KATRIN

Project

Wilson & Penzias

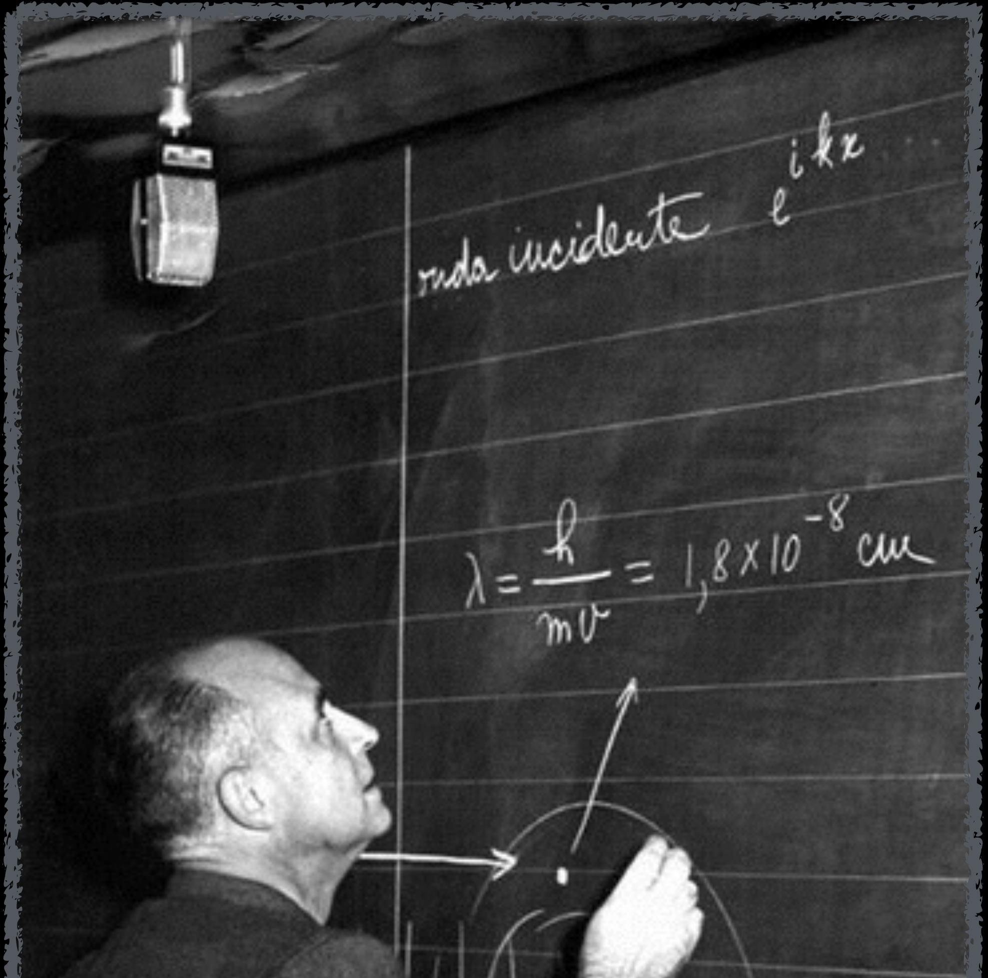
Project 8

&

Alternative Paths in Beta Decay Experiments

Gran Sasso National Laboratory
May 14th 2014

Joseph A. Formaggio
MIT



Neutrino mass measurements have a long history in physics, predating the Standard Model itself.

It should therefore be no surprise that our quest still continues to understand this fundamental property, both in its own right as well as its theoretical implications.

80 a. – Tentativo di una teoria dei raggi β

LA MASSA DEL NEUTRINO.

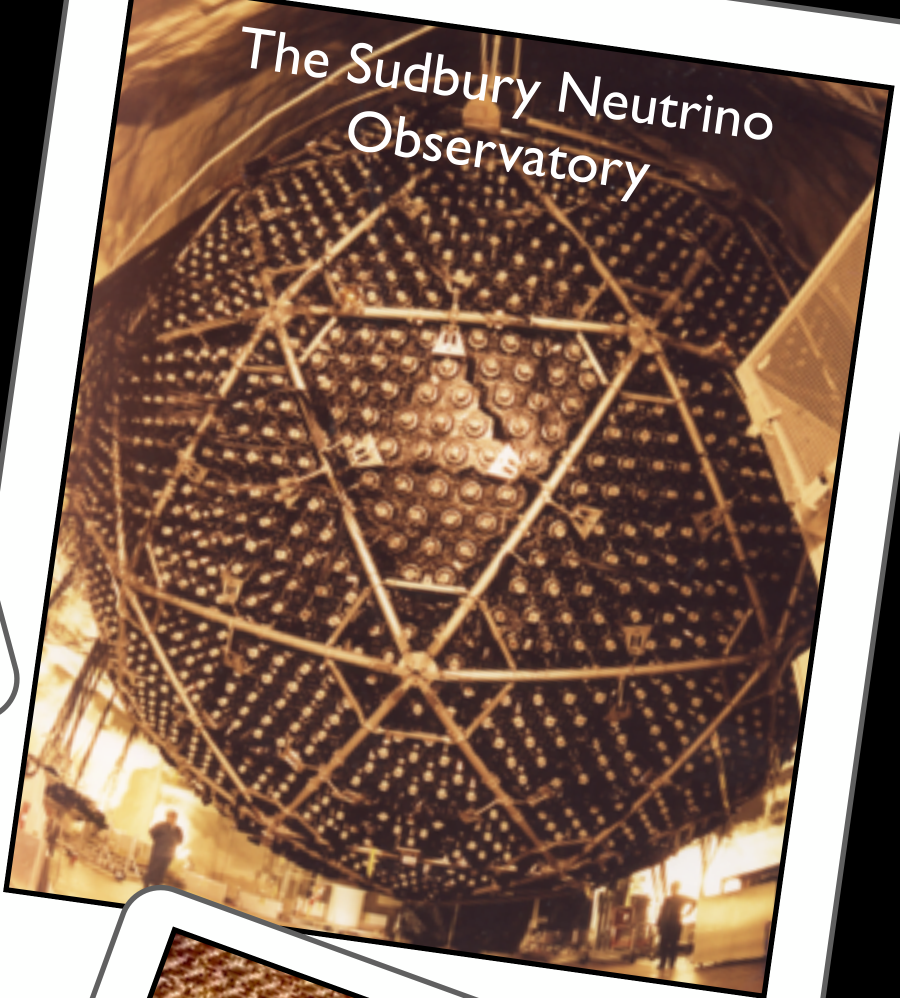
probabilità di transizione (32) determina tra l'altro la forma continuo dei raggi β. Discuteremo qui come la forma di questo spettro dipende dalla massa di quiete del neutrino, in modo da poter determinare questa massa da un confronto con la forma sperimentale dello spettro stesso. La massa μ interviene in (32) tra l'altro nel fattore p_σ^2/v_σ. La dipendenza della forma della curva di distribuzione dell'energia da μ, è marcata specialmente in vicinanza della energia massima E_0 dei raggi β. Si riconosce facilmente che la curva di distribuzione per energie E prossime al valore massimo E_0, si comporta, a meno di un fattore indipendente da E, come

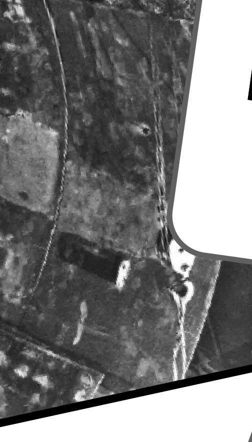
$$\frac{p_\sigma^2}{v_\sigma} = \frac{1}{c^3}(\mu c^2 + E_0 - E)\sqrt{(E_0 - E)^2 + 2\mu c^2 (E_0 - E)}. \quad (36)$$

Nella fig. 1 la fine della curva di distribuzione è rappresentata per μ = 0, e per un valore piccolo e uno grande di μ. La maggiore somiglianza con le

Fig. 1.

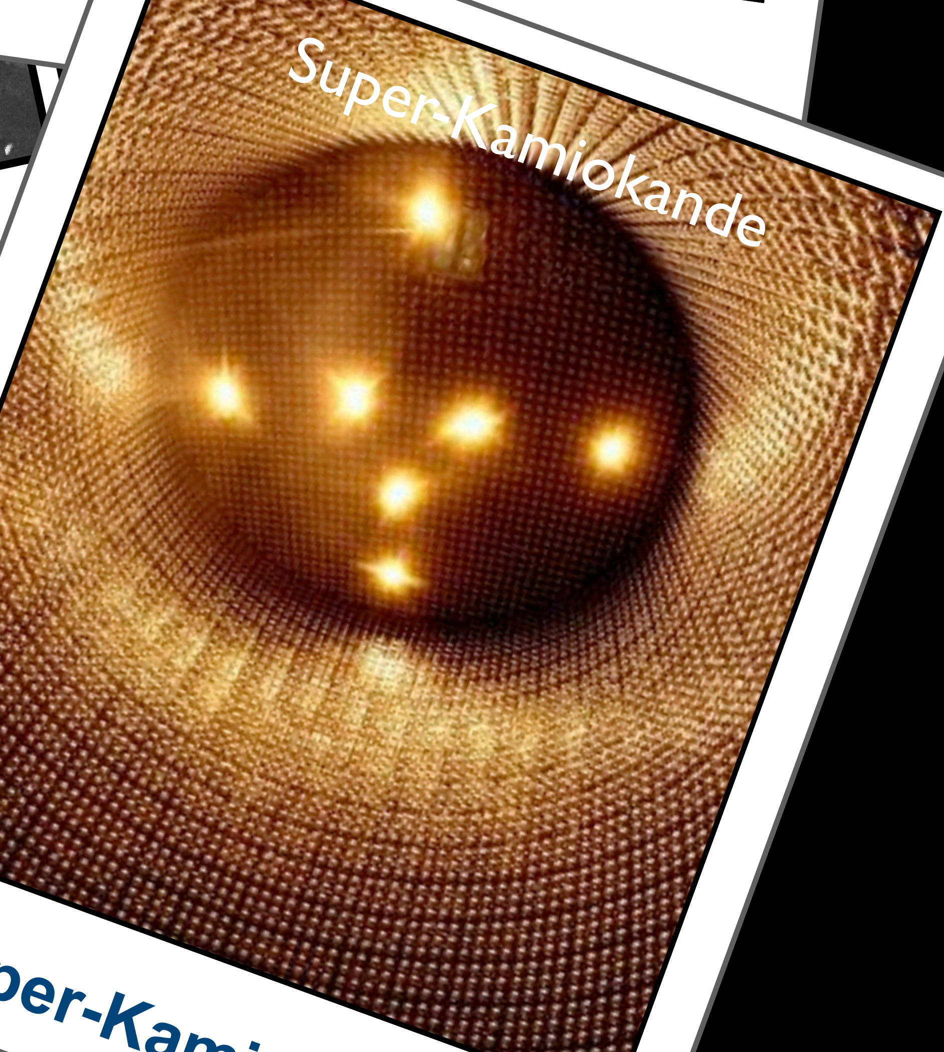
MINOS





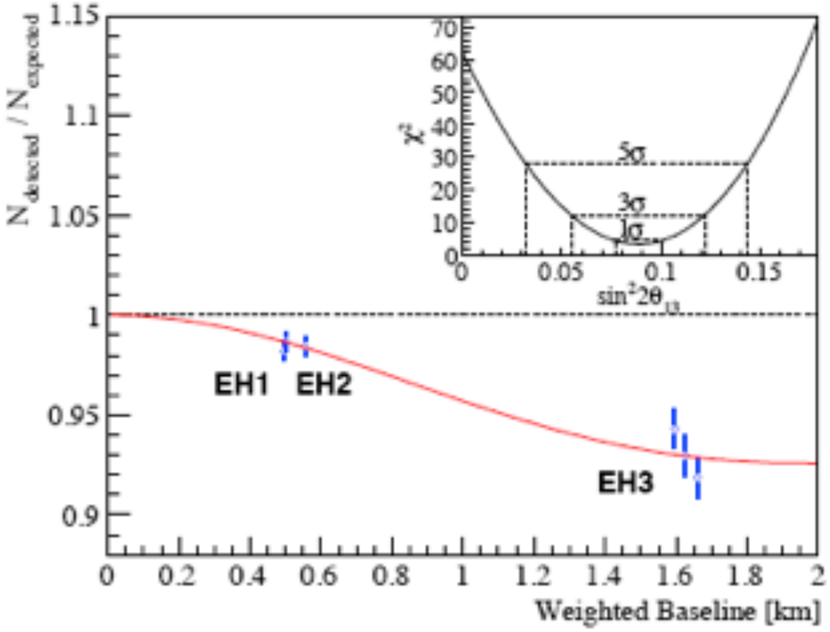
omestake

KamLAND



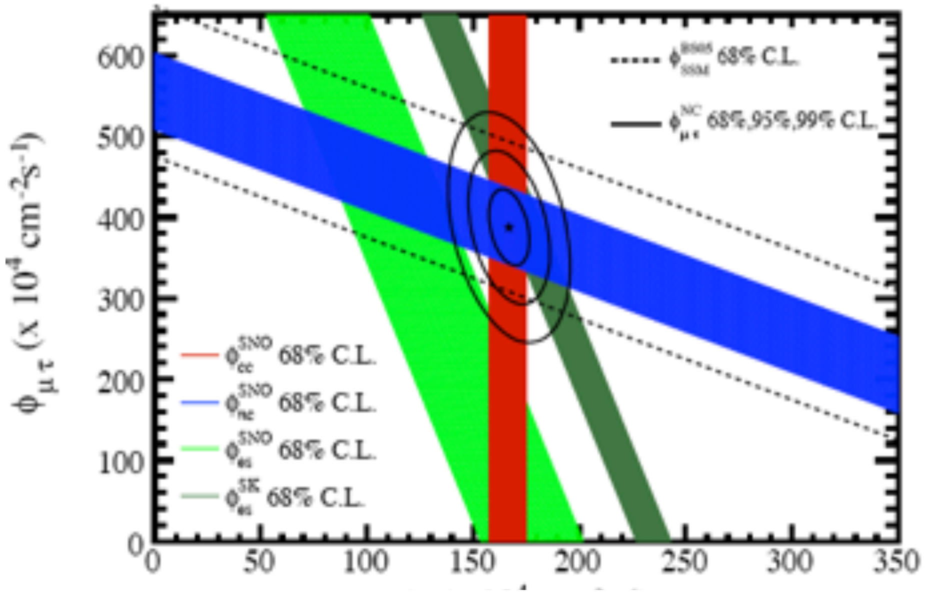
Super-Kam

The phenomena of neutrino oscillations is now firmly established.



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

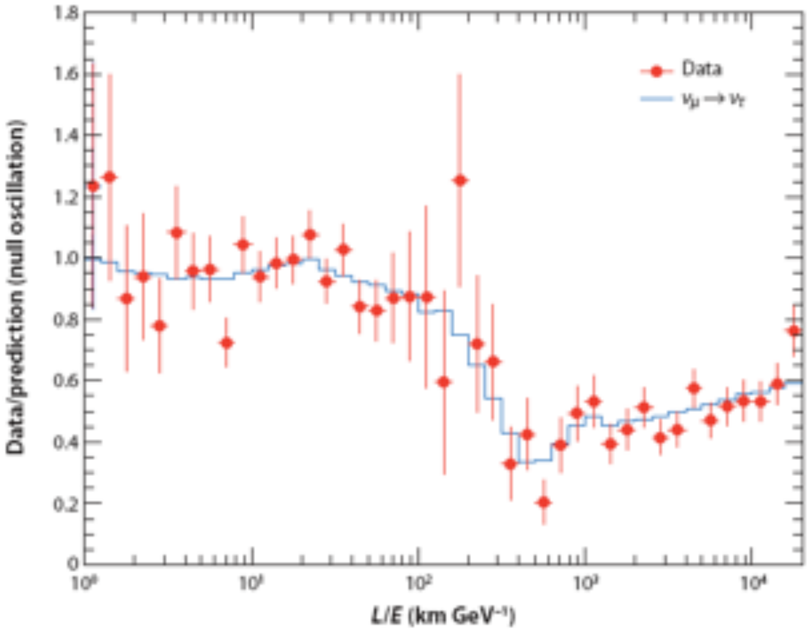
Reactor & Long Baseline



$$\sin^2(\theta_{12}) = 0.307 \pm 0.016$$

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

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)

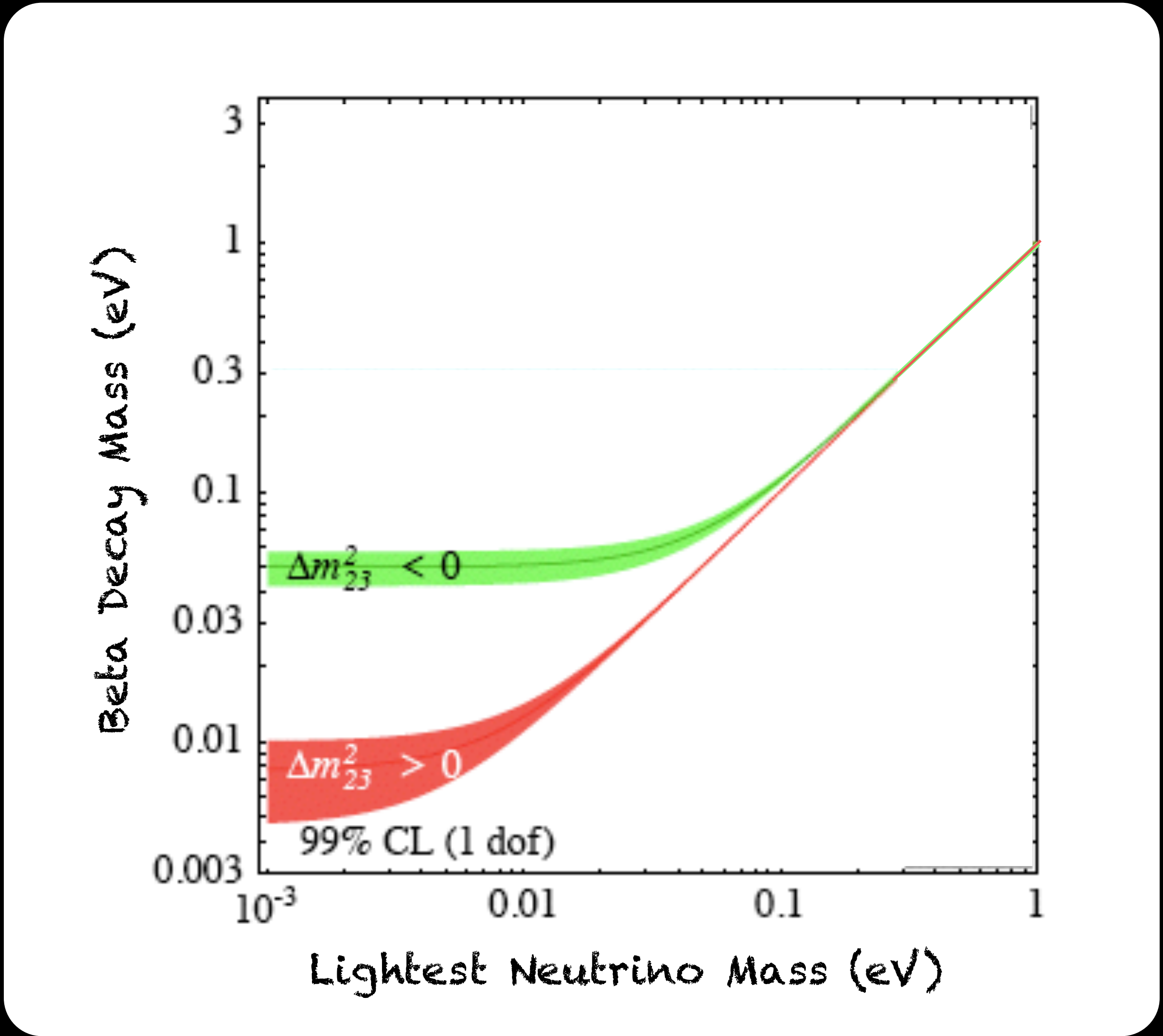
Precision measurements now exist on all three mixing angles to date.

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

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

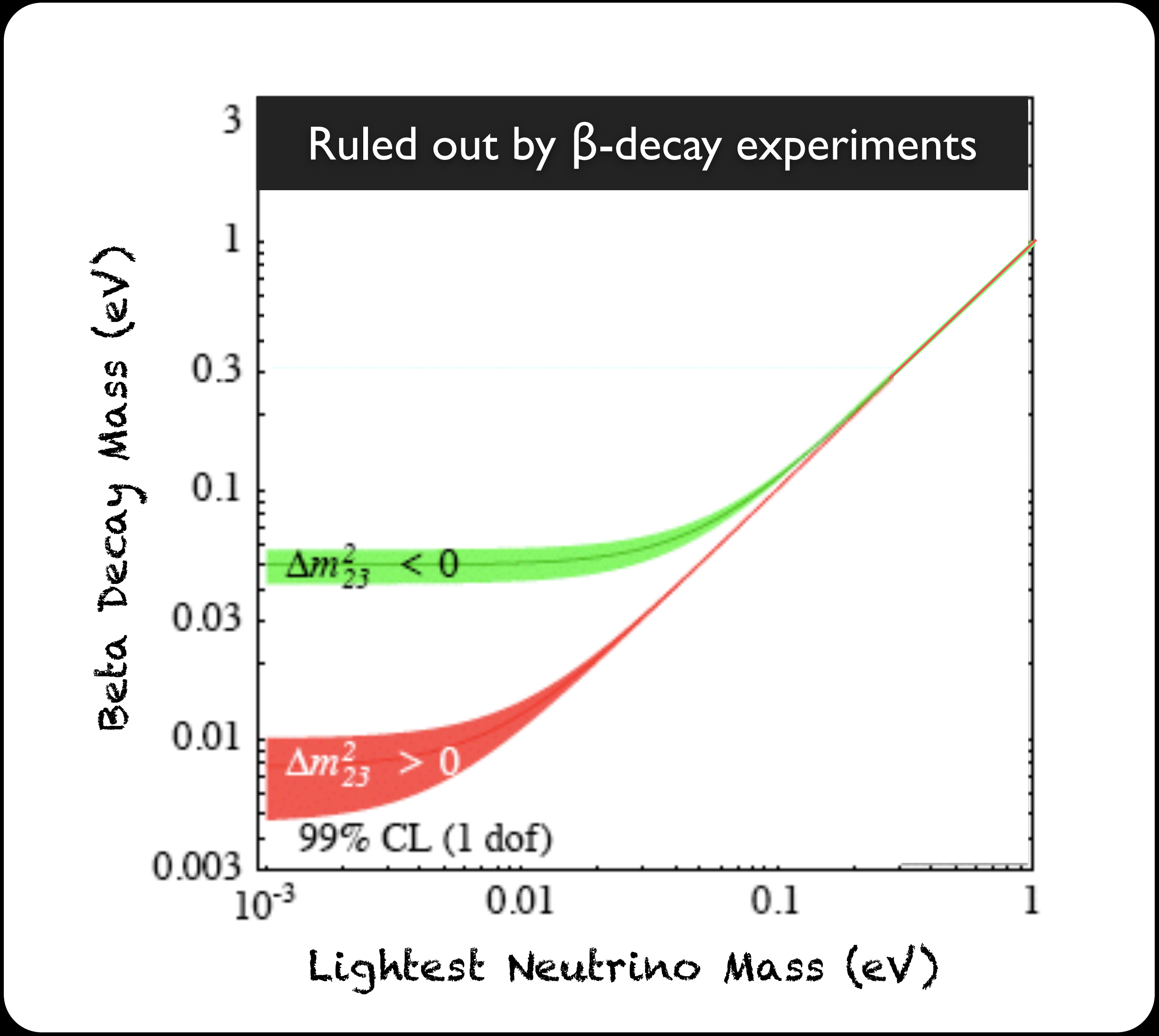
0vββ Measurements

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

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.



$m_\nu > 2$ eV (eV scale, current)

Neutrinos ruled out as dark matter

$m_\nu > 0.2$ eV (degeneracy scale)

Impact on cosmology and $0\nu\beta\beta$ reach

$m_\nu > 0.05$ eV (inverted hierarchy)

Resolve hierarchy if null result

$m_\nu > 0.01$ eV (normal hierarchy)

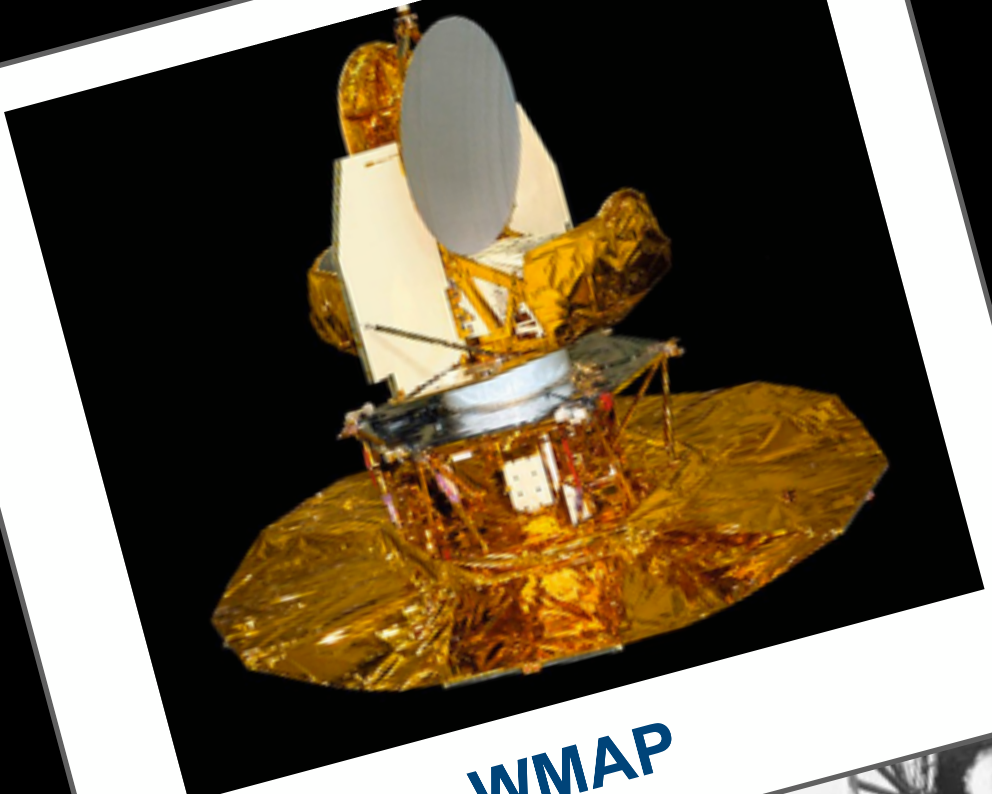
Oscillation limit; possible $C\nu B$ detection

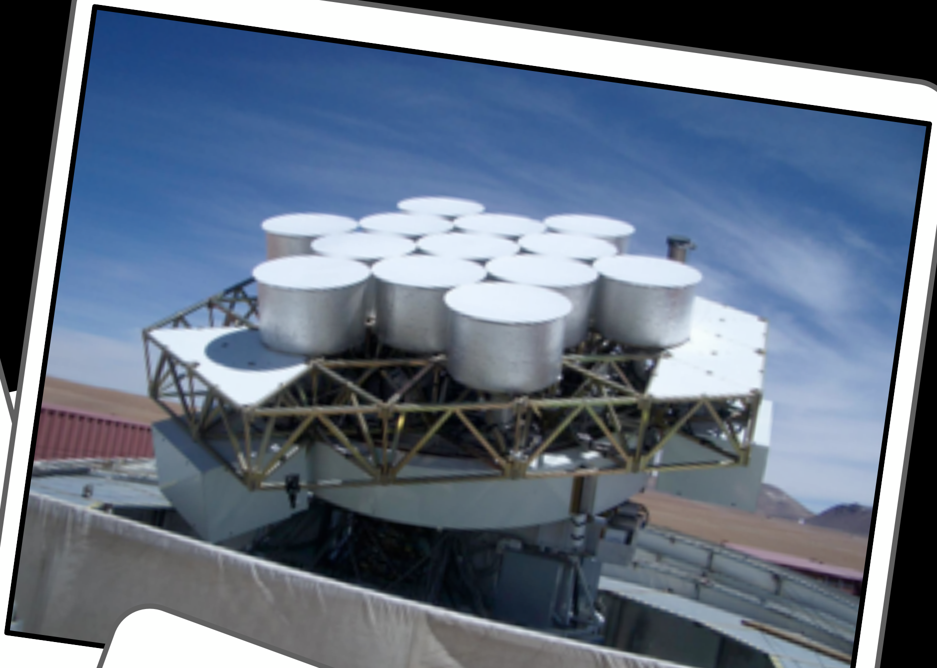
The Era of Precision Cosmology

Wilson & Penzias

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

The Era of Precision Cosmology


WMAP




Wi


Sloan Digital Sky Survey


Atacama Cosmology Telescope

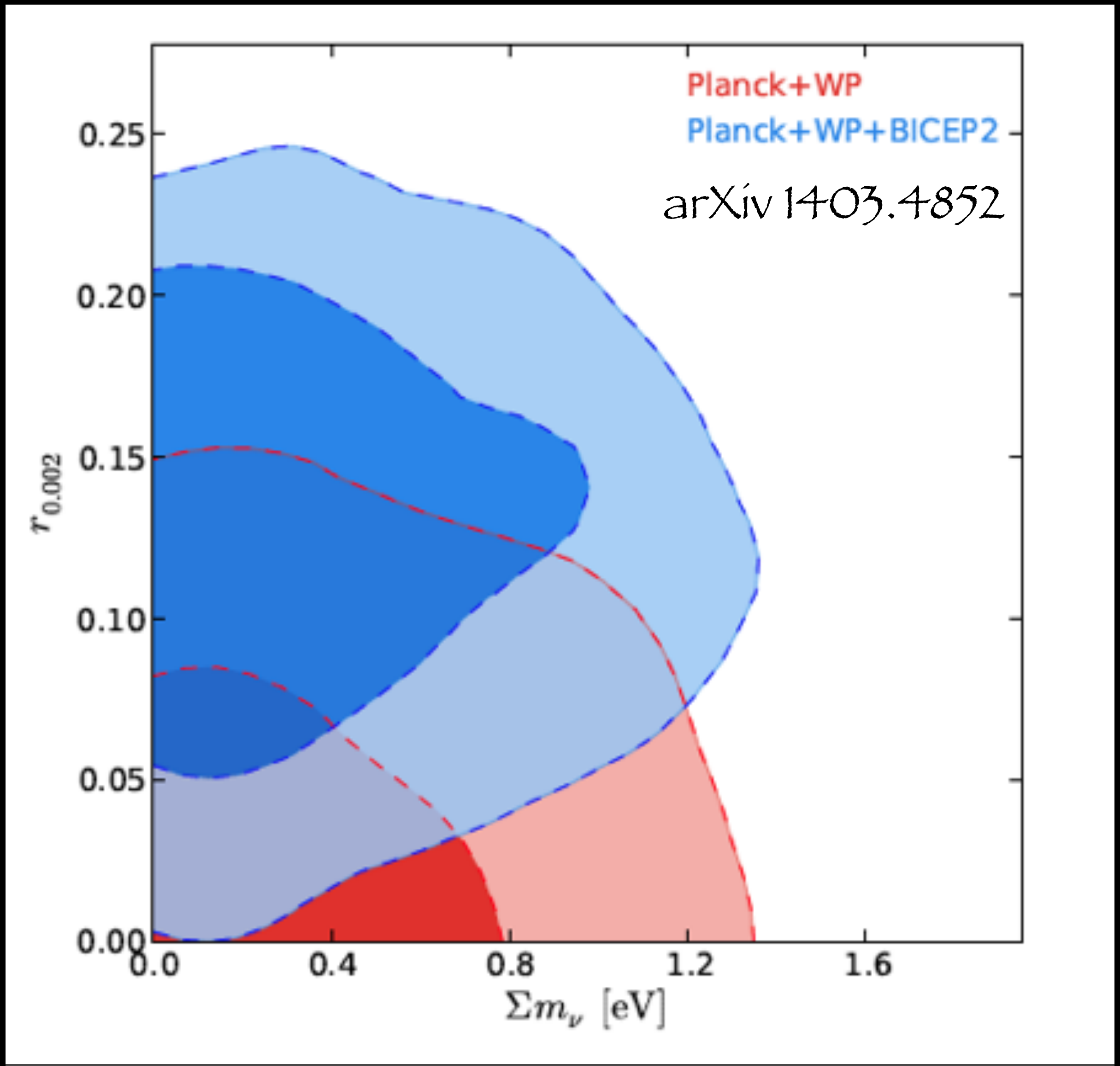
Cosmology has had a similar trajectory as neutrino physics, from inception to present day

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, BICEP2) that alter the fits or in some cases favor finite masses.



arXiv 1403.4852

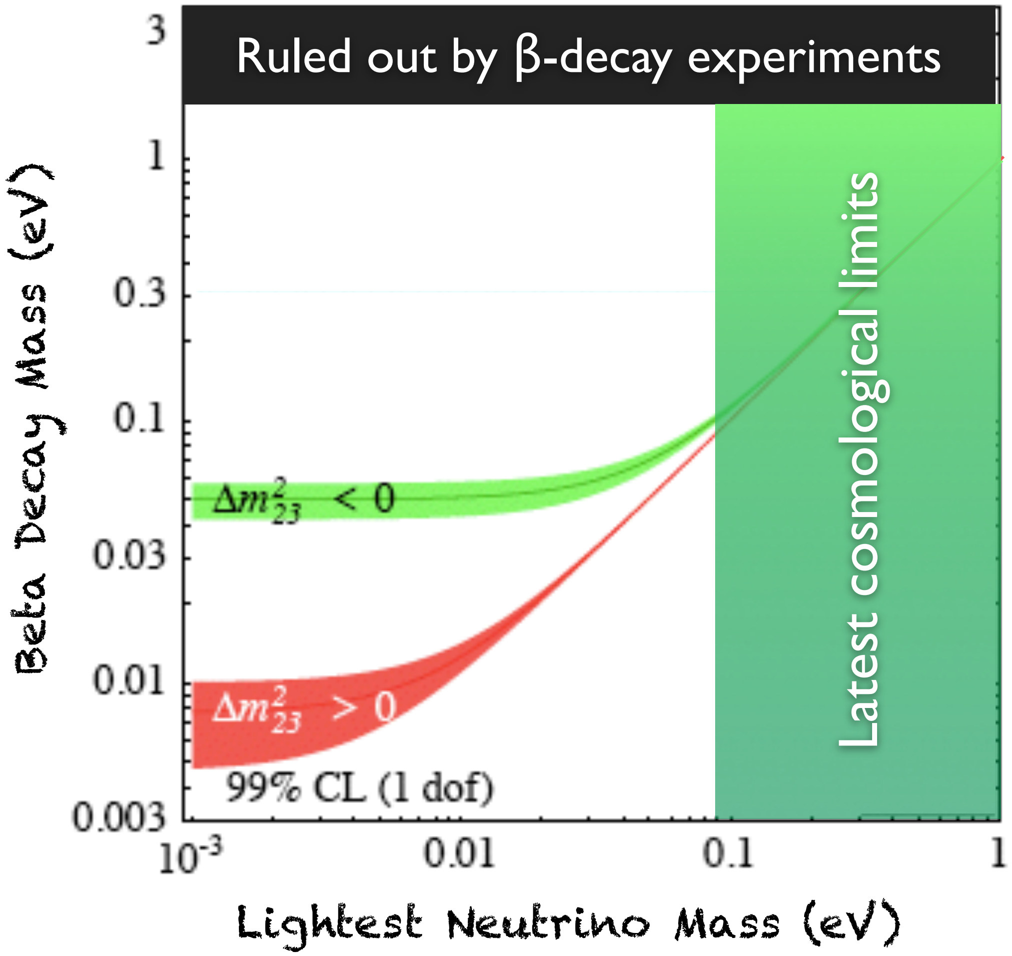
Fit	Σm
Planck + WP + HighL	< 0.66 eV
Planck + WP + HighL + BAO	< 0.23 eV
Planck + SZ Clusters	0.37 ± 0.20 eV

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.

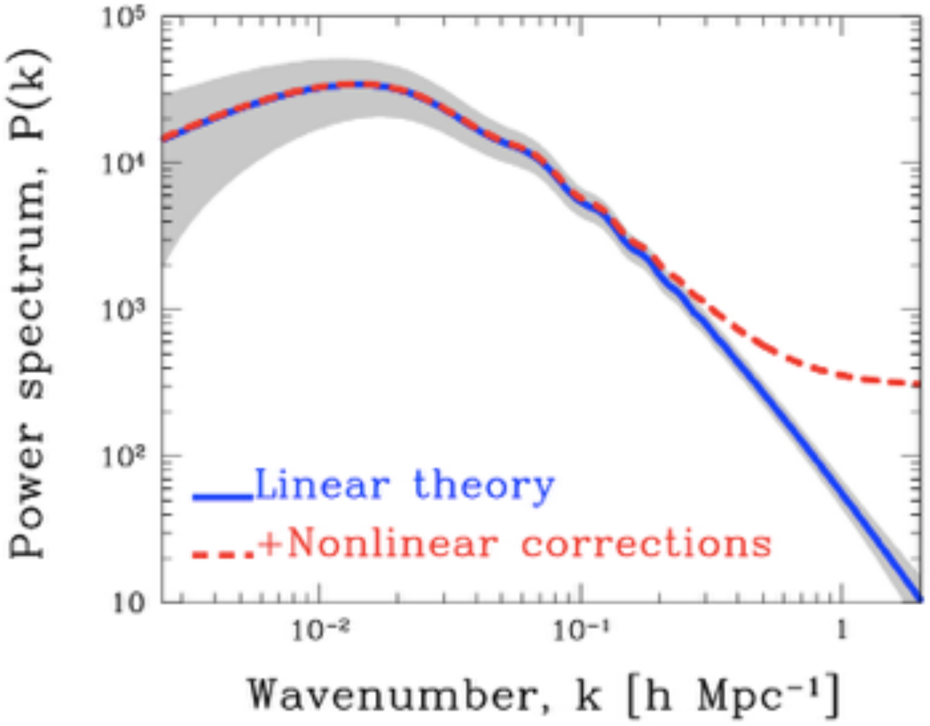
$$\frac{\Delta P}{P} \simeq -12\frac{\Omega_\nu}{\Omega_m} \simeq 1\%$$

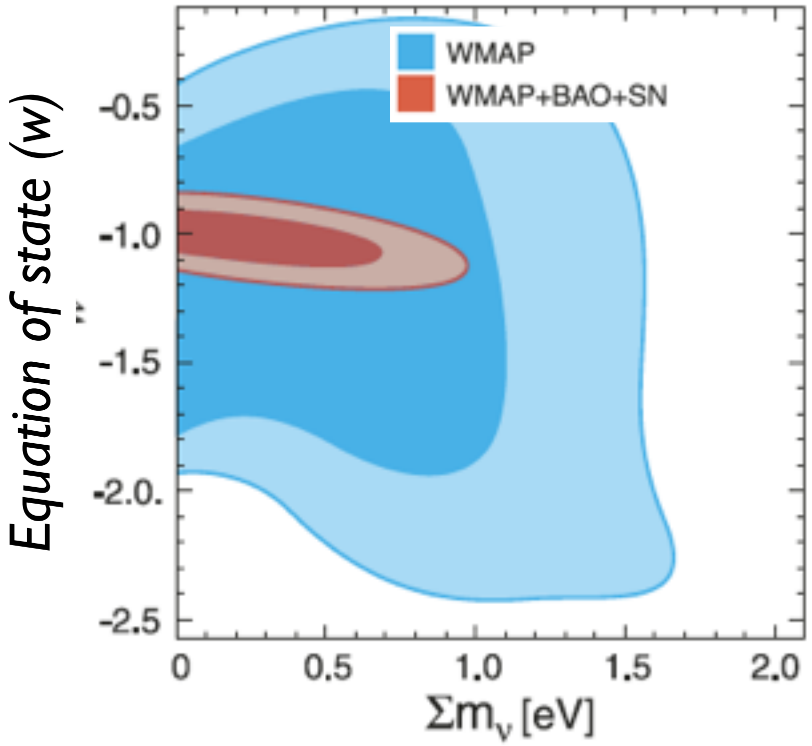
- Moving to the normal hierarchy scale now requires 1% precision on the power spectrum.



S. Hannestad
Phys. Rev. Lett 95 221301

Y. Y. Y. Wong, 2010

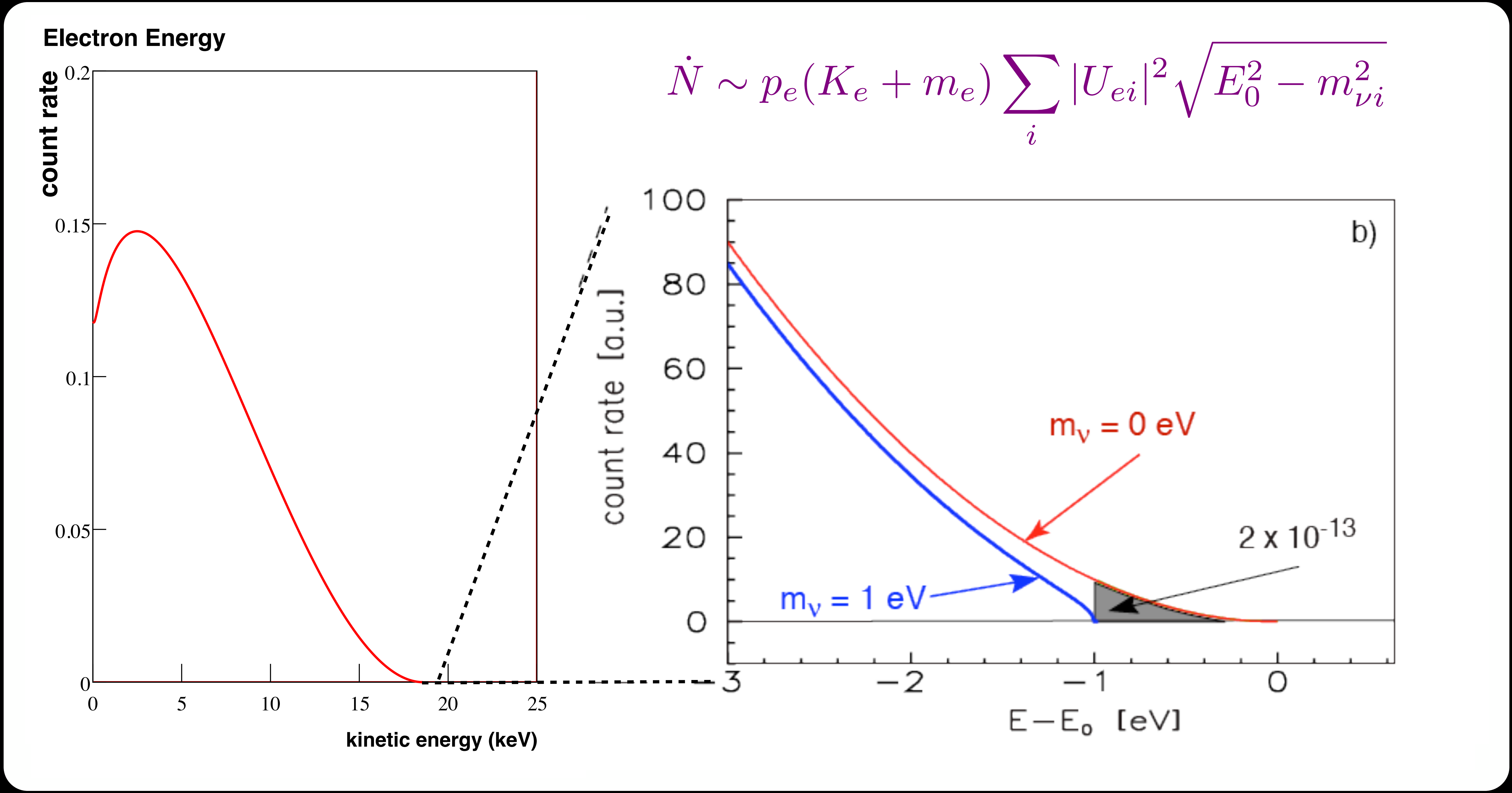




Nonlinearities

Degeneracies

Direct Probes

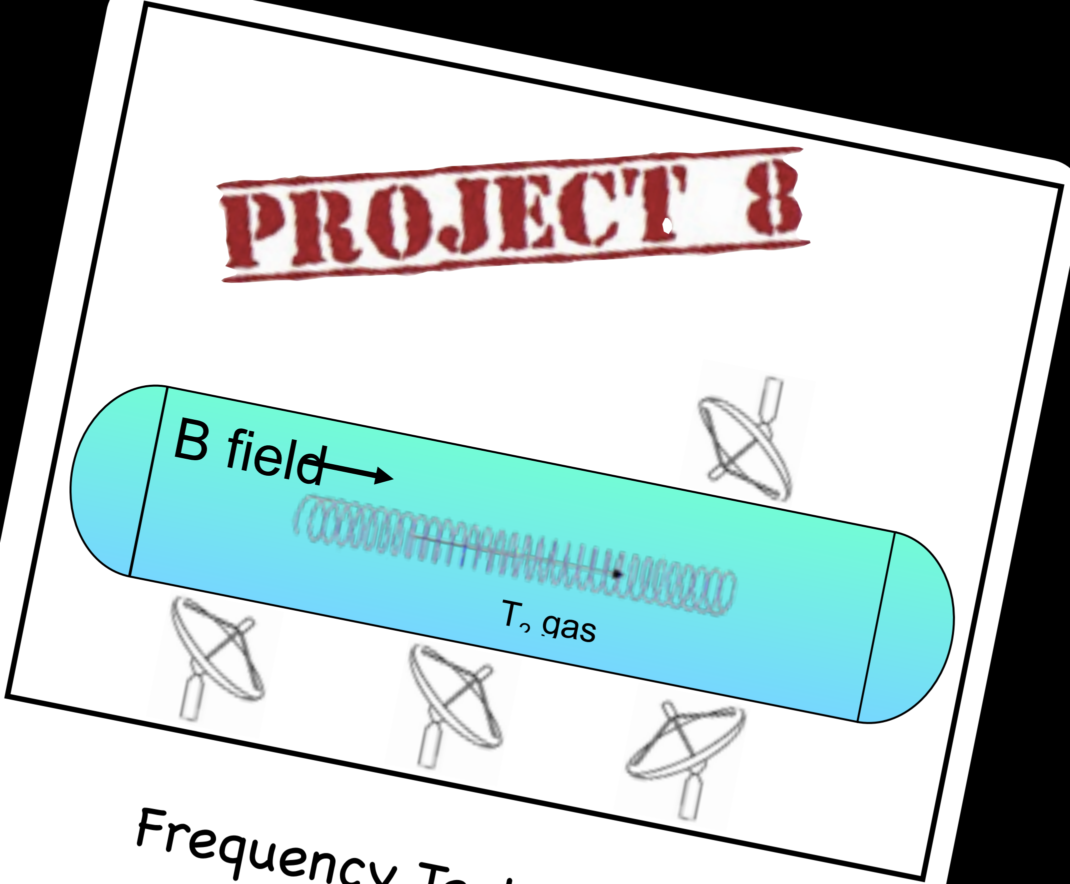


$$\dot{N} \sim p_e(K_e + m_e)\sum_i |U_{ei}|^2\sqrt{E_0^2 - m_{\nu i}^2}$$

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:

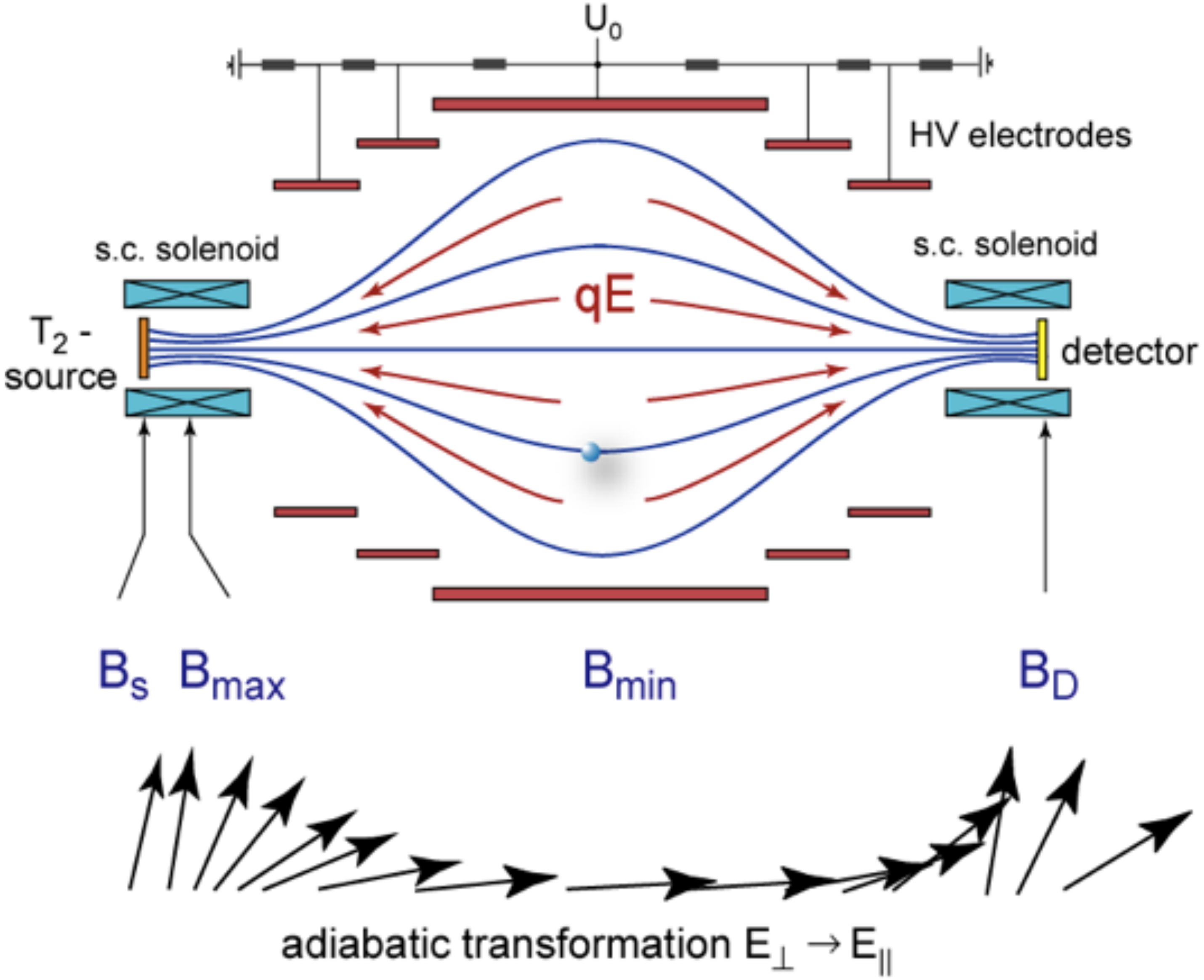
ECHO, HOLMES and Project 8

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

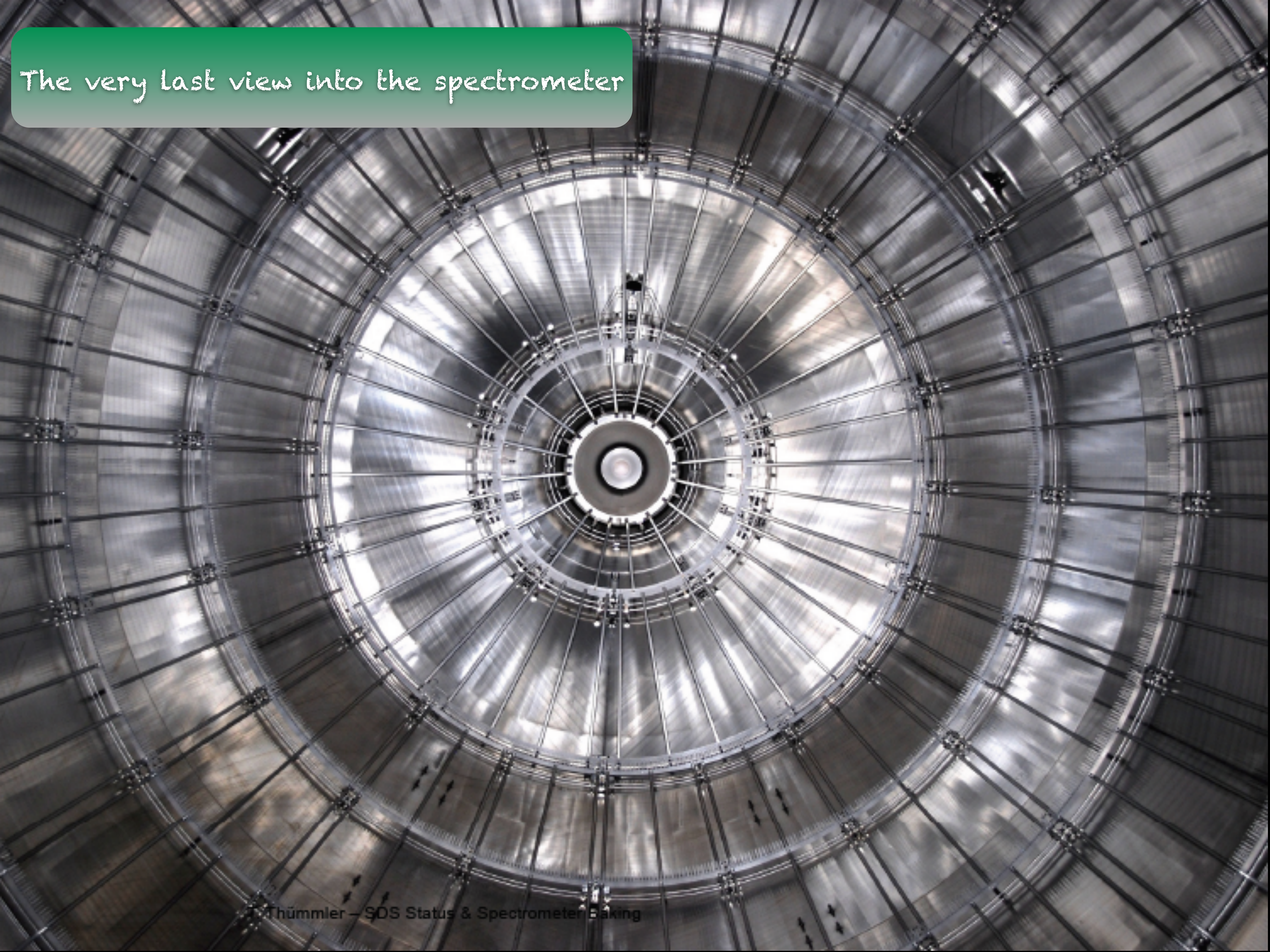
($\Delta E/E$ = B_{min}/B_{max} = 0.93 eV)

The Main Spectrometer

Recent milestone:

Final pump port closed and sealed.

The very last view into the spectrometer



SDS Commissioning

“First Light”

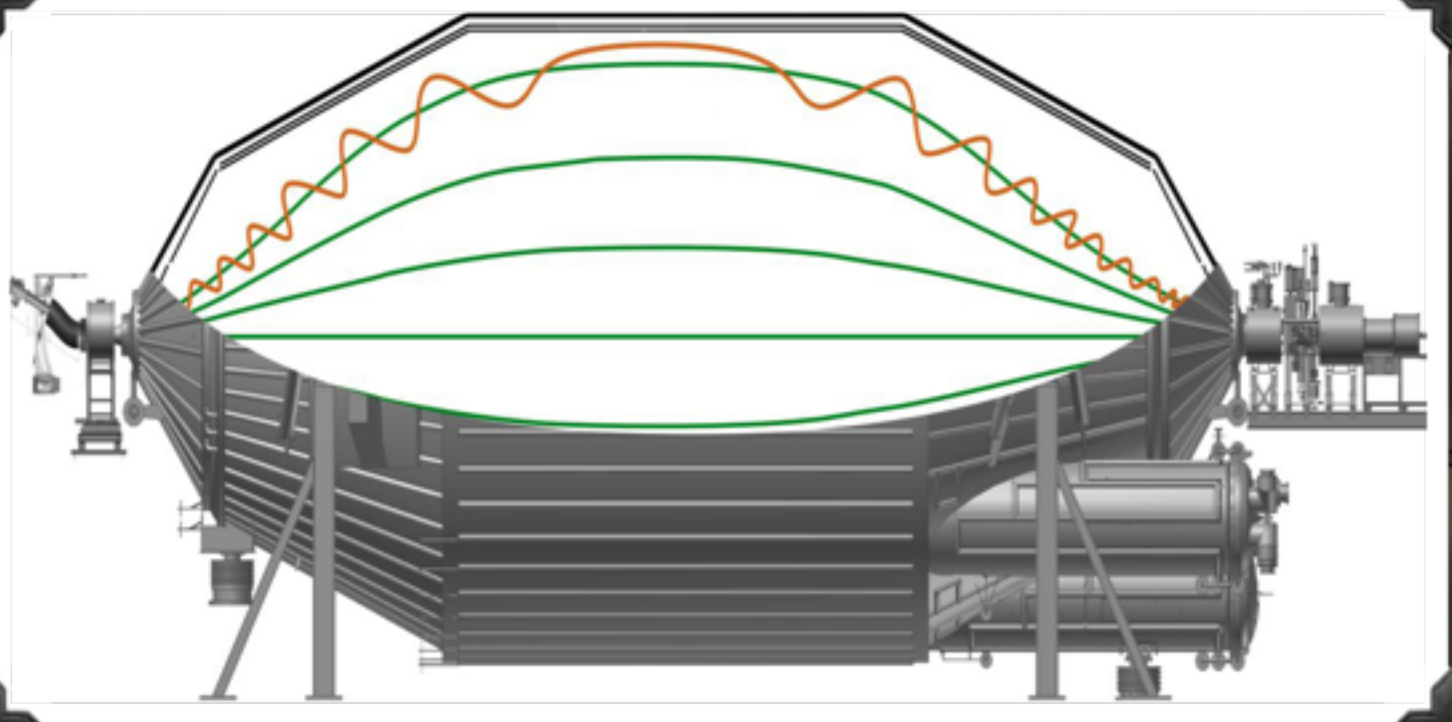
First time pre-spectrometer, main spectrometer, and detector are all connected.

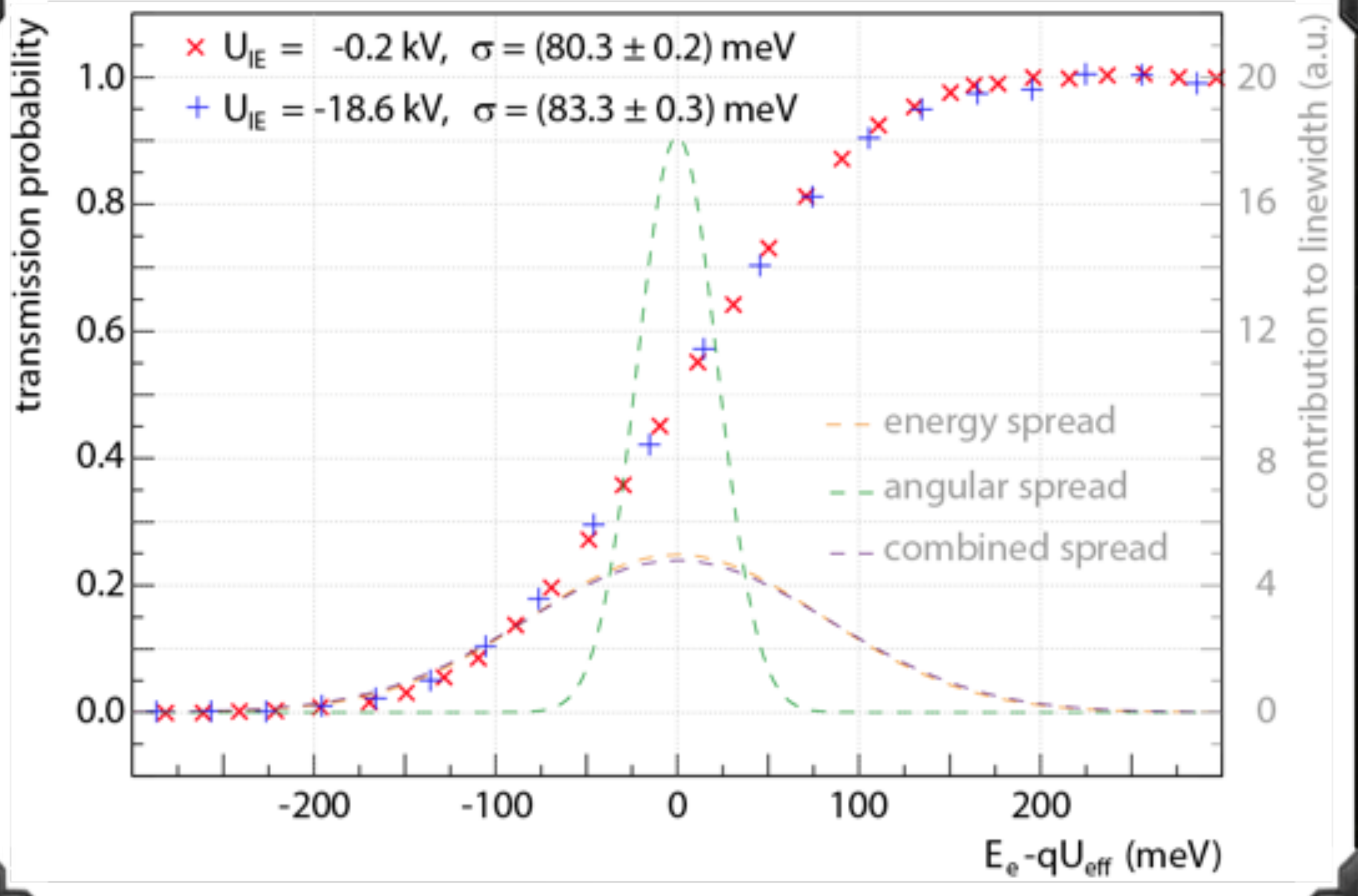
First electrons in this combined system now recorded.

Adiabatic guidance and electric retarding work as expected.

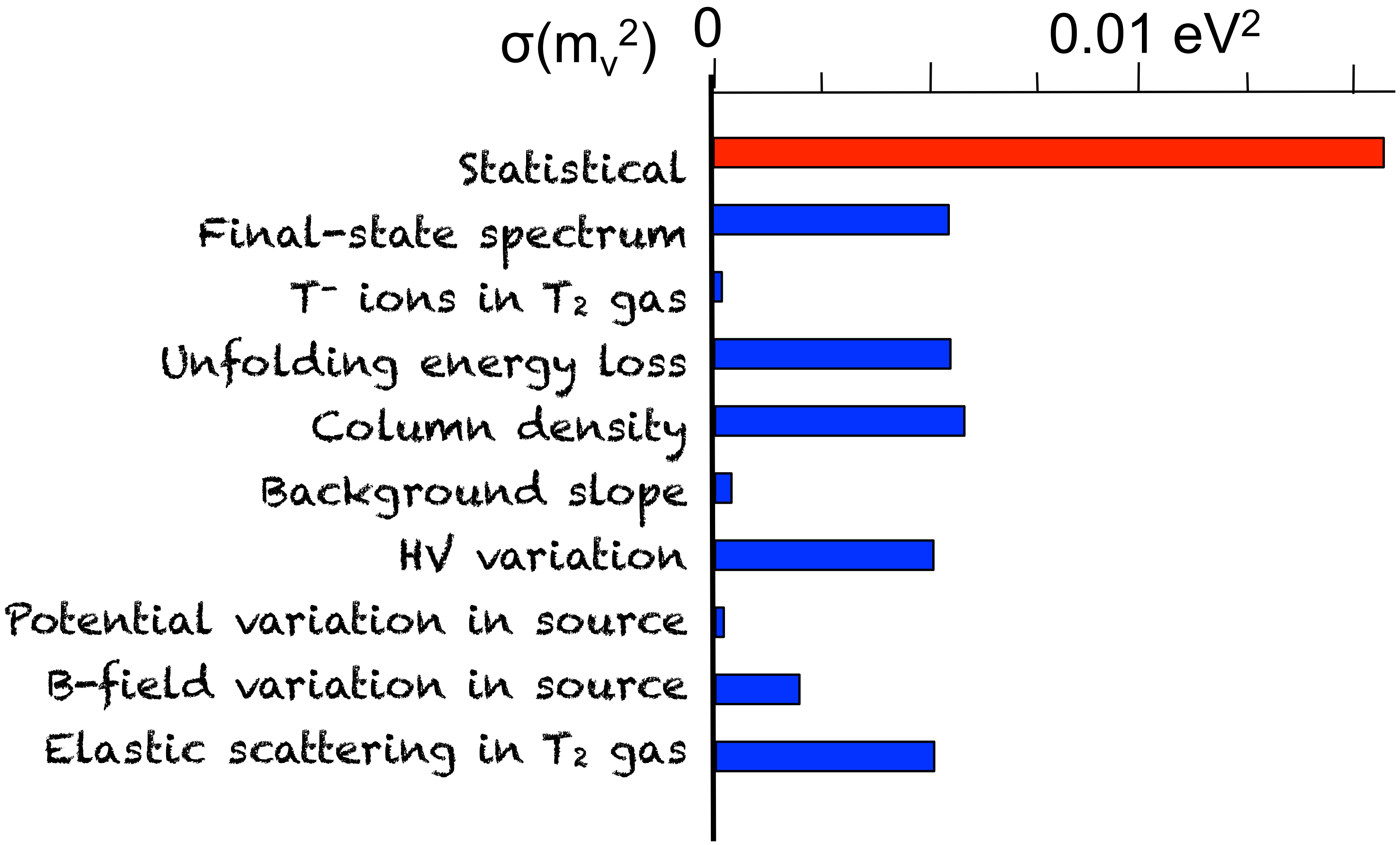
Backgrounds measured and several background reduction techniques demonstrated.

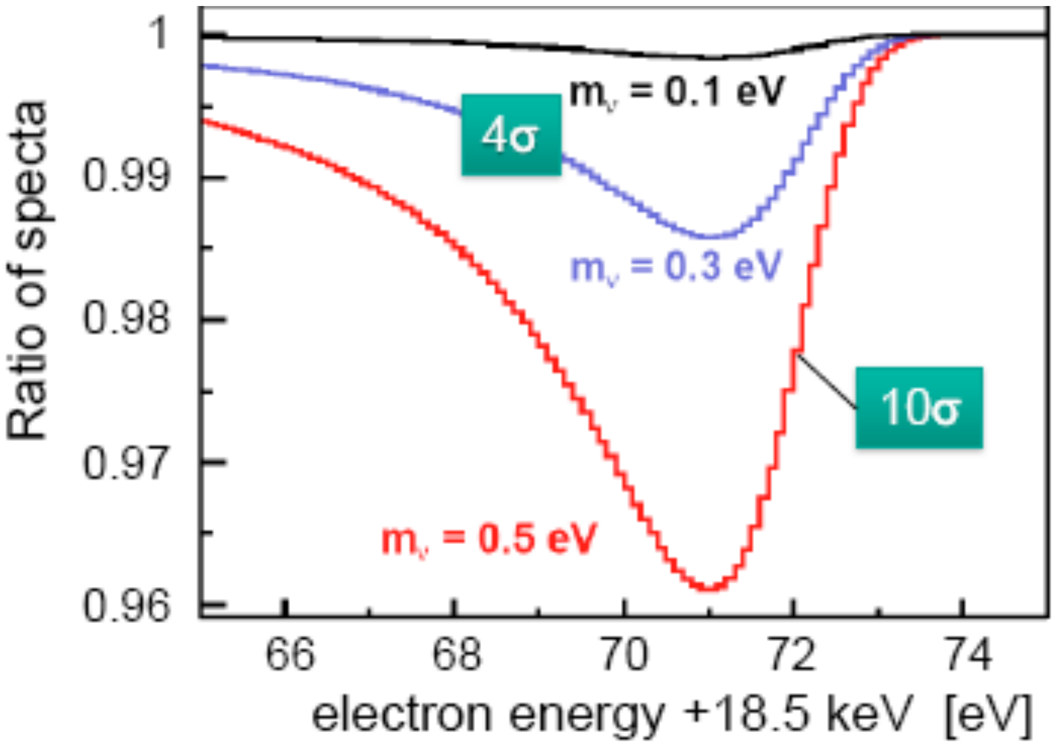
Second phase commissioning program to commence in summer 2014.

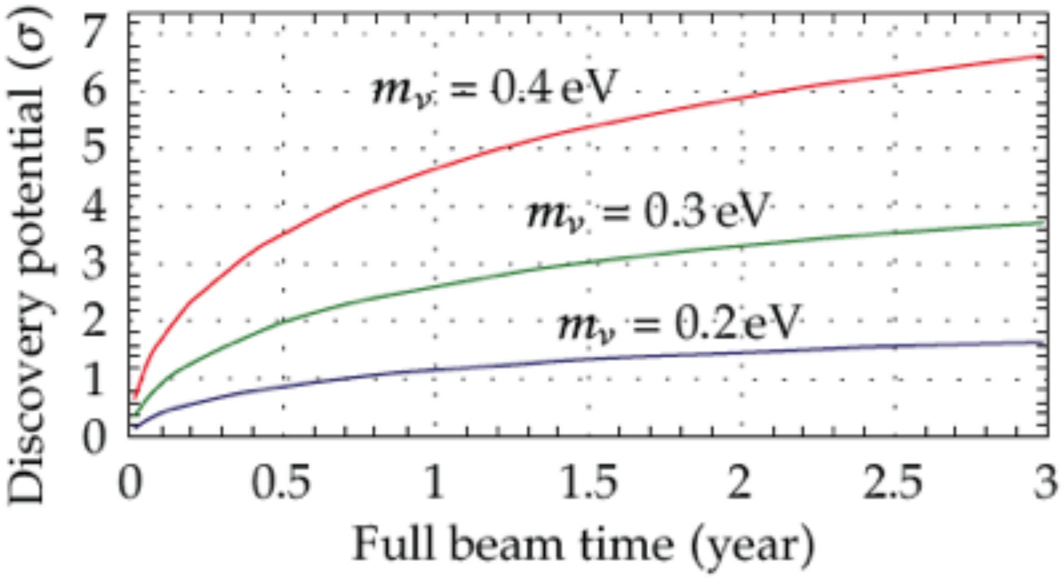




Projected Sensitivity







Neutrino Mass Goals

Discovery: 350 meV (at 5 σ)

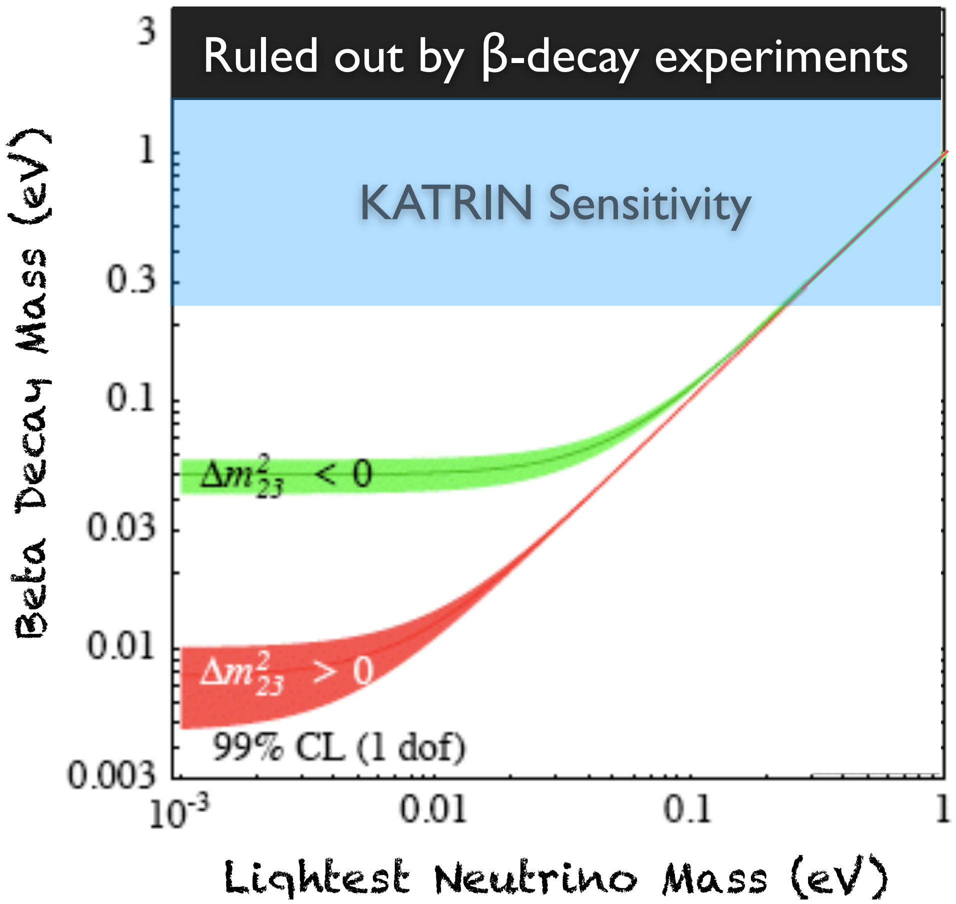
Sensitivity: 200 meV (at 90% C.L.)

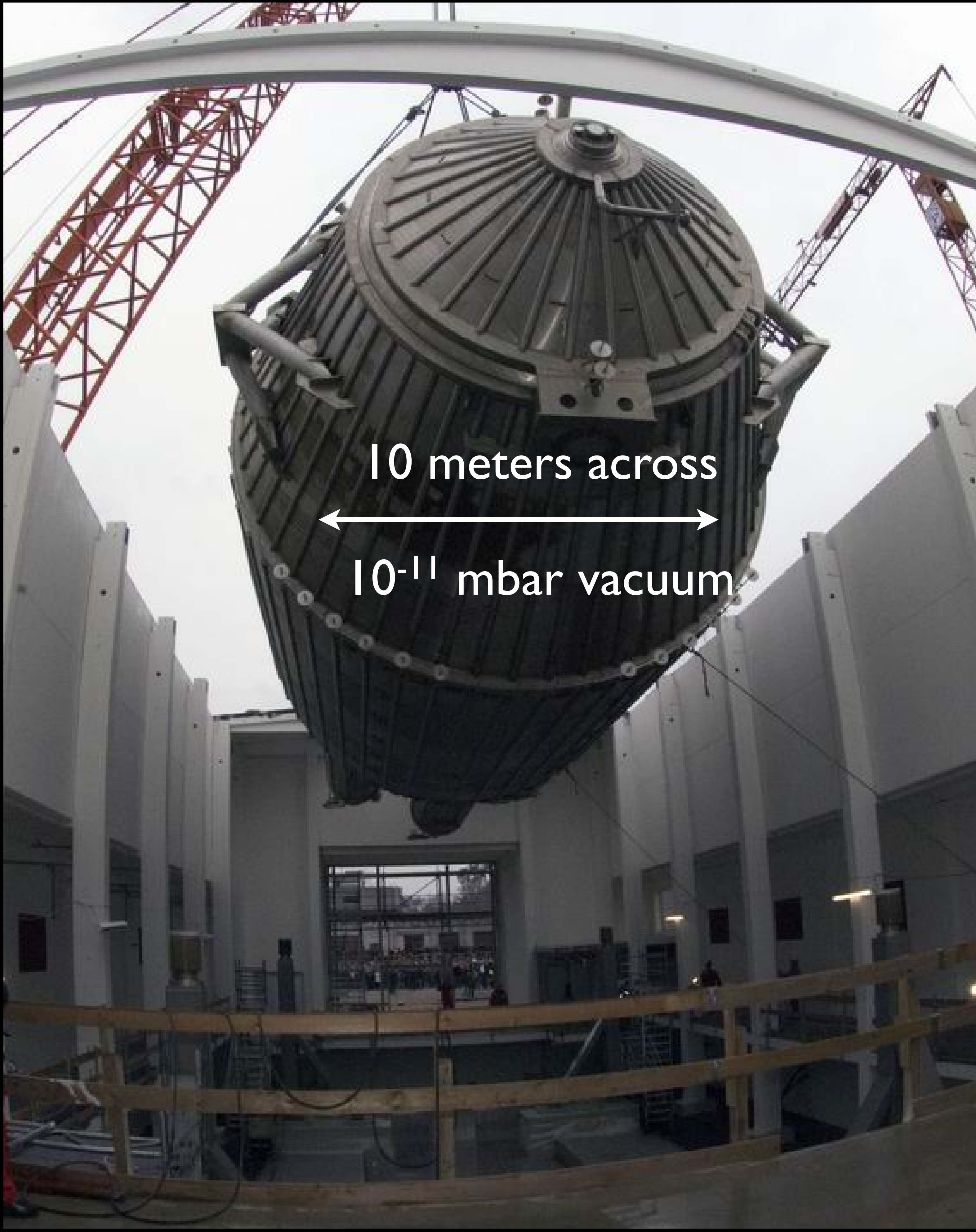
Partial loading in 2015.

Full Tritium Running in 2016.

Can we push further?

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

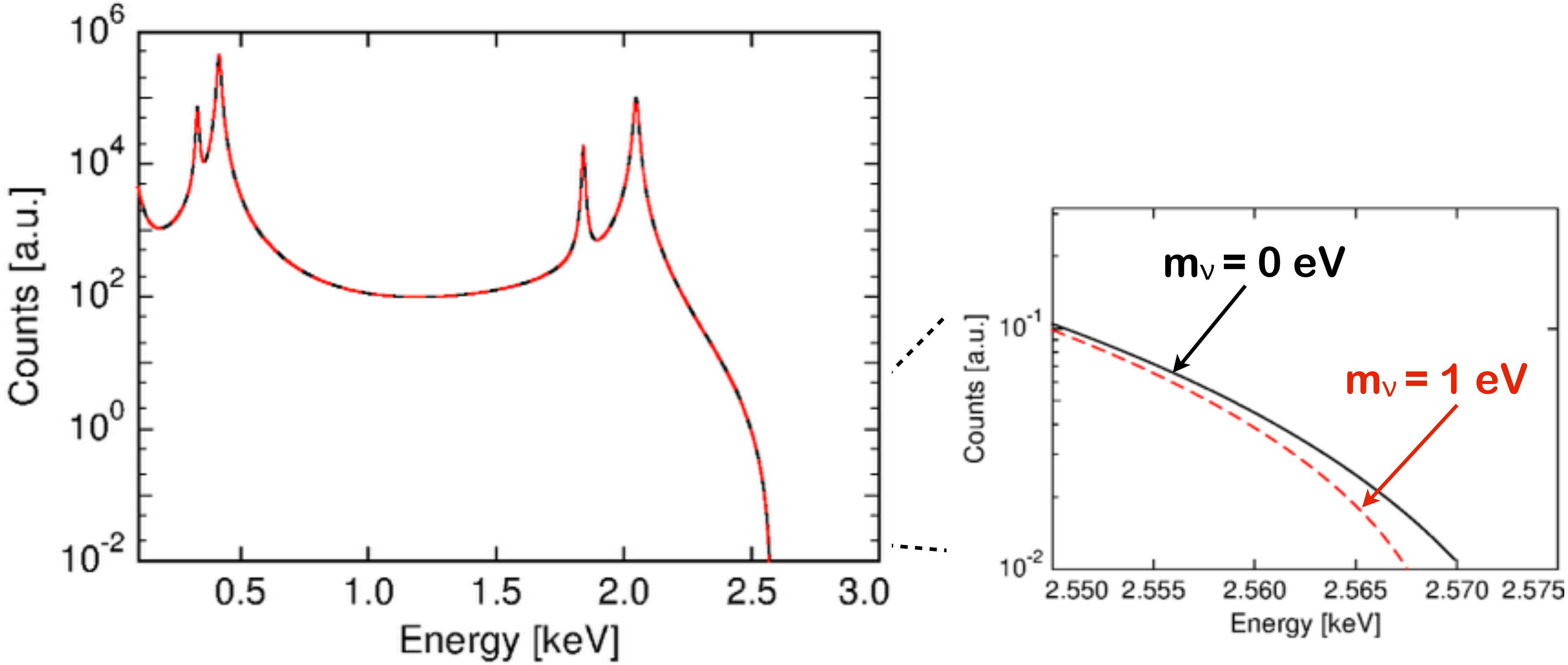




10 meters across

10^{-11} mbar vacuum

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

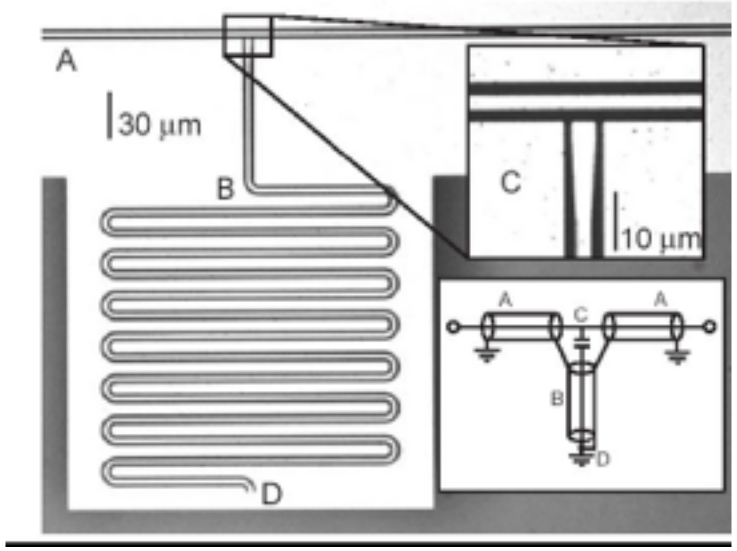


New ~~kid~~ isotope on the block:

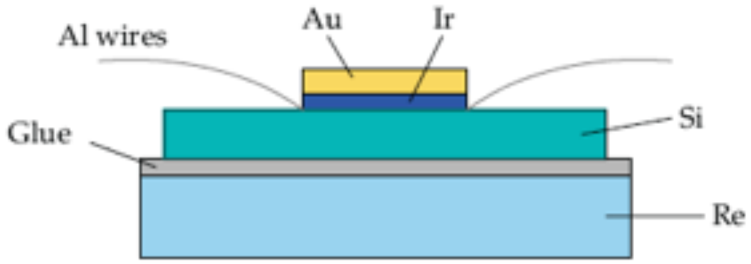
Electron Capture

The HOLMES Experiment

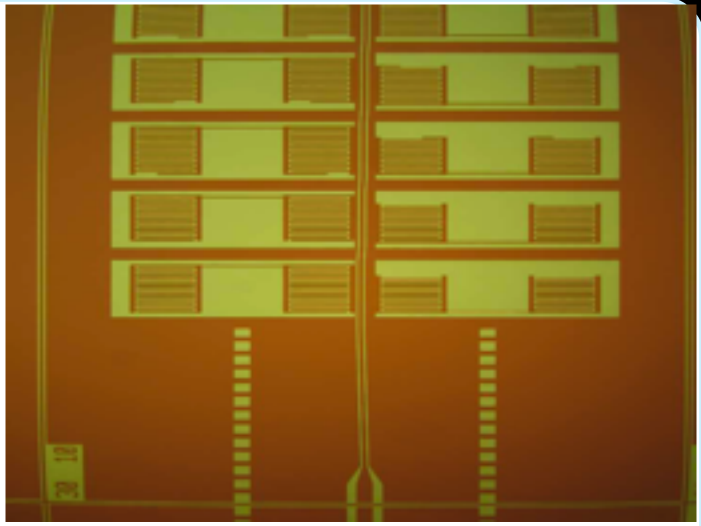
Technologies:

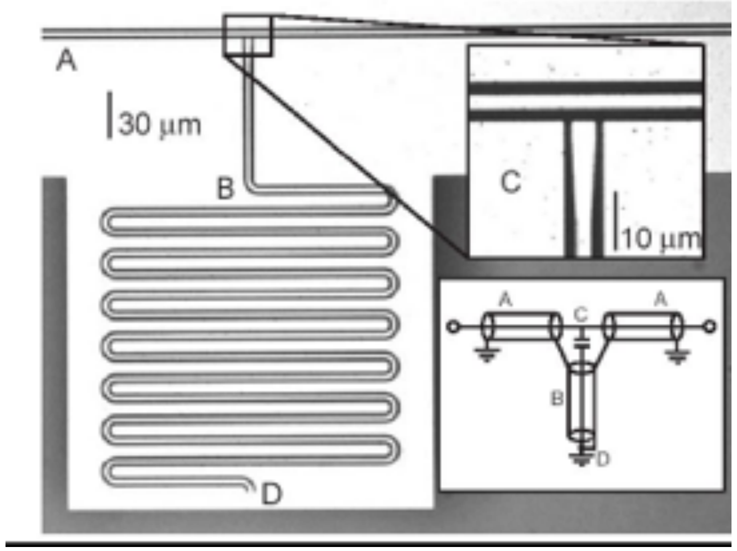


Superconducting Resonators



Transition Edge Sensors



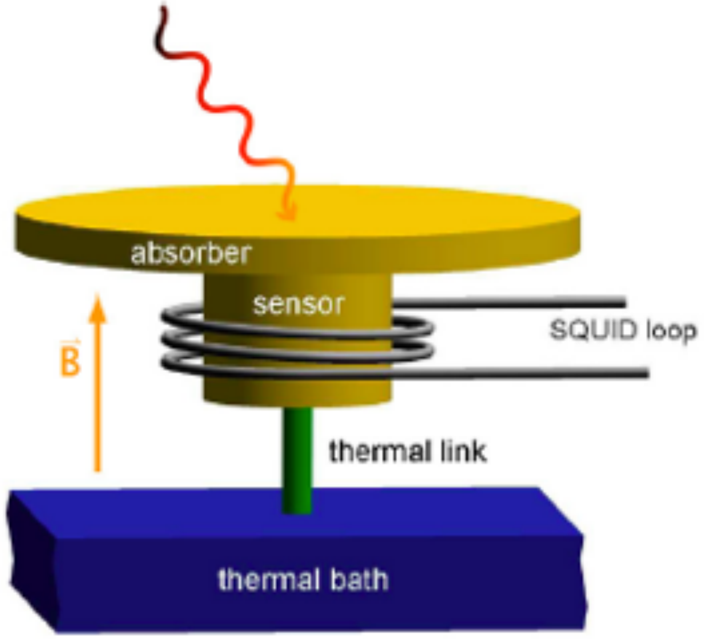


HOLMES

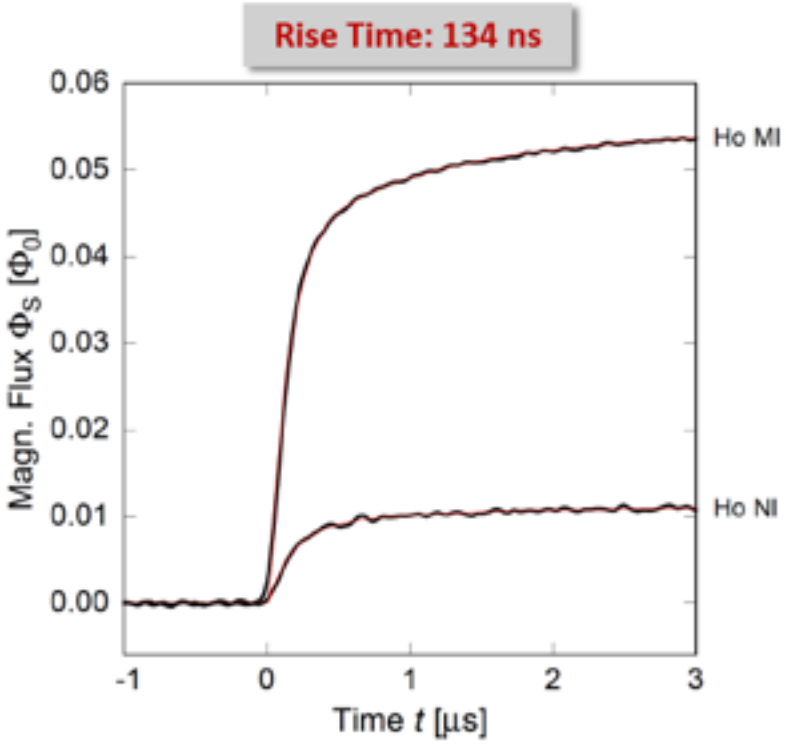
- MARE (Phase I) explored various technology approaches, such as Transition-Edge Sensors (TES) and Microwave Kinetic Inductance Detectors (MKIDs).
- Successful extraction of Ho^+ ions for metal production and implantation onto detectors.
- Successful funding received for one thousand channel Ho detector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

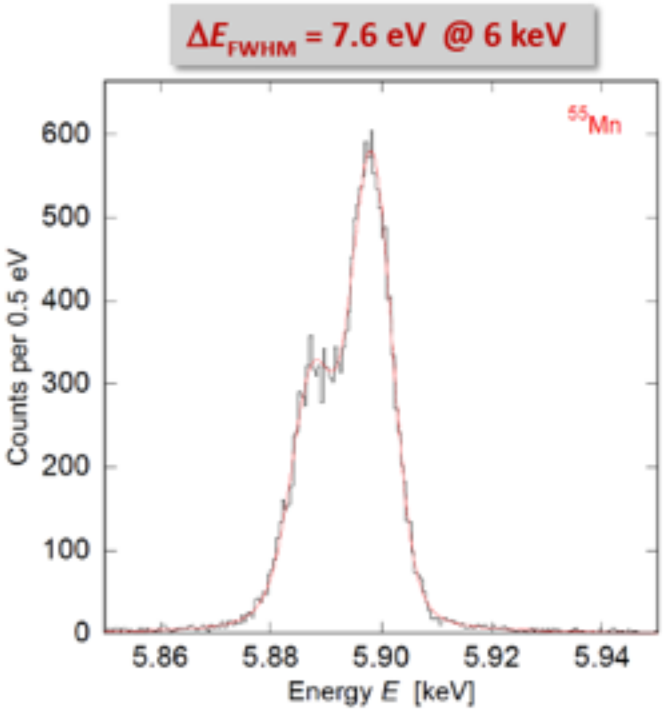
The ECHo Experiment

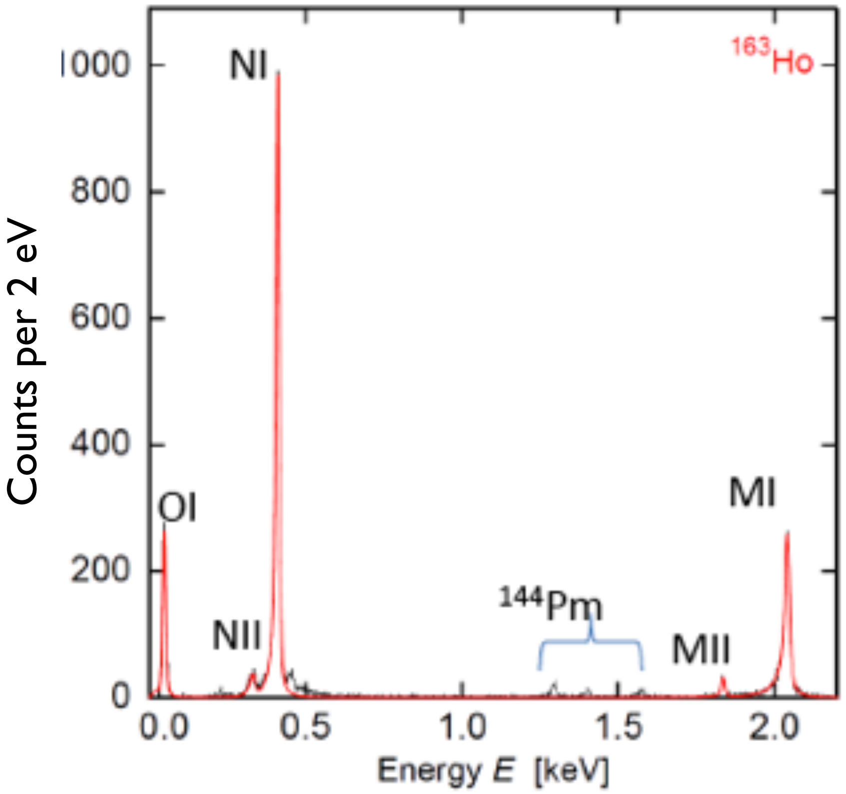
Technology:



Metallic Magnetic Calorimeters

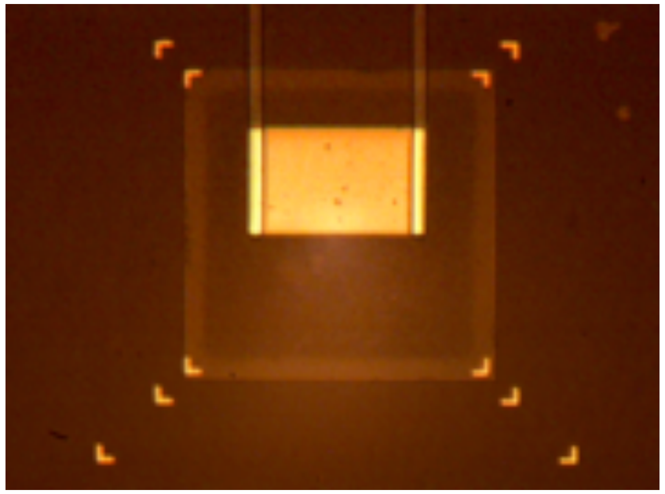

Rise Time: 134 ns


ΔE_{FWHM} = 7.6 eV @ 6 keV



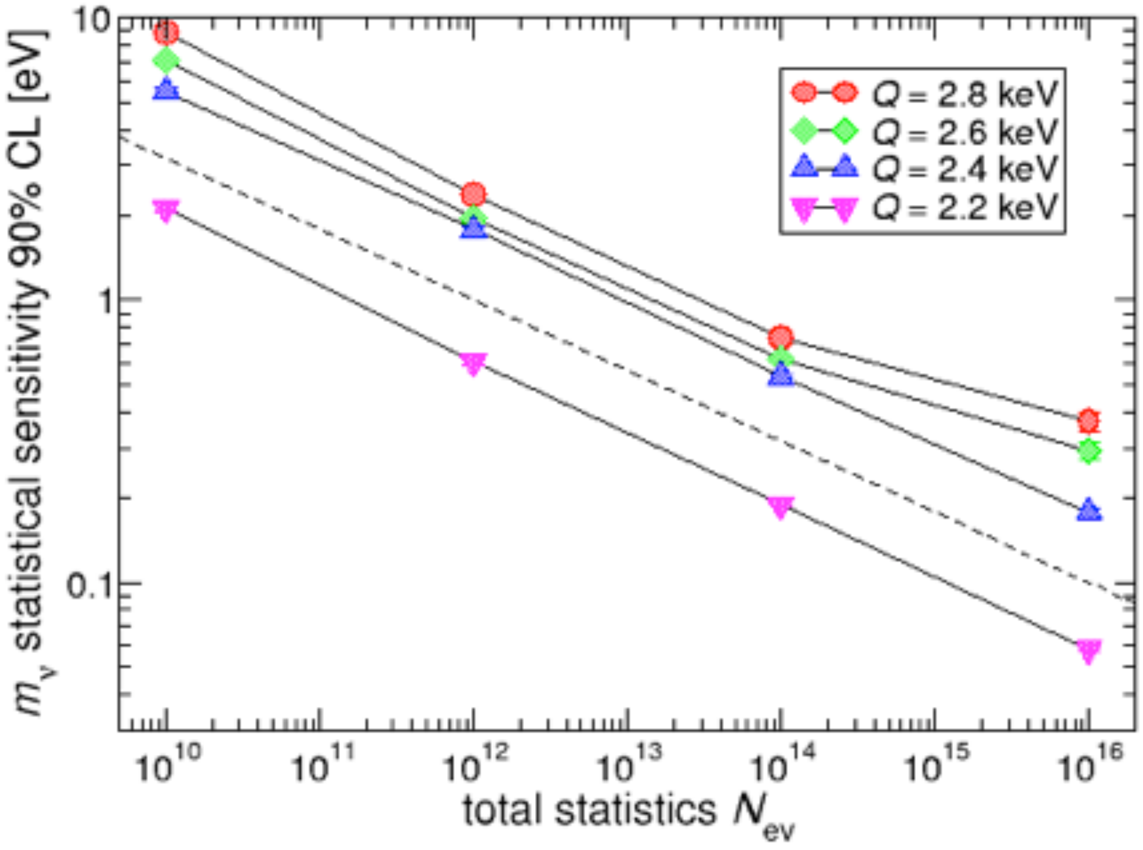
- The ECHo experiment uses metallic magnetic calorimeters to achieve goals.
- Fast rise times and good energy resolutions and linearity demonstrated.
- Endpoint measured at 2.80 ± 0.08 keV.

Advantages & Challenges



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

Challenges:



Source Activity

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

Detector Response

$\Delta E_{FWHM} < 10$ eV
$\tau_{risetime} < 1$ µs

- 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

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

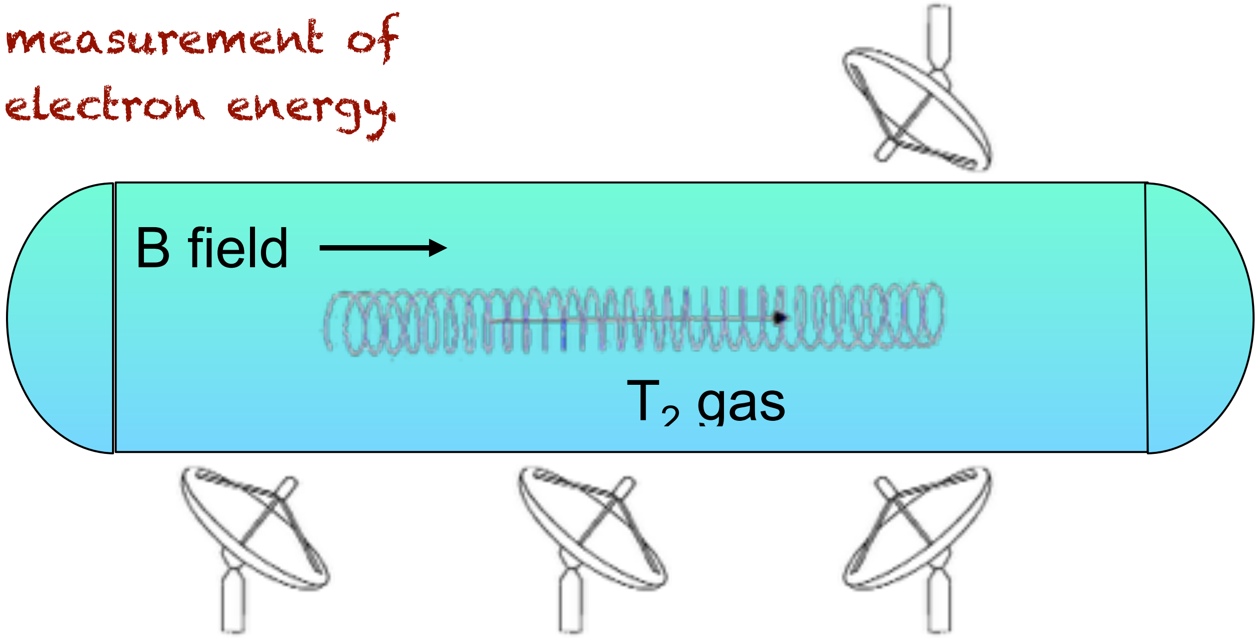
"Never measure anything but frequency."

A. L. Schawlow

- Use cyclotron frequency to extract electron energy.

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

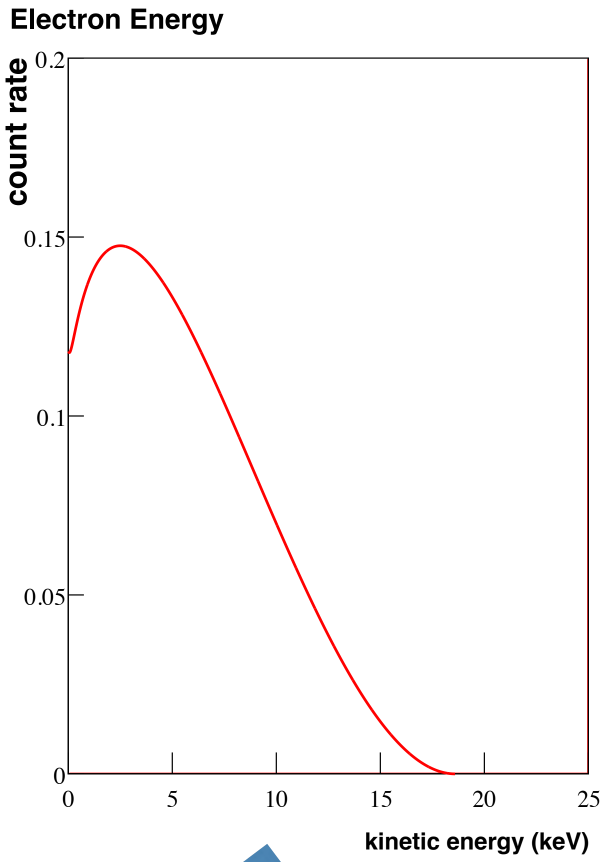
- Non-destructive measurement of electron energy.



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

Unique Advantages

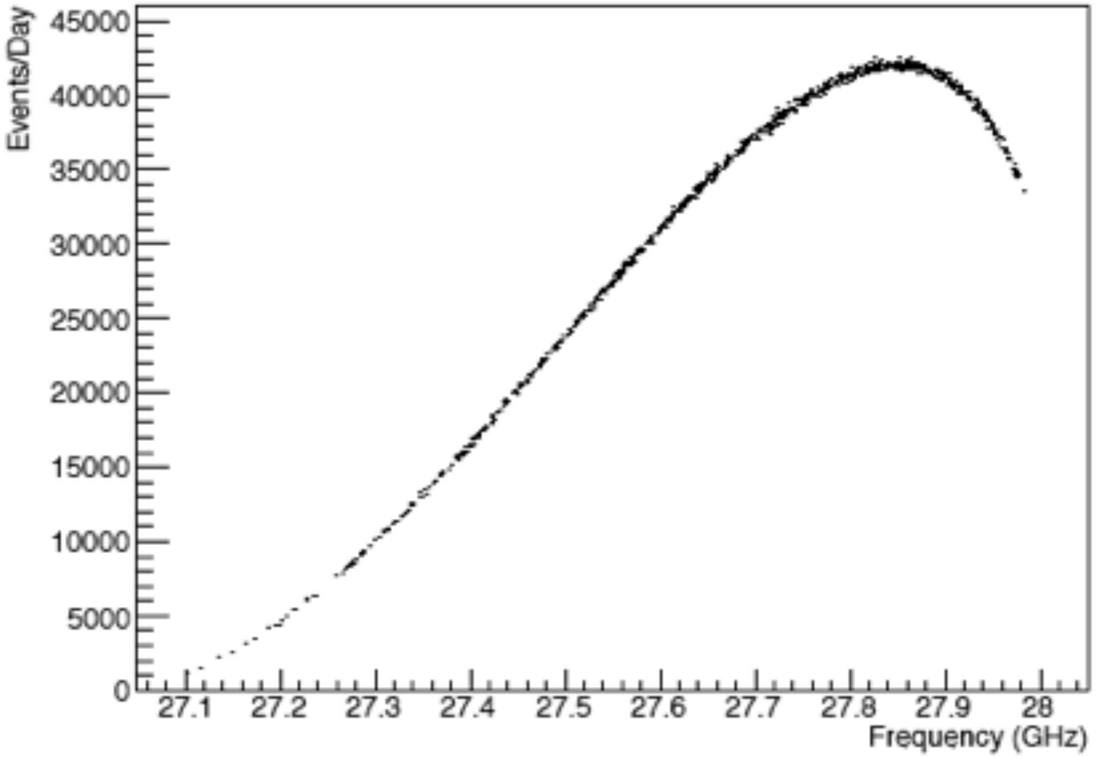
- **Source = Detector** (no need to separate the electrons from the tritium)
- **Frequency Measurement** (can pin electron energies to well-known frequency standards)
- **Full Spectrum Sampling** (full differential spectrum measured at once, large leverage for stability and statistics)



Beta spectrum

Cyclotron Frequency

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



Beta (frequency) spectrum

…and Challenges

- Power Emitted

  Less than 1 fW of power radiated (depends on antenna geometry) is challenging.

- Confinement Period

  One needs time to make sufficiently accurate measurement (> 10 μs).

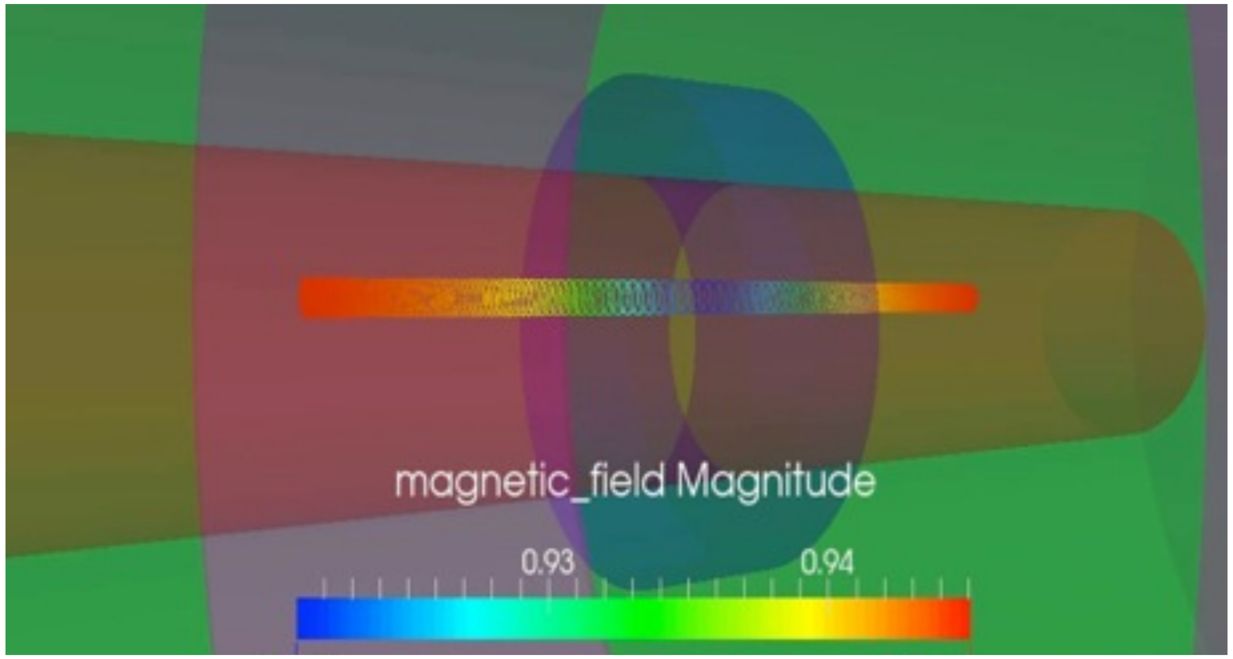
  Employ magnetic bottle for trapping.

- Full Spectrum

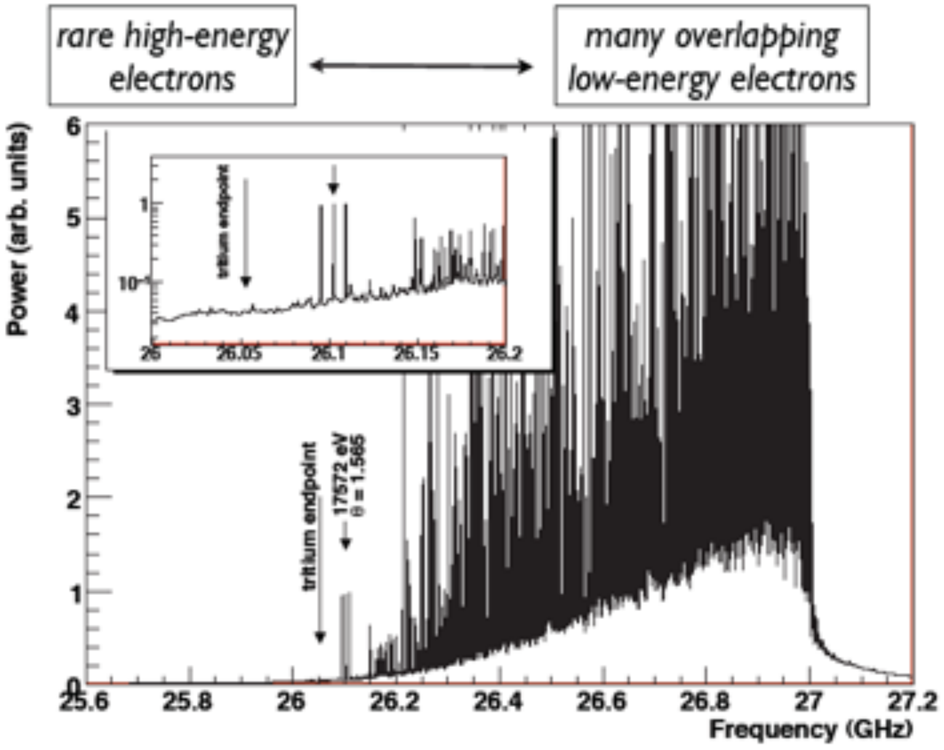
  The full spectrum is available. Fortunately, linearity of frequency space helps separate regions of interest.

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

(Free) Radiative Power Emitted



Simulation of electron motion in magnetic bottle



100,000 tritium decays in 30μs

Simulation of beta (frequency) spectrum

Project 8 Collaboration

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Pacific Northwest National Lab

* indicates graduate student

A Phased Approach

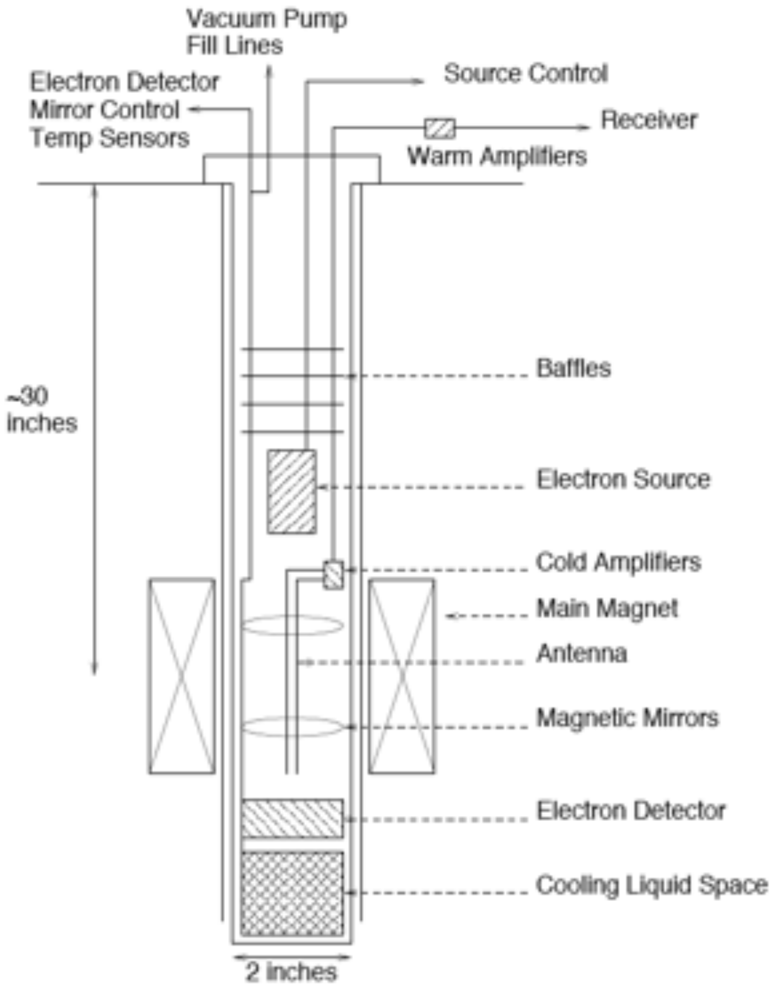
Given the novelty of the project, we are pursuing a phased approach toward neutrino mass measurements:

	Timeline	Scientific Goal	Source	R&D Milestone
Phase I	2010-2014	Proof of principle; Kr spectrum	83m	Single electron detection
Phase II	2014-2016	T-He mass difference	T	Tritium spectrum; calibration and error studies
Phase III	2016-2018	0.2 eV scale	T	
Phase IV	2018+	0.05 eV scale	T	High rate sensitivity

We have commenced Phase I, we are designing Phase II

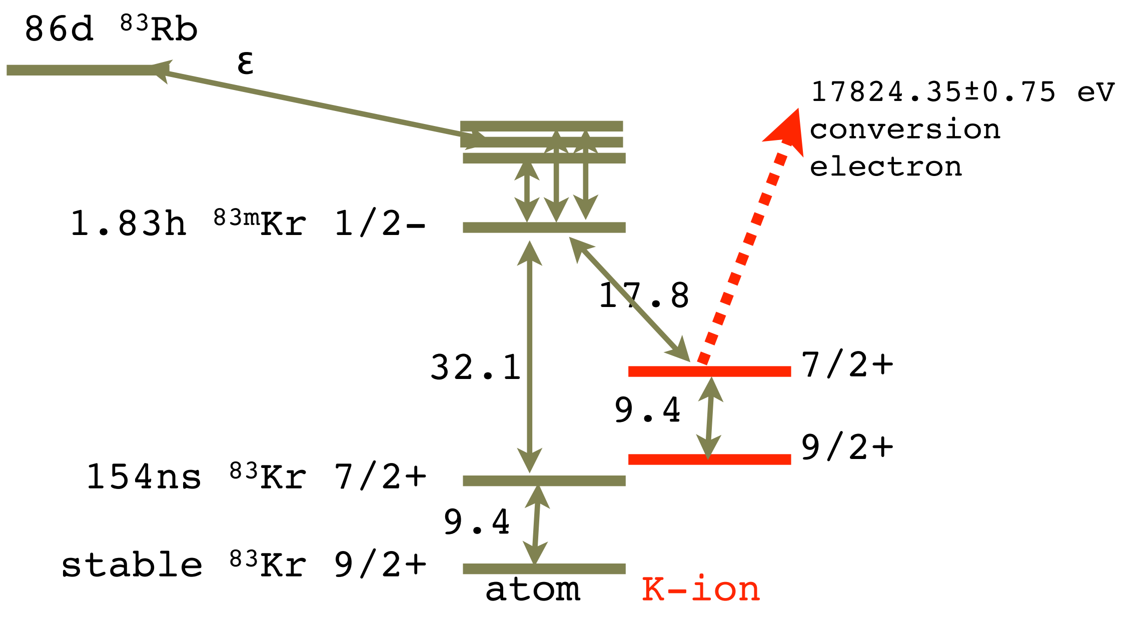
Basic Layout of Phase I

- Gas/Electron System
  Provides mono-energetic electrons for signal detection.
- Magnet System
  Provides magnetic field and trapping of electrons.
- RF Detection/Calibration System
  Detection of microwave signal.

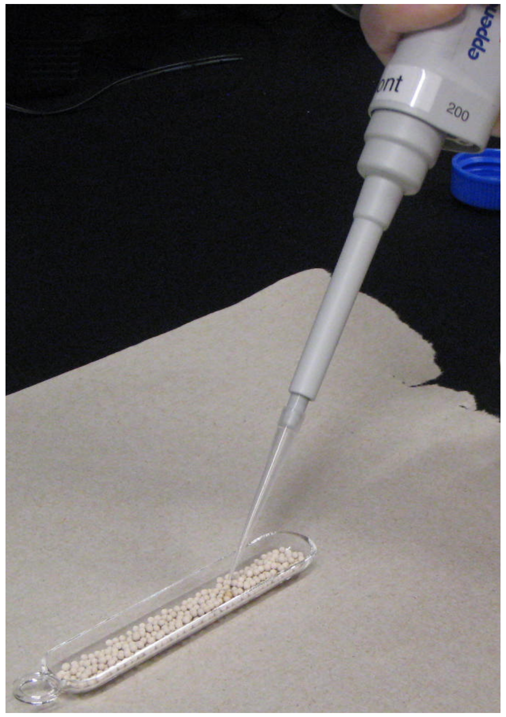


The Electron Source

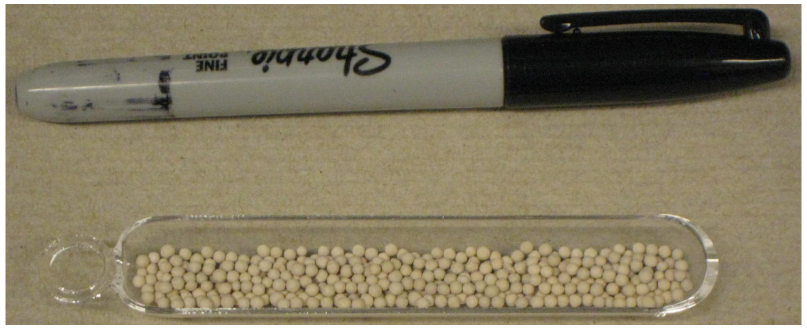
Initial Demonstration Source: ^{83m}Kr



Conversion electrons at
30 and 32 keV also exist.



Zeolite
loading



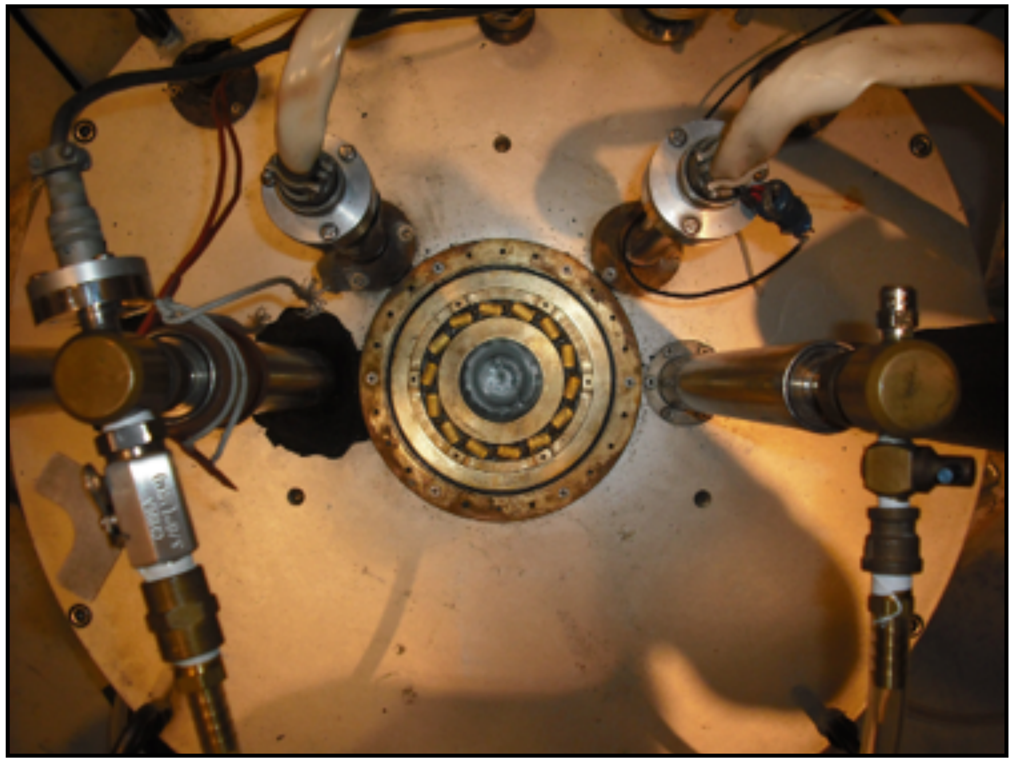
Mono-energetic gaseous electron source

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

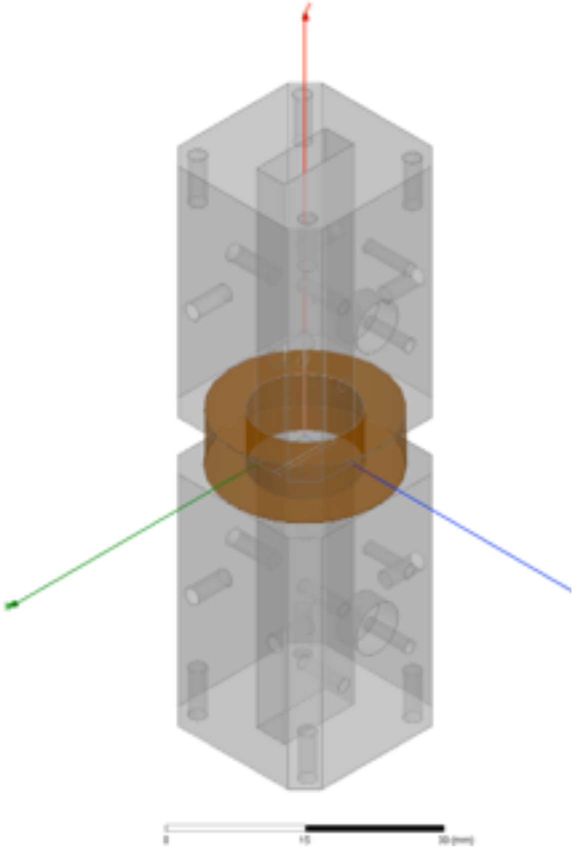
First phase (single electron detection) requires single electron detection.

Using ^{83m}Kr (^{83}Rb implanted in zeolite beads) as source

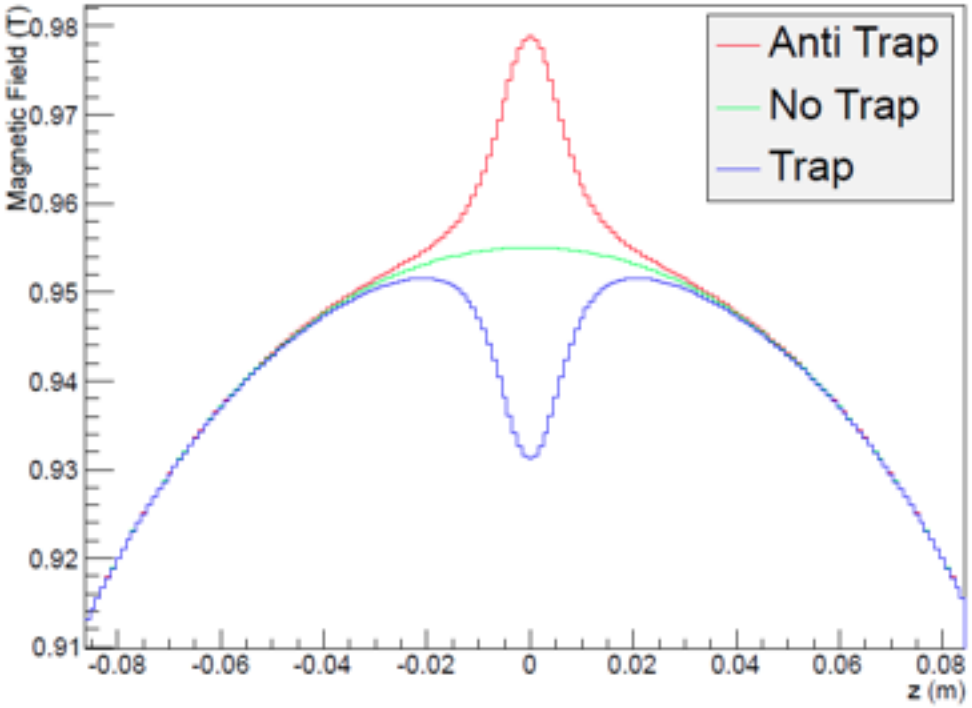
The Magnet System



Main Superconducting Magnet
1 T field (27 GHz)



~100 G Trapping coil



Trapping / Anti-trapping configuration

Using 0.94 Tesla field, where signal occurs at ~26 GHz.

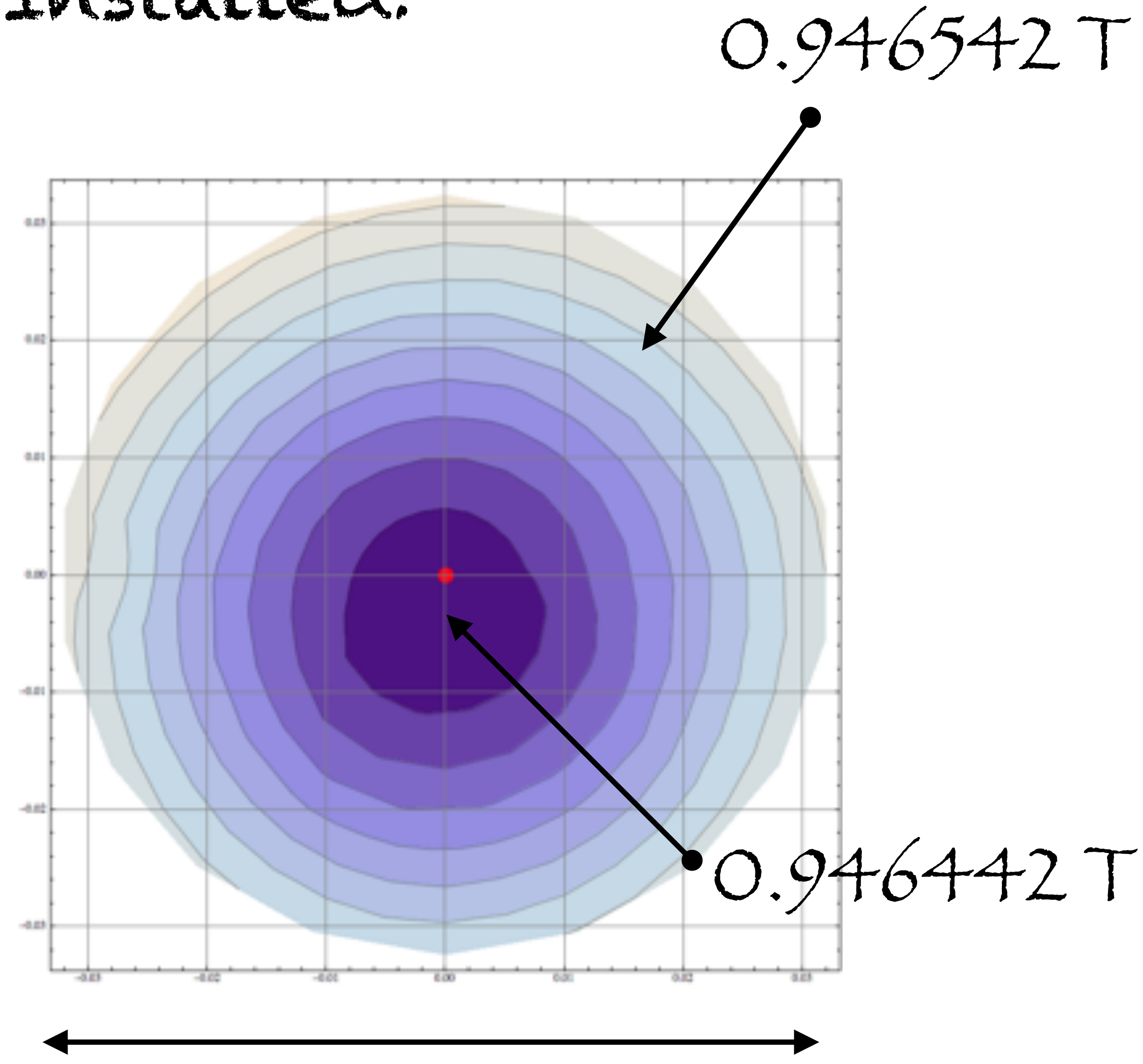
Electrons are trapped in a small "magnetic bottle" provided by a small trapping coil.

Trapping coil provides means to observe electron for sufficient time to extract signal.

New NMR Magnet Installed!

Old
“Green Giant”

New Bruker
NMR Magnet



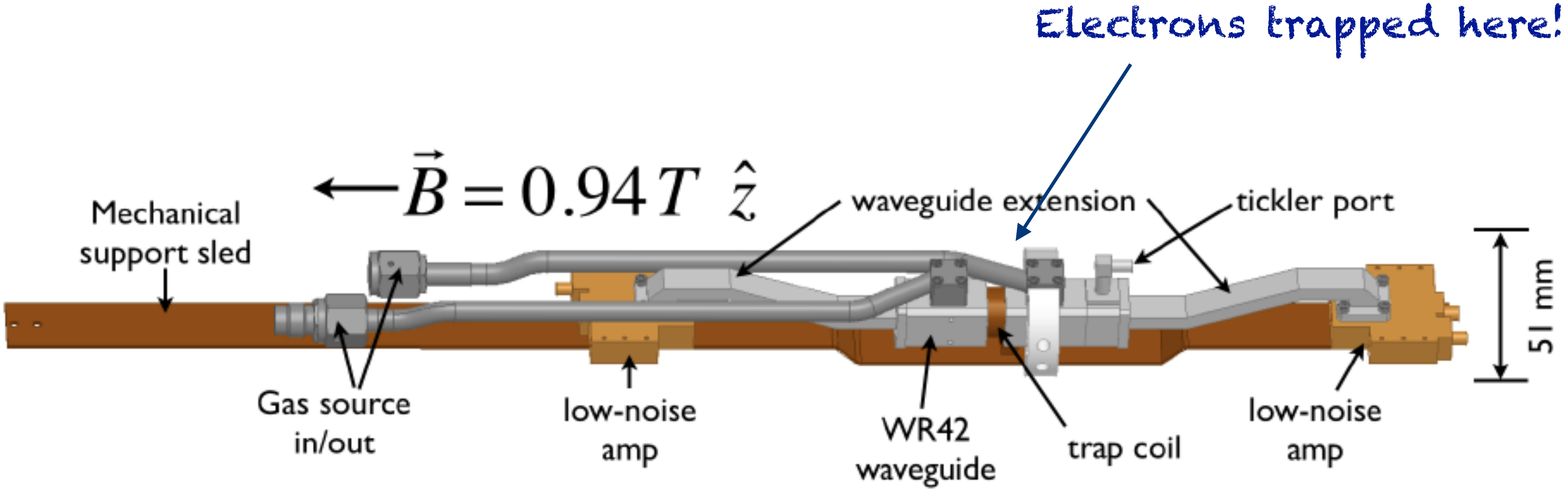
6 cm

As of 2014, new NMR magnet installed for prototype.

Magnet much easier to use and maneuver for testing.

Improved field homogeneity and stability.

The RF Detection System

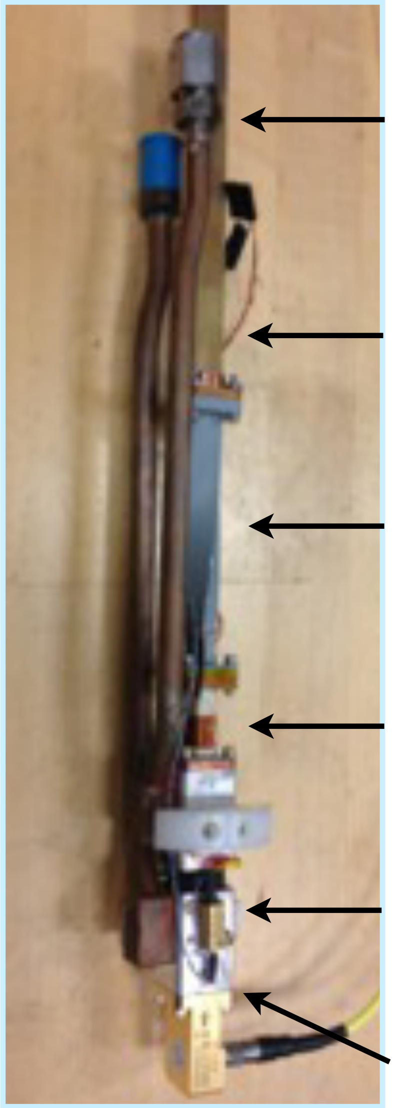


Basic Layout of "Detector"

Fundamental frequency is carried via WR-42 waveguide to low-noise amplifiers.

Signal is mixed down to MHZ range, further amplified, and then digitized to data for analysis.

The RF Detection System



Gas source in/out

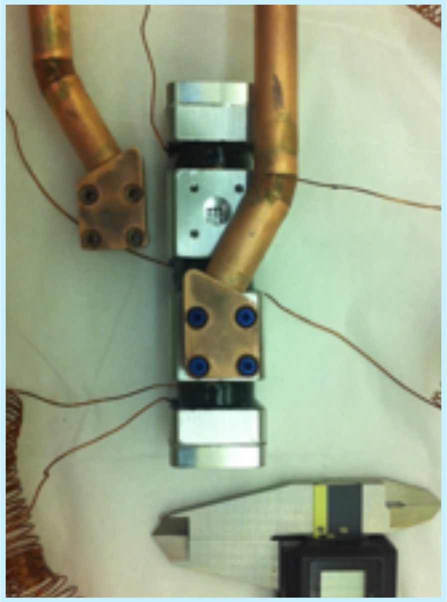
WR-42 waveguide

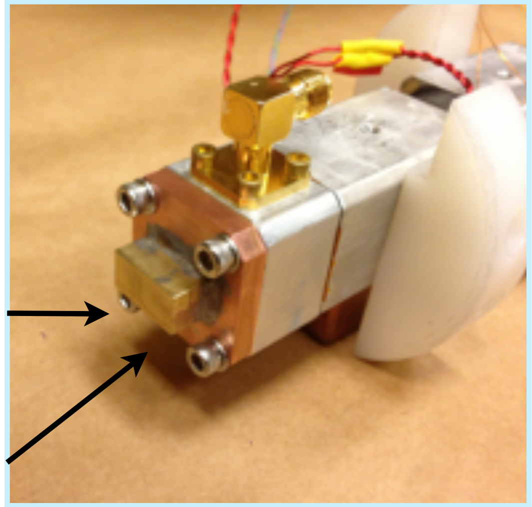
WR-42 twist

DPPH source

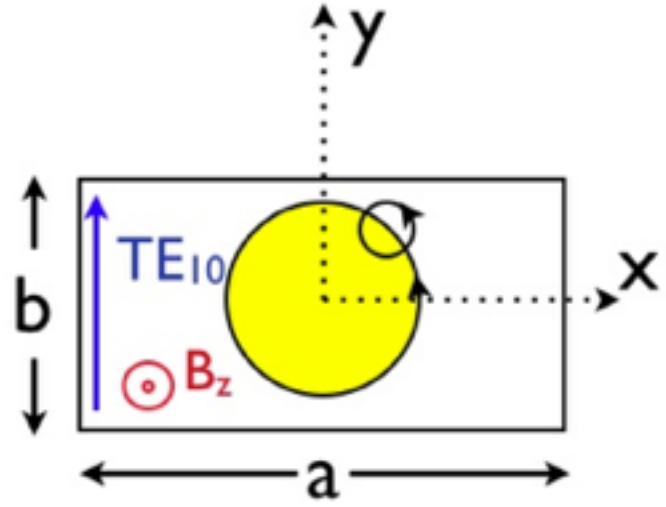
Trapping section

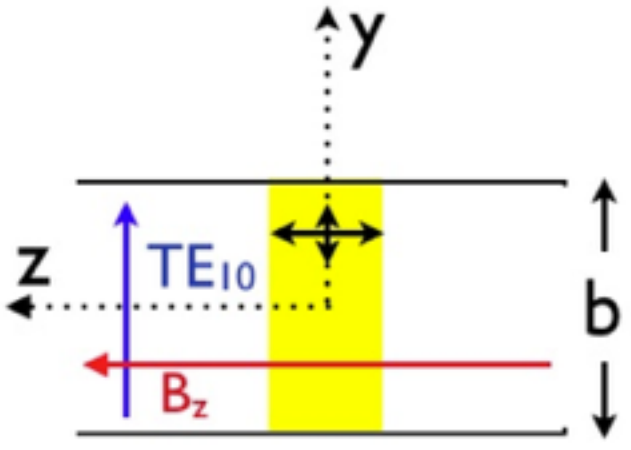
Tickler port





RF waveguide used as main chamber

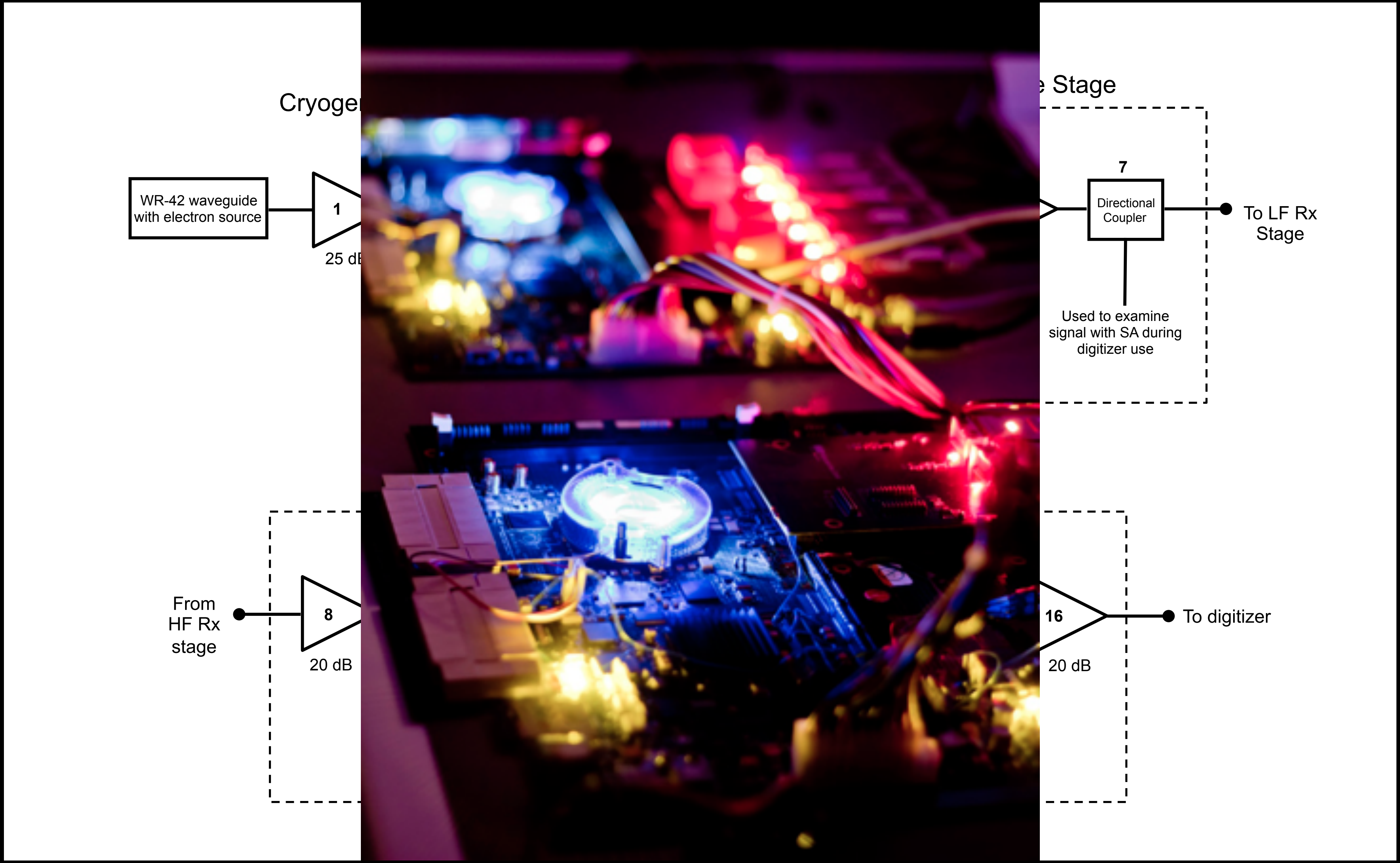




Fundamental frequency is carried via WR-42 waveguide to low-noise amplifiers.

Signal is mixed down to MHZ range, further amplified, and then digitized to data for analysis.

The Signal Chain & Digitization

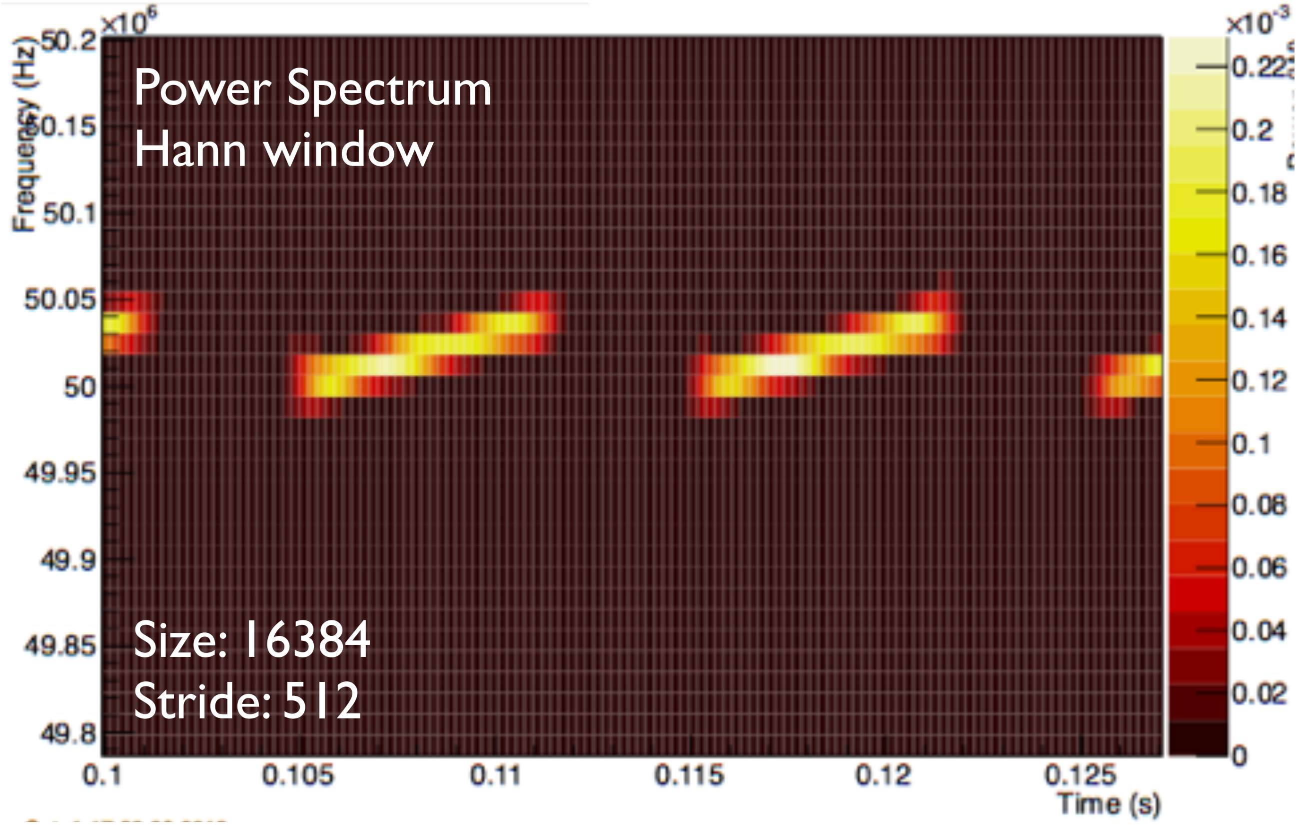


Fundamental frequency is carried via WR-42 waveguide to low-noise amplifiers.

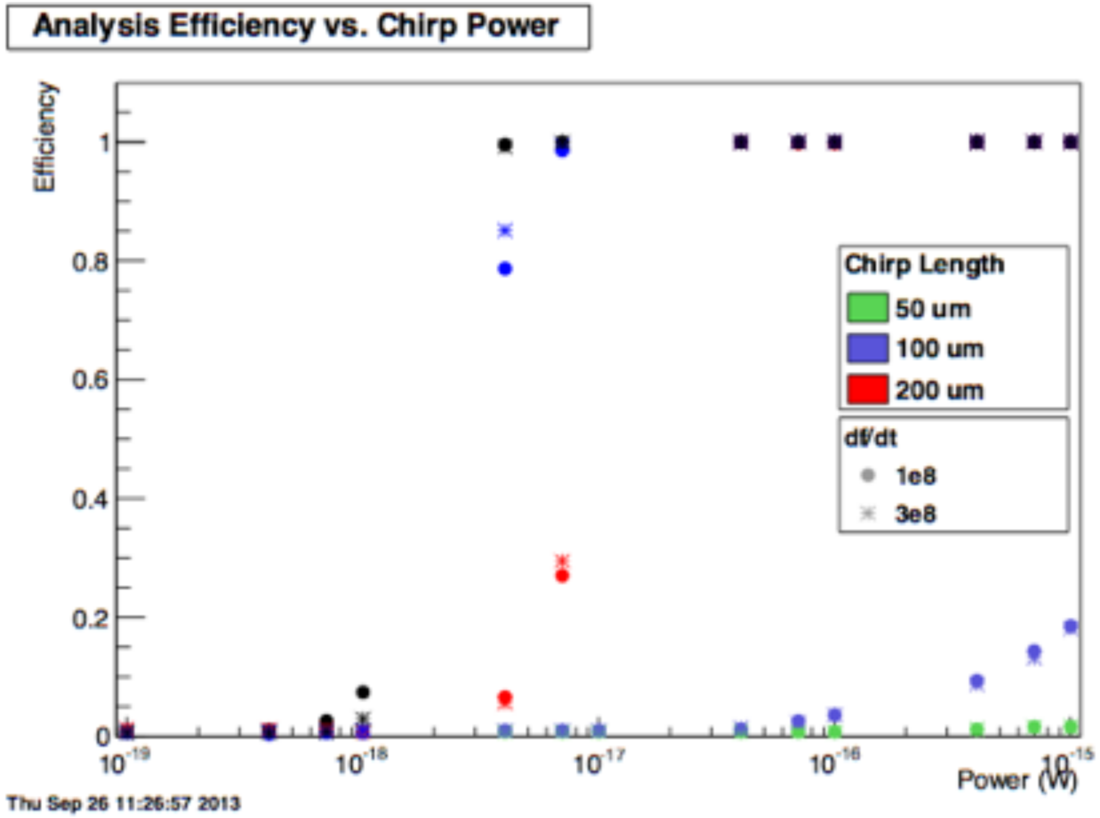
Signal is mixed down to MHZ range, further amplified, and then digitized to data for analysis.

Developing CASPER-ROACH system for future triggering and data processing.

What Does a Signal Look Like?



Simulated "Chirp" Signal



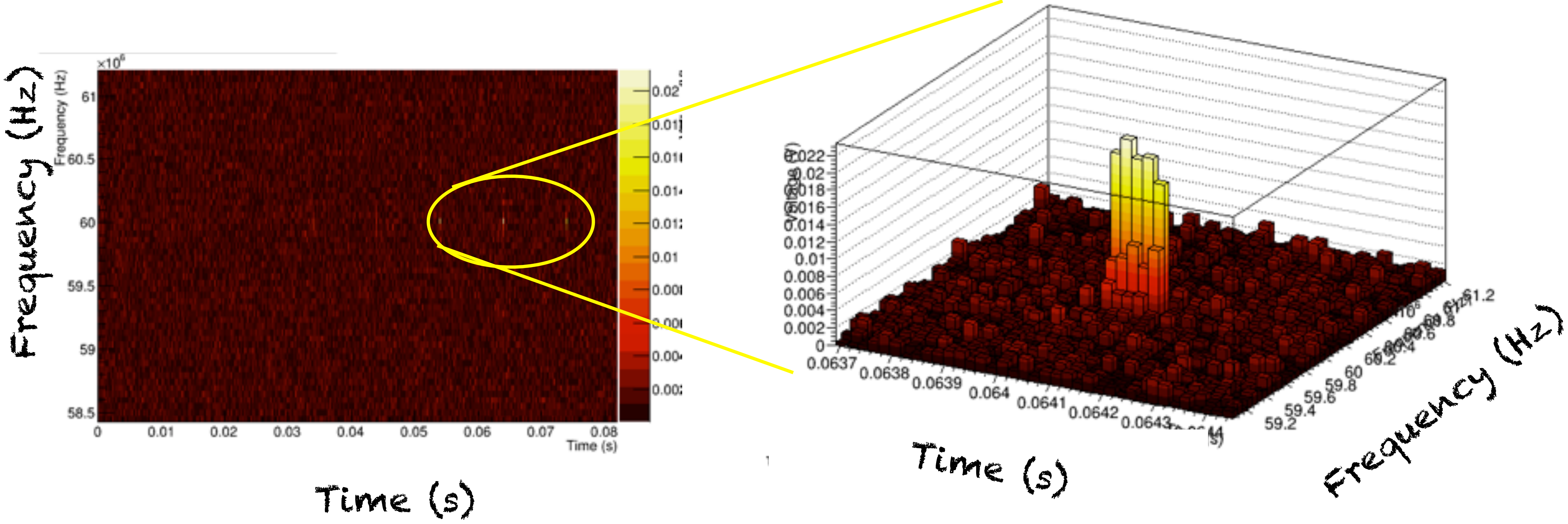
Efficiency for finding candidates

Signal exhibits itself as a short duration pulse ("chirp") in frequency.

Signal is digitized in frequency/time space and scanned for clusters.

Sensitivity studies demonstrate excellent efficiency down to 10^{-17} fW for 50 μs signals.

Calibrating the Signal



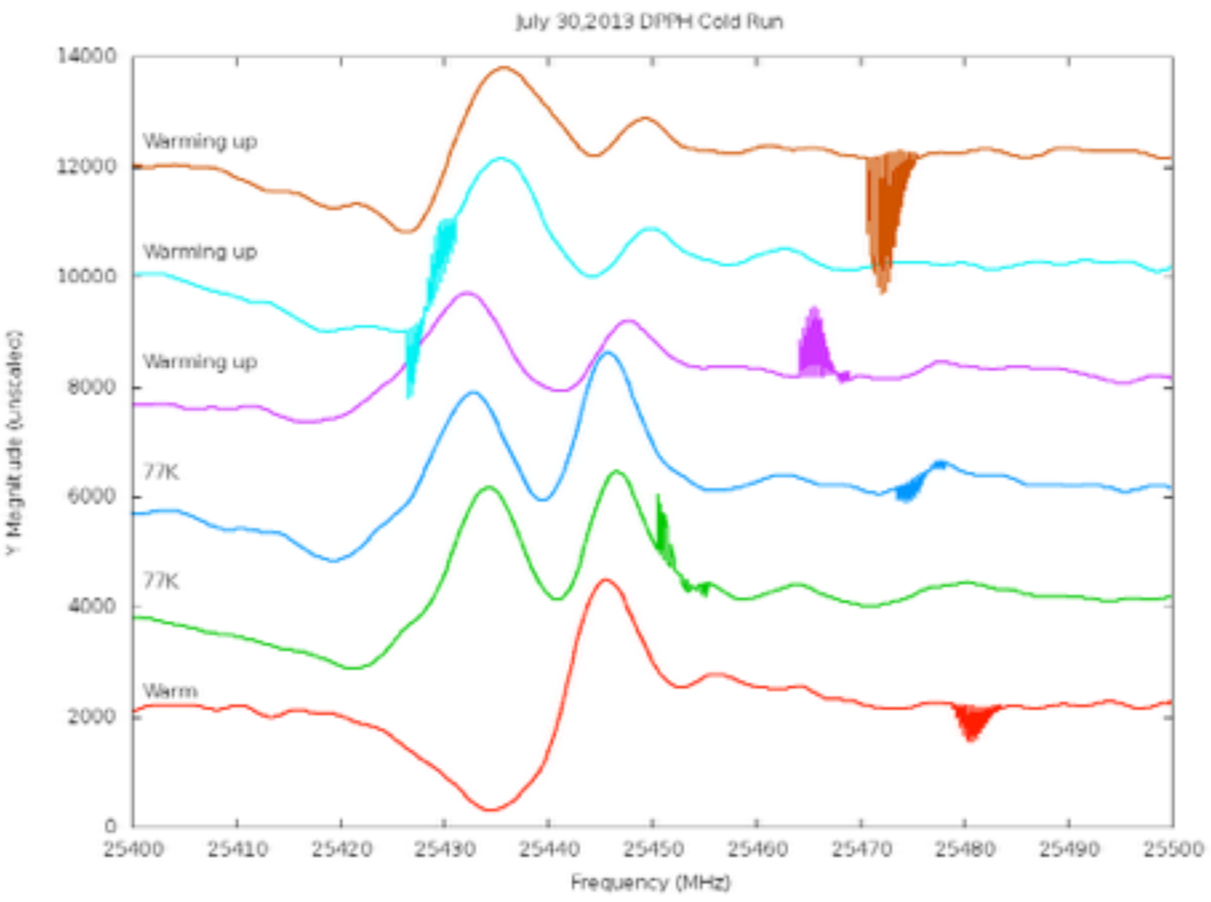
Injected Fake Signal

We have the ability to insert artificial chirps and tones into our cavity.

Using an RF switch, the fake-signal can be "pulsed".

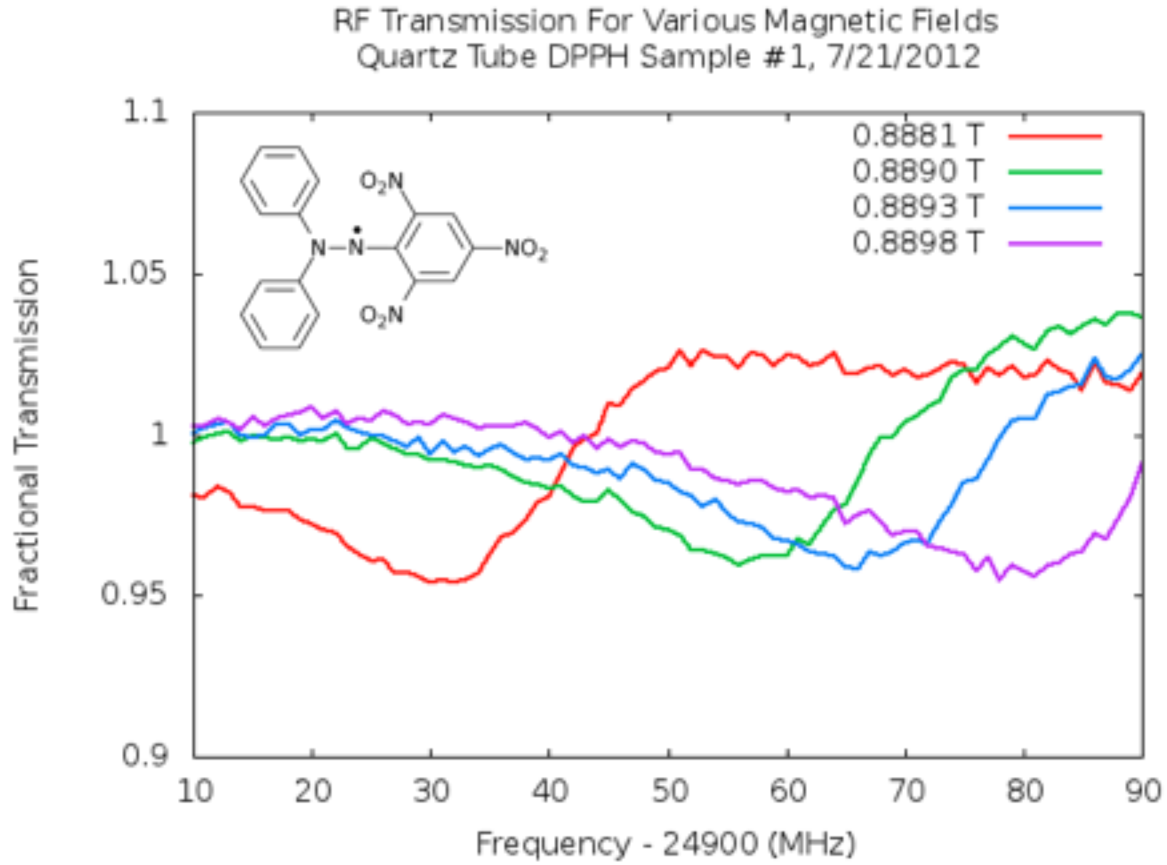
Tests system's sensitivity to amplitude and duration.

Radio-frequency (RF) Calibration



In-situ measurement of magnetic field
via DPPH absorption

ESR Measurement



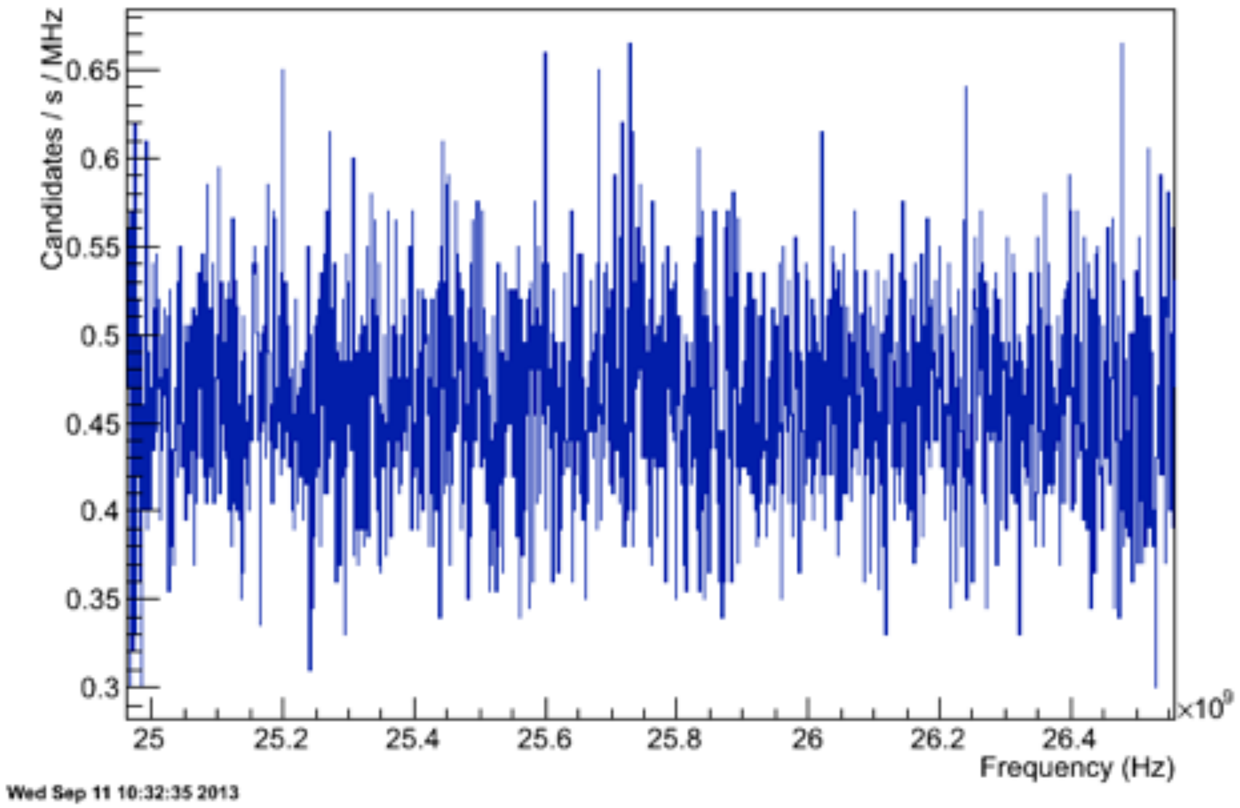
Magnetic field monitoring

Can use absorption of RF line from ESR to monitor field strength in-situ.

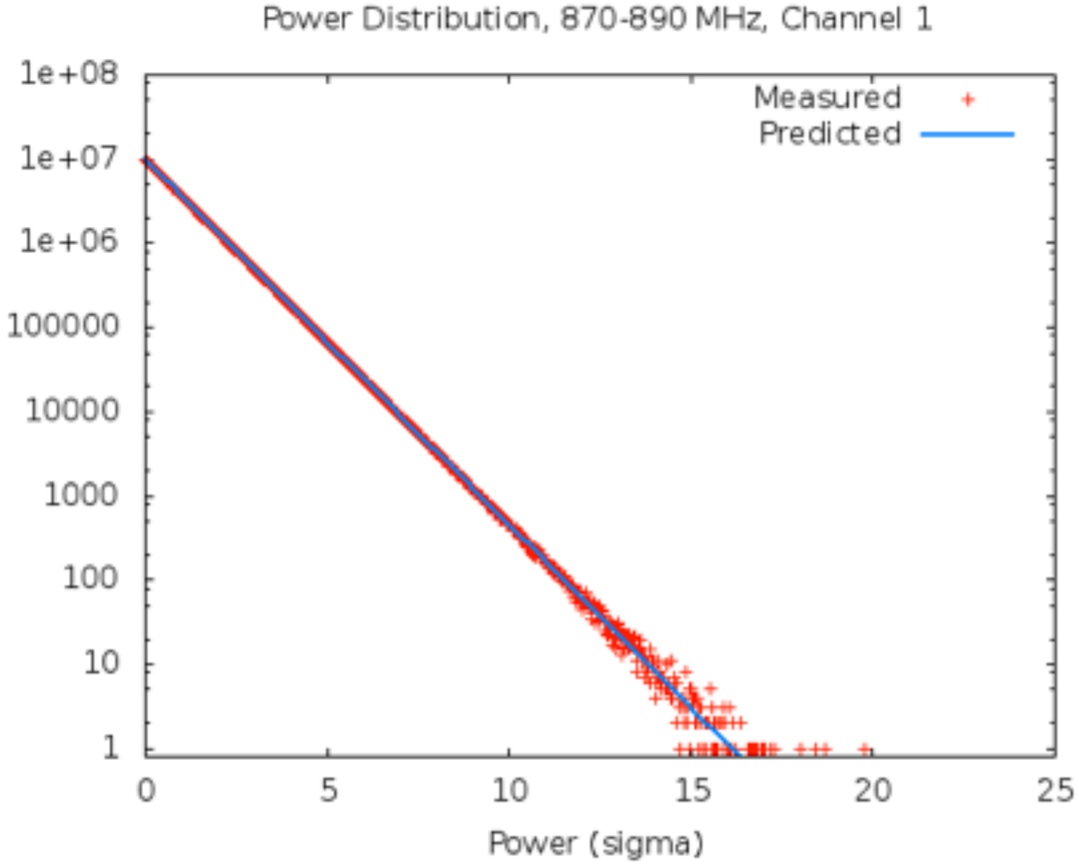
Using DPPH source for testing of RF system + magnetic field monitoring.

System works well in new NMR magnet.

Testing System on the January Data



Candidate background spectrum

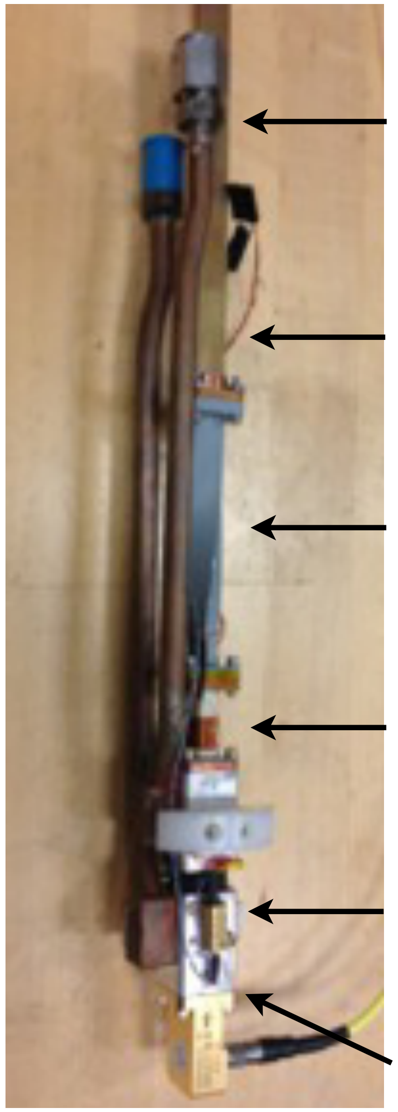


Thermal noise spectrum, January run (Not a fit)

Short (8 hour) test run taking in January, 2013.

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

Preparing for Run II



Gas source in/out

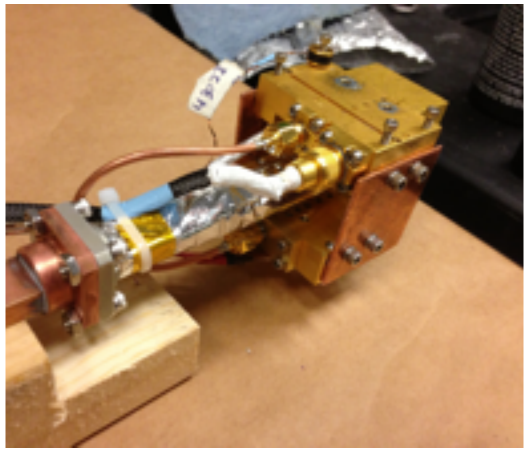
WR-42 waveguide

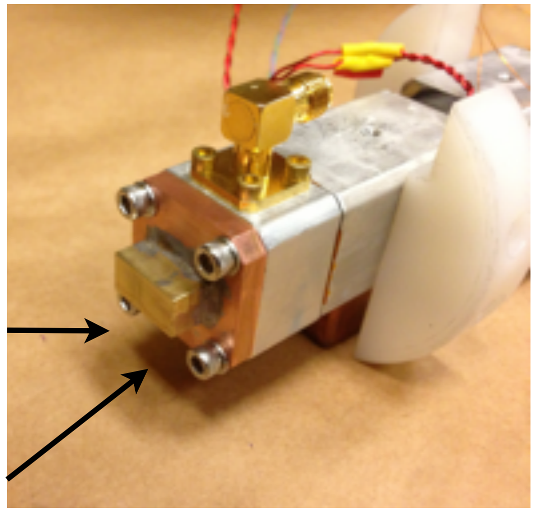
WR-42 twist

DPPH source

Trapping section

Tickler port





System	Specification	Achieved
Magnetic Field	1 T Field 10	< few 10 DPPH Monitoring
Gas System	10	< 10 PIPS detector
Noise Temperature	T	T
Sensitivity Analysis	SNR > 10 for 0.5 fW signal	SNR > 10 dB for 0.1 fW

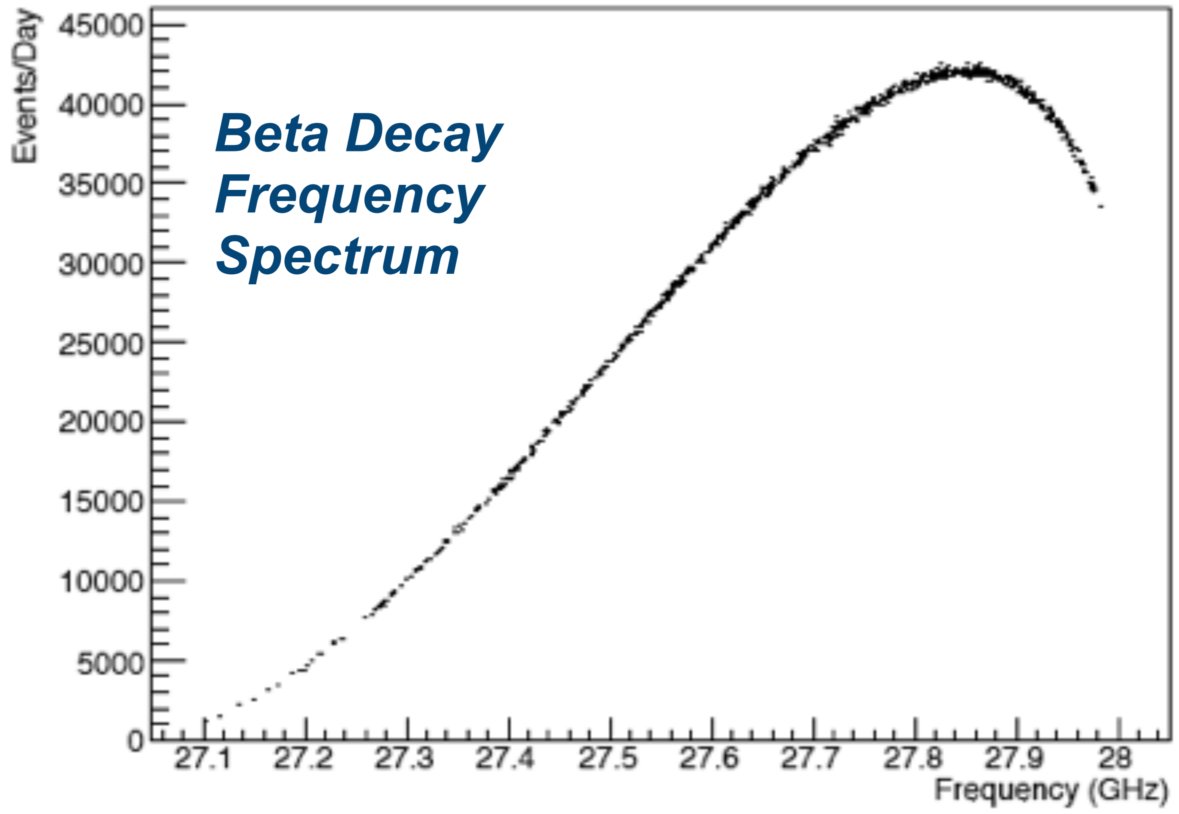
A new run is planned with a target noise temperature down to ~ 50K.
System undergoing commissioning now.

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

Attempting to
see the
inverted
scale...

Sensitivity to Neutrino Masses

- There are distinct advantages that are specific to frequency-based measurements:
- You get the entire spectrum (and background) at once.
- The background is extremely small:
    - There is no detector.
    - There might not even be any surfaces.
    - Cosmic ray interactions and radioactive backgrounds are interacting with a gas, very little target material.



$$\frac{dN}{dE_e} = 3rt(E_0 - E_e)[(E_0 - E_e)^2 - m_\nu^2]^{1/2}$$

Mass sensitivity depends on:

Target activity (volume x density)

Background

Field homogeneity

Lifetime of electron in trap (density)

Final states, doppler shifts, temperature

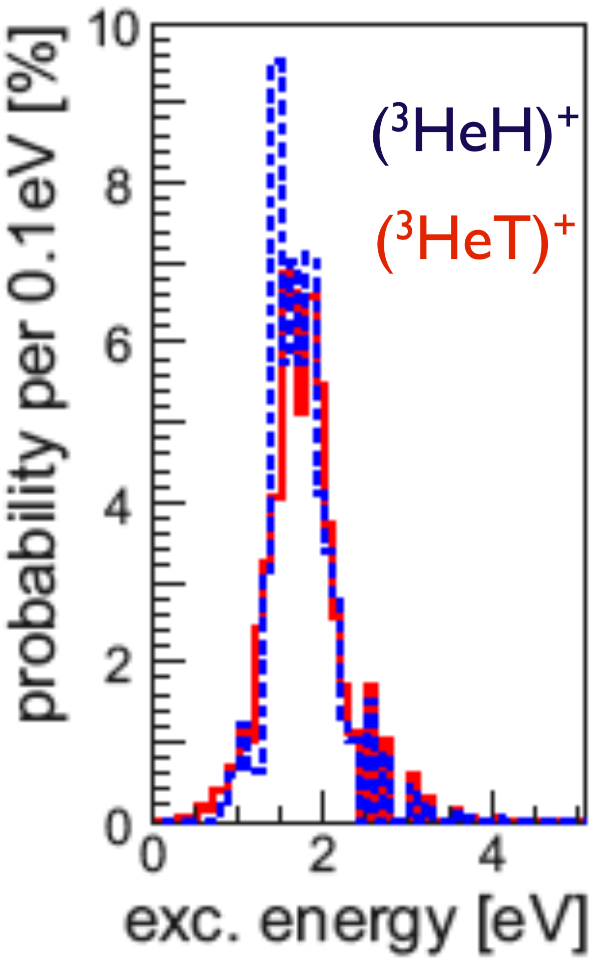
Moving Beyond the Degeneracy Scale

- 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)

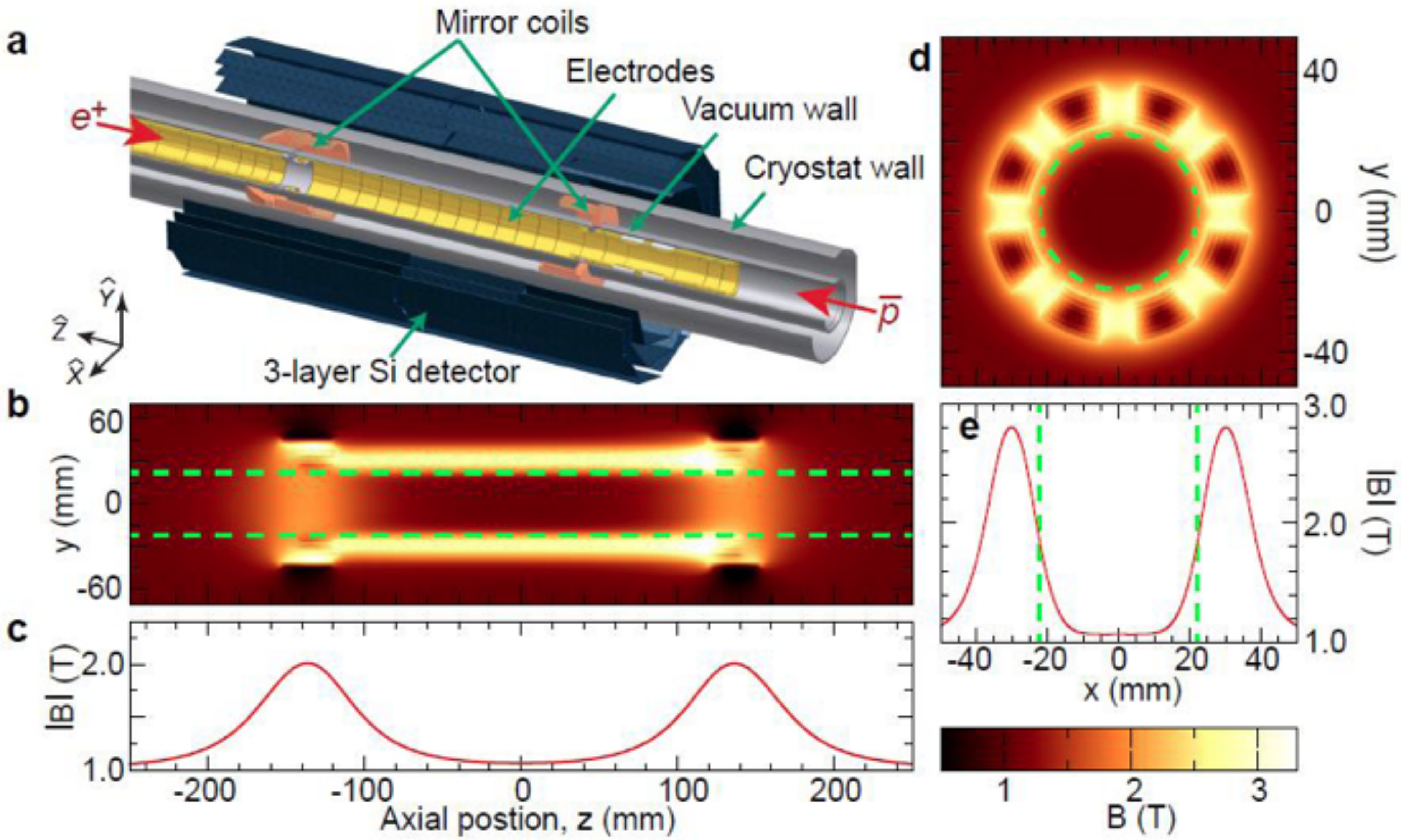
rotational

vibrational

Inherent 0.36 eV final state smearing



Trapping of Atomic Tritium



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

Similar design to anti-hydrogen trapping:

Solenoidal field for uniformity

Pinch coils for axial confinement

Ioffe multipoles for radial confinement

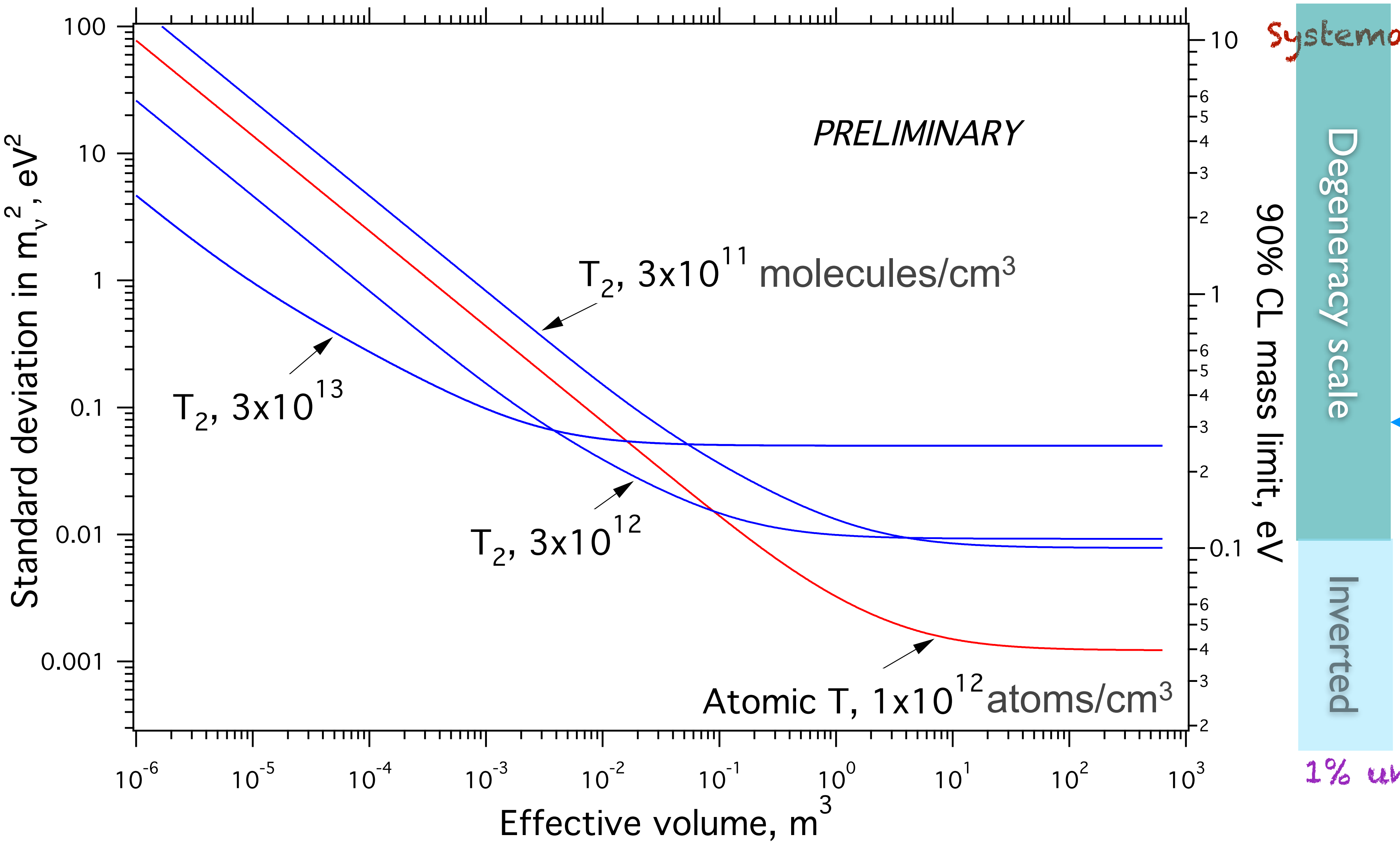
Cooling polarized tritium down to ~ 1K is necessary (and the main challenge)

In order to achieve atomic tritium purity, it is necessary to cool and trap polarized atomic tritium in both a radial and axial magnetic trap (Ioffe-Pritchard traps).

Technique quite similar to hydrogen BEC (MIT) and anti-hydrogen trapping (ALPHA).

Densities low, so recombination is highly suppressed.

Projected Sensitivity (Molecular & Atomic)



Systematics include:

Statistical uncertainties
(1 year run)

Final state interactions

Volume ≈ 0.05 m^3

Thermal broadening

(≈ 70 mCi)

Scattering

Volume ≈ 5 m^3

Background

(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.

Degeneracy and Beyond...

Spectroscopy (KATRIN)

Technique PROVEN. State-of-the-art.

Experiment soon to commence with 0.2 eV reach.

Integral measurement with TOF possibility.

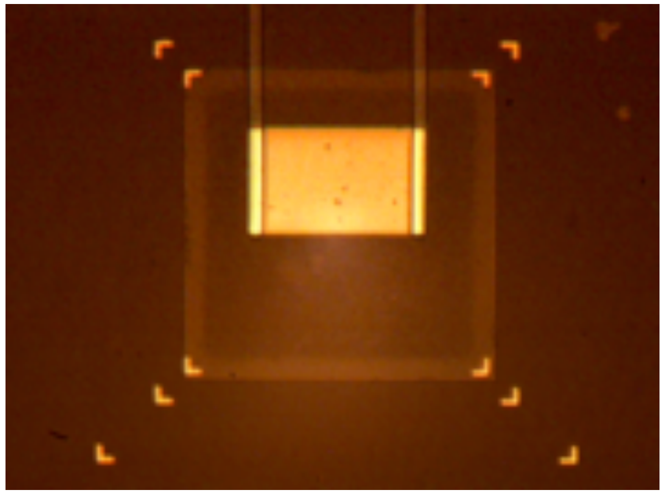
$$T_2 \rightarrow (T \cdot {}^3He^+) + e^- + \bar{\nu}_e$$

Calorimetry (HOLMES & ECHO)

Technique highly advanced.

New experiment(s) planned to reach 0.1 eV scale.

Statistics & systematics next hurdle.



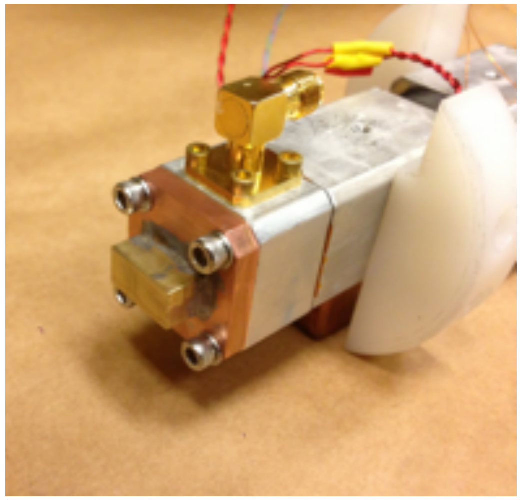
$$^{163}Ho + e^- \rightarrow {}^{163}Dy^* + \nu_e$$

Frequency (Project 8)

Technique in R&D phase, with results soon.

Potential of scalability and exploring atomic sources to inverted scale.

Need to establish the limits of the technique.

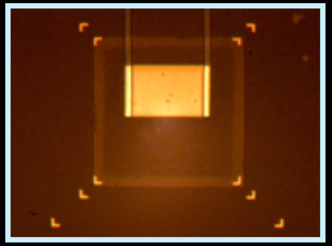


$$^3H \rightarrow {}^3He^+ + e^- + \bar{\nu}_e$$

... but the road is long.

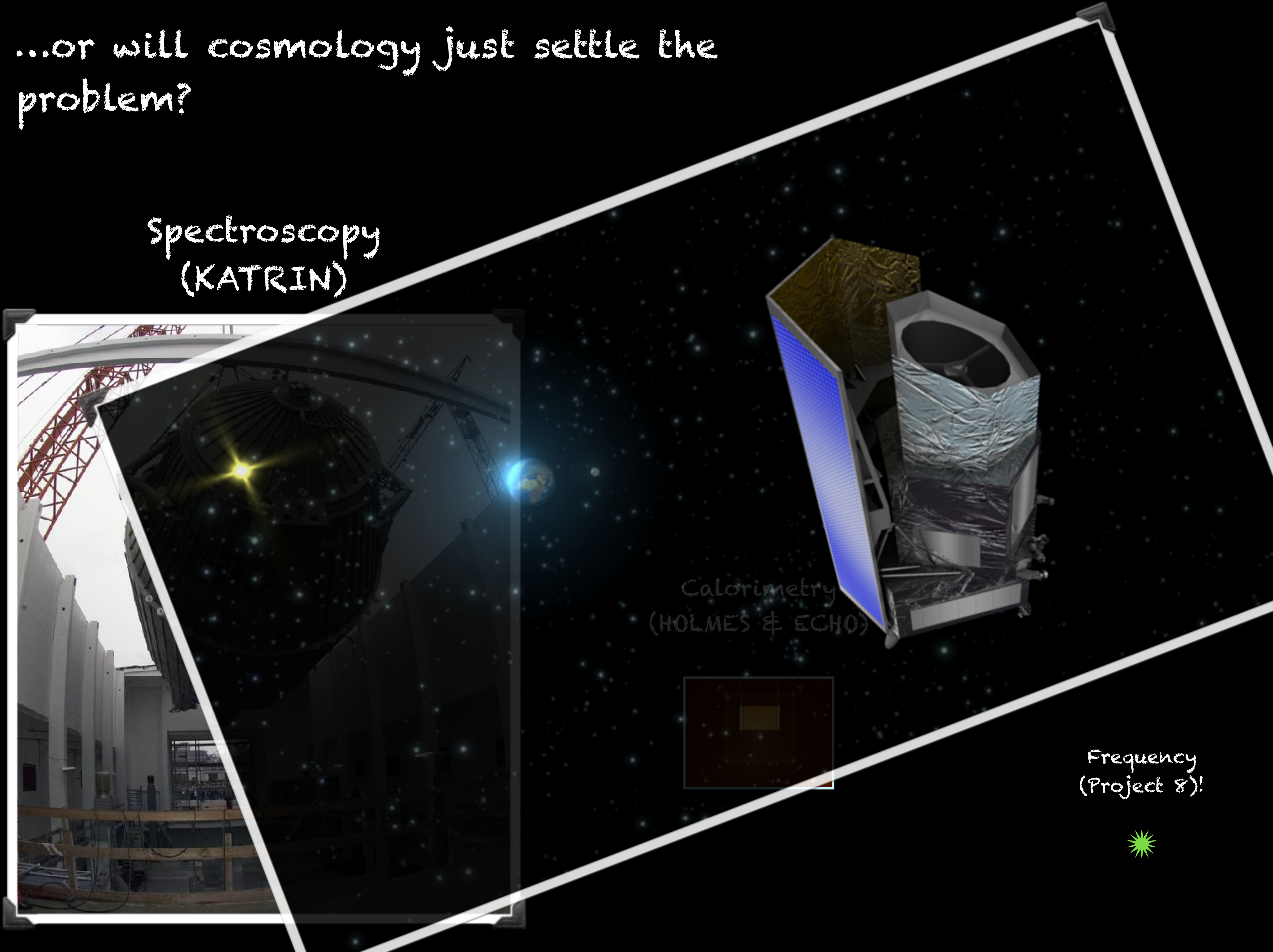
Spectroscopy
(KATRIN)

Calorimetry
(HOLMES & ECHO)



Frequency
(Project 8)!

…or will cosmology just settle the problem?

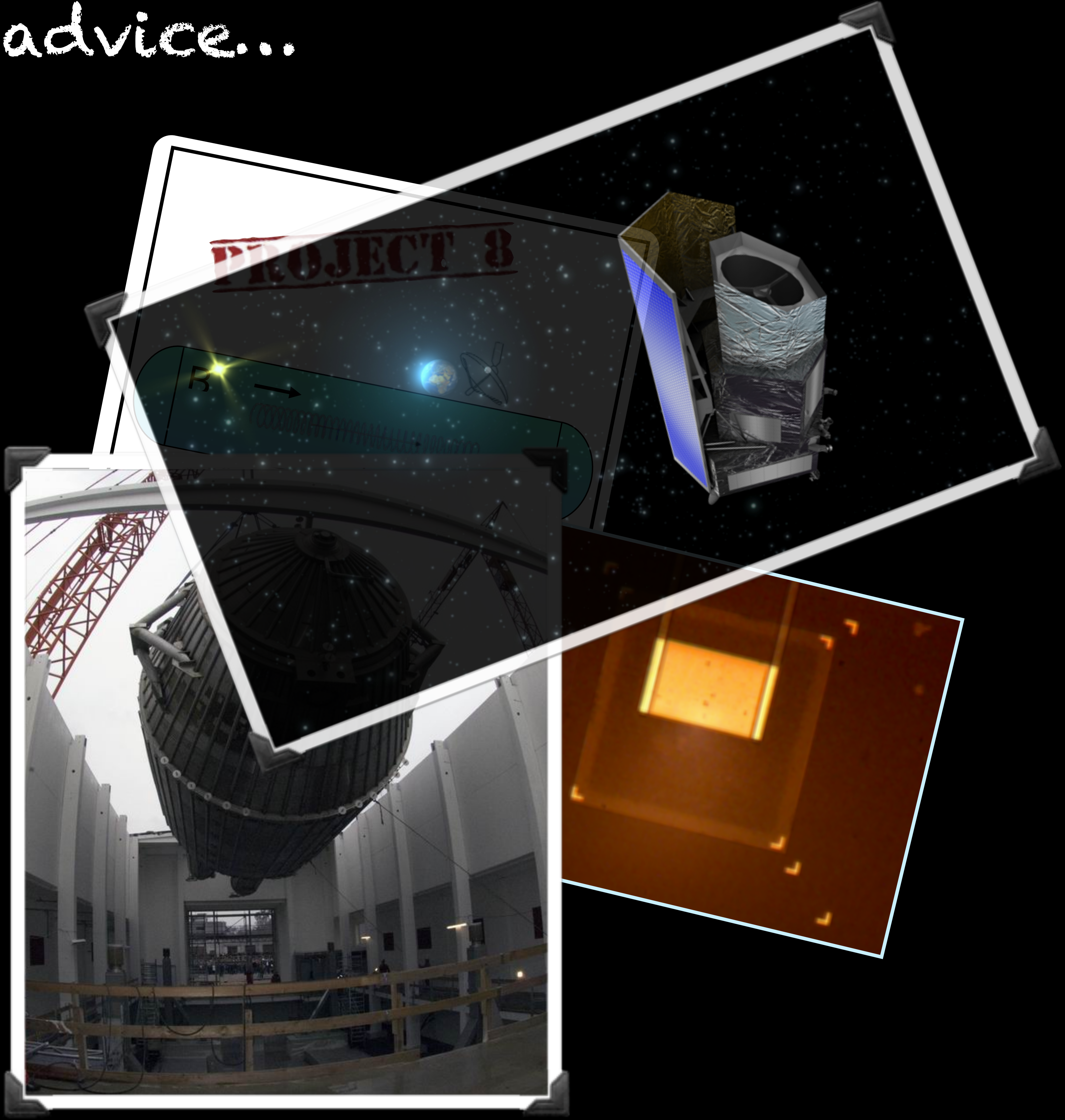


Spectroscopy
(KATRIN)

Calorimetry
(HOLMES & ECHO)

Frequency
(Project 8)!

Some good advice...



"Joe, you are wrong..."

[It matters not that cosmology may measure it first. Thermal cosmology track neutrinos over eons, from being relativistic to non-relativistic. A positive measurement of neutrino mass in cosmology AND nuclear physics would be the ultimate confirmation of that model.]

[You can't beat that kind of impact...] - G. Fuller

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

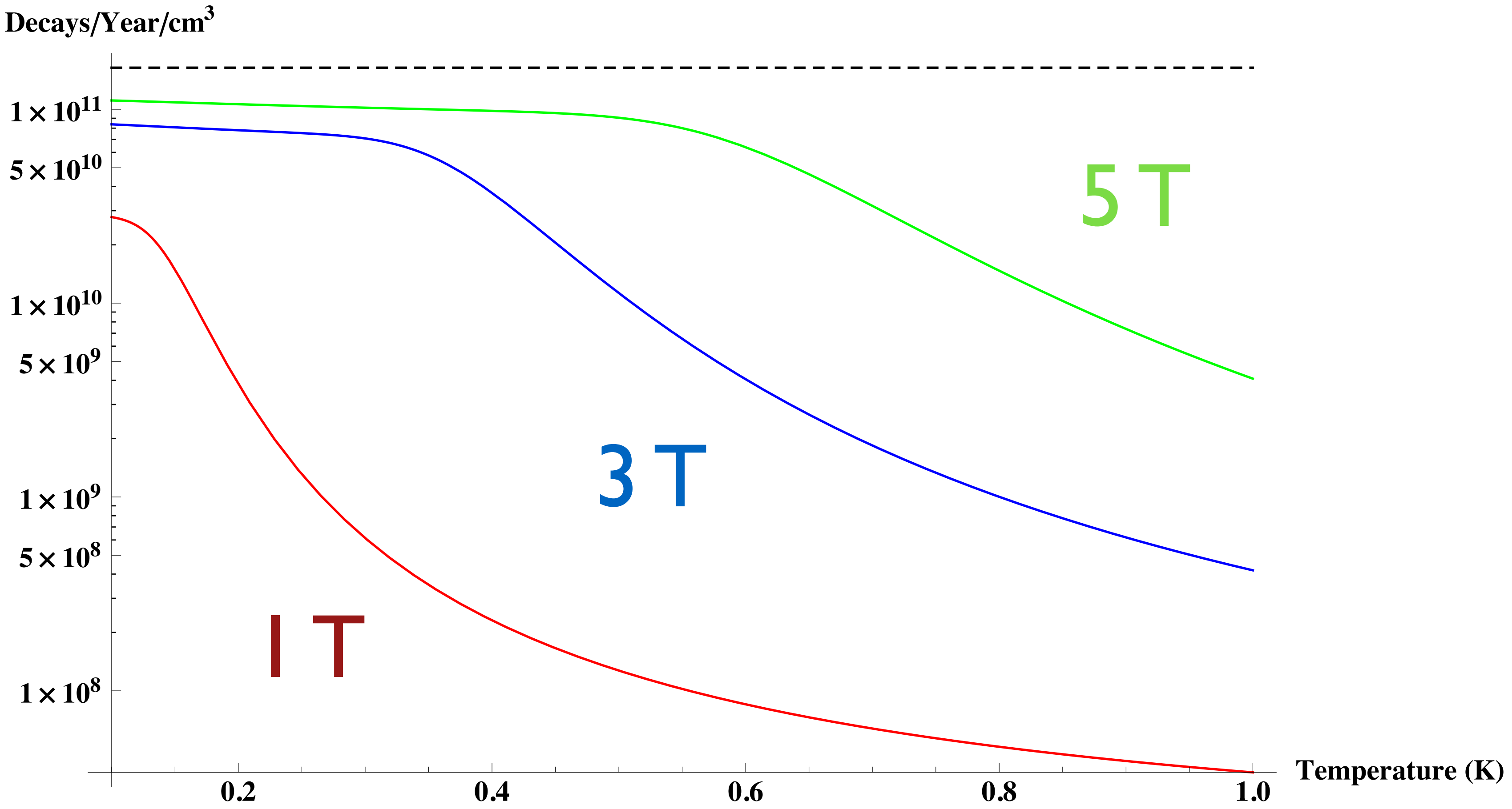
Over the next decade, KATRIN, ECHO and HOLMES can probe the degeneracy scale.

Project 8 introduces a new technique into the mix. Potentially extendable to the inverted scale.

Lots of exciting work to come!

Thank you for your attention

Trapping of Atomic Tritium



Important to cool tritium target to clear out T_2 contamination and keep source stable.

Source increases in stability with magnetic field and temperature.

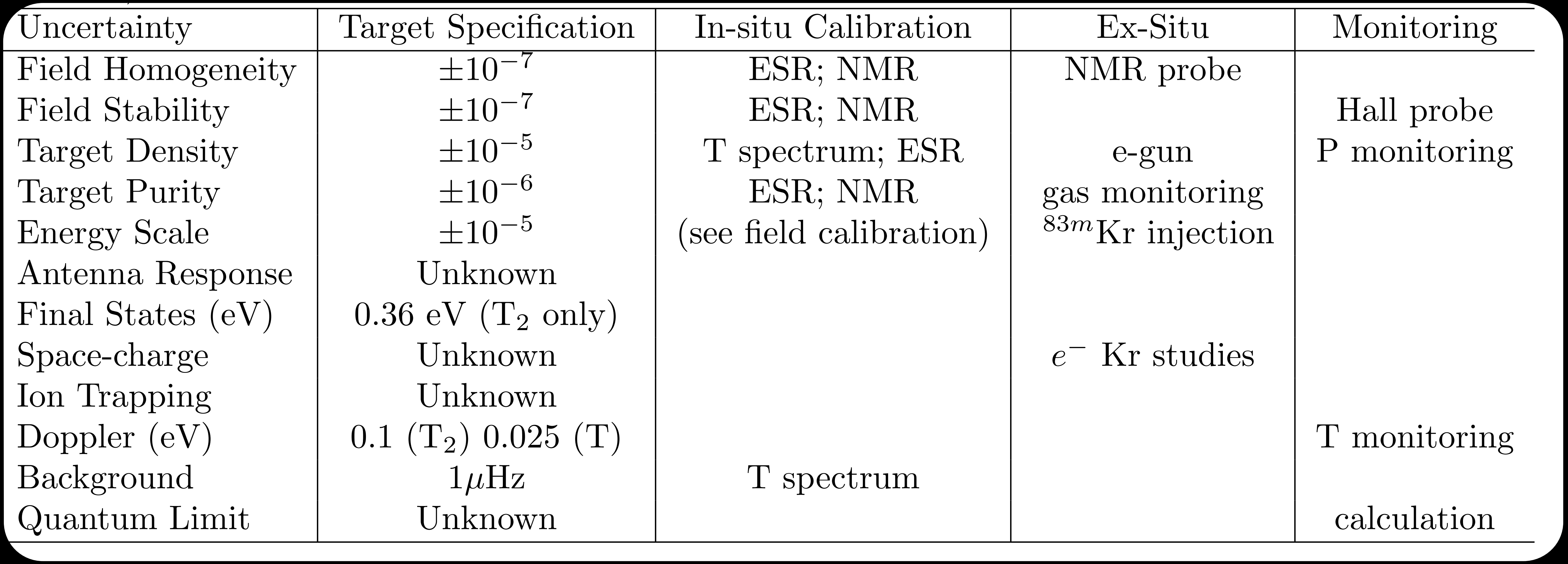
Stability based on hydrogen trapping (preliminary)

In order to achieve atomic tritium purity, it is necessary to cool and trap polarized atomic tritium in both a radial and axial magnetic trap (Ioffe-Pritchard traps).

Technique quite similar to hydrogen BEC (MIT) and anti-hydrogen trapping (ALPHA).

Densities low, so recombination is highly suppressed.

Systematics and Target Specifications

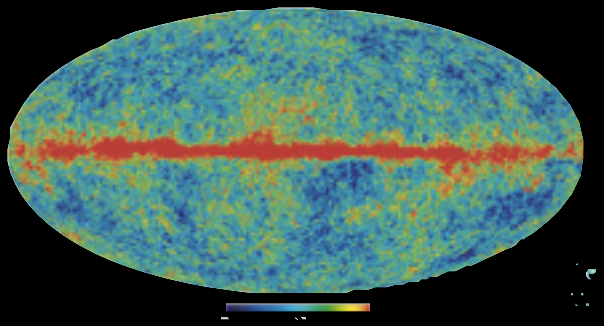


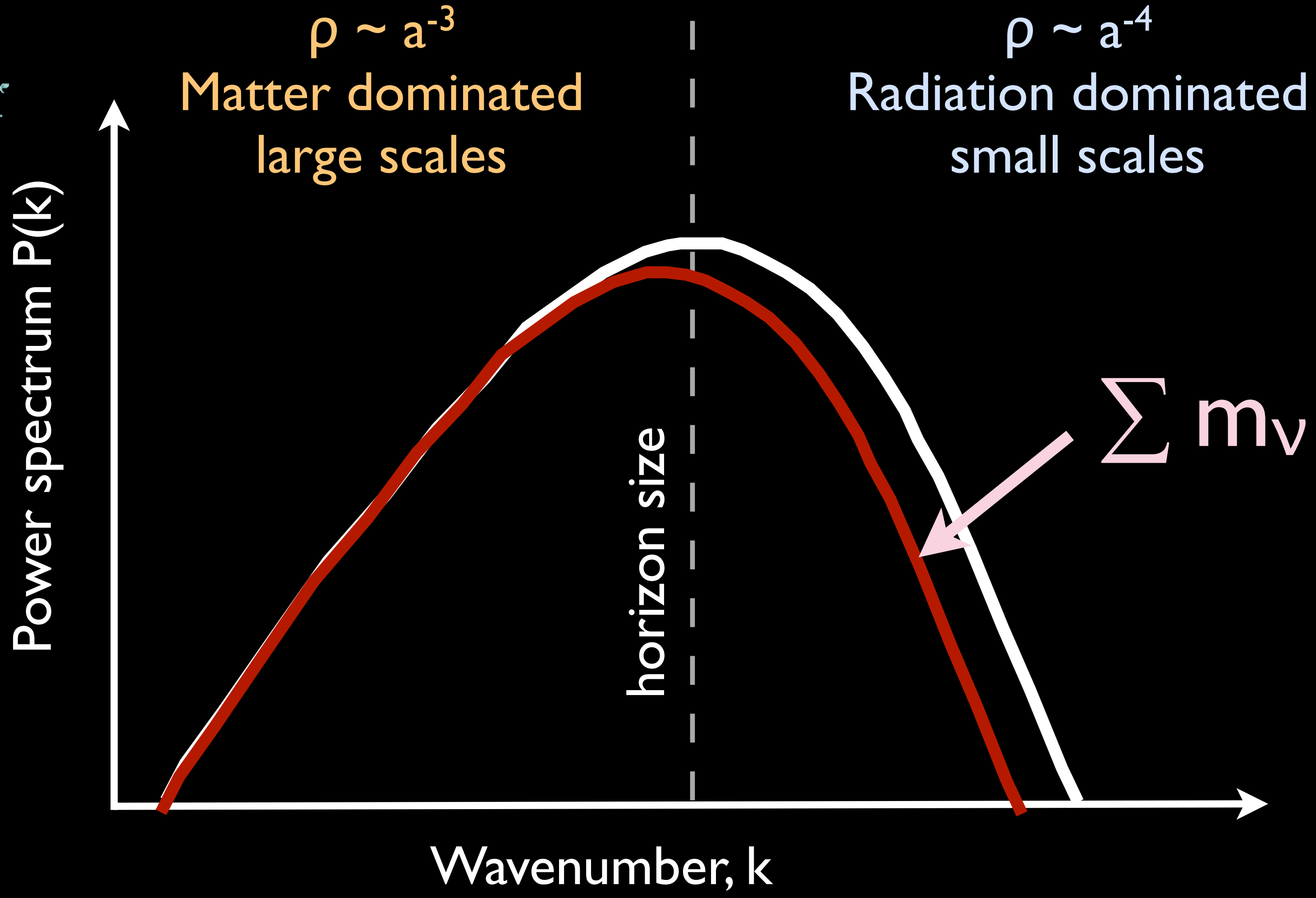
Uncertainty	Target Specification	In-situ Calibration	Ex-Situ	Monitoring
Field Homogeneity	$\pm 10^{-7}$	ESR; NMR	NMR probe	
Field Stability	$\pm 10^{-7}$	ESR; NMR		Hall probe
Target Density	$\pm 10^{-5}$	T spectrum; ESR	e-gun	P monitoring
Target Purity	$\pm 10^{-6}$	ESR; NMR	gas monitoring	
Energy Scale	$\pm 10^{-5}$	(see field calibration)	^{83m}Kr injection	
Antenna Response	Unknown			
Final States (eV)	0.36 eV (T_2 only)			
Space-charge	Unknown		e^- Kr studies	
Ion Trapping	Unknown			
Doppler (eV)	0.1 (T_2) 0.025 (T)			T monitoring
Background	1μHz	T spectrum		
Quantum Limit	Unknown			calculation

Systematic table is being built in order to guide next atomic tritium design.

The Strategy
(a naive view)

WMAP Temperature Map



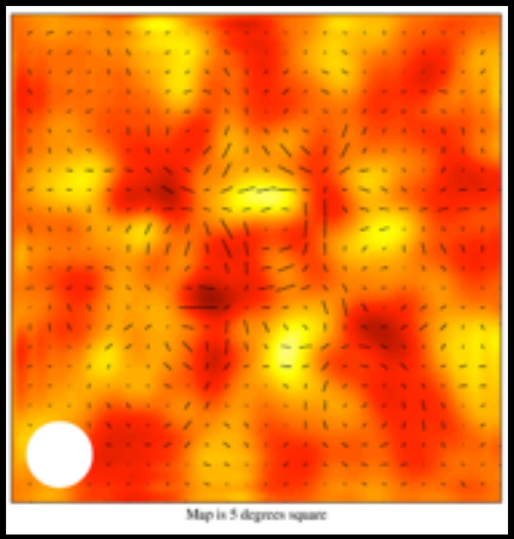


$$\delta(x) = (\rho(x) - \bar{\rho})/\bar{\rho}$$

Neutrinos come to affect the power spectrum,

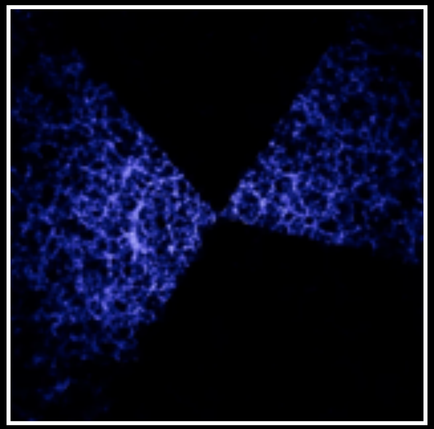
particularly at small distance scales

$$P(k) = \langle |\delta(k)|^2 \rangle$$

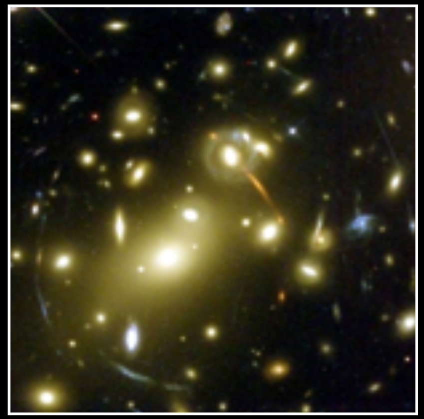


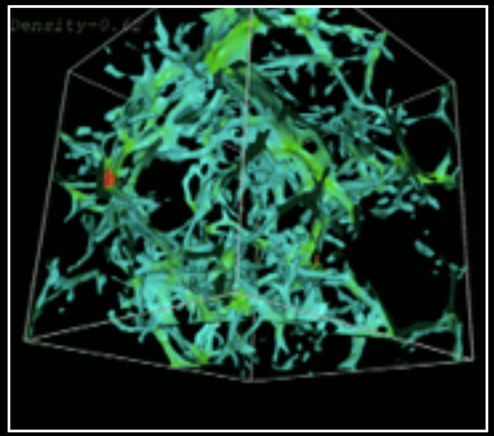
CMB Polarization

Galaxy Surveys



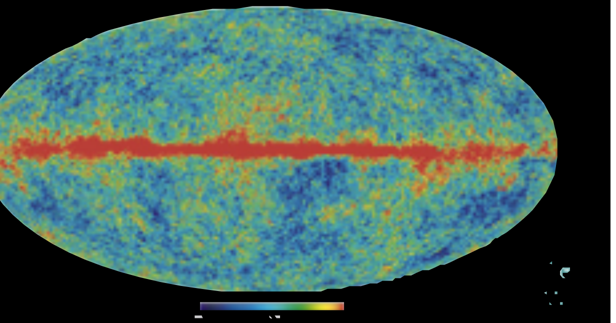
Weak lensing

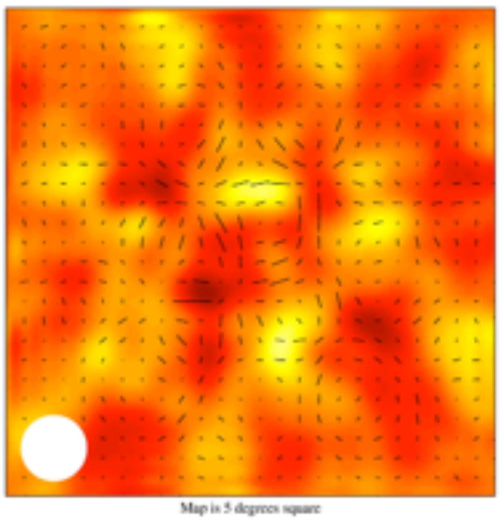




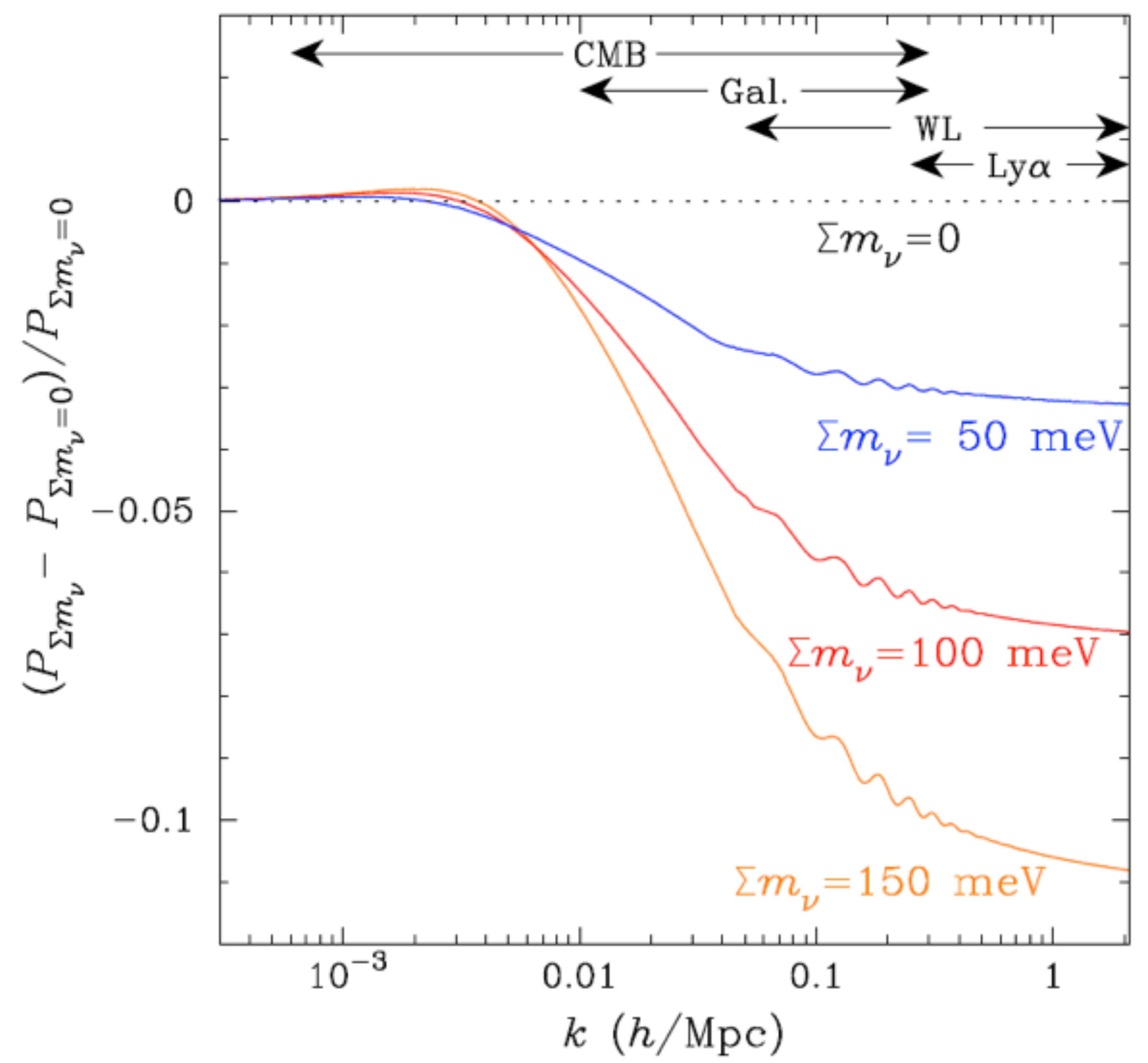
Lyman α

Temperature Map



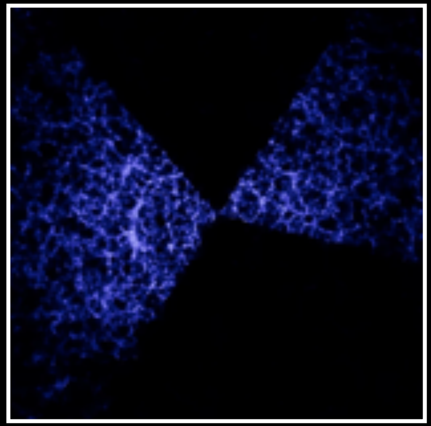


CMB Polarization



Large scale structure tends to weaken power spectrum at small wavelengths...

Galaxy Surveys



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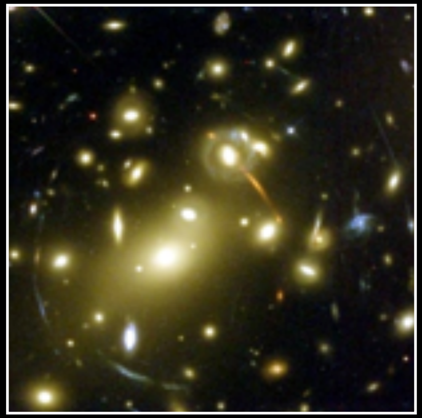

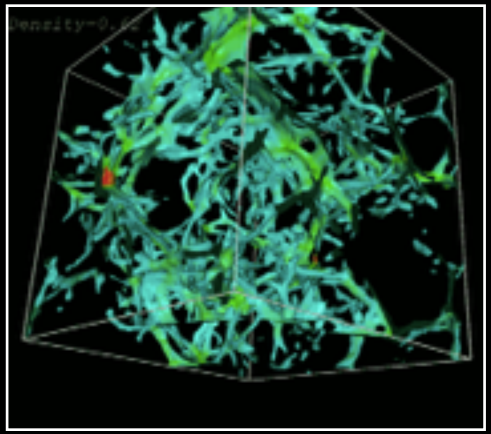

Lyman α