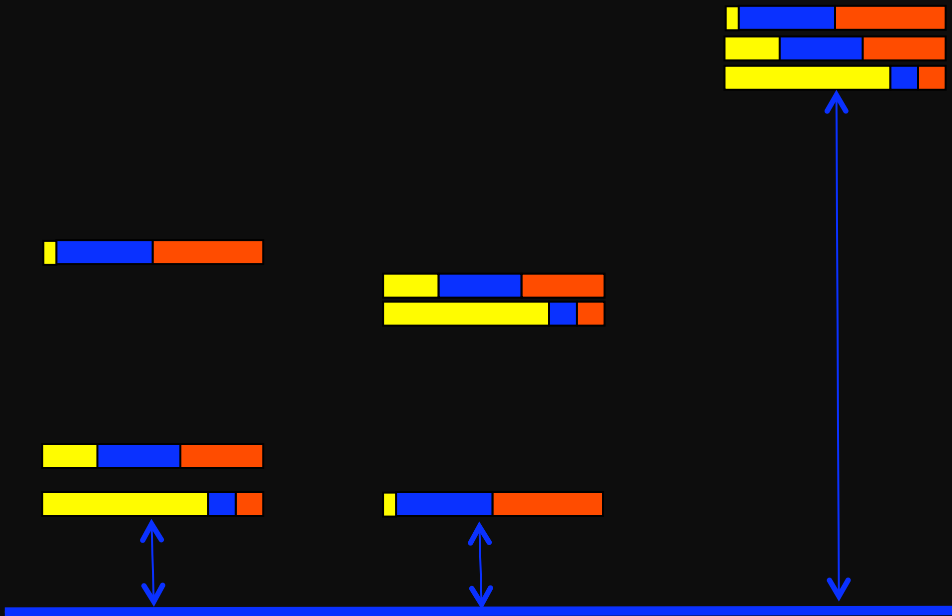
Weighing neutrinos – what is the mass scale?

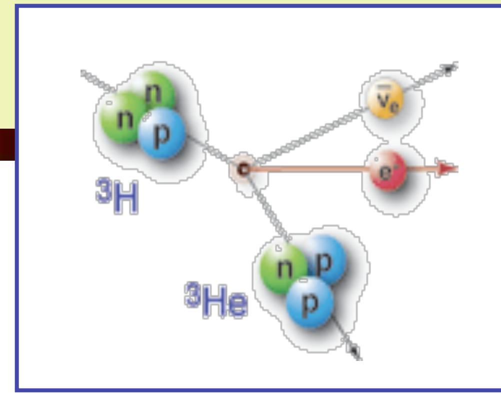


Particle Physics

Cosmology

Hamish Robertson
University of Washington
Intensity Frontier, Washington DC, 12/1/11

Neutrino mass from Beta Spectra



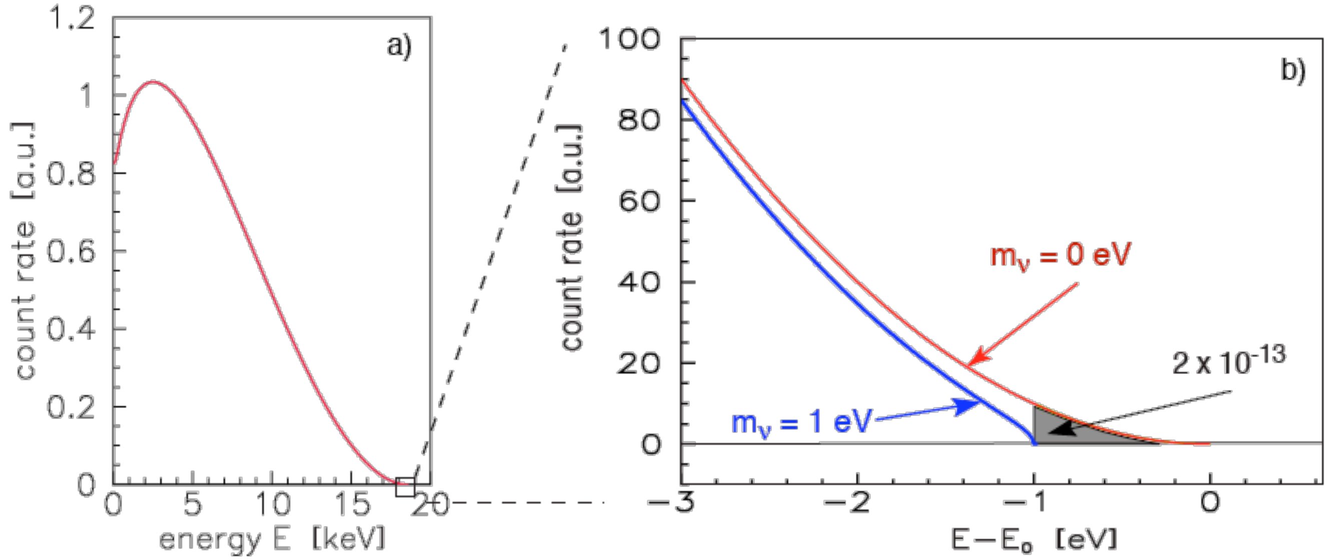
With flavor mixing:

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

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

mixing — neutrino masses

from oscillations — mass scale



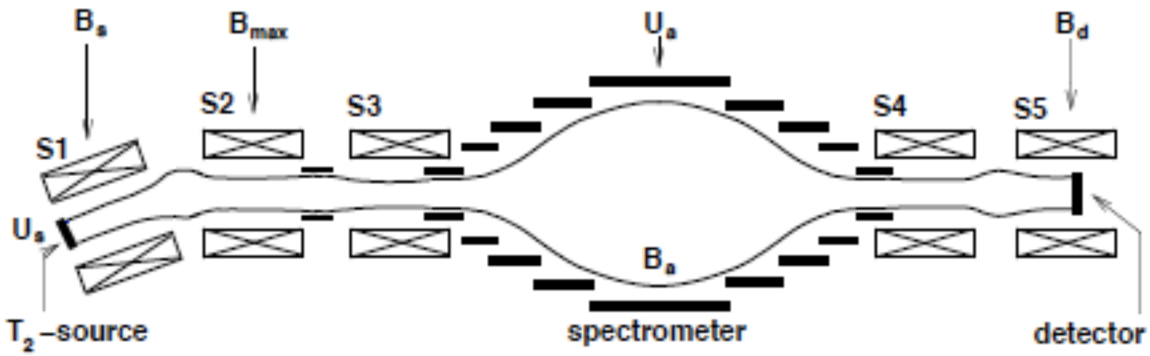
Current status of direct mass measurement

Mainz: solid T_2, MAC-E filter

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

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

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

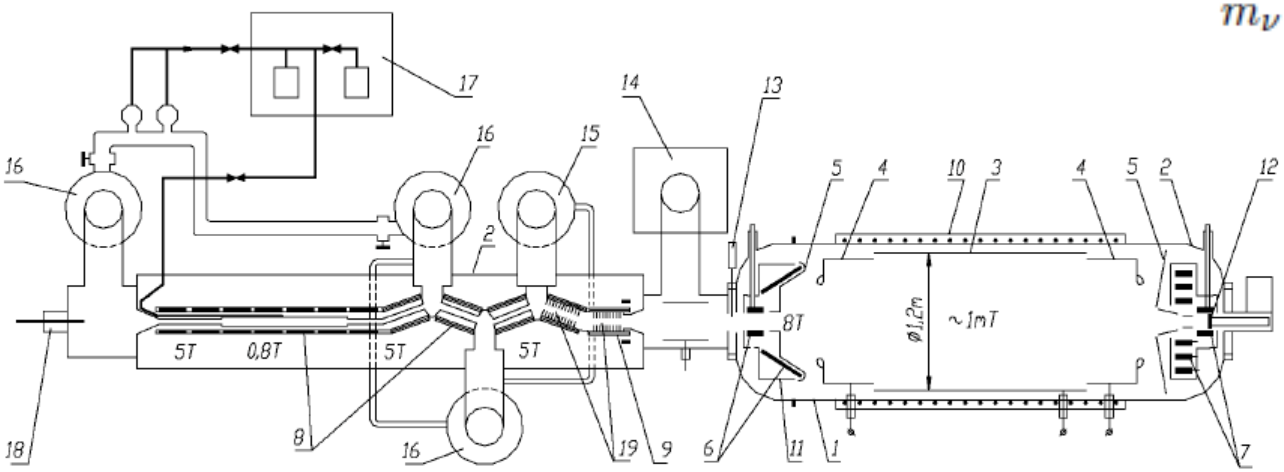


Troitsk: gaseousT_2, MAC-E filter

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

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

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

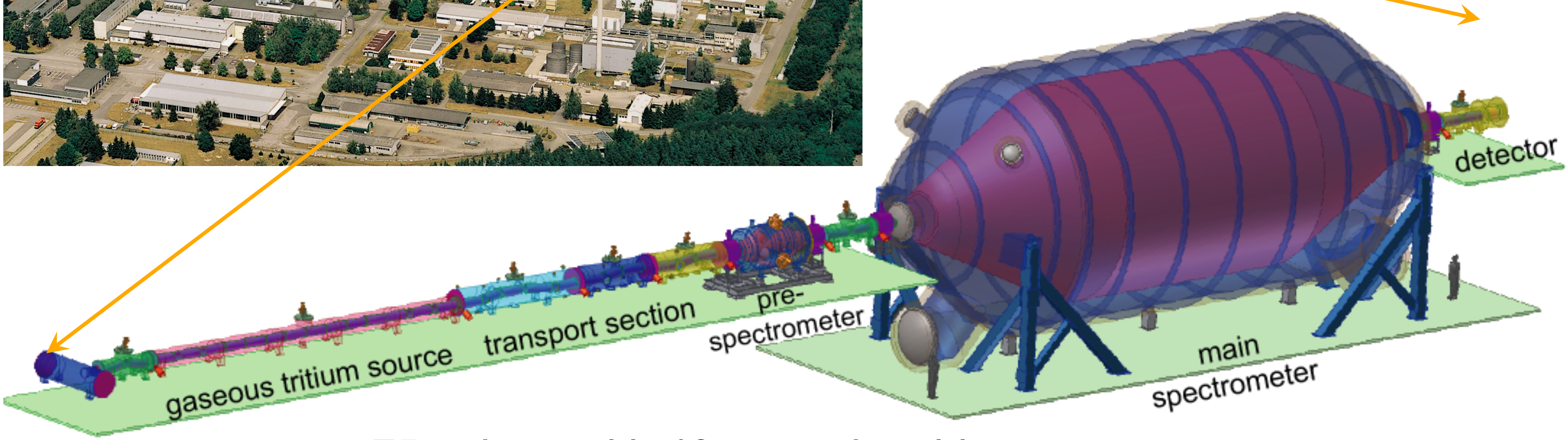


Together:…
$m_\nu < 2$ eV

KATRIN

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

5 countries
13 institutions
100 scientists

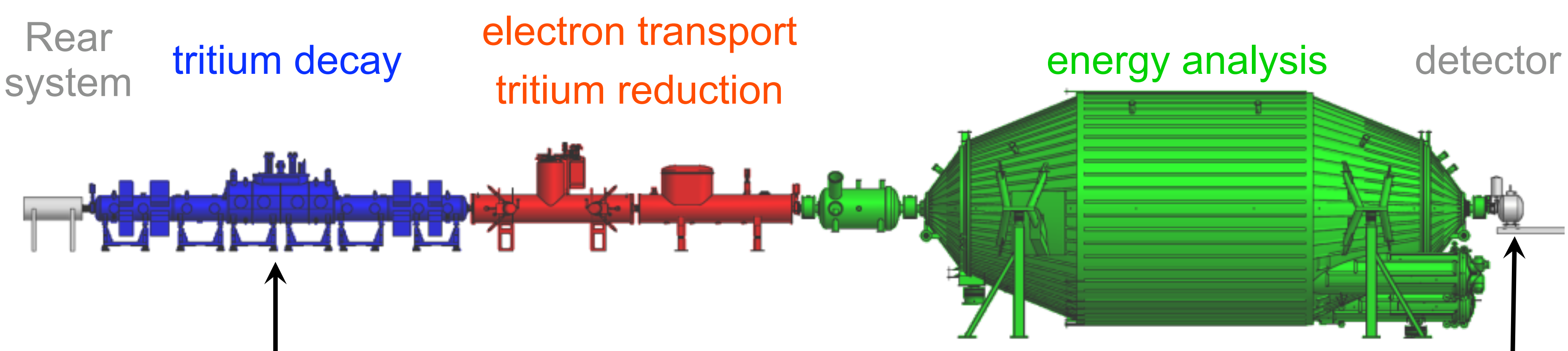


~ 75 m long with 40 s.c. solenoids

Description of KATRIN

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

Draws on 3 decades of tritium neutrino experiments



β-decay rate: $\mathbf{10^{11}}$ Hz

T_2 pressure: $\mathbf{10^{-6}}$ mbar

about **14** orders of magnitude →

background rate: $\mathbf{10^{-2}}$ Hz

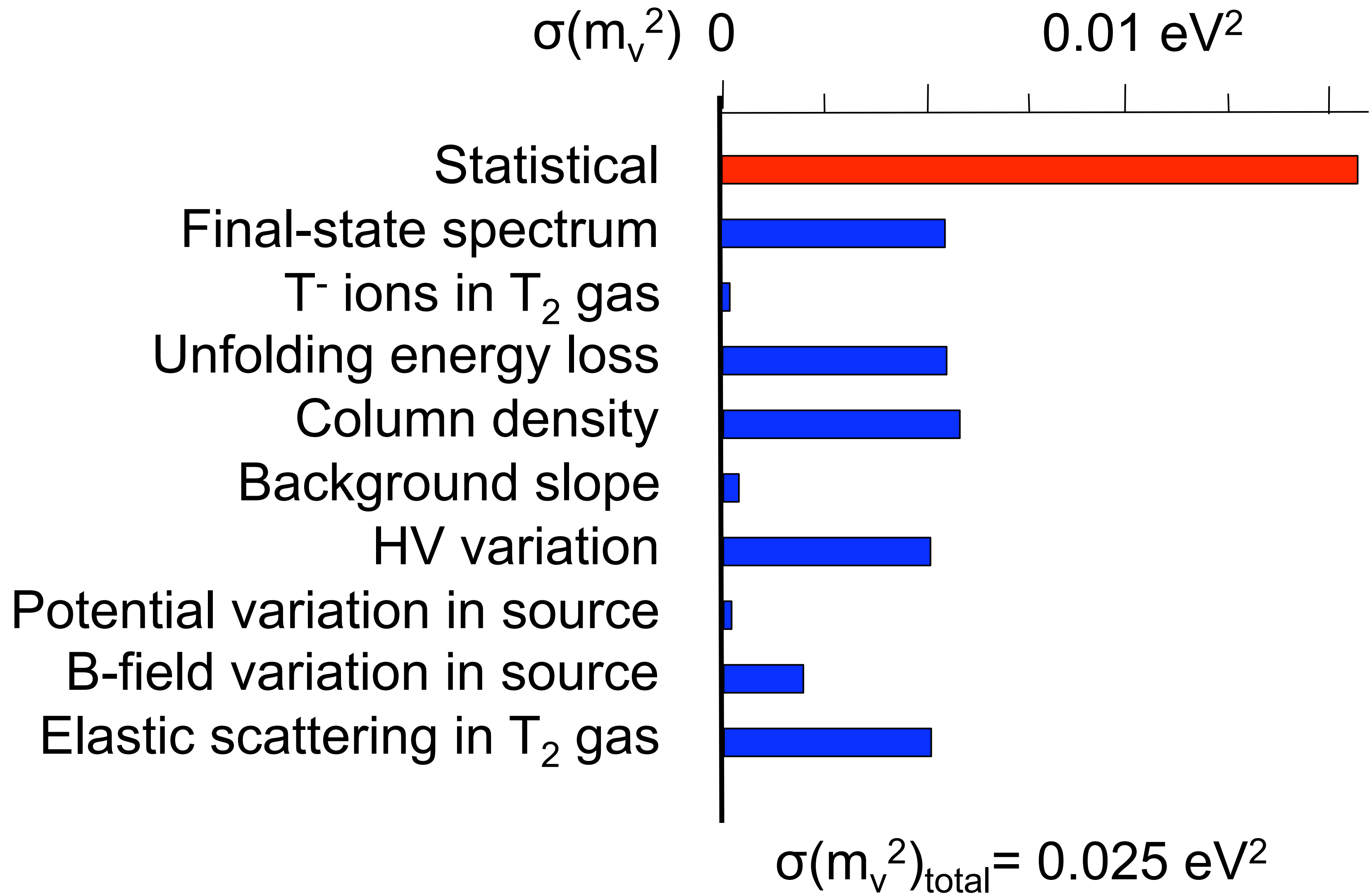
T_2 pressure: $\mathbf{10^{-20}}$ mbar

70 m

P.J. Doe

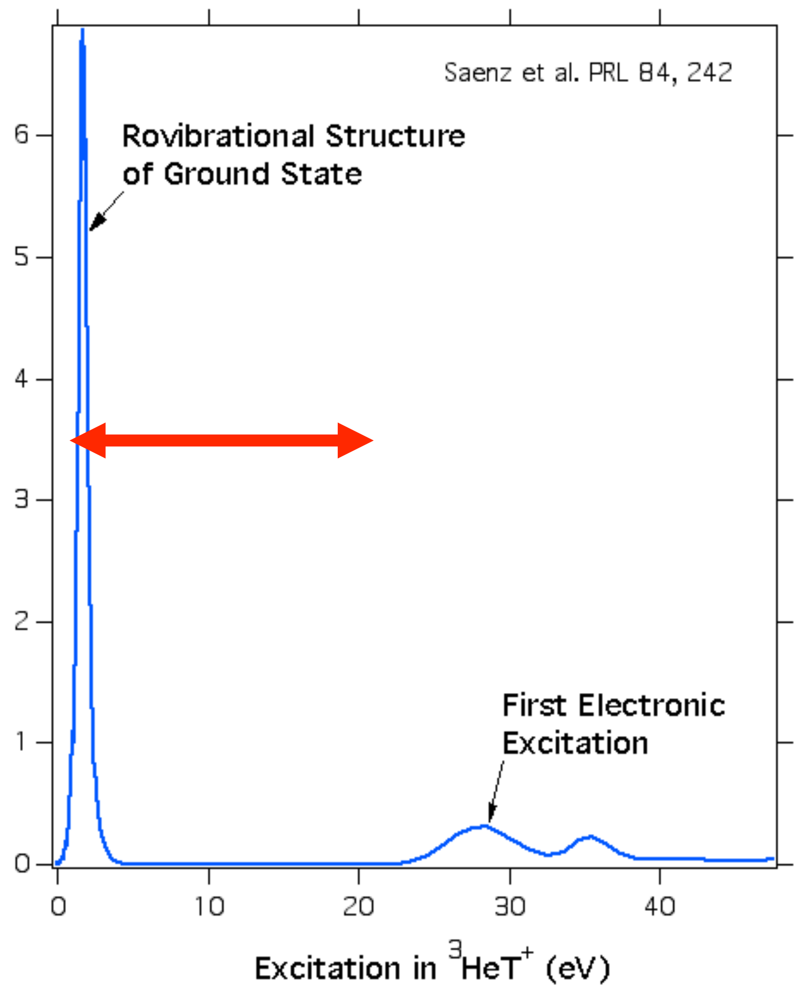
Arrival in Leopoldshafen: Nov 24, 2006

KATRIN's uncertainty budget

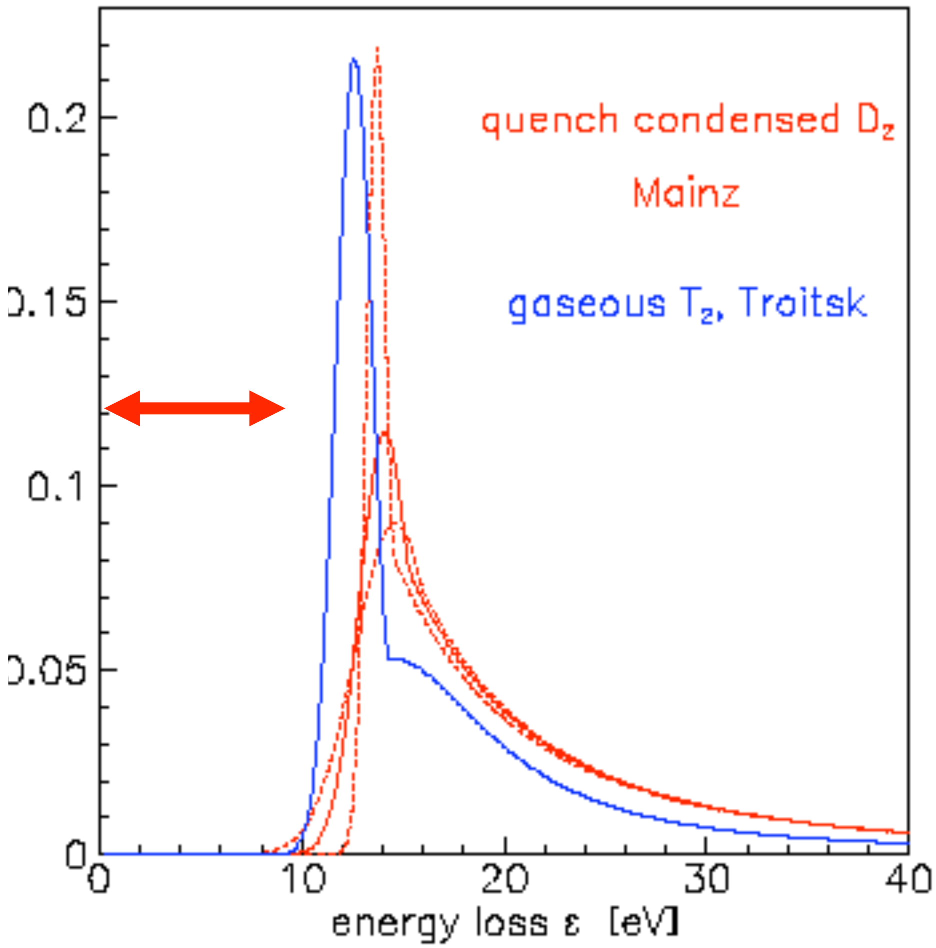


A window to work in

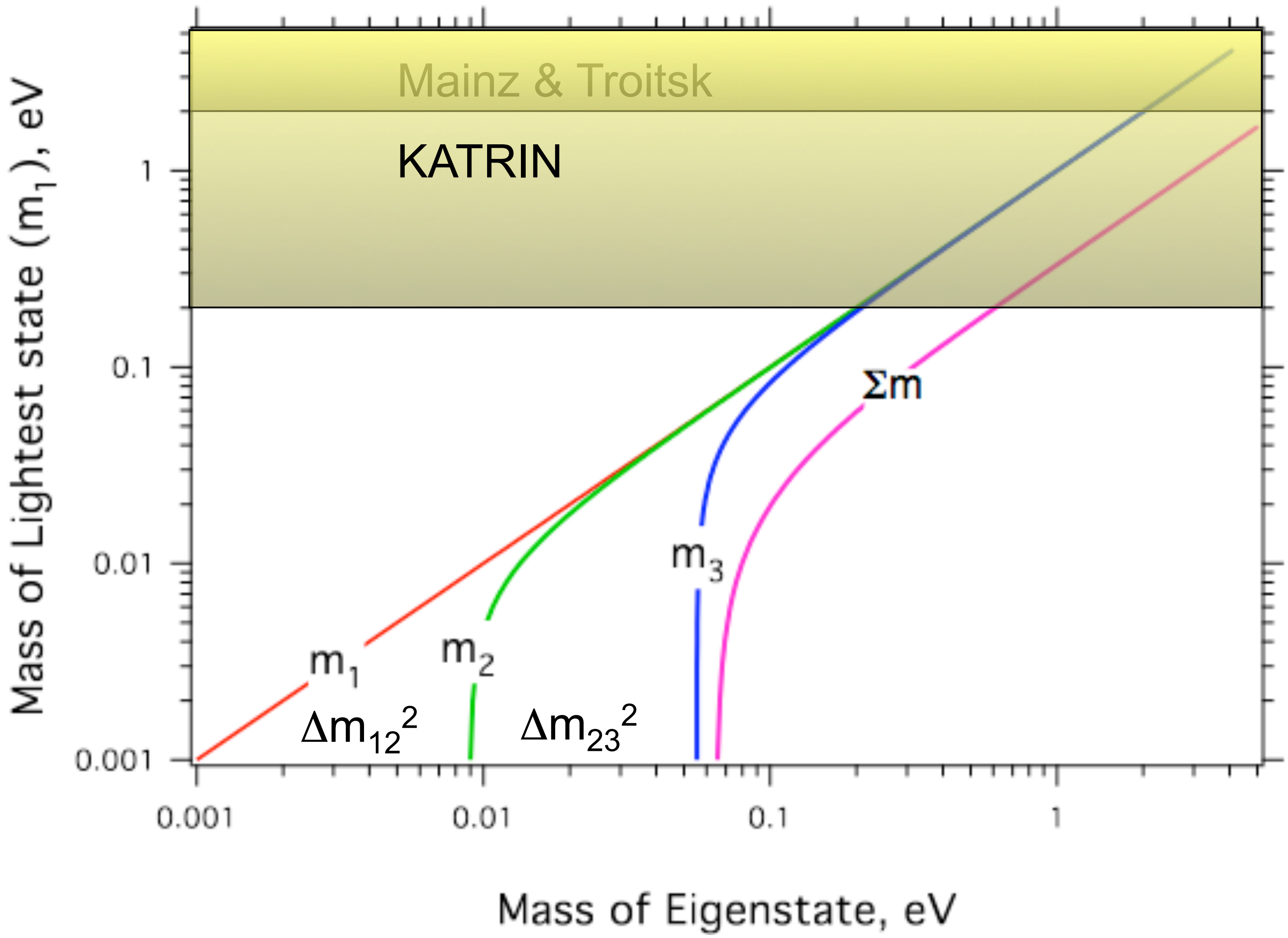
Molecular Excitations



Energy loss function

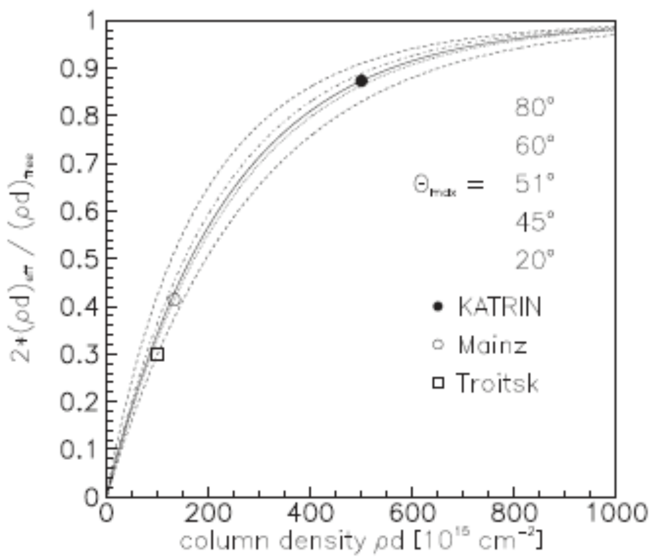


Mass Range Accessible



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.

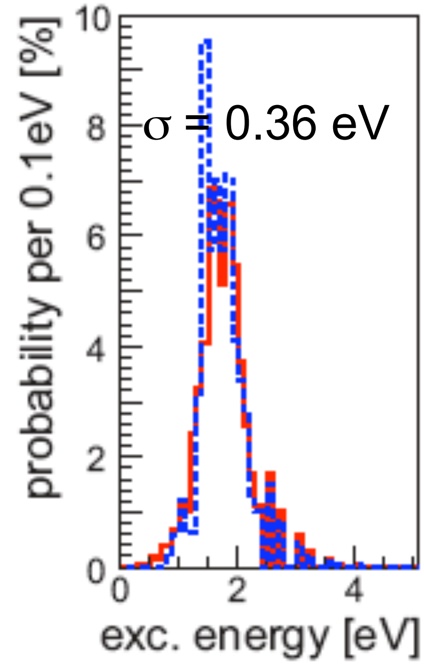


Source T_2 column density near max

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

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.

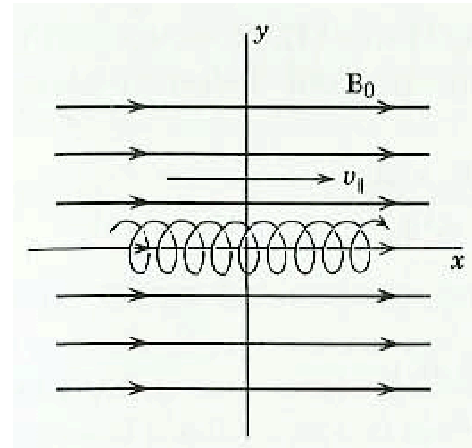
	Tritium	^{187}Re
Endpoint	18.58 keV	2.47 keV
Branch to last eV	2×10^{-13}	6×10^{-11}
Half-life	12.32 y	4.32×10^{10} y
Mass: 200 meV	20 μg	700 g
Mass: 20 meV	20 mg	700 kg

Cyclotron radiation from tritium beta decay

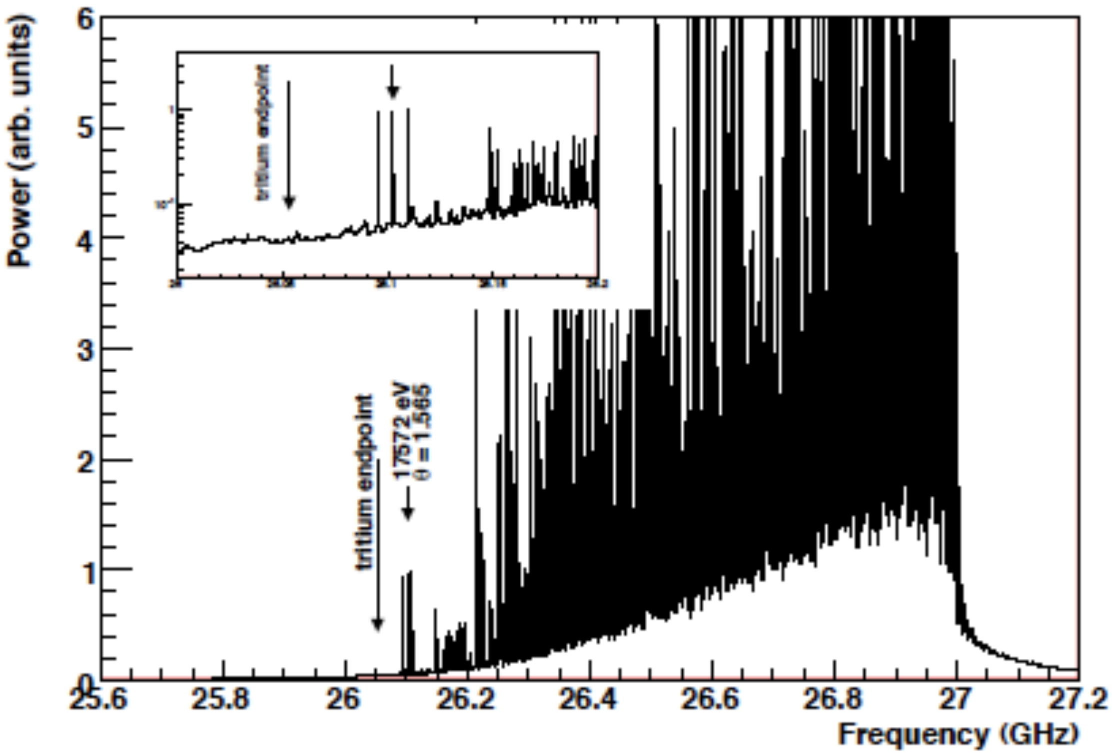
(B. Monreal and J. Formaggio, PRD 80:051301, 2009)

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

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

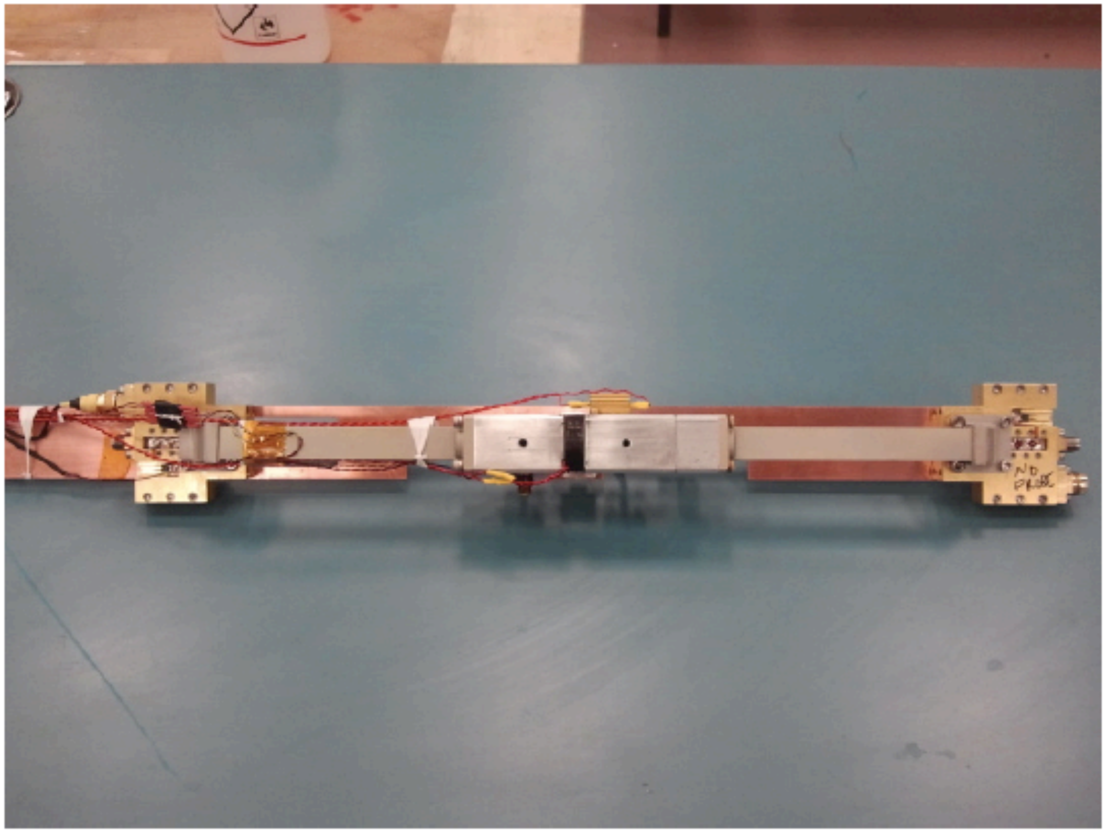


Radiated power ~ 1 fW



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

Project 8 prototype at University of Washington

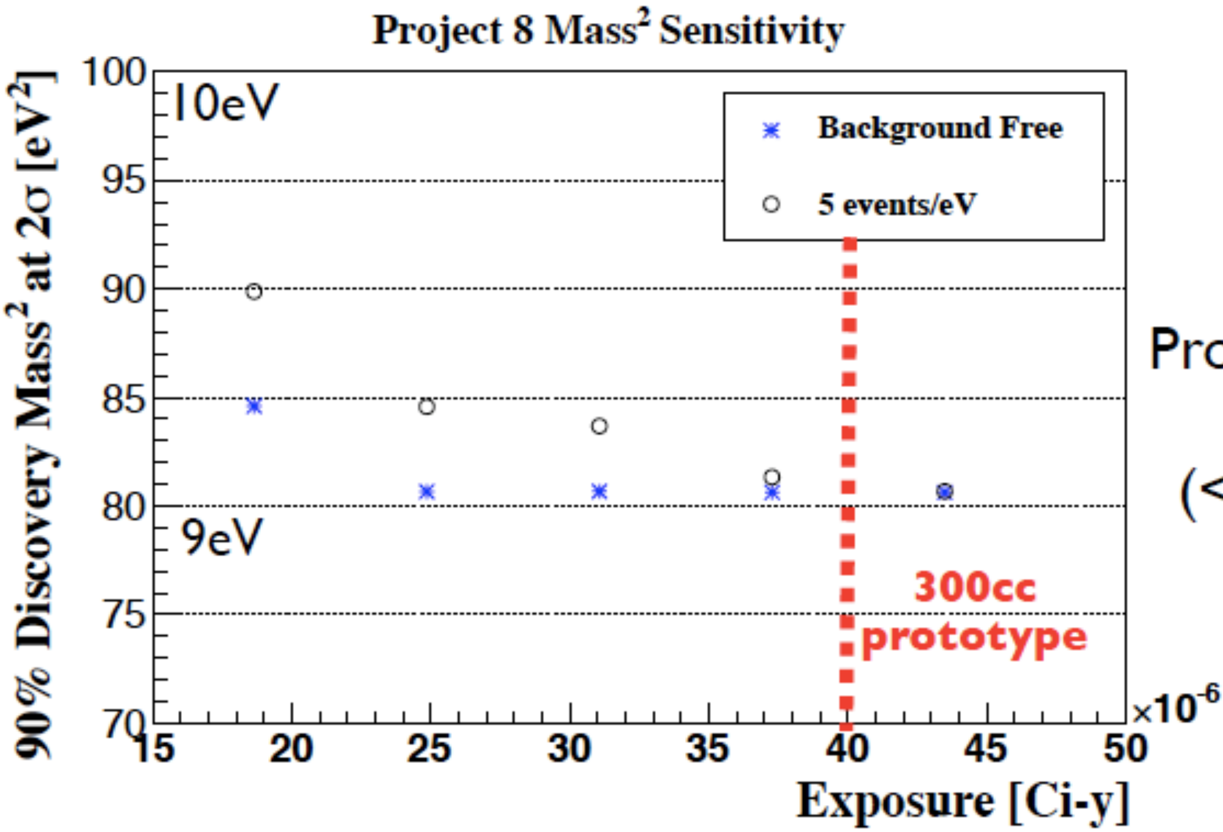


Trap coil, sample cell, waveguide, and two NRAO amplifiers

Magnet cooldown

Project 8 prototype

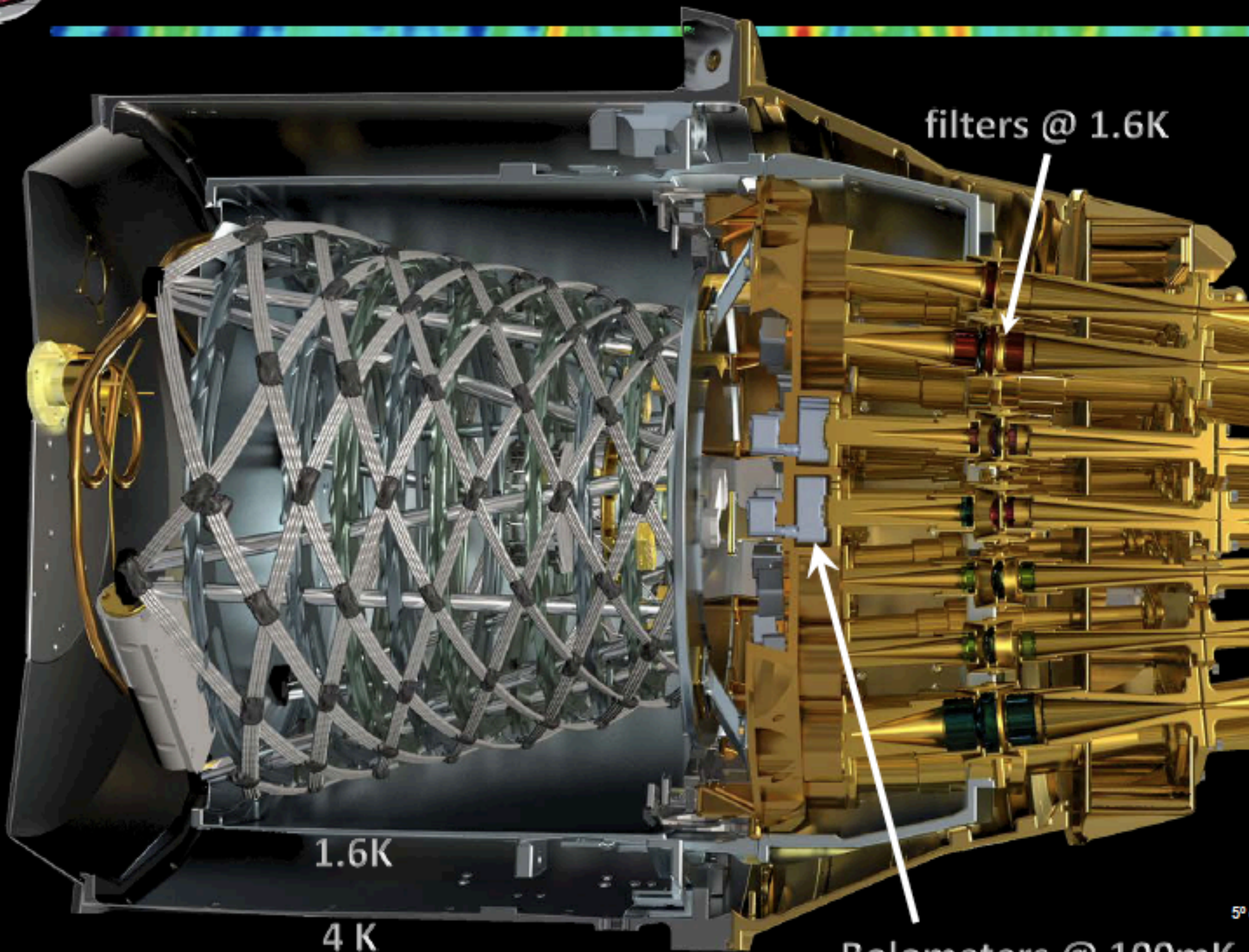
~ 40 μCi of T_2 (KATRIN is ~ 3 Ci)

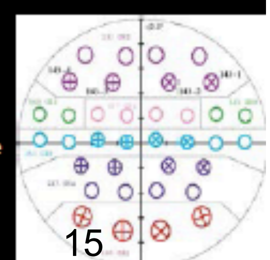


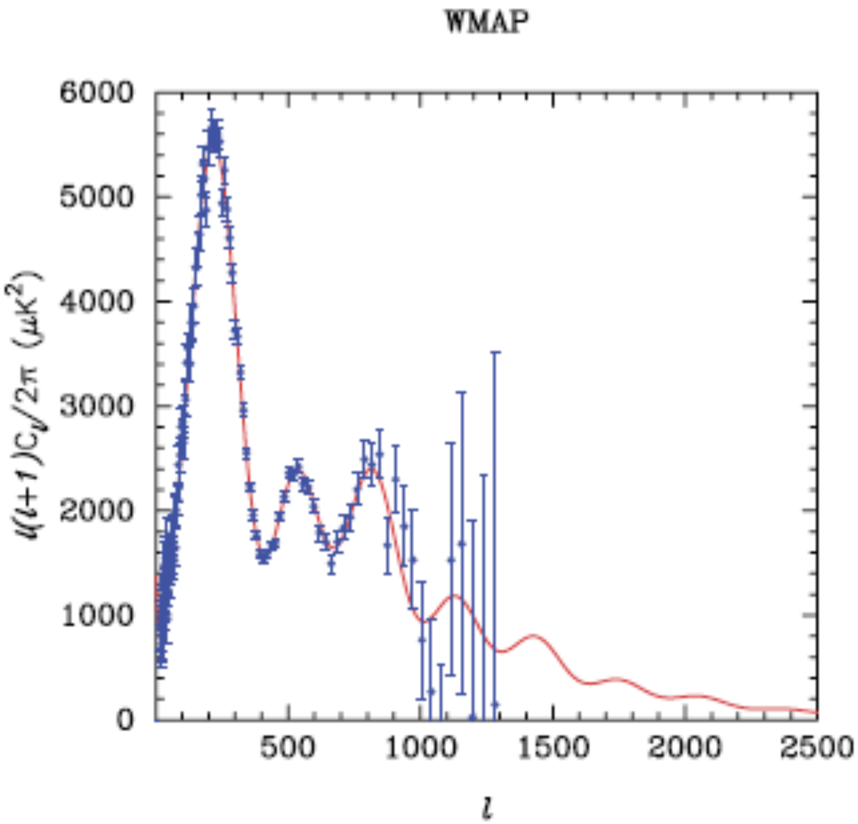
Prototype in "maximum resolution" mode (< 5000 Bq/cm³, 1eV)

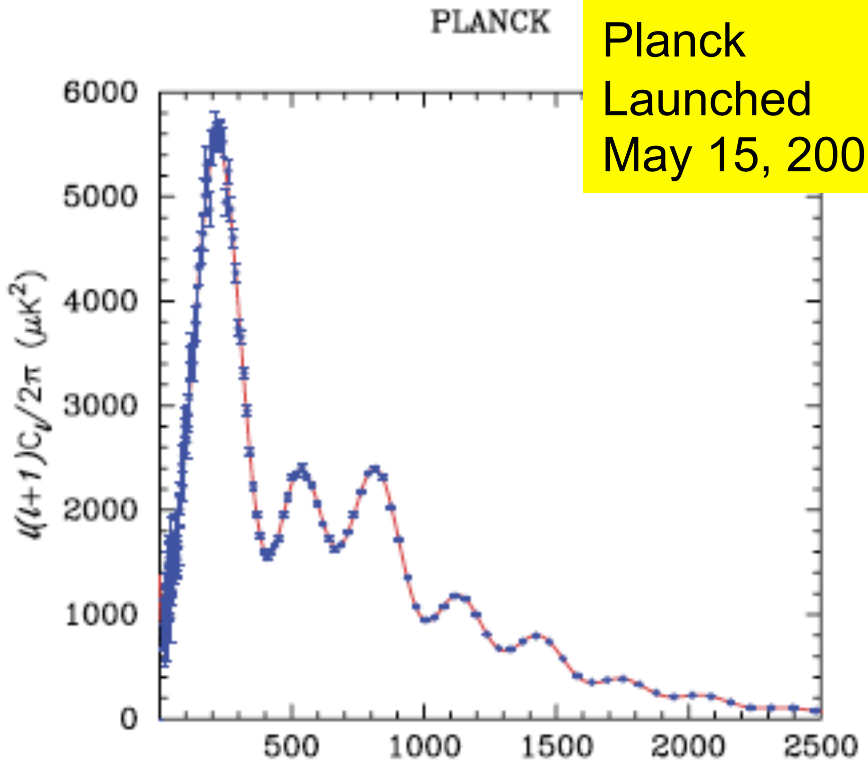
B. Monreal

Planck HFI cut-away







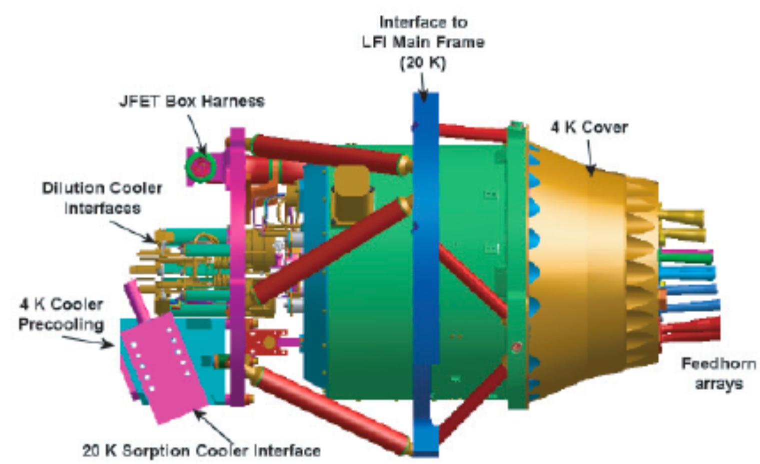


Planck
Launched
May 15, 2009

Present ΛCDM constraints on Σm_ν:
~ 0.6 eV

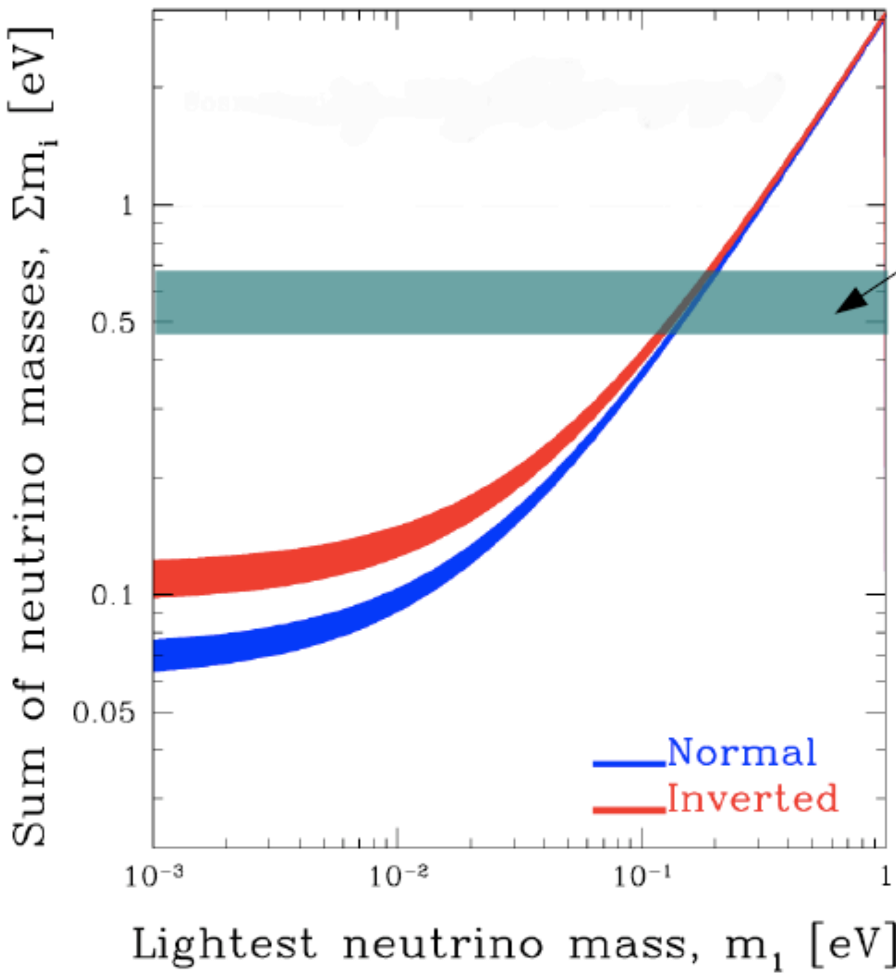
Planck sensitivity:

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



From Planck "Bluebook"

Present constraints...



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

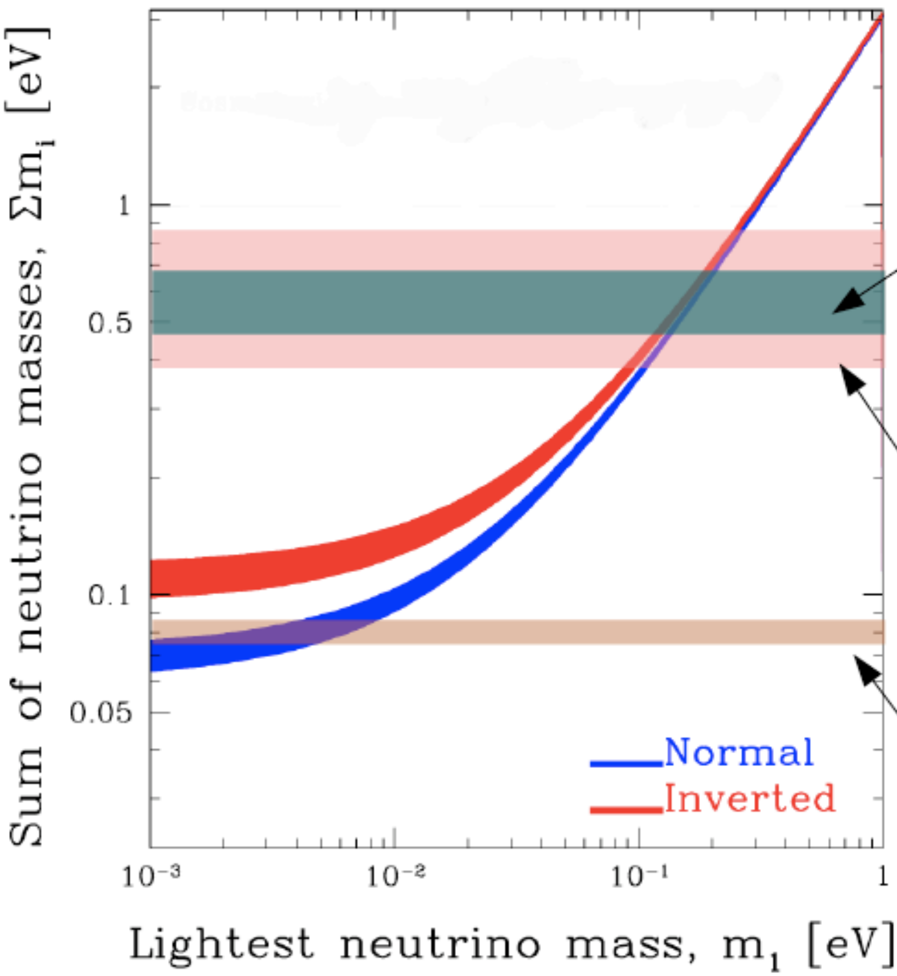
$$\sum m_\nu < 0.44 \rightarrow 0.76\,\mathrm{eV} \quad (95\%\,\mathrm{CI})$$

depending on the model complexity

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

Y.Y.Y. Wong

Present constraints and future sensitivities...



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

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

depending on the model complexity

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

Planck alone (1 year)

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

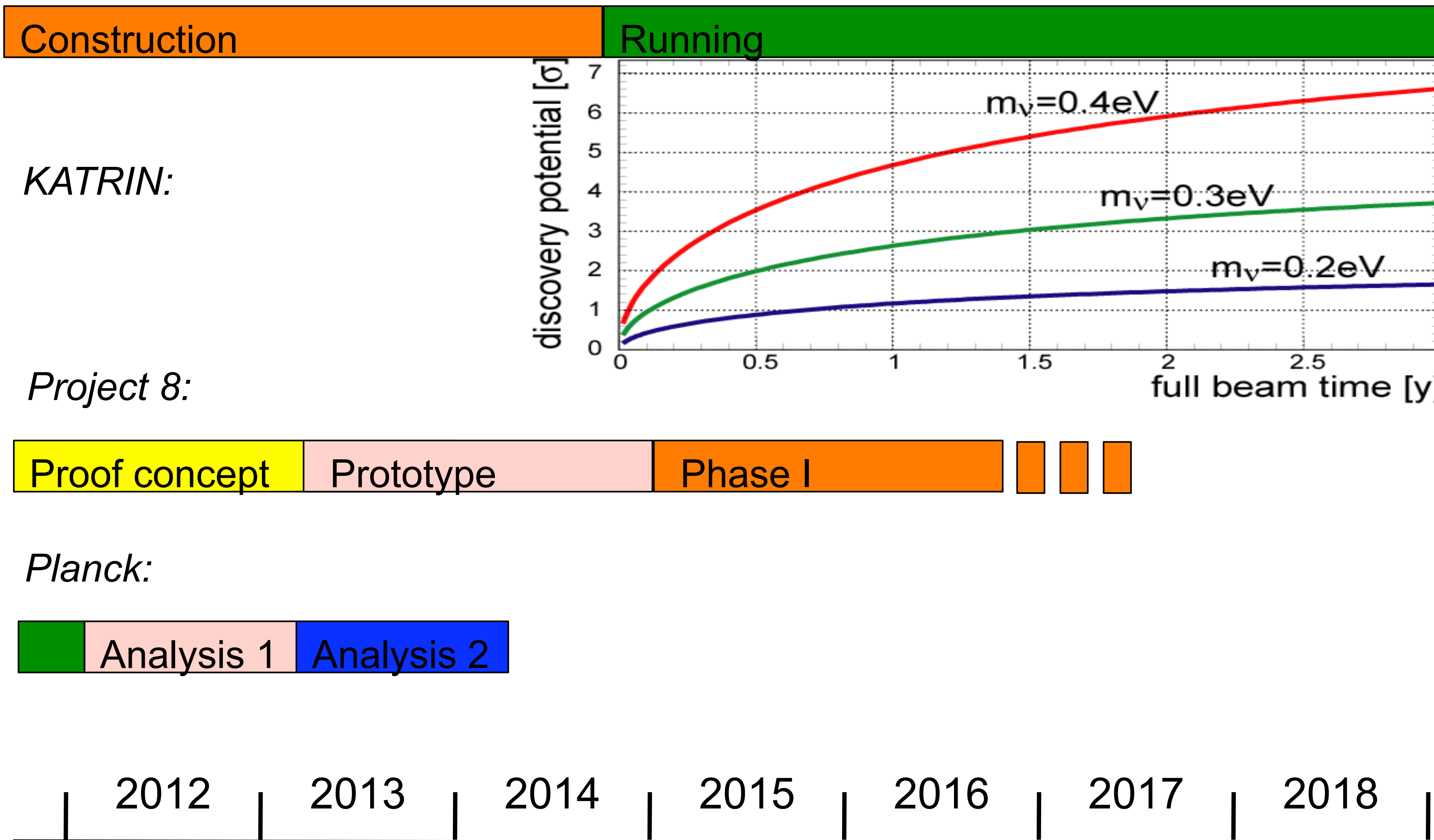
Perotto et al. 2006

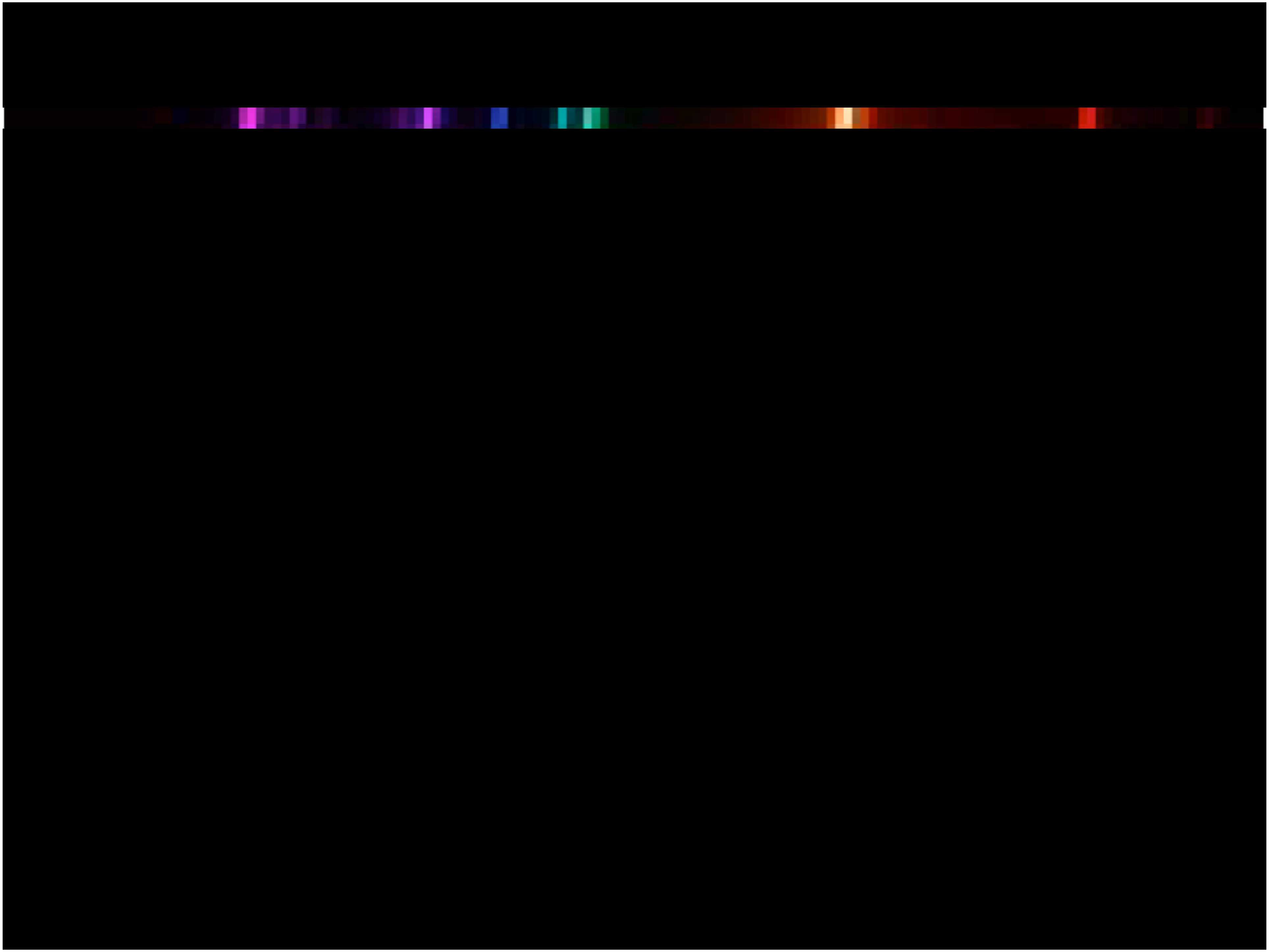
Planck+Weak lensing (LSST)

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

Hannestad, Tu & Y³W 2006

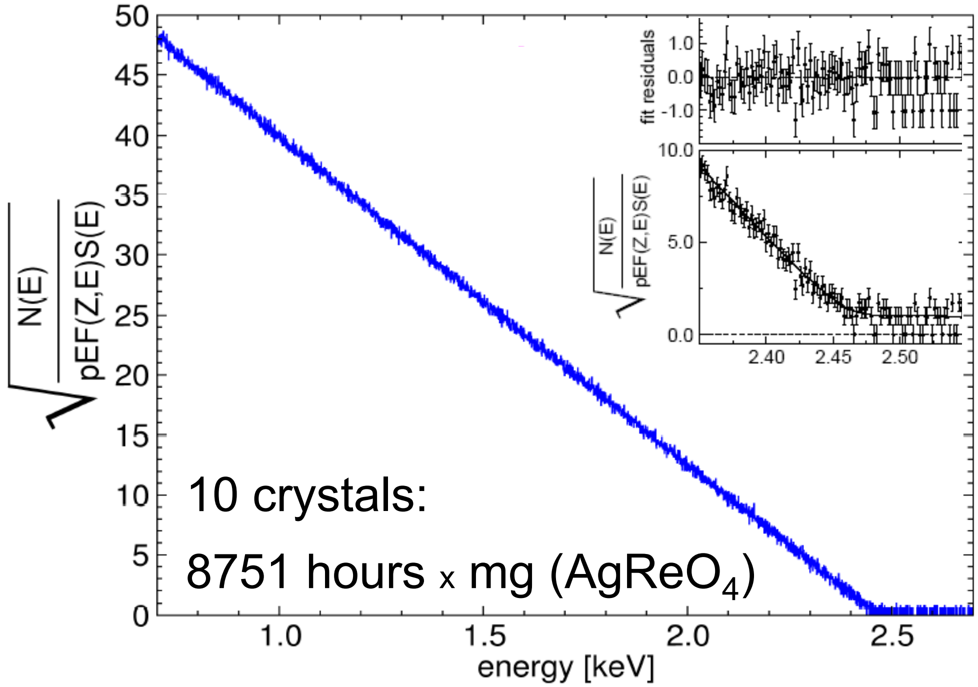
Neutrino mass: some milestones





Microcalorimeters for ^{187}Re ß-decay

MIBETA: Kurie plot of 6.2 $\times 10^6$ ^{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

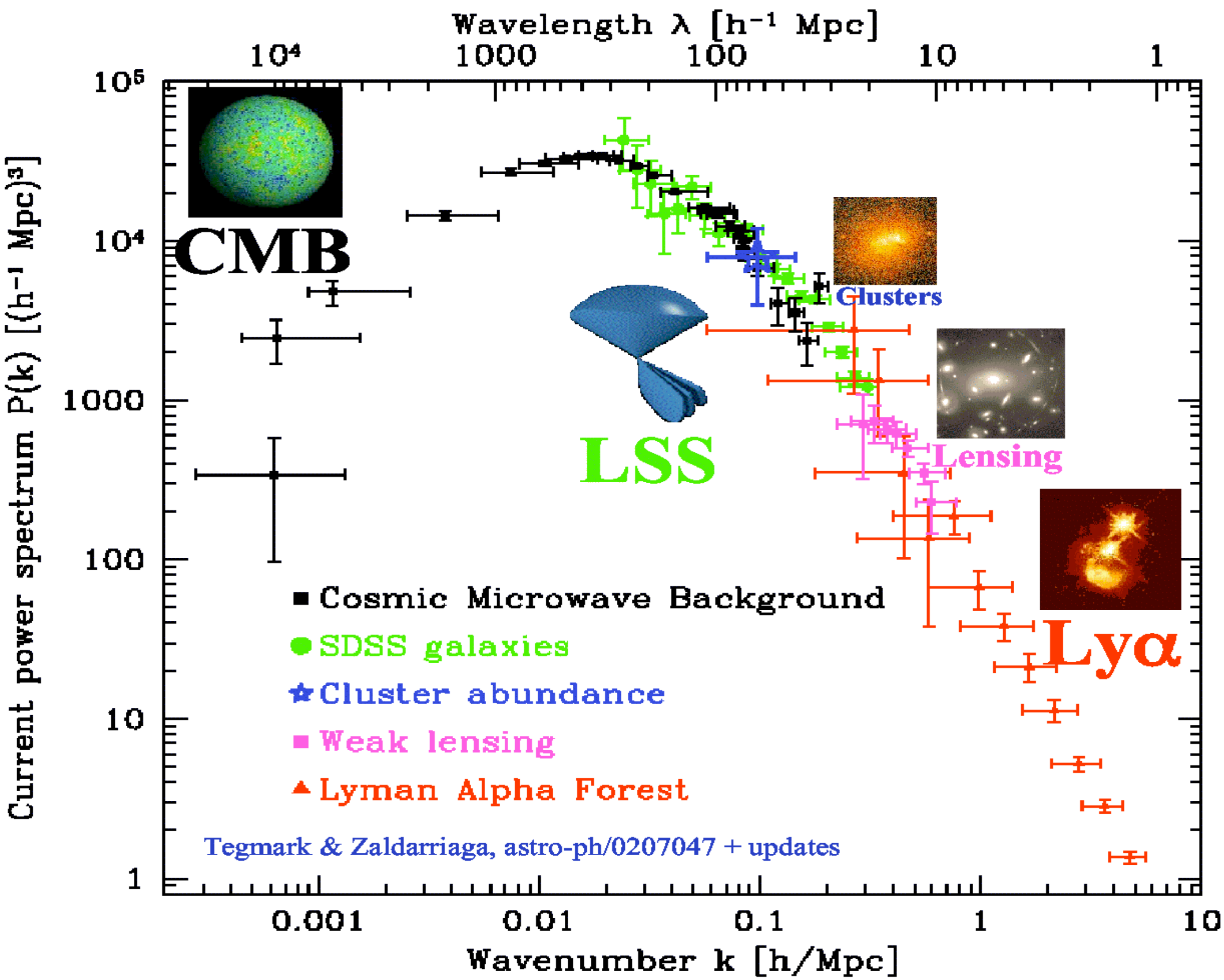
MIBETA (Milano)
$AgReO_4$
m(ν) < 15 eV

Nucl. Instr. Meth. 125 (2004) 125

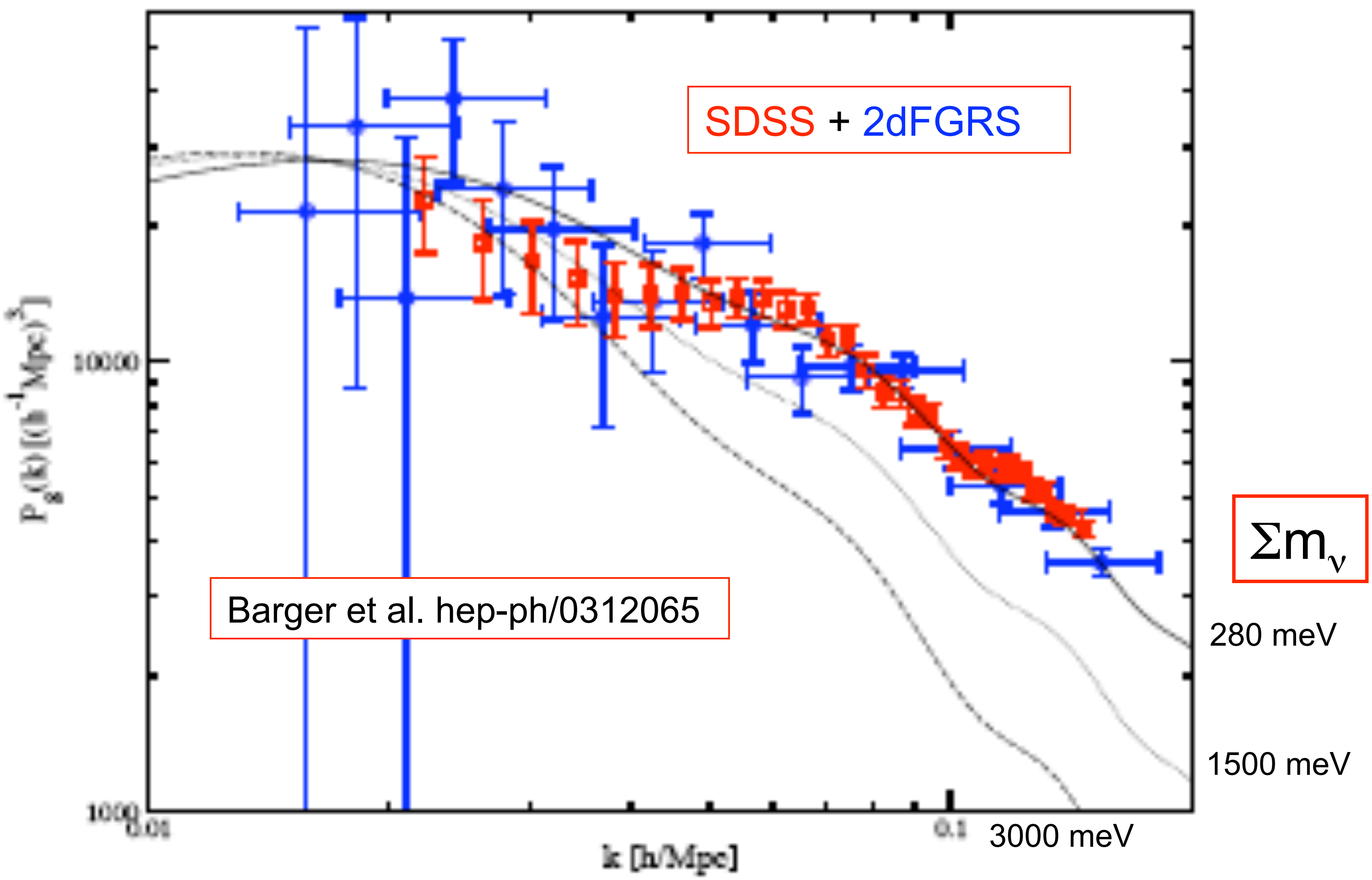
MARE (Milano, Como, Genoa, Trento, US, D)
Phase I : m(ν) < 2.5 eV

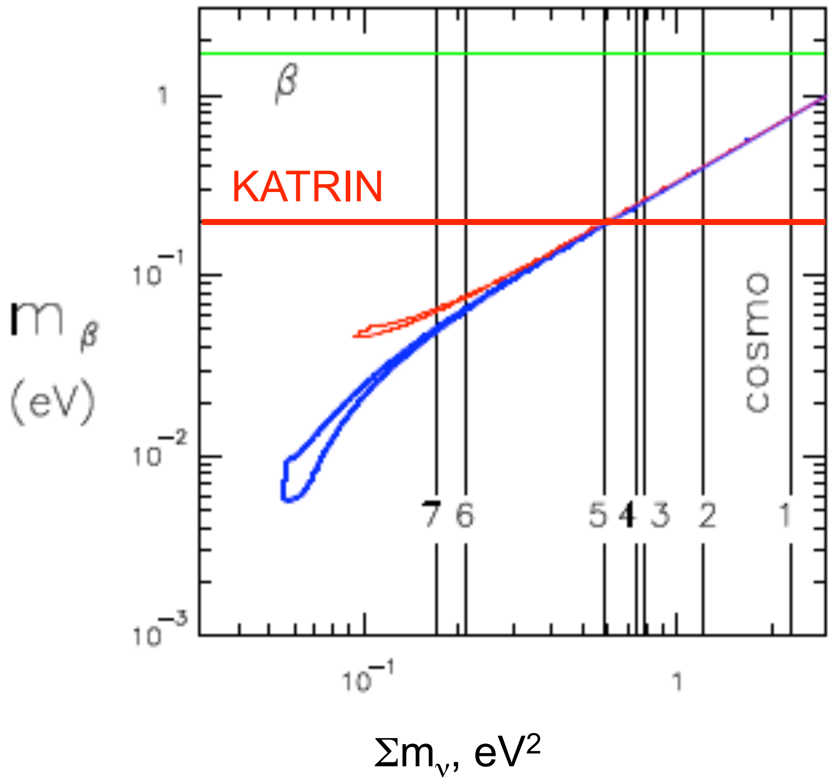
hep-ex/0509038

Neutrino mass from cosmology



Even small m_ν influences structure





2σ bounds from :

- ν oscillation data
- β decay
- cosmology

normal hierarchy

inverted hierarchy

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 and mixing parameters

Δm_{21}^2	$7.59^{+0.21}_{-0.21} \times 10^{-5}$ eV^2	
$\|\Delta m_{32}^2\|$	$2.40^{+0.12}_{-0.11} \times 10^{-3}$ eV^2	
Σm_i	> 55.3 meV (90% CL)	< 6900 meV (90% CL)*
θ_{12}	$33.7^{+0.9}_{-0.9}$ deg	
θ_{23}	$45^{+4.0}_{-3.5}$ deg	
θ_{13}	$8.1^{+1.7}_{-1.1}$ deg	Non-Gaussian error!
$\sin^2\theta_{13}$	$0.021^{+.022}_{-.018}$(99.7% CL)	~ Gaussian error

Marginalized 1-D 1-σ uncertainties.

*C. Kraus et al., Eur. Phys. J. C40, 447 (2005)
Other refs, see HR, 0807.4258v1

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

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

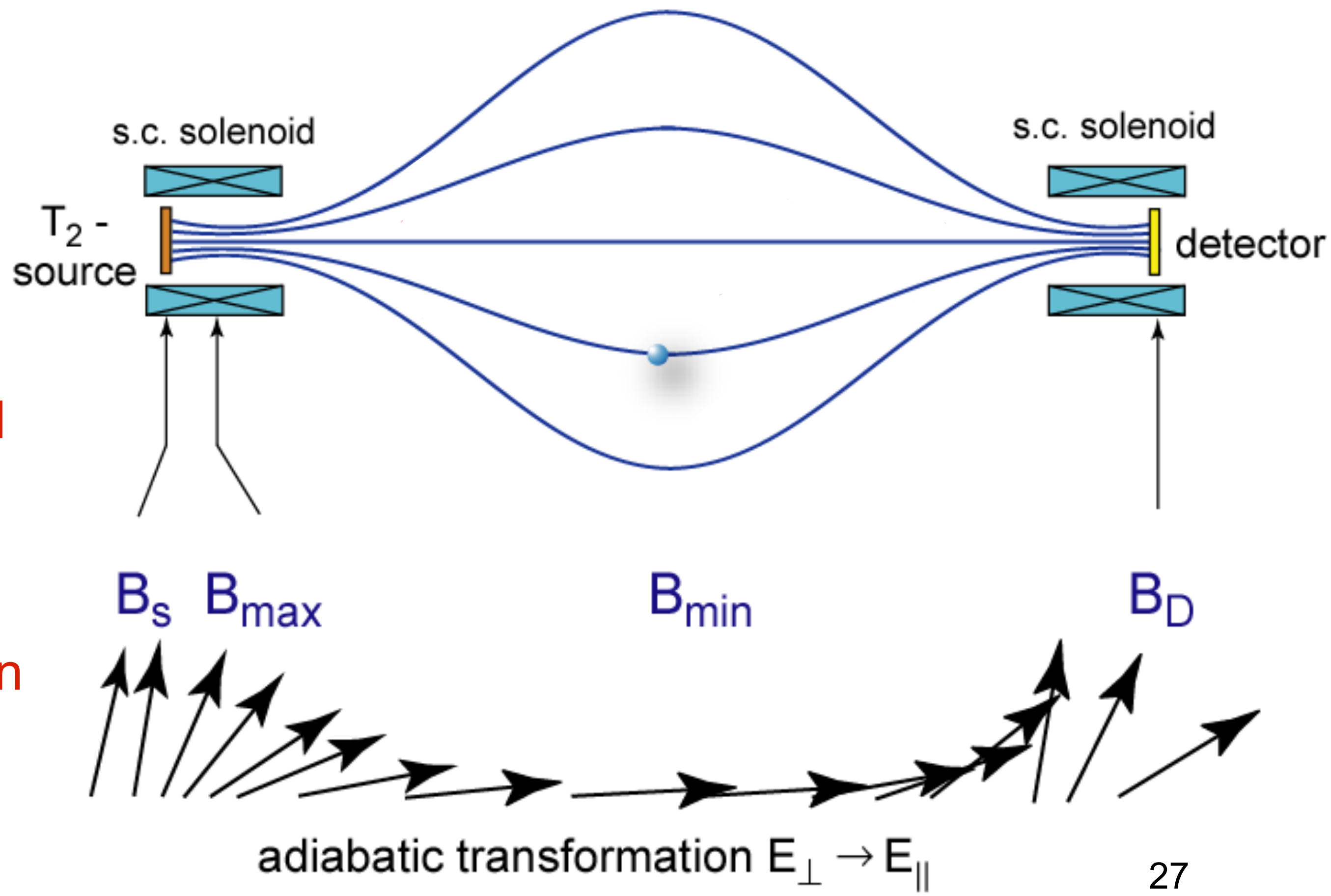
Because U_{e3} is also small, this is accurate down to m_0 = 30 meV !

Principle of MAC-E Filter

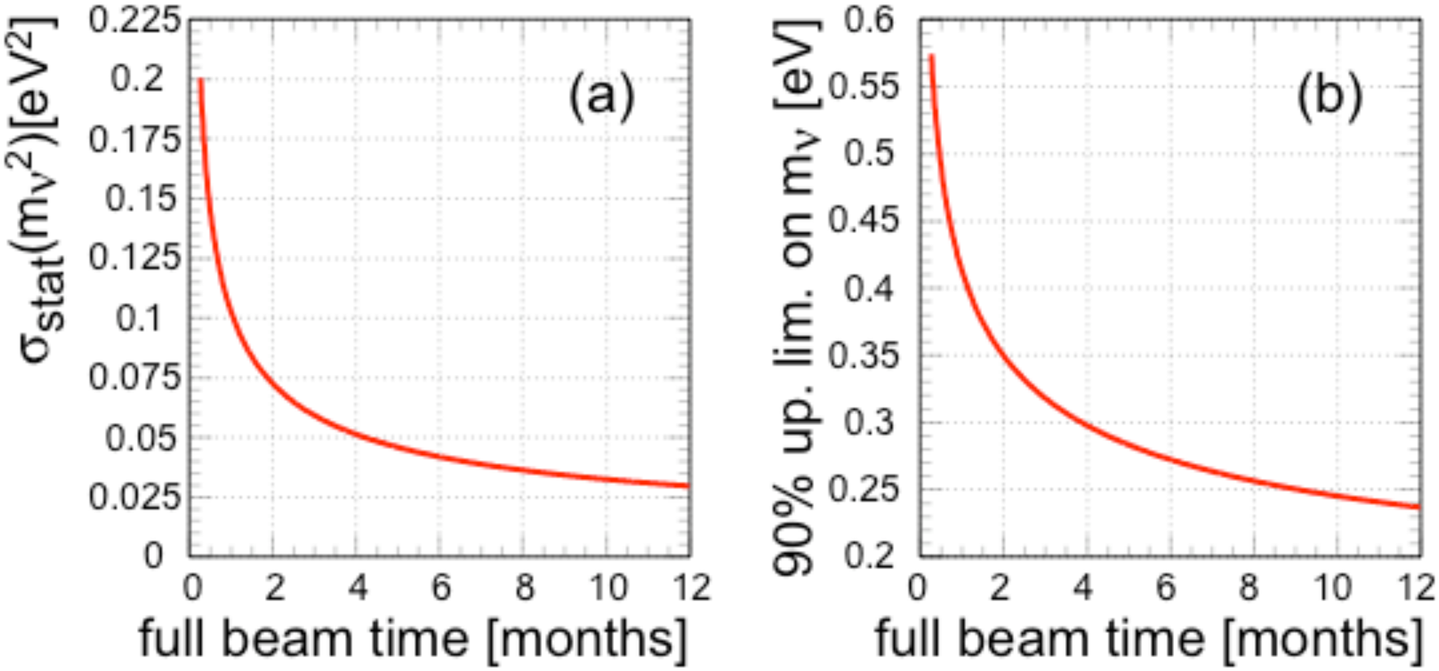
Adiabatic magnetic guiding of β´s along field lines in stray B-field of s.c. solenoids:
B_{max} = 6 T
B_{min} = 3×10^{-4} T

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

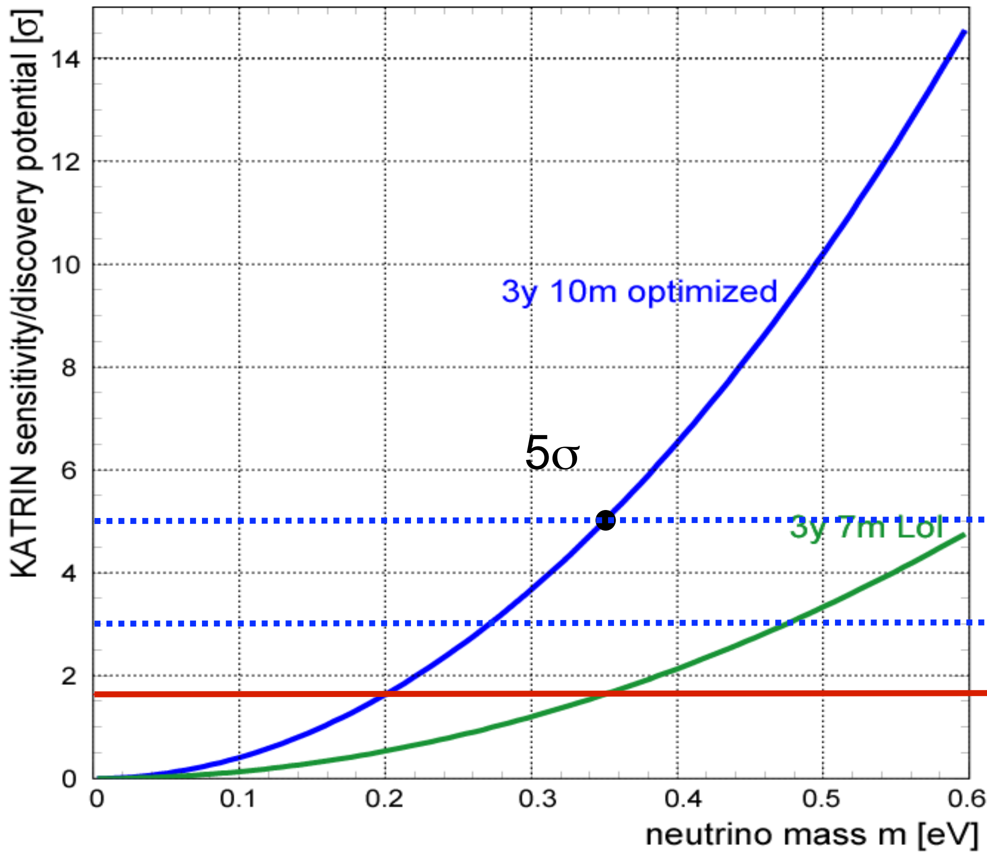
High pass filter with integral β transmission for E>qU



Sensitivity with run time



KATRIN:
sensitivity and discovery potential



Expectation for 3 full beam years:

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

discovery potential:

m_ν = 0.35eV (5σ)

m_ν = 0.27eV (3σ)

sensitivity:

m_ν < 0.2eV (90%CL)

Systematic Uncertainties

source of systematic shift	achievable/projected accuracy	systematic shift $\sigma_{syst}(m_\nu^2)[10^{-3}eV^2]$
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 < 6 (including a more realistic e-gun model)
monitoring of ρd $[E_0 - 40\,\mathrm{eV}, E_0 + 5\,\mathrm{eV}]$	$\Delta\epsilon_T/\epsilon_T < 2 \cdot 10^{-3}$ $\Delta T/T < 2 \cdot 10^{-3}$ $\Delta\Gamma/\Gamma < 2 \cdot 10^{-3}$ $\Delta p_{inj}/p_{inj} < 2 \cdot 10^{-3}$ $\Delta p_{ex}/p_{ex} < 0.06$	$< \frac{\sqrt{5} \cdot 6.5}{10}$
background slope	$< 0.5\,\mathrm{mHz/keV}$ (Troitsk)	< 1.2
HV variations	$\Delta HV/HV < 3\,\mathrm{ppm}$	< 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	$\sigma_{syst,tot} = \sqrt{\sum \sigma_{syst}^2} \simeq 0.01\,\mathrm{eV}^2$	

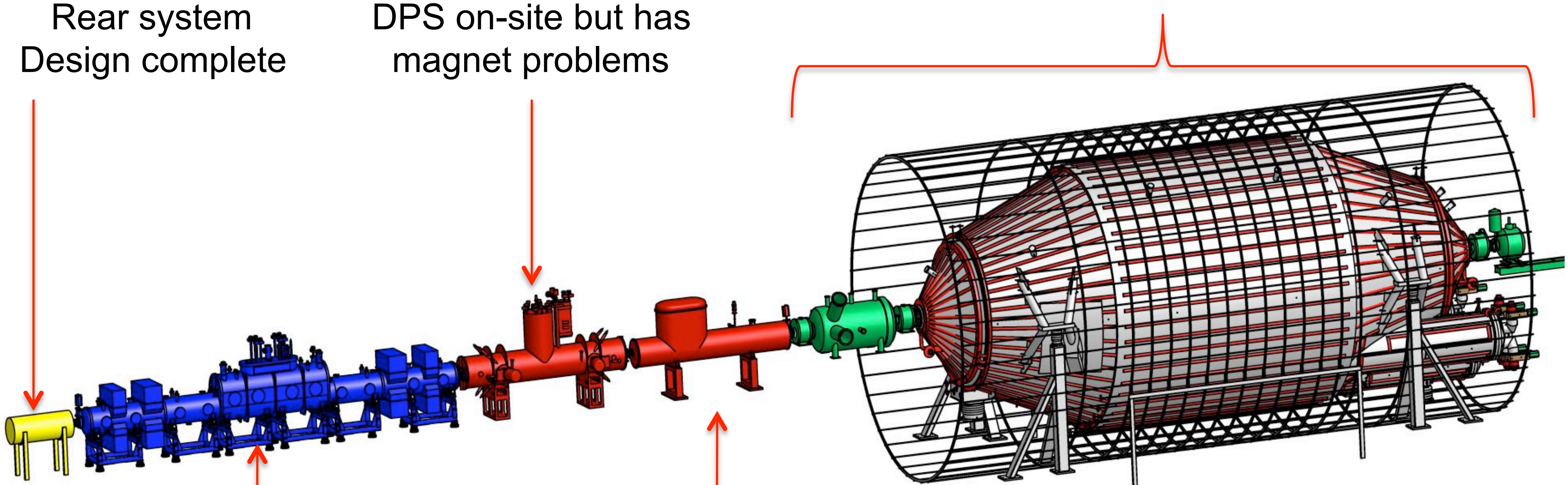
TABLE IV: Summary of sources of systematic errors on m_ν^2, the achievable or projected accuracy of experimental parameters (stabilization) and the individual effect on m_ν^2 for an analysis interval of $[E_0 - 30\,\mathrm{eV}, E_0 + 5\,\mathrm{eV}]$ if not stated otherwise.

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