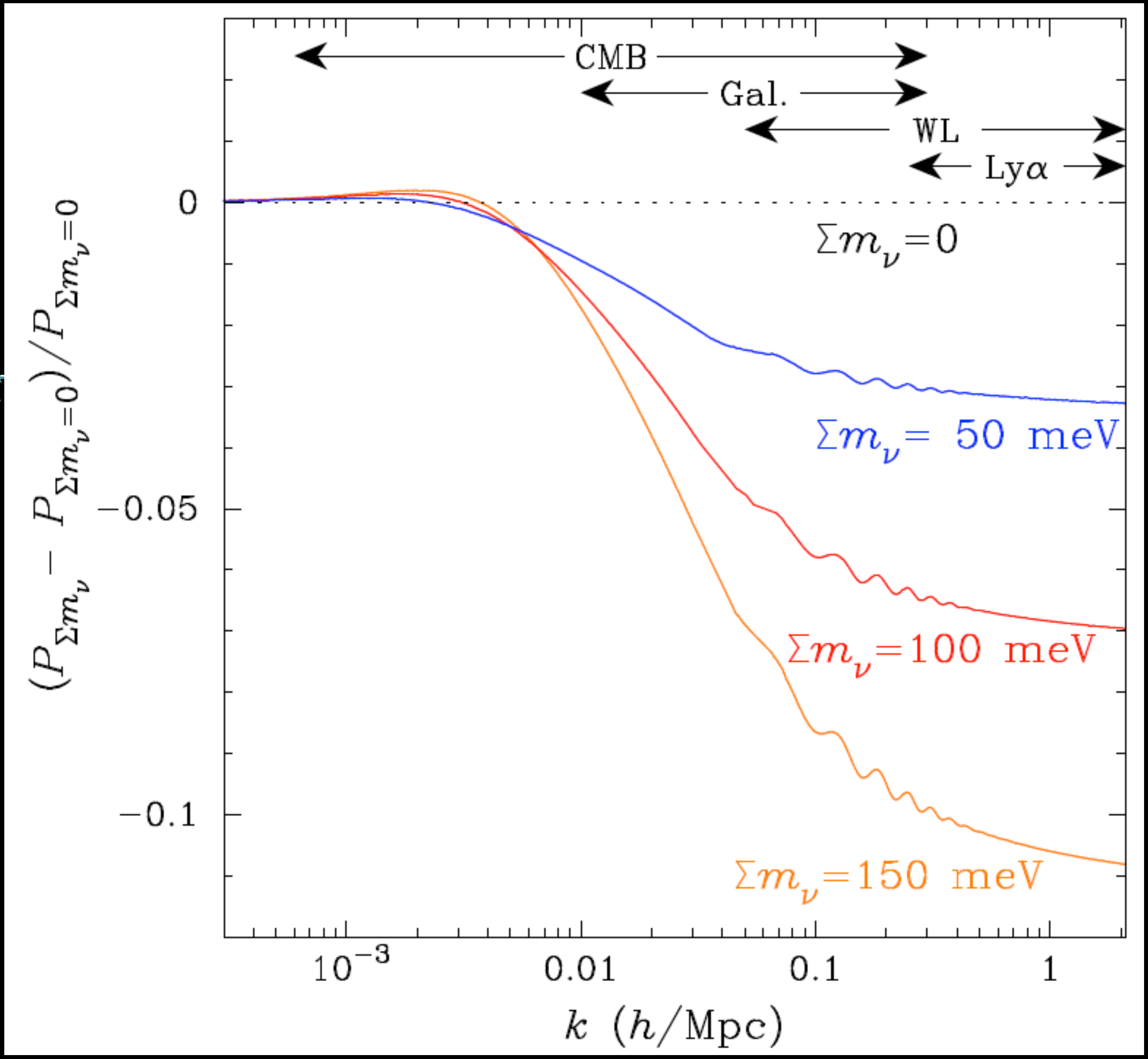
particularly at small distance scales

Temperature Map

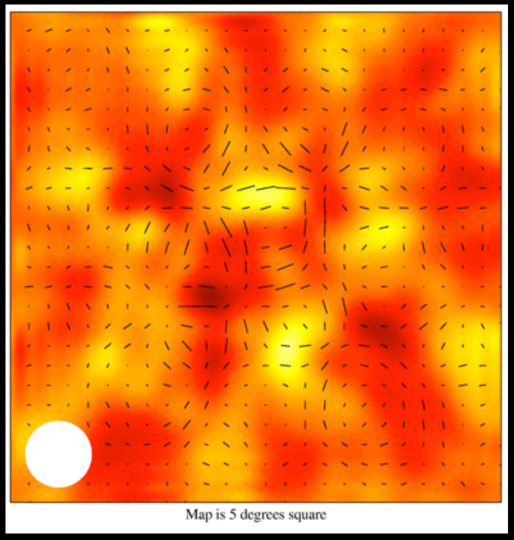


Galaxy Surveys

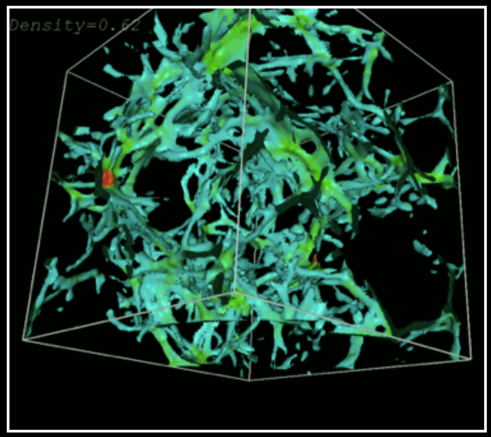




Weak lensing



CMB Polarization



Lyman α

Large scale structure tends to weaken power spectrum at small wavelengths...

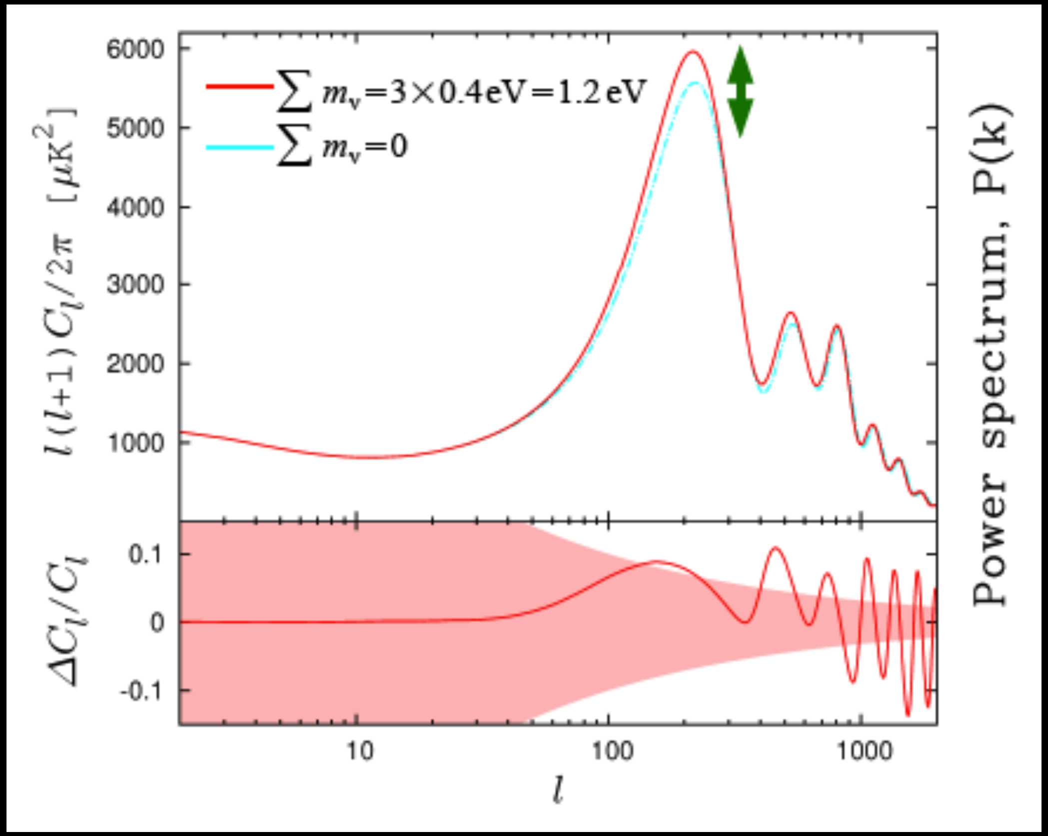
Neutrino Physics & Cosmology

- Two primary cosmology measurements that link directly to neutrino physics:

  (1) Number of neutrino species

  (2) Sum of neutrino masses

- Both large scale structure (LSS) and CMB anisotropies (CMB), particularly CMB gravitational lensing, can be used to measure these quantities.



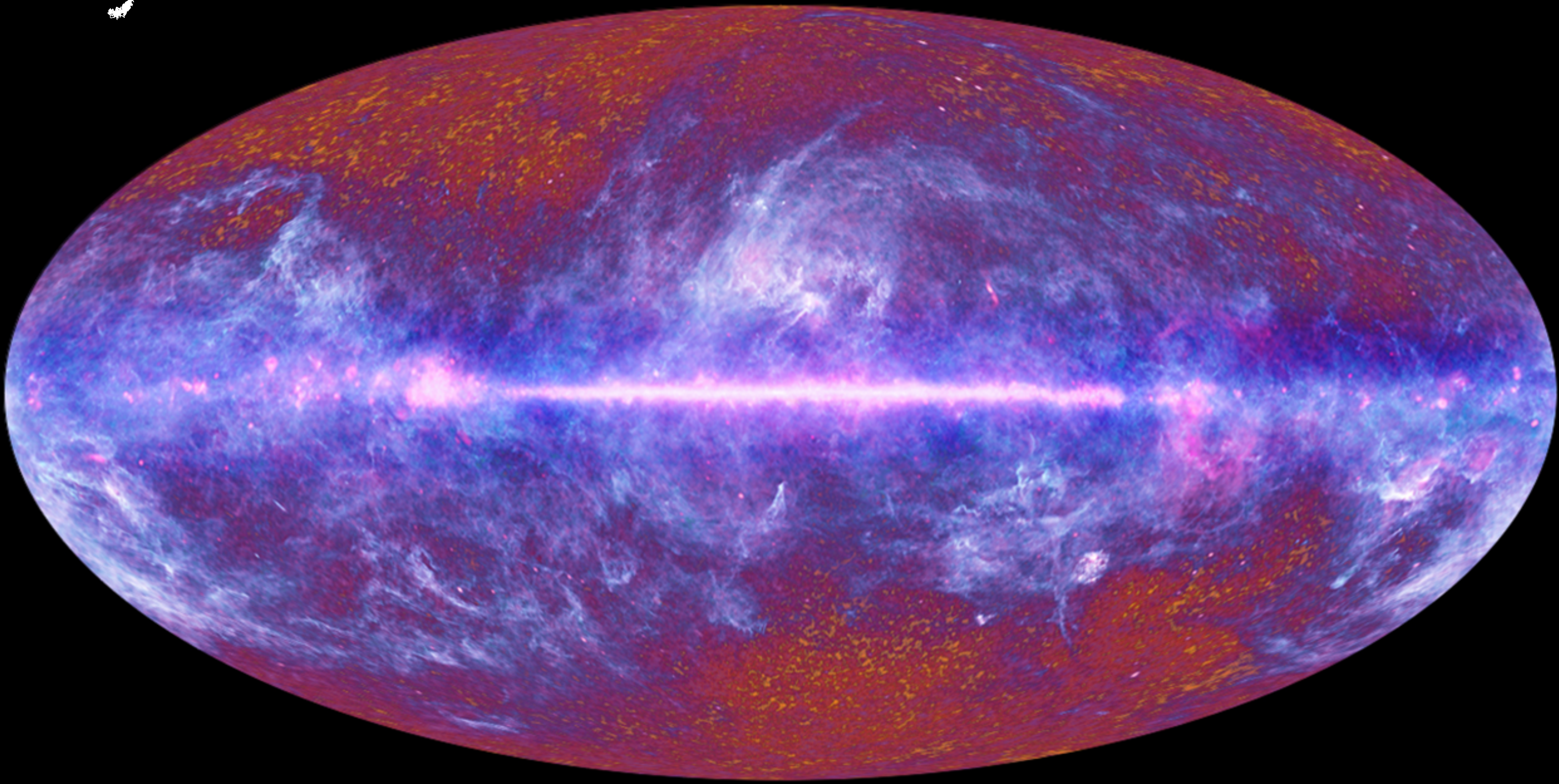
$$\Omega_R h^2 = [1 + N_{\text{eff}}\frac{7}{8}(\frac{4}{11})^{\frac{4}{3}}]\Omega\gamma h^2$$

$$\Omega_\nu = \frac{\rho_\nu}{\rho_{\text{critical}}} = \frac{\sum_i^{n_\nu} m_{\nu,i}}{\rho_{\text{critical}}}$$

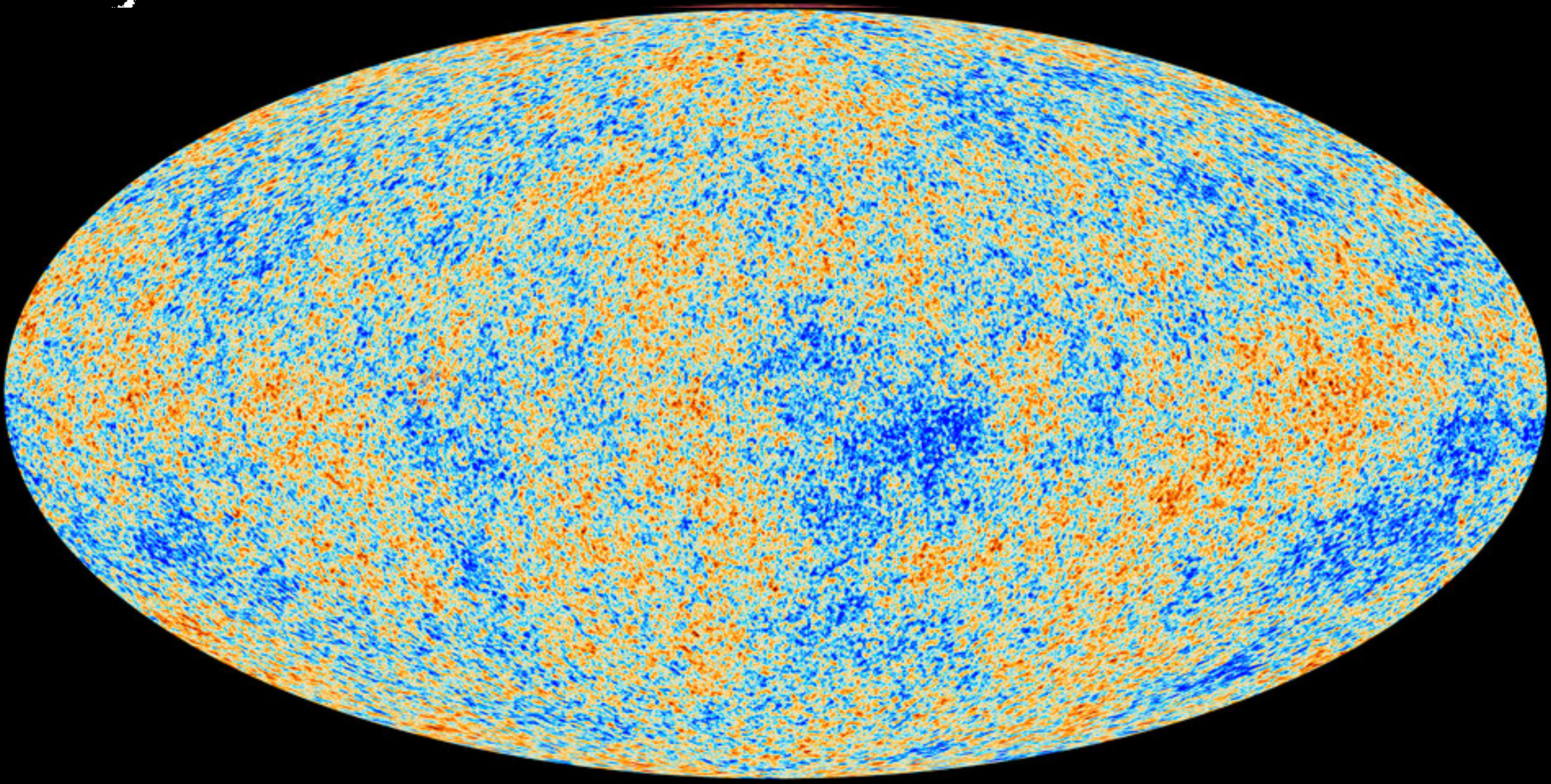
Planck Satellite:

Launched May 14th, 2009

The Microwave sky...



The Microwave sky...

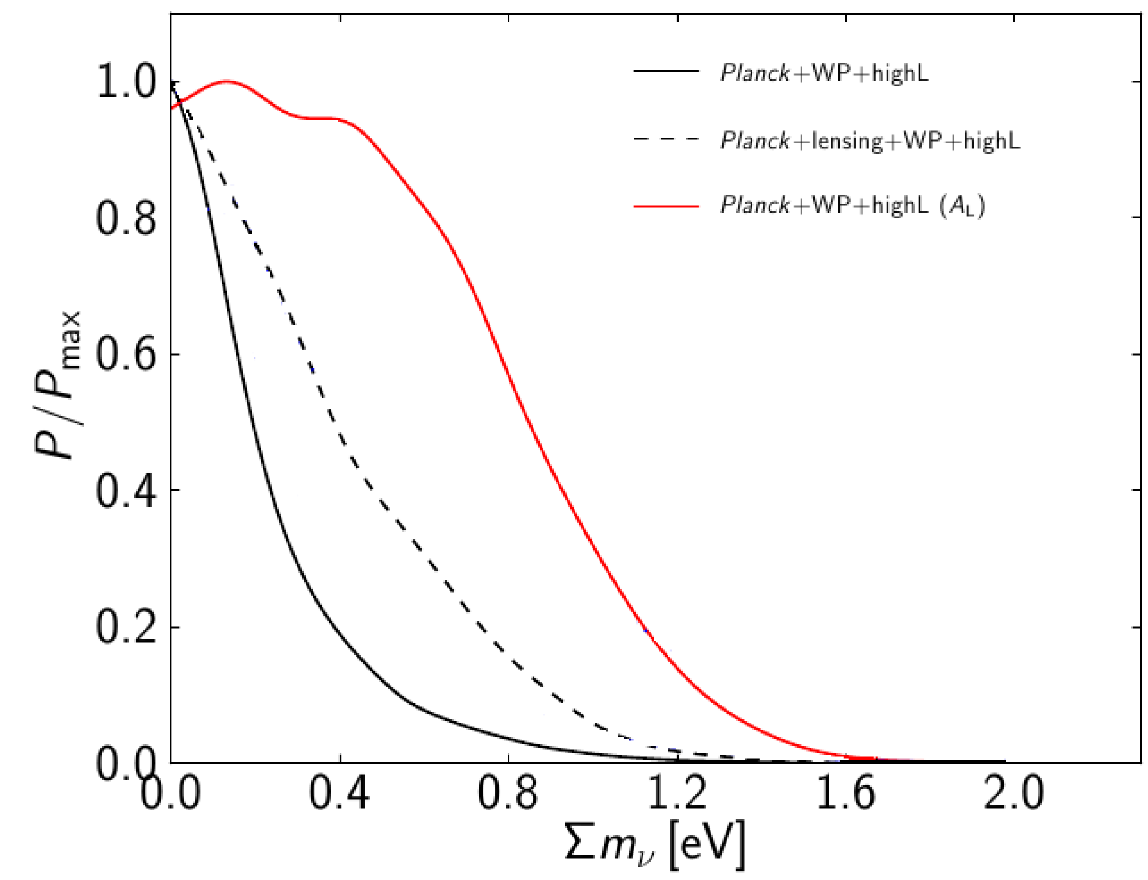


PLANCK Results

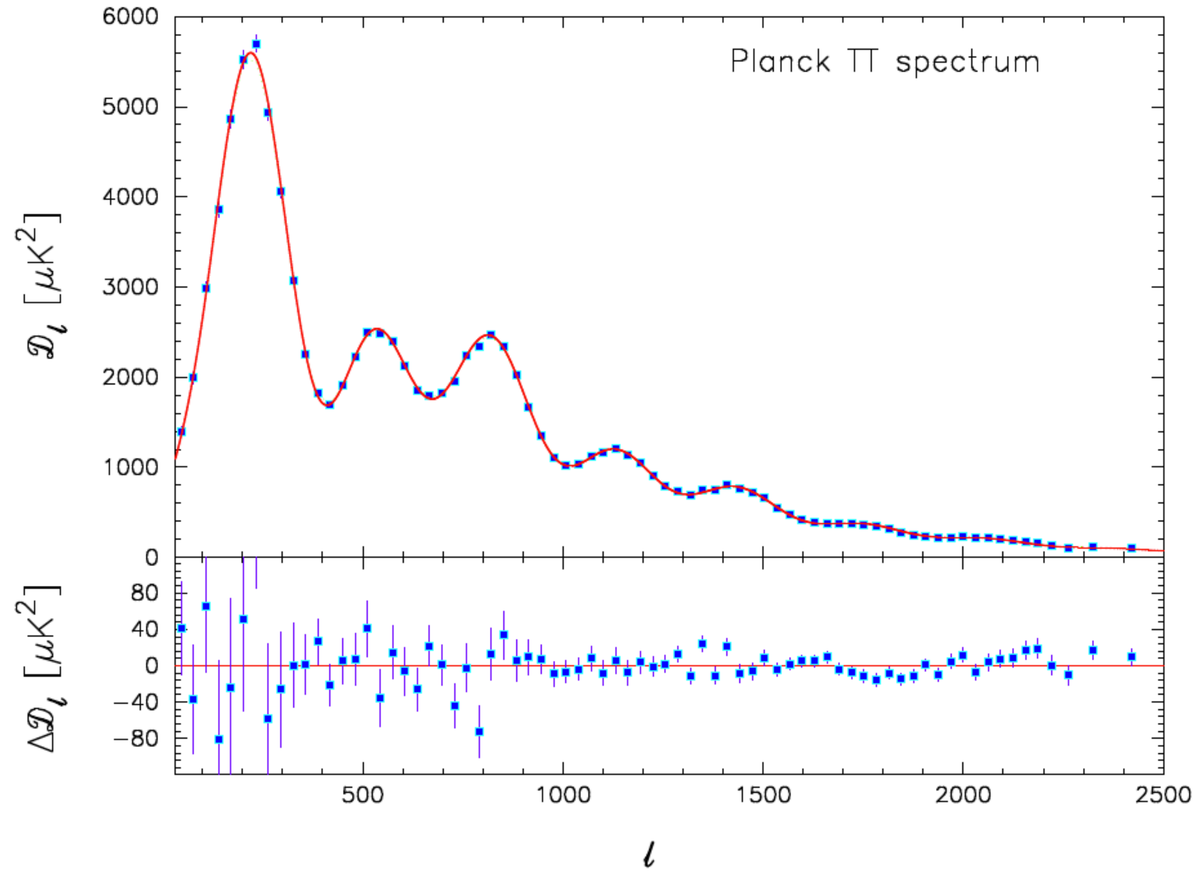
- The basic PLANCK analysis looks at 6 main cosmological parameters. Neutrino masses are added as extensions to that model.

- Most conservative data combinations see no evidence for neutrino masses.

- Certainly tension exists with certain parameters (SZ clusters, Hubble constant, BICEP2) that alter the fits or in some cases favor finite masses.



Source: Planck *Results XVI*

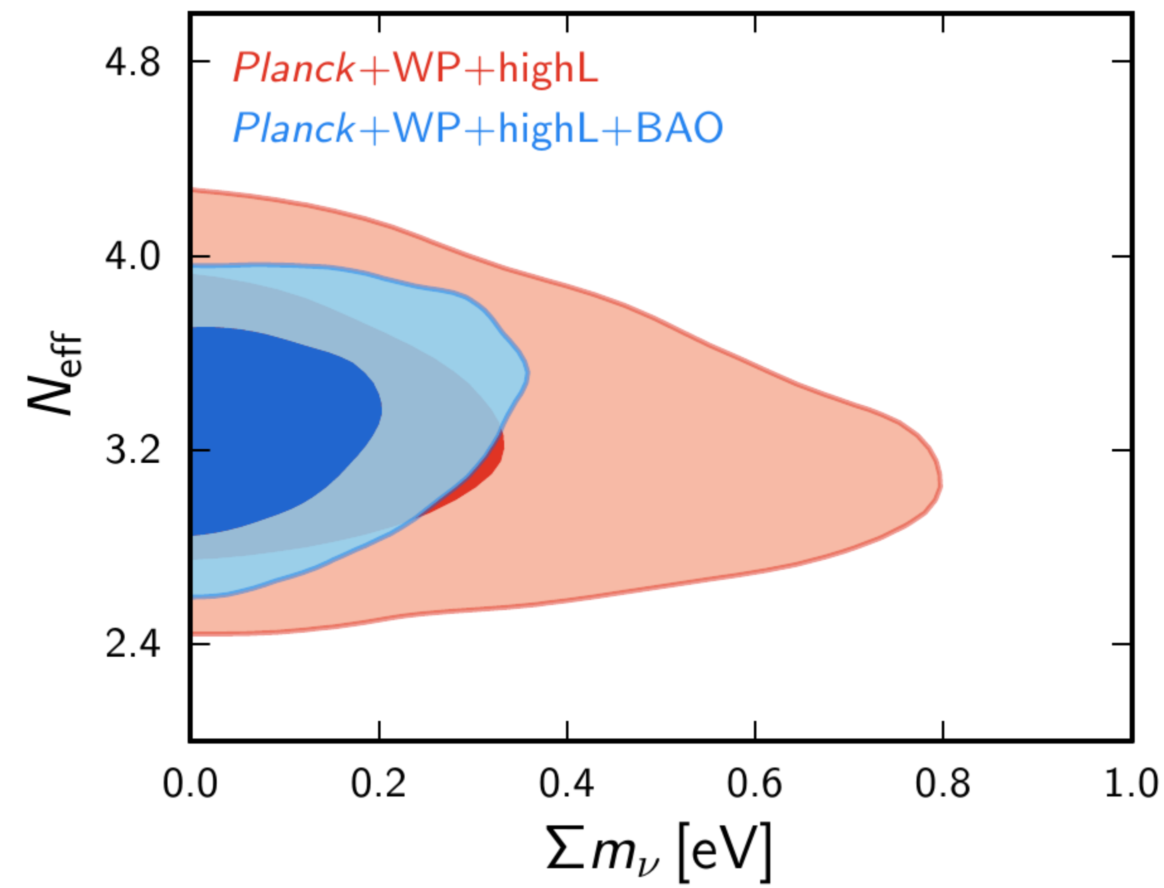


PLANCK Results

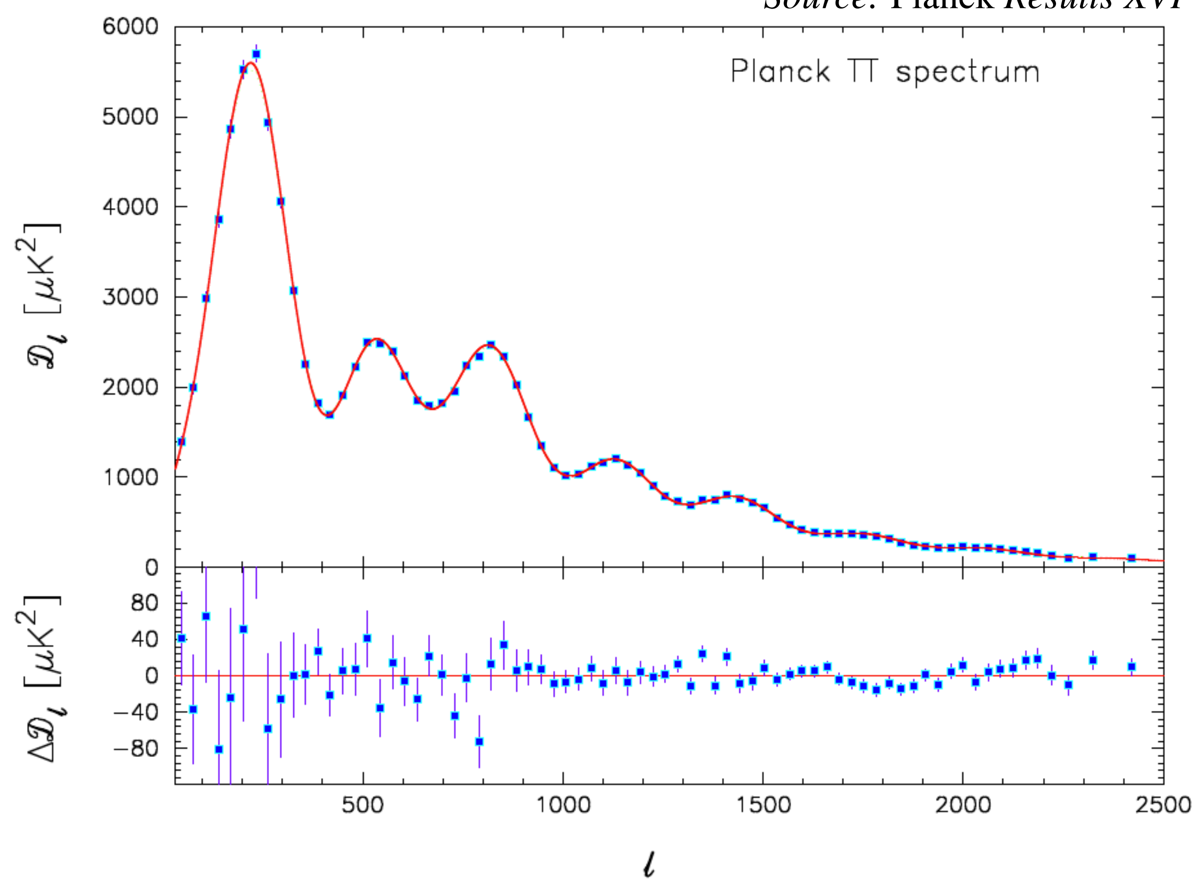
- The basic PLANCK analysis looks at 6 main cosmological parameters. Neutrino masses are added as extensions to that model.

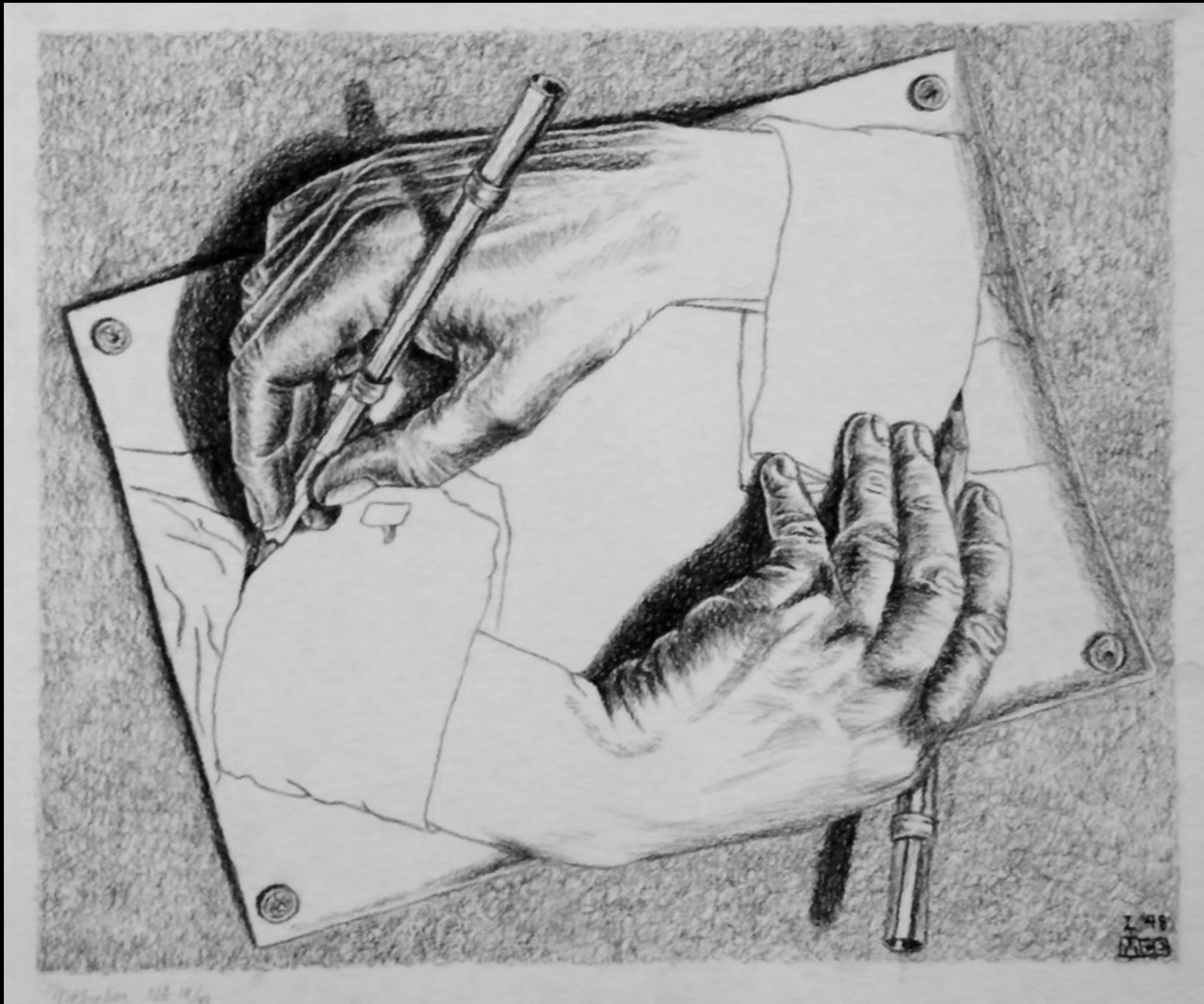
- Most conservative data combinations see no evidence for neutrino masses.

- Certainly tension exists with certain parameters (SZ clusters, Hubble constant, BICEP2) that alter the fits or in some cases favor finite masses.



Source: Planck *Results XVI*

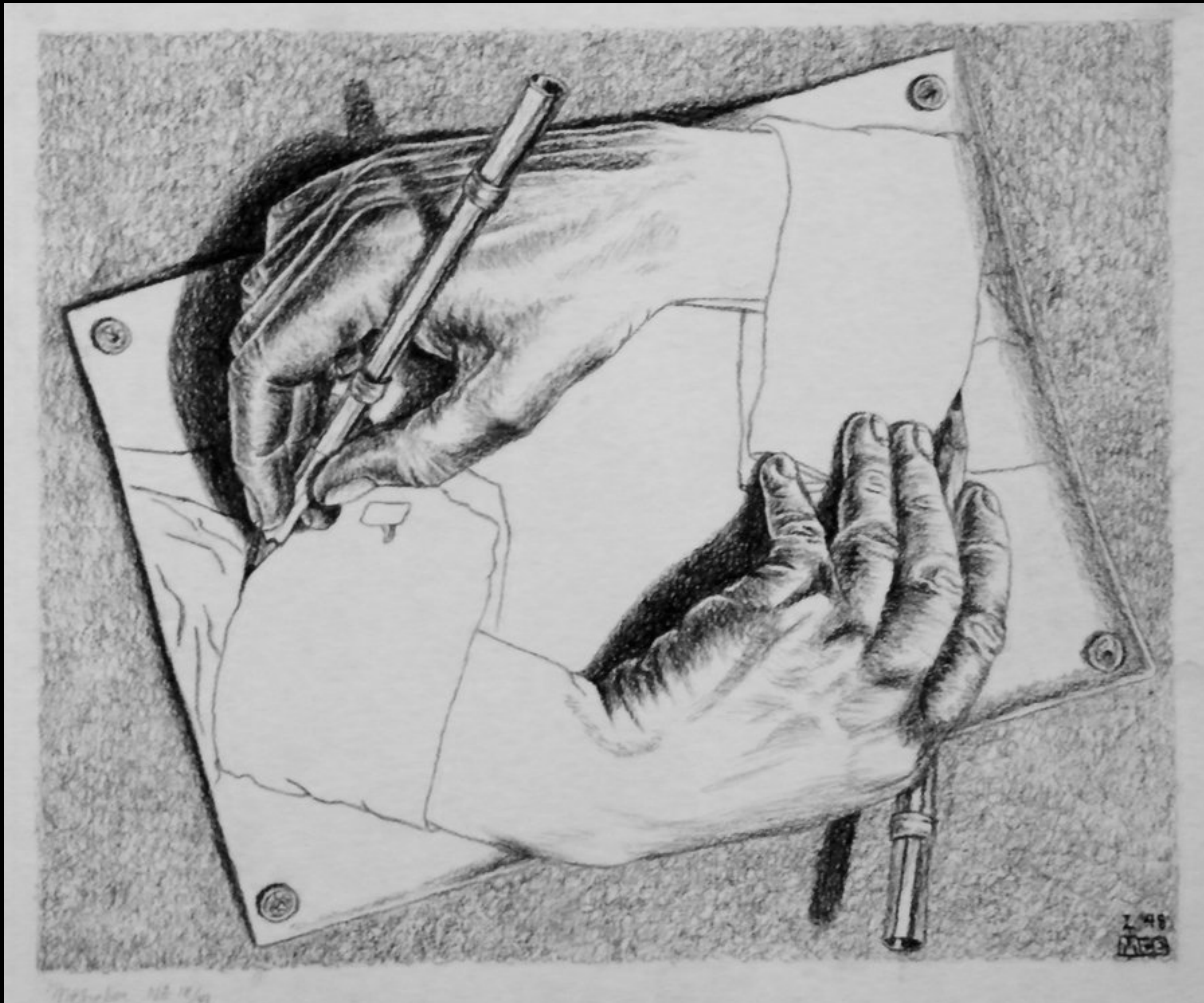




Neutrinoless Double
Beta Decay

$$\langle m^2_{\beta\beta} \rangle = \mid \sum_i^{n_\nu} U^2_{ei} m_{\nu,i} \mid^2$$

0νββ Measurements



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

$$\Delta L = 2$$

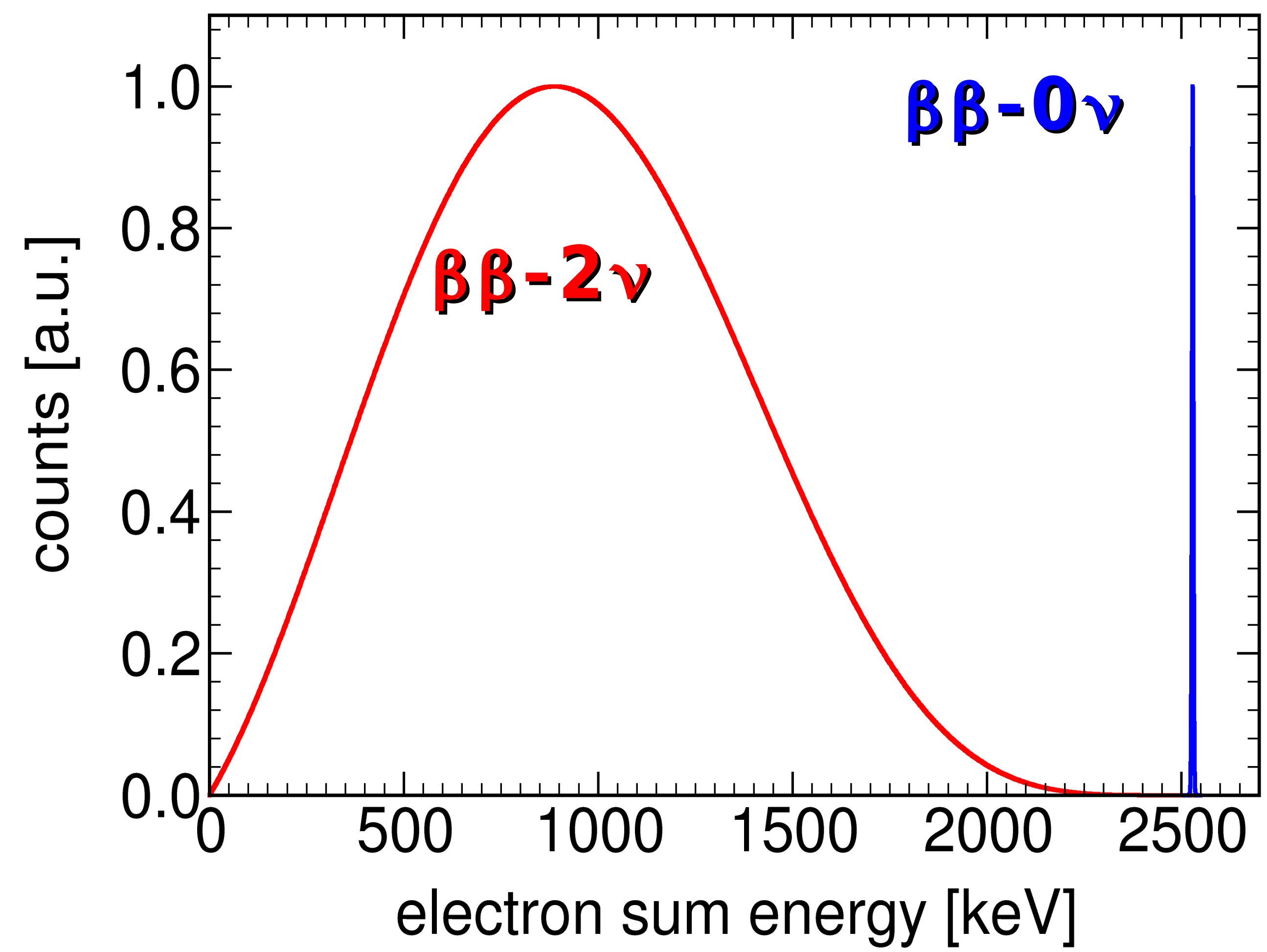
What would a positive signal mean?

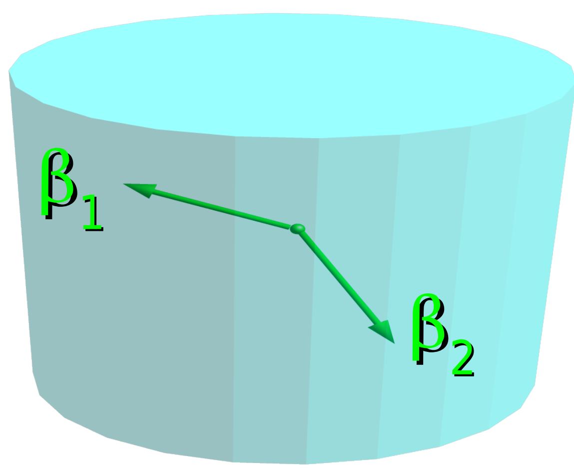
A lot, actually, since the Standard Model conserves B-L.

- Demonstrate that neutrinos are Majorana fermions.
- Shed light on the neutrino mechanism
- Probe into the causes for the matter anti-matter asymmetry in the universe

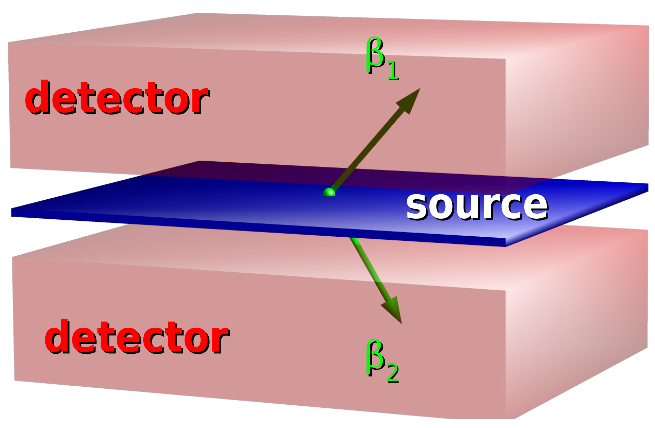
Simple in principle...

- Clean Signature
  Sum of electrons is at a single energy
- Know where to look
  Occurs at endpoint of the allowed decay, well-separated from bulk ββνν.
- Particle detection
  (we know how to detect electrons well)





Source = detector



Source ≠ detector

...but not in practice

- Background Suppression

  The key to success in all these experiments is background suppression

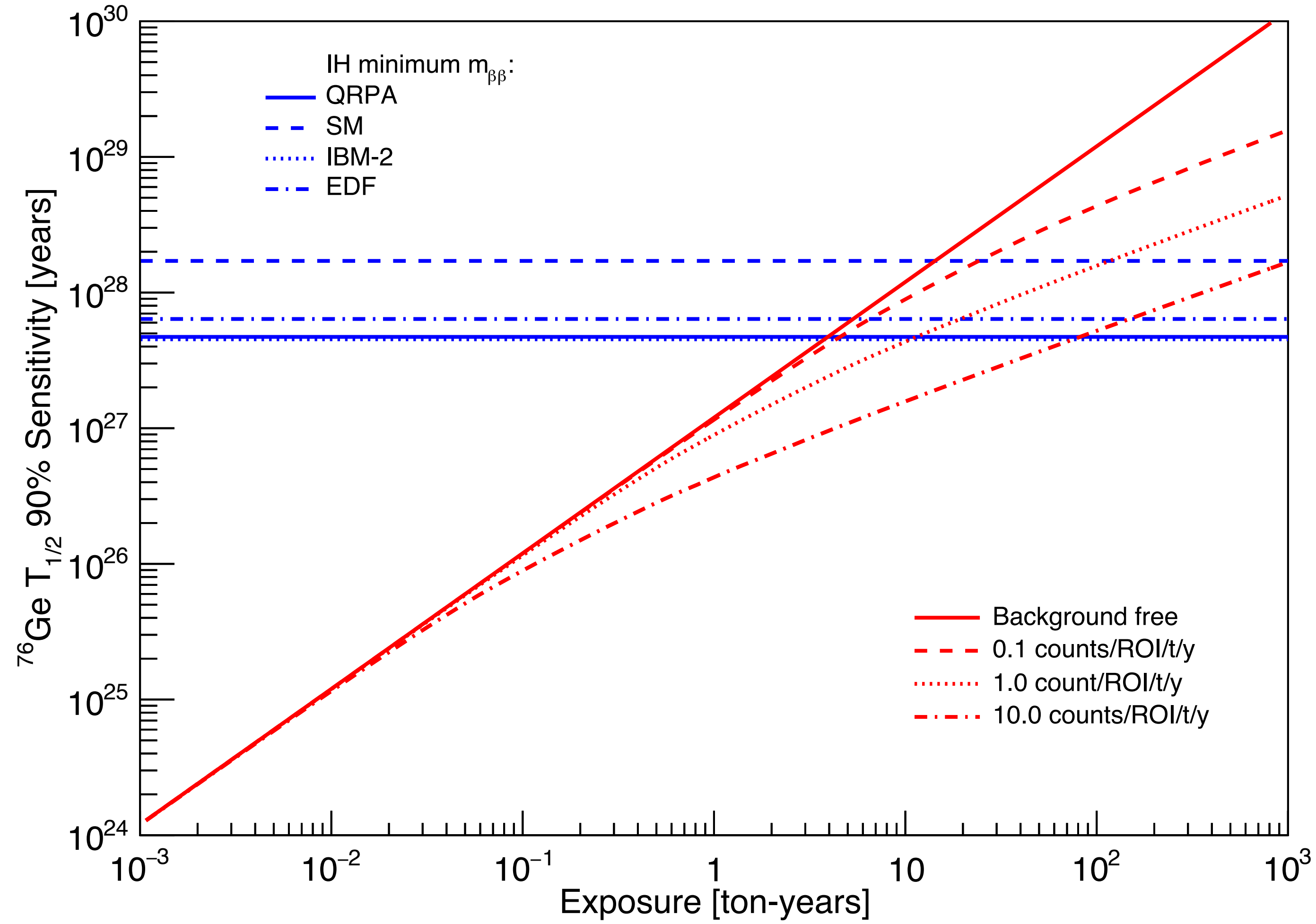
- Isotope Abundance

  Often trading high Q value for poor abundance

- Rarity of Process

  Rarest process (yet) to be measured.

J. Detwiler



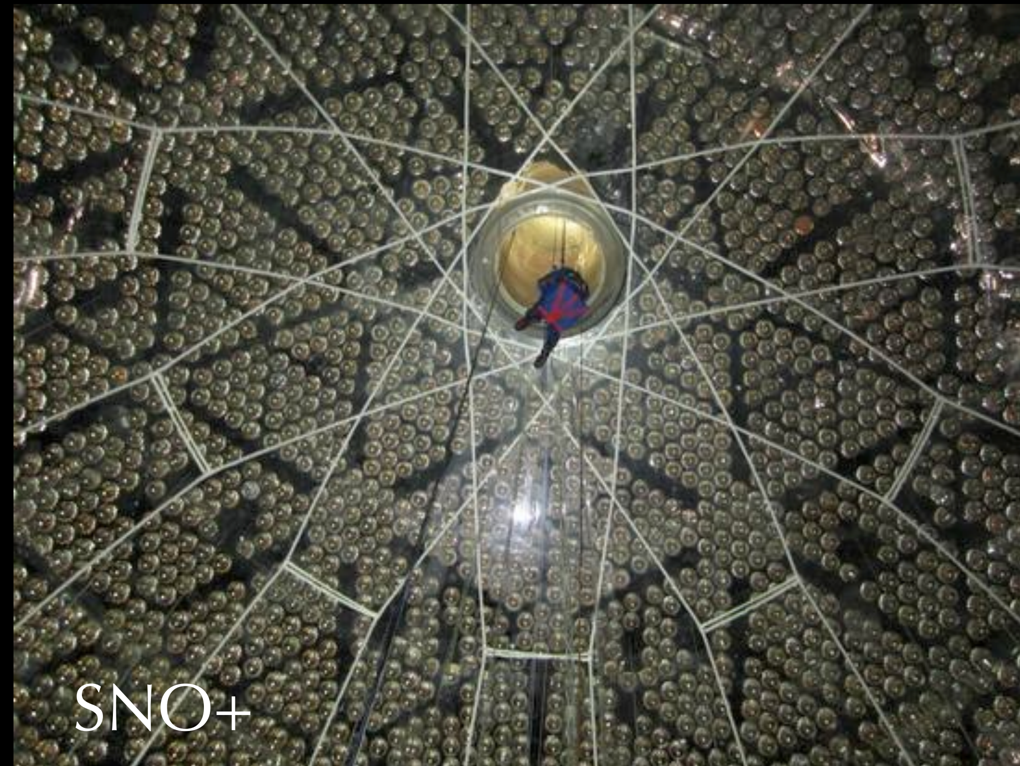
^{76}Ge example, but similar sensitivities for other $0\nu\beta\beta$ isotopes.

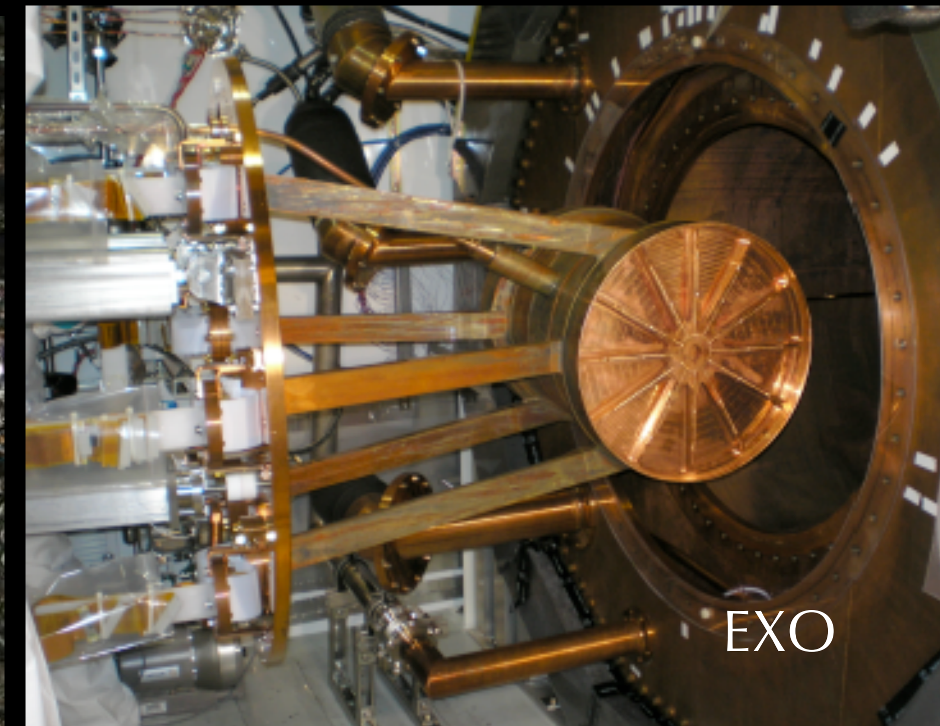
Background free

$$\left[T_{1/2}^{0\nu}\right] \propto \varepsilon ff \cdot I_{abundance} \cdot Source\ Mass \cdot Time$$

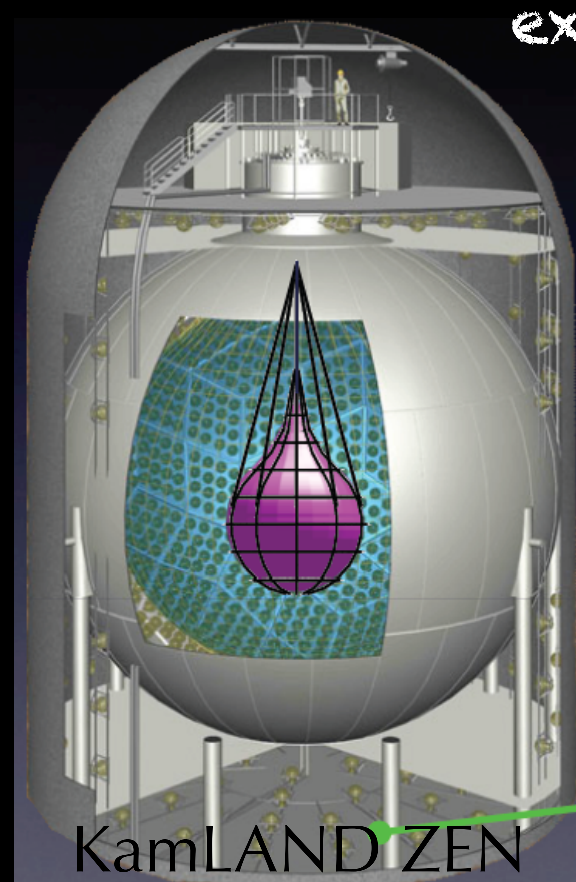
Background limited

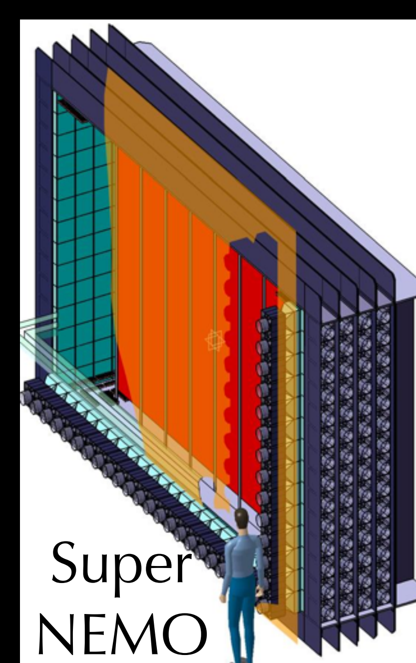
$$\left[T_{1/2}^{0\nu}\right] \propto \varepsilon ff \cdot I_{abundance} \cdot \sqrt{\frac{Source\ Mass \cdot Time}{Bkg \cdot \Delta E}}$$

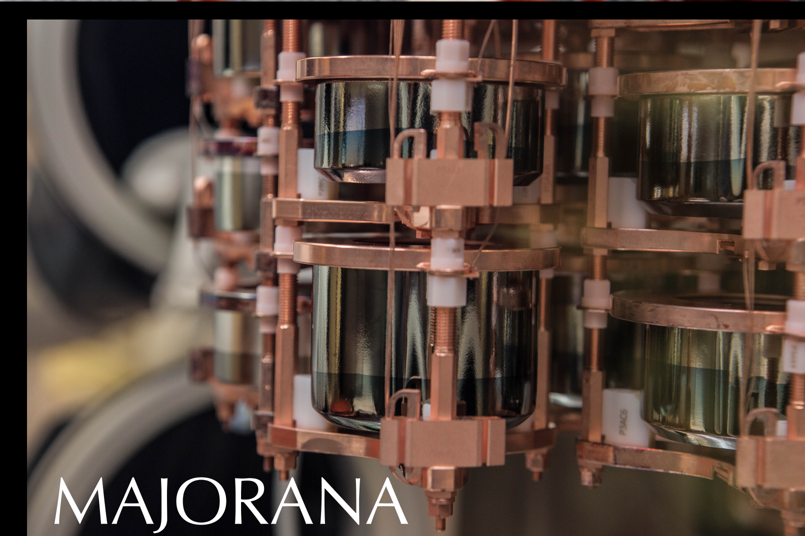


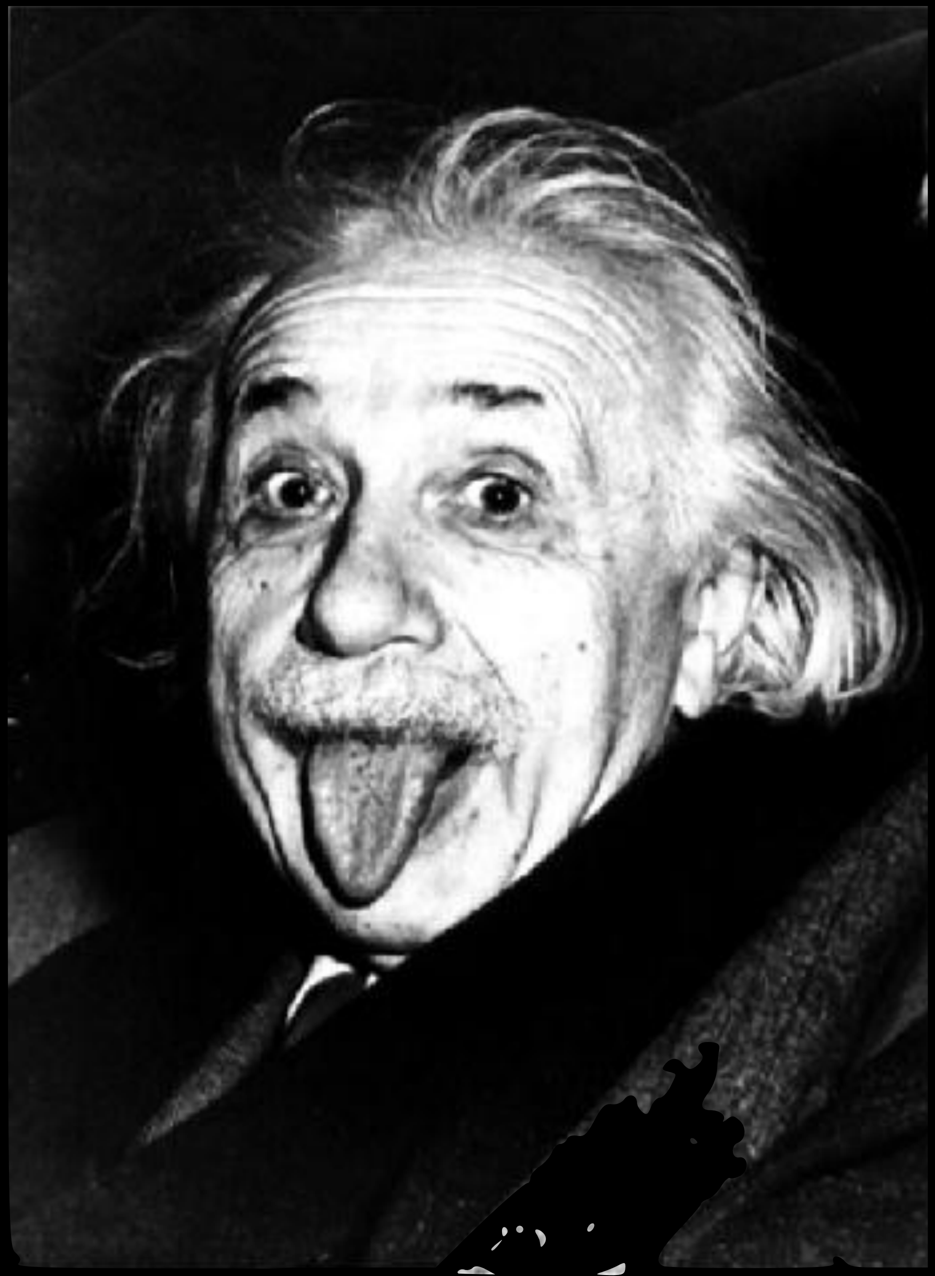


Many,
many
experiments...





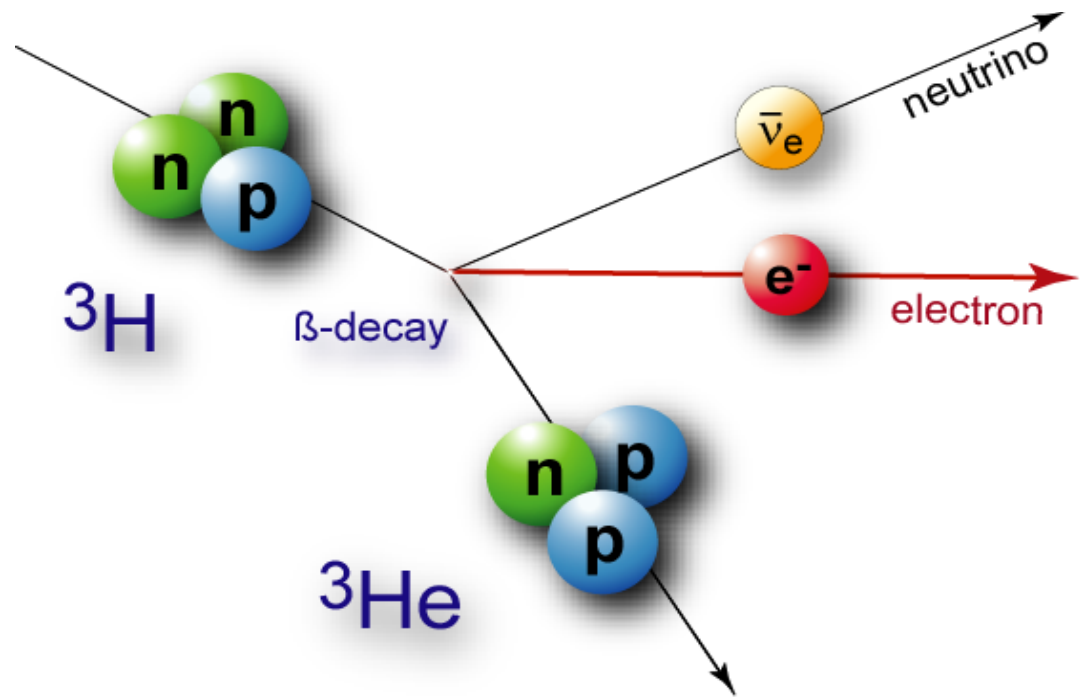




$$\langle m_\beta \rangle^2 = \sum_i^{n_\nu} \mid U_{ei} \mid^2 m_{\nu,i}^2$$

Beta Decay Measurements

Direct Probes



$$^3H \rightarrow {}^3He^+ + e^- + \nu_e$$

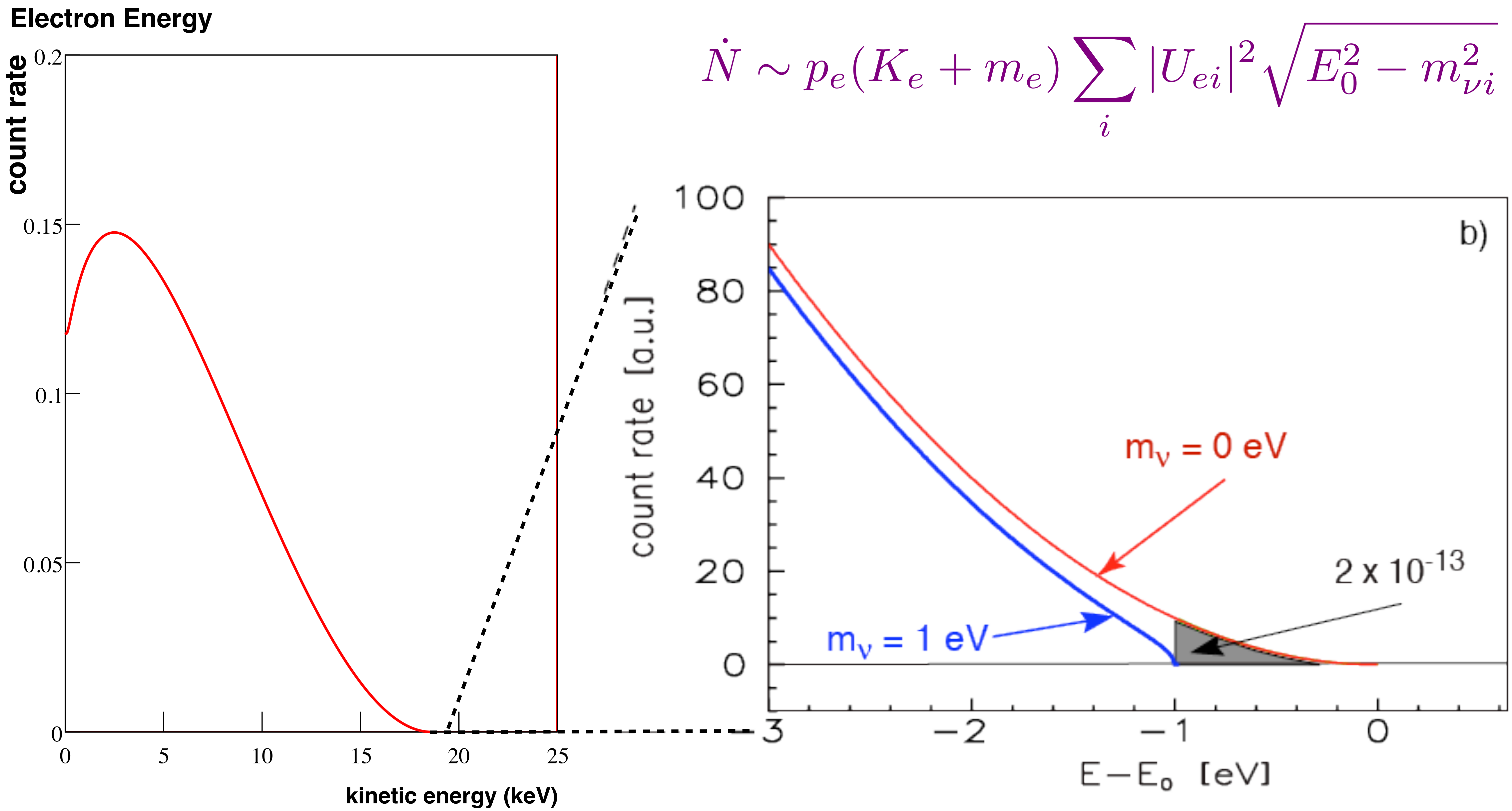
Beta Decay

A kinematic determination of the neutrino mass

No model dependence on cosmology or nature of mass

Direct Probes

$$\dot{N} \sim p_e(K_e + m_e) \sum_i |U_{ei}|^2 \sqrt{E_0^2 - m_{\nu i}^2}$$



Beta Decay

A kinematic determination of the neutrino mass

No model dependence on cosmology or nature of mass

Neutrinos from Radioactivity

- The phase space of the decay (i.e. how many different states can occupy a particular momentum).

Neutrinos from Radioactivity

- The phase space of the decay (i.e. how many different states can occupy a particular momentum).

Transition	ΔI	Parity change?
Superallowed	0, ± 1	No
Allowed	0, ± 1	No
1st Forbidden	0, ± 1	Yes
Unique 1st Forbidden	± 2	Yes
2nd Forbidden	± 2	No
3rd Forbidden	± 3	Yes

Spin of states govern type of exchange
E.g.: $0^+ \rightarrow 0^+$ is superallowed

Neutrinos from Radioactivity

- The phase space of the decay (i.e. how many different states can occupy a particular momentum).

Transition	ΔI	Parity change?
Superallowed	0, $\pm$ 1	No
Allowed	0, $\pm$ 1	No
1st Forbidden	0, $\pm$ 1	Yes
Unique 1st Forbidden	$\pm$ 2	Yes
2nd Forbidden	$\pm$ 2	No
3rd Forbidden	$\pm$ 3	Yes

Spin of states govern type of exchange
E.g.: $0^+ \rightarrow 0^+$ is superallowed

Fermi Function

$$\frac{dN}{dE} = C \times |M|^2 F(Z,E) p_e (E + m_e^2)(E_0 - E) \sum_i |U_{ei}|^2 \sqrt{(E_0 - E)^2 - m_i^2}$$

Matrix Element

Phase space

Neutrinos from Radioactivity

- The phase space of the decay (i.e. how many different states can occupy a particular momentum).
- Corrections due to the Coulomb field, or Fermi function.

Transition	ΔI	Parity change?
Superallowed	0, ± 1	No
Allowed	0, ± 1	No
1st Forbidden	0, ± 1	Yes
Unique 1st Forbidden	± 2	Yes
2nd Forbidden	± 2	No
3rd Forbidden	± 3	Yes

Spin of states govern type of exchange
E.g.: $0^+ \rightarrow 0^+$ is superallowed

Fermi Function

$$\frac{dN}{dE} = C \times |M|^2 F(Z,E) p_e (E + m_e^2)(E_0 - E) \sum_i |U_{ei}|^2 \sqrt{(E_0 - E)^2 - m_i^2}$$

Matrix Element

Phase space

Neutrinos from Radioactivity

- The phase space of the decay (i.e. how many different states can occupy a particular momentum).
- Corrections due to the Coulomb field, or Fermi function.
- The matrix element related to the initial and final states of the decay.

Transition	ΔI	Parity change?
Superallowed	0, ± 1	No
Allowed	0, ± 1	No
1st Forbidden	0, ± 1	Yes
Unique 1st Forbidden	± 2	Yes
2nd Forbidden	± 2	No
3rd Forbidden	± 3	Yes

Spin of states govern type of exchange
E.g.: $0^+ \rightarrow 0^+$ is superallowed

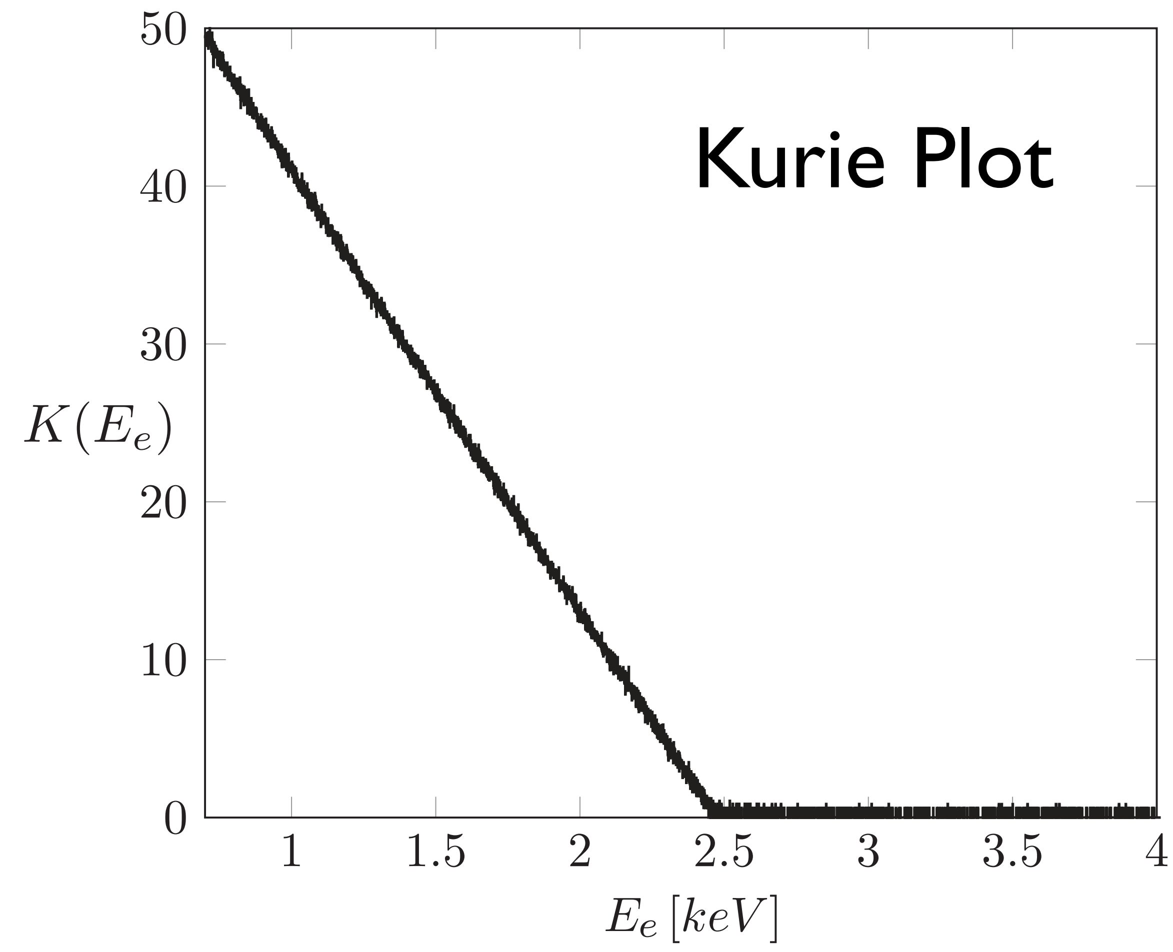
Fermi Function

$$\frac{dN}{dE} = C \times |M|^2 F(Z,E) p_e (E + m_e^2)(E_0 - E) \sum_i |U_{ei}|^2 \sqrt{(E_0 - E)^2 - m_i^2}$$

Matrix Element

Phase space

Fermi's Golden Rule



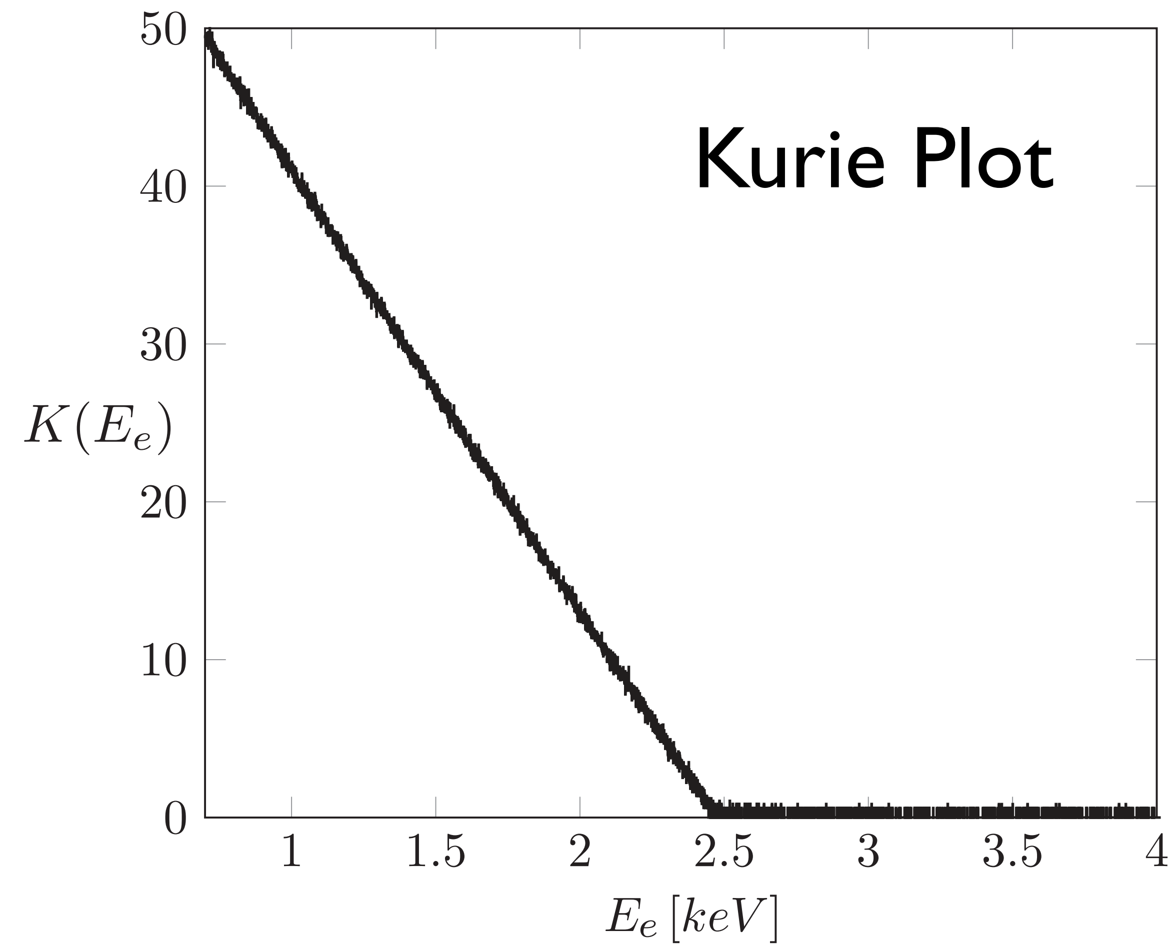
$$d\Gamma_\beta \simeq \int \frac{d\boldsymbol{p}_e}{(2\pi)^3}\frac{d\boldsymbol{p}_\nu}{(2\pi)^3}|\mathcal{H}_{fi}|^2 2\pi\delta(E_0 - E_e - E_\nu)$$

$$|\mathcal{H}_{fi}|^2 \simeq F(Z,E_e)\frac{G_F^2}{2}|V_{ud}|^2|M_{fi}|^2$$

$$d\Gamma_\beta = F(Z,E_e)\frac{G_F^2|V_{ud}|^2}{2\pi^3}|M_{fi}|^2 p_e E_e (E_0 - E_e)\sqrt{(E_0-E_e)^2 - m_\nu^2}$$

Fermi's Golden Rule

The effect of neutrino mass is almost entirely an effect due to phase space.



$$d\Gamma_\beta \simeq \int \frac{d\boldsymbol{p}_e}{(2\pi)^3}\frac{d\boldsymbol{p}_\nu}{(2\pi)^3}|\mathcal{H}_{fi}|^2 2\pi\delta(E_0 - E_e - E_\nu)$$

$$|\mathcal{H}_{fi}|^2 \simeq F(Z, E_e)\frac{G_F^2}{2}|V_{ud}|^2|M_{fi}|^2$$

$$d\Gamma_\beta = F(Z, E_e)\frac{G_F^2|V_{ud}|^2}{2\pi^3}|M_{fi}|^2 p_e E_e (E_0 - E_e)\sqrt{(E_0 - E_e)^2 - m_\nu^2}$$

The $\pi\sqrt{2}$ Magnetic Spectrometer

- Bergkvist constructs first tritium source experiment in Stockholm.
- Double focusing spectrometer; first to fully tackle energy resolution, energy loss and final states coherently.
- Achieved best limit of the time (m_ν < 55 eV).

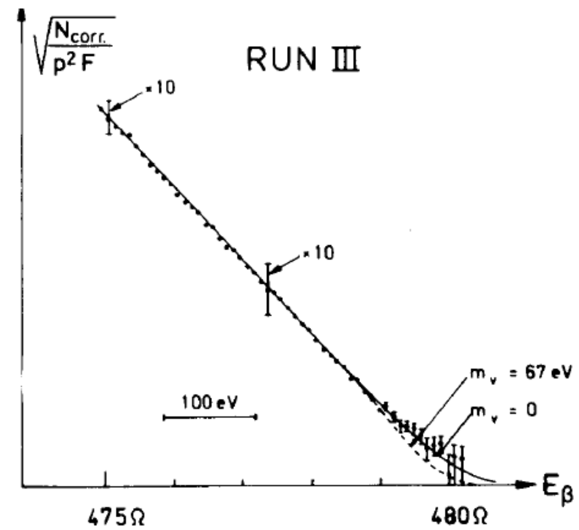


Fig. 20. Kurie plots of data from runs I–III. The data exhibited have been subjected to a very slight correction for distortion in the measured spectrum. The theoretical curves have been fitted to the data in the way discussed in connection with fig. 18.

Nuclear Physics B39 (1972) 317–370. North-Holland Publishing Company

A HIGH-LUMINOSITY, HIGH-RESOLUTION STUDY OF THE END-POINT BEHAVIOUR OF THE TRITIUM β-SPECTRUM (I). BASIC EXPERIMENTAL PROCEDURE AND ANALYSIS WITH REGARD TO NEUTRINO MASS AND NEUTRINO DEGENERACY

Karl-Erik BERGKVIST
Research Institute for Physics, and University of Stockholm, Stockholm, Sweden

Received 23 September 1971
(Revised 13 December 1971)

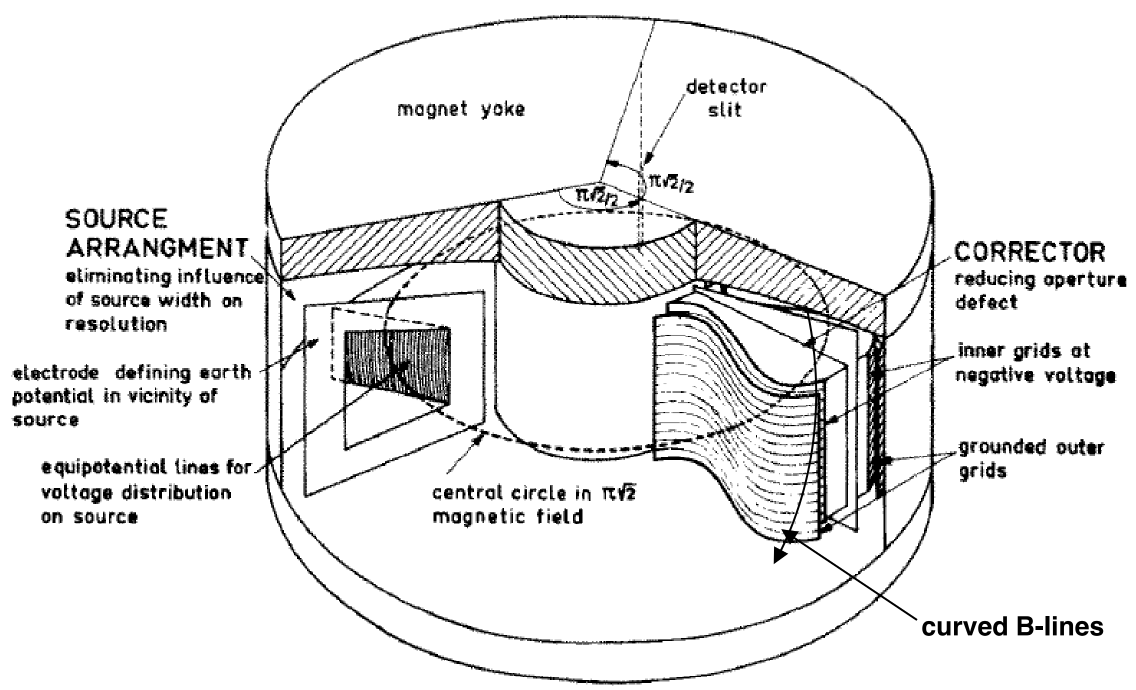
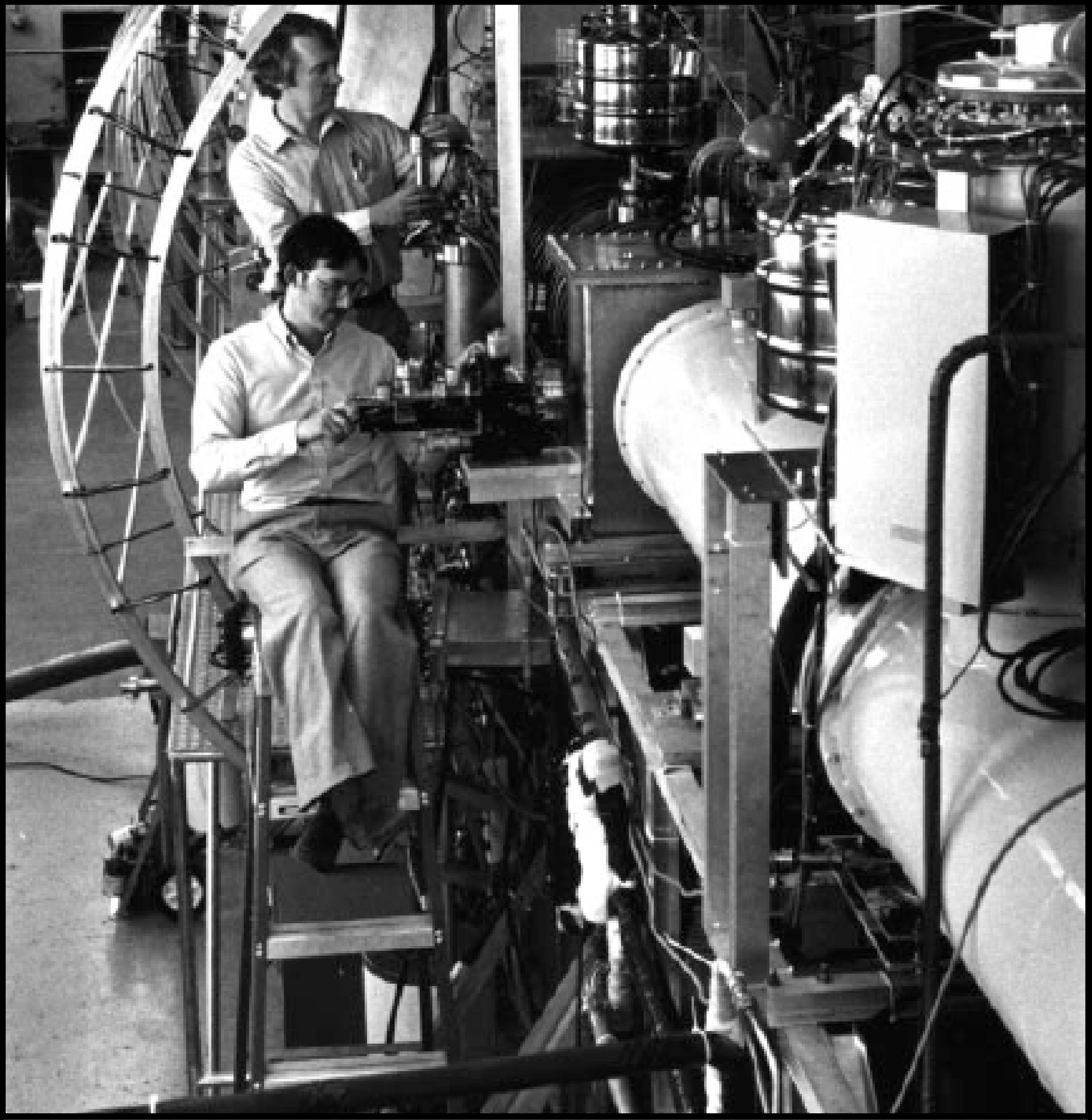


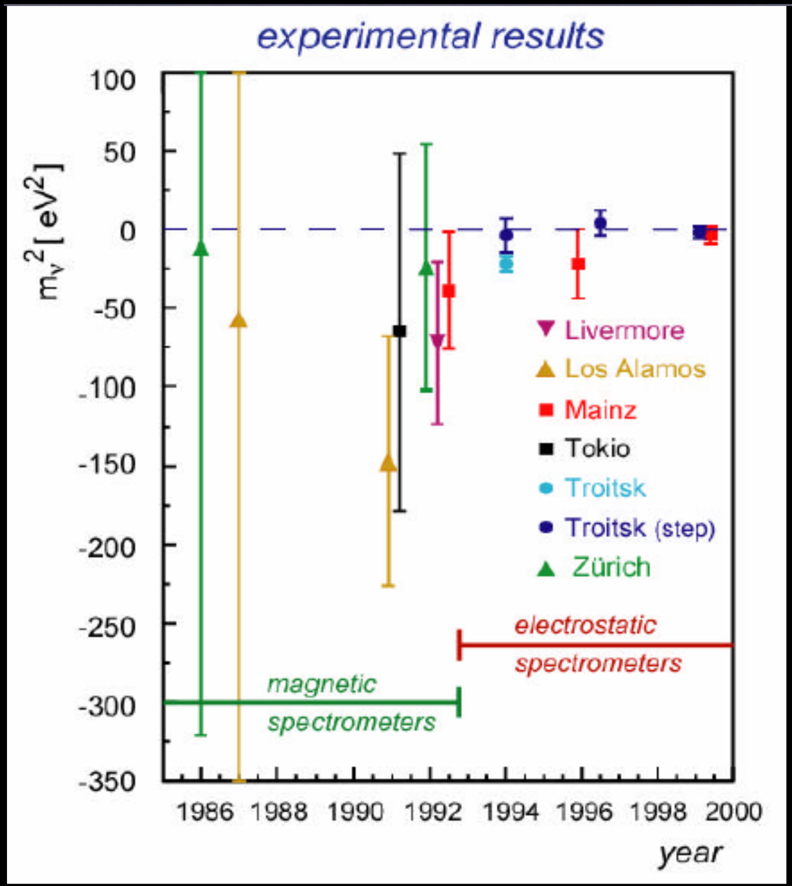
Fig. 3. Basic components of electrostatic-magnetic spectrometer employed in the present investigation of the end-point region of the tritium β-spectrum.

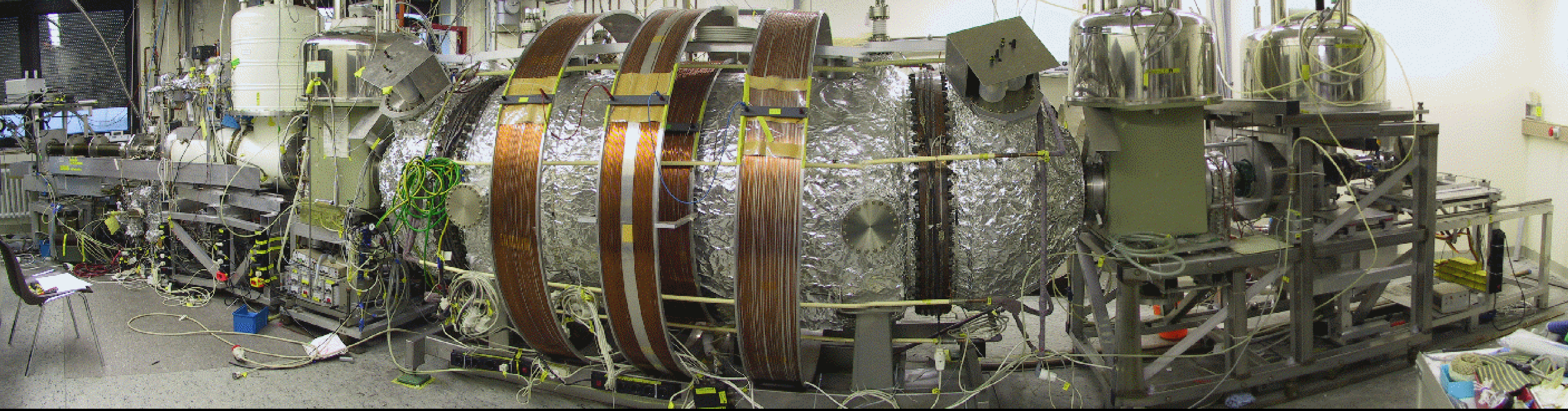
Los Alamos

- Robertson, Bowles, Wilkerson and others at Los Alamos devise the first gaseous tritium source experiment to circumvent earlier issues seen with solid state sources.

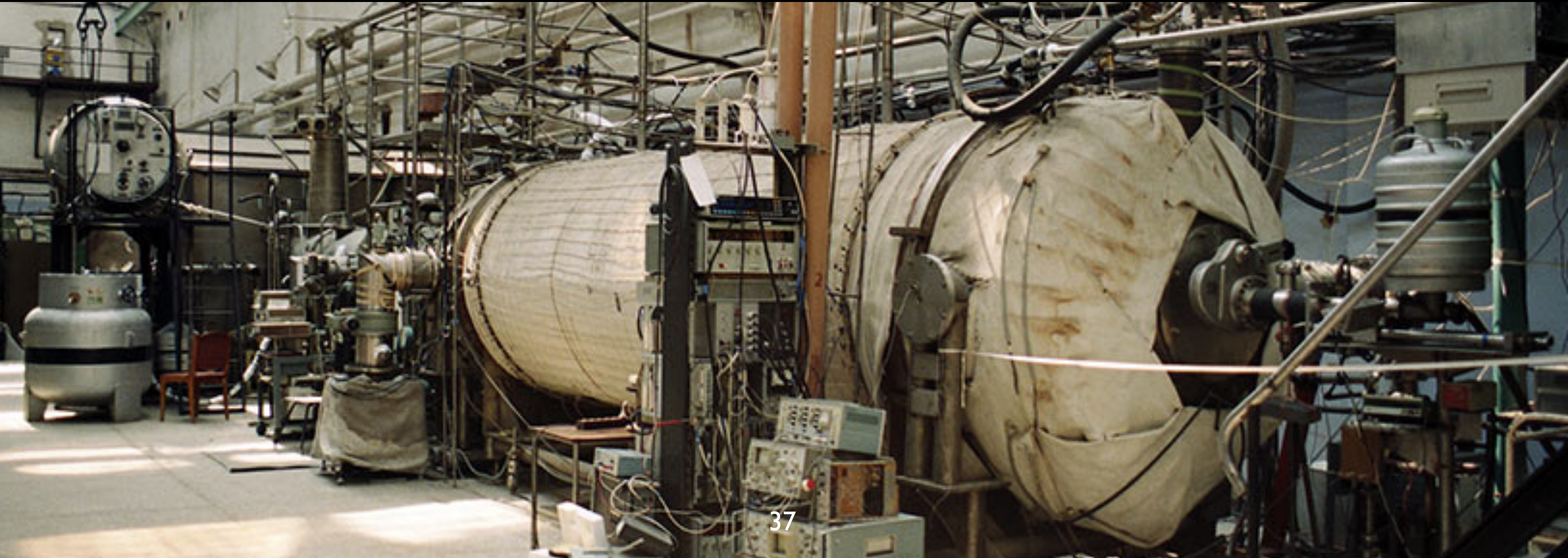
- Their limit of 27 eV rules out a previous signal for neutrino mass. Sets stage for gaseous sources in future designs.







Mainz & Troitsk



Current Techniques

Spectroscopy (KATRIN)

Magnetic Adiabatic Collimation with Electrostatic Filtering

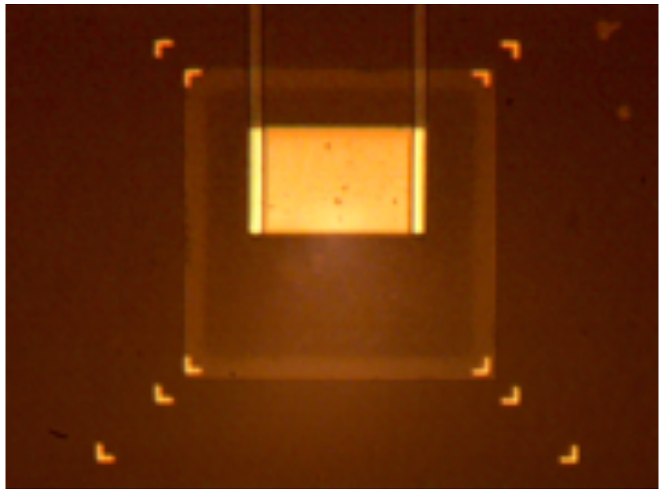
State-of-the-Art technique

$$T_2 \rightarrow (T \cdot {}^3He^+) + e^- + \bar{\nu}_e$$

Calorimetry (HOLMES, ECHO & NUMECS)

Technique highly advanced.

New experiment(s) planned to reach ~eV scale.

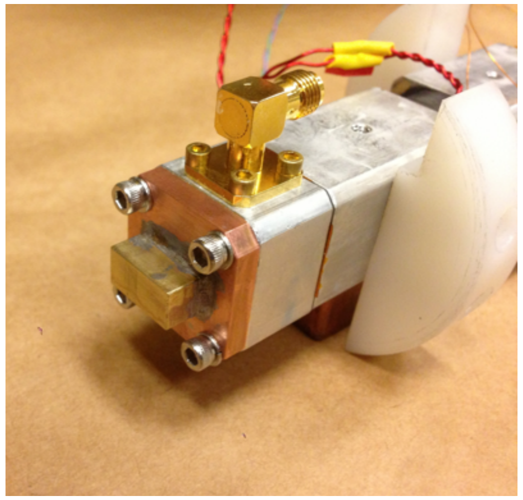


$${}^{163}Ho + e^- \rightarrow {}^{163}Dy^* + \nu_e$$

Frequency (Project 8)

Radio-frequency spectroscopy for beta decay

R&D phase (new results)



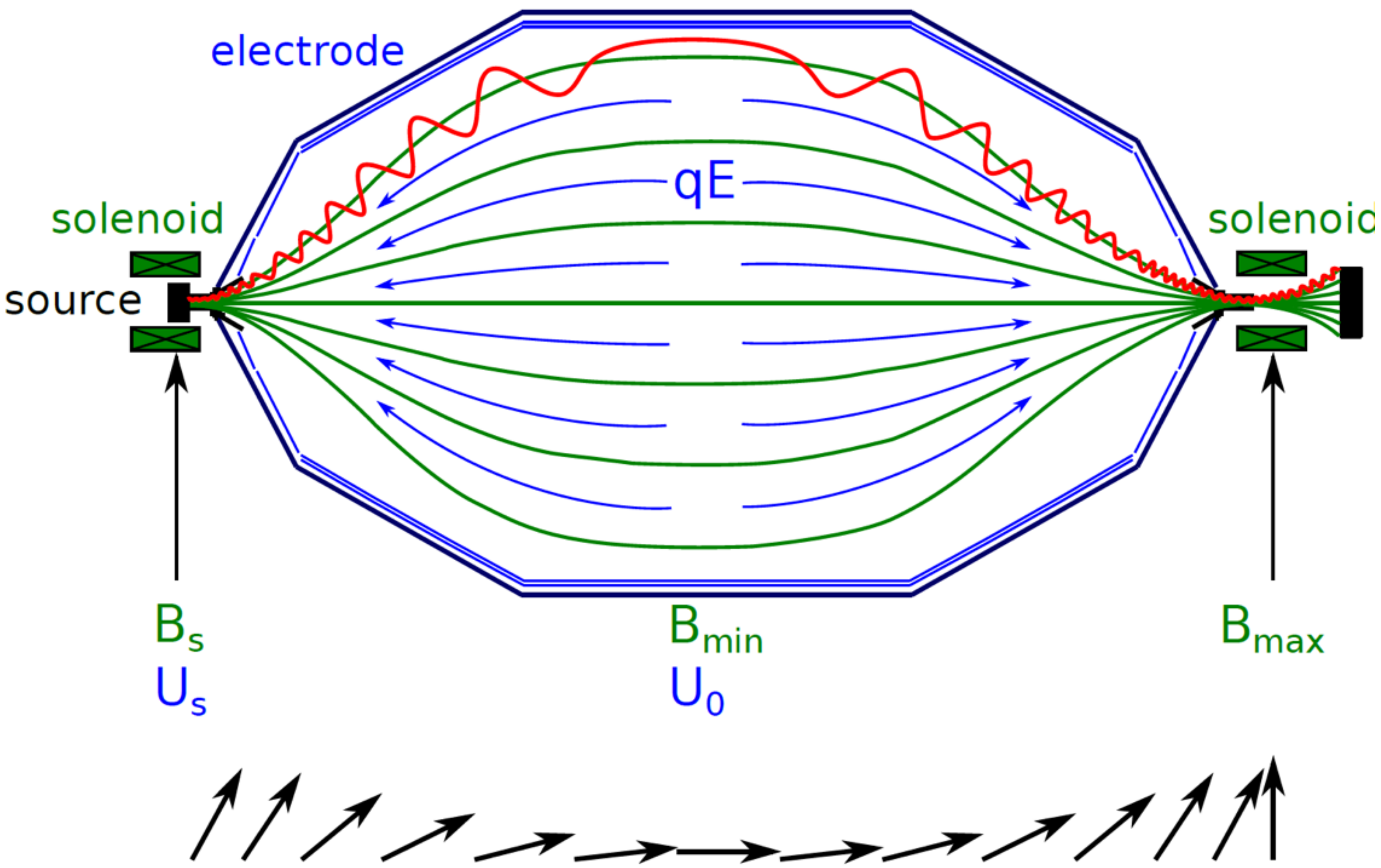
$${}^3H \rightarrow {}^3He^+ + e^- + \bar{\nu}_e$$

MAC-E Filter Technique

KATRIN

$$T_2 \rightarrow \ (T \cdot \ ^3He^+) + e^- + \bar{\nu}_e$$

Spectroscopic: MAC-E Filter



adiabatic transformation of e⁻ momentum

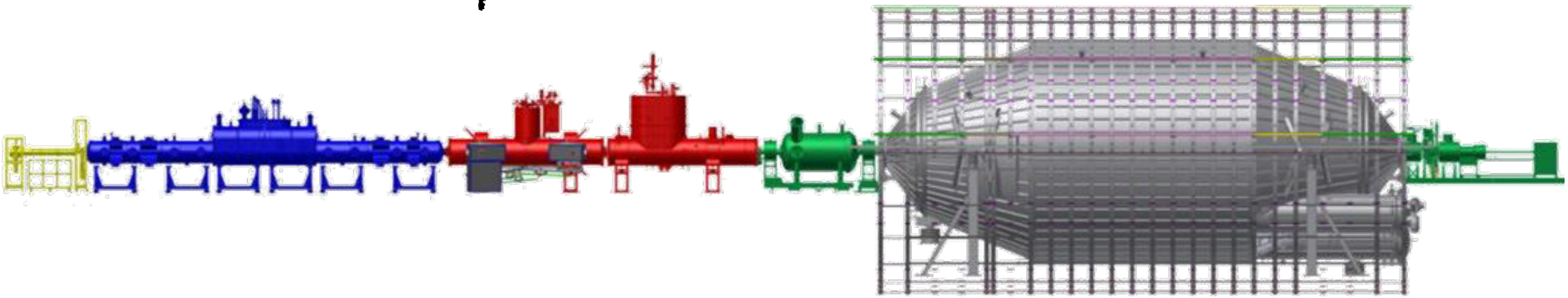
Inhomogeneous magnetic guiding field.

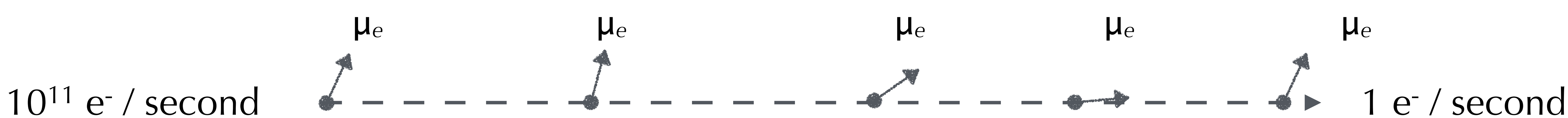
Retarding potential acts as high-pass filter

High energy resolution

($\Delta E/E = B_{min}/B_{max} = 0.93$ eV)

The KATRIN Setup



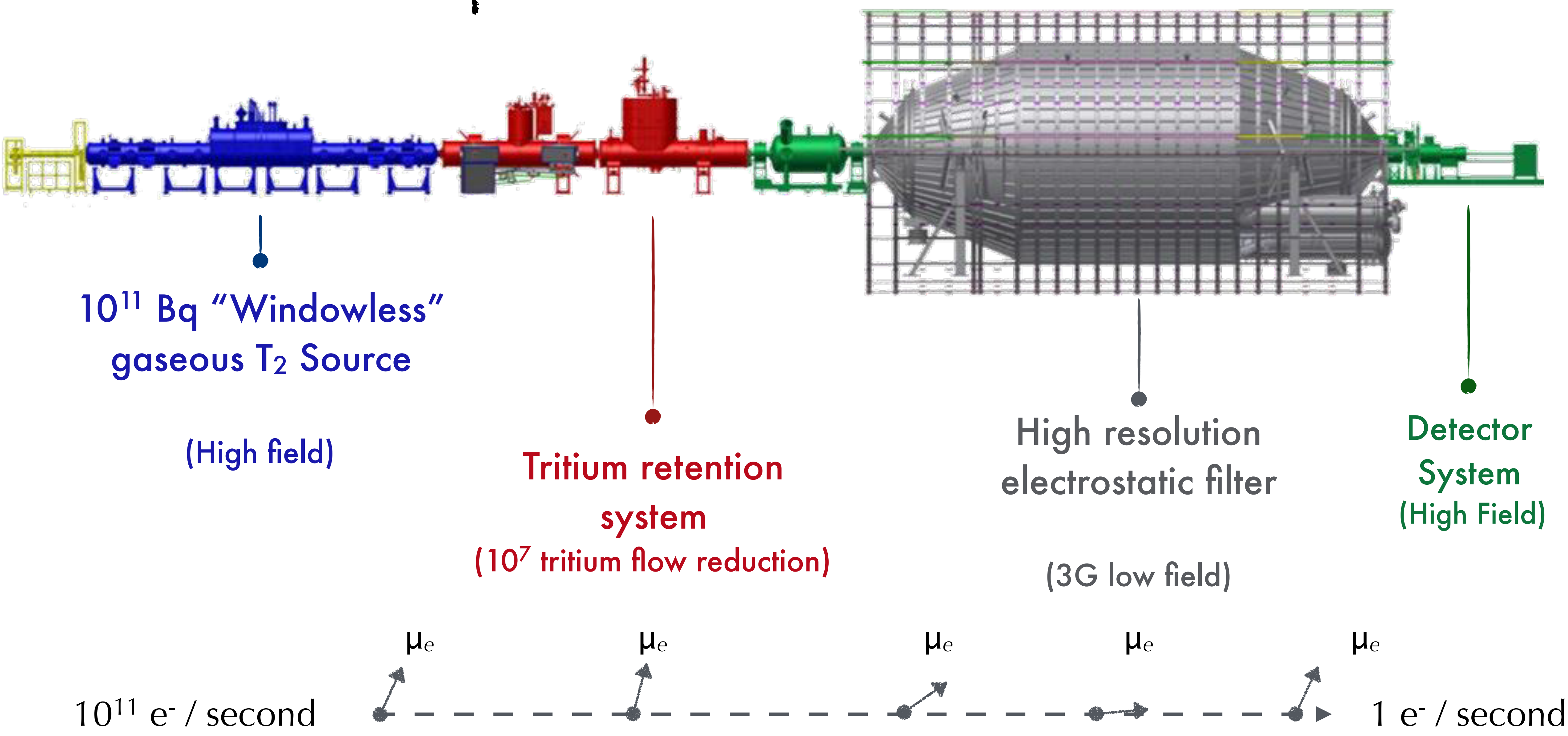


Adiabatic transport ensures high retention of phase space for decay

$$\frac{\Delta E}{E} = \frac{B_{\min}}{B_{\max}} \rightarrow 0.93 \text{ eV}$$

Energy resolution scales as the ratio of minimum / maximum fields

The KATRIN Setup



Adiabatic transport ensures high retention of phase space for decay

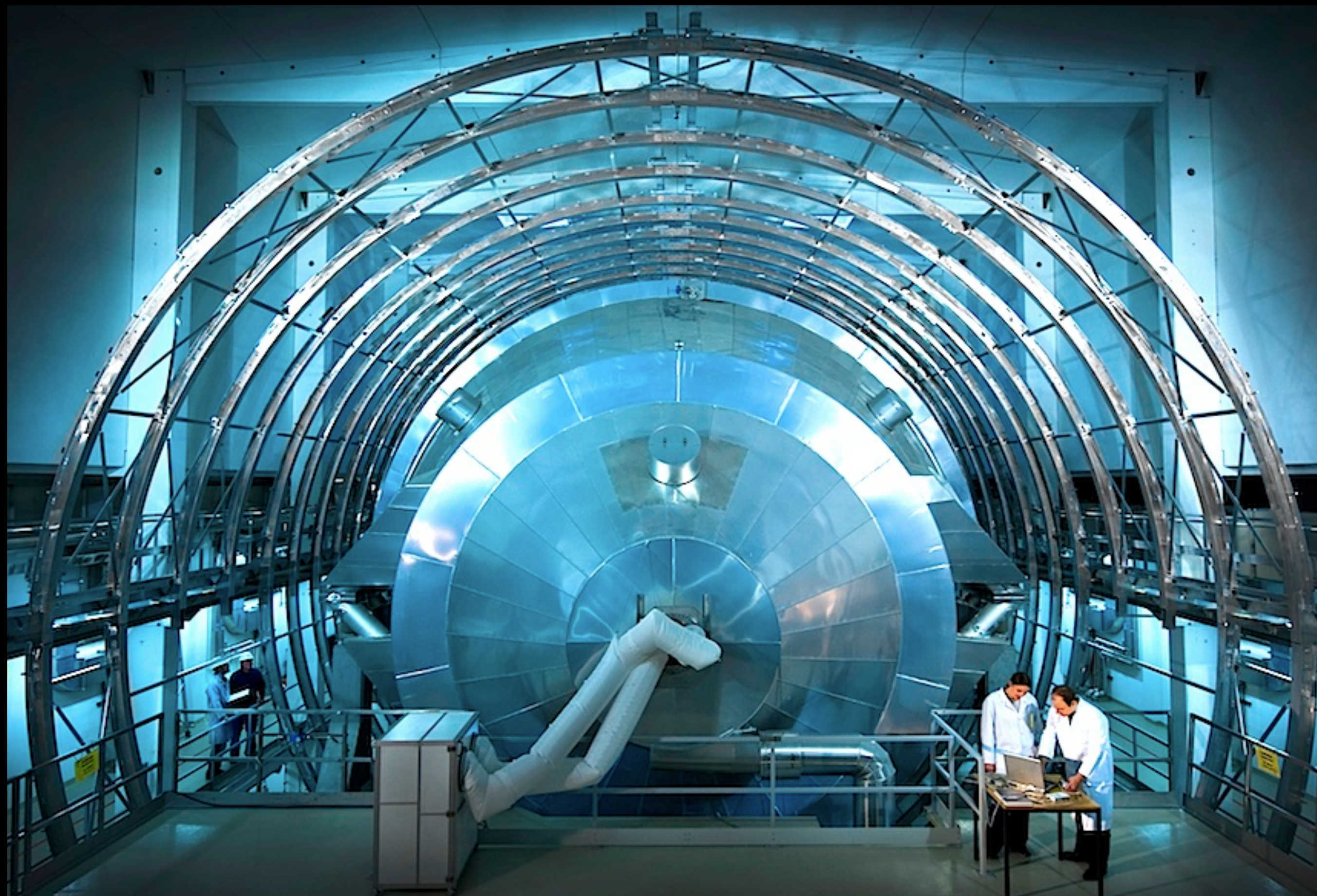
$$\frac{\Delta E}{E} = \frac{B_{\text{min}}}{B_{\text{max}}} \rightarrow 0.93 \text{ eV}$$

Energy resolution scales as the ratio of minimum / maximum fields

The Journey...

UNITED KINGDOM
Sea
Belfast
Dublin
IRELAND
Irish Sea
Isle of Man (U.K.)
Leeds
Manchester
Liverpool
Birmingham
Cardiff
London
Celtic Sea
DENMARK
Copenhagen
Malmö
Bornholm
Kaliningrad
RUSSIA
Vilnius
Minsk
Mahilyow
BELARUS
Hrodna
Homyel'
Gdańsk
Hamburg
Bremen
Berlin
Poznań
Warsaw
Brest
Kiev
Amsterdam
NETH.
Rotterdam
Oder
POLAND
Łódź
Rivne
Essen
Leipzig
Elbe
Wrocław
Cologne
Bonn
GERMANY
UKRAINE
Brussels
Lille
BEL.
Prague
Vistula
L'viv
Kraków
Frankfurt am Main
Guernsey (U.K.)
Jersey (U.K.)
Luxembourg
LUX.
CZECH REPUBLIC
Brno
SLOVAKIA
Chernivtsi
CARPATHIAN MTS.
Chişinău
Paris
Seine
Stuttgart
Bratislava
Iaşi
MOLDOVA
Strasbourg
Rhine
Munich
Danube
Vienna
Budapest
Cluj-Napoca
Nantes
Loire
LIECH.
AUSTRIA
Zürich
Bern
Vaduz
HUNGARY
ROMANIA
Bay of Biscay
FRANCE
Geneva
SWITZ.
ALPS
Ljubljana
Zagreb
Bucharest
SLOVENIA
Lyon
MASSIF CENTRAL
Milan
Venice
Turin
Po
DINARIC ALPS
BOSNIA AND HERZEGOVINA
Belgrade
Danube
Varna
Bordeaux
Genoa
CROATIA
Serbia
Bilbao
Toulouse
MONACO
SAN MARINO
Sarajevo
BULGARIA
Andorra la Vella
Marseille
Ligurian Sea
Florence
APENNINES
Montenegro
Sofia
Porto
PYRENEES
ANDORRA
ITALY
Adriatic Sea
Podgorica
Skopje
Istanbul
Zaragoza
Corsica
Rome
F.Y.R.O.M.
Madrid
Barcelona
VATICAN CITY
Tirana
ALB.
Thessaloniki
PORTUGAL
Tagus
Naples
Lisbon
SPAIN
Valencia
Balearic Sea
Sardinia
Tyrrhenian Sea
GREECE
Aegean Sea
TURKEY
İzmir
BALEARIC ISLANDS
Athens
Sevilla
Cagliari
Ionian Sea
Gibraltar (U.K.)
Málaga
Mediterranean Sea
Palermo
Sicily
Strait of Gibraltar
Ceuta (SPAIN)
Alborán Sea
Algiers
Melilla (SPAIN)
Oran
Tunis
Crete
Rabat
Casablanca
MOROCCO
ALGERIA
TUNISIA
Valletta
MALTA
Scale 1: 19,500,000
Lambert Conformal Conic Projection, standard parallels 40°N and 56°N
0 300 Kilometers
0 300 Miles

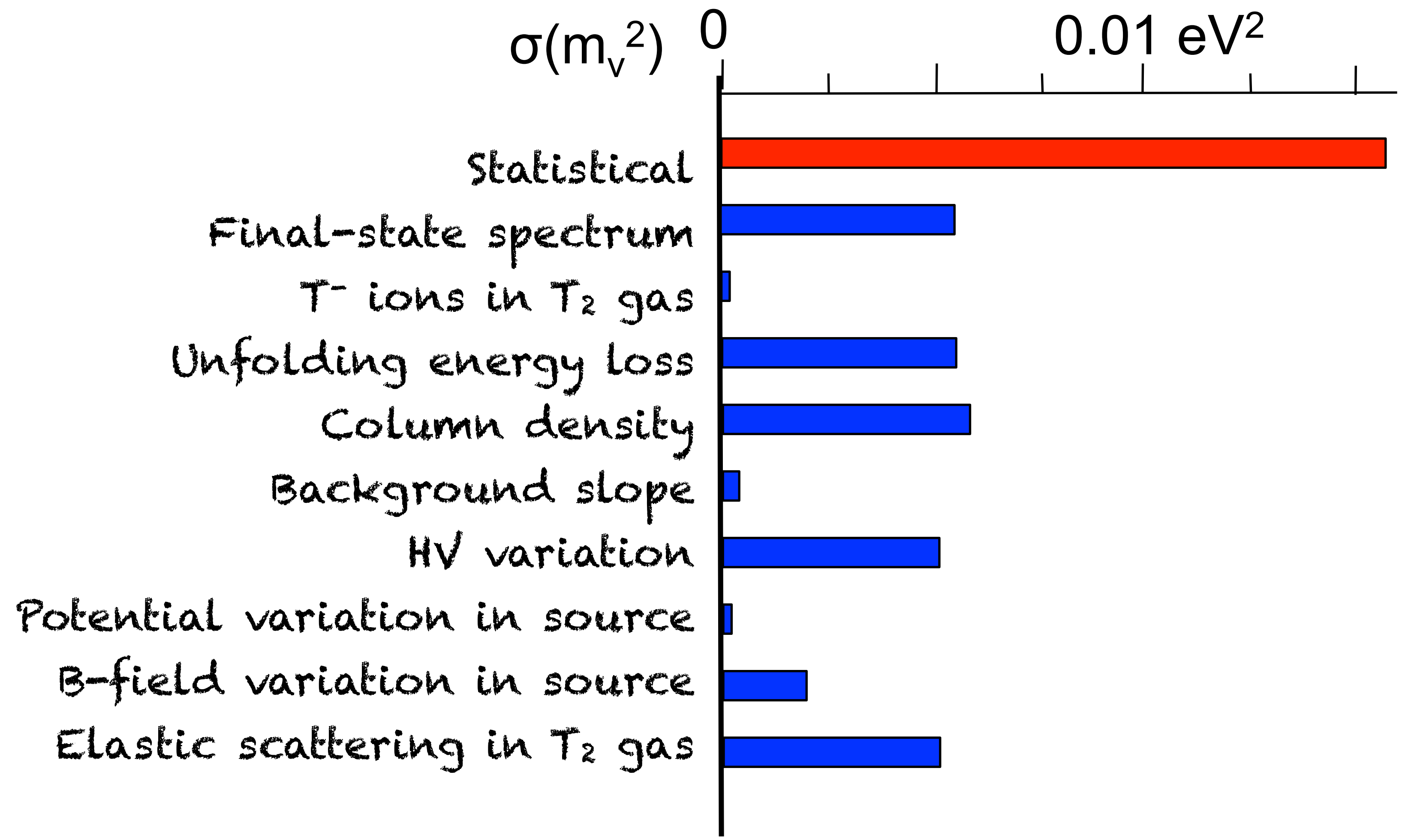
…and the arrival.

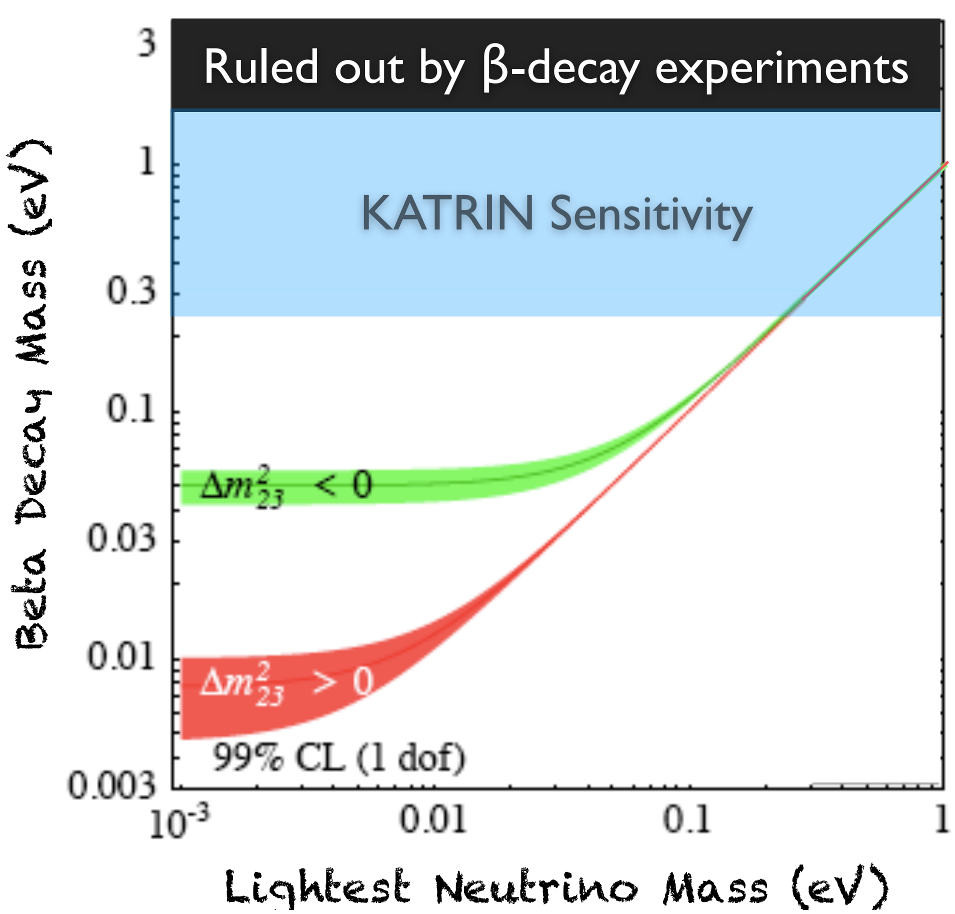


All components of the experiment, including the source, now on site and being commissioned.

Main spectrometer commissioned and provides more precise spectrometer of its kind.

Projected Sensitivity





Neutrino Mass Goals

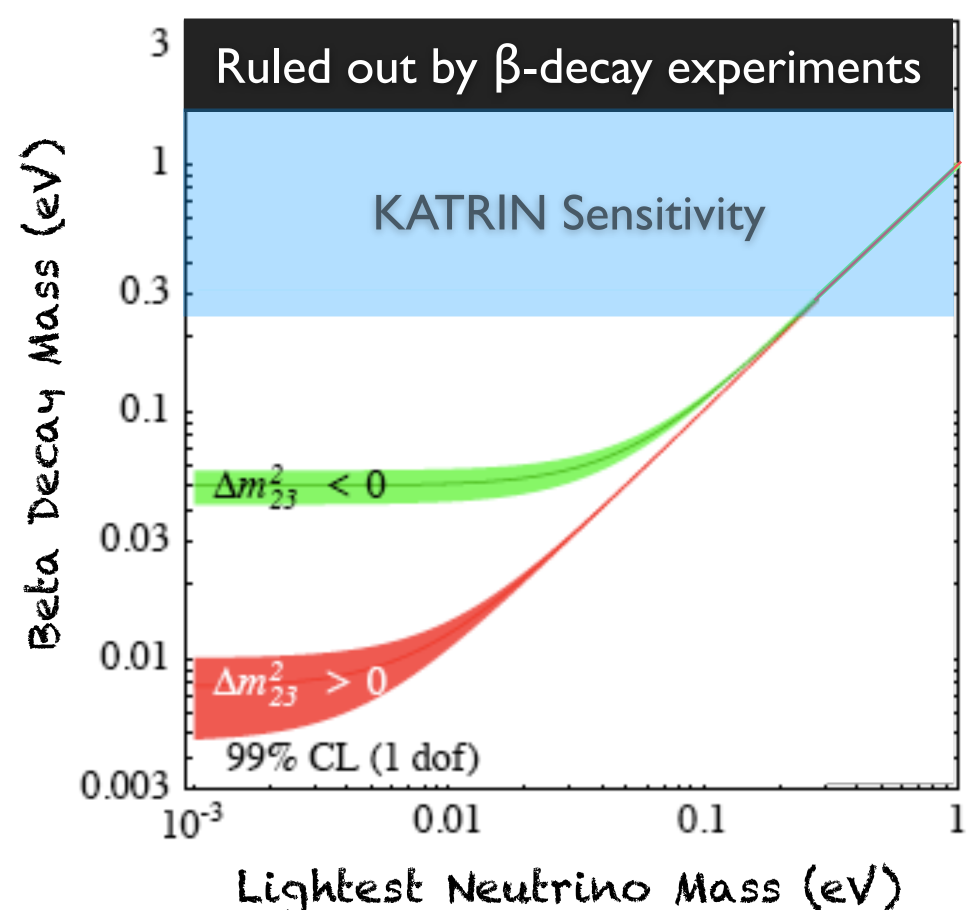
Discovery: 350 meV (at 5σ)

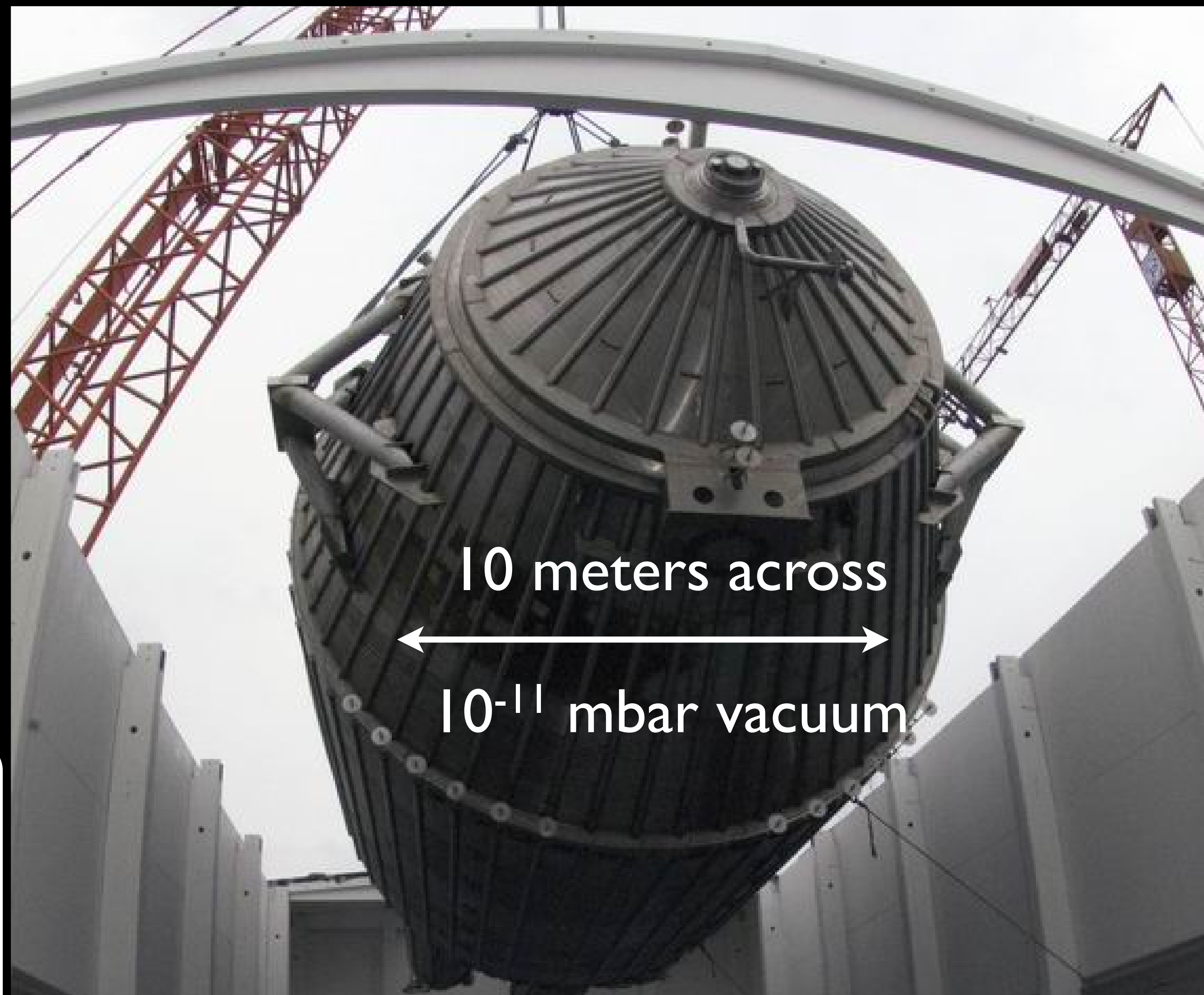
Sensitivity: 200 meV (at 90% C.L.)

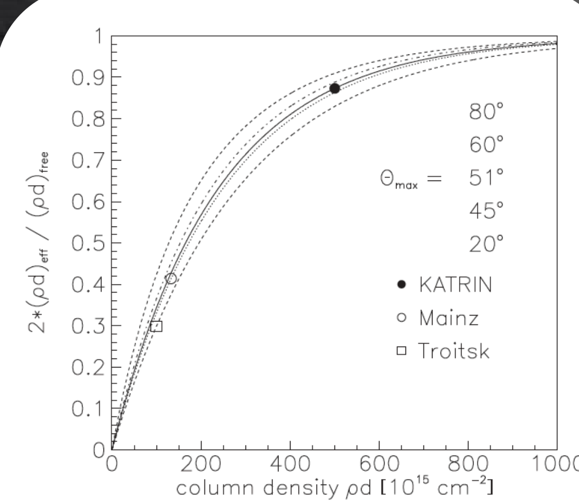
Data taking to commence in 2016.

Can we push further?

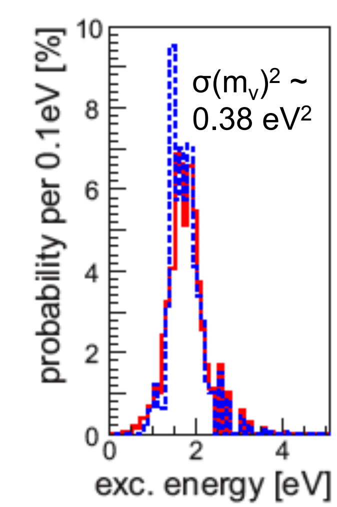
- Can direct measurements push to the inverted ordering scale?
- To do so, they must have better scaling law.



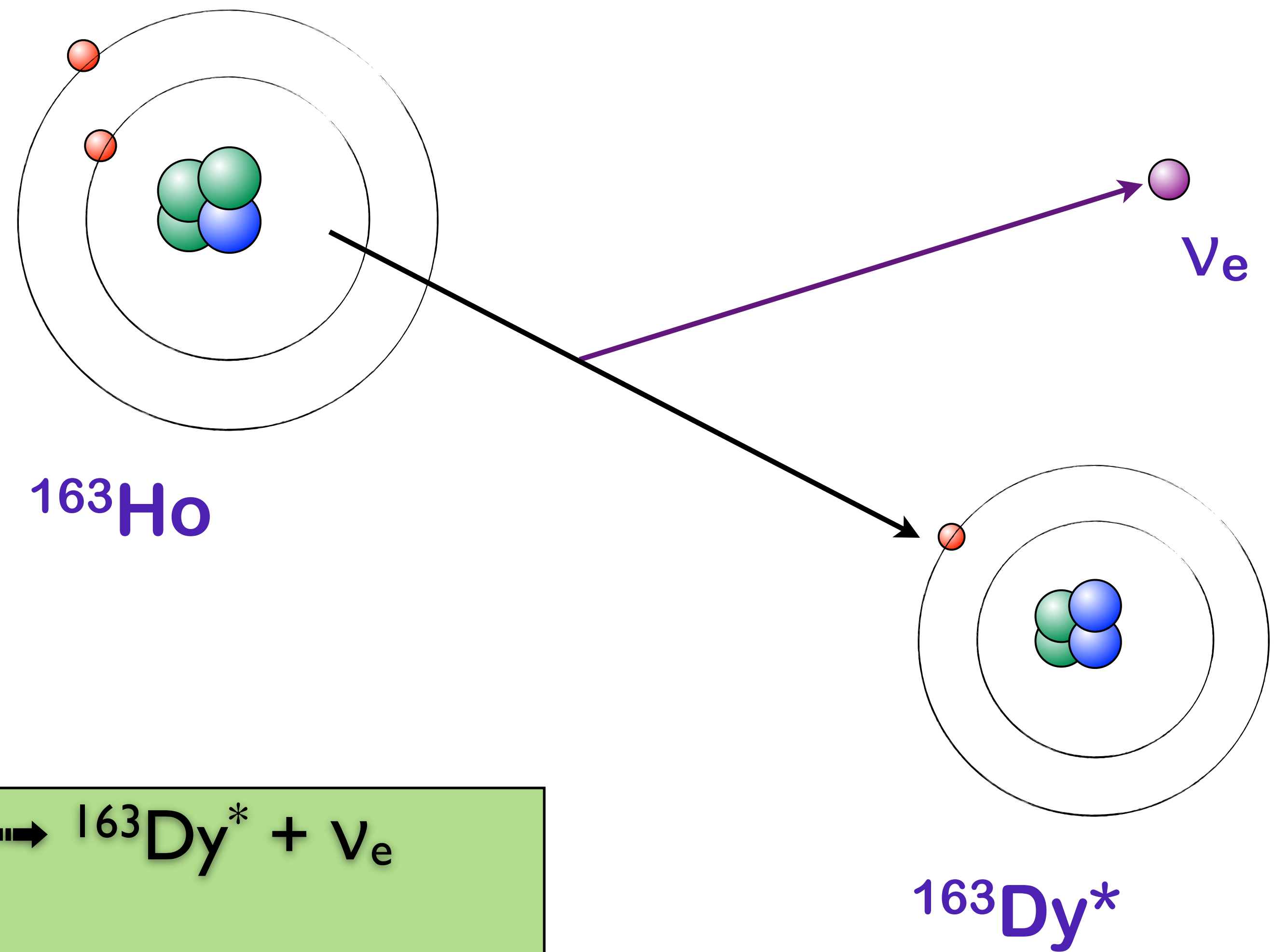




Source column density at max



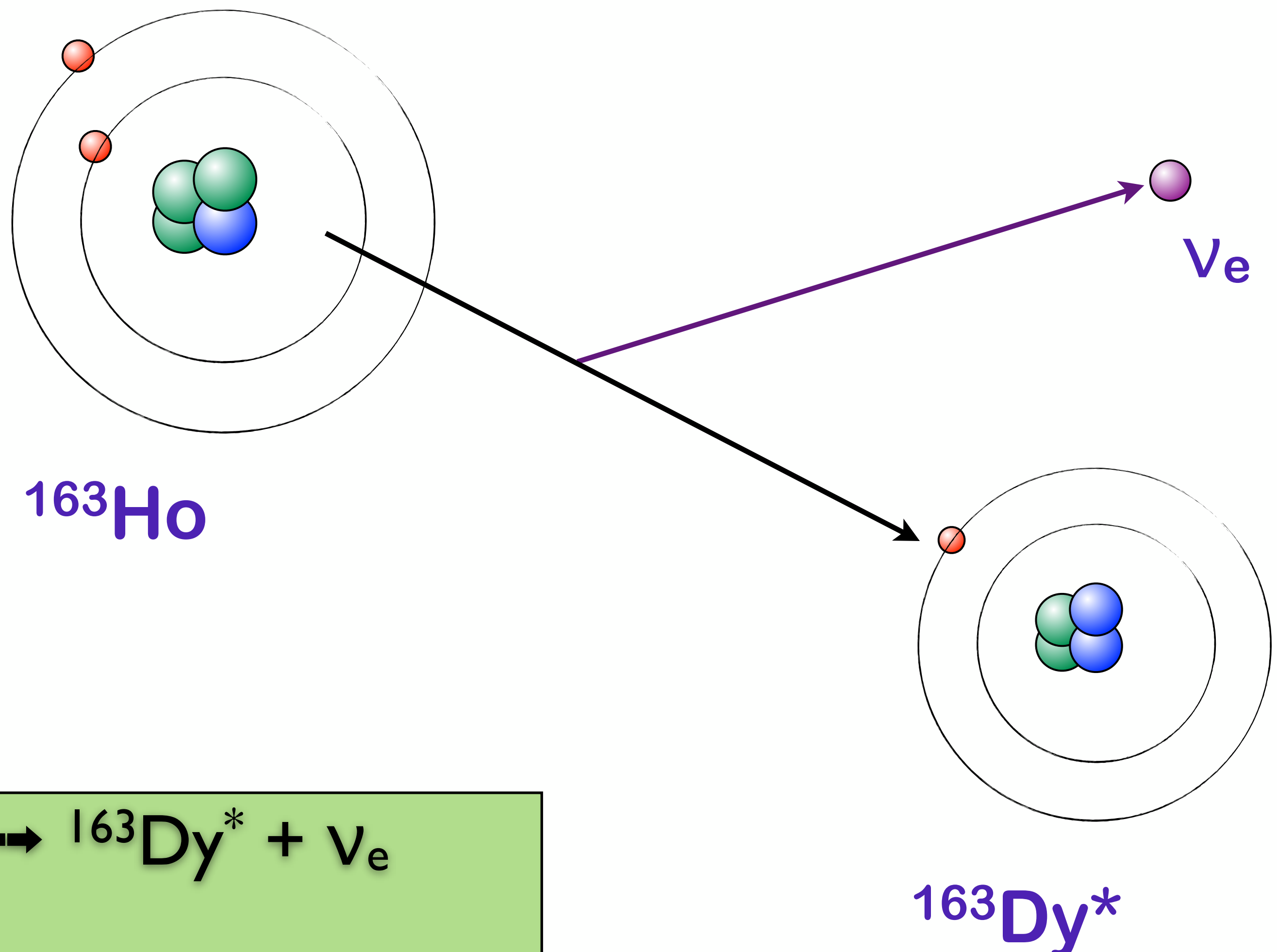
Rovibrational states of THe^+



$$^{163}\mathrm{Ho} + e^- \rightarrow {}^{163}\mathrm{Dy}^* + \nu_e$$

$$^{163}\mathrm{Dy}^* \rightarrow {}^{163}\mathrm{Dy} + \mathrm{E.C.}$$

New kid on the block: Electron Capture

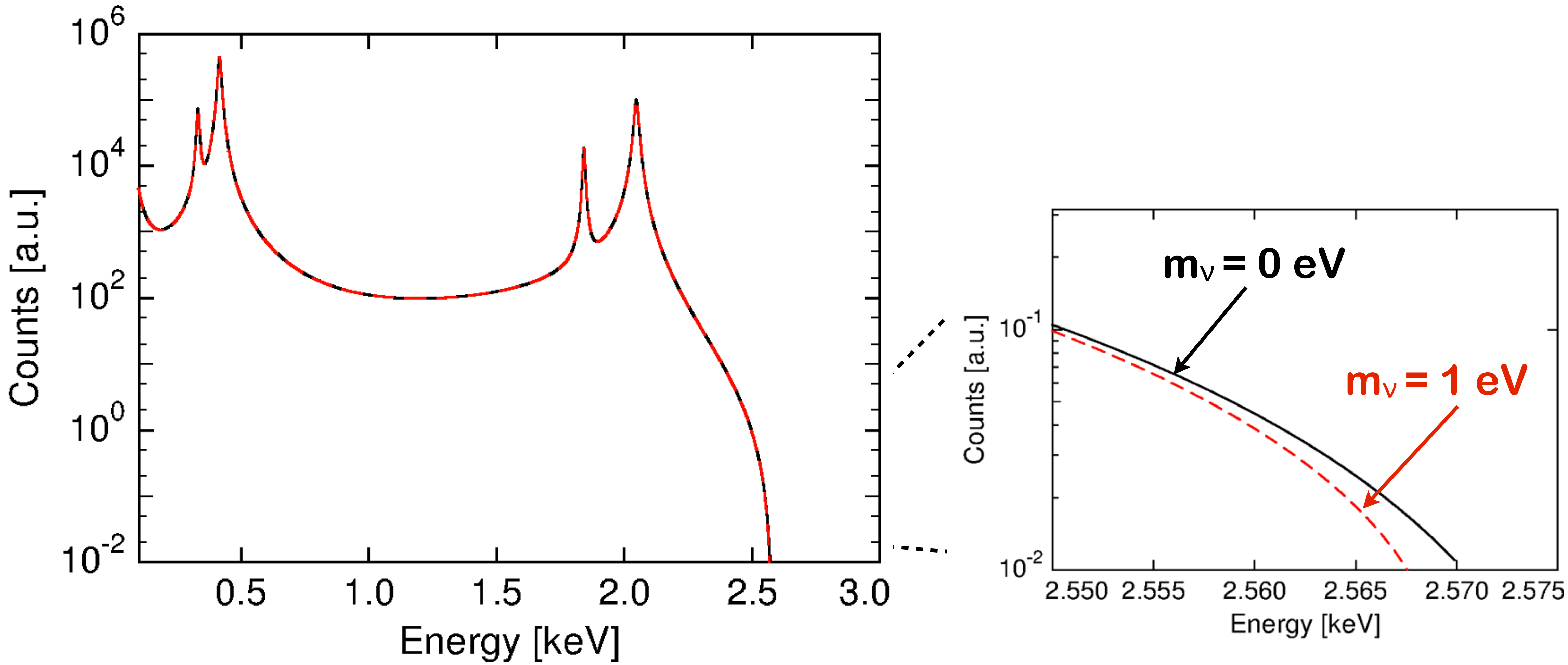


$$^{163}\mathrm{Ho} + e^- \rightarrow {}^{163}\mathrm{Dy}^* + \nu_e$$

$$^{163}\mathrm{Dy}^* \rightarrow {}^{163}\mathrm{Dy} + \mathrm{E.C.}$$

New ~~kid~~ isotope on the block:
Electron Capture

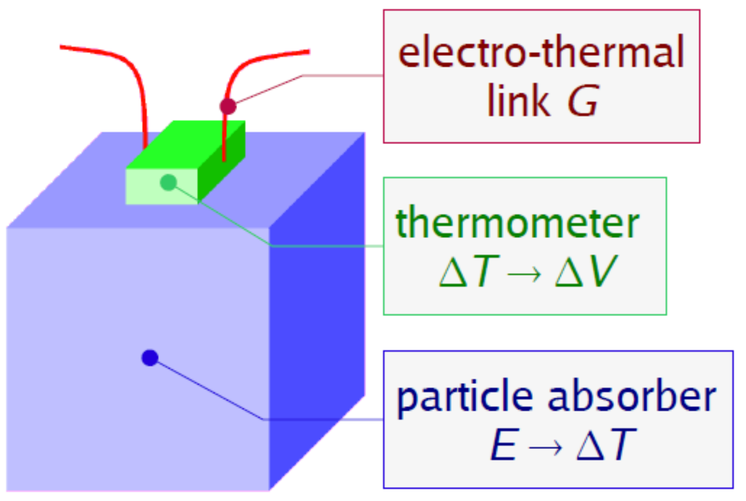
$$\dot{N} \sim (Q_{EC} - E_C)^2 \sum_i |U_{ei}|^2 \sqrt{1 - \frac{m_{\nu i}^2}{(Q_{EC} - E_C)^2}} \sum_H B_H \psi_H^2(0) \frac{\frac{\Gamma_H}{2\pi}}{(E_{EC} - E_H)^2 + \frac{\Gamma_H^2}{4}}$$



New ~~kid~~ isotope on the block: Electron Capture

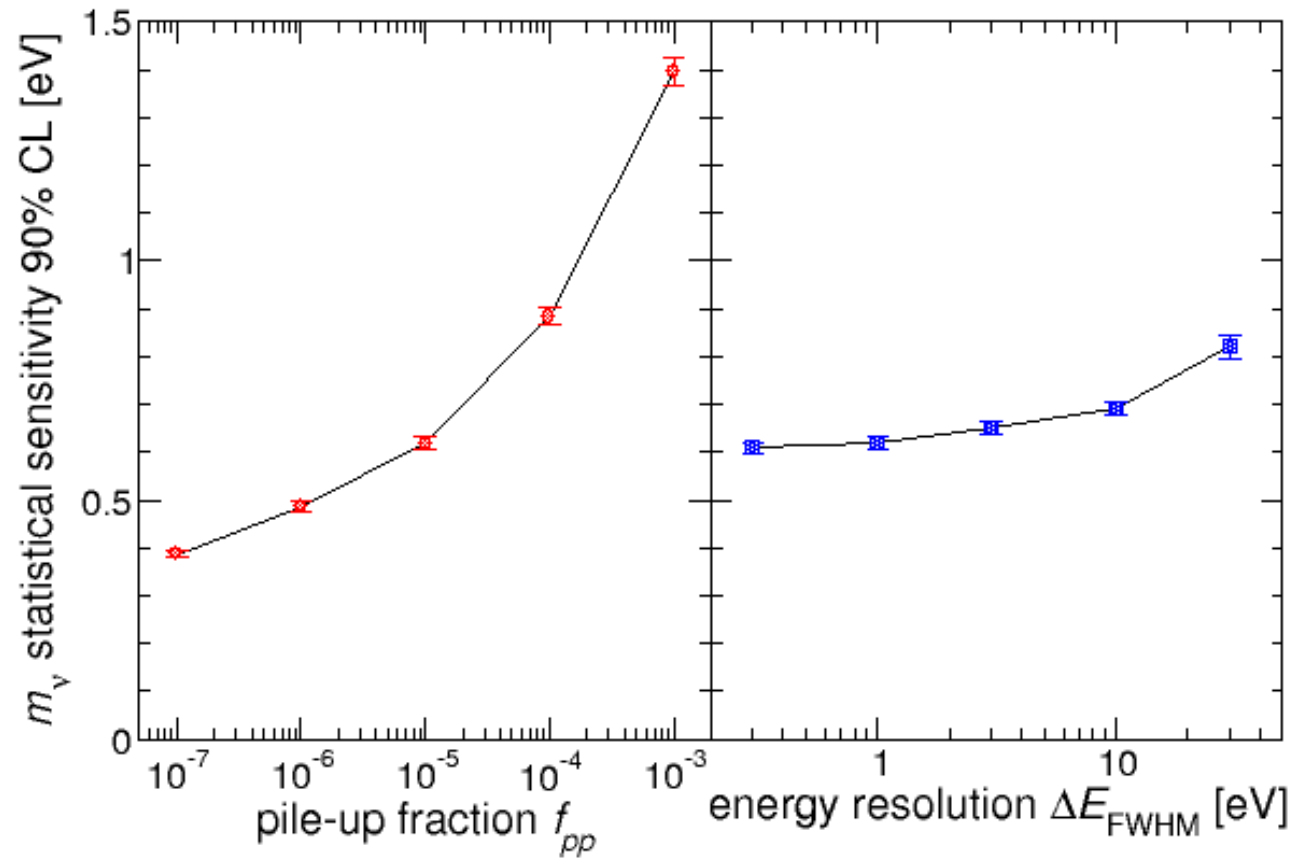
Advantages & Challenges

Calorimetry



$$^{163}\mathrm{Ho} + \mathrm{e}^- \rightarrow {}^{183}\mathrm{Dy}^* + \nu_e$$

Challenges:



Source Activity

$N_{ev} > 10^{14}$ to reach sub-eV level

Detector Response

$\Delta E_{FWHM} < 10$ eV

$\tau_{risetime} < 1$ µs

- **Advantages:**

  Source = detector

  No backscattering

  No molecular final state effects.

  Self-calibrating

- **Experimental Challenges:**

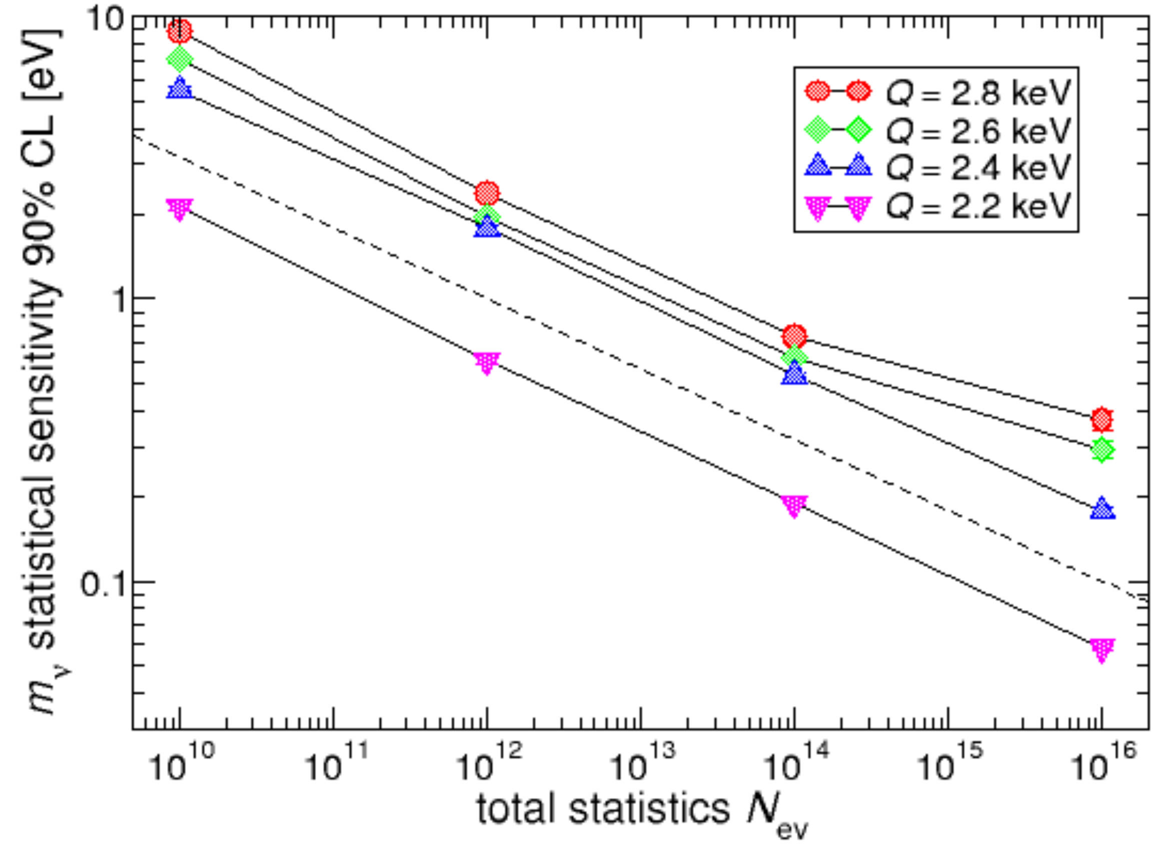
  Fast rise times to avoid pile-up effects.

  Good energy resolution & linearity

  Sufficient isotope production

Advantages & Challenges

Challenges:



Source Activity

$N_{ev} > 10^{14}$ to reach sub-eV level

Detector Response

$\Delta E_{FWHM} < 10$ eV
$\tau_{risetime} < 1$ µs

- **Advantages:**

  Source = detector

  No backscattering

  No molecular final state effects.

  Self-calibrating

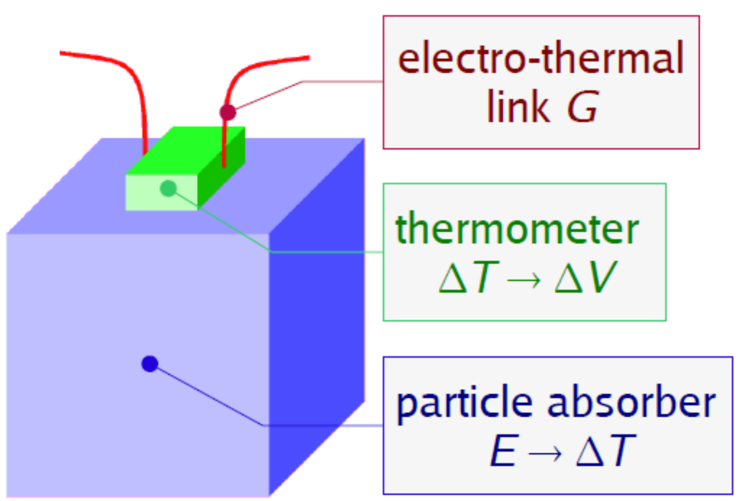
- **Experimental Challenges:**

  Fast rise times to avoid pile-up effects.

  Good energy resolution & linearity

  Sufficient isotope production

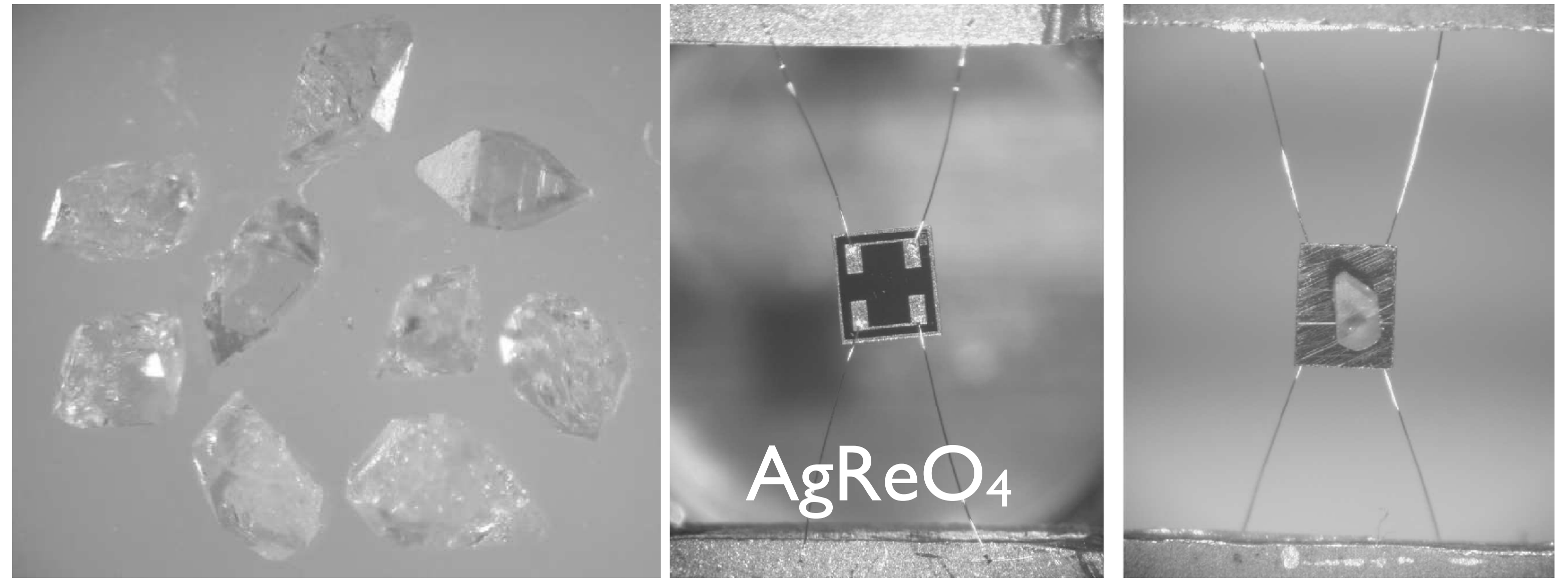
Calorimetry



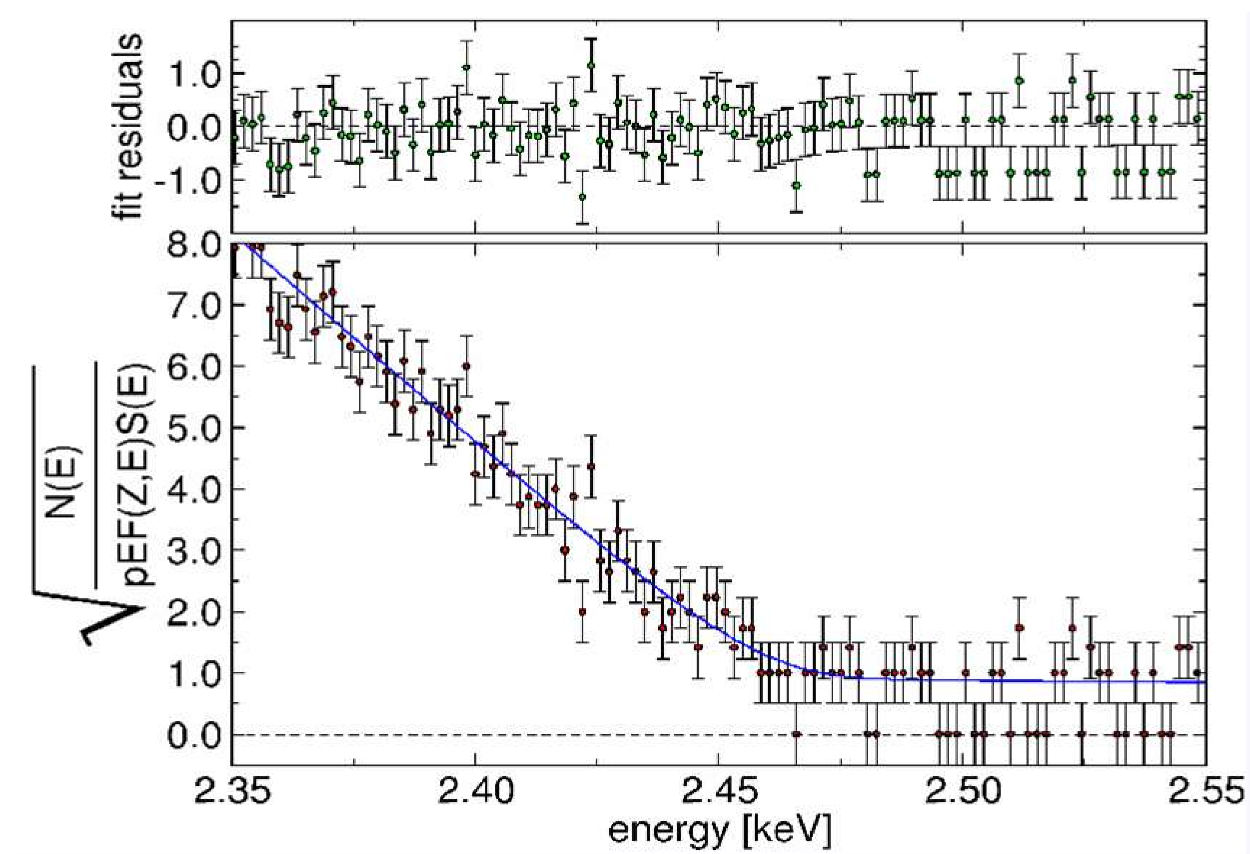
$$^{163}\mathrm{Ho} + \mathrm{e}^- \rightarrow {}^{183}\mathrm{Dy}^* + \nu_e$$

Their Predecessor

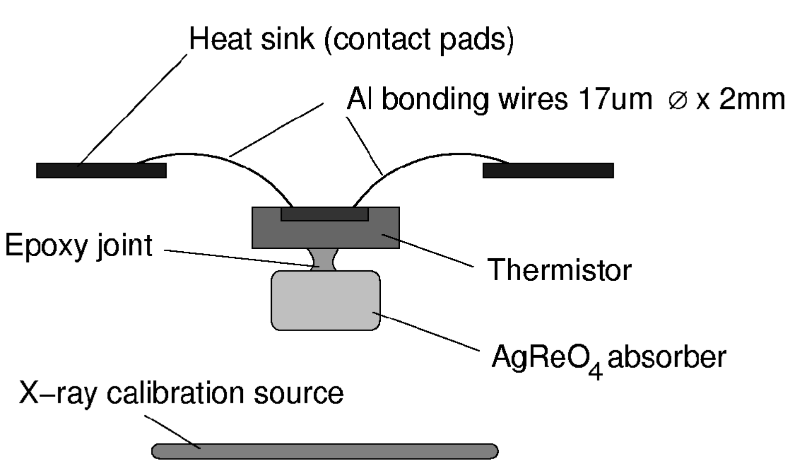
MARE



MARE provides the first β decay measurement of ^{187}Re using calorimetry

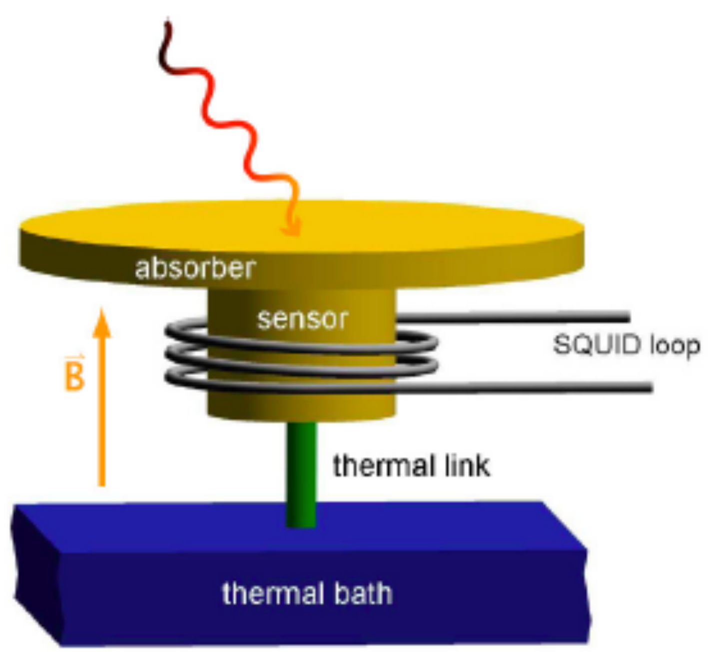


Calorimetry

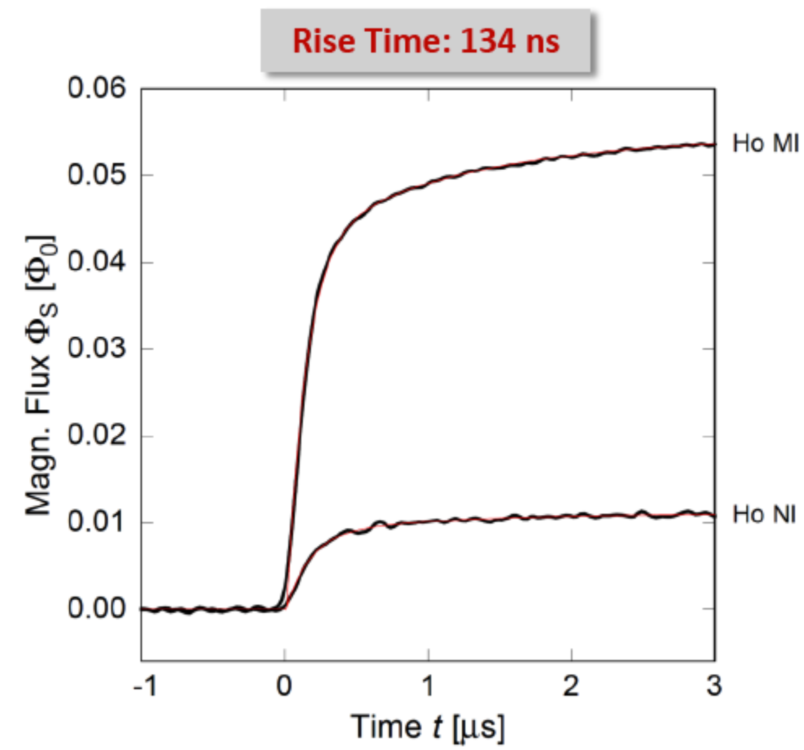


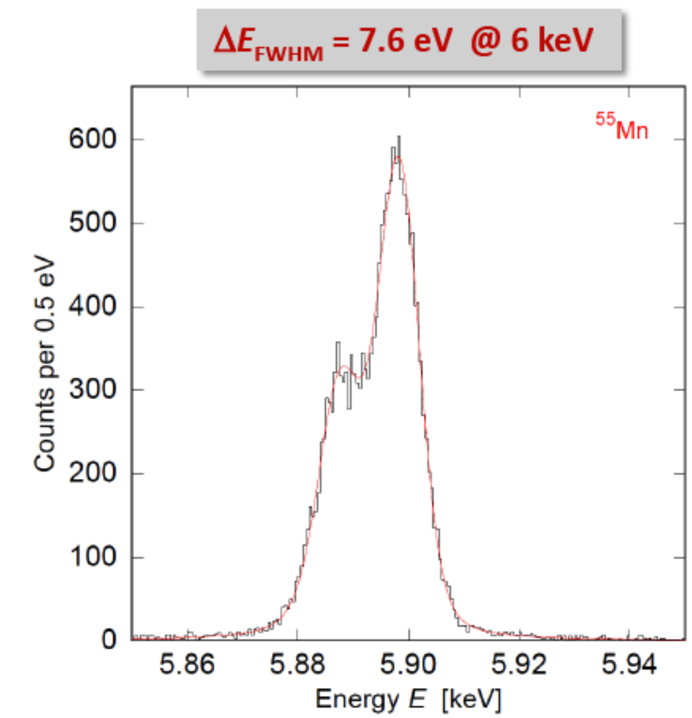
The ECHo Experiment

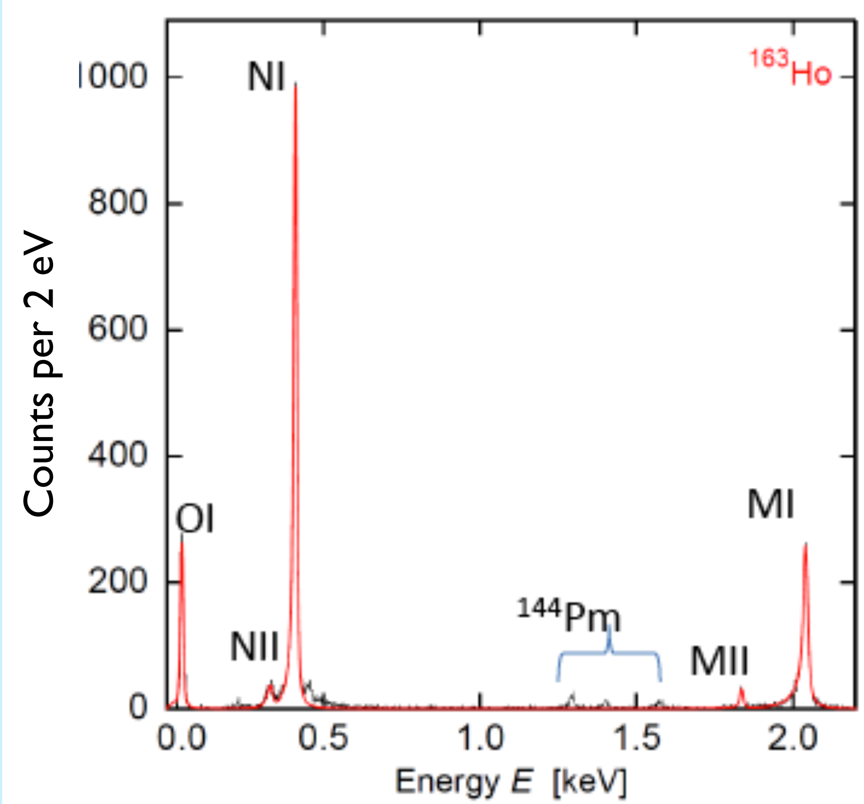
Technology:



Metallic Magnetic Calorimeters



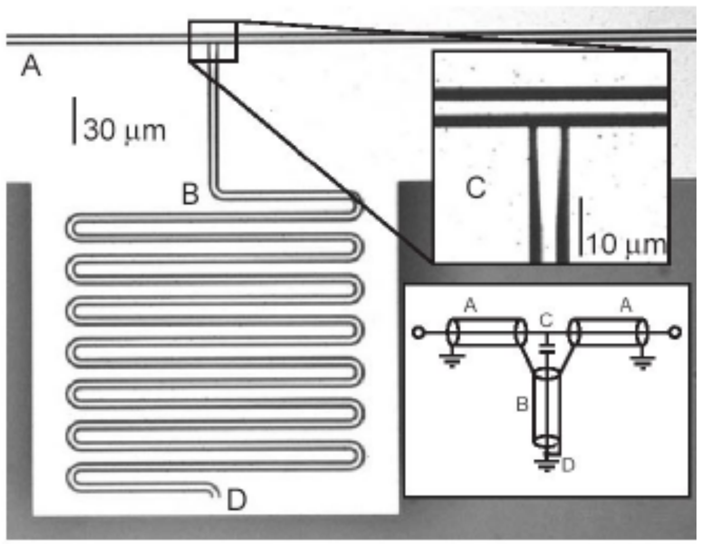




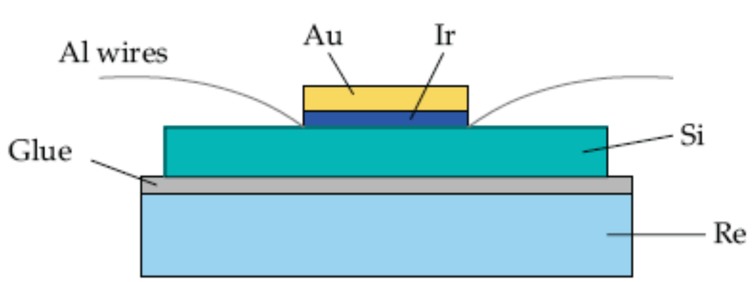
- The ECHo experiment uses metallic magnetic calorimeters to achieve goals.
- Fast rise times and good energy resolutions and linearity demonstrated.
- Endpoint measured at 2.80 ± 0.08 keV.

The HOLMES Experiment

Technologies:



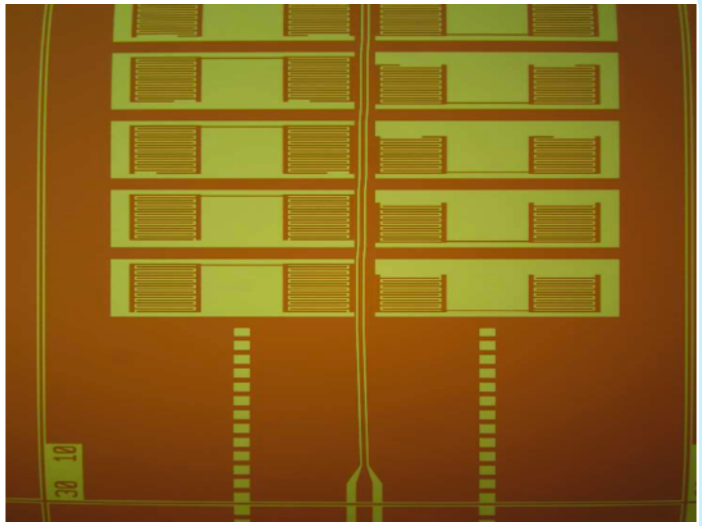
Superconducting Resonators

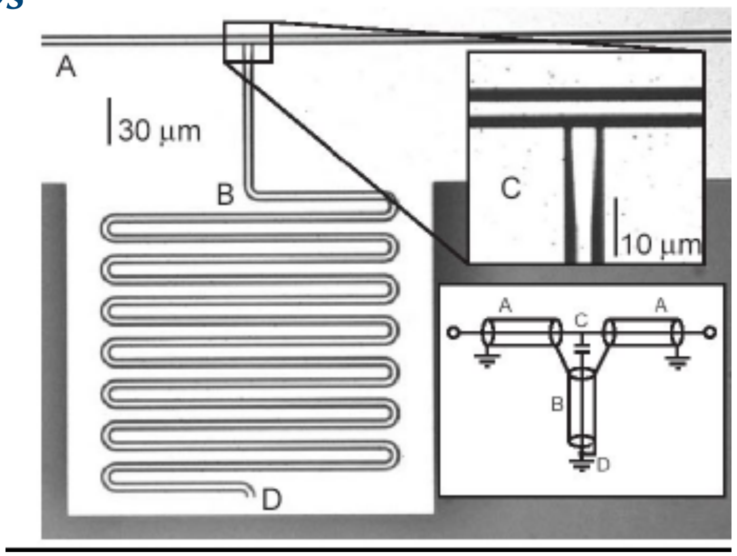


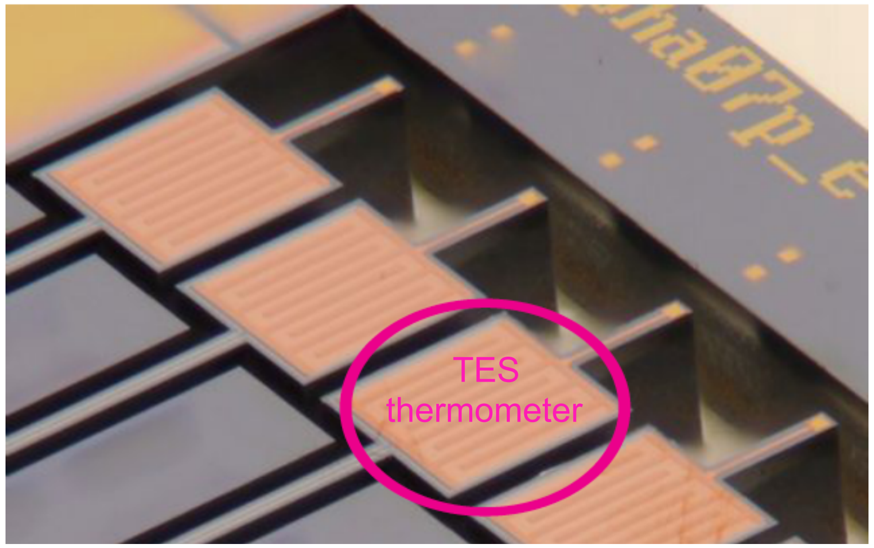
Transition Edge Sensors

HOLMES (Italy)

transition edge sensors / MKIDs







NuMECS (USA)

transition edge sensors

Project 8

Coherent radiation emitted can be collected and used to measure the energy of the electron in non-destructively.

PROJECT 8

Frequency Approach

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

I. I. Rabi

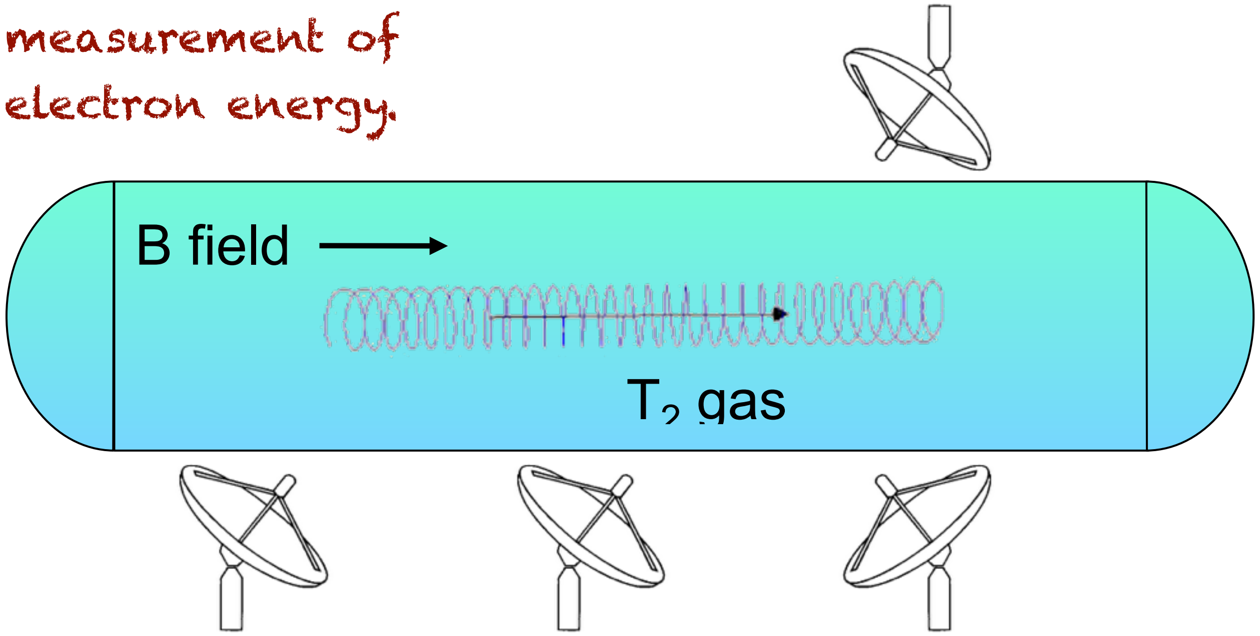
"Never measure anything but frequency."

A. L. Schawlow

- Use cyclotron frequency to extract electron energy.

$$\omega(\gamma) = \frac{\omega_0}{\gamma} = \frac{eB}{K + m_e}$$

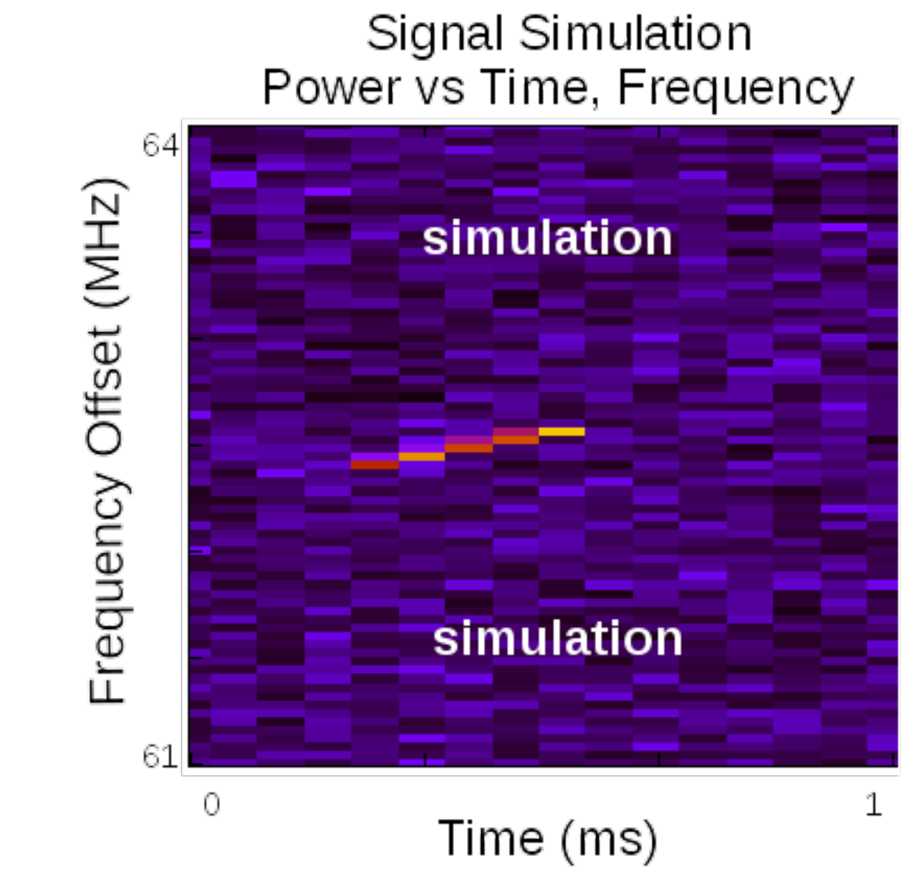
- Non-destructive measurement of electron energy.

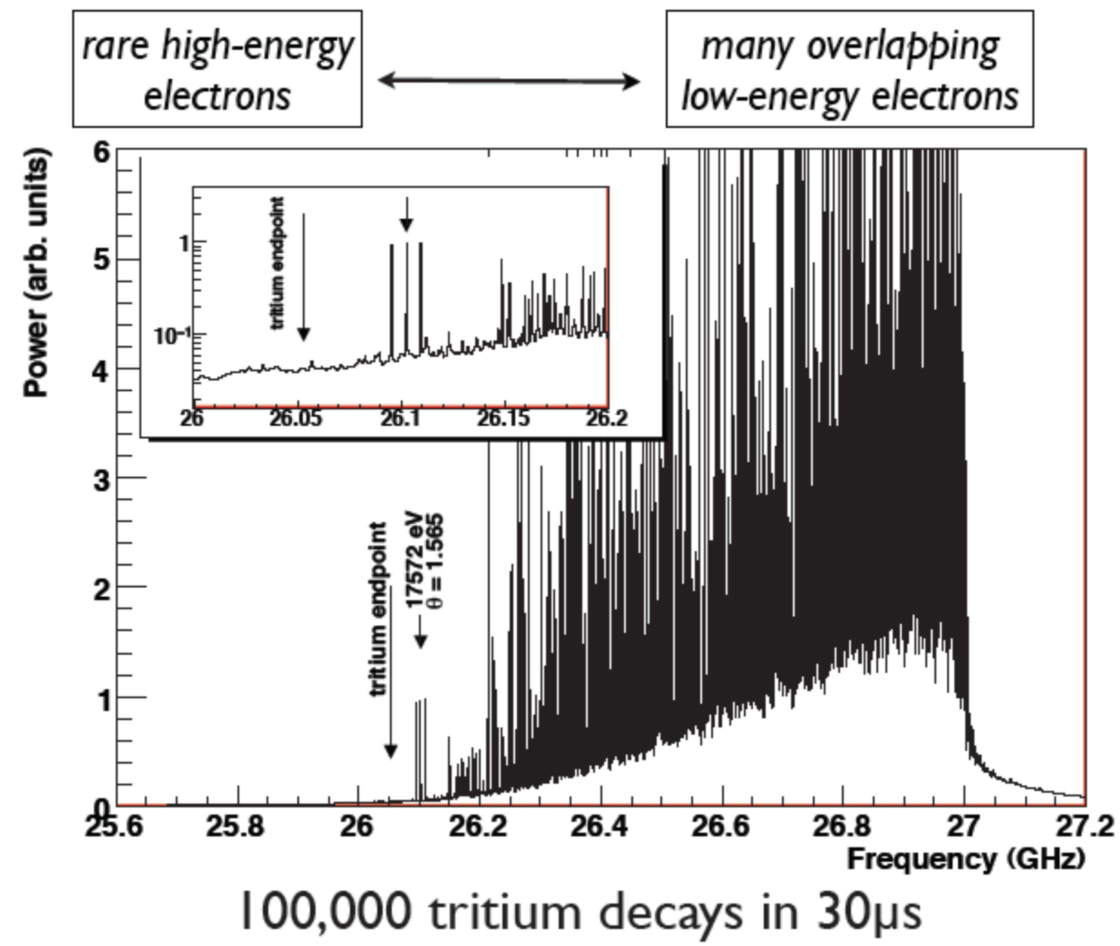


B. Monreal and JAF, Phys. Rev D80:051301

Unique Advantages

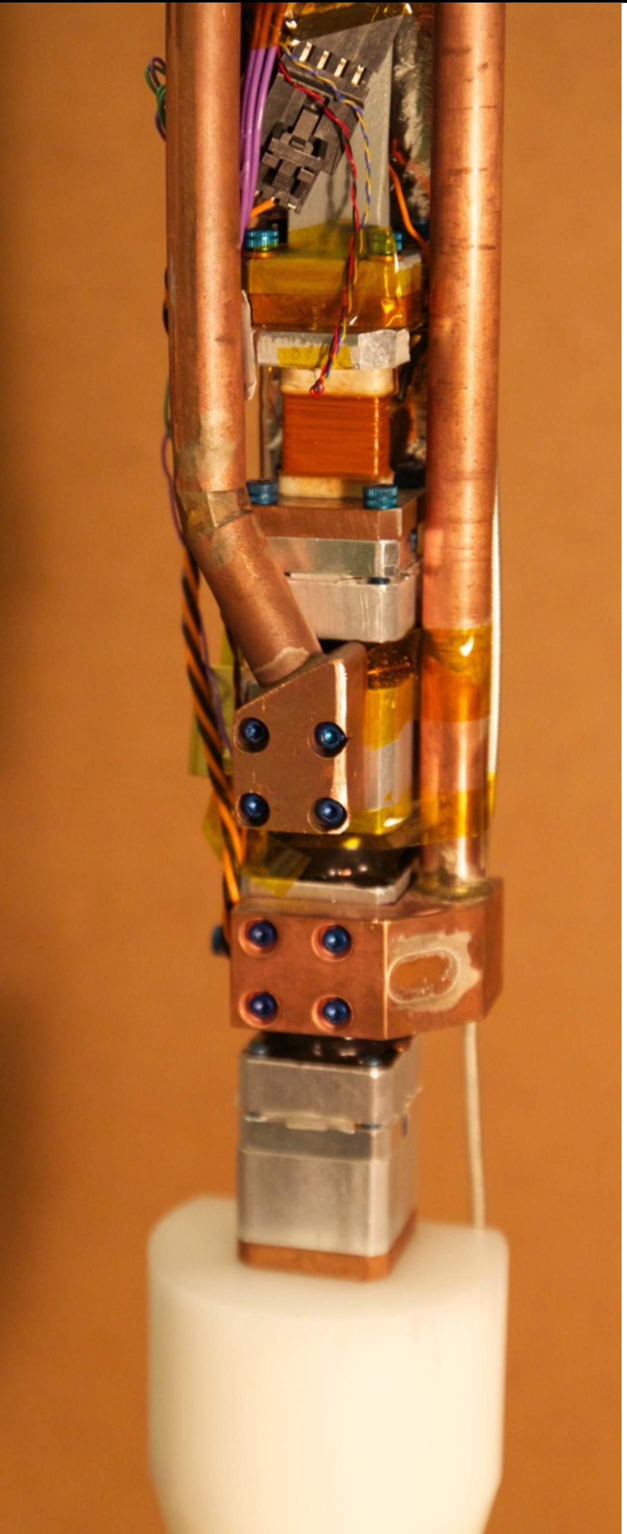
- **Source = Detector**
  (no need to extract the electrons from the tritium)
- **Frequency Measurement**
  (can pin electron energies to well-known frequency standards)
- **Full Spectrum Sampling**
  (full spectrum measured at once, large leverage for stability and statistics)

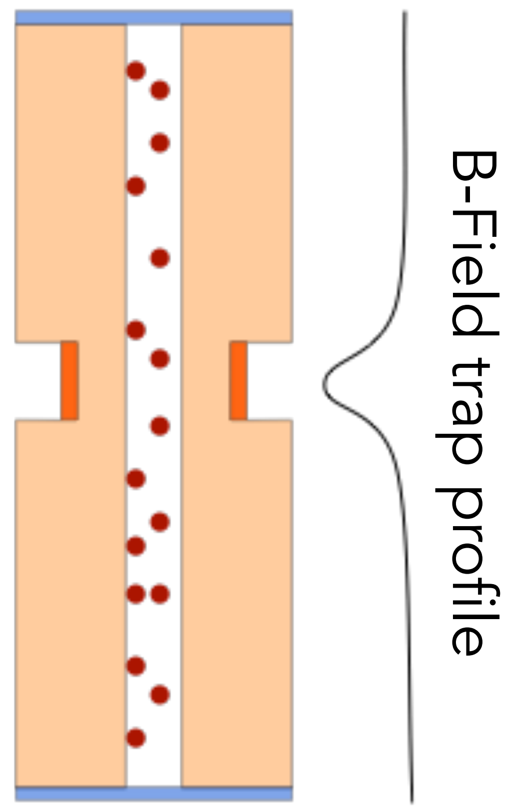


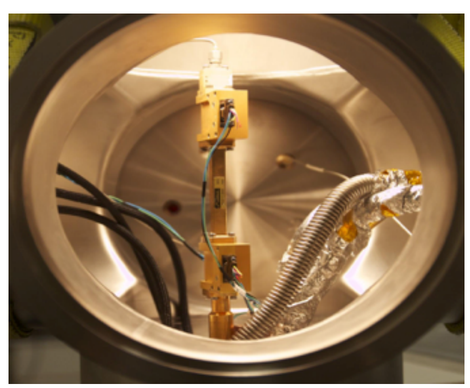


Simulation of beta (frequency) spectrum

The Apparatus







Waveguide Cut-away

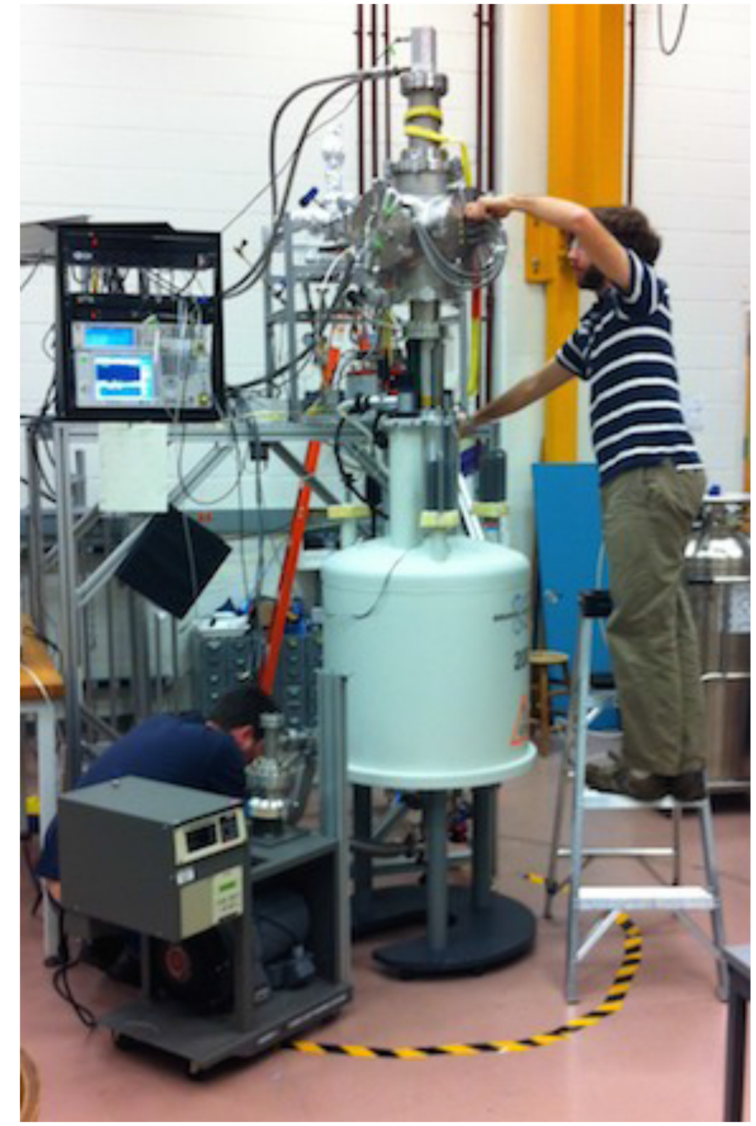
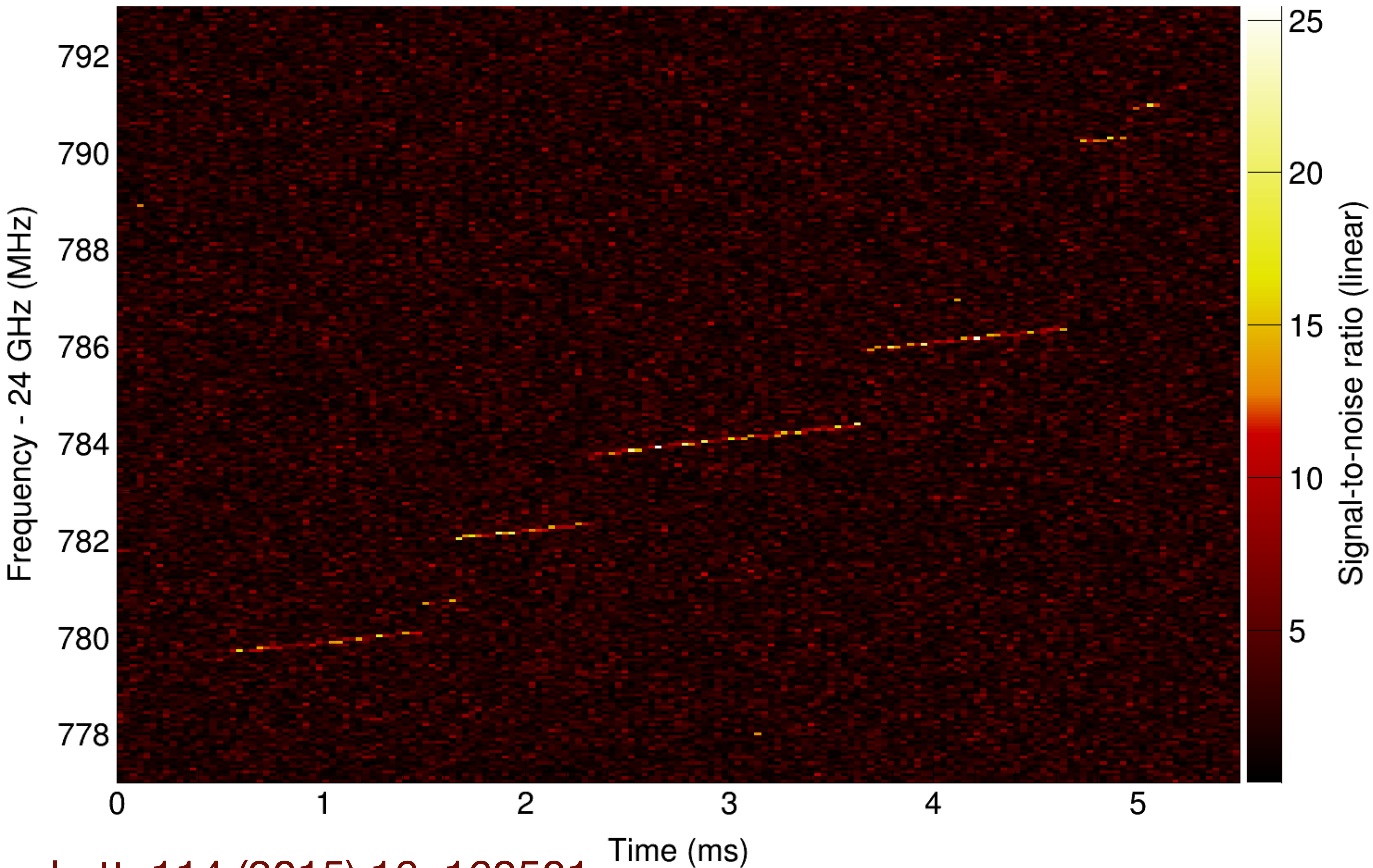


Photo of apparatus

Cyclotron frequency coupled directly to standard waveguide at 26 GHz, located inside bore of NMR 1 Tesla magnet.

Magnetic bottle allows for trapping of electron within cell for measurement.

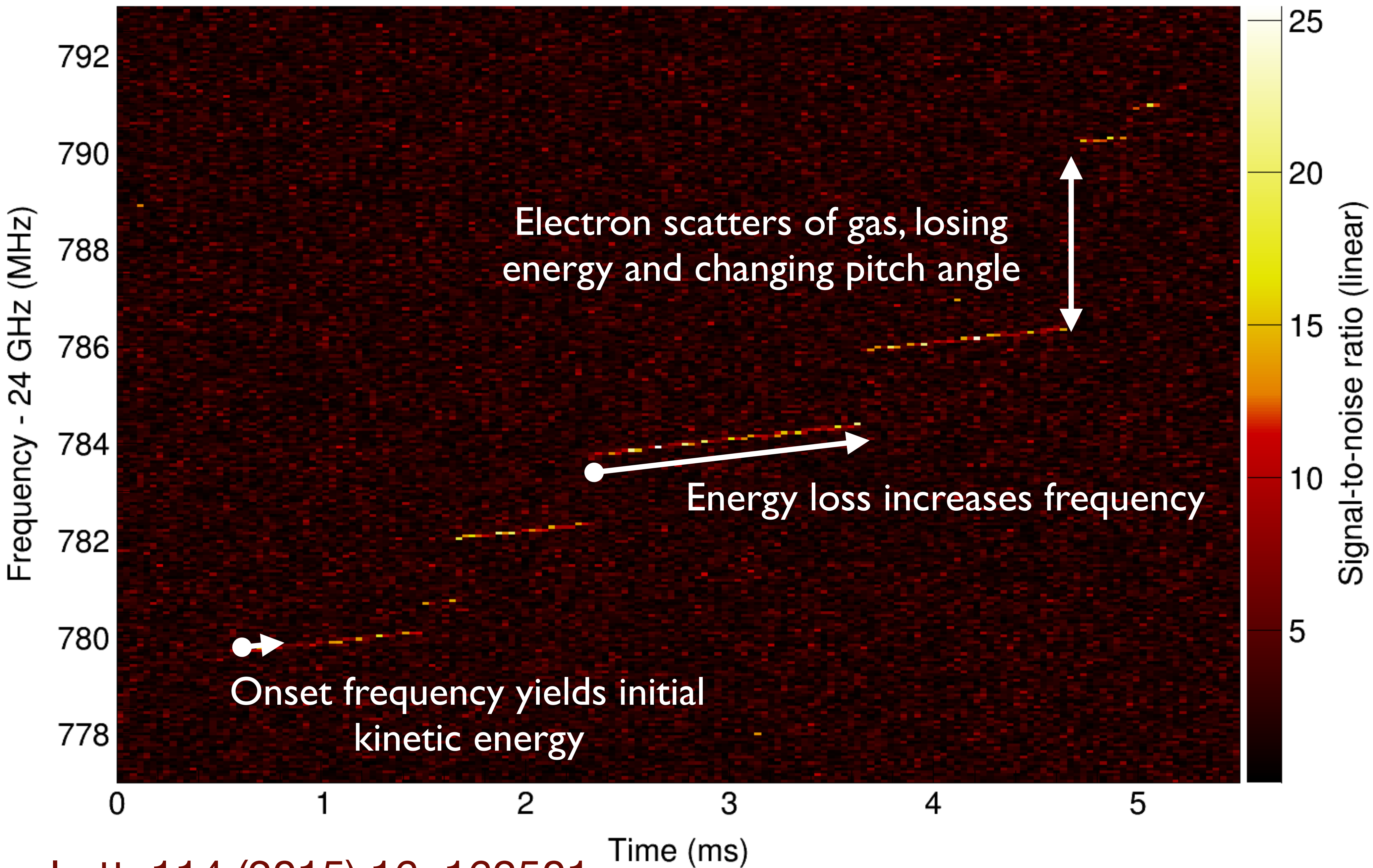
Project 8's "Event Zero"



Phys. Rev. Lett. 114 (2015) 16, 162501

Cyclotron Radiation Emission Spectroscopy (CRES) for single relativistic electrons now experimentally demonstrated.

Project 8's "Event Zero"



Phys. Rev. Lett. 114 (2015) 16, 162501

Exhibits all predicted characteristics:

- Onset frequency
- Energy loss due to cyclotron radiation
- Quantum jumps due to inelastic scattering

- The quest for neutrino mass has a long and very rich history, filled with remarkable people possessing remarkable ingenuity.
- We are by no means done. Oscillations provide a prediction that can and should be tested.
- Frontiers in beta decay, neutrinoless double beta decay and cosmology can now all feed into this remarkable measurement.

Thank you for
your attention