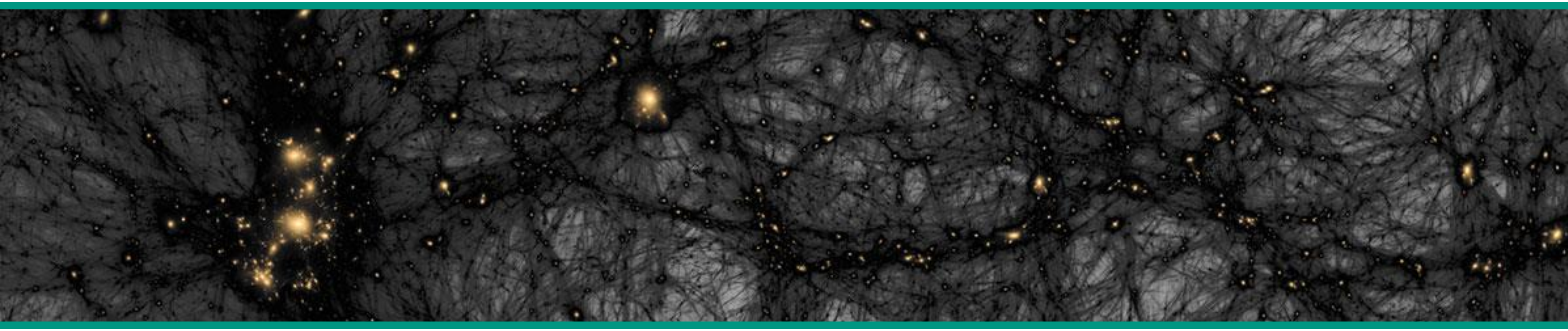
Astroparticle physics I – Dark Matter

Winter term 23/24 Lecture 23 Feb. 15, 2024



Recap of Lecture 22

- $\boldsymbol{Axion}$ **detection:** $\boldsymbol{LSW}$ **experiments** & **dielectric haloscopes** ($\boldsymbol{MADMAX}$)

  - $\boldsymbol{L}$**ight–**$\boldsymbol{S}$**hining–through–**$\boldsymbol{W}$**alls**: $\boldsymbol{ALPS - II}$ set–up at $\boldsymbol{DESY}$

  - second order weak effect: coupling of two $\mathbf{120}\ \boldsymbol{m}$ long optical cavities (dipole $\boldsymbol{B}$ – field from $\boldsymbol{HERA}$ magnets), separated by wall ⇨ sensitivity to $\boldsymbol{ALPs}$

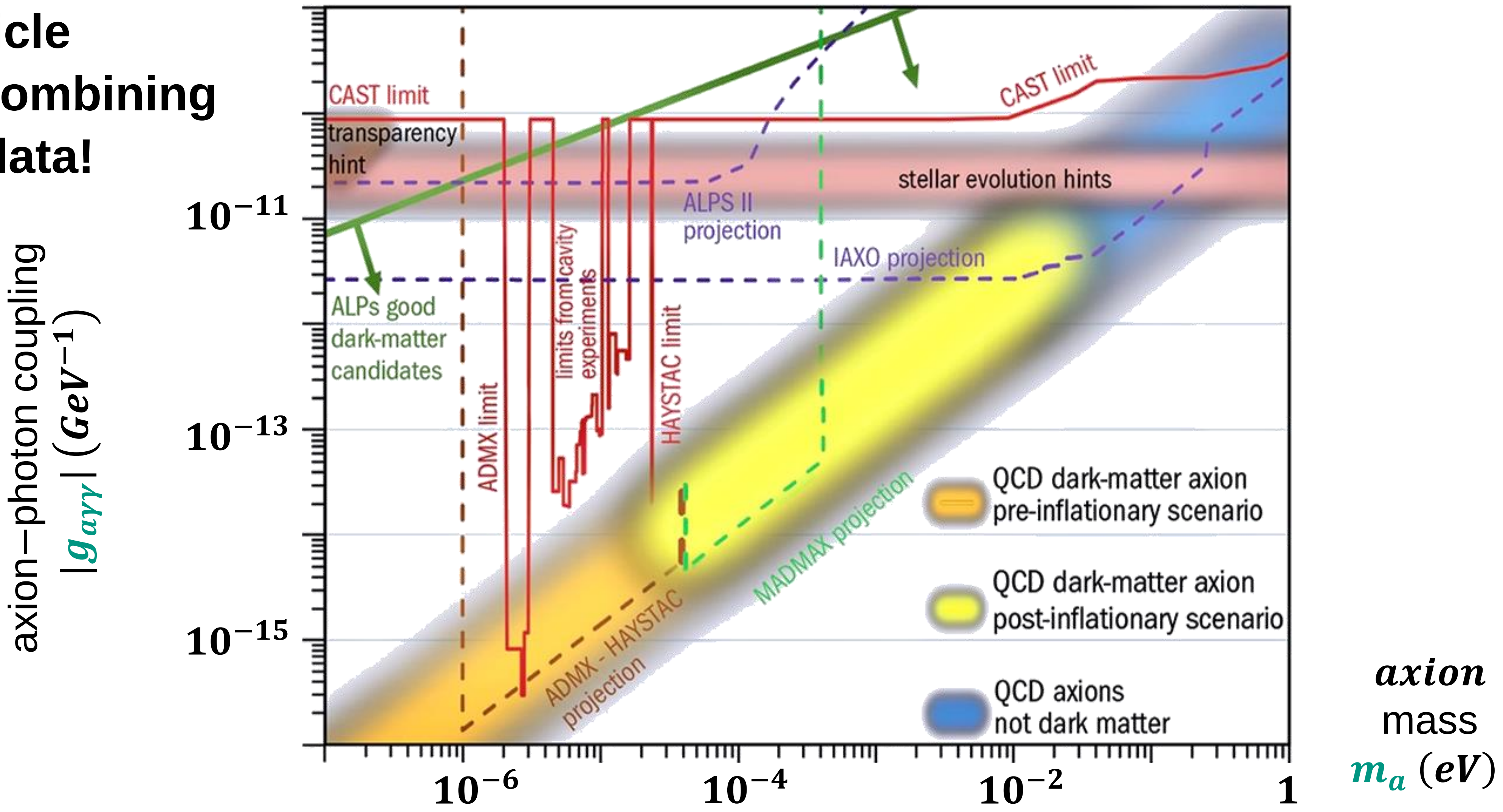
  - **dielectric haloscopes**: coherent emission of **radiowaves** from surfaces of dielectric discs (large value of $\boldsymbol{\varepsilon_R}$)

  - $\boldsymbol{MADMAX}$: ongoing $\boldsymbol{R\&D}$ efforts & prototyping of key componenta (discs & positioning via actuators, strong $\sim \mathbf{9} \ldots \mathbf{10}\ \boldsymbol{T}$ dipole magnets)

  - very active field of research, both in theory & experiment

Recap of sensitivities & hints: a comparison

- **Astroparticle physics: combining all *axion* data!**



4.6.2 keV – neutrinos

- **active neutrinos as HDM**

- smallness of the ν – mass:
  pointing to **new energy scale**

- strong **mixing effects** are
  observed via flavour oscillations

SM – overview

eV – neutrinos

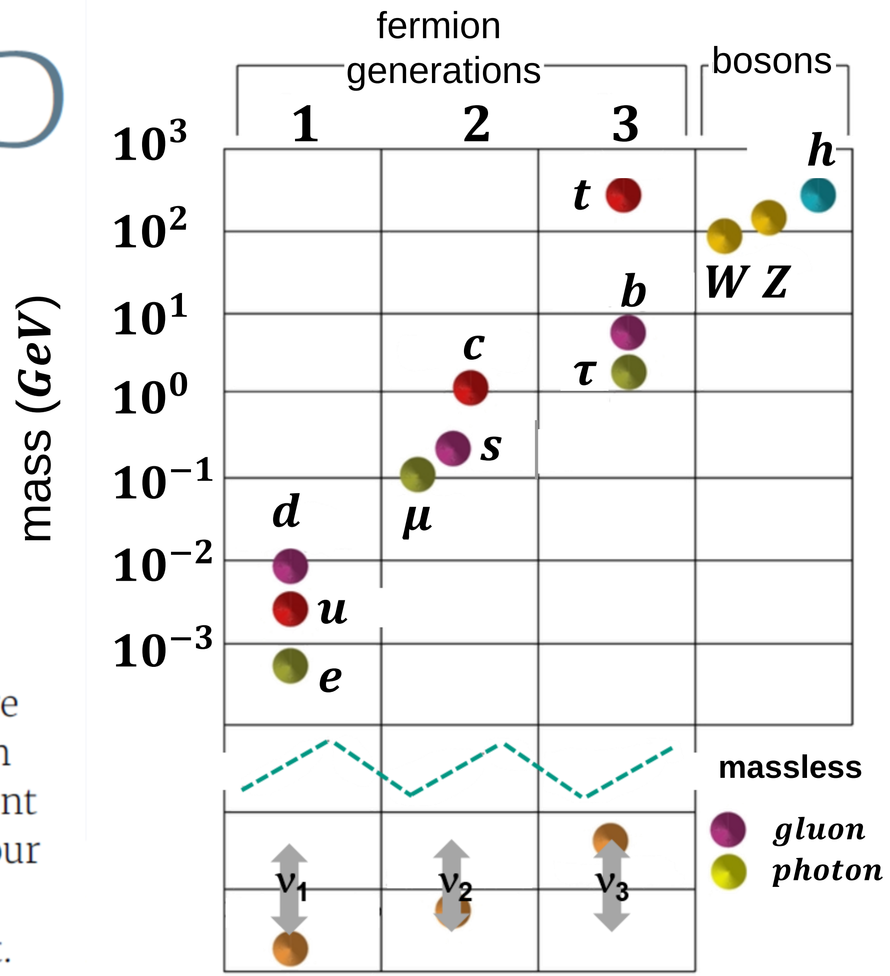
- **active neutrinos as HDM**

- smallness of the ν – mass: pointing to **new energy scale**

- strong **mixing effects** are observed via flavour oscillations

WHO ORDERED ALL OF THAT?

Explaining the bizarre pattern of fermion types and masses has led theorists to explore more complex symmetry groups than the Standard Model's, with recent work suggesting that the "flavour scale" could be at a much lower energy than previously thought.



eV – neutrinos: mixing effects

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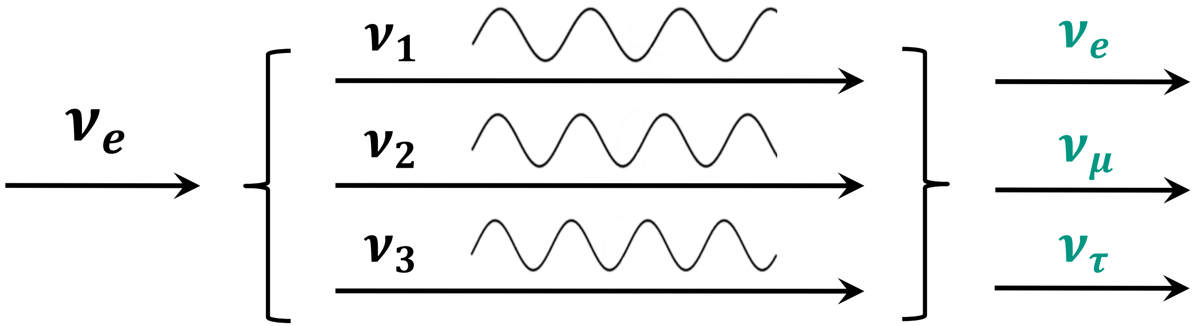
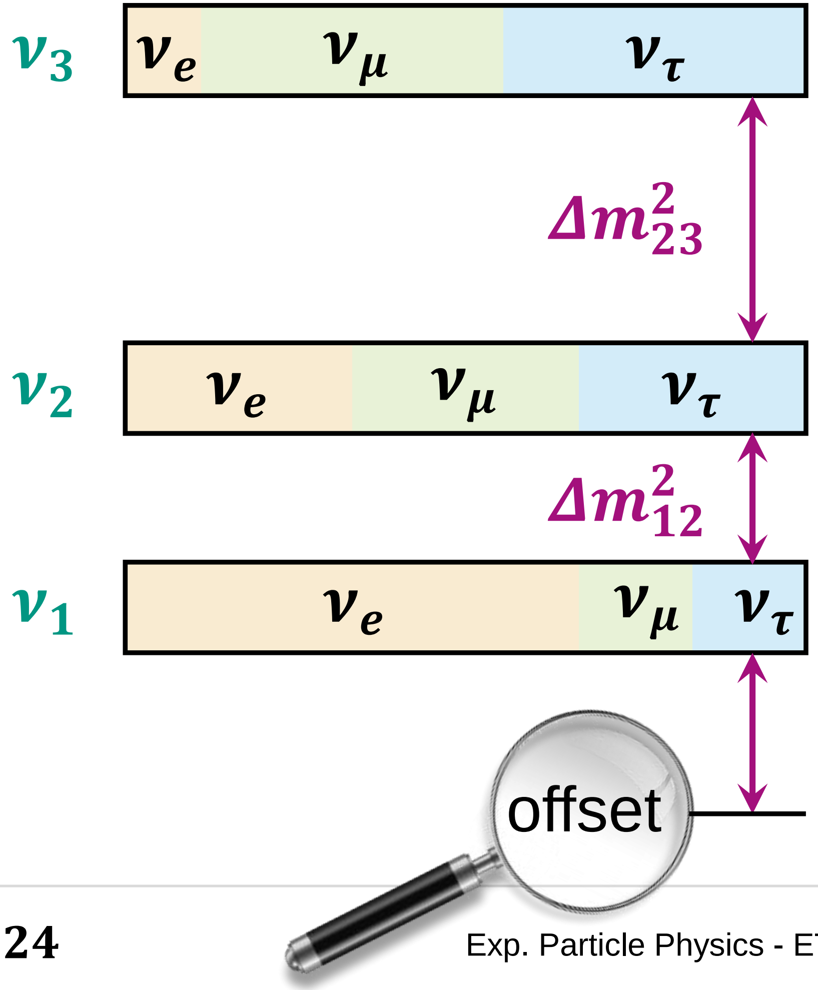
- QM – **basics: mass eigenstates** $(\nu_1, \nu_2) \neq$ **flavour eigenstates** (ν_e, ν_μ)

\- ν – **oscillations*** give access to parameters:

mass splittings Δm_{ij}^2 $\Delta m_{ij}^2 = |m_i^2 - m_j^2|$

mixing angles θ_{ij} $\theta_{12}, \theta_{23}, \theta_{13}$



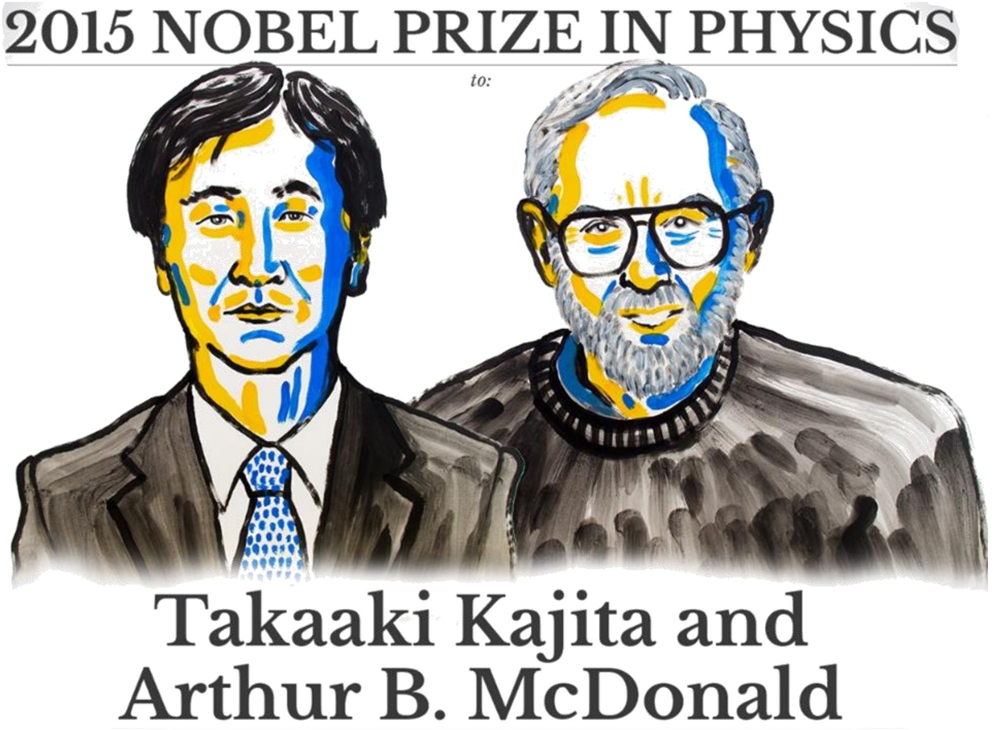


*see $ATP - II$: summer term 2024

eV – neutrinos: mixing effects

- **QM – basics: mass eigenstates $(\nu_1, \nu_2) \neq$ flavour eigenstates (ν_e, ν_μ)**

- **ν – oscillations**: major impact for both **particle / astroparticle physics**



Sterile neutrinos in the νMSM

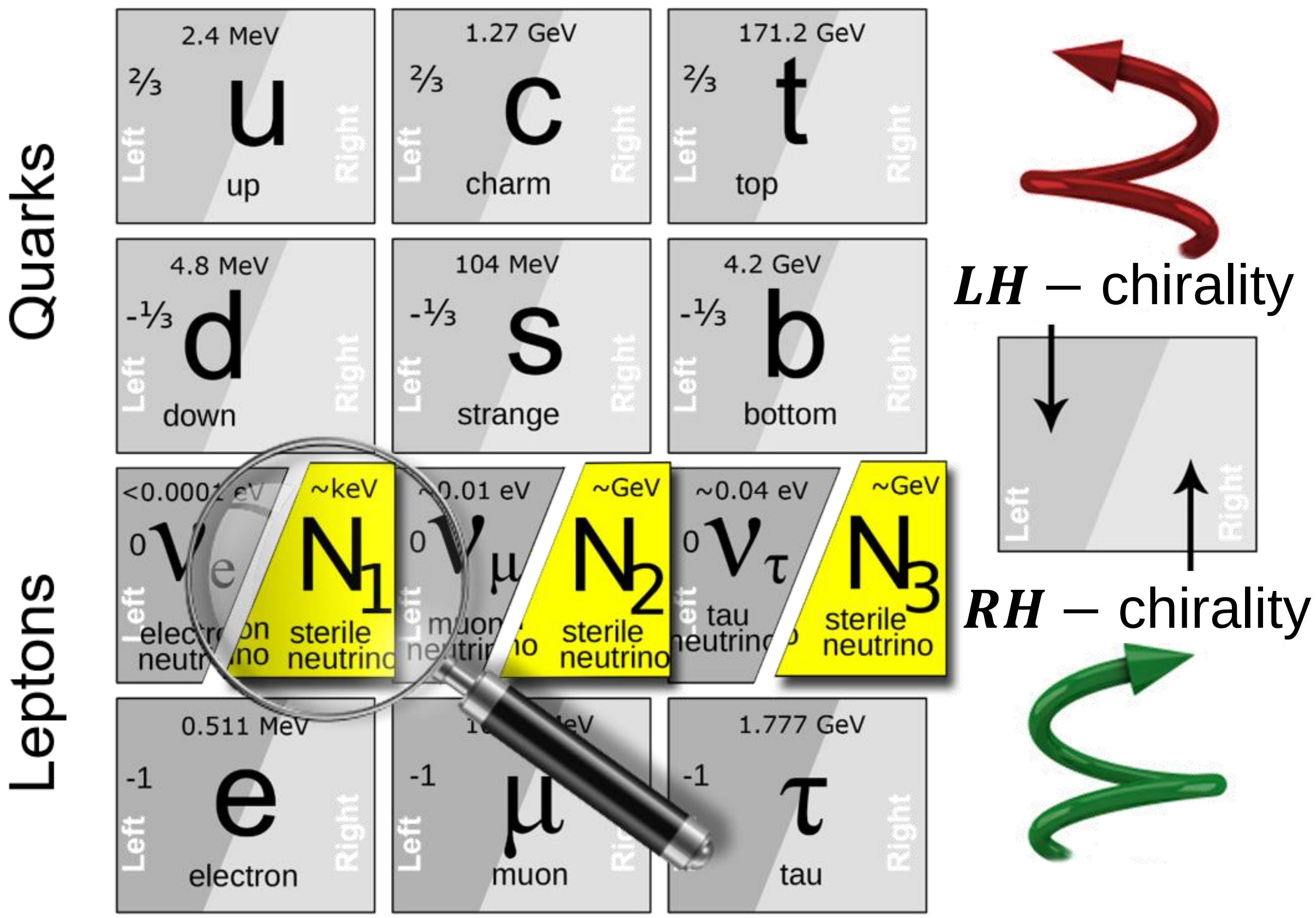
- **Sterile neutrinos as WDM**

- **minimum** extension of the Standard Model: νMSM

- only added: **sterile** neutrinos as RH – counterparts of active neutrinos
  ⇨ **3** new neutral fermions

- **1** light state: $N_1 \sim keV$ – scale
  2 quasi–degenerate heavy states $N_{2,3} \sim GeV$ – scale

$nuMSM$ – model



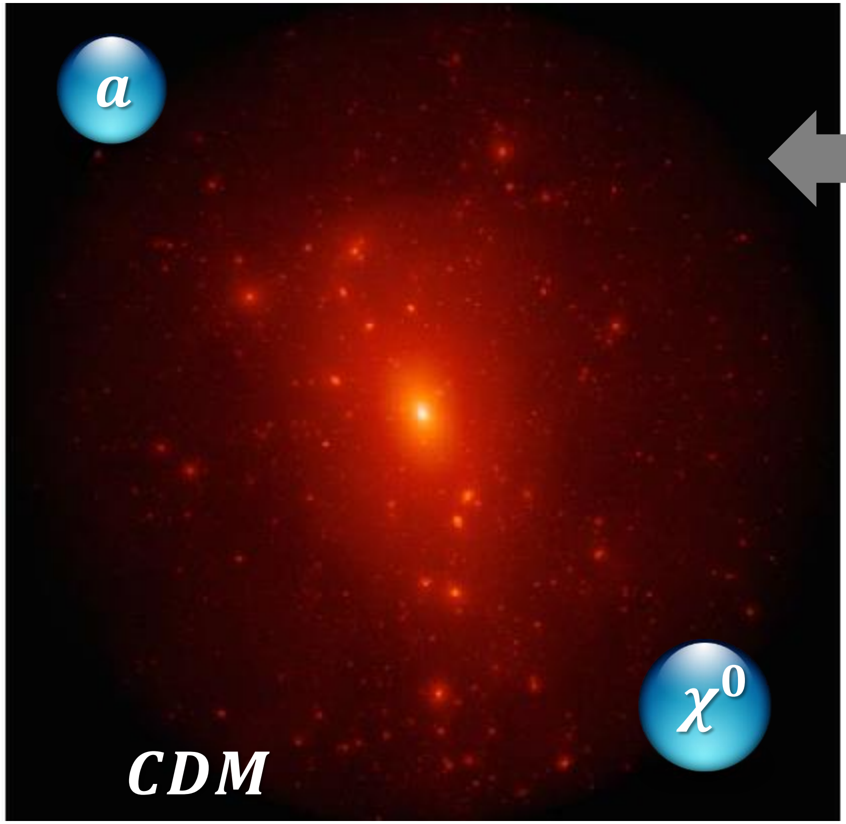
keV – steriles act as Warm Dark Matter (WDM)

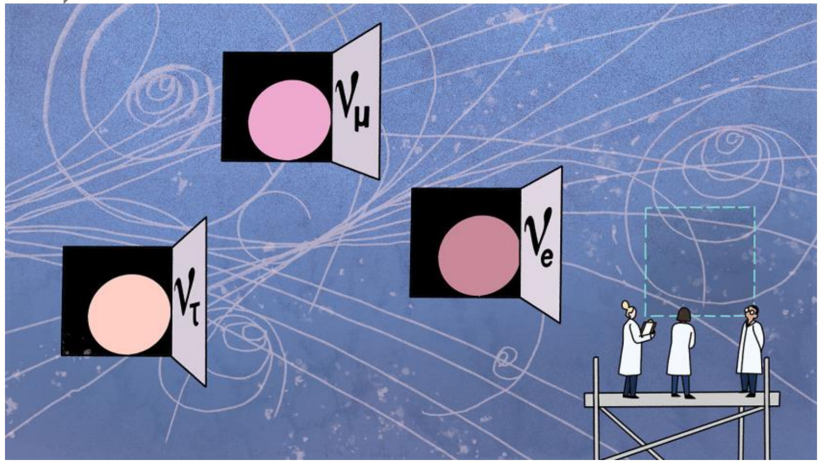
- keV – steriles as WDM could solve the problem of missing dwarf galaxies

- a persistent problem in cosmology: we see **less dwarf galaxies than predicted**

- sterile neutrinos act as WDM – neither HDM nor CDM

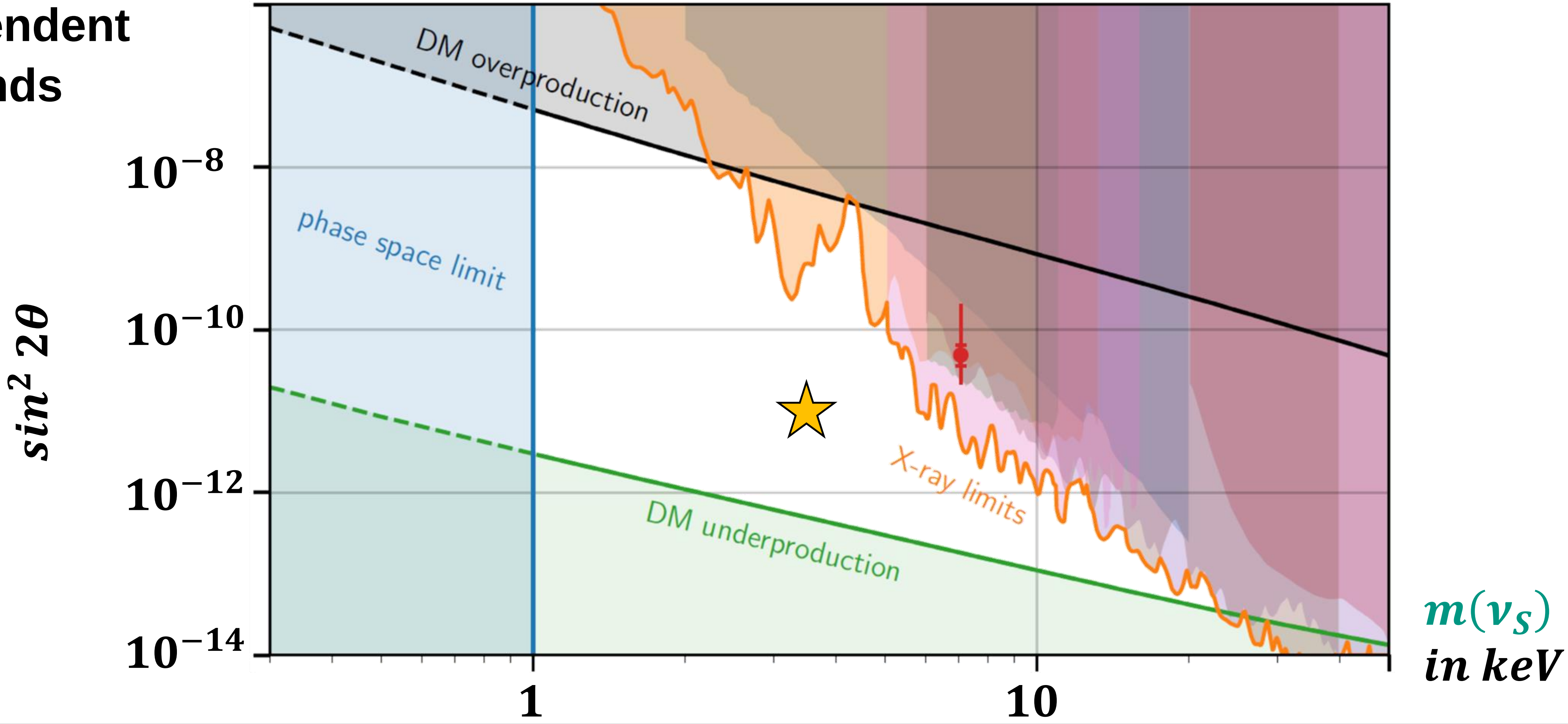
- WDM solves many issues related to dwarf galaxies, both locally (Milky Way, Andromeda) & beyond





$keV -$ steriles: cosmological bounds

- model-dependent bounds



keV – steriles: a signal observed in X – rays?

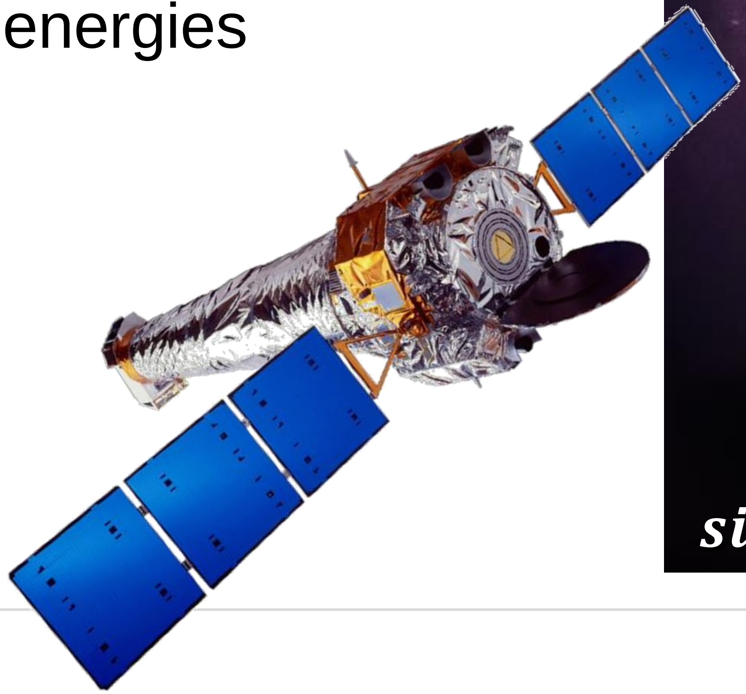
- **Observation of a weak X – ray line in clusters at $E = 3.55\ keV$: from ν_s?**

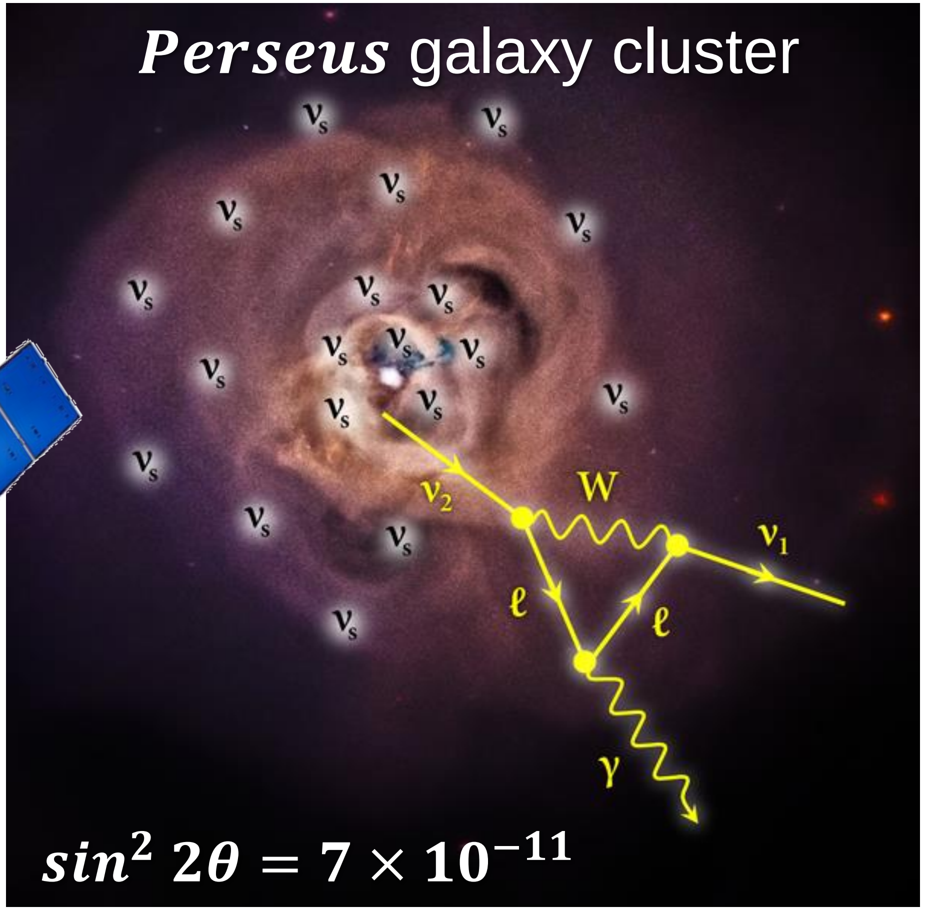
- results of leading X – ray observatories ($Chandra$, $XMM - Newton$):

  ⇨ data point to the existence of a **weak emission line** at X – ray energies

$$E_\gamma = 3.55\ keV$$

- observed in many (not all) galaxy clusters





keV – steriles: a signal observed in X – rays?

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- **Observation of a weak X – ray line in clusters at $E = 3.55\ keV$: from ν_s?**

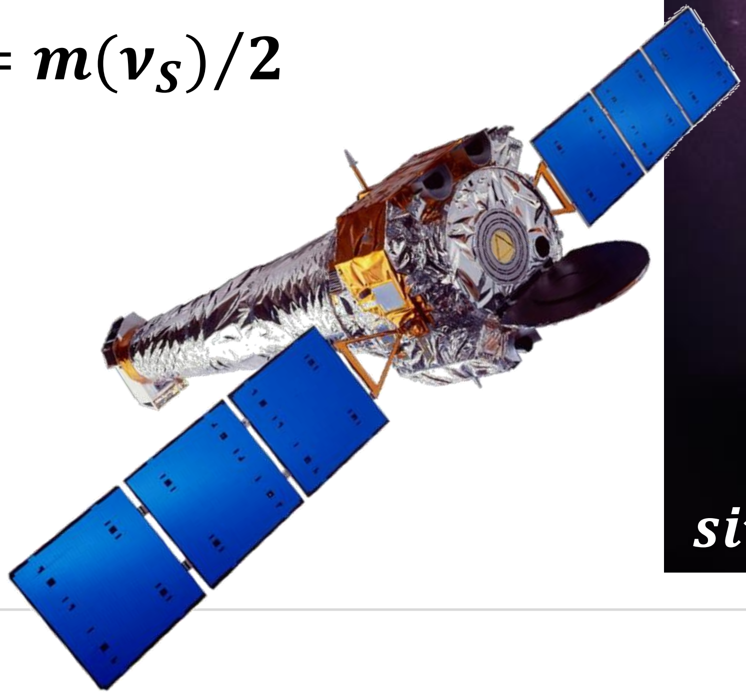
- is this the signature of a **decaying sterile neutrino ν_s**?

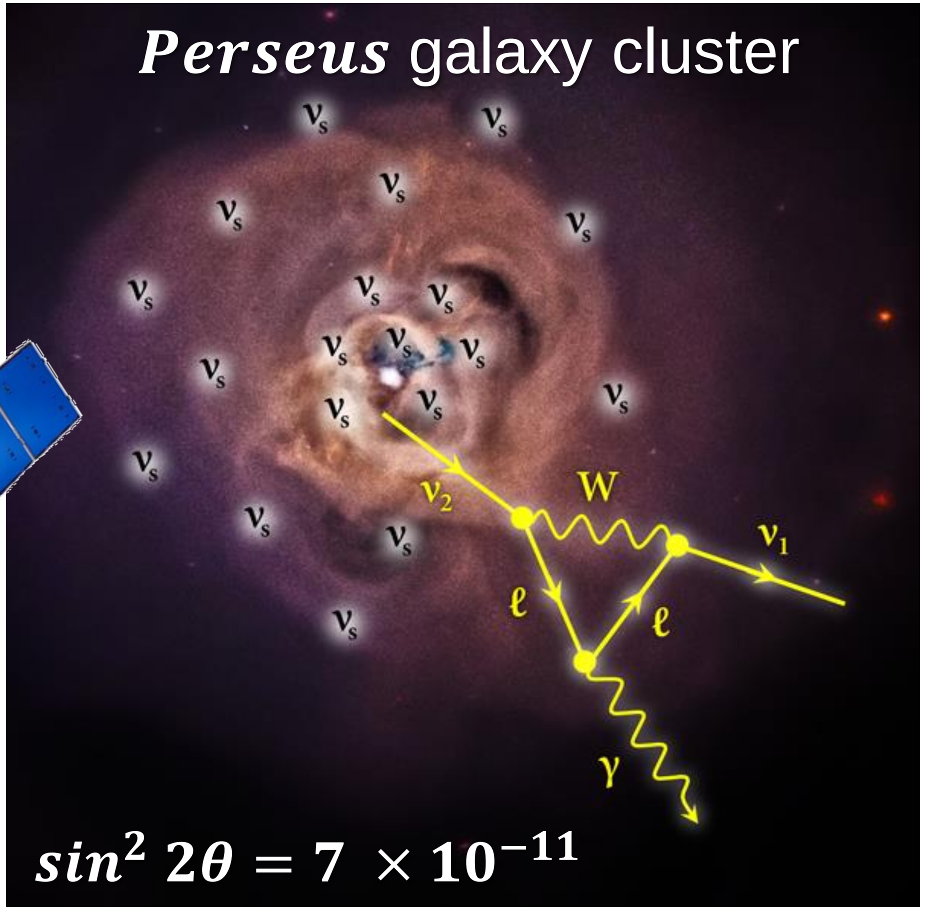
⇨ mass: $m(\nu_S) = 7.1\ keV$

decay: X – ray line at $E_\gamma = m(\nu_S)/2$

$$E_\gamma = 3.55\ keV$$

- sterile neutrino would act as ´*Warm Dark Matter*´





keV – steriles: a signal observed in X – rays?

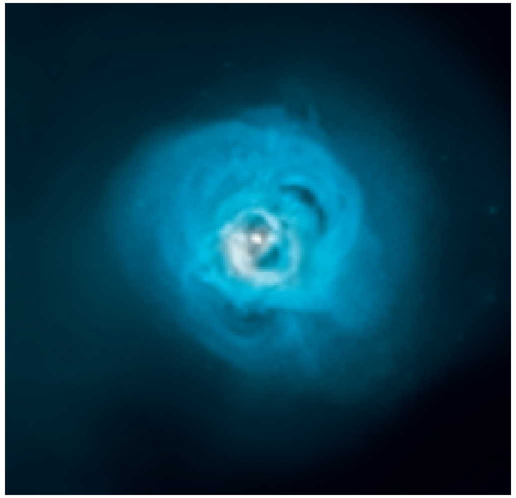
- Observation of a **weak X – ray line** in clusters at $E = 3.55\ keV$

CERN COURIER

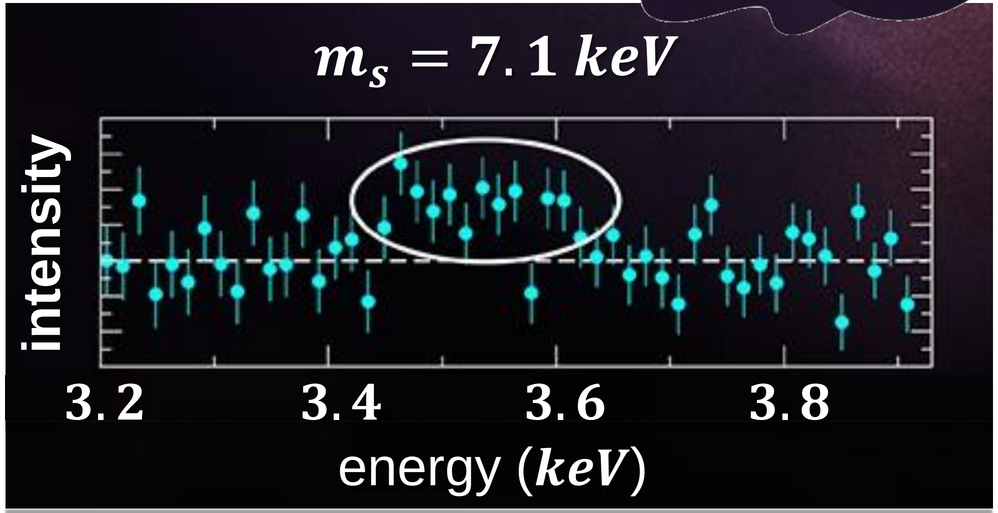
Jul 23, 2014

Do X-rays reveal a sterile neutrino?

A detailed study of galaxy clusters using NASA's Chandra X-ray Observatory and ESA's XMM-Newton has found a mysterious X-ray signal. One intriguing possibility is that the X-rays are produced by the decay of sterile neutrinos - a candidate particle for dark matter -



Perseus galaxy cluster



keV – steriles: signature in $KATRIN$

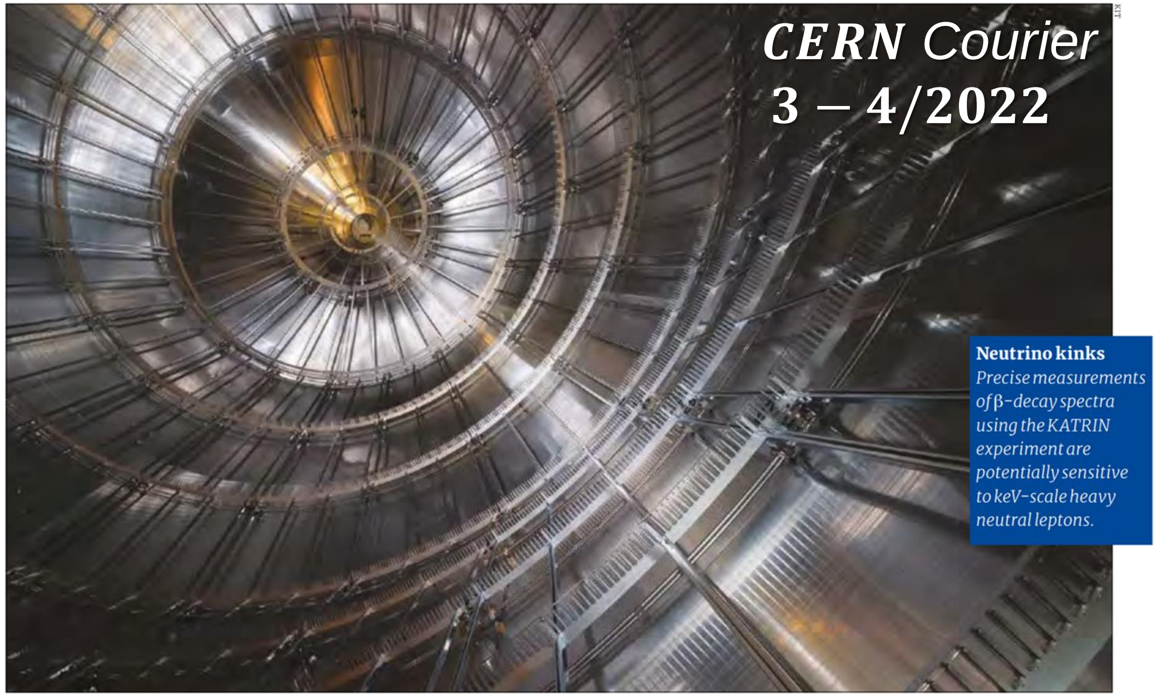
- **Search for a ´kink´ in the β – spectrum**

- tritium $\boldsymbol{\beta}$ – spectrum allows to investigate sterile neutrinos with masses

$$m(\nu_s) < 18.6\ keV$$

- $\boldsymbol{KATRIN}$ is ideally suited to perform a **world–leading** search for sterile $\boldsymbol{\nu}$´$\boldsymbol{s}$ in the $\boldsymbol{keV}$ – range from $\mathbf{2026 \ldots 2028}$

- $\boldsymbol{KATRIN}$: this measurement phase is performed within the $\boldsymbol{TRISTAN}$ program with **optimized tritium** source & novel **high–resolution detector** system

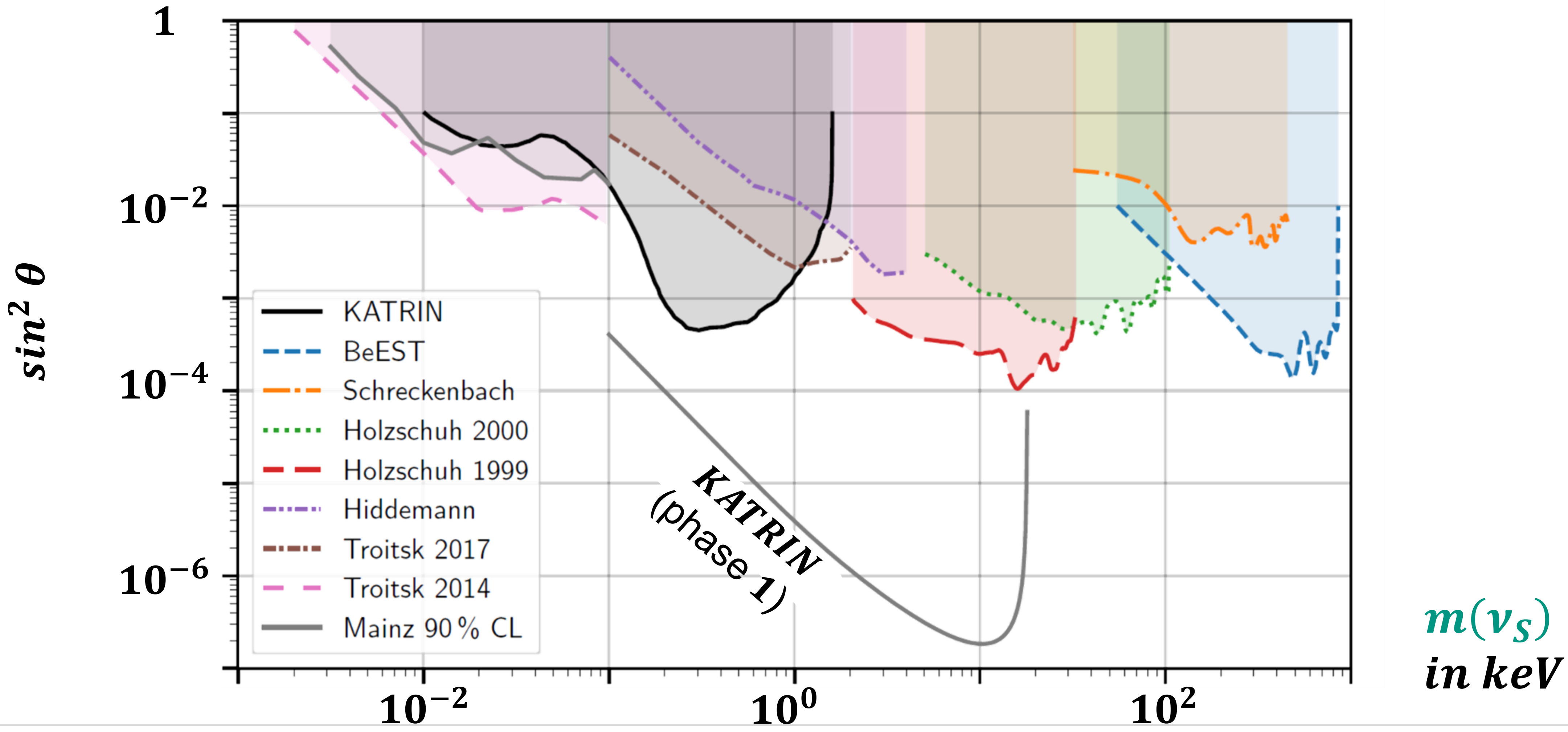


TURNING THE SCREW ON RIGHT-HANDED NEUTRINOS

Extending the elementary-particle inventory with heavy neutral leptons could solve the key observational shortcomings of the Standard Model, explain Alexey Boyarsky and Mikhail Shaposhnikov, with some models placing the new particles in reach of current and proposed experiments.

$keV-$ steriles: stat. sensitivity of $KATRIN$ & others

- $KATRIN$ will advance today´s experimental sensitivity by many orders

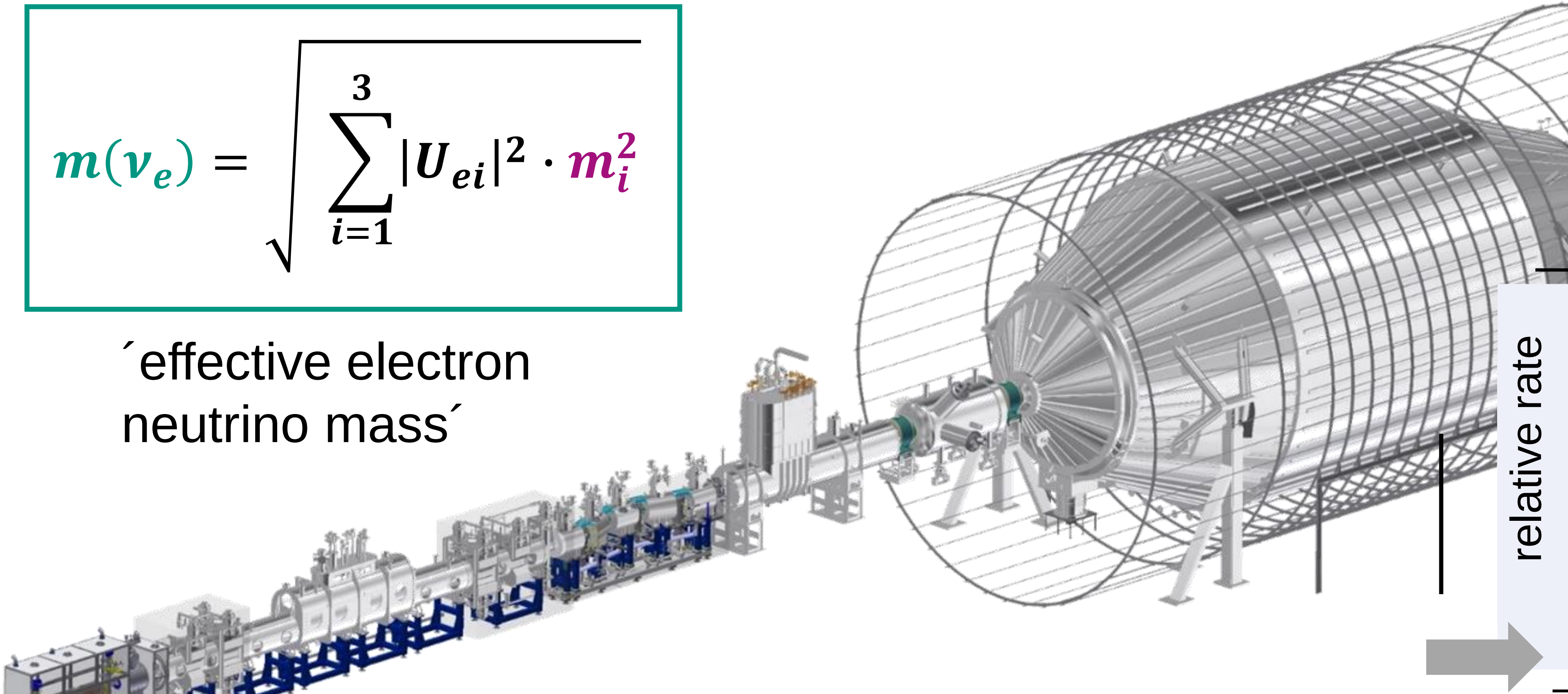


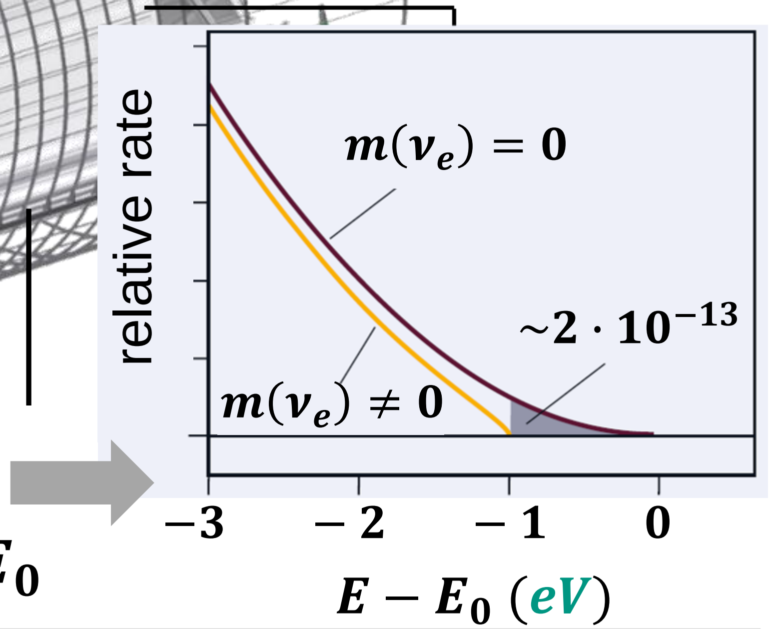
Recap: $KATRIN$ neutrino mass experiment*

- ´effective mass´ of the electron neutrino ν_e: incoherent sum of masses m_i

$$m(\nu_e) = \sqrt{\sum_{i=1}^{3} |U_{ei}|^2 \cdot m_i^2}$$

´effective electron neutrino mass´



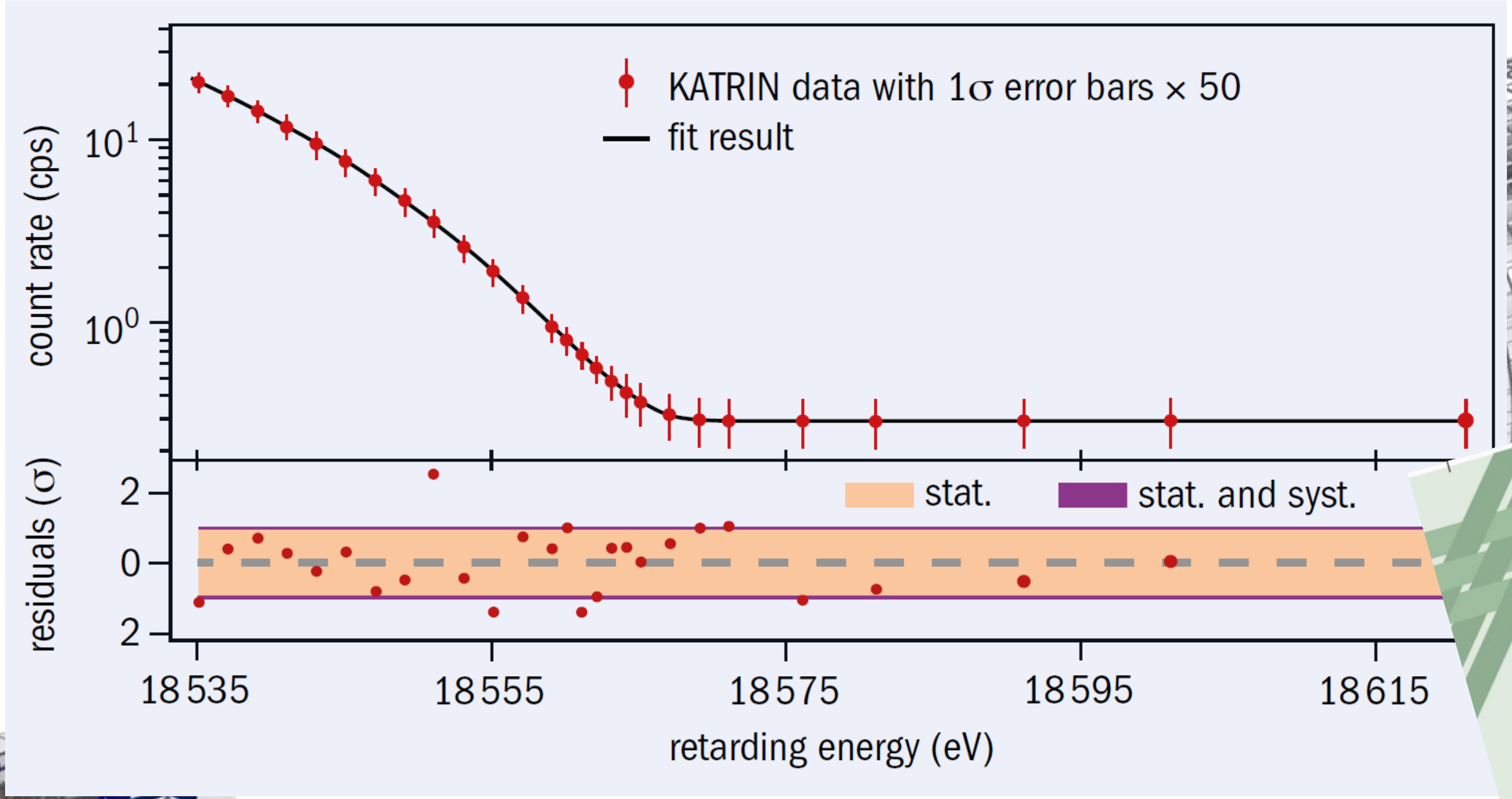


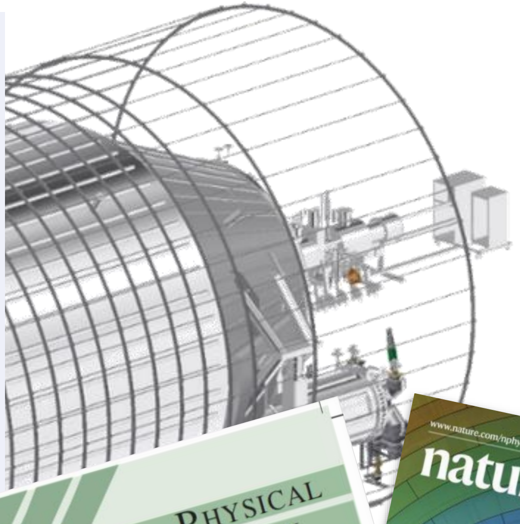
signature of ν – mass $m(\nu_e)$ close to E_0

*see Lect. #11

$KATRIN$ neutrino mass experiment

- ´effective mass´ of the electron neutrino ν_e: integral scan

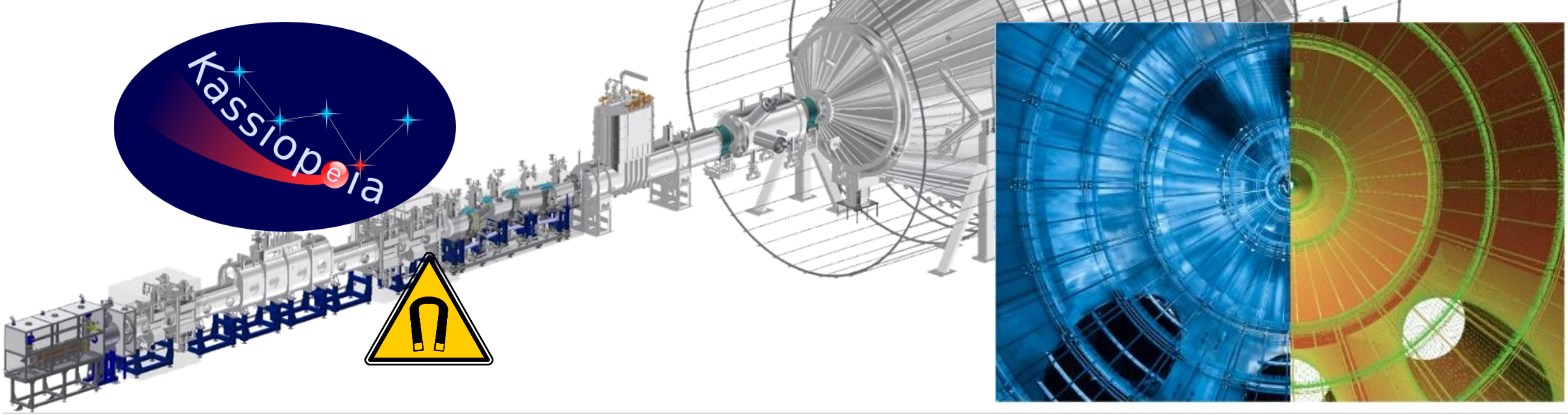




KATRIN neutrino mass experiment

■ ´effective mass´ of the electron neutrino ν_e: one tool to study systematics

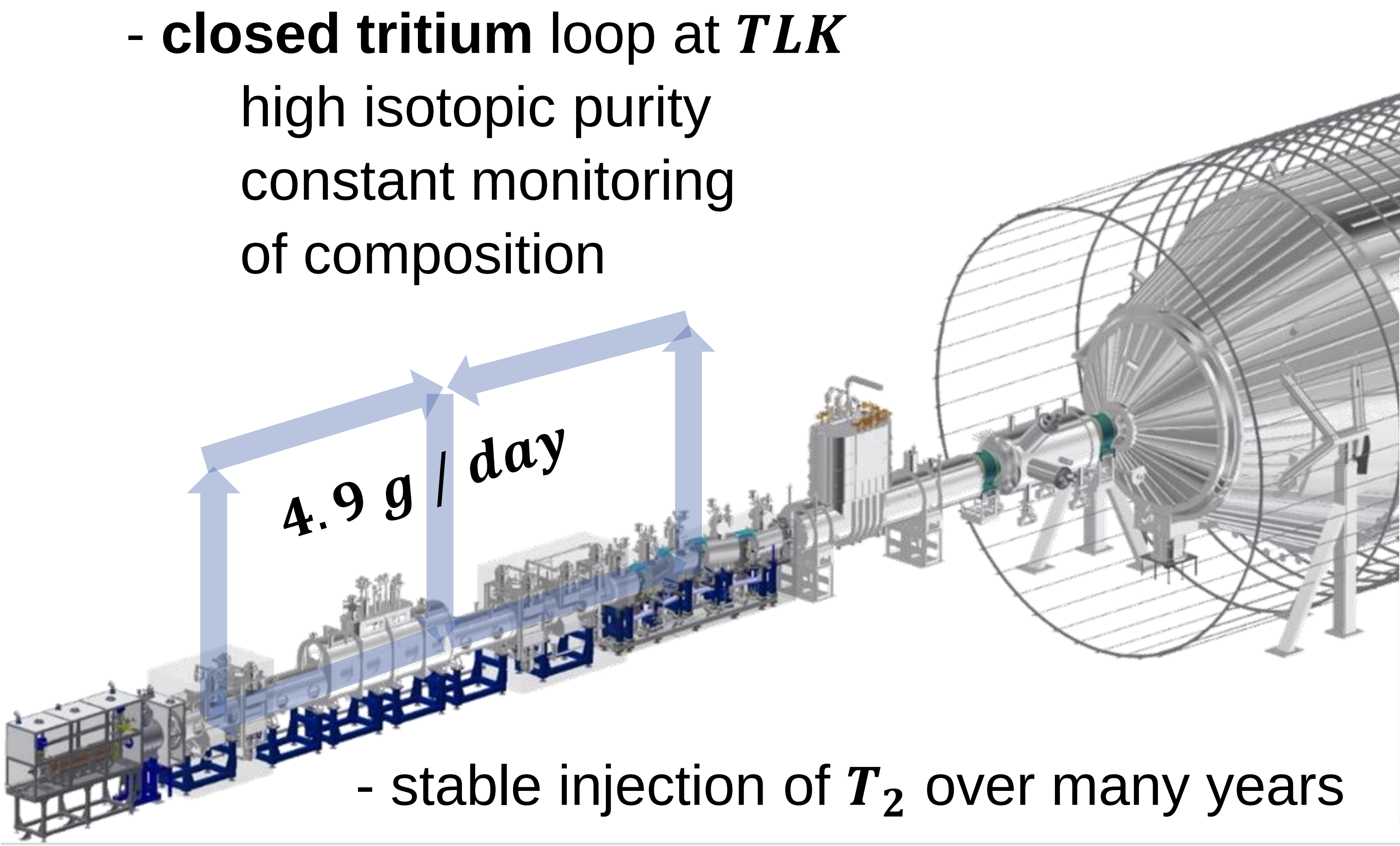
- precise **tracking of electrons** in electromagnetic fields: backscattering, source scattering, post acceleration
…



$KATRIN$ experiment: adjusting the β – luminosity

- Windowless Gaseous Tritium Source ($WGTS$): a highly versatile tool

  - **closed tritium** loop at TLK
    high isotopic purity
    constant monitoring
    of composition



  - stable injection of T_2 over many years

$KATRIN$ experiment: adjusting the β – luminosity

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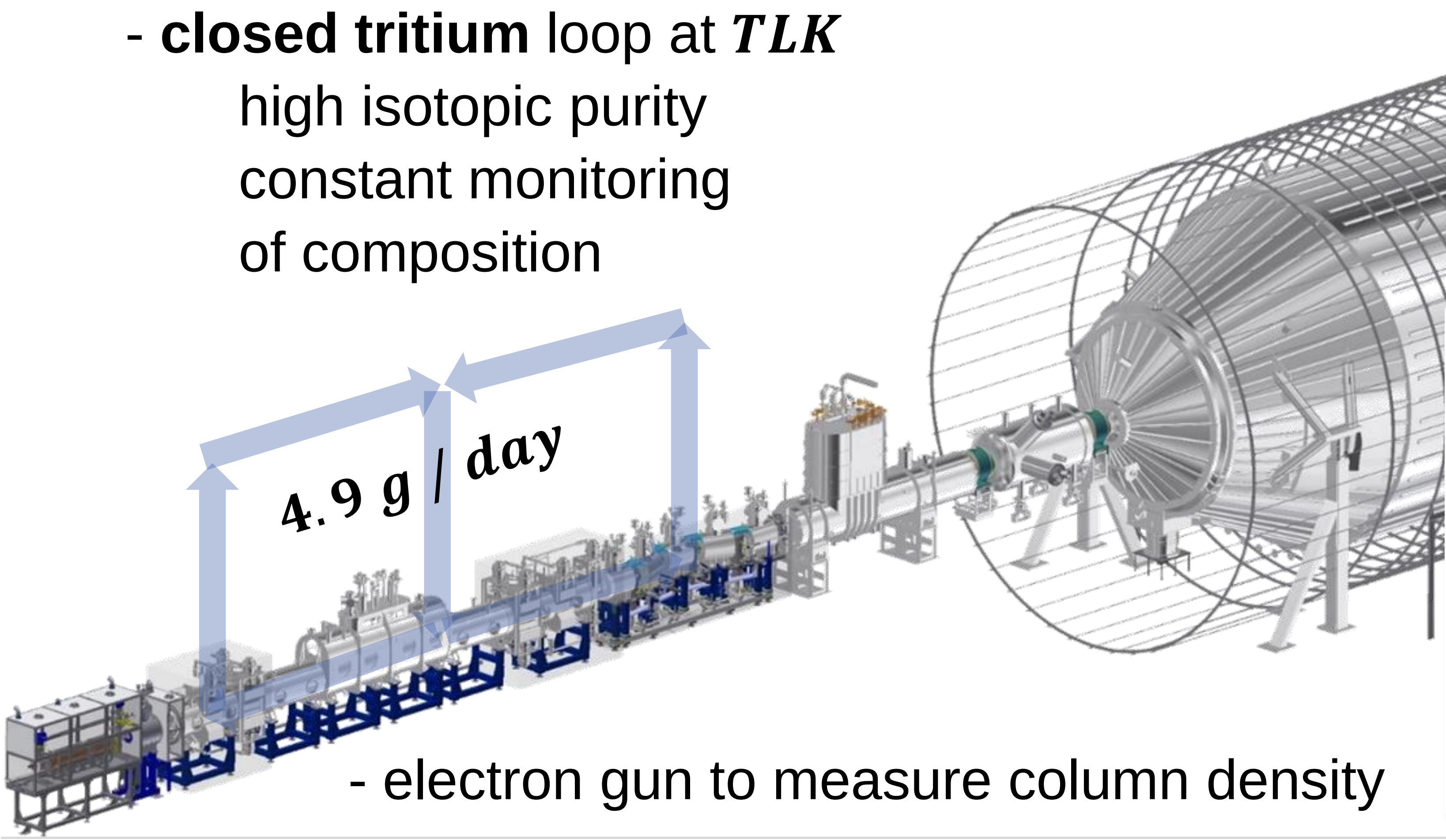
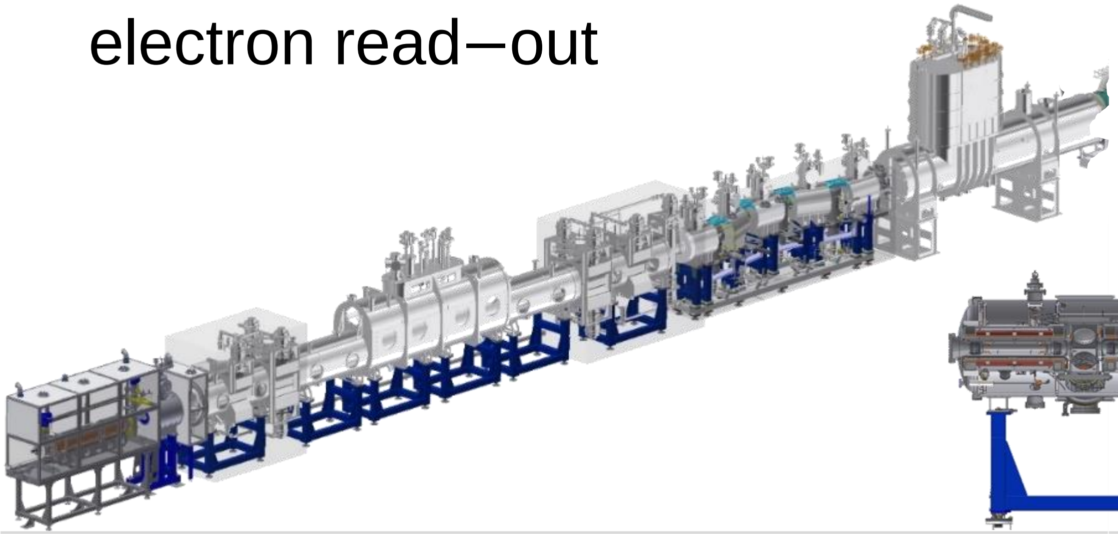


  - electron gun to measure column density

$KATRIN$ experiment: adjusting the β –luminosity

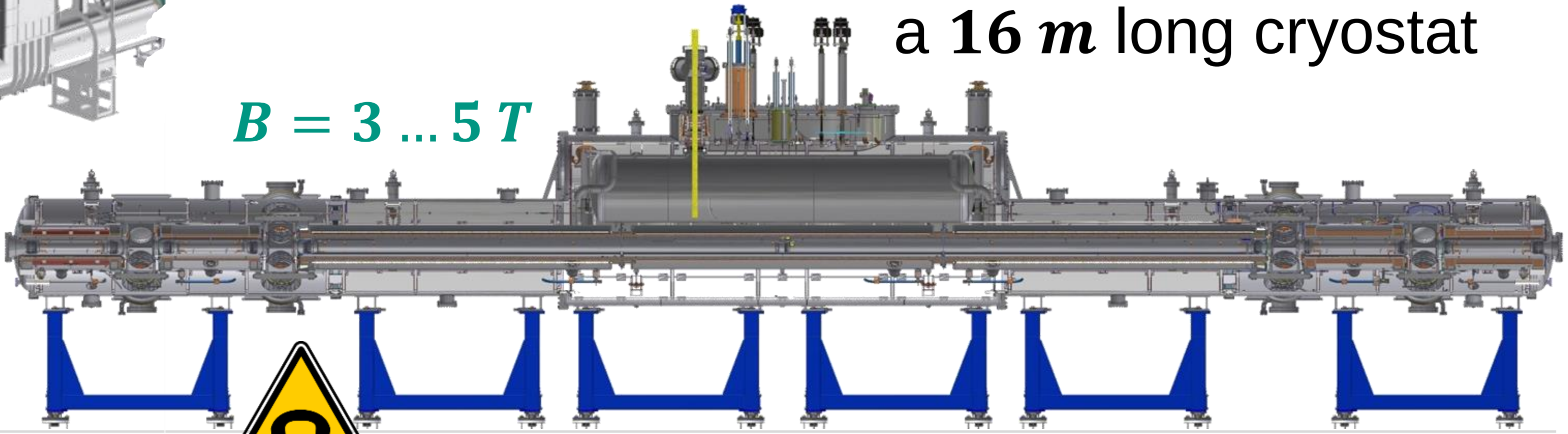
Windowless Gaseous Tritium Source ($WGTS$): a highly versatile tool

- tritium $\boldsymbol{\beta}$ – intensity can be varied by $\mathbf{2 \ldots 3}$ orders of magnitude by adjusting the **inlet pressure p_{in}**
- this allows to work at **vastly different count rates**: adjust to capabilities of electron read–out



a $\mathbf{16}\ \boldsymbol{m}$ long cryostat

$\boldsymbol{B = 3 \ldots 5\ T}$



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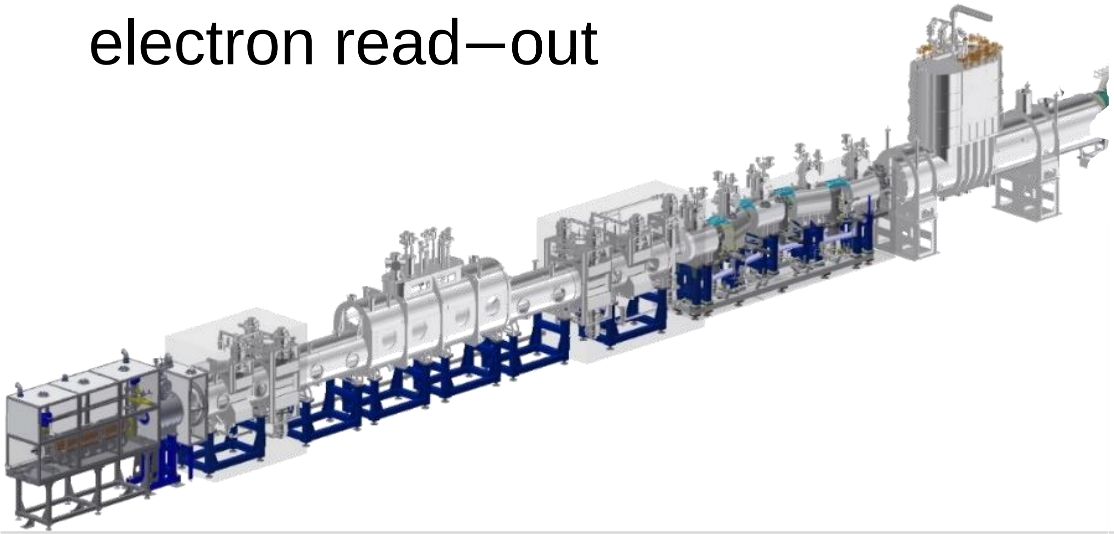
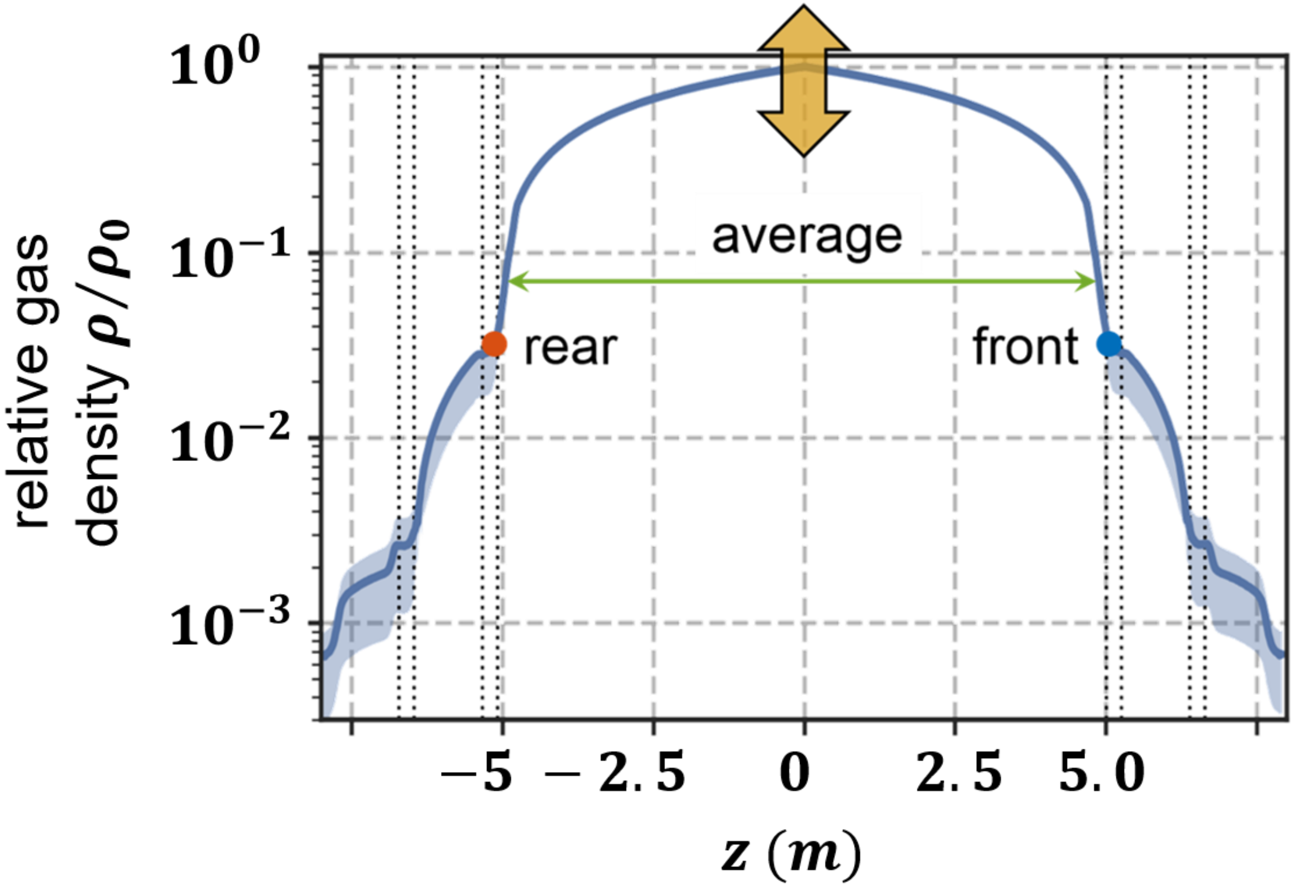
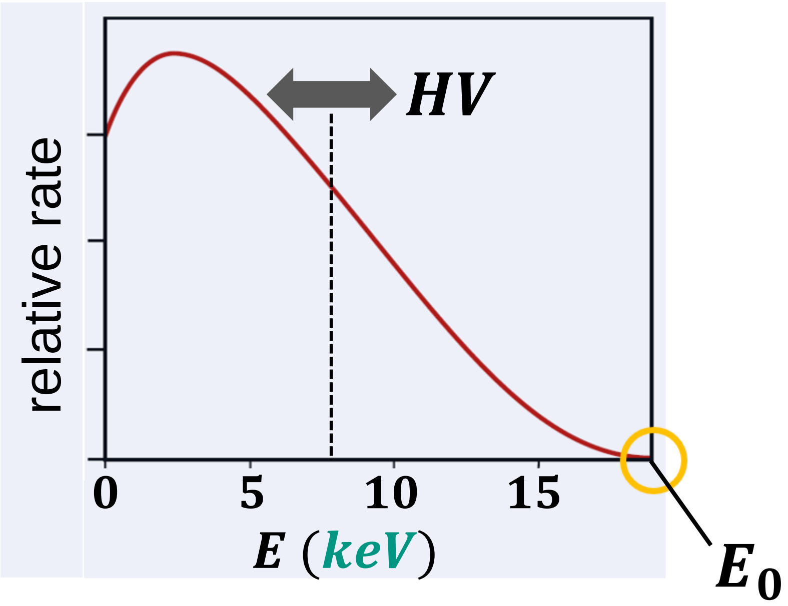


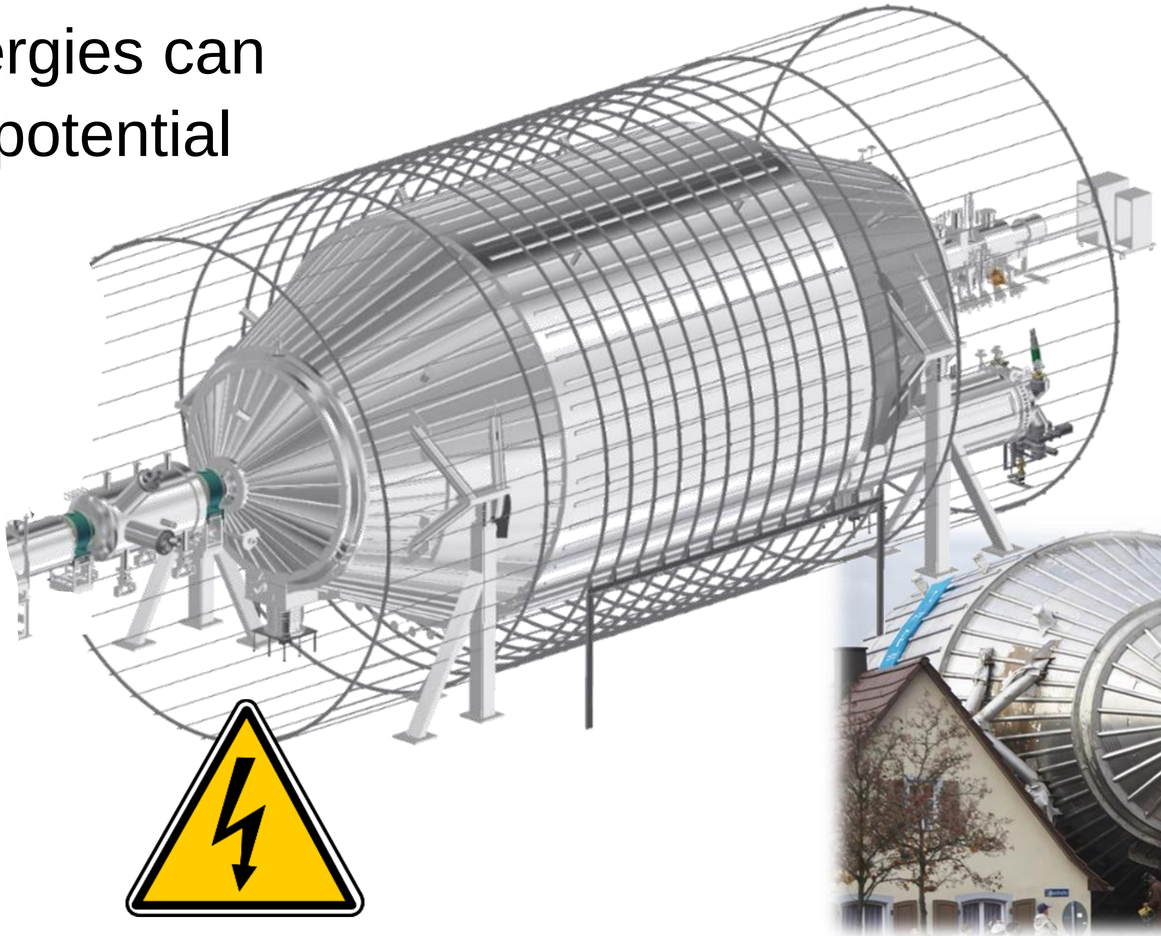


$KATRIN$ experiment: adjusting the lower cut–off

- **the electrostatic spectrometer: a highly versatile tool**

- the lower **cut–off** of electron energies can be adjusted by the spectrometer potential

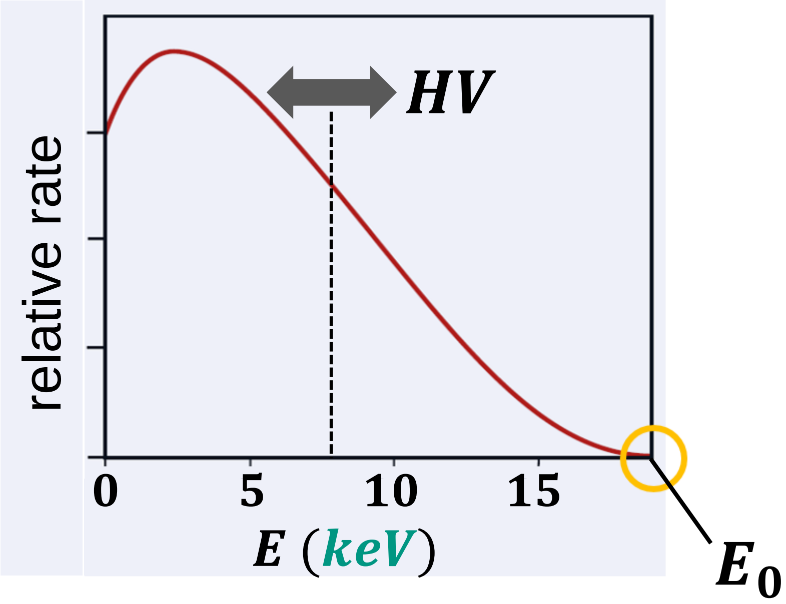




$KATRIN$ experiment: adjusting the lower cut−off

- **the electrostatic spectrometer: inner electrode system**

- $\mathbf{24.000}$ wires are mounted with a precision of $\mathbf{200}\ \boldsymbol{\mu m}$: **fine−tuning**



keV – steriles: signature in $KATRIN$

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- Search for a ´kink´ in the β – spectrum

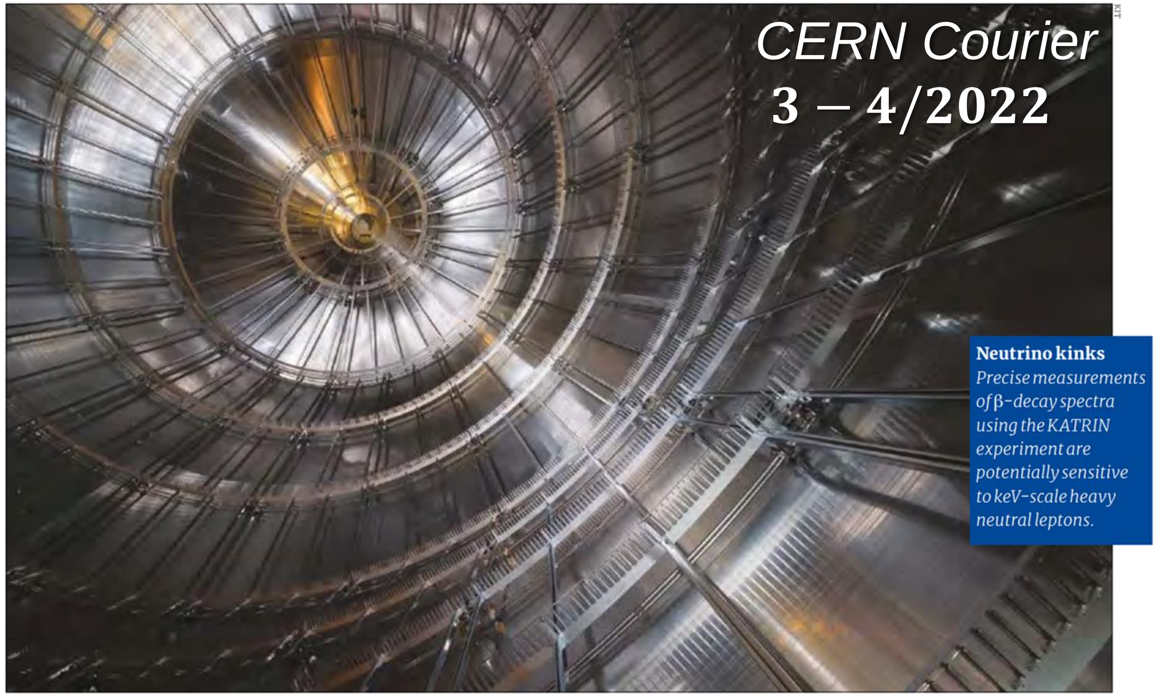
- tritium β – spectrum allows to investigate sterile neutrinos with masses

$$m(\nu_s) < 18.6\ keV$$

- energy spectrum of decay electrons:

$$\frac{dN}{dE} = \cos^2\theta_S \cdot \frac{dN}{dE}(m_{active}) + \sin^2\theta_S \cdot \frac{dN}{dE}(m_{sterile})$$

mixing angle θ_S



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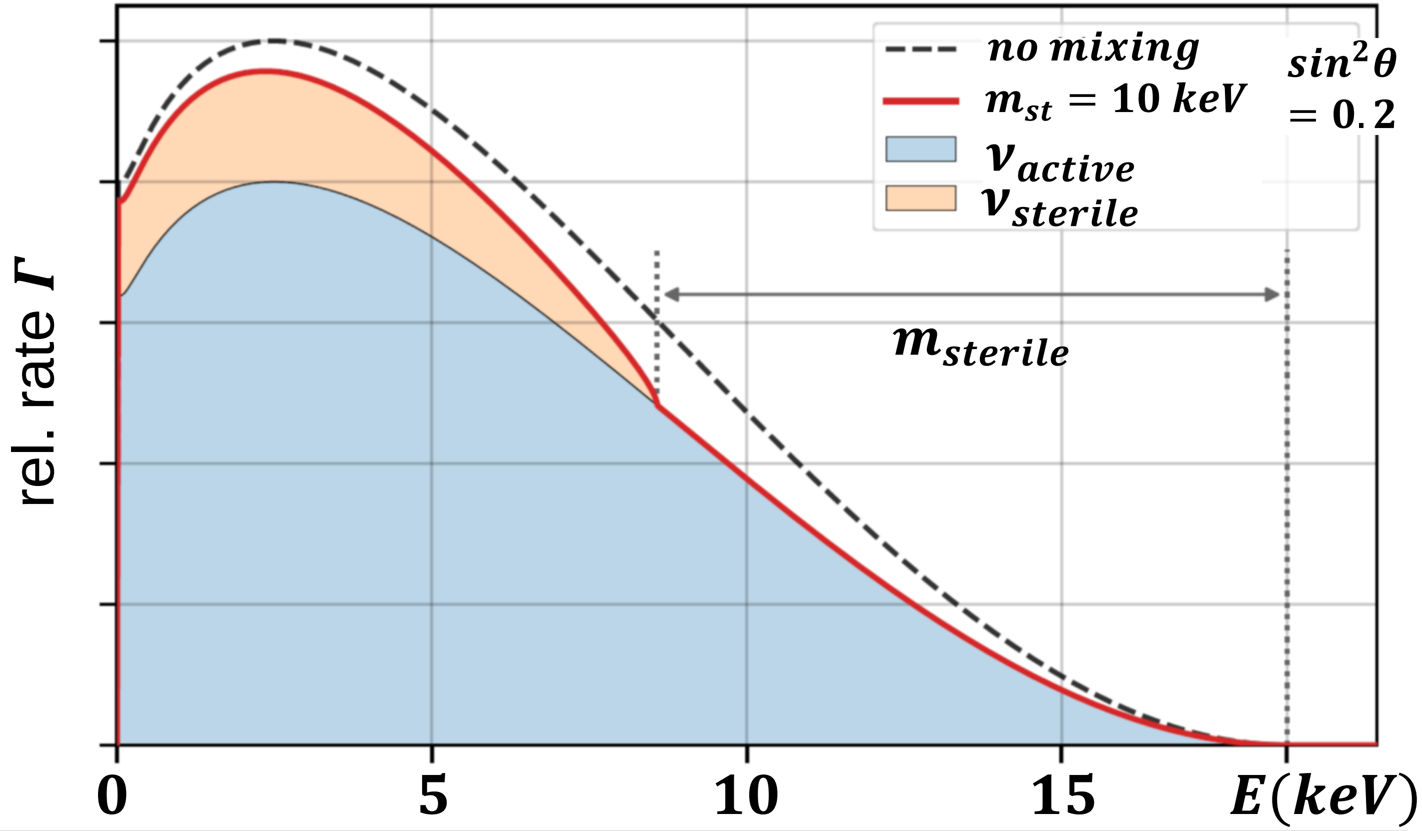
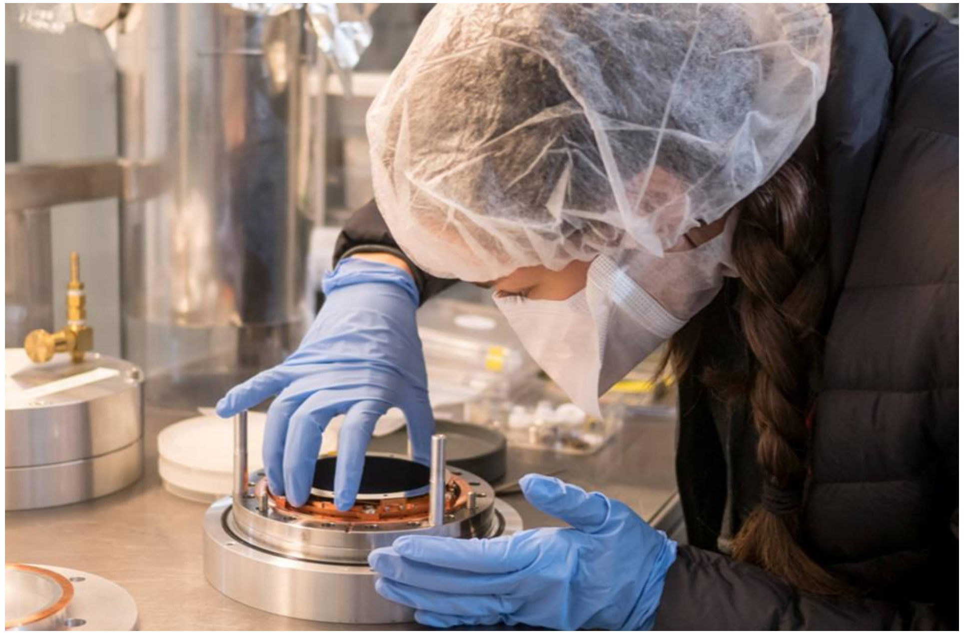
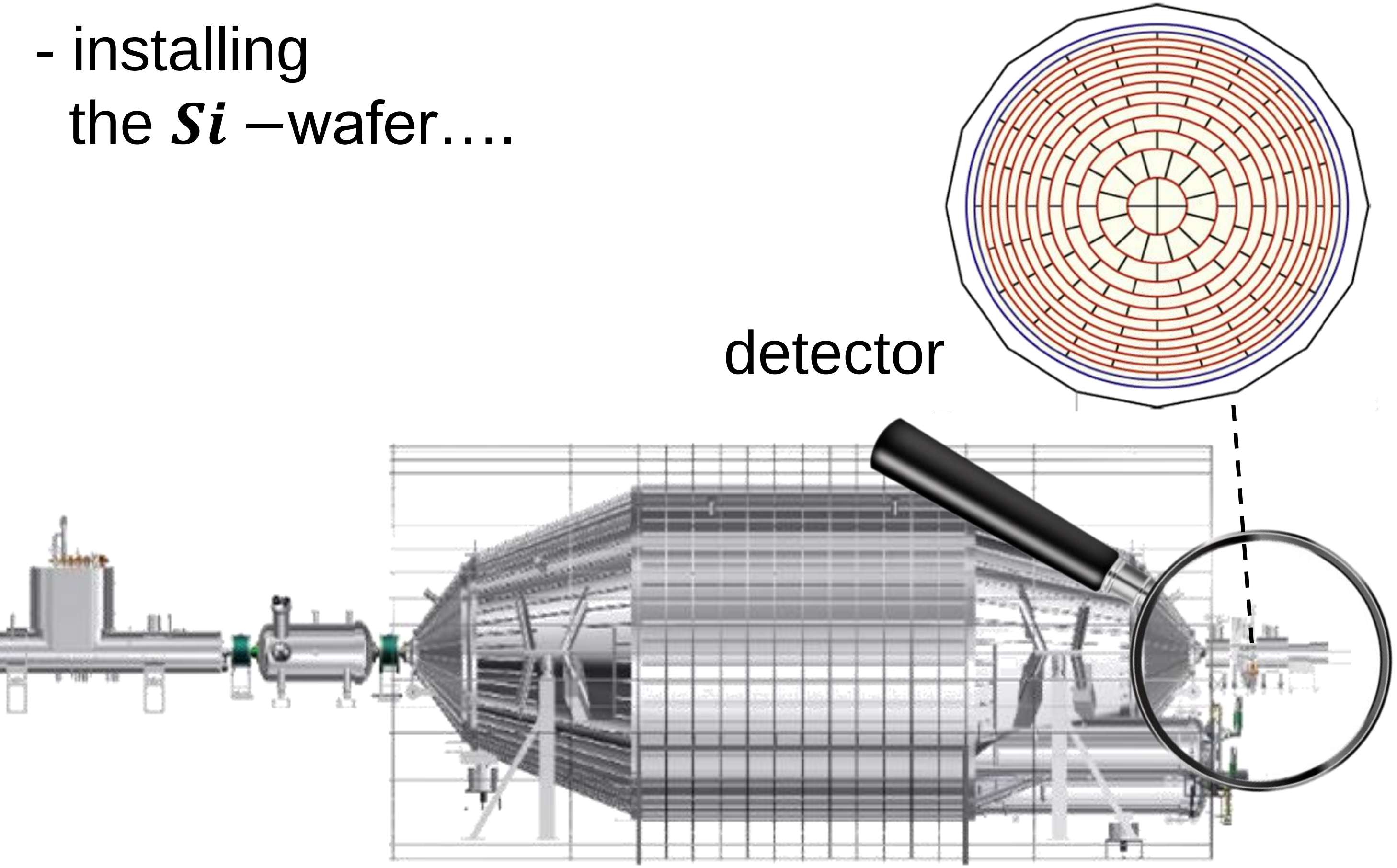


eV – mass scale: existing detector for $KATRIN$

- FPD **detector:** a segmented $Si - PIN$ – detector for electron identification



- installing
  the Si –wafer….



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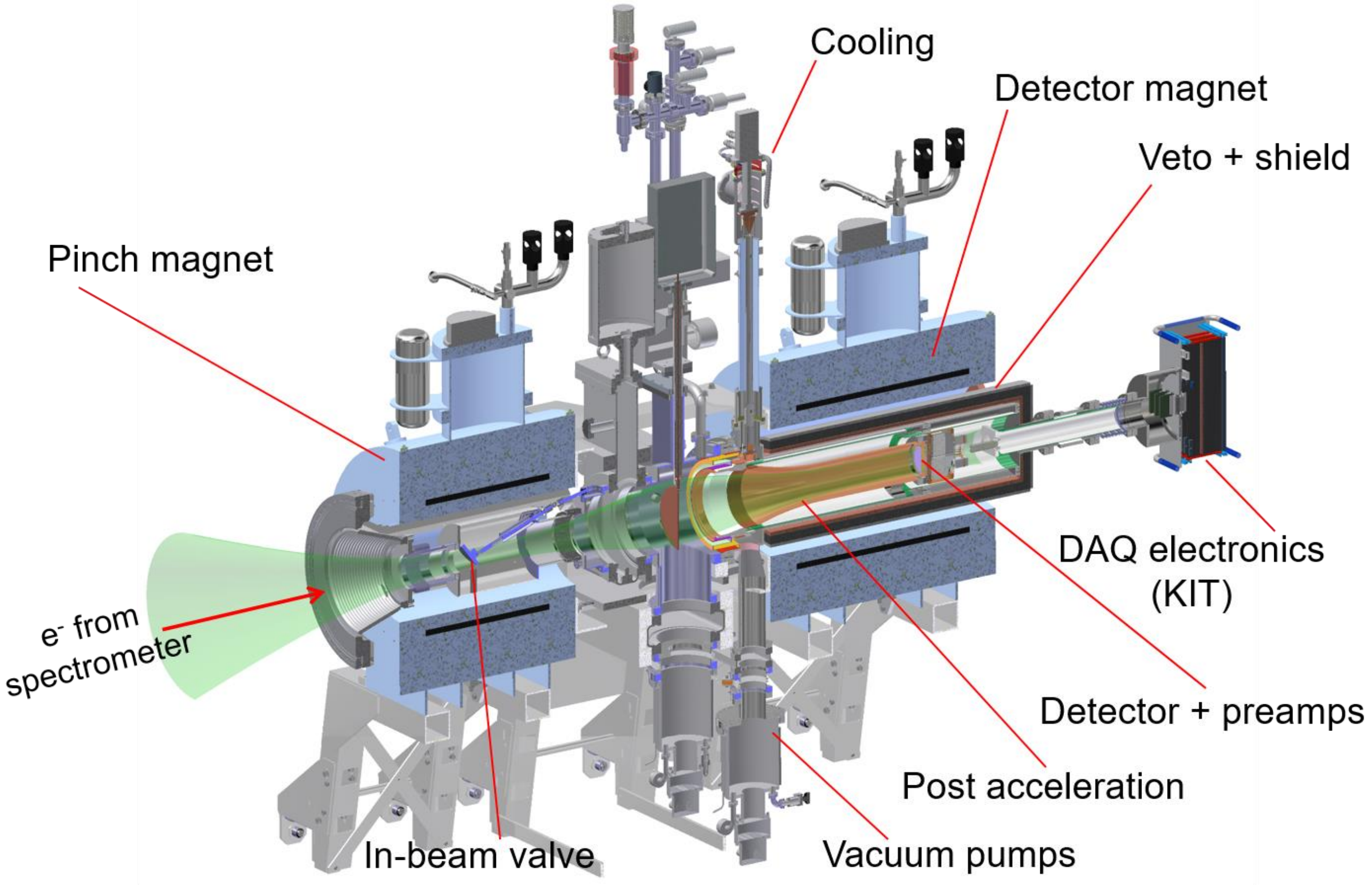

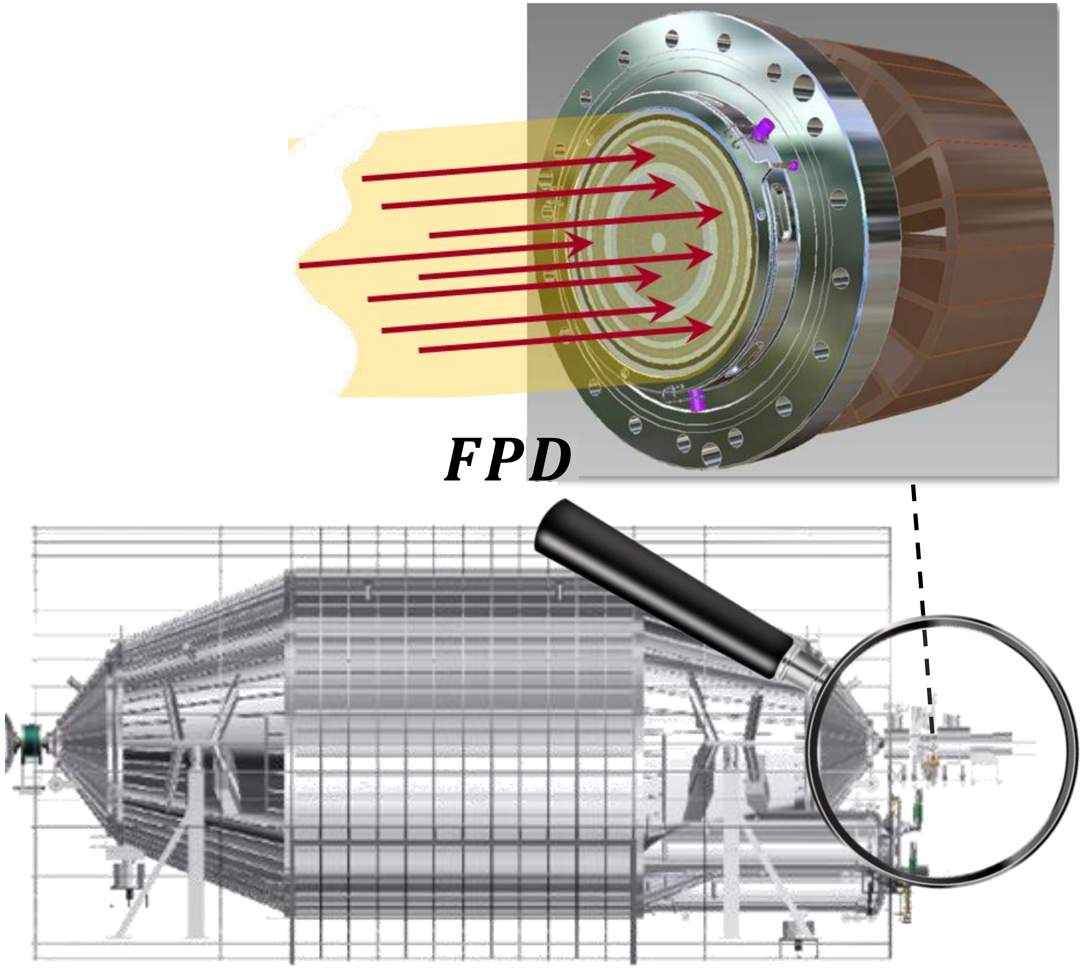

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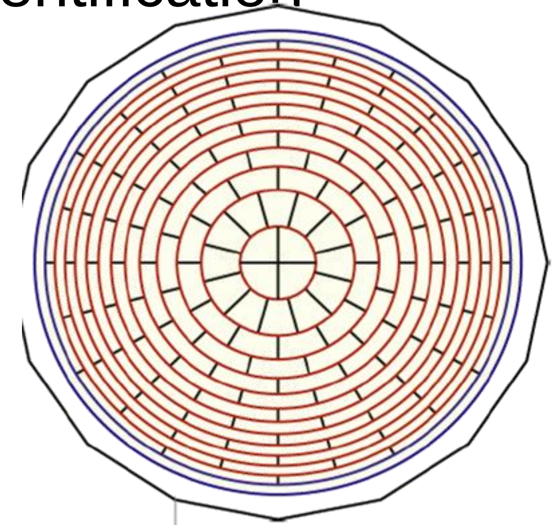
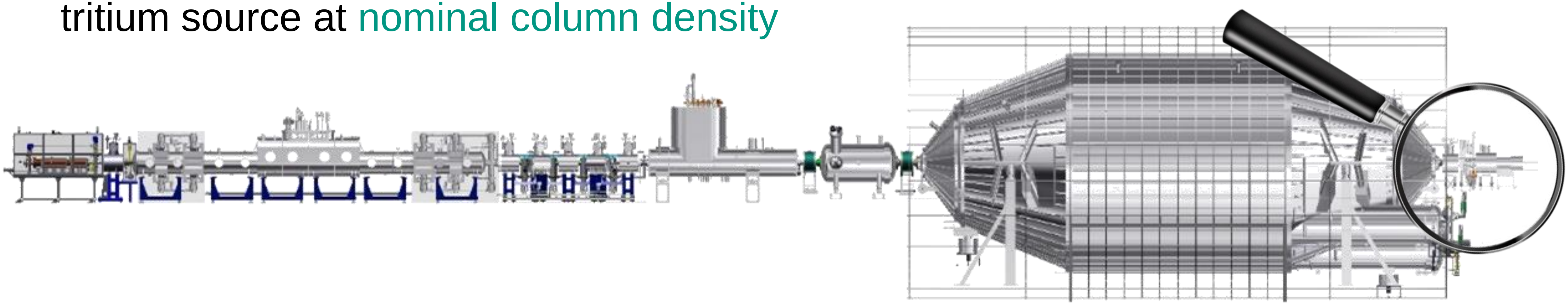


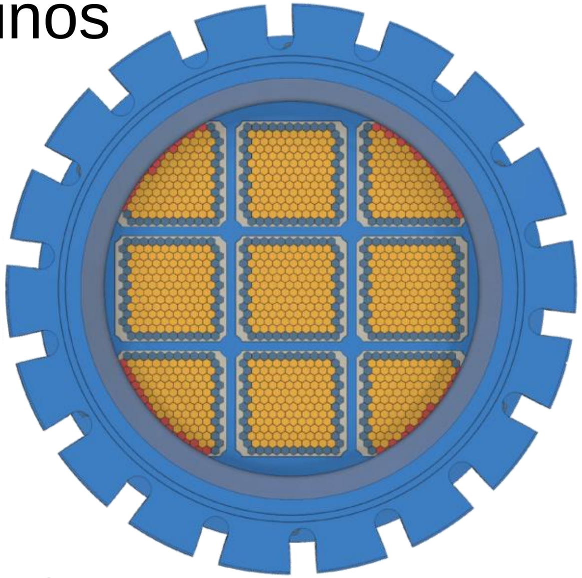
- moderate energy resolution: ability to detect the transmitted electron with $\boldsymbol{\Delta E \approx 2 \ldots 3\ keV}$ within a rather narrow energy window centered at $\boldsymbol{E = 18.6\ keV}$

- needs to handle only a small rate of $\boldsymbol{\beta}$ – decay electrons (narrow scan interval close to $\boldsymbol{E_0}$): optimimized for $\boldsymbol{m(\nu_e)}$ with tritium source at nominal column density



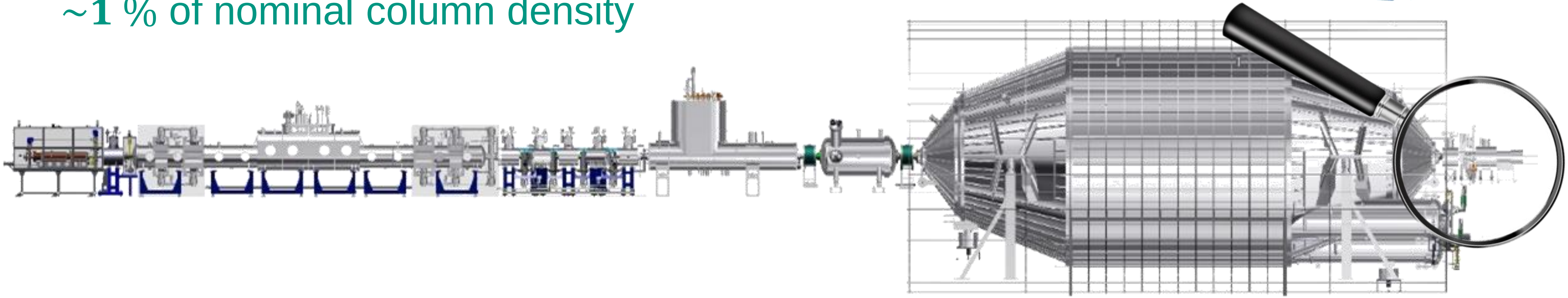
$keV-$ steriles: a new detector for $KATRIN$

- $\boldsymbol{TRISTAN}$ **detector:** $\boldsymbol{TR}$itium $\boldsymbol{I}$nvestigation on $\boldsymbol{ST}$erile ($\boldsymbol{A}$) $\boldsymbol{N}$eutrinos



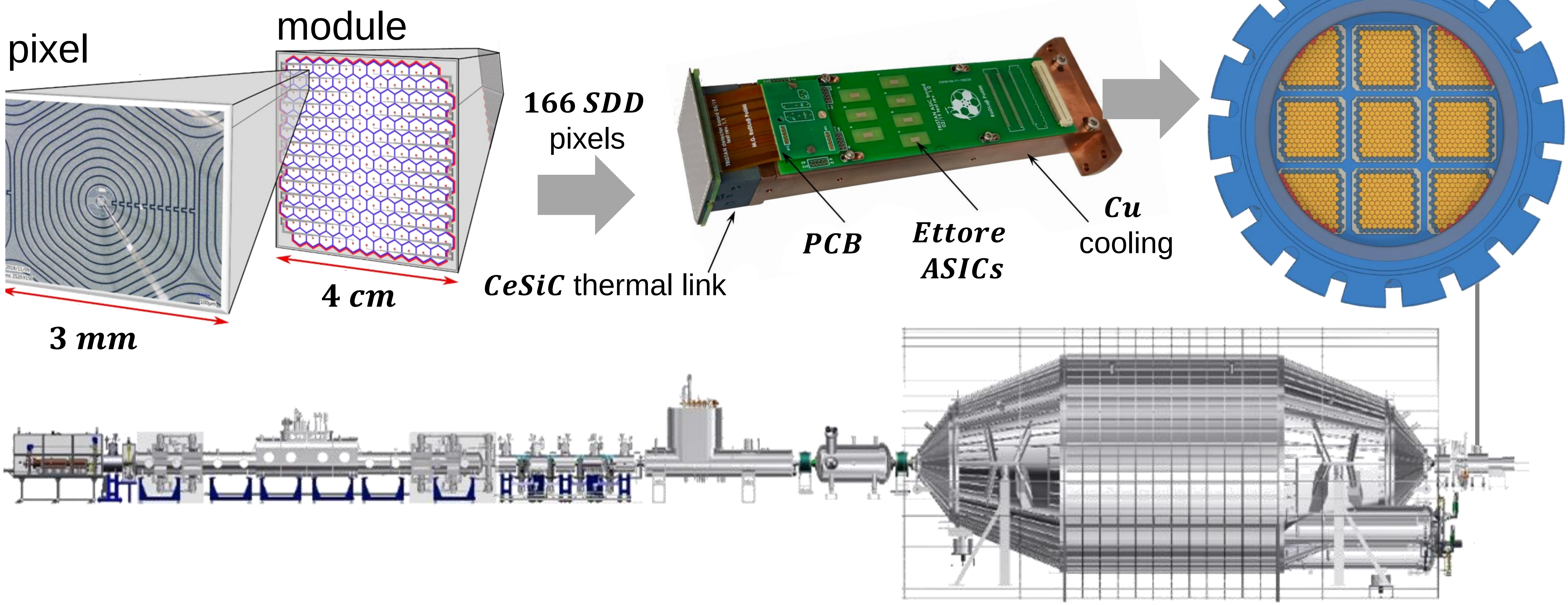
- excellent energy resolution: ability to detect the expected **kink–like signature** i.e. $\boldsymbol{\Delta E \approx 200 \ldots 300\ eV}$ over entire energy interval from $\boldsymbol{E = 0 \ldots 18.6\ keV}$

- must be able to handle **huge** rate of $\boldsymbol{\beta}$ – decay electrons even when operating the tritium source at $\sim$**1** % of nominal column density



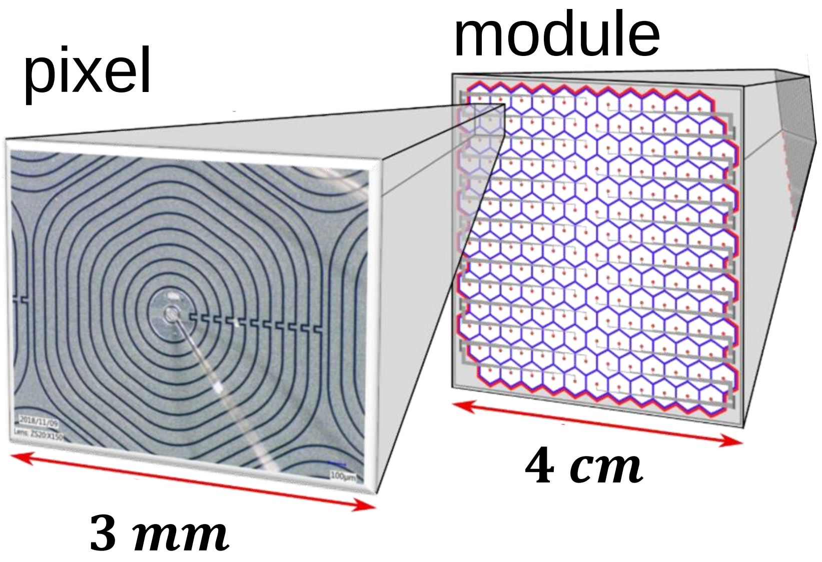
keV – steriles: a new SDD detector for $KATRIN$

- $\boldsymbol{S}$ilicon $\boldsymbol{D}$rift $\boldsymbol{D}$etectors ($\boldsymbol{SDD}$): a novel detector technology

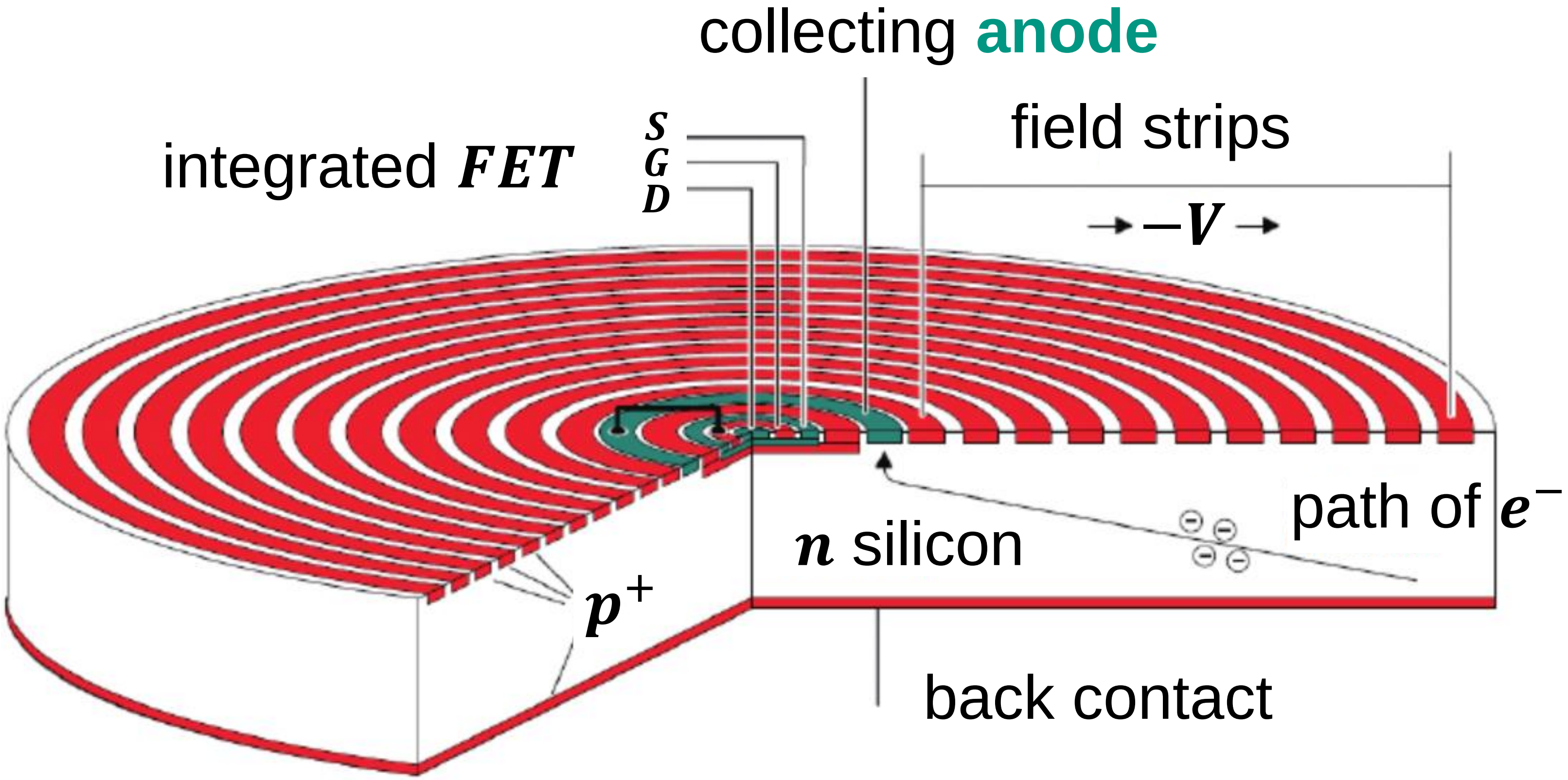


keV – steriles: a new SDD detector for $KATRIN$

- $\boldsymbol{S}$ilicon $\boldsymbol{D}$rift $\boldsymbol{D}$etectors (SDD): working principle

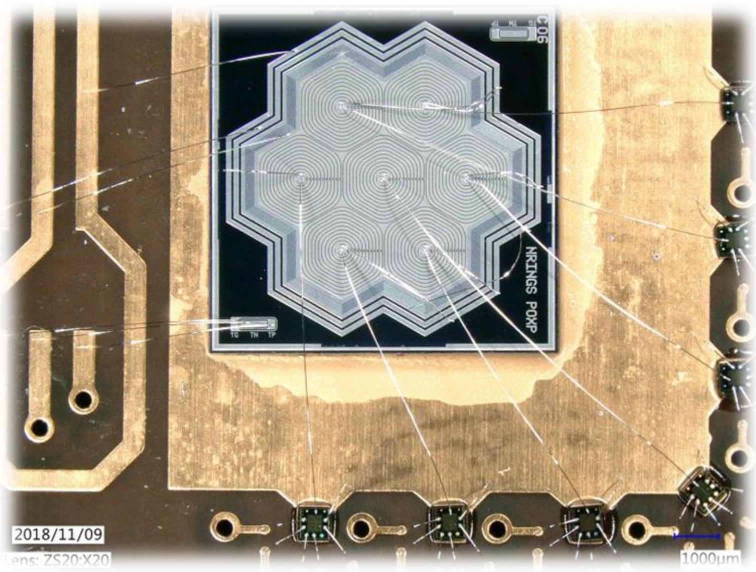


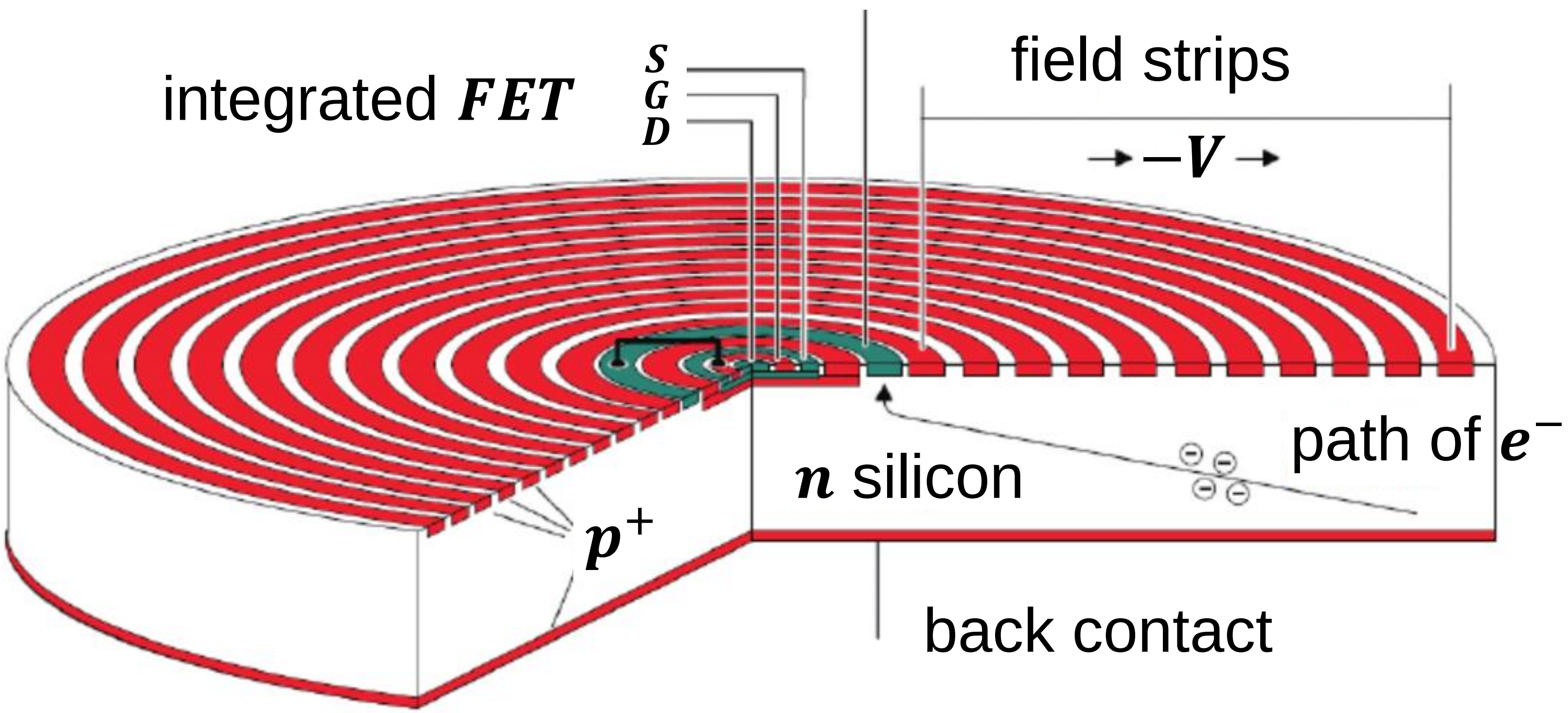
- SDD unit with integrated $jFET$: e^- are funneled to **anode** by drift field formed by circular field strips



$keV -$ steriles: a new SDD detector for $KATRIN$

- **Silicon Drift Detectors (SDD): early prototypes are being tested**





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$KATRIN$ experiment – ongoing studies

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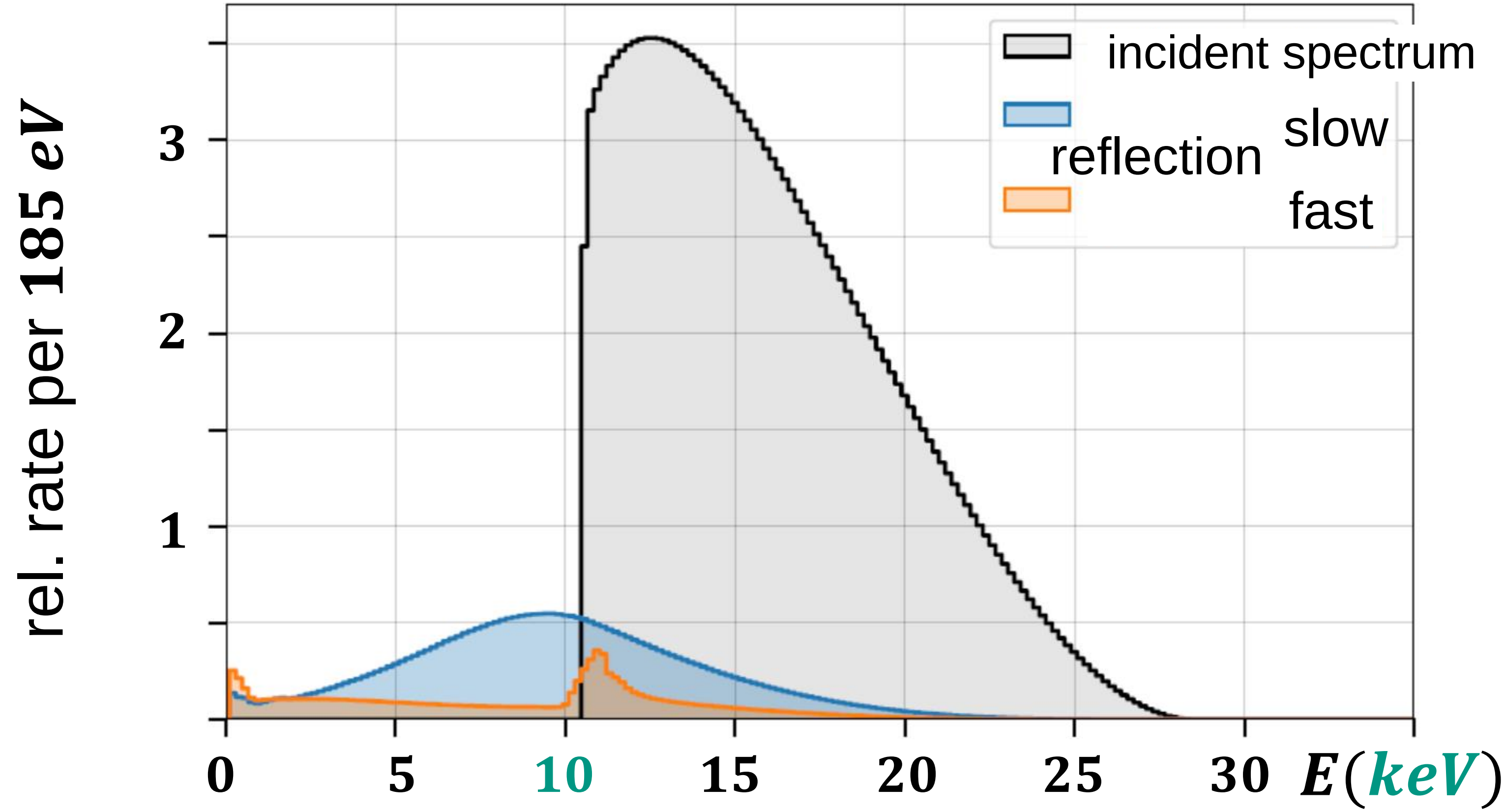
- **Search for sterile $\nu\acute{}s$: implement a Post−Acceleration Electrode (PAE)**

  - careful study of **systematic effects** due to post−acceleration & back−scattering

  - purpose of PAE: allows detection of low−energy electrons by constant (post) acceleration with $\Delta U = 10\ kV$ (planned)

  - systematic effects due to **backscattering** (at surface of SDD & ΔU)



$keV-$ steriles: stat. sensitivities (integral scan)

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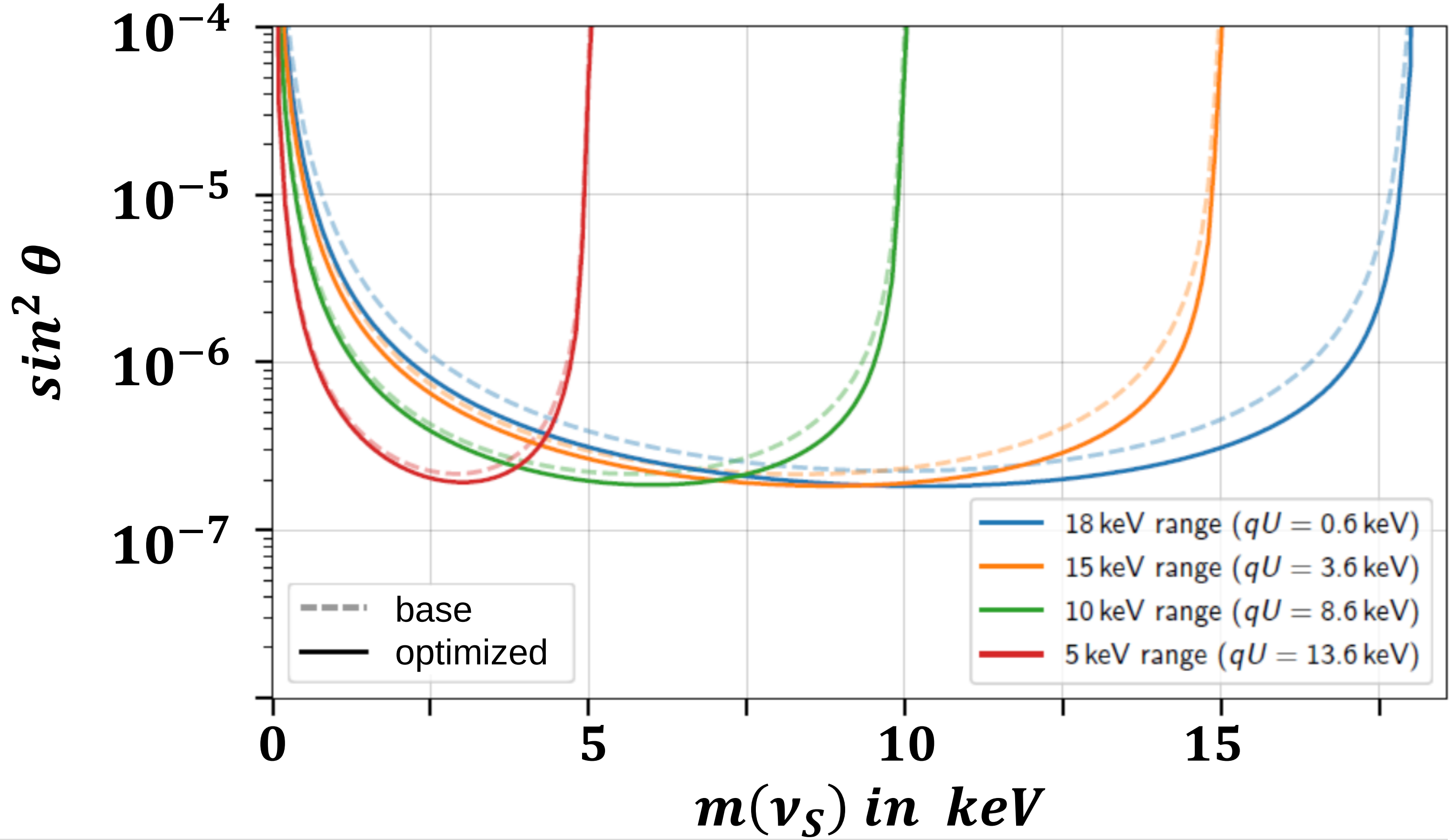
■ Impact of different scan strategies & other optimisation procedures

- $\mathbf{95\%}\ \boldsymbol{CL}$ exclusion limits for $\boldsymbol{keV}-$ steriles after $\mathbf{1}\ \boldsymbol{yr}$ of $\boldsymbol{KATRIN}$ data taking

- collected statistics: $\boldsymbol{N_{ev}} \approx \mathbf{2.95 \times 10^{15}}$

- impact of different scan strategies: here an **INDEPENDENT** cross check can be provided by an **integral scan** with excellent sensitivity



$keV -$ steriles: evolution of stat. sensitivities

Impact of collected data sample over time in differential mode ($m_s = 10\ keV$)

- evolution of statistical sensitivity ($95\%\ CL$) for fixed mass $m_s = 10\ keV$

- $10^5\ cps$ per pixel &
  936 ´golden´ pixels

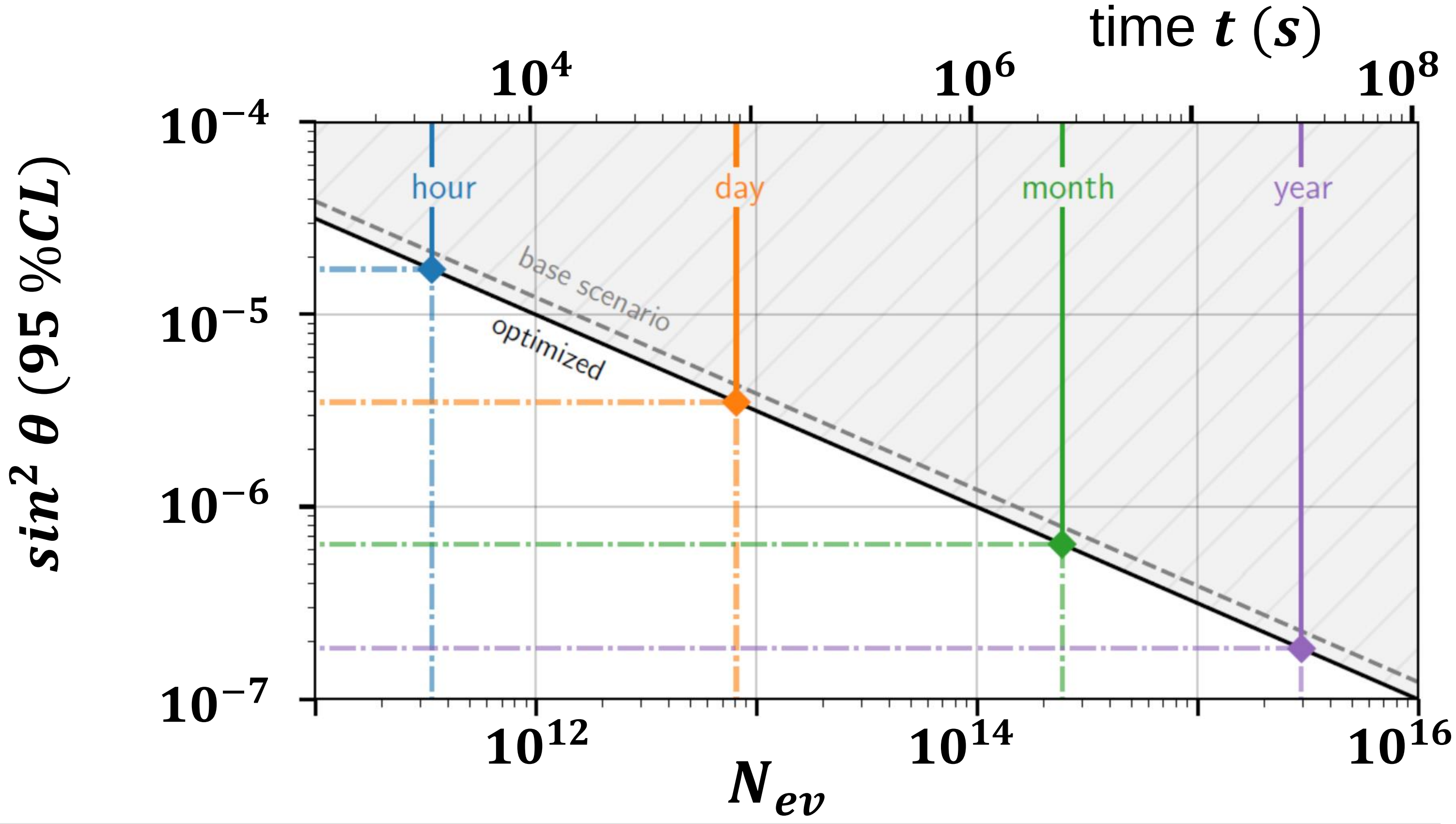
- sensitivities obtained after

  $1\ hr$

  $1\ day$

  $1\ month$

  $1\ yr$



keV – steriles: impact of systematic effects

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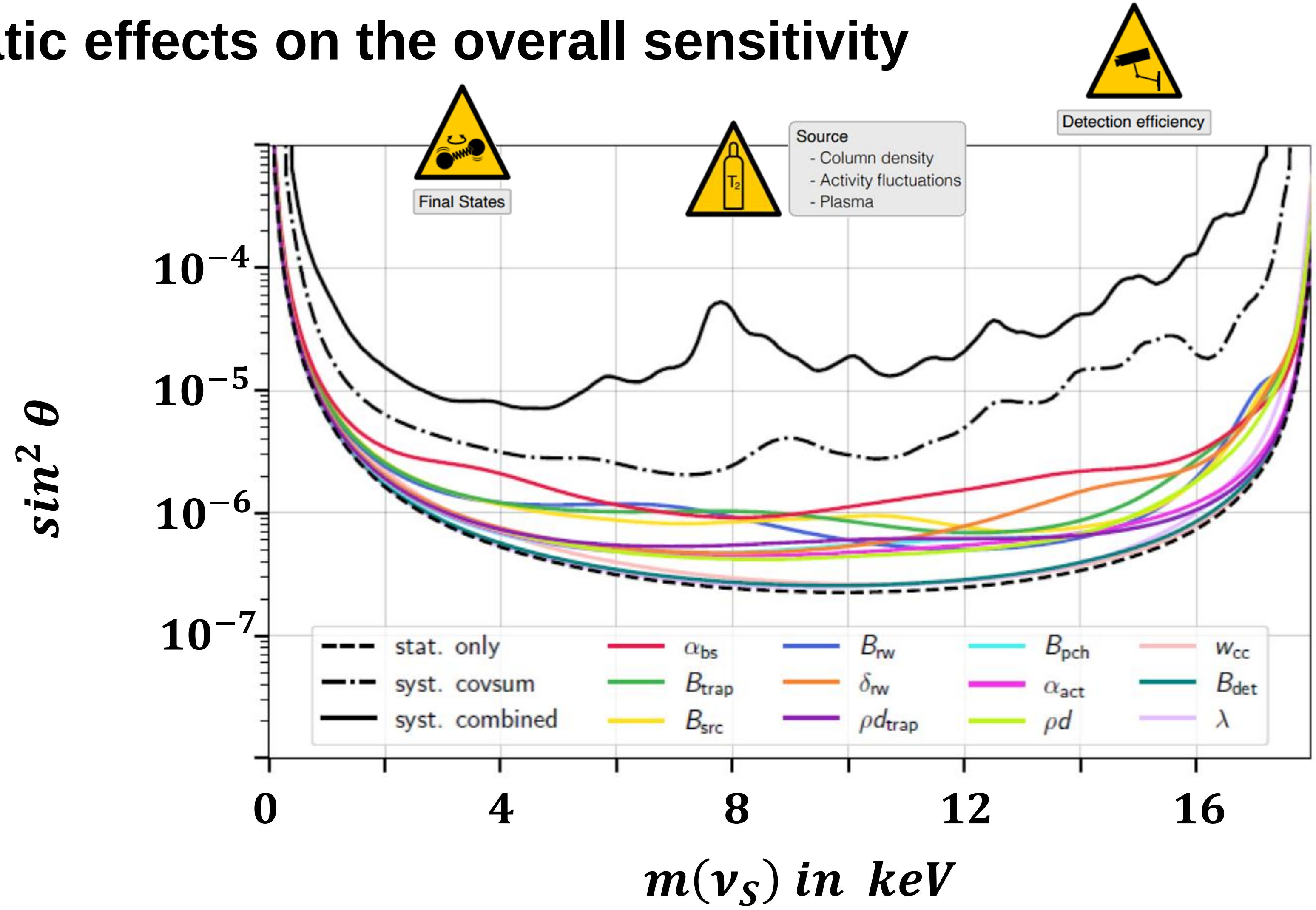
Impact of various systematic effects on the overall sensitivity

- careful investigation of the impact of **12 systematic effects** on the sensitivity, individually (example: magnetic field B_{det}), and overall*

- systematics, systematics, systematics …



* individual covariances (covsum)
simultaneous fluctuations (combined)

$keV-$ steriles: evolution of overall sensitivity

■ **Impact of collected data sample over time in differential mode ($m_s = 10\ keV$)**

- evolution of overall sensitivity ($95\%\ CL$) for fixed mass $m_s = 10\ keV$

- $10^5\ cps$ per pixel & 936 ´golden´ pixels

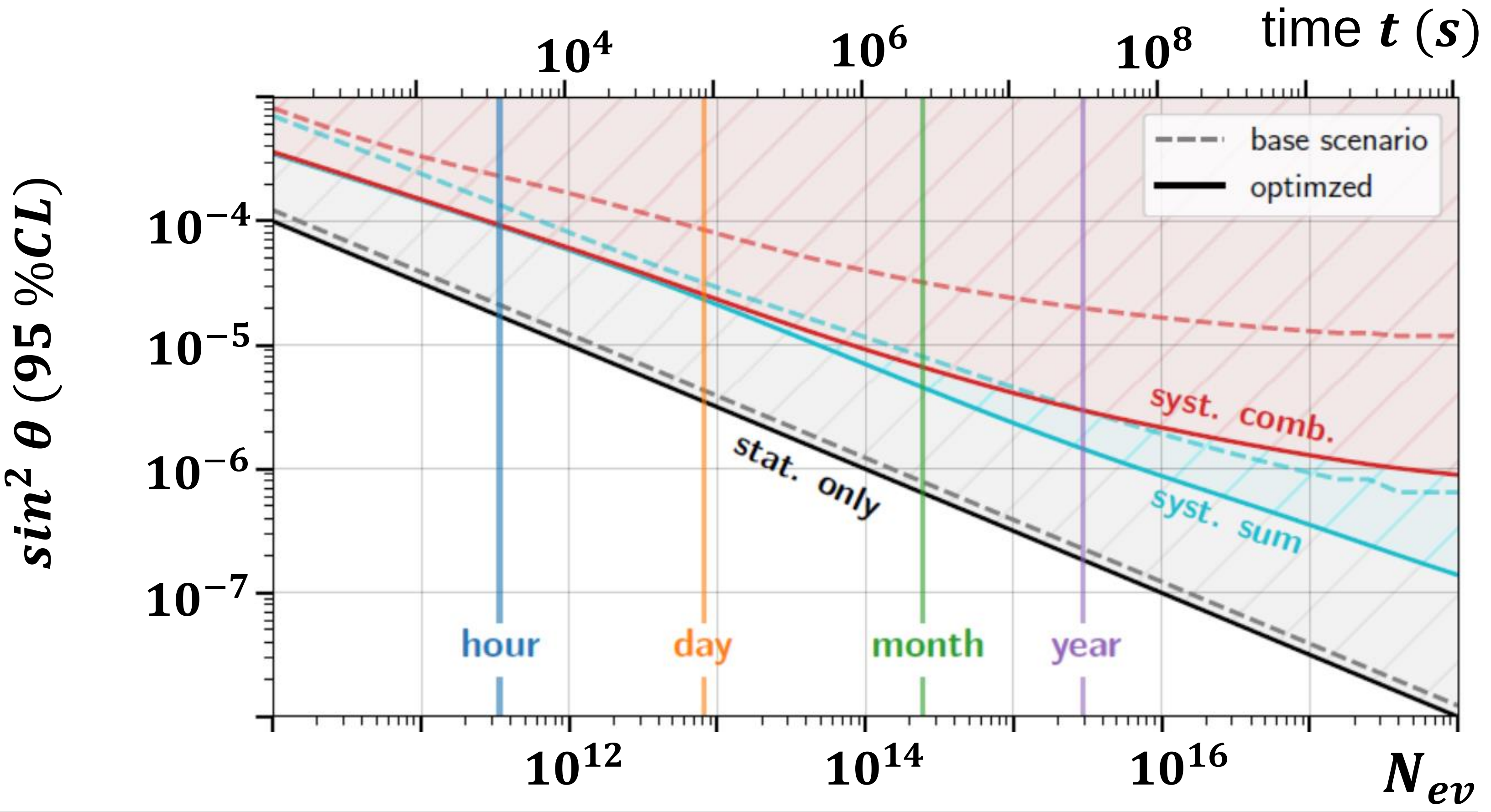
- sensitivities obtained after

$1\ hr$

$1\ day$

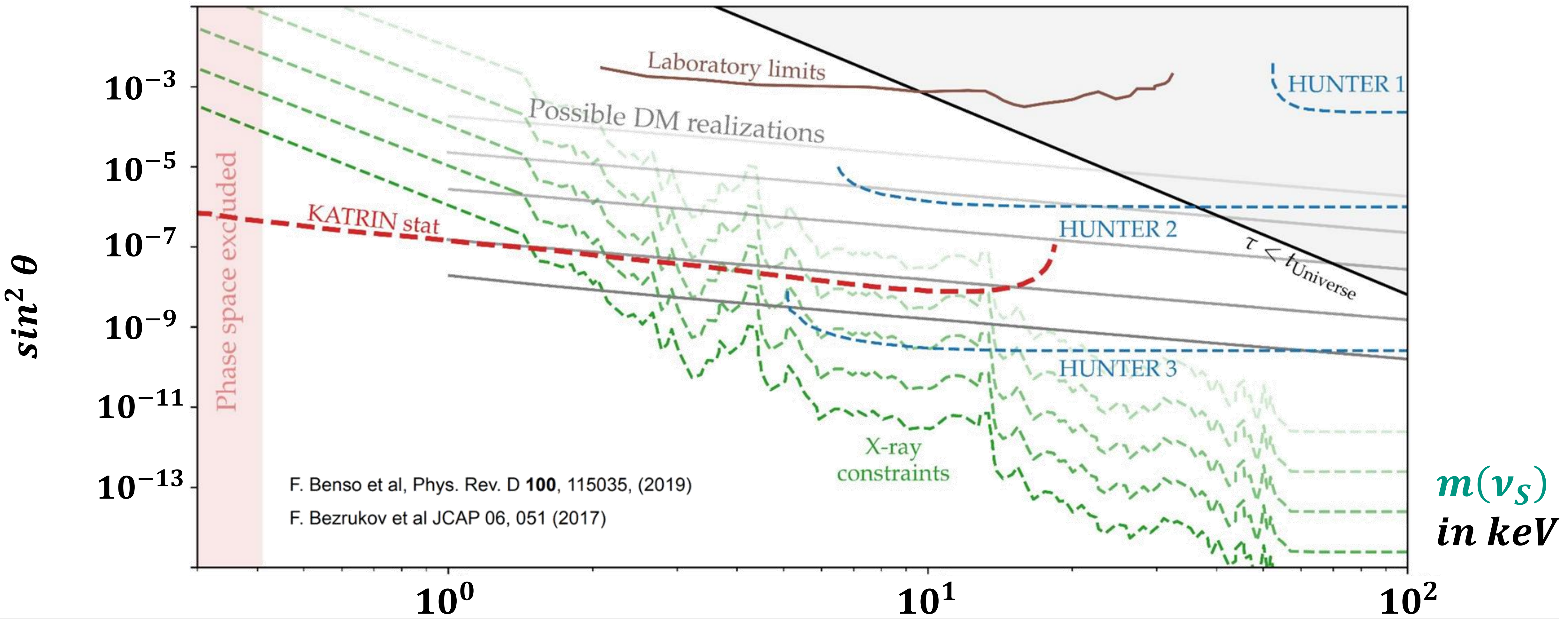
$1\ month$

$1\ yr$



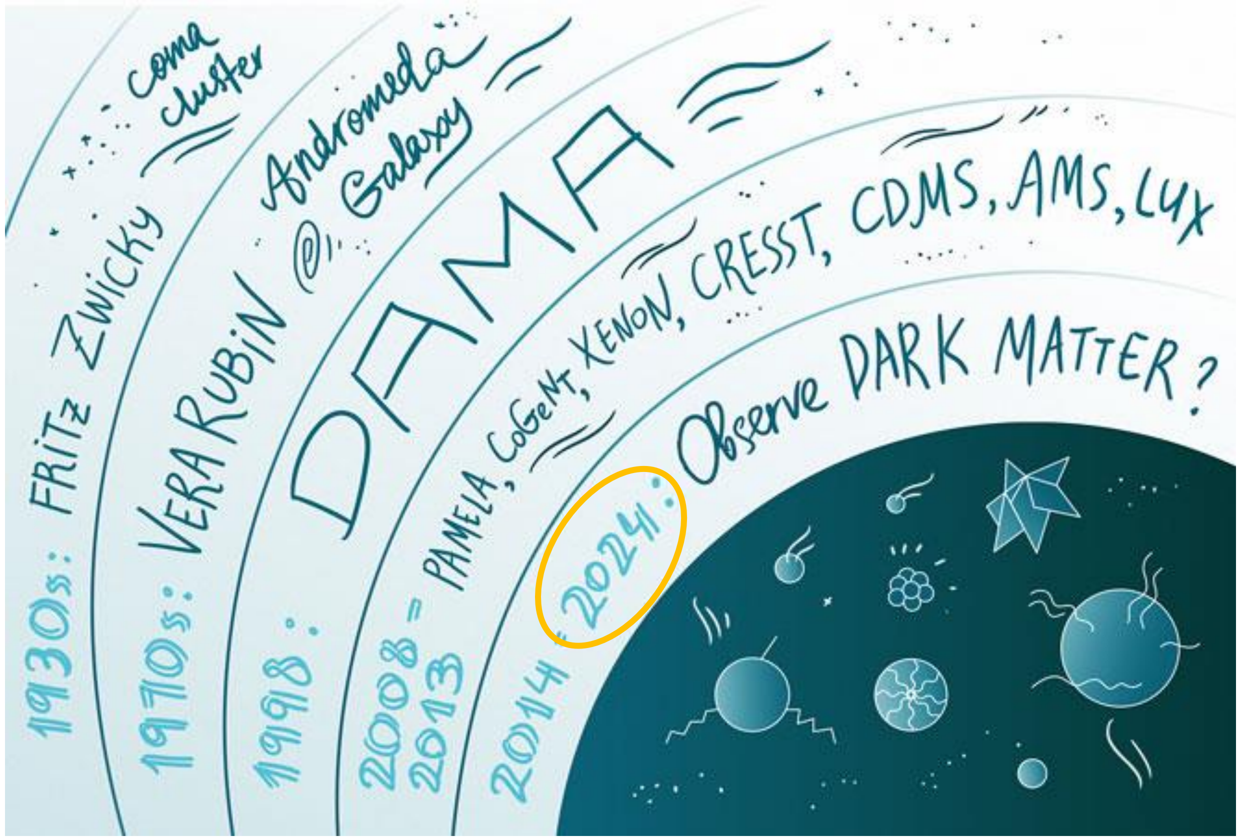
$keV-$ steriles: sensitivity of $KATRIN$ & others

- $KATRIN$ will advance today´s experimental sensitivity by many orders



Dark Matter: *neutralinos*, *axions* & *neutrinos*

- **Coming decade** will be decisive in our quest to unravel the nature of DM



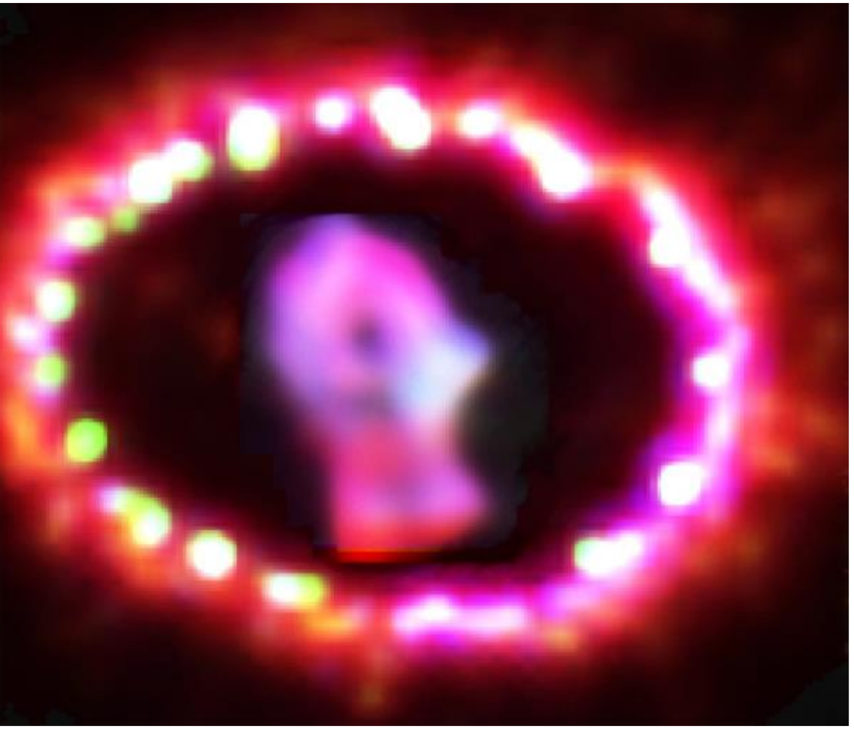
search for exceedingly
rare processes

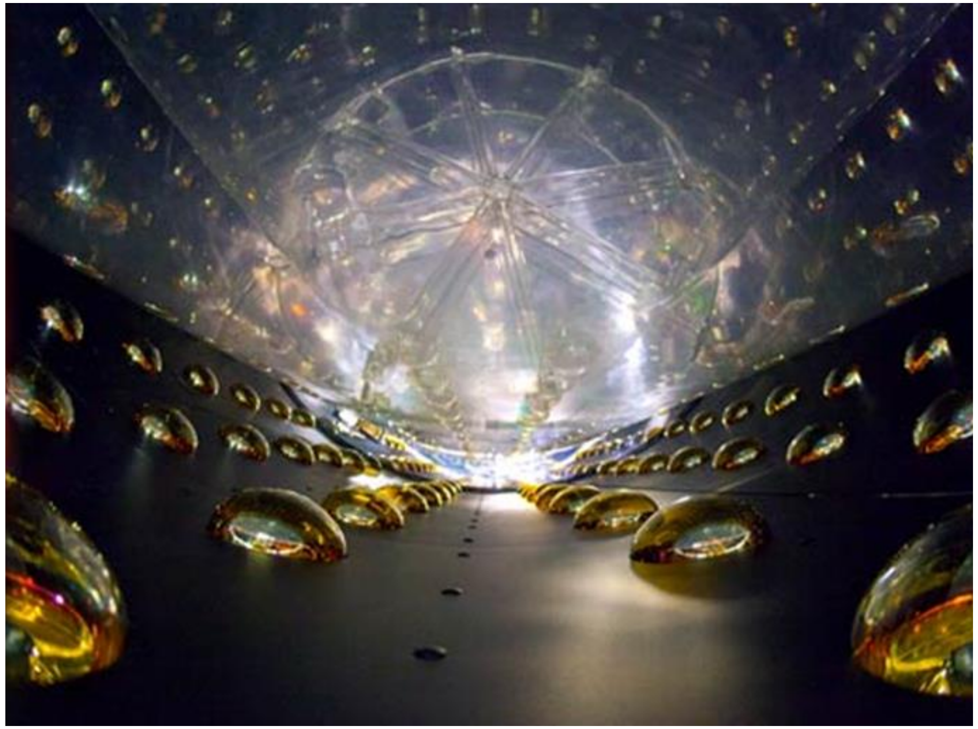
$ATP-II$: Topics in the summer term 2024

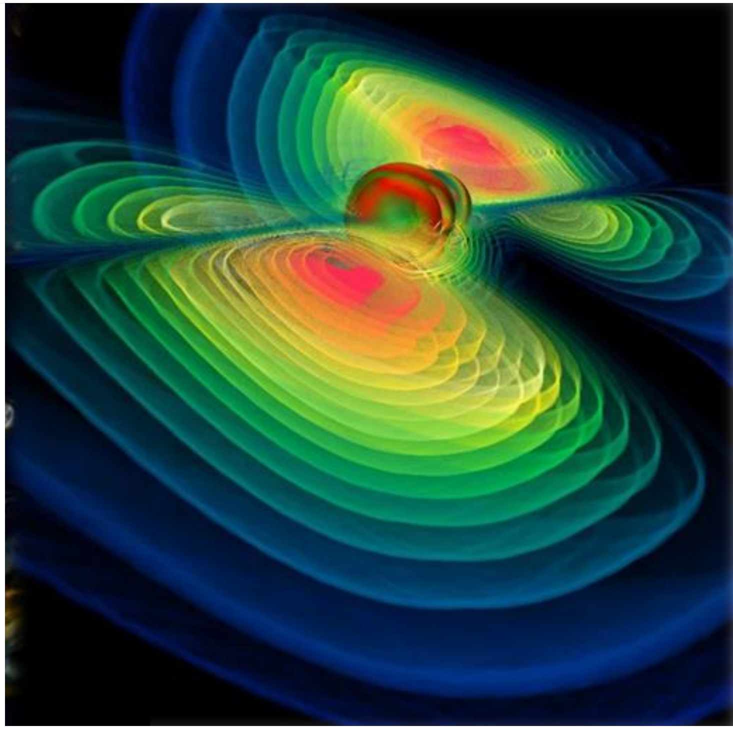
- **Stay tuned…**

Astroparticle physics – II

particles & stars







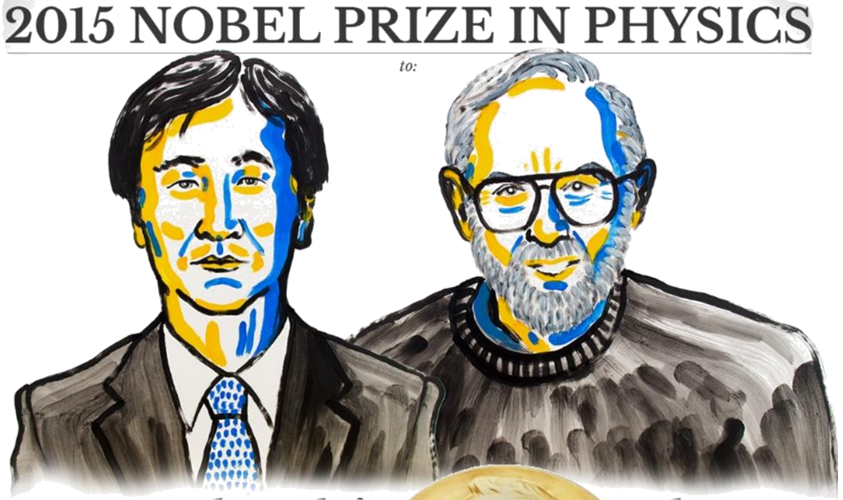
supernovae **neutrinos** **gravitational waves**

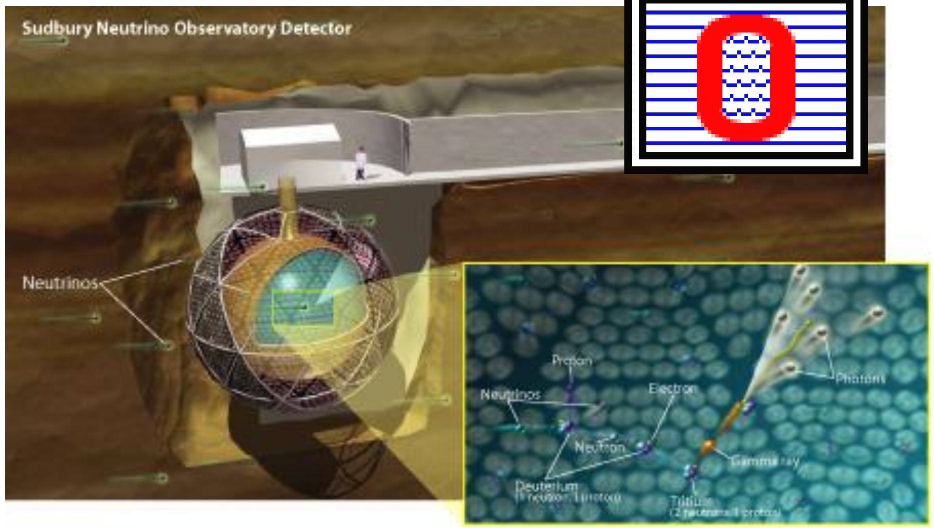
$ATP - II$: Topics in the summer term 2024

- **Stay tuned…**

Astroparticle physics – II

particles & stars



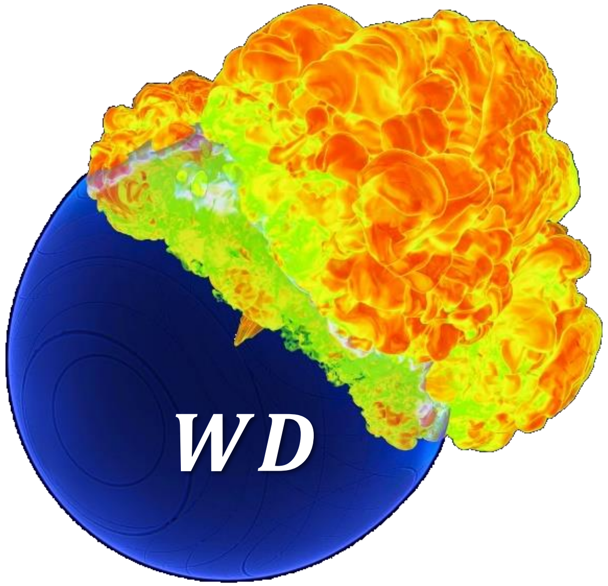


$ATP - II$: Topics in the summer term 2024

- **Stay tuned…**

Astroparticle physics – II

particles & (exploding) stars



Supernova!!


next galactic supernova

$ATP - II$: Topics in the summer term 2024

- **Stay tuned…**

Astroparticle physics – II

particles & (explosive gravitational) waves

$$R_{\mu\nu} - \frac{1}{2} R\, g_{\mu\nu} + \Lambda\, g_{\mu\nu} = \frac{8\pi G}{c^4} T_{\mu\nu}$$

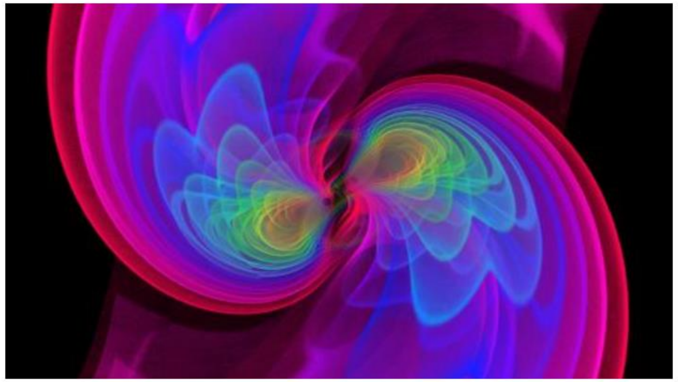
Barry C. Barish

Kip S. Thorne

Rainer Weiss
Prize share: 1/2

+++ EILMELDUNG +++

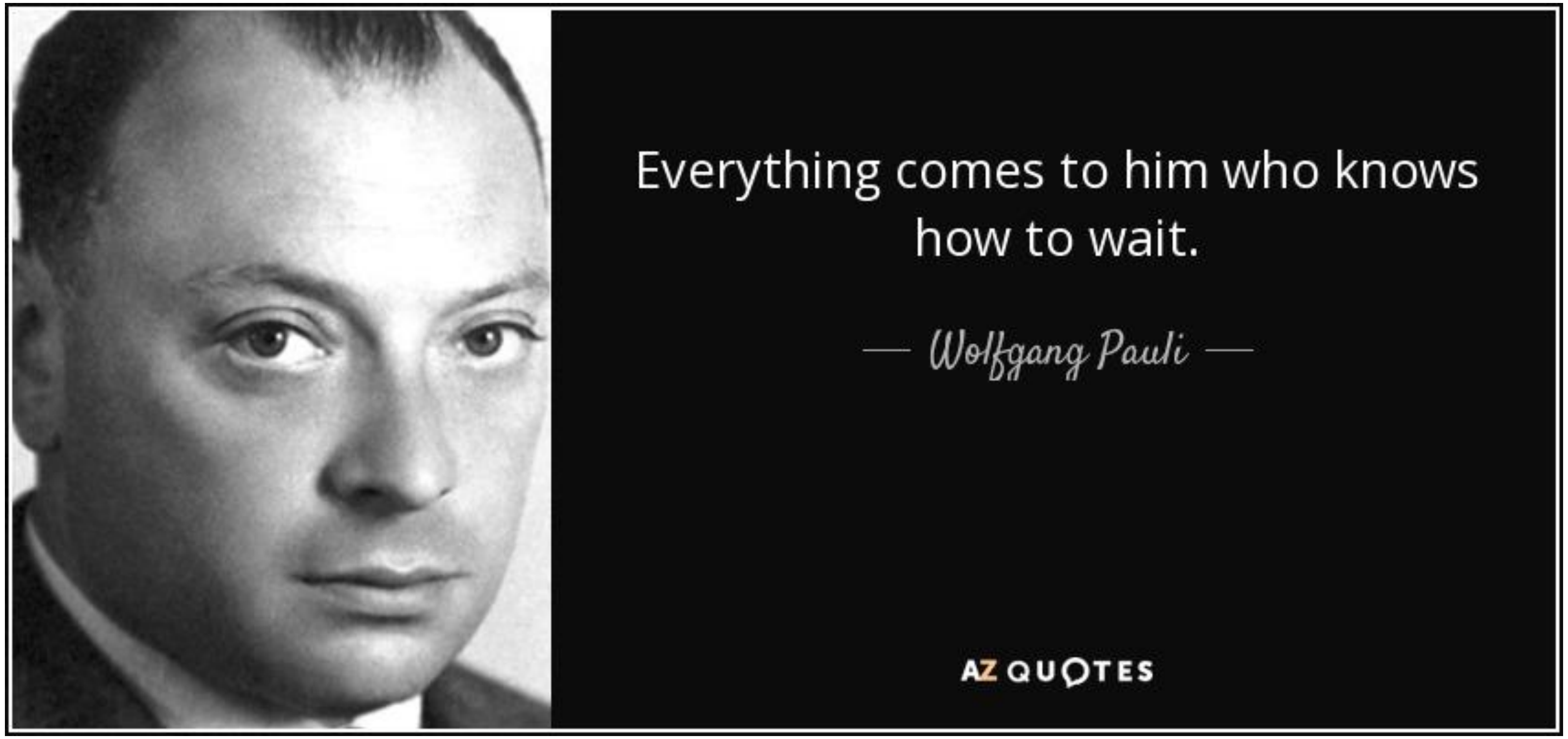
Physik-Nobelpreis geht an Gravitationswellen-Forscher



Albert Einstein sagte Gravitationswellen vor hundert Jahren voraus, für den Nachweis bekommen nun drei Forscher den Physik-Nobelpreis. Die Auszeichnung geht an die US-Wissenschaftler Rainer Weiss, Kip Thorne, Barry Barish. mehr...

ASTROPARTICLE PHYSICS … ON THE MOVE!

- *Axions, neutrinos, neutralinos*: **a lot to explore in the coming years…**



THANK YOU