The neutrino mass scale: Where do we go?

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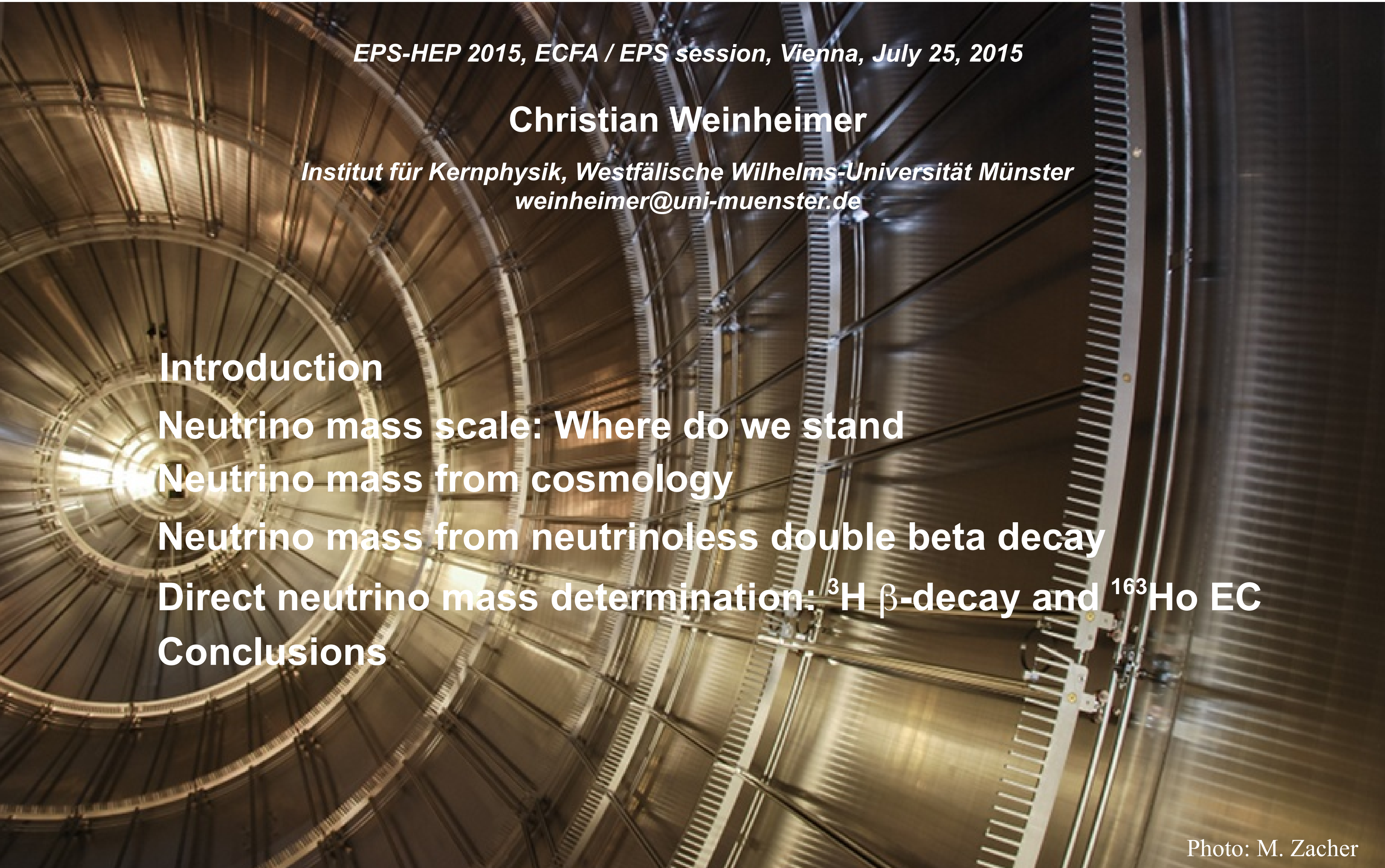

EPS-HEP 2015, ECFA / EPS session, Vienna, July 25, 2015

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- Introduction
- Neutrino mass scale: Where do we stand
- Neutrino mass from cosmology
- Neutrino mass from neutrinoless double beta decay
- Direct neutrino mass determination: ^{3}H β-decay and ^{163}Ho EC
- Conclusions

Photo: M. Zacher

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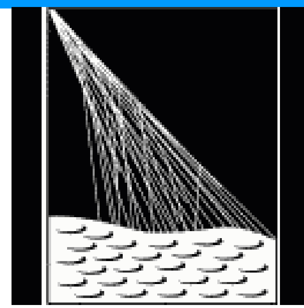
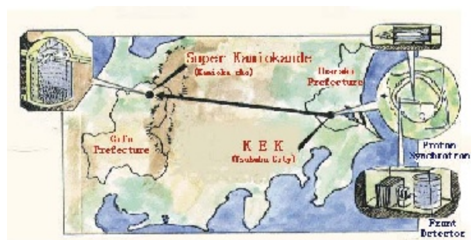
Positive results from ν oscillation experiments

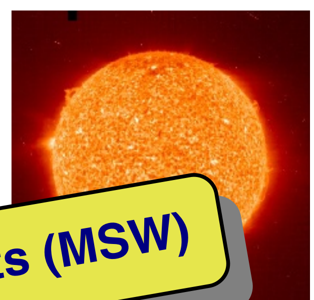
atmospheric neutrinos
(Kamiokande,
Super-Kamiokande, ...)



accelerator neutrinos
(K2K, T2K, MINOS,
OPERA, MiniBoone)

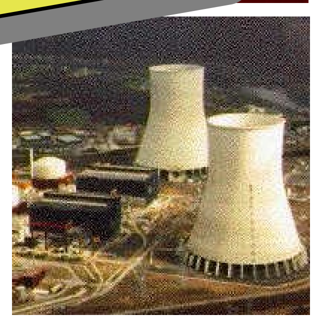


solar neutrinos
(Homestake, Gallex,
Sage, Super-Kamiokande,
SNO, Borexino)



Matter effects (MSW)

reactor neutrinos
(KamLAND, CHOOZ, Daya Bay,
DoubleCHOOZ, RENO, ...)



⇒ non-trivial ν-mixing

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} \cdot \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

with:

$0.37 < \sin^2(\theta_{23}) < 0.63$ maximal!

$0.26 < \sin^2(\theta_{12}) < 0.36$ large !

$0.018 < \sin^2(\theta_{13}) < 0.030$ 8.9°

$7.0\ 10^{-5}\ \mathrm{eV}^2 < \Delta m_{12}^2 < 8.2\ 10^{-5}\ \mathrm{eV}^2$

$2.2\ 10^{-3}\ \mathrm{eV}^2 < |\Delta m_{13}^2| < 2.6\ 10^{-3}\ \mathrm{eV}^2$

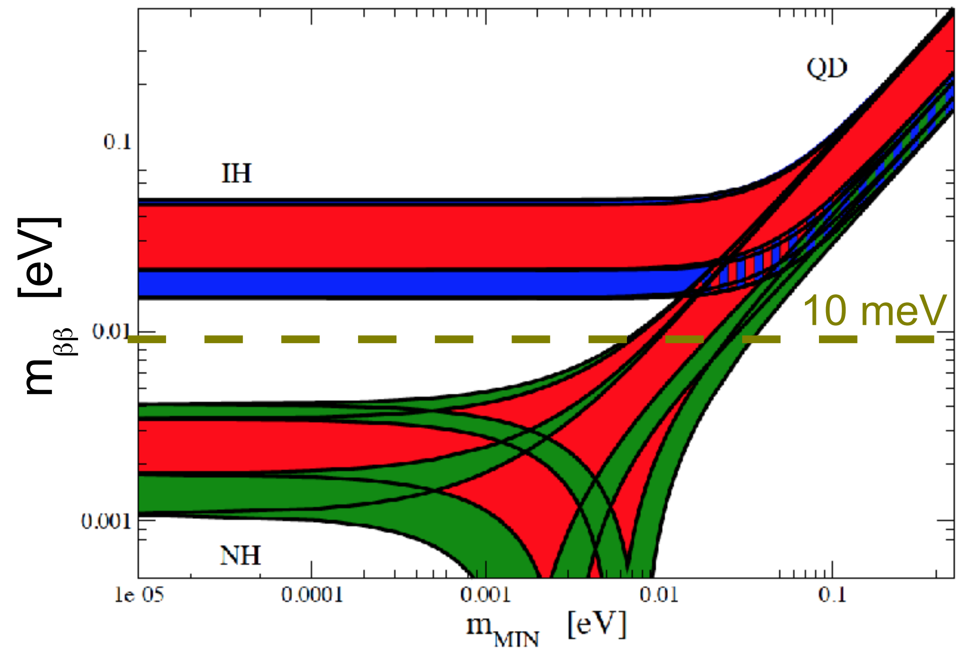
⇒ $m(\nu_j) \neq 0$, but unknown !

additional sterile neutrinos ?

Neutrino mass patterns - degenerated, normal & inverted hierarchy

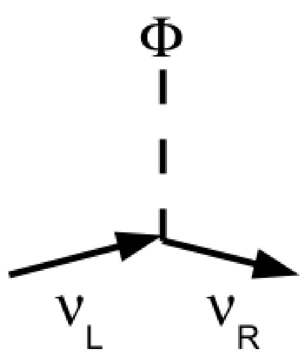
Results of recent oscillation experiments:

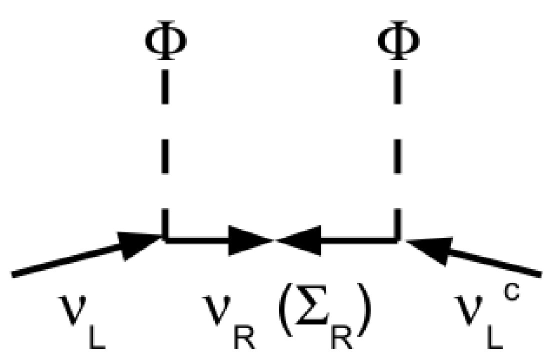
Θ_{23}, Θ_{12}, Θ_{13}, Δm^2_{23}, Δm^2_{12}

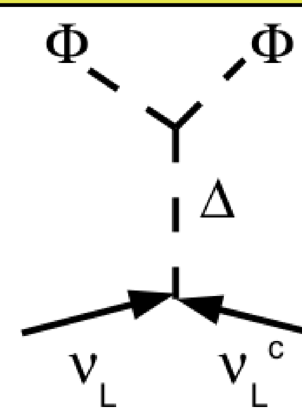


pdg 2014

Non-zero neutrino masses go beyond the usual Yukawa coupling to the Higgs → Beyond the Standard Model physics







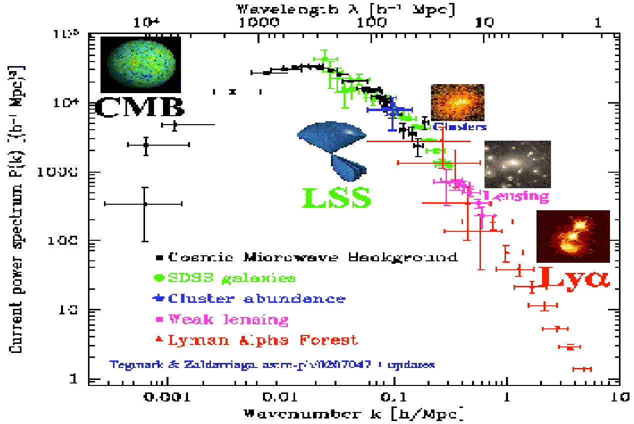
Three complementary ways to the absolute neutrino mass scale

1) Cosmology

very sensitive, but model dependent

compares power at different scales

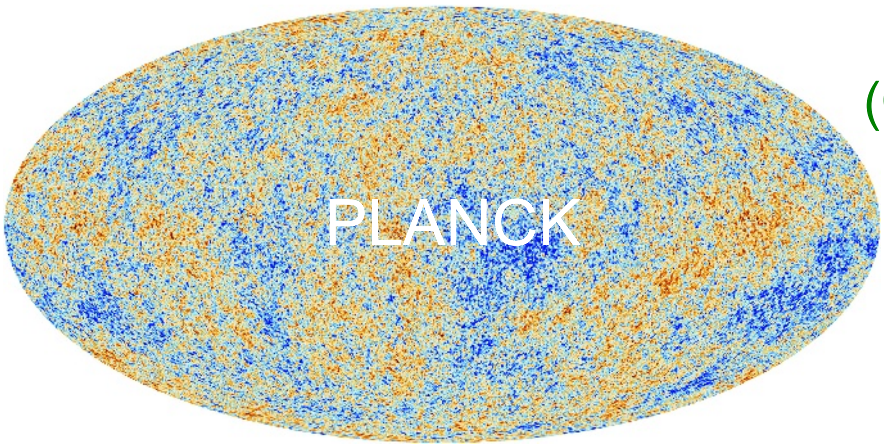
current sensitivity: $\Sigma m(\nu_i) \approx 0.23$ eV

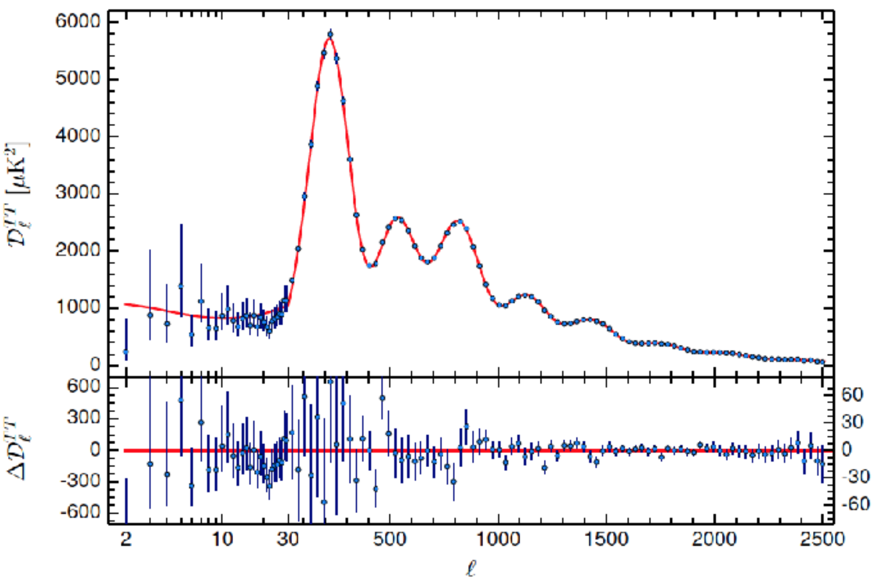


Neutrino mass from cosmology

measurement of CMBR

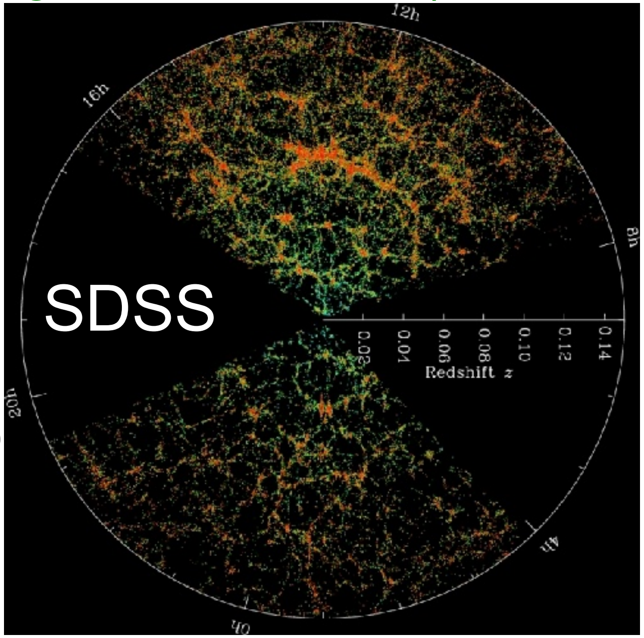
(Cosmic Microwave Background Radiation)





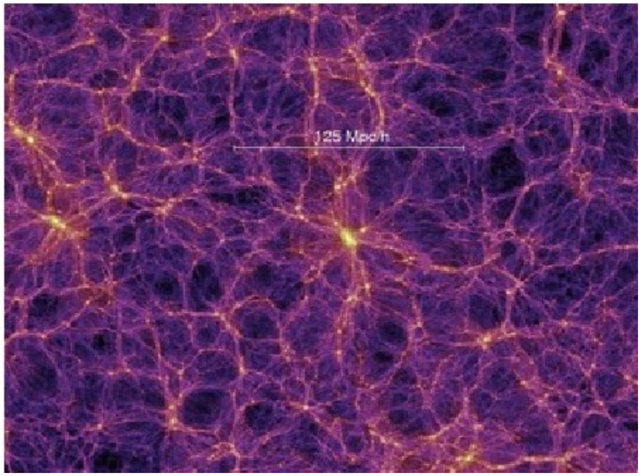
Planck Collaboration:
P. A. R. Ade et al., arXiv:1502.01589

measurement of
matter density
distribution LSS
(Large Scale Structure)
by 2dF, SDSS, ...

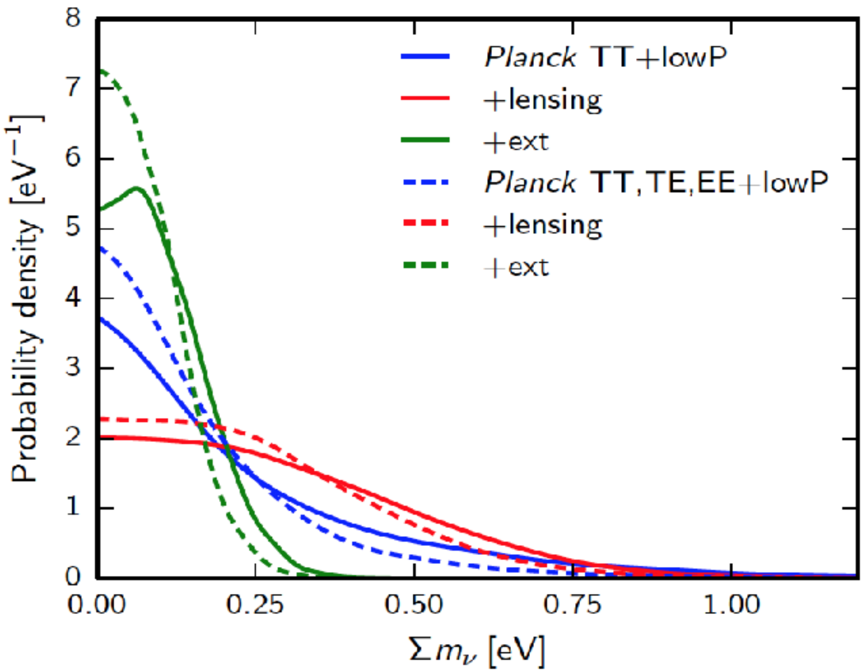


compare to
numeric. models
including relic
neutrino densitiy
of 336 cm^{-3}

Millenium simulation →
http://www.mpa-garching.mpg.de/galform/presse/



Neutrino mass from cosmology



$$\sum m_\nu < 0.72 \text{ eV} \quad \textit{Planck} \text{ TT+lowP};$$

$$\sum m_\nu < 0.21 \text{ eV} \quad \textit{Planck} \text{ TT+lowP+BAO};$$

$$\sum m_\nu < 0.49 \text{ eV} \quad \textit{Planck} \text{ TT, TE, EE+lowP};$$

$$\sum m_\nu < 0.17 \text{ eV} \quad \textit{Planck} \text{ TT, TE, EE+lowP+BAO}.$$

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

Planck Collaboration: P. A. R. Ade et al., arXiv:1502.01589

Relies on ΛCDM model !
Is this fully correct, there are some discrepancies ?
More than 95% of the energy distribution in the universe is not known (dark energy, dark matter)

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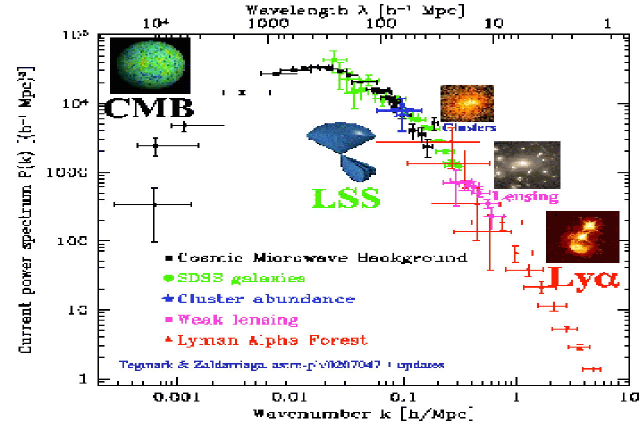
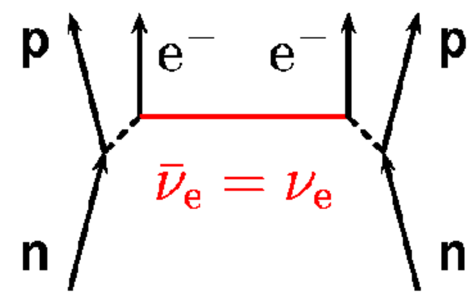


2) Search for $0\nu\beta\beta$

Sensitive to Majorana neutrinos

First upper limits by EXO-200, KamLAND-Zen, GERDA



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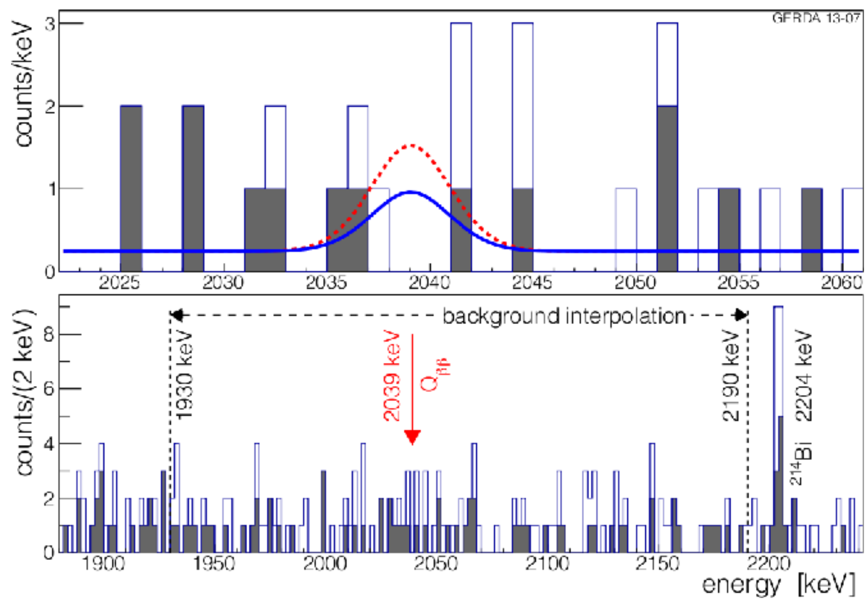
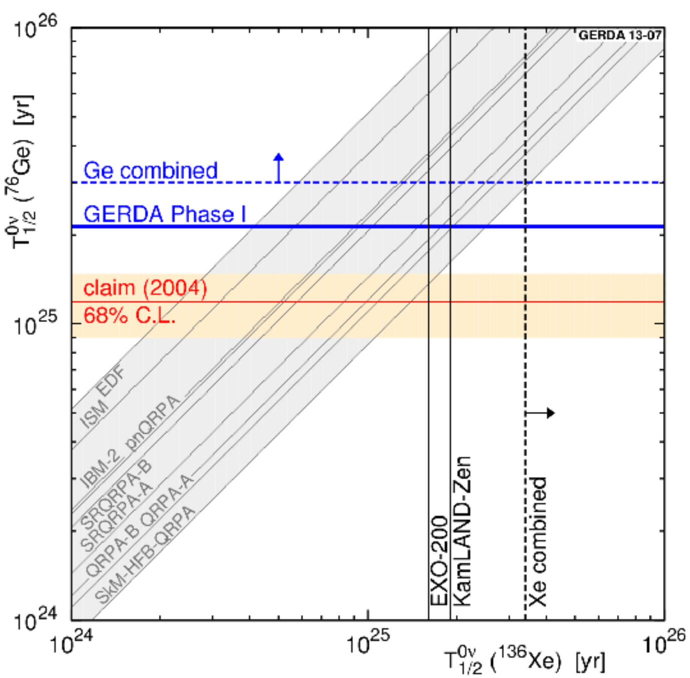
Results from GERDA phase 1

Very low background
& high energy resolution:

18 kg enriched Ge detectors in LAr



GERDA I
PRL 111 (2013) 122503



$T_{1/2} > 2.1\ 10^{25}$ yr (90% C.L.)

$T_{1/2} > 3.0\ 10^{25}$ yr (90% C.L.) (using all ^{76}Ge experiments)

$m_{\beta\beta} < 0.2 – 0.4$ eV (using all ^{76}Ge experiments)

Former claim strongly disfavored

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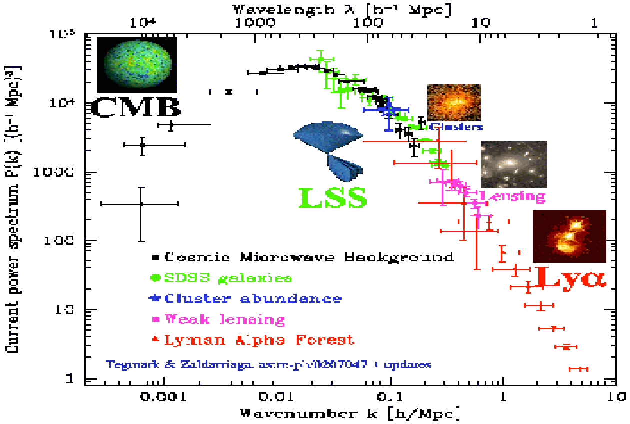

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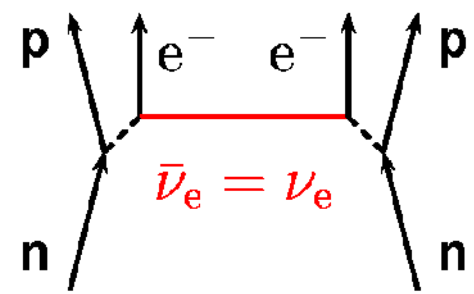


3) Direct neutrino mass determination:

No further assumptions needed, use $E^2 = p^2c^2 + m^2c^4 \Rightarrow m^2(\nu)$ is observable mostly

Time-of-flight measurements (ν from supernova)

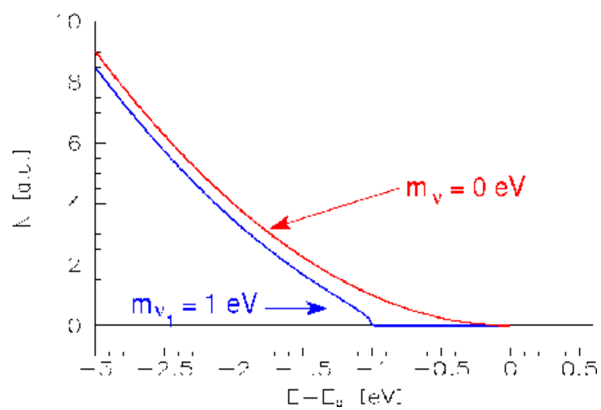
SN1987a (large Magellan cloud) $\Rightarrow m(\nu_e) < 5.7$ eV

Kinematics of weak decays / beta decays

measure charged decay prod., E-, p-conservation

β-decay searchs for $m(\nu_e)$ - tritium, ^{187}Re β-spectrum

- ^{163}Ho electron capture (EC)



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Direct determination of $m(\nu_e)$ from β decay

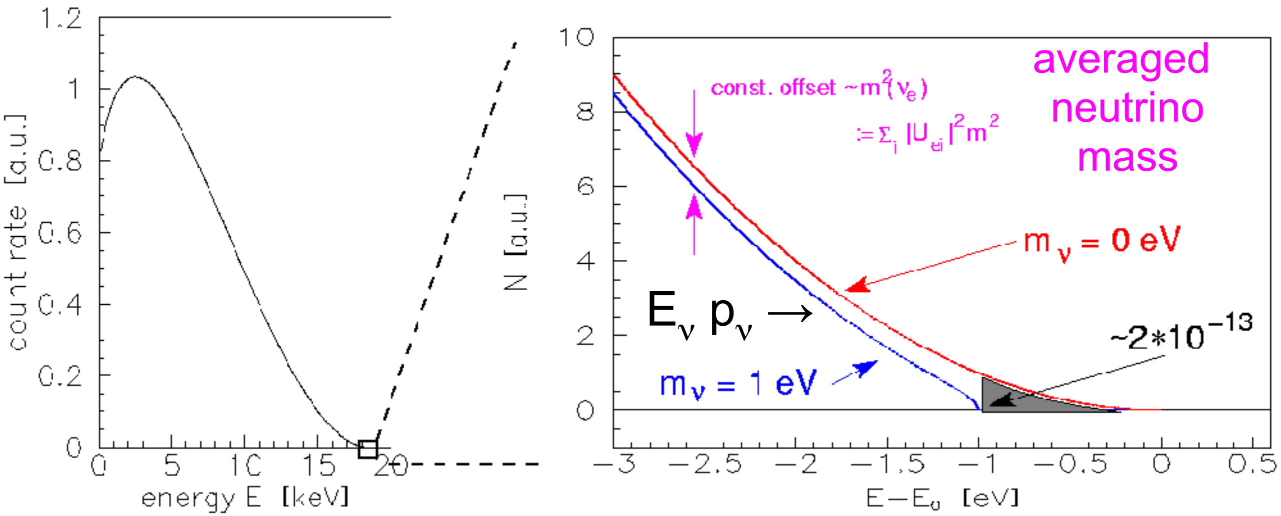
β decay: $(A,Z) \rightarrow (A,Z+1)^+ + e^- + \bar{\nu}_e$

Complementary to $0\nu\beta\beta$ and cosmology

β: $dN/dE = K\ F(E,Z)\ p\ E_{tot}\ (E_0-E_e)\ \sqrt{(E_0-E_e)^2 - \text{"}m(\nu_e)\text{"}^2}$

phase space: p_e E_e E_ν p_ν

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



m(ν) < 2 eV (Mainz, Troitsk)

Review:
G. Drexlin, V. Hannen, S. Mertens, C. Weinheimer, Adv. High Energy Phys., 2013 (2013) 293986

Need: low endpoint energy ⇒ **Tritium ^3H (^{187}Re, ^{163}Ho)**
very high energy resolution &
very high luminosity & ⇒ **MAC-E-Filter**
very low background **(or bolometer for ^{187}Re, ^{163}Ho)**

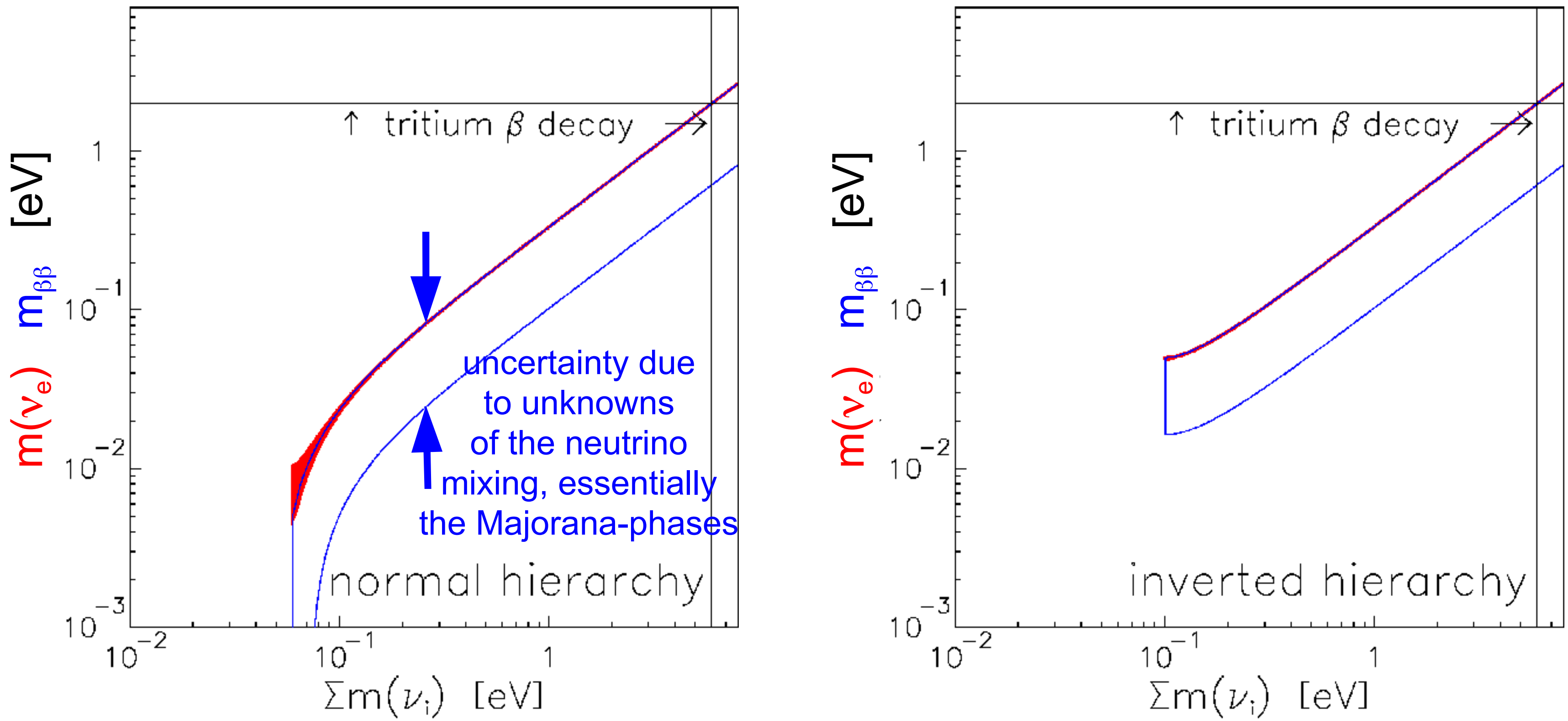
Comparison of the different approaches to the neutrino mass

Direct kinematic measurement: $m^2(\nu_e) = \Sigma |U_{ei}^2| m^2(\nu_i)$ (incoherent)

Neutrinolesss double β decay: $m_{\beta\beta}(\nu) = | \Sigma |U_{ei}^2| e^{i\alpha(i)} m(\nu_i)|$ (coherent)

if no other particle is exchanged (e.g. R-violating SUSY)

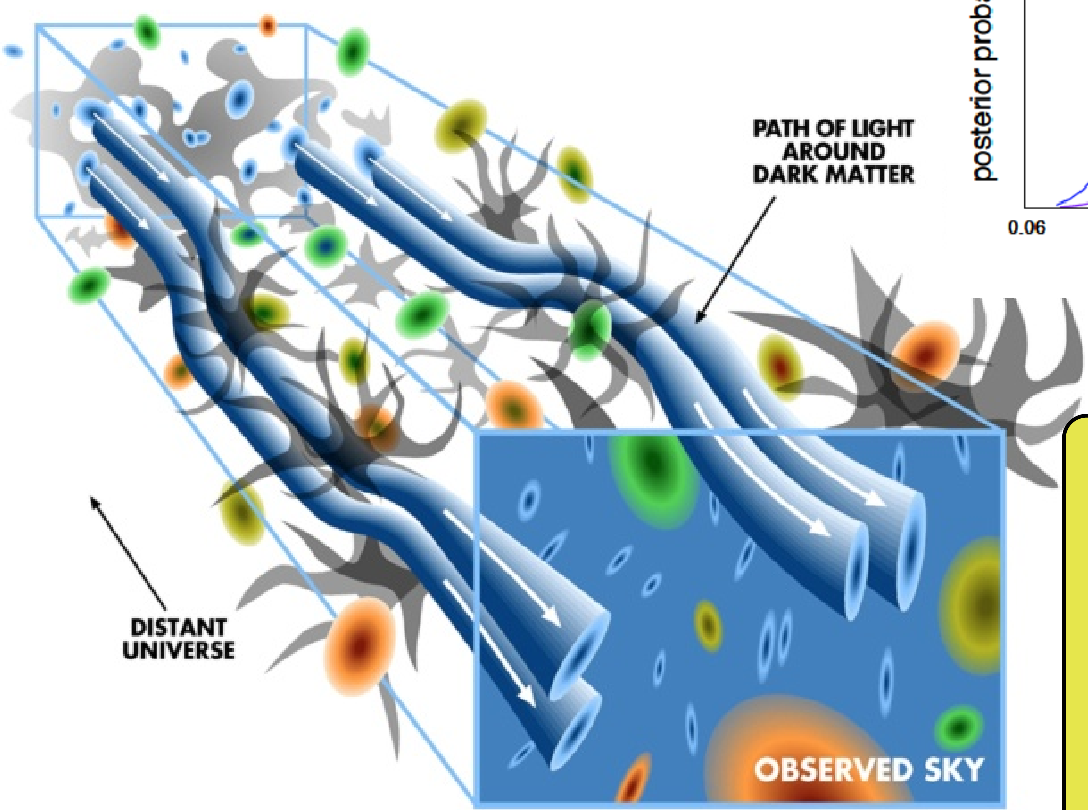
problems with uncertainty of nuclear matrix elements

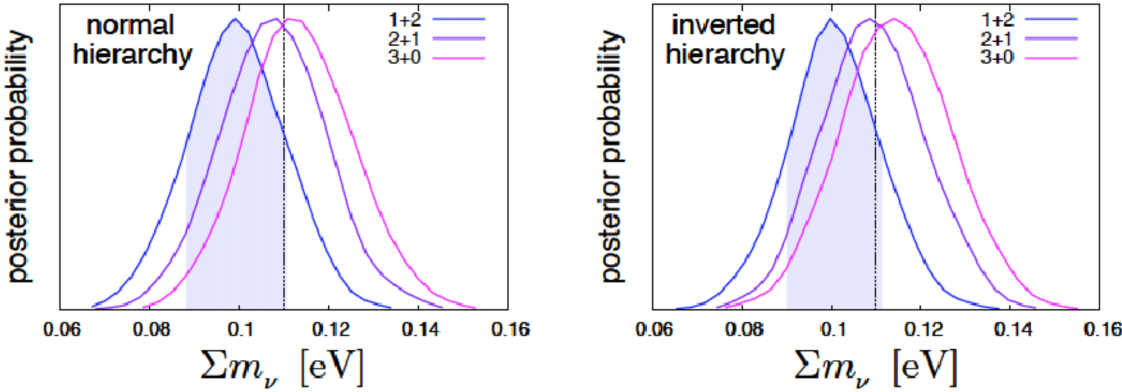


⇒ absolute scale/cosmological relevant neutrino mass in the lab by single β decay

Future on neutrino mass results from cosmology

In addition to Planck CMB data (temperature + polarisation)
use cosmic shear by weak graviational lensing and galactic power specrum
measured with EUCLID (VIS+NISP space-borne telescope by ESA)





"..Euclid will very likely provide a positive detection of neutrino mass ..,
the exact nature of the neutrino mass spectrum remains out of its reach .."
J. Hamann S. Hannestad Y.Y.Y. Wong
JCAP 11 (2012) 52, **arXiv:1209.1043**

Future on neutrino mass results from $0\nu\beta\beta$ → sensitivity: $T_{1/2} > 10^{26}$ yr , $m_{\beta\beta} < 100$ meV

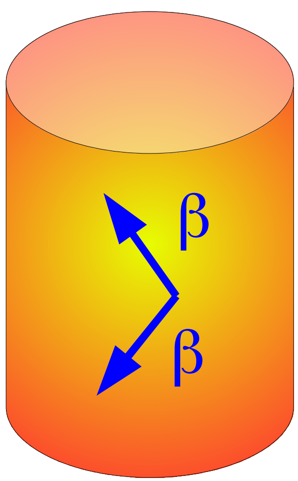
$m_{\beta\beta} \sim (1/\text{enrichment})^{1/2} \cdot (\Delta E \cdot bg / M \cdot t)^{1/4}$

⇒ mass → > 100 kg, high enrichment, very low background *bg*

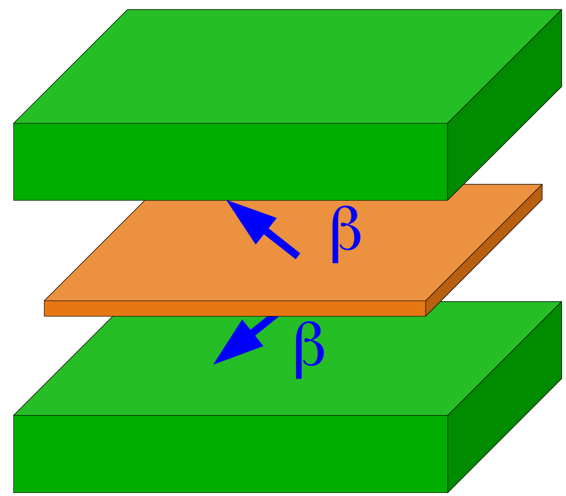
2 ways to measure both β-electrons:

semiconductor, cryogenic bolometer, liquid scintillator

source = detector



tracking calorimeter



detector

source

detector

very sensitive | **gives more information on mechanism if observed**

running: GERDA I/II, EXO-200, KamLAND-Zen
setting up: CUORE, SNO+, Majorana
planned: COBRA, Lucifer, AMORE, ...

finished: NEMO-3
setting up: SuperNEMO
planned: MOON

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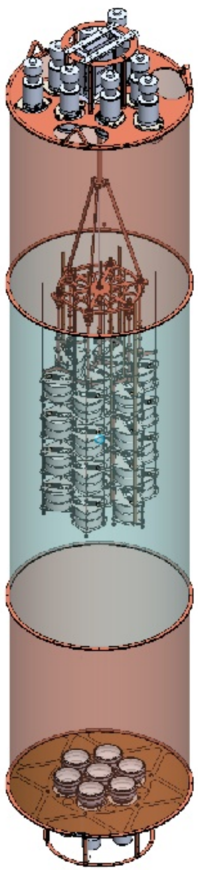
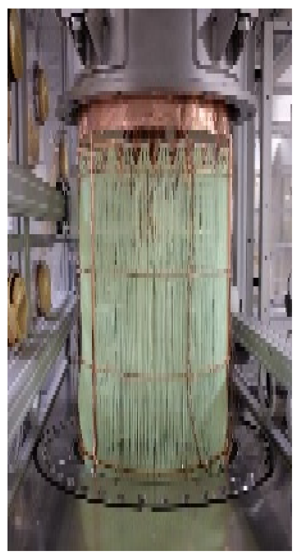
Future on neutrino mass results from $0\nu\beta\beta$
$\rightarrow$ sensitivity: $T_{1/2} > 10^{26}$ yr , $m_{\beta\beta} < 100$ meV

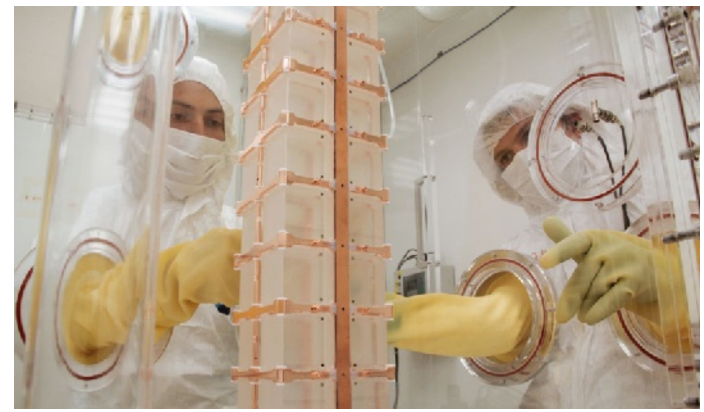
GERDA II @LNGS starting in 2015:
^{76}Ge, 38 kg better BEGe detectors
lower bg rate due to active veto
(WLF, PMT)



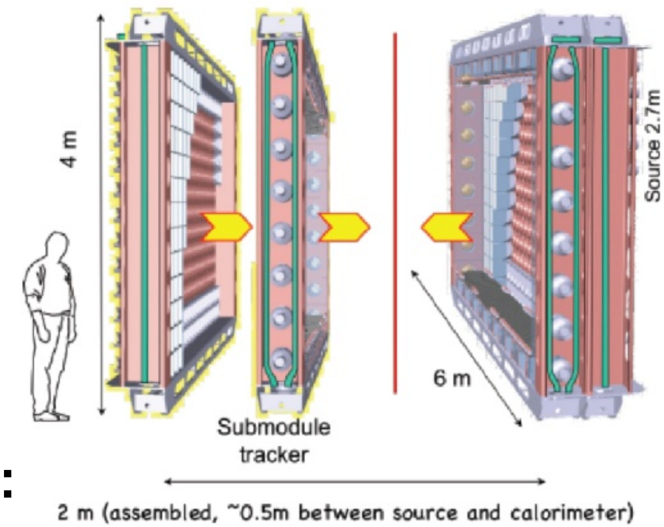


Majorana demonstrator at DUSEL:
^{76}Ge, similar goal as GERDA II

CUORE@LNGS under commissioning:
^{130}Te, cooldown of cryostat to < 10 mK successful
bg goal reached
& demonstrated
(CUORE-0)
detector towers
all mounted



SuperNemo @Canfranc&LSM: demonstrator being built:
^{82}Se, aim: $6\ 10^{24}$ yr



Other experiments:
^{130}Te: SNO+,
^{100}Mo: AMORE, LUNIEU
^{136}Xe: nEXO, NEXT, KamLAND-Zen

Future on neutrino mass results from $0\nu\beta\beta$
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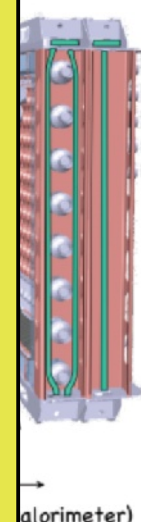


Different methods to reach O(100) kg detectors with bg rate of 10^{-3} cnts/(kg year keV)
(or larger detectors with less energy resolution, but in addition: $2\nu\beta\beta$ becomes unavoidable background)

$\rightarrow$ cover degenerated neutrino mass region & start attacking inverted hierarchy region

increase mass and lower bg:
purer materials and surface event discrimination:
e.g. BEGe+PSA or dual read-out (light+heat)

But no way yet to become sensitive to normal hierarchy neutrino mass scenarios

Majorana demonstrator at DUSEL:
^{76}Ge, similar goal as GERDA II

^{100}Mo: AMORE, LUNIEU
^{136}Xe: nEXO, NEXT, KamLAND-Zen

Future on neutrino mass results from direct neutrino mass determination

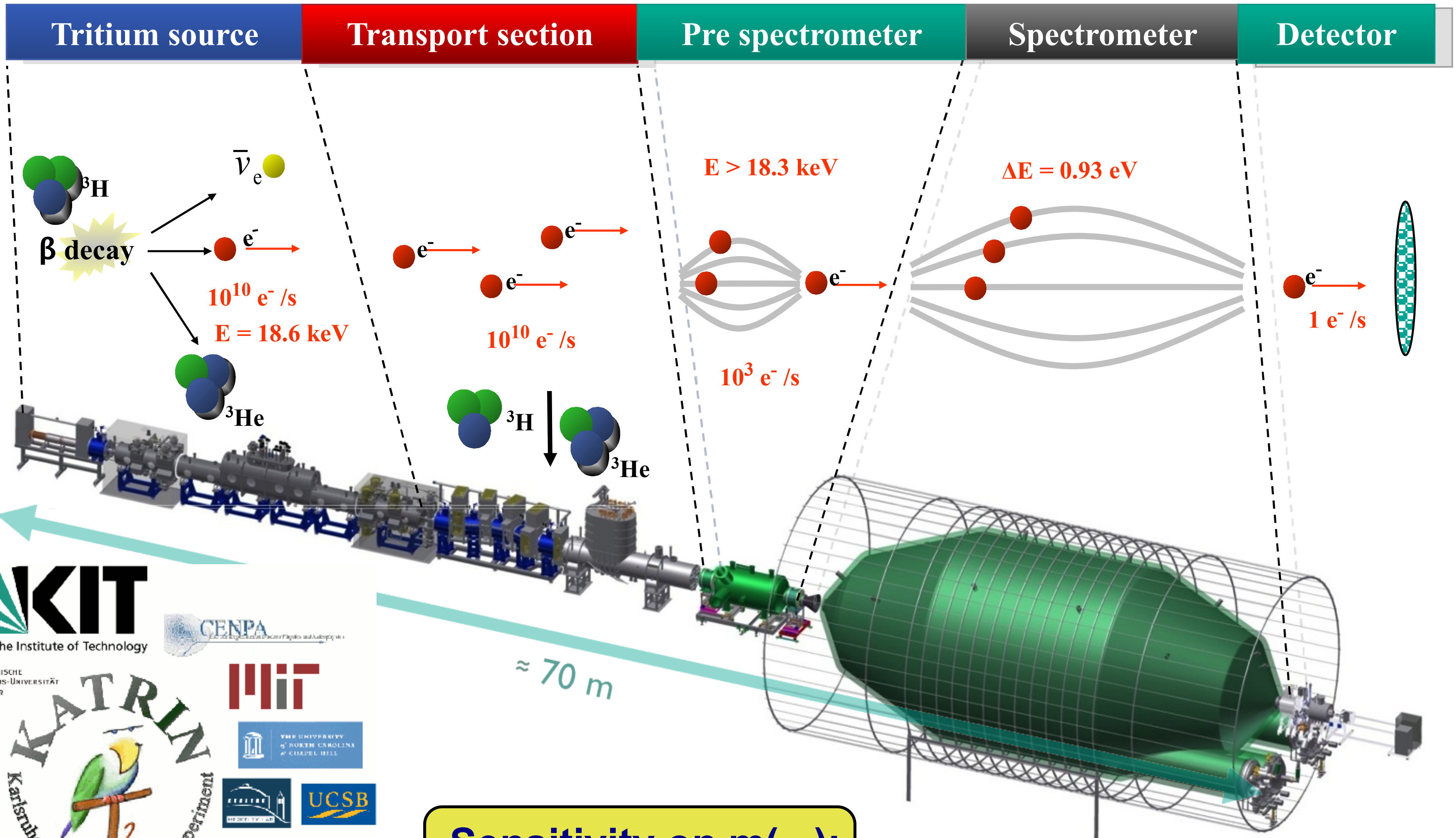
Under setting up and commissioning:

- KATRIN experiment (tritium β-spectroscopy)

Future approaches and/or test experiments:

- Micro calorimeters to investigate EC of ^{163}Ho:
  ECHo, HOLMES, NuMECS
- Project 8
- Time-of-flight with KATRIN
- PTOMELY ?

The Karlsruhe Tritium Neutrino Experiment
KATRIN - overview



Sensitivity on m(ν_e):

2 eV → 200 meV

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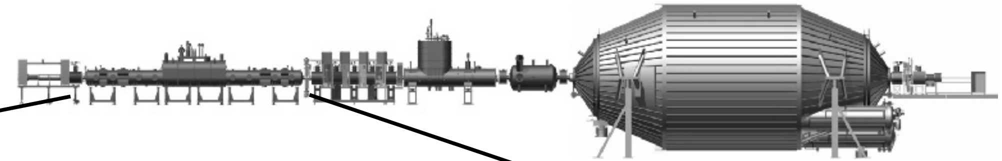
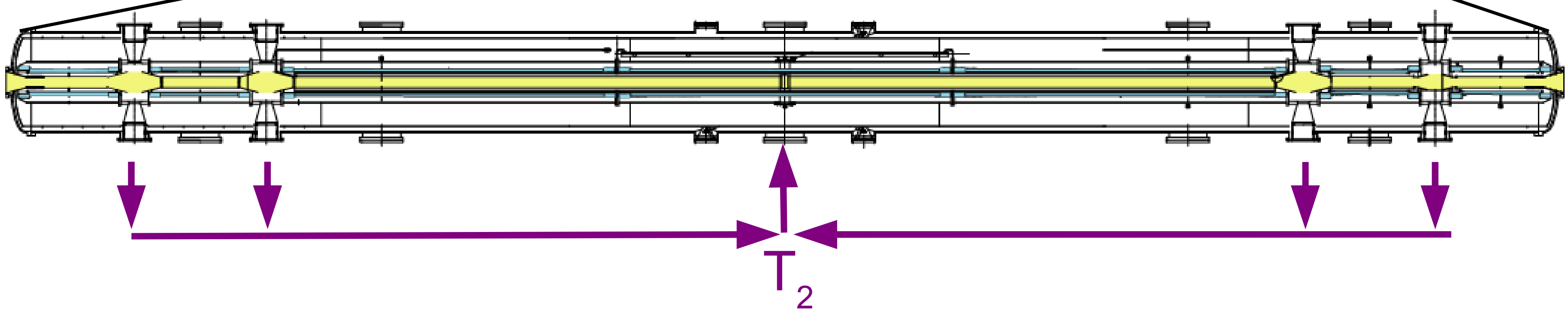
Molecular Windowless Gaseous Tritium Source WGTS

per mill stability source strength request:
$dN/dt \sim f_T \cdot N / \tau \sim n = f_T \cdot p\, V / R\, T$
tritium fraction f_T & ideal gas law

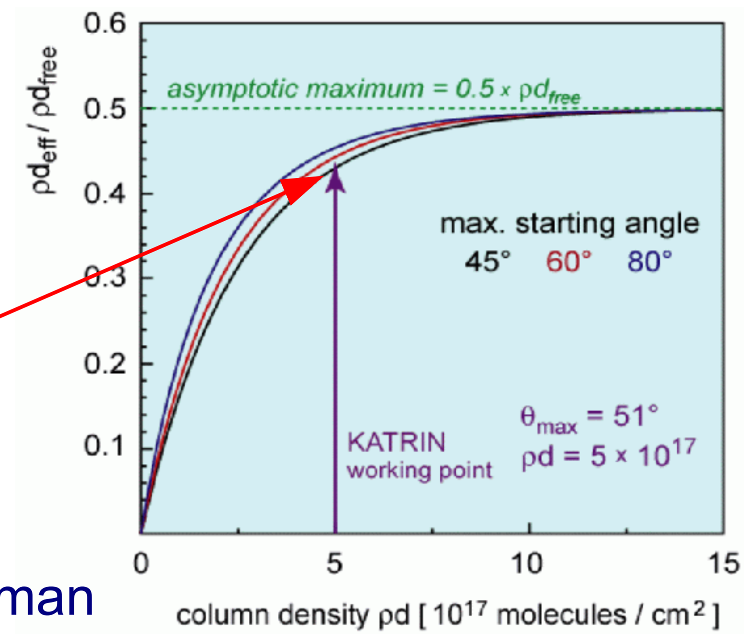




WGTS: tub in long superconducting solenoids
⊘ 9cm, length: 10m, T = 30 K

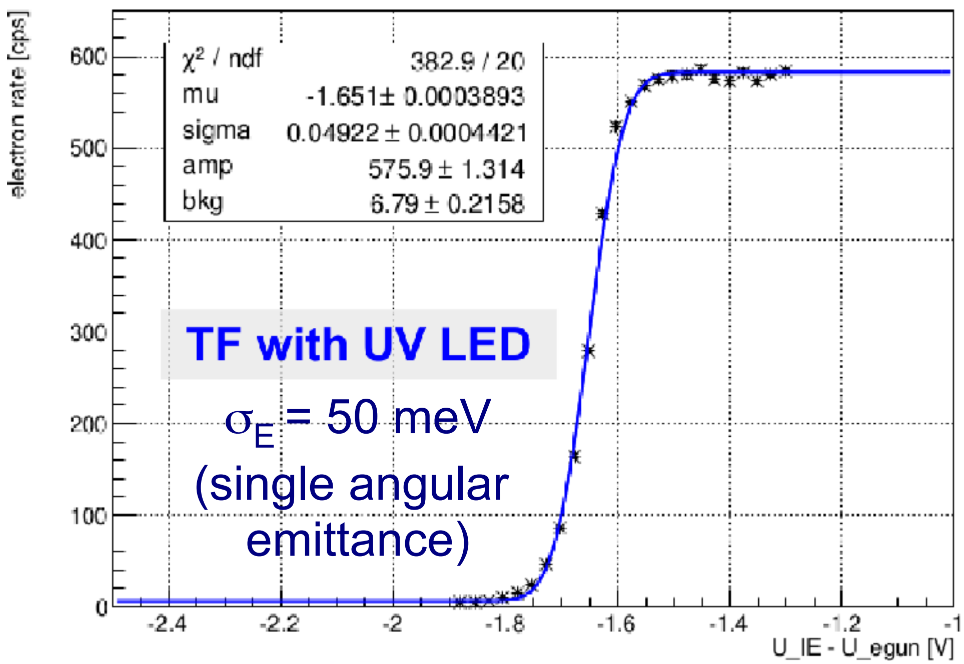
Tritium recirculation (and purification)
p_{inj} = 0.003 mbar, q_{inj} = 4.7Ci/s

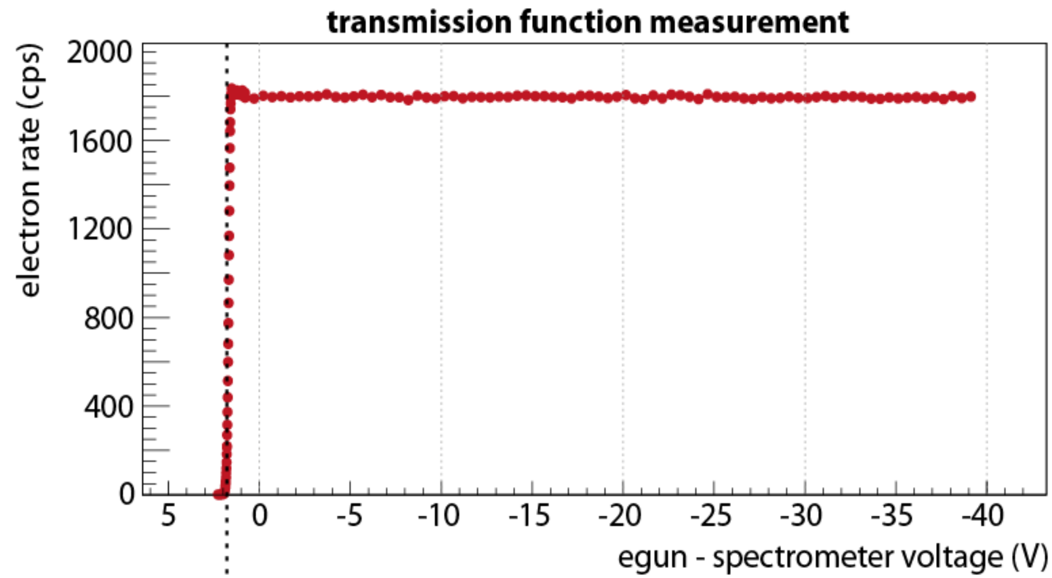
allows to measure with near to maximum count rate using
$\rho d = 5 \cdot 10^{17}/cm^2$
with small systematics

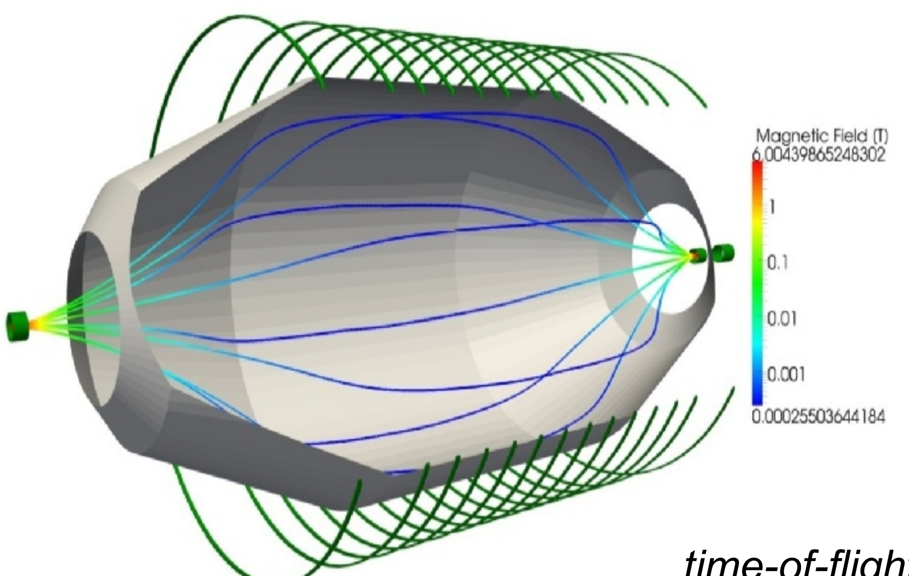


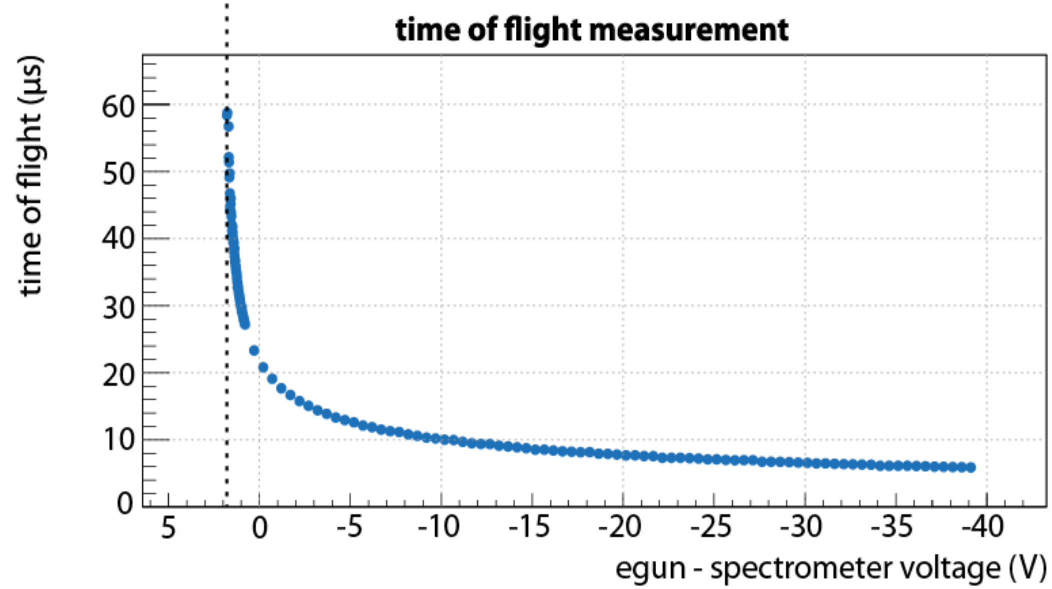
check column density by e-gun, T_2 purity by laser Raman

Commissioning of main spectrometer (ΔE = 0.93 eV) and detector









time-of-flight, see also N. Steinbrink et al., NJP 15 (2013) 113020

Radon induced background
^{219}Rn from getter and artefical ^{220}Rn source

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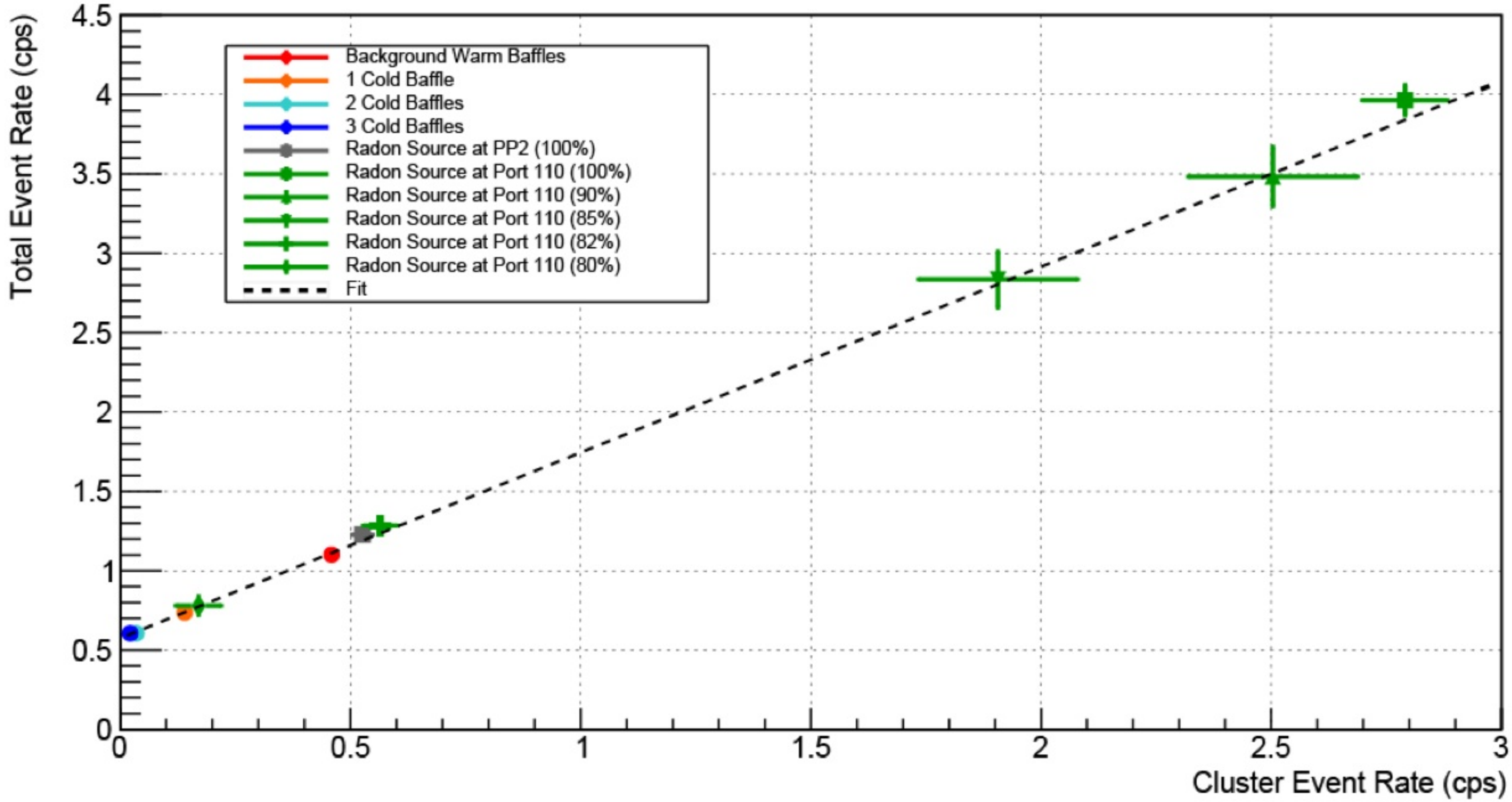


→ radon-induced background is very efficiently eliminated by LN_2 baffles

→ residual non-radon background of about 600 mcps in winter 2015

→ optimal magnetic field settings: 477 mcps = reference background rate (SDS2)

SDS2b after baking to reach better understanding of residual background:
bg < 300 mcps reached (July 2015, preliminary)

KATRIN status & time line

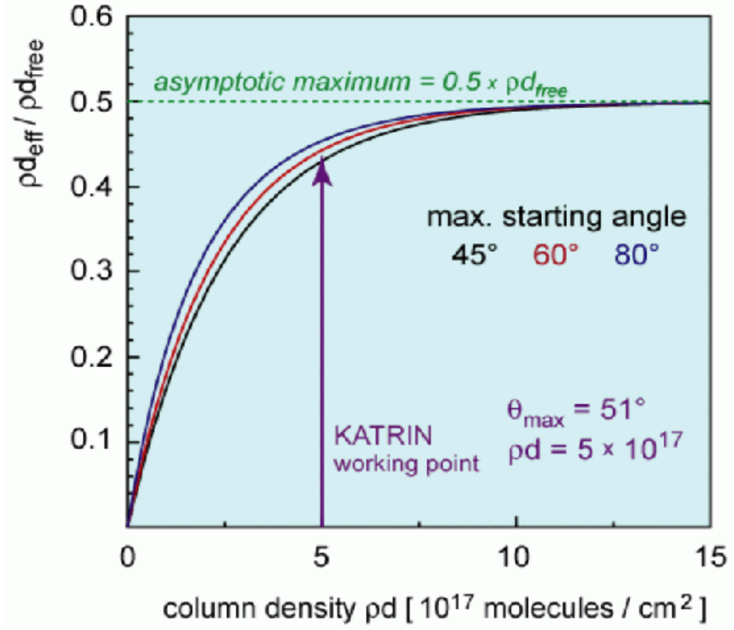
- Commissioning of spectrometer & detector SDS IIb finished in August 2015
- Commissioning of tritium source & transport section: up to summer 2016
- Tritium data taking: start in 2016
- sensitivity: 200 meV

Can KATRIN be largely improved ? Problems to be solved

1) The source is already opaque
→ need to increase size transversally
magnetic flux tube conservation
requests larger spectrometer too
but a Ø100m spectrometer is not feasible

Possible ways out:

a) source inside detector (compare to 0νββ) using cryogenic bolometers (ECHo, HOLMES, ..)



ECHo neutrino mass project: ^{163}Ho electron capture with metallic magnetic calorimeters

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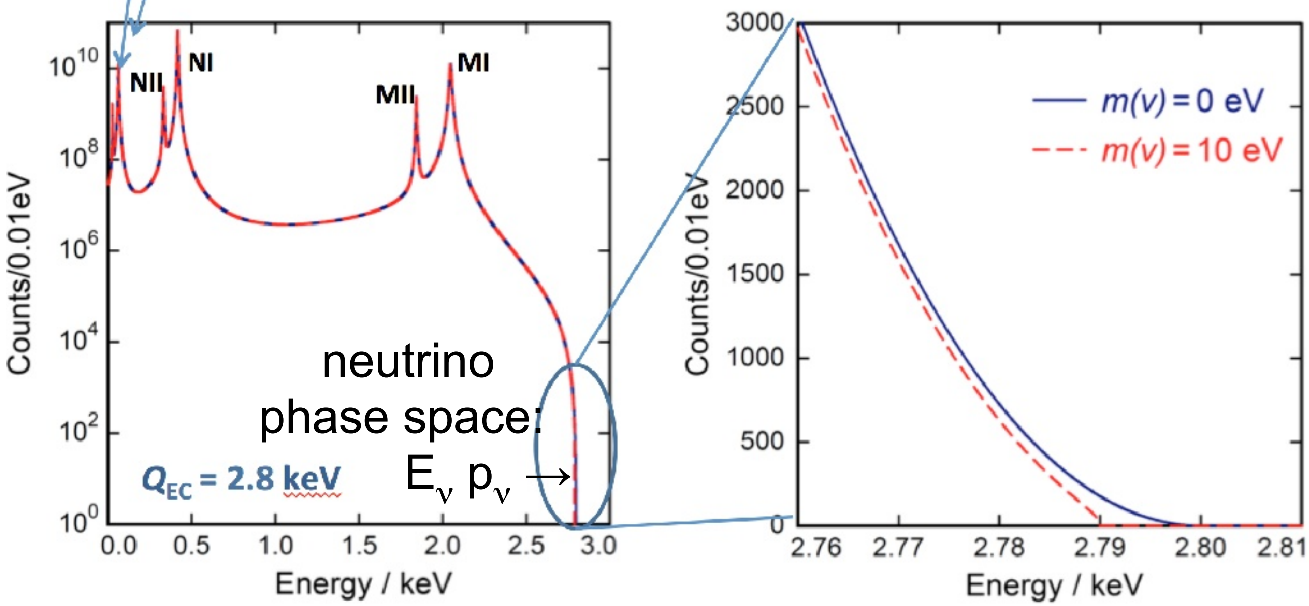
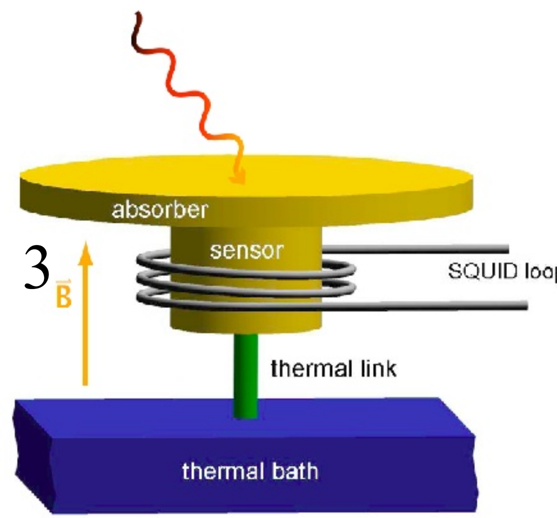
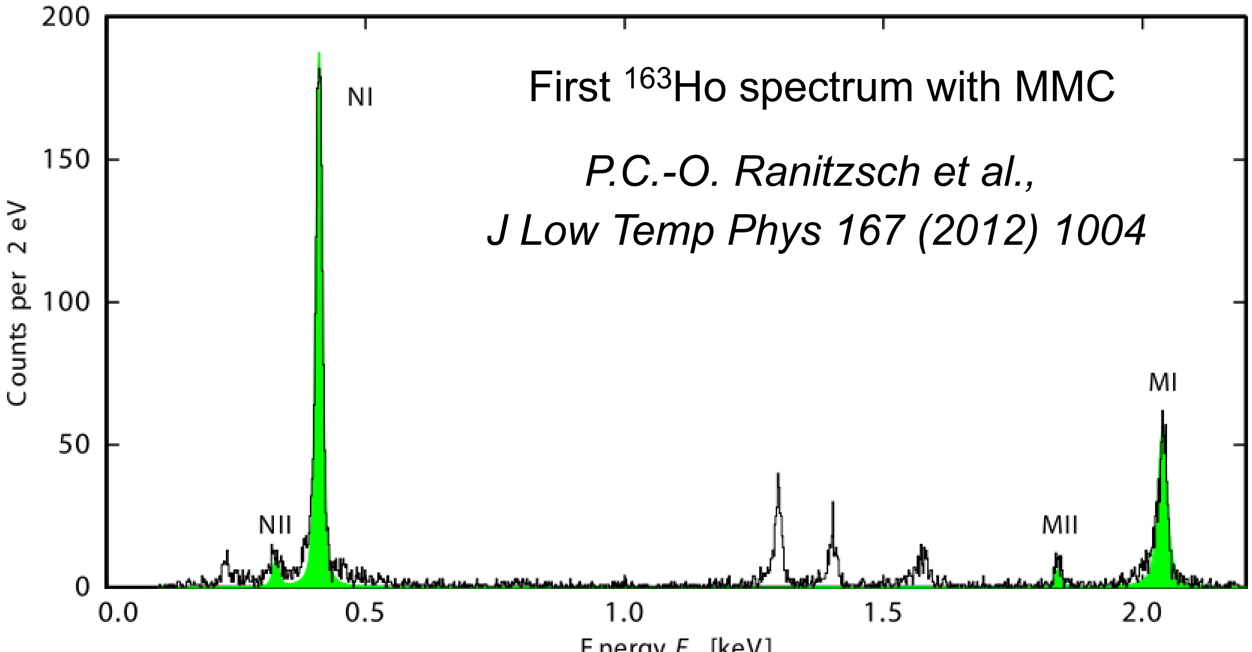
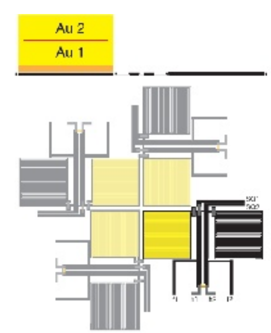
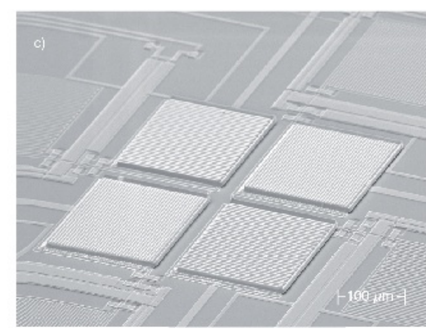
$$^{163}\text{Ho} + e^- \rightarrow {}^{163}\text{Dy}^* + \nu_e \rightarrow {}^{163}\text{Dy} + \gamma/e^- + \nu_e$$









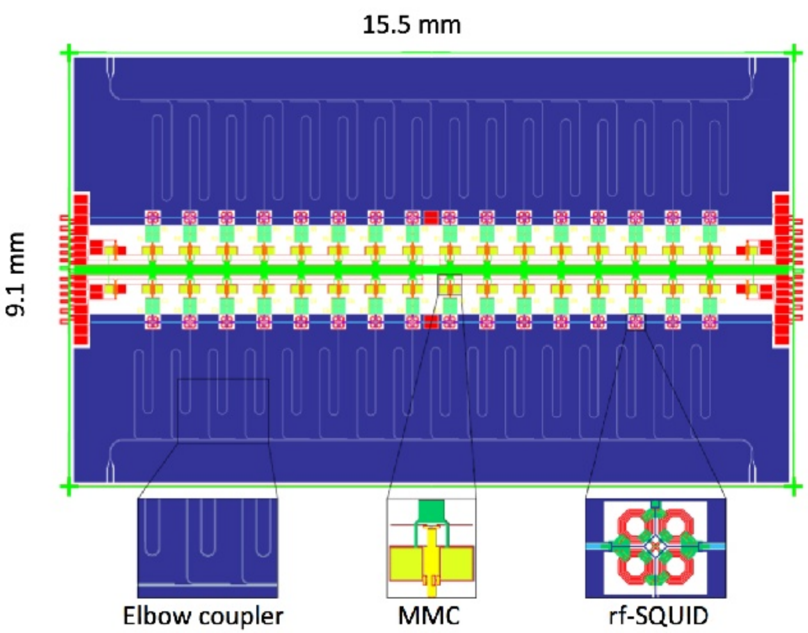


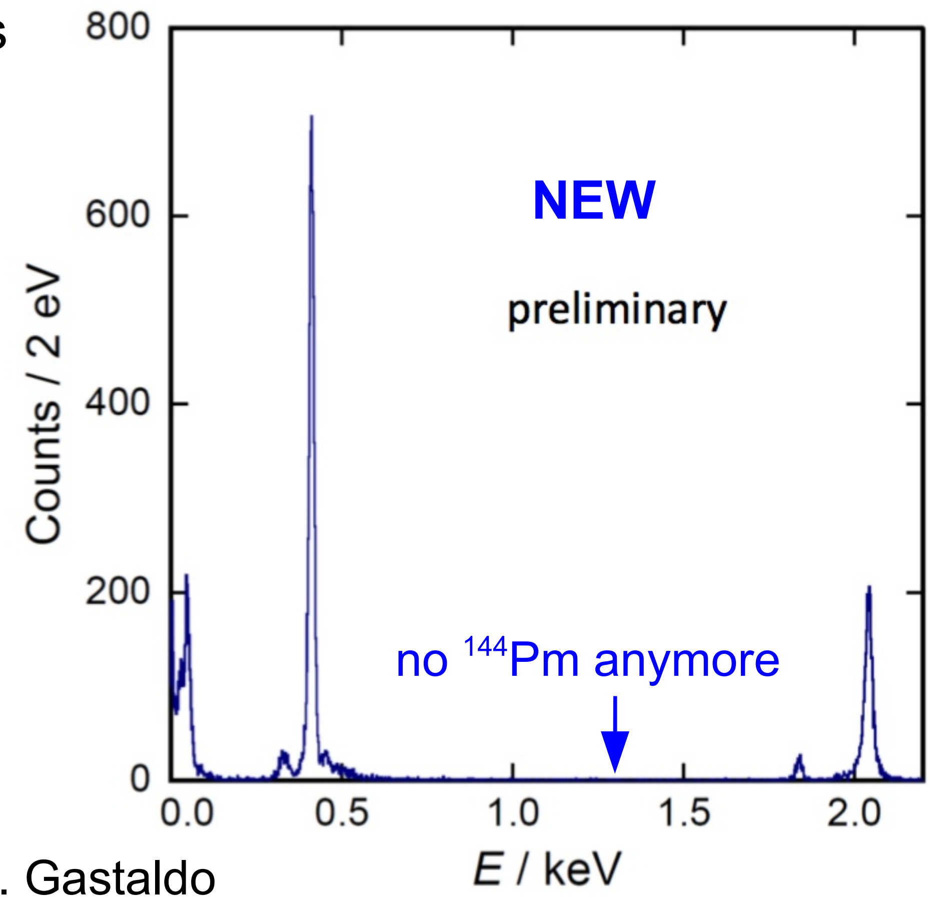
courtesy L. Gastaldo

ECHo neutrino mass project: ^{163}Ho electron capture with metallic magnetic calorimeters

Recent achievements by ECHo:

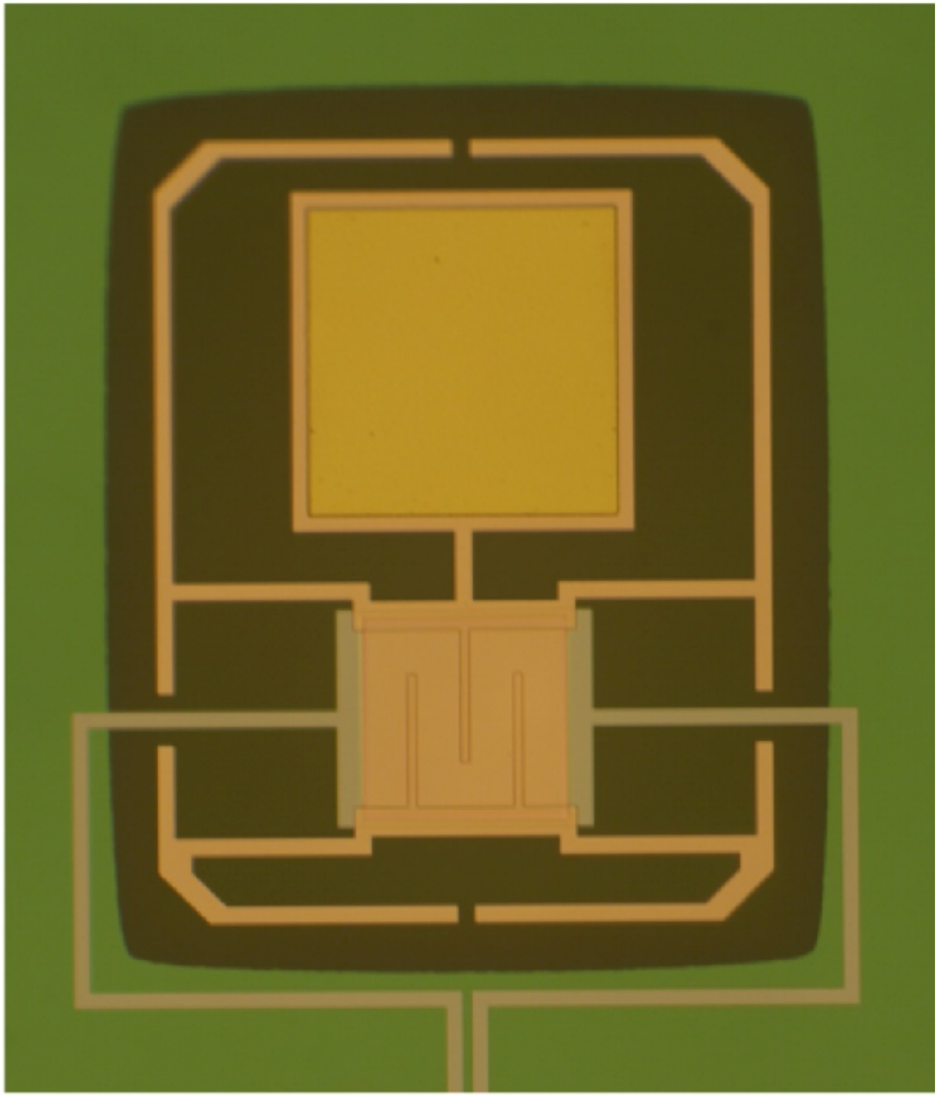
- new Q-value: 2.8 keV (independently by MMC & Penning trap, was 2.5 keV before!)
- new source production: chemical purification + mass separation → no ^{144}Pm or ^{166m}Ho
- very good energy resolution of this technology (ΔE_{FWHM} = 1.6 eV at 6 keV)
- ultra-short response (pile-up!): risetime 90 ns
- 128 pixels: microwave SQUID multiplexing
- funding for ECHo-1k





courtesy L. Gastaldo

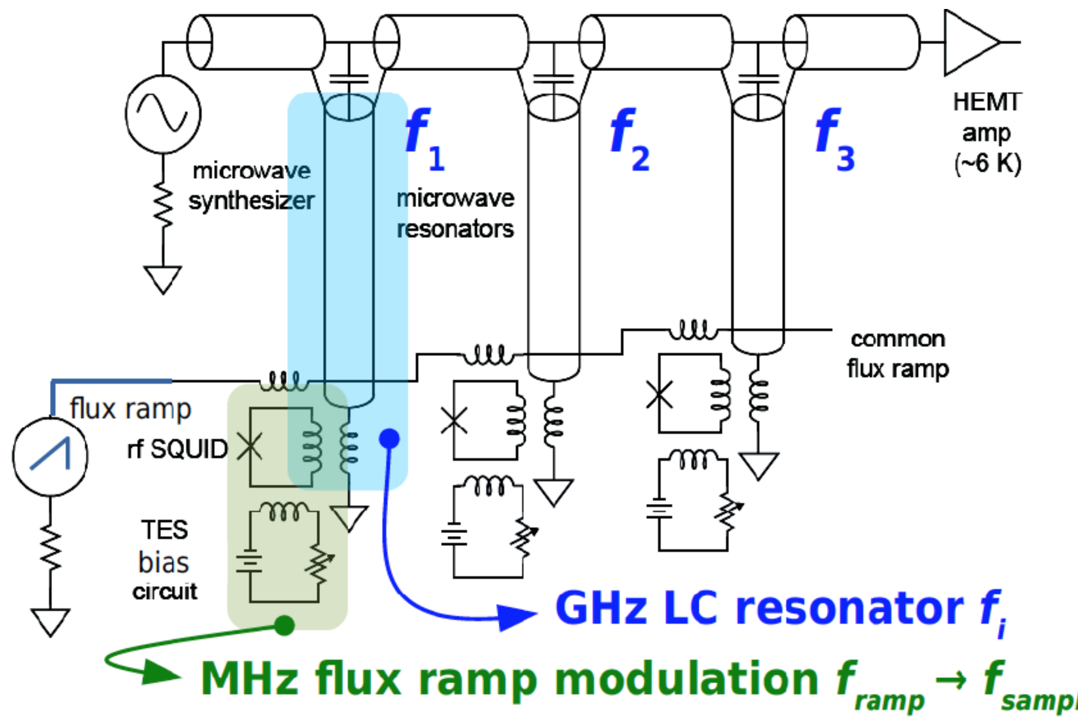
HOLMES: cryogenic calorimeter with transition edge sensor (TES) read-out



Prediction from test measurements:

$\Delta E_{FWHM} \approx 3$ eV, $\tau_{rise} \approx 6$ µs, $\tau_{decay} \approx 130$ µs

radiofrequency SQUID multiplexing



funding by ERC grant

courtesy A. Nucciotti

Westfälische Wilhelms-Universität Münster

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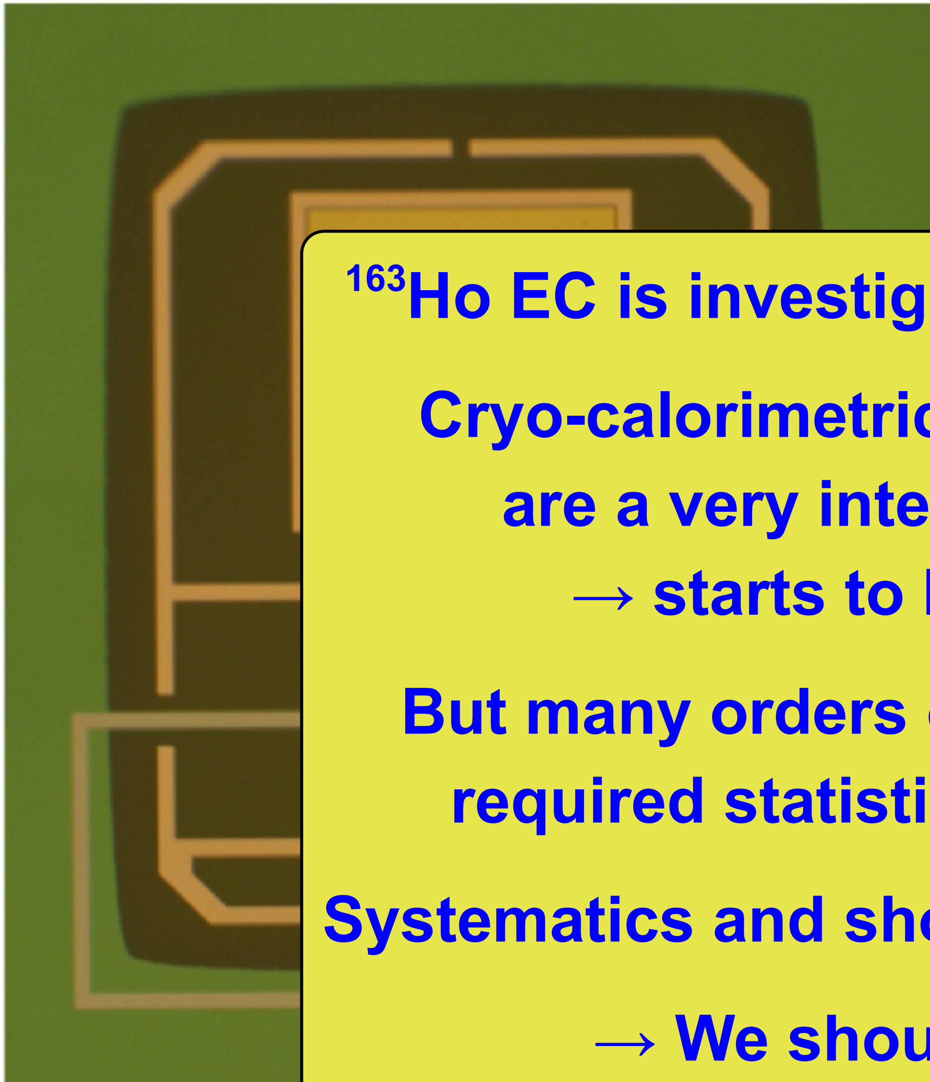

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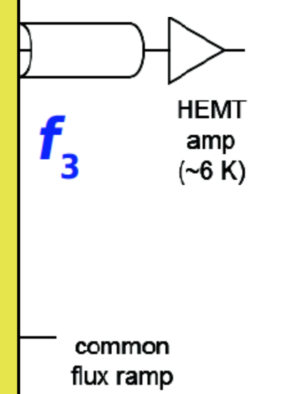
^{163}Ho EC is investigated by 3 collaborations

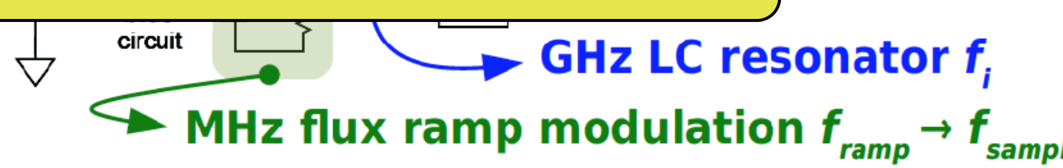
Cryo-calorimetric multipixel detectors are a very interesting technology → starts to become scalable

But many orders of magnitude to go for required statistics and background !

Systematics and show stoppers on the way?

→ We should stay tunned !





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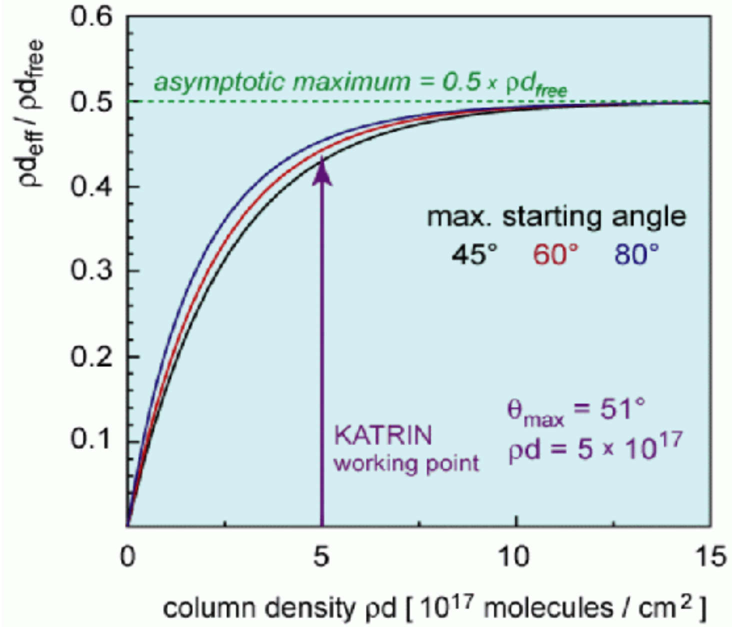
Can KATRIN be largely improved ?
Problems to be solved

1) The source is already opaque
→ need to increase size transversally
magnetic flux tube conservation
requests larger spectrometer too
but a Ø100m spectrometer is not feasible



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b) hand-over energy information of β electron
to other particle (radio photon),
which can escape tritium source (Project 8)

Project 8's goal: Measure coherent cyclotron radiation of tritium β electrons

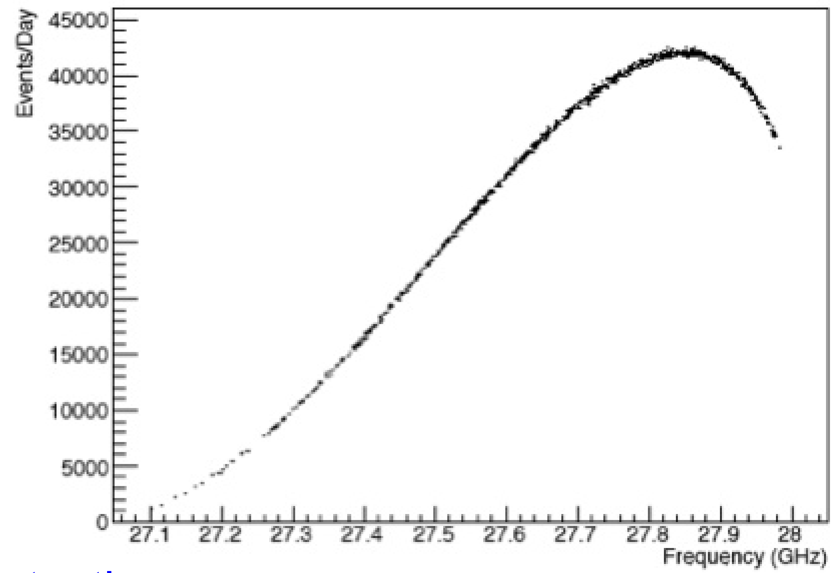
General idea: *B. Monreal and J. Formaggio, PRD 80 (2009) 051301*

- Source = KATRIN tritium source technology :

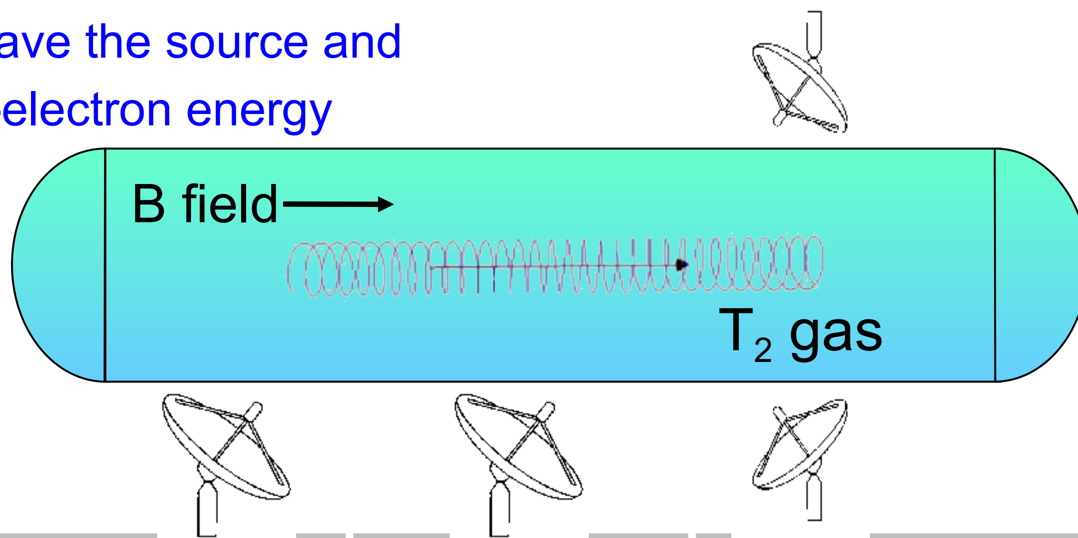
  uniform B field + low pressure T_2 gas

  β electron radiates coherent cyclotron radiation

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



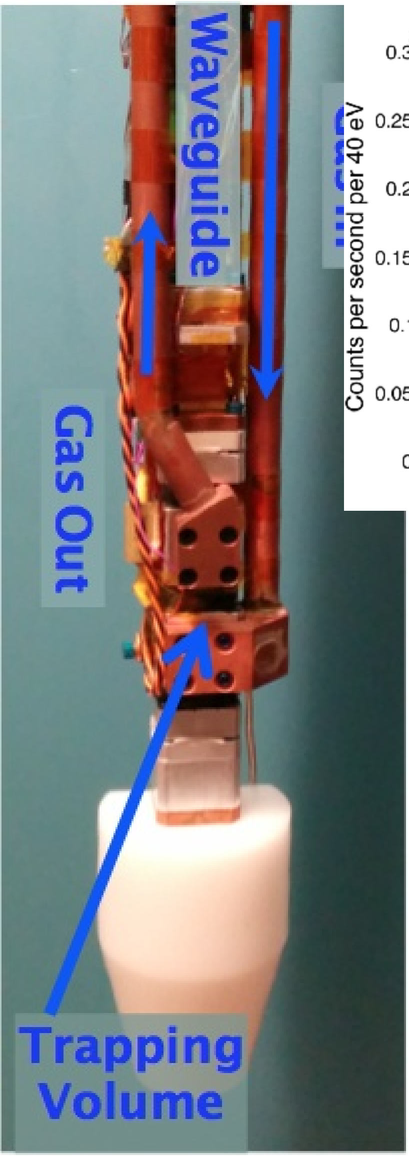
- Antenna array (interferometry) for cyclotron radiation detection
  since cyclotron radiation can leave the source and
  carries the information of the β-electron energy

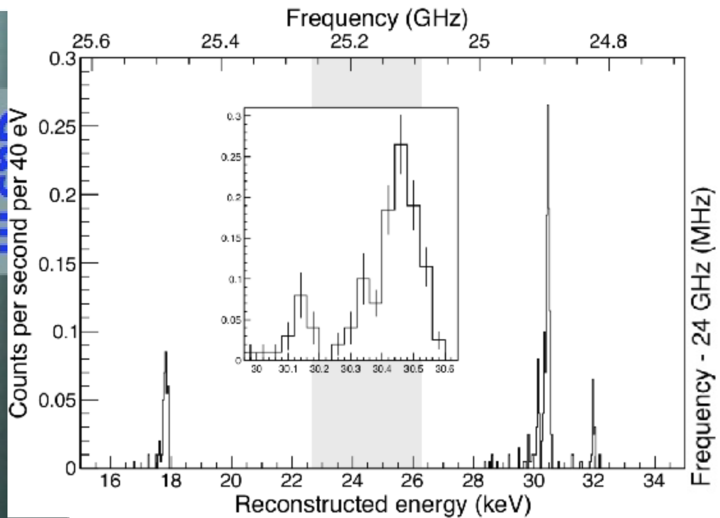


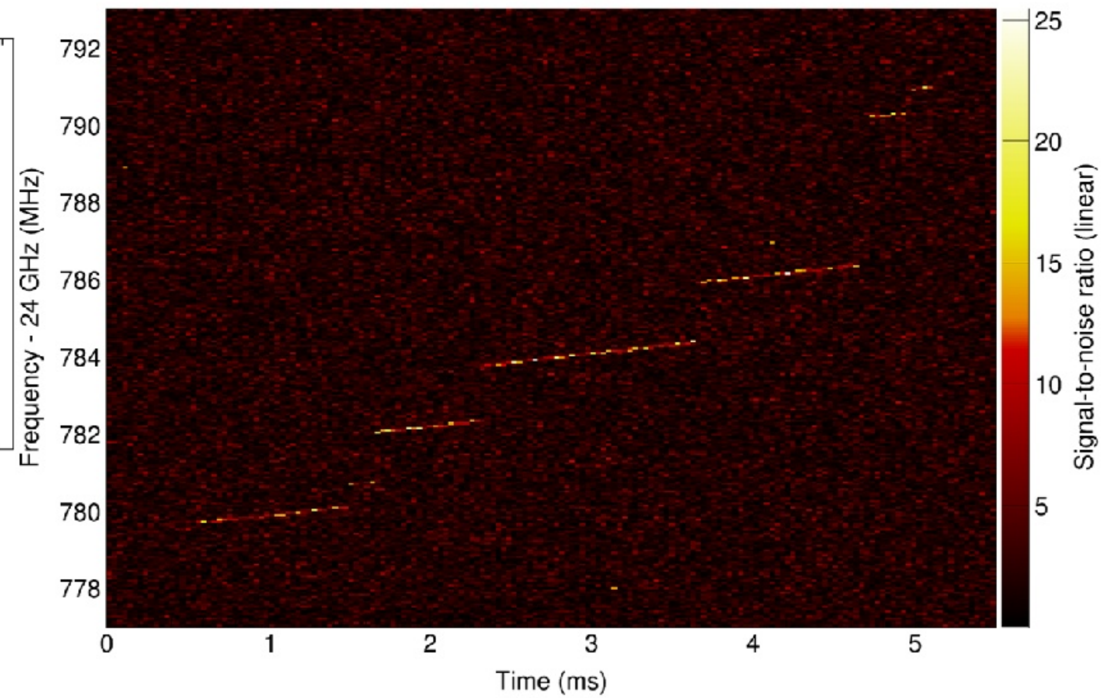
Project 8's phase 1: detection single electrons from ^{83m}Kr

Westfälische Wilhelms-Universität Münster

D. M. Asner et al., Phys. Rev. Lett. 114, 162501







courtesy J. Formaggio, RGH Robertson

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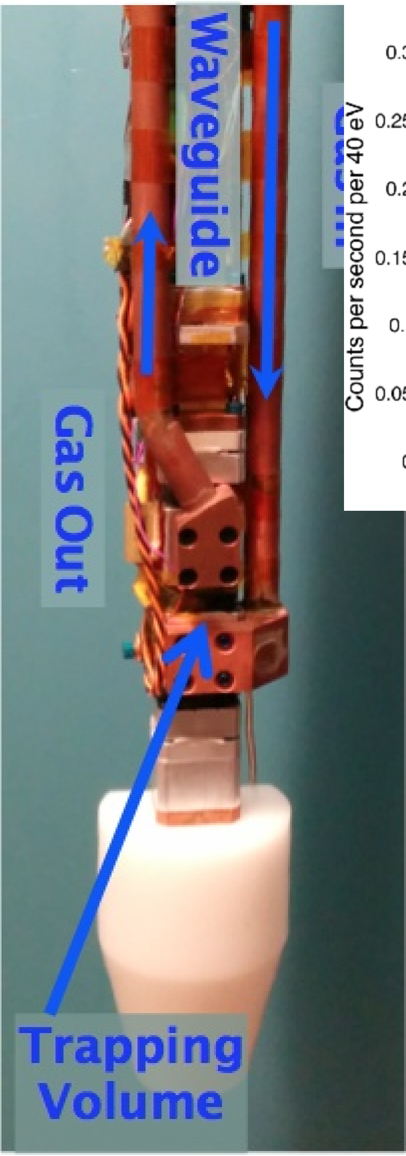

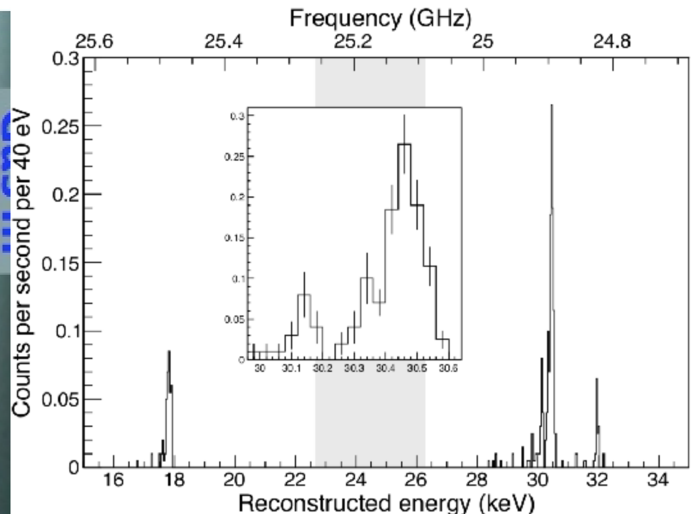

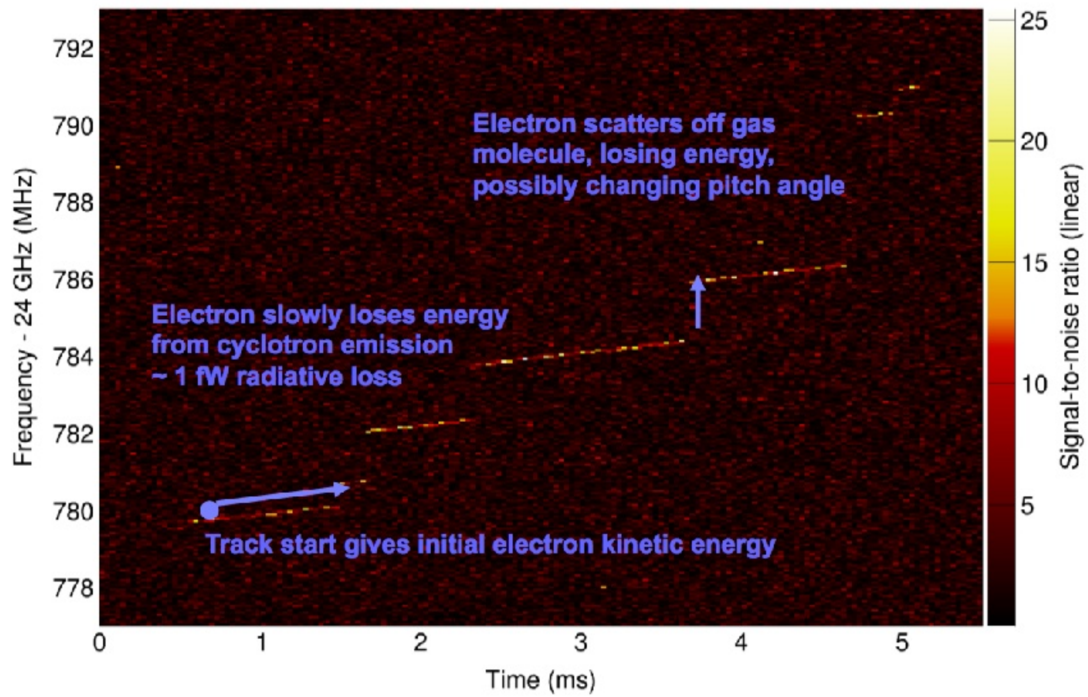

First detection of single electrons successfull but still a lot of R&D necessary
- Is a large scale experiment possible ?
- What are the systematic uncertainties & other limitations?

courtesy J. Formaggio, RGH Robertson

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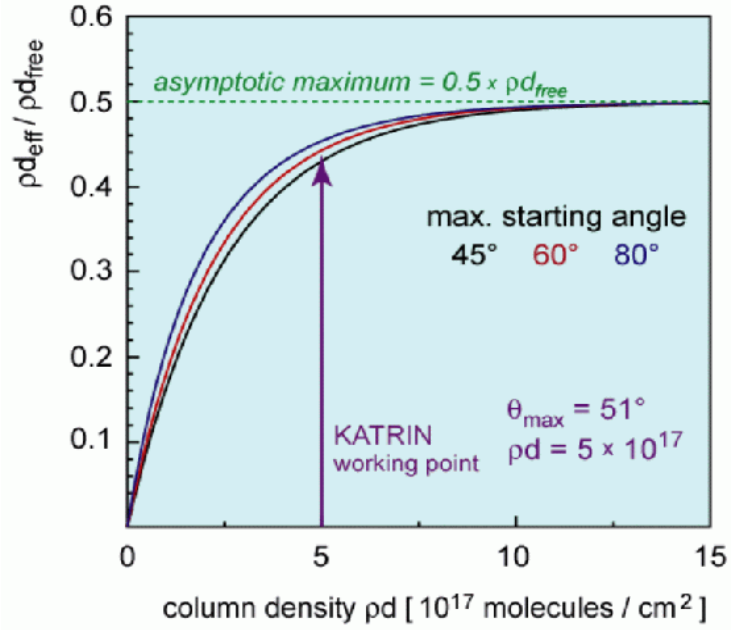

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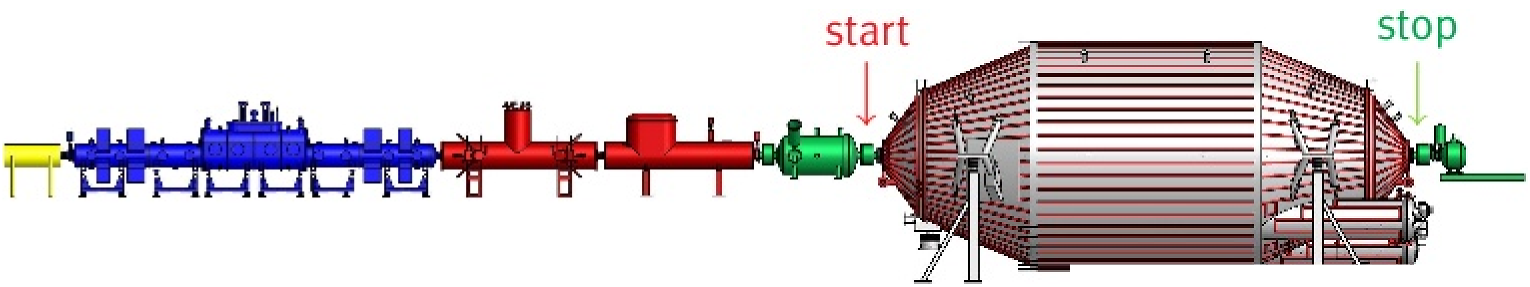
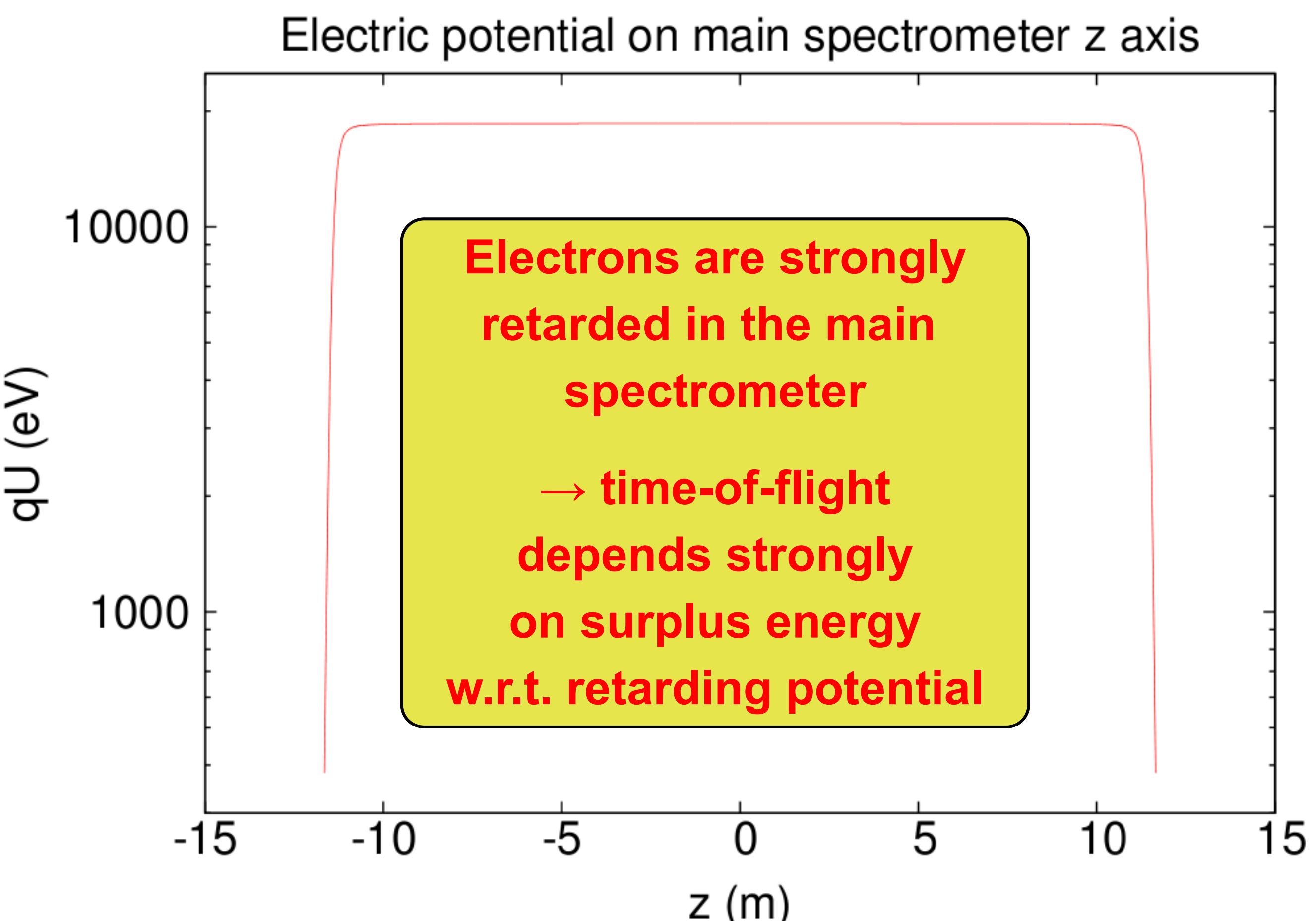
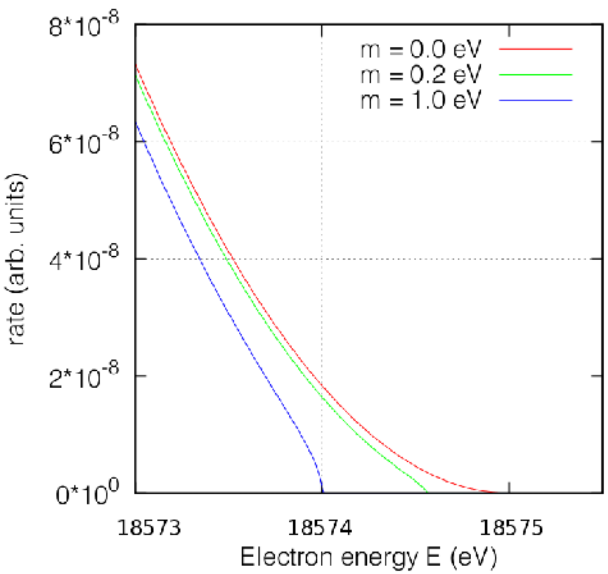
Alternative spectroscopy: measure time-of-flight TOF through KATRIN spectrometer





Electrons are strongly retarded in the main spectrometer

→ time-of-flight depends strongly on surplus energy w.r.t. retarding potential



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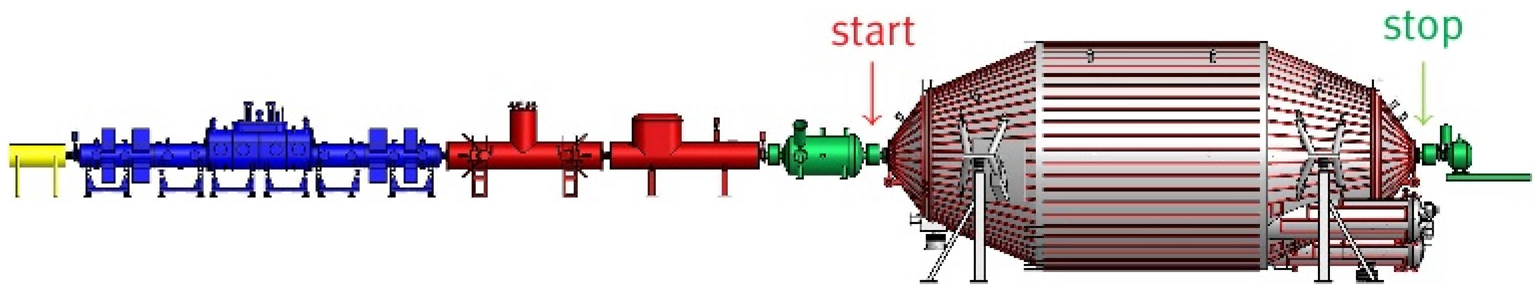

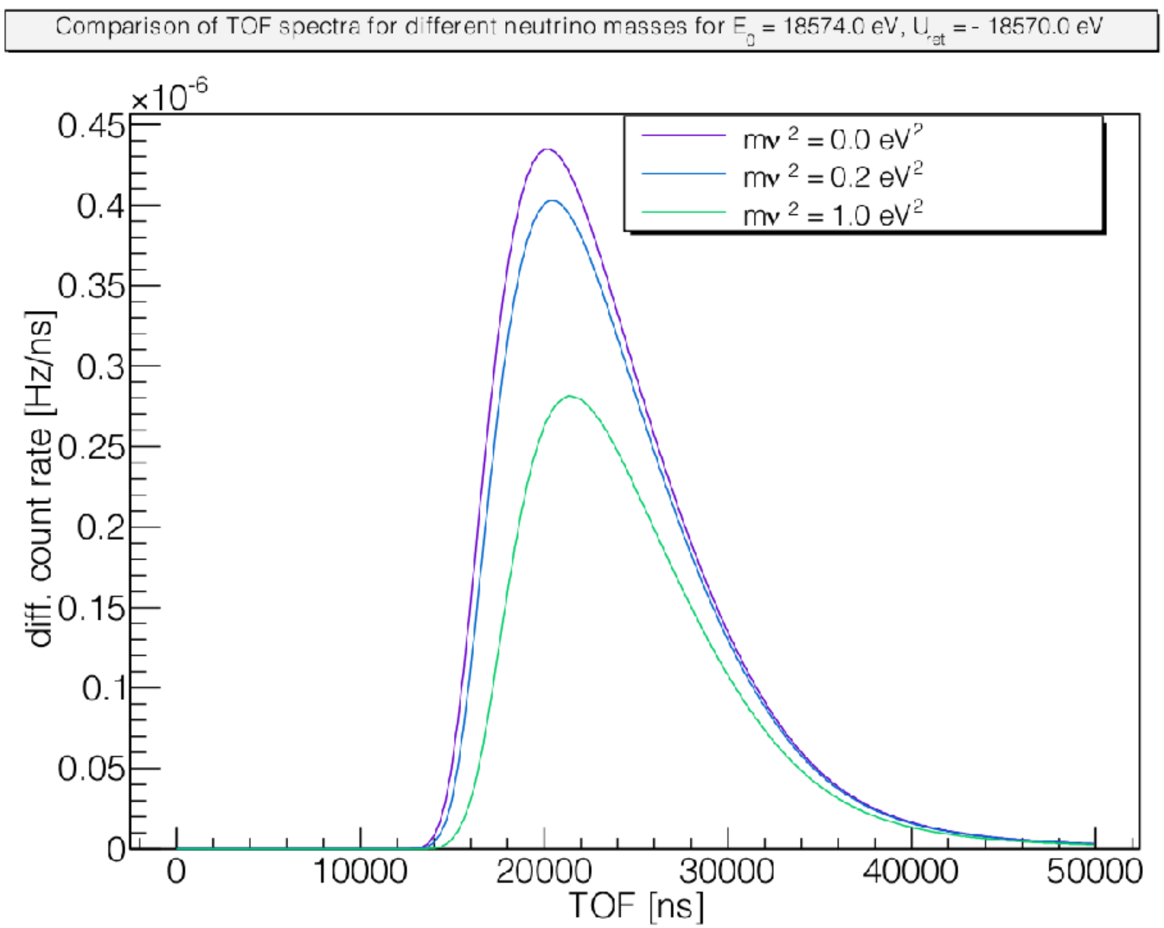

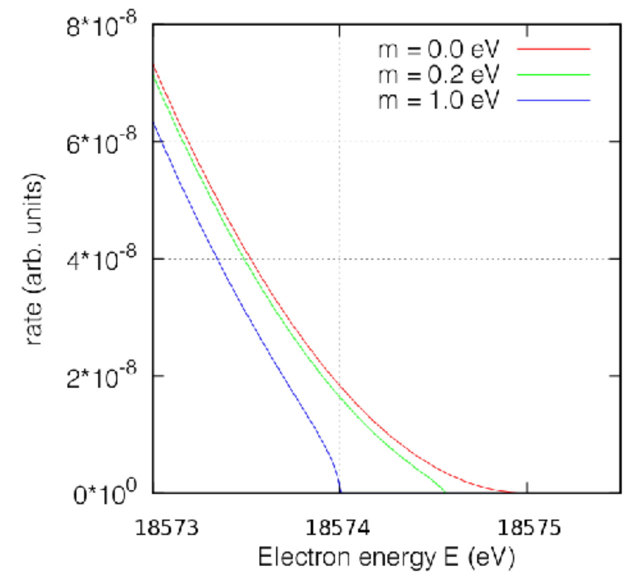

Time-of-flight spectrum corresponds to a full energy spectrum

→ sensitive to the neutrino mass

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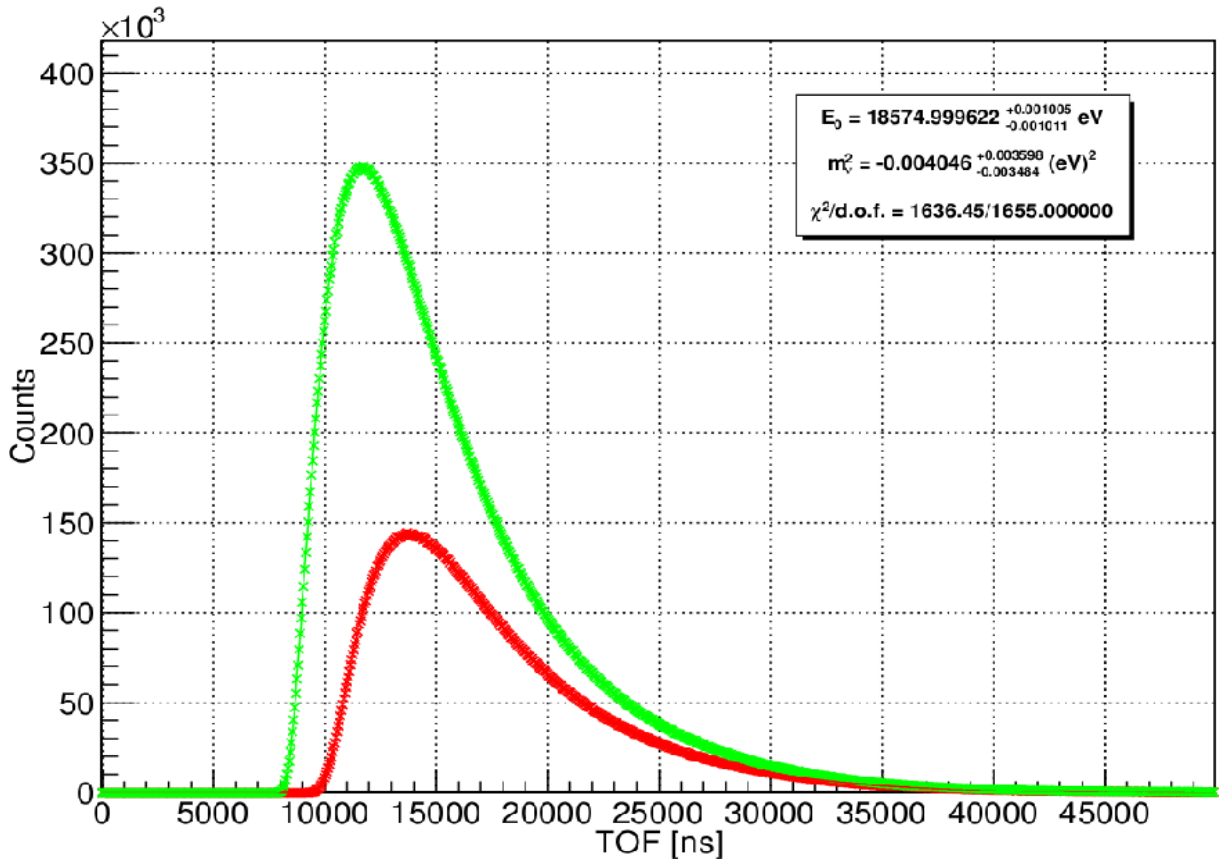
Sensitvity improvement on $m^2(\nu_e)$ by ideal TOF determination

Measure at 2 (instead of ≈30) different retarding potentials since TOF spectra contain already all the information

→ Factor 5 improvement in m_ν^2 w.r.t. standard KATRIN in ideal case !



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

Coincidence request between start and stop signal → nice background suppression

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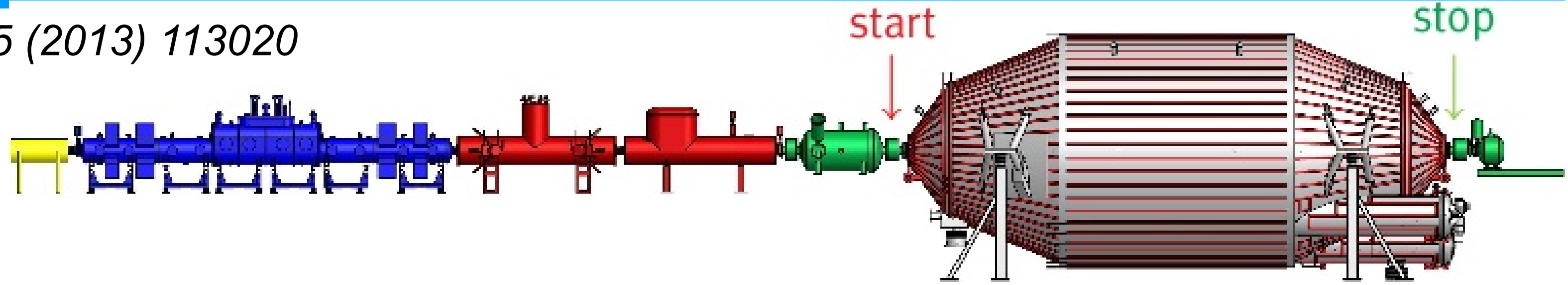
How to realize time-of-flight spectroscopy @KATRIN

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



Advantage: measure β-spectrum by time-of-flight at one (a few) retarding potential(s)

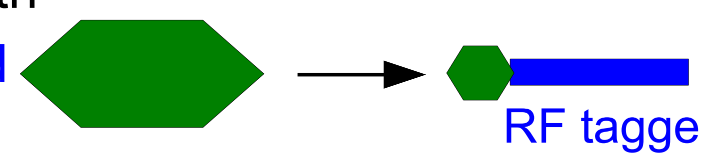
Stop: Can measure time-of-arrival with KATRIN detector with Δt = 50 ns → ok

Start: e^--tagger: Need to determine time-of-passing-by of e^- before main spectrometer without disturbing energy and momentum by more than 10 meV:

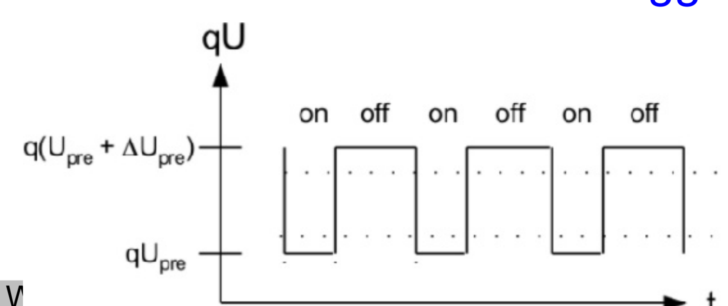
→ factor 5 in $\Delta m(\nu)^2_{stat}$ under ideal conditions

added value: significant background reduction !

One implementation: reduce pre spectrometer length
& add a Project 8-type tagger within a long solenoid
or another type of electron tagger



or: Use pre spectrometer as a „gated-filter"
by switching fast the retarding voltage
→ as sensitive on m(ν) as standard KATRIN !



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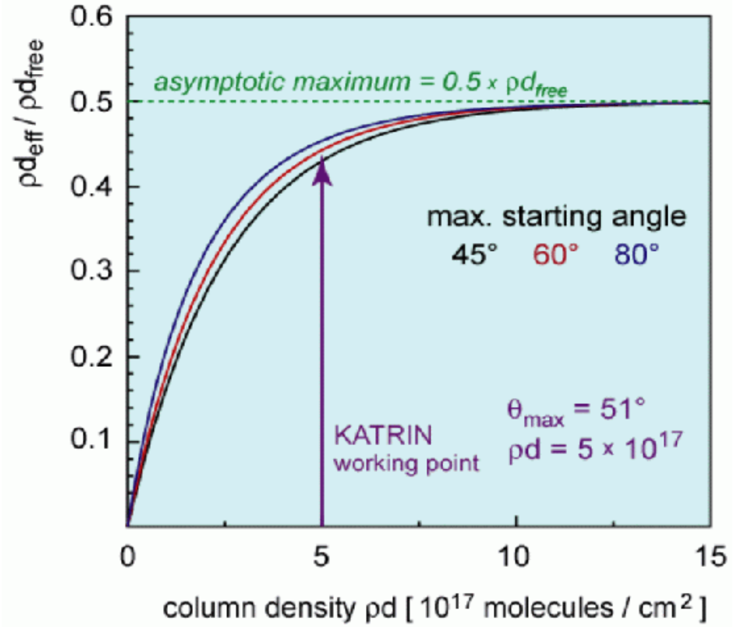

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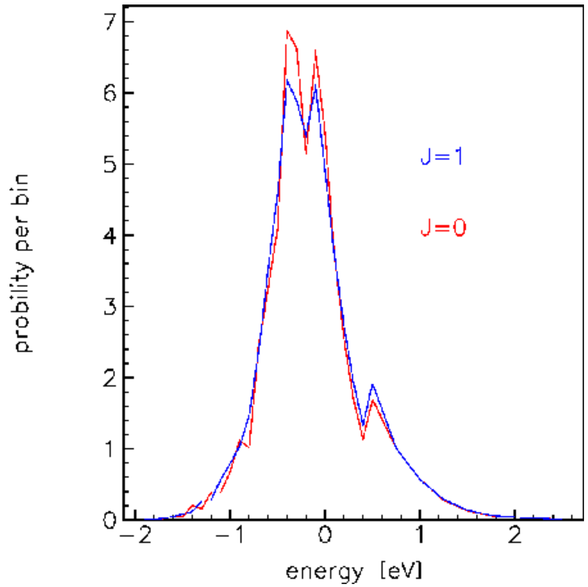

2) Resolution is limited to σ = 0.34 eV when using molecular tritium by the excitation of ro-vibrational states in the final state

→ use atomic tritium

Princeton Tritium Observatory for Light, Early-universe, Massive-neutrino Yield (PTOLEMY)

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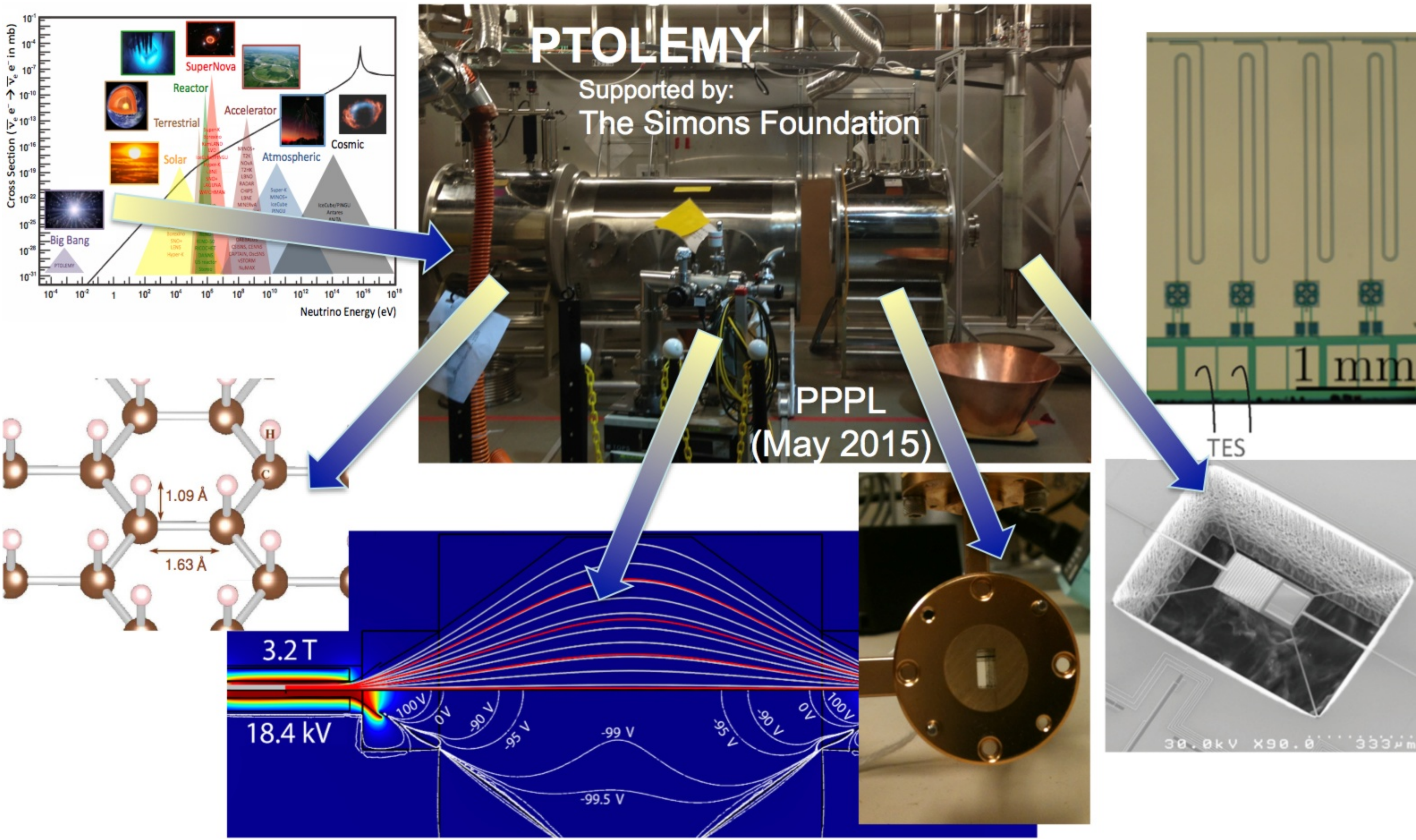

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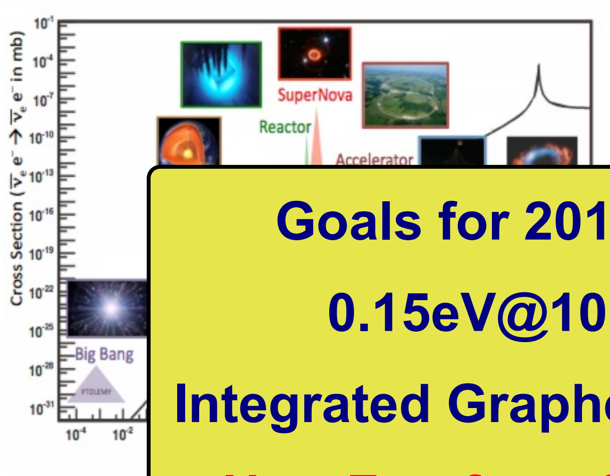
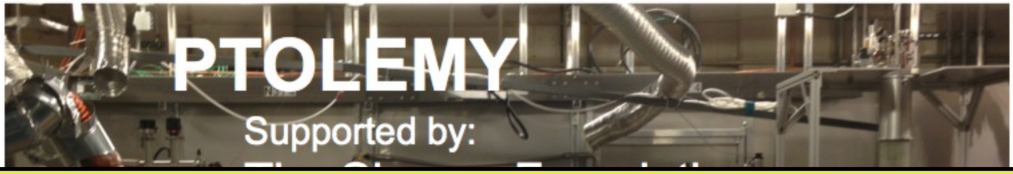
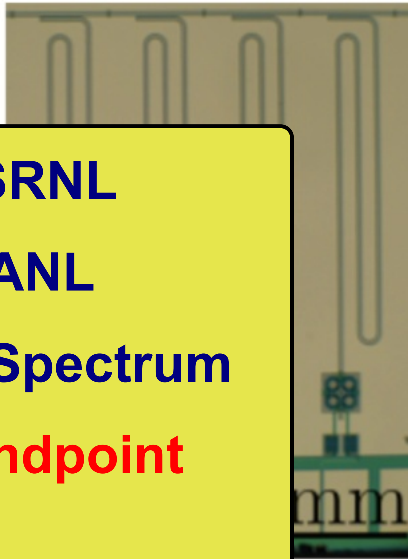
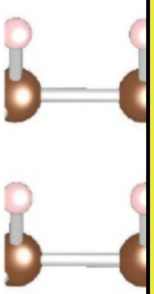








Goals for 2015: Tritium-loaded Graphene Surface from SRNL

0.15eV@100eV TES Energy Resolution from Goddard/ANL

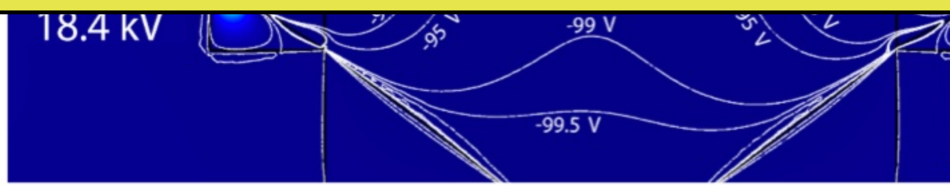
Integrated Graphene / TES into 1% MAC-E Filter to Measure Spectrum

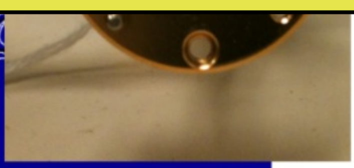
New Forefront for Calorimeter-based Methods @ Tritium Endpoint

But to get enough statistics requires a special trick to overcome Lionville's magnetic flux conservation

Will this really work?

arXiv:1307.4738





Conclusions

Search for the neutrino mass scale & pattern: Beyond the SM physics

Threefold way to the neutrino mass scale:

- Cosmology:

CMB, LSS, cosmic shear (EUCLID, by graviational waves):
detection of neutrino mass expected, but no details of spectrum
dependent on cosmological model

- Neutrinoless double beta decay:

Several experiments close start for $T_{1/2} > 10^{26}$ yr and $m(\nu) < 100$ meV
GERDA II, MAJORANA, CUORE, ..
larger mass, lower background (sophisticated methods)
lepton flavour violation required and tested

- Direct neutrino mass measurements:

KATRIN is close to start ($m(\nu) < 200$ meV)
significant R&D on ^{163}Ho micro calorimeters (ECHo, HOLMES, ...)
new ideas like Project 8, ...

THANK YOU FOR YOUR ATTENTION !