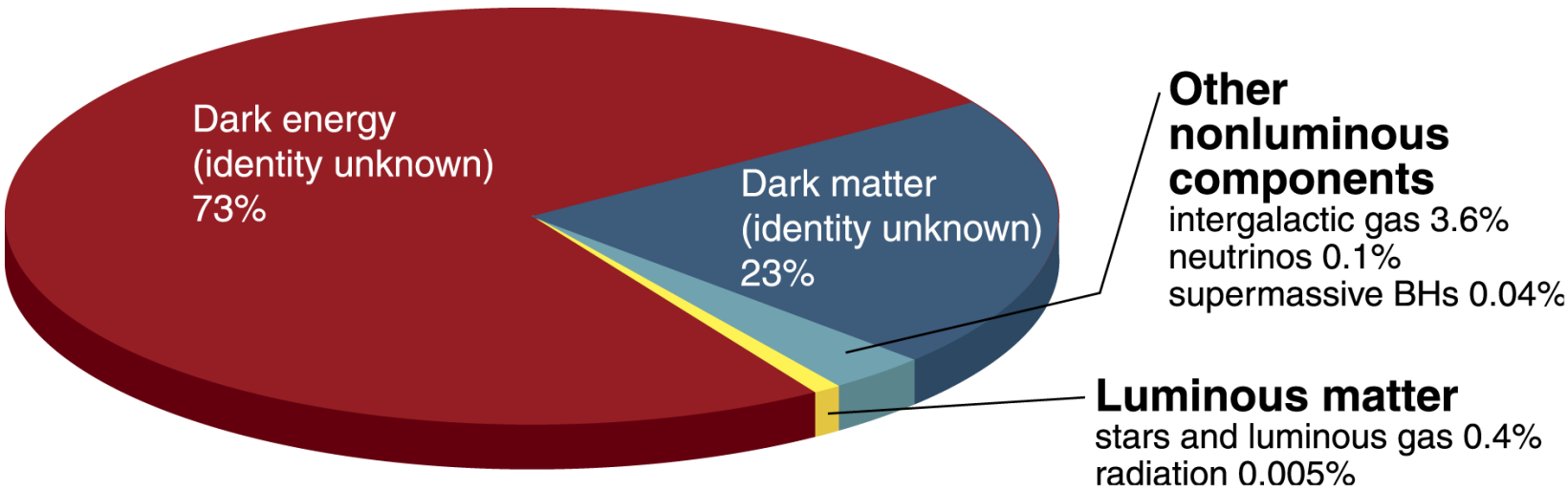
# Neutrino mass, lepton number, and the origin of matter

Hamish Robertson, FSv Town Meeting, Chicago Aug. 10, 2012

# The Universe -- A very odd place




And why is there **matter** but no **antimatter**?

Sakharov's criteria:

*Baryon number not conserved…*

*CP violated…*

*Universe not in equilibrium at some point…*

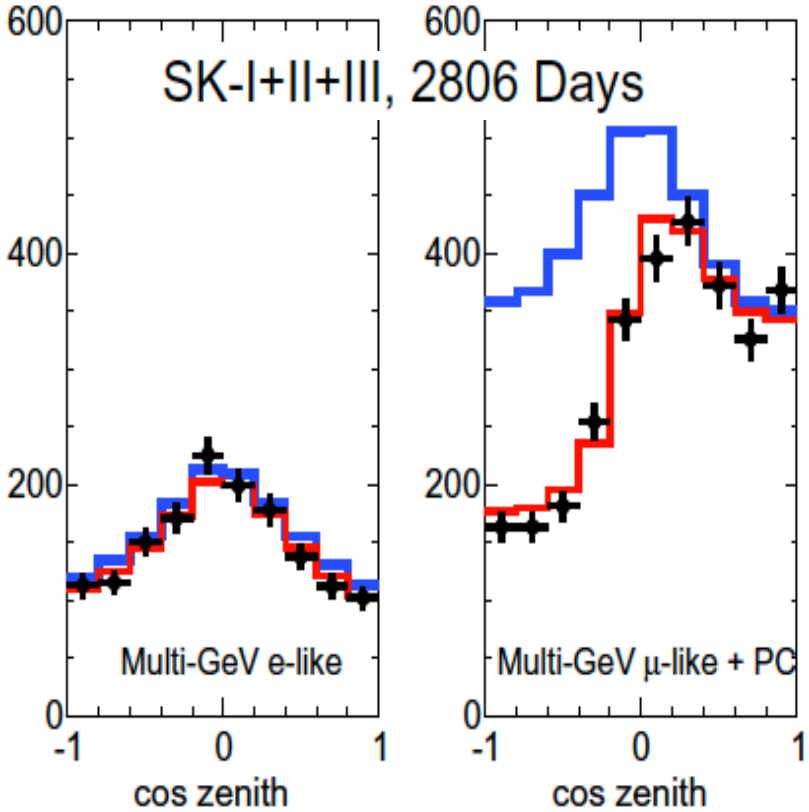
# The big questions

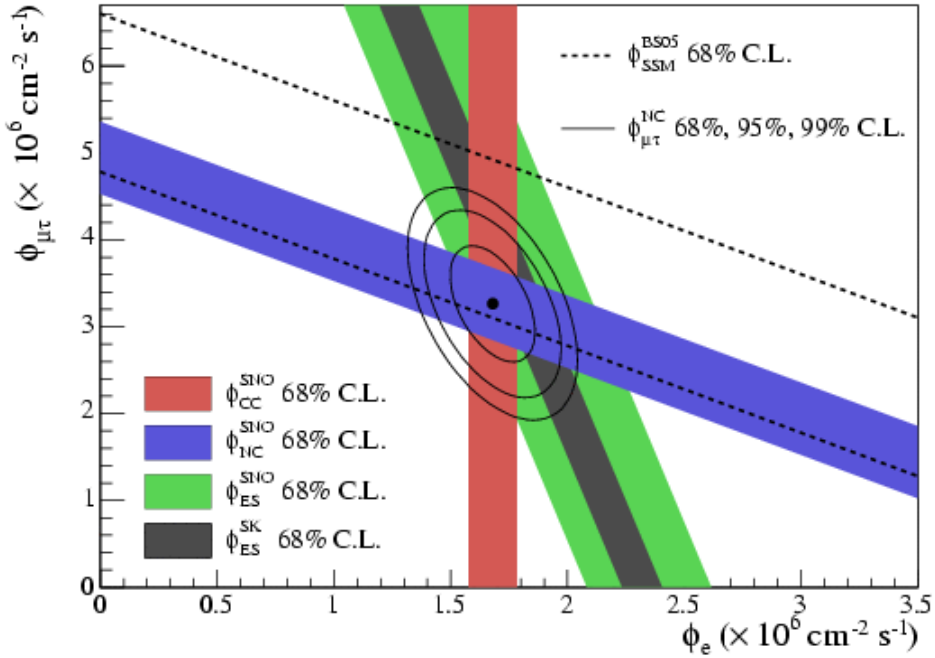
1. Major scientific discoveries since 2007
2. Compelling and unique science to be done in the next 5 years
3. Vision for 2020
4. International Context

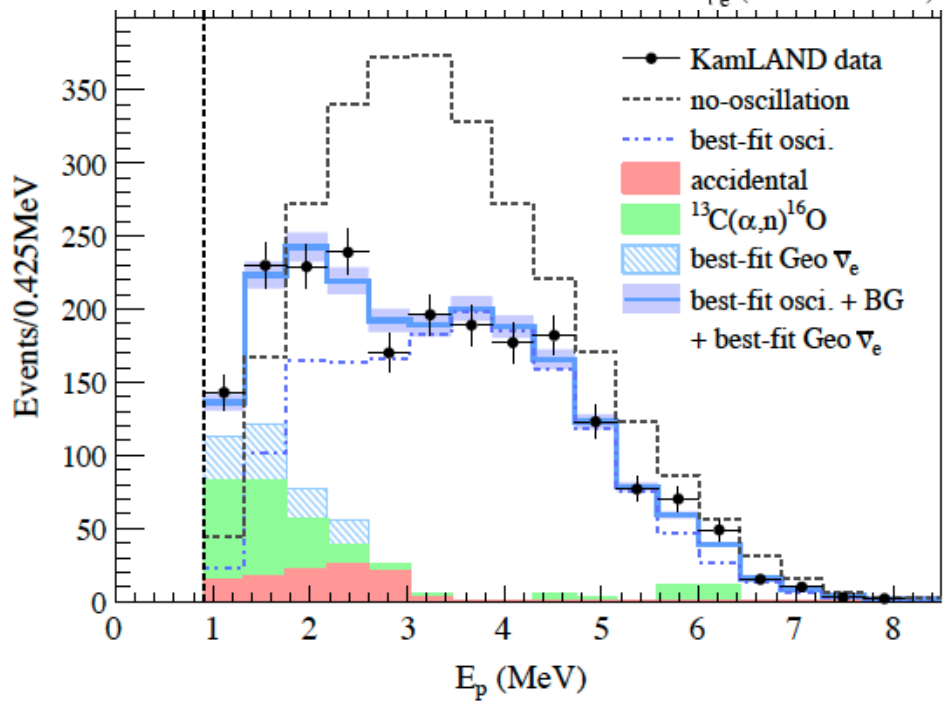
# The big questions

- 1. Major scientific discoveries since 2007
  - $\theta_{13}$ measured!
  - Higgs found!
  - Borexino, SNO, SK, KamLAND results
  - MiniBooNE results
  - Nuclear theory of DBD
  - EXO and KamLAND results for $^{136}$Xe $2\nu\beta\beta$, $0\nu\beta\beta$
  - Idea to use cyclotron radiation for neutrino mass measurement

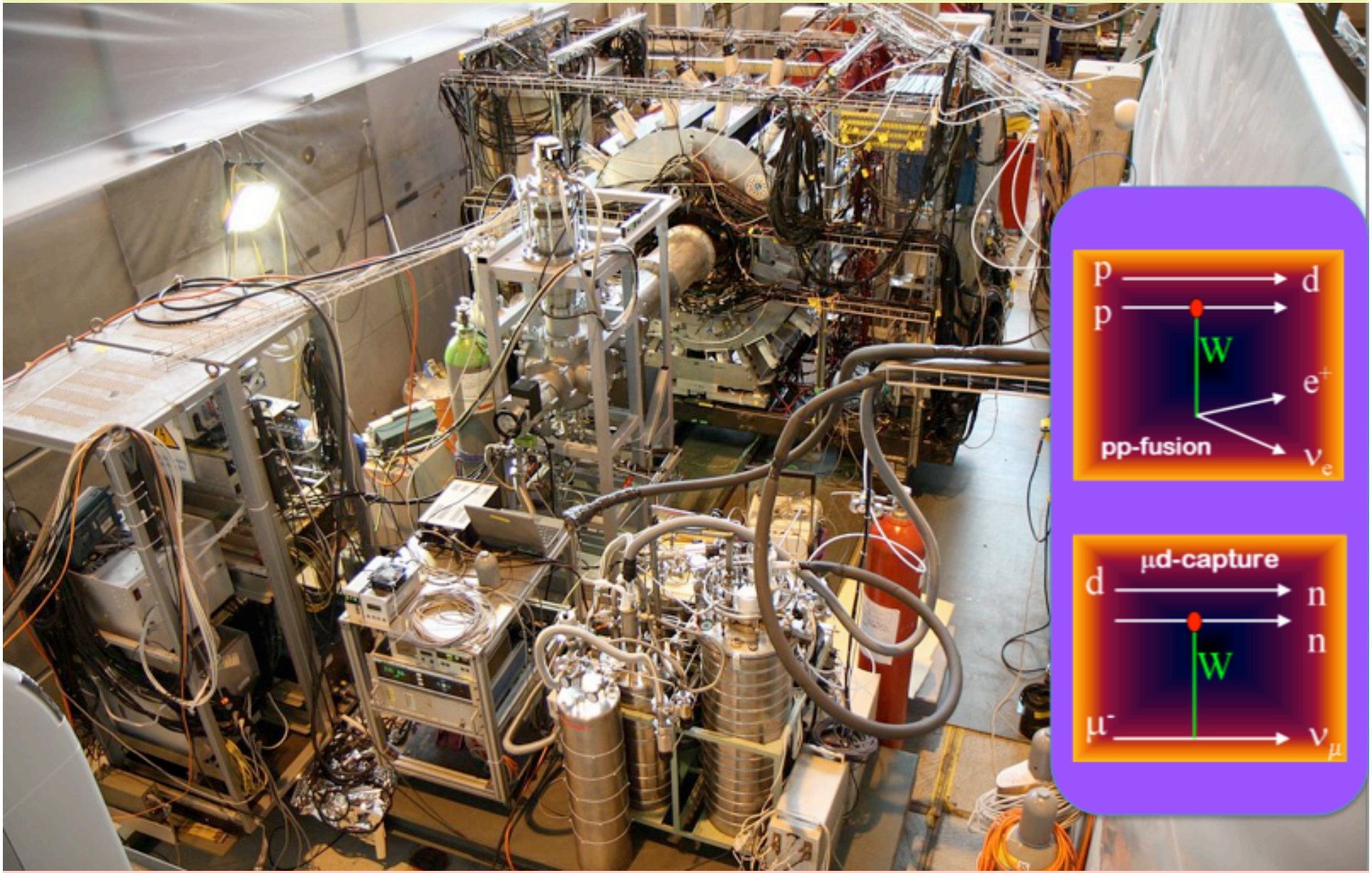
# Neutrinos oscillate, have mass



# Calibrating the Sun & SNO – MuSun at PSI




P. Kammel

# The MNSP Mixing Matrix and oscillations

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

Unitary matrix: 9 parameters not all independent.

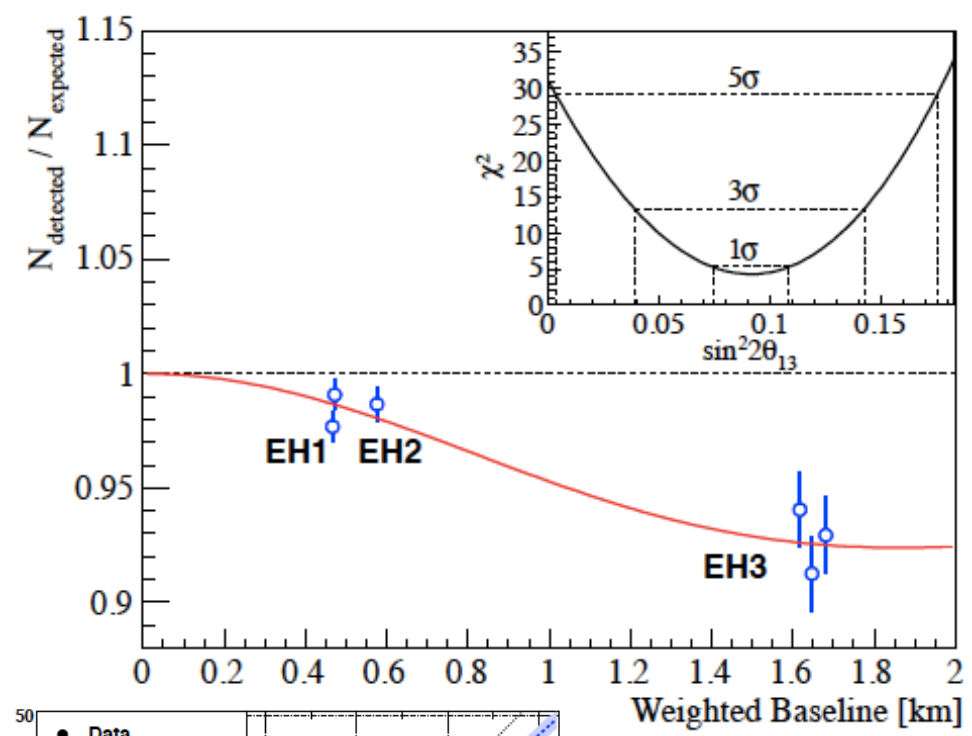
3 trig angles enough to describe oscillations. There are also CP-violating phase(s).

$$\nu_e = U_{e1}\nu_1 + U_{e2}\nu_2 + U_{e3}\nu_3$$

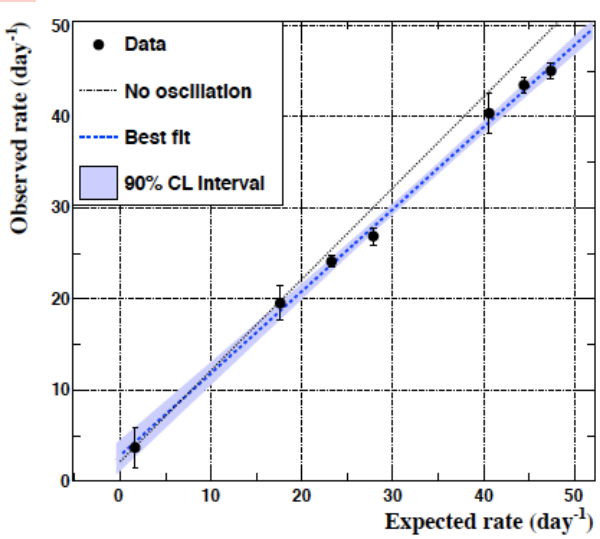
$$\lambda = \frac{h}{p} \qquad p_i - p_j \approx (m_j^2 - m_i^2)\frac{L}{2E}$$

Depends on **mass-squared differences × distance**, & the **sizes of the $U_{ei}$**

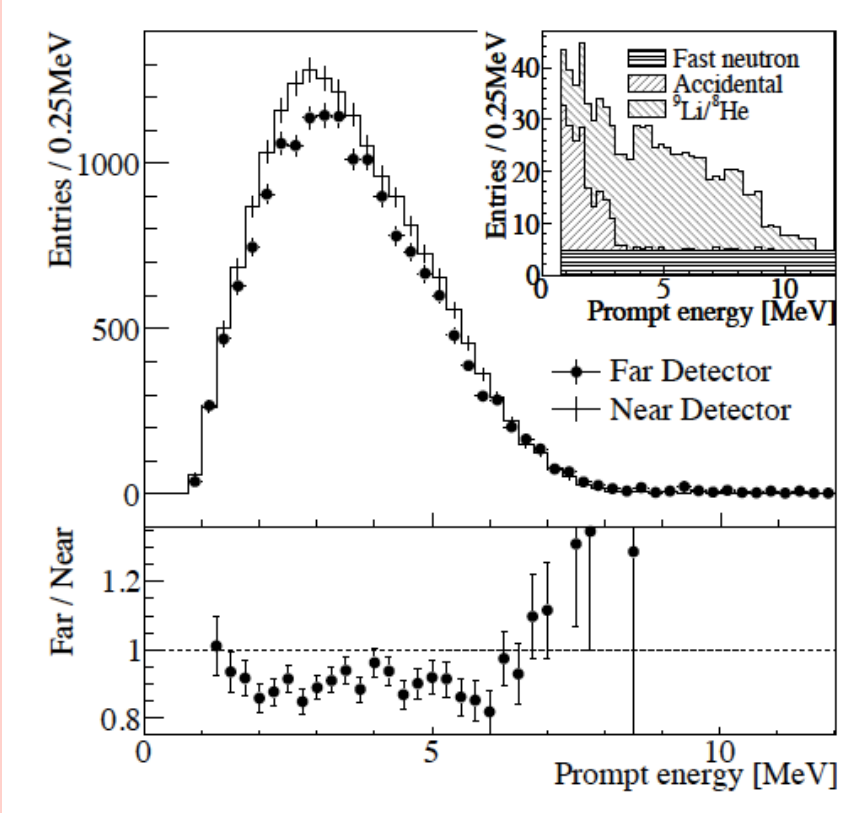
# $\Theta_{13}$ Measured!




Daya Bay




Double Chooz




RENO

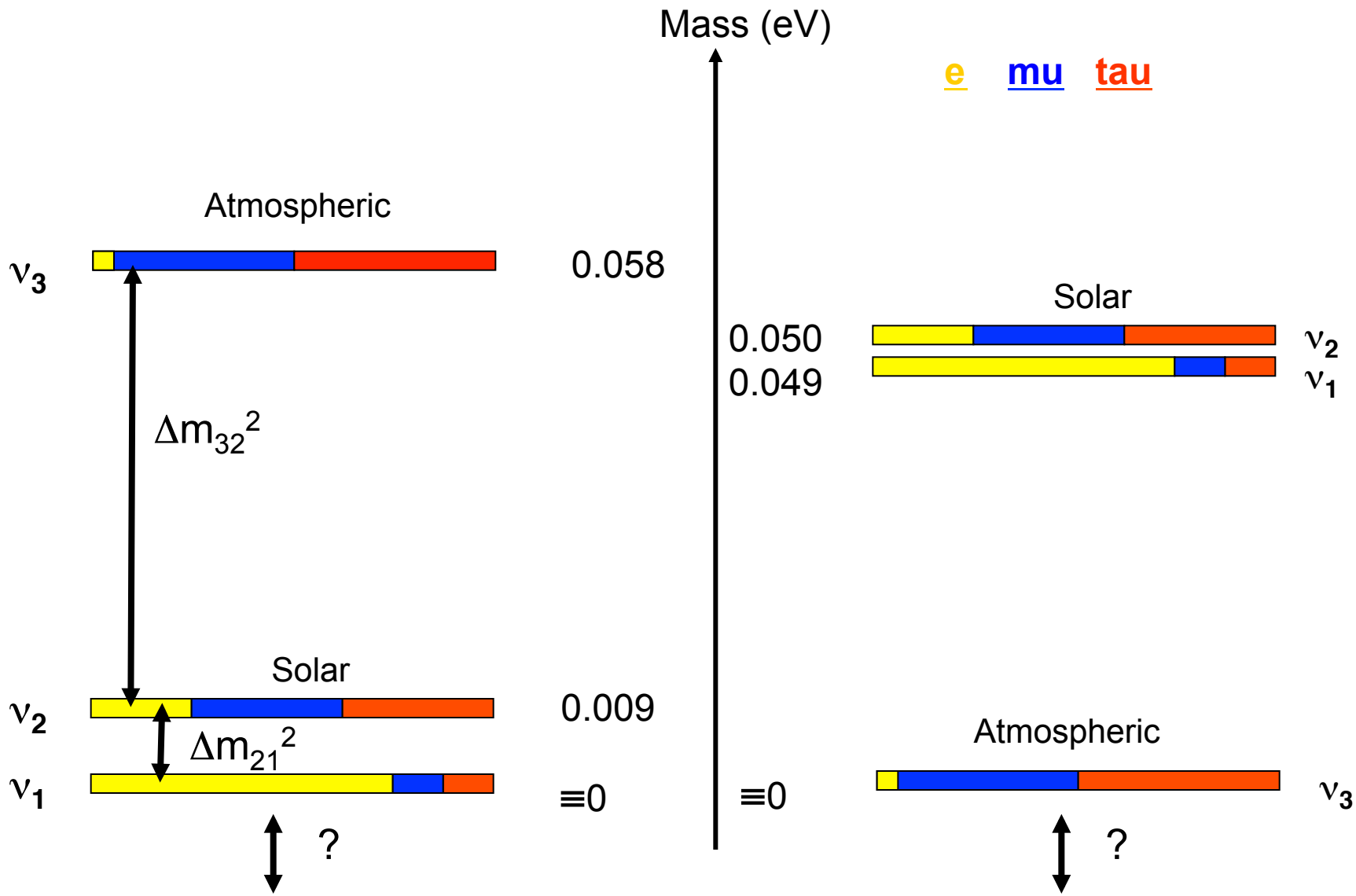
# Mass and mixing parameters

| | | |
|---|---|---|
| $\Delta m_{21}^2$ | $7.54^{+0.21}_{-0.21} \times 10^{-5}$ eV$^2$ | |
| $\lvert\Delta m_{32}^2\rvert$ | $2.42^{+0.12}_{-0.11} \times 10^{-3}$ eV$^2$ | |
| $\Sigma m_i$ | > 0.055 eV (90% CL) | < 6.9 eV (90% CL)* |
| $\theta_{12}$ | $34.1^{+0.9}_{-0.9}$ deg | |
| $\theta_{23}$ | $39.2^{+1.8}_{-1.8}$ deg | |
| $\theta_{13}$ | $9.1^{+0.6}_{-0.7}$ deg | |
| $\sin^2\theta_{13}$ | $0.025^{+.003}_{-.003}$ | |

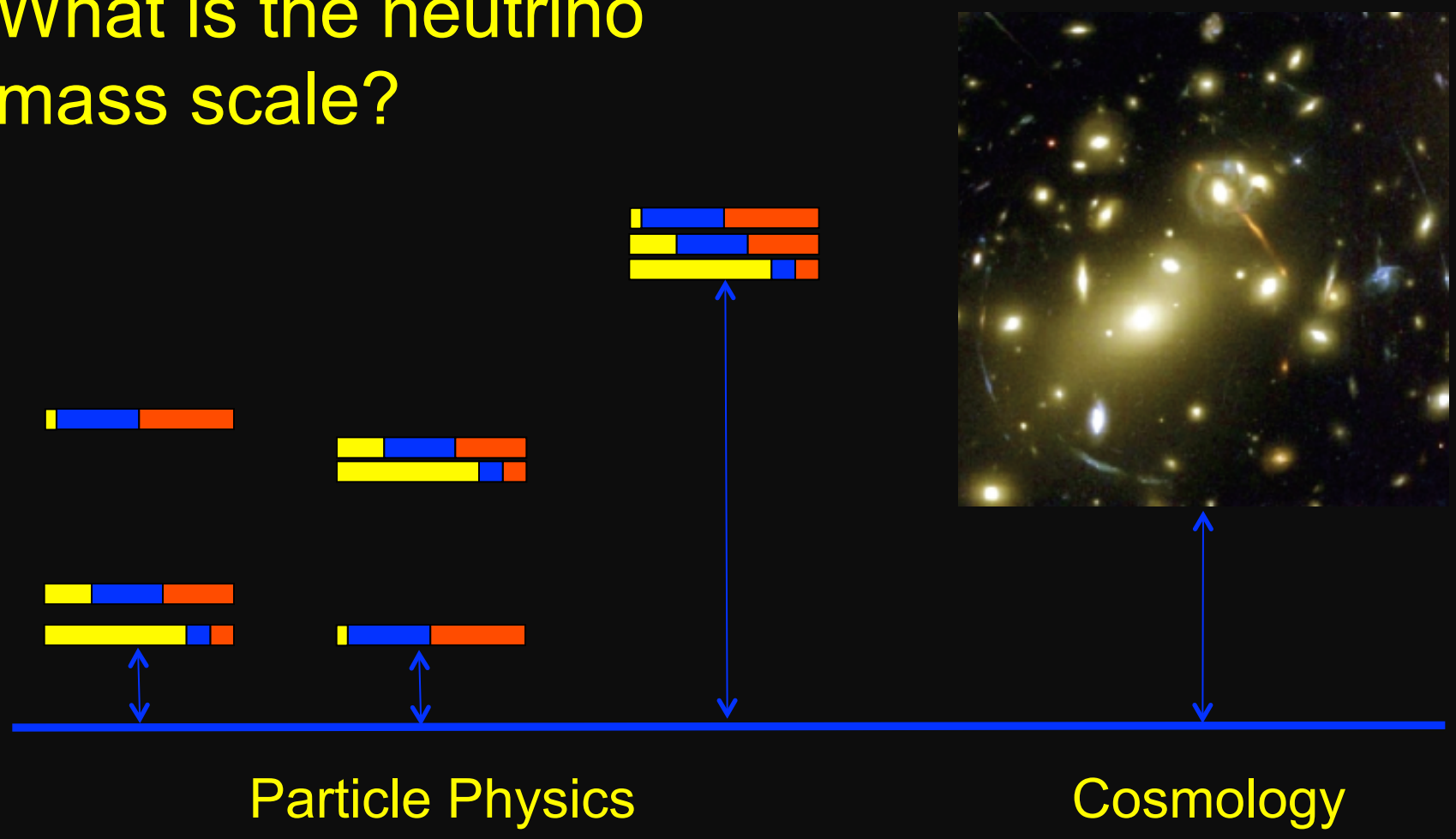
Marginalized 1-D 1-$\sigma$ uncertainties.

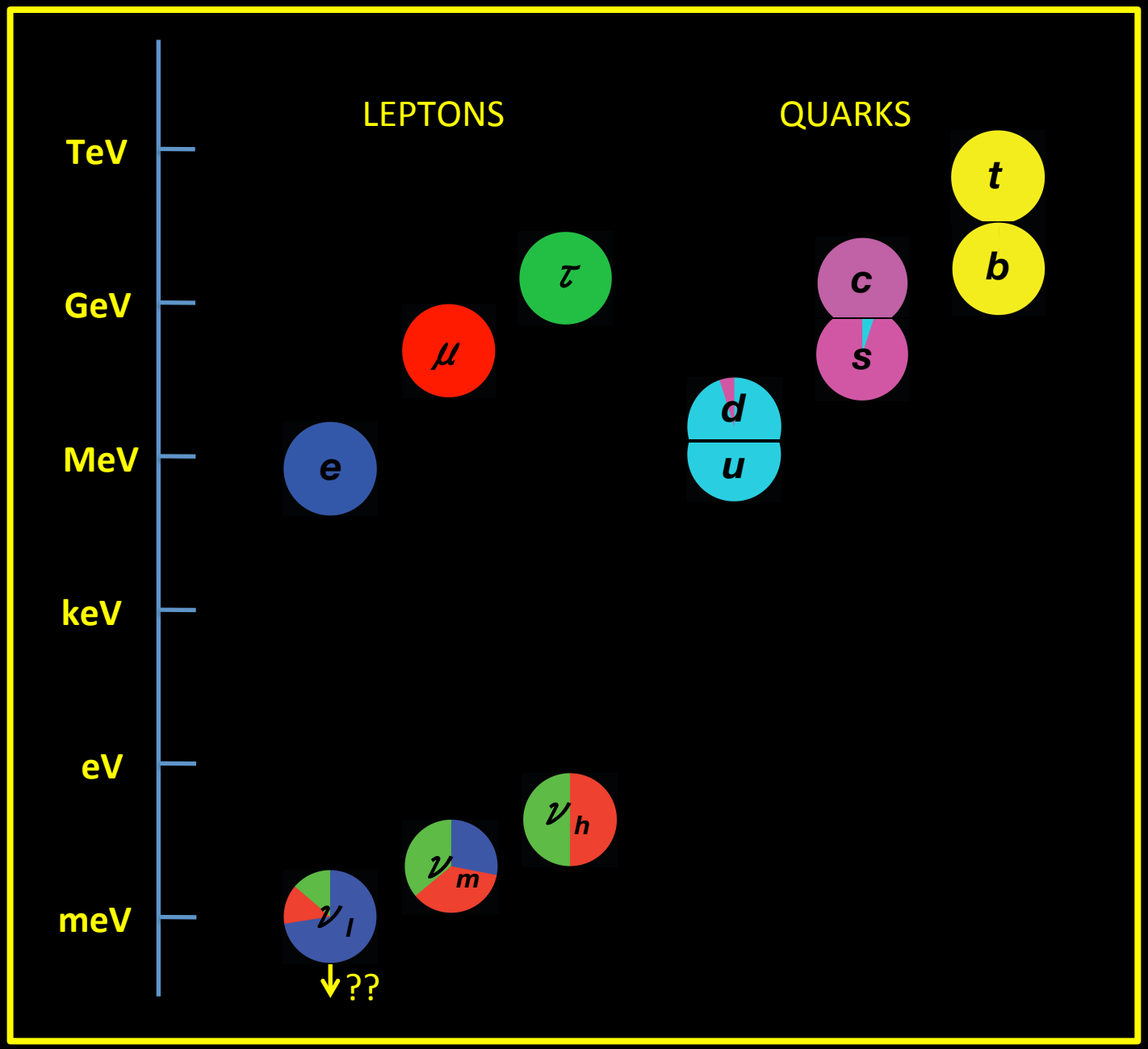
*C. Kraus et al., Eur. Phys. J. C40, 447 (2005)
Other refs, see Fogli et al. 1205.5254

# Neutrino mass spectrum and flavor content



# What is the neutrino mass scale?




LEPTONS
QUARKS
TeV
GeV
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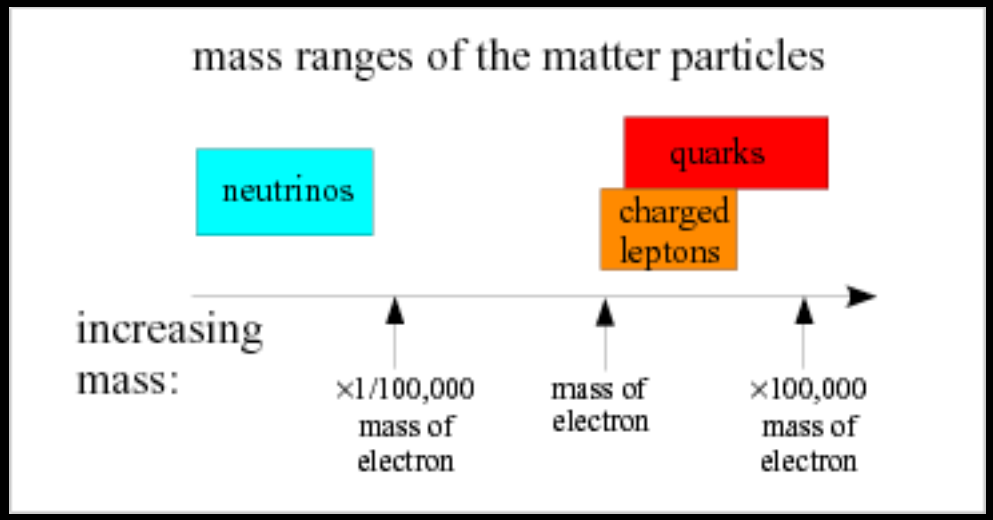
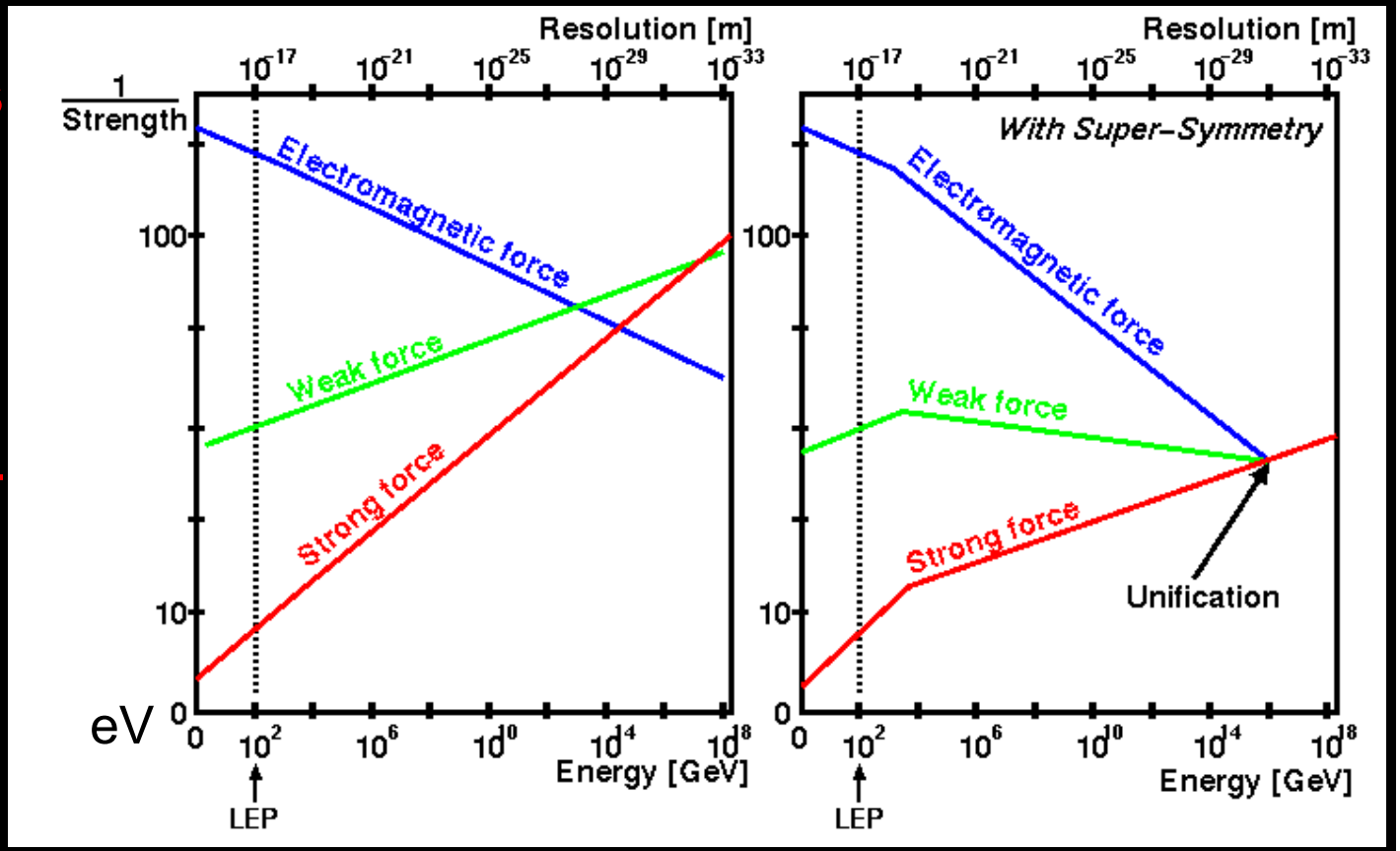



# Why is neutrino mass so small?

Neutrino mass is not a feature of the SM

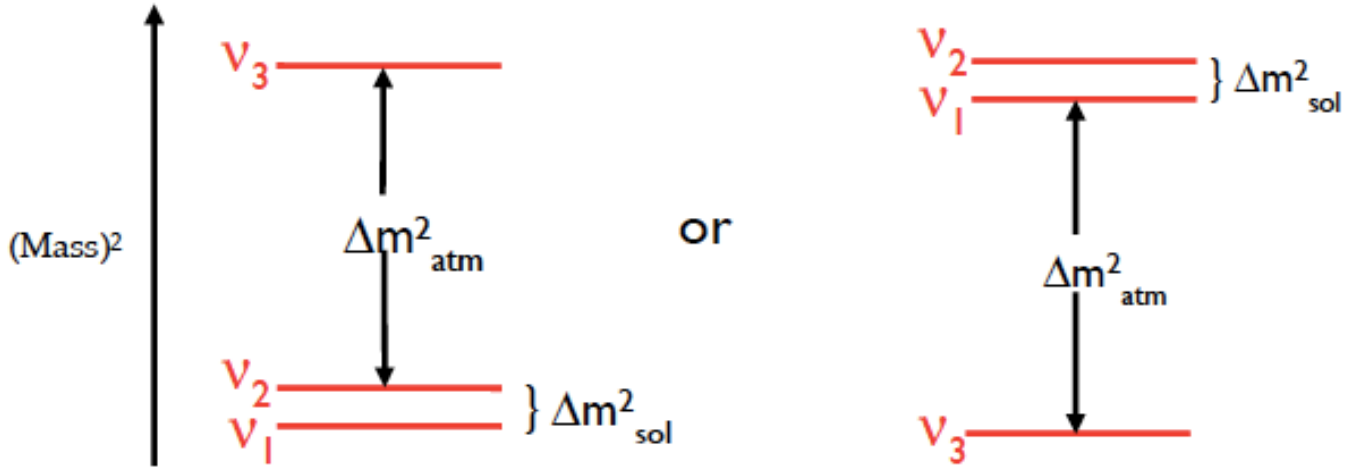
A signal of unification? See-saw model:

$$m_\nu = \frac{m_D^2}{M}$$



# Determining Neutrino Mass

J.F. Wilkerson




- Oscillation measurements (relative masses)
  - provide lower bound, assuming $m_1 = 0$ (normal) or $m_3 = 0$ (inverted)
- Cosmology and astrophysics (model dependent)
  - measures $\Sigma m_\nu$ based on assumptions of number density in early universe and cosmological model(s)
- $0\nu\beta\beta$ decay (model dependent)
  - if neutrinos are Majorana particles **&** understand lepton number violating process **&** accurate calculation of nuclear matrix element
- Direct kinematic measurements (model independent)

# Matter-Antimatter Asymmetry ($\Delta B \neq 0$) from Leptogenesis

MNSP Lepton Mixing Matrix

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

$$\begin{pmatrix} 0.7 & 0.7 & 0.2e^{i\delta} \\ -0.5 & 0.5 & 0.7 \\ 0.5 & -0.5 & 0.7 \end{pmatrix}$$

$$\begin{pmatrix} big & big & small \\ big & big & big \\ big & big & big \end{pmatrix}$$

CKM Quark Mixing Matrix

$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = \begin{pmatrix} U_{ud} & U_{us} & U_{ub} \\ U_{cd} & U_{cs} & U_{cb} \\ U_{td} & U_{ts} & U_{tb} \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$

$$\begin{pmatrix} 0.97 & 0.22 & 0.003e^{i\delta} \\ -0.22 & 0.97 & 0.04 \\ 0.01 & -0.04 & 0.999 \end{pmatrix}$$

$$\begin{pmatrix} big & small & very\ tiny \\ small & big & tiny \\ tiny & tiny & big \end{pmatrix}$$

**$\delta$ gives CP violation**

Why?

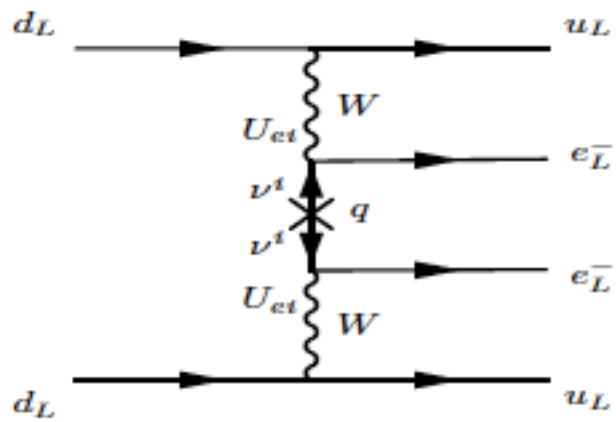
- Difficult to generate a baryon asymmetry $\Delta B \neq 0$ using quark matrix CP violation
- Generate using CP or CPT violation in the lepton sector

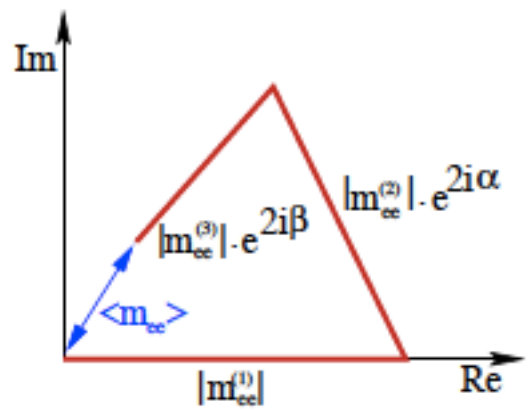
  → B-L processes then convert a neutrino excess to baryon excess

  (Sign and magnitude may be able to generate the observed baryon asymmetry)

# Neutrinoless Double Beta Decay

Are neutrinos their own antiparticles?
Is lepton number conserved?



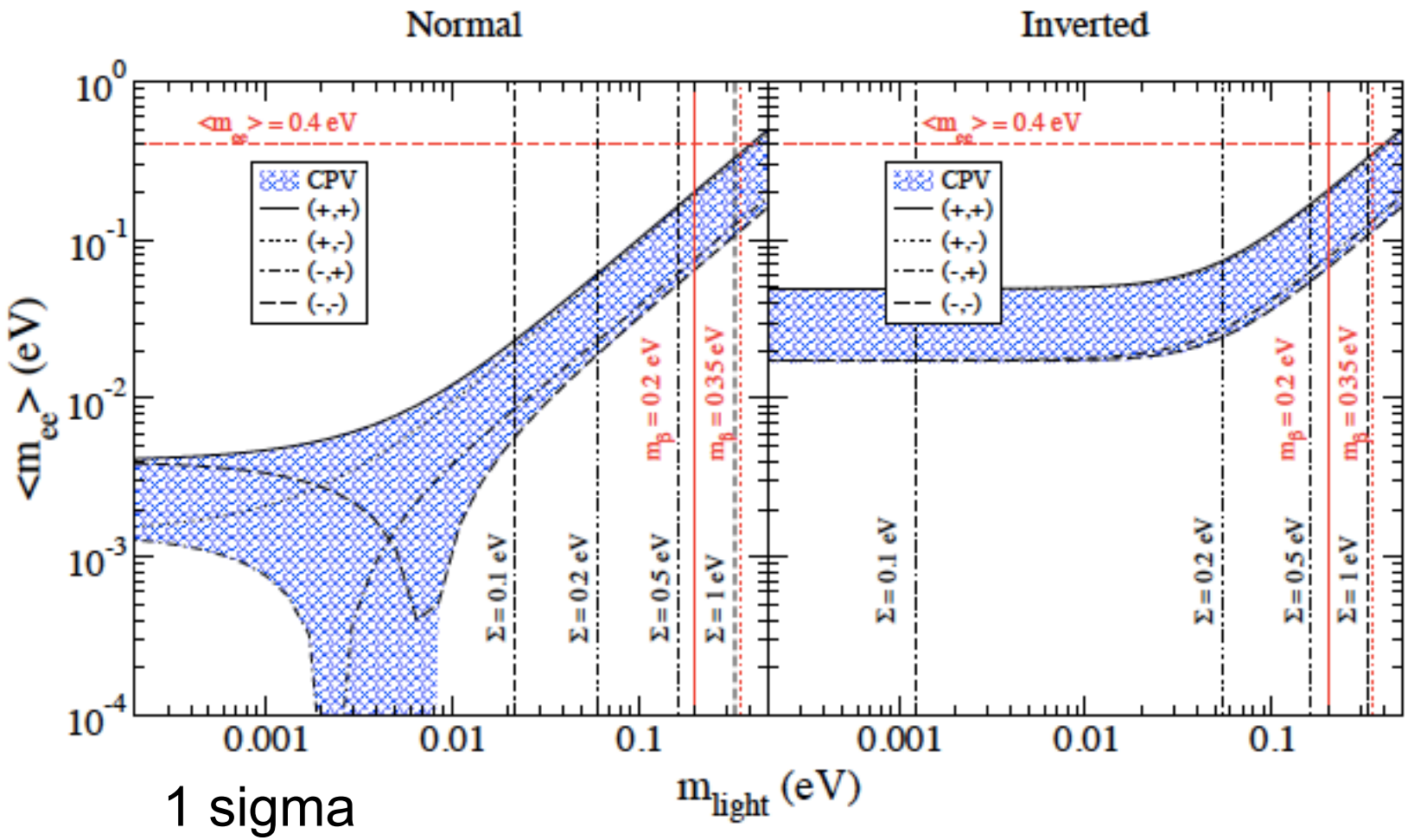




Decay rate: $$\left[\tau_{1/2}^{(0\nu)}\right]^{-1} = G_{0\nu}\left|M_{0\nu}\right|^2\left(\frac{\langle m_\nu\rangle}{m_e}\right)^2$$

$$\langle m_{ee}\rangle = \left|\sum U_{ei}^2 m_i\right| = \left||m_{ee}^{(1)}| + |m_{ee}^{(2)}|\, e^{2i\alpha} + |m_{ee}^{(3)}|\, e^{2i\beta}\right|$$

W. Rodejohann, 1206.2560

# Neutrinoless Double Beta Decay



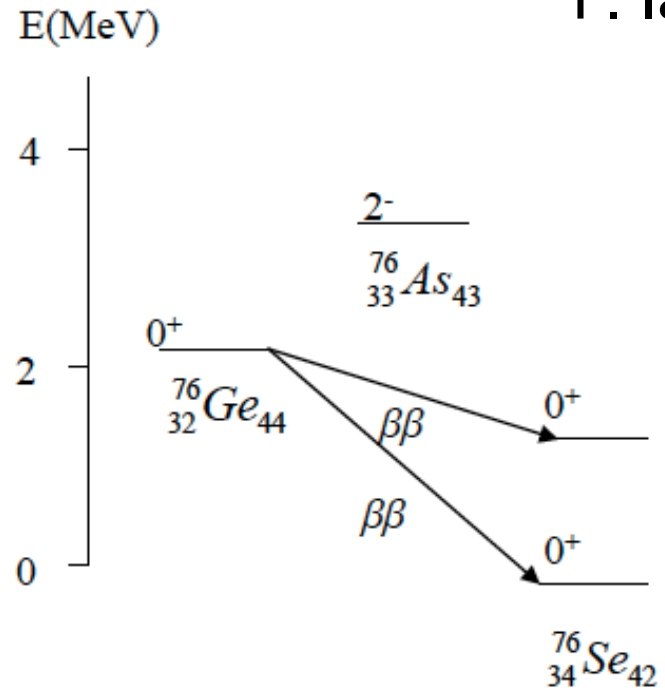

1 sigma

# INTRODUCTION

F. Iachello

## Fundamental Process $0\nu\beta\beta$:

$$ {}^{A}_{Z}X_{N} \rightarrow {}^{A}_{Z+2}Y_{N-2} + 2e^{-} $$




Half-life for the process:

$$ \left[ T_{1/2}^{0\nu\beta\beta}(0^{+} \rightarrow 0^{+}) \right]^{-1} = G_{0\nu} \left| M_{0\nu} \right|^{2} \left| f_{b}(m_{i}, U_{ei}) \right|^{2} $$

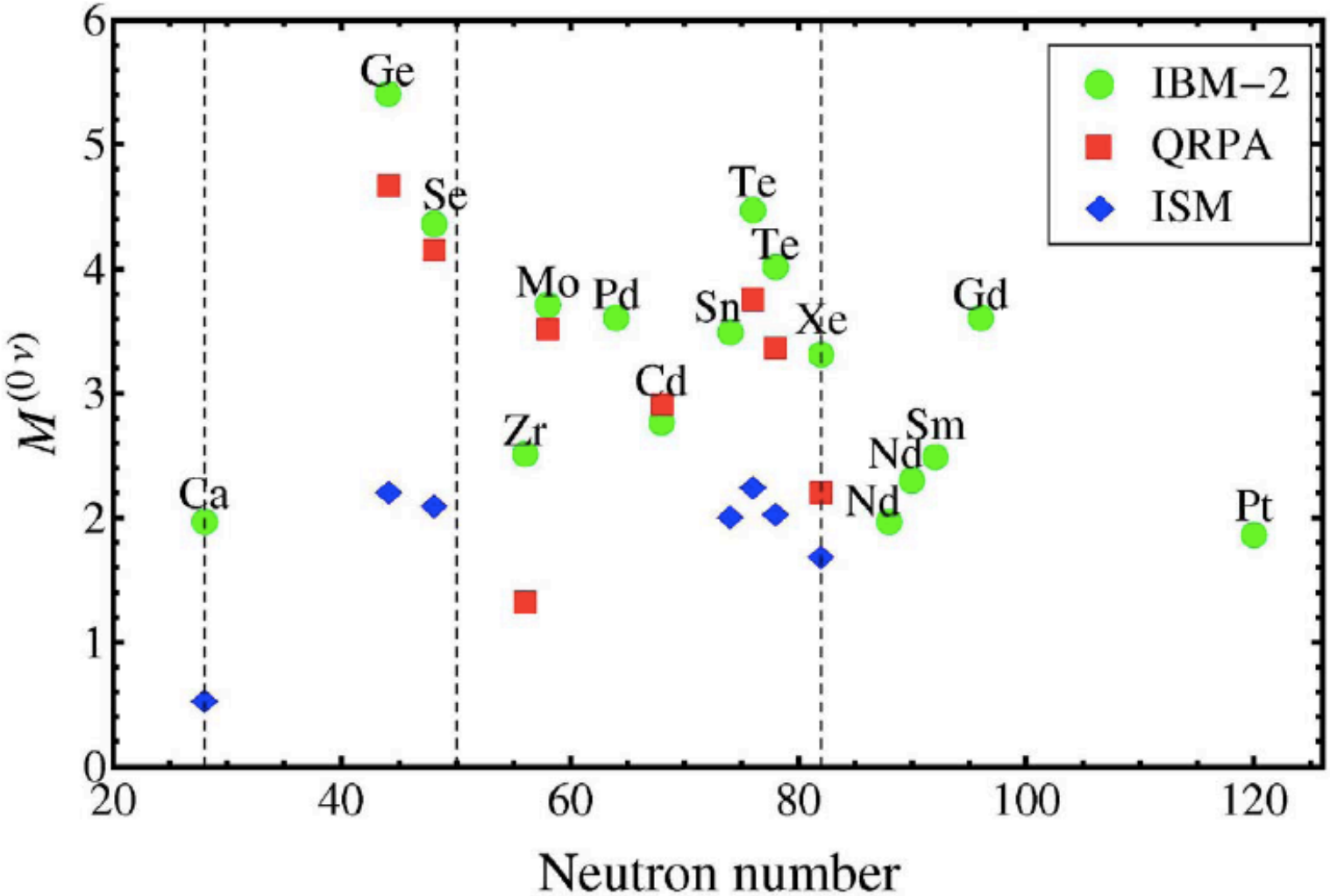
Beyond the standard mode
(Particle physics)

Phase-space factor
(Atomic physics)

Matrix elements
(Nuclear physics)

# IBM-2 RESULTS (JAN 2012)
# LIGHT NEUTRINO EXCHANGE

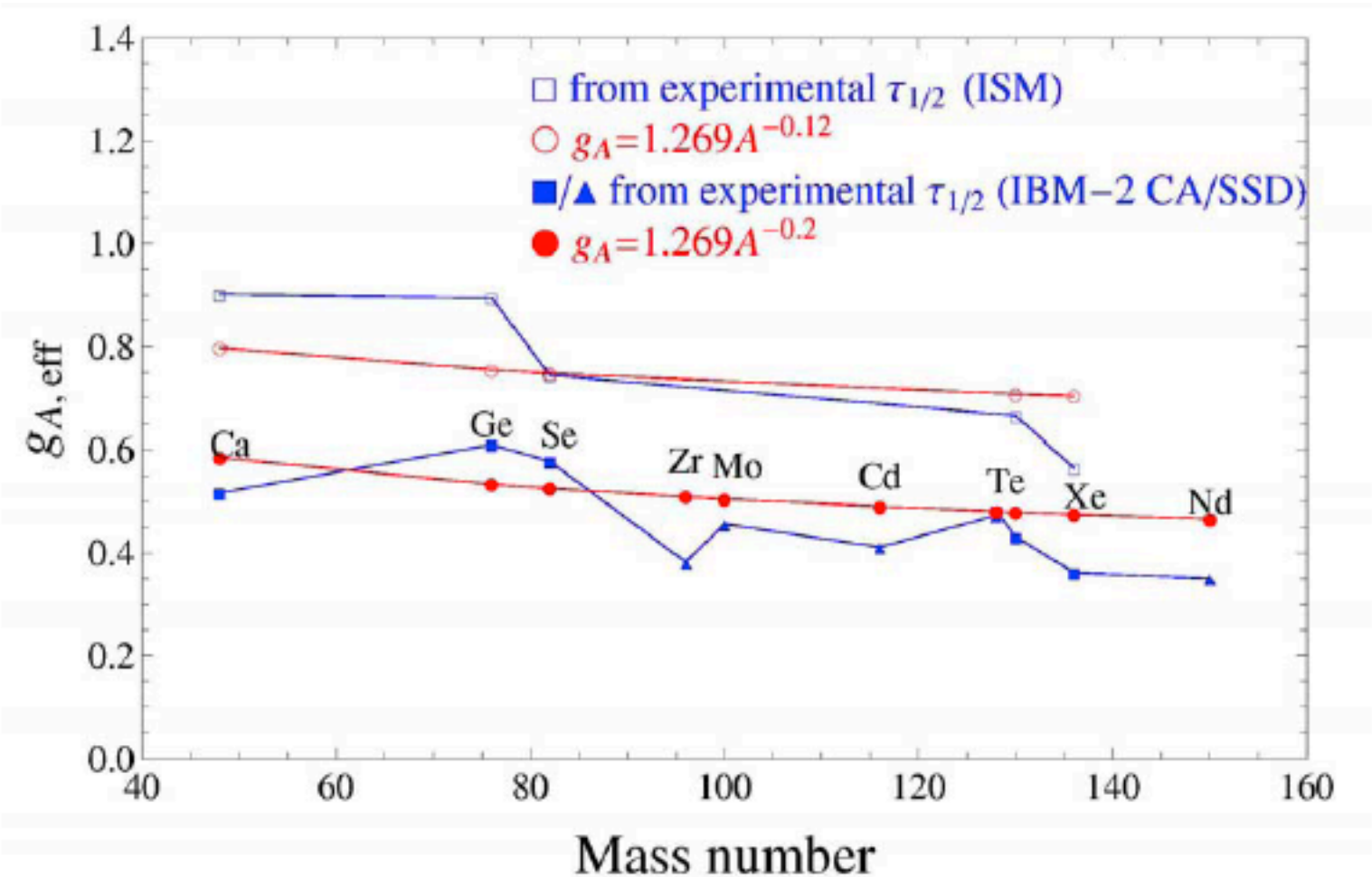
F. Iachello




IBM-2 from J. Barea and F. Iachello, Phys. Rev. C 79, 044301 (2009) and to be published.
QRPA from F. Šimkovic *et al.*, Phys. Rev. C 77, 045503 (2008).
ISM from E. Caurier *et al.*, Phys. Rev. Lett. 100, 052503 (2008).

F. Iachello

$g_A$ is strongly renormalized in 2νββ…



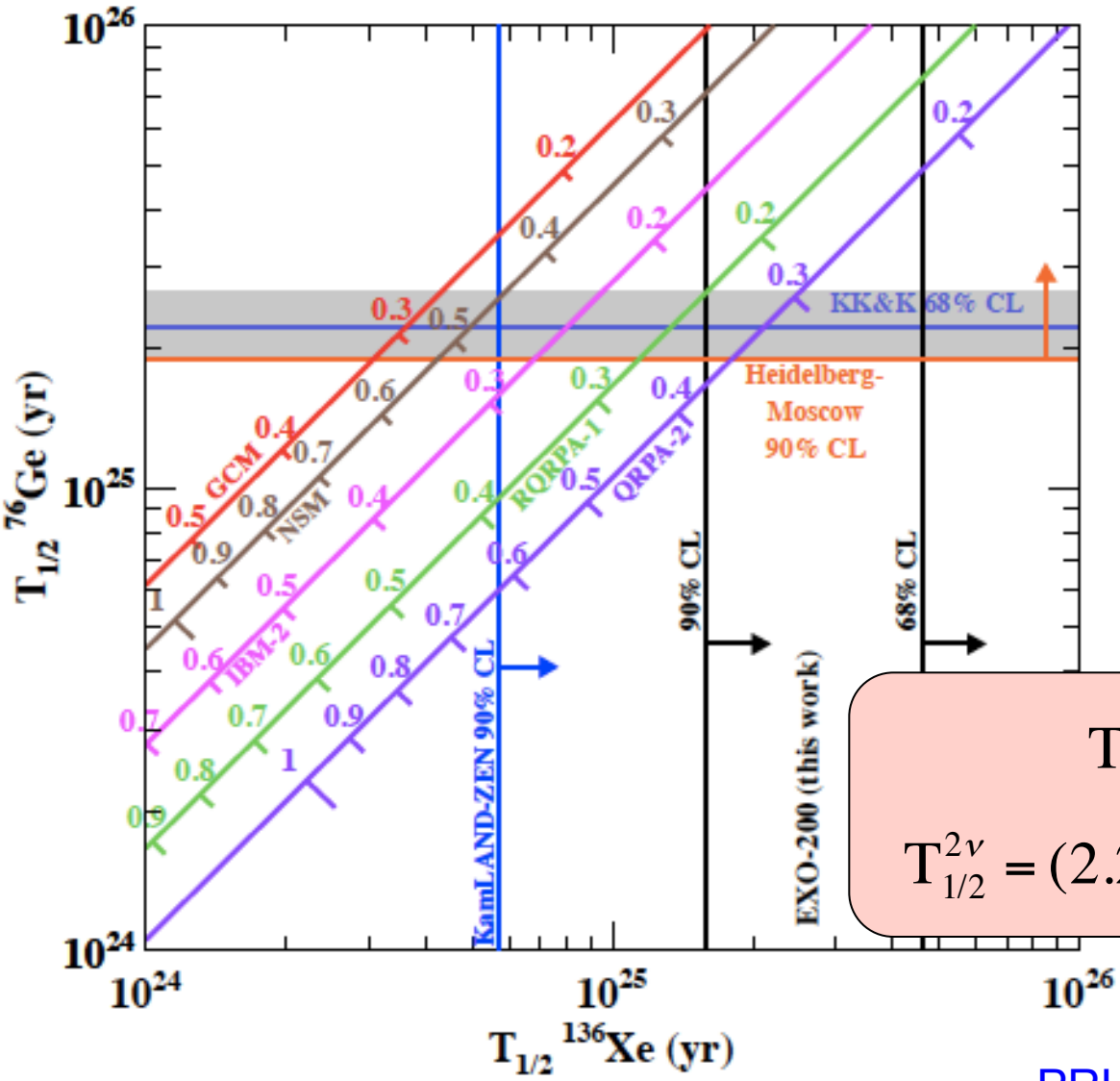

…but free-nucleon value is used in most 0νββ calculations. The decay rate ~$g_A^4$! (potentially a factor of 40.)

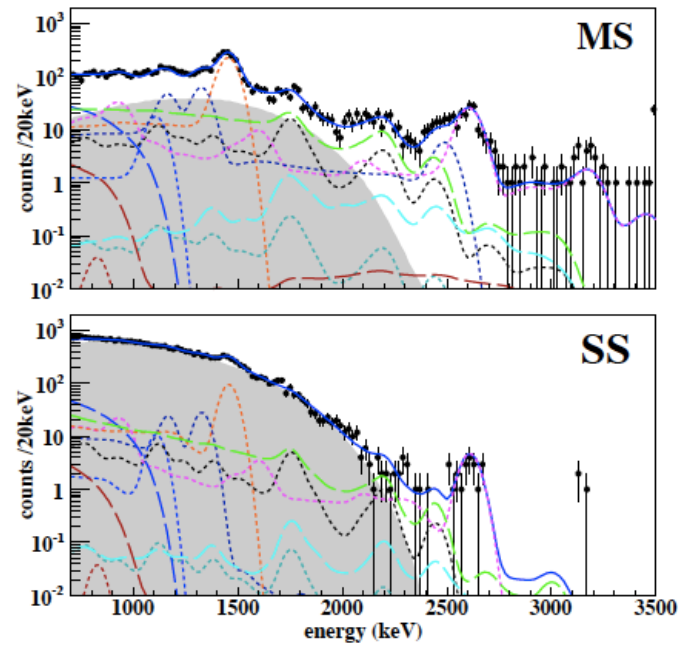
# Large-scale experiments

**Table 4.** Details of the most advanced experiments. Given are life-time sensitivity and the expected limit on $\langle m_{ee} \rangle$, using the NME compilation from figure 5.

| Experiment | Isotope | Mass [kg] | Sensitivity $T^{0\nu}_{1/2}$ [yrs] | Status | Start of data-taking | Sensitivity $\langle m_\nu \rangle$ [eV] |
|---|---|---|---|---|---|---|
| GERDA | $^{76}$Ge | 18 | $3 \times 10^{25}$ | running | $\sim$ 2011 | 0.17-0.42 |
| | | 40 | $2 \times 10^{26}$ | in progress | $\sim$ 2012 | 0.06-0.16 |
| | | 1000 | $6 \times 10^{27}$ | R&D | $\sim$ 2015 | 0.012-0.030 |
| CUORE | $^{130}$Te | 200 | $6.5 \times 10^{26*}$ | in progress | $\sim$ 2013 | 0.018-0.037 |
| | | | $2.1 \times 10^{26**}$ | | | 0.03-0.066 |
| MAJORANA | $^{76}$Ge | 30-60 | $(1-2) \times 10^{26}$ | in progress | $\sim$ 2013 | 0.06-0.16 |
| | | 1000 | $6 \times 10^{27}$ | R&D | $\sim$ 2015 | 0.012-0.030 |
| EXO | $^{136}$Xe | 200 | $6.4 \times 10^{25}$ | running | $\sim$ 2011 | 0.073-0.18 |
| | | 1000 | $8 \times 10^{26}$ | R&D | $\sim$ 2015 | 0.02-0.05 |
| SuperNEMO | $^{82}$Se | 100-200 | $(1-2) \times 10^{26}$ | R&D | $\sim$ 2013-15 | 0.04-0.096 |
| KamLAND-Zen | $^{136}$Xe | 400 | $4 \times 10^{26}$ | running | $\sim$ 2011 | 0.03-0.07 |
| | | 1000 | $10^{27}$ | R&D | $\sim$ 2013-15 | 0.02-0.046 |
| SNO+ | $^{150}$Nd | 56 | $4.5 \times 10^{24}$ | in progress | $\sim$ 2012 | 0.15-0.32 |
| | | 500 | $3 \times 10^{25}$ | R&D | $\sim$ 2015 | 0.06-0.12 |

# EXO measures $^{136}$Xe 2νββ, limits 0νββ



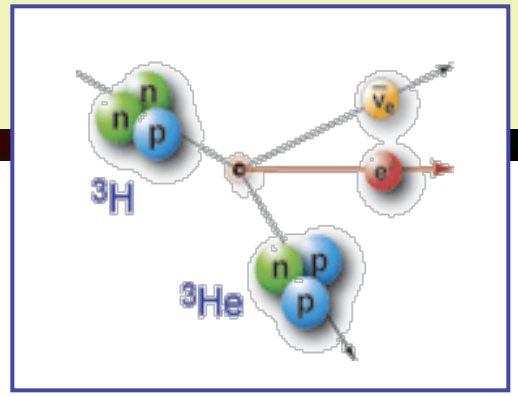




$$T^{0\nu}_{1/2} \geq 1.6 \times 10^{25} \quad \text{yr}$$

$$T^{2\nu}_{1/2} = (2.23 \pm 0.017 \pm 0.22) \times 10^{21} \quad \text{yr}$$

PRL 109, 032505 (2012)

# Neutrino mass from Beta Spectra




With flavor mixing:

$$\frac{dN}{dT} = \frac{G_F \cos\theta_C}{2\pi^3} |M_{\rm nuc}|^2 F(Z,T)(T+m)(T^2+2mT)^{1/2}(T_0-T)\sum_i |U_{ei}|^2 \left[(T_0-T)^2 - m_i^2\right]^{1/2}$$

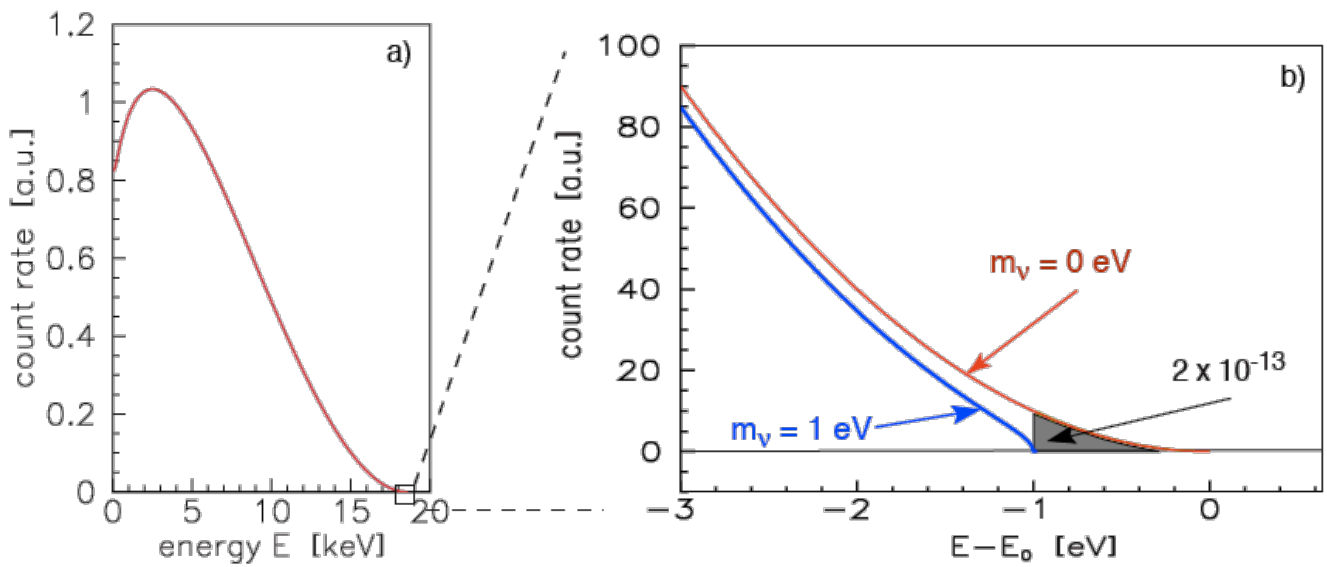
$$m_i^2 = \Delta m_{i0}^2 + m_0^2$$

mixing

neutrino masses

from oscillations

mass scale



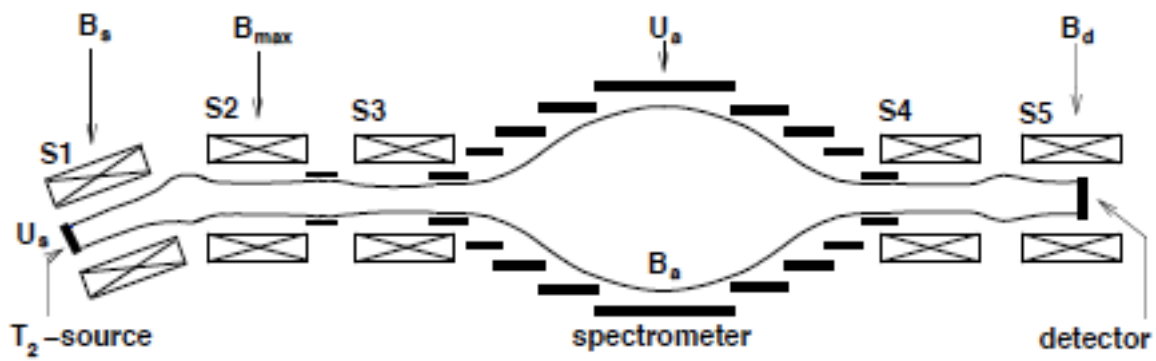
# Current status of direct mass measurement

Mainz: solid $T_2$, MAC-E filter

C. Kraus et al., Eur. Phys. J. C40, 447 (2005)

$$m^2(\nu_e) = (-0.6 \pm 2.2_{\text{stat}} \pm 2.1_{\text{syst}})$$

$$m(\nu_e) < 2.3\ \text{eV}/c^2 \quad (95\%\ \text{C.L.})$$

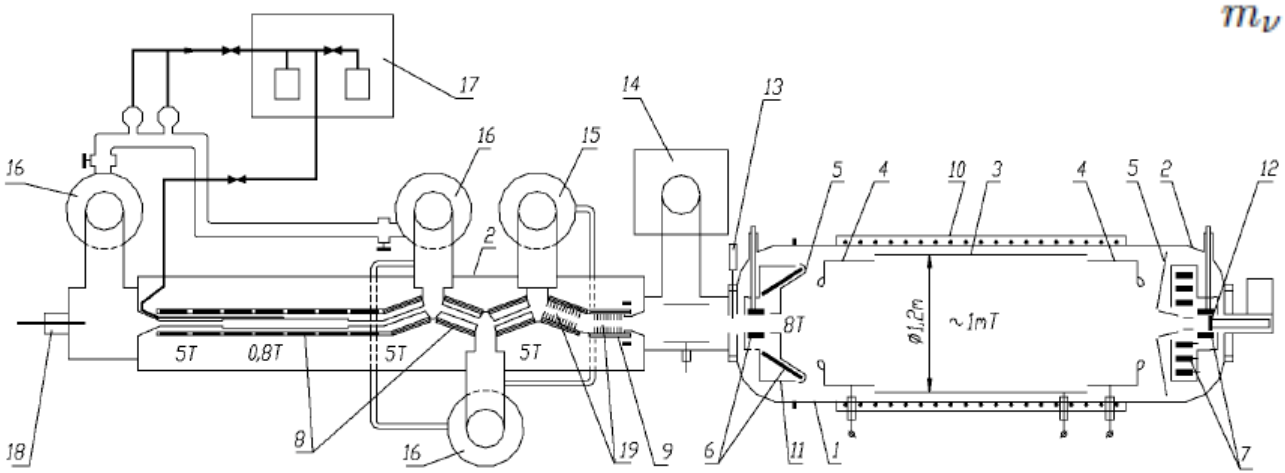



Troitsk: gaseous$T_2$, MAC-E filter

V. Aseev et al., PRD in press (2011)

$$m_\nu^2 = -0.67 \pm 1.89_{stat} \pm 1.68_{syst}$$

$$m_\nu < 2.05\ eV,\ 95\%\ C.L.$$

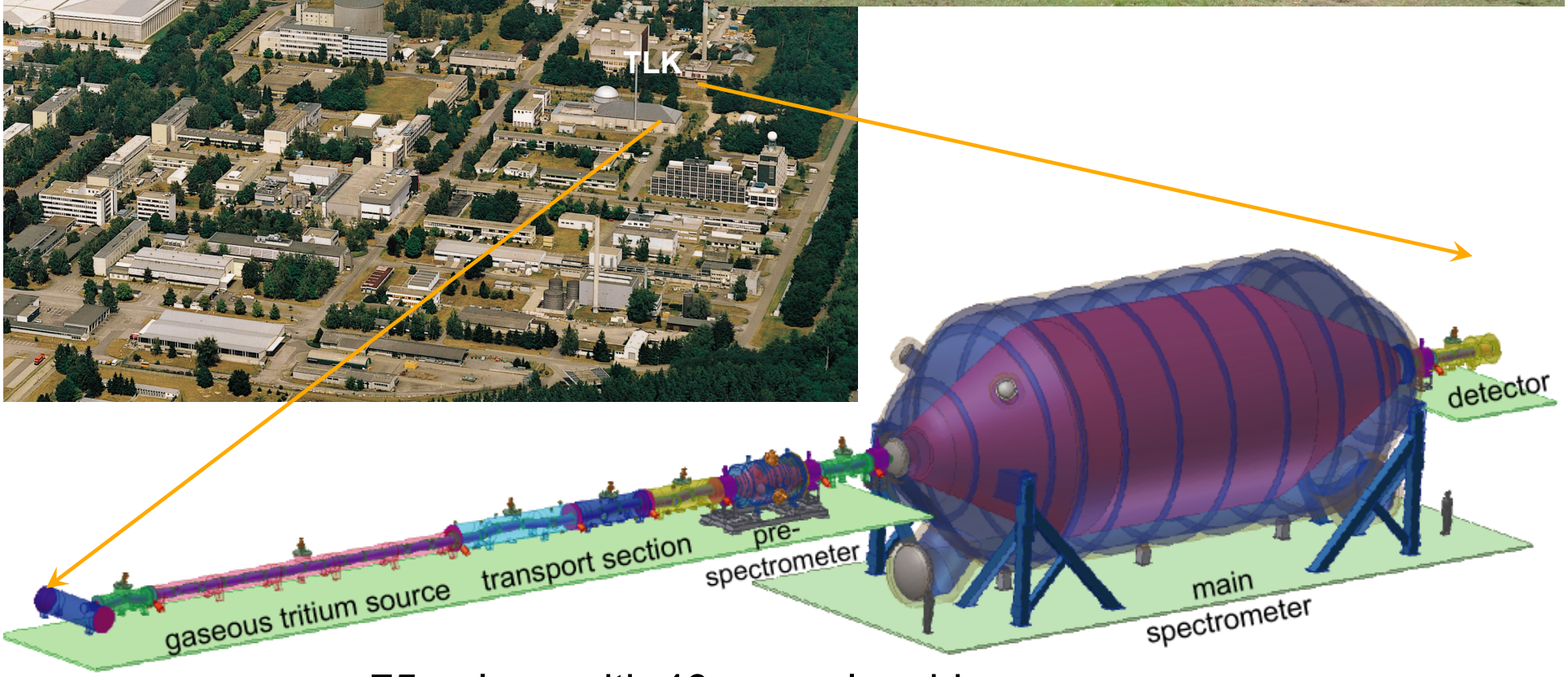



Together:…
$m_\nu < 2$ eV

# KATRIN

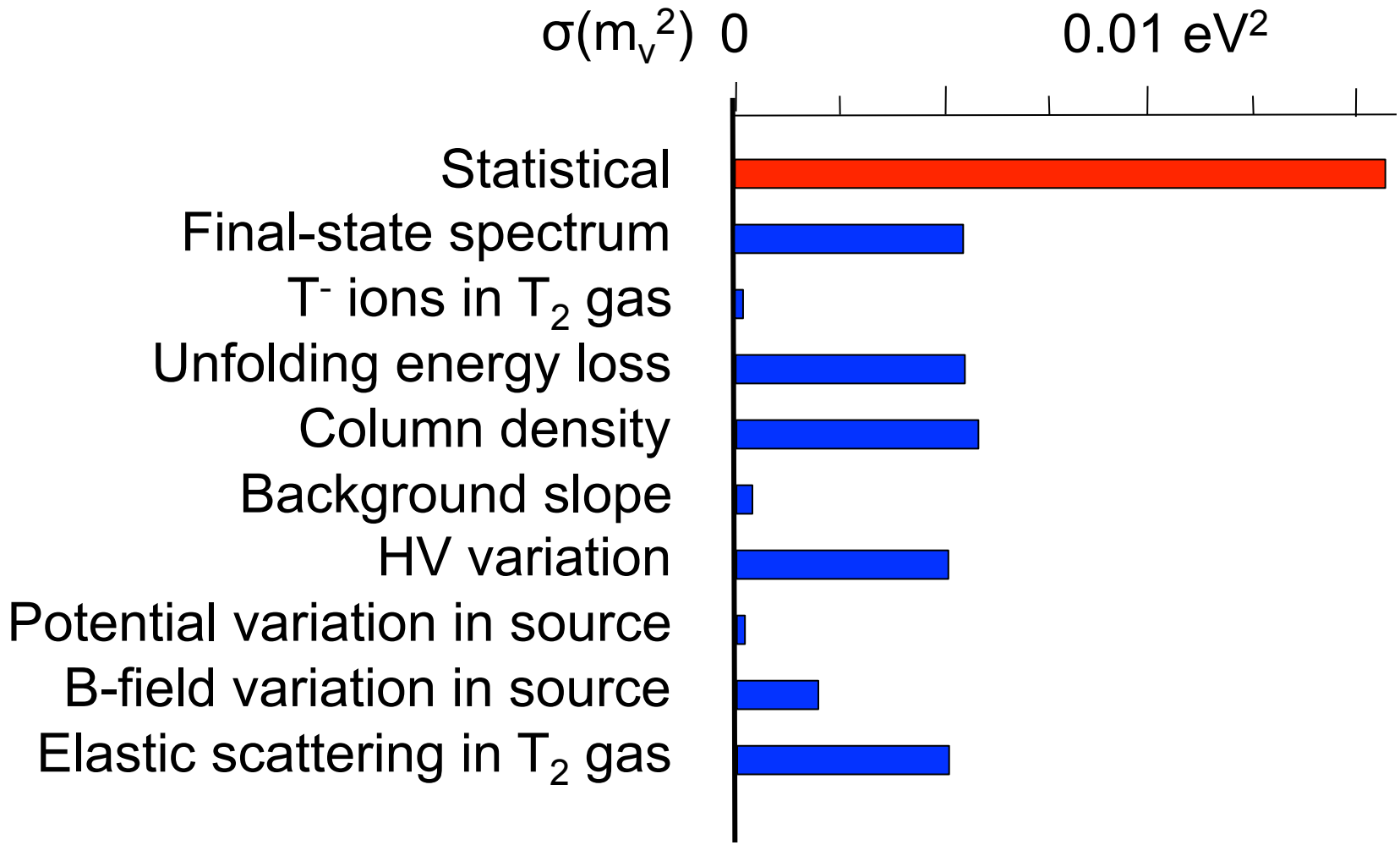
At Karlsruhe Institute of Technology
unique facility for closed $T_2$ cycle:
Tritium Laboratory Karlsruhe

5 countries
13 institutions
100 scientists




~ 75 m long with 40 s.c. solenoids

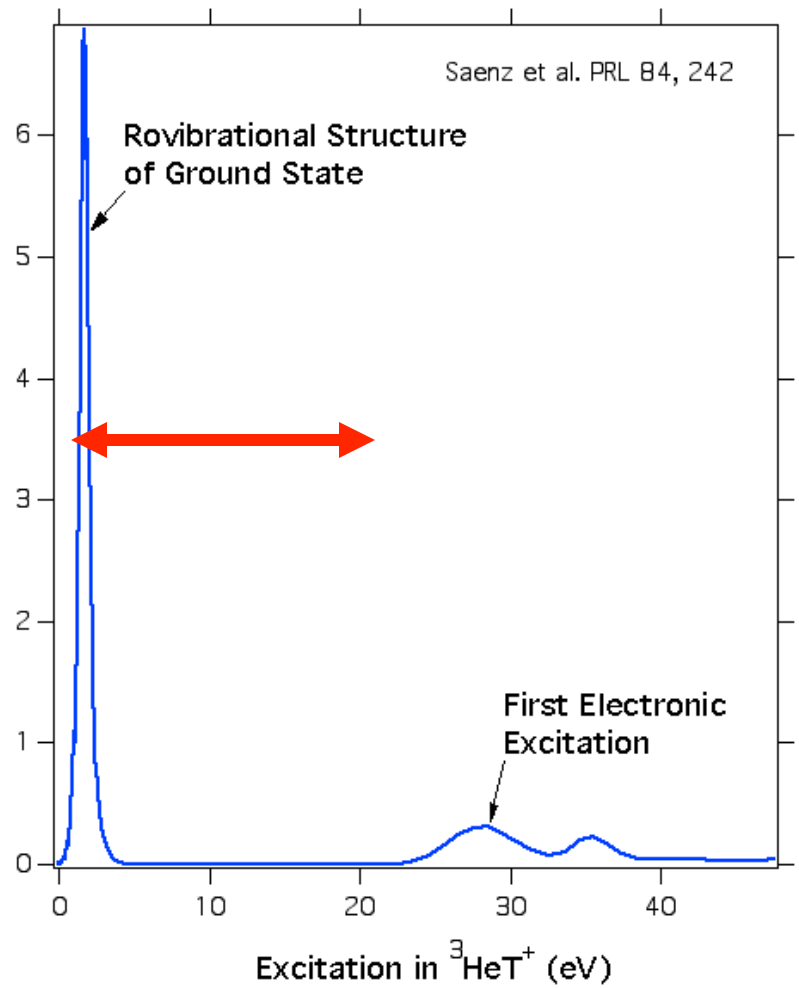
# KATRIN's uncertainty budget



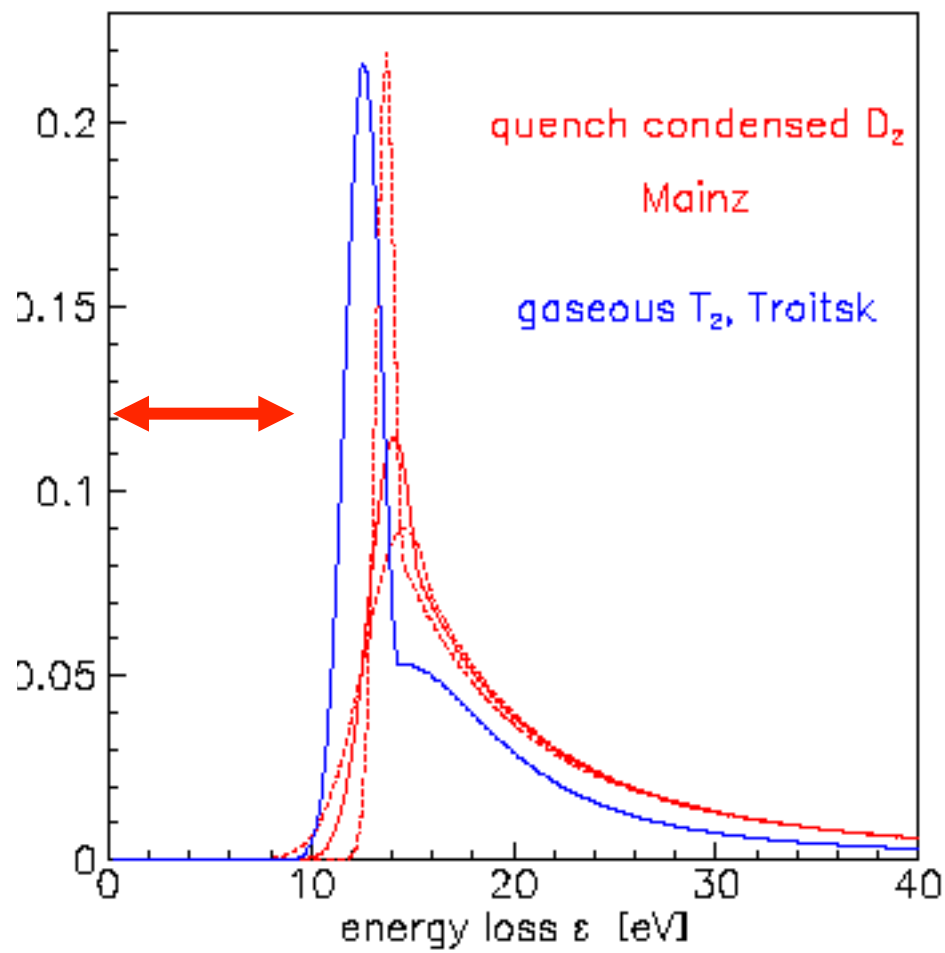

$\sigma(m_\nu^2)_{total} = 0.025\ eV^2$

# A window to work in

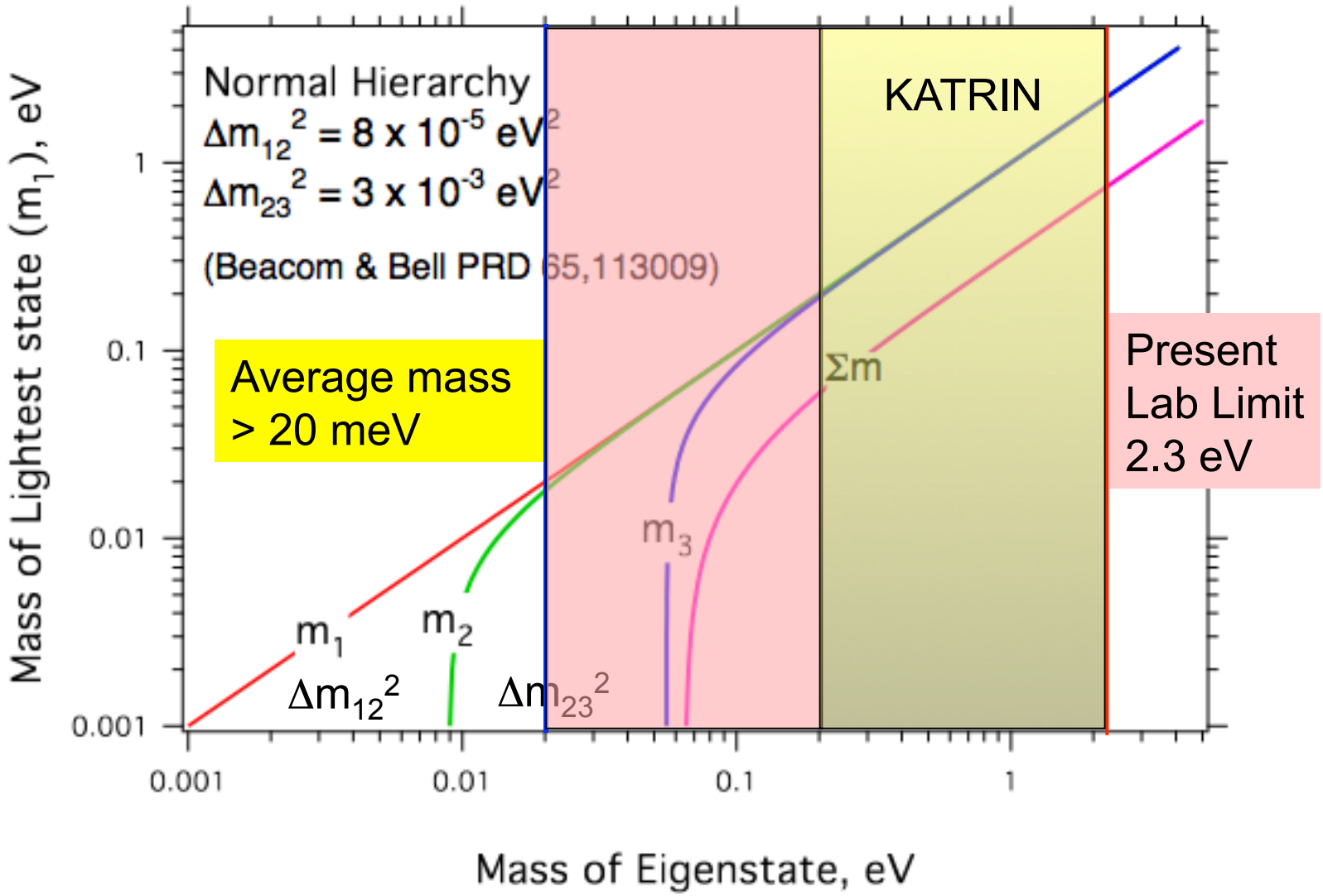
## Molecular Excitations




## Energy loss function

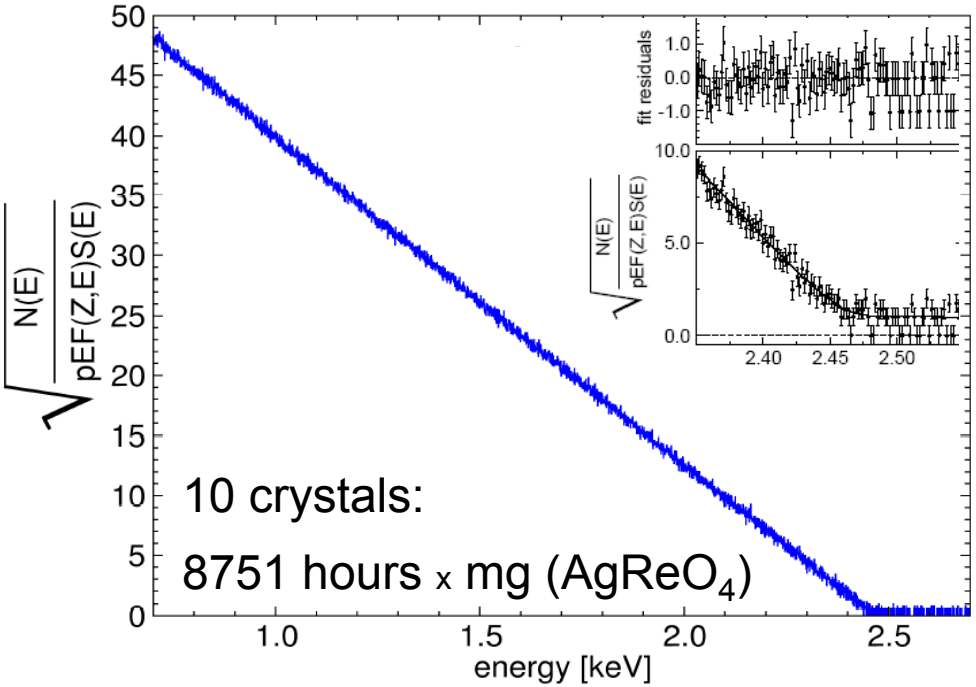


# Mass Range Accessible



# Microcalorimeters for $^{187}$Re ß-decay

**MIBETA:** Kurie plot of 6.2 ×10$^6$ $^{187}$Re ß-decay events (E > 700 eV)




$E_0 = (2465.3 \pm 0.5_{stat} \pm 1.6_{syst})$ eV

$m_\nu^2 = (-112 \pm 207 \pm 90)$ eV$^2$

MANU2 (Genoa)
metallic Rhenium
m(ν) < 26 eV

Nucl. Phys. B (Proc.Suppl.) 91 (2001) 293

MIBETA (Milano)
$AgReO_4$
m(ν) < 15 eV

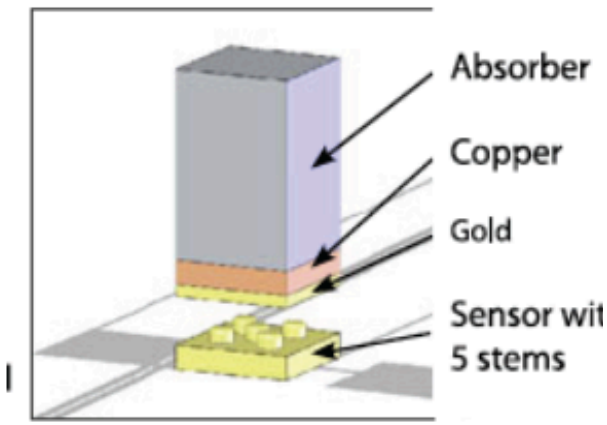
Nucl. Instr. Meth. 125 (2004) 125

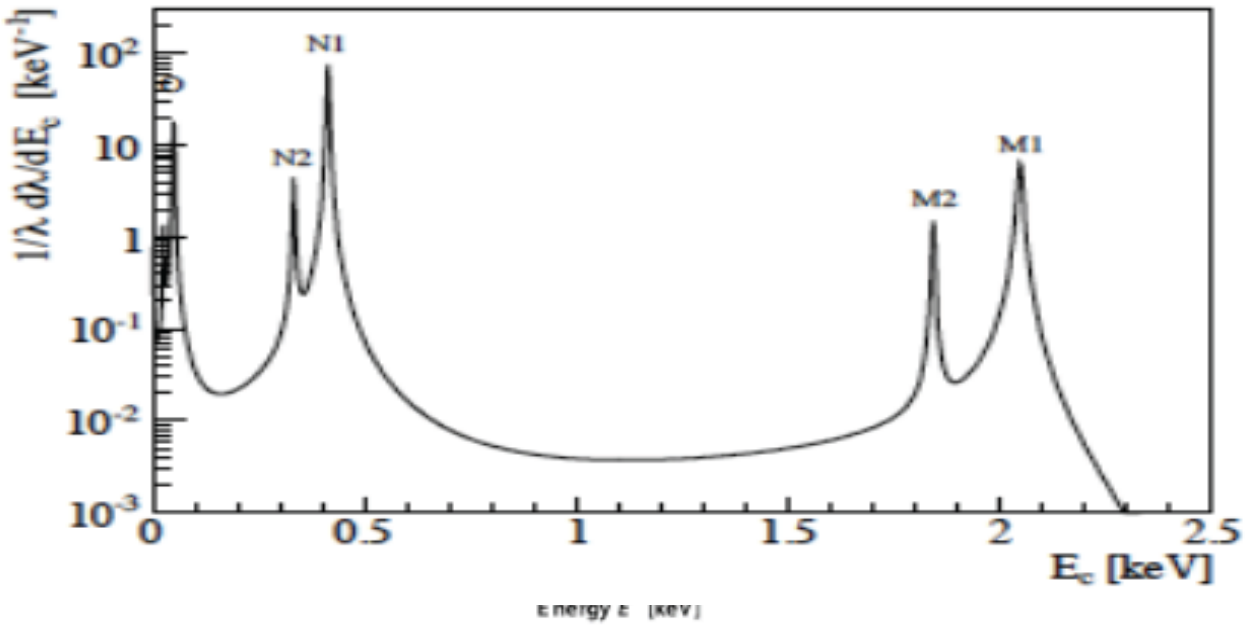
MARE (Milano, Como, Genoa, Trento, US, D)
Phase I : m(ν) < 2.5 eV

hep-ex/0509038

# Electron Capture Holmium Expt (ECHO)

- Using low-temperature Metallic Magnetic Calorimeters to study both $^{187}$Re and $^{163}$Ho.
  - should be able to achieve ultimate resolution ~ 2 eV and rise-times of 90 ns



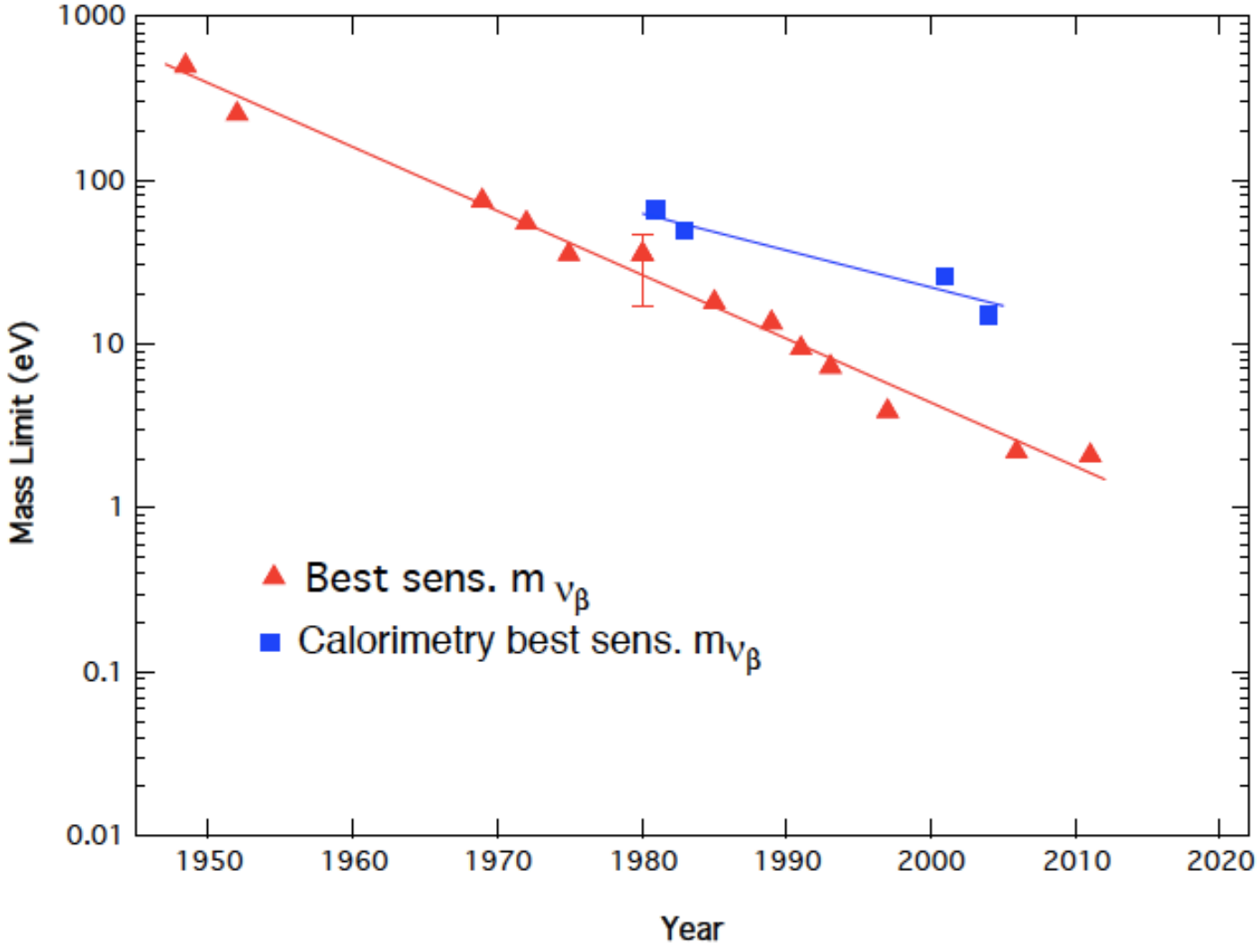

  - report $Q_{EC}$ = 2.80 ± 0.16 keV
  - shapes of N and M lines not entirely understood



J.F. Wilkerson

# Neutrino Mass from β decay

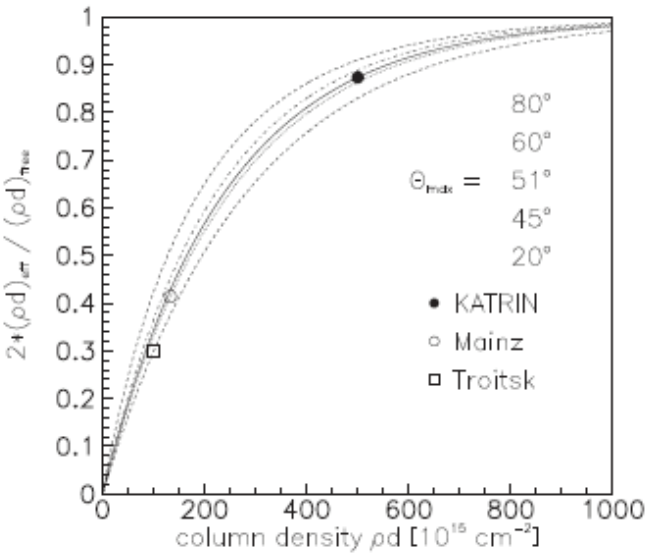
J.F. Wilkerson




To date, best sensitivities reached with spectrometer based tritium β-decay measurements

# The Last Order of Magnitude

If the mass is NOT in the 200-2000 meV window, but <200 meV, how can we measure it?
KATRIN may be the largest such experiment possible.

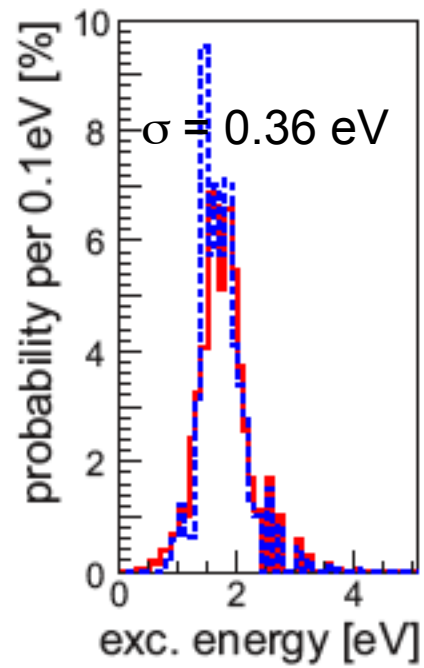



Source $T_2$ column density near max

Size of experiment now: Diameter 10 m.

$$\sigma(m_\nu^2) = k\frac{b^{1/6}}{r^{2/3}t^{1/2}},$$

Next diameter: 300 m!




Rovibrational states of $THe^+$, $HHe^+$ molecule

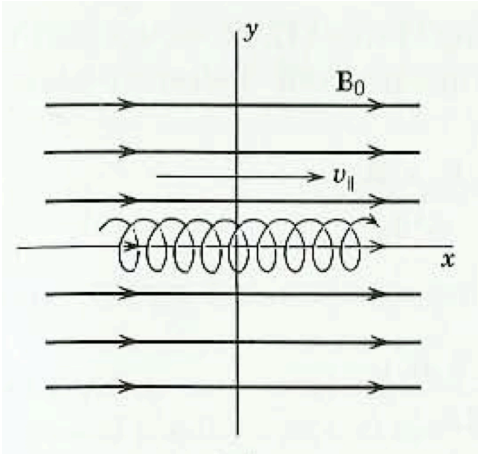
PROJECT 8

# Cyclotron radiation from tritium beta decay

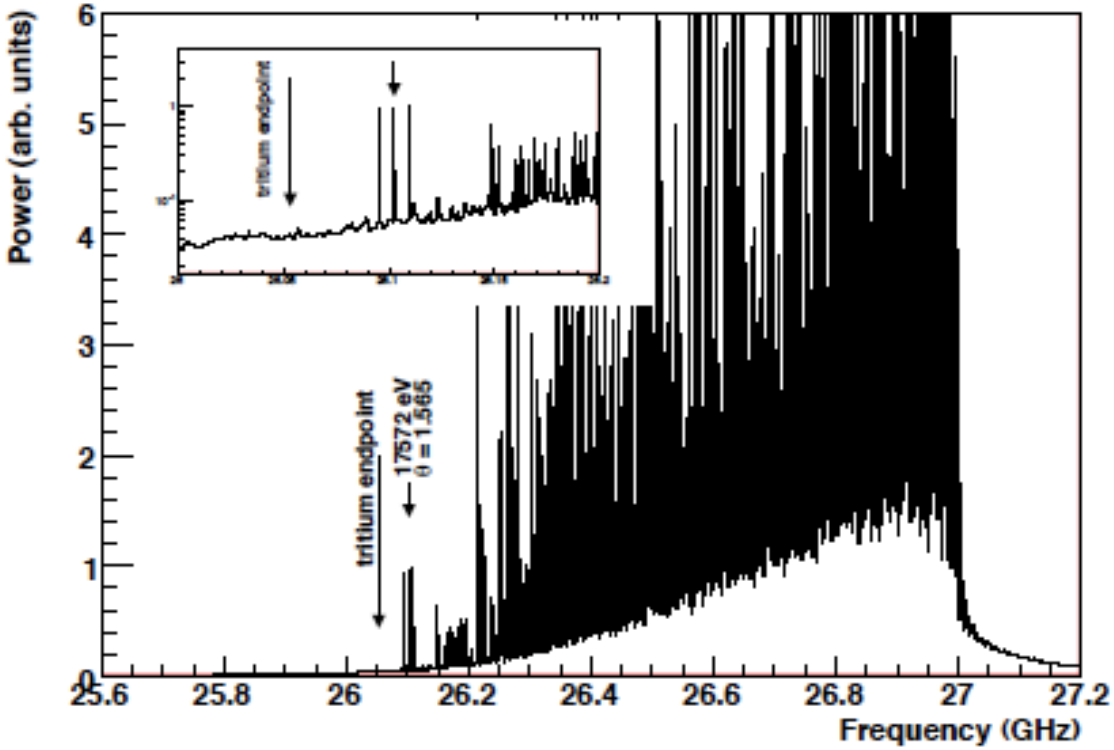
(B. Monreal and J. Formaggio, PRD 80:051301, 2009)

$$\omega = \frac{qB}{\gamma m} \equiv \frac{\omega_c}{\gamma}$$

$$\omega_c = 1.758820150(44) \times 10^{11} \text{ rad/s/T}$$



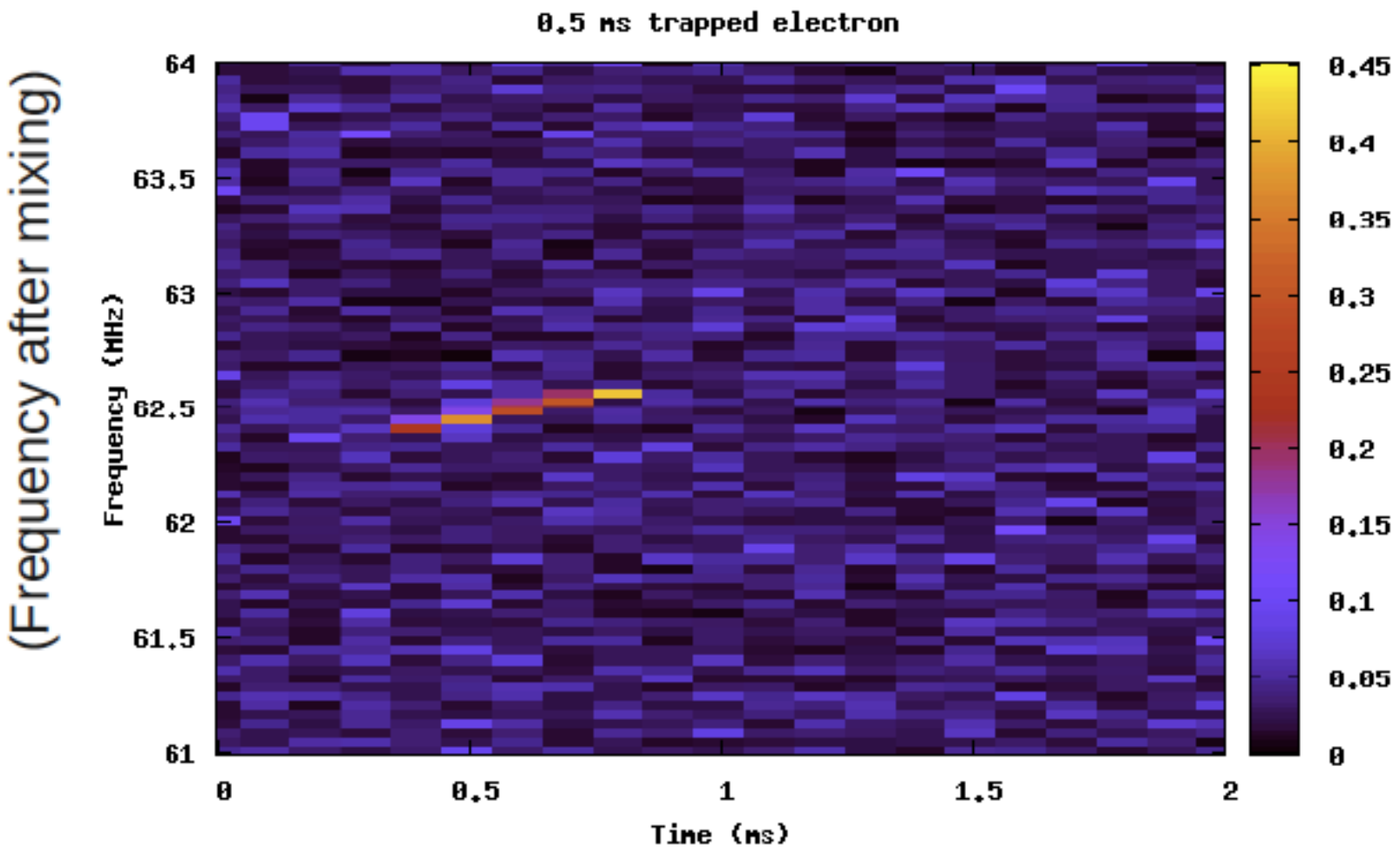

Radiated power ~ 1 fW




| Parameter | Value | Unit |
|---|---|---|
| Electron energy | 18.6 | keV |
| $\beta$ | 0.2627 | |
| $\gamma$ | 1.0364 | |
| Field | 1 | T |
| $\omega_c$ | 27.009 | GHz |

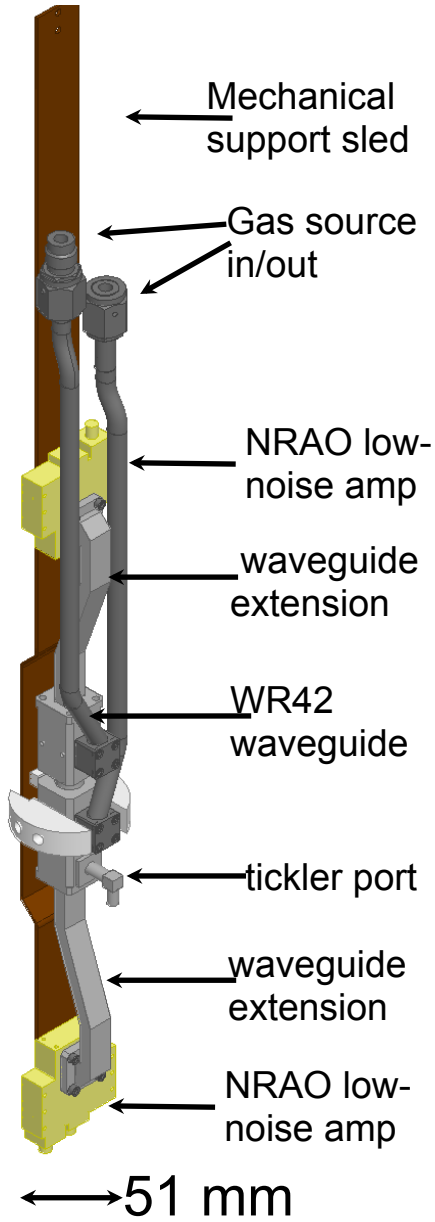
# Signal is a rising “chirp” in frequency

## Current detector simulation




simulation M. Leber

# Project 8 Waveguide Prototype

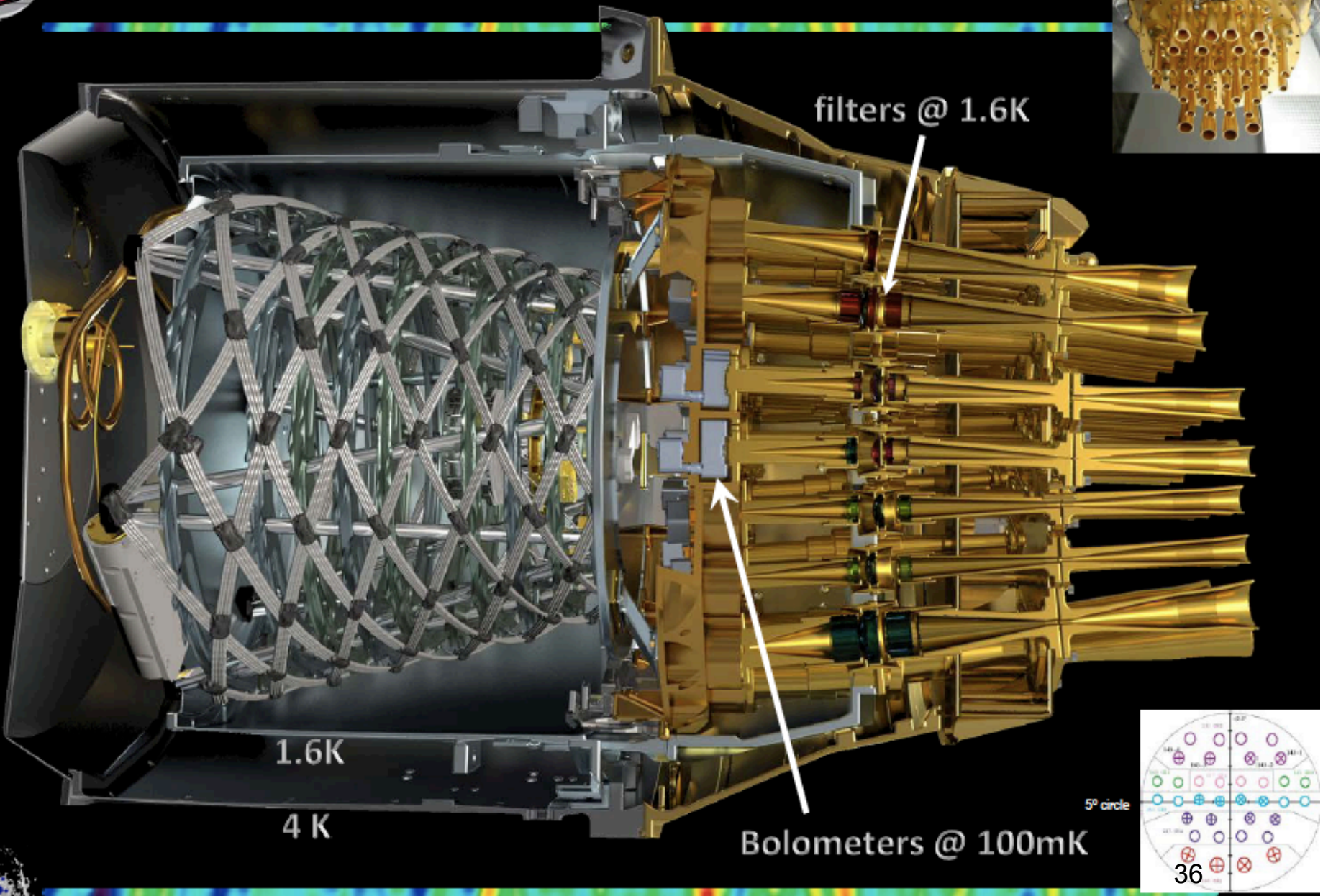


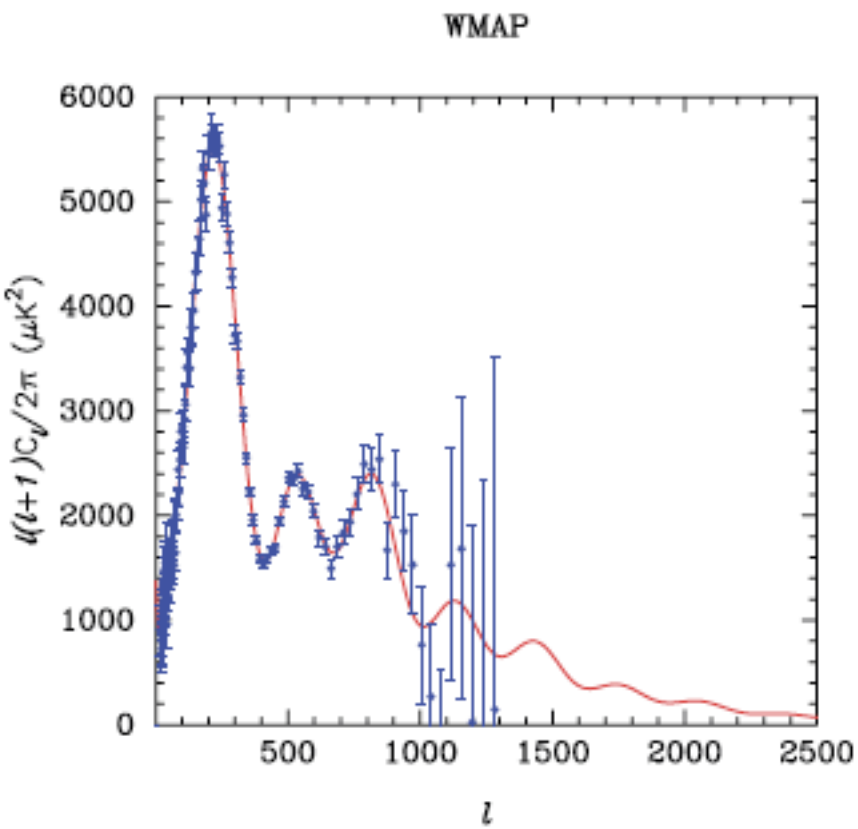

- Monolithic assembly inserted into 2-in diameter vertical bore of 1T s.c. magnet
- DPPH EPR source allows precise mapping of field strength
- Source gas flows directly through waveguide fiducial volume.
- Trap coil (not shown) around waveguide center provides a shallow parabolic trap for nearly perpendicular electrons
- Cyclotron power transported in both directions to low-noise 30 GHz amplifiers loaned by NRAO

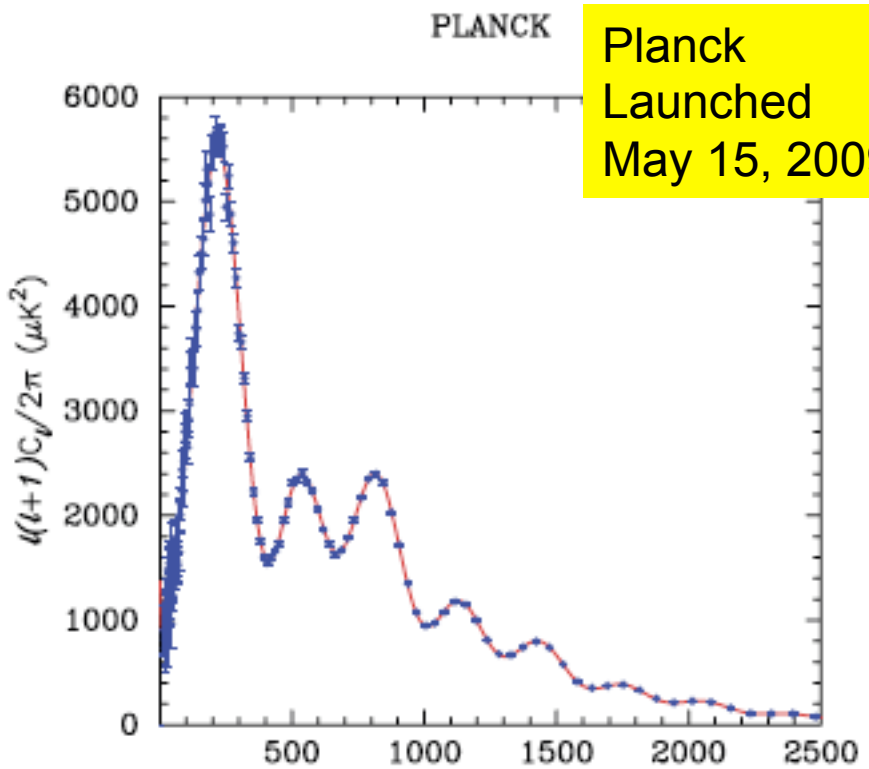
B. Vandevender

# Planck

## HFI cut-away





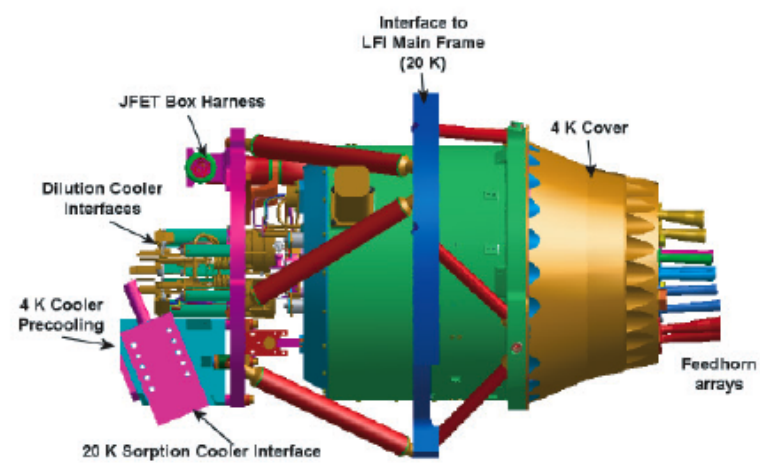

Planck Launched May 15, 2009

Present ΛCDM constraints on $\Sigma m_\nu$:

~ 0.6 eV

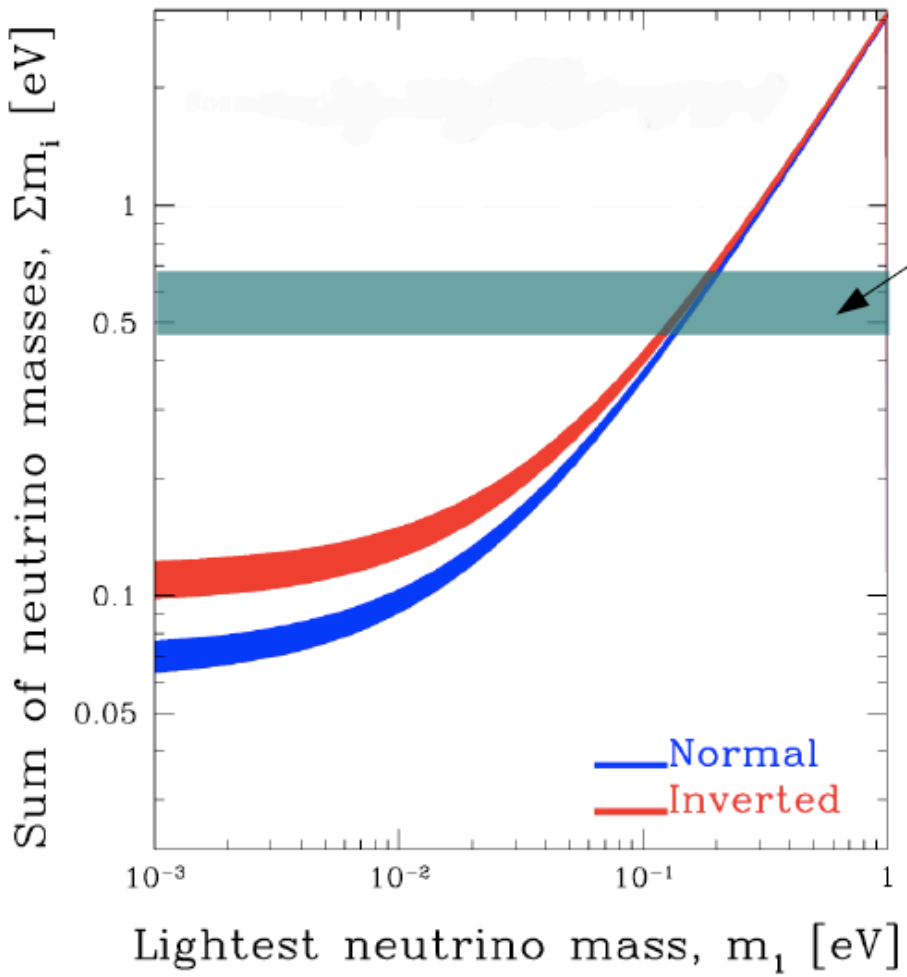
Planck sensitivity:

1. Planck only 0.26 eV
2. Planck + SDSS 0.2 eV
3. CMBR + grav. lensing 0.15 eV




From Planck "Bluebook"

# Present constraints...




CMB (WMAP7+ACBAR+BICEP+QuaD)
+ LSS (SDSS-HPS)
+ HST+SNIa

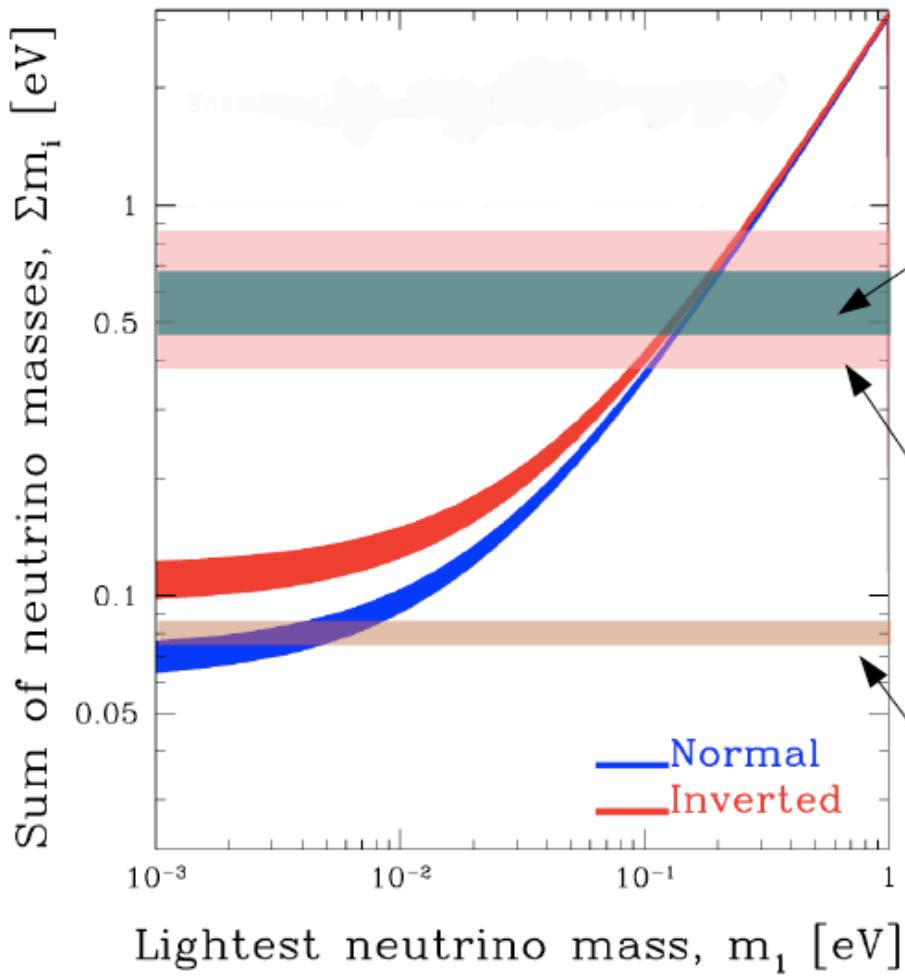
$$\sum m_\nu < 0.44 \rightarrow 0.76\ \text{eV} \quad (95\%\ \text{CI})$$

depending on the model complexity

Hannestad, Mirizzi, Raffelt & Y³W 2010
Gonzalez-Garcia et al. 2010, etc.

Y.Y.Y. Wong

# Present constraints and future sensitivities…




CMB (WMAP7+ACBAR+BICEP+QuaD)
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depending on the model complexity

Hannestad, Mirizzi, Raffelt & Y³W 2010
Gonzalez-Garcia et al. 2010, etc.

Planck alone (1 year)

$$\sum m_\nu < 0.38 \rightarrow 0.84\,\text{eV} \quad (95\%\,\text{CI})$$

Perotto et al. 2006

Planck+Weak lensing (LSST)

$$\sum m_\nu < 0.074 \rightarrow 0.086\,\text{eV} \quad (95\%\,\text{CI})$$

Hannestad, Tu & Y³W 2006

Y.Y.Y. Wong

# Major objectives in Neutrino Physics

**Known Unknowns**

- ~~$\theta_{13}$~~
- Hierarchy
- Mass
- CP violation
- Majorana or Dirac

**Unknown Unknowns**

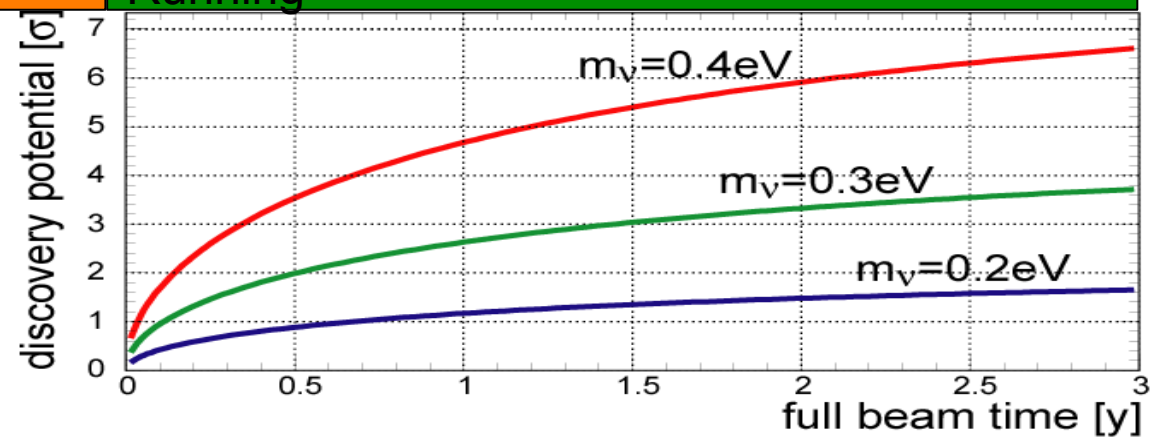
- ~~OPERA~~
- $N_\nu \sim 4$ from cosmology
- LSND, MiniBooNE
- Reactor anomaly
- Ga source anomaly

(DOE Nuclear Physics plays a strong role)

# Neutrino mass: some milestones

Construction | Running

*KATRIN:*




*Project 8:*

Proof concept | Prototype | Phase I

*Planck:*

Analysis 1 | Analysis 2

2012 | 2013 | 2014 | 2015 | 2016 | 2017 | 2018

# The Neutrino Portfolio in DOE-NP and NSF

Capital Equipment  Participation

Solar neutrinos:

SNO, Borexino, SNO+

Neutrino mass:

KATRIN, Project 8

Double Beta Decay:

CUORE, Majorana & COGENT, SNO+, EXO, KamLAND-Zen

Oscillations, UHE neutrinos:

KamLAND, IceCube, MiniBooNE (from LSND), Daya Bay

Theory:

Supernova physics, phenomenology, DBD

# The big questions

4. International Context

KamLAND, SK, T2K in Japan

Daya Bay in China

SNO+ in Canada

KATRIN in Germany

CUORE in Italy

Majorana/GERDA will join forces for 1-T Ge. Is SURF 4850 deep enough, or will this go to Canada or China?

EXO-200, MINOS, MiniBooNE in US

EXO-1-T probably in Canada

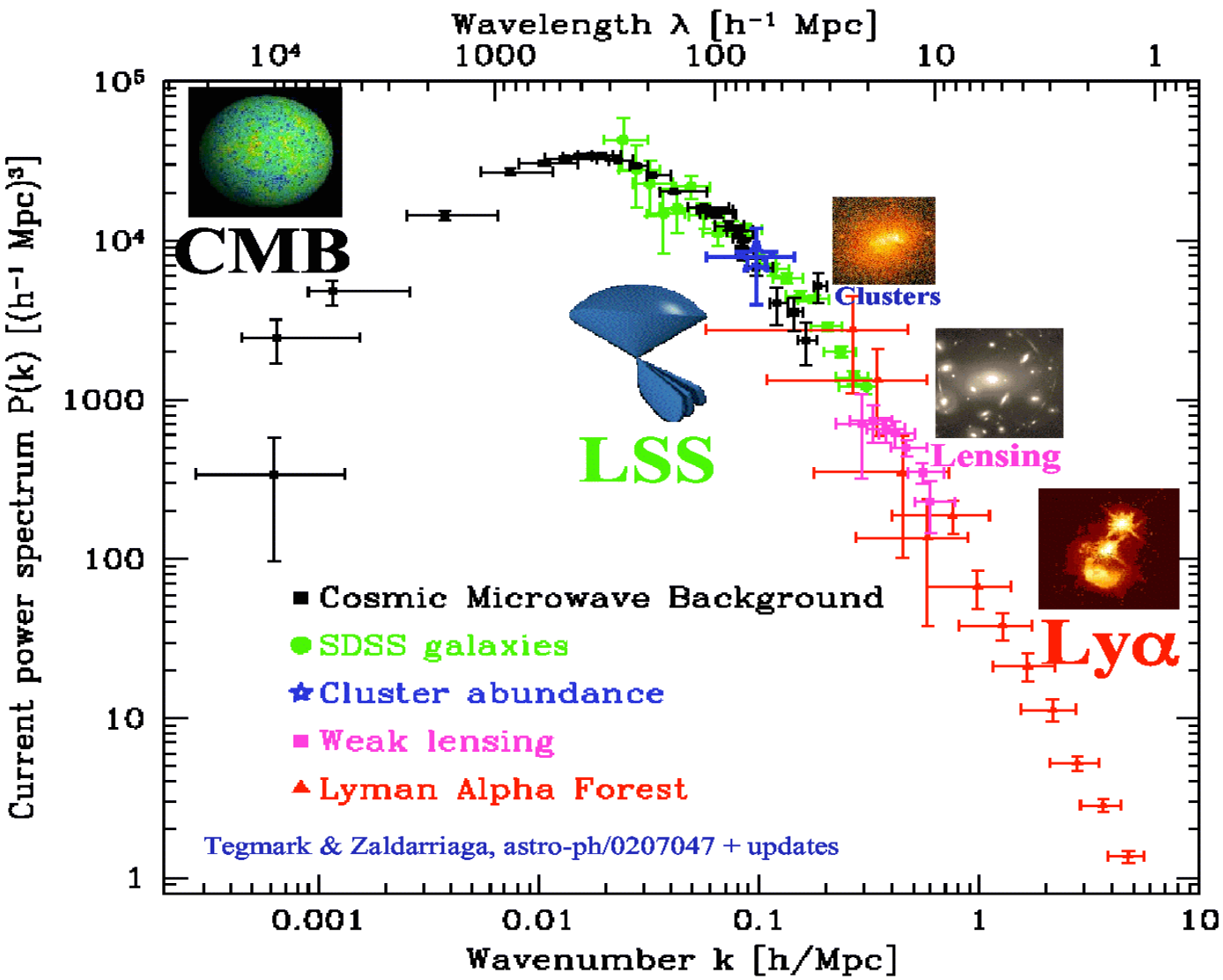
IceCube at the South Pole under US Administration

The cost and difficulty involved at the neutrino frontier makes international collaboration all but essential. But this should not exclude the possibility of doing *some* experiments in the US.

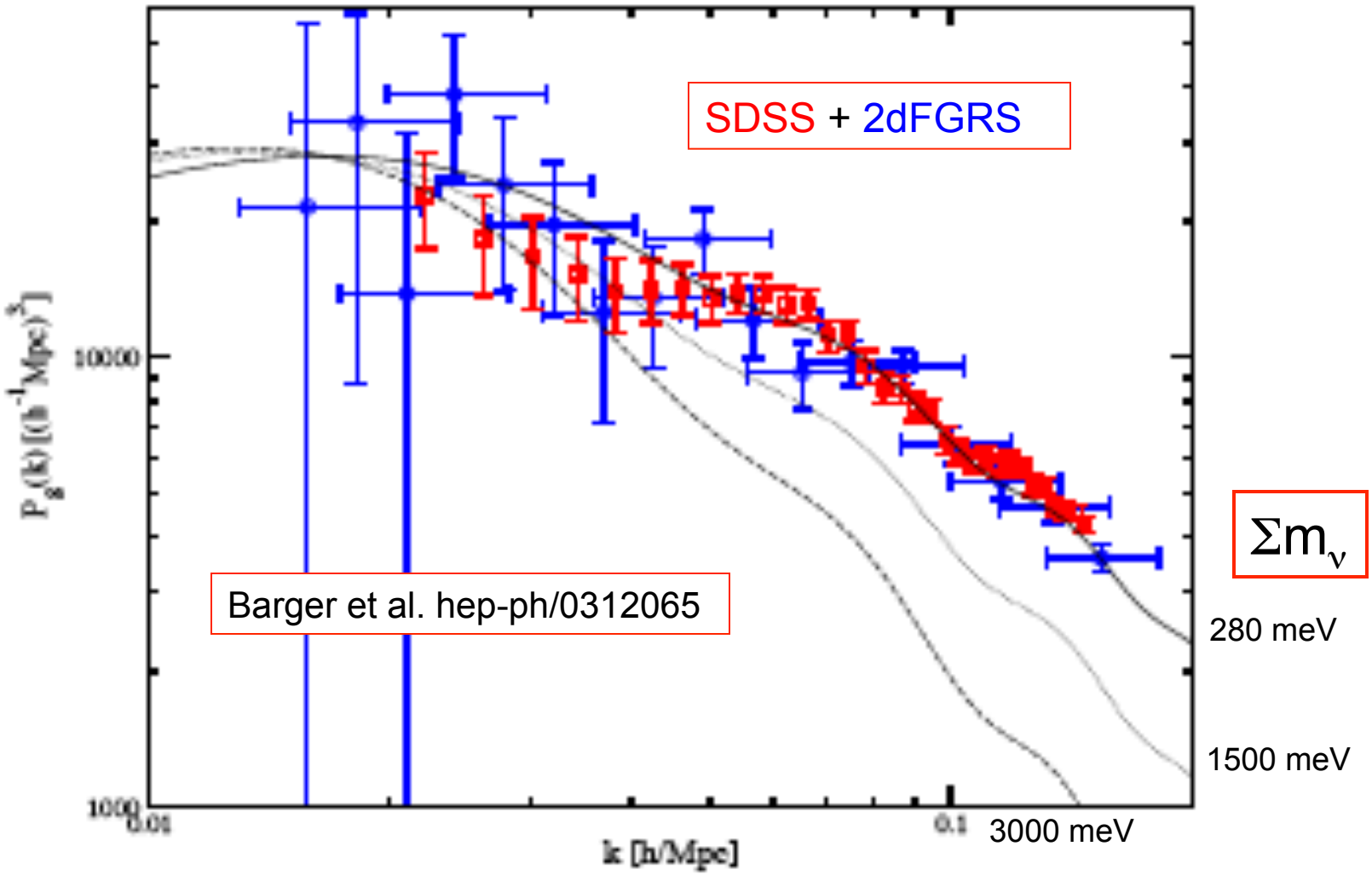
# The big questions

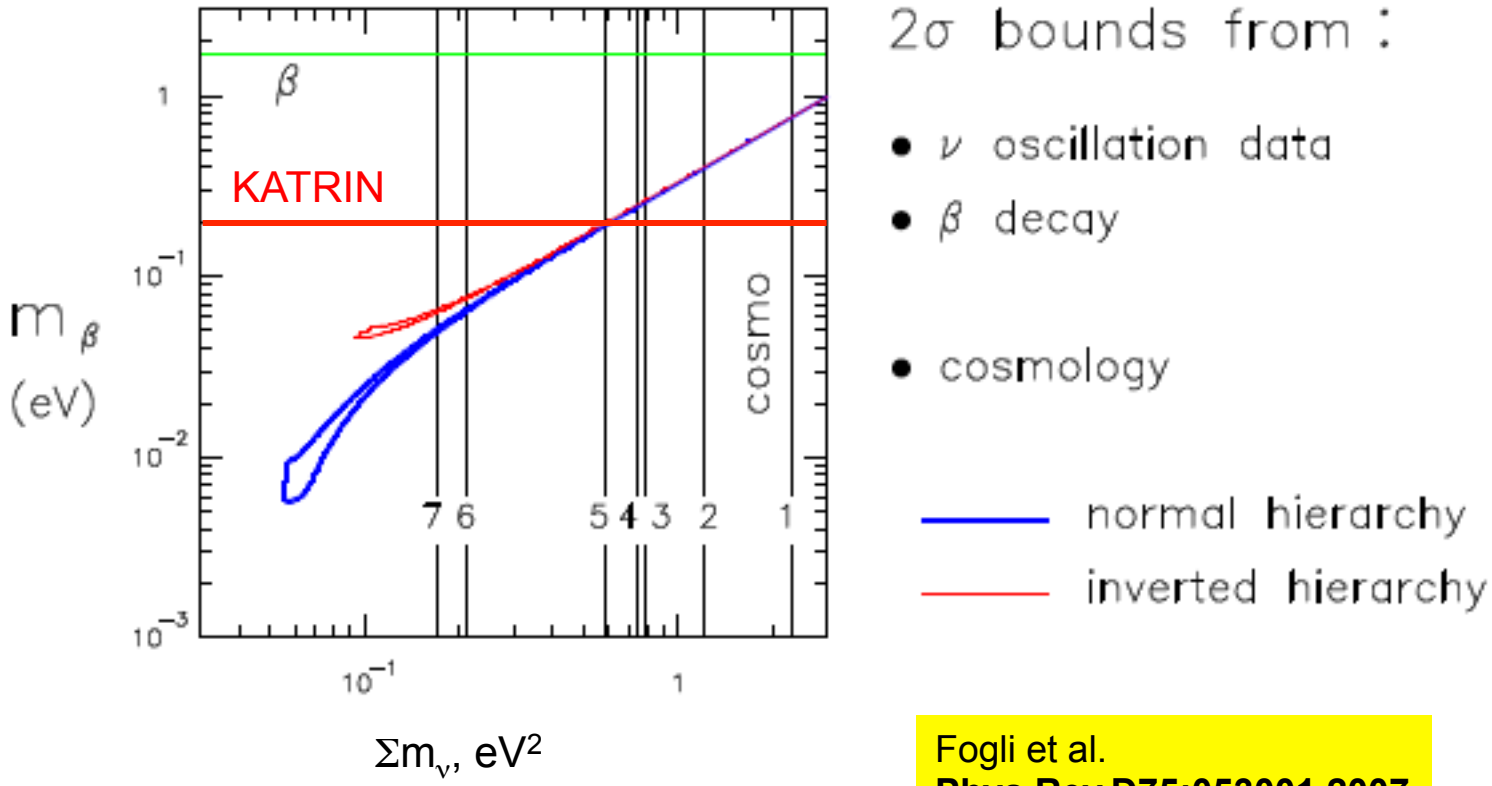
2. Compelling and unique science to be done in the next 5 years
   - KATRIN mass measurement
   - 0νββ searches: Ge, Te, Xe, Nd, …
   - SNO+: CNO, luminosity constraint tested
3. Vision for 2020 (2030 in neutrino units)
   - Direct mass measurement to +/- 20 meV
   - Neutrinos are Majorana [or Dirac]
   - Hierarchy is Normal [or Inverted]
   - CP violation is found in neutrino sector [or limited]
   - Sterile neutrinos are found [or limited]
   - Solar luminosity ratio (neutrinos/photons) measured to 1%

# Neutrino mass from cosmology



# Even small $m_\nu$ influences structure






Fogli et al.
**Phys.Rev.D75:053001,2007**

| Case | Cosmological data set | Σ bound (2σ) |
|---|---|---|
| 1 | WMAP | < 2.3 eV |
| 2 | WMAP + SDSS | < 1.2 eV |
| 3 | WMAP + SDSS + $SN_{Riess}$ + HST + BBN | < 0.78 eV |
| 4 | CMB + LSS + $SN_{Astier}$ | < 0.75 eV |
| 5 | CMB + LSS + $SN_{Astier}$ + BAO | < 0.58 eV |
| 6 | CMB + LSS + $SN_{Astier}$ + Ly-α | < 0.21 eV |
| 7 | CMB + LSS + $SN_{Astier}$ + BAO + Ly-α | < 0.17 eV |

# Mass eigenstates

With flavor mixing:

$$\frac{dN}{dT} = \frac{G_F \cos\theta_C}{2\pi^3} |M_{\rm nuc}|^2 F(Z,T)(T+m)(T^2+2mT)^{1/2}(T_0-T)\sum_i |U_{ei}|^2 \left[(T_0-T)^2 - m_i^2\right]^{1/2}$$

mixing neutrino masses

$$m_i^2 = \Delta m_{i0}^2 + m_0^2$$

from oscillations mass scale

If $\Delta m^2$ is << $m_0^2$, we can neglect it. But $\Sigma|U_{ei}|^2 = 1$. We regain our original formula: --

$$\frac{dN}{dT} = \frac{G_F \cos\theta_C}{2\pi^3} |M_{\rm nuc}|^2 F(Z,T)(T+m)(T^2+2mT)^{1/2}(T_0-T)\left[(T_0-T)^2 - m_0^2\right]^{1/2}$$

Because $U_{e3}$ is also small, this is accurate down to $m_0$ = 30 meV !

# Principle of MAC-E Filter

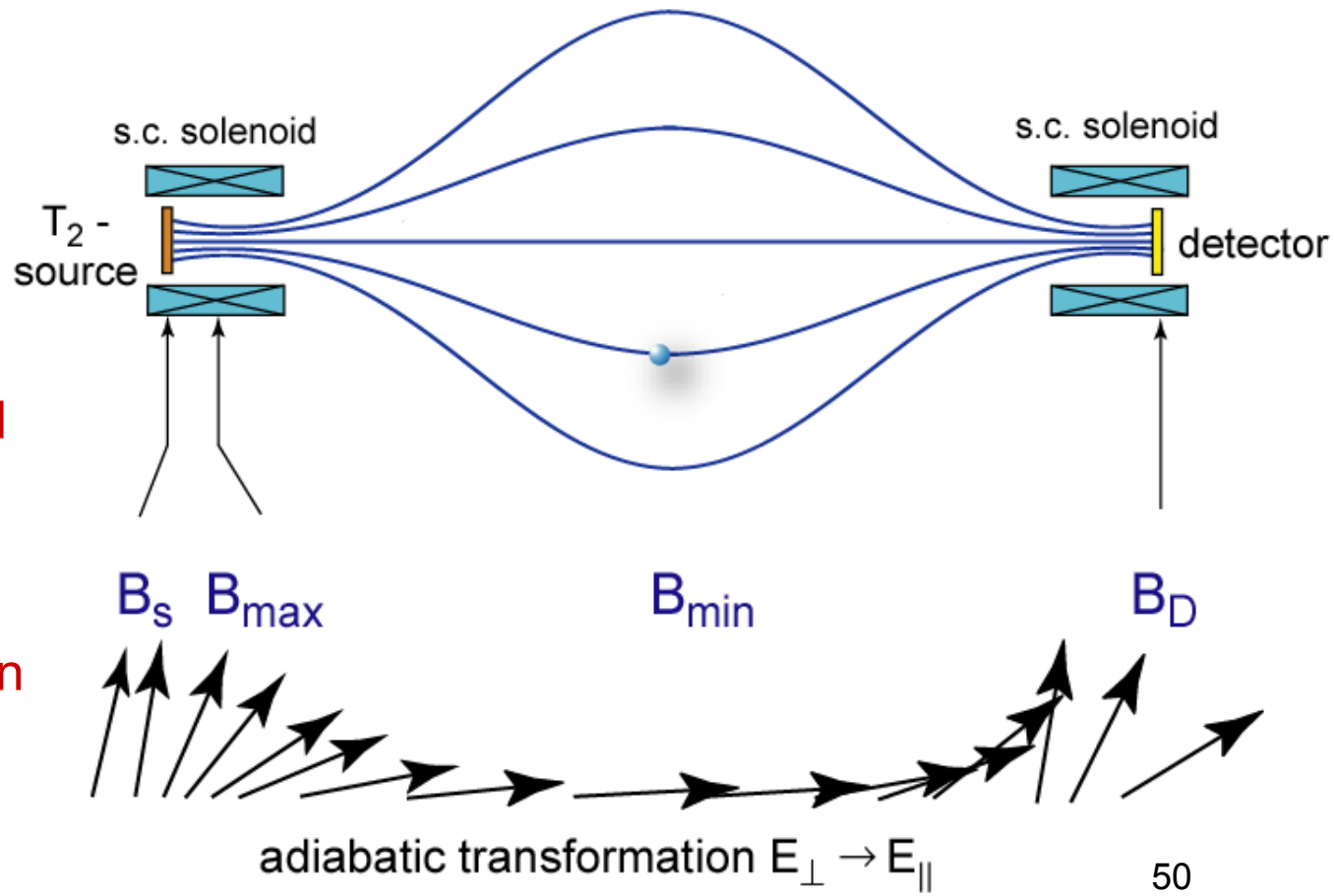
Adiabatic magnetic guiding of β´s along field lines in stray B-field of s.c. solenoids:

$B_{max}$ = 6 T

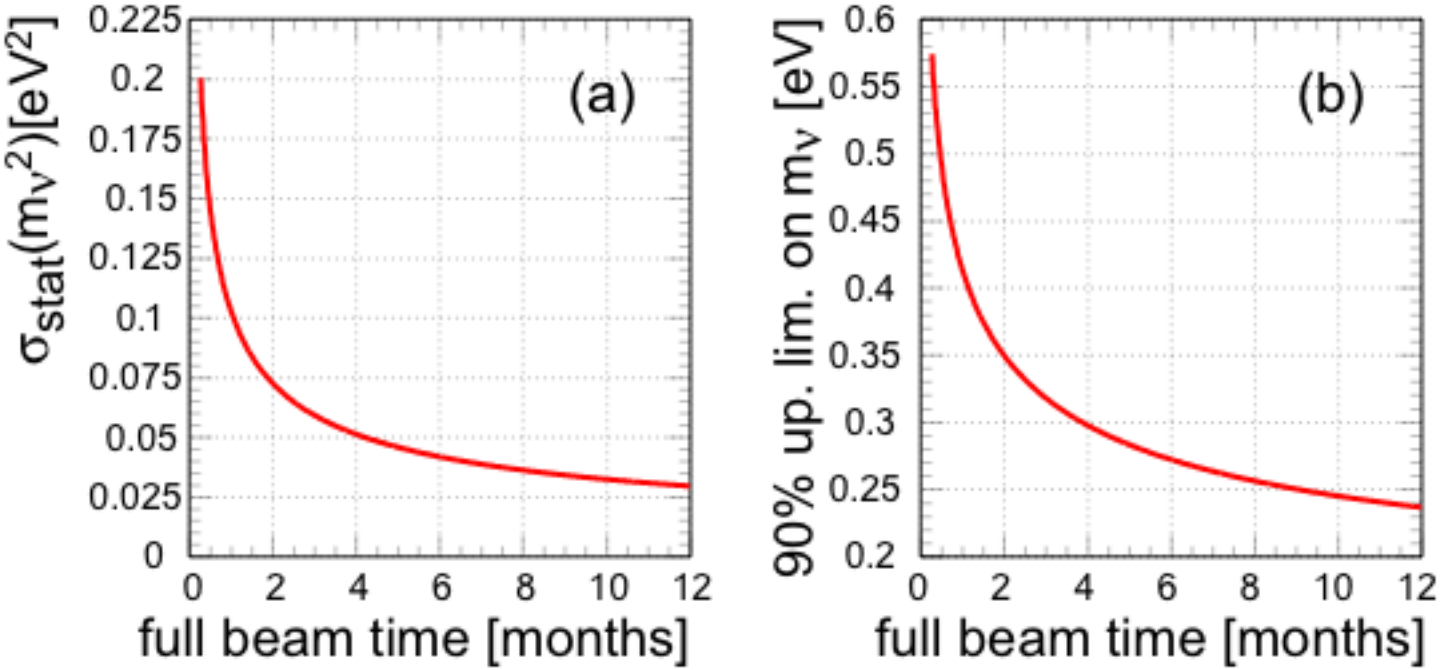
$B_{min}$ = 3×10$^{-4}$ T

Energy analysis by static retarding E-field with varying strength:

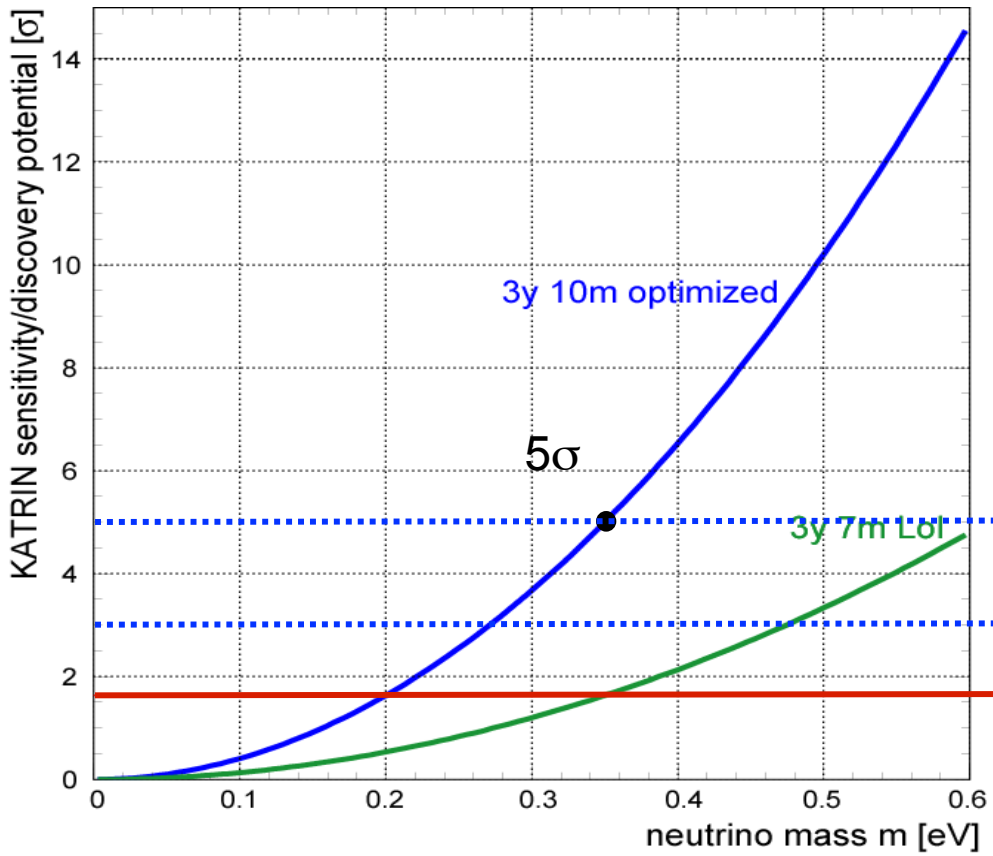
High pass filter with integral β transmission for E>qU



# Sensitivity with run time



# KATRIN:
# sensitivity and discovery potential




Expectation for 3 full beam years:

$\sigma_{syst} \sim \sigma_{stat}$

discovery potential:

$m_\nu$ = 0.35eV (5σ)

$m_\nu$ = 0.27eV (3σ)

sensitivity:

$m_\nu$ < 0.2eV (90%CL)

# Systematic Uncertainties

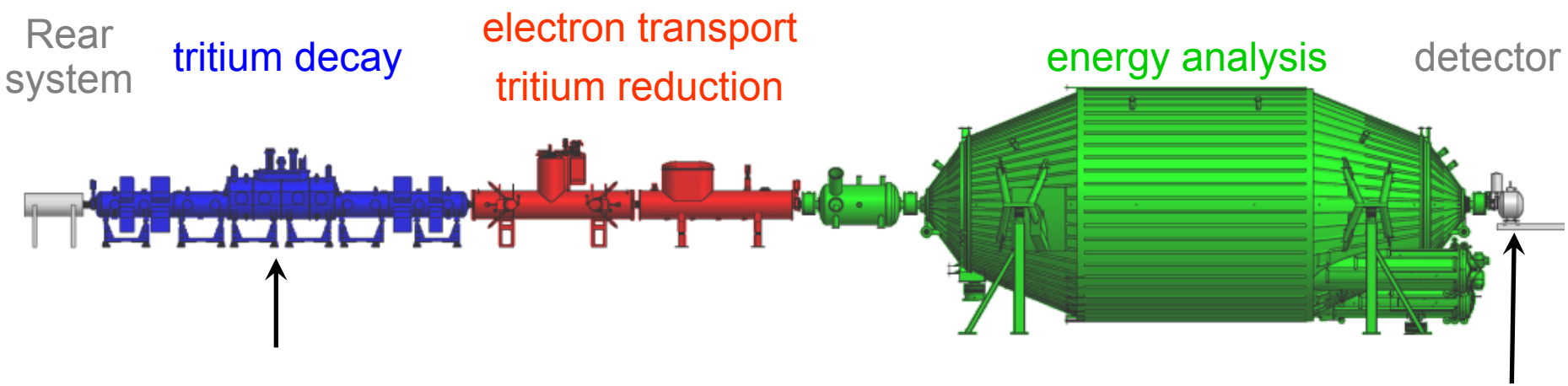
| source of systematic shift | achievable/projected accuracy | systematic shift $\sigma_{syst}(m_\nu^2)[10^{-3}\mathrm{eV}^2]$ |
|---|---|---|
| description of final states | $f < 1.01$ | $< 6$ |
| $T^-$ ion concentration $n(T^-)/n(T_2)$ | $< 2 \cdot 10^{-8}$ | $< 0.1$ |
| unfolding of the energy loss function (determination of $f_{res}$) | | $< 2$<br>$< 6$ (including a more realistic e-gun model) |
| monitoring of $\rho d$ $[E_0 - 40\,\mathrm{eV}, E_0 + 5\,\mathrm{eV}]$ | $\Delta\epsilon_T/\epsilon_T < 2 \cdot 10^{-3}$<br>$\Delta T/T < 2 \cdot 10^{-3}$<br>$\Delta\Gamma/\Gamma < 2 \cdot 10^{-3}$<br>$\Delta p_{\mathrm{inj}}/p_{\mathrm{inj}} < 2 \cdot 10^{-3}$<br>$\Delta p_{\mathrm{ex}}/p_{\mathrm{ex}} < 0.06$ | $< \frac{\sqrt{5} \cdot 6.5}{10}$ |
| background slope | $< 0.5\,\mathrm{mHz/keV}$ (Troitsk) | $< 1.2$ |
| HV variations | $\Delta\mathrm{HV}/\mathrm{HV} < 3\,\mathrm{ppm}$ | $< 5$ |
| potential variations in the WGTS | $\Delta U < 10\,\mathrm{meV}$ | $< 0.2$ |
| magnetic field variations in WGTS | $\Delta B_S/B_S < 2 \cdot 10^{-3}$ | $< 2$ |
| elastic $e^-$ - $T_2$ scattering | | $< 5$ |
| identified syst. uncertainties | $\sigma_{\mathrm{syst,tot}} = \sqrt{\sum \sigma_{\mathrm{syst}}^2} \approx 0.01\,\mathrm{eV}^2$ | |

TABLE IV: Summary of sources of systematic errors on $m_\nu^2$ , the achievable or projected accuracy of experimental parameters (stabilization) and the individual effect on $m_\nu^2$ for an analysis interval of $[E_0 - 30\,\mathrm{eV}, E_0 + 5\,\mathrm{eV}]$ if not stated otherwise.

# Description of KATRIN

**KA**rlsruhe **TRI**tium **N**eutrino experiment, location: Karlsruhe Institute of Technology

*Draws on 3 decades of tritium neutrino experiments*




β-decay rate: **$10^{11}$** Hz

$T_2$ pressure: **$10^{-6}$** mbar

about **14** orders of magnitude

background rate: **$10^{-2}$** Hz

$T_2$ pressure: **$10^{-20}$** mbar

70 m



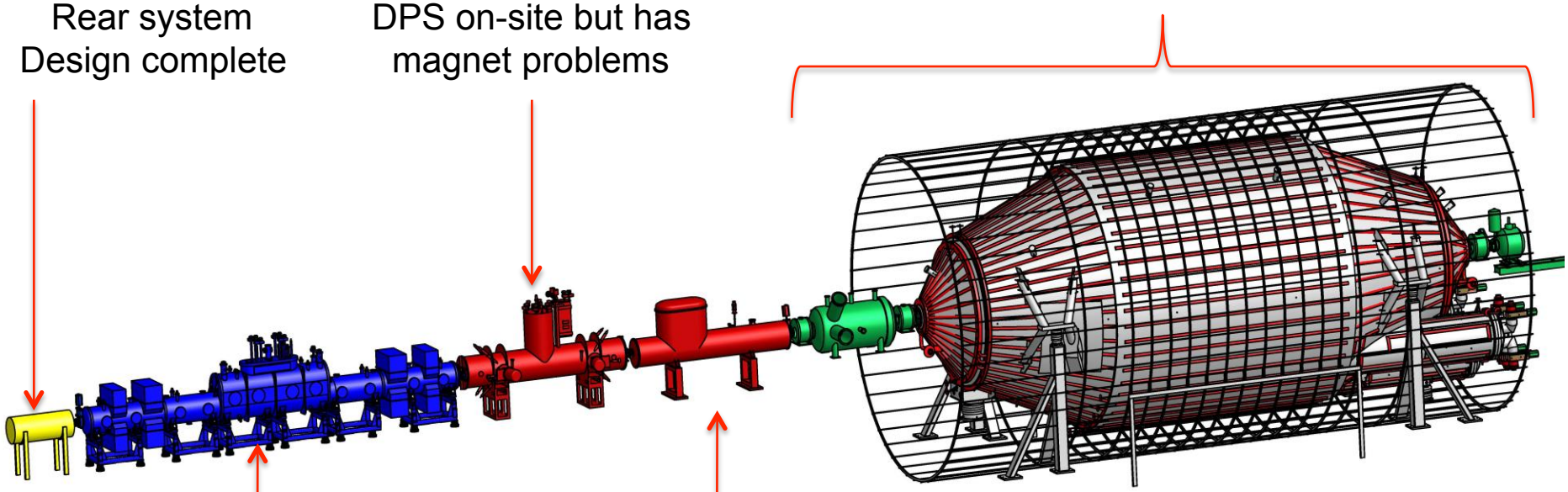
P.J. Doe

# Status of KATRIN components

Pre-spectrometer, main spectrometer, field coils, detector on site at KIT

Rear system
Design complete

DPS on-site but has magnet problems



WGTS demonstrator successful
Problems with magnets
Delivery late 2013

CPS delivery to KIT June 2012



P.J. Doe

# Arrival in Leopoldshafen: Nov 24, 2006

# $U_{MNSP}$ - Neutrino Mixing Matrix

## Present and Future Measurements

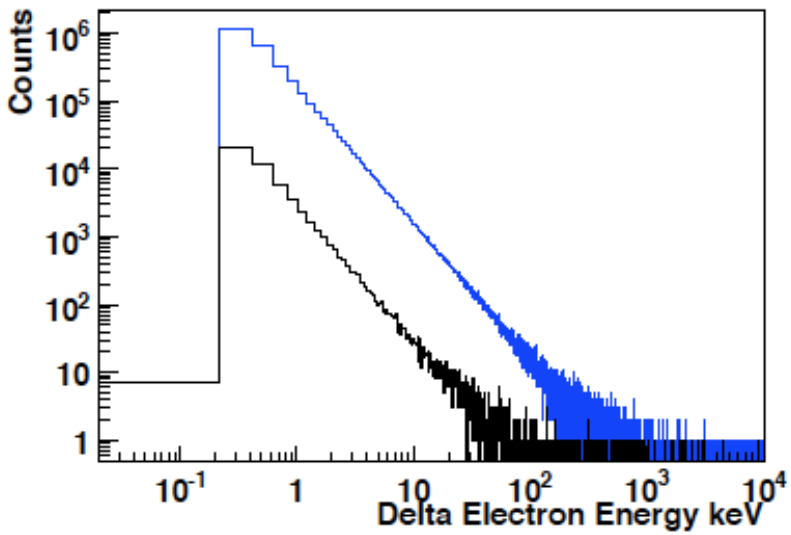
| | | |
|---|---|---|
| Solar | $\theta_{12} = 32.3°$ | *large* |
| Atmospheric | $\theta_{23} = 45°$ | *maximal* |
| Chooz + SK | $\theta_{13} < 10°$ at 90% CL | *small … at best* |

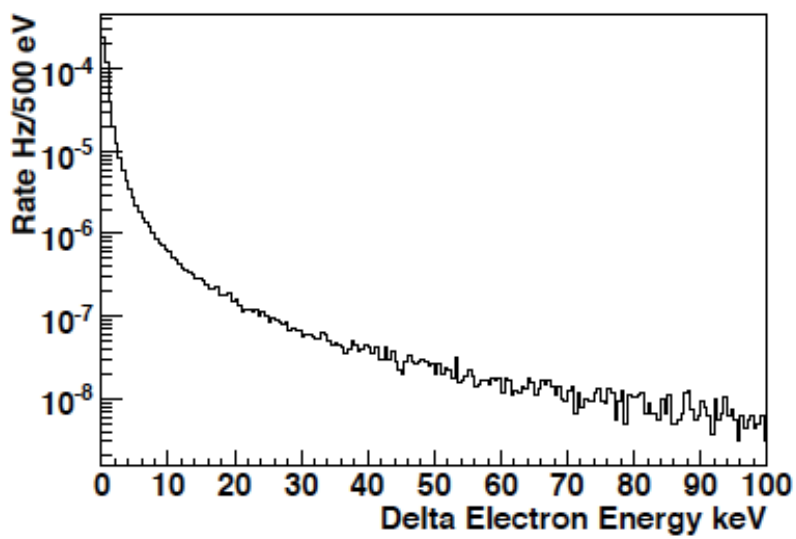
$$U = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix}$$

$$= \underbrace{\begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_{23} & \sin\theta_{23} \\ 0 & -\sin\theta_{23} & \cos\theta_{23} \end{pmatrix}}_{\substack{\text{atmospheric } \nu \\ \text{present} \\ \text{accelerator } \nu \\ \text{future}}} \times \overbrace{\underbrace{\begin{pmatrix} \cos\theta_{13} & 0 & e^{-i\delta_{CP}}\sin\theta_{13} \\ 0 & 1 & 0 \\ -e^{i\delta_{CP}}\sin\theta_{13} & 0 & \cos\theta_{13} \end{pmatrix}}_{\text{reactor and accelerator } \nu \text{ future}}}^{\textit{Dirac phase}} \times \underbrace{\begin{pmatrix} \cos\theta_{12} & \sin\theta_{12} & 0 \\ -\sin\theta_{12} & \cos\theta_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}}_{\substack{\text{solar } \nu \\ \text{present} \\ \text{solar } \nu \\ \text{future}}} \times \overbrace{\underbrace{\begin{pmatrix} 1 & 0 & 0 \\ 0 & e^{i\alpha/2} & 0 \\ 0 & 0 & e^{i\alpha/2+i\beta} \end{pmatrix}}_{\substack{0\nu\beta\beta \text{ experiments} \\ \text{future}}}}^{\textit{Majorana phases}}$$

# Background cont'd

Michelle Leber calculated the cosmic-ray delta intensity for KATRIN (about 3 Ci of tritium). [muonionization.pdf]




Blue: primary muons.
Black: secondaries.

KATRIN target background is 0.01 Hz

For P8 with the same source strength, this background is ~3 x $10^{-10}$ Hz/eV at the endpoint!

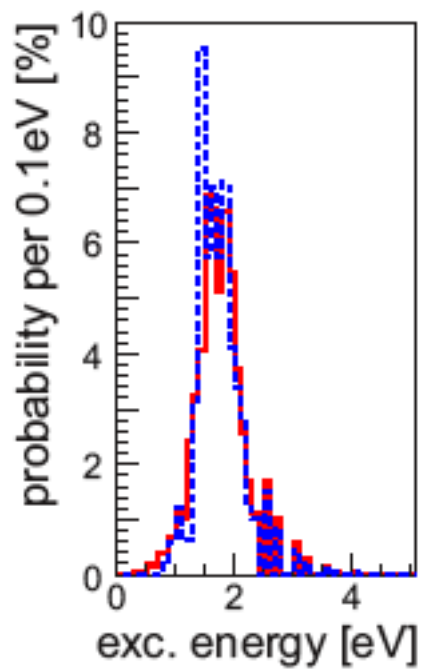
# Count rate, Background, and Resolution

For a background *b* and count rate *r*, the optimum energy window to count in is

$$\Delta E = \left(\frac{2b}{r}\right)^{1/3}$$

The best *useful* resolution is then ΔE ~2.35*0.36 = 0.9 eV. For a given *r*, we then know what background we should try to reach.

With molecular $T_2$ the rovibrational width of the ground-state molecular ion $THe^+$ limits the effective resolution: $\sigma$ = 0.36 eV



# Resolution

The energy resolution is related to the frequency resolution by:

$$\frac{d\omega}{\omega} = -\frac{T}{T + m_0 c^2}\frac{dT}{T}$$

1 eV → 2 x $10^{-6}$ in frequency.

The B-field must be uniform to at least this level.

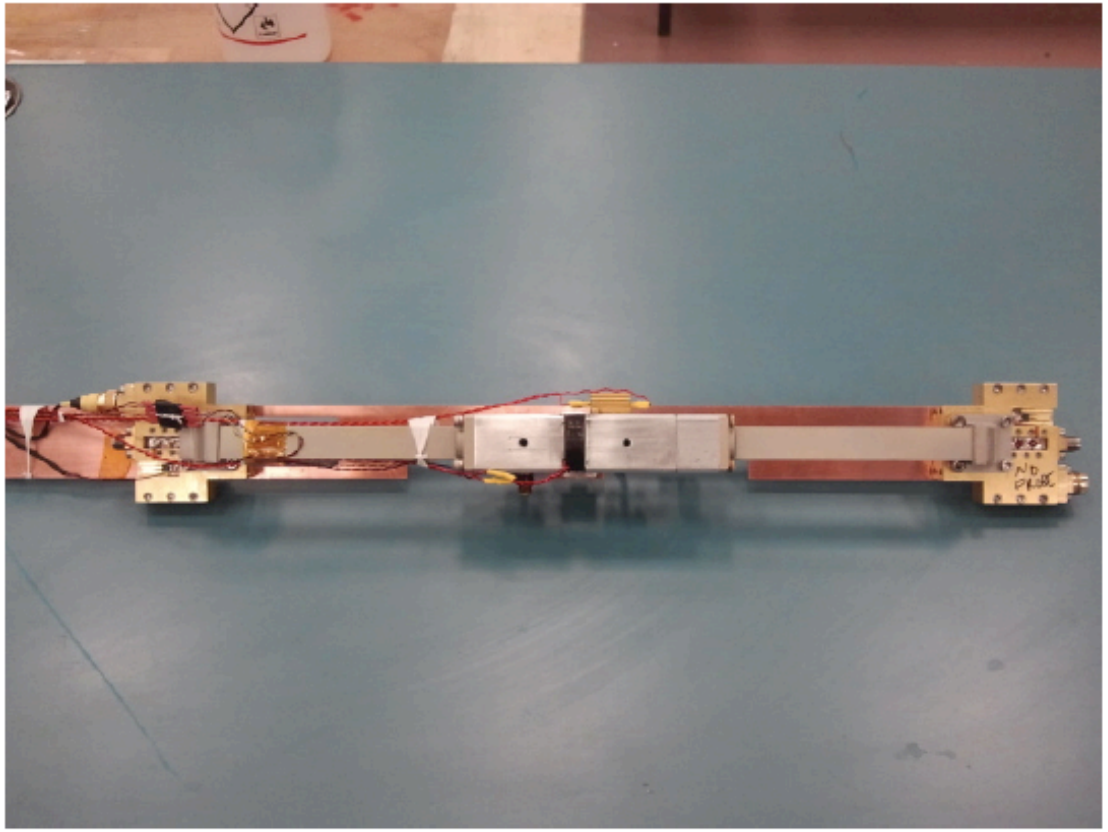
Cyclotron emission interrupted after a random time (by a collision) gives a Lorentzian line.

But such lines have infinite variance.

$$\Delta\omega = \Gamma = \frac{1}{\tau}$$

At 30 GHz, τ = 2.7 μs

# Project 8 prototype at University of Washington



Trap coil, sample cell, waveguide, and two NRAO amplifiers

## Magnet cooldown

# Sensitivity to Neutrino Mass

Statistical accuracy depends only on rate, background, time.

$$\sigma(m_\nu^2) = k\frac{b^{1/6}}{r^{2/3}t^{1/2}},$$

*k* is of order 1.

KATRIN will achieve 0.01 $eV^2$. What does this translate to for P8? Choose $b = 10^{-3}$ Hz and $t = 10^7$ s.

Full-acceptance activity = $1.6 \times 10^8$ Bq (4.3 mCi). Does not include decays that are not observable for various geometrical reasons.

# CAN we use a cavity?

The size of the cavity must be large enough to accommodate an orbiting electron.

$$\frac{\text{Electron gyroradius}}{\text{Cyclotron wavelength}} \qquad \frac{r_{cyc}}{\lambda_{cyc}} = \frac{\beta}{2\pi} << 1$$

Yes!

# Total decay rate

The total rate of decays scales inversely as the cyclotron frequency squared.

$$R = \frac{C(2\pi)^3 c^2}{\beta \sigma_0 \omega_c^2 \tau_m} \frac{\Delta\omega_c}{\omega_c}.$$

Arbitrarily selecting 100 MHz we get a cavity volume of about 8 $m^3$ and a gross decay rate therein of 4.4 x $10^8$ Bq. However there are two acceptance factors, one for the useful active volume inside the cavity, the other for the solid angle to trap an electron. Together these factors might be 0.01 – 0.1.

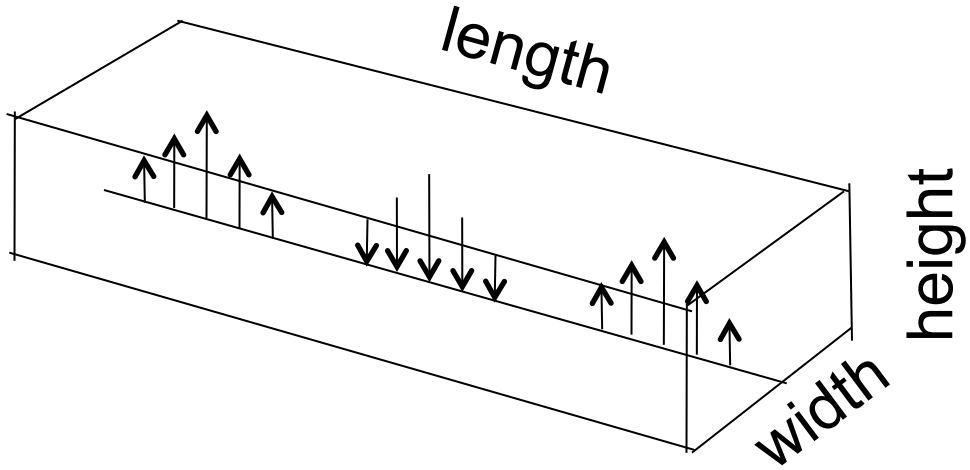
To this level of precision, it looks feasible to reach 200 meV, except for the noise.

# Using a cavity

- Doppler effect goes away, at least to a good approximation.
- Larger trapping angles can be used, more intensity
- Frequency selectivity can be used to discriminate against uninteresting decays
- Coupling of energy from electron to amplifier can be enhanced (?)
- We still have the axial sidebands, but they can be muted with a bathtub trap

# Cavity miscellany

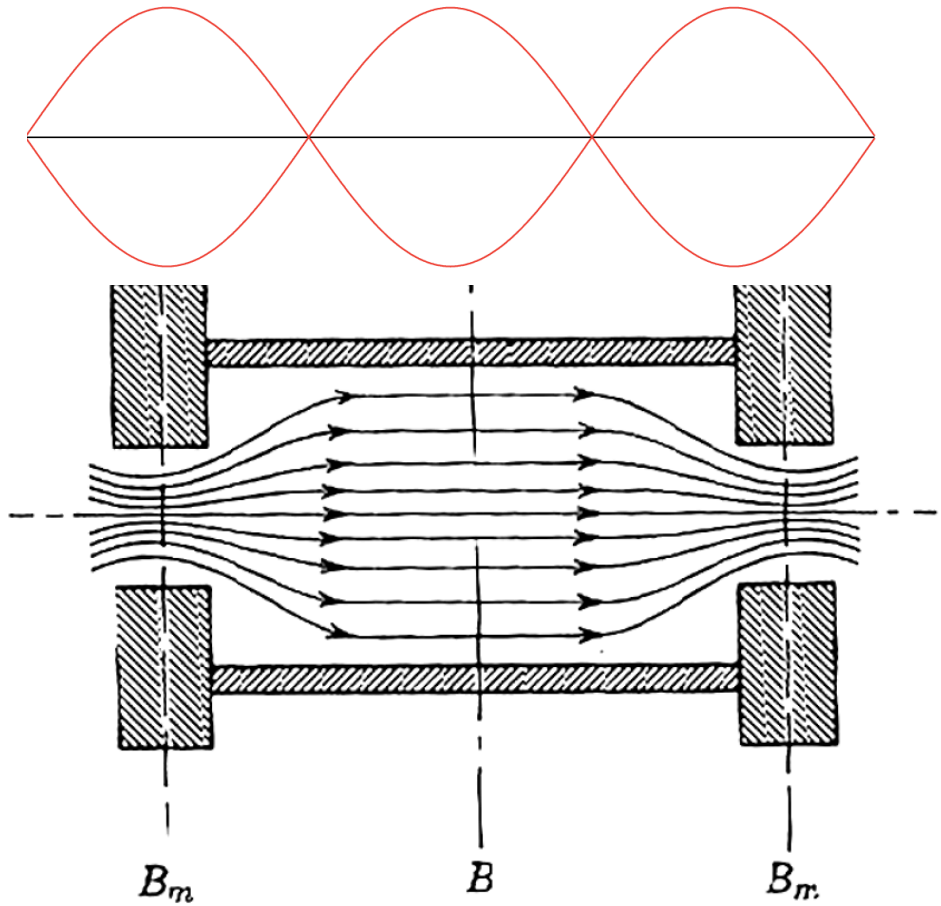
- Rectangular cavity which is long in some dimension and supports a transverse electric mode is $TE_{103}$, for example. There are 3 half-cycles in the "long" dimension, one in the "wide" dimension, and none in the transverse "height".



# A magnetic trap

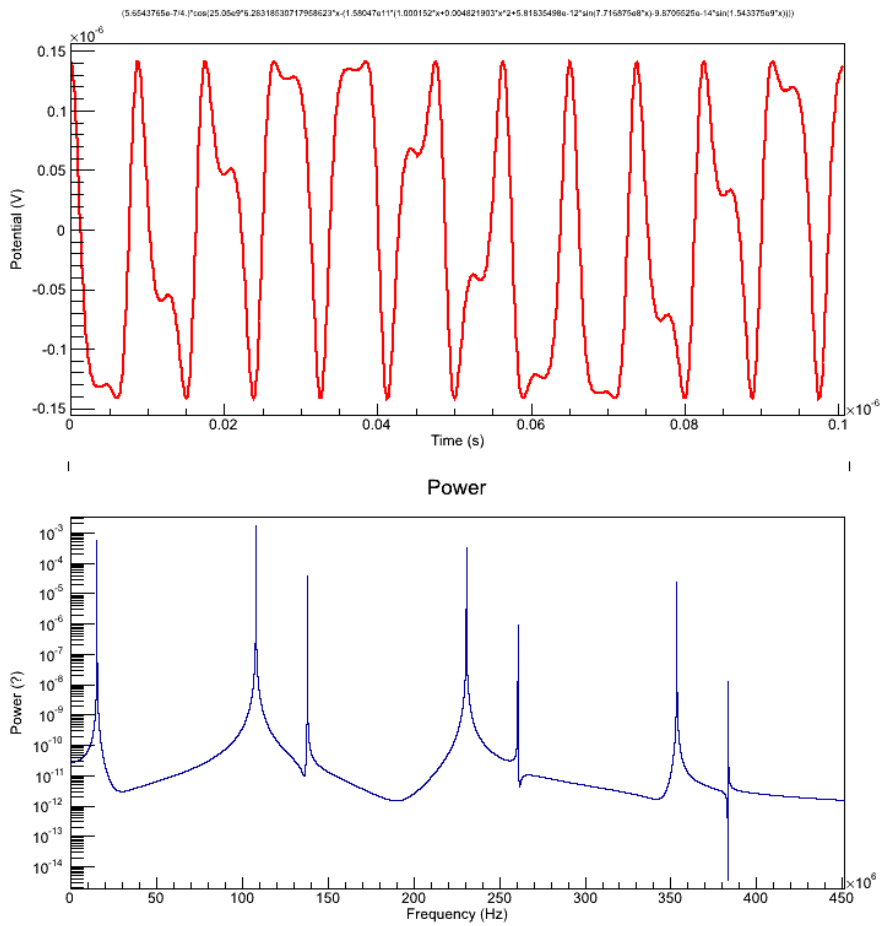
To measure ω accurately, electron must describe ~$10^6$ orbits. Total distance is many km. Need a trap.

But now the frequency is not constant. So, ignore frequency during reflections, and treat as Ramsey s.o.f. system with bursts of radiation separated by spaces.




This can be a relatively low-field trap, 100 G, conventional coils.

# Project 8 Waveguide Prototype




FFT of simulated 100-μs-long 17.8 keV event (the upper plot shows just the first 100 ns)

The fundamental cyclotron frequency (after mixing) is ≈107 MHz

Sideband at ≈15 MHz is the trap frequency. It is actually negative (below one of the oscillator frequencies) for the conditions used in the calculation.

Also significant power in higher harmonics, these are outside of our bandwidth. The peaks at ≈135, 260... MHz are artifacts of analytical mixing calculations (*i.e.*, not capturing the true transfer function of an image reject mixer).



B. Vandevender

# Phased approach

- Use 30-GHz waveguide and NRAO receivers, detect monochromatic lines from $^{83m}$Kr.
- Move down to 2.2 GHz, repeat $^{83m}$Kr, prepare to use $^{3}$H.
- Move down to 100 MHz, 70K cavity, SQUID amplifier, measure $^{83m}$Kr.
- Make $^{3}$H measurement using $T_2$ molecule.
- If necessary, atomic $^{3}$H measurement: Magnetic Ioffe-style trap, 4 K cavity, atomic source.

# PROJECT 8

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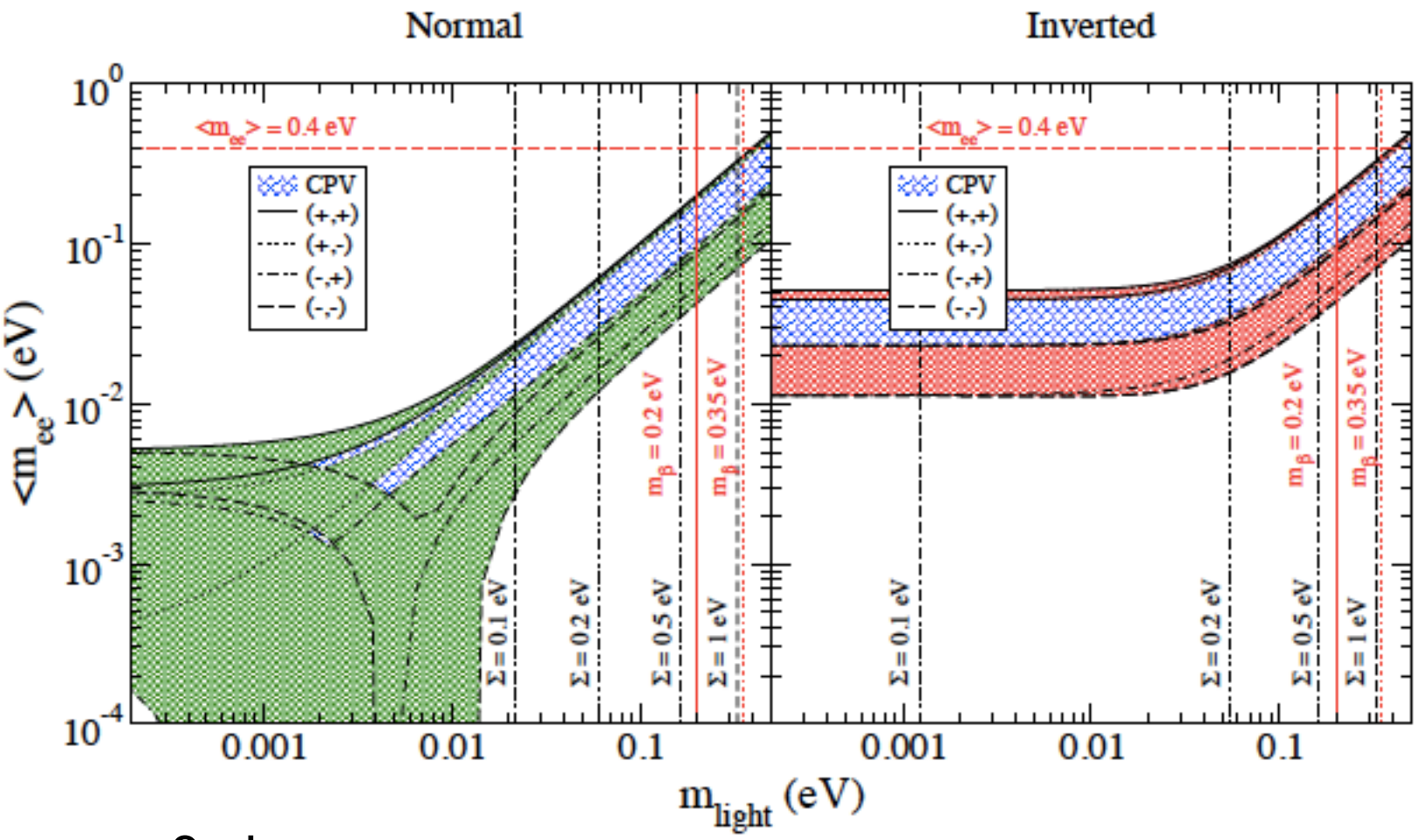
# To measure the mass

KATRIN will explore the range $600 < \Sigma m < 6900$ meV beginning ~2015. Perhaps it will be in that range, as H. Klapdor-Kleingrothaus proposes.

If it is below 600 meV, what new laboratory experiment can be devised? There are exciting new ideas around…

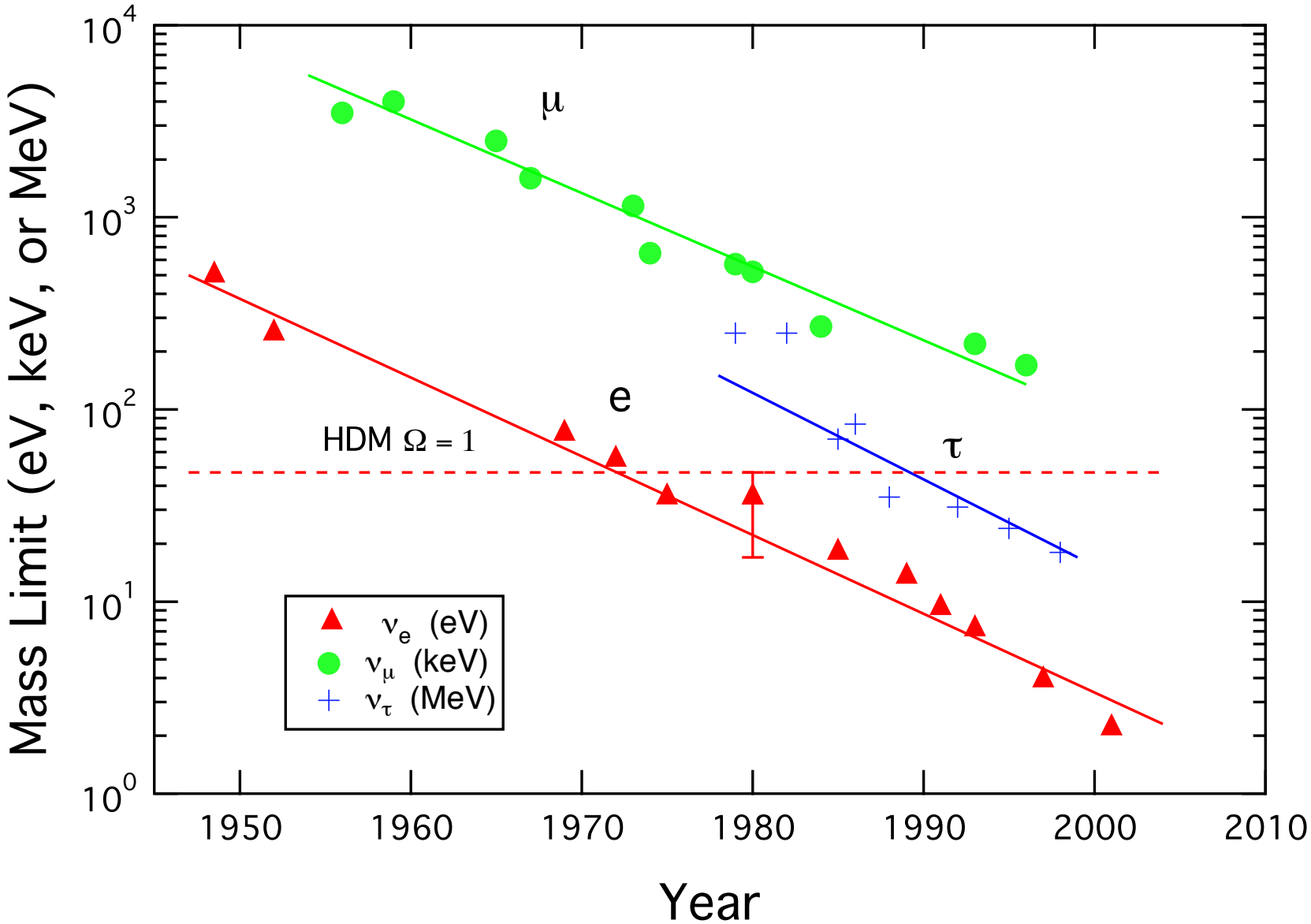
The mass of the lightest neutrino might be close to 0, but a measurement with $\Sigma m \sim 60$ meV sensitivity would be essentially definitive even if it saw no mass. The hierarchy would be established, and cosmology constrained.

# Neutrinoless Double Beta Decay




3 sigma

# History of neutrino mass searches



# The MNSP matrix as Euler rotations

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

$$U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix}$$ "Atmospheric"

$$\times \begin{pmatrix} c_{13} & 0 & e^{-i\delta} s_{13} \\ 0 & 1 & 0 \\ -e^{i\delta} s_{13} & 0 & c_{13} \end{pmatrix}$$ "Reactor"

$$\times \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$ "Solar"

$$\times \begin{pmatrix} 1 & 0 & 0 \\ 0 & e^{i\alpha} & 0 \\ 0 & 0 & e^{i(\beta+\delta)} \end{pmatrix}$$ Majorana phases

(Note, this builds in unitarity.)

$s_{13} = \sin\theta_{13}$ etc…

# The Last Order of Magnitude

KATRIN's limits: a) Source and Detector are separate, b) spectrum taken point by point.
MARE $^{187}$Re uses microcalorimeters: Source=Detector, spectrum all at once. BUT pileup limits size of each to few mg.

| | Tritium | $^{187}$Re |
|---|---|---|
| Endpoint | 18.58 keV | 2.47 keV |
| Branch to last eV | $2 \times 10^{-13}$ | $6 \times 10^{-11}$ |
| Half-life | 12.32 y | $4.32 \times 10^{10}$ y |
| Mass: 200 meV | 20 μg | 700 g |
| Mass: 20 meV | 20 mg | 700 kg |