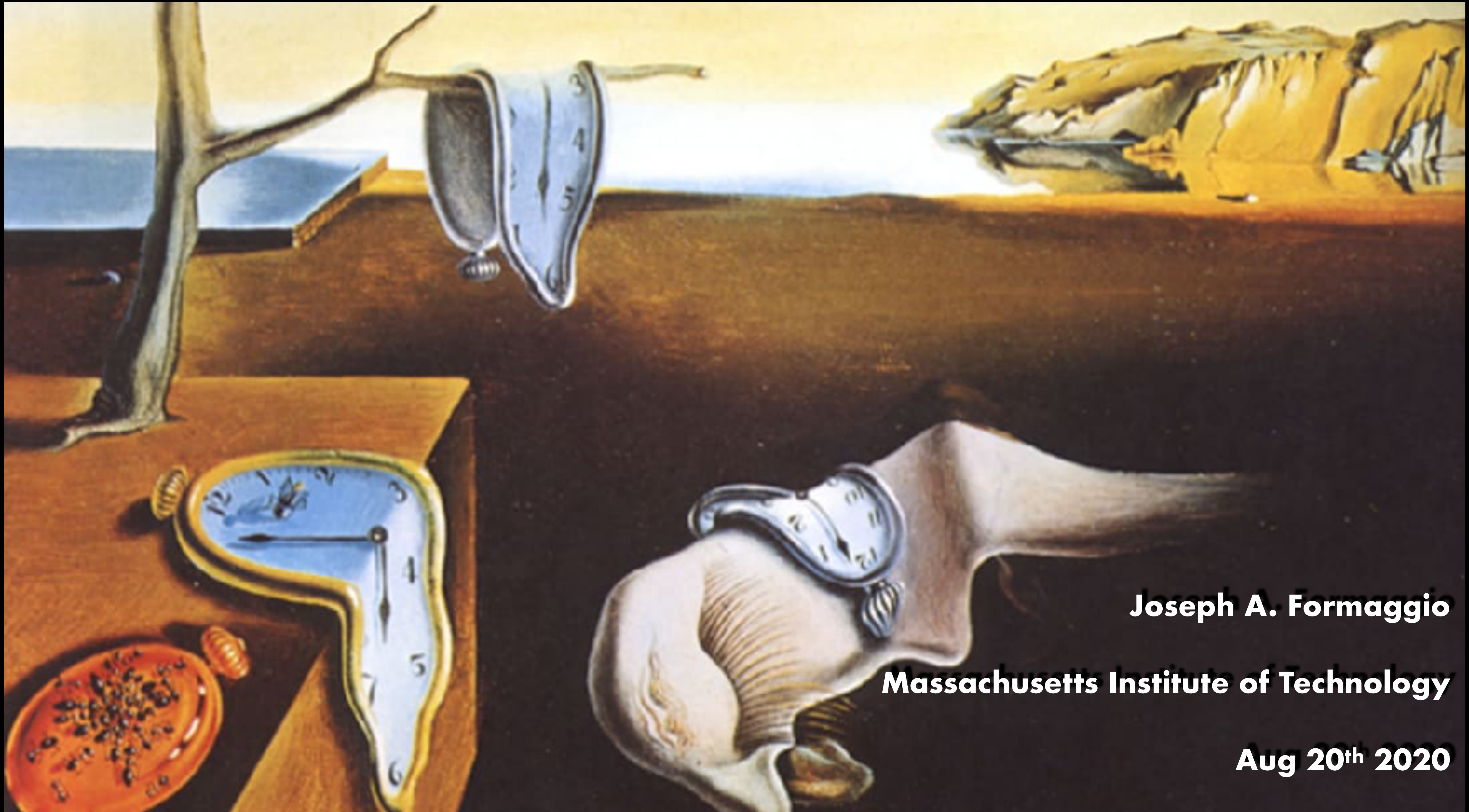
Trying to weigh the lightest particles in the universe

(without losing your patience)



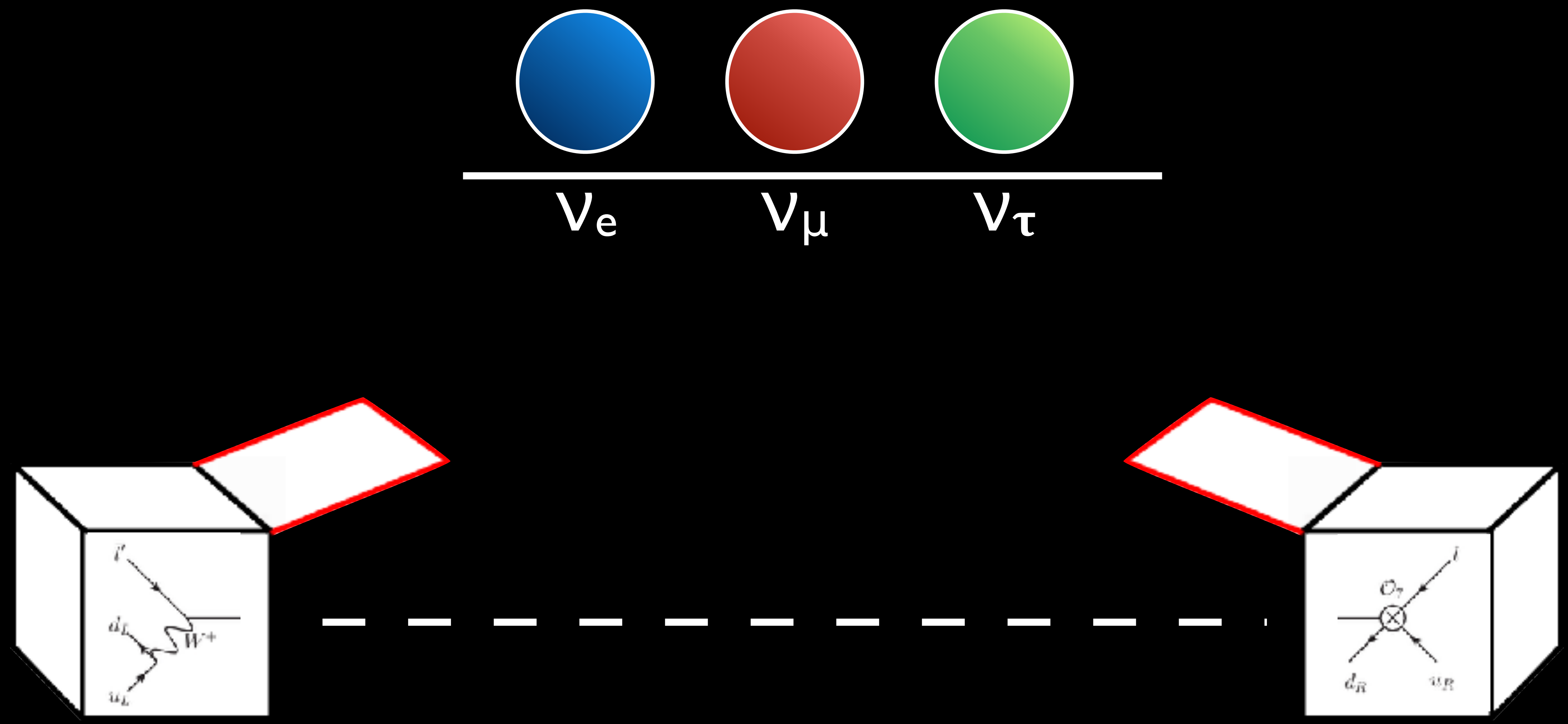
Joseph A. Formaggio

Massachusetts Institute of Technology

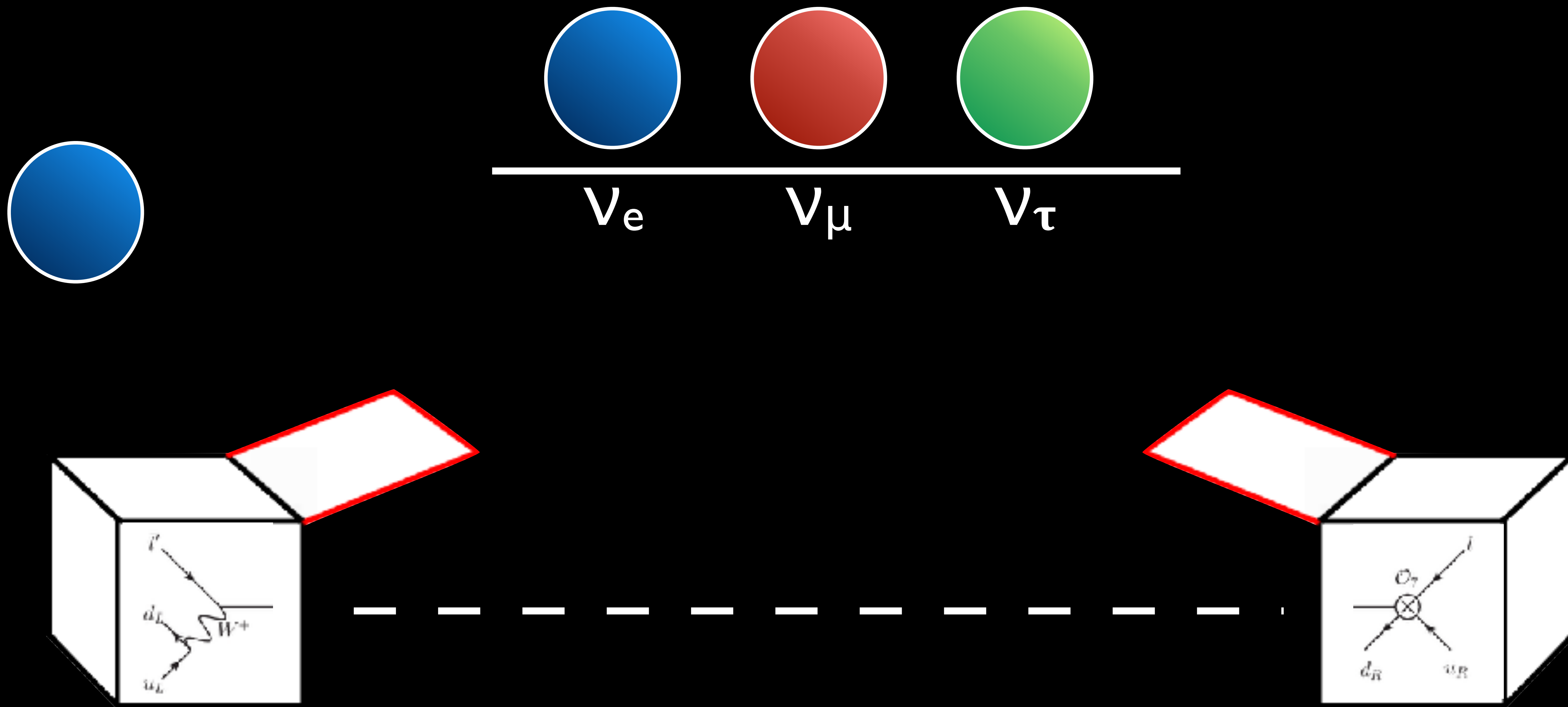
Aug 20th 2020

We now know neutrinos have mass.

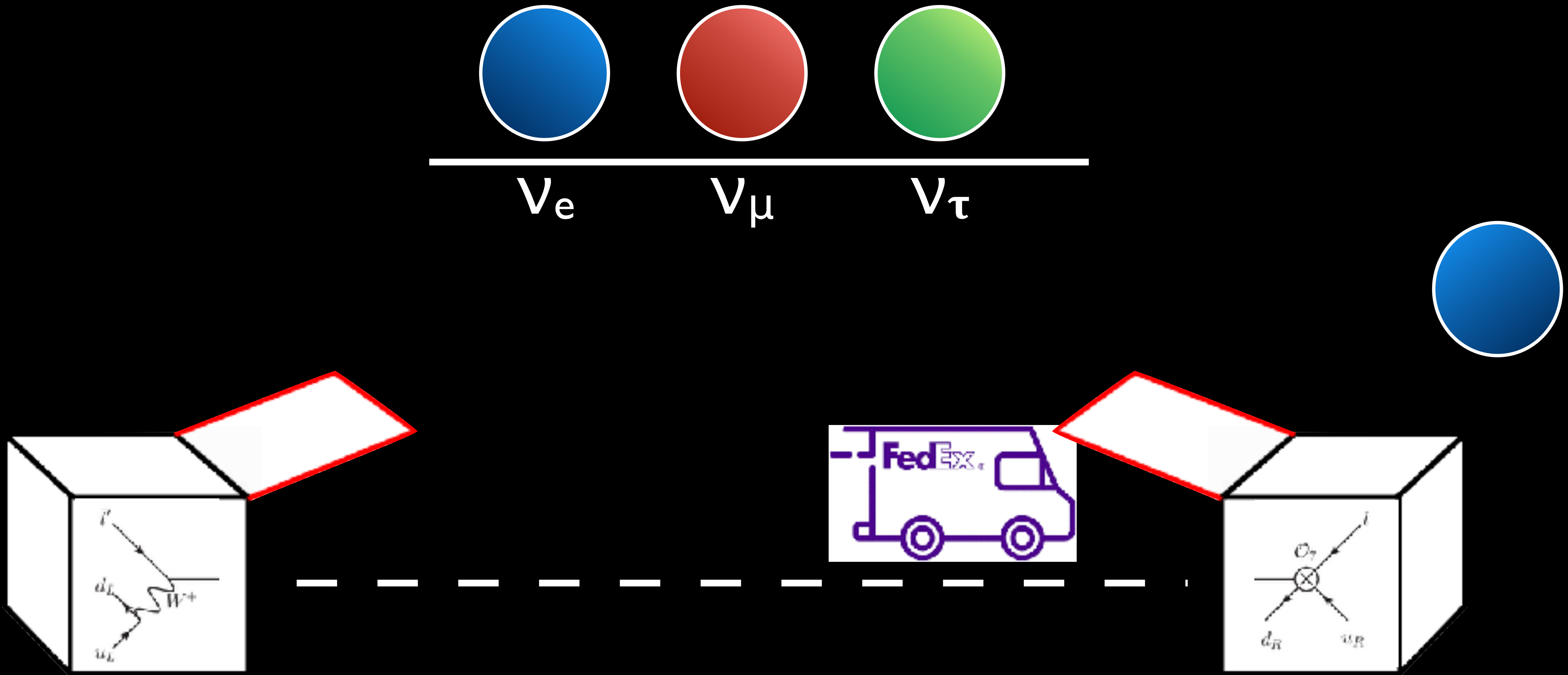
How?



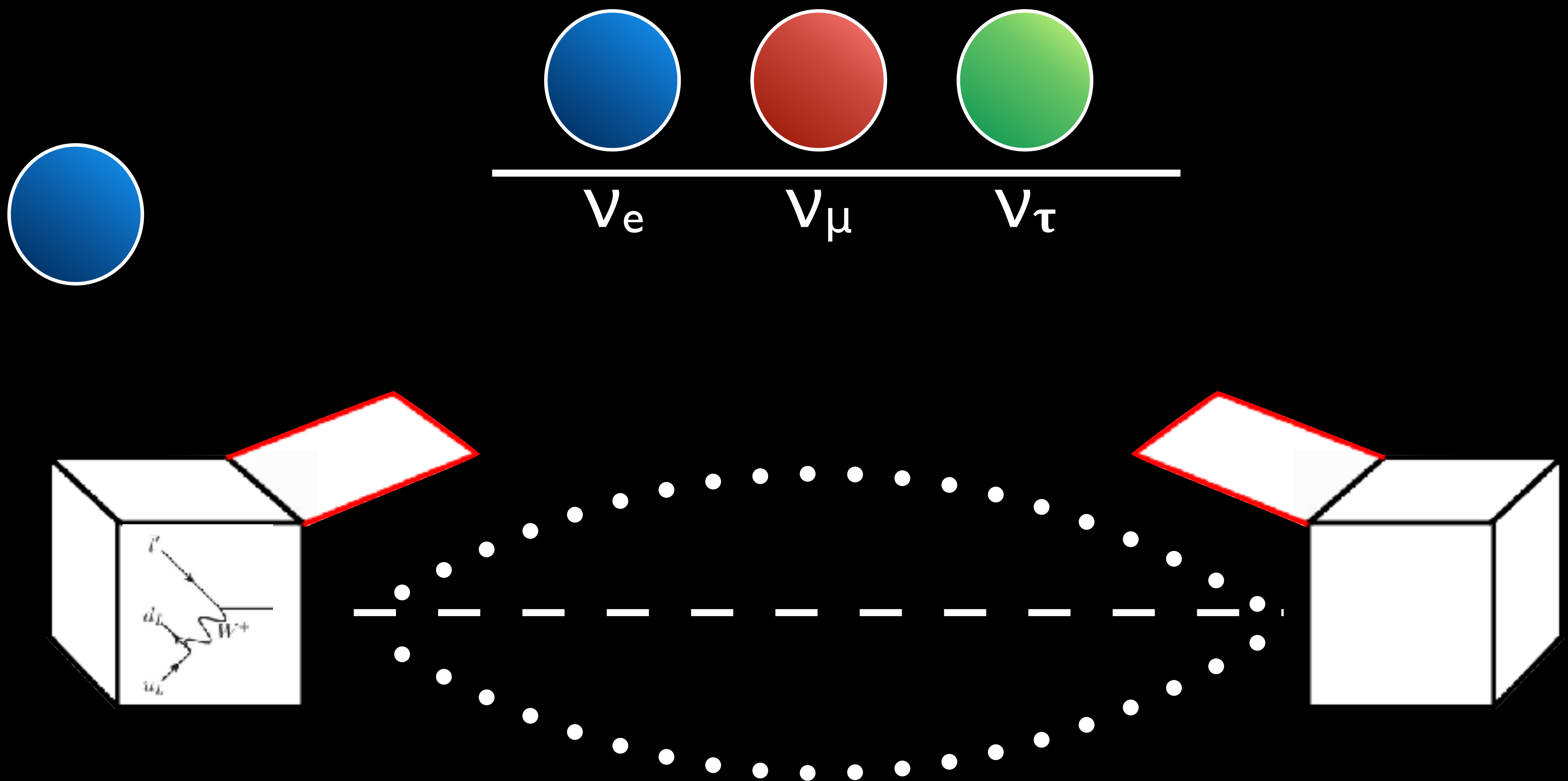
Neutrino flavors can be tagged by their partner leptons (e, μ, and τ)



Neutrino flavors can be tagged by their partner leptons (e, μ, and τ)

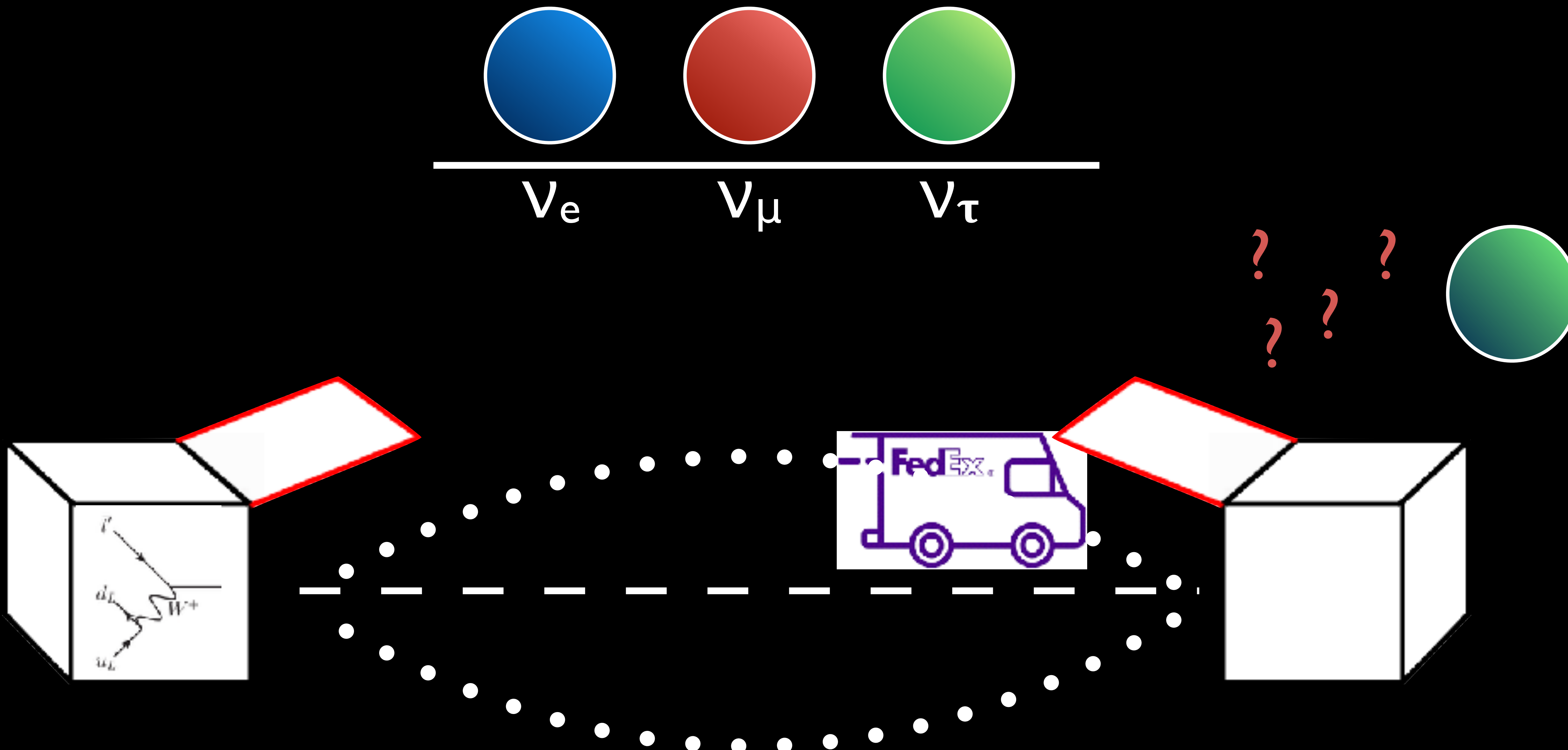


Neutrino flavors can be tagged by their partner leptons (e, μ, and τ)



But if neutrinos have different masses, then the propagating neutrino can interfere (mix) with the other mass states.

Flavor oscillations imply mass *differences*.



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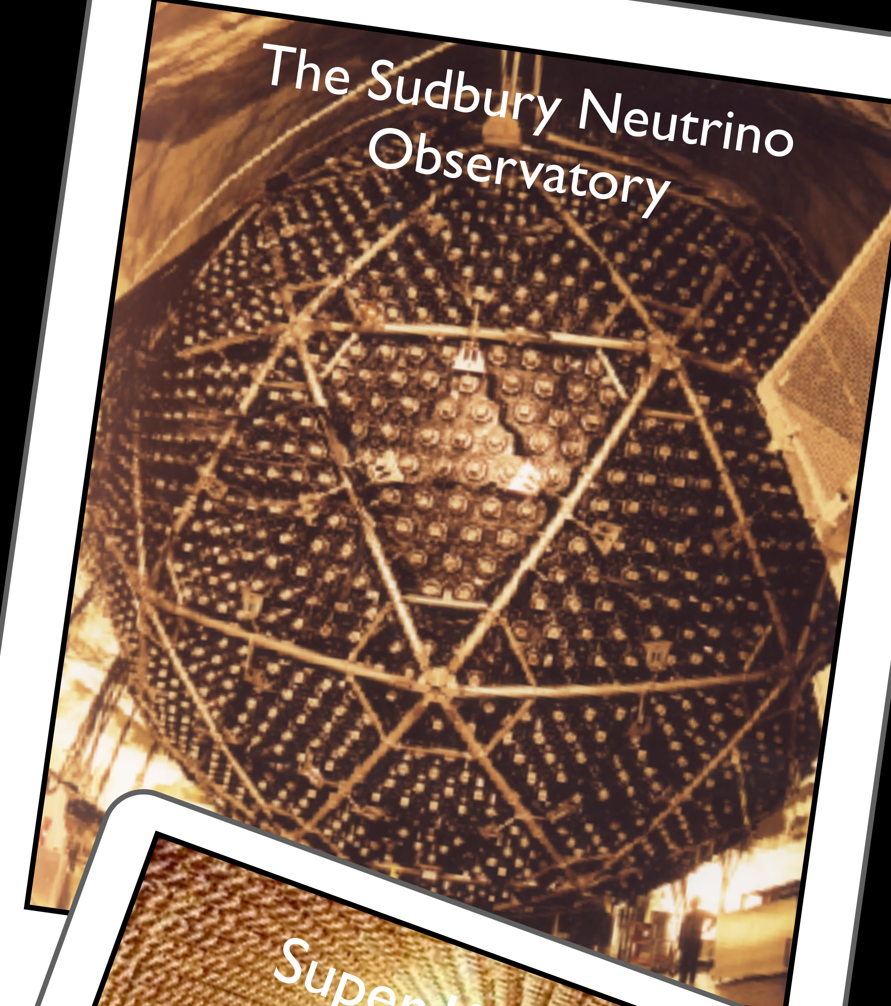
Flavor oscillations imply mass *differences*.

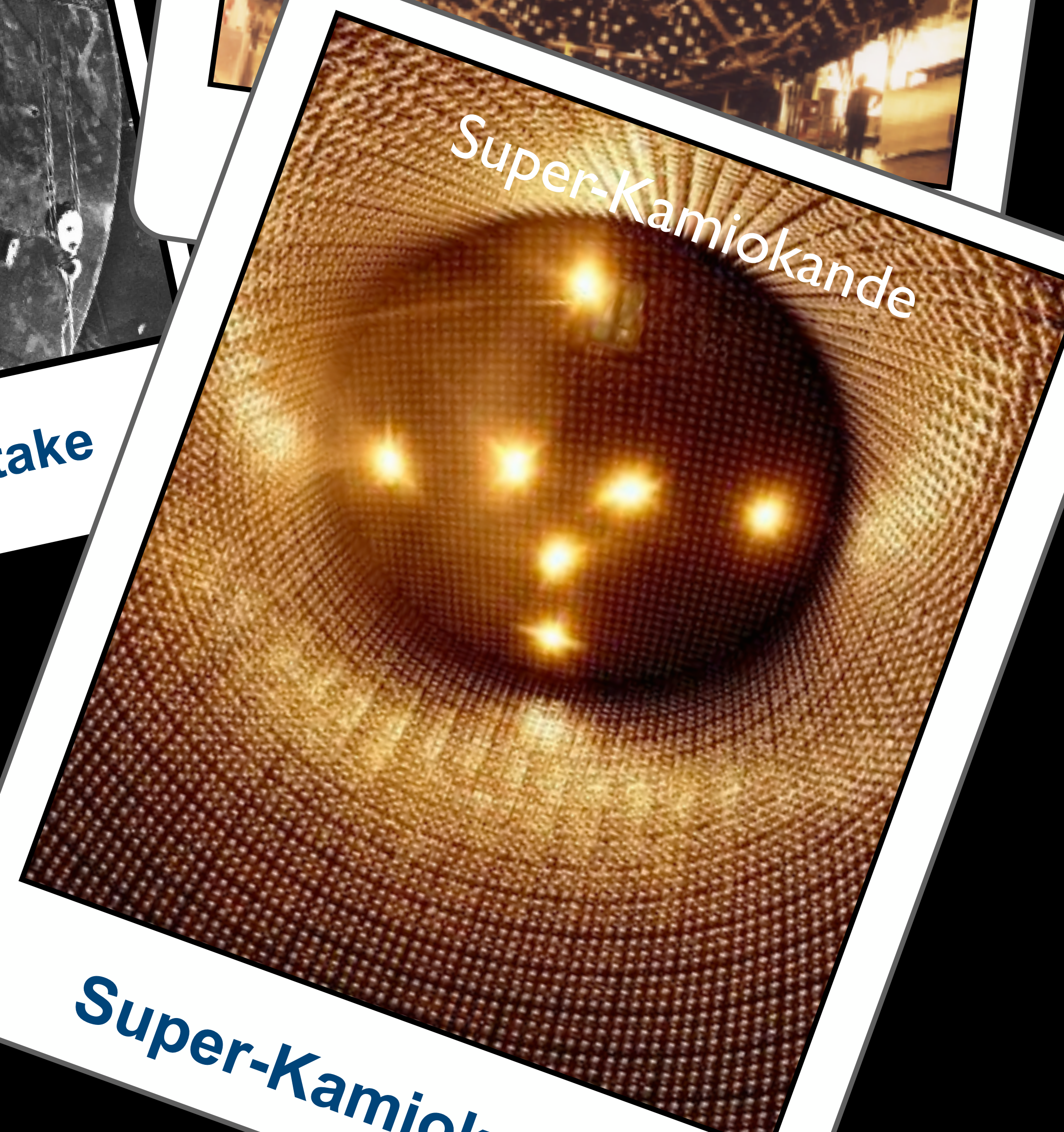
Ray Davis Jr., Homestake

MINOS

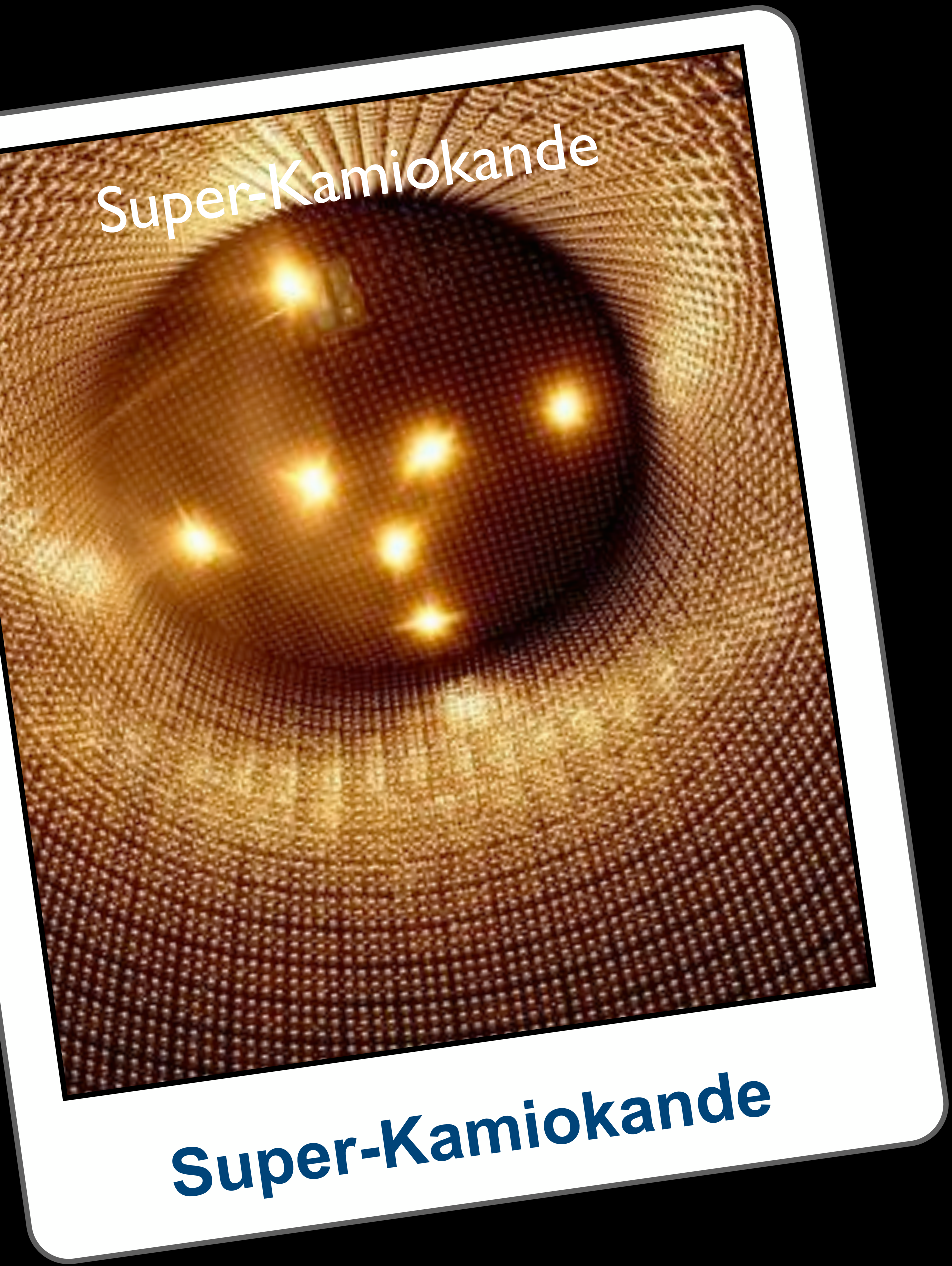


Ray Davis Jr., Homestake

KamLAND



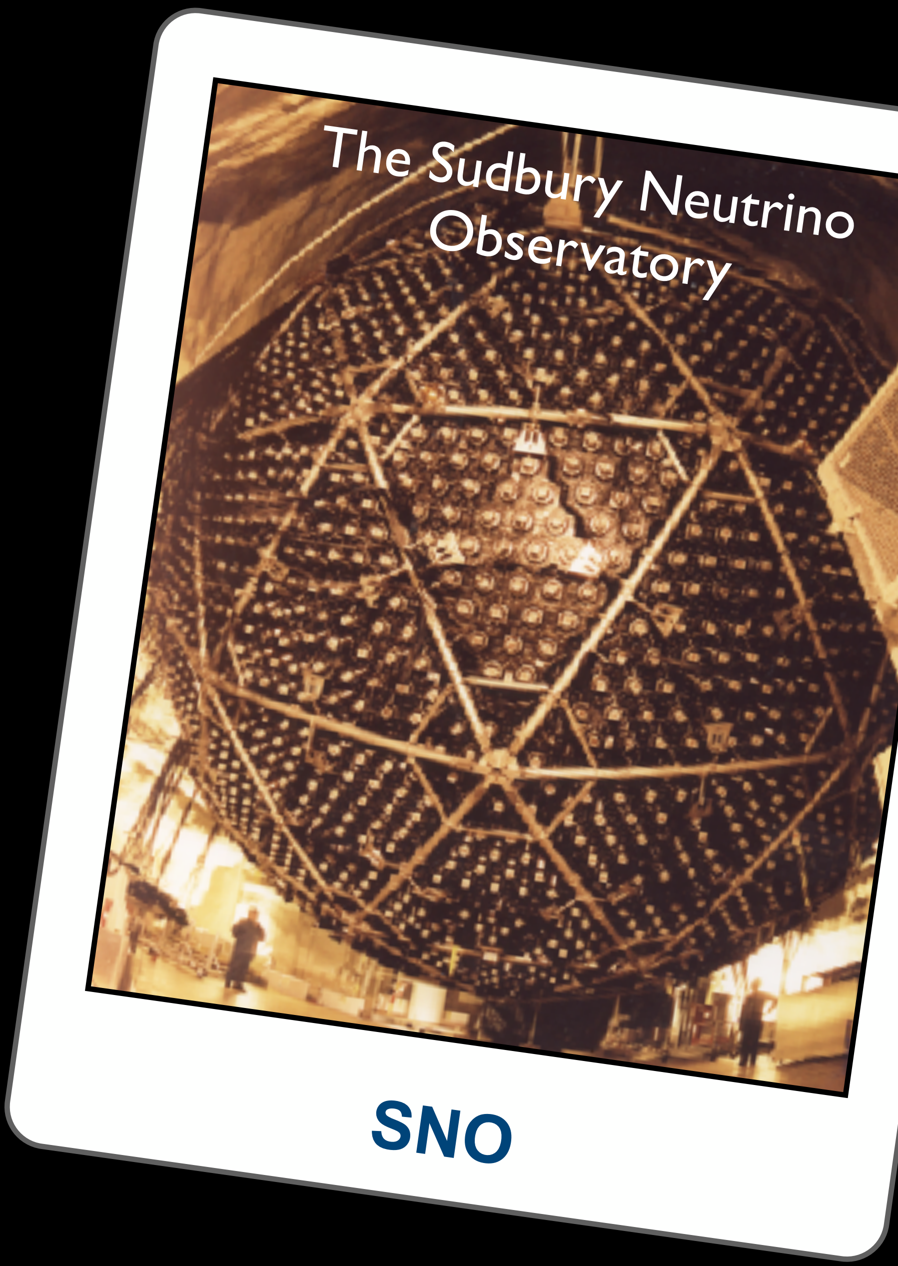
Super-Kamiokande



A myriad of experiments demonstrated that neutrinos transmute flavor (oscillate).

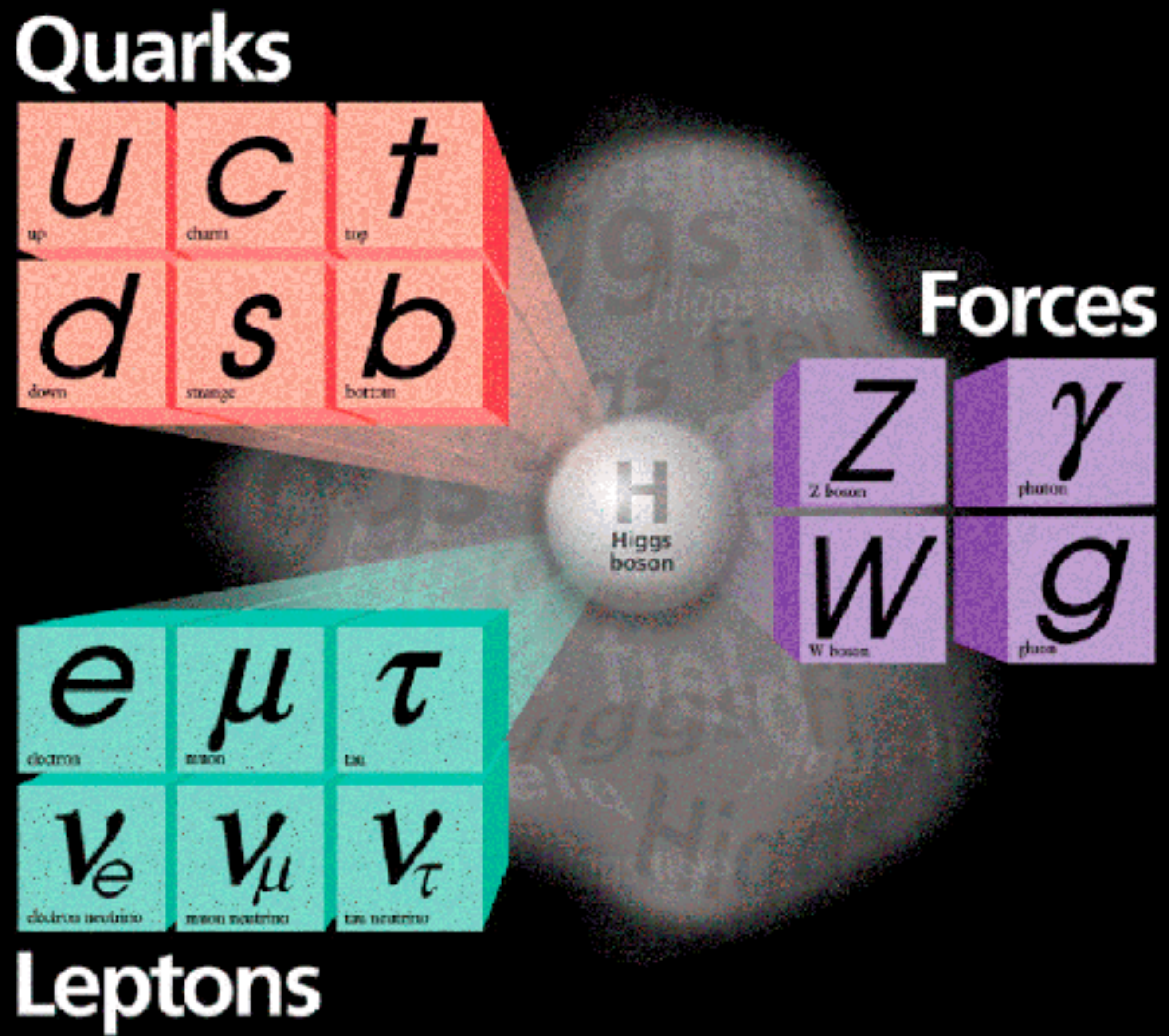
Proof that neutrinos must have mass.

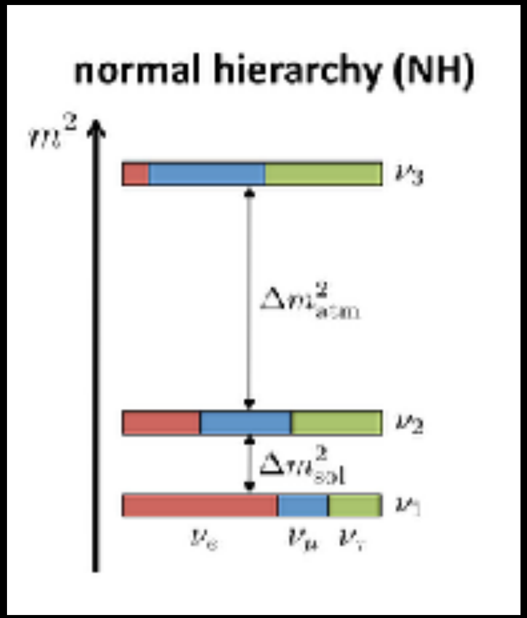
There are predictions that stem from alteration of the Standard Model.

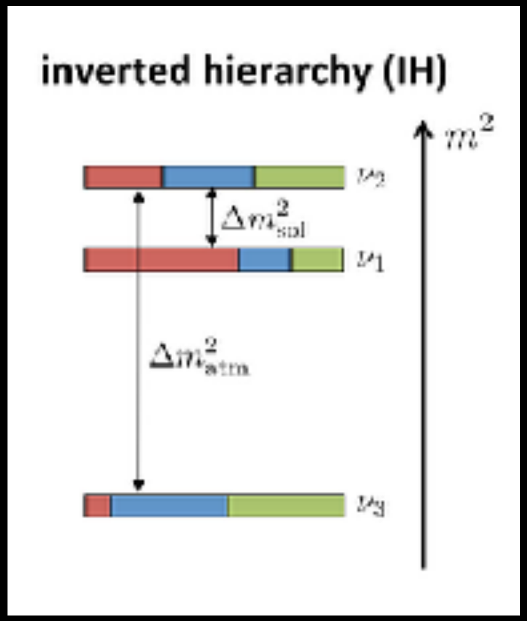


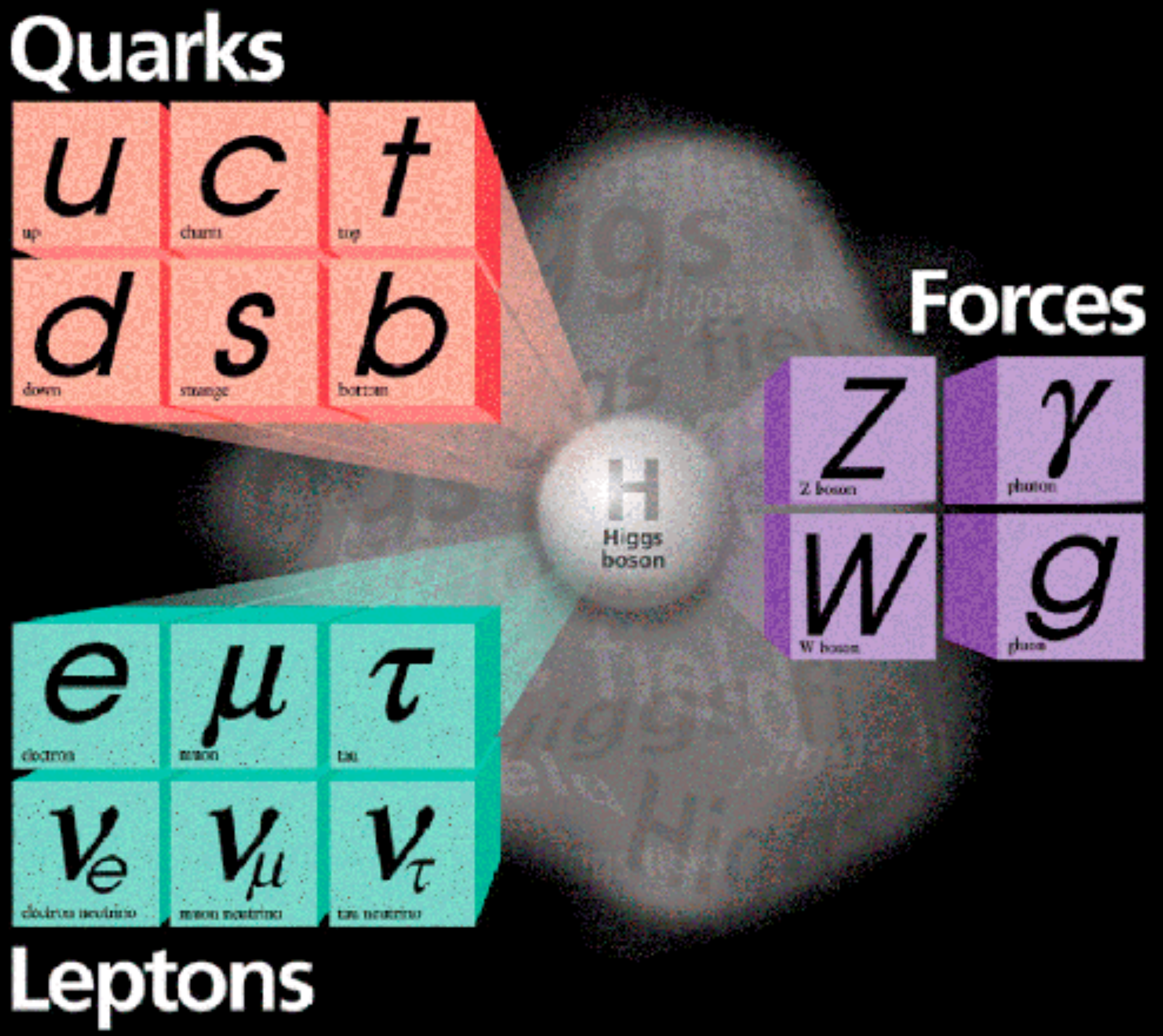
Takaaki Kajita
(Super-Kamiokande)

Arthur B. McDonald
(Sudbury Neutrino Observatory)


Quarks
u
up
c
charm
t
top
d
down
s
strange
b
bottom
Forces
Z
Z boson
γ
photon
W
W boson
g
gluon
H
Higgs boson
e
electron
μ
muon
τ
tau
νe
electron neutrino
νμ
muon neutrino
ντ
tau neutrino
Leptons



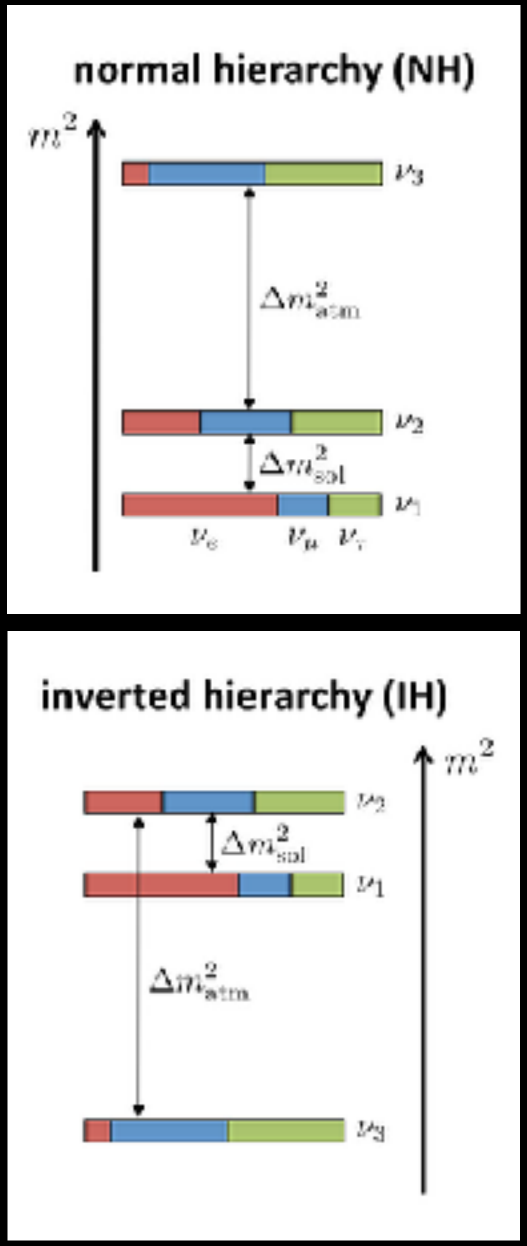


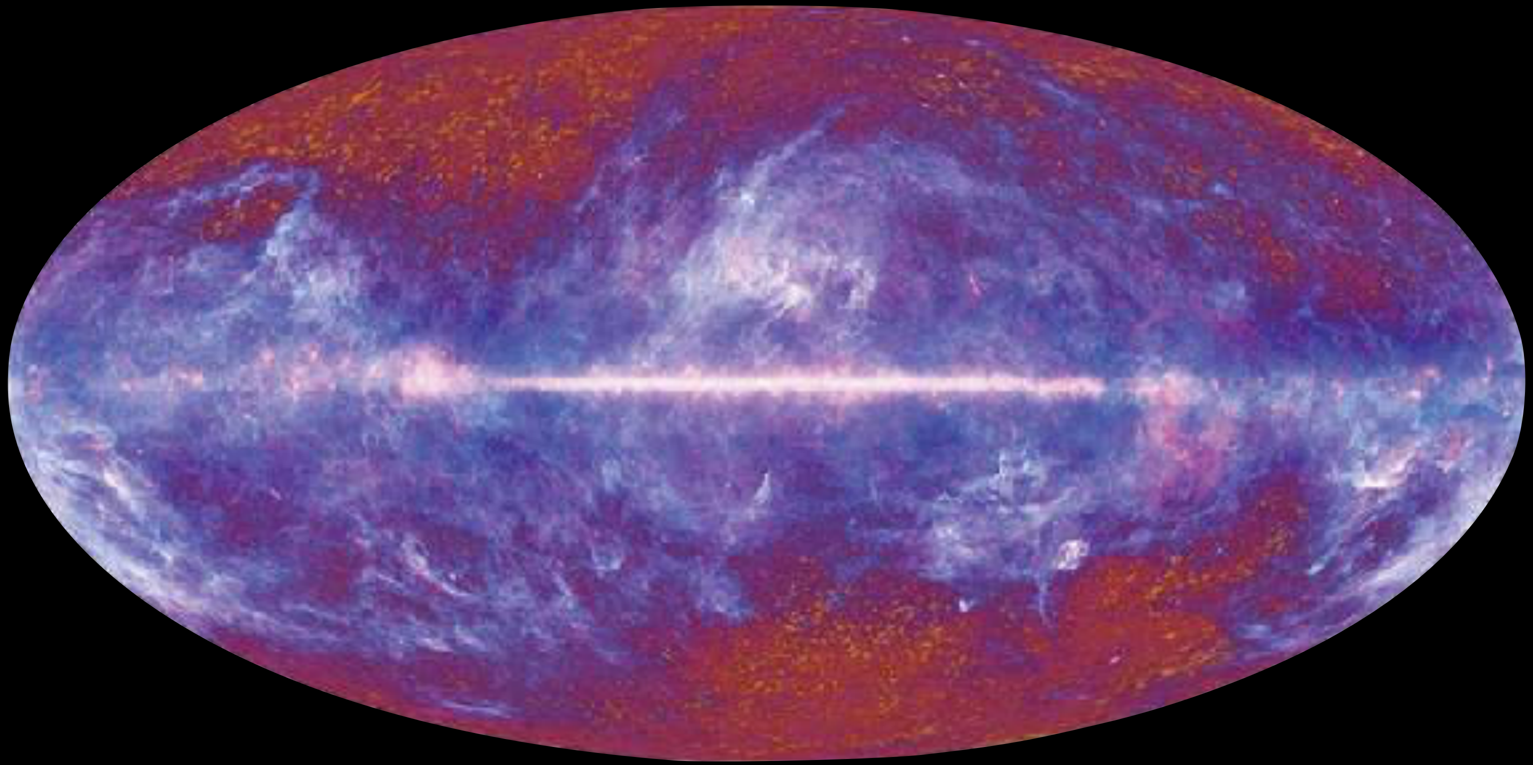


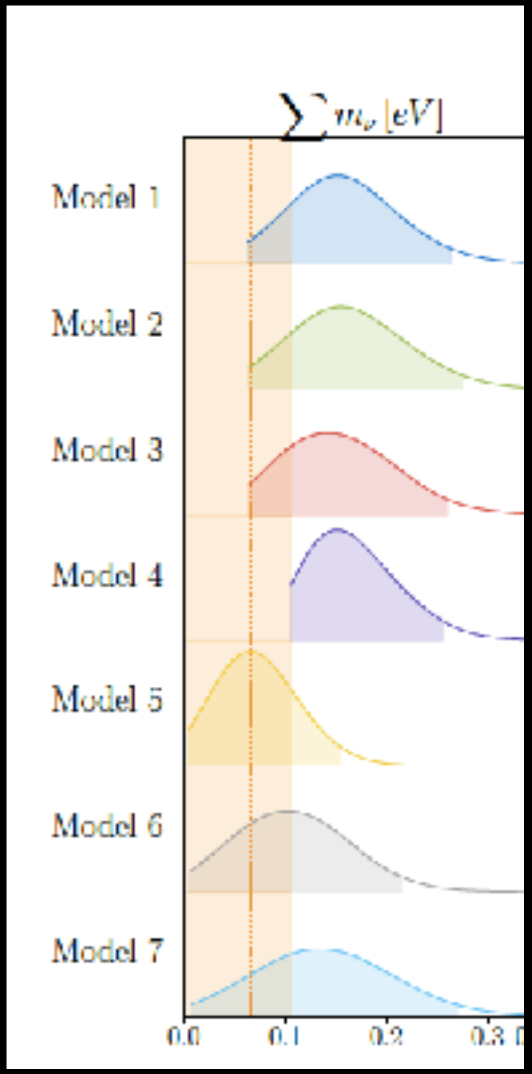
The Origin of Mass

The mechanism by which particles gain mass in the Standard Model may not apply for neutrinos.

The neutrino mass mechanism remains unknown.







The Origin of Mass

The mechanism by which particles gain mass in the Standard Model may not apply for neutrinos.

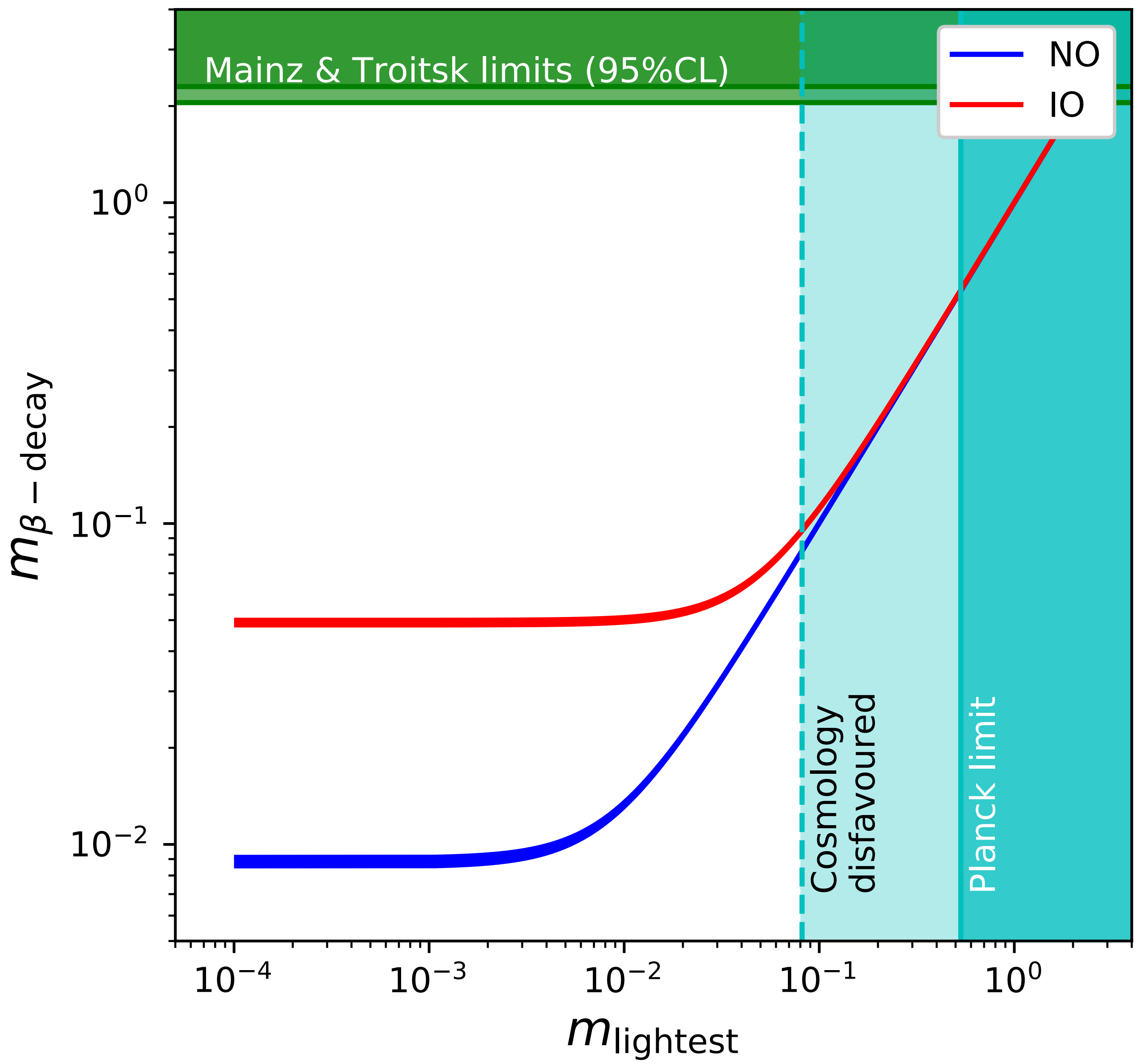
The neutrino mass mechanism remains unknown.

Impact on Cosmology

Given the primordial abundance of neutrinos, even a small finite mass has a measurable impact on cosmic evolution.

Measurable in next generation of experiments.

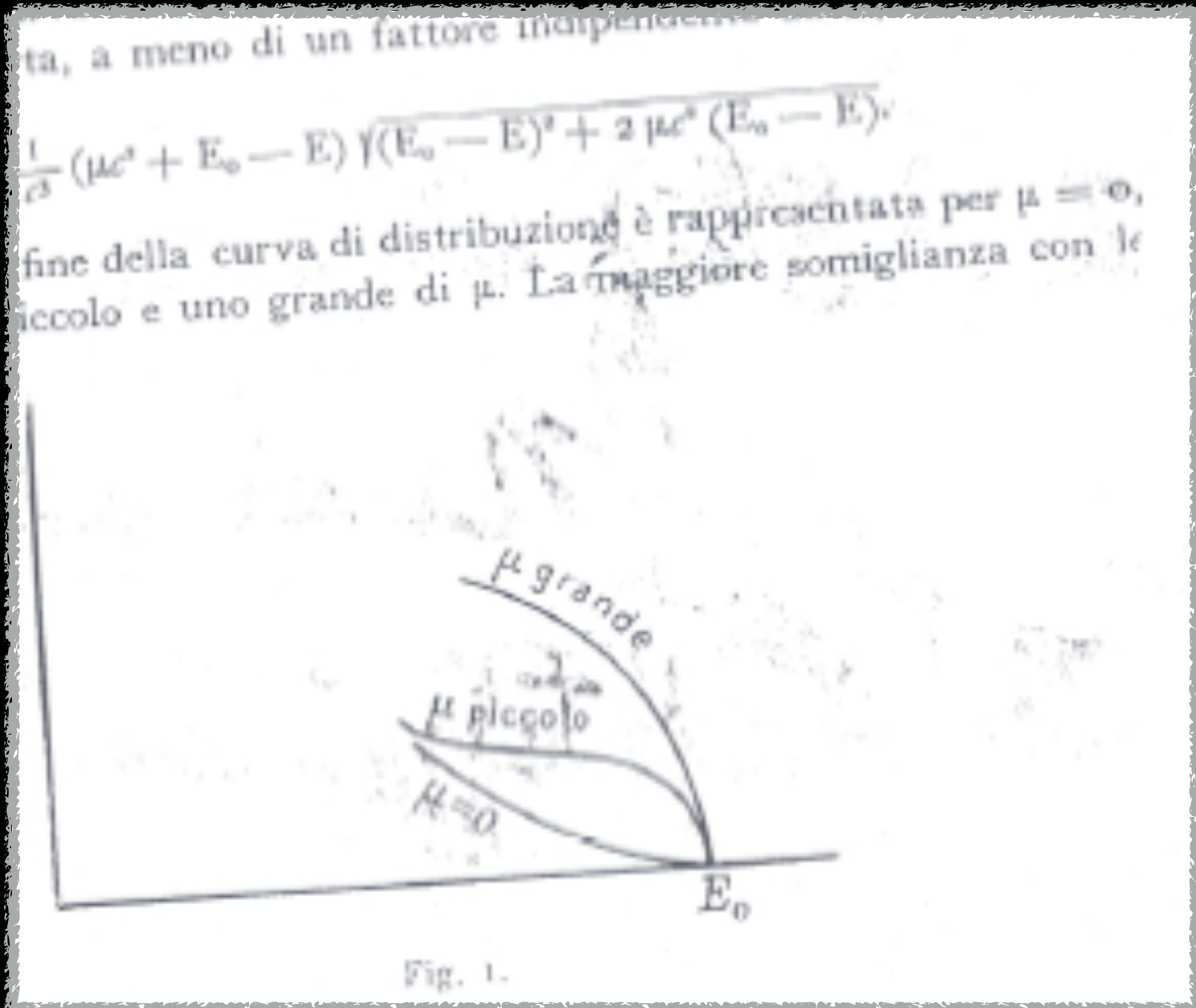
Landscape Outlook



Created using www.nu-fit.org

Cosmology (@ 50 meV) and 0νββ (@ 15 meV) has the potential to probe the deepest into the oscillation prediction for the mass scale over the next decade.

However, the method with the most strongly tested assumptions is direct kinematic searches through beta decay.

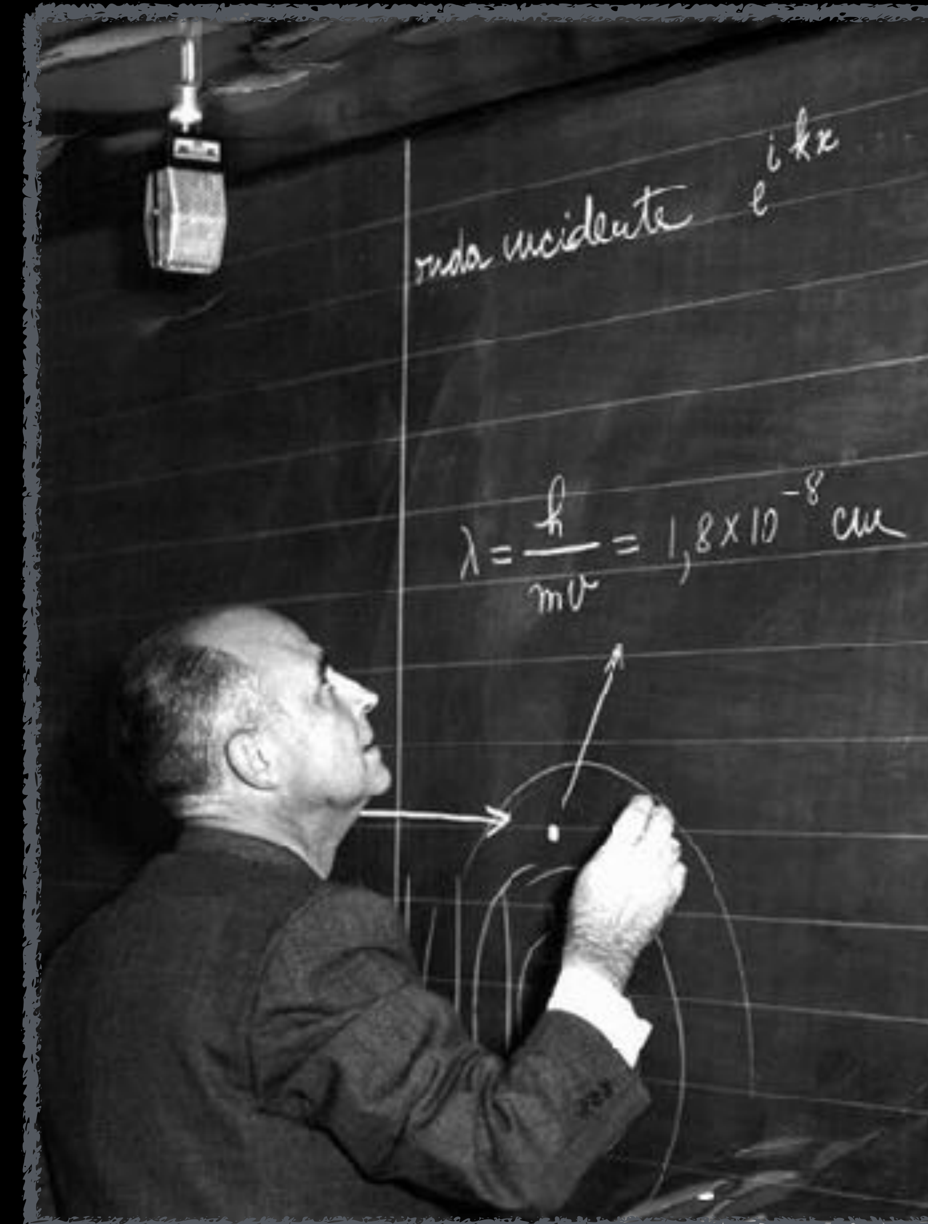

ta, a meno di un fattore indipen

$$\frac{1}{c^3}(\mu c^2 + E_0 - E)\sqrt{(E_0 - E)^2 + 2\mu c^2 (E_0 - E)}.$$

fine della curva di distribuzione è rappresentata per $\mu = 0$,

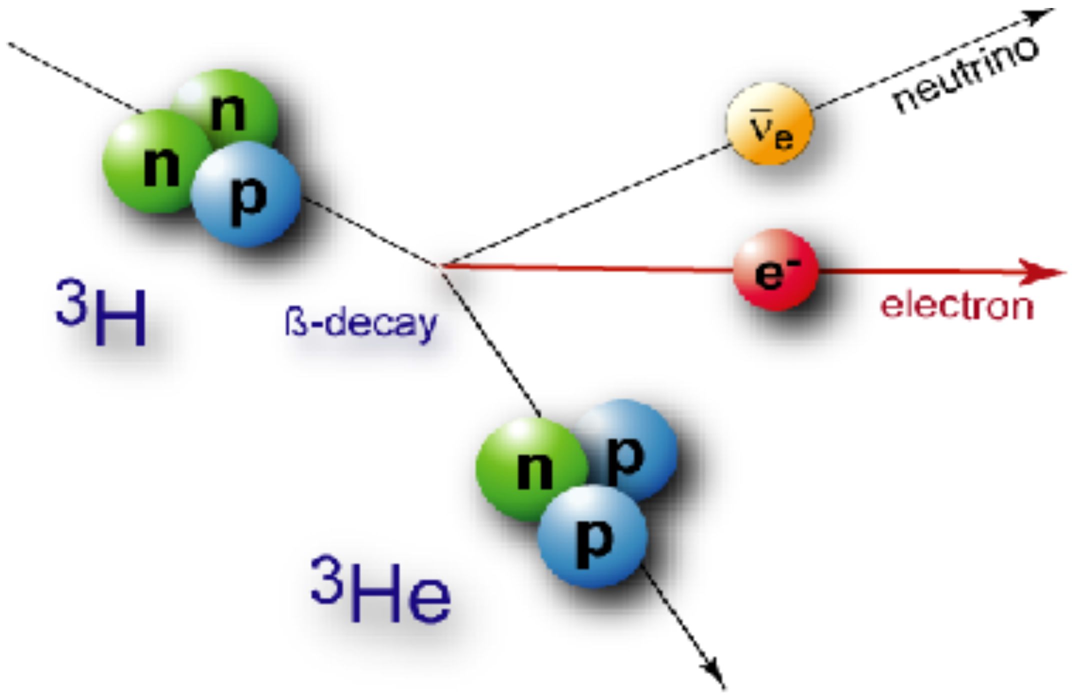
iccolo e uno grande di μ. La maggiore somiglianza con le

Fig. 1.



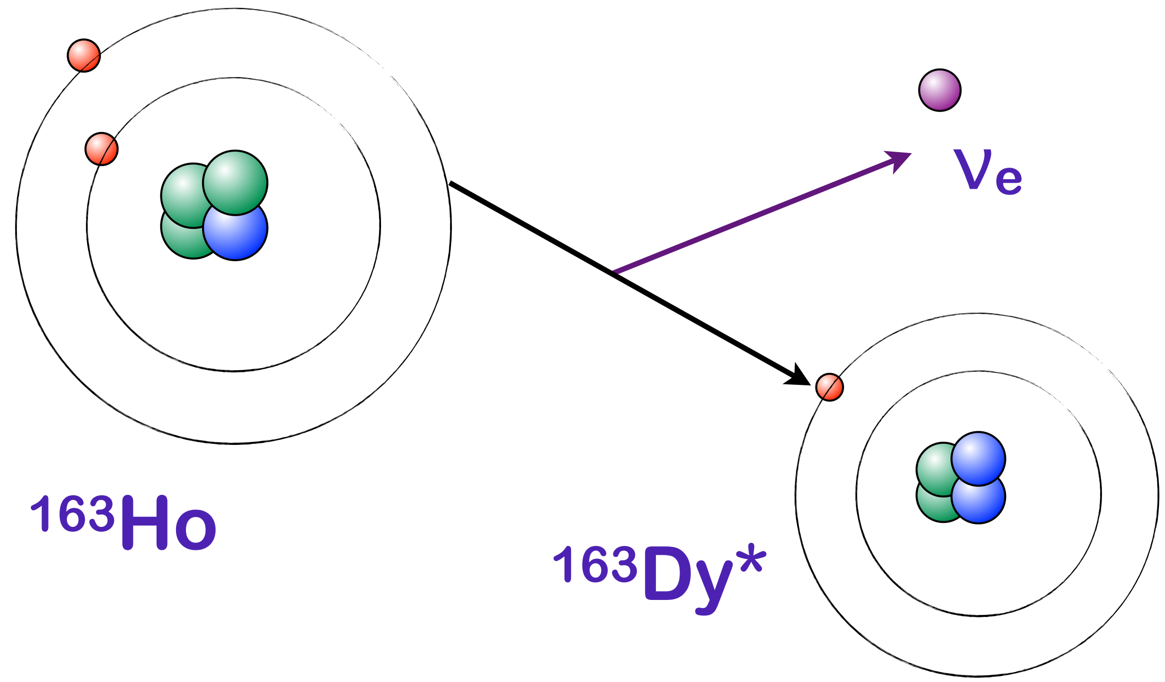
Enrico Fermi
1934

Tritium beta decay



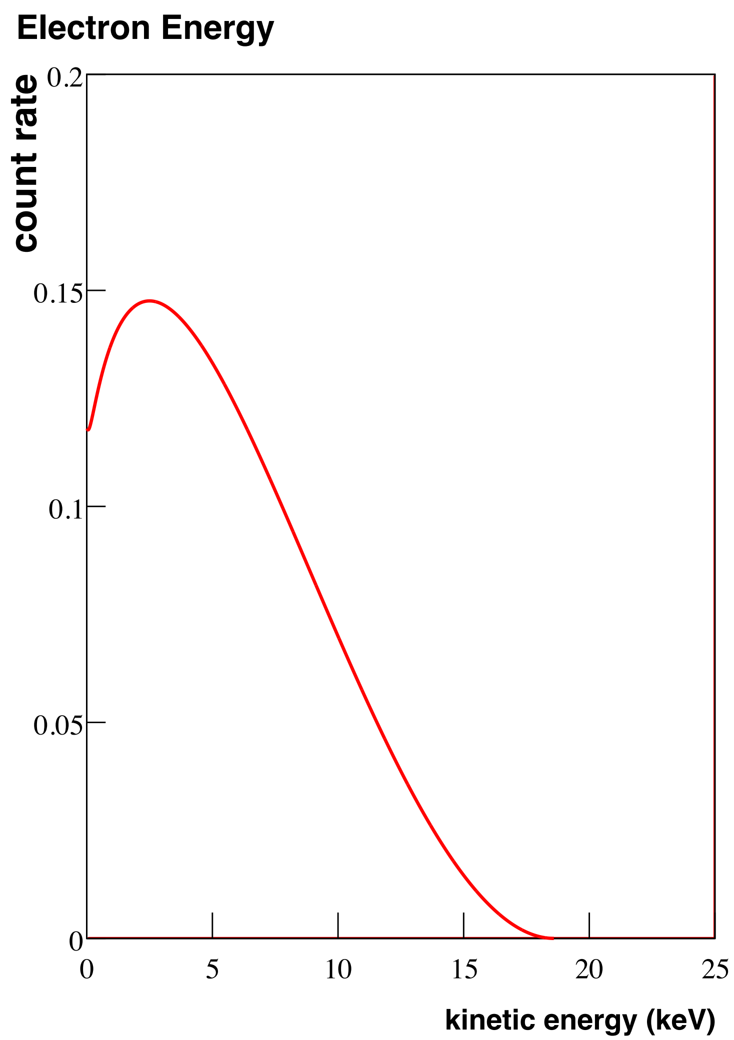
$$^3\mathrm{H} \rightarrow \ ^3\mathrm{He}^+ + e^- + \bar{\nu}_e$$

Holmium electron capture



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

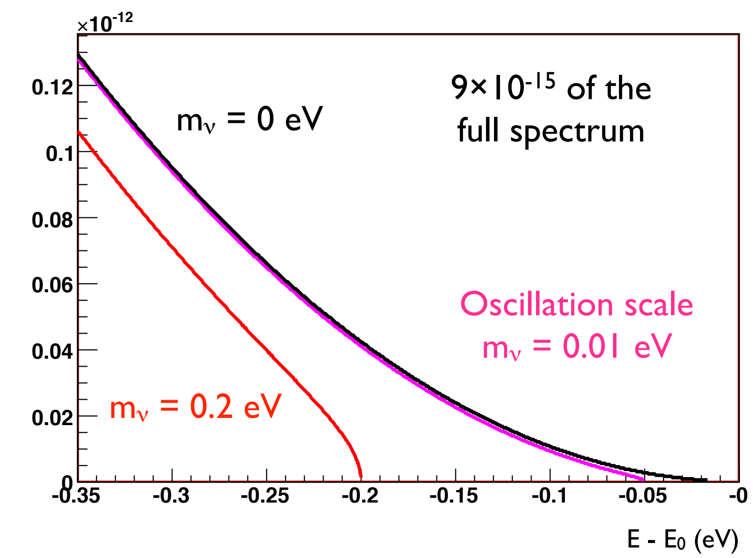
Kinematic spectra from beta decay or electron capture embed the neutrino mass near the endpoint.

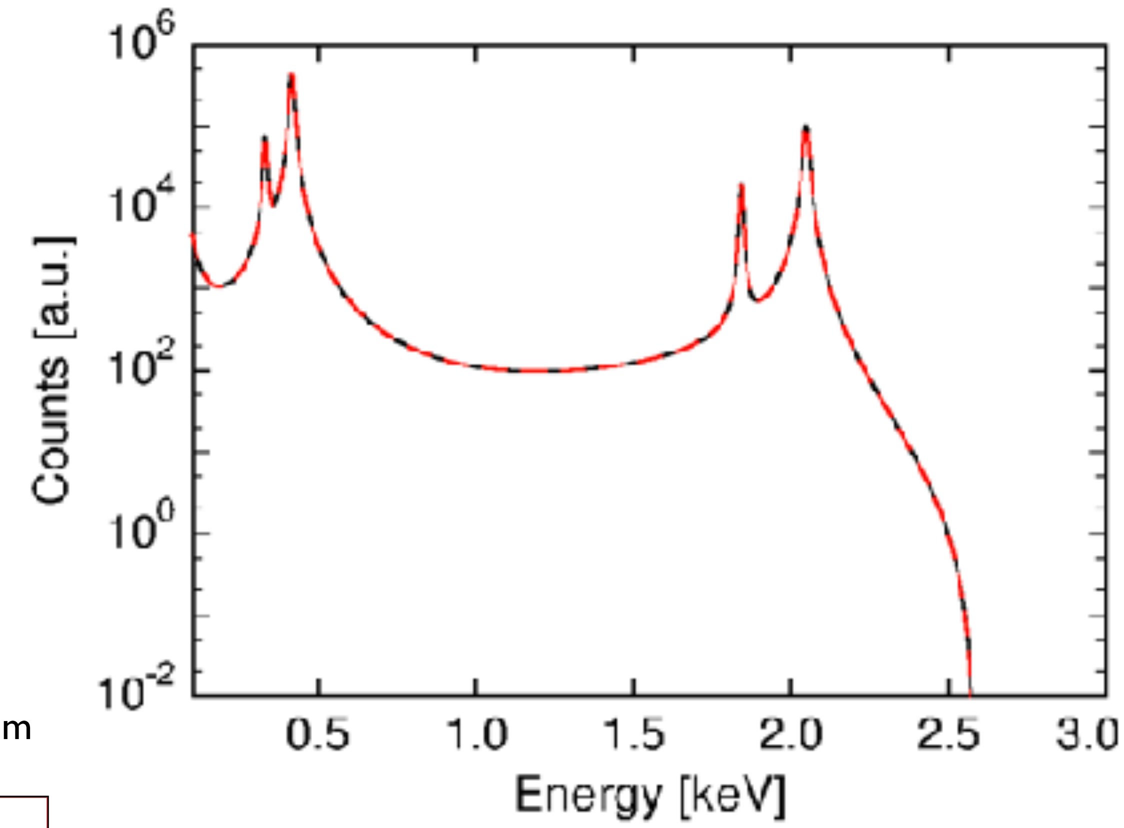


$$\dot{N} \propto p_\nu E_\nu$$

In both cases, differential spectrum depends on the neutrino momentum.

Endpoint of the Tritium β-decay Spectrum





$$m_\beta^2 = \sum_i |U_{ei}|^2 m_{\nu i}^2$$

Necessary Conditions:

High Flux and High Precision

Electron transfers all of its energy to the absorbing medium.

Calorimetric
(Cryogenic Bolometers)

Electromagnetic filtering of electrons of selected energy.

Electromagnetic Collimation
(MAC-E Filter)

Use photon spontaneous emission from electron in magnetic field.

Frequency-Based
(Cyclotron Radiation Emission Spectroscopy)

Electromagnetic filtering of electrons of selected energy.

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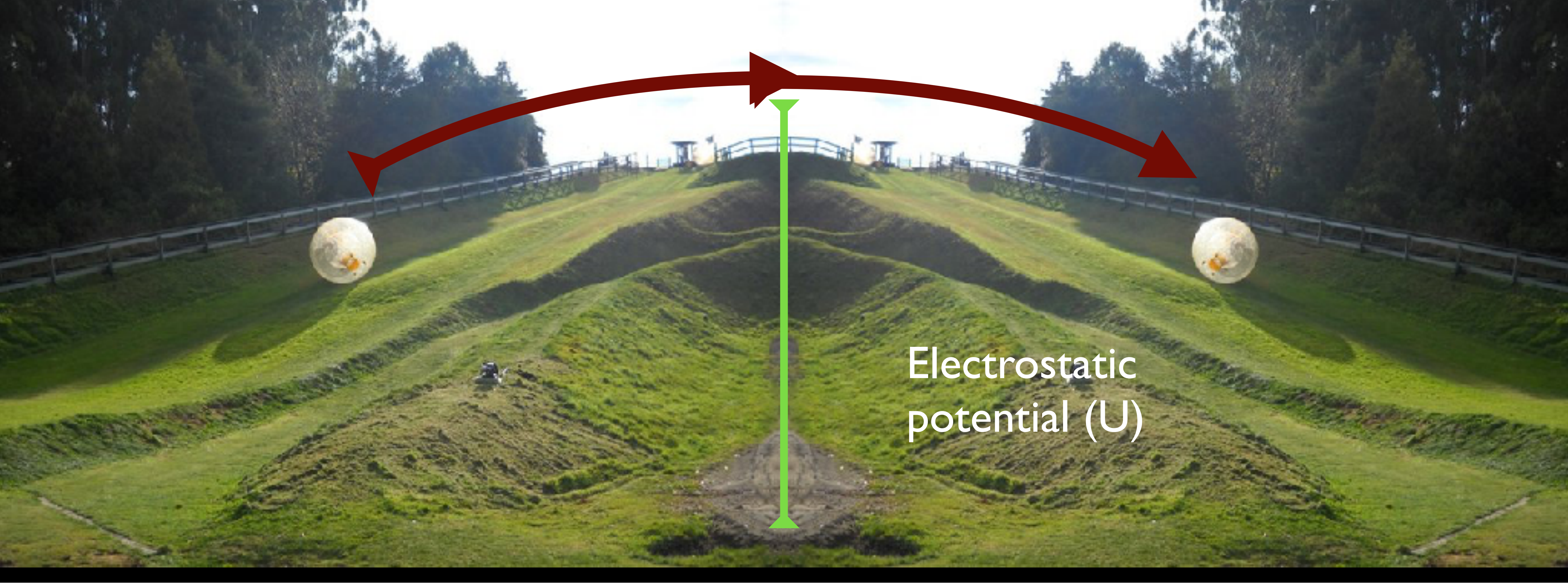
(MAC-E Filter)



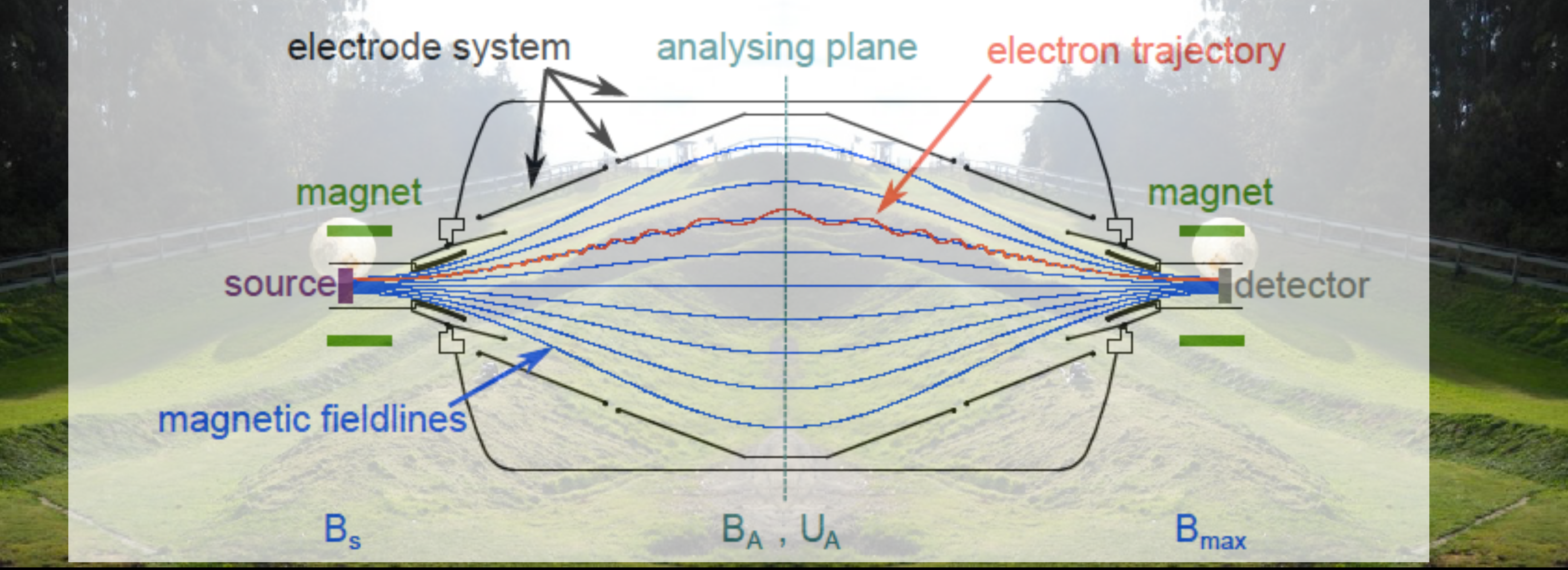
High Magnetic Field (Bs)

Low Field
B_A

High Magnetic Field (Bs)

Magnetic Adiabatic Collimation
with
Electrostatic Filtering

(only those with enough energy can make it up the hill)



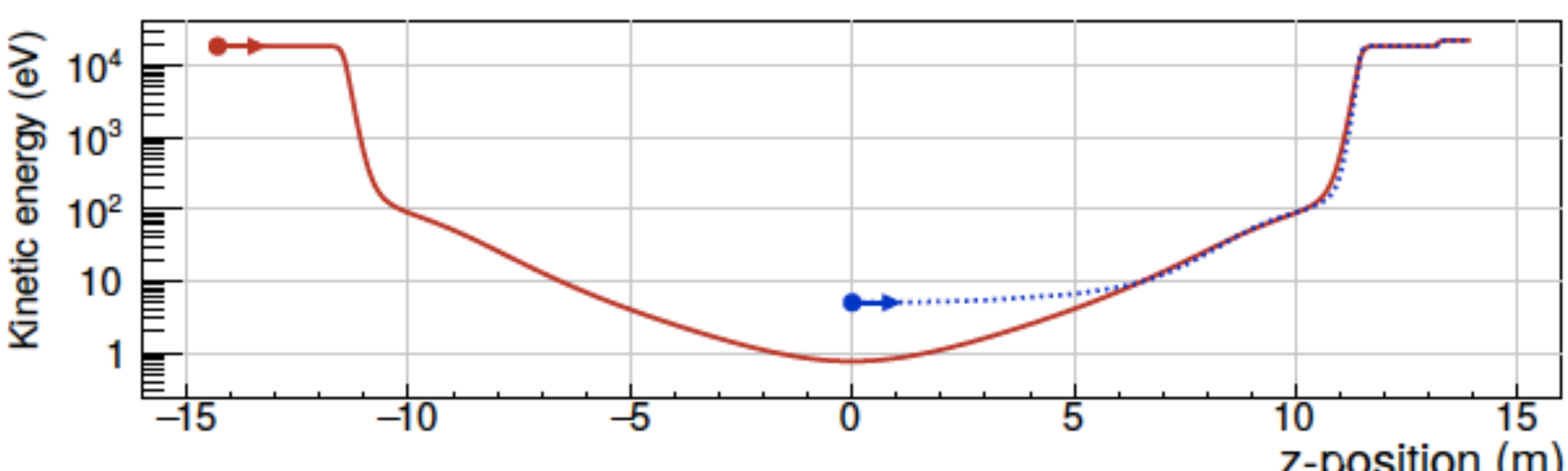
High Magnetic Field (Bs)

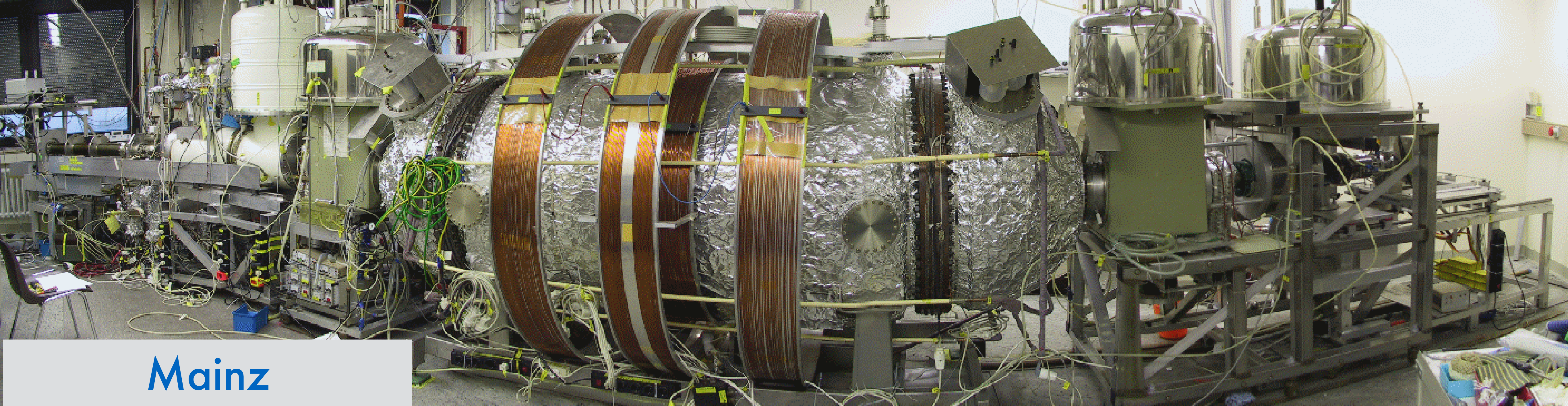
Low Field B_A

High Magnetic Field (Bs)

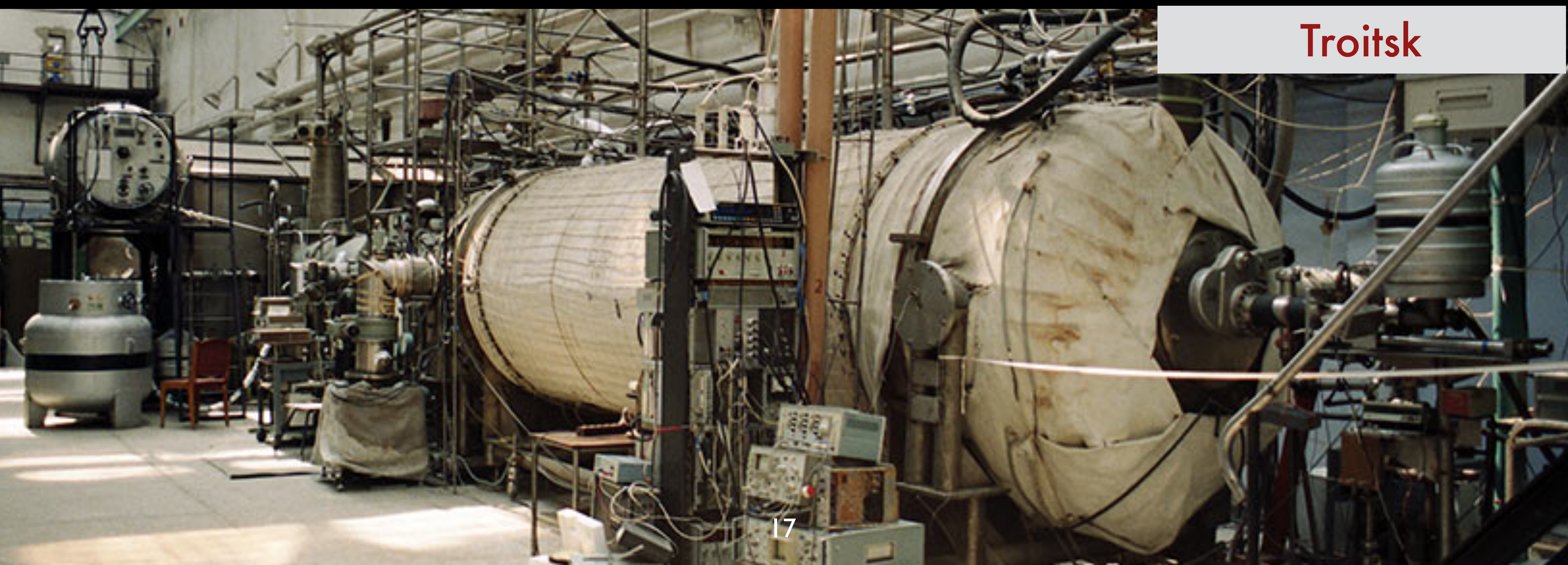
μ_e μ_e μ_e μ_e μ_e

10^{11} e⁻ / second — 1 e⁻ / second

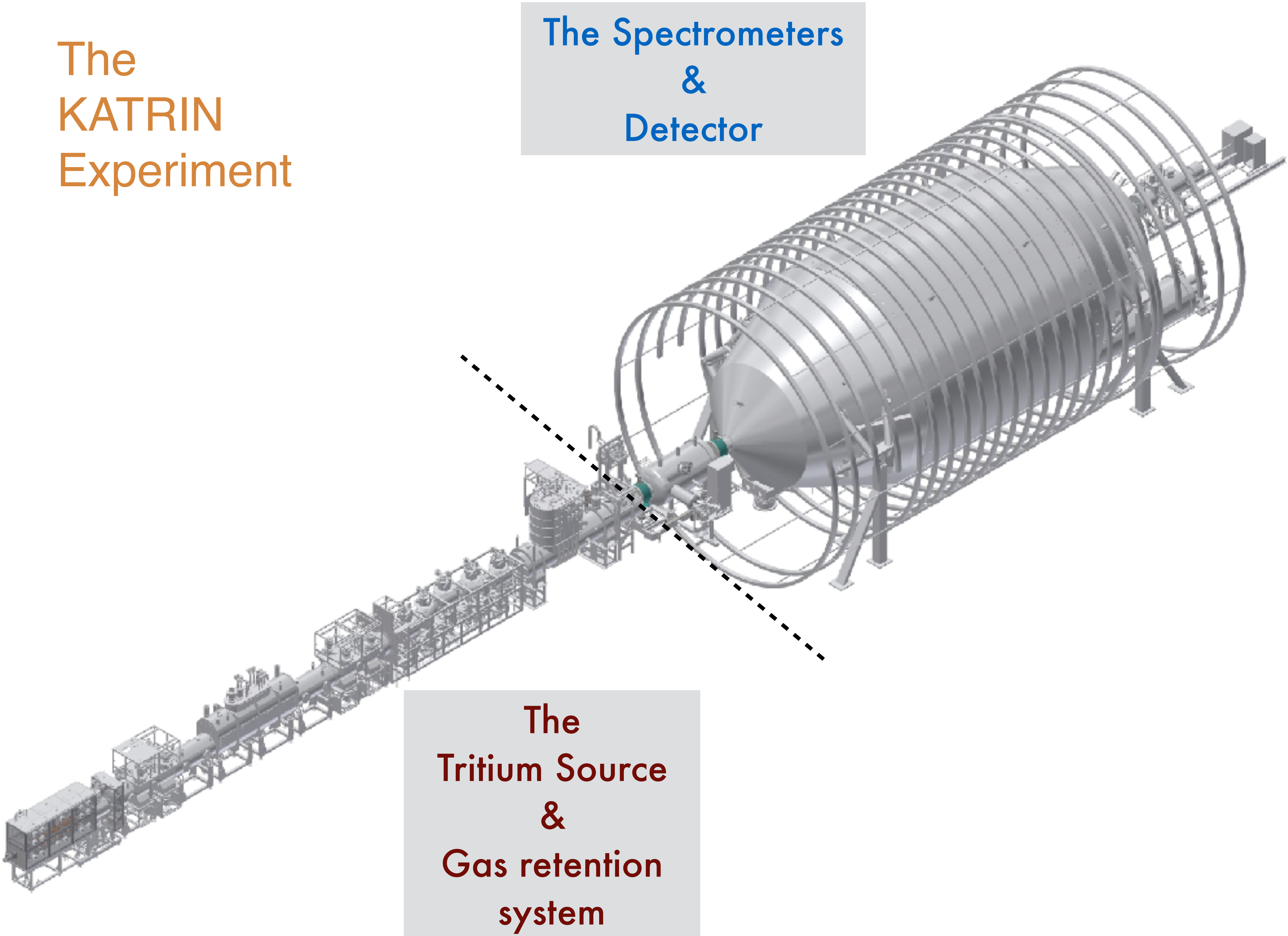




Predecessor Experiments



The KATRIN Experiment



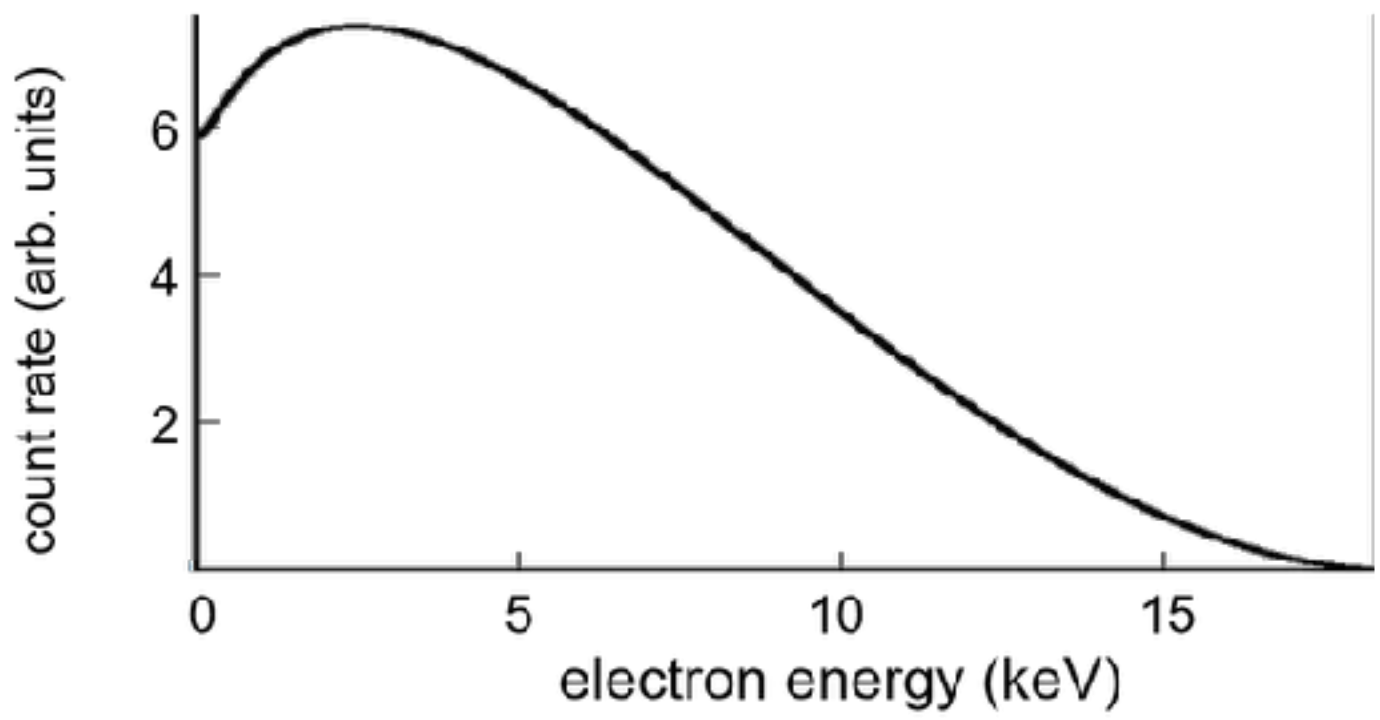
KATRIN's 1st Neutrino mass campaign

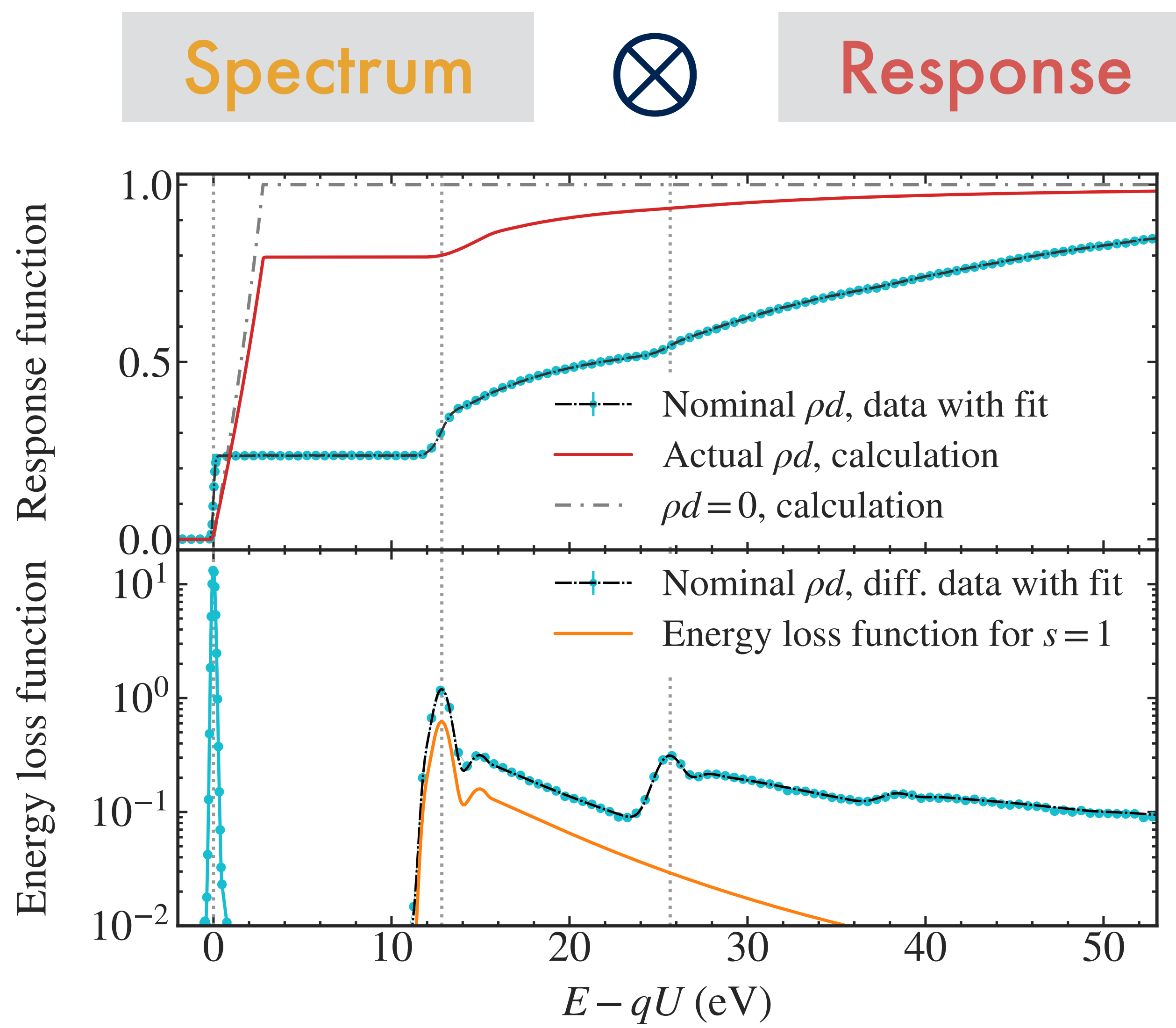
April 10 until May 13, 2019 (780 hours)

High source activity (0.66 Ci)

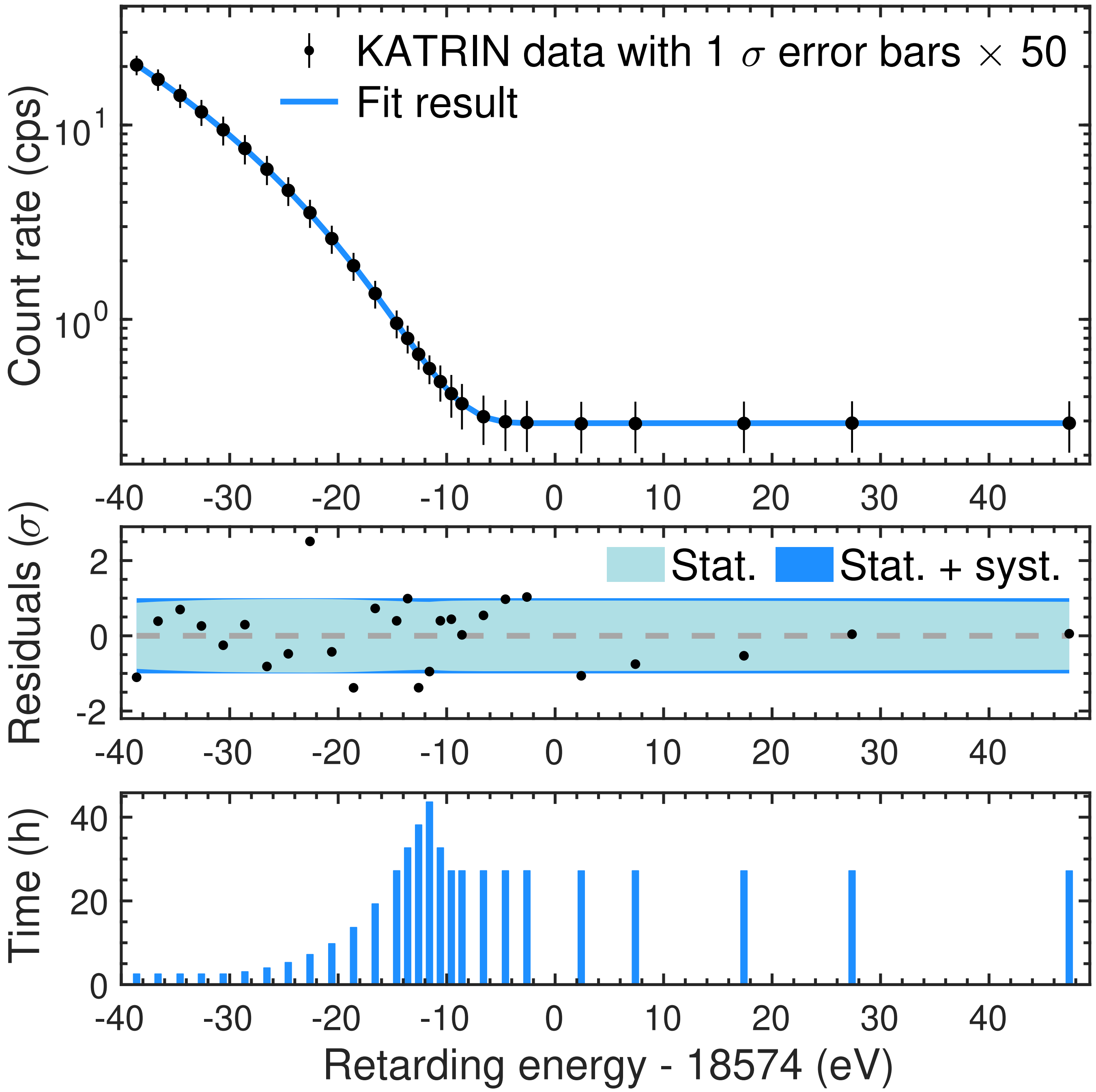
High purity (97.5% T_2)

Combining data from runs & pixels

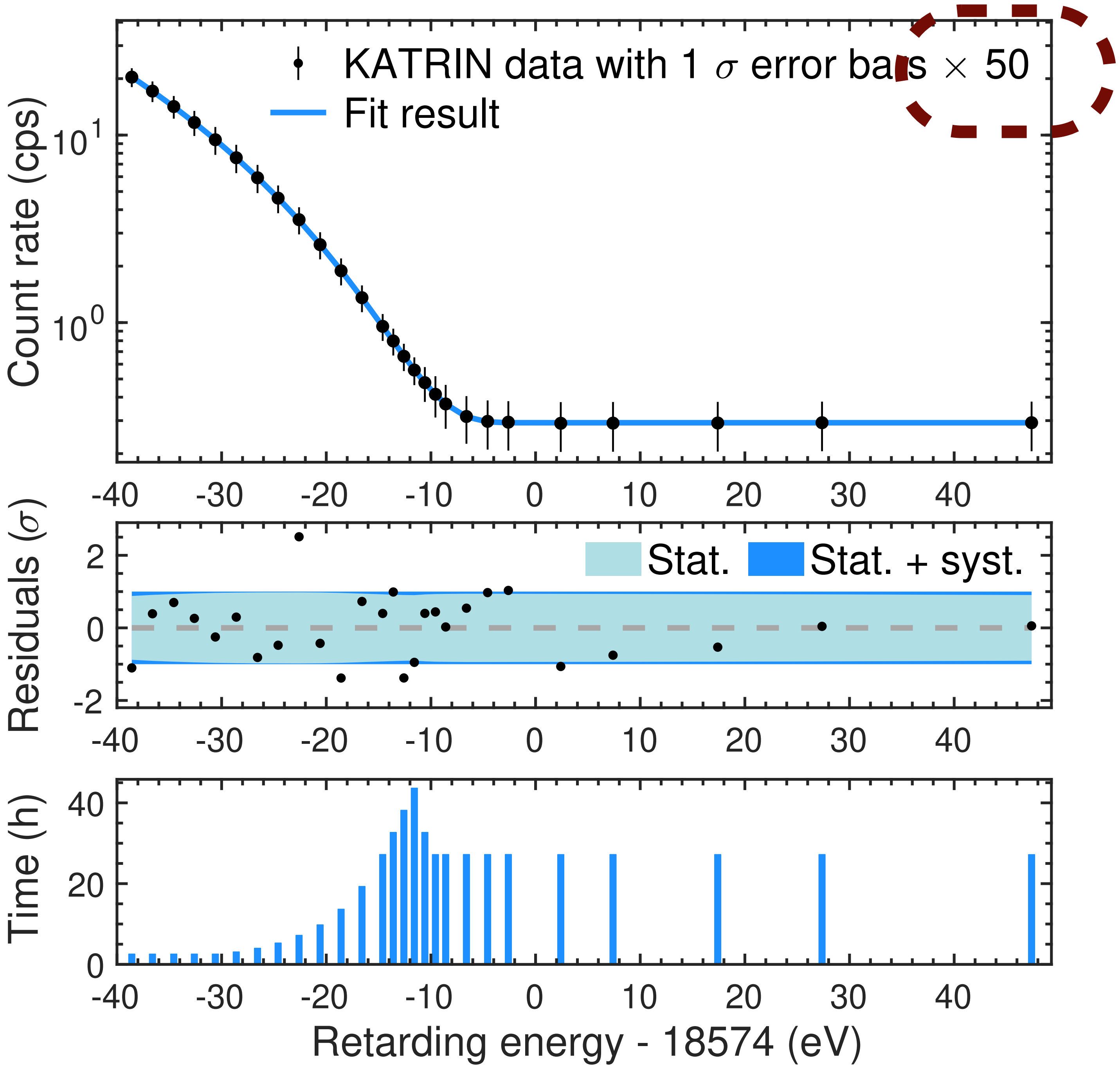




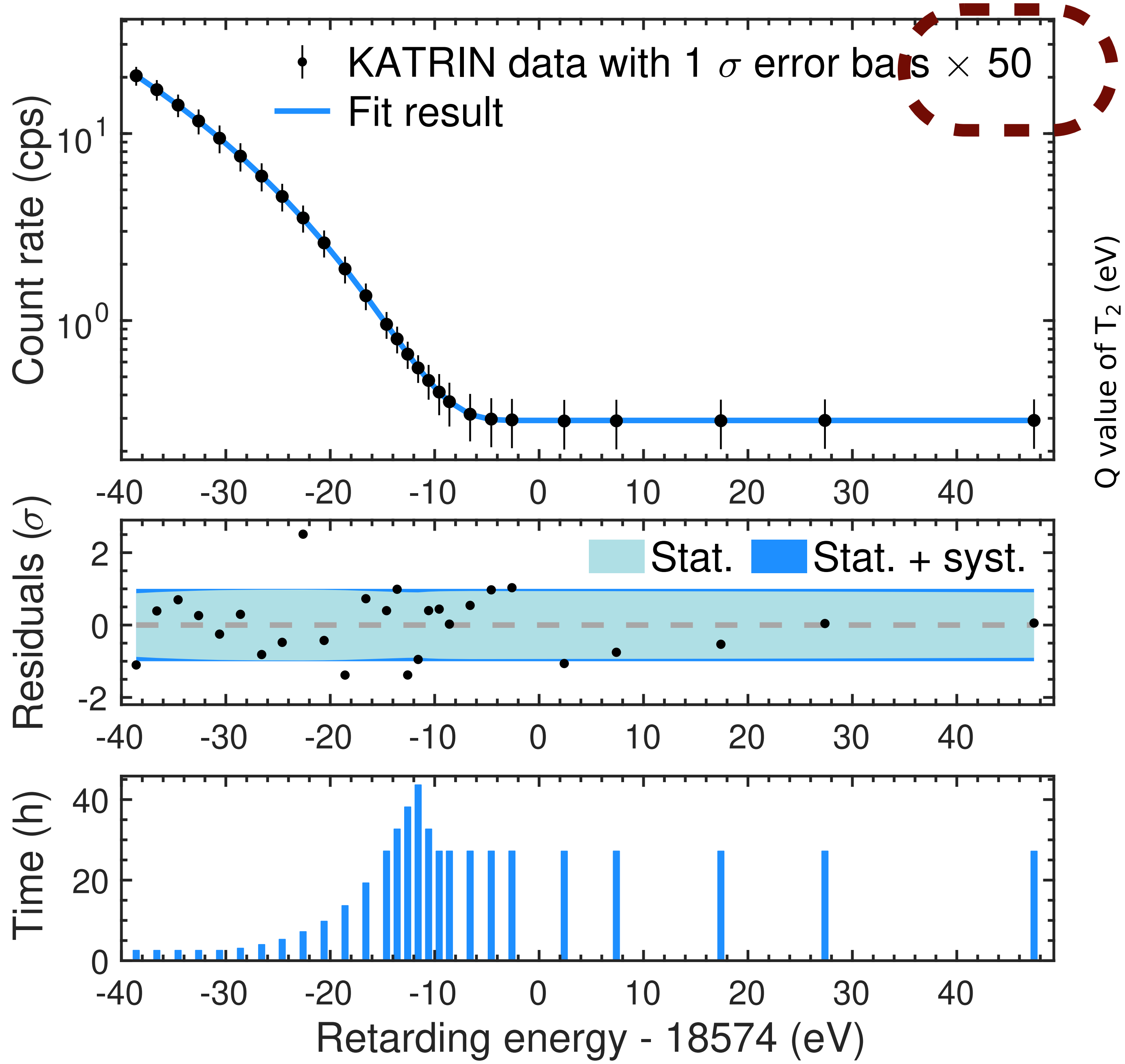
KATRIN's 1st Measurement

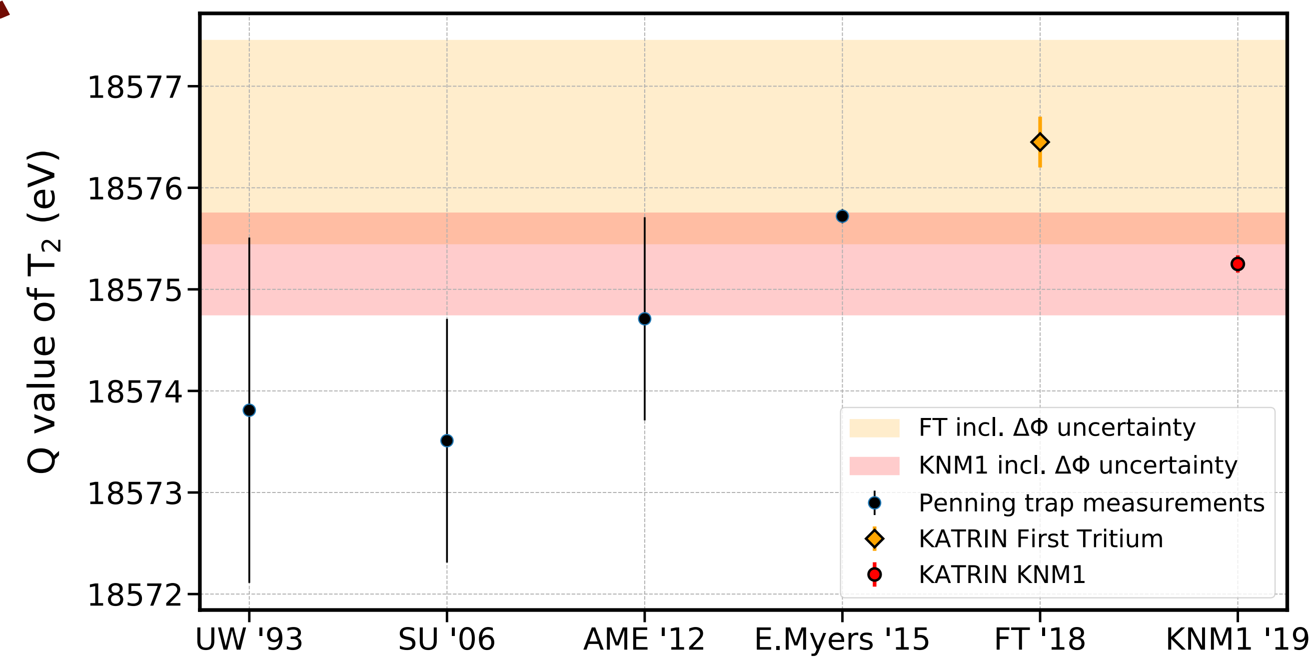


KATRIN's 1st Measurement



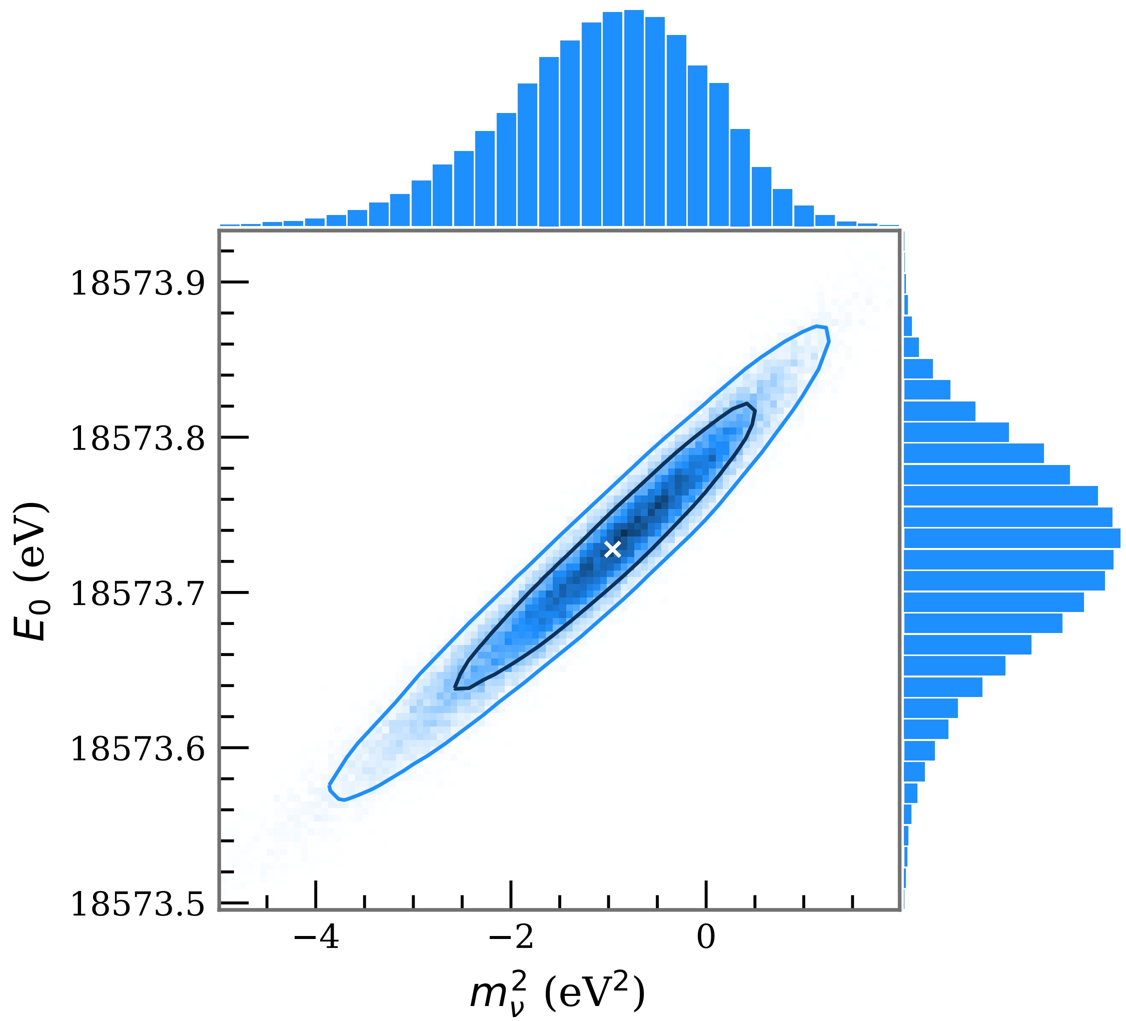
KATRIN's 1st Measurement



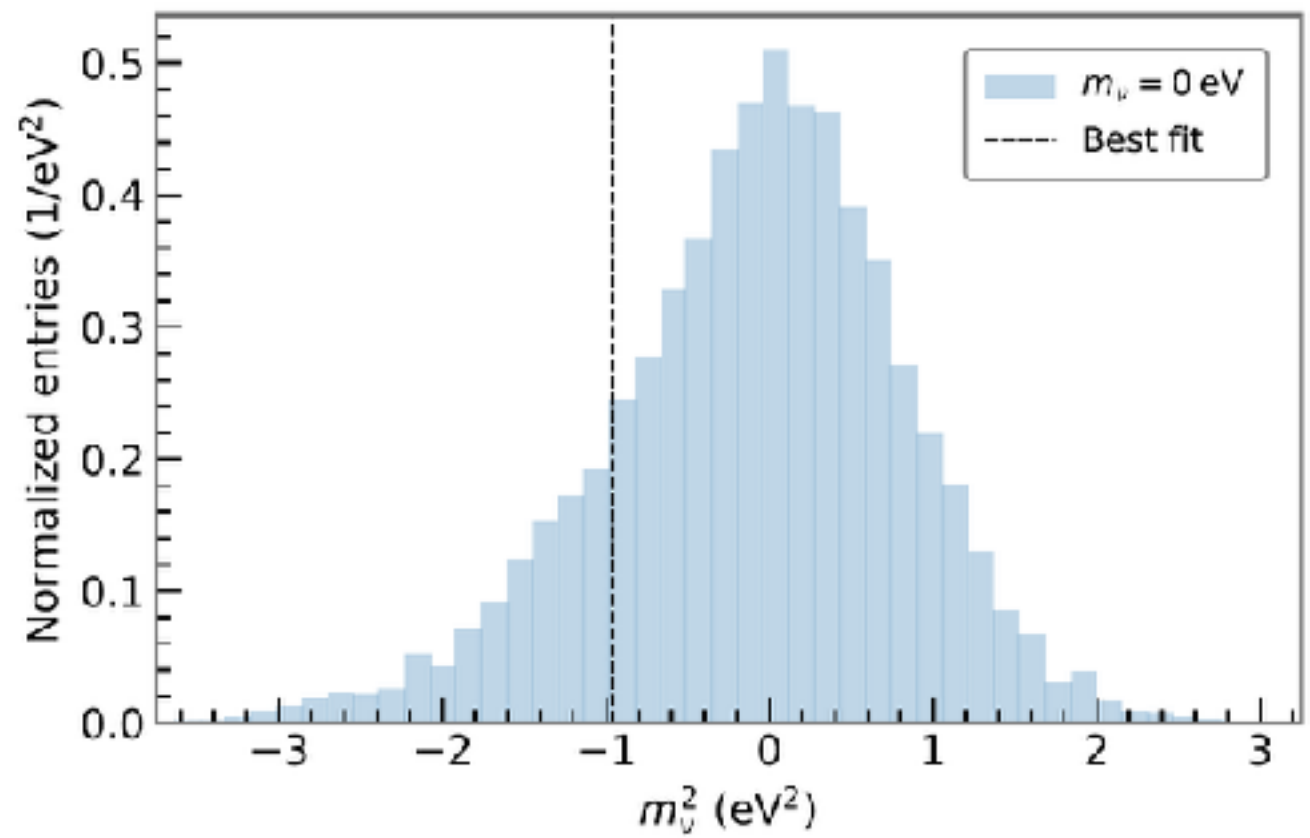


Endpoint consistent with atomic trap measurements

KATRIN's 1st Measurement



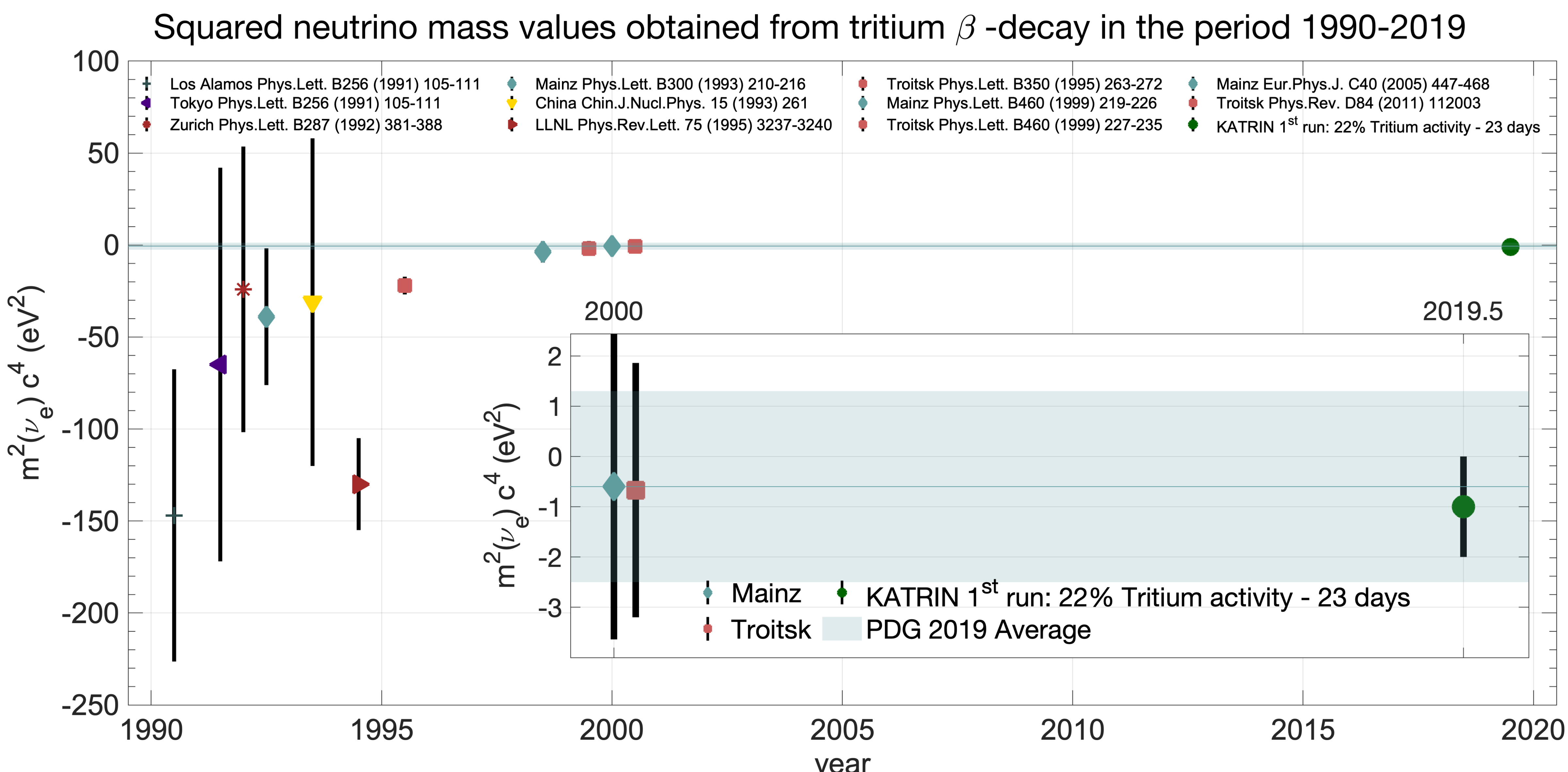
Extracted Best Fit



MC Ensemble

$$m^2(\nu_e) = (-1.0^{+0.9}_{-1.1})\ \text{eV}^2\ (90\%\ \text{C.L.})$$

KATRIN's 1st Measurement



$$m(\nu_e) < 1.1 \text{ eV (90\% C.L.)}$$

Factor of 2 improvement in 30 days!

Electron transfers all of its energy to the absorbing medium.

Calorimetric
(Cryogenic Bolometers)

Electromagnetic filtering of electrons of selected energy.

Electromagnetic Collimation
(MAC-E Filter)

Use photon spontaneous emission from electron in magnetic field.

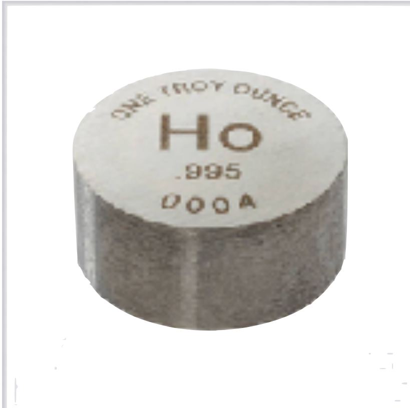
Frequency-Based
(Cyclotron Radiation Emission Spectroscopy)

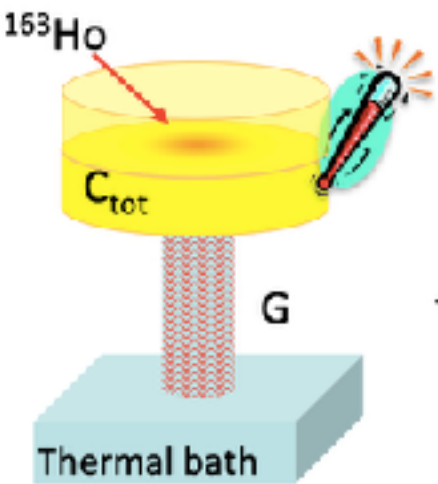
Electron transfers all of its energy to the absorbing medium.

Calorimetric

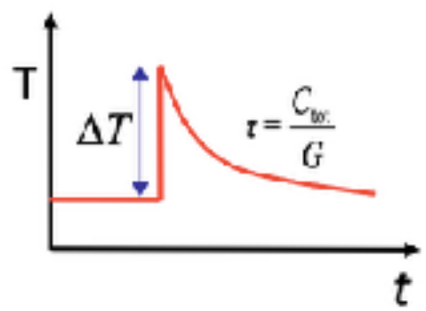
(Cryogenic Bolometers)

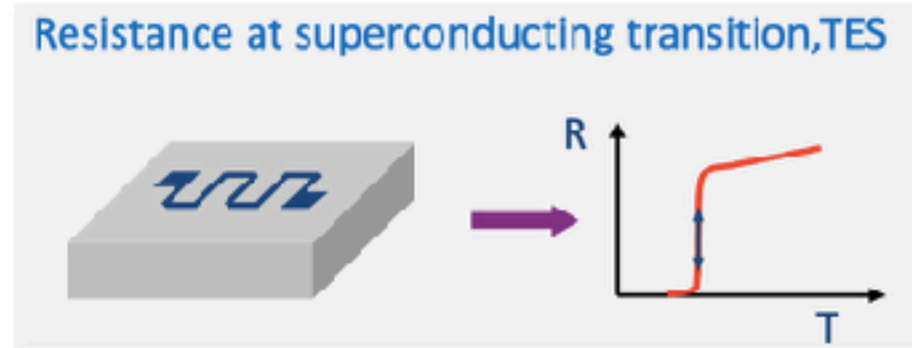
Modern Calorimetric Experiments





$$\Delta T \simeq \frac{E}{C_{tot}}$$



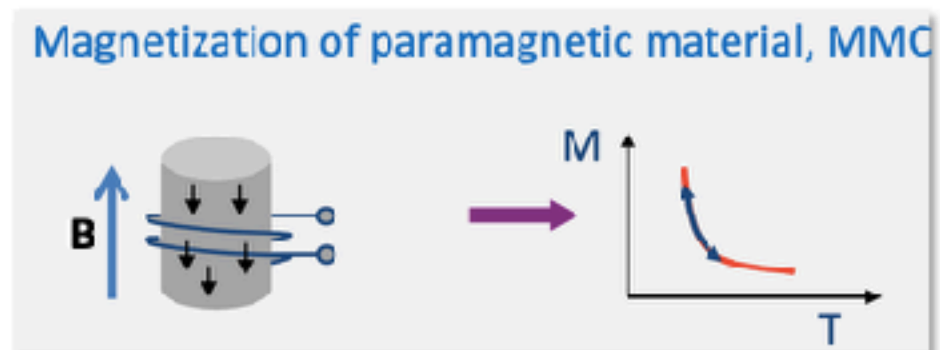


HOLMES

NuMECS

Detector arrays produced at NIST (Boulder US)

K.D. Irwin and G.C. Hilton, Topics in Applied Physics 99 (2005) 63



ECHo

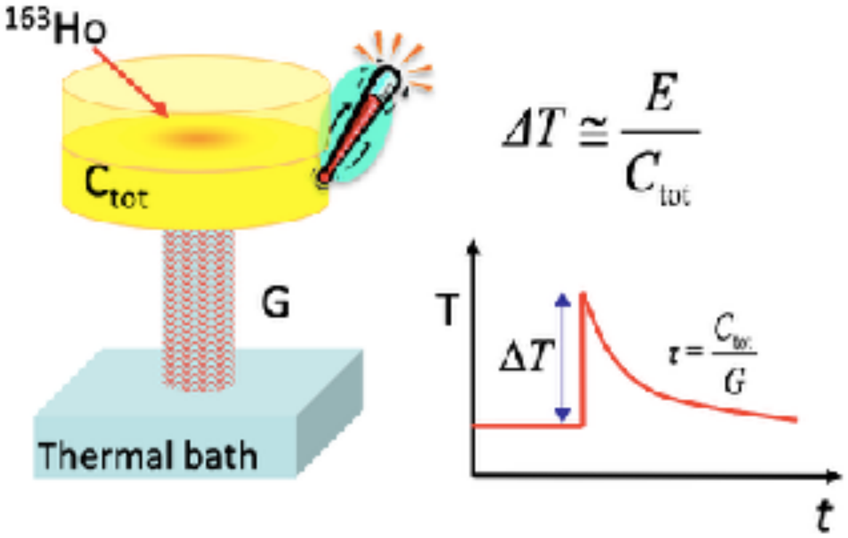
Detector arrays produced at KIP, Heidelberg University

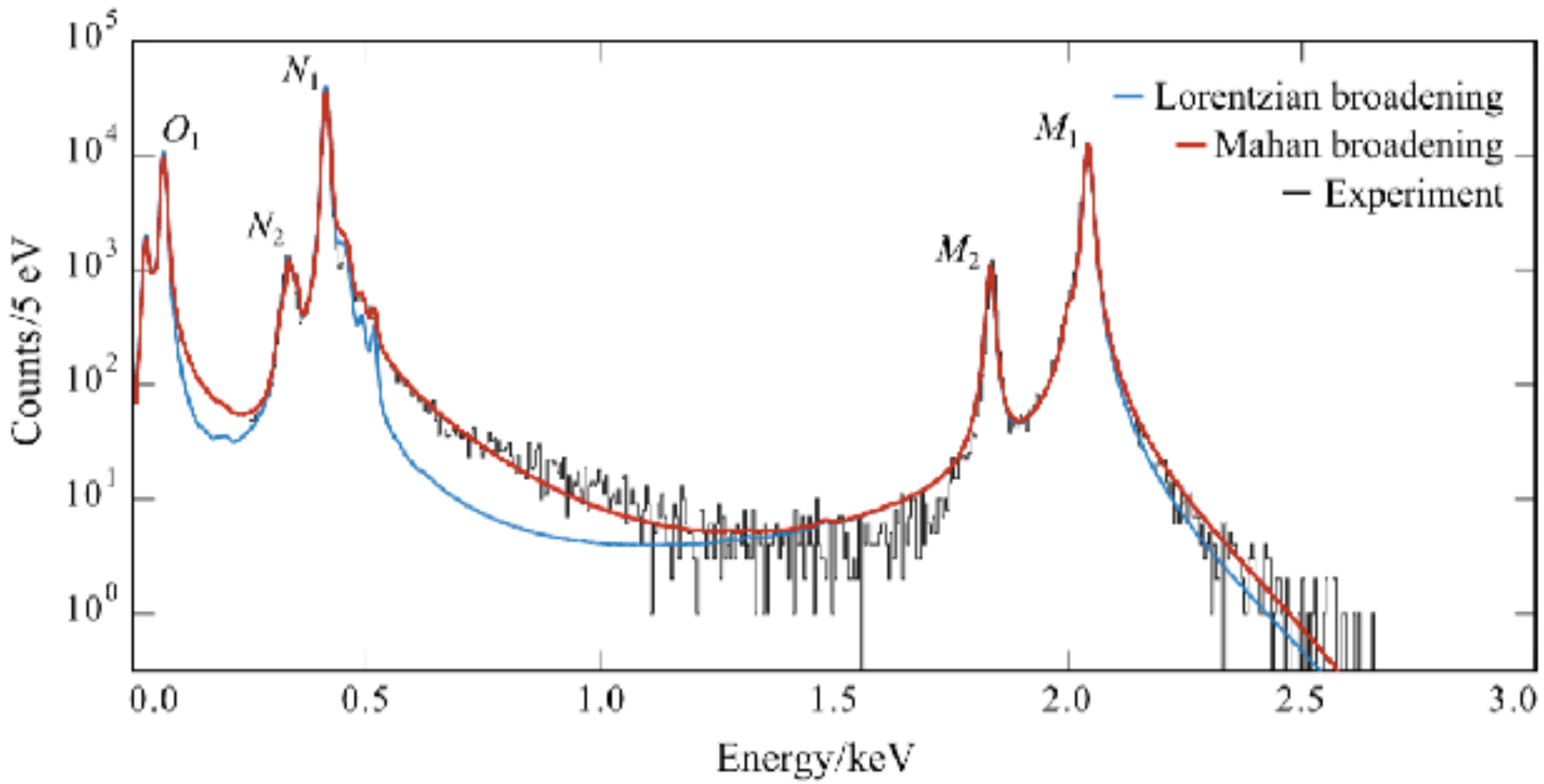
A.Fleischmann, C. Enss and G. M. Seidel, Topics in Applied Physics 99 (2005) 63

Micro calorimeters which are sensitive to changes in temperature (energy deposition).

Contain the full decay energy.

Modern Calorimetric Experiments





C. Velte et al., Eur. Phys. J. C (2019) 79:1026 M. Brass, M. Haverkort, https://arxiv.org/abs/2002.05989

Micro calorimeters which are sensitive to changes in temperature (energy deposition).

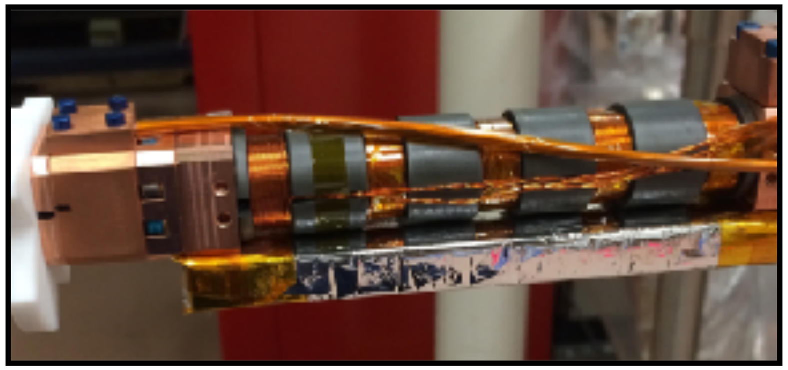
Contain the full decay energy.

Use photon spontaneous emission from electron in magnetic field.

Frequency-Based

(Cyclotron Radiation Emission Spectroscopy)

Cyclotron Radiation Emission Spectroscopy (CRES)



Frequency Approach

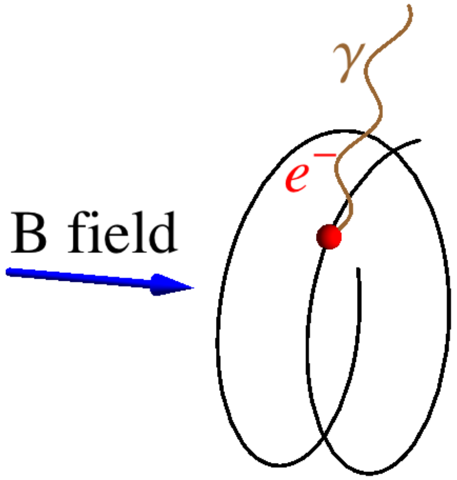
$$^3\mathrm{H} \rightarrow {}^3\mathrm{He}^+ + e^- + \bar{\nu}_e$$

"Never measure anything but frequency."

A. L. Schawlow

O. Heaviside

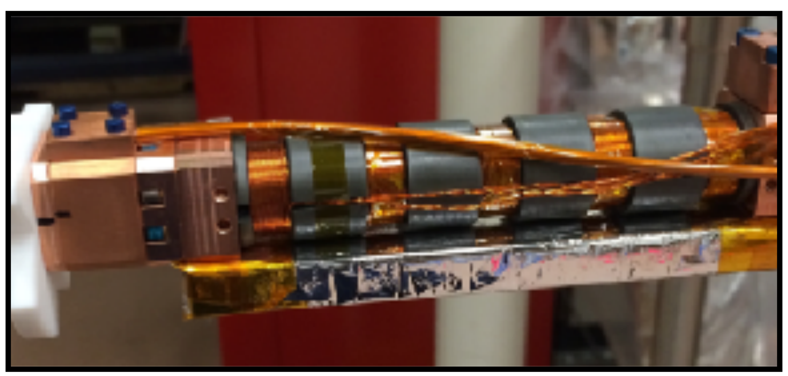
Use frequency measurement of cyclotron radiation from single electrons:



- *Source transparent to microwave radiation*
- *No e- transport from source to detector*
- *Leverages precision inherent in frequency techniques*

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

Cyclotron Radiation Emission Spectroscopy (CRES)



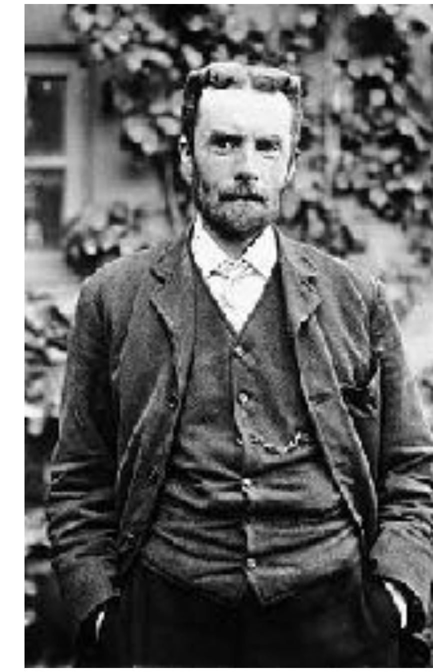
PROJECT 8

Frequency Approach

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

A. L. Schawlow

"Never measure anything but frequency."



O. Heaviside

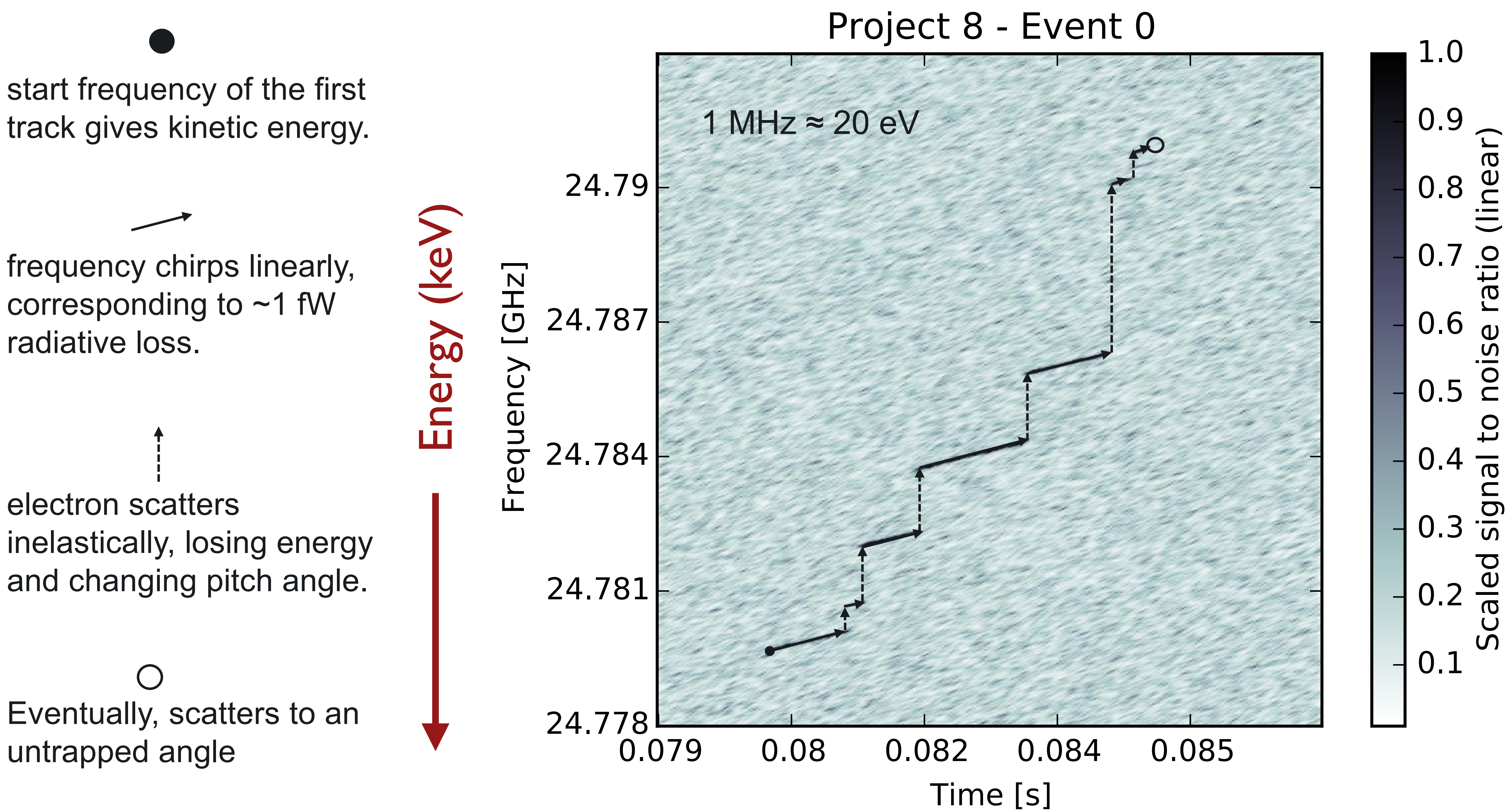
$$f_c = \frac{f_{c,0}}{\gamma} = \frac{1}{2\pi} \frac{eB}{m_e c^2 + E_{\mathrm{kin}}}$$

$$f_{c,0} = 27.992\ 491\ 10(6)\ \mathrm{GHz\ T^{-1}}$$

- *Narrow band region of interest (@26 GHz).*
- *Small, but detectable power emitted.*

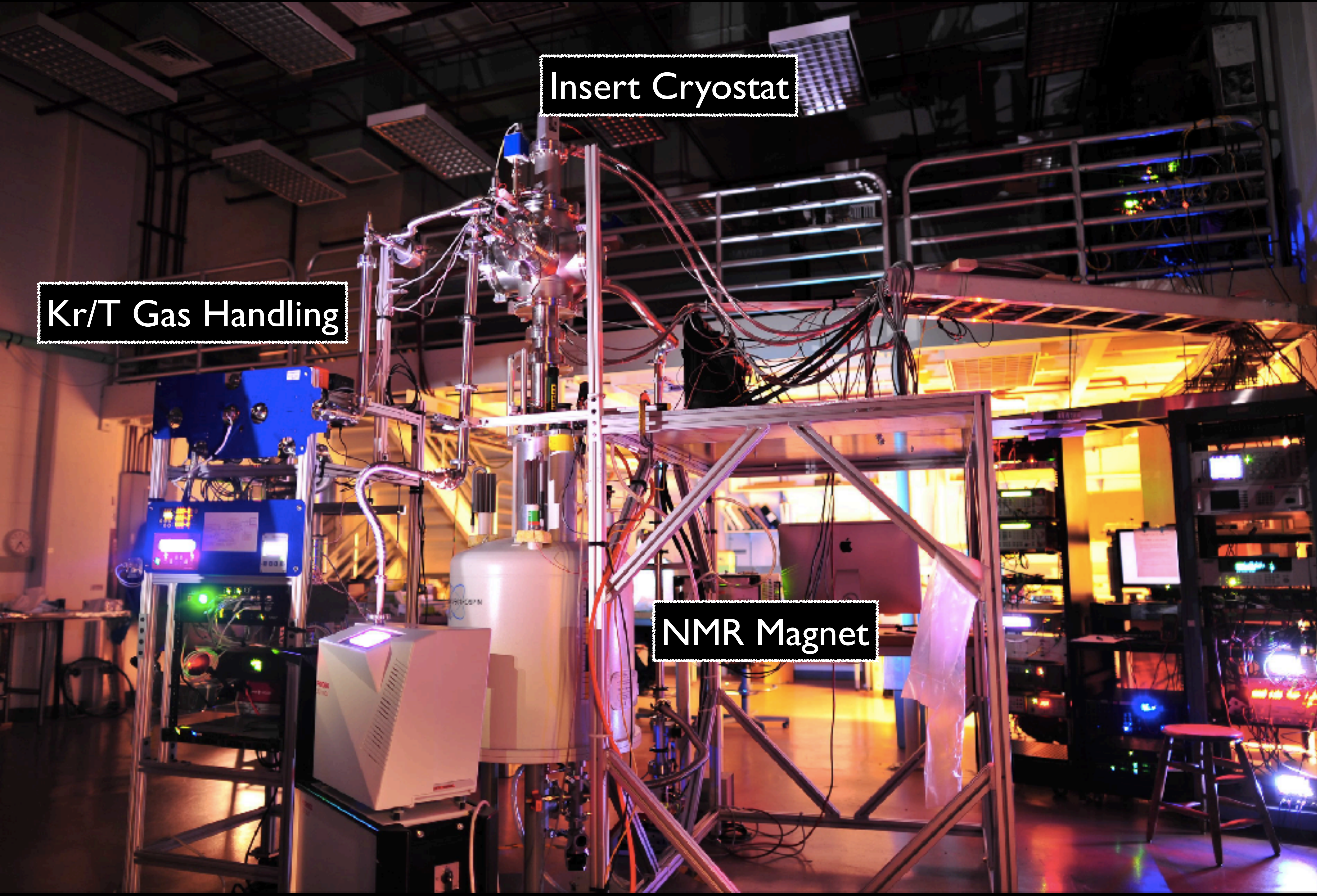
$$P\left(17.8\,\mathrm{keV}, 90^{\circ}, 1\,\mathrm{T}\right) = 1\,\mathrm{fW}$$
$$P\left(30.2\,\mathrm{keV}, 90^{\circ}, 1\,\mathrm{T}\right) = 1.7\,\mathrm{fW}$$

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

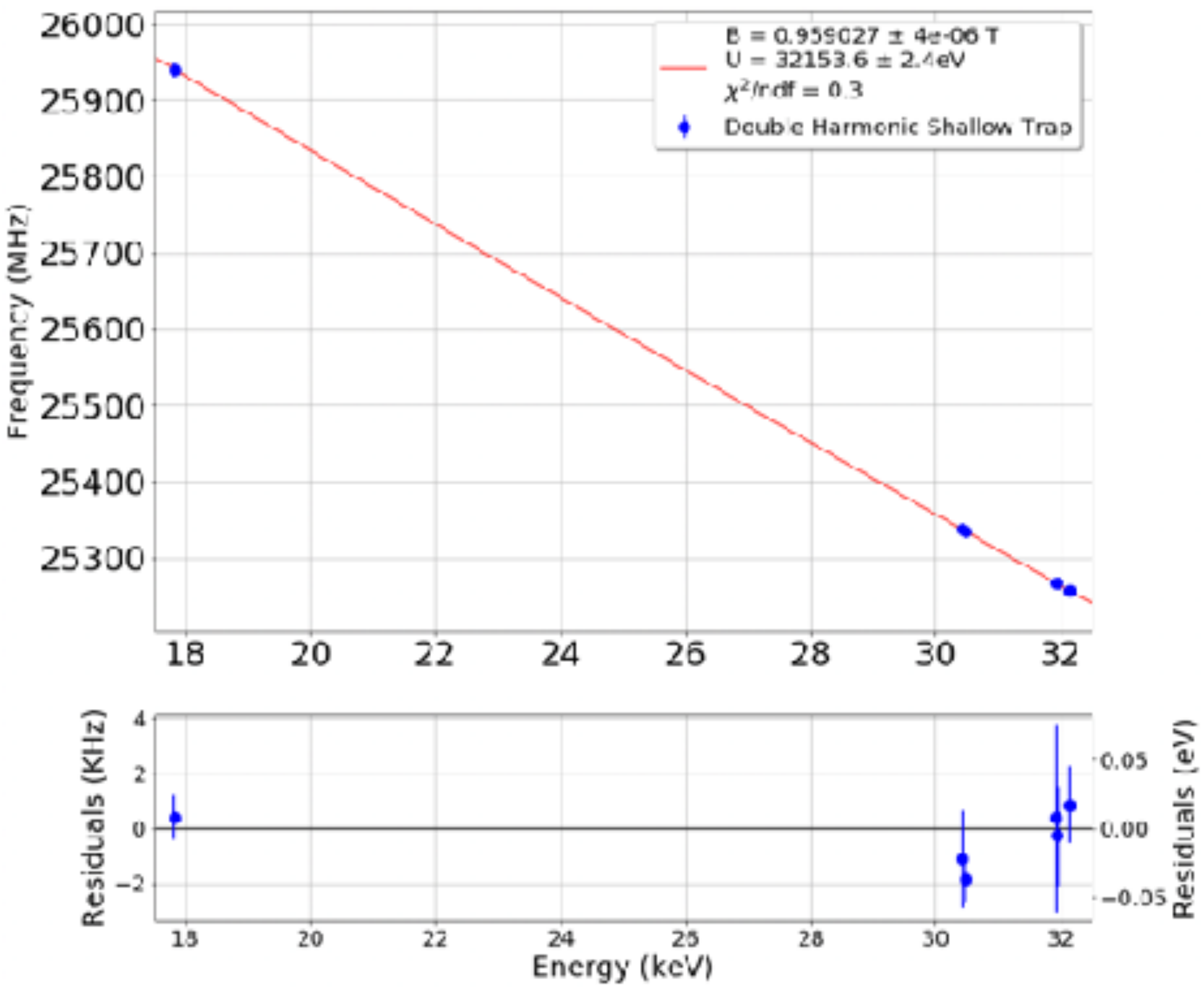


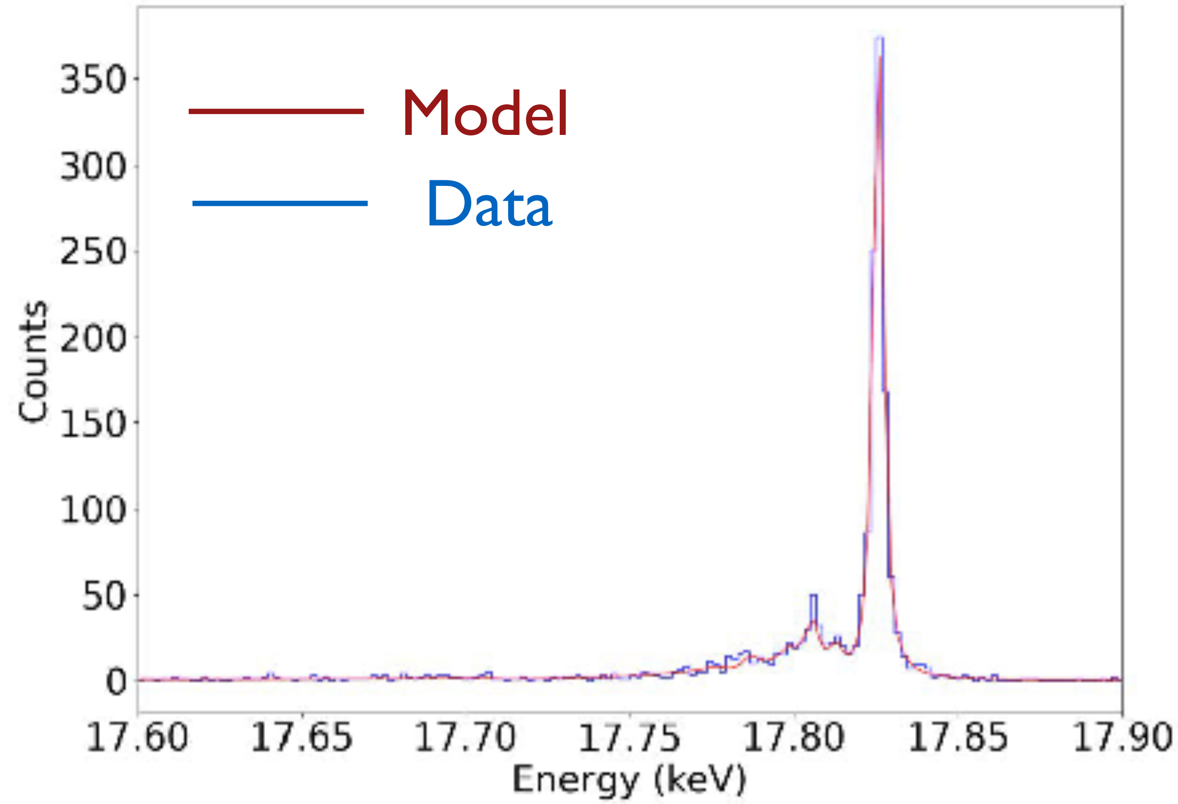
A "typical" event

(actually, this was our first event)


Insert Cryostat
Kr/T Gas Handling
NMR Magnet

Shallow Trap Linearity Measurements





- 32-keV γ energy: (32153.6 ± 2.4) eV
  - Vénos, et al: (32151.7 ± 0.5) eV
    Appl. Radiat. Isot. **63** 323-7 (2005)

We can also test the linearity of the technique by measuring multiple mono-energetic lines from ^{83m}Kr.

Excellent agreement with previous measurements.

First tritium CRES spectrum

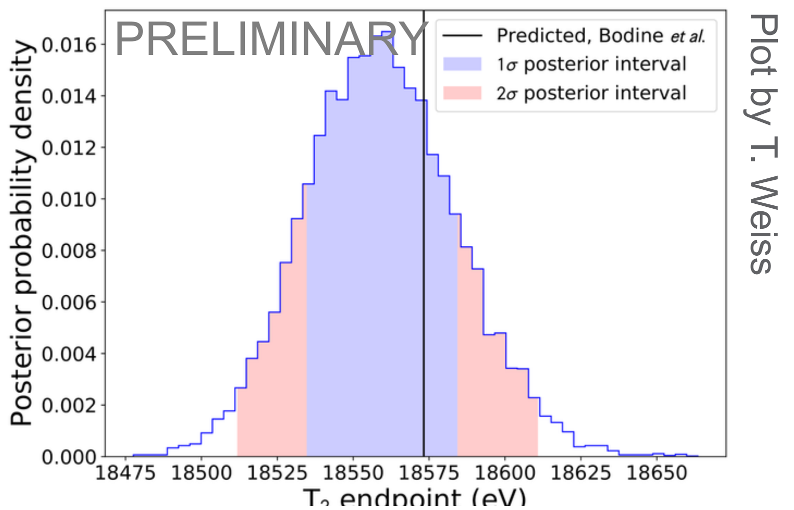
T_2 endpoint result:

$$E_0 = \left(18559.4^{+24.9}_{-24.7}\right)\ \mathrm{eV}$$

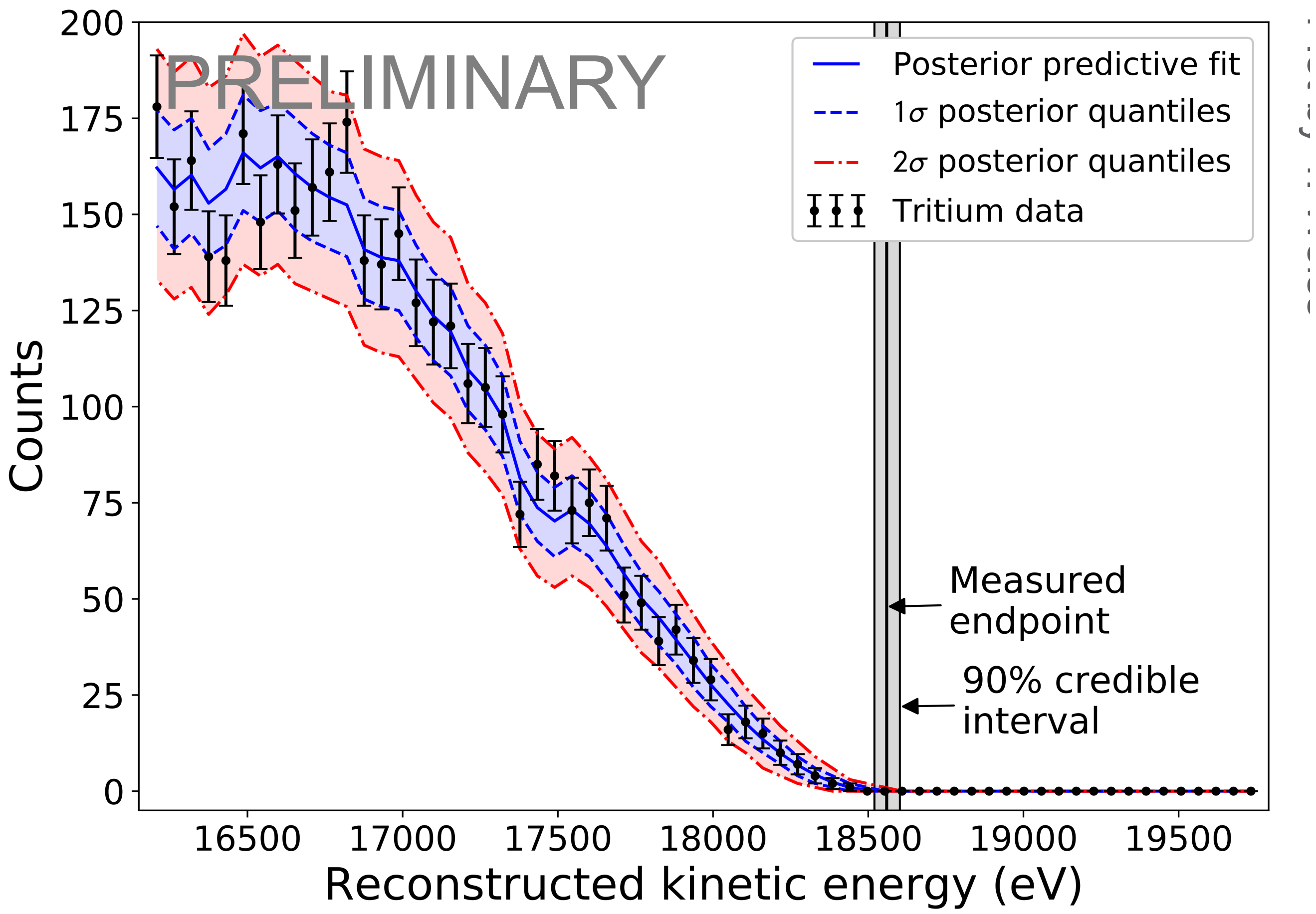
Background rate:

$$\leq 3\times10^{-10}\mathrm{eV}^{-1}\mathrm{s}^{-1}\ (90\%\ \mathrm{C.I.})$$

Posterior distribution

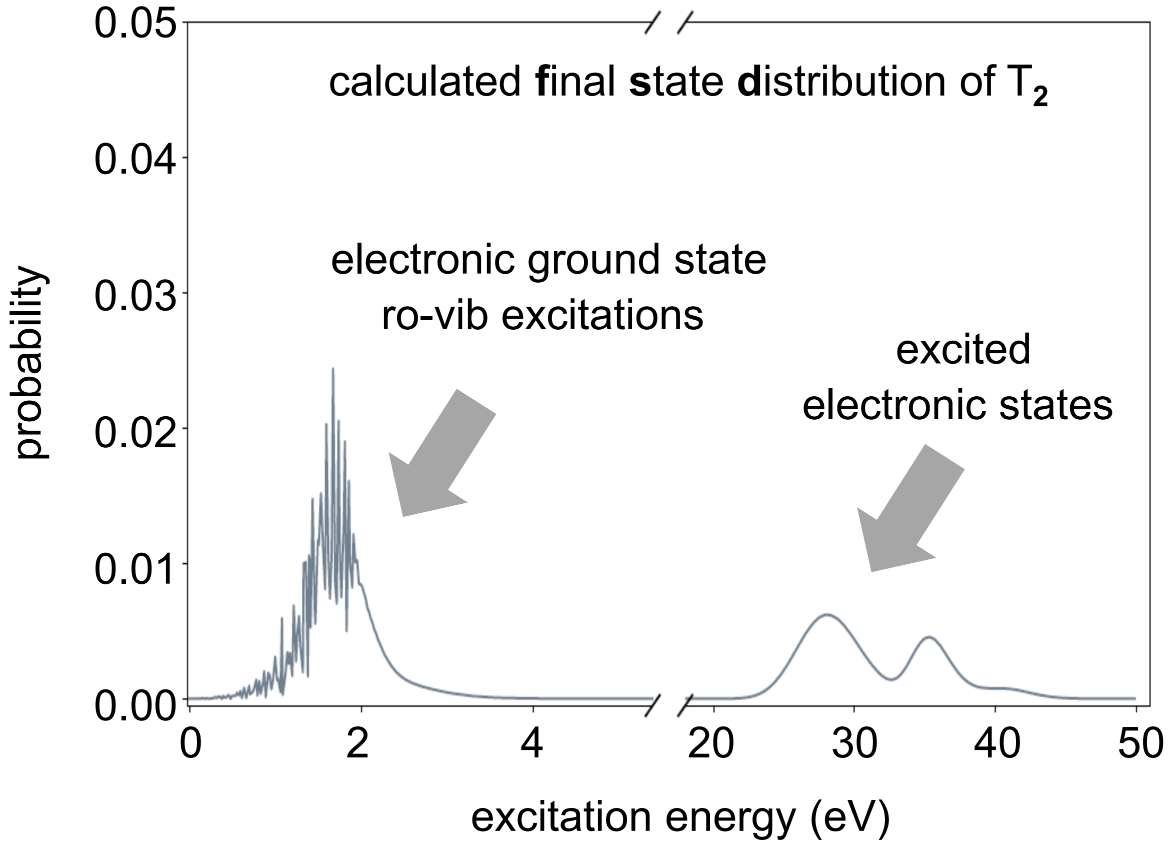


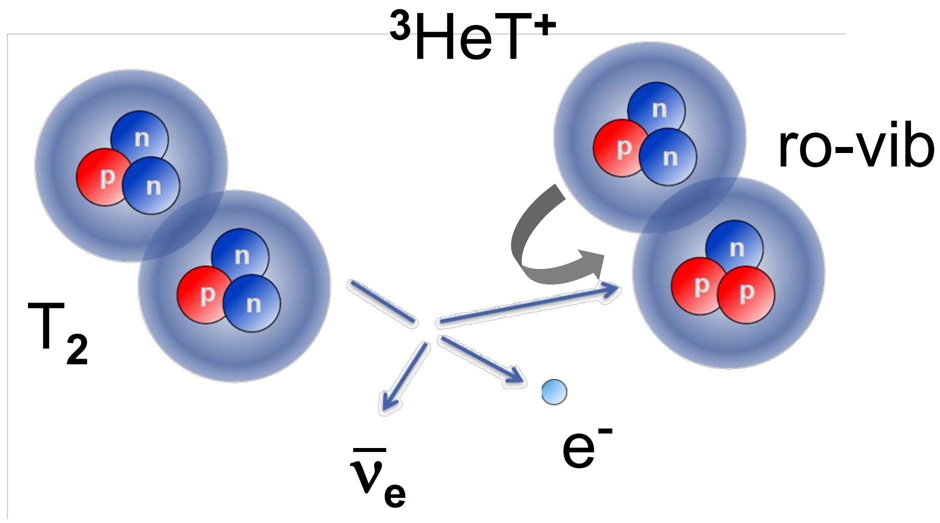
Energy spectrum and posterior fit



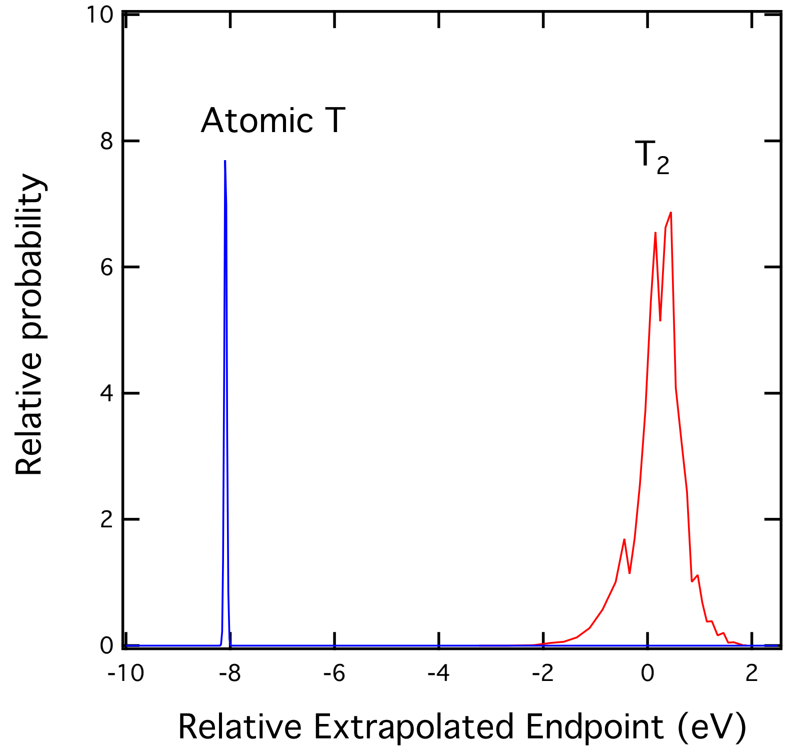
We extract a first tritium spectrum using the CRES technique.

Background levels controlled to better than <0.3 nHz/eV.



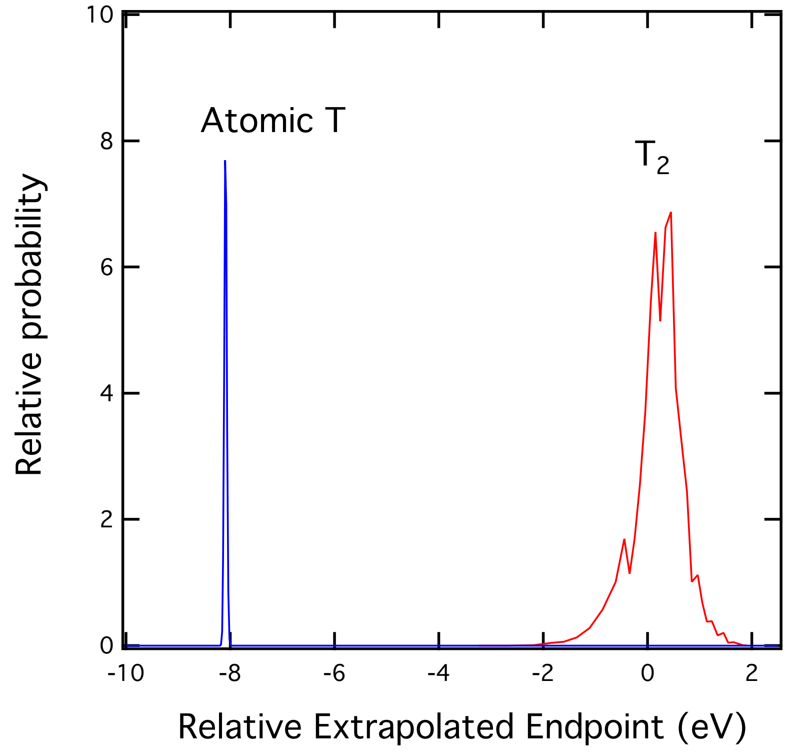


Need to overcome molecular final states to reach "inverted" scale.



Atomic tritium provides a narrower profile, allowing one to access inverted scale.

Need to overcome molecular final states to reach "inverted" scale.

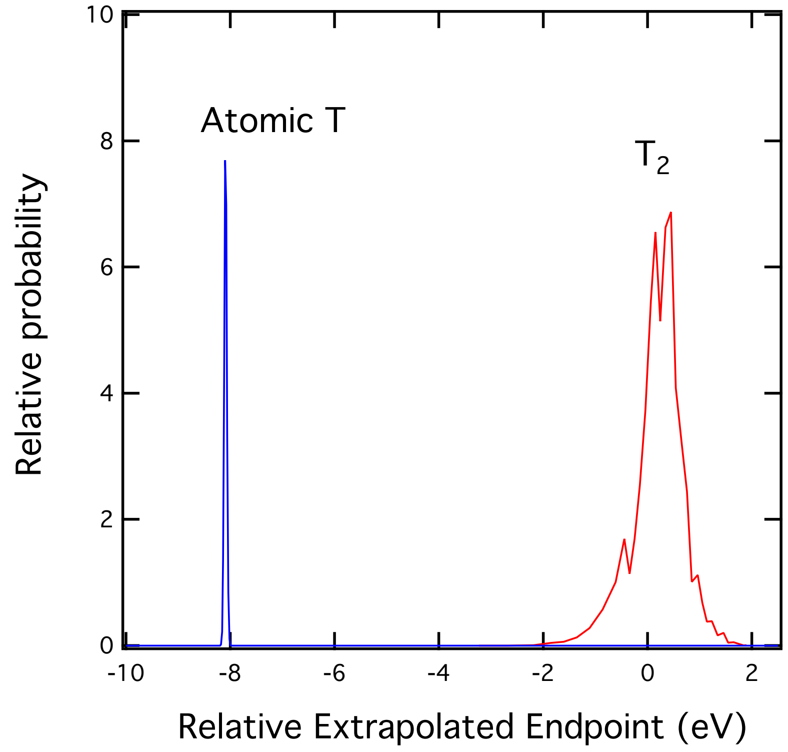


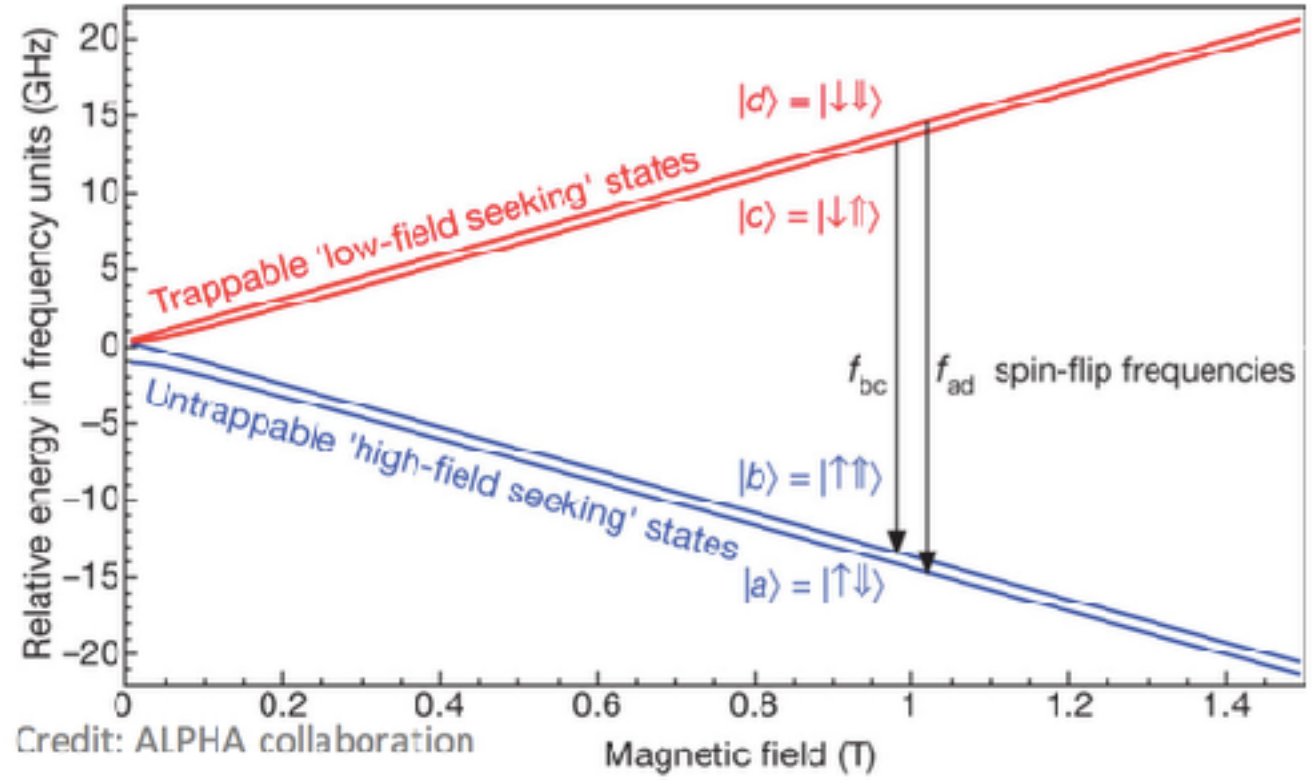
Atomic tritium provides a narrower profile, allowing one to access inverted scale.

Need to overcome molecular final states to reach "inverted" scale.

Challenges?

How to create?
How to trap?
How to keep purity?





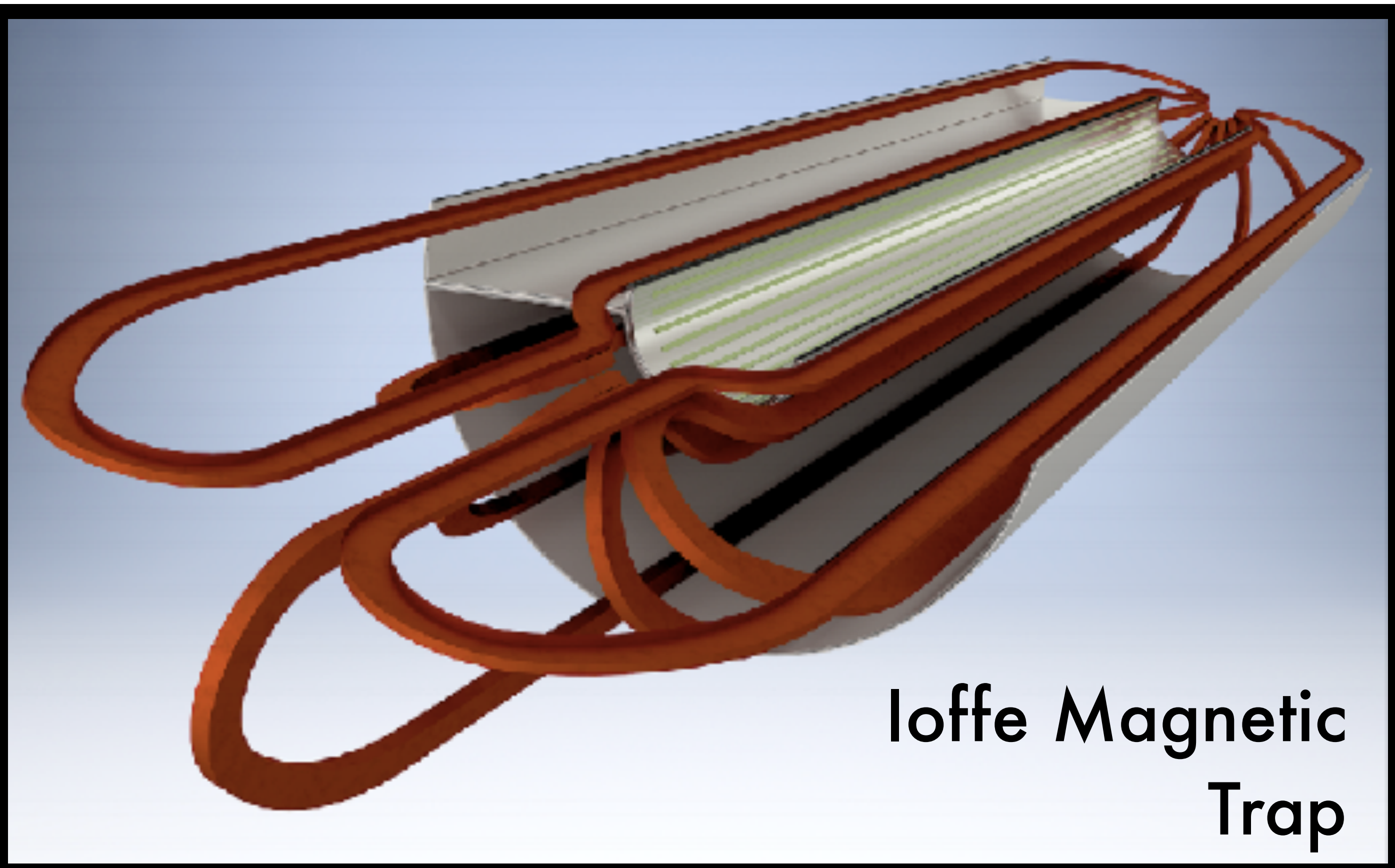
H,D and T have unpaired electrons (non-zero μ)

Atom tend to (anti-)align with B-field if change is adiabatic

Potential energy…

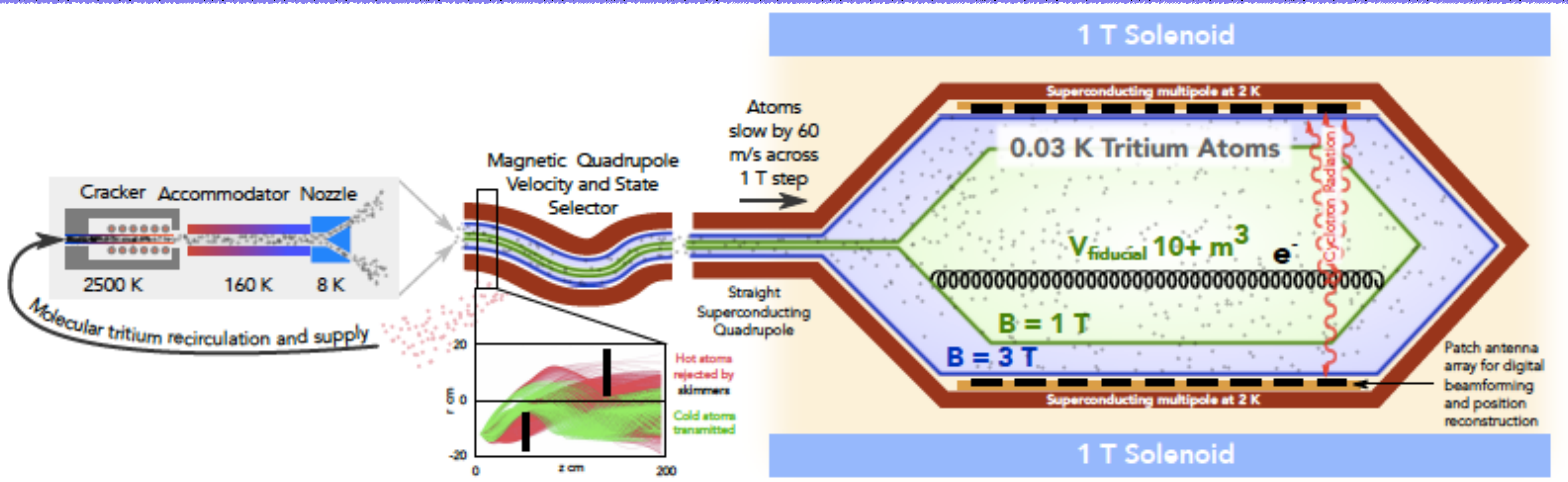
$$\Delta E = -\vec{\mu} \cdot \vec{B}$$

(atoms follow field mimimim)



Solution: A large volume magnetic trap for T atoms

Phase IV

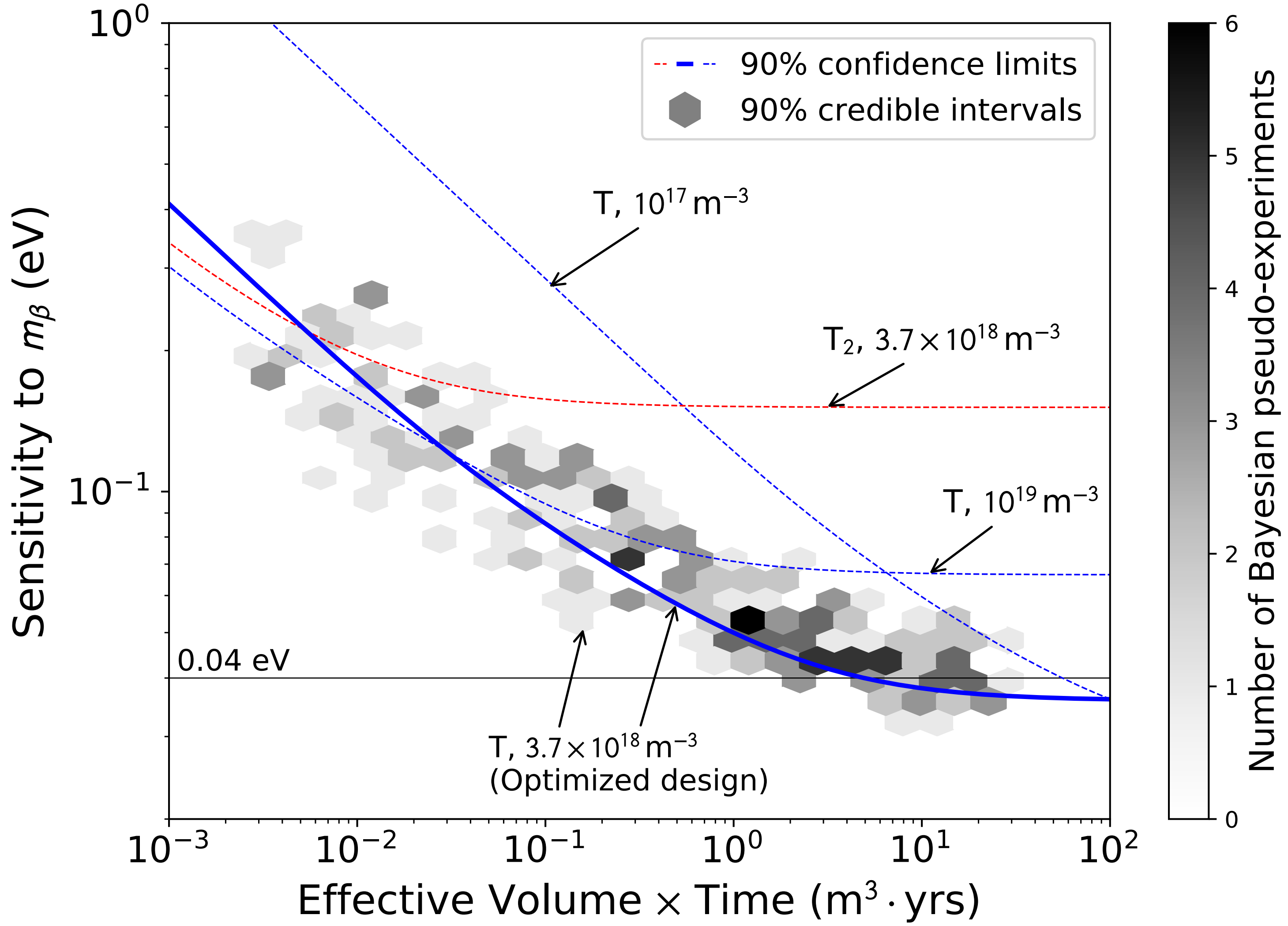


Ultimate atomic tritium experiment combines R&D from Phase III into large RF array tritium trap.

Atomic source, transport, and trap combined for large (m^3) instrumented volume.

Target Mass Sensitivity

m_β < 40 meV



Systematics and Sensitivity

Optimized density of 3.7x10^{18} atoms/m^3

Assume exposure of 5 m^3 y

Full Bayesian analysis

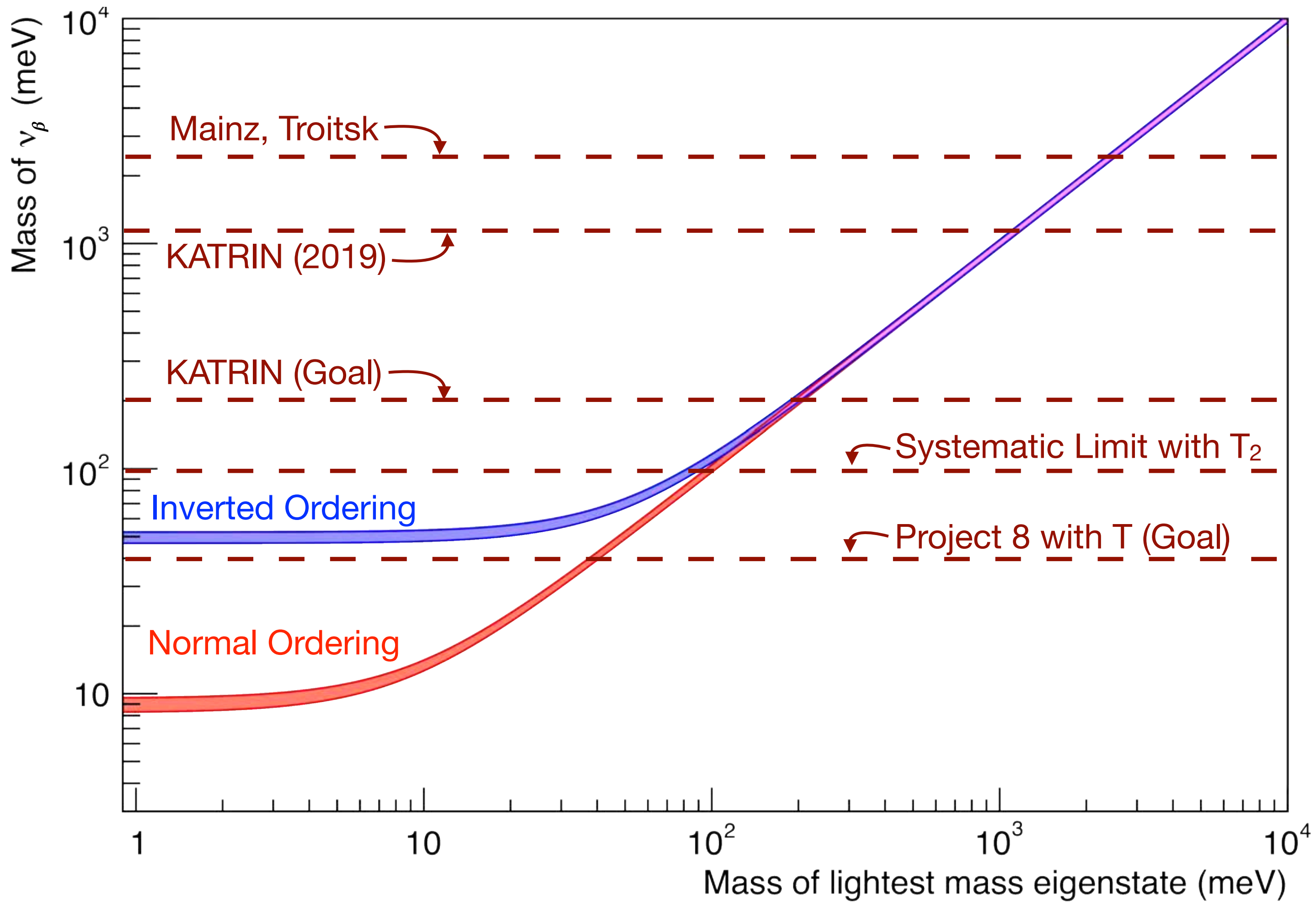
Magnetic field uniformity of 0.1 ppm

Optimal energy resolution:

$$\sigma_E \cong (115 \pm 2)\ \text{meV.}$$

Phase IV

Goal: Break into the inverted neutrino mass scale



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Phase IV

Goal: Break into the inverted neutrino mass scale

A Quick Summary

KATRIN is now taking data, finally pushing the mass scale limit below the eV scale for the first time.

Calorimetric experiments such as ECHO and HOLMES are progressing well toward the eV scale.

The CRES technique through Project 8 is pusing forward, with the eventual target of using an atomic tritium source.


A Quick Summary
Thank you for your attention