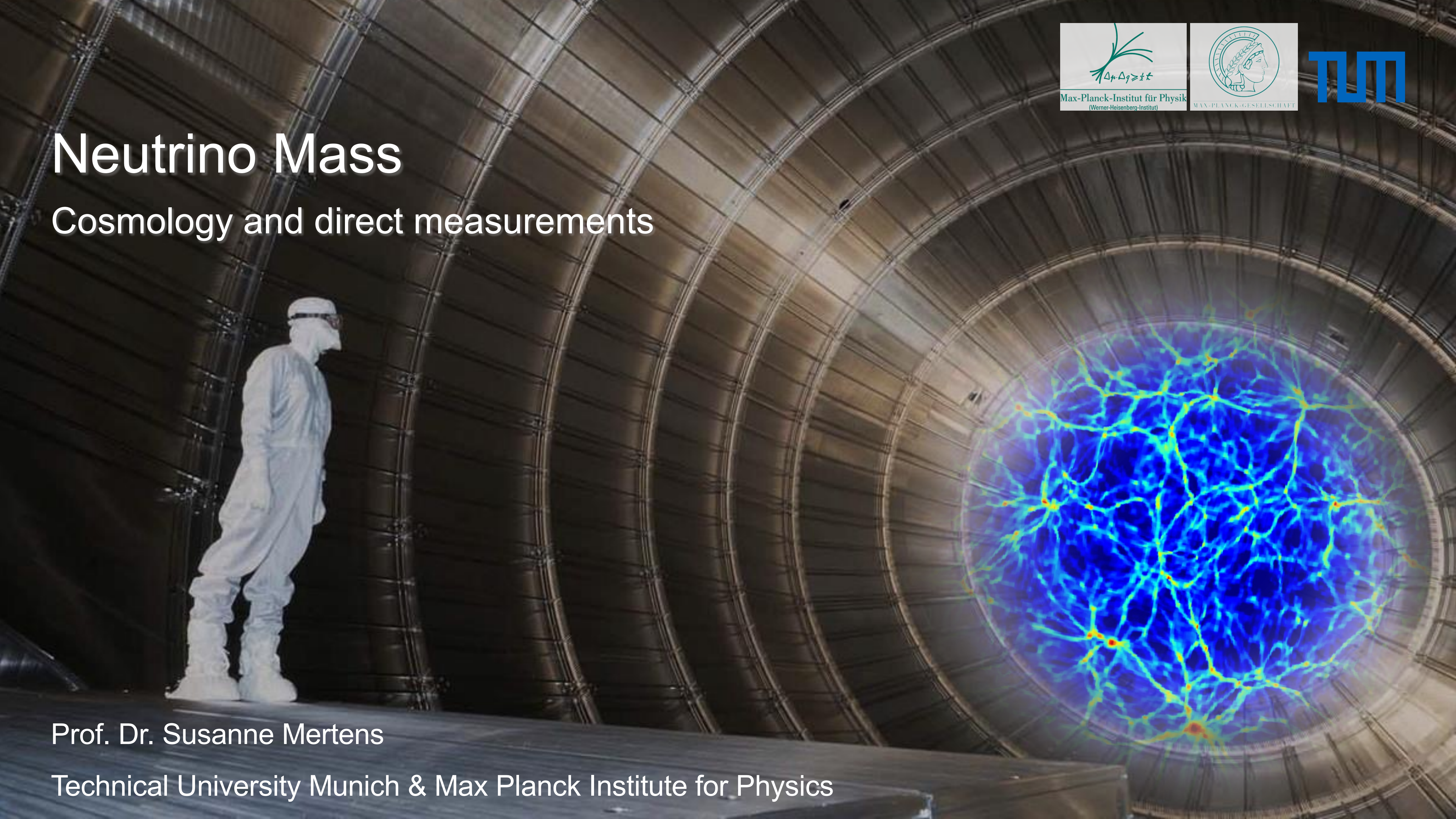


Neutrino Mass

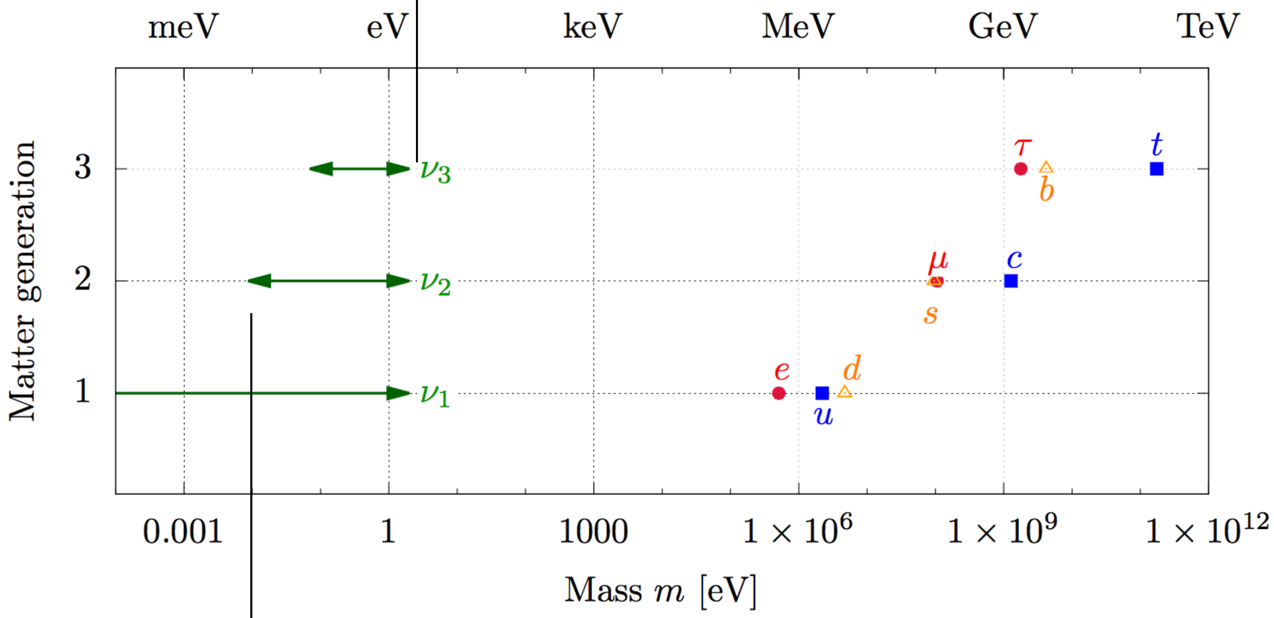
Cosmology and direct measurements

Prof. Dr. Susanne Mertens

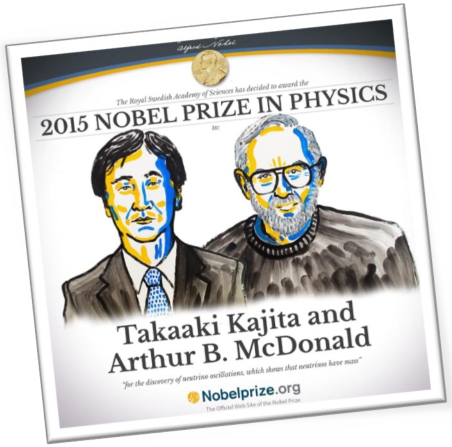
Technical University Munich & Max Planck Institute for Physics

Neutrino mass

Upper bound
from direct measurements



Lower bound
from oscillation experiments



Neutrino mass

Cosmology

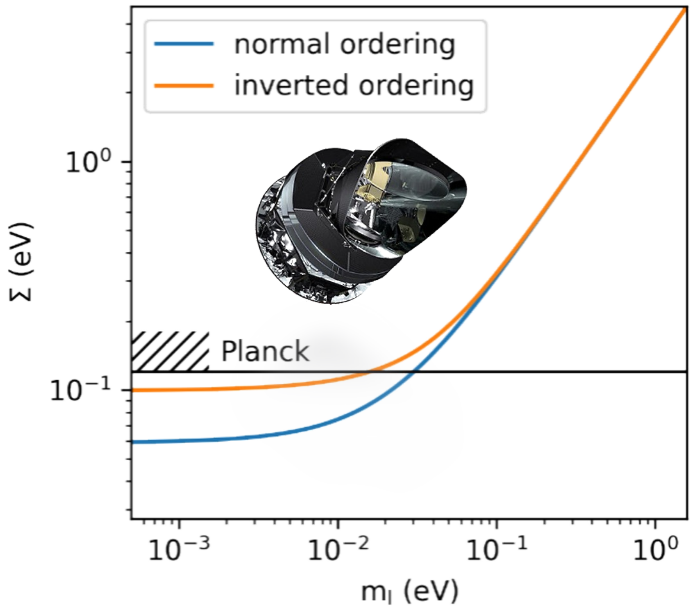
$$\Sigma = \sum_i m_i$$

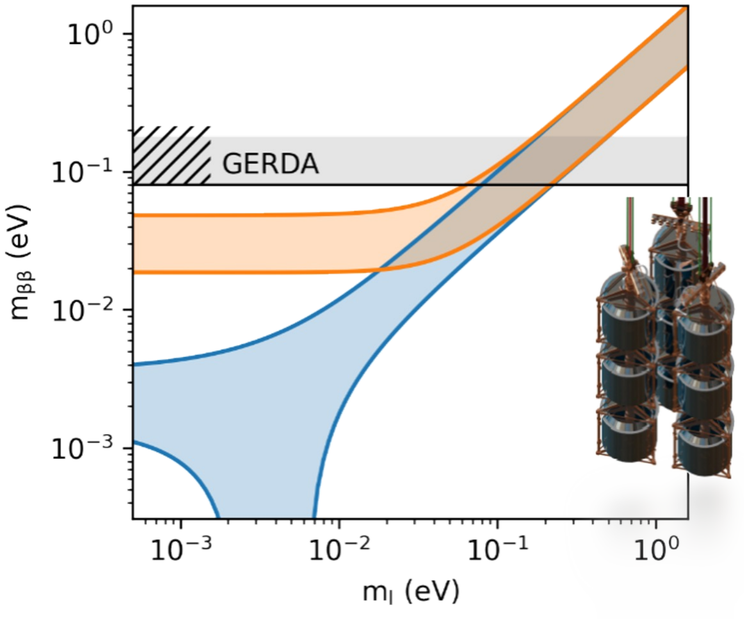
Neutrinoless ßß decay

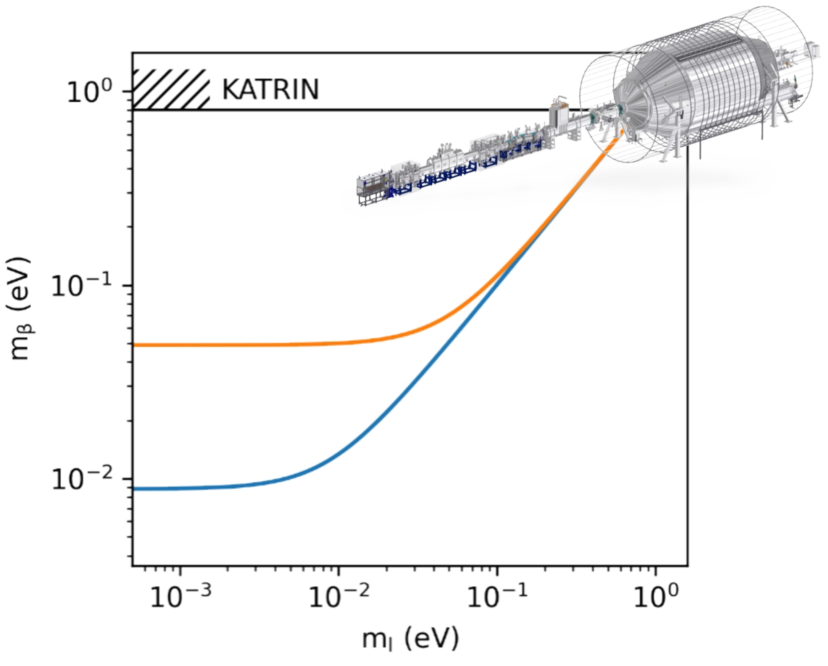
$$m_{\beta\beta} = |\sum_i U_{ei}^2 m_i|$$

ß-decay kinematics

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







Neutrino mass

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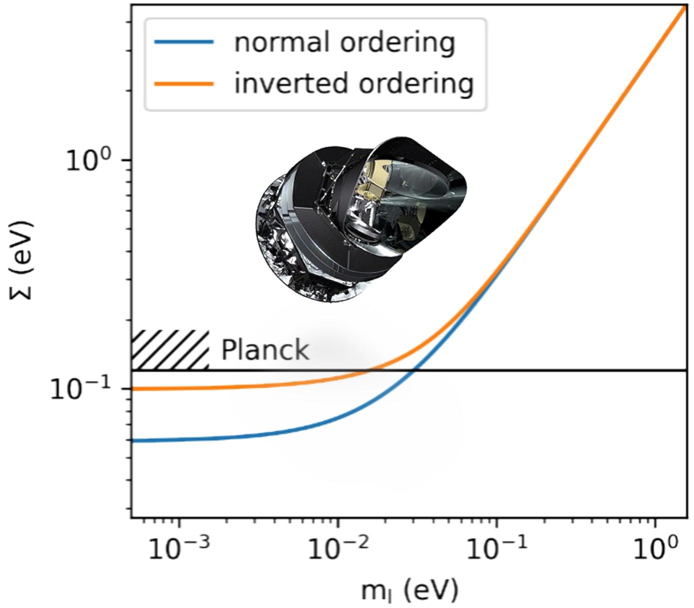
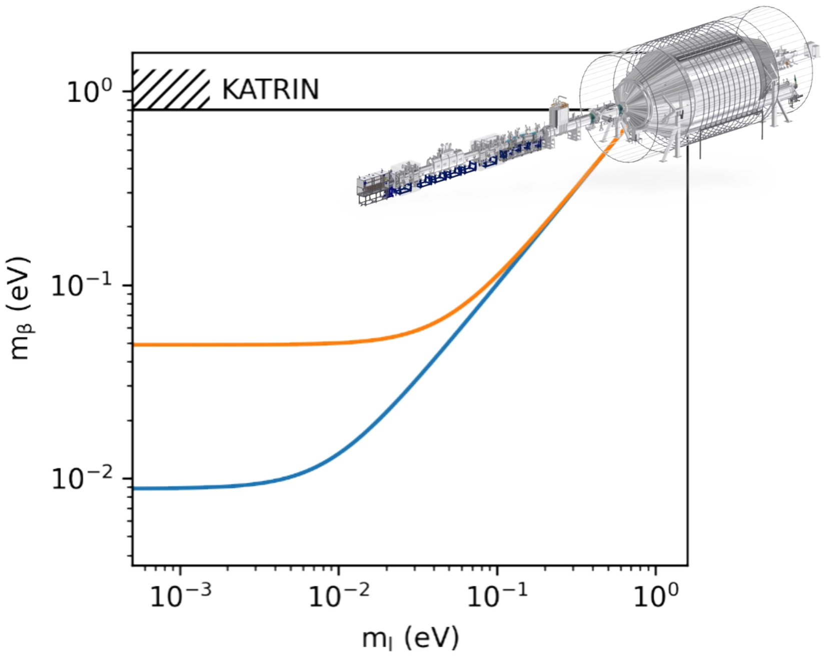




General Idea

- Influence on the expansion rate of the universe
- Influence on structure growth

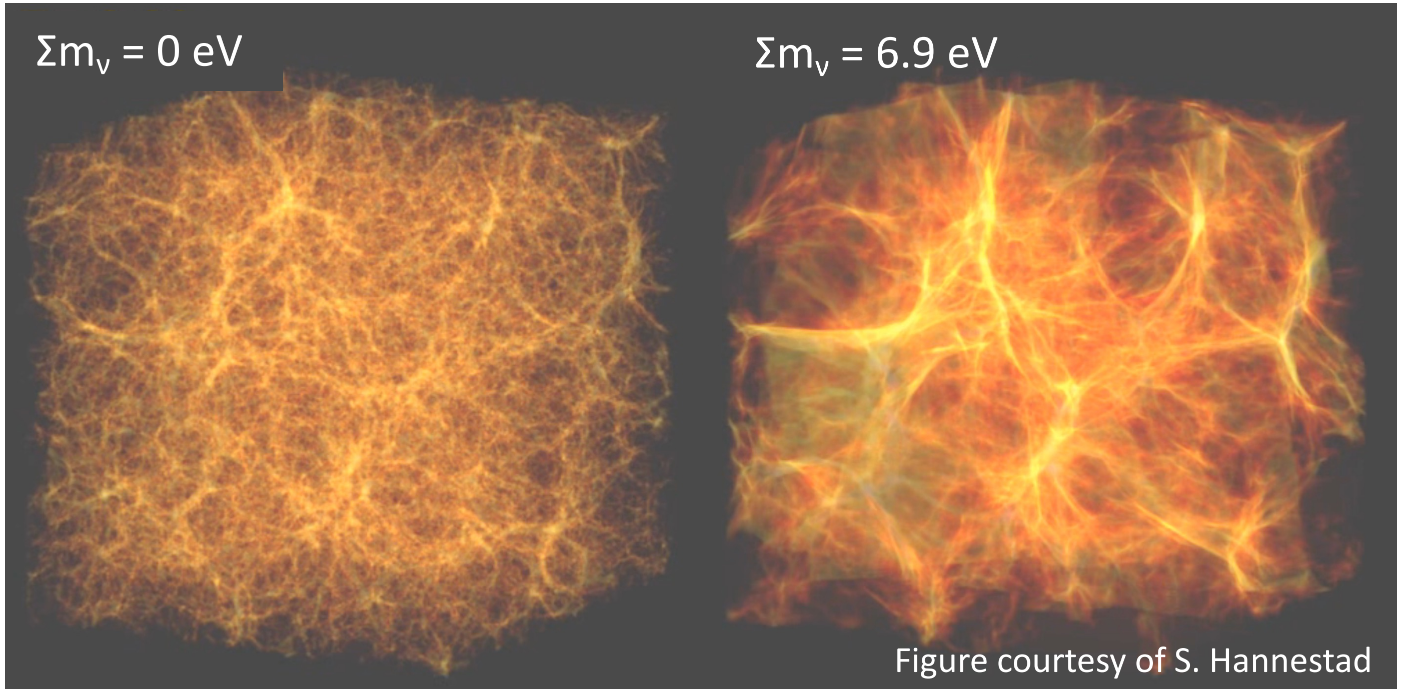
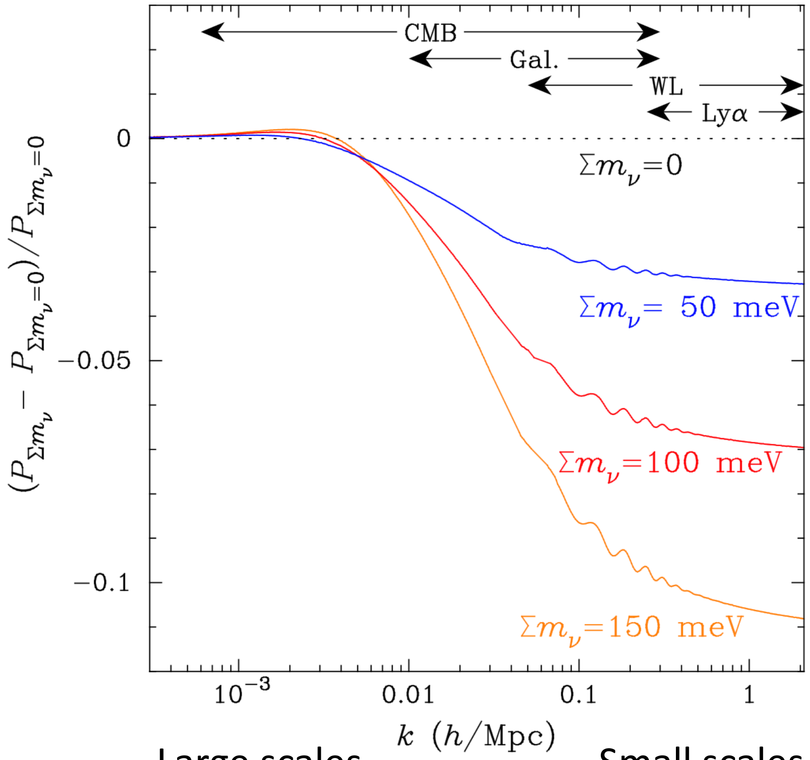


Figure courtesy of S. Hannestad

Matter power spectrum P relative to P(Σm_ν = 0 eV)



Large scales

Small scales

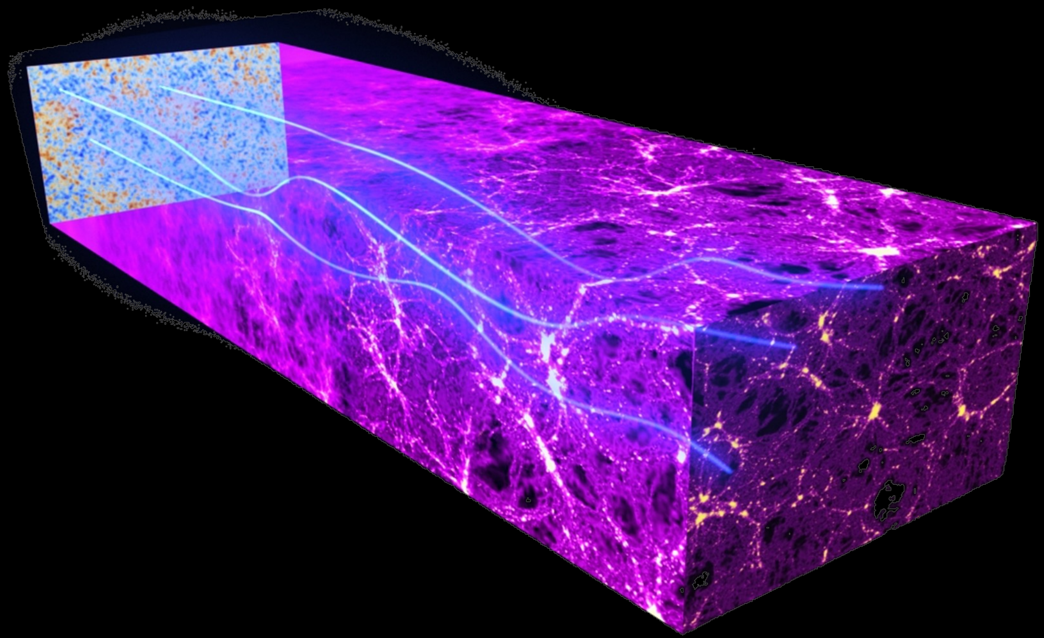
Cosmological probes

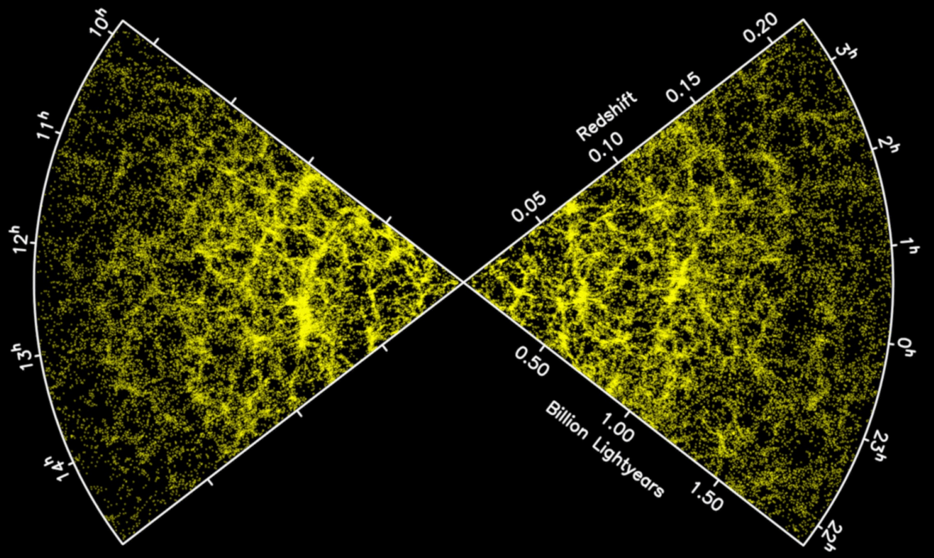
Cosmic microwave background

- CMB temperature anisotropy
- CMB polarization
- CMB lensing

Galaxy surveys

- 3-d galaxy distribution
- weak lensing at different redshift
- Lyman-α forest





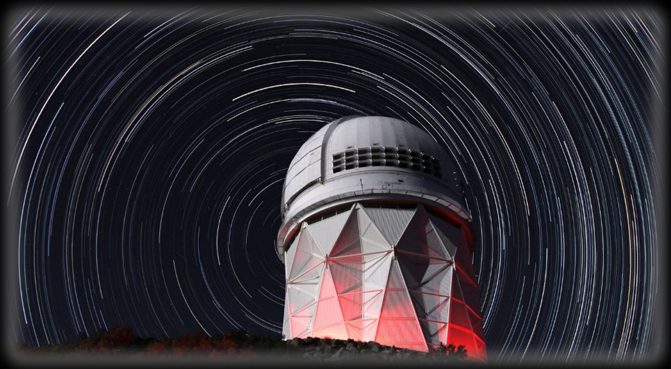
Missions (past & present)

Cosmic microwave background

Planck satellite

- Operated from 2009 – 2013
- Currently best limits on the neutrino mass

Galaxy surveys



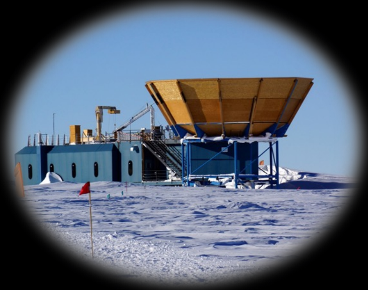
Dark Energy Spectroscopic Instrument (DESI)

- Operation from 2021 – 2026
- World’s largest galaxy redshift survey

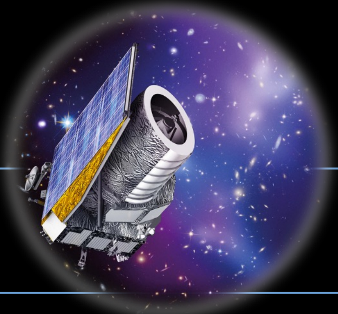
Missions (future)

Cosmic microwave background

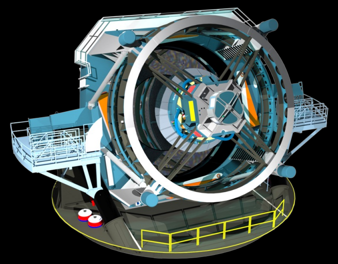
- Simons Observatory (1808.07445)
  ground-based
  near future
- CMB-S4 (1610.02743)
  ground-based
  future
- LiteBIRD (1801.06987)
  space-based
  launch: 2027

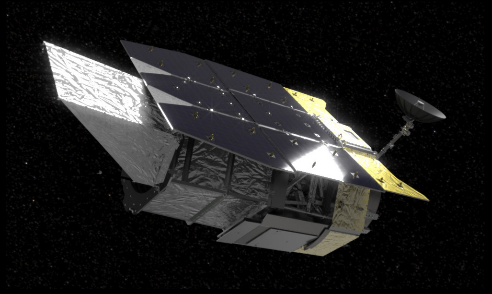


Galaxy surveys

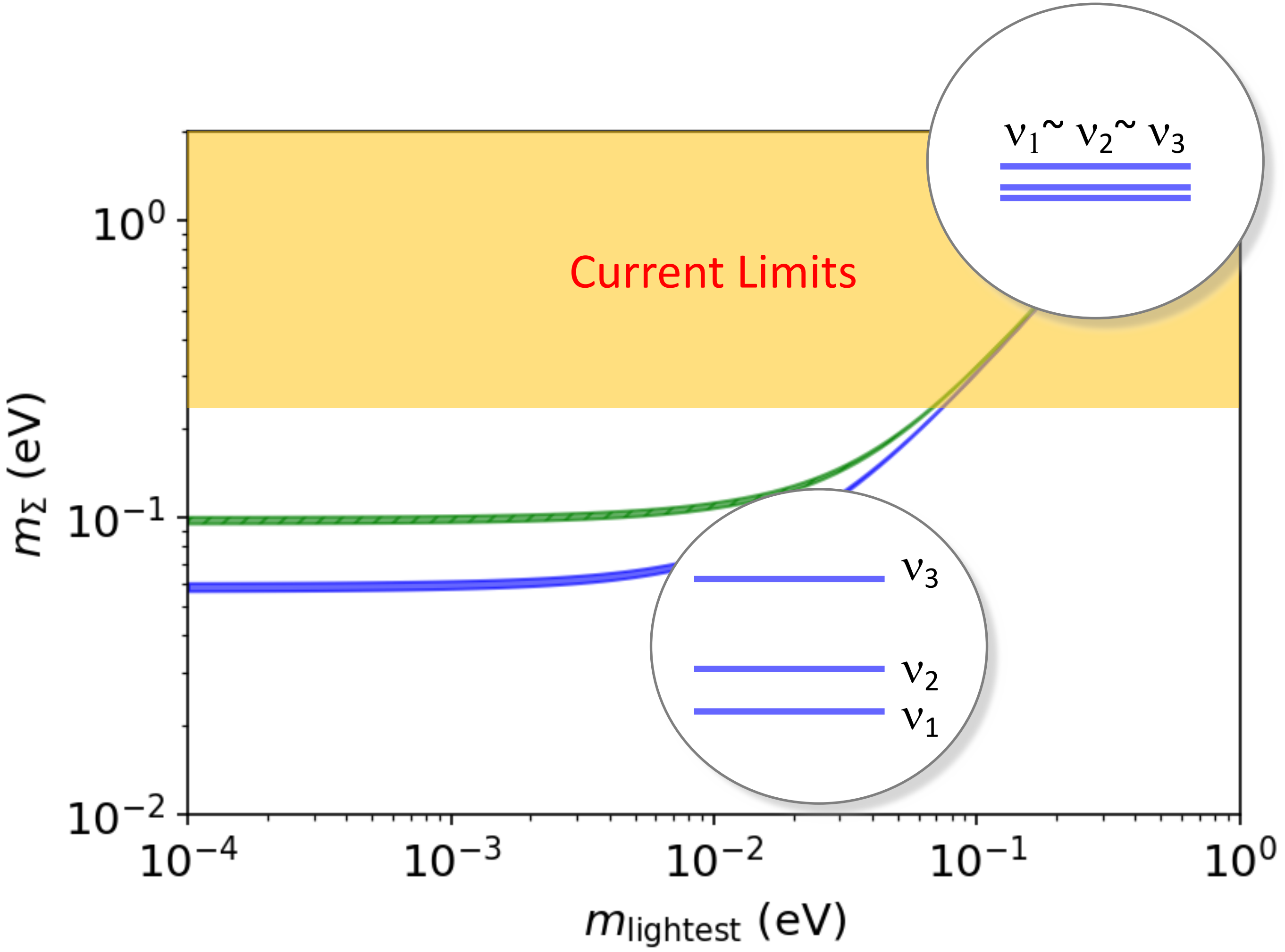


- EUCLID (1110.3193)
  imaging and spectroscopy space telescope
  launch: 2023
- LSST (Vera Rubin Obs.) (0912.0201)
  ground-based
  start: 2023
- WFIRST (now: NGRST) (1208.4012)
  space-based
  launch: 2027





Where do we stand?

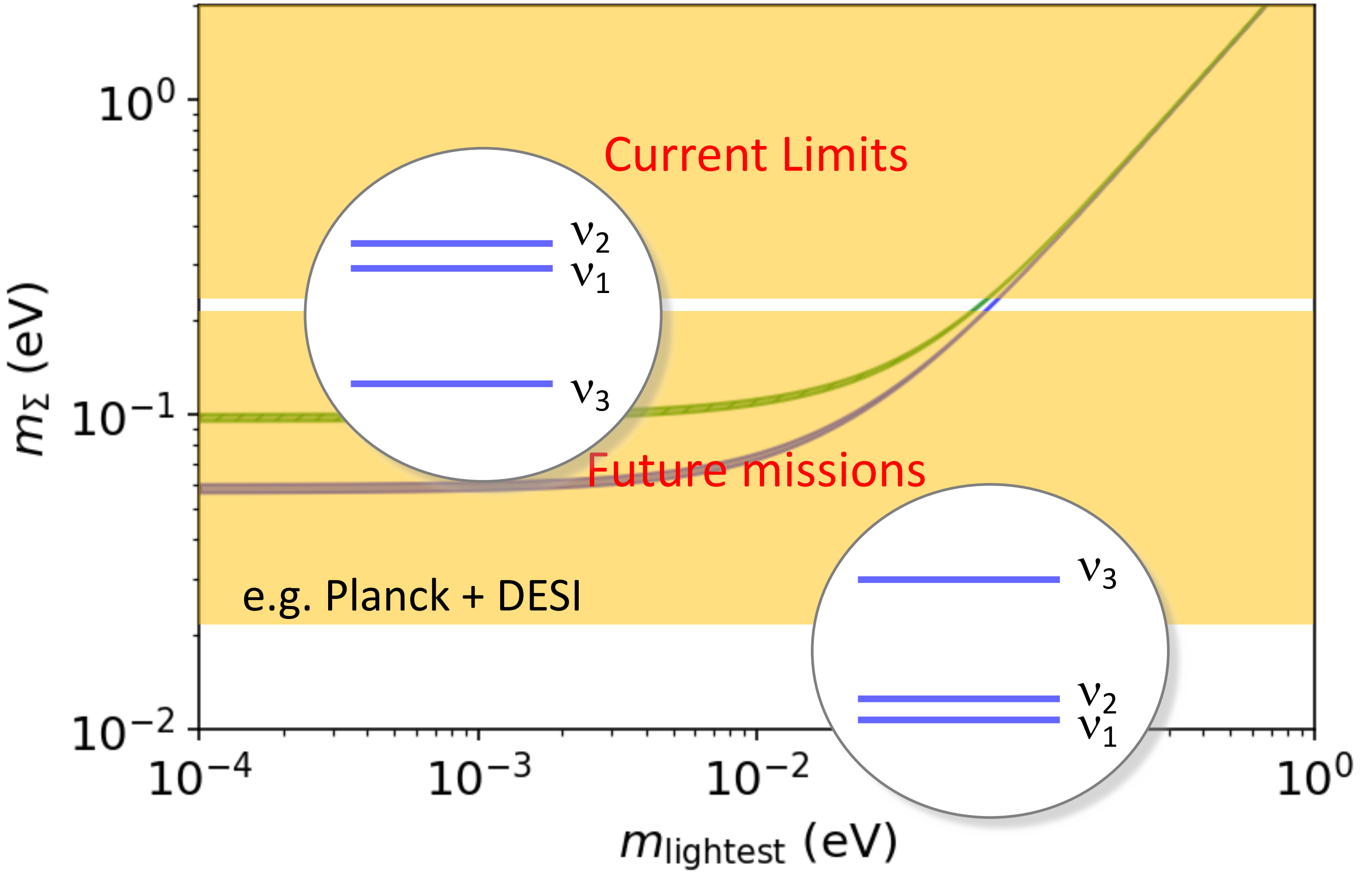


Current best limits:

Planck 2018: arXiv:1807.06209v1

- $\sum m_\nu < 540$ meV (TT + lowE)
- $\sum m_\nu < 260$ meV (TTTEEE + lowE)
- $\sum m_\nu < 240$ meV (TTTEEE + lowE + lensing)
- $\sum m_\nu < 120$ meV (TTTEEE + lowE + lensing + BAO)

Where do we go?



Current best limits:

Planck 2018: arXiv:1807.06209v1

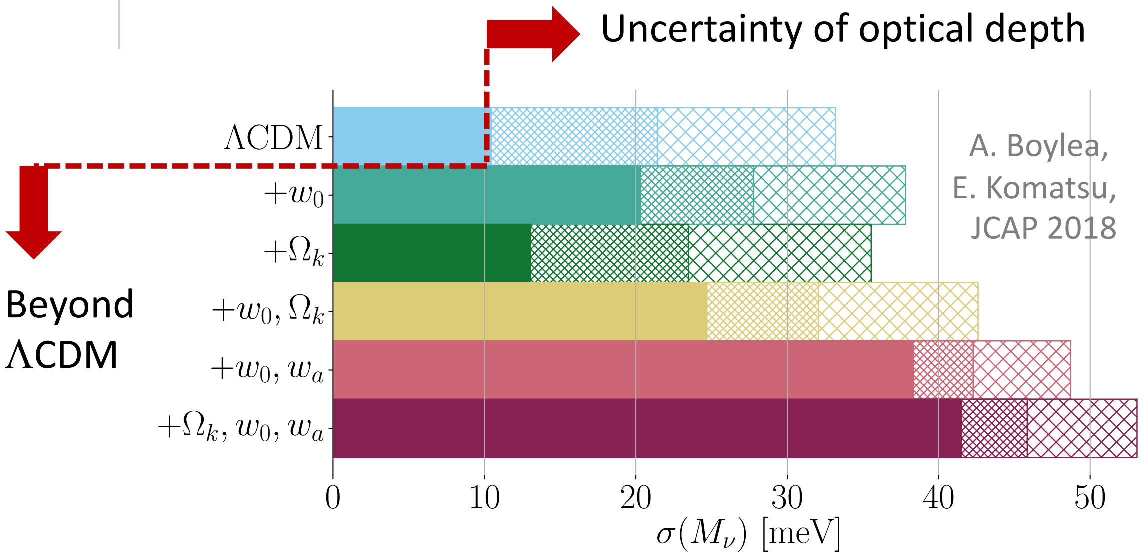
- $\sum m_\nu <$ 120 - 540 meV

Future missions:

- $\sigma(\sum m_\nu) \sim 50$ meV (CMB)
- $\sigma(\sum m_\nu) \sim 20$ meV (CMB + BAO)
- $\sigma(\sum m_\nu) \sim 10$ meV (CMB + BAO + LSS)

Model dependence

Cosmology

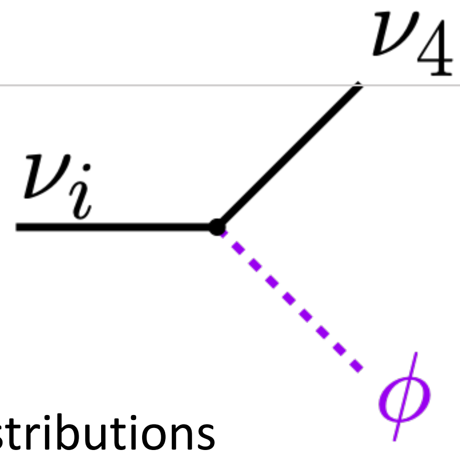


\+ modified dark energy e.o.s.

\+ curvature of space

\+ time-dep. dark energy

Neutrino physics



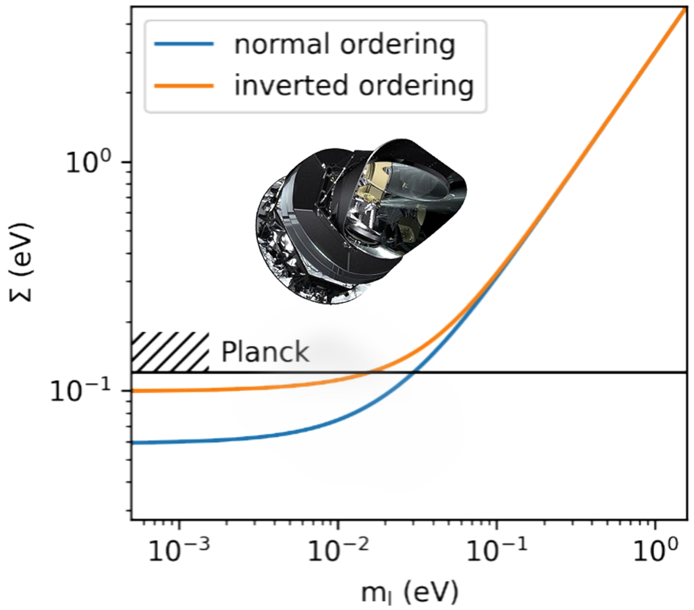
- Non-standard p or T distributions
  Farzan & Hannestad 1510.02201
  Oldengott et al. 1901.04352
  Alvey, Escudero, Sabti, Schwetz 2111.14870v
- Invisible neutrino decay
  Escudero, López-Pavón, Rius, Sandner 2007.04994
  Chacko et al. 1909.05275, 2112.13862
- Time-dependent neutrino mass
  Dvali & Funcke 1602.03191
  Lorenz et al. 2102.13618

➢ Bounds relaxed up to $\sum m_\nu < 3$ eV

Neutrino mass

Cosmology

$$\Sigma = \sum_i m_i$$

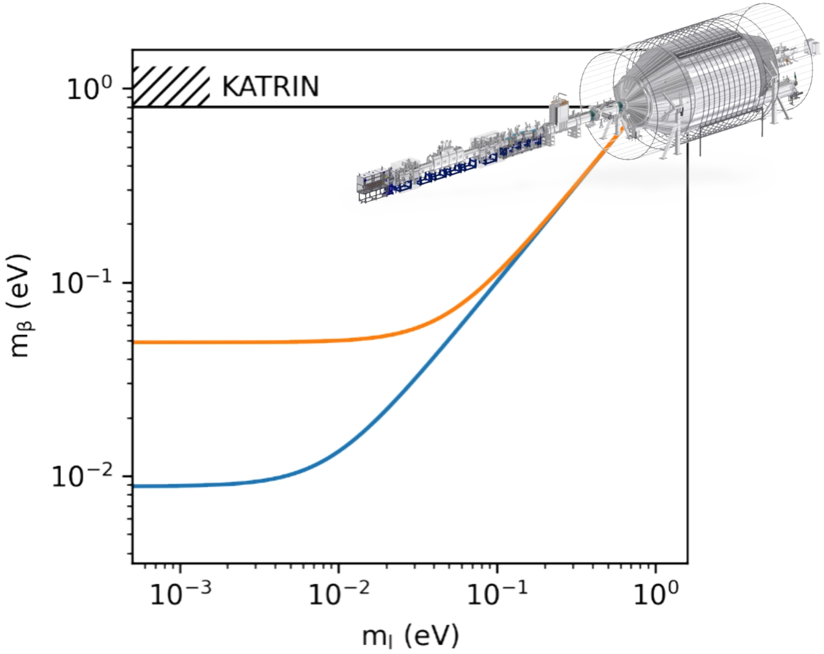


Neutrinoless ßß decay

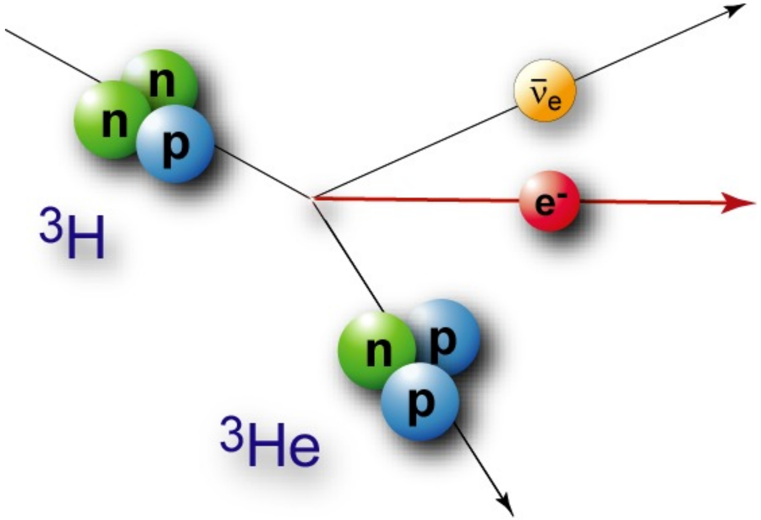
$$m_{\beta\beta} = |\sum_i U_{ei}^2 m_i|$$

ß-decay kinematics

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

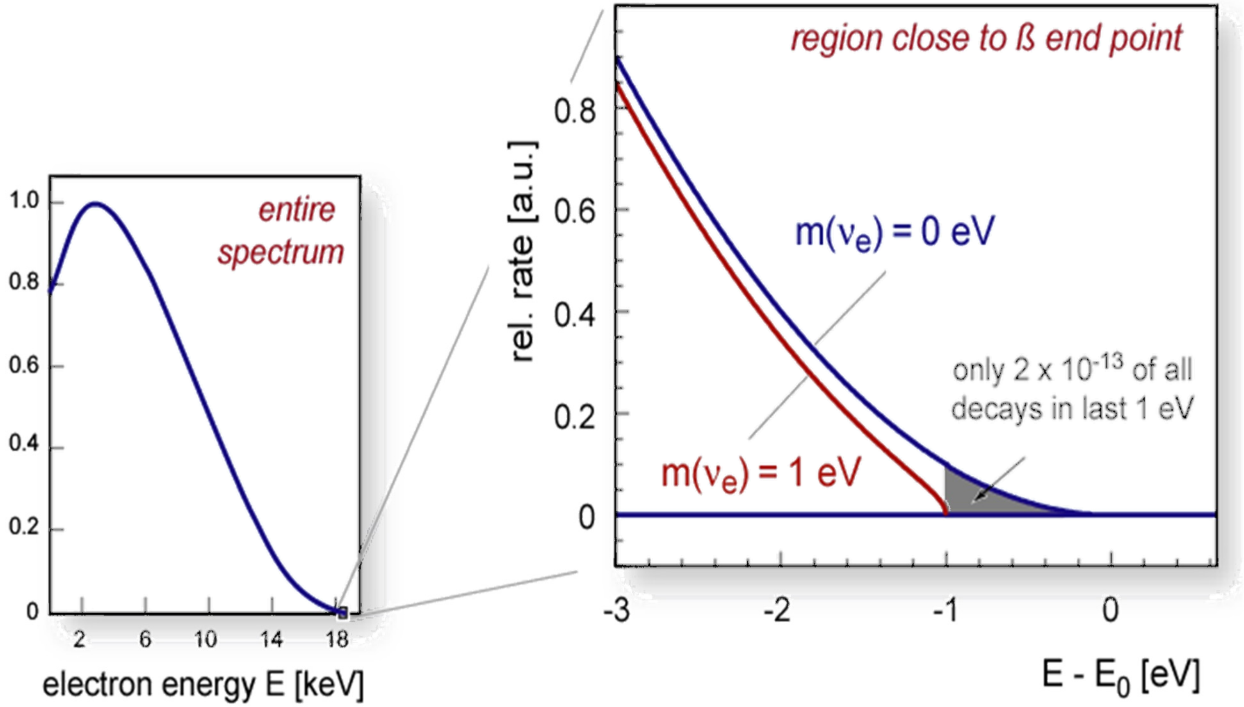


General idea



- ✓ Independent of cosmology
- ✓ Independent of neutrino nature

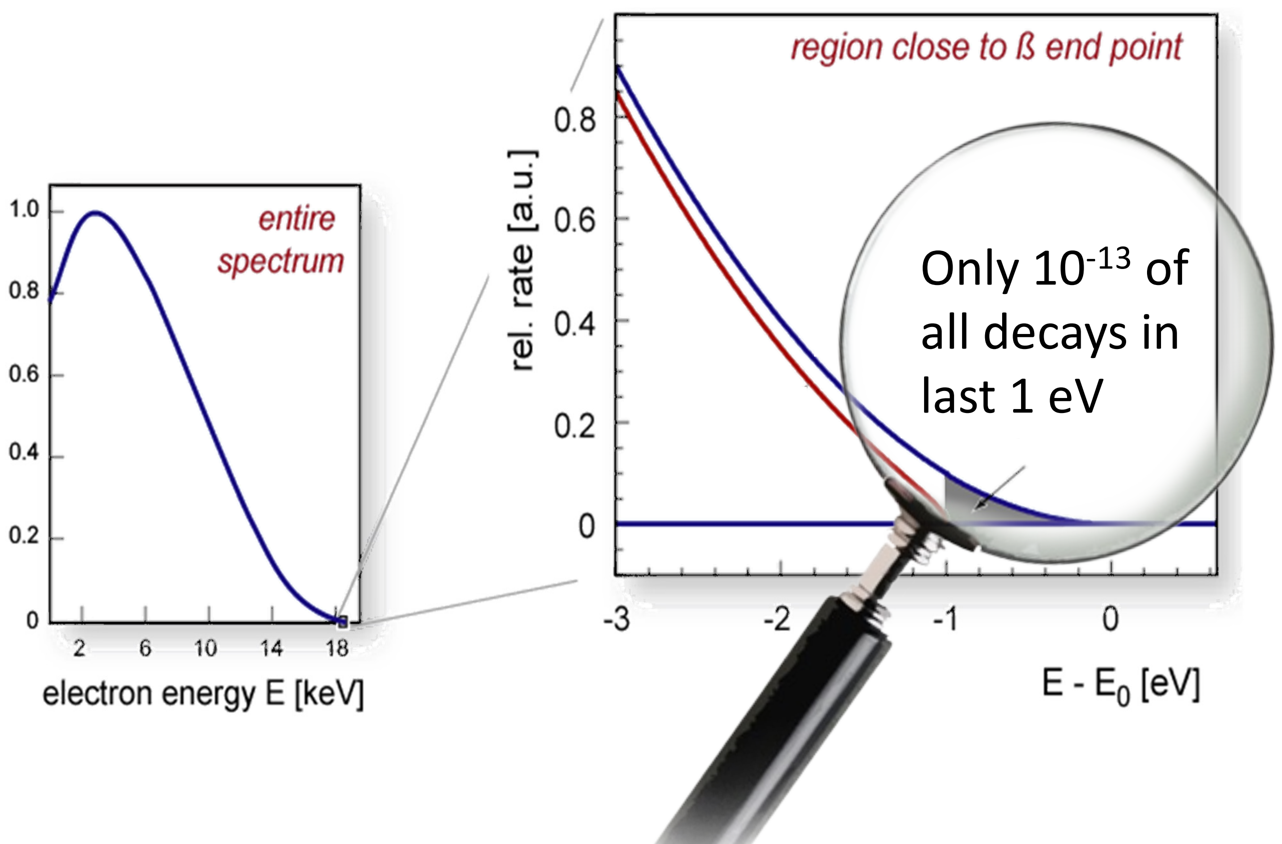
$$m^2(\nu_e) = \sum_i |U_{ei}|^2 \cdot m_i^2$$



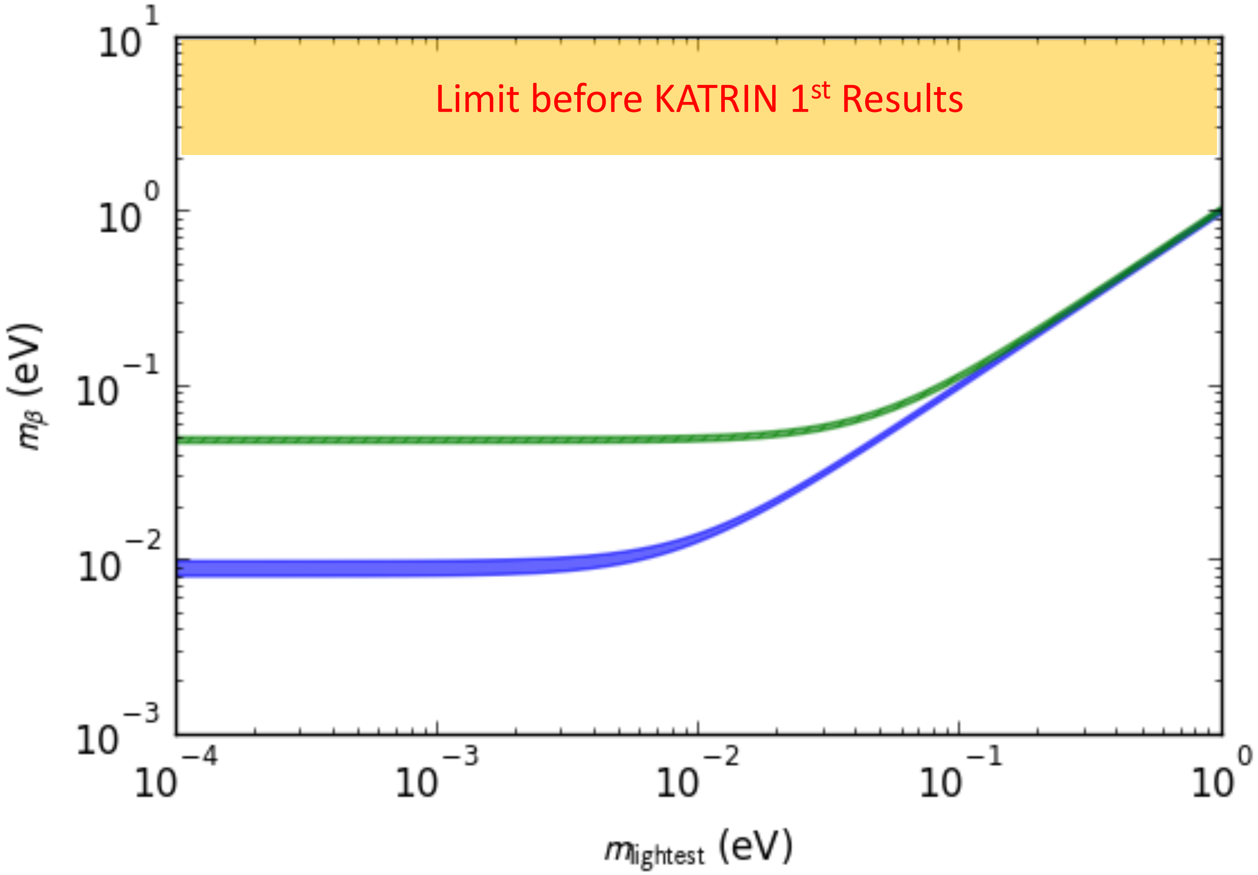
The challenge

Key requirements:

- Strong β-decaying source
  - Tritium (12.3 years, E_0 = 18.6 keV)
  - Holmium (4500 years, E_0 = 2.8 keV)
- Excellent energy resolution (~ 1 eV)
- Low background (< 100 mcps)



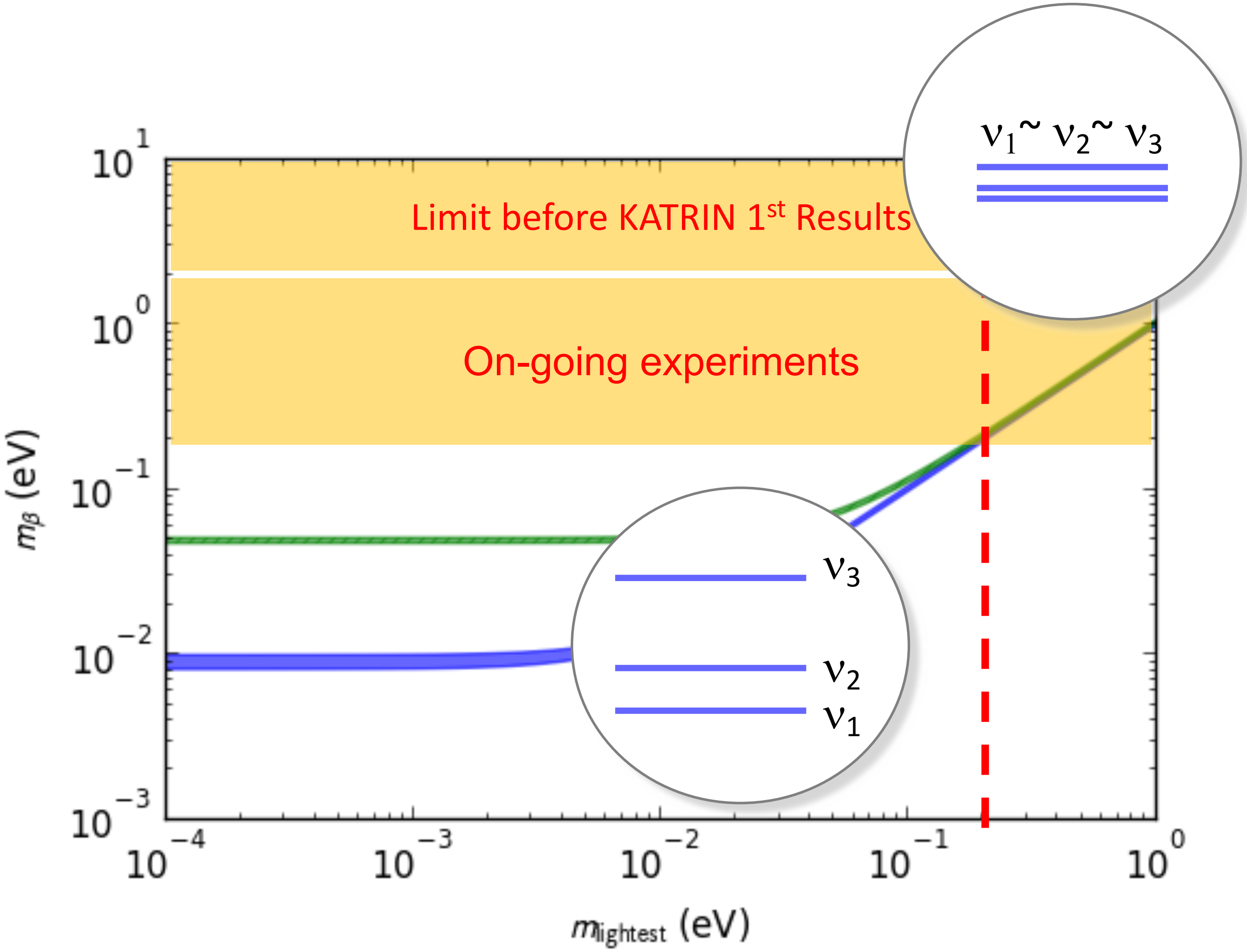
Where do we stand?



- Limit before KATRIN 1st Results: Mainz and Troitsk Experiment

  V. N. Aseev et al., Phys. Rev. D 84 (2011) 112003
  Kraus, C., Bornschein, B., Bornschein, L. et al. Eur. Phys. J. C (2005)

Where do we stand?



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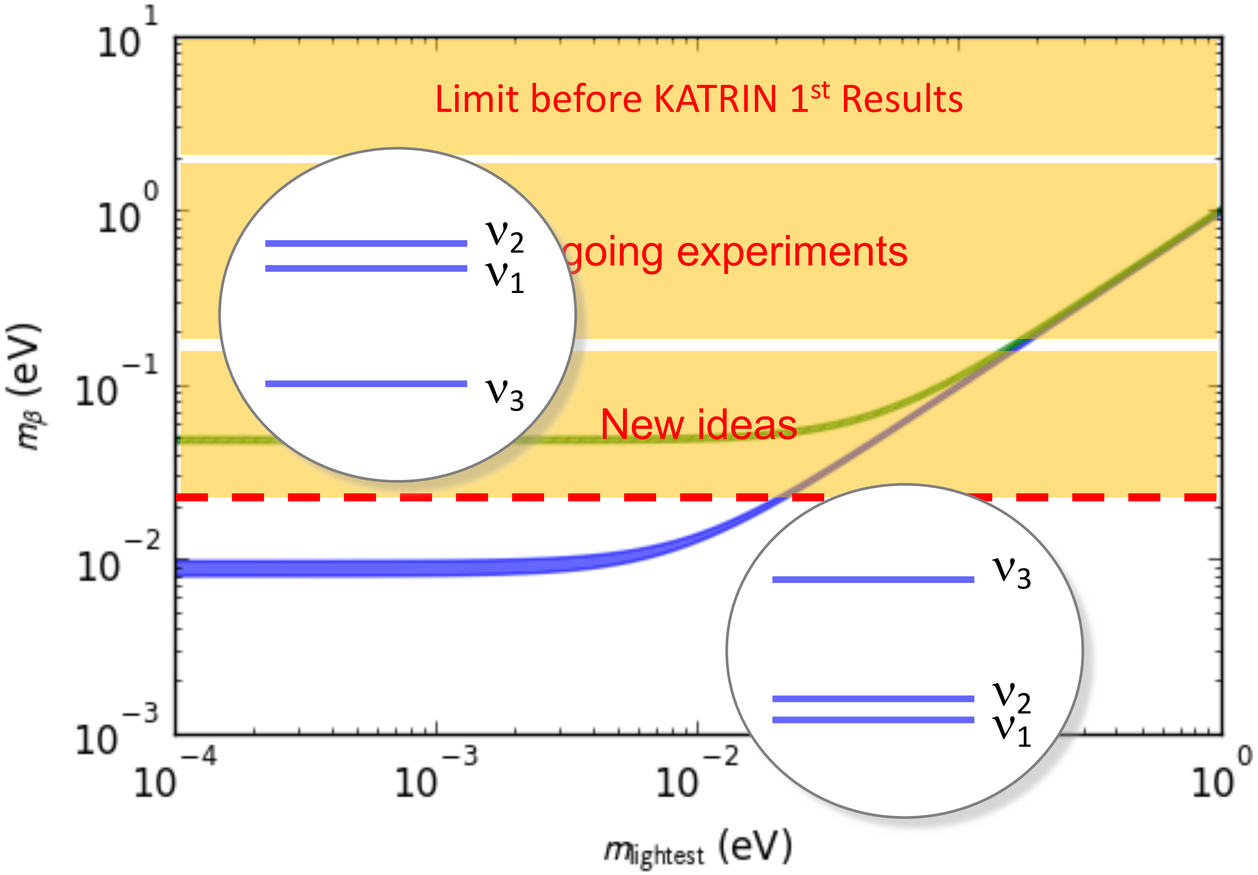
  Kraus, C., Bornschein, B., Bornschein, L. et al. Eur. Phys. J. C (2005)
- Ongoing experiments: Distinguish between **degenerate** and **hierarchical** scenario

Where do we stand?



- Limit before KATRIN 1st Results:
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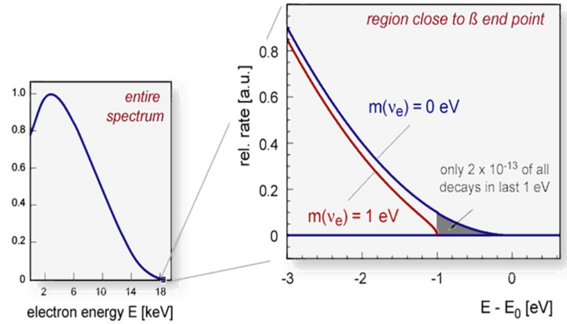
  V. N. Aseev et al., Phys. Rev. D 84 (2011) 112003
  Kraus, C., Bornschein, B., Bornschein, L. et al. Eur. Phys. J. C (2005)
- Ongoing experiments:
  Distinguish between **degenerate** and **hierarchical** scenario
- New ideas:
  Resolve **normal** vs **inverted** neutrino mass hierarchy

Experimental efforts

Electrostatic filter (MAC-E)

counting above threshold



frequency

Cyclotron Radiation

Phonons

heat

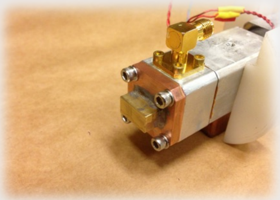
Experimental efforts

Electrostatic filter (MAC-E)

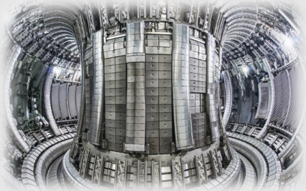
KATRIN
(Tritium)

Cyclotron Radiation

Project-8
(Tritium)



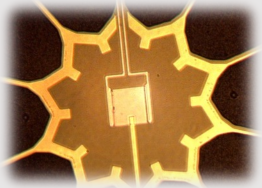
QTNM
(Tritium)



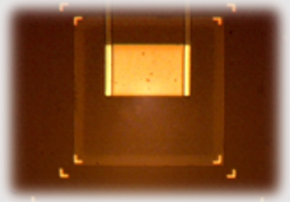
Phonons

Ptolemy
(Tritium)

Holmes
(Holmium)



ECHo
(Holmium)



Experimental efforts

KATRIN
(Tritium)

Electrostatic filter (MAC-E)

Cyclotron Radiation

Phonons

KATRIN

- **Experimental site: Karlsruhe Institute of Technology (KIT)**
- **International Collaboration (150 members)**
- **Design sensitivity: 0.2 eV (90% CL)**
  (5 years of measurement time)

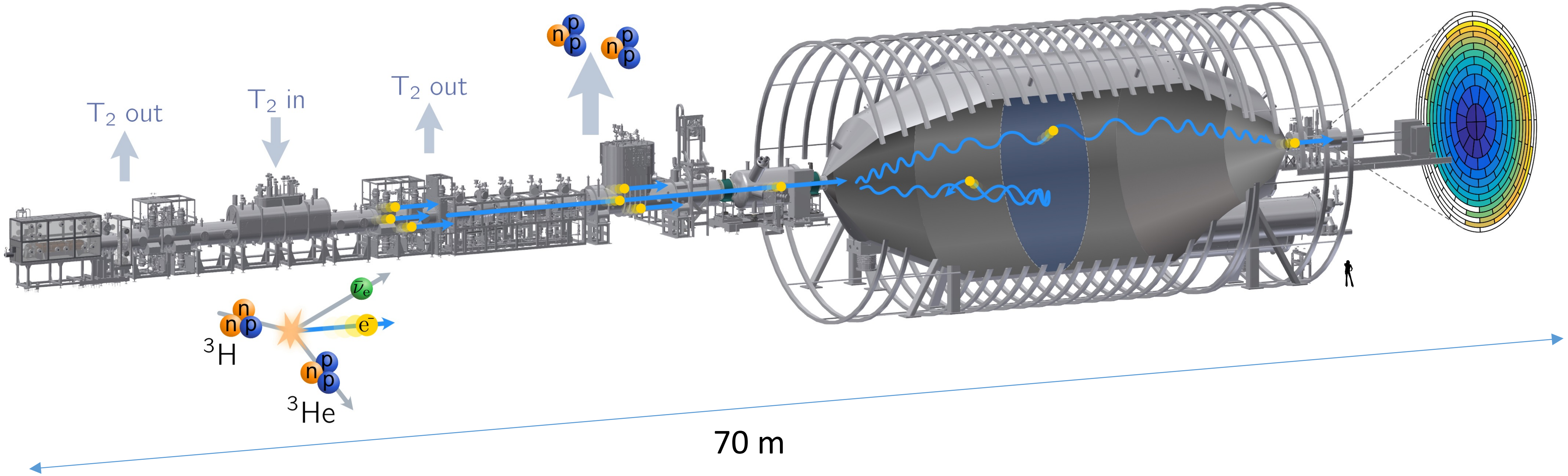
Karlsruher Institut für Technologie
Max-Planck-Institut für Kernphysik Heidelberg
University of Washington
Case Western Reserve University
Westfälische Wilhelms-Universität Münster
Massachusetts Institute of Technology
Max-Planck-Institut für Physik (Werner-Heisenberg-Institut)
The University of North Carolina at Chapel Hill
The Czech Academy of Sciences
Hochschule Fulda University of Applied Sciences
Carnegie Mellon University
Universidad Complutense Madrid
Università degli Studi di Milano Bicocca
cea
Johannes Gutenberg Universität Mainz
Technische Universität München
universität bonn
Politecnico Milano 1863
Humboldt-Universität zu Berlin
Bergische Universität Wuppertal
Berkeley Lab
Russian Academy of Sciences

Working Principle

Tritium source
- Gaseous T_2
- 10^{11} T_2 decays/s

Spectrometer
- Electrostatic filter
- MAC-E filter principle

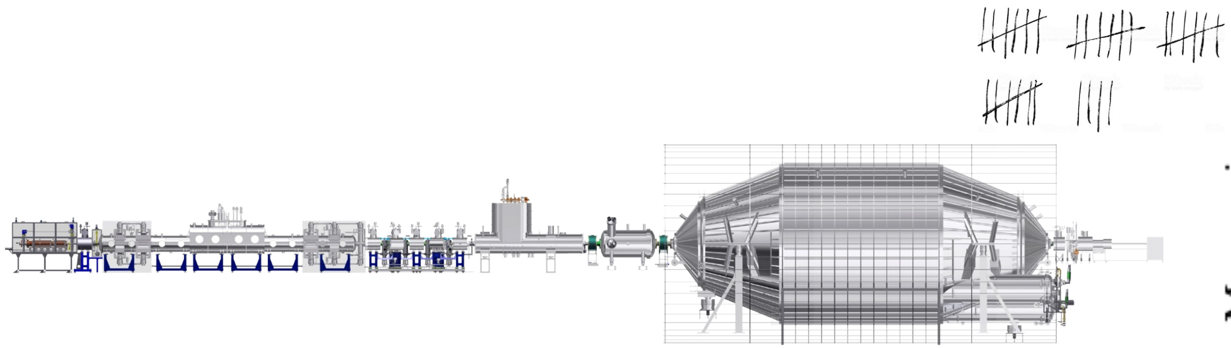
Detector
- Counts electrons

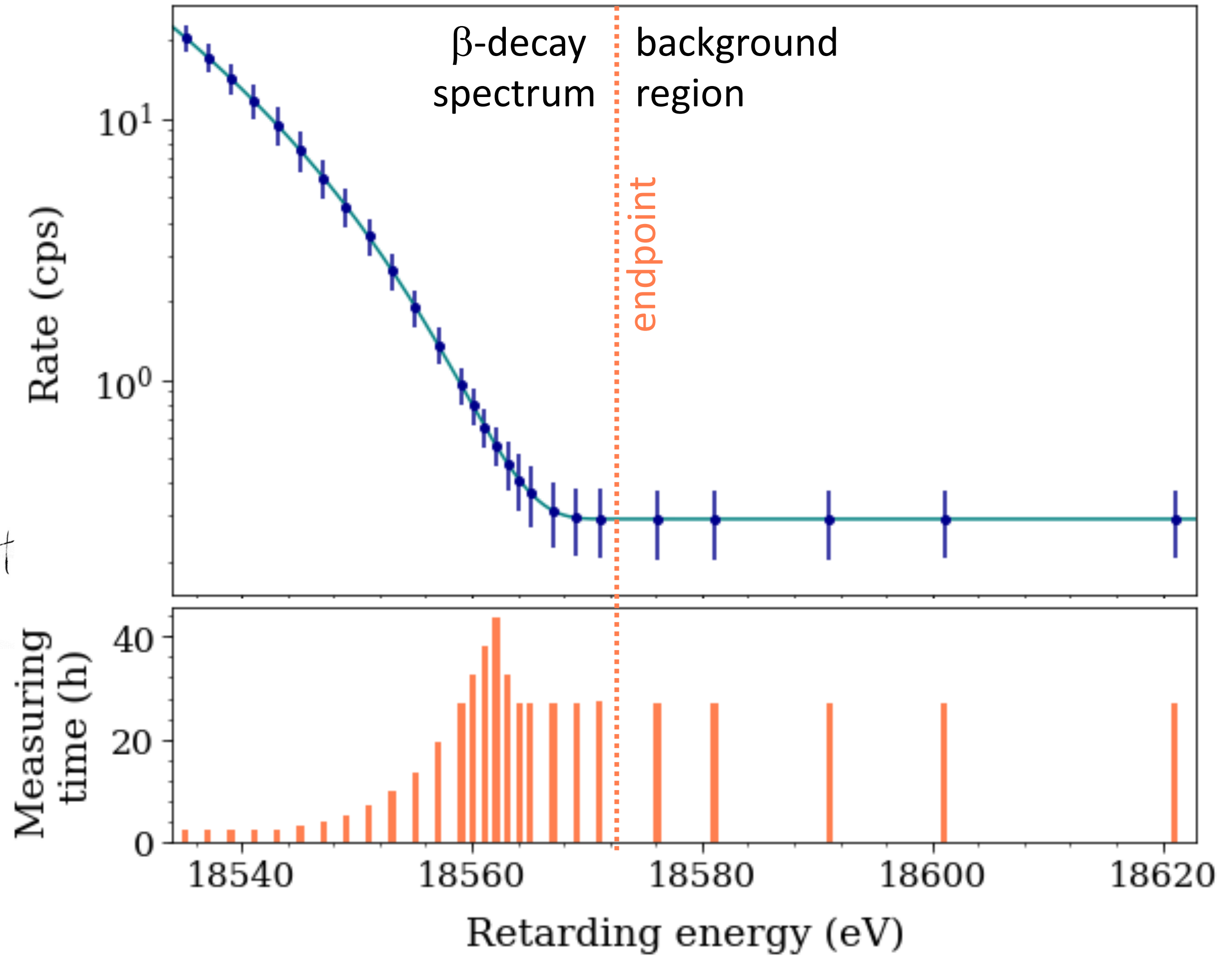


Measurement strategy

β-scans:

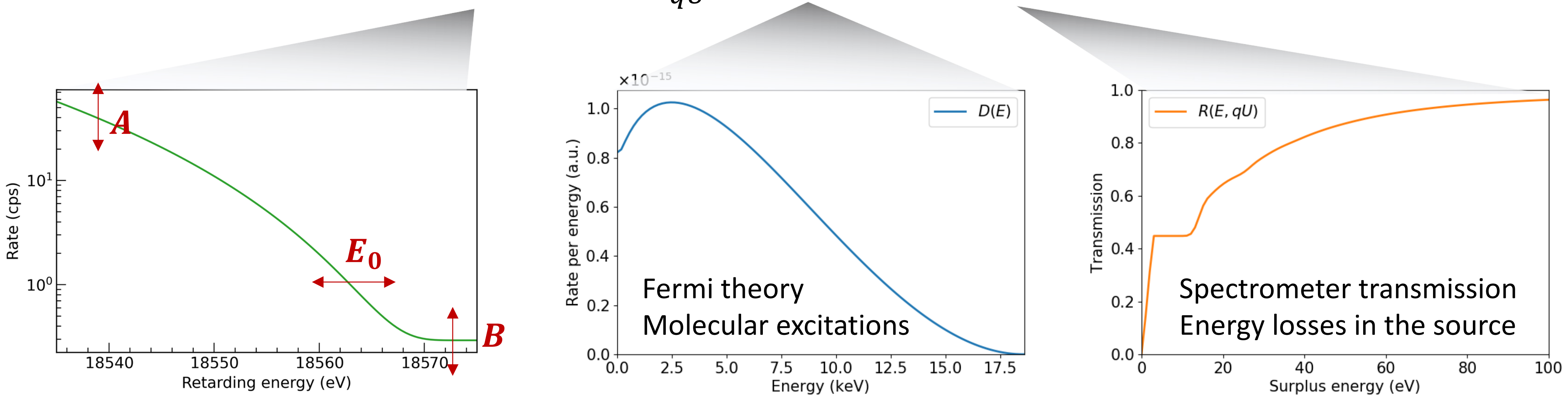
- Scan points: **30 HV set points**
- Scan interval: **E_0 – 40 eV , E_0 + 130 eV**
- Scan time: **2 hours**





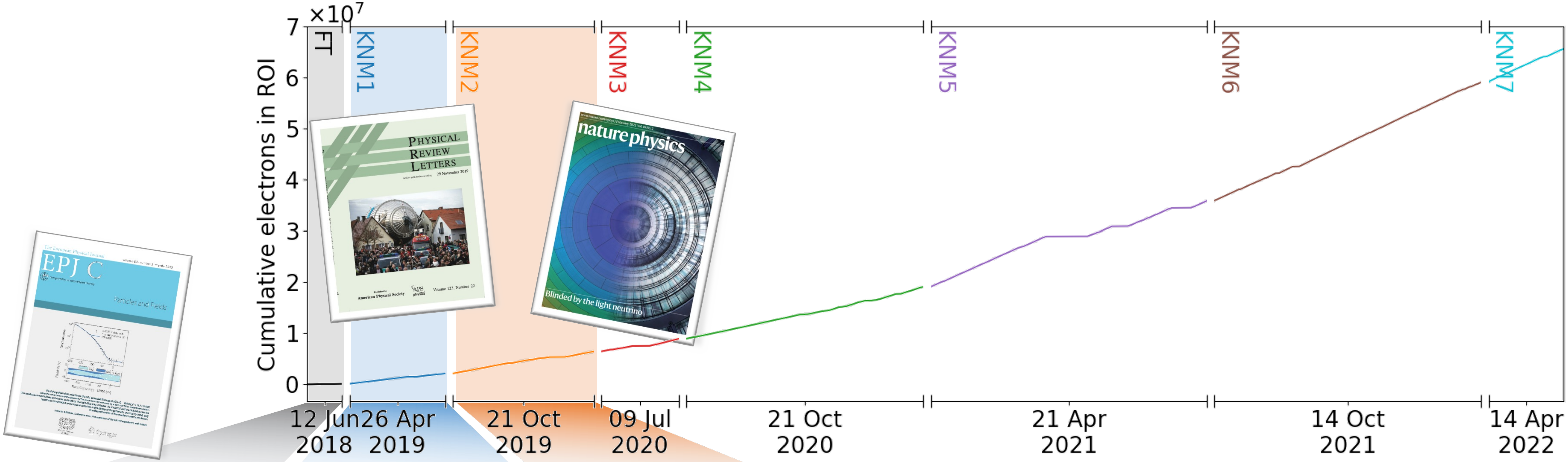
Analysis strategy

- Fit of theoretical prediction: $\Gamma(qU) \propto \boldsymbol{A} \cdot \int_{qU}^{E_0} D(E; \boldsymbol{m_\nu^2}, \boldsymbol{E_0}) \cdot R(qU, E)\, dE + \boldsymbol{B}$



- Free parameters: $\boldsymbol{m_\nu^2}, \boldsymbol{E_0}, \boldsymbol{B}, \boldsymbol{A}$
- Blinded analysis: 1) freeze inputs on MC, 2) blinded model, 3) three independent teams

KATRIN Data Taking Overview



- Commissioning
- Only 0.5% tritium

EPJ C 80, 264 (2020)

- 1^{st} m_ν campaign
- $m_\nu < 1.1$ eV

PRL. 123, 221802 (2019)

Phys. Rev. D 104, 012005 (2021)

- 2^{nd} m_ν campaign
- $m_\nu < 0.8$ eV

Nat. Phys. **18,** 160–166 (2022)

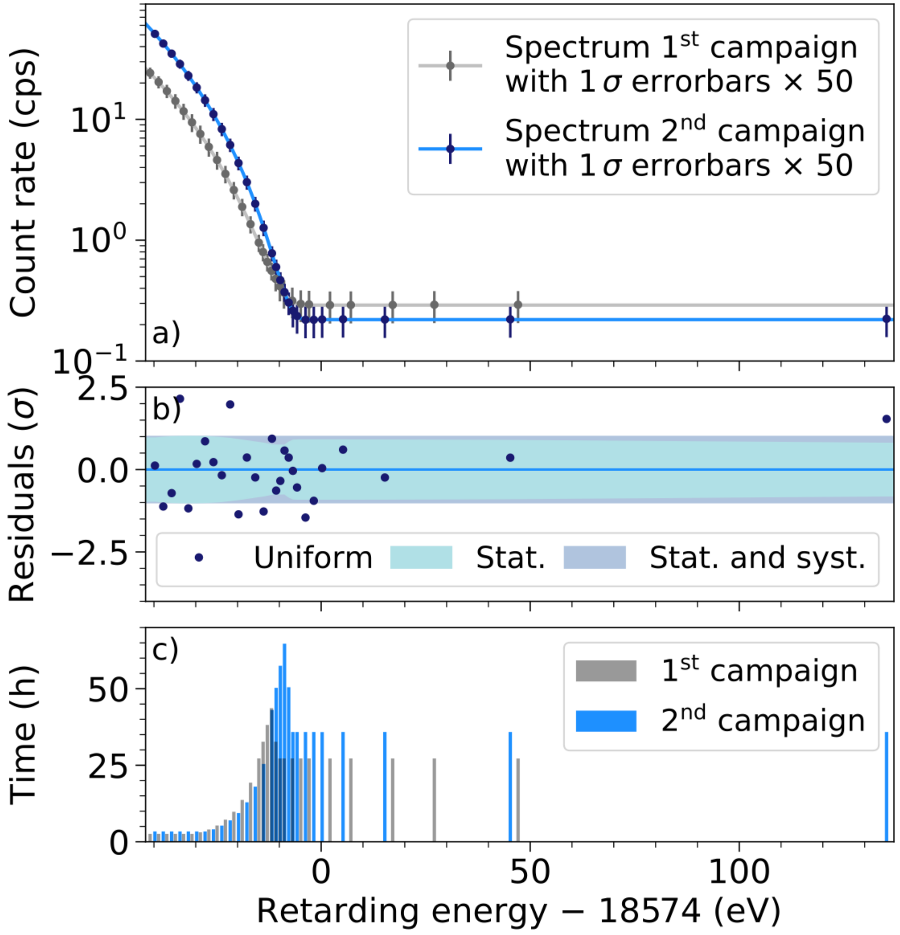
+ sterile and relic neutrino searches:

PRL 126, 091803 (2021)

PRD 105, 072004 (2022)

arXiv:2202.04587 (2022)

First neutrino mass results



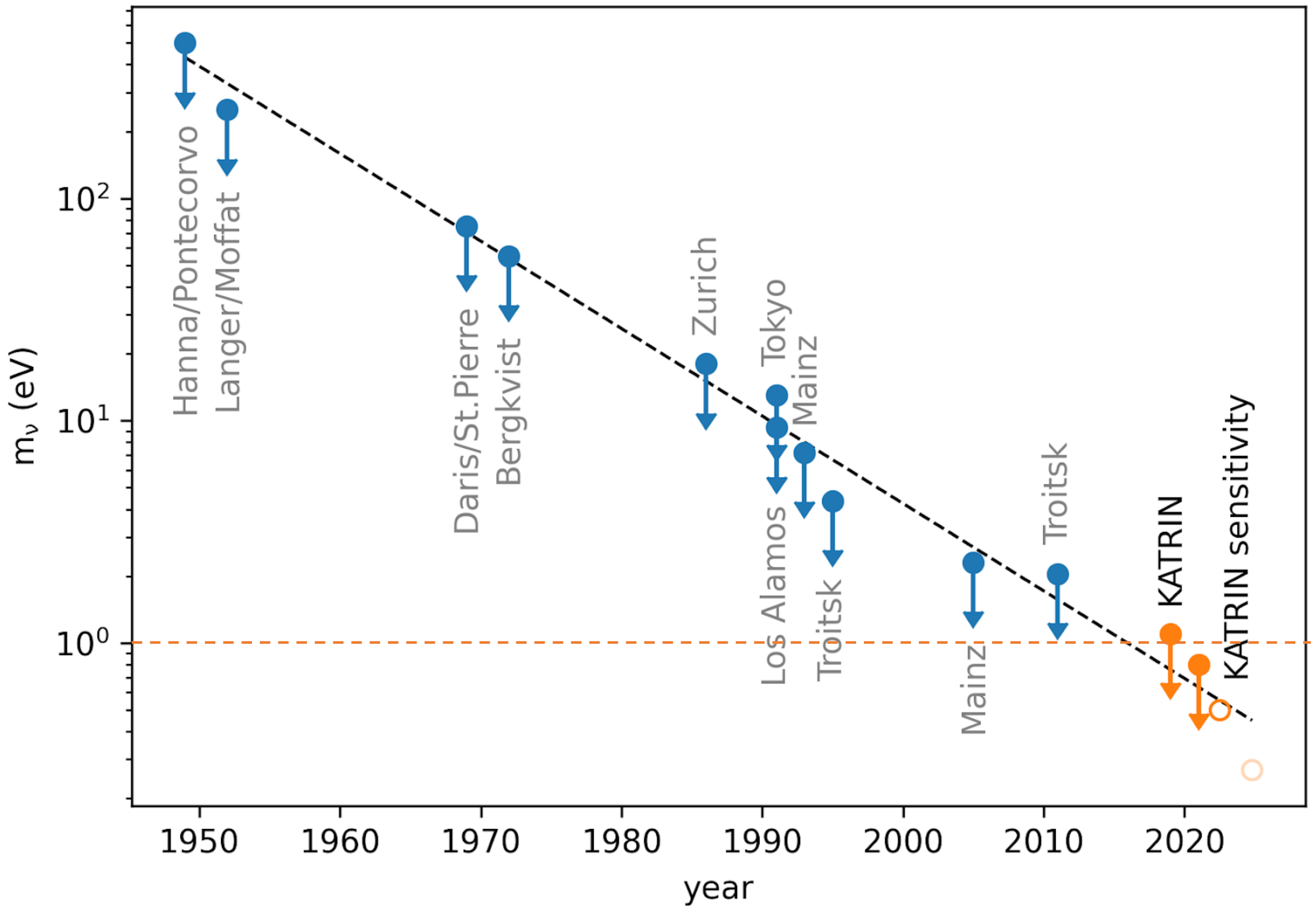
First campaign:

- total statistics: 2 million events (22 days)
- excellent goodness-of-fit: p-value = 0.56
- best fit: $m_\nu^2 = \left(-1.0^{+0.9}_{-1.1}\right)$ eV² (stat. dom.)
- limit: $m_\nu < 1.1$ eV (90% CL)

Second campaign:

- total statistics: 4 million events (31 days)
- excellent goodness-of-fit: p-value = 0.8
- best fit: $m_\nu^2 = \left(0.26^{+0.34}_{-0.34}\right)$eV² (stat. dom.)
- limit: $m_\nu < 0.9$ eV (90% CL)

Historical context

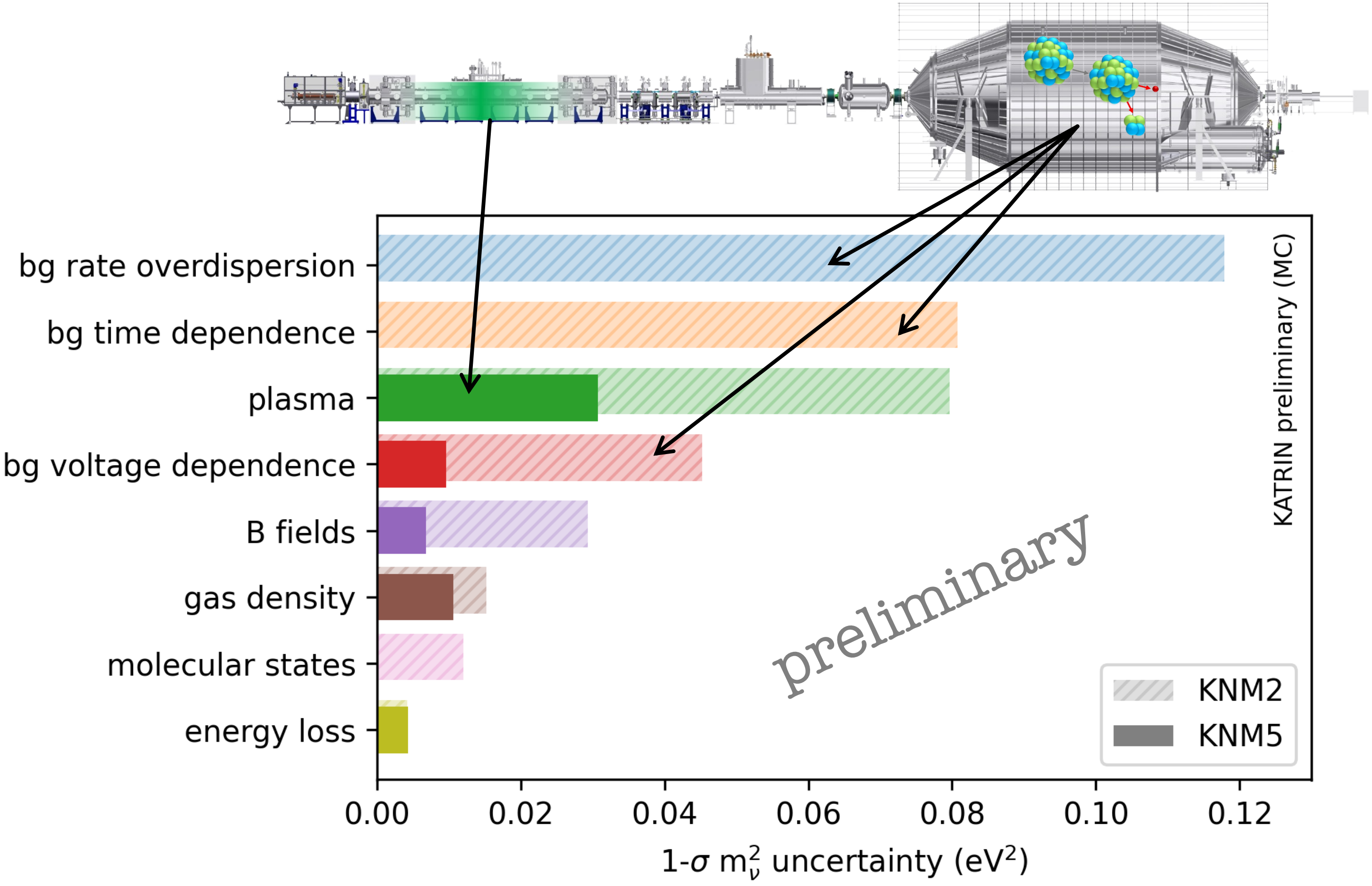


1st and 2nd campaign combined limit:

- $m_\nu < 0.8$ **eV (90% CL)**
- **first direct neutrino-mass experiment to reach sub-eV sensitivity and limit**

KATRIN Collab. Nat. Phys. **18,** 160–166 (2022)

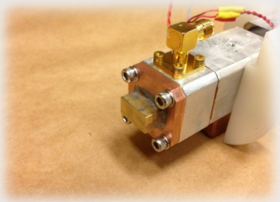
KATRIN outlook

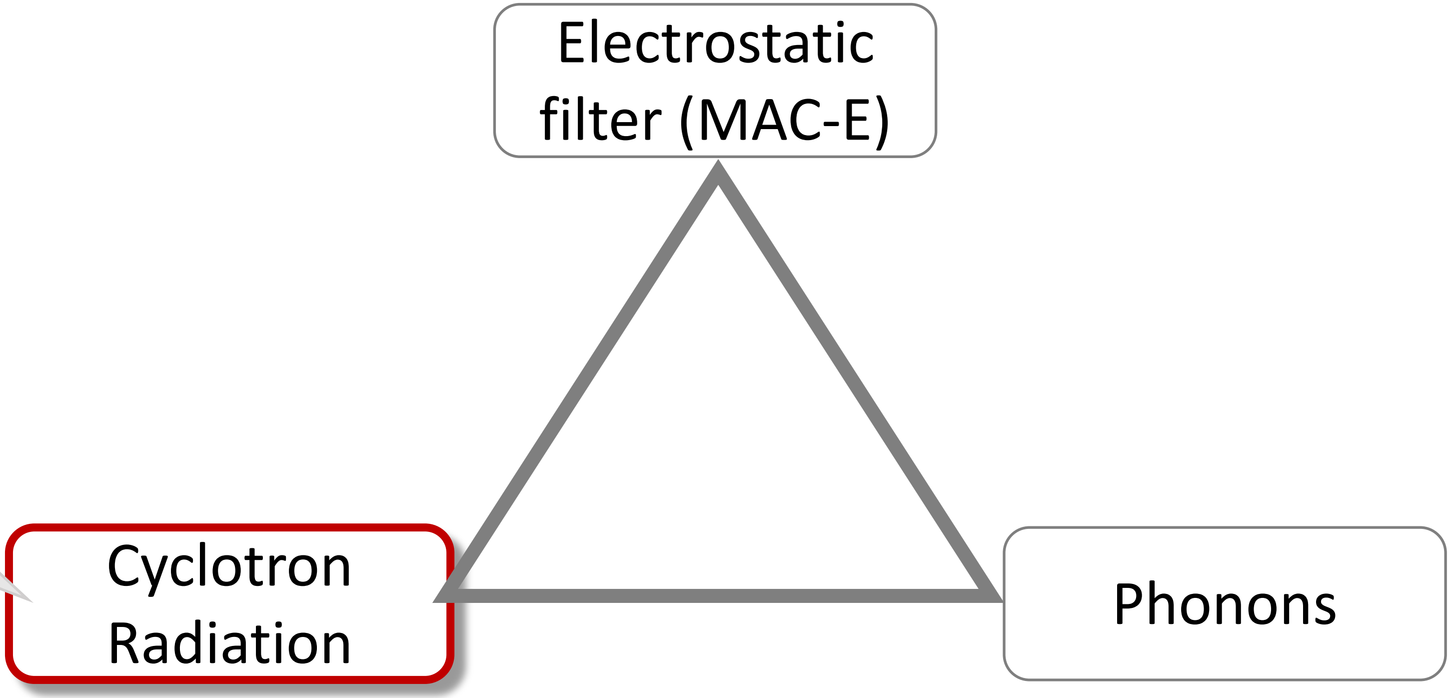


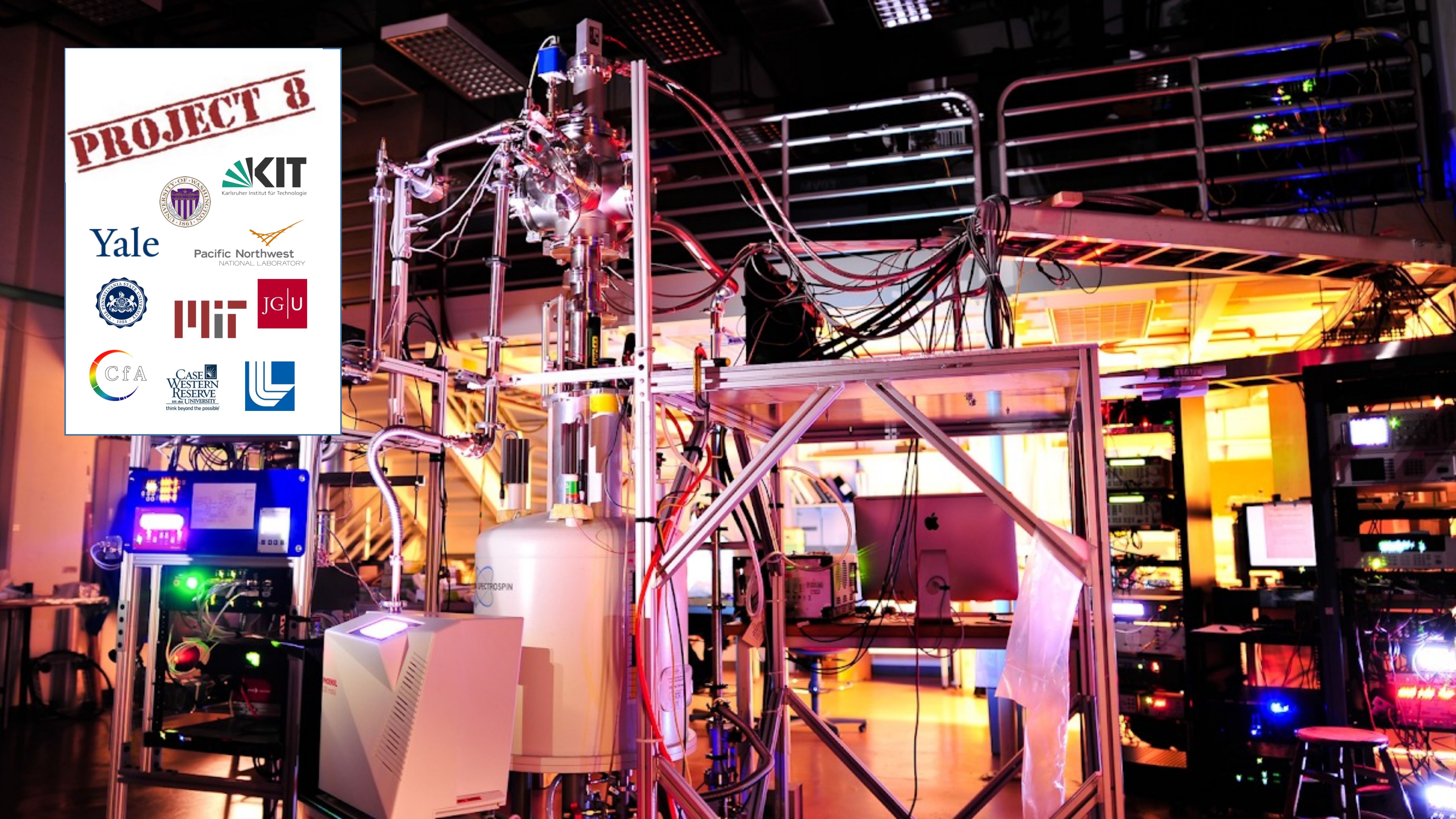
- Major improvements:
  - **Reduced background** (÷ 2) thanks to new electro-magnetic field setting
    Lokhov et al arXiv:2201.11743 (2022)
  - **Reduced systematics** thanks to high-statistics krypton calibration
    J. Sentkerestiová et al, JINST 13 (2018)
- Next unblinding this summer ☺
- Final goal (2025):
  $m_\nu < 0.2 - 0.3$ **eV (90% CL)**

Experimental efforts

Project-8
(Tritium)





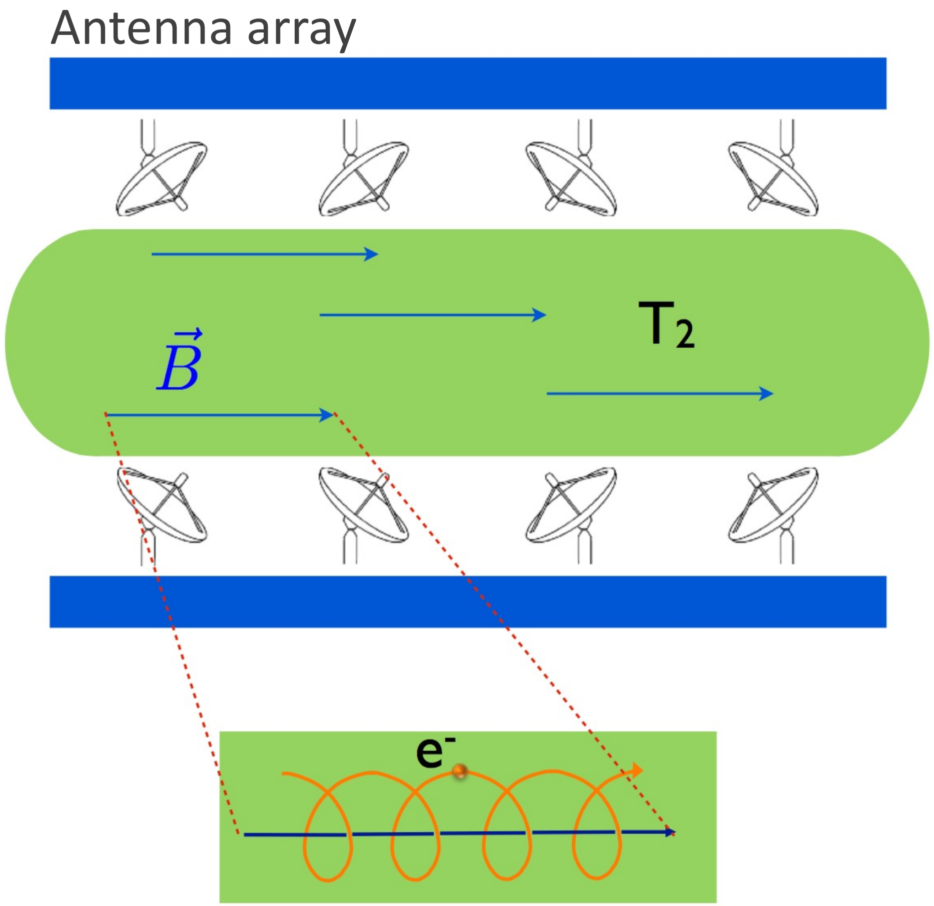

PROJECT 8
KIT
Karlsruher Institut für Technologie
Yale
Pacific Northwest
NATIONAL LABORATORY
JG|U
CfA
CASE WESTERN RESERVE UNIVERSITY
think beyond the possible
SPECTROSPIN

Working principle

- Cyclotron Radiation Emission Spectroscopy (CRES)

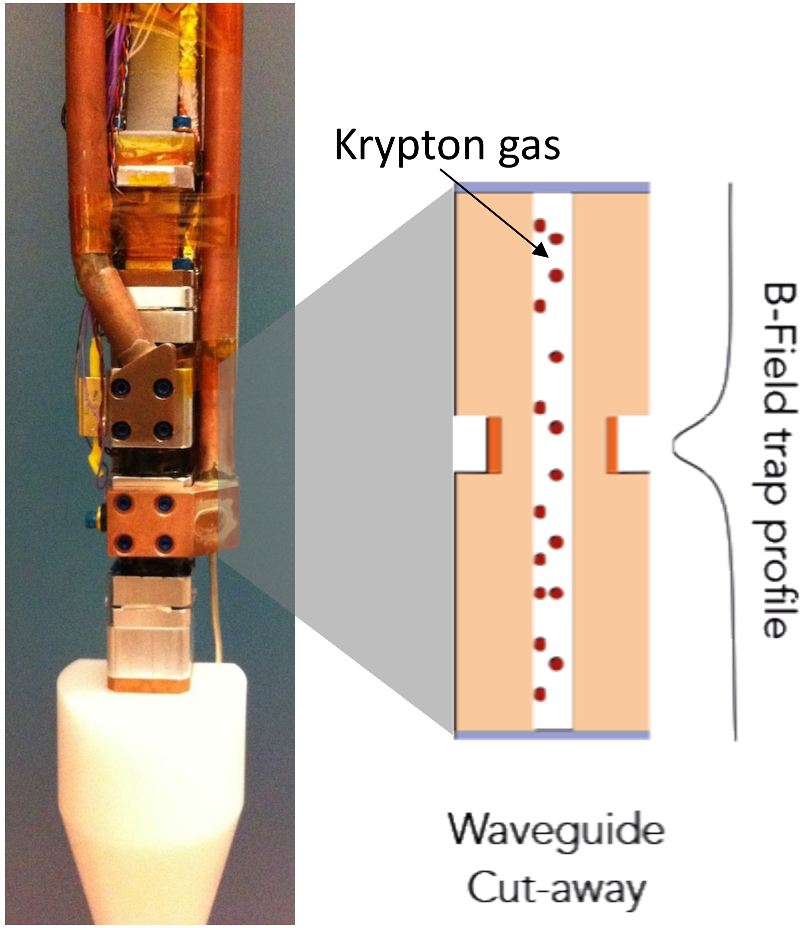
$$\omega(\gamma) = \frac{\omega_0}{\gamma} = \frac{eB}{E + m_e}$$

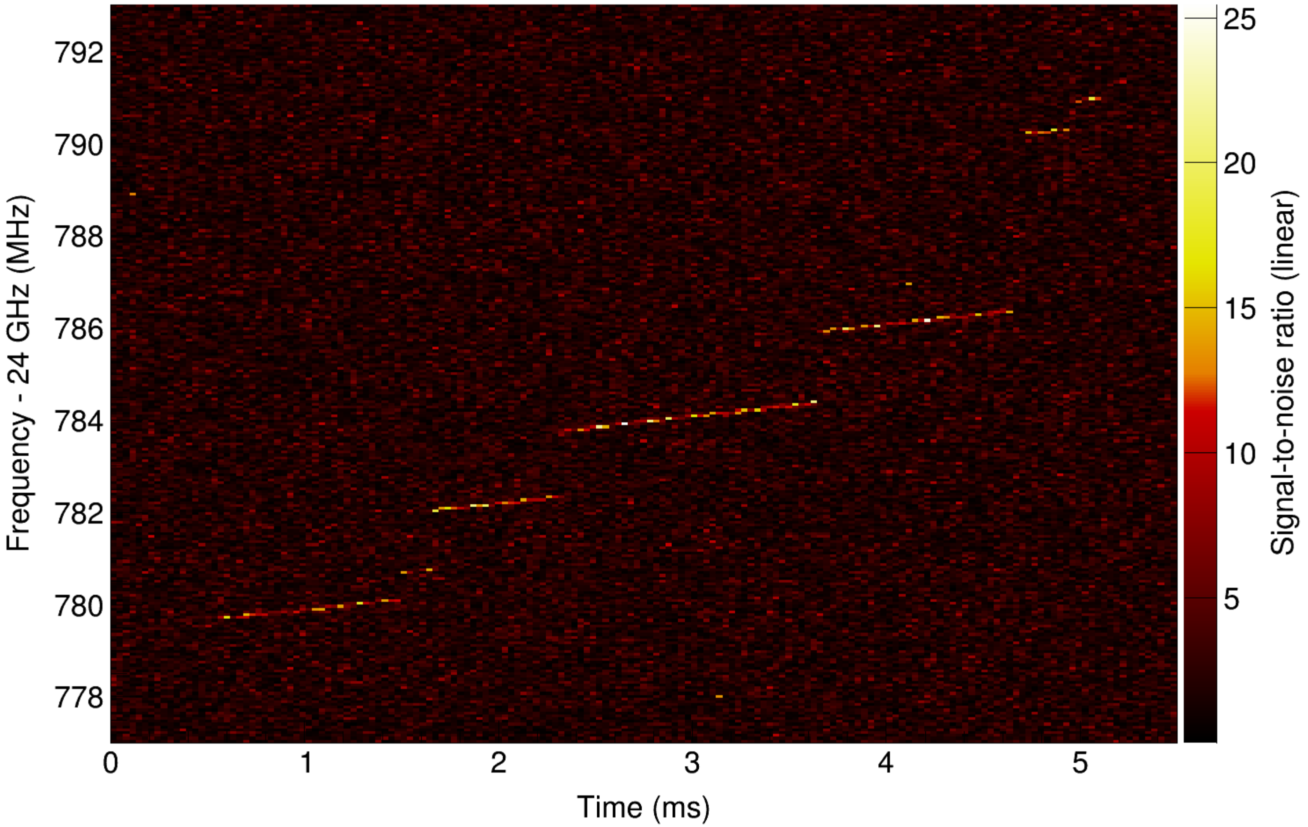
- Advantages
  - ✓ eV-scale differential measurement
    - ✓ Low background
    - ✓ High statistics
  - ✓ „source = detector“ concept



B. Monreal and Joe Formaggio, Phys. Rev D 80:051301

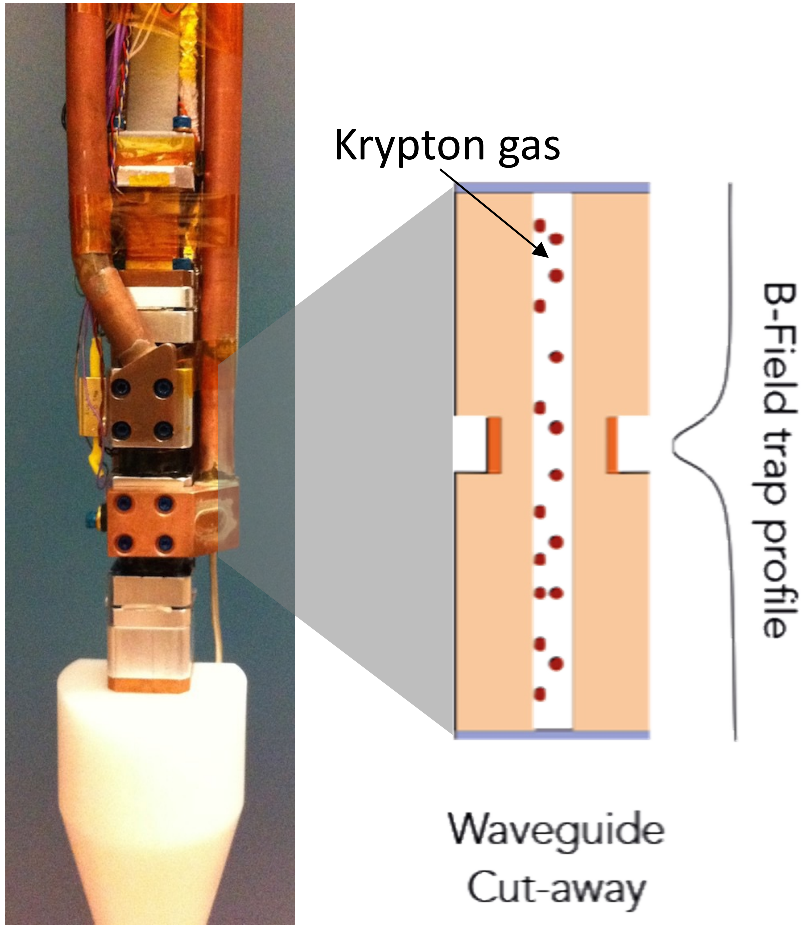
Project 8 – *proof of concept*

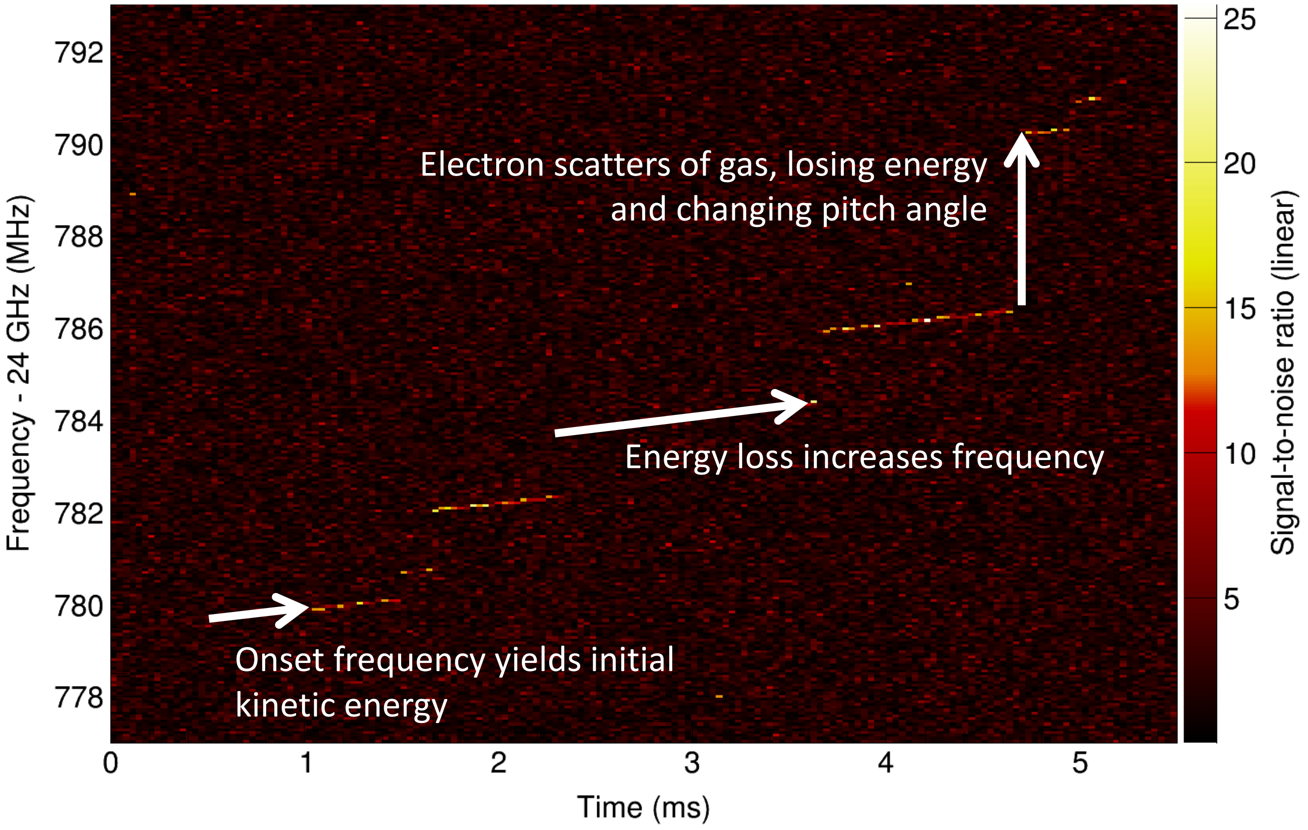




D.M. Asner et al., Phys. Rev. Lett. 114, 162501 (2015)

Project 8 – *proof of concept*

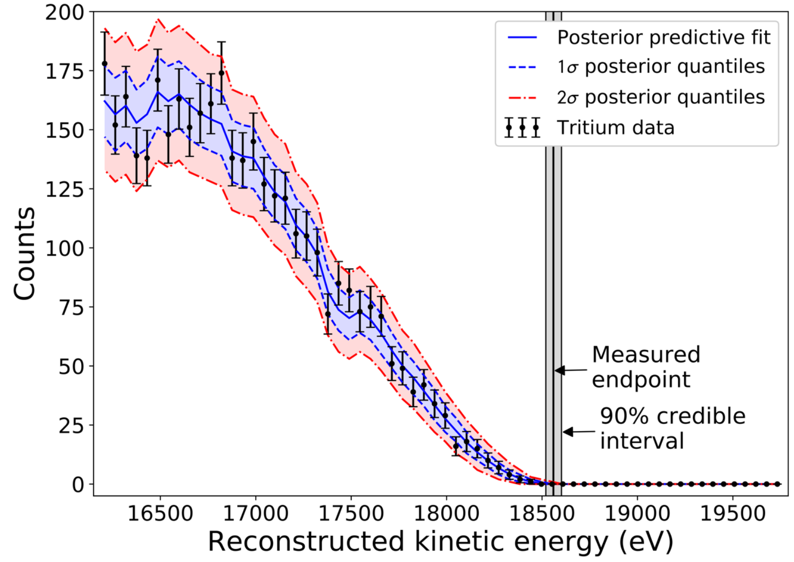




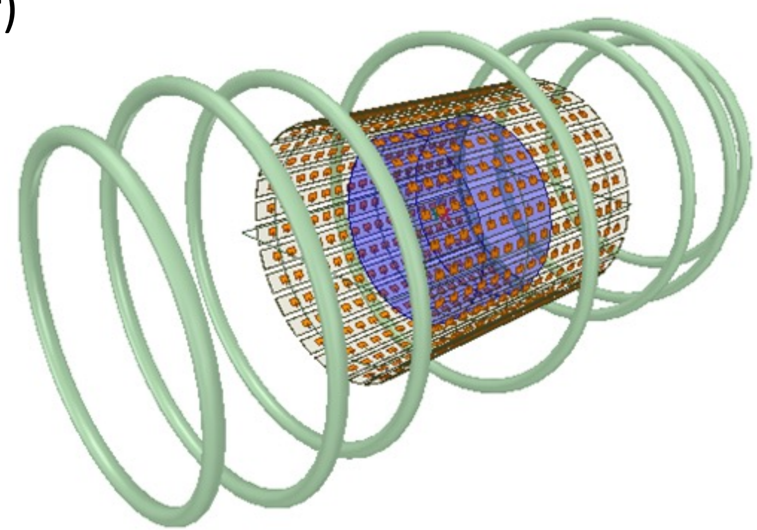
D.M. Asner et al., Phys. Rev. Lett. 114, 162501 (2015)

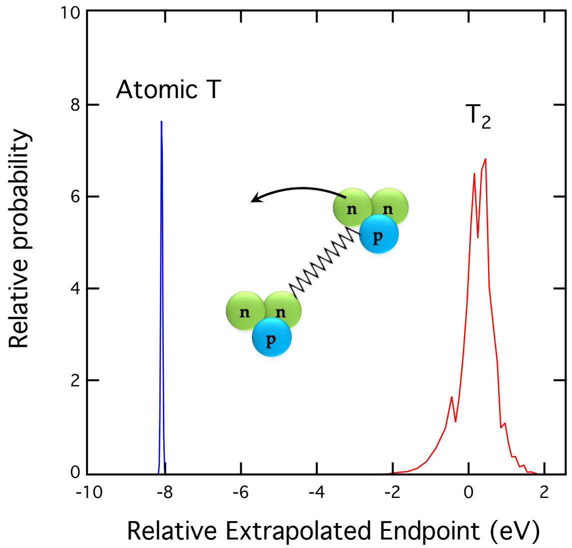
Project 8

- **Recent Achievements**
  - ✓ First tritium spectra measured
    ΔE = 2 eV (FWHM), b < 3 x 10^{-11} eV^{-1} s^{-1}
  - ✓ **First neutrino mass limit: m_{ν} < 185 eV (90% CI.)**
- **Next steps / challenges:**
  - large-volume traps (m^3)
    (antenna array or cavity resonator)
  - develop atomic tritium source
- **Ultimate goal:**
  - 40 meV sensitivity
    arXiv:2203.07349 (2022)

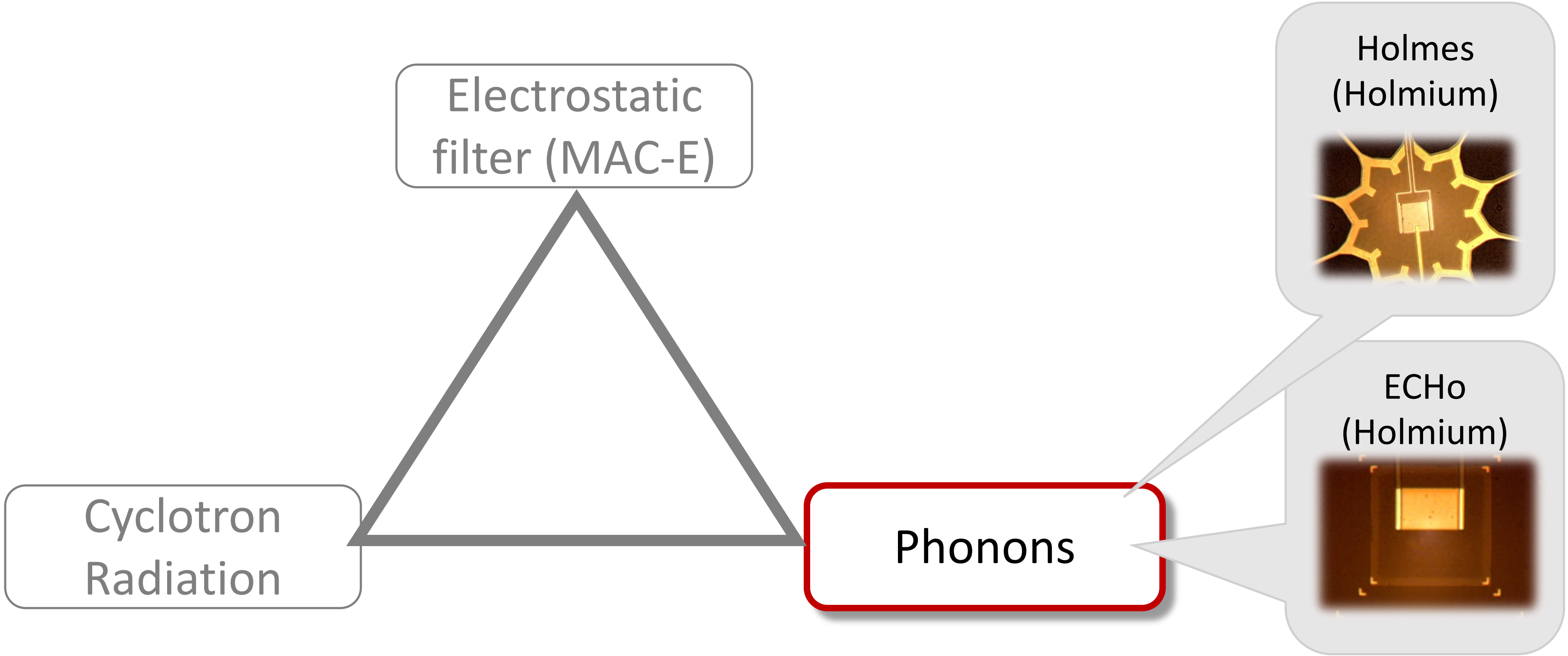


15 cm

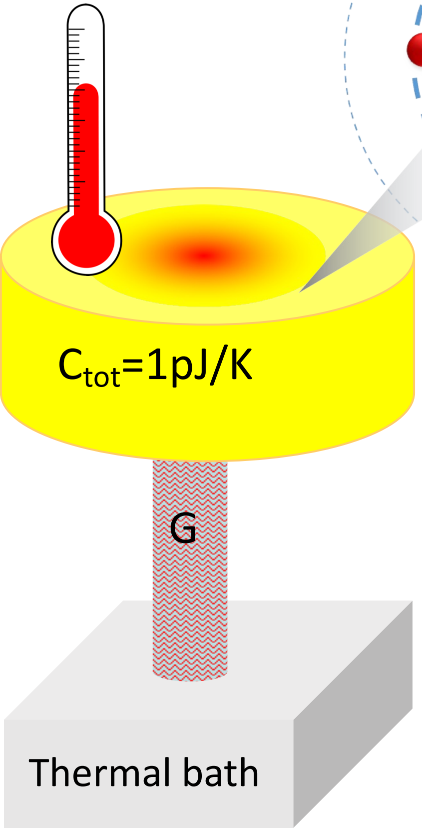


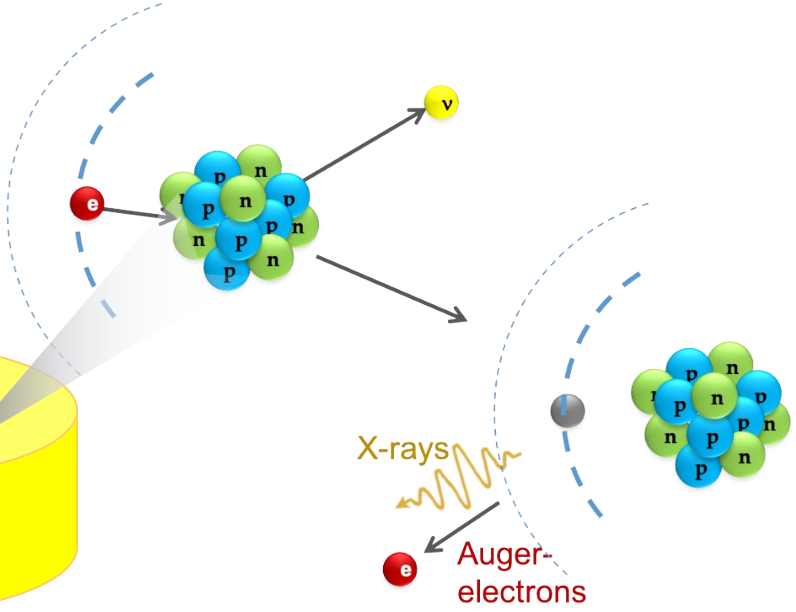


Experimental efforts

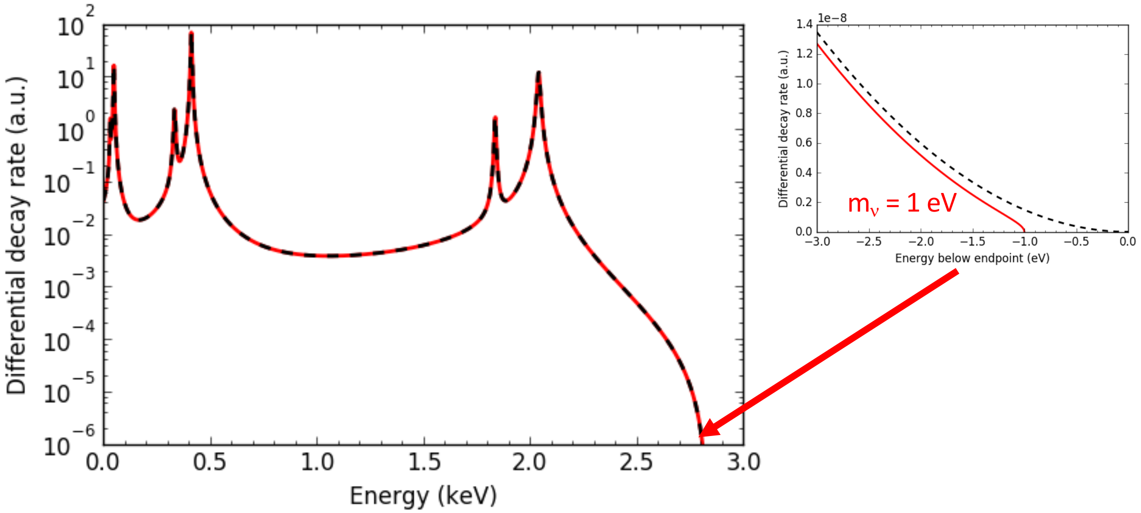


Working principle





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

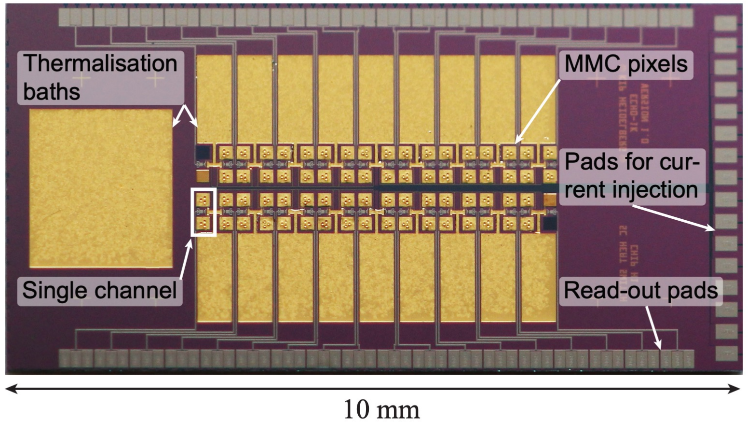


- Low-temperature micro-calorimetry
  A. De Rujula and M. Lusignoli, *Phys. Lett.* **118B** (1982)
- Advantages:
  - ✓ eV-scale differential measurement
  - ✓ „source = detector“ concept

Experiments

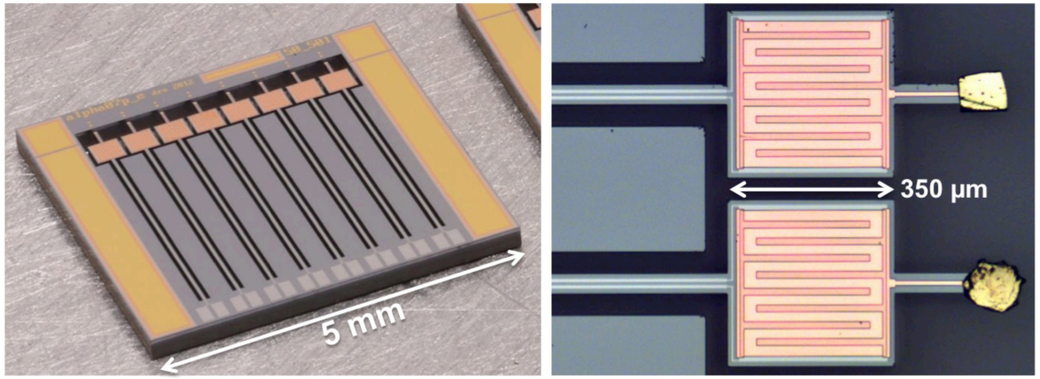
ECHo

- metallic magnetic calorimeters (MMC)
  L. Gastaldo et al. Eur. Phys. J. Spec. Top. 226 (2017)



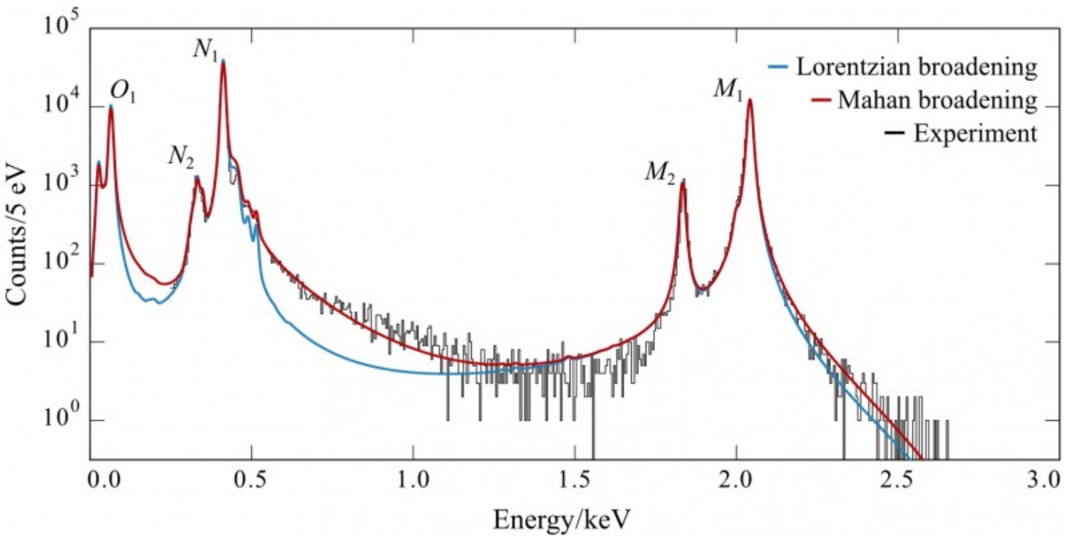
HOLMES

- transition edge sensors (TES)
  J Low Temp Phys **184,** 492–497 (2016)

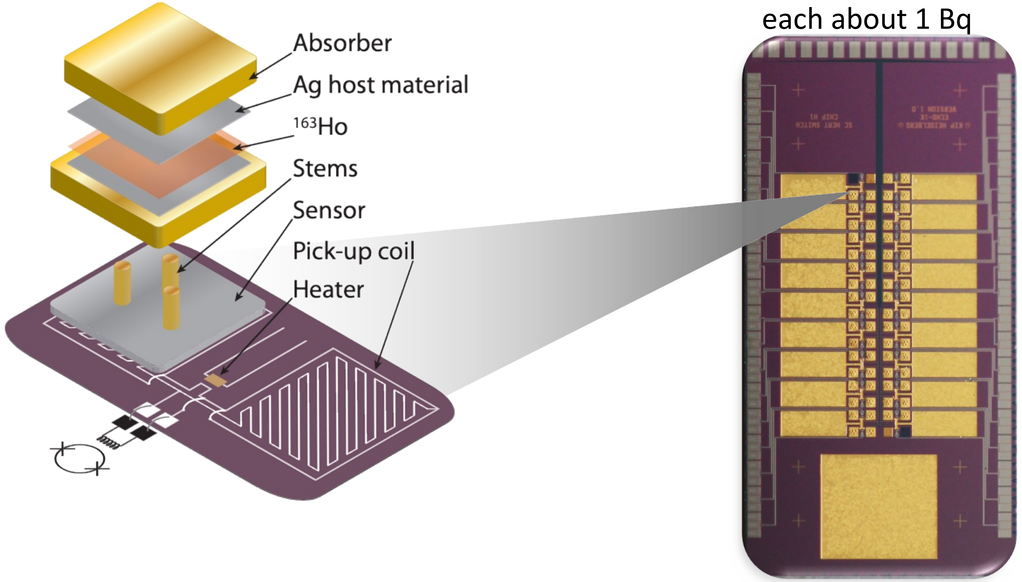


Status - ECHo

- **Achievements**
  - ✓ first holmium spectra measured
    ΔE = 5 eV (FWHM), b < 1.6 x 10^{-4} eV^{-1} $pixel^{-1}$ day^{-1}
  - ✓ first neutrino mass limit: *m* < 150 eV (95% C.L.)
    EPJ-C 79 1026 (2019)
  - ✓ refined theoretical calculations
    Phys.Rev.C 97 (2018) and *New J. Phys.* 22 (2020) 093018
  - ✓ ***Phase-1 of ECHo* completed: ~60 Bq (10^8 events)**
    EPJ-C 81, 963 (2021)
- **Next steps/challenges**
  - Scaling to higher activity per pixel and more pixels
- **Ultimate goal:**
  - 10 MBq (= 10^5 pixel) → low sub-eV sensitivity



60 pixel,
each about 1 Bq



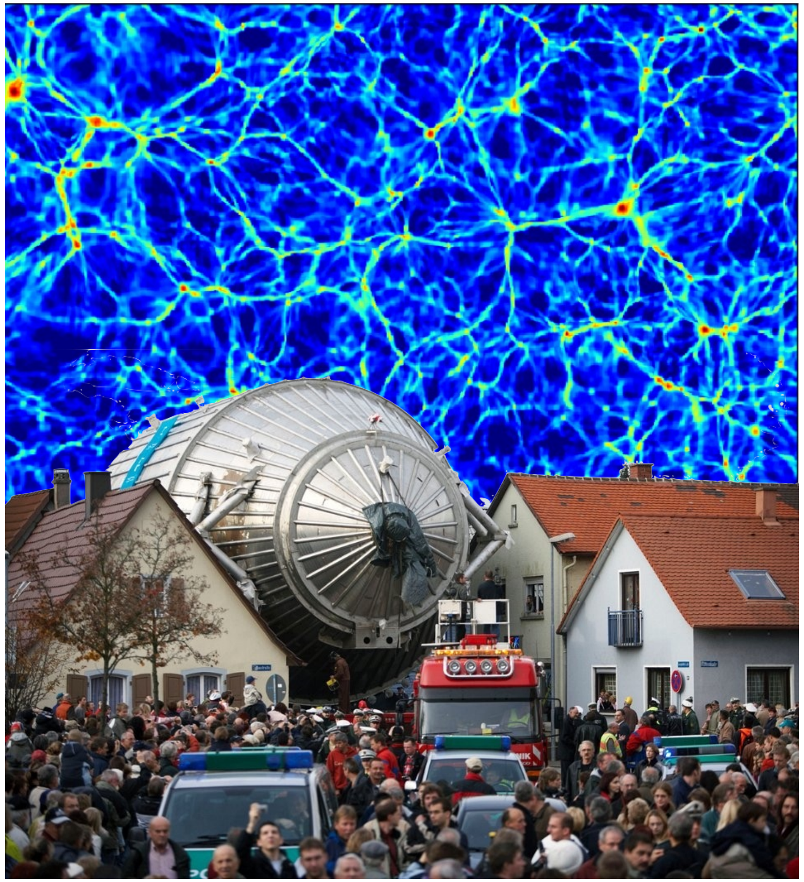
Summary

Cosmology

- Best limits on the neutrino mass so far
- Future missions aim for neutrino mass detection!
- Cosmology measures energy density of hot dark matter

Single beta decay

- Independent of cosmology and neutrino nature
- KATRIN reached the first sub-eV limit and has only started
- Promising ideas to push the sensitivity into the hierarchical neutrino mass regime



Thank you for your attention

Dr. Susanne Mertens

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