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Understanding Neutrino Properties, and their Mass Measurement

Particle Physics Seminar, University of Birmingham, Nov. 3, 2021

Christian Weinheimer – Institute for Nuclear Physics, University of Münster

- Current key issues in neutrino physics
- Highlights from
  - neutrino oscillation experiments
  - search for $0\nu\beta\beta$
- Direct search for $m(\nu)$
  - recent results from KATRIN
- Conclusions

Neutrinos in the Standard Model
- extended by neutrino masses -

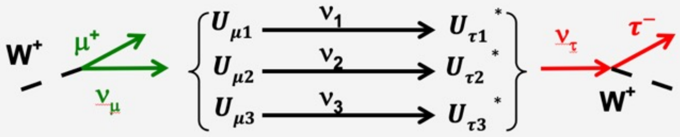
Neutral, spin ½, 3 flavours, only weak interaction

3 flavour eigenstates and mass eigenstates differ:

$m(\nu) \neq 0$ and ν mixing

$$U_{PMNS} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_{23} & \sin\theta_{23} \\ 0 & -\sin\theta_{23} & \cos\theta_{23} \end{pmatrix} \cdot \begin{pmatrix} \cos\theta_{13} & 0 & \sin\theta_{13} e^{-i\delta_{CP}} \\ 0 & 1 & 0 \\ -\sin\theta e^{i\delta_{CP}}{}_{13} & 0 & \cos\theta_{13} \end{pmatrix} \cdot \begin{pmatrix} \cos\theta_{12} & \sin\theta_{12} & 0 \\ -\sin\theta_{12} & \cos\theta_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \cdot \begin{pmatrix} e^{i\eta_1} & 0 & 0 \\ 0 & e^{i\eta_2} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

→ ν flavour oscillation, CP violation via U_{PNMS} possible

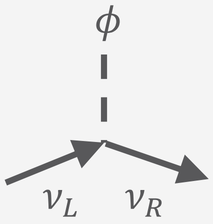


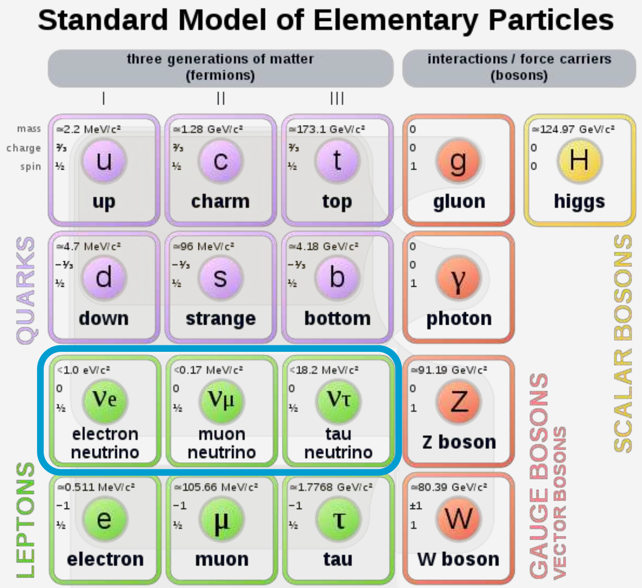
Neutral: particle character unclear:

Dirac or Majorana ($\upsilon = \bar{\upsilon}$) ?

Neutrino masses so much lighter:

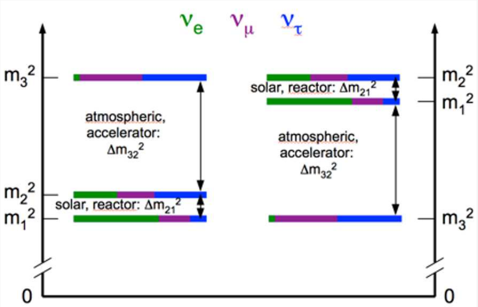
Yukawa coupling to the Higgs ?





modified from en.wikipedia.org

Current key issues



SM BSM

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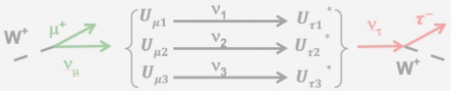

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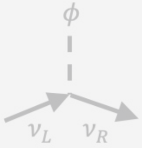

1. Ordering: $m(\nu_3) > m(\nu_{2,1})$ (NO) or $m(\nu_{2,1}) > m(\nu_3)$ (IO) ?
2. CP violating phase $0 \neq \delta_{CP} \neq \pi$?
3. Lepton-number violation by Majorona ν ?

   } *possibly connected to baryon-asymmetry of the universe via leptogensis?* (items 2 and 3)

4. Absolute neutrino mass
   neutrino mass generation likely BSM
   10^9 more ν than atoms → cosmological relevant: structure formation
5. Is there a 4th or even a 5th light sterile neutrino ?
6. Are there more BSM effects ?

BSM via coherent elastic neutrino nucleon scattering CEνNS ?

In addition, ν are interesting messenger for other physics:

e.g. from fusion inside the sun, from supernovae or UHE neutrino from “cosmic accelerators“

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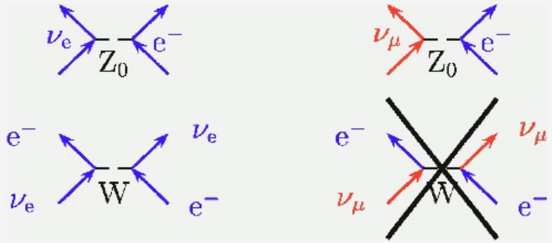
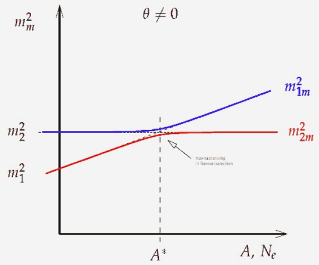
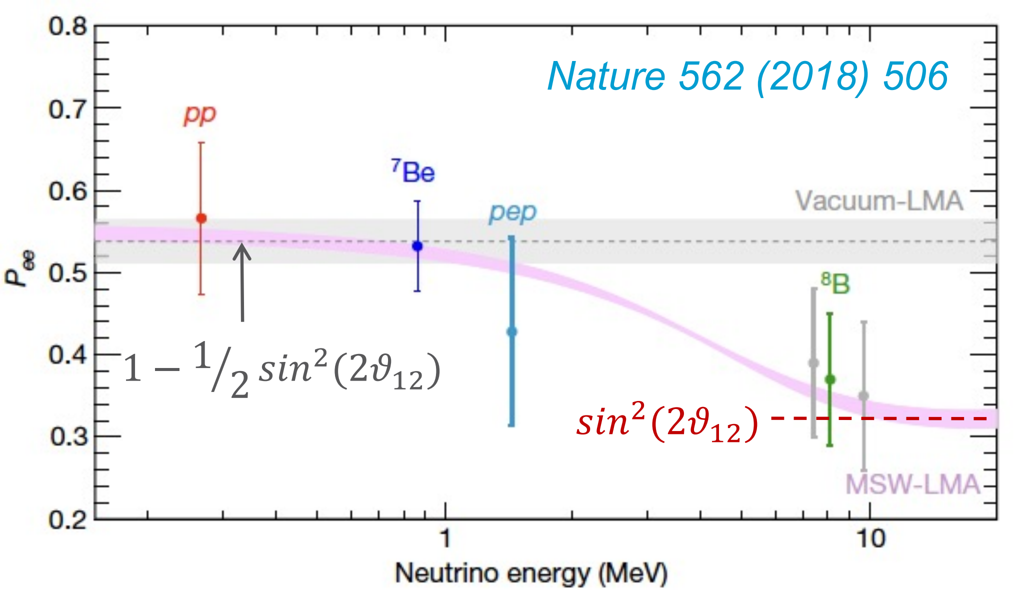
Borexino proved matter-enhanced oscillation (MSW)

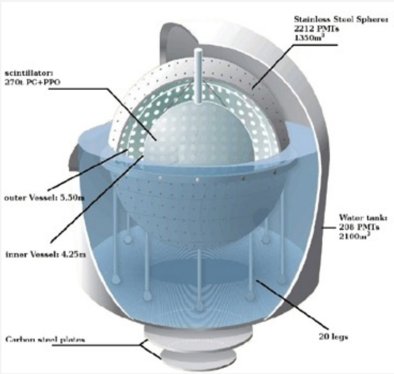


- Matter-enhanced neutrino oscillation is due to the additional CC coherent forward scattering of $\boldsymbol{\nu_e}$ on $\boldsymbol{e^-}$ in matter in contrast to $\boldsymbol{\nu_\mu, \nu_\tau}$

- **MSW: nearly complete ν flavour transformation possible**
  if the electron density meets the resonance condition, e.g. for ^{8}B solar ν_e
  & if the neutrino mass ordering is matching, here $m(\nu_2) > m(\nu_1)$







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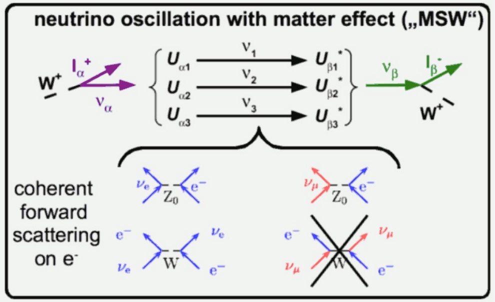
solar ν: $m(\nu_2) > m(\nu_1)$



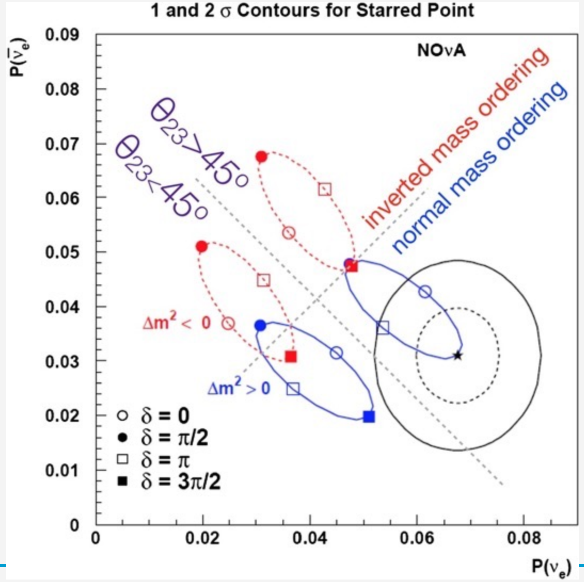
Long baseline: ordering and CP violation

ν oscillation in vacuum: $P(\nu_\alpha \to \nu_\beta) = \left|\sum_j U^*_{\alpha j}\, U_{\beta j} e^{-i\frac{m_i^2}{2E}L}\right|^2 = \delta_{\alpha\beta} - 4\sum_{i>j}\Re(U^*_{\alpha i}U_{\alpha j}U_{\beta i}U^*_{\beta j})sin^2\left(\frac{\Delta m^2_{ij}}{4E}L\right) + 2\sum_{i>j}\Im(U^*_{\alpha i}U_{\alpha j}U_{\beta i}U^*_{\beta j})sin^2\left(\frac{\Delta m^2_{ij}}{2E}L\right)$

Look for ν_e appearance in ν_μ off-axis beam: $P(\nu_\mu \to \nu_e)$, compare to $P(\bar{\nu}_\mu \to \bar{\nu}_e)$

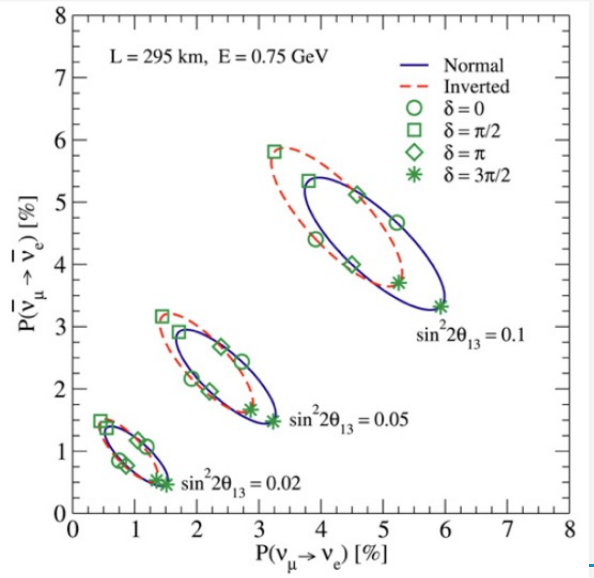
with CP-violation (CP-phase $\delta \neq 0$ or π) and with matter effects (L-dependent):

$$P(\nu_\mu \to \nu_e) \neq P(\bar{\nu}_\mu \to \bar{\nu}_e)$$ (→ still ellipses in bi-event plot)

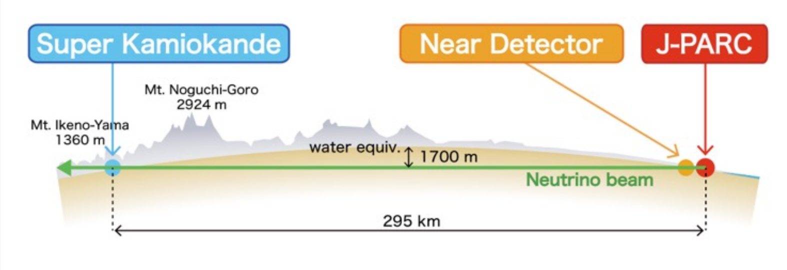


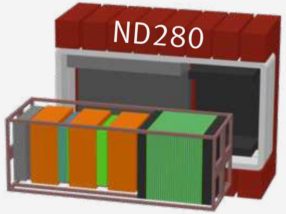
NOνA, 810 km
M.D. Messier,
Nucl. Phys. B 908 (2016) 151

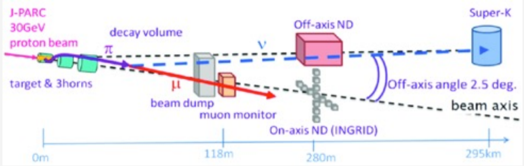
T2K
H. Nunokawa, S. Park,
J.W.F. Valle
Prog. Part. Nucl. Phys.
60 (2008) 338



NOνA, T2K: Search for $\nu_\mu \to \nu_e, \nu_\mu$ and $\bar{\nu}_\mu \to \bar{\nu}_e, \bar{\nu}_\mu$







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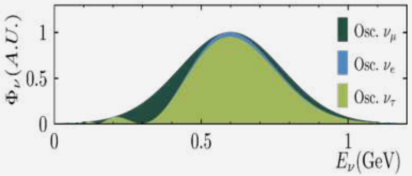
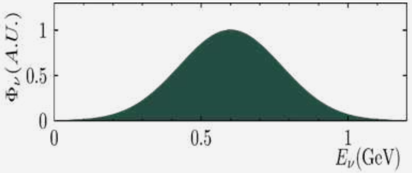
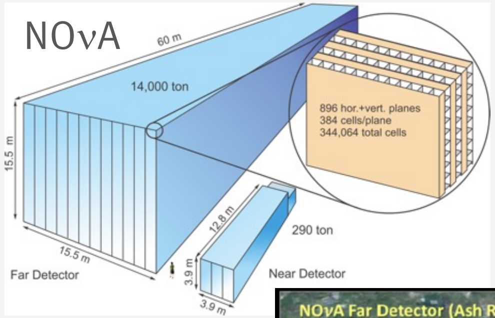
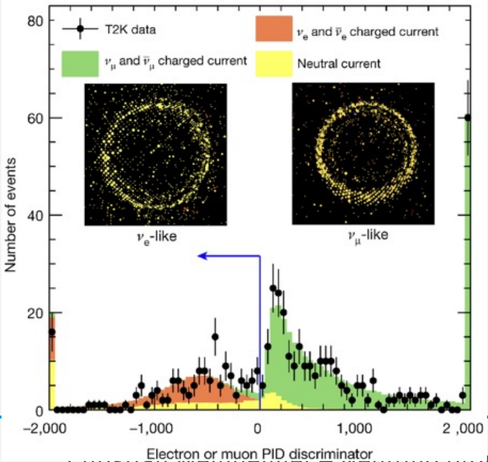
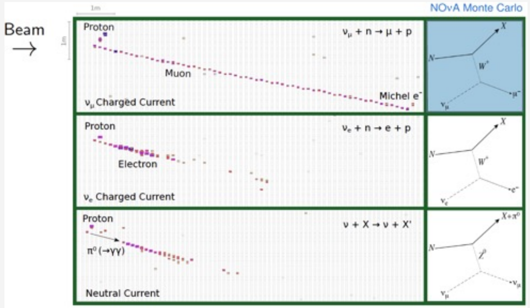




courtesy S. Dolan

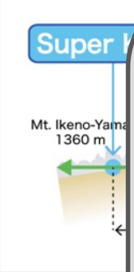


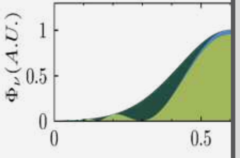




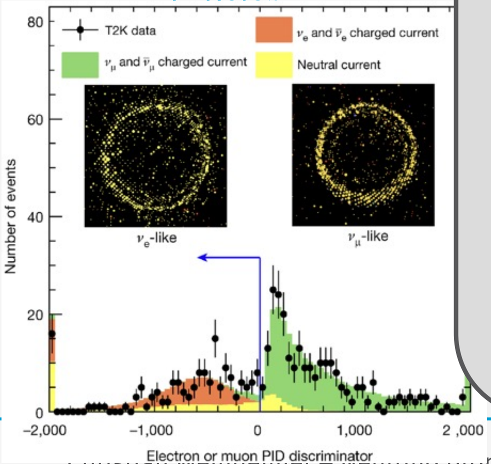
M. Strait, Neutrino Telescopes 2021

NOνA, T2K: Search for $\nu_\mu \rightarrow \nu_\mu$ and $\bar{\nu}_\mu \rightarrow \bar{\nu}_\mu$

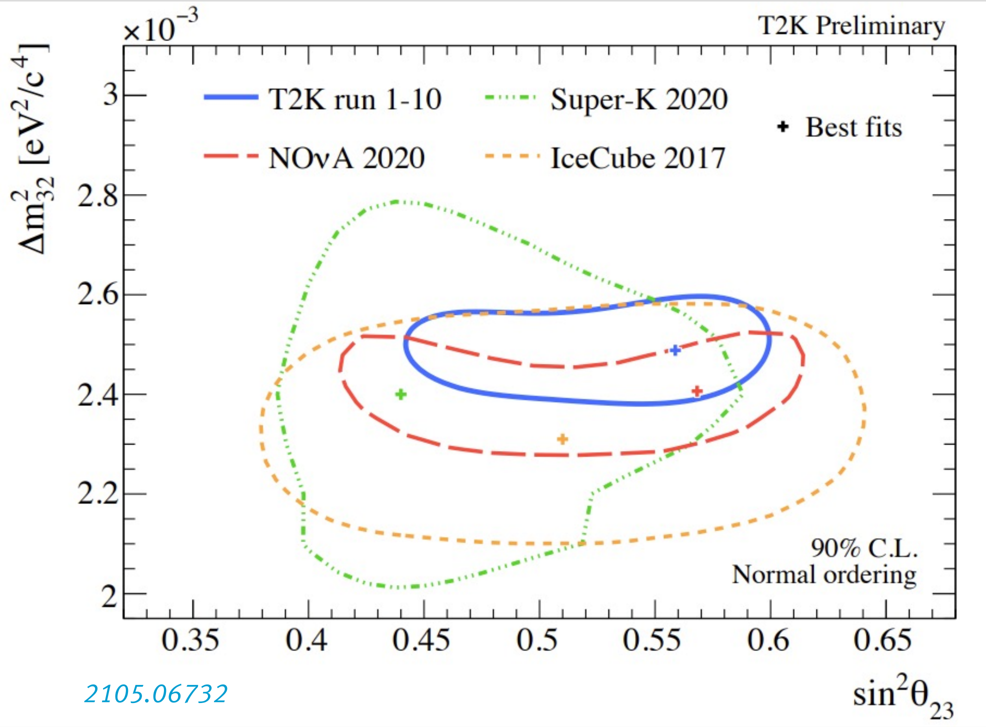




courtesy

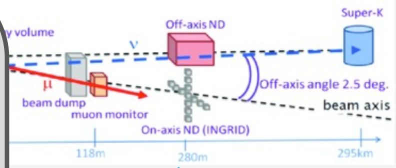


$$N_\mu(E_\nu) = P(\nu_\mu \rightarrow \nu_\mu) \cdot \sigma(E_\nu) \cdot \Phi(E_\nu) \cdot \epsilon(E_\nu)$$



2105.06732

$sin^2\theta_{23}$: degeneracy w.r.t. octant
good agreement among all experiments



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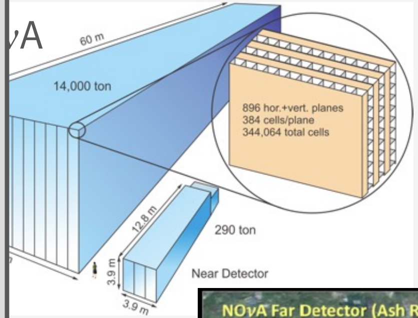
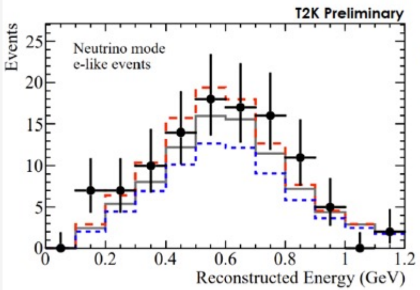
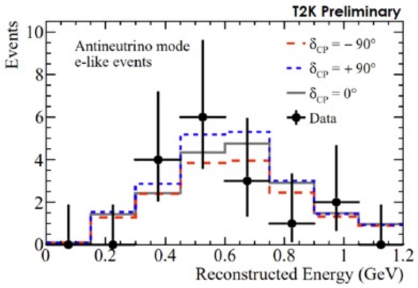


M. Strait, Neutrino Telescopes 2021

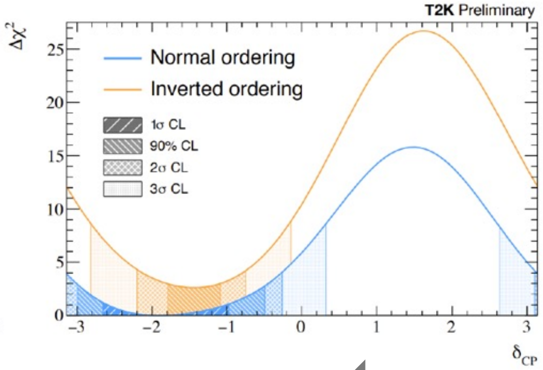
NOνA, T2K: Search for $\nu_\mu \to \nu_e$ & $\bar{\nu}_\mu \to \bar{\nu}_e$ appearance





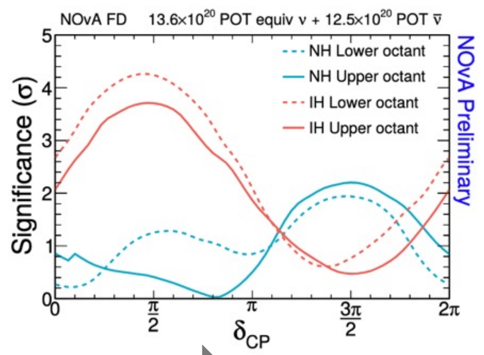
- Large region excluded at 3σ
- CP-conservation (0,±) excluded at 90%
- Weak preference for normal mass ordering

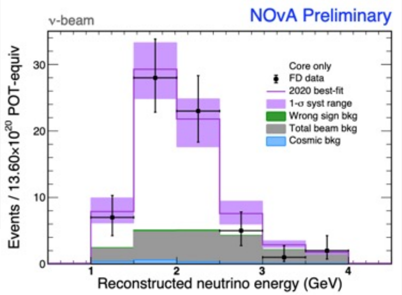
courtesy S. Dolan

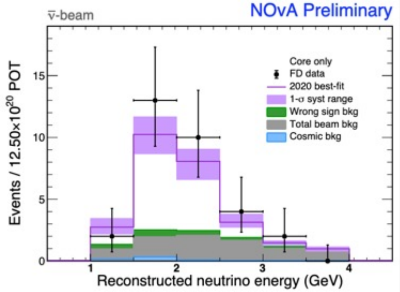


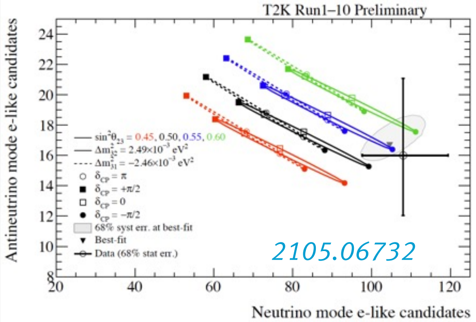
$$N_e(E_\nu) = P(\nu_\mu \to \nu_e) \cdot \sigma(E_\nu) \cdot \Phi(E_\nu) \cdot \epsilon(E_\nu)$$

M. Strait, Neutrino Telescopes 2021









2105.06732

Please note different offset

T2K: runs 1-10, 33% more protons for ν_μ run w.r.t. *Nature 580 (2020) 339*
excludes CP conservation at 90% C.L.

NOnA and T2K: both prefer NO, IO: δ_{CP} in good agreement, NO: some tension w.r.t. δ_{CP}

Discrepancy is statistically not compelling yet !
NOνA and T2K are performing common analysis

NOνA and T2K both are going to increase statistics by factor 2.5
& improve systematics (e.g. upgrade of beam power, ND280, Gd in SK)

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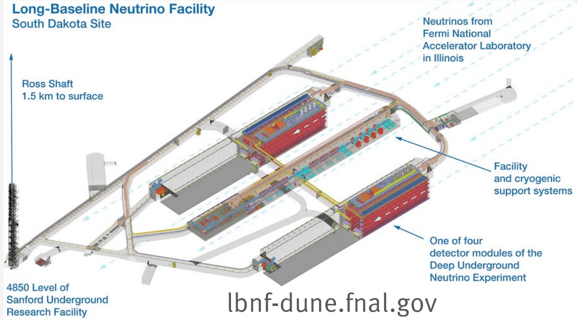
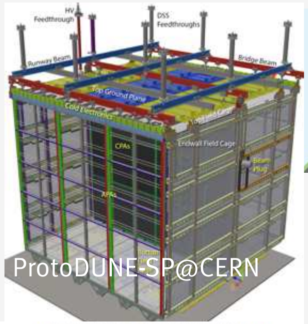
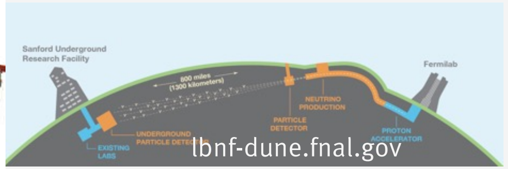
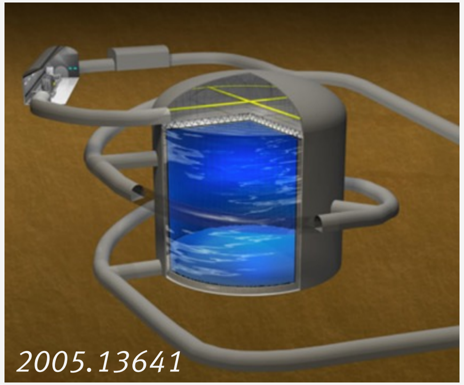
Determination of δ_{CP}: DUNE and Hyper Kamiokande

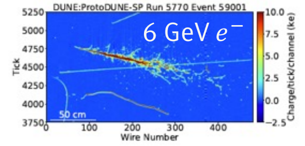








detectors 1,2: each 17 kt LAr
detector 1: vertical drift
detector 2: probably horizontal drift
evacuation started, ν beam in 2029
later THEIA? (water-based liquid scintillation detector: WbLS)



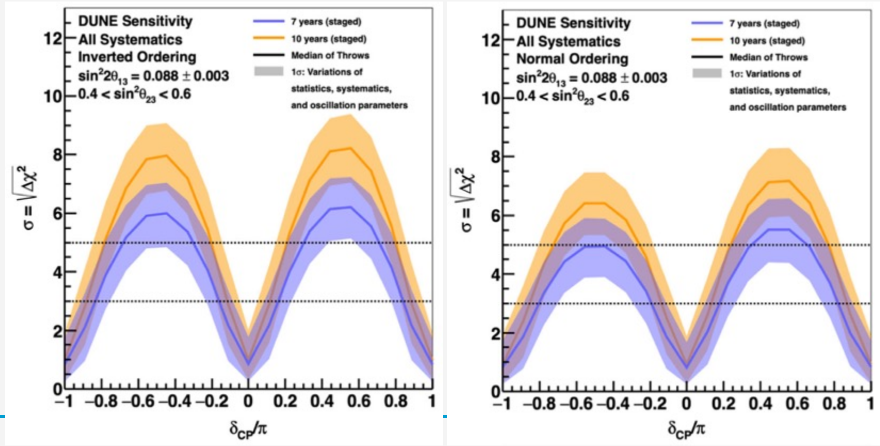
2007.06722

Hyper-Kamiokande: 260 kt water
→ 188kt fiducial (8.4x SK)

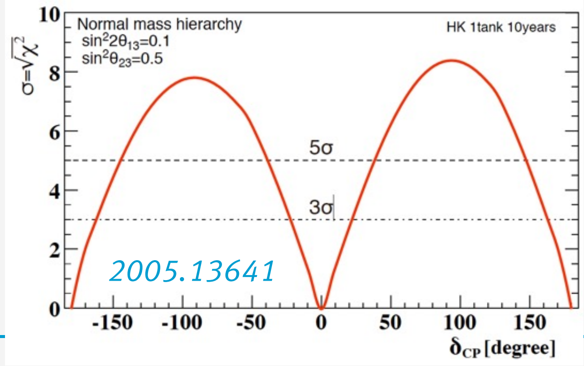
increase beam power: 500 kW → 1.3 MW
increase horn current: 250 kA → 320 kA
→ 10% more neutrinos & less wrong sign

upgrade near detectors, e.g. ND280

P. de Perio, CAP 2021



EPJC (2020) 80, 978



Excavation started
begin water filling & commissioning in 2027

Other physics:
solar ν, nucleon decay, supernova ν, …

JUNO, 20 kT liquid scintillator

Oscillation physics:

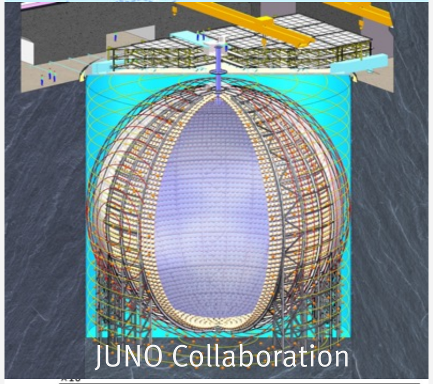
- distinguish mass ordering by 3σ after 6 yrs of exposure, better together with LBL
- improvement of $sin^2 2\theta_{12}$, Δm^2_{21}, $|\Delta m^2_{32}|$ to 0.6% after 6 yrs (2104.02565)
- 2 planned Taishan reactor cores will not be built in the near term → less statistics but compensated nearly by gain in photo-efficiency, linearity and other factors

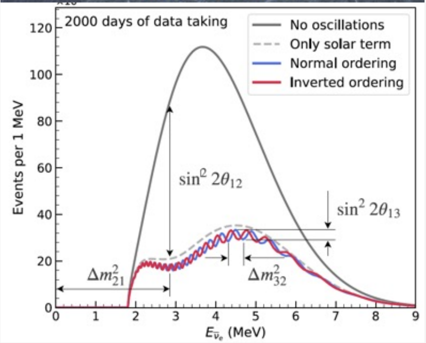
Non-oscillation neutrino physics:

- solar neutrinos: ^{8}B 60k events at 30k bg, helps differentiate low/high metallicity models
- geo neutrinos: down to 5% flux precision
- supernova neutrinos: a few 1000 events (ν_e and $\nu_{\mu,\tau}$) for galactic core-collapse SN
- Diffuse supernova background: 3σ after 10 yrs
- p-decay: expect to improve w.r.t. Super Kamiokande in kaon and possibly other channels

Timeline:

- tunnel und underground hall excavation finished, expected to complete construction end of 2022



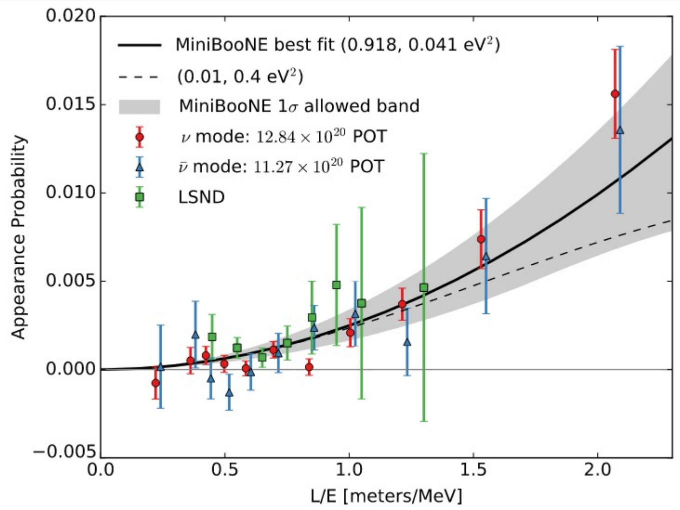


courtesy A. Göttel, and 2104.02565

KM3NeT/ORCA is dedicated to solve the ordering too
6 strings operating, full operation expected in 2025,
R. Shanidze EPS HEP 2021

Short baseline program at Fermilab

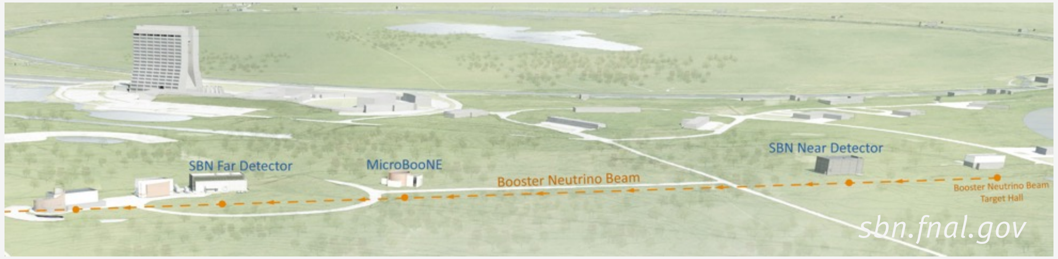
Solve MiniBooNE $\nu_e, \bar{\nu}_e$ appearance signal
"low energy excess of electromagnetic activity"



PRL 121 (2018) 221801

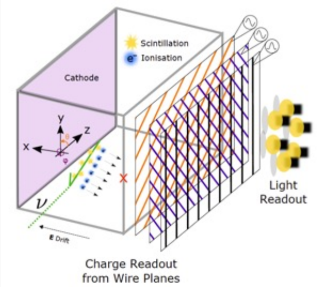
Continue developing LAr TPC technology

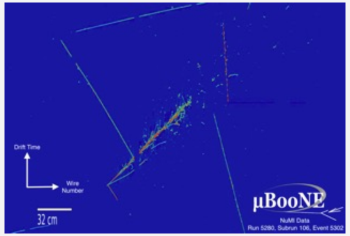
Short baseline program at Fermilab with LAr detectors



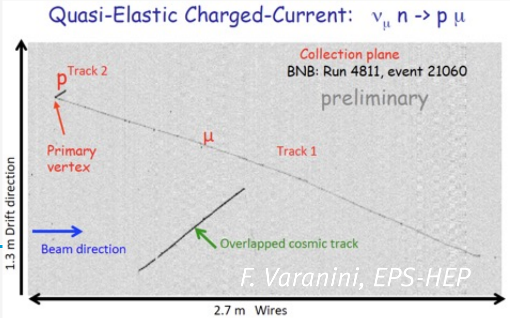
MicroBooNE measured flux-averaged
inclusive $\nu_e, \bar{\nu}_e$ CC total cross section on Ar, excellent PID, e.g. γ/e^-

2101.04228

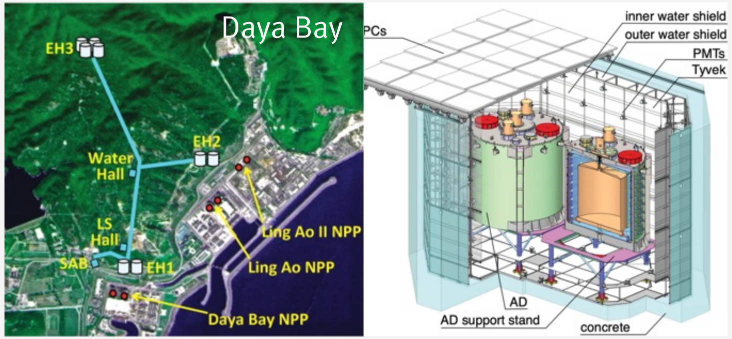


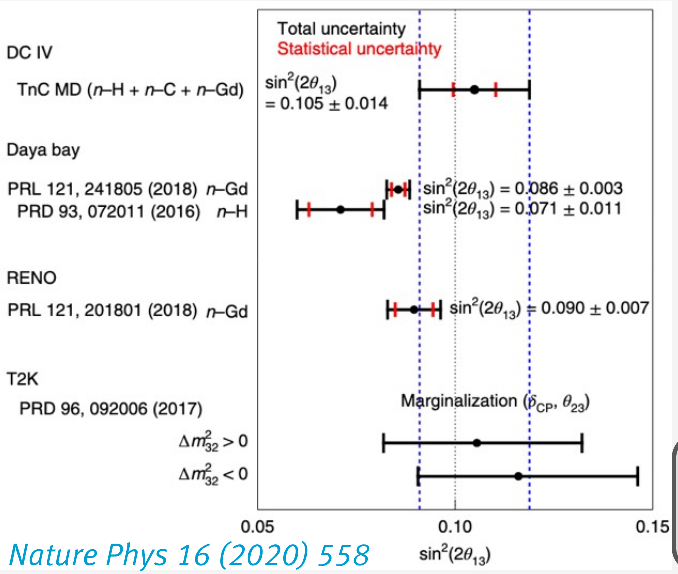


ICARUS has successfully taken first data



"Long baseline" reactor experiments: θ_{13} & more





Nature Phys 16 (2020) 558

Checking LSND/MiniBooNE puzzle in 3+1 scenario with Daya Bay and MINOS/MINOS+:

$$P^{SBL}_{\overset{(-)}{\nu}_\mu \to \overset{(-)}{\nu}_e} = 4|U_{e4}|^2|U_{\mu4}|^2 \sin^2\left(\frac{\Delta m^2_{41} L}{4E}\right)$$

$$4|U_{e4}|^2|U_{\mu4}|^2 = \sin^2 2\theta_{14} \sin^2 \theta_{24} \equiv \sin^2 2\theta_{\mu e}$$

courtesy: R. Mandujano

Constrained by $\overline{\nu}_e$ disappearance (Daya Bay and Bugey-3)

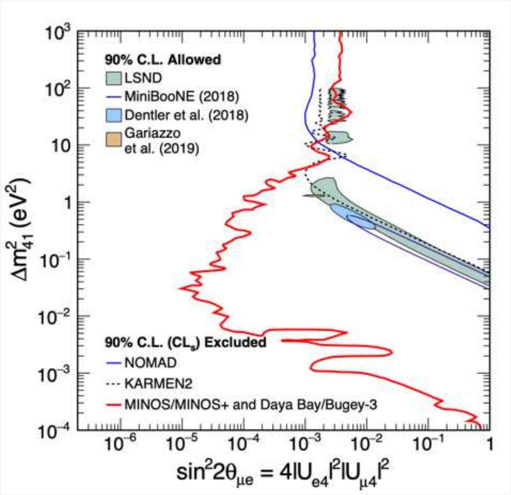
Constrained by $\overset{(-)}{\nu}_\mu$ disappearance (MINOS & MINOS+)

→ exclusion of small Δm_{41} values

T. Schwetz at EPS HEP 2021:
"Sterile oscillation explanation of LSND/MiniBonNE robustly disfavoured"

$$\sin^2\theta_{13} = 0.0220 \pm 0.0007$$

(PDG2021 using Double Chooz, Reno, Daya Bay)



Phys Rev Lett 125 (2020) 07801

New: First MicroBooNE ν_e result

MicroBooNE at similar position in same ν beam as MiniBooNE

Data: February 2016 to July 2018, $7 \cdot 10^{20}$ POT in neutrino mode

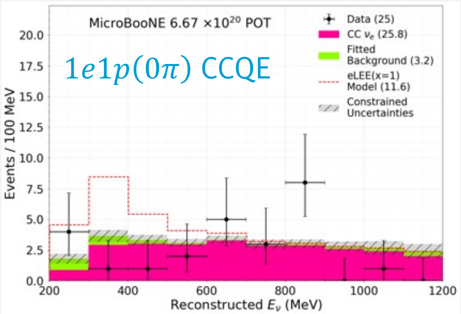
Different channels and different reconstruction methods

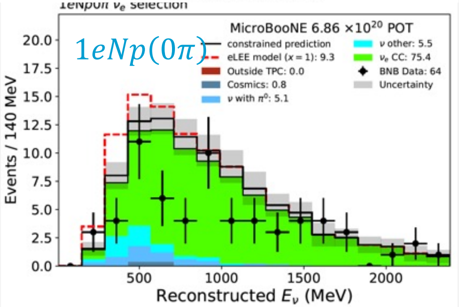
ν_e Final State	Signal Constraints	Reconstruction Approach
$1e1p(0\pi)$ CCQE	ν_μ CCQE	Deep-Learning [55]
$1eN(\geq 1)p0\pi$, $1e0p0\pi$	ν_μ CC	Pandora [56]
$1eX$	ν_μ CC, ν_μ CC π^0, ν_μ NC π^0	Wire-Cell [57]

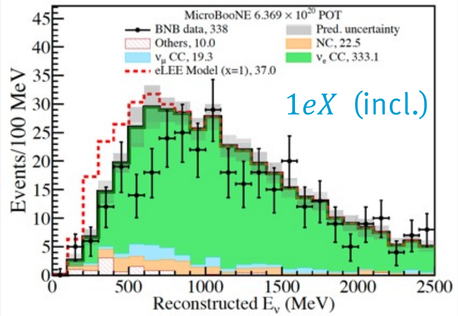
No excess of ν_e with several inclusive and exclusive hadronic final states

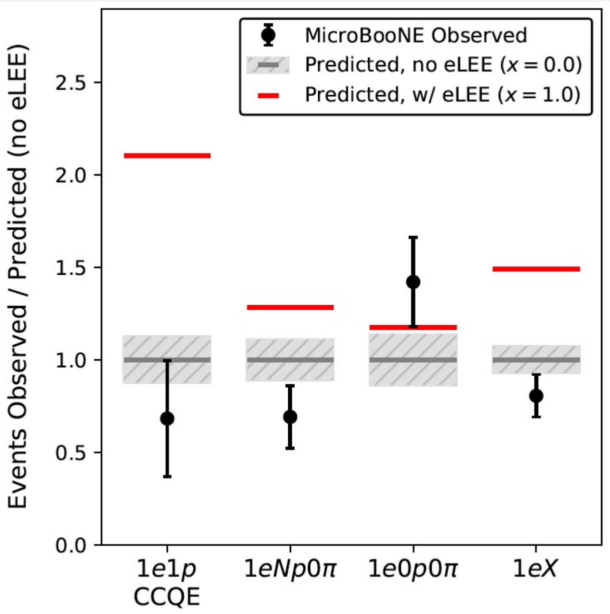
"MicroBooNE results are inconsistent with ν_e interpretation of MiniBooNE excess"

arXiv:2110.14054









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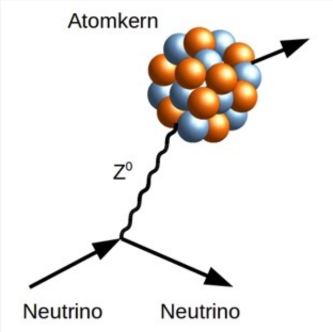
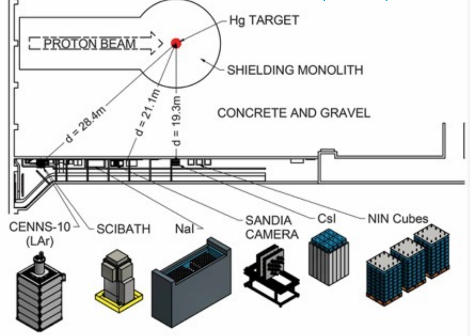
CEνNS: coherent elastic ν nucleon scattering

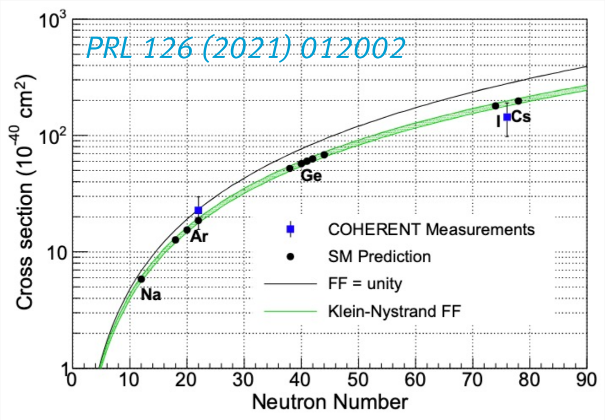
CEνNS observed on argon by COHERENT



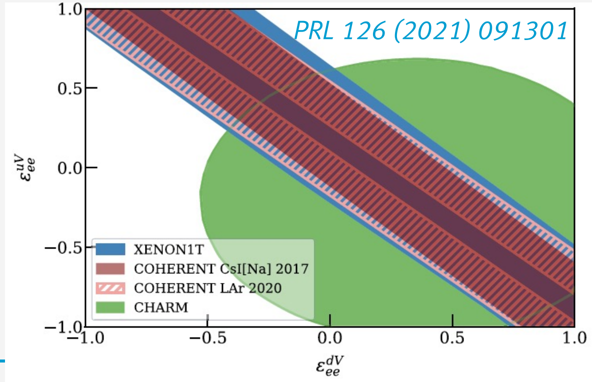
www.mpi-hd.mpg.de

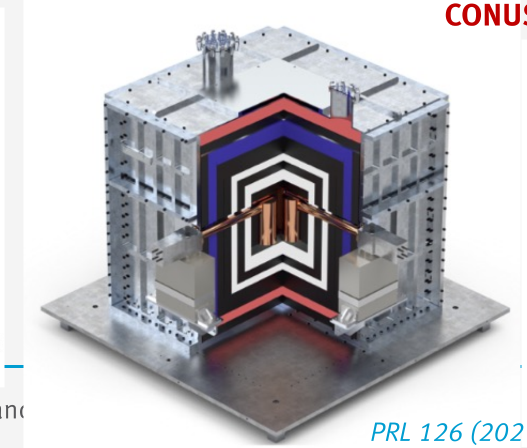
Science 337 (2017) 1123





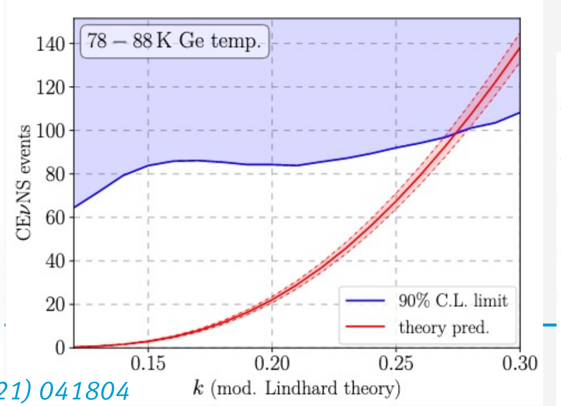
CEνNS open a new window for searching for BSM physics: NSI, Dirac vs Majorana





CONUS limit

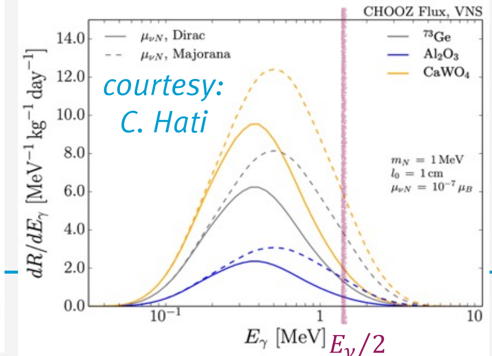
CEνNS upper limit on Ge



PRL 126 (2021) 041804

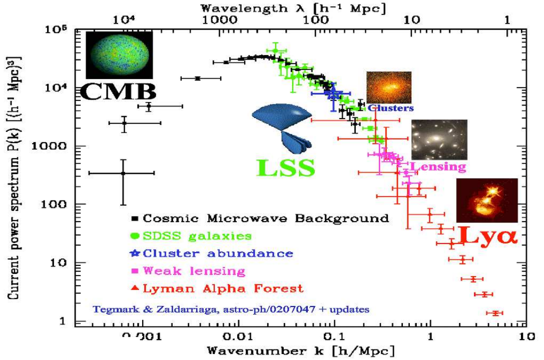
NUCLEUS@CHOOZ

e.g. differentiate Dirac/Majorona ν in radiative CEνNS

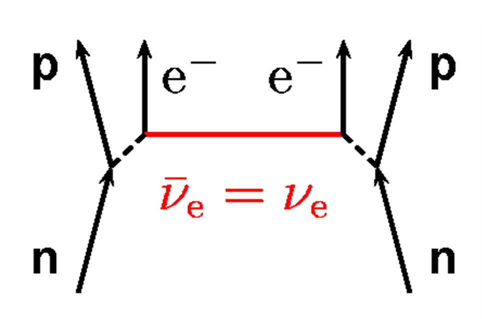


Three complementary ways to the absolute neutrino mass scale

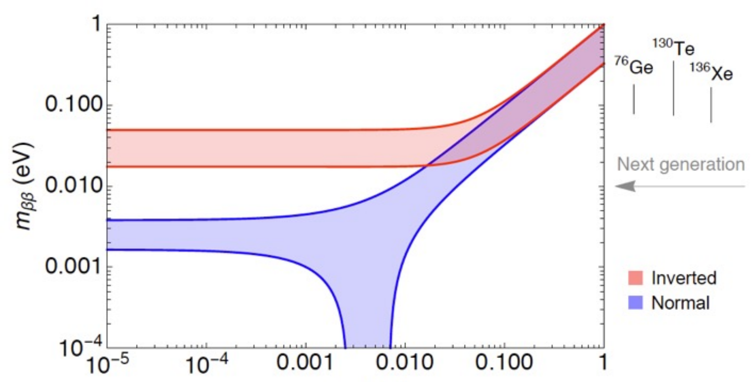
1) **Cosmology:** $\sum_i m(\nu_i) = 3 \cdot \overline{m(\nu_i)}$
very sensitive, but model dependent, compares power at different scales
current upper limit: $\sum_i m(\nu_i) \approx$ 0.12 eV (CMB+BAO)
not far from minimal values for 60 meV (NO), 100 meV (IO)



2) **Search for 0νββ:** $m_{\beta\beta} := \left|\sum_i U_{ei}^2 \cdot m(\nu_i)\right|$
sensitive to Majorana neutrinos only, nuclear matrix elements
upper limits by EXO-200, KamLAND-Zen, GERDA, CUORE
disclaimer: $m_{\beta\beta}$ are valid only, if 0νββ works dominantly via ν exchange
Discovery of 0νββ would proof lepton number violation !



$$T_{1/2}^{0\nu} \propto \begin{cases} a \cdot \varepsilon \cdot M \cdot t & \text{for background index } B = 0 \\ a \cdot \varepsilon \cdot \sqrt{\frac{M \cdot t}{B \cdot \Delta E}} & \text{for } B \neq 0 \end{cases}$$



Y. Müller EPS HEP 21

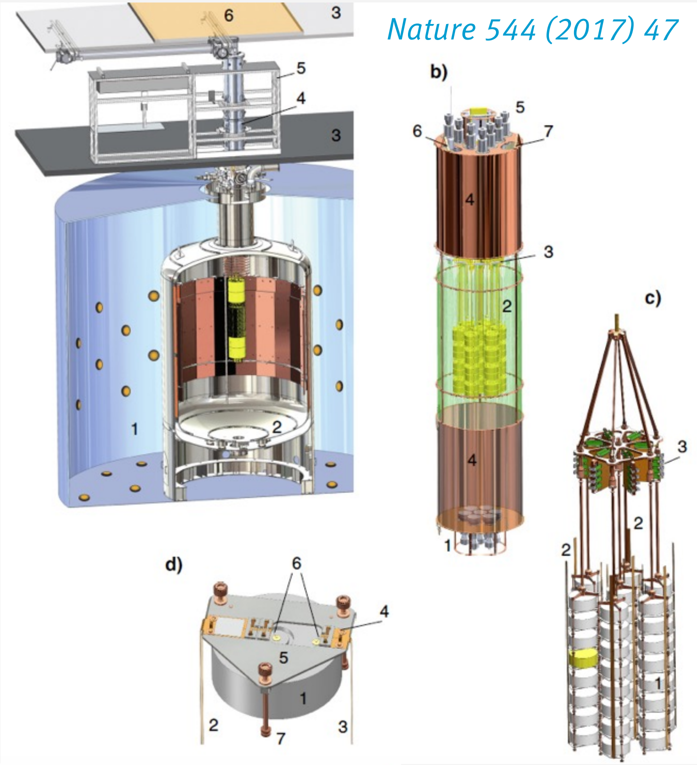
GERDA at LNGS – final result

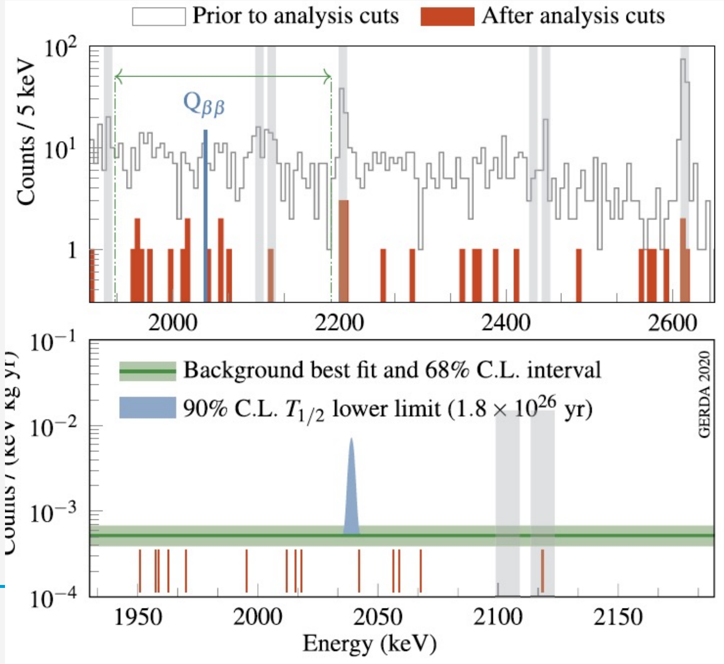
enrichment of ^{76}Ge: $\approx 87\%$
exposure: 127.2 kg*yr
energy resolution: $\approx$ 3 keV (FWHM)
background index: $B = 5.2^{+1.6}_{-1.3} \cdot 10^{-4}$ counts/(keV kg yr)

➞ lower limit: $\boldsymbol{T^{0\nu}_{1/2} > 1.8 \cdot 10^{26}}$ **yr (90% C.L.)**

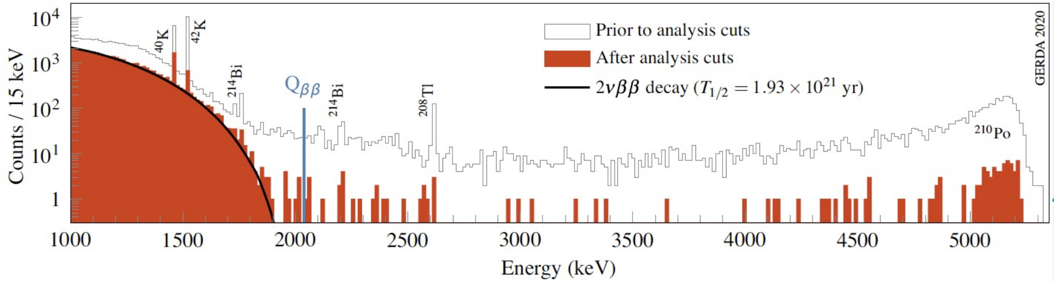
➞ upper mass limit: $\boldsymbol{m_{\beta\beta} < 79 - 180}$ **meV** (without g_A quenching)

Nature 544 (2017) 47





PRL 125 (2020) 252502



^{76}Ge: LEGEND-200 at LNGS and LEGEND-1000

WWU MÜNSTER

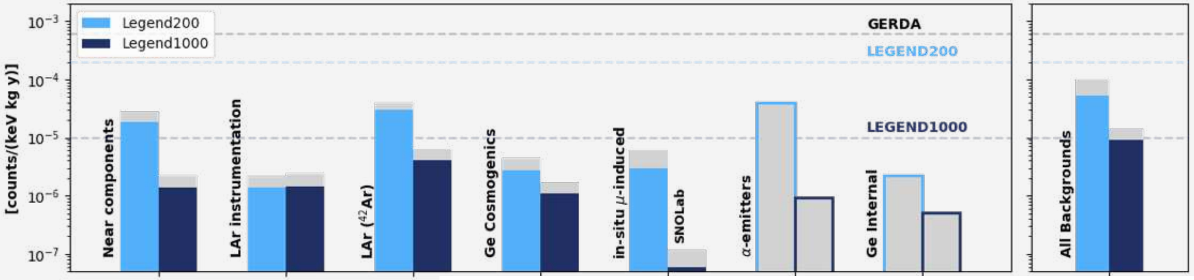
based on GERDA+Majorana technologies

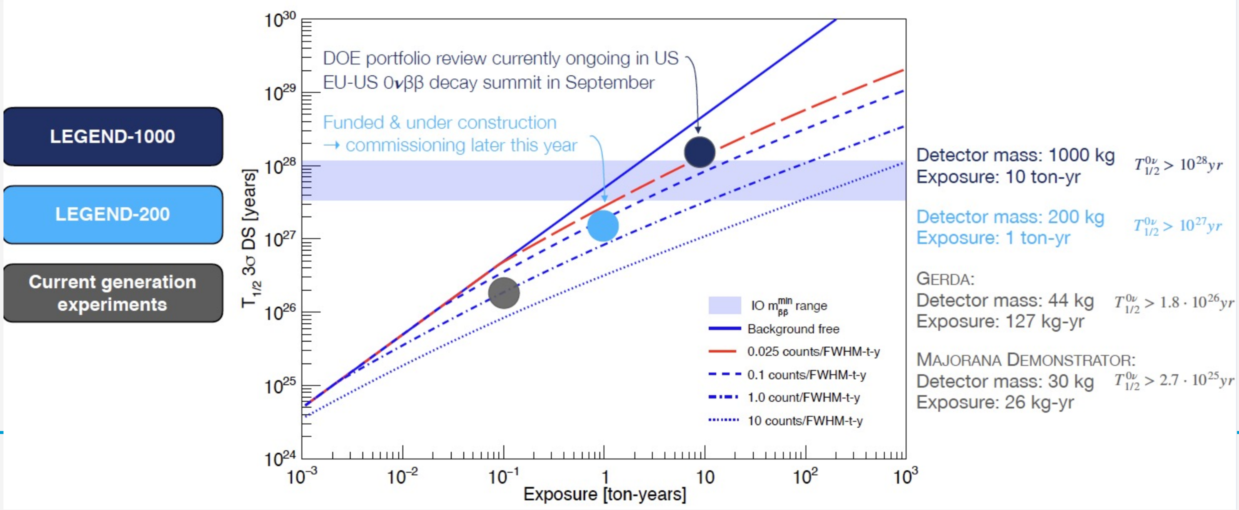
enriched ^{76}Ge, PPC/BEGe/ICPC detectors (→event topology)

LEGEND-200: start data taking (140-150 kg) still in 2021

upgrade by another 50 kg in 2022

LEGEND -1000: future plan, PCDR 2107.11462





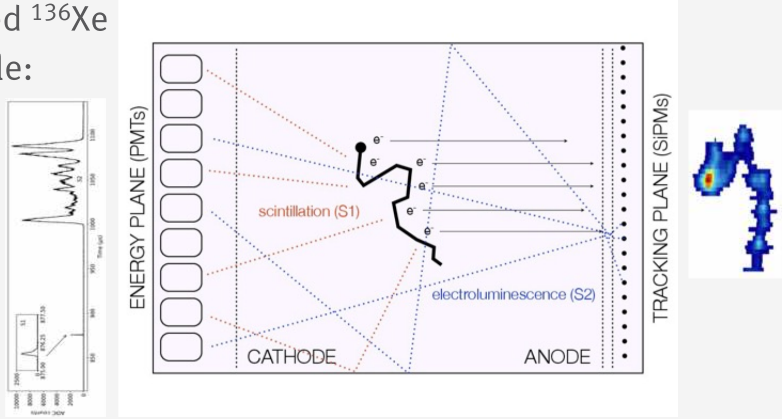
M. Willers, EPS HEP 2021

Future of xenon-based 0νββ experiments

NEXT: GXe TPC

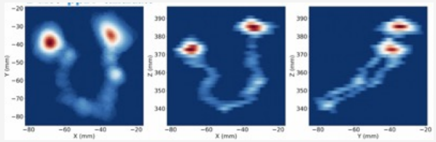
enriched ^{136}Xe

principle:

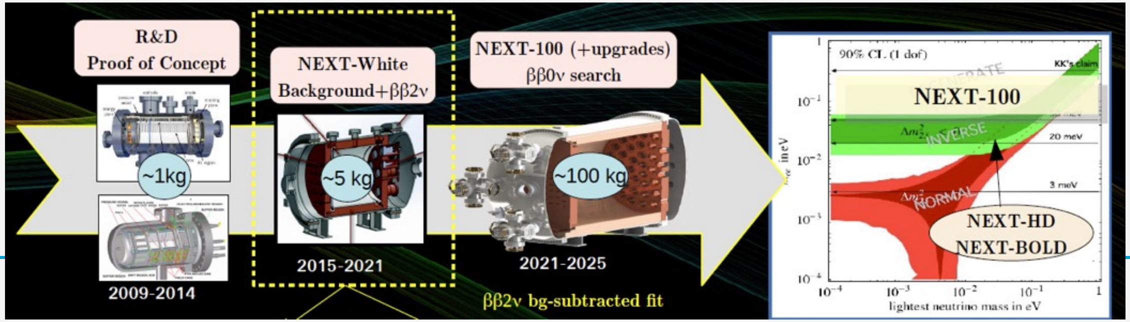


advantage of GXe TPC: 2-times better energy resolution

topology of ββ event

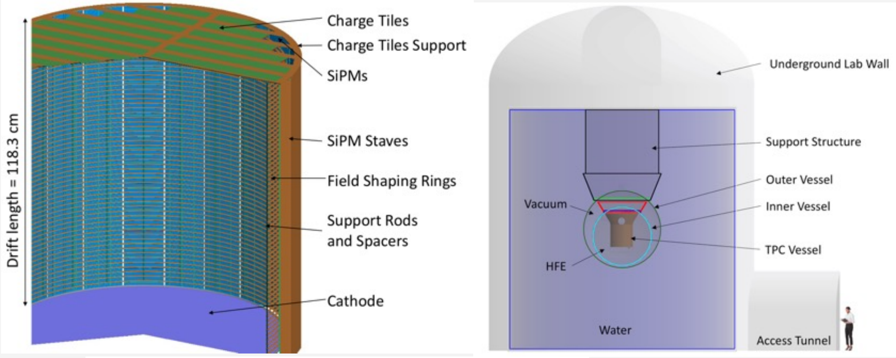


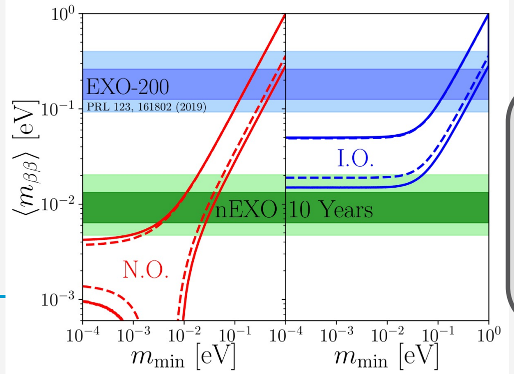
P. Novella, EPS HEP 2021



nEXO: LXe TPC

enriched ^{136}Xe:	5 t
energy resolution:	≈ 46 keV (FWHM)
background index:	$B = 7 \cdot 10^{-5}$ counts/(FWHM kg yr)
→ **expected sensitivity (10 yr):**	$T^{0\nu}_{1/2} > 1.35 \cdot 10^{28}$ **yr (90% C.L.)**
→ **expected sensitivity (10 yr):**	$m_{\beta\beta} < 5 - 20$ **meV**





2106.16243

The dark matter experiments DARWIN will have a sensitivity of $2.4 \cdot 10^{27}$ yr, EPJC 80 (2020) 808

J. Masbou, EPS HEP 2021

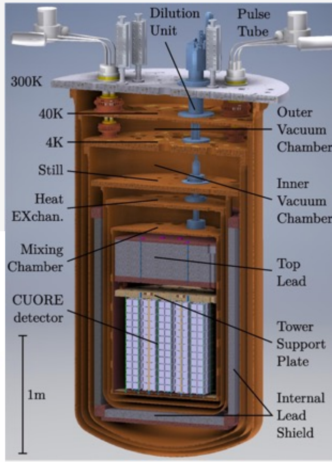
CUPID in CUORE cryostat at LNGS

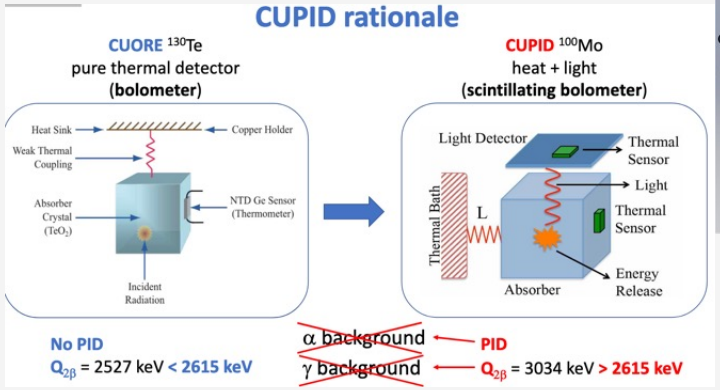
WWU MÜNSTER

enrichment of ^{100}Mo: 95%
mass (^{100}Mo) in $Li_2{}^{100}MoO_4$: 240 kg
energy resolution: 5 – 7 keV (FWHM)
background index: $B = 1 \cdot 10^{-4}$ counts/(keV kg yr)

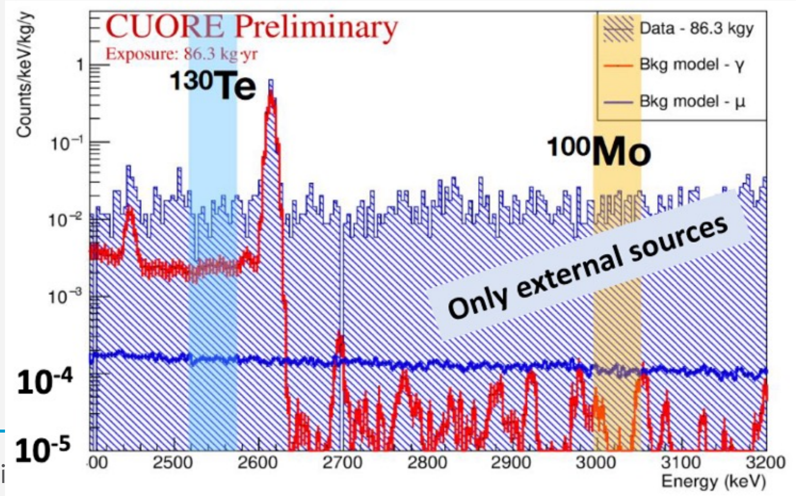
→ exp. sensitivity (10yr): $T^{0\nu}_{1/2} > 1.4 \cdot 10^{27}$ yr (90% C.L.)

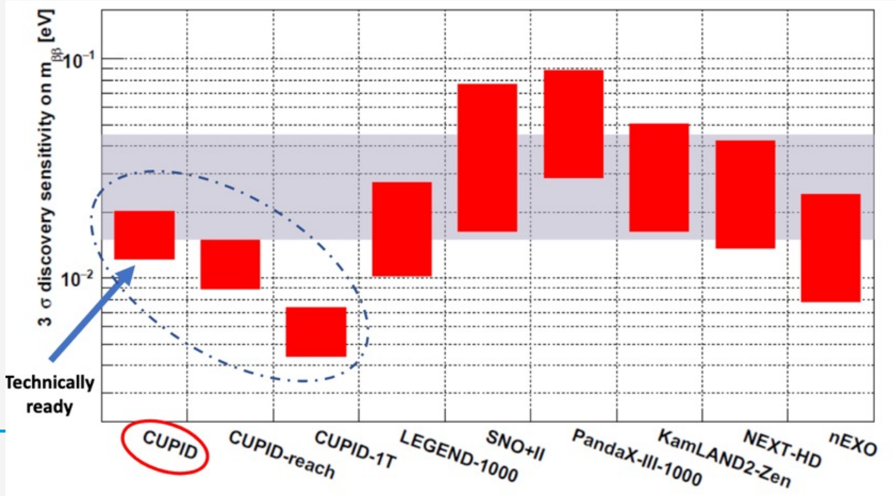
→ exp. sensitivity (10yr): $m_{\beta\beta} < 10 - 17$ meV





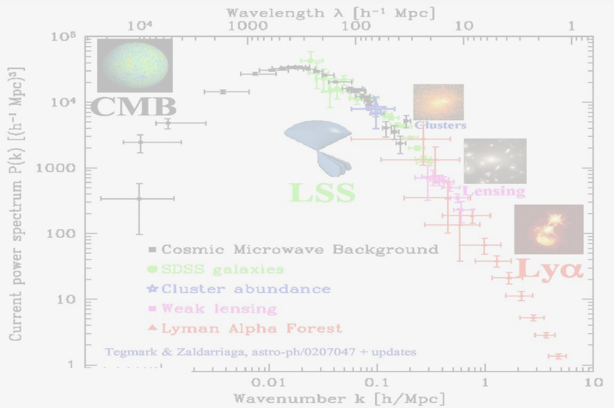
A. Guiliani, Neutrino Telescopes 2021





Three complementary ways to the absolute neutrino mass scale

WWU MÜNSTER



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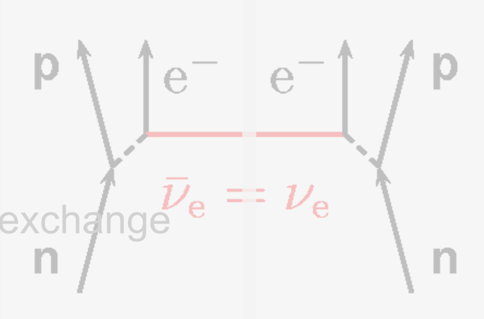
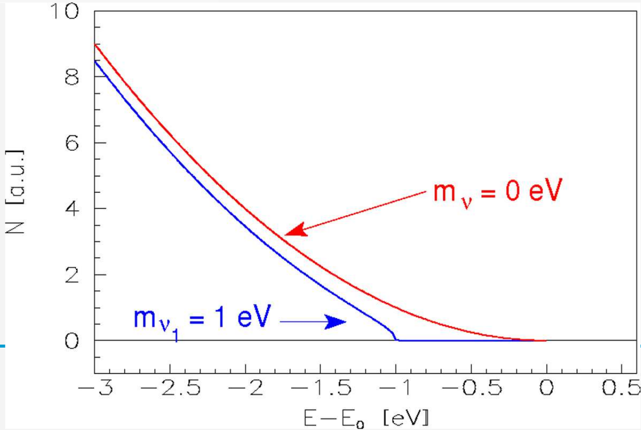


3) **Direct neutrino mass determination:** $m^2(\nu_e) \coloneqq m_\beta^2 \coloneqq \sum_i |U_{ei}|^2 \cdot m^2(\nu_i)$
no further assumptions needed, use $E^2 = p^2c^2 + m^2c^4 \rightarrow m^2(\nu)$
Time-of-flight measurements (ν from supernova)
Kinematics of weak decays / beta decays, e.g. tritium, ^{163}Ho
measure charged decay prod., E-, p-conservation



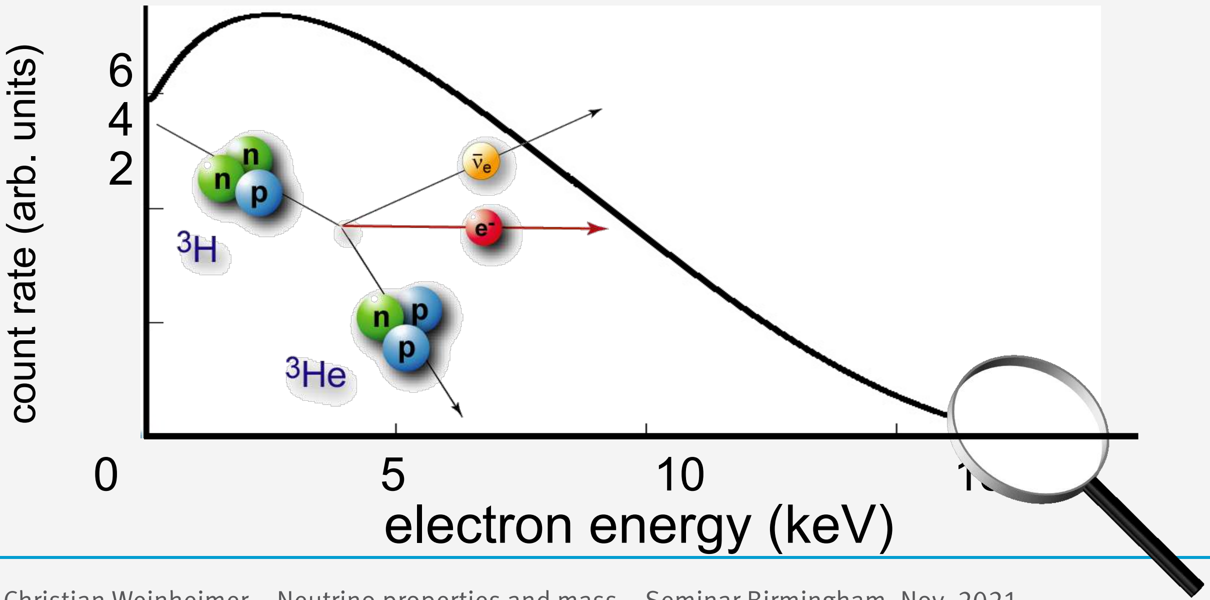
Direct determination of "$m(\nu_e)$" from β-decay (EC)

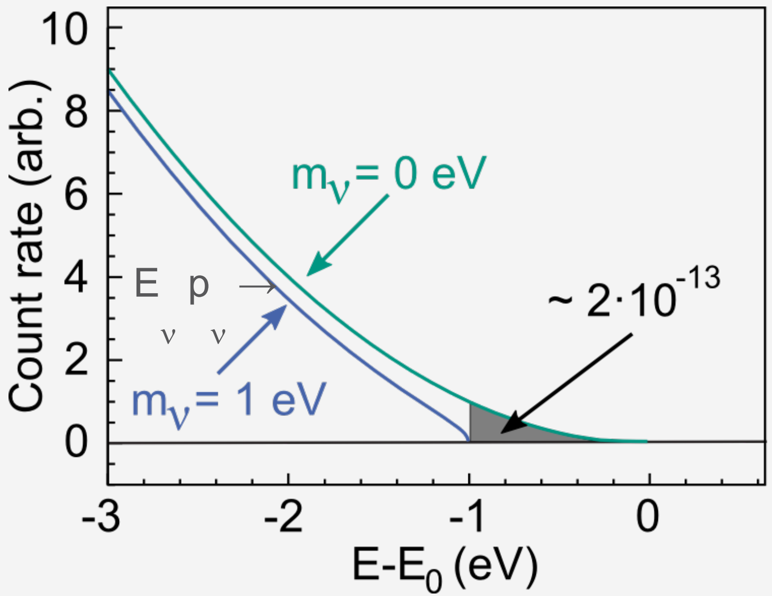
$$\beta: \frac{dN}{dE} = K \cdot F(E,Z) \cdot p \cdot E_{tot} \cdot (E_0 - Ee) \cdot \sum_i |U_{ei}|^2 \cdot \sqrt{(E_0 - E_e)^2 - m^2(\nu_i)}$$

essentially phase space: p_e E_e E_ν p_ν

with "electron neutrino mass": $"m^2(\nu_e)" := \sum_i |U_{ei}|^2 \cdot m^2(\nu_i)$, complementary to 0νββ & cosmology

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





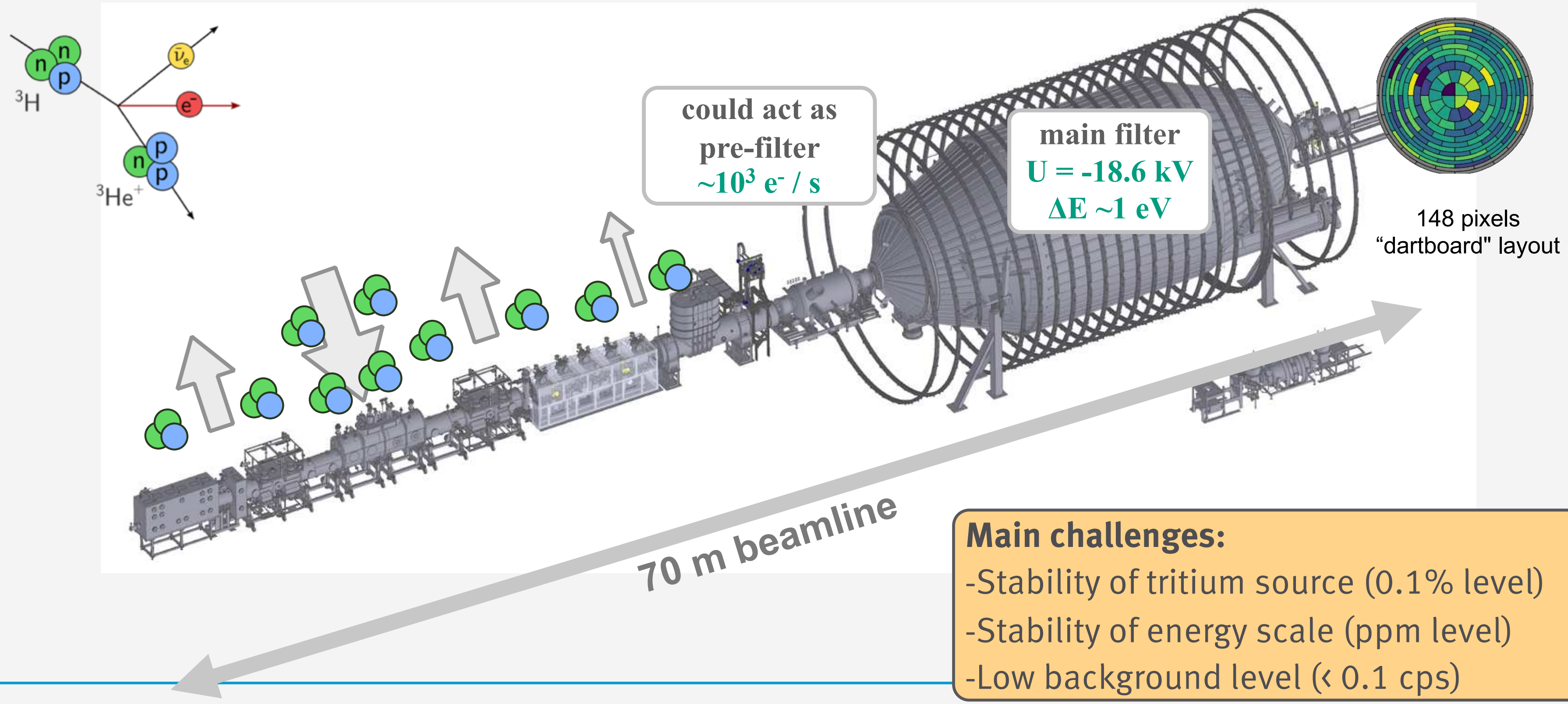
The KArlsruhe TRItium Neutrino experiment KATRIN

windowless gaseous T_2 source
10^{11} e⁻ / s

tritium pumping & e⁻ transport
T_2 flow reduction $>10^{14}$

high-pass energy filters
MAC-E filter

counting detector
< 1 e⁻ / s



Main challenges:
- Stability of tritium source (0.1% level)
- Stability of energy scale (ppm level)
- Low background level (‹ 0.1 cps)

The KArlsruhe TRItium Neutrino experiment KATRIN

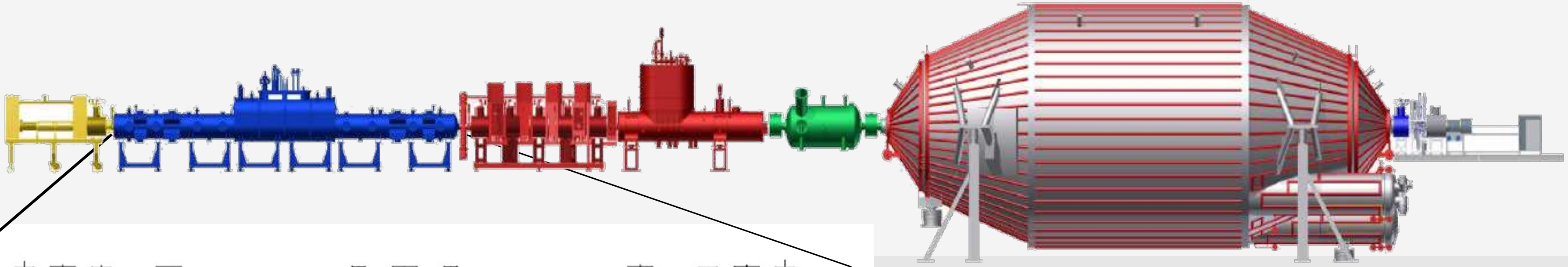
The international KATRIN Collaboration: 150 people from 20 (6) instituions (countries)

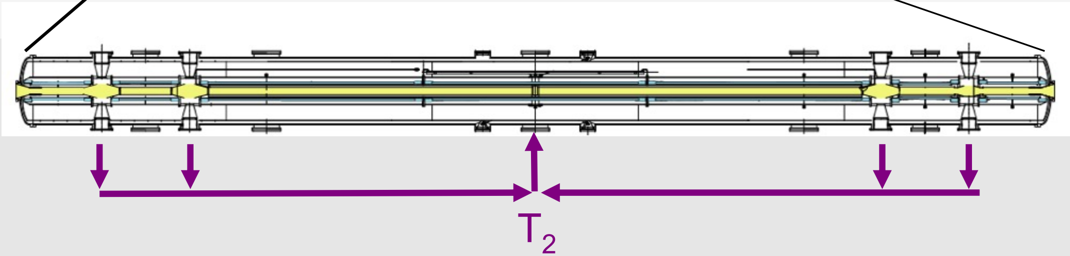
KIT Karlsruhe Institute of Technology
WWU MÜNSTER
CENPA
cea
Max-Planck-Institut für Physik
TUM
universität bonn
universität mainz
MIT
THE UNIVERSITY of NORTH CAROLINA at CHAPEL HILL
Berkeley Lab
Max-Planck-Institut für Kernphysik
Carnegie Mellon University
Humboldt-Universität zu Berlin
CASE WESTERN RESERVE UNIVERSITY EST. 1826
BERGISCHE UNIVERSITÄT WUPPERTAL

Funded by:

Bundesministerium für Bildung und Forschung
HELMHOLTZ GEMEINSCHAFT
DFG
MAX-PLANCK-GESELLSCHAFT
DEPARTMENT OF ENERGY UNITED STATES OF AMERICA
Czech Republic: MŠMT MINISTRY OF EDUCATION YOUTH AND SPORTS
Russian Academy of Sciences Founded in 1724

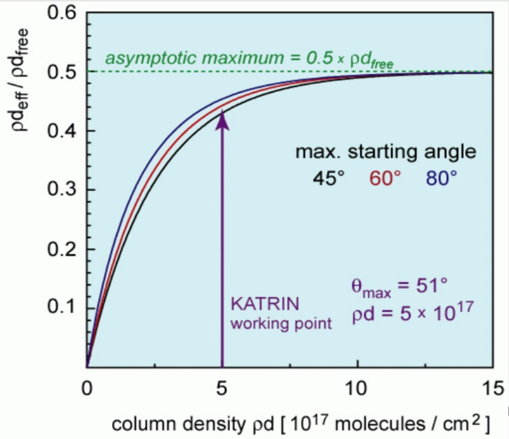
The Windowless Gaseous Molecular Tritium Source





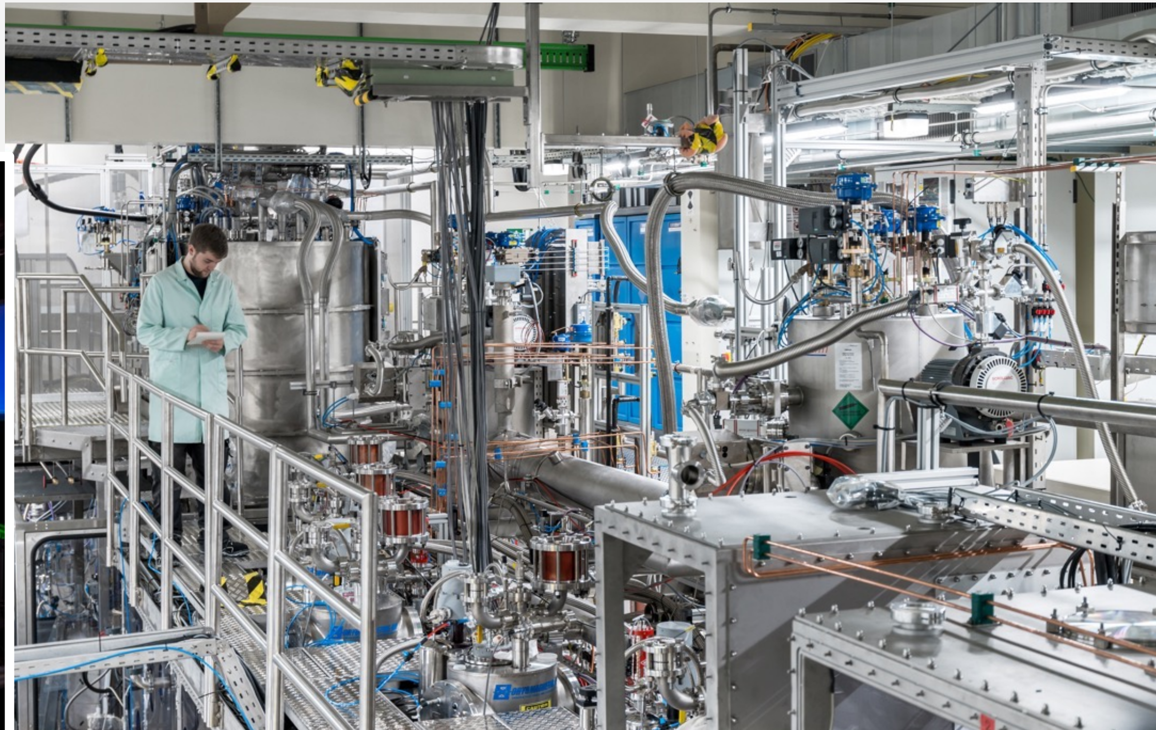
column density $5\cdot10^{17}$ T_2/cm^2 luminosity $1.7\cdot10^{11}$ Bq

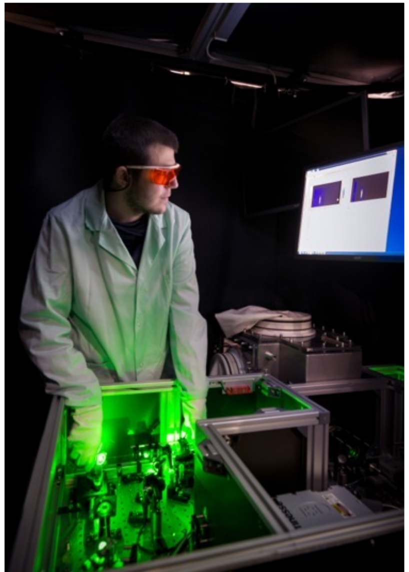
beam tube	Ø = 9 cm , L = 10 m
guiding field	3.6 T (2.52 T)
temperature	T = 30 K ± 30 mK (80 K),
T_2 flow rate	$5\cdot10^{19}$ molecules/s (40 g of T_2 / day)
T_2 purity	95% ± 0.1 %
T_2 inlet pressure	10^{-3} mbar ± 0.1 %



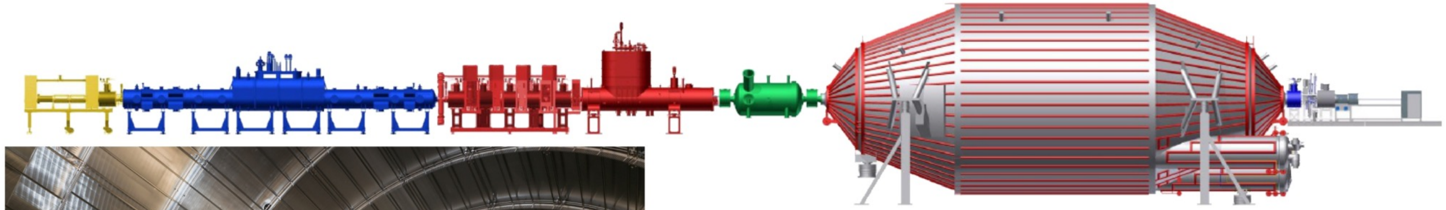

WGTS at Tritium Laboratory Karlsruhe

Photos: source & transport section





The main spectrometer: an integrating high resolution MAC-E Filter



-18.6 kV retardation voltage, σ < 60 mV/years

energy resolution (0% → 100% transmission): 0.93 (2.7) eV

Ultra-high vacuum, pressure < 10^{-11} mbar

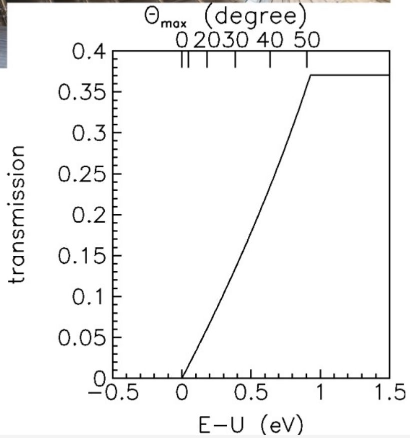
Precision voltage (ppm) at vessel and double layer wire electrode system for background reduction and field shaping

Air coils for earth magnetic field compensation

→ integral transmission function:

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

= 0.93 eV (2.7 eV)



The KATRIN electron detector FPD

Focal plane detection system

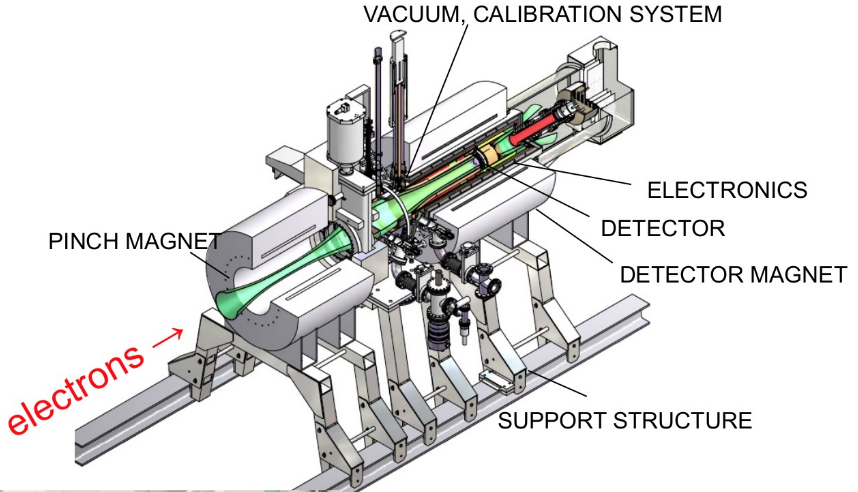
segmented Si PIN diode:
90 mm Ø, 148 pixels, 50 nm dead layer

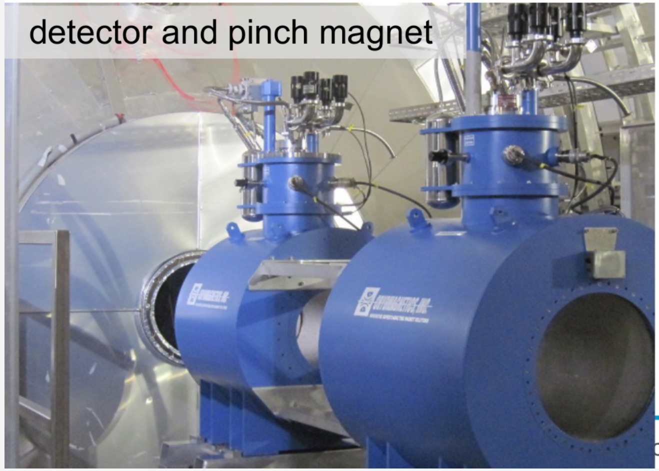
energy resolution ≈ 1 keV

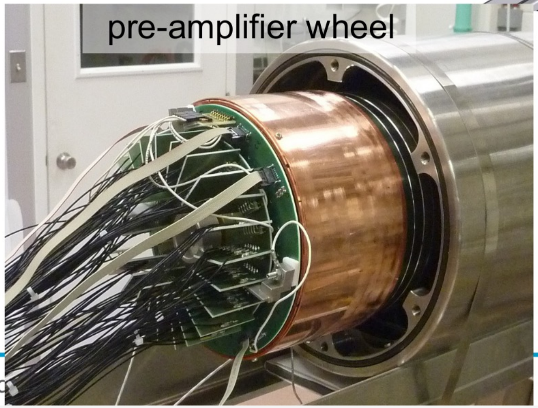
pinch and detector magnets up to 6 T

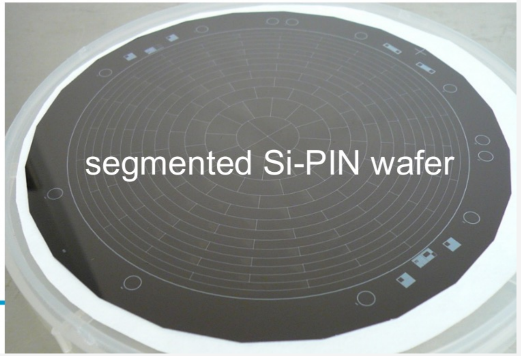
post acceleration (10kV)

active veto shield

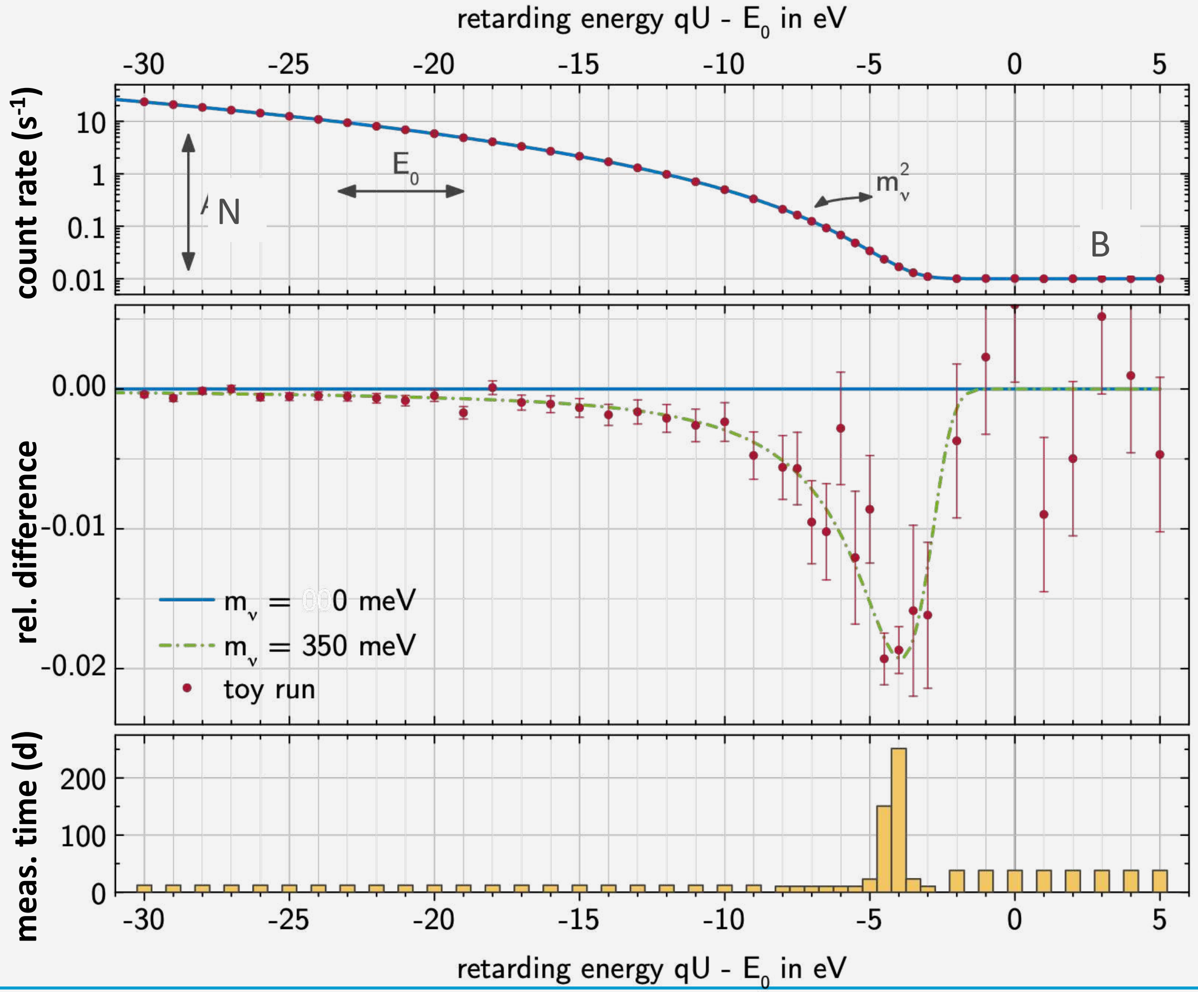








The measurement principle



Direct **shape** measurement of **integrated β spectrum**
Four fit parameters:

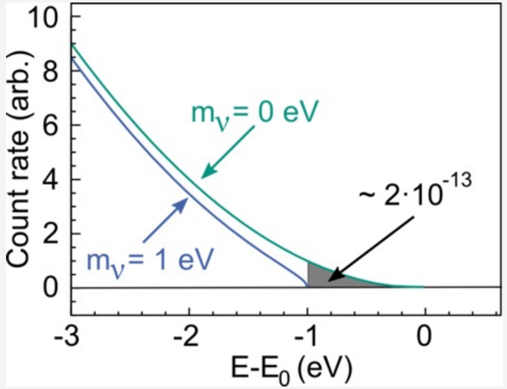
spectrum norm. **N**	spectrum endpoint **E_0**
background rate **B**	squared mass **m^2_ν**

~10^{-8} of all β-decays in scan region ~40 eV below endpoint

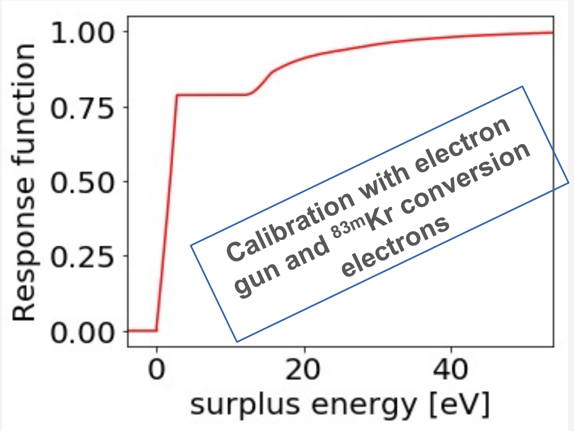
EPJ C 79 (2019) 204

Model of the experimental spectrum

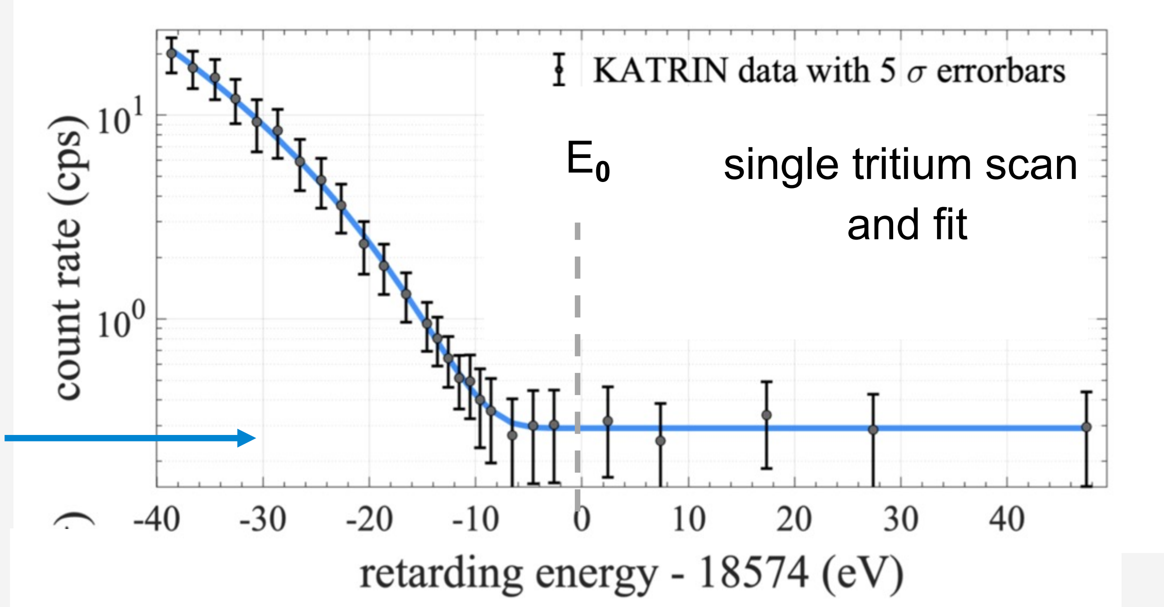
- **Beta spectrum: $R_\beta(E,m^2(\nu_e))$**



- **Experimental response: f(E-qU)**



$\otimes$

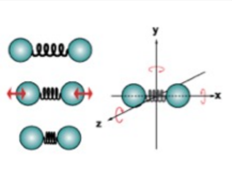


$$R(qU) = A_s \cdot N_T \int_{qU}^{E_0} R_ß(E, m^2(\nu_e)) \cdot f(E - qU)\, dE + R_{bg}$$

PRL 123 (2019) 221802, EPJ C 79 (2019) 204
+ detailed analysis PRD 104 (2021) 012005
+ energy loss measurement EPJ C 81 (2021) 579

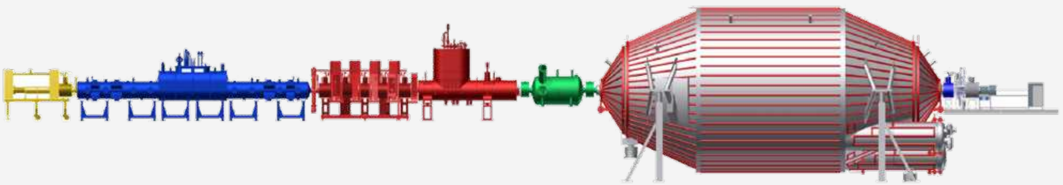
Systematic effects and uncertainties

Molecular final states
-quantum-chemical
-computations



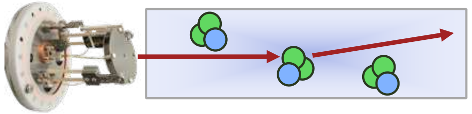
Source electric potential
-plasma properties
-surface conditions

Magnetic fields
-source
-spectrometer
-detector



Detection efficiency

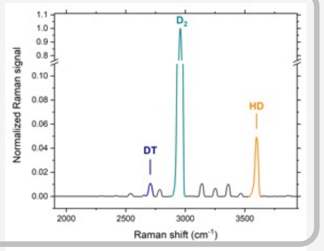
Energy loss by scattering



EPJ C 79 (2019) 204
EPJ C 81 (2021) 579

Activity fluctuations
-column density
-tritium (T_2, DT, HT)
-concentration

Sensors 20 (2020) 4827



Background
-dependence on retarding potential
-time structure due to trapped electrons

arXiv:2011.05107

Three complementary strategies to include systematics in the fit:
(a) covariance matrix, (b) Monte-Carlo propagation, (c) pull-term method

see PRL 123 (2019) 221802 + detailed analysis PRD 104 (2021) 012005

First neutrino mass result

1^{st} science run of KATRIN in spring 2019

- ν-mass: best fit result

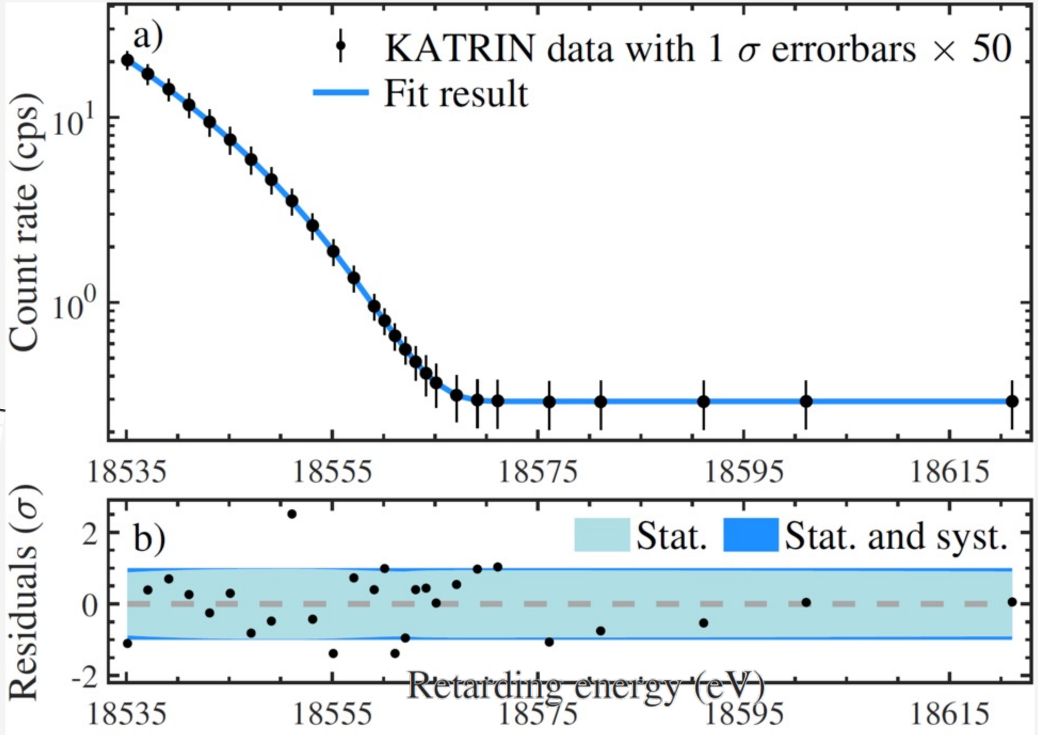
  $m^2(\nu_e) = -1.0^{+0.9}_{-1.1}$ eV²

- ν-mass: new upper limit

  $m(\nu_e) < 1.1$ **eV (90% C.L. Lokhov – Tkachov)**

  $m(\nu_e) < 0.8$ eV (90% C.L. Feldman-Cousins)

  $m(\nu_e) < 0.9$ eV (90% C.L. Bayesian, flat prior m^2>0



Excellent data quality

Compared to previous experiments:

- Improvement of statistics (x2)
- Reduction of systematics (÷6)

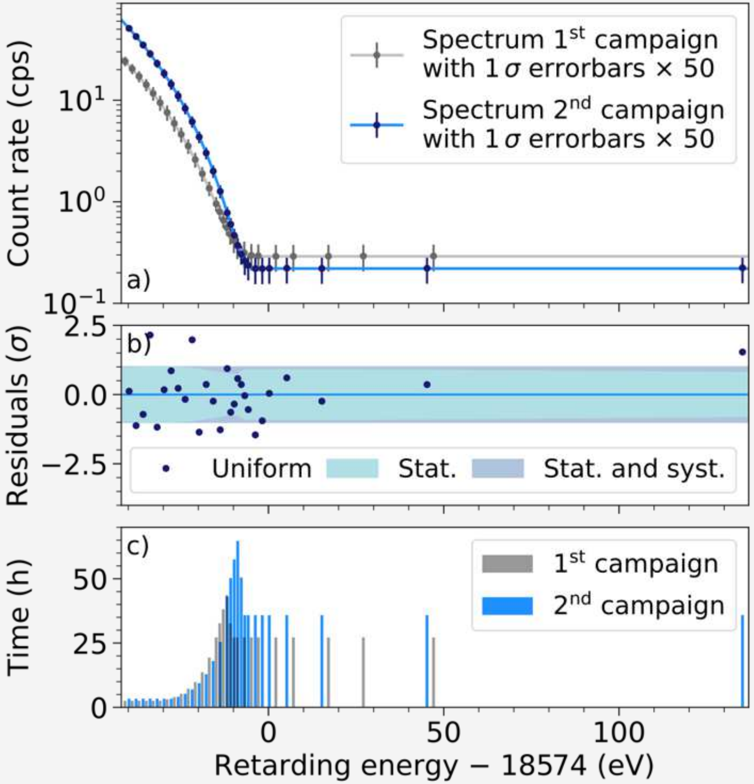
Only 9 days out of 1000 live days!

PRL 123 (2019) 221802 + detailed analysis PRD 104 (2021) 012005

Improvements of 2nd campaign compared to 1st one

	1st campaign PRL 123 (2019) 221802	2nd campaign This talk, arXiv:2105.08533
Campaign date	April-May 2019	Sept-Nov 2019
Total scan time	522 h (274 scans)	744 h (361 scans)
Source activity	25 GBq	98 GBq
Background	290 mcps	220 mcps
Tritium purity	97.6%	98.7%
Electrons in RoI	2 Mio	4.3 Mio

2^{nd} KATRIN neutrino mass campaign



PRL 123 (2019) 221802
arXiv:*2105.08533 (subm. to Nature Physics)*

$m^2(\nu) = (0.26^{+0.34}_{-0.34})$ **eV²**

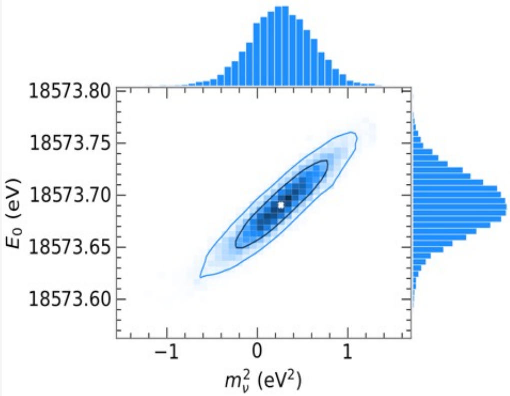
→ compatible with zero

$E_0 = 18573.69 \pm 0.03\ eV$

→ Q-value : 18575.2 ± 0.5 eV

good agreement with Penning trap exp.:

Q = 18575.72 ± 0.07 eV, PRL 114 (2015) 013003



Frequentist limit: $m_\nu < 0.9$ **eV (90% CL)**

Same for Feldman & Cousins and Lokhov & Tkachov

less than sensitivity, due to positive fit result

2105.08533

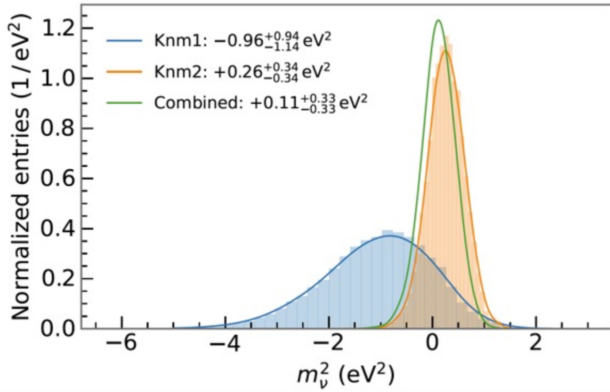
Bayesian: $m_\nu < 0.85$ **eV (90% CI)**

Lokhov & Tkachov, Phys. Part. Nucl. 46 (2015) 347
Feldman & Cousins, Phys. Rev. D57 (1998) 3873

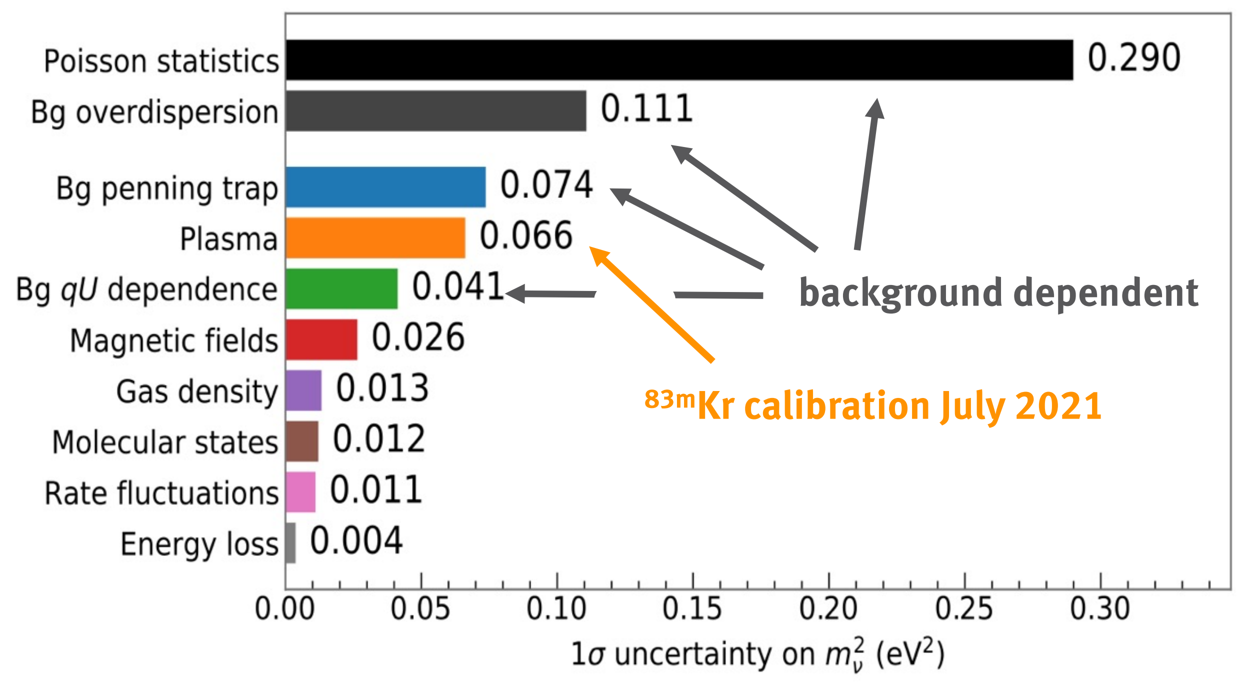
Combine 1^{st} & 2^{nd} campaign:

Freq. im.: $m_\nu < 0.8$ **eV (90% CL)**

Bayes: $m_\nu < 0.7$ **eV (90% CL)**

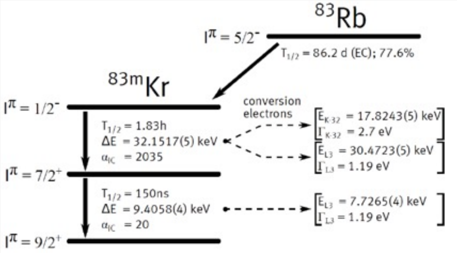


Systematics budget of analysis of 2nd campaign

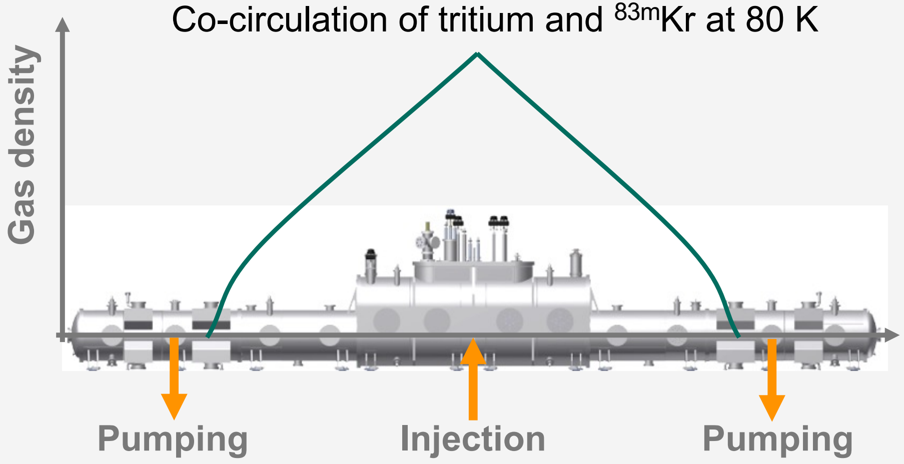


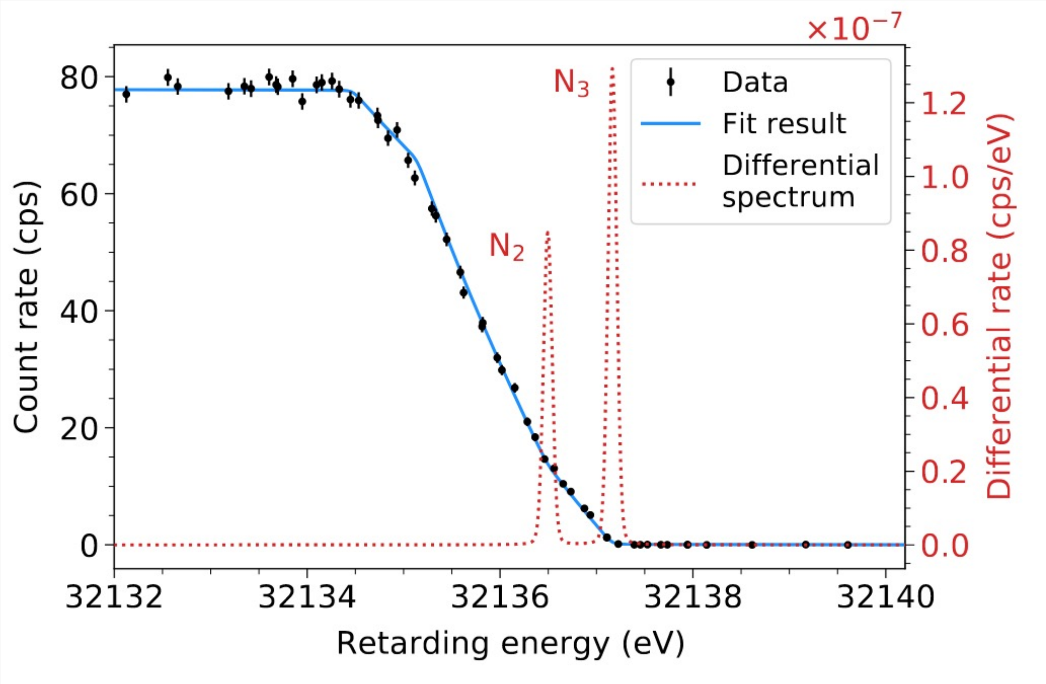
arXiv:*2105.08533 (subm. to Nature Physics)*

Improving source-related systematics



Co-circulation of tritium and ^{83m}Kr at 80 K





Data of 2020 krypton run at 40% tritium column density used to constrain systematics in 2nd campaign *arXiv:2105.08533*

Since then: New operation mode with stable co-circulation at high column density at 80 K

Summer 2021: 10 GBq Krypton generator (activity x6) ➜ further reduction of plasma systematics

Improving background

Main component of background (arXiv:2011.05107):

Highly excited (neutral) Rydberg atoms ionized in the volume of main spectrometer

Very low kinetic energy of background e⁻

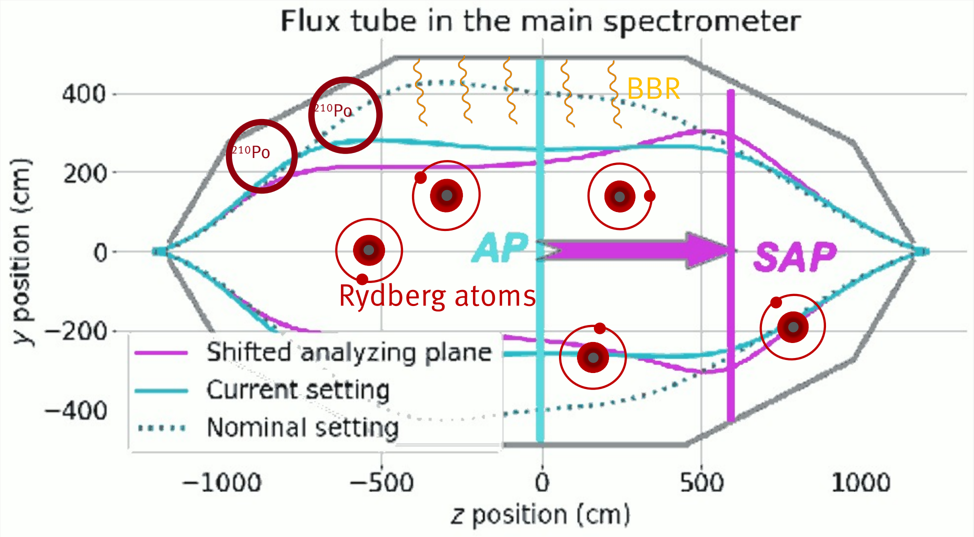
⇨ **Volume dependent background rate**

Reduce "downstream" volume of magnetic flux:

„shifted analyzing plane" (SAP)

⇨ Factor **2 signal/background** improvement

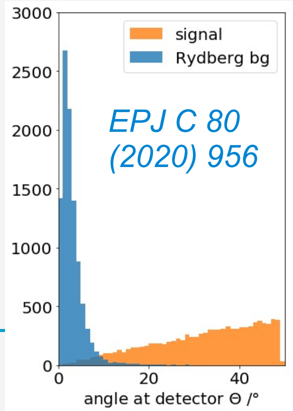
implemented in neutrino mass scans of 2020 ☑

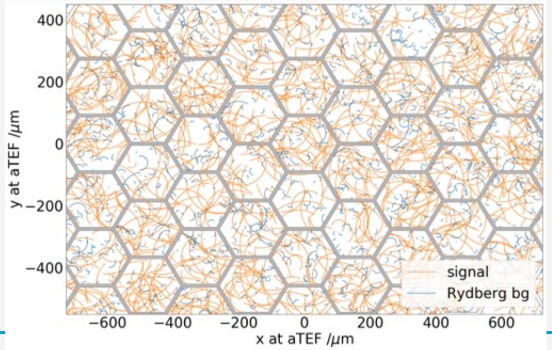


Further reduction of background planned:

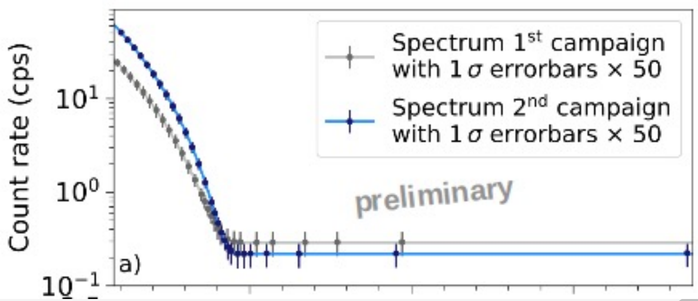
Make use of angular distribution of background electrons

a very new idea: angular threshold filter
(*"active transverse energy filter"*, aTEF)

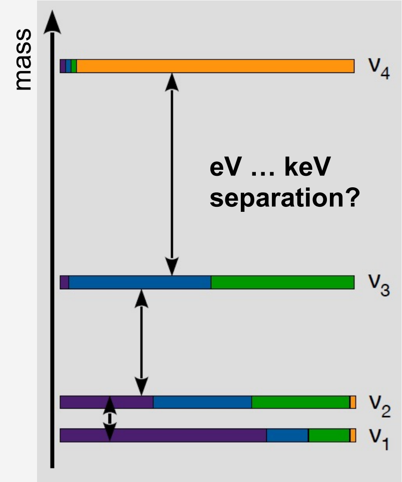




KATRIN „beyond the neutrino mass“



Is there a fourth (sterile) neutrino?



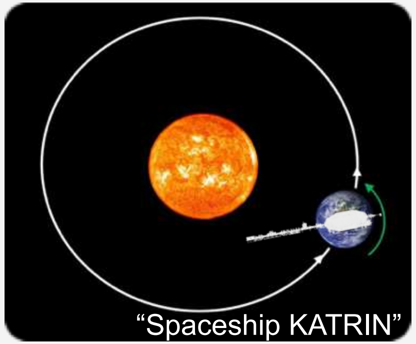
Neutrino mixing: “Kink” in normal β-spectrum (eV scale) or deep β-spectrum (keV scale)

β-spectrum of high statistics and precision

Constrain local overdensity of cosmic relic neutrinos (peak search)

Search for exotic weak interactions (spectrum shape)

Search for Lorentz invariance violation (sidereal modulation)

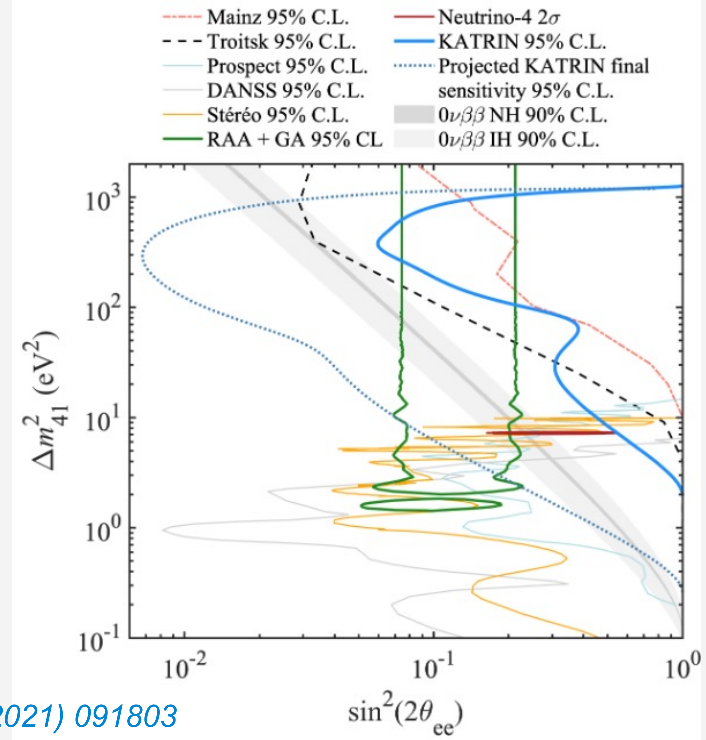


Sterile neutrino searches in KATRIN

eV-scale sterile neutrinos:

new exclusion from the first science run

complementary probe of sterile ν



PRL 126 (2021) 091803

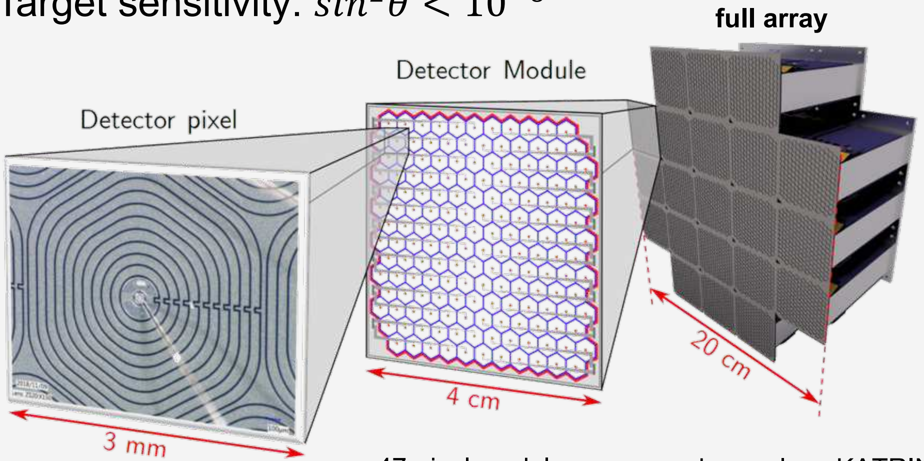
keV-scale sterile neutinos: TRISTAN at KATRIN:

novel multi-pixel Silicon Drift Detector array

large count rates

excellent energy resolution

Target sensitivity: $sin^2\theta < 10^{-6}$



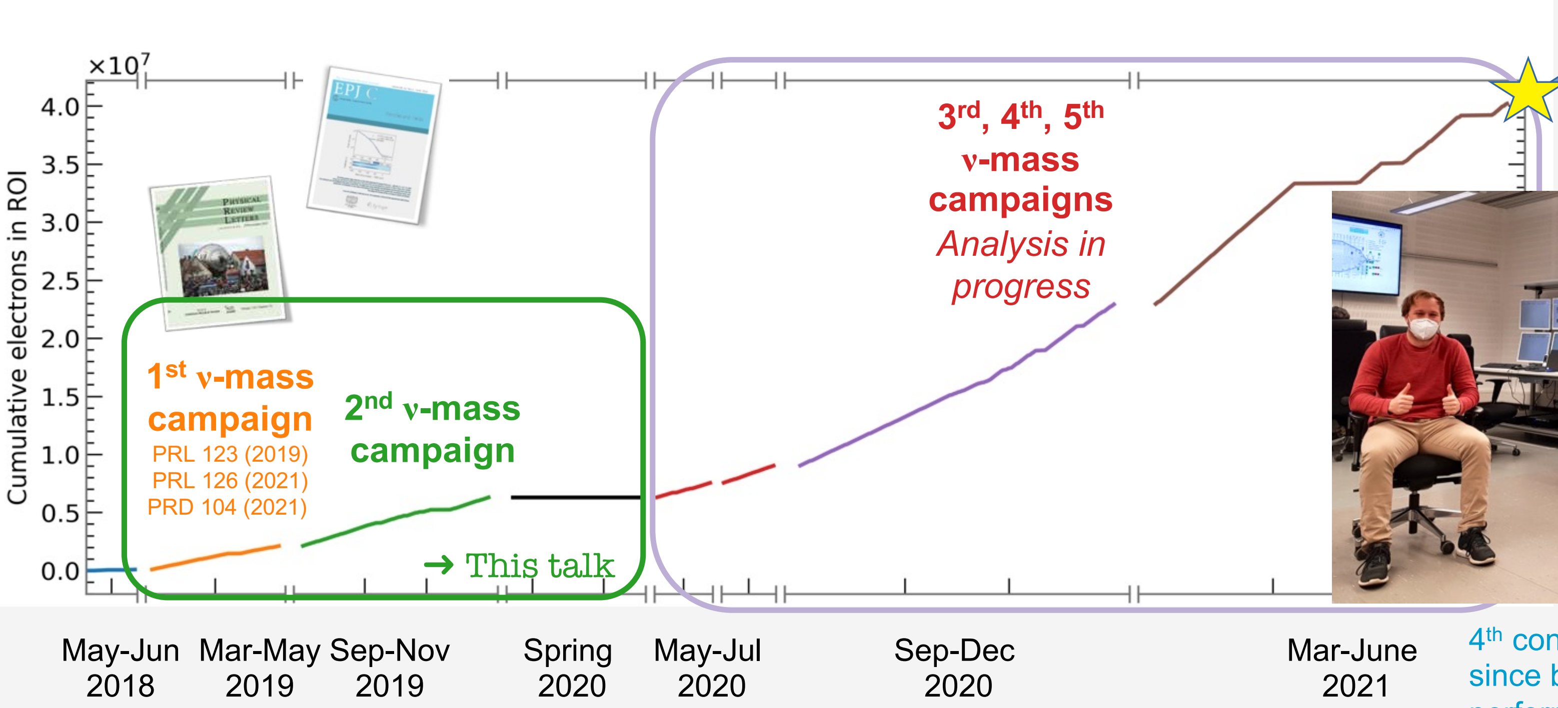
47-pixel module testing at monitor spectrometer now

aim: replace KATRIN focal-plane detector in 2025

J.Phys.G 46 (2019) 6, 065203, JINST 14 (2019) 11 P11013, J. Phys. C. Ser. 1468 (2020) 012177

KATRIN data taking continues

Start of 6th neutrino-mass campaign* on August 19, 2021:



4th consecutive measurement campaign since beginning of the pandemic, performed under all necessary precautions.

Conclusions

- ν physics remains super important for particle physics & beyond
  keeps being an important gateway to BSM physics
- Hierarchy and δ_{CP} are being resolved by LBL oscillation experiments with accelerator, reactor & atmospheric ν:
  now: T2K, NOνA, IceCube coming: JUNO, ORCA, Hyper Kamiokande, DUNE
- Low energy puzzles: $\nu_e, \bar{\nu}_e$ appearance, reactor neutrino anomaly, bump in reactor ν spectrum
  are being attacked by short baseline reactor experiments, SBN program, KATRIN
  new MicroBooNE results question MiniBooNE/LSND $\nu_e, \bar{\nu}_e$ appearance
- CEνNS has been established and will an important tool for precision studies and BSM searches
- Lepton number violation will be searched for by 0νββ
  excellent final result by GERDA, LEGEND-200 will soon start to attack 10^{27} yr sensitivity
  CUPID, LEGEND-1000, nEXO: even more sensitive experiments with 10^{28} yr sensitivity
- Direct neutrino mass experiments:
  KATRIN presents 1st sub-eV limit,
  much more data, lower background rate and better systematics, goal: 0.2 eV sensitivity
  (new projects for the future to reach beyond KATRIN: ECHo, HOLMES, Project 8)

Conclusions

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Many thanks for those who helped me with material & discussions for the underlying review talk at EPS HEP 2021:

S. Calvez, S.J. Dolan, G. Drexlin, J. Formaggio, A. Göttel, M. Gonchar, G. Gratta, P. Guzowski, C. Hati, T. Lasserre, A. Lokhov, M. Licciardi, M. Lindner, S. Mertens, R.C. Mandujano, S. Schönert, T. Tashiro, M. Uchita, K. Valerius

Thank you all for your attention

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