Wavelet analysis as a tool to detect the kink-signature of keV-neutrinos in the tritium β – decay spectrum

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Chalonge Meudon Workshop Paris, 4th – 6th June 2014

Outline

- ν-measurements with the KATRIN experiment
- Sterile keV-neutrinos in tritium β – decay
- Introduction to wavelet transform
- Wavelet transform of the tritium β – decay spectrum

Talk by Marc Korzeczek (Friday 14.30):
Statistical wavelet analysis & results

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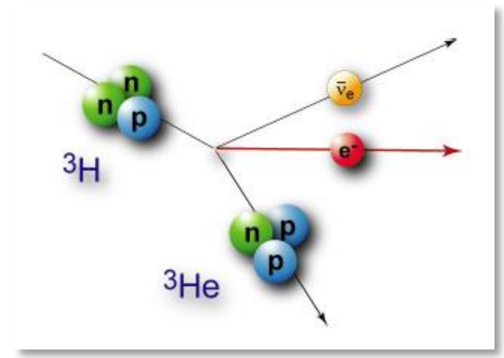
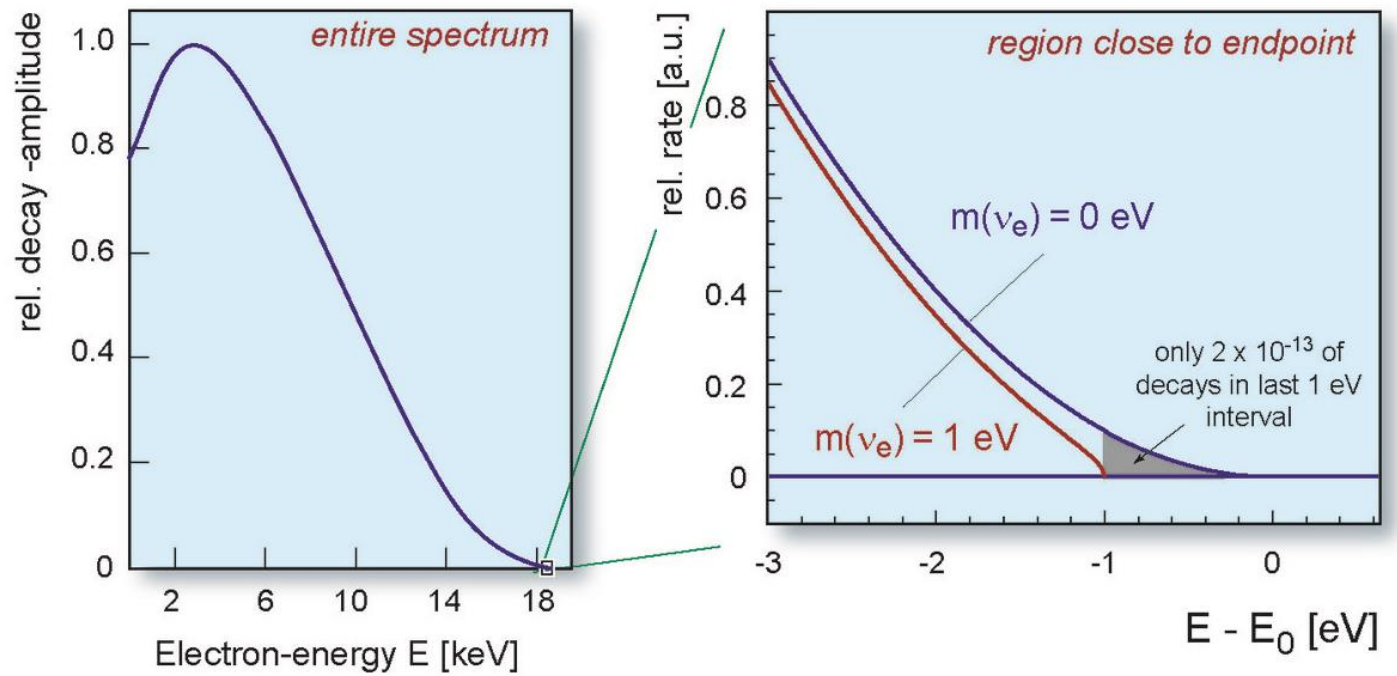
KArlsruhe TRItium Neutrino experiment

Tritium β – decay experiment for direct measurement of $m(\bar{\nu}_e)$



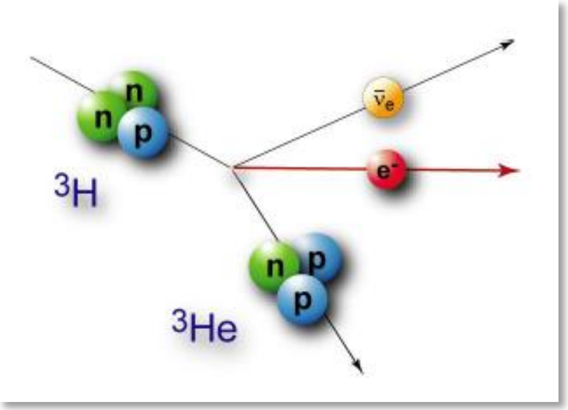


KArlsruhe TRItium Neutrino experiment

Predecessor experiments:

Mainz: $m(\bar{\nu}_{\mathrm{e}}) < 2.3$ eV
C.Kraus et al., Eur. Phys. J. C 40 (2005) 447

Troitsk: $m(\bar{\nu}_{\mathrm{e}}) < 2.05$ eV
V.N. Aseev et al., Phys. Rev. D 84 (2011) 112003



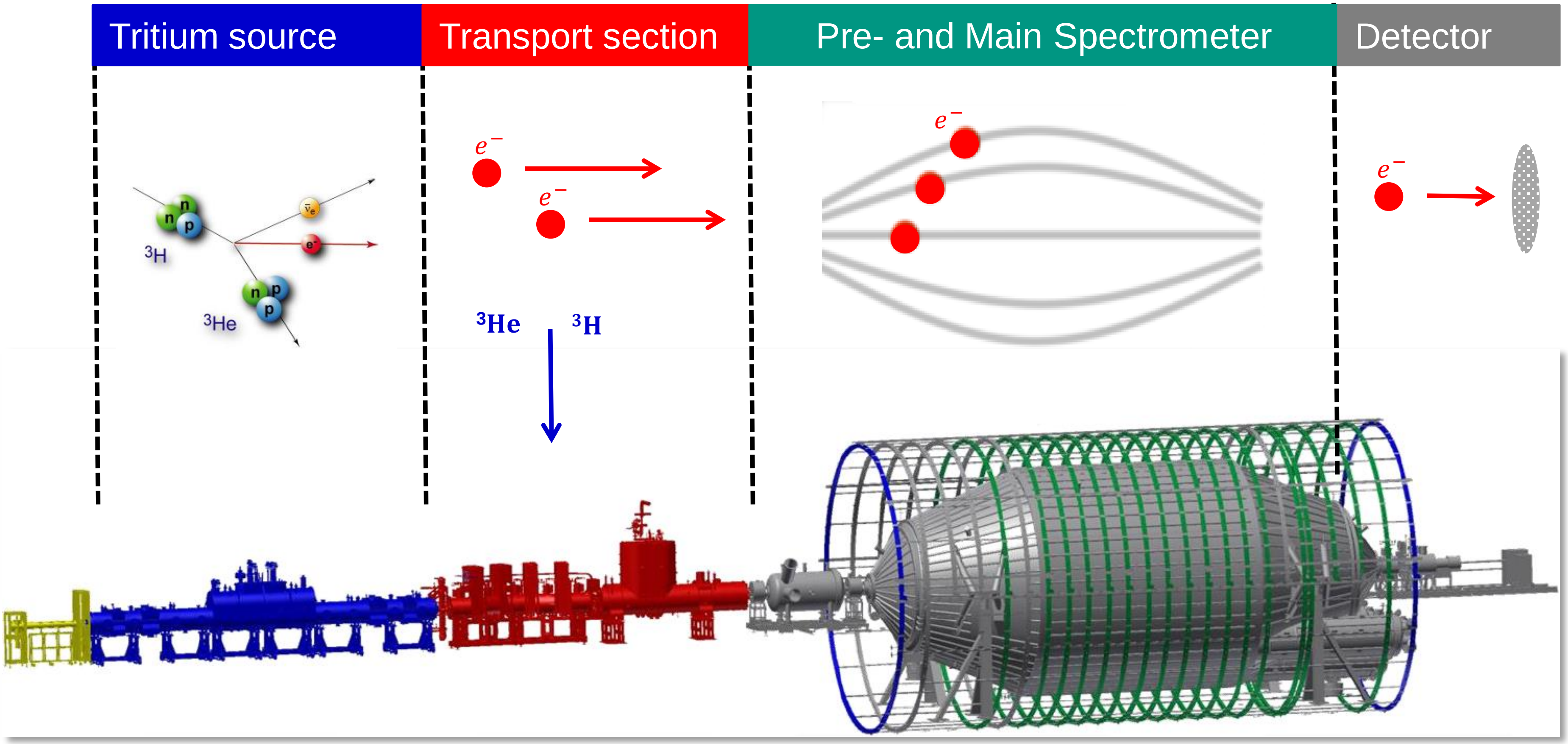
KATRIN:

upper limit: $\boldsymbol{m(\bar{\nu}_{\mathrm{e}}) <}$ **200 meV** (90% CL)

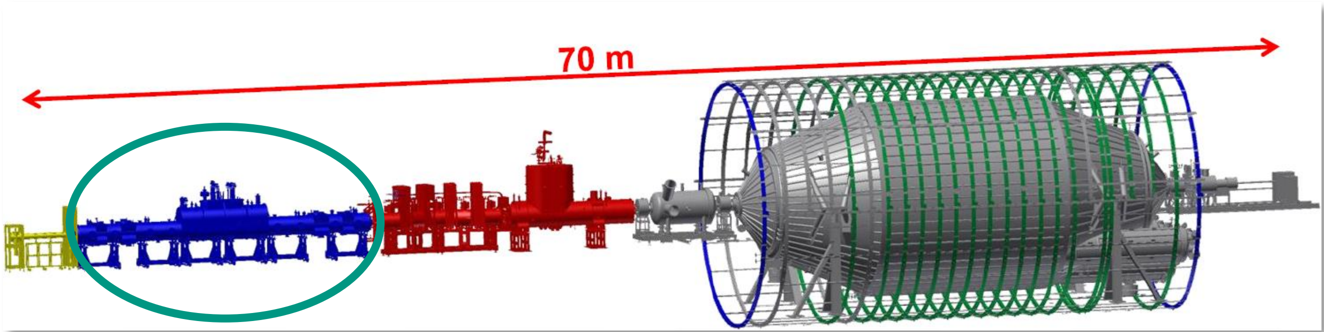
discovery: $\boldsymbol{m(\bar{\nu}_{\mathrm{e}}) >}$ **350 meV** ($\geq 5\sigma$)

→ model-independent measurement of $m(\bar{\nu}_e)$, based only on kinematic relations and energy-momentum conservation

KATRIN: Experimental setup



KATRIN: Tritium source



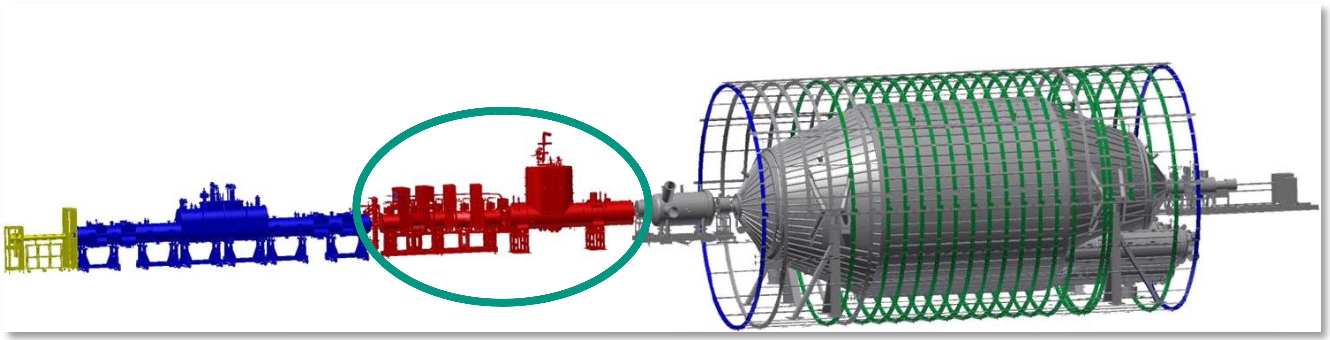
High luminosity (10^{11}) and stability (10^{-3})

WGTS = Windowless Gaseous Tritium Source

Advantages of tritium:

- low endpoint energy ($E_0 = 18.6\ \mathrm{keV}$)
- simple nuclear structure
- superallowed transition
- suitable life-time of 12.3 years
  → high luminosity

KATRIN: Transport section



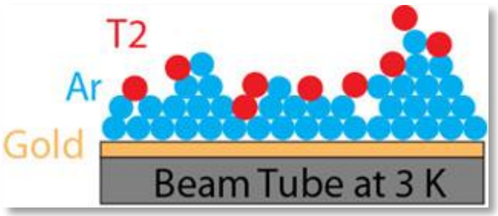
Task: Adiabatically guiding of beta electrons from source to spectrometer and elimination of tritium flow towards spectrometer

Differential Pumping Section:

→Tritium and ion flow reduction with turbomolecular pumps

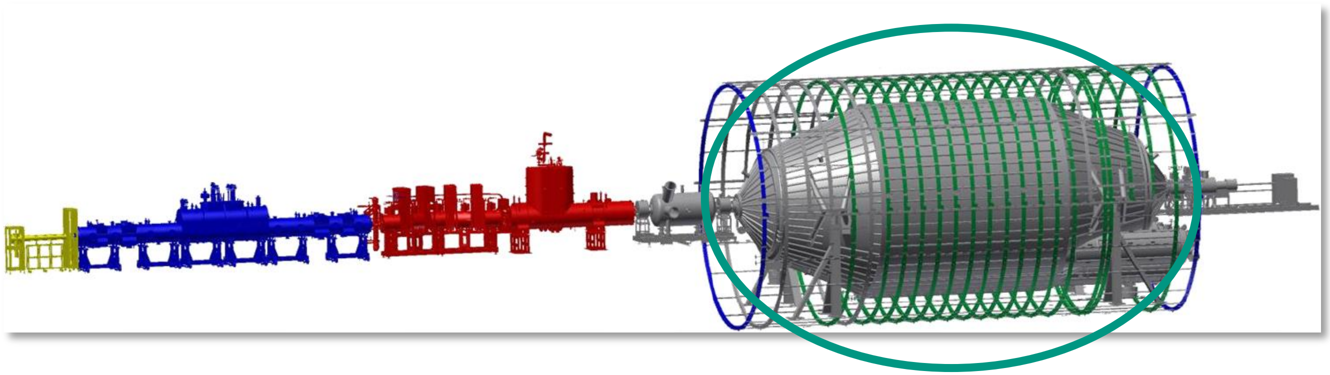
Cryogenic Pumping Section:

→ Tritium trapping by cryo-sorption on Argon frost

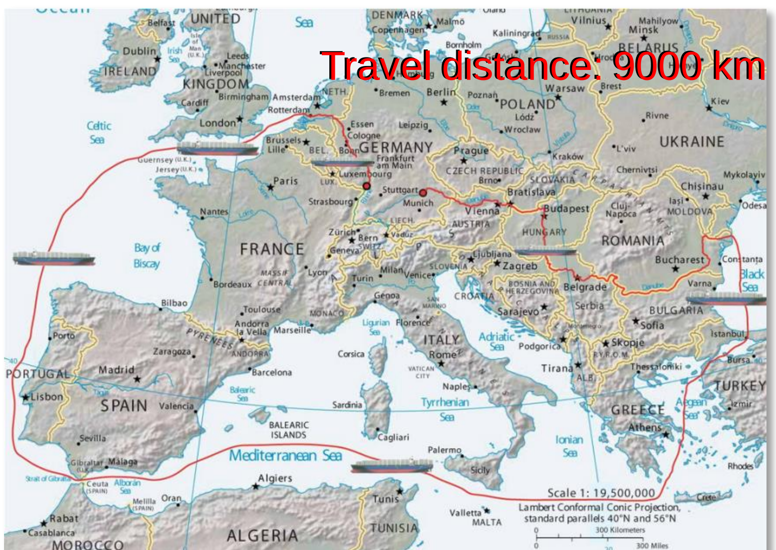


Tritium flow suppression by nine orders of magnitude

KATRIN: Main Spectrometer



Task: High precision measurement of the kinetic energy of β electrons

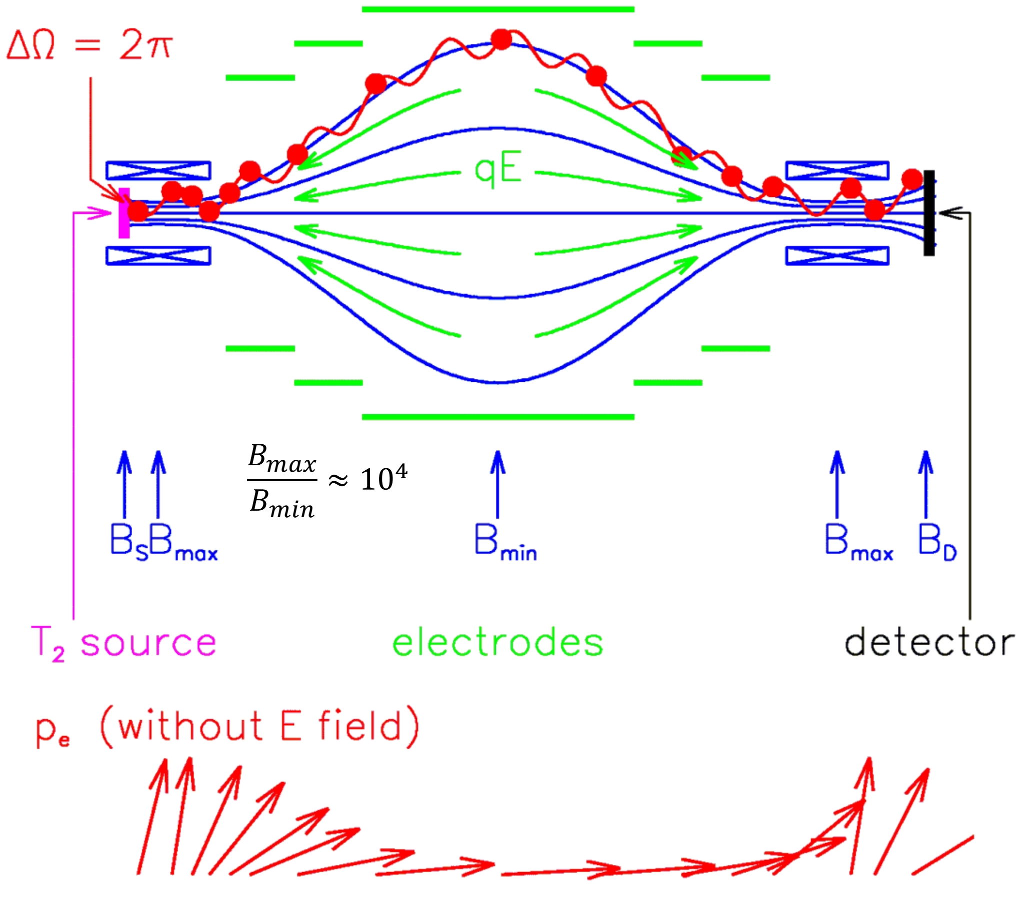


- **Electrostatic spectrometer in MAC-E-Filter mode**

  (**M**agnetic **A**diabatic **C**ollimation combined with an **E**lectrostatic **Filter**)

KArlsruhe TRItium Neutrino experiment

KATRIN Main Spectrometer – MAC-E-Filter

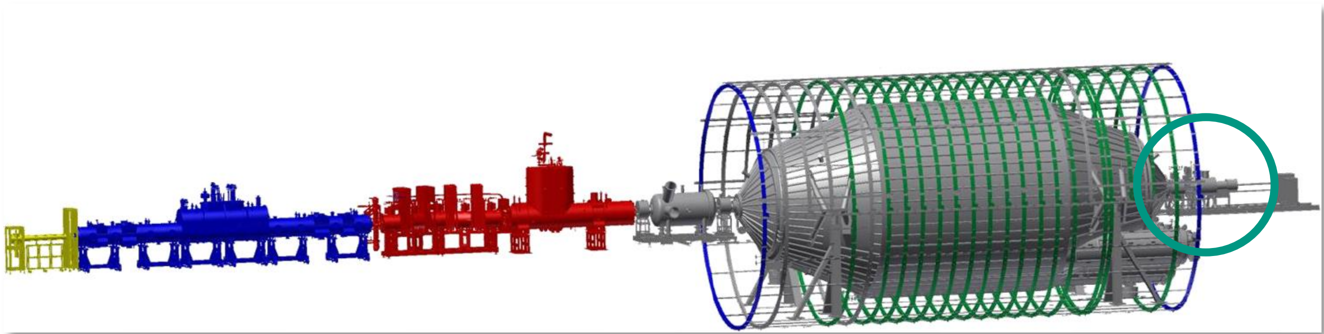


Magnetic moment: $\mu = E_\perp / B = const.$

- Adiabatic guiding of electrons along magnetic field lines
- Conversion of transversal to longitudinal energy
- Electron beam runs against electrostatic barrier
- Spectrometer acts as integrating high-pass-filter

$$\Delta E = 0.93\ \text{eV}$$

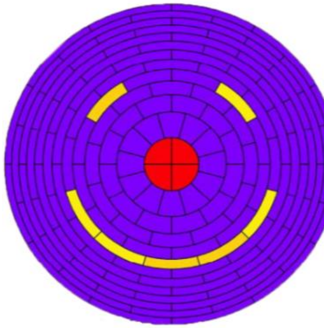
KATRIN: Focal Plane Detector



Task: Count electrons *and* provide, spatial, temporal and *energy* information

→ *discriminate background*

monolithic PIN diode array on 5“ waver with 148 pixels



KATRIN Status quo

- Successful commissioning of spectrometer and detector section
  - Background measurements
  - Background reduction
  - Electron transmission function
- Next commissioning phase in summer/autumn 2014
- Start of tritium operation: 2016

IDEA: Use KATRIN (source) to detect keV-neutrinos as well!

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Why sterile neutrinos?

- Mass of active neutrinos can be explained by introducing right-handed sterile neutrinos

$\begin{pmatrix} e^- \\ \nu_e \end{pmatrix}_L$ Isospin dubletts

e_R^-
ν_R Isospin singuletts

→ No gauge interactions!

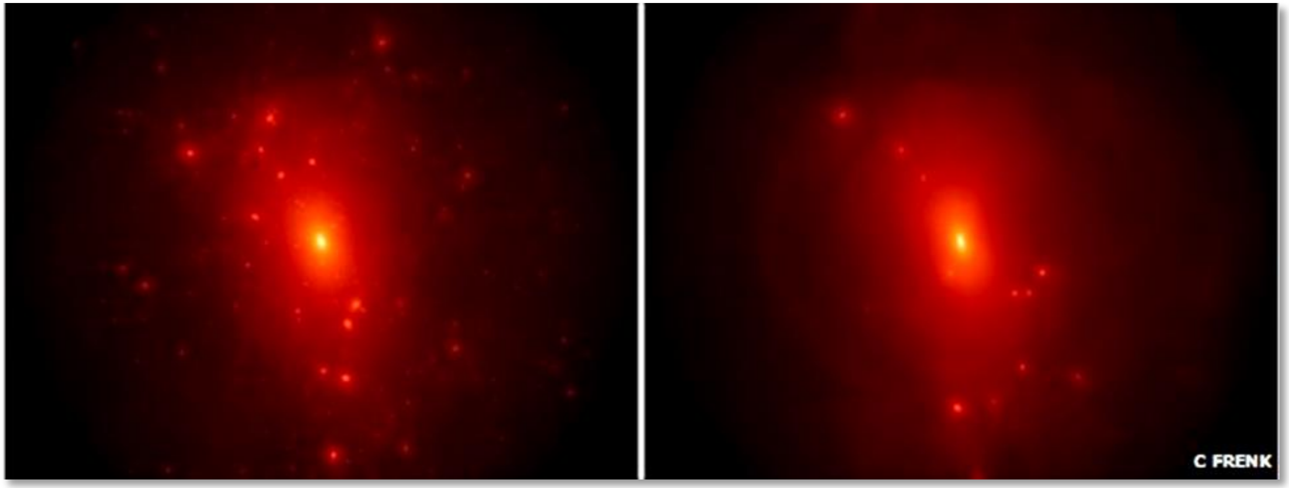
- Seesaw mechanism

High Majorana mass term naturally creates light neutrino mass eigenstates.

Talk: Dietrich Bodeker

Sterile keV-neutrinos in cosmology

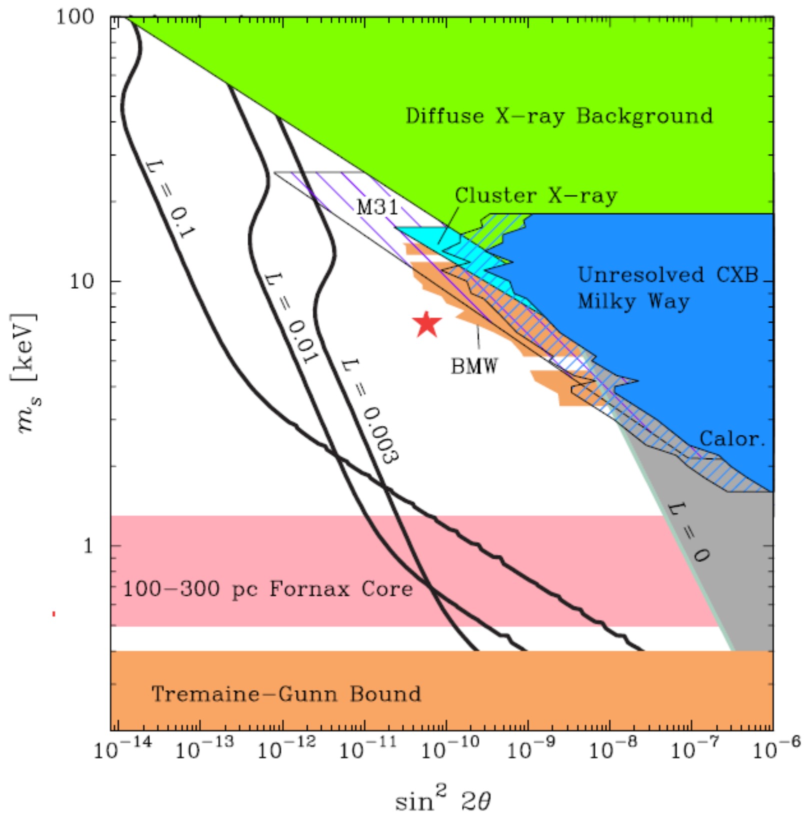
CDM WDM



- WDM mitigates problems of structure formation (number of dwarf galaxies)
- Candidate for WDM: sterile neutrinos in mass range of a few keV

Talks: Norma Sanchez, …

Sterile keV-neutrinos in cosmology



Talk: Esra Bulbul

Analysis of XMM Newton telescope data points at

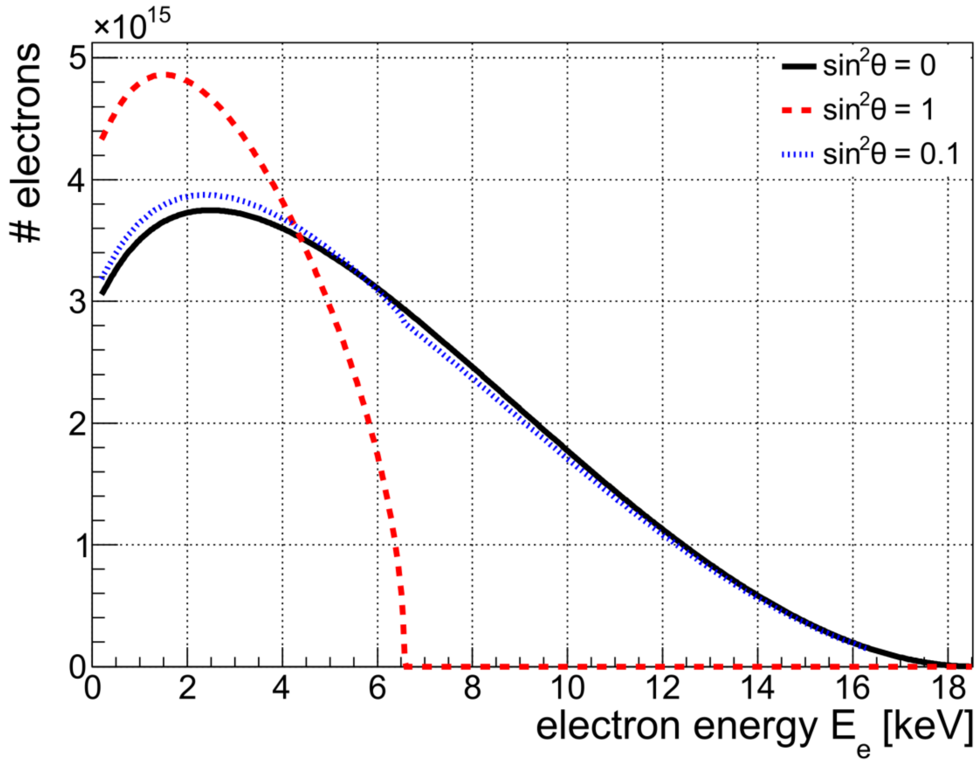
$$\boldsymbol{m_s = 7.1\ \text{keV},\ \sin^2\theta = 1.75 \cdot 10^{-11}}$$

[Bulbul *et al,* arXiv:1402.2301v1 [astro-ph.CO], 2014,10th February]

keV-neutrinos in tritium β – decay

Mixing of keV-neutrinos and light neutrinos with mixing angle θ:

$$\frac{d\Gamma}{dE_e} = \sin^2\theta \left(\frac{d\Gamma}{dE_e}\right)_{m_{heavy}} + \cos^2\theta \left(\frac{d\Gamma}{dE_e}\right)_{m_{light}}$$



m_{heavy}: mass eigenstate of sterile keV neutrino

m_{light}: effective mass of active neutrinos

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

$$m_{heavy} \gg m_{light}$$

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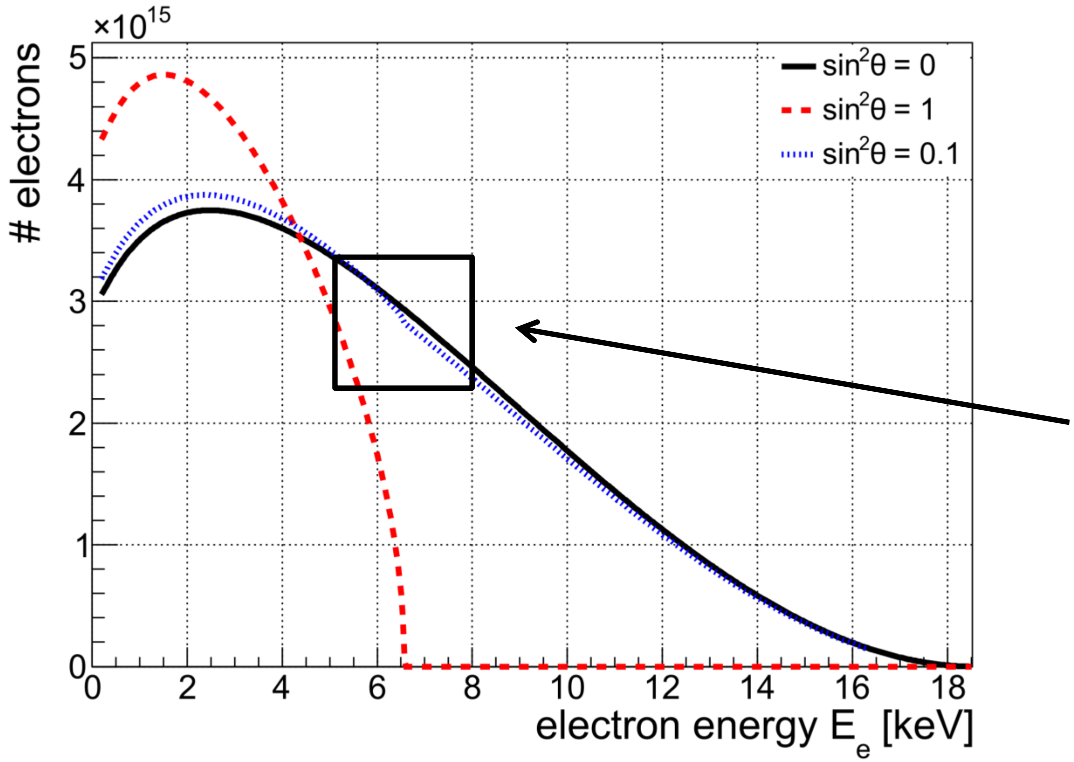

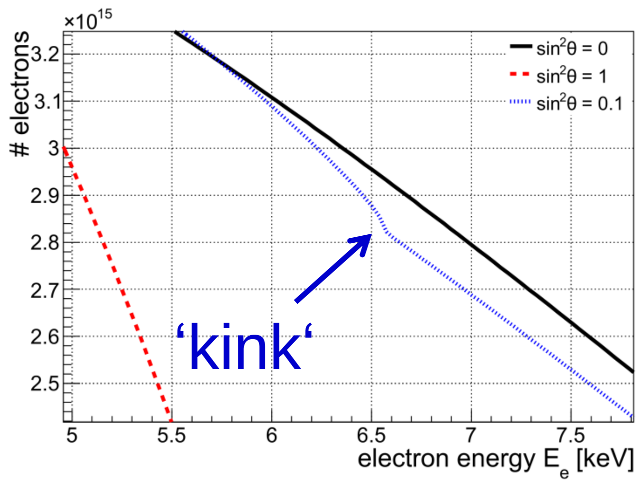

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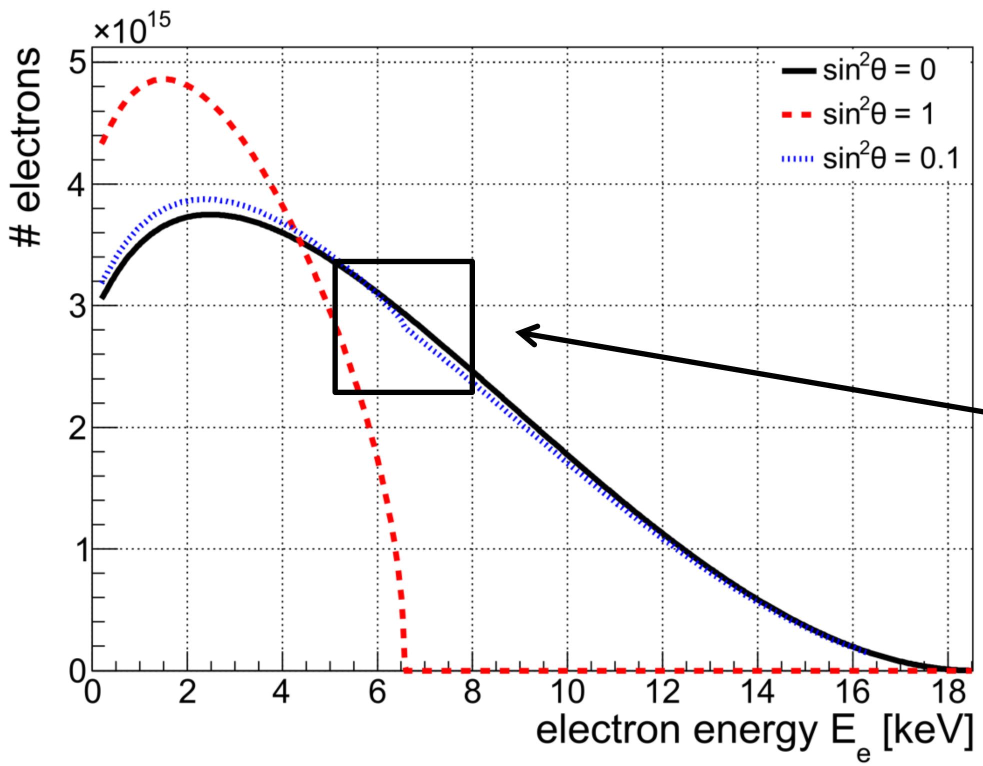
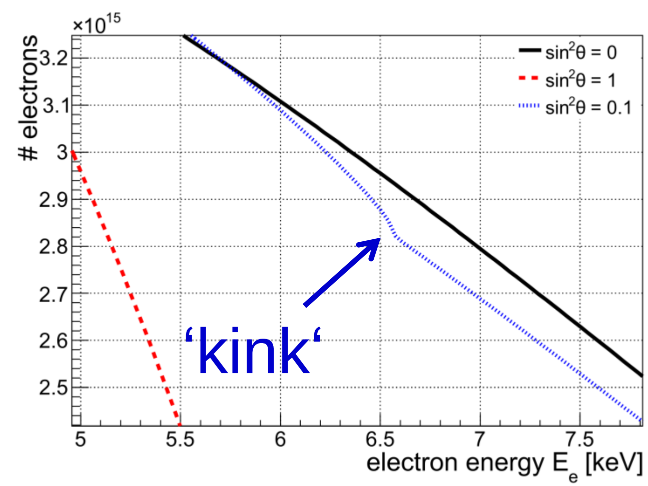


Task: Find the kink!



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Fourier Transform vs. Wavelet Transform

- Fourier Transform (FT):

$$F(\omega) = \frac{1}{\sqrt{2\pi}} \int f(t) e^{-i\omega t} \mathrm{d}t$$

FT provides information about the frequencies ω, which are contained in the signal f(t), but there is no information about the point in time.

- Continuous Wavelet Transform (CWT):

$$\mathrm{CWT}(s,\tau) = \frac{1}{\sqrt{s}} \int f(t) \Psi^{*}_{s,\tau} \left(\frac{t-\tau}{s} \right) dt$$

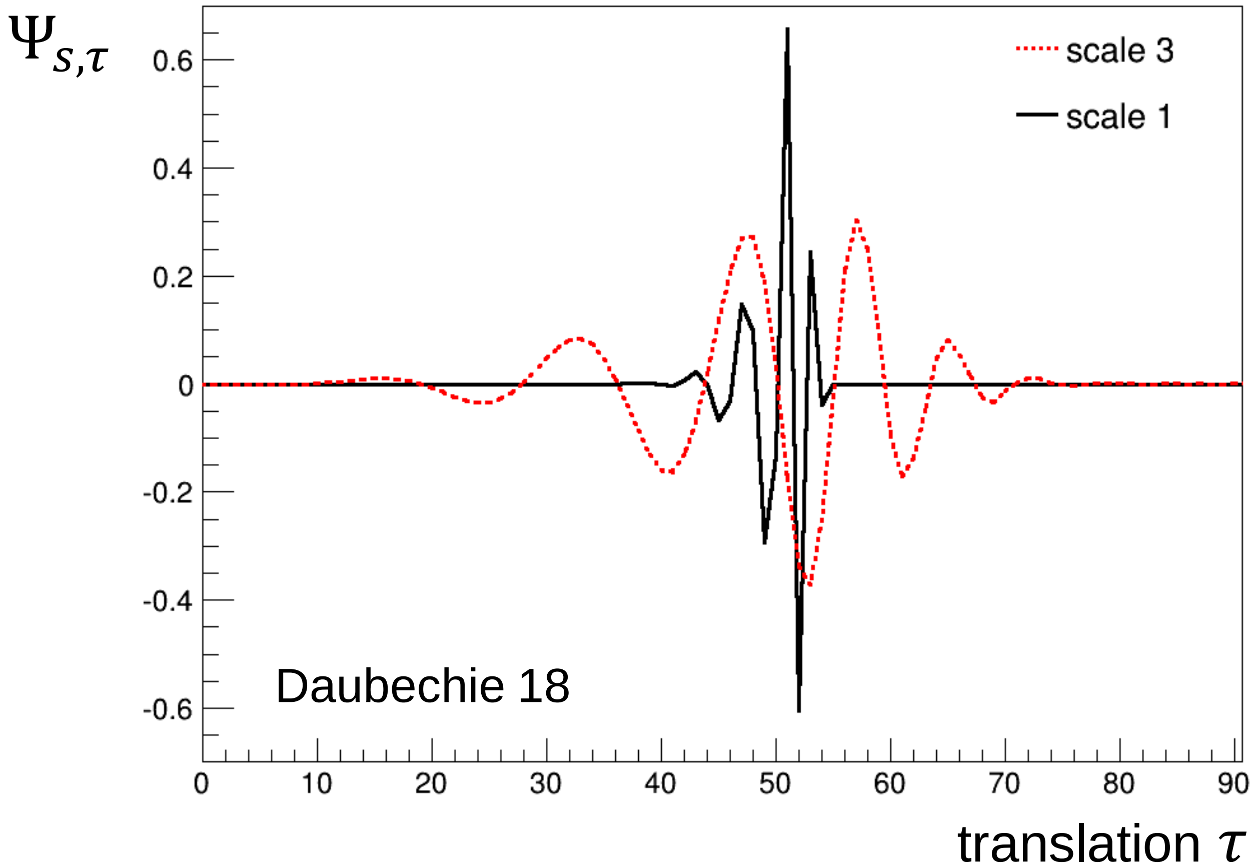
- CWT is a convolution of a signal f(t) with wavelets $\Psi_{s,\tau}$.

  It is a multiresolutional technique with time (translation τ) and frequency (scale *s*) resolution.

Discrete Wavelet Transform (DWT)

For a discrete signal the Discrete Wavelet Transform is used.

There are different discrete wavelet families $\Psi_{s,\tau}$ (e.g. *Daubechie* wavelets).



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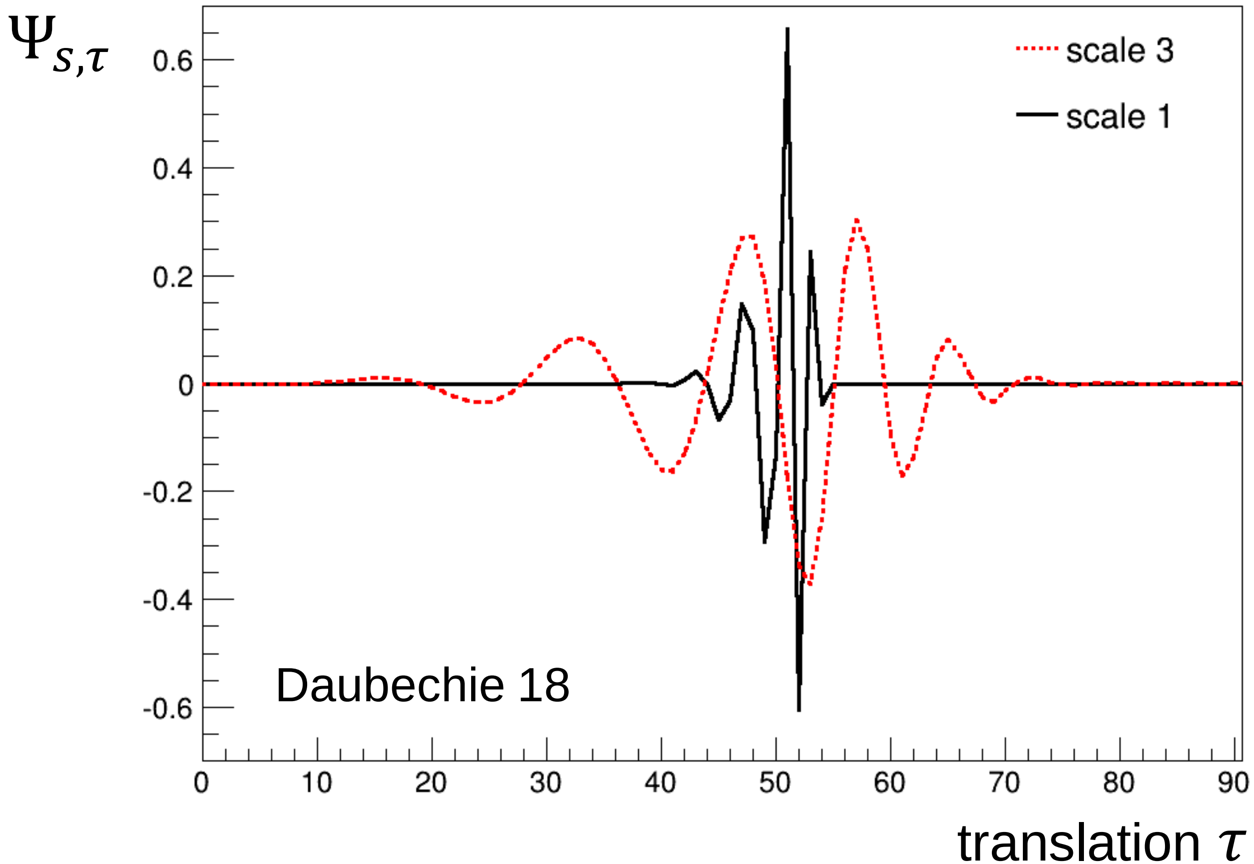
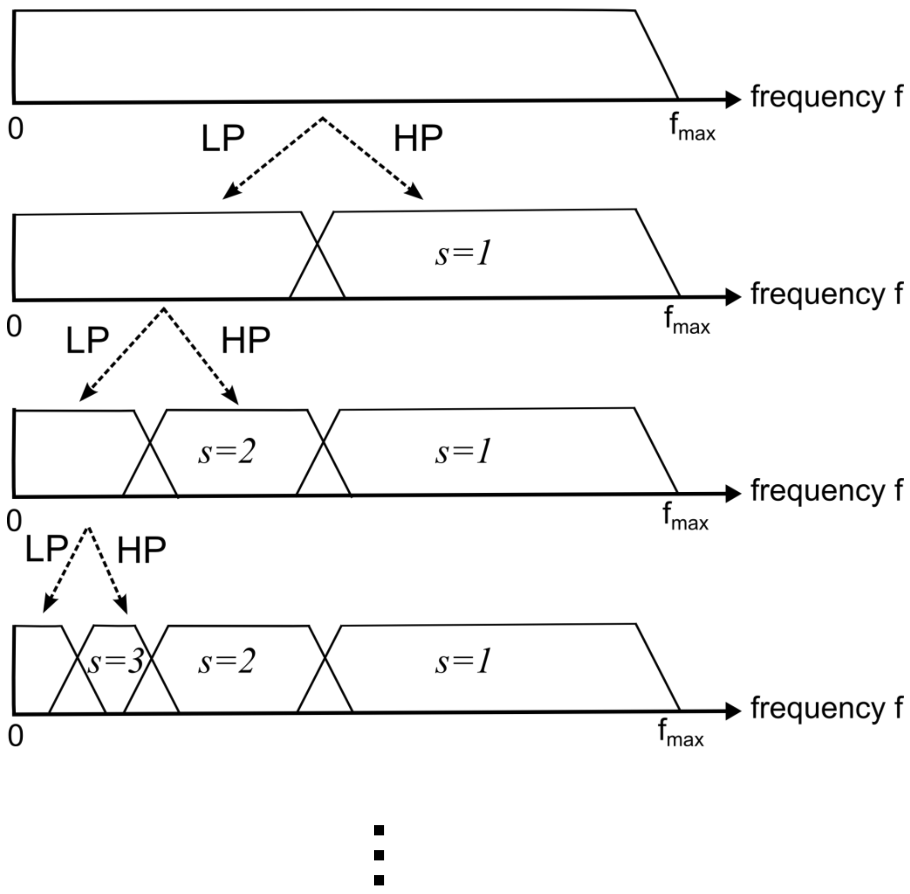


small scale
=
high frequency

Idea of DWT: sub-band coding

- Apply highpass (HP) and lowpass (LP) filters to signal
- Upper frequency range is transformed and provides power values *(scale 1),* the lower part represents a smoothed signal
- Apply another HP and LP filter to lower range

  →Get power values of *scale 2*
- …



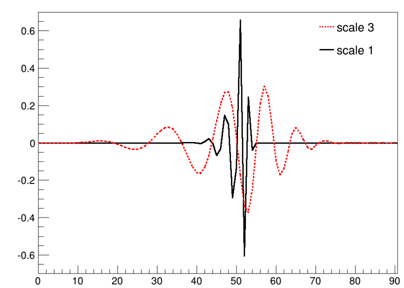
Technical realization of DWT

DWT is a linear operation and can be written as a transformation matrix T:

$$T = \begin{pmatrix} c_0 & \dots & \dots & c_{n-1} & 0 & 0 & \dots & \dots & 0 \\ c_{n-1} & -c_{n-2} & \dots & -c_0 & 0 & 0 & \dots & \dots & 0 \\ 0 & 0 & c_0 & \dots & \dots & c_{n-1} & 0 & \dots & 0 \\ 0 & 0 & c_{n-1} & -c_{n-2} & .. & -c_0 & 0 & \dots & 0 \\ . & . & . & . & . & . & . & . & . \\ . & . & . & . & . & . & . & & . \\ c_2 & \dots & c_{n-1} & 0 & \dots & \dots & 0 & c_0 & c_1 \\ c_{n-3} & \dots & c_0 & 0 & \dots & \dots & 0 & c_{n-1} & c_{n-2} \end{pmatrix}$$

$c_0, \dots c_{n-1}$: Daubechie coefficients, e.g. *n=18* for Daubechie 18

Odd rows: Lowpass filter, provide smoothed signal
Even rows: Highpass filter, provide detail power values



Why wavelet transform?

- DWT offers time (in our case: energy) and frequency resolution
- Wavelet is sensitive to kink-like features, which appear at a certain energy in the spectrum → model independent
- High frequency components of kink-signature are picked out by the wavelets

IDEA: Transform tritium β – decay spectrum with DWT, use power spectrum to find a quantity in an appropriate scale, which can detect the kink.

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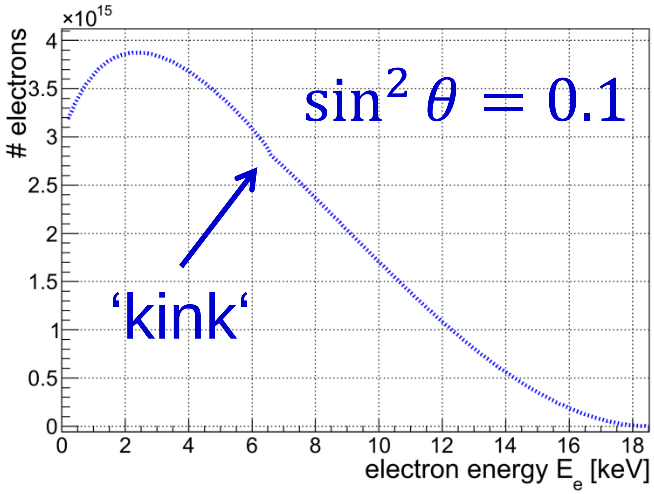
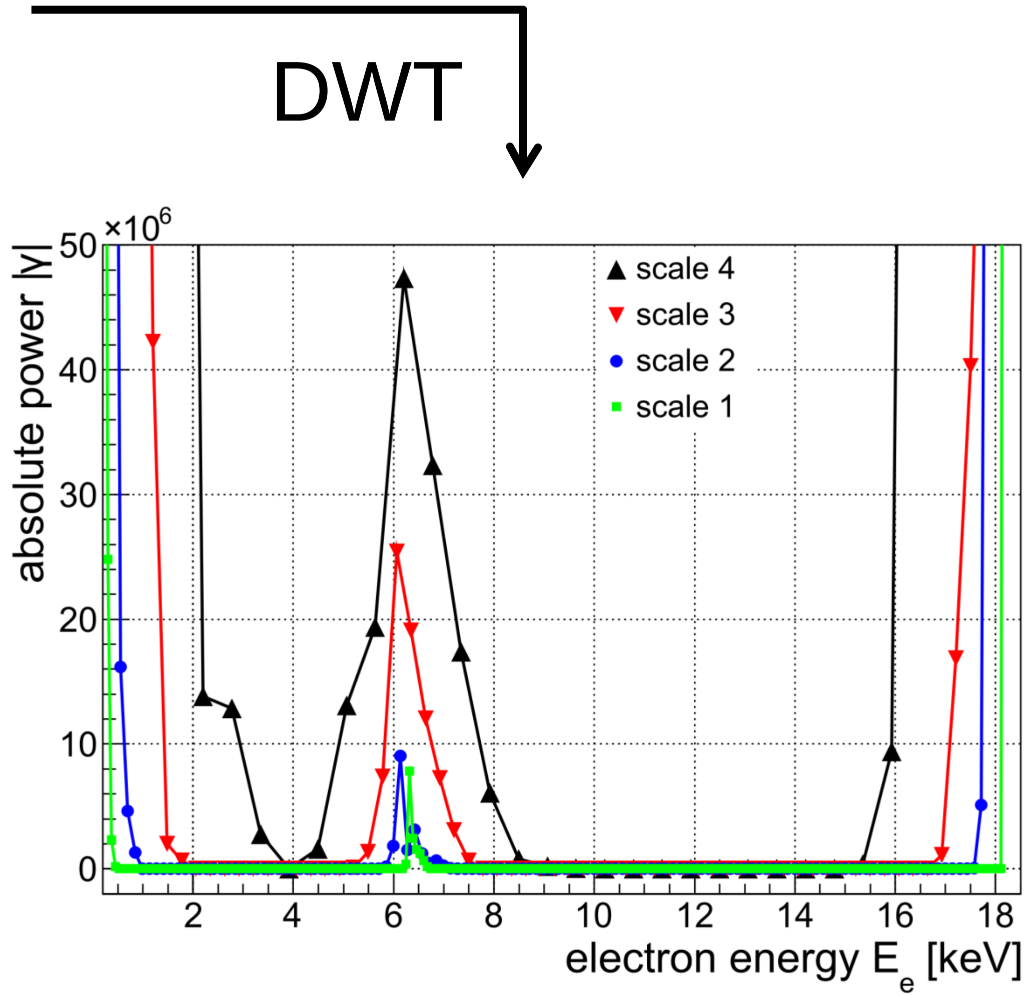
DWT of tritium β – decay spectrum





Small kink in β-decay spectrum results in **large power values** at kink-position!

Outlook: Explicit statistical wavelet analysis of tritium β – decay spectrum

Explicit analysis method of tritium β – decay spectrum as well as results will follow in:

„Statistical wavelet analysis to detect keV-neutrinos with a KATRIN-like experiment“

(by Marc Korzeczek)

Statistical sensitivity to active-sterile mixing with a KATRIN-like experiment down to $\mathbf{\sin^2 \theta = 6 \cdot 10^{-7}}$

Summary

- KATRIN is under construction to measure $m(\bar{\nu}_e)$ with a sensitivity of 200 meV.
- Ultra-luminous KATRIN tritium source could be used to measure the entire tritium β – decay spectrum to look for sterile keV neutrinos
- Sterile keV neutrinos are well motivated by cosmology
- Wavelet transform is a very promissing method to detect the kink-signature of keV-neutrinos in tritium β – decay. It is a multiresolutional technique and offers both time and frequency resolution.
- DWT is very sensitive to the high frequency components caused by a kink-signatur in the spectrum

Special thanks to

Susanne Mertens, Guido Drexlin, Alan Poon