Neutrino mass and lepton number

Hamish Robertson, P5 Meeting, FNAL Nov. 2, 2013

WHAT WE KNOW: MASS AND MIXING PARAMETERS

	Oscillation	Kinematic
$\Delta m_{21}{}^2$	$7.54^{+0.21}_{-0.21}$ x 10^{-5} eV^2	
$\lvert\Delta m_{32}{}^2\rvert$	$2.42^{+0.12}_{-0.11}$ x 10^{-3} eV^2	
Σm_i	> 0.055 eV (90% CL)	< 5.4 eV (95% CL)*
θ_{12}	$34.1^{+0.9}_{-0.9}$ deg	
θ_{23}	$39.2^{+1.8}_{-1.8}$ deg	
θ_{13}	$9.1^{+0.6}_{-0.7}$ deg	
$\sin^2\theta_{13}$	$0.025^{+.003}_{-.003}$	

Marginalized 1-D 1-σ uncertainties.

*C. Kraus et al., Eur. Phys. J. C40, 447 (2005); V. Aseev et al. PRD in press.
Other refs, see Fogli et al. 1205.5254

AMONG THE THINGS WE STILL WANT TO KNOW:

Are neutrinos their own antiparticles?

- Lepton number violation. Proton decay not found (yet). Many theories conserve only B-L.
- Matter-antimatter asymmetry of universe requires B nonconservation

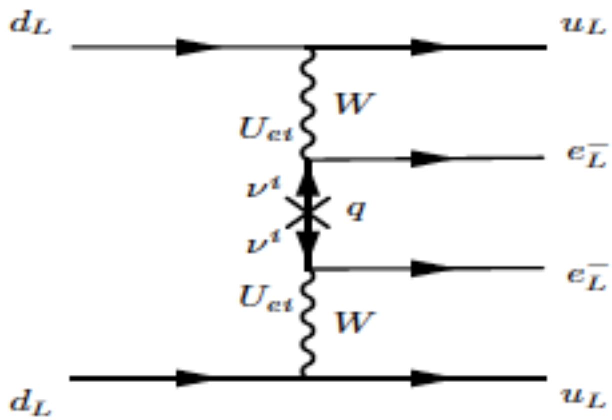
What is the mass?

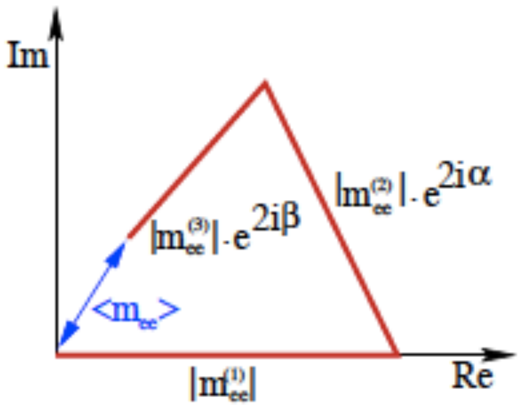
- Large-scale structure influenced by mass.
- Theories of mass still at early stage

And many other things…

NEUTRINOLESS DOUBLE BETA DECAY

Are neutrinos their own antiparticles? Is lepton number conserved?





W. Rodejohann, 1206.2560

Decay rate per unit mass:

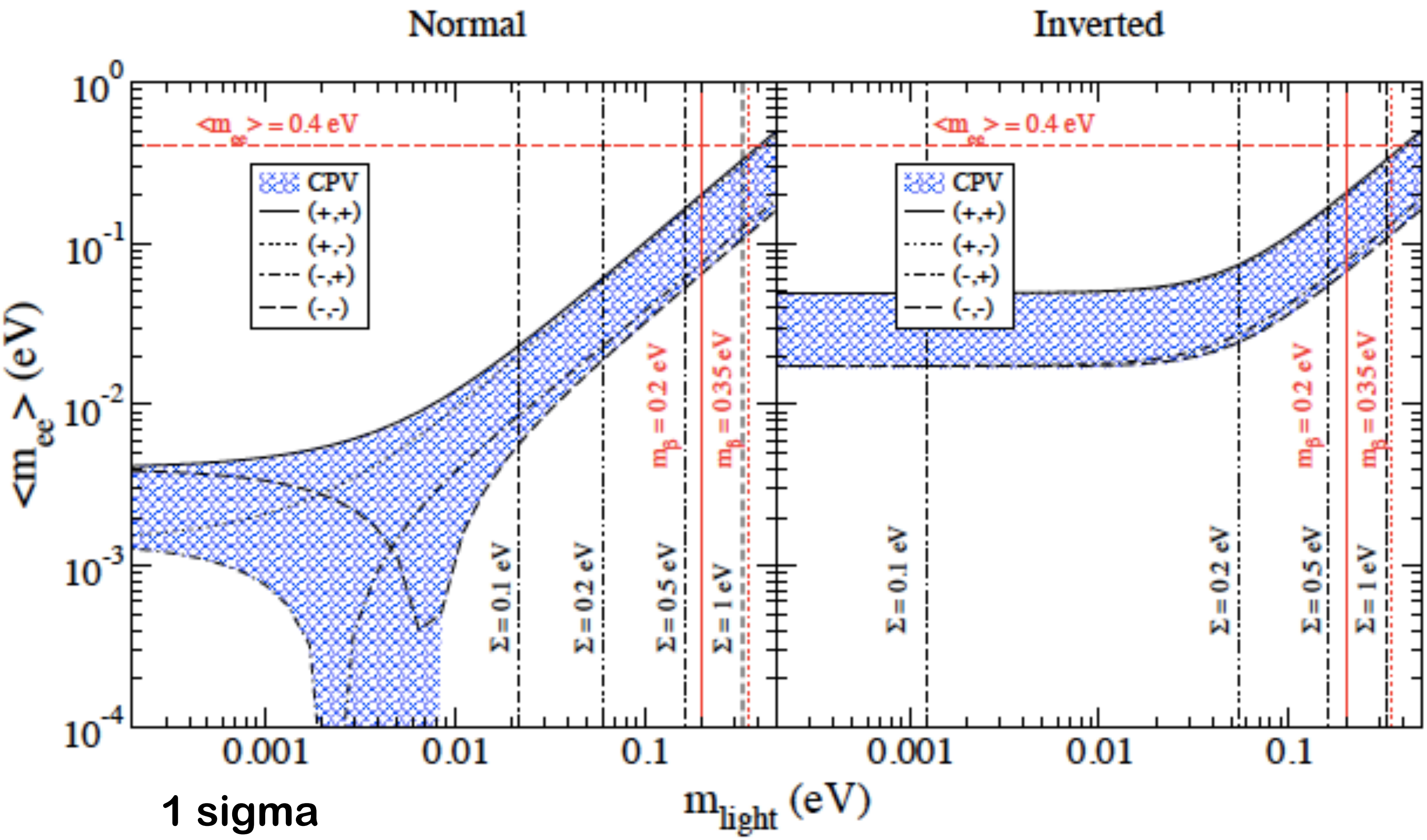
$$\lambda_{0\nu}\frac{N}{M} = \frac{\ln(2) N_A}{A m_e^2} G_{0\nu}^{(0)} g_A^4 |M_{0\nu}|^2 |\langle m_{ee}\rangle|^2$$

$$\equiv \Gamma_{0\nu}\, |M_{0\nu}|^2\, |\langle m_{ee}\rangle|^2$$

$$\langle m_{ee}\rangle = \left|U_{e1}^2 m_1 + U_{e2}^2 m_2 e^{i\alpha} + U_{e3}^2 m_3 e^{i\beta}\right|$$

NEUTRINOLESS DOUBLE BETA DECAY

Depends on m_ν but not a \`direct' measurement

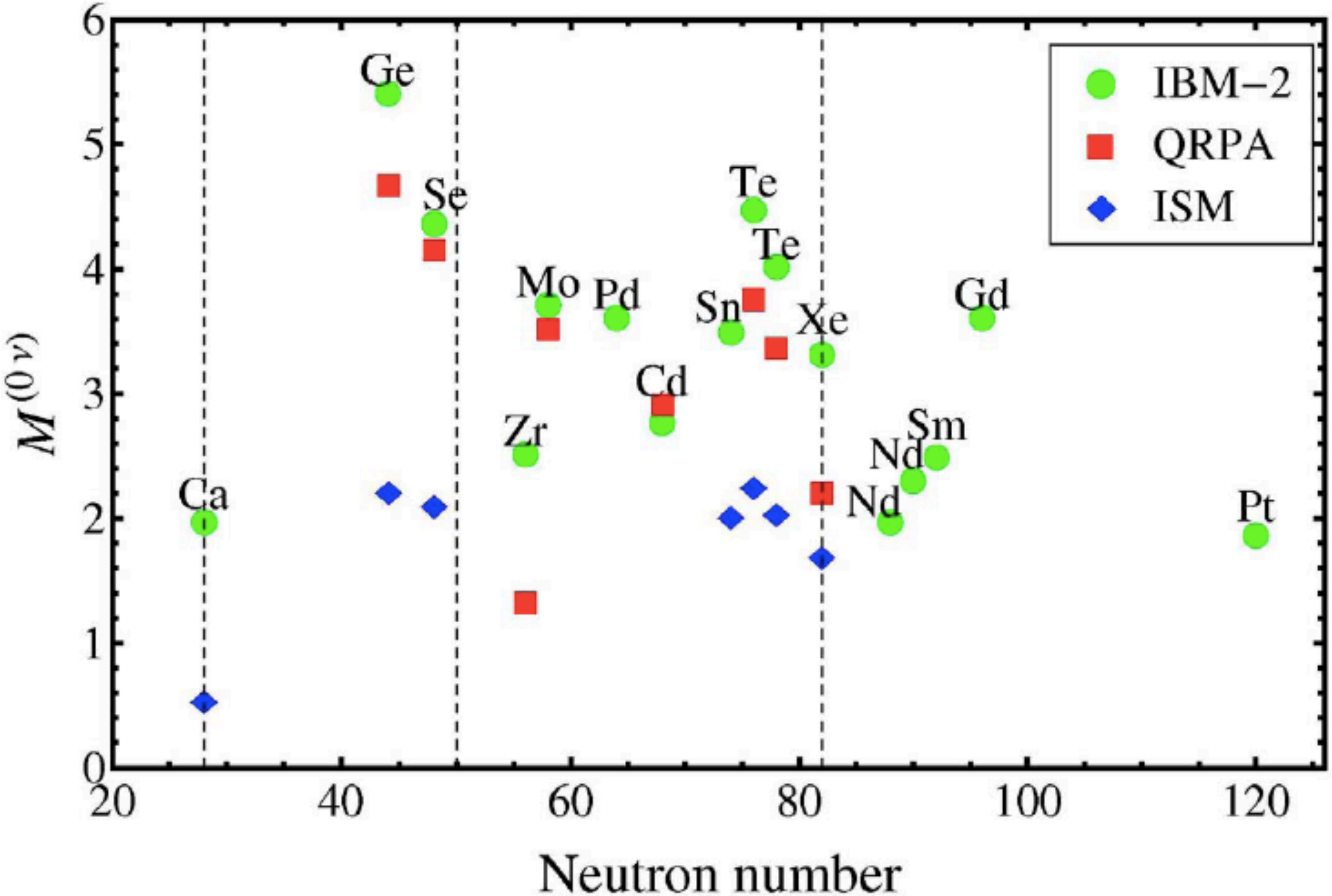


1 sigma

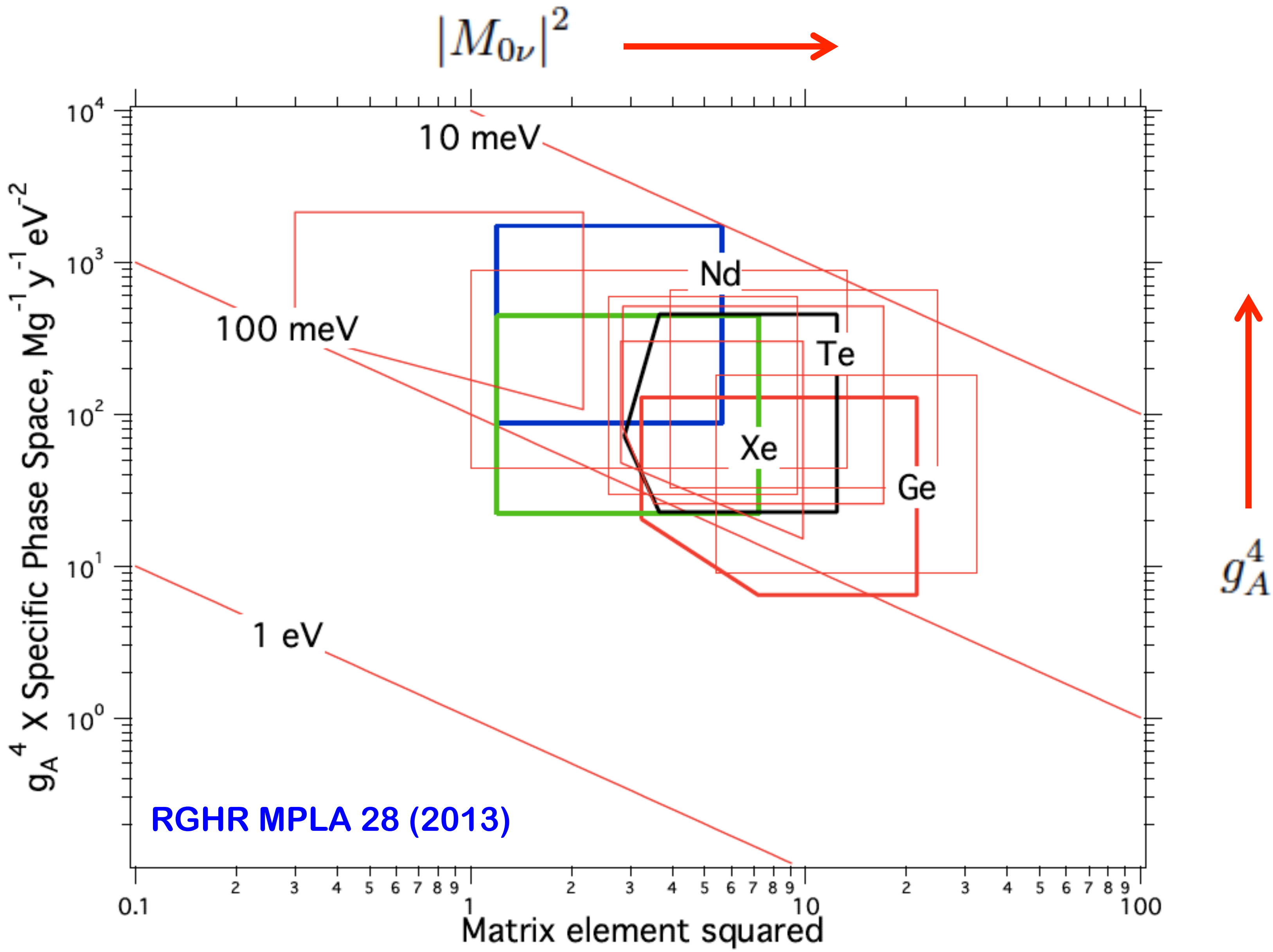
W. Rodejohann, 1206.2560

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).



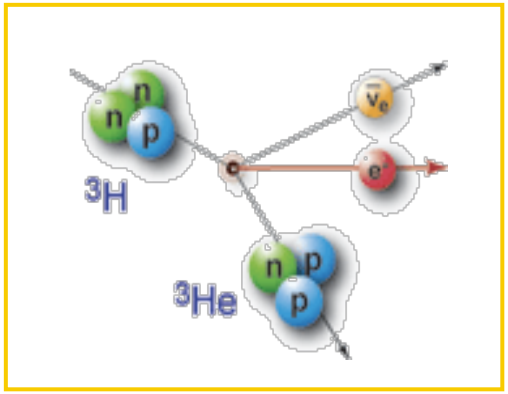
Regions contain calculated matrix elements (SM, QRPA, IBM, GCM) and range of g_A values (free nucleon down to $2\nu\beta\beta$ fits).

Decay rate ~ 1000 per tonne per year per eV^2

LARGE-SCALE EXPERIMENTS

Experiment	Isotope	Mass	Technique	Status	Location
AMoRE [164, 165]	^{100}Mo	50 kg	$CaMoO_4$ scint. bolometer crystals	Devel.	Yangyang
CANDLES [166]	^{48}Ca	0.35 kg	CaF_2 scint. crystals	Prototype	Kamioka
CARVEL [167]	^{48}Ca	1 ton	CaF_2 scint. crystals	Devel.	Solotvina
COBRA [168]	^{116}Cd	183 kg	^{enr}Cd CZT semicond. det.	Prototype	Gran Sasso
CUORE-0 [151]	^{130}Te	11 kg	TeO_2 bolometers	Constr. (2013)	Gran Sasso
CUORE [151]	^{130}Te	206 kg	TeO_2 bolometers	Constr. (2014)	Gran Sasso
DCBA [169]	^{150}Ne	20 kg	^{enr}Nd foils and tracking	Devel.	Kamioka
EXO-200 [152, 153, 154]	^{136}Xe	200 kg	Liq. ^{enr}Xe TPC/scint.	Op. (2011)	WIPP
nEXO [155]	^{136}Xe	5 t	Liq. ^{enr}Xe TPC/scint.	Proposal	SNOLAB
GERDA [150, 170]	^{76}Ge	~35 kg	^{enr}Ge semicond. det.	Op. (2011)	Gran Sasso
GSO [171]	^{160}Gd	2 t	Gd_2SiO_5:Ce crys. scint. in liq. scint.	Devel.	
KamLAND-Zen [156, 158]	^{136}Xe	400 kg	^{enr}Xe dissolved in liq. scint.	Op. (2011)	Kamioka
LZ [161]	^{136}Xe	600 kg	Two-phase ^{nat}Xe TPC/scint	Proposal	SURF
LUCIFER [172, 173]	^{82}Se	18 kg	ZnSe scint. bolometer crystals	Devel.	Gran Sasso
MAJORANA [147, 148, 149]	^{76}Ge	30 kg	^{enr}Ge semicond. det.	Constr. (2013)	SURF
MOON [174]	^{100}Mo	1 t	^{enr}Mo foils/scint.	Devel.	
SuperNEMO-Dem [162]	^{82}Se	7 kg	^{enr}Se foils/tracking	Constr. (2014)	Fréjus
SuperNEMO [162]	^{82}Se	100 kg	^{enr}Se foils/tracking	Proposal (2019)	Fréjus
NEXT [159, 160]	^{136}Xe	100 kg	gas TPC	Devel. (2014)	Canfranc
SNO+ [39, 175, 176]	^{130}Te	800 kg	Te-loaded liq. scint.	Constr. (2013)	SNOLAB

NEUTRINO MASS FROM BETA SPECTRA



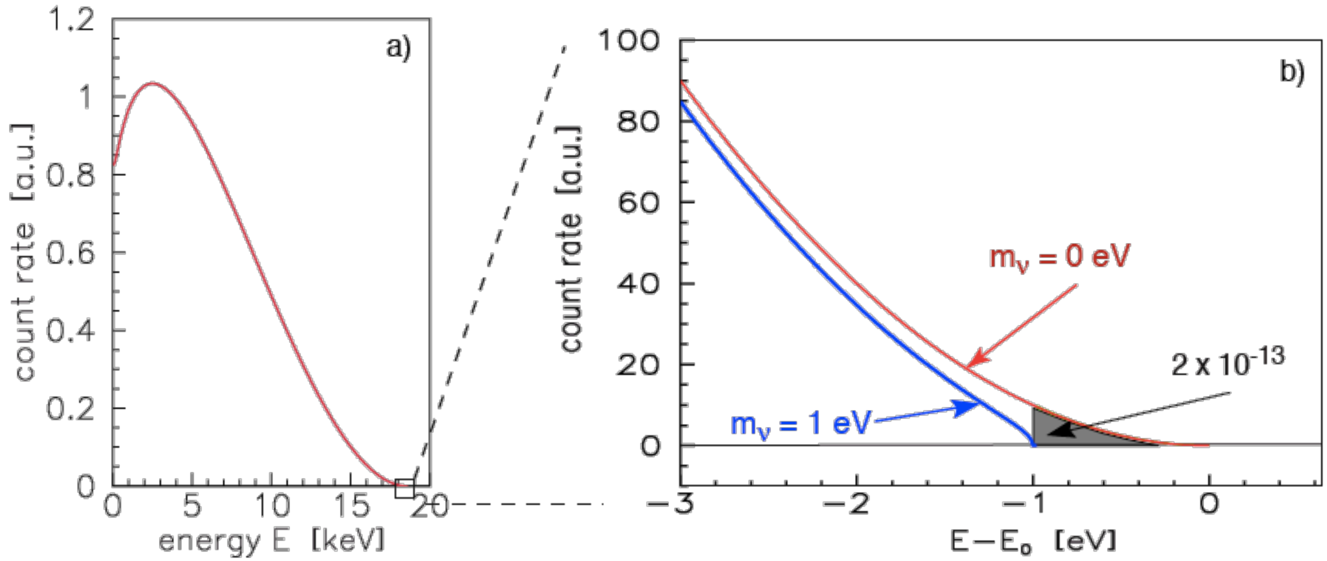
With flavor mixing:

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

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

from oscillations (Δm_{i0}^2) mass scale (m_0^2)

mixing ($|U_{ei}|^2$) neutrino masses (m_i^2)



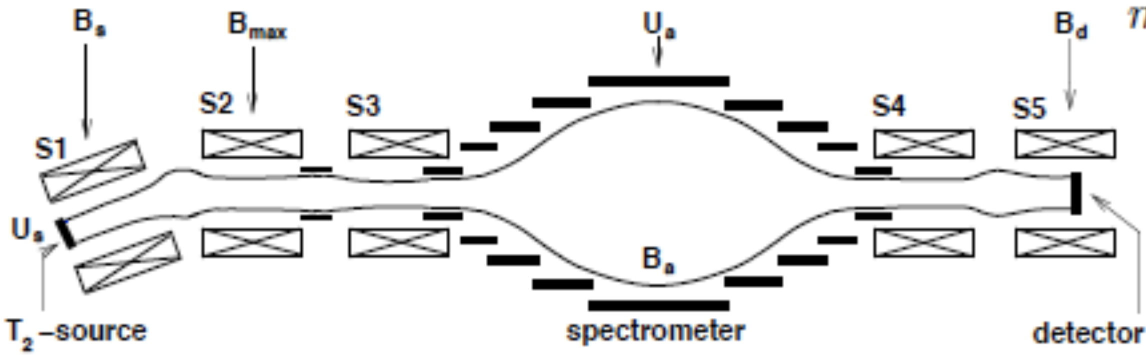
CURRENT STATUS OF DIRECT MASS MEASUREMENT

Mainz: solid T_2, MAC-E filter

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

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

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

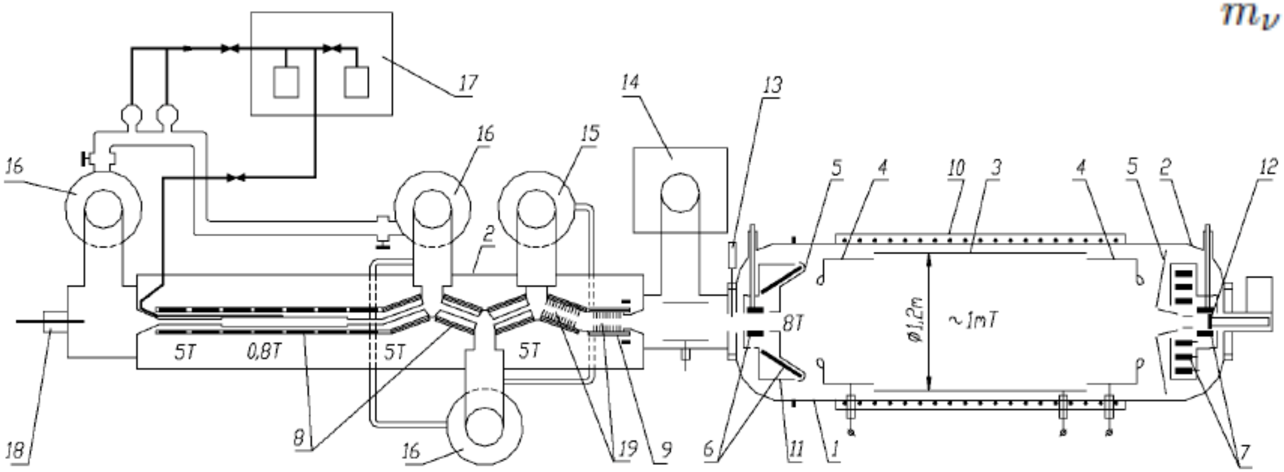


Troitsk: gaseousT_2, MAC-E filter

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

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

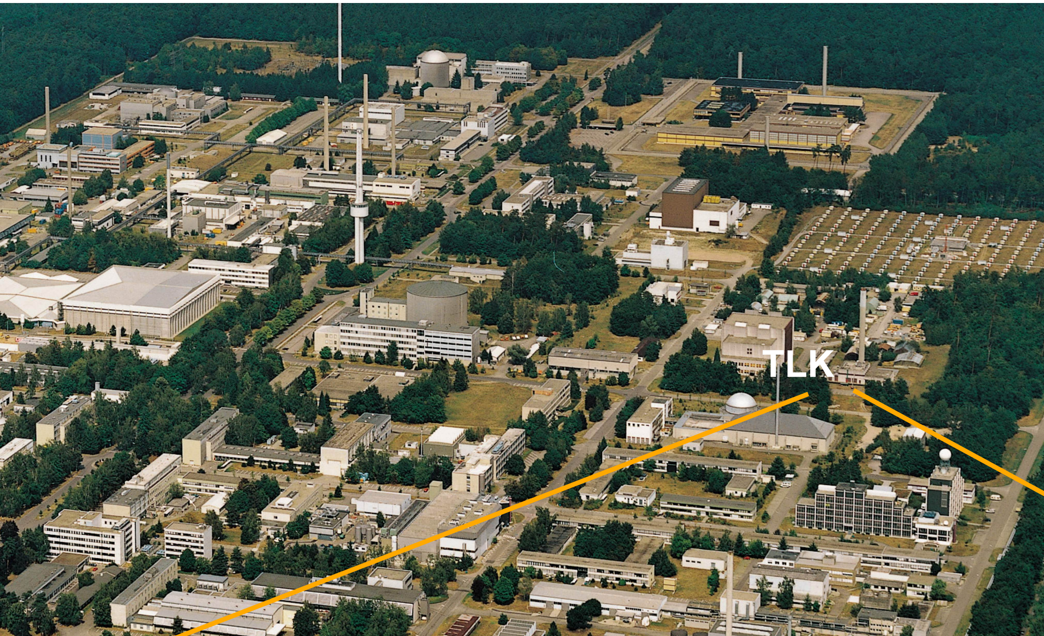
$$m_\nu < 2.05\ eV,\ 95\%\ C.L.$$



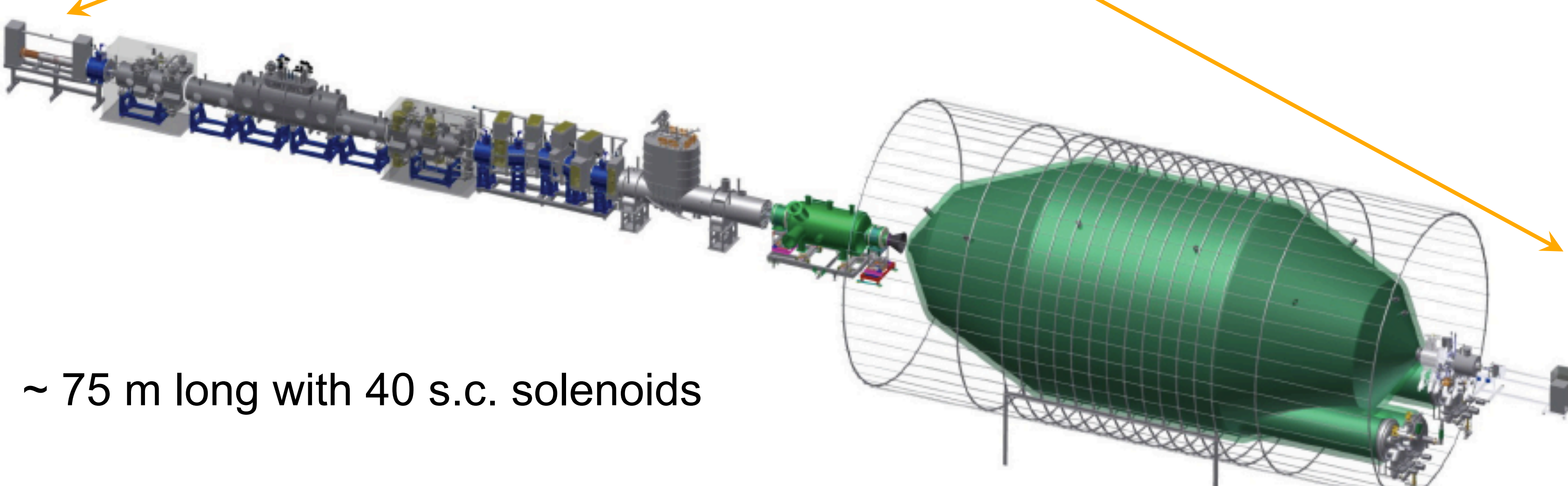
Together:…
$m_\nu < 1.8$ eV
(95% CL)

KATRIN

A kinematic method, based on β decay of tritium.
Sensitivity: 0.2 eV (90% CL)



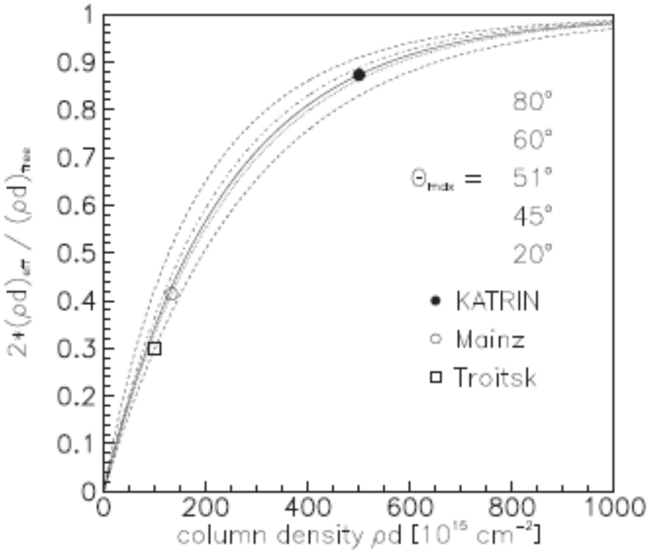
At Karlsruhe Institute of Technology
Closed T_2 cycle:
Tritium Laboratory Karlsruhe



~ 75 m long with 40 s.c. solenoids

THE LAST ORDER OF MAGNITUDE

If the mass is NOT in the 0.2 – 2 eV window, but < 0.2 eV, how can we measure it?
KATRIN may be the largest such experiment possible.

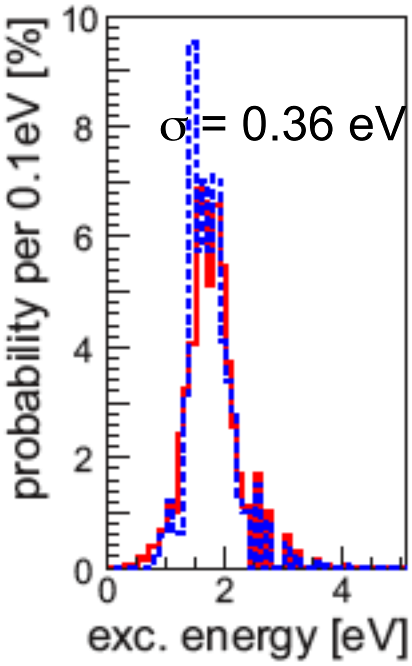


Source T_2 column density near max

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!

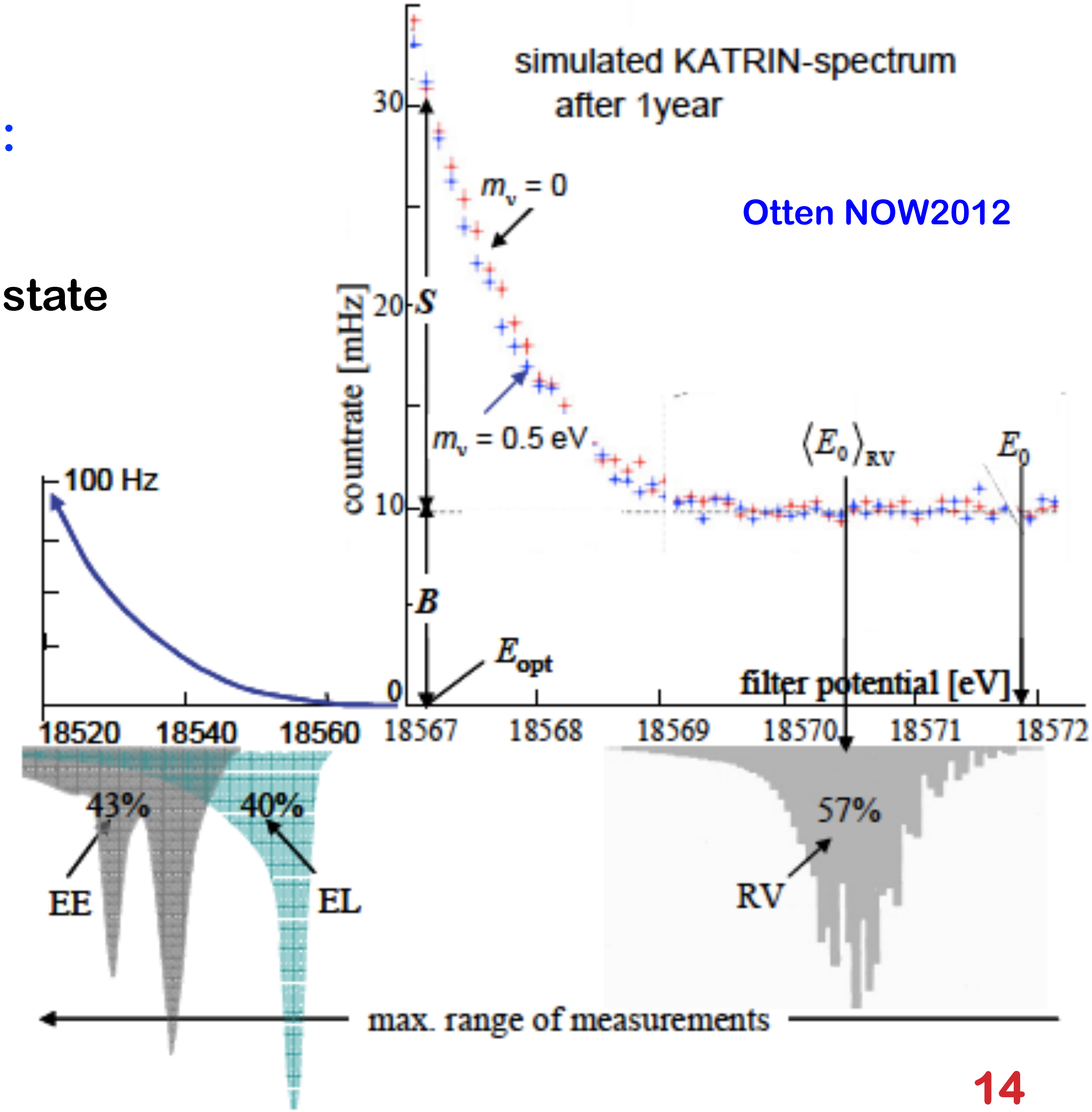


Rovibrational states of THe^+, HHe^+ molecule

FINAL-STATE SPECTRUM OF THe$^+$

β decay of molecular T_2:

The rotational-vibrational excitation of the THe+ final state broadens the effective instrumental line width



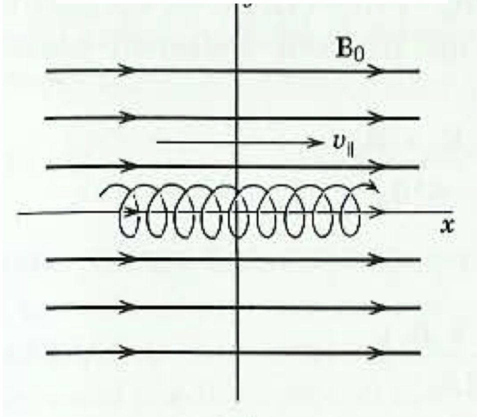
CYCLOTRON RADIATION FROM TRITIUM BETA DECAY

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

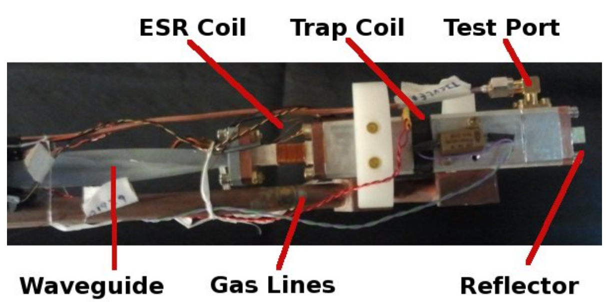
PROJECT 8

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

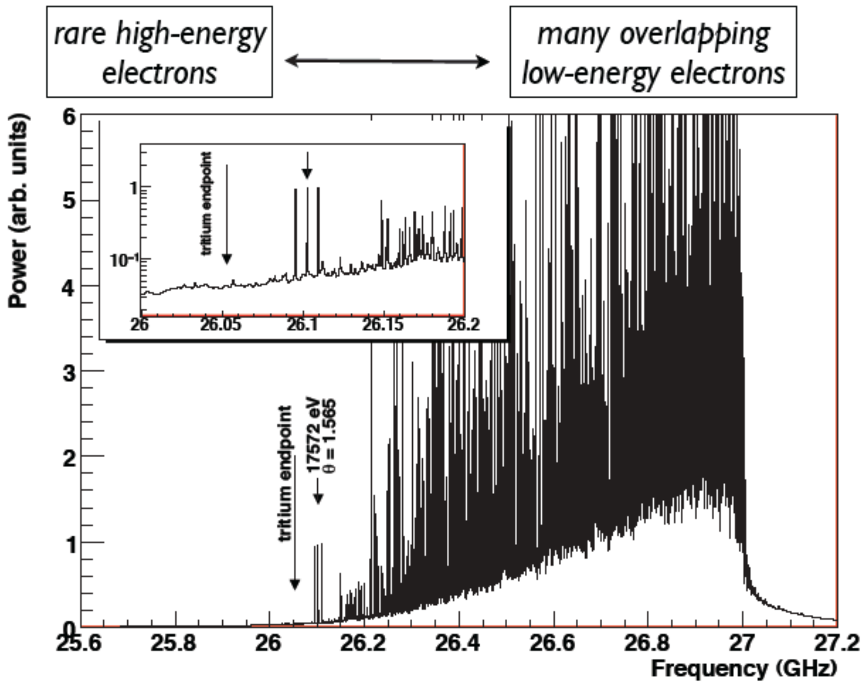
$$\omega_c = 1.758820150(44) \times 10^{11} \text{ rad/s/T}$$



Parameter	Value	Unit
Electron energy	18.6	keV
β	0.2627	
γ	1.0364	
Field	1	T
ω_c	27.009	GHz

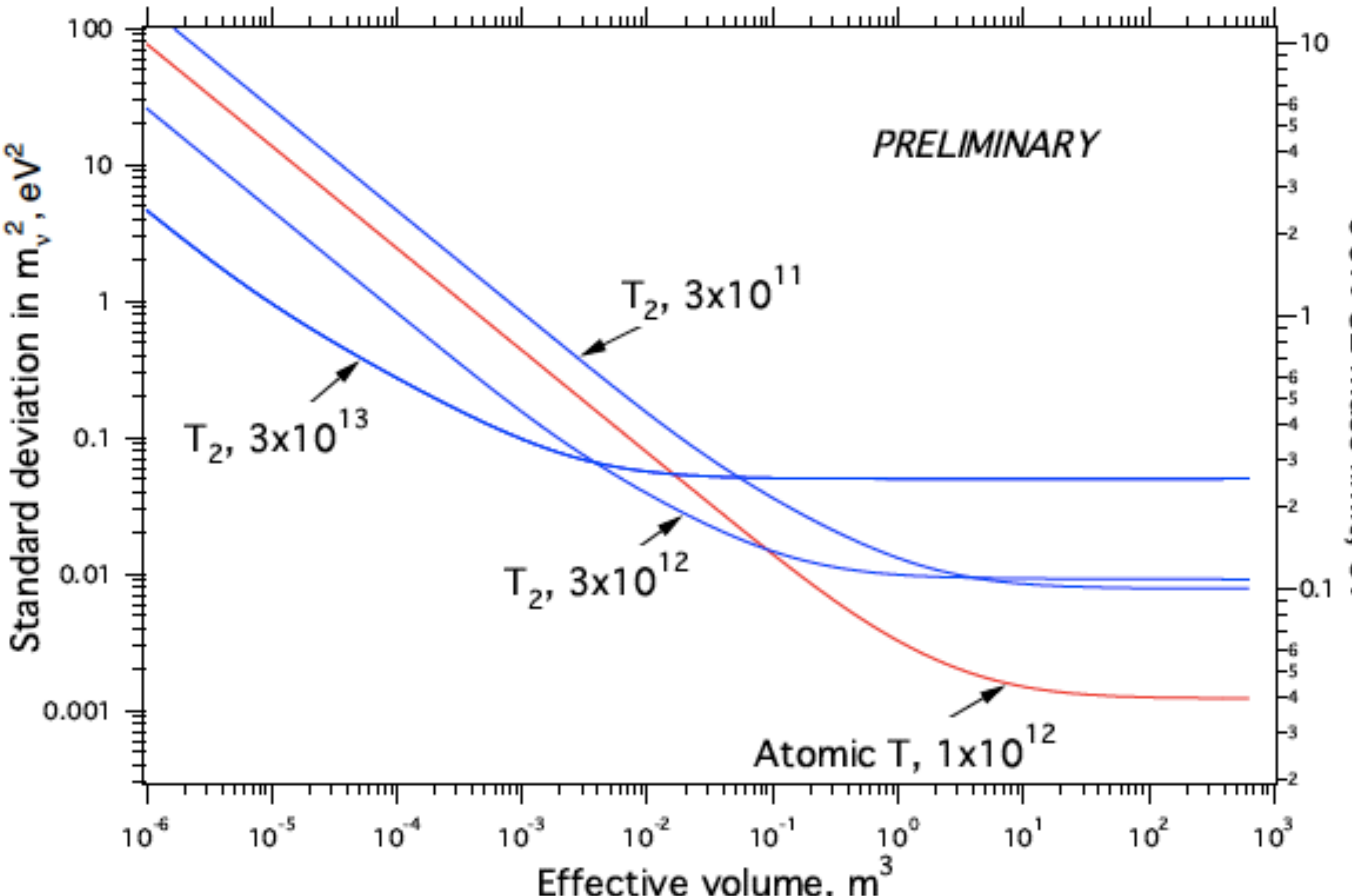


25.5-GHz waveguide cell

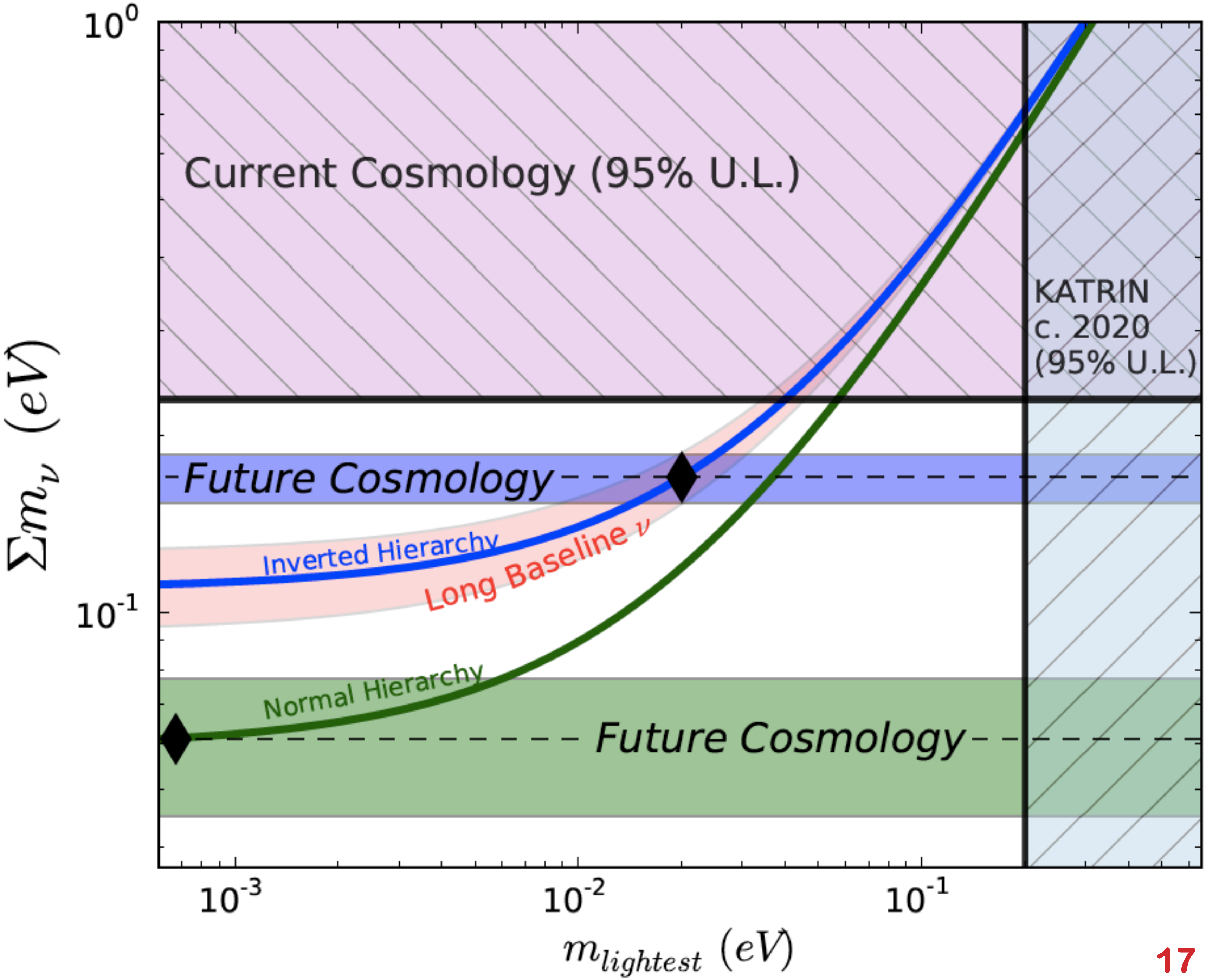


100,000 tritium decays in 30μs

PROJECT 8 SENSITIVITY VS. VOLUME

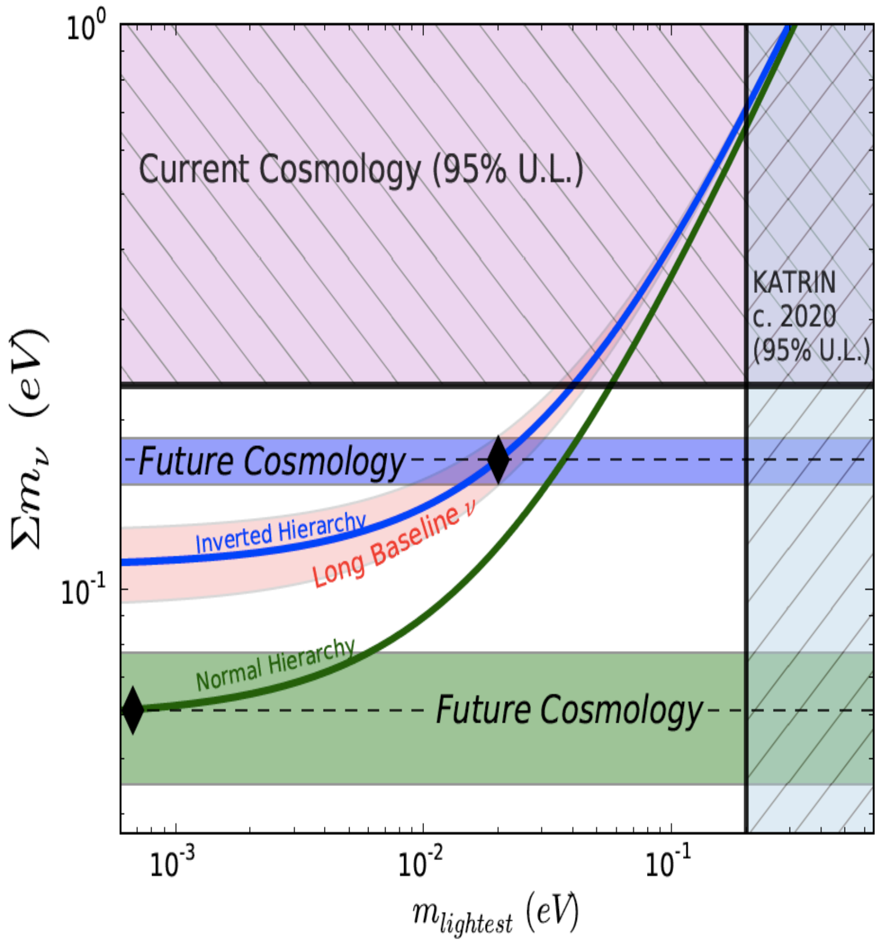


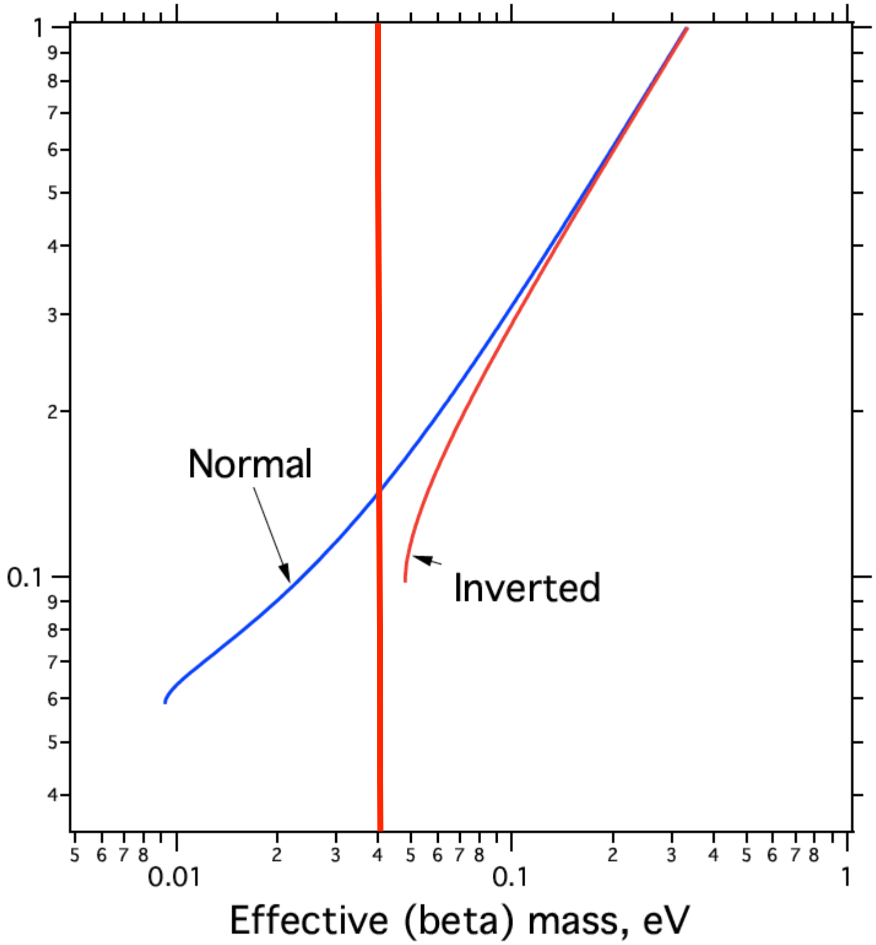
1309.7093v1



10^0
10^{-1}
10^{-3}
10^{-2}
10^{-1}
Σm_ν (eV)
$m_{lightest}$ (eV)
Current Cosmology (95% U.L.)
KATRIN
c. 2020
(95% U.L.)
Future Cosmology
Inverted Hierarchy
Long Baseline ν
Normal Hierarchy
Future Cosmology

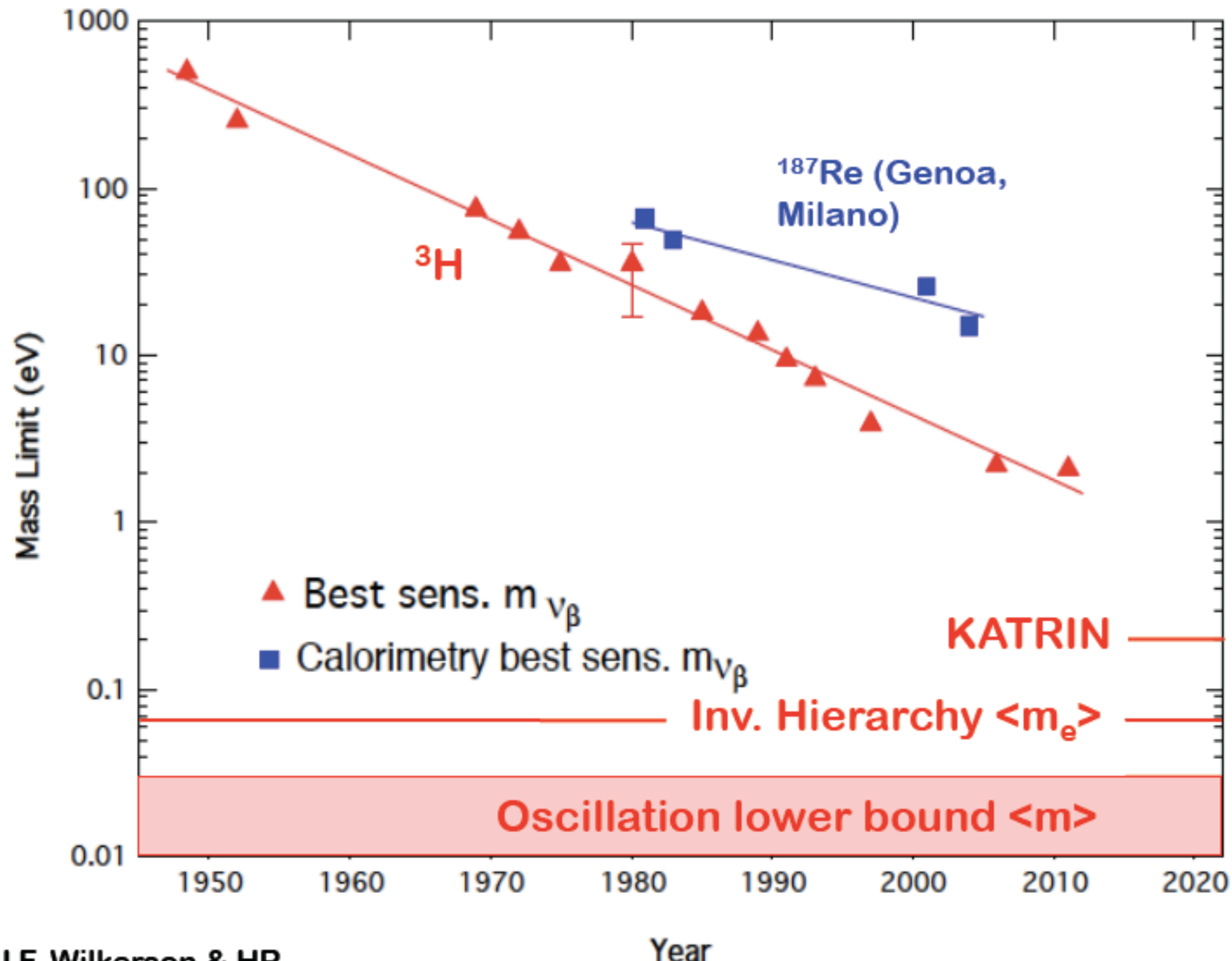
COSMOLOGY AND m_β





$$m_\beta^2 = \Sigma_i |U_{ei}|^2 m_i^2$$

NEUTRINO MASS LIMITS FROM BETA DECAY

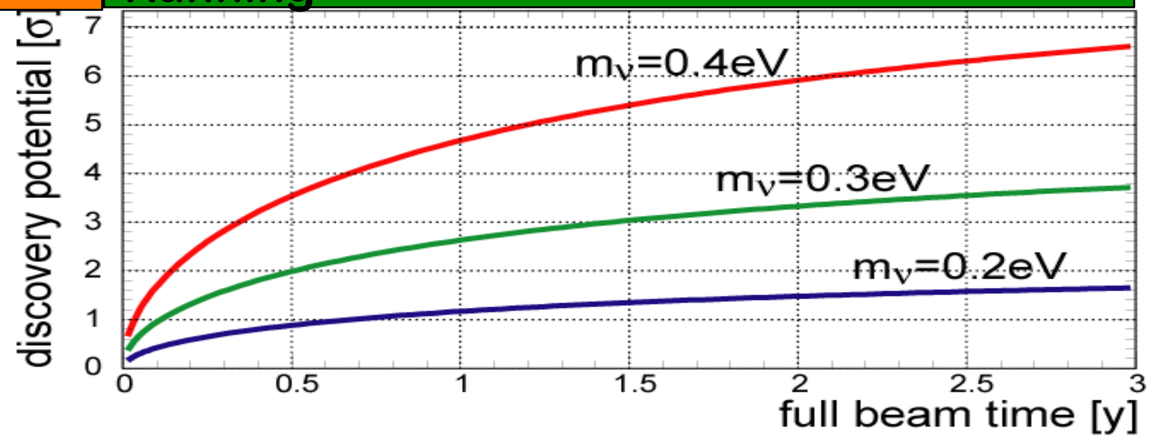


J.F. Wilkerson & HR

NEUTRINO MASS: SOME MILESTONES

Construction | Running

KATRIN:



Project 8:

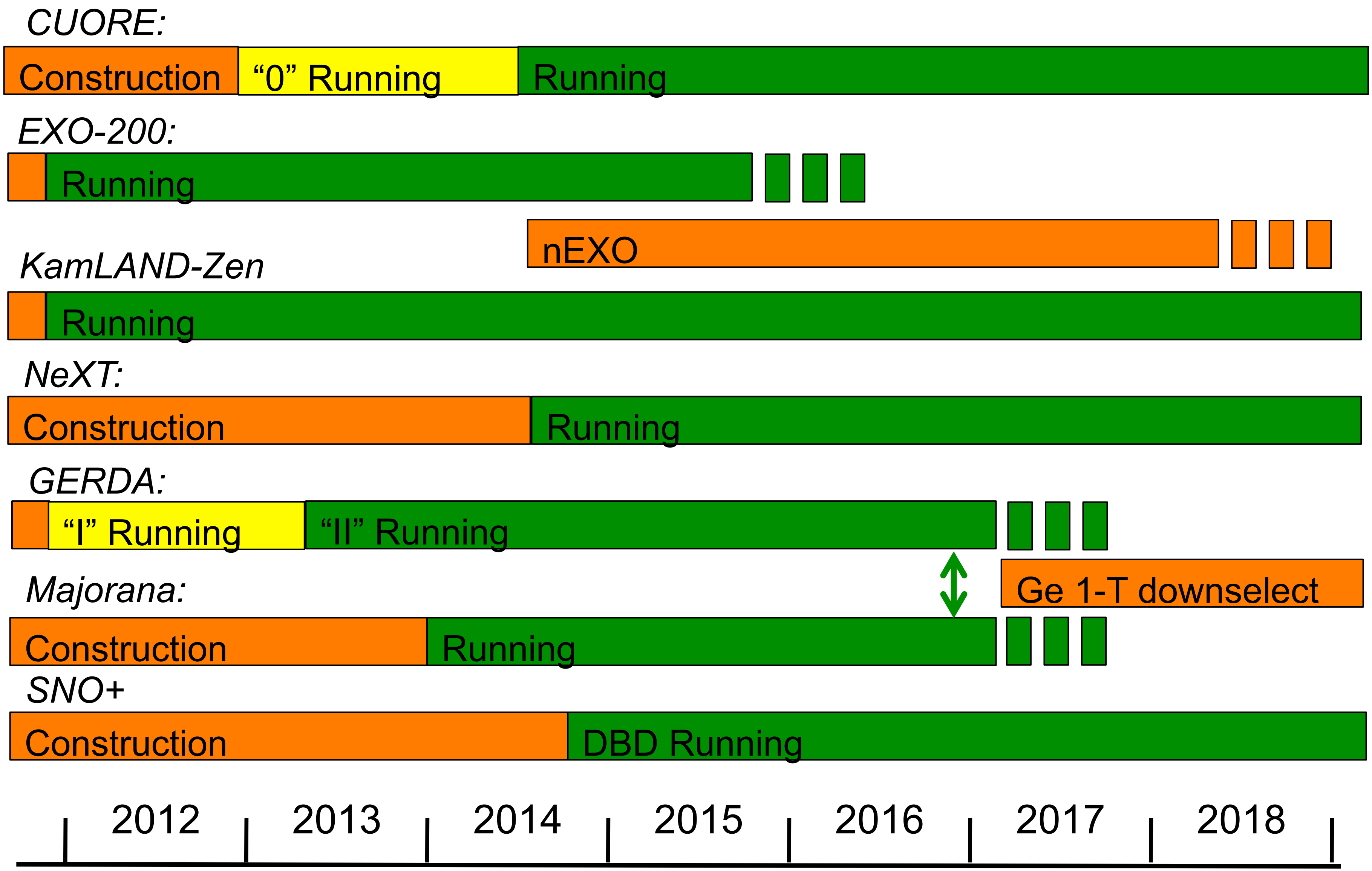
Proof concept | Prototype | Phase I

Planck:

Analysis 1 | Analysis 2

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

Double Beta Decay: some milestones



SUMMARY

Direct mass measurements are largely model independent:

- Majorana or Dirac
- No nuclear matrix elements
- No complex phases
- No cosmological degrees of freedom

One experiment in construction (KATRIN); 2015 start.

Three experiments in R&D (Project 8, ECHo, PTOLEMY)

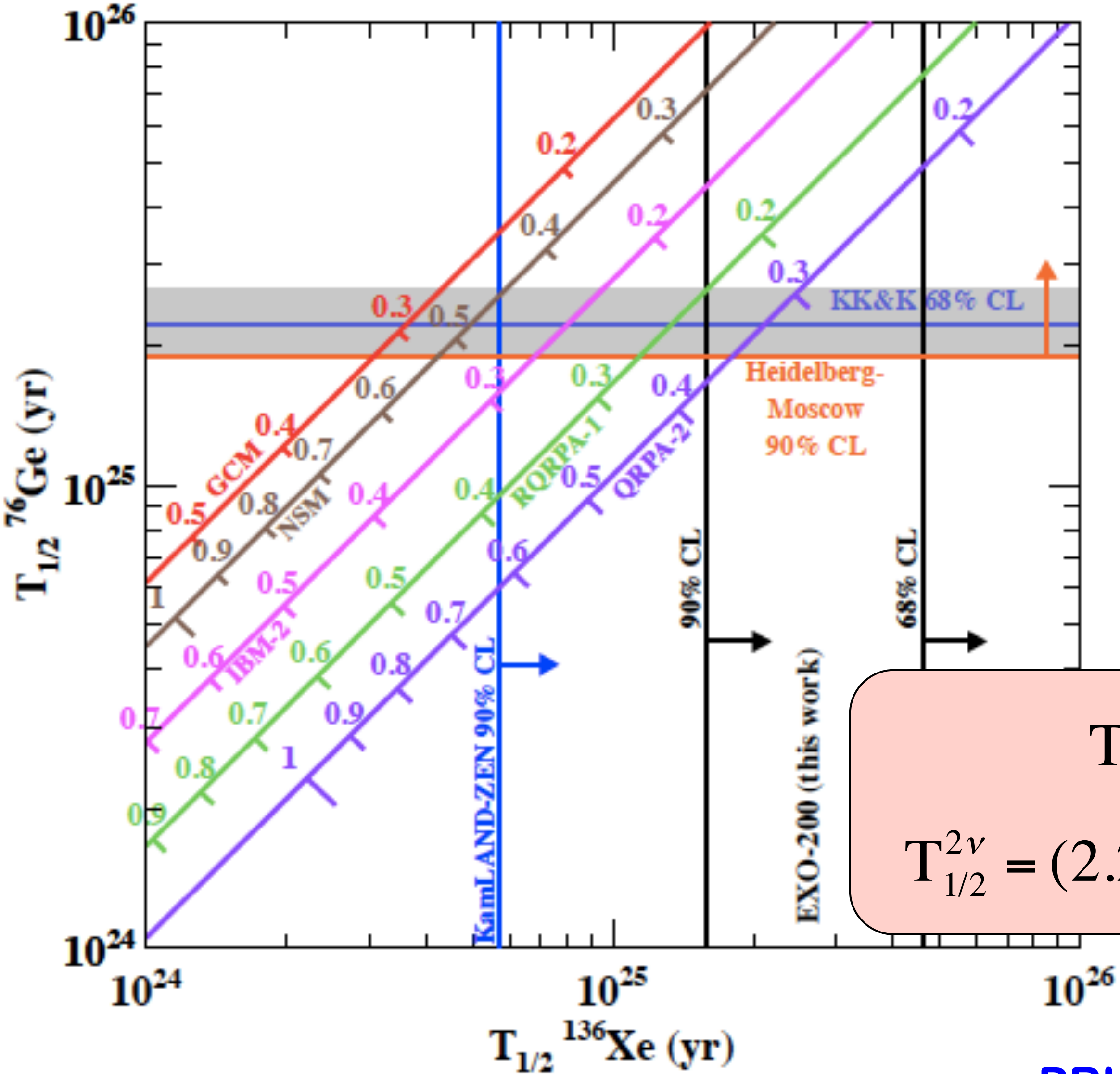
Double beta decay is only practical means to determine Majorana/Dirac nature of ν

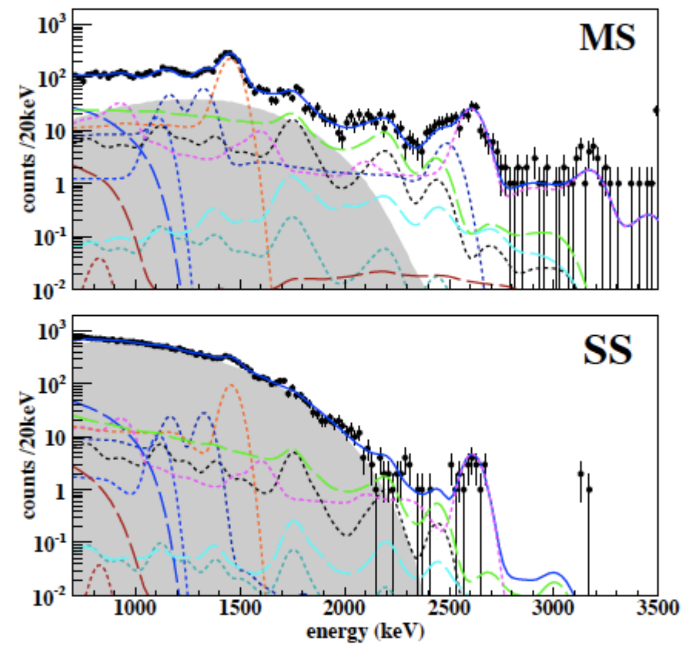
- Observation of neutrinoless mode is unambiguous evidence for L violation
- Mass determination depends on g_A, nuclear matrix elements

Tonne scale needed to reach ~30 meV level.

3 isotopes, ^{76}Ge, ^{130}Te, ^{136}Xe are candidates for scale up

EXO MEASURES ^{136}Xe 2νββ, LIMITS 0νββ

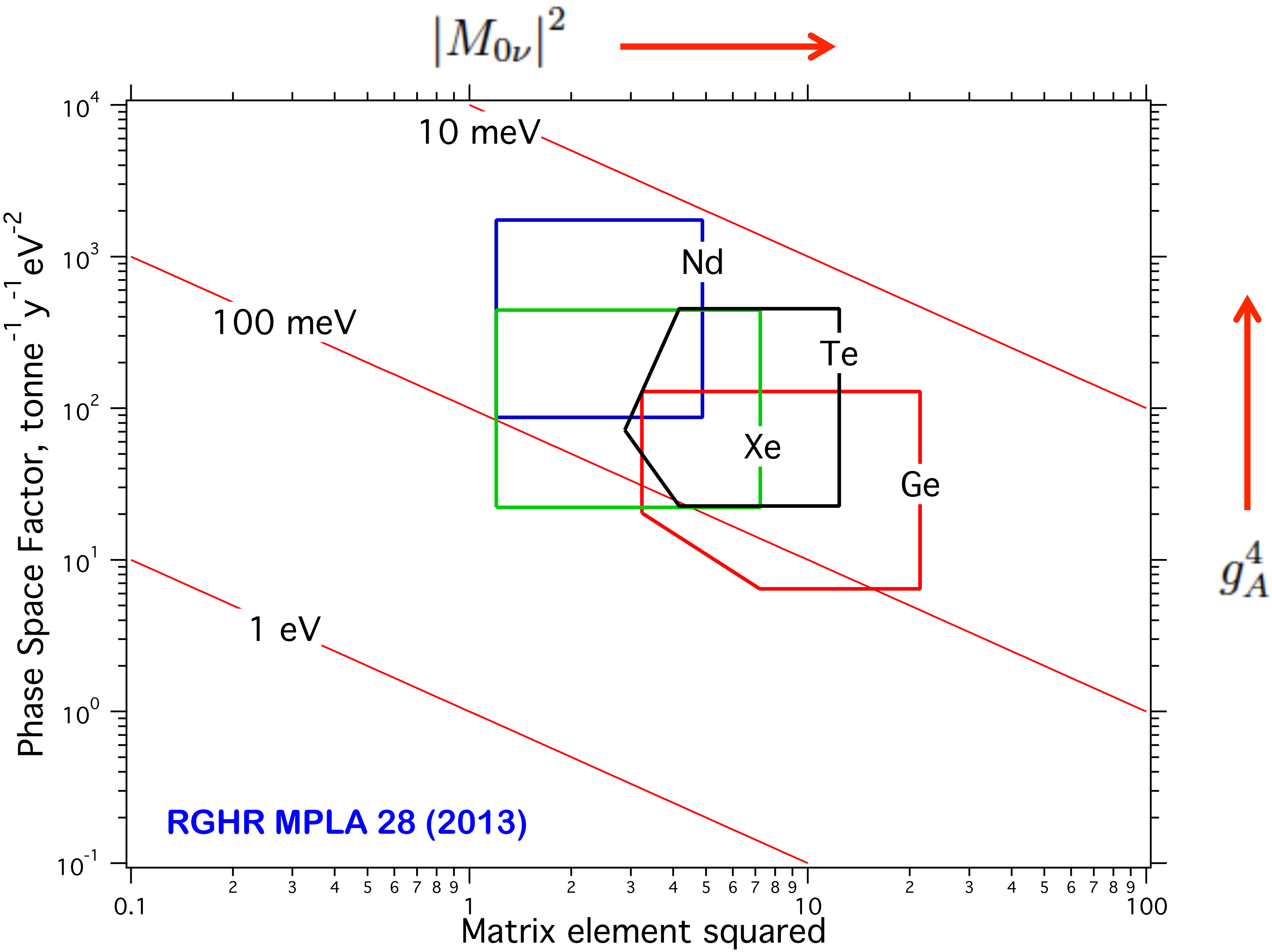




$$T_{1/2}^{0\nu} \geq 1.6\times10^{25} \text{ yr}$$

$$T_{1/2}^{2\nu} = (2.23 \pm 0.017 \pm 0.22)\times10^{21} \text{ yr}$$

PRL 109, 032505 (2012)



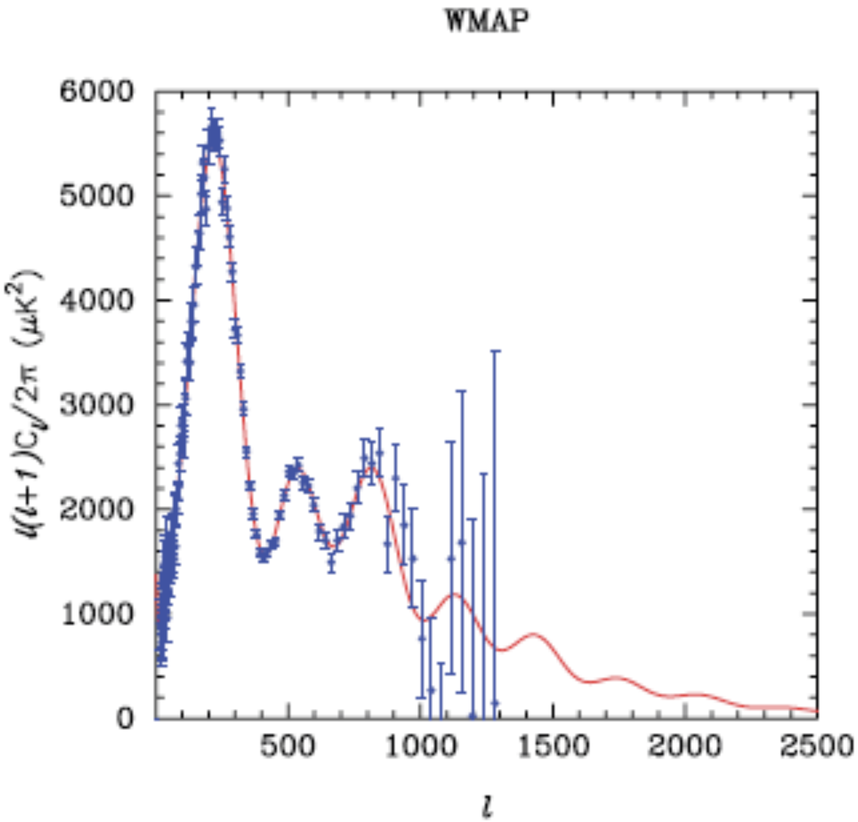
Regions contain calculated matrix elements (SM, QRPA, IBM, GCM) and range of g_A values (free nucleon down to $2\nu\beta\beta$ fits).

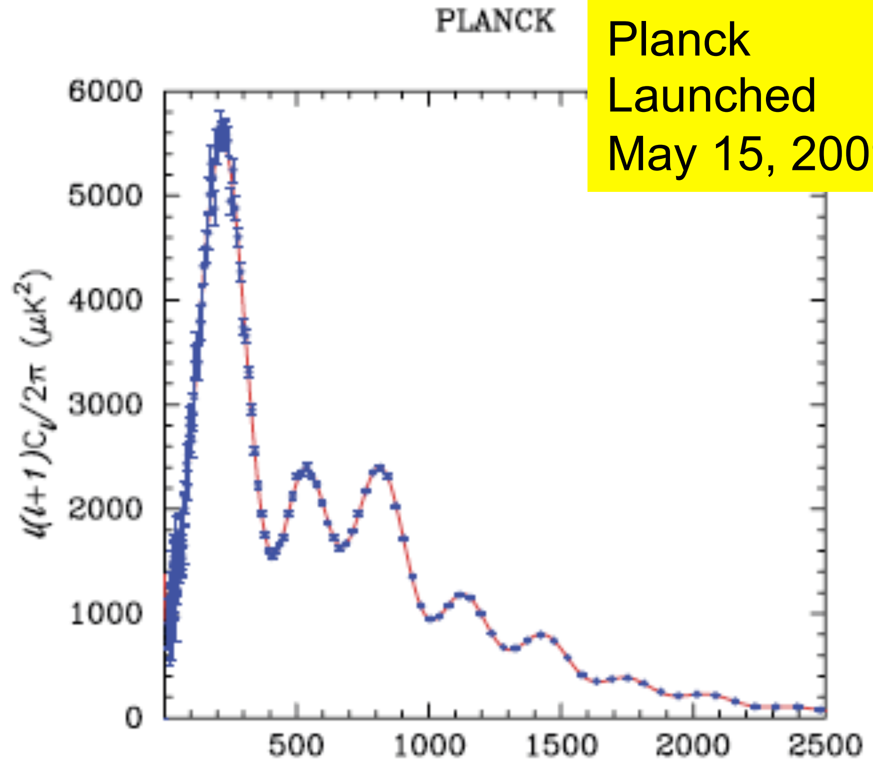
WHITE PAPERS

PTOLEMY: Development of a relic neutrino detection experiment… 1307.4738

KATRIN: Neutrino mass from the beta decay of tritium. 1307.5486

PROJECT 8: Project 8: Determining neutrino mass from tritium beta decay using a frequency-based method. 1309.7093





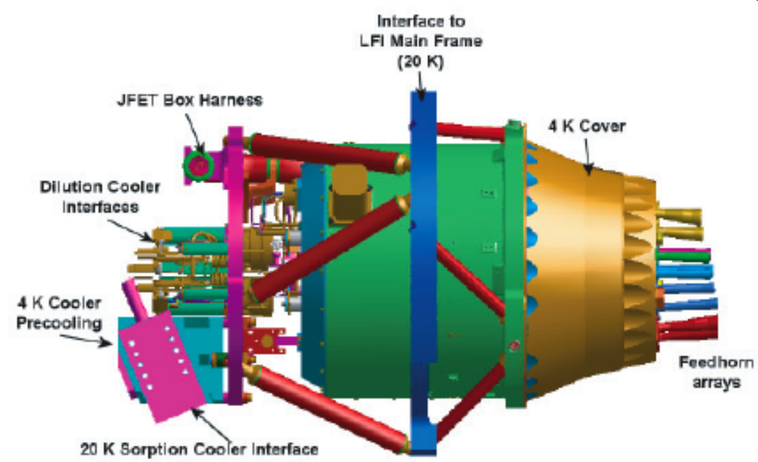
Planck
Launched
May 15, 2009

Present ΛCDM constraints on Σm_ν:

~ 0.6 eV

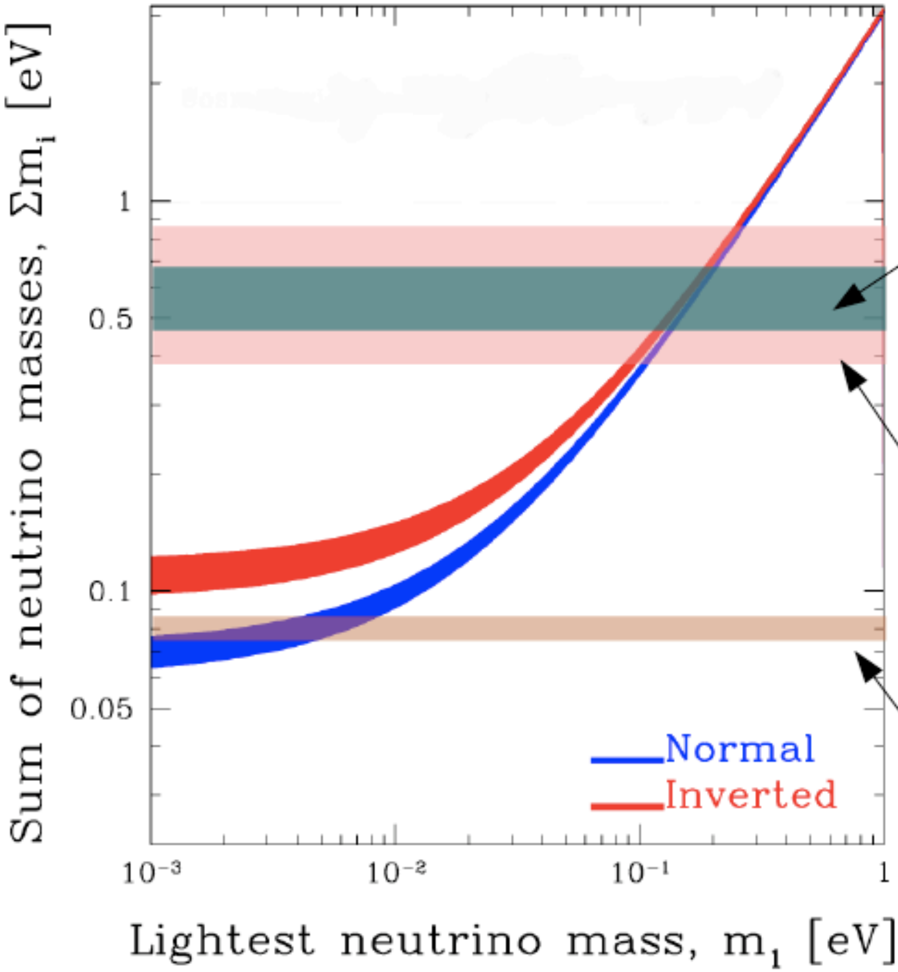
Planck sensitivity:

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



From Planck "Bluebook"

Present constraints and future sensitivities...



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 & Y[3]W 2010
Gonzalez-Garcia et al. 2010, etc.

Planck alone (1 year)

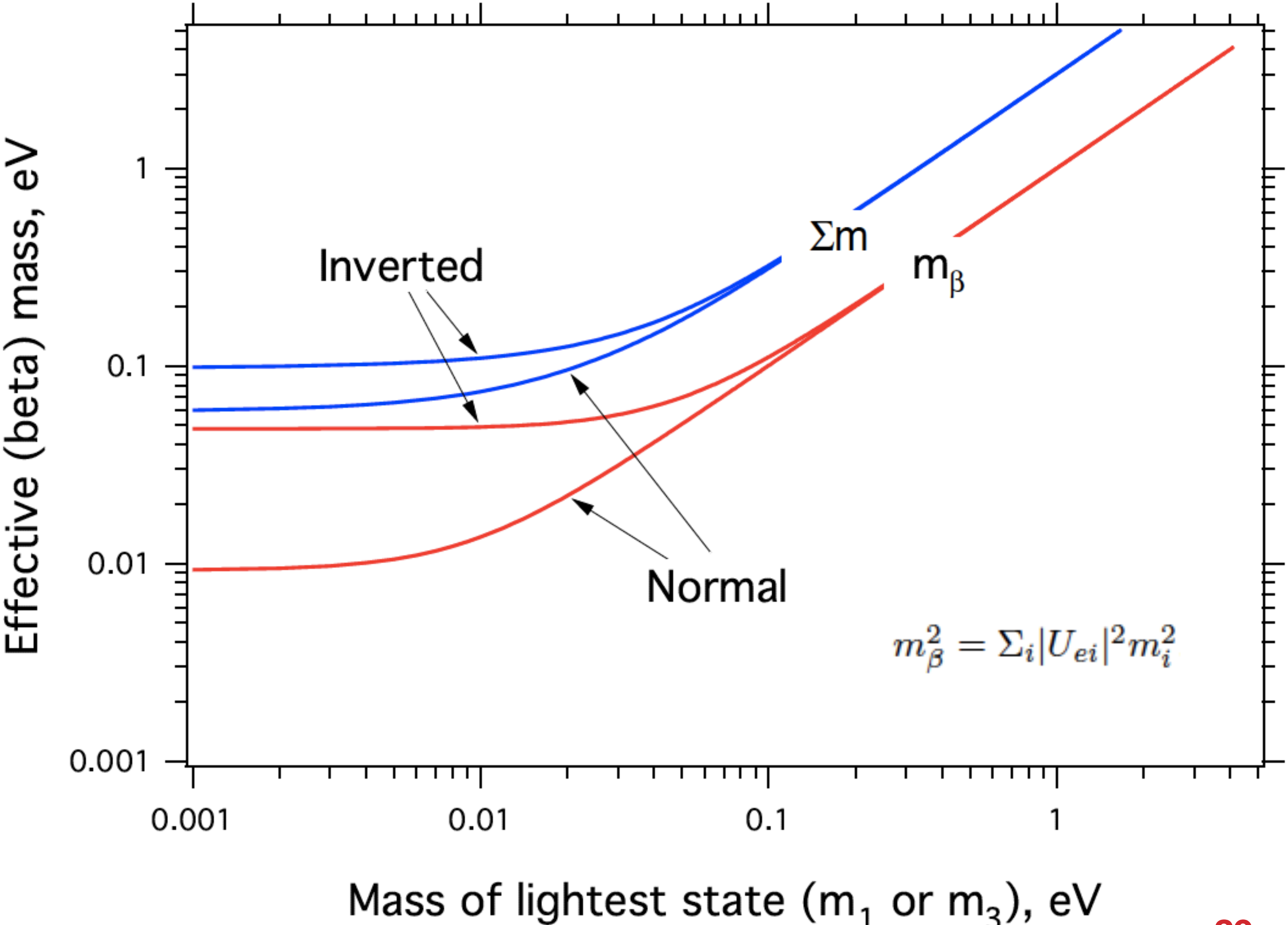
$$\sum m_\nu < 0.38 \rightarrow 0.84\,\text{eV} \quad (95\,\%\,\text{CI})$$

Perotto et al. 2006

Planck+Weak lensing (LSST)

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

Hannestad, Tu & Y[3]W 2006


Effective (beta) mass, eV
Mass of lightest state (m_1 or m_3), eV
Inverted
Normal
Σm
m_β
$m_\beta^2 = \Sigma_i |U_{ei}|^2 m_i^2$
0.001
0.01
0.1
1

FIRST PLANCK ANALYSIS (MARCH 2013)

Planck XVI

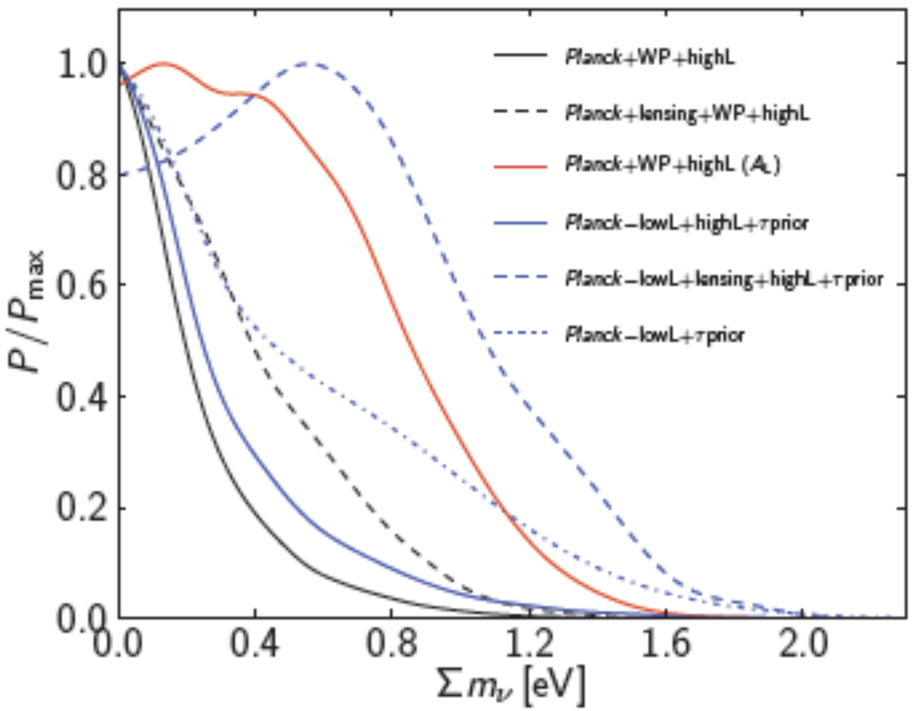
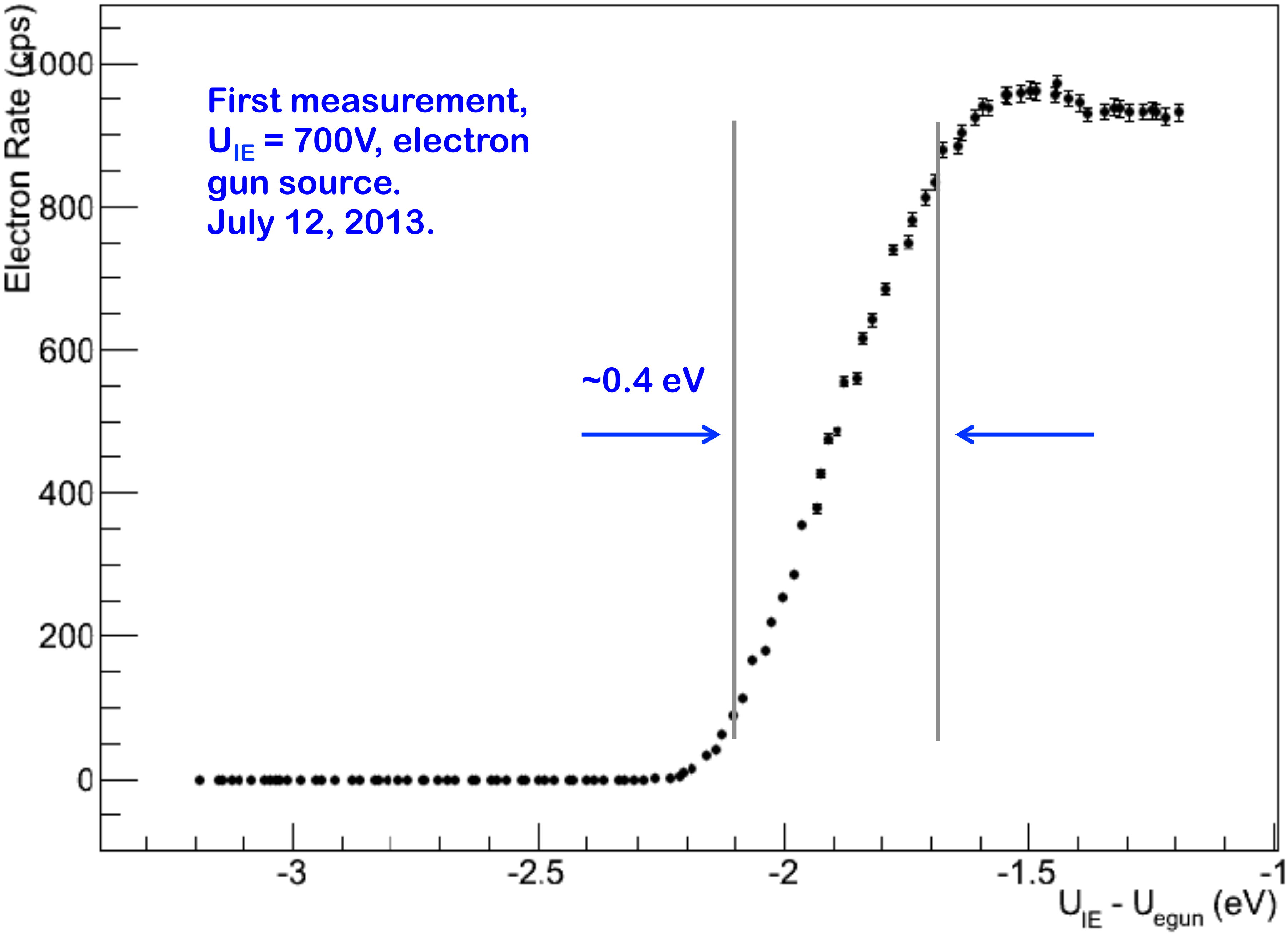


Fig. 26. Marginalized posterior distributions for $\sum m_\nu$ in flat models from CMB data. We show results for *Planck*+WP+highL without (solid black) and with (red) marginalization over A_L, showing how the posterior is significantly broadened by removing the lensing information from the temperature anisotropy power spectrum. The effect of replacing the low-ℓ temperature and (*WMAP*) polarization data with a τ prior is shown in solid blue (*Planck*−lowL+highL+τprior) and of further removing the high-ℓ data in dot-dashed blue (*Planck*−lowL+τprior). We also show the result of including the lensing likelihood with *Planck*+WP+highL (dashed black) and *Planck*−lowL+highL+τprior (dashed blue).

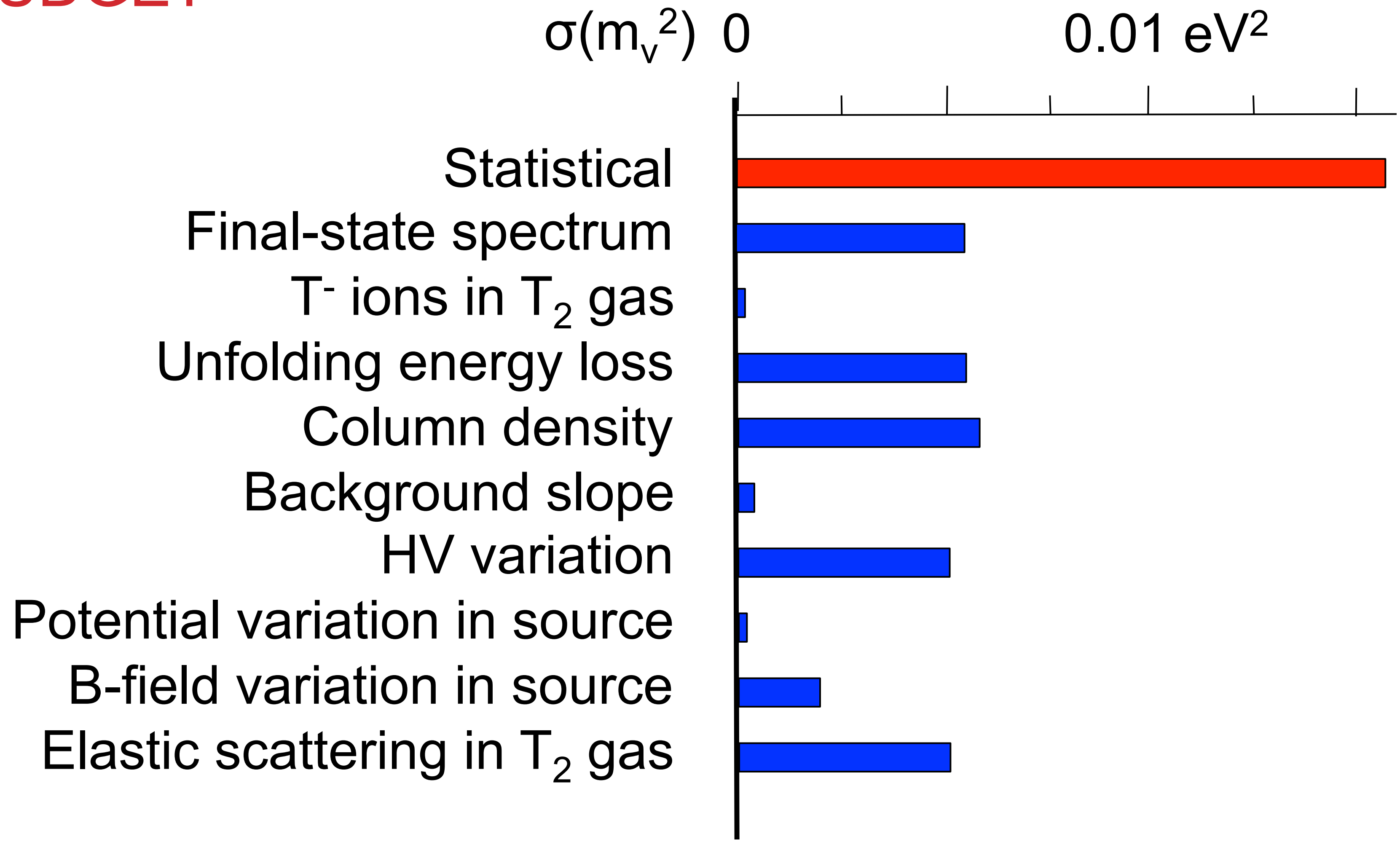
WP = WMAP Polarization data
A_L = weak lensing parameter
τ = optical depth at recombination

"…Planck lensing likelihood favours larger Σ m than the temperature power spectrum."

Transmission Function Measurement



KATRIN' S UNCERTAINTY BUDGET

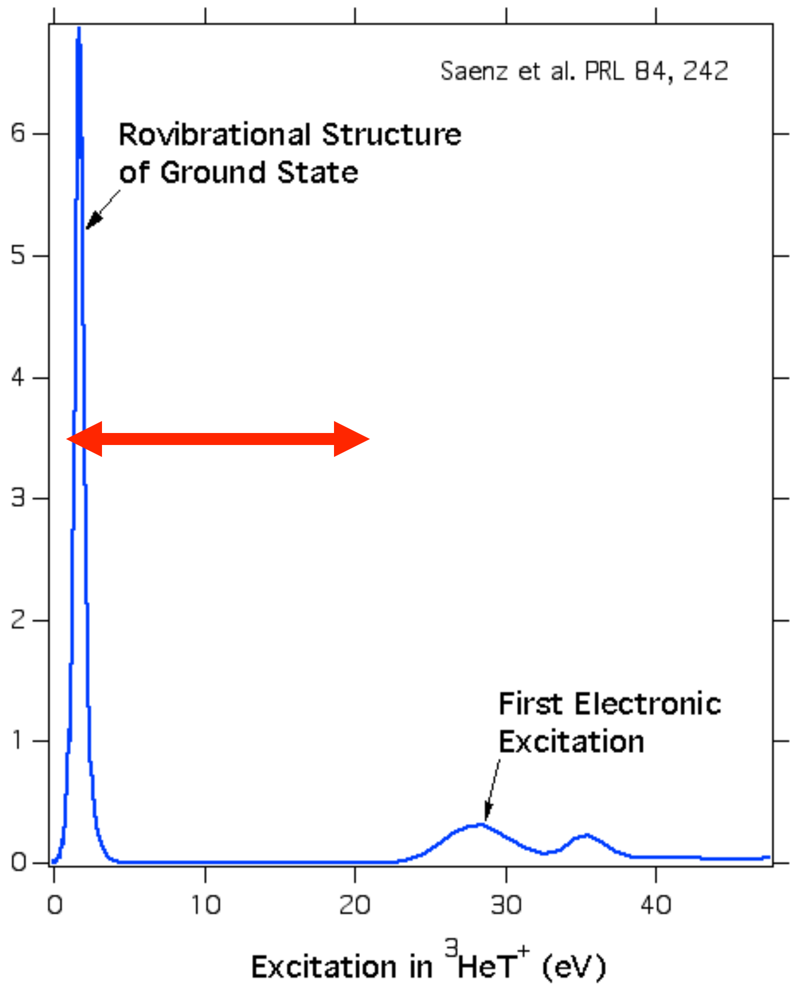


$\sigma(m_\nu^2)_{total} = 0.025$ eV^2

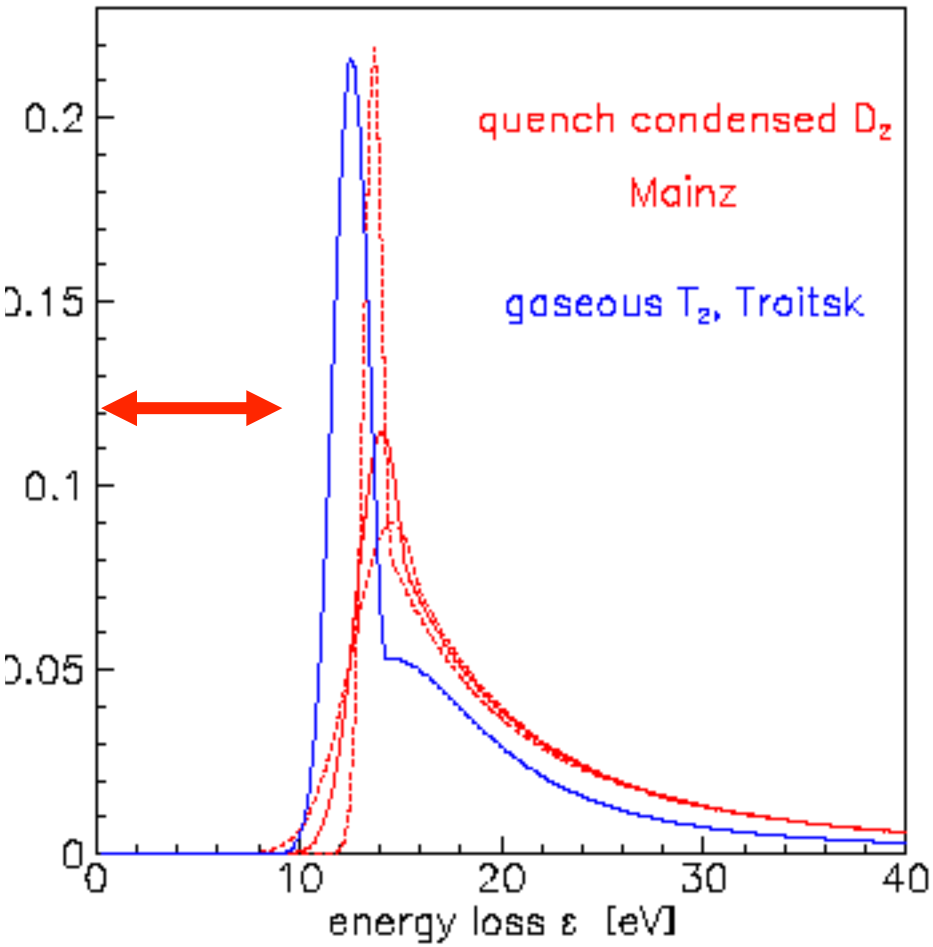
$m_\nu < 0.2$ eV (90 % CL)

A WINDOW TO WORK IN

Molecular Excitations

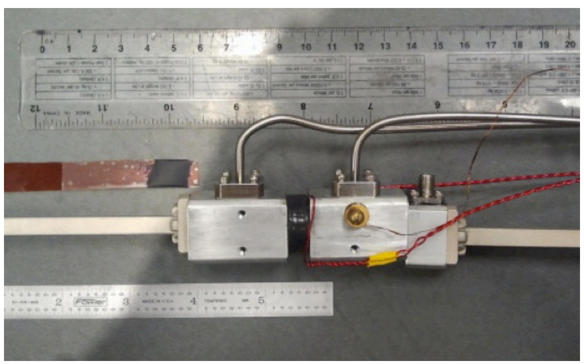


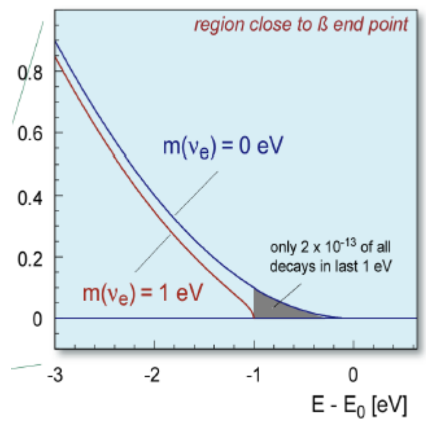
Energy loss function

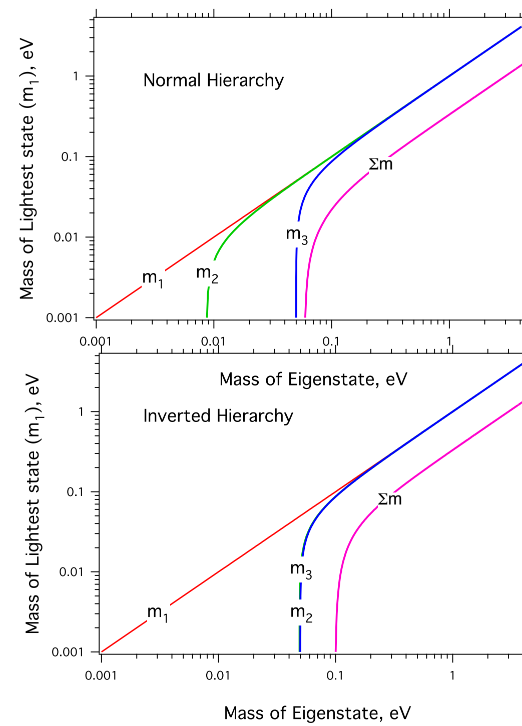


PROJECT 8: A PHASED APPROACH

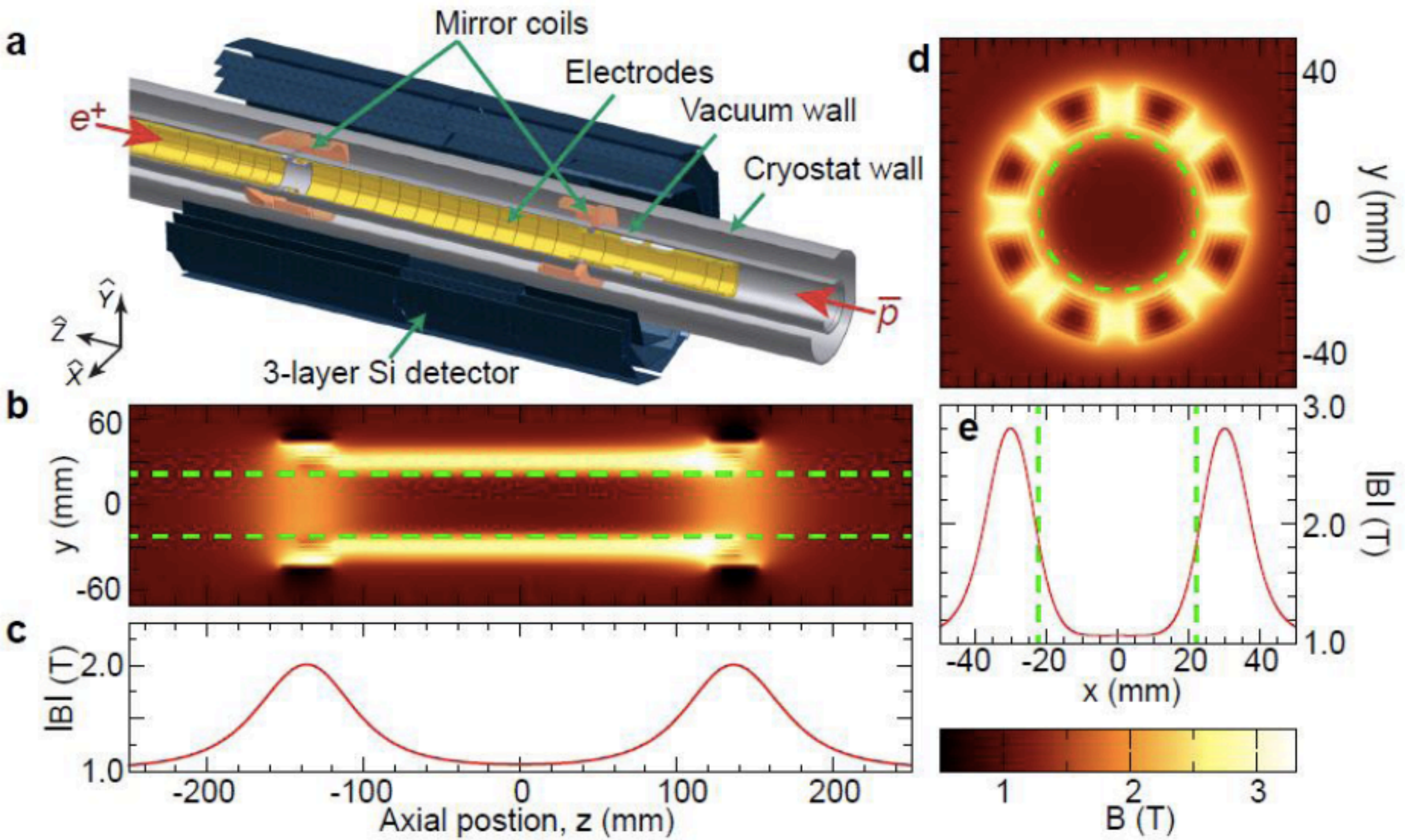
Phase: Timeline	I 2010-2014	II 2014-2016	III 2016-2017	IV 2018+
Science Goals	Proof of Principle; Kr Spectrum	T-He Mass Difference	$m_\nu < 2$ eV	$m_\nu < 0.2$ eV
Source	^{83m}Kr	Molecular ^{3}H	Molecular ^{3}H	Atomic ^{3}H
R & D Milestones	Single electron detection	Tritium spectrum; calibration and systematic error studies	High rate sensitivity	





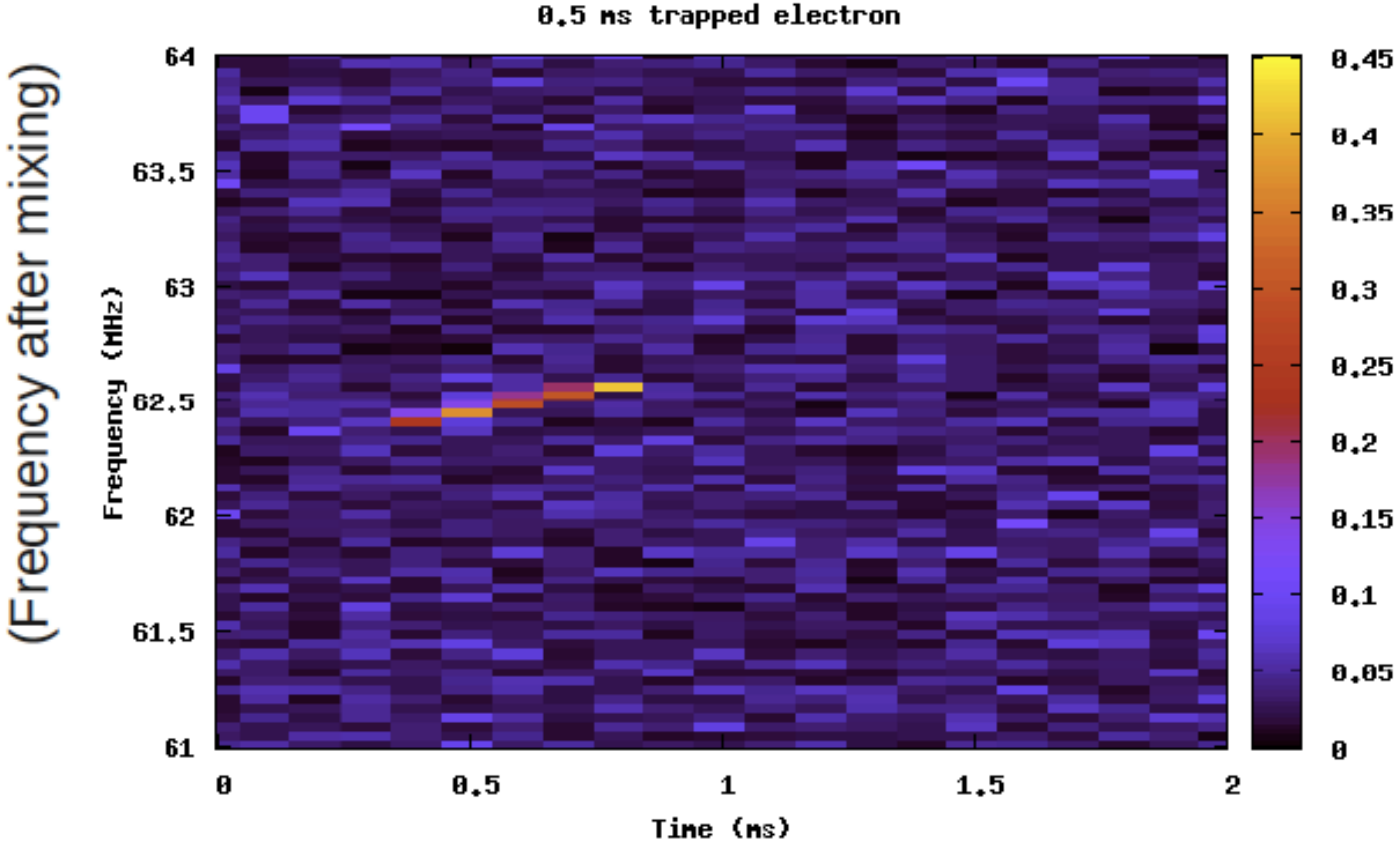


ALPHA'S ANTIHYDROGEN TRAP



ALPHA Collaboration: Nature Phys.7:558-564,2011; arXiv 1104.4982

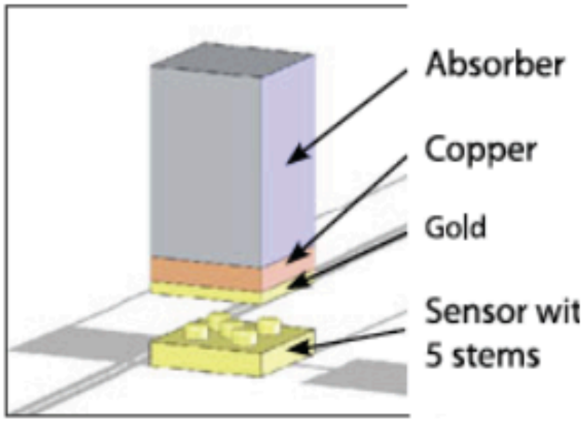
SIGNAL IS A RISING "CHIRP" IN FREQUENCY

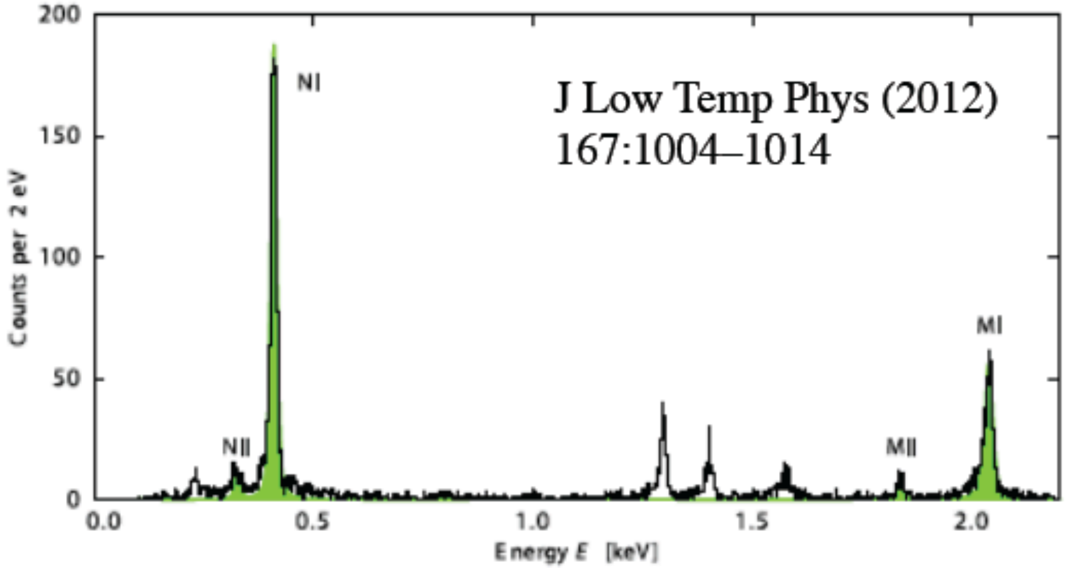


simulation M. Leber

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

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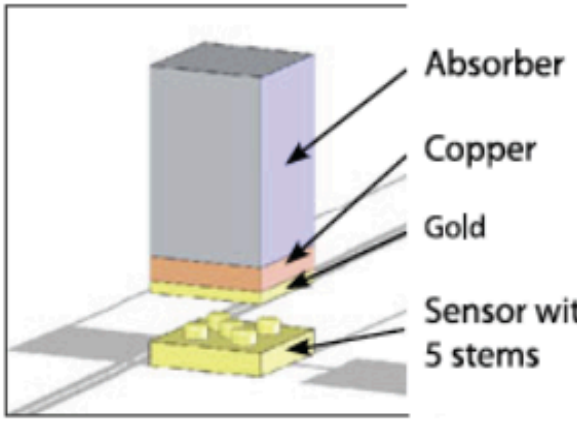

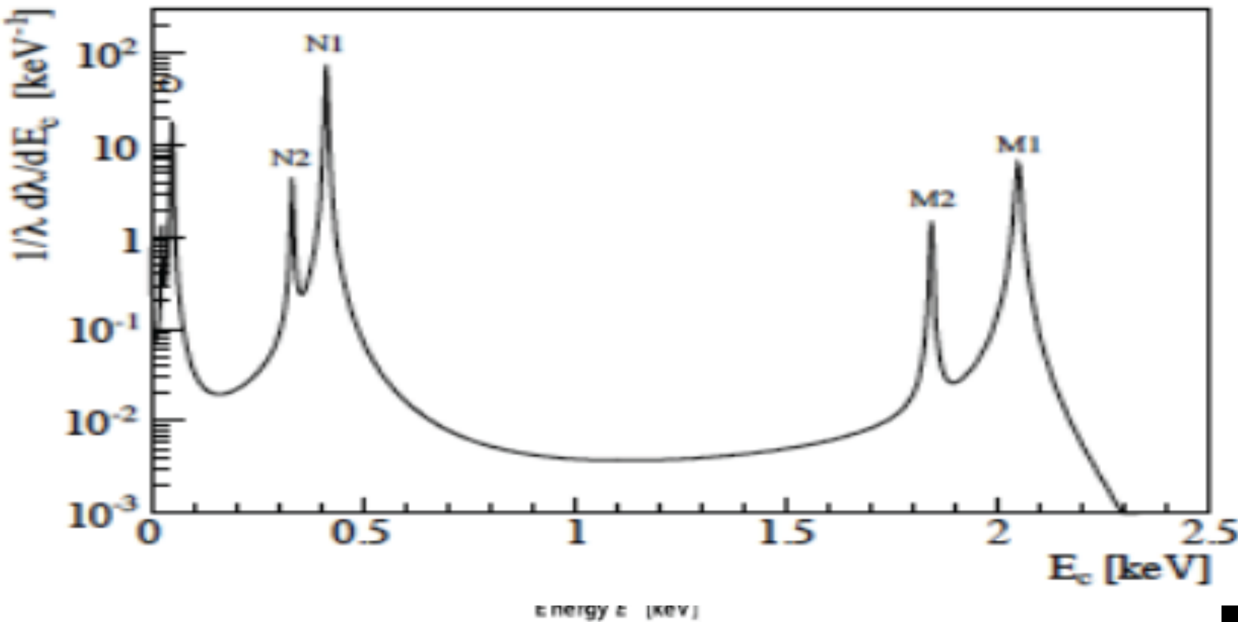

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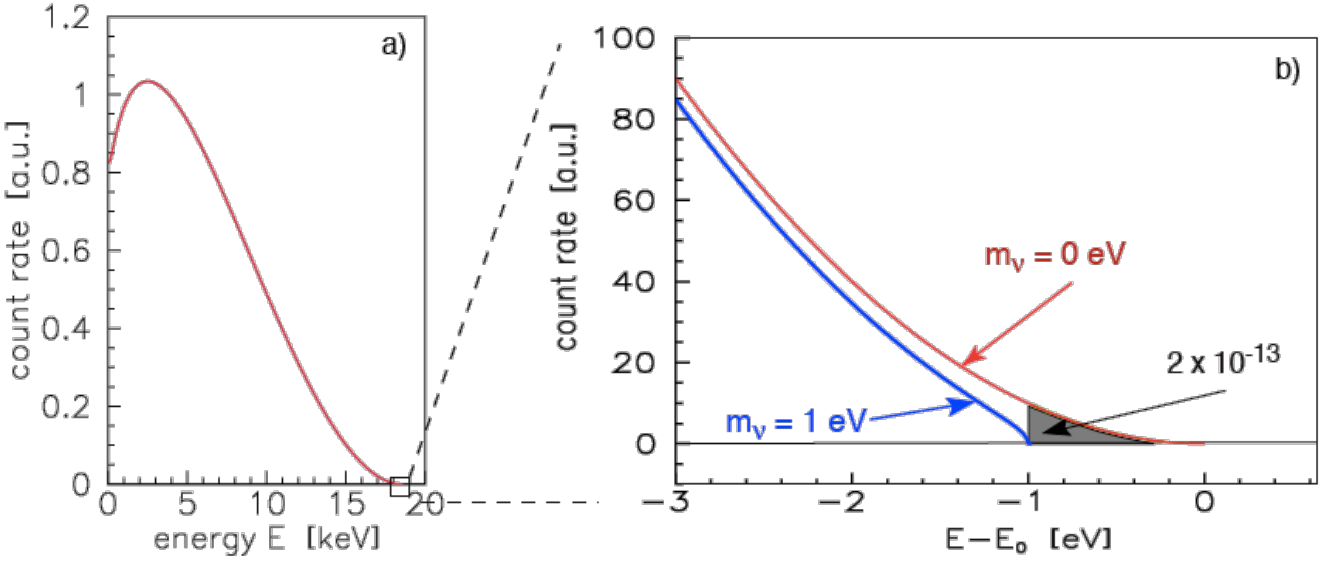
CAPTURE OF RELIC NEUTRINOS

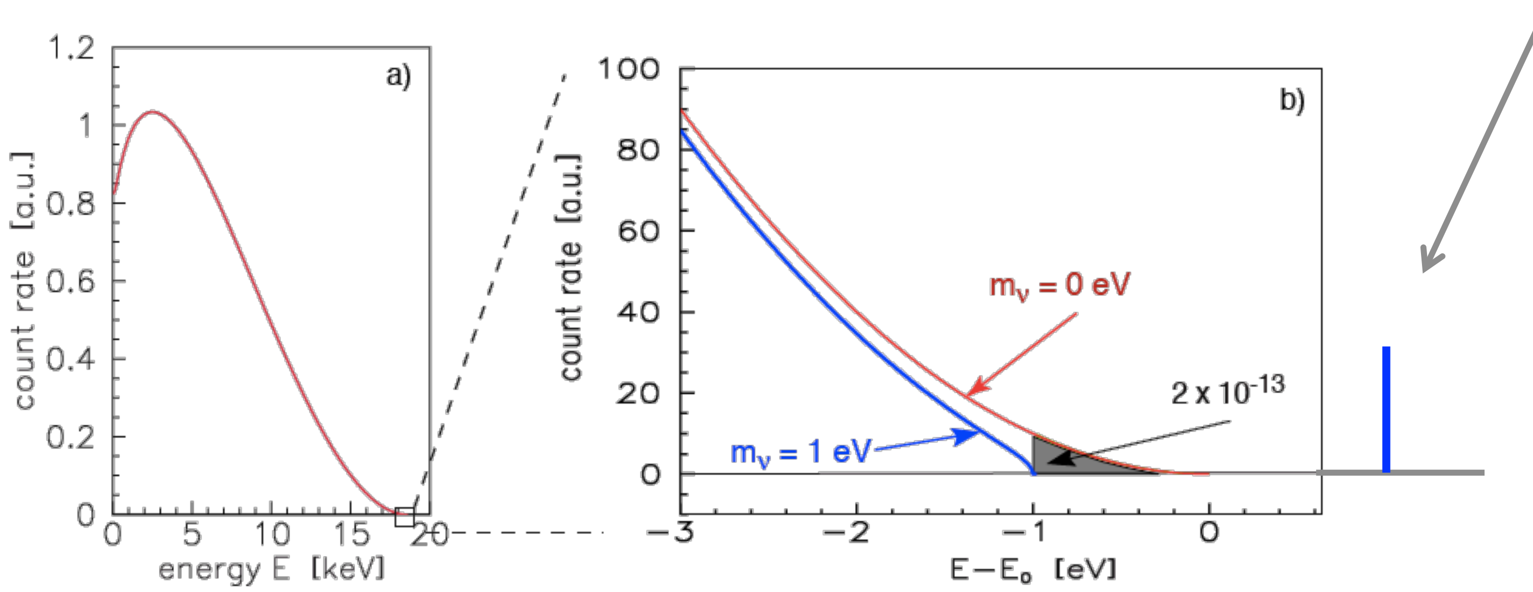
PTOLEMY project



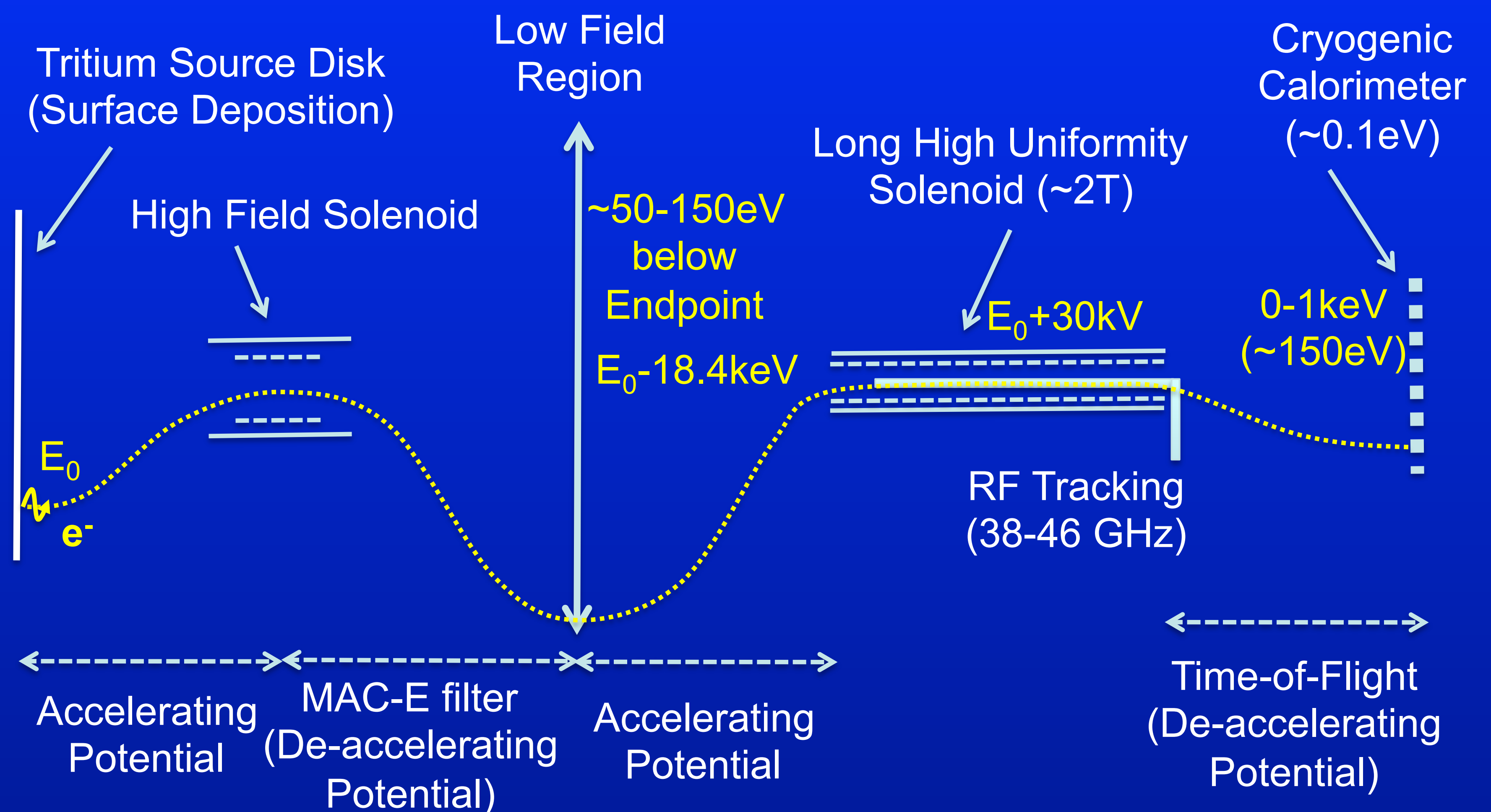
CAPTURE OF RELIC NEUTRINOS

PTOLEMY project

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



PTOLEMY Experimental Layout



PTOLEMY SUMMARY

100 g of tritium (1 MCi) on 12-m diameter disk.

Relic capture rate ~ 10/year without local clustering.

Also presumably able to measure mass, active and sterile.

Transition-edge sensor array to provide basic 0.1-eV resolution.

Tagging with RF cyclotron radiation a la Project 8.

Necessary to understand quantum effects of binding of T_2 on surface.

NEUTRINO MASS PHYSICS IMPACT

Neutrino Mass Sensitivity	Scale	Possible Experiments	Impact
$m_\nu < 2$ eV (current sensitivity)	eV	Mainz, Troitsk, Project 8 (Phase II)	Neutrinos ruled out as primary dark matter
$m_\nu > 0.2$ eV	Degeneracy	KATRIN Project 8 (Phase III)	Cosmology, $0\nu\beta\beta$ reach
$m_\nu > 0.05$ eV	Inverted Hierarchy	Project 8 (Phase IV)	Resolve hierarchy if null result, Cosmology, $0\nu\beta\beta$ reach
$m_\nu > 0.01$ eV	Normal Hierarchy	Unknown	Oscillation limit, possible relic neutrino sensitivity