New neutrino mass constraints from the KATRIN experiment

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for the KATRIN Collaboration

1. Neutrino masses
2. KATRIN experiment
3. New analysis
4. What happens next?

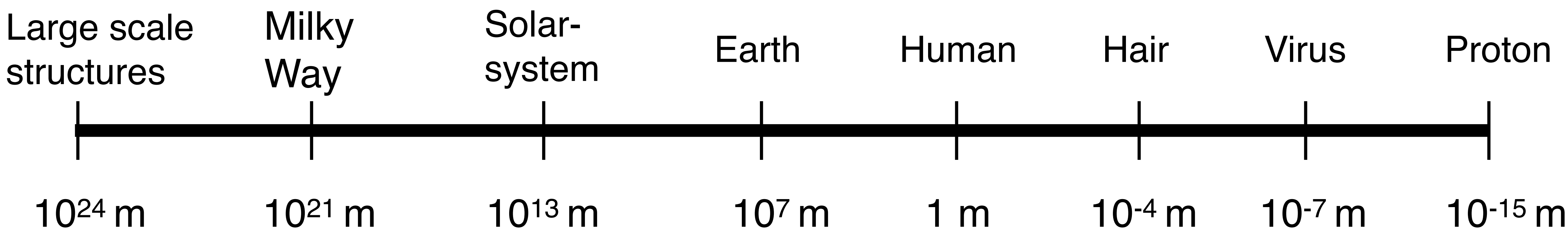
LIP Seminar
virtual, March 24th 2022

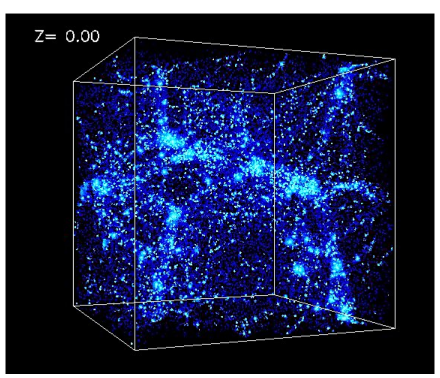
Neutrinos (ν)

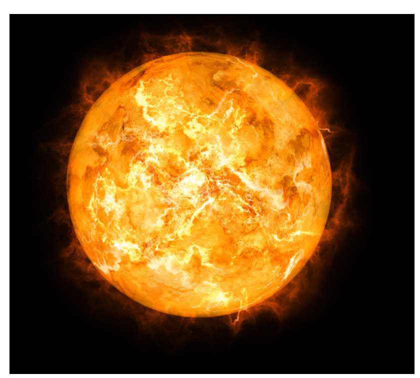
- Most abundant matter particle in the Universe: 336 cm^{-3}
- Influence physics on smallest and largest scales
- Interact only via weak force - difficult to study

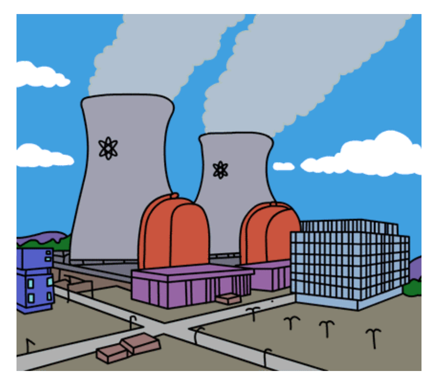
I am an
electron anti-neutrino

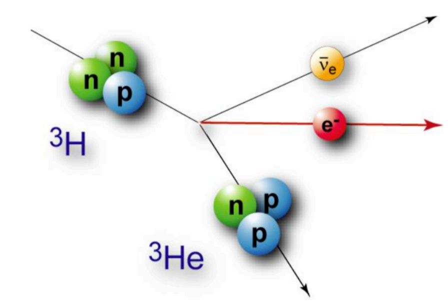
Length scale:





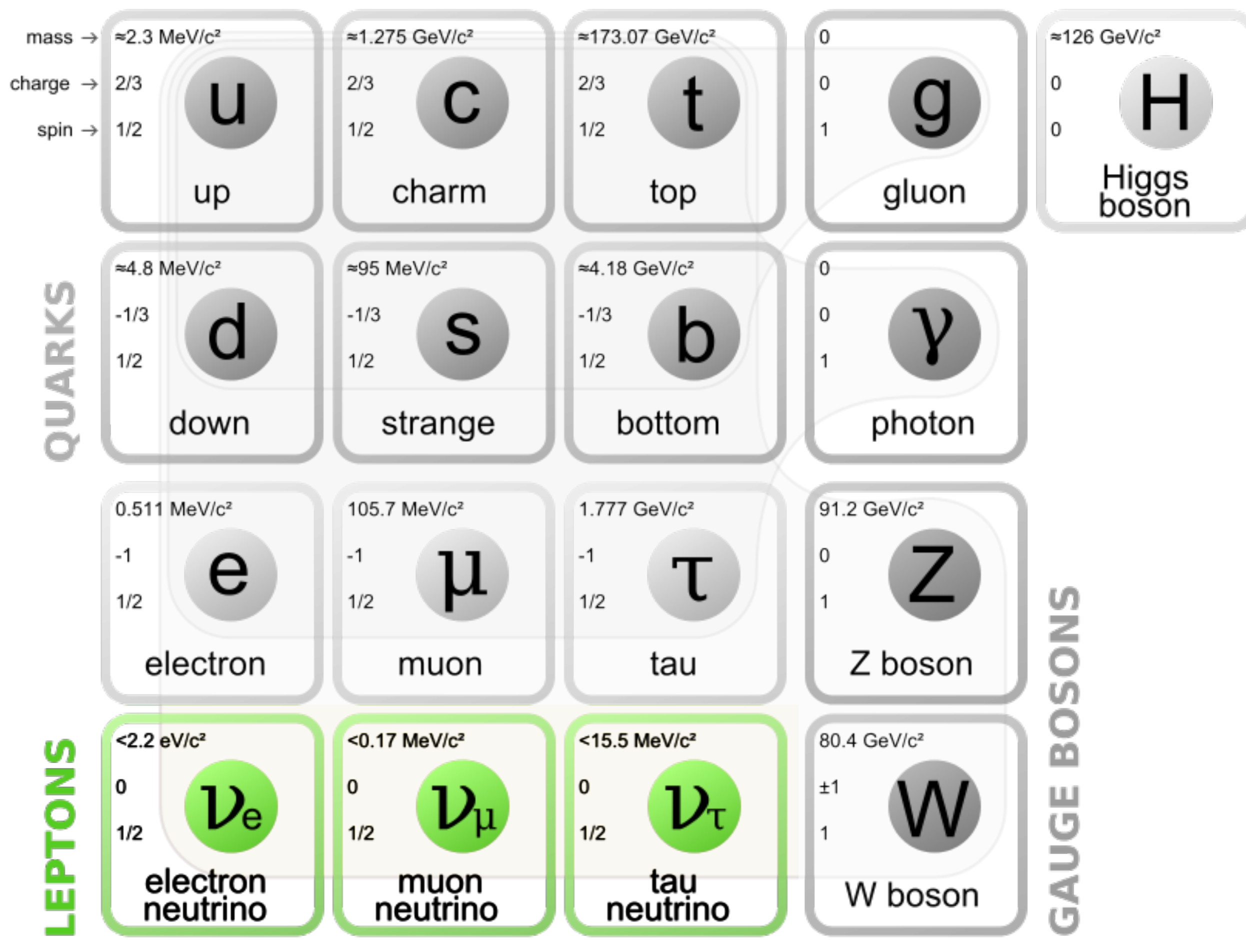


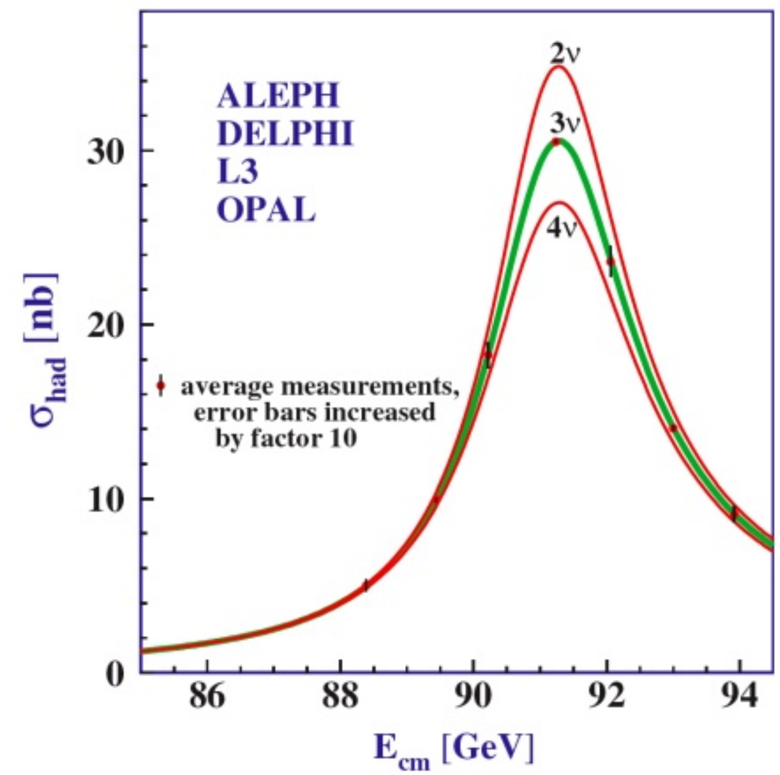




Methods of neutrino physics:
cosmology, particle physics, nuclear physics

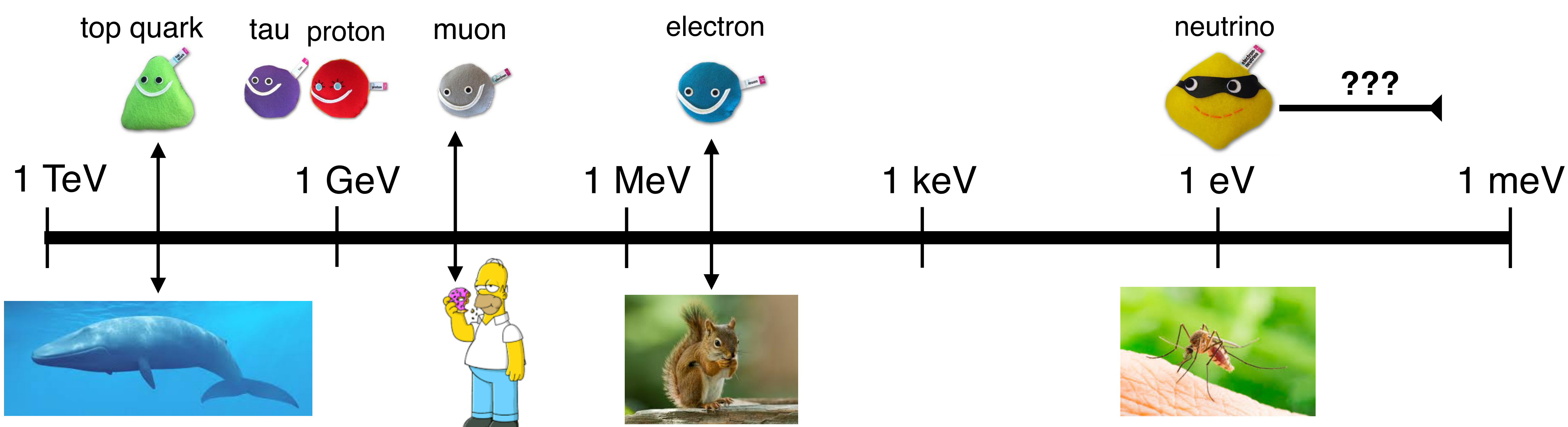
Neutrinos in the Standard Model





- 3 neutrino flavors from Z decay width
- Much lighter than other fermions

Mass scale:



Neutrino Parameters

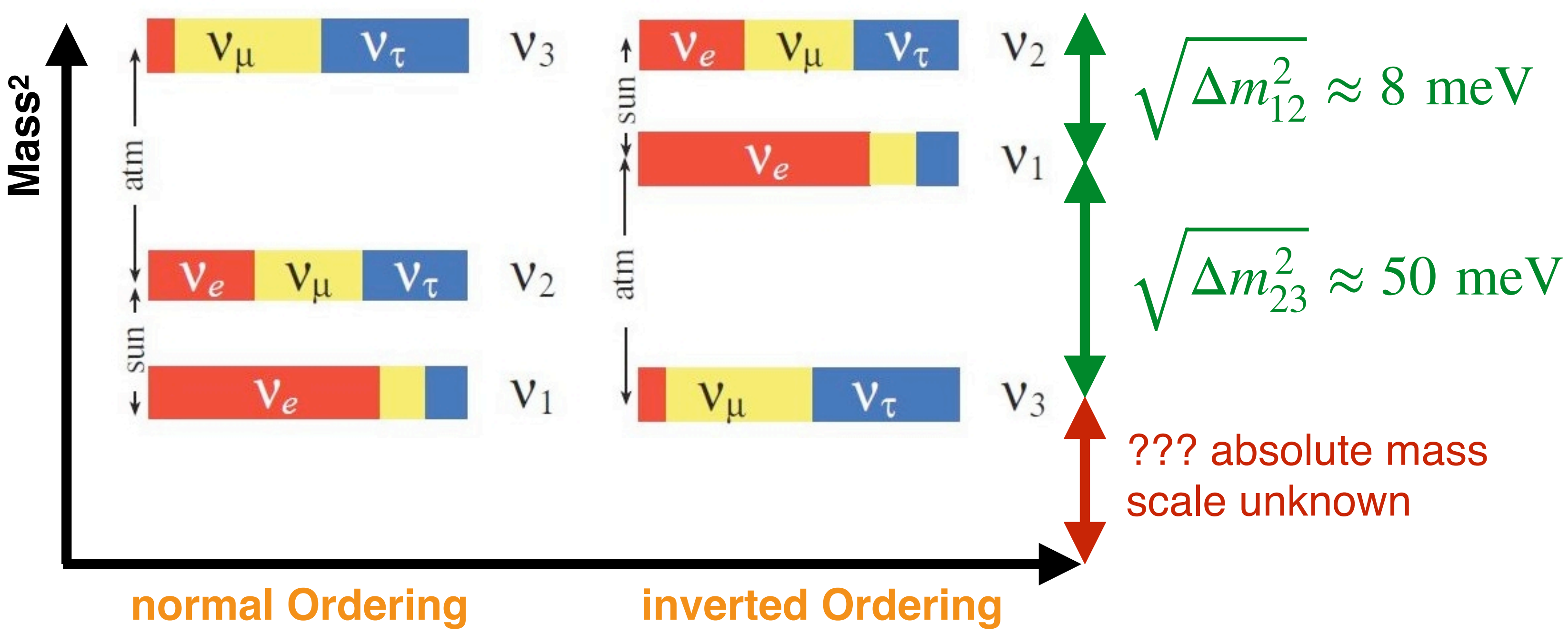
Neutrino oscillation: Mixing of Flavor and mass eigenstates

$$|\nu_{\text{flavor}}> = \sum_i U^*_{\alpha i} \cdot |\nu_{\text{mass}}>$$

PMNS (Pontecorvo-Maki-Nakagawa-Sakata):

$$U_{\alpha i} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c\Theta_{23} & s\Theta_{23} \\ 0 & -s\Theta_{23} & c\Theta_{23} \end{pmatrix} \begin{pmatrix} c\Theta_{13} & 0 & s\Theta_{13} \cdot e^{-i\delta} \\ 0 & 1 & 0 \\ -s\Theta_{13} \cdot e^{-i\delta} & 0 & c\Theta_{13} \end{pmatrix} \begin{pmatrix} c\Theta_{12} & s\Theta_{12} & 0 \\ -s\Theta_{12} & c\Theta_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} 1 & 0 & 0 \\ 0 & e^{-i\alpha/2} & 0 \\ 0 & 0 & e^{-i\beta/2} \end{pmatrix}$$

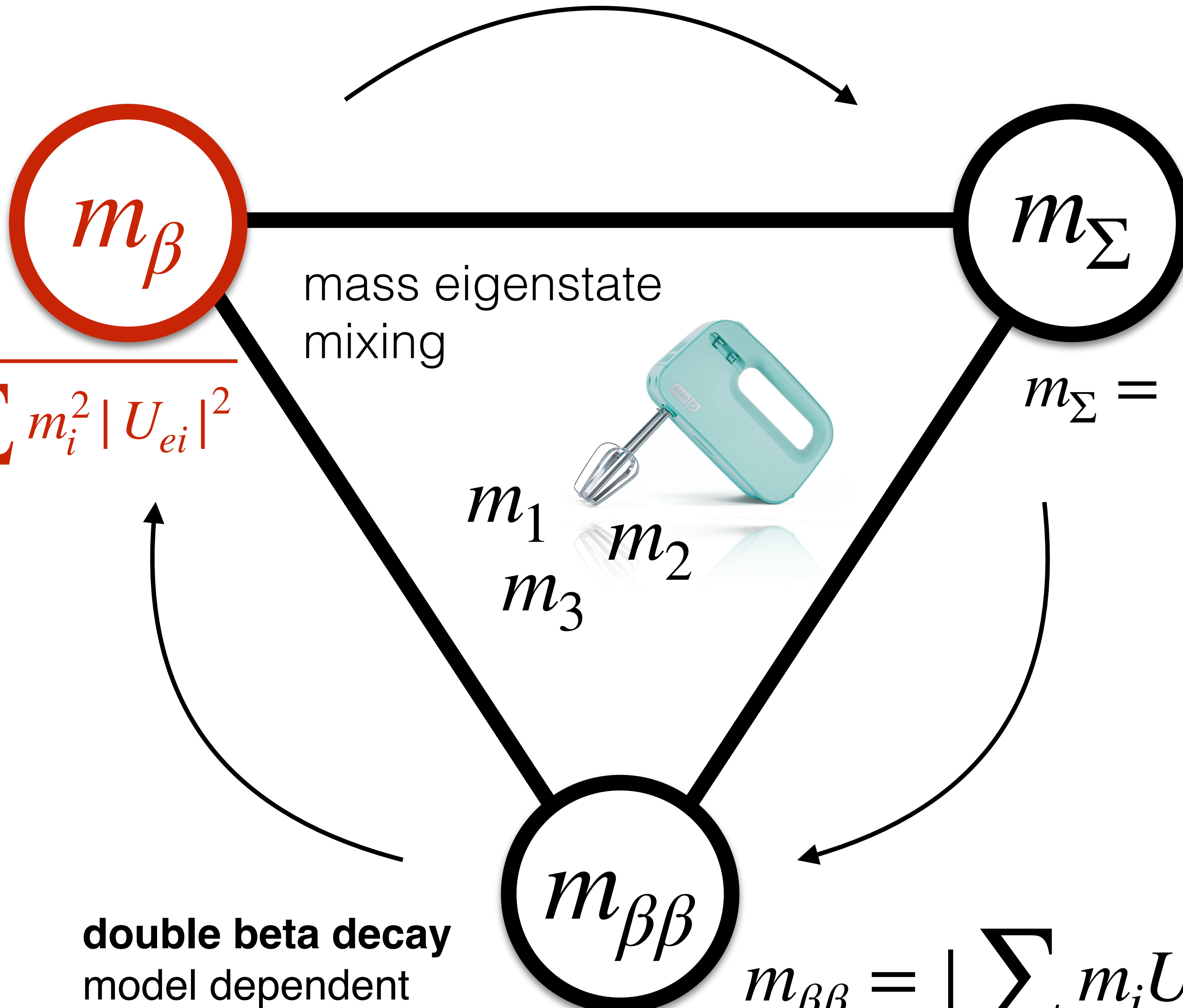
Neutrino masses:



- Precision measurements with oscillation: $\Theta_{12}, \Theta_{13}, \Theta_{23}, \Delta m^2_{12}, \Delta m^2_{23}$
- Upcoming oscillation measurements (subdominant matter effects): CP phase $e^{i\delta}$, ordering $\text{sign}(\Delta m^2_{23})$
- Not accessible with oscillations: absolute mass scale, Dirac ($\nu \neq \bar{\nu}$) or Majorana ($\nu = \bar{\nu}, \alpha, \beta$)

Can be measured in neutrino mass and double beta decay experiments

Different Neutrino Mass Observables



β-decay (kinematic)
model independent

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

cosmology
model dependent
- ΛCDM

$$m_\Sigma = \sum_i m_i$$

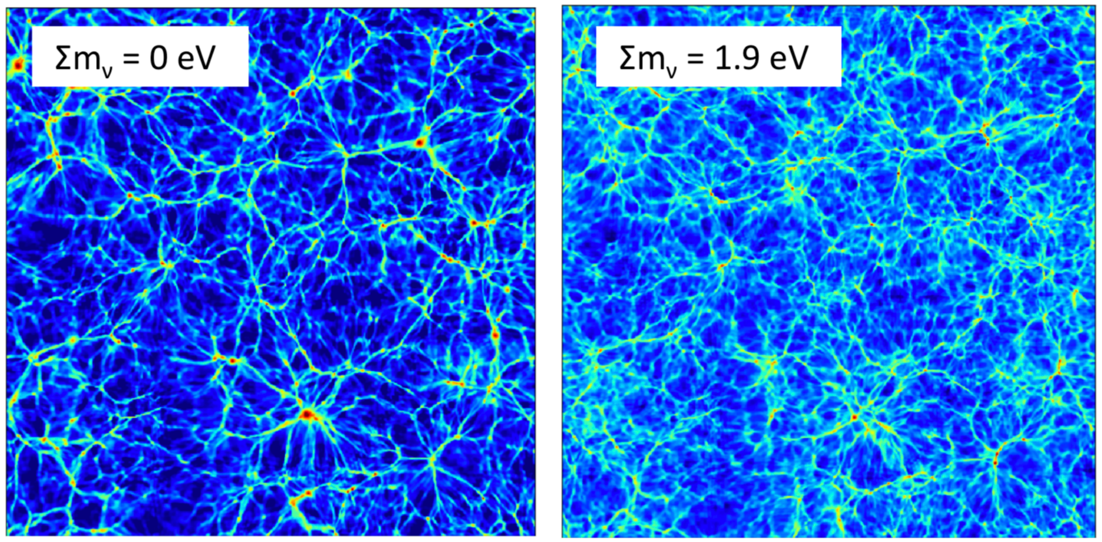
double beta decay
model dependent
- lepton number violation
- light Majorana neutrino exchange

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

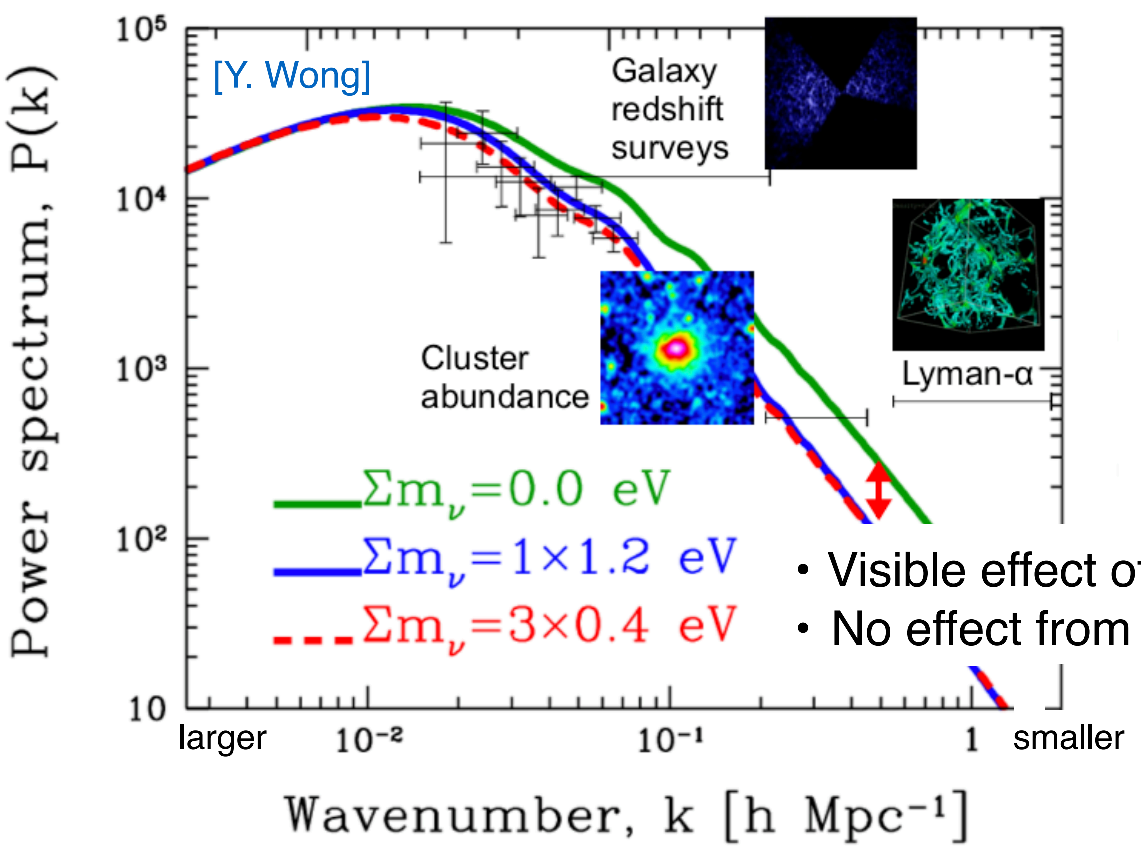
Cosmological m_Σ Signatures

Matter distributions influenced by m_Σ

Heavy neutrinos wash out gravitational wells
and disfavor small structures



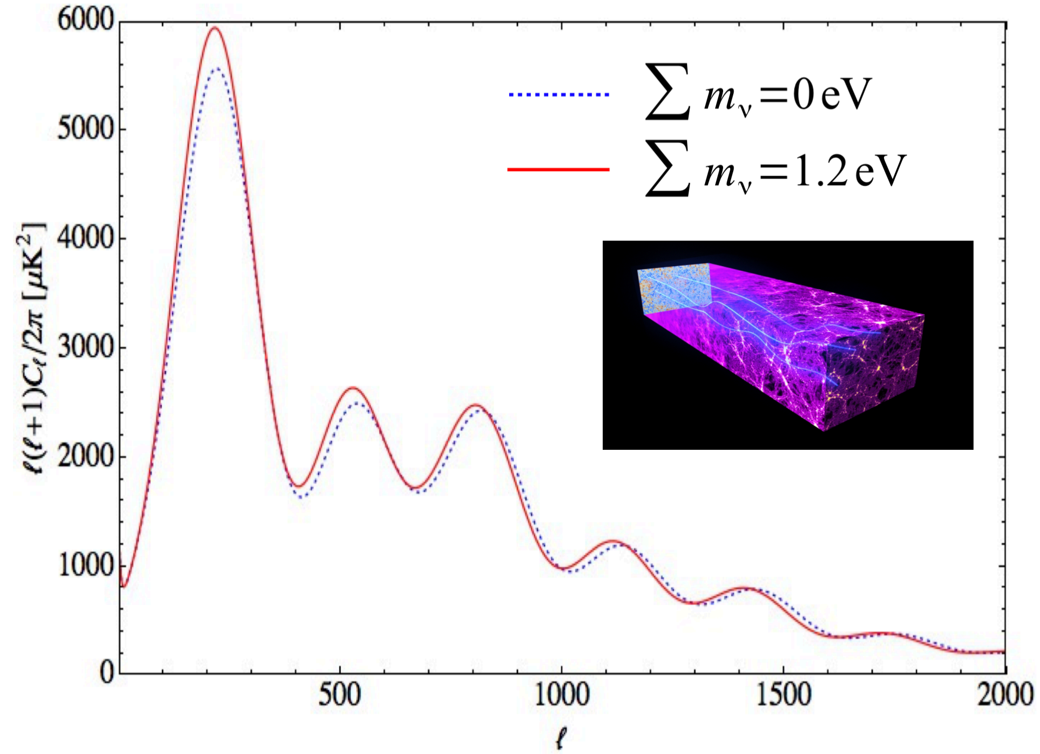
power spectrum of matter distribution



- Visible effect of m_Σ
- No effect from flavor

Cosmic microwave background (CMB) influenced by m_Σ

CMB anisotropies / lensing



Current limits: [arXiv:1807.06209v2]
- $m_\Sigma < 120$ meV (95% CL) Planck + BAO
- tightest bound on neutrino mass

Future limits:
- $m_\Sigma \sim 20$ meV (CMB-S4 + BAO)
- mass ordering with 2-4 σ

(assuming ΛCDM)

Neutrinoless Double Beta Decay

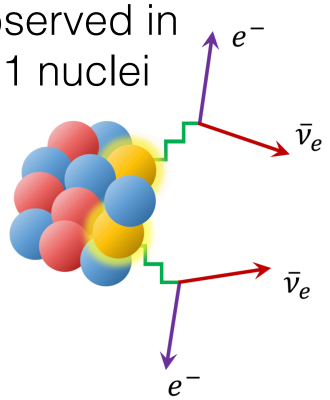
Double beta decays:

$$2\nu\beta\beta : (Z, A) \rightarrow (Z+2, A) + 2e^- + 2\bar{\nu}_e$$

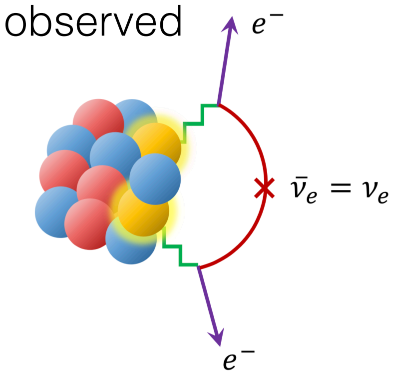
$$0\nu\beta\beta : (Z, A) \rightarrow (Z+2, A) + 2e^-$$

lepton number violation
majorana neutrinos

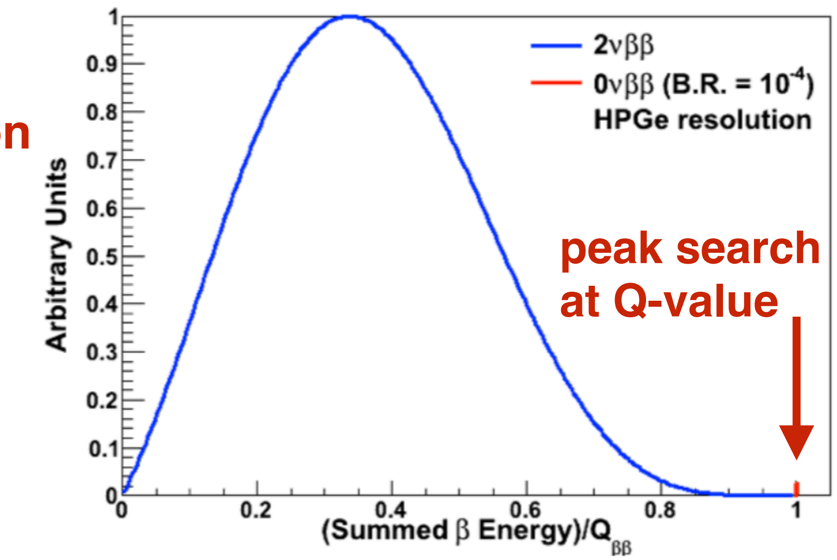
observed in 11 nuclei



to be observed



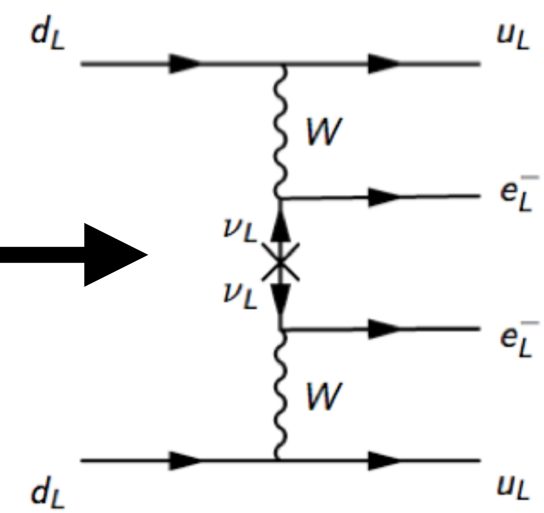
Experimental signature:



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

nuclear models to convert $T_{1/2}$ to $m_{\beta\beta}$

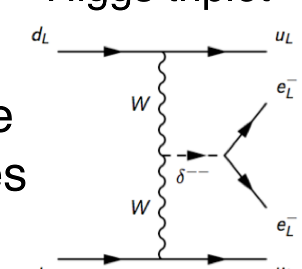
light Majorana neutrinos



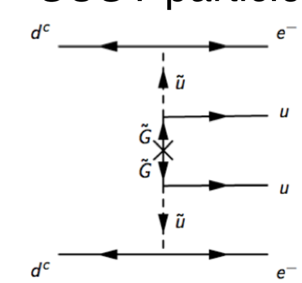
- Neutrino mass only probed under assumption of light Majorana neutrino exchange
- Nuclear model uncertainties to convert measured $T_{1/2}$ to $m_{\beta\beta}$
- Current limits: 60-170 meV
- Future limits: 9-21 meV

other possible LNV processes

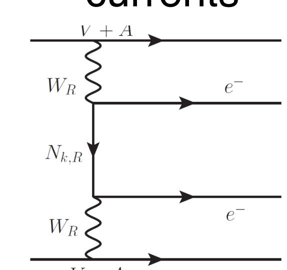
Higgs triplet



SUSY particle

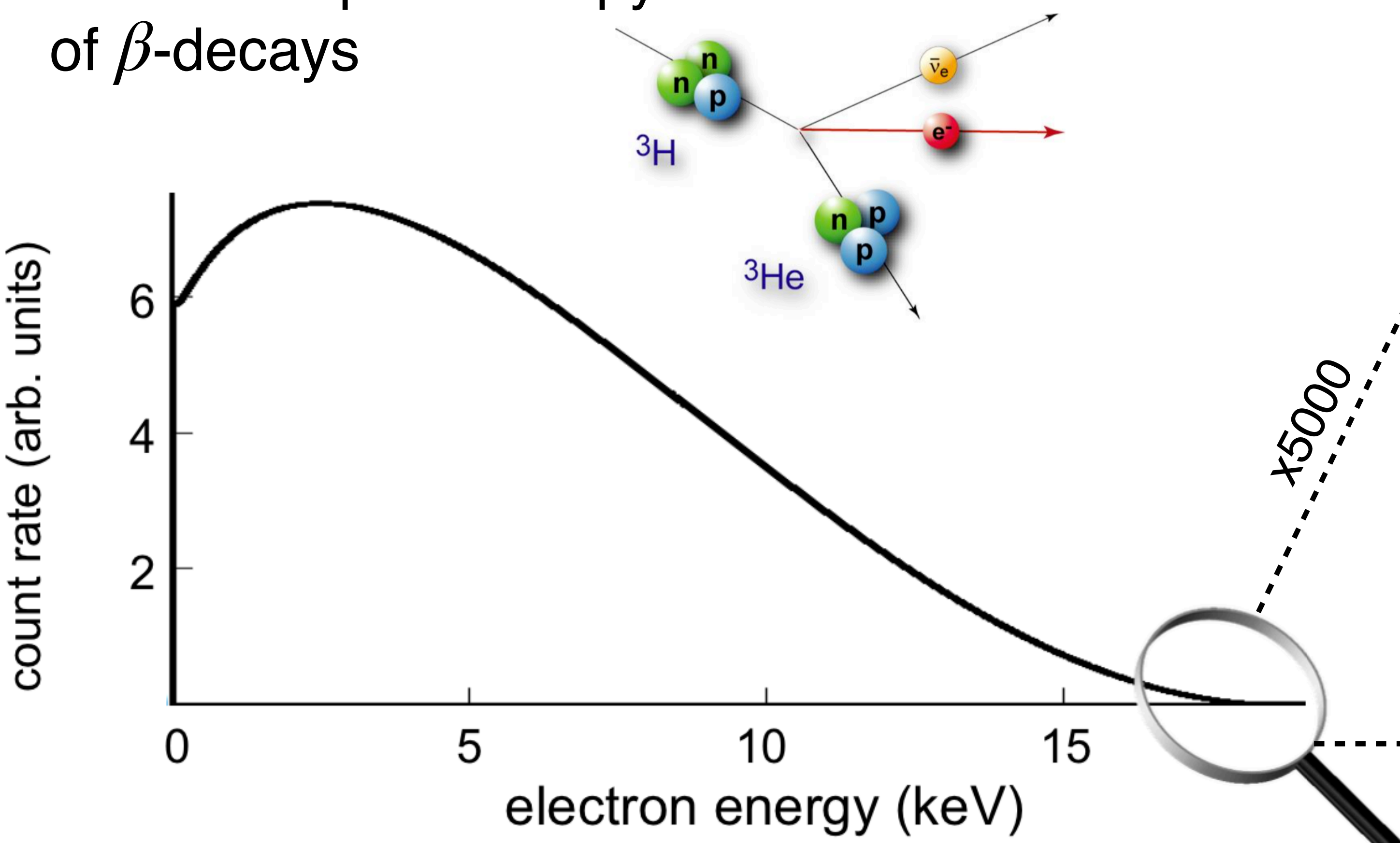


right handed currents



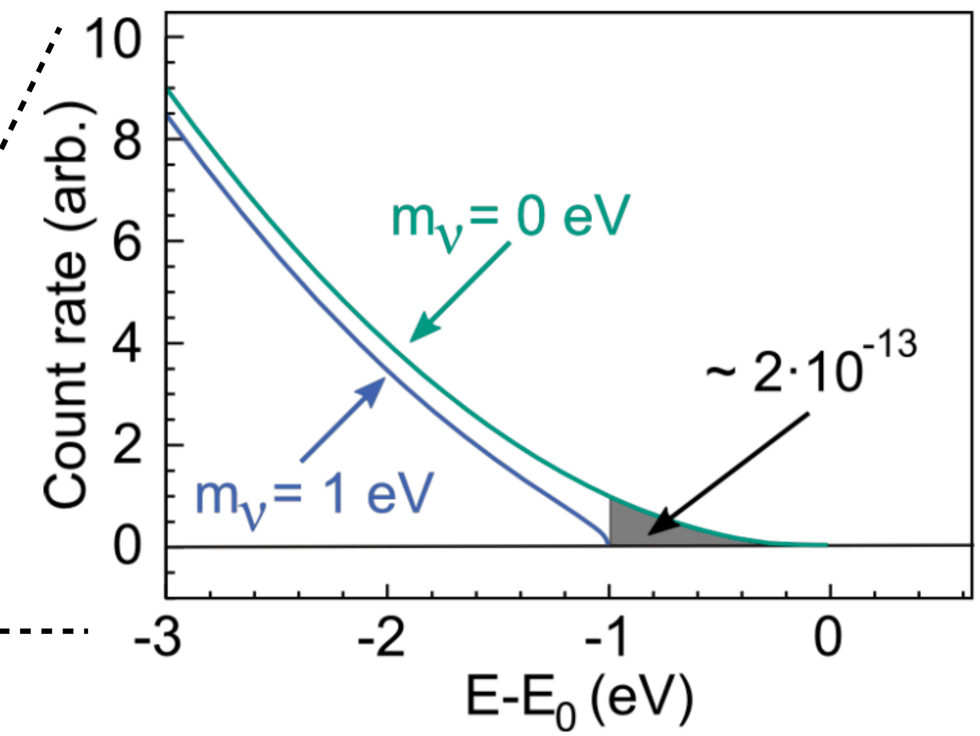
Beta Decay Measurements

Precision spectroscopy of β-decays



Experimental signature:

- Spectral distortion at endpoint



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

- Appears in β-spectrum:

$$\frac{d\Gamma}{dE_e}(m_{\nu_i}) = C \cdot p_e E_e \cdot \sqrt{(E_e - E_0)^2 - m_{\nu_i}^2} \cdot (E_e - E_0) \cdot F(E_e, Z)$$

normalization — Observable — Relativistic Fermi function

- No model dependence (only kinematics)

Experimental Challenges:

- High resolution
- Low background
- Convenient isotope: half-life, Q-value

^{3}H (12 yr, 18.6 keV), ^{163}Ho (4600 yr, 2.8 keV)

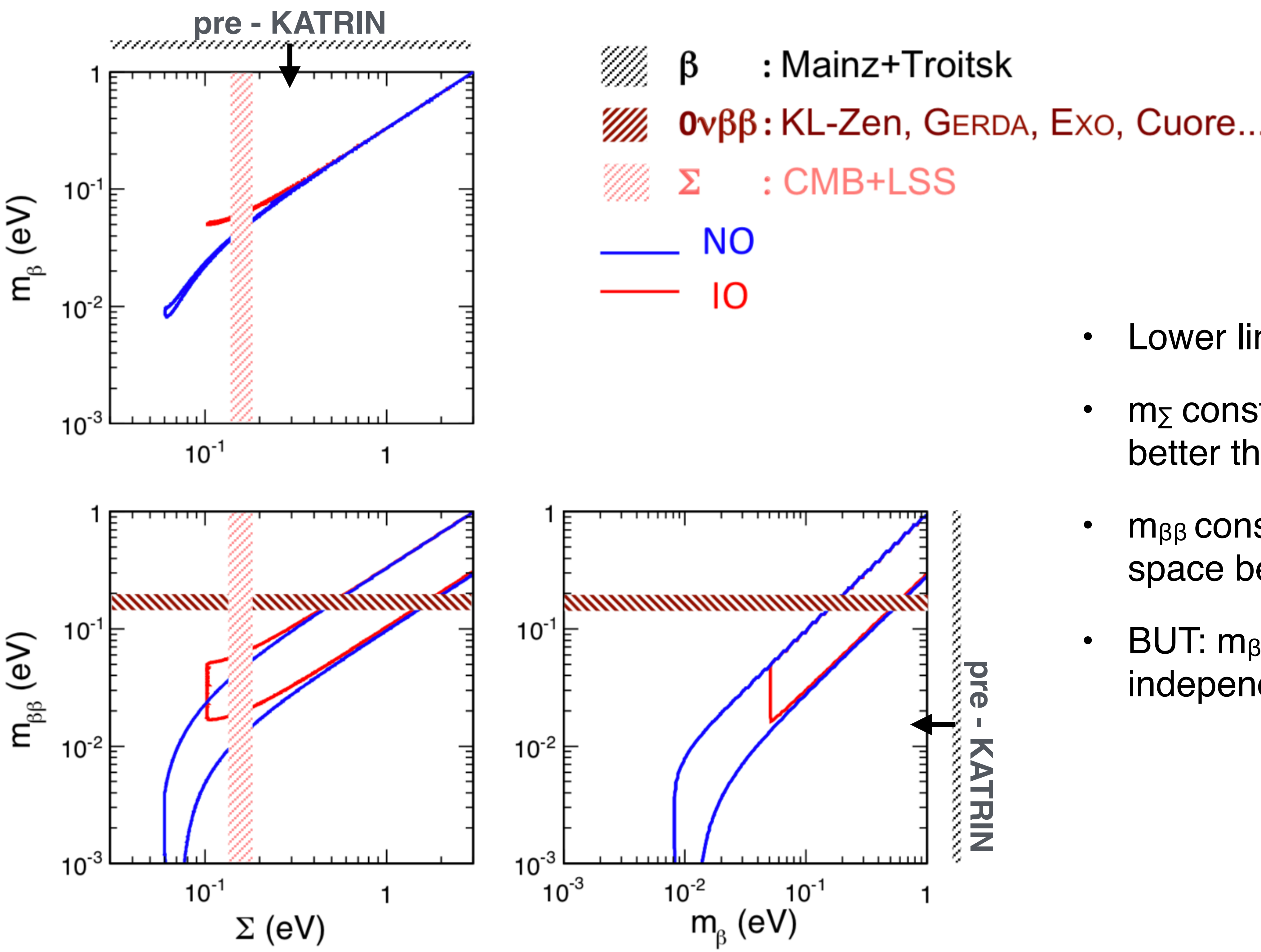
Other kinematic limits [pdg]**:**

- SN1987: $m_{\nu_e} < 5.8$ eV
- π-decay: $m_{\nu_\mu} < 190$ keV
- τ-decay: $m_{\nu_\tau} < 18.2$ MeV

Global Picture pre-Katrin (2019)

(assuming no sterile neutrinos)

[from Eligio Lisi, TAUP19]

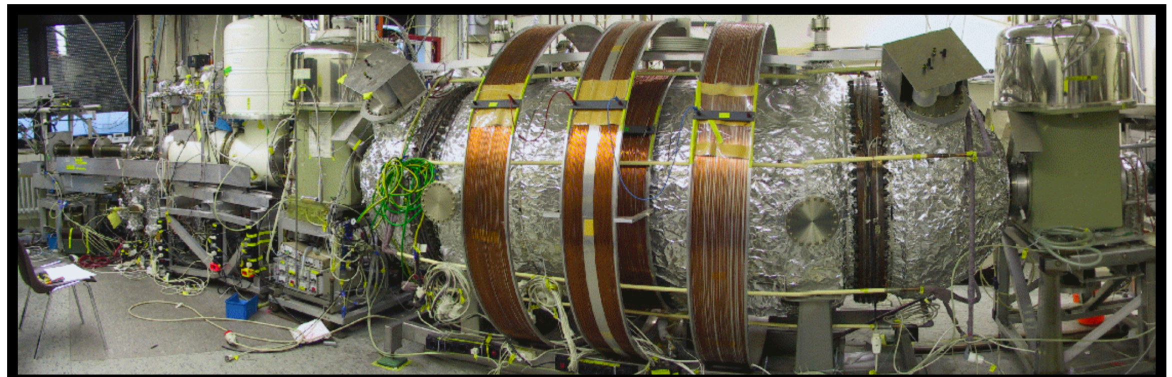


- Lower limit on m_β at 8 - 50 meV
- m_Σ constrains parameter space better than m_β
- $m_{\beta\beta}$ constrains parameter space better than m_β
- BUT: m_β is the only model independent measurement

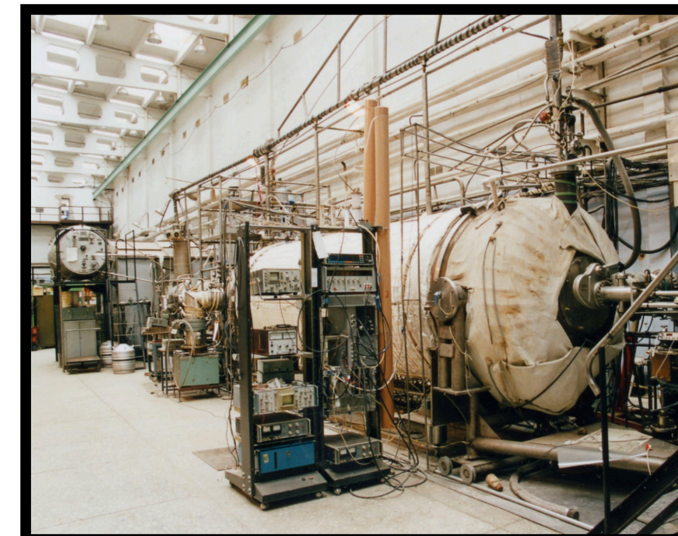
History of Neutrino Mass Measurements

Los Alamos Tritium Experiment
Gaseous T_2 source: $m_\nu < 9.3$ eV

Mainz Neutrino Mass Experiment
MAC-E filter, solid state T_2 source: $m_\nu < 2.3$ eV



Troitsk Neutrino Mass Experiment
MAC-E filter, gaseous T_2 source:
$m_\nu < 2.05$ eV



Hanna & Pontecorvo, Phys. Rev. 75, 983 (1949)
Proportional counter: $m_\nu < 500$ eV

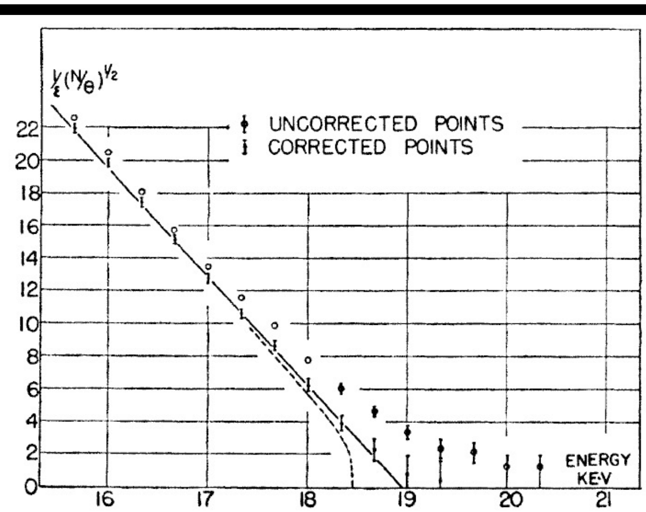
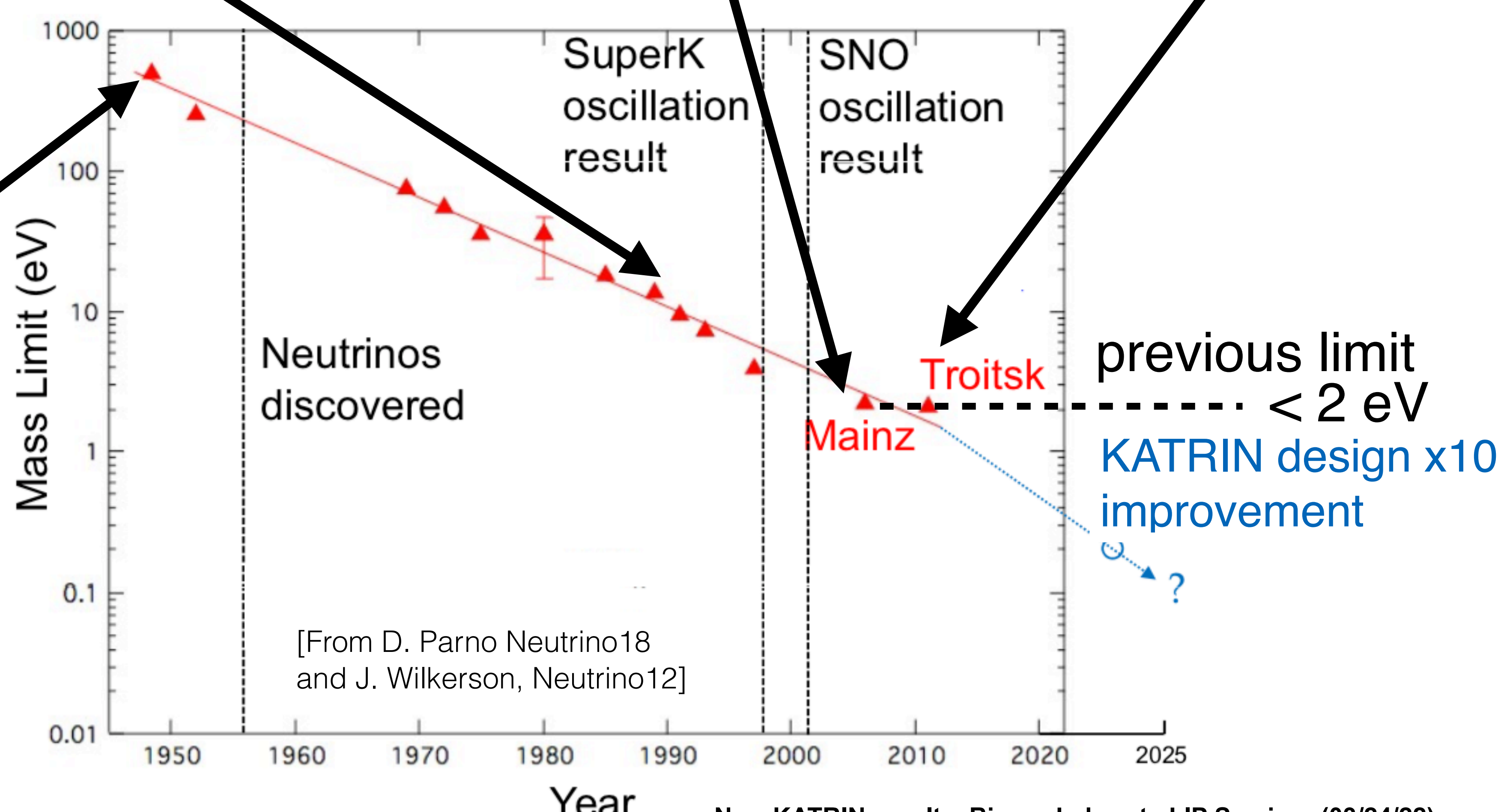
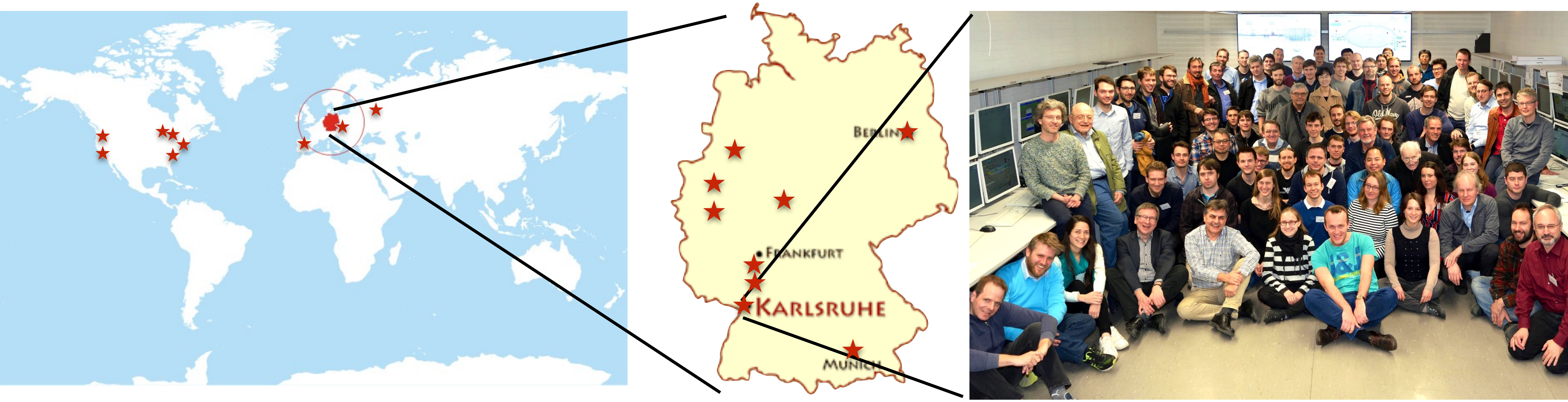


FIG. 2. "Kurie" plot of the end of the H³ spectrum. The theoretical curve (shown dotted) corresponding to a finite neutrino mass of 500 ev (or 1 kev —see text) has been included for comparison.



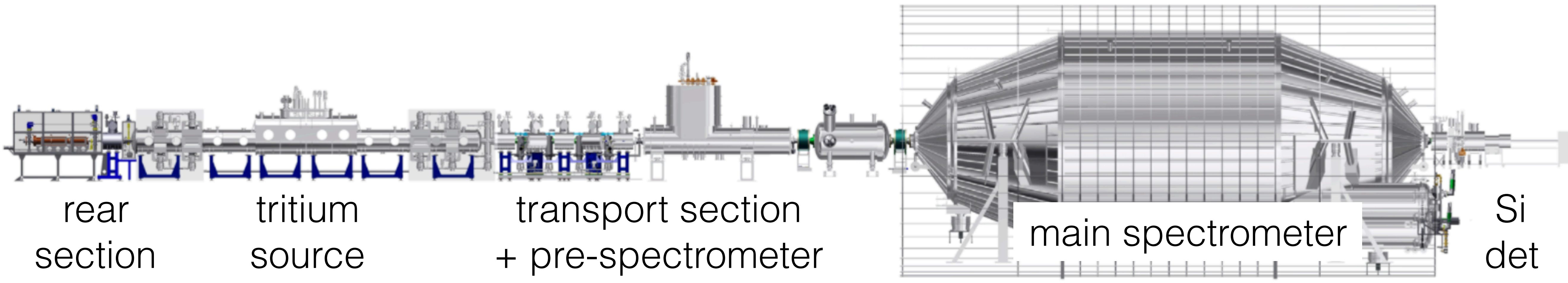
KATRIN - KArlsruhe TRItium Neutrino Experiment



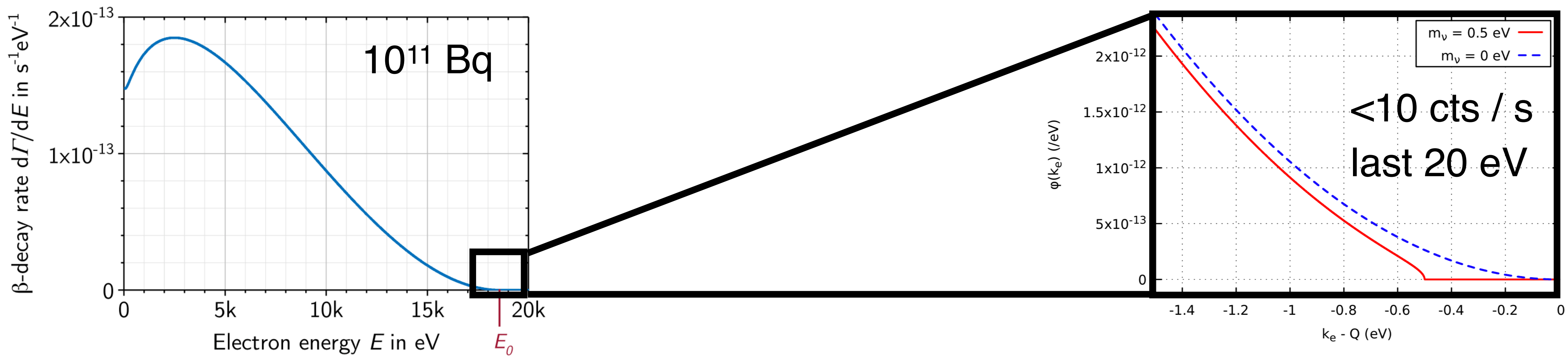
130 scientists in 20 institutions from 5 countries

Funding and support from: **Helmholtz Association** (HGF), **Ministry for Education and Research BMBF** (05A17PM3, 05A17PX3, 05A17VK2, and 05A17WO3), **Helmholtz Alliance for Astroparticle Physics** (HAP), and **Helmholtz Young Investigator Group** (VH-NG-1055) in Germany; **Ministry of Education, Youth and Sport** (CANAM-LM2011019), cooperation with the **JINR Dubna** (3+3 grants) 2017–2019 in the Czech Republic; and the **Department of Energy** through grants DE-FG02-97ER41020, DE-FG02-94ER40818, DE-SC0004036, DE-FG02-97ER41033, DE-FG02-97ER41041, DE-AC02-05CH11231, and DE-SC0011091 in the United States.

The KATRIN Beamline

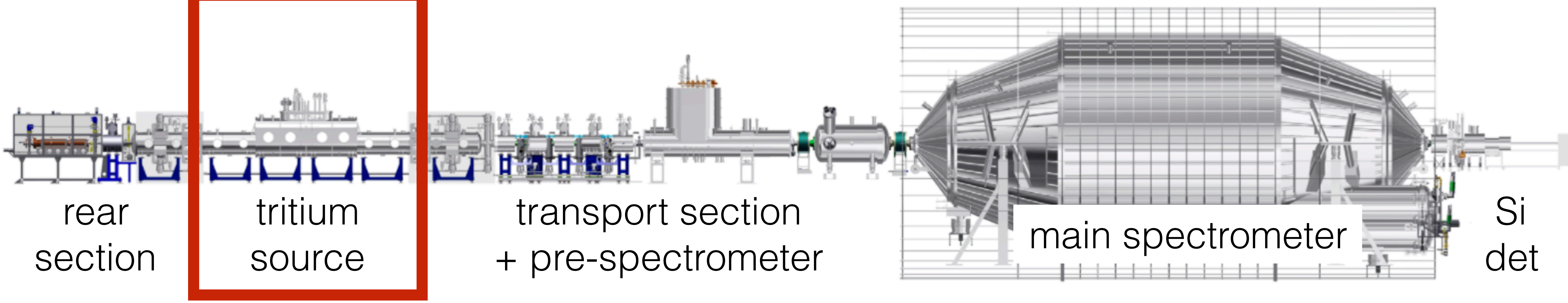


70 m beam line



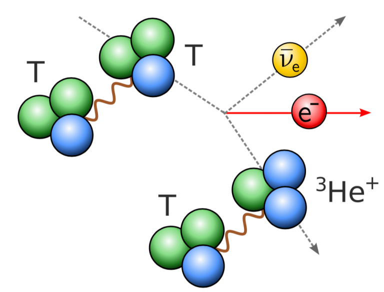
integral spectrum
at endpoint

The KATRIN Beamline: Source



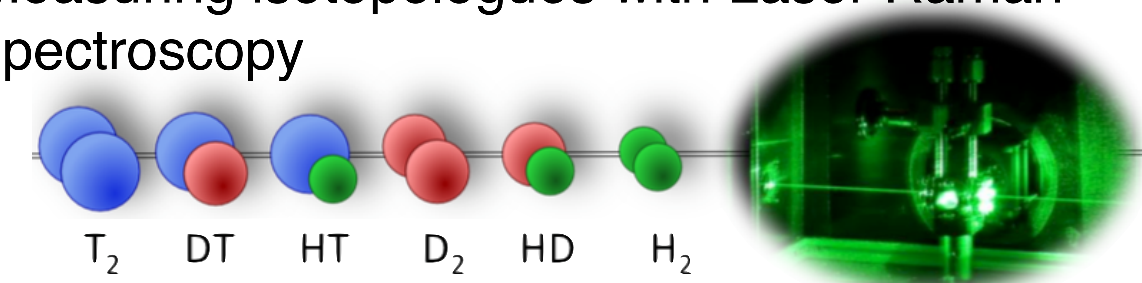
Tritium:

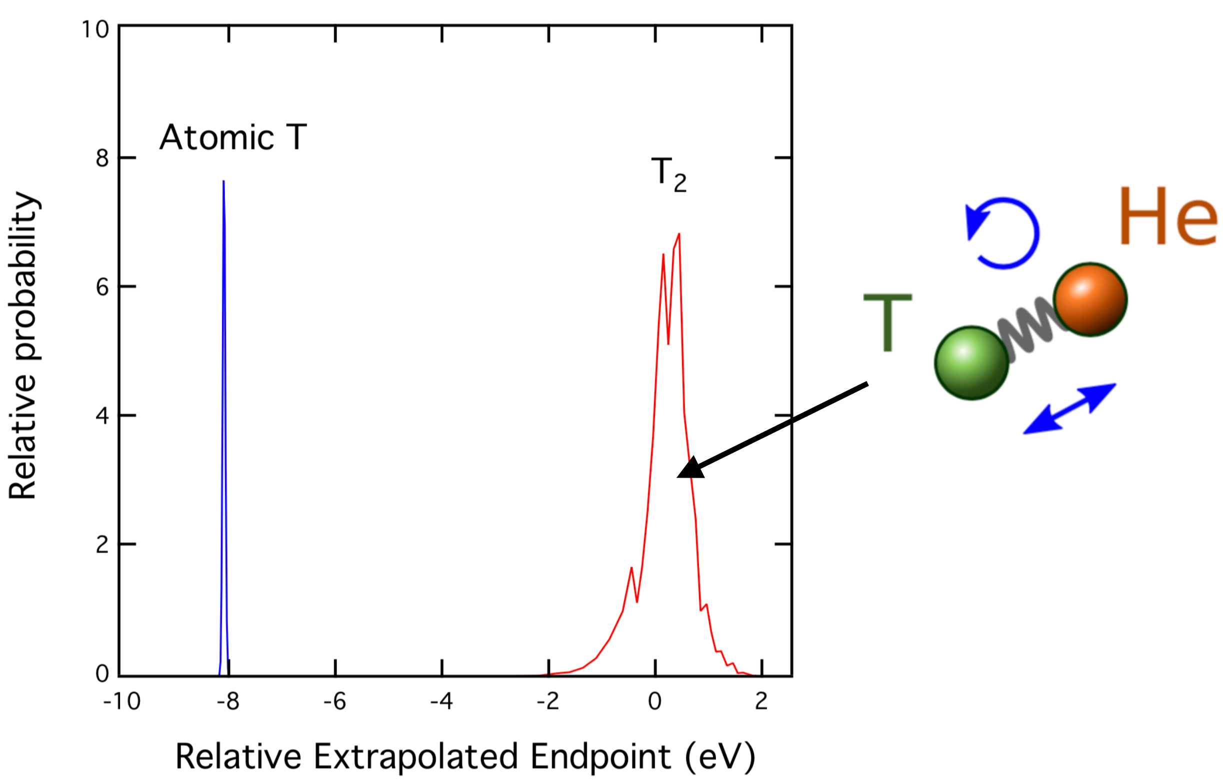
- $T_{1/2}$ = 12.3 yr
- Q-value 18.6 keV (m_ν <0.0002 keV)
- Super allowed beta decay

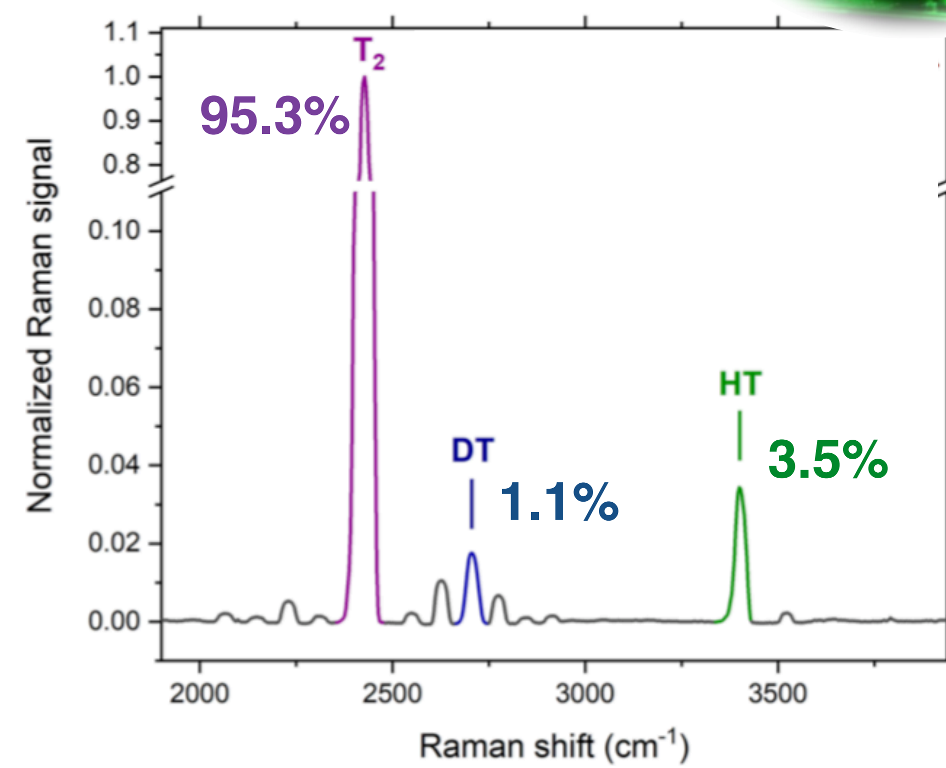


Molecular tritium:

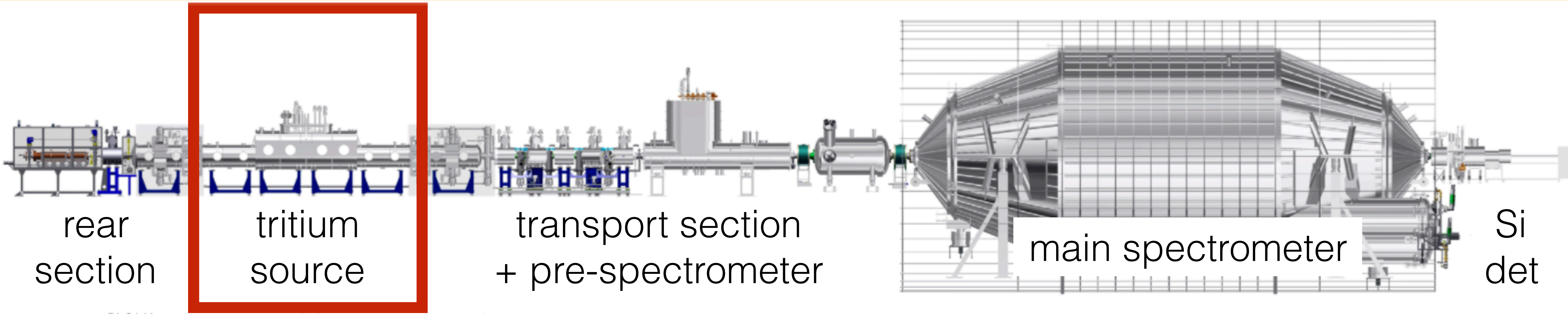
- Complicated final state distribution
- Measuring isotopologues with Laser Raman spectroscopy





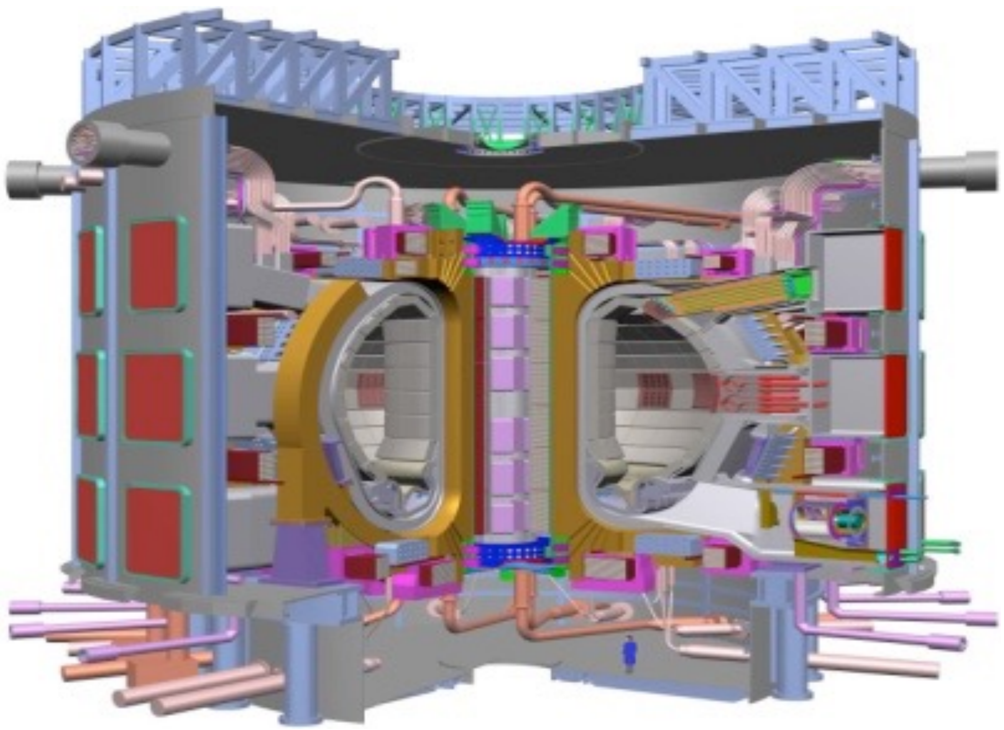


The KATRIN Beamline: Source



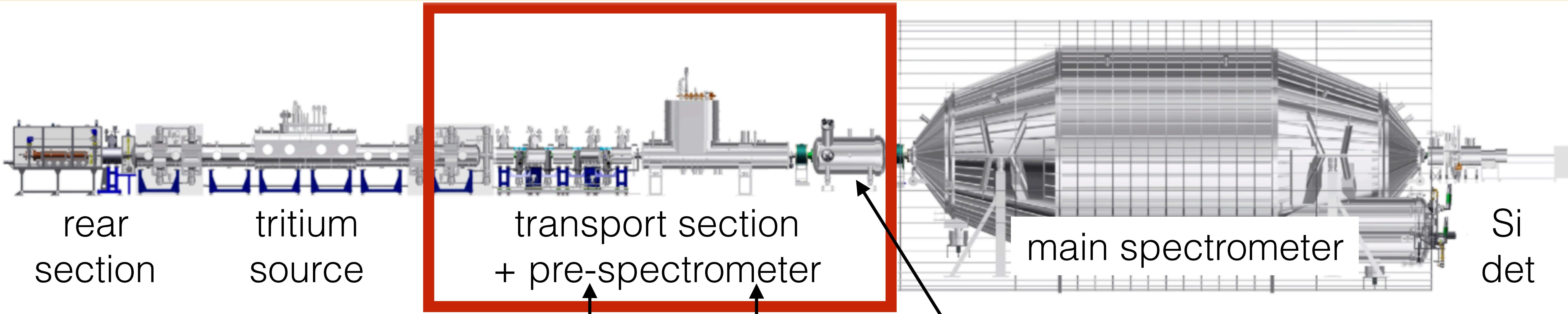
Windowless gaseous tritium source:

- Up to 40 g tritium throughput per day
- 10^{17} molecules / cm^2
- Highest T throughput worldwide
  - (20 kg world inventory)
- Continuous circulation to achieve constant high tritium purity >95%



T_2 throughput similar to ITER fusion reactor

The KATRIN Beamline: Transport Section



Transport section:

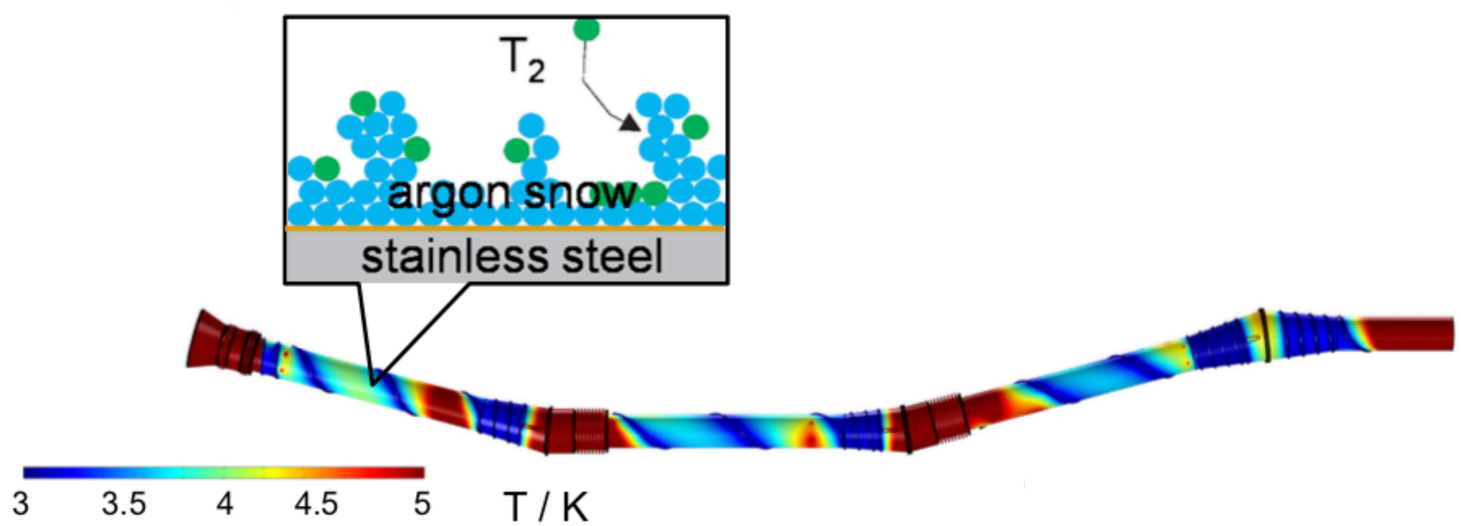
- Adiabatic electron transport
- Remove tritium by factor 10^{14}
- Monitoring of beam intensity
- Calibration source deployment

Pre-spectrometer:

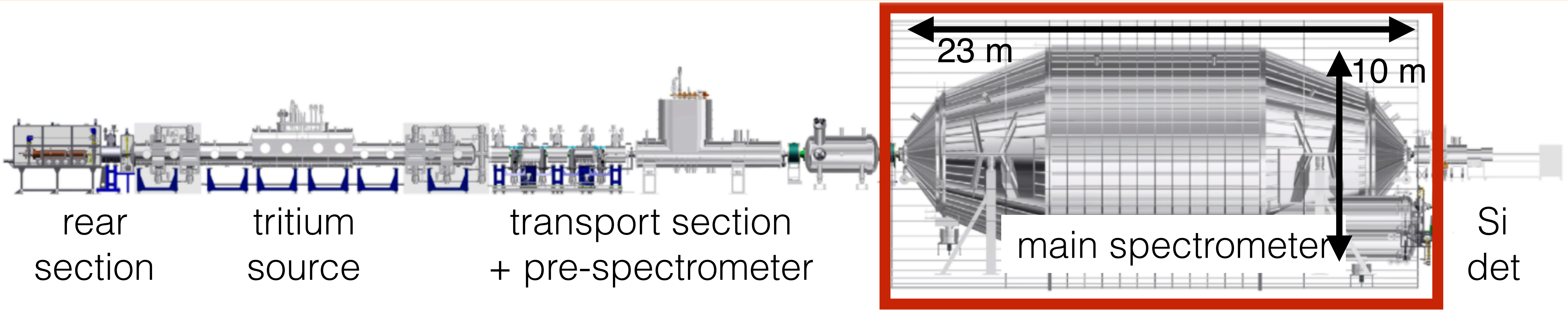
- Remove bulk of low energy electrons to ≈1000 e^-/s

1. Differential pumping with 12 TMP (x10^7)

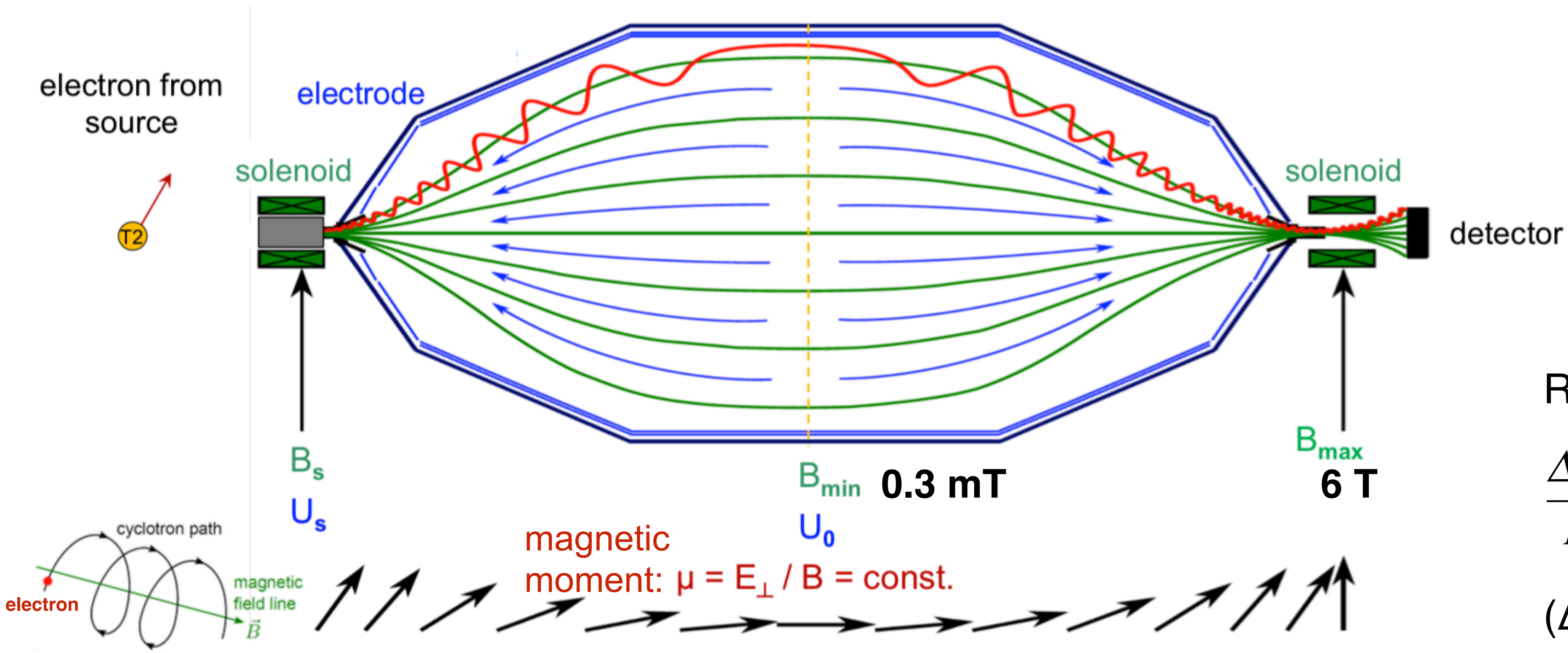
2. Cryogenic pumping with argon frost (x10^7)



The KATRIN Beamline: Main Spectrometer



Magnetic Adiabatic Collimation + Electrostatic filter (MAC-E)



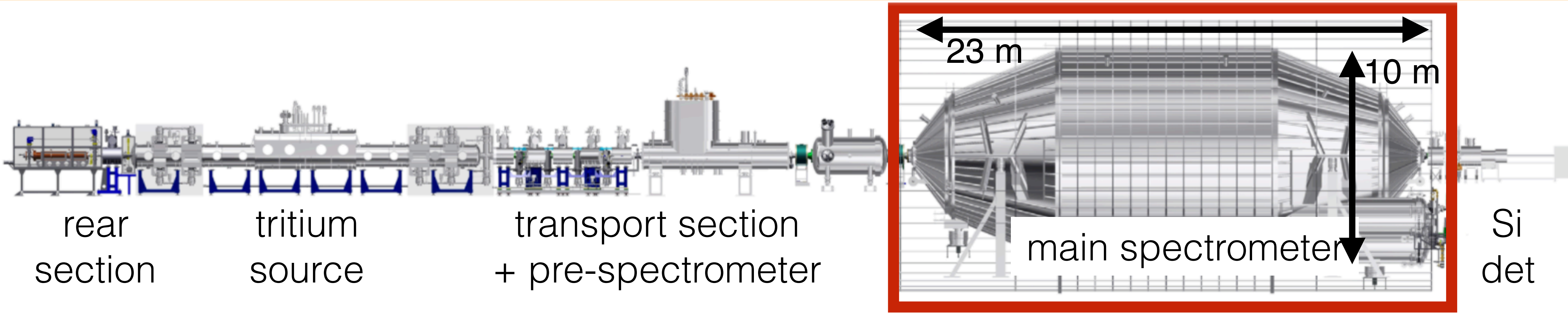
Resolution:

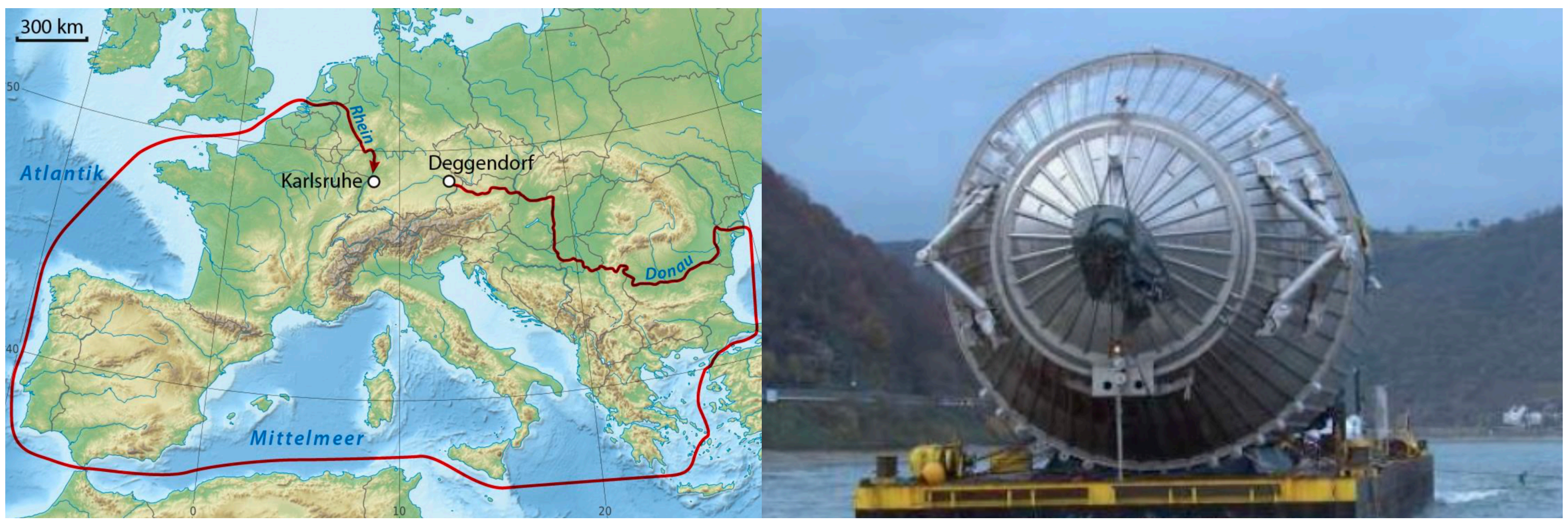
$$\frac{\Delta E}{E} = \frac{B_{\min}}{B_{\max}}$$

(ΔE = 0.93 eV)

- Magnetic fields convert $E_\perp$ to $E_{||}$ in analyzing plane
- Electrostatic filter applied in analyzing plane

The KATRIN Beamline: Main Spectrometer

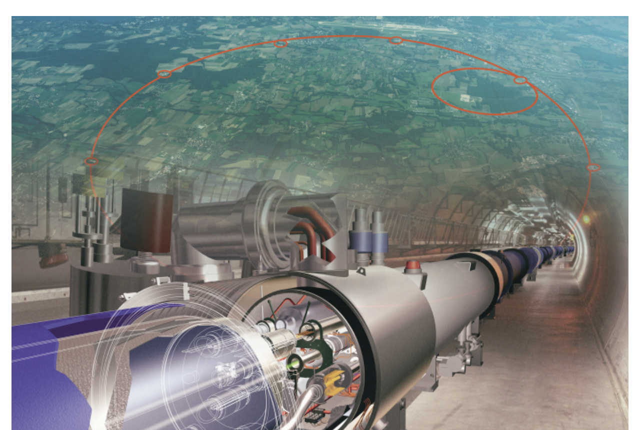




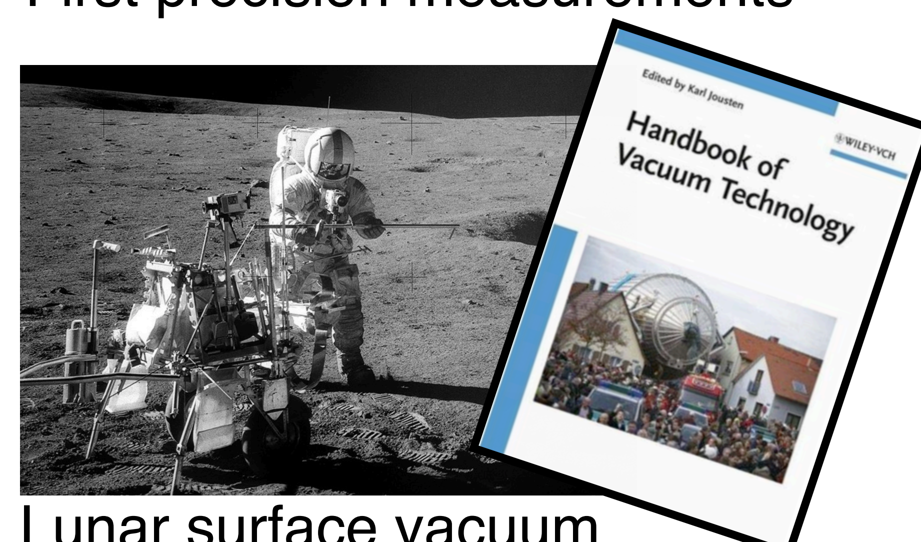
2006: first 8000 km. too big for land transport

First precision measurements

- 23 m length, 10 m diameter
- Turbo molecular pumps create world largest ultra high vacuum (1250 m^3 at 10^{-11} mbar)

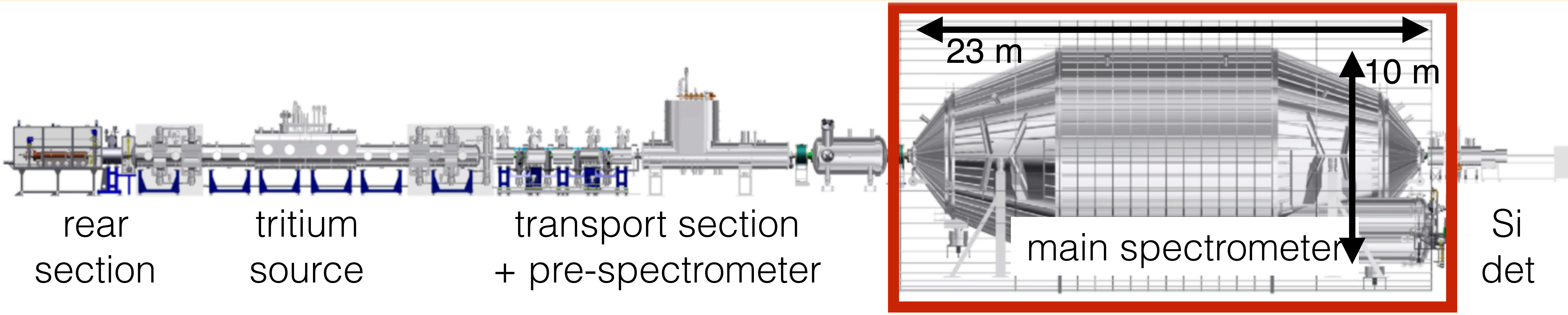


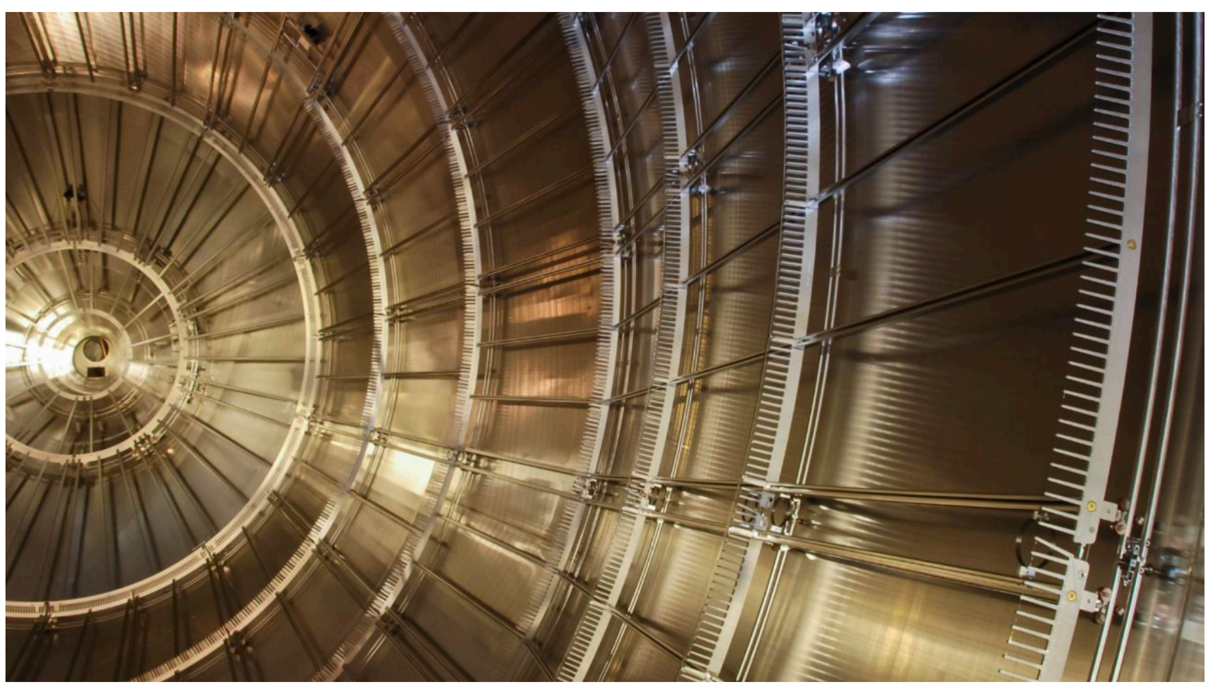
LHC: 154 m^3 UHV

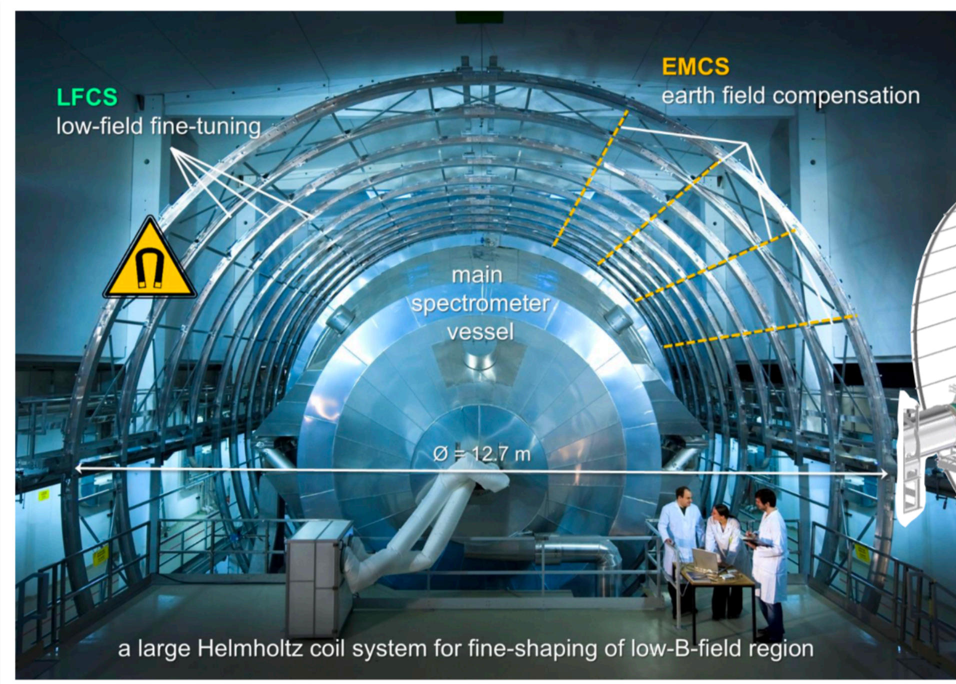


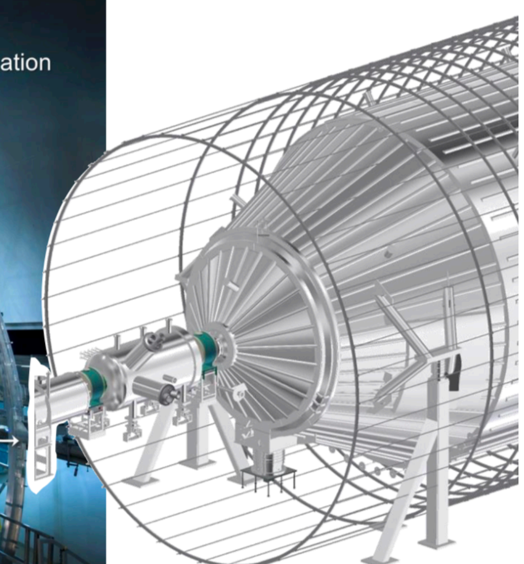
Lunar surface vacuum

The KATRIN Beamline: Main Spectrometer









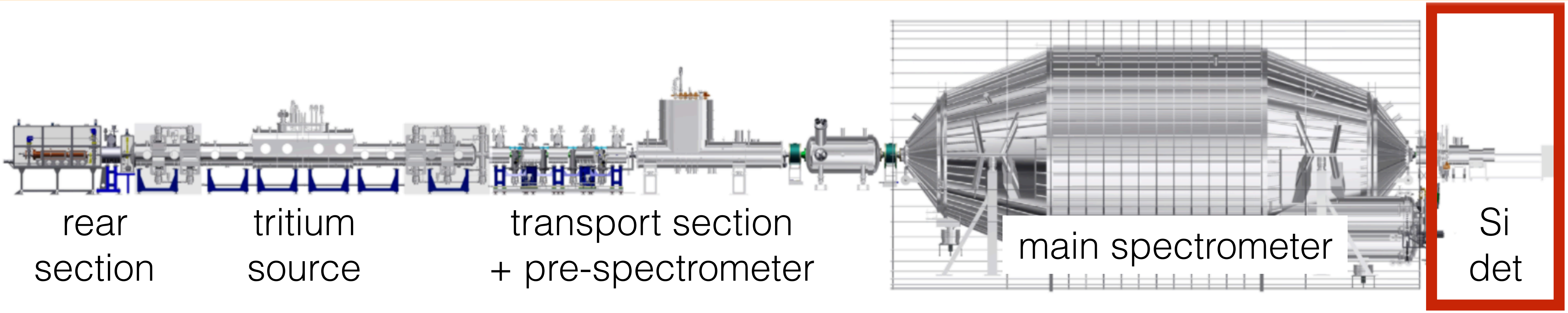
Inner electrode system for E-field shaping:

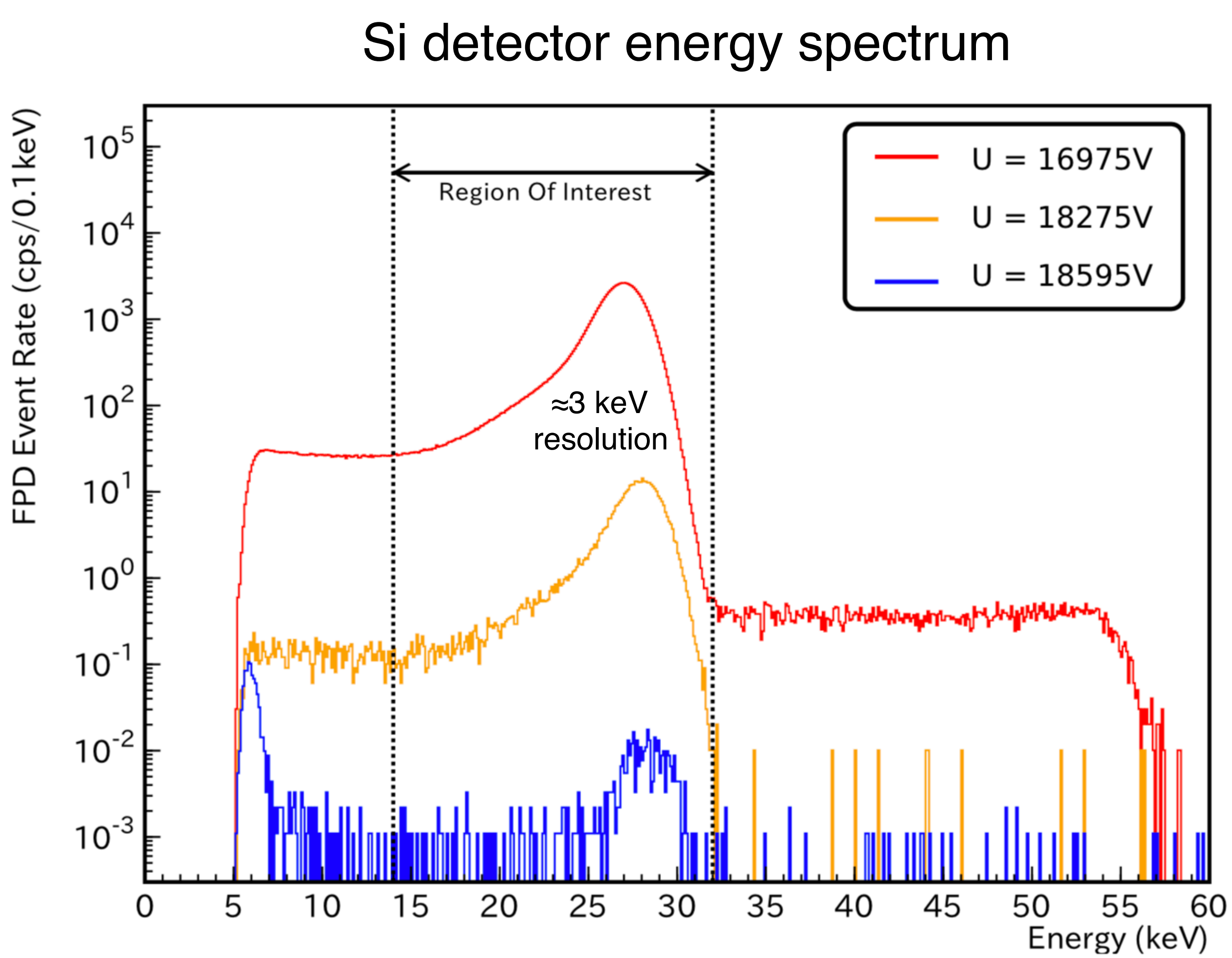
- Fine-tuning of electric field
- Background rejection of charged particles from wall

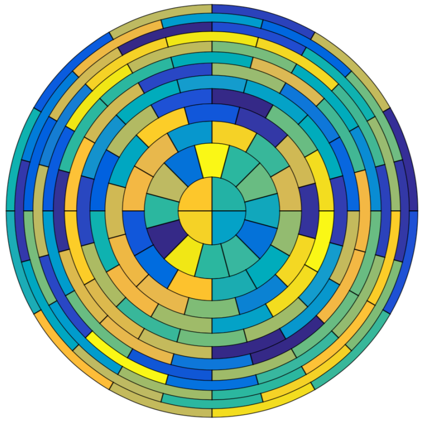
Outer air-coil system for B-field shaping:

- Fine-tuning of 2 mT B-field in analyzing plane
- Compensation of earth magnetic field

The KATRIN Beamline: Focal Plane Detector



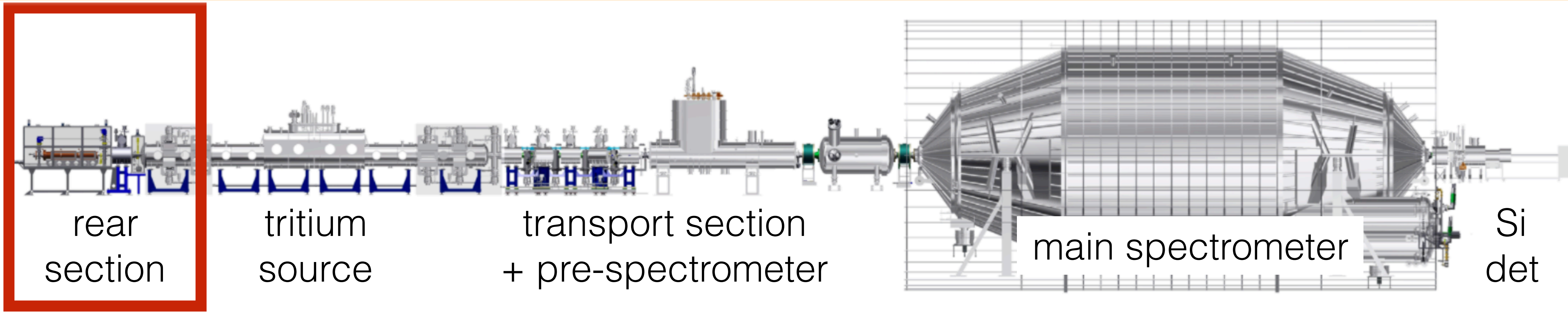


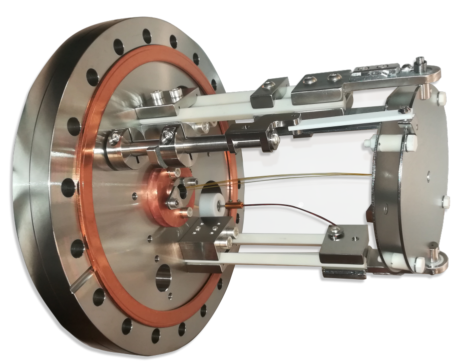


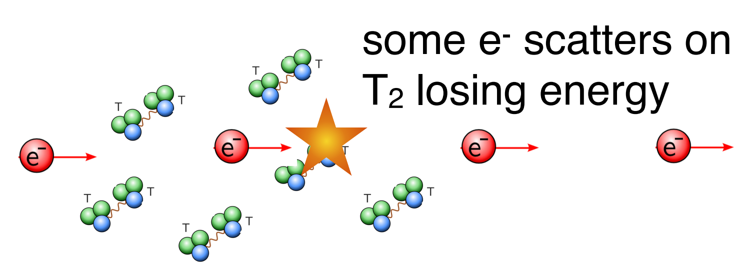
Focal plane detector:

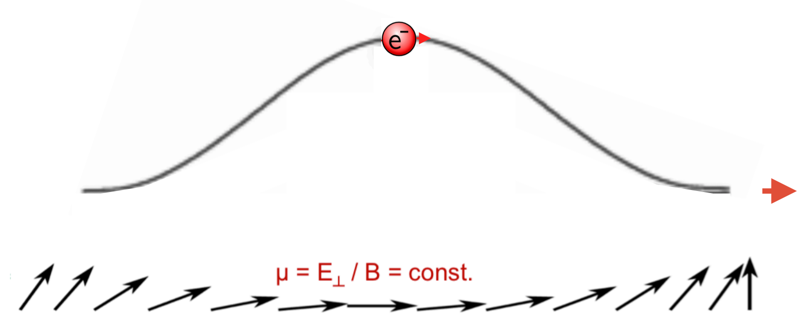
- 148 pixel Si-pin detector
- Counting electrons which pass main spectrometer

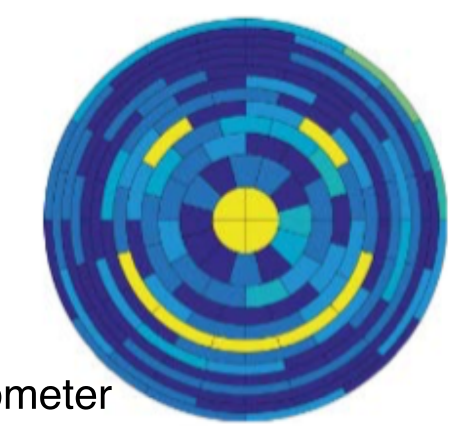
The KATRIN Beamline: Electron Gun









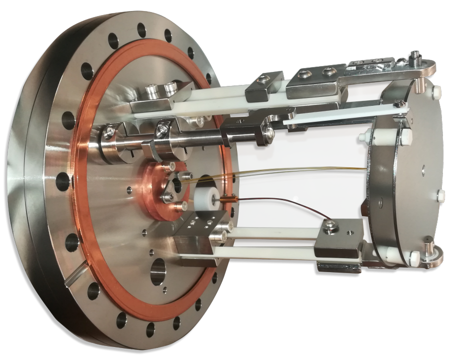


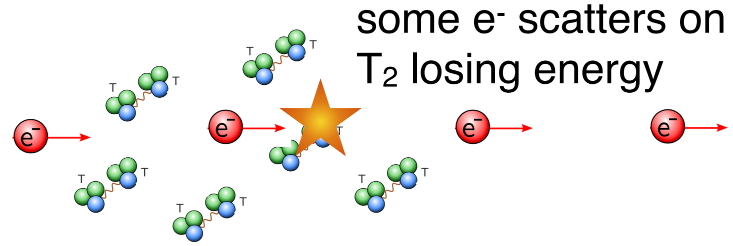
e^- trajectories through different parts of the spectrometer have slightly different response functions

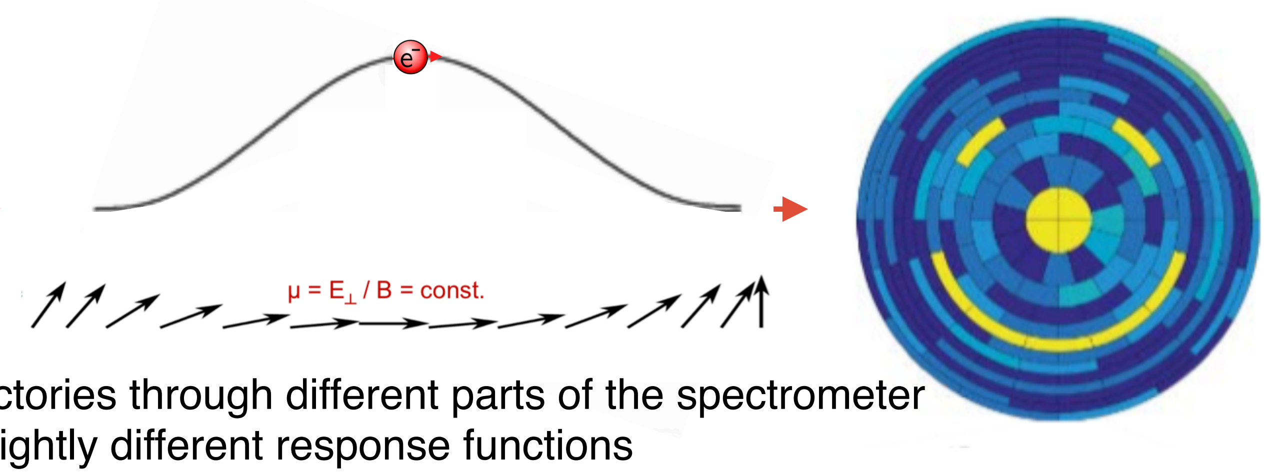
Electron gun:

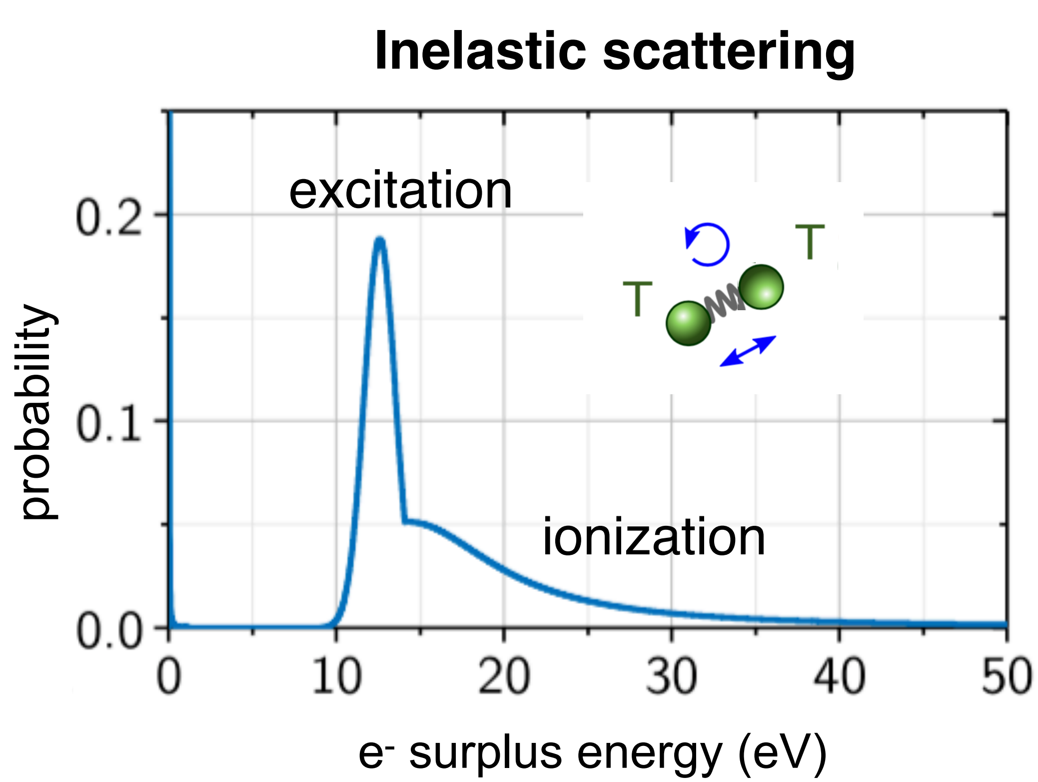
- Mapping of analyzing plane with angular selected monoenergetic e^-
- Understanding source systematics
  - Electron scattering
  - In-situ monitoring of column density

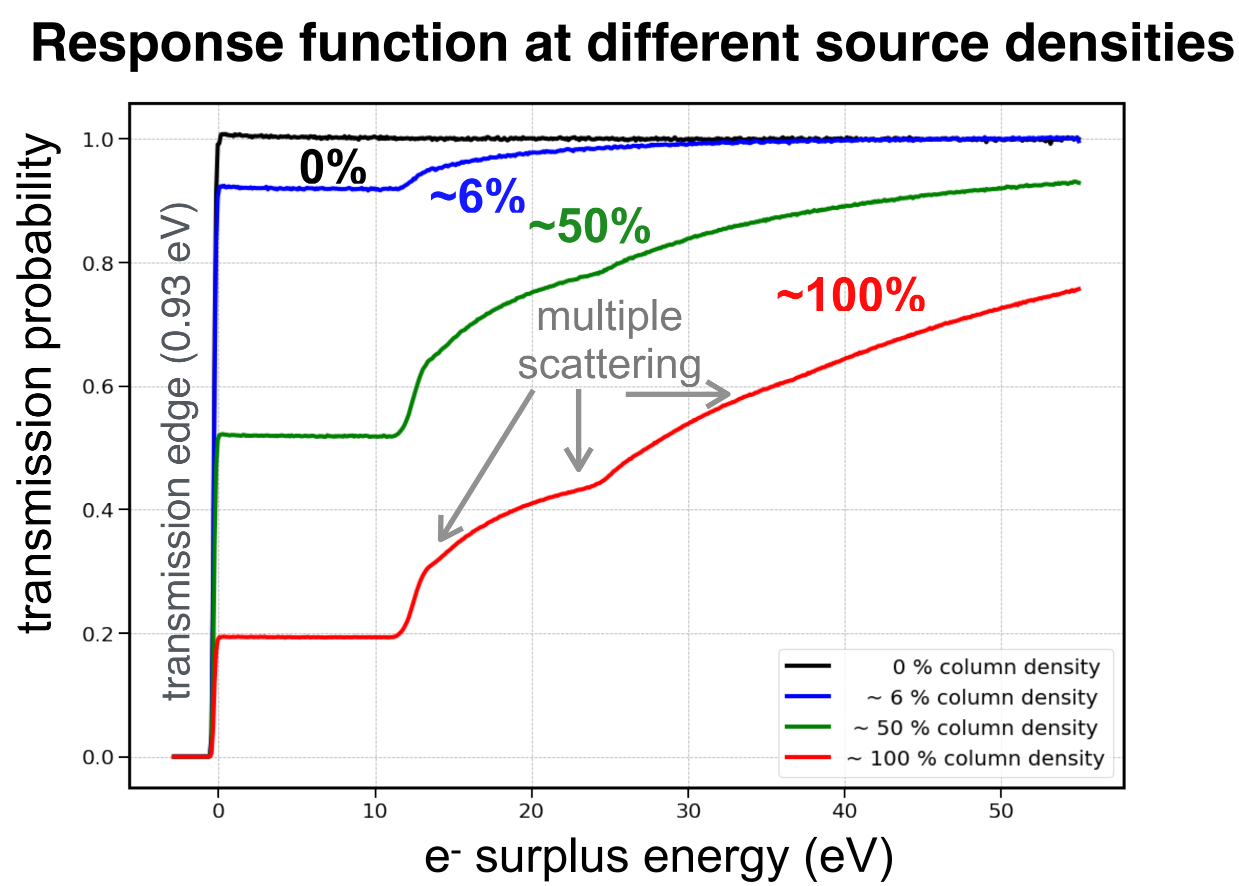
Energy Loss Function and Response











- ≈ 70% of electron scatter in source and loose energy
- Literature knowledge of energy loss function not precise enough for final sensitivity
- Electron loss function measured in-situ with electron gun and novel ToF technique

Eur. Phys. J. C (2021) **81**: 579

Plasma Effects

Tritium source is a plasma:

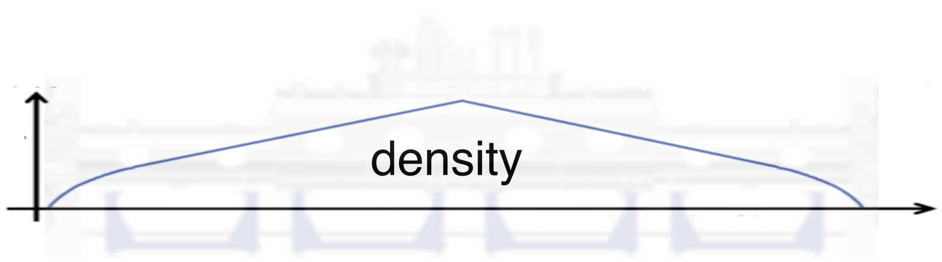
- 10^{11} Bq ionizes T_2 (≈ 30 per decay)
- 30 K ion temperature
- keV e^- temperature
- magnetic field, pumping
- coupled to gold plated rear wall

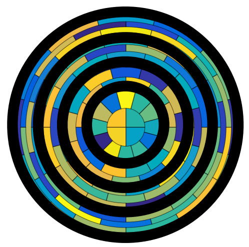
Consequences:

- Plasma distribution and instabilities:
  random energy smearing
- Location dependent potential:
  un-scattered e^- see different potential than scattered e^-

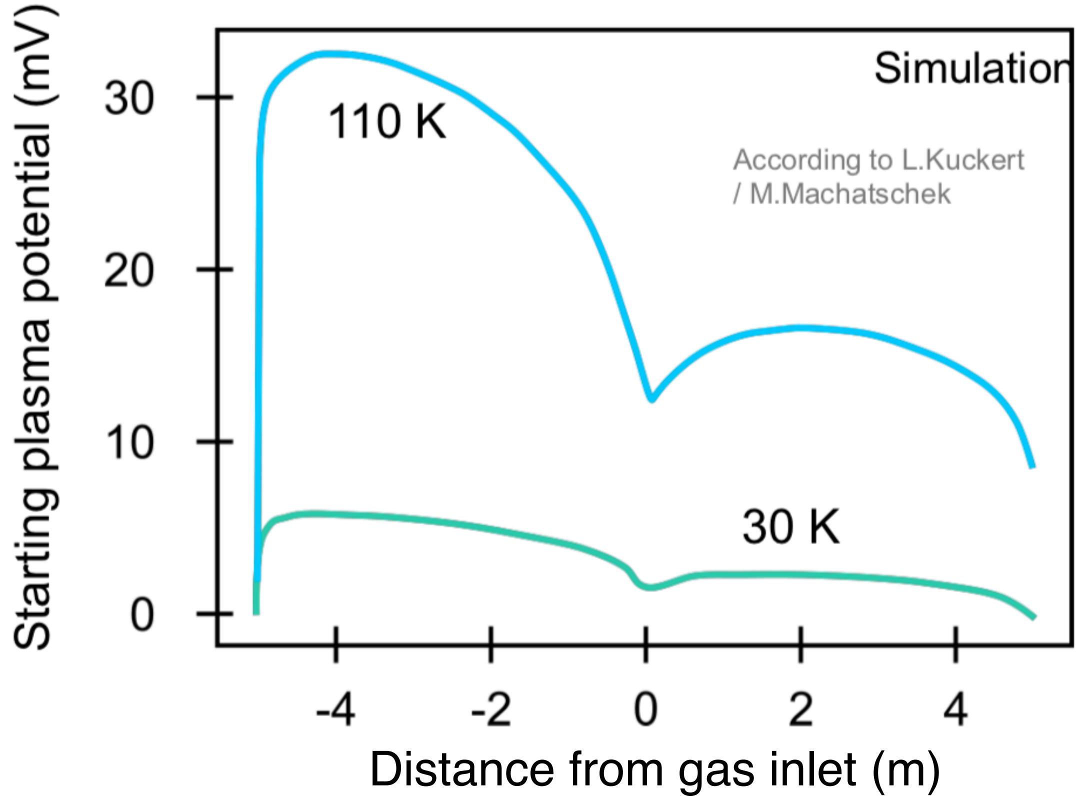
Solution:

- Two systematic parameters (shift and smear)
- Calibration with ^{83m}Kr (operation at higher temperature)
- Pixel-ring segmented analysis (radial)

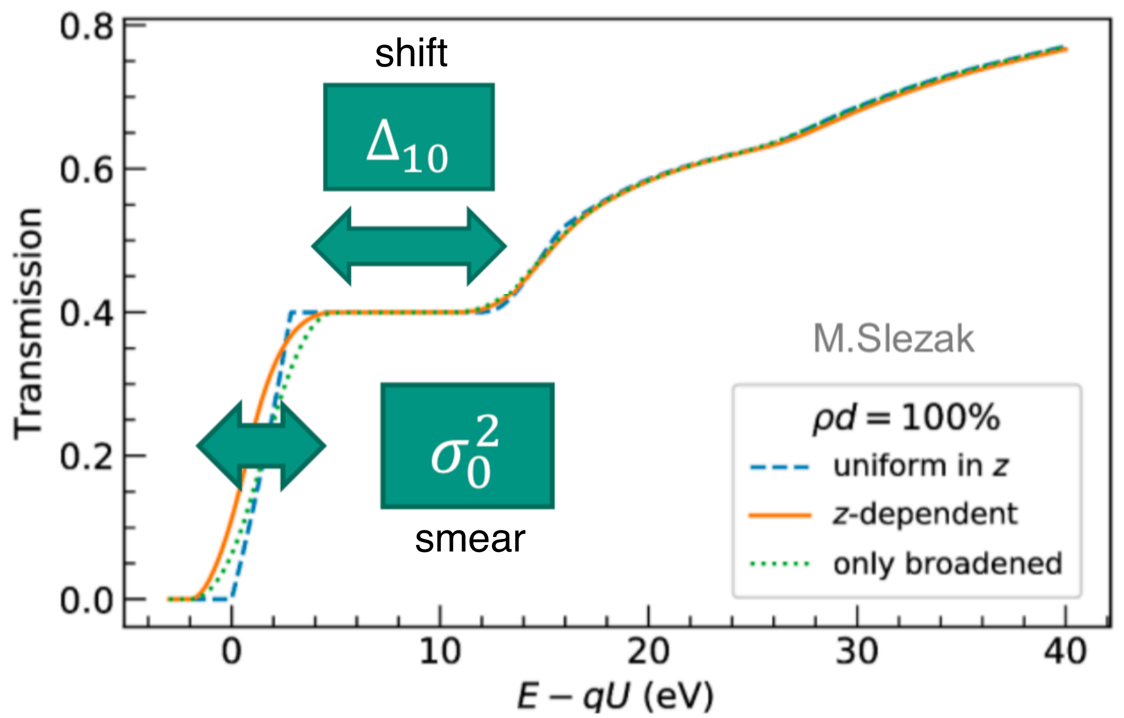




Location dependent potential

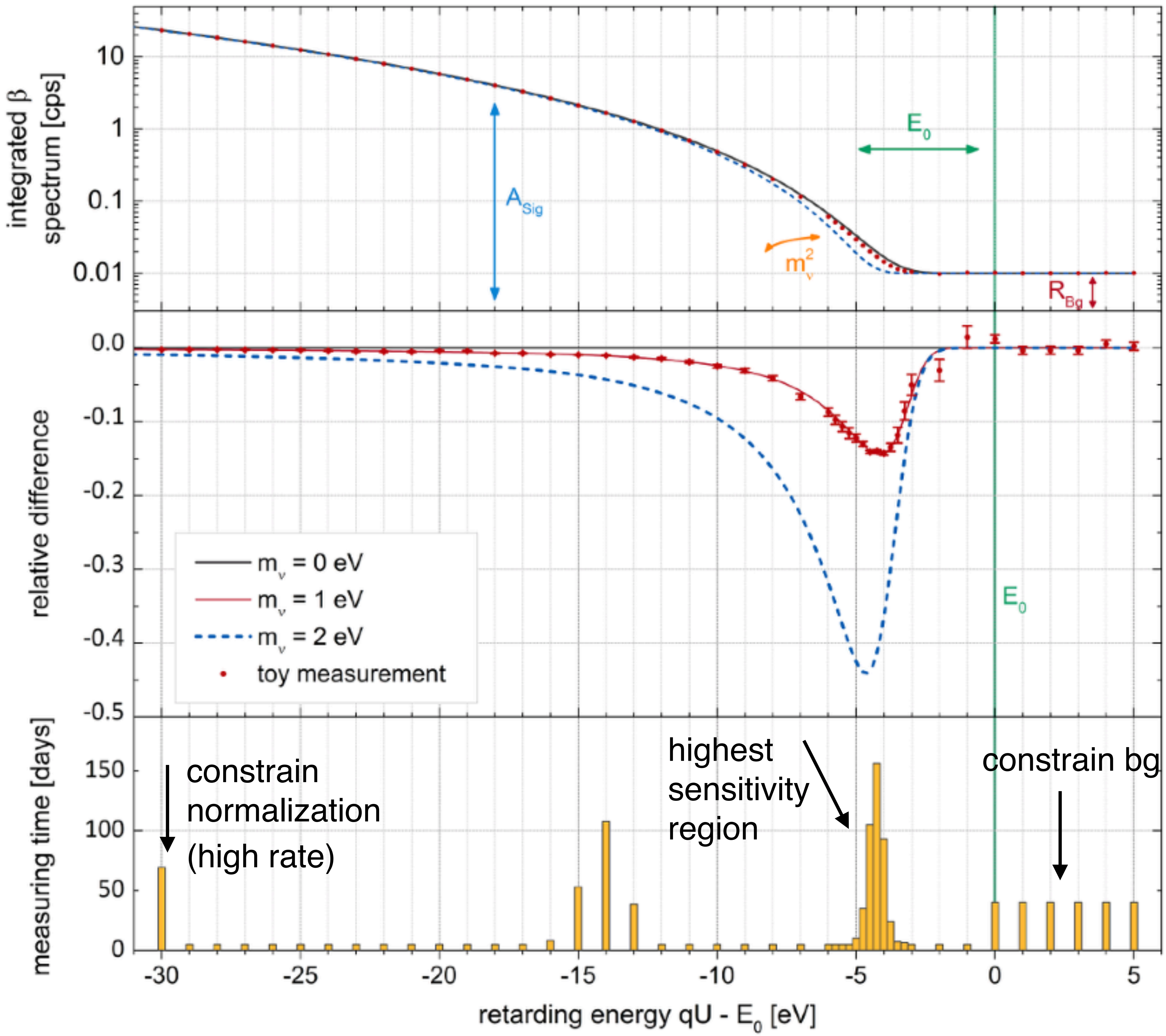


Effect on response function



Measurement Concept

Illustration only



Integrated spectrum

- Run: complete scan of all HV points
- 4 fit parameters to describe spectrum
- Background is flat

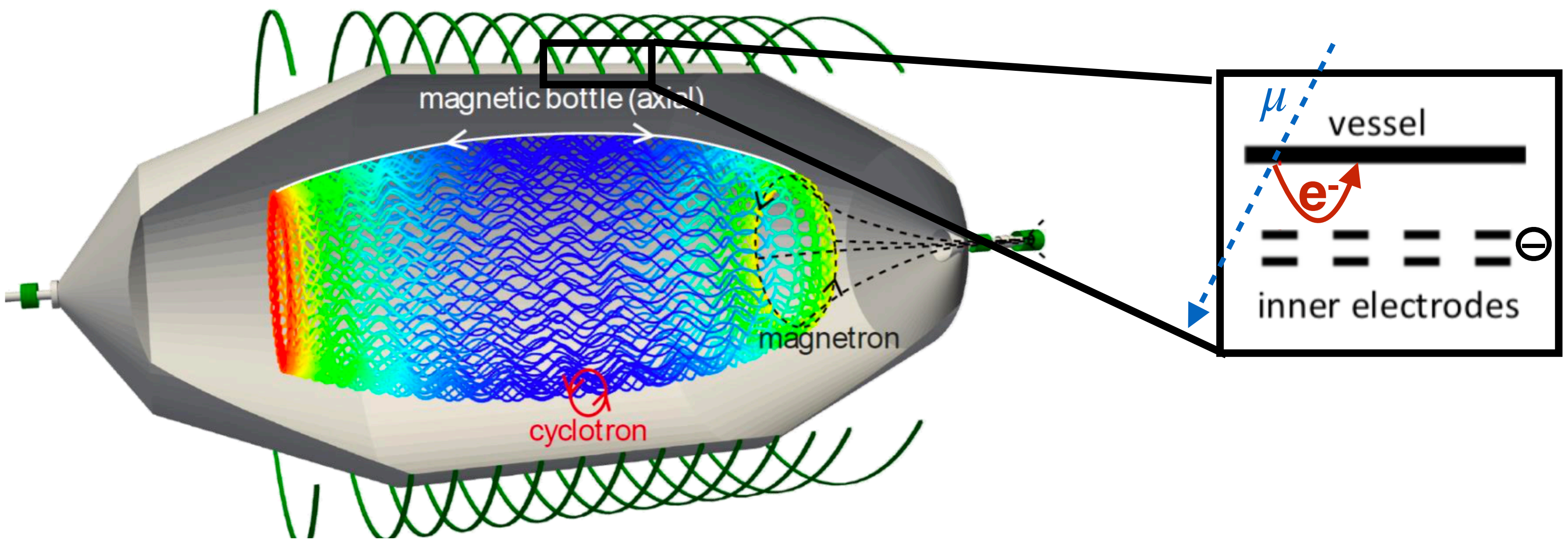
Residuals

- Most sensitive region around endpoint
- With higher background the sensitive region moves lower in energy
- Statistical fluctuations can result in “negative m^2”

Measuring time distribution

- Choose HV points and statistics in each point
- Optimize for sensitivity e.g. constrain background, normalization

Backgrounds



Main expected electron source:

- e^- from muon interaction in vessel (above ground)
- Effectively mitigated by inner electrode system

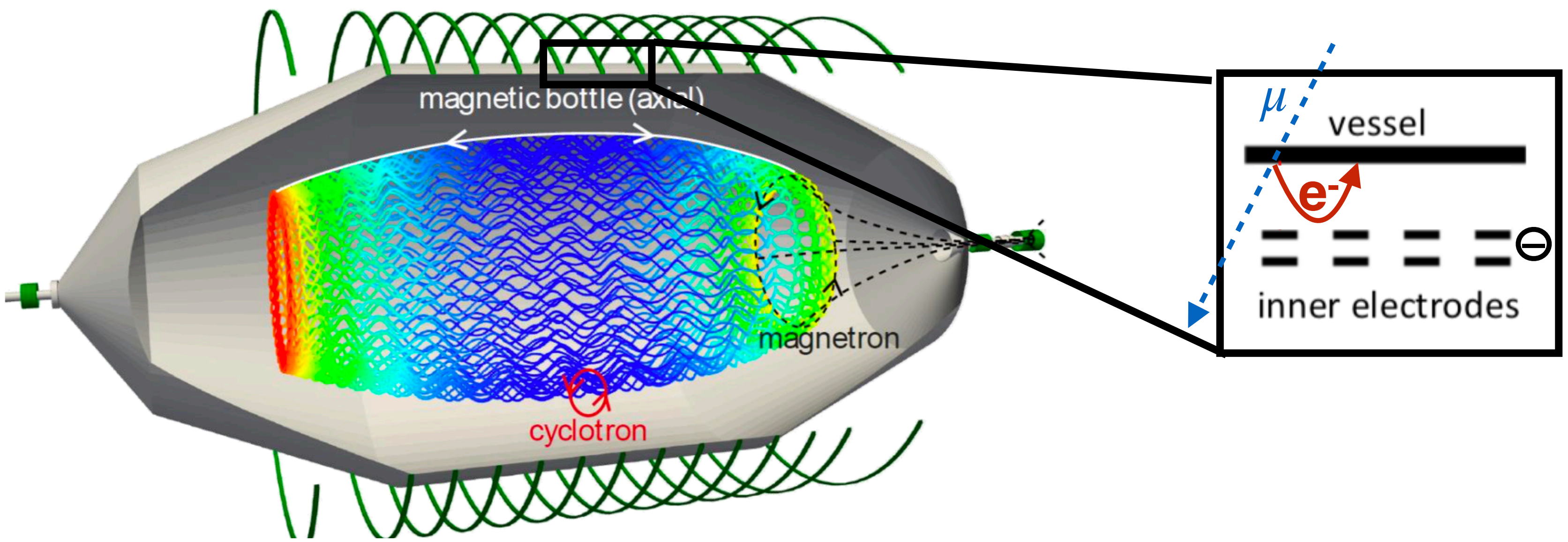
Signal:

- e^- have $E \approx 0$ keV in analyzing plane

Background:

- All low energy e^- in main spectrometer volume can mimic signal
- Background e^- are detected independent of qU: background flat in integral spectrum

Initially observed background 50x higher than expected!



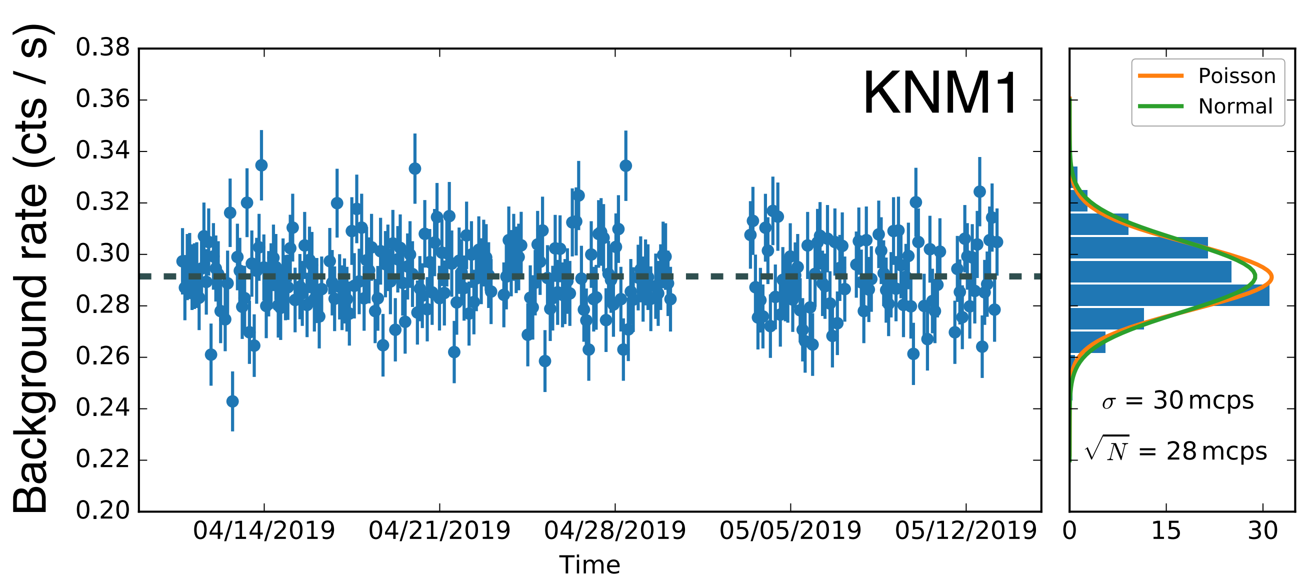
- MAC-E filter can store fast e⁻ through "magnetic bottle" effect
- Stored e⁻ ionize residual gas creating low e⁻ secondary electrons

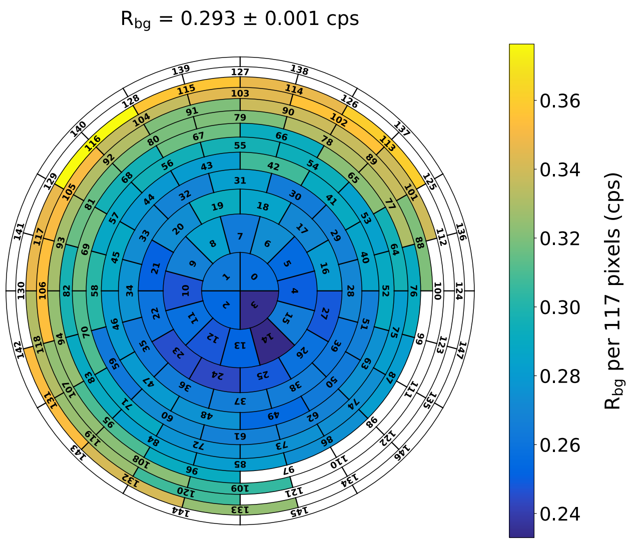
1. ^{219}Rn ($T_{1/2}$ = 4s) from getter material in pumps

- Decays in spectrometer creating fast e⁻ which are stored
- Creates time varying background rate
- Largest systematic

2. Rydberg atoms from vessel walls

- ^{210}Pb / ^{210}Po decays spatter out atoms in highly excited Rydberg states
- Ionize in main volume creating radial dependent background





Change of measurement and analysis strategy largely mitigates impact on sensitivity

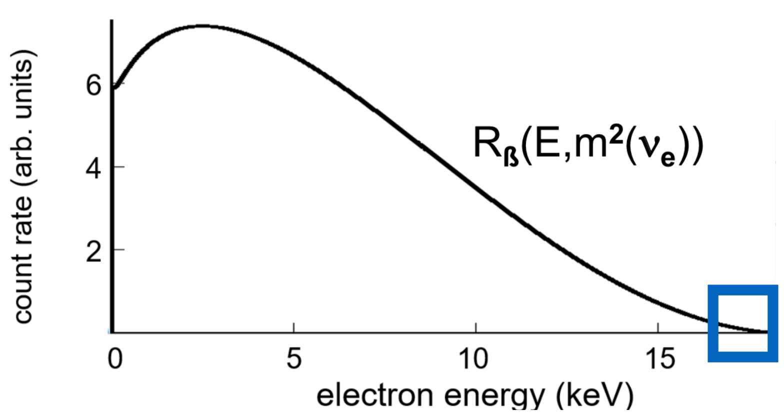
Fit Model

model → [fit] ← **data**

- 4 parameter fit
- normalization (A), endpoint (E_0), constant background (R_{bg}), neutrino mass (m_β^2)

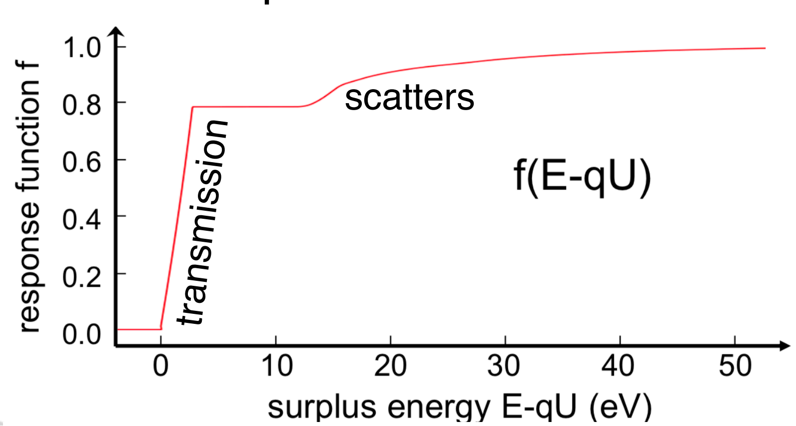
Beta spectrum:

- Multiple spectra from T_2, DT, HT
- Various final states



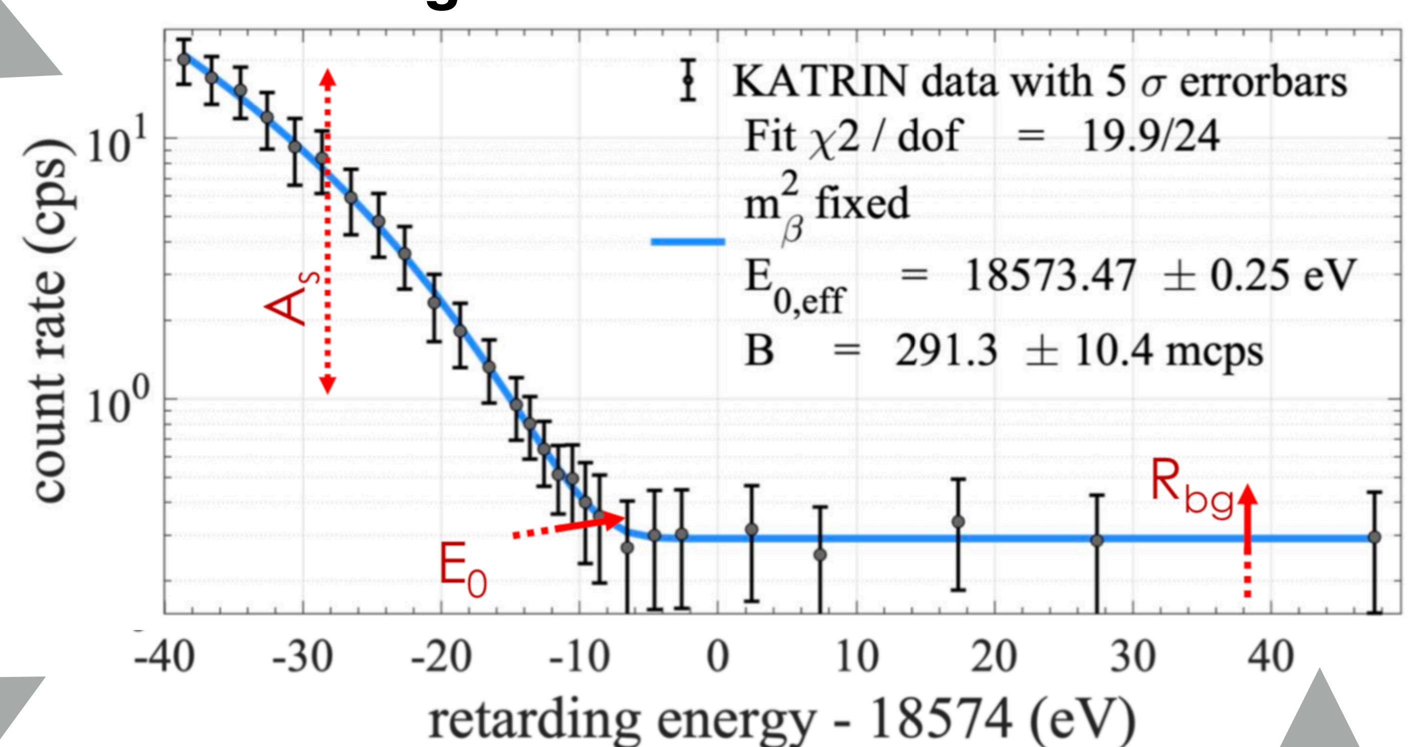
Response function:

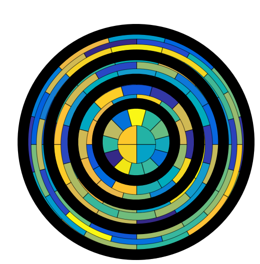
- Transmission: B-fields
- Source density: Probability of scatter
- Electron energy loss: If scatter occurs
- Source potential: Plasma effects



$$R(qU) = A_s \cdot N_T \int_{qU}^{E_0} R_ß(E, m^2(\nu_e)) \cdot f(E - qU)\, dE + R_{bg}$$

Fit on single run



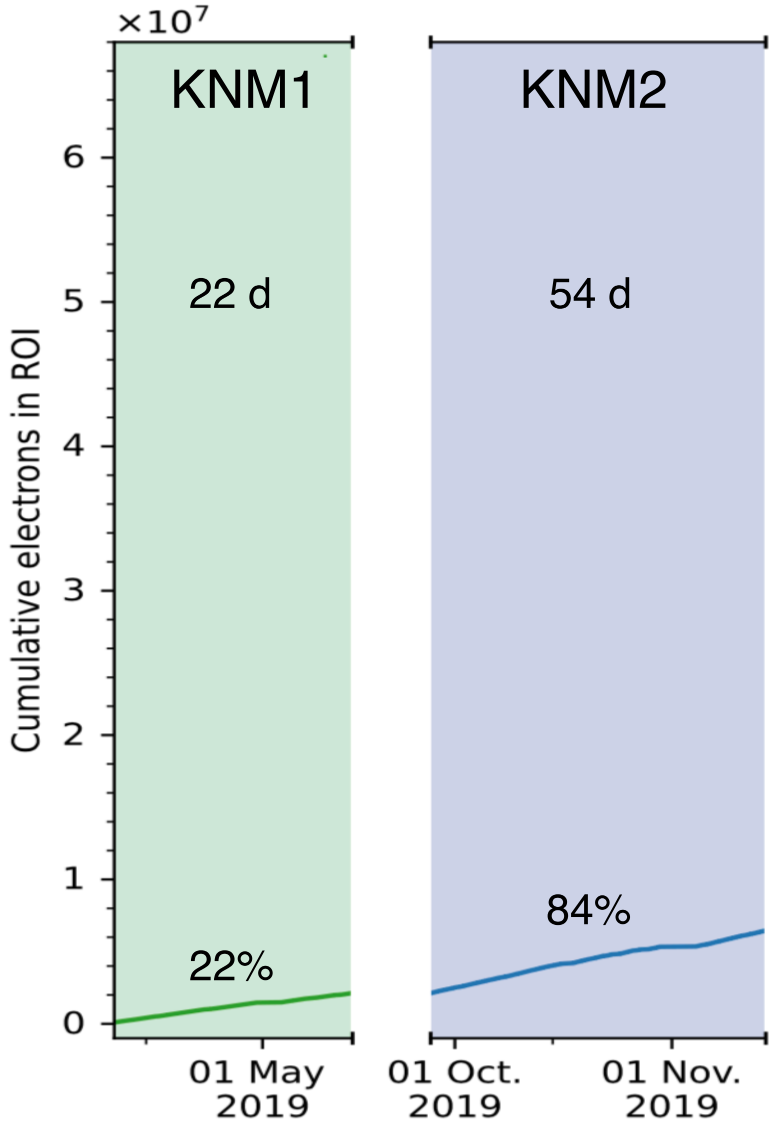


and pixelation

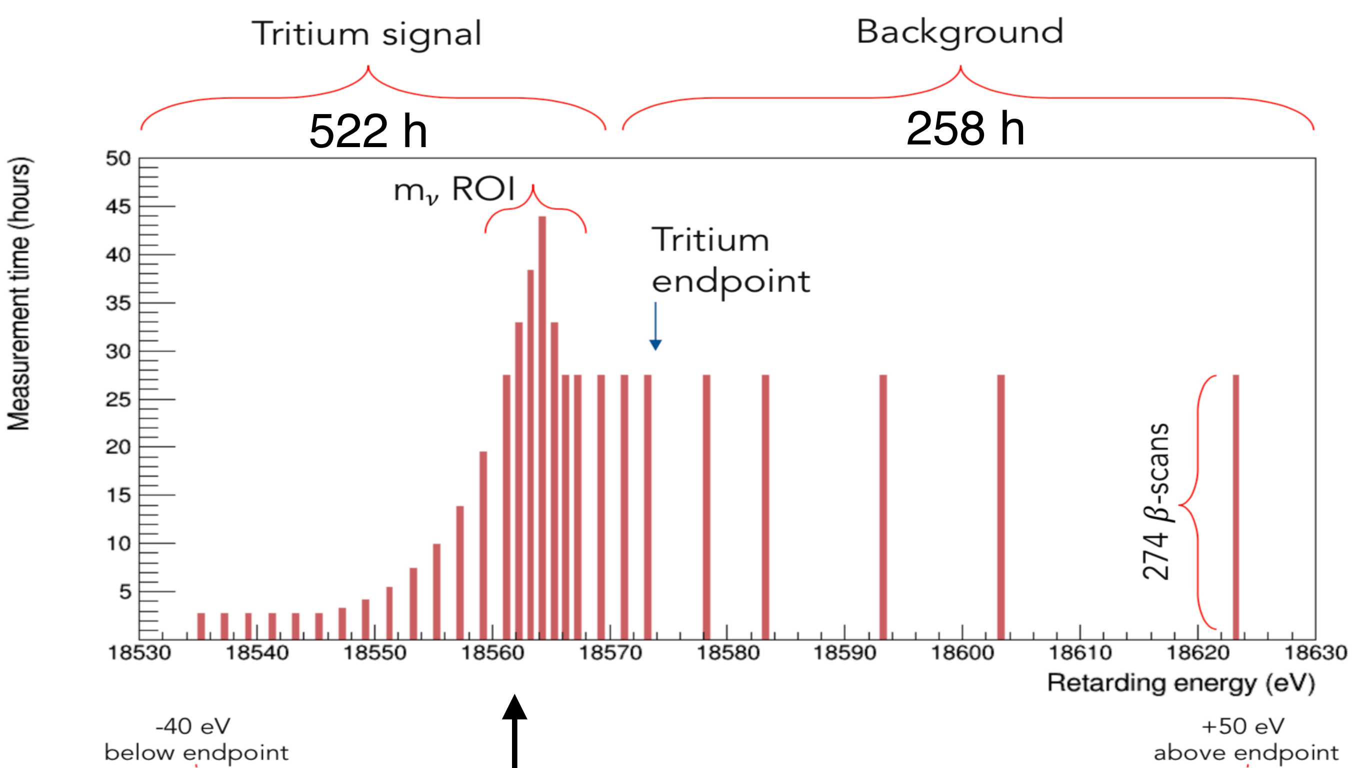
Constant background

- Time varying component
- Potential slope

Current Datasets



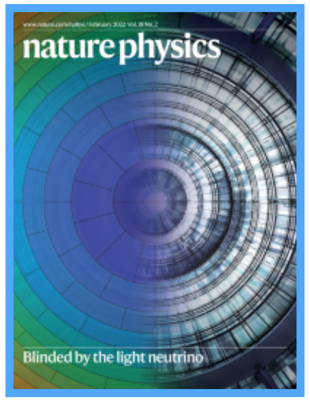
for KNM1



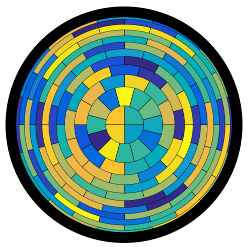
- 274 scans
- 2.5 h per scans
- 27 HV set-points
- 34 mV HV reproducibility

- Optimized for sensitivity
  - ROI for m_β^2
  - Background constraint

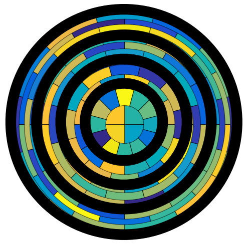
1st results:
PRL 123, 221802 (2019)



2nd results:
Nature Phys. 18, 160 (2022)



KNM1
uniform



KNM2
12 rings

Blinding Scheme

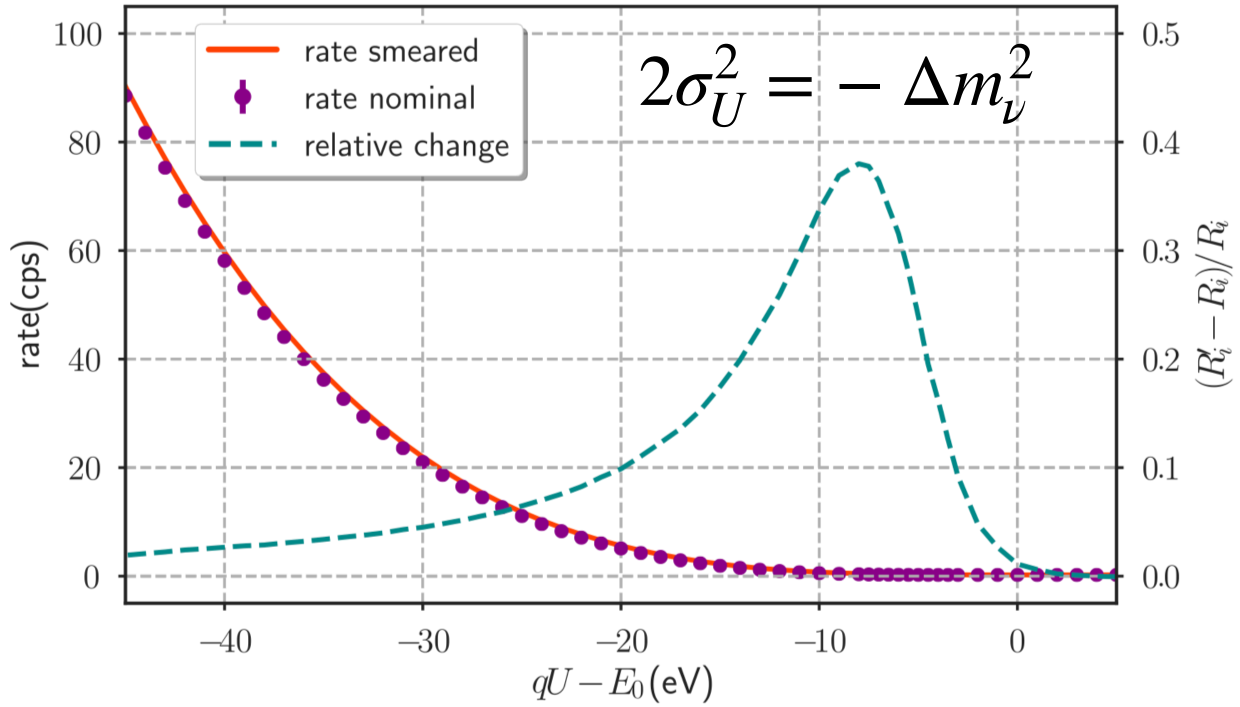
Three independent analysis teams

1. Develop individual analysis on
- MC data (with all slow control information)
- Single data runs (not enough statistics to be sensitive to neutrino mass)

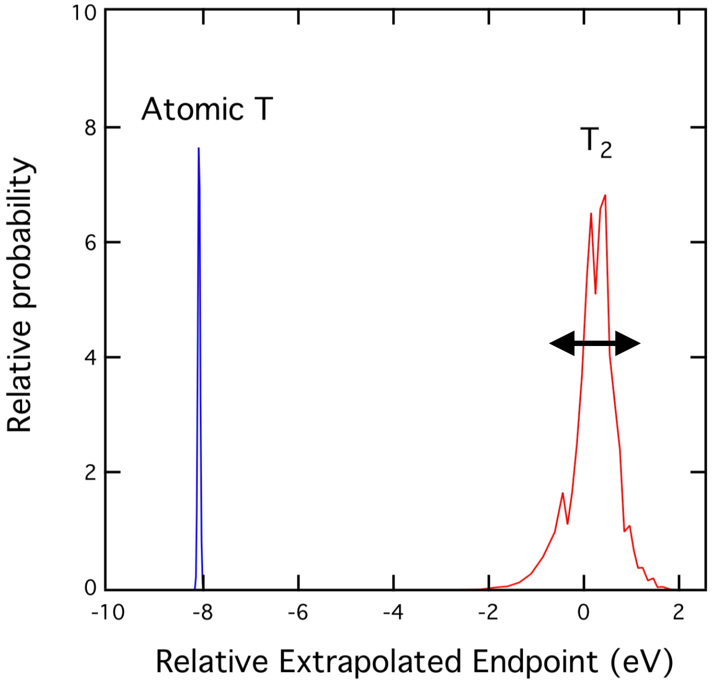
2. Model blinding:
- Cross validate analysis on full data set with “blinded model”

3. Unblinding:
- …

Smearing the model results in an effective negative neutrino mass



Smear FSD with hidden random value to blind model for 2. validation step

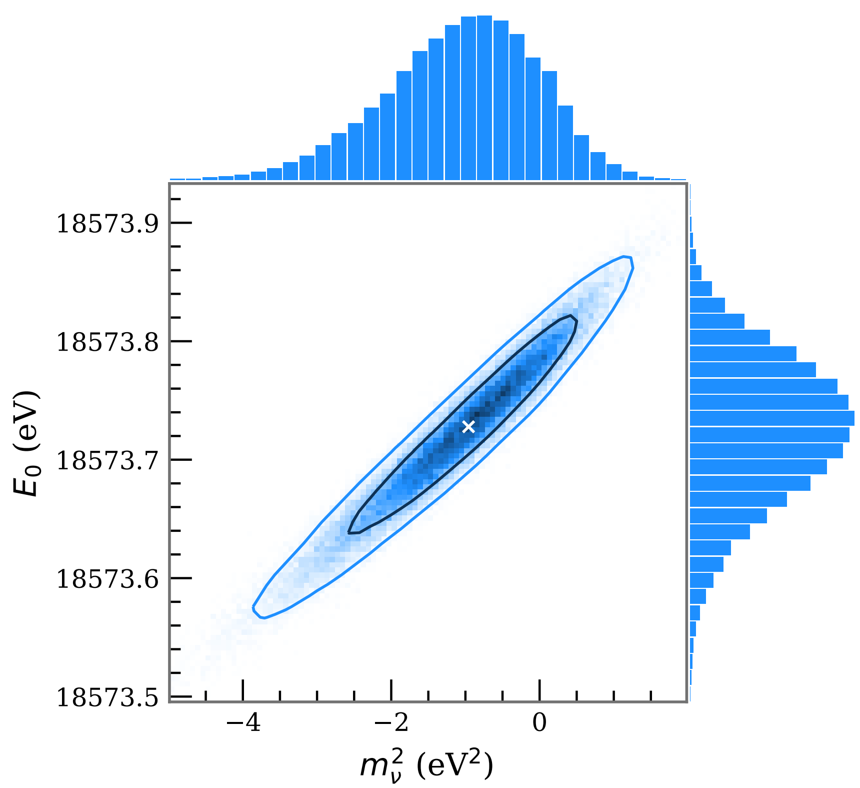


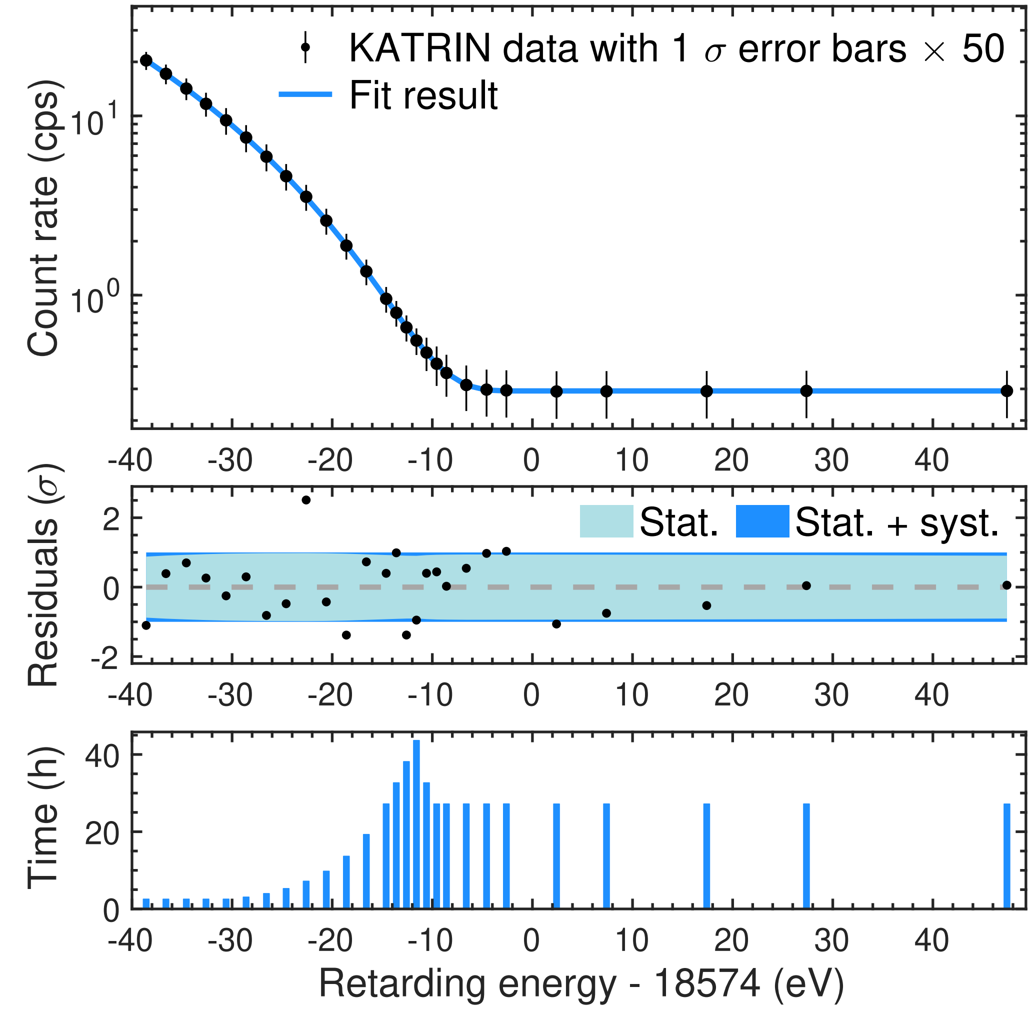
Results KNM1

PRL 123, 221802 (2019)

Best fit value: $m_\beta^2 = -1.0^{+0.9}_{-1.1}\ \mathrm{eV}^2$

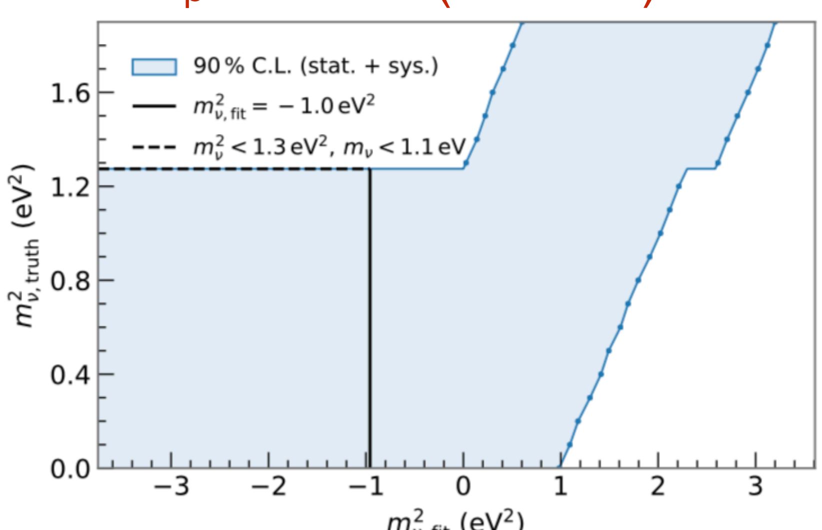
(1.2 sigma fluctuation)





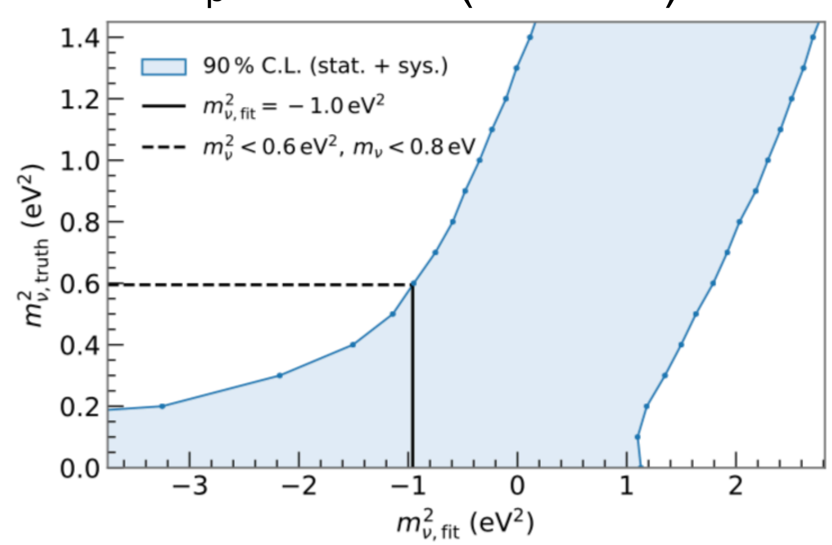
Limit setting:

Lokhov-Tkachov (LT) official:
m_β < 1.1 eV (90% CL)

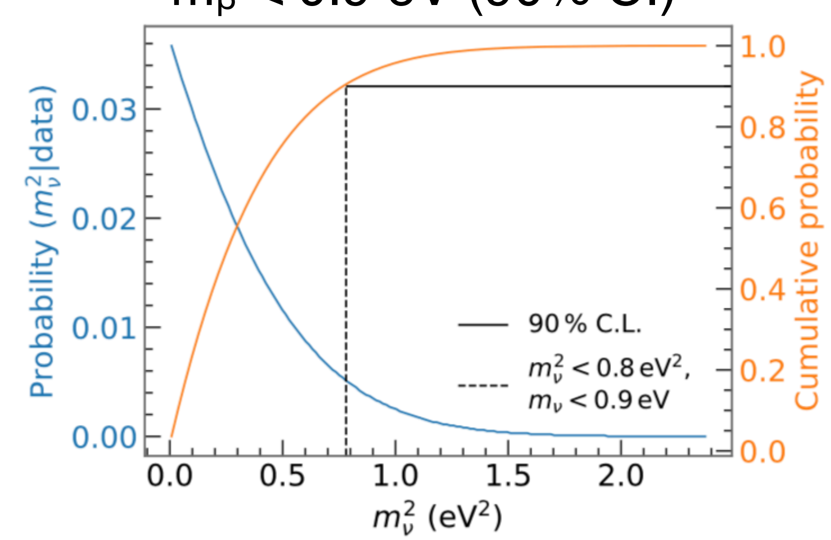


values <0 identical to sensitivity
Phys. Part. Nucl. 46, 347 (2015)

Feldman-Cousins (FT):
m_β < 0.8 eV (90% CL)



Bayesian flat prior $m_\beta^2 > 0$:
m_β < 0.9 eV (90% CI)



Results KNM2

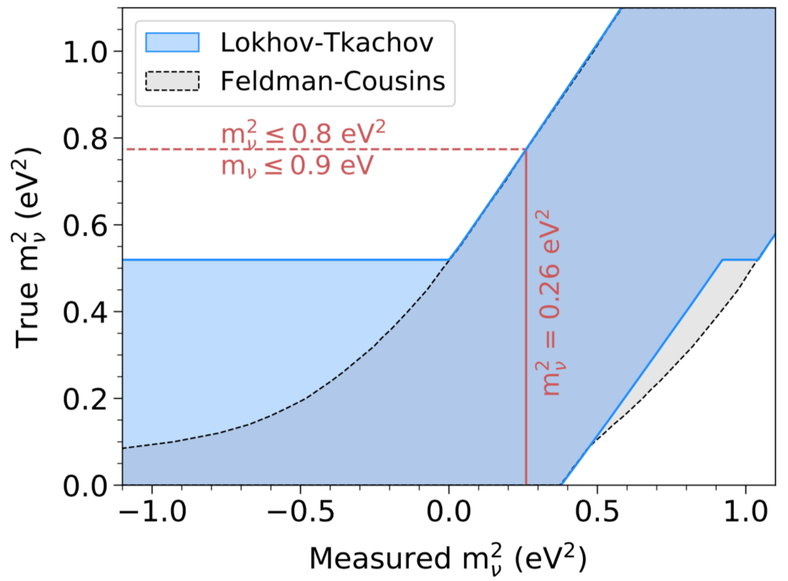
Nature Physics
18, 160 (2022)

Best fit value: $m_\beta^2 = 0.26^{+0.34}_{-0.34}\ \mathrm{eV}^2$

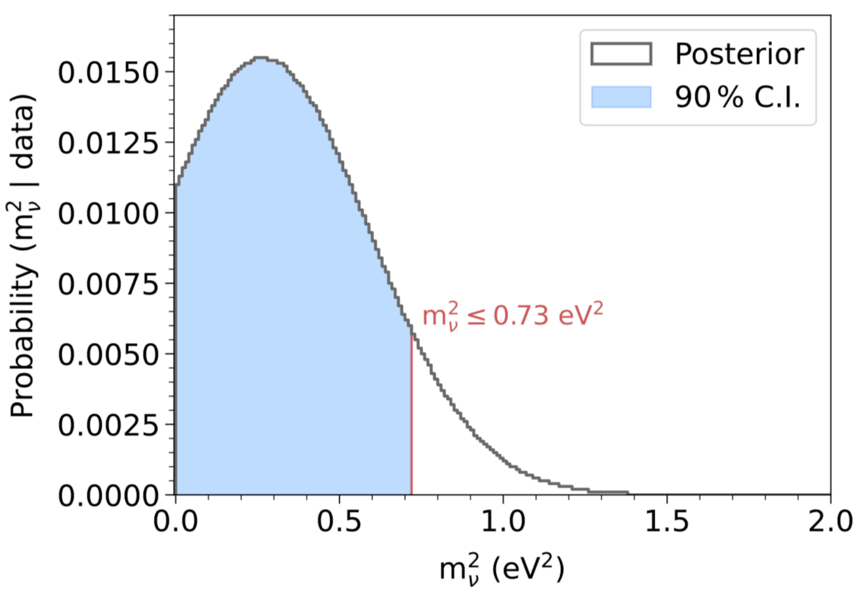
(0.8 sigma fluctuation)

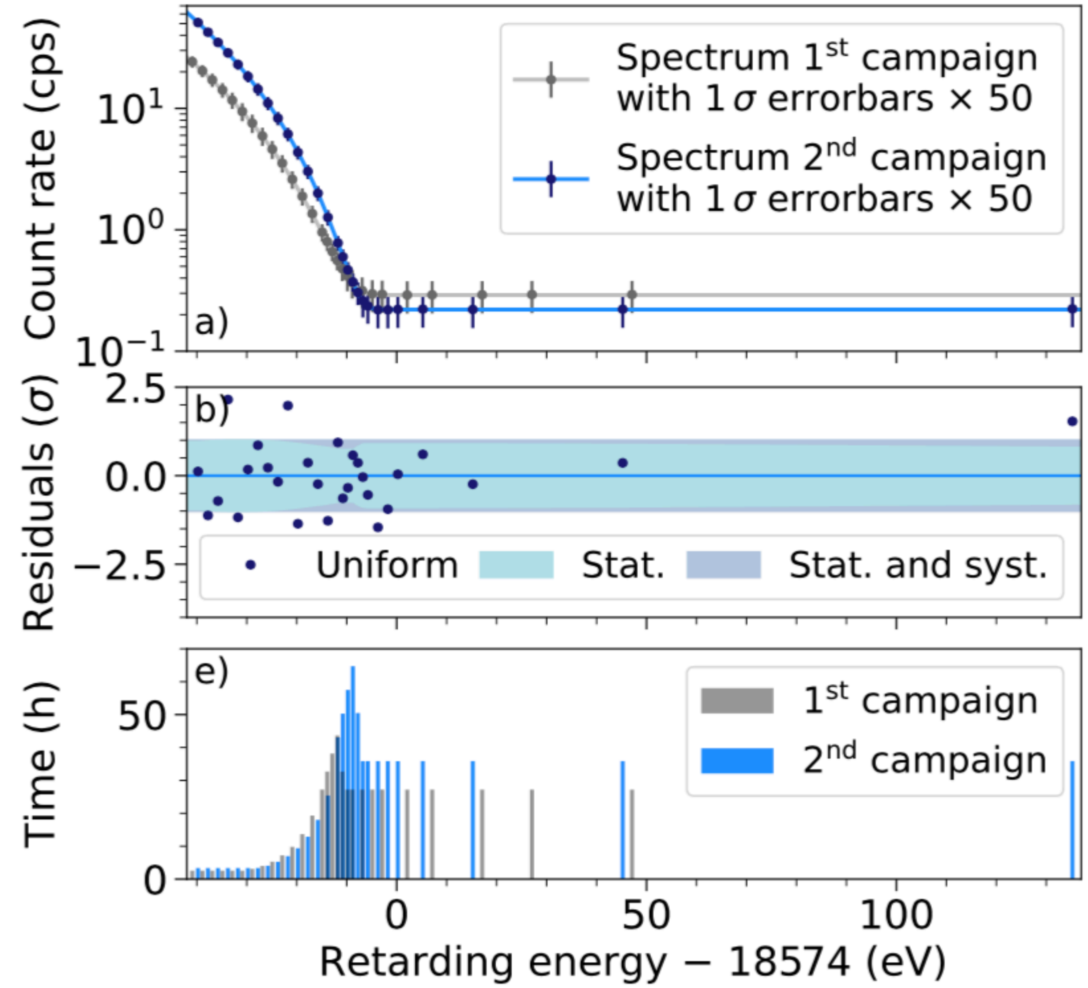
Limit setting:

LT and FC: $m_\beta < 0.9$ eV (90% CL)



Bayesian: $m_\beta < 0.85$ eV (90% CI)





Uncertainty budget:

- Total: 0.34 eV²
- Statistics: 0.29 eV²
- Systematic: 0.18 eV²

Cross check of Q-value:

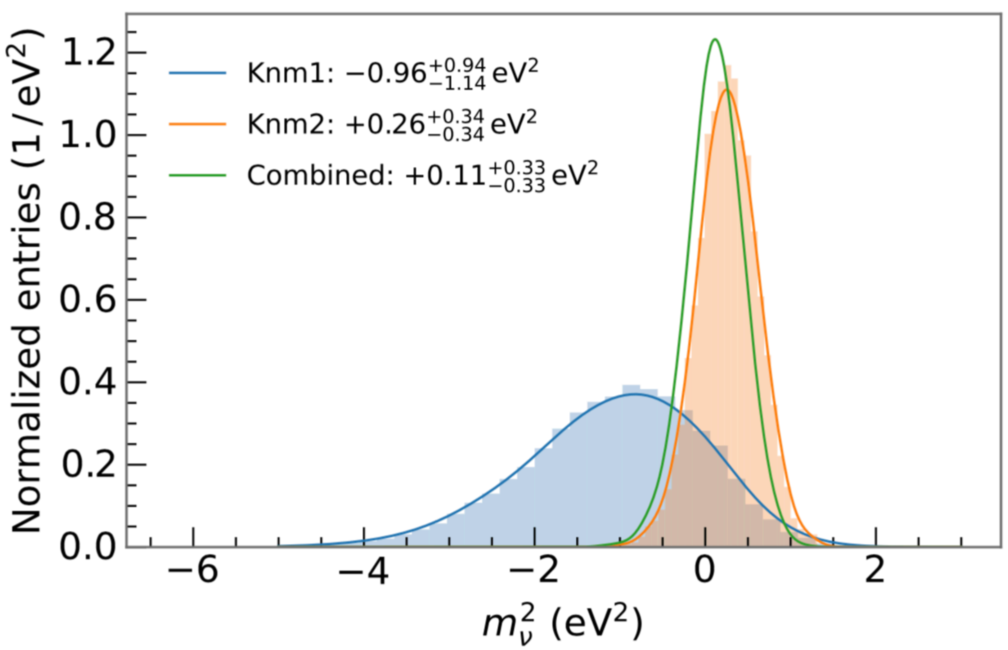
	KNM1 [eV]	KNM2 [eV]
endpoint	18573.7 ± 0.1	18573.69 ± 0.03
Q-value	18575.2 ± 0.5	18575.2 ± 0.6

literature Q-value = 18575.72 ± 0.07 eV
good agreement illustrating stability of energy scale

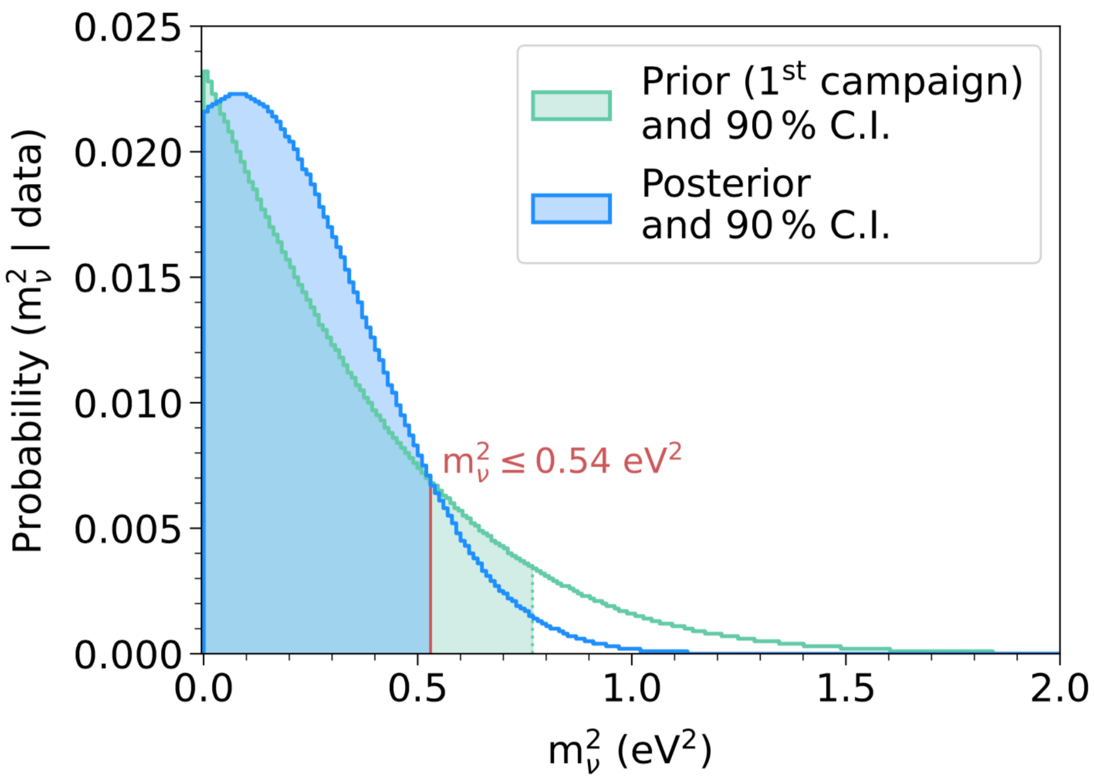
Results Combined KNM1 + KNM2

Nature Physics
18, 160 (2022)

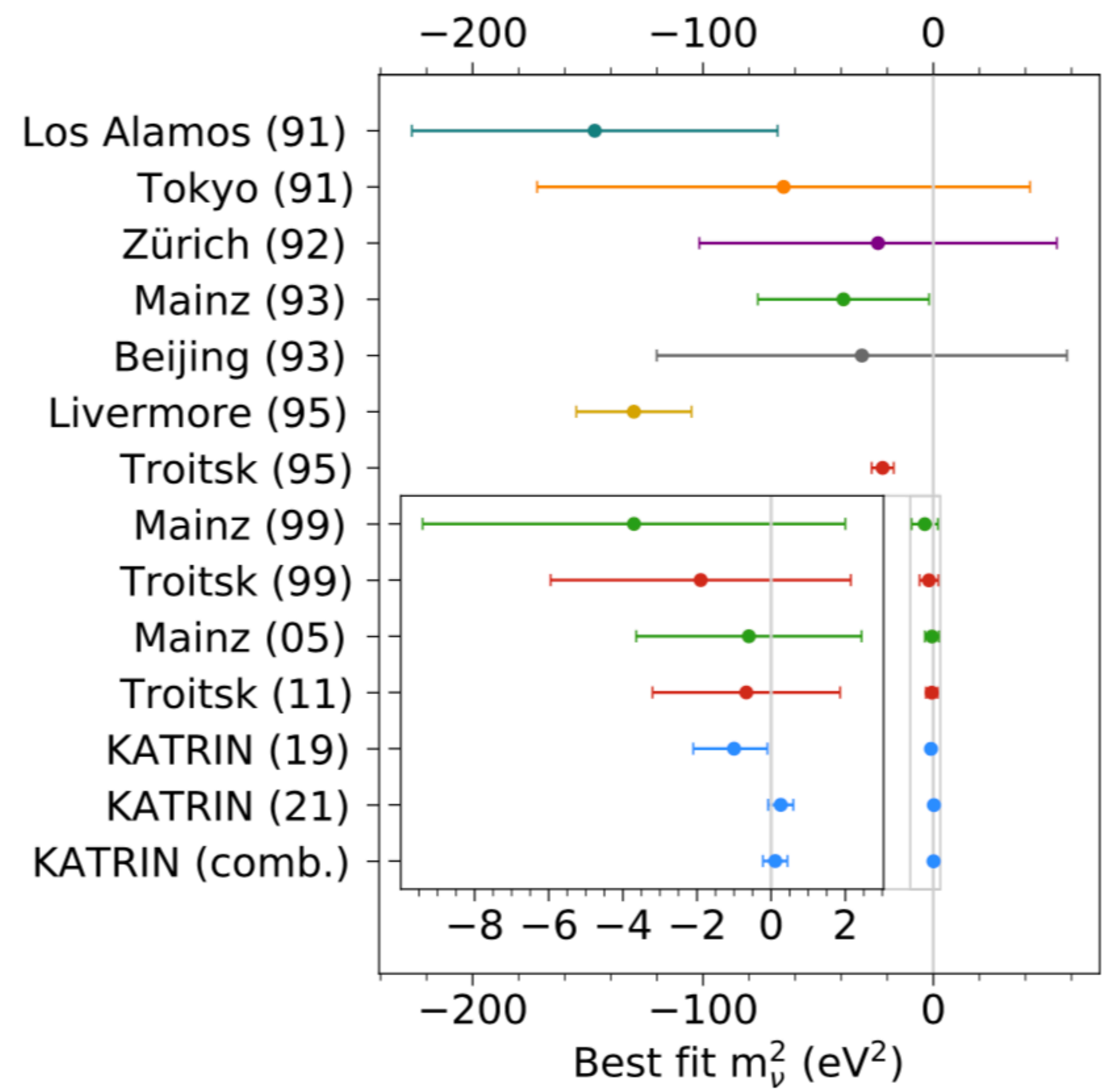
Frequentist likelihoods (multiplication or combined fit)



Bayesian posteriors (KNM1 posterior as KNM2 prior):



Best fit:	$m_\beta^2 = 0.1 \pm 0.3\ \mathrm{eV}^2$
Limits LT and FC:	$m_\beta < 0.8\ \mathrm{eV}$ (90% CL)
Limits Bayesian:	$m_\beta < 0.73\ \mathrm{eV}$ (90% CI)



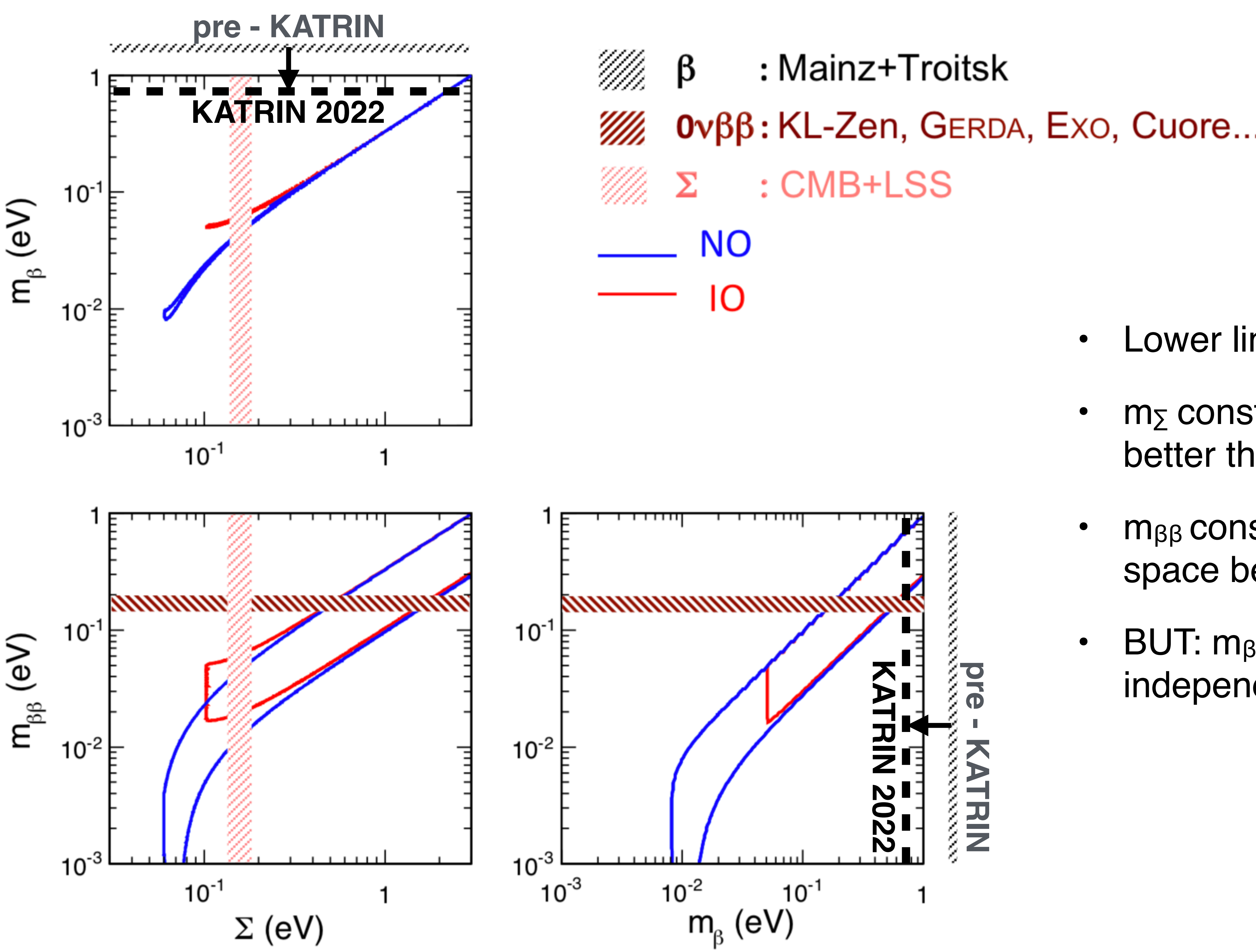
3 months KATRIN data better than Mainz, Troitsk

- Statistics x6, systematics x12
- First sub-eV neutrino mass sensitivity in lab
- Multiple independent blind analyses

Global Picture 2022

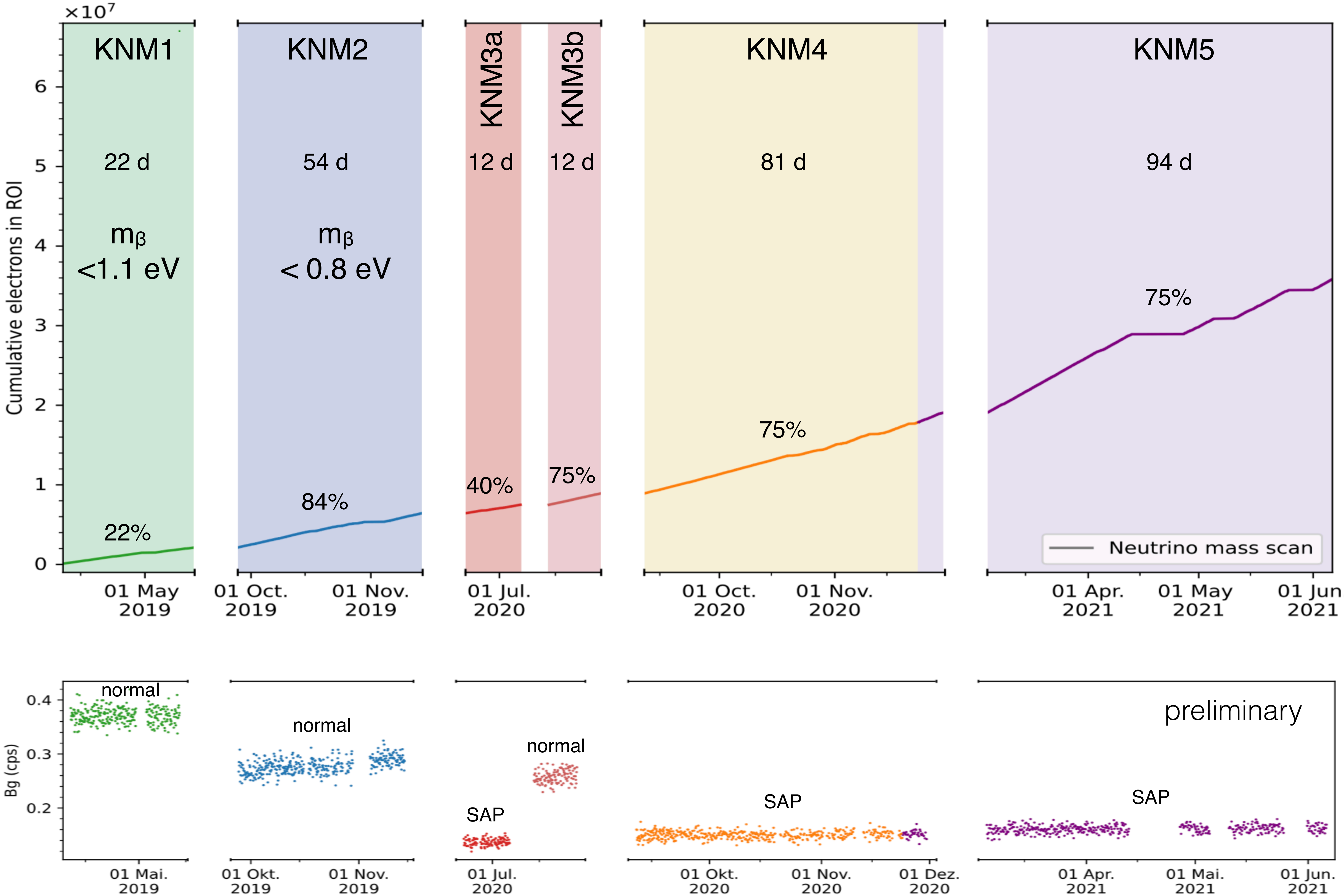
(assuming no sterile neutrinos)

[from Eligio Lisi, TAUP19]



- Lower limit on m_β at 8 - 50 meV
- m_Σ constrains parameter space better than m_β
- $m_{\beta\beta}$ constrains parameter space better than m_β
- BUT: m_β is the only model independent measurement

Future Datasets



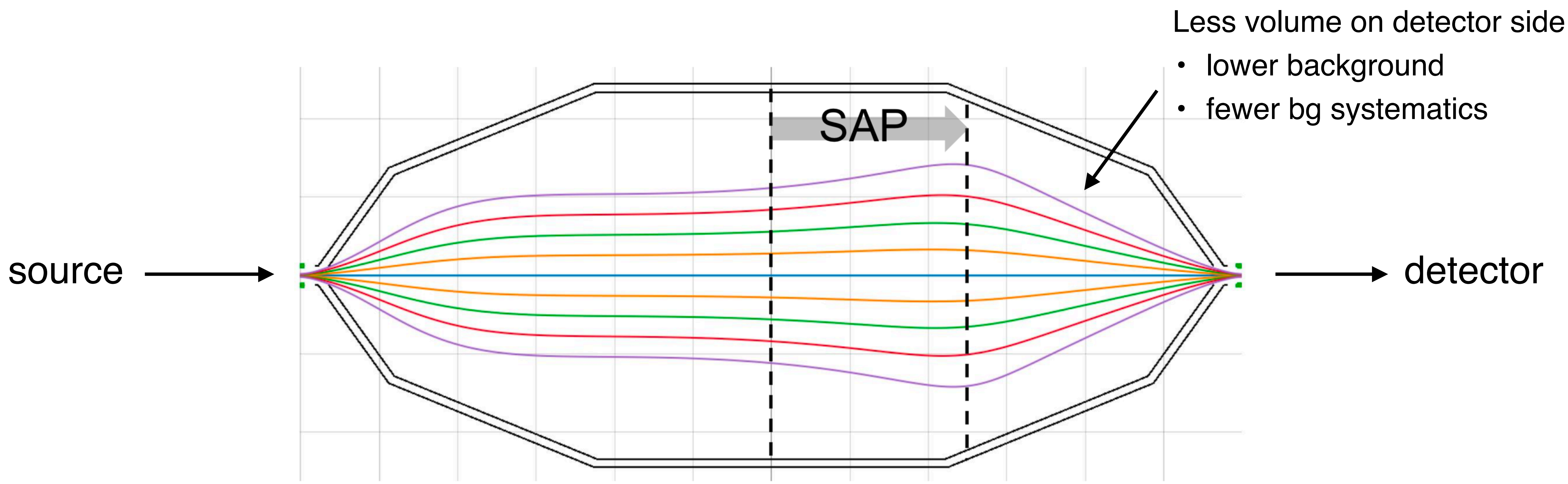
KNM6 on disk

KNM7 started

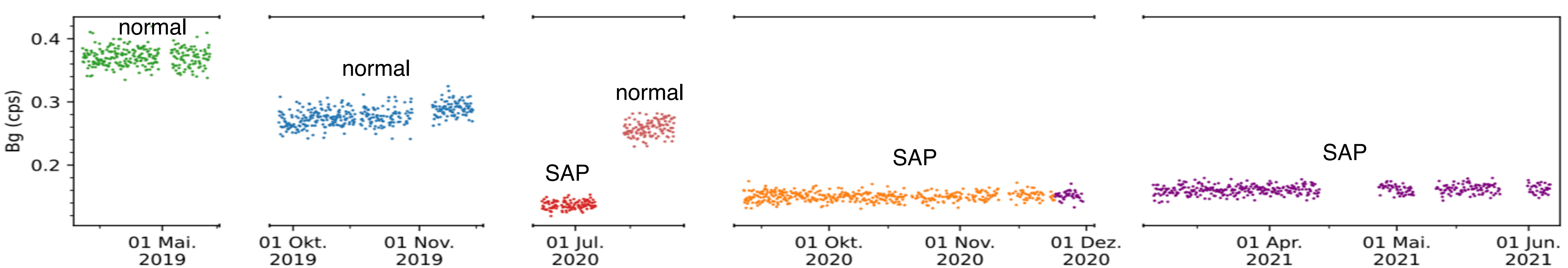
Future Datasets

Shifted analyzing plane (SAP):

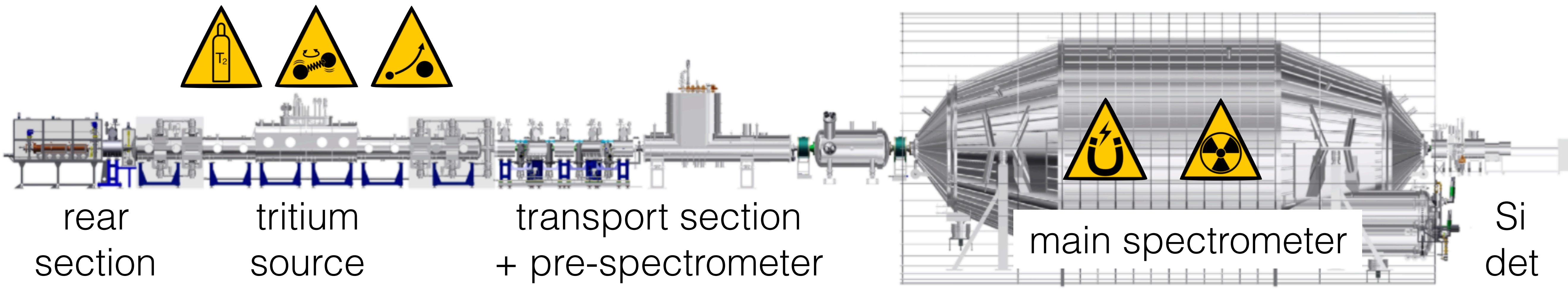
- Move maximum of potential from center of spectrometer towards the detector side

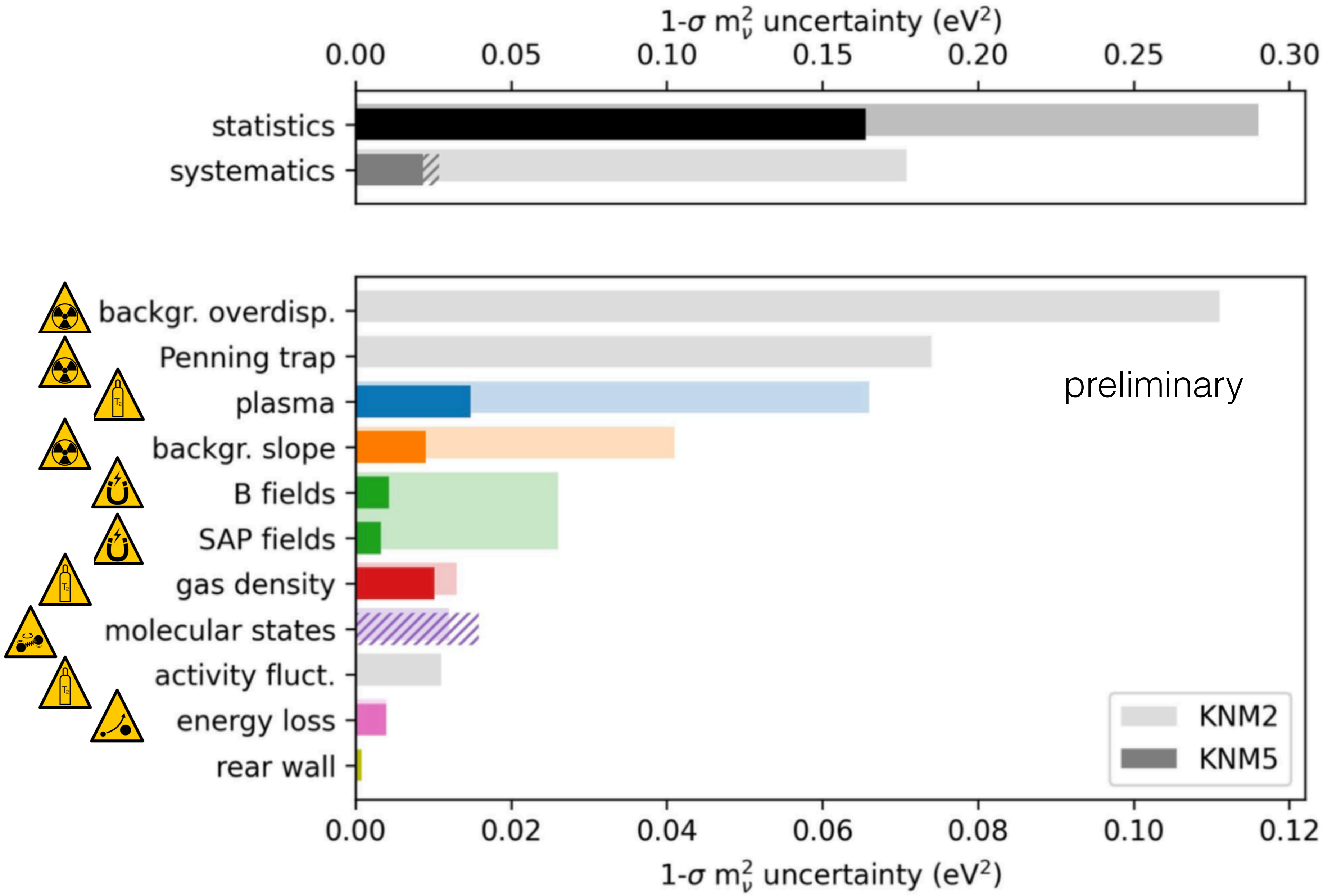


x2 background reduction



Future Systematics and Outlook for KATRIN





Comparison KNM2 vs KNM5:

- Higher statistics (longer run)
- Reduced systematics (x6)
  - SAP mode
  - Source operation

Largest future systematics:

- Plasma effects
- Finals state distribution

Final sensitivity:

- 1000 days in 5 yr
- Sensitivity: 0.2 eV (90% CL)
- Discovery potential: 0.35 eV (3σ)

Other searches with KATRIN data:

- Sterile neutrino search
- CvB relic neutrinos
- Lorentz violation

Future of Neutrino Mass Measurements

- Sensitivity 200 meV > 20 meV
- σ(statistic) != σ(systematic)
- Improve
  - **statistics (source strength)**
  - **resolution (B-fields)**
  - **systematics (finals state distribution)**

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- statistics (x100 larger)
  - source density at maximum (scatters)
  - increase source radius by x10
  - spectrometer radius scales by x10

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[S. Enomoto DBD2018]

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Future of Neutrino Mass Measurements

[S. Enomoto DBD2018]

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- statistics (x100 larger)
  - source density at maximum (scatters)
  - increase source radius by x10
  - spectrometer radius scales by x10

- Measurement approach at feasibility limit

Future of Neutrino Mass Measurements

Statistics - Increase source density:

1. Extract electron energy by measuring cyclotron radiation (e^- remains inside source)
2. Cryogenic bolometers (source = detector)

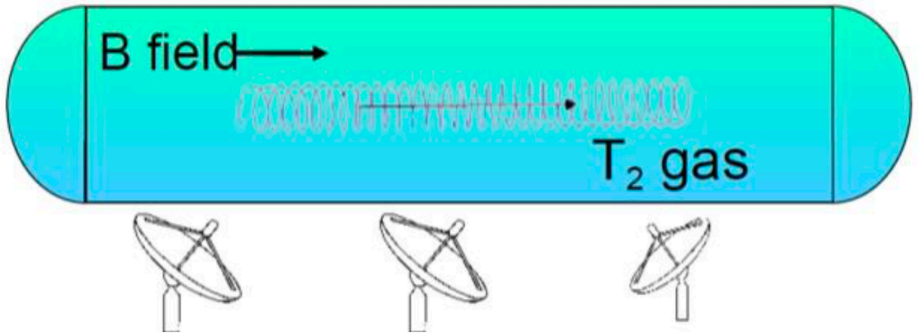
Resolution:

1. Frequency measurement
2. Cryogenic bolometers with lower Q-value isotope ^{163}Ho (2.8 keV)

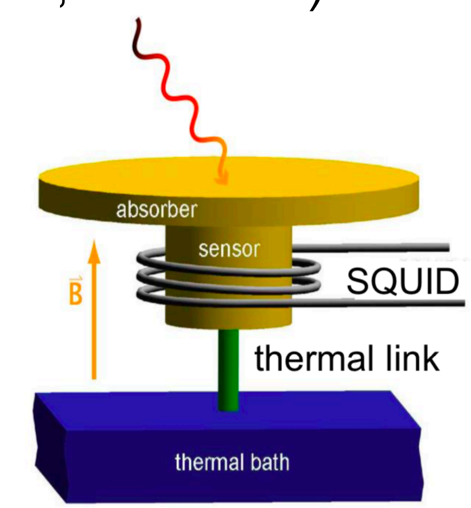
Final State Systematics:

1. Better theoretical calculations
2. Use atomic tritium
3. Use calorimeter measuring total energy

Frequency measurement with atomic tritium
(Project 8)



Bolometric calorimeters with ^{163}Ho
(ECHo, Holmes)



Conclusion

- Neutrino mass measured in three different observables
  - KATRIN measures the neutrino mass with tritium beta decays

Cosmology

$$m_{\Sigma} = \sum_i m_i$$

Neutrinoless DBD

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

Beta-Decay

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

- Latest KATRIN results: (1st and 2nd datasets combined) Nature Phys. 18, 160 (2022)

$$m_{\beta}^2 = 0.1 \pm 0.3 \text{ eV}^2 \qquad m_{\beta} < 0.8 \text{ eV } (90\,\% \text{ CL})$$

  - Still strongly dominated by statistics

- Future measurements:
  - 7th measurement campaign started (combined release 3,4,5 - expect late 2022)
  - Improvements on background reduction established
  - Full KATRIN sensitivity (1000 d): 0.2 eV (90% CL) or 0.35 eV (3σ)

Thank you for the invitation!

National Energy Research Scientific Computing Center

Thanks to NERSC for supporting the KATRIN analysis at LBL