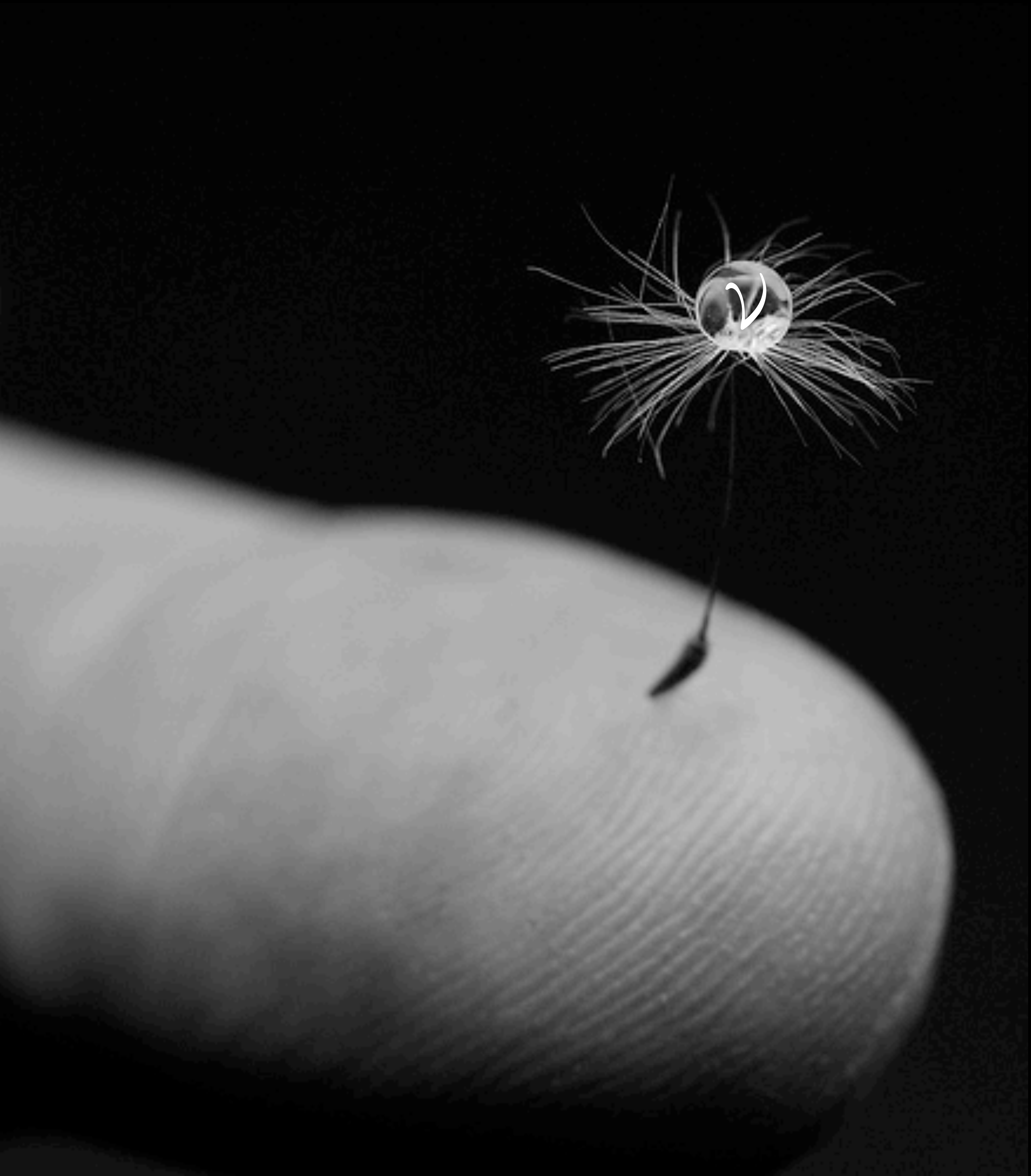
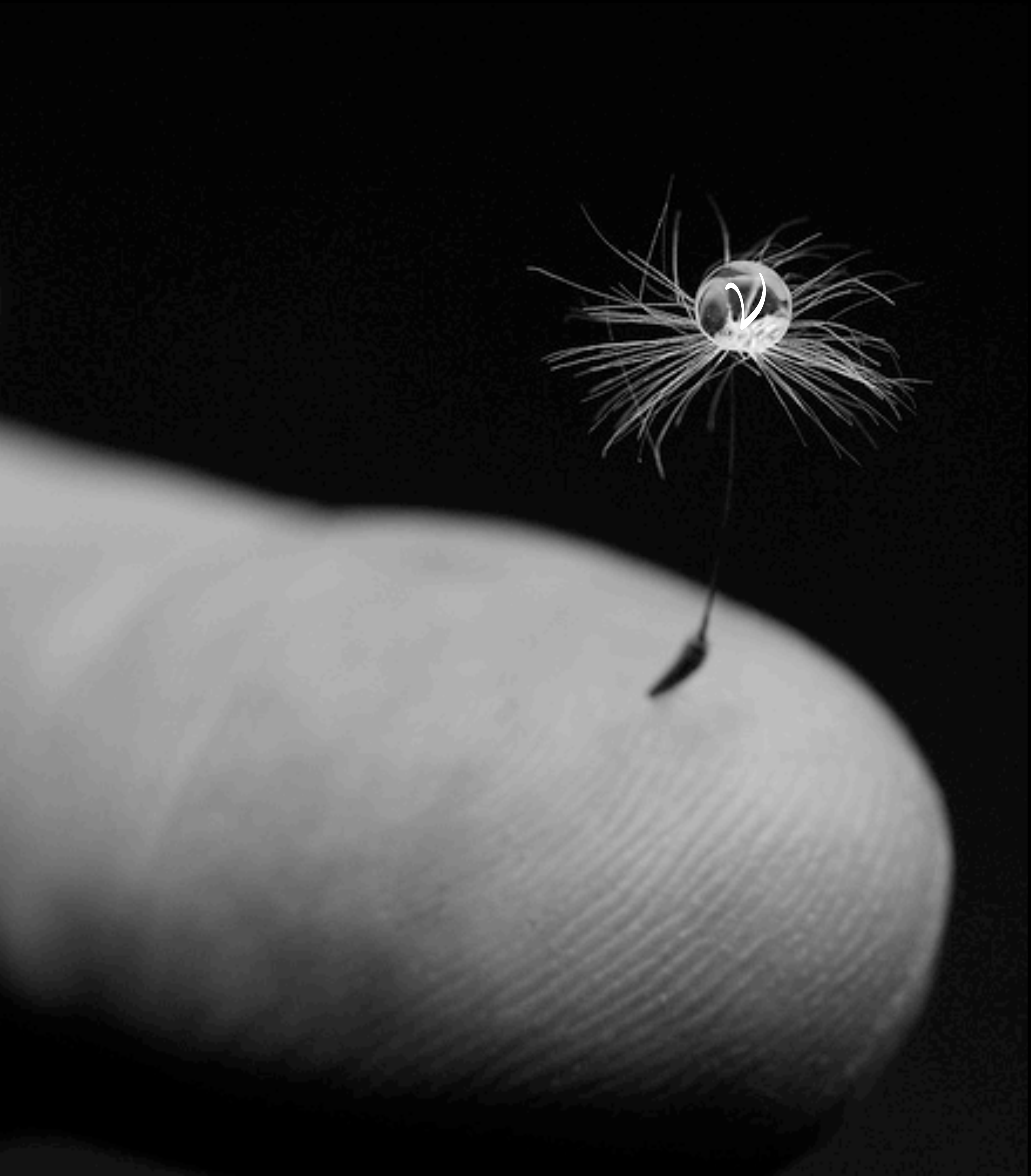


Weighing

Neutrinos

Columbia University
April 13th, 2011

J.A. Formaggio
MIT



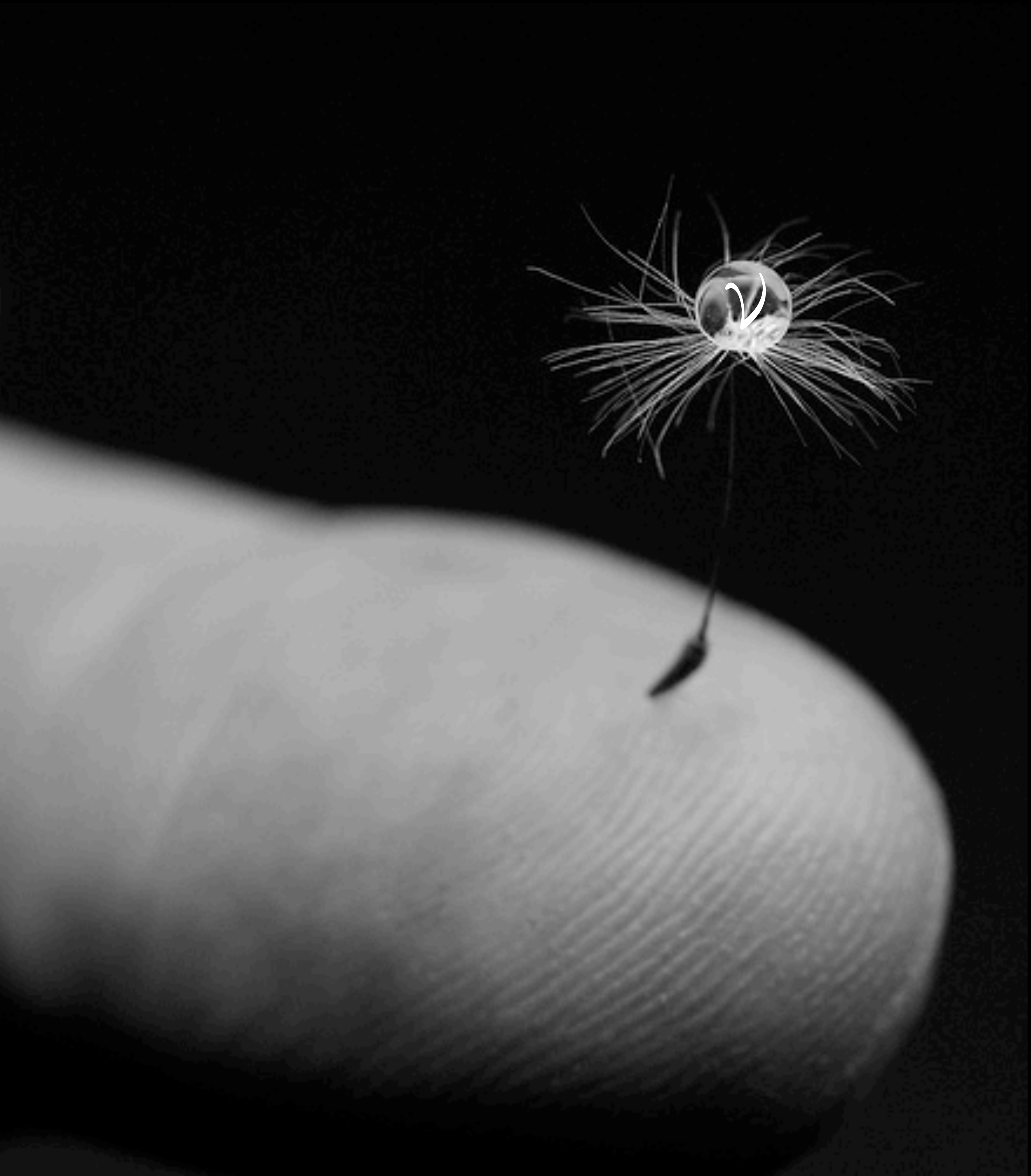
What we will cover:

The role that neutrinos play.

Measuring neutrinos from the Heavens

Measuring neutrinos on Earth

Connecting back?



What we will cover:

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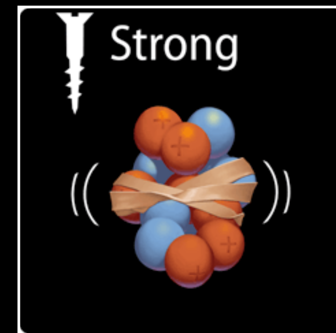
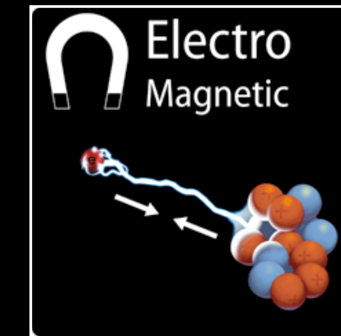
Connecting back?

Within the Framework

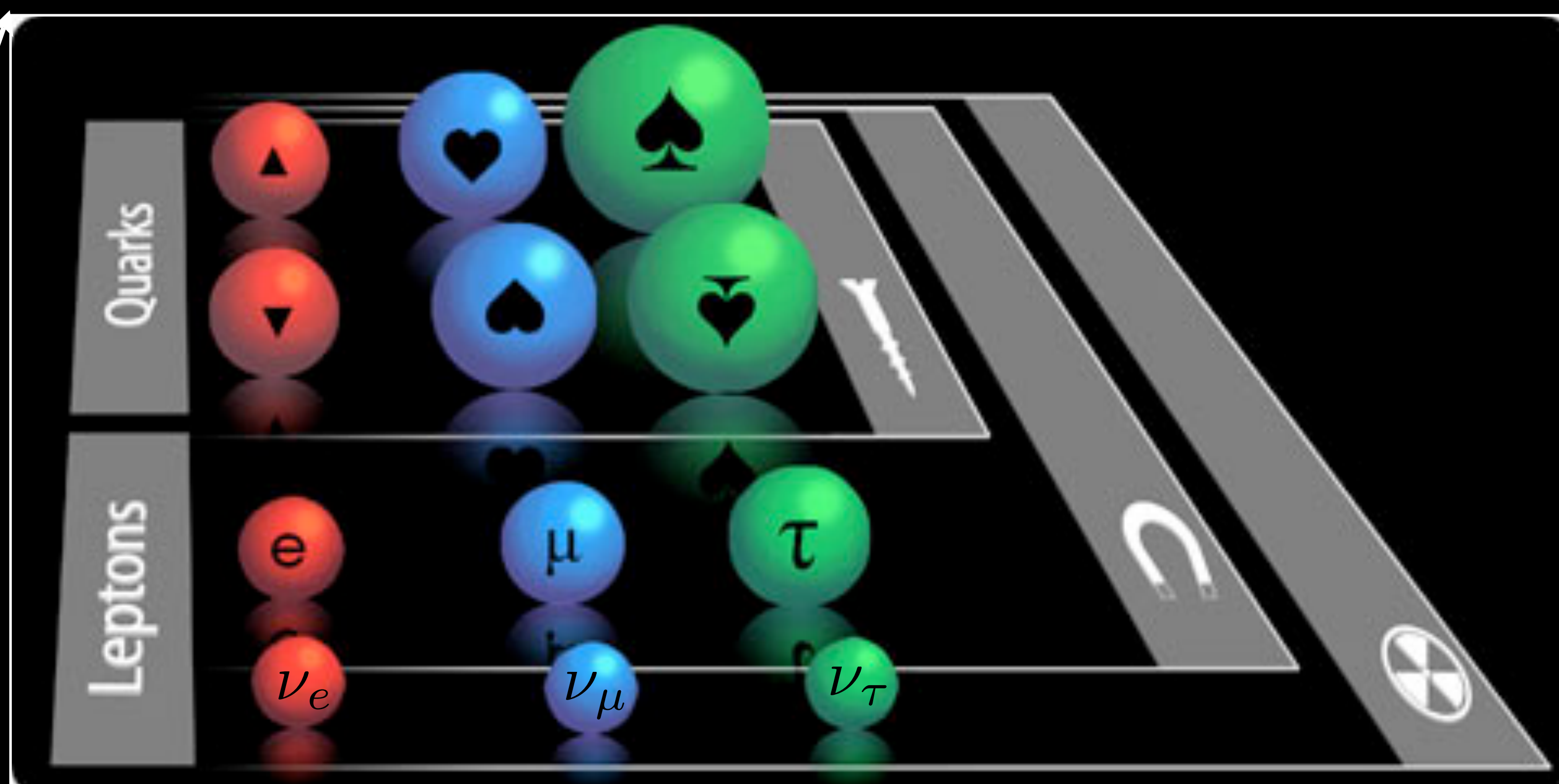


Binds nucleii;
mediated by gluons;
only couples to quarks

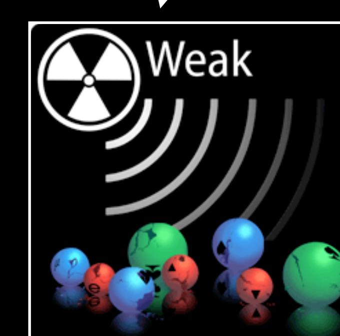


Couples to charge;
mediated by photons;
felt by quarks and leptons

Spin 1



Spin 1/2



Common to all particles;
mediated by the $W^{\pm}/Z^0$ bosons.

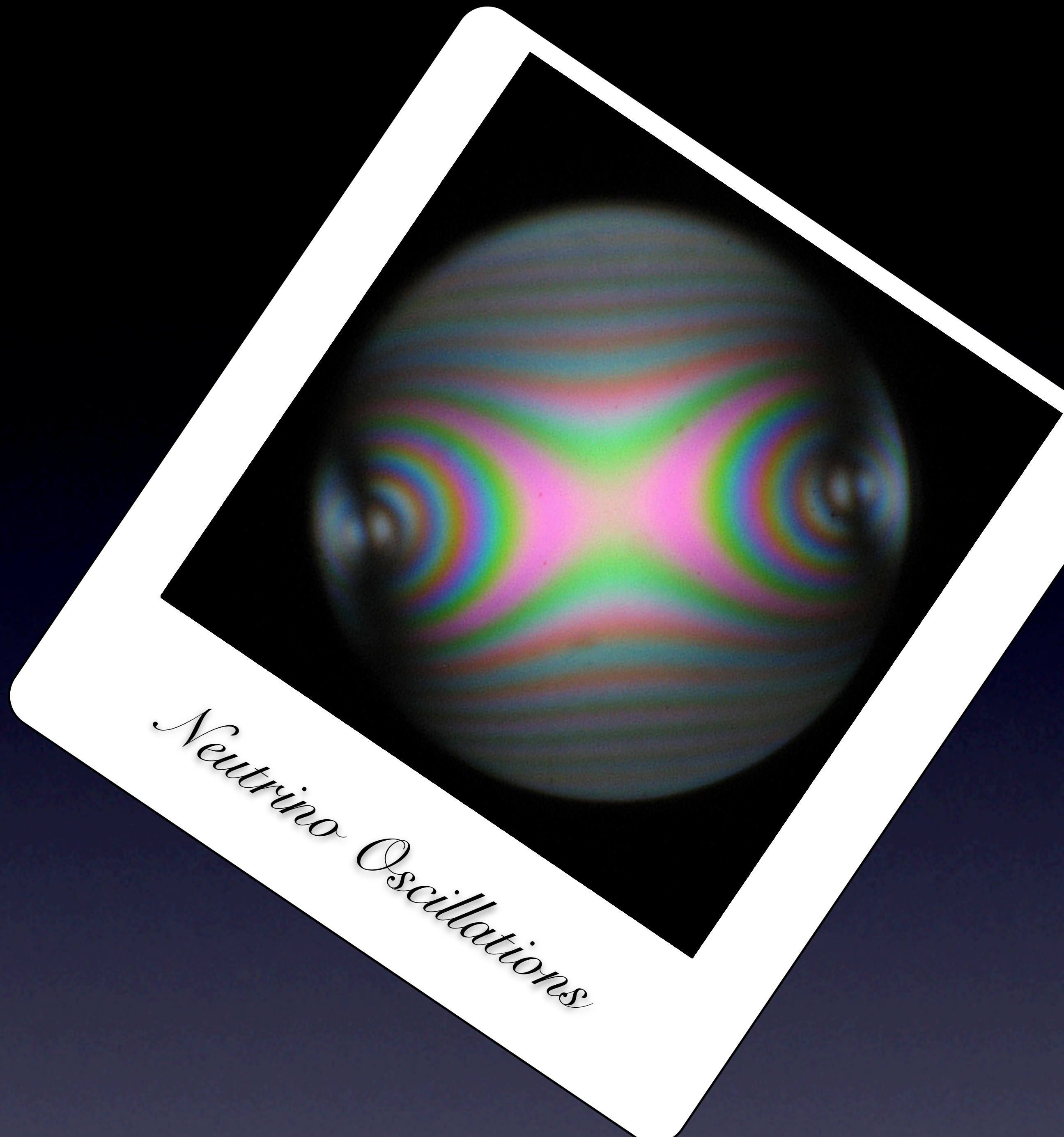
The First Crack of the Standard Model

- Experiments, in particular oscillation experiments carried out over the last forty years, have revealed that neutrinos do possess a small and finite mass.

- Neutrino mass has provided the first contradiction in the Standard Model. What else can we learn from neutrino masses?

How do we measure masses?

Neutrino mass can be measured using several different but complimentary techniques.



How do we measure masses?

Neutrino mass can be measured using several different but complimentary techniques.

Neutrino Oscillations

- In general, we have a 3 x 3 matrix that describes neutrino mixing (the Maki-Nakagawa-Sakata-Pontecorvo, or MNSP mixing matrix):

- However, the picture simplifies if one of the mixing angles is small...

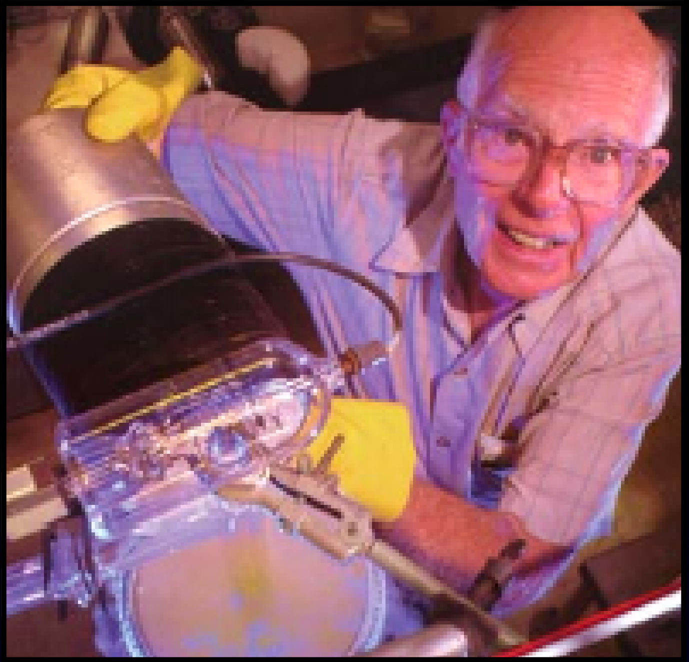
Bruno Pontecorvo

$$= \underbrace{\begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_{23} & \sin\theta_{23} \\ 0 & -\sin\theta_{23} & \cos\theta_{23} \end{pmatrix}}_{\text{atmospheric, long baseline}} \times \underbrace{\begin{pmatrix} \cos\theta_{13} & 0 & e^{-i\delta_{CP}}\sin\theta_{13} \\ 0 & 1 & 0 \\ -e^{i\delta_{CP}}\sin\theta_{13} & 0 & \cos\theta_{13} \end{pmatrix}}_{\text{reactor, accelerator}} \times \underbrace{\begin{pmatrix} \cos\theta_{12} & \sin\theta_{12} & 0 \\ -\sin\theta_{12} & \cos\theta_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}}_{\text{solar, KamLAND}} \times \underbrace{\begin{pmatrix} 1 & 0 & 0 \\ 0 & e^{i\alpha/2} & 0 \\ 0 & 0 & e^{i\alpha/2+i\beta} \end{pmatrix}}_{0\nu\beta\beta}$$

- Depends only on two fundamental parameter and two experimental parameters (for a given neutrino species).

$$\mathcal{P}_{\text{surv}} = 1 - \sin^2 2\theta \sin^2(\frac{\Delta m^2}{4E_\nu}L)$$

A Rich History... Solar Sector



Raymond Davis, Jr.

60s

Ray Davis begins construction of Homestake

Bahcall provides solar flux predictions

70s

Homestake (^{37}Cl) measurements

Solar puzzle begins

80s

SAGE (^{71}Ga) begins operations

MSW mechanism proposed

90s

Helioseismology models compared

GALLEX (^{71}Ga) online

Super-K (H_2O) online

GNO operational

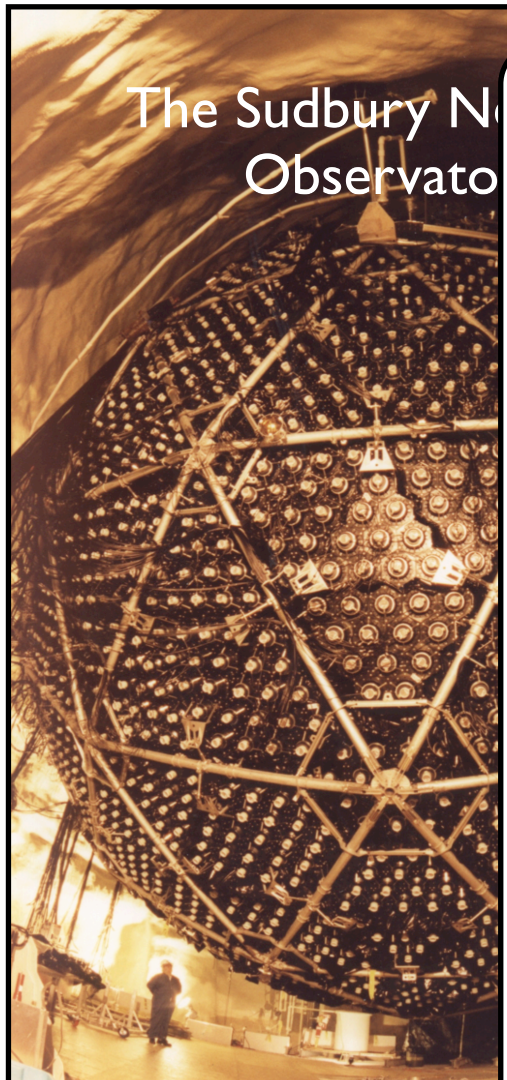
00s

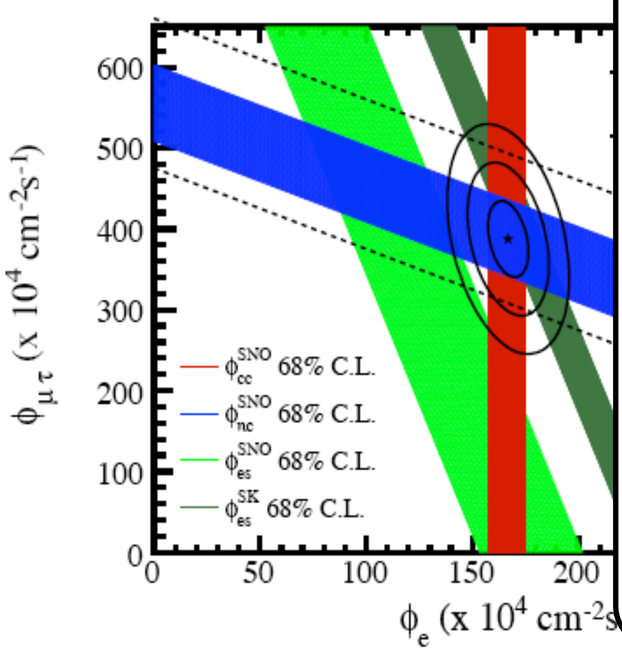
SNO (D_2O) takes data

Solar puzzle SOLVED

Borexino!

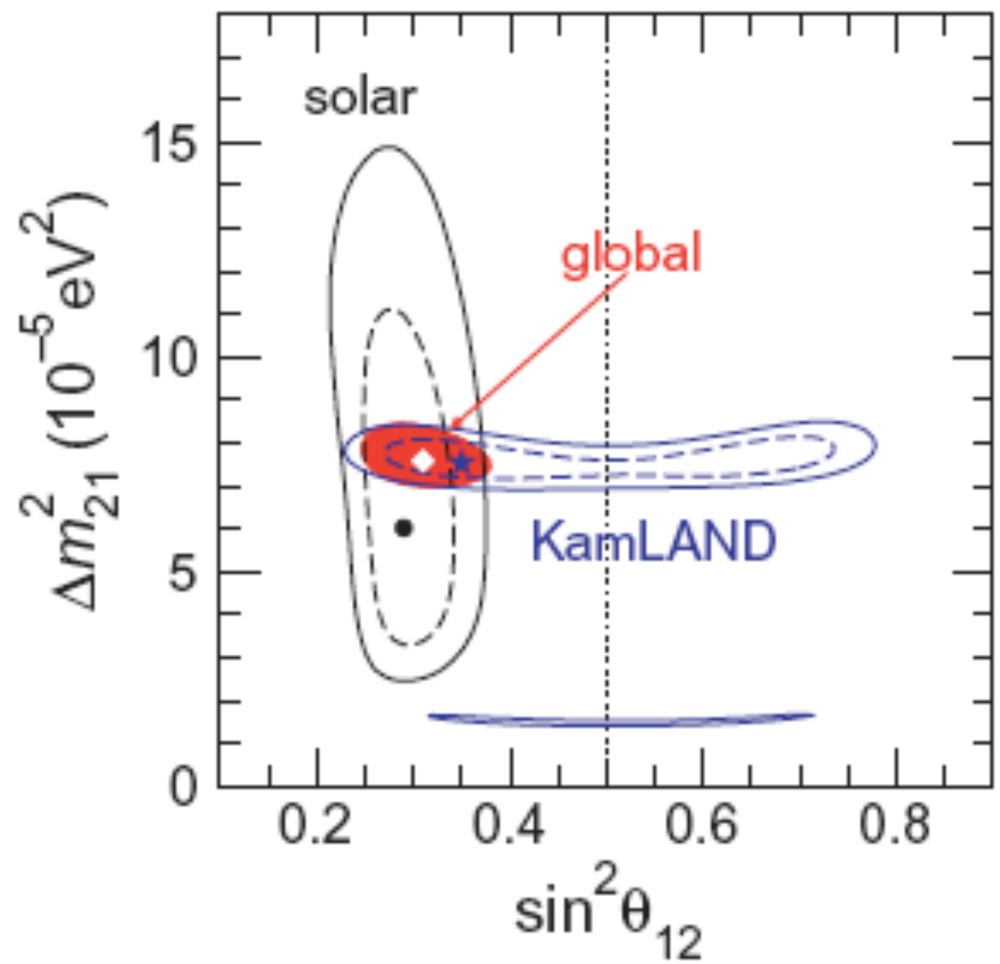
1[st] results from KAMLAND





Phys. Rev. Lett 101:111301 (2008)

Solar & Reactor Data

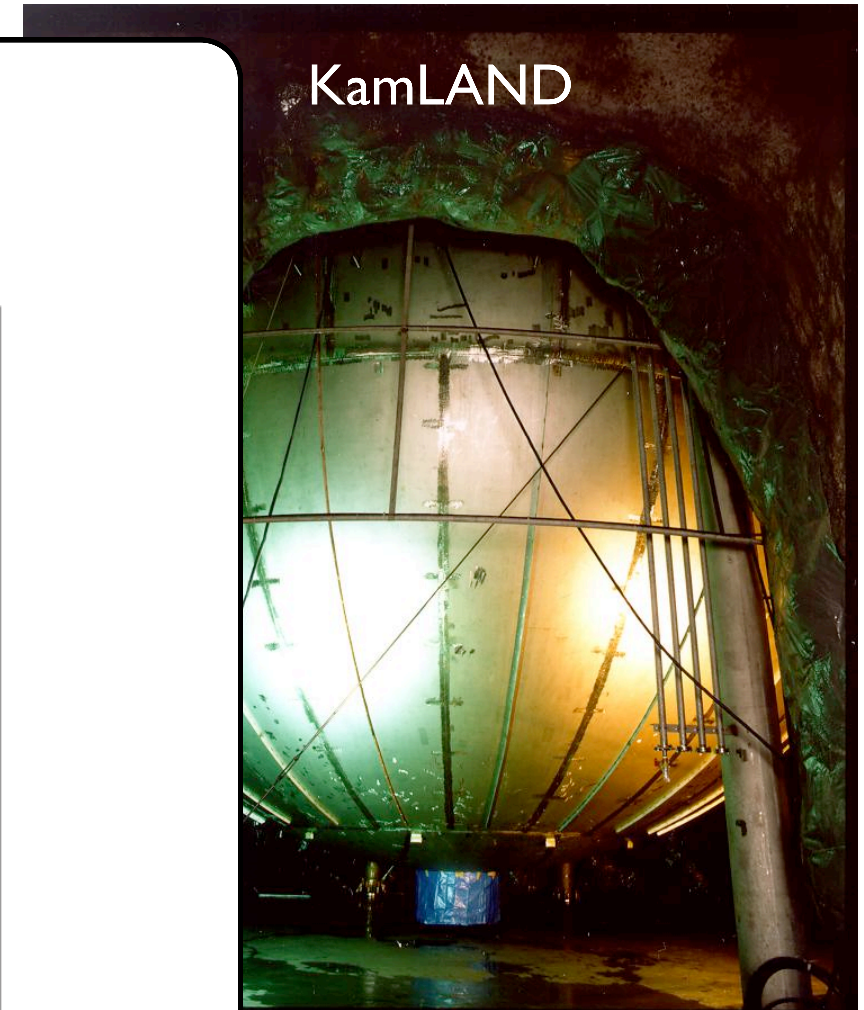


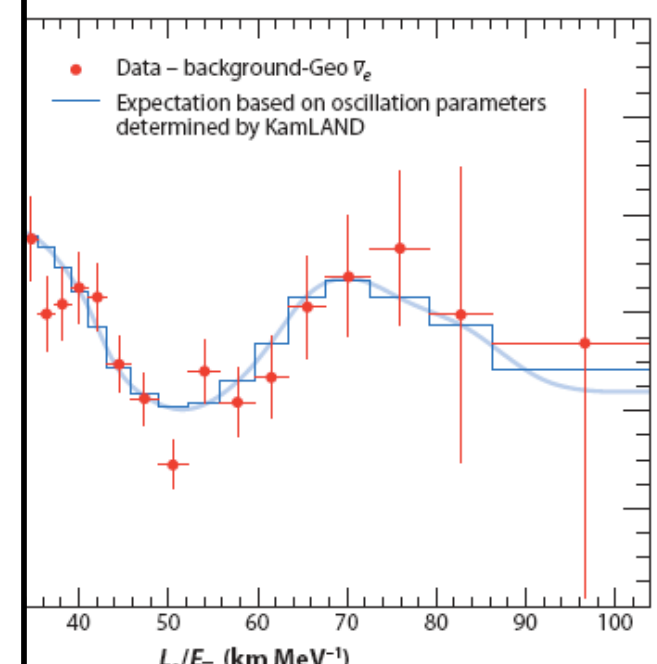
Fit Results:

$$\sin^2\theta_{12} = 0.304^{+0.022}_{-0.016}$$

$$\Delta m^2_{12} = 7.65^{+0.23}_{-0.20} \times 10^{-5}\ \text{eV}^2$$

Schwetz et al, NJP 10 (2008) 113011





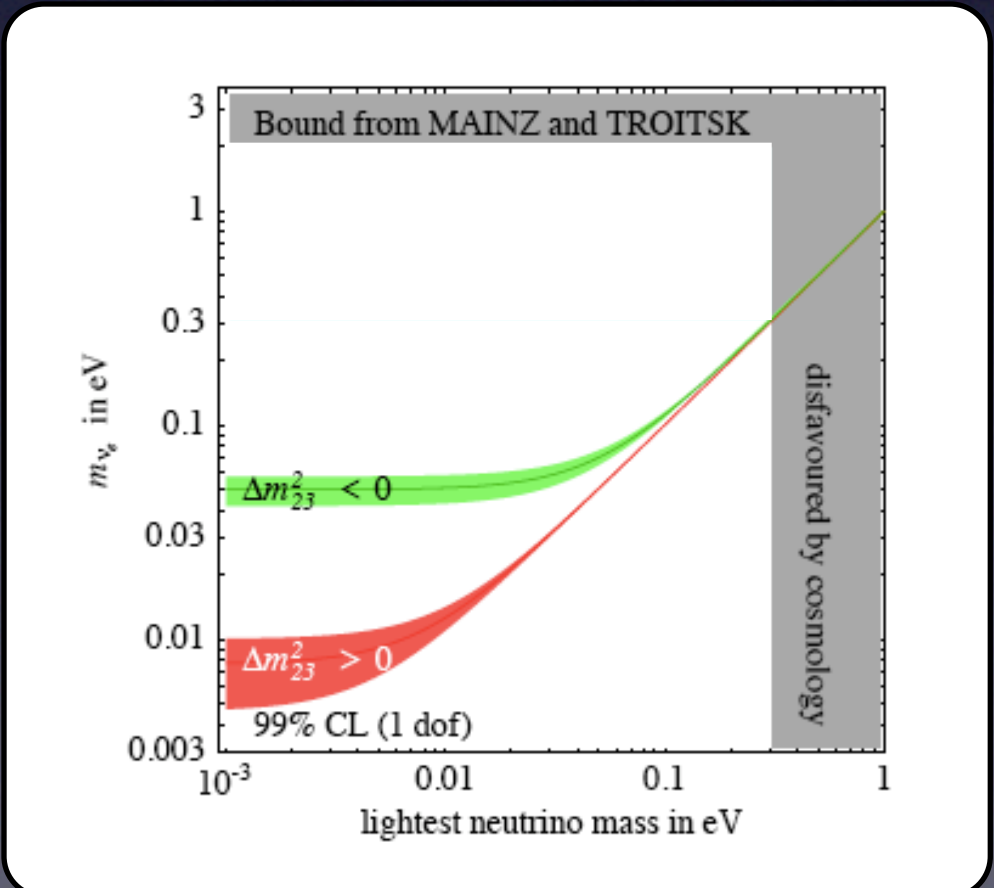
Phys. Rev. Lett. 100:221803 (2008)

Q & A

<u>What We Know</u>

(1) Neutrinos *do* have mass (and we measure these mass differences very well).

(2) Neutrinos mix (and we know most of those mixing constants very well)



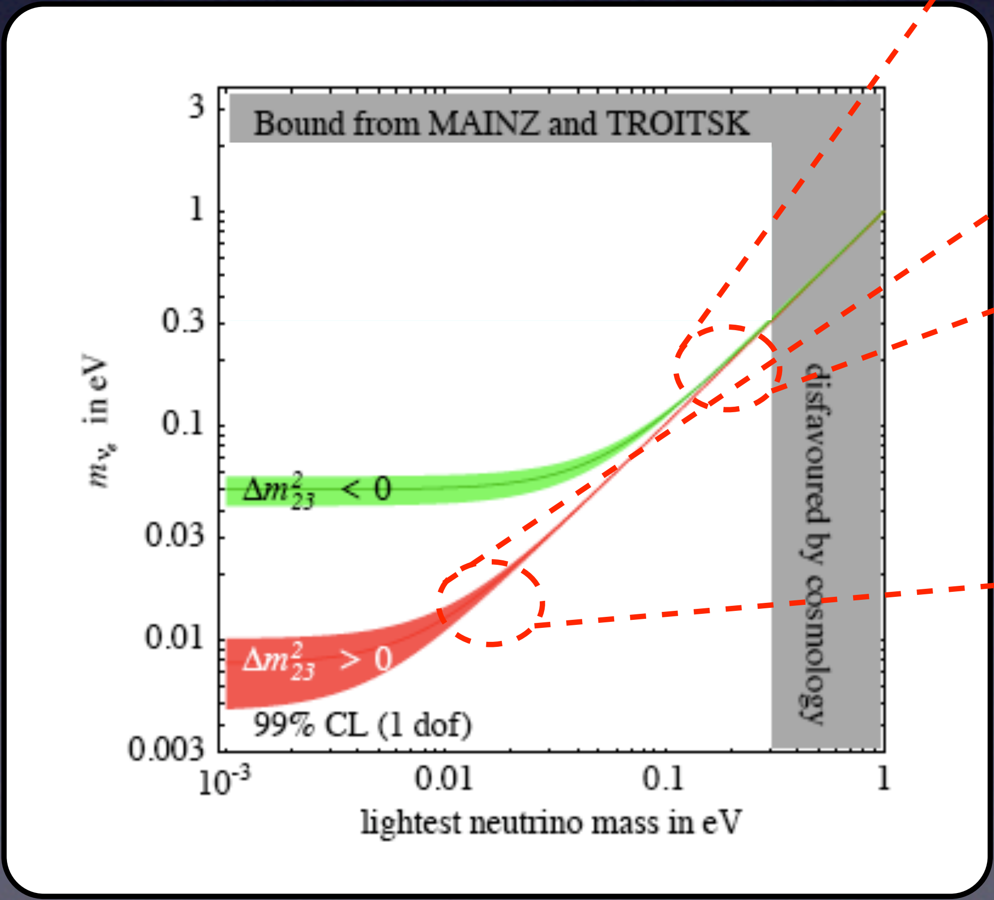
Q & A

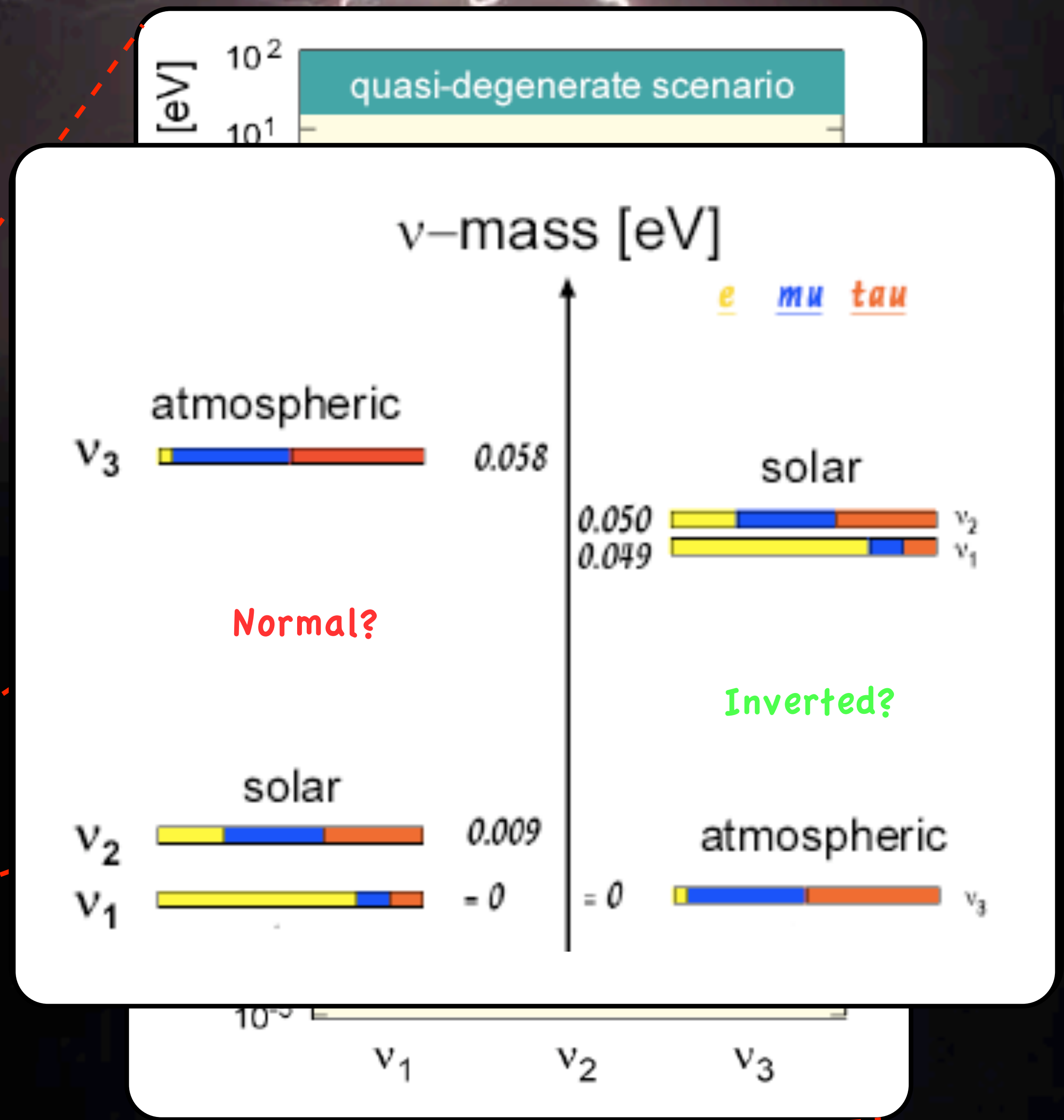
<u>What We Don't Know</u>

(1) What is the absolute scale of neutrinos?

(2) What is the hierarchy (normal or inverted)?

(3) What is the nature of neutrino mass?





Generally...

Know << Don't Know

What we will cover:

The role that neutrinos play.

Measuring neutrinos from the Heavens

Measuring neutrinos on Earth

Connecting back?

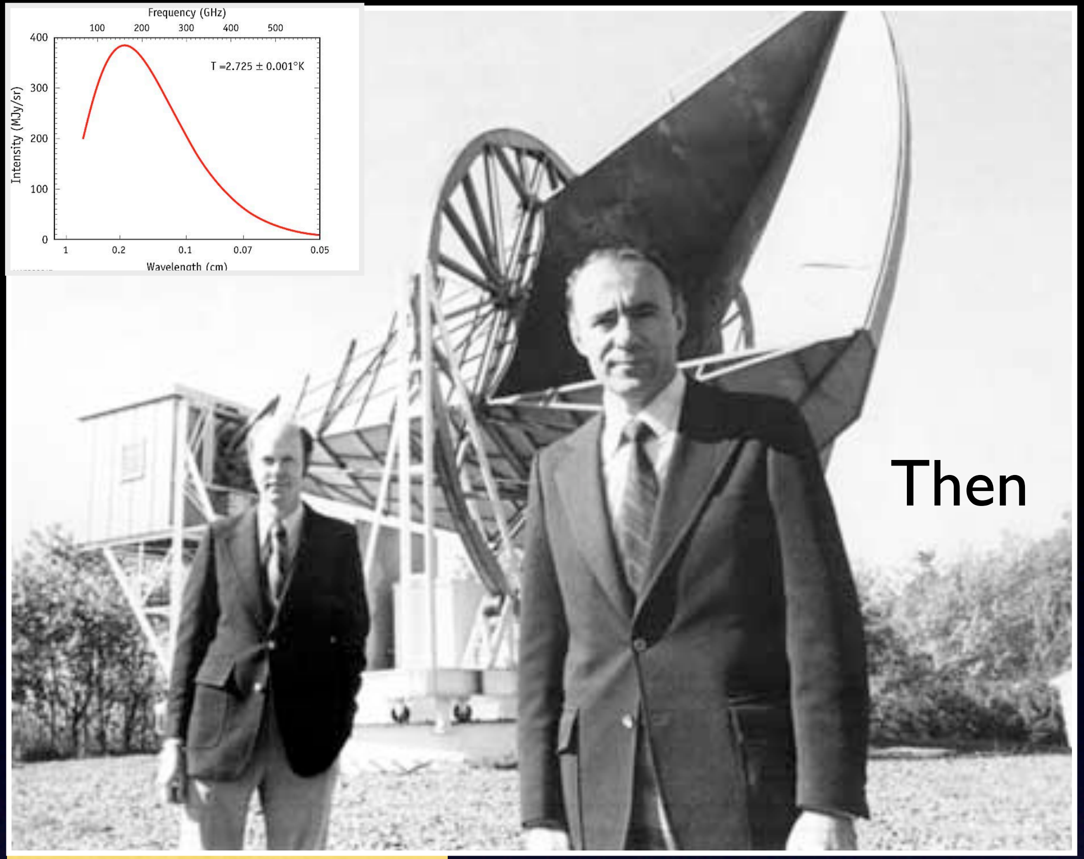
The Triumph of Cosmology

- The combination of the standard model of particle physics and general relativity allows us to relate events taking place at different epochs together.

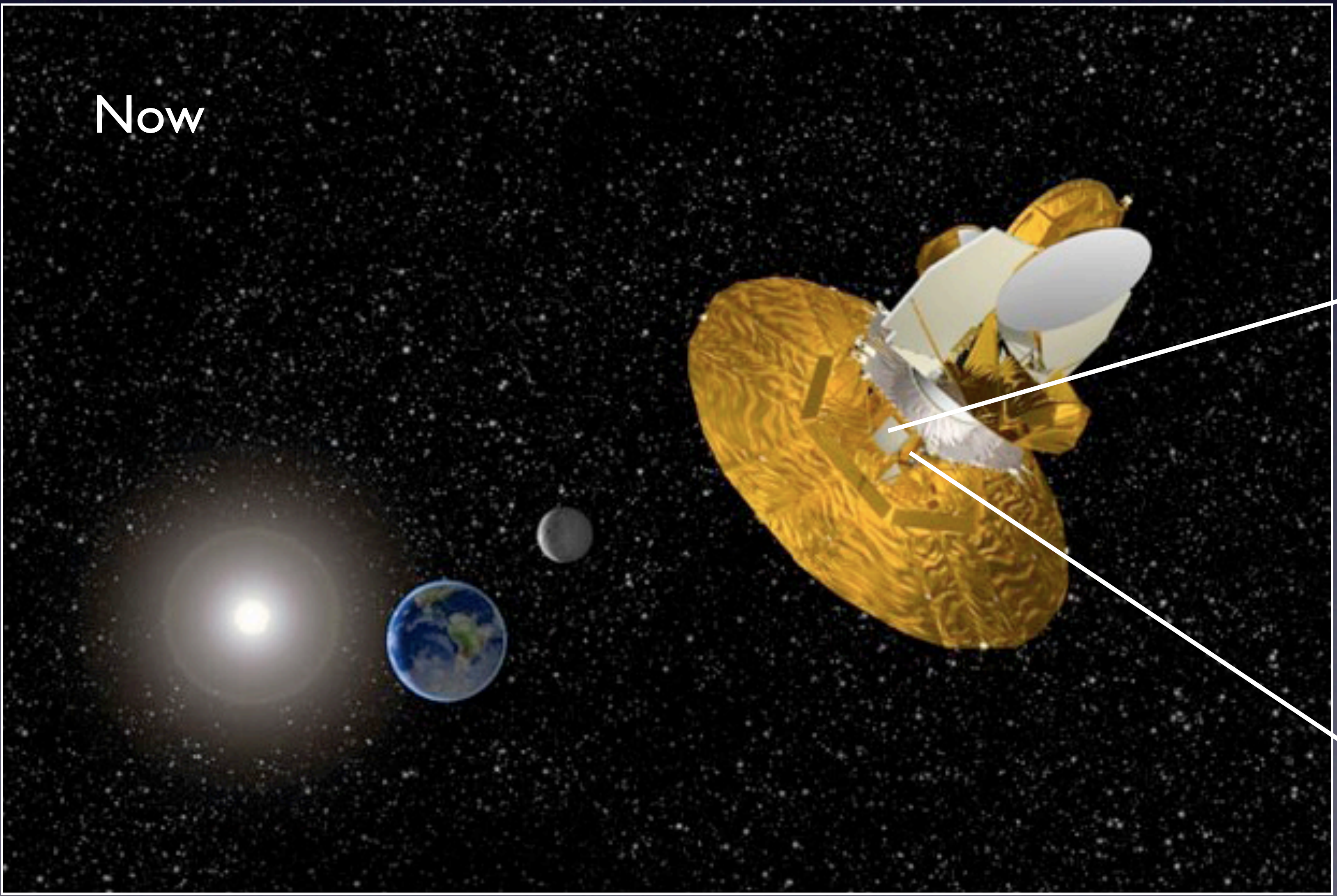
- Neutrinos leave their imprint on each of these processes.

The Cosmic Microwave Background

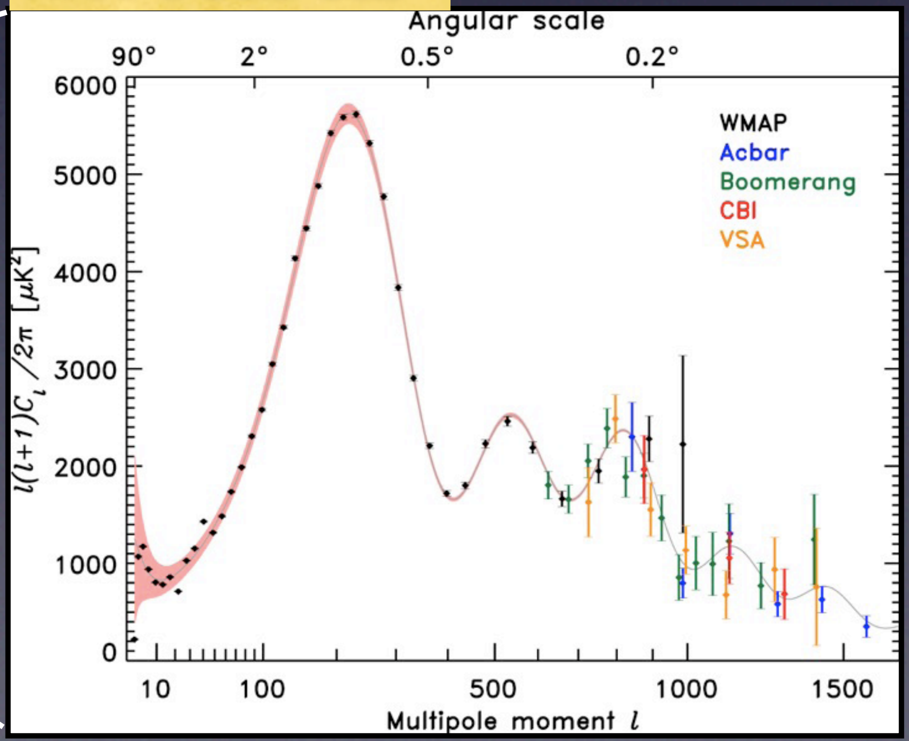
- Mapping the cosmic microwave background has reach unprecedented precision and, along with that, great predictive power.



Wilson and Penzias

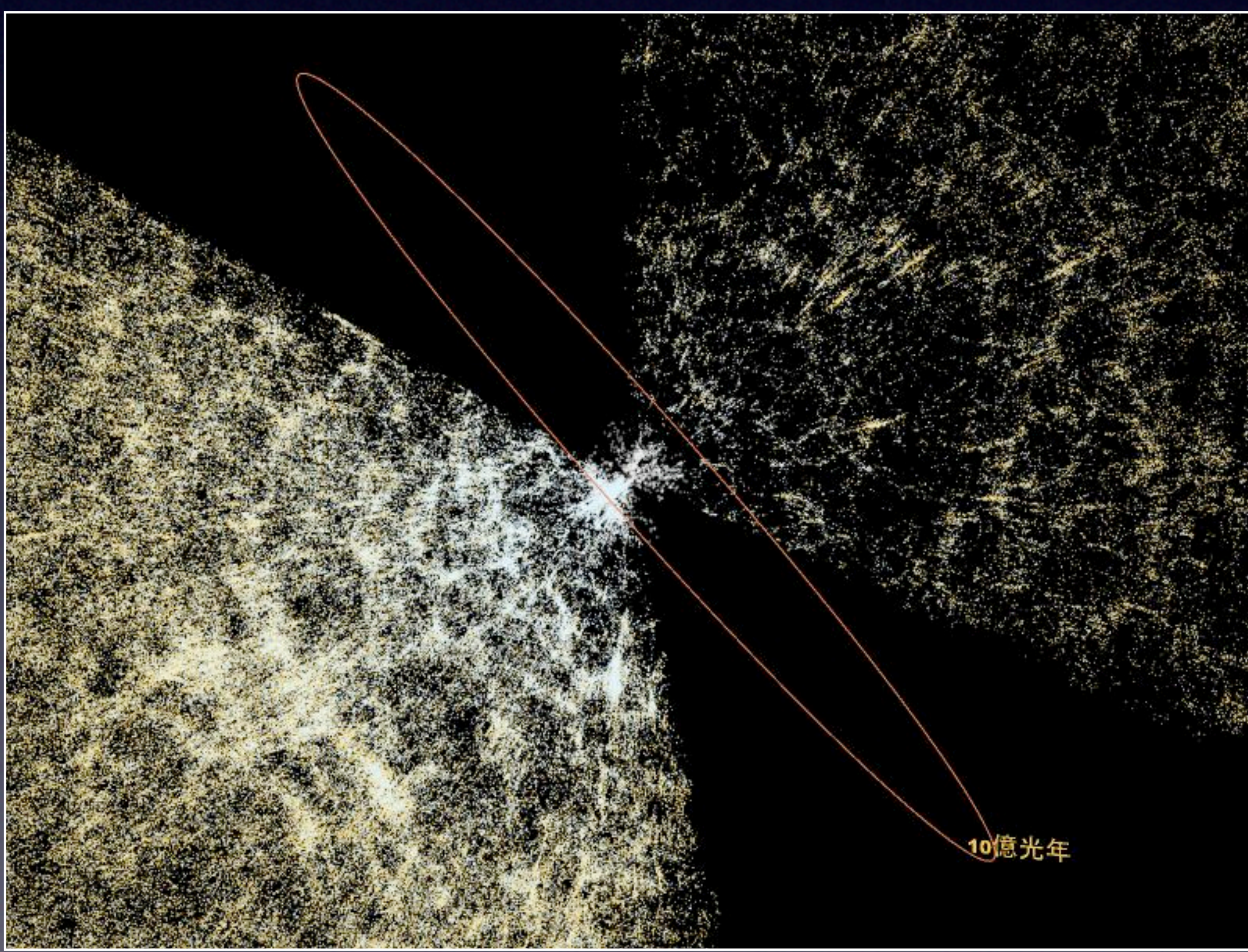


WMAP & Other Data



Large Scale Structure

- Neutrinos can also affect the clustering of galaxies (affected both by the number of neutrino species and the mass of the neutrinos)



Large Scale Sctructure

Just cold dark matter

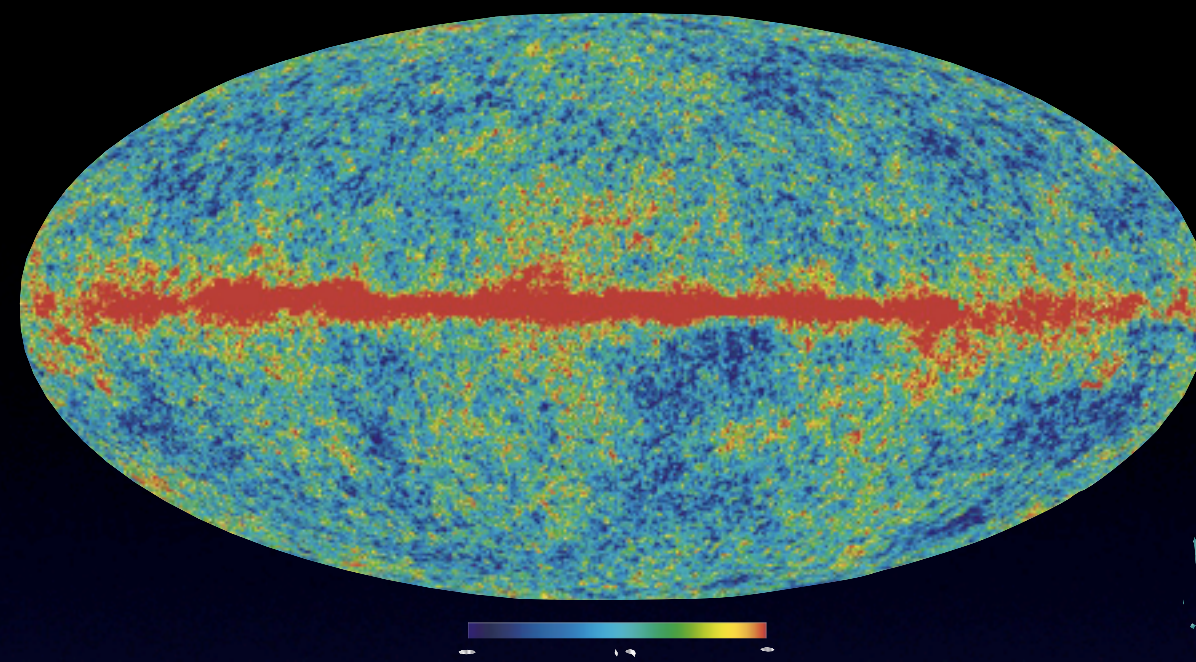
↓

Cold dark matter with neutrino mass

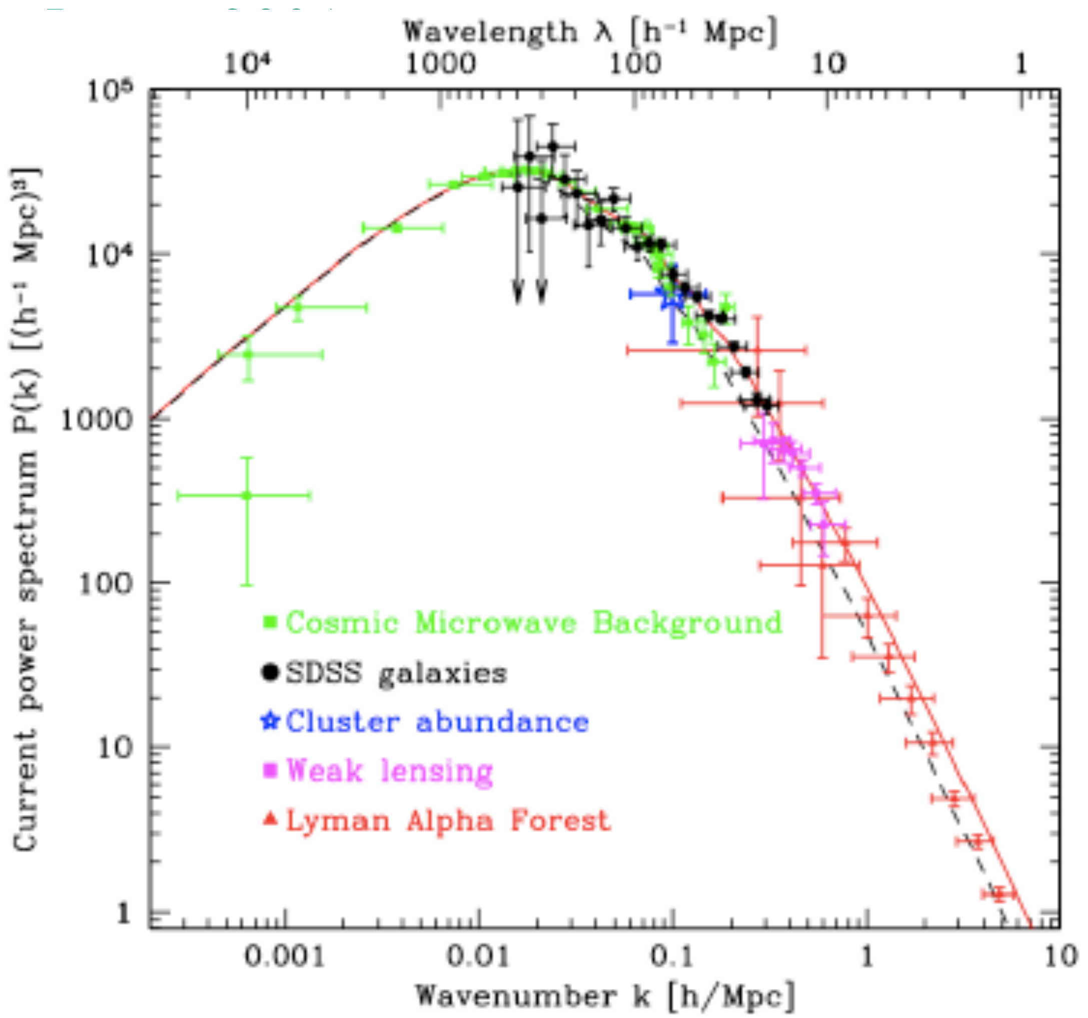
Colombi, Dodelson, & Widrow 1995

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

Neutrino Mass Sensitivity



WMAP Temperature Map (2006)



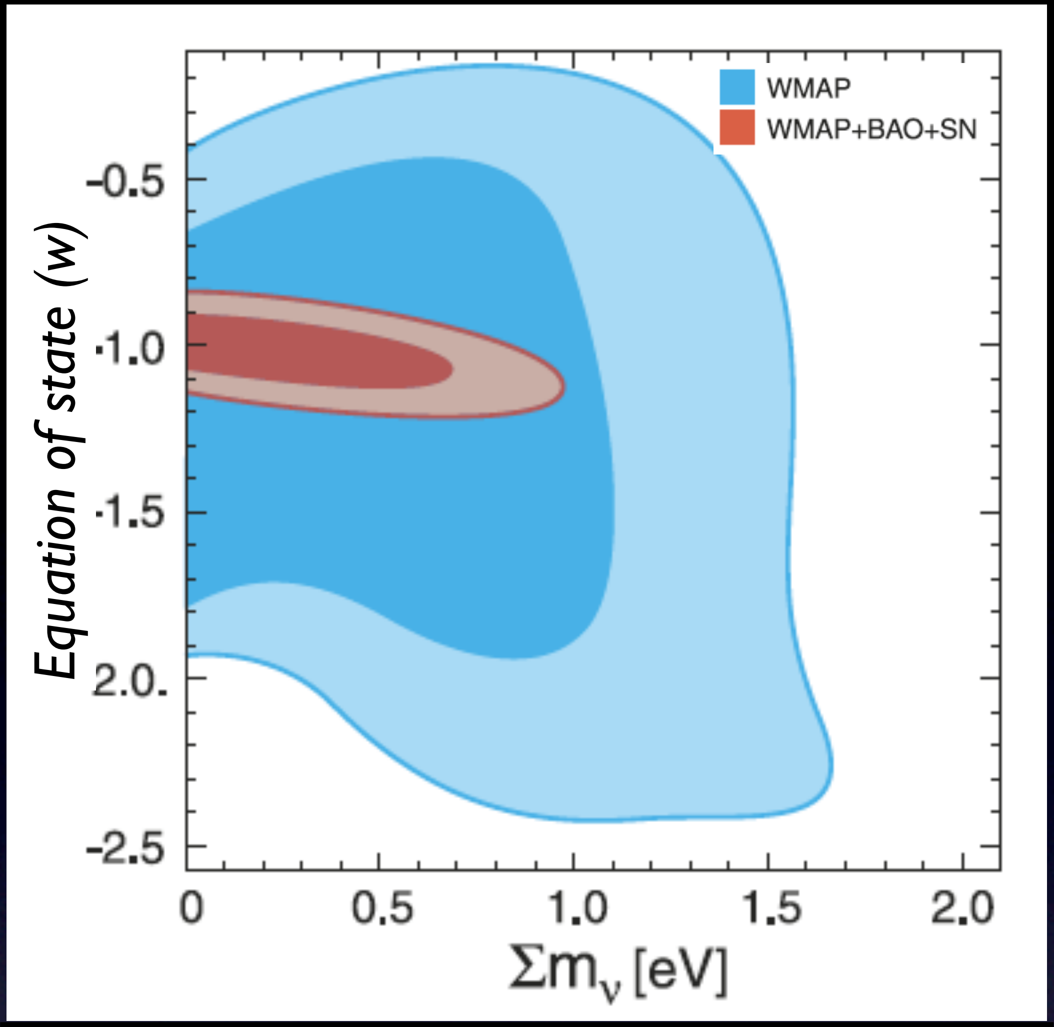
Tegmark 2005

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

Cosmology places constraints on the energy density of neutrinos.

Limits & Datasets

- Strong limits can be further achieved by combining data collected from WMAP, Sloan Digital Sky survey (SSDS), and others.
- Tensions in data highlighted by change in limits.
- Relaxation of certain assumptions also highlights string model dependencies.



S. Hennestad, Phys. Rev. Lett.95.221301

E. Komatsu et al, Astrophys.J.Suppl.180:330-376,2009

(Fogli, arXiv:060806v1)

$\Sigma\, m_\nu < 2.3$ eV (WMAP5) **2σ Limits**

$\Sigma\, m_\nu < 1.2$ eV (WMAP5+SDSS)

$\Sigma\, m_\nu < 0.8$ eV (WMAP5+SDSS+SN+BBN)

$\Sigma\, m_\nu < 0.6$ eV (CMB+LSS+SNIa+BAO)

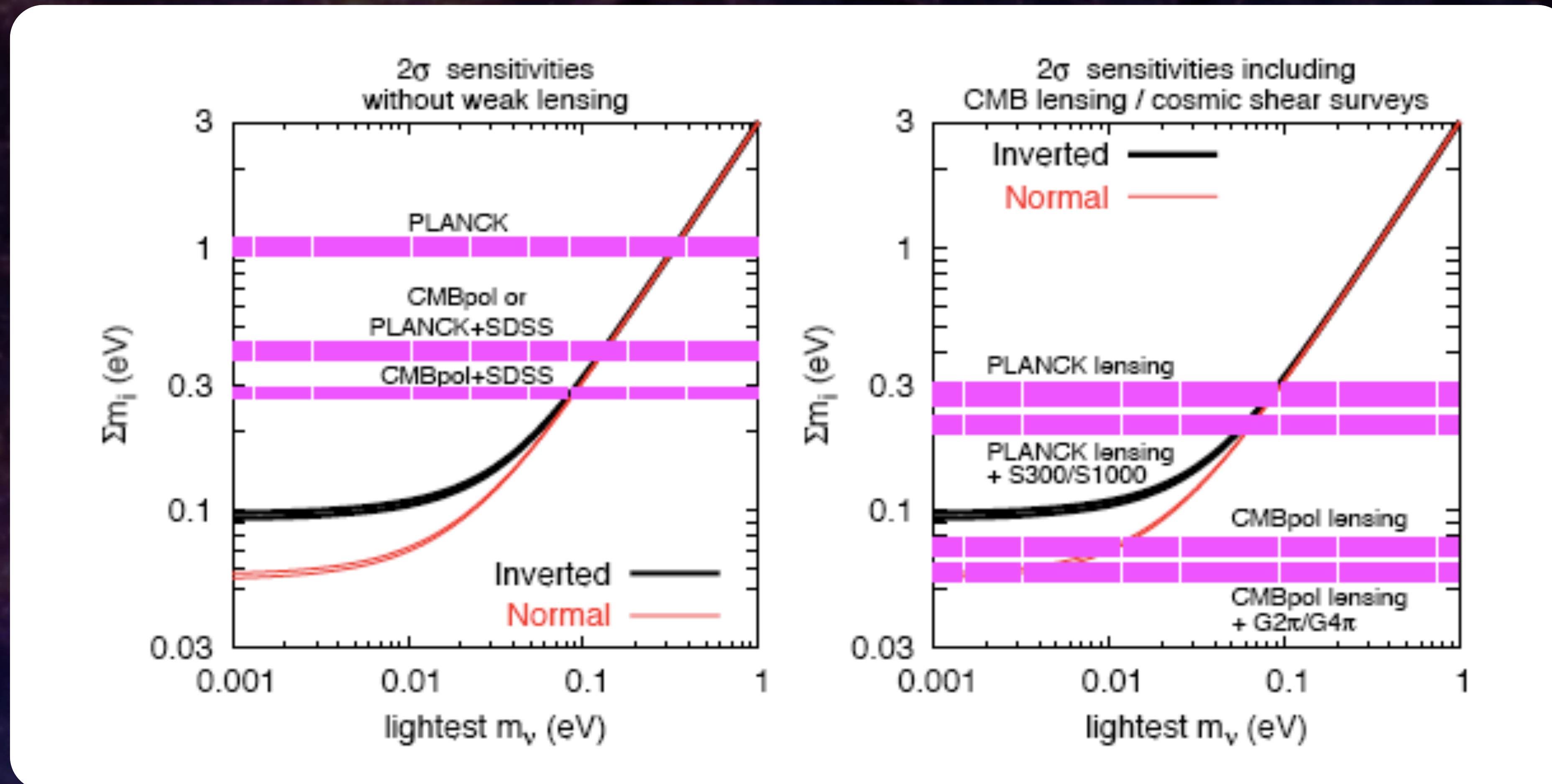
$\Sigma\, m_\nu < 0.2$ eV (CMB+LSS+SNIa+Ly-α)

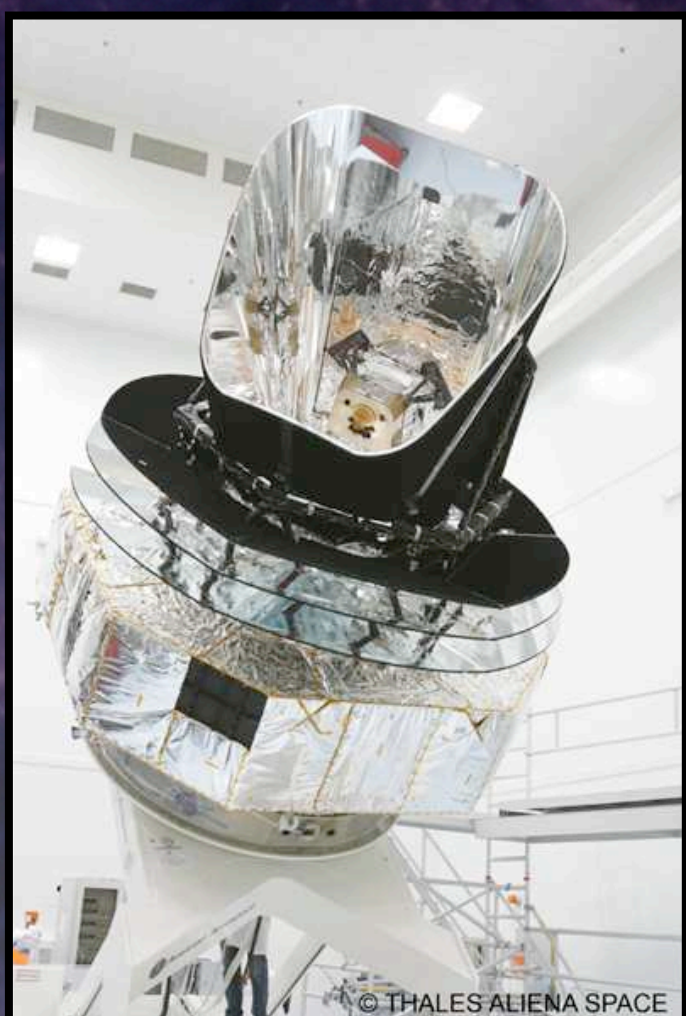
New Frontiers

Planck Satellite:

Launched May 14th, 2009

New Frontiers





- Enhanced sensitivity to the microwave background should provide stronger constraint on neutrino mass from cosmological sources:
- Should be able to push down to $\sum m_\nu \sim 100$ meV at 95% C.L. by combining with other observations.

"...down they fell, driven headlong from the pitch of heaven, down into this deep...", Paradise Lost

What we will cover:

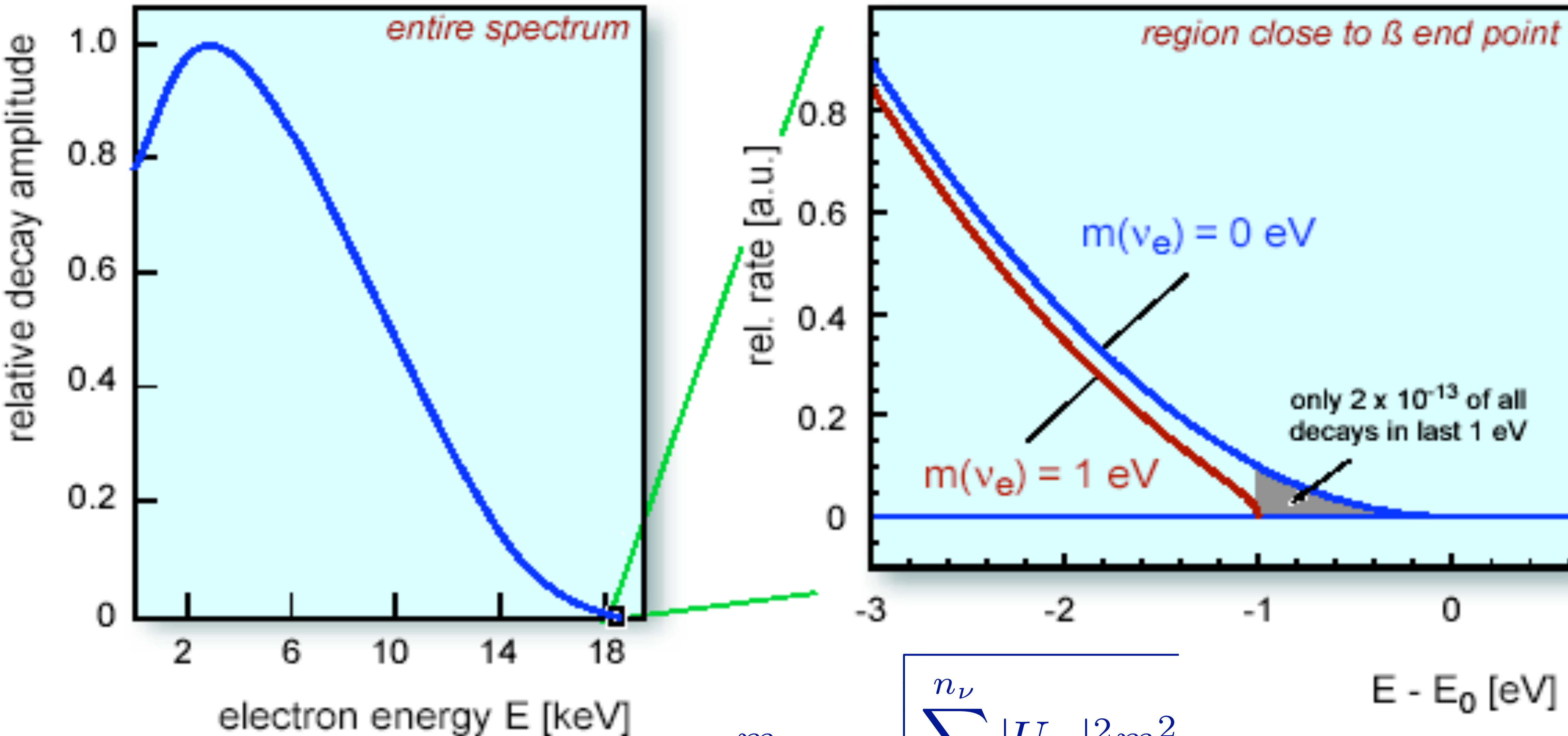
The role that neutrinos play.

Measuring neutrinos from the Heavens

Measuring neutrinos on Earth

Connecting back?

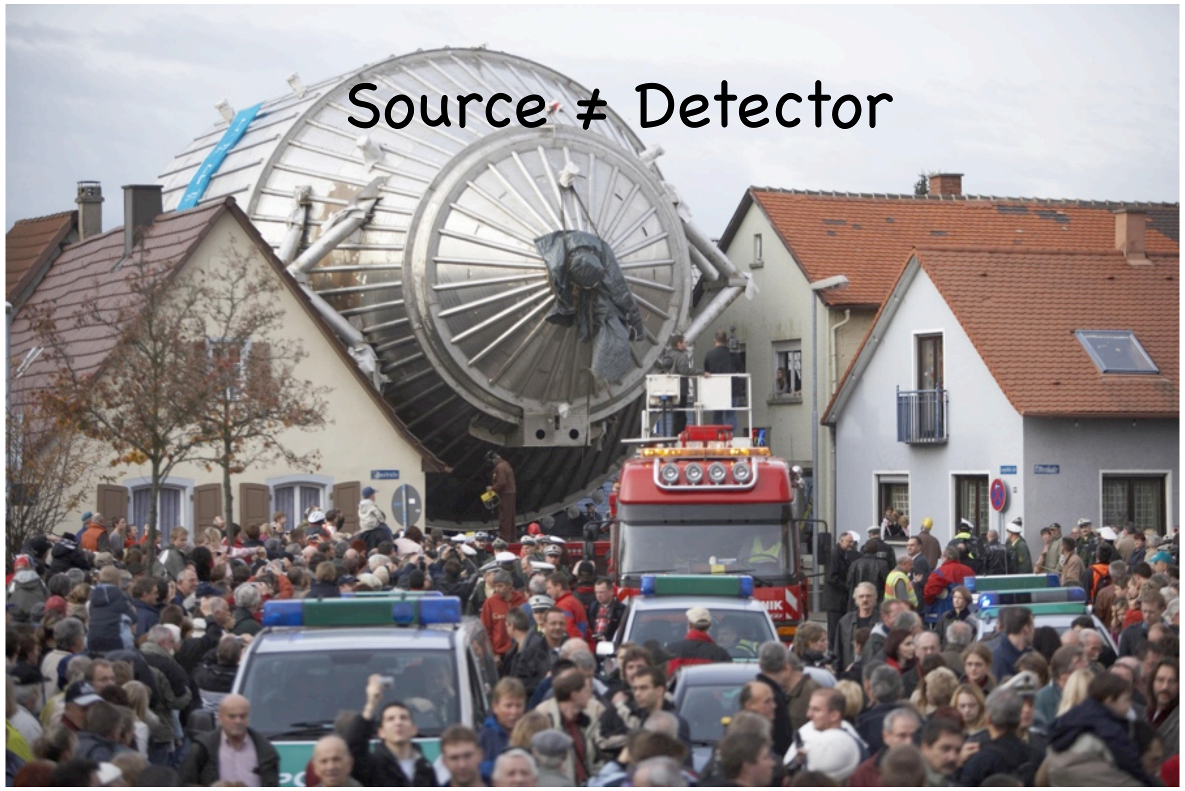
Direct Probes



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

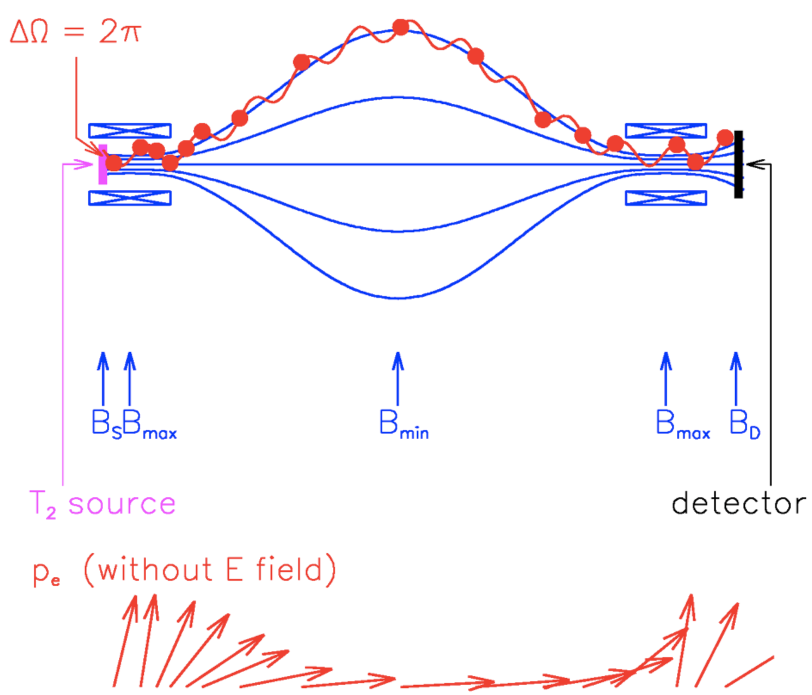
Beta decay allows a *kinematic* determination of the neutrino mass

No dependence on cosmological models or matrix elements



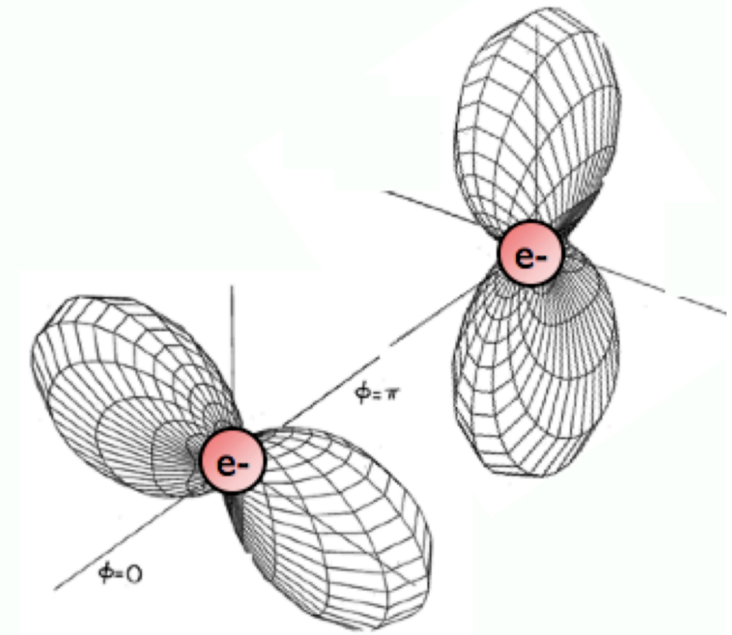
KATRIN

Spectroscopy



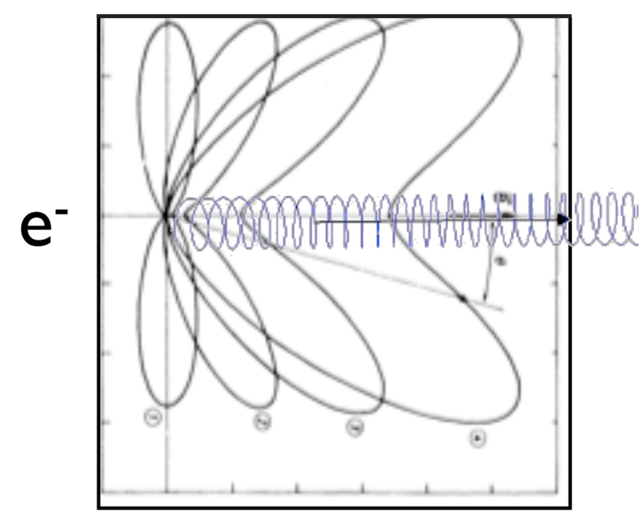
$$^3\mathrm{H} \rightarrow {}^3\mathrm{He}^+ + e^- + \bar{\nu}_e$$

Source = Detector



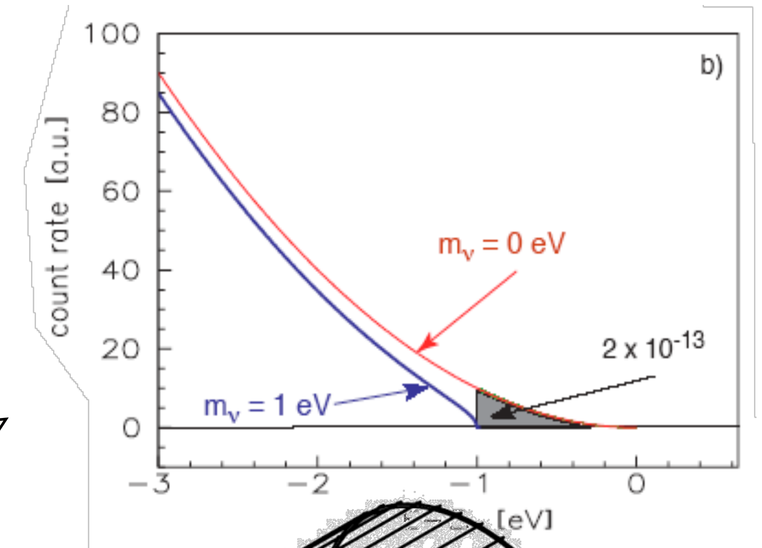
Project 8

Frequency



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

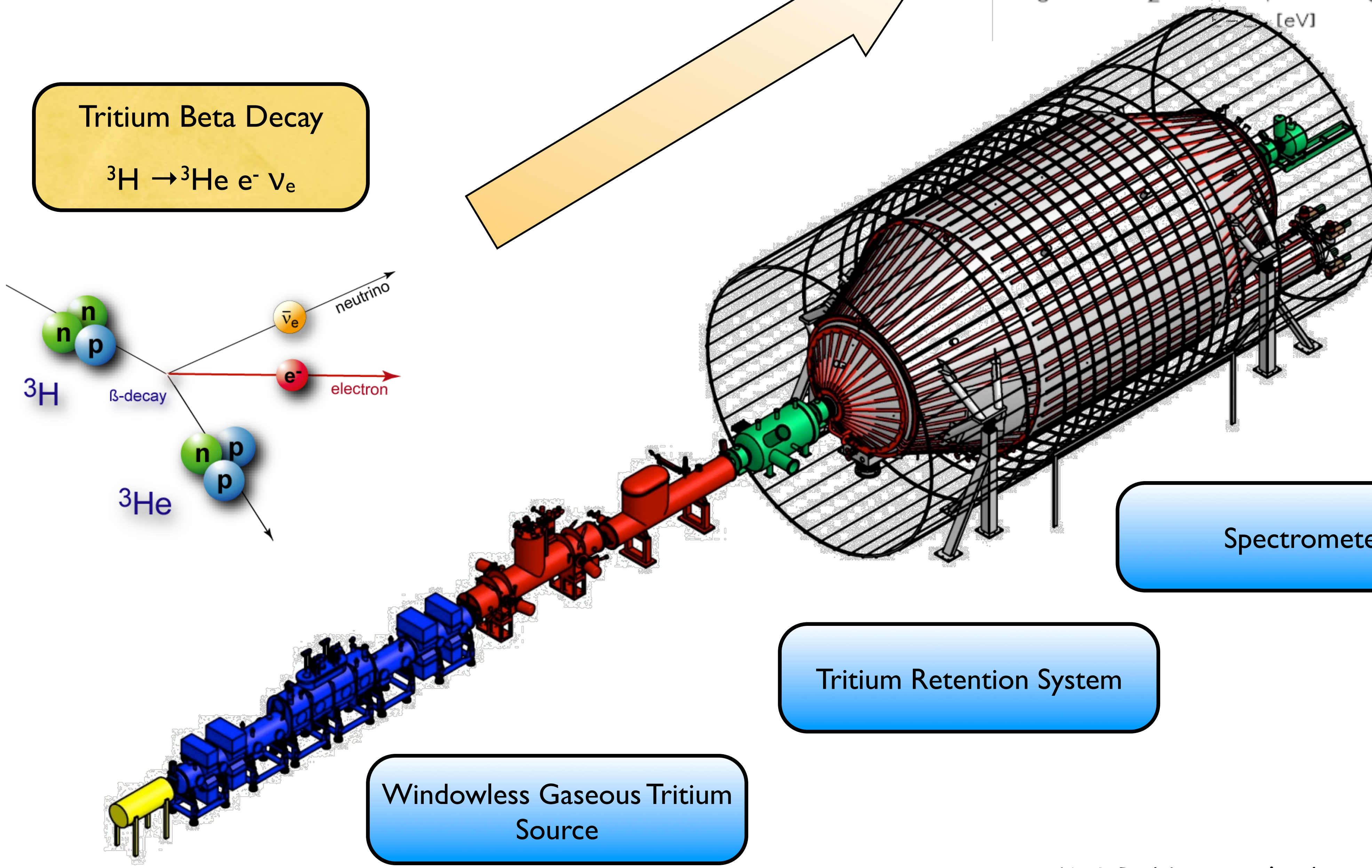
The KATRIN Experiment



Electron Beta Decay Spectrum

Tritium Beta Decay

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



Electron Detector

Spectrometer

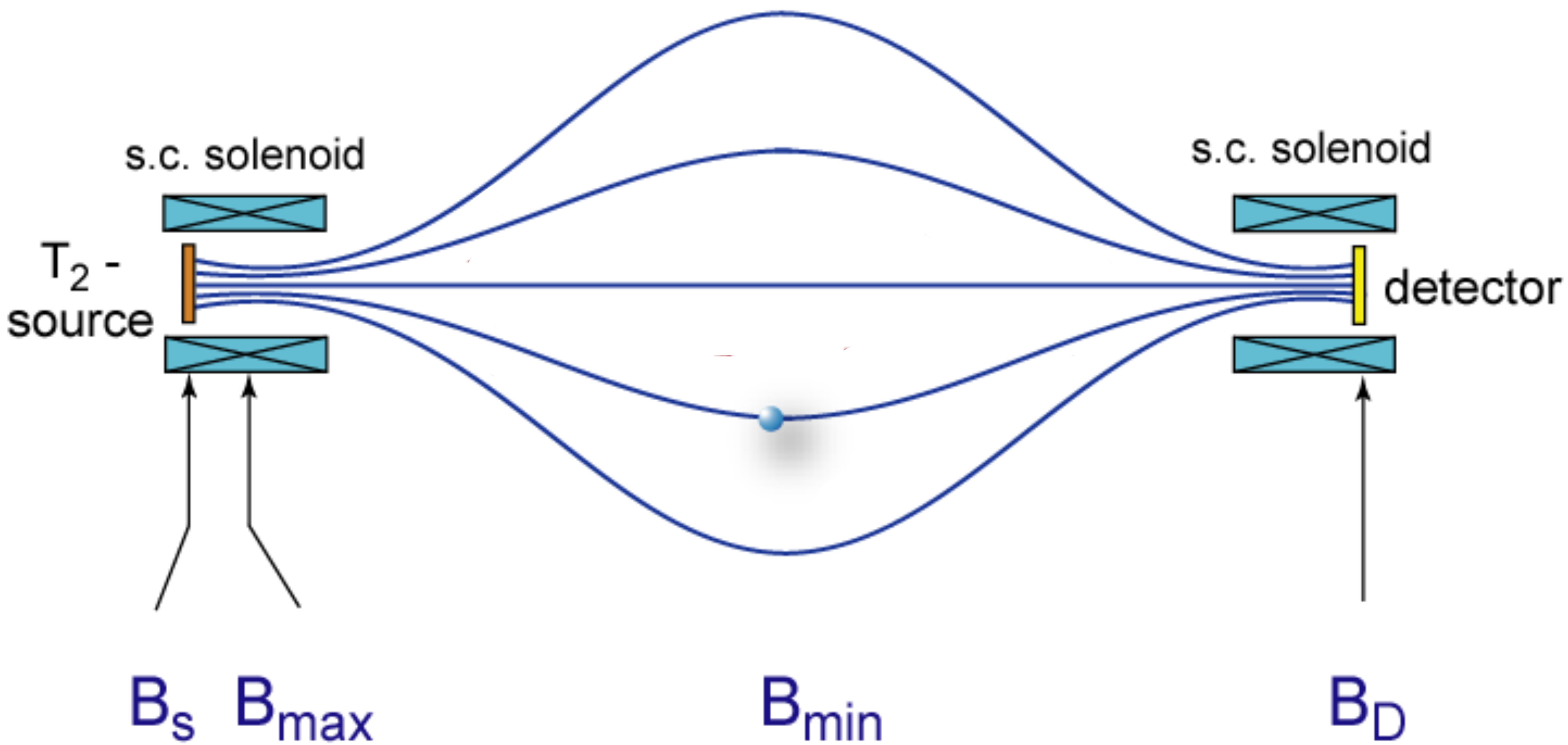
Tritium Retention System

Windowless Gaseous Tritium Source

Rear Calibration & Monitoring

- KATRIN uses the beta decay from (gaseous) tritium to probe the absolute neutrino mass scale.

The MAC-E Filter Technique

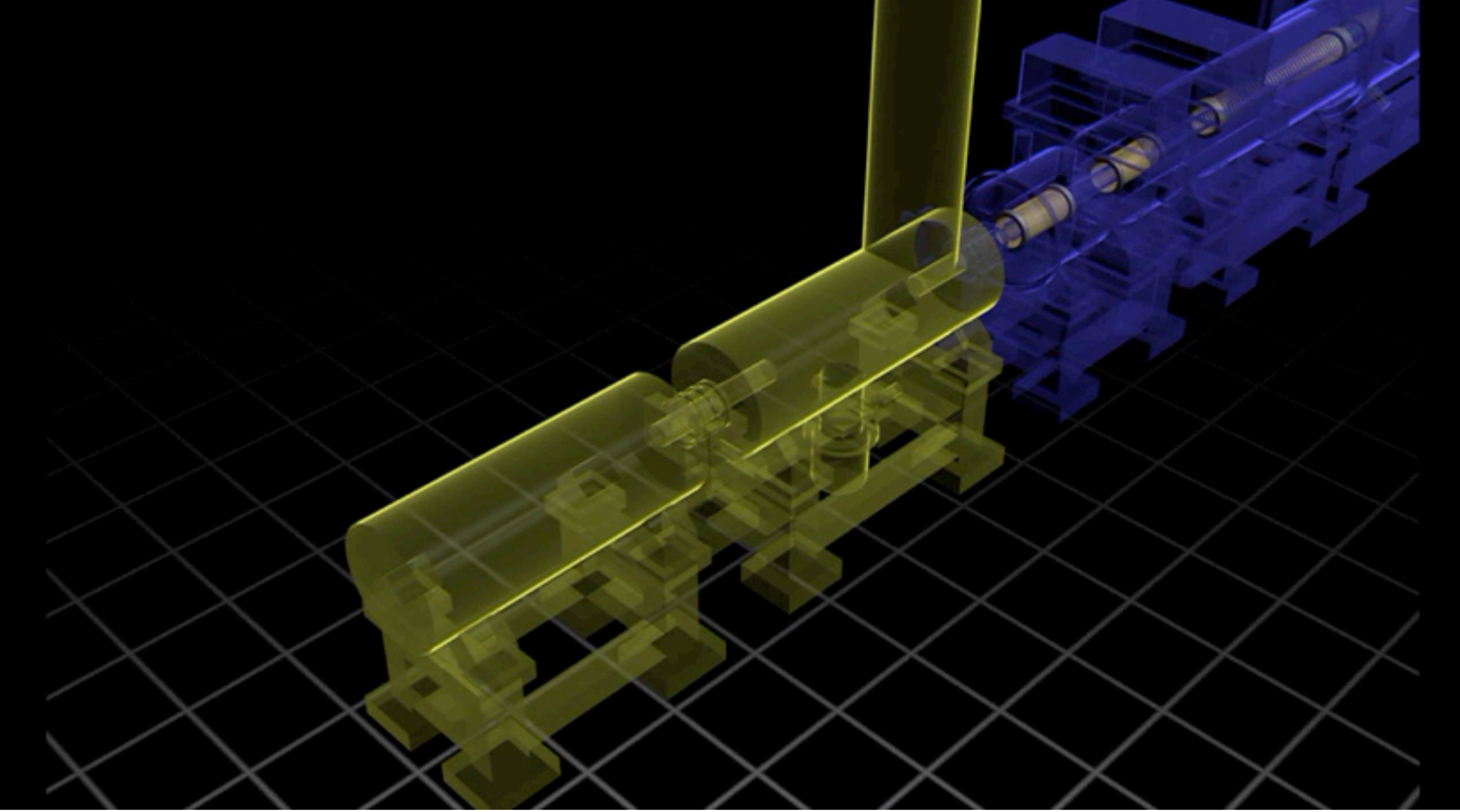


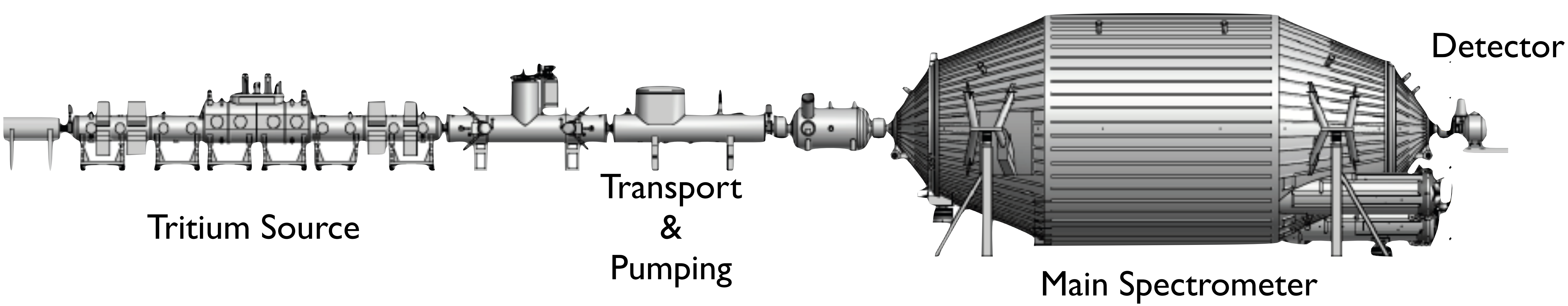
Magnetic Adiabatic Collimation:

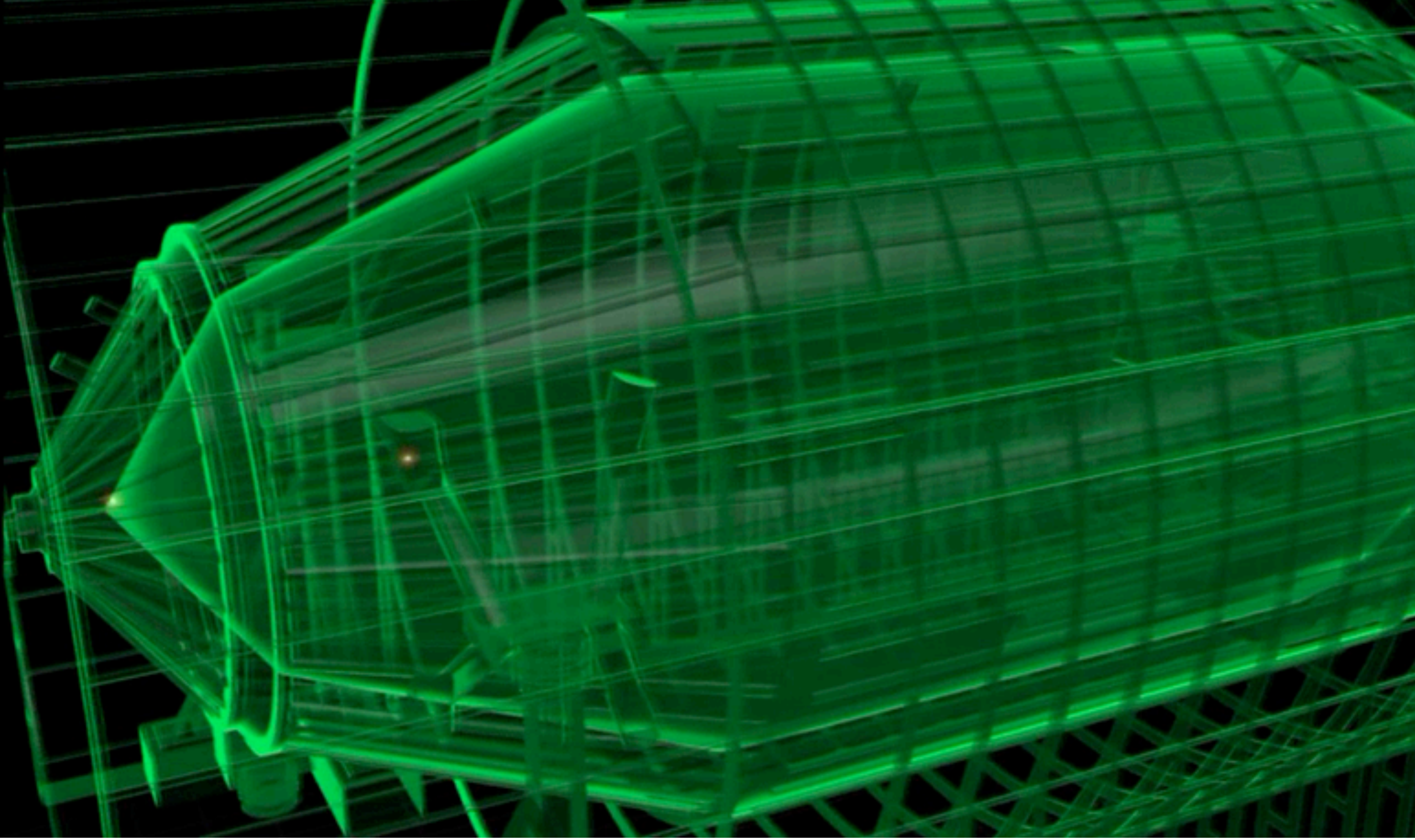
- Use adiabatic guiding to move β-particles along B-field lines.
- Field constrained by 2 s.c magnets.

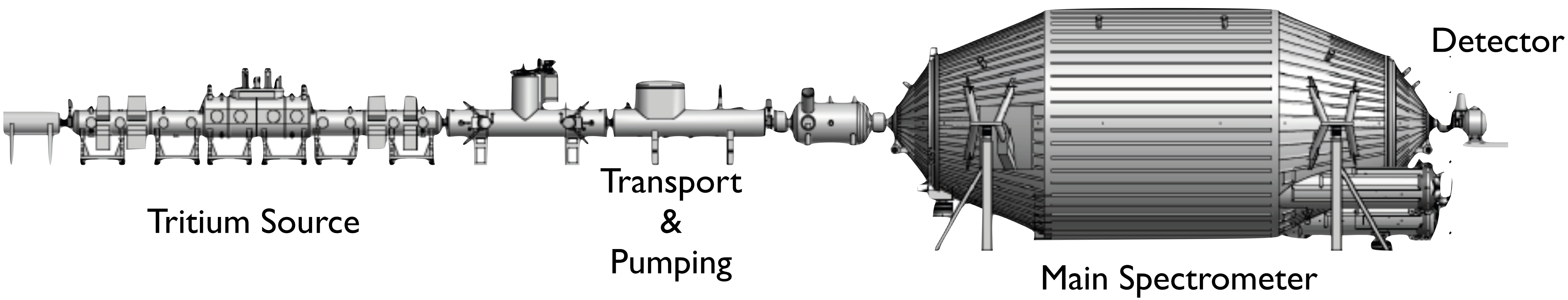
Electrostatic Filter:

- Use retarding potential to remove β^- particle below threshold.
- High pass filter (variable potential)

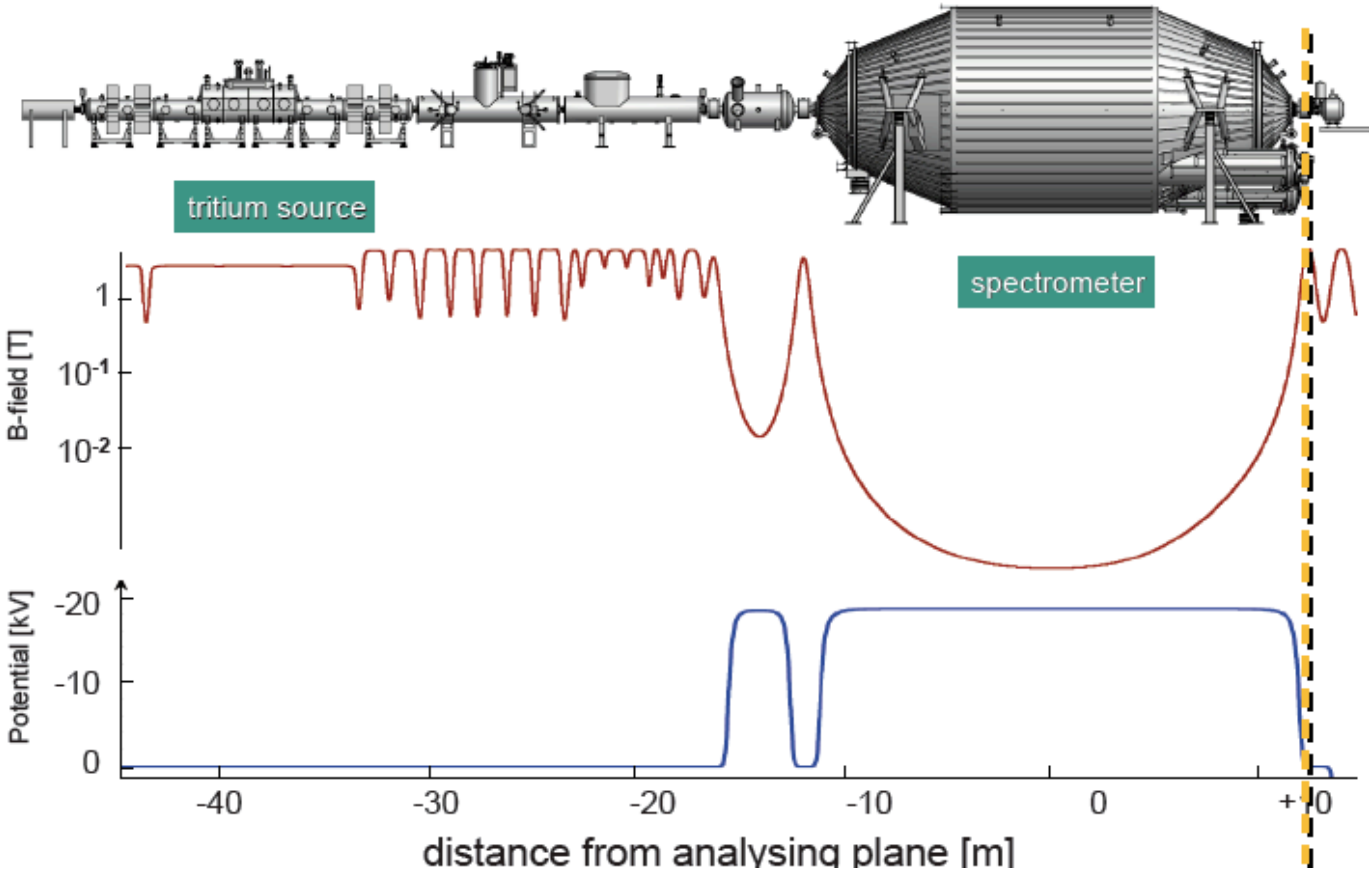



Detector
Transport
&
Pumping
Tritium Source
Main Spectrometer



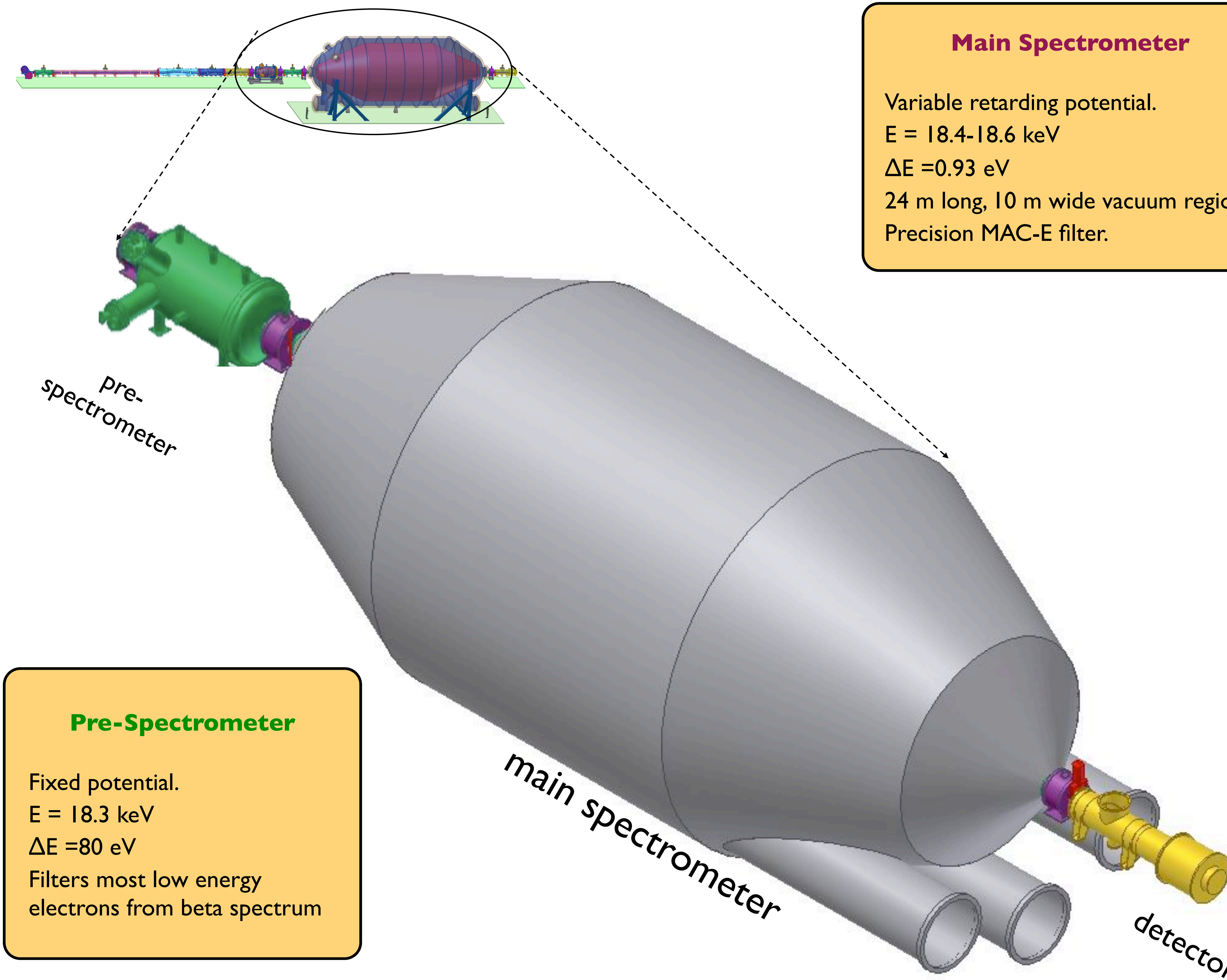

Detector
Transport
&
Pumping
Tritium Source
Main Spectrometer

Electromagnetic Fields



Main Spectrometer

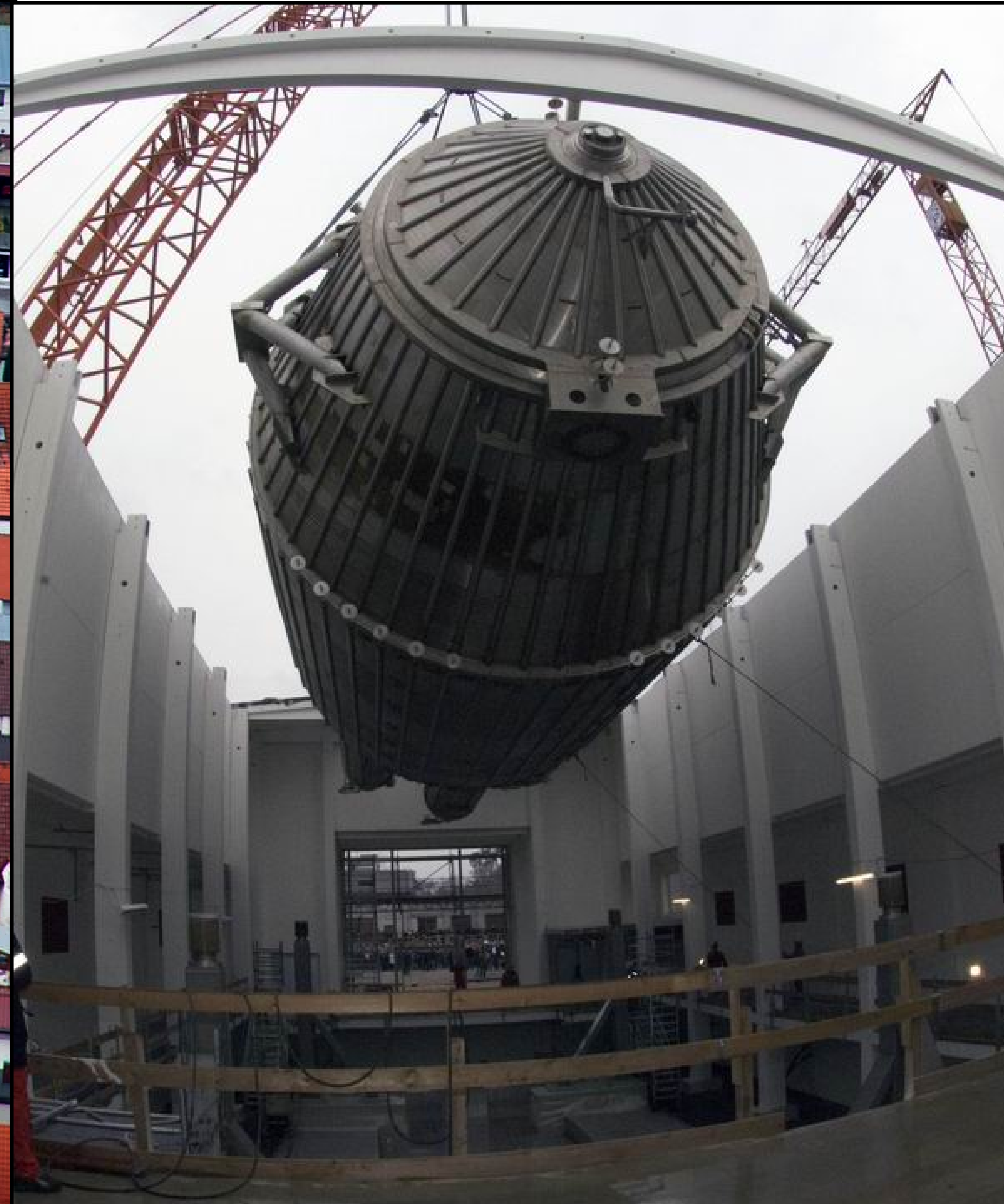
Variable retarding potential.
E = 18.4-18.6 keV
ΔE =0.93 eV
24 m long, 10 m wide vacuum region.
Precision MAC-E filter.



Pre-Spectrometer

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


PHOTO



KATRIN Lands!

KATRIN Lands!

Wire installation

Cryostat housing

WGTS Demonstrator

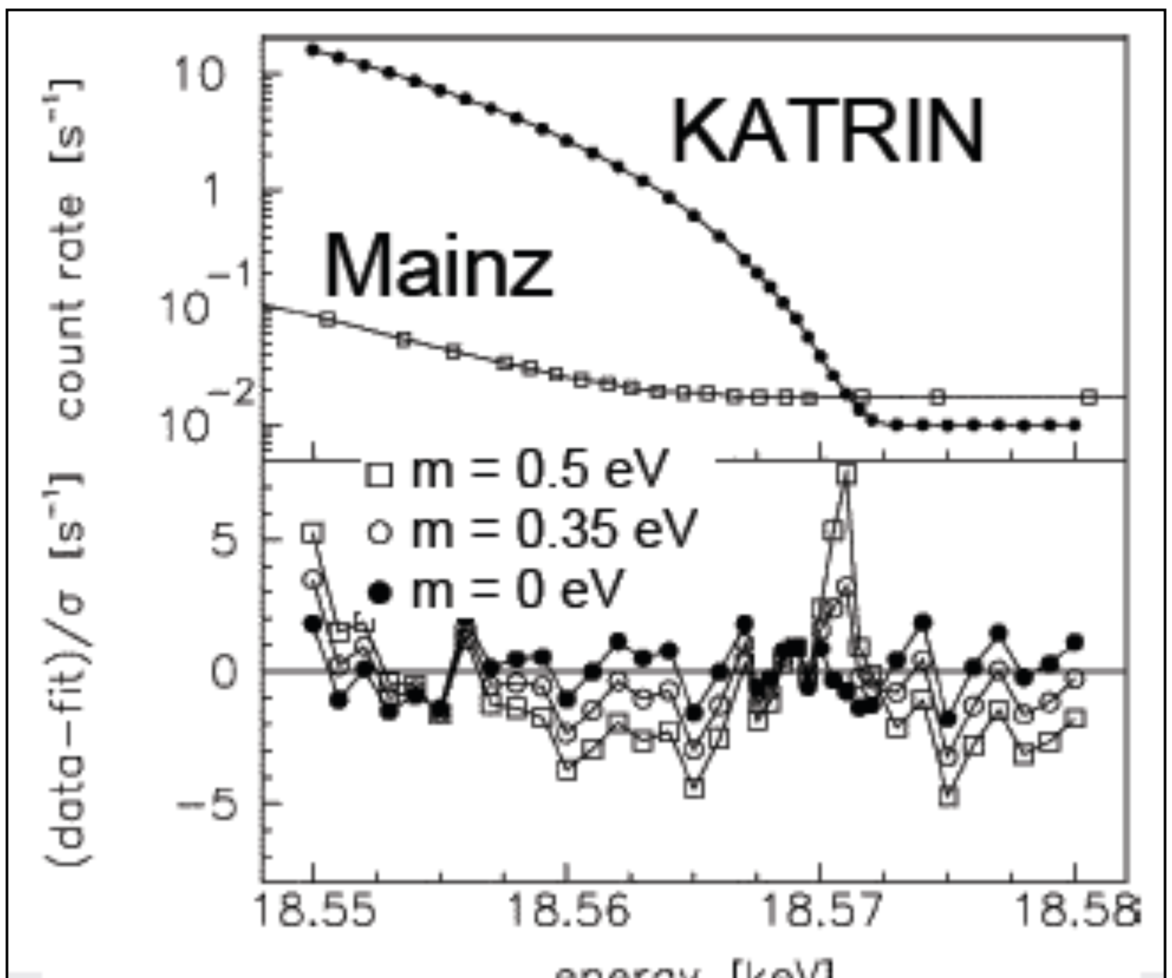
Focal Plane Detector

Final Sensitivity

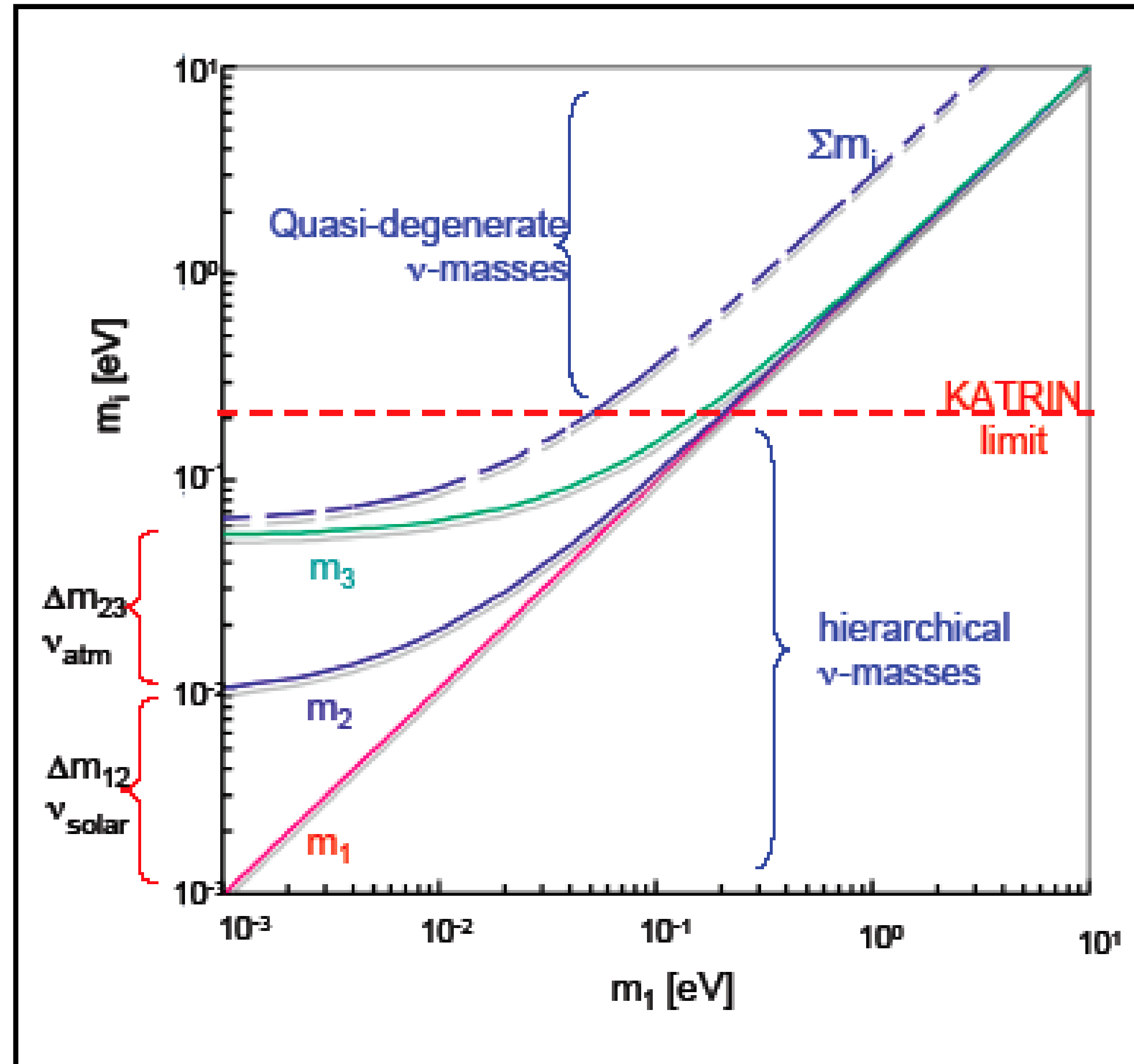
Neutrino Mass Sensitivity

350 meV (at 5σ)

200 meV (at 90% C.L.)



Statistics & Sensitivity



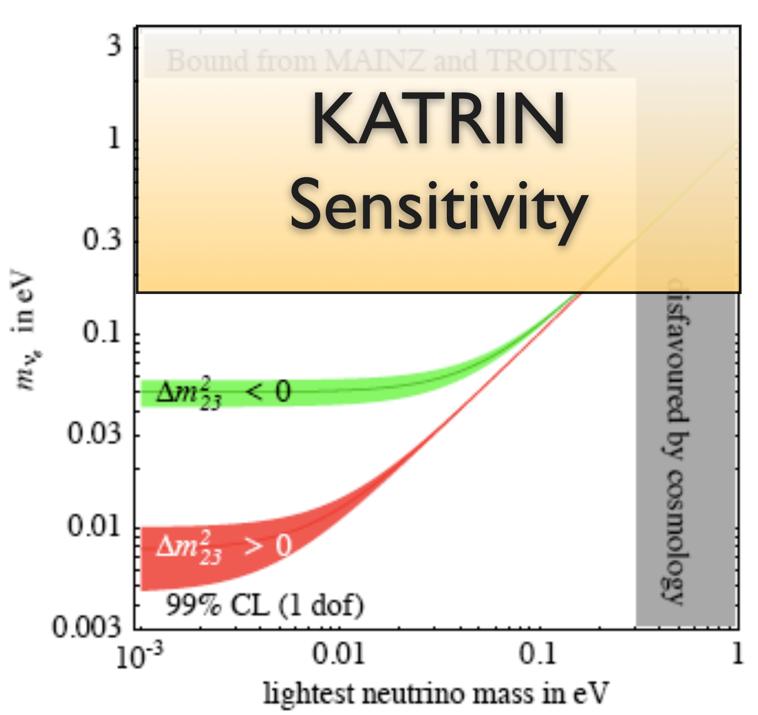
Mass sensitivity

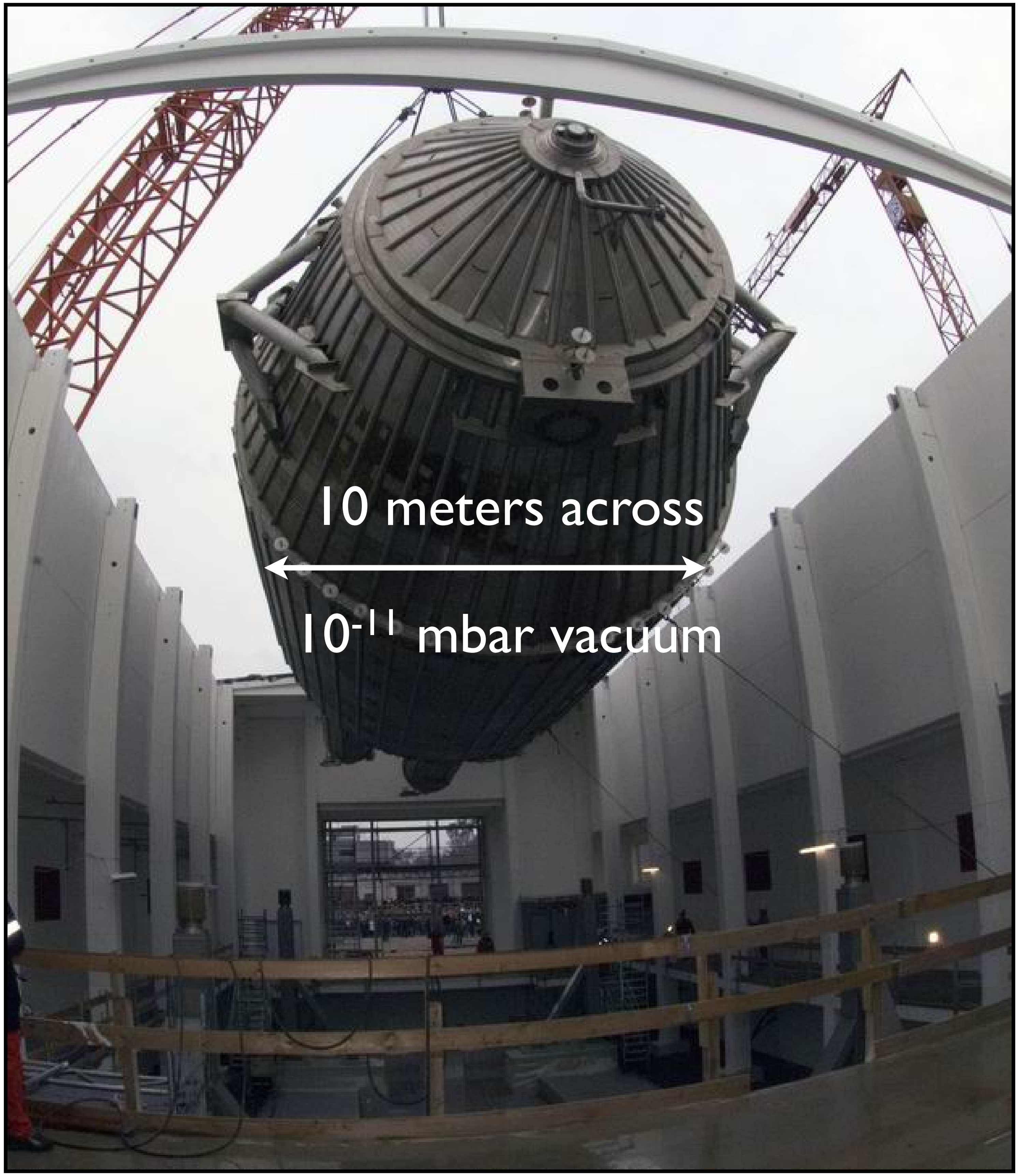
- Slotted to begin taking data in 2012. Will achieve sub-eV sensitivity after just a few months of operation.
- Final sensitivity at the 200 meV level (90% C.L.)

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.





Measuring Energy with Frequency

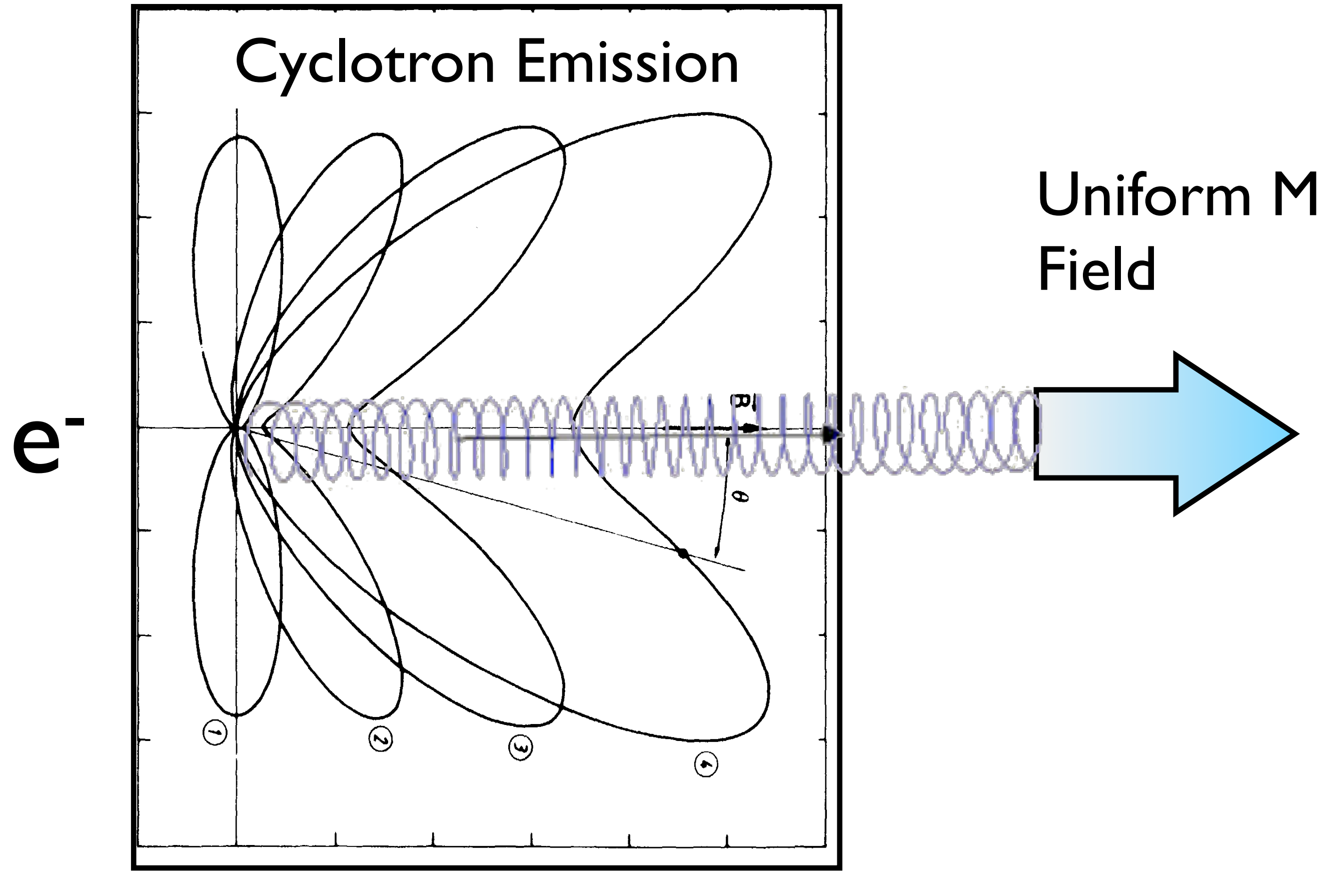
- Take advantage of cyclotron *radiation* created by a relativistic electron moving in a uniform magnetic field.

- This provides a non-destructive means of measuring the electron energy, escaping the limitations of Louiville's theorem.

I. I. Rabi

"Never measure anything but frequency."

A. L. Schawlow



Measuring Energy with Frequency

- In a uniform magnetic field, an electron will undergo cyclotron motion.
- *Emitted* frequency is independent of pitch angle of the electron and depends solely on the relativistic boost.

I. I. Rabi

"Never measure anything but frequency."

A. L. Schawlow

Cyclotron Frequency

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

electron mass

kinetic energy

Radiative Power Emitted

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

The Concept

Cyclotron Frequency

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

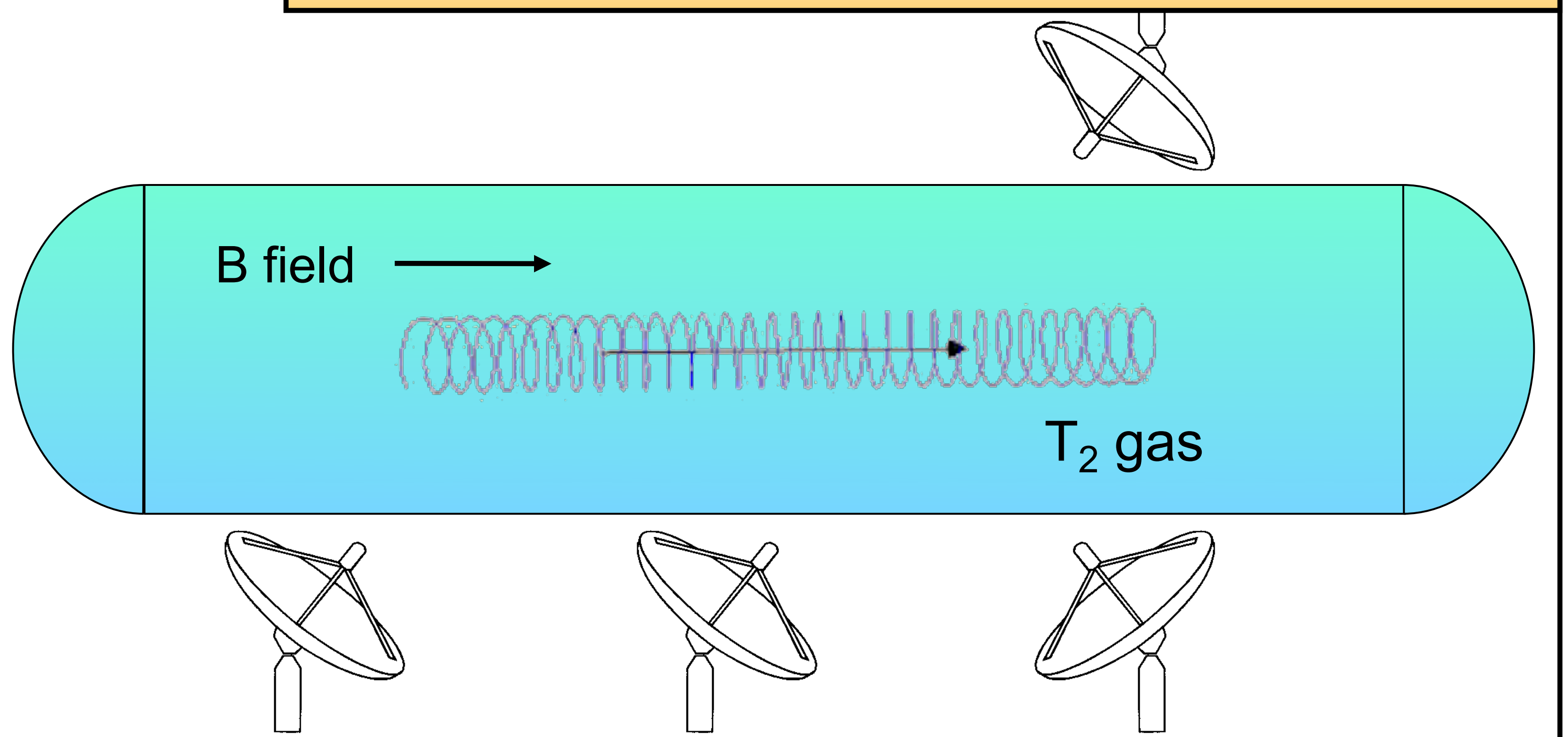
- Coherent radiation emitted can be collected and used to measure the energy of the electron in a non-destructive manner.

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
Published in Phys. Rev. D80:051301 (2009).

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



Energy Resolution & Power

- Since this is now a frequency measurement, the energy resolution is determined by how long one can observe the radiation.

$$\Delta\omega \propto \frac{1}{T}$$

- For a 1 eV resolution, this corresponds to a frequency resolution of 2 x 10^{-6}, or 30 μs integration time.

- This time scale also sets the maximum density o the T_2 source (before electron scatters), around 10^{11} atoms/cm^3.

- At a 1 Tesla field, about 10^{-15} W of power is emitted by the electron.

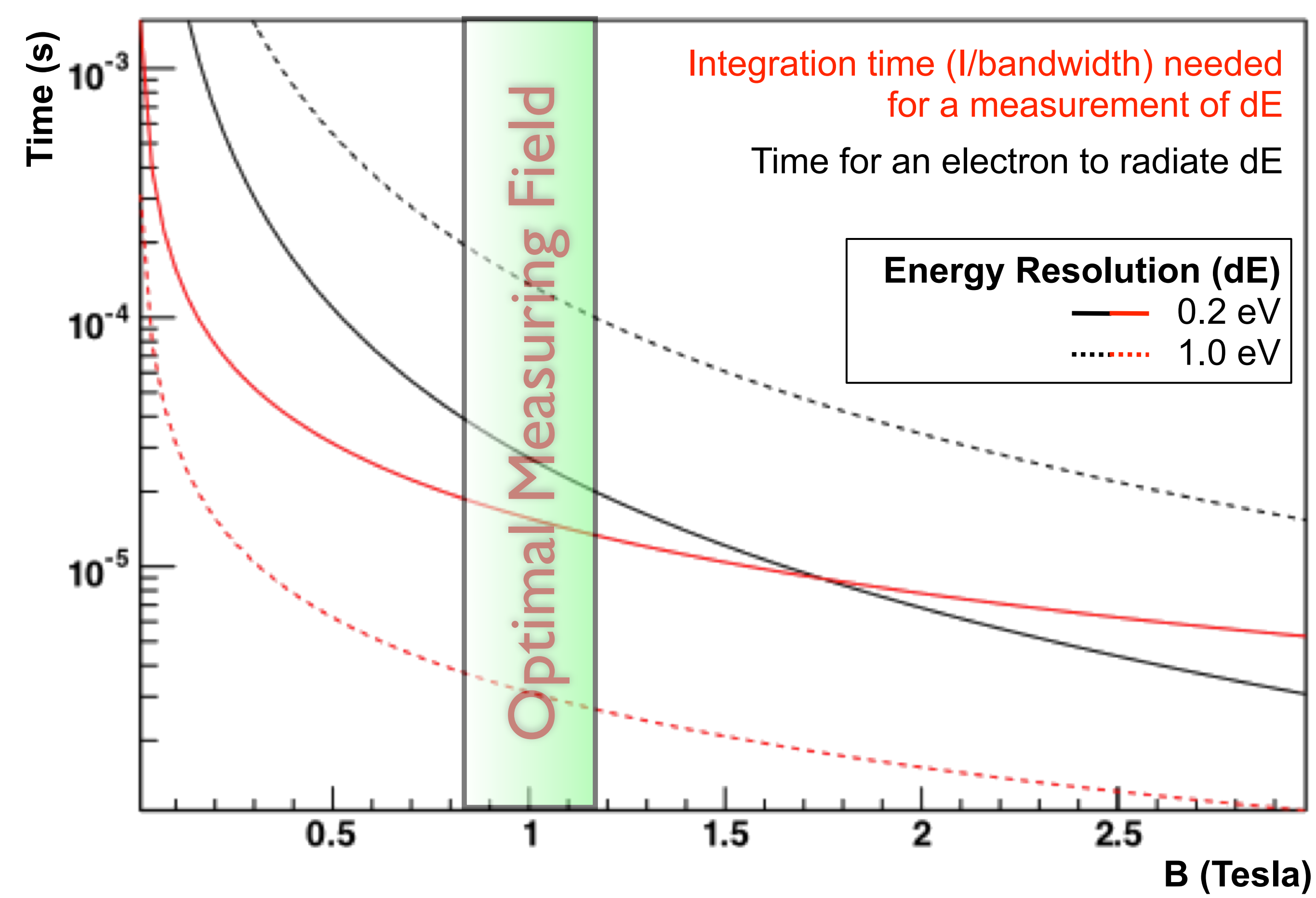
- With 50 kHz bandwidth, noise temperature of 20K yields ~10^{-18} W.

Ultimate Resolution

$\delta\omega/\omega \cong 10^{-6}$ (great!)

in 30 μs... (hard)

(however, keep in mind longer measuring times possible)



Energy Resolution & Power

- Since this is now a frequency measurement, the energy resolution is determined by how long one can observe the radiation.

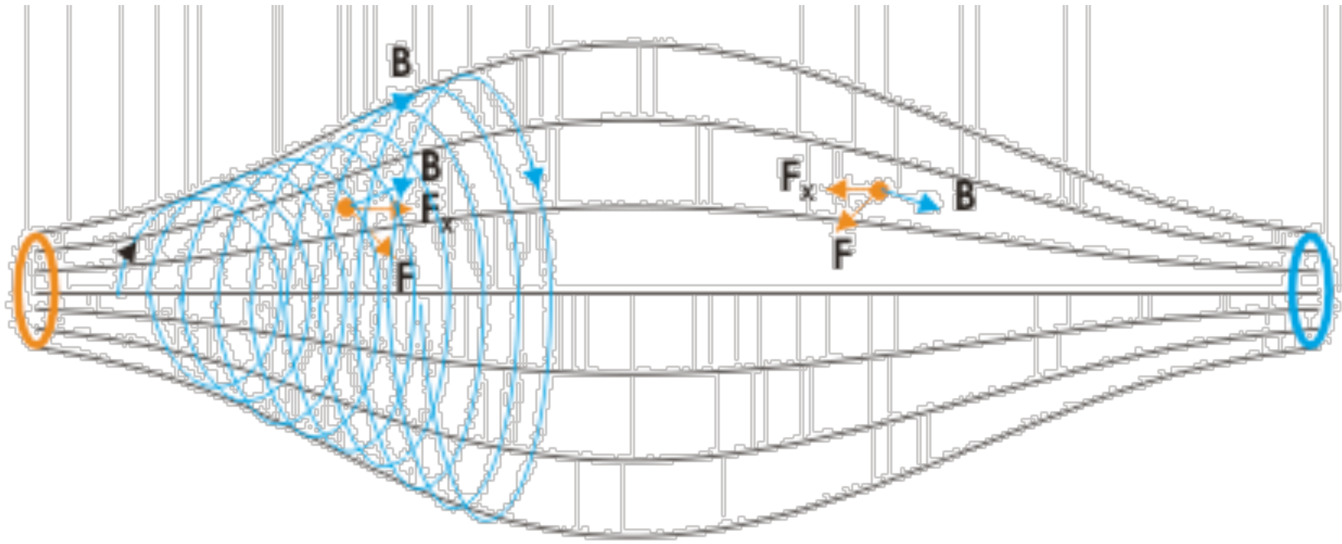
$$\Delta\omega \propto \frac{1}{T}$$

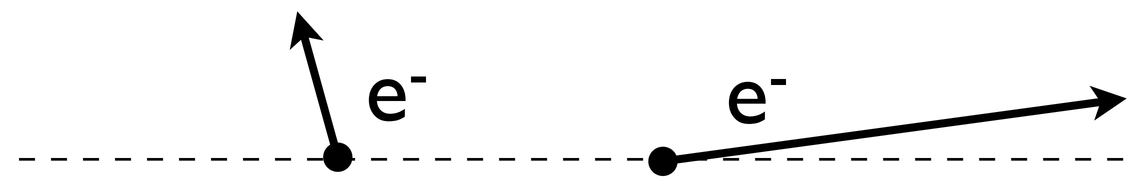
- For a 1 eV resolution, this corresponds to a frequency resolution of 2×10^{-6}, or 30 μs integration time.

- This time scale also sets the maximum density of the T_2 source (before electron scatters), around 10^{11} atoms/cm^3.

- At a 1 Tesla field, about 10^{-15} W of power is emitted by the electron.

- With 50 kHz bandwidth, noise temperature of 20K yields ~10^{-18} W.





High pitch angles: strong signals, longer measurement time, trapped.

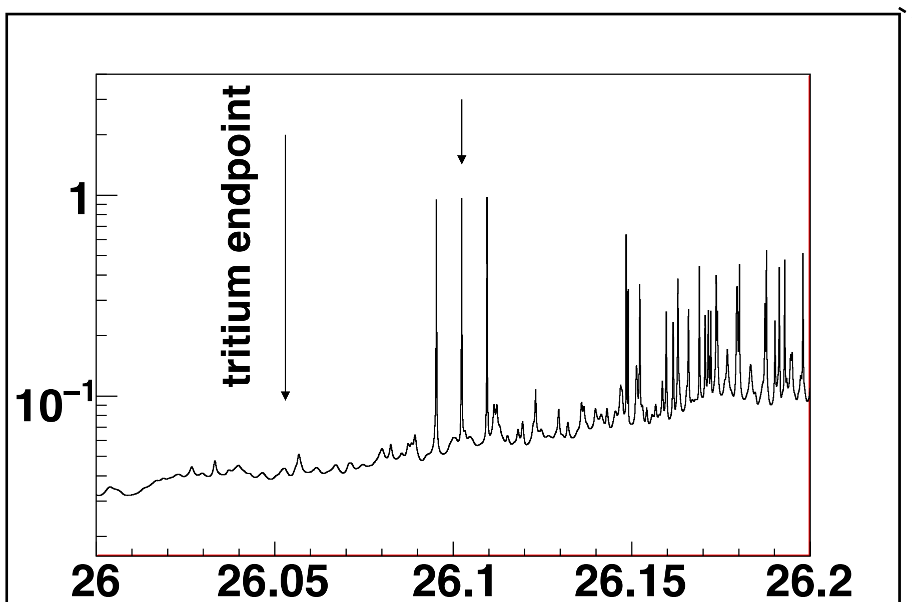
Low pitch angles: weak signals, short measurement time, quick exit

Signal Enhancement

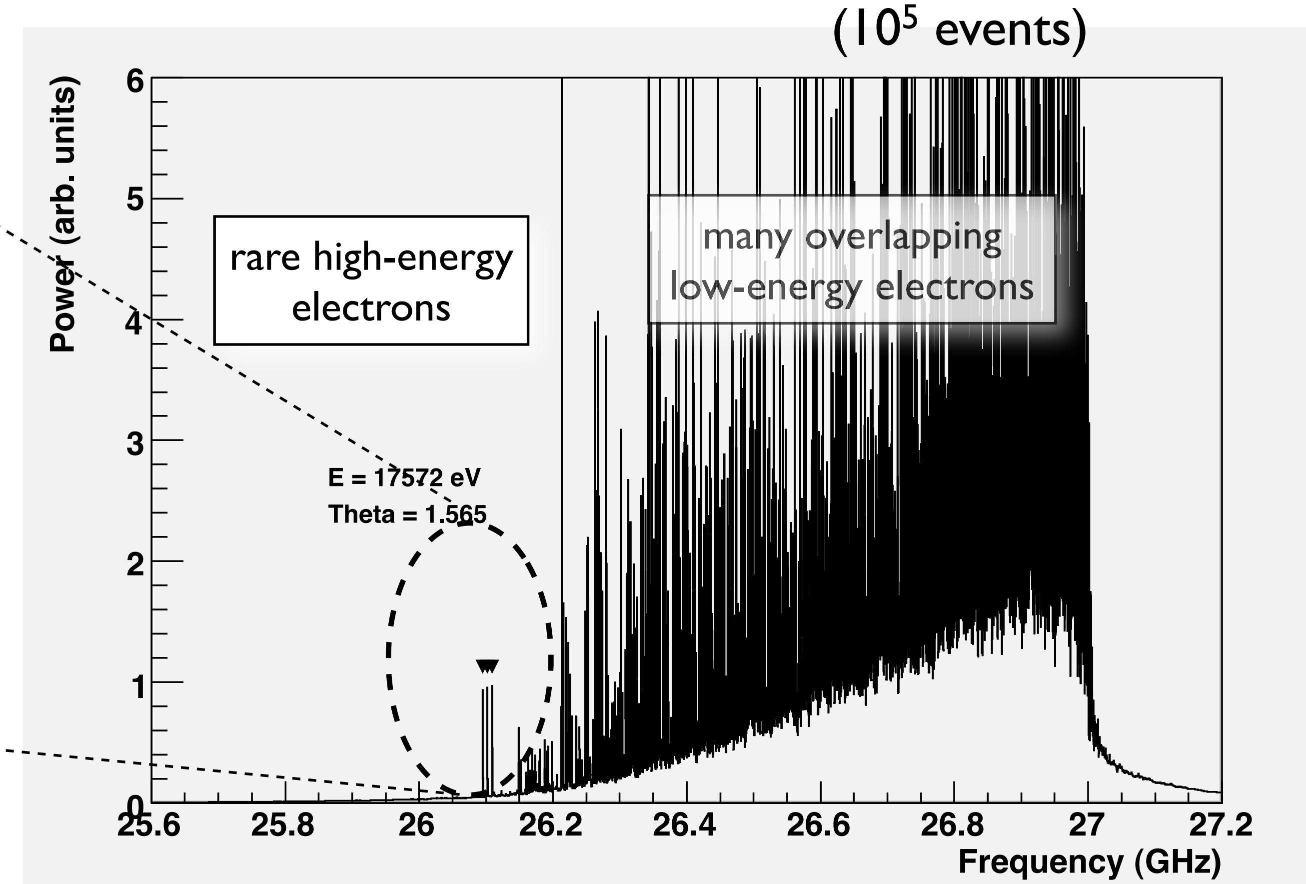
Electrons with motion parallel to field have weaker signals *and* shorter measurement times.

Sample Tritium Simulation

- 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.



Simulation run (10^5 events)



Project 8

- A small proto-collaboration has formed to explore this experimental possibility:

Massachusetts Institute of Technology & Haystack Observatories.

J.A. Formaggio, N. S. Oblath, D. Furse, P. Fisher,

A. Rogers and S. Doelman

University of California, Santa Barbara

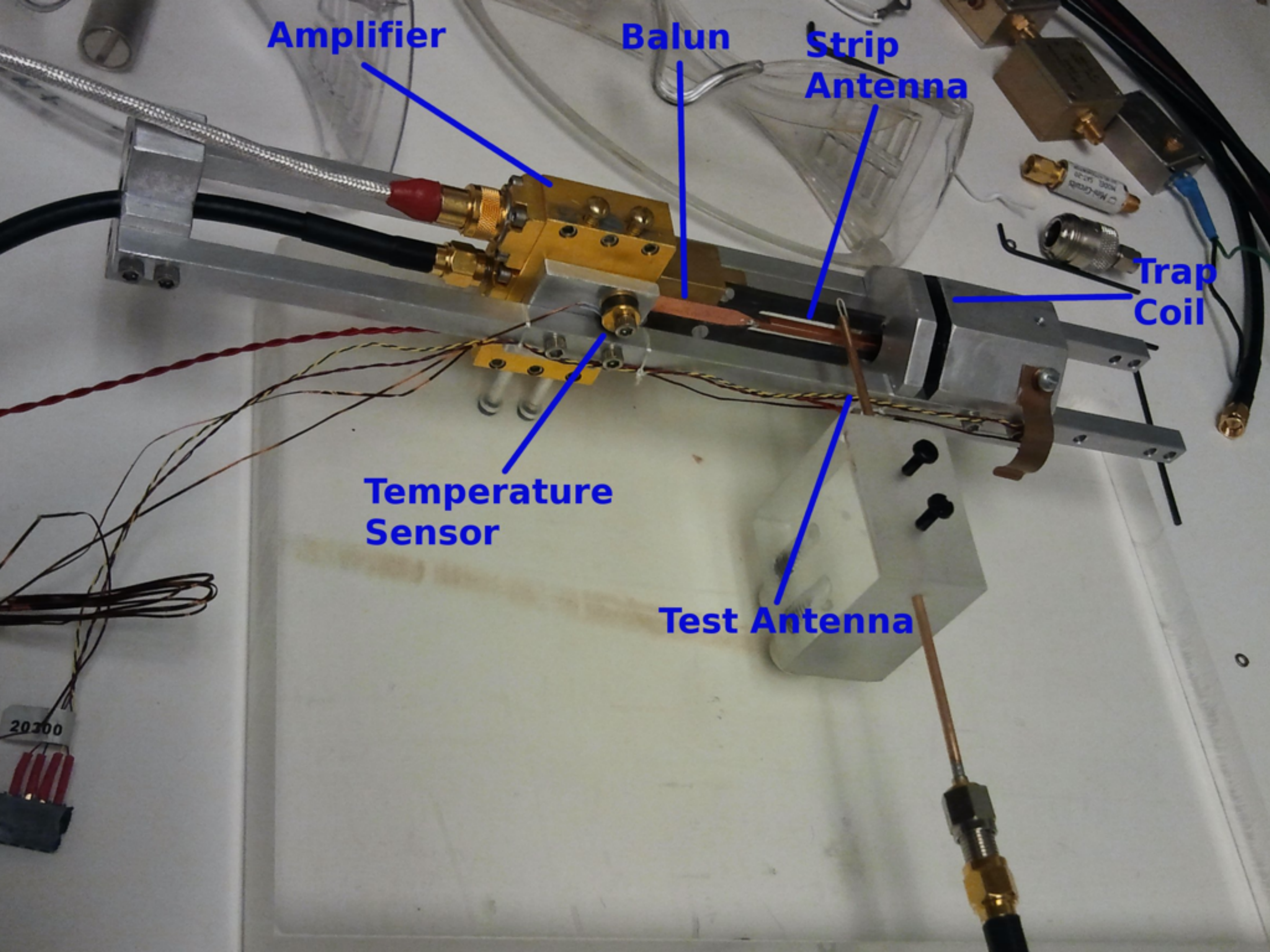
B. Monreal, M. Leber and M. Bahr

University of Washington

R.G.H. Robertson, P. Doe, L. Rosenberg, M. Miller,
G. Rybka,, B.VanDevender, L. Bodine, J. Heilman

National Radio Astronomy Observatory

R. Bradley



Amplifier
Balun
Strip Antenna
Trap Coil
Temperature Sensor
Test Antenna
20300

Plan to “go cold” in next few weeks.

"...and Prometheus was punished for giving fire back to mankind..."

What we will cover:

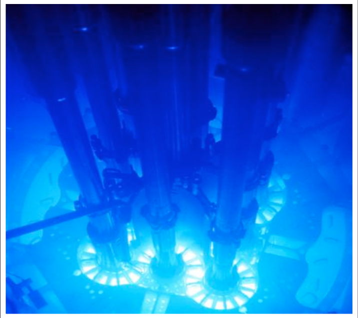
The role that neutrinos play.

Measuring neutrinos from the Heavens

Measuring neutrinos on Earth

Connecting back?

We have a good track record...



Neutrinos from reactors.

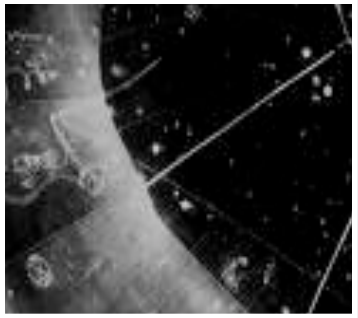
Detected (1950s)

Neutrinos from the sun.

Detected (1960s)

Neutrinos from the atmosphere.

Detected (1960s)

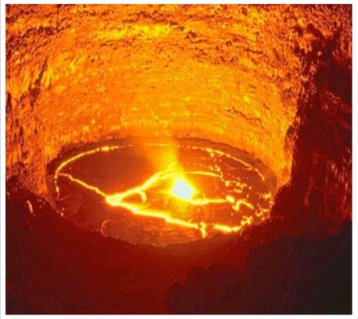


Neutrinos from accelerators.

Created & detected (1960s)

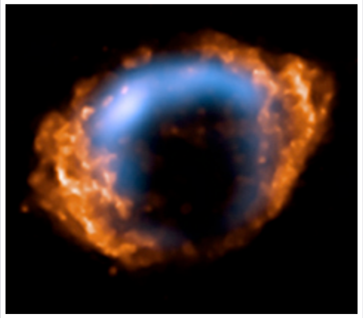
Neutrinos from supernovae.

Detected (1980s)



Neutrinos from the Earth.

Detected (2000s)



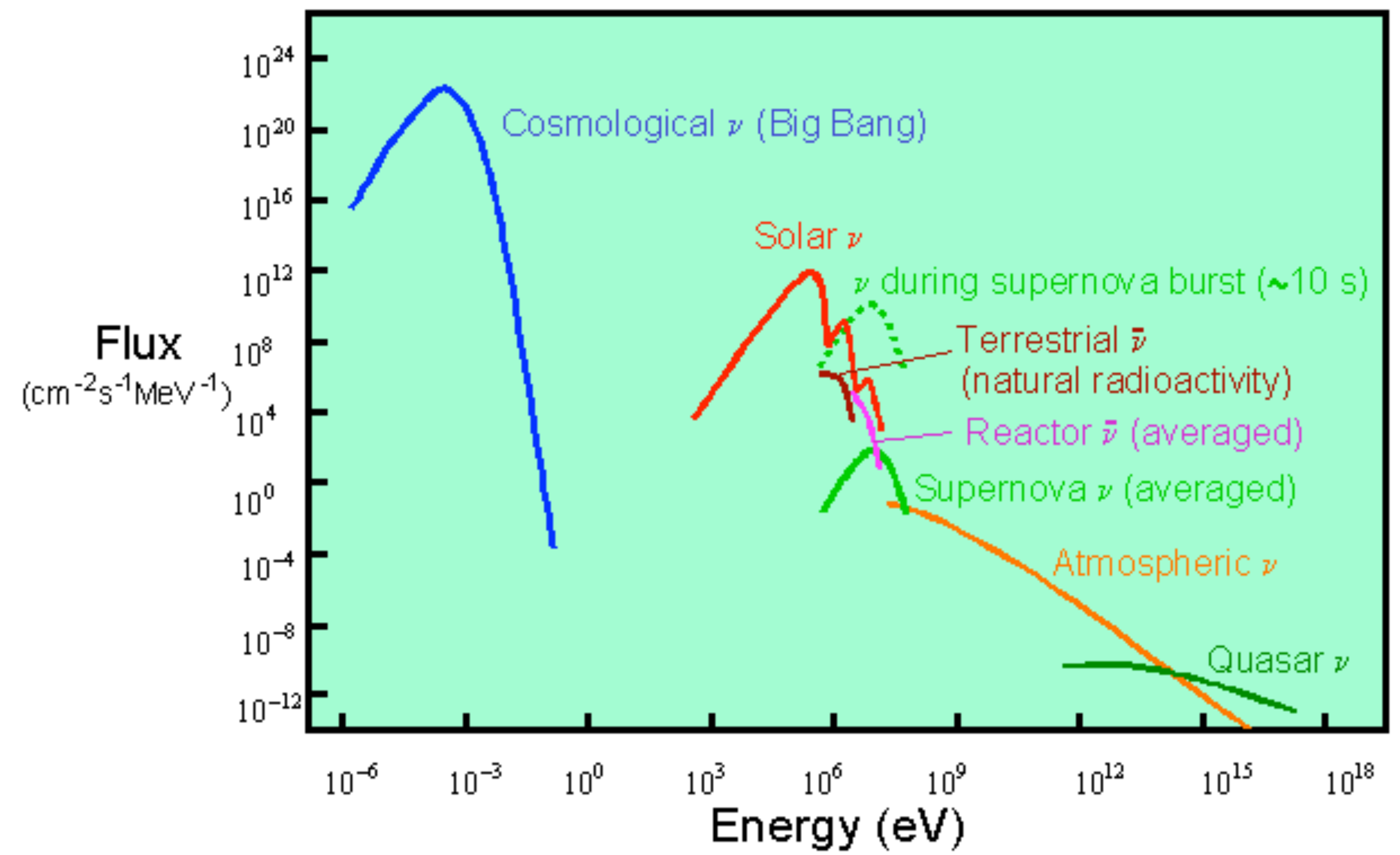
Neutrinos from galactic sources.

Not yet (but close!)

Neutrinos from the Big Bang.

Not even close...

Why is it so hard???



Flux on earth of neutrinos from various sources, in function of energy

- Cosmological neutrinos comprise the most intense natural source of neutrinos available to us from nature.
- The cosmological photon background has been measured incredibly well. The noise from the early big bang still rings today.

So??

What's the problem?!

Why is it so hard?

"Choice. The problem is choice."

- Actually, the problem is THRESHOLD.

- Consider, for example, ordinary inverse beta decay.

$$E_\nu + m_p \geq m_e + m_n$$

- But here the kinetic energy from relics is very small.

$$< K > \simeq 1.95 \text{ K } (0.17 \text{ meV})$$

$$\bar{\nu}_e + p \to e^+ + n$$

- Since energy is conserved, you need the neutrino to have enough energy to initiate the process.

- For most nuclei, you just do not have enough energy. You need a threshold-less process.

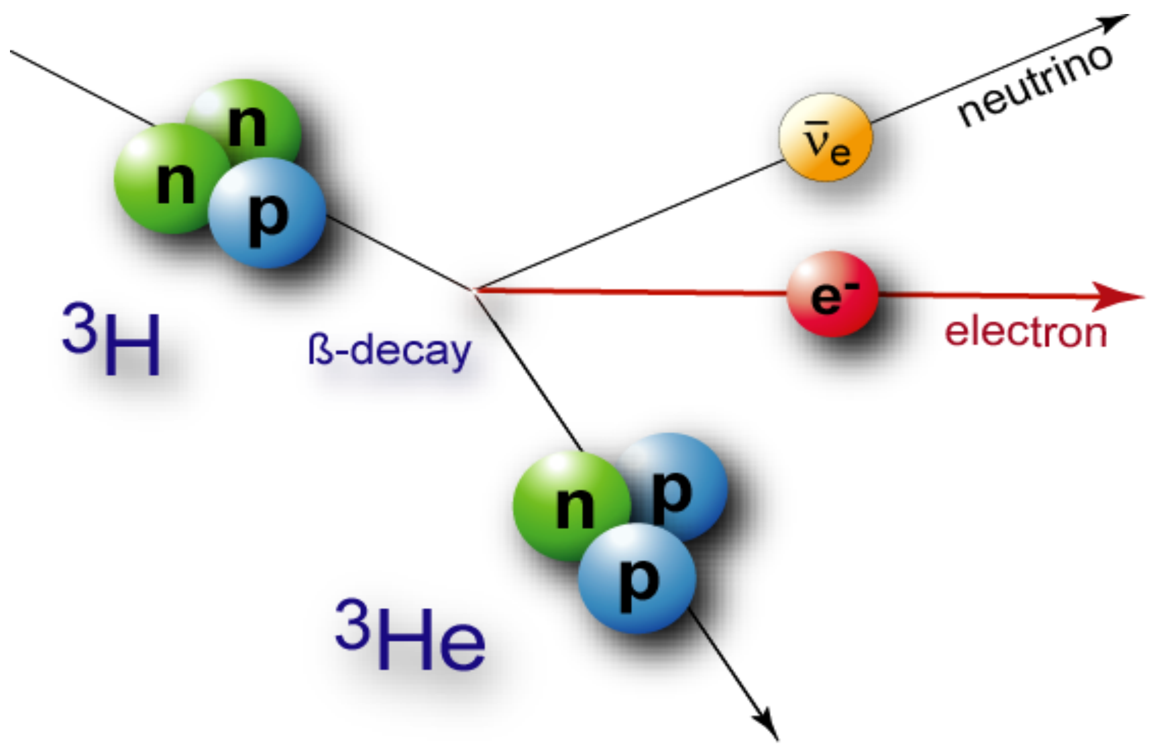
Some quotes....

"About every neutrino physicist goes through a phase in his or her career and asks 'There's got to be a way to measure the relic neutrino background...'" *P. Fisher*

Neutrino Capture

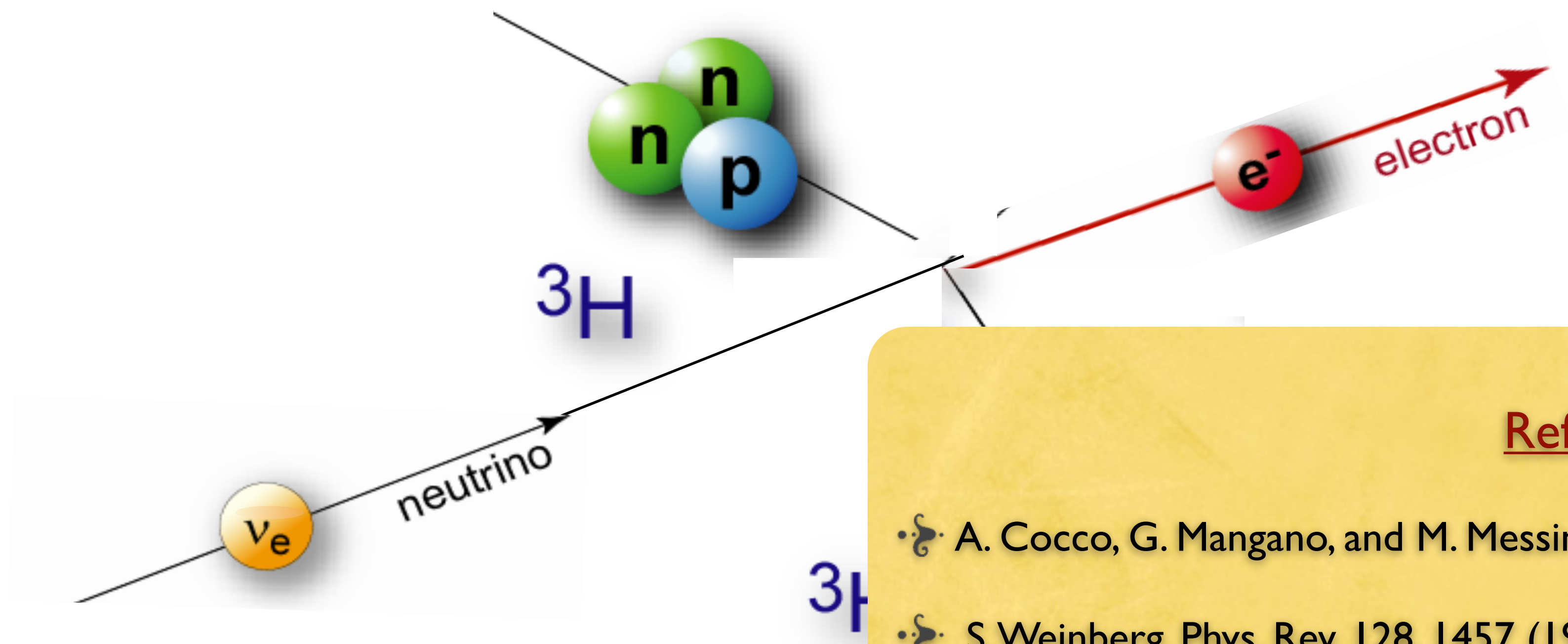
Instead of beta decay...

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



Neutrino Capture

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



References

- A. Cocco, G. Mangano, and M. Messina, hep-ph/0703075 (2007).
- S. Weinberg, Phys. Rev. 128, 1457 (1962).
- T. W. Donnell and J. D. Walecka, Ann. Rev. Nucl. Sci. 25, 329 (1975).

The process is energetically allowed even at zero momentum.

This threshold-less reaction allows for relic neutrino detection

Detecting the Impossible

$$\lambda_\nu = \int \sigma_\nu \cdot v \cdot f(p_\nu)(\frac{dp}{2\pi})^3$$

Neutrino Capture Rate

$$\sigma_\nu \cdot \frac{v}{c} = (7.84 \pm 0.03) \times 10^{-45} cm^2$$

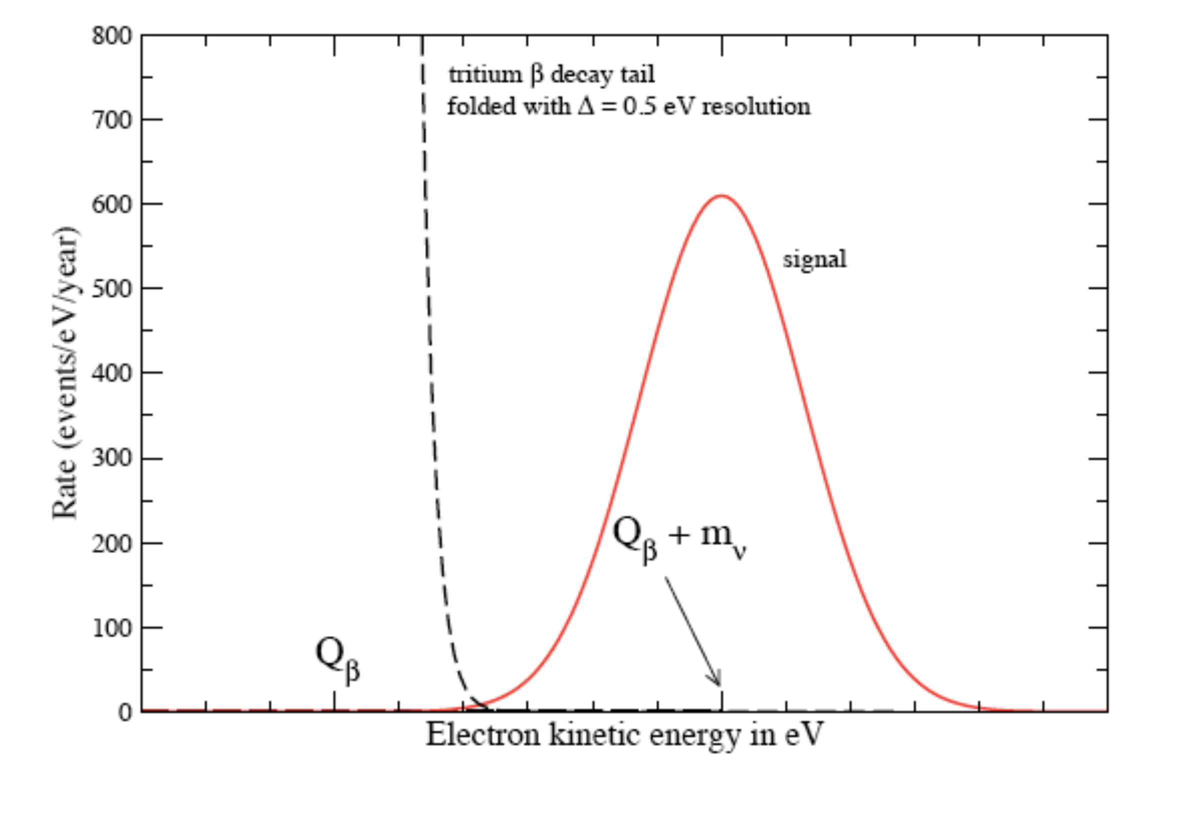
Tritium Cross-Section

- Has three main advantages:

(i) The process is exothermic. There is enough energy for the decay to occur (because beta decay will happen anyway). Thus, it is threshold-less.

(ii) Electron energy is almost mono-energetic, after the endpoint energy.

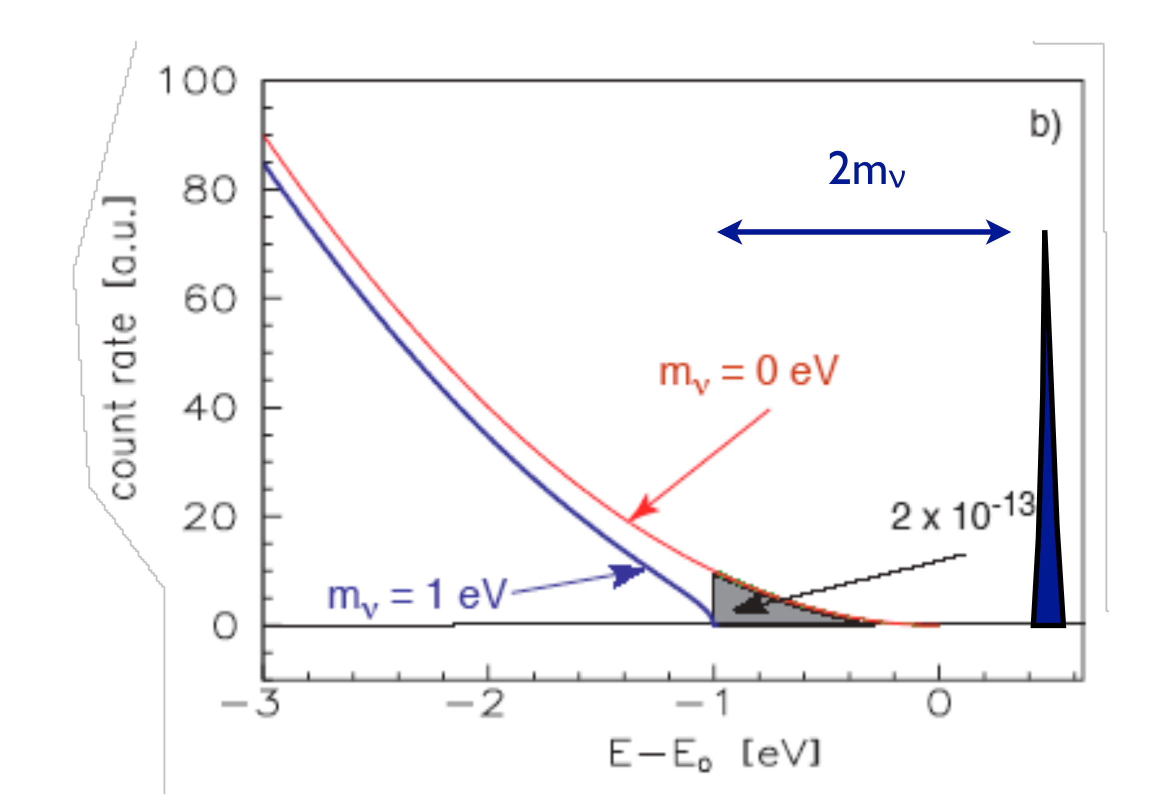
(iii) For tritium, 100 g corresponds to 10 events/year.



The CνB and KATRIN

- Any beta-decay endpoint experiment can search for the CνB, including KATRIN.
- An analysis of KATRIN's sensitivity highlights its limitations: target mass, resolution, and backgrounds.

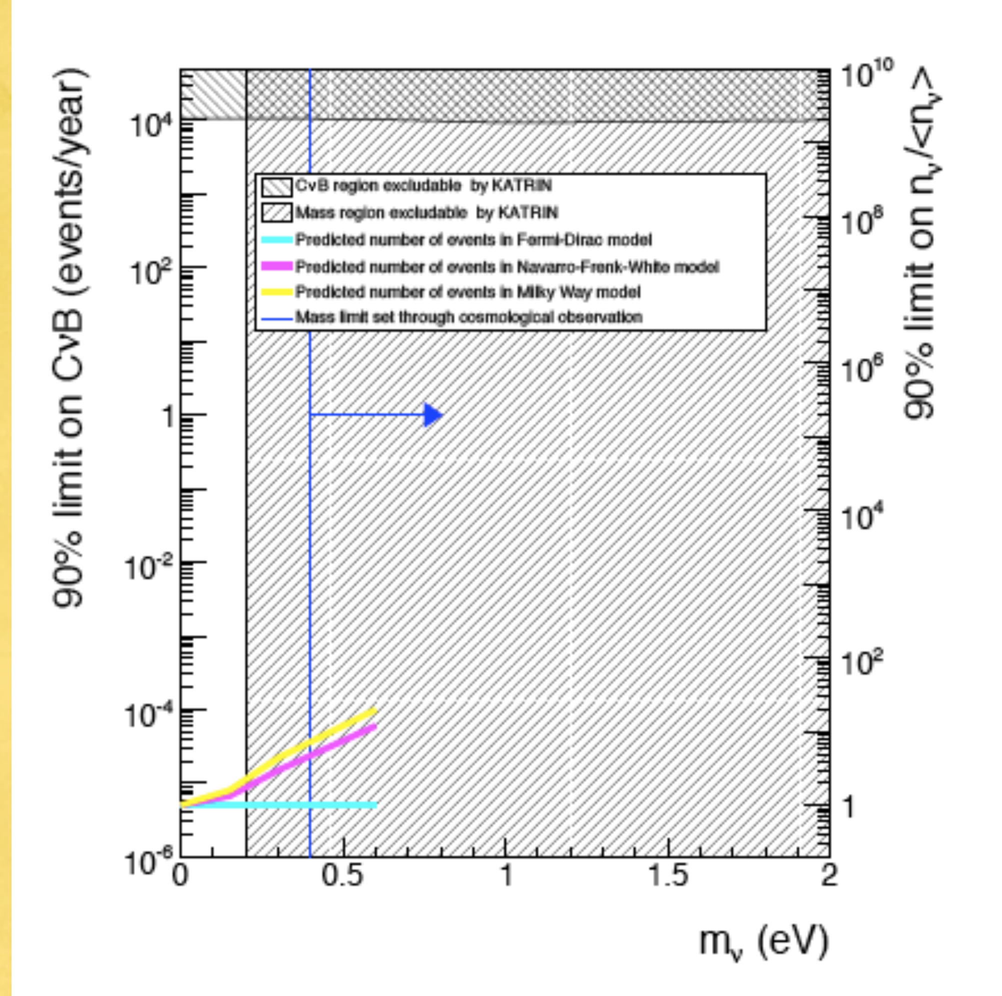
Sample neutrino capture signal with nominal beta decay background.

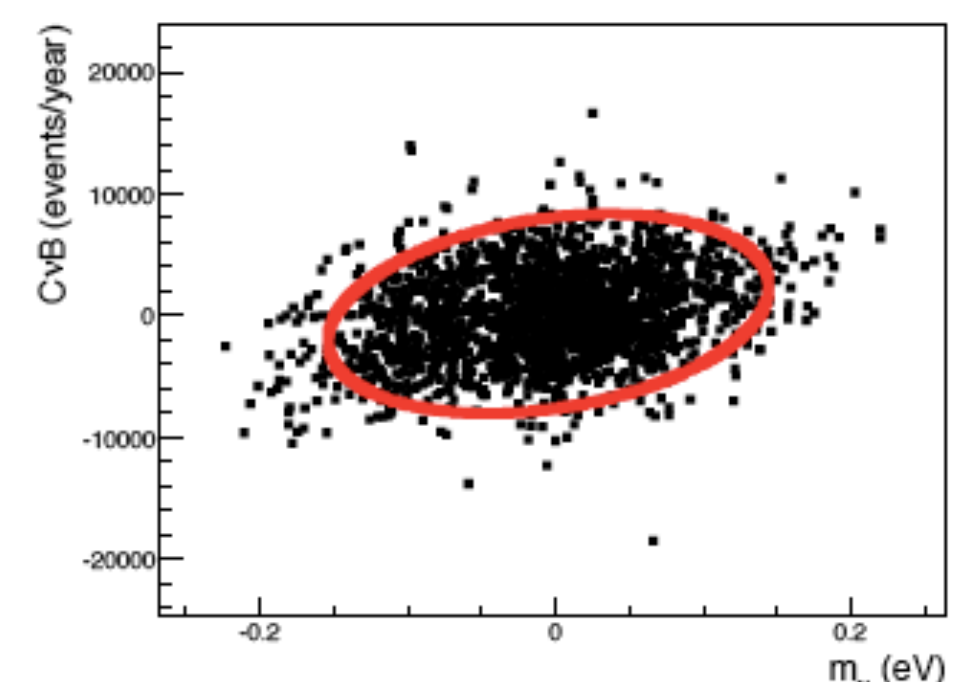


KATRIN's sensitivity to CνB.

A. Kaboth, J. Formaggio, and B. Monreal

Phys Rev. D 82 062001



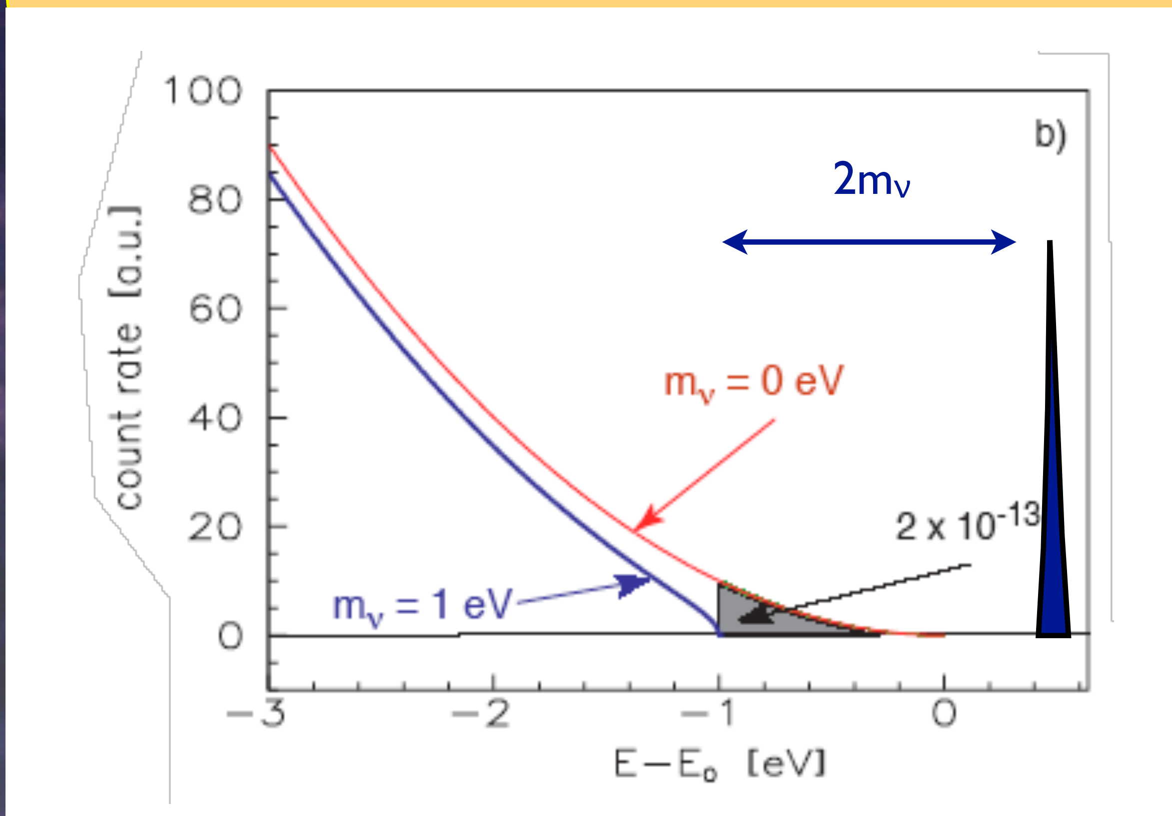


(a) $m_\nu = 0.0$ eV

Advantages and Challenges

- Any beta-decay endpoint experiment can search for the CνB, including KATRIN.
- An analysis of KATRIN's sensitivity highlights its limitations: target mass, resolution, and backgrounds.

Sample neutrino capture signal with nominal beta decay background.



Target Mass:

Tritium provides the optimal target.

Good news: 100 grams yields 10 events/year

Bad news: High activity targets (~1 MCi) of tritium necessary.

Energy Resolution:

The signature places a signal after the beta end-point.

Good news: Initial searches need only 10x improvement.

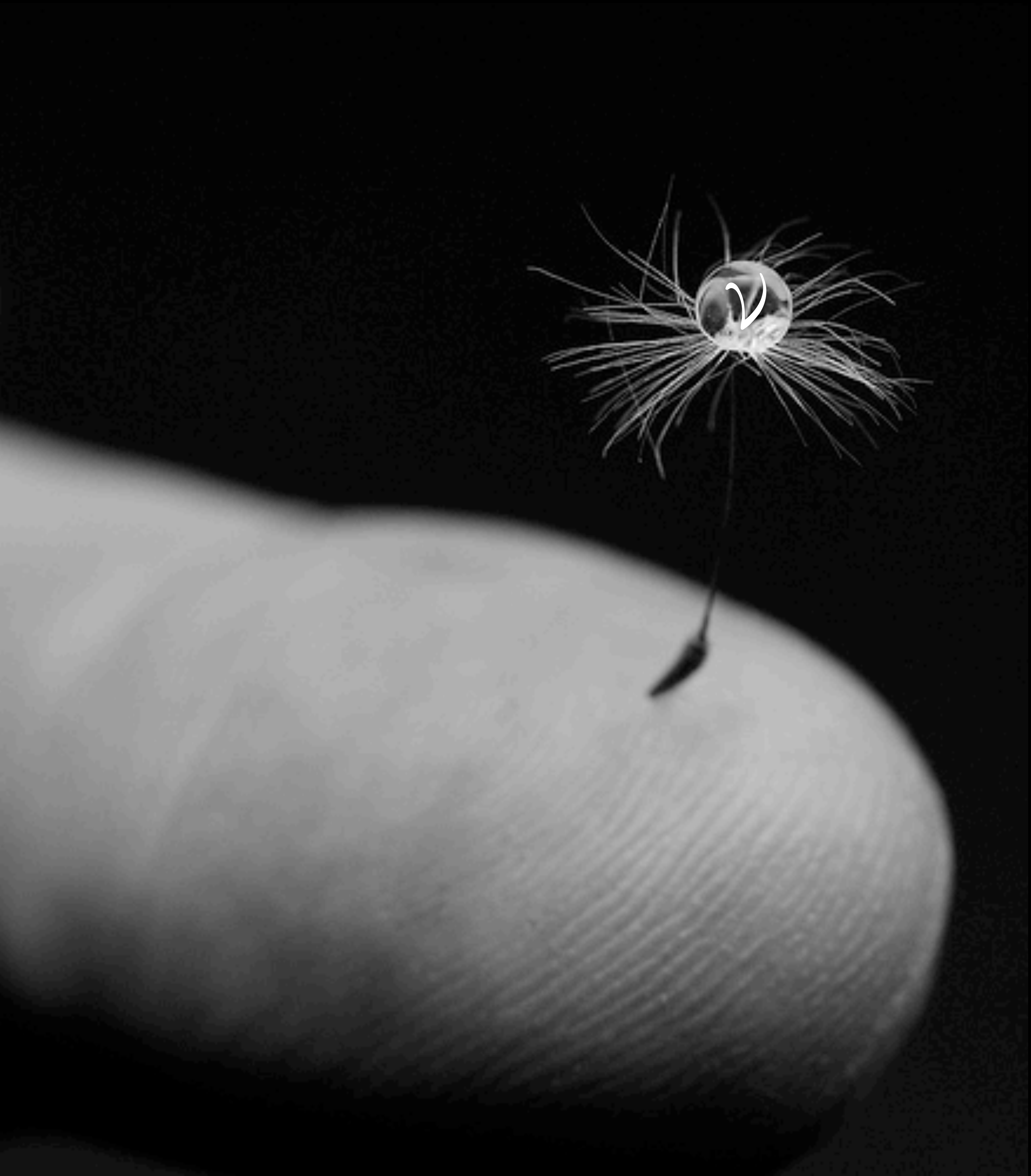
Bad news: This is still very difficult.

Backgrounds:

Beta endpoint experiments have incredible signal-to-background separation.

Good news: Advantages with underground facilities.

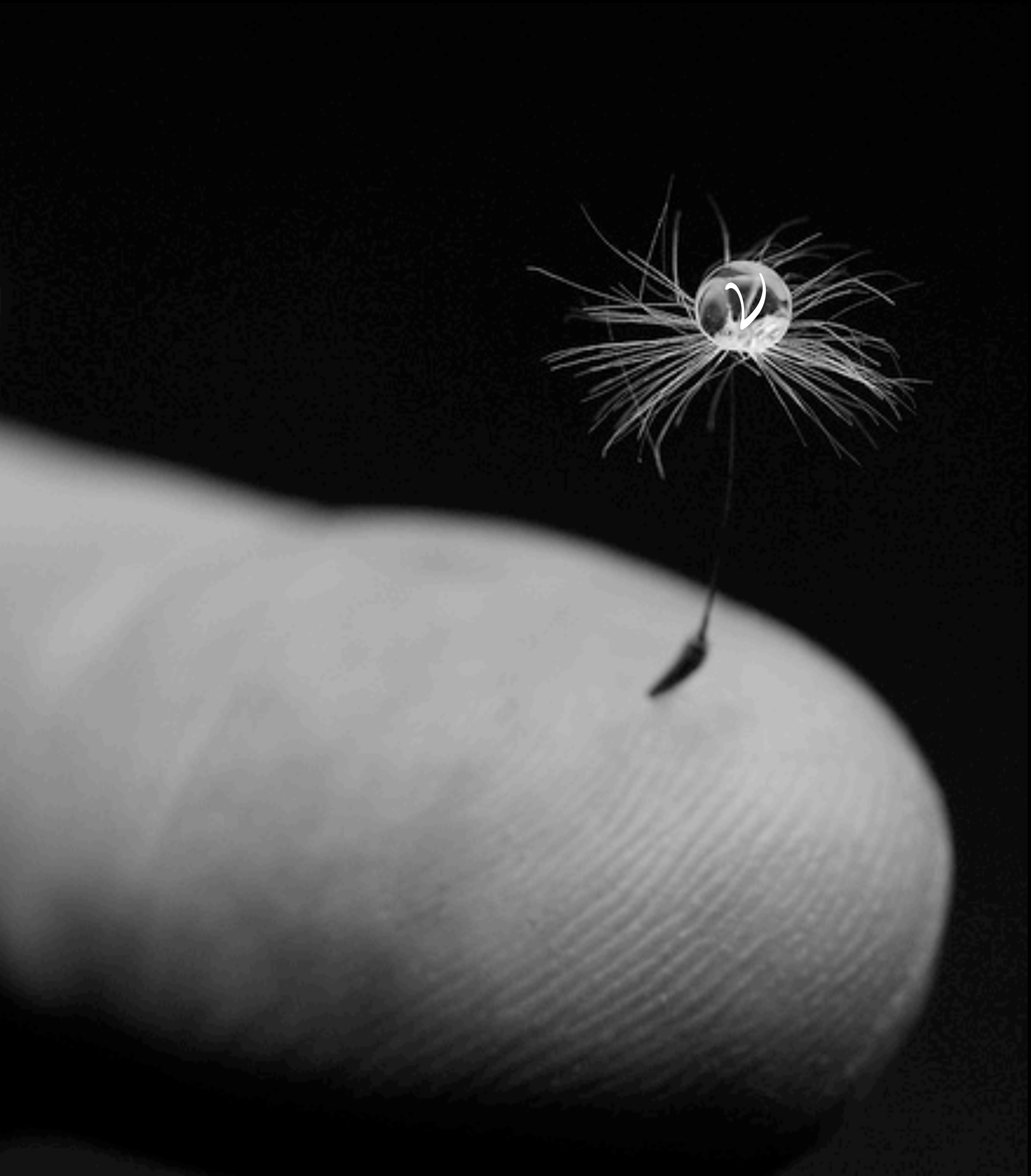
Bad news: Given the necessary target mass, background rejection will be a serious challenge.



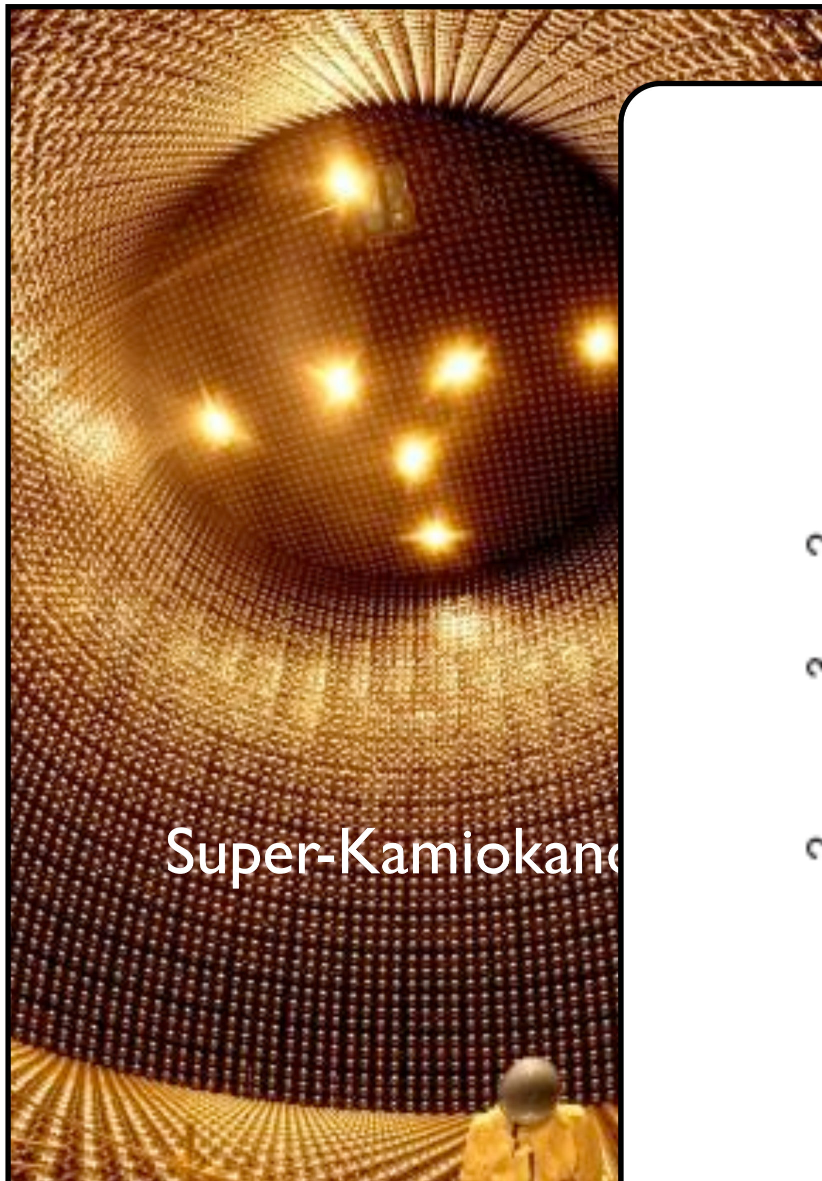
Neutrino masses provide a unique window into the world of particle physics, offering a first glimpse of where new physics might begin.

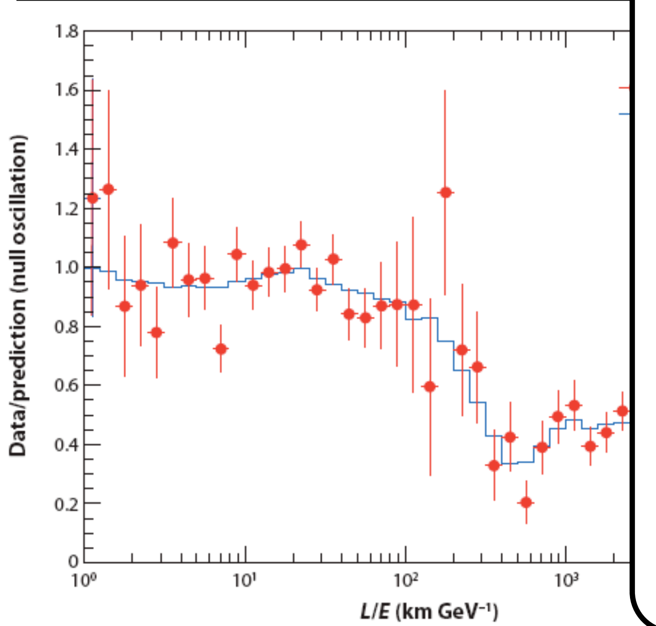
Over the next decade, many experiments will push to determine the absolute neutrino mass scale, from a variety of approaches.

Certain techniques used to measure neutrino mass can even be extended, providing a glimmer of hope of extending back to cosmology.



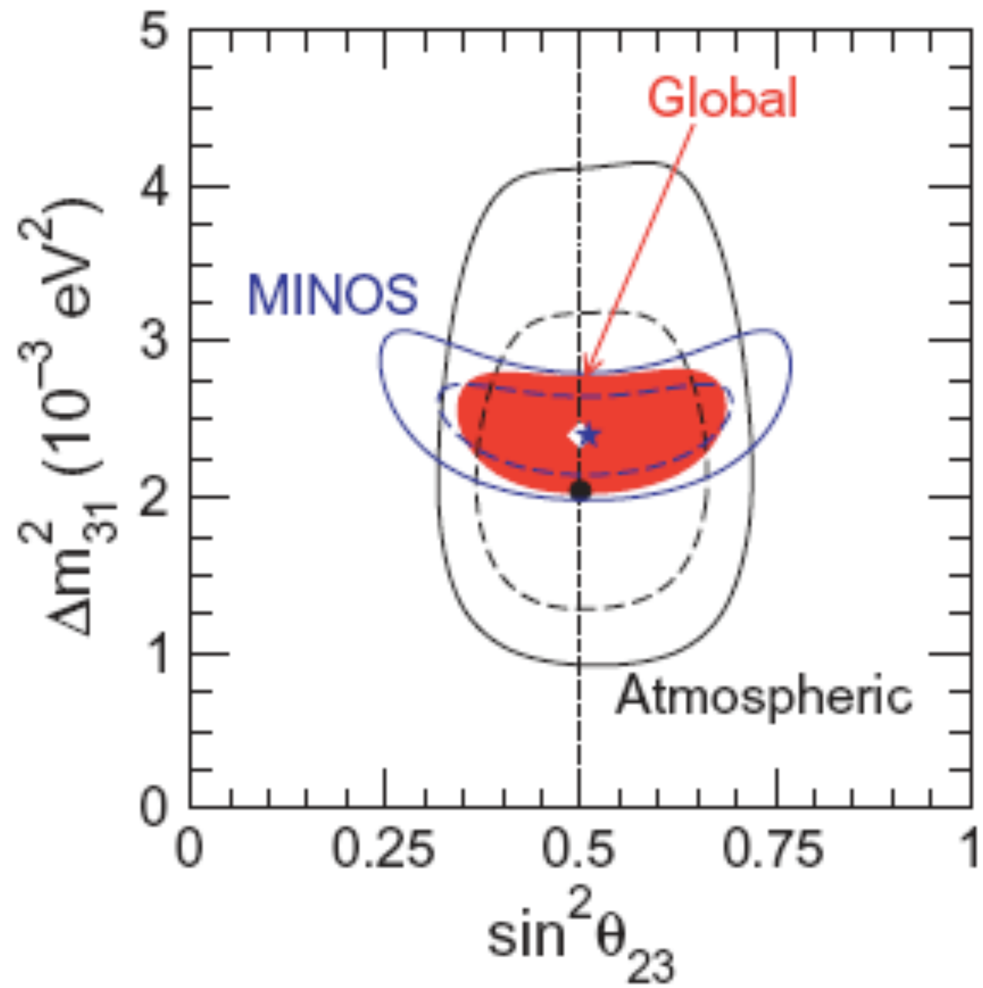
Thank you for your attention





Phys. Rev. Lett. 93:101801 (2004)

Long Baseline & Atmospheric

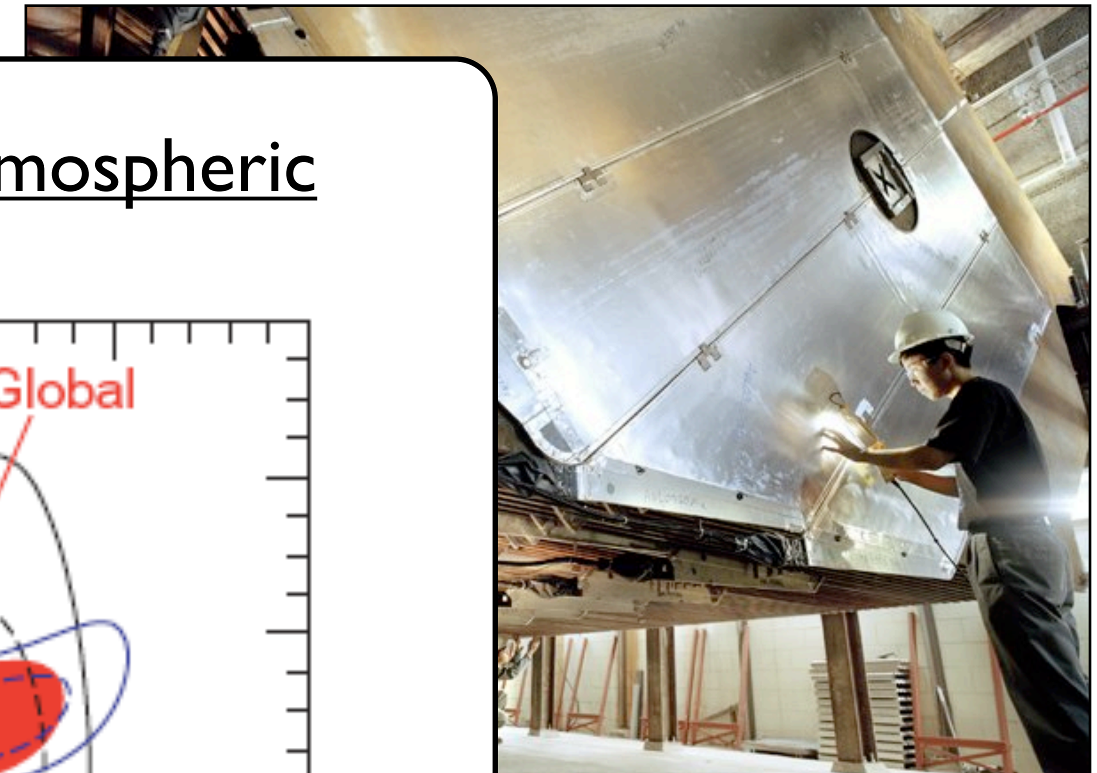


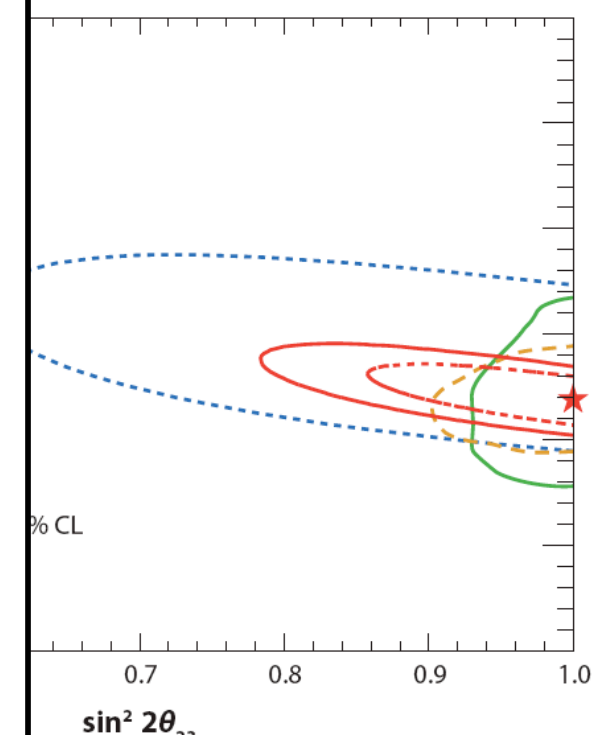
Fit Results:

$$\sin^2\theta_{23} = 0.50^{+0.07}_{-0.06}$$

$$|\Delta m^2_{31}| = 2.40^{+0.12}_{-0.11} \times 10^{-3}\ \mathrm{eV}^2$$

Schwetz et al, NJP 10 (2008) 113011





Camilieri, Lisi, Wilkerson Ann. Rev. 57 (2008).

Some More Quotes....

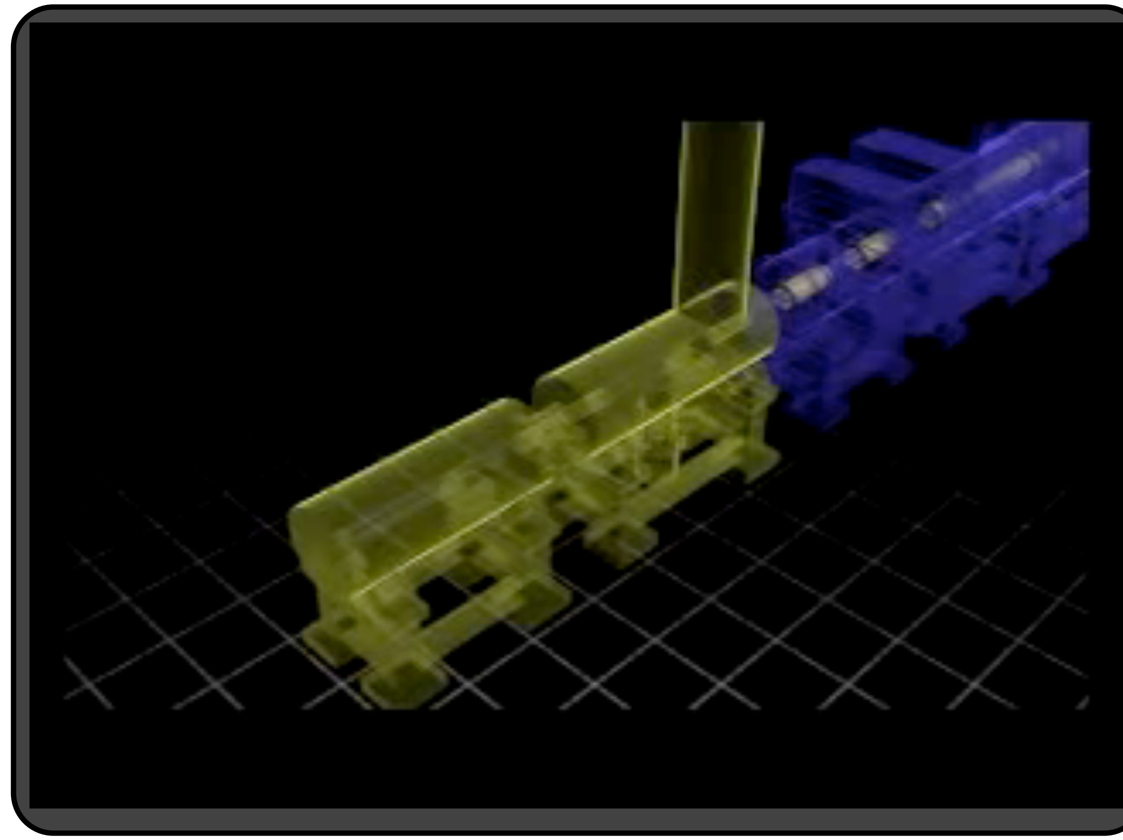
"About every neutrino physicist goes through a phase in his or her career and asks 'There's got to be a way to measure the relic neutrino background...'" *P. Fisher*

"... In all fairness, this method [neutrino capture] appears to have survived the longest." *P. Fisher*

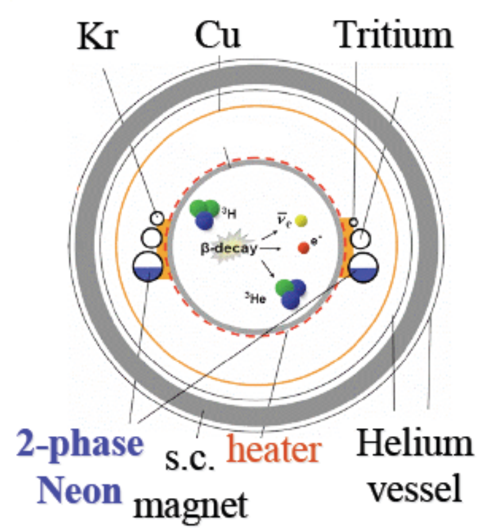
"Anyone who can measure relic neutrinos via neutrino capture will have made an amazing neutrino mass measurement..." *G. Drexlin*

"If it were easy, we'd be done by now..." *my translation*

The Windowless Gaseous Tritium Source (WGTS)

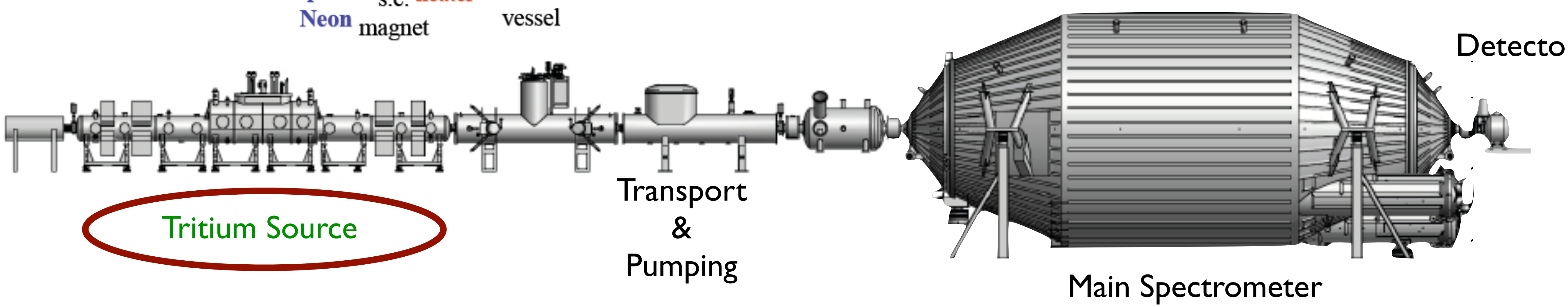


- Gaseous tritium source provides source of beta-decay electrons.
- Use of injection + differential pumping to provide well-controlled gas column density.
- In-situ monitoring of purity of gas via laser Raman spectroscopy.

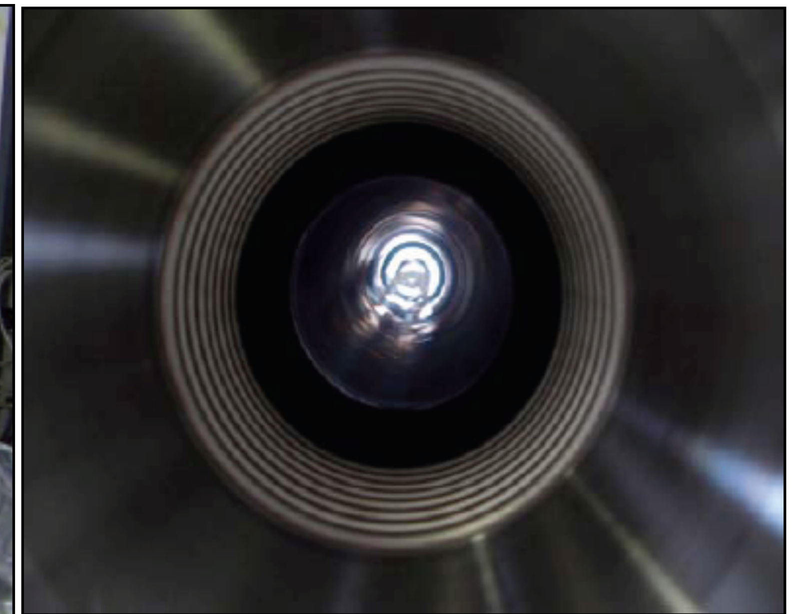


T_2 Specifications

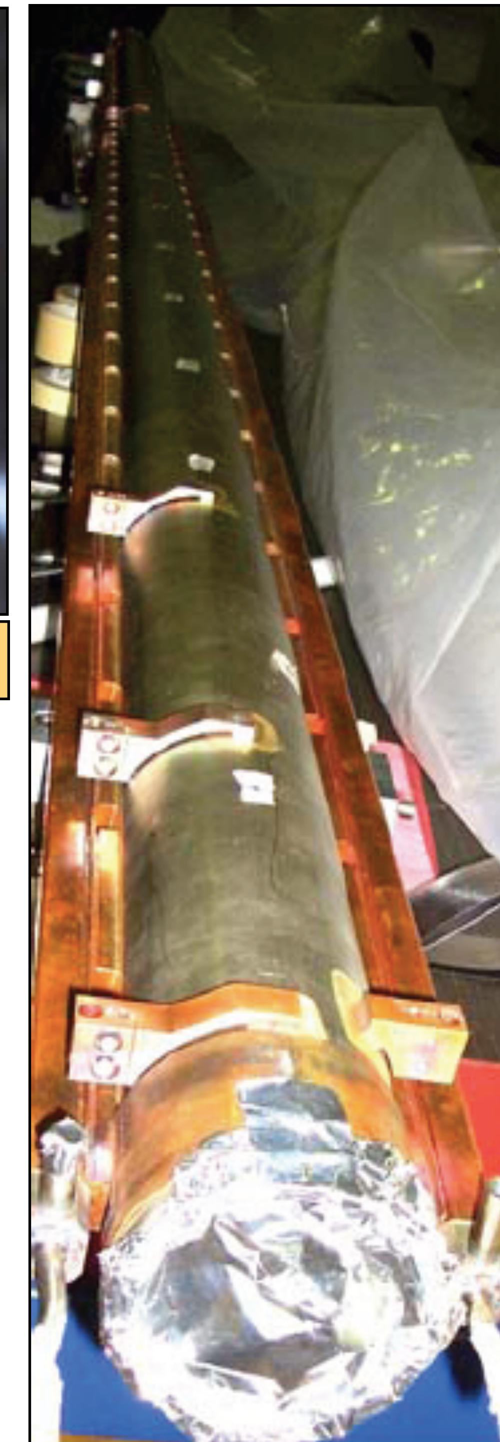
- Tritium activity: 1.7×10^{11} Bq
- Tritium throughput: 40 g T_2/day
- Temp. stability $\pm$ 0.03 mK @ 27K
- Electron flux: 10^{11} β/s
- Column Density: 5×10^{17} cm^{-2}



10 m Beam tube



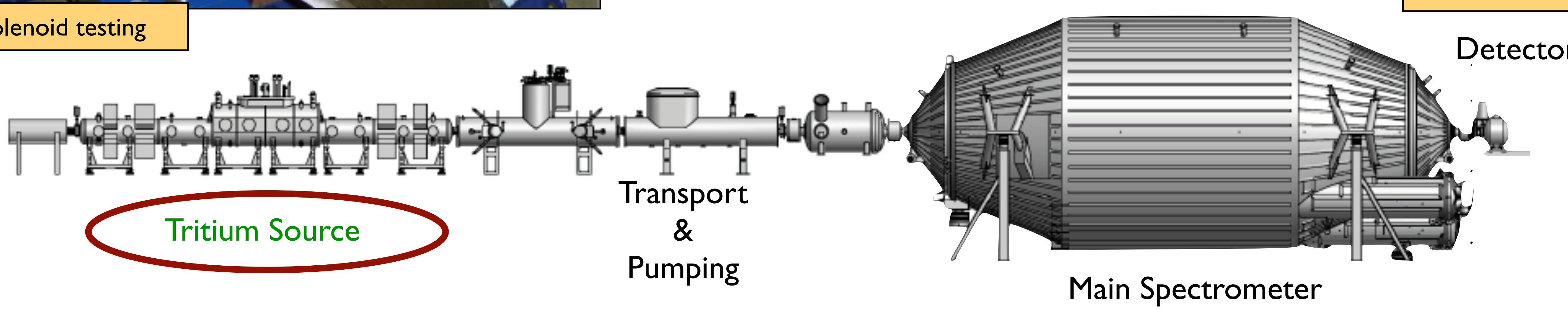
Beam alignment (< 0.5 mm)



Beam tube

Solenoid testing

Next milestone: the demonstrator (to achieve 27 ± 0.03 K neon stability)

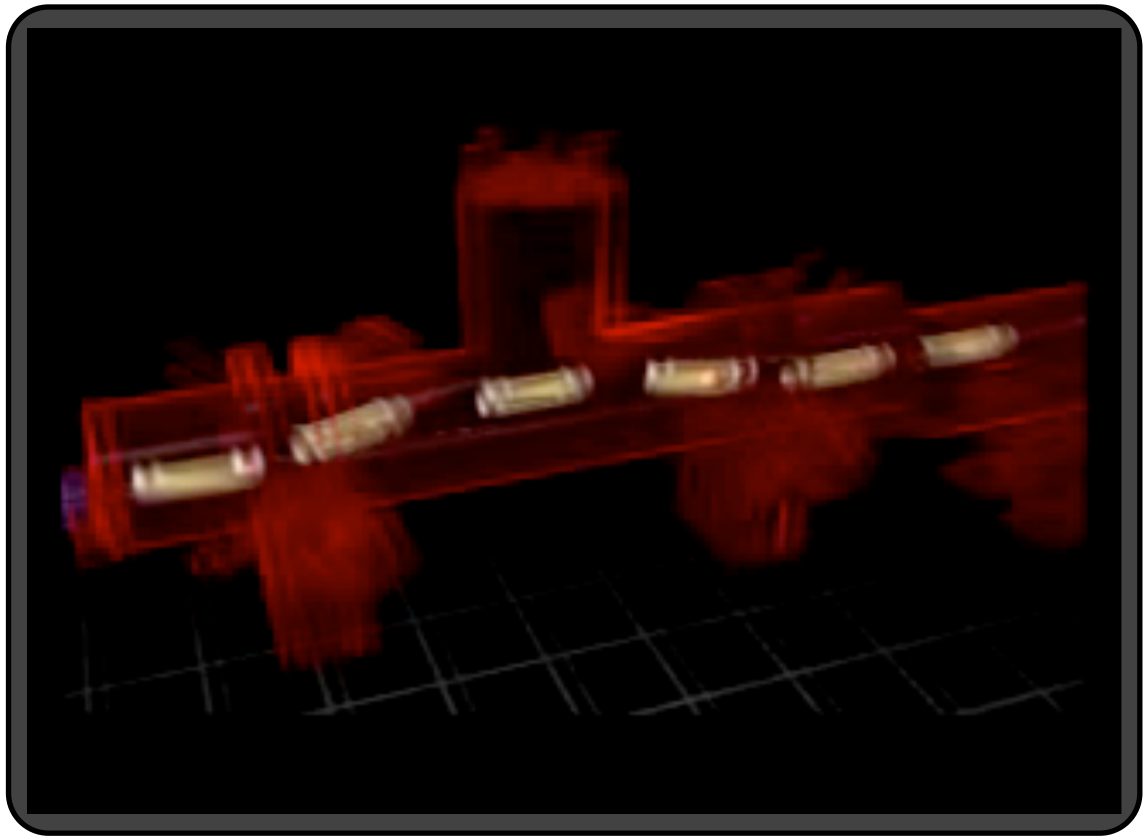


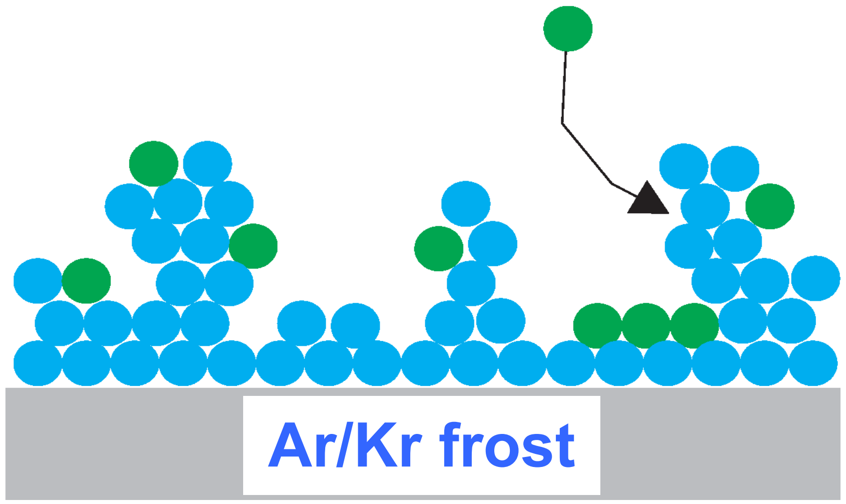
Tritium Retention Systems

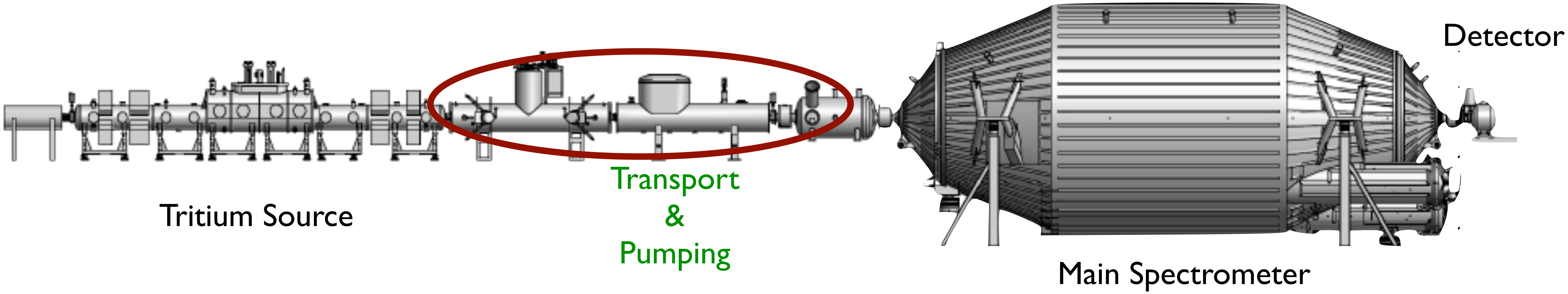
Includes both differential and cryo-absorption pumping systems.

The differential pumping system's goal is to reduce tritium flow to less than 10^{-14} mbar l/s (factor of 10^{7} reduction!)

Cryo-pumping system makes use Ar/Kr frost at 3-4 K to trap residual tritium gas for further 10^{7} reduction.

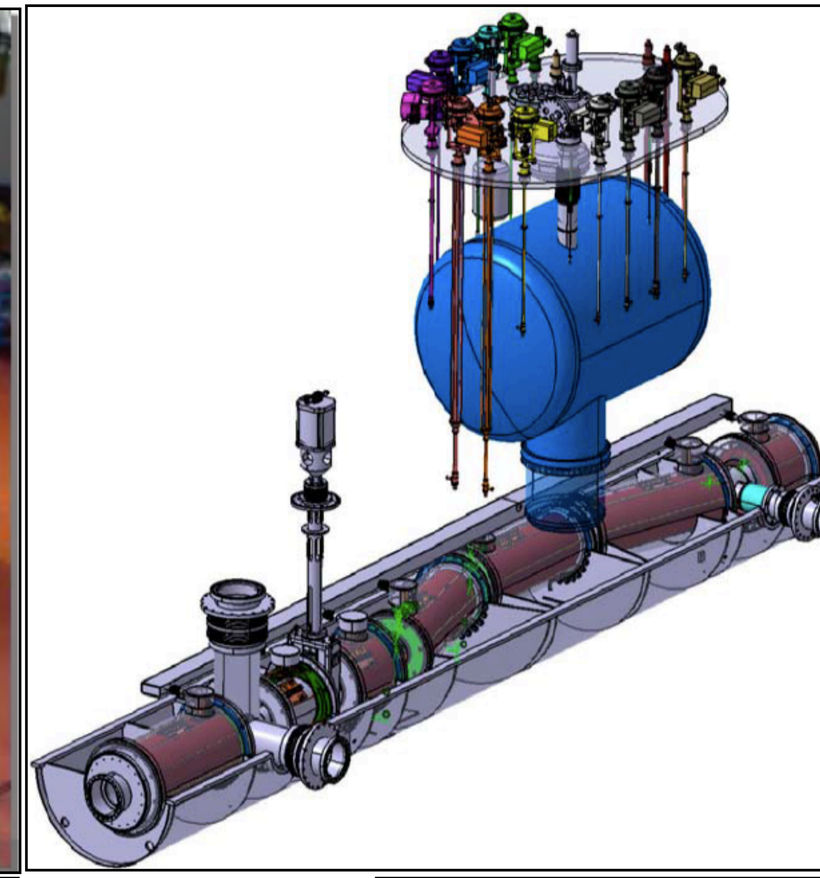






Cryostat housing

Transport tube

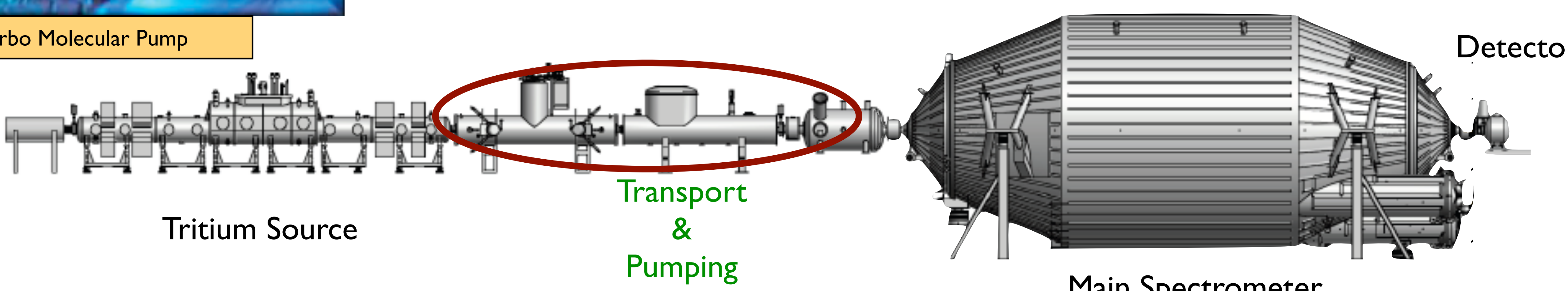


CPS design

Turbo Molecular Pump

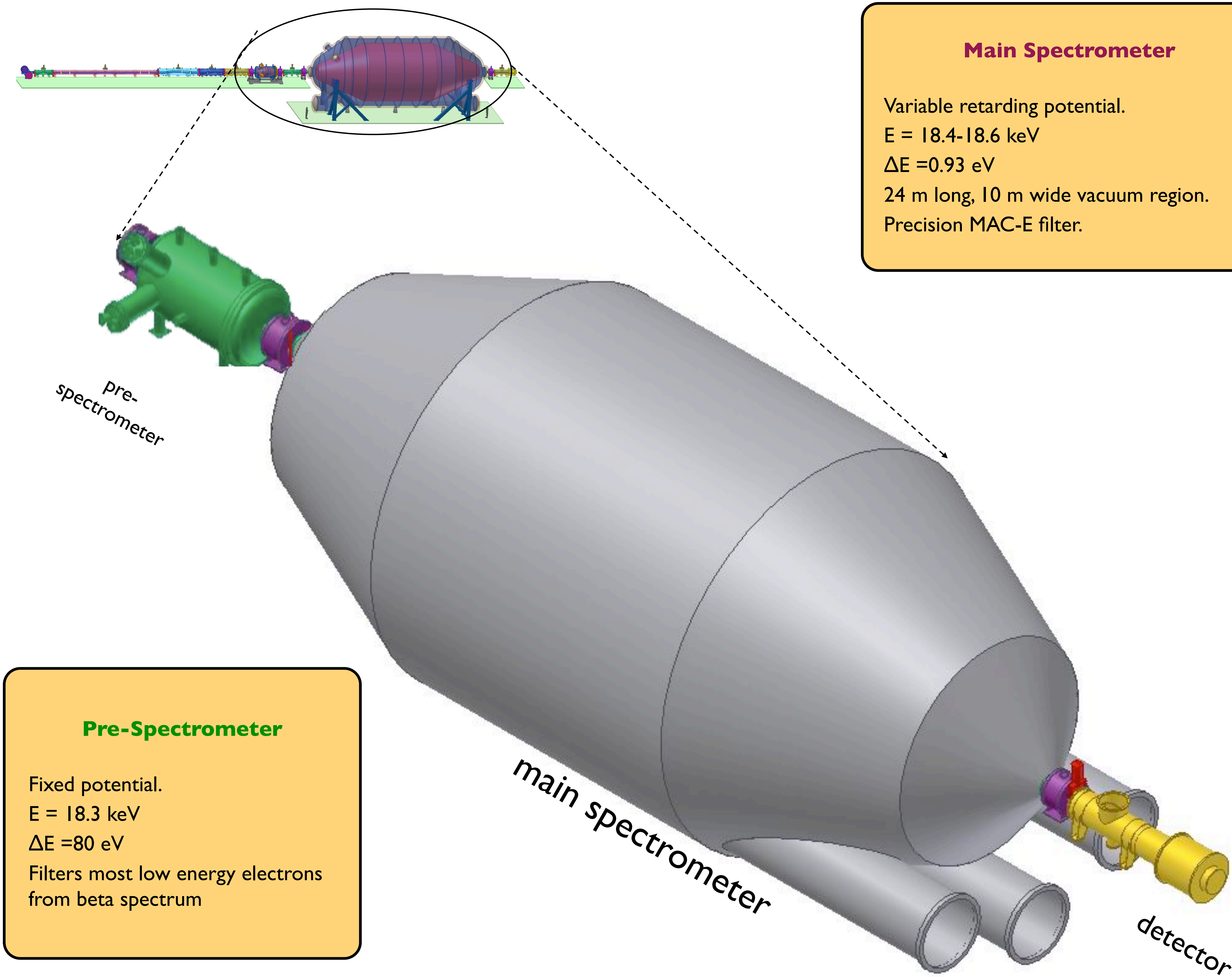
Differential pumping system (DPS2-F) components now delivered to FZK for testing and assembly.

Cryo system being built. Delivery expected in 2010.



Main Spectrometer

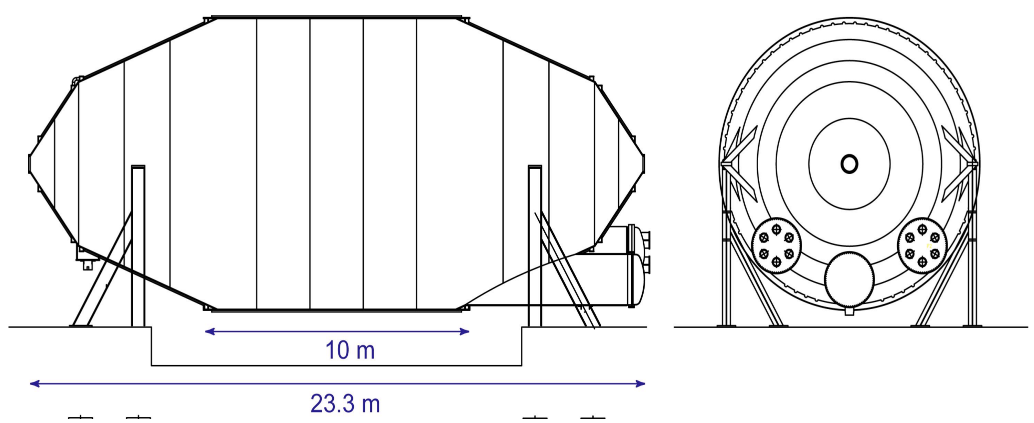
Variable retarding potential.
E = 18.4-18.6 keV
ΔE =0.93 eV
24 m long, 10 m wide vacuum region.
Precision MAC-E filter.

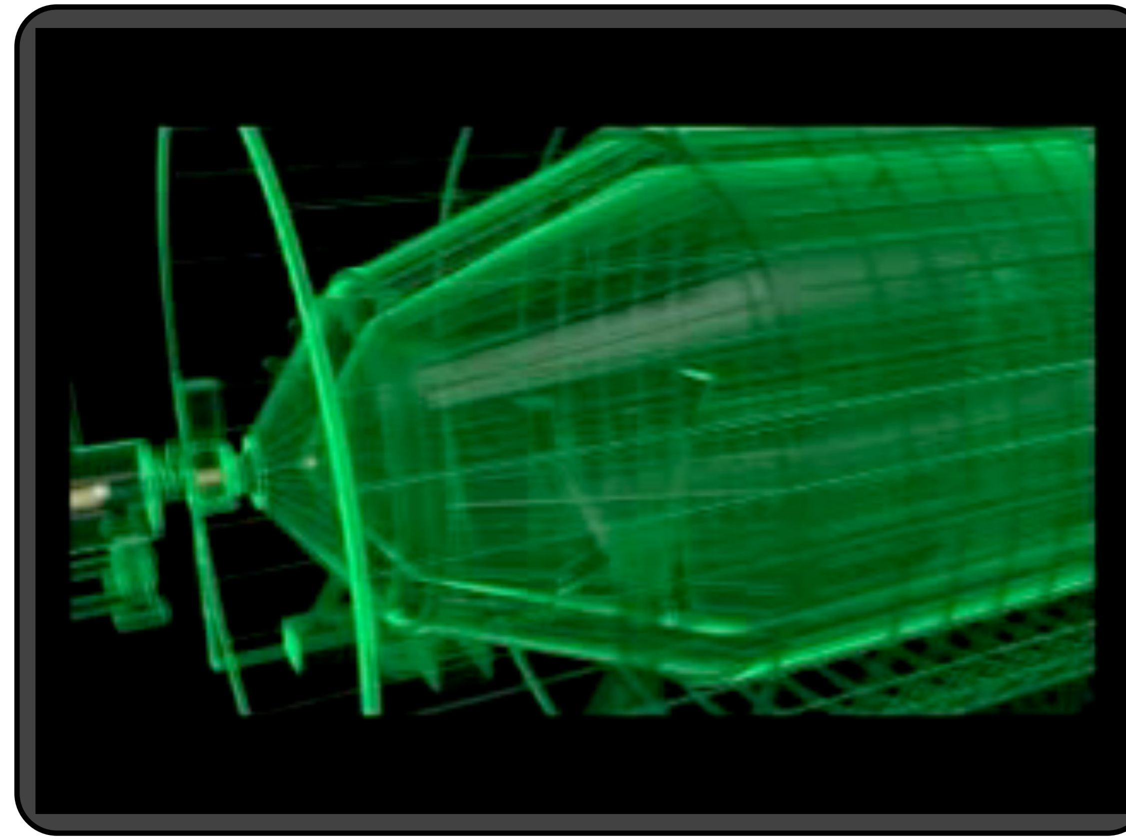


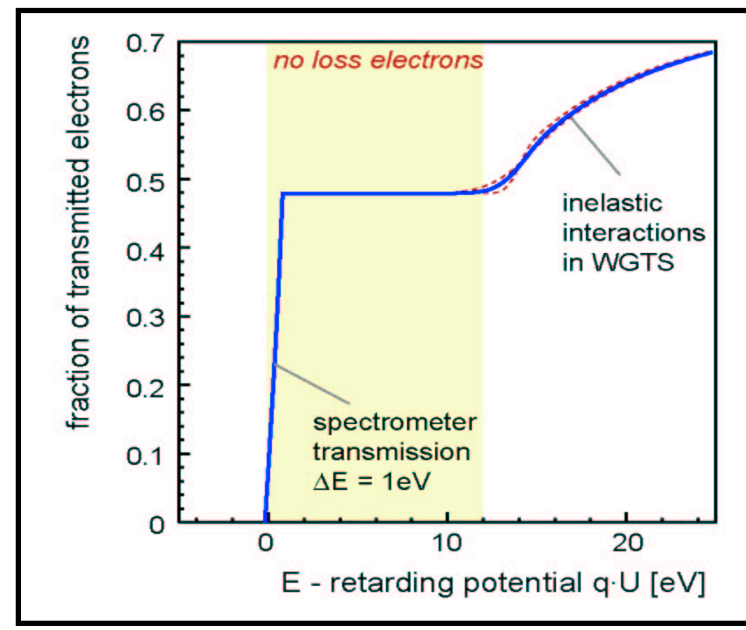
Pre-Spectrometer

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

The Main Spectrometer



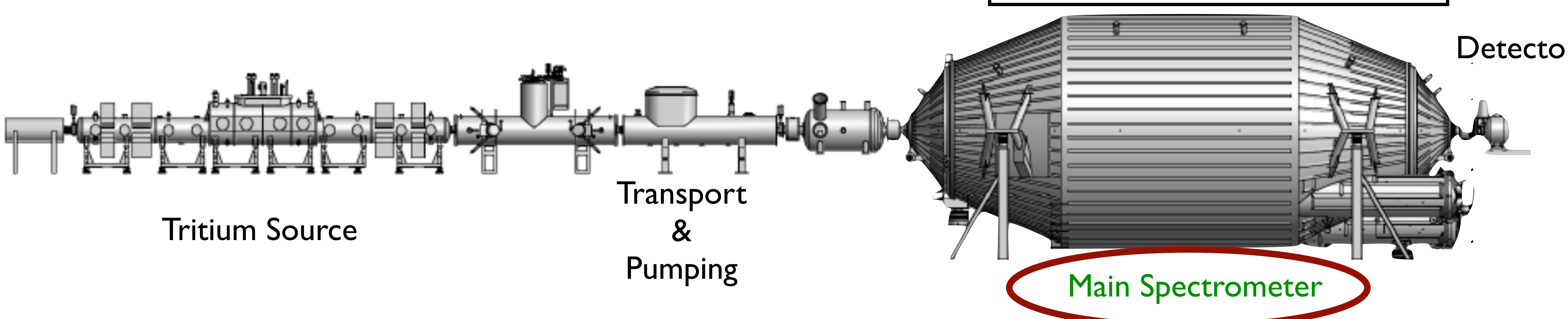


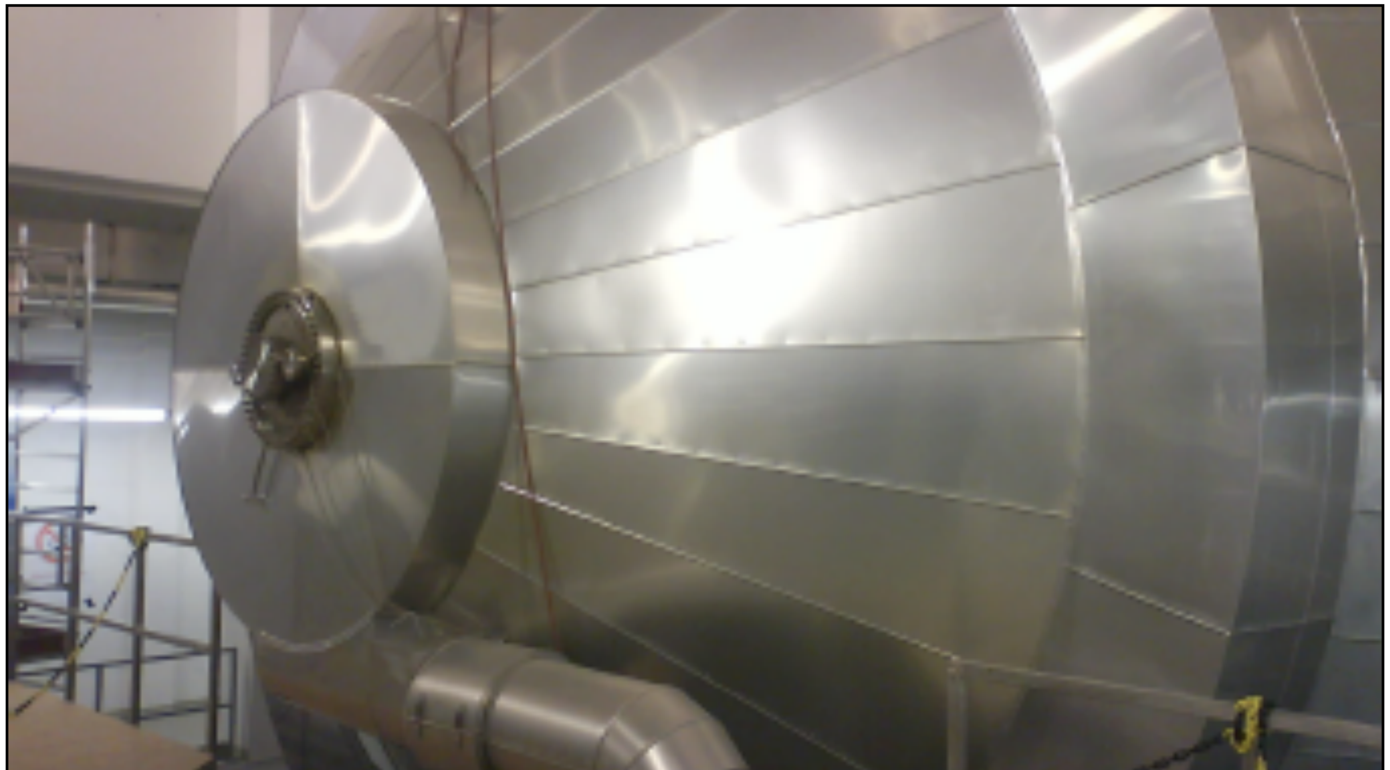


Provides precision transport of particles above selected energy threshold: high pass filter!

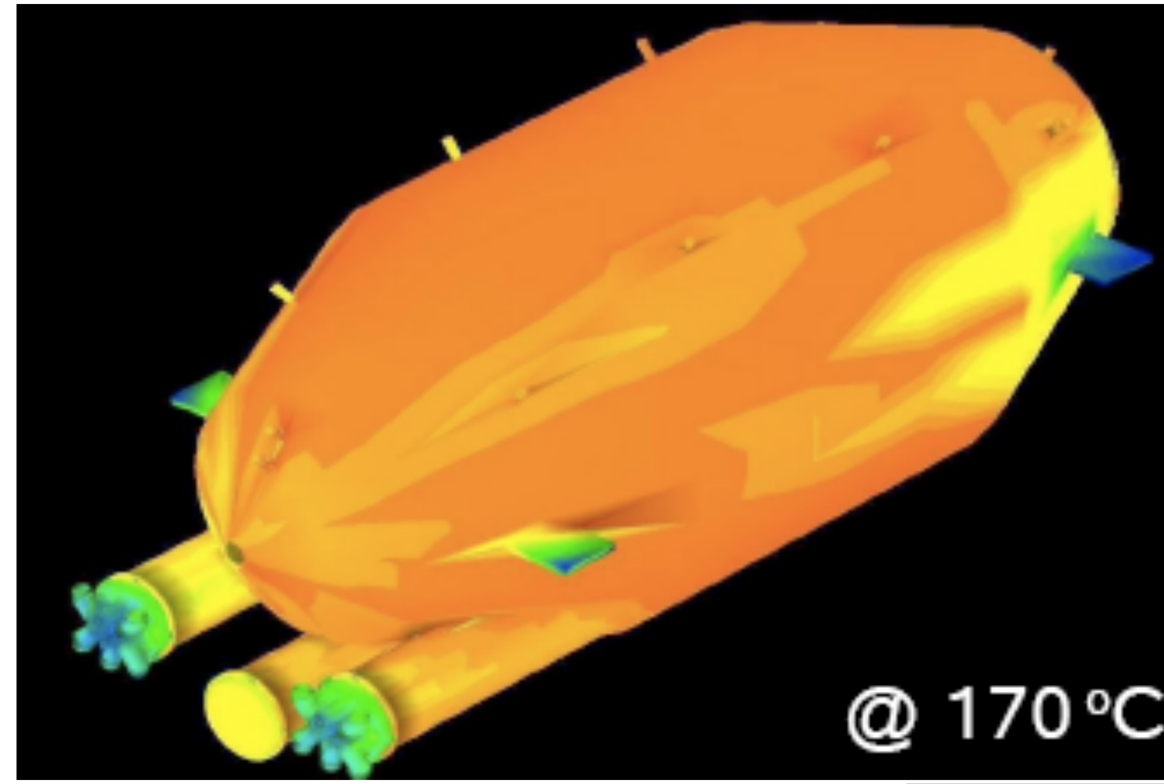
Combination of precision high voltage and low magnetic field (with correction air coils).

Inherent resolution of ΔE = 0.93 eV.





Thermal insulation



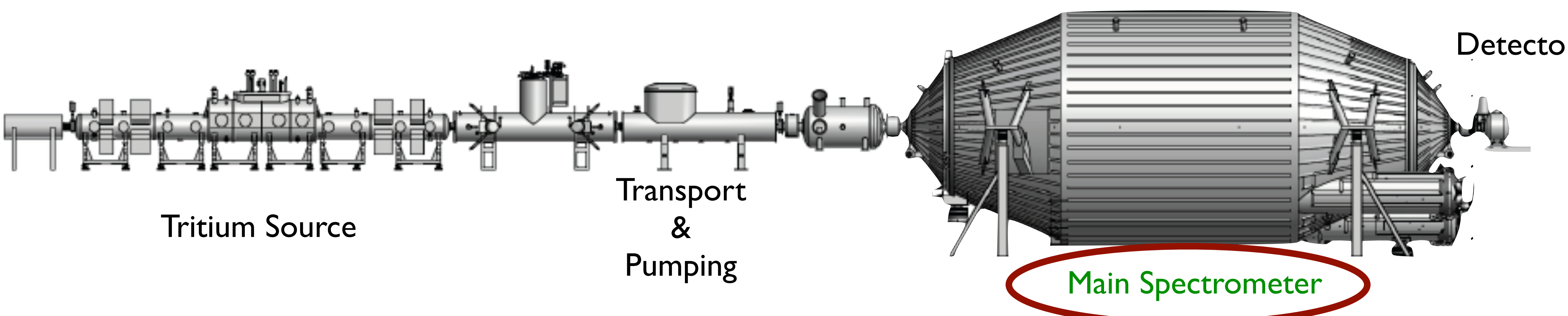
Bake-out

Since its faithful journey:

Successful bake-out of full vessel.

Successful test of vacuum system. Final pressure: 10^{-11} mbar.

Preparation for wire mesh installation.

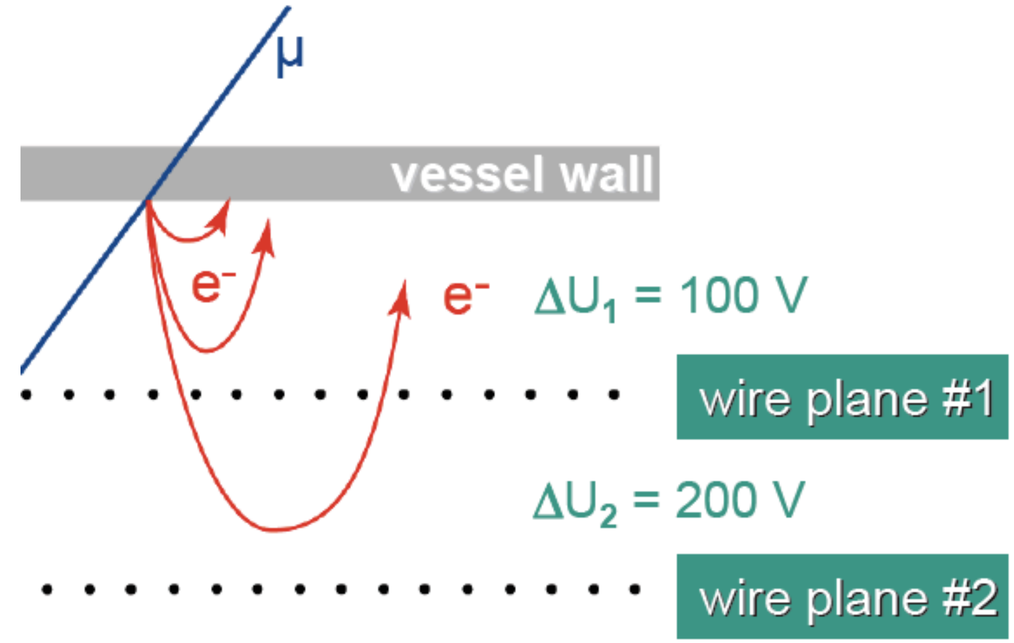


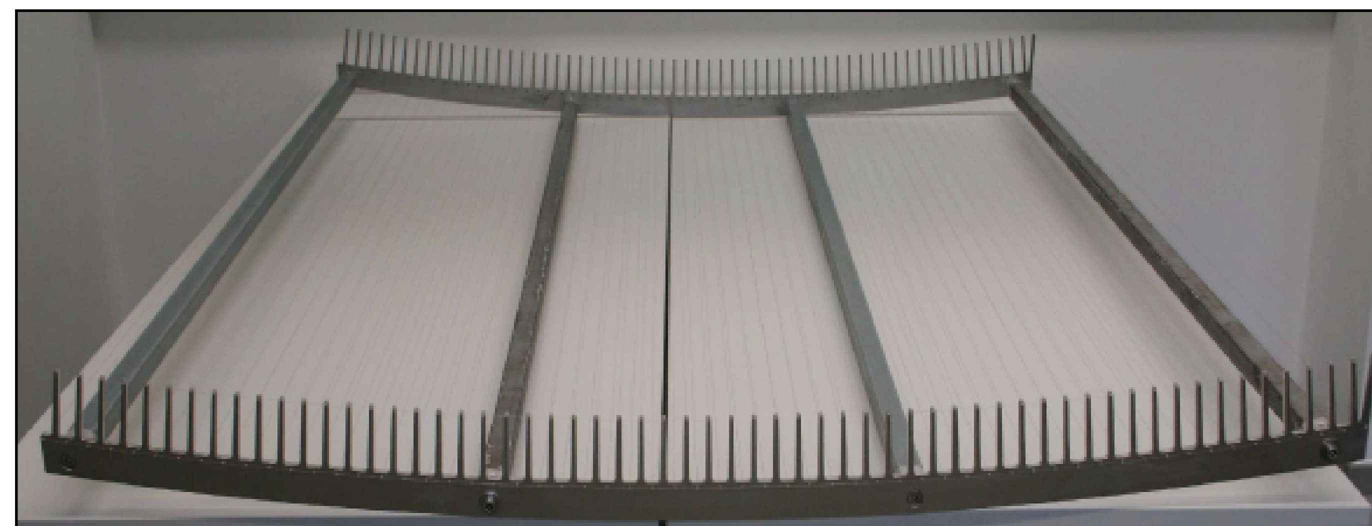
wire quality control

preparing for grid installation

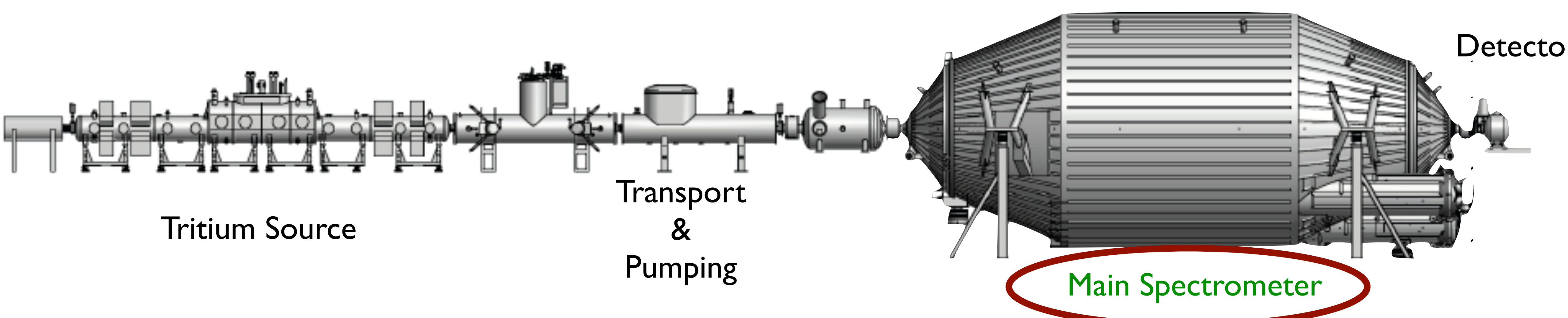
Installation of low mass wire mesh commencing.

Low mass wire grid will provide significant background reduction from cosmic ray interactions.

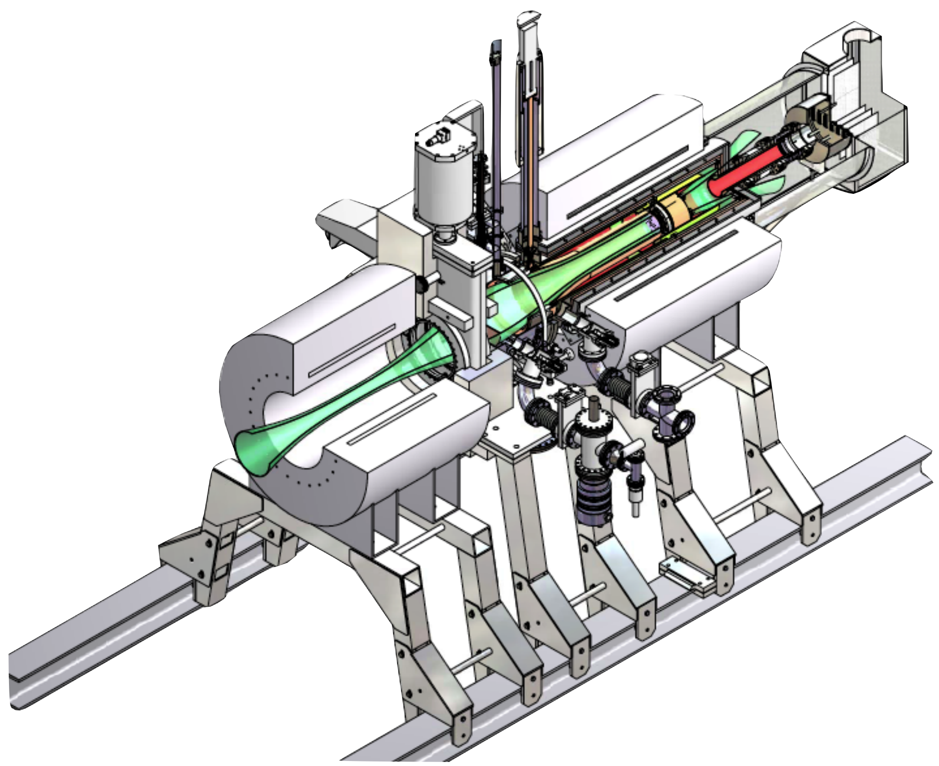


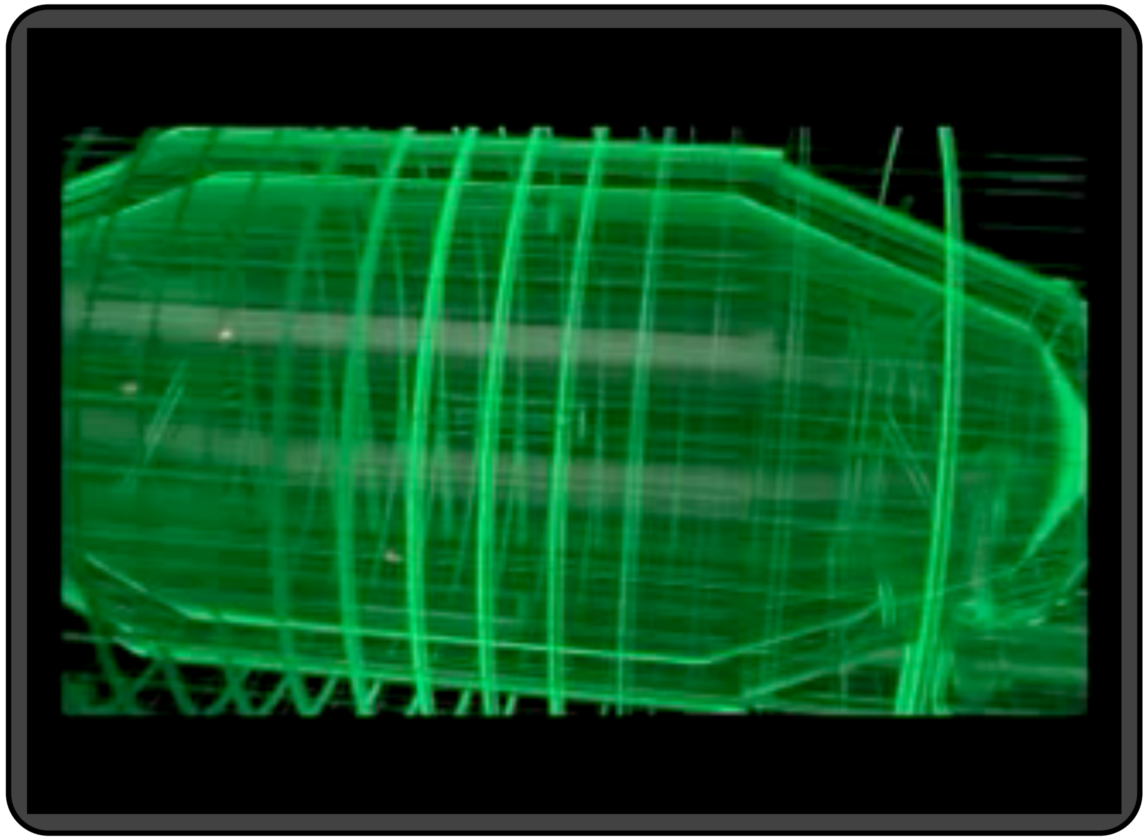


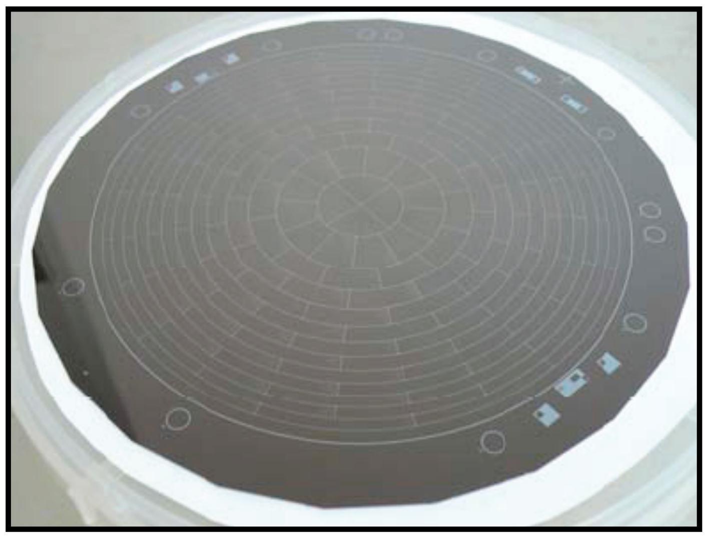
single wire "comb"



The Detector



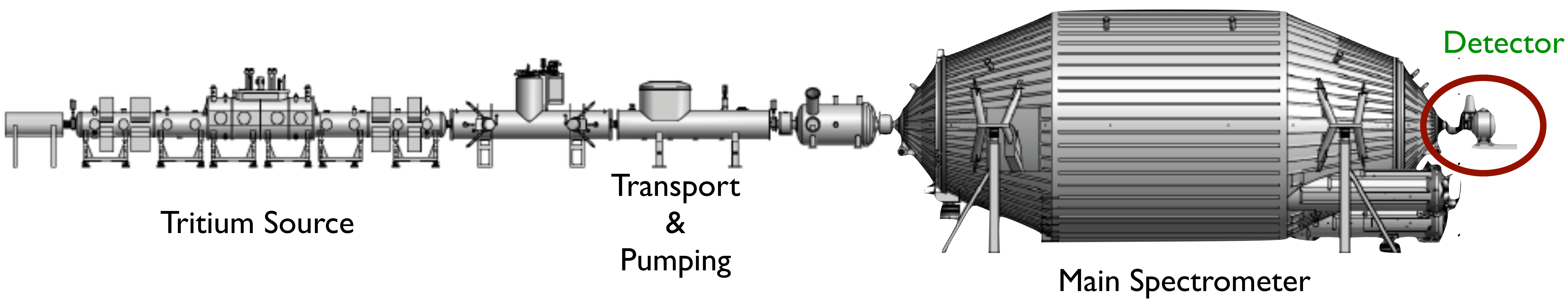




Final electron detection occurs on a segmented silicon detector (148 pixels for spatial resolution).

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

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

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Brest
Łódź
Wrocław
Leipzig
Prague
CZECH REPUBLIC
Brno
Kraków
L'viv
Rivne
Kiev
UKRAINE
Chernivtsi
SLOVAKIA
Bratislava
Vienna
AUSTRIA
Munich
Budapest
HUNGARY
Cluj-Napoca
ROMANIA
CARPATHIAN MTS.
Iași
MOLDOVA
Chișinău
Ljubljana
SLOVENIA
Zagreb
Bucharest
Danube
Oder
Vistula
Elbe
Dnipro
Tunis
TUNISIA
ALGERIA
MOROCCO
MALTA
Bursa
Izmir
Rhodes
300 Kilometers
300 Miles
DWE
2006/10/06 11:12