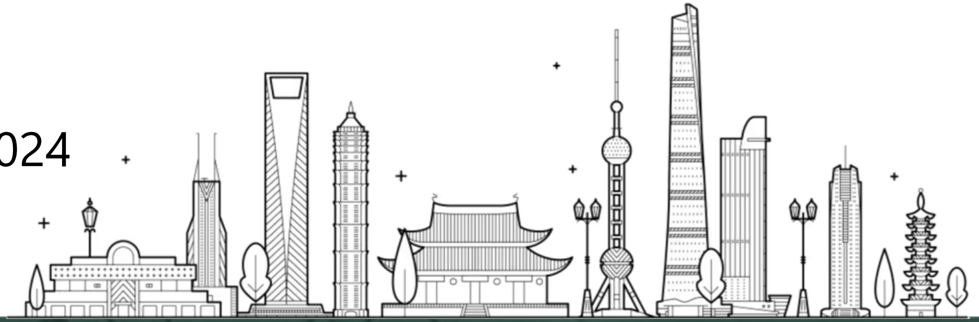
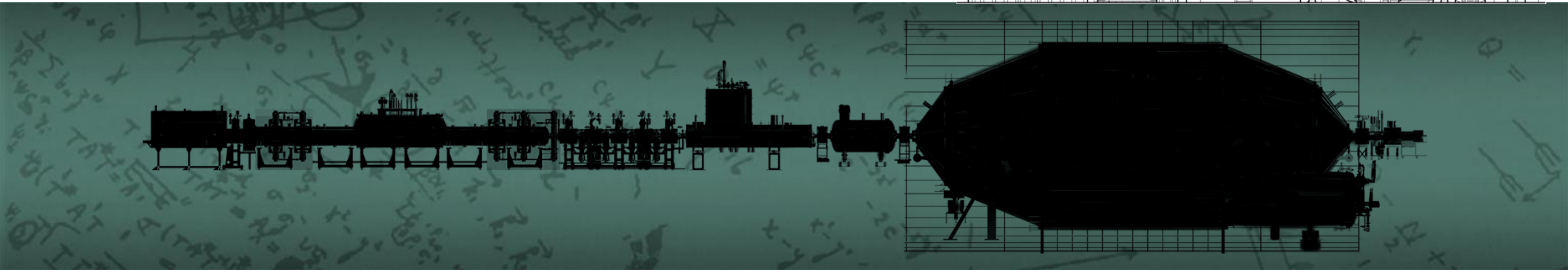
Neutrino mass measurements with the KATRIN experiment

Dr. Dominic Hinz on behalf of the KATRIN collaboration

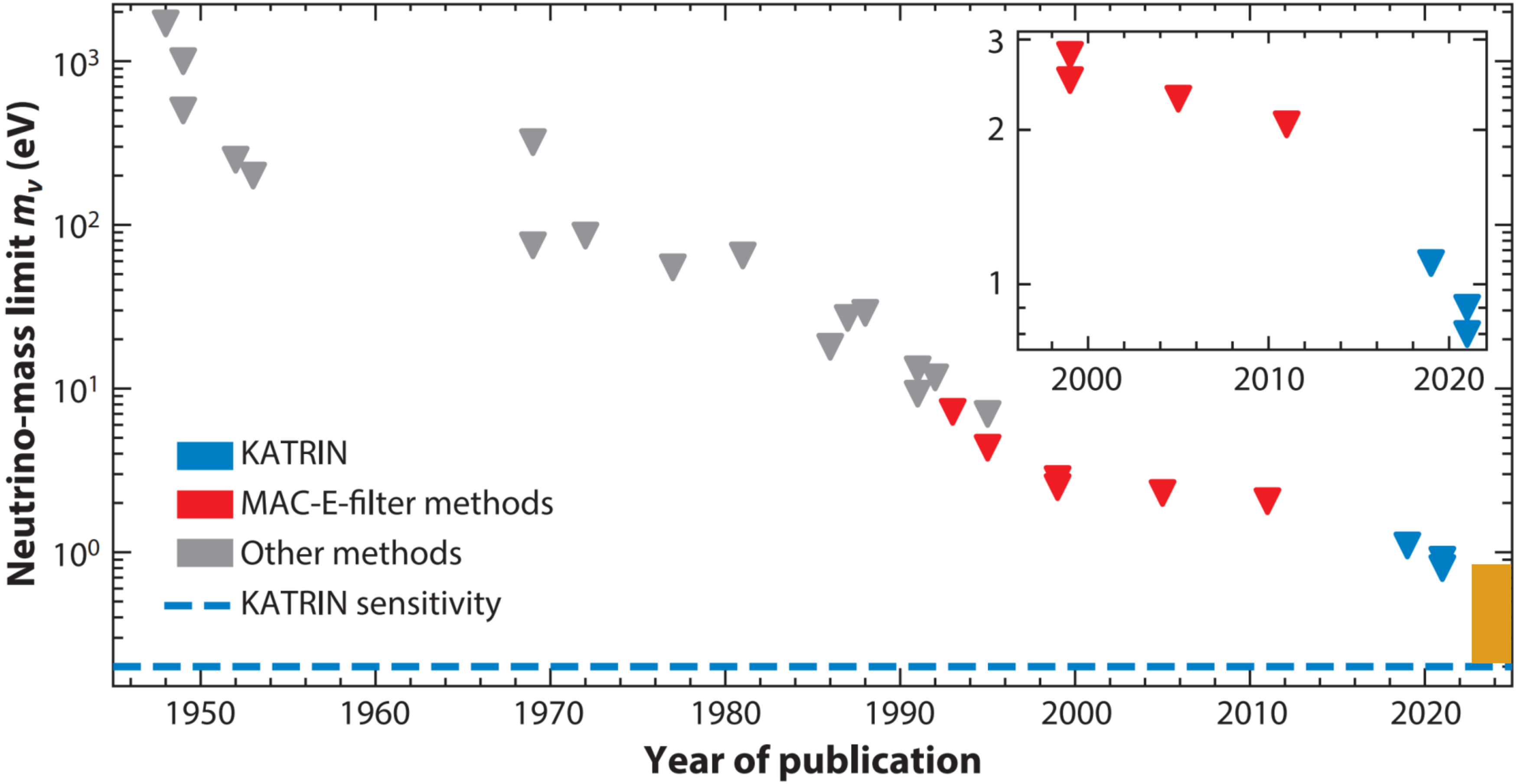
8th Shanghai Symposium on Particle Physics and Cosmology SPCS 2024





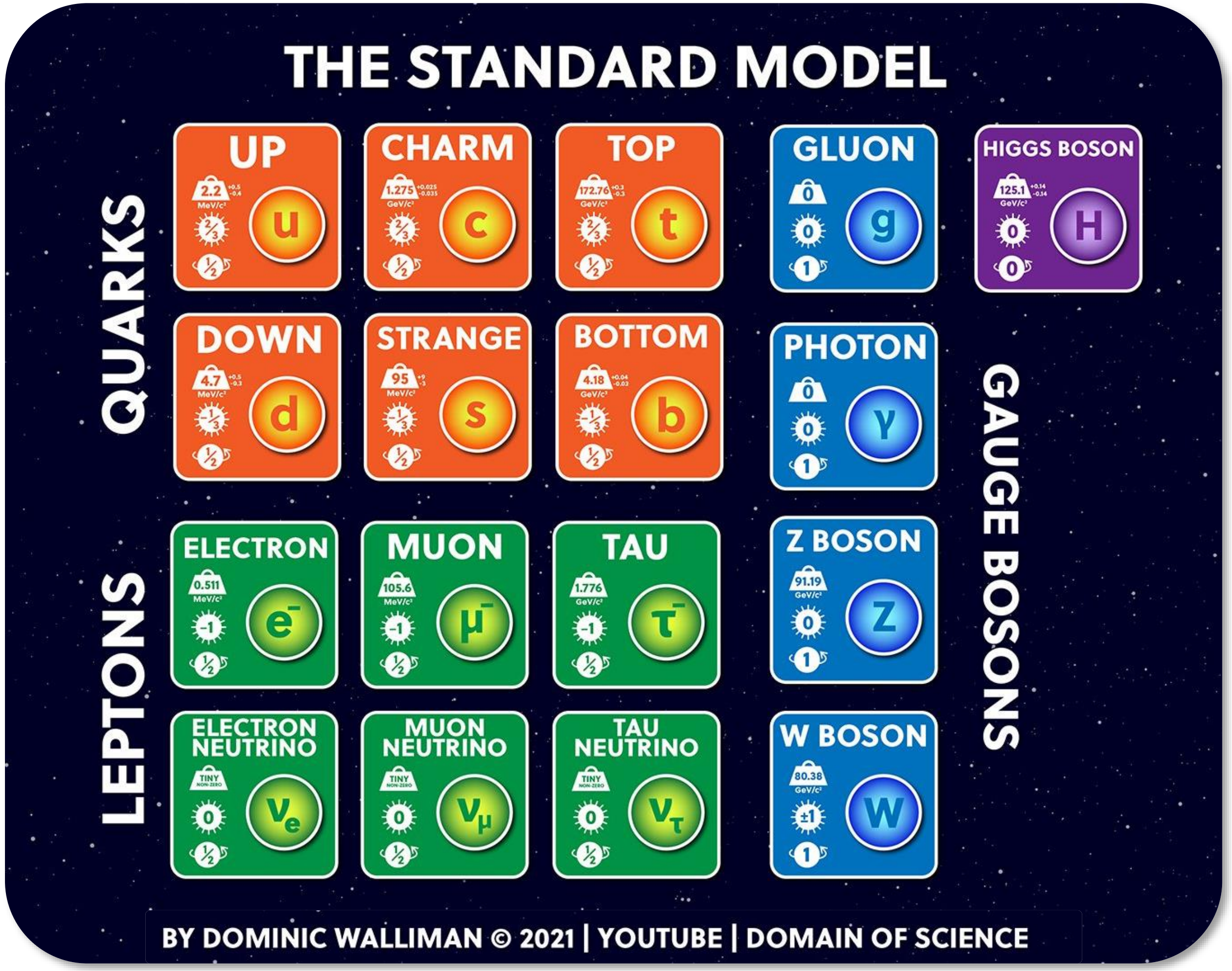
History of direct neutrino mass determination

https://doi.org/10.1146/annurev-nucl-101920-113013



New data release this year

Standard Model neutrinos



- Fundamental particle
- Only weak interaction
- Predicted to be massless

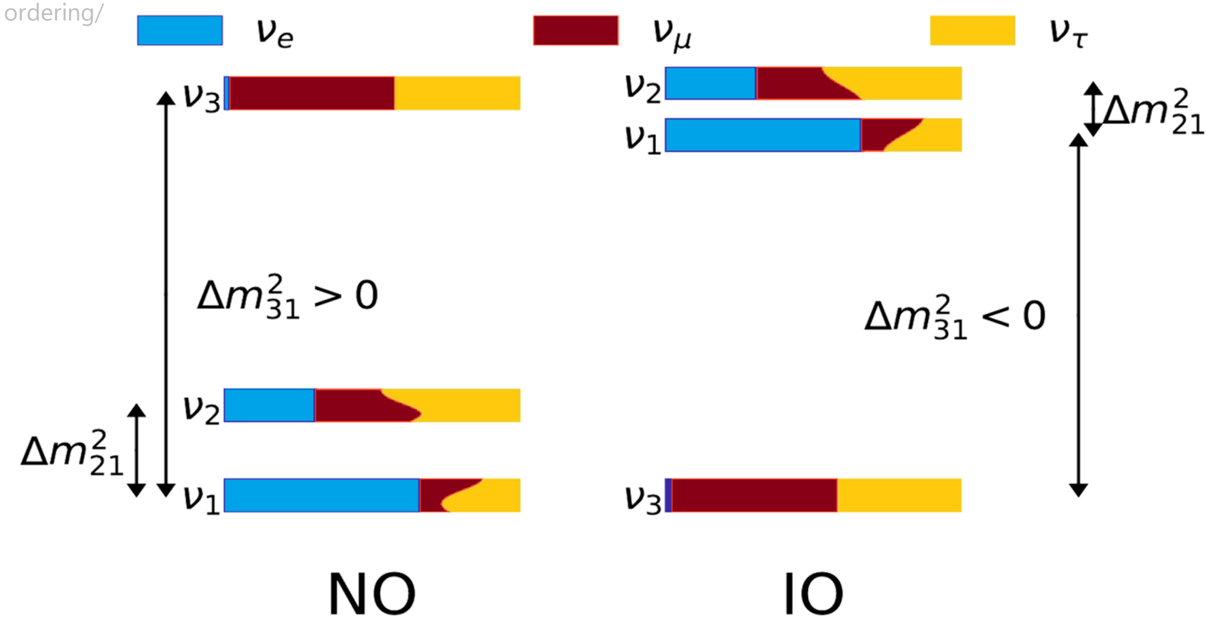
- Neutrino oscillations
  - → non-zero mass
  - → information on mass squared difference

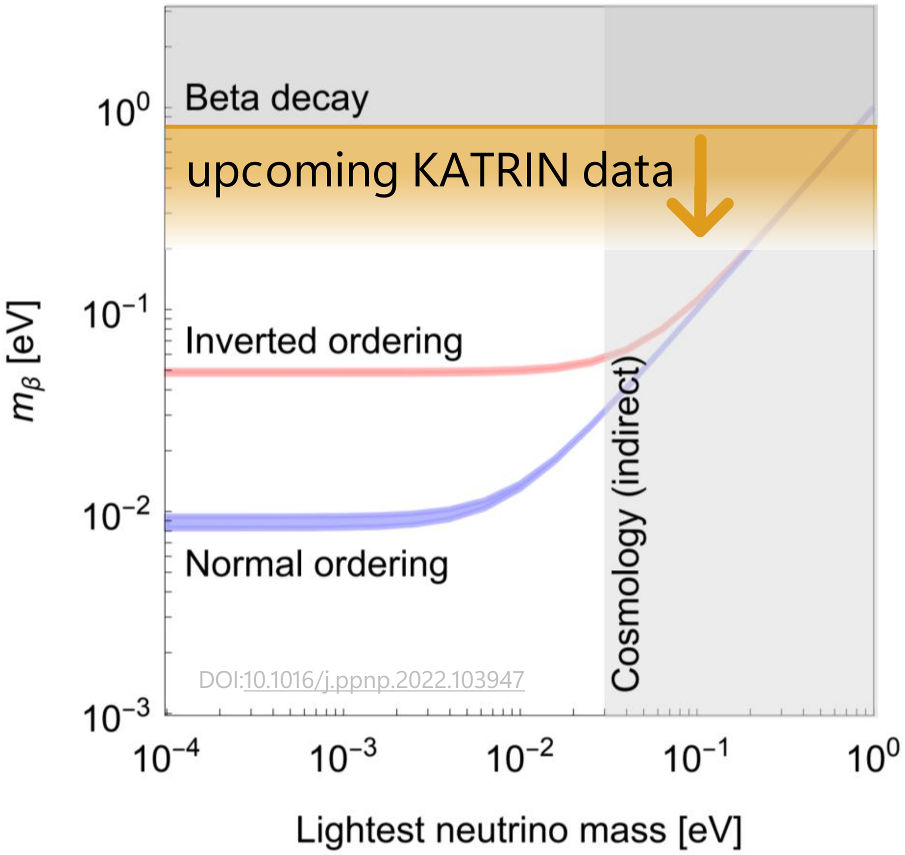
Talk by Shun Zhou

Talk by Concha Gonzalez-Garcoa

Neutrino mass ordering

https://globalfit.astroparticles.es/2018/07/03/neutrino-mass-ordering/

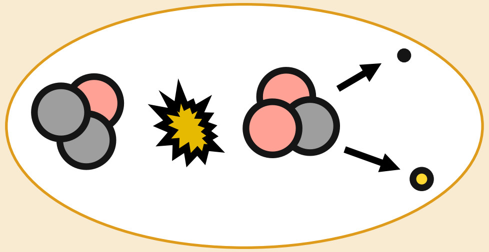




- Oscillation experiments → $\Delta m^2_{ij} = m^2_i - m^2_j$
- Ordering not sufficiently well known

Measuring the neutrino mass

β-decay

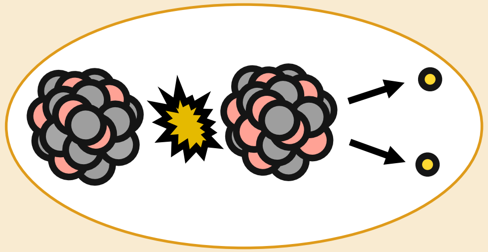


Direct kinematic measurement of electron energy

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

Real neutrino

0νββ-decay



Kinematic measurement of electron energy of hypothetic decay

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

Virtual neutrino

Cosmology

Model-dependent investigation of cosmological observations: CMB, BAO, lensing

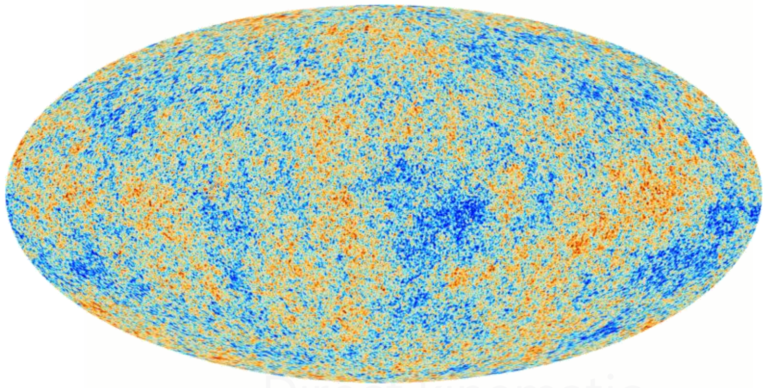
$$M_\nu = \sum_{i=1}^{3} m_i$$

Sum of neutrino masses

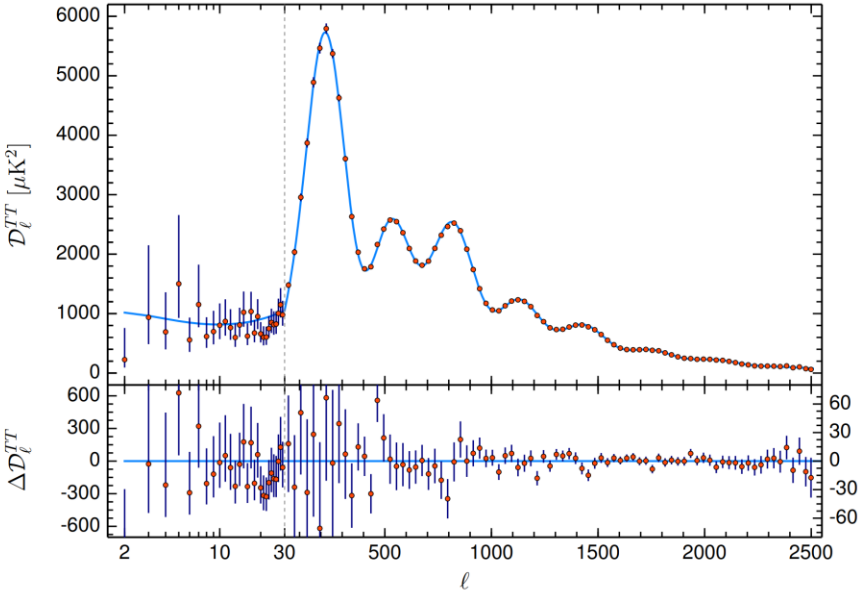
Measuring the neutrino mass

Talk by Stefano Gariazzo

Cosmology



Planck 2018, Astron.Astrophys. 641 (2020) A6



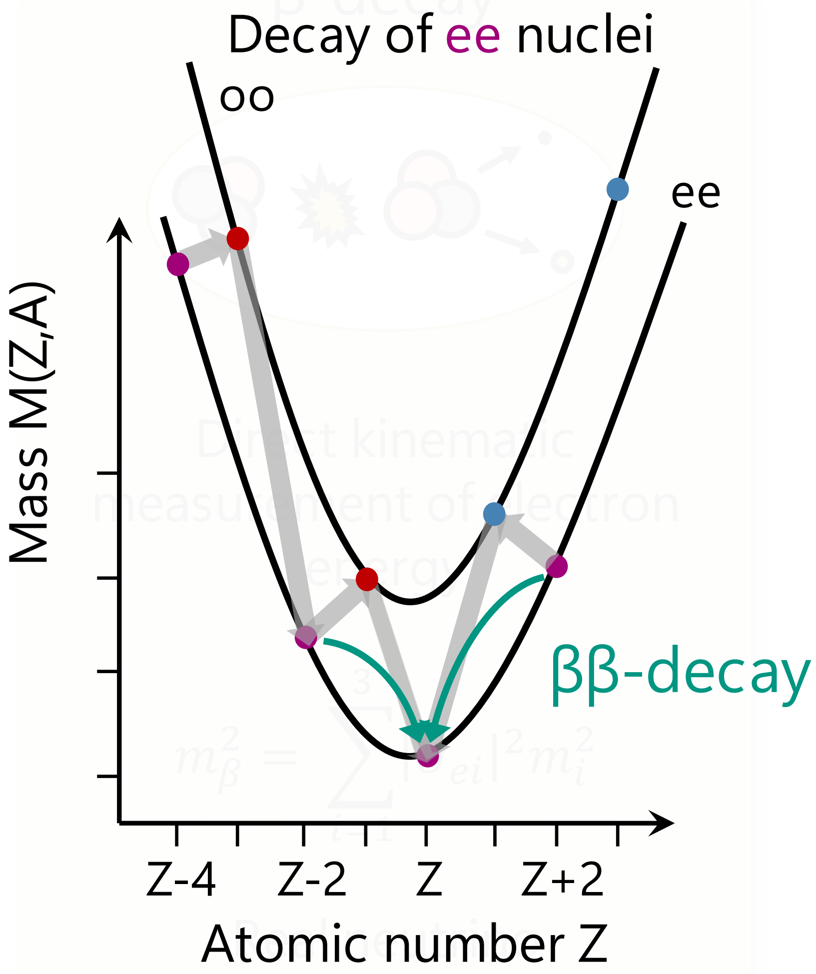
- Investigations of the Cosmic Microwave background (CMB) temperature power spectrum
- Baryon acousting oscillations (BAO)
- Gravitational lensing
- ΛCDM Model

$$M_\nu = \sum m_i \lesssim 100 \text{ meV}$$

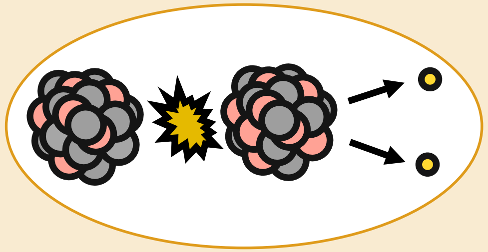
Di Valentino et al., Phys.Rev.D 106 (2022) 4, 043540

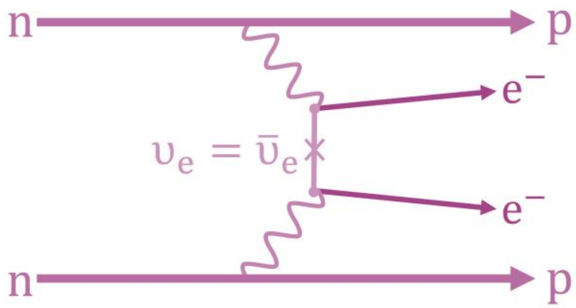
Measuring the neutrino mass

Talk by Shaobo Wang



0νββ-decay





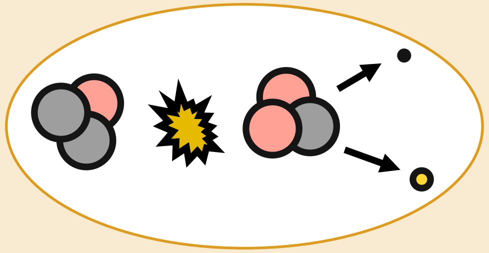
$$|m_{\beta\beta}| = \frac{m_e^2}{G^{0\nu\beta\beta}\,|\mathcal{M}^{0\nu\beta\beta}|^2\,T_{1/2}^{0\nu\beta\beta}} = \left|\sum_{i=1}^{3} U_{ei}^2 m_i\right|$$

- Majorana nature of neutrinos particle = antiparticle
- 2νββ-decay rare process: $T_{1/2} > 10^{23}$ years
- Model dependent on transition matrix element $\mathcal{M}^{0\nu\beta\beta}$ and phase space factor $G^{0\nu\beta\beta}$
- Experiments: LEGEND (^{76}Ge), KamLAND-Zen (^{136}Xe) and SuperNemo (^{100}Mo)

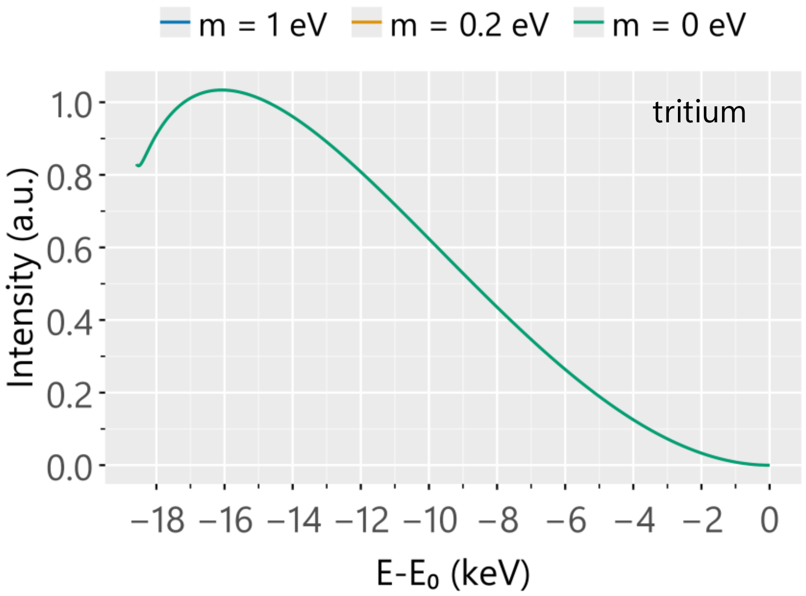
$$m_{\beta\beta} < 50\ \text{meV}\ \textit{to}\ 150\ \text{meV}$$

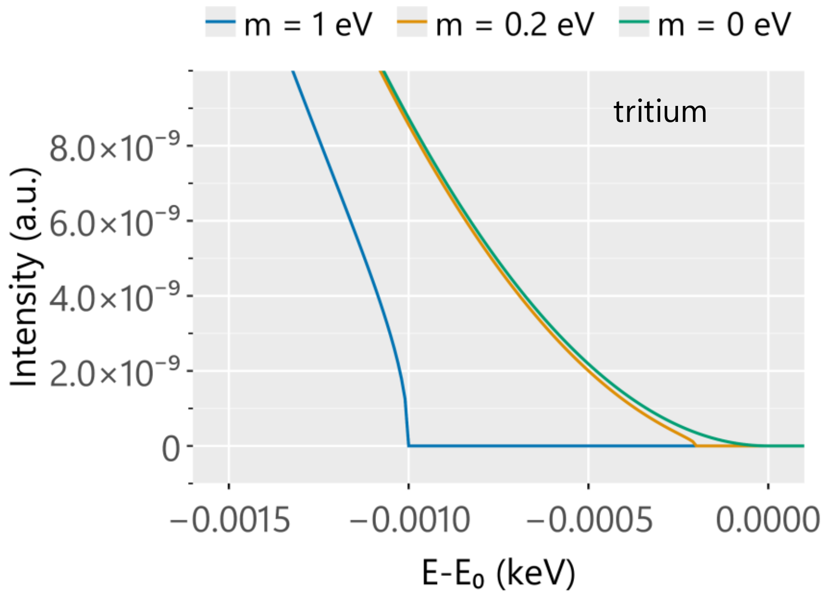
Measuring the neutrino mass

β-decay



$$E = (m_M - m_T)\cdot c^2 = m_e c^2 + T_e + m_\nu c^2 + T_\nu$$





- Neutrino mass imprints as missing energy at the endpoint of the β –spectrum
- Incoherent sum of mass eigenstates

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

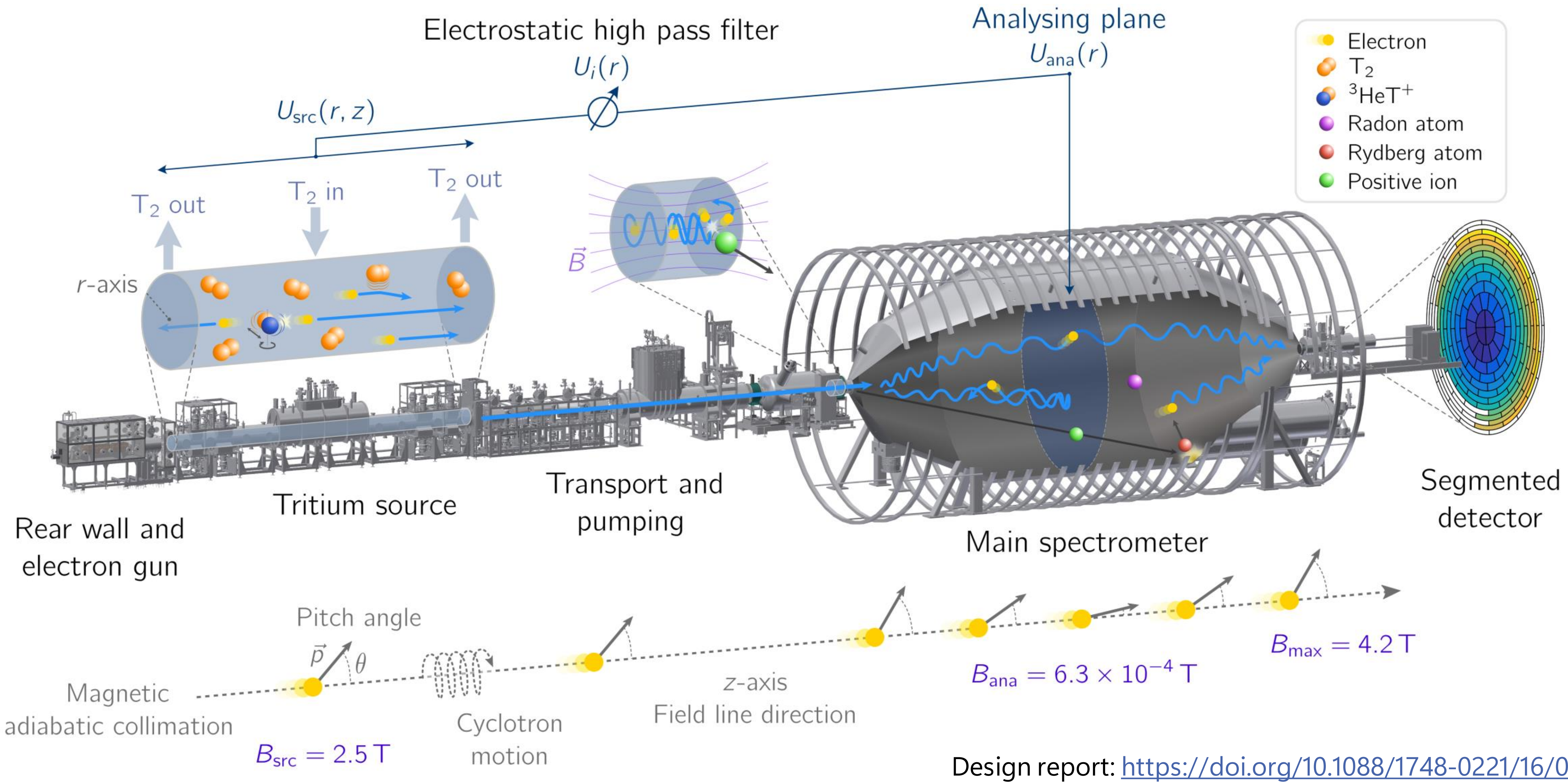
- Direct measurement

$$\frac{d\Gamma}{dE} = \frac{G_F^2 \cos^2(\theta_C)}{2\pi^3}\,|\mathcal{M}|^2\, F(Z,E)\,p(E+m_e)\cdot \sum_{i=1}^{3} |U_{ei}|^2 \epsilon \sqrt{\epsilon^2 - m_i^2}\,\Theta(\epsilon - m_i)$$

$$\epsilon = E_0 - E$$

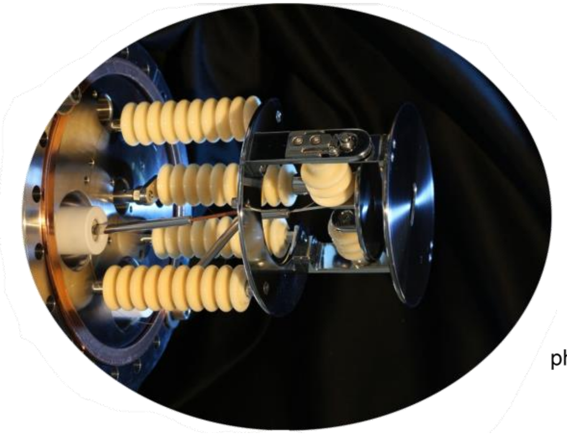
KATRIN: KArlsruhe TRItium Neutrino Experiment

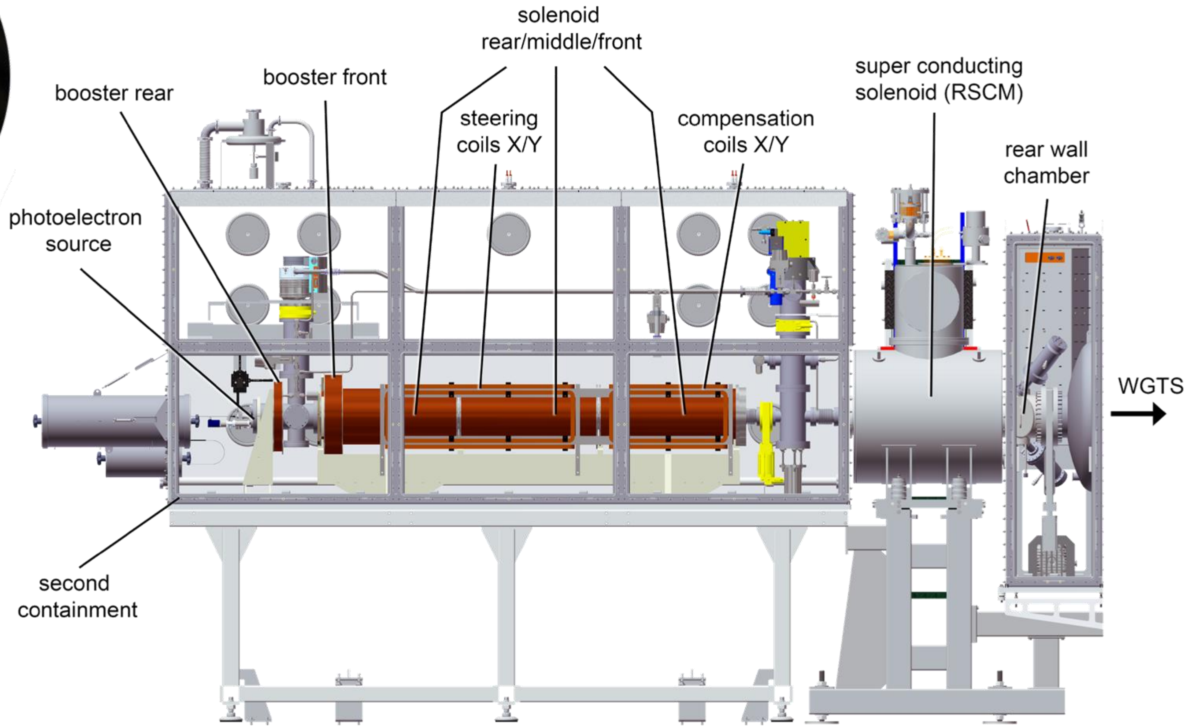
The KATRIN Experiment



Design report: https://doi.org/10.1088/1748-0221/16/08/T08015

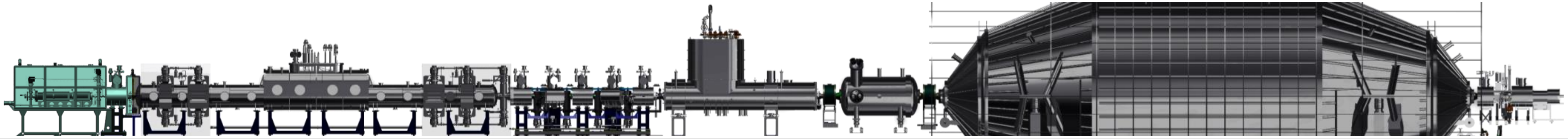
Rear section



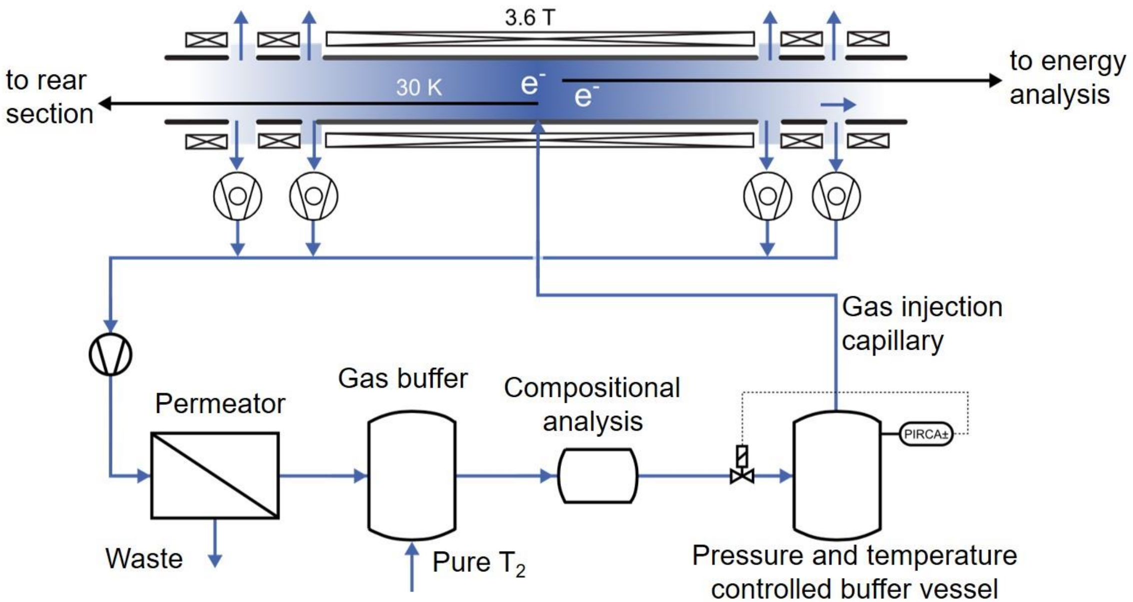


- Rear end of experiment
- Golden plated titanium rear wall
  - Plasma potential coupling

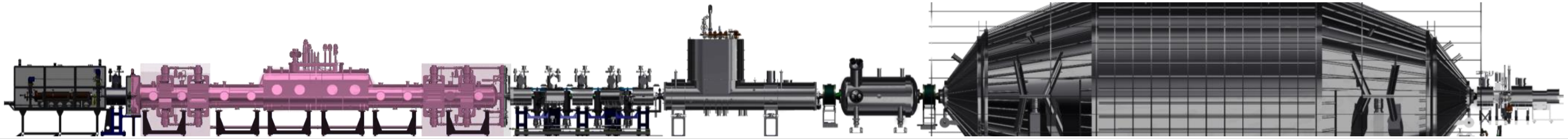
- Calibration technique: electron source
  - Narrow energy and angle width



Tritium source

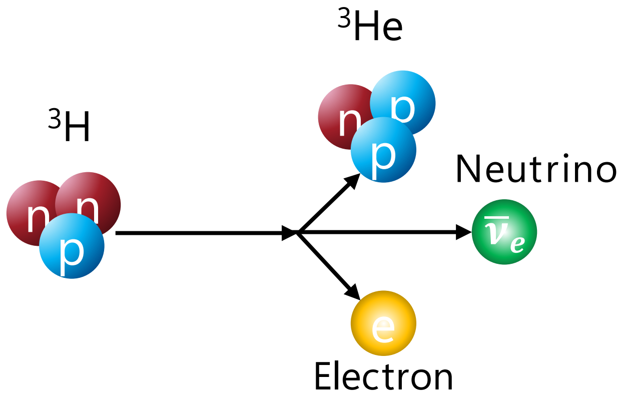


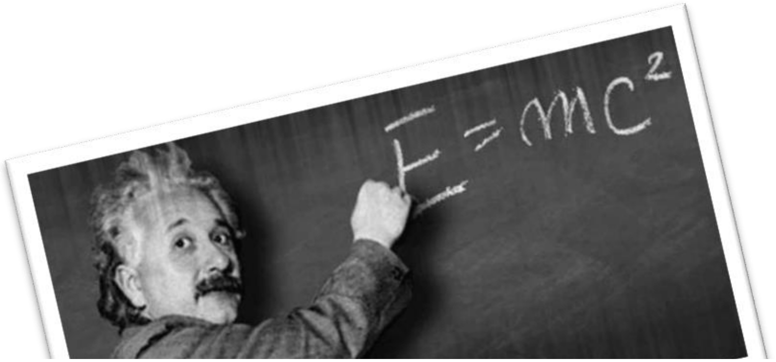
- 10m long Windowless Gaseous Tritium Source (WGTS)
- Stable density of tritium (σ ~ 0.1%/h)
- Gas composition with high tritium purity (>95%)
- Activity ~100 GBq
- Stable cryostat temperature (mK scale)



Why do we use tritium?

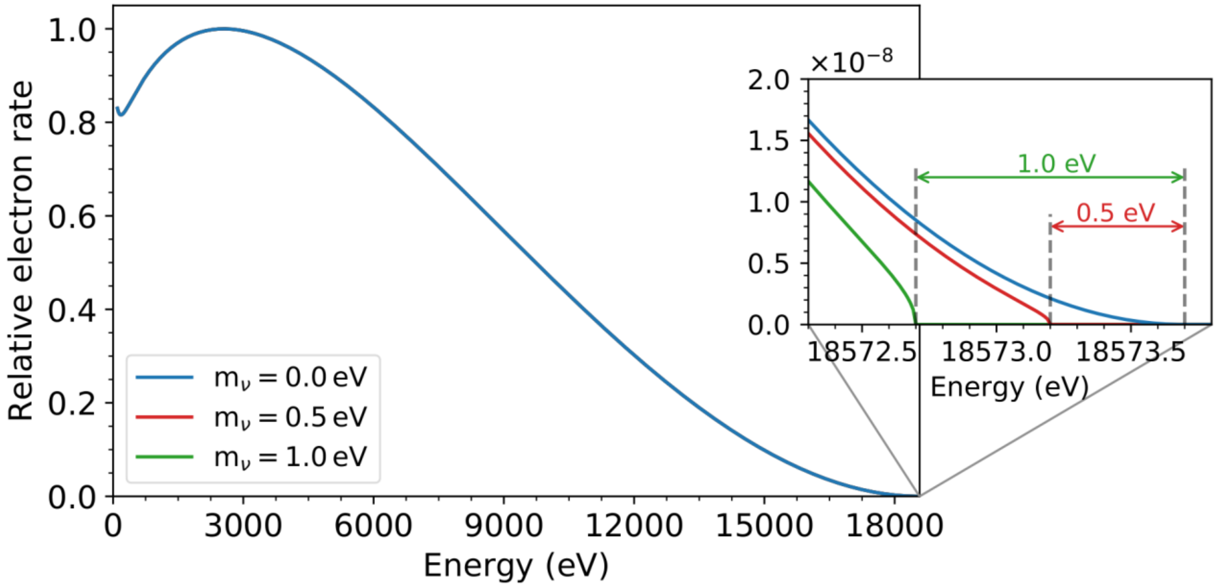
- Halflife of 12.3 years
- Low endpoint of 18.57 keV



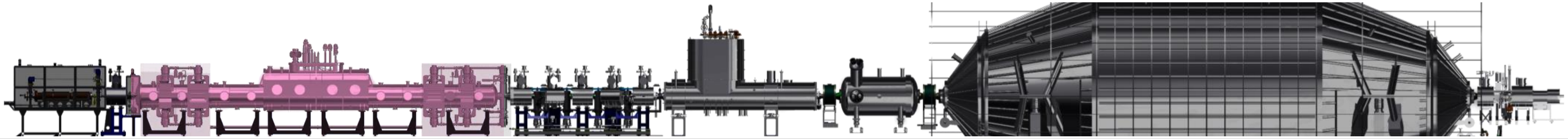


- Endpoint shifts with neutrino mass
- Precise measurement of spectrum tail
- → Neutrino mass m_ν as missing energy at Beta decay

$$E = (m_M - m_T) \cdot c^2 = m_e c^2 + T_e + m_\nu c^2 + T_\nu$$

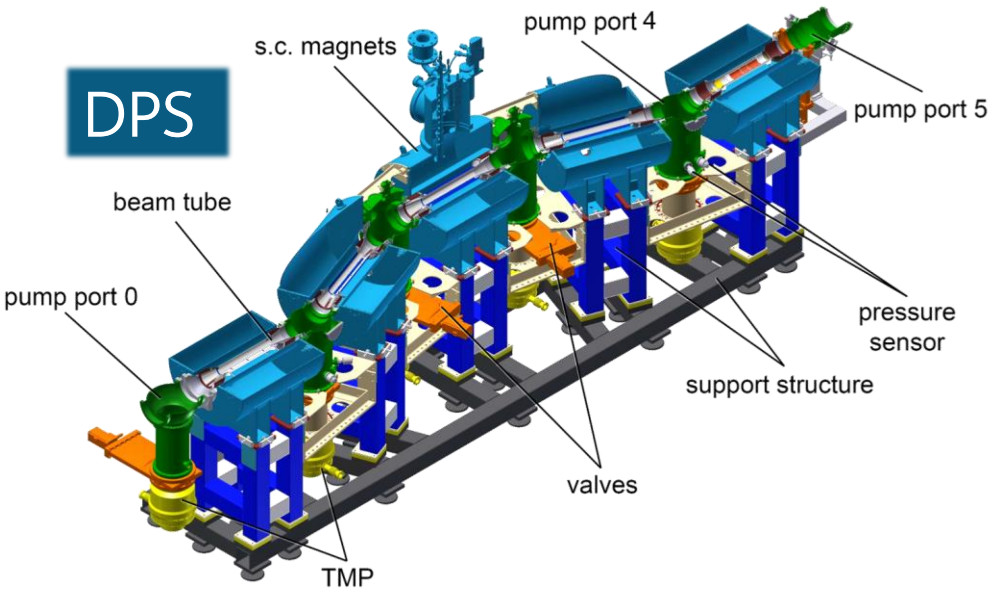


- Best limit before KATRIN: $m_\nu < 2\ \text{eV}/c^2$

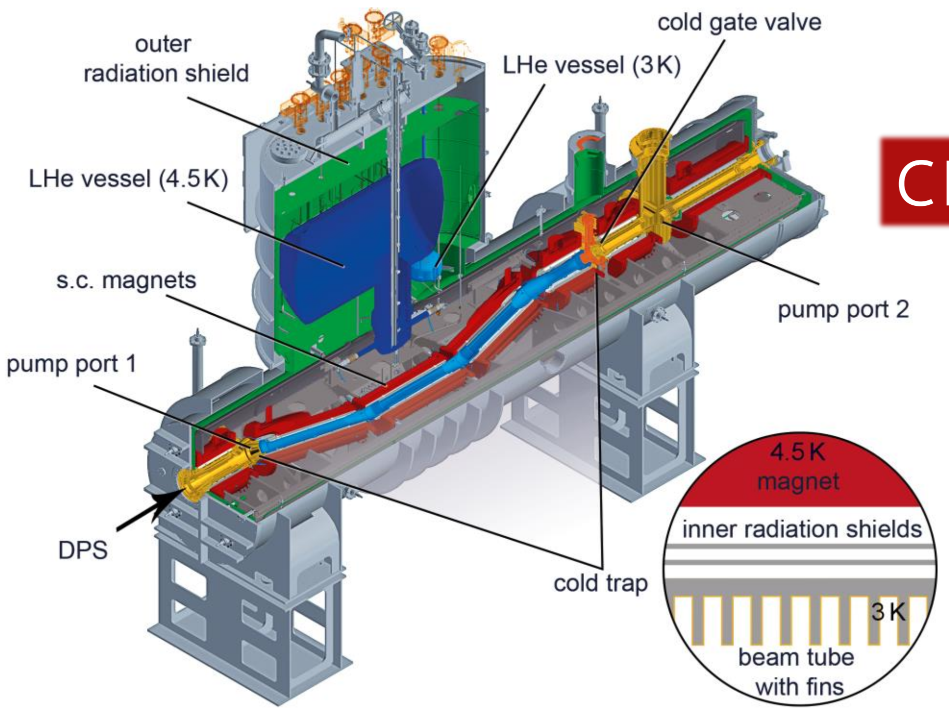


Transport and Pumping section

DPS

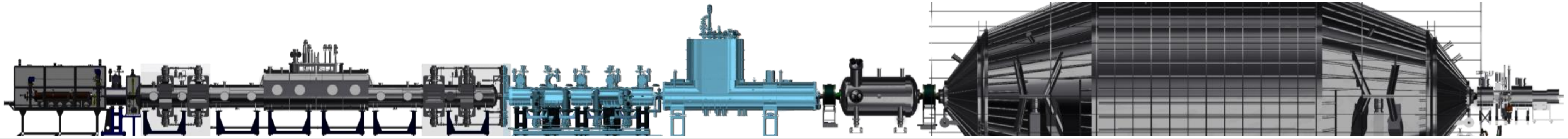


CPS



- Magnetic chicane
  - Efficient pumping of neutral molecules
  - Charged electrons guided magnetically
- Tritium reduction by $4 \cdot 10^3$

- Cryo-cooled golden beam tube fins
  - Condensed Argon frost layer
  - Large surface with tritium capture capability
- Tritium reduction by $\geq 10^8$

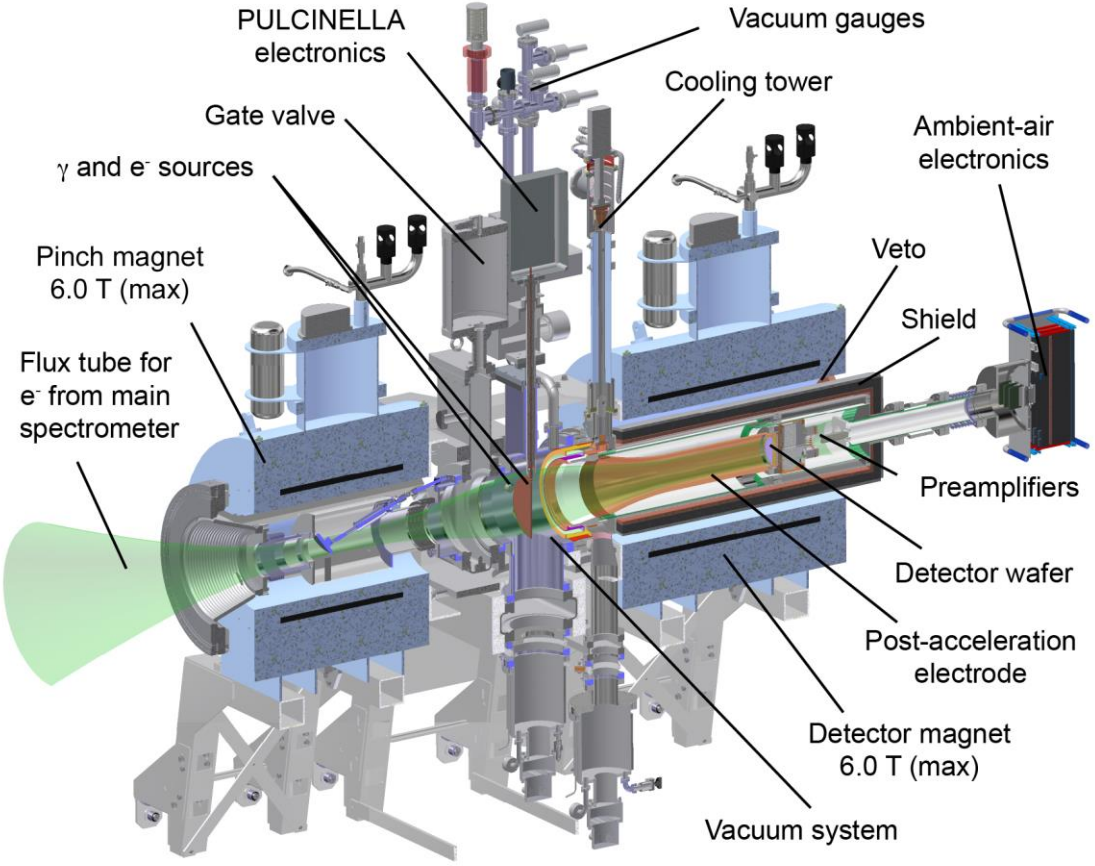


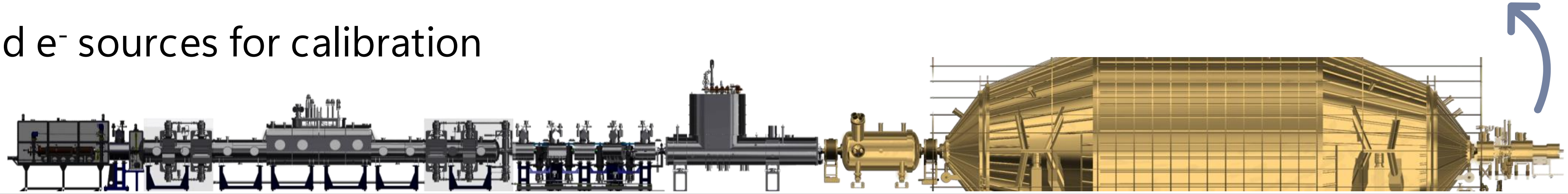
Spectrometer and detector section

- Pre and Main spectrometer
- Spectroscopy of β-decay electrons with high resolution (~1 eV)
  - High voltage with inner wire electrode system
  - → MAC-E-filter principle

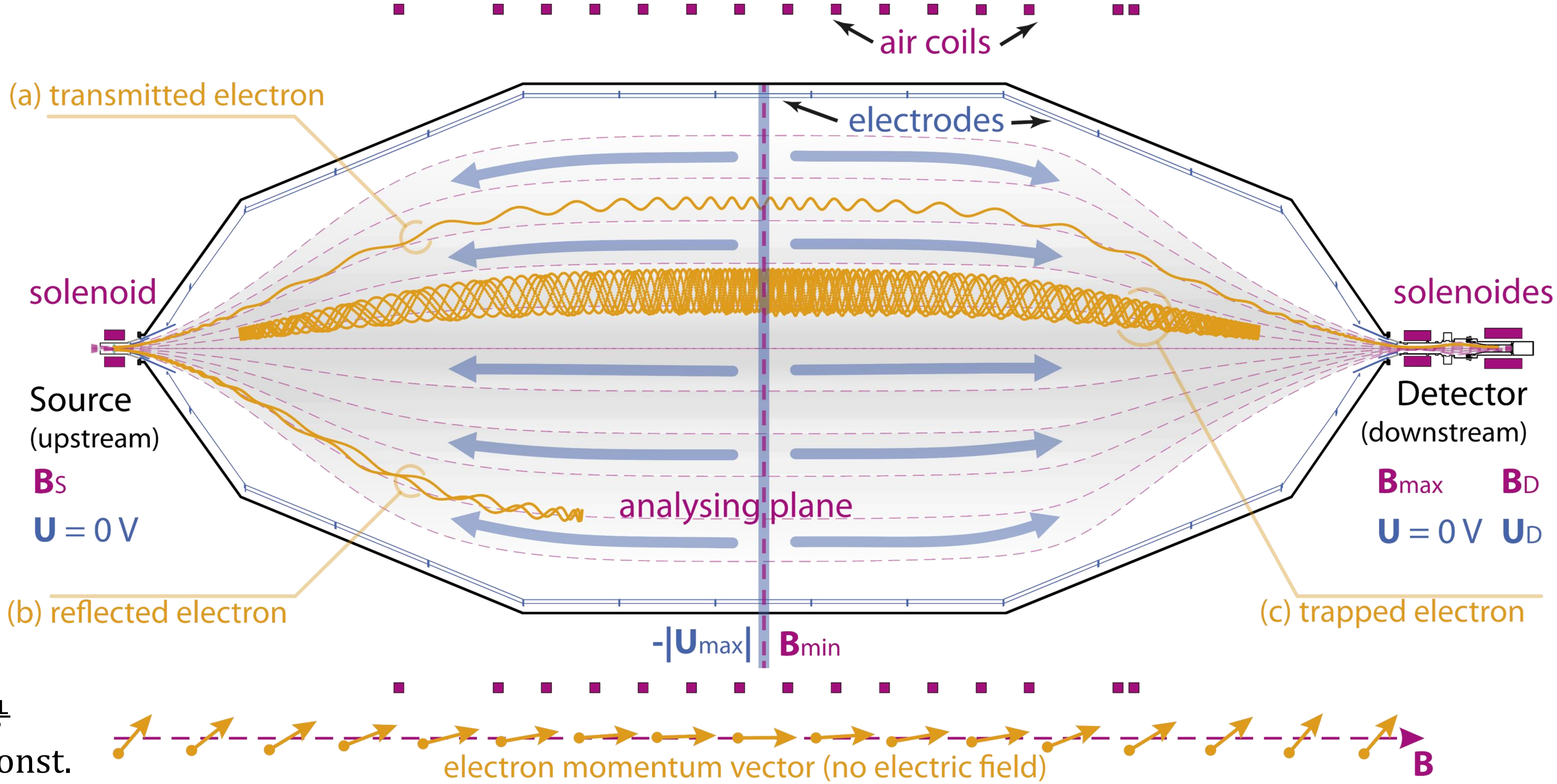
- Focal plane dector (FPD)
  - Segmented Silicon pin detector
  - 148 pixels of same size
  - Up to 10^5 e^-/s
  - In high magnetic field up to 6 T

- γ and e^- sources for calibration





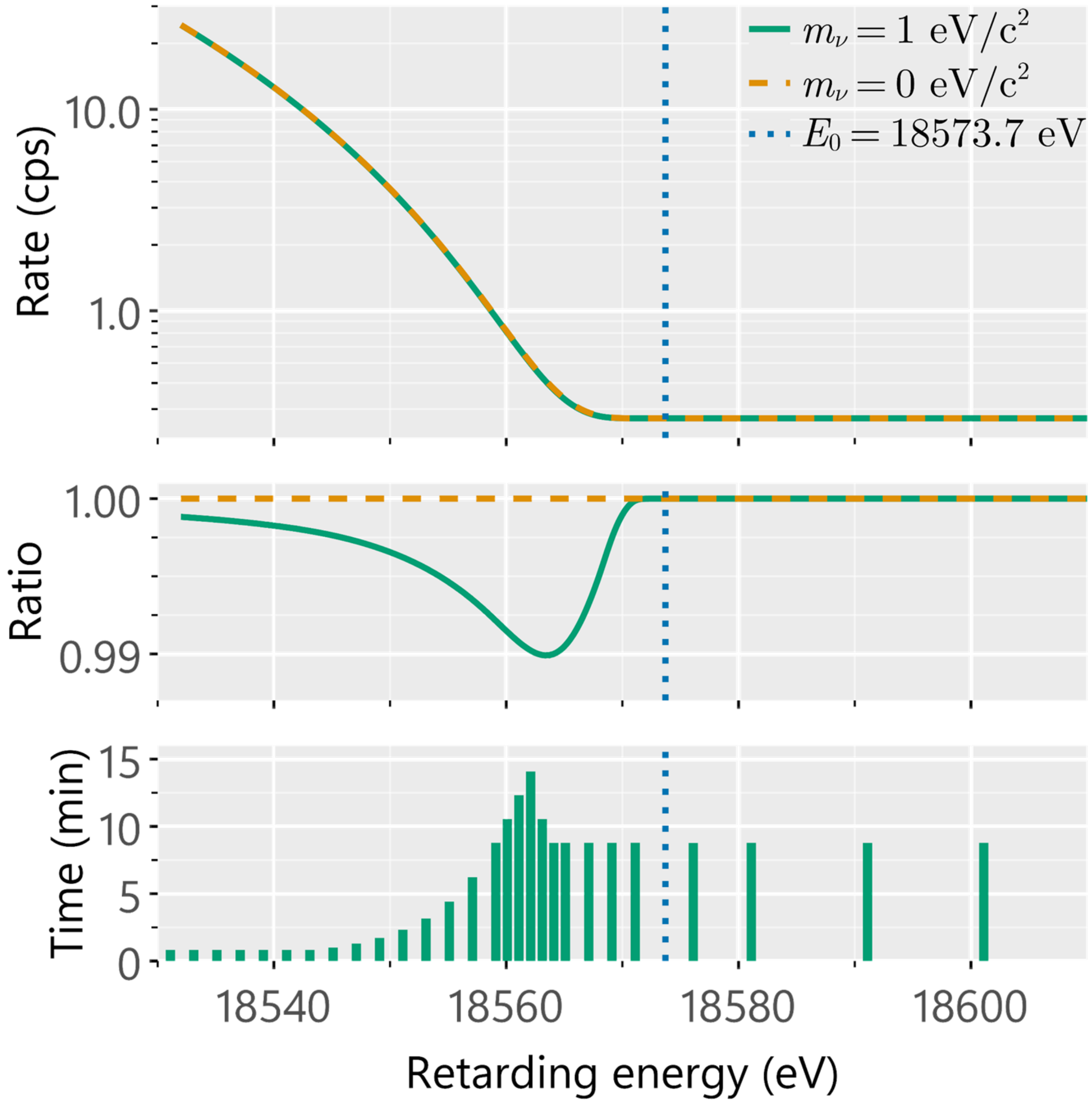
The MAC-E filter principle



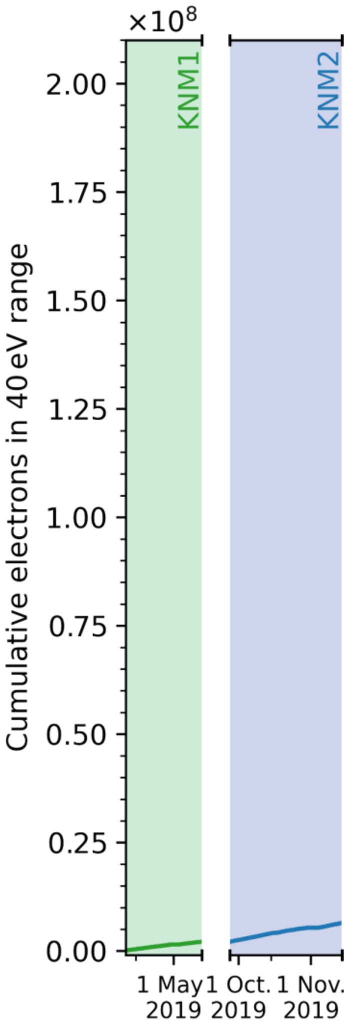
$\mu = \frac{E_\perp}{B} = \text{const.}$

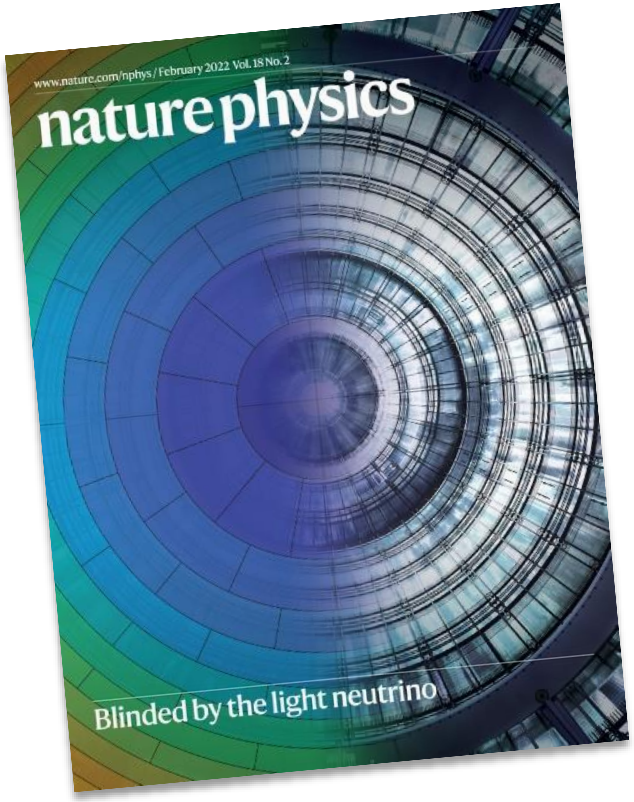
Taking data with KATRIN

- Integral measurement of β-spectrum
- Neutrino mass signature largest at E_0
- Optimised Measurement Time Distribution (MTD)
  - 2-3 hour scans
  - O(100) scans per campaign
- Background rate beyond E_0
- Stack data points with same conditions
- Analysis window: [E_0 – 40 eV, E_0 + 135 eV]



Data aqusition

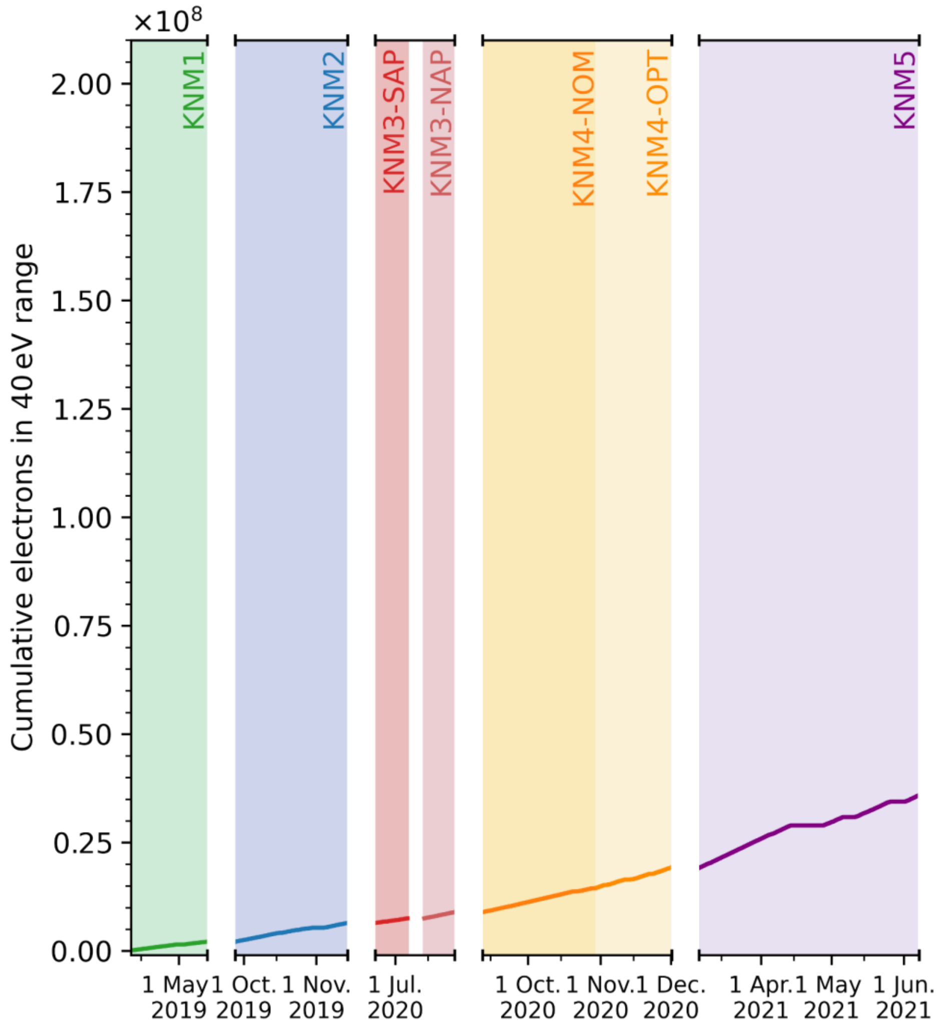




First KATRIN limit
with ~6 million electrons in analysing window
$m_\nu < 0.8$ eV (90% C.L.)

Nat. Phys. **18**, 160–166 (2022).
https://doi.org/10.1038/s41567-021-01463-1

Data aqusition



Direct neutrino-mass measurement based on 259 days of KATRIN data

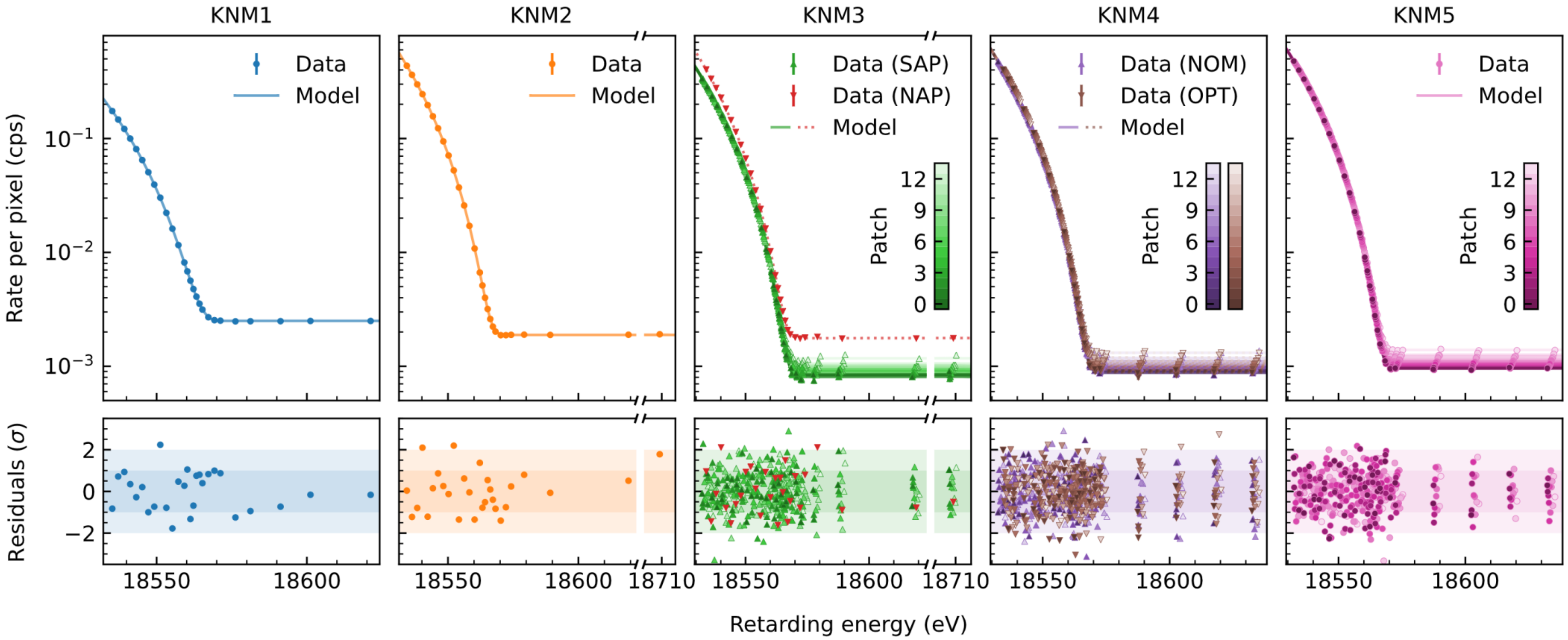
New limit with first 5 campaigns (6 times more statistics)

m_ν < 0.45 eV (90% C.L.)

Submitted to arXiv:2406.13516

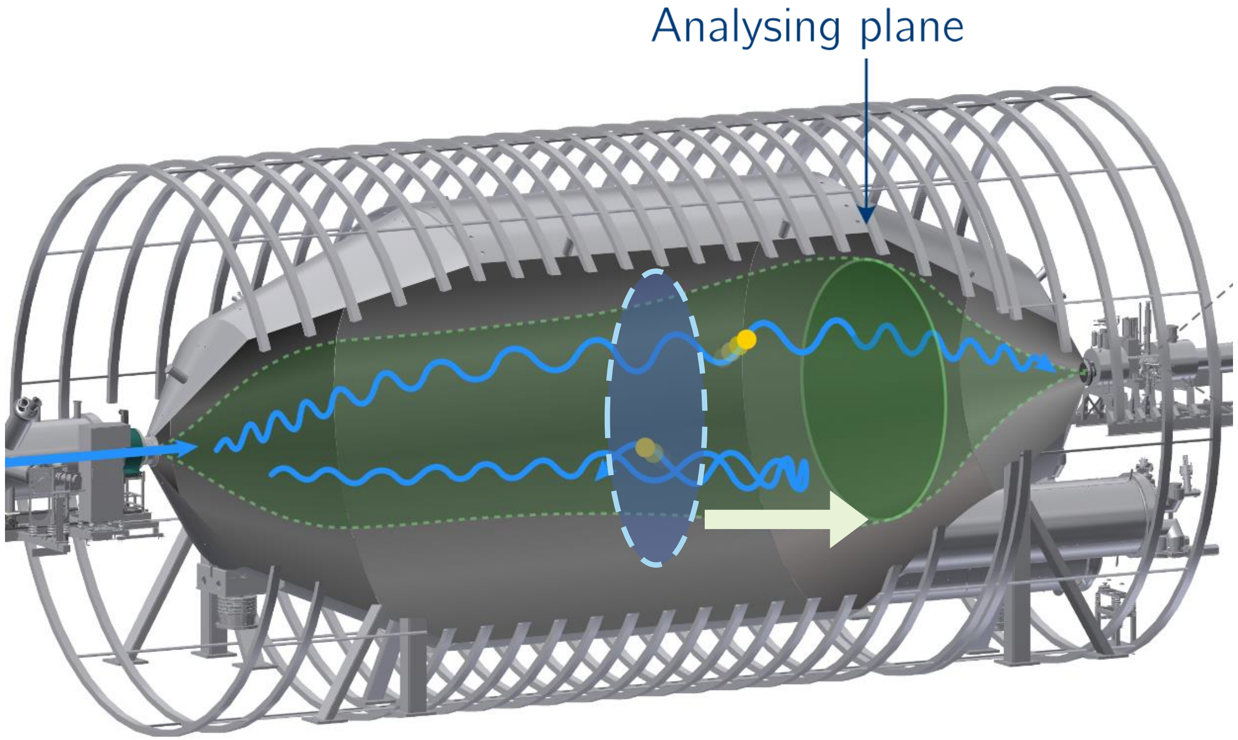
https://arxiv.org/abs/2406.13516

Data combination

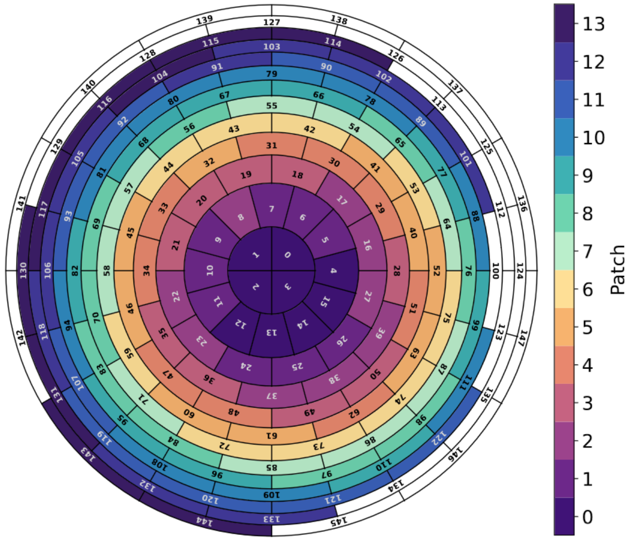


- 59 stacked spectra with a total of 1609 data points
- Computationally expensive model evaluations with 144 correlated systematic parameters
- Experimental improvements regarding background suppression and other systematic effects

Background suppression: Shifted analysing plane (SAP)

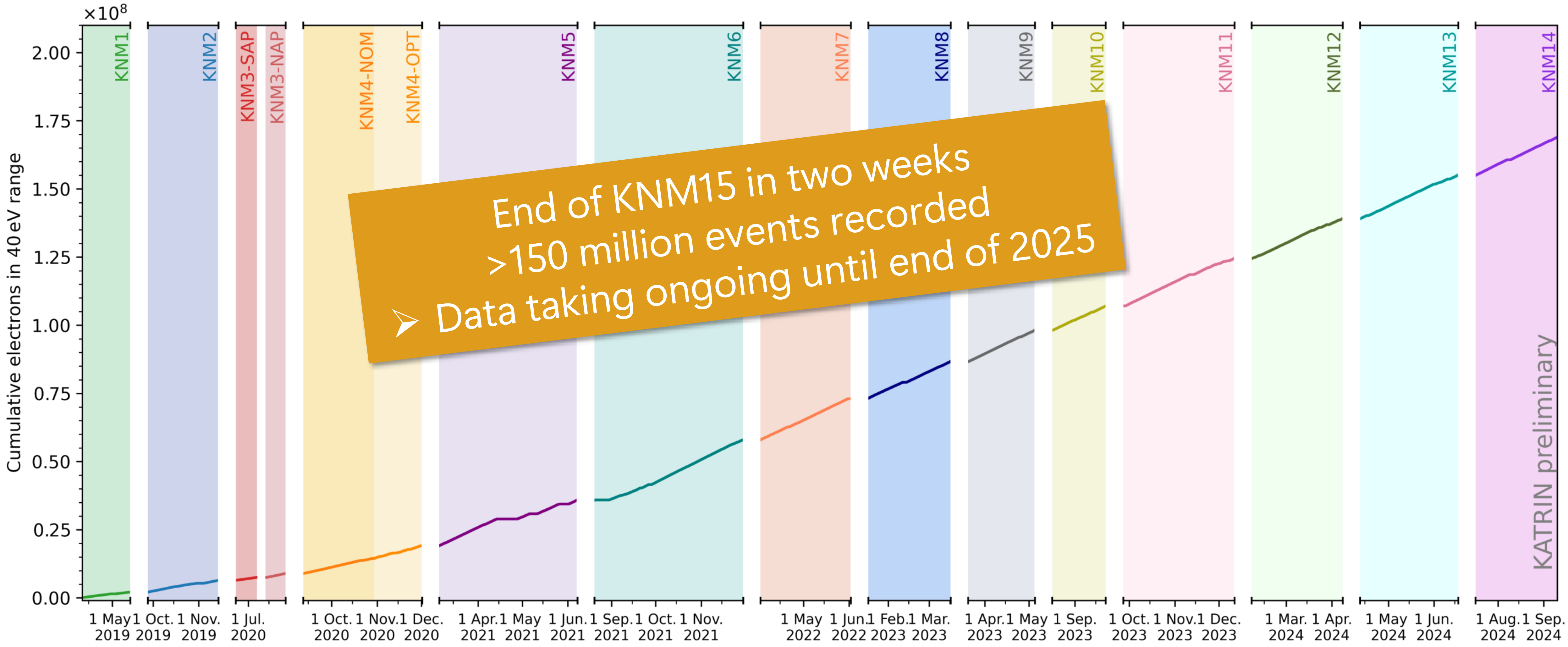


Main spectrometer



- Magnetic field minimum and potential maximum shifted towards detector
- Significant reduction of the sensitive fluxtube volume → factor 2 in background rate
- Inhomogeneous EM-fields → More segmented data and calibration mandatory

Data aqusition

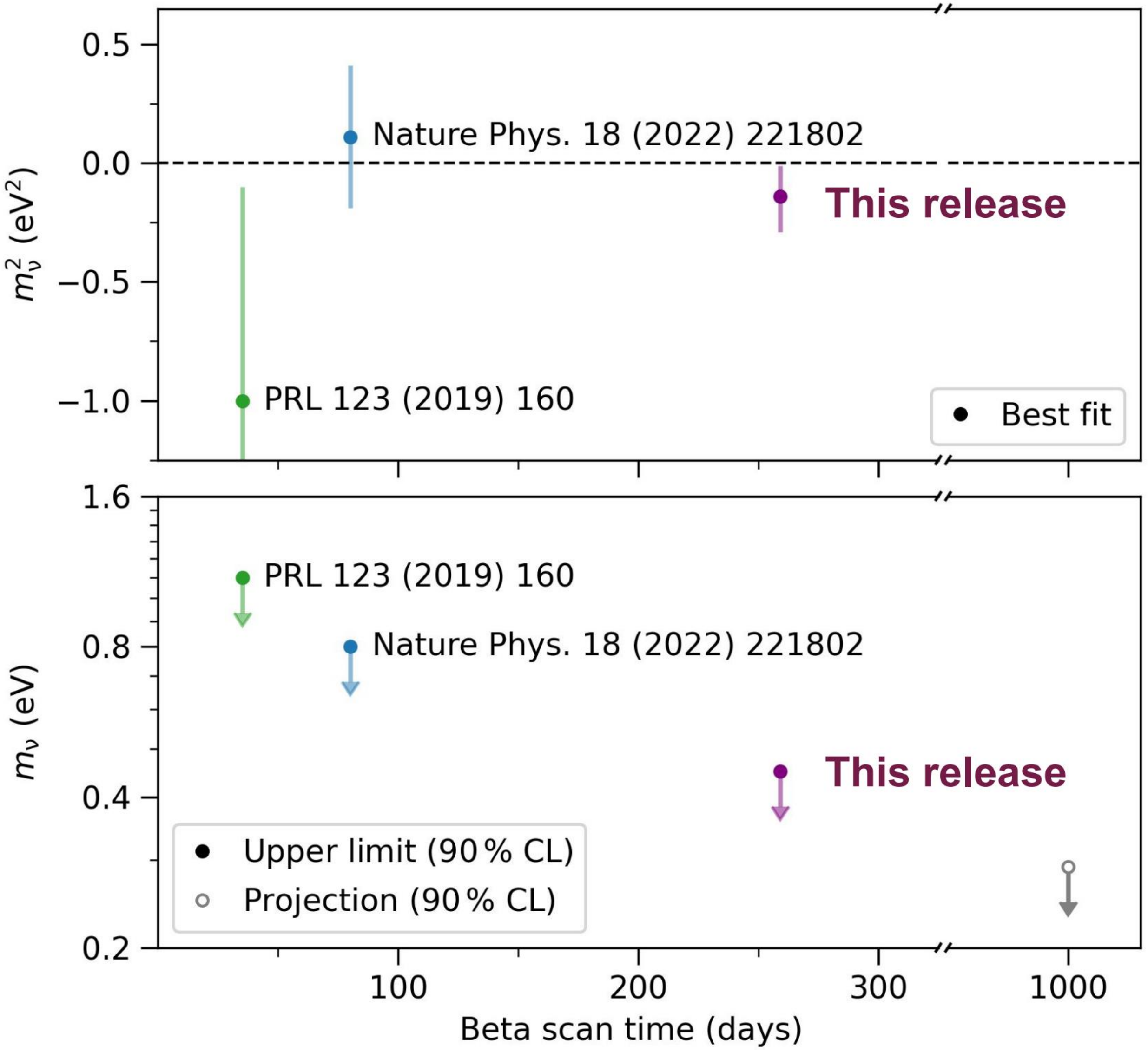


KATRIN experiment status

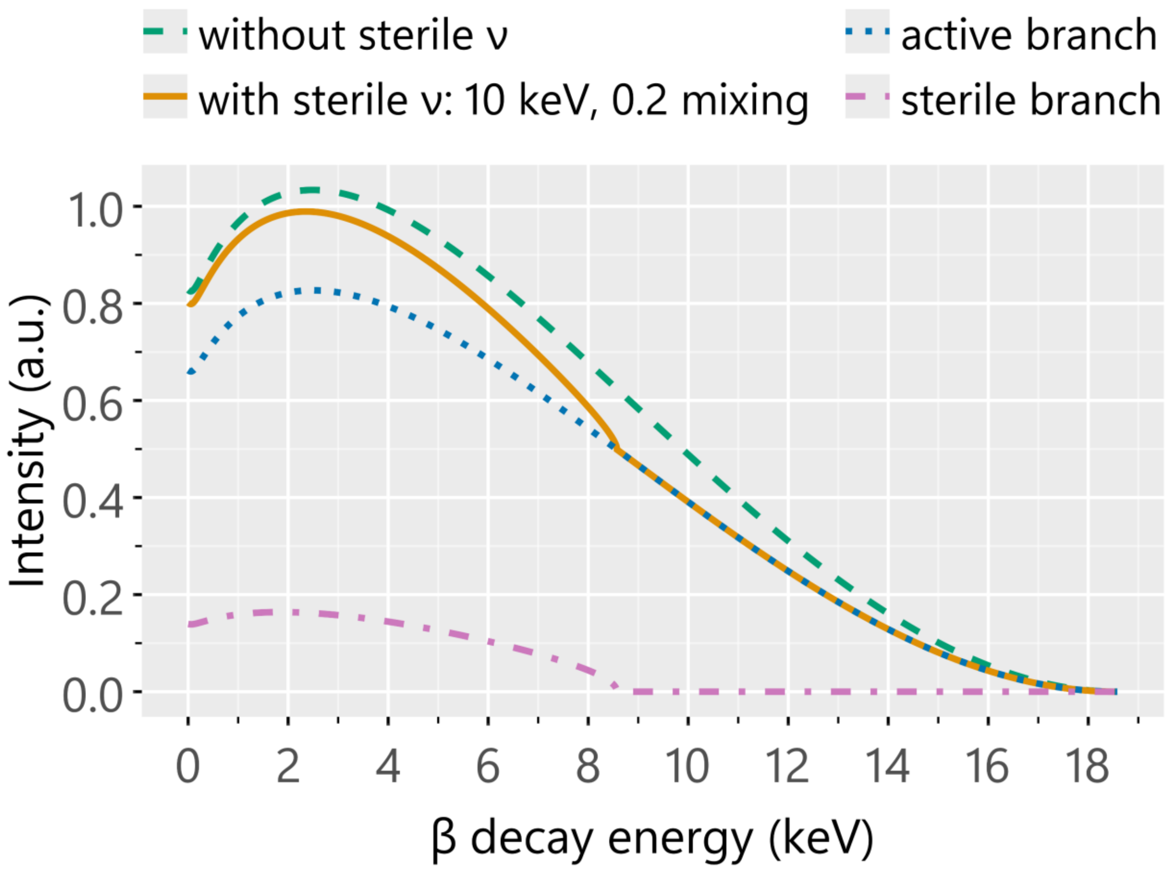
- New KATRIN release improves upper limit on the neutrino mass by a factor of 2:

$m_\nu < 0.45$ eV (90% C.L.)

- Ongoing analysis:
  - 70% of total anticipated data recorded with improvements in systematics
  - Several beyond standard model physics searches: eV-sterile, exotic interactions, light bosons, relic ν, …
- Ongoing data taking in 2025 → 1000 days of beta scanning
  - Target sensitivity $m_\nu < 0.3$ eV/c^2

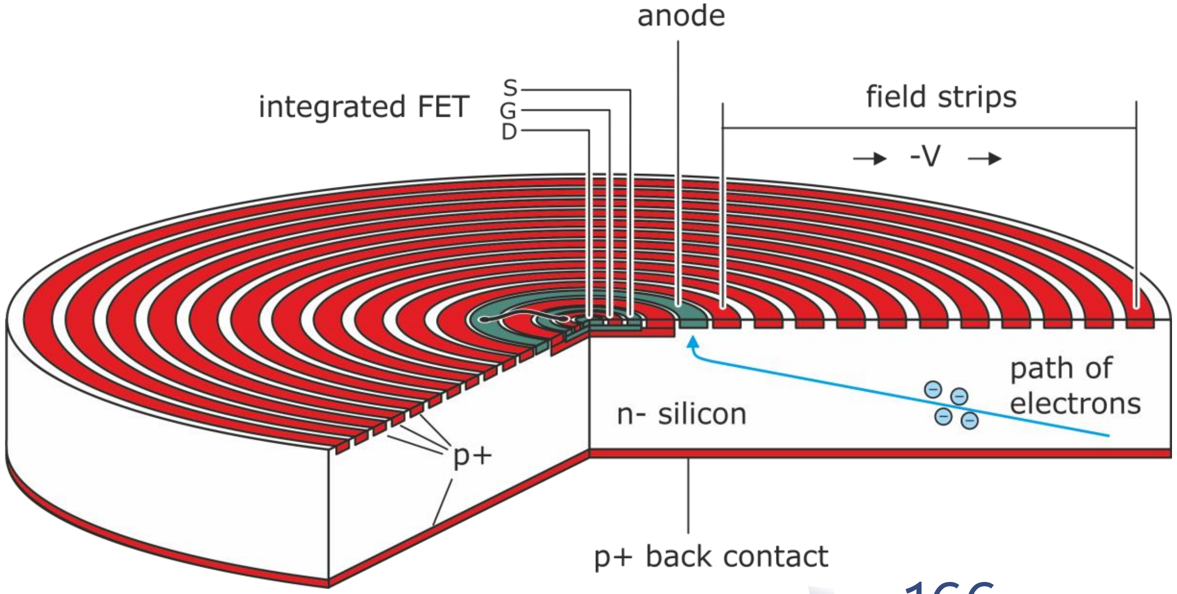


KATRIN beyond 2025 – sterile neutrino search



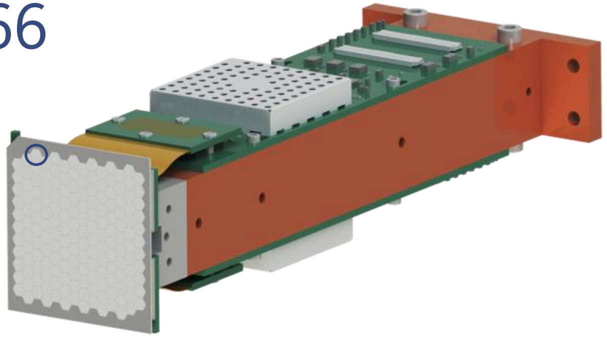
- Minimal standard model extension
- Dark matter contribution in the universe
- Active branch: $\propto \cos^2(\theta)\frac{d\Gamma}{dE}(m_\beta)$
- Sterile branch: $\propto \sin^2(\theta)\frac{d\Gamma}{dE}(m_s)$

Sterile neutrino search – TRISTAN Upgrade

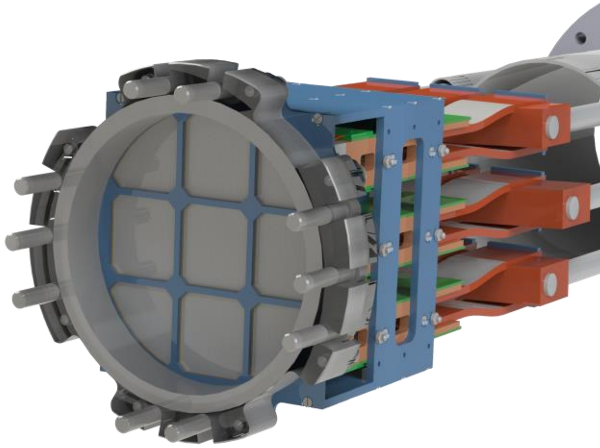


- TRISTAN detector upgrade to search for keV sterile neutrinos starting in 2026
  - Novel SDD array
    - Good energy resolution: 300 eV @ 20 keV
    - High count rate resolution: 10^5 cps/pixel
  - Different measurement mode
    - Measurement of entire beta spectrum

x166



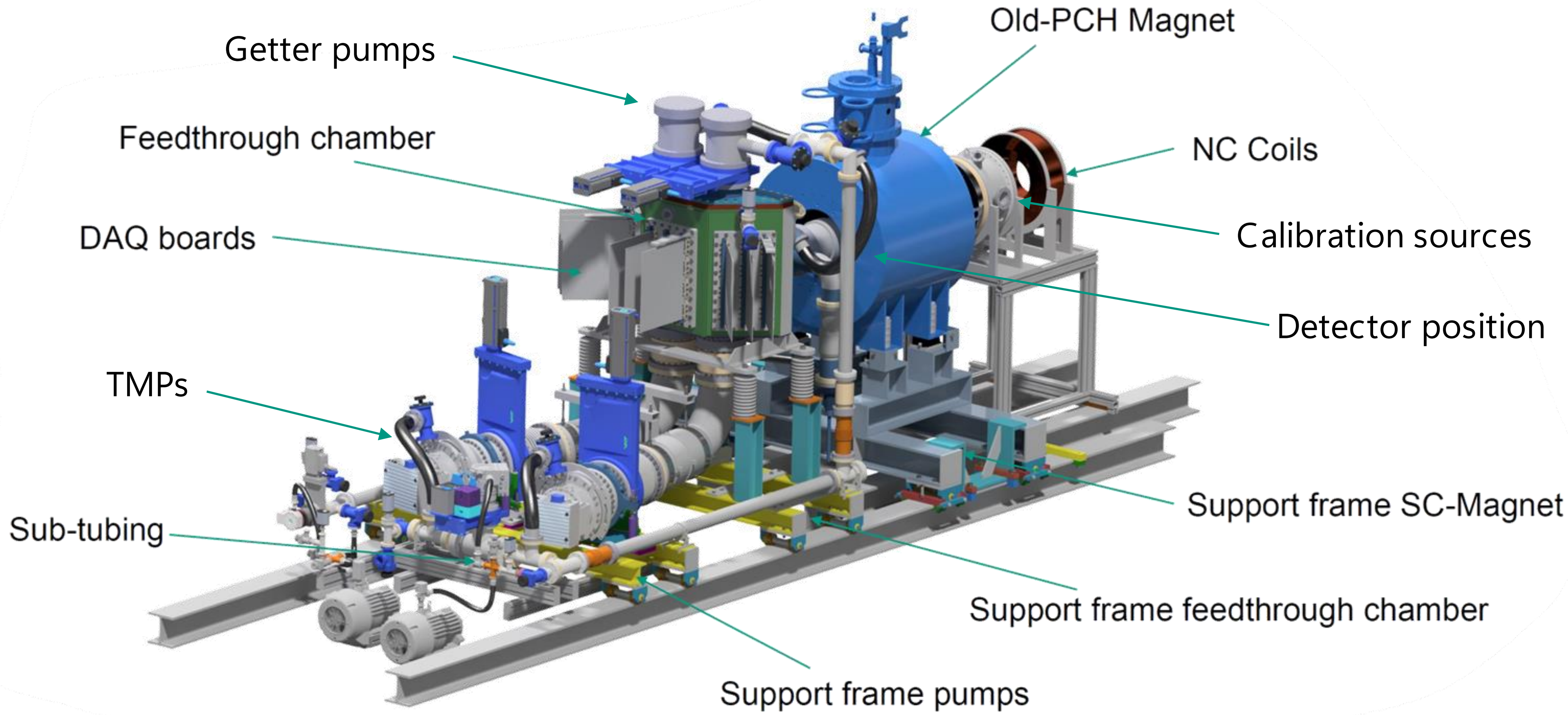
x9



Tristan

TUM | MAX PLANCK SEMICONDUCTOR LABORATORY | XGLAB | POLITECNICO MILANO 1863 | UNIVERSITA' DEGLI STUDI DI MILANO BICOCCA

Sterile neutrino search – TRISTAN Upgrade: Timeline



- 2024: Assembling 3 modules together at detector replica
- 2025: Full operation of 9 modules in replica for final characterisation measurements
- 2026: Installation in the KATRIN beamline and data taking

KATRIN Collaboration

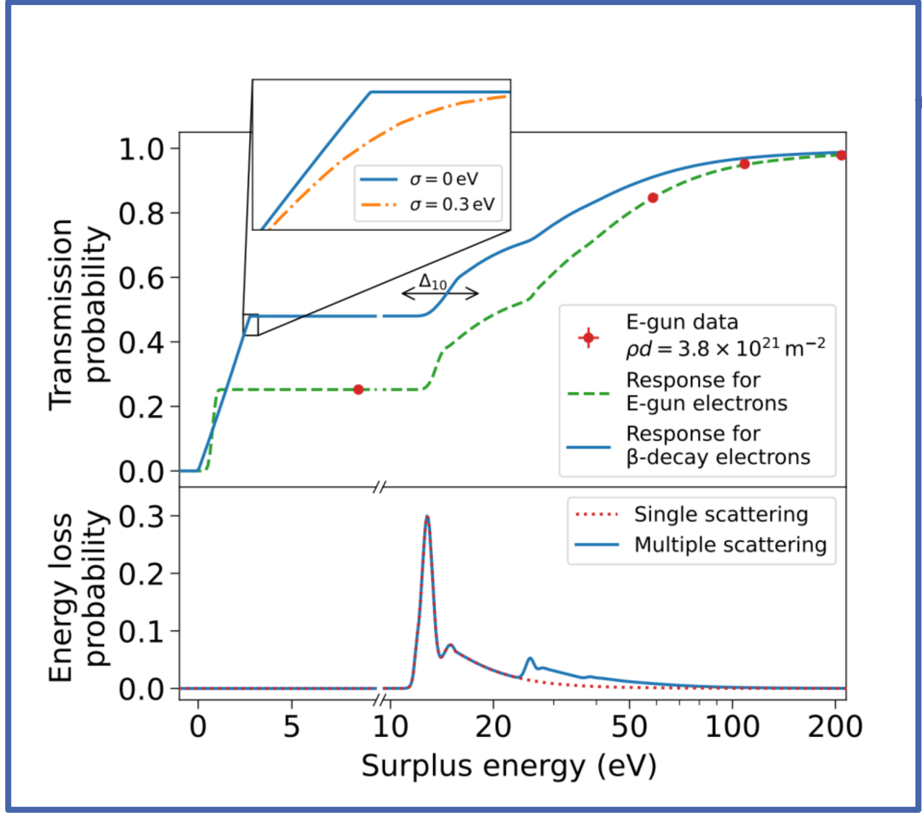
47th Collaboration meeting, October 2024, Karlsruhe

Data analysis at KATRIN

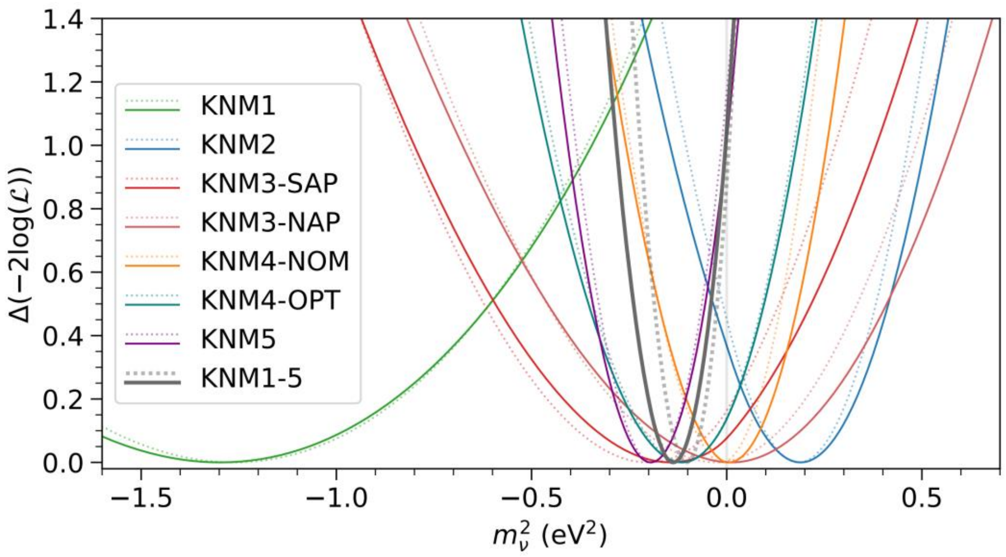
Theoretical spectrum

$$\frac{d\Gamma}{dE} = \frac{G_F^2 \cos^2(\theta_C)}{2\pi^3} |\mathcal{M}|^2 F(Z,E) p(E+m_e) \cdot \sum_{i=1}^{3} |U_{ei}|^2 \epsilon \sqrt{\epsilon^2 - m_i^2} \Theta(\epsilon - m_i)$$

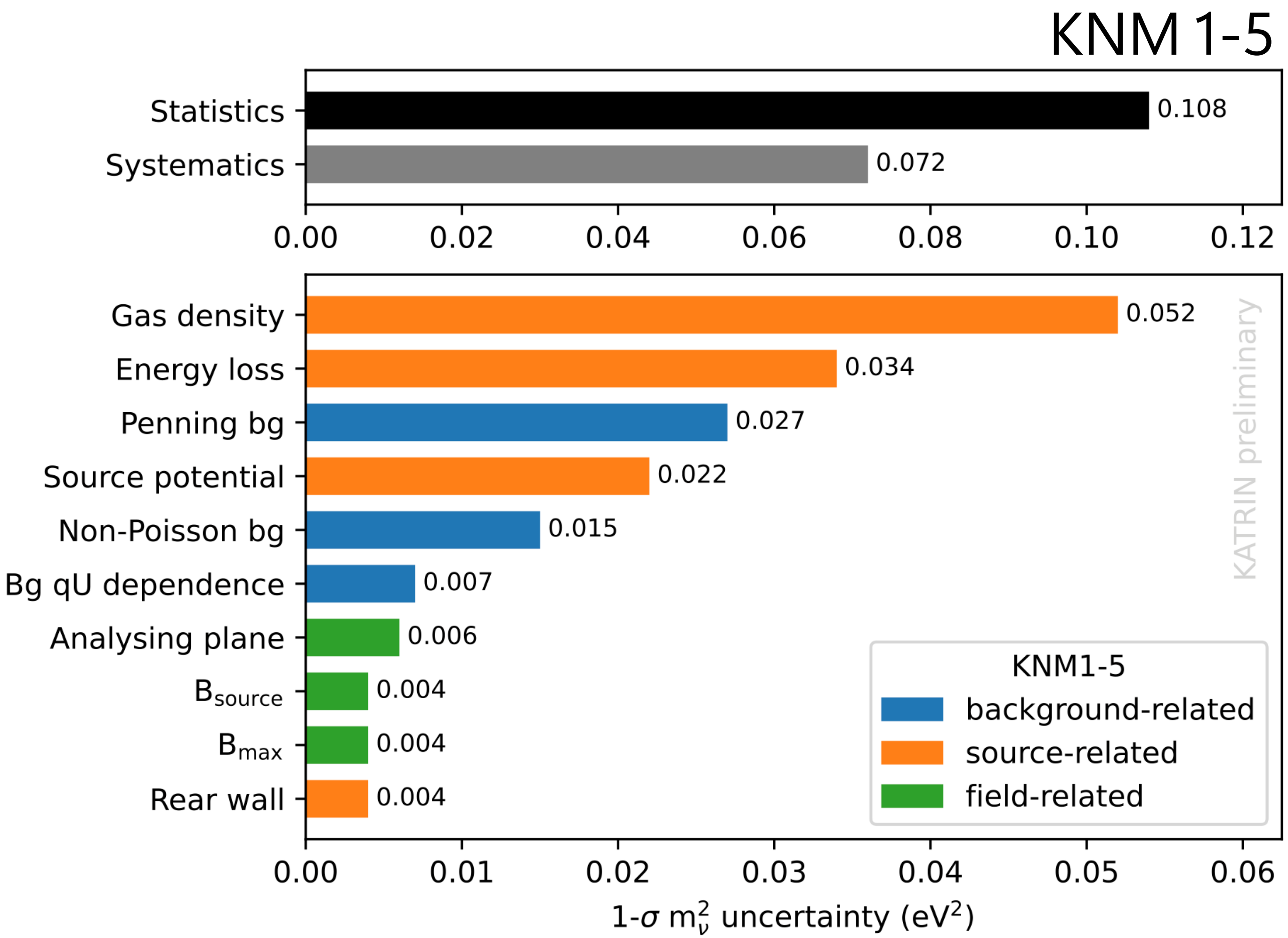
Experimental response

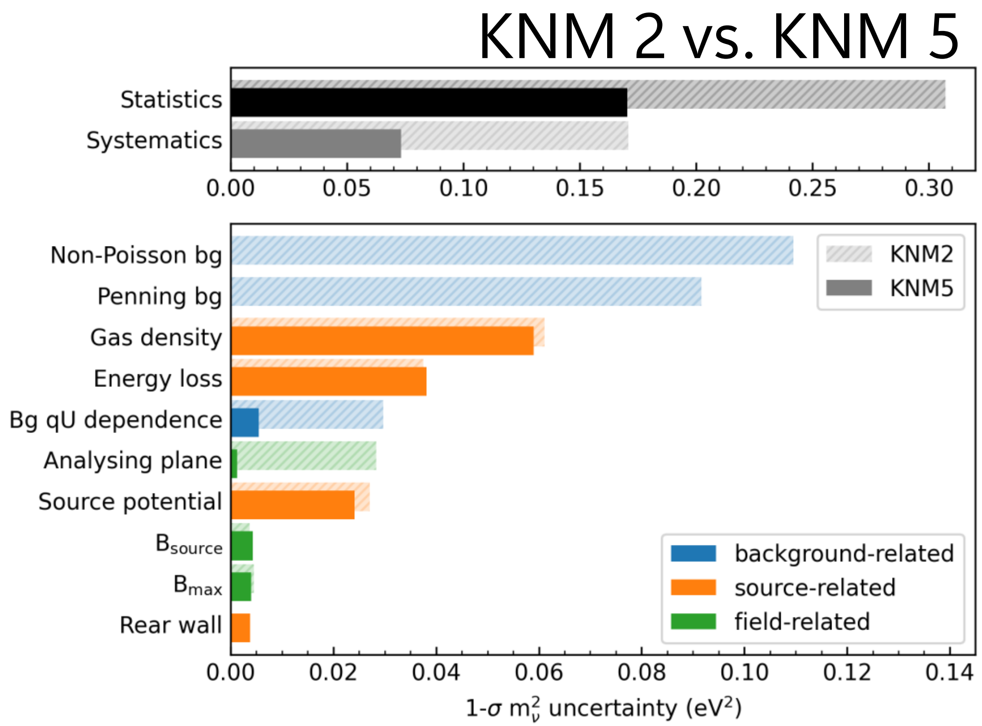


- Modelling the integrated spectrum
- Add systematic effects
- Systematic uncertainty propagation by pull-terms
- Minimising the negative log-likelihood profile

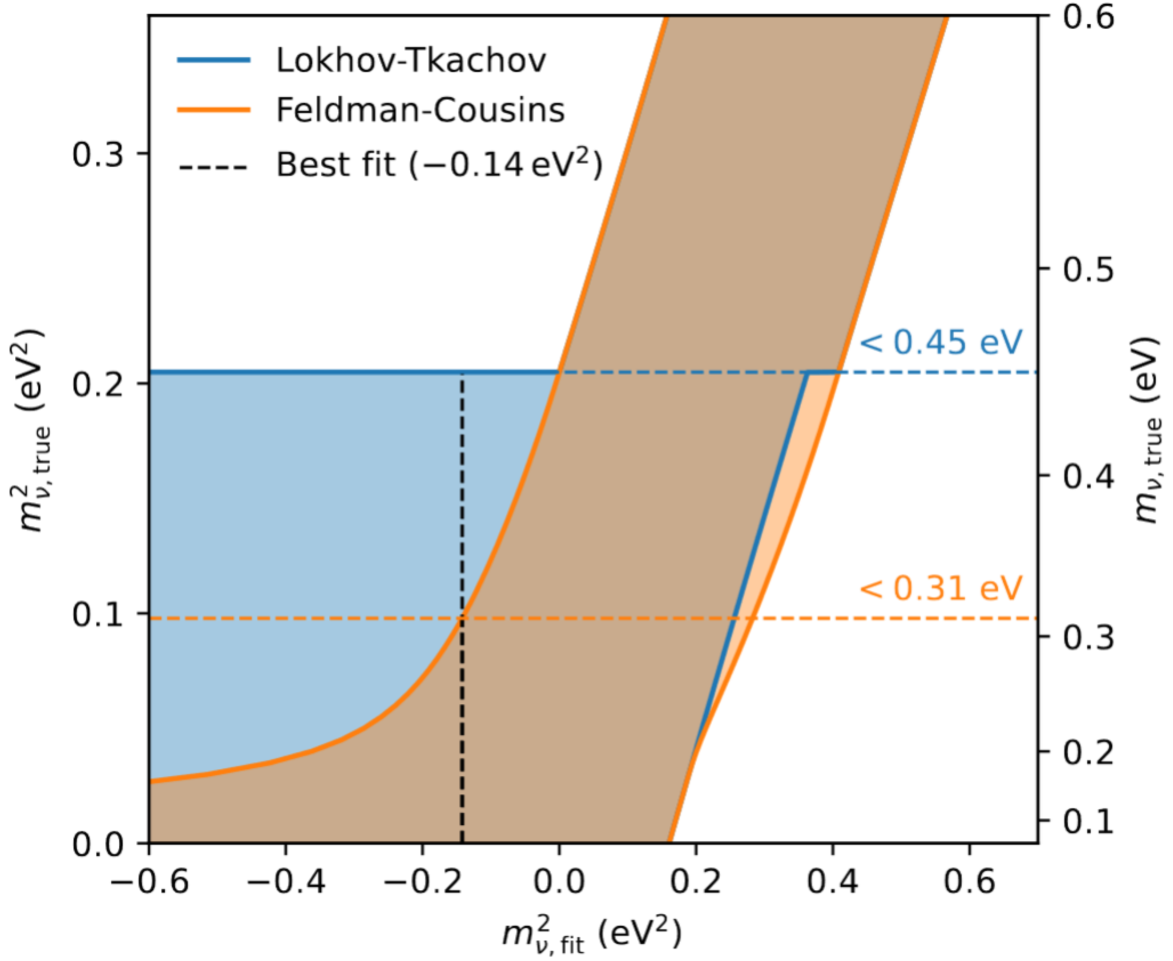


Systematics budget KNM 1-5





Limit Setting



- Upper limit by Lokhov-Tkachov construction:

$$m_\nu < 0.45\, eV\ (90\%\, C.L.)$$

  - Returns sensitivity for negative m_ν^2 best fits
  - Statistical underfluctuations do not produce stricter limit
  - More conservative approach than Feldman-Cousins

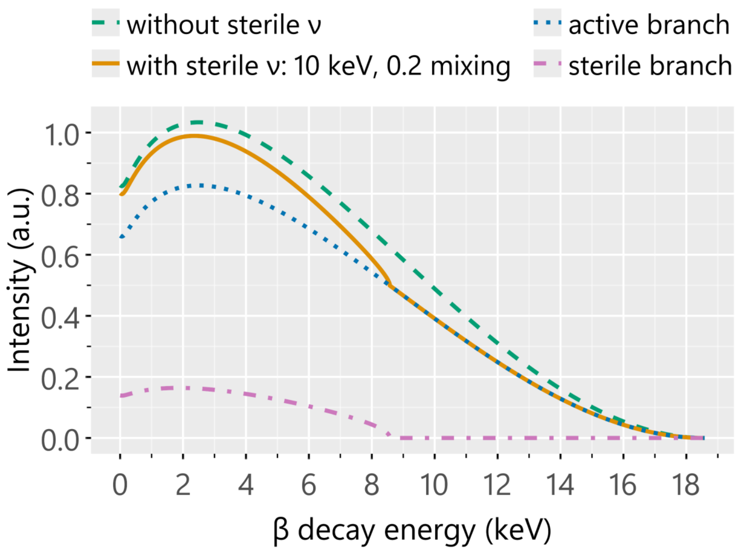
- Upper limit by Feldman-Cousins construction:

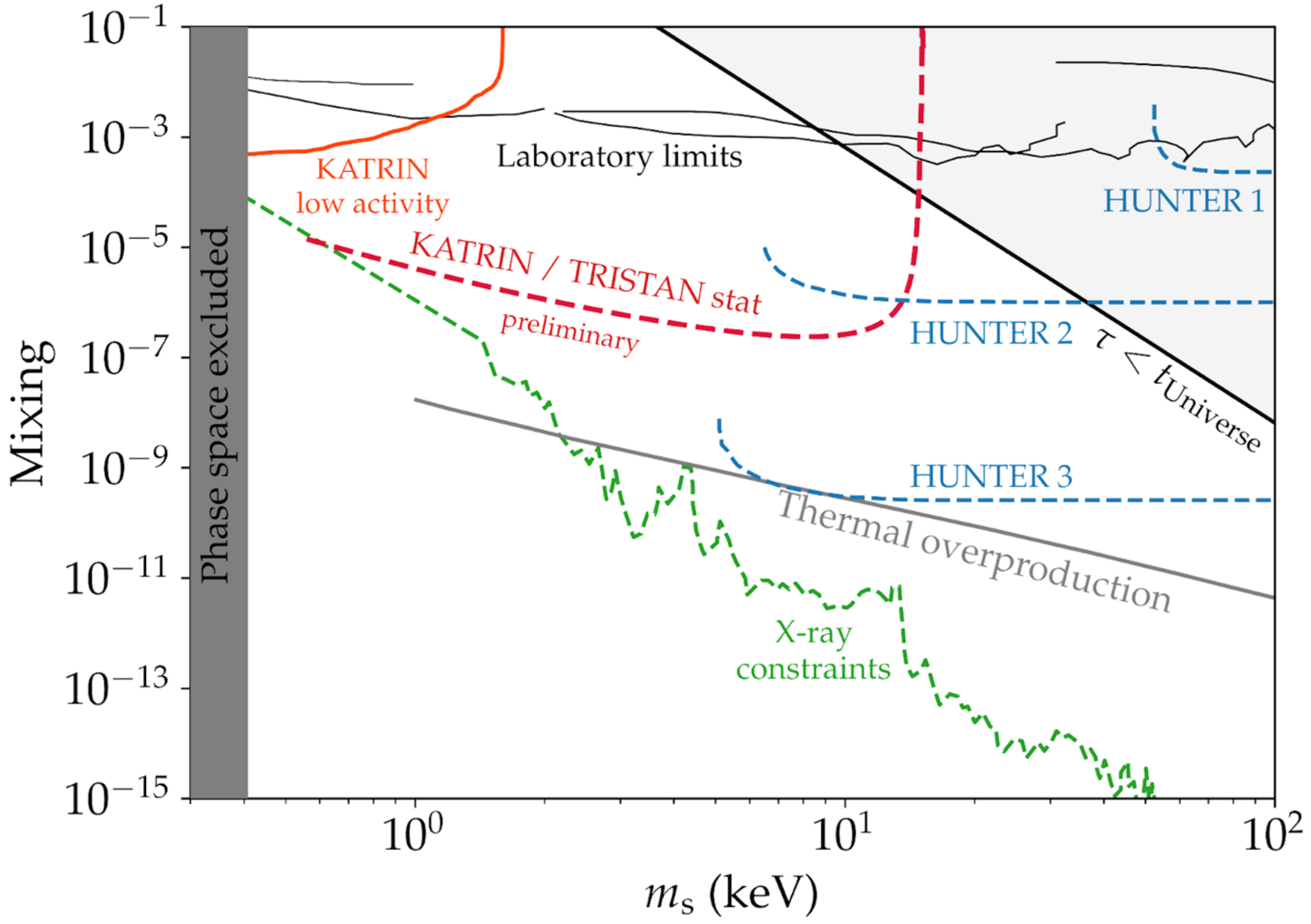
$$m_\nu < 0.31\, eV\ (90\%\, C.L.)$$

Sterile Neutrinos

- Minimal standard model extension
- Dark matter contribution in the universe

- Active branch: $\propto \cos^2(\theta) \frac{d\Gamma}{dE}(m_\beta)$
- Sterile branch: $\propto \sin^2(\theta) \frac{d\Gamma}{dE}(m_s)$





Impressions