# Search for keV-scale sterile neutrinos with β-decays

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Flavour and Dark Matter

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# Outline

- what is a keV-scale sterile neutrino?
- motivation for possible keV-scale sterile neutrinos

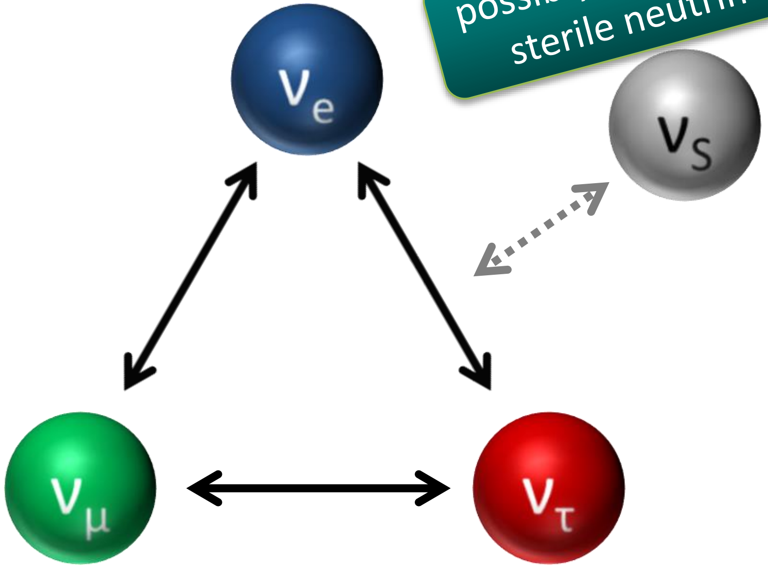
- experimental searches for sterile ν using β-decay
  - $\beta^-$-decay (KATRIN/TRISTAN)
  - electron capture (ECHo)
  - further efforts

- conclusion and outlook

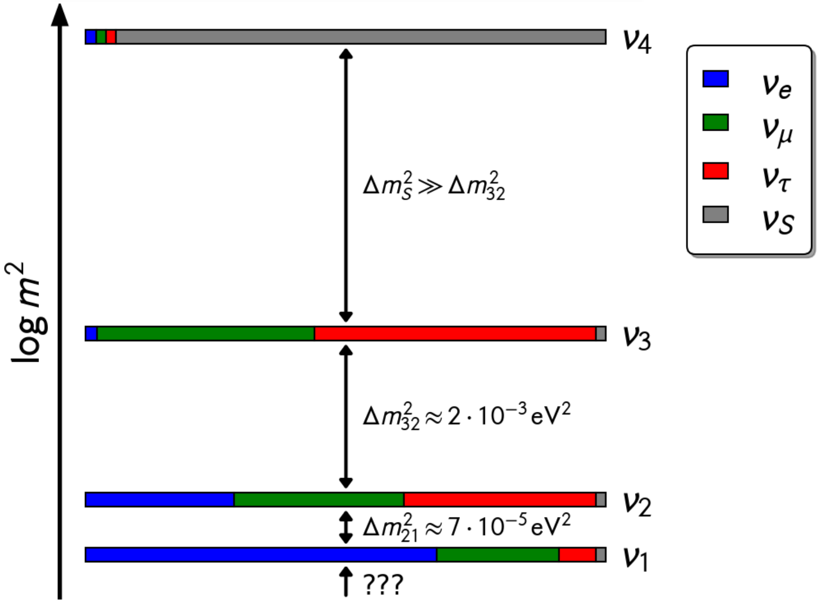
# What is a sterile neutrino?

- hypothetical neutral lepton with no ordinary weak interactions
- can mix with active neutrinos

possibly more that 1 sterile neutrino




keV-scale sterile ν = keV-scale massive ν which is mostly sterile



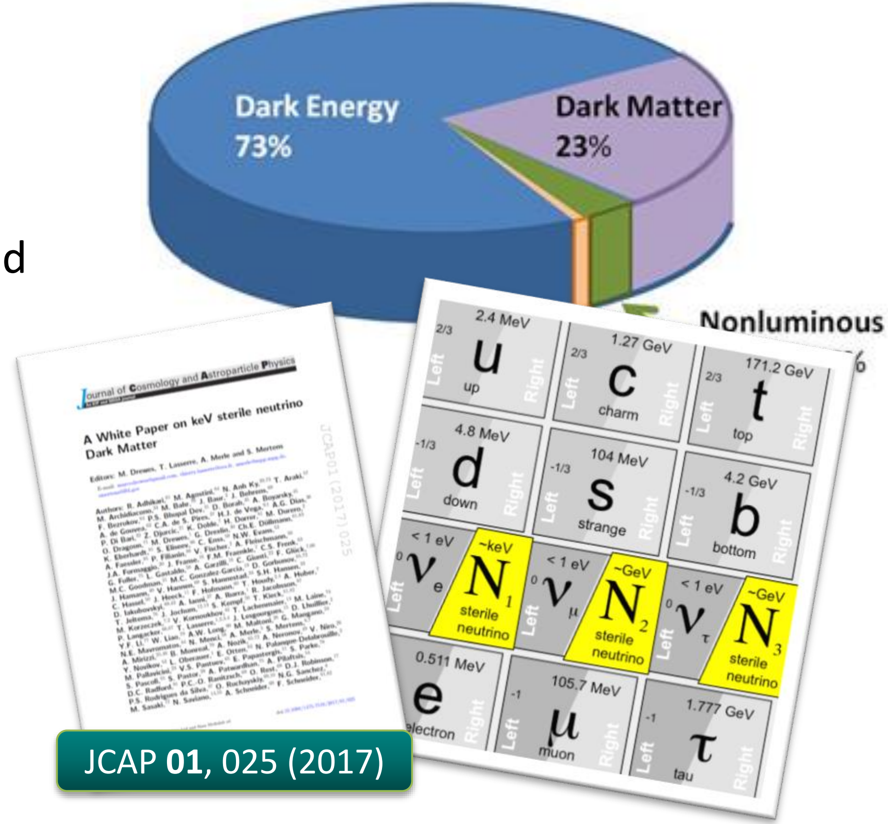
# Motivation for keV-scale sterile neutrinos

## Energy content of the Universe

- need of non-baryonic dark matter
- active neutrinos only < few %
- 95 % of the Universe‘s content not understood

## Physics beyond the Standard Model

- ν-minimal SM: minimal extension to solve a maximal number of open questions
- $N_1$ in keV region: dark matter
- $N_2$, $N_3$ in GeV region: give masses to νs and produce baryon asymmetry of the Universe




JCAP **01**, 025 (2017)

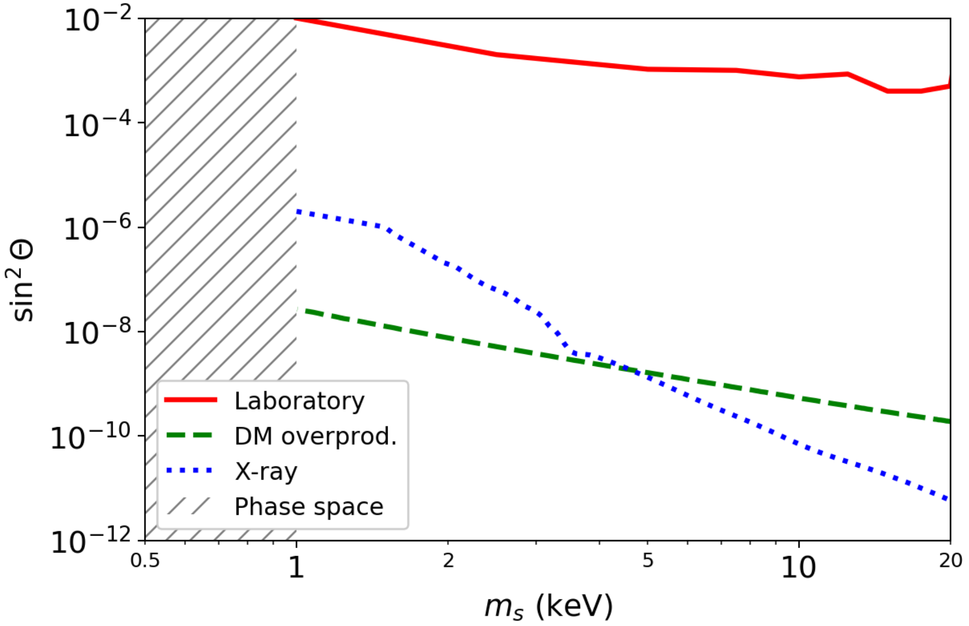
# Current constraints on keV-scale sterile ν

- phase-space density constraints
- x-ray constraints
- dark matter overproduction
- **laboratory experiments**

➢ need laboratory input

➢ very small mixing angle: $\sin^2\theta < 10^{-6}$ (!)

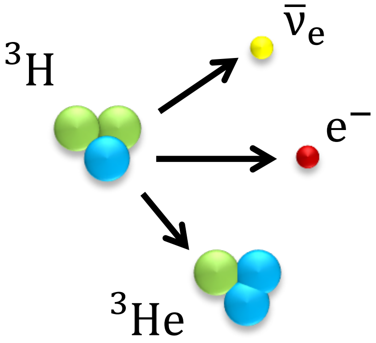
How do we get to $10^{-6}$ with laboratory experiments?



# β-decay and sterile neutrino

**Nuclear β-decay:**

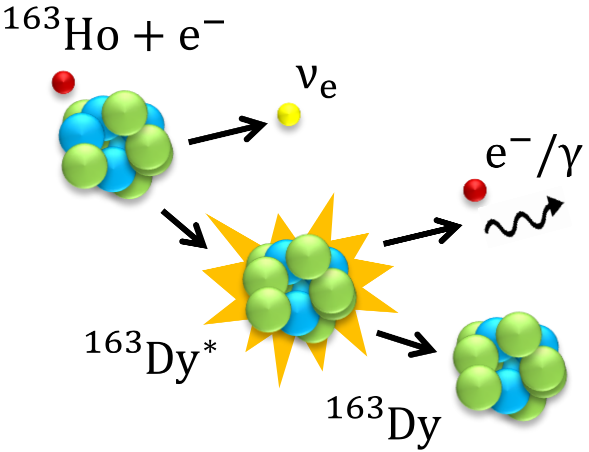
- $^{3}\mathrm{H} \rightarrow {}^{3}\mathrm{He} + \mathrm{e}^{-} + \bar{\nu}_{\mathrm{e}}$
- neutrino mass from kinematical measurement of electron energy spectrum




**Electron capture:**

- $^{163}\mathrm{Ho} + \mathrm{e}^{-} \rightarrow {}^{163}\mathrm{Dy}^{*} + \nu_{\mathrm{e}} \rightarrow {}^{163}\mathrm{Dy} + \mathrm{e}^{-}/\gamma + \nu_{\mathrm{e}}$
- neutrino mass from calorimetric measurement of de-excitation energy spectrum

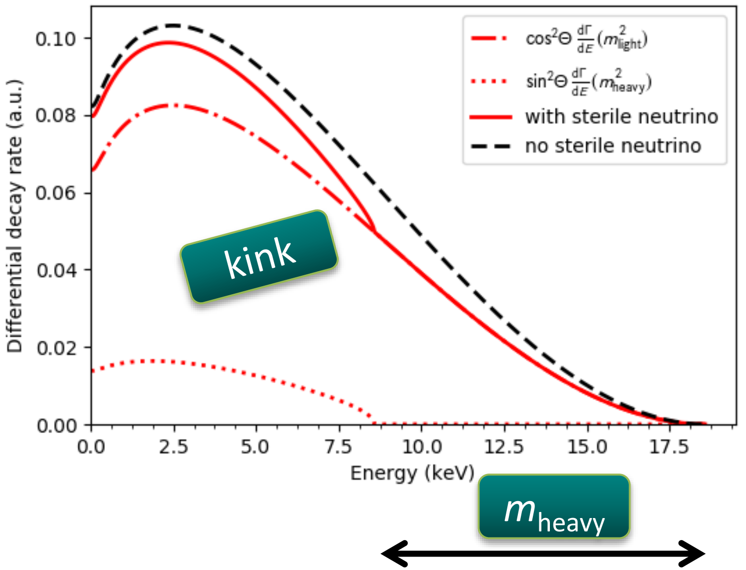
➢ with probability $|U_{ei}|^2$ the neutrino eigenmass is $m_i$

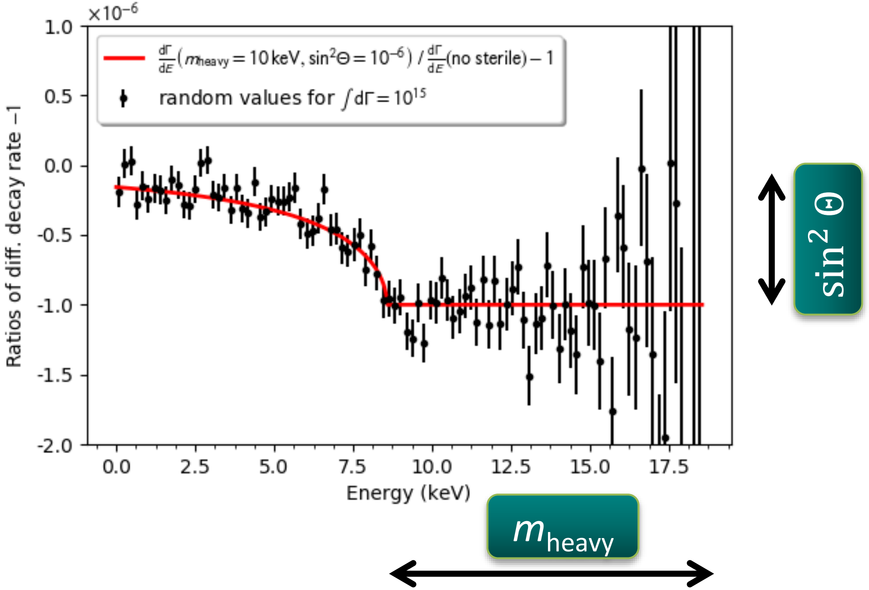


# Tritium β-decay sterile neutrino observables

- electron energy spectrum: $\frac{\mathrm{d}\Gamma}{\mathrm{d}E} = \sum_i |U_{ei}|^2 \frac{\mathrm{d}\Gamma}{\mathrm{d}E}(m_i^2)$
  - three light masses not experimentally resolved, sterile mixing small

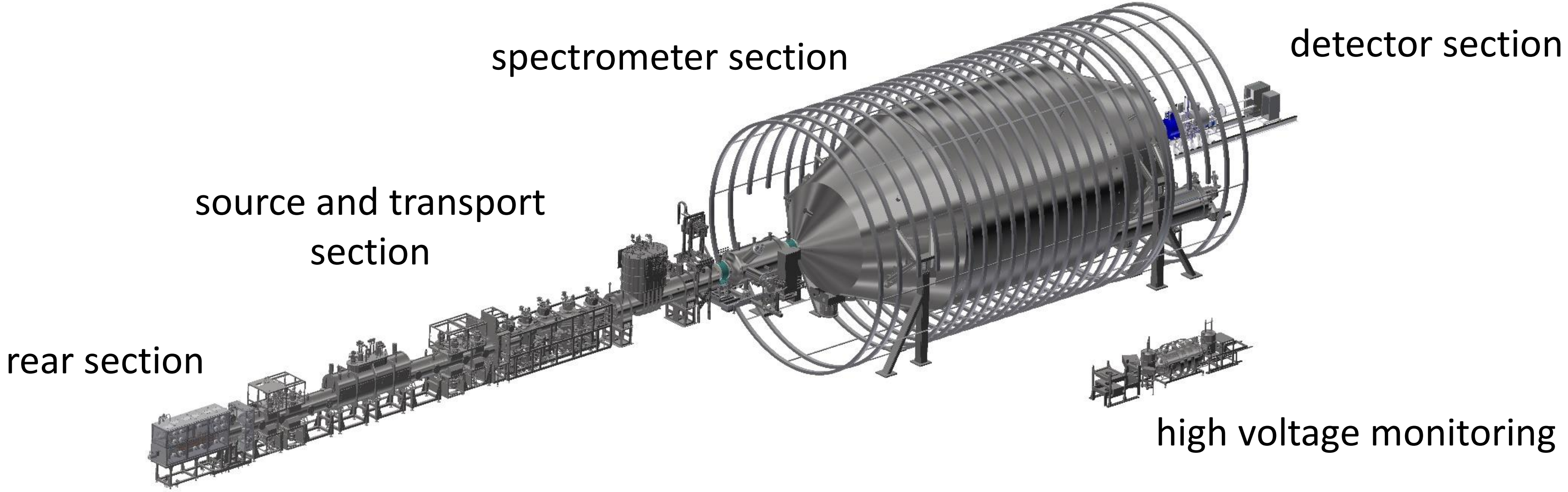
➢ $\frac{\mathrm{d}\Gamma}{\mathrm{d}E} \approx \cos^2\Theta \frac{\mathrm{d}\Gamma}{\mathrm{d}E}(m_{\mathrm{light}}^2) + \sin^2\Theta \frac{\mathrm{d}\Gamma}{\mathrm{d}E}(m_{\mathrm{heavy}}^2)$



# Karlsruhe Tritium Neutrino experiment

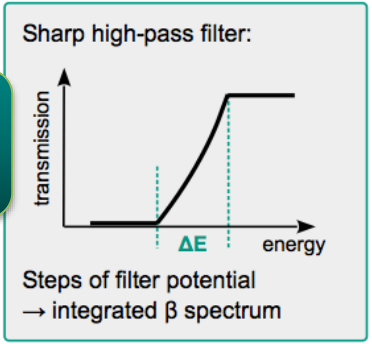
- precision measurement of tritium β-decay electron spectrum shape
- high-luminosity Windowless Gaseous Tritium Source (WGTS)
- adiabatic guidance of electrons through 70 m long setup



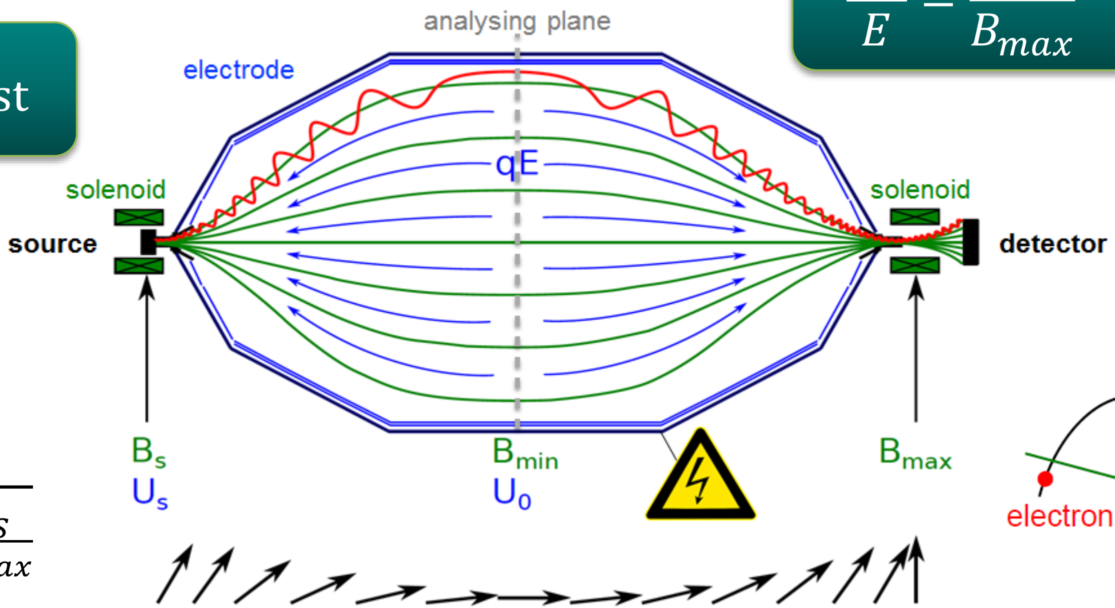
# KATRIN electron spectroscopy

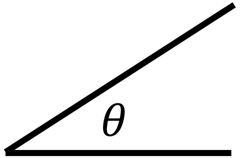
- Magnetic Adiabatic Collimation with Electrostatic Filter (MAC-E Filter)
- large angular acceptance (51° in forward direction)
- high energy resolution (< 1 eV @ 18.6 keV)

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

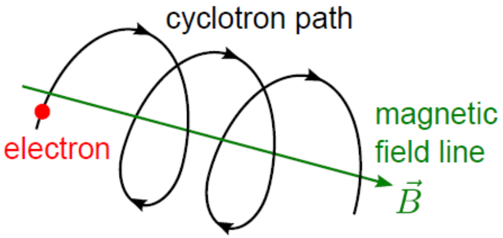



$$\mu = \frac{E_{\perp}}{B} = \text{const}$$




$$\theta = \arcsin\sqrt{\frac{B_S}{B_{max}}}$$



# KATRIN/TRISTAN project

- KATRIN provides high-luminosity tritium source and high angular acceptance: ~$10^{10}$ $e^-$/s → 2-3 years
- current detector system capable of “only“ $10^6$ $e^-$/s
- ➢ phased approach

**“Phase 0” Feasibility run**

- before ν mass measurement
- ➢ use existing setup without hardware modifications
- ➢ reduce count rate arriving at the detector

**“Phase 1” Full statistics**

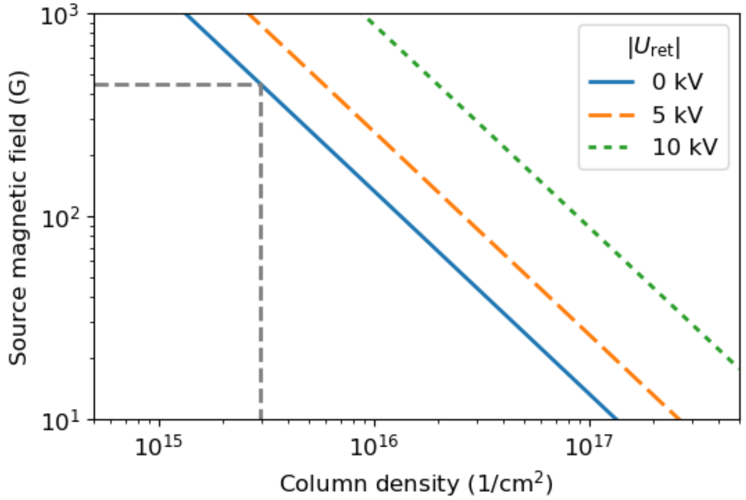
- after ν mass measurement
- ➢ R&D for a new detector system
- ➢ detailed investigation of systematic effects

S. Mertens et al., JCAP **02**, 020 (2015)

# Phase 0 measurement concept

- lower amount of tritium in WGTS→ fewer decays
- lower magnetic field of the WGTS → fewer transmitted electrons (mag. mirror)
- ➢ combination of both to achieve lower count rate

Target rate of $10^6$ $e^-/s$

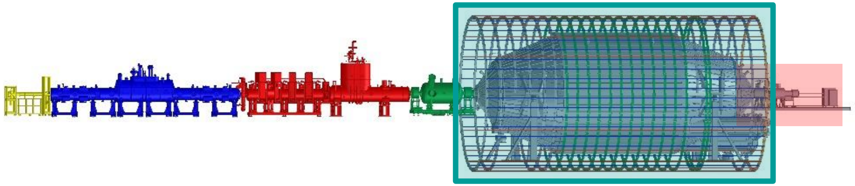



- ➢ tritium amount ~150× lower than nominal
  - reduce scattering in source
  - source stability
- ➢ acceptance angle ~5° (nominal 51°)
  - limit non-adiabaticity

# Measurement techniques

**Integral measurement**

change retarding potential in steps to cut lower part of spectrum

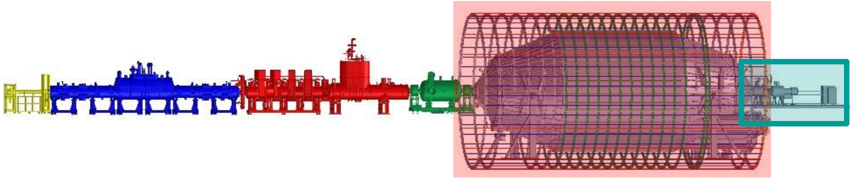


use KATRIN detector to count electrons

rate stability

**Differential measurement**

set main spectrometer to 0 kV or small non-zero potential



use KATRIN detector to measure β-spectrum

detector response

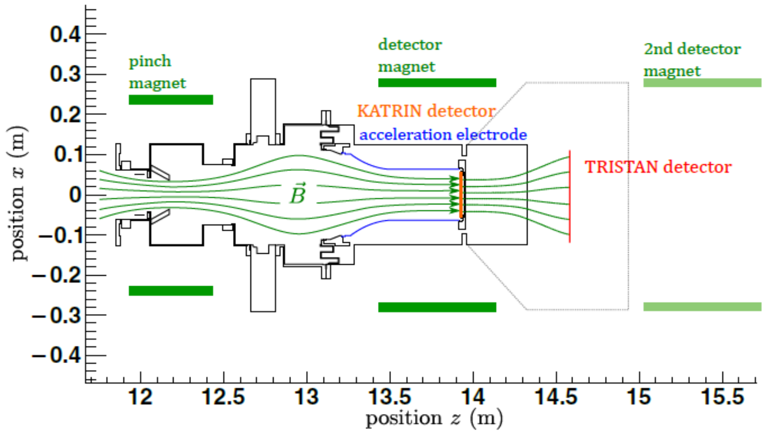
- WGTS parameter stability
- non-adiabaticity
- retarding-potential-dependent effects

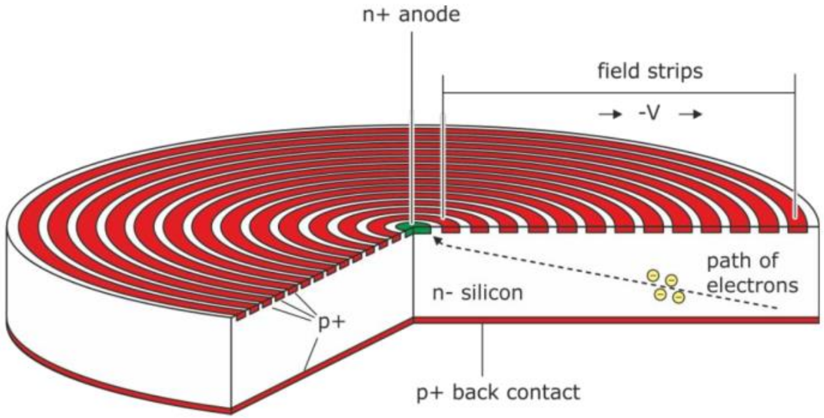
- energy resolution
- dead layer thickness
- backscattering

**simultaneous fit of both measurements with one β-spectrum**

# Phase 1 – new detector system

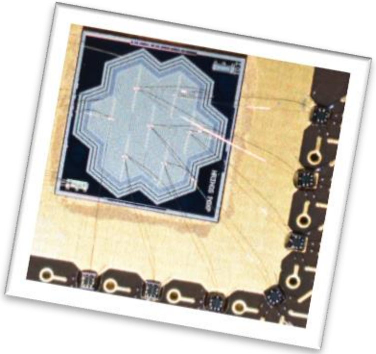
- for handling high rates: many-pixel silicon drift detector
- requirements:
  - minimize charge sharing (larger pixel area) and backscattering (smaller B-field)
  - energy resolution of 300 eV @ 30 keV, thin entrance window of < 100 nm
  - reduce ADC non-linearities by waveform digitization @ 100 MHz
  - multiplicity detection in neighboring pixels at FPGA level



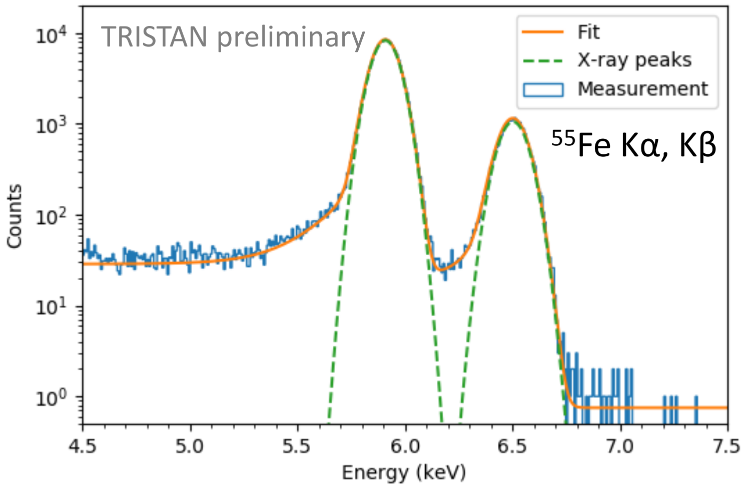



# 7-pixel detector prototype

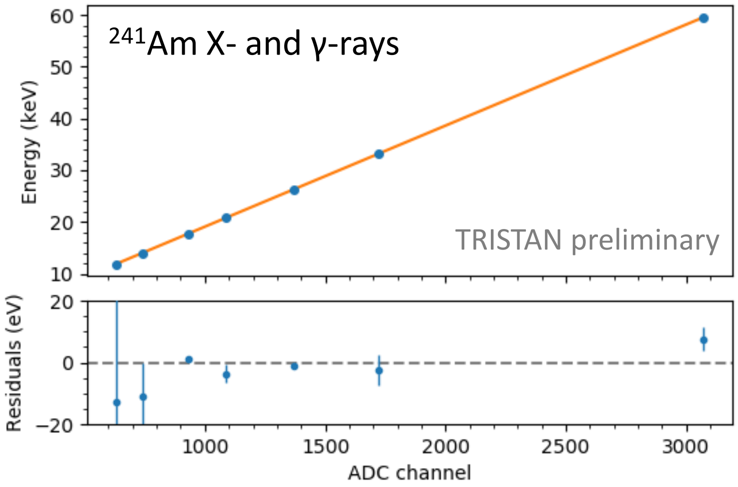
- produced by Halbleiterlabor (HLL) of the Max Planck Society
- read out by charge-sensitive pre-amplifier “CUBE” from XGLab
- novel production method for thin entrance window



140 eV (FWHM) @ 5.9 keV




non-linearity < 0.1 %

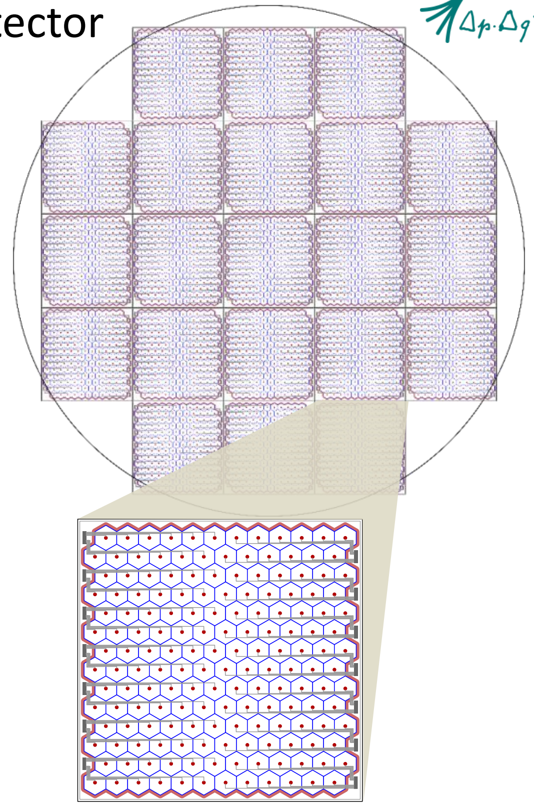



S. Mertens et al., in prep.

# Towards final detector system

- integrated nJFET, 3 mm pixel diameter
- 166 pixels in module, 4×4 cm$^2$, expected Feb 2019
- 21 modules, 20 cm diameter, expected 2023
- test of prototype and sterile neutrino analysis framework in Troitsk nu-mass experiment setup

full detector

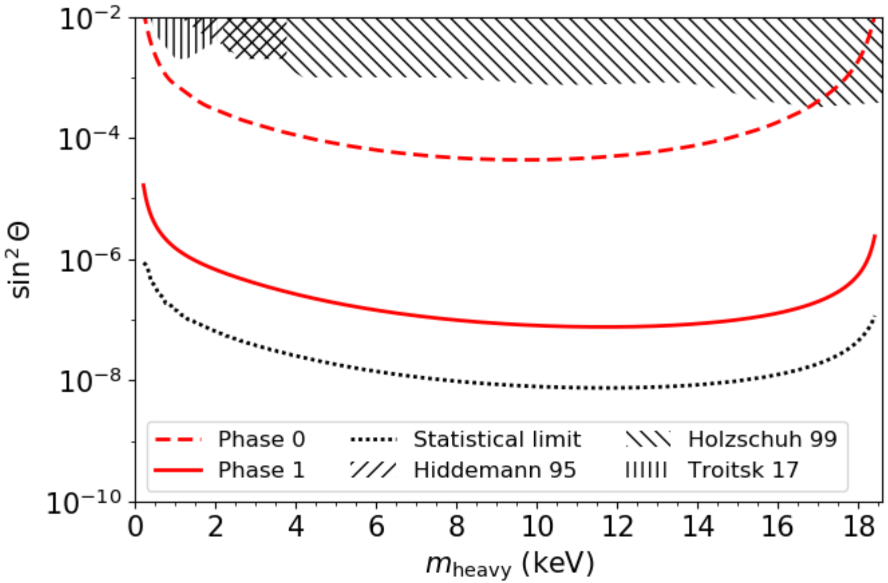


detector module

# Statistical sensitivity to sterile neutrino

- understanding of systematic effects critical
- under investigation:
  - ➢ backscattering from KATRIN rear wall
  - ➢ scattering on tritium molecules in the WGTS
  - ➢ adiabaticity
  - ➢ detector energy response
- phased approach:
  - – Phase 0: $6 \cdot 10^{11}$ electrons
  - – Phase 1: $10^{16}$ electrons

95 % C.L.

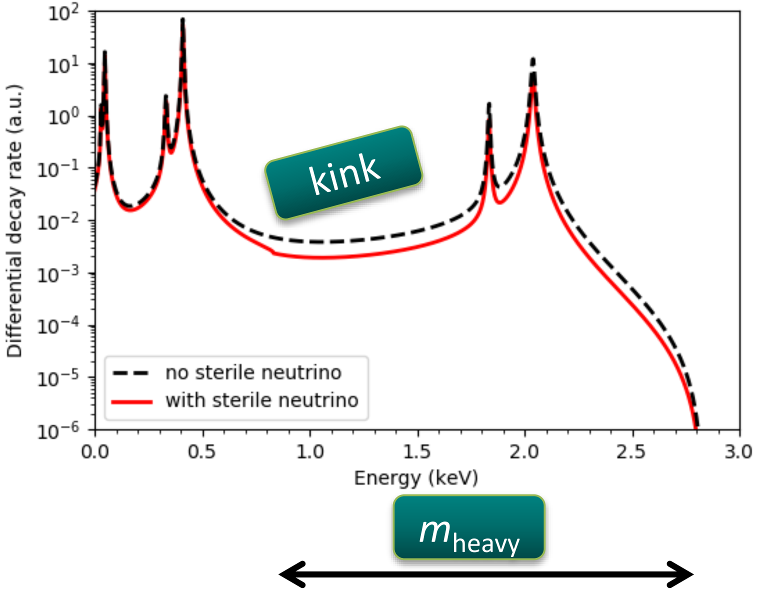


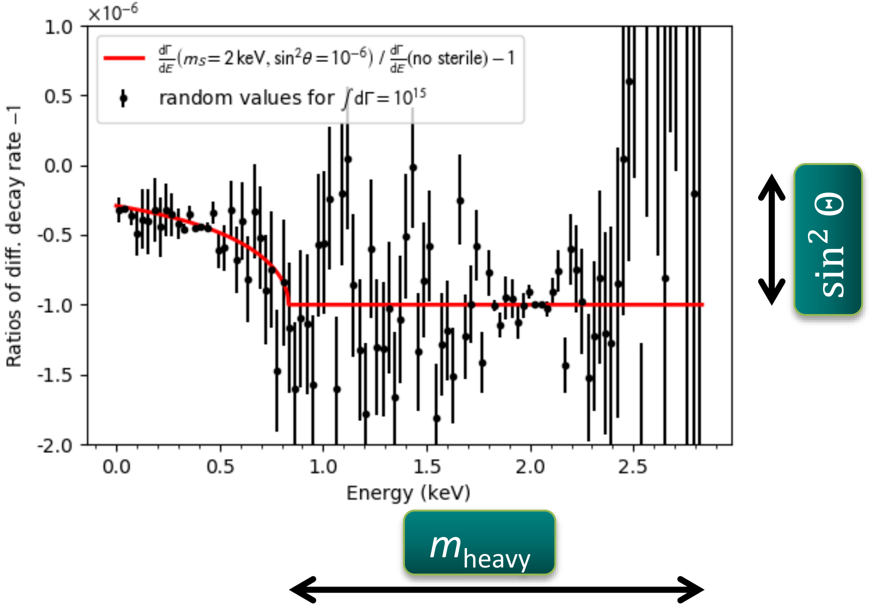


K. H. Hiddemann et al., J. Phys. G **21**, 639 (1995)
E. Holzschuh et al., Phys. Lett. B **451**, 247 (1999)
J. N. Abdurashitov et al., JETP Lett. **105**, 753 (2017)

# $^{163}$Ho e$^-$ capture sterile neutrino observables

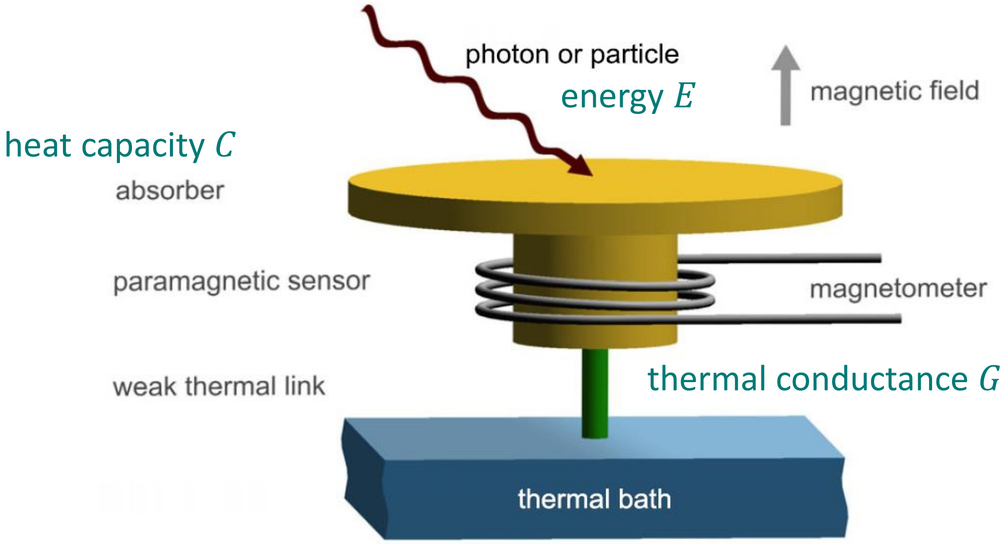
- similarly as for tritium β-decay, mass limited to 2.8 keV (Q-value)
- capture process from 3rd or higher shells, s- or $p_{1/2}$-levels
- $\frac{\mathrm{d}\Gamma}{\mathrm{d}E} \approx \cos^2\Theta \frac{\mathrm{d}\Gamma}{\mathrm{d}E}(m^2_{\text{light}}) + \sin^2\Theta \frac{\mathrm{d}\Gamma}{\mathrm{d}E}(m^2_{\text{heavy}})$



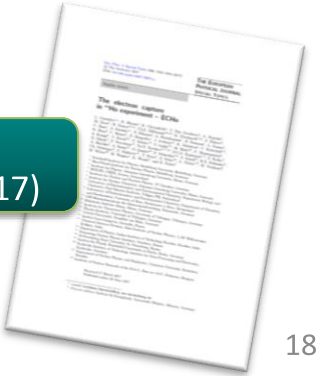



# Electron Capture $^{163}$Holmium experiment

- calorimetric measurement (source ⊂ detector) of de-excitation energy spectrum
- metallic magnetic calorimeters with SQUID magnetometer readout
- small activity per detector to limit pile-up due to finite time resolution → many detectors




- temperature change $\Delta T \simeq E/C$
- decay time constant $\tau = C/G$
- ➢ change of magnetization → magnetic flux → SQUID signal



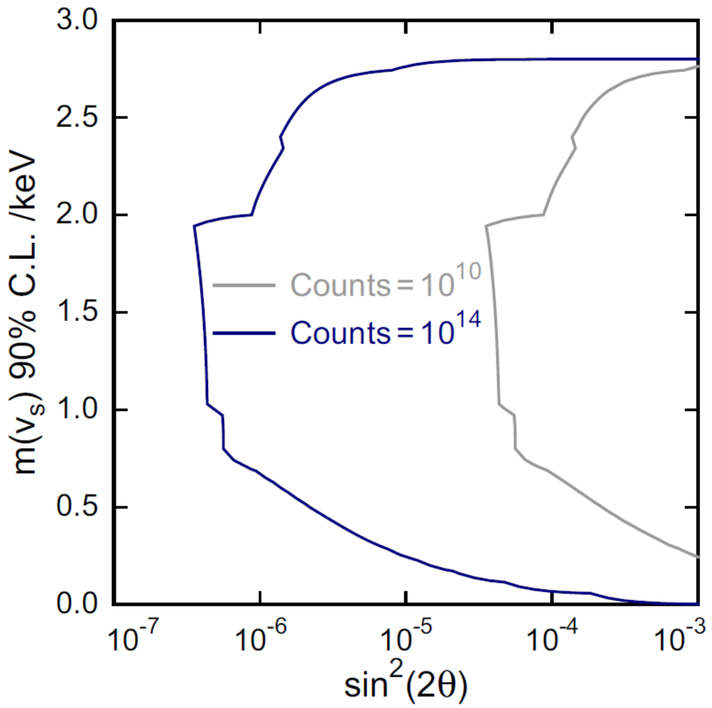
L. Gastaldo et al.,
EPJ Spec. Top. **226**, 623 (2017)

# Statistical sensitivity to sterile neutrino

- full spectrum automatically obtained in measurement of neutrino mass

- requirements:
  - understanding of full spectrum (higher order excitation states)
  - precise knowledge of endpoint energy
  - identification and reduction of background below pile-up contribution

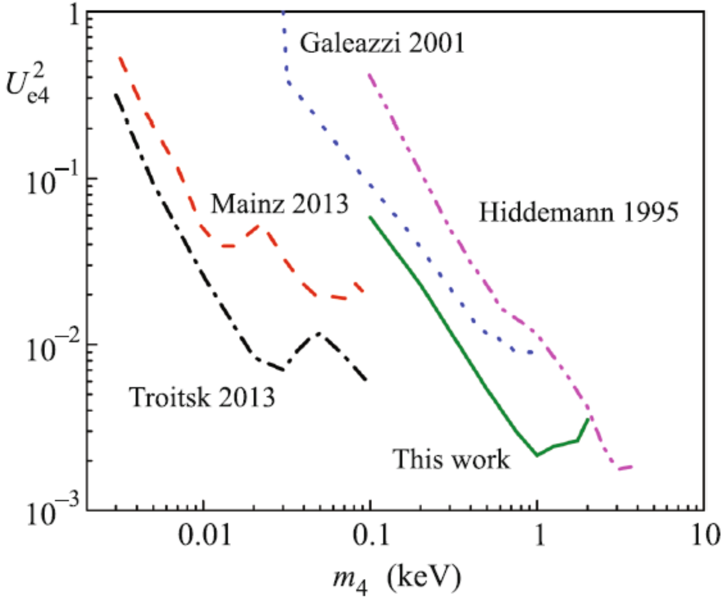
- phased approach:
  - ECHo-1k: $10^{10}$ electrons (ν mass < 10 eV)
  - ECho-1M: $10^{14}$ electrons (ν mass < 1 eV)




ref.: L. Gastaldo et al., EPJ Spec. Top. **226**, 1623 (2017)

# Further similar activities

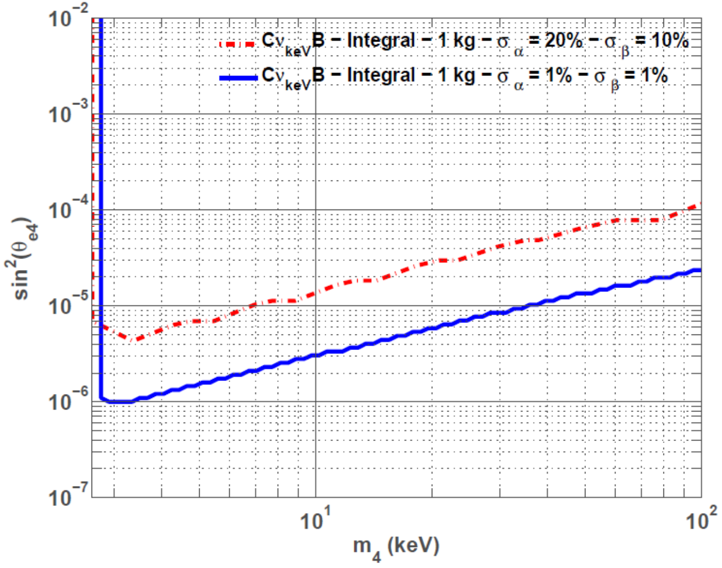
- Troitsk nu-mass experiment to search for keV-scale sterile neutrino
  - ➢ D. N. Abdurashitov et al., JINST **10**, T10005 (2015), J. N. Abdurashitov et al., JETP Lett. **105**, 753 (2017)*
- Project 8 experiment
  - – ν mass by cyclotron radiation spectroscopy
  - ➢ A. A. Esfahani et al., J. Phys. G **44**, 054004 (2017)
- PTOLEMY experiment
  - – search for cosmic ν background by high-resolution calorimetry with multi-band MAC-E selection
  - ➢ S. Betts et al., arXiv:1307.4738
- electron capture: HOLMES
  - ➢ B. Alpert et al., EPJ C **75**, 112 (2015)

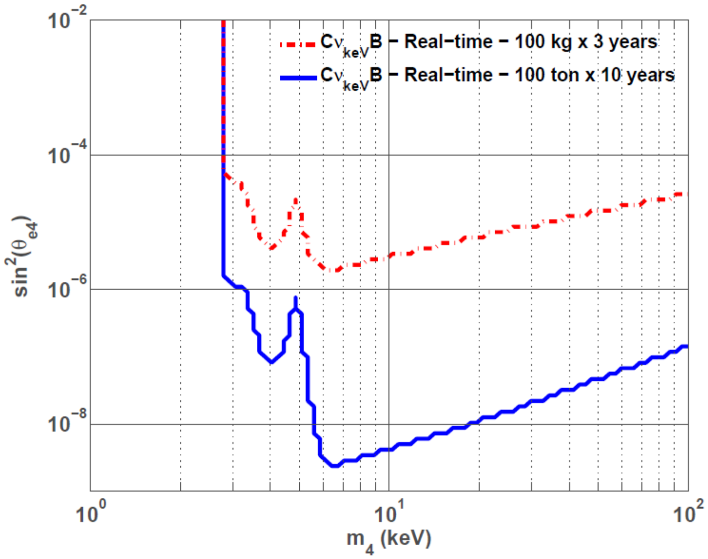



from ref *

# More exotic idea

- neutrino capture on *stable* nucleus: $\nu(m \gtrsim Q_{EC}) + {}^{163}\mathrm{Dy} \rightarrow {}^{163}\mathrm{Ho}^{+} + e^{-}$
  - ➢ counting number of $^{163}$Ho atoms in rare-earth ores (integral approach)
  - ➢ real-time detection inside an active $^{163}$Dy-based detector (differential approach)




T. Lasserre et al.
arXiv: 1609.04671

# Conclusion & outlook

- keV-scale sterile neutrinos viable dark matter candidates
- stringent limits from astrophysical observations
  - need input from laboratory experiments

- approaches to search for keV-scale sterile neutrino in laboratory using β-decay
  - TRISTAN @ KATRIN (tritium β-spectroscopy)
  - ECHo (electron capture)
  - further efforts
- more ideas?

# Thank you for your attention!