Direct Neutrino Mass Measurements

Coherent Neutrino Scattering

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Massachusetts Institute of Technology

Neutrino Telescopes 2021

A bit of context behind the two topics…

We would like to invite you to give one of these Challenge talks. The argument(s) would be "New technologies for measuring neutrino masses" together with "Neutrino coherent scattering”.

-- Mauro Mezzetto

*Yes, I am happy to partake in the Challenge talks! One question of clarification: are you asking me to give a talk on **both** of these topics […]?*

-- Me

Yes — Mauro

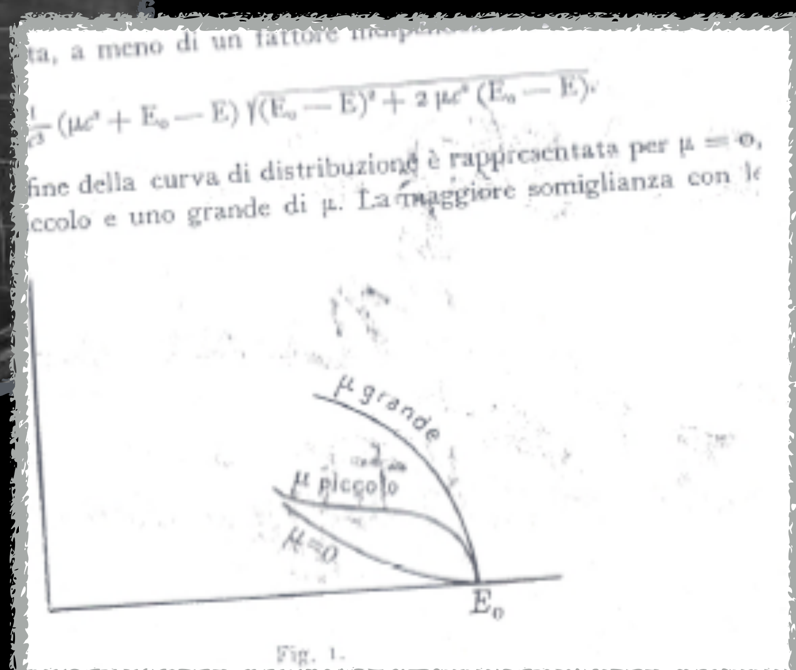
Ok <gulp>

— Me

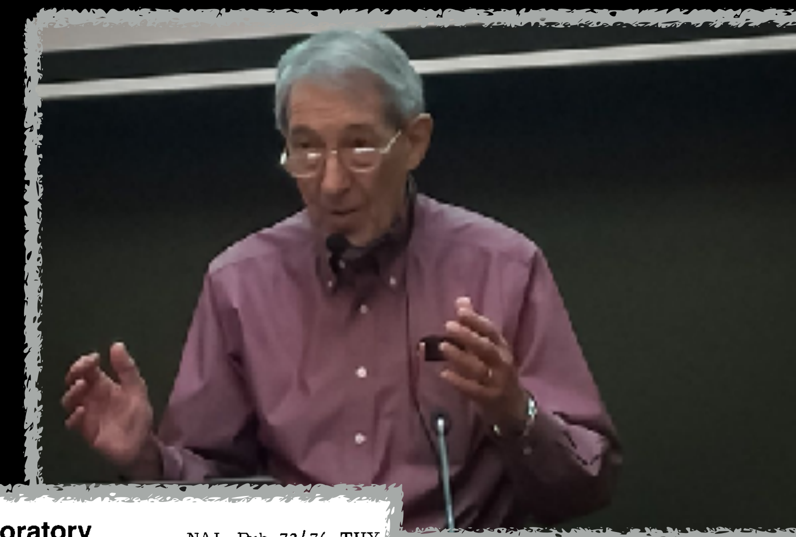
Luckily, there are some similarities...

... for one, these challenges are **long** standing

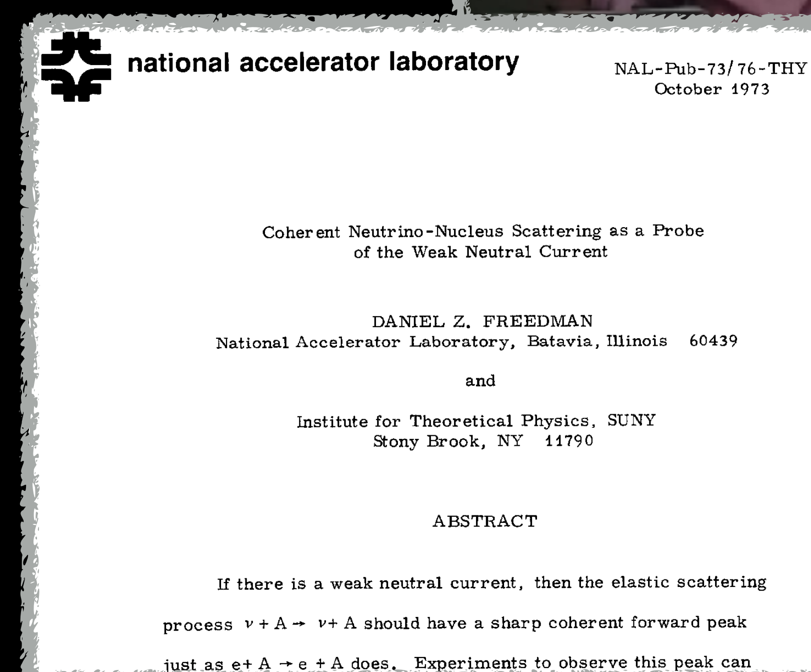
E. Fermi



Neutrino Mass (1934)



D. Z. Freedman



national accelerator laboratory

NAL-Pub-73/76-THY
October 1973

Coherent Neutrino-Nucleus Scattering as a Probe of the Weak Neutral Current

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National Accelerator Laboratory, Batavia, Illinois 60439

and

Institute for Theoretical Physics, SUNY
Stony Brook, NY 11790

ABSTRACT

If there is a weak neutral current, then the elastic scattering process $\nu + A \to \nu + A$ should have a sharp coherent forward peak just as $e + A \to e + A$ does. Experiments to observe this peak can

Neutrino Coherent Scattering (1974)

Both measurements access key neutrino properties…

ν Mass Scale

$$m_\beta^2 = \sum_{i=1}^{3} |U_{ei}|^2 m_i^2$$

Incoherent sum of neutrino mass eigenstates.

Relates directly to the energy-momentum dispersion of neutrinos.

ν Weak Probe

Probes the weak coupling of neutrinos to nuclei.

Coherent interaction with entire nucleus.

Both measurements access key neutrino properties…

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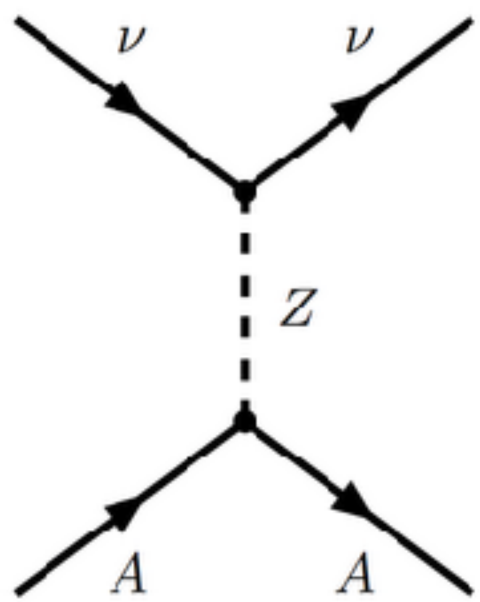
ν Weak Probe

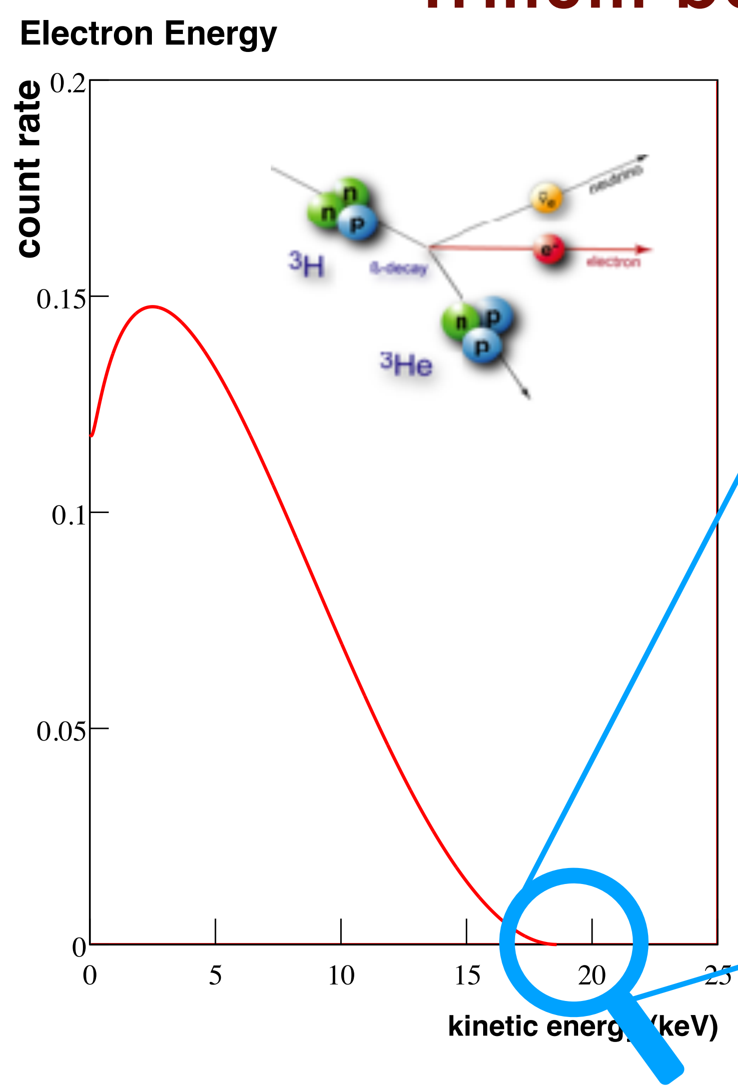


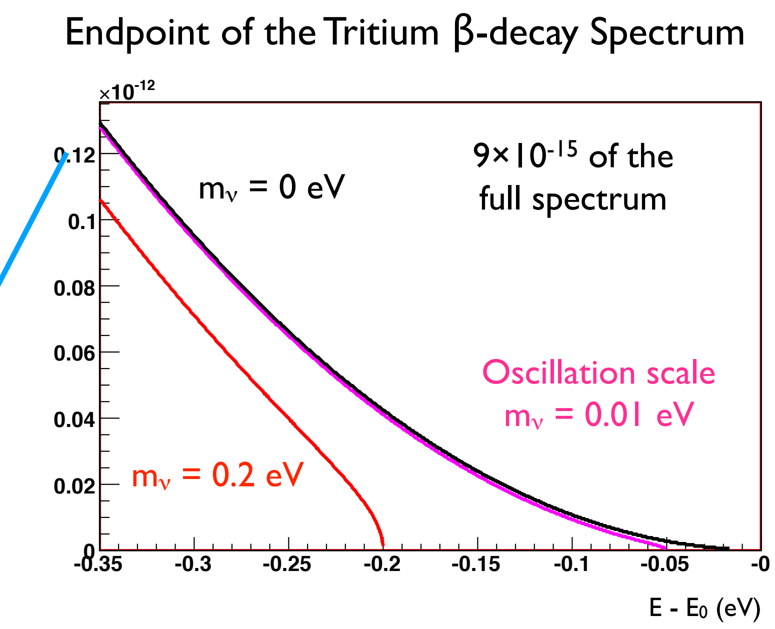
Probes the weak coupling of neutrinos to nuclei.

Coherent interaction with entire nucleus.

and in principle, the measurements are simple.

Tritium beta decay

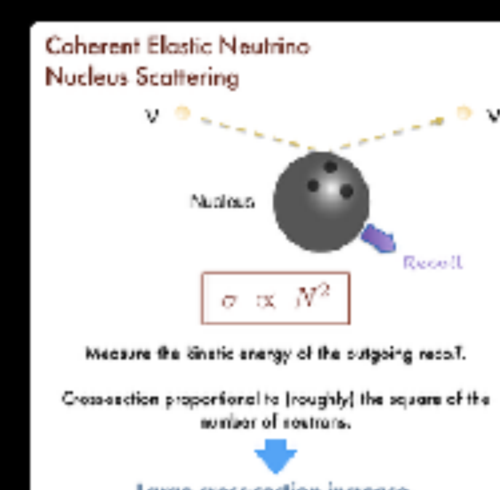




$$\dot{N} \propto p_\nu E_\nu$$

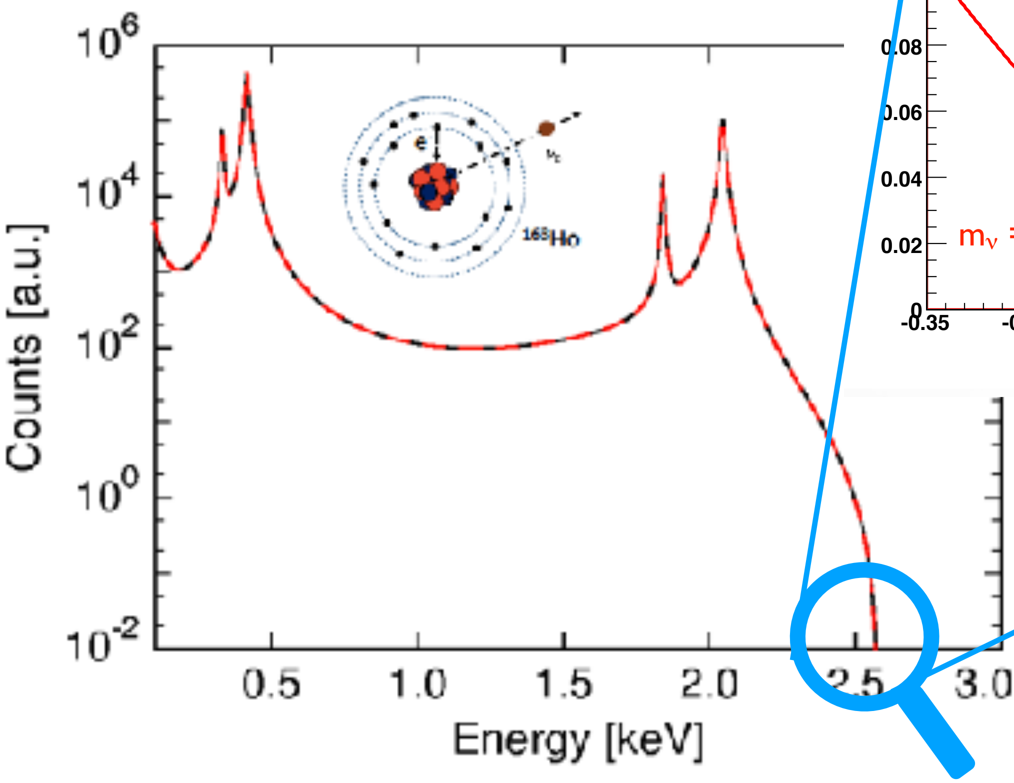
$$^{3}\mathrm{H} \;\rightarrow\; ^{3}\mathrm{He}^{+} \;+\; e^{-} \;+\; \bar{\nu}_e$$

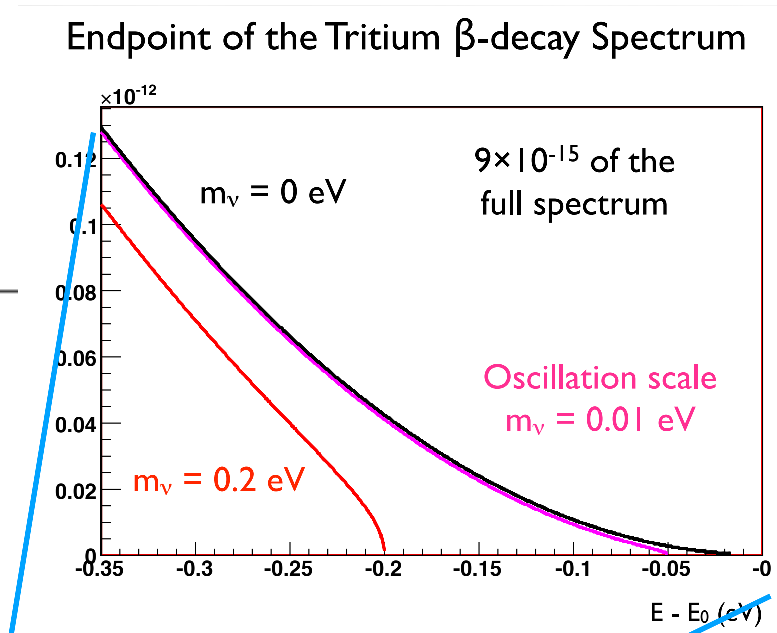
Measure the kinetic energy spectrum of the decay electron (for beta decay), or de-excitation energy (for electron capture).



and in principle, the measurements are simple.

Holmium electron capture

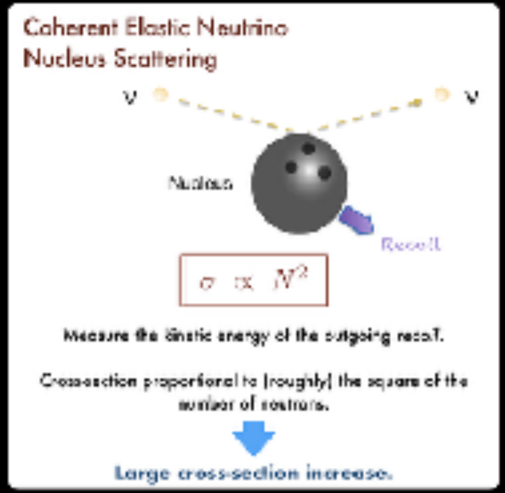




$$\dot{N} \propto p_\nu E_\nu$$

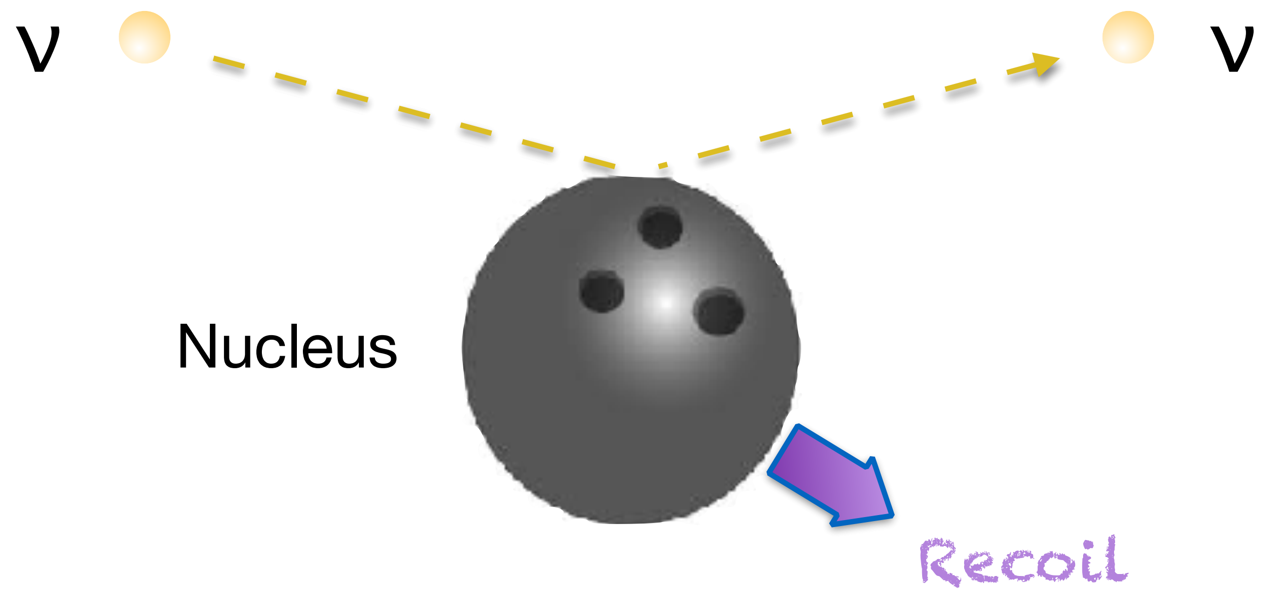
$$^{163}\mathrm{Ho} + e^- \rightarrow \ ^{163}\mathrm{Dy}^* + \nu_e$$

Measure the kinetic energy spectrum of the decay electron (for beta decay), or de-excitation energy (for electron capture).



and in principle, the measurements are simple.

Coherent Elastic Neutrino Nucleus Scattering

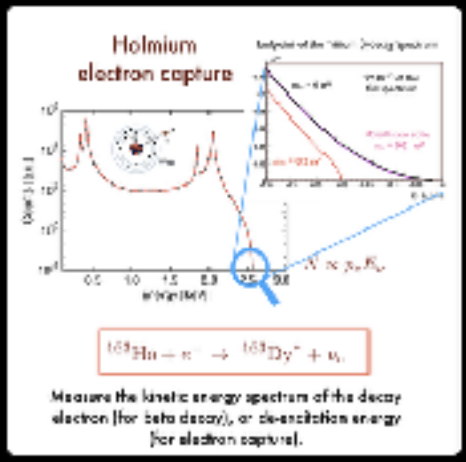


$$\sigma \propto N^2$$

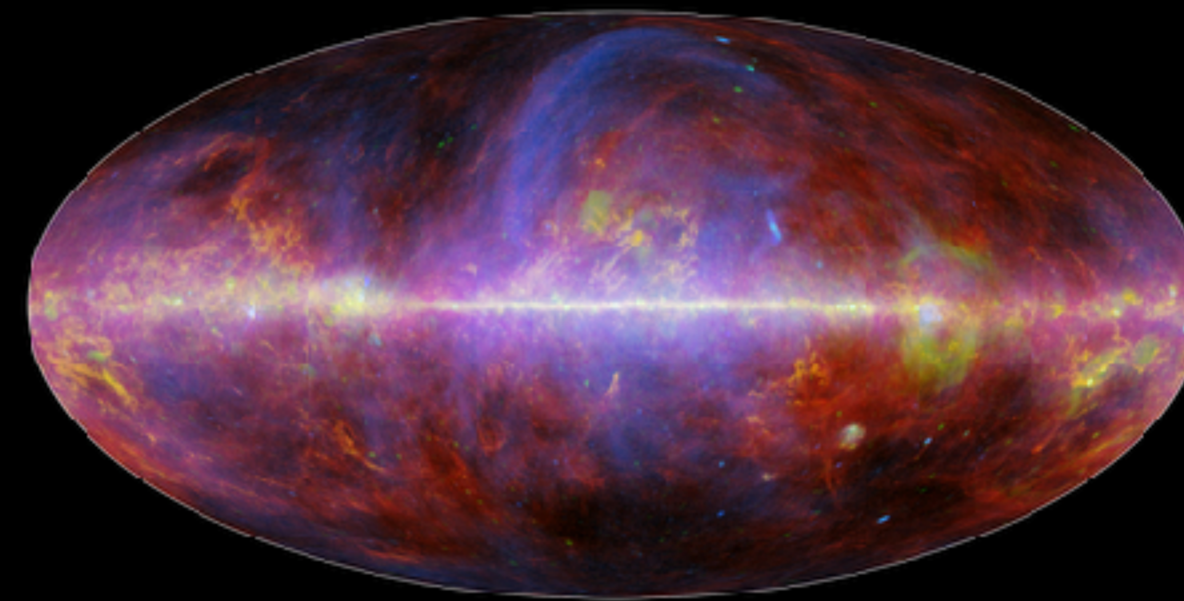
Measure the kinetic energy of the outgoing *recoil*.

Cross-section proportional to (roughly) the square of the number of neutrons.

Large cross-section increase.



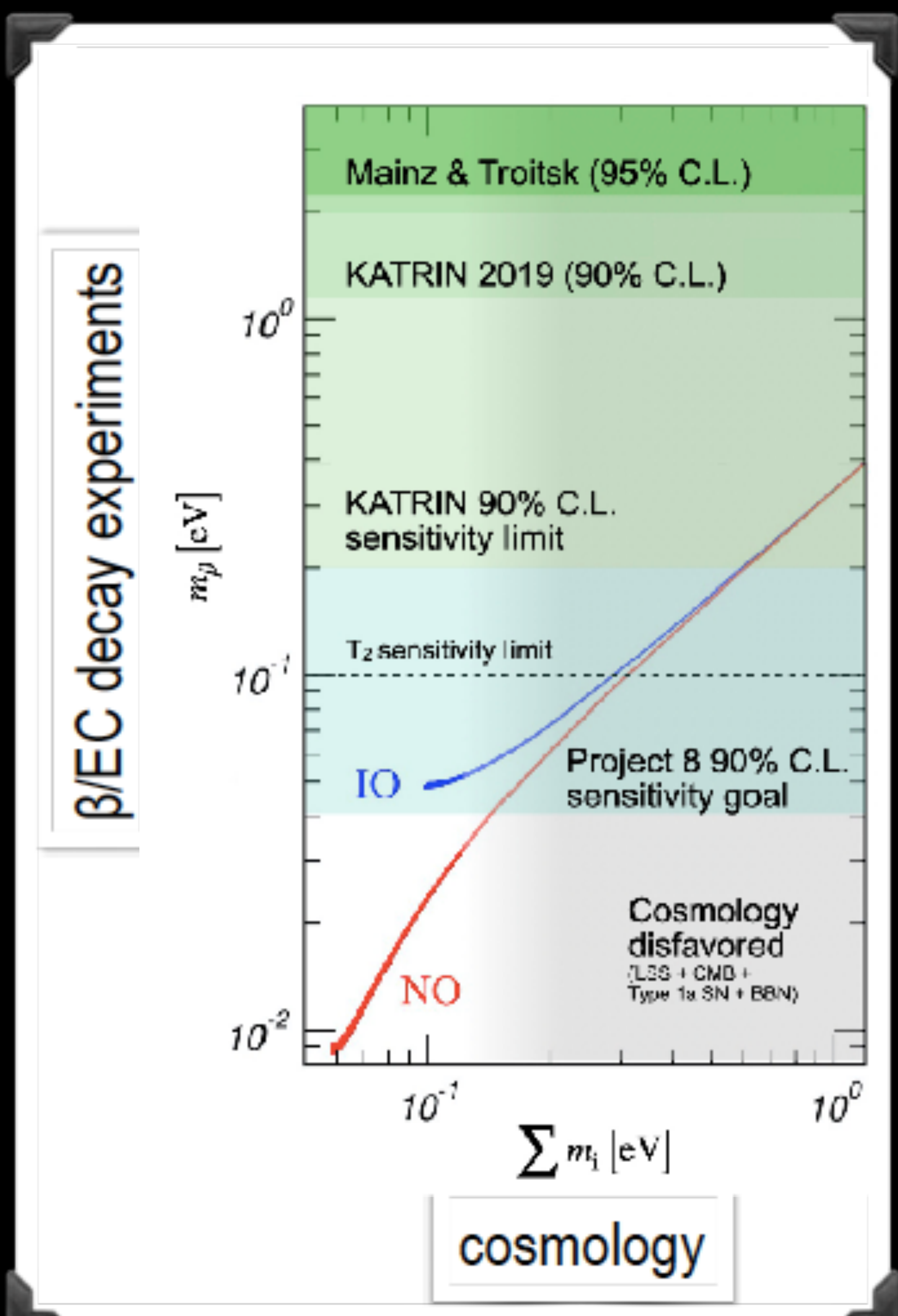
and also connect to other branches of physics.



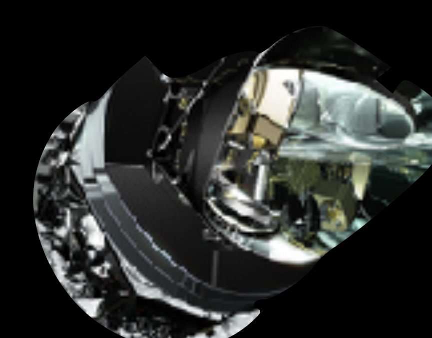
Neutrino mass connects back to cosmological observations.

$$\Sigma \equiv \sum_{i=1}^{3} m_i$$

PLANCK & Sky Map

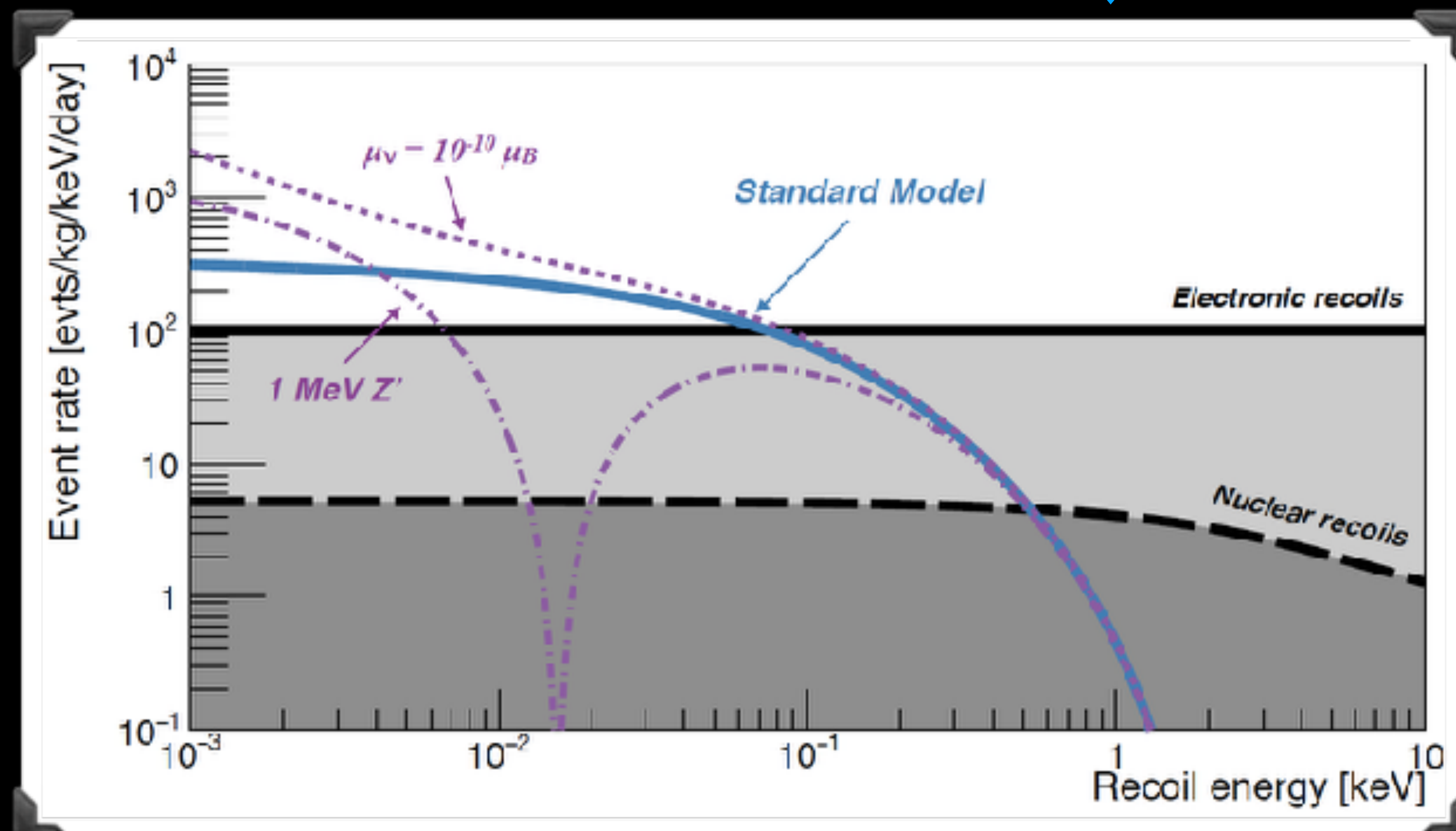


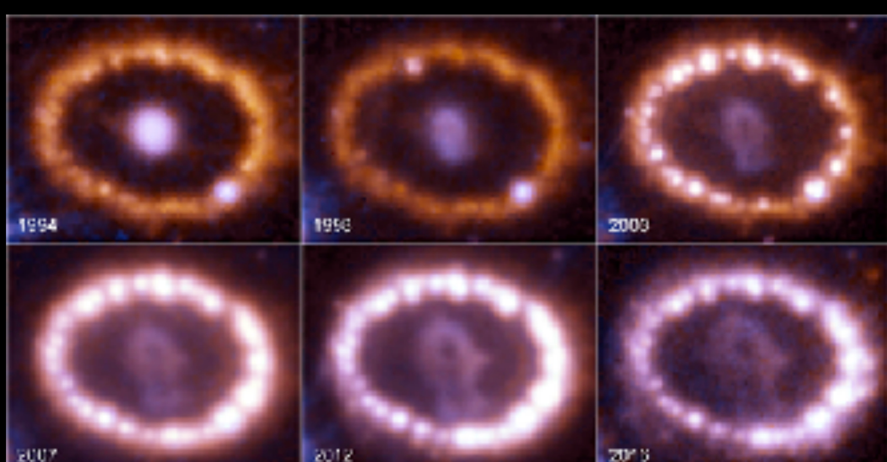
Limits on the neutrino mass scale from cosmology are affected by model *extensions* (such as additional parameters) or *new physics* (neutrino self-interaction or dark matter interactions).



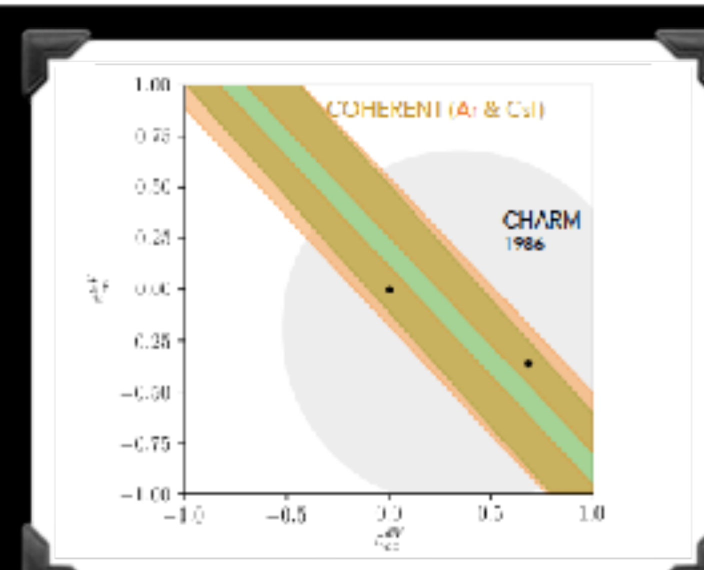
The coherent process likewise provides allows insight into new physics at small momentum exchange.

and also connect to other branches of physics.





Also gives insight into supernova physics, nuclear structure, solar physics and much more.



A World-wide effort is already underway for direct measurements.

Electron transfers all of its energy to the absorbing medium.

Calorimetric
(Cryogenic Bolometers)

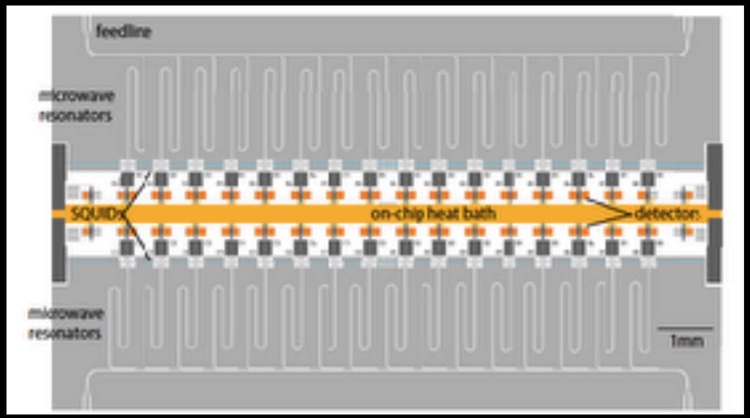
Electromagnetic filtering of electrons of selected energy.

Electromagnetic Collimation
(MAC-E Filter)

Use photon spontaneous emission from electron in magnetic field.

Frequency-Based
(Cyclotron Radiation Emission Spectroscopy)

ECHo & HOLMES



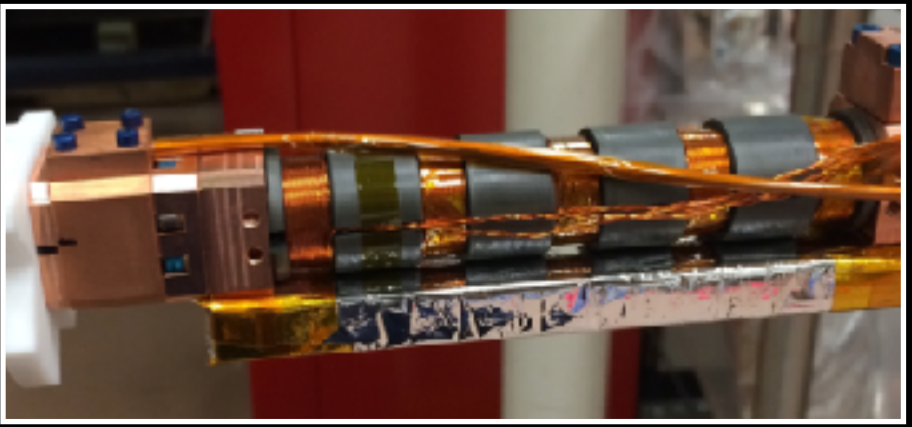
Electron transfers all of its energy to the absorbing medium.

Calorimetric
(Cryogenic Bolometers)

Electromagnetic filtering of electrons of selected energy.

Electromagnetic Collimation
(MAC-E Filter)

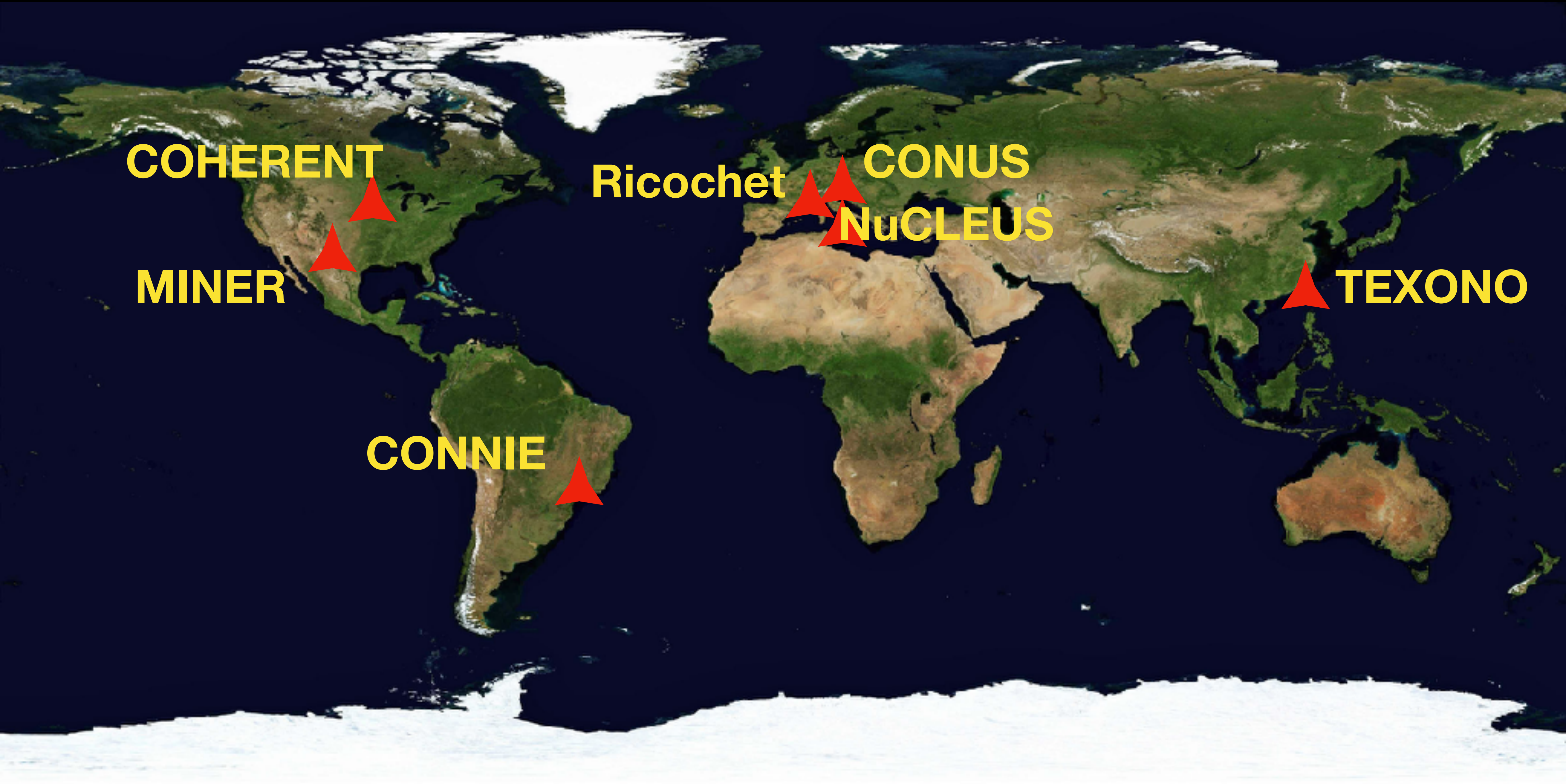
Project 8

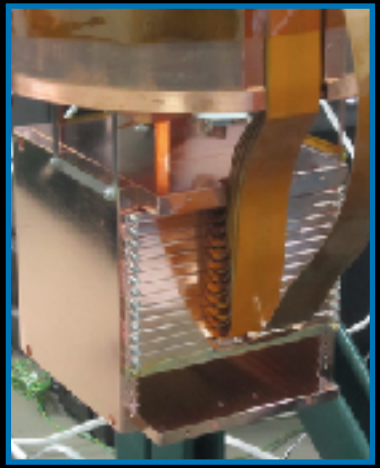


Use photon spontaneous emission from electron in magnetic field.

Frequency-Based
(Cyclotron Radiation Emission Spectroscopy)

A World-wide effort is also underway for coherent neutrino scattering, too.

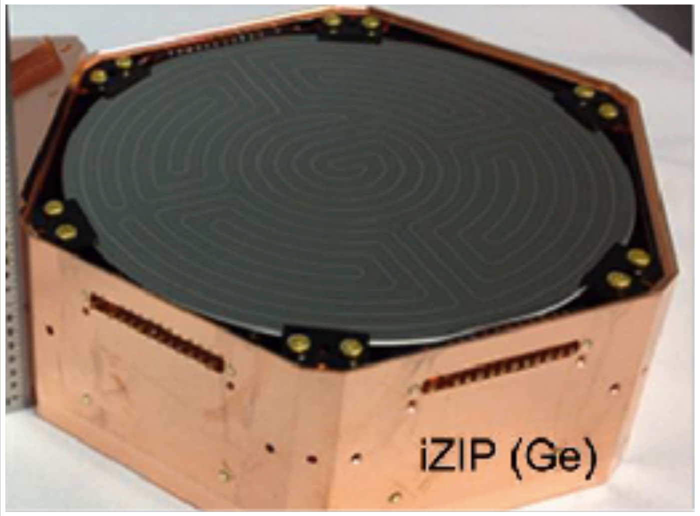


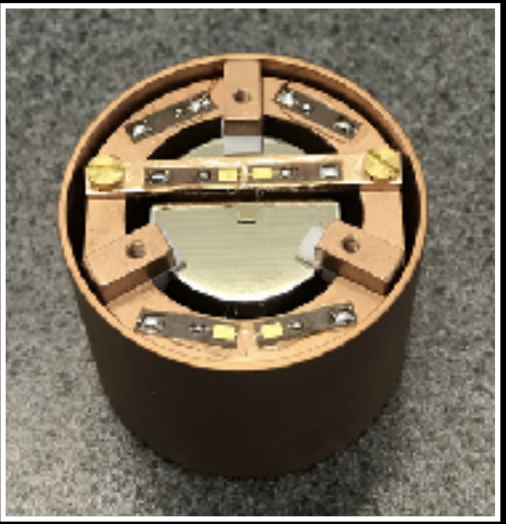


Ionization Detectors
(Germanium & Si-CCD)

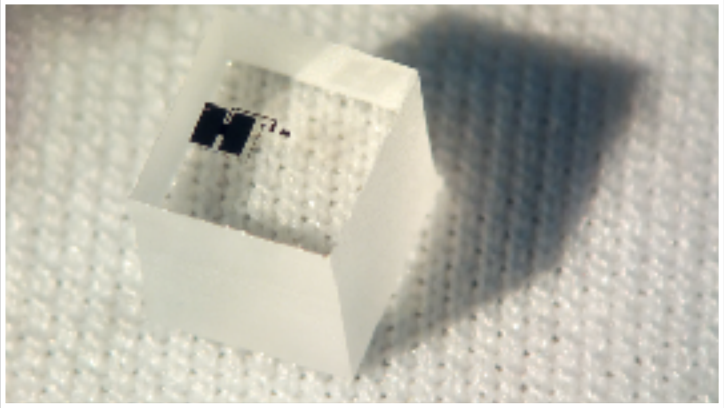
Large mass, keV scale

CONUS, CONNIE, TEXONO





MINER, Ricochet, NuCLEUS

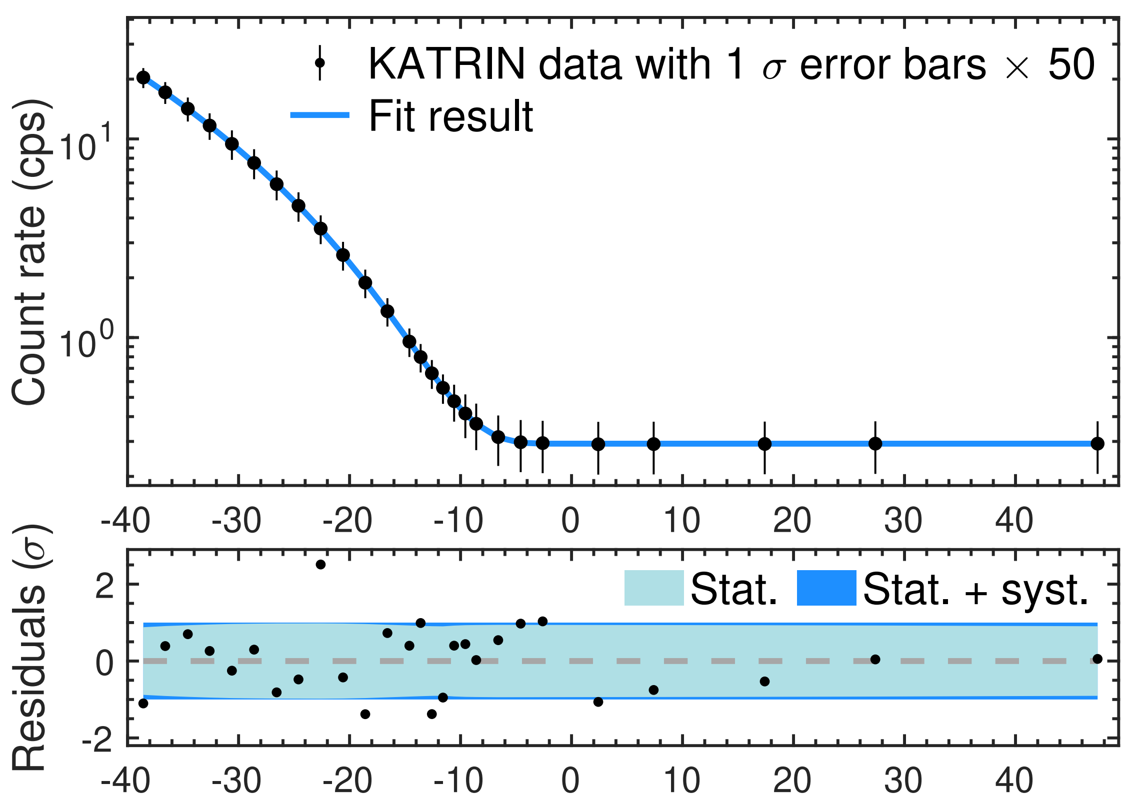


Cryogenic Bolometers

Smaller detectors, sub-keV scale

particle discrimination via
ionization, photon tagging

We have made **great** strides in last few years...



2 million events, 780 hours of data.

Excellent goodness-of-fit: p-value=0.56.

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

$$m_\beta \leq 1.1\ \mathrm{eV}\ (90\%\ \mathrm{C.L.})$$

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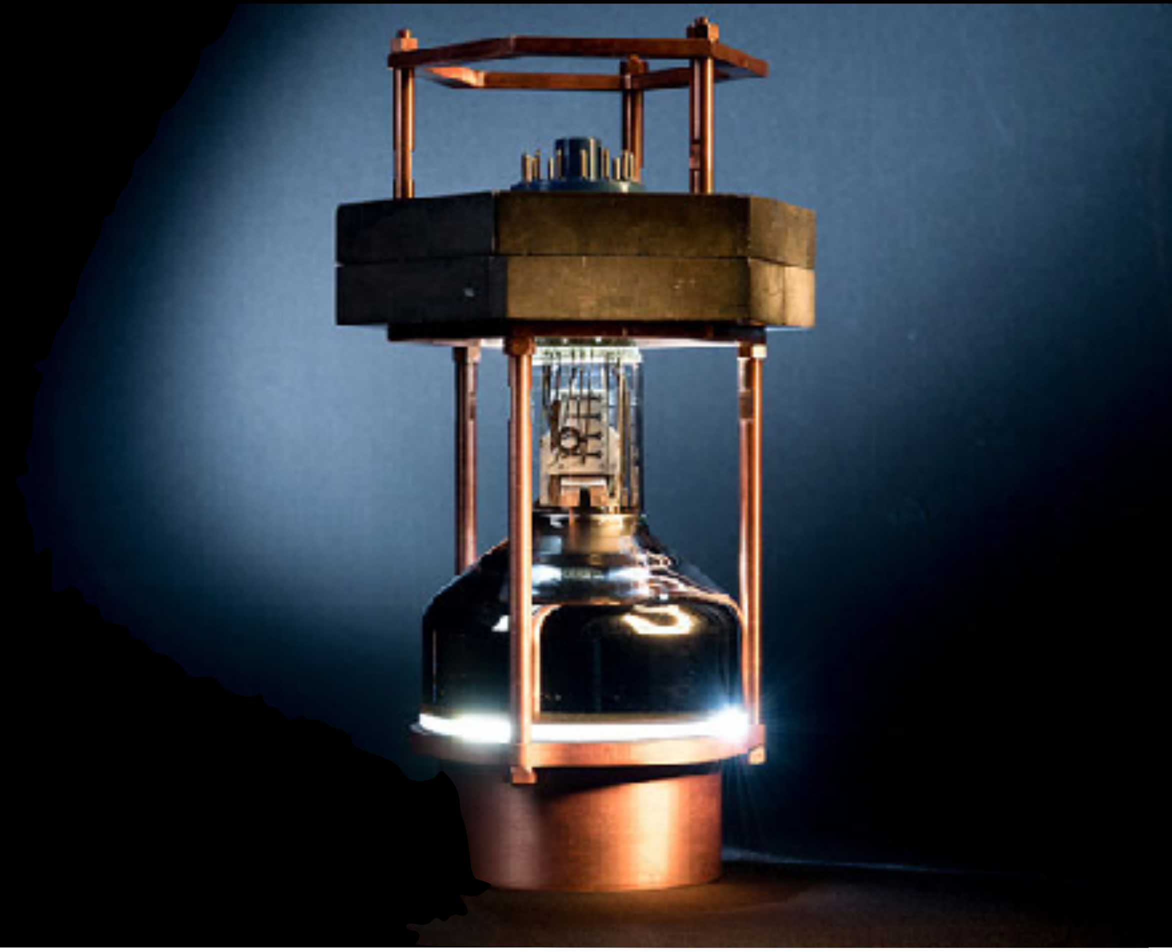
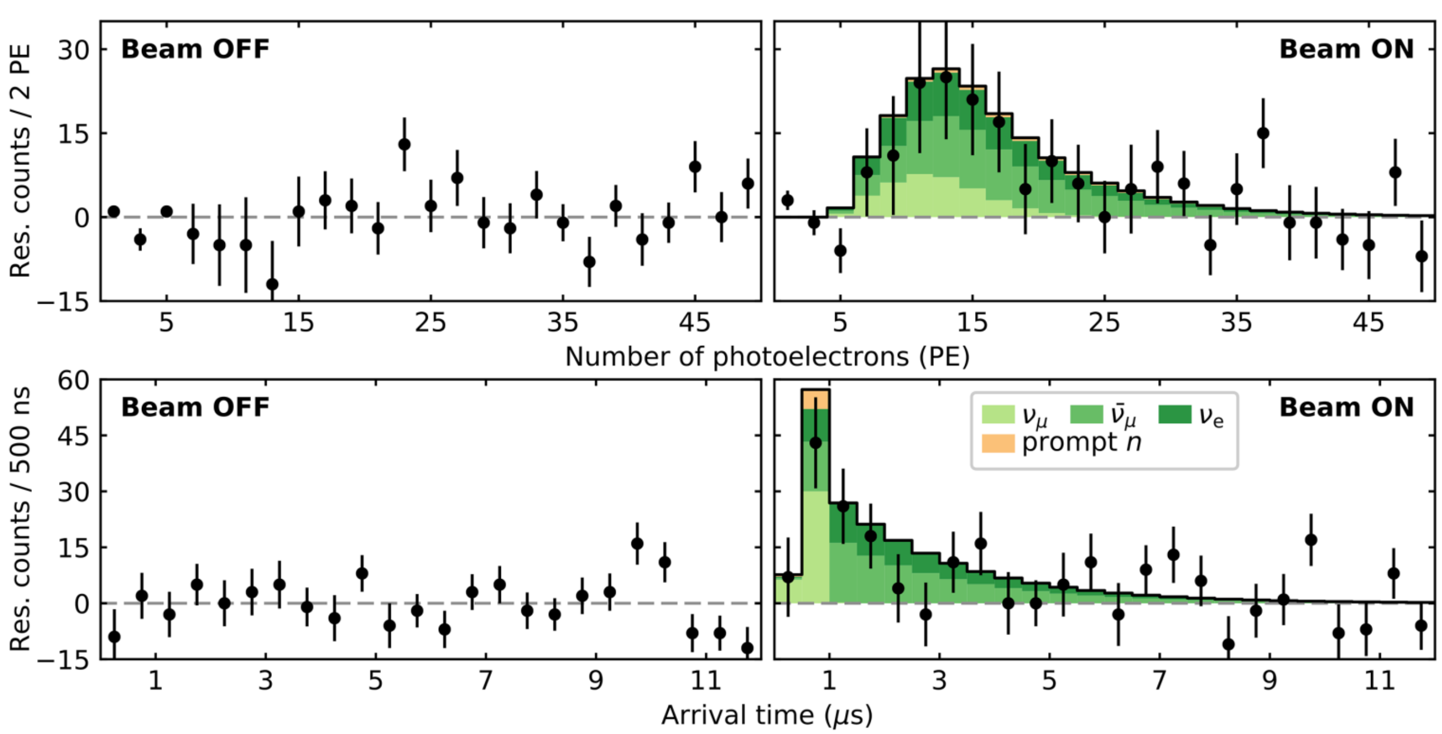
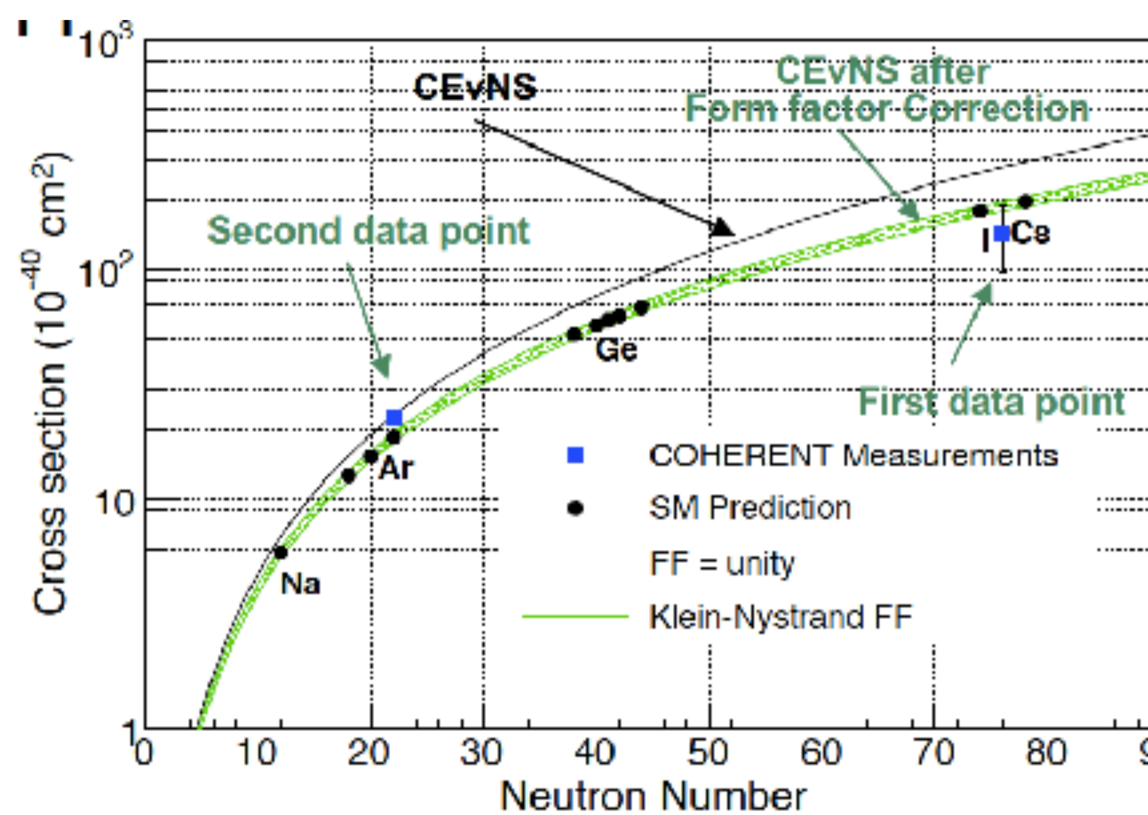


Process finally measured at the spallation neutron source by the COHERENT collaboration.

Now measured for Cs and Ar targets.

COHERENT SNS



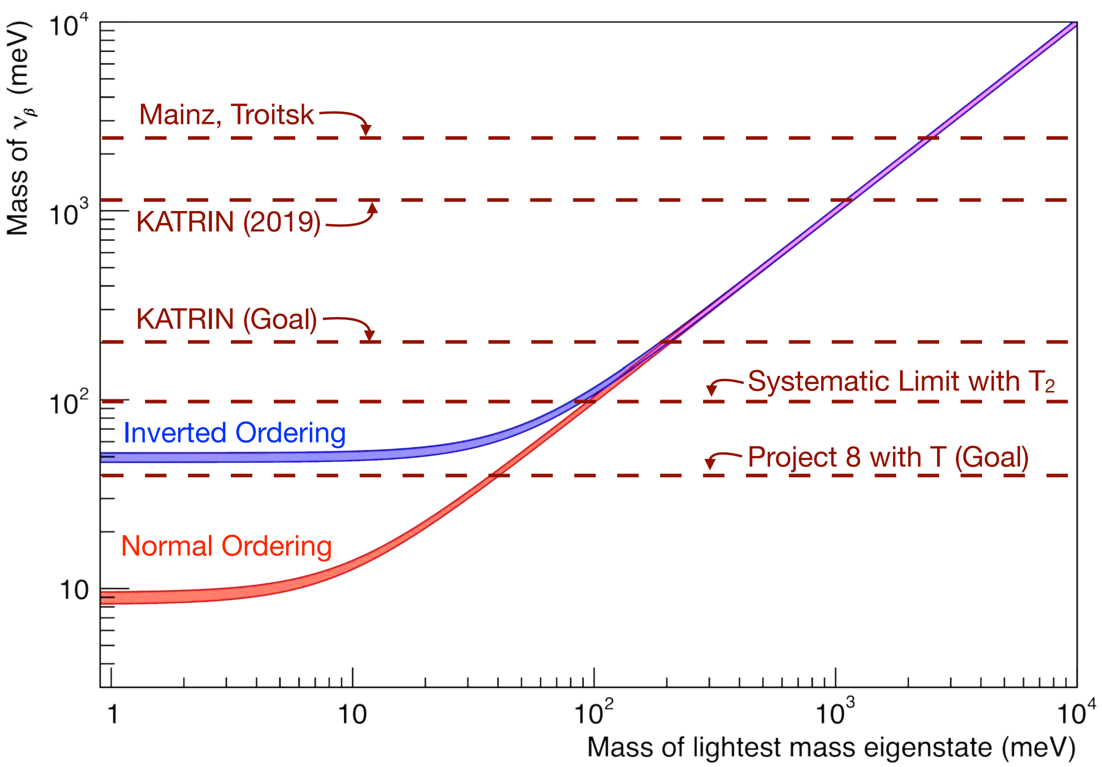


but both programs have ambitious goals.

ν Mass

Resolve whether the neutrino mass scale is quasi-degenerate in the next few years.

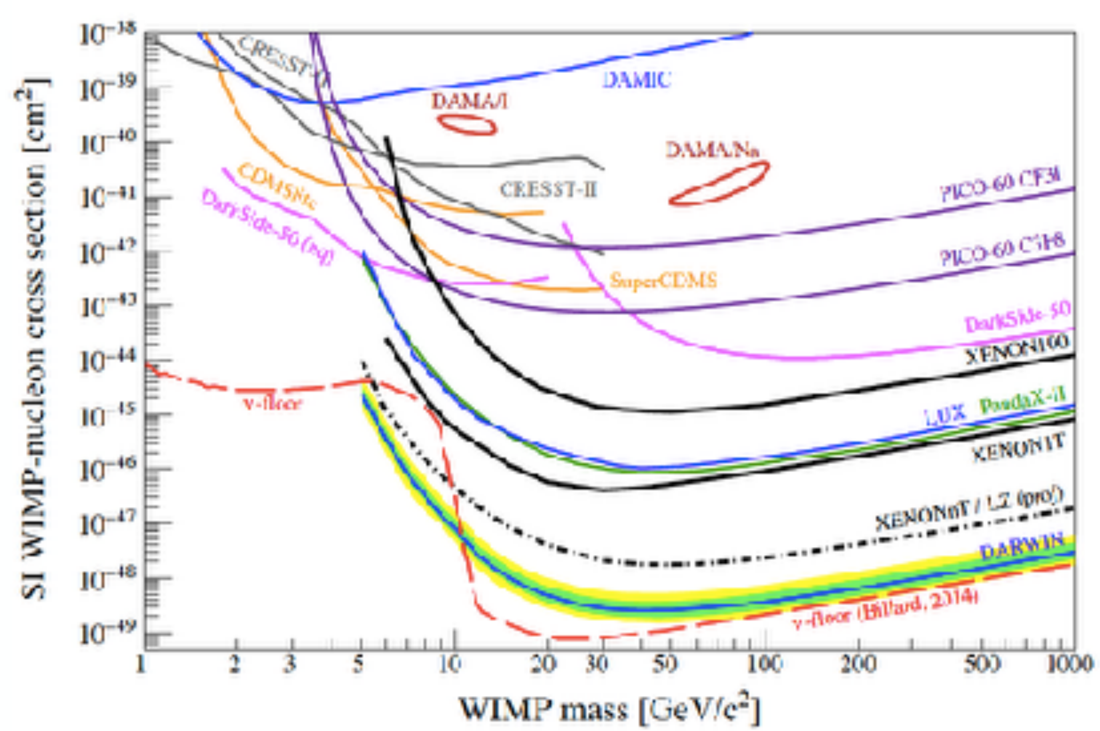
And eventually push down to the inverted ordering scale.



ν Coherent Scattering

A first detection from reactor neutrinos in the next few years.

Build O(10 kg) detectors over the next decade.



Does the technology being pursued get us there?

So, both these measurements have a common wish list...

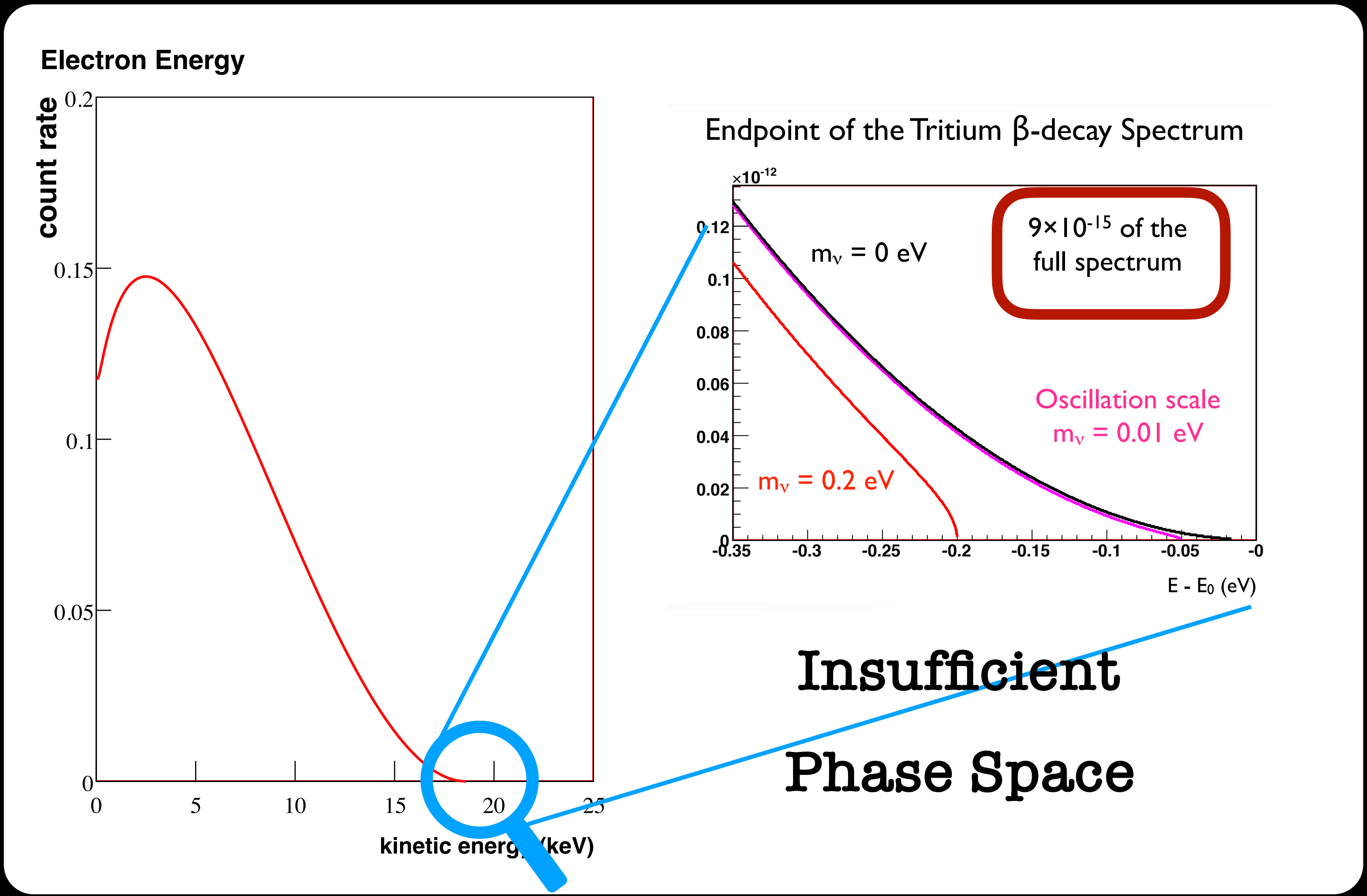
Sufficient statistics

Background Reduction

Superior Energy Resolution

Common challenges:

Sufficient Statistics



Only a tiny fraction of the spectrum yields information about the neutrino mass.

Large activities are required in order to probe the spectrum at the few eV level.

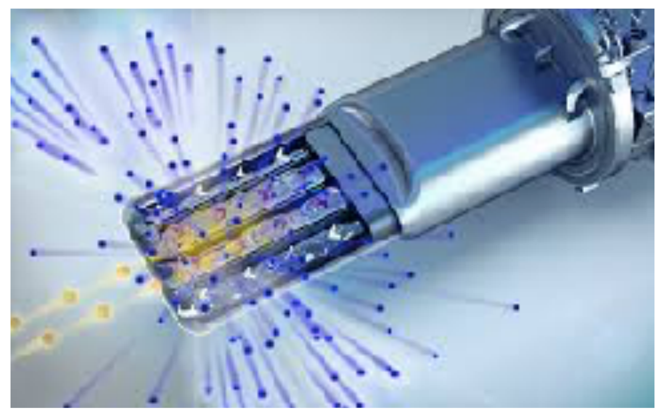
Common challenges:

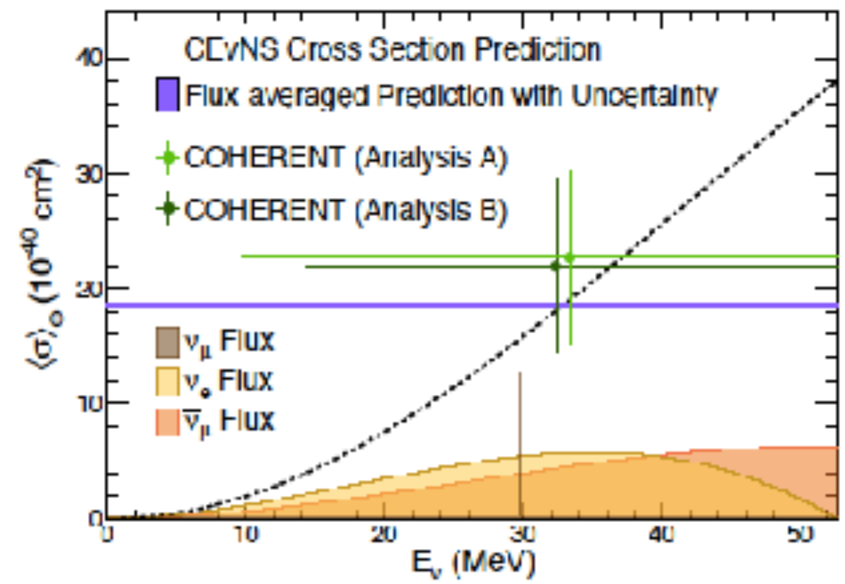
Sufficient Statistics

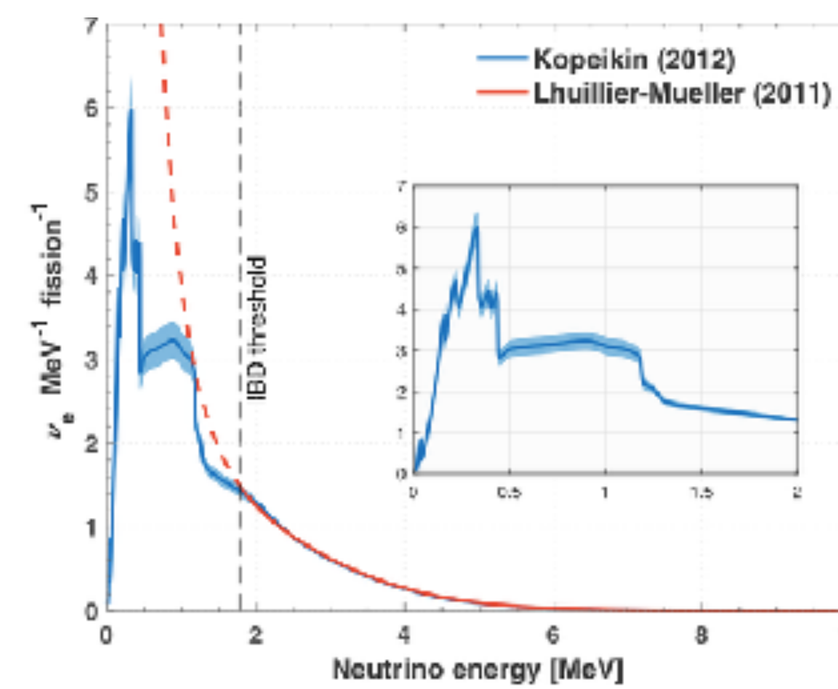
In the case of coherent scattering, coherence helps a lot.

That said, the cross-sections are still small.

Two work-arounds: operate at higher energies (COHERENT), or with large fluxes (nuclear reactors).



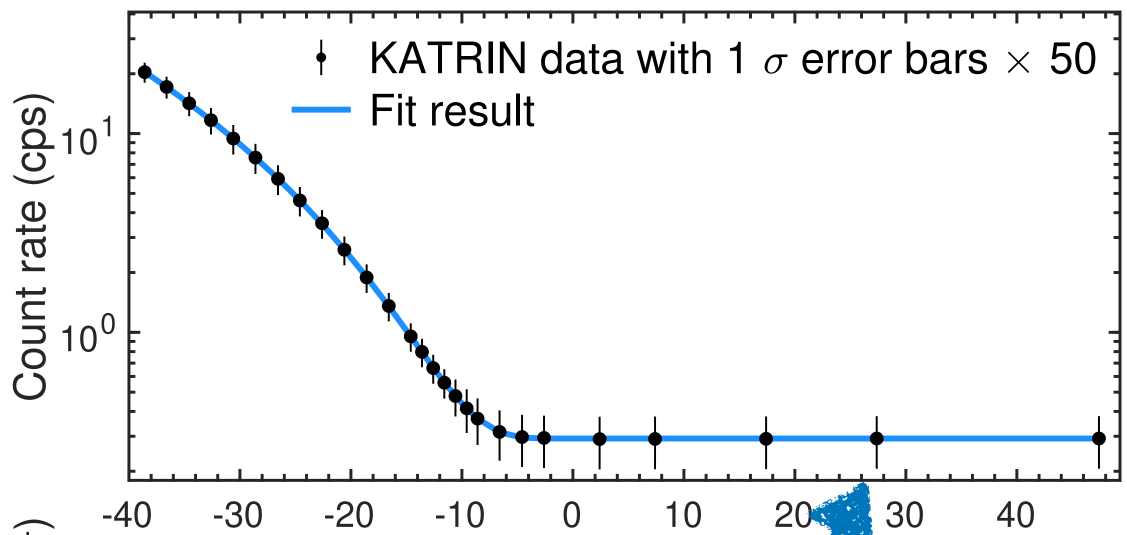


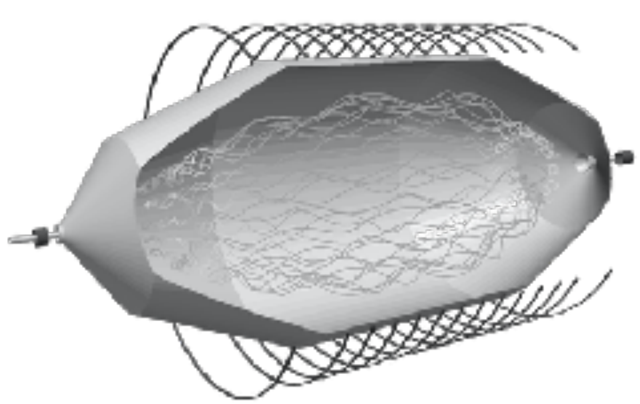


Common challenges:

Overcoming Backgrounds

Direct Measurements

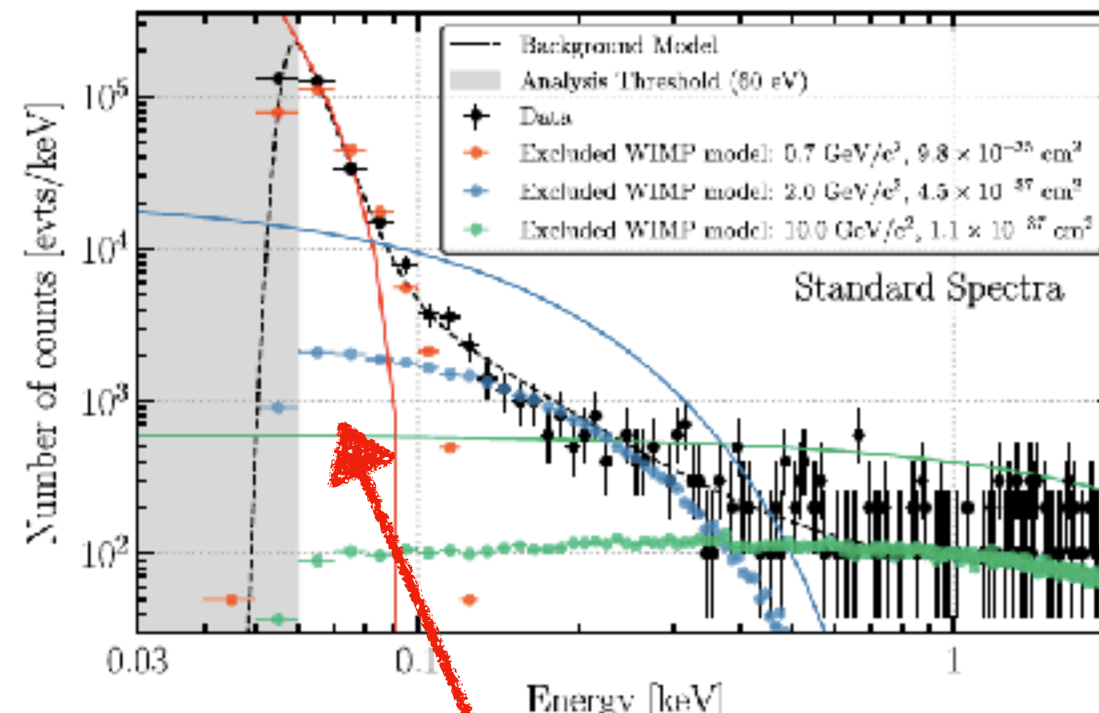




Rydberg atoms

Radon decays

CENNS Detectors



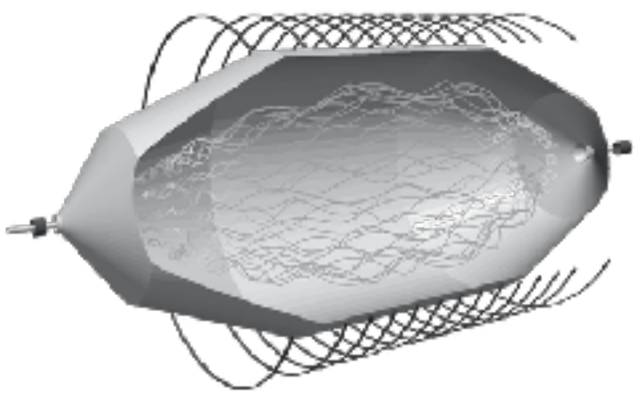
Background "wall"

Reduction of backgrounds is crucial for experiments of both sorts, though the causes for these backgrounds depends on the specific technology deployed.

Common challenges:

Overcoming Backgrounds

Direct Measurements

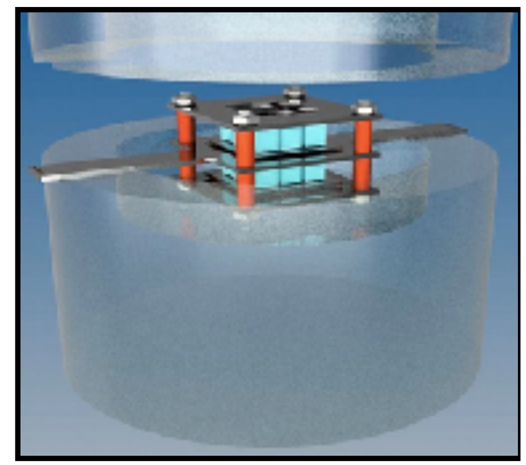


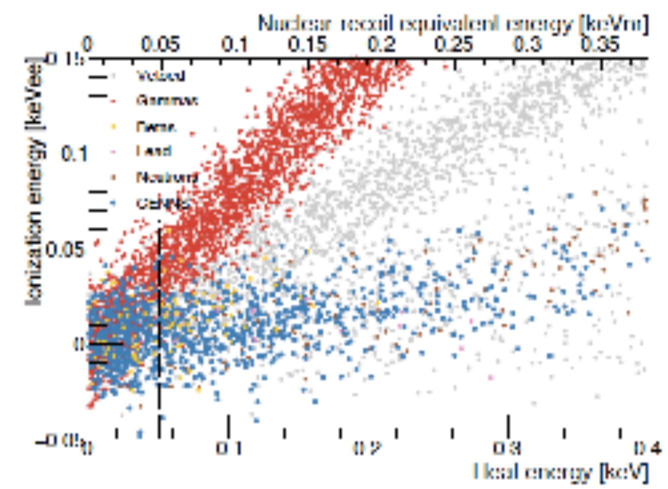
Magnetic field optimization

Radon removal

Magnetic shielding from surfaces

CENNS Detectors





Active Veto

Passive shielding

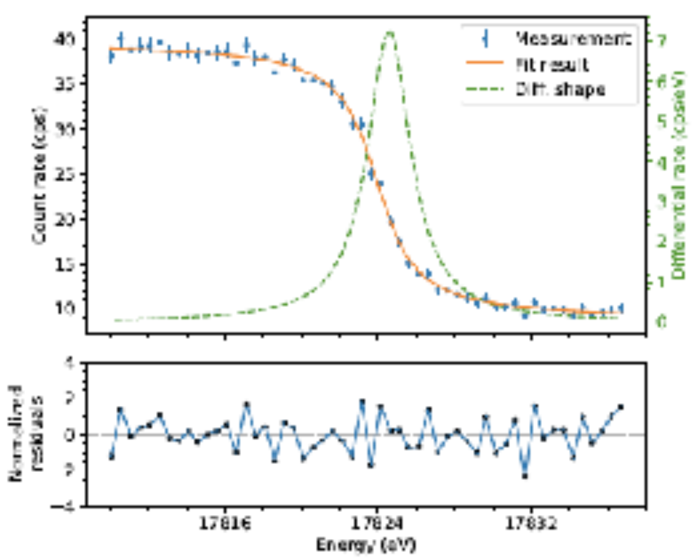
Electron/recoil event discrimination

Different mitigation strategies are used which also depend on the technology that is deployed.

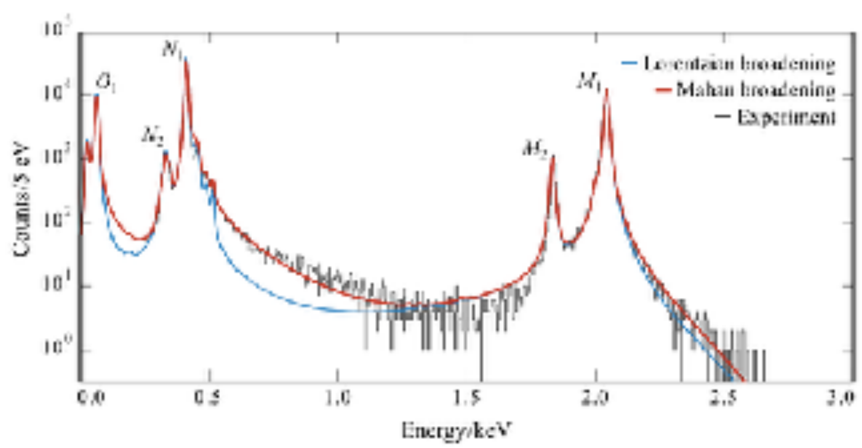
Common challenges:

Superior energy resolution

Direct Measurements

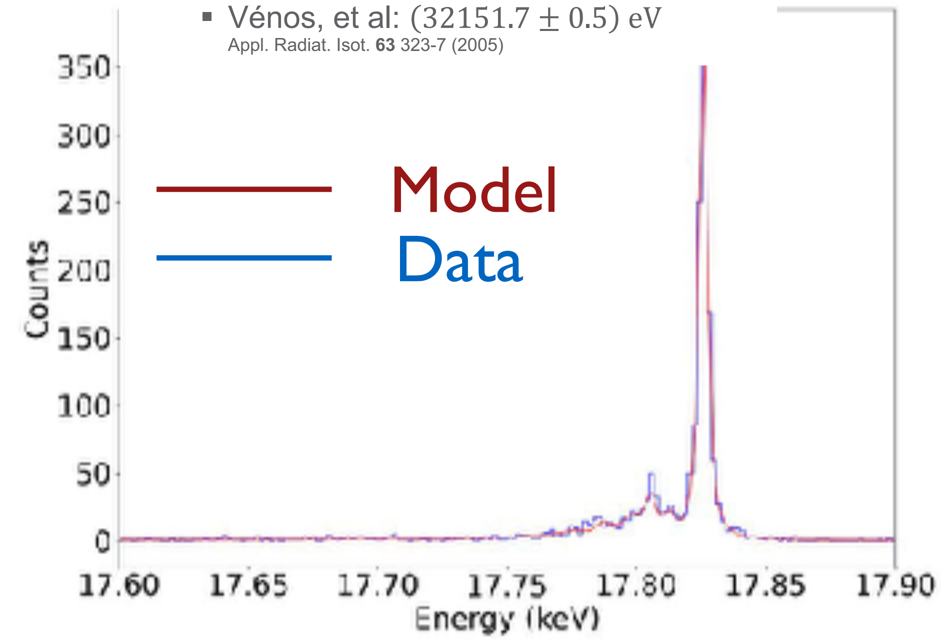


KATRIN



ECHo

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



Project 8

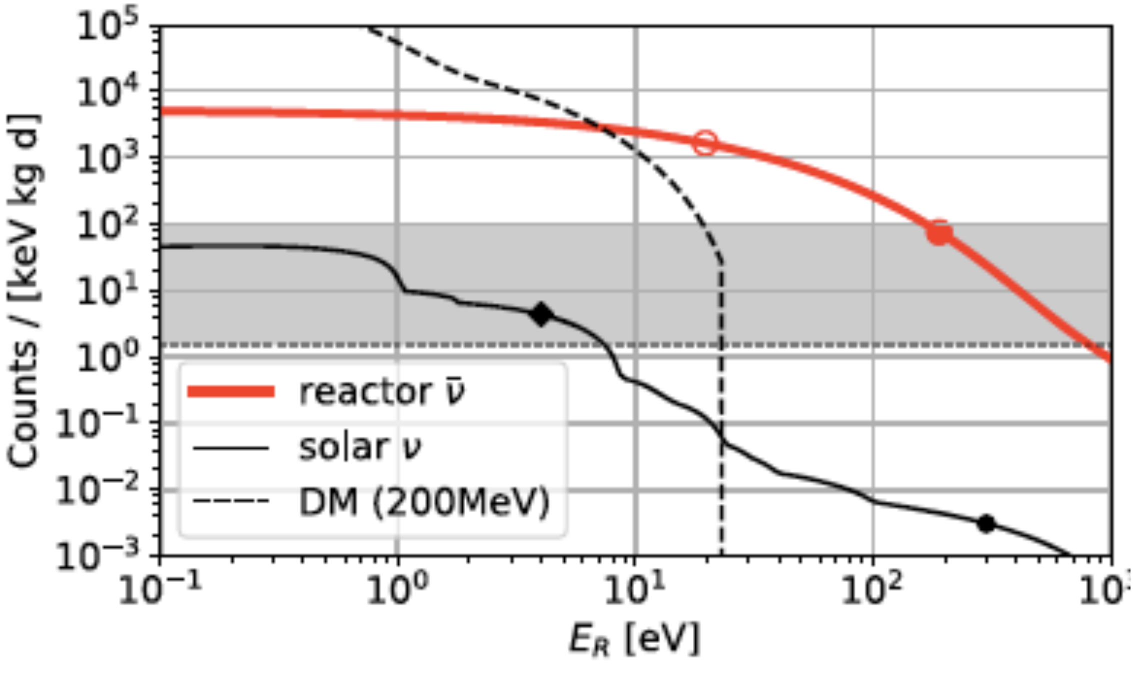
For direct measurements, energy resolution is needed to extract the spectral shape near the endpoint.

Order few eV resolution now achieved by major efforts.

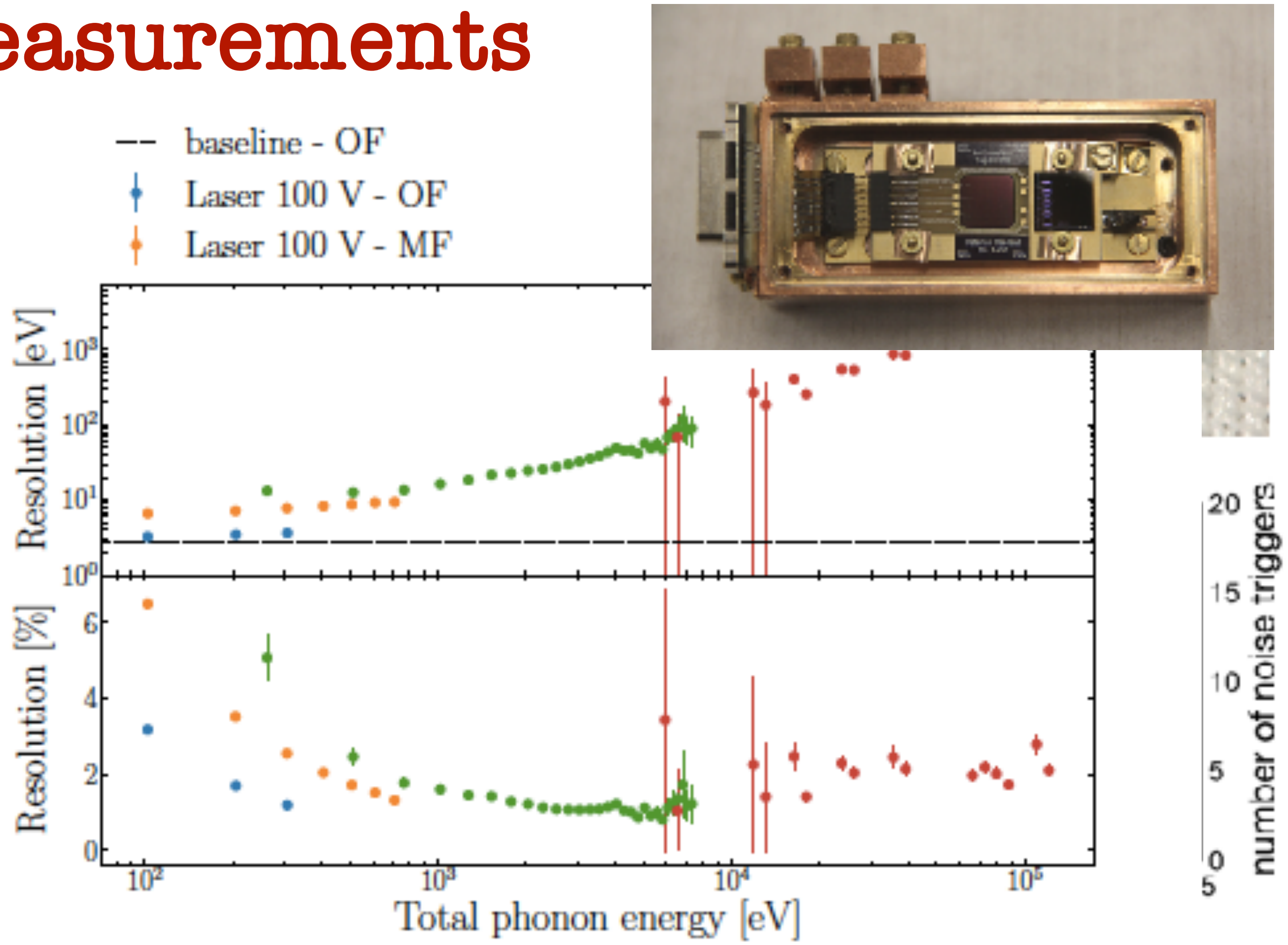
Common challenges:

Superior energy resolution

CENNS Measurements



Lower recoil energy = Higher flux



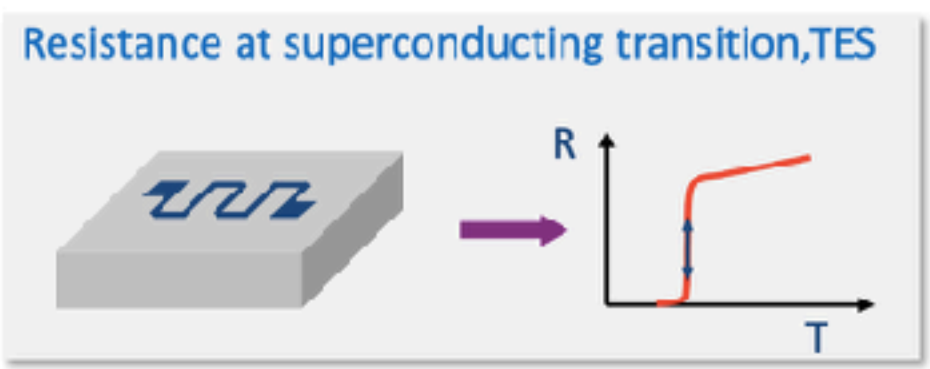
For CENNS measurements, energy resolution is needed to move the energy threshold for recoils as low as possible.

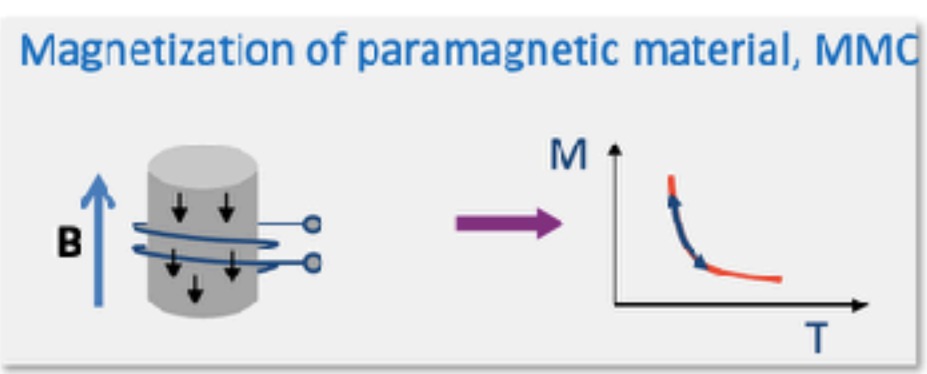
Sufficient statistics

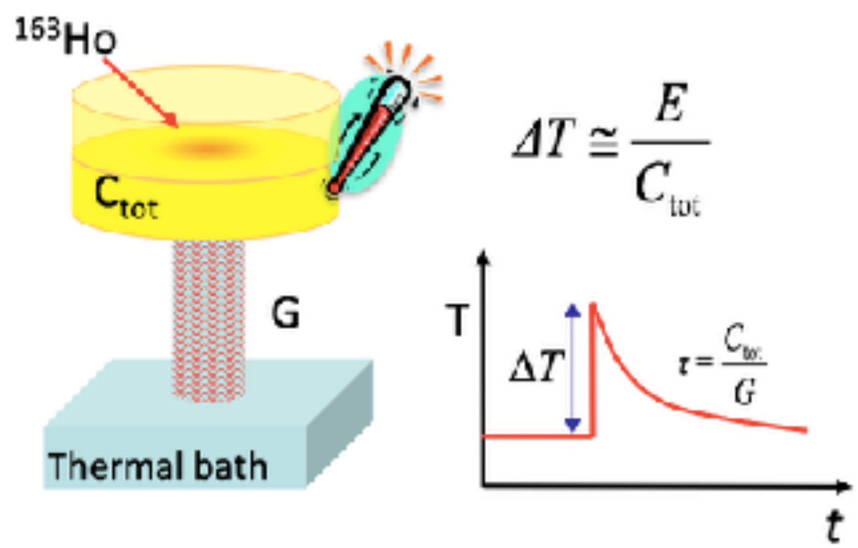
Background Reduction

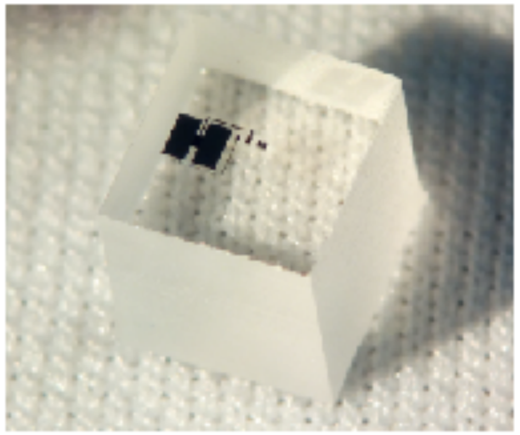
Superior Energy Resolution

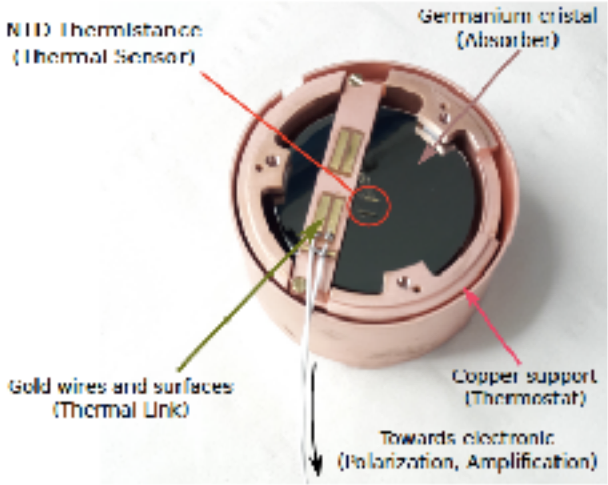
In certain cases, experiments in both categories implement very similar technology to achieve their goals.











e.g.: Magnetic μ-calorimters, Transition Edge Sensors, and NTDs

Sufficient statistics

Background Reduction

Superior Energy Resolution

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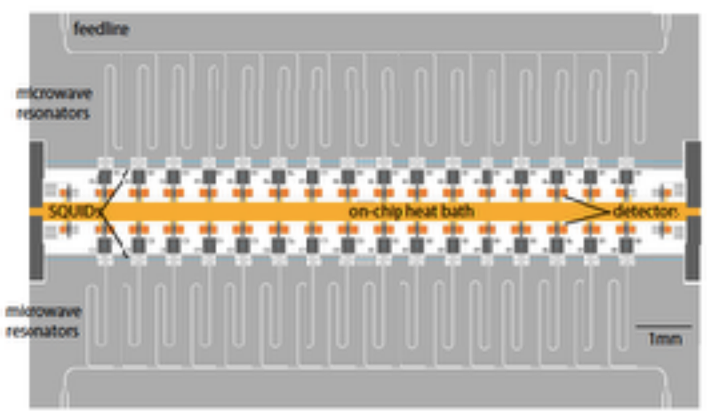
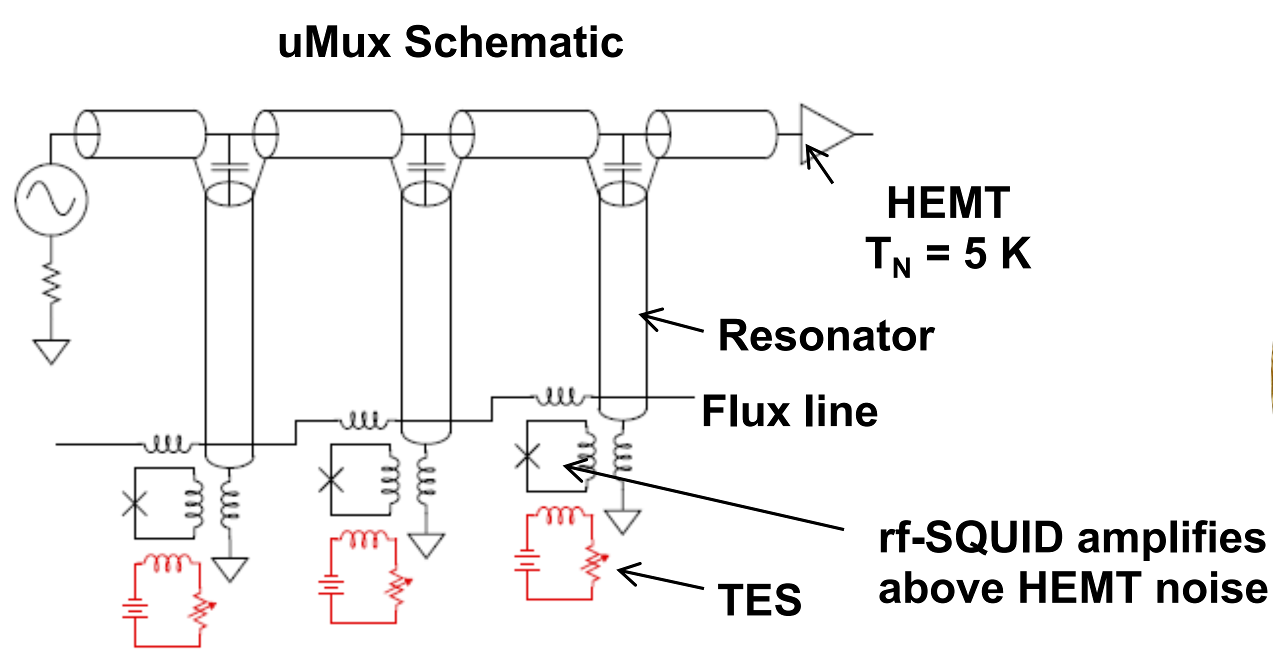
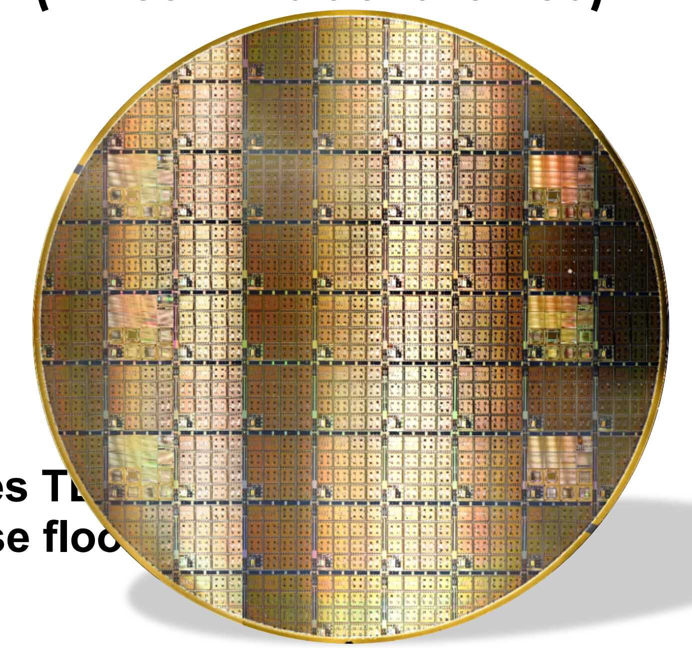


MMC array (ECHo)



Resonator chip array (Lincoln Laboratories)



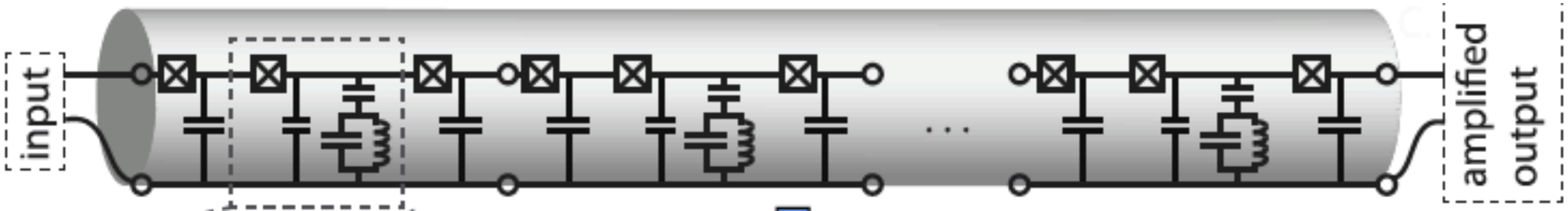
e.g. Multiplexing of signals to increase target mass

Sufficient statistics

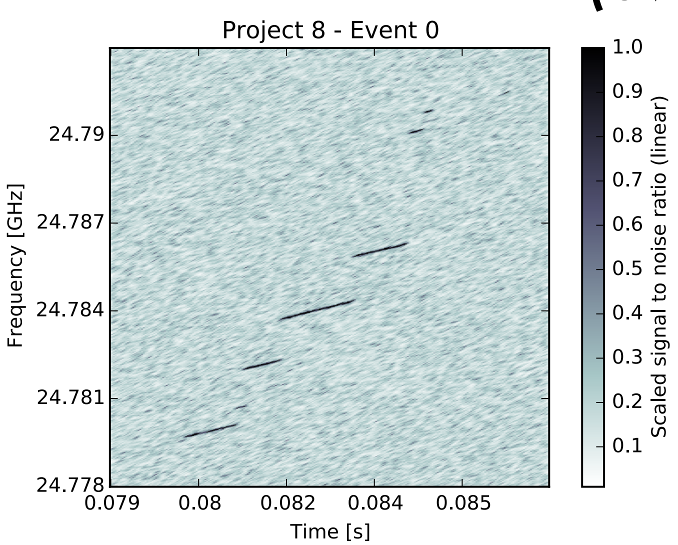
Background Reduction

Superior Energy Resolution

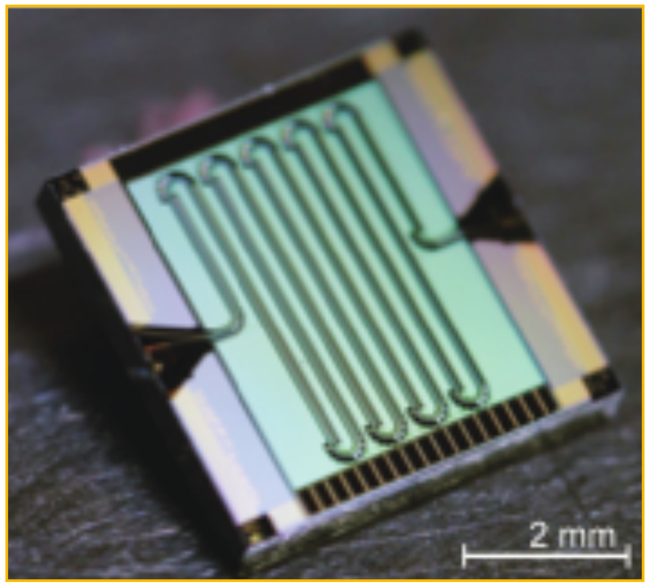
In certain cases, experiments in both categories implement very similar technology to achieve their goals.



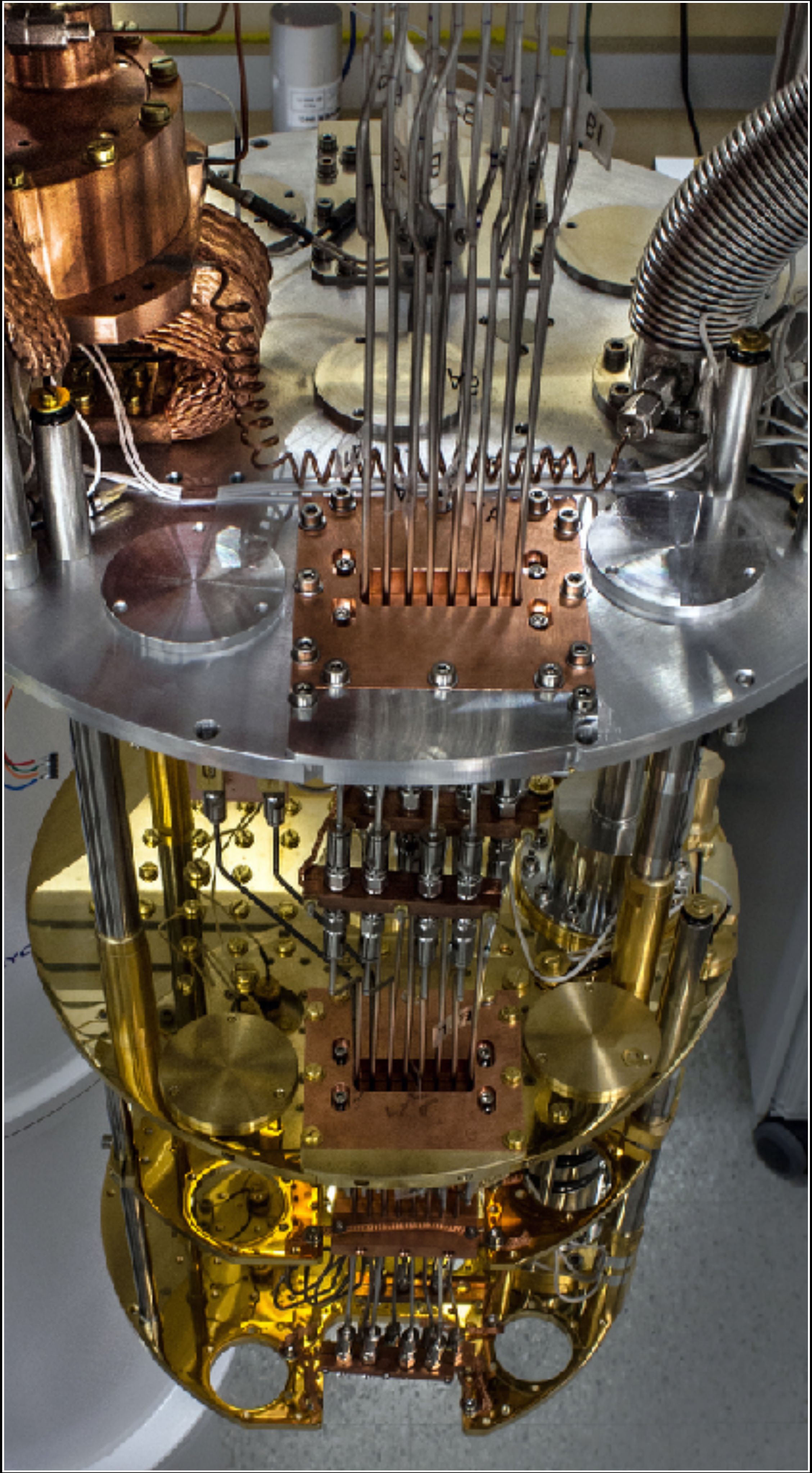
Traveling Wave Parametric Amplifier
(over 2000 Josephson junctions)



Detecting
microwave signals
at femtowatt scale



e.g. Operating at the quantum noise limit for microwave detection

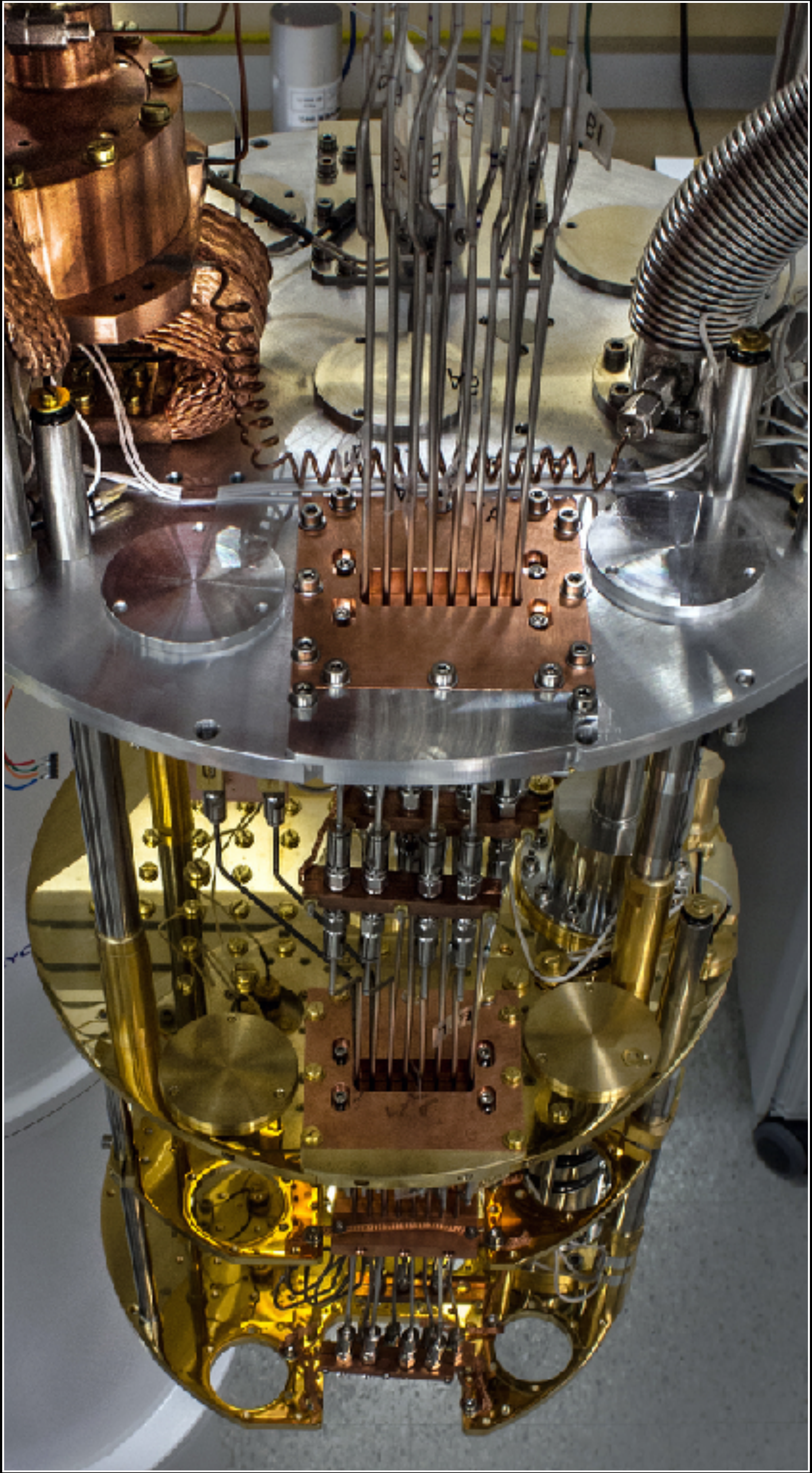


Much of these advances are due to great advances in superconducting technology.

High quality production of JJ junctions, superconducting leads.

Driven by strong recent development for superconducting circuits for quantum computing.

However, unique challenges still remain for using these new technologies for neutrino physics:



Do these technology scale?

Can they operate in harsh environments?

What backgrounds lurk in this new space?

But half the fun is the challenge.

"We choose to go to the Moon. We choose to go to the Moon in this decade and do the other things, not because they are easy, but because they are hard."

Thank you for
your attention.

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[3] J. Billard, J. Johnston, B. Kavanagh, “Prospects for exploring New Physics in Coherent Elastic Neutrino-Nucleus Scattering”, JCAP 11 (2018), 016.

[4] KATRIN Collaboration, “Improved Upper Limit on the Neutrino Mass from a Direct Kinematic Method by KATRIN”, Phys.Rev.Lett. 123 (2019) 22, 221802.

[5] COHERENT Collaboration, “First Constraint on Coherent Elastic Neutrino-Nucleus Scattering in Argon”, Phys.Rev.D 100 (2019) 11, 115020.

[6] COHERENT Collaboration, "Observation of Coherent Elastic Neutrino-Nucleus Scattering”, Science 357 (2017) 6356, 1123-1126.

[7] R. Strauss and N. Oblath, Neutrino 2020 plenary sessions.

[8] EDELWEISS Collaboration, “Searching for low-mass dark matter particles with a massive Ge bolometer operated above ground,” Phys. Rev. D. 99 (2019) 082203.

[9] K. O’Brien et al., “Resonant Phase Matching of Josephson Junction Traveling Wave Parametric Amplifiers” PRL 113, 157001 (2014).

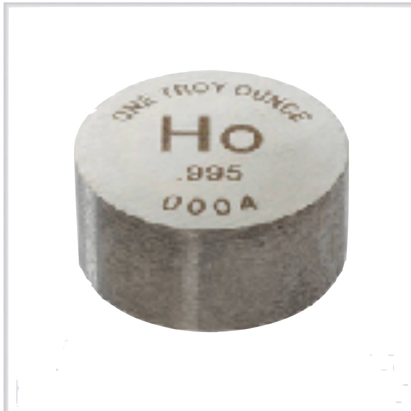
[10] J. A. Formaggio, A. de Gouvêa, R.G. H. Robertson, “Direct Measurements of Neutrino Mass” e-Print: 2102.00594 [nucl-ex] (2021).

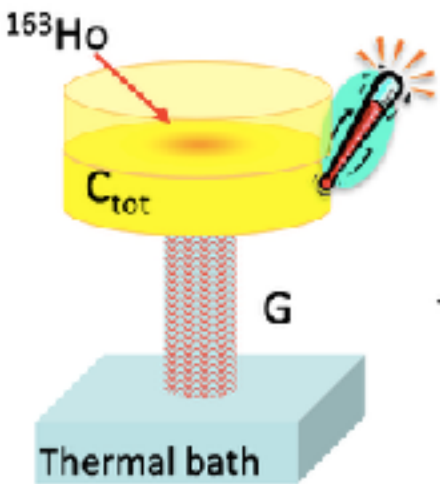
[11] R. Chen et al, “Design and Characterization of a Phonon-Mediated Cryogenic Particle Detector “, e-Print: 2021.1243v1 [physics-ins.det] (2021).

Backup Slides

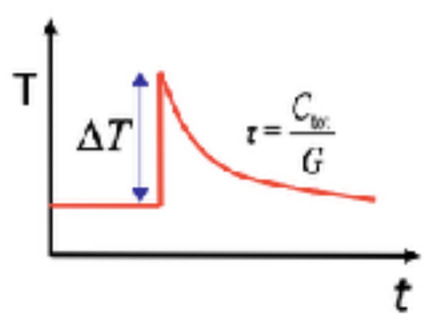
(In case people ask questions)

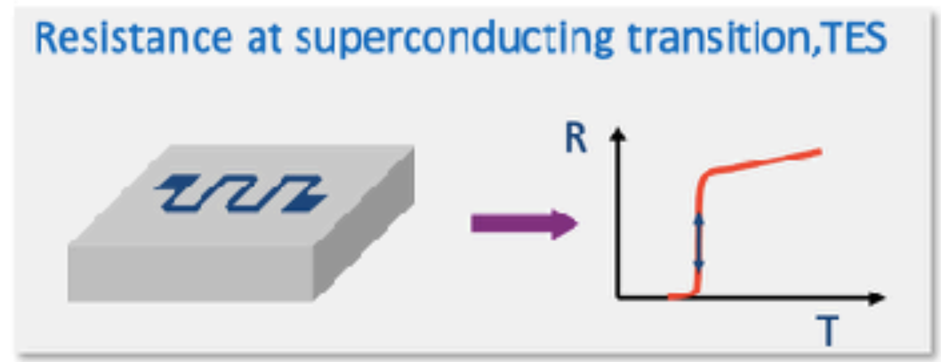
Modern Calorimetric Experiments





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



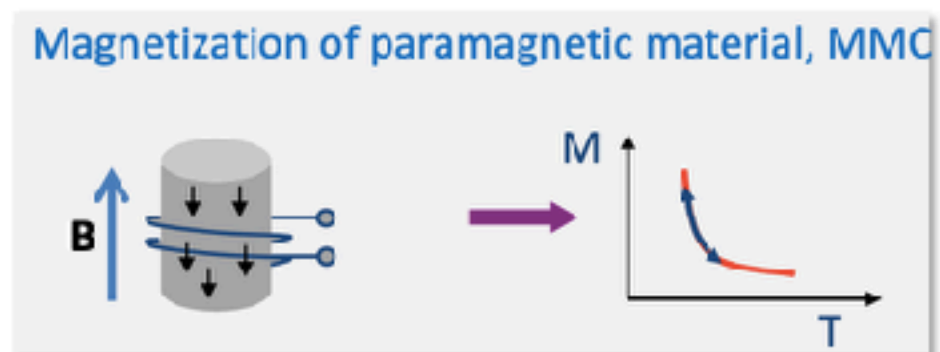


K.D. Irwin and G.C. Hilton, Topics in Applied Physics 99 (2005) 63

HOLMES

NuMECS

Detector arrays produced at NIST (Boulder US)



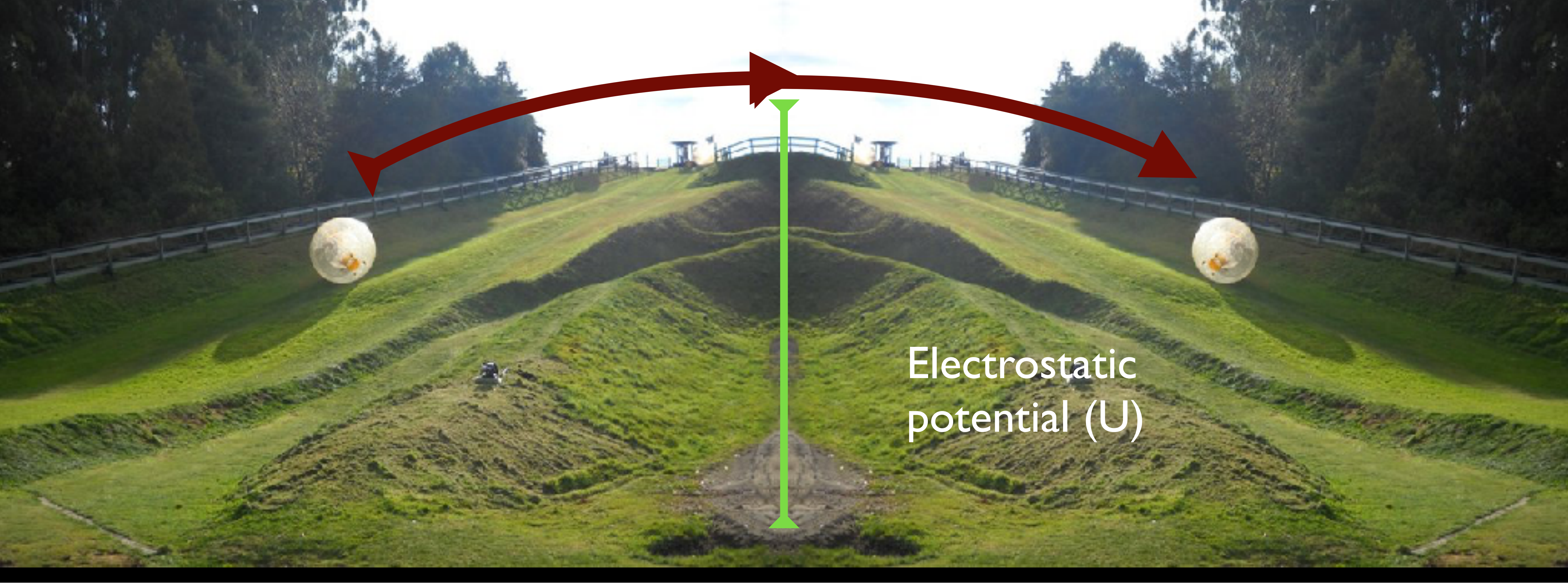
A.Fleischmann, C. Enss and G. M. Seidel, Topics in Applied Physics 99 (2005) 63

ECHo

Detector arrays produced at KIP, Heidelberg University

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

Contain the full decay energy.



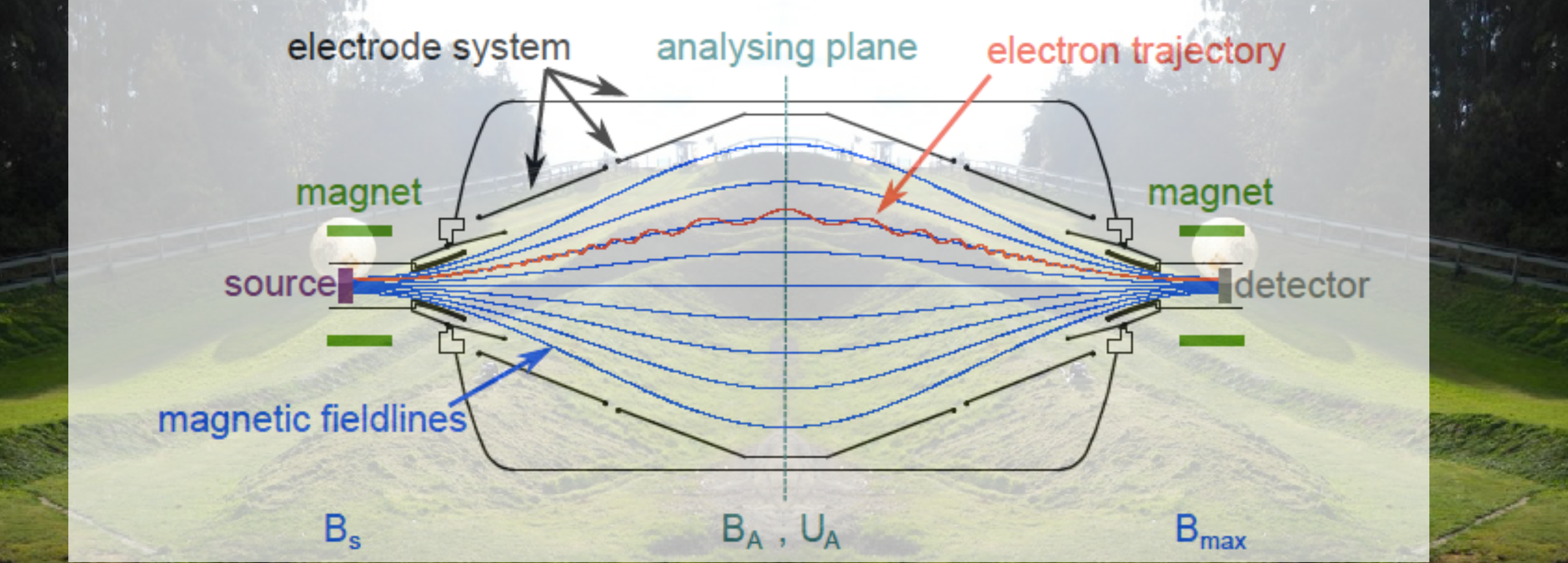
High Magnetic Field (Bs)

Low Field
B_A

High Magnetic Field (Bs)

Magnetic Adiabatic Collimation
with
Electrostatic Filtering

(only electrons with enough energy can overcome potential barrier)



High Magnetic Field (Bs)

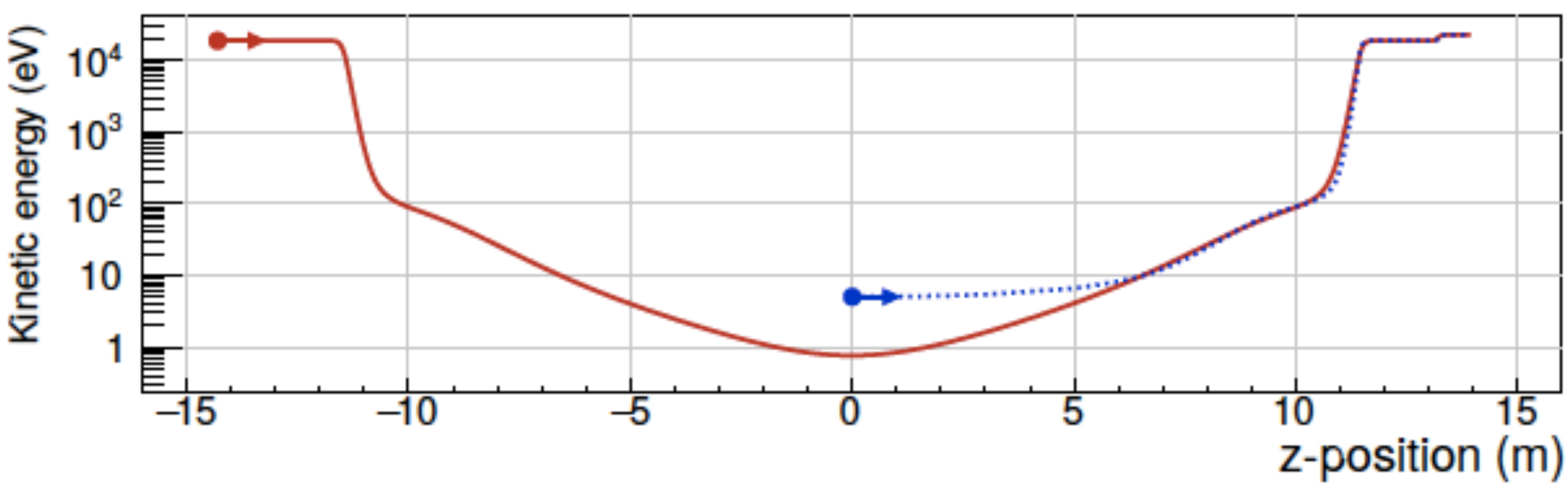
Low Field B_A

High Magnetic Field (Bs)

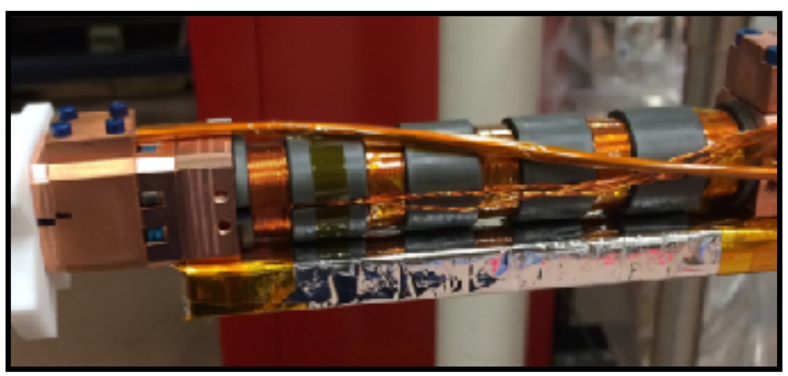
μ_e μ_e μ_e μ_e μ_e

10^{11} e^- / second

1 e^- / second



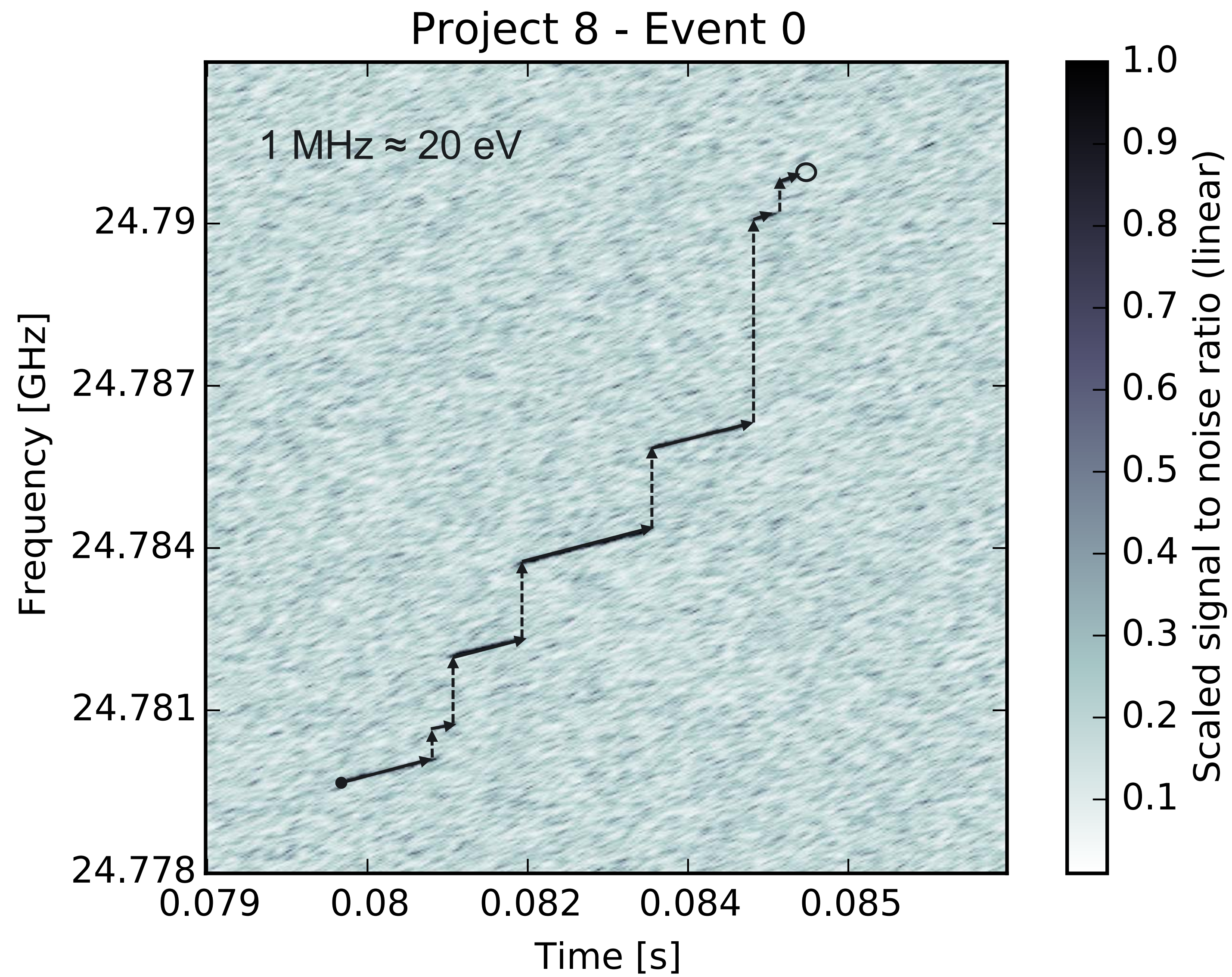
Cyclotron Radiation Emission Spectroscopy (CRES)

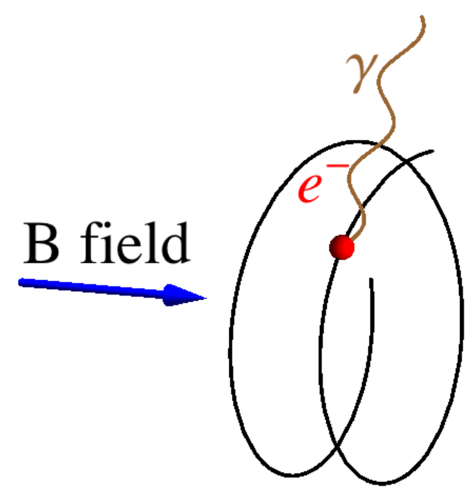


PROJECT 8

Frequency Approach

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





- *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

KATRIN Outlook

KATRIN continues to collect data (Runs 2 & 3 already obtained).
A 1000 day data set is expected to reach design goal.

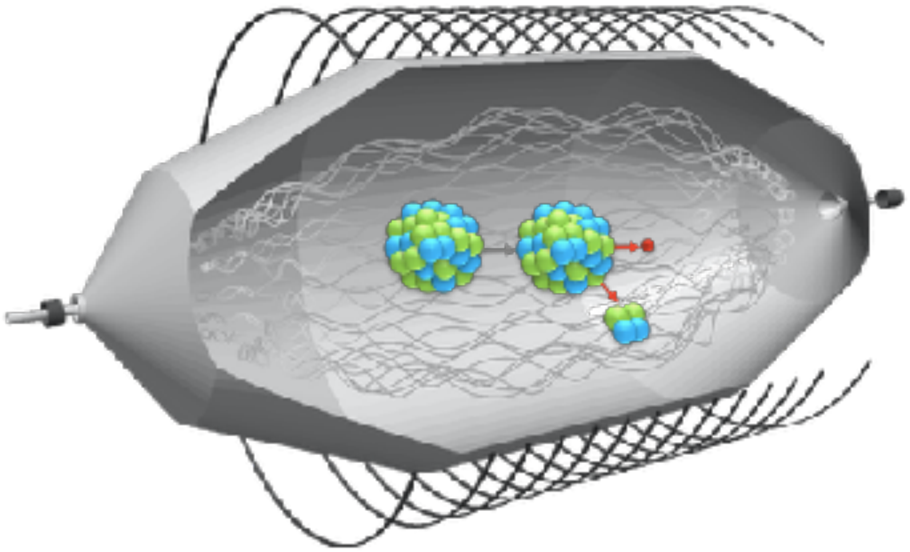
Comprehensive campaign to reduce and mitigate backgrounds, including radon and Rydberg events.

Better measurement/control of plasma instabilities in source.

Target Sensitivity:

200 meV (90% C.L.)

Increased statistics



Background mitigation

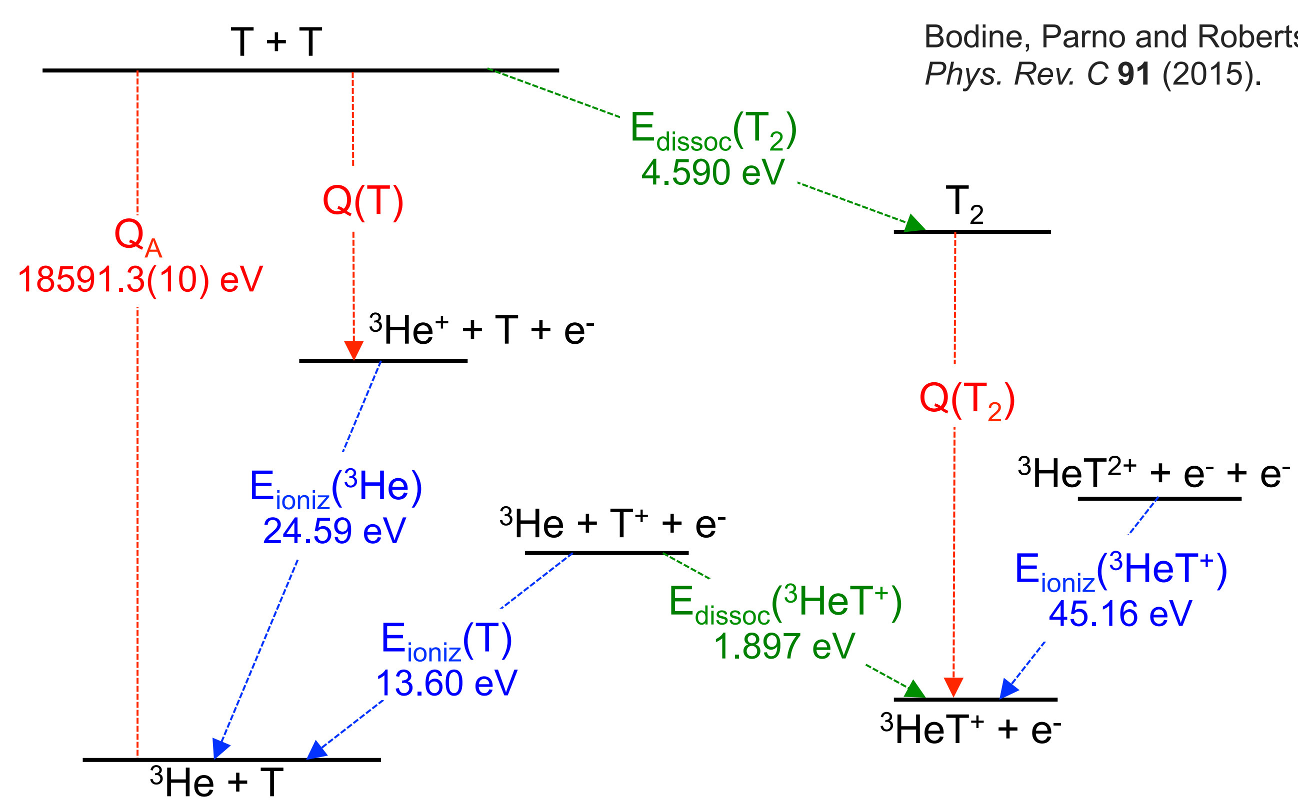
Assessment of plasma effects

Beyond the Degeneracy Scale

Any experiment with a molecular tritium (T_2) source will have a systematic penalty associated with uncertainty in the width of rotational and vibrational states of the daughter $^3HeT^+$ populated in the decay.

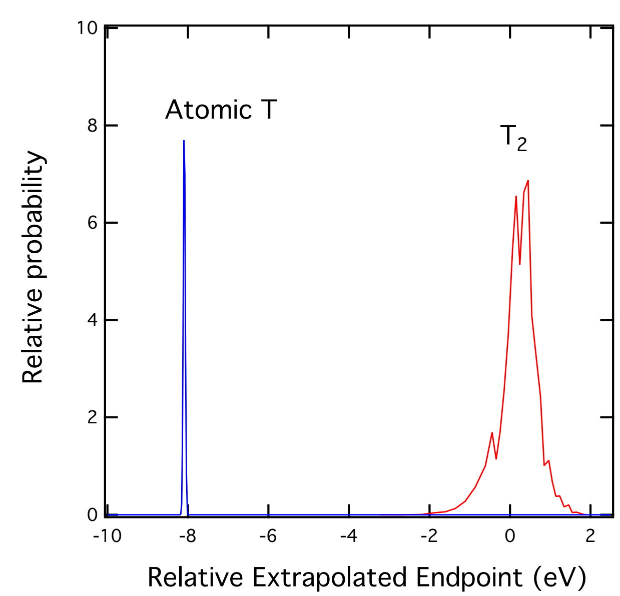
In order to push to the next target mass scale (IO), one will need to switch to an *atomic* tritium source.

Bodine, Parno and Robertson, *Phys. Rev. C* **91** (2015).

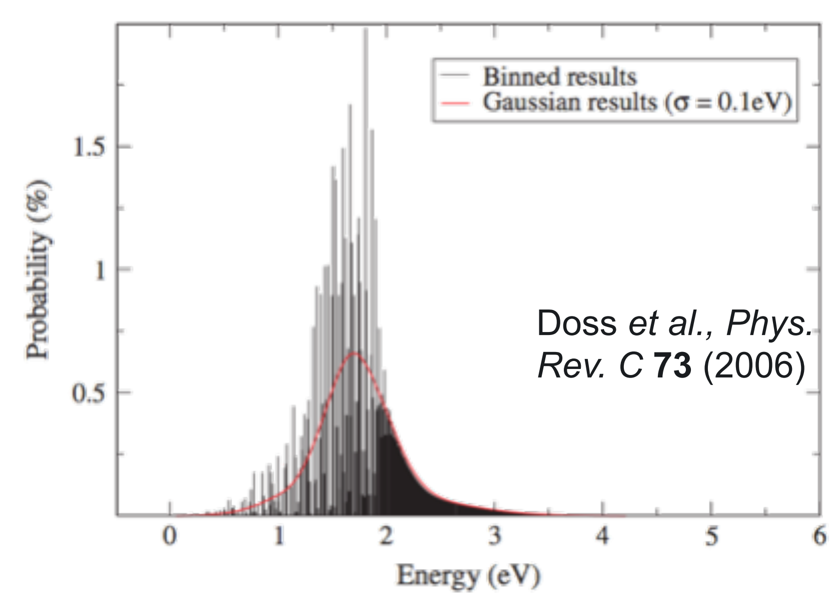


Comparison of T_2 and T decay schemes

Comparison of T_2 and T ground states



rotation and vibration of *molecular* $^3HeT^+$ daughter



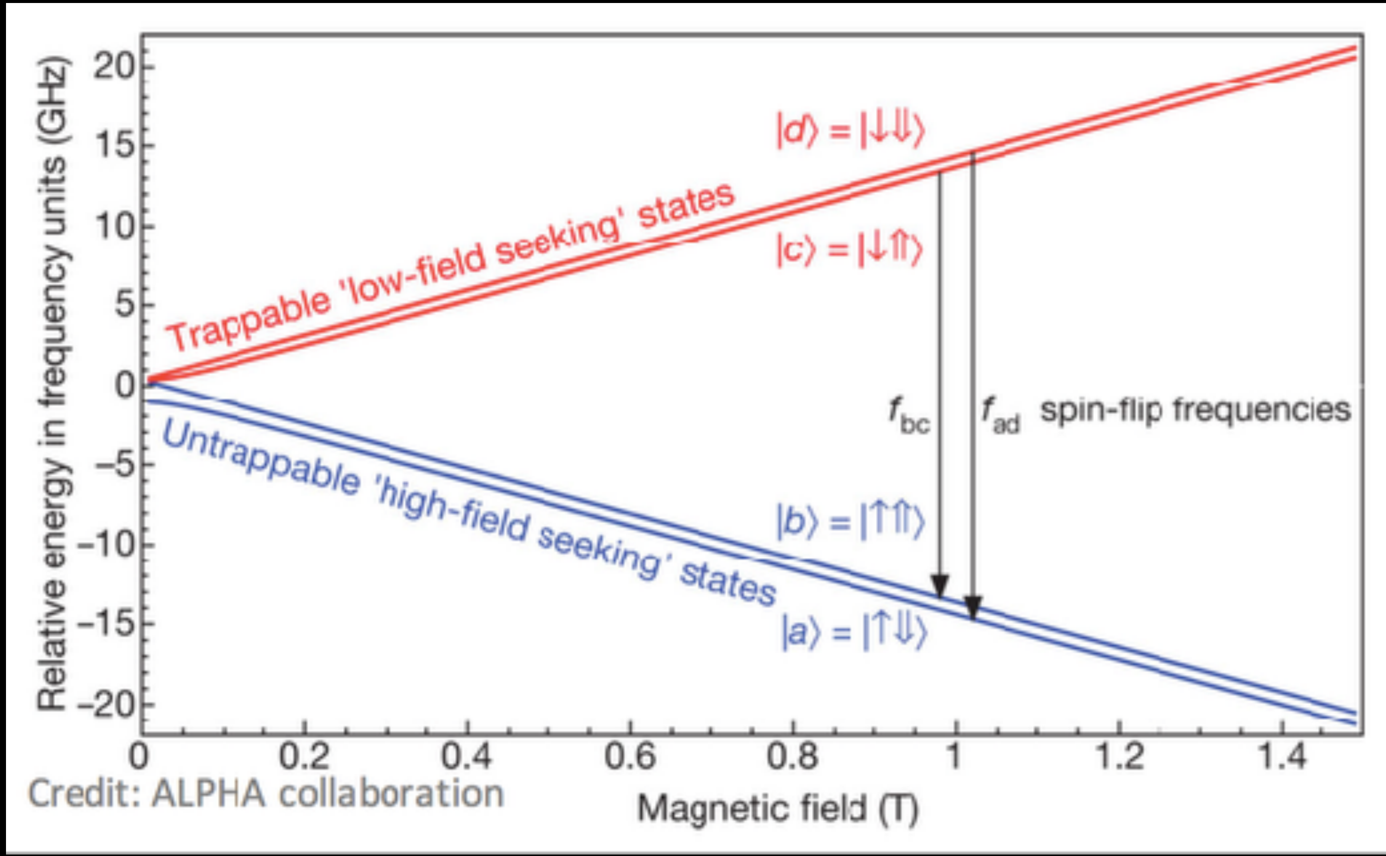
Transition to an Atomic Source (Phase III)

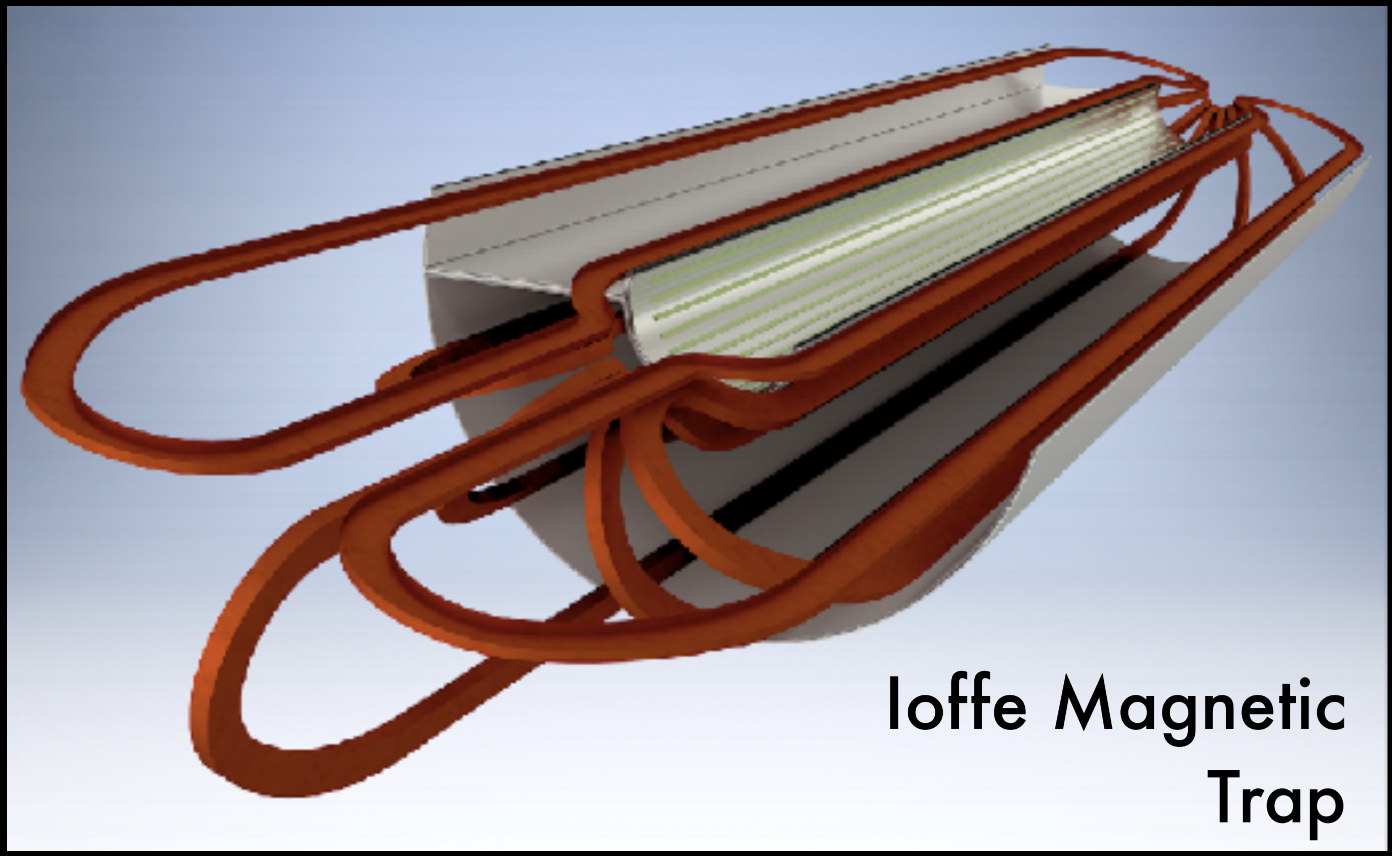
The endpoint for T_2 is higher than for atomic tritium. Thus, any atomic tritium experiment must be extremely pure (T_2 / T< 10^{-5}).

At low densities, recombination occurs mainly on surfaces. Thus a magnetic trap is necessary to prevent recombination. Can utilize magnetic moment of atomic tritium.

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

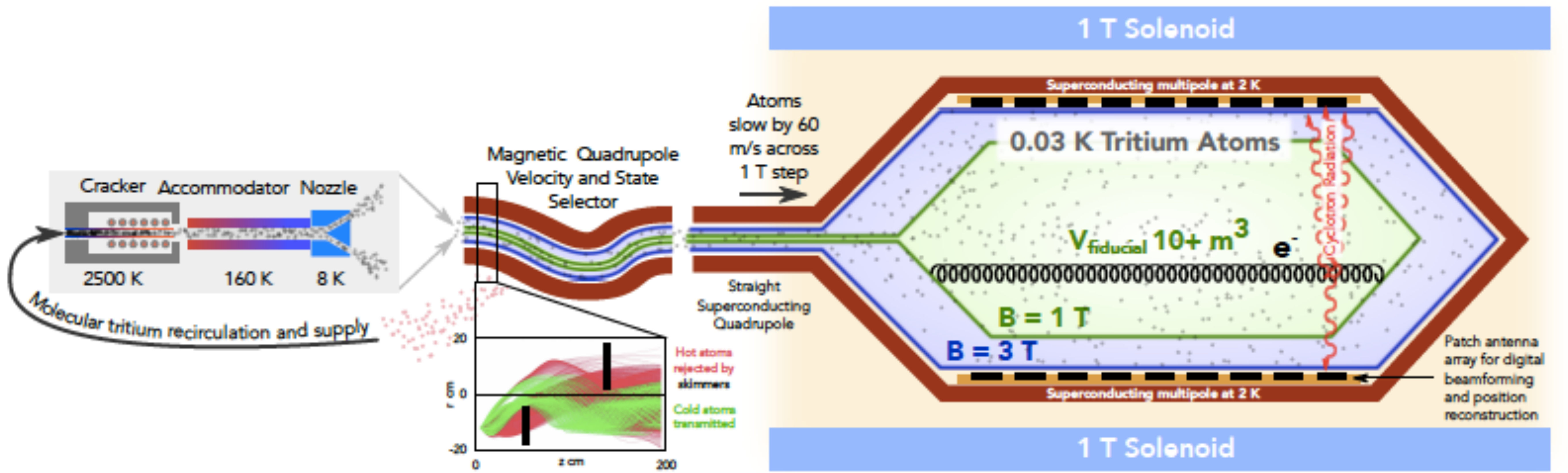
Ioffe traps and Halbach arrays can have large fields near surfaces, with a large uniform region in the center suitable for CRES.





Solution: A large volume magnetic trap for T atoms

Toward an Inverted Ordering Experiment



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

- Conversion from molecular to atomic.
- Demonstrate transport, cooling and trapping of tritium.
- Detection via CRES antenna array

Current Project 8 R&D effort (Phase III) focused on developing these technologies.

Target Mass Sensitivity

$m_\beta < 40$ meV