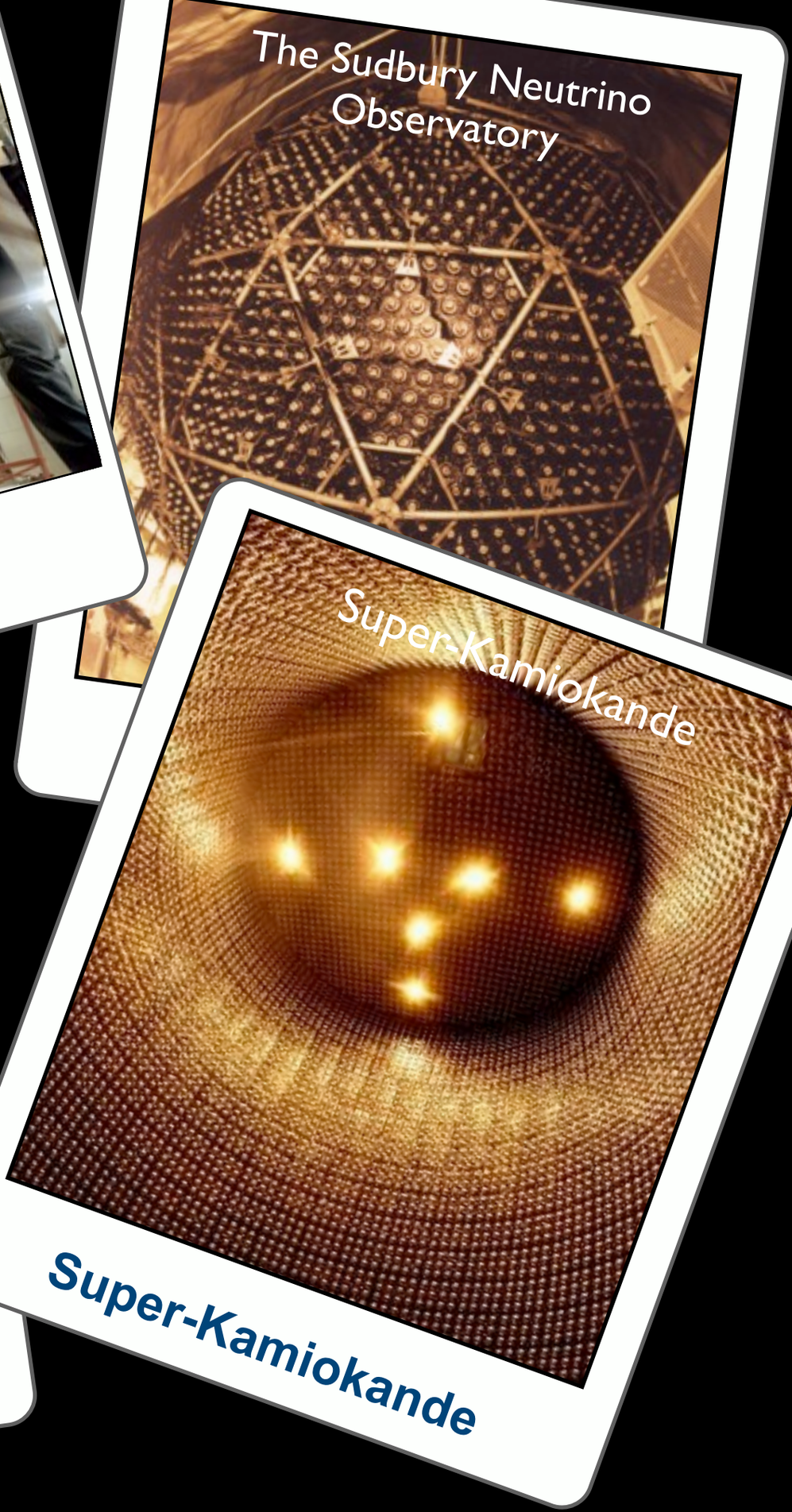
Measuring the Mass Scale of Neutrinos

J.A. Formaggio
Massachusetts Institute of Technology

Body of Evidence



The phenomena of neutrino oscillations is now firmly established.

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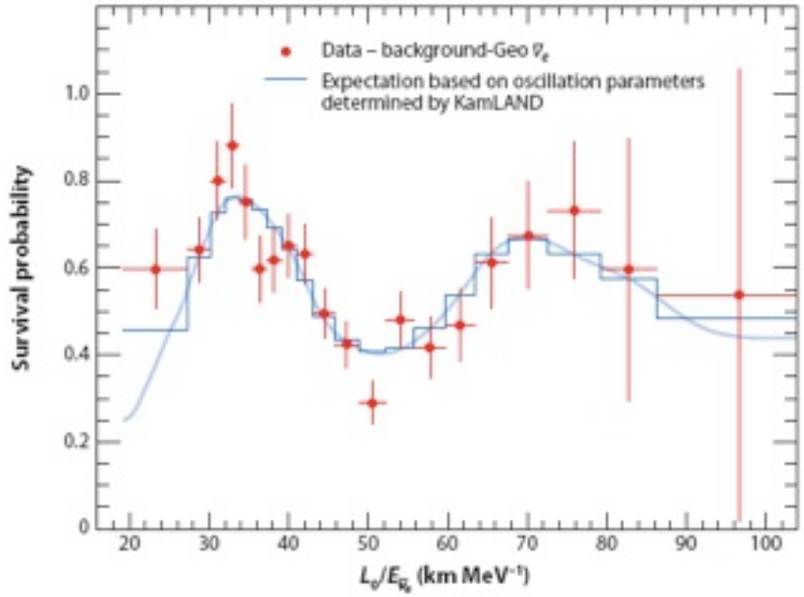
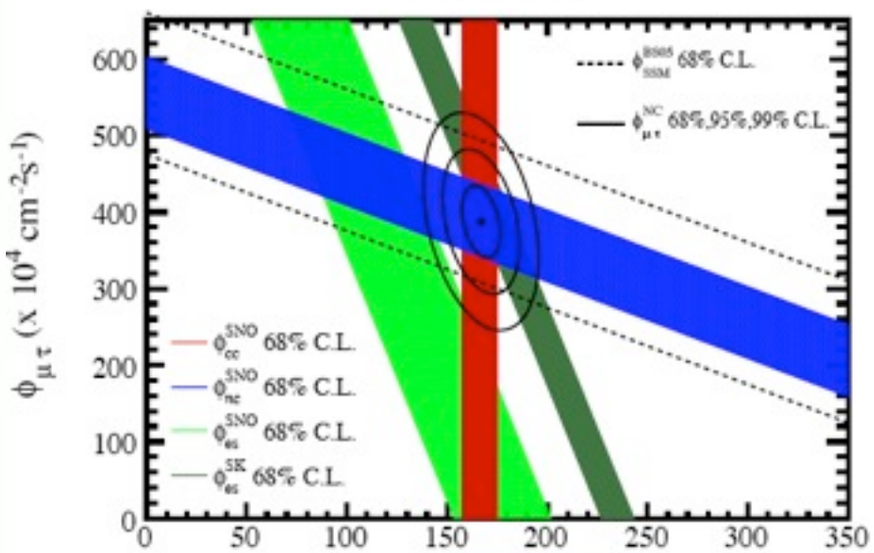


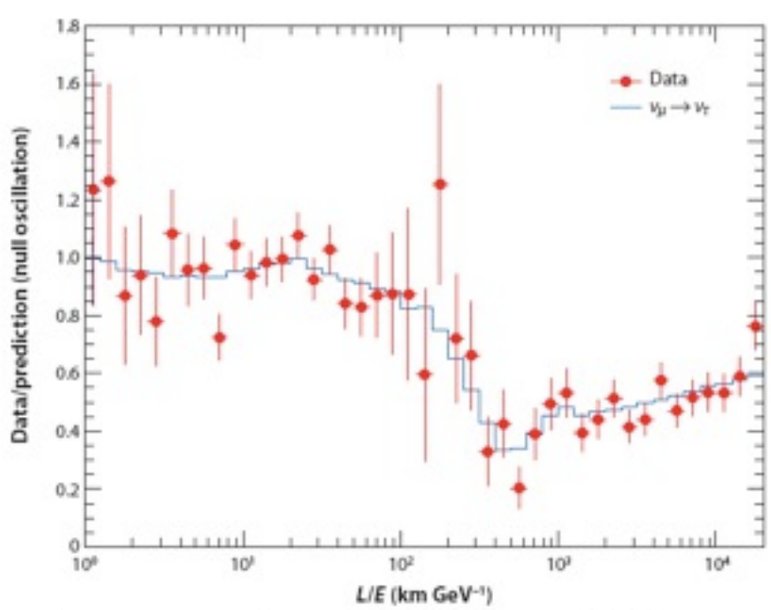
$$\sin^2(\theta_{13}) = 0.0241 \pm 0.0025$$

Reactor & Long Baseline



$$\sin^2(\theta_{12}) = 0.307 \pm 0.016$$
$$\Delta m^2_{12} = (7.54 \pm 0.26) \times 10^{-5}\ \mathrm{eV}^2$$

Solar



$$\sin^2(\theta_{23}) = 0.386 \pm 0.022$$
$$\Delta m^2_{23} = (2.43 \pm 0.09) \times 10^{-3}\ \mathrm{eV}^2$$

Atmospheric

The phenomena of neutrino oscillations is now firmly established.

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

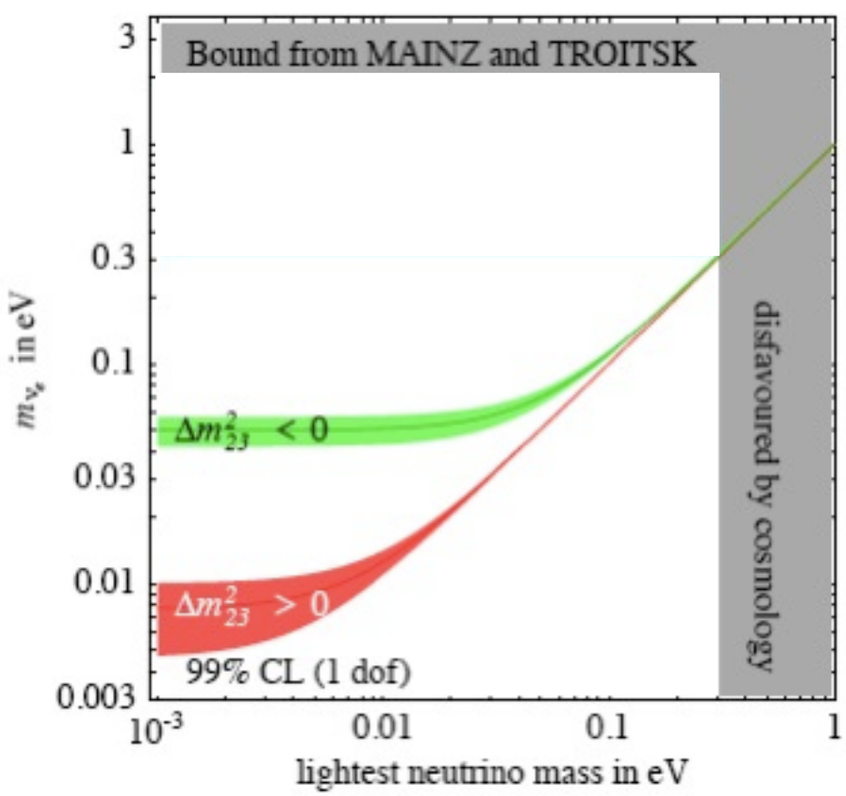
More Questions

<u>What We Don't Know</u>

(1) What is the absolute scale of neutrinos?

(2) What is the mass hierarchy?

(3) What is the nature of neutrino mass?



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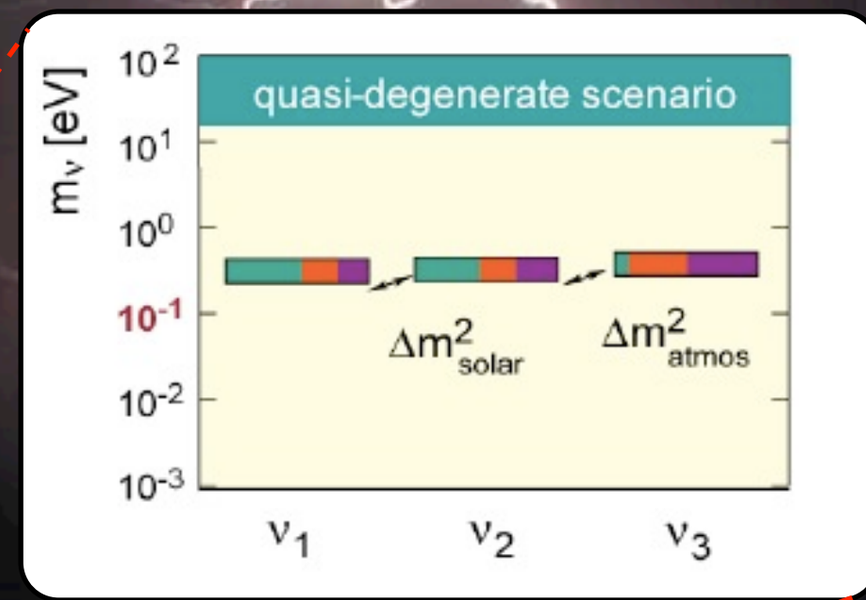

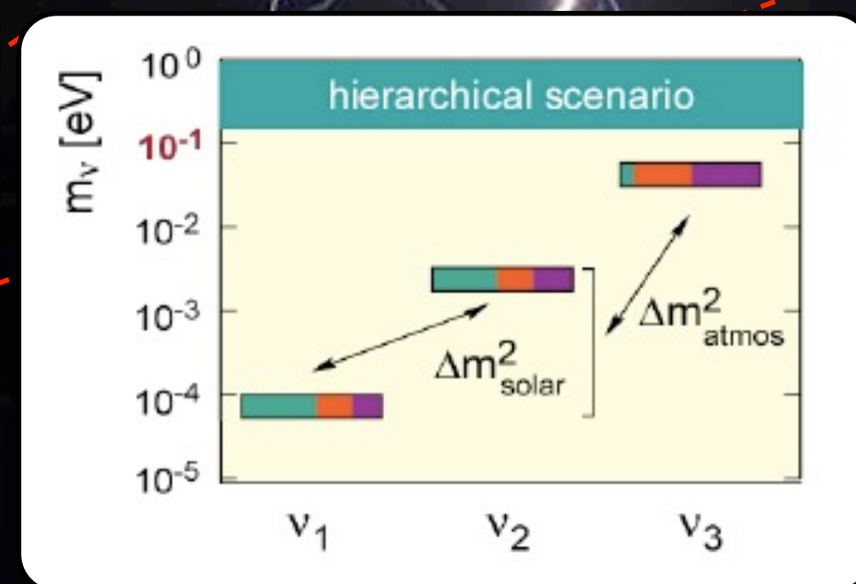

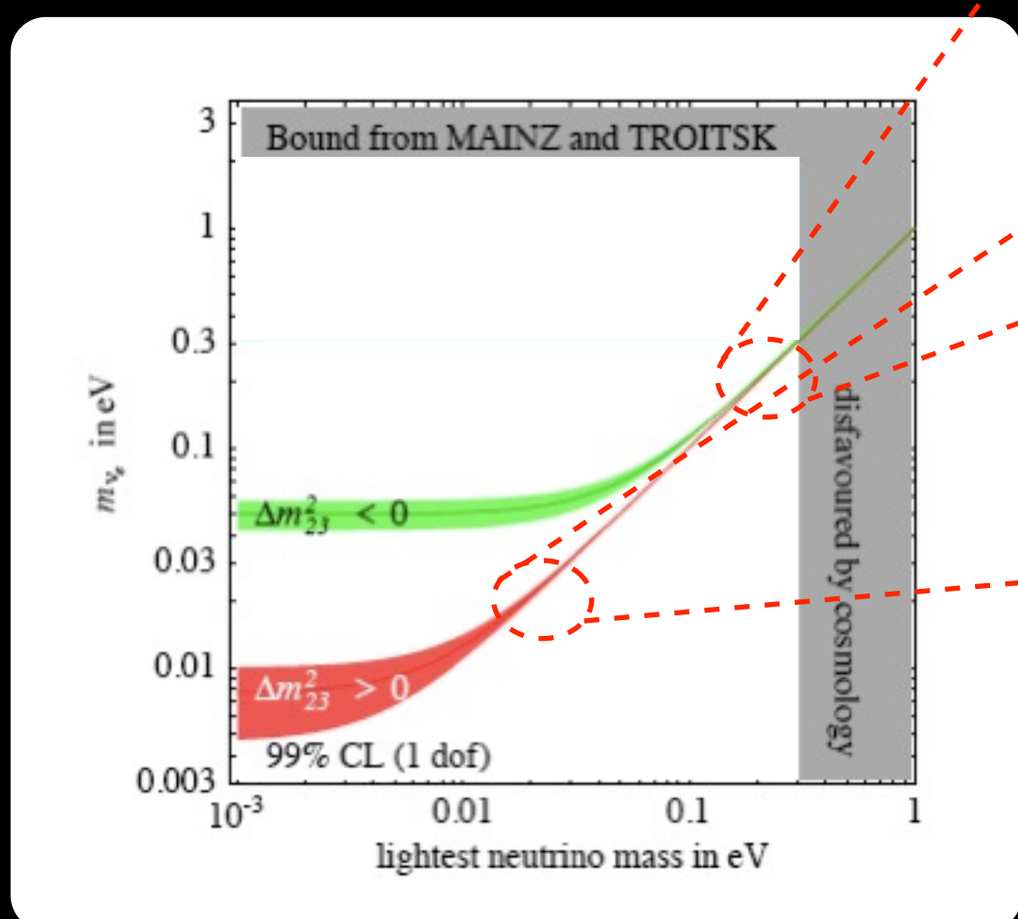

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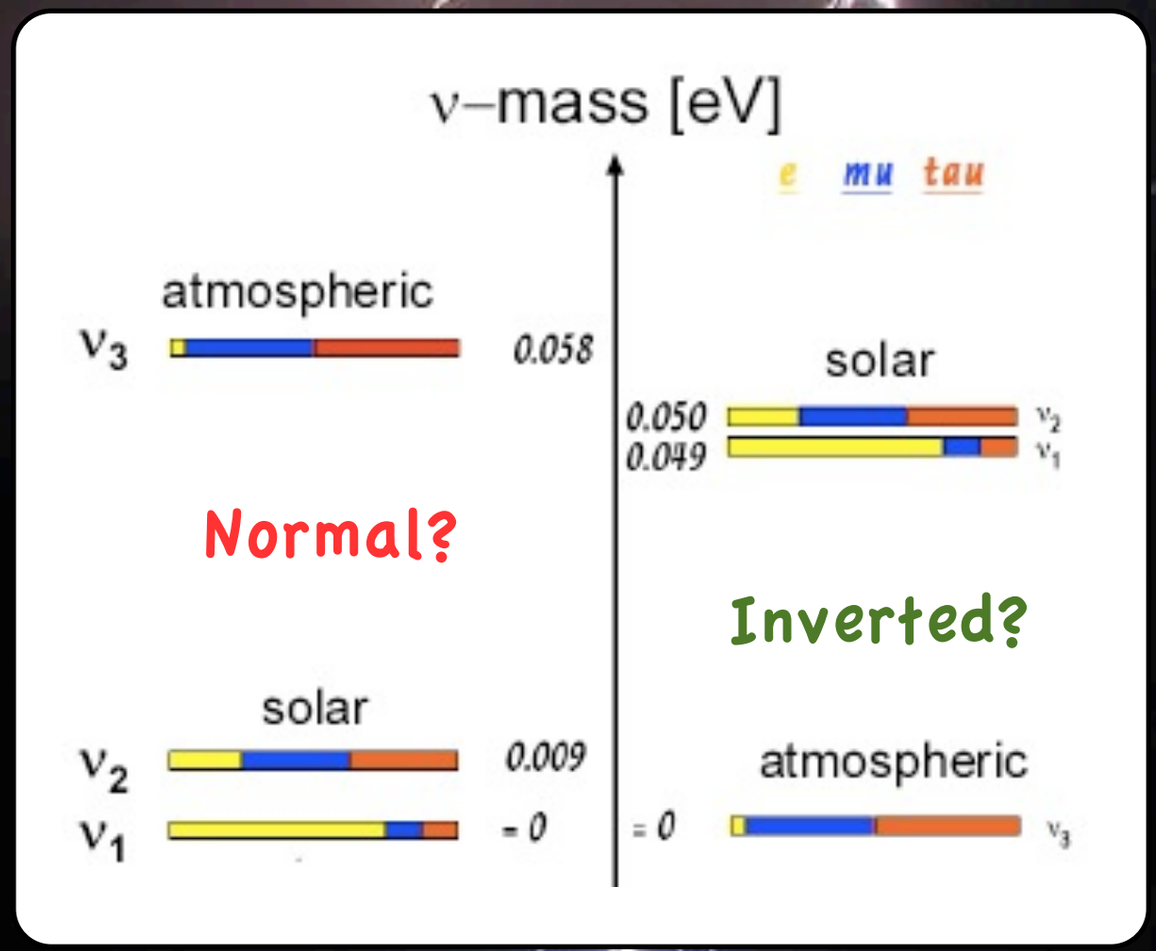

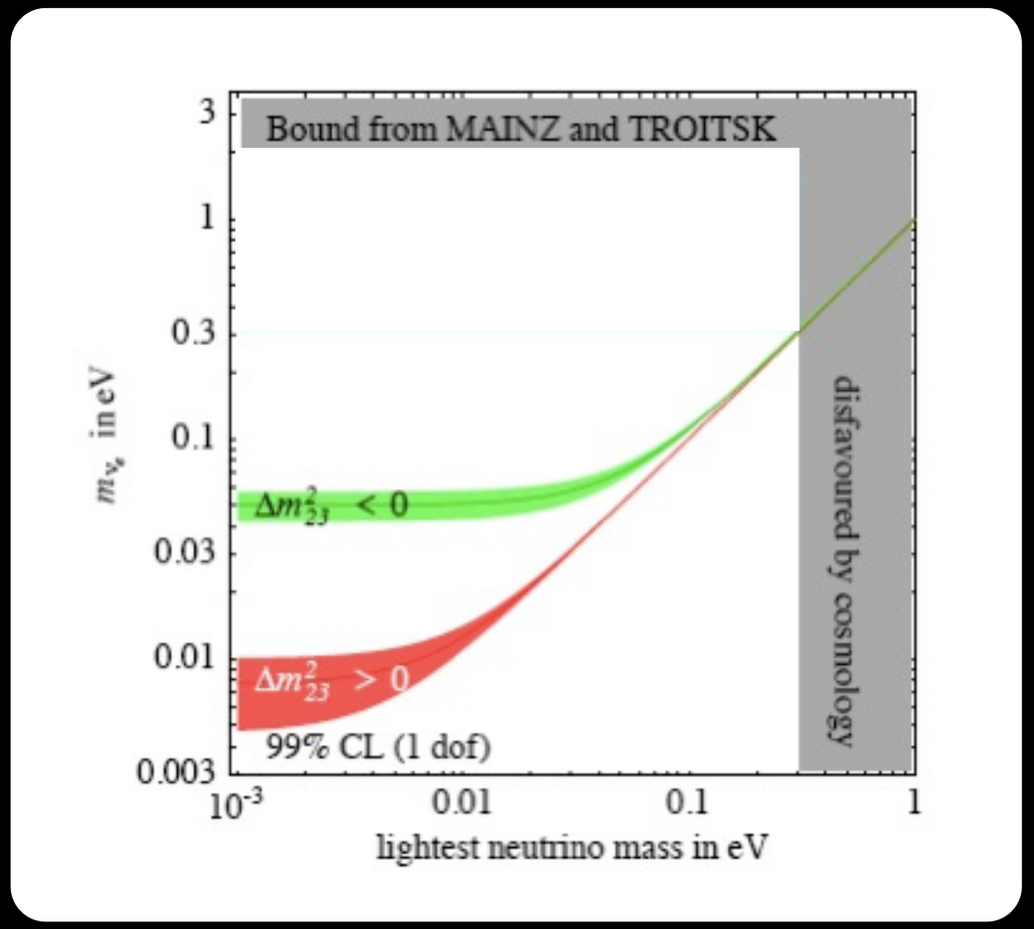

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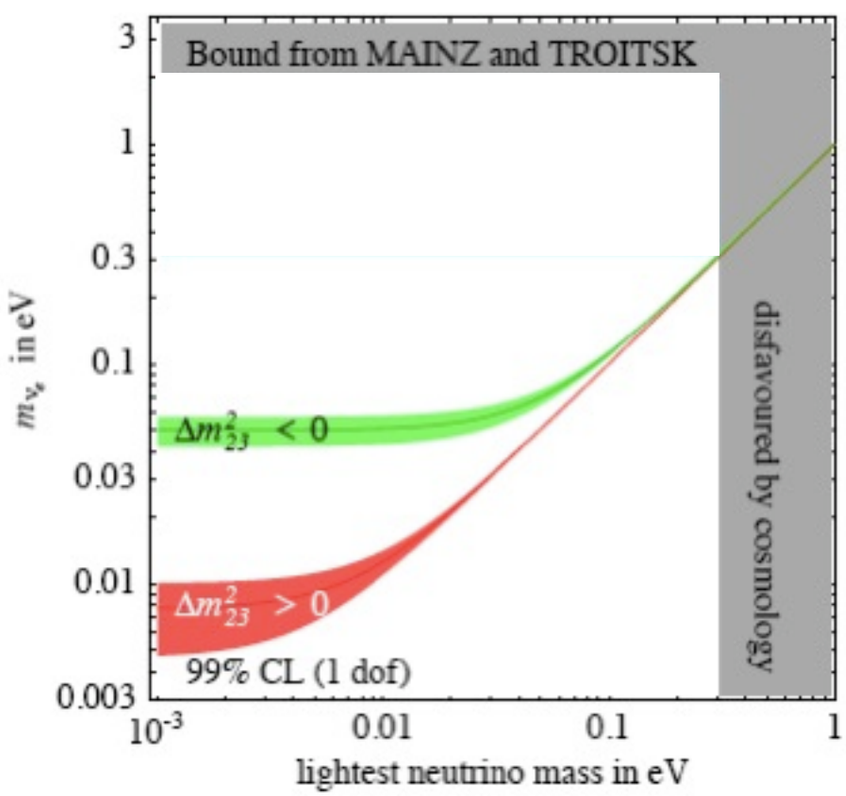
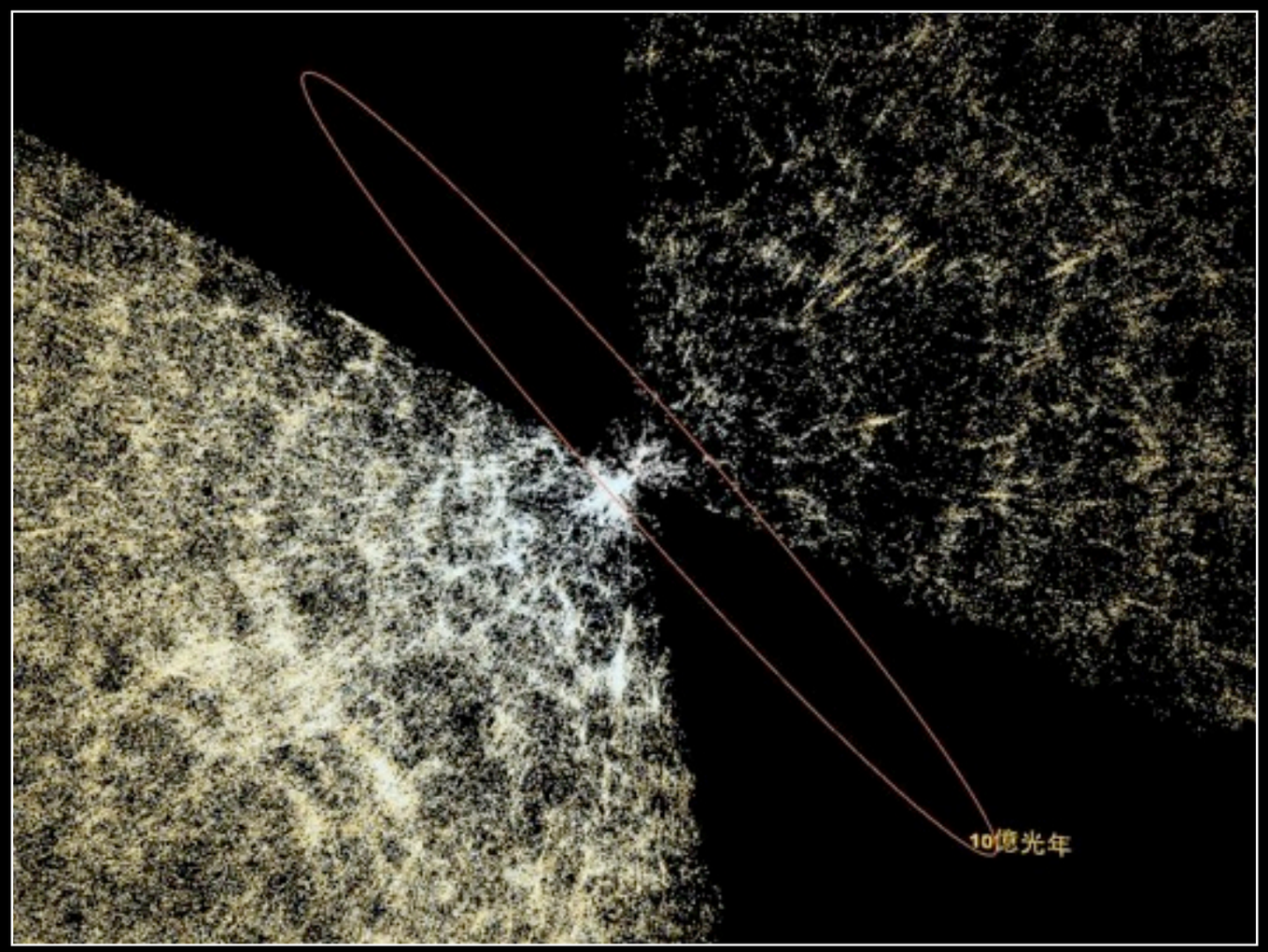


Dirac

Majorana?

Neutrino Masses from Cosmology

- Cosmology looks at the *sum* of neutrino masses (gravitational effect)

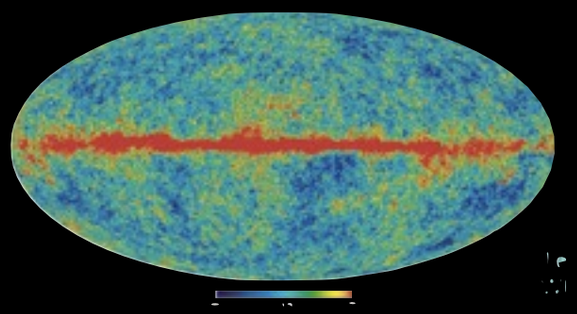


Large Scale Structure

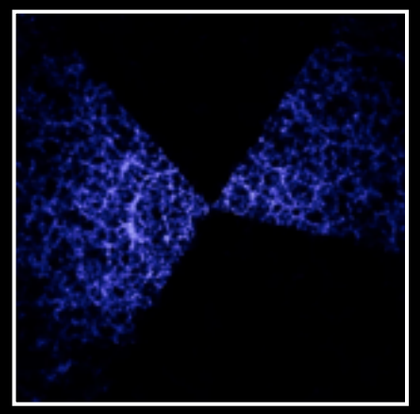
$$\Omega_\nu = \frac{\rho_\nu}{\rho_{\rm critical}} = \frac{\sum_i^{n_\nu} m_{\nu,i}}{\rho_{\rm critical}}$$

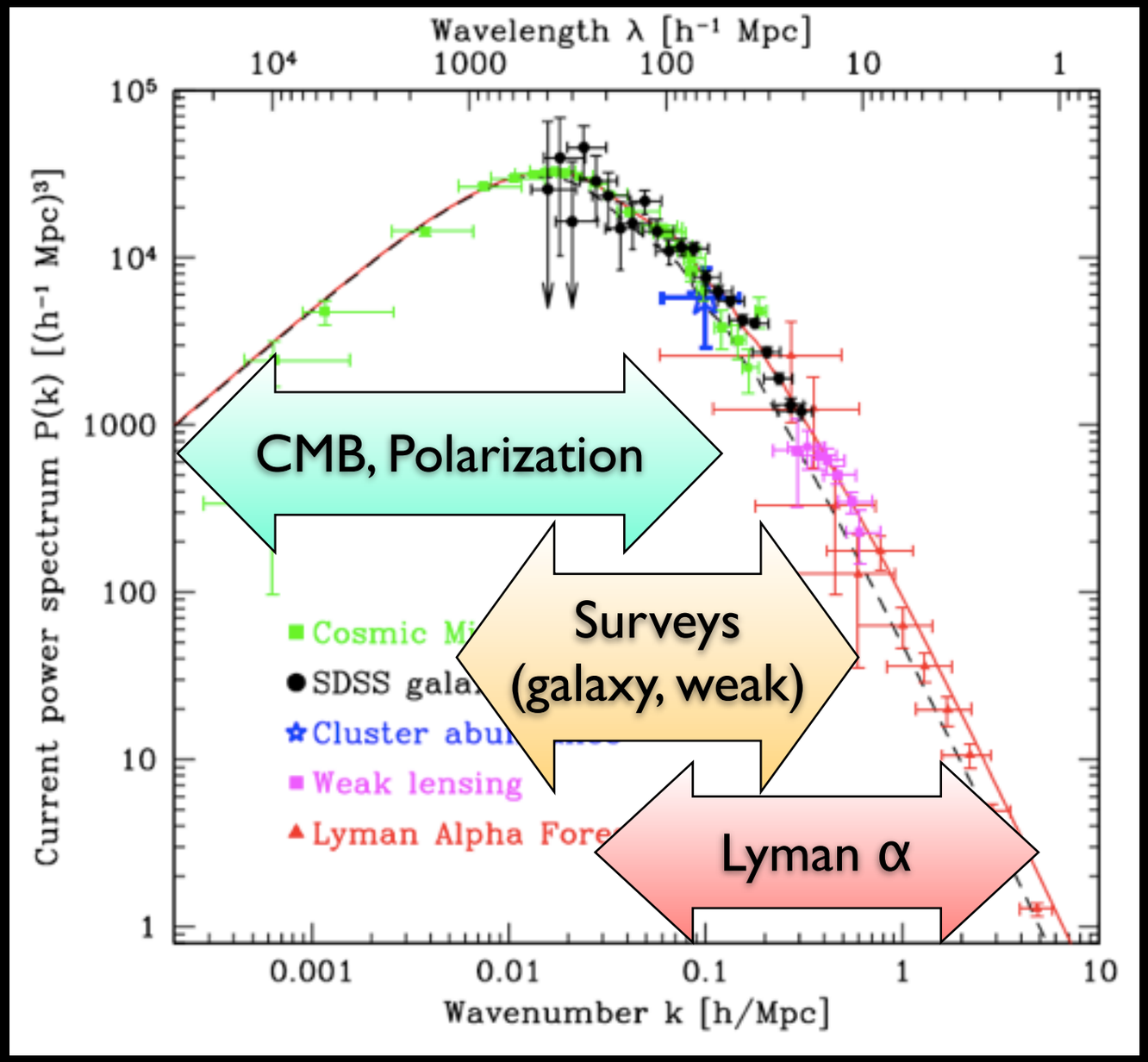
The Strategy
(a naive view)

WMAP Temperature Map

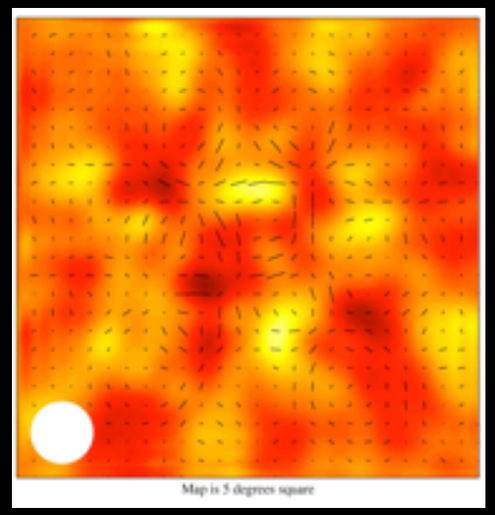


Galaxy Surveys



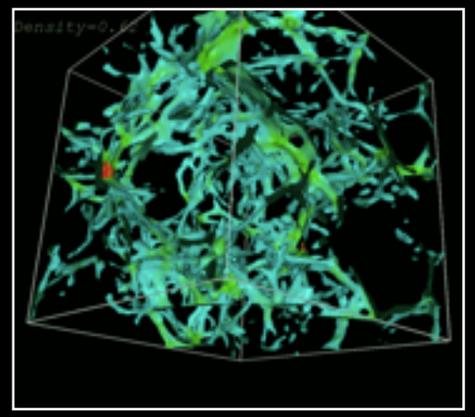


Weak lensing



CMB Polarization

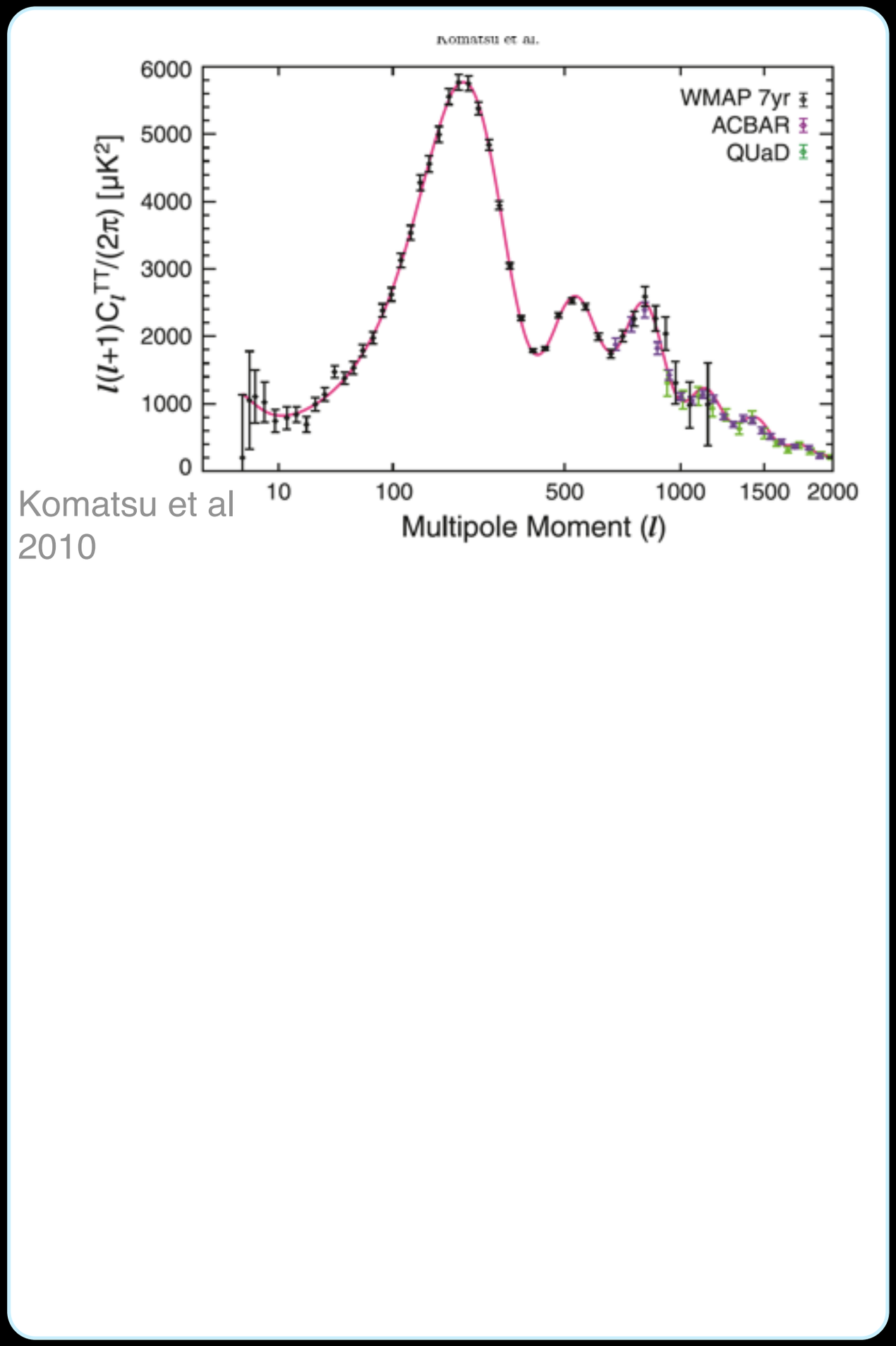
Max Tegmark, 2005



Lyman α

Current Limits

- Limits for neutrino masses depend in part on:
  - Which data is used, and...
  - ...what assumptions are made.



Komatsu et al 2010

Set	$w = -1$	$w \neq -1$
WMAP 7 only	$\Sigma m_\nu < 1.3$ eV	$\Sigma m_\nu < 1.4$ eV
WMAP7 + BAO + HO	$\Sigma m_\nu < 0.58$ eV	$\Sigma m_\nu < 1.3$ eV
WMAP7 + BAO + SN	$\Sigma m_\nu < 0.7$ eV	$\Sigma m_\nu < 0.9$ eV

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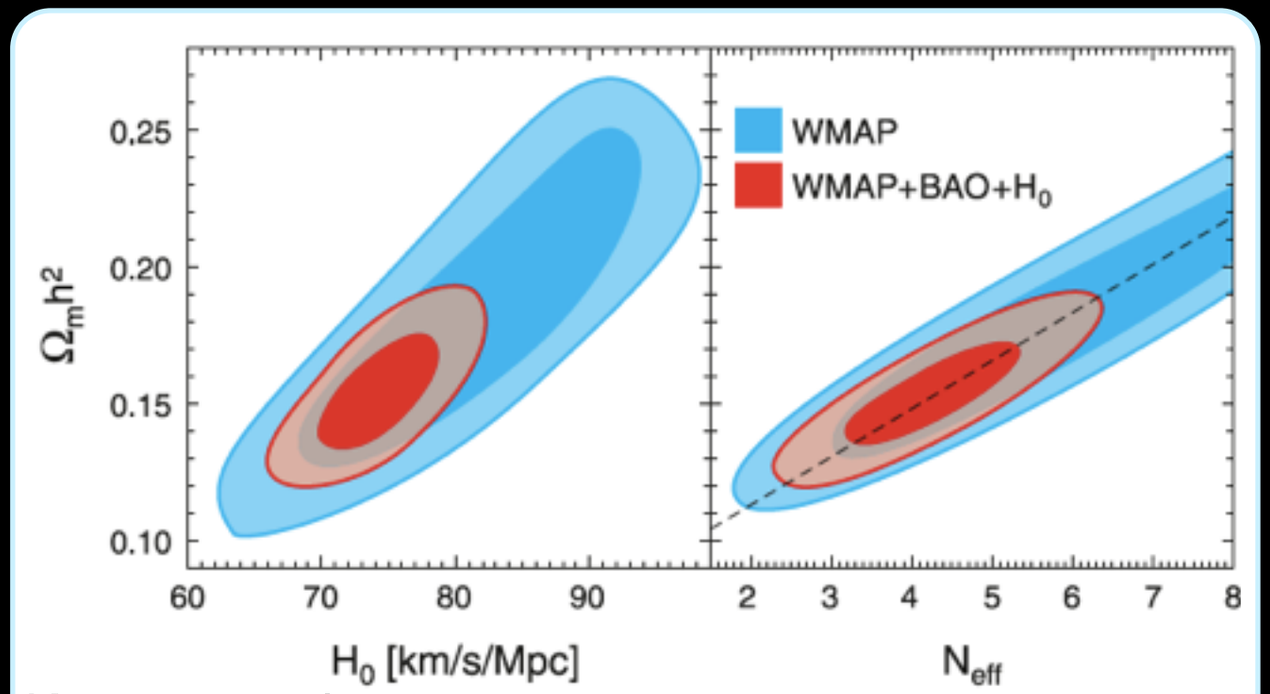
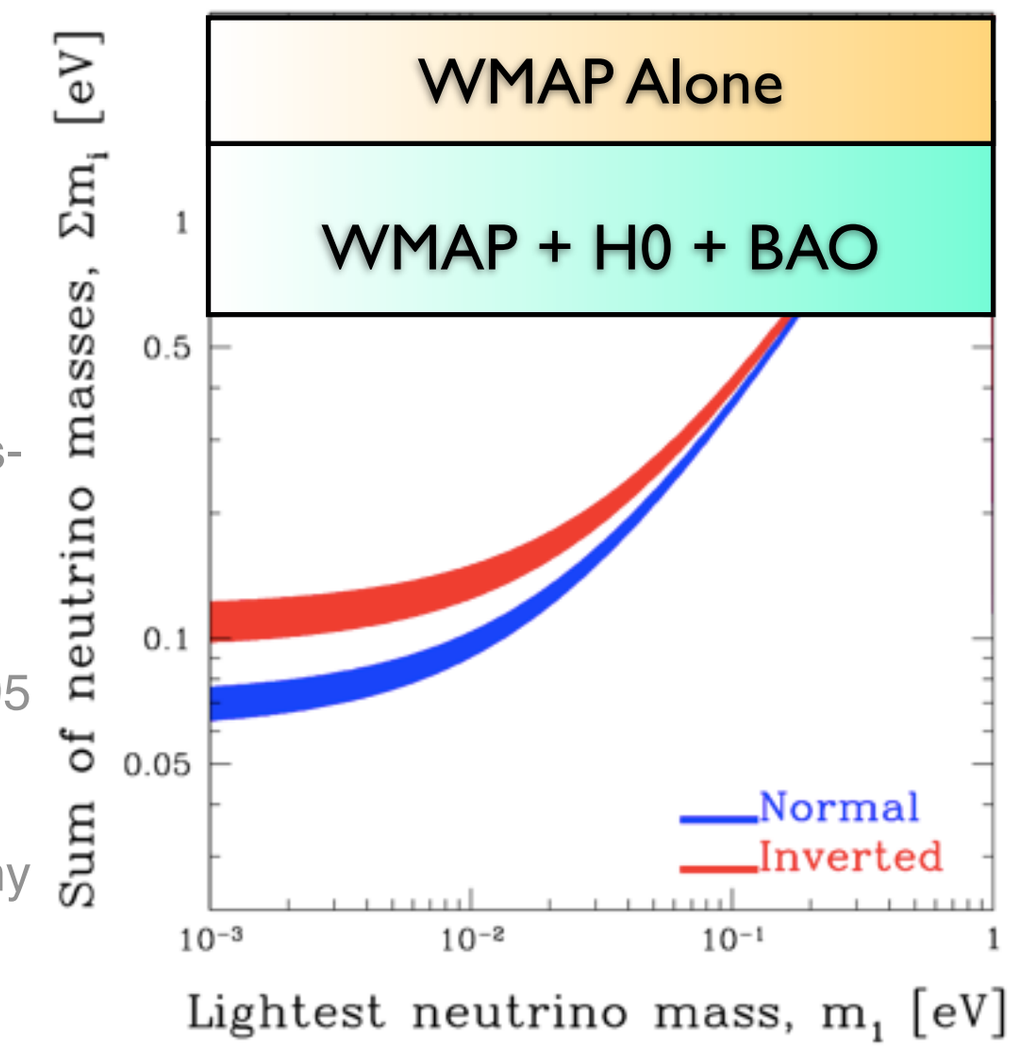


Komatsu et al 2010



Gonzales-Garcia

arXiv: 1006.3795 v2

(and many others)

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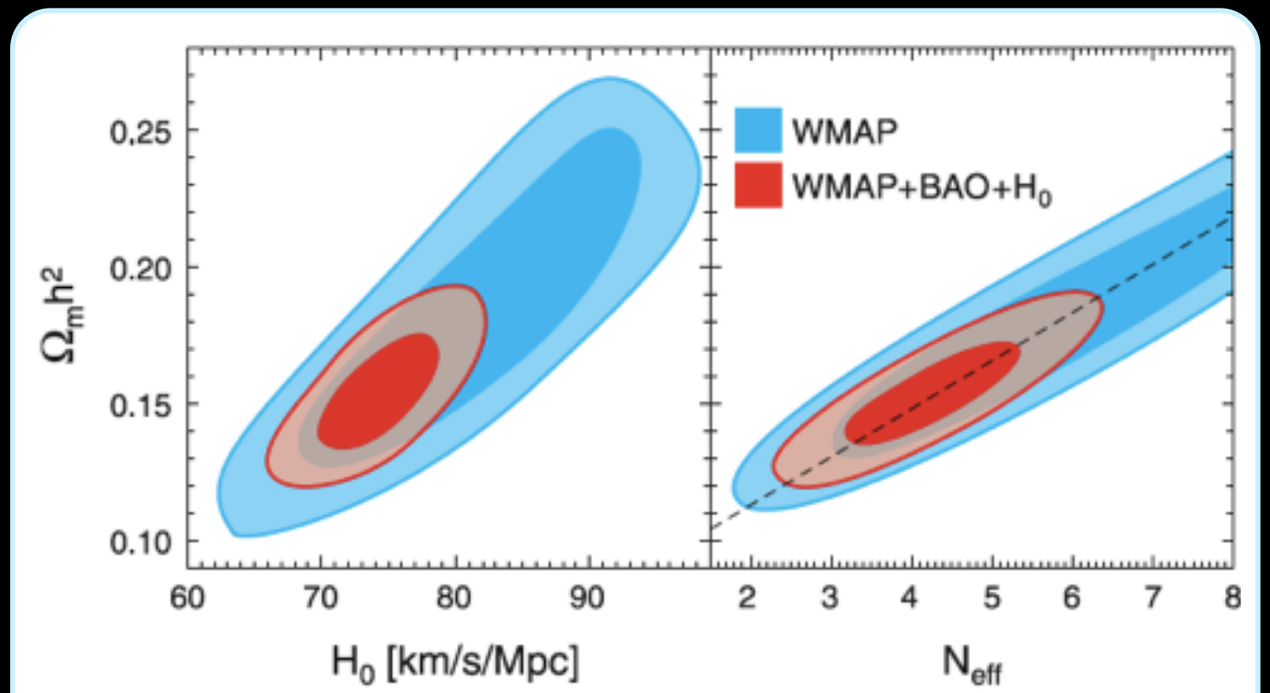

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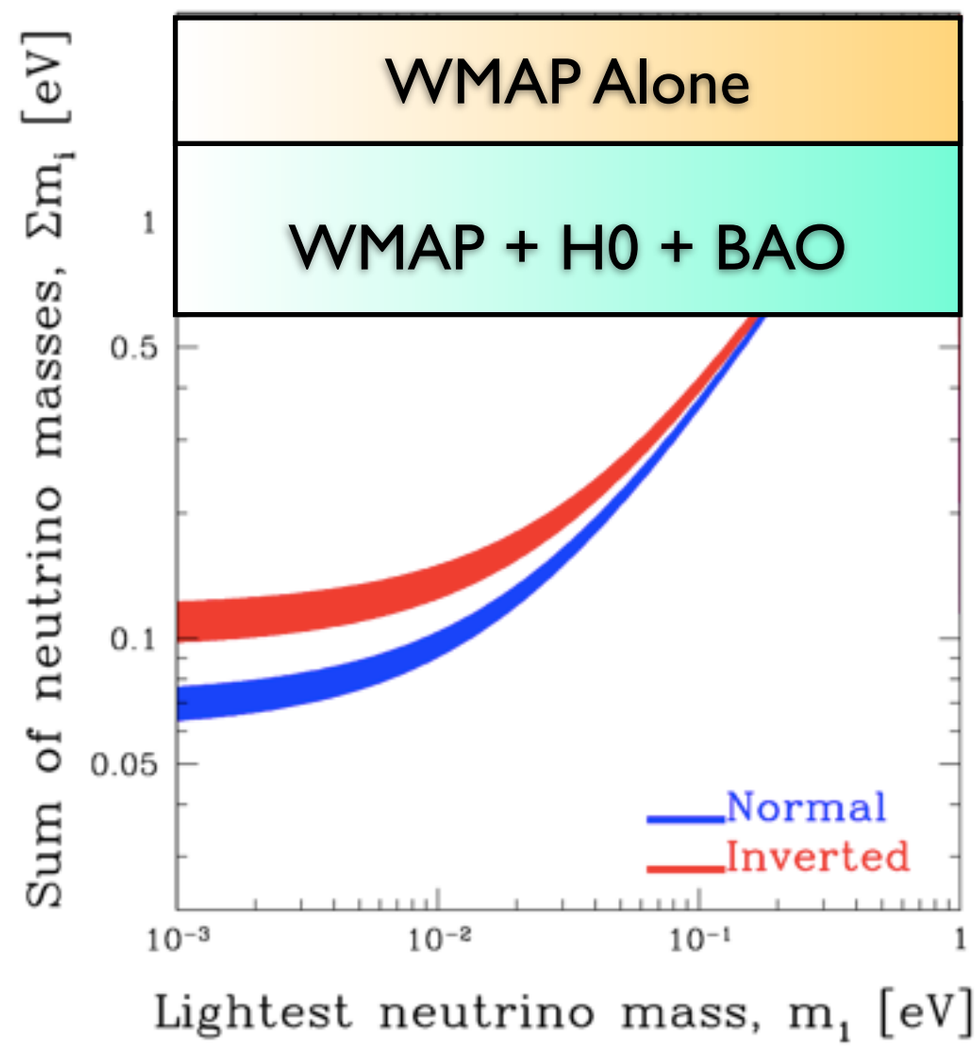

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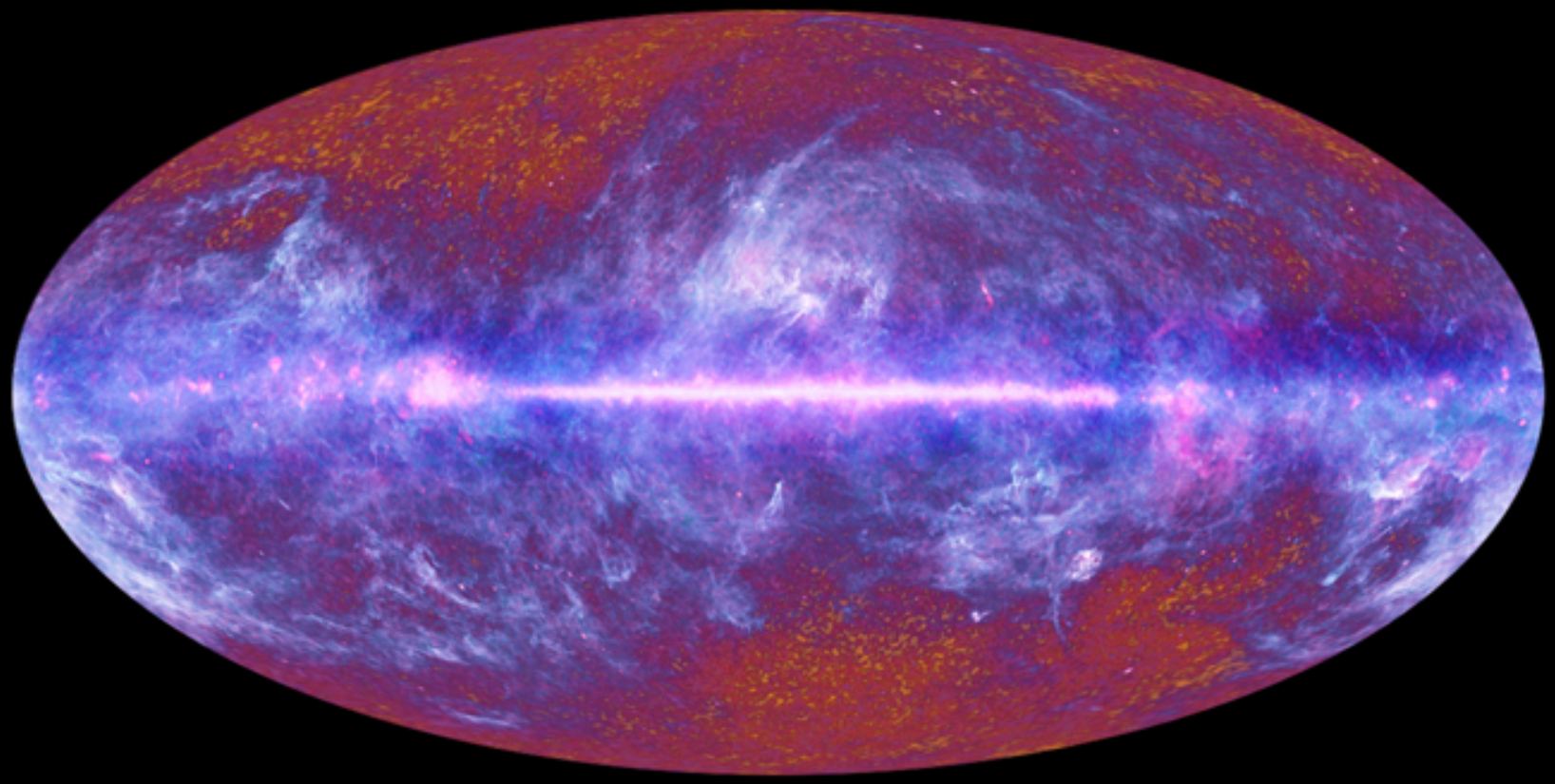
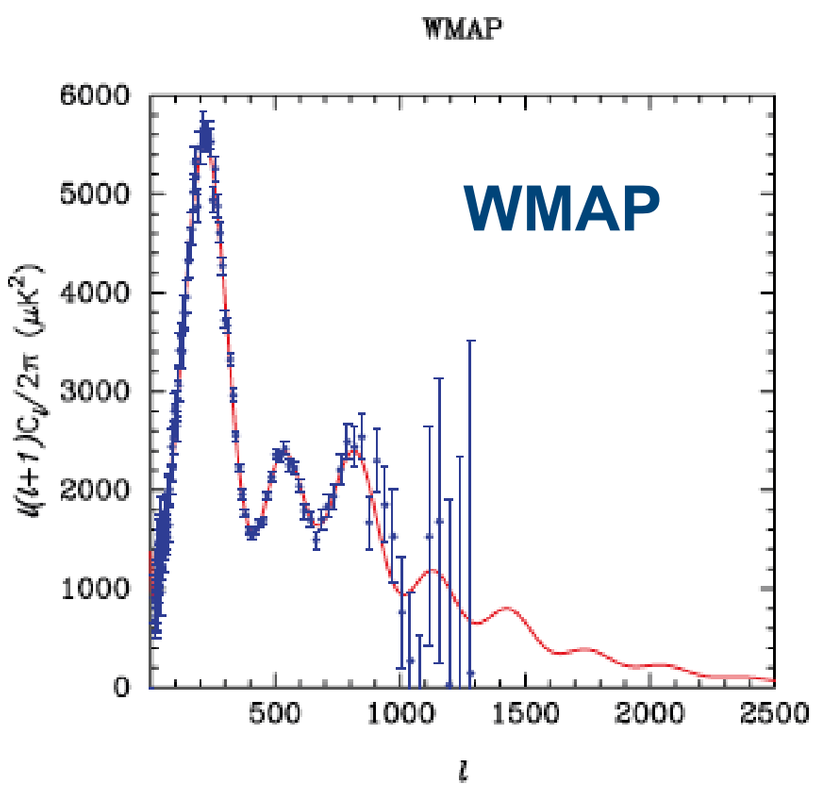
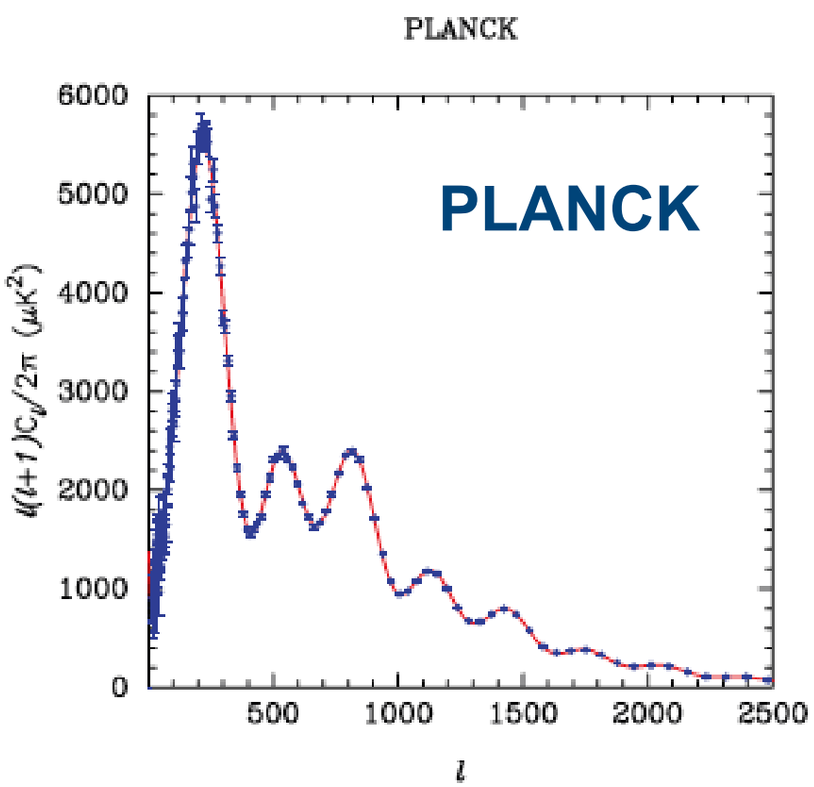
PLANCK



- Planck alone can push neutrino limits down 1 eV.
- Host of new experiments coming to the forefront can push even lower.





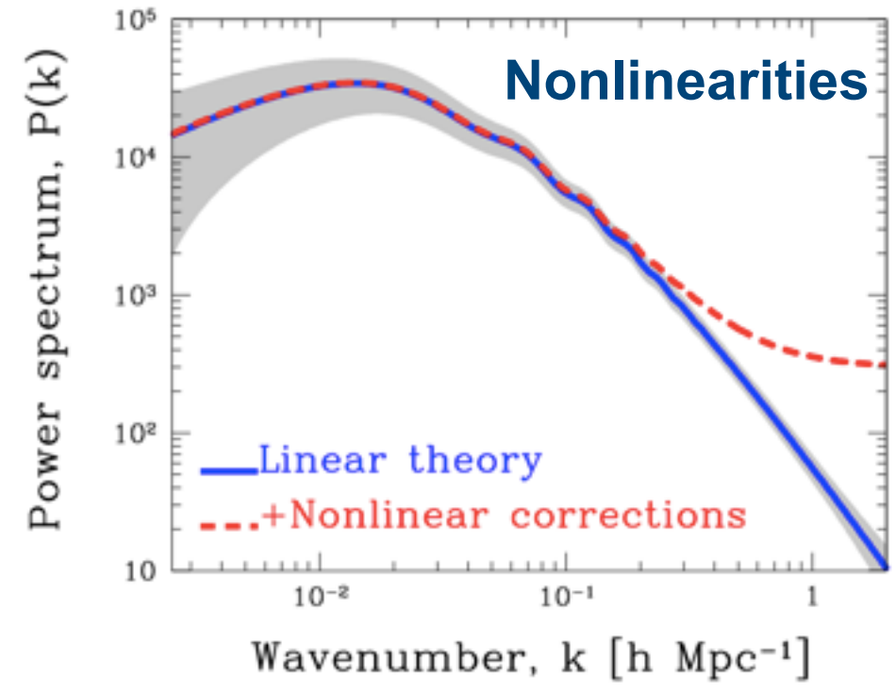
Moving Forward...

Moving to the normal hierarchy scale now requires 1% precision on the power spectrum.

$$\frac{\Delta P}{P} \simeq -12\frac{\Omega_\nu}{\Omega_m} \simeq 1\%$$

Systematic Effects

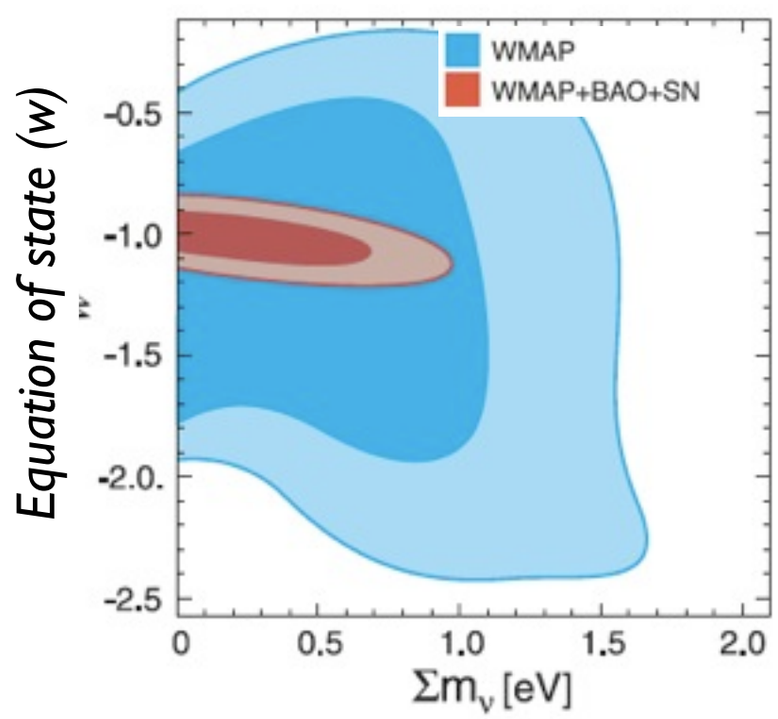
- As precision demands moves to 1%, non-linear effects, degeneracies, baryons, etc. all begin to play a role.
- Numerical simulations and semi-analytical techniques used to address.



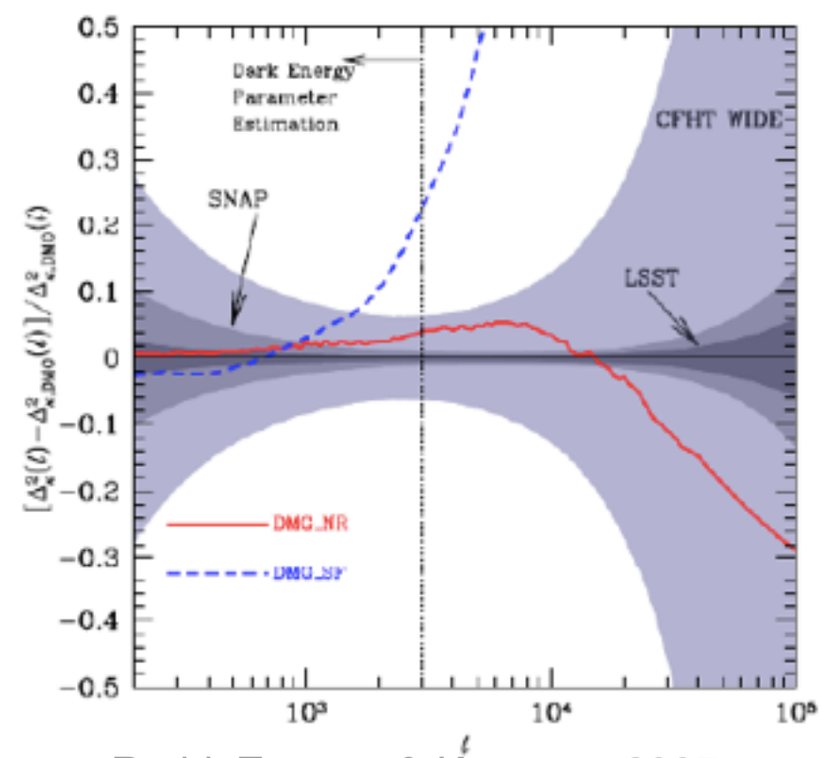
Y. Y. Y. Wong, 2010

Degeneracies

S. Hannestad
Phys. Rev. Lett 95 221301



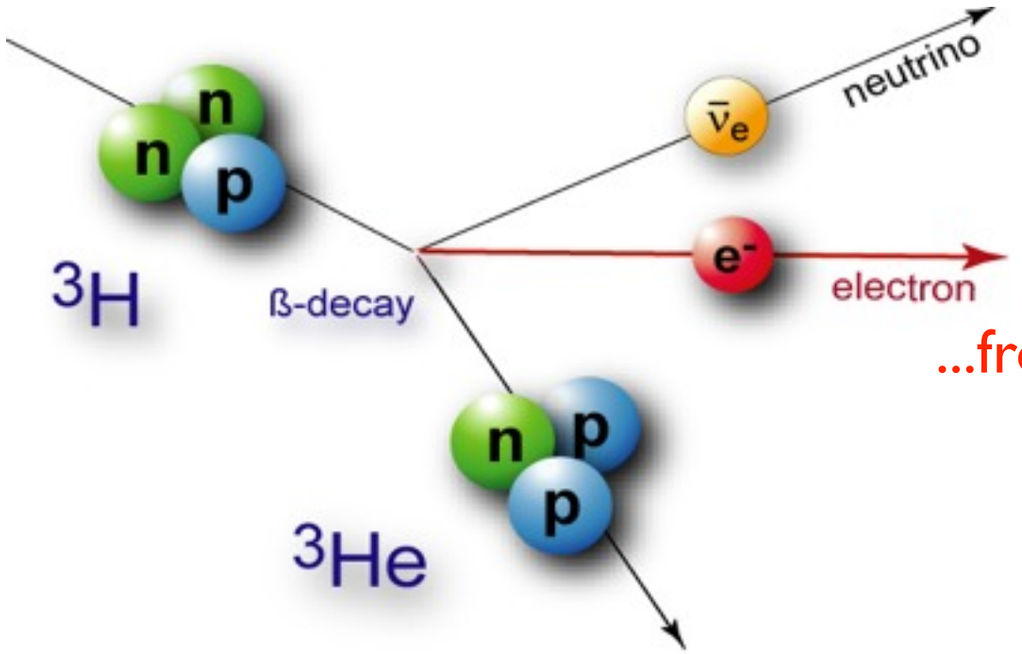
Baryon Effects



Rudd, Zentner & Kravtsov, 2007

Direct Probes

If massive, the neutrino takes away some energy...



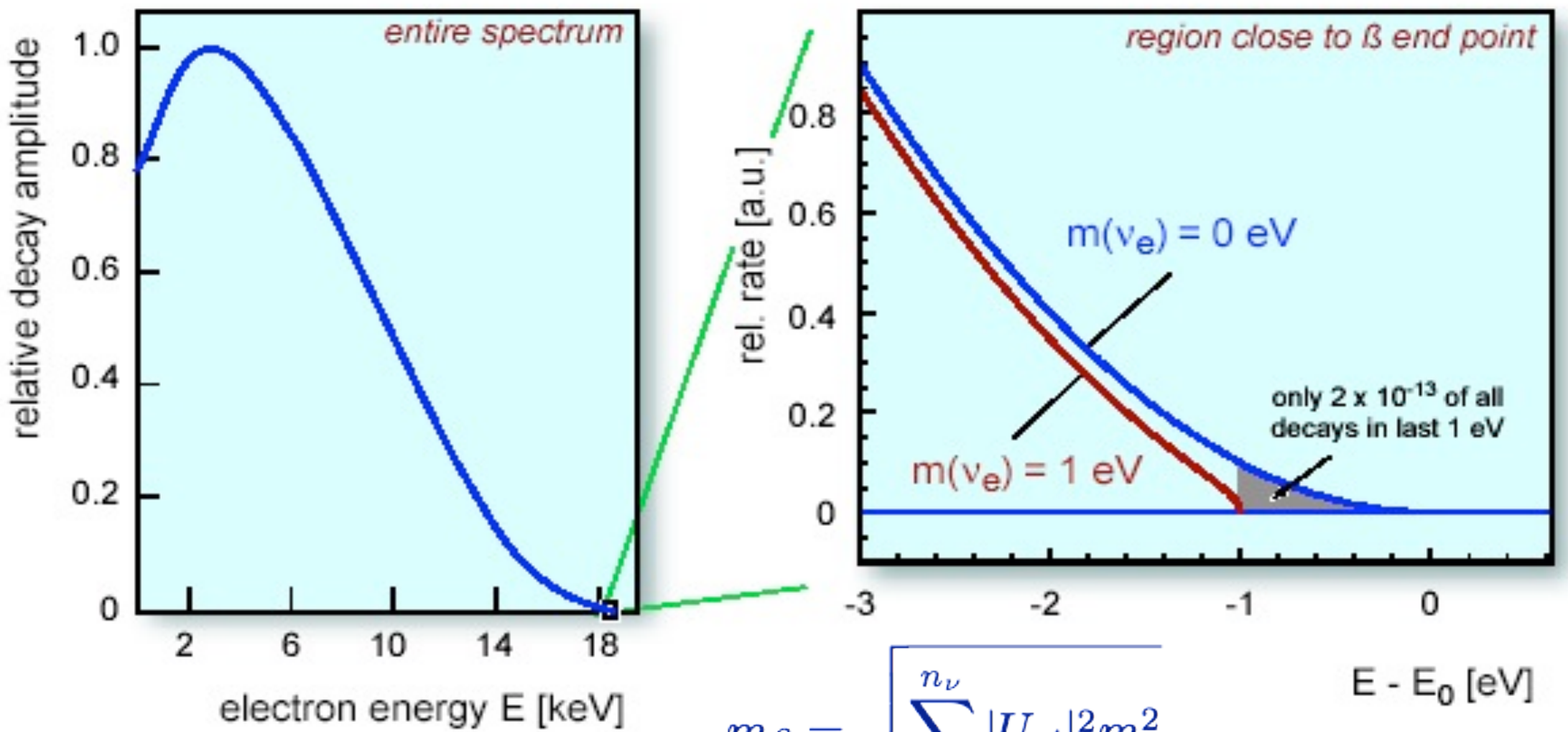
...from the electron (which we detect)

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

Beta decay allows a kinematic determination of the neutrino mass

No dependence on cosmological models or matrix elements

Direct Probes



$$m_\beta = \sqrt{\sum_{i=1}^{n_\nu} |U_{ei}|^2 m_i^2}$$

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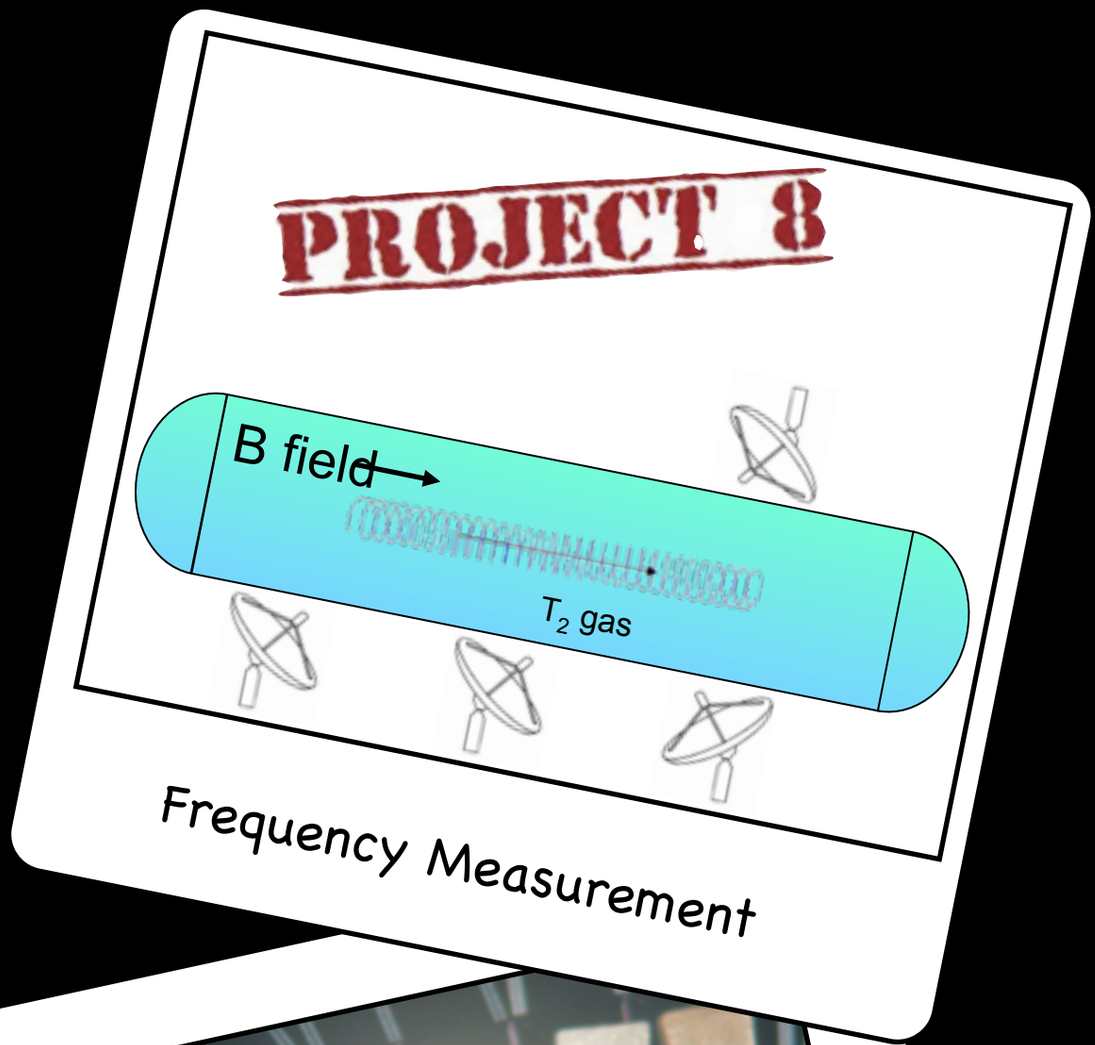


KATRIN
Electromagnetic Spectroscopy

MARE & ECHO
Calorimetry

KATRIN is currently the prominent experiment for beta decay measurements.

New techniques being explored in the future:

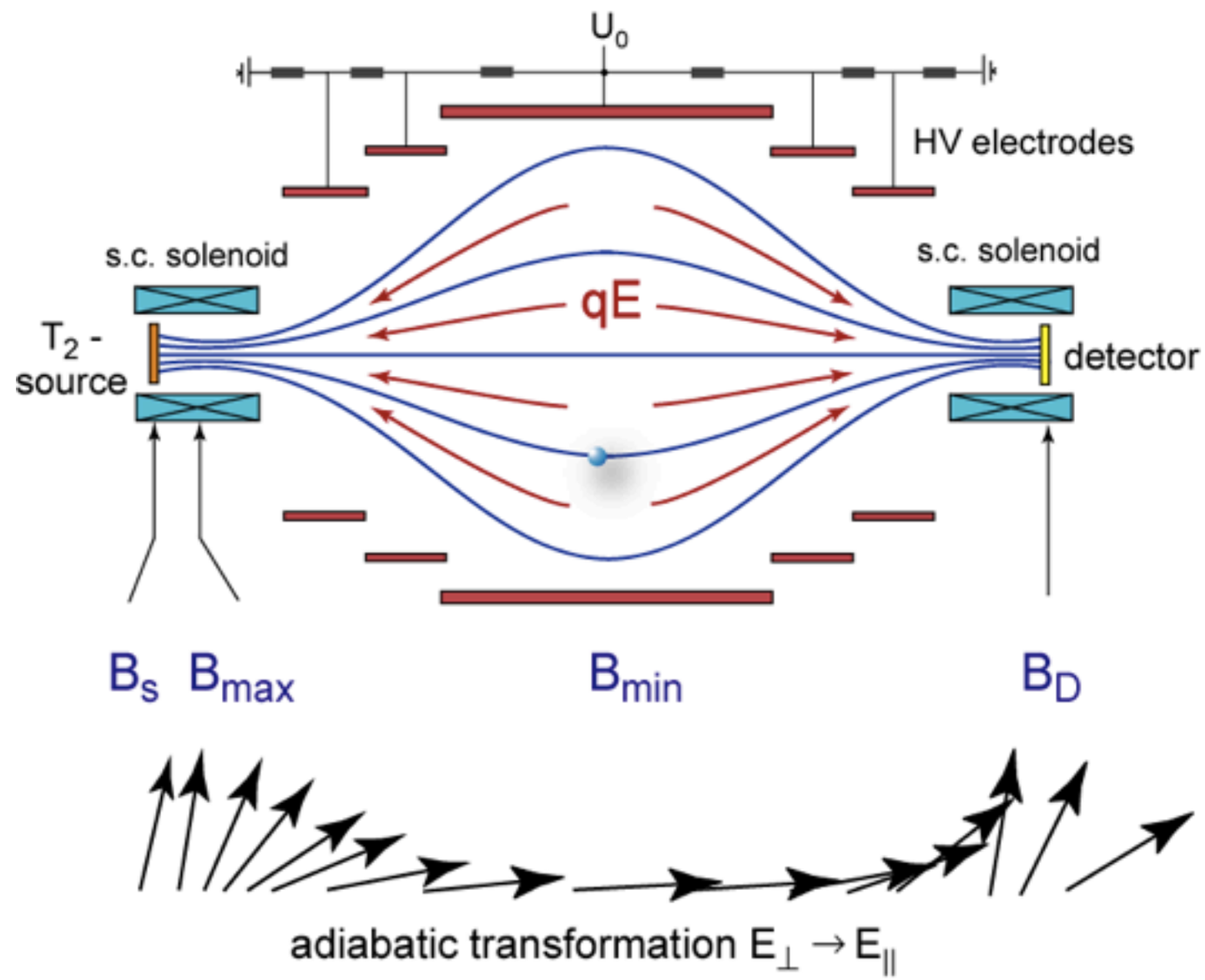
MARE and Project 8

MAC-E Filter Technique

KATRIN

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

Spectroscopic: MAC-E Filter

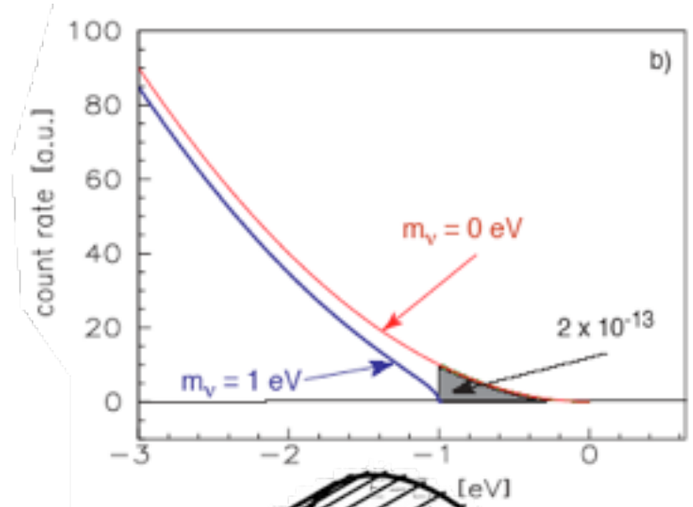


Inhomogeneous magnetic guiding field.

Retarding potential acts as high-pass filter

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

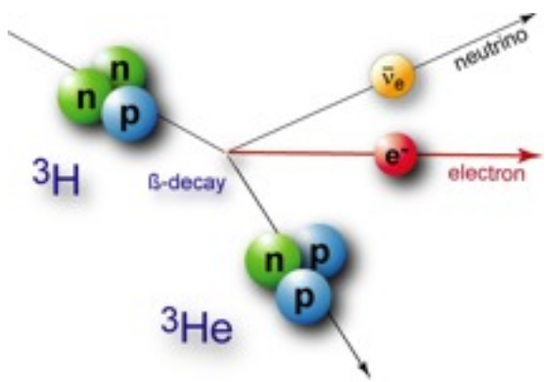
The KATRIN Experiment

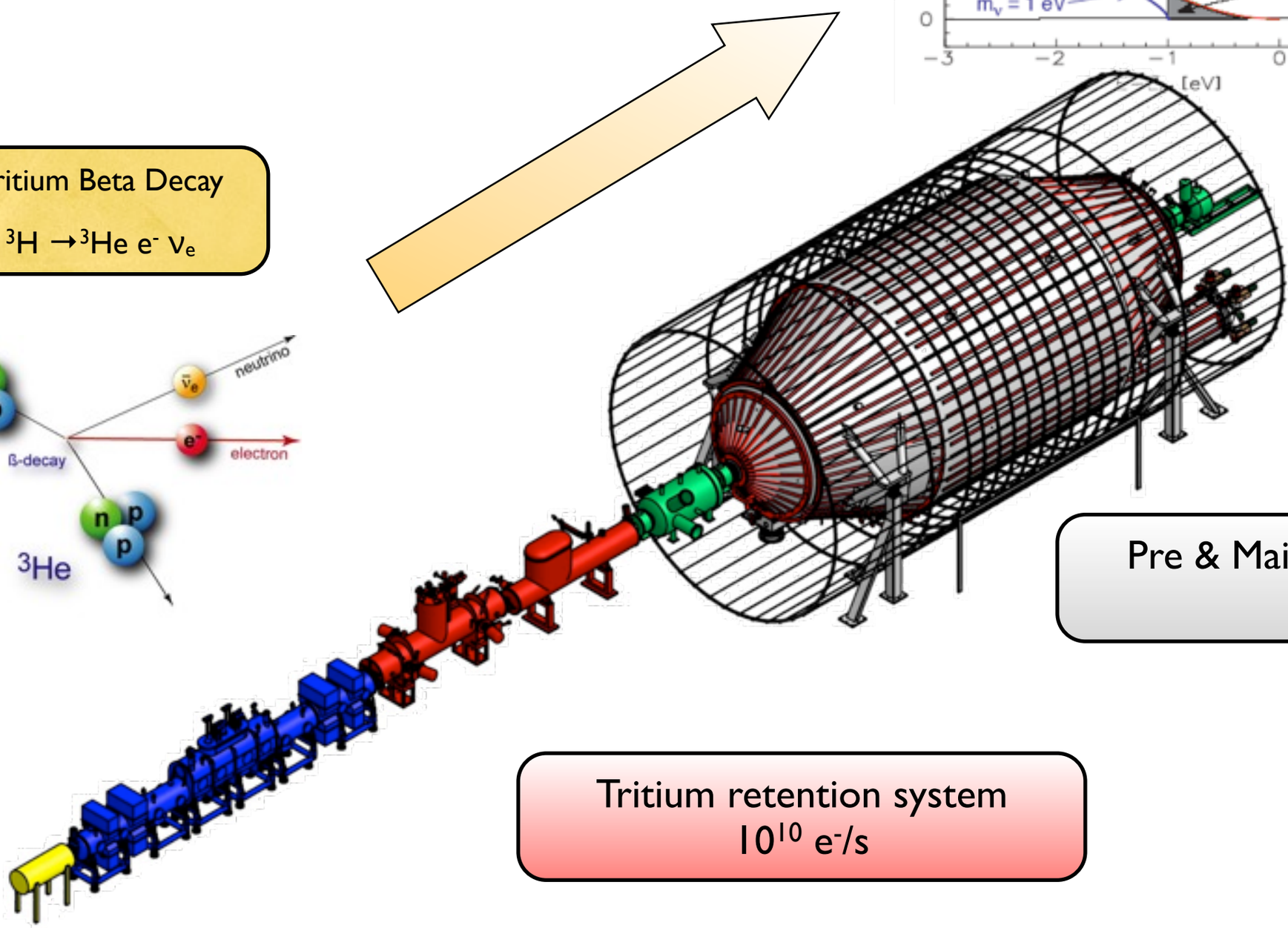


Electron Beta Decay Spectrum

Tritium Beta Decay

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





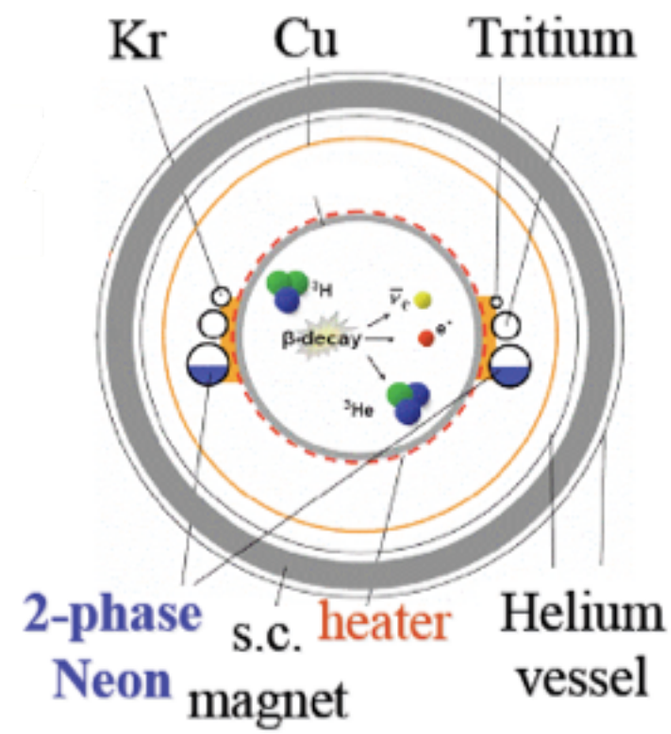
Detector
1 e^-/s

Pre & Main spectrometers
10^3 e^-/s

Tritium retention system
10^{10} e^-/s

Windowless Gaseous Tritium Source
5 x 10^{19} T_2/s

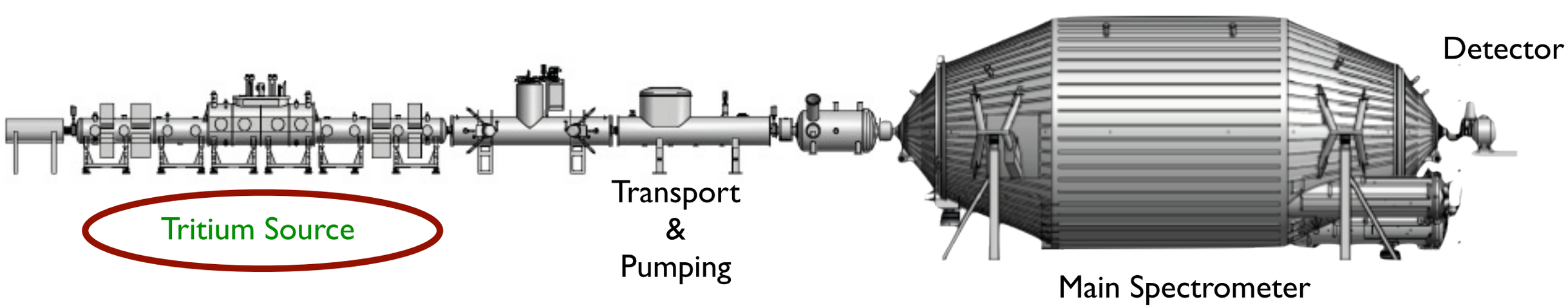
The Windowless Gaseous Tritium Source (WGTS)



- Gaseous tritium source provides source of beta-decay electrons.
- Use of injection + differential pumping to provide well-controlled gas column density.
- In-situ monitoring of purity of gas via laser Raman spectroscopy.

T_2 Specifications

• Tritium activity:	1.7×10^{11} Bq
• Tritium throughput:	40 g T_2/day
• Temp. stability	$\pm$ 0.03 mK @ 30K
• Electron flux:	10^{11} β/s
• Column Density:	5×10^{17} cm^{-2}



Solenoid testing

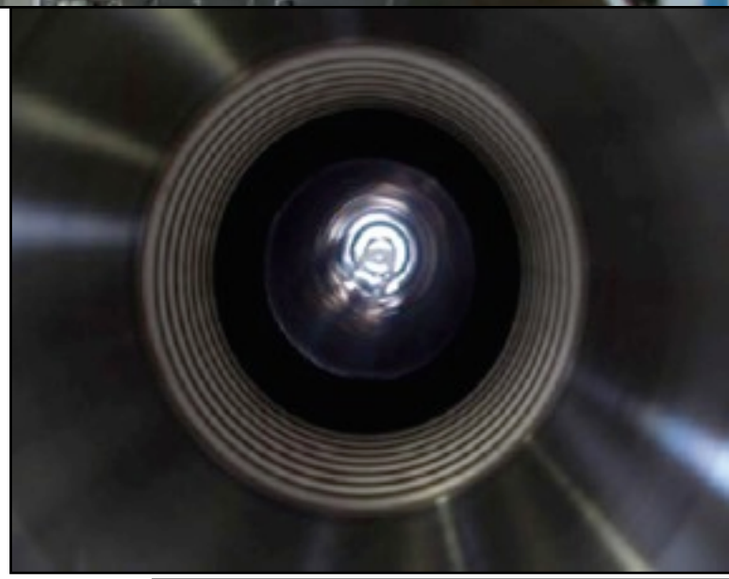
Demonstrator

Recent milestone:

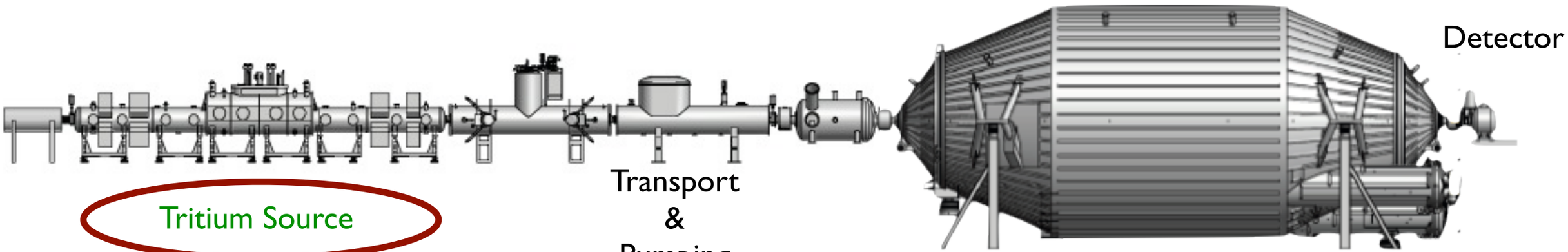
Demonstrator achieves

30 ± 0.03 K neon stability

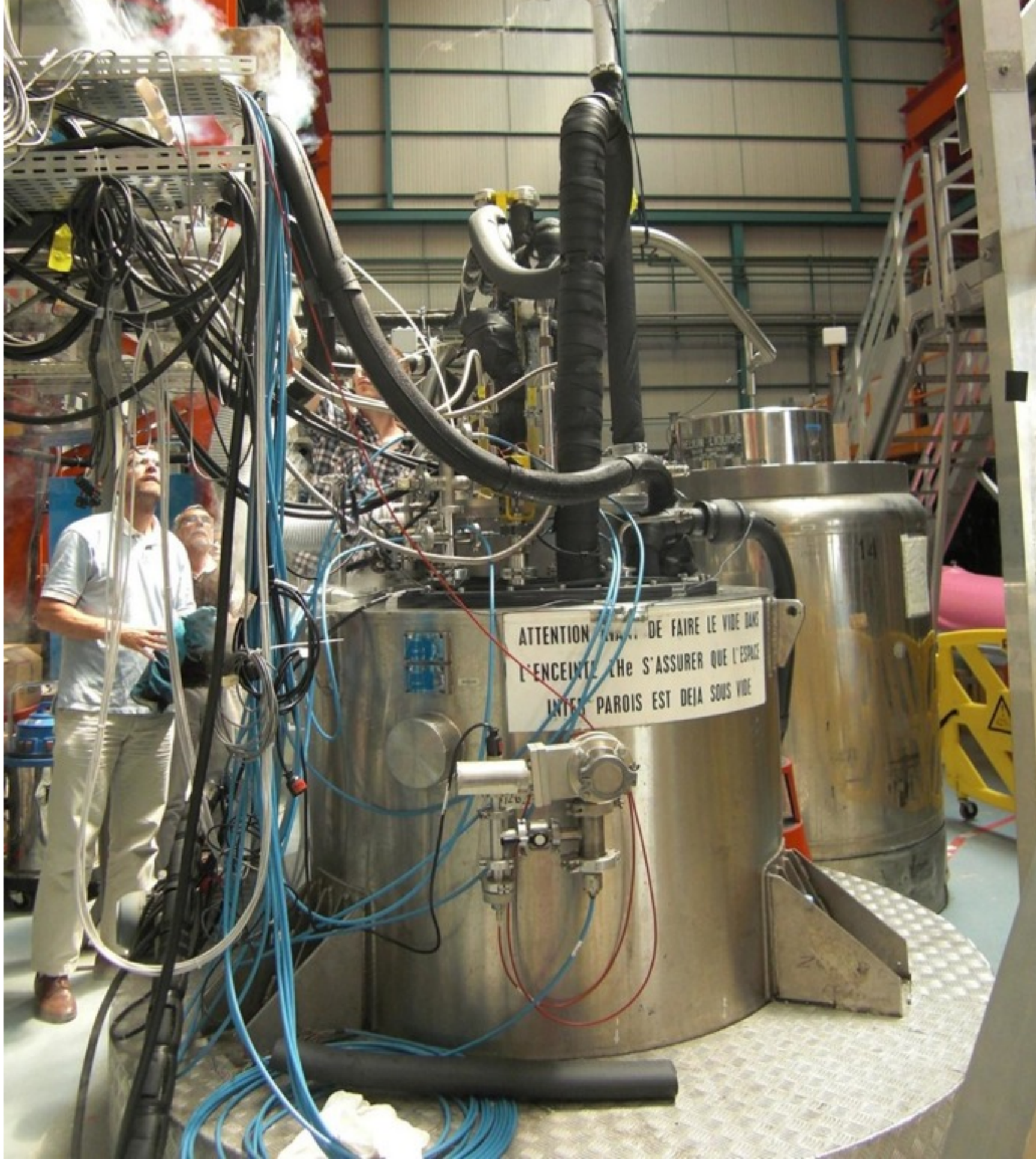
Order of magnitude improvement



Beam alignment (< 0.5 mm)



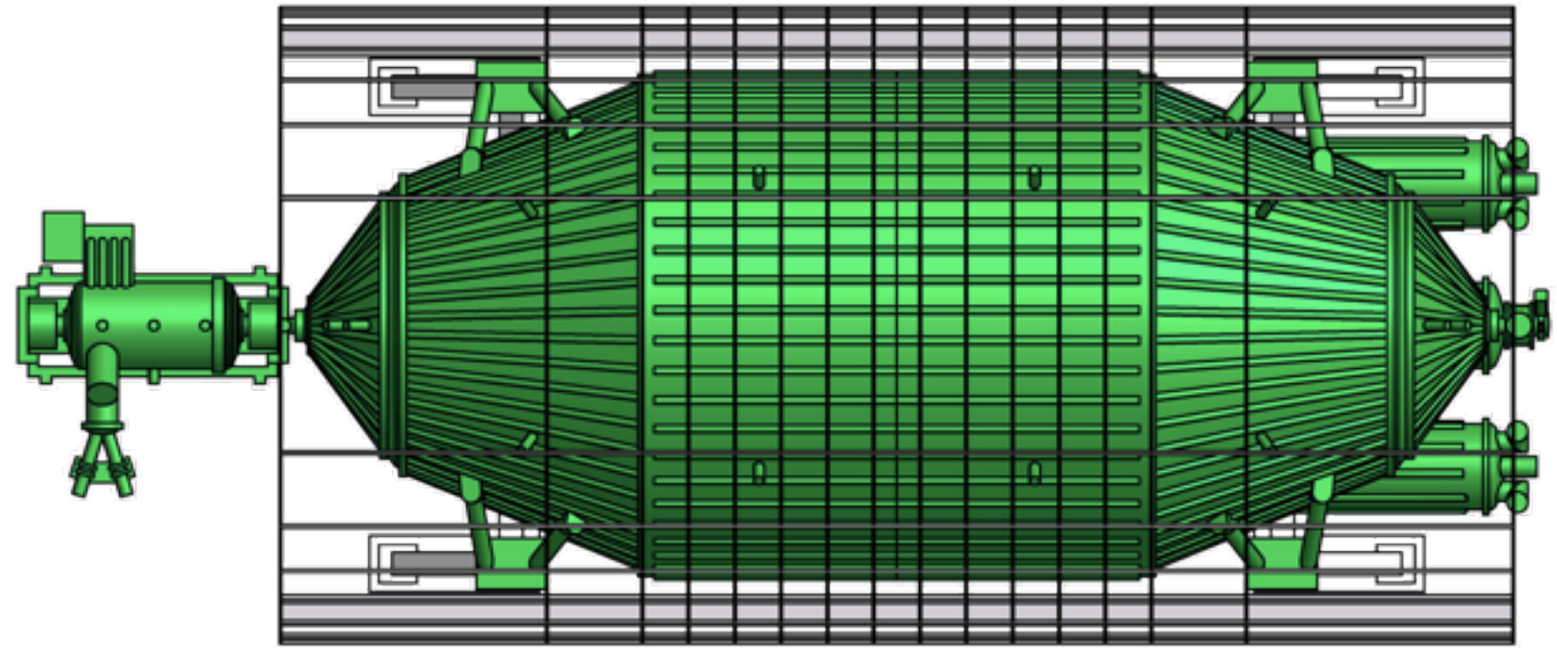
WGTS Magnet Testing at CEA Saclay



Recent milestone:

Main solenoids pass stress tests.

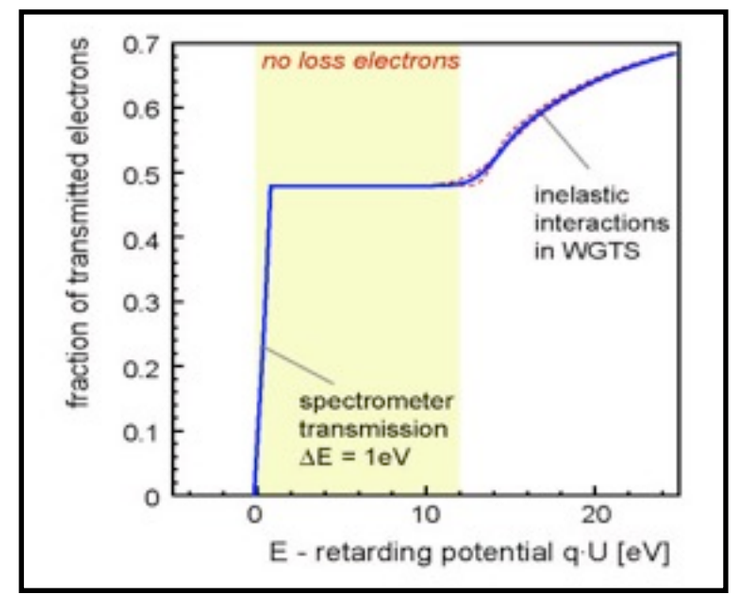
The Main Spectrometer

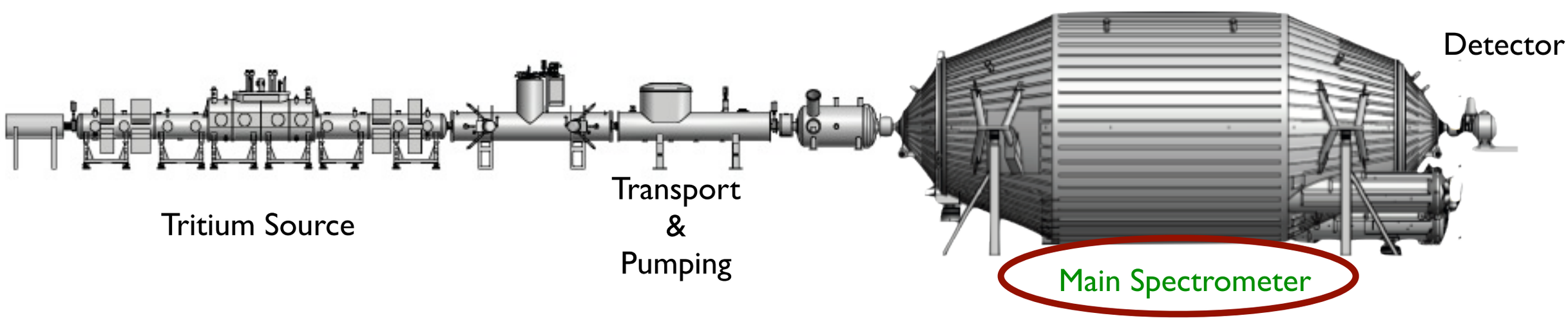


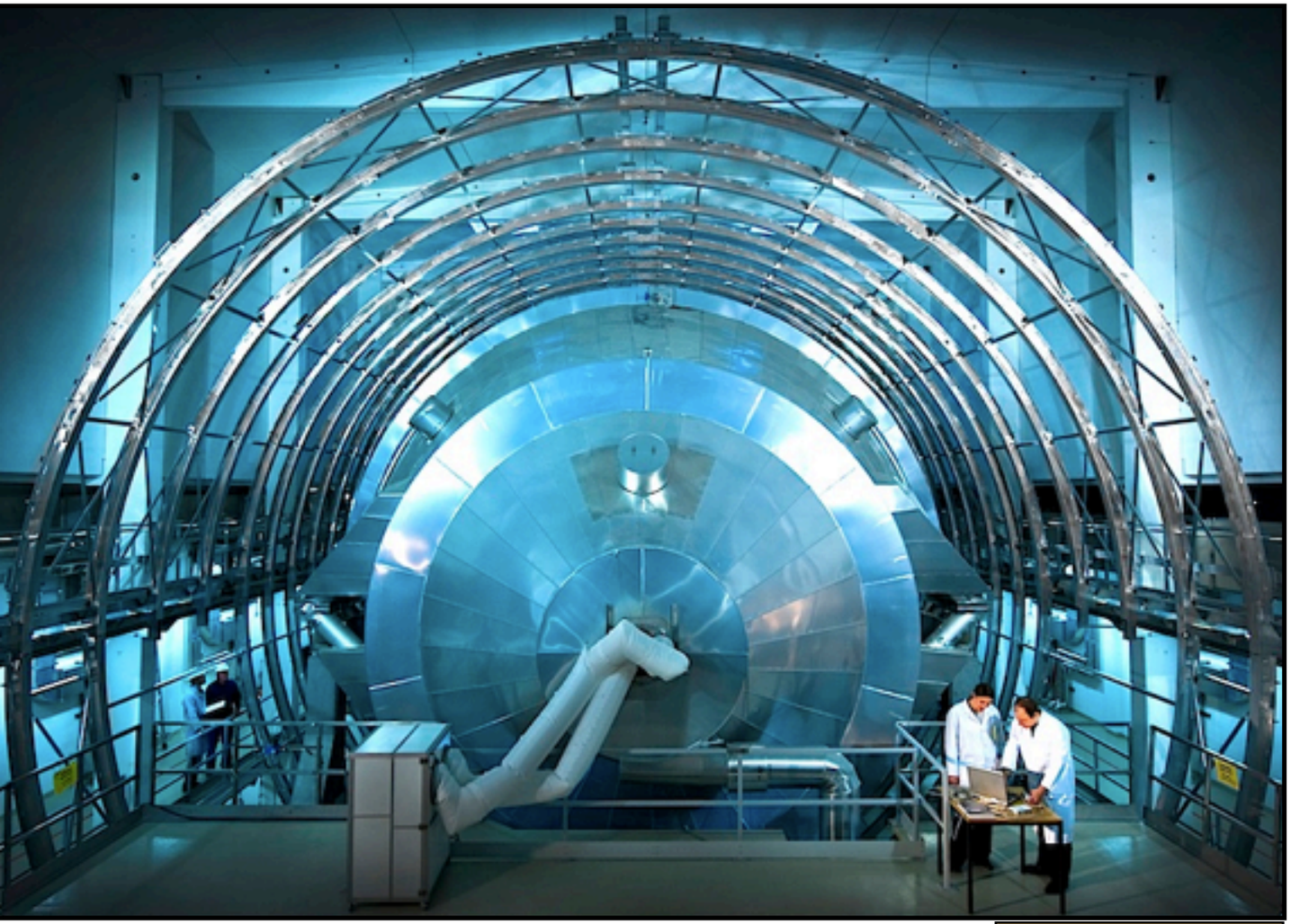
Inner wire electrodes installed for rejection of low energy particles produced from cosmic rays.

Combination of precision high voltage and low magnetic field with correction air coils.

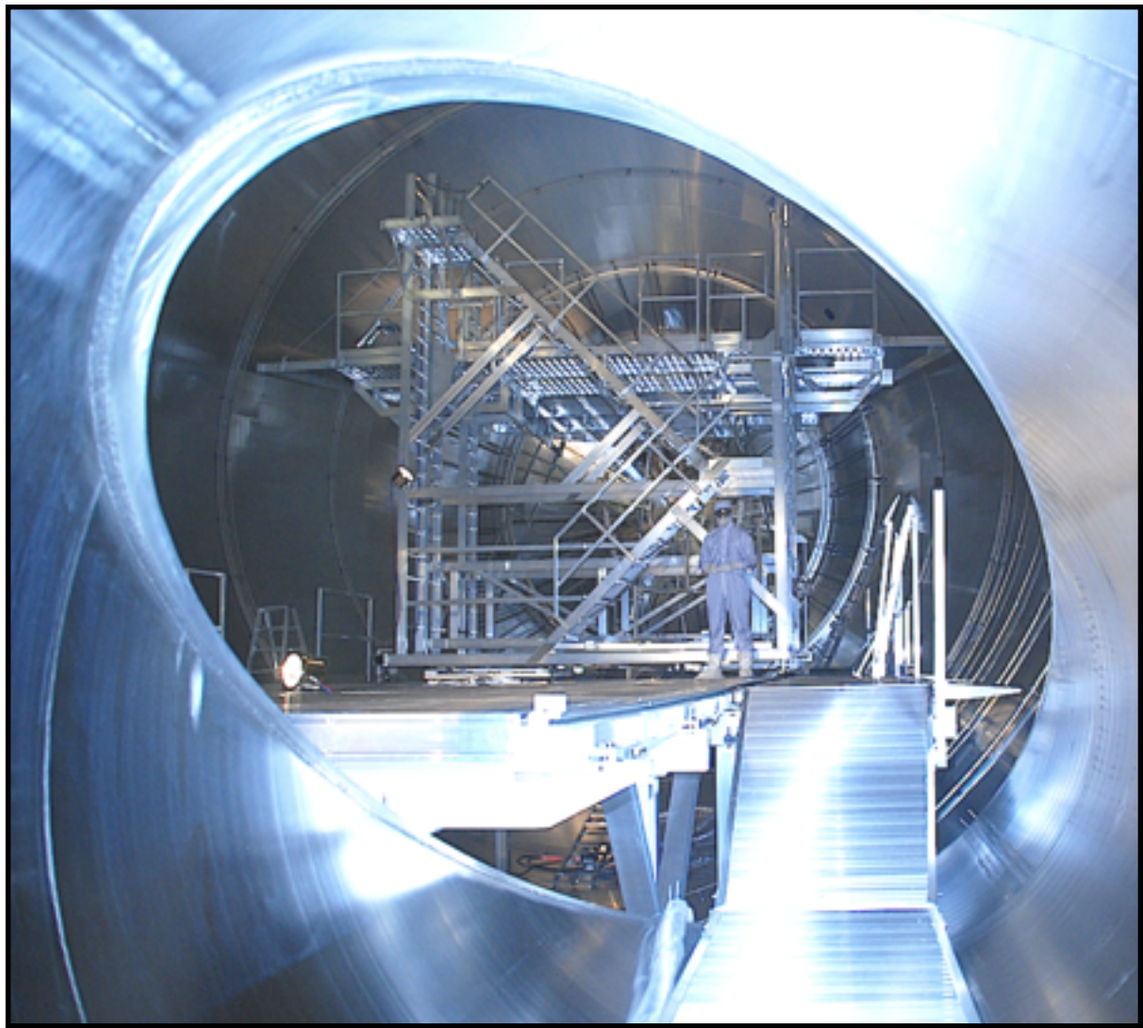
Inherent resolution of $\Delta E = 0.93$ eV.







Air coil testing



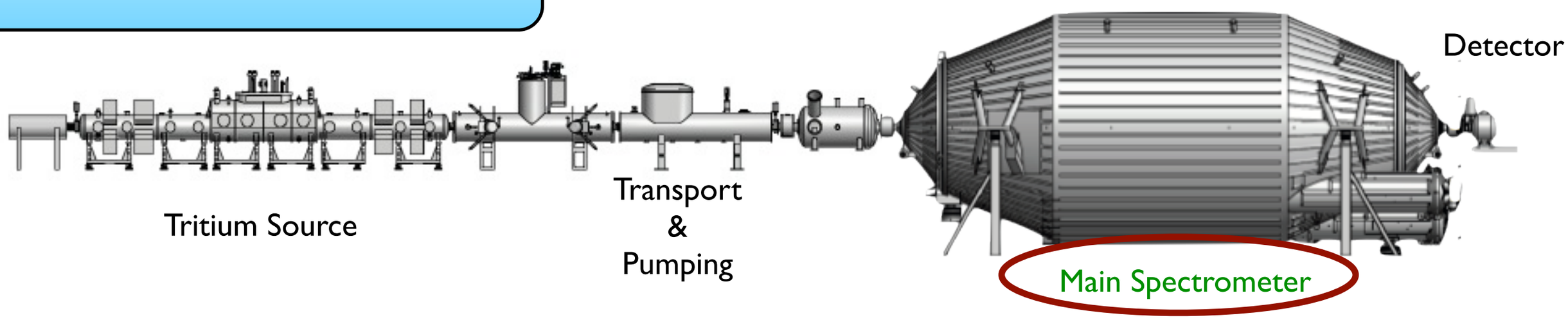
Vessel entrance

Recent milestones:

Air coils fully installed.

Inner wire electrodes installed.

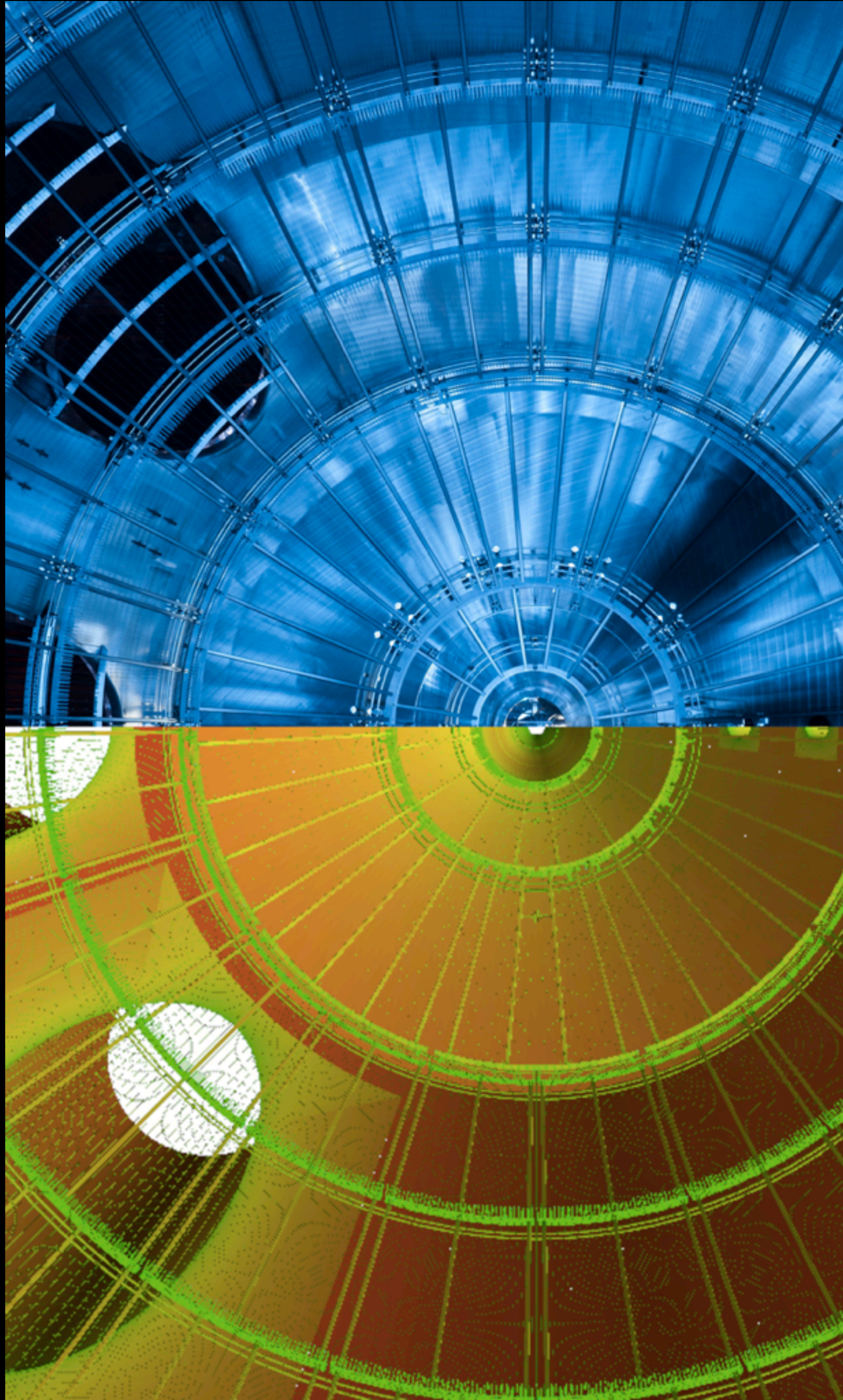
Vessel sealed and undergoing vacuum tests.

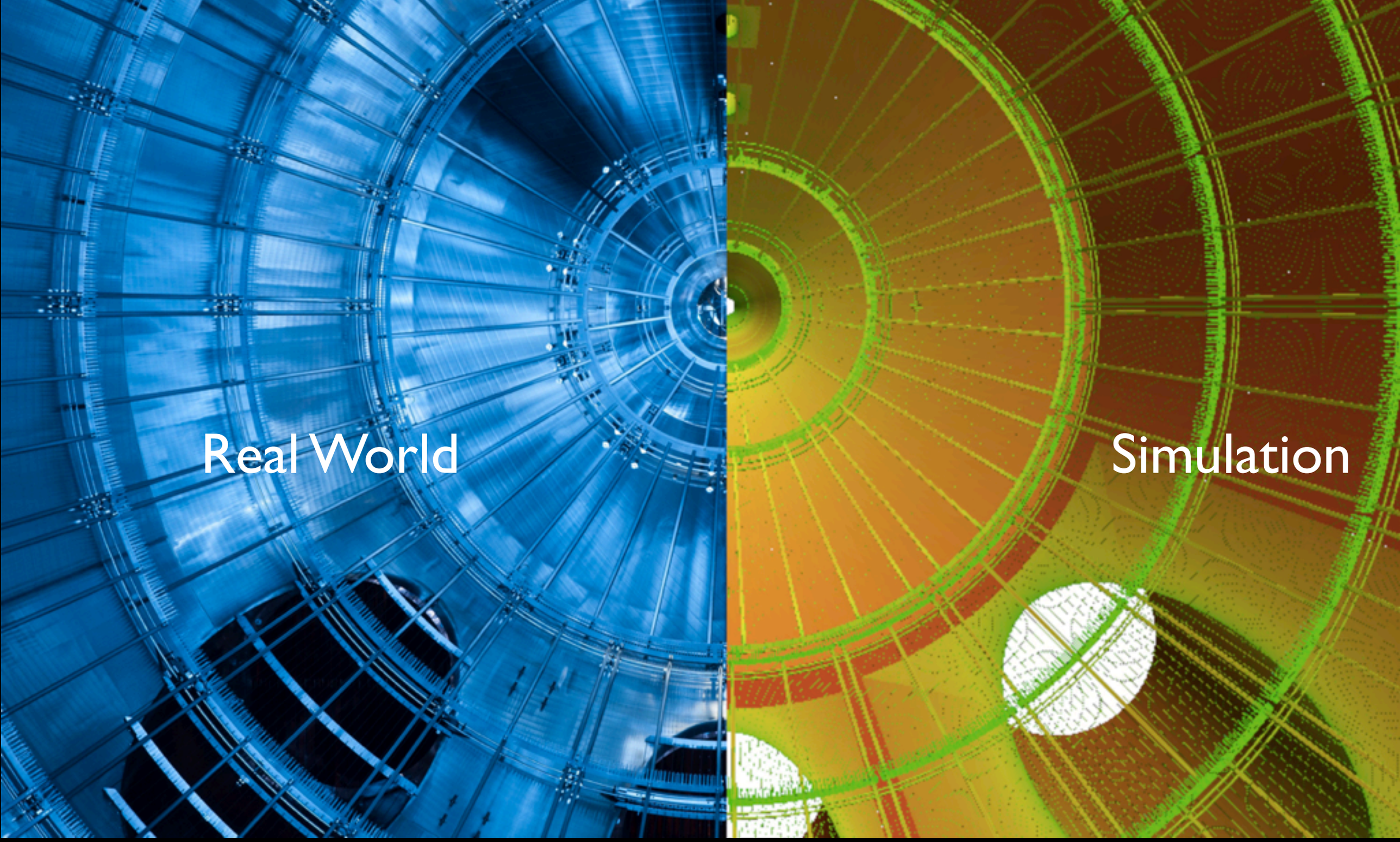


The Main Spectrometer

Recent milestone:

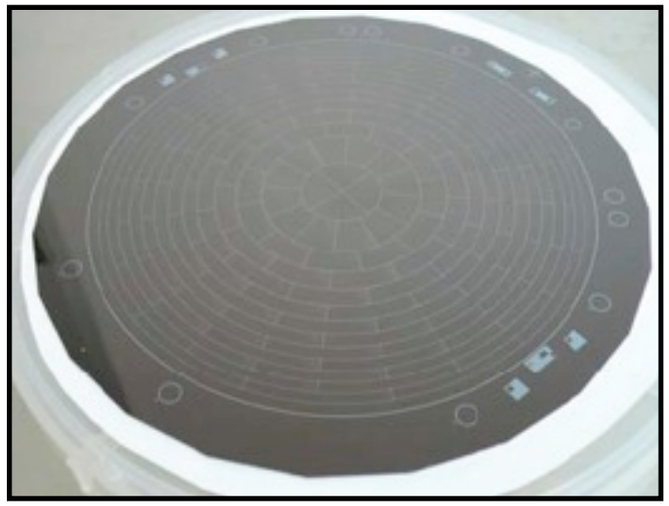
Final pump port closed and sealed as of May 2012

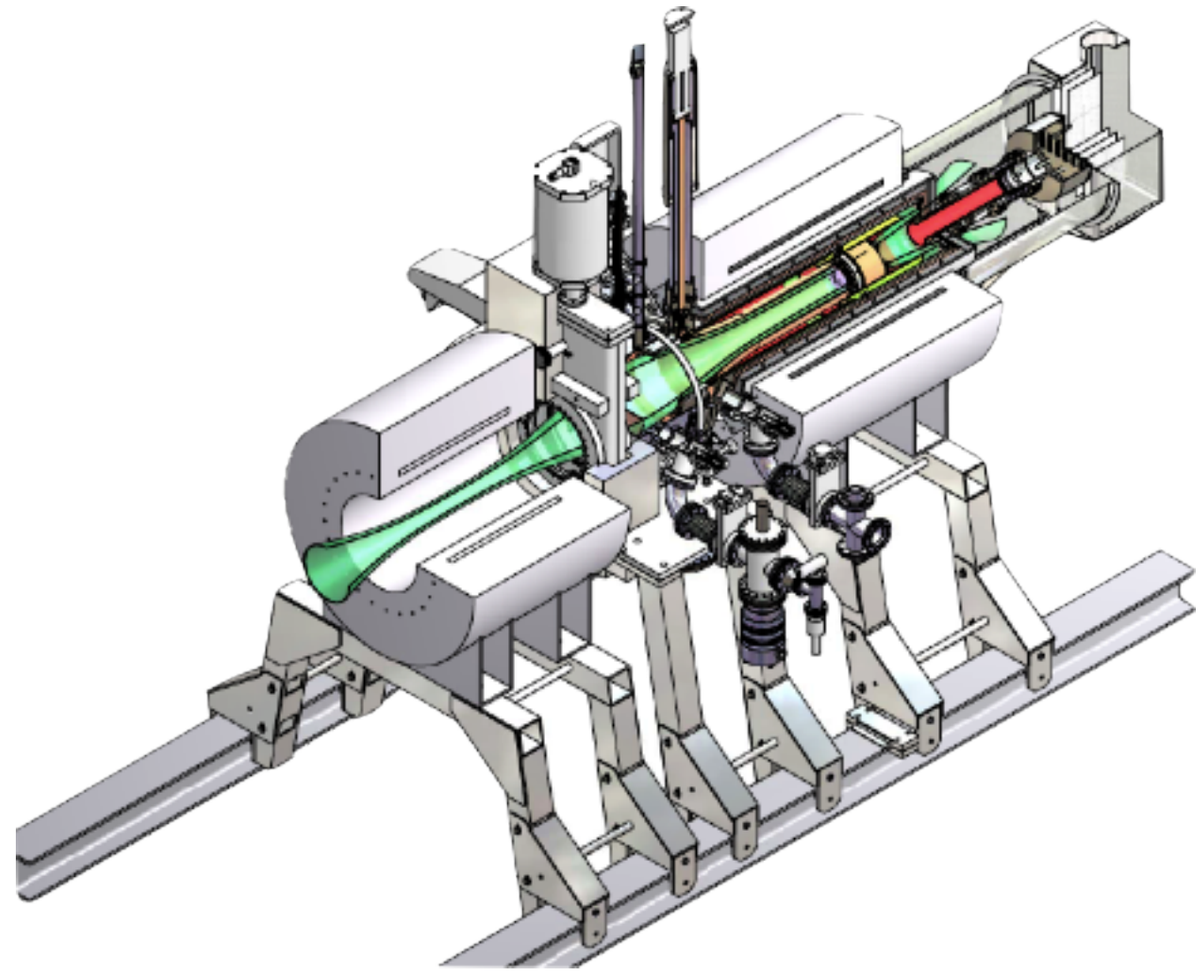




Excellent progress in the simulation of the experiment on this scale.

The Detector

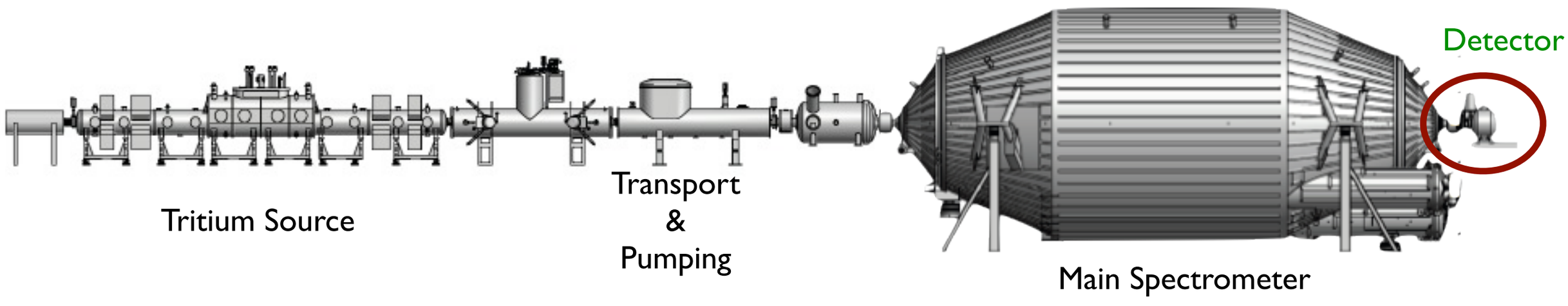




Final electron detection occurs on a segmented silicon detector (148 pixels for spatial resolution).

Two high-field magnets provide final focusing of tritium decay electrons onto detector.

Multiple background reduction techniques (veto, material selection, etc.) employed.

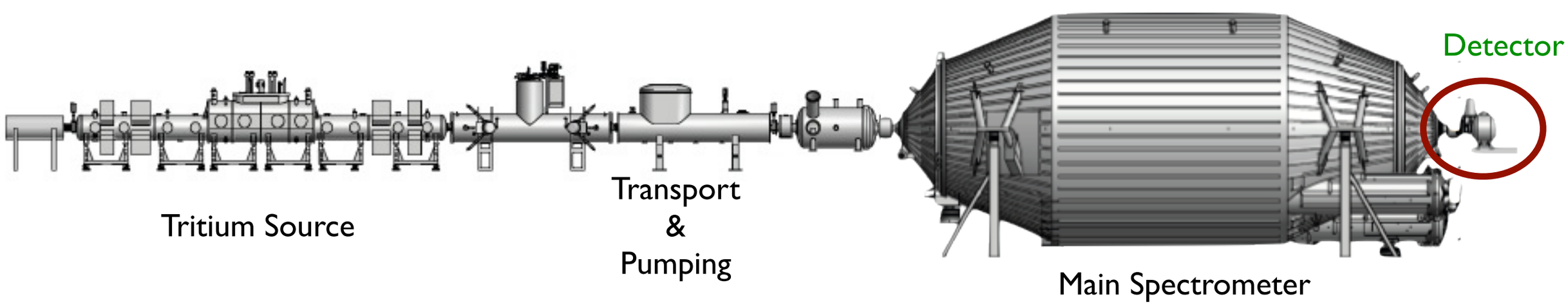


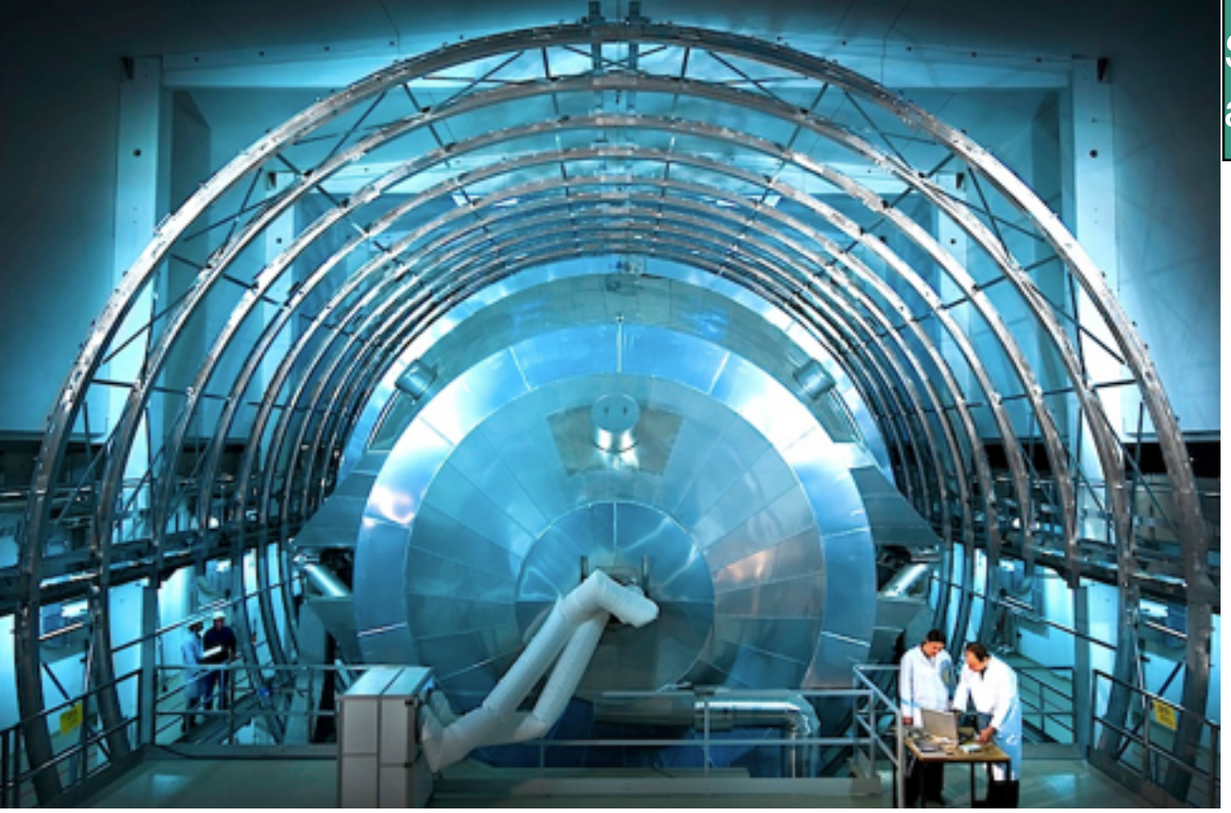
Detector Installation

Recent milestones:

Detector installed at KIT

Undergoing final commissioning in conjunction with main spectrometer.





Spectrometer and air coils

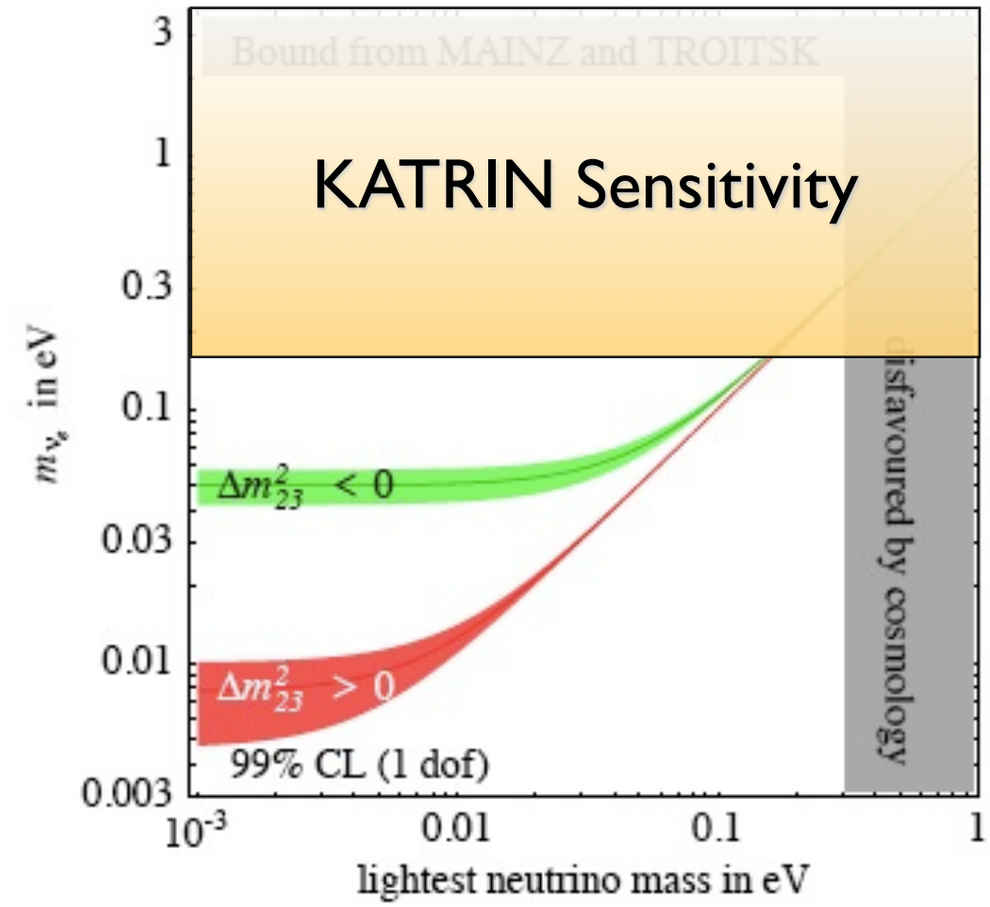
Projected Sensitivity

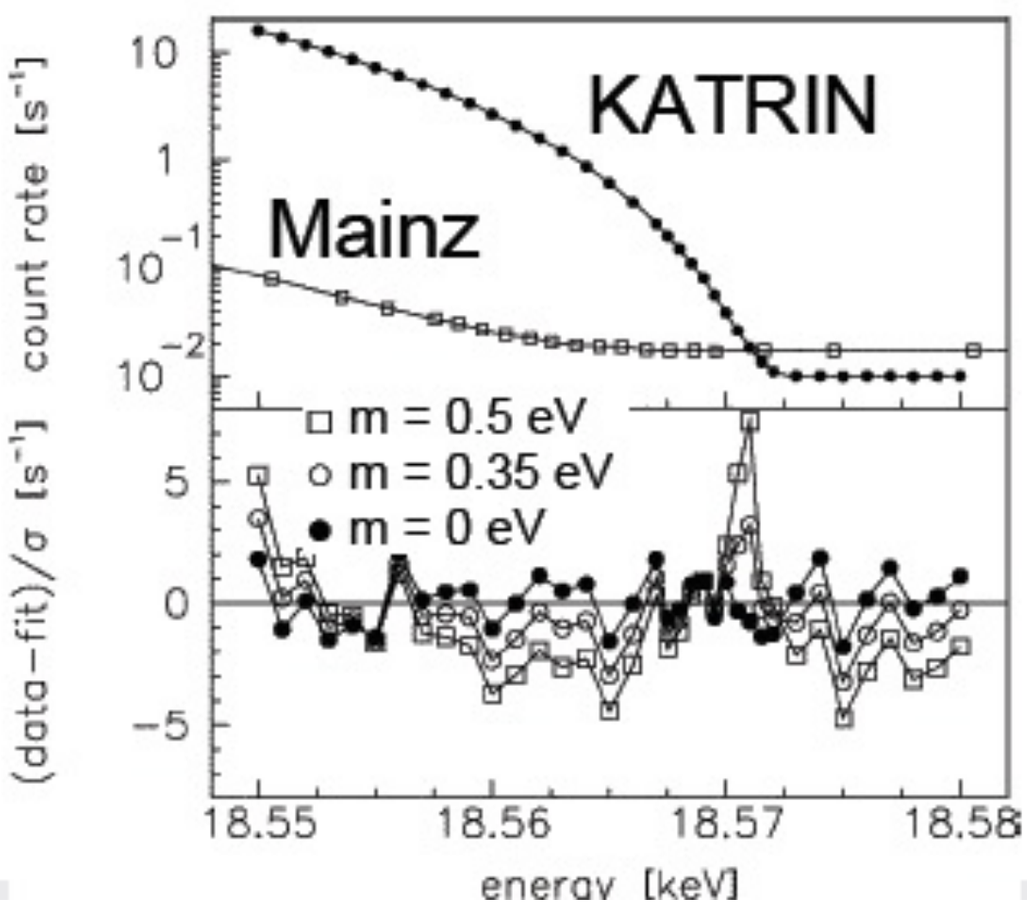
$\Delta m_{\beta,stat}^2 = 0.018$ eV^2

Assumes 3 yr running

$\Delta m_{\beta,sys}^2 = 0.017$ eV^2

Major systematics include source purity, HV stability, source stability and T_2 final states





Neutrino Mass Goals

Discovery: 350 meV (at 5σ)

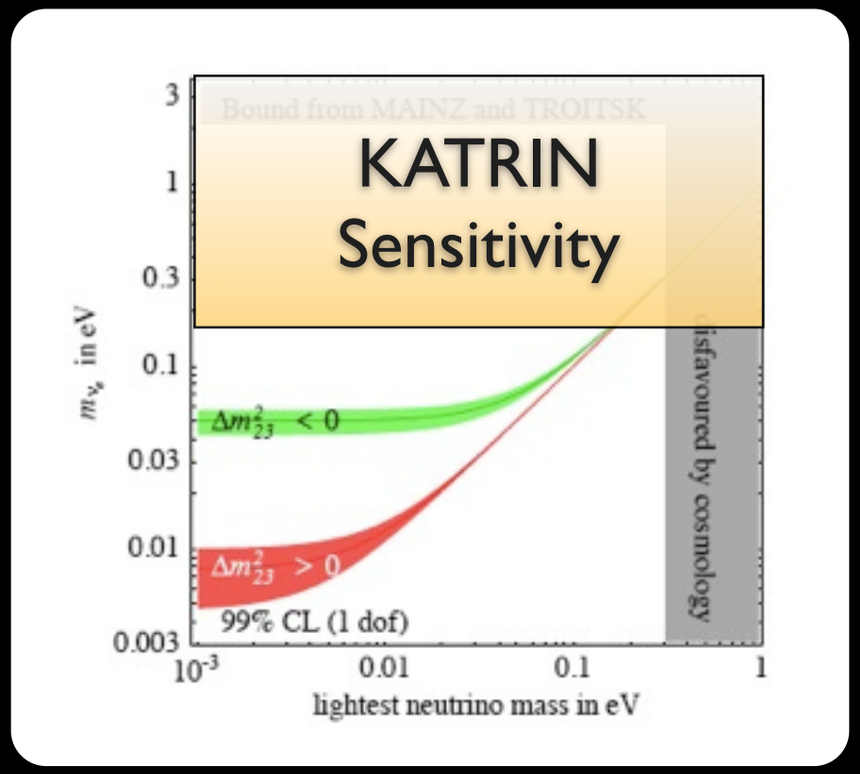
Sensitivity: 200 meV (at 90% C.L.)

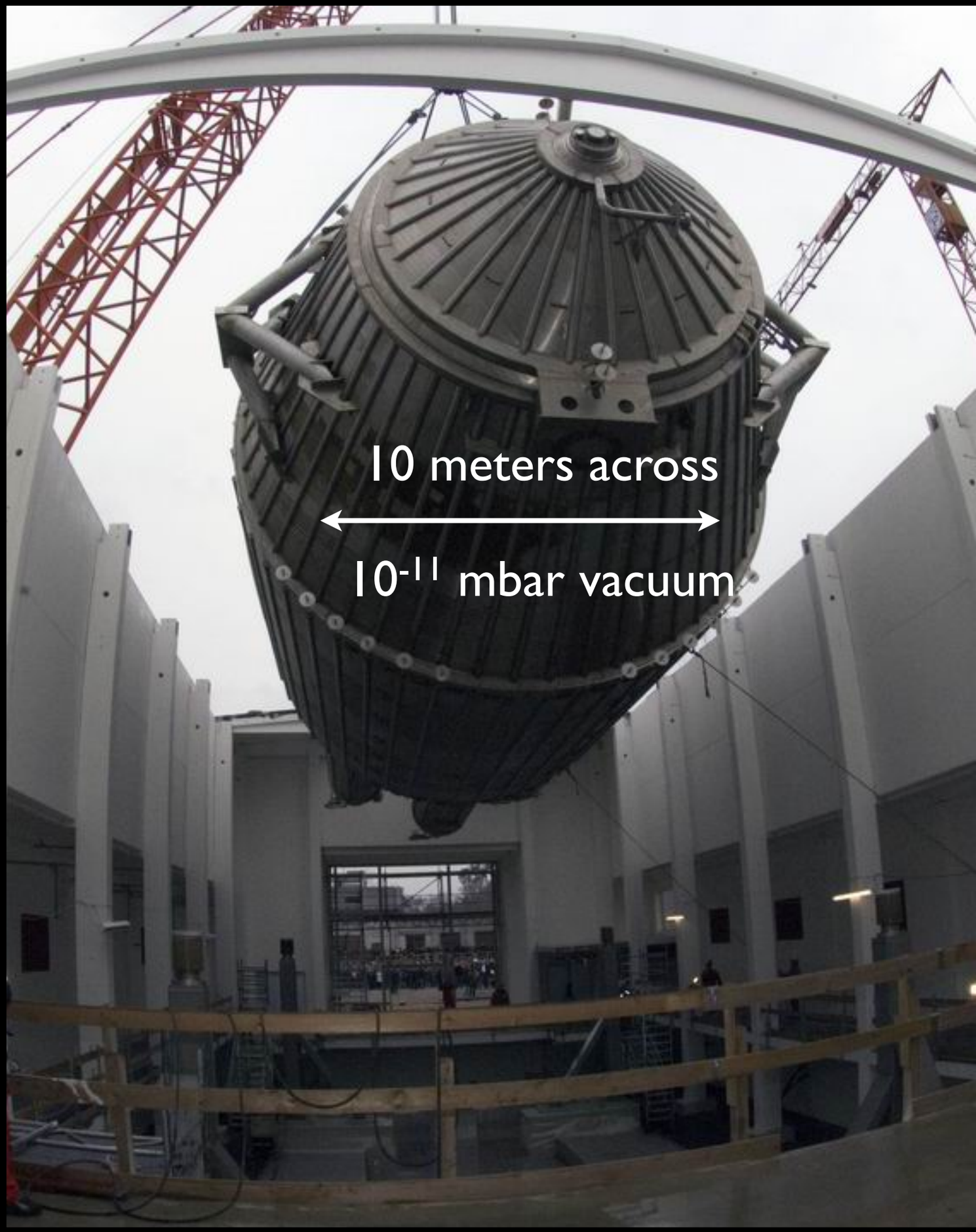
Commence Tritium Running in 2015

Can we push further?

- KATRIN will achieve 200 meV scale. Can direct measurements push lower to the normal hierarchy scale?

- Any future experiment needs to be able to (a) have a better scaling law for increased target mass and (b) improve its energy resolution.

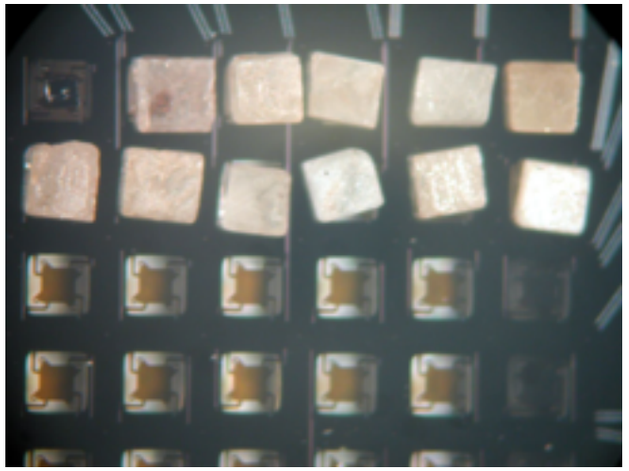




MARE & ECHO

Bolometric:

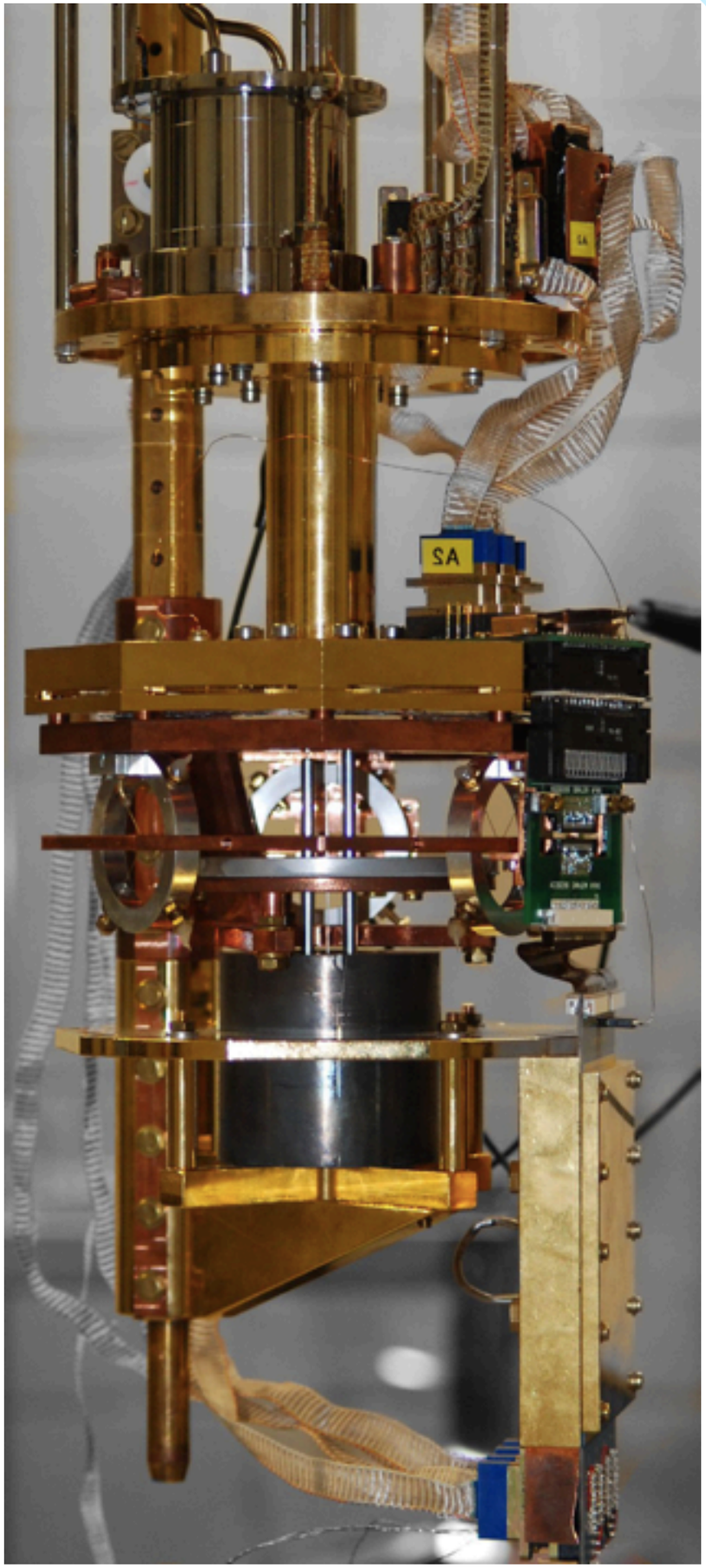
MARE



$$^{187}\mathrm{Re} \rightarrow {}^{187}\mathrm{Os} + e^- + \bar{\nu}_e$$

- Uses ^{187}Re as its beta source (one of the lowest endpoints, 2.3 keV)
- Advantages:
  - No backscattering
  - No atomic or molecular final state effects.
- Disadvantages:
  - Extremely long half-life.
  - Pileup backgrounds.

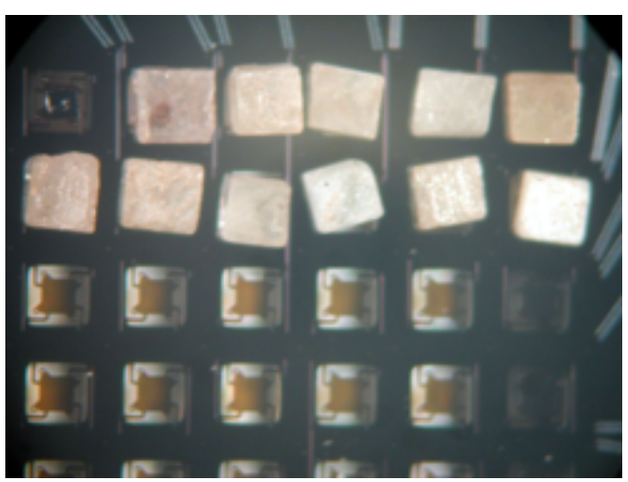
Cryogenic setup in Milan



MARE & ECHO

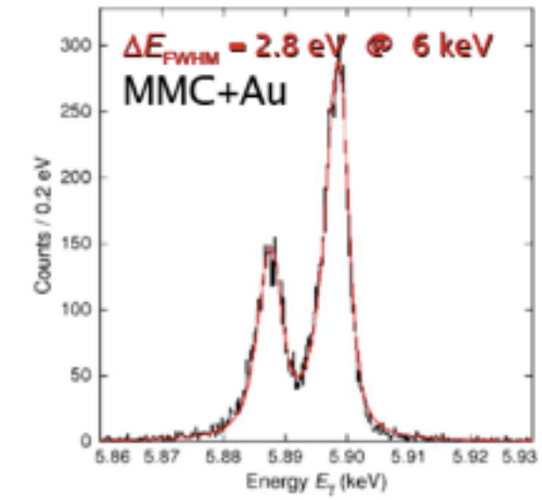
Bolometric:

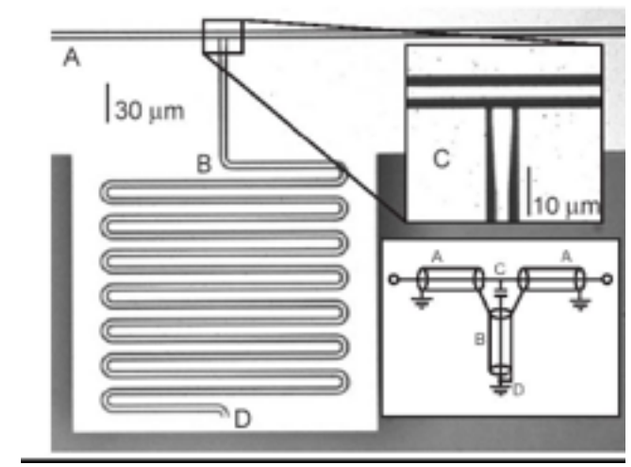
MARE



$$^{187}\mathrm{Re} \rightarrow {}^{187}\mathrm{Os} + e^- + \bar{\nu}_e$$

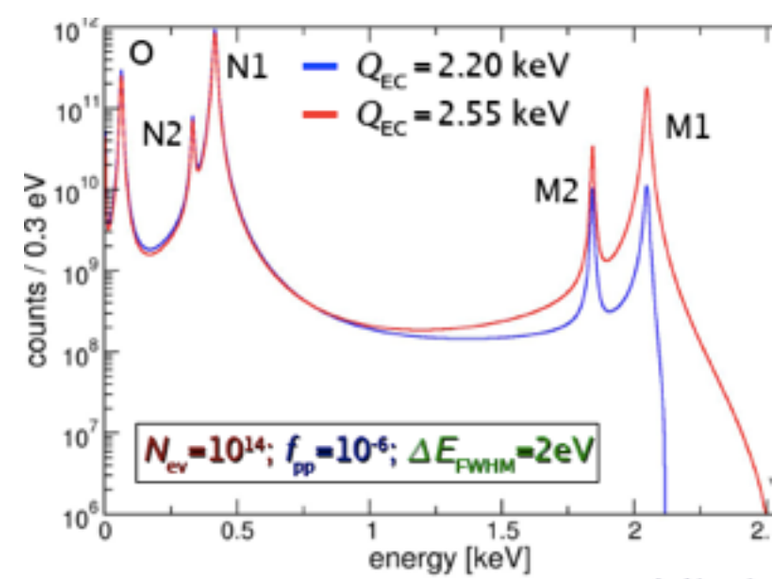
- New Technology:
  - Use of magnetic micro calorimeters. Minimize rise time and energy resolution.
  - MKID devices (1-10 GHz) resonating super-conductors.
  - Reduces pileup, increases pixelation and energy resolution





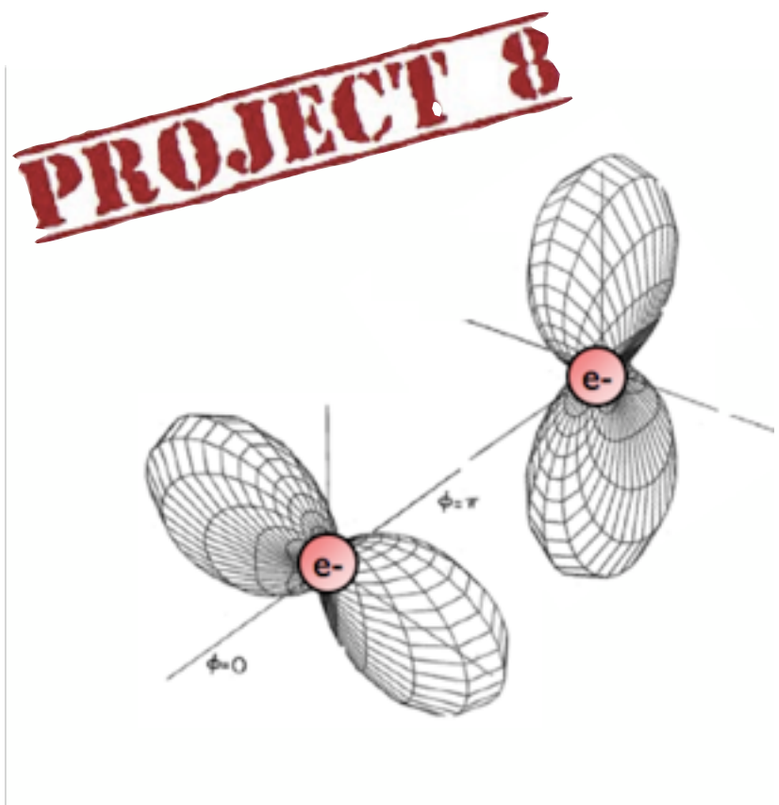
$$^{183}Ho + e^- \rightarrow {}^{163}Dy* + \nu_e$$

- New Isotopes:
  - Also exploring ^{183}Ho electron capture



R&D to lead to eV sensitivity

Project 8



Frequency

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

I. I. Rabi

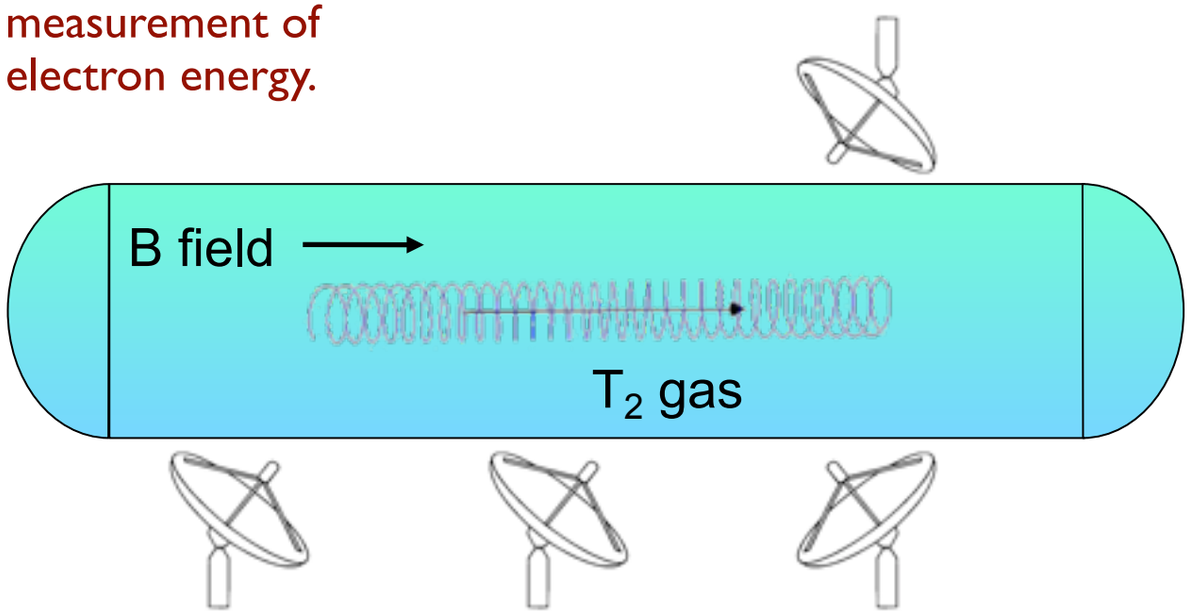
"Never measure anything but frequency."

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 J. Formaggio, Phys. Rev D80:051301

The Concept

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

Cyclotron Frequency

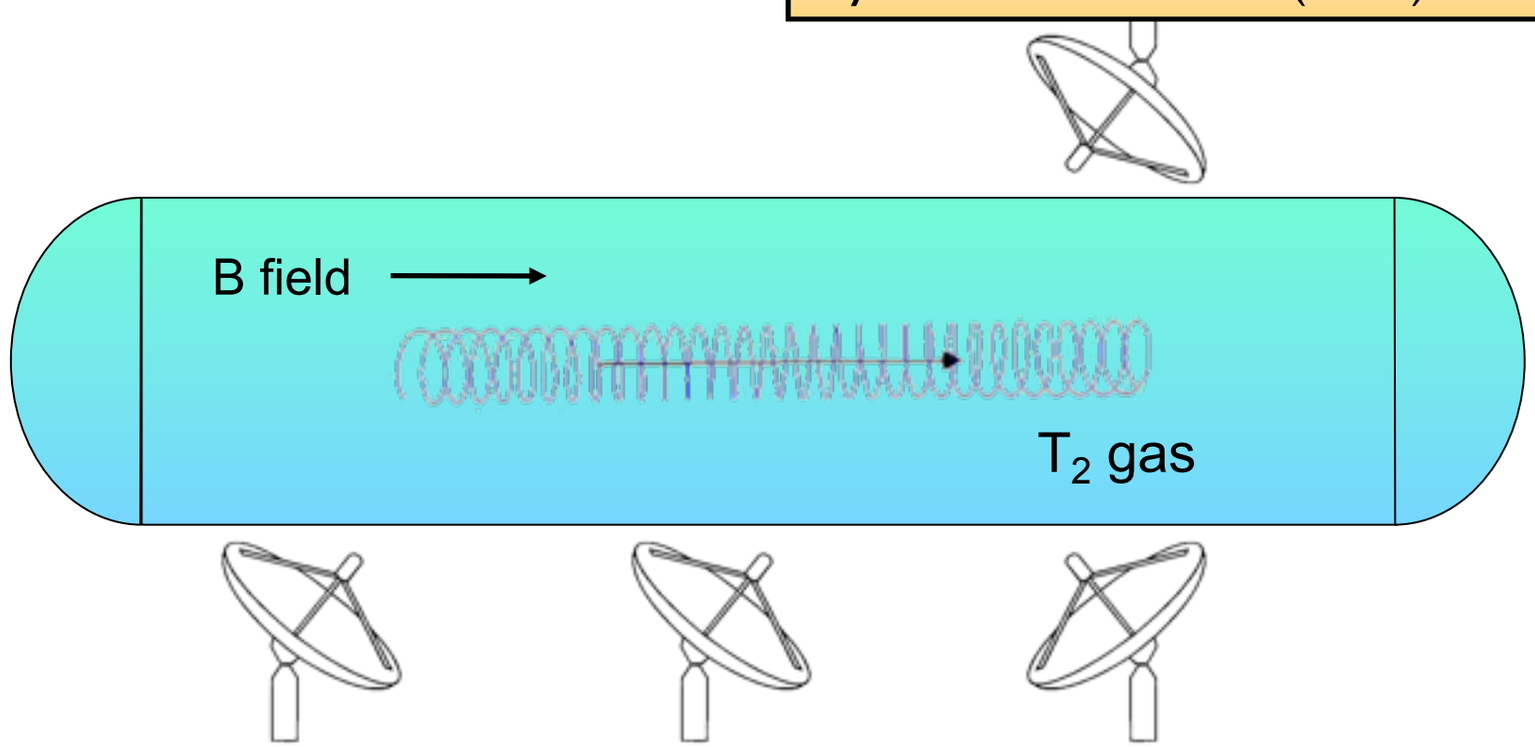
$$\omega(\gamma) = \frac{\omega_0}{\gamma} = \frac{eB}{K + m_e}$$

Radiative Power Emitted

$$P_{\text{tot}}(\beta_{\|}, \beta) = \frac{1}{4\pi\epsilon_0} \frac{2e^2\omega_0^2}{3c} \frac{\beta_{\|}^2}{1-\beta^2}$$

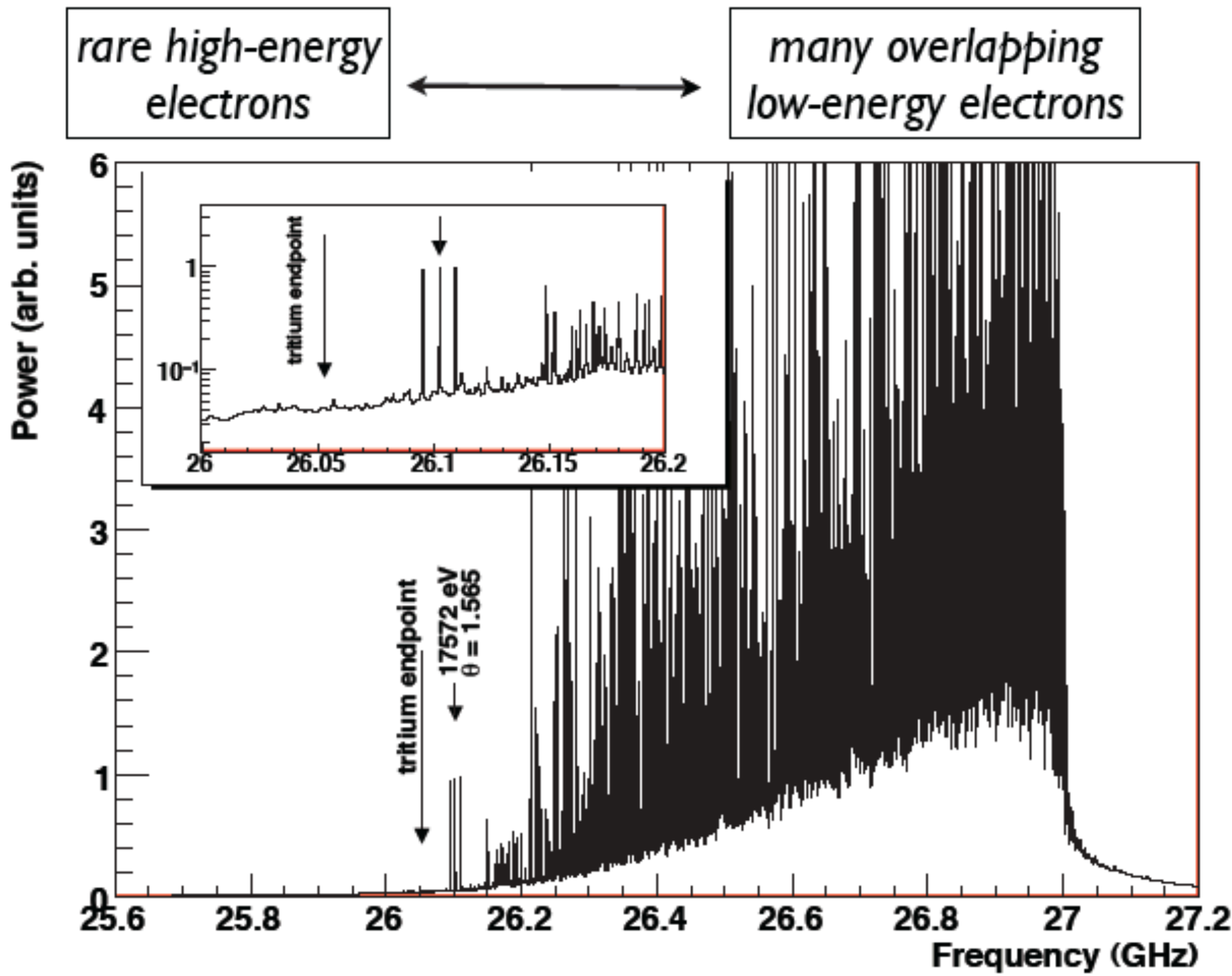
B. Monreal and J. Formaggio
Phys. Rev. D80:051301 (2009).

- Uniform B field
- Low pressure T_2 gas.
- Antenna array for cyclotron radiation detection.



The Tritium Spectrum

- Look at a simulated tritium spectrum watched by a synthetic array (evenly spaced antennas over 10 meter uniform field).
- Low energy electrons dominate at higher frequencies.
- Rare, high energy electrons give a clean signature near endpoint.



100,000 tritium decays in 30μs

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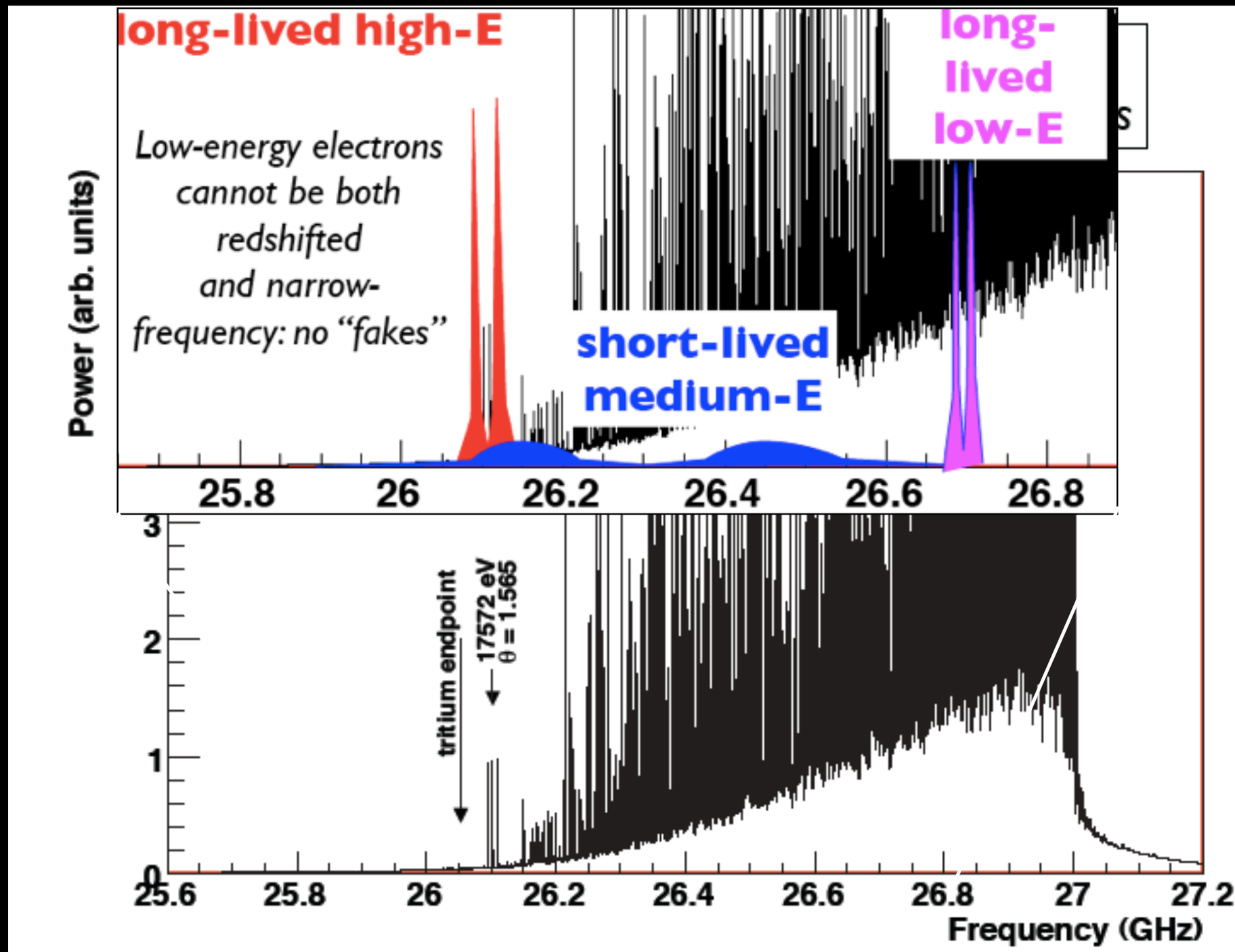
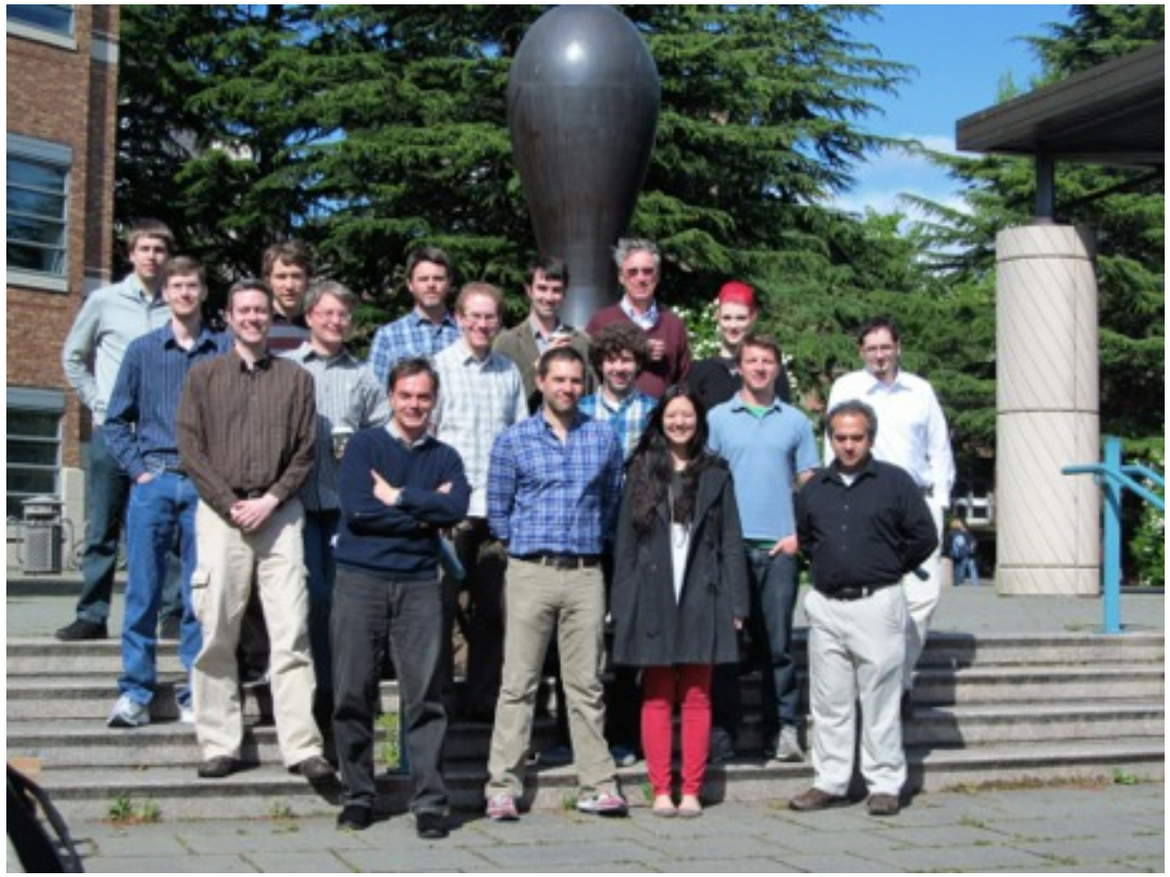


100,000 tritium decays in 30μs

Project 8 Collaboration



J. Formaggio, D. Furse, N. Oblath
Massachusetts Institute of Technology

R. Bradley
National Radio Astronomy Observatory

T. Thuemmler
Karlsruhe Institute of Technology

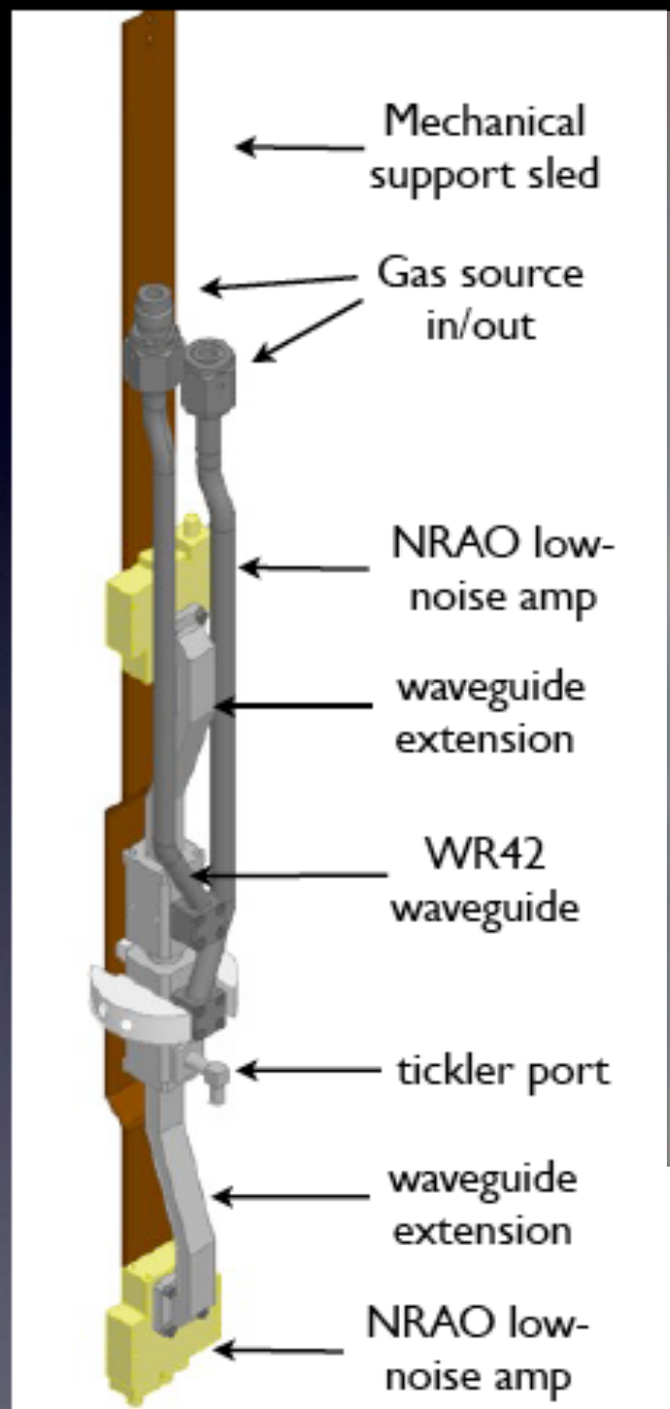
R. Patterson
California Institute of Technology

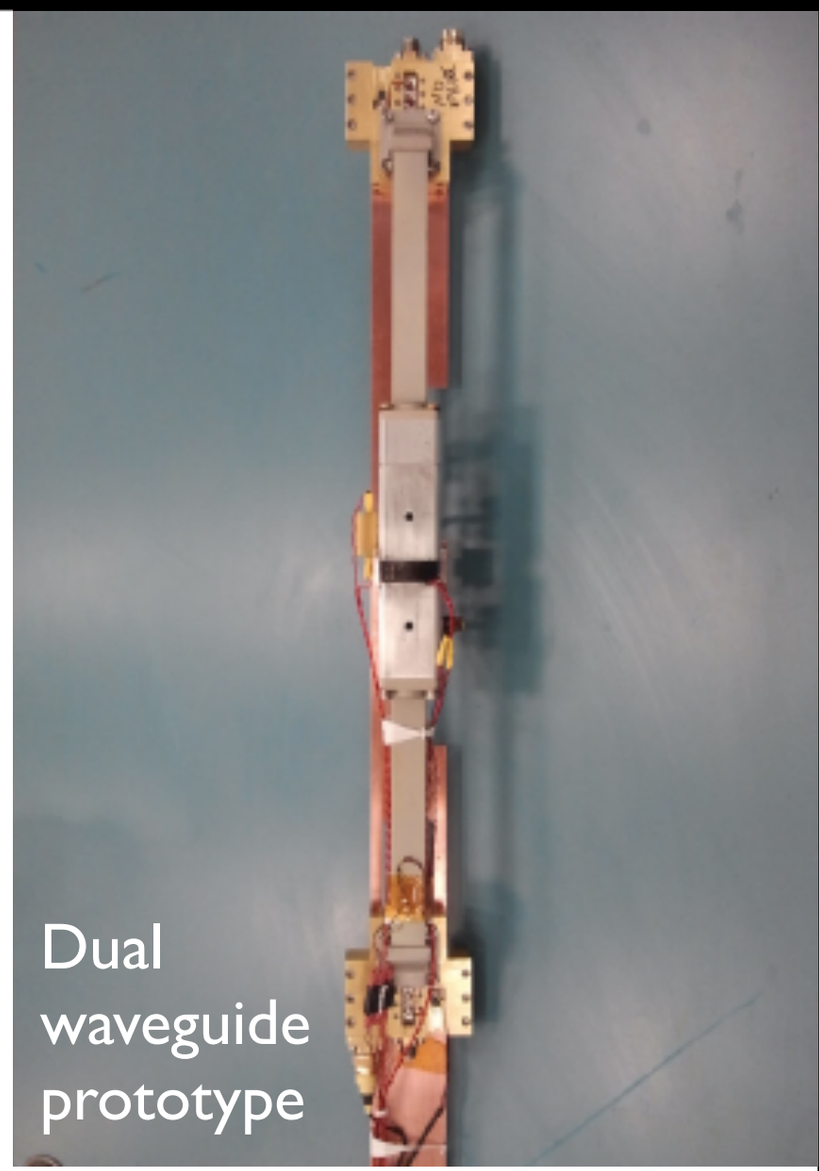
Shepard Doelman, Alan Rogers
Haystack Observatories

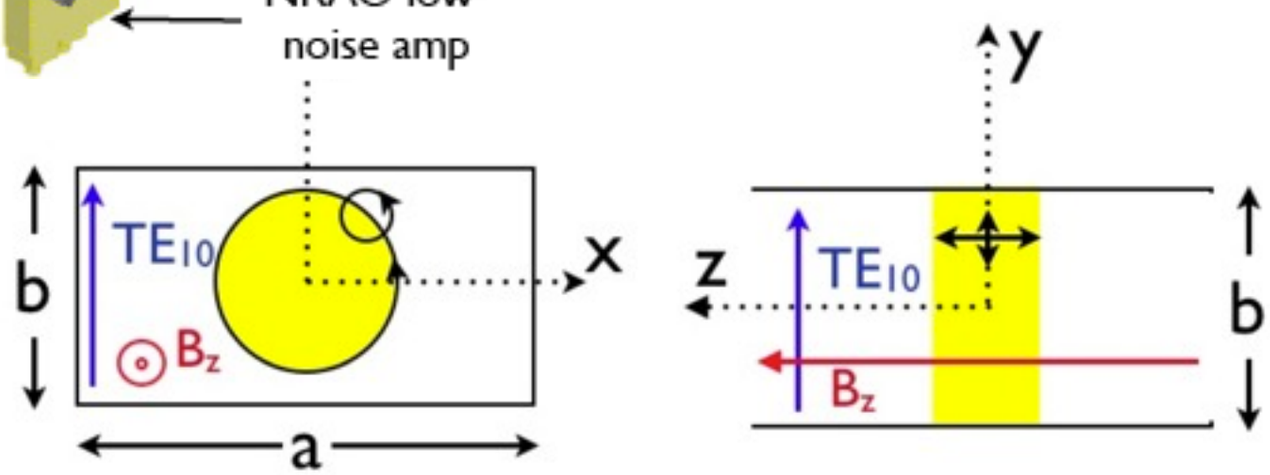
M. Bahr, B. LaRoque, M. Leber, B. Monreal
University of California, Santa Barbara

J. Kofron, L. McBride, R.G.H. Robertson, Leslie Rosenberg, Gray Rybka
University of Washington, Center for Experimental Nuclear Physics and Astrophysics

D.M. Asner, J. Fernandes, A.M. Jones, J.F. Kelly, B.A. VanDevender
Pacific Northwest National Lab







Prototype Status

Monolithic assembly inserted into 2-in diameter vertical bore of 1T s.c. magnet.

Source gas flows directly through waveguide fiducial volume.

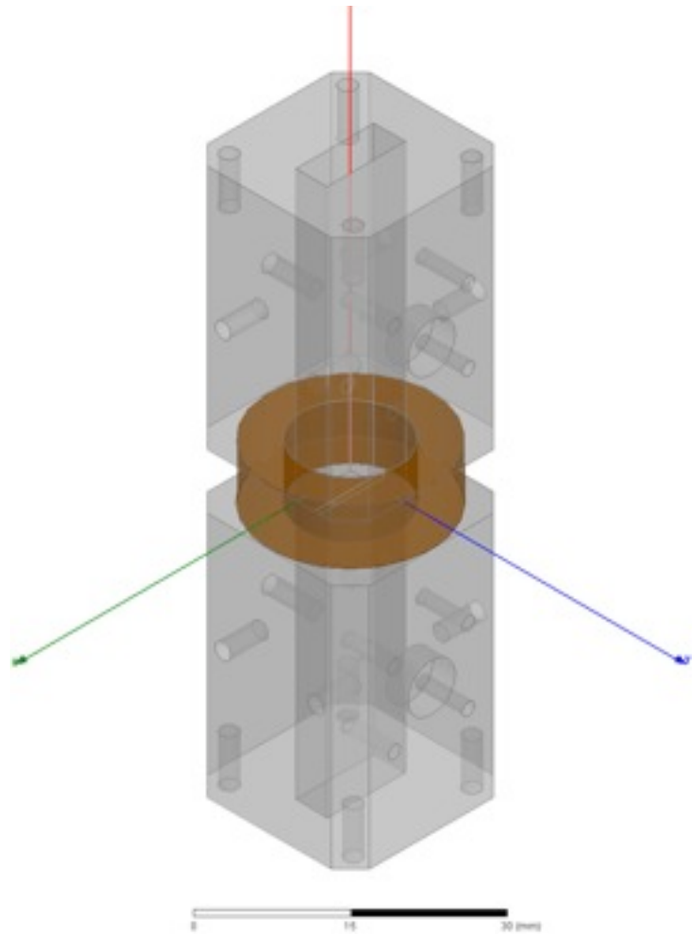
Cyclotron power transported in both

directions to low-noise 30 GHz amplifiers loaned by NRAO.

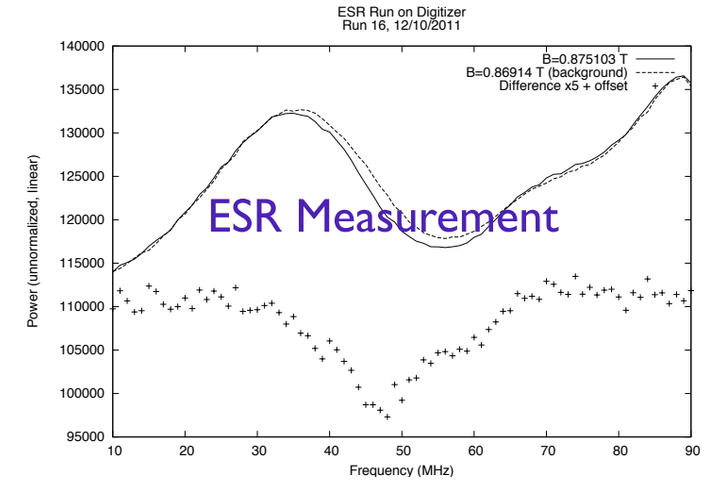
Signal mixed down to lower frequency (250 MHz bandwidth) and fully digitized.

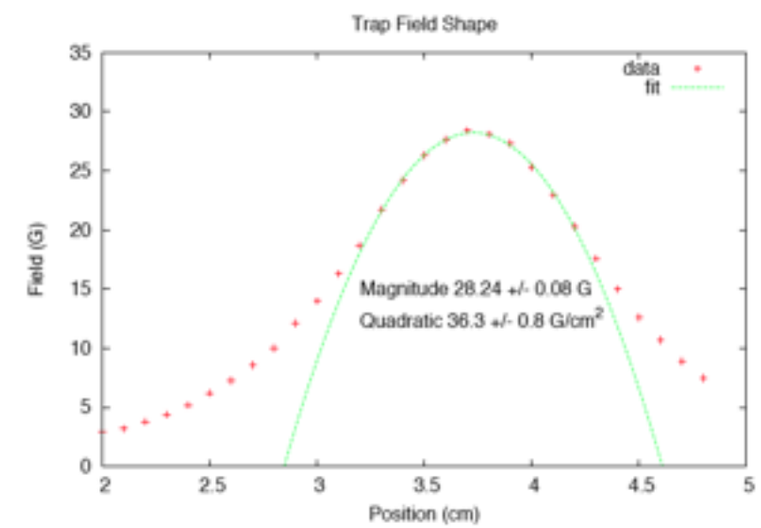
Magnetic Trapping

Magnetic bottle
1 T field (27 GHz)



Trapping coil





Trapping field

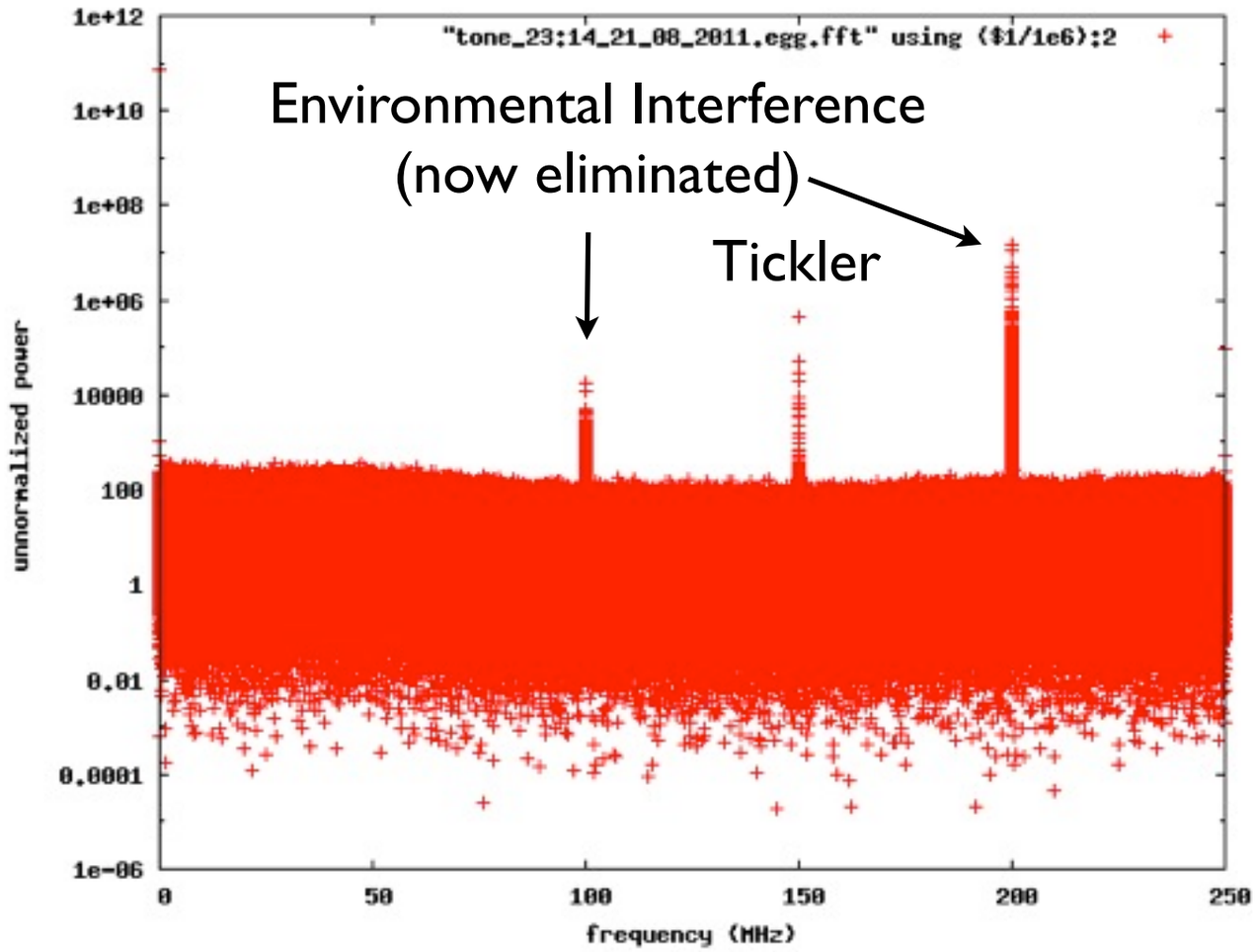
Use 0.93 Tesla field, where signal occurs at ~26 GHz with quadrupole trapping coil.

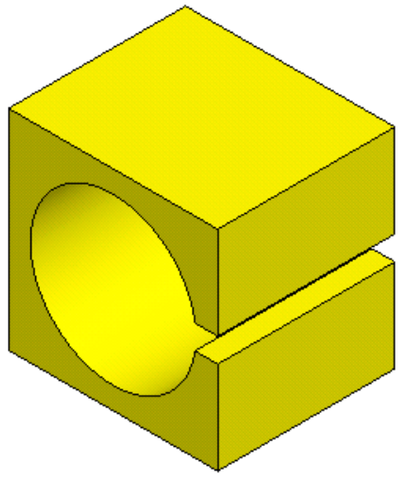
System monitors field in-situ using DPPH ESR monitoring.

Overall stability of prototype $\frac{\Delta B}{B} \sim 1 \times 10^{-5}$

Implies path length ~km.
Trapping will be needed

$$\Delta E = 1\,\mathrm{eV} \quad \Rightarrow \quad \frac{\Delta f}{f} = 2 \times 10^{-6} \quad \Rightarrow \quad t_{\min} = 30\,\mu\mathrm{s}$$





split-ring resonator
f_0 = 2.07 GHz, Q ~10^4

Upcoming Plans

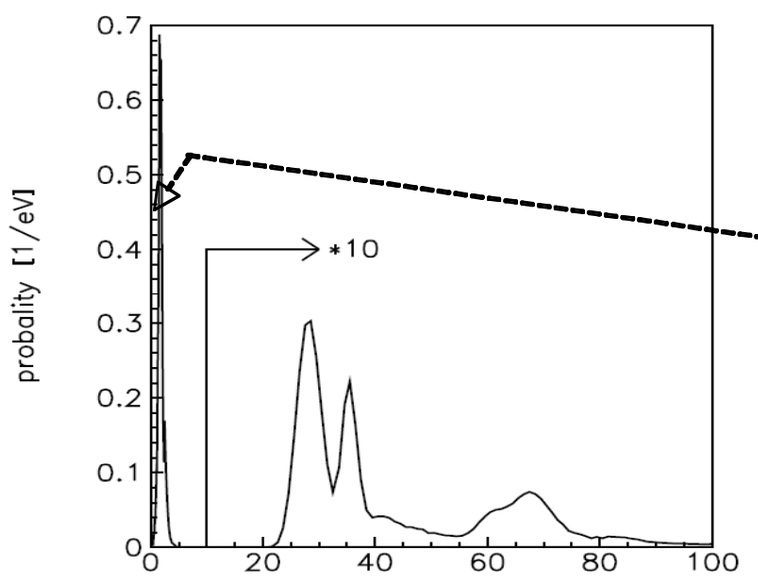
Did first test run in Sep 2011, a more intense run set for later this fall.

System with greater monitoring of vacuum, temperature, and calibration of fields.

In future, also exploring tuned RF cavities, at weaker fields and larger volumes for tritium running.

Moving Beyond the Inverted Scale

- Most effective tritium source achieved so far involves the use of gaseous molecular tritium.
- Method will eventually hit a resolution "wall" which is dictated by the roto-vibrational states of T_2. This places a resolution limit of 0.36 eV.
- One needs to either switch to (extremely pure) atomic tritium or other isotope with equivalent yield.
- High intensity sources of tritium might be achievable using similar techniques as employed in H/D production.
- Main challenge is achieving the purity and transport of atomic tritium. Requires heavy R&D.



Electronic excitation of $^3HeT^+$ (43%)

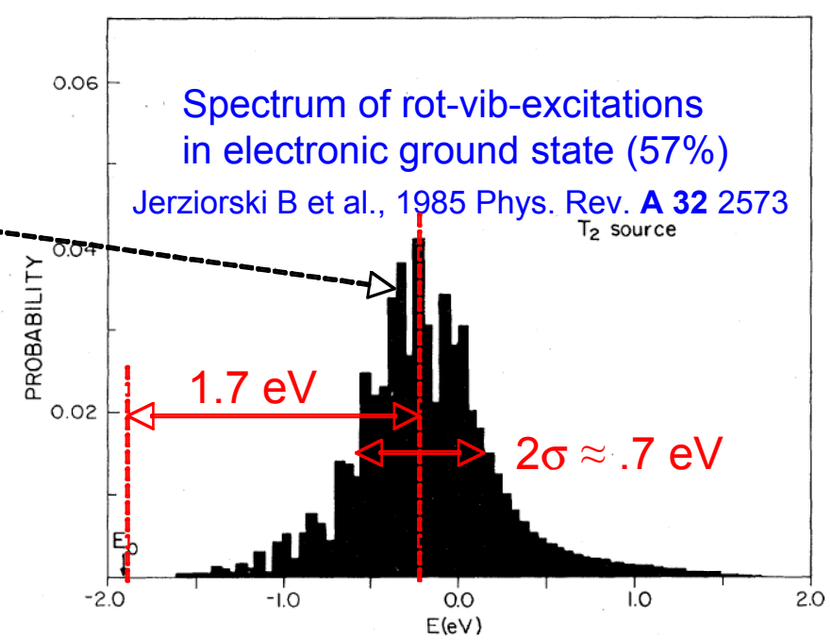
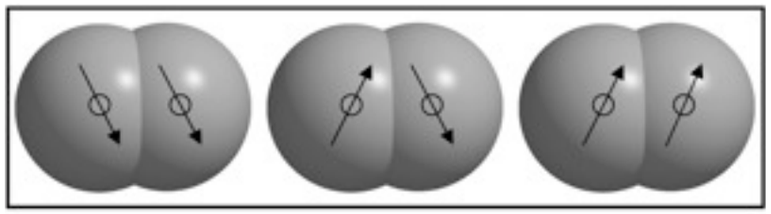
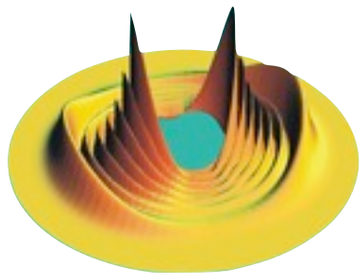
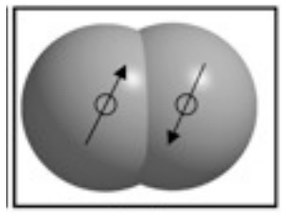


FIG. 1. Probability histogram for transitions to the first (ground) electronic state of the $^3HeT^+$ molecular ion. The energy "zero" is the energy of the ground-state He atom and the T^+ nucleus at infinity. This energy is 1.897 42 eV above the ground rovibronic state of $^3HeT^+$.

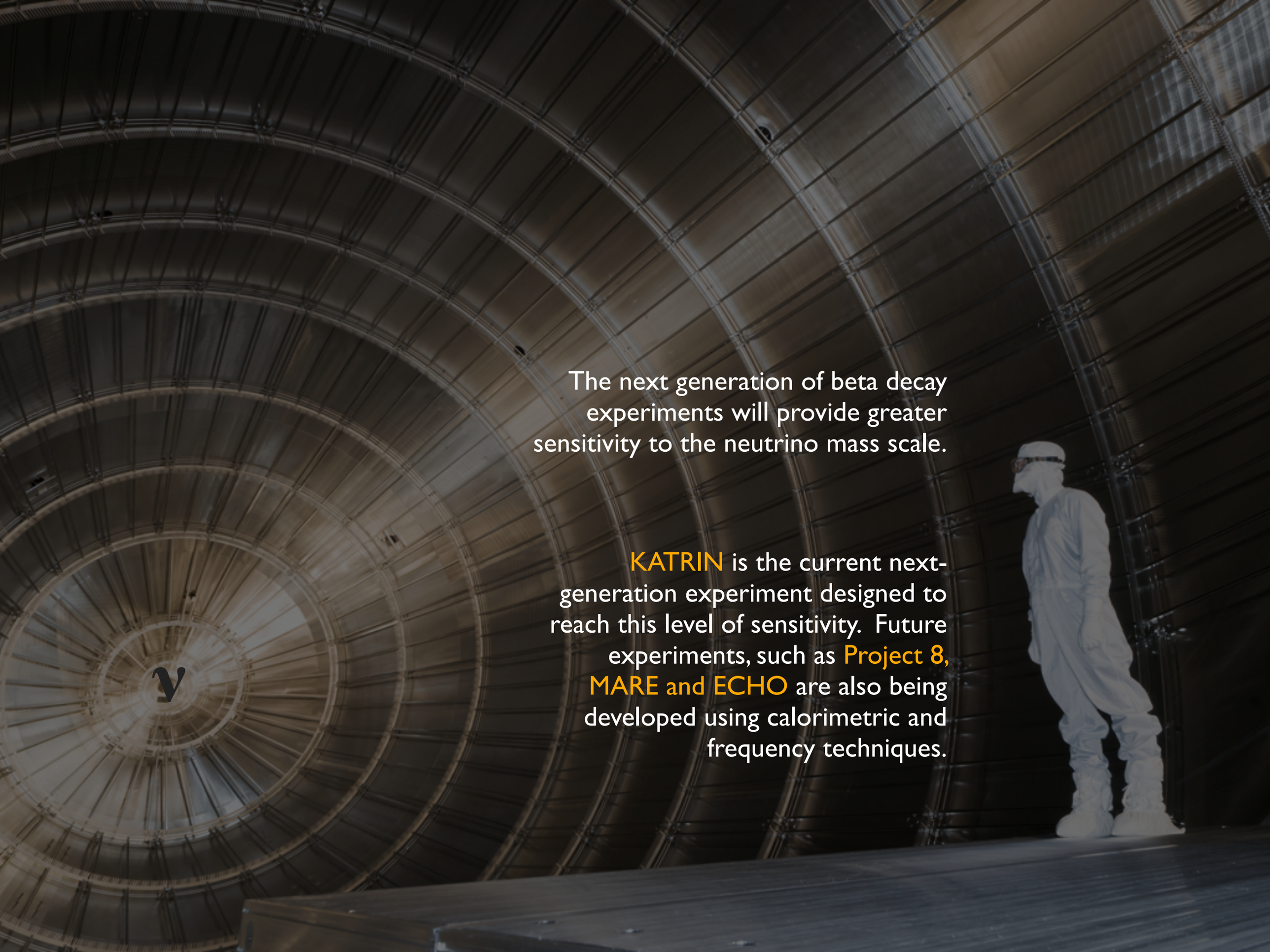


ortho-hydrogen





para-hydrogen

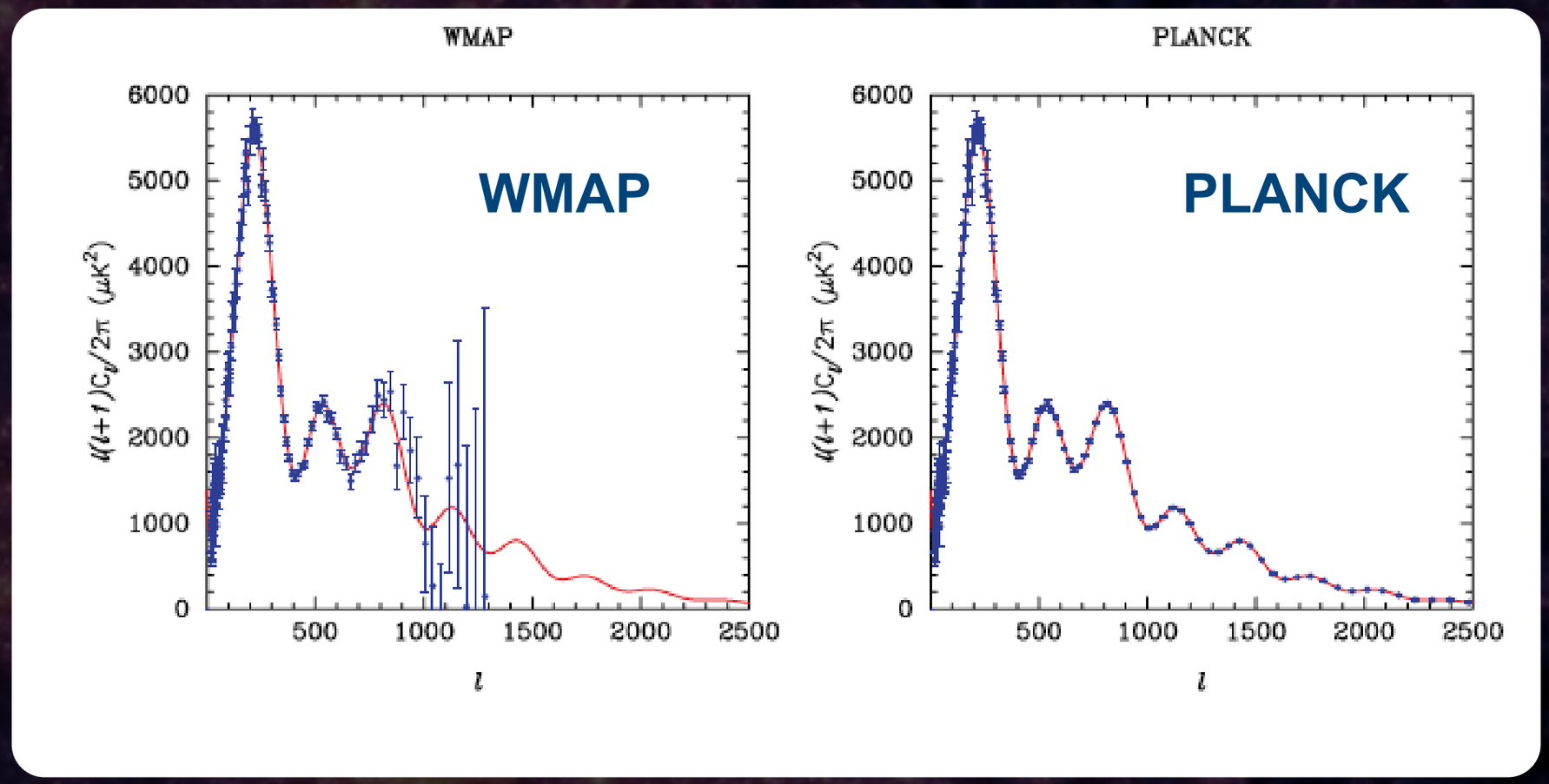


The next generation of beta decay experiments will provide greater sensitivity to the neutrino mass scale.

KATRIN is the current next-generation experiment designed to reach this level of sensitivity. Future experiments, such as Project 8, MARE and ECHO are also being developed using calorimetric and frequency techniques.

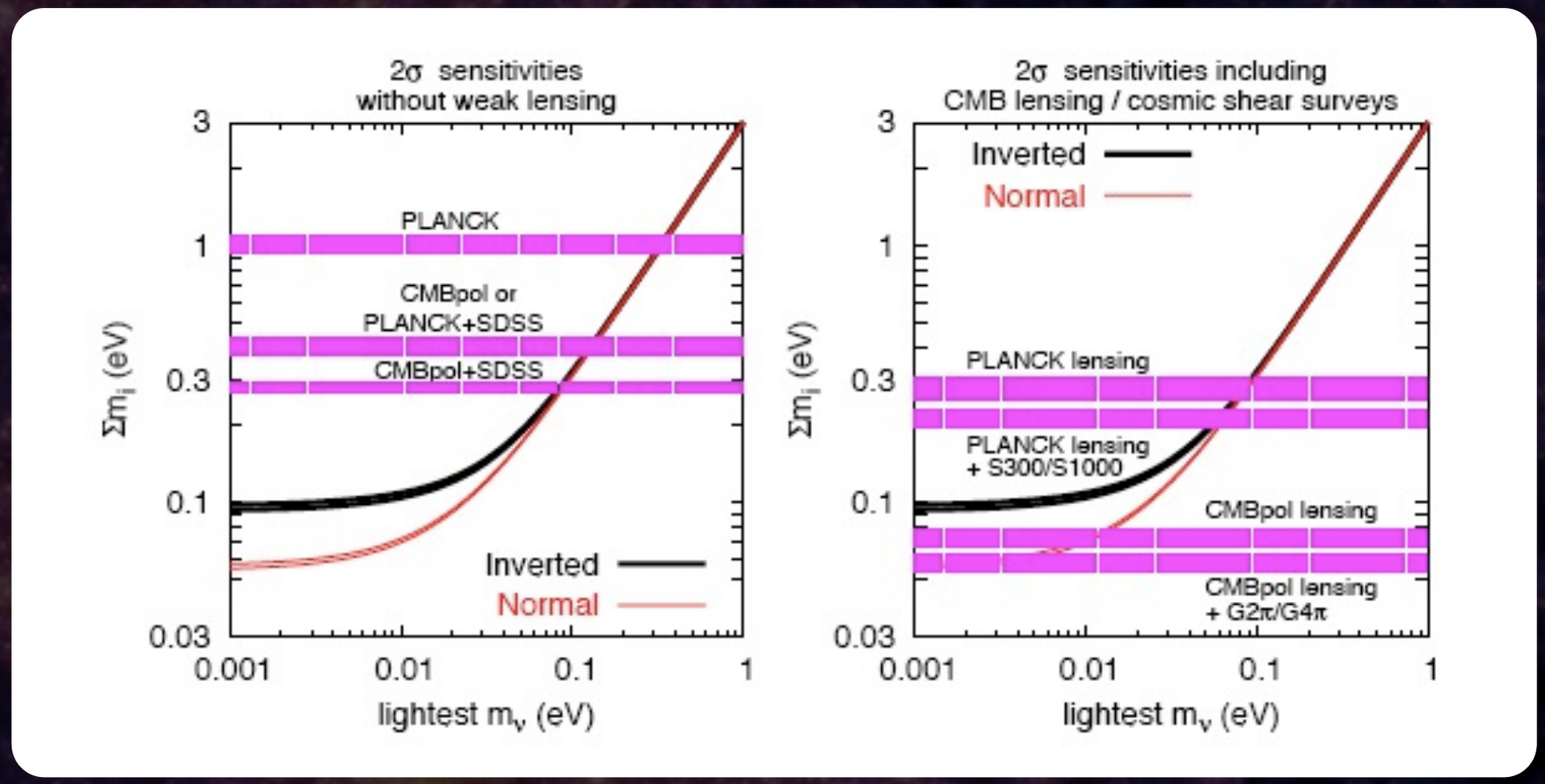
ν
Thank you for your attention

Upcoming Data



- Planck alone can push neutrino limits down 1 eV.
- Host of new experiments coming to the forefront.

Upcoming Data



- Planck alone can push neutrino limits down 1 eV.
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Probe	Current	Mission	Reach
CMB	1.3 eV	CMBPol	0.6 eV
CMB Lensing	None	CMBPol	0.05 eV
Galaxy Distribution	0.6 eV	LSST	0.1 eV
21 cm	None	SKA	0.05 eV

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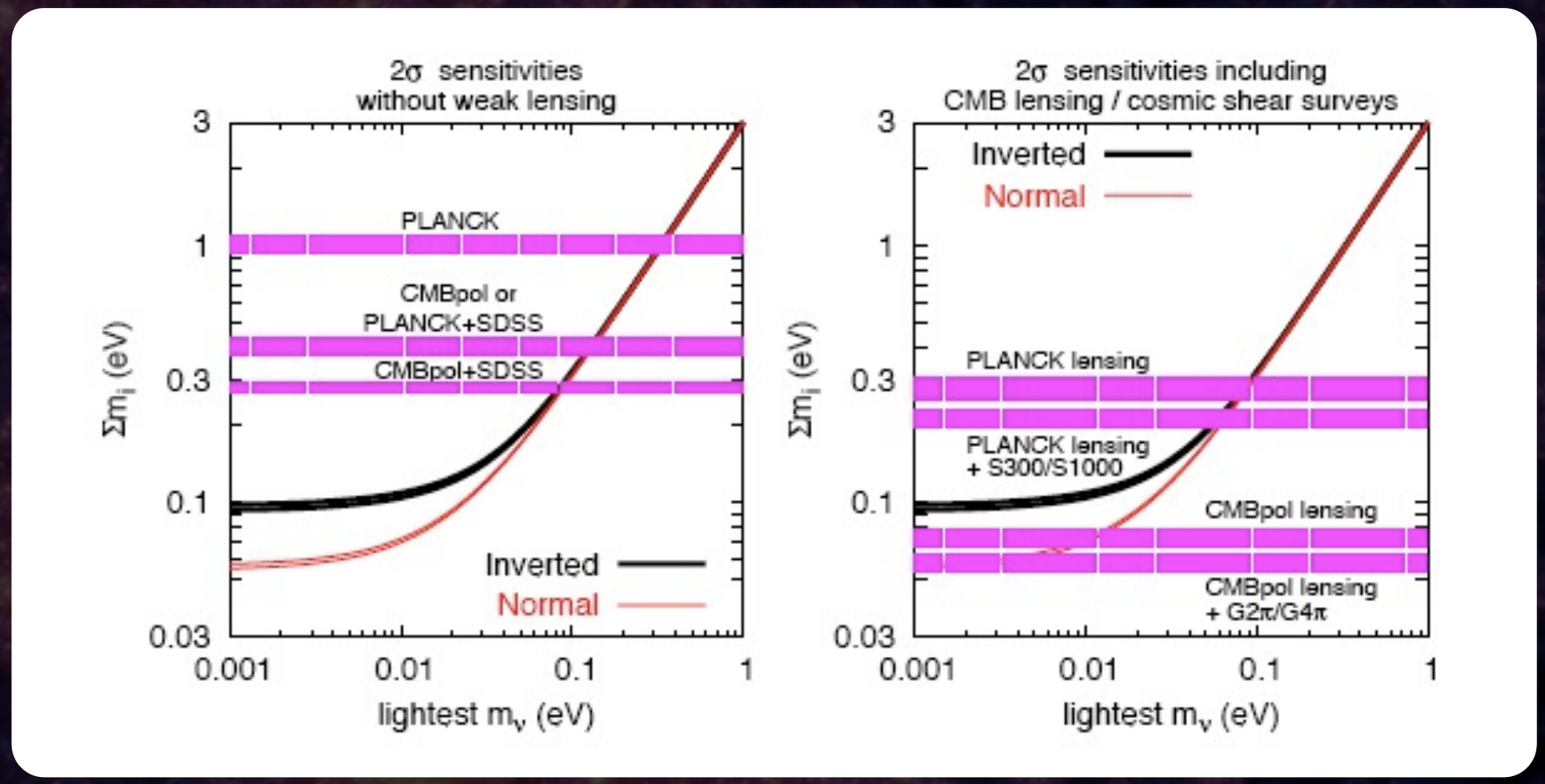

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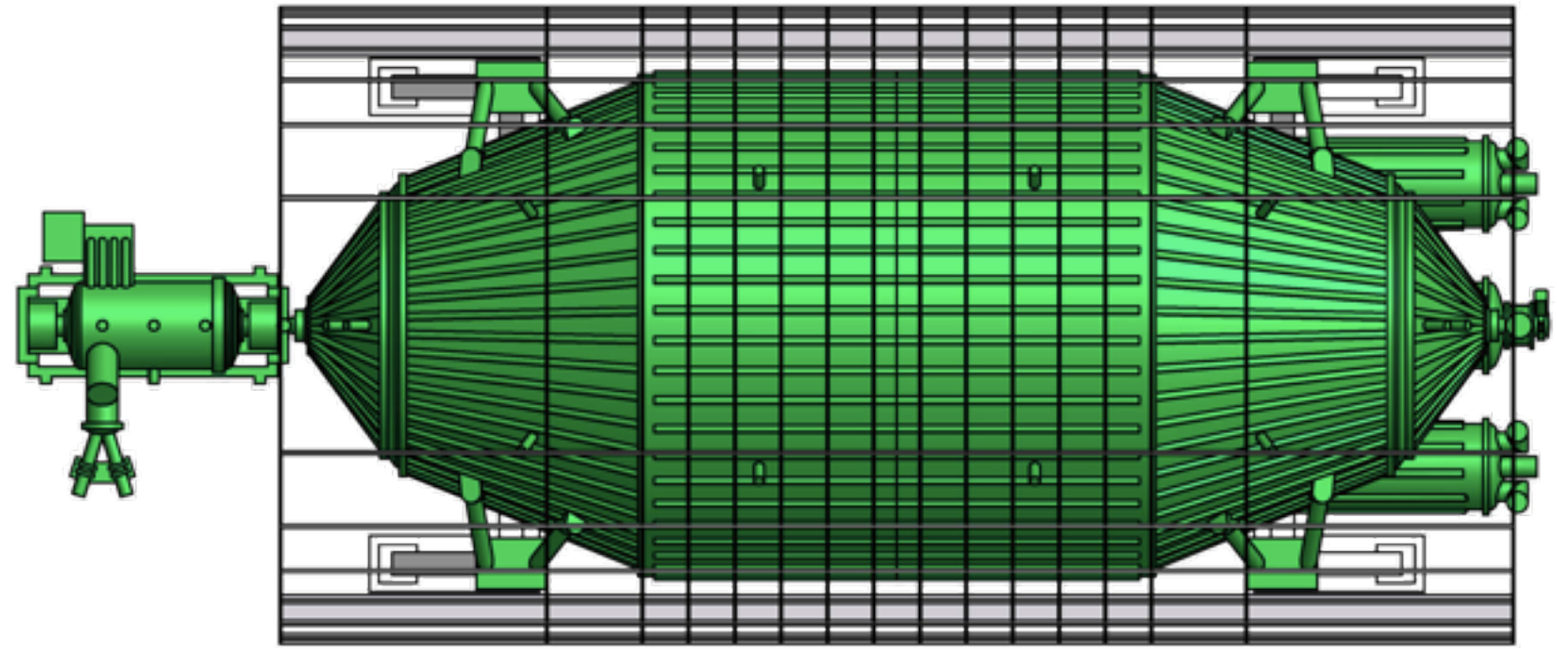
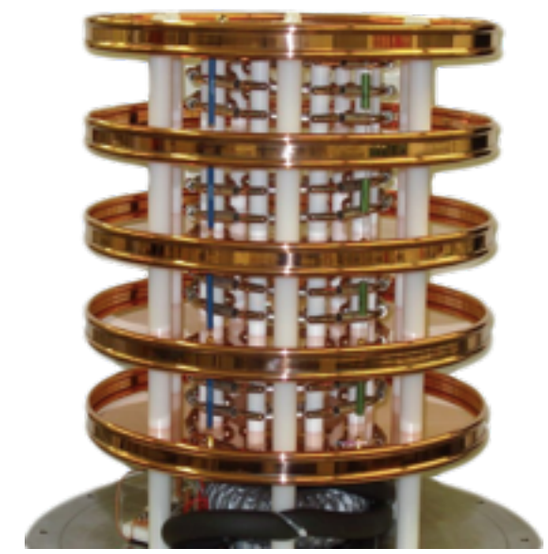
High Voltage Monitoring



KATRIN sensitivity goal requires 60 mV precision at 18.6 kV.

System monitored with high precision HV divider (10^{-6} stability).

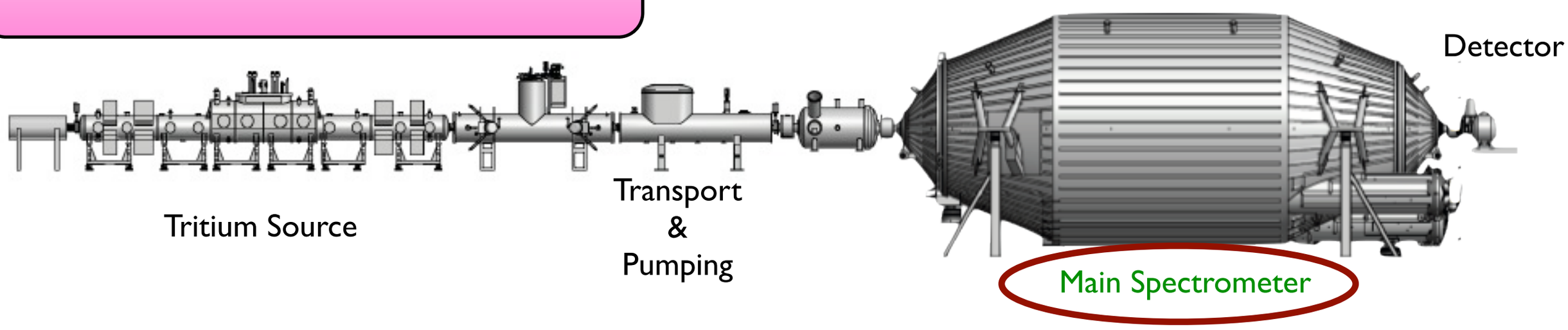
In-situ monitoring of ^{83m}Kr line using refurbished Mainz spectrometer.

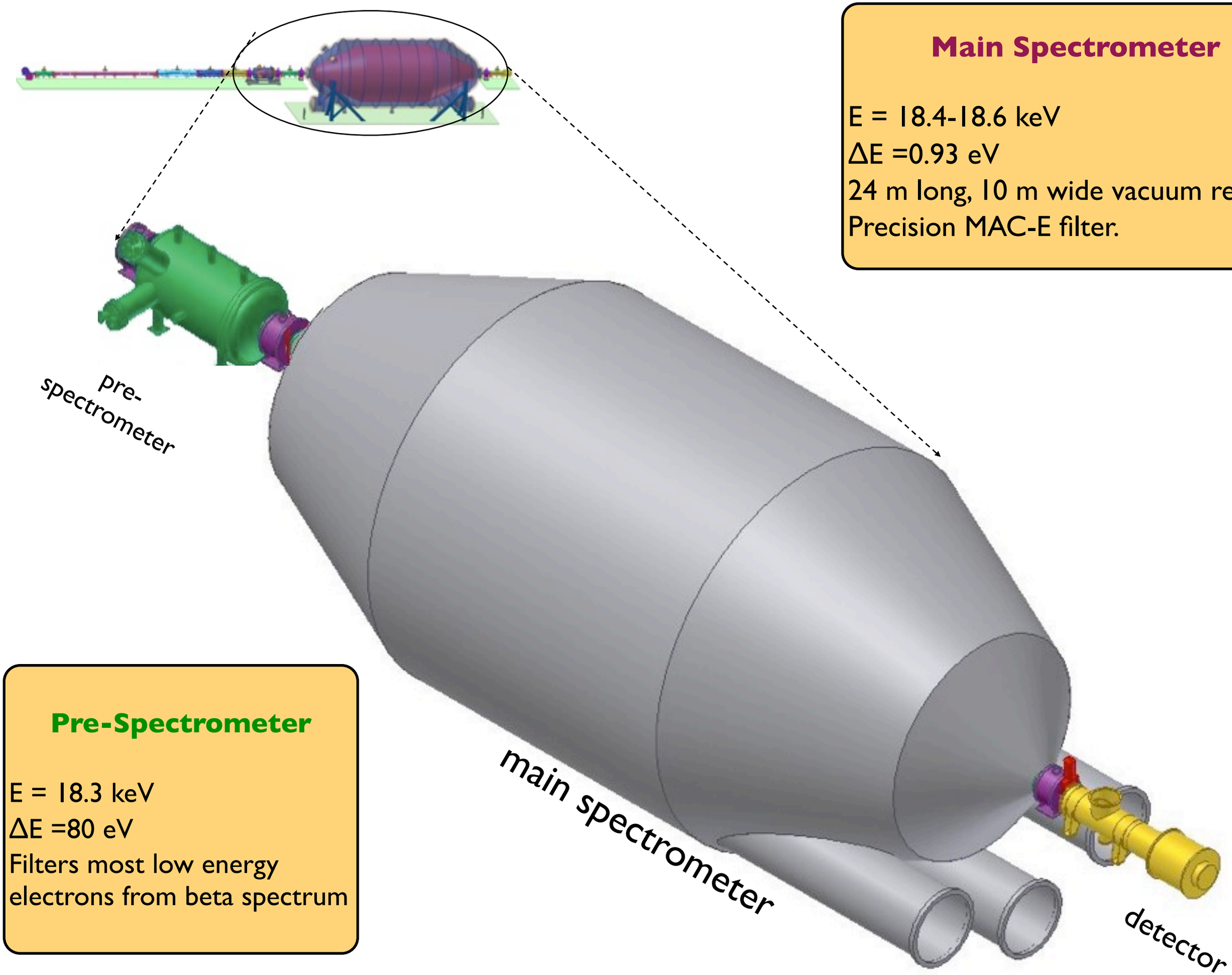


Recent milestones:

Monitor spectrometer installed.

HV stabilization ~x3 better than specification.





Main Spectrometer

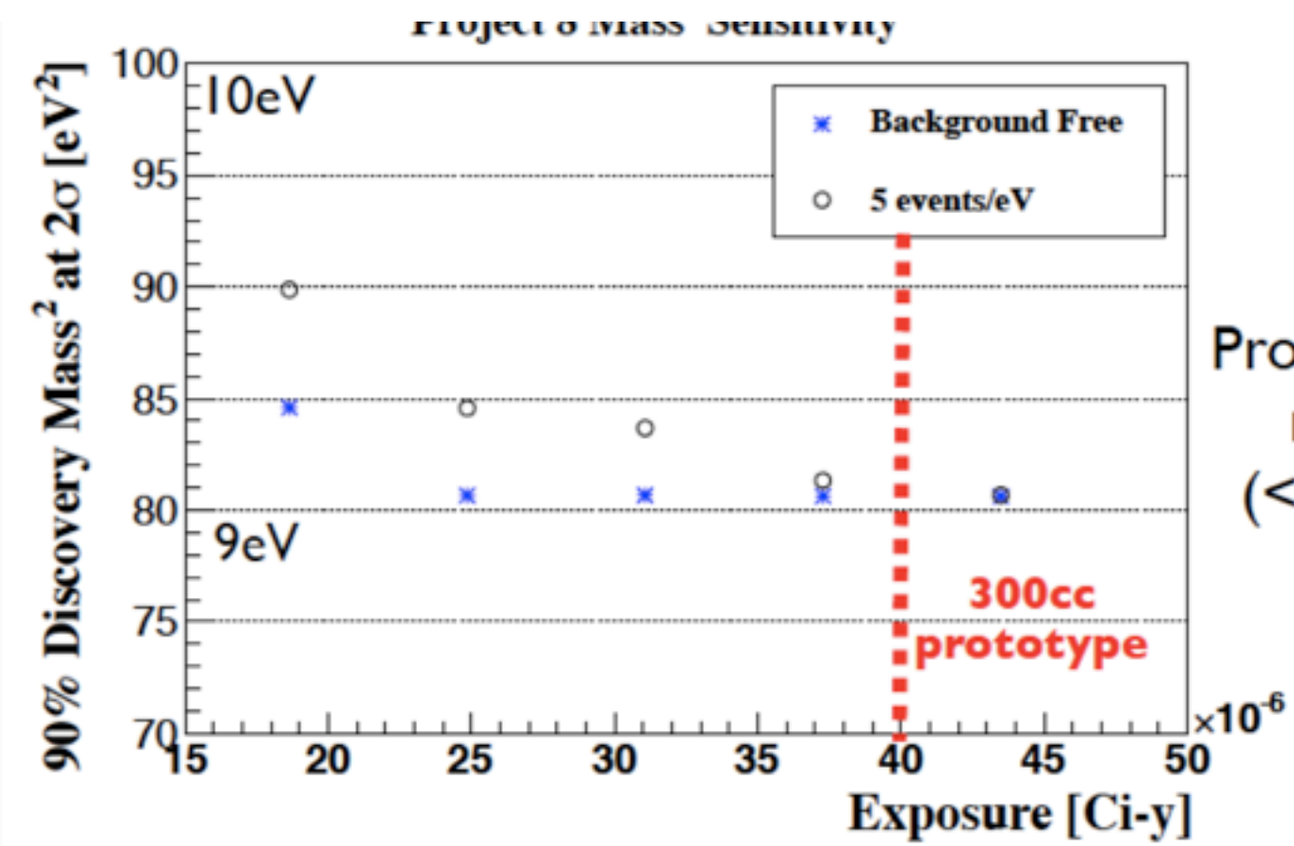
E = 18.4-18.6 keV
ΔE =0.93 eV
24 m long, 10 m wide vacuum region.
Precision MAC-E filter.

Pre-Spectrometer

E = 18.3 keV
ΔE =80 eV
Filters most low energy electrons from beta spectrum

Next Steps

- Continue prototype tests:
  - Next ^{83m}Kr run scheduled in 2 weeks.
  - Provide measurement of Kr line width.
  - Insert small amount of tritium as test
- Continue study of resonant cavities for enhanced detection.
- Begin "scalable design" for few eV precision mass measurement.
- Proposal for large experiment, for 2014.



Prototype in "maximum resolution" mode (< 5000 Bq/cm^3, 1eV)

~ 40 μCi of T_2 (KATRIN is ~ 3 Ci)