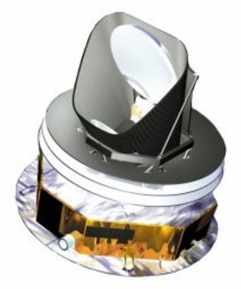
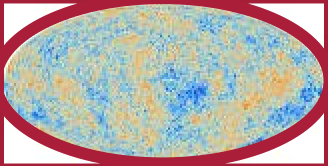
Measuring Neutrino Mass

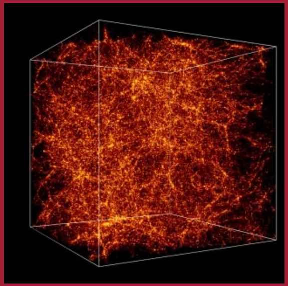
m_ν << mass of other fermions

m_ν crucial for understanding masses in general

$\Rightarrow$ we would like to know it



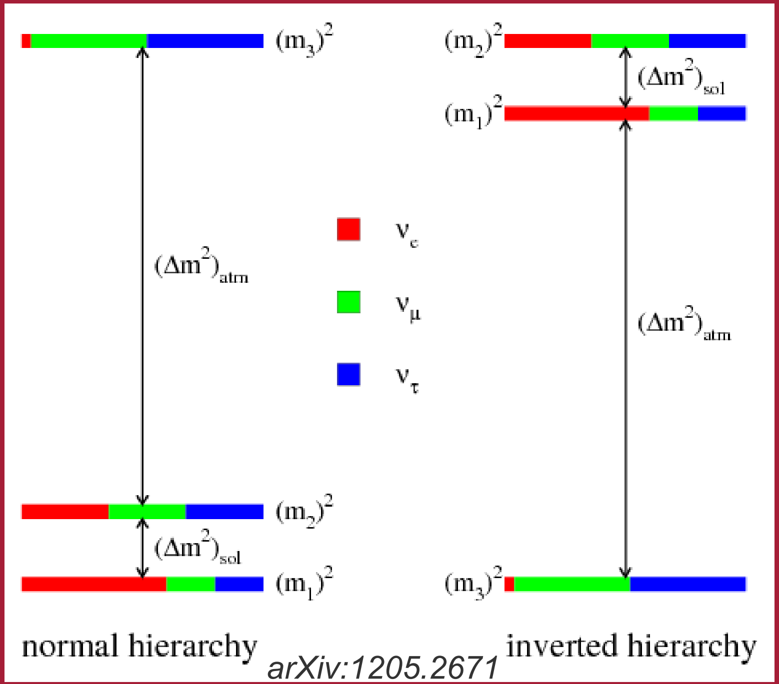




ν_e - Oscillations

$\Delta m_{23}^2 =$

$2{,}4 \cdot 10^{-3}\ \mathrm{eV}^2$



arXiv:1205.2671

$\Delta m_{12}^2 =$

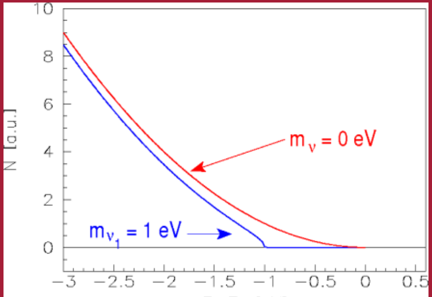
$8 \cdot 10^{-5}\ \mathrm{eV}^2$

we know the sum of the three masses is nonzero

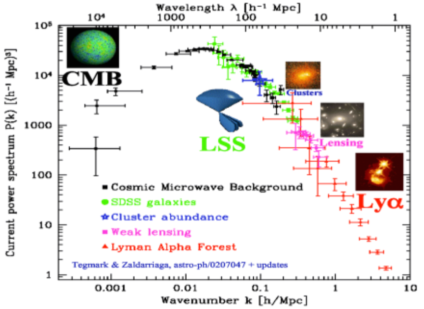
$\Sigma m_i > 67$ meV / 92 meV (nh/ih)

but we do not know the mass scale / the value of the lightest mass

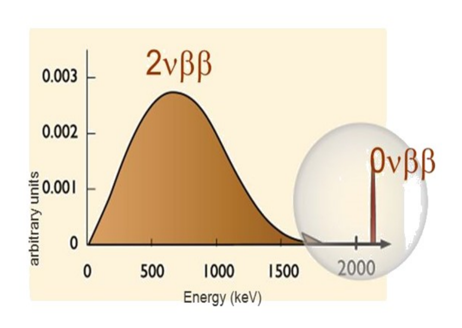
Measuring Neutrino Mass



β-endpoint spectroscopy
- influence on decay kinematics



Cosmology
- influence on structure formation



0ν2β – decay
- influence on decay rate

SN time of flight …

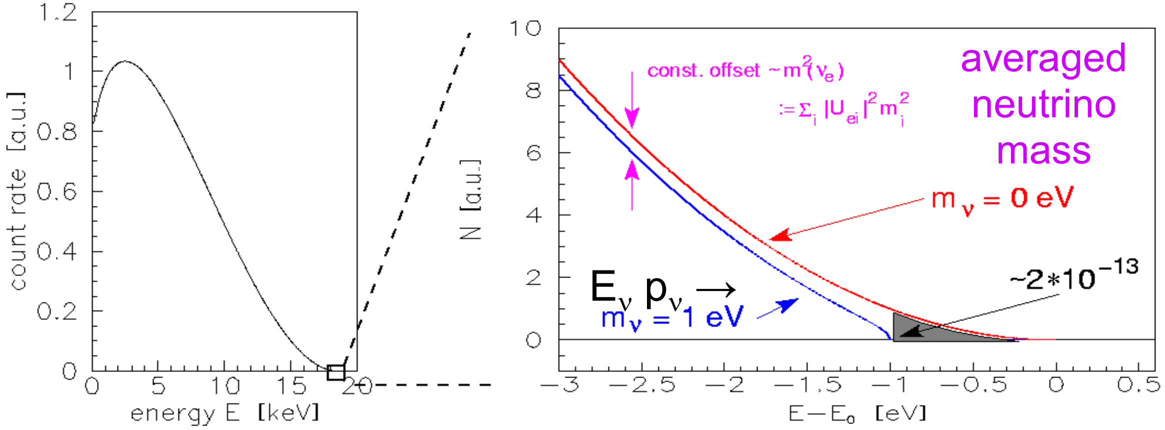
Determination of m_ν from β Decay

β decay: $(A,Z) \rightarrow (A,Z+1)^+ + e^- + \nu_e$

$$dN/dE_e = K\, F(E,Z+1)\, \underbrace{p}_{p_e}\, \underbrace{(E_e + m_e)}_{E_{e,tot}}\, \underbrace{(E_0-E_e)}_{E_\nu}\, \underbrace{\sqrt{(E_0-E_e)^2 - m^2(\nu_e)}}_{p_\nu}$$

phase space:

modified by electronic final states, recoil corrections, radiative corrections)

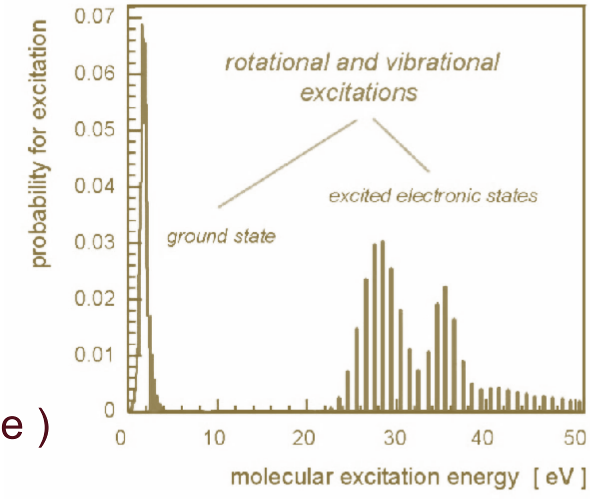


Need:	low endpoint energy	Tritium ^{3}H, (^{187}Re)
	very high energy resolution very high luminosity very low background	MAC-E-Filter or bolometer or new idea

Determination of m_ν from β Decay

electronic final state excited states have to be included:

- excitation energy V_j
- probability W_j



$$dN/dE_e = K\,F(E,Z+1)\,p\,(E_e + m_e)$$

$$\cdot \sum_j W_j\,(E_0-E_e-V_j)\sqrt{(E_0-E_e-V_j)^2 - m^2(\nu_e)}$$

- V_j not seen in MAC-E filter (+ scattering in the source)
- modifies phase space for all types of measurement

ν mixing:

$$dN/dE_e = K\,F(E,Z+1)\,p\,(E_e + m_e)$$

$$\cdot \sum_j W_j\,(E_0-E_e-V_j) \cdot \left(\sum |U_{ei}|^2 \cdot \sqrt{(E_0-E_e-V_j)^2 - m^2(\nu_i)} \right)$$

=> β endpoint measures effective ν mass: $m_\beta = \sum |U_{ei}|^2 \cdot m^2(\nu_i)$

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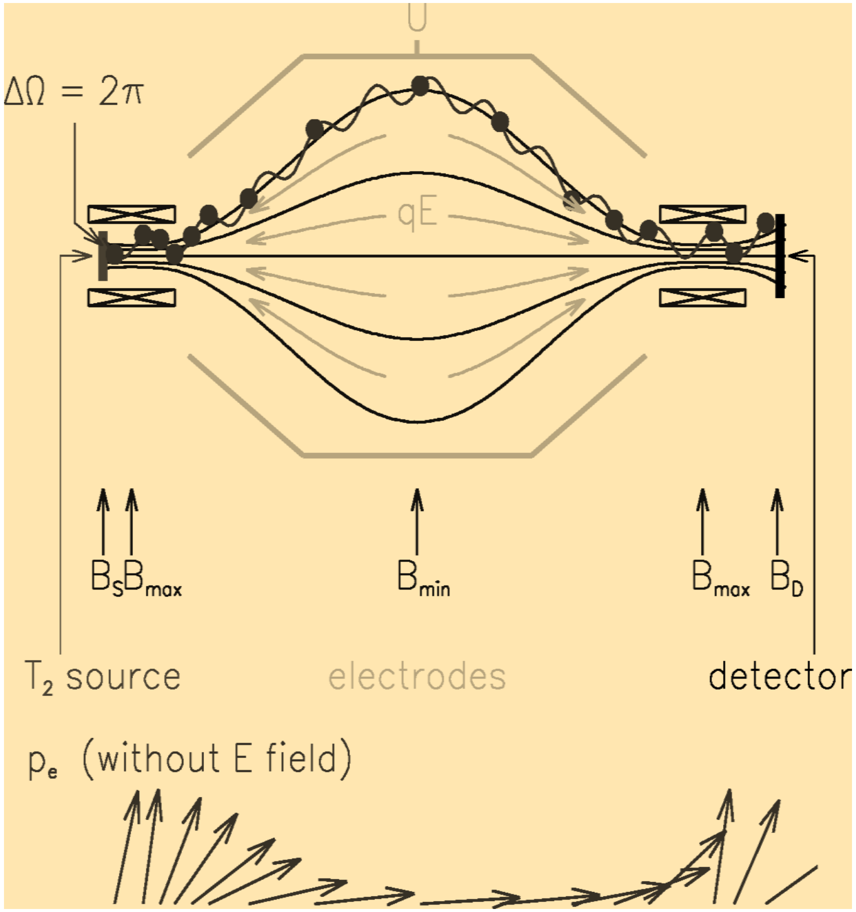
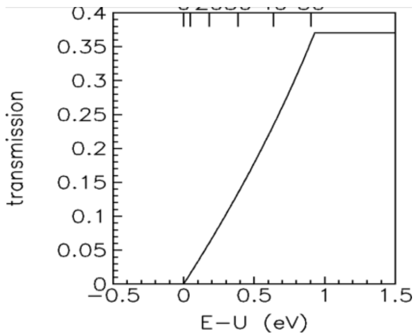
Tritium β-Spectroscopy with a MAC-E-Filter



- magnetic guiding field
- adiabatic transformation:
  $\mu = E_\perp / B = \text{const.}$
  ⇒ parallel e^- beam
- energy analysis by electrostat. retarding field
  $\Delta E = E \cdot B_{min}/B_{max}$
  $= 0.93$ eV (KATRIN)

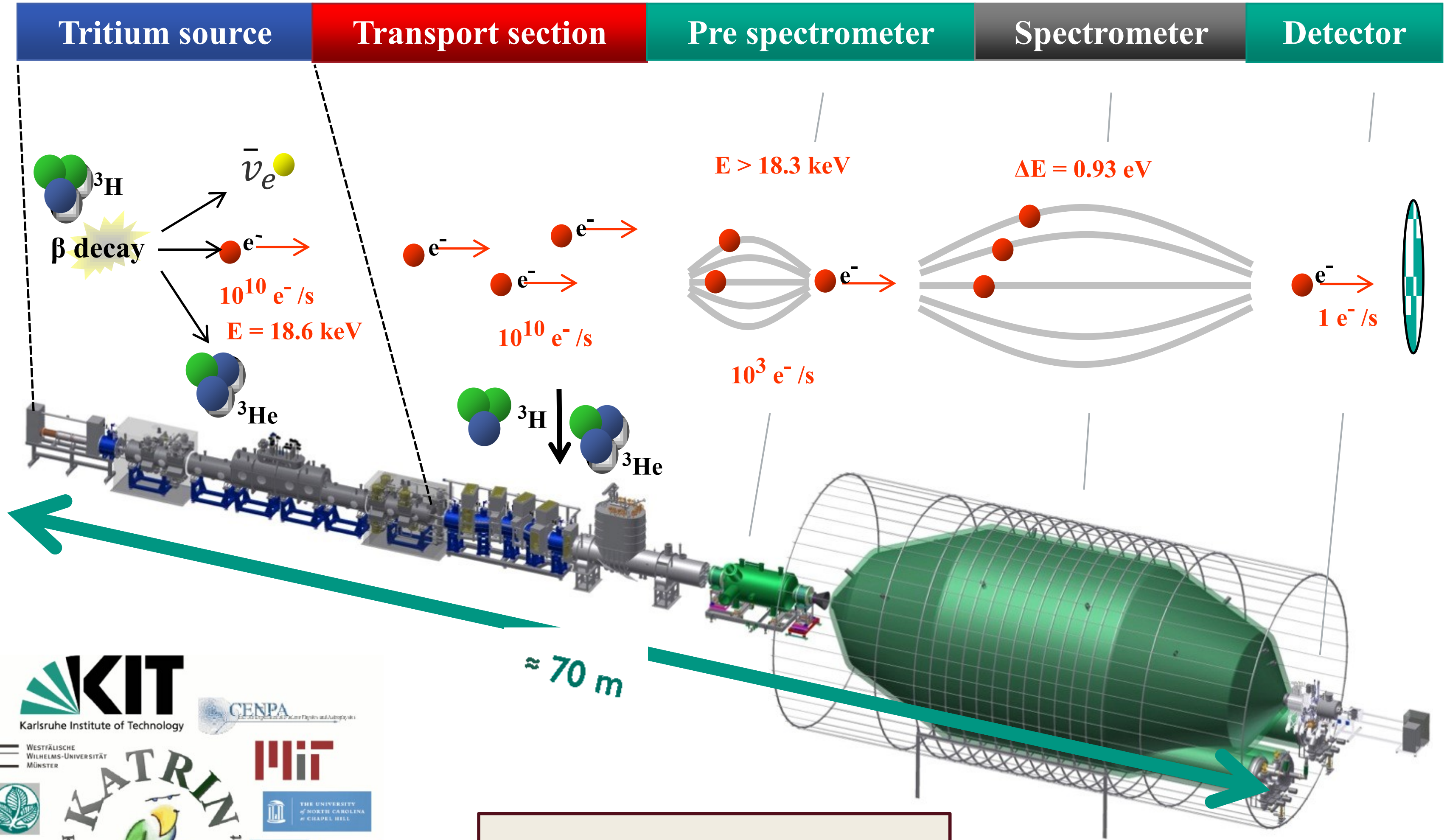
⇒ sharp integrating transmission function



<u>M</u>agnetic <u>A</u>diabatic <u>C</u>ollimation + <u>E</u>lectrostatic <u>Filter</u>
(A. Picard et al., Nucl. Instr. Meth. 63 (1992) 345)

ΔE ~ 1 / spectrometer ∅

KATRIN - The Karlsruhe Tritium Neutrino Experiment



Sensitivity on $m(\nu_e)$:

$2\ eV/c^2 \rightarrow 200 meV/c^2$

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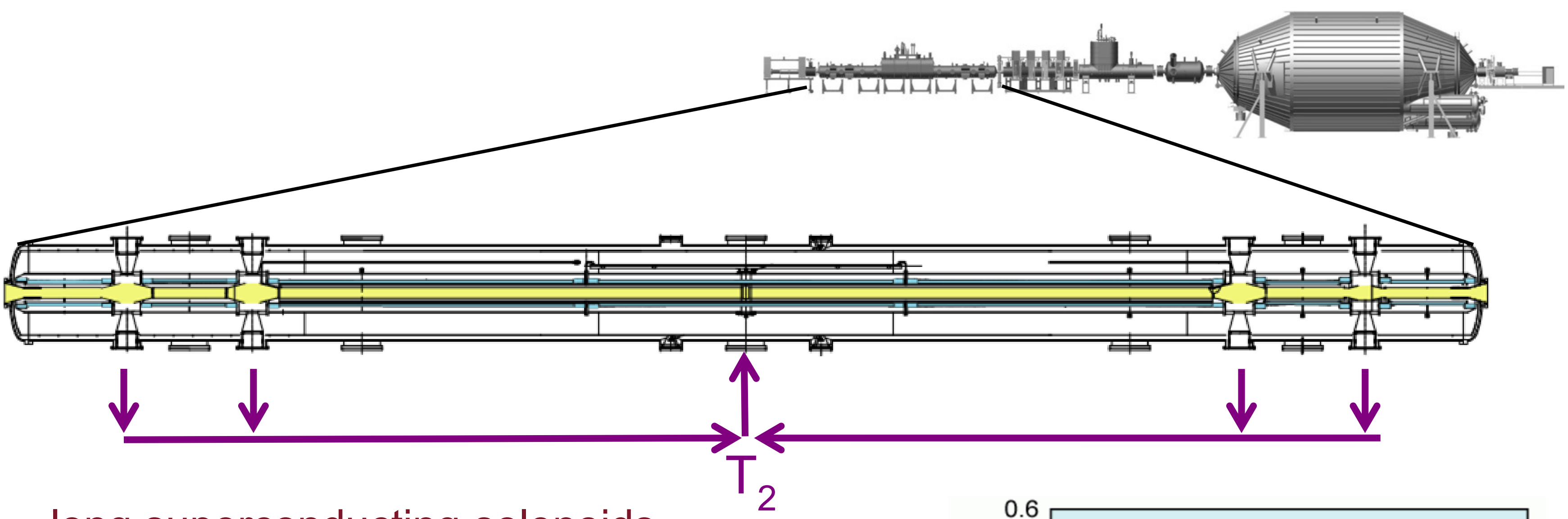
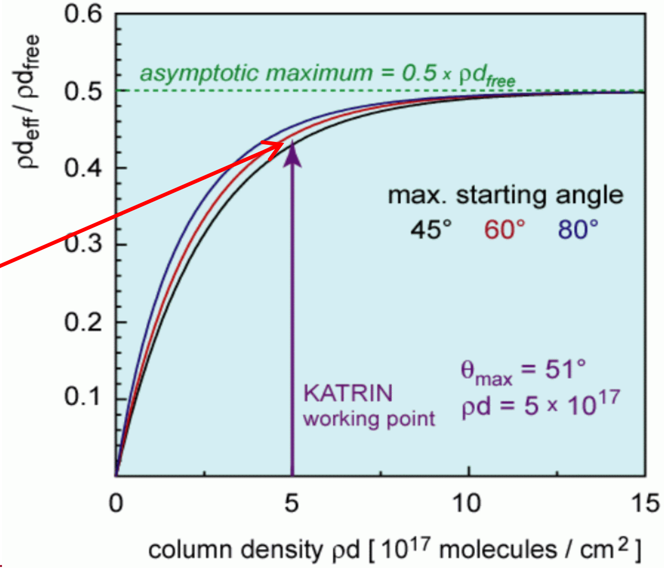
Molecular Windowless Gaseous Tritium Source



long superconducting solenoids
∅ 9cm, length: 10m, T = 30 K

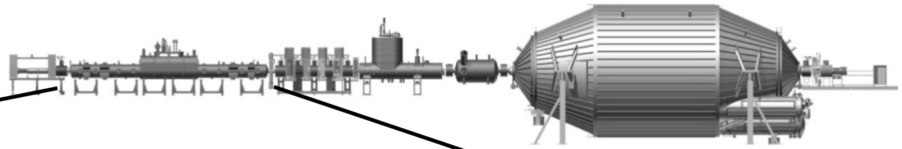
Tritium recirculation (and purification)
p_{inj} = 0.003 mbar, q_{inj} = 4.7Ci/s

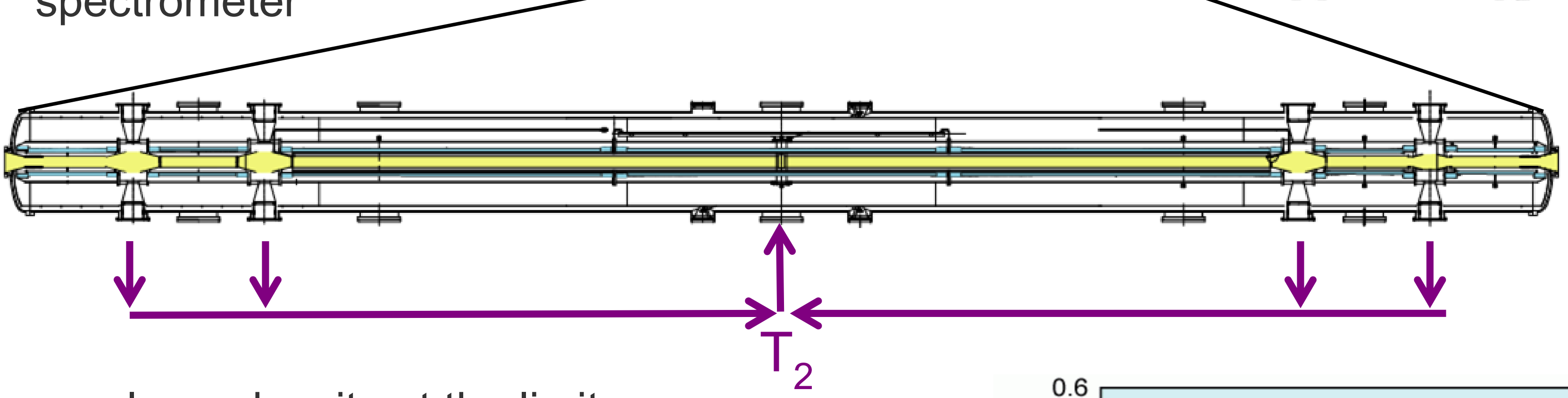
allows to measure with near to maximum count rate using
$\rho d = 5 \cdot 10^{17}/\mathrm{cm}^2$



Molecular Windowless Gaseous Tritium Source

KATRIN
the uiltimate MAC-E type
spectrometer



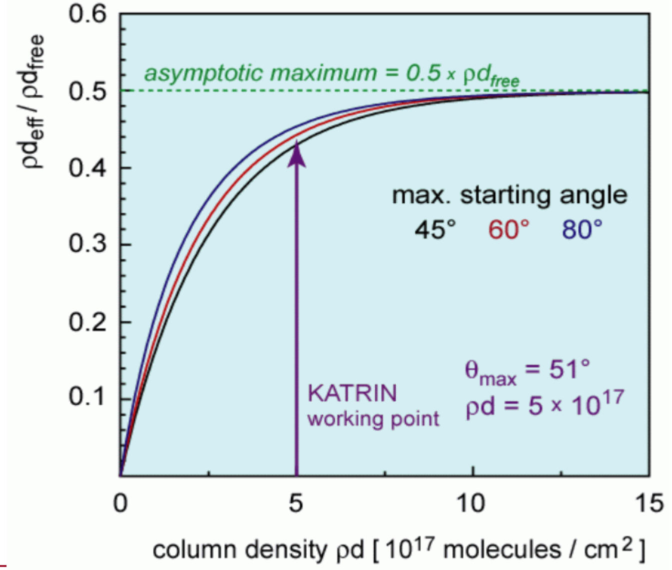


column density at the limit

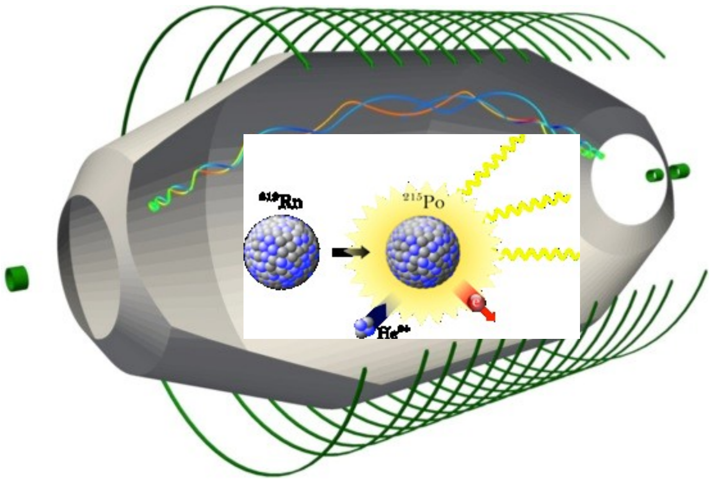
more intensive source
⇒ increase source-∅
⇒ needs larger spectrometer ∅
to keep sensitivity

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

improve sensitivity ΔE
=> even larger spectrometer ∅



KATRIN some News



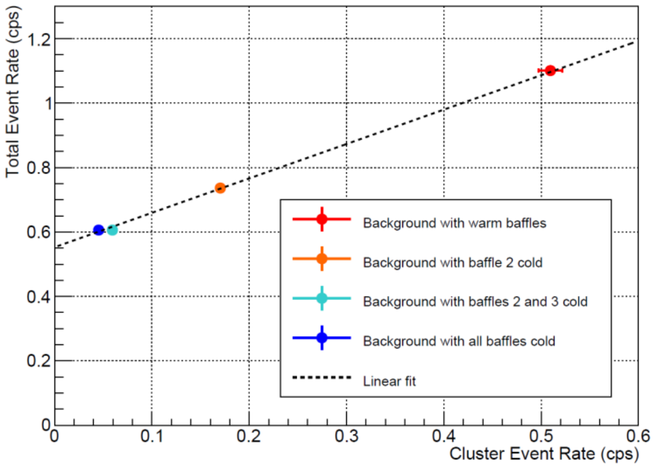
**spectrometer
transmission function (E,θ)**

- **characterized with e-beam**
- **well understood**

so far dominating background:

Rn emanation in getter pumps

- **completely removed by cryogenic baffles**



Systematic Uncertainties

contributions with $\delta m_{\nu}^2 \leq$ 0.007 eV^2 *(80meV)* **each:**

1. inelastic scatterings of β´s inside WGTS
   - **dedicated e-gun measurements**, unfolding of response fct.
2. fluctuations of WGTS column density (required < 0.1%)
   - rear detector, Laser-Raman spectroscopy, T=30K stabilisation, **e-gun measurements**
3. WGTS charging due to remaining ions (MC: < 20mV)
   - **monocrystaline rear plate short-cuts potential differences**
4. final state distribution
   - **reliable quantum chem. Calculations**

tritium source

5. transmission function
   - detailed simulations, **angular-selective e-gun measurements**
6. HV stability of retarding potential on ~3ppm level required
   - **precision HV divider (with PTB)**, **monitor spectrometer beamline**

spectrometer

Systematic Uncertainties

contributions wit

1. inelastic scatterings

- **dedicated** … nse fct.

2. fluctuations of WGT

- rear detec … bilisation,

e

3. WGTS charging du

- **monocrys** … **erences**

4. final state distributi

- **reliable q**

tritium source

5. transmission functi

- detailed s … **urements**

6. HV stability of retar

- **precision HV divi** … **amline**

spectrometer

sensitivity:

m_ν < 0.2eV (90%CL)

discovery potential:

m_ν = 0.3eV (3σ)

m_ν = 0.35eV (5σ)

start 2016/17

5y data taking

Cosmology and Neutrinomass

neutrino is most abundant particle (after photon)

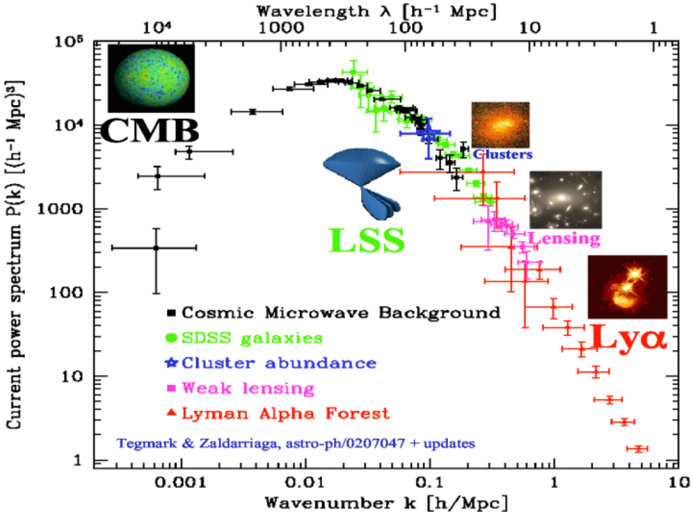
as higher Σm_ν
as higher neutrino contribution
to energy density in the Universe

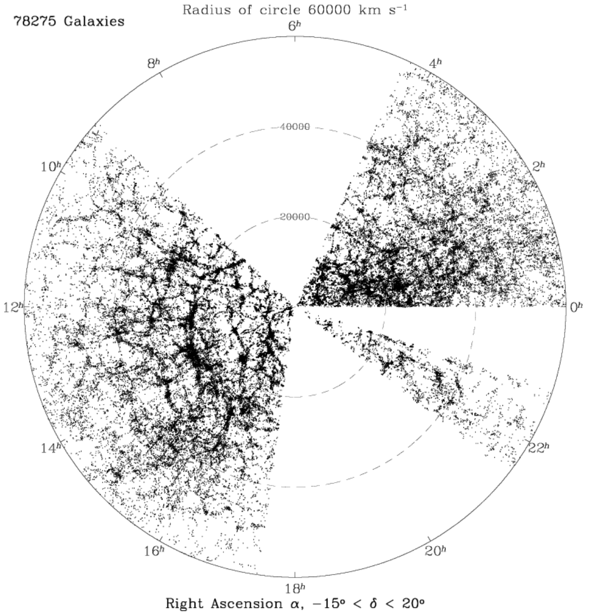
neutrinos are hot dark matter
=> damp structure growth at smaller scales

studying structure at differnt scales and z
is very sensitive to $\boldsymbol{\Sigma m_\nu}$

CMB, galaxy distribution, Lyman α, ...

very sensitive, but model dependent

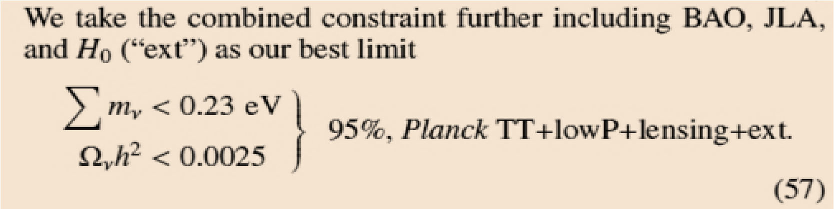




Cosmology and Neutrinomass

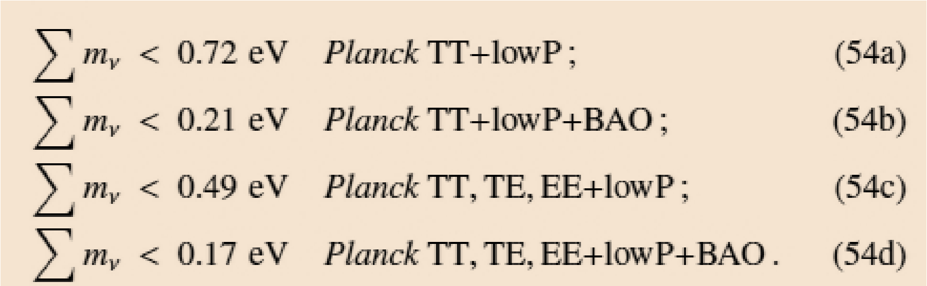
depending on the data sets included

limits on Σm_ν < 0.17 … 0.72 eV



We take the combined constraint further including BAO, JLA, and H_0 ("ext") as our best limit

$$\left.\begin{array}{l}\sum m_\nu < 0.23\ \text{eV}\\ \Omega_\nu h^2 < 0.0025\end{array}\right\}\ 95\%,\ \textit{Planck}\ \text{TT+lowP+lensing+ext.}\qquad (57)$$



$$\sum m_\nu < 0.72\ \text{eV}\quad \textit{Planck}\ \text{TT+lowP};\qquad (54a)$$
$$\sum m_\nu < 0.21\ \text{eV}\quad \textit{Planck}\ \text{TT+lowP+BAO};\qquad (54b)$$
$$\sum m_\nu < 0.49\ \text{eV}\quad \textit{Planck}\ \text{TT, TE, EE+lowP};\qquad (54c)$$
$$\sum m_\nu < 0.17\ \text{eV}\quad \textit{Planck}\ \text{TT, TE, EE+lowP+BAO}.\qquad (54d)$$

Planck best limit

Σm_ν < 0.23 eV

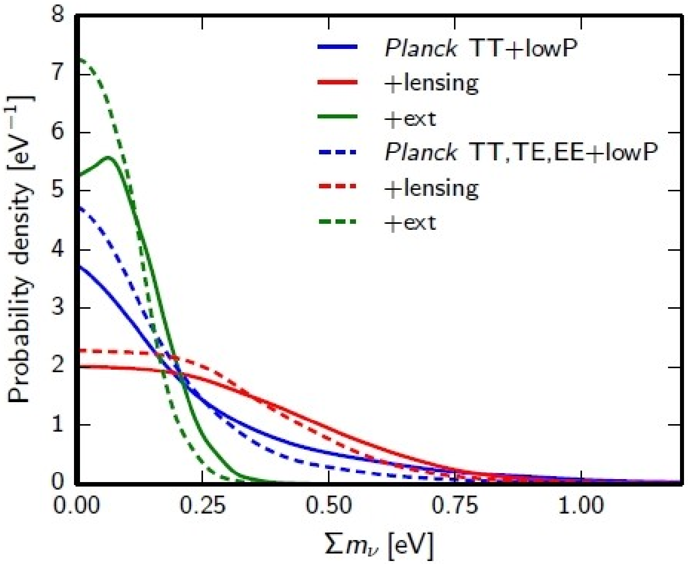


Fig. 30. Constraints on $\sum m_\nu$ for various data combinations.

EUCLID: launch 2020

microlensing (galaxy shapes)

as function of redshift z (spectroscopy)

⇒ 3D structure of a large part of visible Universe

⇒ can get as low as Σm_ν < 10 meV

⇒ must see the effect of neutrino-mass

β Decay vs Cosmology

Planck result

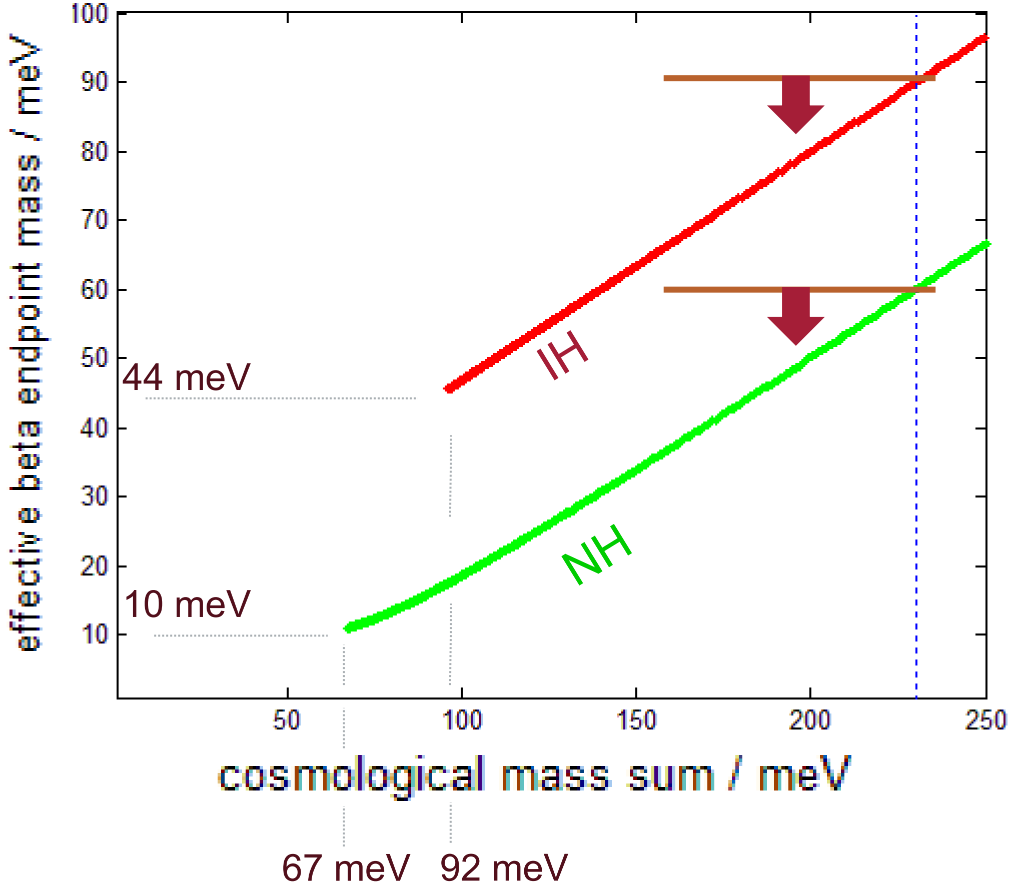
$\Sigma m_i < 230$ meV

corresponds to β limits of

$m_\beta < 60$ meV NH
$m_\beta < 90$ meV IH

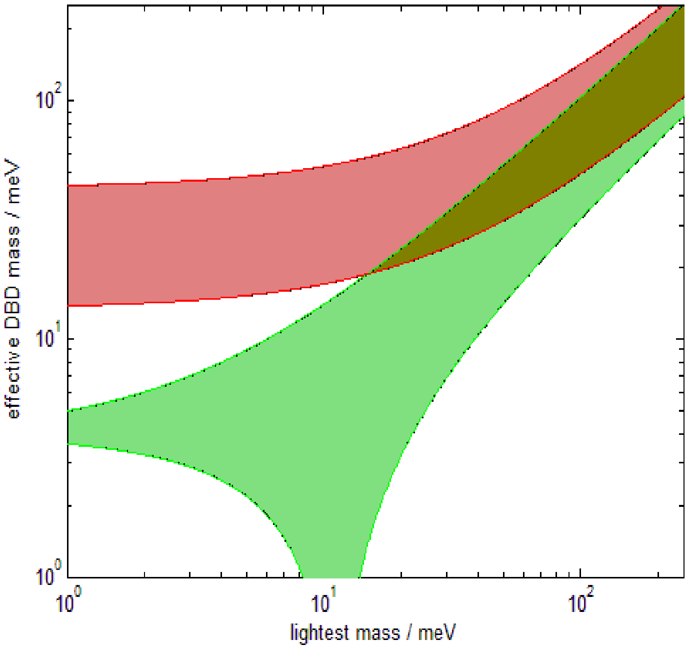
if KATRIN discovers sth, larger than this (sensitivity > 200meV)

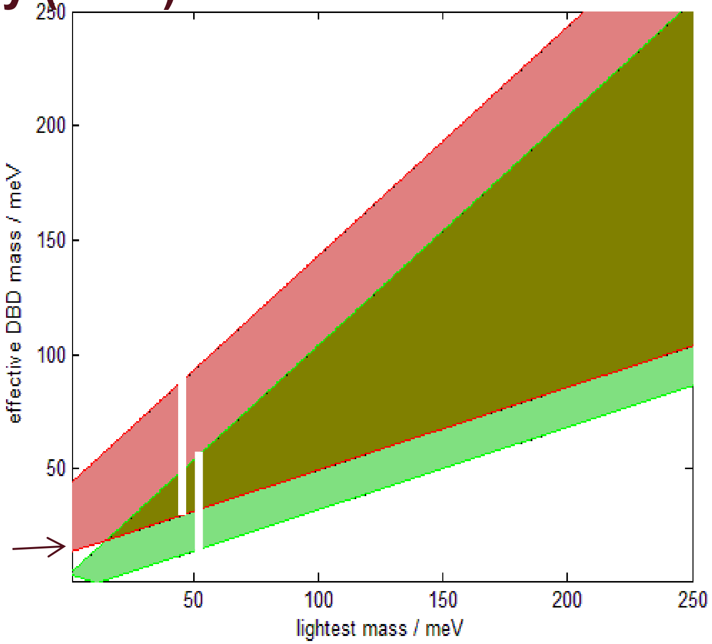
⇒ conflict / tension with cosmology



can we get m_{light}

double beta decay (DBD)





14 meV →

almost no information on m_{light} (may be $m_{light} > 0$)
could tell hierarchy only if

normal hierarchy and effective DBD mass < 14meV
but: errors in matrix elements, we don't know if ν is majorana

not really a mass measurement

DBD is about lepton number violation

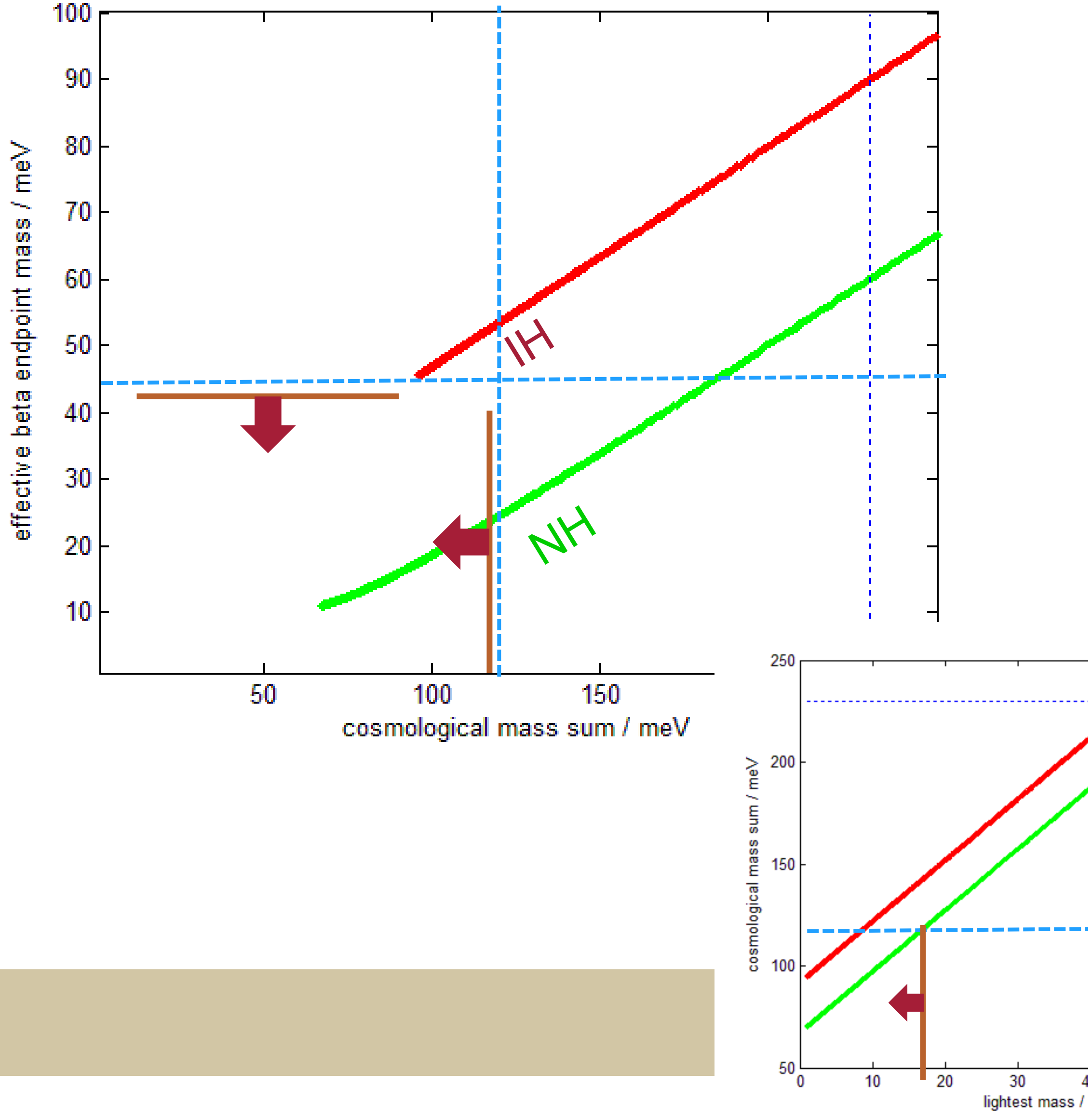
β Decay vs Cosmology

If we had a

~ (4-5) x better KATRIN (44 meV)

and an improved
sensitivity from cosmology

$\Sigma m_i < 120$ meV



cosmol.	β-endpoint
nothing	nothing

=> NH, m_{light} < 20meV

hierarchy	**yes**
m_{light} > 0	**no**

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β Decay vs Cosmology

If we had a

~ (4-5) x better KATRIN (44 meV)

and an improved
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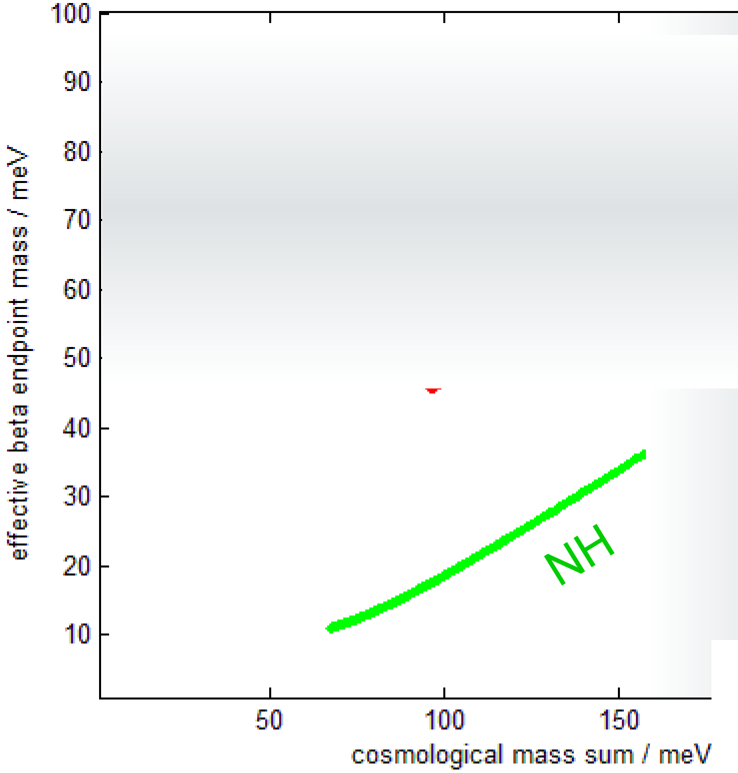
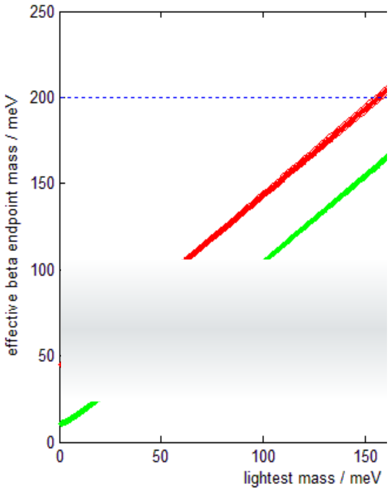
$\Sigma\ m_i < 120$ meV



cosmol.	β-endpoint
yes	yes

=> hierarchy, if errors small enough (+-15meV)
=> possibly $m_{light} > 0$ (relies on cosmology JUNO, ORCA, PINGU can help, NH easier)



hierarchy	**possibly**
m_{light} > 0	**yes**

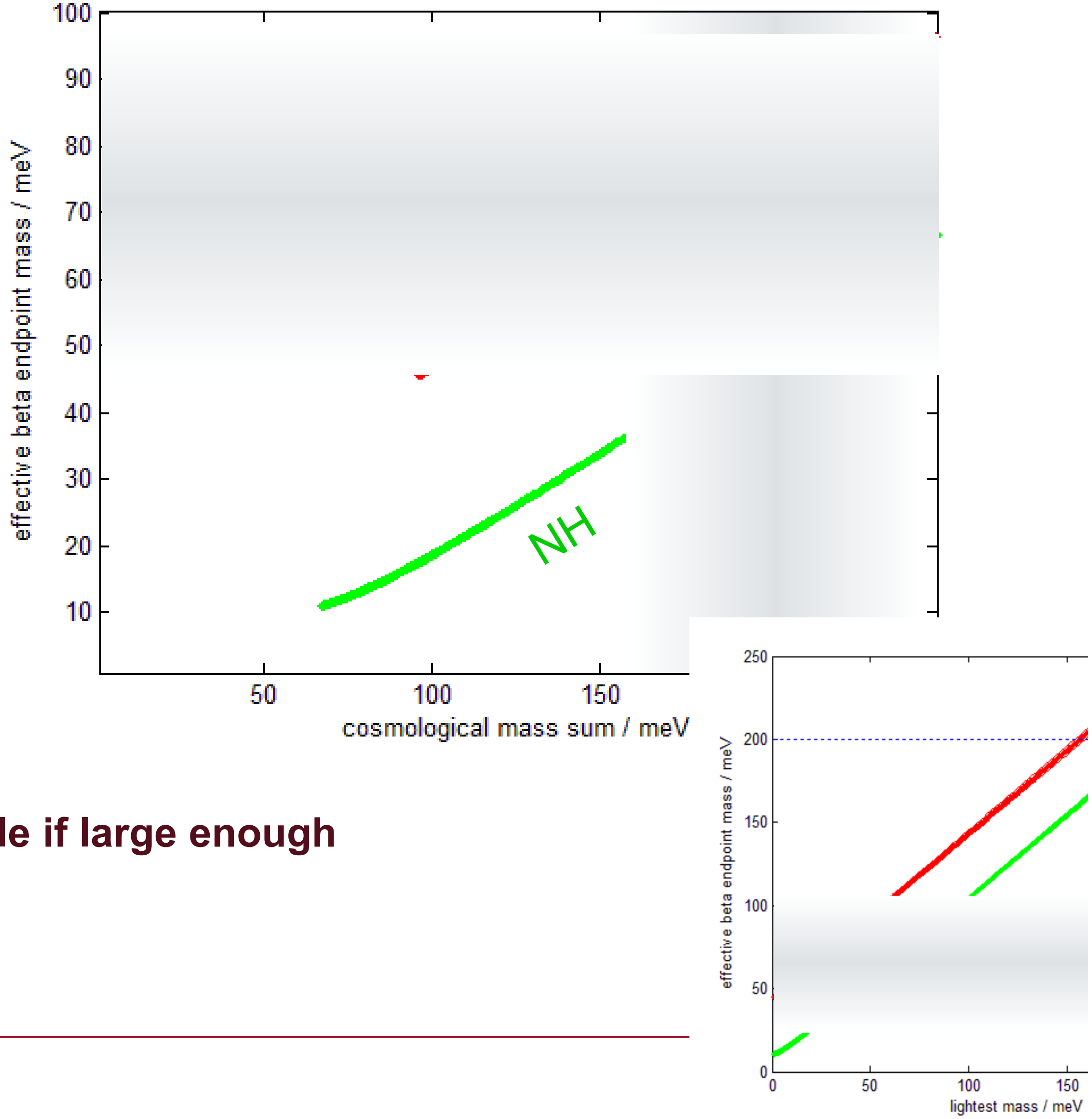
β Decay vs Cosmology

If we had a

~ (4-5) x better KATRIN (44 meV)

and an improved
sensitivity from cosmology

$\Sigma\, m_i < 120$ meV



It is worth the effort to look for techniques beyond KATRIN

- **together with cosmology can get hierarchy**

to get m_{light} > 0 might be possible if large enough

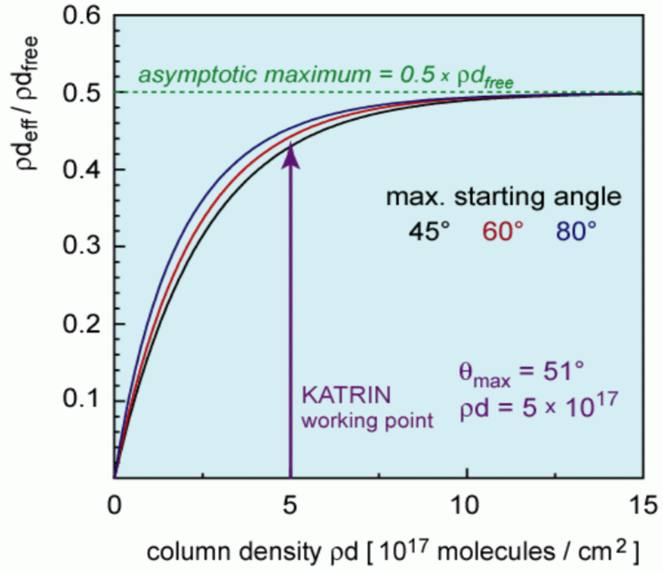
Beyond KATRIN ?

the source is opaque

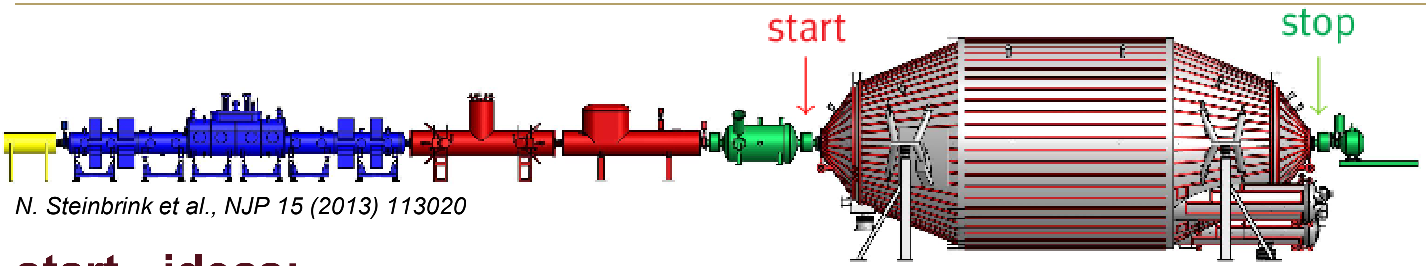
⇒ need to increase source Ø
magnetic flux conservation
requests larger spectrometer too,
but a Ø100m spectrometer is not feasible

⇒ make better use of electrons by **TOF**
(corresponds to higher statistics)

⇒ use synchrotron radiation from source
Project 8



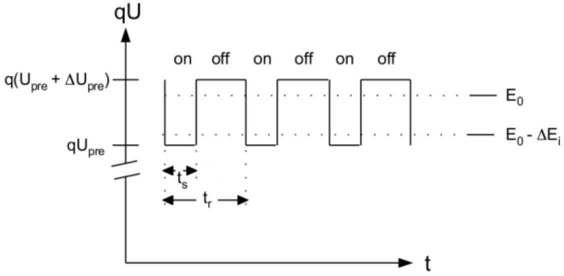
TOF in KATRIN Spectrometer



N. Steinbrink et al., NJP 15 (2013) 113020

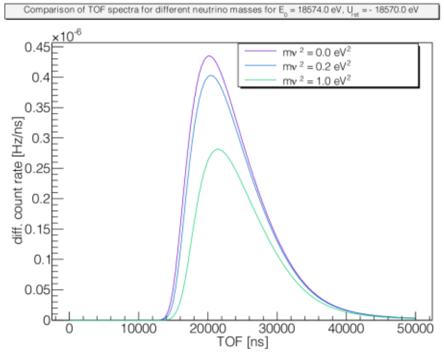
start - ideas:

- e^- tagger: needs to measure electron without disturbing it => ~ 10meV threshold ??
- use pre-spectrometer as gate



stop:

- time of arrival with present detector $\Delta t = 50$ ns → ok



advantage:

- measure many electron energies at one retarding potential
- corresponds to many spectrometer settings at once
- increase of statistics

factor 5 in mass sensitivity under ideal conditions

Project 8: Cyclotron Radiation of β - Electrons

US groups: PNNL, NRAO, Santa Barbara, Washington, MIT and KIT

KATRIN type tritium source
in uniform B field

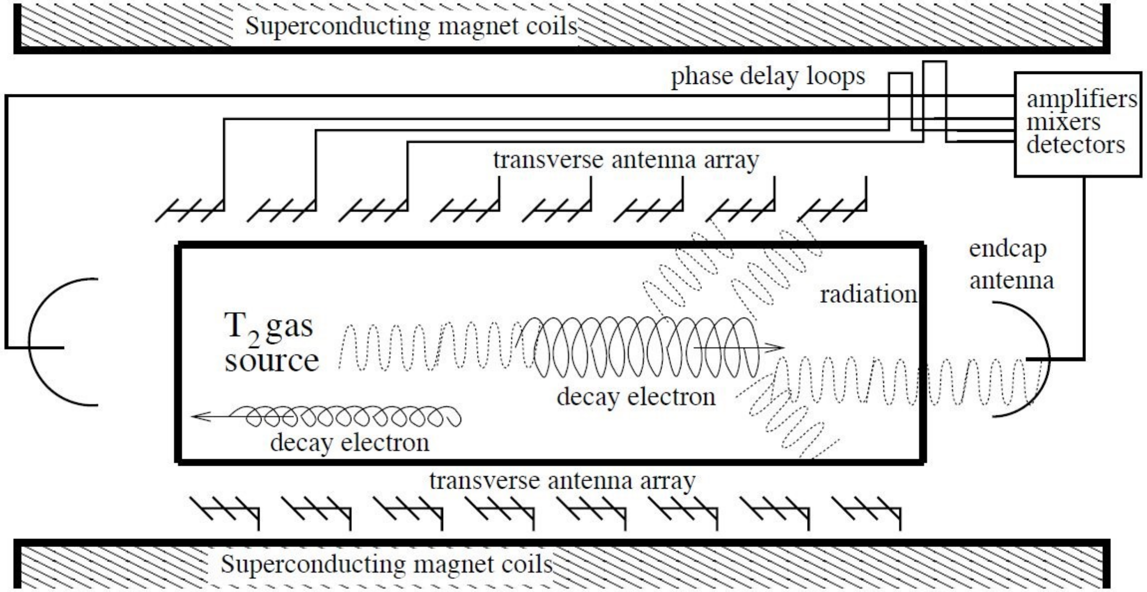
electron radiates
coherent cyclotron
radiation

$$\omega(\gamma) = \frac{\omega_0}{\gamma} = \frac{eB}{K+m_e}$$

antenna array for cyclotron
radiation detection

radiation can leave the source
and carries the information
of the β-electron energy

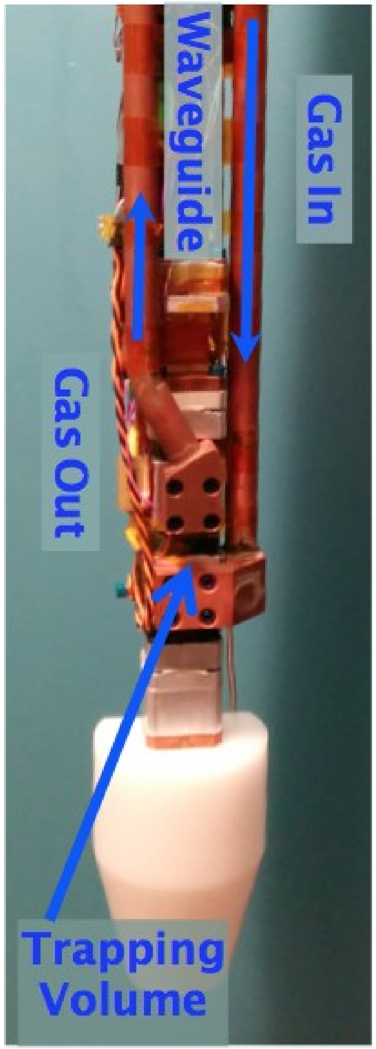
B. Monreal and J. Formaggio, PRD 80 (2009) 051301

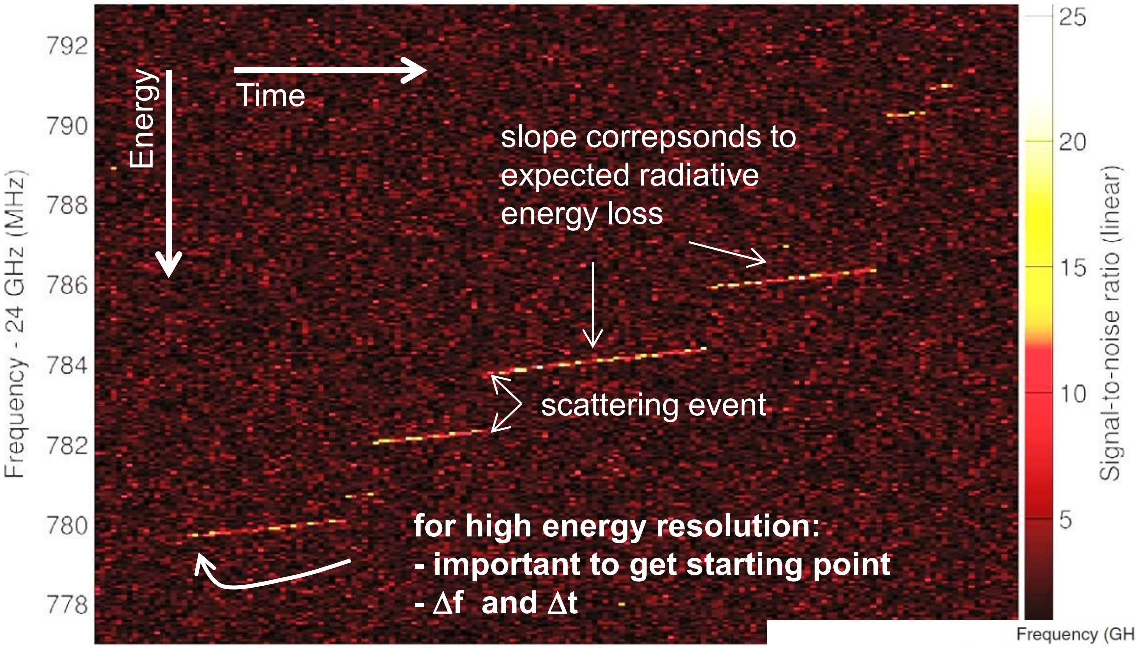


overcomes size limit to tritium source

Project 8: first single Electron Measurement

D. M. Asner et al., arXiv:1408.5362

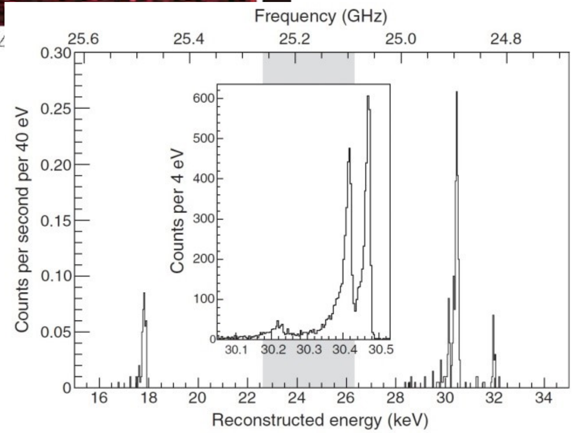




slope correpsonds to expected radiative energy loss

scattering event

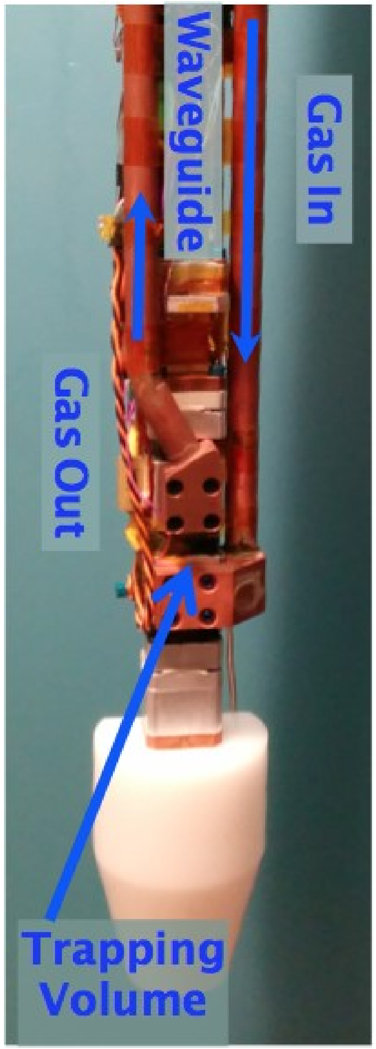
for high energy resolution:
- important to get starting point
- Δf and Δt

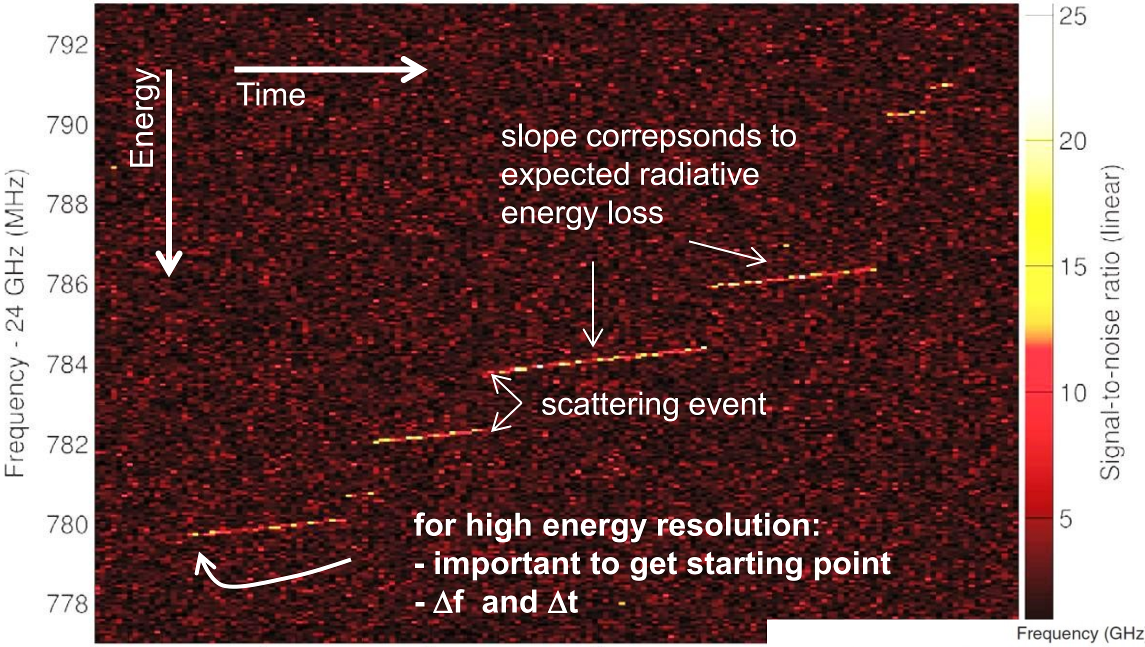


observed lines from Kr source

ΔE ~ 30eV, dominated
by inhom. trapping field
=> should be much better
in large source

Project 8: first single Electron Measurement

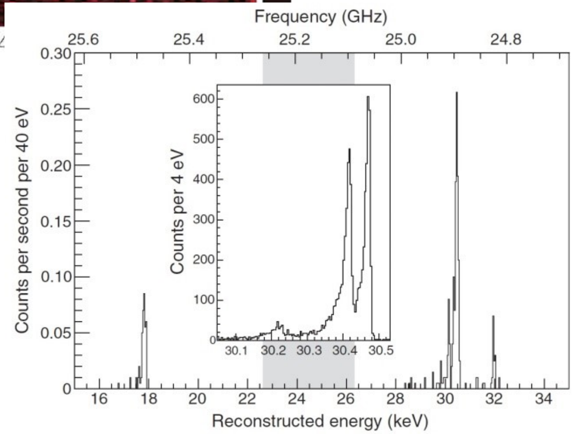




slope correpsonds to expected radiative energy loss

scattering event

for high energy resolution:
- important to get starting point
- Δf and Δt



proof of principle

needs to be developed into a large scale experiment

.

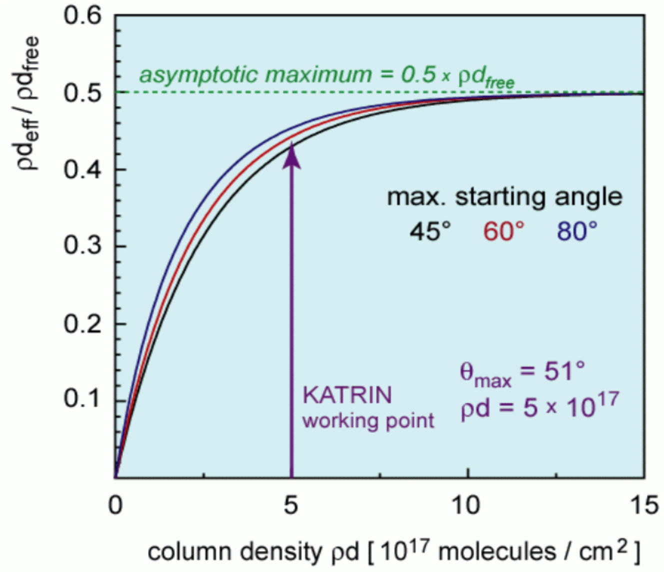
Beyond KATRIN ?

the source is opaque

⇒ need to increase source Ø
magnetic flux tube conservation
requests larger spectrometer too
but a Ø100m spectrometer is not feasible

⇒ make better use of electrons by **TOF**
(corresponds to higher statistics)

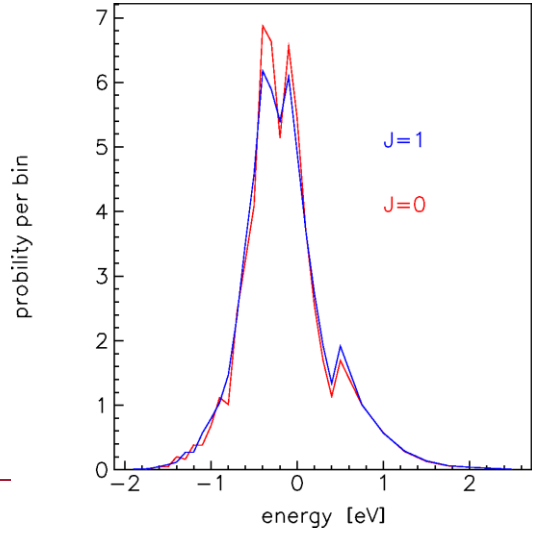
⇒ use synchrotron radiation from source
Project 8



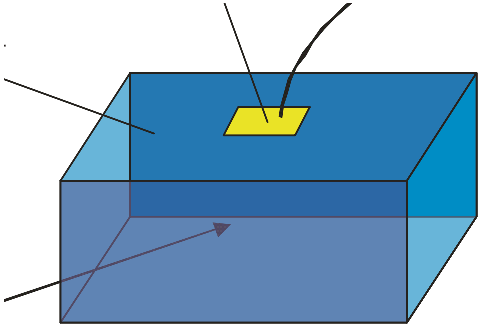
resolution with molecular Tritium
is limited to σ = 0.34 eV (m_β~ 80meV)
by the excitation of vibrational states
in the final state

⇒ **use atomic Tritium?** (Project 8)

⇒ calorimetry: source = detector
ECHO, HOLMES, NuMECS



Cryogenic Calorimeters



$\Delta T = \Delta E / C$

$C \sim T^3$ insulator; $\sim T$ metall

measures full absorbed energy
by temperature rise

high energy resolution ΔE

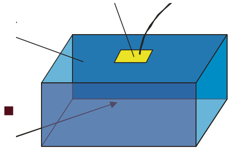
all energy except

energy carried away by ν

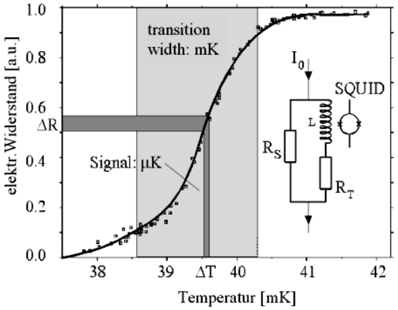
single final state experiment
$\Rightarrow$ no problems with
- inelastic scattering
- excited states
- backscattering …

but still, **phase space might be deformed** by excited states, or multiple de-excitation pathways

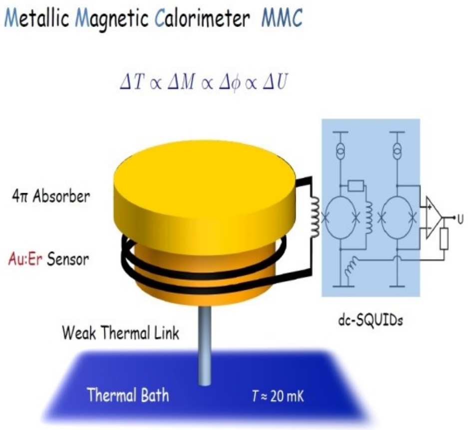
Calorimeters: TES, MMC, NTD …

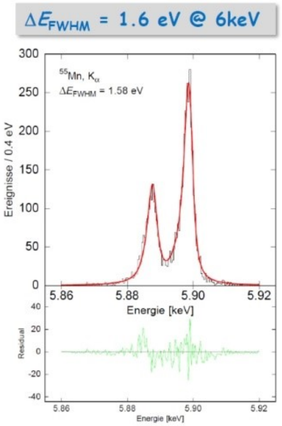


different types cryogenic calorimeters
differ in the way the temperature is measured



TES Superconducting Transition Edge Sensors: ΔT => ΔR
MMC Magnetic Micro Calorimeters: ΔT => ΔM
SQUID => ΔU
NTD semiconductor termistors: ΔT => ΔR => ΔU





no energy filter

⇒ has to cope with entire spectrum
⇒ as low as possible Q-value (Re, Ho)
⇒ pile up problem
⇒ **needs many detectors**
⇒ **needs fast detectors**

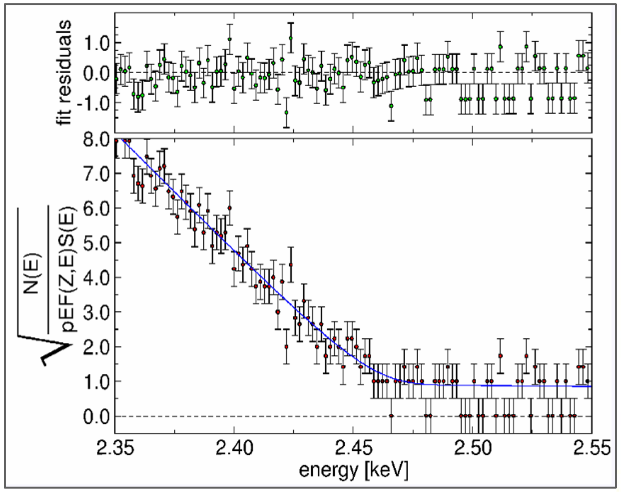
MARE Neutrino Mass Project: ^{187}Re β-Decay with Cryogenic Detectors

Q value: 2.465 keV

MARE (Mibeta, Manu)

- Italy, Germany, USA
- Si NTD Thermistors and TES
- 0.5 mg $AgReO_4$ crystals
- ΔE ~ 28eV

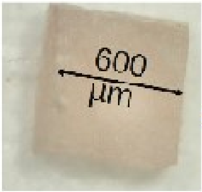
- goal 10^4 - 10^5 detectors

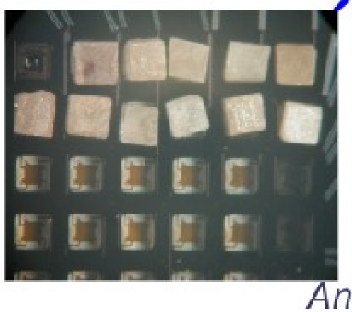


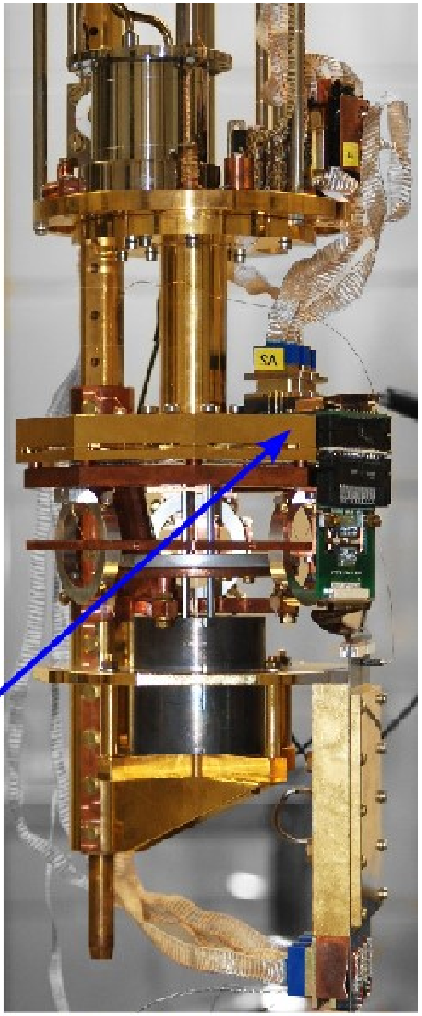
severe problems

- to build high resolution and fast detectors with Re-absorbers
- very large amount of Re were needed

⇒ stopped
⇒ continue with **EC capture in ^{163}Ho**
⇒ HOLMES, ECHO, NuMECS,







Angelo Nucciotti, Meudon 2011

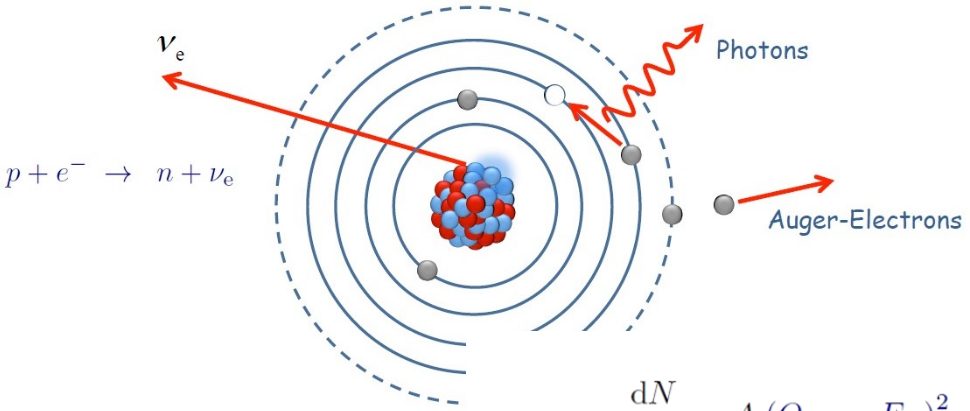
Neutrino Mass from ^{163}Ho Electron Capture

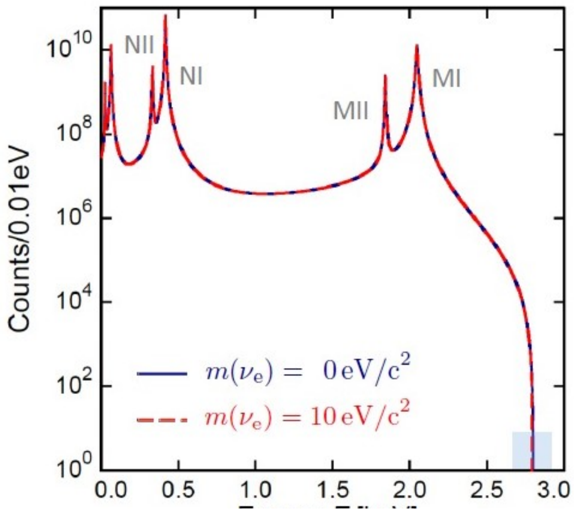
A. De Rujula, M. Lusignoli,
Phys. Lett. B 118 (1982) 429

$$^{163}_{67}\mathrm{Ho} \rightarrow {}^{163}_{66}\mathrm{Dy}^* + \nu_e$$

$$\hookrightarrow {}^{163}_{66}\mathrm{Dy} + E_C$$

Q value: (2.5-2.8) keV



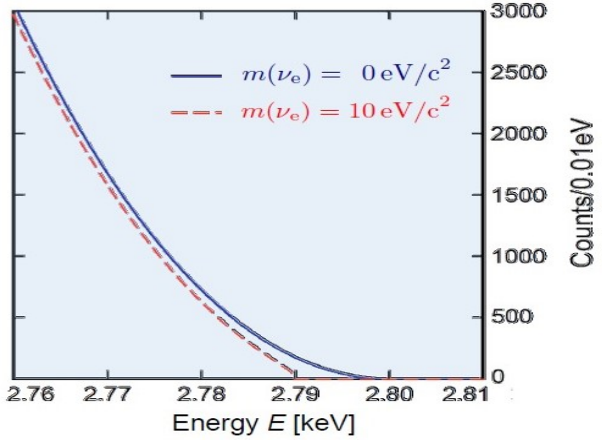


$$\frac{\mathrm{d}N}{\mathrm{d}E_C} = A\,(Q_{EC} - E_C)^2 \sqrt{1 - \frac{m_\nu^2}{(Q_{EC} - E_C)^2}} \sum_j C_j n_j B_j \phi_j^2(0) \frac{\Gamma_j/2\pi}{(E_C - E_j)^2 + \Gamma_j^2/4}$$

HOLMES – TES sensors
INFN (Milano, Genova, LNGS…), NIST, ClTech, PSI, ILL …

ECHO – MMC sensors
Germany (Heidelberg, Mainz, Dresden, Tübingen, Frankfurt, Berlin)
France, Slovakia, Russia, India

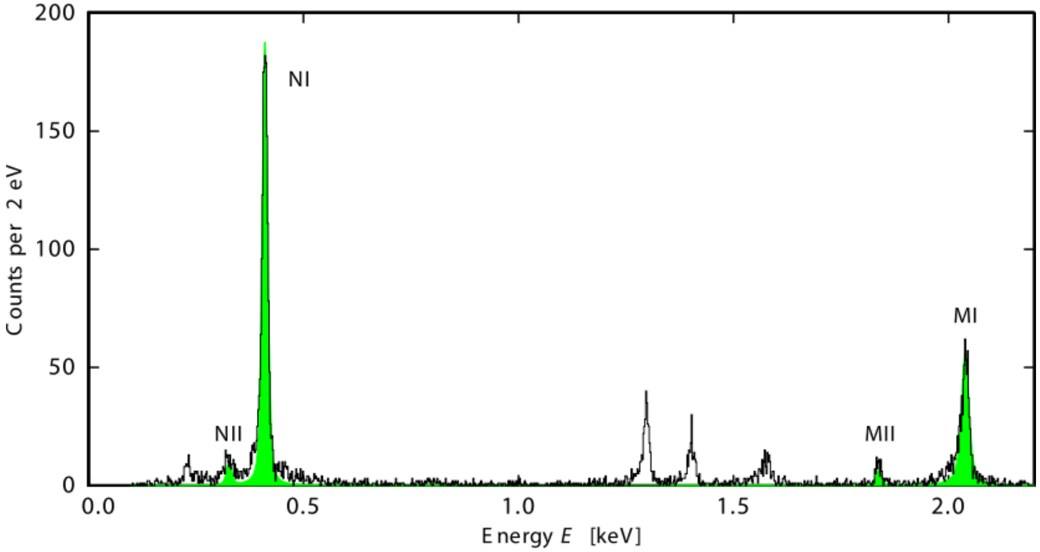
NuMECS
USA



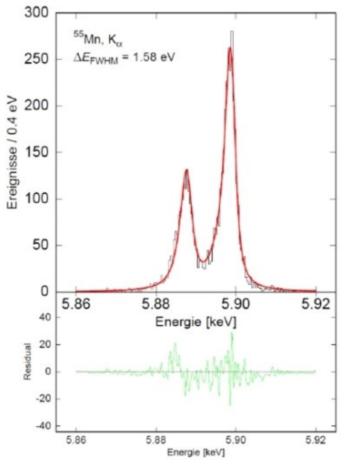
ECHo: ^{163}Ho EC Spectrum with MMC

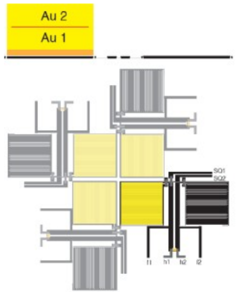
high energy resolution

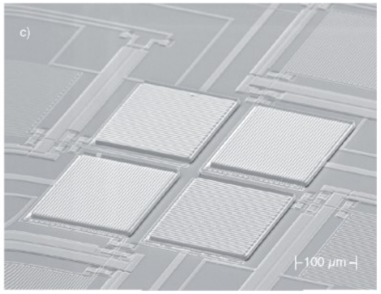
$^{163}\mathrm{Ho} + e^- \rightarrow {}^{163}\mathrm{Dy}^* + \nu_e \rightarrow {}^{163}\mathrm{Dy} + \gamma/e^- + \nu_e$

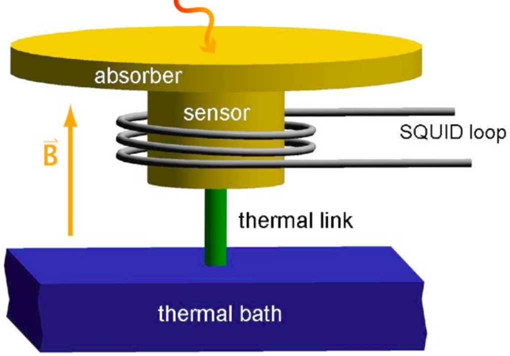


ΔE_{FWHM} = 1.6 eV @ 6keV









courtesy L. Gastaldo

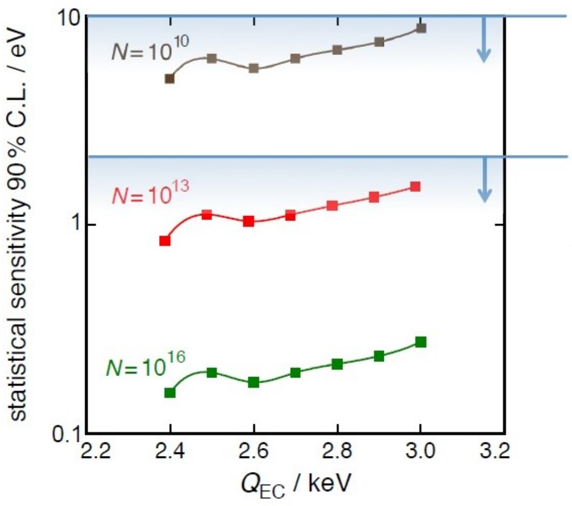
Technology for large Number of Pixels

no filter for events far from endpoint

⇒ **needs large number of counts**

⇒ **needs large number of pixels**

$$\Delta E_{\mathrm{FWHM}} = 3\,\mathrm{eV}, \qquad f_{\mathrm{pu}} = A\,\tau_{\mathrm{R}} = 10^{-6}$$



ECHo-1k

2 x 50 pixel x 10 Bq

4 months ⇒ 10^{10} events

ECHo-1M

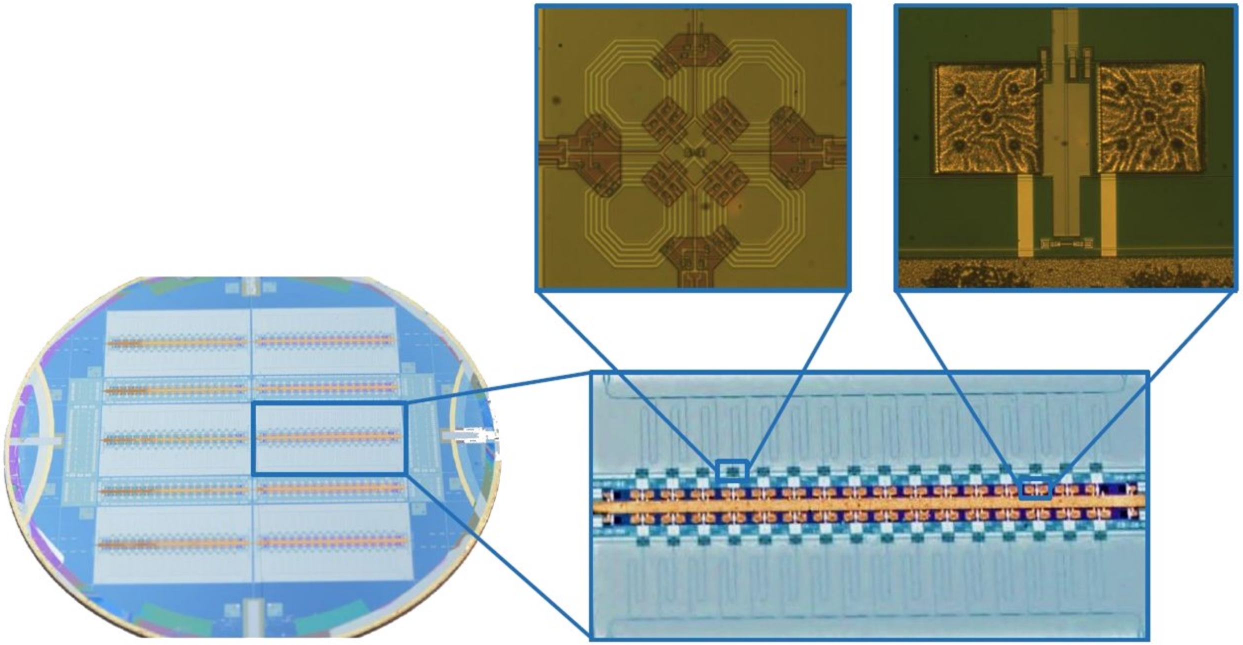
50 x 2000 pixel x 10 Bq

24 months ⇒ 6 x 10^{13} events

needs

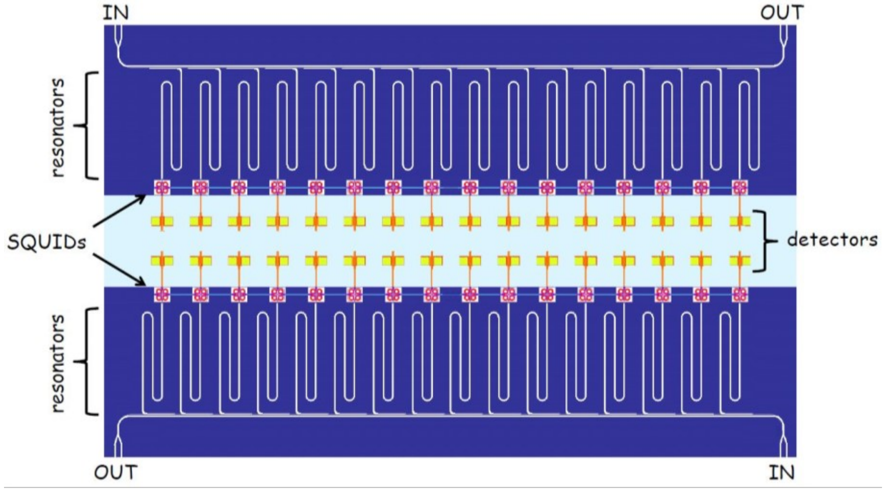
~ 10^{10} counts for m ~ 10 eV

~ 10^{13} counts for m ~ sub 1 eV



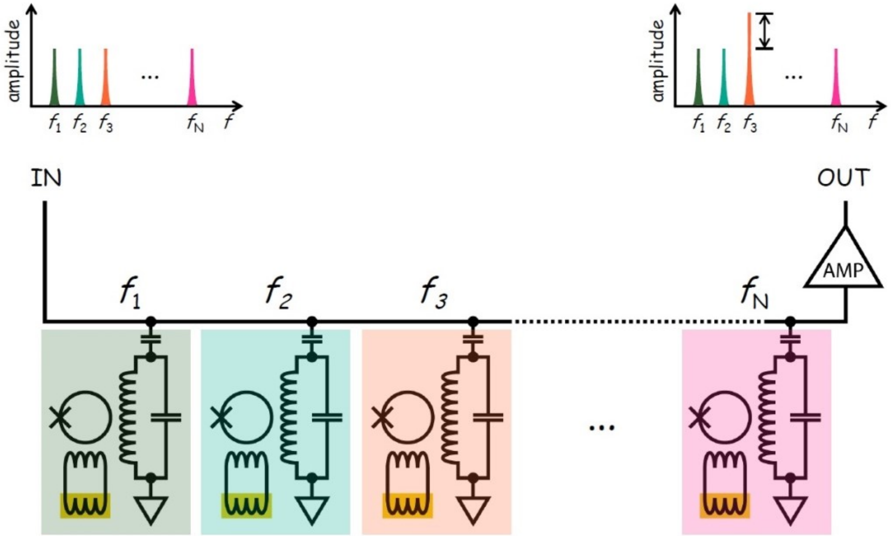
technology to read
out such large
pixel numbers
is available and proven

Technology for large Number of Pixels



no filter for events far from endpoint
⇒ needs large number of counts
⇒ needs large number of pixels

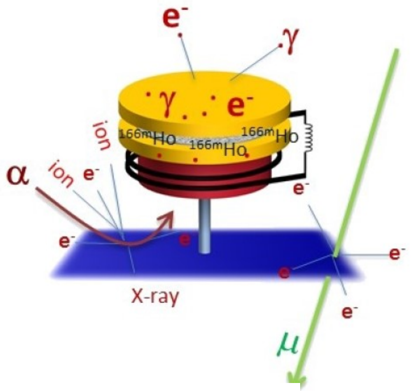
technology is available and proven

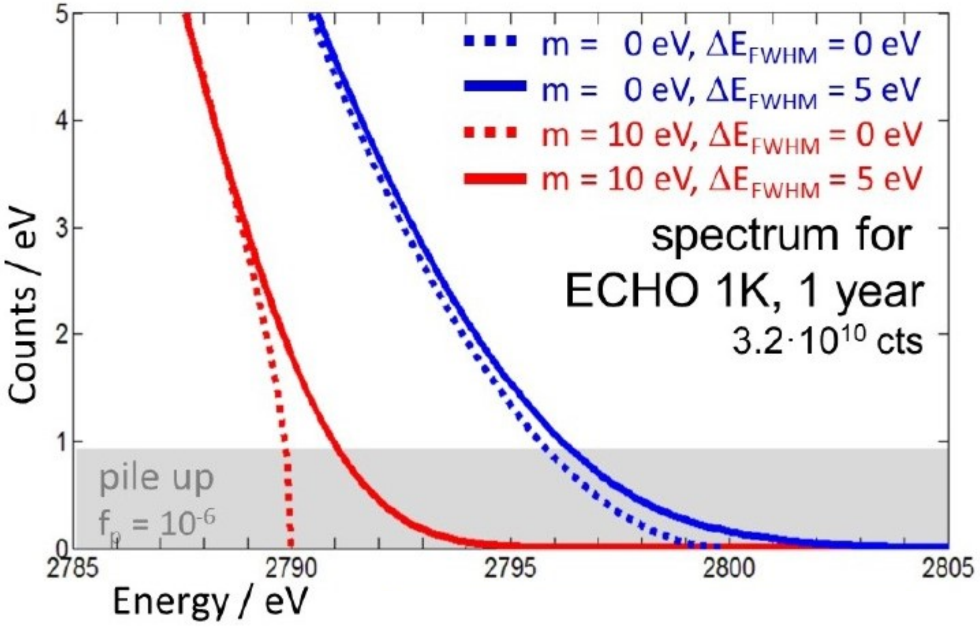


frequency multiplexing

⇒ one line, one amplifier
for many pixels

Backgrounds



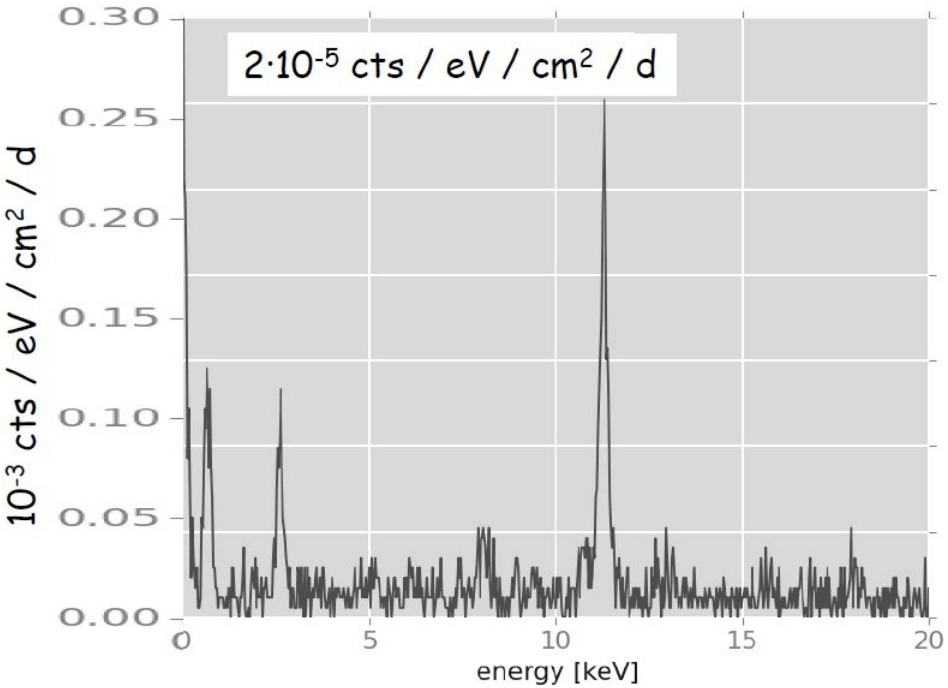


counts in 10eV below Q-value	
expected signal m_ν = 0eV / 10eV	30 / 5
pile up	10
background 10^{-5} cts/ev/d/det	5
sum	45 ±10 / 20 ±7

background level of 10^{-5} cts/eV/d/det or better should be possible

EBERHARD KARLS UNIVERSITÄT TÜBINGEN

Backgrounds: scaling from CRESST



scaled

by mass

~ 10^{-11} cts /eV/det/d

by volume

~ $4{\cdot}10^{-12}$ cts /eV/det/d

by surface

~ 10^{-8} cts /eV/det/d

ECHo

mass	$4{\cdot}10^{-6}$ g / det
volume	$2{\cdot}10^{-7}$ cm³ / det
surface	$4{\cdot}10^{-4}$ cm² / det

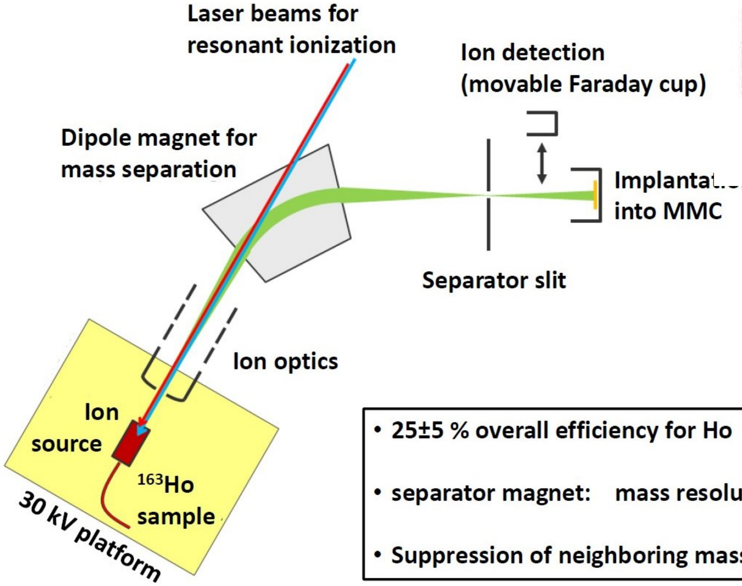
background level of 10^{-5} cts/eV/d/det or better should be possible

Backgrounds: ^{166}Ho in ^{163}Ho-Source

Production of Ho-163 source via n-activation of Er-162-target

chemical purification before and after irradiation

⇒ but still co-production of Ho-166m



- 25±5 % overall efficiency for Ho
- separator magnet: mass resolution ~500
- Suppression of neighboring mass: ~10^5 x

⇒ mass separation
before implantation
into detector pixels

background level of 10^{-5} cts/eV/d/det or better should be possible

Pile up: fast Detectors are very important

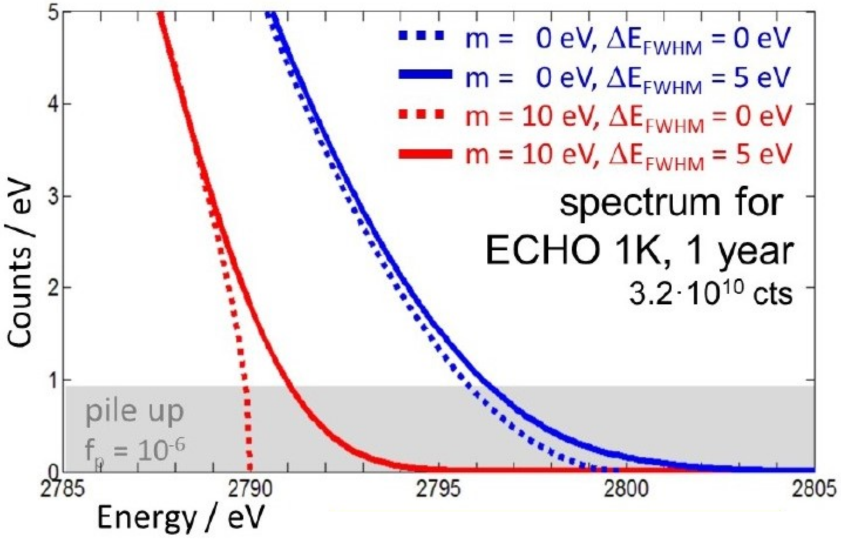
number of pile up events = number of collected events * pile up fraction f_{pp}

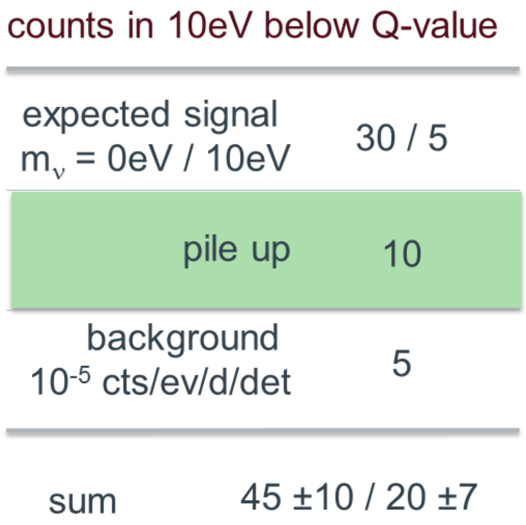
$f_{pp} = \tau_{rise} * A_{det}$

τ_{rise} rise time / time resolution to recognize pile up
A_{det} activity in each detector pixe

fraction of pile up events in last eV: $\sim f_{pp} * 10^{-6}$
fraction of signal counts in last ev: $\sim \quad * 10^{-12}$

maximal tolerable $f_{pp} \sim 10^{-6}$ => $\tau_{rise} < 1\ \mu s$; A_{det} not larger than 10 Bq
=> needs large number of detector pixels





counts in 10eV below Q-value	
expected signal m_ν = 0eV / 10eV	30 / 5
pile up	10
background 10^{-5} cts/ev/d/det	5
sum	45 ±10 / 20 ±7

Calorimeters – next Steps

ECHO – 1K / funded 100 detectors / 10Bq	better than 10eV within 3 years
ECHO – 1M 100000 detectors / 10Bq	better than 1eV within another 3 years
HOLMES / funded 5y (ERC) 1000 detectors / 300 Bq	reach 1 eV sensitivty within 5 years

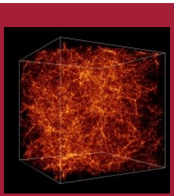
demonstrate scalability

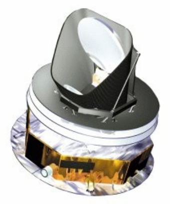
⇒ sub-eV sensitivity

- scalability
- stability of a large number of pixels
- backgrounds
- pile up
- understanding the spectrum
- can one really get ‘beyond KATRIN’

Measuring Neutrino Mass

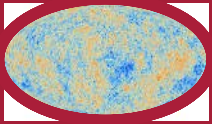
- we know Σm_ν is nonzero





- KATRIN will measure $m_\beta = \Sigma \ |U_{ei}|^2 \ m^2(\nu_i)$
  with 200meV sensitivity

- measurements from cosmology tell $\Sigma m_\nu < 230$ meV …. 700 meV
  will get even better



- we would like to have $m_\beta \sim 45$meV sensitivity or better

  => several techniques:
  TOF, cyclotron radiation, calorimeters

- in ~ 10 years: we will know hierarchy and may be even m_{light}

- possible to look for sterile neutrinos