Neutrino physics: experiments II

The dark side of the Universe, ISAPP, MPIK Heidelberg, May 29/30, 2019

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A reminder: Neutrinos
in the Standard Model of Particle Physics

Neutrino oscillations:
experiments with atmospheric,
solar, accelerator and reactor neutrinos

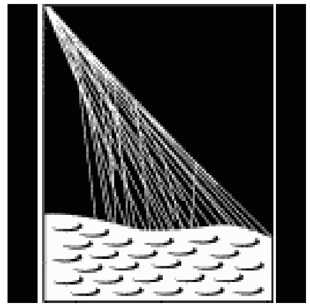
Neutrino masses:
- cosmology and astrophysics
- neutrinoless double β decay
- direct neutrino mass experiments

Search for sterile neutrinos
Coherent elastic neutrino nucleus scattering

Positive results from ν oscillation experiments

atmospheric neutrinos

(Kamiokande, Super-Kamiokande, IceCube, ANTARES)



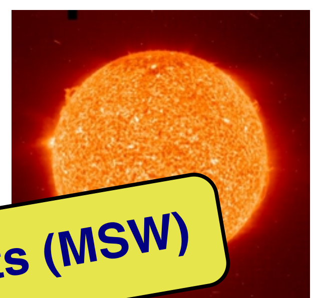
accelerator neutrinos

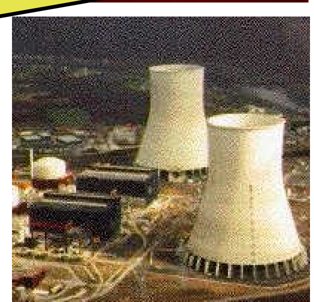
(K2K, T2K, MINOS, OPERA, MiniBoone)

solar neutrinos

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

Matter effects (MSW)





⇒ non-trivial ν-mixing

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

$$|U_{\mathrm{PMNS}}| \sim \begin{pmatrix} 0.8 & 0.5 & 0.1 \\ 0.5 & 0.6 & 0.7 \\ 0.3 & 0.6 & 0.7 \end{pmatrix}$$

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

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

$0.018 < \sin^2(\theta_{13}) < 0.030$ 8.5°

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

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

⇒ $m(\nu_j) \neq 0$, but unknown

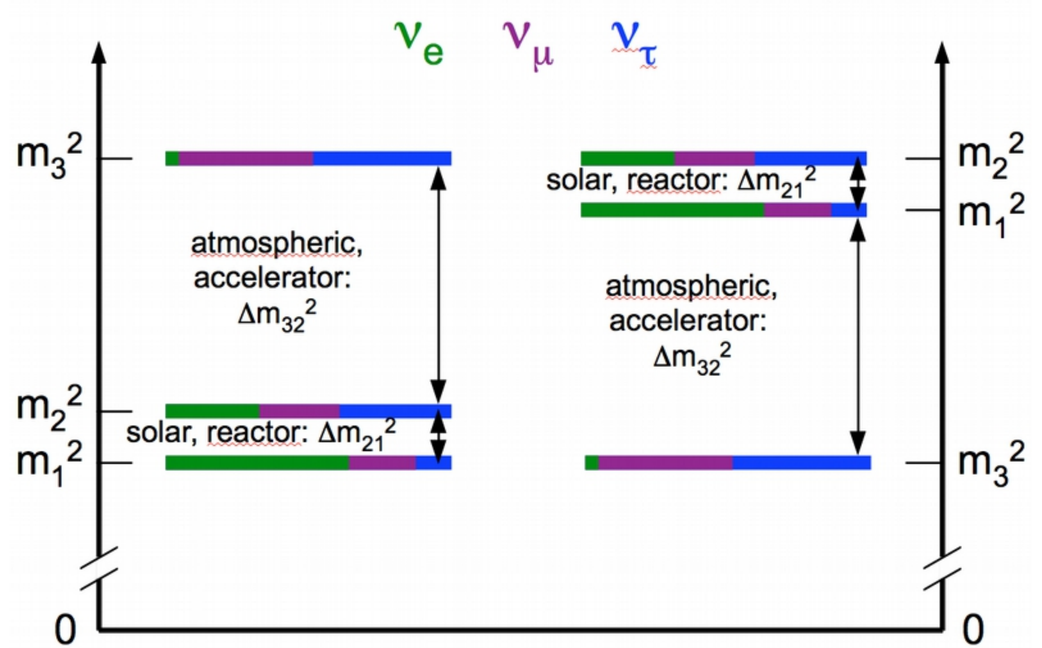
additional sterile neutrinos ?

What next in neutrino physics ?

- Absolute neutrino mass scale ?

  very important since there are 1 billion times more neutrinos than atoms in the universe

  very important since the very small neutrino masses are probably due to more than just the Yukawa coupling to the Higgs



- Neutrino particle character ?

  Are neutrinos their own antiparticles (Majorana particles)

- Hierarchy: $m(\nu_3) > m(\nu_{2,1})$ or $m(\nu_{2,1}) > m(\nu_3)$?

- CP violating phase δ_{CP} ?

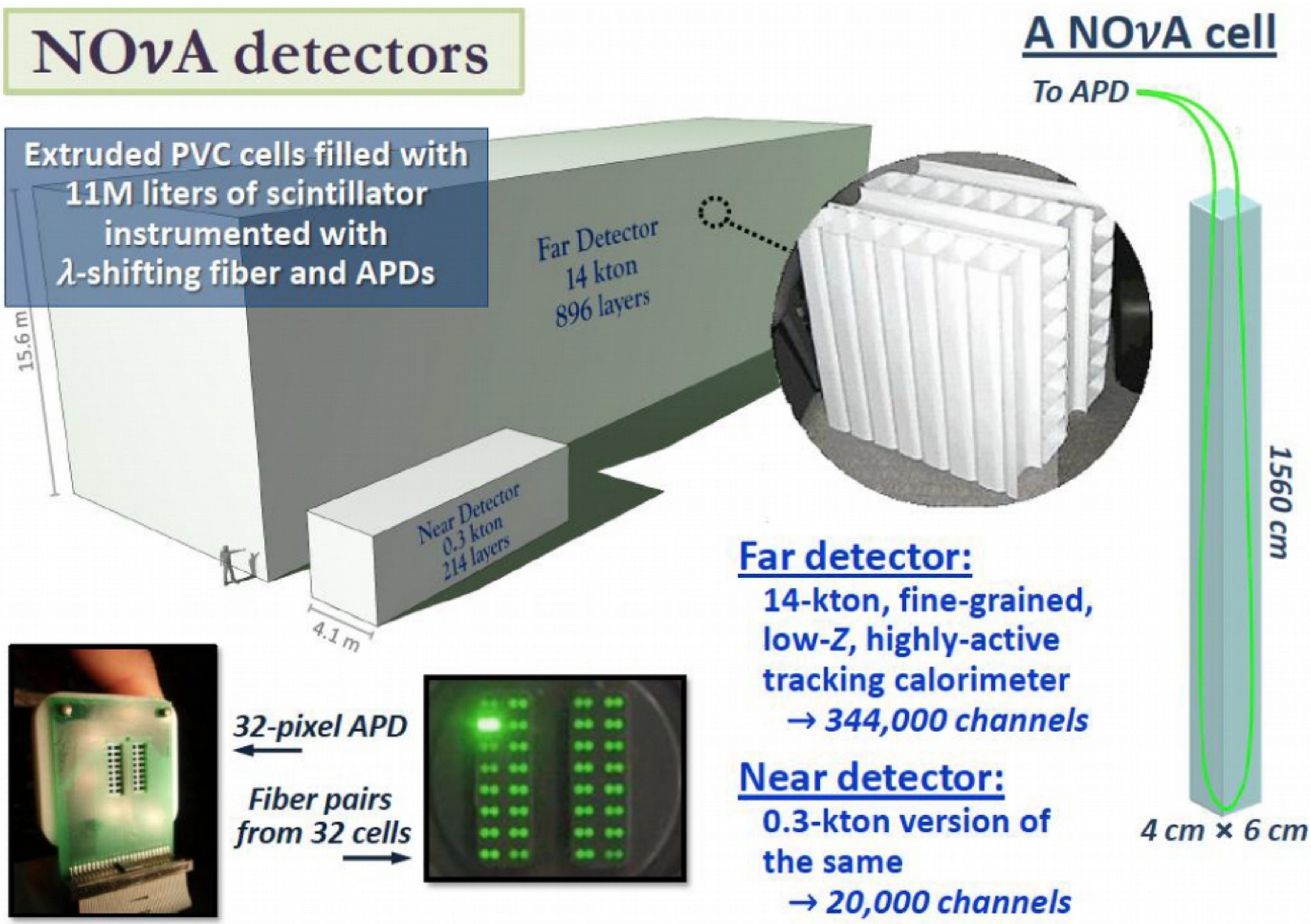
  3x3 unitary mixing matrix U_{PMNS}:

  3 angles and 1 CP violating phase, connected to BAU via leptogensis ?

$$U_{PMNS} = \begin{bmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{bmatrix} \begin{bmatrix} c_{13} & 0 & s_{13}e^{-i\delta_{CP}} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta_{CP}} & 0 & c_{13} \end{bmatrix} \begin{bmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

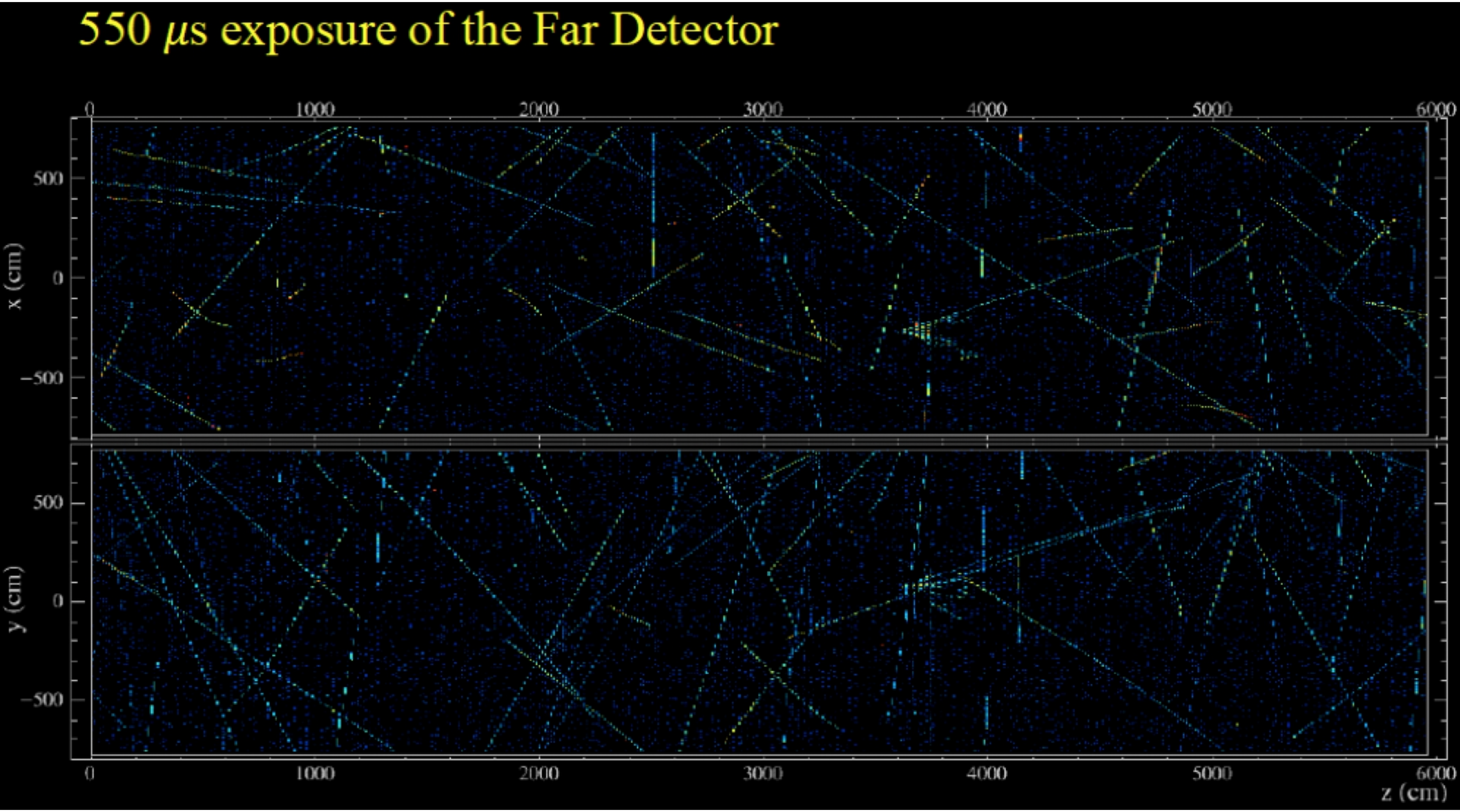
- Is there a 4th or even a 5th light but sterile neutrino ?

NOVA: high granularity detector, off-axis beam, long baseline (810 km)



from Dave Wark, VI Pontecorvo International Neutrino School

NOVA: high granularity detector, off-axis beam, long baseline (810 km)



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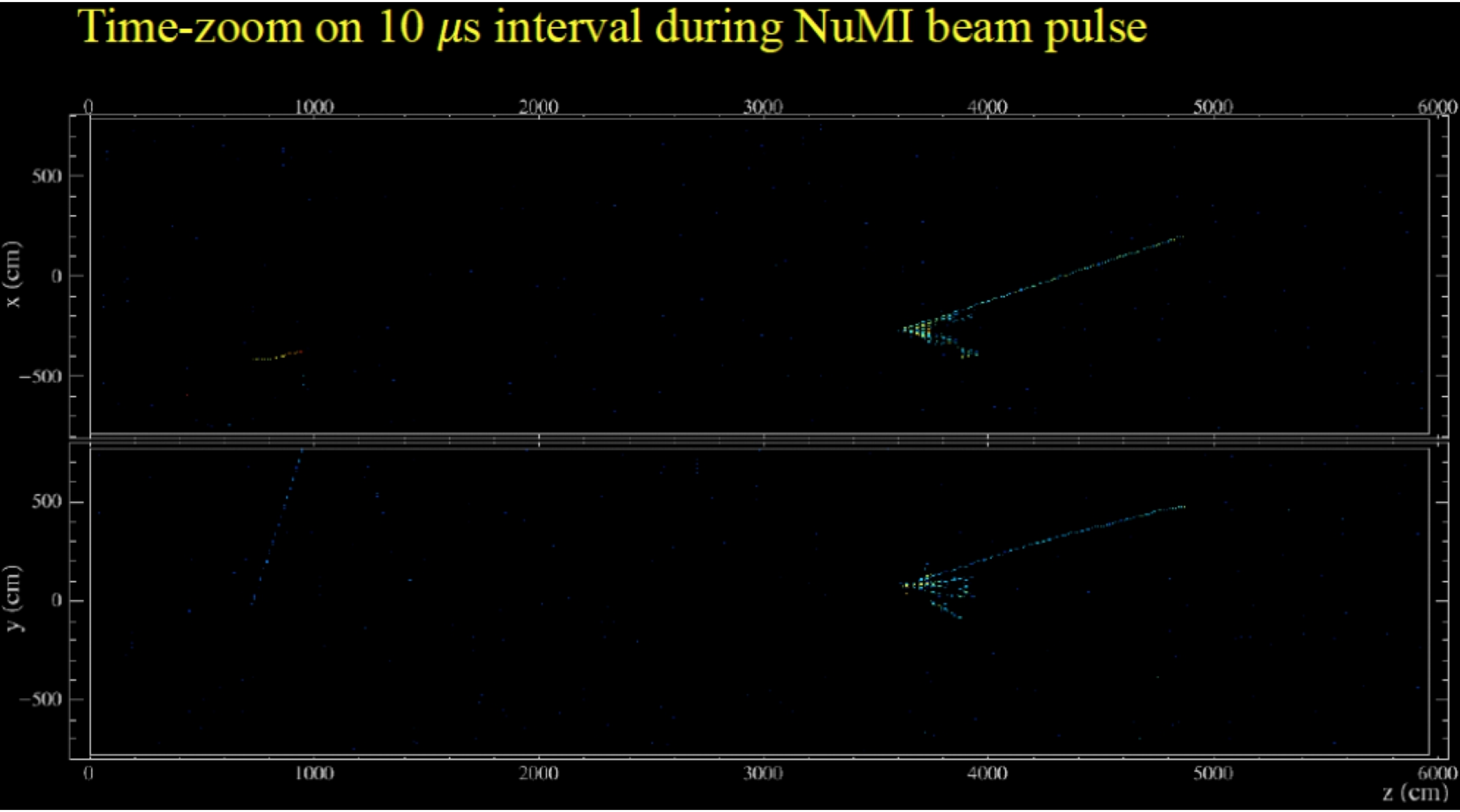

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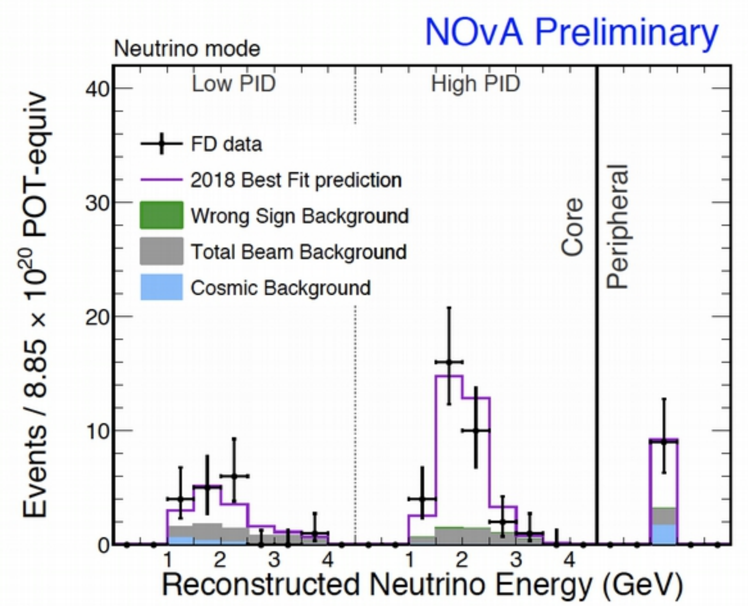
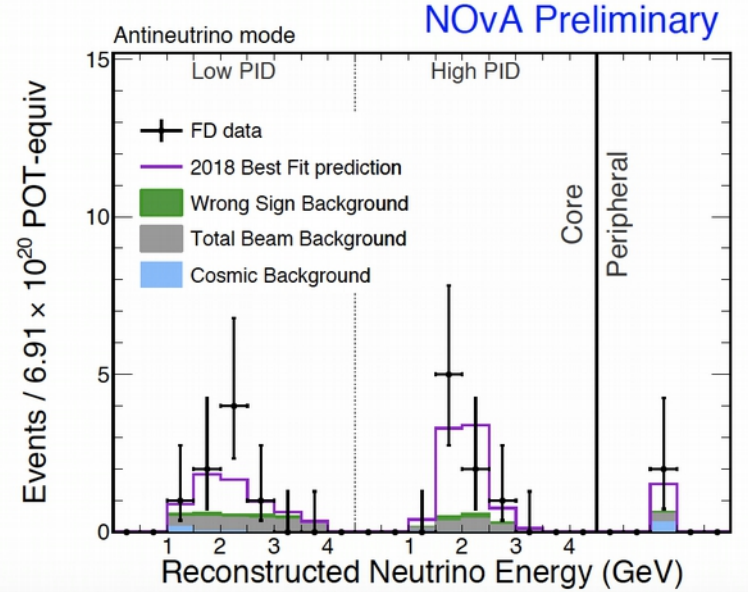
Electron (anti)neutrino appearance

M. Sanchez, Neutrino 2018

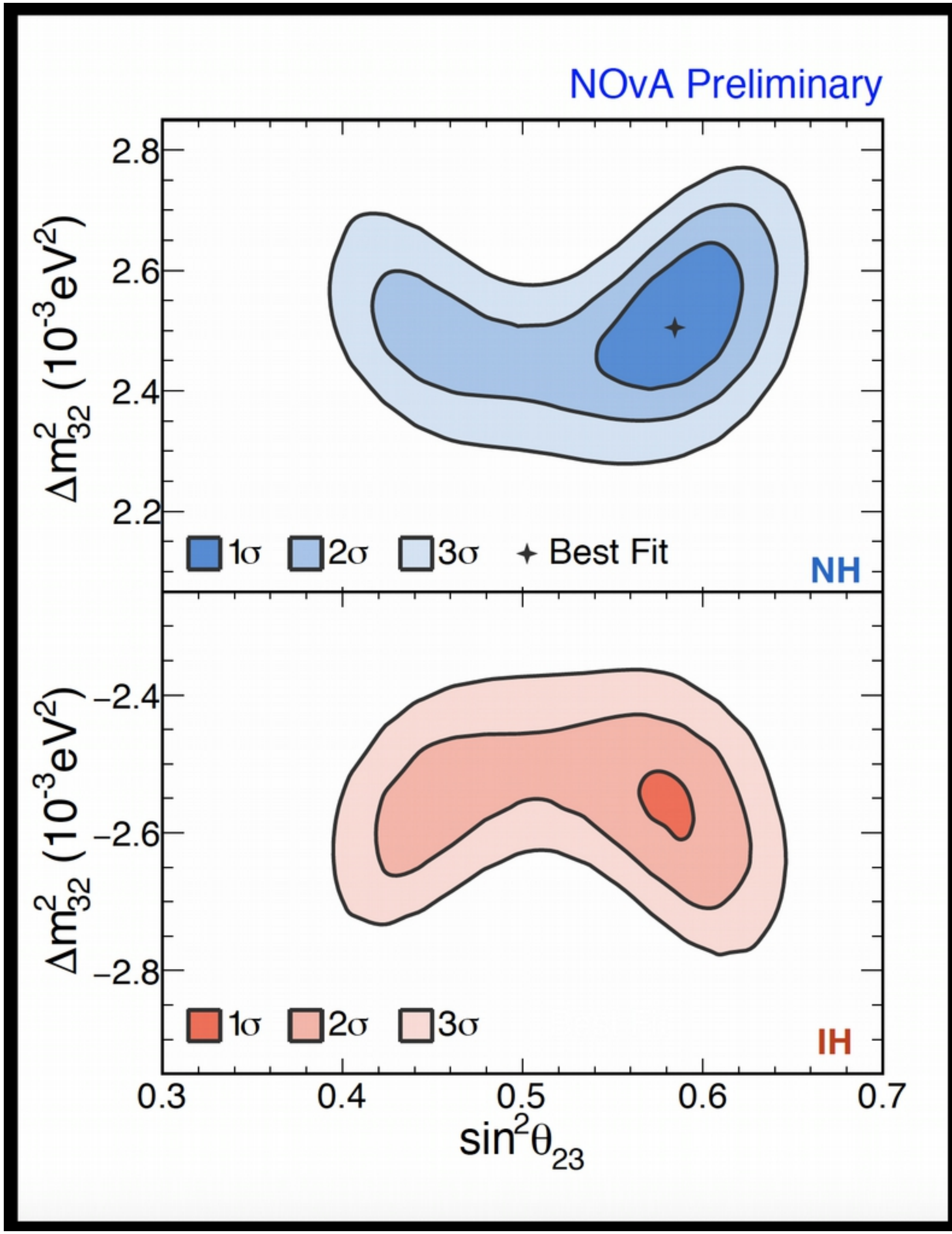
- On the neutrino beam we observe 58 events and expect 15 background interactions:
  - 11 beam, 3 cosmic background and < 1 wrong sign background.
- For the antineutrino beam we observe 18 and expect 5.3 background interactions:
  - 3.5 beam background, < 1 cosmic background and 1 wrong sign background.

> 4σ evidence of electron antineutrino appearance





Electron (anti)neutrino appearance



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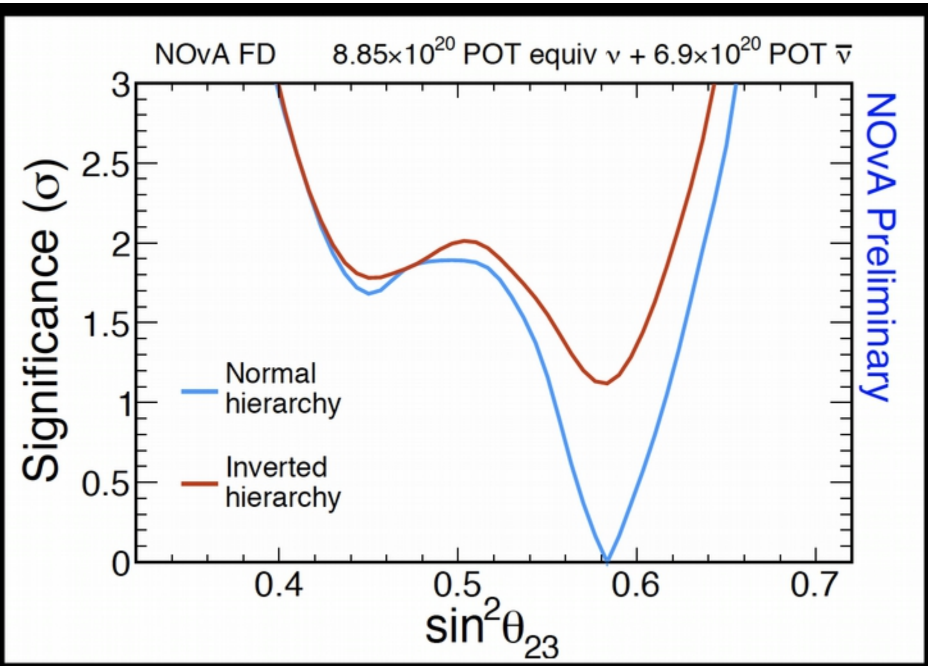
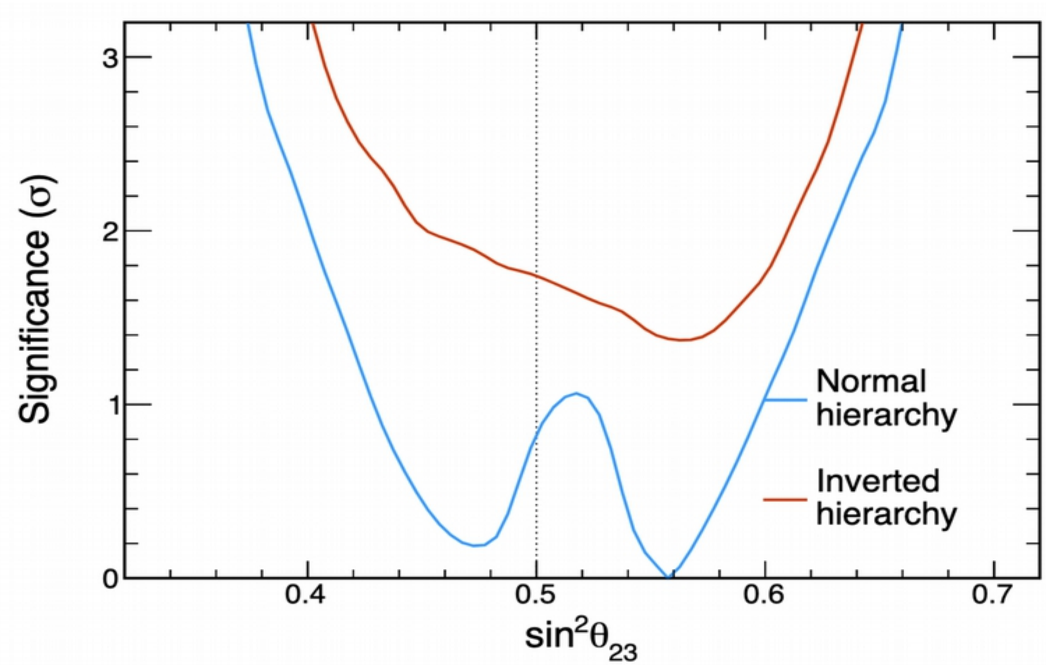


- Best fit:
  Normal Hierarchy
  $\sin^2\theta_{23} = 0.58 \pm 0.03$ (UO)
  $\Delta m^2_{32} = (2.51^{+0.12}_{-0.08}) \cdot 10^{-3}\ \mathrm{eV}^2$

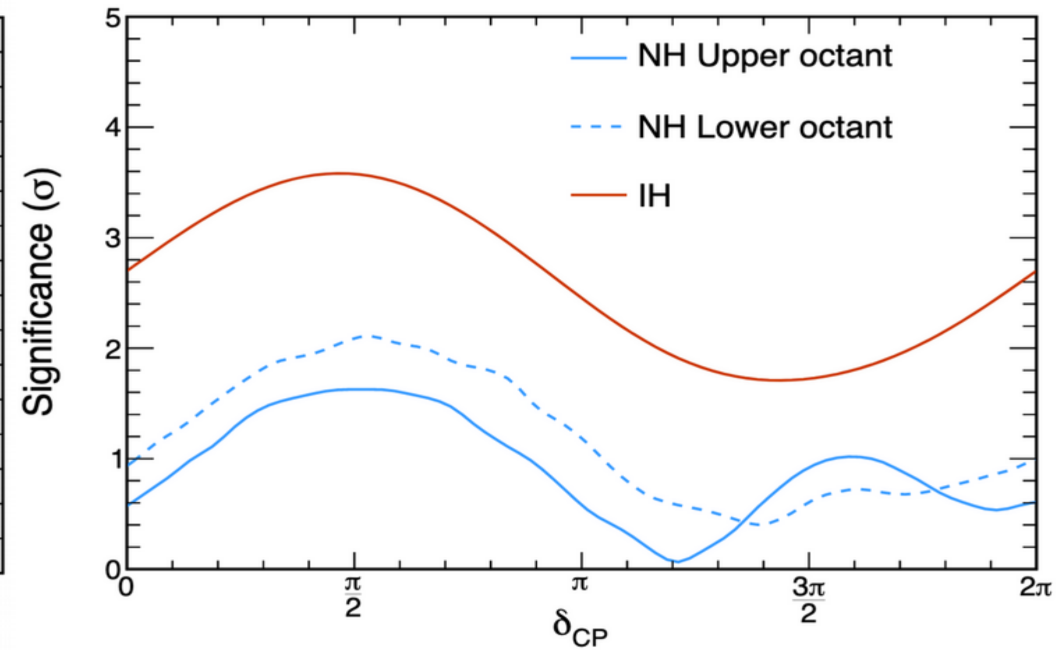
Prefer non-maximal at 1.8σ
Exclude LO at similar level

NOνA: Results from muon disappearance and Electron neutrino appearance

Hierarchy

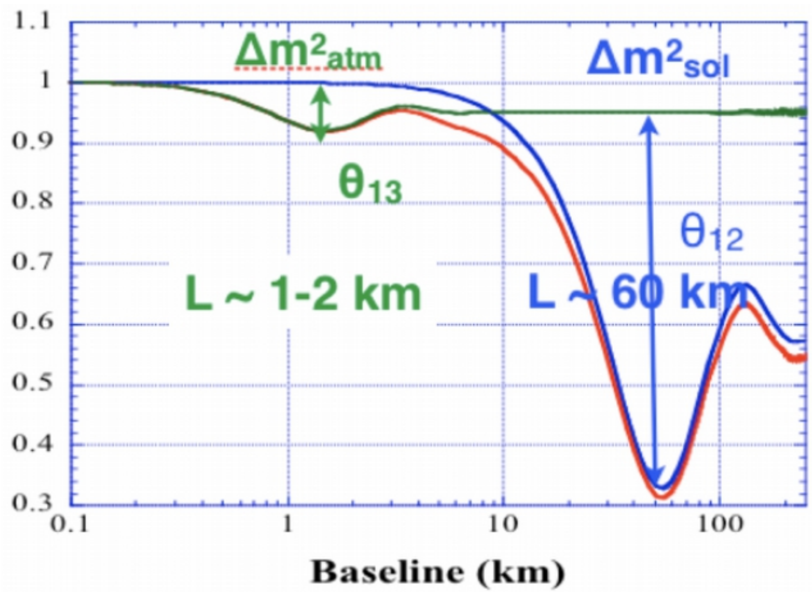


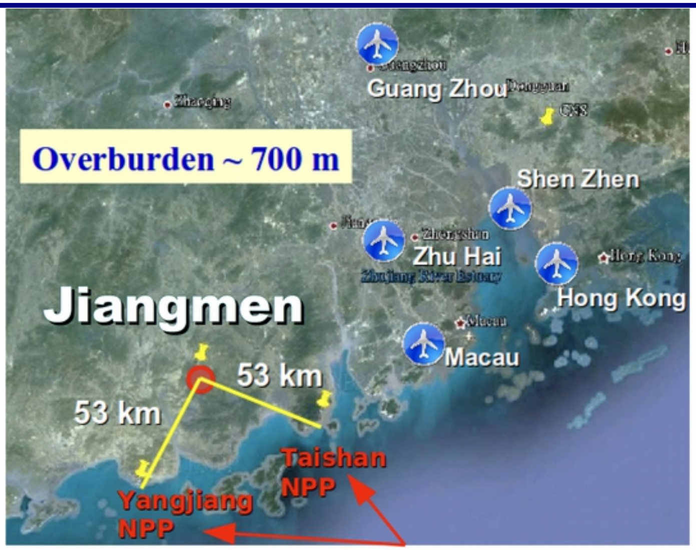
CP phase



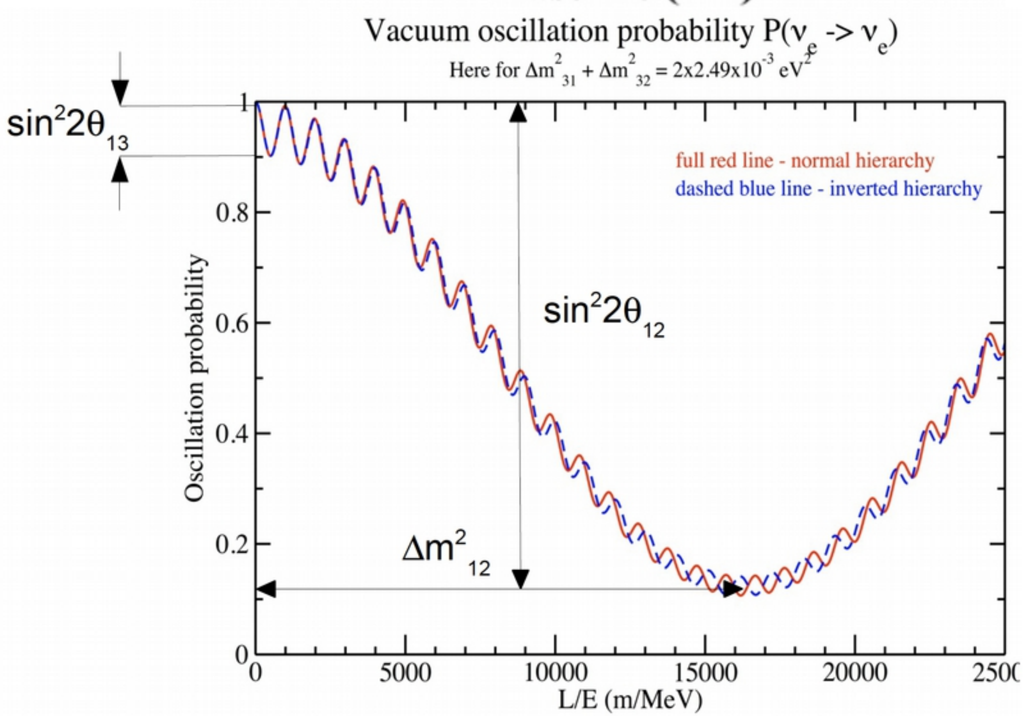
M.A. Acero (NOνA Collaboration), Phys. Rev. D 98 (2018) 032012

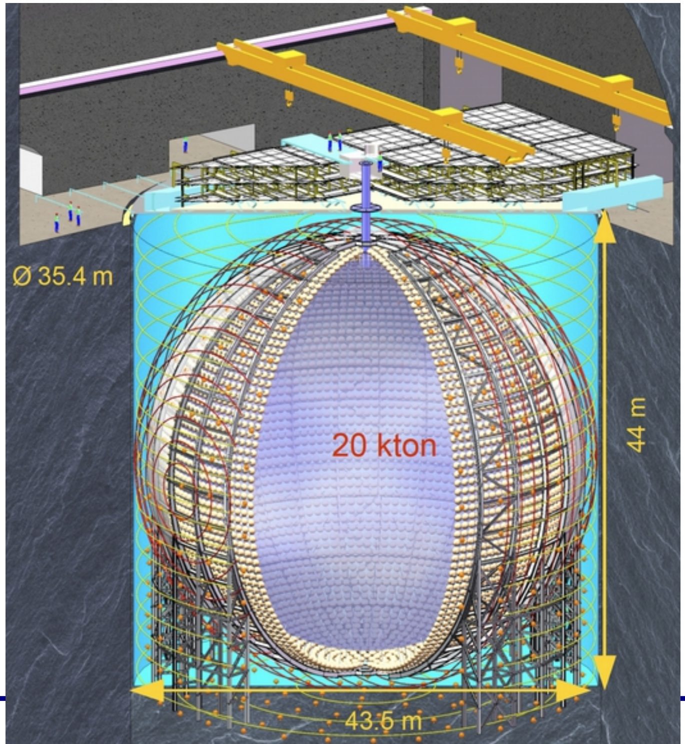
JUNO: 60 km baseline reactor experiment: resolving ν mass hierachy ($m_1<m_2<m_3$ or $m_3<m_1<m_2$)



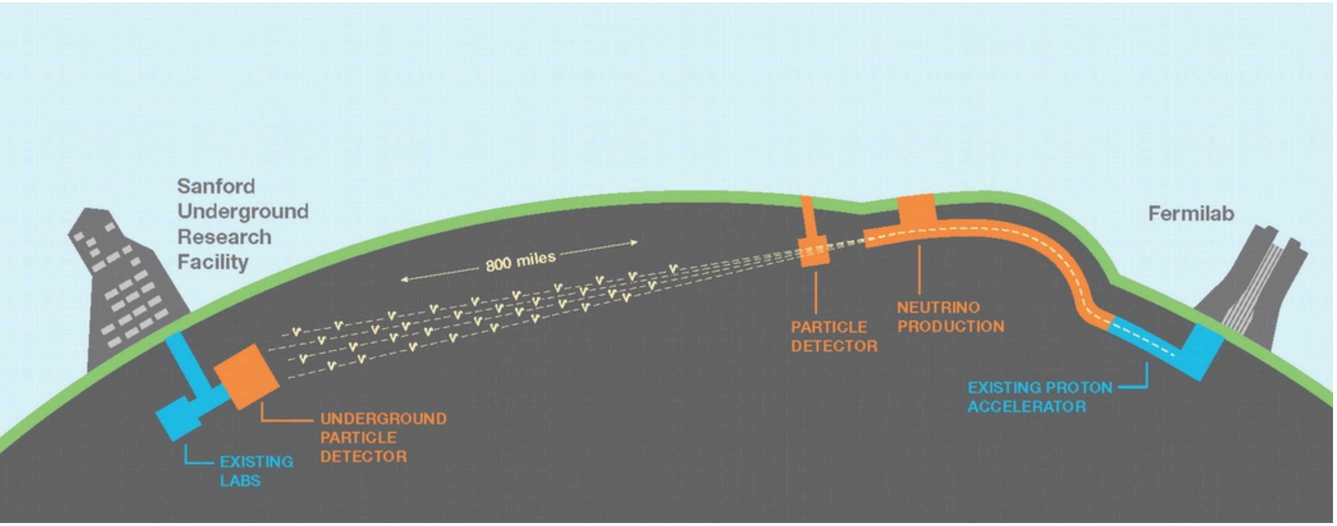


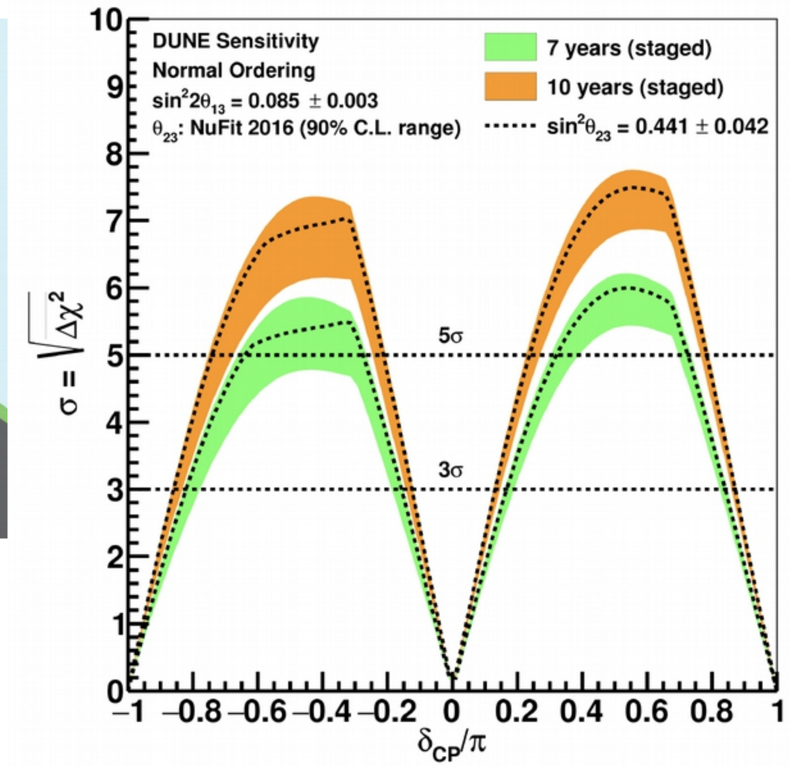
High power nuclear power plants (26.6 GW total power)

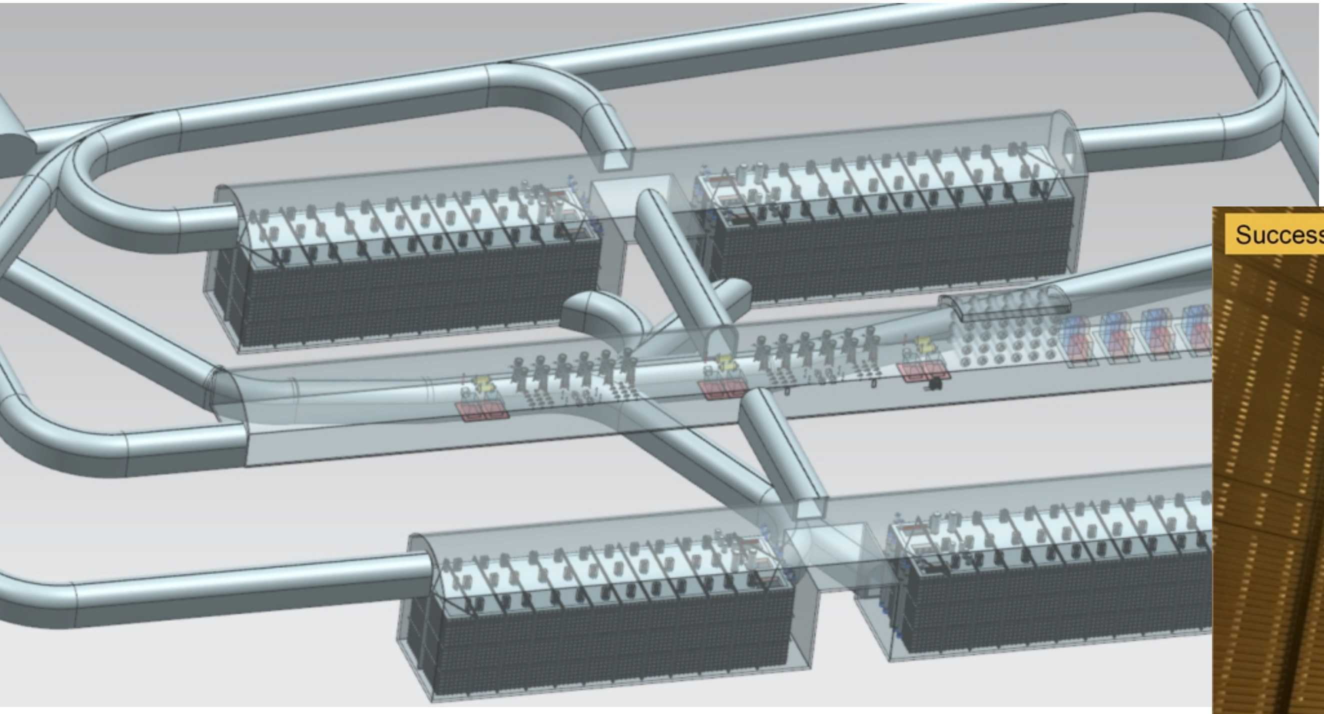


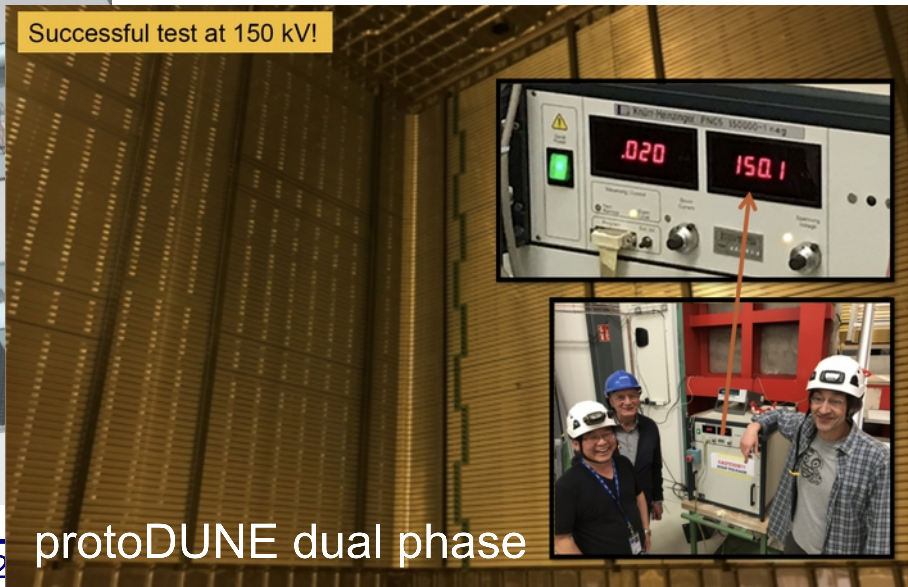


Future: DUNE - 1300km baseline, LAr TPCs: CP & mass ordering









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Neutrino oscillations:
experiments with atmospheric,
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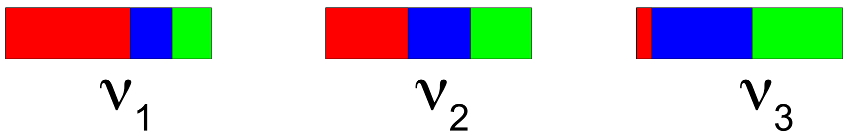
Neutrino masses:
- cosmology and astrophysics
- neutrinoless double β decay
- direct neutrino mass experiments

Search for sterile neutrinos
Coherent elastic neutrino nucleus scattering

Need for the absolute ν mass determination

Results of recent oscillation experiments: Θ_{23}, Θ_{12}, Θ_{13}, Δm^2_{23}, Δm^2_{12}

ν_e ν_μ ν_τ



degenerated masses

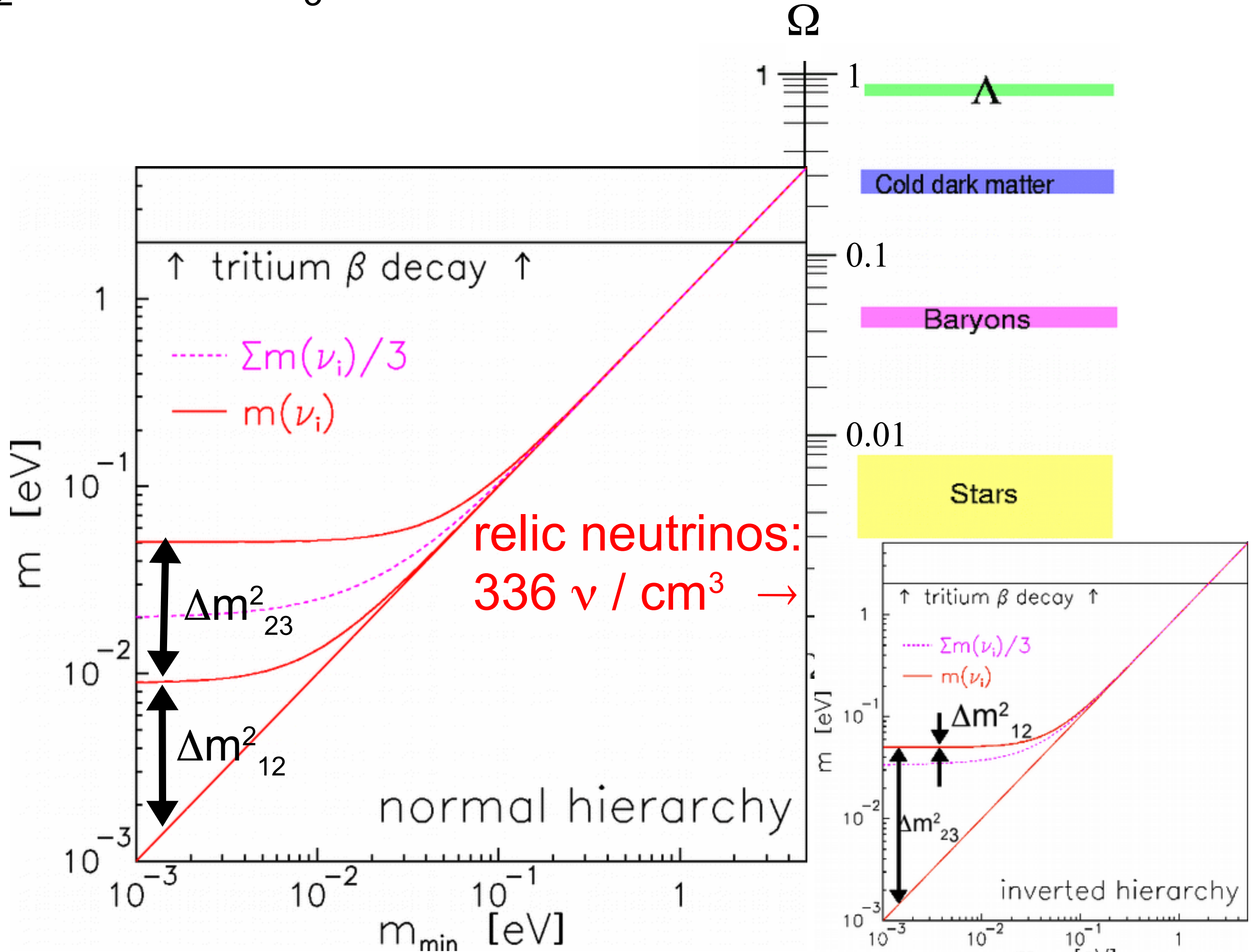
cosmological relevant

e.g. seesaw mechanism type 2

hierarchical masses

e.g. seesaw mechanism type 1

explains smallness of masses, but not large (maximal) mixing



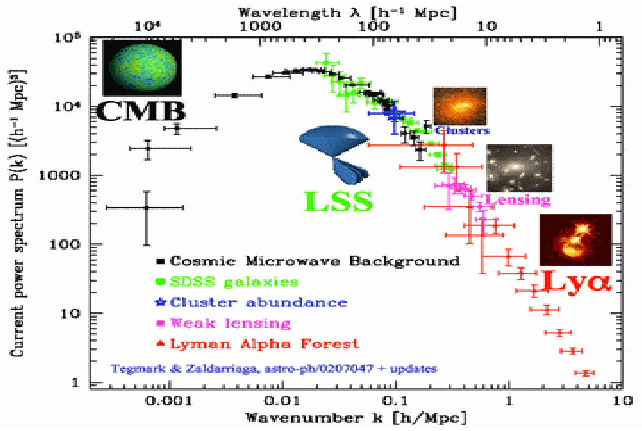
Three complementary ways to the absolute neutrino mass scale

1) Cosmology

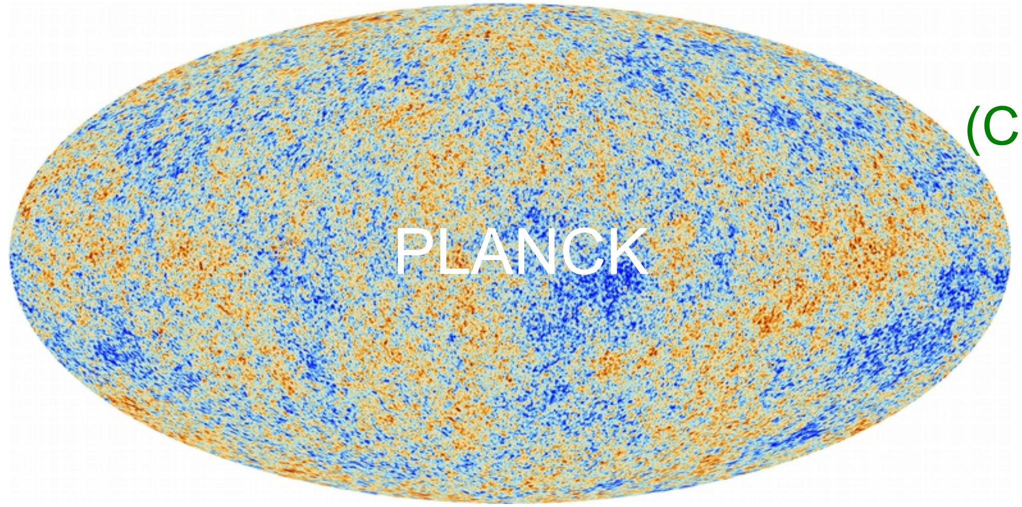
very sensitive, but model dependent

compares power at different scales

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

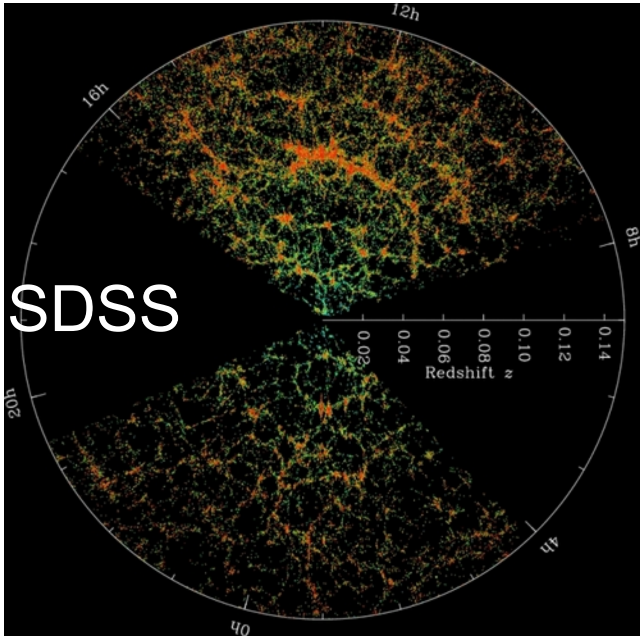


Neutrino mass from cosmology



measurement of CMBR

(Cosmic Microwave Background Radiation)



big bang theory:

neutrino density in universe

$n_\nu = 336 / cm^3$

measurement of matter density distribution

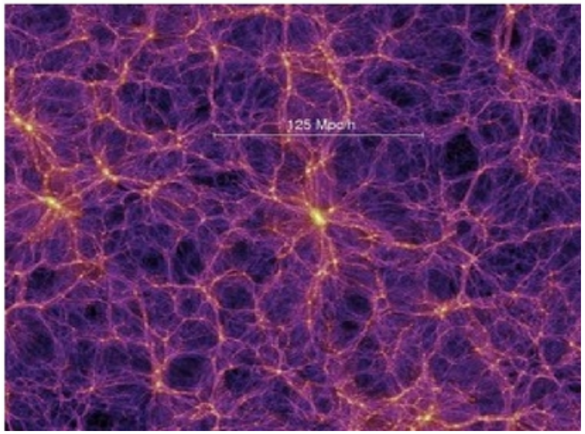
LSS (Large Scale Structure)

2dF, SDSS, ...

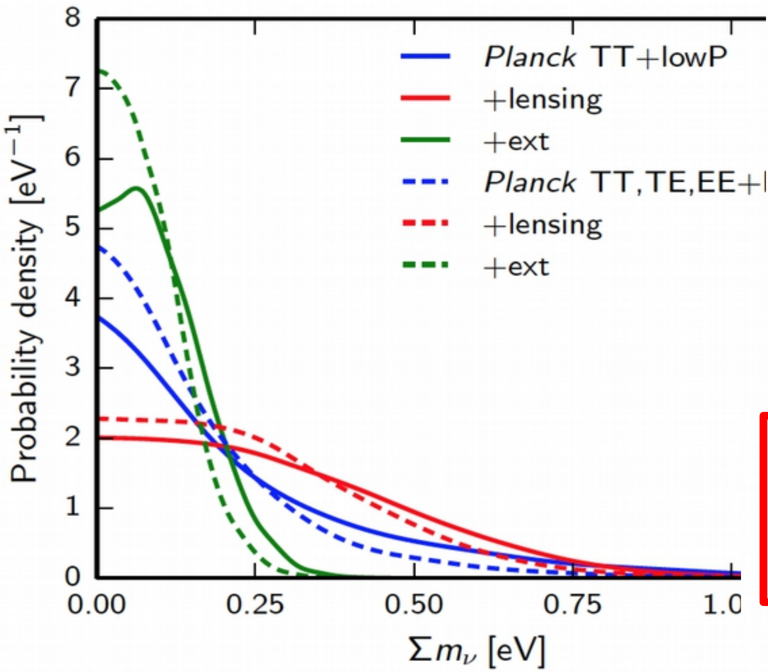
model development

← National Center for SuperComputer Simulations, http://cosmicweb.uchicago.edu/sims.html

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

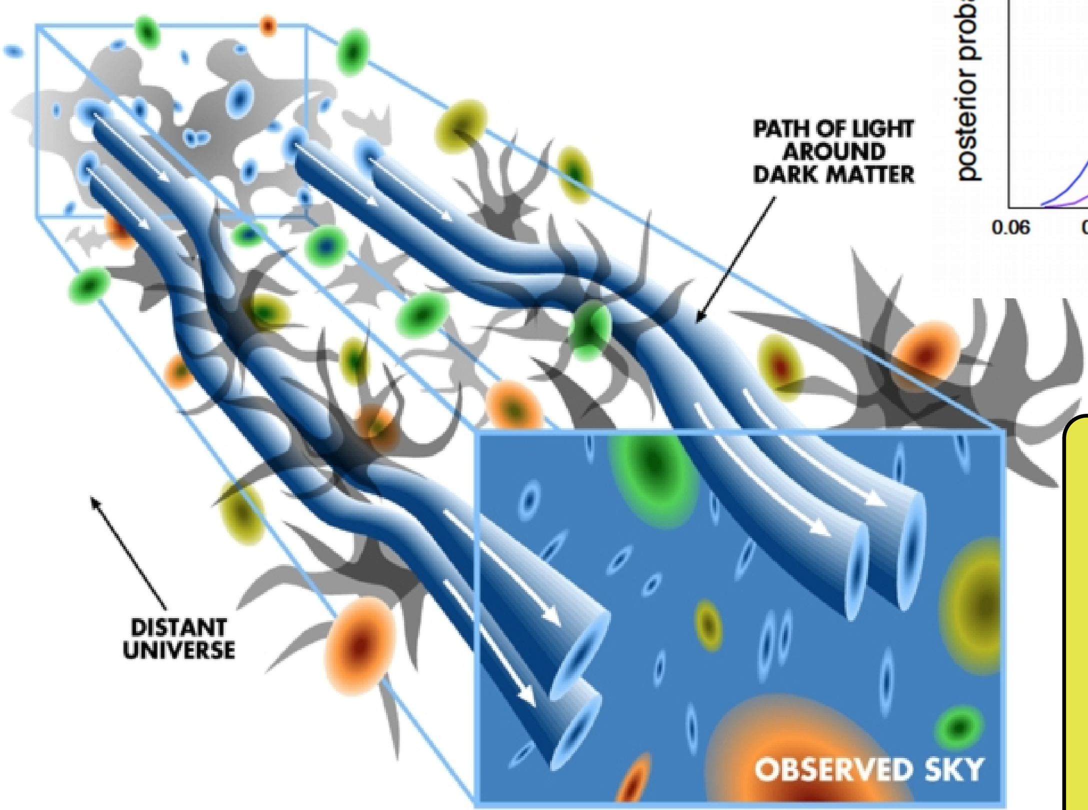
Relies on ΛCDM model !

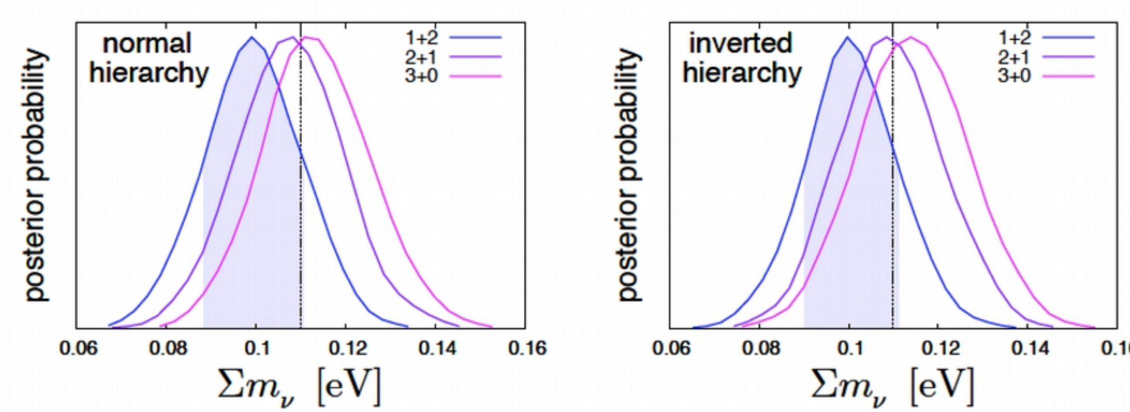
Is this fully correct, there are some discrepancies ?

More than 95% of the energy distribution in the universe is not known (dark energy, dark matter)

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**

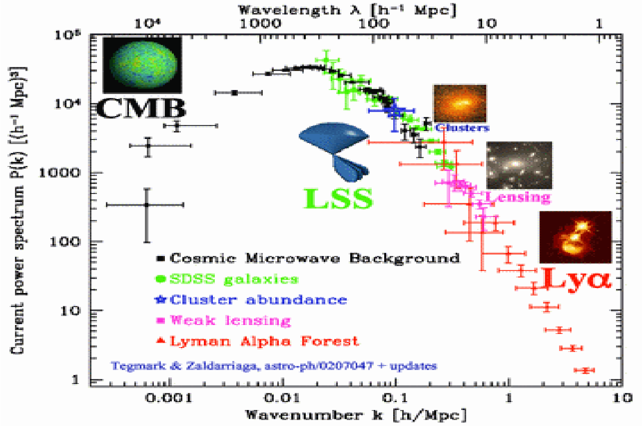
Three complementary ways to the absolute neutrino mass scale

1) Cosmology

very sensitive, but model dependent

compares power at different scales

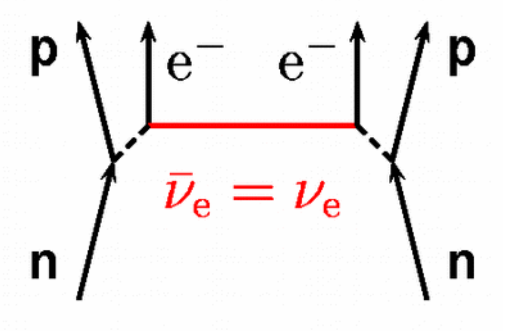
current sensitivity: $\Sigma m(\nu_i) \approx 0.23$ eV



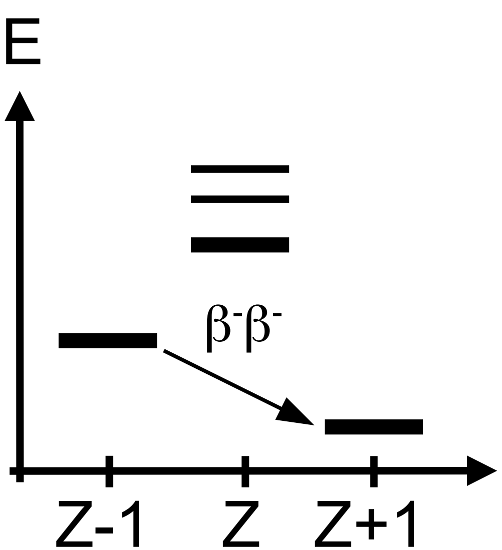
2) Search for $0\nu\beta\beta$

Sensitive to Majorana neutrinos

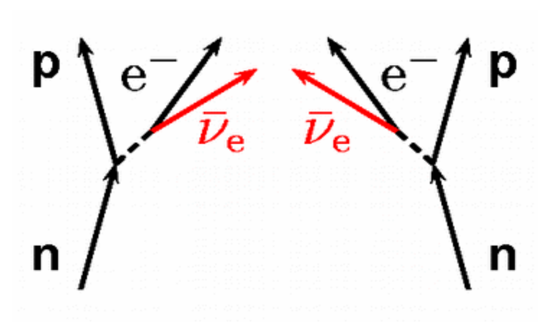
First upper limits (EXO-200, KamLAND-Zen, GERDA, CUORE-0)



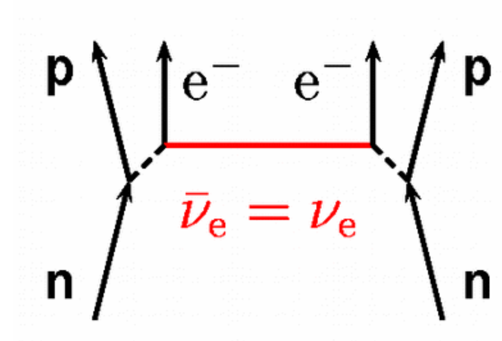
Double β decay



normal (2νββ)



neutrinoless (0νββ)

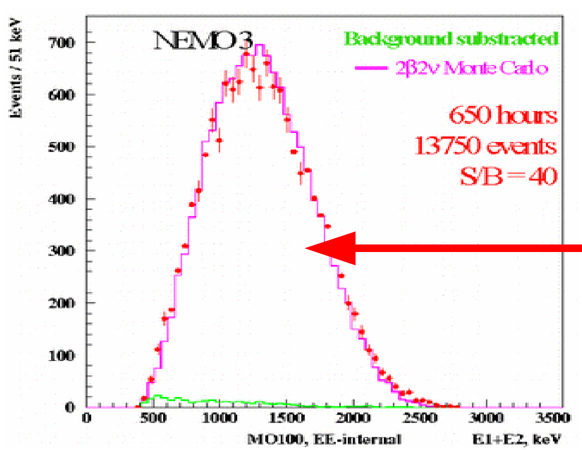


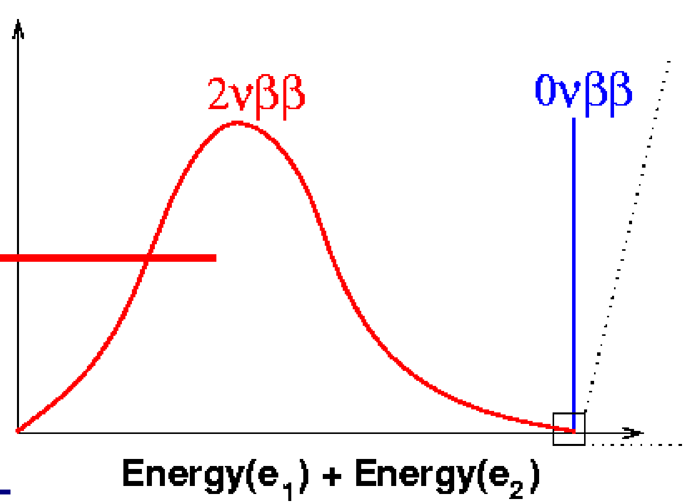
a) $\nu = \bar{\nu}$ (Majorana)

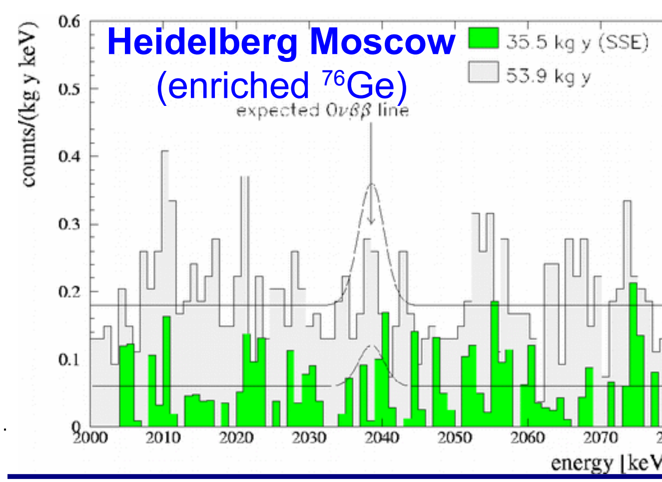
b) unfavored helicity: $m(\nu) \neq 0$

or other new physics

$m_{\beta\beta}(\nu) = |\,\Sigma\, |U_{ei}^2|\, e^{i\alpha(i)}\, m(\nu_i)|$ (coherent)







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

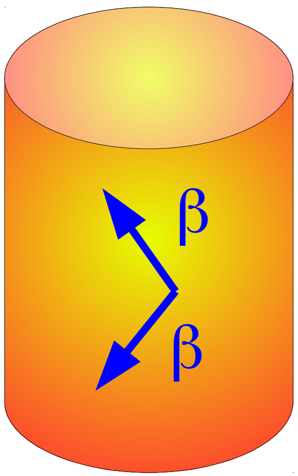
$m_{\beta\beta} \sim (1/\text{enrichment})^{1/2} \cdot (\Delta E \cdot bg\,/\,M \cdot t)^{1/4}$

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

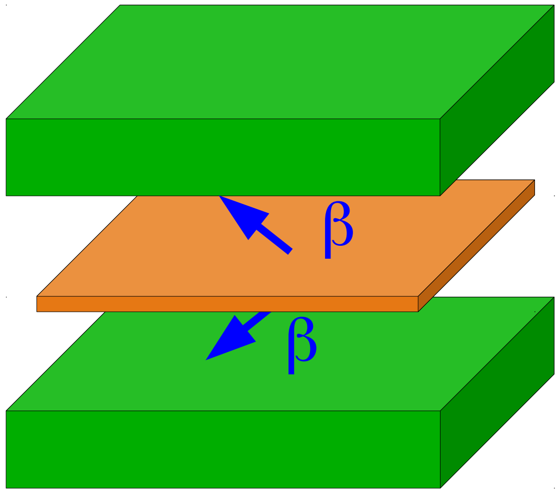
2 ways to measure both β-electrons:

semiconductor, cryogenic bolometer, liquid scintillator

source = detector



tracking calorimeter



detector

source

detector

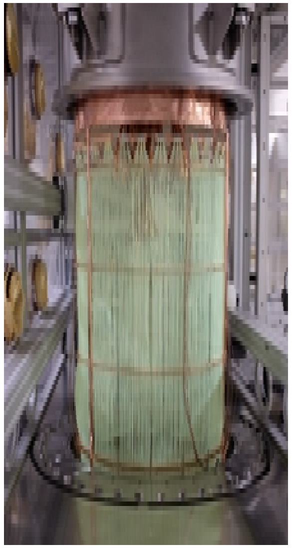
very sensitive | **gives more information on mechanism if observed**

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

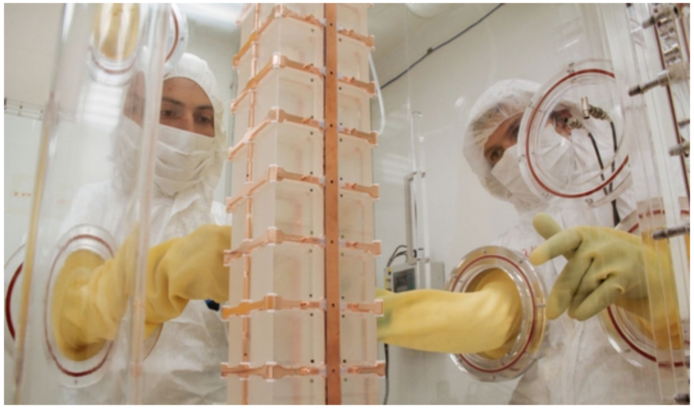
Future on neutrino mass results from $0\nu\beta\beta$ → sensitivity: $T_{1/2} > 10^{26}$ yr , $m_{\beta\beta} < 100$ meV

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

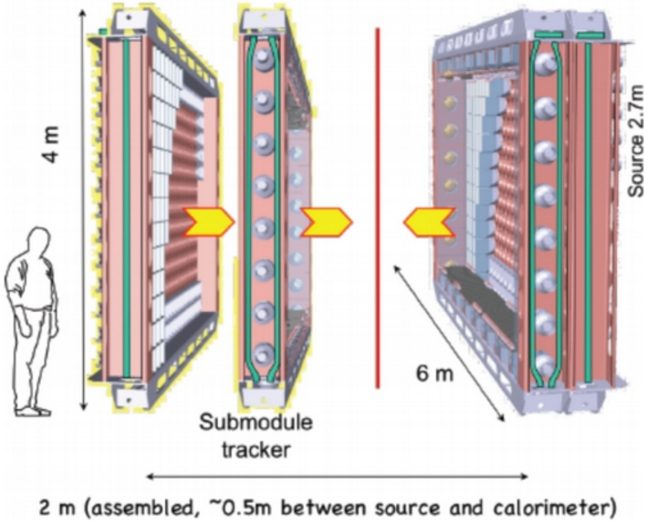


Majorana demonstrator at DUSEL:
^{76}Ge, similar goal as GERDA II

CUORE@LNGS:
^{130}Te: 988 TeO_2 crystals,
total detector mass: nearly 1t at 10 mK!
bg goal reached & demonstrated (CUORE-0)



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

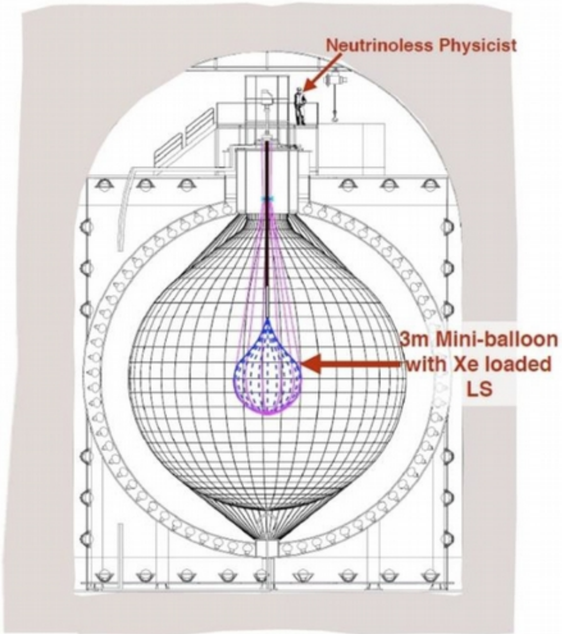


Other experiments:
^{130}Te: SNO+,
^{100}Mo: AMORE, LUNIEU
^{136}Xe: nEXO, NEXT, KamLAND-Zen

KamLAND-Zen: ^{136}Xe

3 m diam. ballon: liquid scintillator loaded with enriched Xenon inserted into KamLAND

$\Delta E \sim 250$ keV FWHM



results: 383 kg Xe / 110 $kg_{isotope}$ in FV

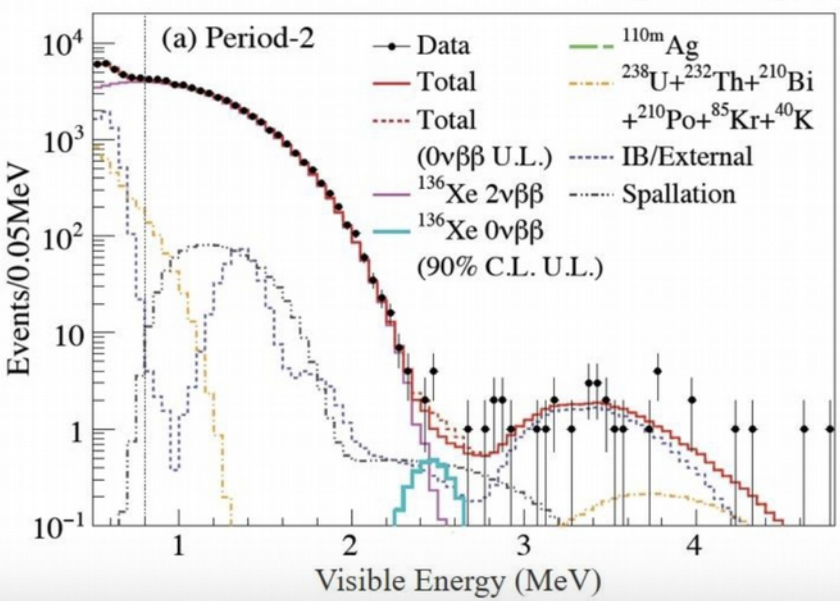
~ 600 kg·yr

$T_{1/2}^{0\nu\beta\beta} > 10.7 \cdot 10^{25}$ yr

sensitivity $5.6 \cdot 10^{25}$ yr

background in ROI ~ 100 / FWHM·$t_{isotope}$·yr

PRL 117 082503 (2016)



starting: **KamLAND Zen 800**

750kg Xe

goal sensitivity

$T_{1/2}^{0\nu\beta\beta} > 4.6 \cdot 10^{26}$ yr

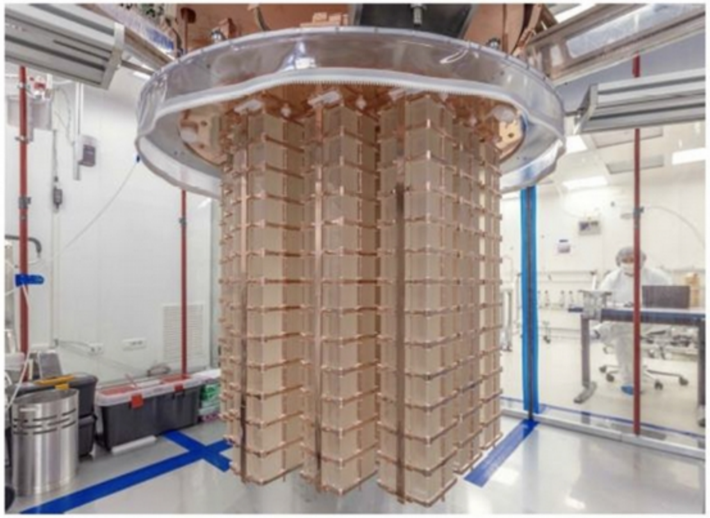
background ~ 10 / FWHM·$t_{isotope}$·yr

plan: **KamLAND2**: 1000 kg

CUORE: : ^{130}Te

calorimetry at mK temperature
in natural TeO_2 crystals ^{130}Te (30%)

CUORE 750 kg TeO_2 (206 kg ^{130}Te)
988 crystals

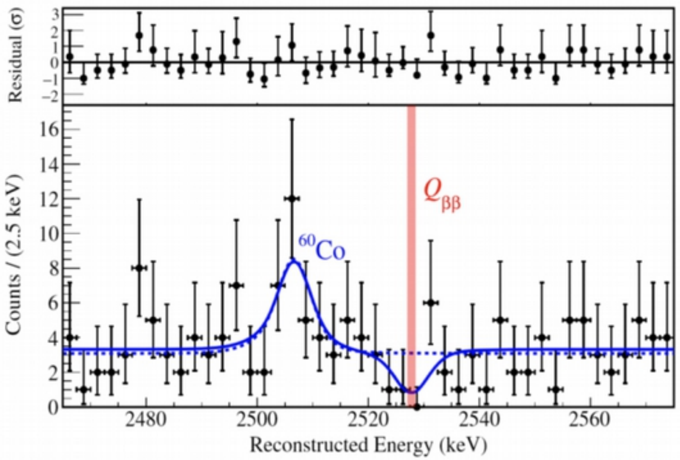


results:
86.3 kg·yr (24 kg·yr ^{130}Te)

ΔE ~ 7.7 keV FWHM

$T_{1/2}^{0\nu\beta\beta} > 1.5 \cdot 10^{25}$ yr

background in ROI
~ 360 / FWHM·$t_{isotope}$ ·yr



Phys.Rev.Lett 120, 132501 (2018)

goals:
goal sensitivity
$T_{1/2}^{0\nu\beta\beta} > 9.5 \cdot 10^{25}$ yr
background
~ 180 / FWHM·$t_{isotope}$·yr

potential upgrade with calorimetry + light
CUORE => CUPID (might interest german groups)
AMORE (Korea) large funding, sensors from D

GERDA phase 2: ^{76}Ge

Majorana Demonstrator

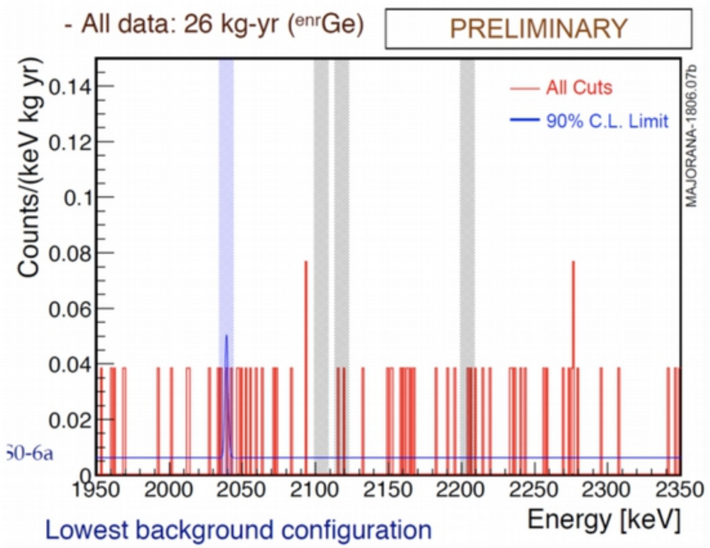
26 kg·yr

background in ROI
15 / FWHM·$t_{isotope}$·yr

Neutrino 2018 conference

sensitivity 4.8 ·10^{25} yr

$T_{1/2}^{0\nu\beta\beta}$ > 2.7·10^{25} yr



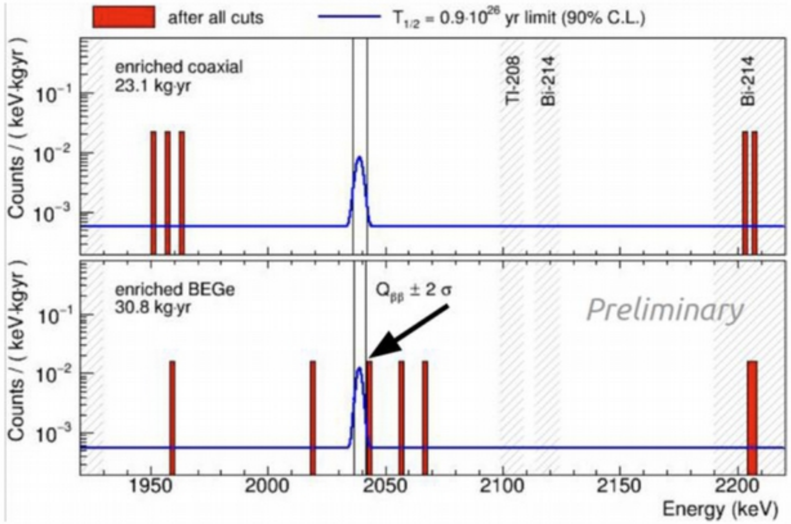
GERDA:

82.4 kg·yr total exposure

background in ROI
2 / FWHM·$t_{isotope}$·yr

sensitivity 11·10^{25} yr

$T_{1/2}^{0\nu\beta\beta}$ > 9·10^{25} yr



first background free 0νββ experiment
→ potential for discovery (up to ~ 10^{26} yr)

makes sense to grow larger (background goal for LEGEND 200 alm ostreached)

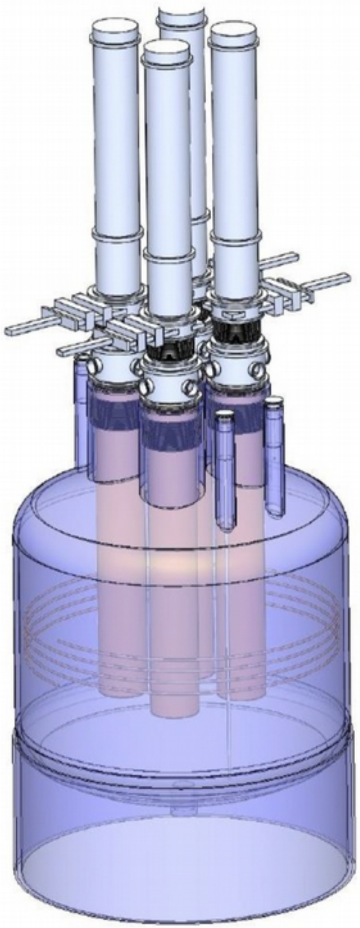
LEGEND: ^{76}Ge

J. Jochum, Astroparticle Physics in Germany – Status and Perspectives 2018

new collaboration formed LEGEND

Majorana + GERDA members + others

⇒ one worldwide collaboration on ^{76}Ge



use GERDA concept and staged approach to 1000kg

LEGEND 200: first 200kg in GERDA setup @ Gran Sasso

- starting 2021
- ^{76}Ge available for 150kg of detectors
- funded by NSF, INFN, MPI, BMBF

sensitivity > 10^{27} yr

⇒ Still needs some ^{76}Ge, but 90% fundend for ~ 190 kg…

background level amost reached (needs x3 improvement cmp. GERDA)

sensitivity > 10^{28} yr

LEGEND 1000: 1000kg phase depends on US down selection process

same for nEXO

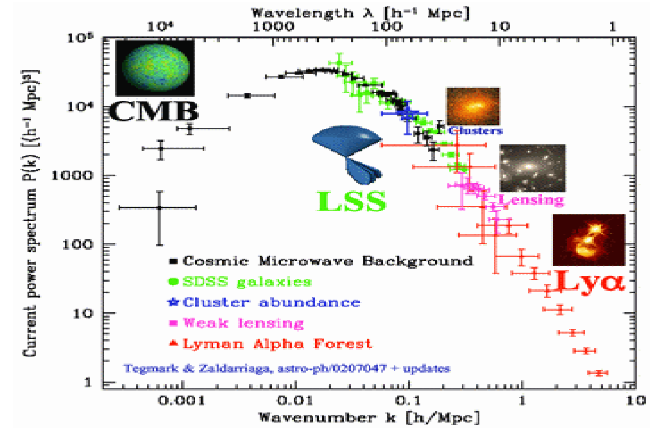
Three complementary ways to the absolute neutrino mass scale

1) Cosmology

very sensitive, but model dependent

compares power at different scales

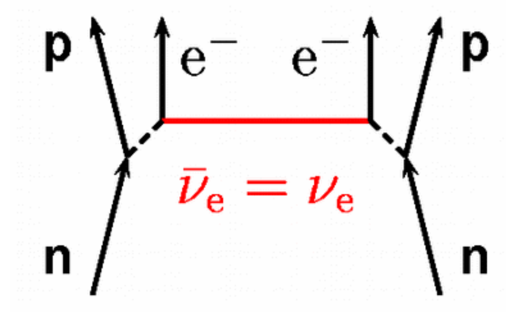
current sensitivity: $\Sigma m(\nu_i) \approx 0.23$ eV



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

Sensitive to Majorana neutrinos

First upper limits (EXO-200, KamLAND-Zen, GERDA, CUORE-0)



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)

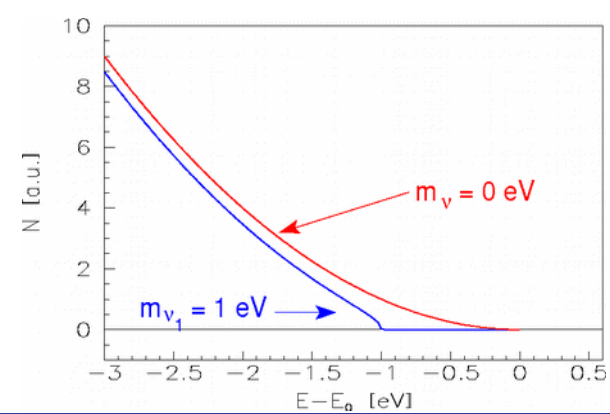
SN1987a (large Magellan cloud) $\Rightarrow m(\nu_e) < 5.7$ eV

Kinematics of weak decays / beta decays

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

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

- ^{163}Ho electron capture (EC)



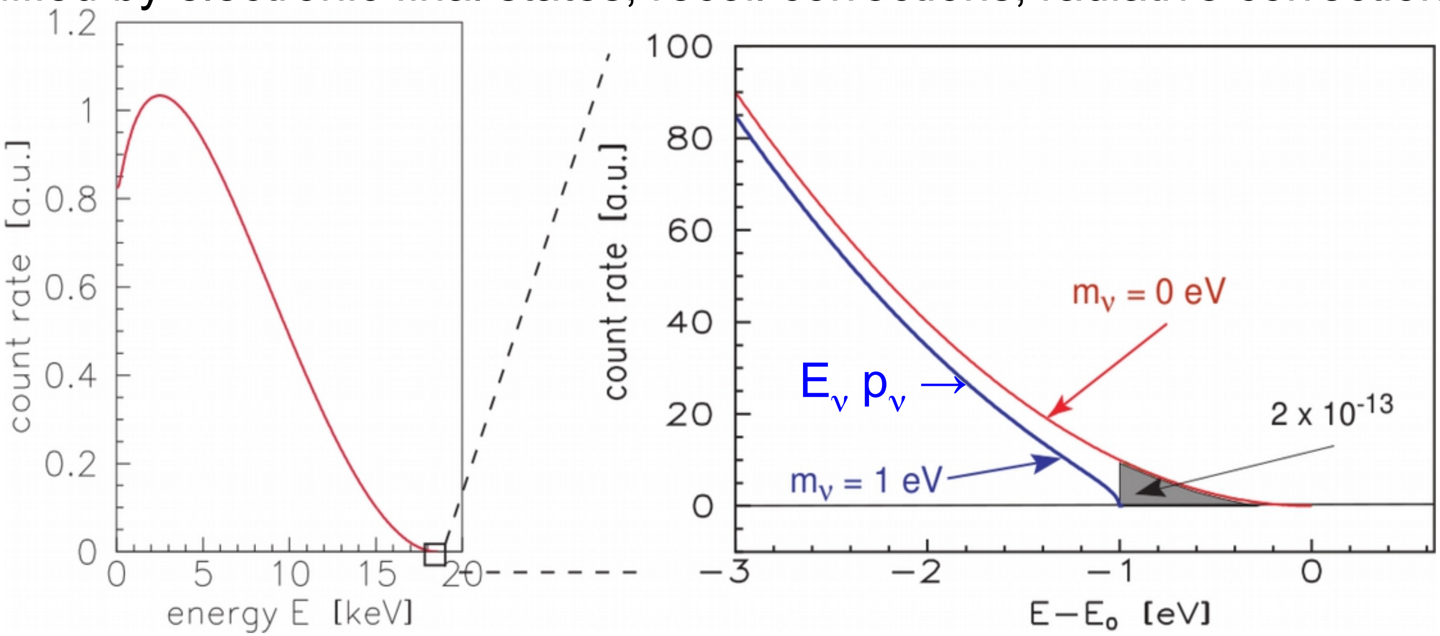
Direct determination of "$m(\nu_e)$" from β-decay (and EC)

β: $dN/dE = K \; F(E,Z) \; p \; E_{tot} \; (E_0-E_e) \; \Sigma |U_{ei}|^2 \sqrt{(E_0-E_e)^2 - m(\nu_i)^2}$

essentially phase space: p_e (under p), E_e (under E_{tot}), E_ν (under (E_0-E_e)), p_ν (under $\Sigma |U_{ei}|^2 \sqrt{(E_0-E_e)^2 - m(\nu_i)^2}$)

with "electron neutrino mass": **"$m(\nu_e)^2$":=** $\Sigma |U_{ei}|^2$ **$m(\nu_i)^2$**, complementary to 0νββ & cosmol.

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

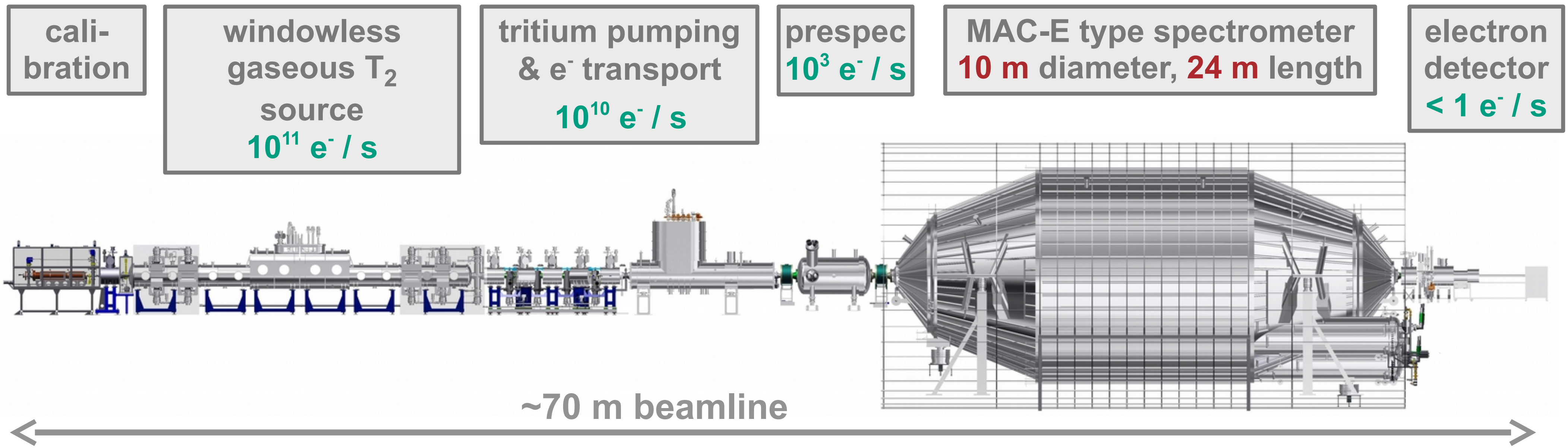


Need: low endpoint energy ⇒ **Tritium ^3H (^{163}Ho)**

very high energy resolution &
very high luminosity &
very low background

} ⇒ **MAC-E-Filter (or cryobolometer for ^{163}Ho)**

The KATRIN experiment at Karlsruhe Institute of Technology



Basic ideas of KATRIN:

- Windowless gaseous molecular tritium source

→ ultra-high luminosity and small systematics

- Huge spectrometer of MAC-E-Filter type

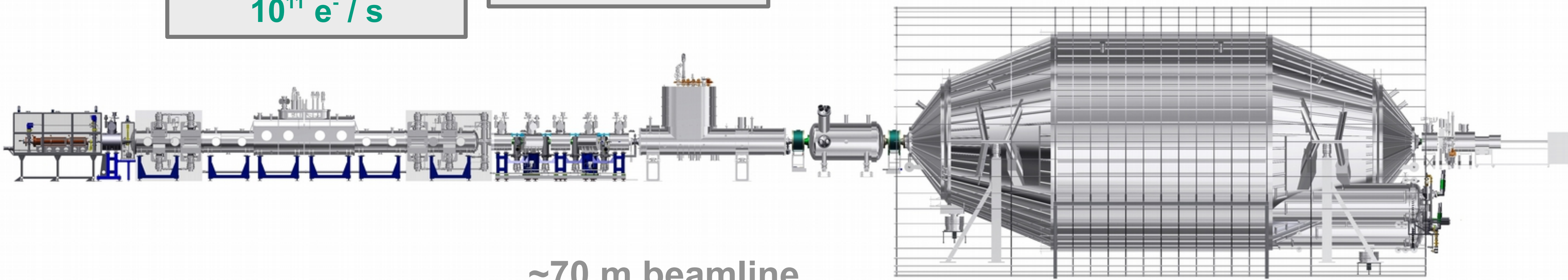
→ ultra-high energy resolution

Sensitivity on $m(\nu_e)$:

2 eV → 200 meV

The KATRIN experiment at Karlsruhe Institute of Technology

cali-bration	windowless gaseous T_2 source 10^{11} e^- / s	tritium pumping & e^- transport 10^{10} e^- / s	prespec 10^3 e^- / s	MAC-E type spectrometer 10 m diameter, 24 m length	electron detector < 1 e^- / s



KATRIN Karlsruhe Tritium Neutrino Experiment = { KIT Karlsruhe Institute of Technology, WWU Münster, CENPA, cea, TUM, Universität Mainz, MIT, The University of North Carolina at Chapel Hill, Berkeley Lab, Max-Planck-Institut für Kernphysik, Max-Planck-Institut für Physik, Bergische Universität Wuppertal, universität bonn, Case Western Reserve University, Carnegie Mellon University, Humboldt-Universität zu Berlin }

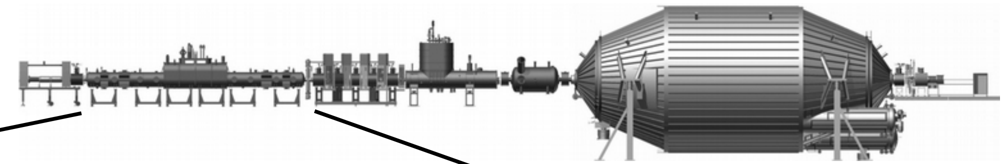

The international KATRIN Collaboration

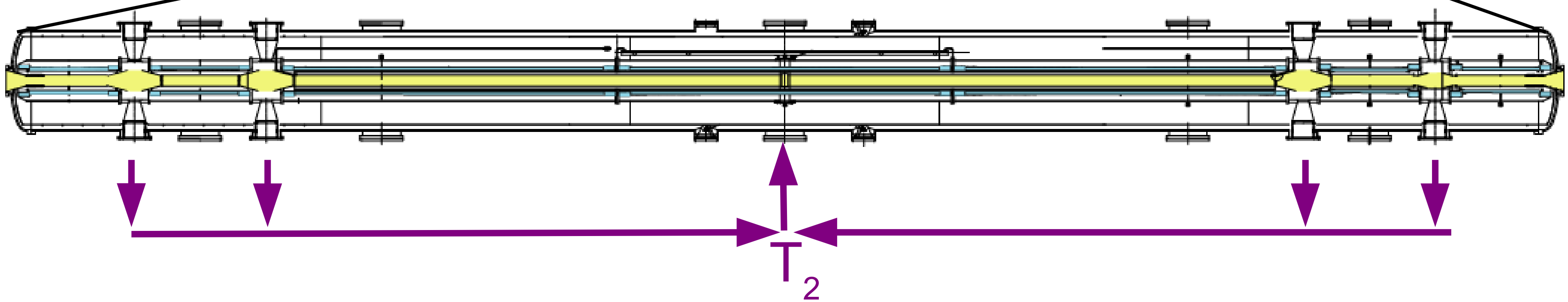
Windowless Gaseous Molecular Tritium Source WGTS

per mill stability source strength request:

$\dot{N} = dN/dt \sim f_T \cdot N / \tau \sim n = f_T \cdot p \; V / R\,T$

tritium fraction f_T & ideal gas law





WGTS:

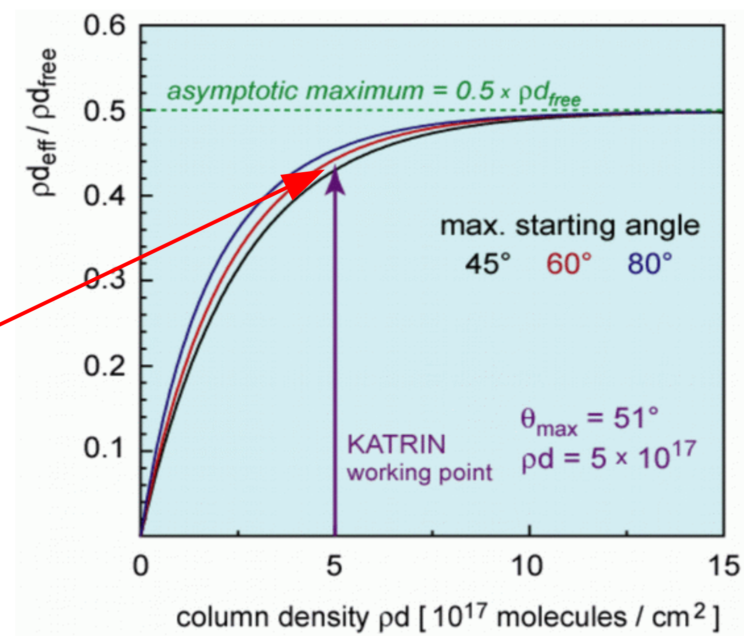
tube in long superconducting solenoids
⊘ 9cm, length: 10m, T = (30 ± 0.03) K

Tritium recirculation (and purification)
p_{inj} = (3 ± 0.003) μbar, q_{inj} = 4.7Ci/s

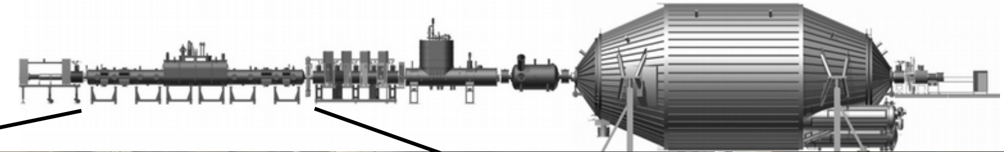
T_2 purity f_T by laser Raman spectr.

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

check column density by e-gun



Windowless Gaseous Molecular Tritium Source WGTS



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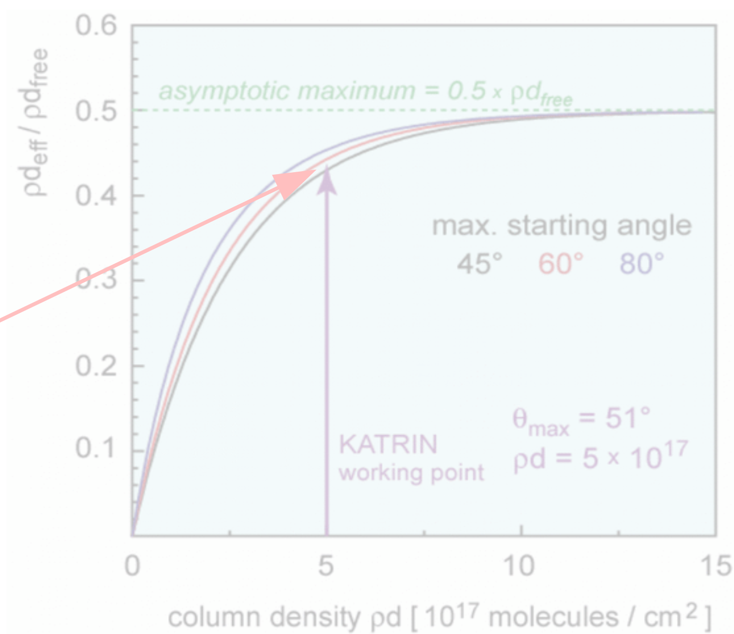
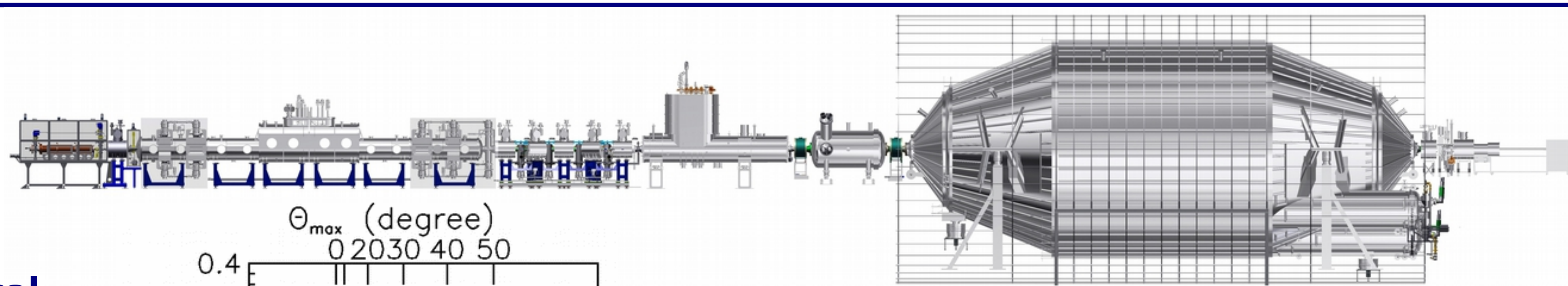
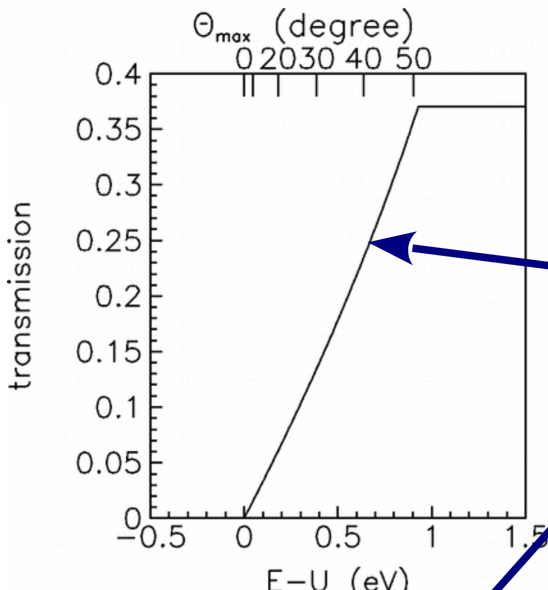


The KATRIN Main Spectrometer: an integrating high resolution MAC-E-Filter

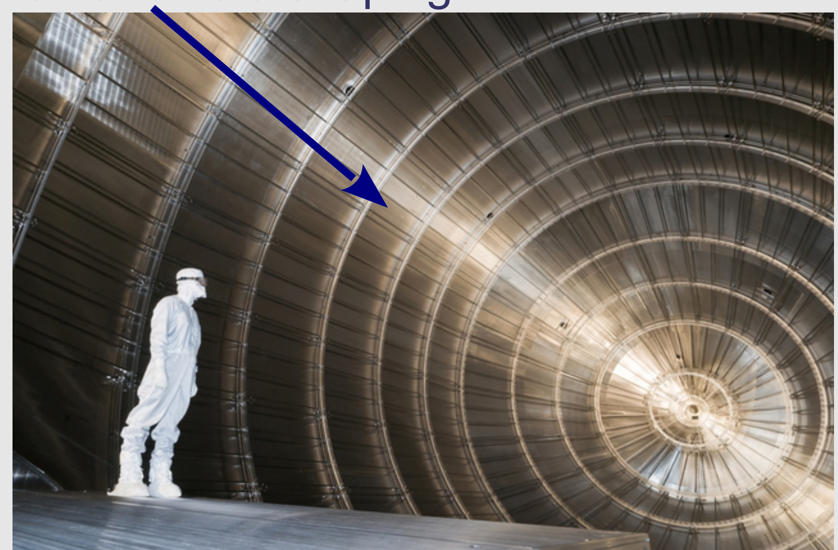


Integral transmission function:

$$\Delta E = E \cdot B_{min}/B_{max} = 0.93\ \text{eV}$$



- 18.6 kV retardation voltage, σ < 60 meV/years
- Energy resolution (0% → 100% transmission): 0.93 eV
- Ultra-high vacuum, pressure < 10^{-11} mbar
- Air coils for earth magnetic field compensation
- Double layer wire electrode for background reduction and field shaping



Focal Plane Detector

Focal plane detection system

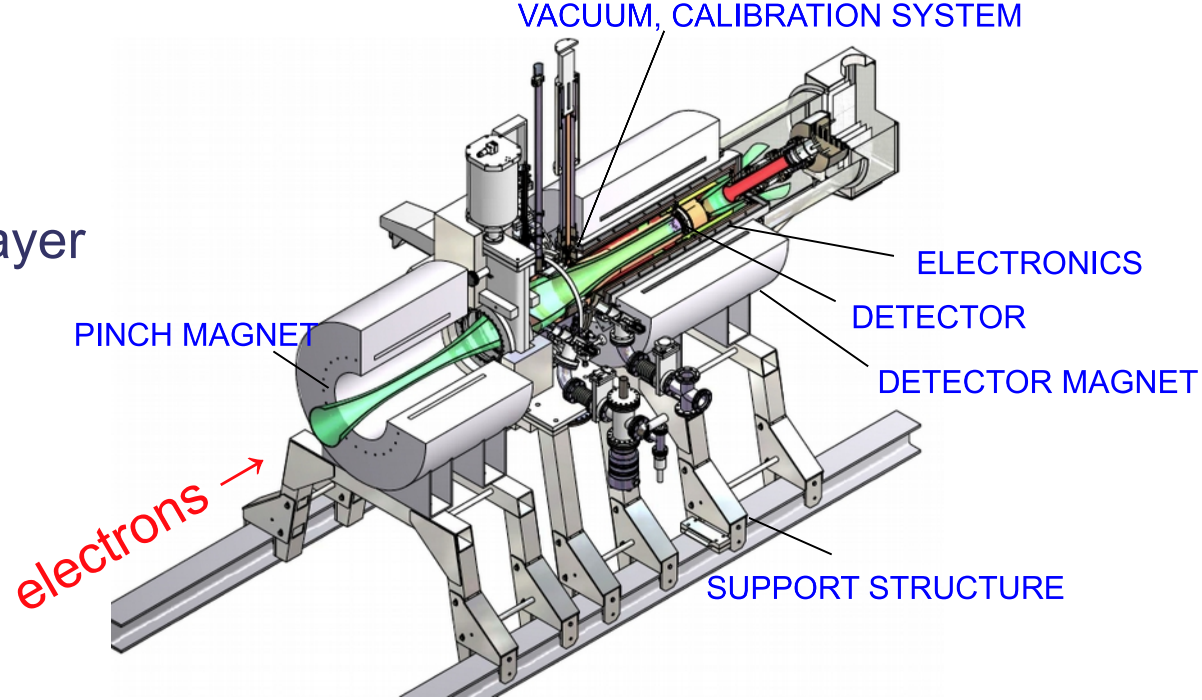
segmented Si PIN diode:
90 mm Ø, 148 pixels, 50 nm dead layer

energy resolution ≈ 1 keV

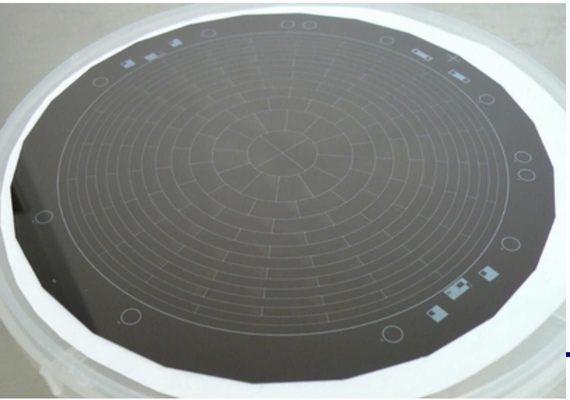
pinch and detector magnets up to 6 T

post acceleration (10kV)

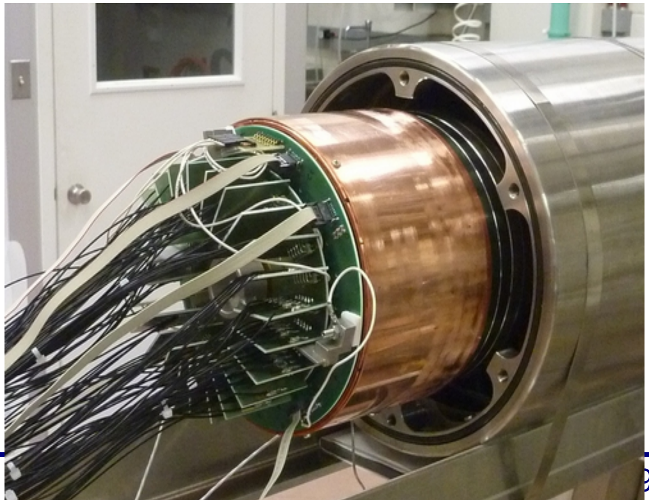
active veto shield

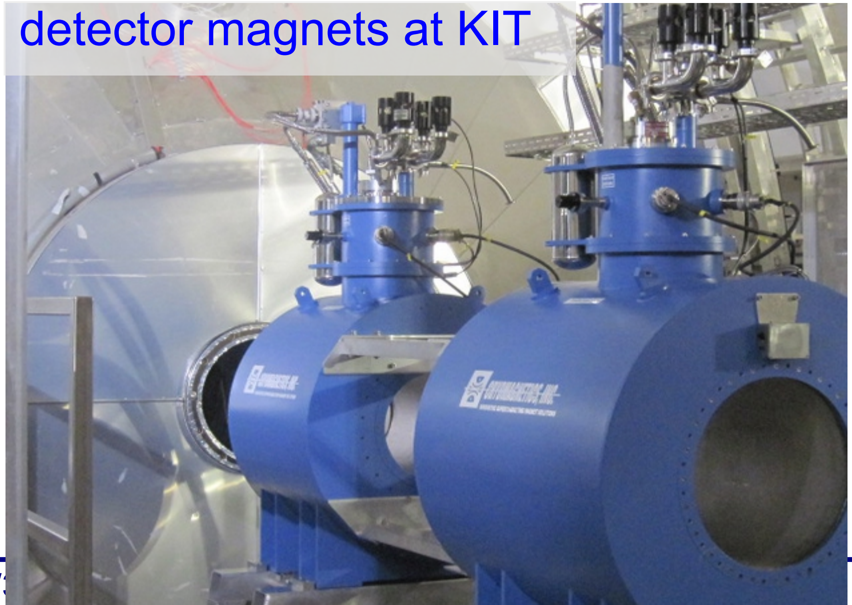


segmented Si-PIN wafer



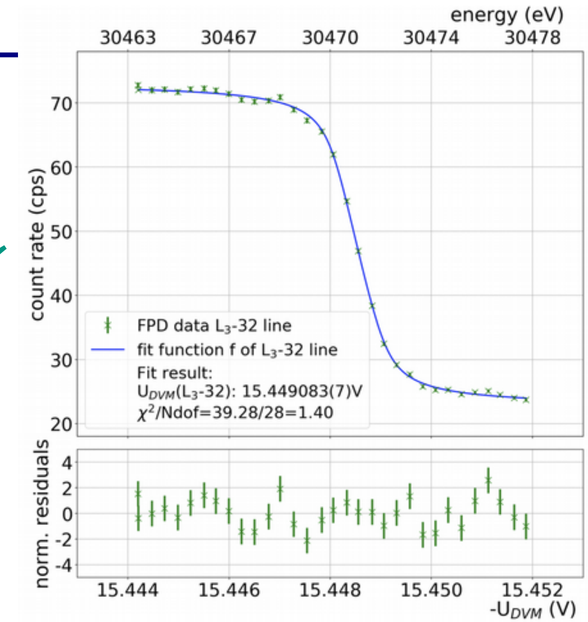
pre-amplifier wheel

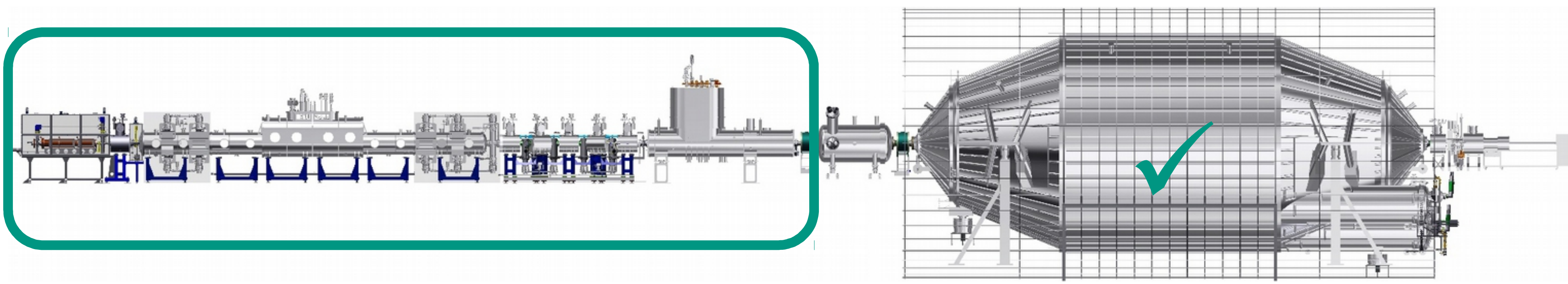




Status of KATRIN before May/June 2018

- KATRIN will investigate $m(\nu_e)$ with 200 meV sensitivity by employing
  - a high-resolution MAC-E filter with < 1 eV energy resolution (e.g. M. Arenz et al., EPJ C 78 (2018) 368) ✓
  - and an ultra-stable high-luminosity windowless gaseous molecular tritium source





Inner loop buffer vessel pressure	WGTS Temperature	Gas composition	Source activity
Active regulation Stability <0.05%	**Two-phase Ne cooling** Stability <1.5mK/h @ 30 K	**Raman spectroscopy** Precison <0.1% in 20 s	**Not yet demonstr**
Priester et al. Vacuum 116 (2015) 42 ✓	*Grohmann et al. Cryogenics 55-56, (2013) 5* ✓	*M. Schlösser et al. J. Mol. Struct. 1044, 24 (2013) 61* ✓	

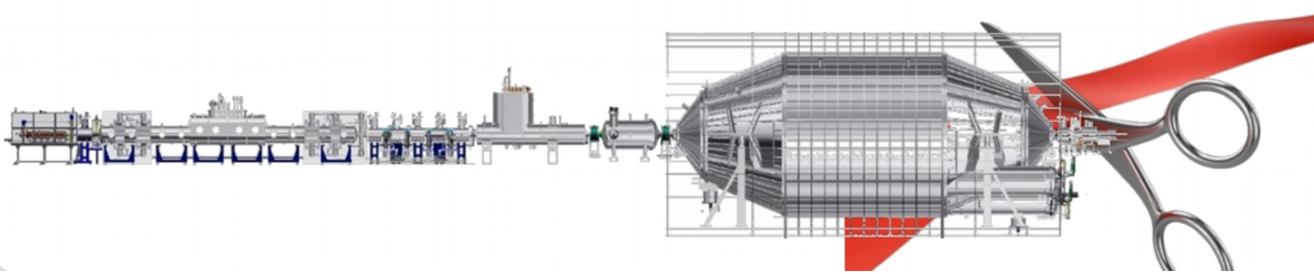
May/June 2018: KATRIN inauguration & first tritium campaign (commissioning)

Motivation:

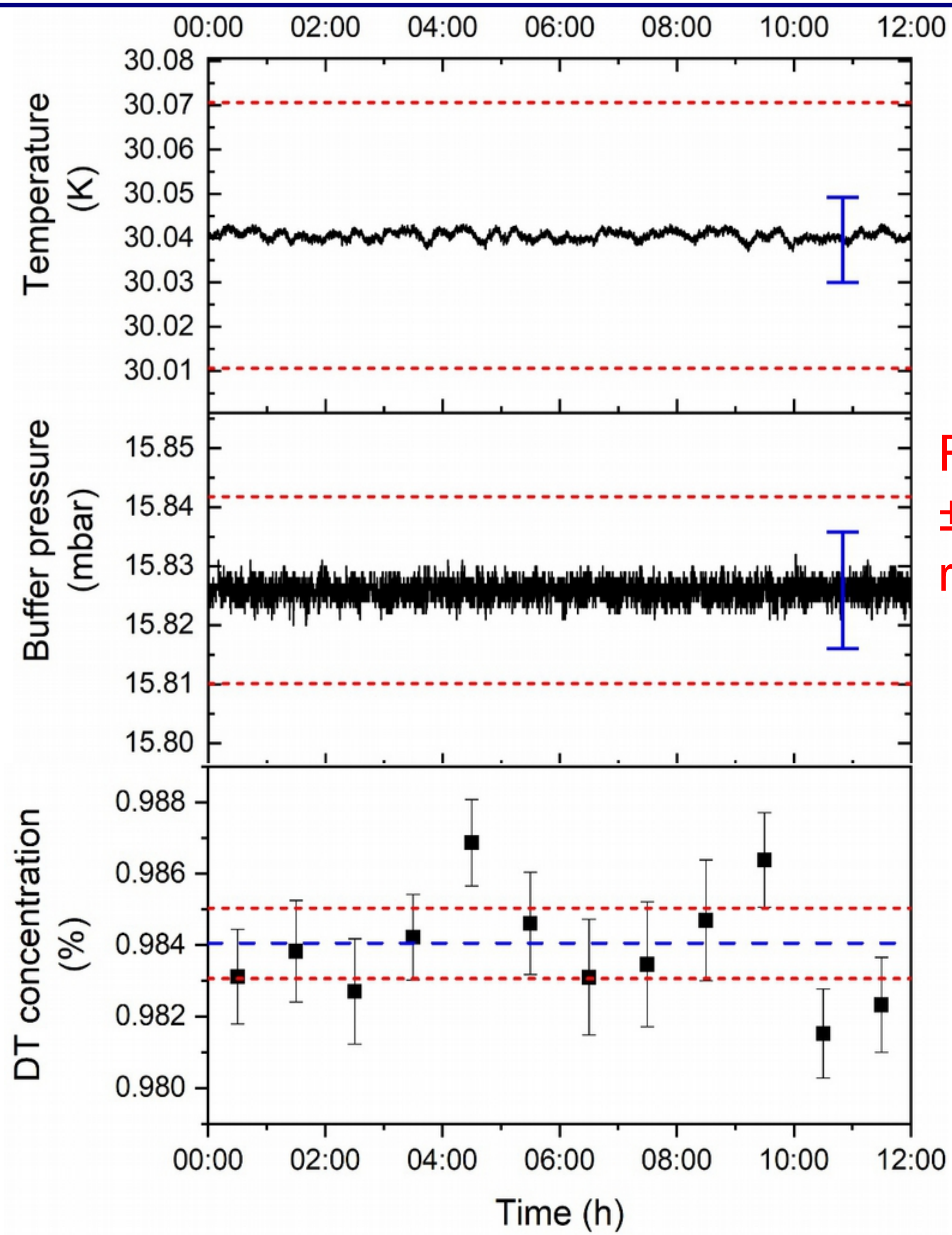
method: inject known gas mix from prepared cylinders (80% of nominal ρd, ~1% DT and ~99% D_2 corresponds to <1% of nominal activity ≈ 500 MBq)

verify functionality of all system components and demonstrate 0.1% global stability

study beta spectrum for systematic effects and test analysis strategies



First tritium campaign: Stability of source parameters during 12 h



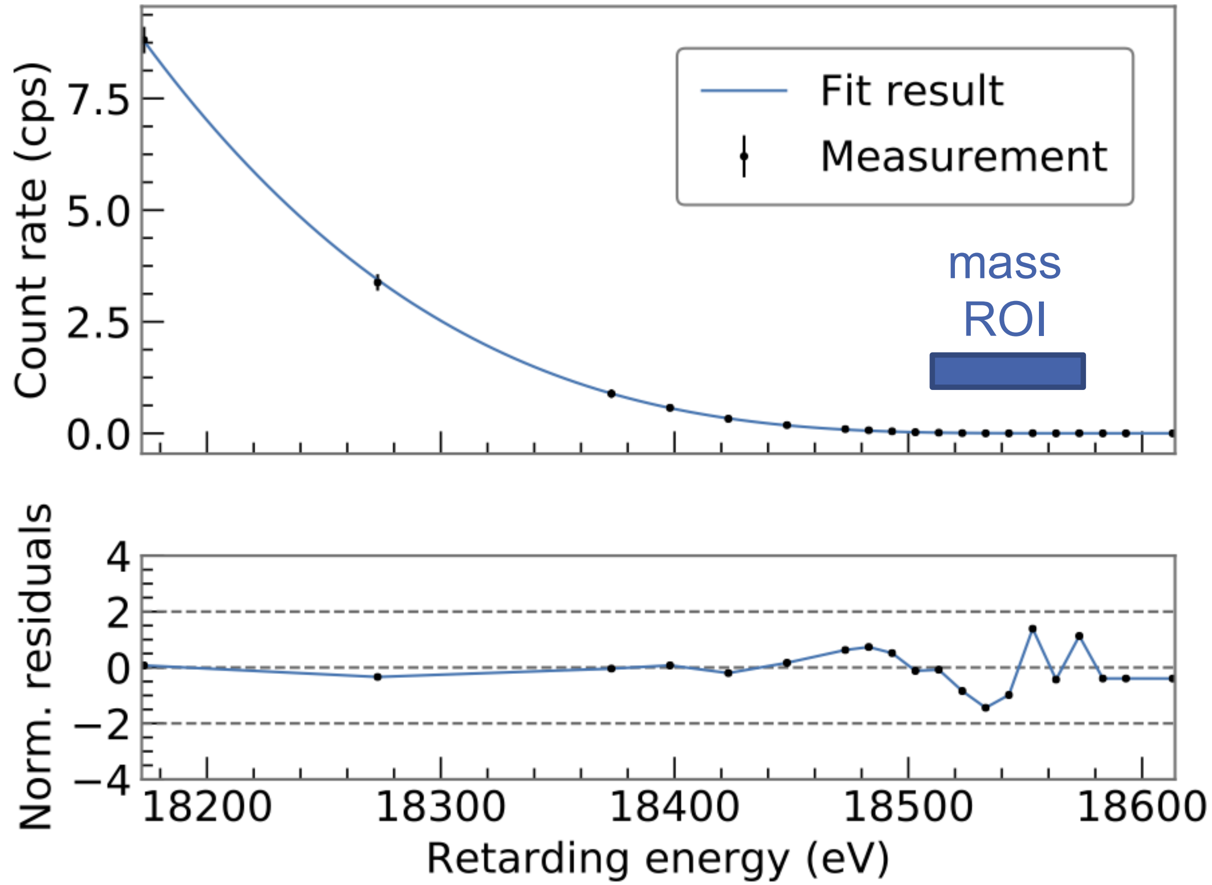
Blue arrow:
systematic

uncertainty

Red dashed line:
± 0.1 % stability
required for
neutrino mass
data taking

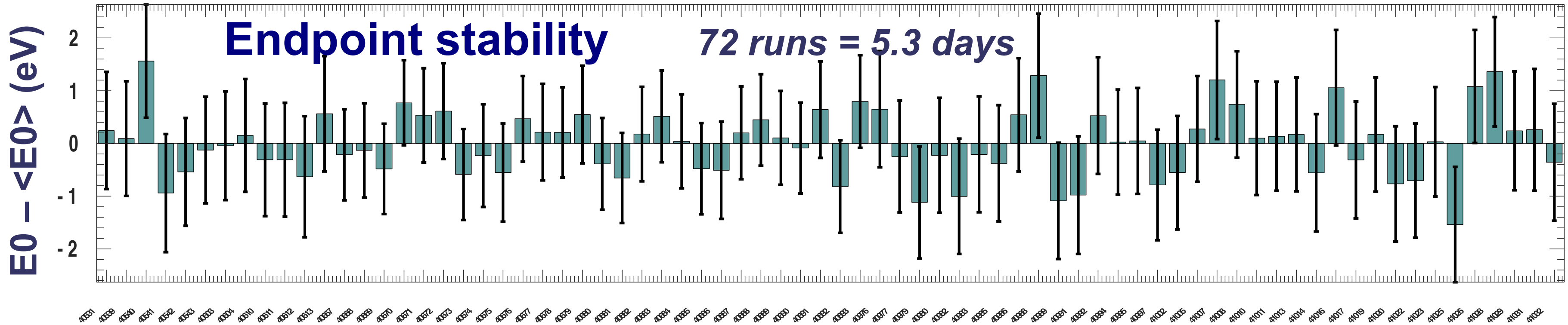
→ source parameters were proven to be stable and within the specifications

Tritium spectrum fit (example)

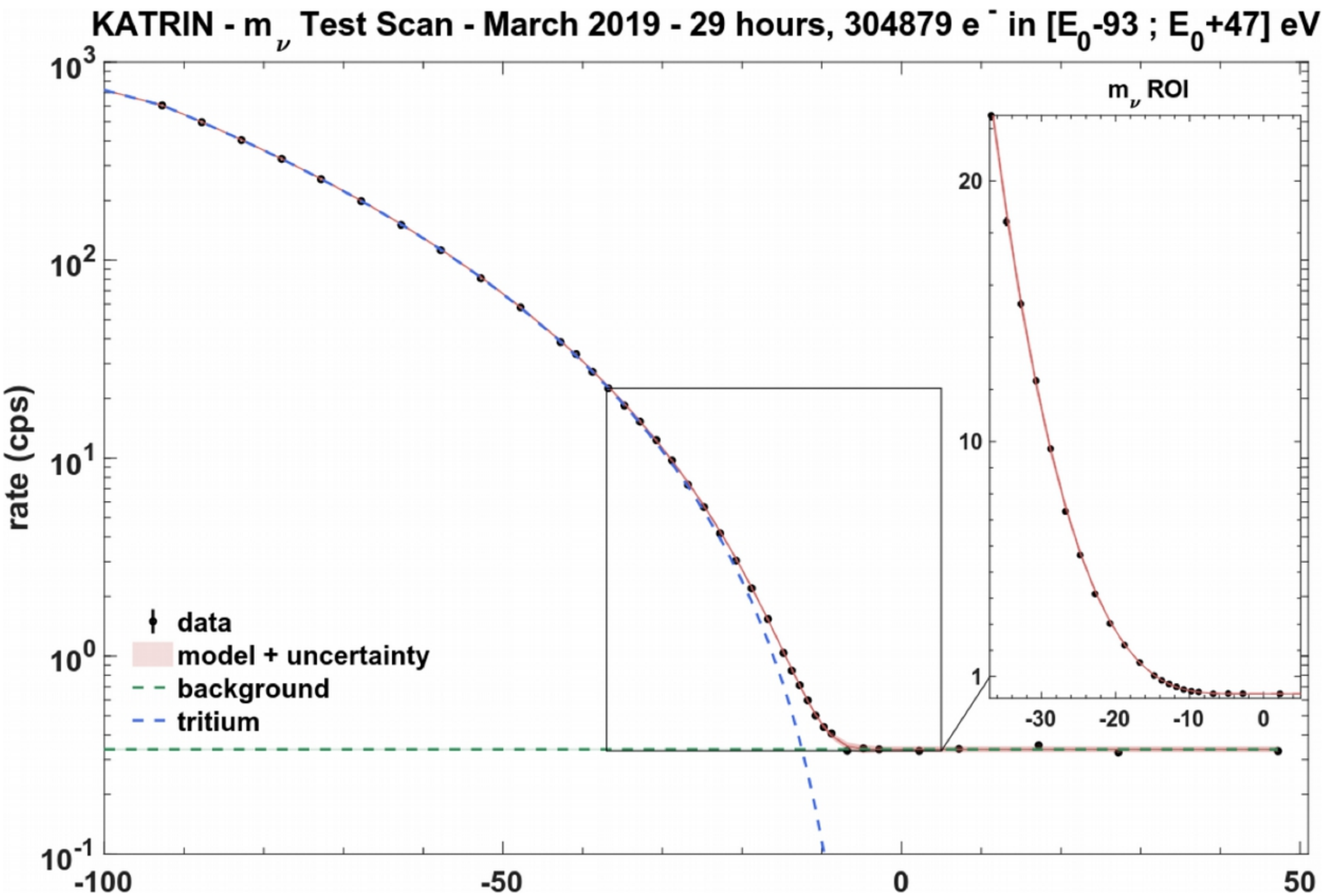


- **Single run (3h), analysis of single detector pixel**
- **ROI extended to 400 eV**
- **Statistics only**

→ very good agreement between data and fit (shape and estimated absolute rate!) & very stable



KATRIN's first science run in 2019



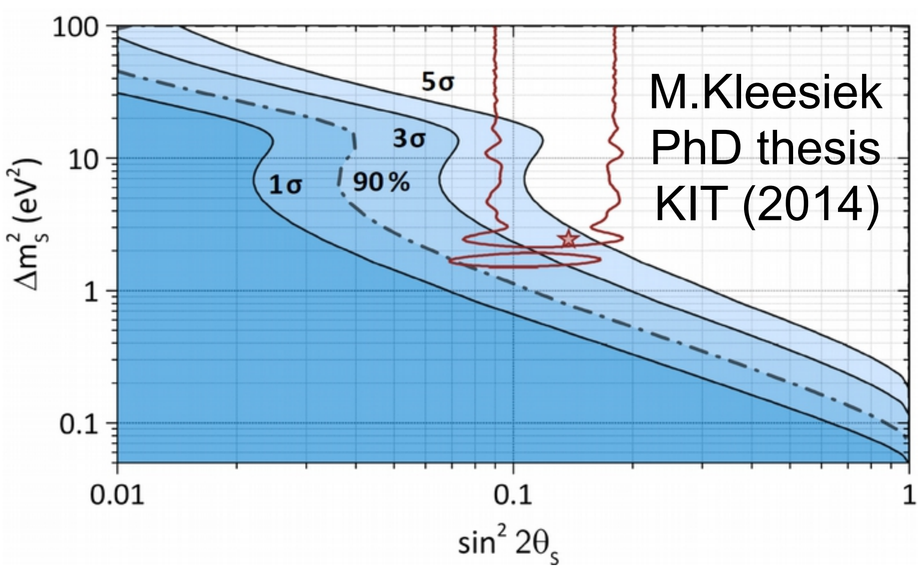
WWU MÜNSTER

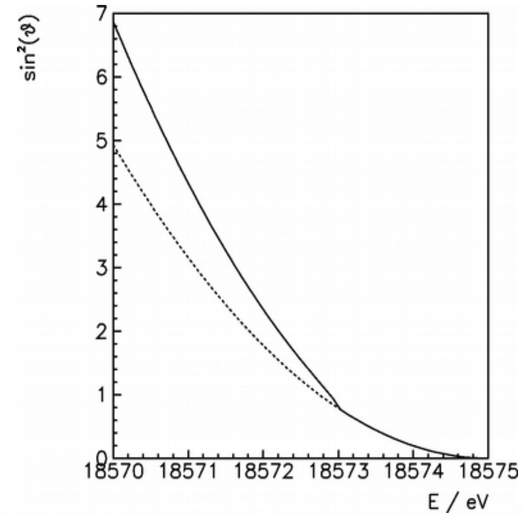
KATRIN will measure an ultra-precise β-spectrum → search for physics beyond the SM

Sterile neutrinos

$$dN/dE = K\ F(E,Z)\ p\ E_{tot}\ (E_0-E_e)\ \left(\cos^2(\theta)\sqrt{(E_0-E_e)^2 - m(\nu_{1,2,3})^2} + \sin^2(\theta)\sqrt{(E_0-E_e)^2 - m(\nu_4)^2} \right)$$

eV ν:

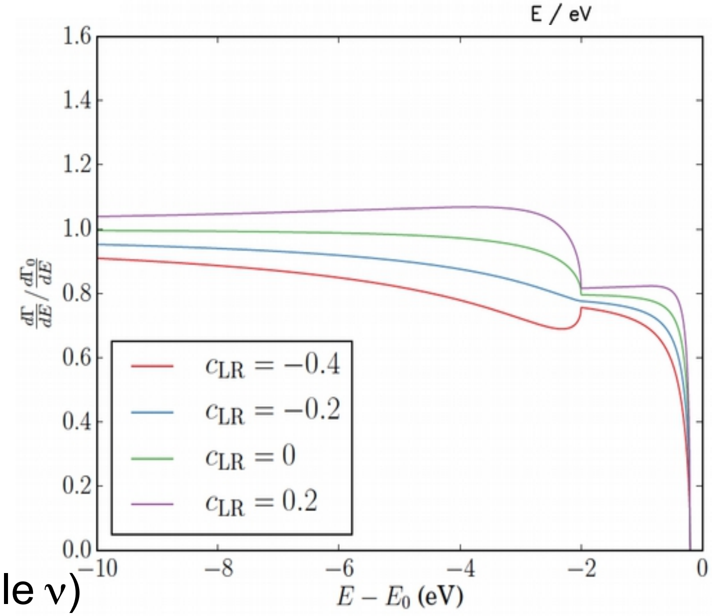




see e.g.:
J. A. Formaggio, J. Barret, PLB 706 (2011) 68
A. Sejersen Riis, S. Hannestad, JCAP02 (2011) 011
A. Esmaili, O.L.G. Peres, arXiv:1203.2632

keV ν:

see e.g.:
S. Mertens et al., JCAP 02 (2015) 020
M. Drewes et al. JCAP 01 (2017) 025



non SM currents, ...

see e.g.: N. Steinbrink et al., JCAP 6 (2017) 15 (RH currents & sterile ν)

Sterile neutrino search with KATRIN: upgrading detector by the project TRISTAN

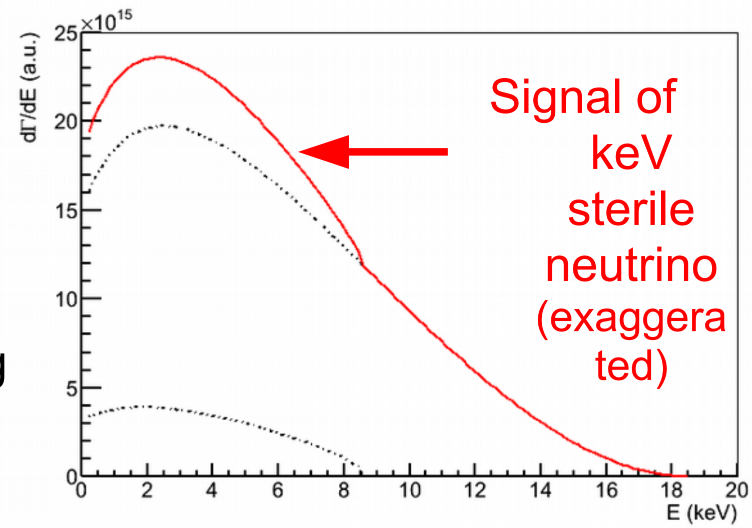
Extension of KATRIN to search for eV – keV sterile neutrinos

Tiny, but characteristic signal further away from the endpoint

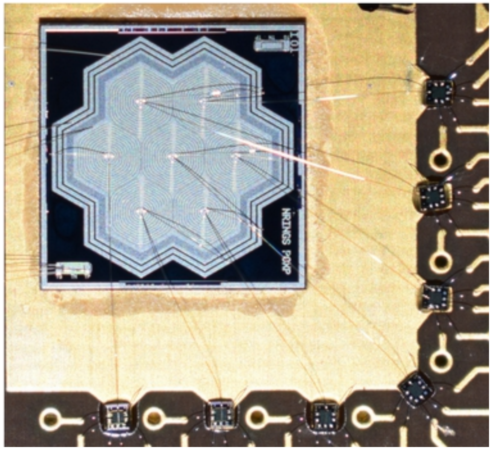
Challenge:
ppm sensitivity needed (high statistics, small systematics)
→ New detector system!

R&D of multi-pixel Silicon Drift Detector (SDD) system ongoing

Excellent performance
demonstrated with
prototype detector system



Signal of keV sterile neutrino (exaggerated)



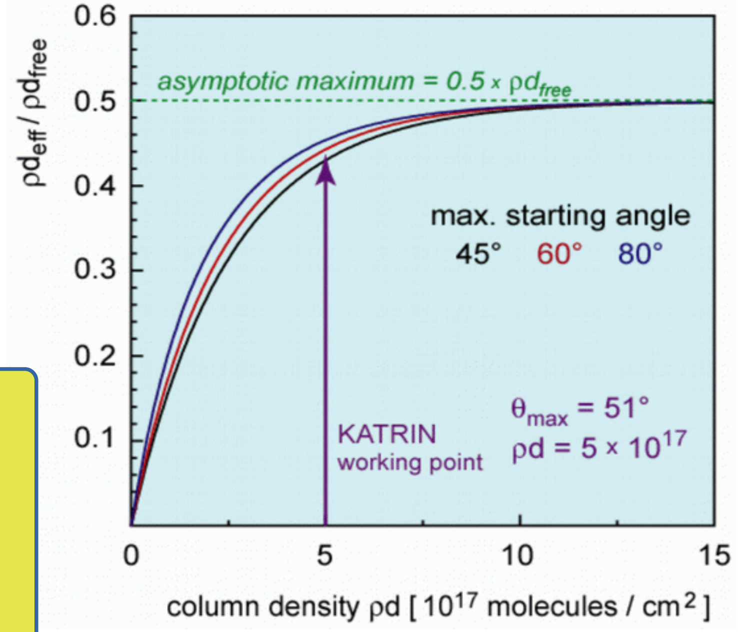
7 pixel TRISTAN prototype

Design of 3500 ch SDD system

S. Mertens, T. Lasserre *et. al.* Phys.Rev. D91 (2015) 4, 042005
S. Mertens, K. Dolde, M. Korzeczek, *et al.* JCAP 1502 (2015) 02, 020
K. Dolde, S.Mertens, D. Radford et. al. NIM-A 848 (2017)
M. Drewes *et. al.*, JCAP 1701 (2017) no.01, 025
A. Boyarsky, M. Drewes, T. Lasserre, S. Mertens, O. Ruchayskiy, arXiv:1807.07938
S. Mertens, et al.: arXiv:1810.06711 [physics.ins-det] (2018)

KATRIN's sensitivity of 200 meV might not be enough
Can we go beyond or improve KATRIN ?

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

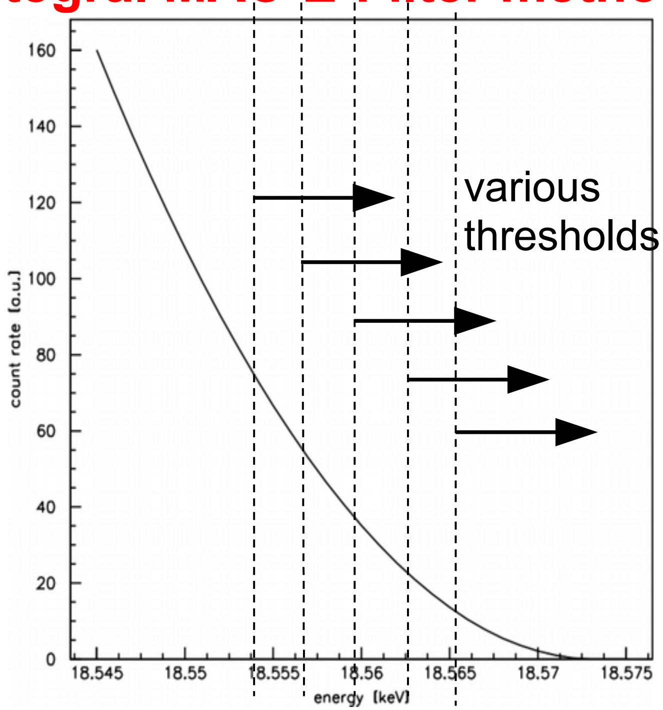


Possible ways out:

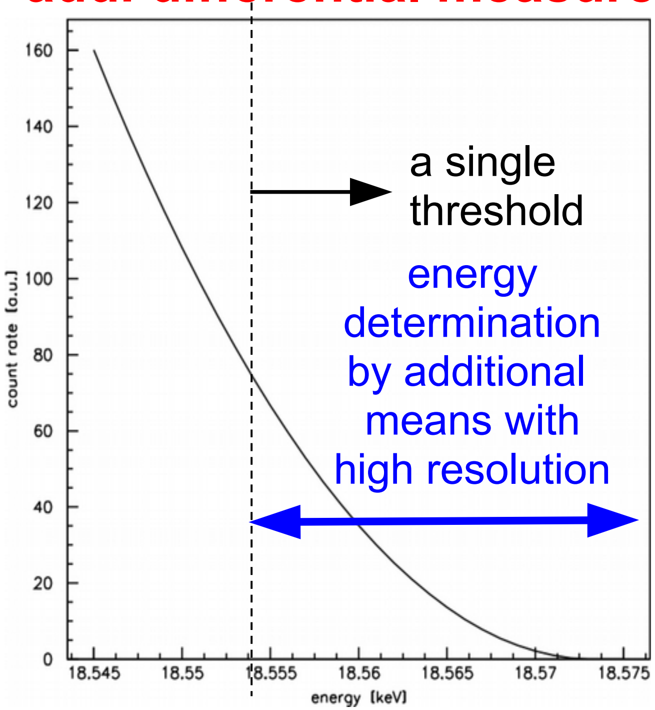
a) make better use of the electrons by differential measurement (e.g. cryo bolometer array or TOF) additional to integral threshold:
→ measure all retarding voltage settings at once
additional benefit: possible background reduction

Gain of additional differential method
avoiding loss of statistics by many filter settings

Integral MAC-E-Filter method | **add. differential measurement**



need many retardation voltages, about 40 different settings, to obtain spectral information



need one retardation voltage to limit count rate and use other means, e.g. high-res. detector to obtain spectral information

→ Differential method: expect naively statistical improvement in m_ν^2 of up to a factor $\sqrt{40}$ w.r.t. standard KATRIN,

i.e. up to a factor of 2.5 in m_ν w.r.t. standard KATRIN !

→ KATRIN could reach < 100 meV with such a method

Numbers are in agreement with simulations in dipl. thesis of A. Mertens, KIT, 2012

Possible ways for an add. differential method at KATRIN

1) Cryo bolometer detector array

Problem: In the KATRIN setup the electons are guided and adiabatically collimated by axial magnetic fields with conserved magnetic flux: 134 Tcm^2 (70% of KATRIN default magnetic fields)

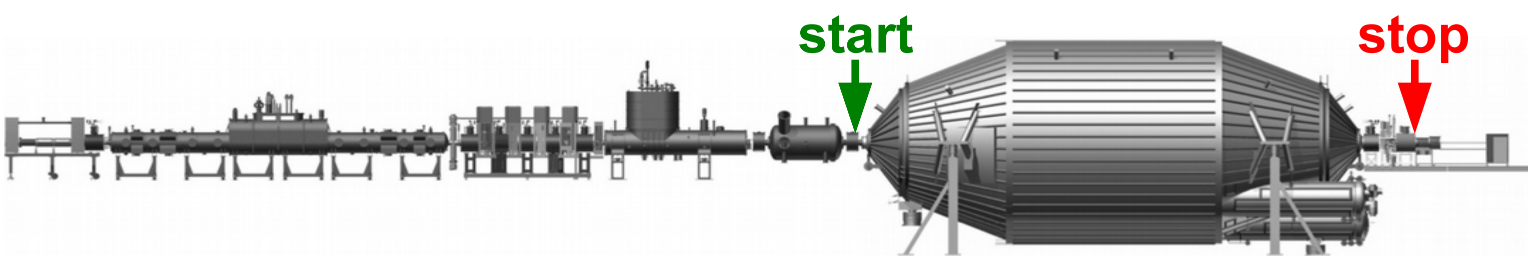
→ Tesla magnetic fields at cryo-bolometer array

Is there a cryo bolometer technology compatible with this?

Or can we separate magnetically the electron absorber from the temperature read-out?

2) Measurement of time of flight

Works in principle since electrons are strongly retarded by the MAC-E-Filter, please see *N. Steinbrink et al., NJP 15 (2013) 113020*



Problem: Can we build an electron tagger to measure the time of start with only little disturbance?

There are some ideas, which are not excluded by first principles ..

Bonus of any differential method: could significantly lower background !

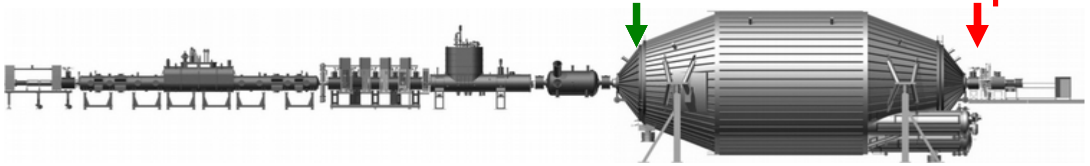
Background mitigation & enhancement of sensitivity by time-of-flight methods (differential method)

Idea: measure time-of-flight to get additional information

→ differentiate background

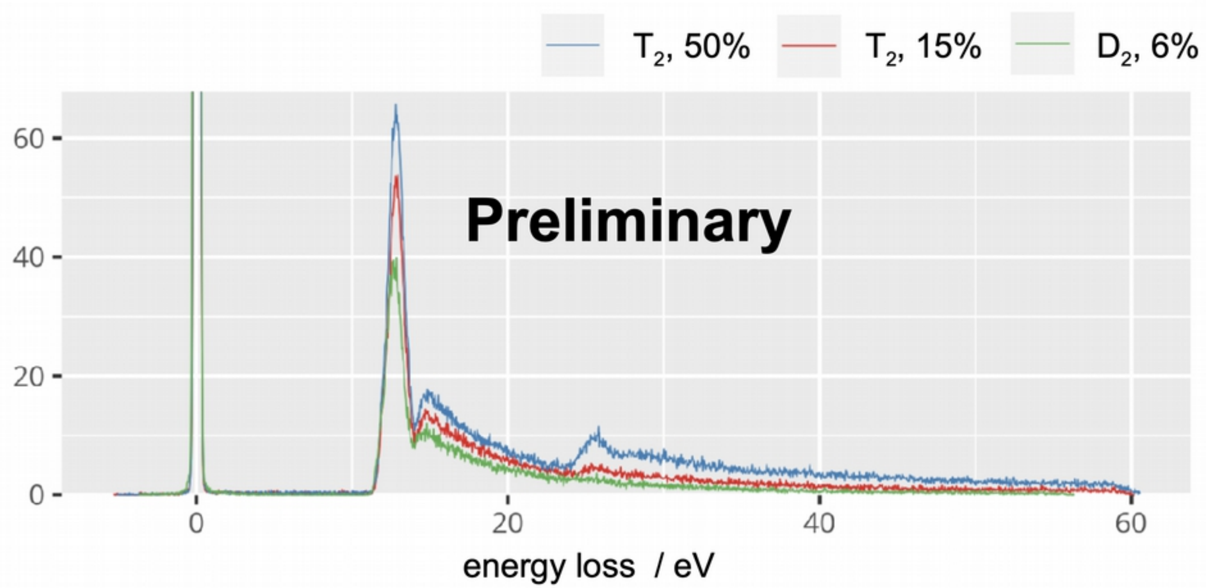
→ increasing sensitivity by factor 2 in m_ν

(N. Steinbrink et al., New J Physics 15 (2013) 113020)

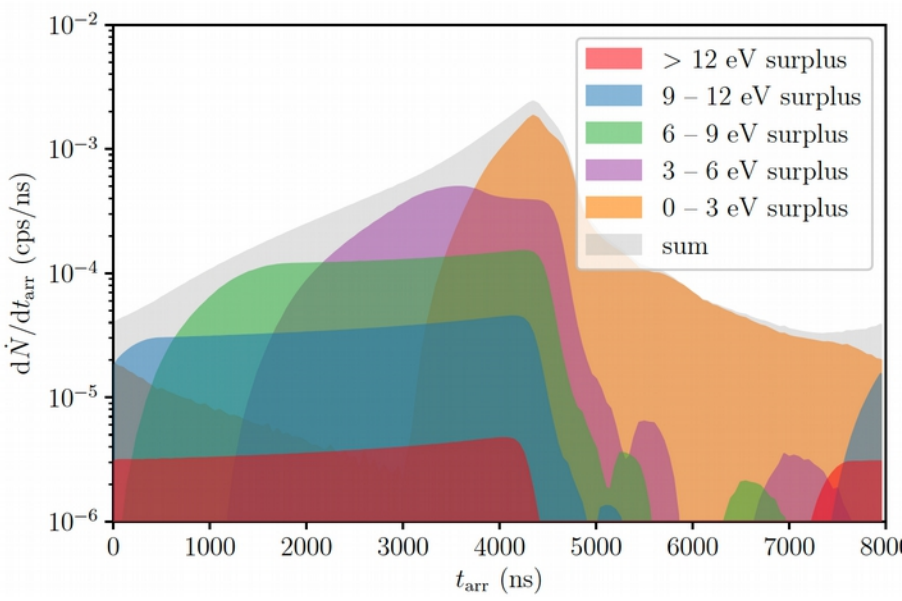


already successfully tested for determination of inelastic scattering
& new idea for implementation: time-focusing time-of-flight

eloss measurements with tof:



time-focusing time-of-flight:



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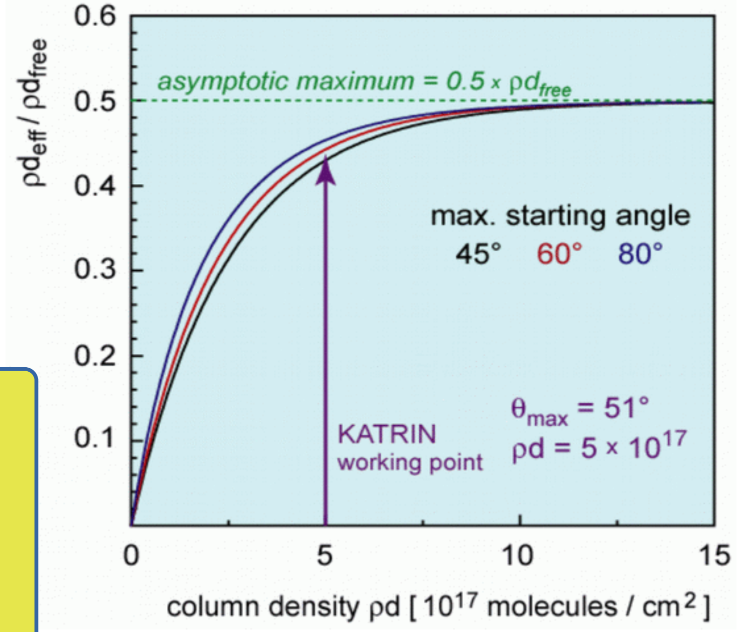

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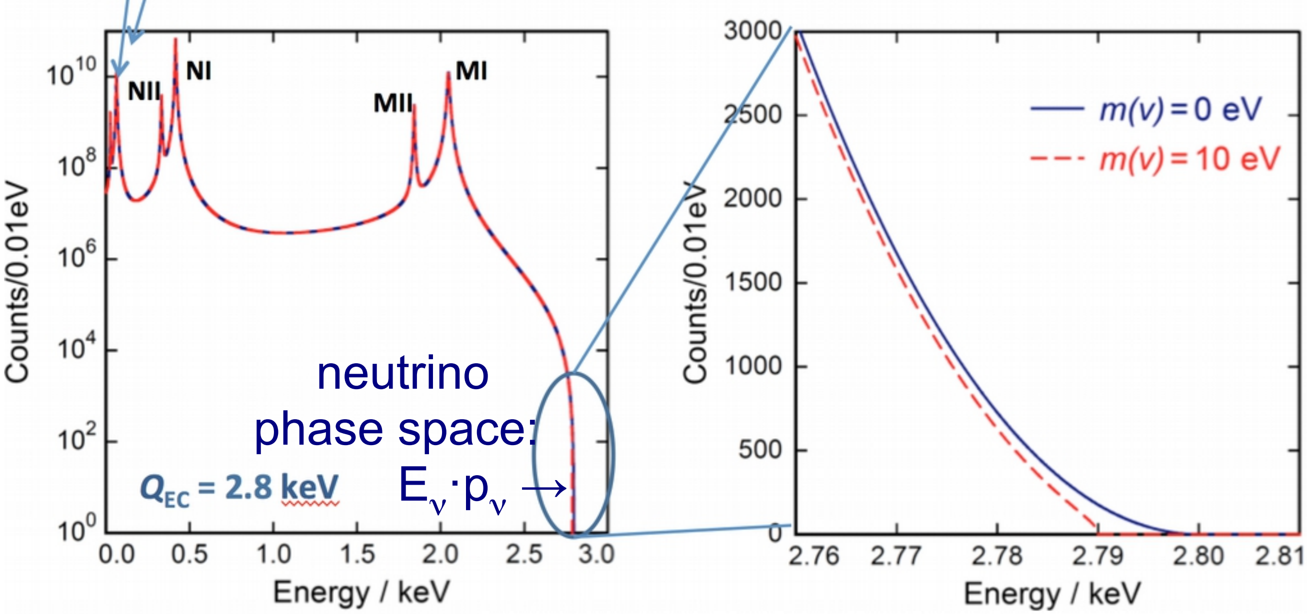
Direct ~~anti~~ neutrino mass measurement from ^{163}Ho electron capture: ECHo, HOLMES

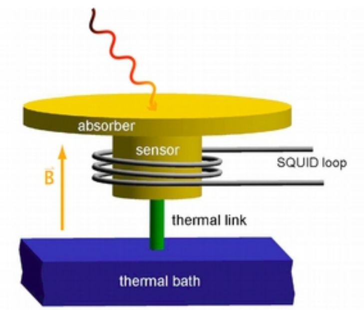
$$^{163}\text{Ho} + e^- \rightarrow {}^{163}\text{Dy}^* + \nu_e \rightarrow {}^{163}\text{Dy} + \gamma/e^- + \nu_e$$



^{163}Ho source inside cryo calorimeter → determine ΔE by temp change ΔT:

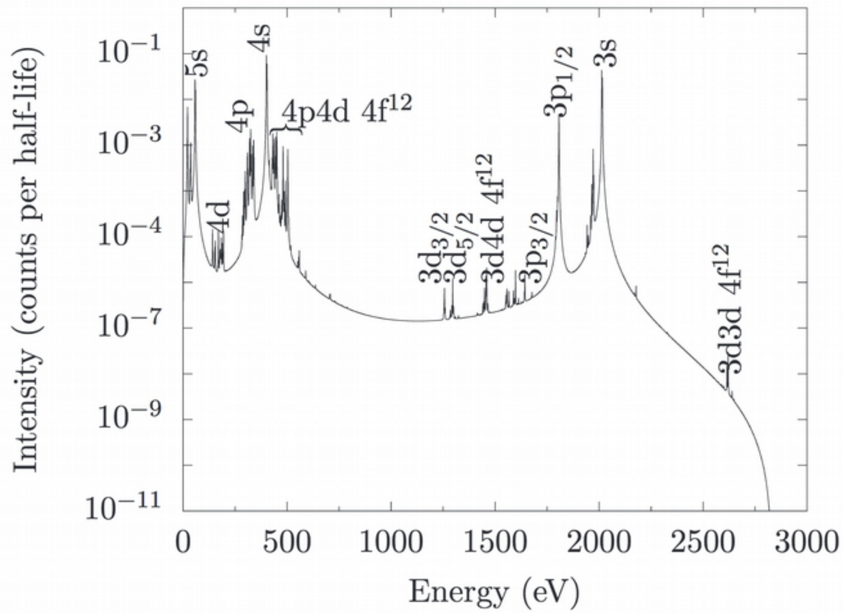
$\Delta T = \Delta E/C$, $C \propto T^3$

ECHo:
metallic magnetic calorimeters: change of magnetic properties

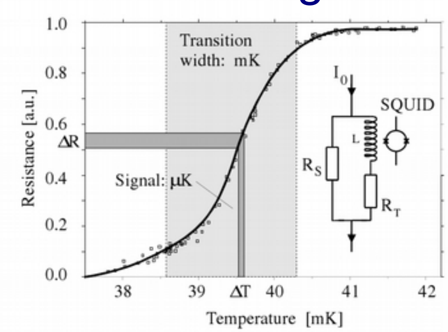


New ab initio spectral calculation:
M. Braß et al.,
PRC **97** (2018) 054620

→ much better agreement with experimental data from ECHo



HOLMES:
sc. transition edge sensors



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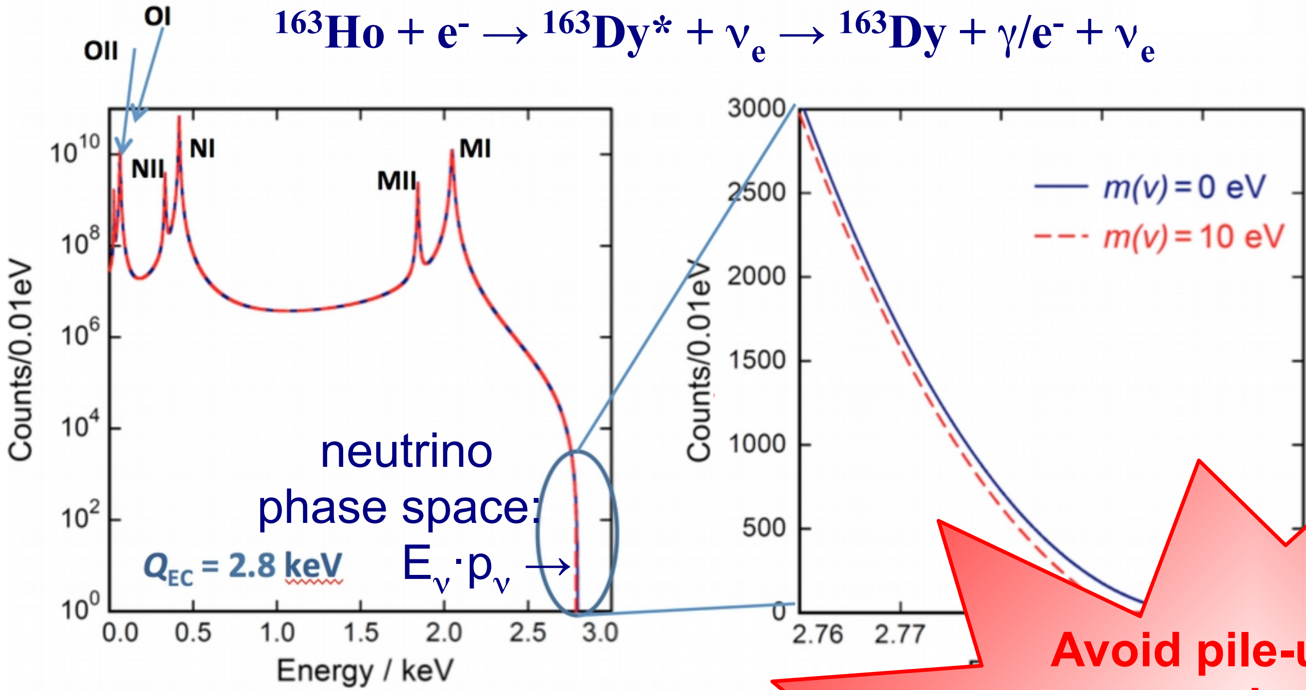

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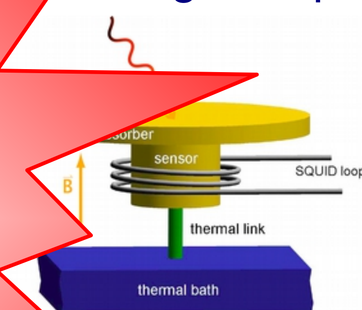
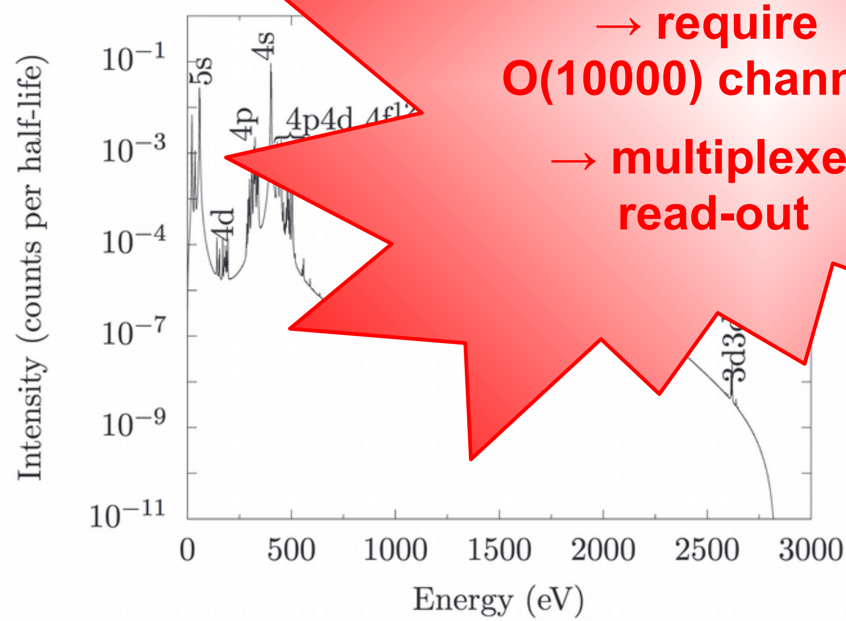


Avoid pile-up → require O(10000) channels

→ multiplexed read-out

New ab initio spectral calculation: M. Braß et al., PRC **97** (2018) 054620

→ much better agreement with experimental data from ECHo



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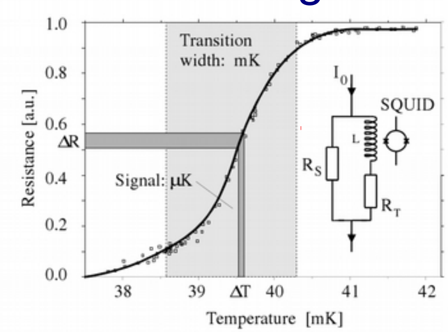
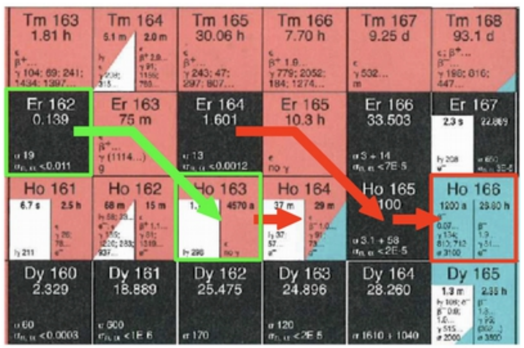
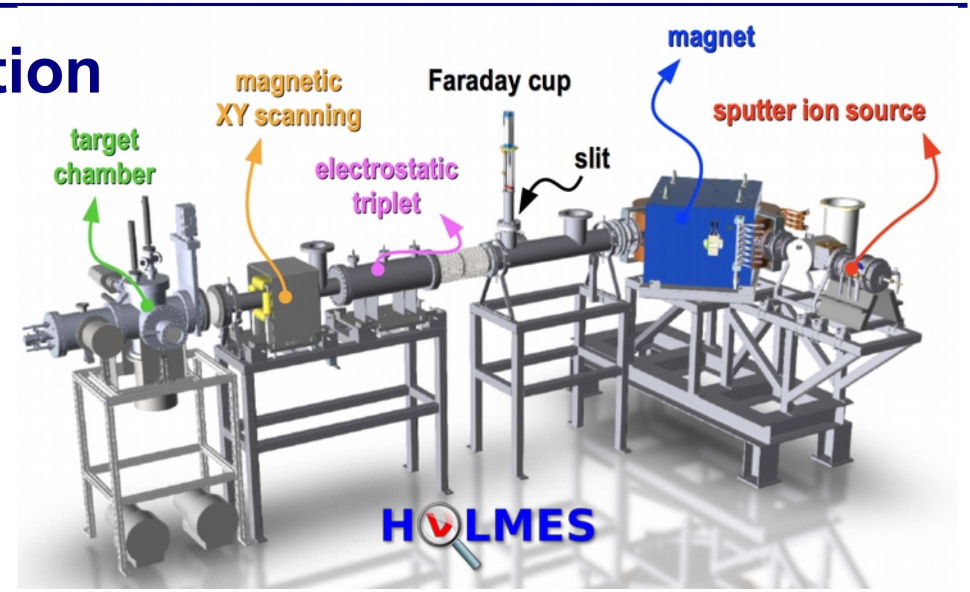


Direct ~~anti~~ neutrino mass measurement from ^{163}Ho electron capture: add. technical challenges

Source by n irradation and implantation





Q-value of ^{163}Ho:

→ long debate of values around 2.5 and 2.8 keV solved:

SHIPTRAP Penning trap measurement:

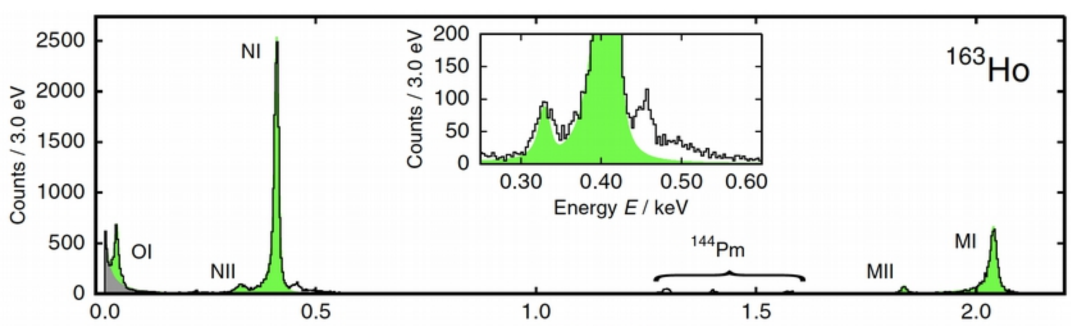
*S. Eliseev et al., PRL **115** (2015) 062501*

$$Q_{EC} = (2.833 \pm 0.030^{stat} \pm 0.015^{syst})\ \text{keV}$$

ECHo precision ^{163}Ho EC spectrum:

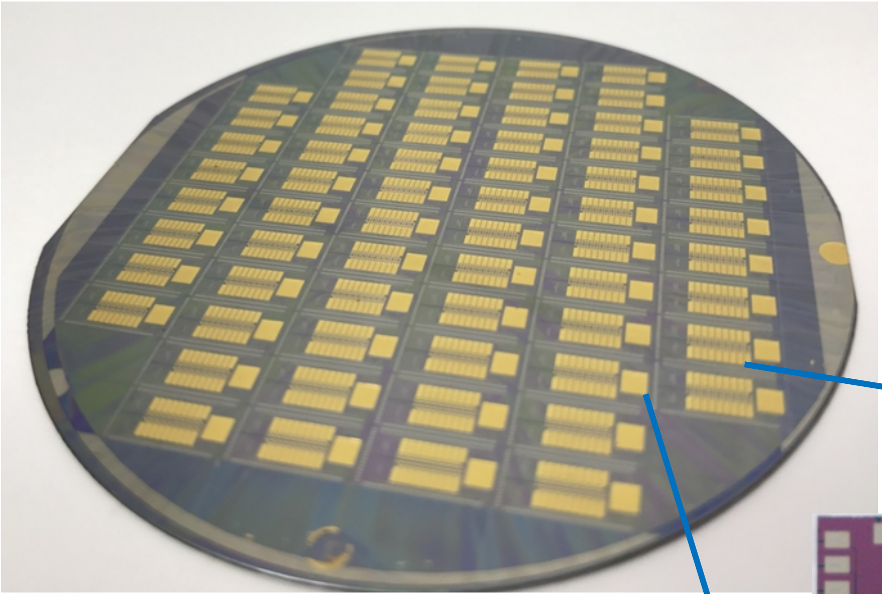
*P. C.-O. Ranitzsch et al., PRL **119** (2017) 122501*

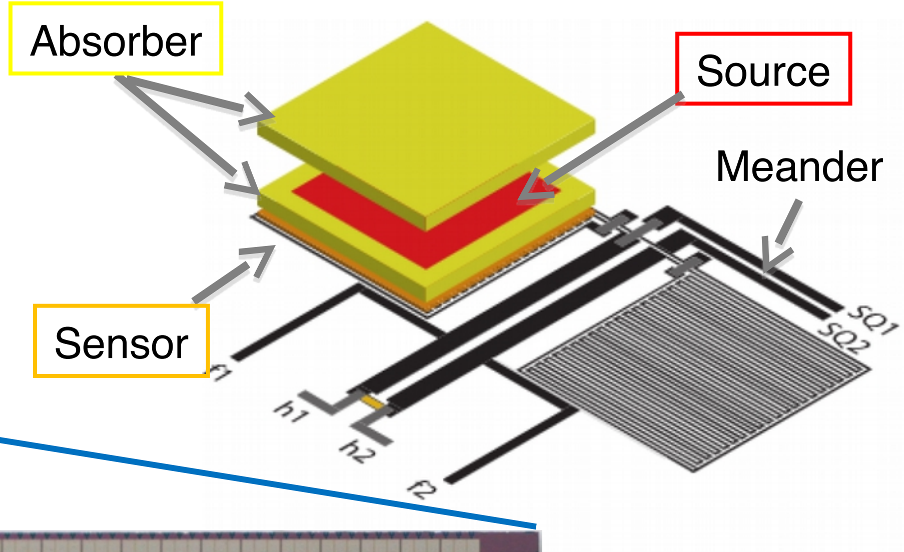
$$Q_{EC} = (2.858 \pm 0.010^{stat} \pm 0.05^{syst})\ \text{keV}$$

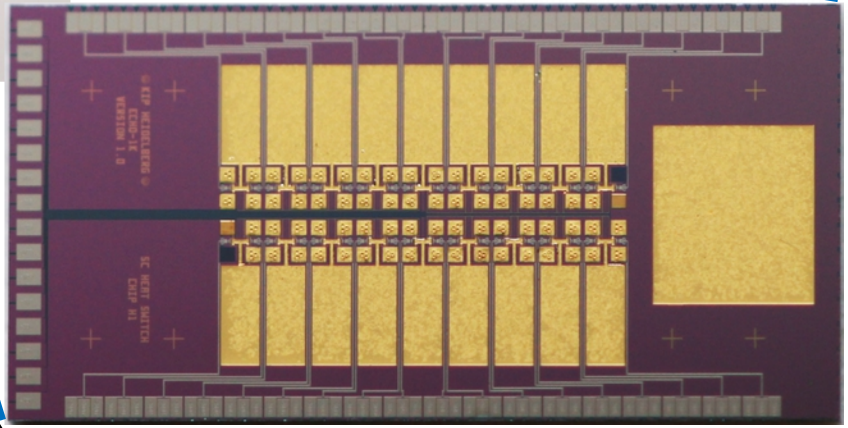


courtesy: L. Gastaldo, A. Nucciotti

Present status of ECHo

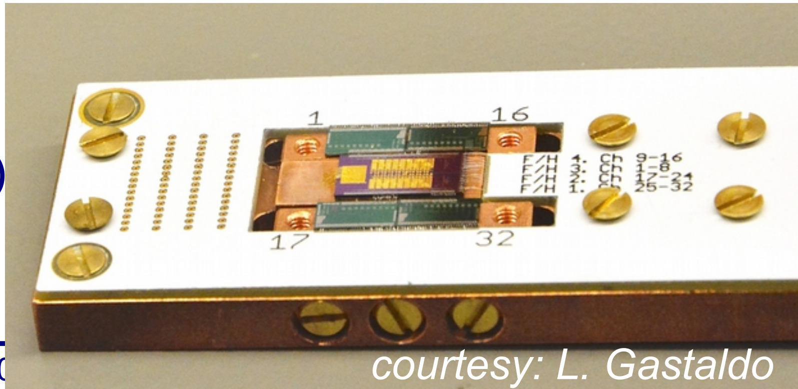






64 pixels which can be loaded with ^{163}Ho
+ 4 detectors for diagnostics

Design performance:
$\Delta E_{FWHM} \sim 5$ eV
$\tau_r \sim 90$ ns (single channel readout)
$\tau_r \sim 300$ ns (microwave-multiplexed read-out)

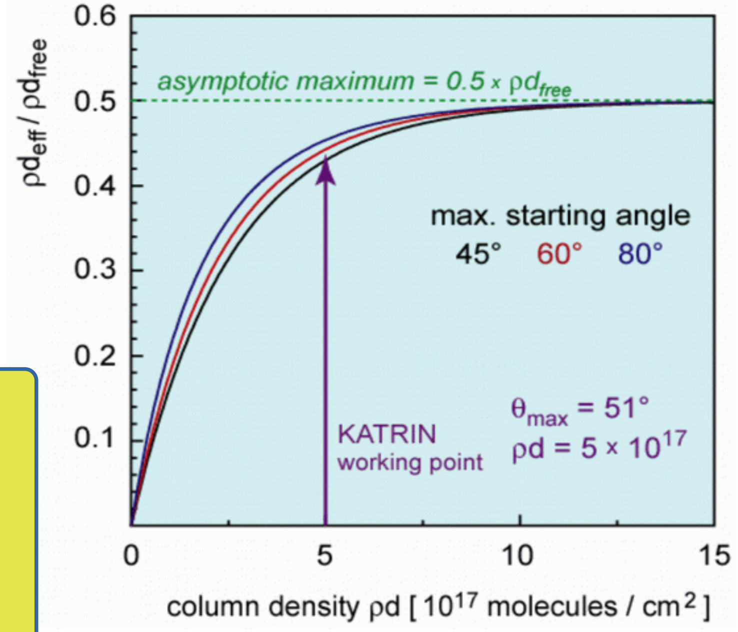


ECHo-1k chip implanted at RISIKO at Univ. of Mainz
→ ^{163}Ho activity per pixel $a \approx 1$ Bq (total activity A ≈ 100 Bq)

4 Front-end chips each with 8 dc-SQUIDs
→ **ECHo has taken spectra with 10^7 counts this summer**

KATRIN's sensitivity of 200 meV might not be enough
Can we go beyond or improve KATRIN ?

Problem: The KATRIN 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) source inside detector (compare to $0\nu\beta\beta$)
using cryogenic bolometers (ECHo, HOLMES, ..)

c) 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*

PROJECT 8

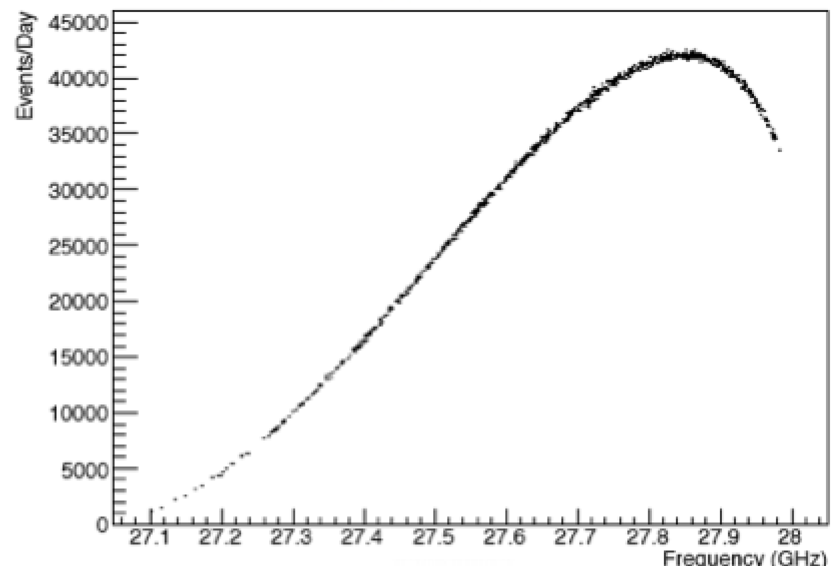
- Source = KATRIN tritium source technology :

  uniform B field + low pressure T_2 gas

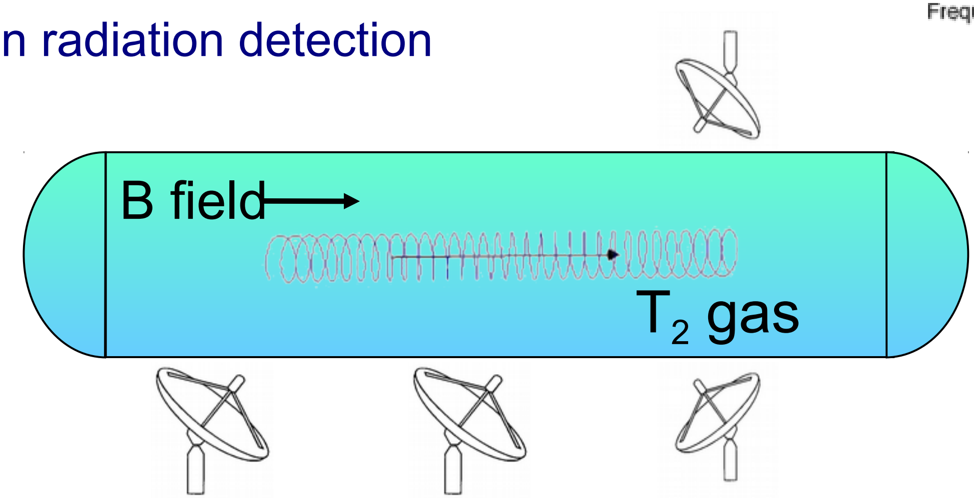
  β electron radiates coherent cyclotron radiation

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

  But tiny signal: P (18 keV, θ=90°, B=1T) = 1 fW

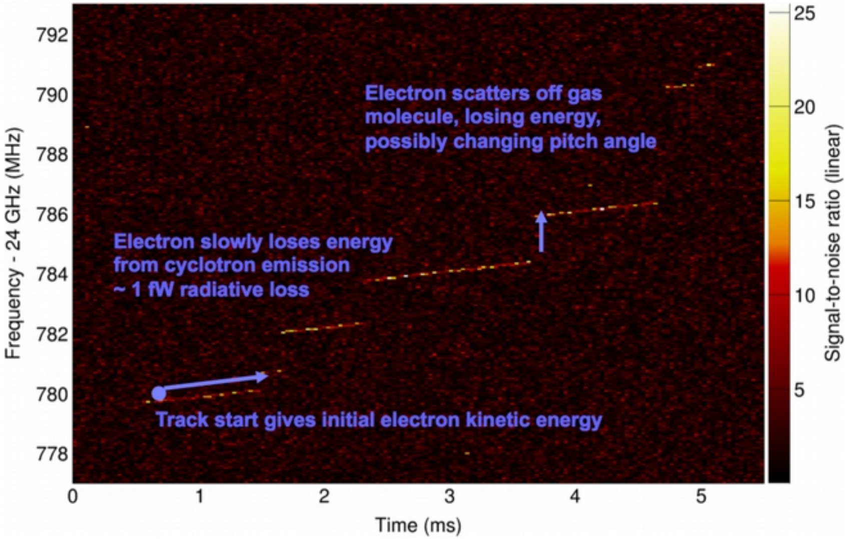


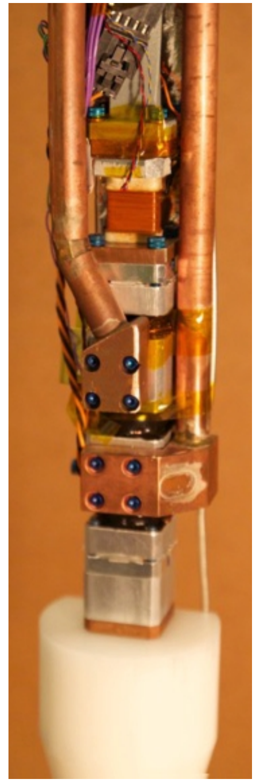
- Antenna array (interferometry) for cyclotron radiation detection
  since cyclotron radiation
  can leave the source and
  carries out the information
  of the β-electron energy



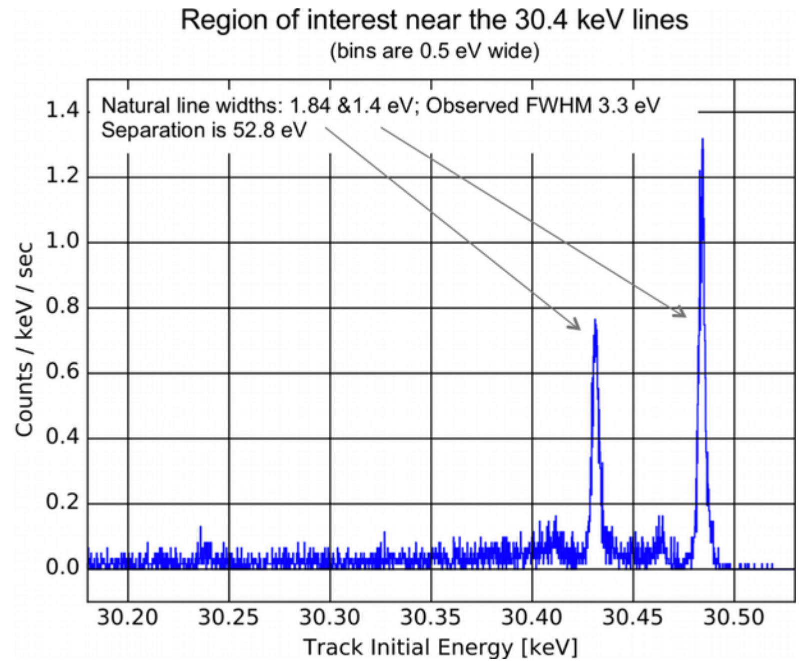
Project 8: phase I (^{83m}Kr) and II (tritium) Proof of principle

Phase I (^{83m}Kr)



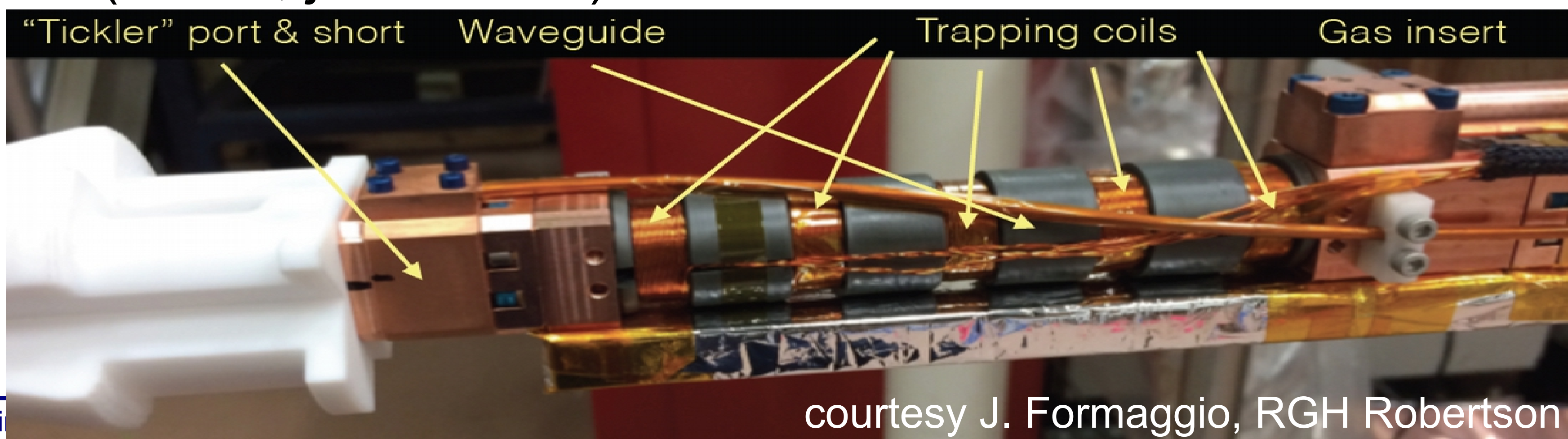


magnetic bottle to trap decay electrons long enough

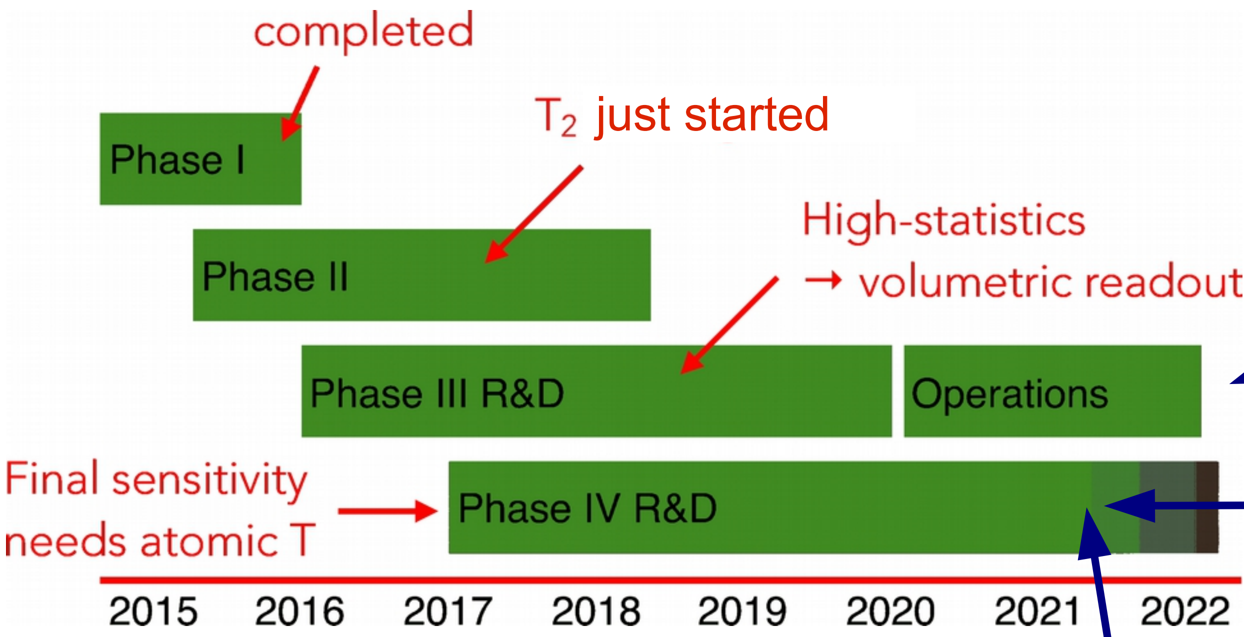


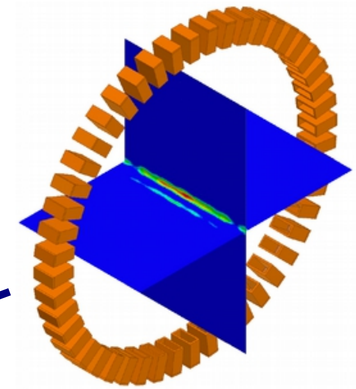
D. M. Asner et al., Phys. Rev. Lett. 114, 162501

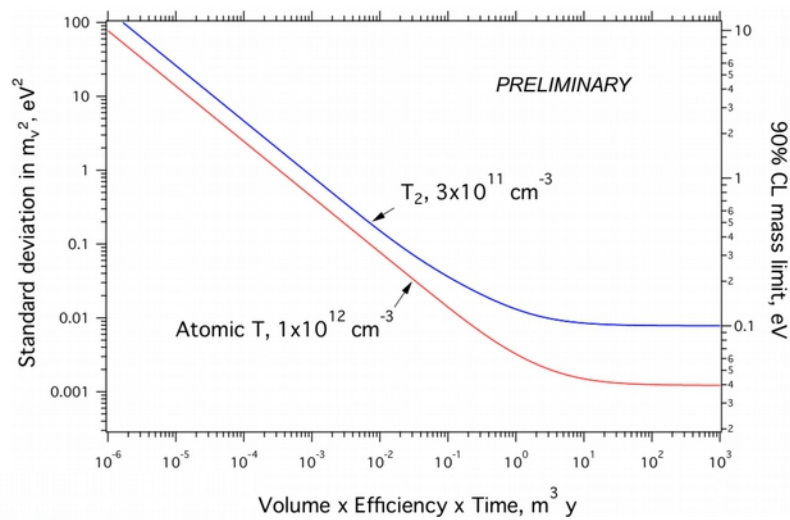
Phase II (tritium, just started)



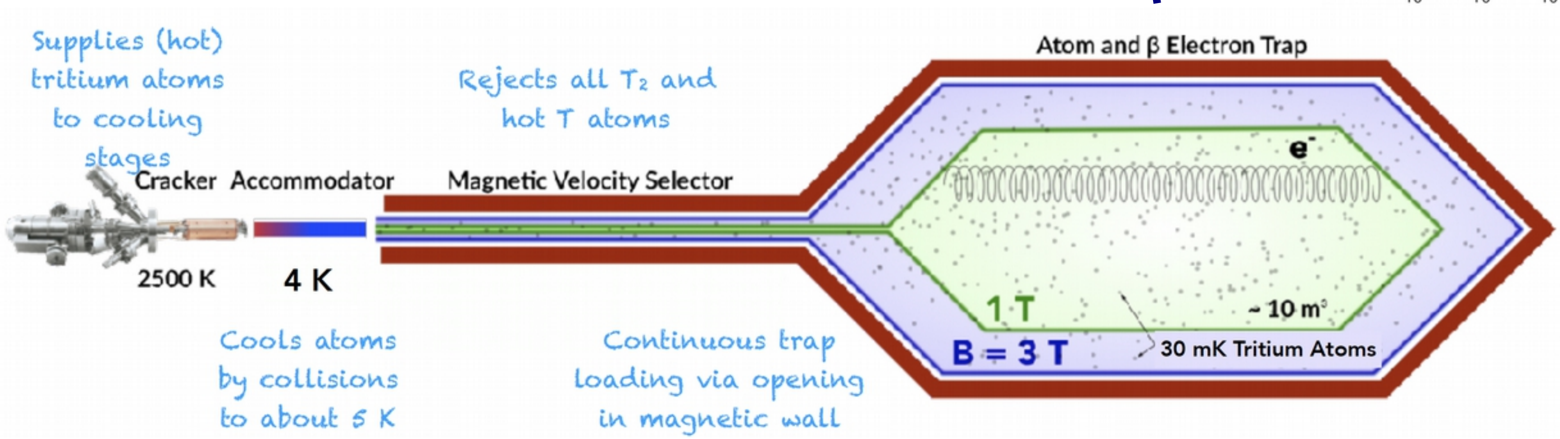
Project 8: longterm perspective







atomar tritium source (higher resolution)



→ 40 - 100 meV should be possible with ≈$10 m^3$ setup

courtesy: S. Böser

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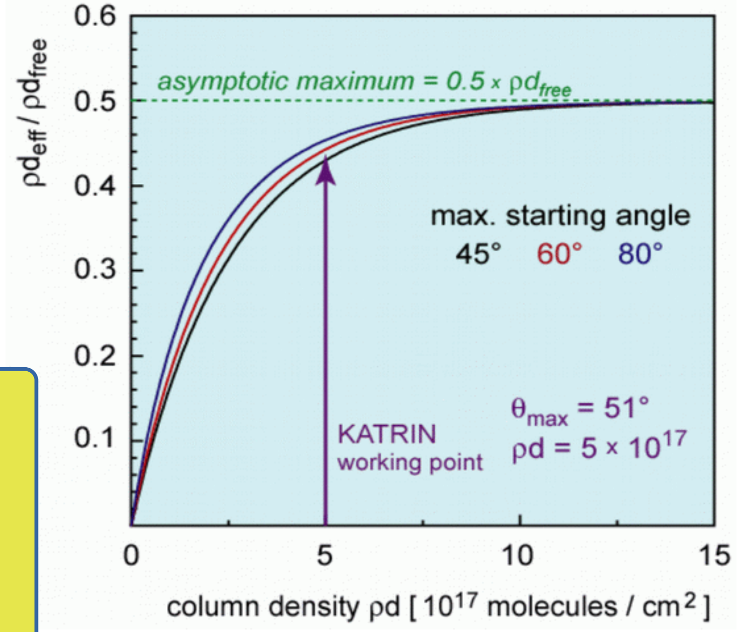

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hand-over energy information of β electron to other particle (radio photon), which can escape tritium source (Project 8)

d) combine all technologies and add new (PTOLEMY)

Neutrino physics: experiments II

The dark side of the Universe, ISAPP, MPIK Heidelberg, May 29/30, 2019

Christian Weinheimer

Institut für Kernphysik, Westfälische Wilhelms-Universität Münster

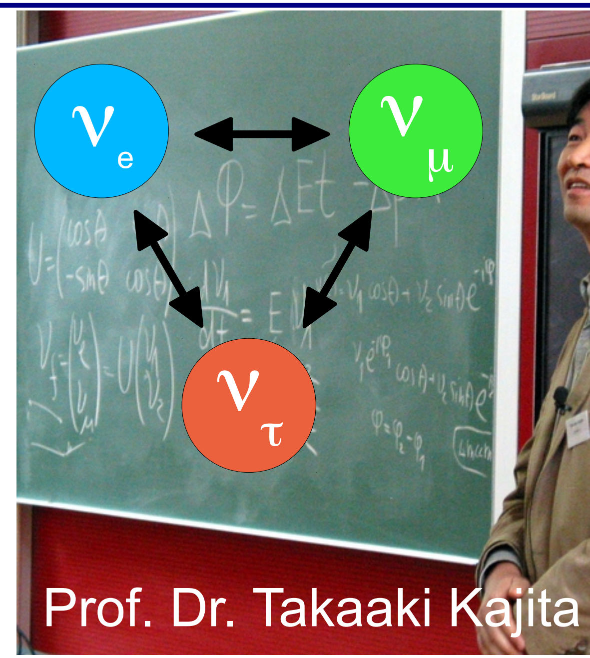
weinheimer@uni-muenster.de

A reminder: Neutrinos
in the Standard Model of Particle Physics

Neutrino oscillations:
experiments with atmospheric,
solar, accelerator and reactor neutrinos

Neutrino masses:
- cosmology and astrophysics
- neutrinoless double β decay
- direct neutrino mass experiments

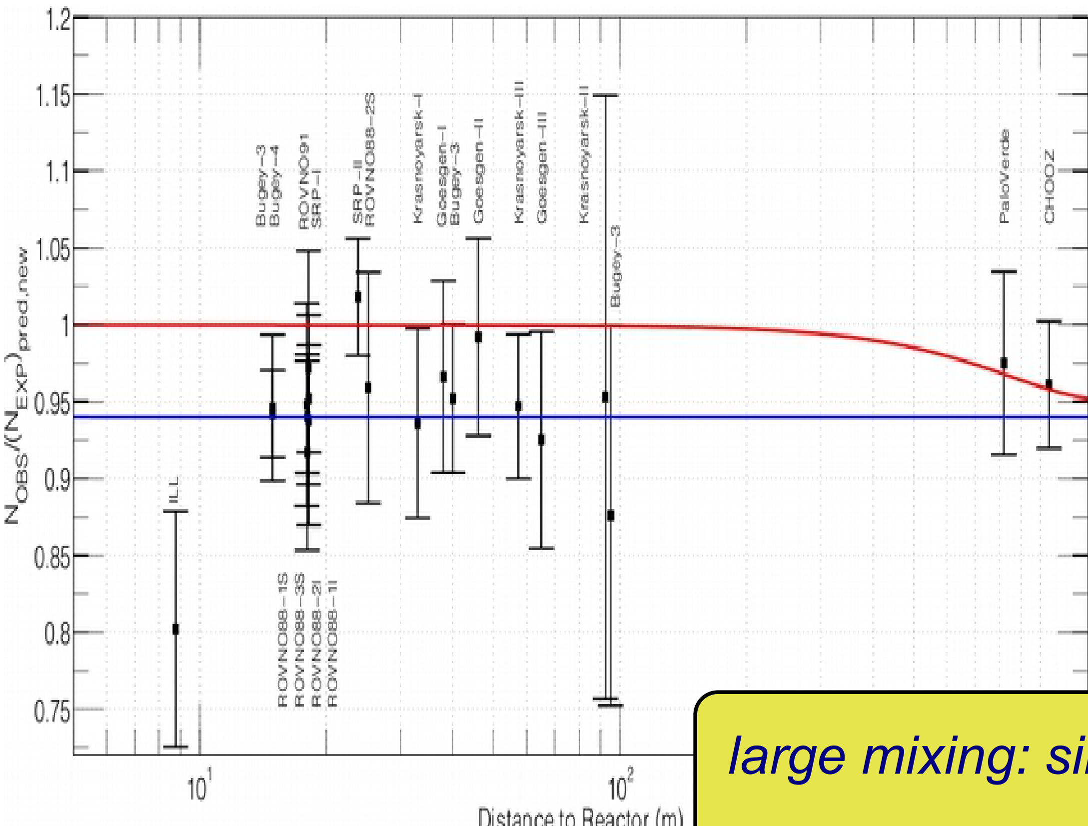
Search for sterile neutrinos
Coherent elastic neutrino nucleus scattering

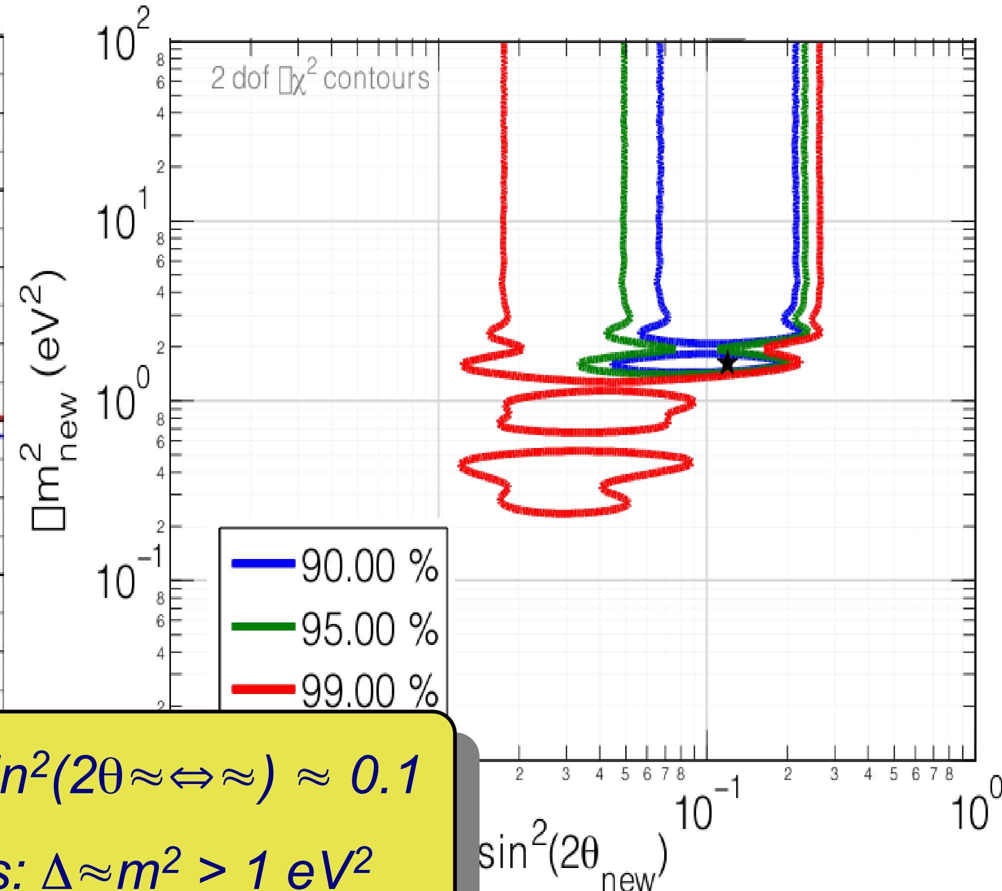


Puzzle: sterile Neutrinos ?

More than 3 neutrinos and/or CPT violation?

- Reevaluation of reactor neutrinos fluxes and use GALLEX/SAGE calibration measurements:
  "reactor antineutrino anomaly": $P_{ee} = 0.943 \pm 0.023$





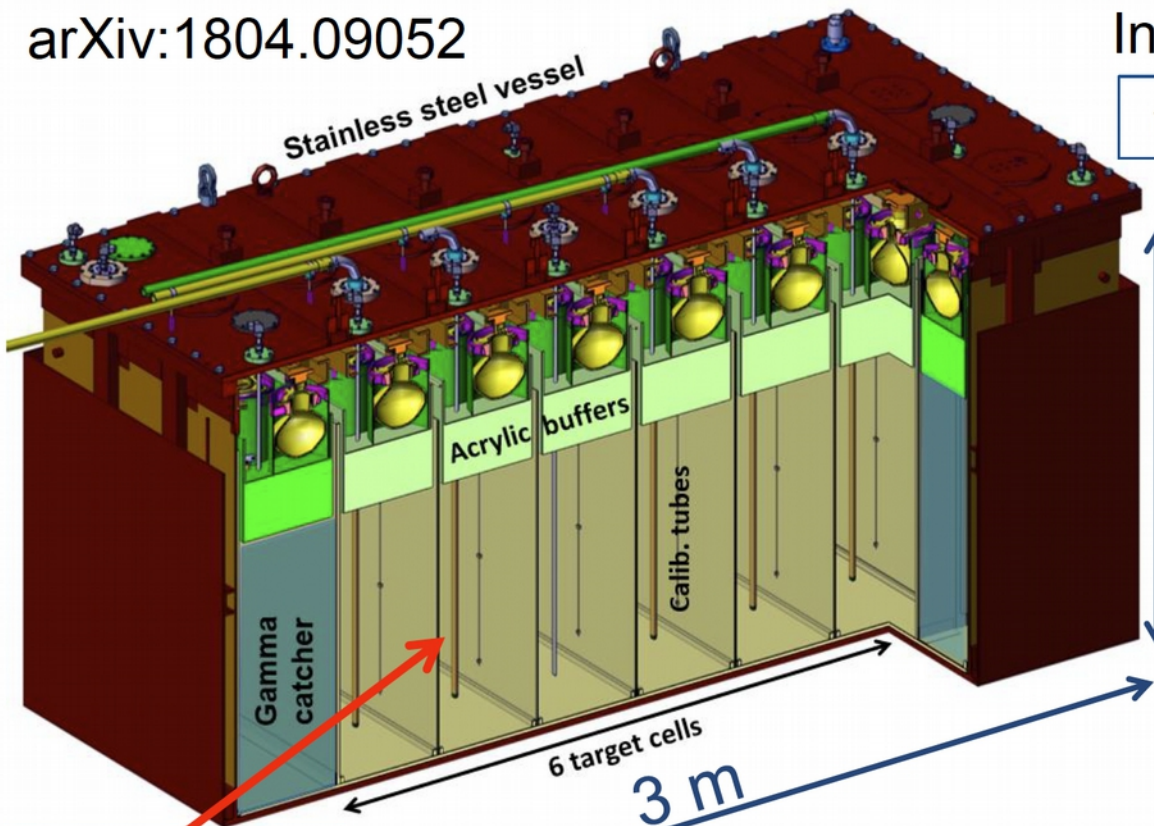
large mixing: sin²(2θ≈⇔≈) ≈ 0.1

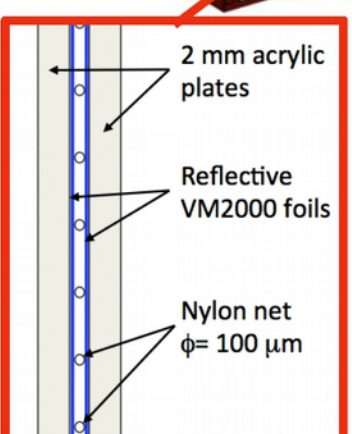
large masses: Δ≈m² > 1 eV²

G. Mention et al., arXiv:1101.2755

STEREO-Experiment at ILL

arXiv:1804.09052



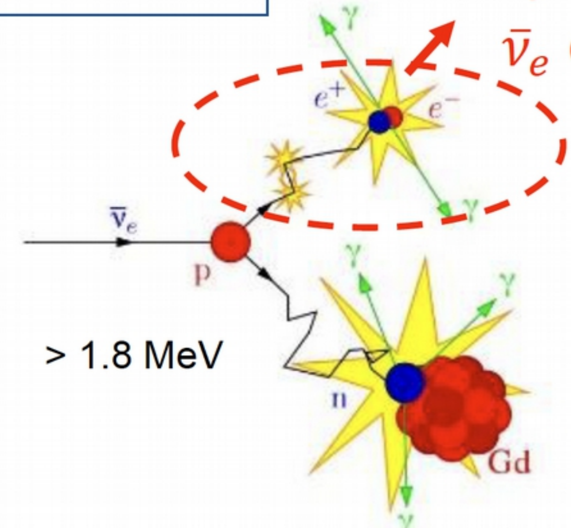


Invert Beta Decay

$$\bar{\nu}_e + p \rightarrow e^+ + n$$

Prompt signal

$\bar{\nu}_e$ energy



> 1.8 MeV

Delayed signal

Mean neutron capture time 16 µs

Target

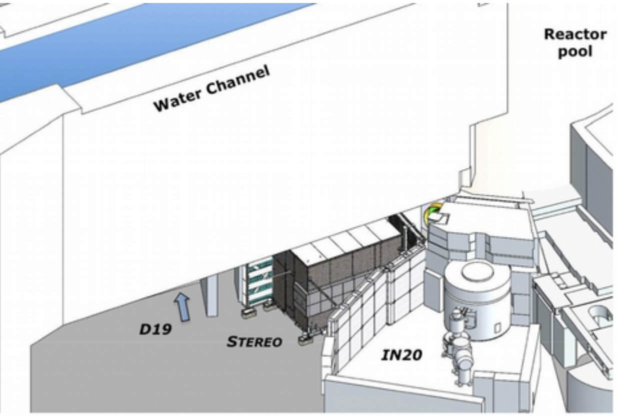
6 cells filled with
Gd-loaded liquid scintillator
4 top PMTs per cell

Gamma-catcher

Outer-crown to detect γ's escaping
from the Target + active shielding
24 PMTs

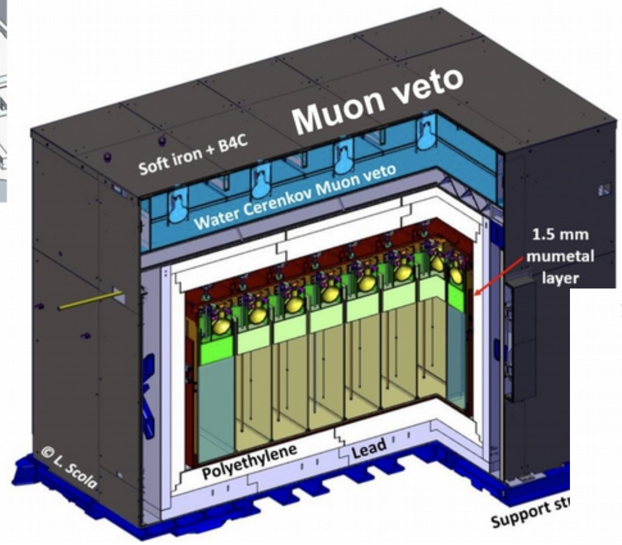
from J. Lamblin, Neutrino 2018

STEREO-Experiment at ILL



Cosmic background

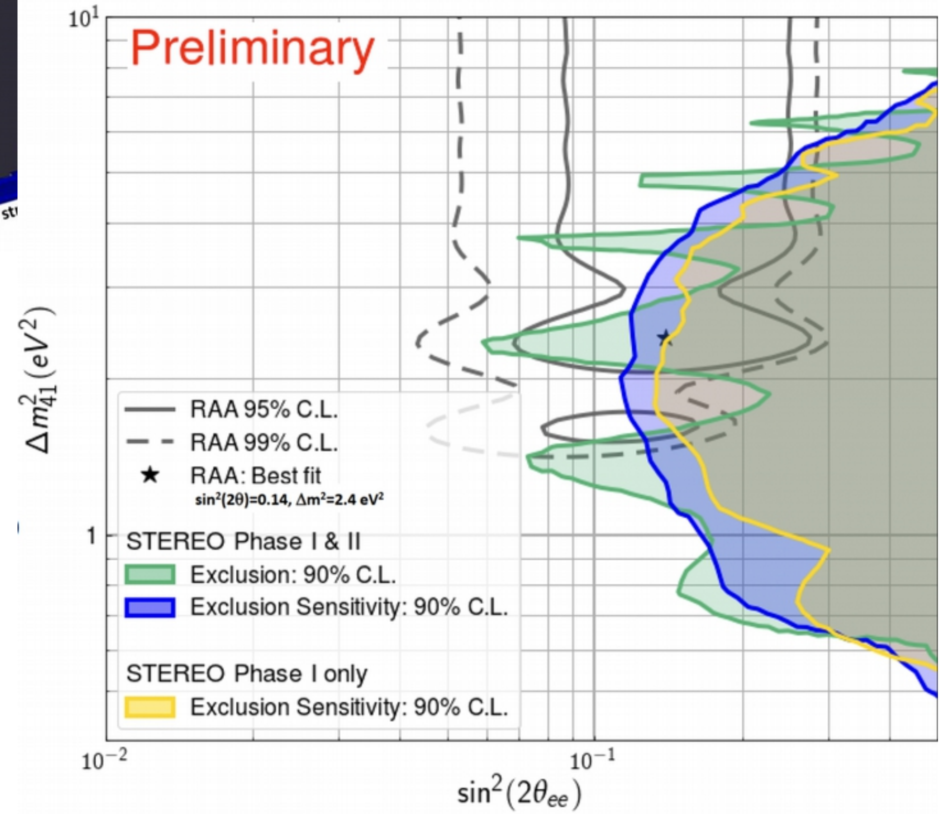
- 15 m.w.e. (Water channel + reactor building)
- Water Cerenkov Muon Veto



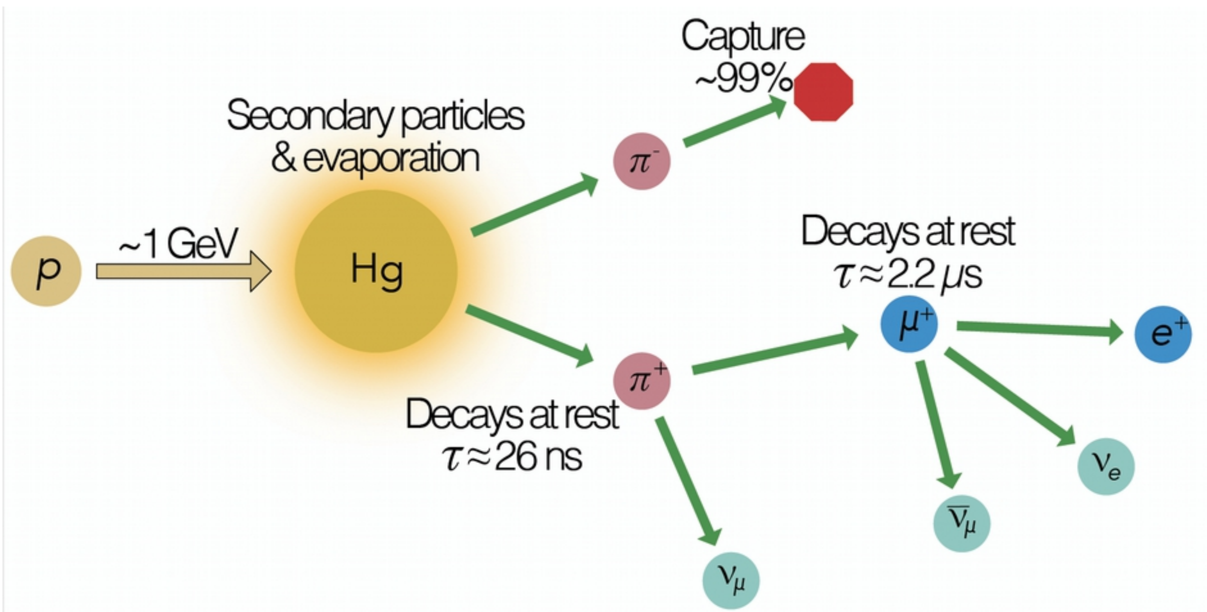
Gamma and neutron background

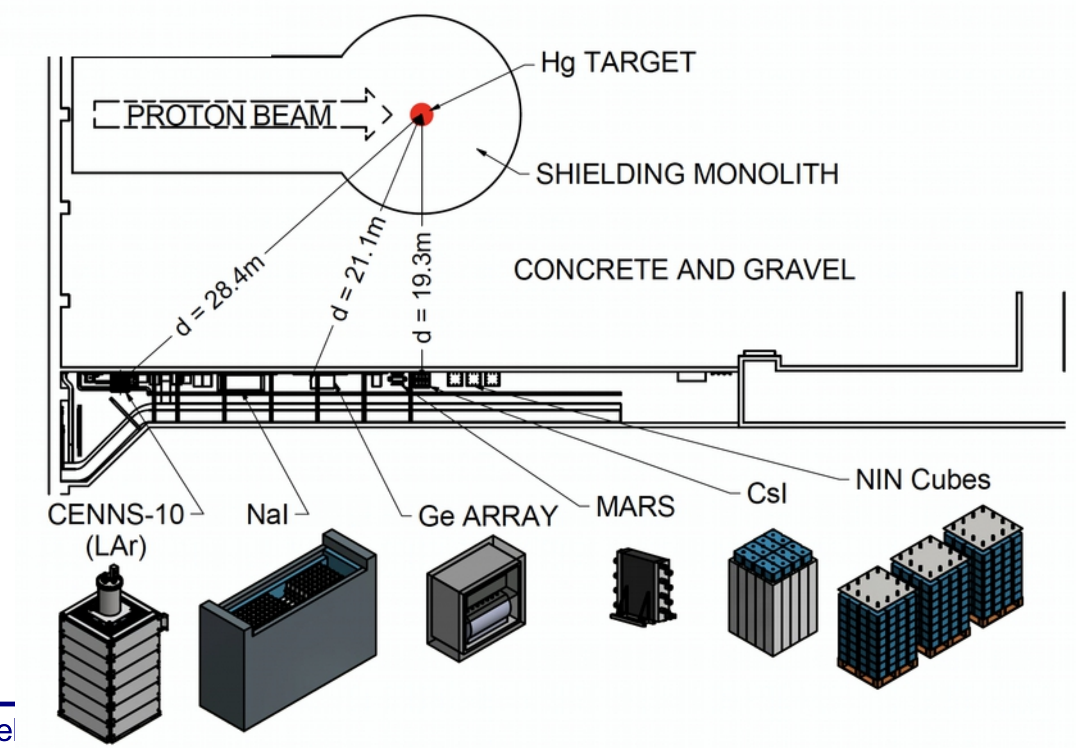
- Lead
- Boron doped polyethylene
- Boron loaded rubber

J. Lamblin, Neutrino 2018



COHERENT at Oakridge NL:
discovery of coherent elastic neutrino nucleus scattering





G.C. Rich, Neutrino 2018

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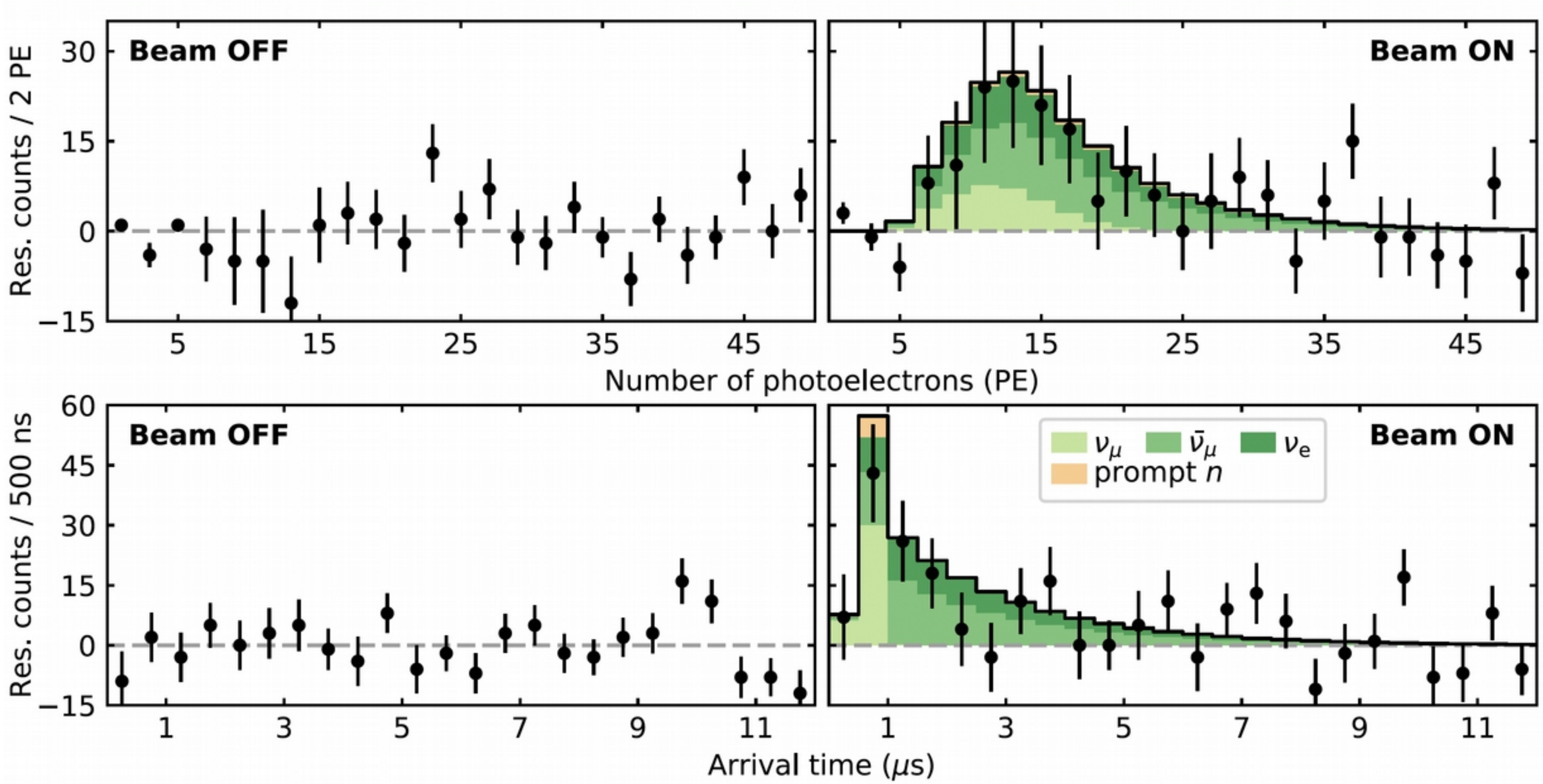
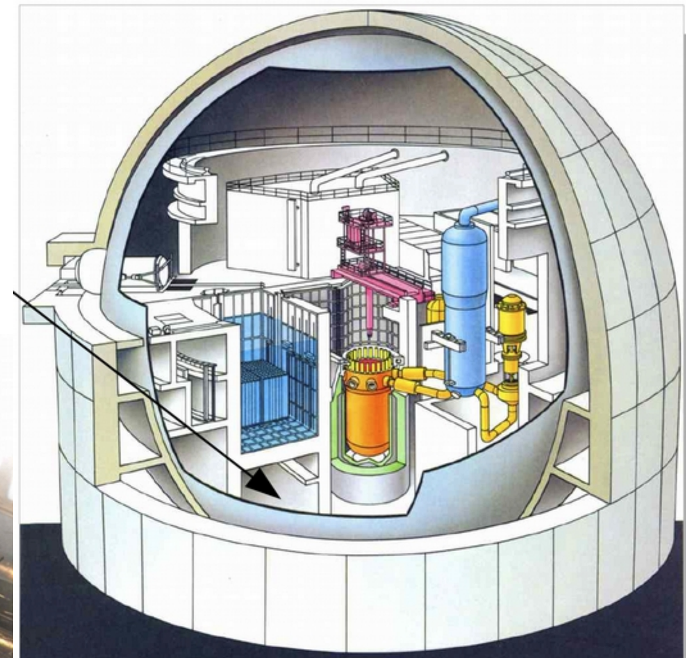
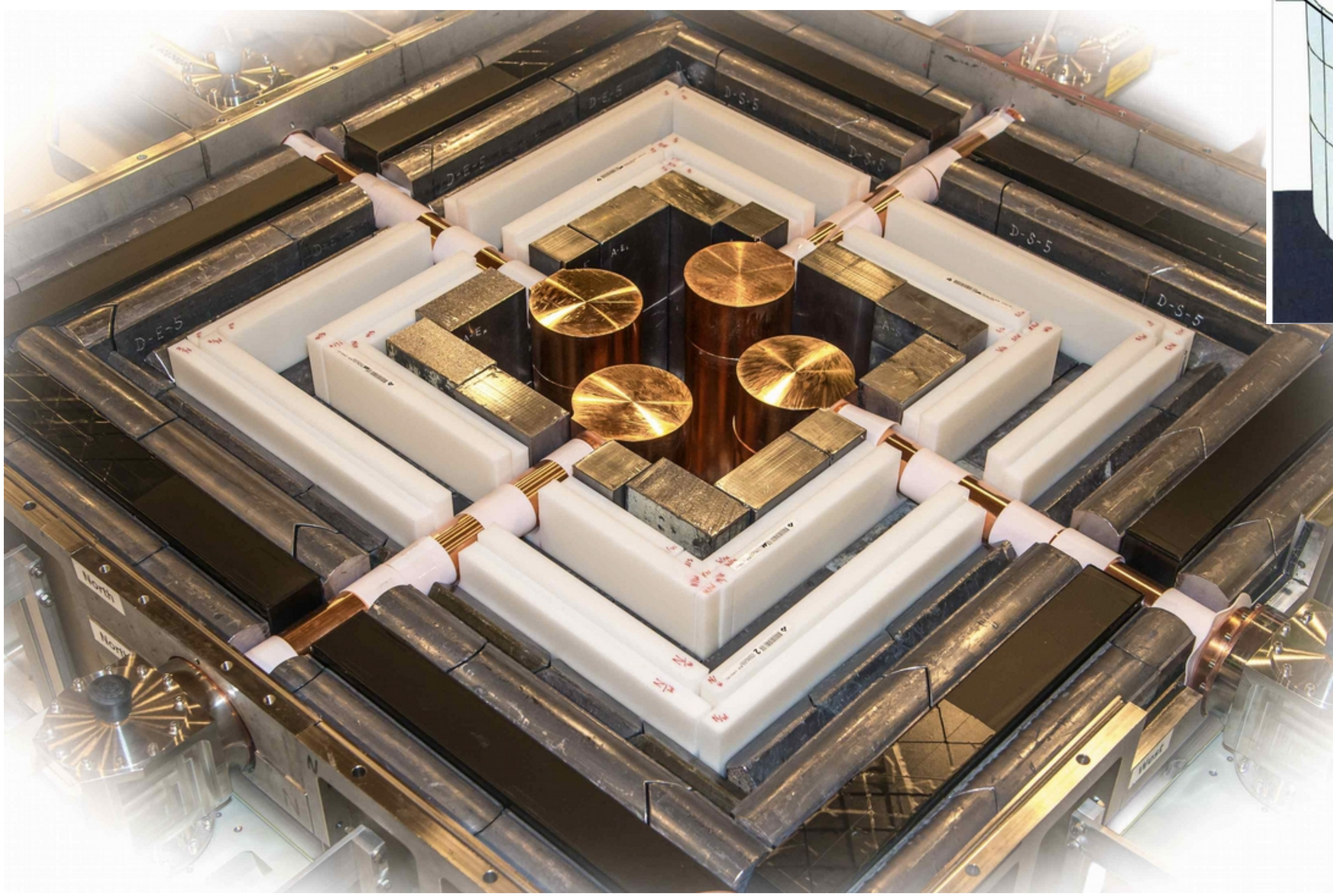


G.C. Rich, Neutrino 2018

CONUS at Brokdorf nuclear power plant

Ultralow threshold Ge detectors
in active & passive shielding
(„artifical depth technology")





W. Maneschg, Neutrino 2018

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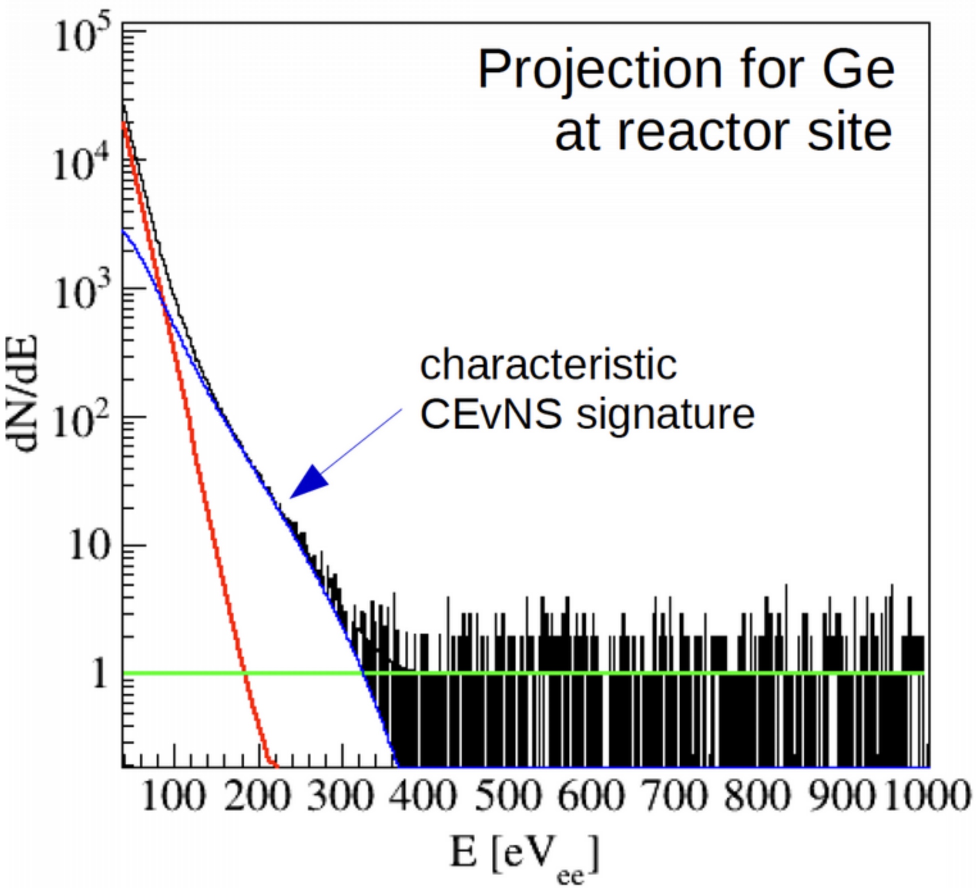

	counts	counts/(d·kg) (*)
reactor OFF (114 kg*d)	582	
reactor ON (112 kg*d)	653	
ON-OFF (exposure corr.)	84	0.94
Significance	**2.4 σ**	2.3 σ

Some systematics still under study

(*) Including stat. uncertainty and above efficiencies

W. Maneschg, Neutrino 2018

Conclusions

After having discovered neutrino oscillations in many channels and measured
the 3 mixing angles and 2 squared mass differences …

What is the neutrino mass ordering: NH or IH?

What is the CP phase?

Are there more than 3 neutrinos (sterile neutrinos)?

What is the neutrino mass (only known hot dark matter component)?
KATRIN is the direct neutrino mass experiment complementary
to cosmological analyses and $0\nu\beta\beta$ searches
There are new approaches beyond KATRIN

Are neutrinos Majorana particles, is there lepton number violation?
$\rightarrow$ maybe the key to the baryon asymmetry of the universe
GERDA II is leading together with KamLAND-Zen
LEGEND 200 will go another order of magnitude in sensitivity

Coherent elastic neutrino nucleus scattering is opening a new door …