TRIN

Ray Davis Jr., Homestake

PLANCK

ilson & Penzias

Year One:

Direct Neutrino Masses post PLANCK

TAUP '13
September 11th, 2013

Joseph A. Formaggio
MIT

Year One:

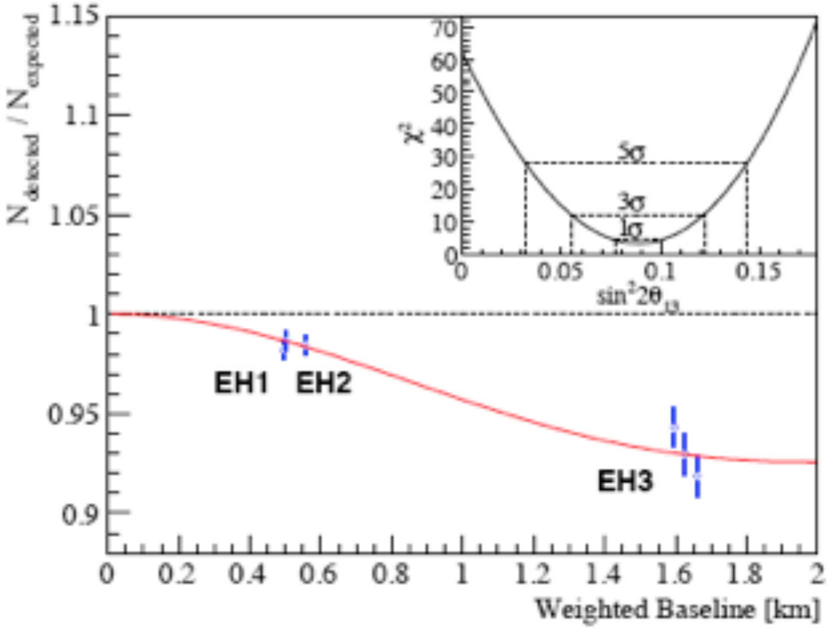
Direct

Neutrino Masses

post PLANCK

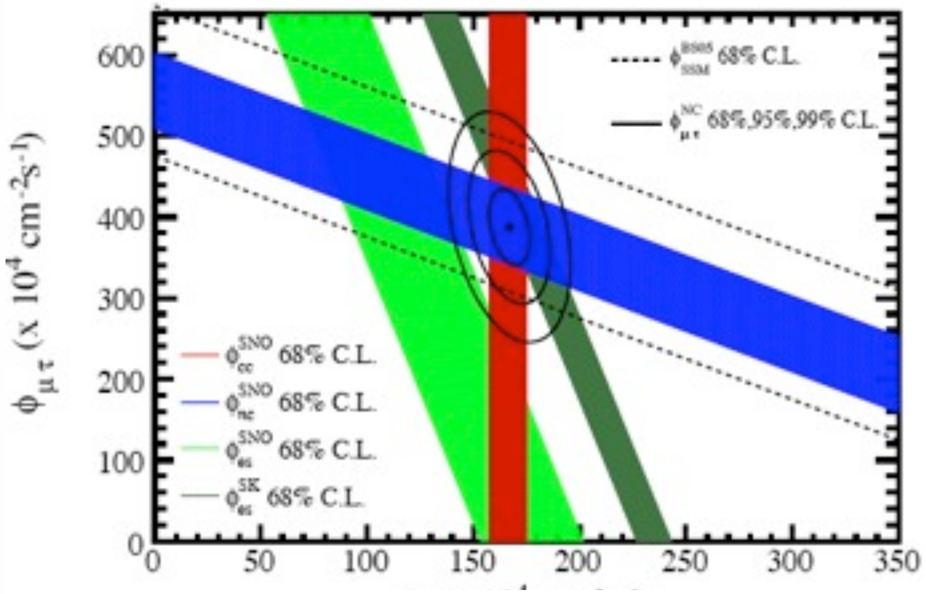
Ray Davis Jr., Homestake

The phenomena of
neutrino
oscillations is now
firmly established.



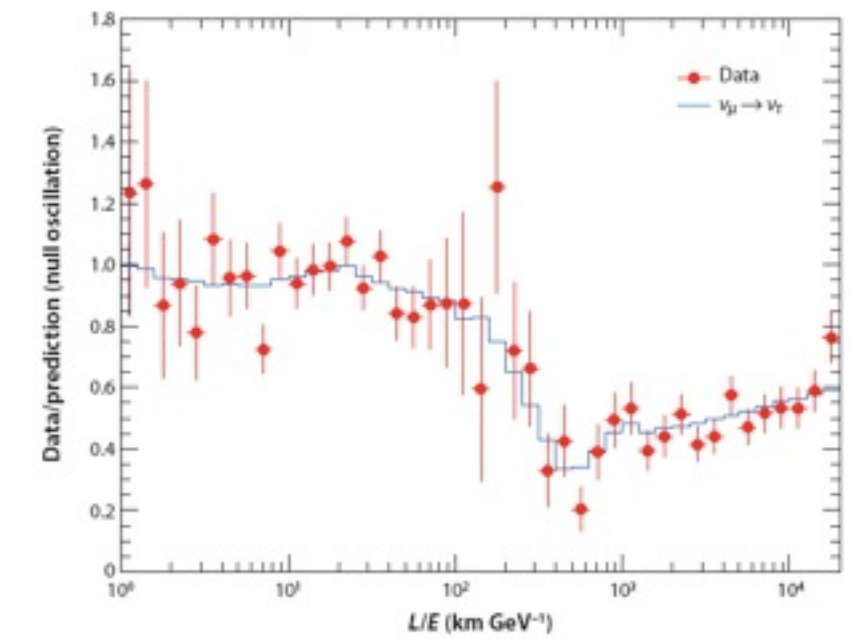
$$\sin^2(\theta_{13}) = 0.0241 \pm 0.0025$$

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

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

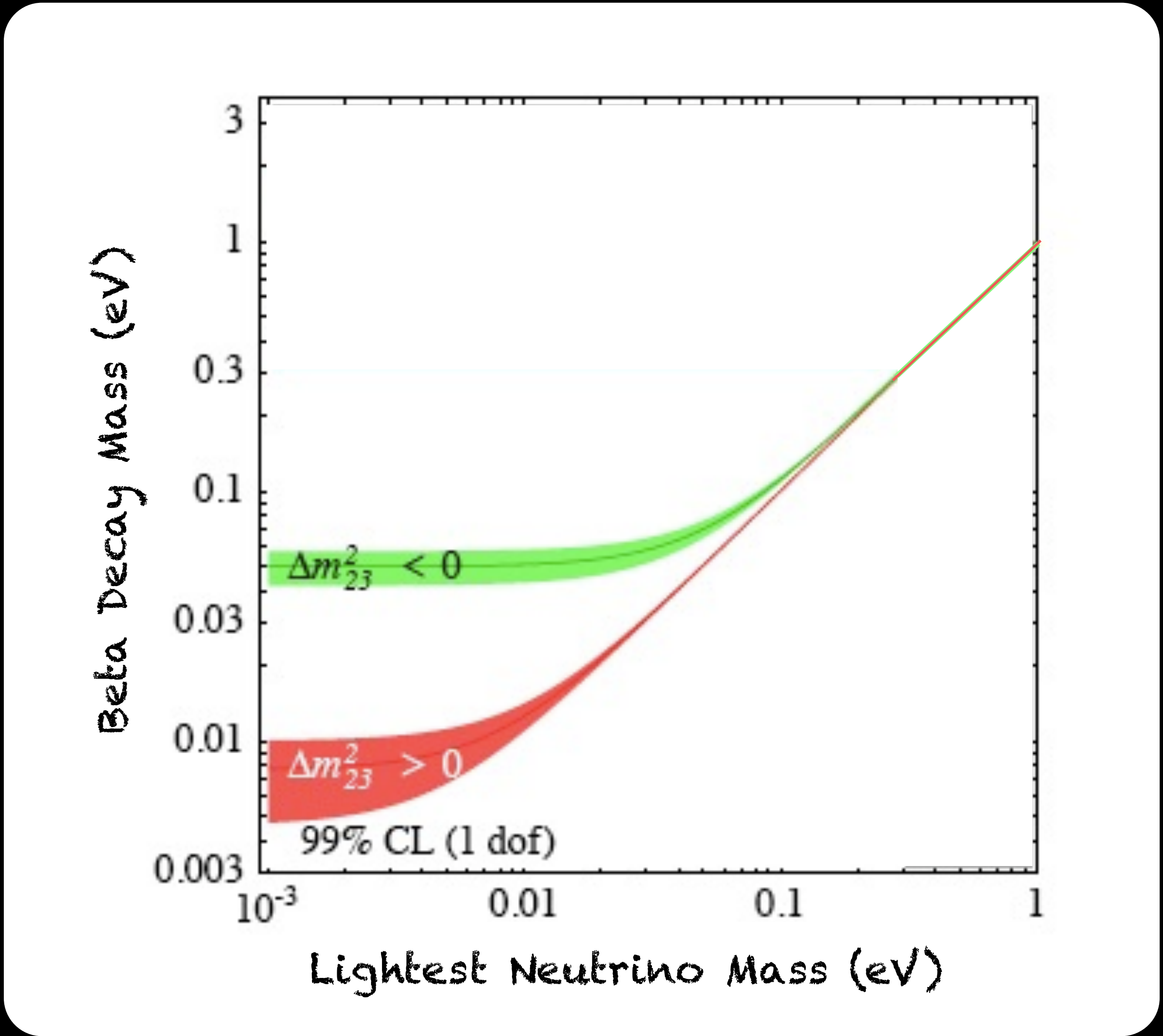
Precision measurements now exist on all three mixing angles to date.

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

Measuring Neutrino Masses

Neutrino oscillations have placed a lower bound on neutrino masses that can be experimentally accessed.

Lower bound depends on hierarchy of neutrinos (inverted or normal)



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

Cosmological Measurements

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

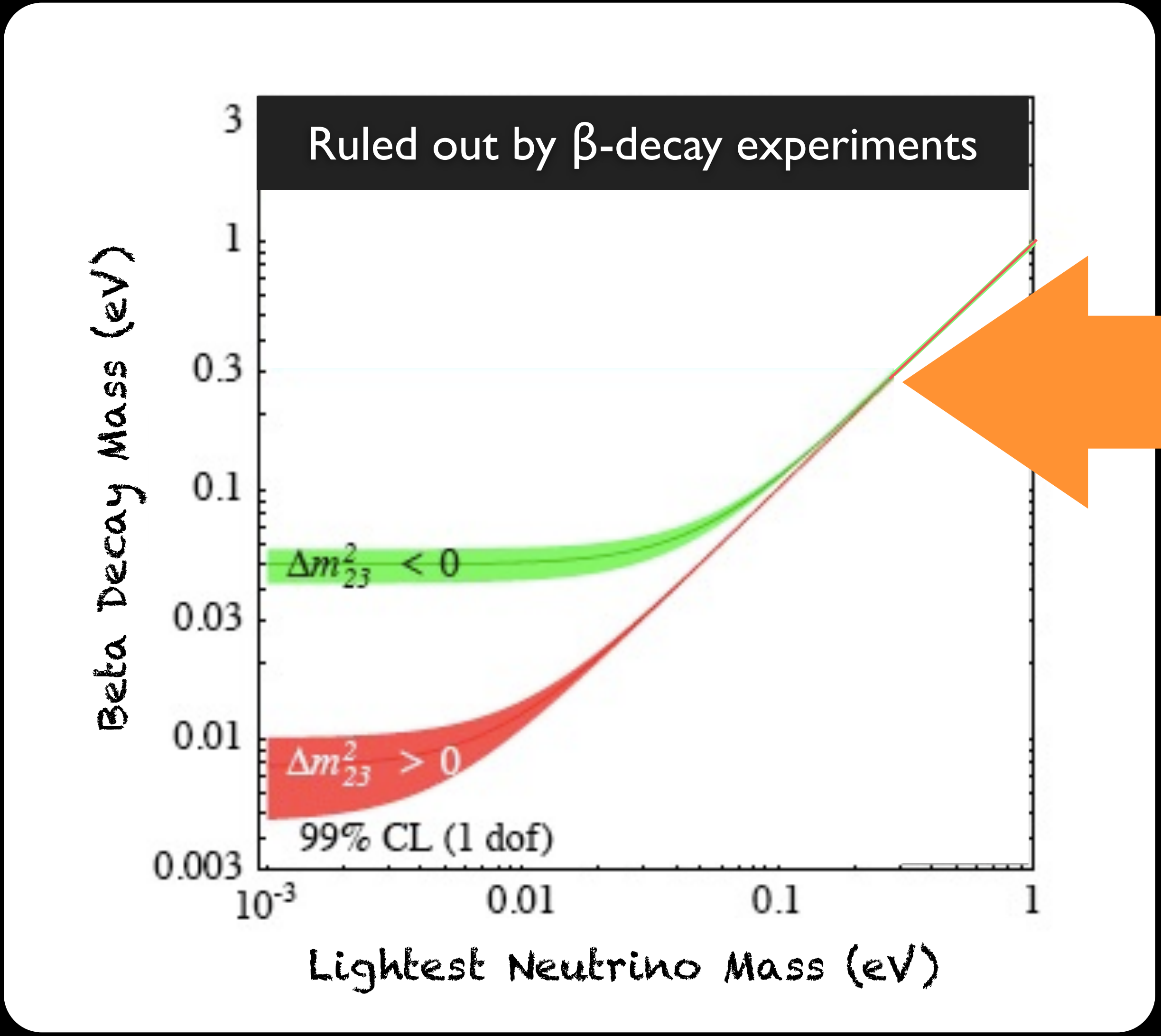
0νββ Measurements

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

Beta Decay Measurements

The Neutrino Mass Scale

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



m_ν > 2 eV (eV scale, current)
Neutrinos ruled out as dark matter

m_ν > 0.2 eV (degeneracy scale)
Impact on cosmology and 0νββ reach

m_ν > 0.05 eV (inverted hierarchy)
Resolve hierarchy if null result

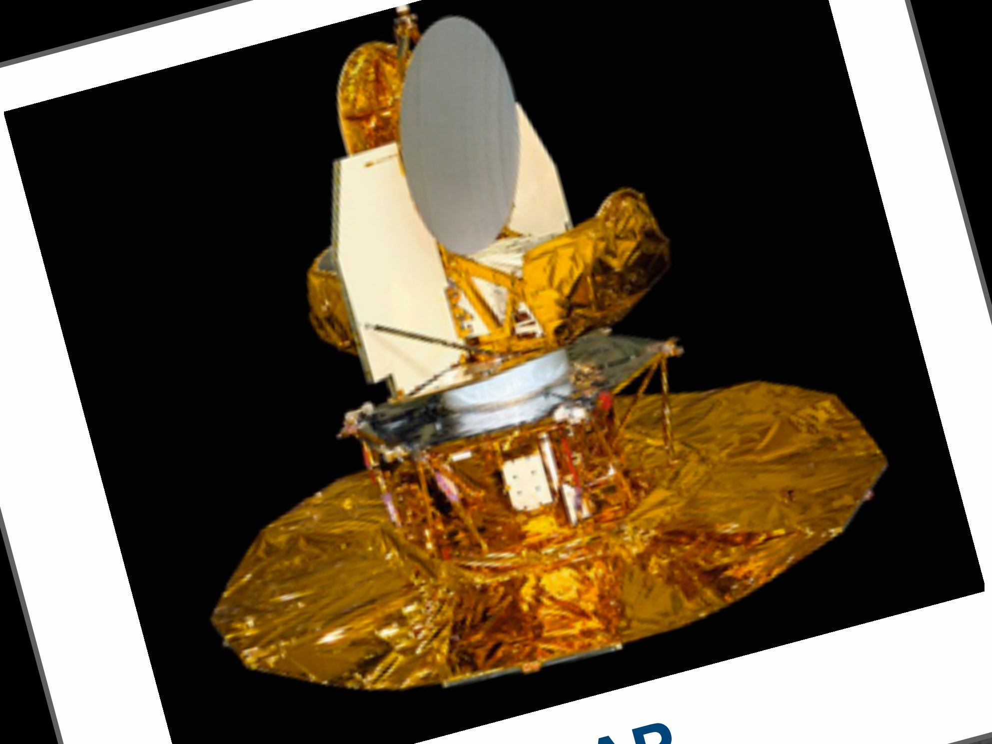
m_ν > 0.01 eV (normal hierarchy)
Oscillation limit; possible CνB detection

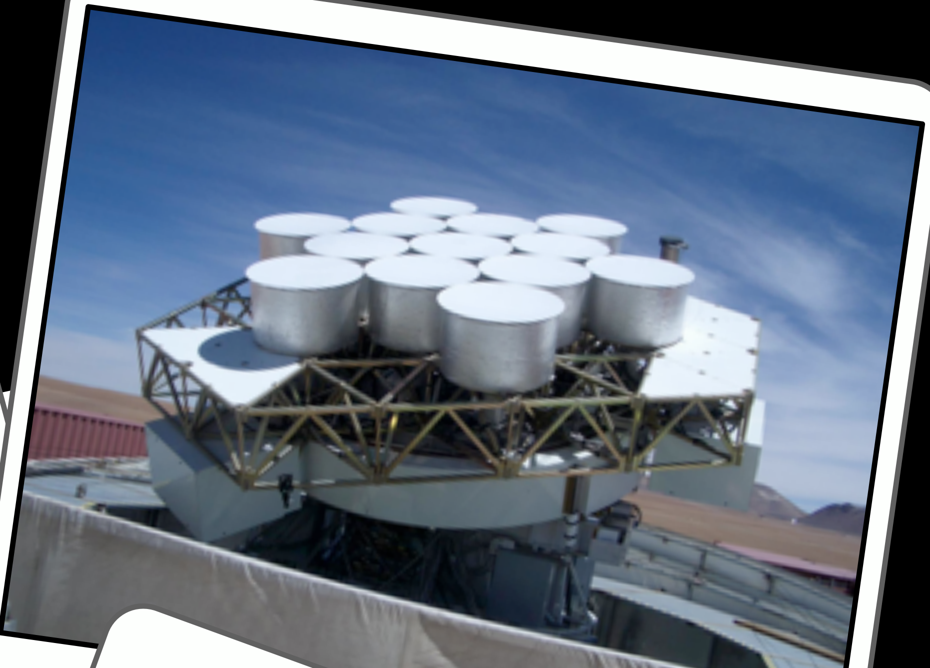
The Era of Precision Cosmology

Wilson & Penzias

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

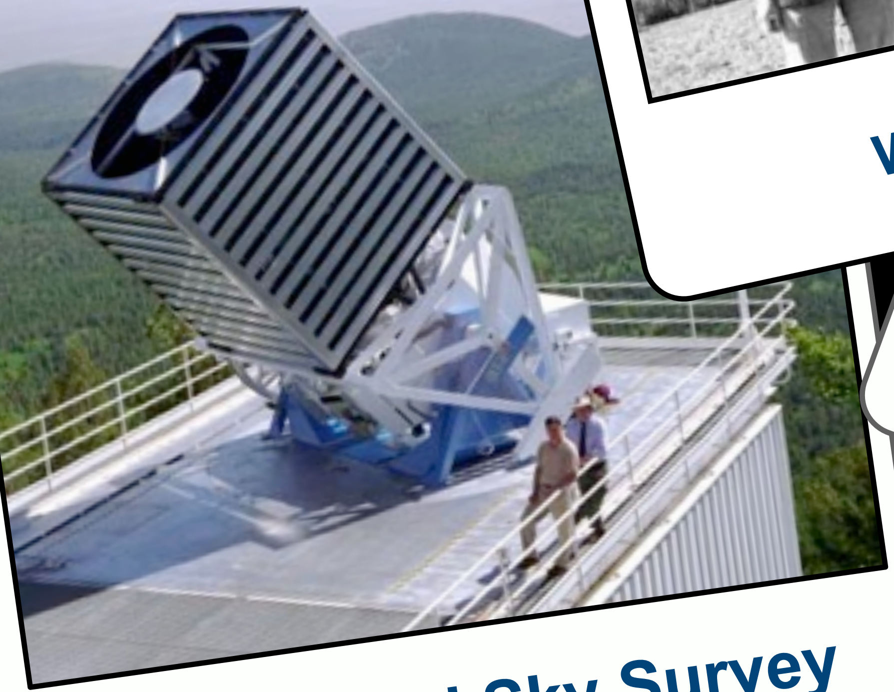
The Era of Precision Cosmology


WMAP




Wil


Atacama Cosmology Telescope


Sloan Digital Sky Survey

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

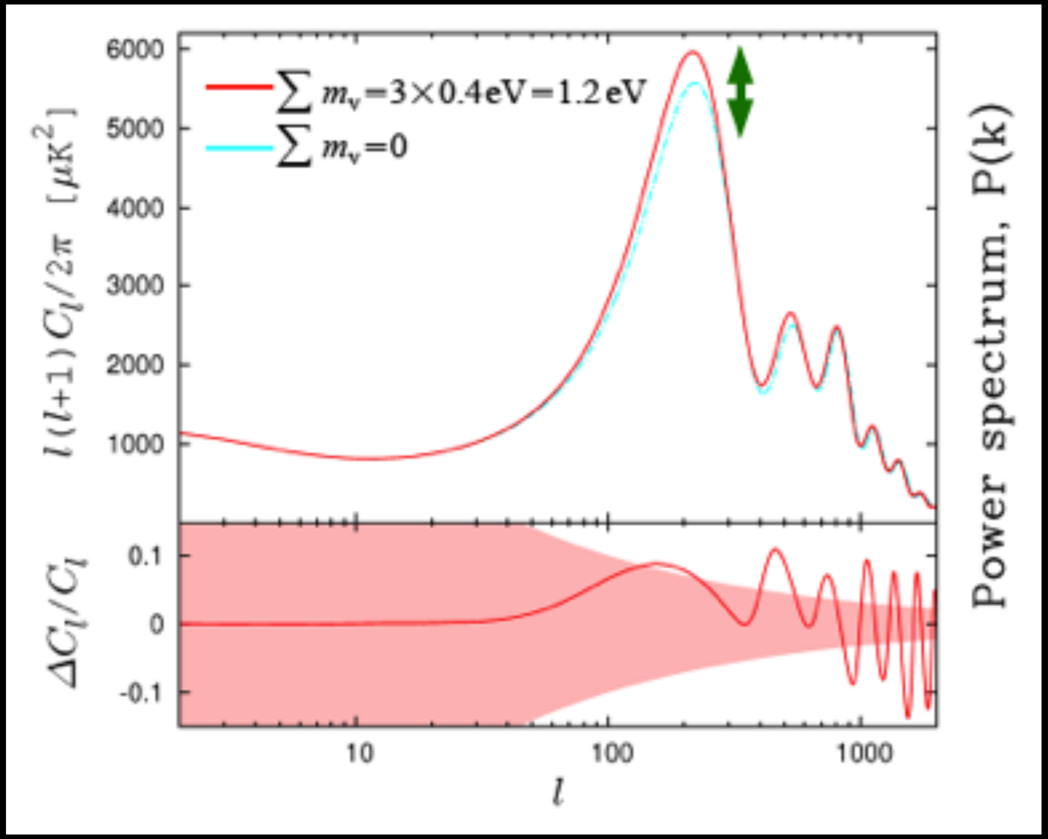
Neutrino Physics & Cosmology

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

  (1) Number of neutrino species

  (2) Sum of neutrino masses

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



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

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

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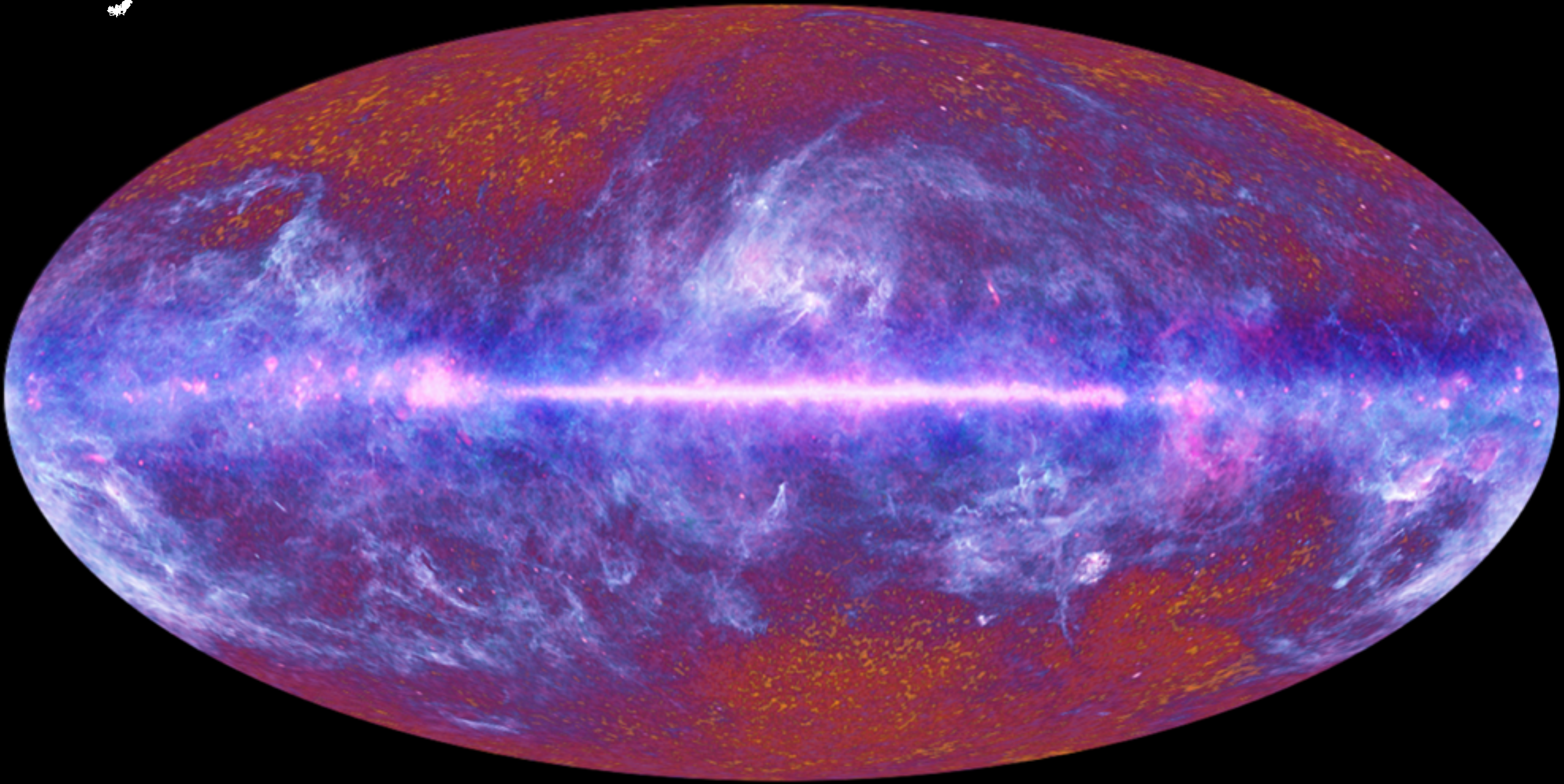
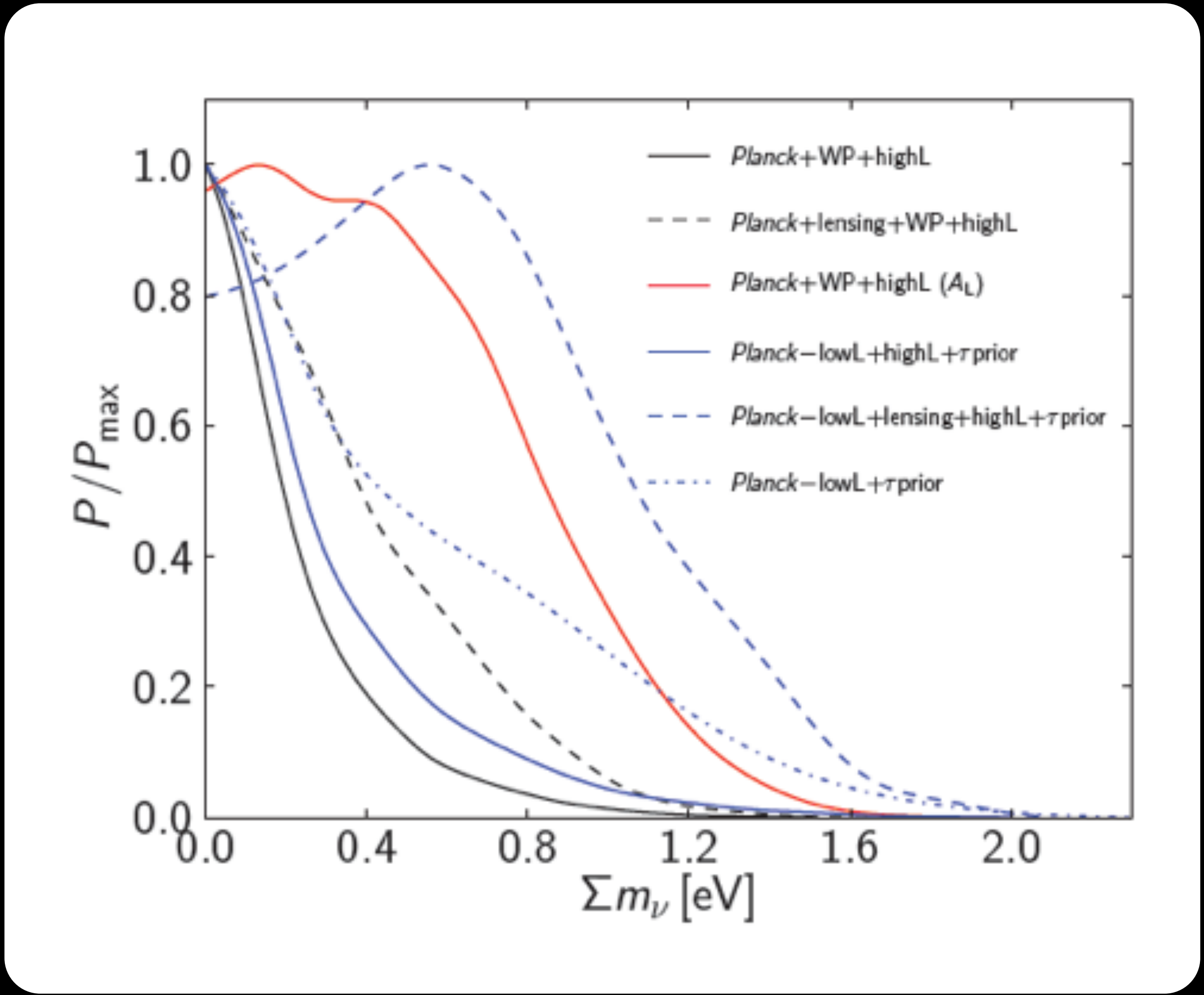
Planck Satellite:

Launched May 14th, 2009

The Microwave sky...



PLANCK Results



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

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

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

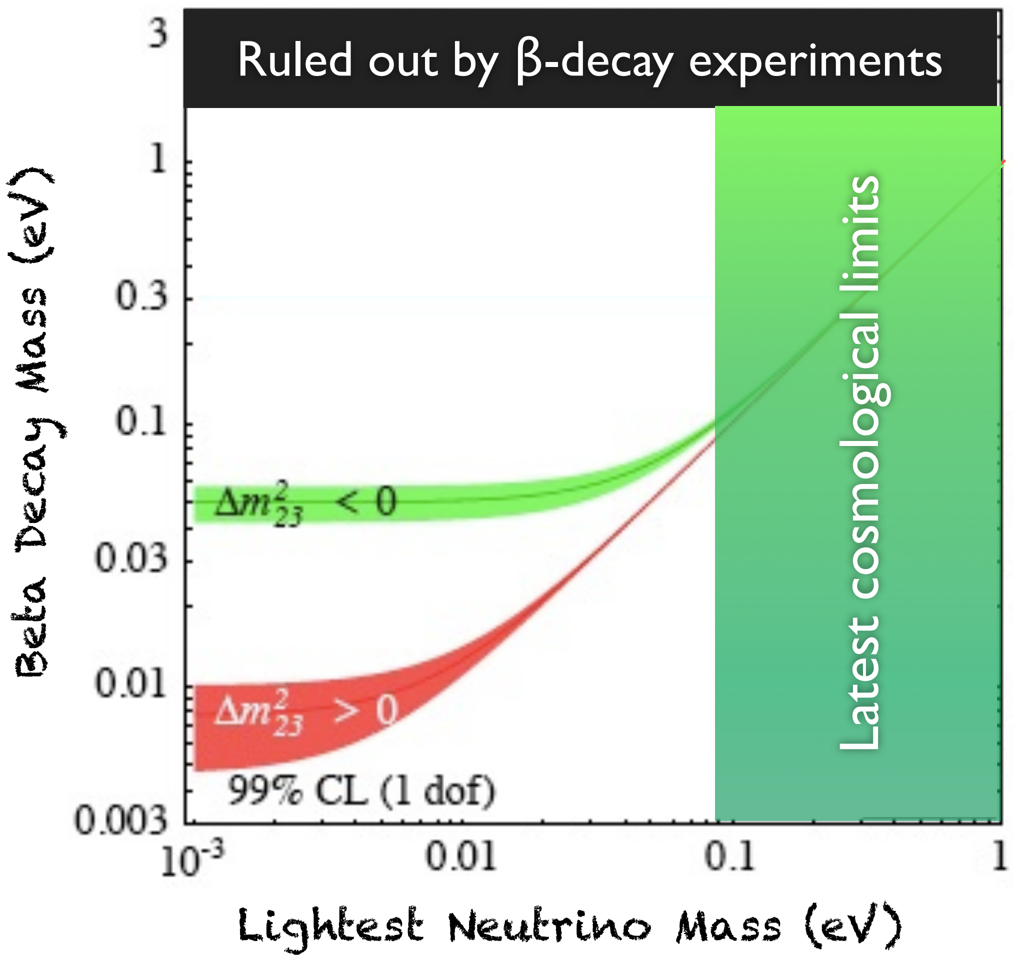
Fit	Σm_ν (95% C.L.)
Planck + WP + HighL	< 0.66 eV
Planck + WP + HighL + BAO	< 0.23 eV
Planck + SZ + BAO	0.22 ± 0.09 eV

Moving Forward...

- Current cosmological limits are starting to push at the degeneracy-inverted scale.
- Future experiments (CMB-IV) could push all the way down to the normal scale.
- Model dependencies and degeneracies will still persist.

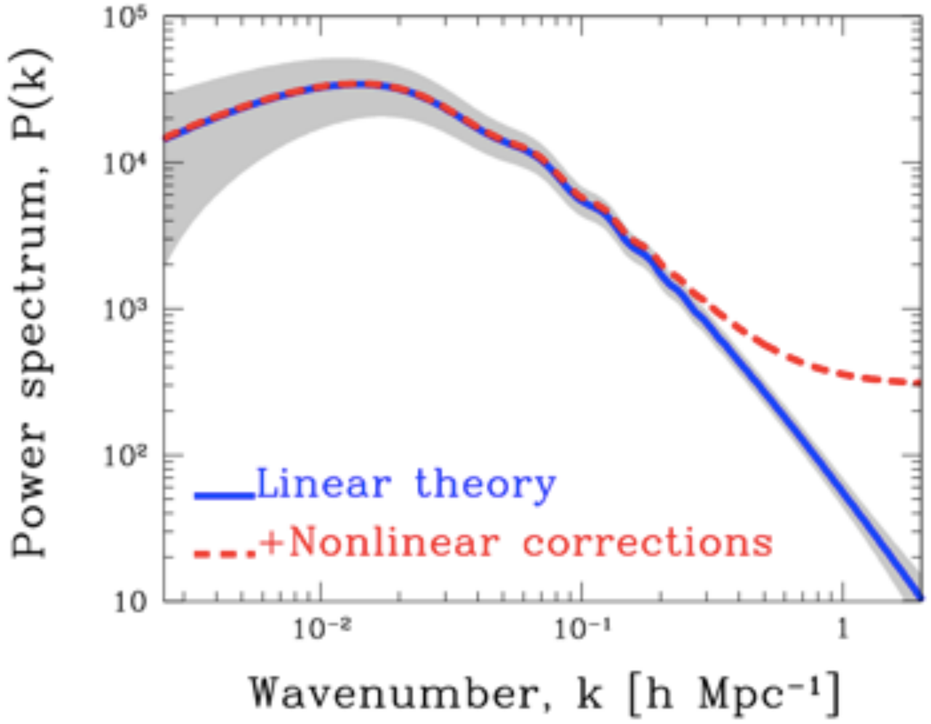
$$\frac{\Delta P}{P} \simeq -12\frac{\Omega_\nu}{\Omega_m} \simeq 1\%$$

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

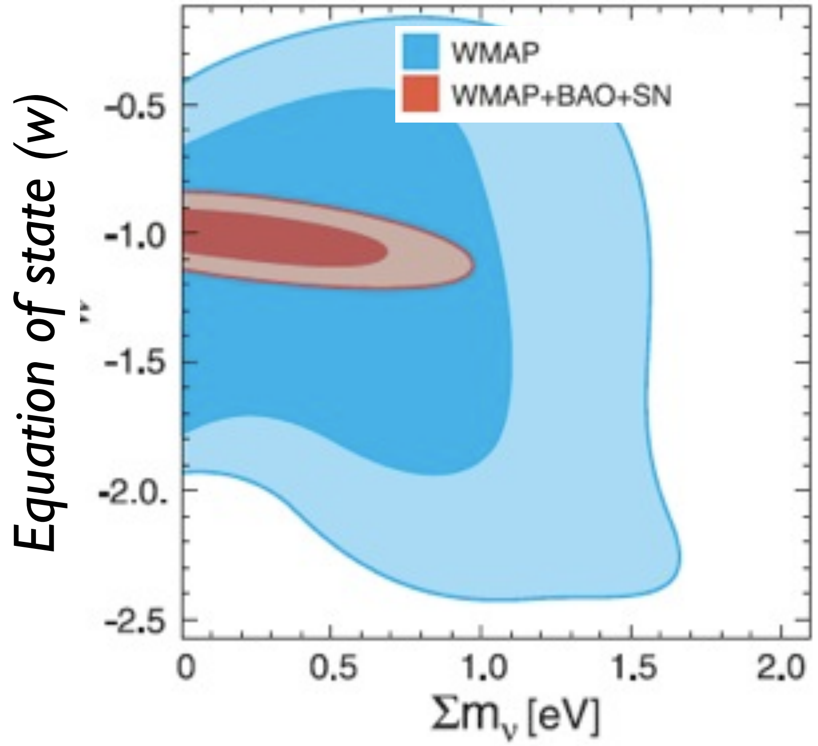


Y. Y. Y. Wong, 2010

S. Hannestad
Phys. Rev. Lett 95 221301

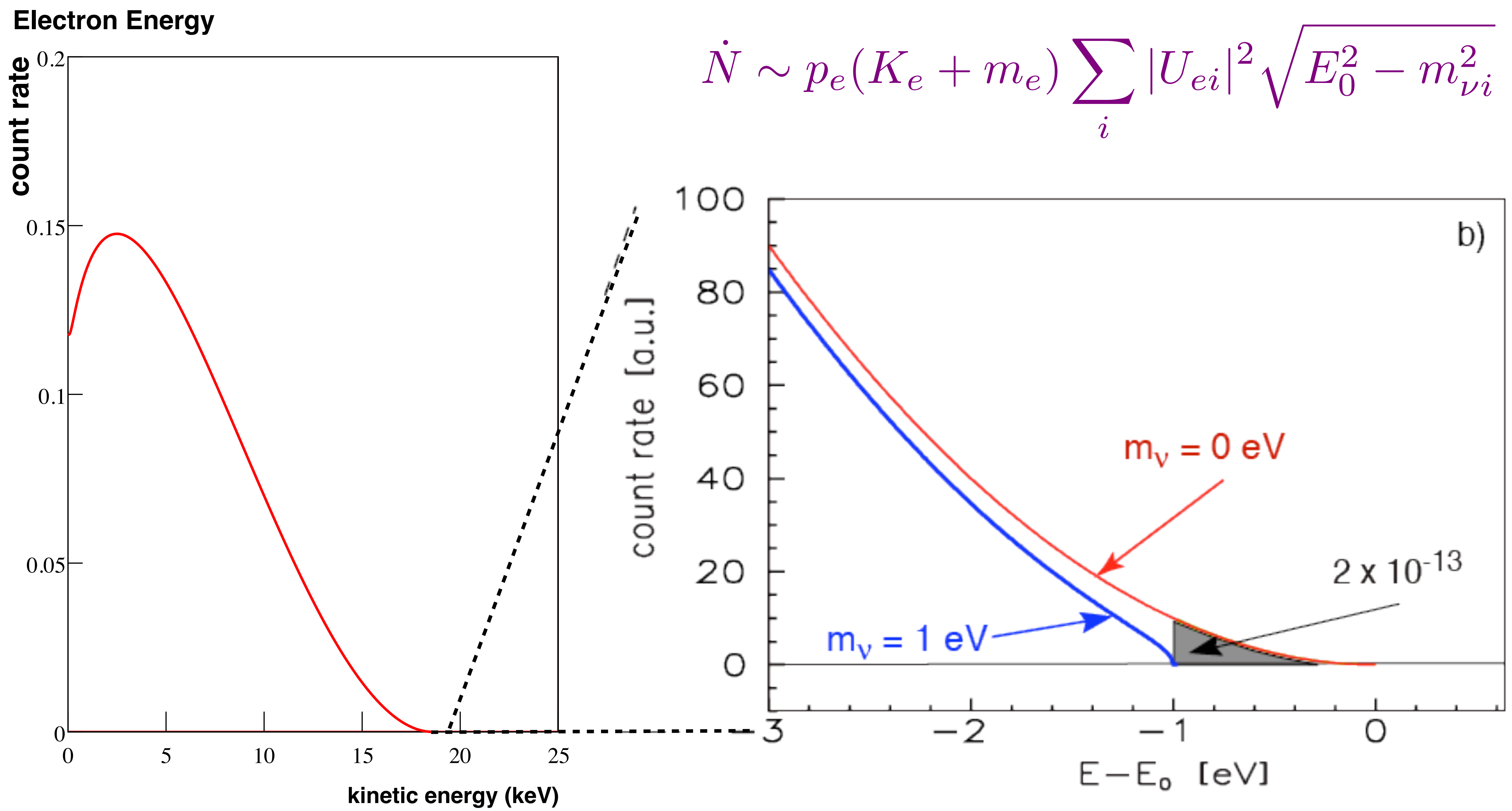


Nonlinearities



Degeneracies

Direct Probes

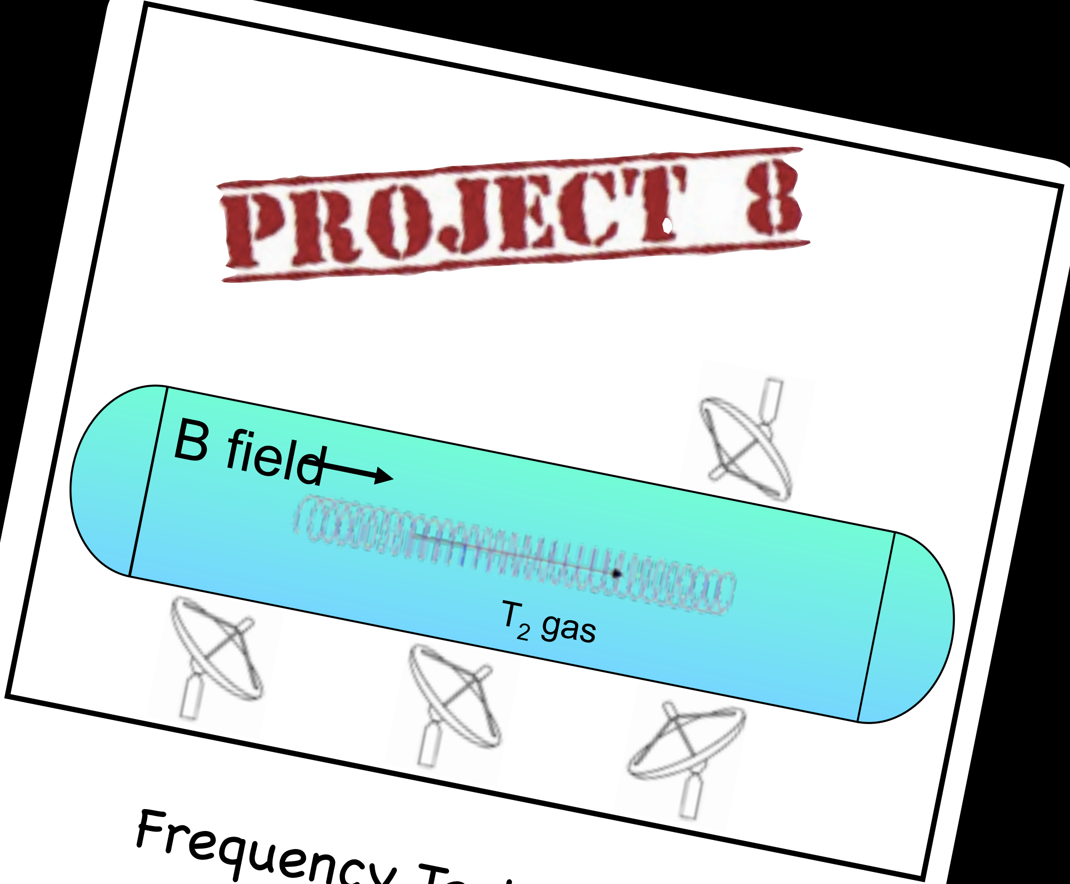


$$\dot{N} \sim p_e(K_e + m_e) \sum_i |U_{ei}|^2 \sqrt{E_0^2 - m_{\nu i}^2}$$

Beta Decay

A kinematic determination of the neutrino mass

No model dependence on cosmology or nature of mass



Frequency Techniques

MARE-HOLMES & ECHO

Calorimetry

KATRIN

Electromagnetic Spectroscopy

KATRIN is currently the prominent experiment for beta decay measurements.

New techniques being explored in the future:

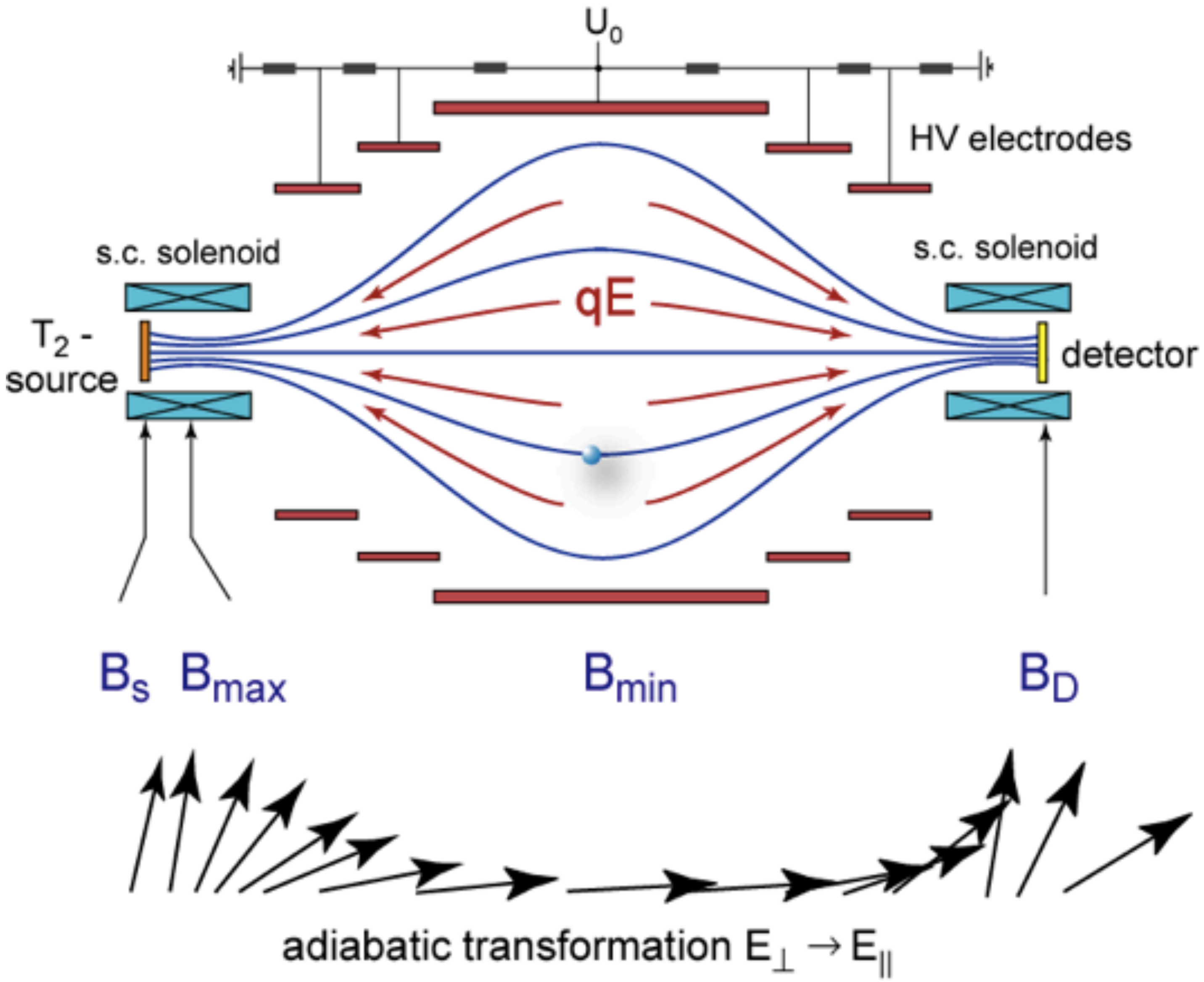
ECHO, MARE-HOLMES and Project 8

MAC-E Filter Technique

KATRIN

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

Spectroscopic: MAC-E Filter

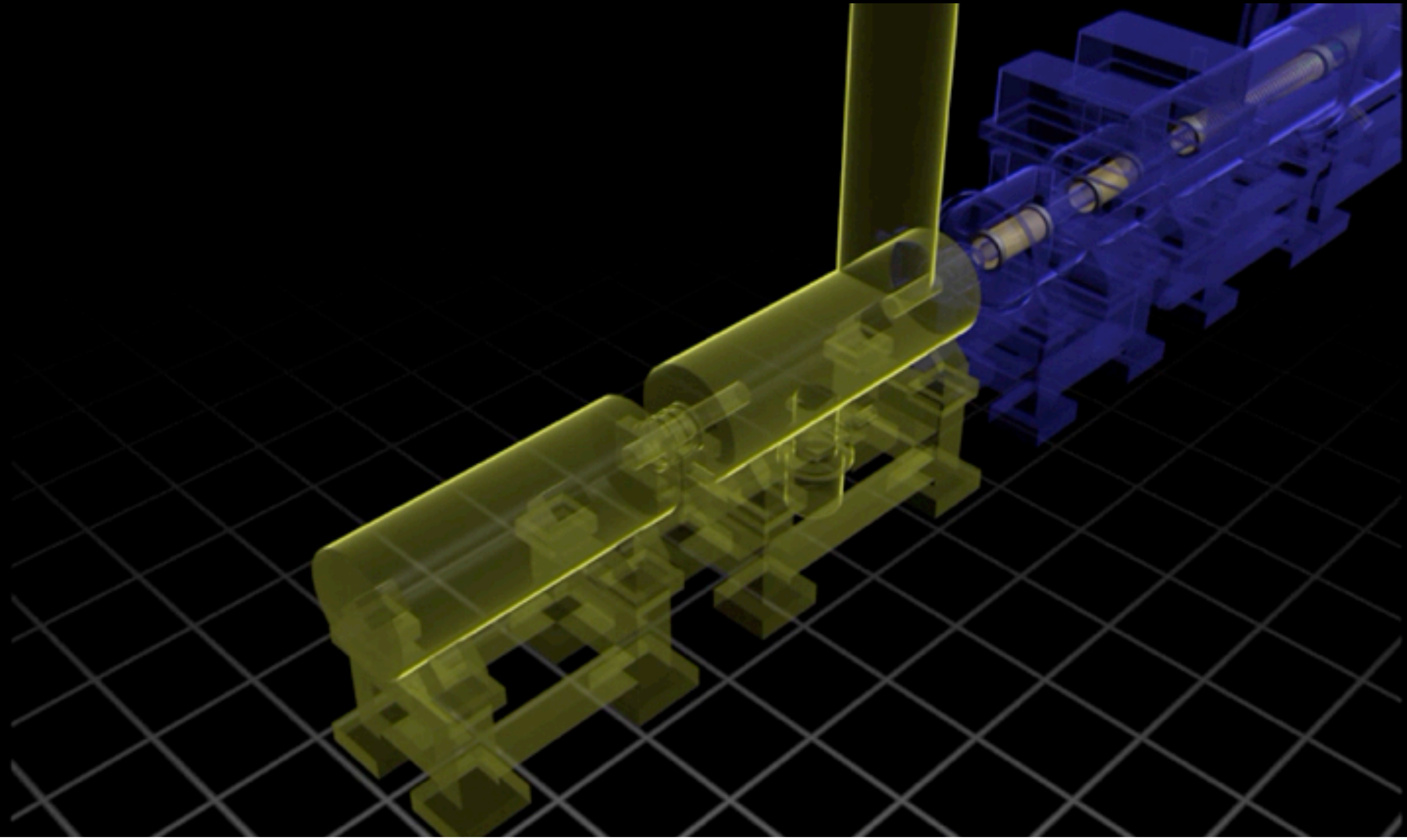


Inhomogeneous magnetic guiding field.

Retarding potential acts as high-pass filter

High energy resolution

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

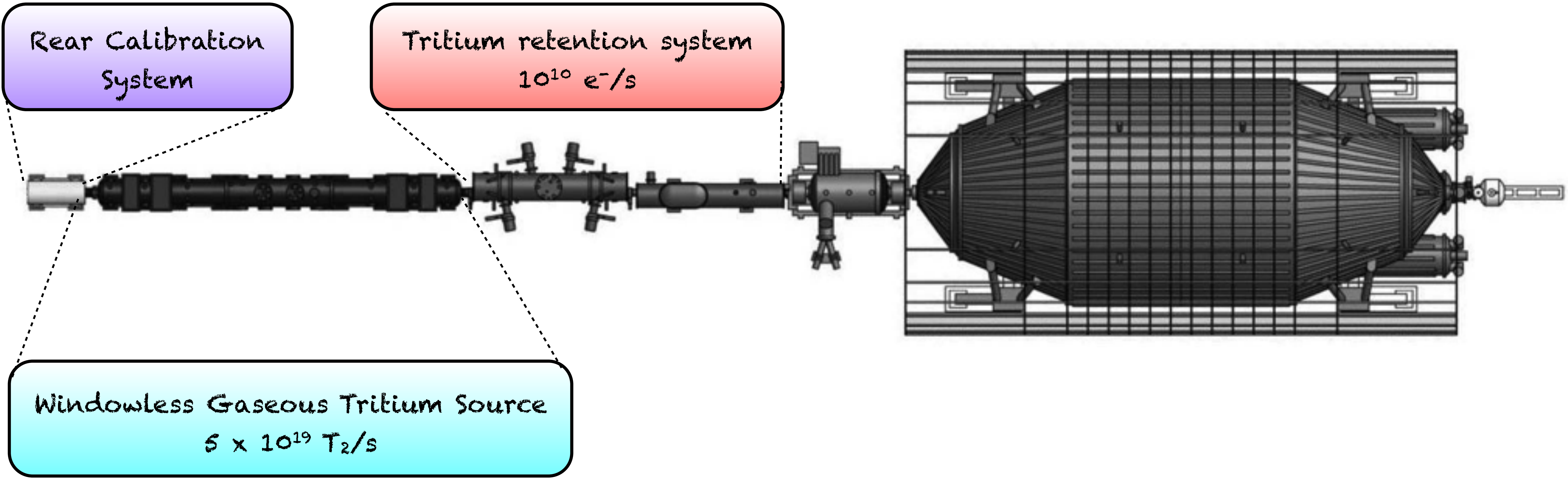


WGTS:

- Injected tritium source with ~few Curie activity.
- Extremely stable pressure/temperature

Tritium Retention System:

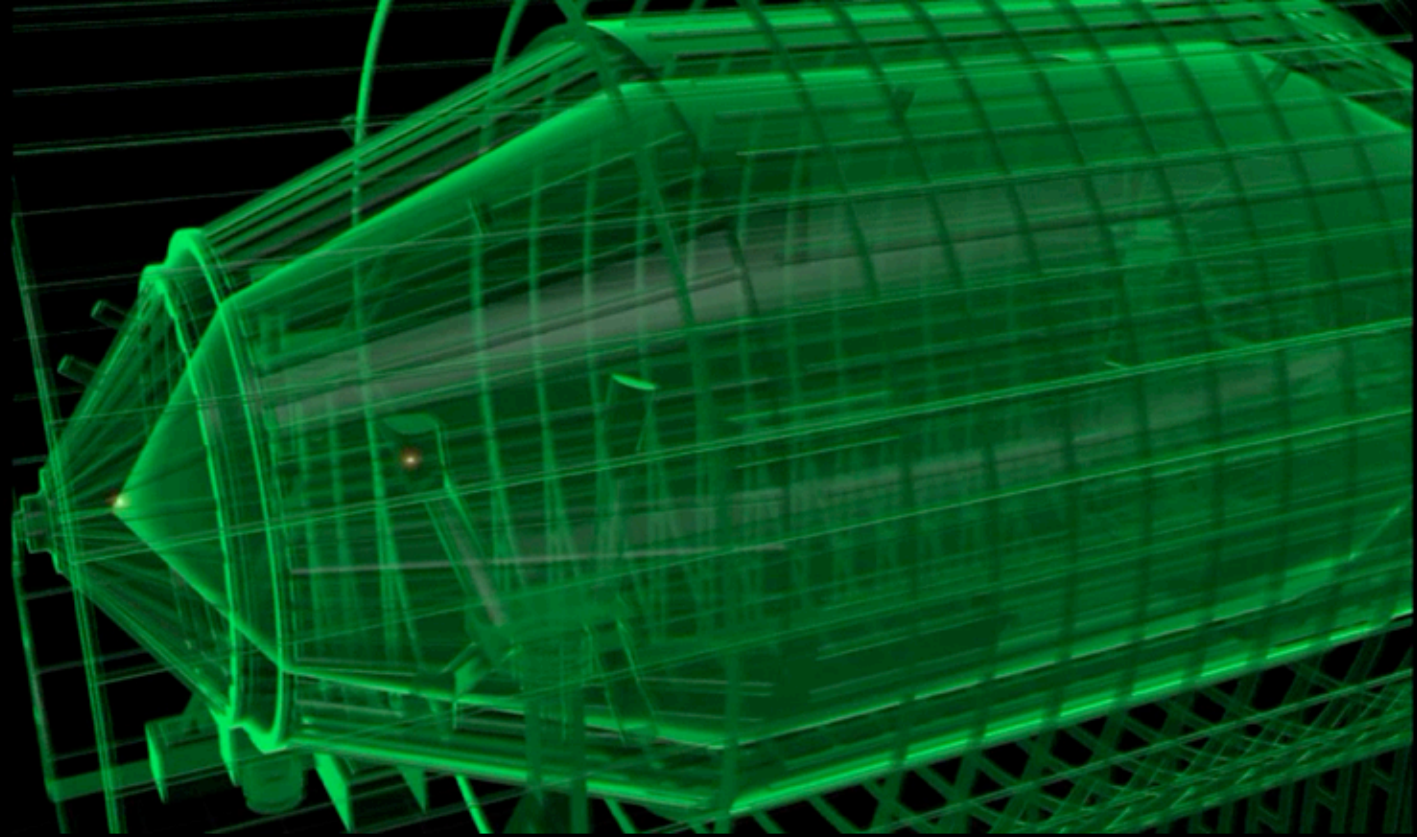
- Designed to reduce tritium flow by 10^{14}



Rear Calibration System

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

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

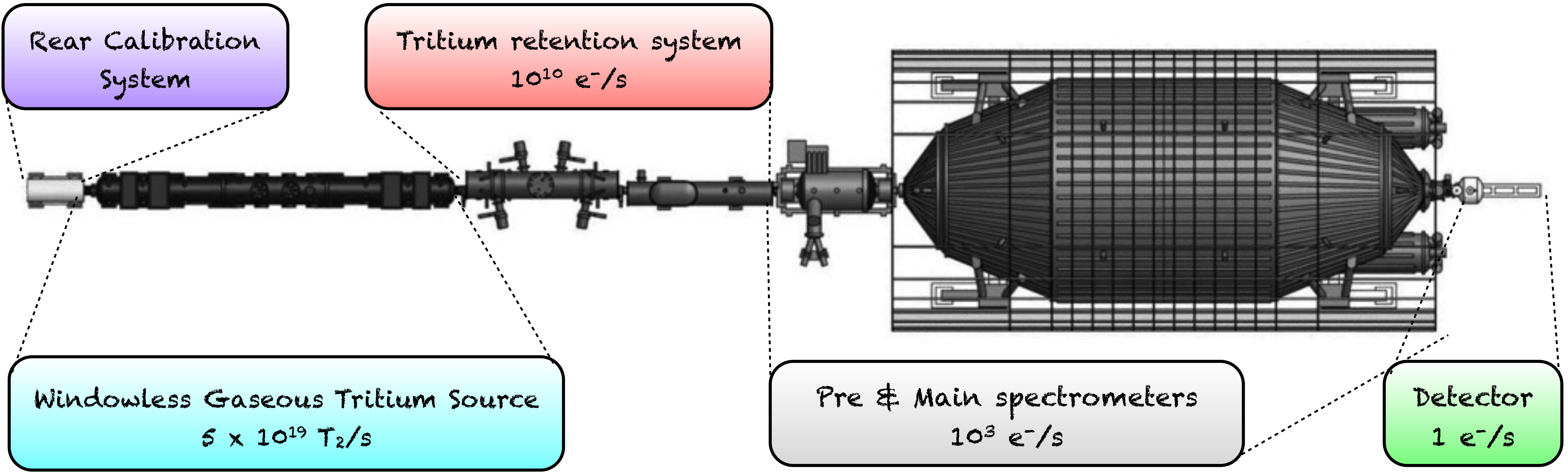


Spectrometers:

- 1 eV resolution transmission function.
- Inner wire electrodes for background reduction.
- Coils to shape low field region.

Detector:

- Position-dependent beta detector.



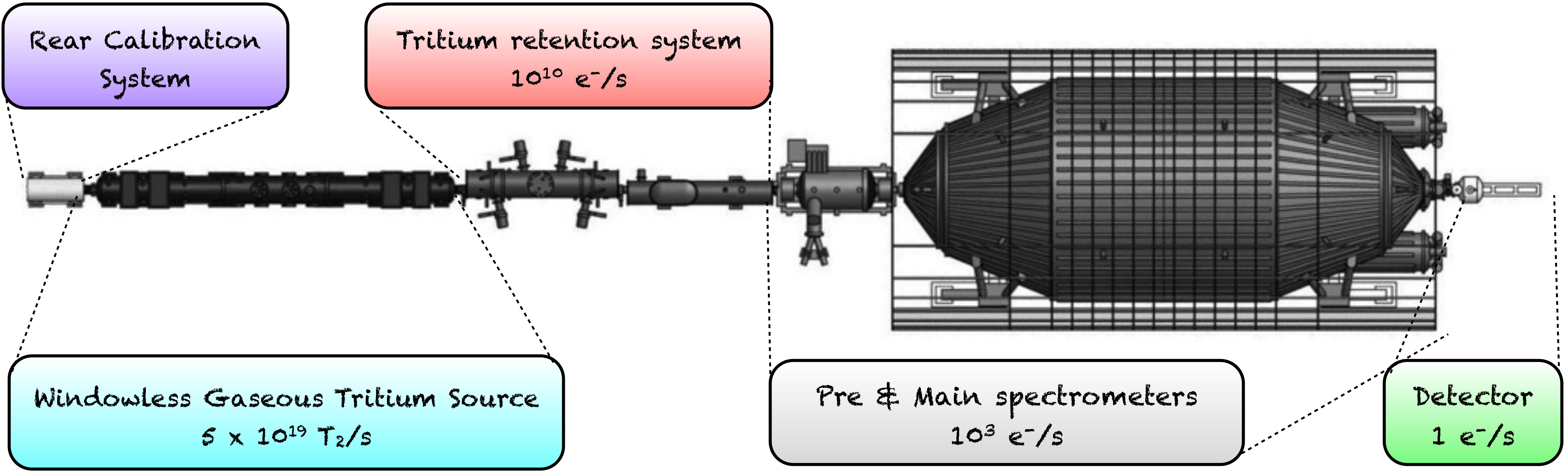
Rear Calibration System

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

Windowless Gaseous Tritium Source
$5 \times 10^{19}\ T_2/s$

Pre & Main spectrometers
$10^{3}\ e^-/s$

Detector
$1\ e^-/s$



Rear Calibration System

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$10^{10}\ e^-/s$

Windowless Gaseous Tritium Source
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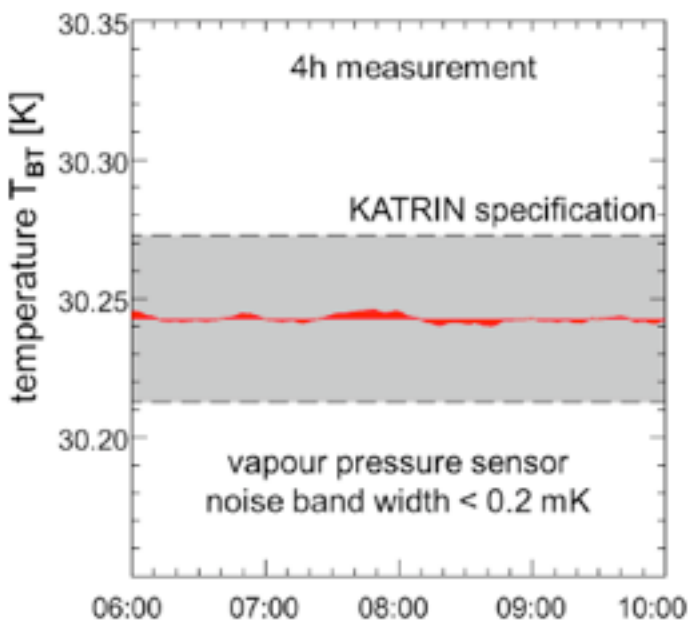
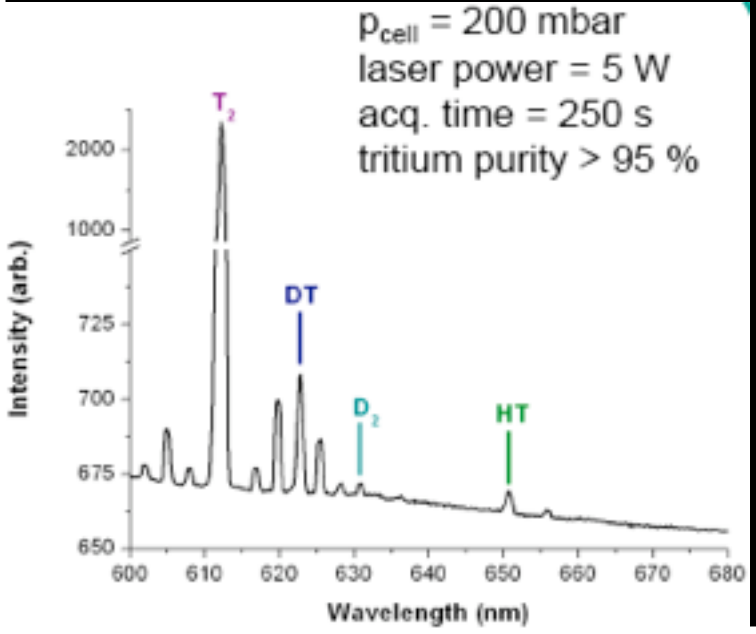
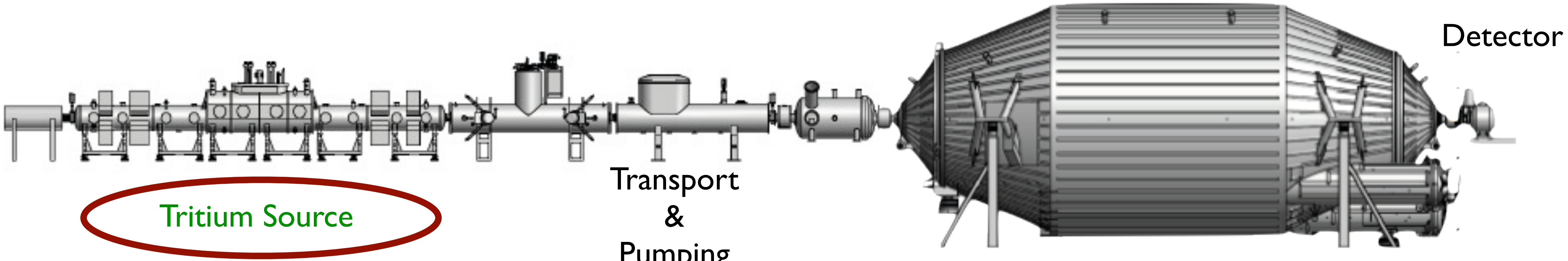
Detector
$1\ e^-/s$

WGTS Demonstrator

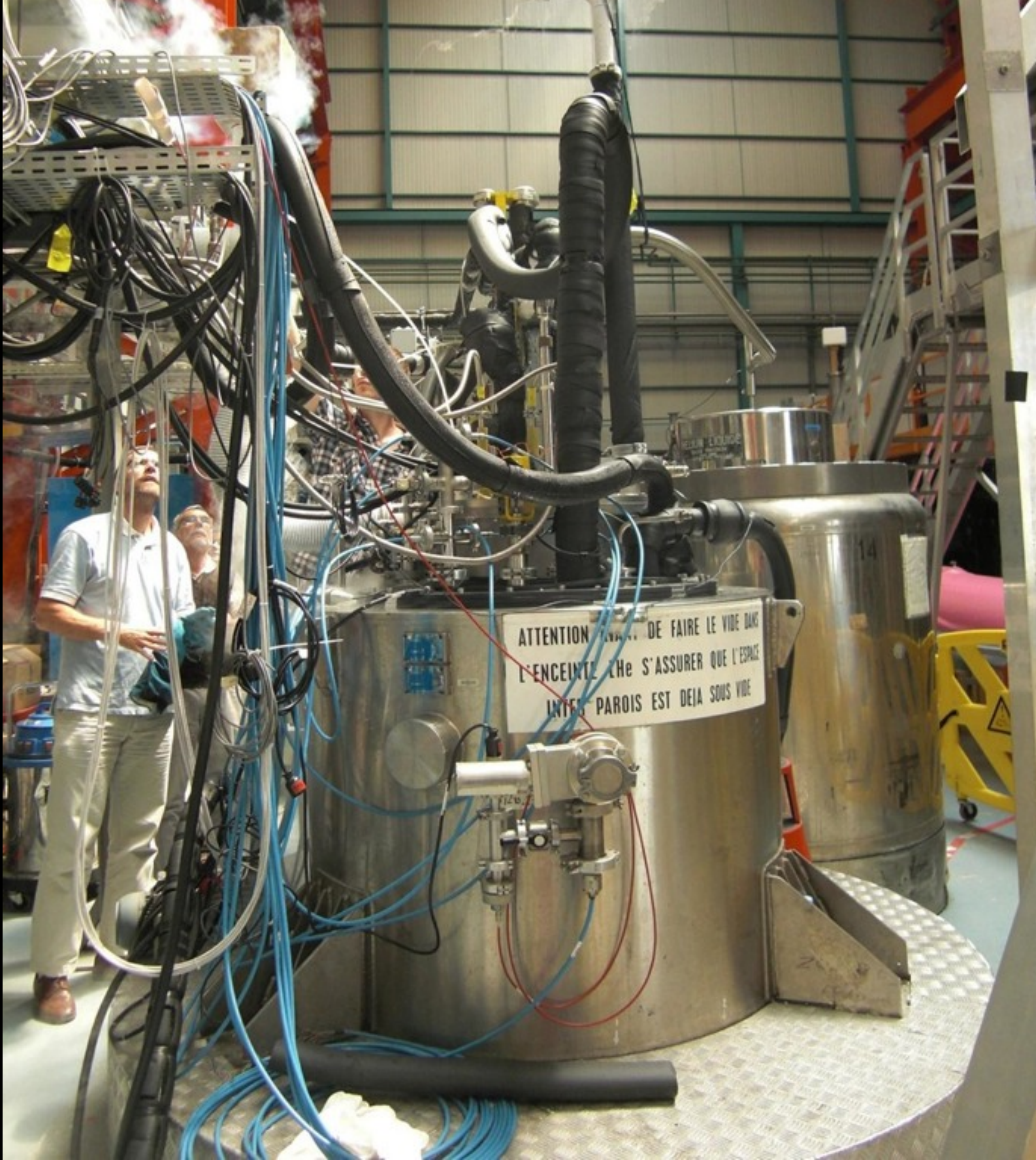




- Provides ~ 2 x 10^{11} Bq of activity (with tritium activity extruded from system).
- Monitoring of tritium purity, pressure & temperature.
- Temperature stability of $\pm$3.6 mK recently achieved (x10 better than specification).



WGTS Magnet Testing at CEA Saclay



Recent milestone:

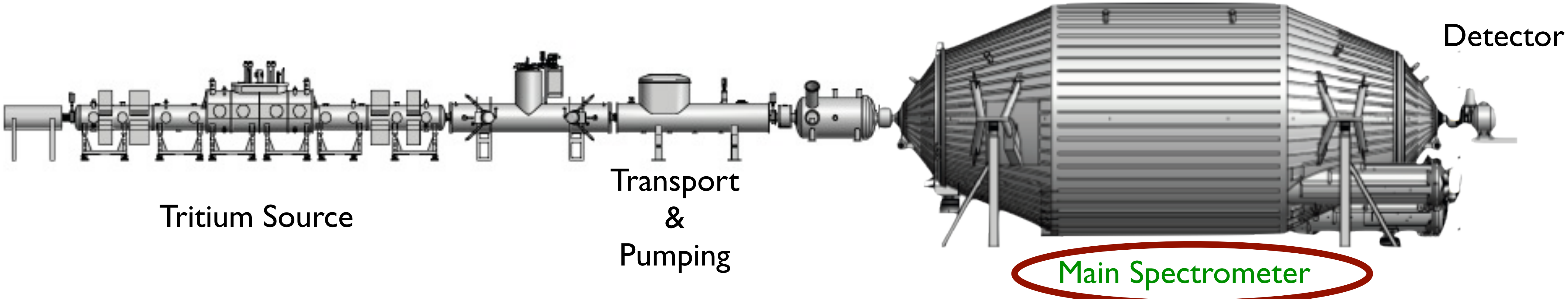
Main solenoids pass stress tests.

Field- Compensation Air Coils

Inner electrode wire mesh

High Voltage Divider

- A 10 m diameter analyzing spectrometer with 1:2000 energy resolution (0.93 eV)
- Extremely stable high voltage of main vessel.
- Few ~ppm precision divider and monitoring spectrometer.

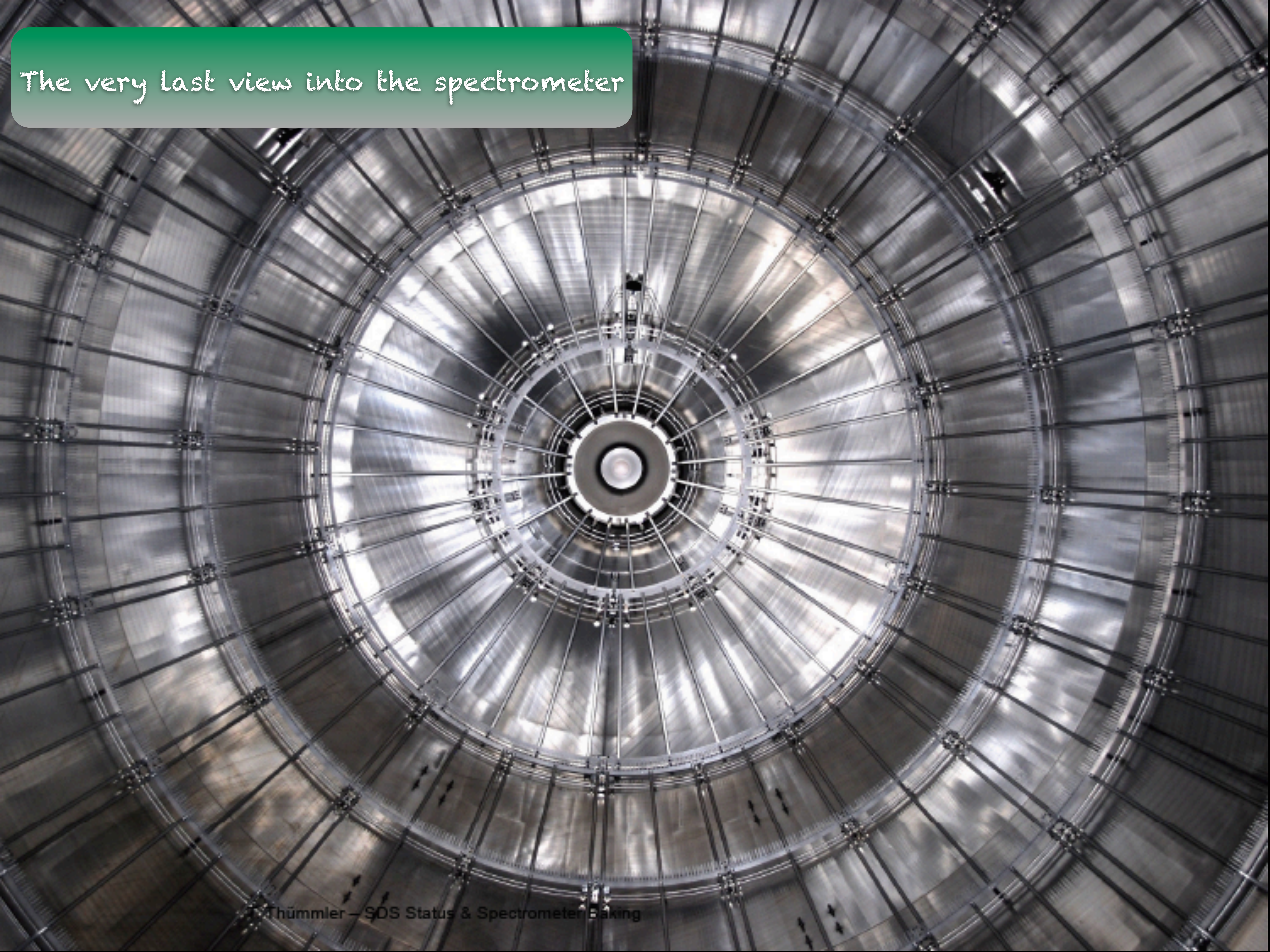


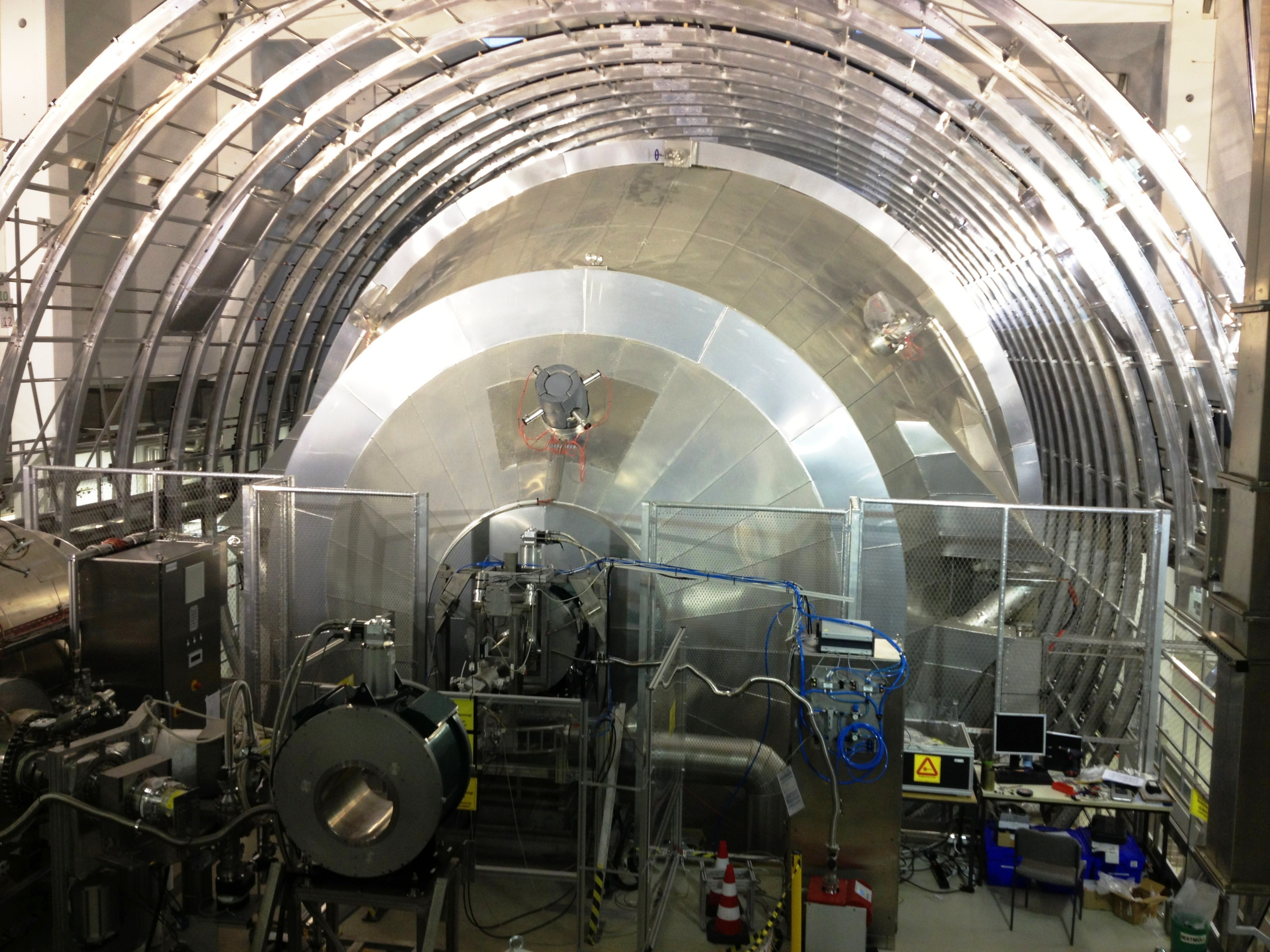
The Main Spectrometer

Recent milestone:

Final pump port closed and sealed.

The very last view into the spectrometer





"First Light"

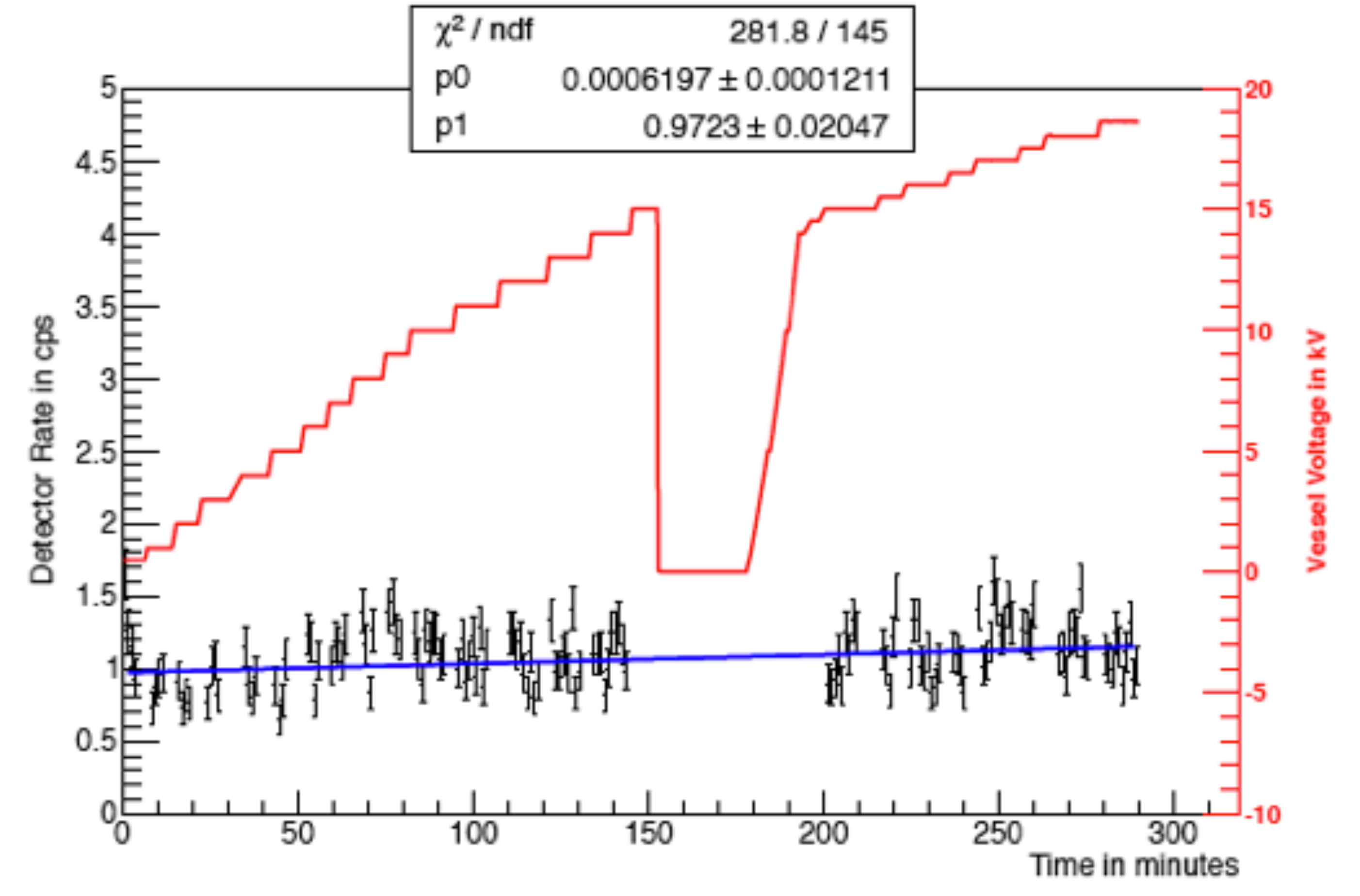
First time pre-spectrometer, main spectrometer, and detector are all connected.

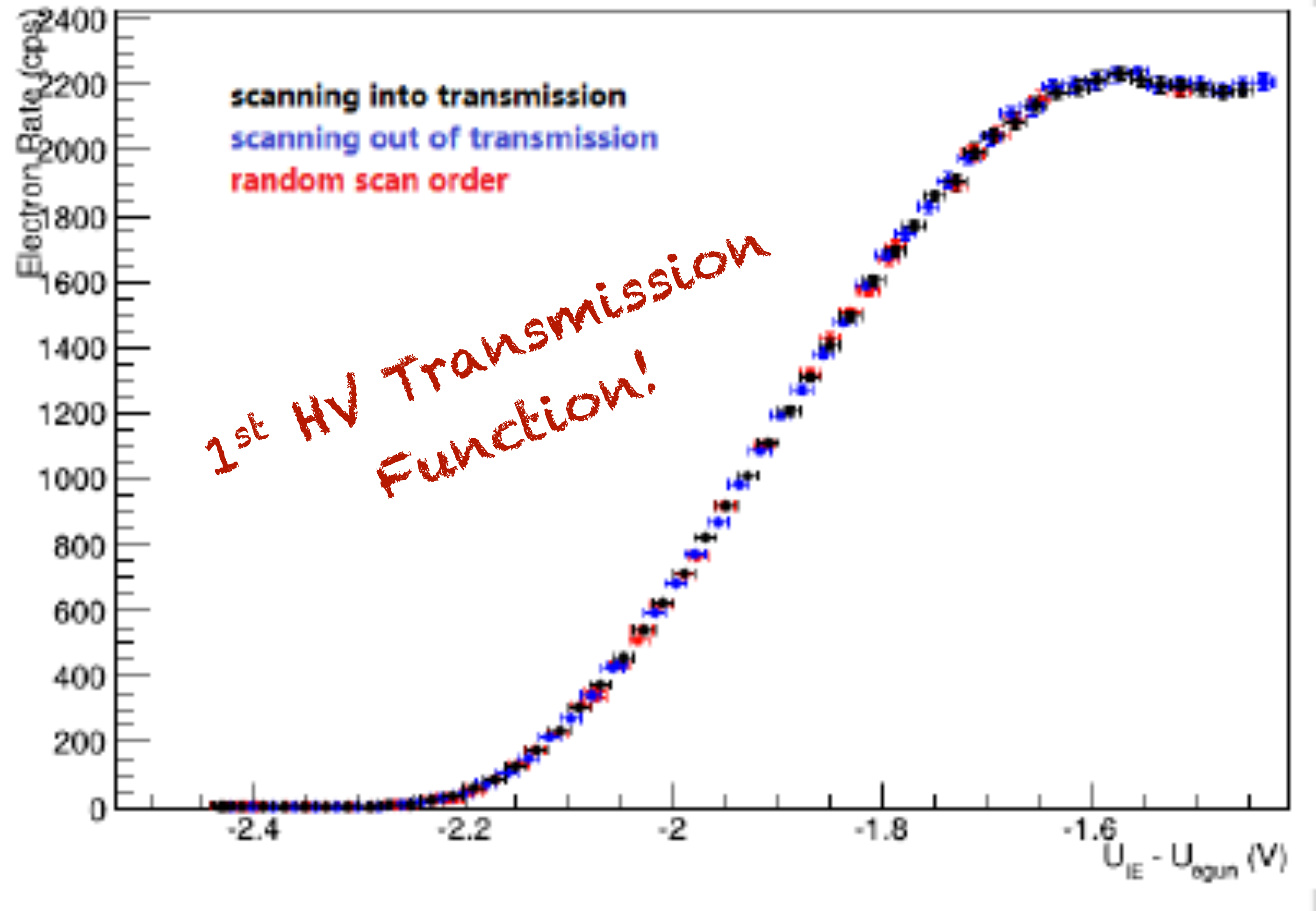
First electrons in this combined system now recorded.

Background at 1 Hz, appears to be radon-dominated.

Will be reduced when cold baffles & screening potential are applied.

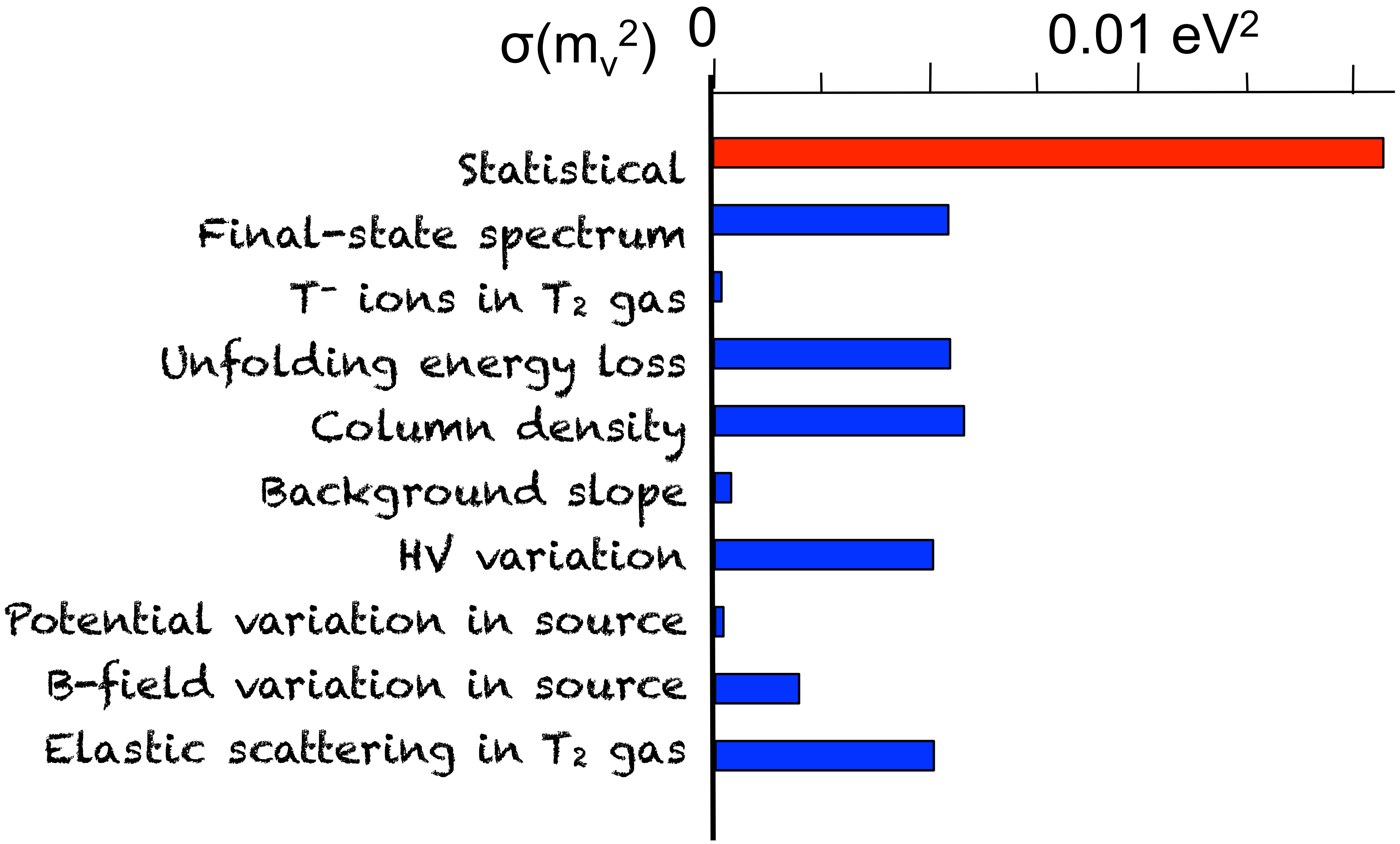
Commissioning program of the main spectrometer well underway!

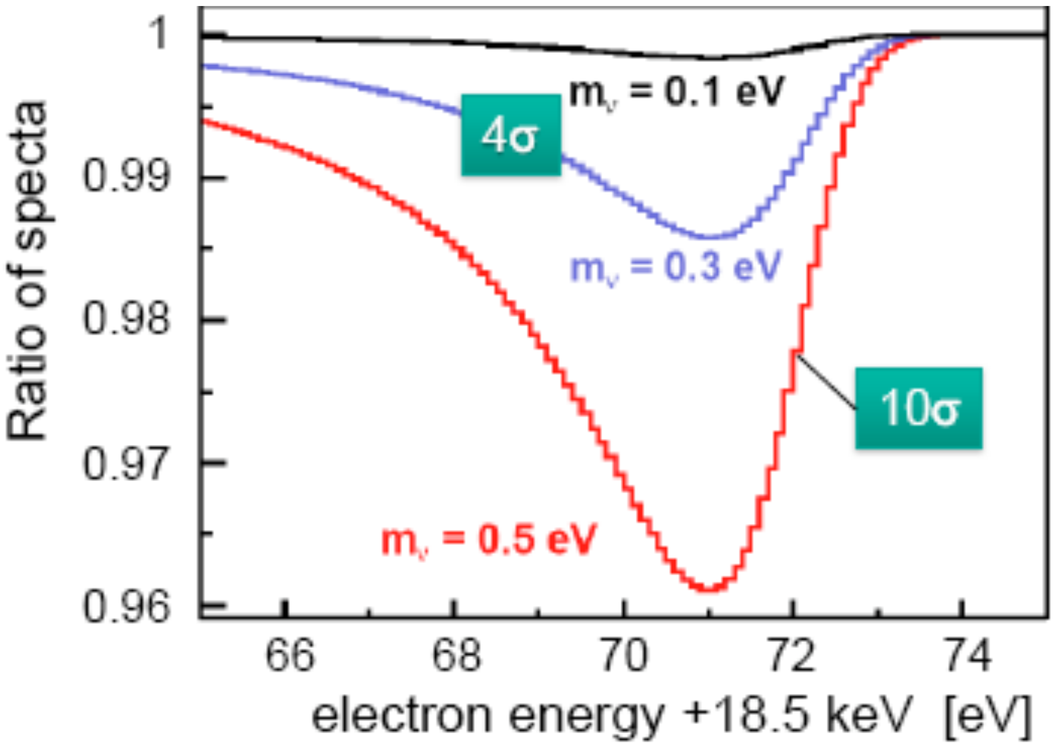


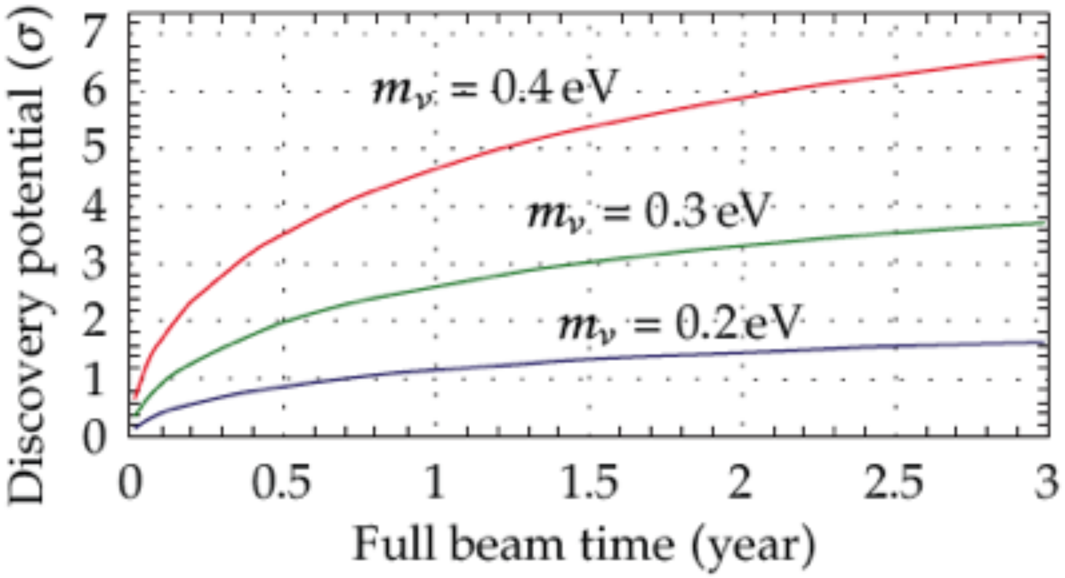


1st HV Transmission Function!

Projected Sensitivity







Neutrino Mass Goals

Discovery: 350 meV (at 5σ)

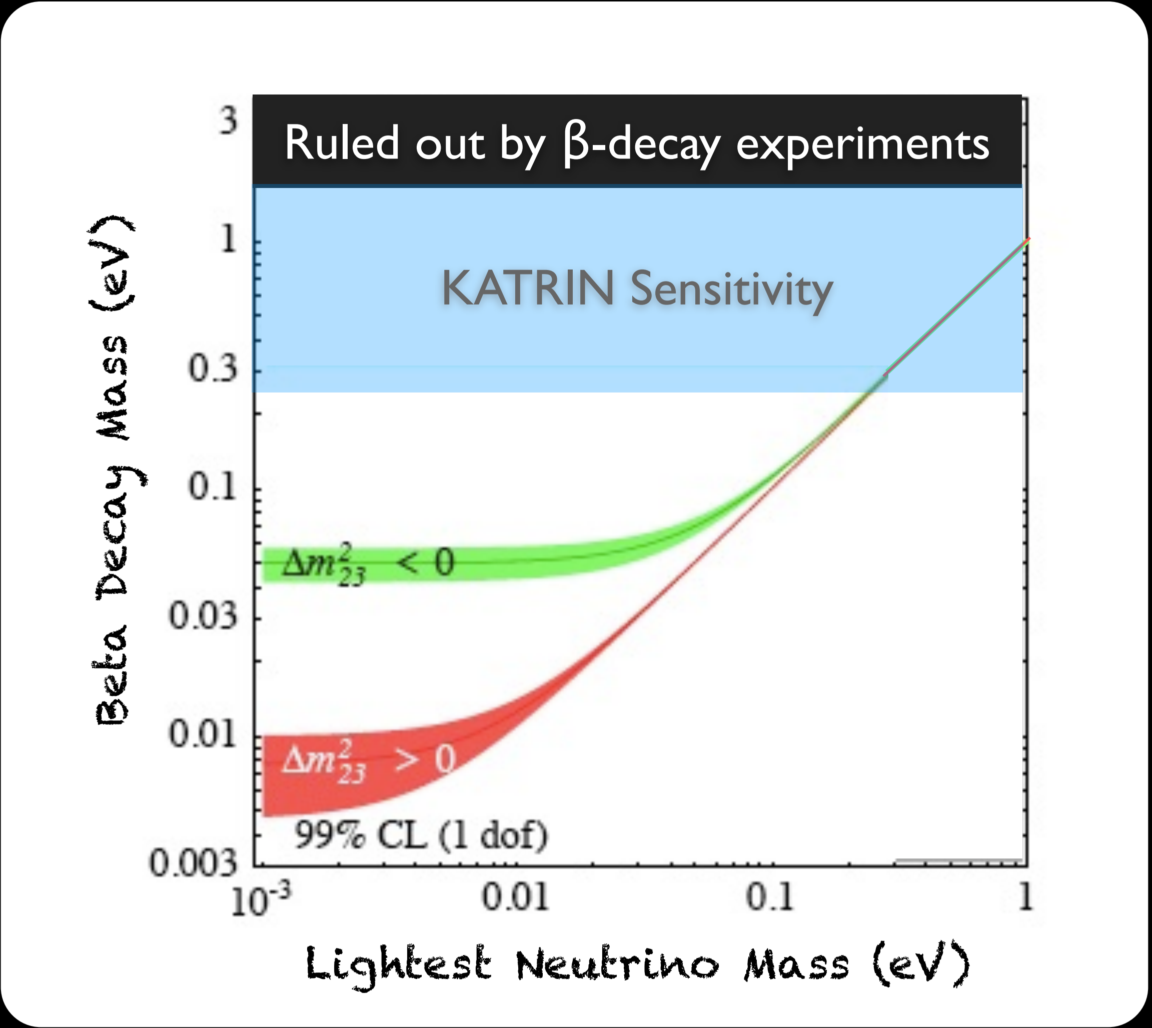
Sensitivity: 200 meV (at 90% C.L.)

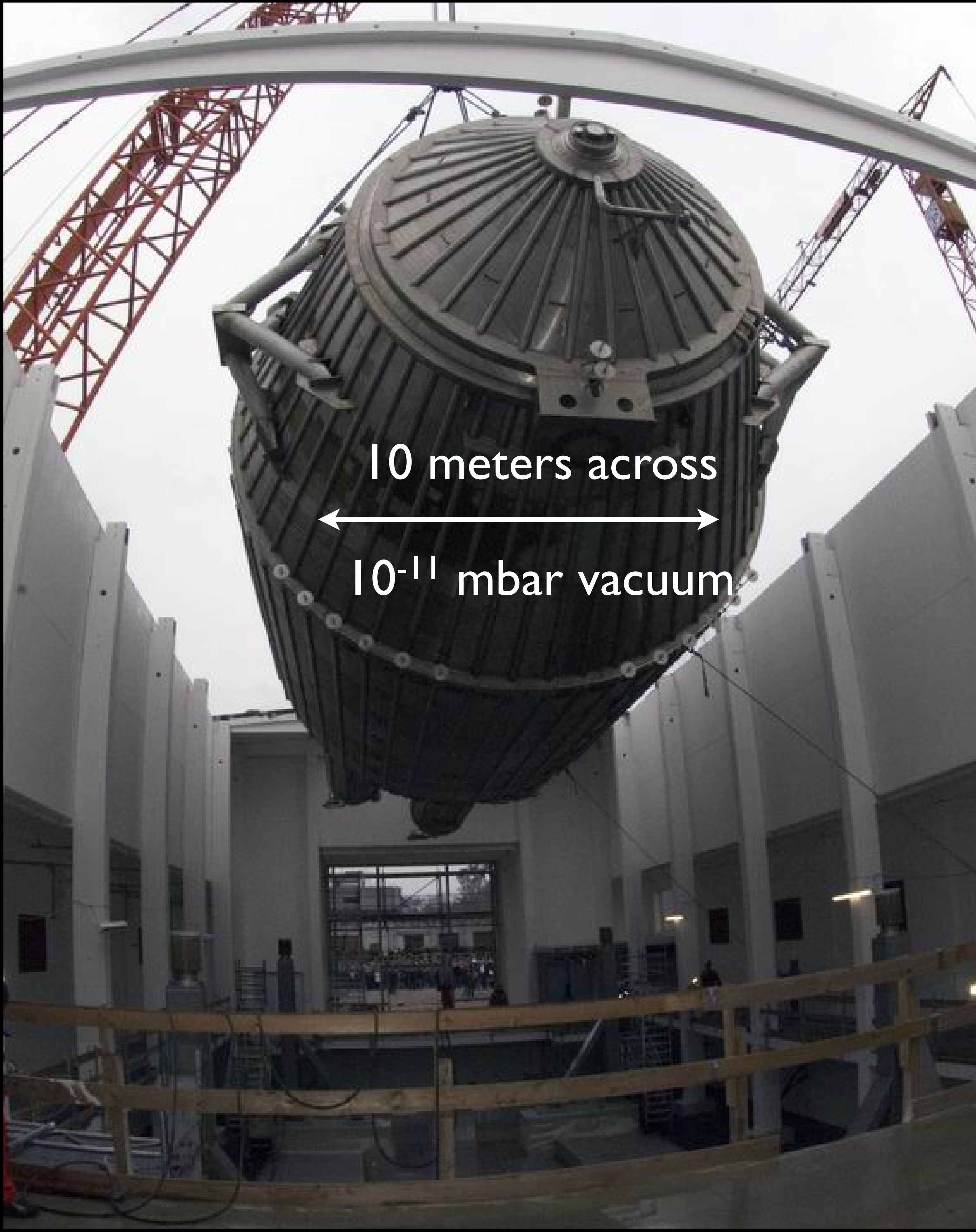
Partial loading in 2014.

Full Tritium Running in 2015

Can we push further?

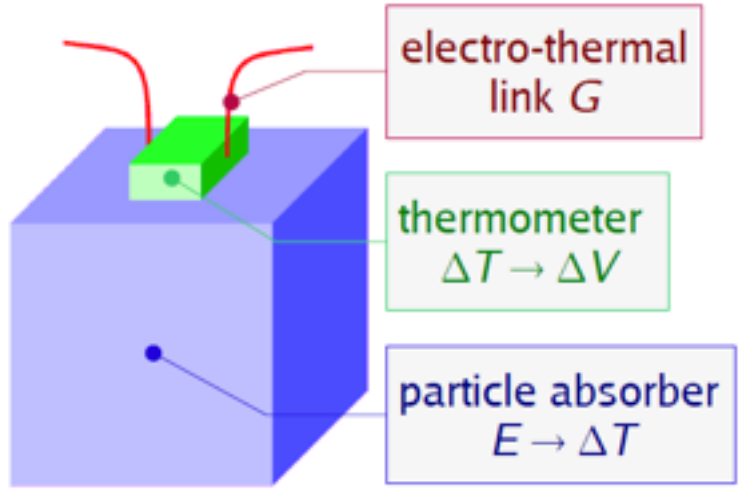
- Can direct measurements push to the inverted hierarchy scale?
- To do so, they must have better scaling law.





Calorimetric Techniques

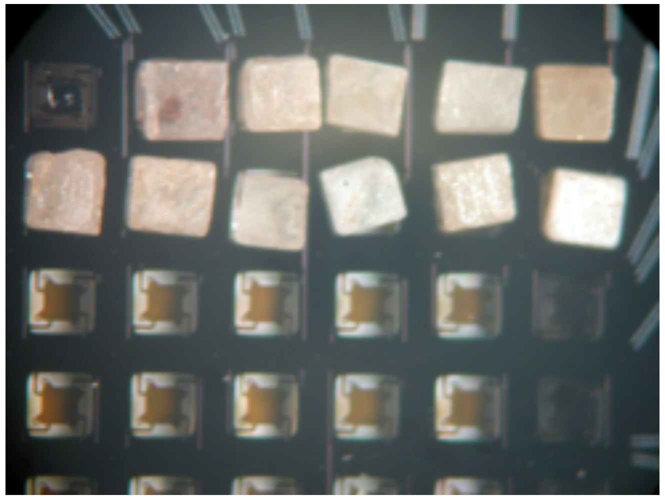
Calorimetry



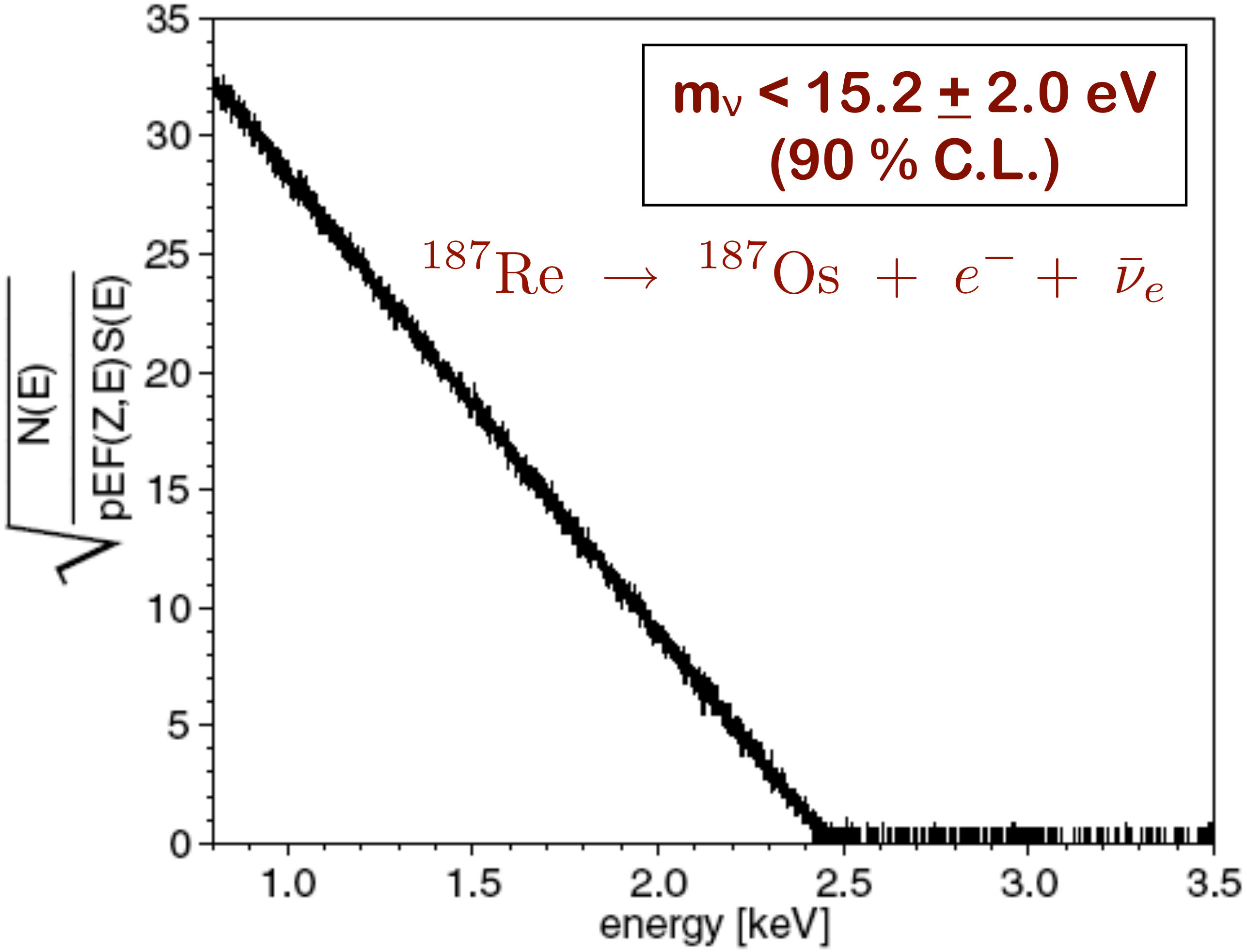
electro-thermal link G

thermometer $\Delta T \rightarrow \Delta V$

particle absorber $E \rightarrow \Delta T$



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



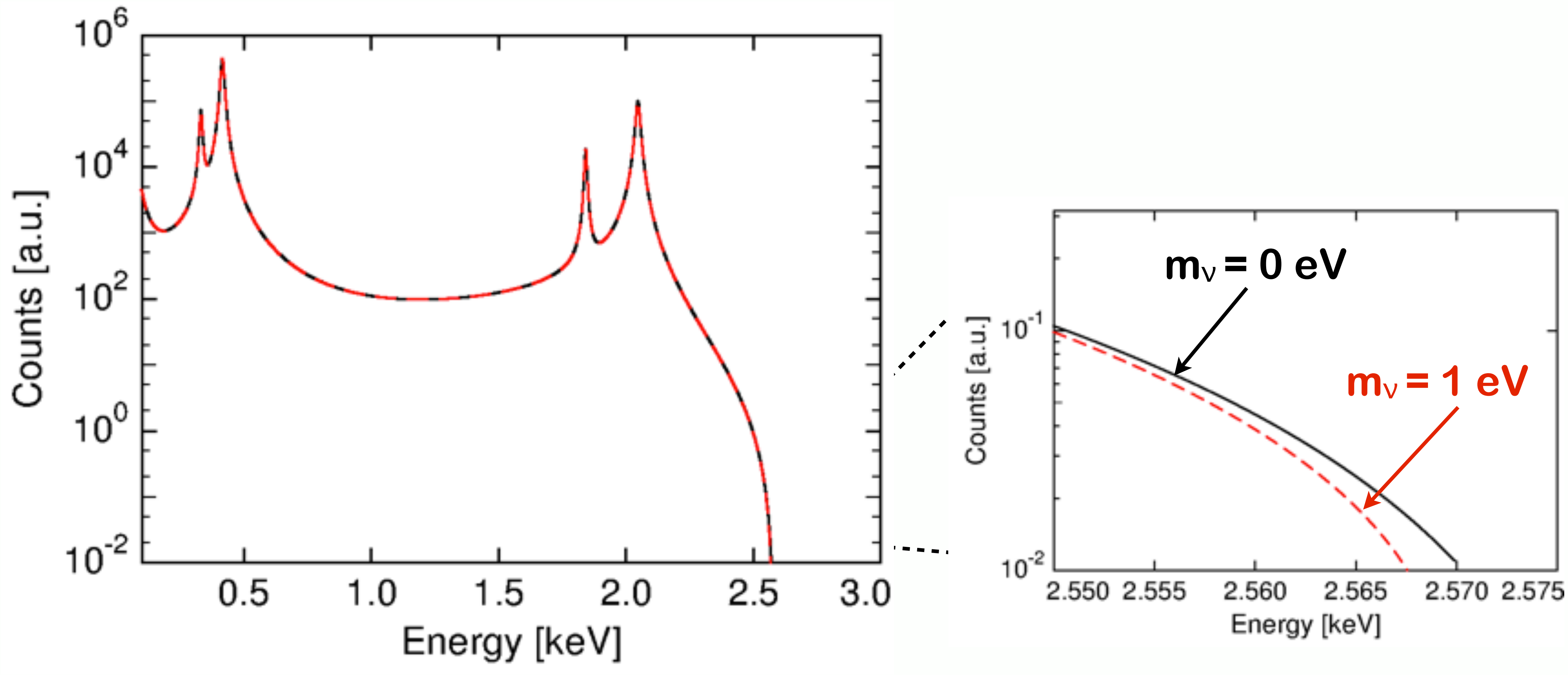
$m_\nu < 15.2 \pm 2.0$ eV (90 % C.L.)

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

Phys. Rev. Lett. 91 161802 (2003)

- The use of low temperature calorimetry for beta decay has focused on isotopes with the lowest endpoint energy.
- Particularly, ^{187}Re as beta source (one of the lowest endpoints, 2.3 keV).
- More recently, ^{163}Ho electron capture (De Rujula and Lusignoli, 1982) has been the subject of R&D over the past several years.

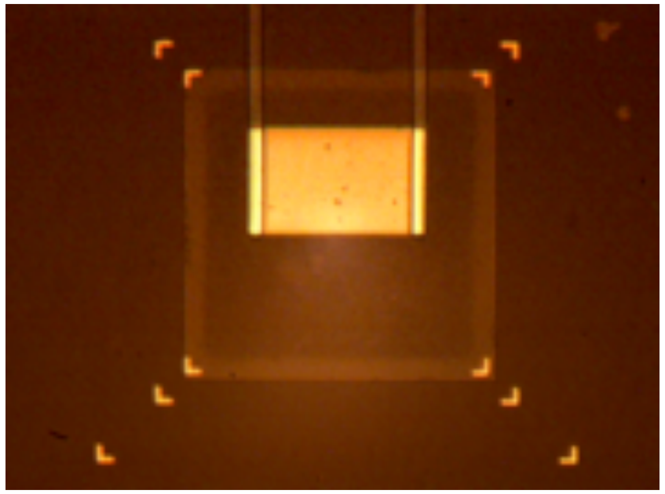
$$\dot{N} \sim (Q_{EC}-E_C)^2 \sum_i |U_{ei}|^2 \sqrt{1-\frac{m_{\nu i}^2}{(Q_{EC}-E_C)^2}} \sum_H B_H \psi_H^2(0) \frac{\frac{\Gamma_H}{2\pi}}{(E_{EC}-E_H)^2+\frac{\Gamma_H^2}{4}}$$



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

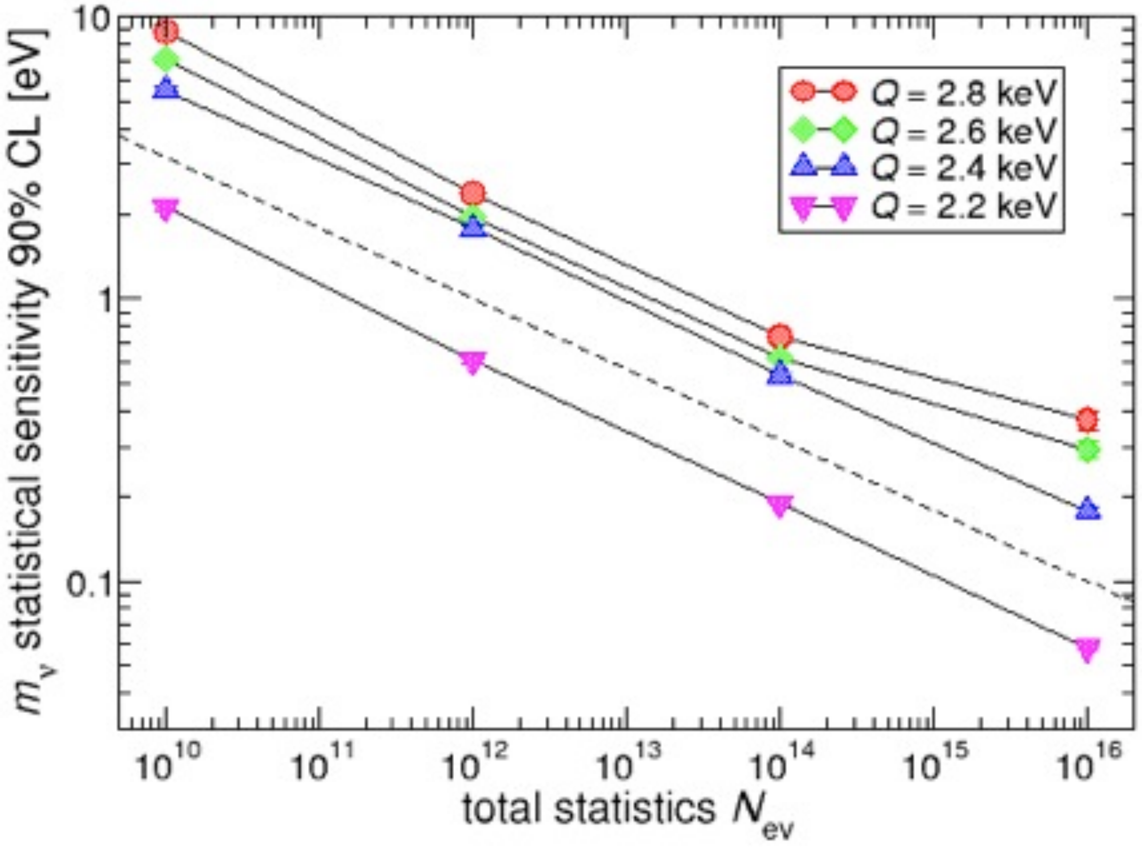
Advantages & Challenges

Isotopes of Interest:



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

Challenges:



Source Activity

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

Detector Response

$\Delta E_{FWHM} < 10$ eV

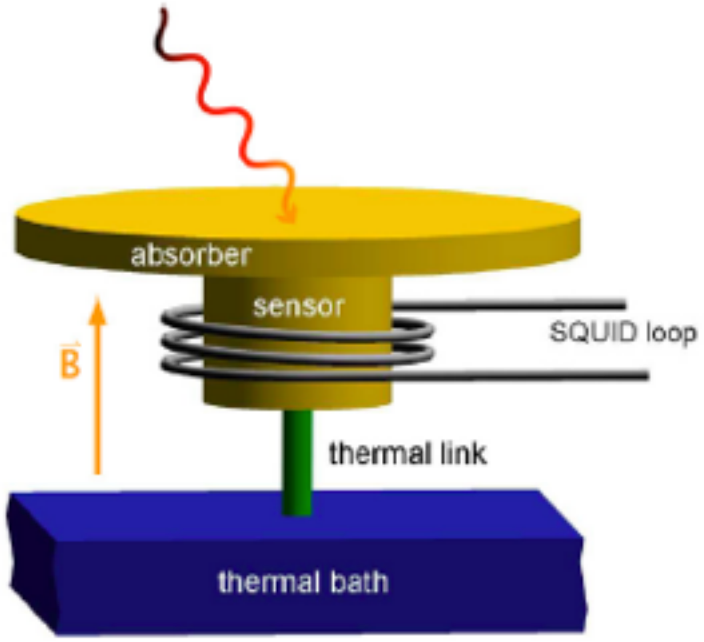
$T_{risetime} < 1\ \mu s$

- **Advantages:**
  - Source = detector
  - No backscattering
  - No molecular final state effects.
  - Self-calibrating

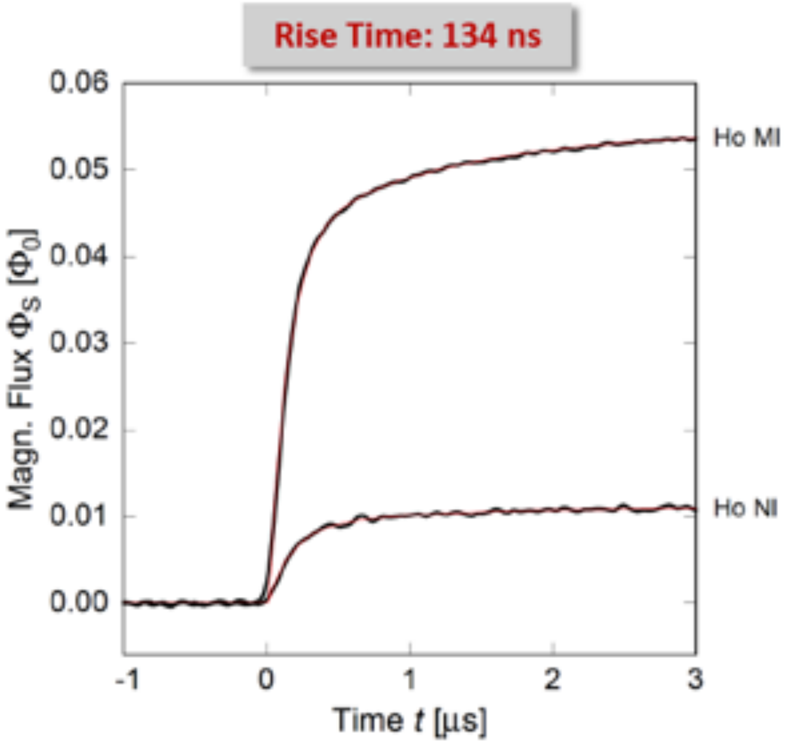
- **Experimental Challenges:**
  - Fast rise times to avoid pile-up effects.
  - Good energy resolution & linearity
  - Abundant isotope production

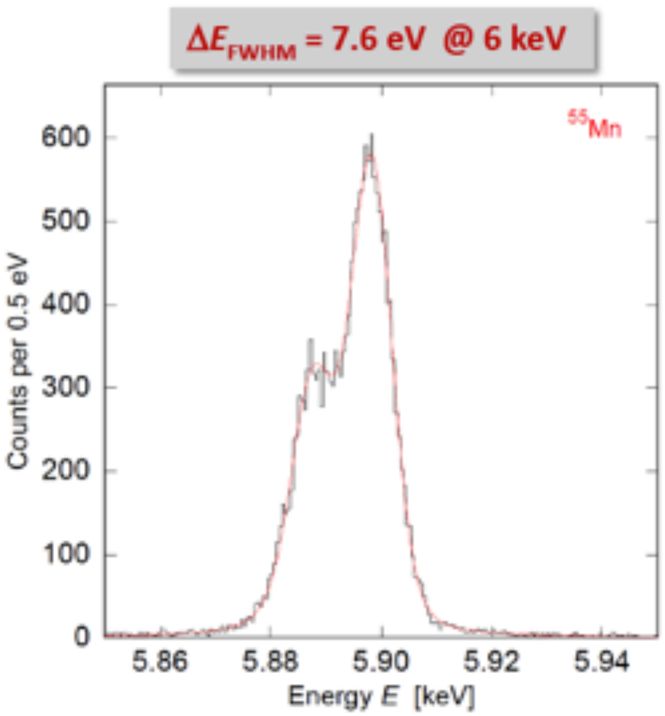
The ECHo Experiment

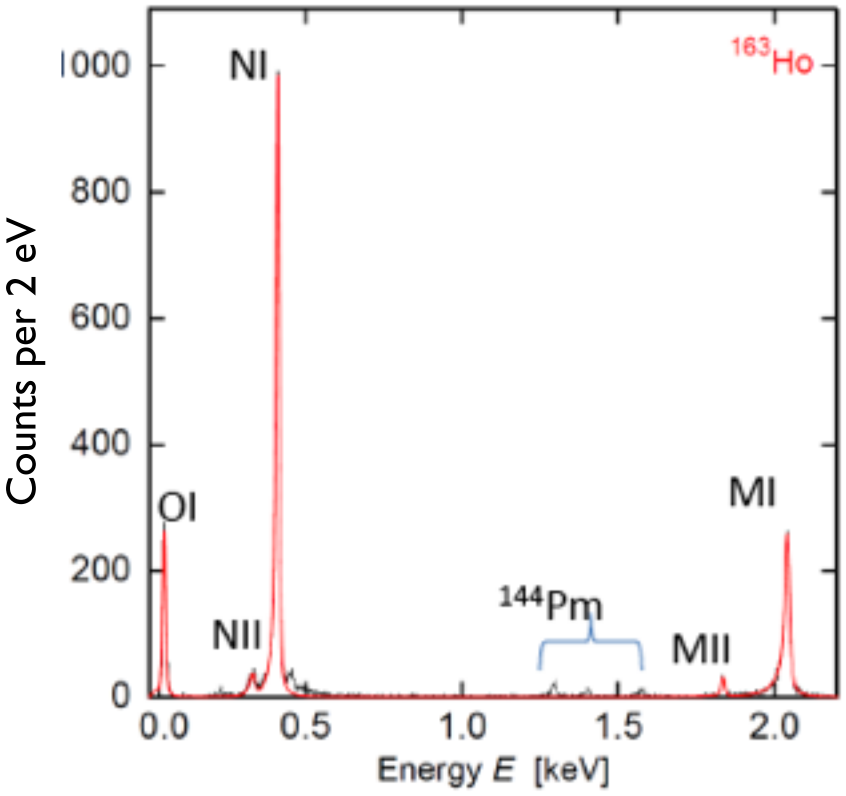
Technology:



Metallic Magnetic Calorimeters



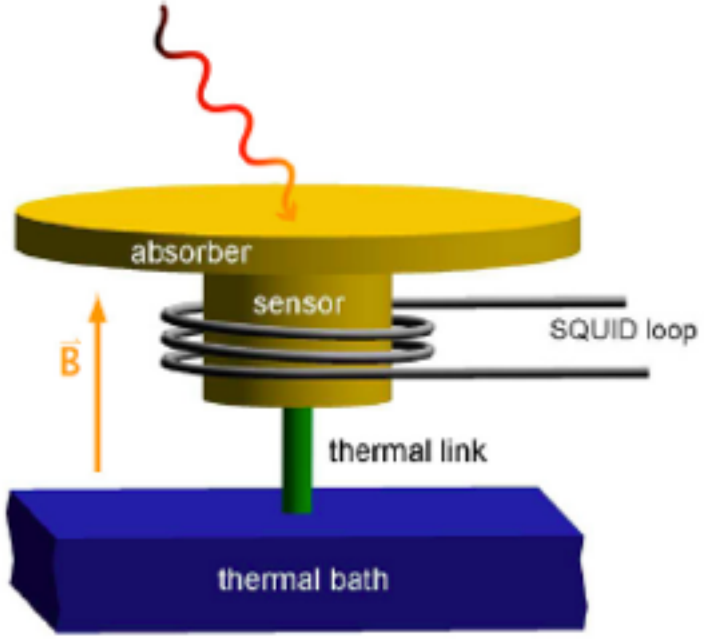




- The ECHo experiment uses metallic magnetic calorimeters to achieve goals.
- Fast rise times and good energy resolutions and linearity demonstrated.
- Endpoint measured at 2.80 ± 0.08 keV.

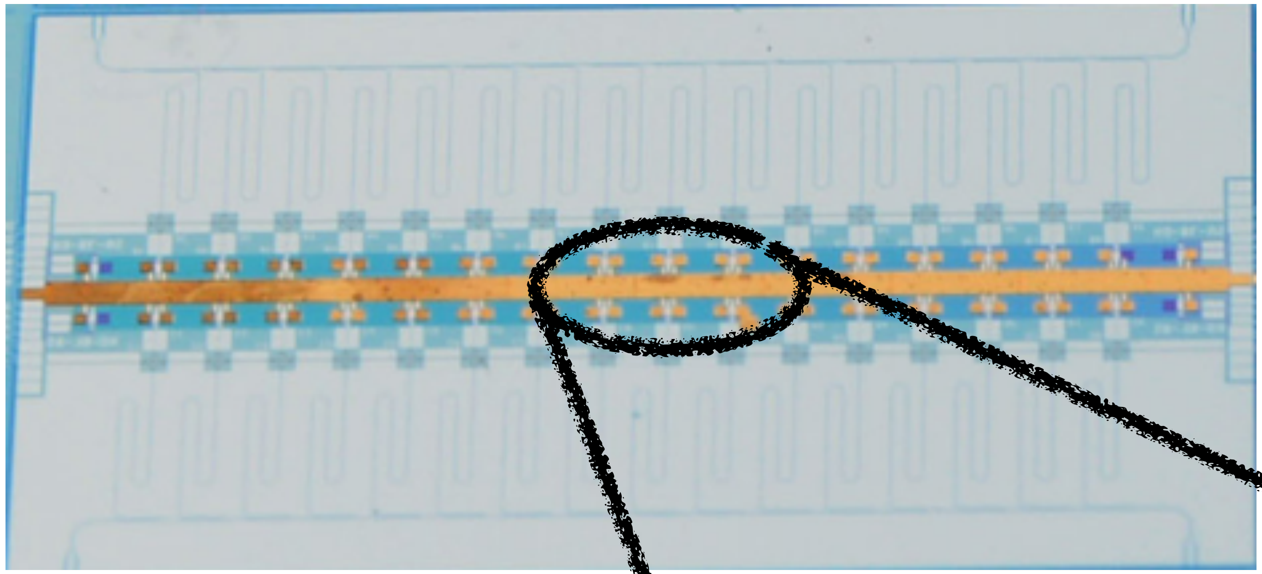
The ECHo Experiment

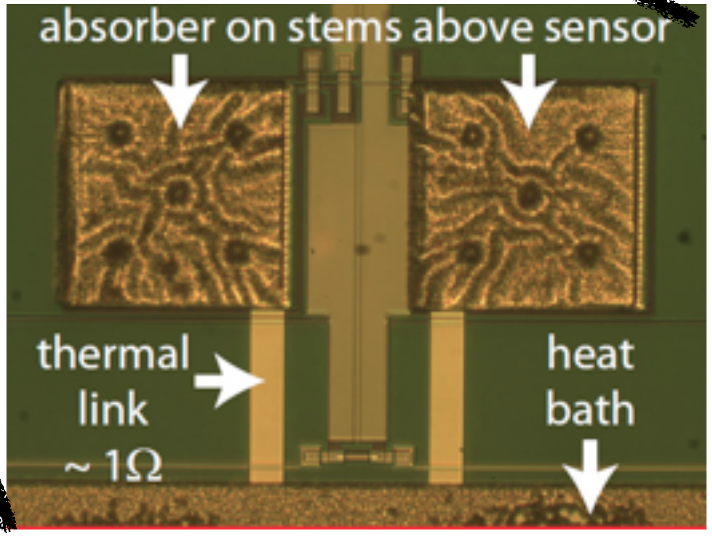
Technology:



Metallic Magnetic Calorimeters

Future Steps

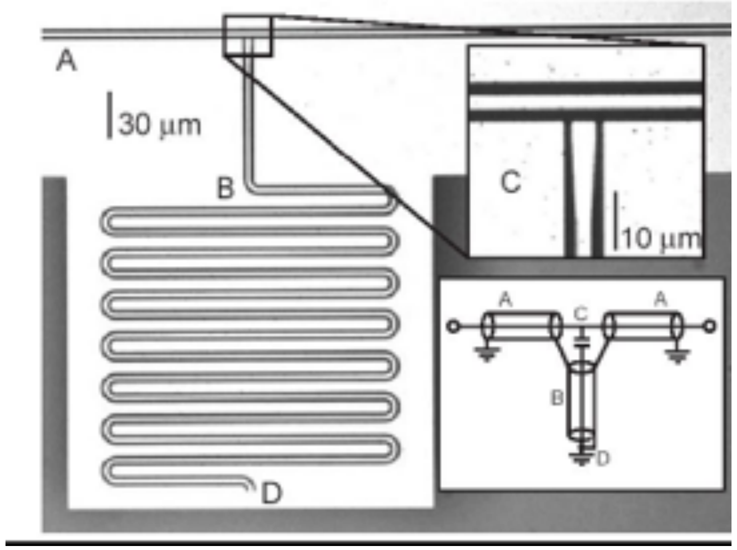




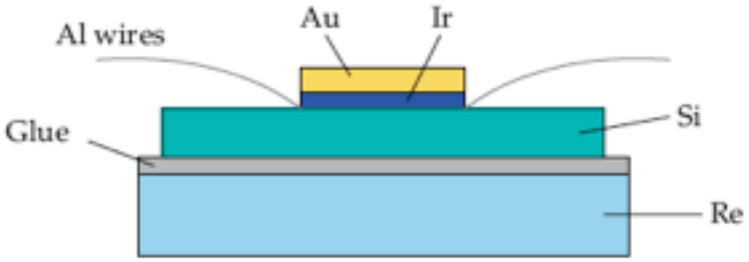
- Collaboration moving toward multi-pixel experiments to increase sensitivity.
- Studies of solid state effects and further investigation of holmium endpoint.

The HOLMES Experiment

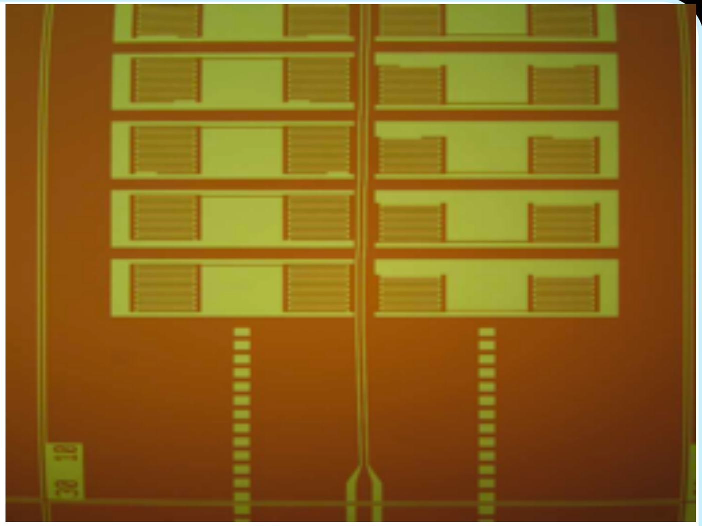
Technologies:

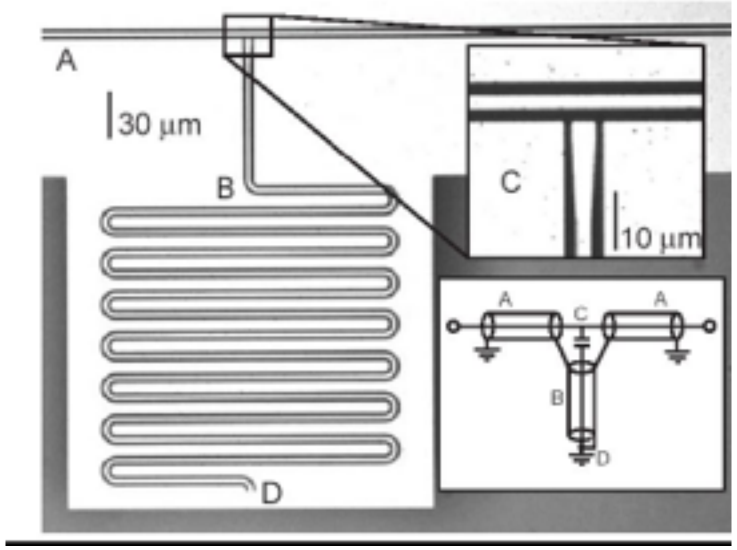


Superconducting Resonators



Transition Edge Sensors





MARE-HOLMES

- MARE (Phase I) explored various technology approaches, such as Transition-Edge Sensors (TES) and Microwave Kinetic Inductance Detectors (MKIDs).
- Successful extraction of Ho^+ ions for metal production and implantation onto detectors.
- Successful funding received for one thousand channel Ho detector experiment (the HOLMES experiment).

Project 8

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

PROJECT 8

Frequency Approach

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

I. I. Rabi

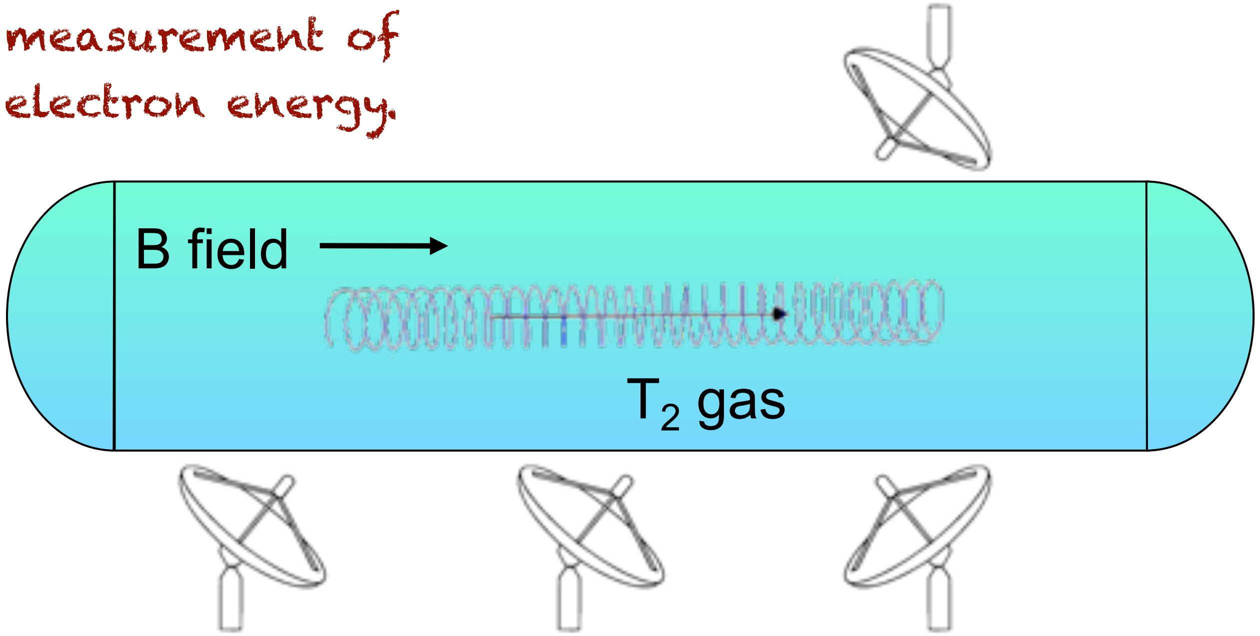
"Never measure anything but frequency."

A. L. Schawlow

- Use cyclotron frequency to extract electron energy.

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

- Non-destructive measurement of electron energy.



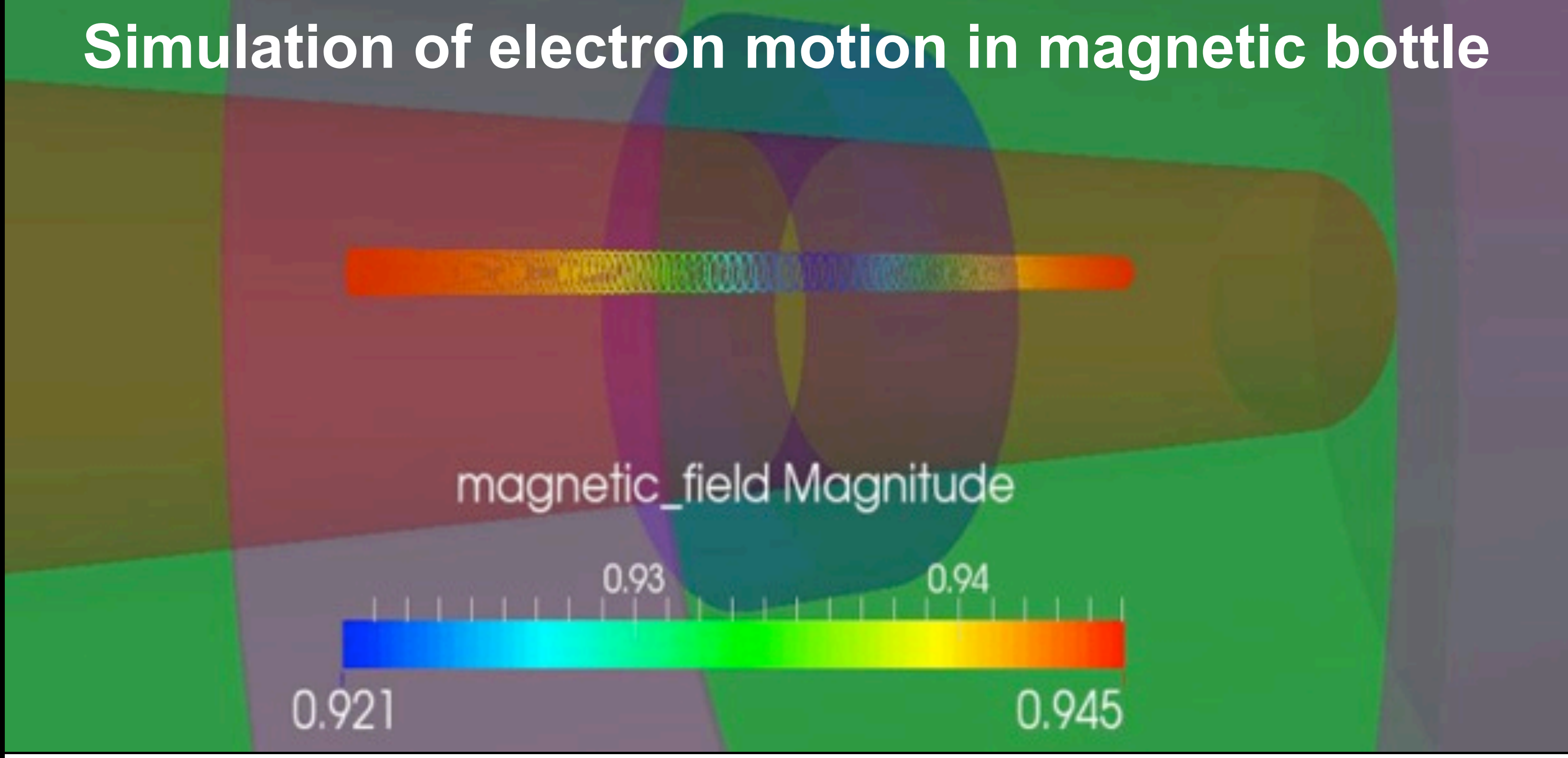
B. Monreal and JAF, Phys. Rev D80:051301

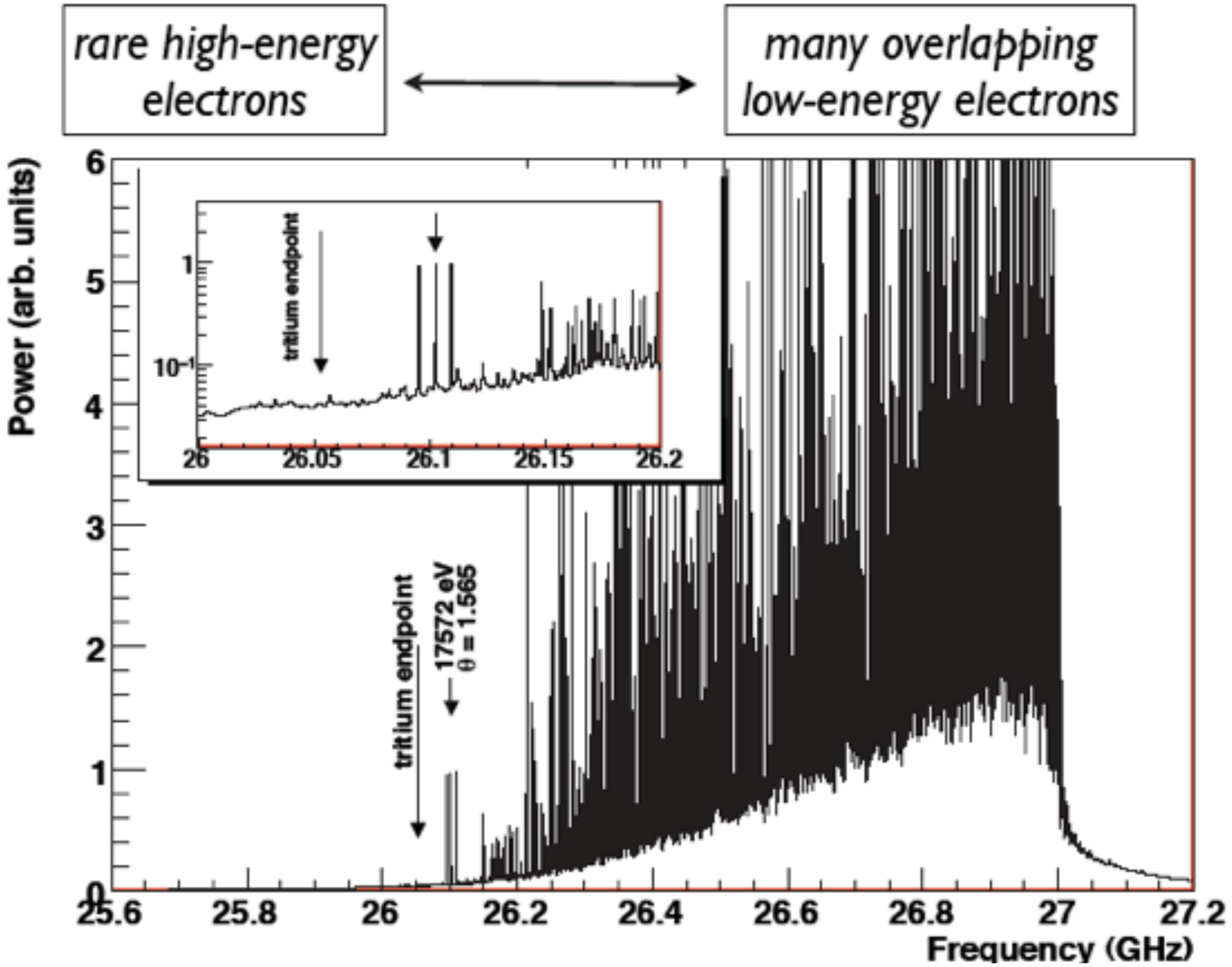
Unique Advantages

- Source = Detector
  (no need to separate the electrons from the tritium)

- Frequency Measurement
  (can pin electron energies to well-known frequency standards)

- Full Spectrum Sampling
  (full spectrum measured at once, large leverage for stability and statistics)

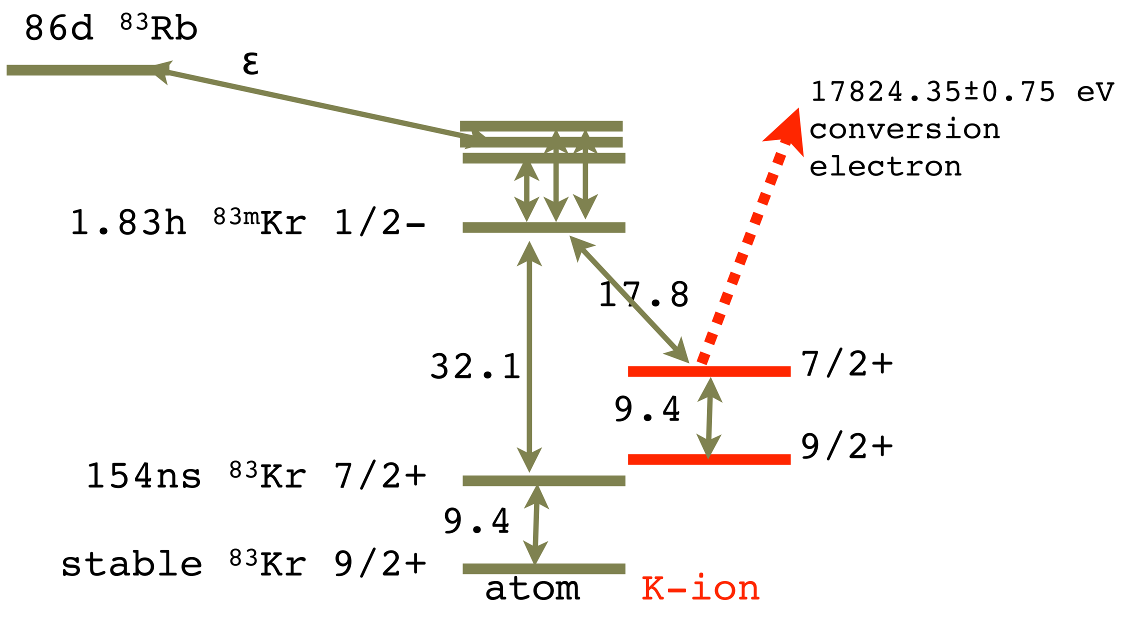

Simulation of electron motion in magnetic bottle



Simulation of beta (frequency) spectrum

A Phased Approach

Initial Demonstration Source: ^{83m}Kr



Conversion electrons at
30 and 32 keV also exist.

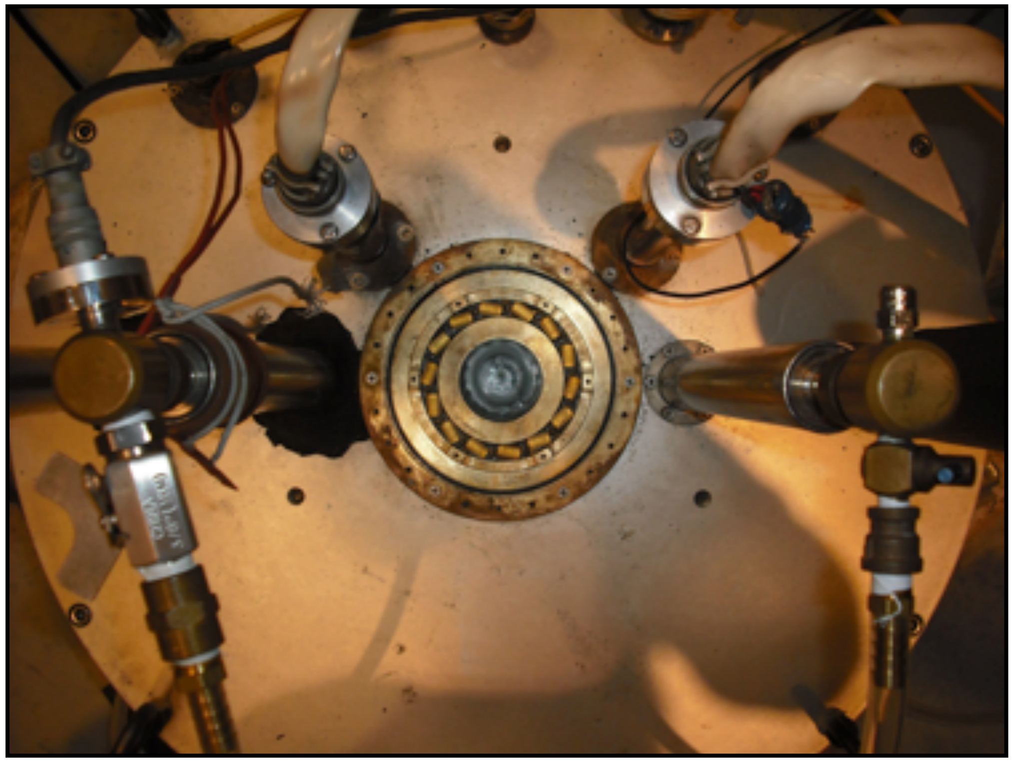
Mono-energetic gaseous electron source

Collaboration taking a phased approach to understand scaling and systematics of the experiment.

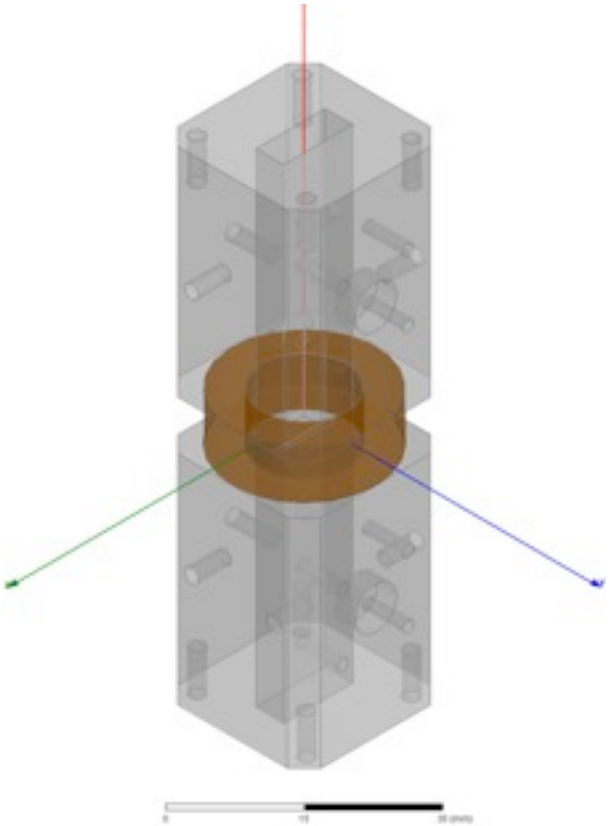
First phase (single electron detection) underway.

Design for second stage well under way.

Status of Phase I (Single Electron Detection)



Main Superconducting Magnet
1 T field (27 GHz)



~100 G Trapping coil

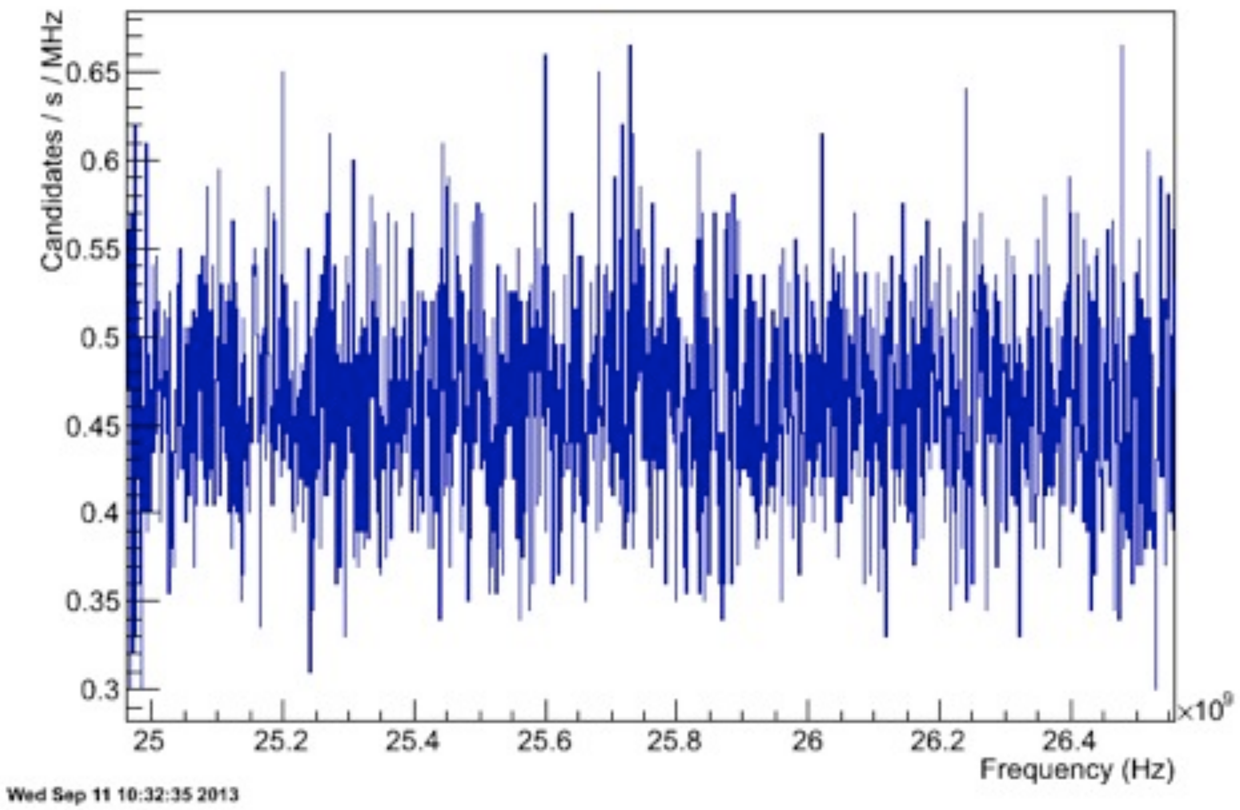
Magnet Cooldown

Using 0.93 Tesla field, where signal occurs at ~26 GHz with trapping coil
About 0.5 fW of radiated power.

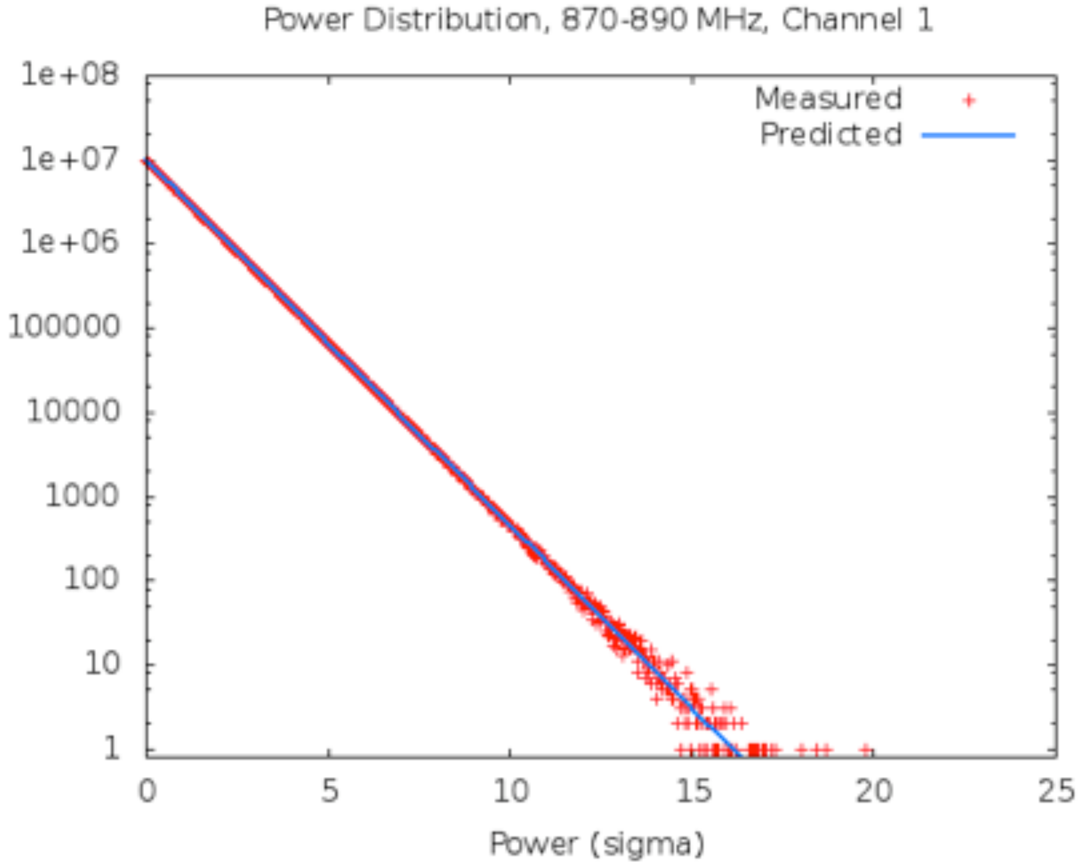
Waveguides designed for 26 GHz signal with low noise amplifiers and full digitization

First data in January with rather large (~150 K) temperatures as initial test of system.

Status of Phase I (Single Electron Detection)



Candidate background spectrum



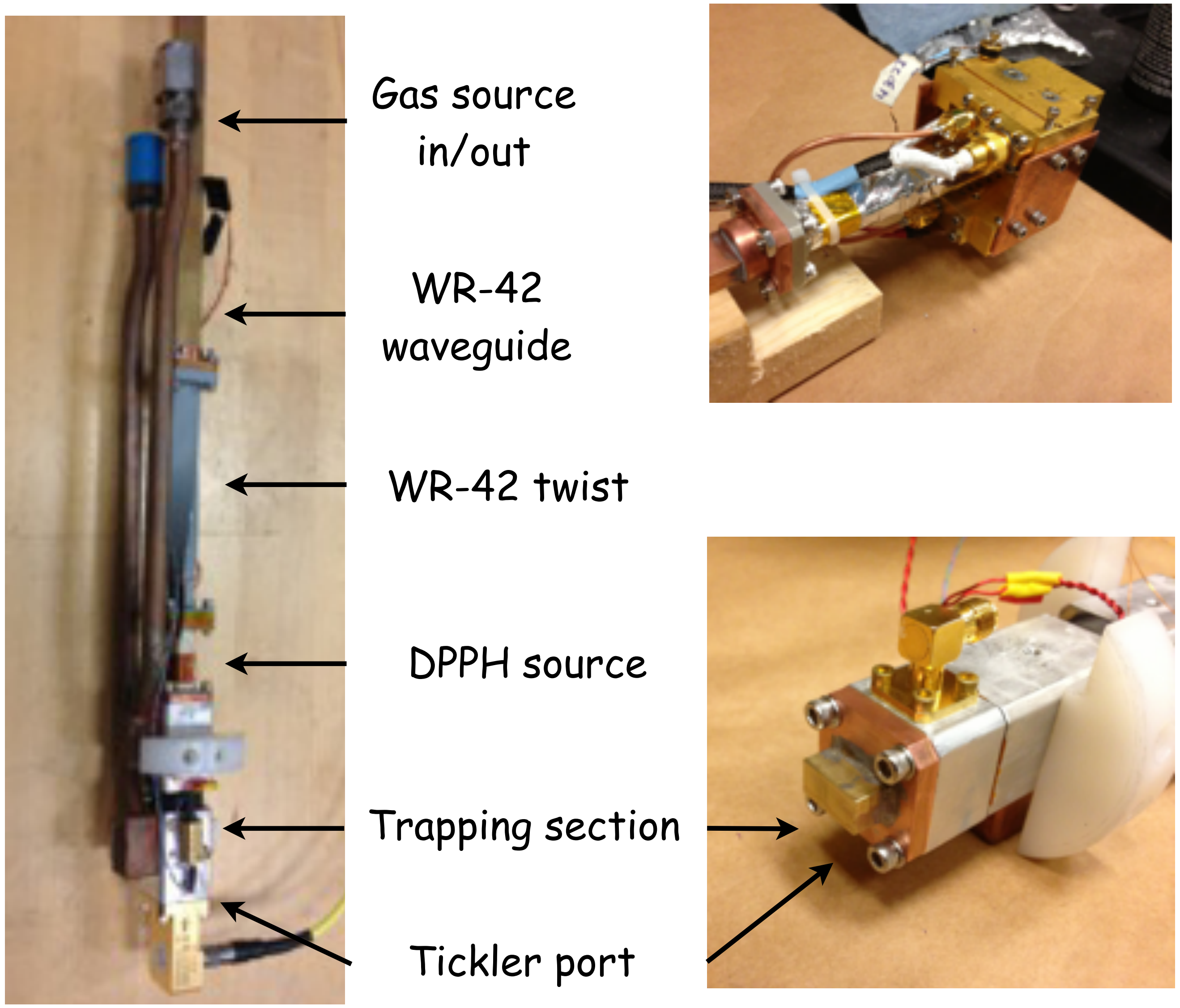
Thermal noise spectrum, January run
(Not a fit)

Using 0.93 Tesla field, where signal occurs at ~26 GHz with trapping coil
About 0.5 fW of radiated power.

Waveguides designed for 26 GHz signal with low noise amplifiers and full digitization

First data in January with rather large (~150 K) temperatures as initial test of system.

Status of Phase I (Single Electron Detection)



Gas source in/out

WR-42 waveguide

WR-42 twist

DPPH source

Trapping section

Tickler port

System	Specification	Achieved
Magnetic Field	1 T Field 10^{-4} accuracy	< few 10^{-5} DPPH Monitoring
Gas System	10^{-6} Torr	< 10^{-7} Torr PIPS detector
Noise Temperature	$T_{sys} < 50$ K	$T_{sys} \sim 35$ K
Sensitivity Analysis	SNR > 12 for 0.4 fW signal	SNR > 10 dB for 0.5 fW @ room temp.

New run will improve the noise temperature down to ~ 35K.
System undergoing commissioning now.

Analysis & simulation show signal efficiency of >90% for electrons down
Sensitivity of < 0.1 fW and >50 μs trapping time.

Use electron spin resonance (ESR) for in-situ calibration of magnetic field.

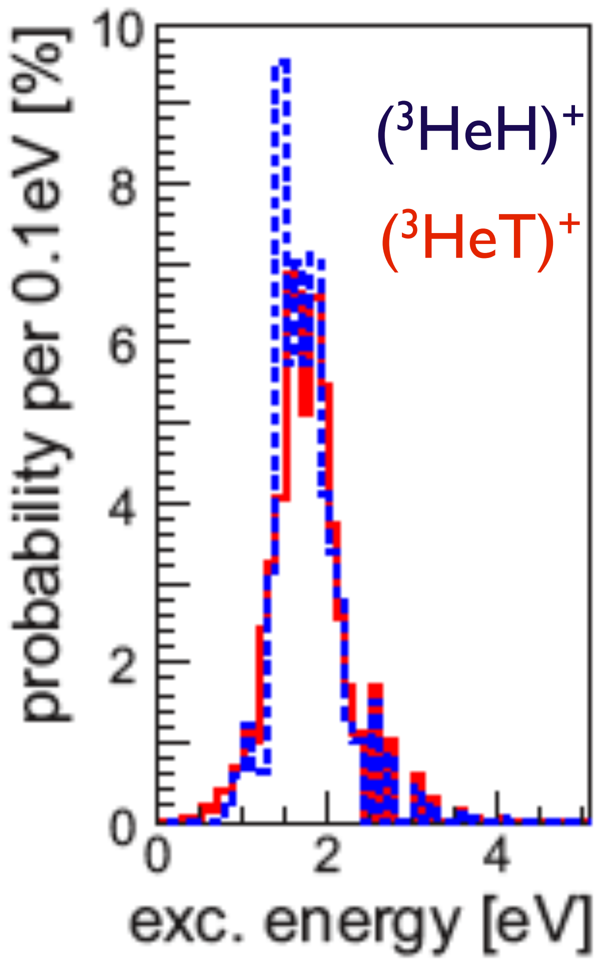
Moving Beyond the Degeneracy Scale

- 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 rotational-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.
- The trapping conditions necessary for electrons also lends itself for atomic trapping of atomic tritium (R. G. H. Robertson)

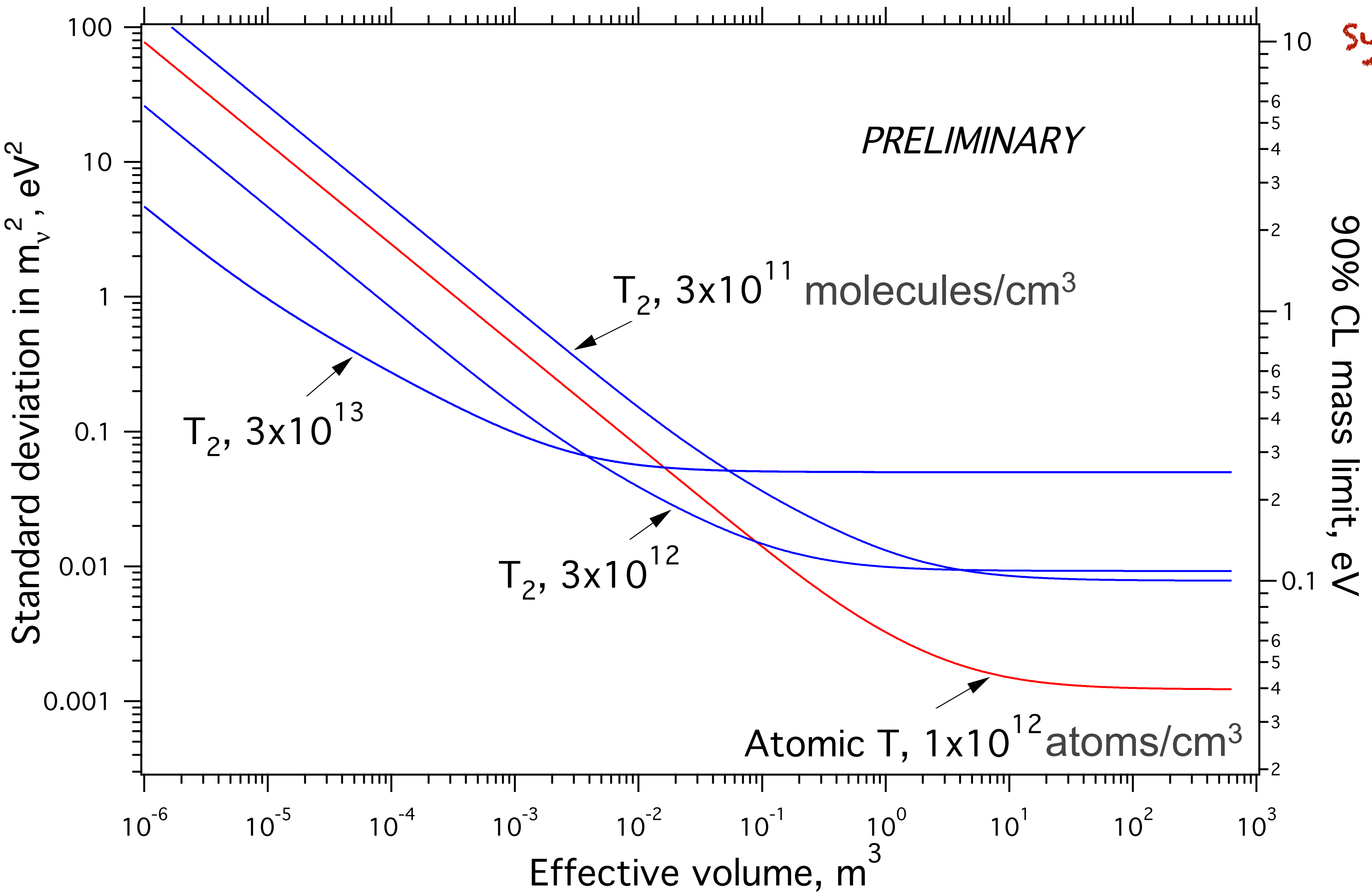
rotational

vibrational

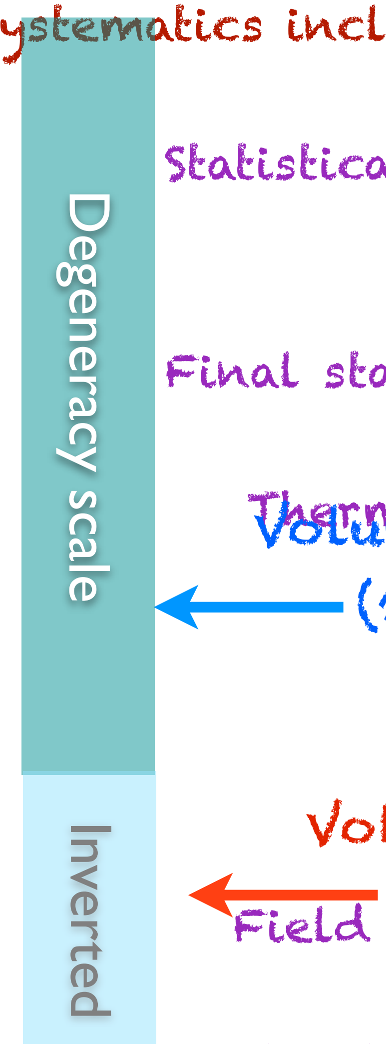
Inherent 0.36 eV final state smearing



Projected Sensitivity (Molecular & Atomic)



Systematics include:



Statistical uncertainties
(1 year run)

Final state interactions

Thermal broadening

Volume ≈ 0.05 m^3
(≈ 70 mCi)

Scattering

Background

Volume ≈ 5 m^3
(0.25 Ci)

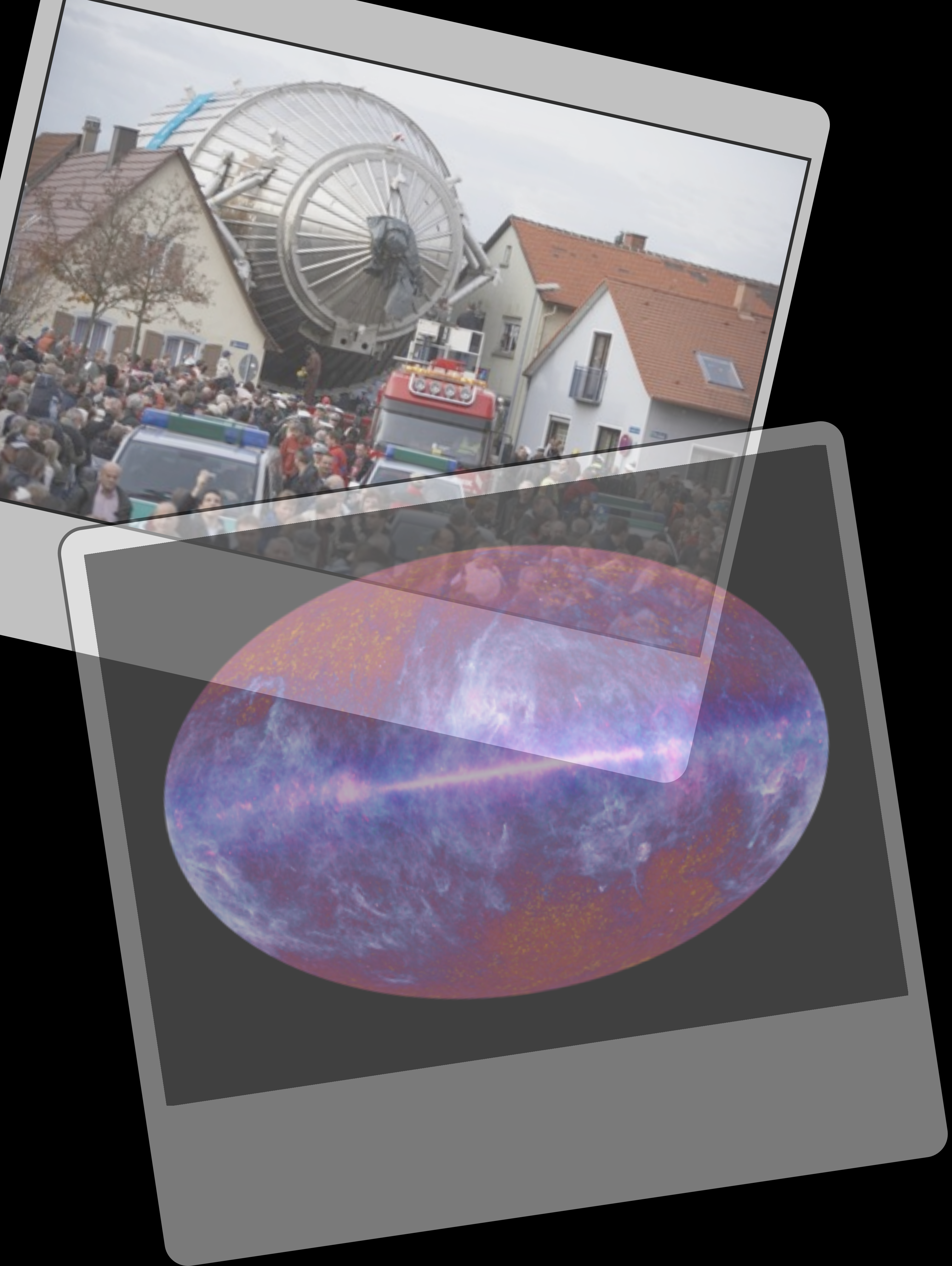
Field inhomogeneity

1% uncertainty in resolution
distribution

Sensitivity for both molecular and atomic tritium are shown.

Systematics include final state interactions, thermal broadening, statistical uncertainties, and scattering.

Can calibrate against frequency standards.



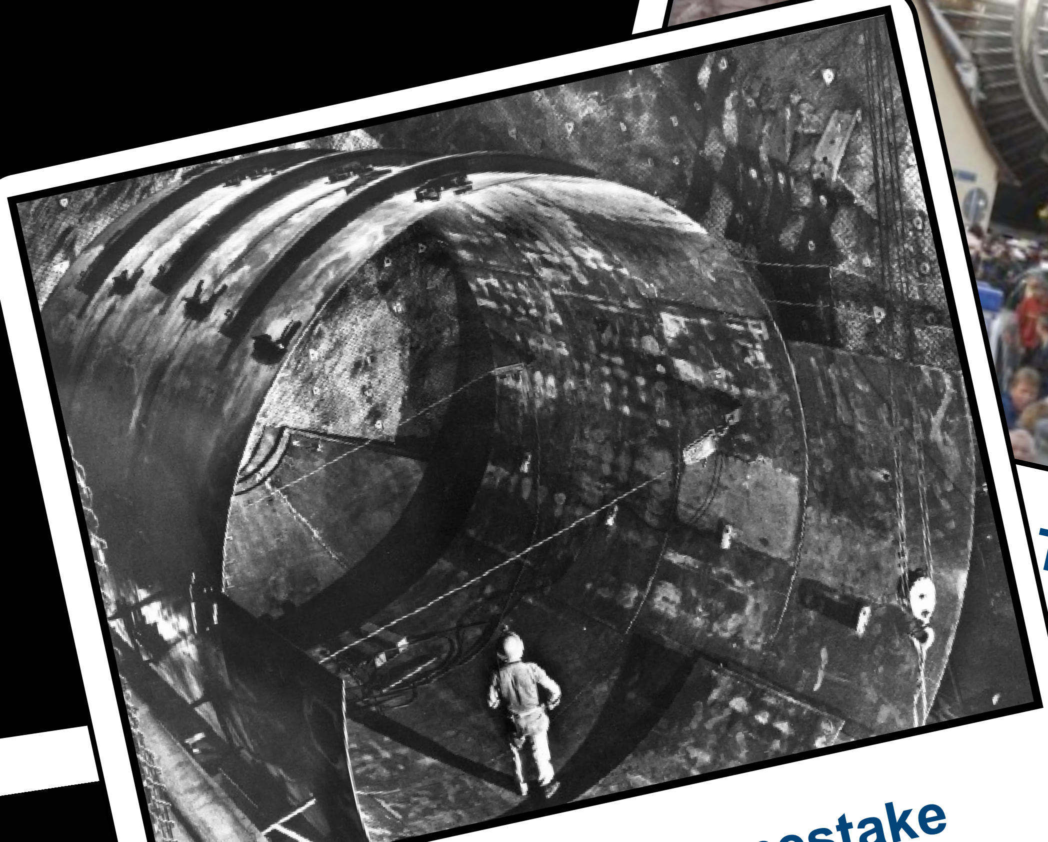
It is rare in our field that two systems are completely orthogonal except for only a few key quantities.

Direct probes may provide a robust test of cosmology (and vice-versa).

Disagreement on a signal would point to new physics; agreement would be an outstanding triumph.

It should truly be an exciting decade!

TRIN



Ray Davis Jr., Homestake

PLANCK

ilson & Penzias

Thank you for your attention

Ray Davis Jr., Homestake

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Special thanks to Loredana Gastaldo, Flavio Gatti, Angelo Nunciotti, Klaus Blaum, Guido Drexlin, and my Project 8 and KATRIN collaborators.