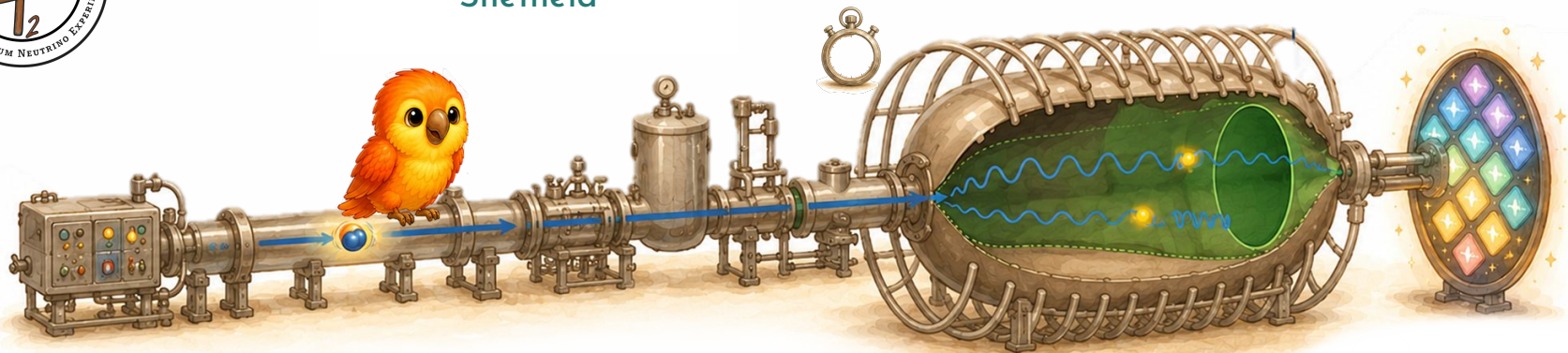




PASCOS 2026
Sheffield



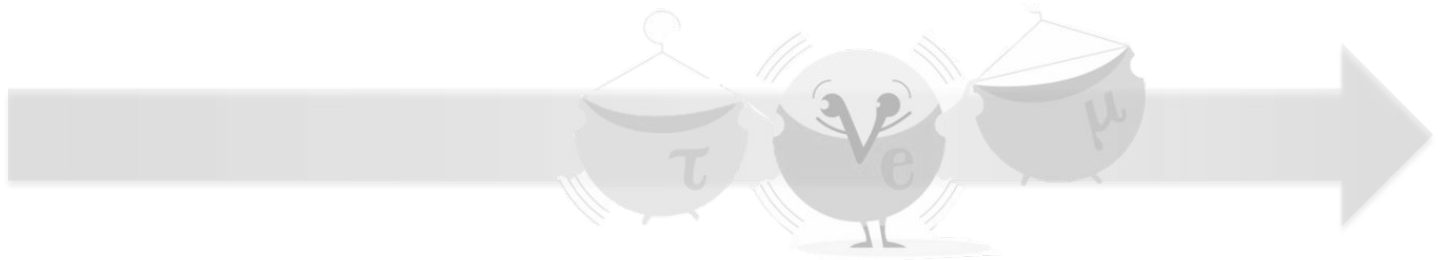
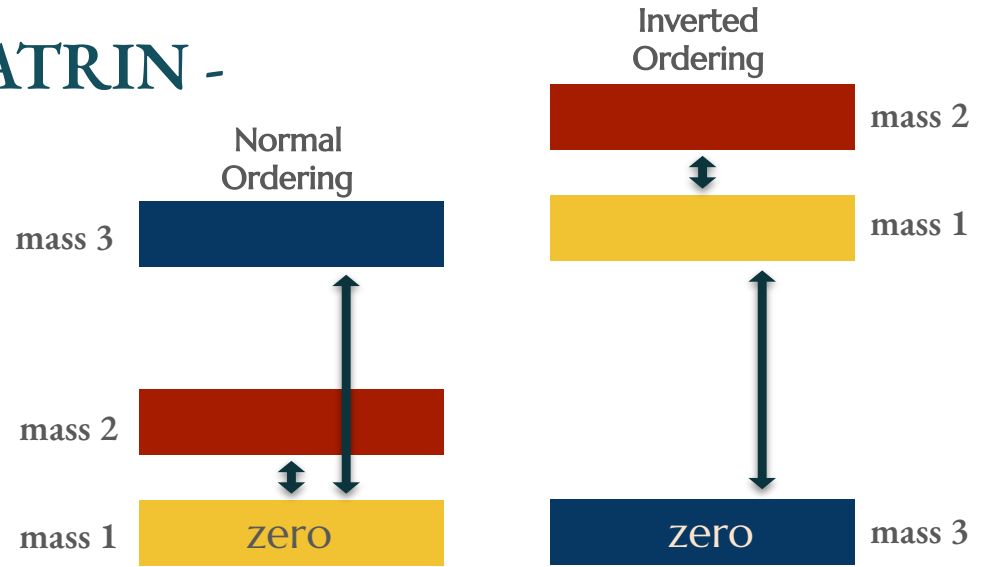
KATRIN++

Towards probing the inverted mass hierarchy with
direct neutrino mass measurements

Svenja Heyns for the KATRIN Collaboration

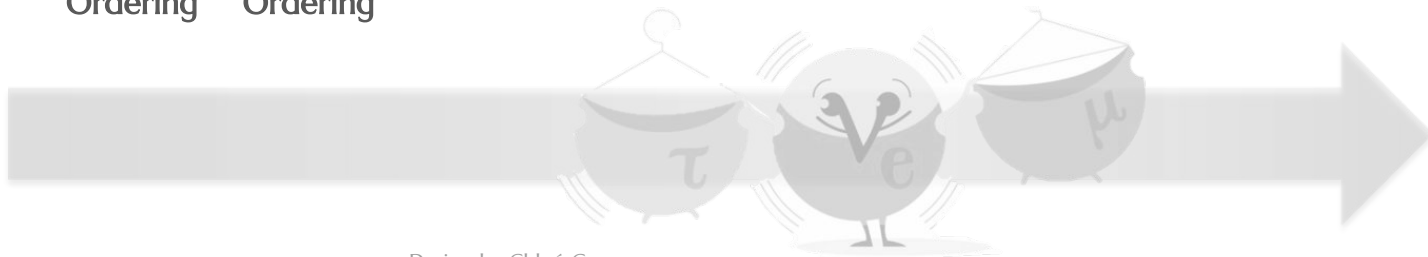
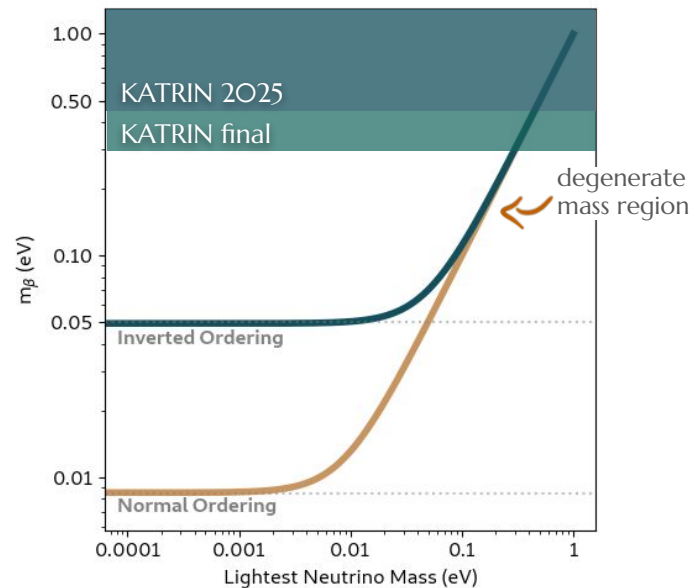
Neutrino mass beyond KATRIN - closing the gap

- non-zero mass confirmed by neutrino oscillation
→ mass eigenstates \neq flavour eigenstates



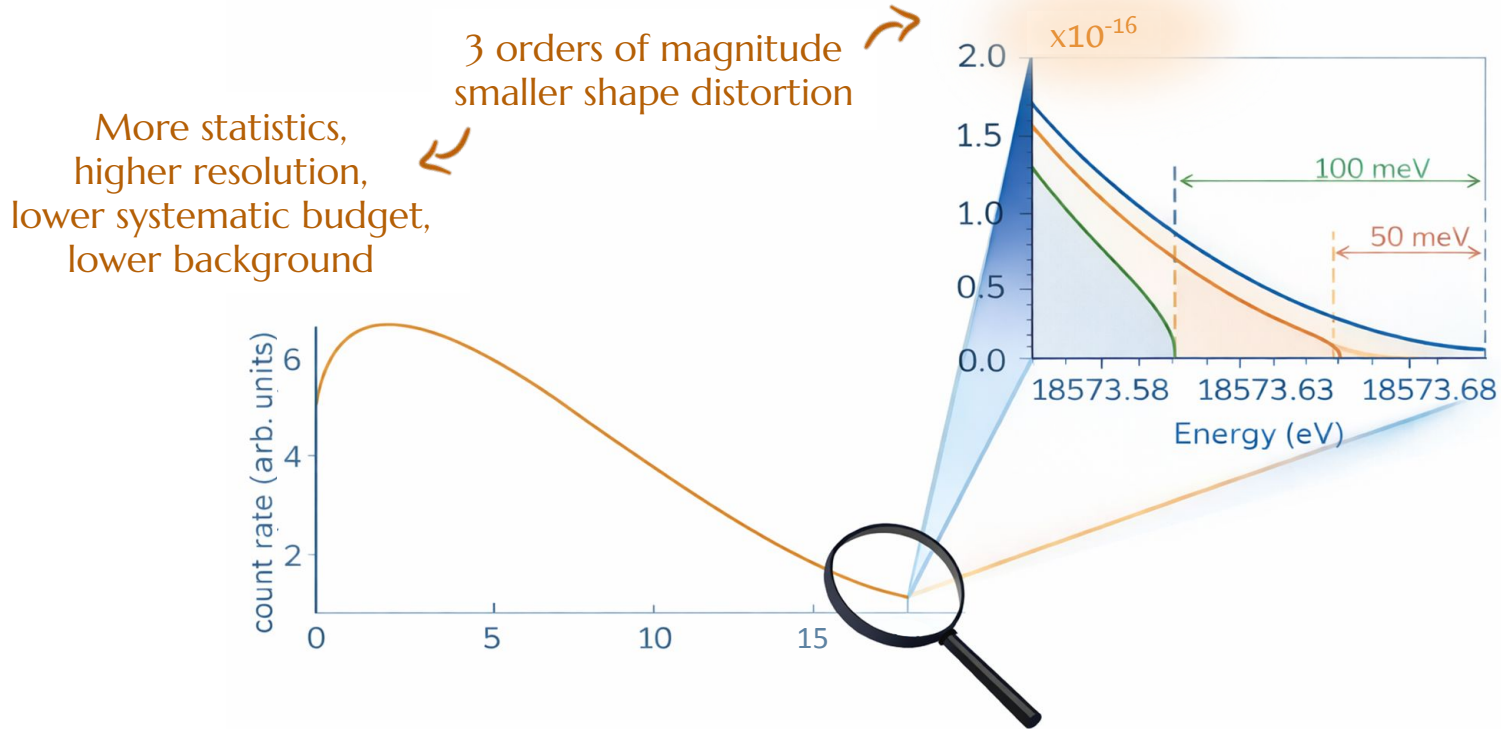
Neutrino mass beyond KATRIN - closing the gap

See also: KATRIN Collaboration, *Input to the European Strategy for Particle Physics - 2026 Update*, <https://indi.to/5TR9w>



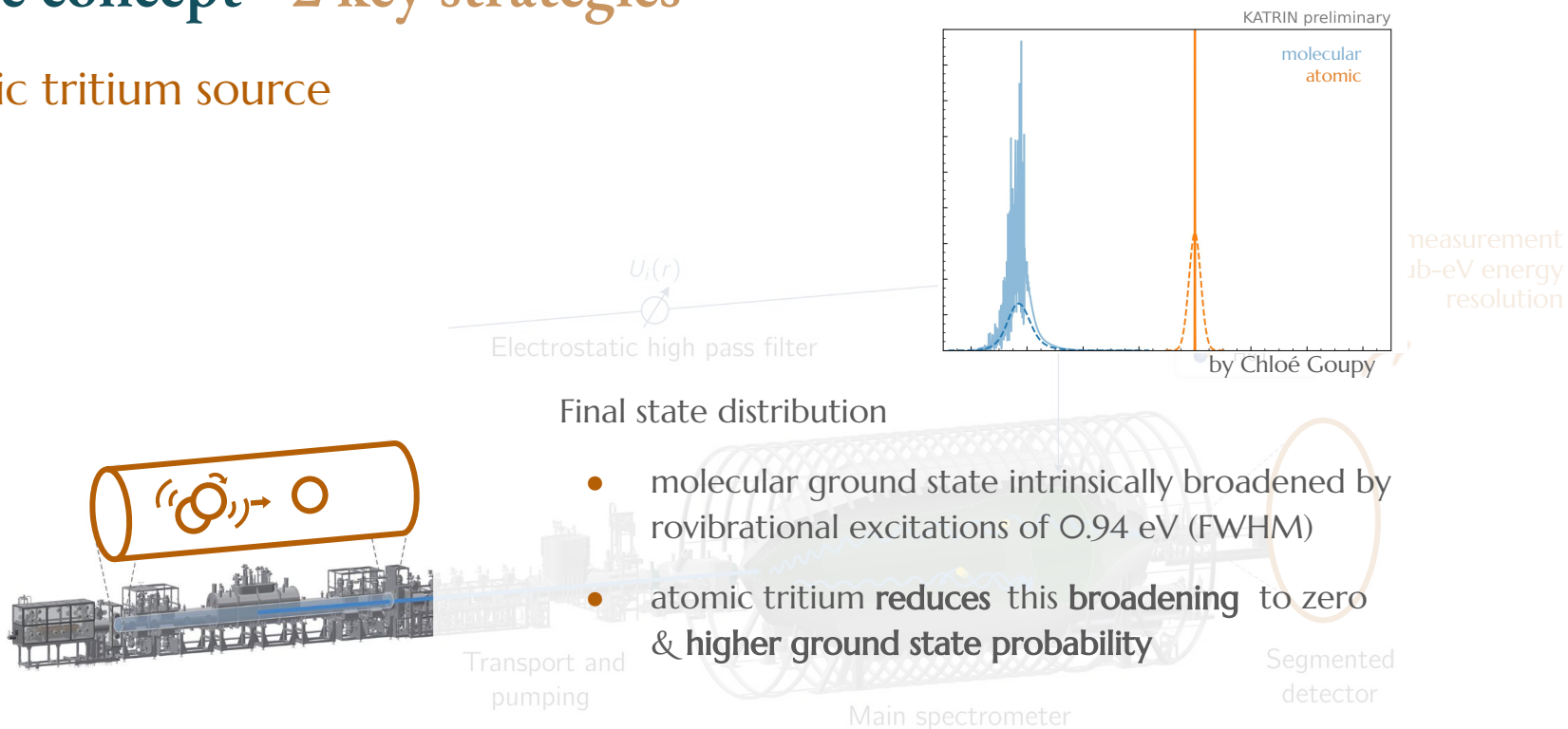
Design by Chloé G.

Neutrino mass signature - Tritium beta decay



Source concept - 2 key strategies

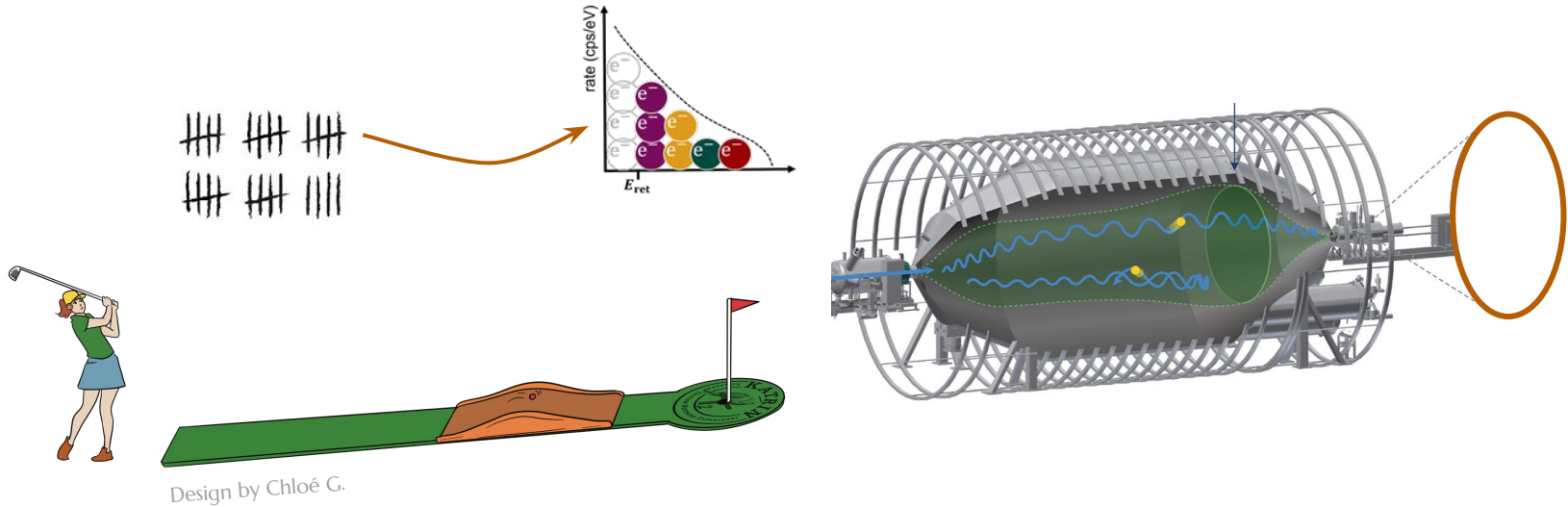
1 Atomic tritium source



Detector concept - 2 key strategies

2 Sub-eV energy resolution

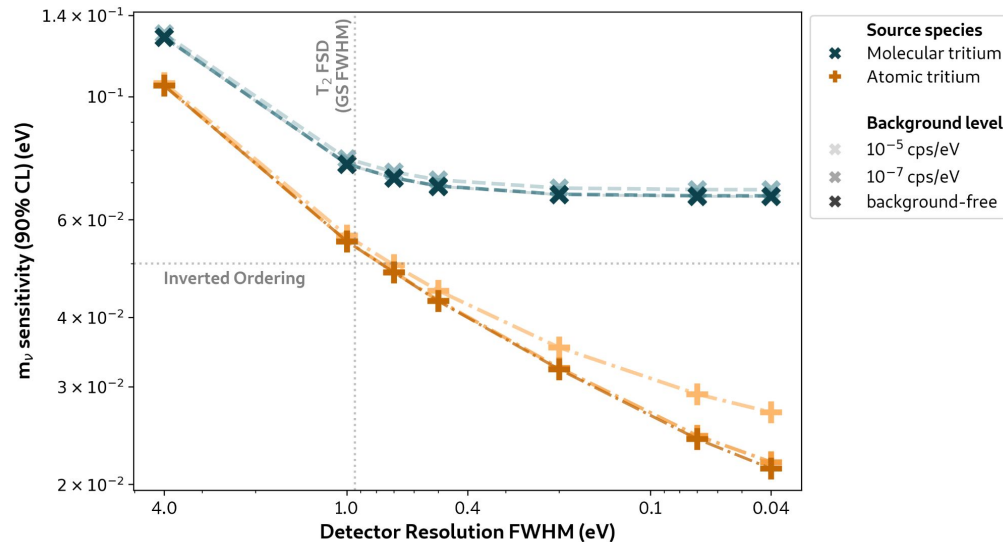
- (a) fixed energy barrier
- (b) resolve each electron's energy individually



➔ Stronger signal with higher precision in short time

Pushing down sensitivity - and technology...

How to reach inverted mass ordering



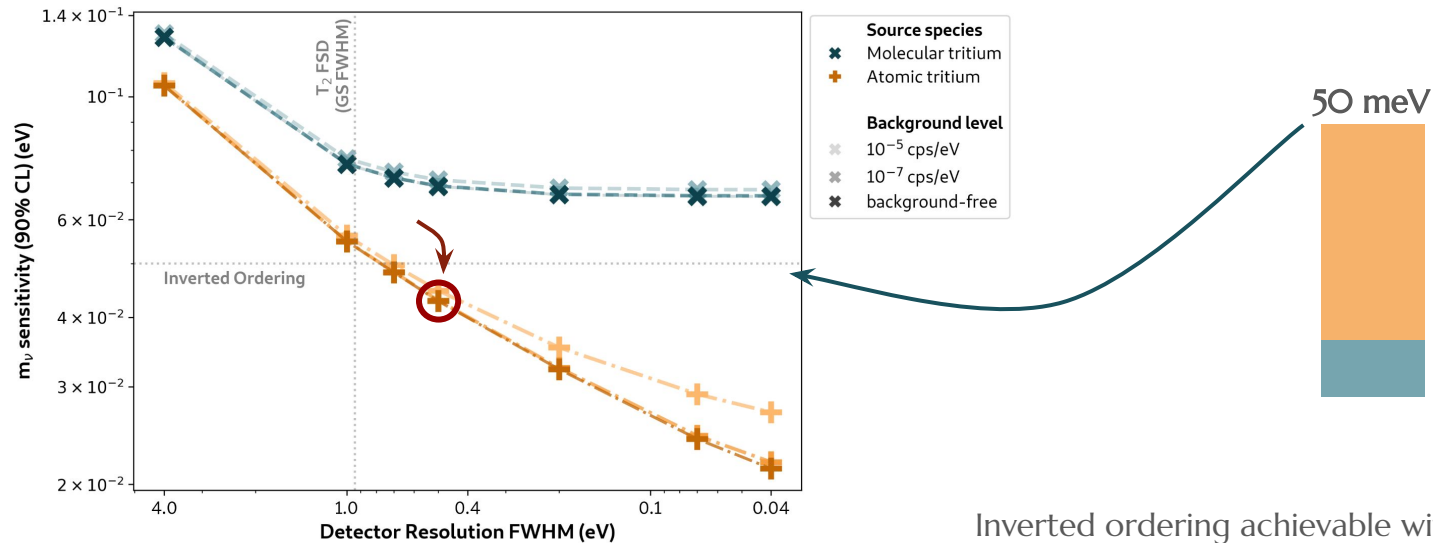
1000 days of measurement

Tritium inventory as KATRIN source

- Molecular tritium naturally limited by FSD broadening
- Atomic tritium essential once detector resolutions < 700 meV FWHM available
- No significant improvement for background levels below 10^{-7} cps/eV

Pushing down sensitivity - and technology...

How to reach inverted mass ordering



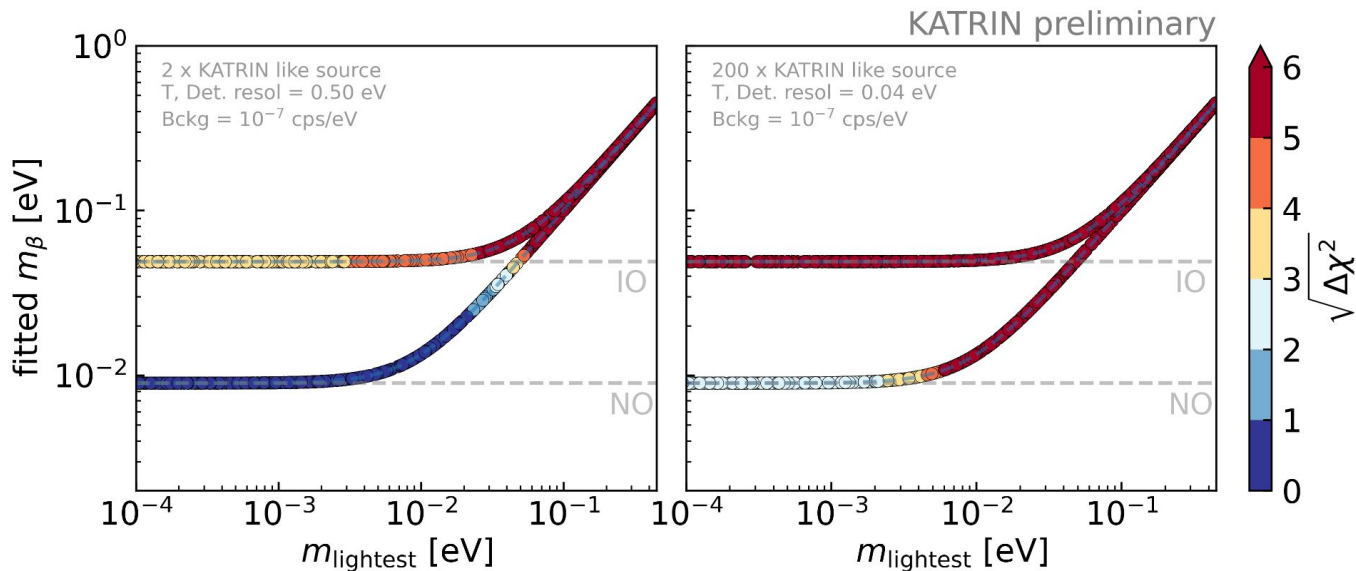
1000 days of measurement

Tritium inventory as KATRIN source

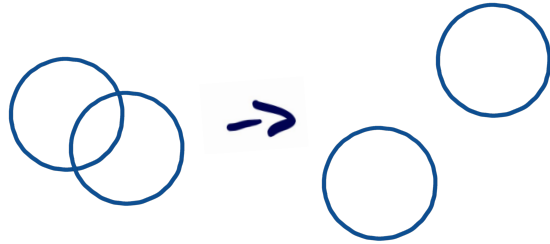
Inverted ordering achievable with **atomic tritium** source, **KATRIN source strength** and effective energy resolution of **500 meV FWHM**

Pushing down sensitivity - discovery of neutrino mass

Example setup configurations

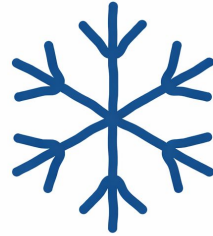


Atomic tritium source - Strategy



Producing

Identify best dissociation method for tritium



Cooling

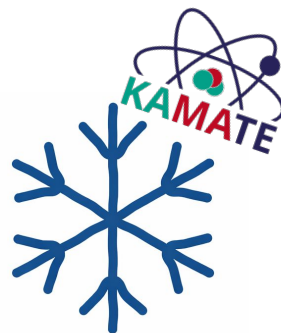
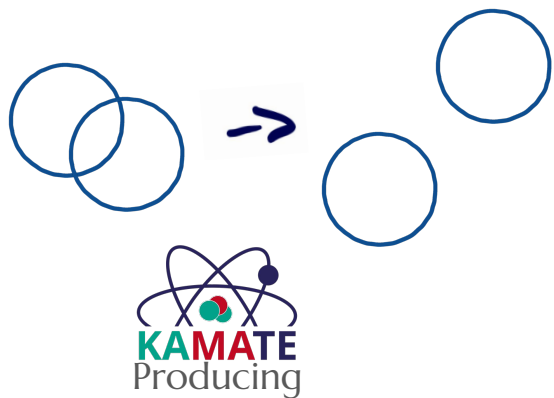
Develop mechanism for cooling to milli-Kelvin



Trapping

Magnetically trap large inventory with long life-time

Atomic tritium source - Strategy



Cooling

Identify best dissociation method for tritium



Develop mechanism for cooling to milli-Kelvin

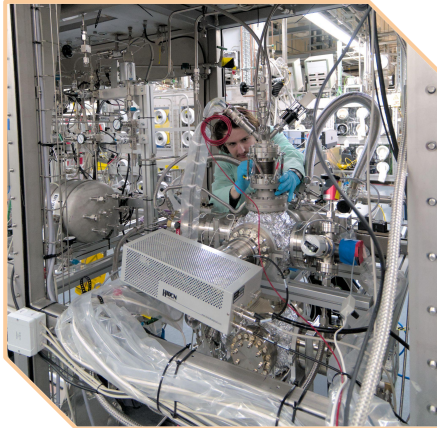
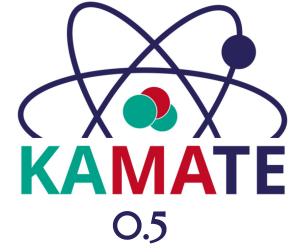


Trapping

Magnetically trap large inventory with long life-time

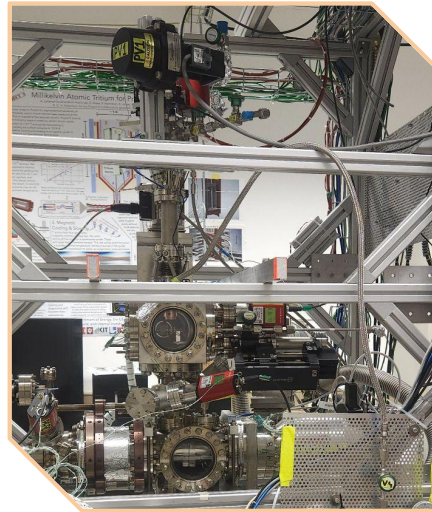


Atomic tritium source - Identify best source

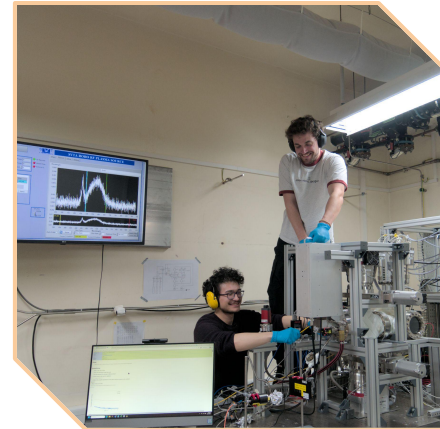


Thermal dissociator 

Thermal dissociator

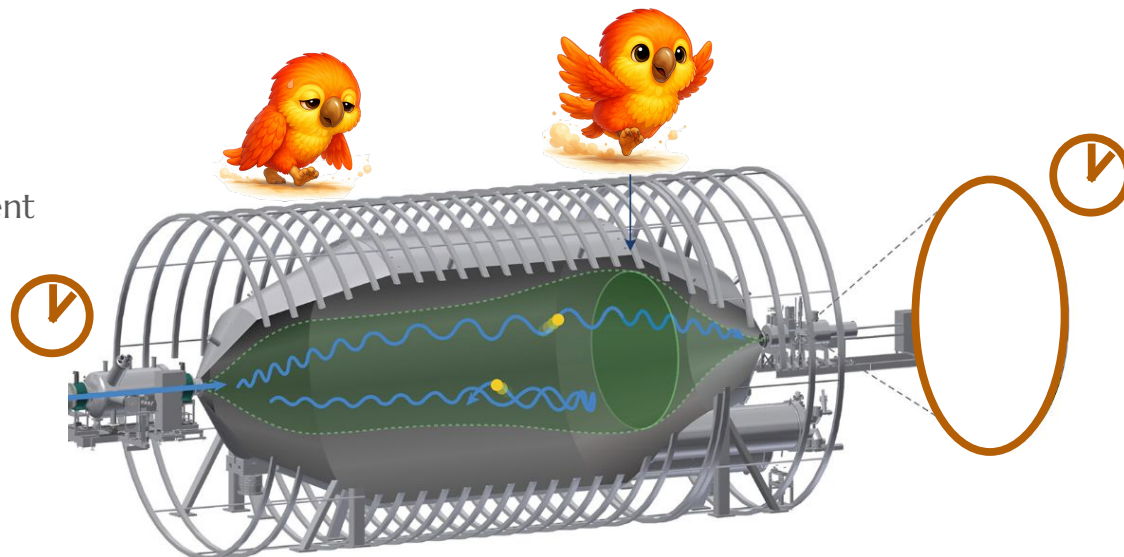


Plasma source



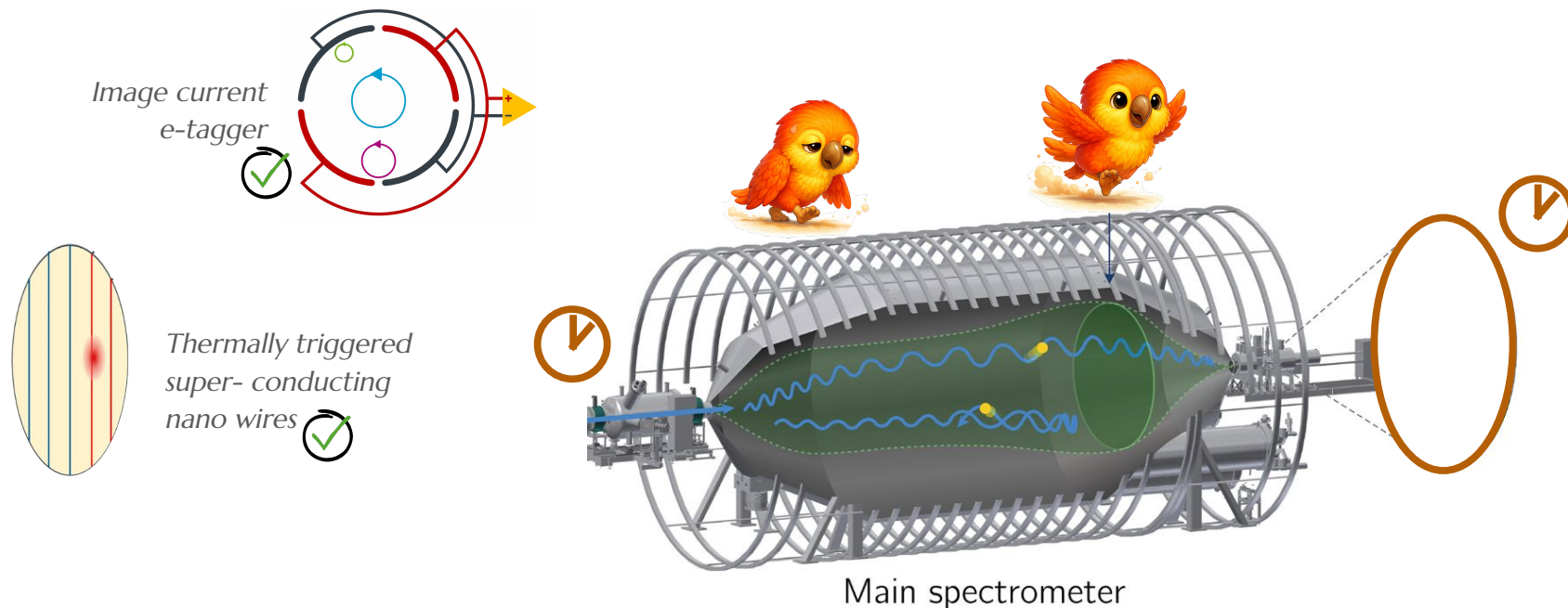
Sub-eV energy resolution - Transversal Energy Compensator & Time-of-Flight

- **Transversal Energy Compensator**
reducing broadening by compensating longitudinal with transversal energy
- **Time-of-Flight detection**
for quasi-differential measurement with fixed retarding potential and minimal impact electron tagger
- **Upgrade** to KATRIN setup with significantly improved **energy resolution & statistics**

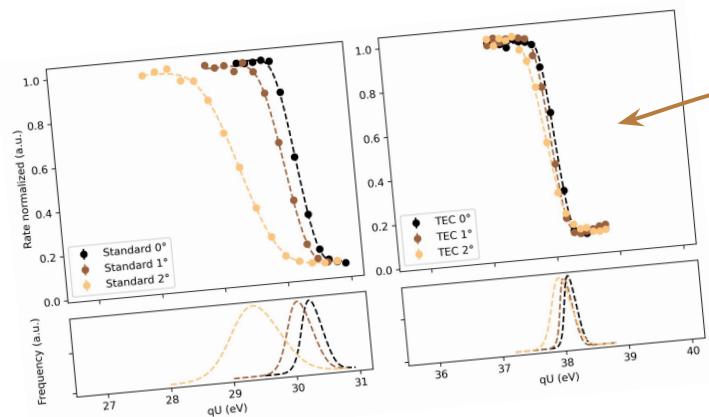


Main spectrometer

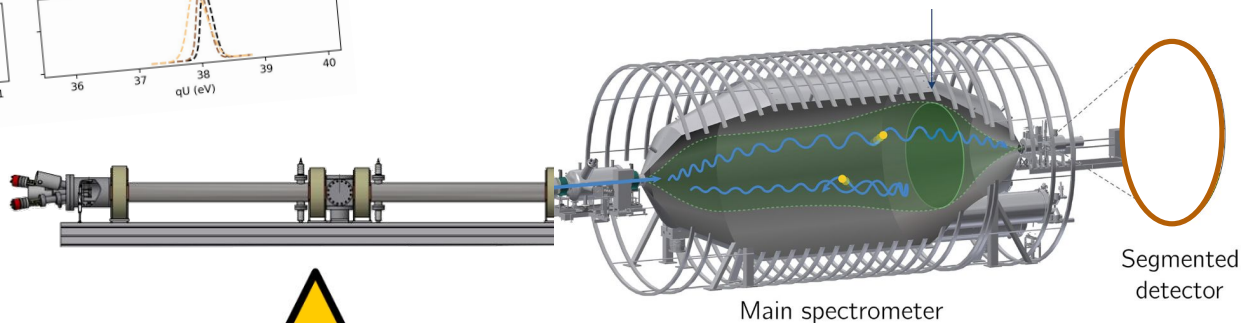
Sub-eV energy resolution - Transversal Energy Compensator & Time-of-Flight



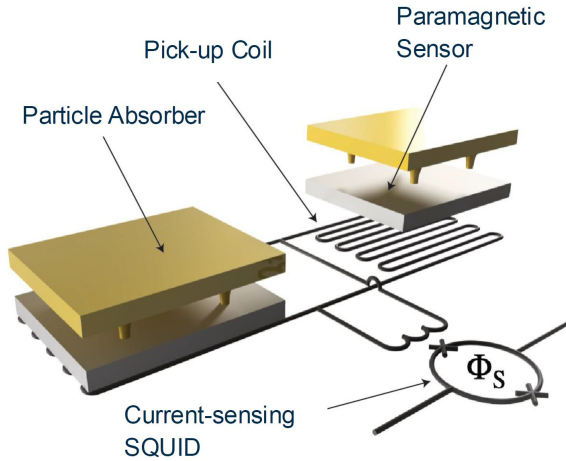
Sub-eV energy resolution - Transversal Energy Compensator & Time-of-Flight



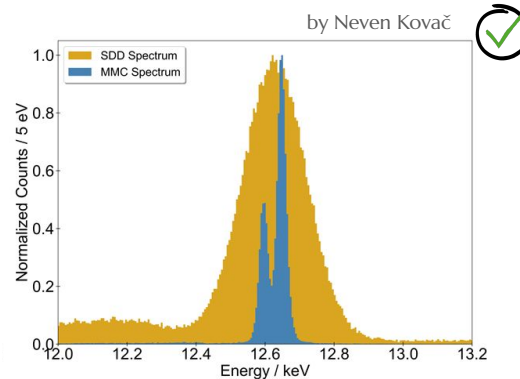
successfully tested



Sub-eV energy resolution - Quantum sensor arrays



Sketch by M. Müller



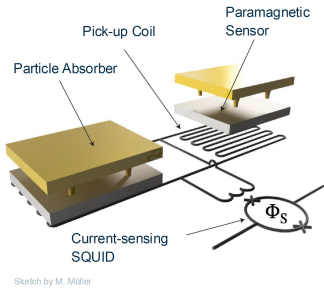
N. Kovac et.al., *Comparison of the detector response and calibration function of metallic microcalorimeters for X-ray photons and external electrons*, Nuclear Instruments and Methods in Physics Research A (2025)



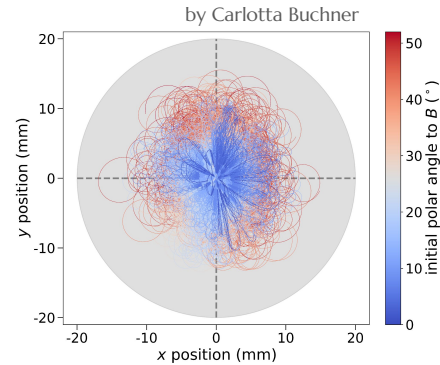
Test setup at Institute of Micro- and Nanoelectronic systems

- Successful **proof-of-principle** for detecting external electrons in ELECTRON project

Sub-eV energy resolution - Planned demonstrator setup

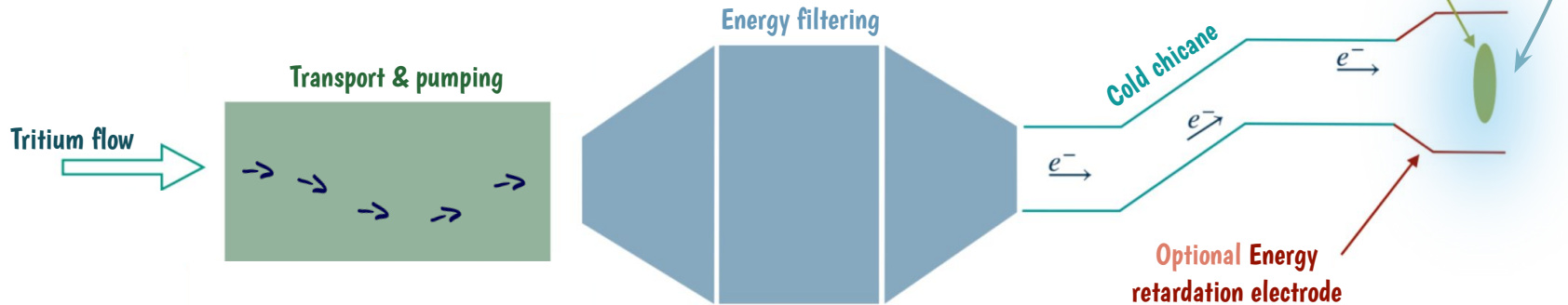


Testing & commissioning of 4cm² MMC detector array with sub-eV resolution



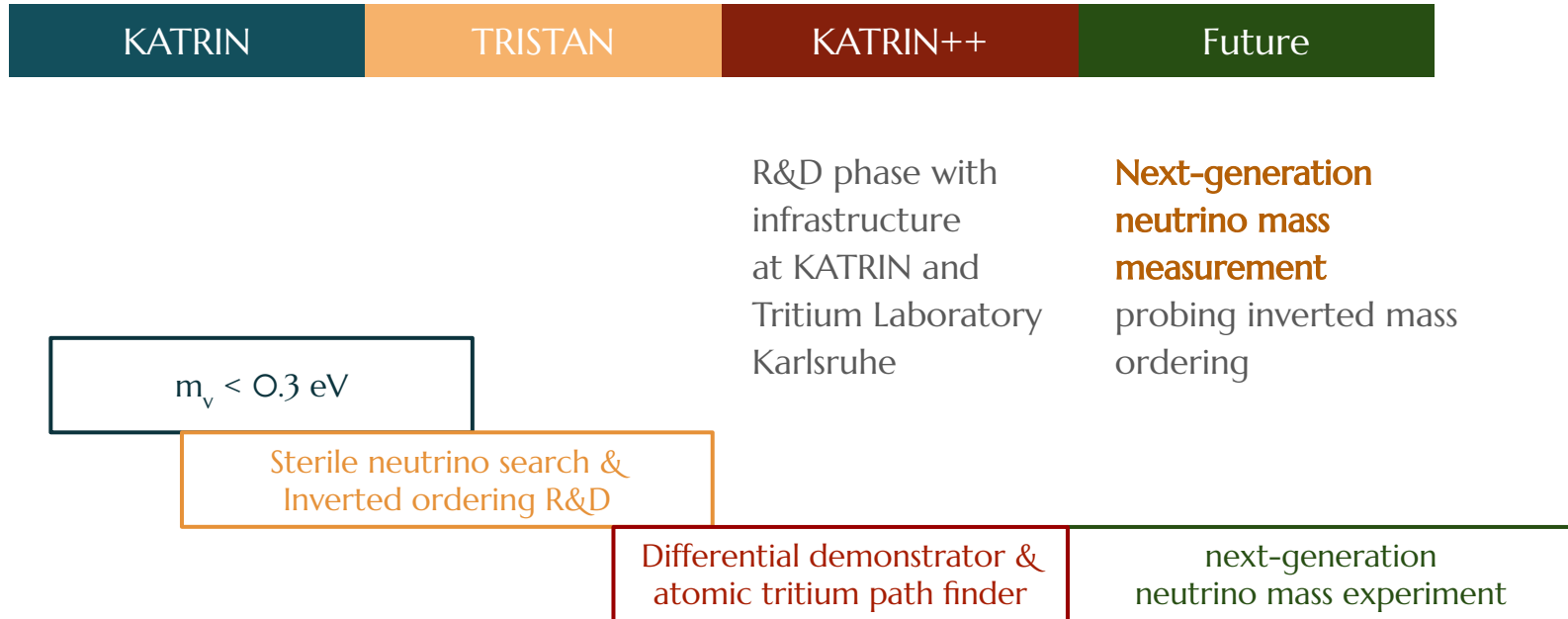
20 milli Kelvin

Quantum sensor detector array



Timeline - neutrino mass search

...with KATRIN++ & many more



Timeline - neutrino mass search

...with KATRIN++ & many more



PROJECT 8



$m_\nu < 0.3 \text{ eV}$

Sterile neutrino search & Inverted ordering R&D

Differential demonstrator & atomic tritium path finder

next-generation neutrino mass experiment

R&D phase with infrastructure at KATRIN and Tritium Laboratory Karlsruhe

Next-generation neutrino mass measurement probing inverted mass ordering



Timeline - neutrino mass search

...with KATRIN++ & many more



PROJECT 8



R&D phase with infrastructure at KATRIN and Tritium Laboratory Karlsruhe

Next-generation neutrino mass measurement
probing inverted mass ordering

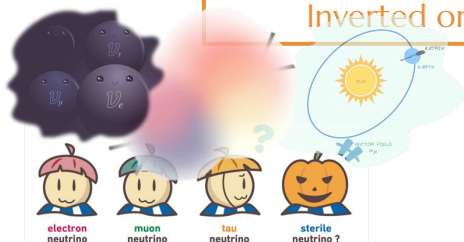


$$m_\nu < 0.3 \text{ eV}$$

Sterile neutrino search & Inverted ordering R&D

Differential demonstrator & atomic tritium path finder

next-generation neutrino mass experiment



The KATRIN Collaboration



...and more

Thanks for
your attention!





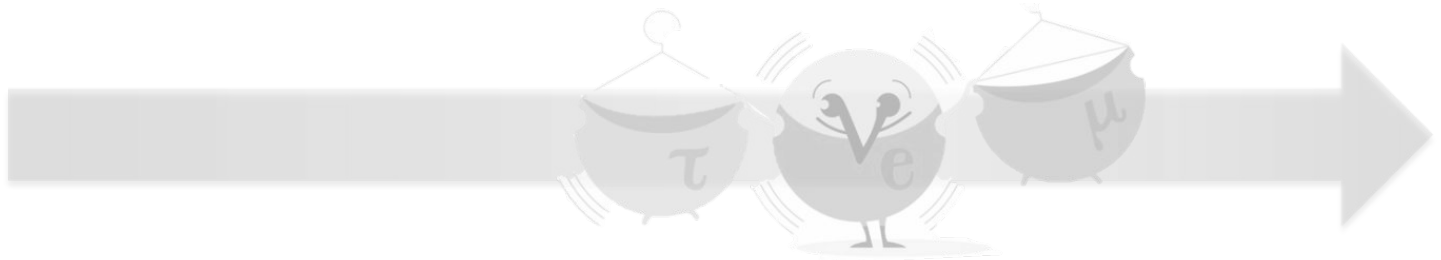
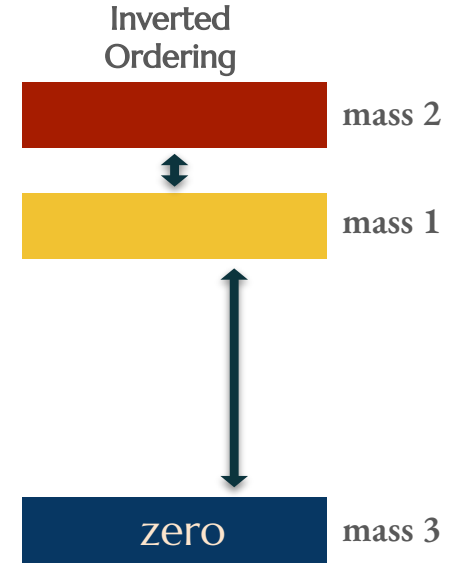
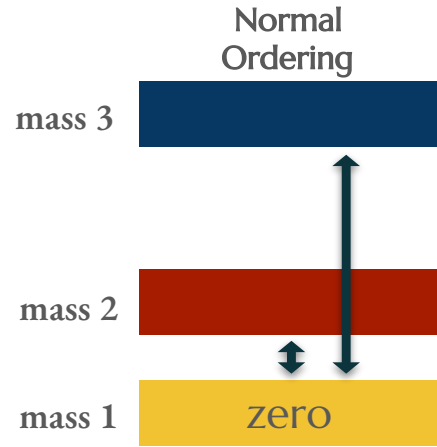
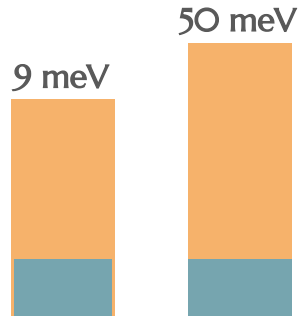
Backup

Neutrino mass beyond KATRIN - closing the gap

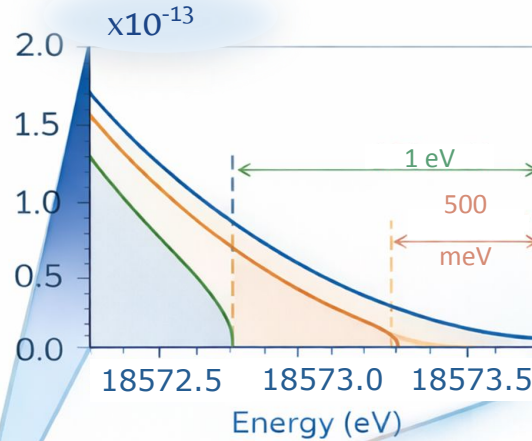
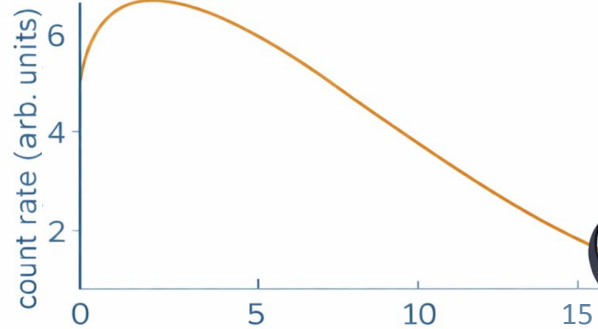
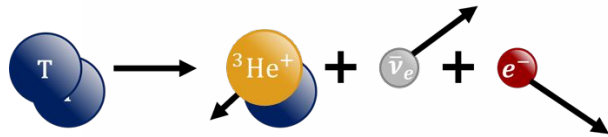
- non-zero mass confirmed by neutrino oscillation
→ mass eigenstates \neq flavour eigenstates



Neutrino mass beyond KATRIN - closing the gap

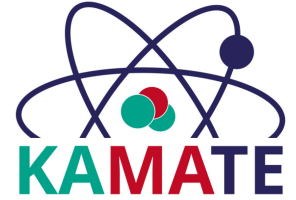


Neutrino mass signature - Tritium beta decay



Atomic tritium - KAMATE

Hardware development



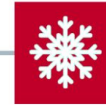
KAMATE 0.5



KAMATE 1.0



KAMATE 2.0



KAMATE 3.0

Identify best source.

- **Hydrogen** setups at TLK & Mainz

1st Tritium Operation.

- KAMATE 0.5 with **Tritium** at TLK

Cooling I.

- Down to **100K** by wall-interactions (Accomodator)

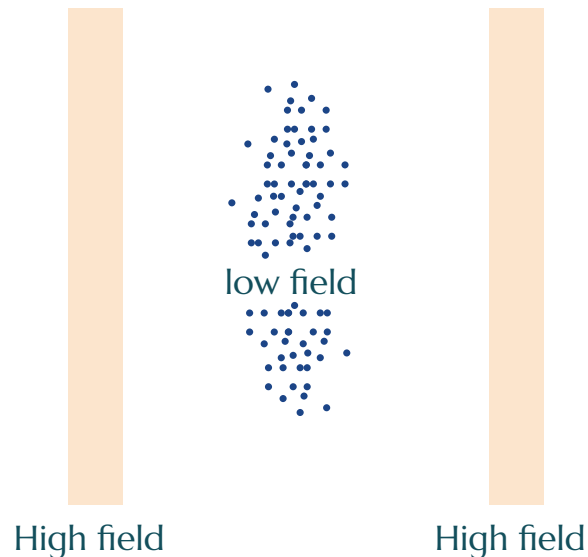
Cooling II.

- Down to **1K** by expansion (nozzle)

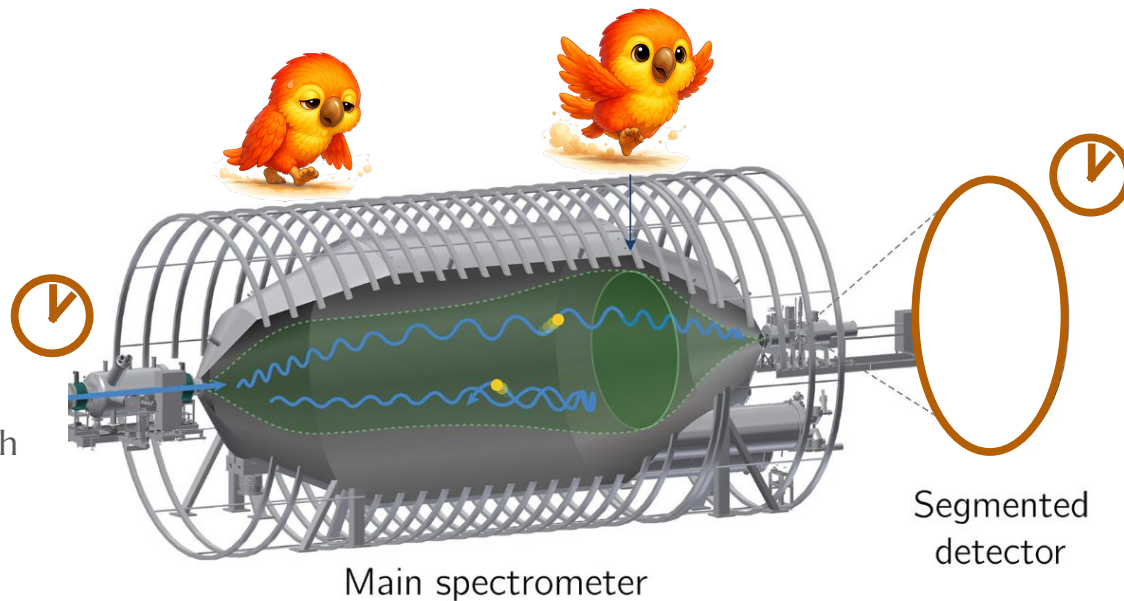
Atomic tritium source - Trapping

- Trapping low-field seekers with magnetic walls
- Extending life-time & inventory
- Same technological development for neutrino mass experiments & precision spectroscopy

Goal:
Flux of 10^{15} atoms/s

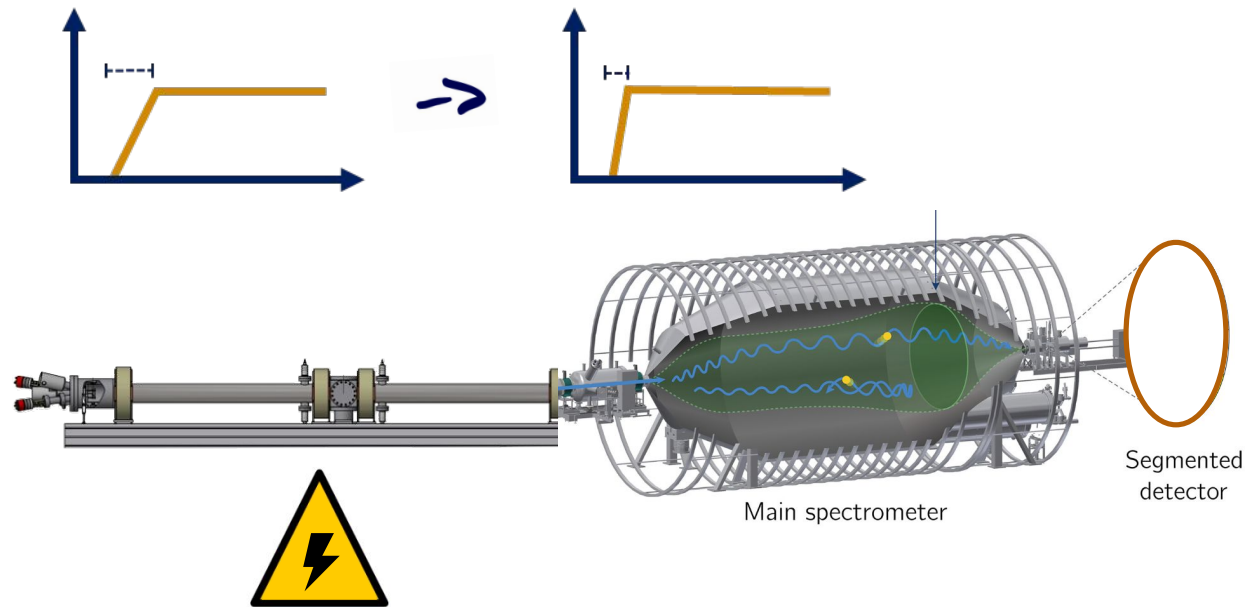


Sub-eV energy resolution - Transversal Energy Compensator & Time-of-Flight

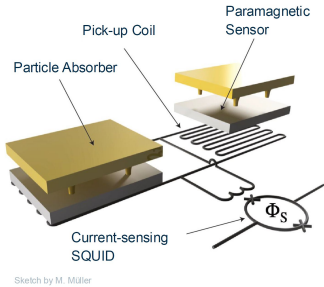


- Upgrade to KATRIN setup with significantly improved **energy resolution & statistics**

Sub-eV energy resolution - Transversal Energy Compensator & Time-of-Flight

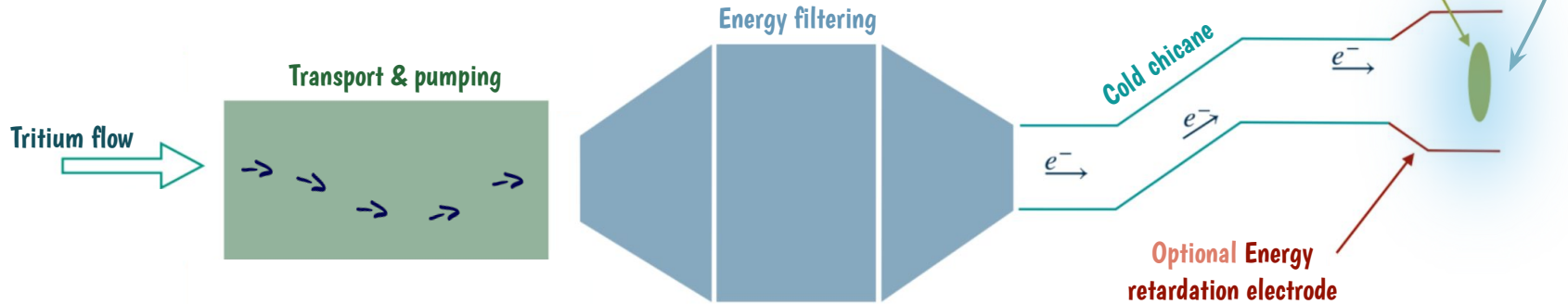


Sub-eV energy resolution - Demonstrator setup



Testing & commissioning of 4cm² MMC detector array with sub-eV resolution

colder than the universe
20 milli Kelvin

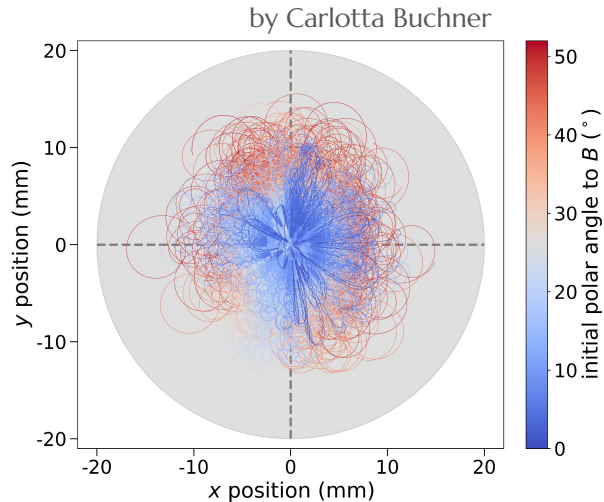


Sub-eV energy resolution - Cold Chicane

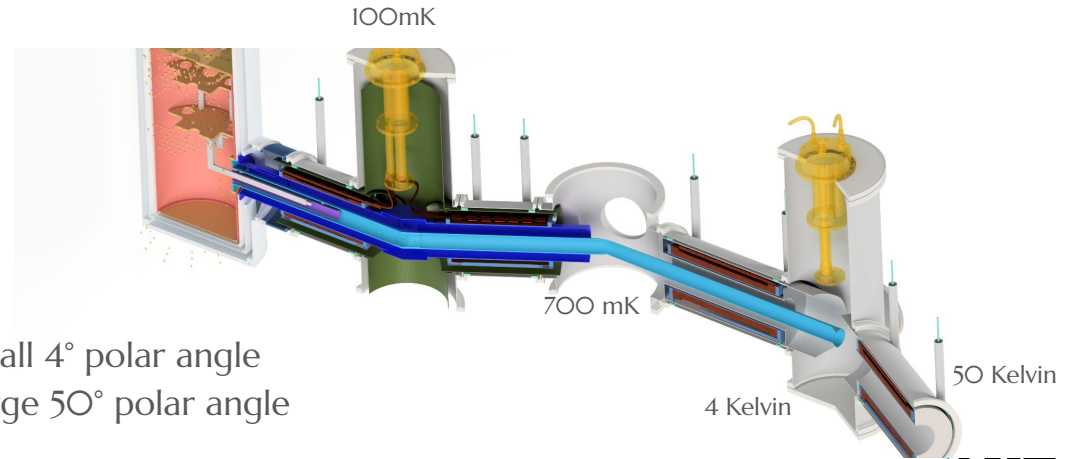
Hardware development

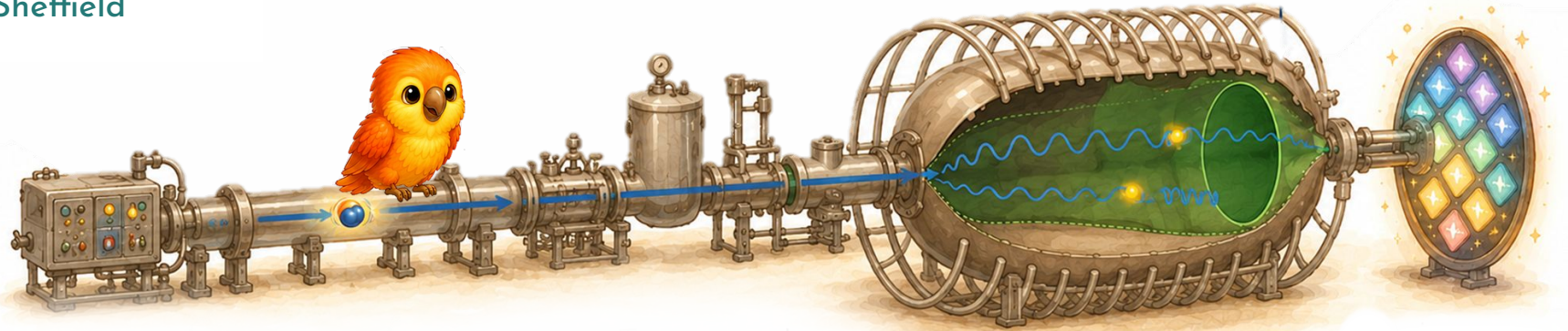
Electron guidance towards detector:
from 300 K to 100 mK
& ~1 T to 30 mT

- 5 superconducting magnets
- 20 mm radius
- Multi-layer cryostat shielding



- Small 4° polar angle
- Large 50° polar angle

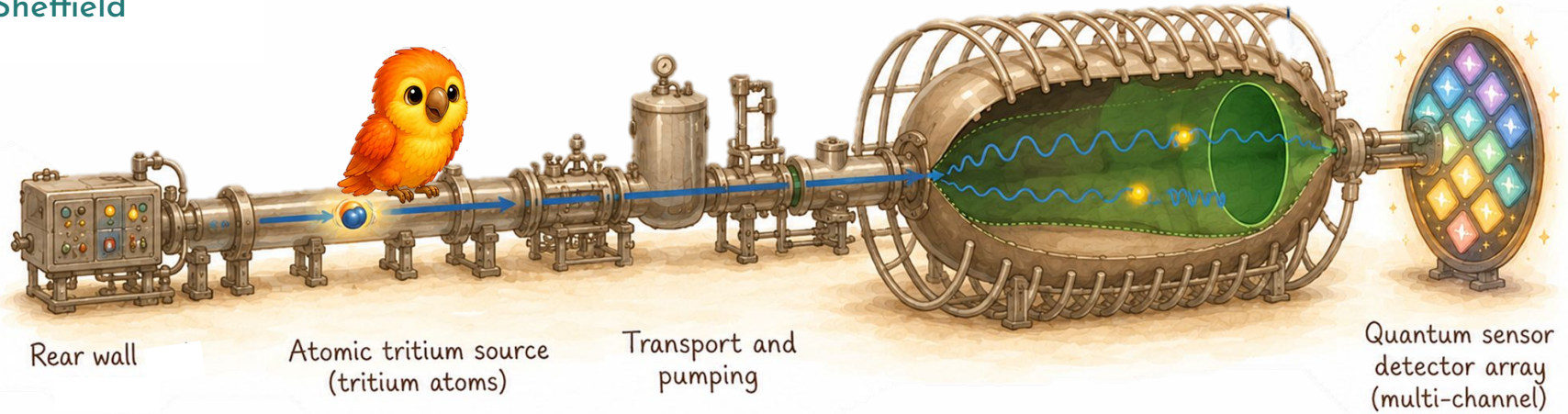




KATRIN++

Towards probing the inverted mass hierarchy with
direct neutrino mass measurements

Svenja Heyns for the KATRIN Collaboration



KATRIN++ -

Towards probing the inverted mass hierarchy with
direct neutrino mass measurements

Svenja Heyns for the KATRIN Collaboration