KATRIN motivation - neutrino masses in cosmology and particle physics

Photo: M. Zacher

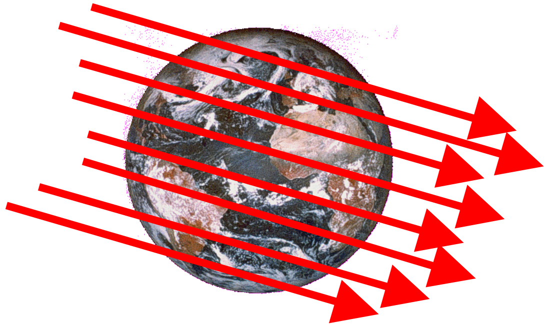
- Neutrinos
- Evidence for non-zero neutrino masses
- Importance of neutrino masses for particle physics & cosmology
- 3 complementary ways to the neutrino mass
- Key methods for an experiment with 200 meV sensitivity (quasi-degenerate regime)

Neutrinos in the Standard Model of particle physics

	generation 1	2	3
leptons	ν_e	ν_μ	ν_τ
	e	μ	τ
quarks	u	c	t
	d	s	b

normal matter

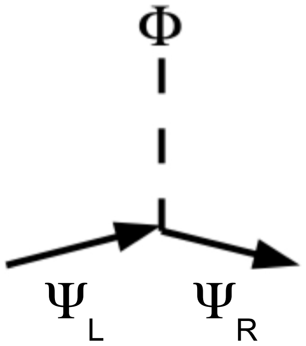
Neutral, spin ½,
Only weak interaction (W,Z very heavy):
$\lambda_\nu \approx$ light years at MeV scale
interaction rate increases linearly with E_ν usually



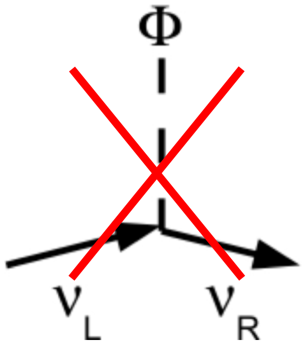
The most abundant particle in the universe: 336 / cm^3
(together with the particle of light, the photon)

Mass terms in the Standard Model:

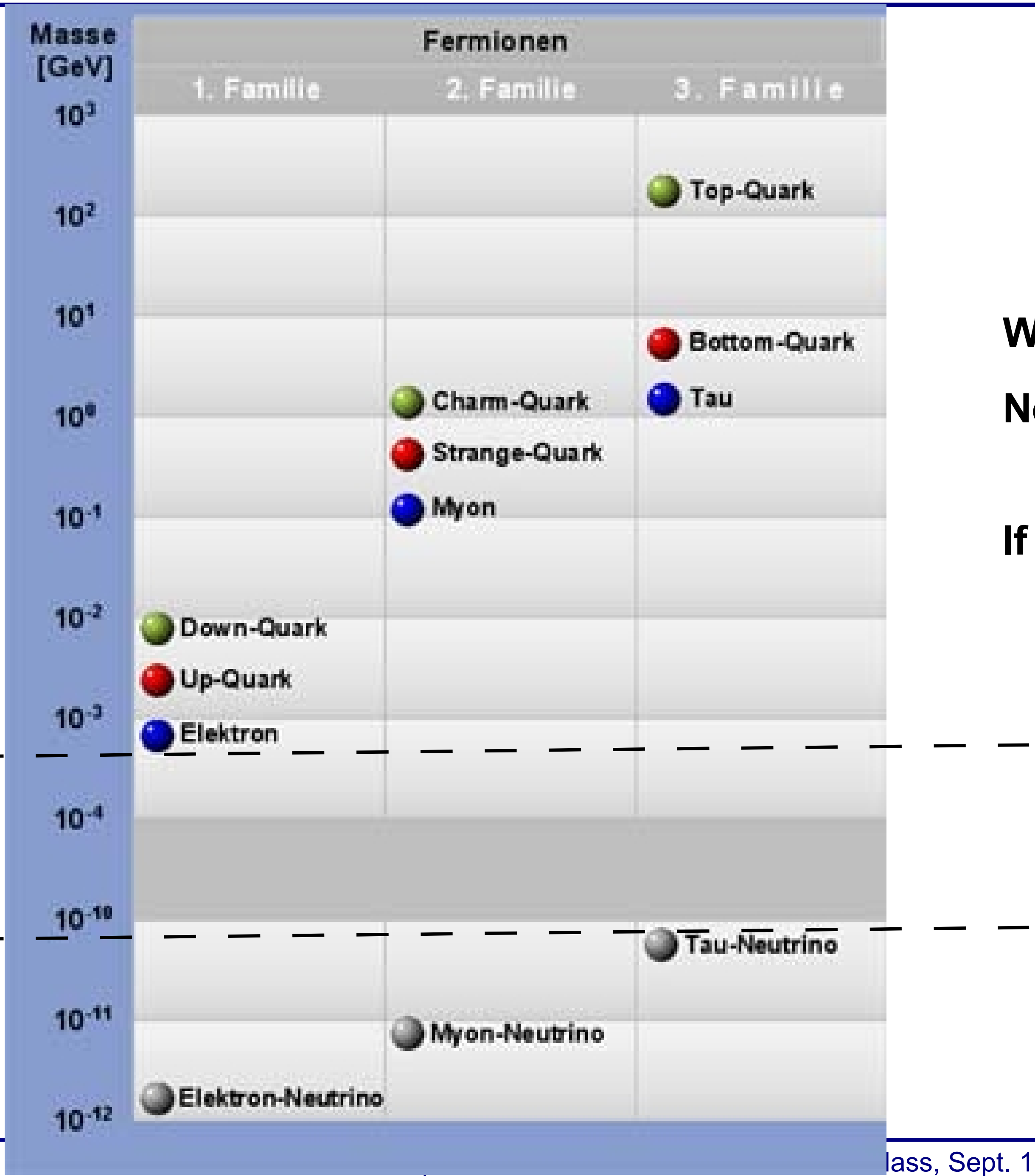
coupling to the Higgs



In original SM ν only left-handed: ν_L
→ difficult to account for mass term:
Yukawa coupling to the Higgs
did not exist in the SM



Neutrinos are much more lighter than all other fundamental mass particles



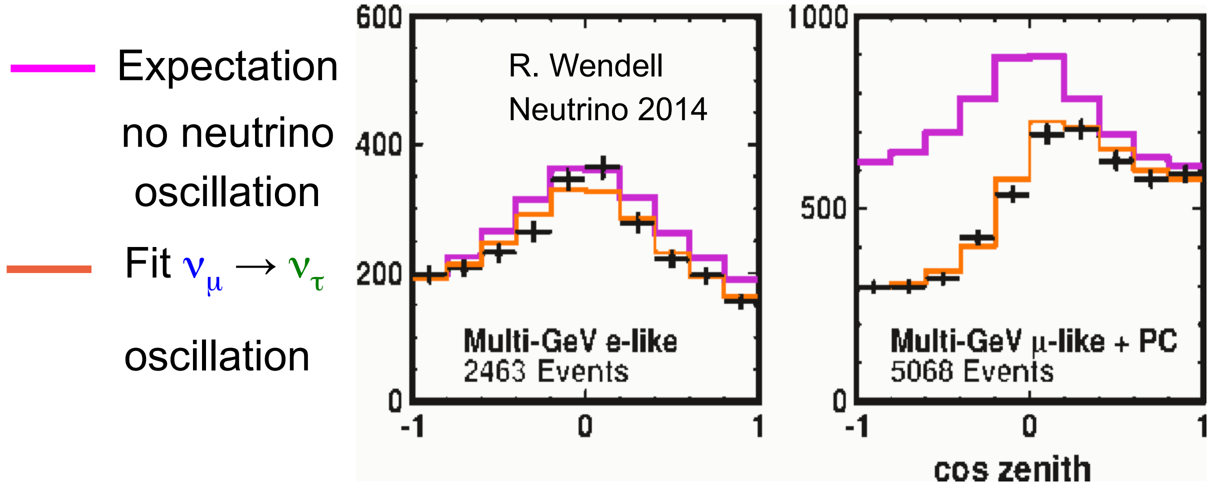
> 1 million

Why are neutrinos so much lighter ?

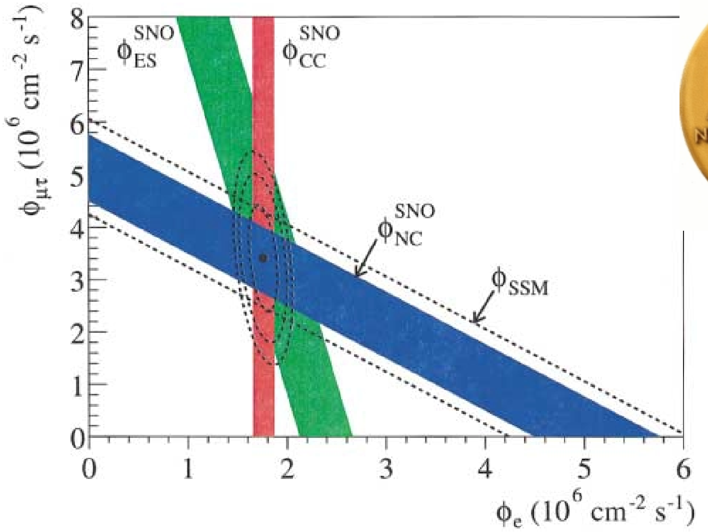
Neutrinos were thought to be massless
up to the millenium

If they have tiny masses
their extreme tinyness of masses
should require
a different mass generation process,
not just a Yukawa coupling to the Higgs !

Discovery of atmospheric ($\nu_\mu \rightarrow \nu_\tau$) & solar ($\nu_e \rightarrow \nu_\mu/\nu_\tau$) neutrino oscillations $\rightarrow m(\nu) \neq 0$



Nobel Prize in physics 2015



⇒ neutrino oscillation

$$\nu_\mu \rightarrow \begin{Bmatrix} \cos\theta \xrightarrow{\nu_2} \sin\theta \\ -\sin\theta \xrightarrow{\nu_3} \cos\theta \end{Bmatrix} \rightarrow \nu_\tau$$

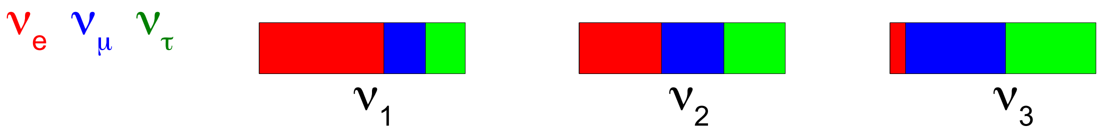
$\Rightarrow \Delta m^2_{ij} \Rightarrow \quad m(\nu_j) \neq 0$

but unknown absolute scale

$m(\nu_j)$ not accessible by osc. exp.

Importance of neutrino mass for particle physics and cosmology

Results of recent oscillation experiments: Θ_{23}, Θ_{12}, Θ_{13}, $|\Delta m^2_{13}|$, Δm^2_{12}



degenerated masses

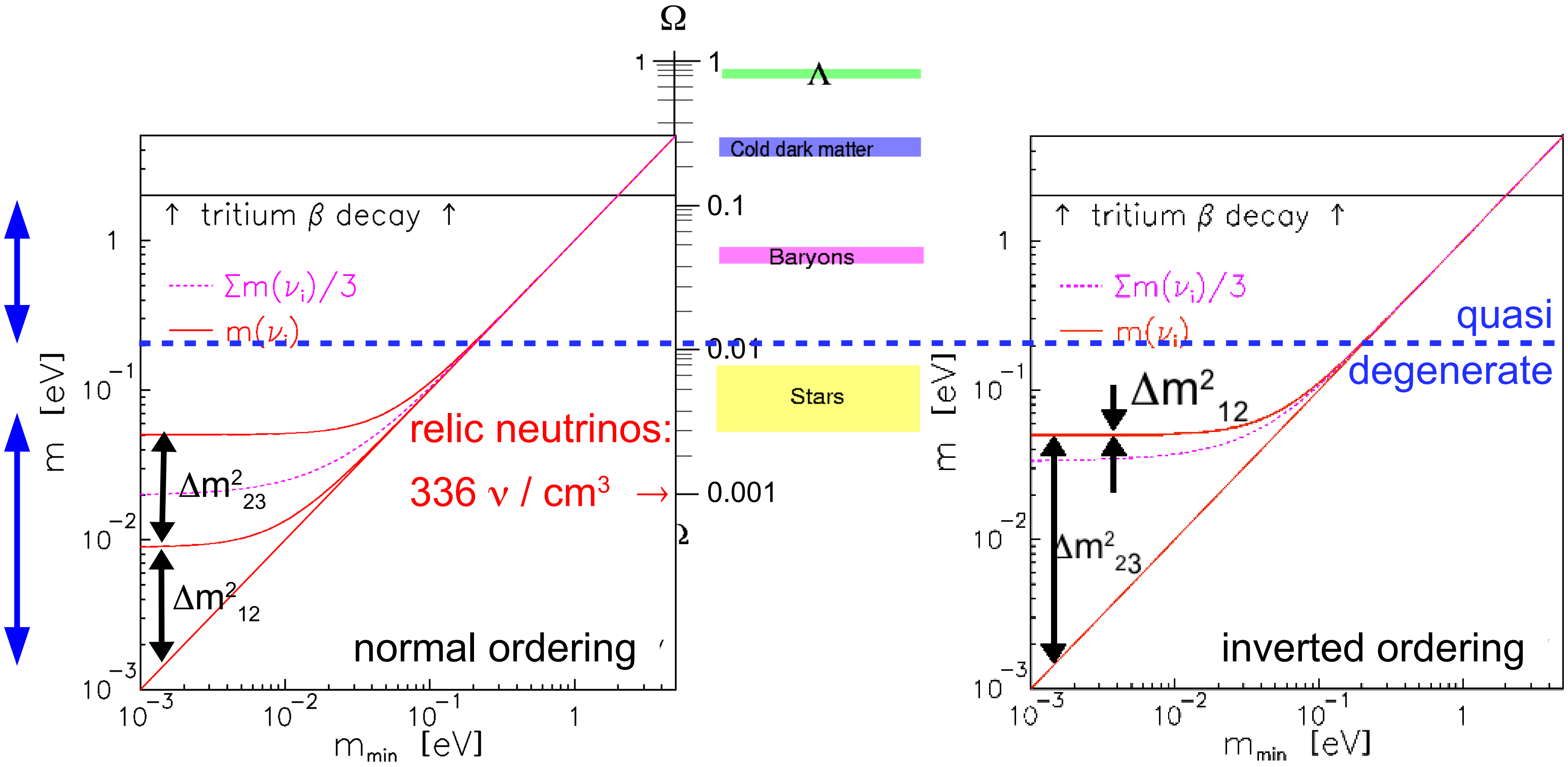
cosmological relevant

e.g. seesaw mechanism type 2

hierarchical masses

e.g. seesaw mechanism type 1

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



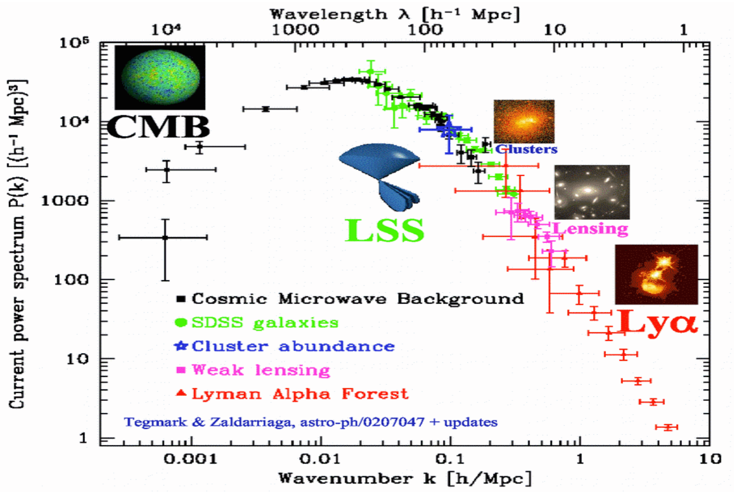
Three complementary ways to the absolute neutrino mass scale

1) Cosmology

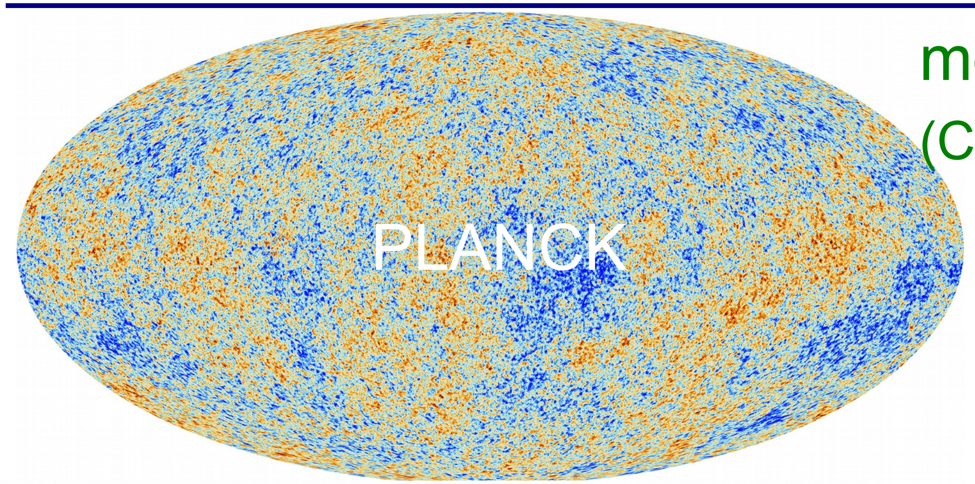
very sensitive, but model dependent

compares power at different scales

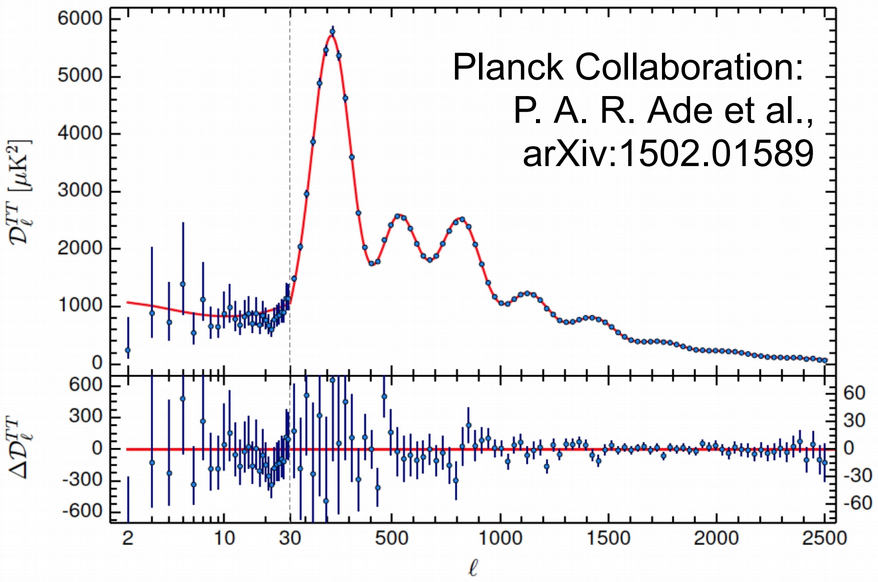
current sensitivity: $\Sigma m(\nu_i) \approx 0.12$ eV



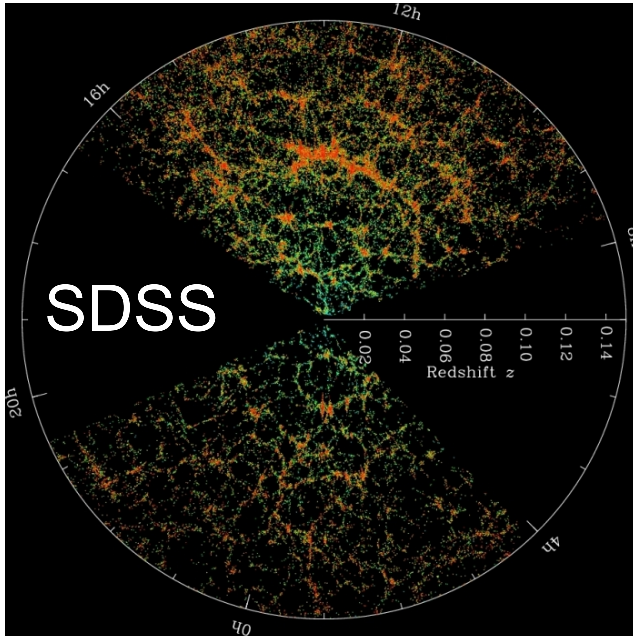
Neutrino mass from cosmology



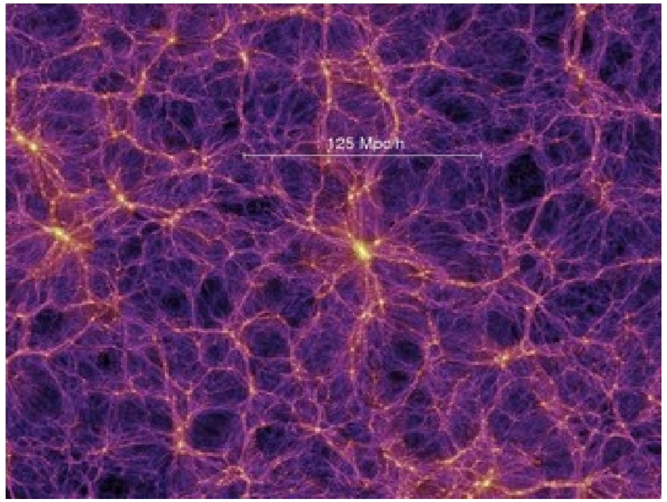
measurement of CMBR
(Cosmic Microwave Background Radiation)



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



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



Millenium simulation →
ɿpa-garching.mpg.de/galform/presse/

Applying ΛCDM model: $\Sigma_i m(\nu) < 0.12$ eV (Planck 2018 data with baryon accoustic oscillations from LSS)
but neutrino mass limit is model dependent
Please note, that more than 95% of the energy distribution in the universe of ΛCDM is not known

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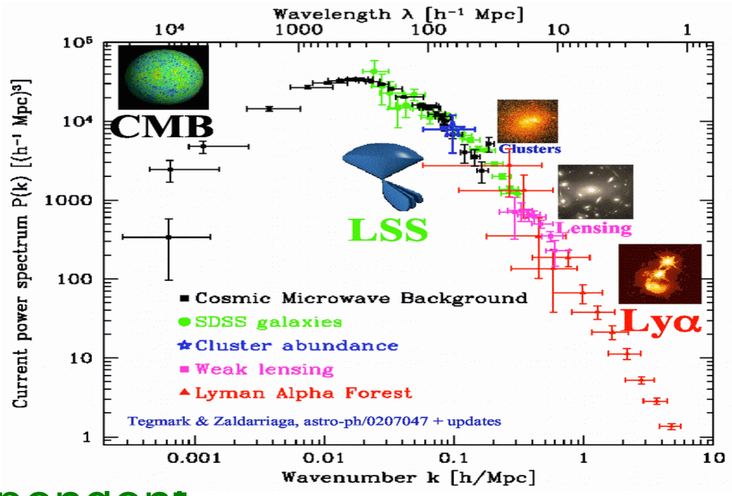
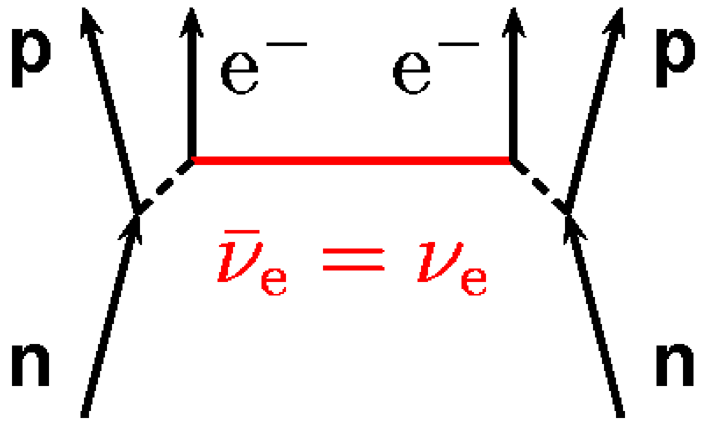


2) Search for $0\nu\beta\beta$

Sensitive to Majorana neutrinos, model-dependent

Upper limits by EXO-200, KamLAND-Zen, GERDA, CUORE



3) Direct neutrino mass determination:

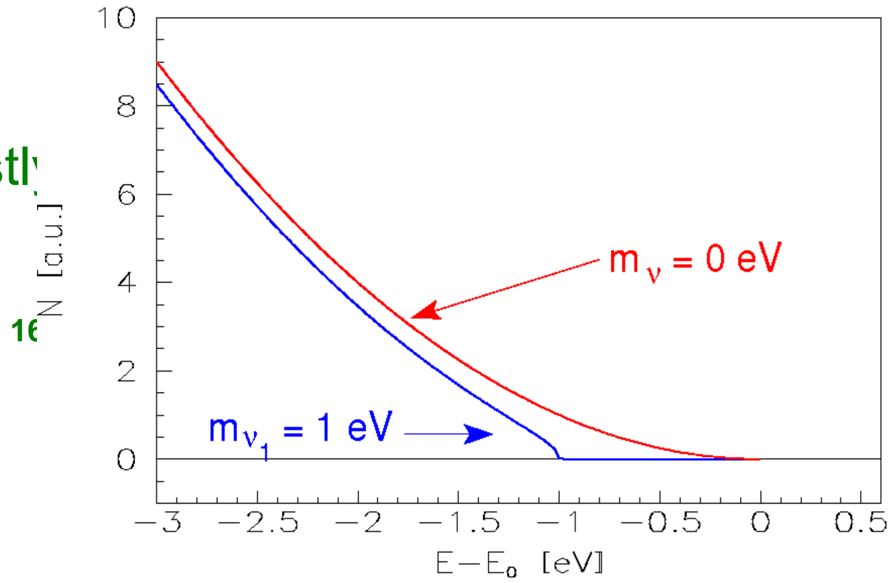
No further assumptions needed,   use $E^2 = p^2c^2 + m^2c^4$

$\Rightarrow m^2(\nu)$ is observable mostl

Time-of-flight measurements (ν from supernova)

Kinematics of weak decays / beta decays, e.g. tritium, 16

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



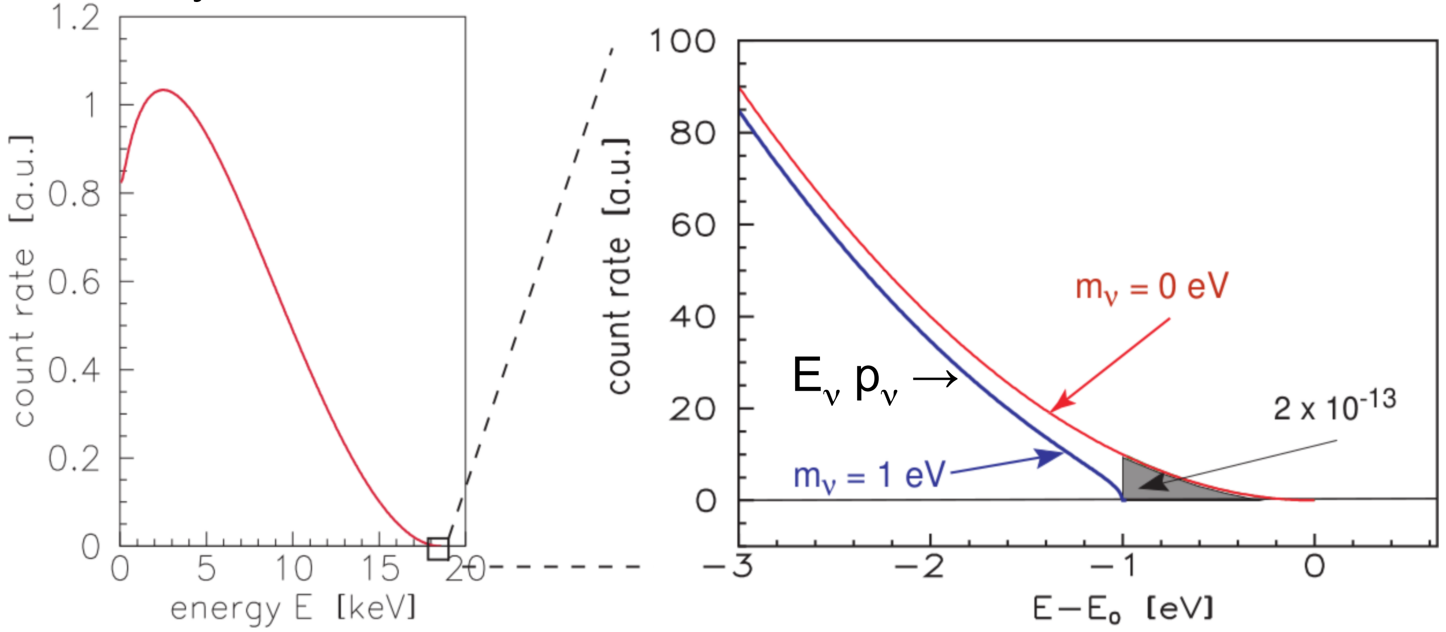
Direct determination of “$m(\nu_e)$“ from β-decay (and EC)

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

essentially phase space: p_e E_e E_ν p_ν

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

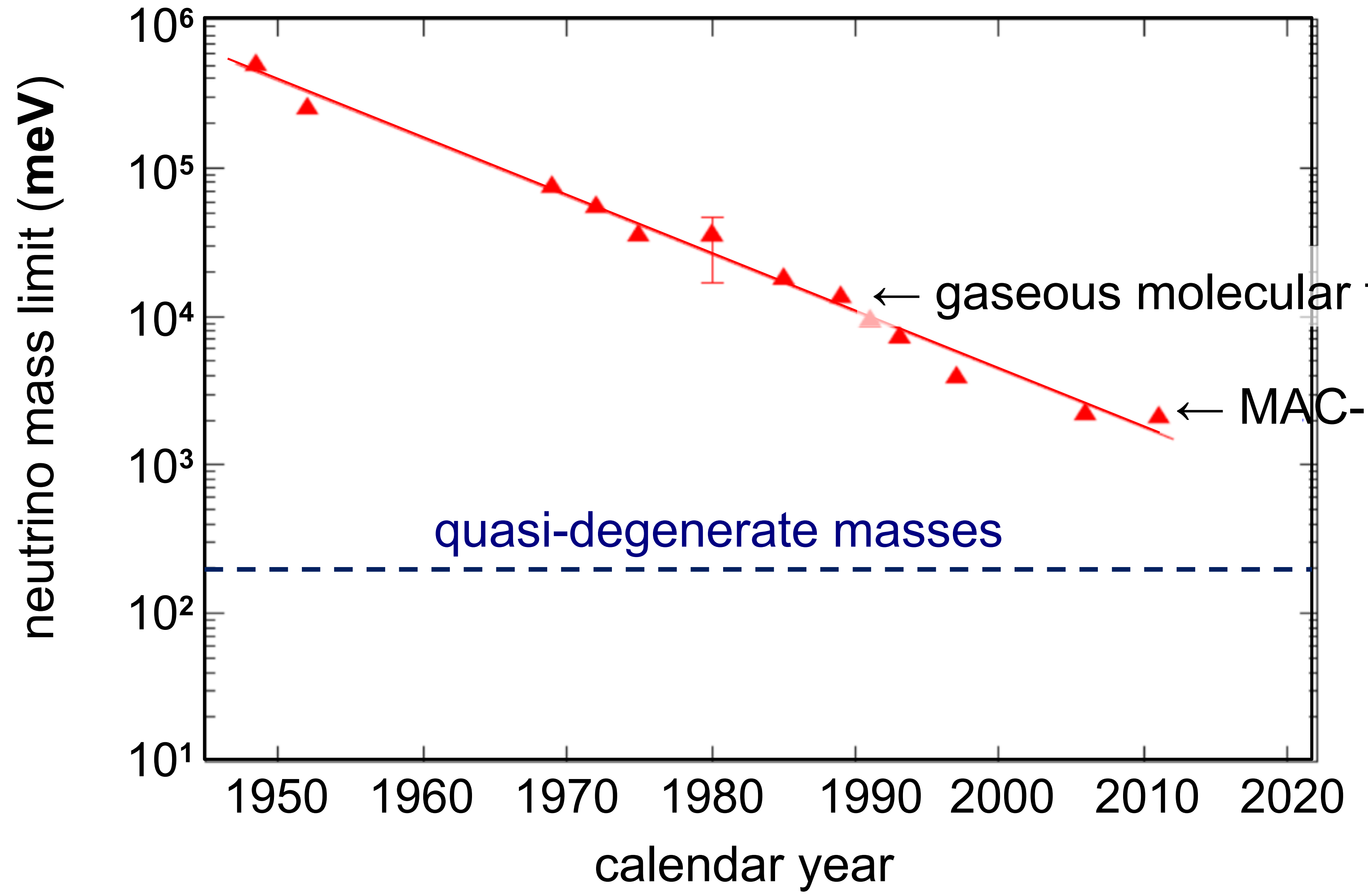
(modified by electronic final states, recoil corrections, radiative corrections)



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

Moore's law of direct neutrino mass experiments

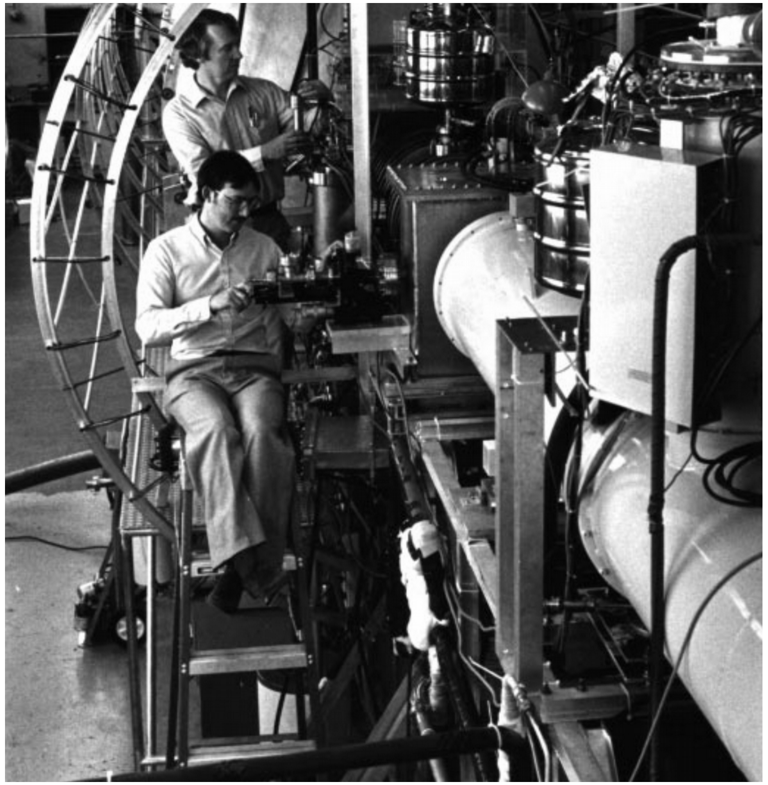
Experimental progress over past decades due to **new technologies**



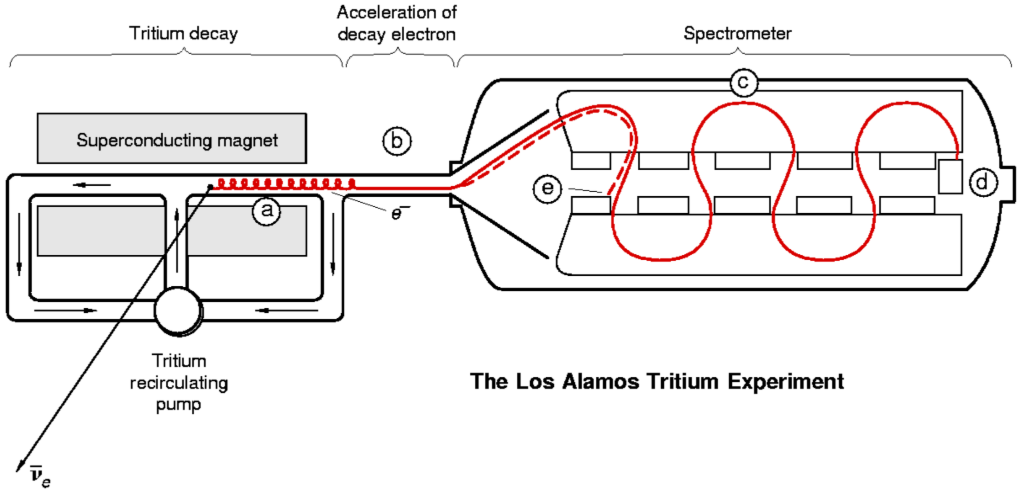
$m(\nu_e)$ < 2 eV (95% CL)

*courtesy of JF Wilkerson

Milestones for 200 meV sensitivity:
a windowless gaseous tritium source → small systematics

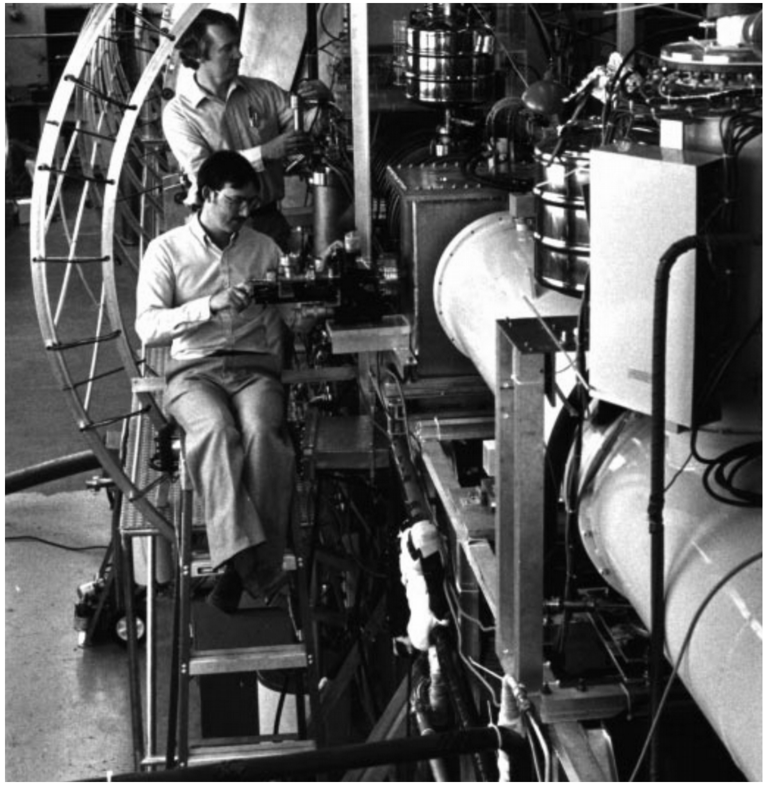


Los Alamos Tritium Experiment: R.G.H. Robertson et al.



The Los Alamos Tritium Experiment

Milestones for 200 meV sensitivity: MAC-E filter,
a high resolution & large acceptance spectrometer → huge statistics



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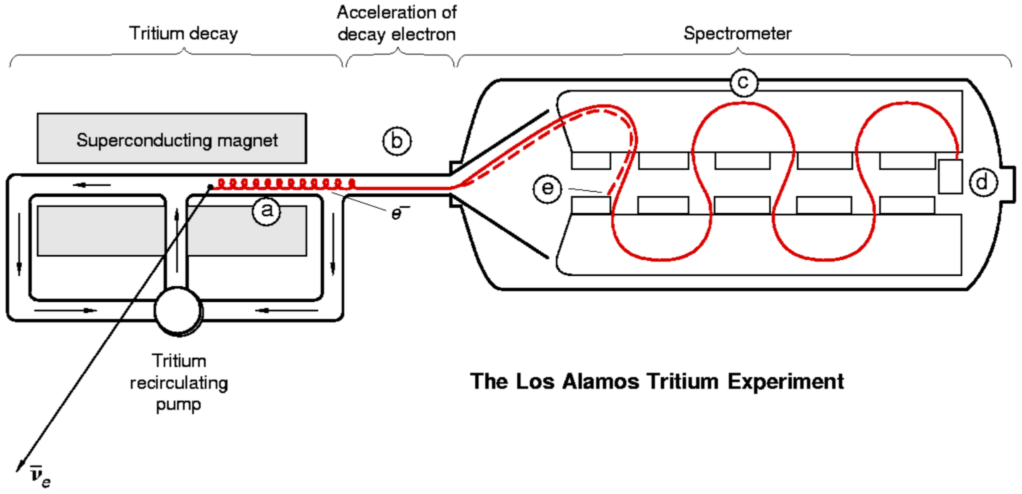
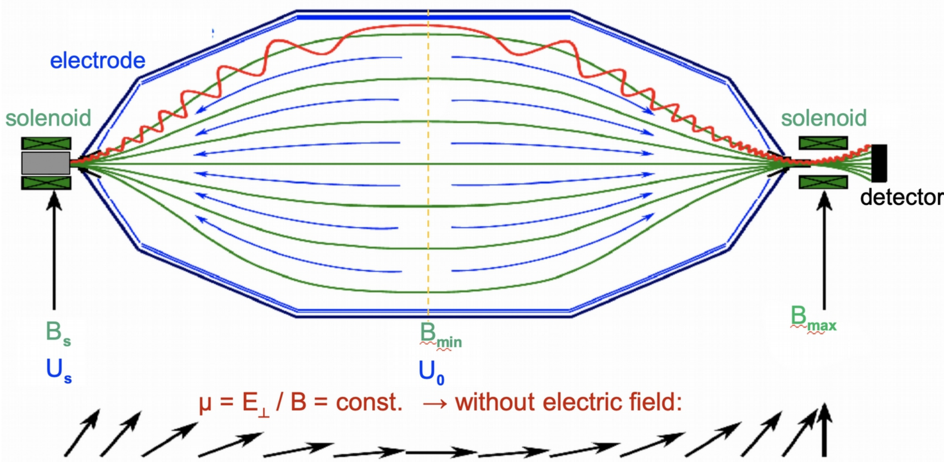
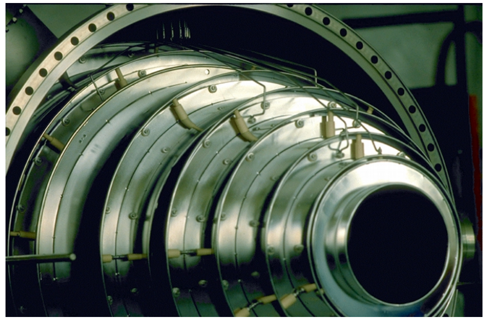
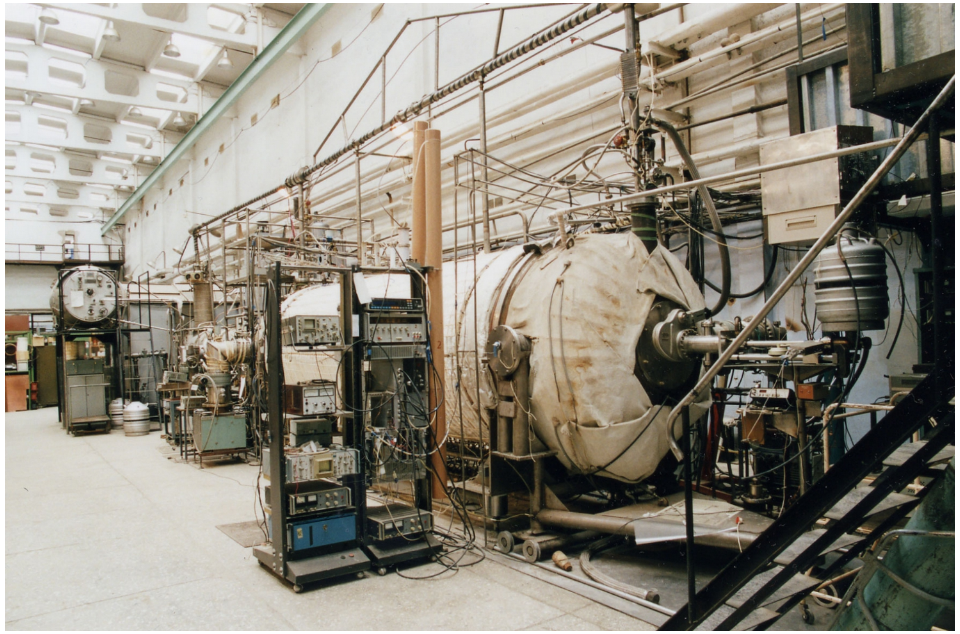
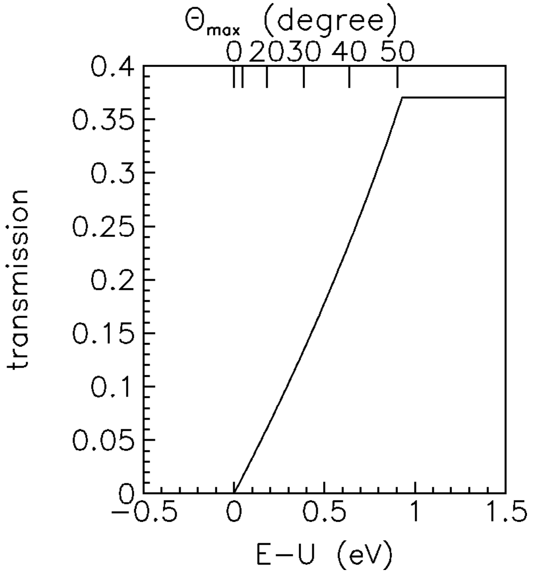


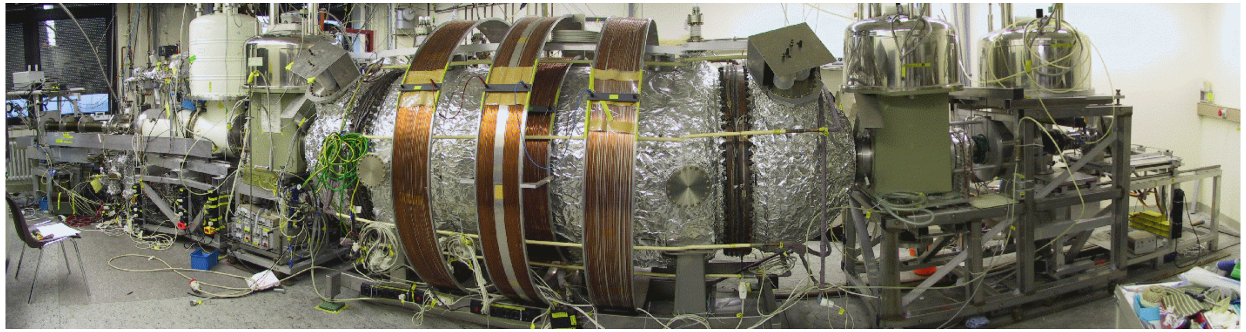








Mainz Neutrino Mass Experiment: E.-W. Otten, J. Bonn et al.



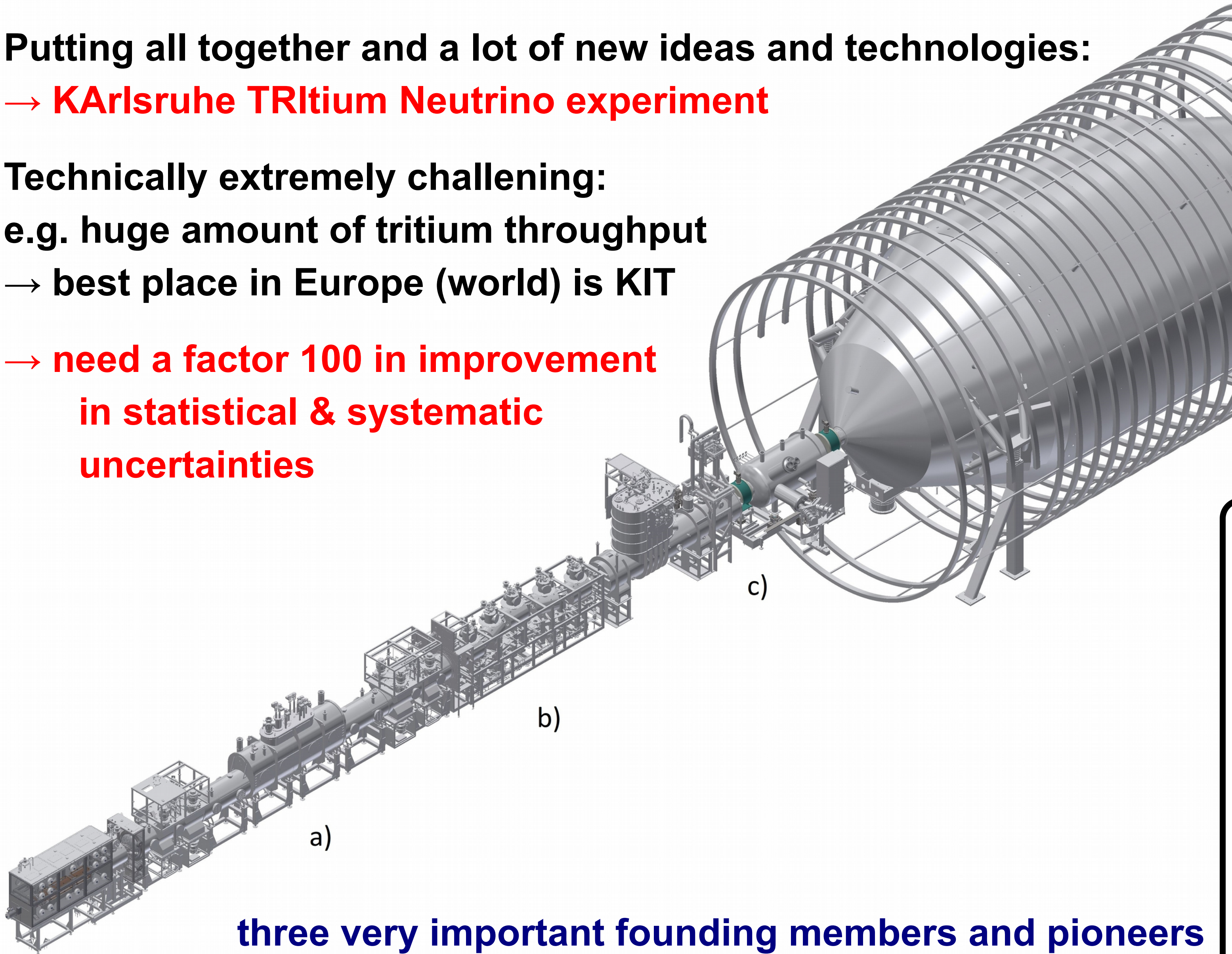
Troitsk Neutrino Mass Experiment: V. M. Lobashev et al.

Many challenges to obtain 200 meV sensitivity: factor 100 improvement of stat. + sys. uncertainties

Putting all together and a lot of new ideas and technologies:
→ KArlsruhe TRItium Neutrino experiment

Technically extremely challenging:
e.g. huge amount of tritium throughput
→ best place in Europe (world) is KIT

→ need a factor 100 in improvement in statistical & systematic uncertainties



three very important founding members and pioneers passed away on the long road of KATRIN

Dr. Jochen Bonn
1944 - 2012

Prof. Dr. Vladimir M. Lobashev
1934 - 2011

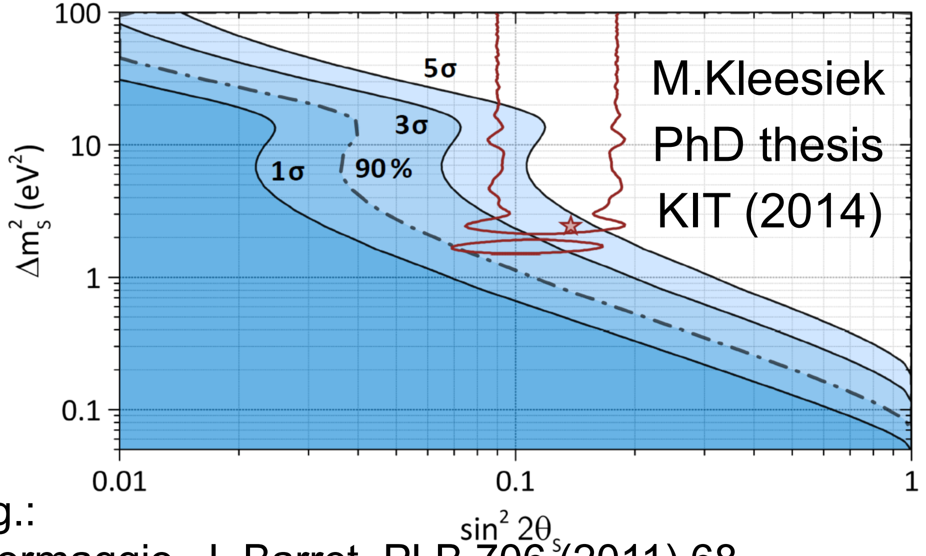
Prof. Dr. Dr. h.c. Ernst-W. Otten
1934 - 2019

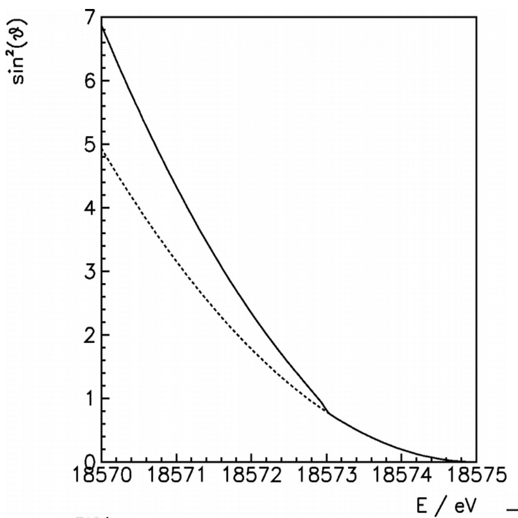
Other interesting searches for physics beyond the Standard Model accessible with KATRIN

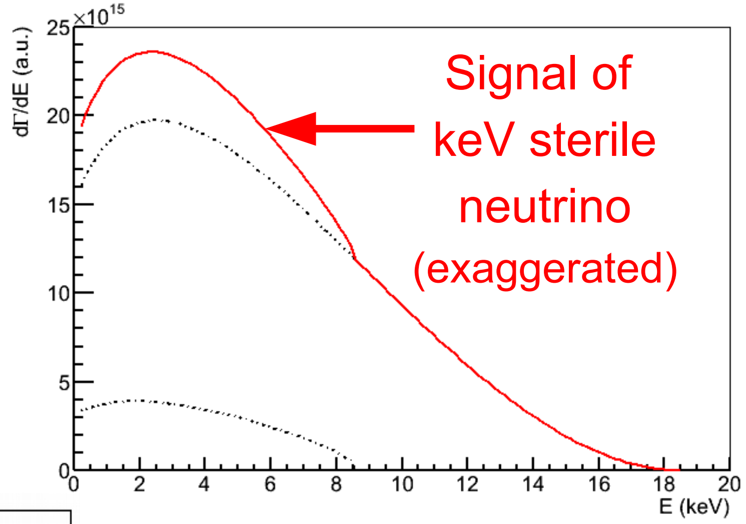
Sterile neutrinos

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

eV ν:



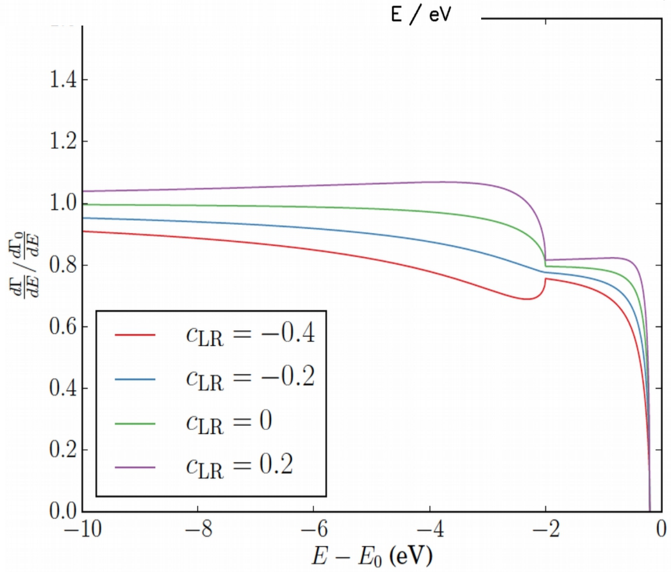


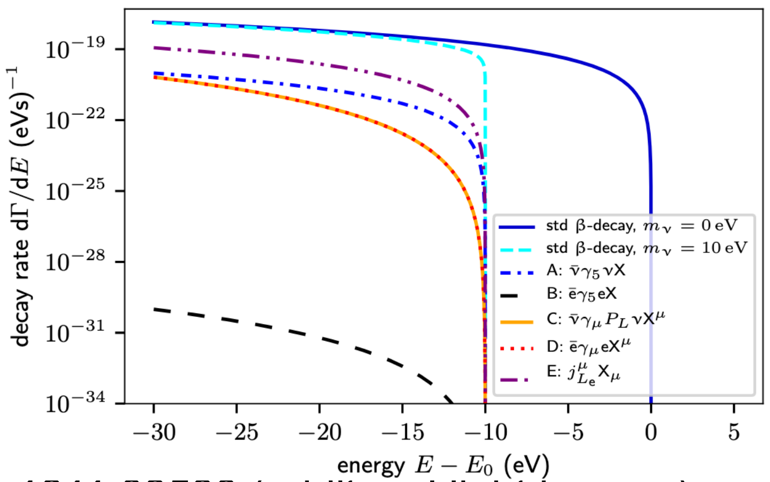


see e.g.:
J. A. Formaggio, J. Barret, PLB 706 (2011) 68
A. Sejersen Riis, S. Hannestad, JCAP02 (2011) 011
A. Esmaili, O.L.G. Peres, arXiv:1203.2632

keV ν:

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





non SM currents, additional light bosons, ...

see e.g.: N. Steinbrink et al., JCAP 6 (2017) 15 (RH currents & sterile ν) or G. Arcadi et al., arXiv:1811.03530 (additonal light bosons)