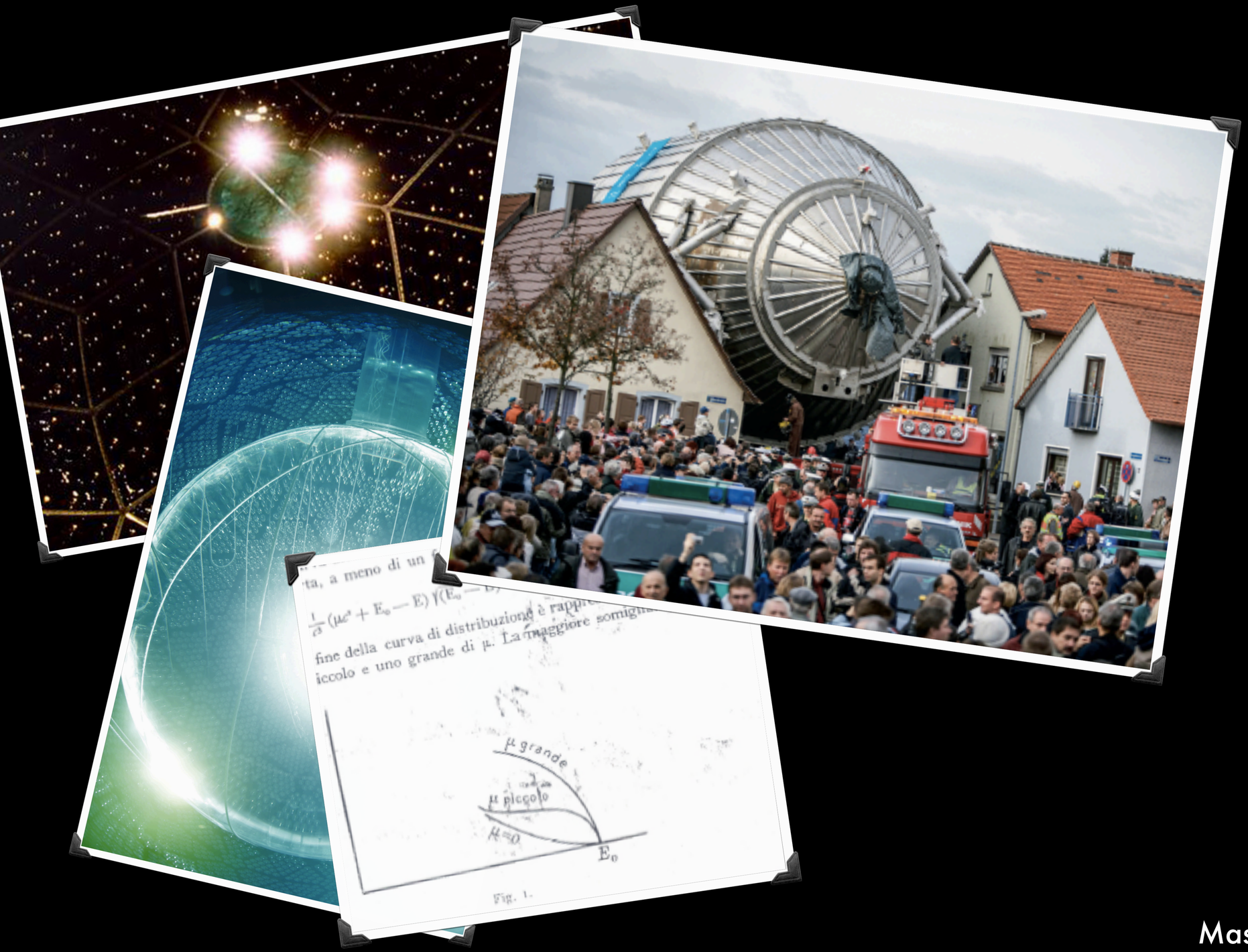
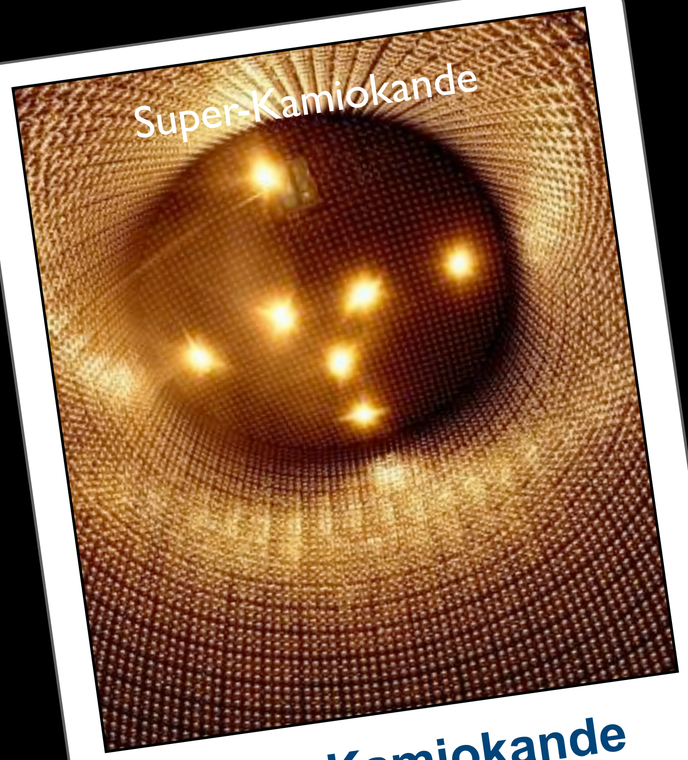


The Scale and Nature of Neutrino Mass

Snowmass
Seattle, WA July 2022

Joseph A. Formaggio
Massachusetts Institute of Technology

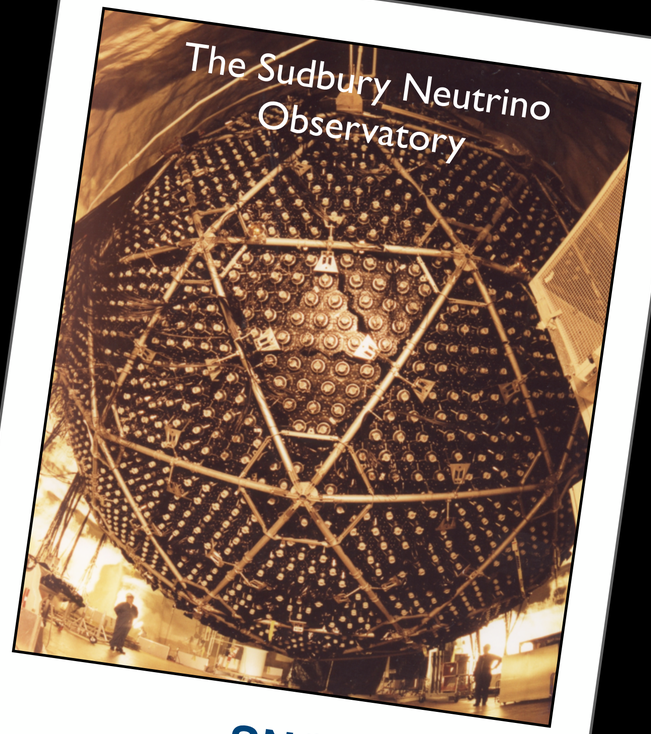


Super-Kamiokande

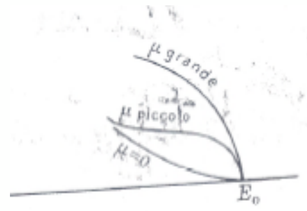
A myriad of experiments helped demonstrate that neutrinos transmute flavor (oscillations).

With oscillations established, there are *predictions* that stem from alteration of the Standard Model.

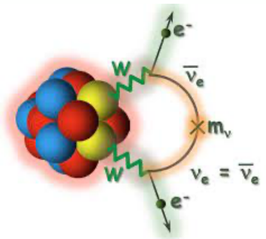
Today, I will focus on two of those predictions.



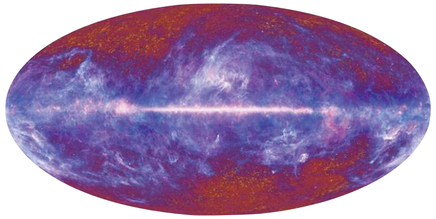
SNO



Beta Decay Decay



$0\nu\beta\beta$

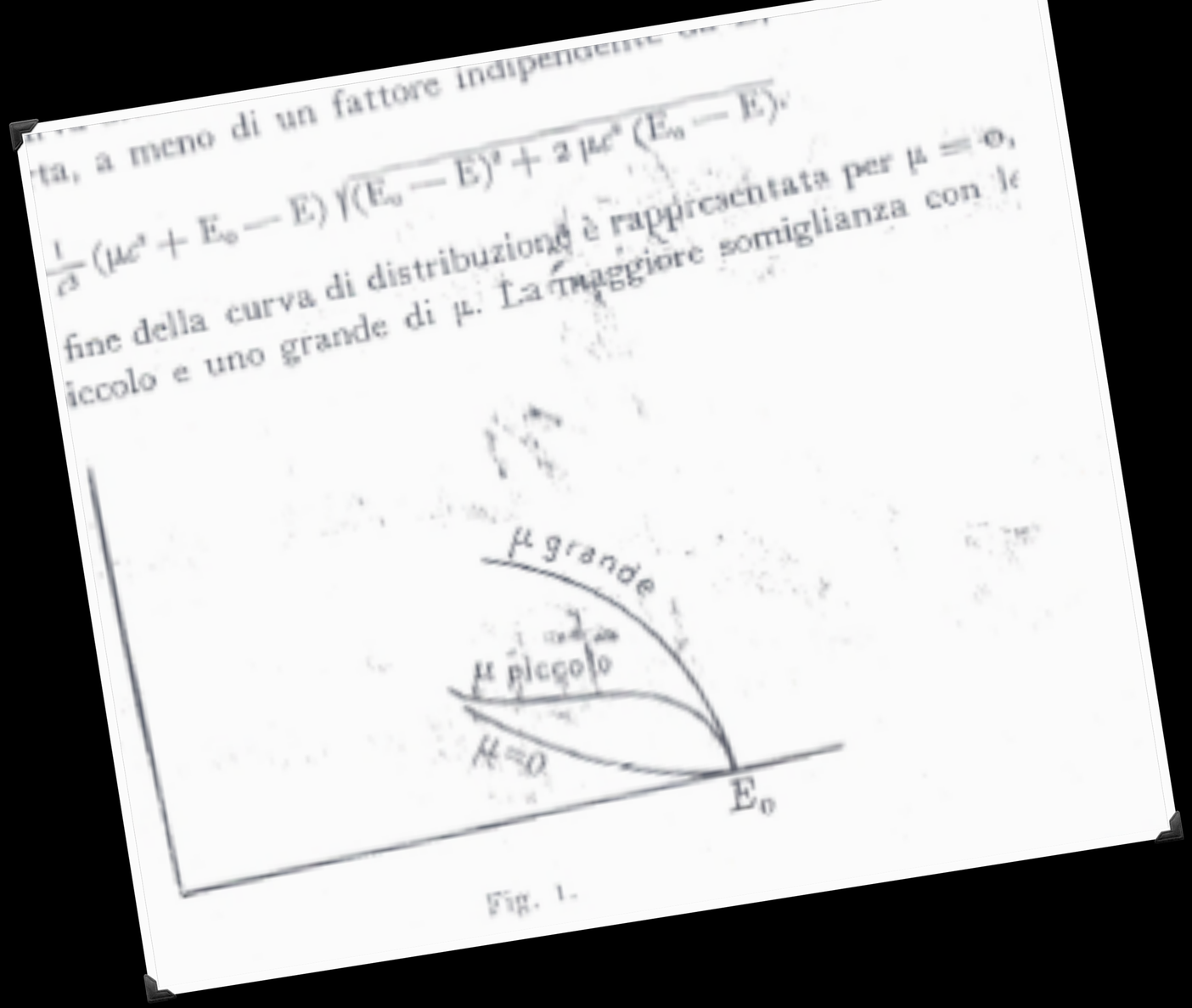


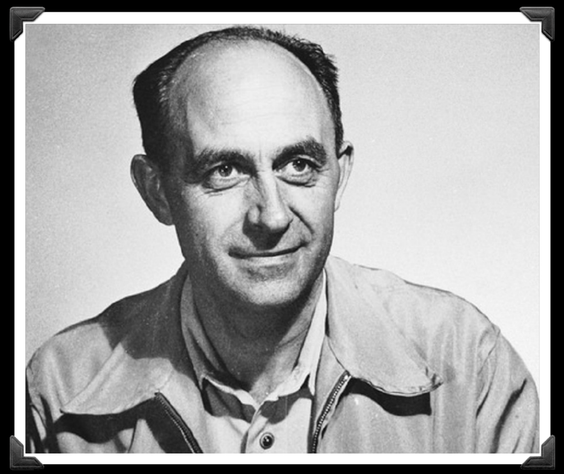
Cosmological Constraints

First Unknown: The Mass Scale

$$E \stackrel{?}{=} p\,c$$

Any direct method must rely on kinematics to determine the neutrino mass.

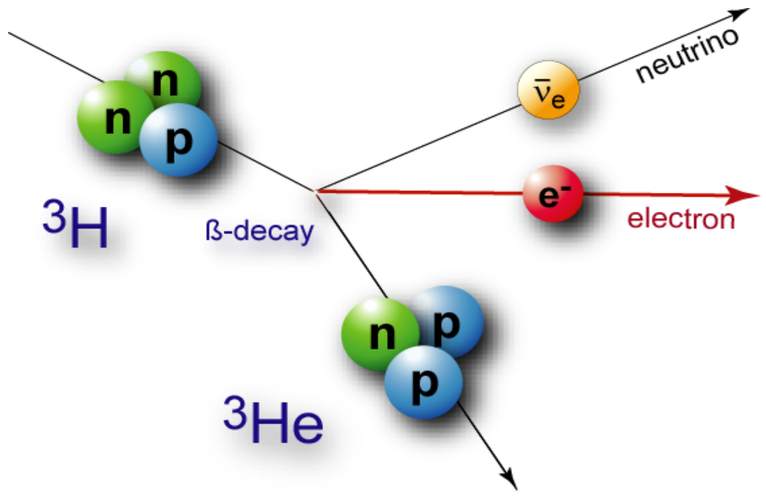




"Arriviamo cosi a concludere che l a massa del neutrino e uguale a zero o, in ogni caso, piccola in confronto della massa dell'elettrone (~) ..."

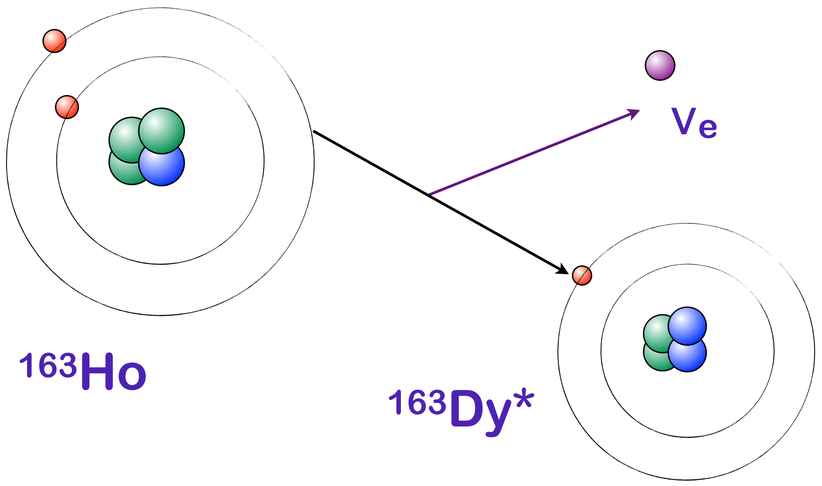
In his seminal 1934 paper, Fermi already sketches out how one can do this.

Tritium beta decay



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

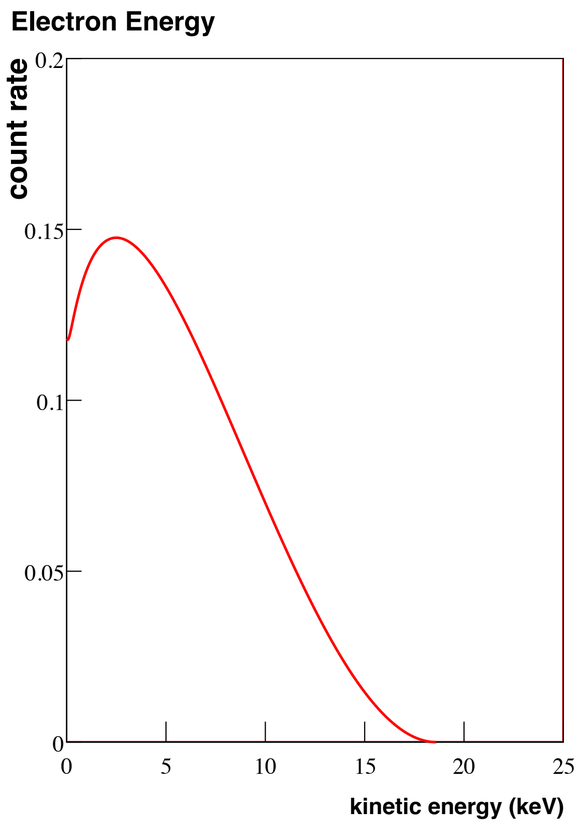
Holmium electron capture



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

For both beta decay and electron capture, the information about the neutrino mass comes from the phase space dependence on the neutrino momentum.

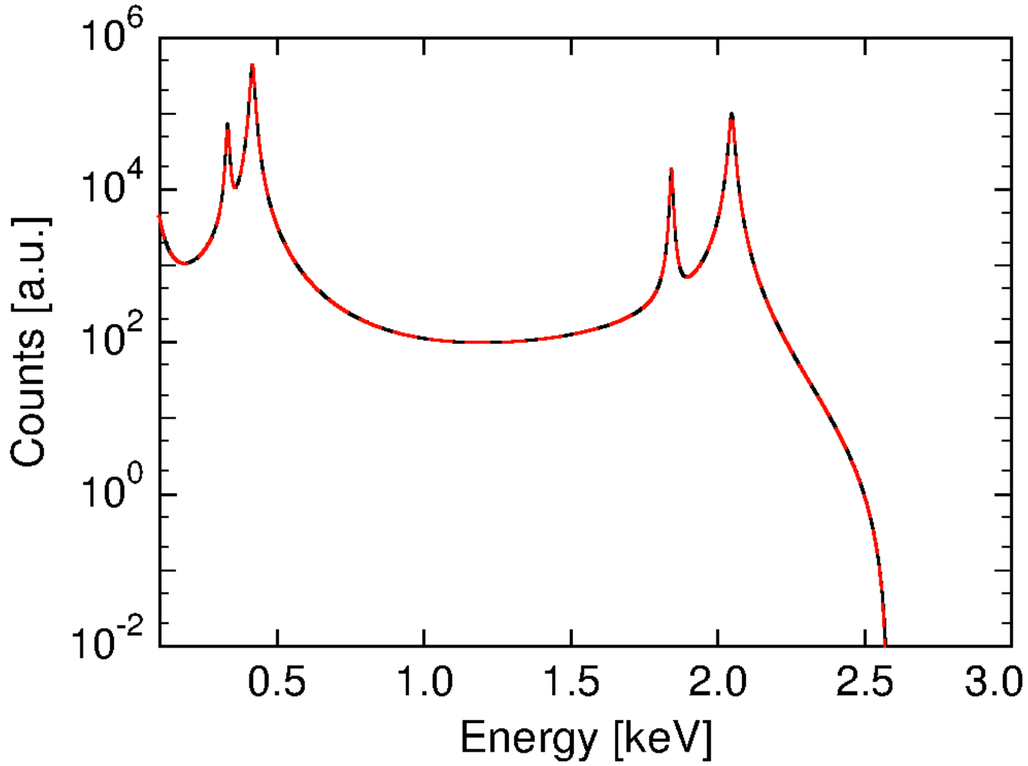
Tritium beta decay



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

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

Holmium electron capture



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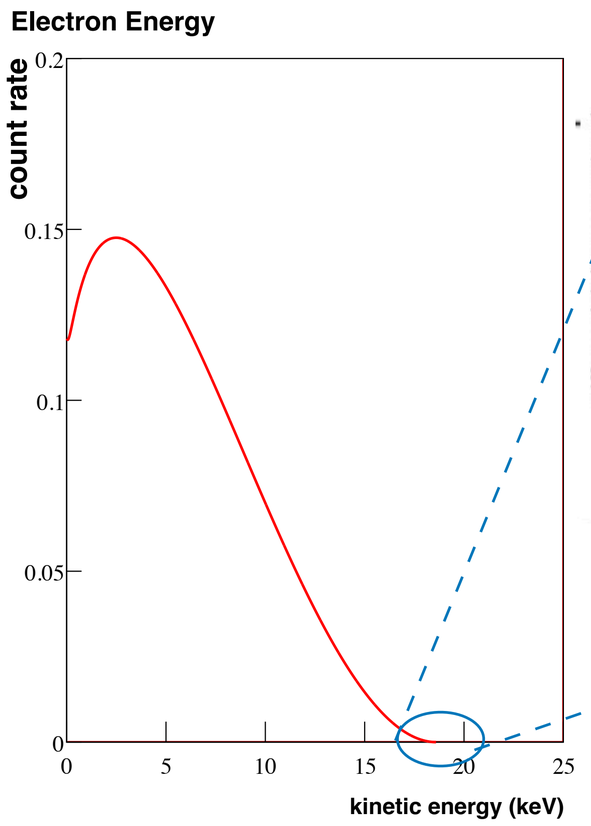
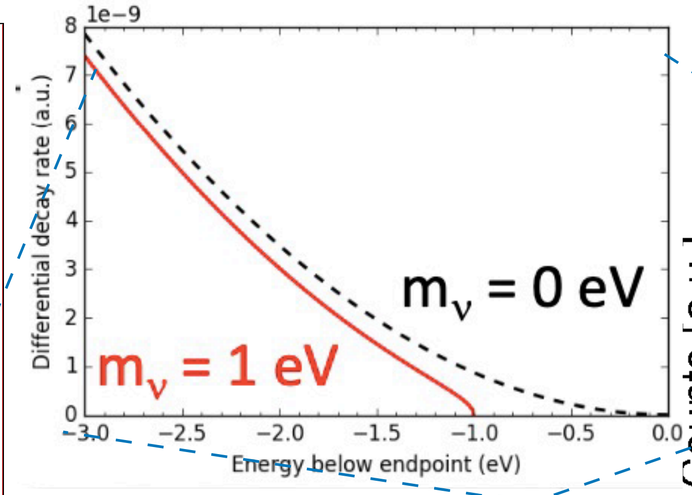
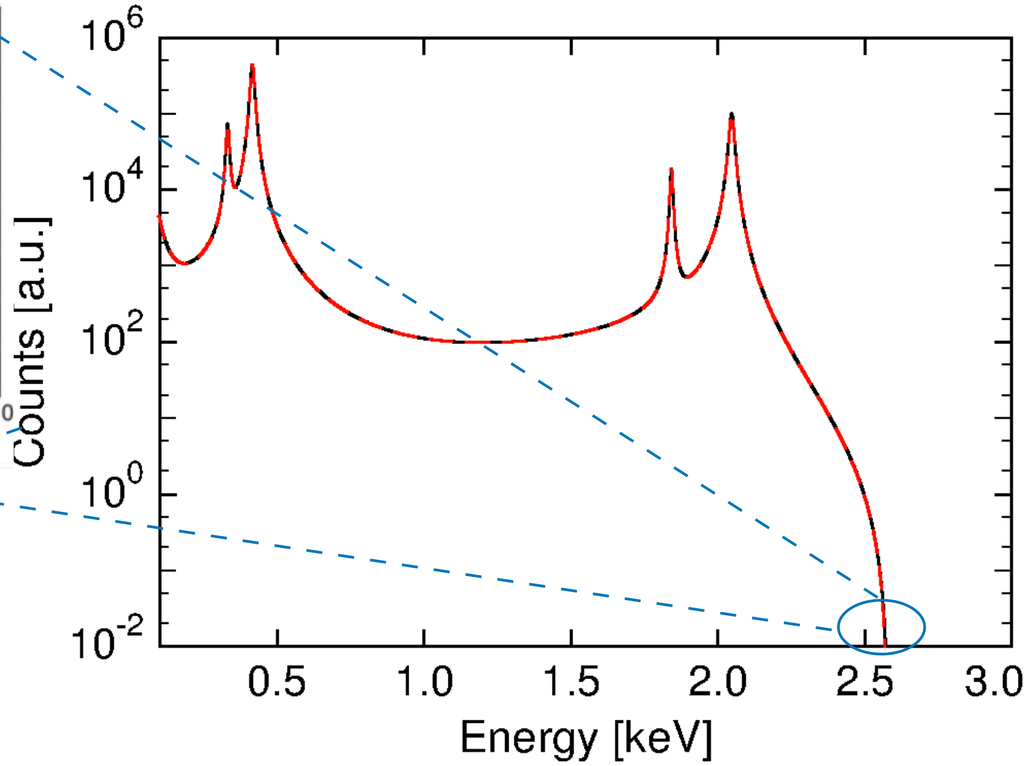
Tritium beta decay





$$m_\beta = \sqrt{\sum_i |U_{ei}|^2 m_i^2}$$

Holmium electron capture



<u>Challenges for this measurement:</u>

Low backgrounds

High source activity

Exquisite energy resolution and linearity

Electromagnetic filtering of electrons of selected energy.

Electromagnetic Collimation
(MAC-E Filter)

Electron transfers all of its energy to the absorbing medium.

Calorimetric
(Cryogenic Bolometers)

Use photon spontaneous emission from electron in magnetic field.

Frequency-Based
(Cyclotron Radiation Emission Spectroscopy)

Electromagnetic Collimation w/ Electrostatic Filtering

(MAC-E Filter)

Main Experiment:

KATRIN

Strengths:

magnetic collimation

intense molecular tritium source

precision electrostatic potential

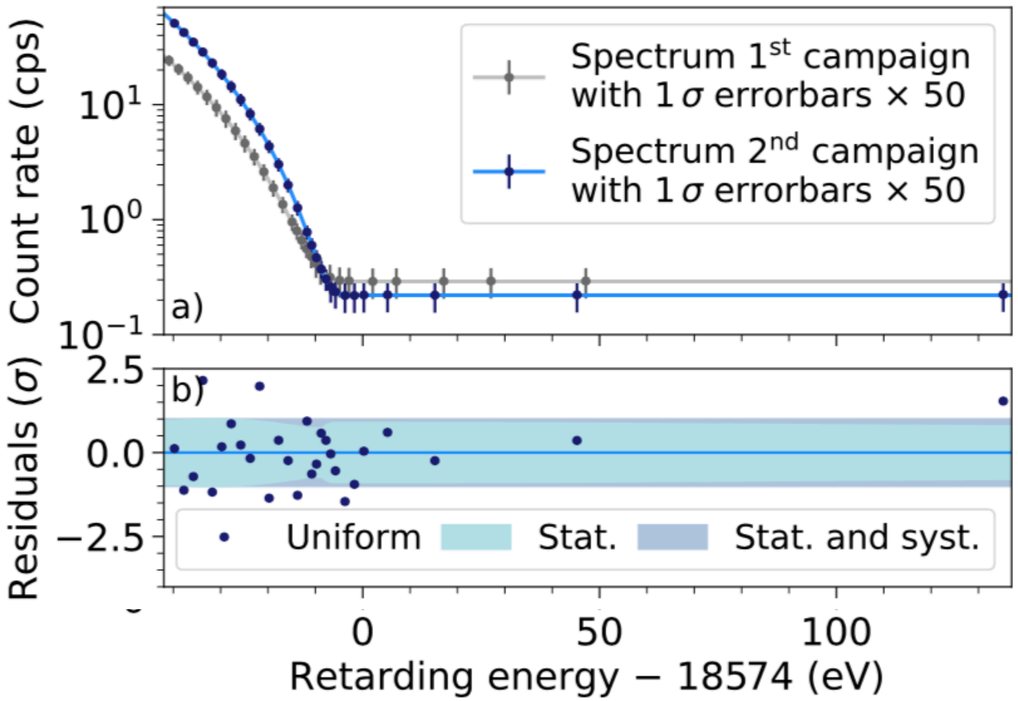
Status & Future:

Running since 2019

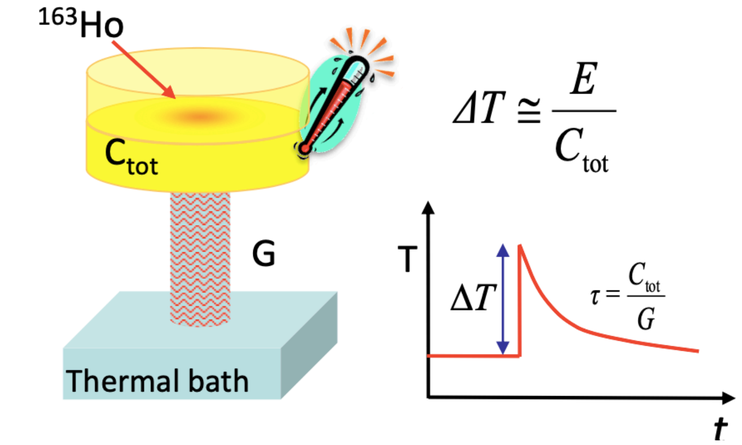
First sub-eV mass limit

Will run until 2024*,

Sensitivity of 0.2 eV/c^2 (90% C.L.)

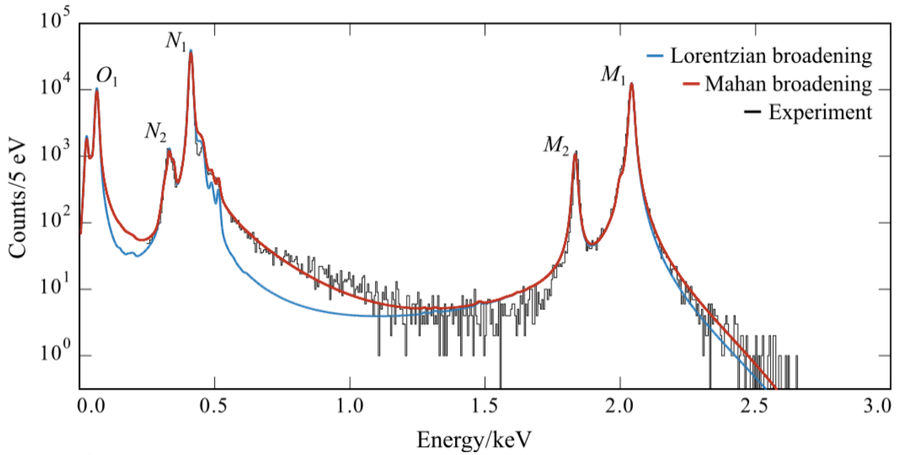


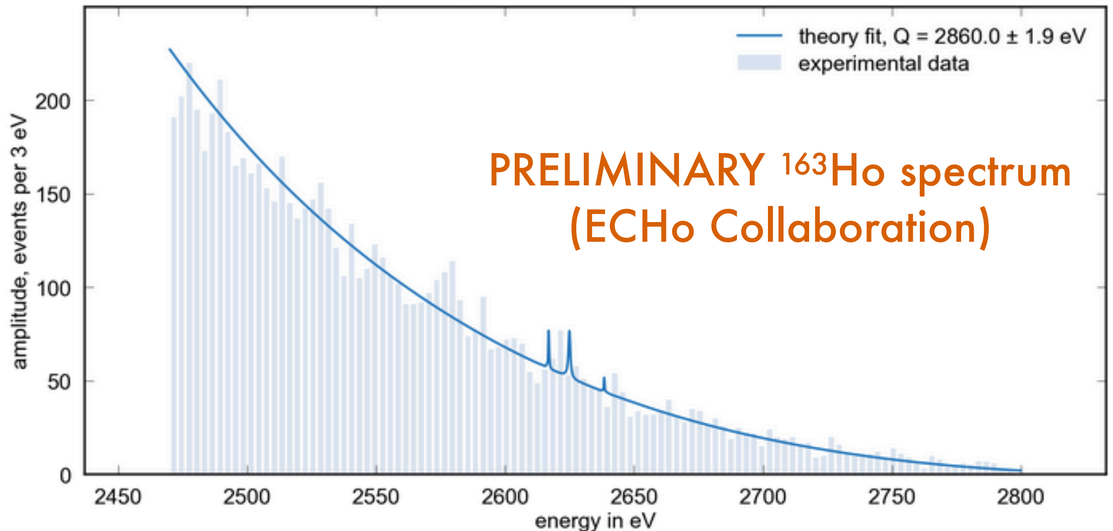
Limits (LT & FC)	$m_\beta < 0.8$ eV
Limits (Bayesian)	$m_\beta < 0.73$ eV



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

$$\tau = \frac{C_{tot}}{G}$$





Calorimetric
(Cryogenic Bolometers)

Main Experiment(s):
ECHo & HOLMES

Strengths:
All energy from (electron capture) decay collected through phonons.
High resolution micro calorimeters.
High channel multiplexing.

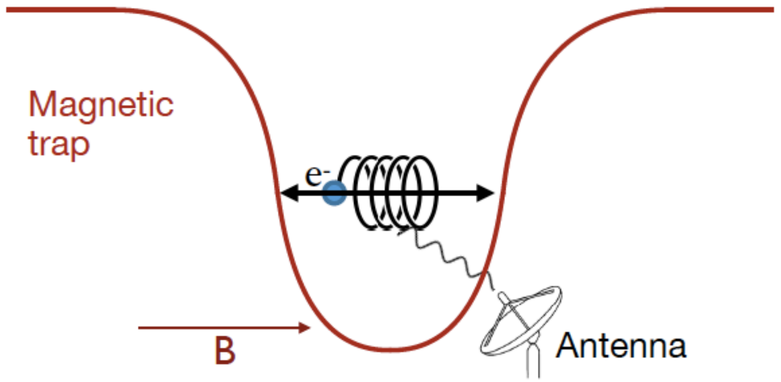
Status & Future:
Current limits at < 150 eV/c^2
Expected to release < 20 eV/c^2 scale soon.
Pushing for 100k+ channels to reach sub-eV scale.

Frequency-Based
(Cyclotron Radiation Emission Spectroscopy)

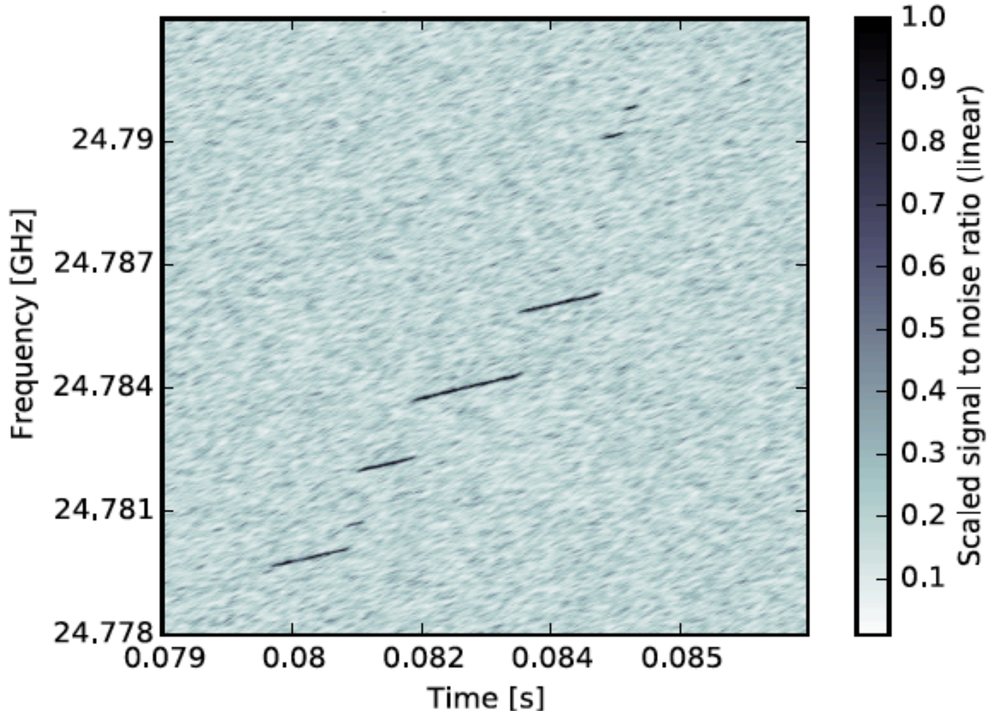
Main Experiment:
Project 8

Strengths:
Energy measured from (cyclotron) frequency.
High resolution, low backgrounds.
Non-destructive electron measurement.

Status & Future:
Current limit at < 169 eV/c^2
Scaling to sub-eV cavity experiment.
Pushing for a 40 meV/c^2 atomic tritium measurement



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

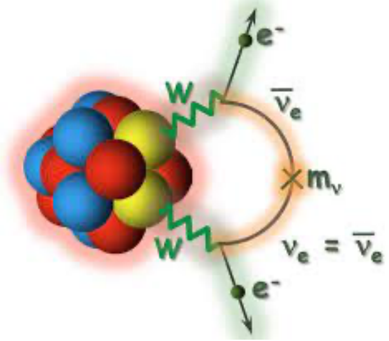


Second Unknown:
The Nature of Mass

$$\nu \stackrel{?}{=} \bar{\nu}$$

To answer the question of whether neutrinos are Majorana particles (are neutrinos and anti-neutrinos the same)?

In principle, this should be an "easy" measurement



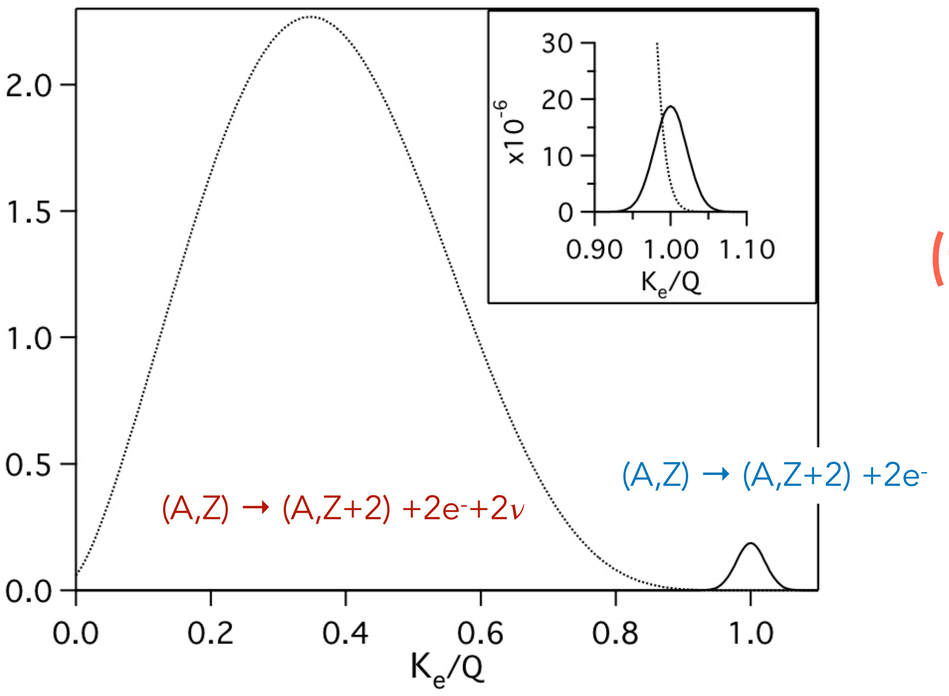
In practice, it's really hard.

$$\langle m_{\beta\beta} \rangle = \left| \sum_i U_{ei}^2 m_i \right|$$

The signature is known (two electrons).

It's a mono-energetic peak.

The energy of the peak is known (at the endpoint).



Backgrounds controlled at the event/ton/year/eV level.

High energy resolution (to reduce $2\nu\beta\beta$ contribution).

Sufficient isotope needed (now at the ton-scale)

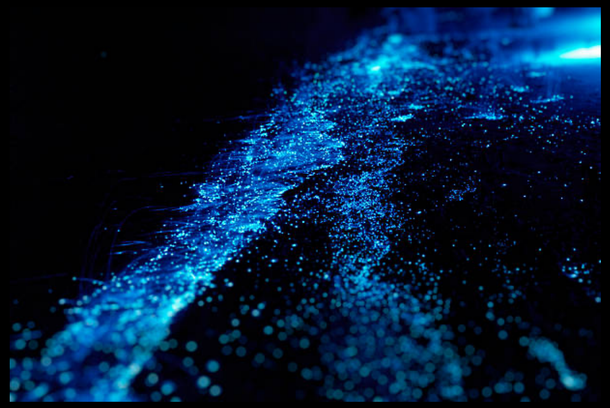
However, a positive measurement would reveal lepton number violation and the Majorana nature of the neutrino.

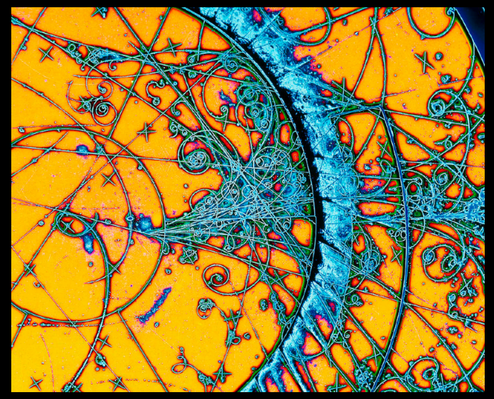
Electron transfers all of its energy to the absorbing medium.

Calorimetric
(Charge ∨ Phonon)

Using light to measure energy

Scintillation
(Loaded scintillators)





Event reconstruction of two electron signature

Topological Reconstruction
(Time Projection Chambers)

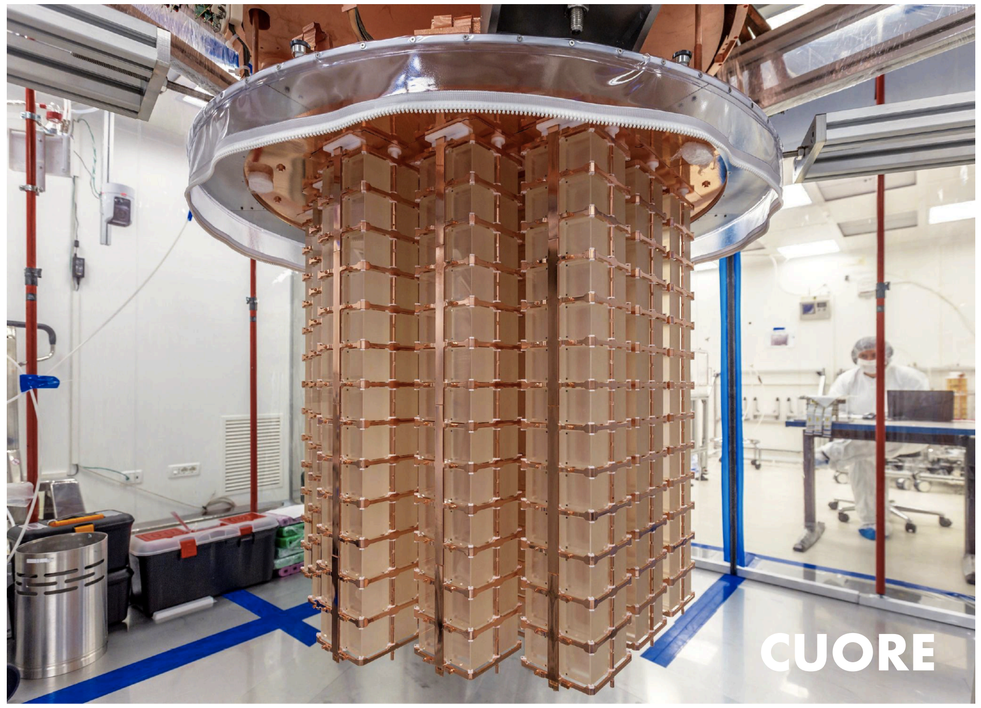
Calorimetric
(Charge ∨ Phonon)

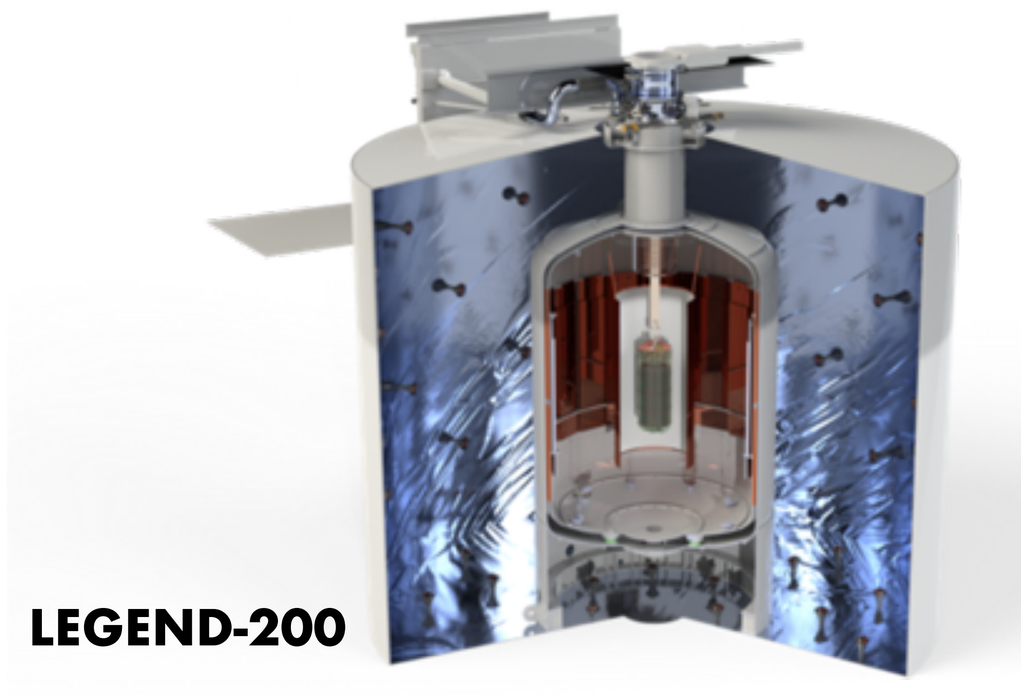
Current Incarnations: CUORE, MAJORANA, GERDA
Future Experiments: LEGEND-200/1000, CUPID

Strengths:
All these cryogenic calorimenters have exhibited exquisite energy resolution.

CUPID aims to reduce background through alpha rejection, LEGEND through pulse shape and vetoing.

Future:
LEGEND-200 is already commissioning, while CUPID will reuse much of CUORE's infrastructure.
Both aim at normal ordering scale.





Scintillation
(Loaded scintillators)

Planned Experiments: SNO+, KamLAND-Zen

Strengths:

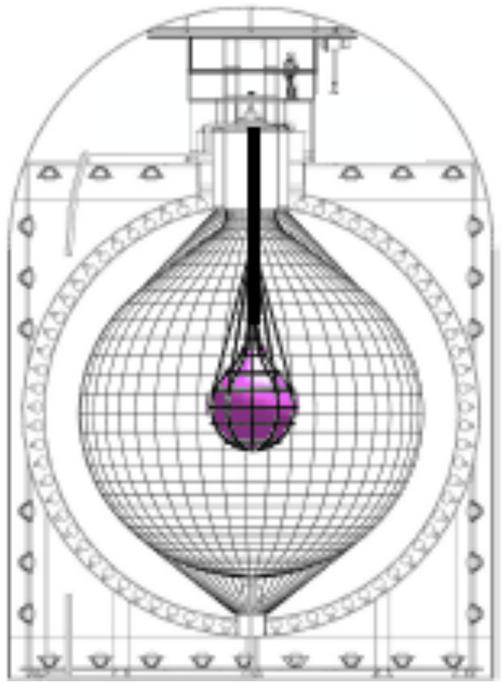
Scalability, possible to pack large quantities of relevant isotope to reach the ton-scale.

Excellent background vetoing/rejection.

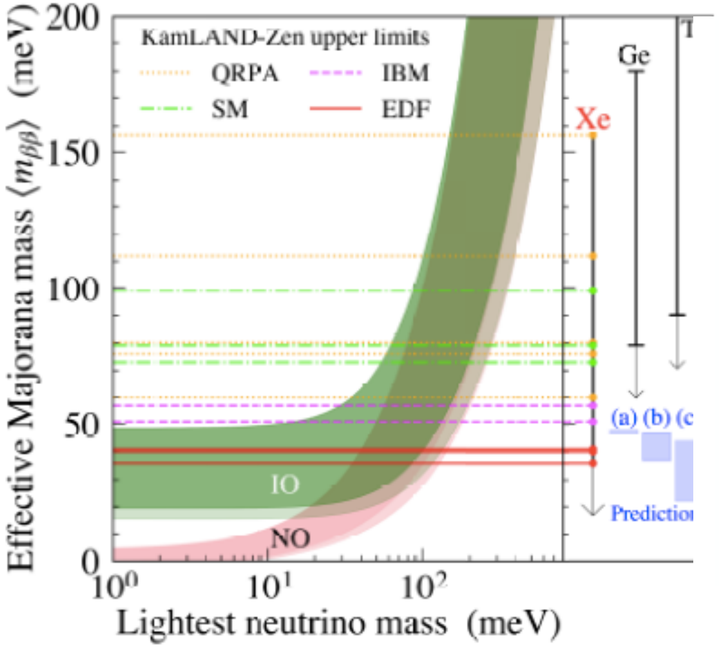
Future:

KamLAND-Zen 800 (800 kg) already sets most stringent limits using ^{136}Xe, and SNO+ will soon run with ^{nat}Te.

R&D for future large loaded scintillator detectors include novel photon sensors and photon collection techniques, new cocktails, and adapting other neutrino detectors for $0\nu\beta\beta$.



KAMLAND-ZEN



$T^{1/2} > 2.3\times10^{26}$ yr

$$\left(T^{0\nu}_{1/2}\right)^{-1} = G^{0\nu}|M^{0\nu}|^2\langle m_\nu\rangle^2$$

NME ($M^{0\nu}$) : 1.11–4.77
($g_A \sim 1.27$)

$\langle m_{\beta\beta}\rangle$ < 36-156 meV

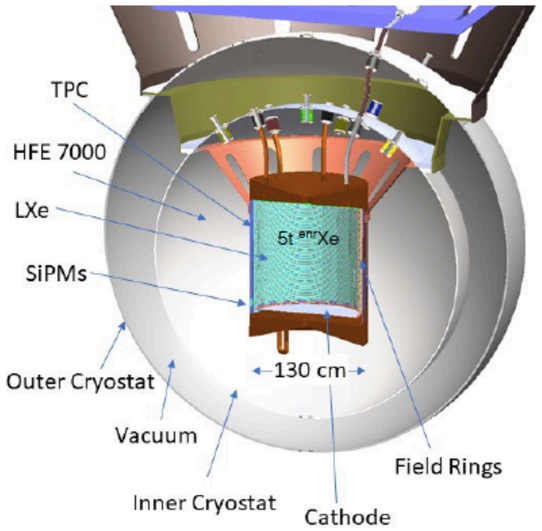
First search for inverted mass ordering

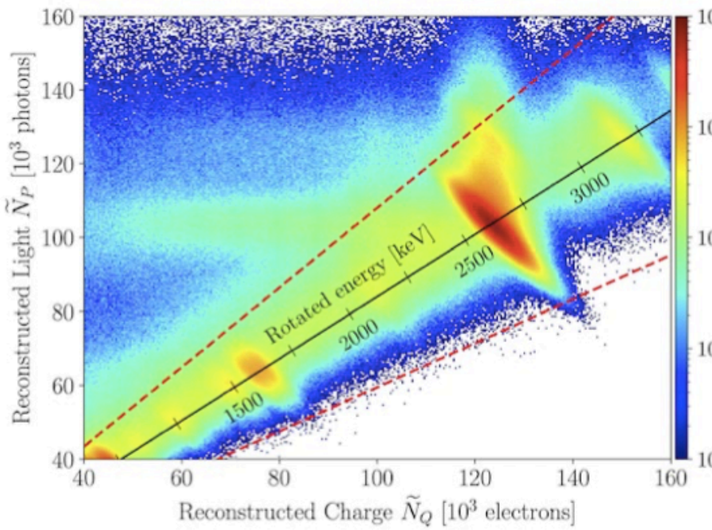
Topological Reconstruction
(Time Projection Chambers)

Current Experiments: EXO, NEXT-White
Planned Experiments: nEXO, Darwin, NEXT-BOLD

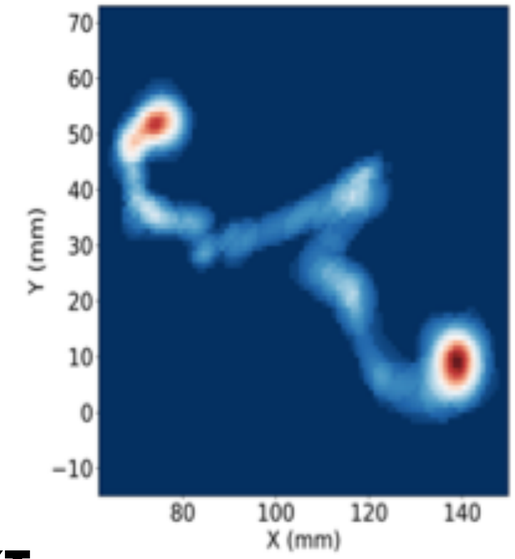
Strengths:
nEXO: Use of light and charge to reconstruct events
NEXT: Use of event topology (two electrons) for background rejection.

Future:
Both experiments seek larger TPCs to increase mass sensitivity in next generation experiments. R&D for barium tagging continues, for ultimate background rejection.





nEXO

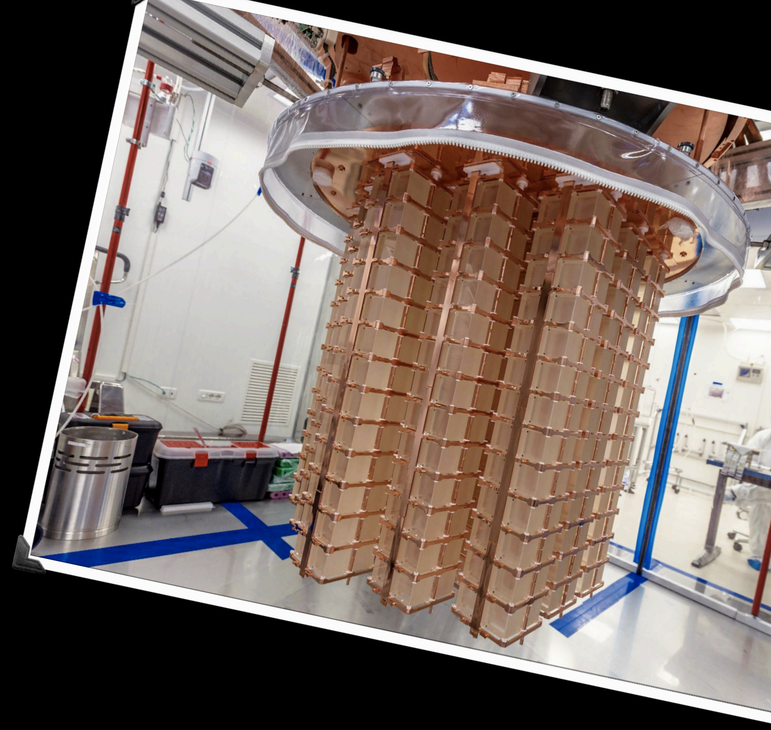


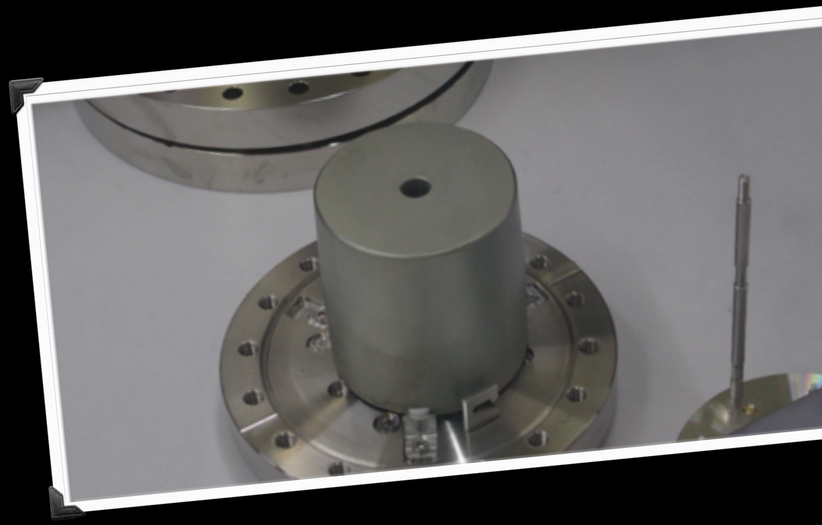
NEXT

There is a huge array of different technologies that span the gambit of particle physics detectors...

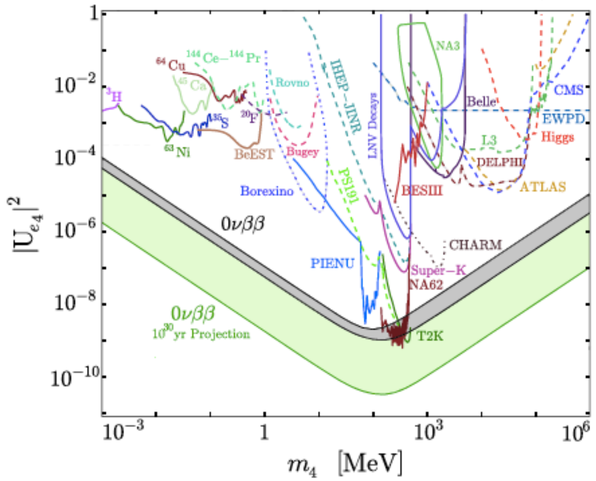
Liquid scintillators, calorimeters, bolometers, liquid/gas TPCs, radio-frequency antennas, etc.

This overlap also applies to physics reach as well.



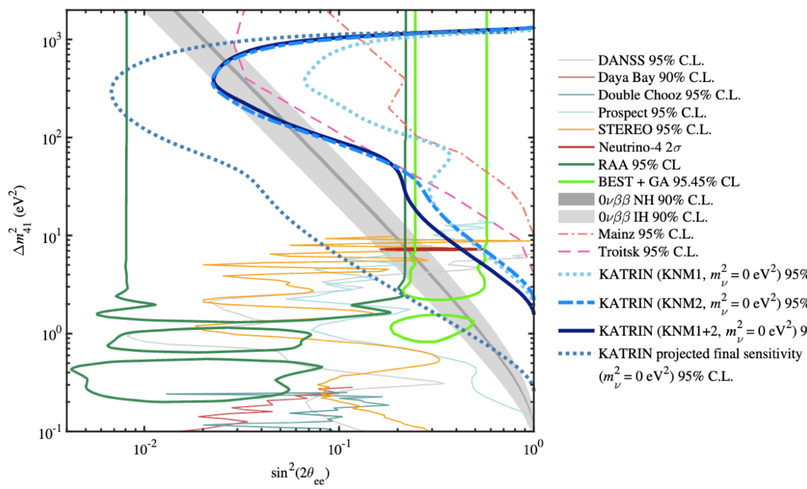


PHYSICAL REVIEW D 104, 112007 (2021)



Overlap with 0νββ
&
DM/light steriles

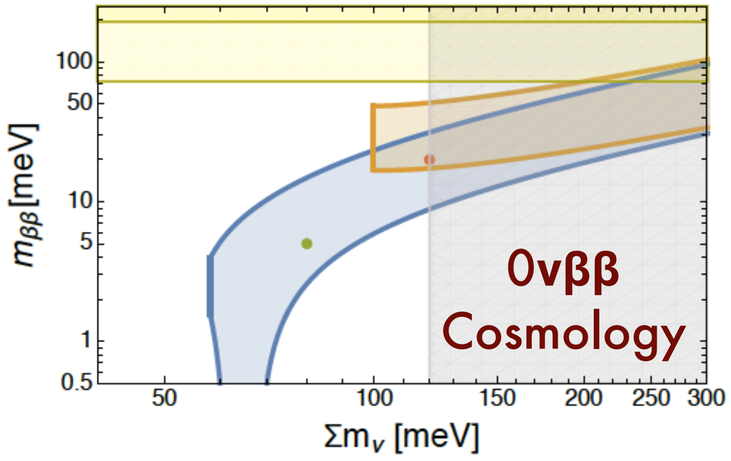
KATRIN Collab, PRD 105, 072004 (2022)

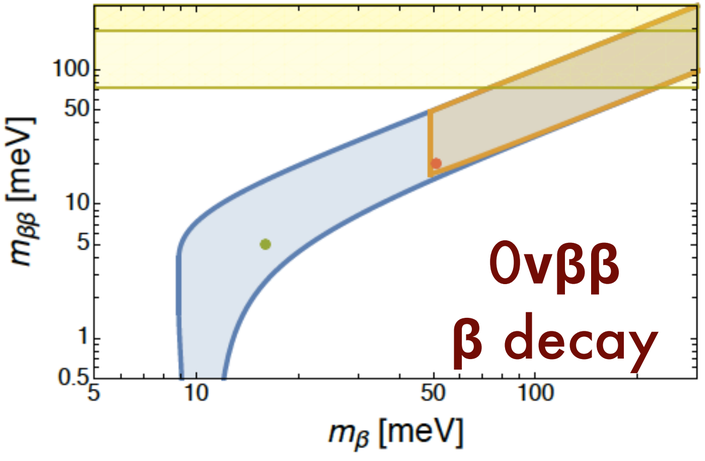


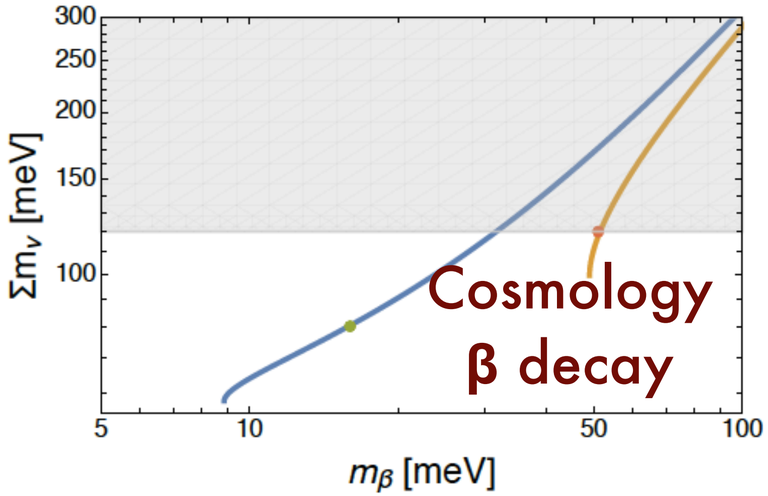
β-decay
&
sterile neutrinos

Synergies

- *Excellent synergies with other initiatives.*
- *In 0νββ, with large scale detectors for neutrinos and dark matter (e.g. THEIA, Darwin)*
- *In direct measurements, with sensitivity to sterile neutrino states and other BSM physics.*
- *For all, direct comparisons with cosmological measurements also taking place this decade.*







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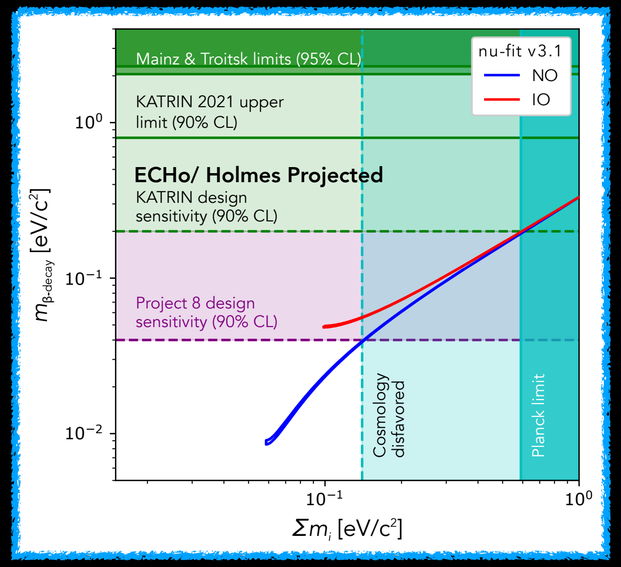
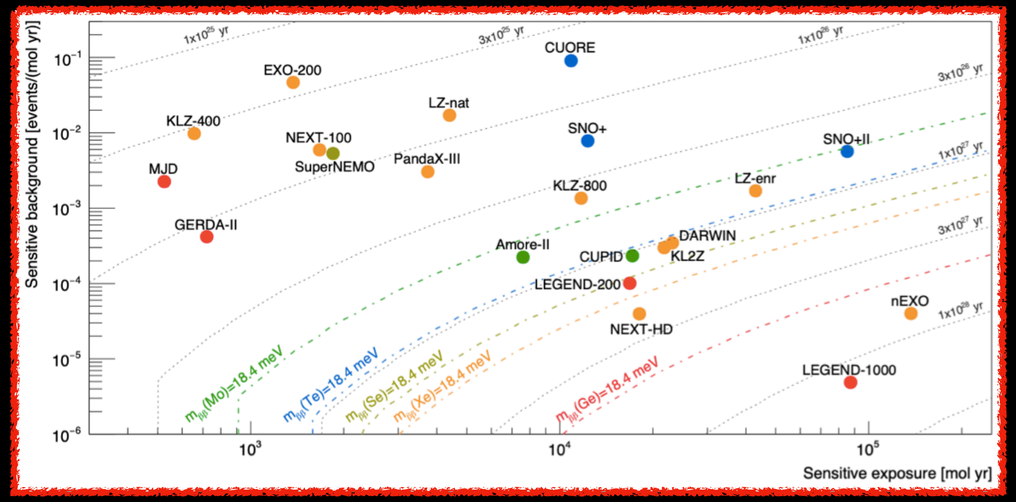
Over the Horizon...



Direct Mass Measurements

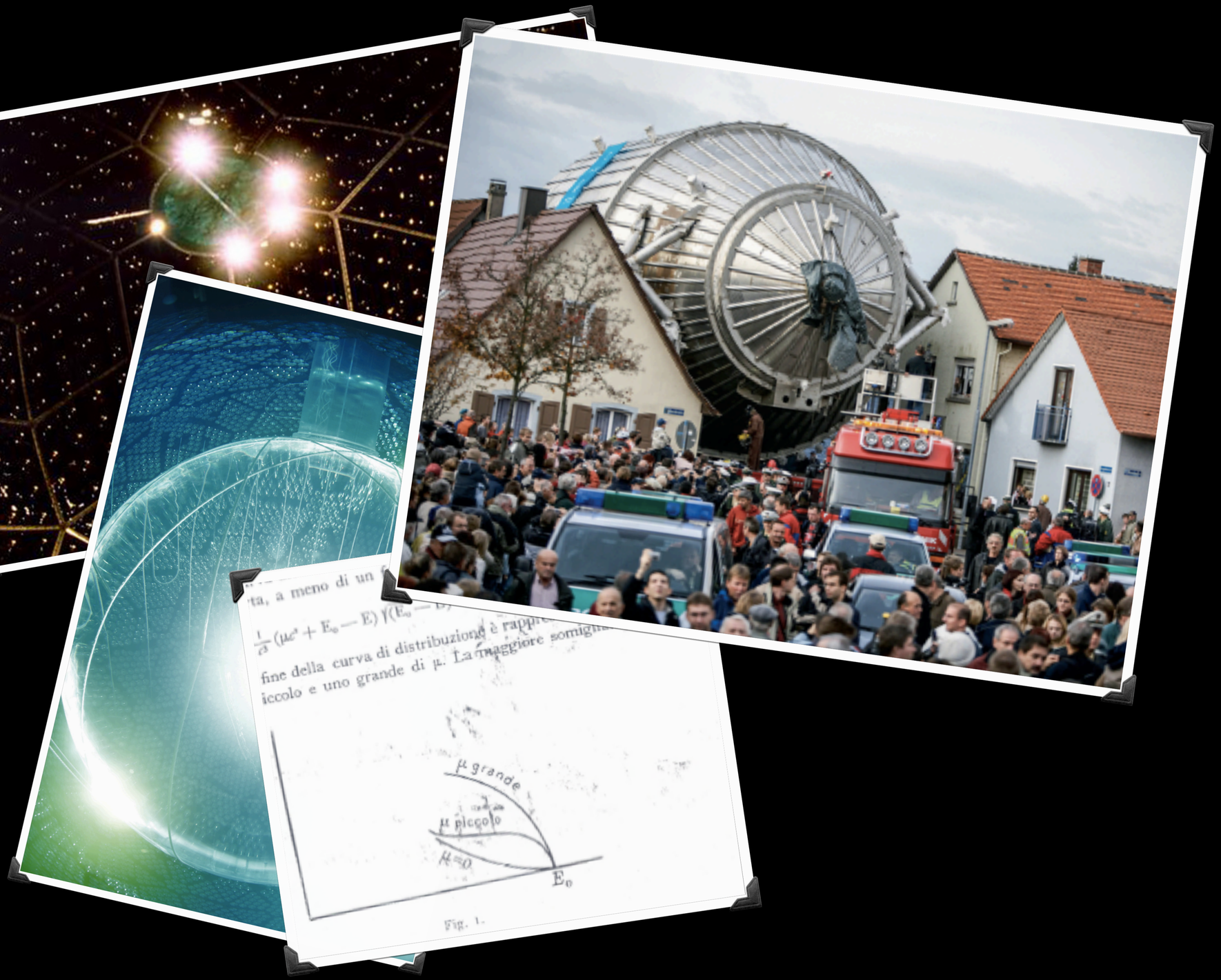
- *KATRIN is slotted to fully exploring the degeneracy mass scale.*
- *Microcalorimetry experiments (ECHo, HOLMES) will focus on multiplex scaling to 1M+ channels in order to break the sub-eV scale. US also seeking participation.*
- *CRES technology (Project 8) aims to push efficiency and size of the experiment while maintaining low backgrounds/high resolution. Future efforts also to switch to atomic tritium, to push to inverted ordering scale.*

Over the Horizon...



Neutrinoless Double Beta Decay

- *Several global large scale efforts (CUPID, LEGEND, nEXO,etc.) either underway or being built. First glimpse at the inverted scale already in reach, with more to follow.*
- *R&D in new scintillator technology, new phonon/photon readouts, and better doping cocktails also underway to provide a path to ton-scale experiments.*
- *Progeny tagging (mainly, barium) still a very active area of research from nEXO / NEXT for background elimination.*
- *Low background materials, access to isotopes with sufficient quantities for ton-scale experiments still a formidable challenge.*



This is a good decade for neutrino mass enthusiasts.

Years of technological investment is about to bear fruit!