Detecting the neutrinos

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1. Discovery : missing Energy and Momentum
2. Lepton number, lepton flavour, neutrinos and antineutrinos
    charged current neutrino interactions
3. Neutrinos and the Standard Model: Neutral Currents
4. The three families of neutrinos
5. Neutrinos from the Universe: solar neutrinos, atmospheric neutrinos

5’. Supernova neutrinos

6. Neutrino properties: measuring the neutrino mass?
7. Neutrino oscillations and CP violation
8. On-going and future neutrino experiments on oscillations
9. What is the origin of neutrino masses?
10. Neutrino-less double-beta experiments
11. See-saw, sterile neutrinos
12. Conclusions

many reactions, beam types and detection techniques
here I will follow the physics

Neutrino mass…

The simple fact that neutrinos transform during their flight from source to detector is a proof that they have mass.

Particle that has no mass cannot transform:

$\tau_{lab} = \gamma\, \tau_{particle} = E/m\, \tau_{particle}$ if $m \to 0 \Rightarrow \tau_{lab} \to \infty$!

Neutrino oscillations are sensitive to mass differences Δm_{ij}^2

$$P_\mu(|\nu_e(t)\rangle) = \sin^2 2\theta \sin^2(1.27 \Delta m_{12}^2 L / E)$$

How can one detect the neutrino mass itself?

There are presently 3 different methods

-- kinematic method (the most direct and most difficult)

-- effect of neutrino mass on the early universe

-- neutrinoless double beta decay

β-decay: absolute ν-mass

model independent, kinematics

status: $m_\nu < 2$ eV

potential: $m_\nu \approx 0.2$ eV

e.g.: KATRIN, ECHO, HOLMES, Project-8, ...

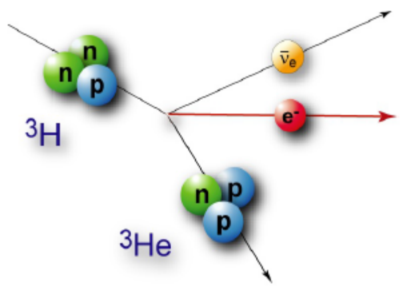
0νββ-decay: eff. Majorana mass

model-dependent (CP-phases)

status: $m_{\beta\beta} < 0.1$ eV

potential: $m_{\beta\beta} \approx$ 20-50 meV

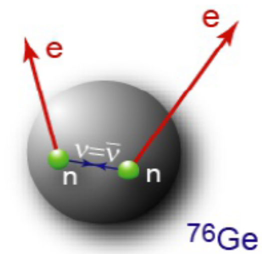
e.g.: GERDA, KamLAND-Zen, CUORE, EXO, Majorana, Nemo 3, ...



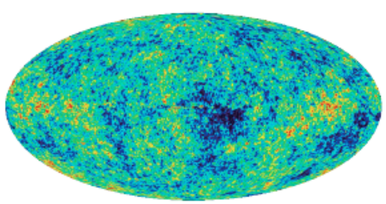
m_ν

neutrino mass measurements

$m_{\beta\beta}$



Σm_i

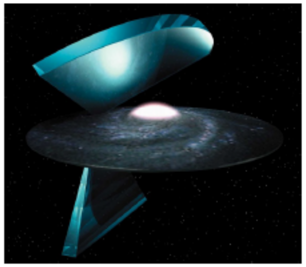


cosmology: ν hot dark matter Ω_ν

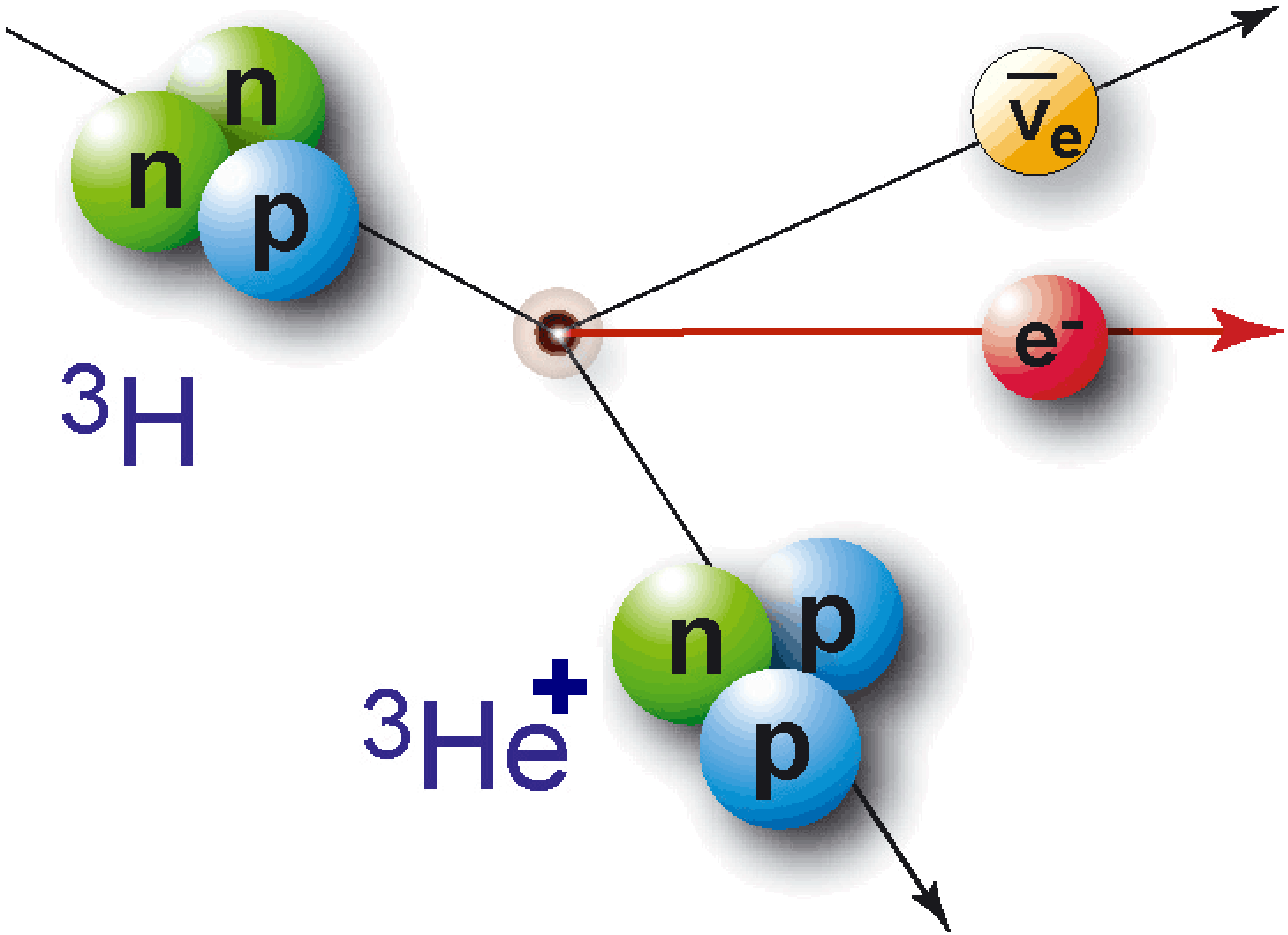
model dependent, analysis of CMB and structure formation data

status: $\Sigma m_\nu < 0.23$ eV

(Planck Collaboration, A&A 594 (2016) A13)



Electron antineutrino mass measurement in tritium β decay



Electron antineutrino mass measurement in tritium β decay

What is measured

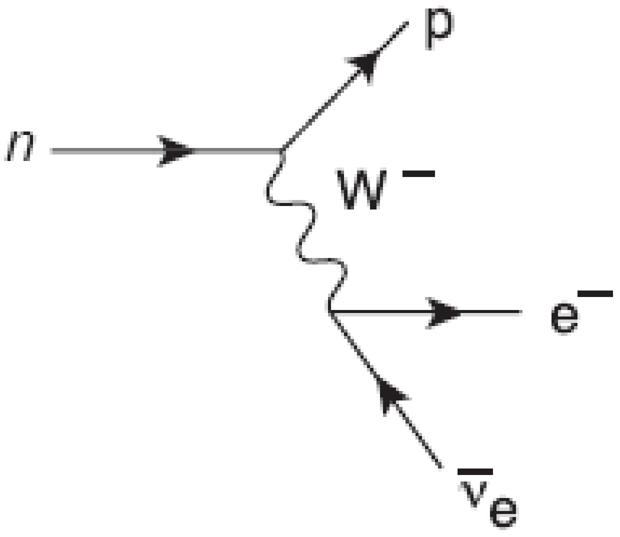
e- spectrum in β decay

$$(\mathrm{Z}, \mathrm{A}) \rightarrow (\mathrm{Z}+1, \mathrm{A})^{+} + \mathrm{e}^{-} + \bar{\nu}_{\mathrm{e}}$$

The only variable measured is electrons kinetic energy

The goal of the measurement is to determine a value for the mass of the electron antineutrino

$$m^2(\nu_{\mathrm{e}}) = \sum_{\mathrm{i}} |U_{e i}|^2 \cdot m^2(\nu_{\mathrm{i}})$$



Why the measurement is of importance

Neutrino oscillation experiments can only measure squared mass differences, not masses.

Neutrino-less Double β decay Measures this:

$$m_{ee} = \left| \sum m(\nu_j) \mid U_{ej} \mid^2 e^{i\phi_j} \right|$$

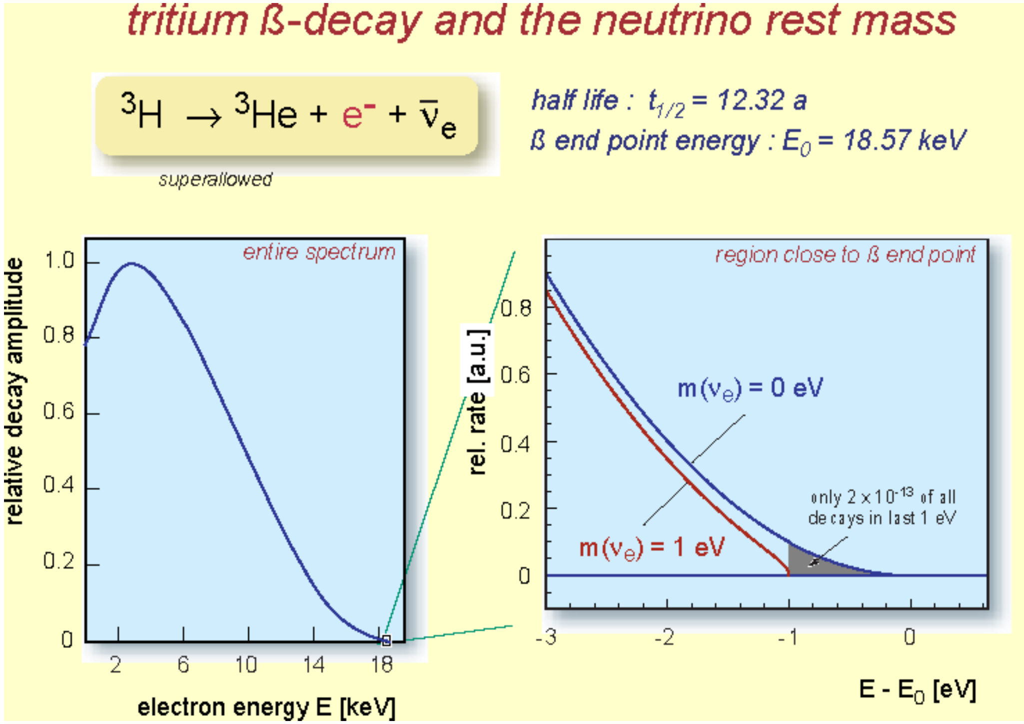
which can be obtained with high precision, but involves the phase factor and relies on the fact that neutrinos have a Majorana mass term

Kinematic measurement is model independent

Importance in:

- Cosmology: An average neutrino mass of 1 eV would contribute to the energy and matter distribution of the universe by 8 % in units of the critical density
- Particle physics: Probe for new theoretical models beyond the standard model (See-saw, SUSY, String theory etc.)

Why tritium β decay is ideal



Tritium decay provides high luminosity in the shaded area. The reasons for that is:

- Tritium and ^{187}Re have the lowest possible E_0, but tritium is preferred due to:
  - Much higher tritium decay rate, ^{187}Re half life is 2.46×10^{-10} times smaller
  - Less inelastic scattering in the source
  - Simpler excitation states in daughter Helium.

The differential decay rate

In the low-energy limit and by hiding the hadronic part in C we get this expression (Approximations made by neglecting mass terms at one point)

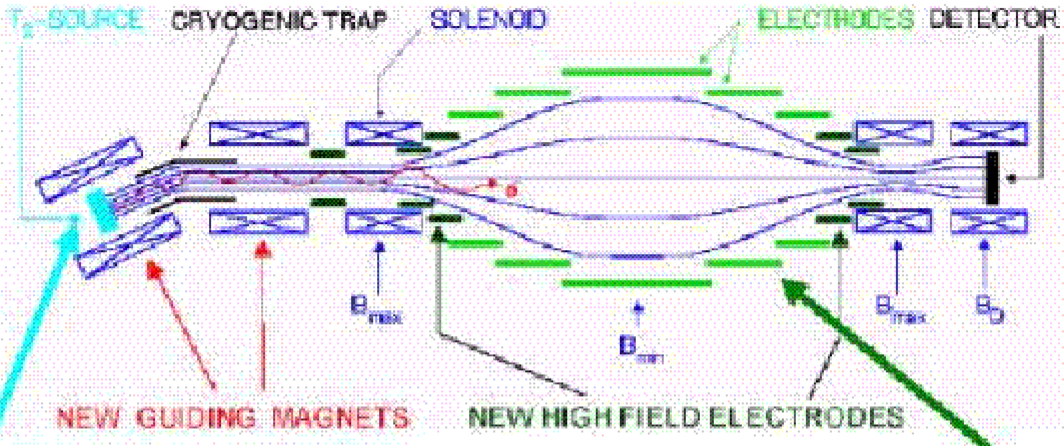
$$\frac{dR}{dE} = N\,\frac{G_F^2 C}{\pi^3}\,p(E + m_e c^2)(E_0 - E)\sqrt{(E_0 - E)^2 - m^2(\nu)c^4}$$

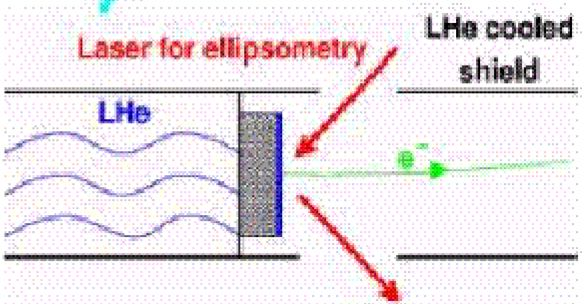
Comparison with the formula used in the Mainz experiment:

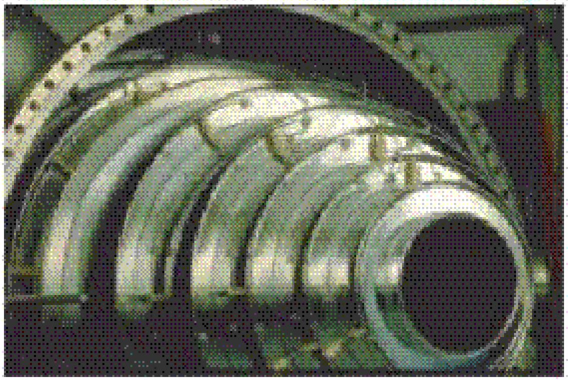
$$\frac{dR}{dE} = N\,\frac{G_F^2}{2\pi^3 \hbar^7 c^5}\cos^2(\Theta_C)\,|M|^2\,F(E, Z+1)\,p(E + m_e c^2)$$

$$\times \sum_{ij} P_i (E_0 - V_i - E)\,|U_{ej}|^2\,\sqrt{(E_0 - V_i - E)^2 - m^2(\nu_j)c^4}$$

Mainz Neutrino Mass Experiment since 1997







- T_2 Film at 1.86 K
- quench-condensed on graphite (HOPG)
- 45 nm thick (≈130ML), area 2cm²
- Thickness determination by ellipsometry

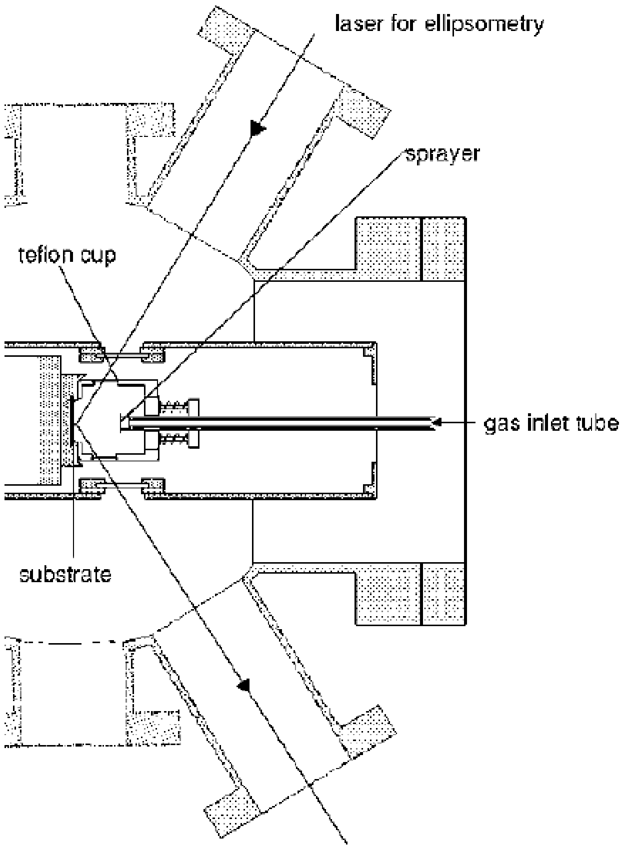
Mainz
ν group
2001:

J. Bonn
B. Bornschein*
L. Bornschein
B. Flatt
Ch. Kraus
B. Müller
E.W. Otten
J.P. Schall
Th. Thümmler**
Ch. Weinheimer**

* → FZ Karlsruhe
** → Univ. Bonn

The source

- T_2 is prepared on a substrate held at 1.9K
  - The tritium gas is analyzed with a quadrupole mass spectrometer.
  - The pressure in the tritium gas inlet tube is between 10^{-2} and 10^{-1} mbar.
  - Gas is sprayed on a HOPG substrate (Highly Oriented Pyrolytic Graphite) held at 1.9K.
  - The gas is quench condensed on the film (80-100 Å at a time)
  - The growth of the layers is controlled optically (3 min/run)
  - Length of the whole film preparation is between 10 and 25 min.
  - Typical run values thickness 417±30 Å, purity 75%±10%



MAC-E-Filter

- Magnetic Adiabatic Collimation followed by an Electrostatic Filter.
- Silicon (semiconductor) detector in five rings, only the central three are used to derive values.
- High resolution: $\Delta E_{\mathrm{k}} / E_{\mathrm{k}} = B_{\mathrm{a}} / B_{\mathrm{max}} = 1/4000.$
- $U_{0\,\mathrm{eff}}$ = -18370 V
- Adiabatic motion $\mu = \dfrac{\frac{1}{2} m v_{\perp}^{2}}{B}$ $\Delta\Omega \approx 2\pi$
- The diameter and length of the spectrometer
  Mainz:
  D=1m and L=4m
  Troitsk:
  D= 1.5 m and L=7 m.

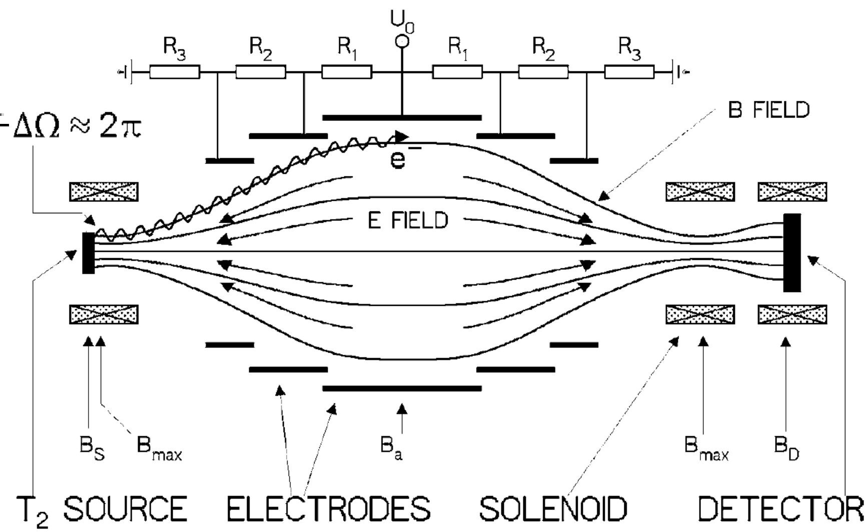
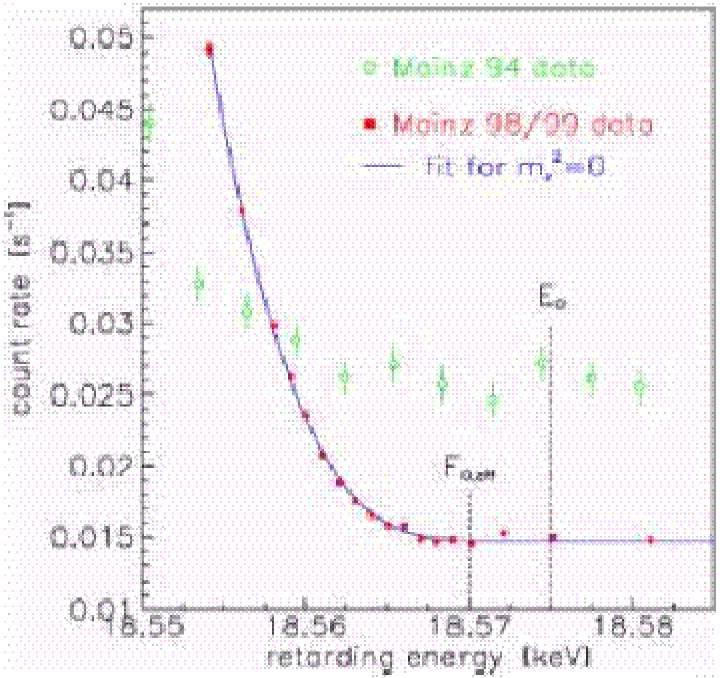
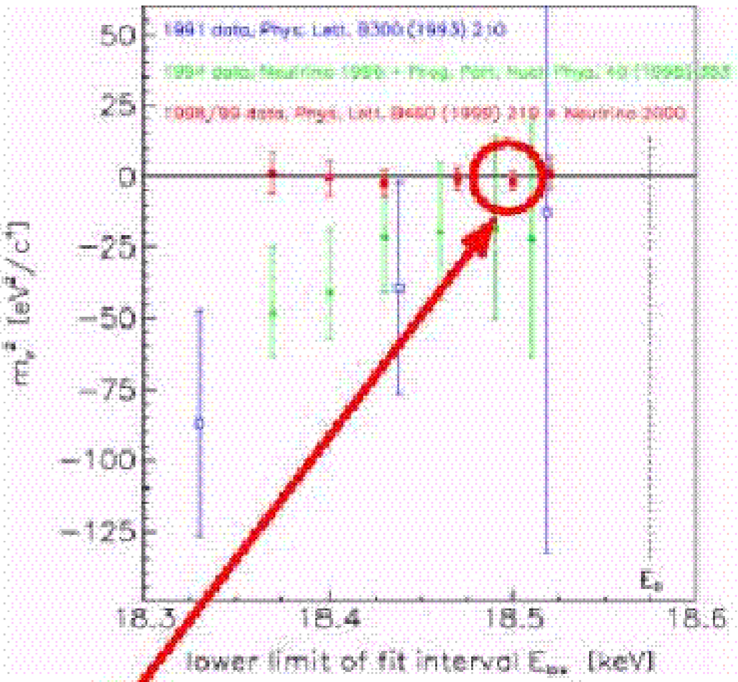


Fig. 1. Schematic sketch of the Mainz spectrometer (MAC-E-Filter).

Mainz data of 1998,1999





$m^2(\nu) = -1.6 \pm 2.5 \pm 2.1\ eV^2$ (χ^2/d.o.f. = 125/121)

$\Rightarrow$ $m(\nu) < 2.2$ eV (95% C.L.)

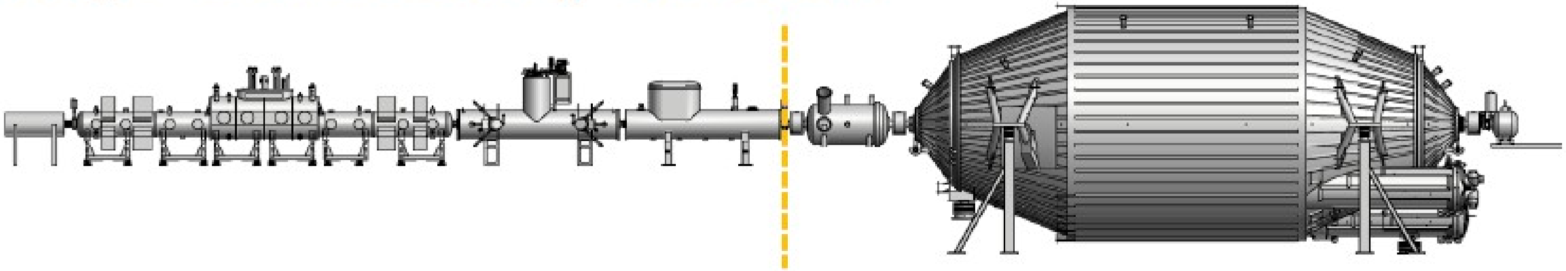
(J. Bonn et al., Nucl. Phys. B (Proc. Suppl.) 91 (2001) 273)

KATRIN experiment programmed to begin in 2008. Aim is to be sensitive to $m_{\nu_e} < 0.2$ eV

slide from my lectures in 2006

New experiment KATRIN at KARLSRUHE aims at $mc^2 \sim 0.2$ eV

large scale facility KATRIN



ß-spectroscopy at tritium endpoint $E_0 = 18.6$ keV

↳ improve precision by factor 100 (pinnacle of long history)

↳ fully adiabatic (meV-range) particle transport over > 50 m

↳ 10^{11} Bq source ⇔ 10^{-2} Bq background

tritium handling

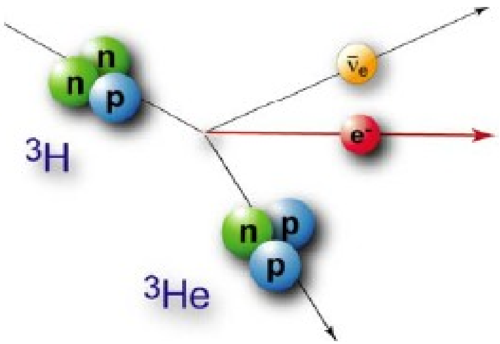
- stable supply of high purity T_2
- tritium retention factor $>10^{14}$

UHV techniques

- $p < 10^{-11}$ mbar in large spectrometers

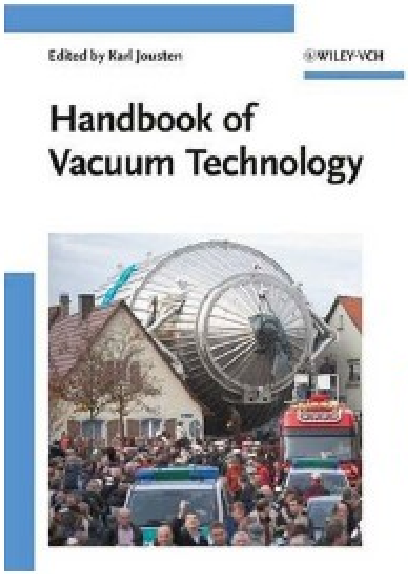
cryo engineering

- 10^{-3} temperature stabilisation of source at 27K



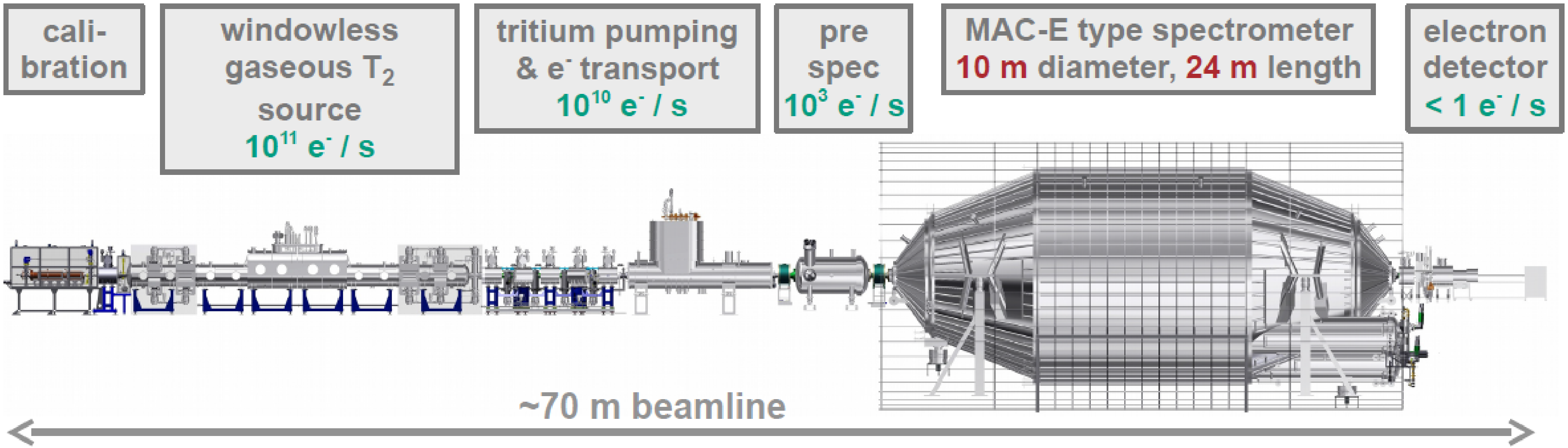
Physics run in 2019-2023!

spectrometer - transport



Oct. – Nov. 2006: 8800 km sea-going voyage from Deggendorf-FZK

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 $m(\nu_e)$:

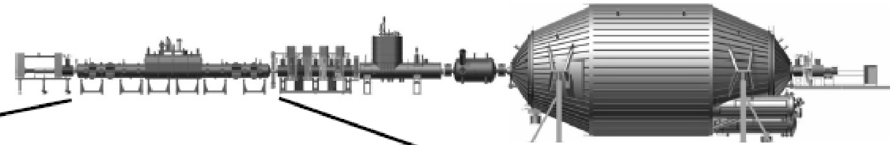
2 eV → 200 meV

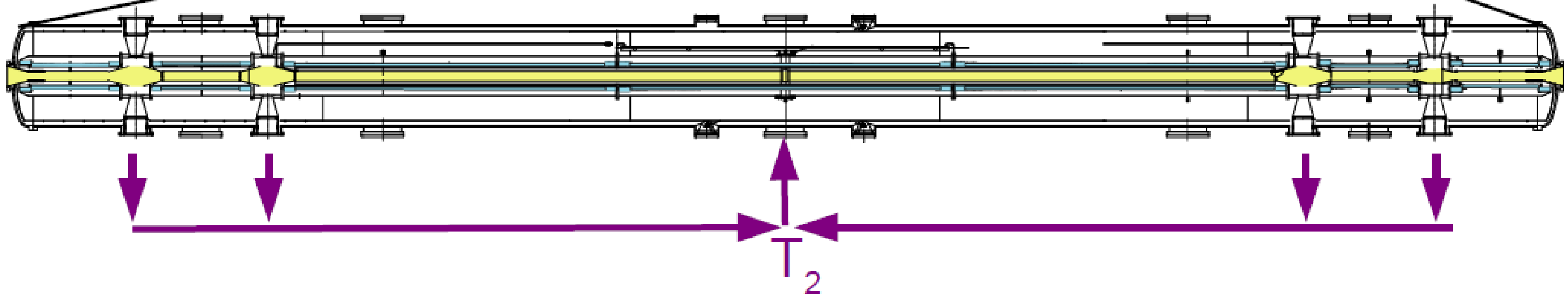
Windowless Gaseous Molecular Tritium Source WGTS

per mill stability source strength request:

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

tritium fraction f_T & ideal gas law





WGTS:

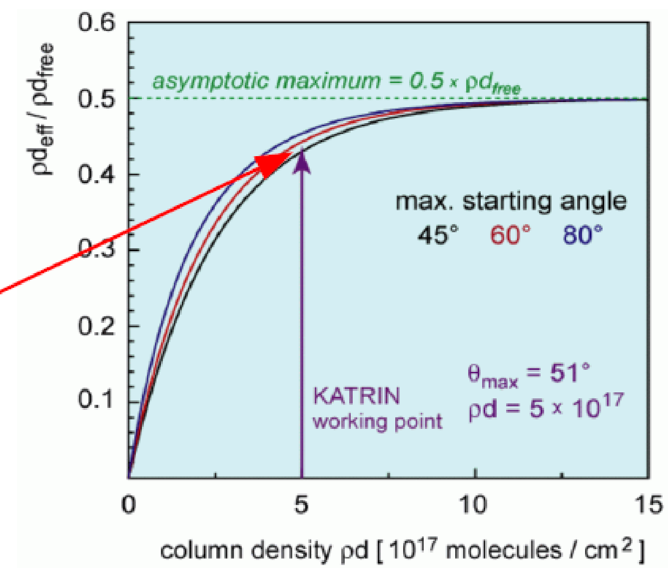
tube in long superconducting solenoids
⊘ 9cm, length: 10m, T = (30 ± 0.03) K

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

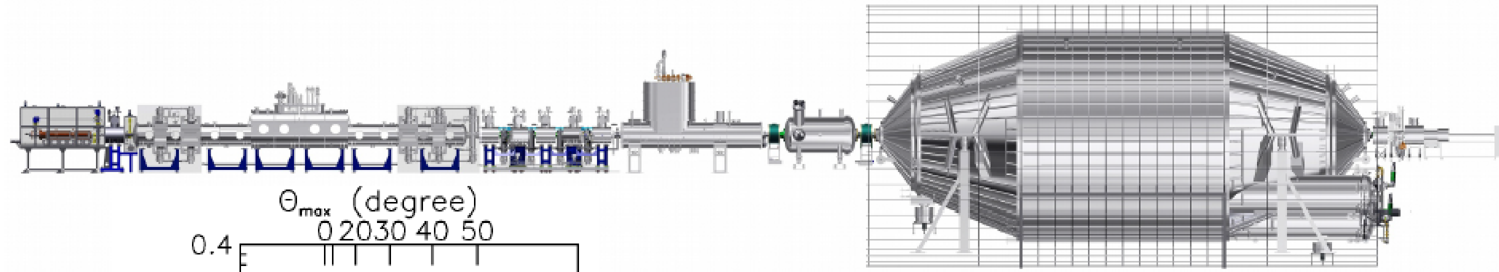
T_2 purity f_T by laser Raman spectr.

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

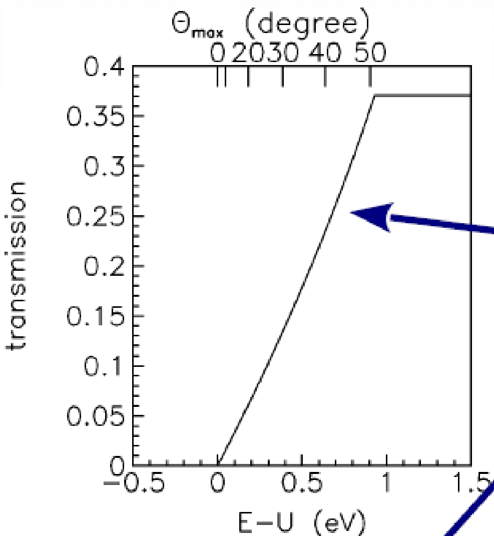
check column density by e-gun



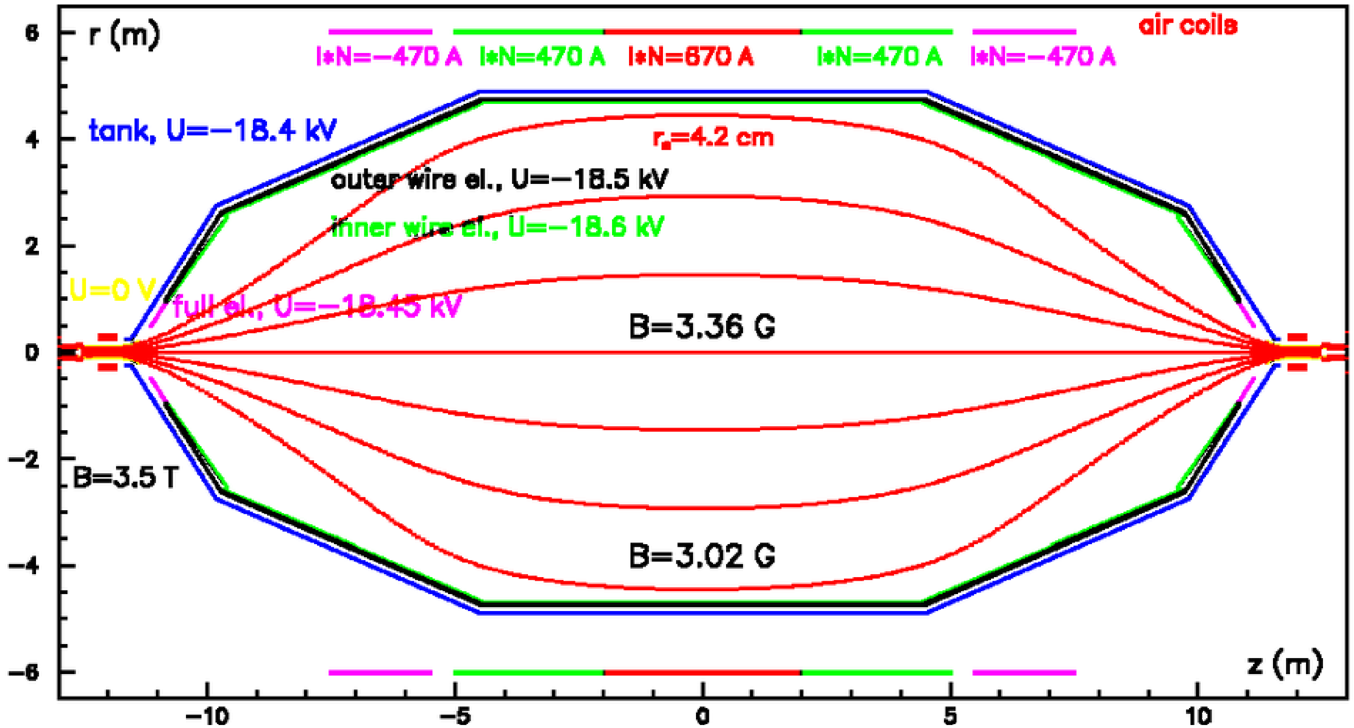
The KATRIN Main Spectrometer: an integrating high resolution MAC-E-Filter



Integral transmission function:
$\Delta E = E \cdot B_{min}/B_{max}$ = 0.93 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



: Electromagnetic design of the KATRIN main spectrometer with two-layer wire electrodes

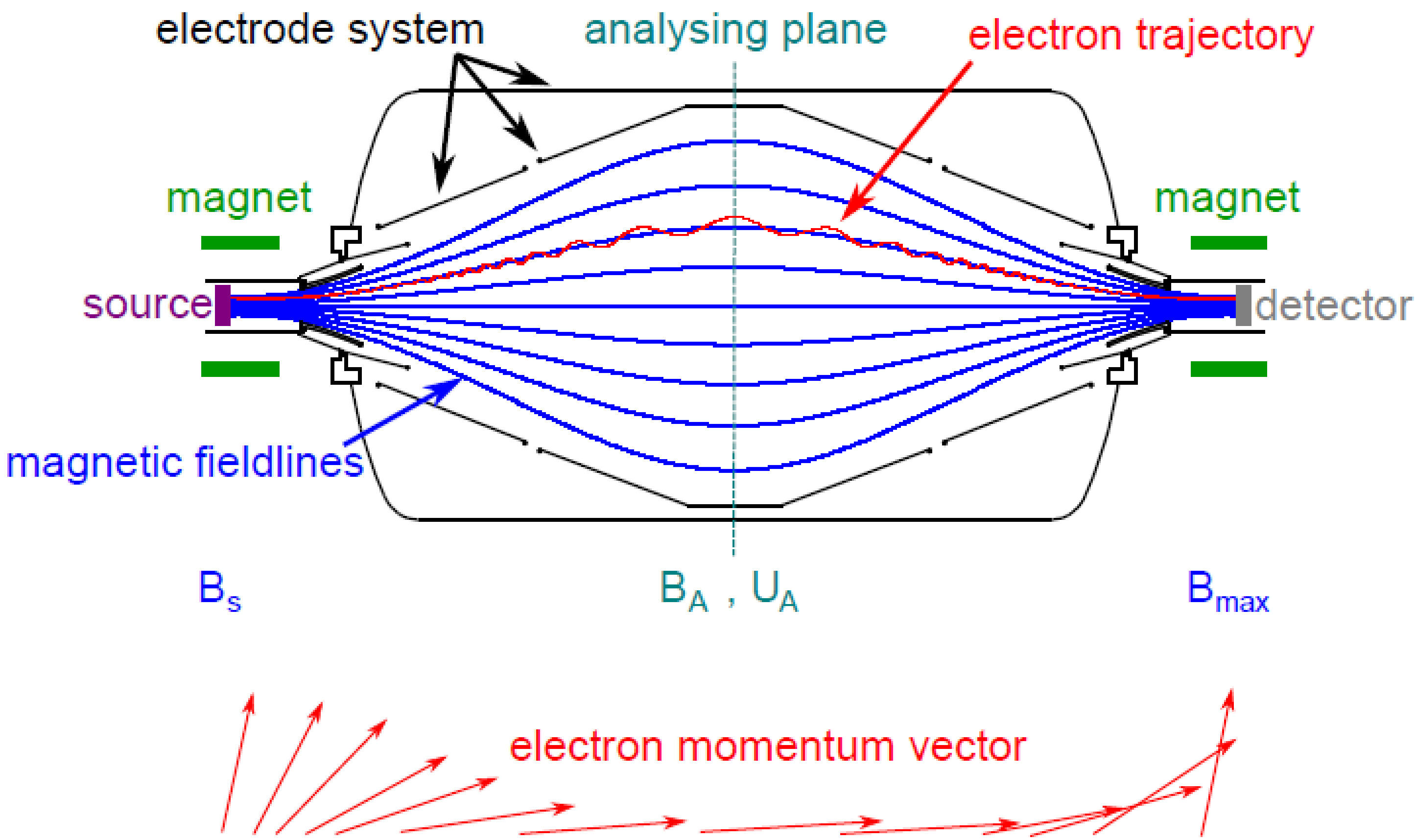
Take electrons of any momentum orientation in high B-field (B = 3.5 T) and make the adiabatic transformation to longitudinal momentum in very small B-field (B_{min} = 3.36 G)   (1T = 10’000 G)

Conservation of angular momentum

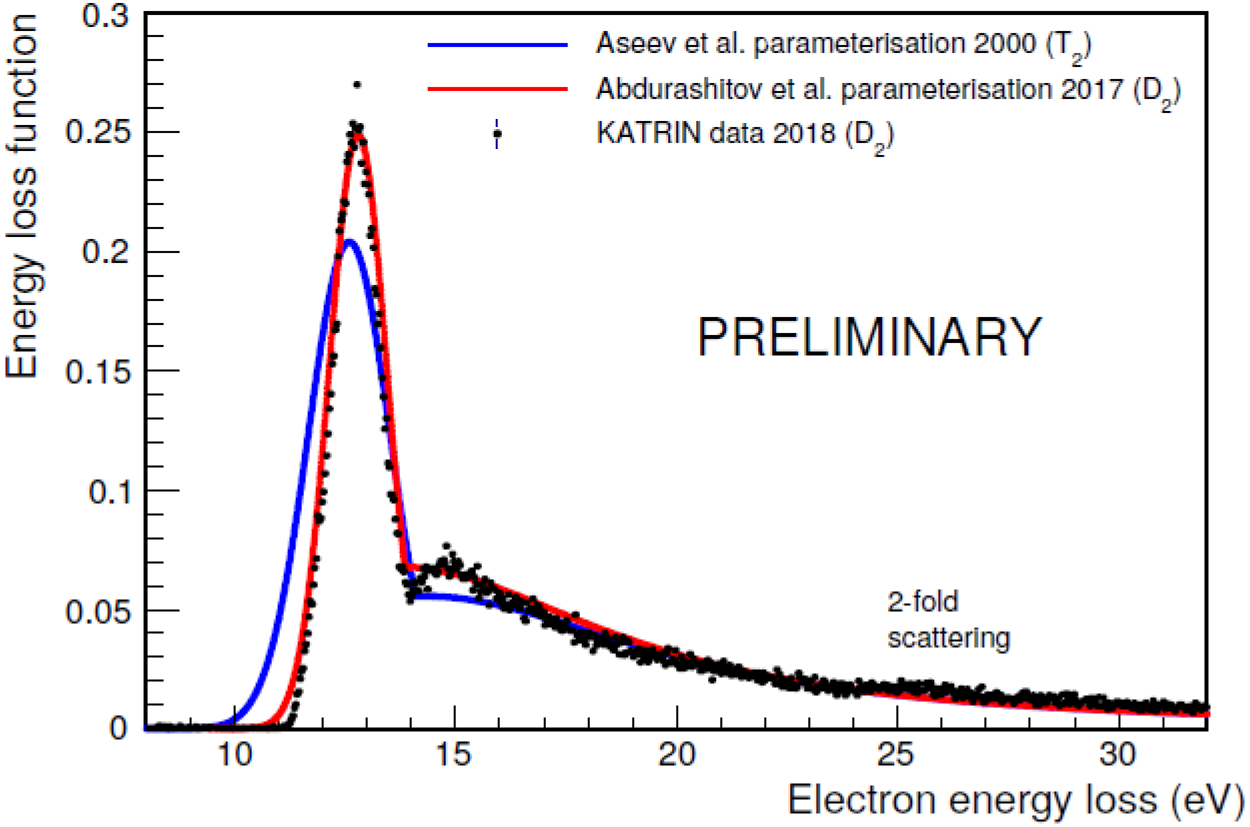
$L = P_T.R$ with $R = P_T/0.3B$ → $L = P_T^{\,2}/0.3B$ =Cte → P_T scales as 1/sqrt(B)

Magnetic Adiabatic Collimation & Electrostatic filter

- Align electrons along electrostatic field
- Select all signal electrons with $E > qU_A \left(1 + \frac{B_A}{B_{max}}\right)$



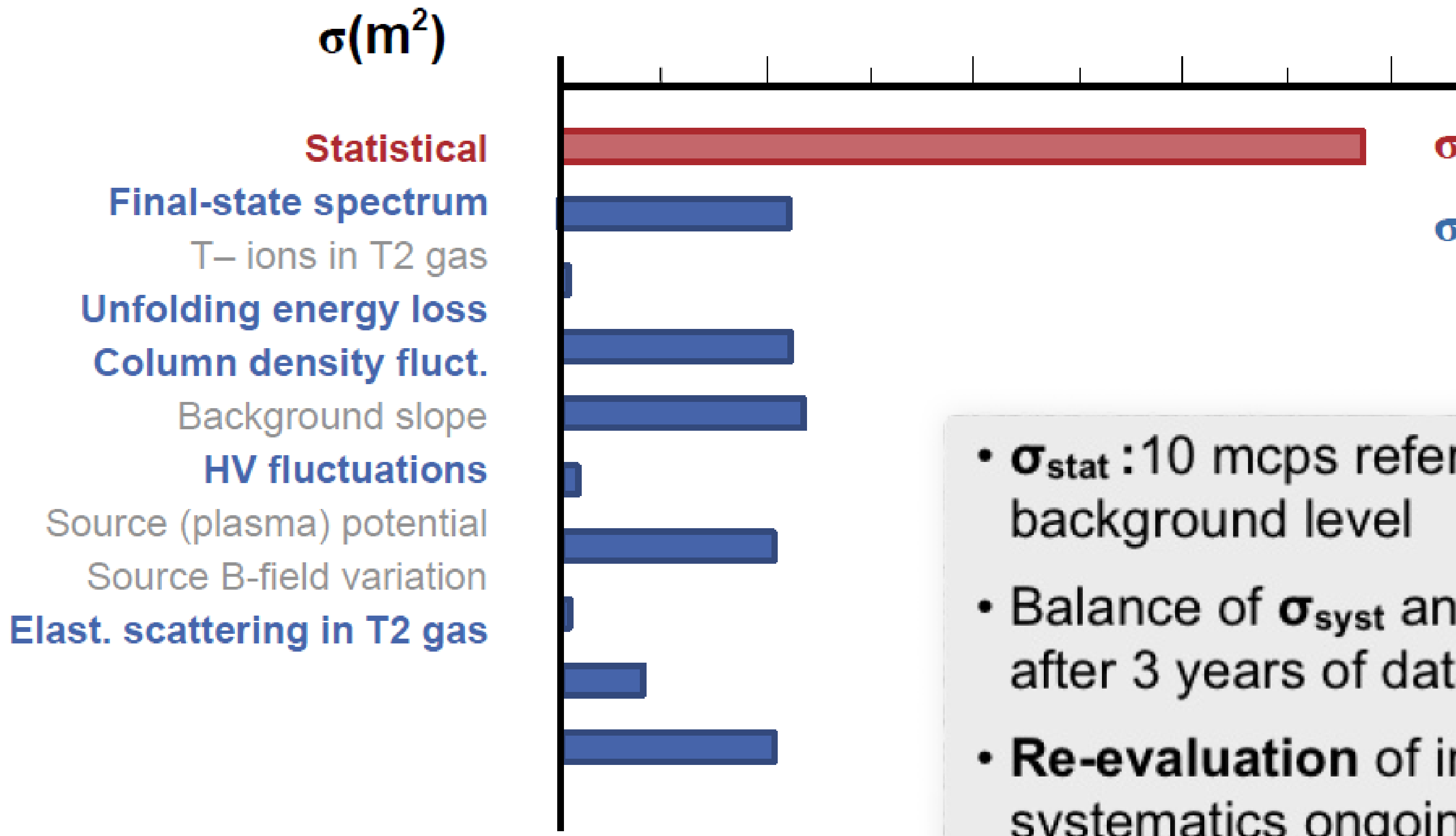
- Electron gun data (0.2 eV resolution)
- Time of flight measurement



⇒Refines KATRIN model

data taken in 2018 presented at Moriond EW 2019 (March) by V. Sibille

KATRIN's uncertainty budget (design sensitivity, ~2004):



$\sigma(m^2)_{stat} = 0.018$ eV

$\sigma(m^2)_{syst} = 0.017$ eV

- σ_{stat} : 10 mcps reference background level
- Balance of σ_{syst} and total σ_{stat} after 3 years of data
- **Re-evaluation** of individual systematics ongoing during system characterisation

Statistical & systematic uncertainties

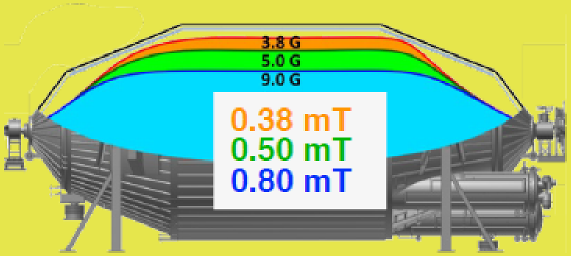
3 yr of data taking

sensitivity on the neutrino mass (stat.+sys. uncertainties):

→ 200 meV (design value)

Higher (Rydberg) background rate

→ using larger data range (E_0-60 eV) and a bit less energy res.:



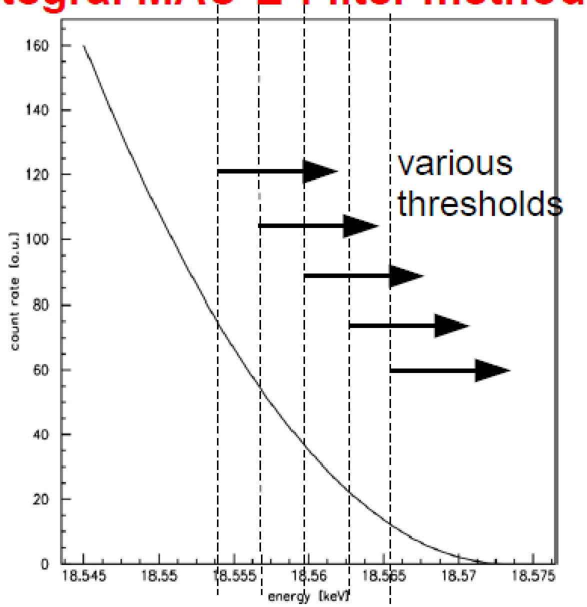
→ 240 meV (without further mitigation of the Rydberg background)

„Science“ data taking 2019 – 2023

and hopefully beyond with upgrades

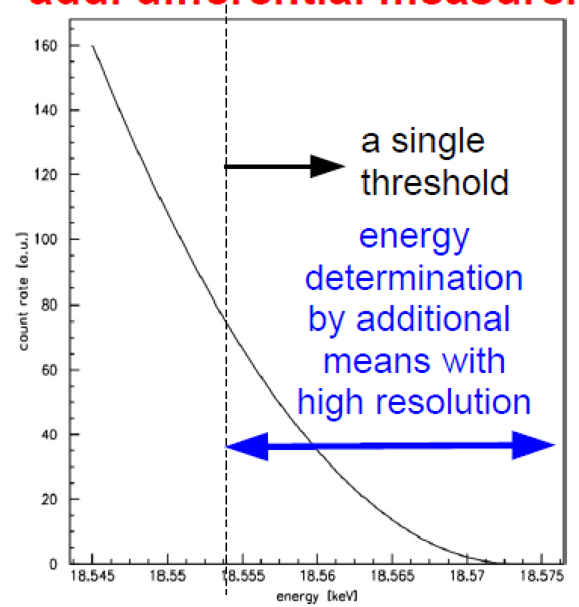
Gain of additional differential method
avoiding loss of statistics by many filter settings

Integral MAC-E-Filter method



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

add. differential measurement



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,

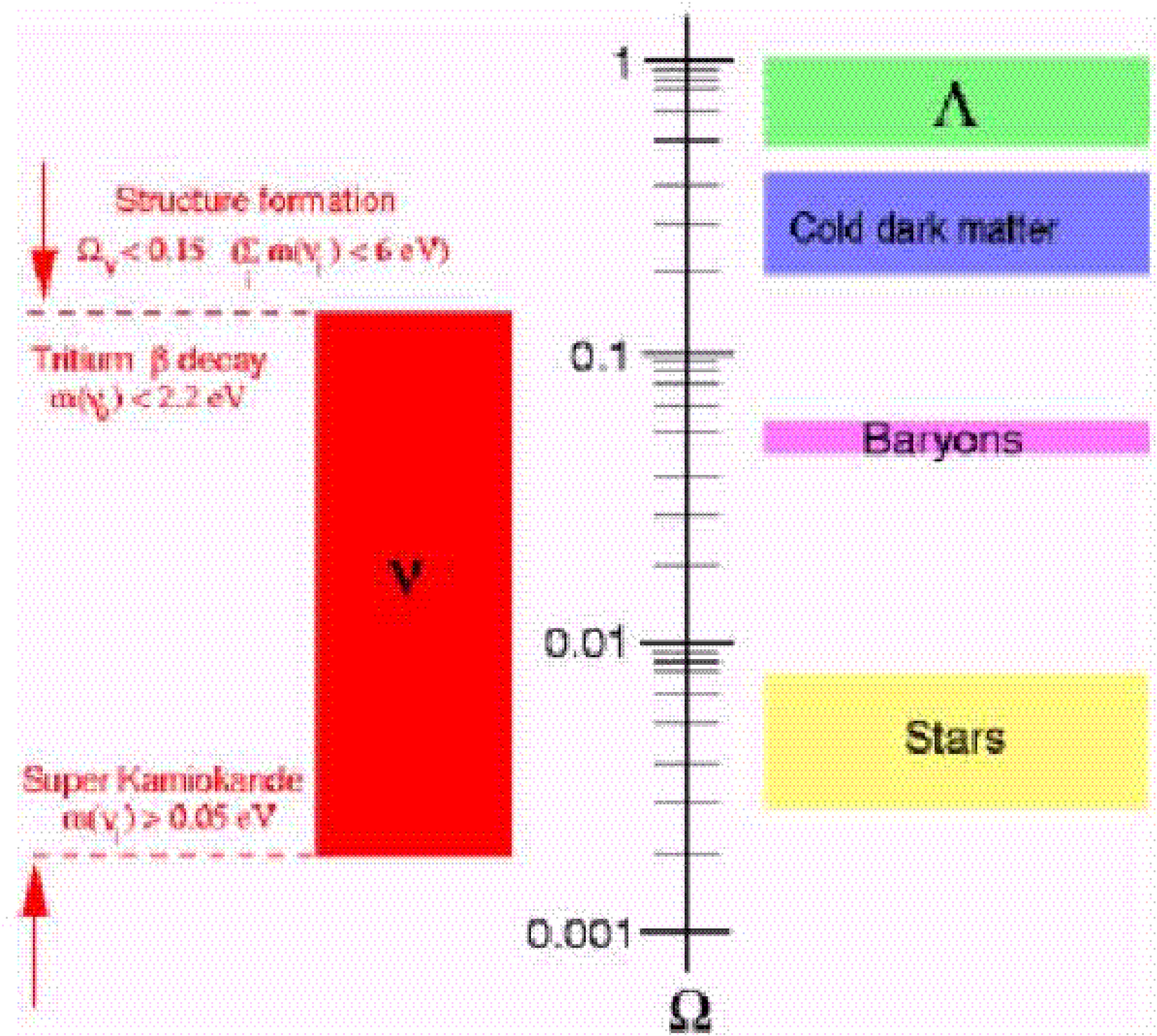
i.e. up to a factor of 2.5 in m_ν w.r.t. standard KATRIN !

→ KATRIN could reach < 100 meV with such a method

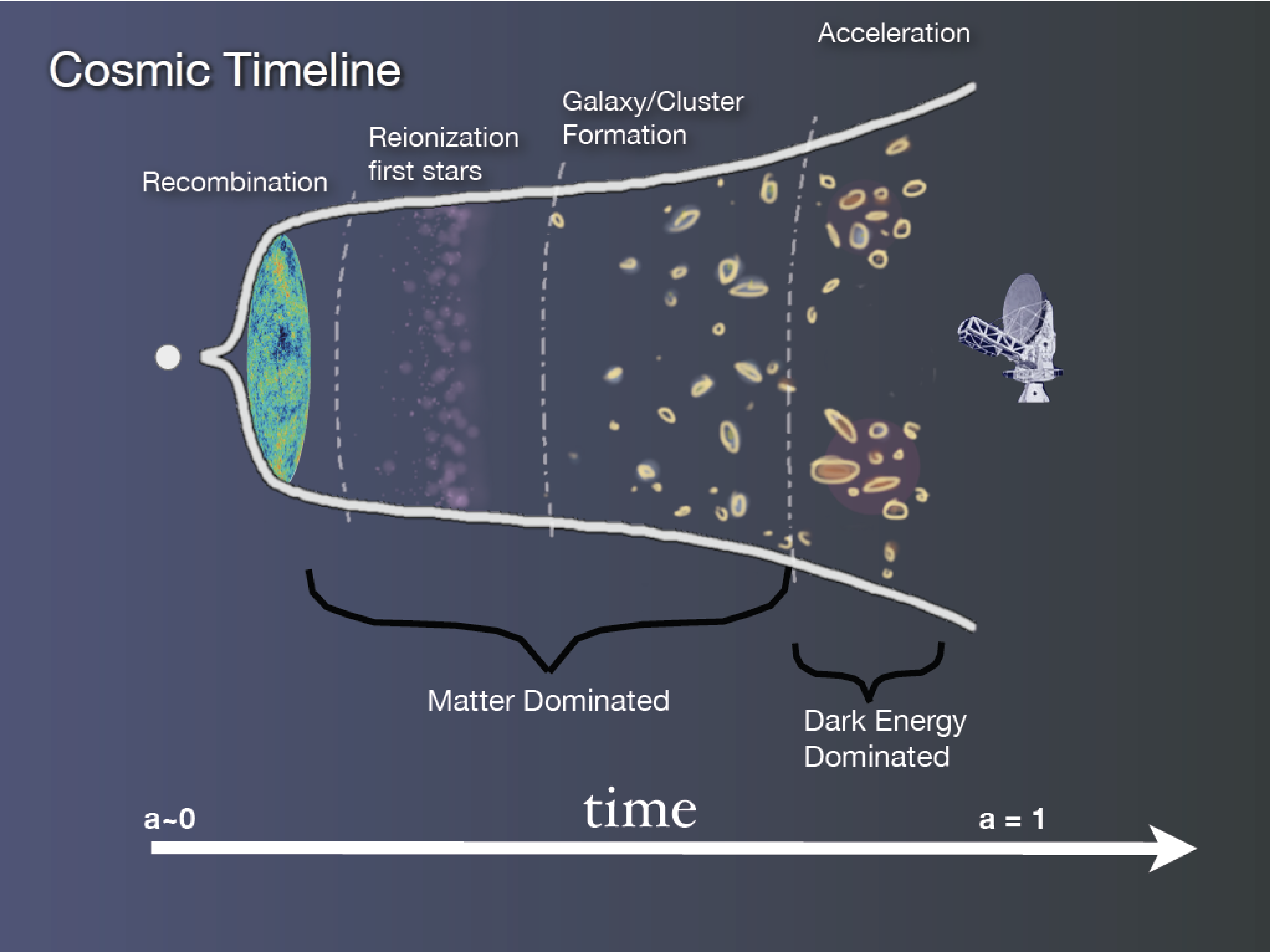
← Numbers are in agreement with simulations in dipl. thesis of A. Mertens, KIT, 2012

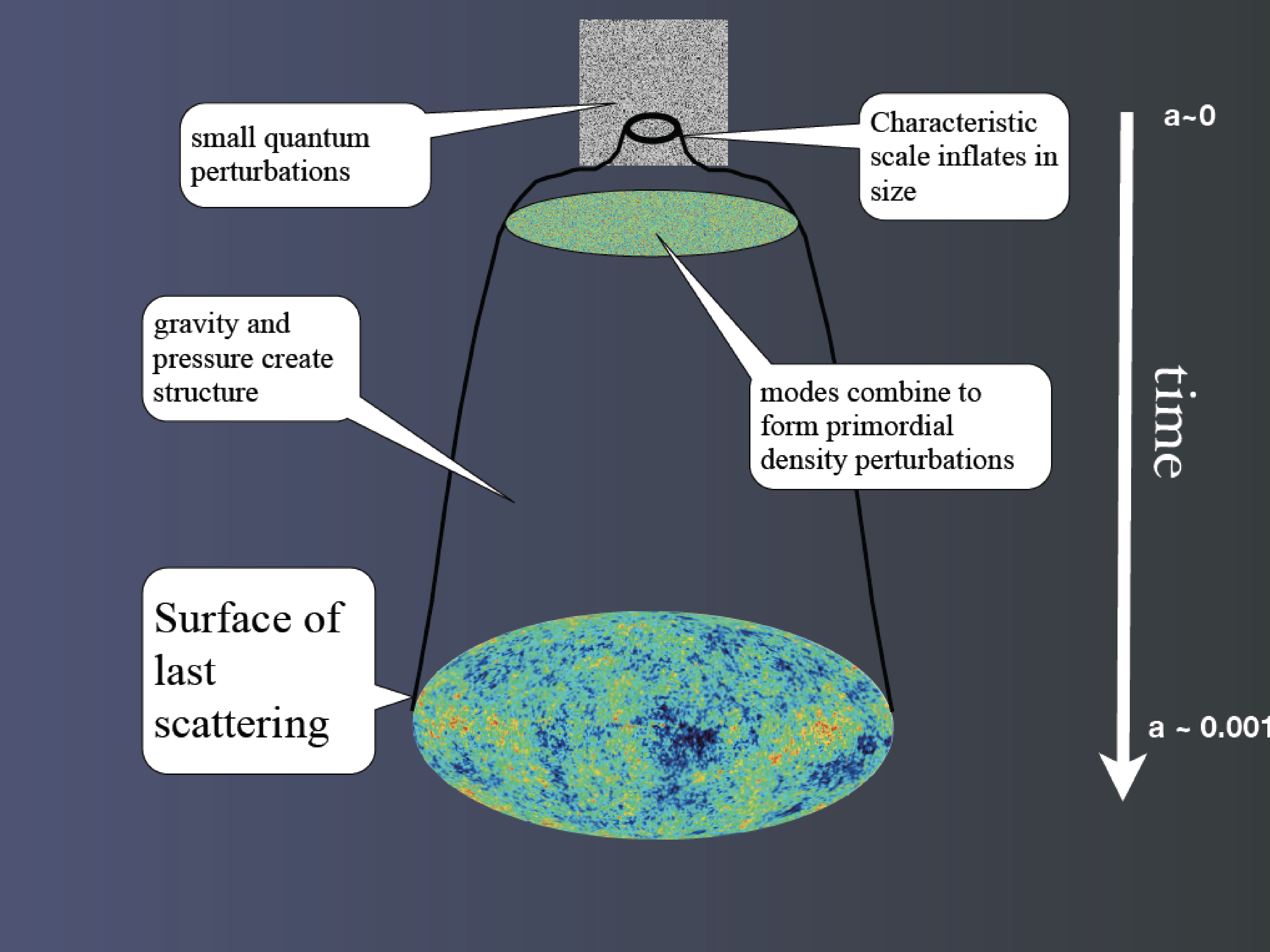
What IS the neutrino mass?????

Cosmology and neutrino mass



There is a long way to go to match direct measurements of neutrino masses with oscillation results and cosmological constraints


Cosmic Timeline
Acceleration
Galaxy/Cluster Formation
Reionization first stars
Recombination
Matter Dominated
Dark Energy Dominated
time
a~0
a = 1


small quantum perturbations
Characteristic scale inflates in size
a~0
gravity and pressure create structure
modes combine to form primordial density perturbations
time
Surface of last scattering
a ~ 0.001

Direct exploration of the Big Bang -- Cosmology

measurements of the large scale structure of the universe using a variety of techniques

-- Cosmic Microwave Background
-- observations of red shifts of distant galaxies with a variety of candles.
Big news in 2002 : Dark Energy or cosmological constant

→large scale structure in space, time and velocity is determined by early universe fluctuations, thus by mechanisms of energy release (neutrinos or other hot dark matter)

The early universe is sensitive to neutrinos which are carriers of fast, weakly interacting, kinetic energy.

Number of neutrino (or neutrino-like) degrees of freedom

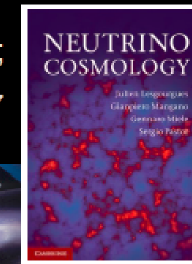
controls the size of the effects

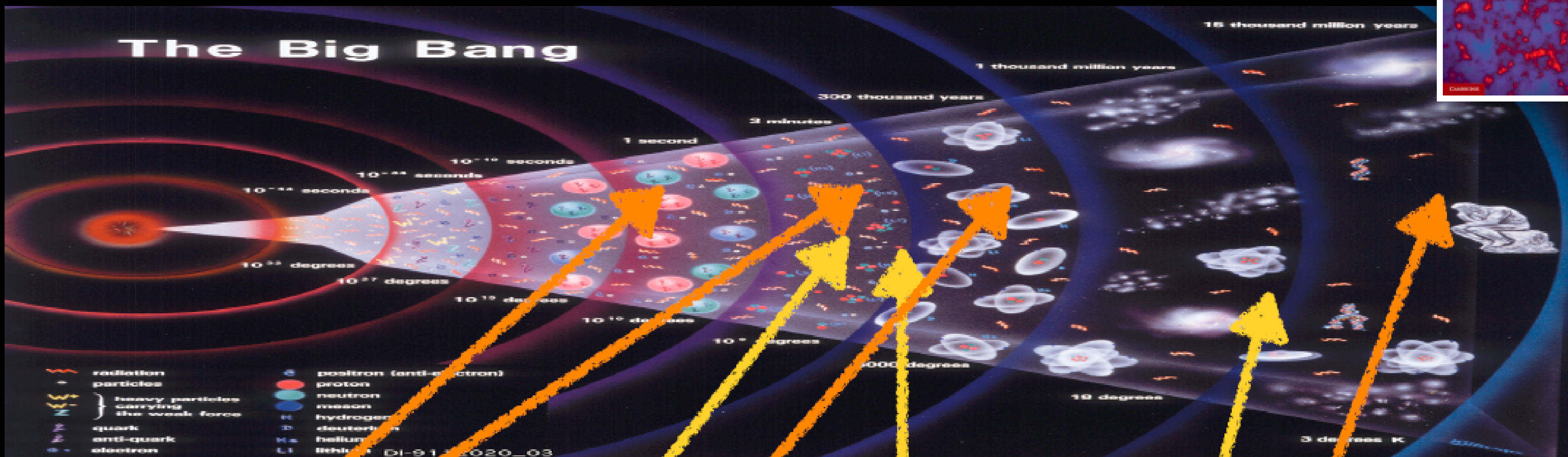
Mass of neutrinos

controls the velocity of neutrinos and the energy at which they stop being relevant

What neutrino effects are we testing?

JL & Pastor Pys. Rep. 2016; JL, Mangano, Miele, Pastor “Neutrino Cosmology” CUP;
Drewes et al. 1602.04816; PDG review: JL & Verde “Neutrinos in Cosmology”; Gerbino & Lattanzi 2017





relativistic **neutrino** contribution to early expansion

metric fluctuations during non-relativistic **neutrino** transition (early ISW)

non-relativistic **neutrino** contribution to late expansion rate (acoustic angular scale)

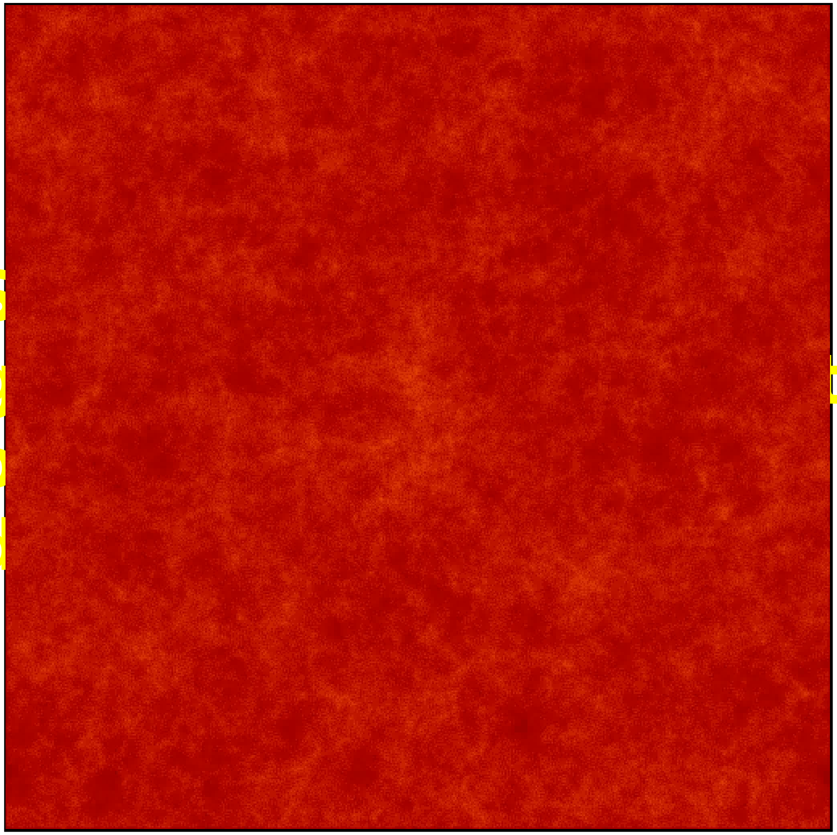
neutrino slow down early dark matter clustering

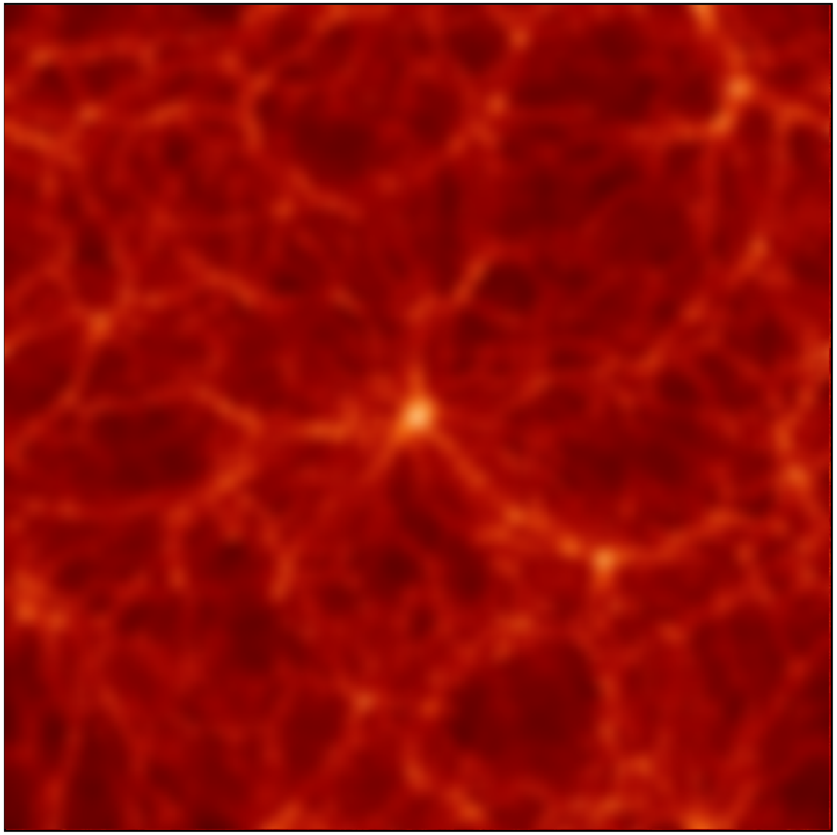
neutrino propagation and dispersion velocity

neutrino slow down late ordinary/dark matter clustering

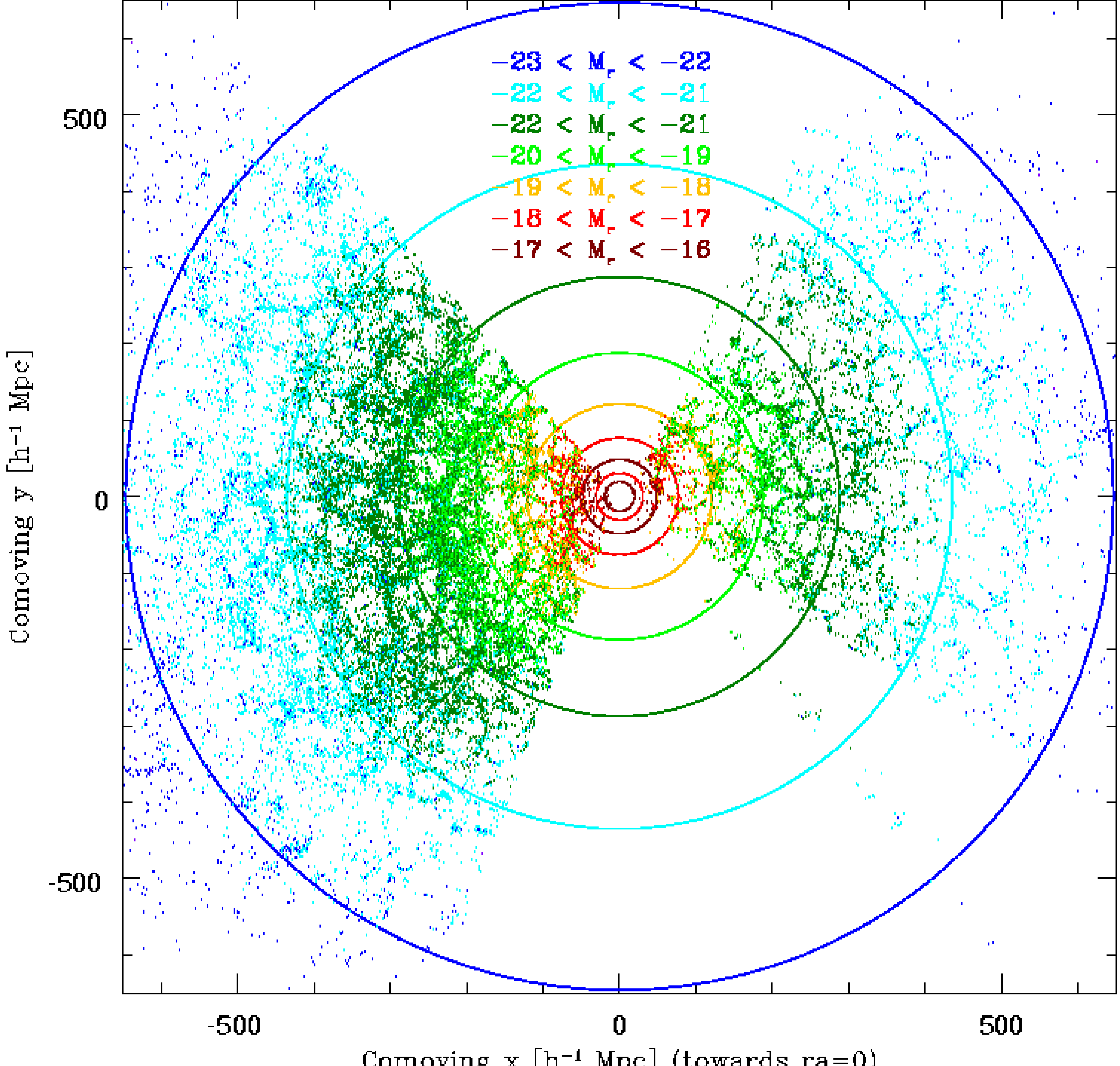
Formation of Structure

Smooth	→	Structured





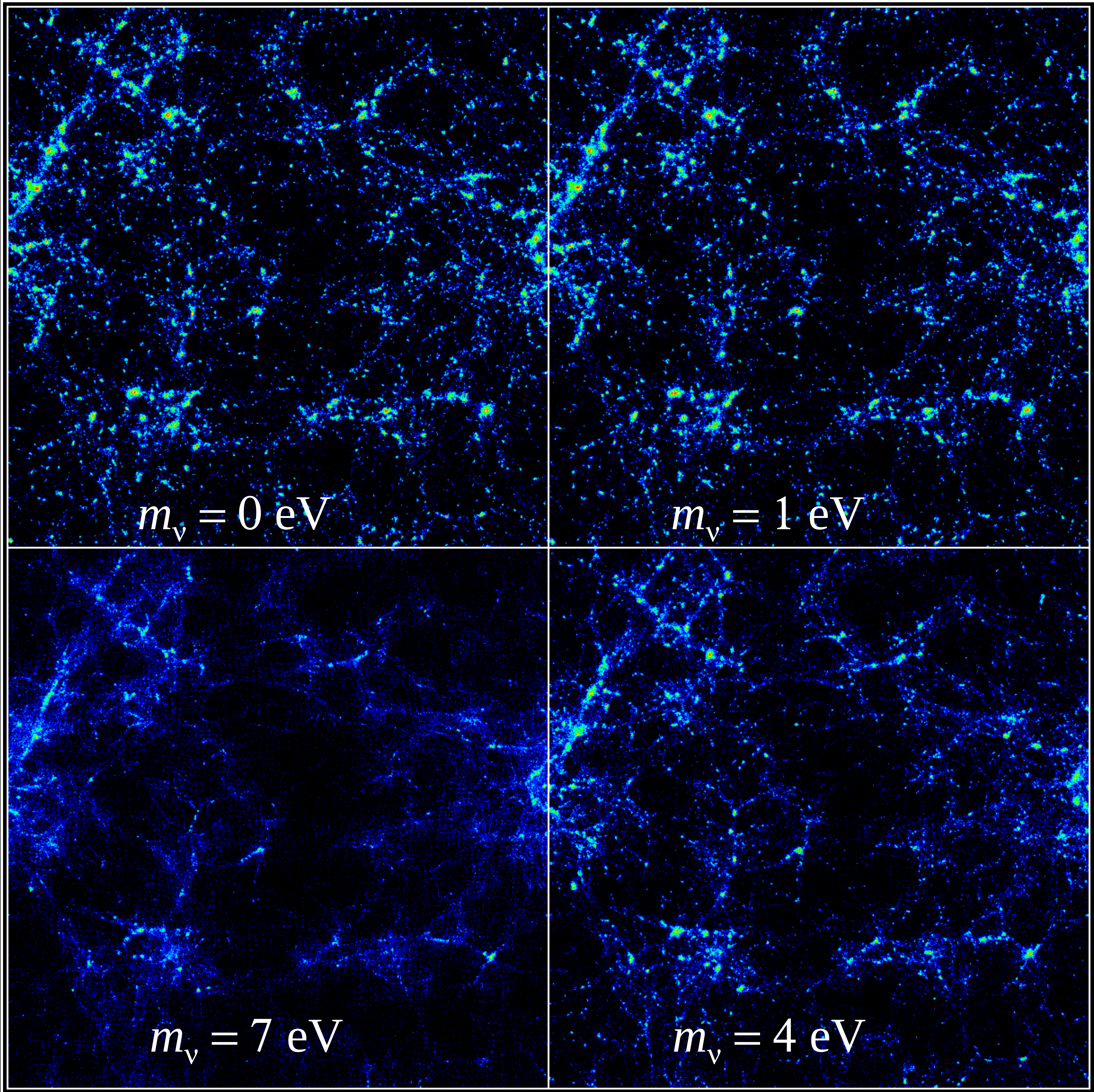
fraction of hot dark matter
uppresses small-scale structu

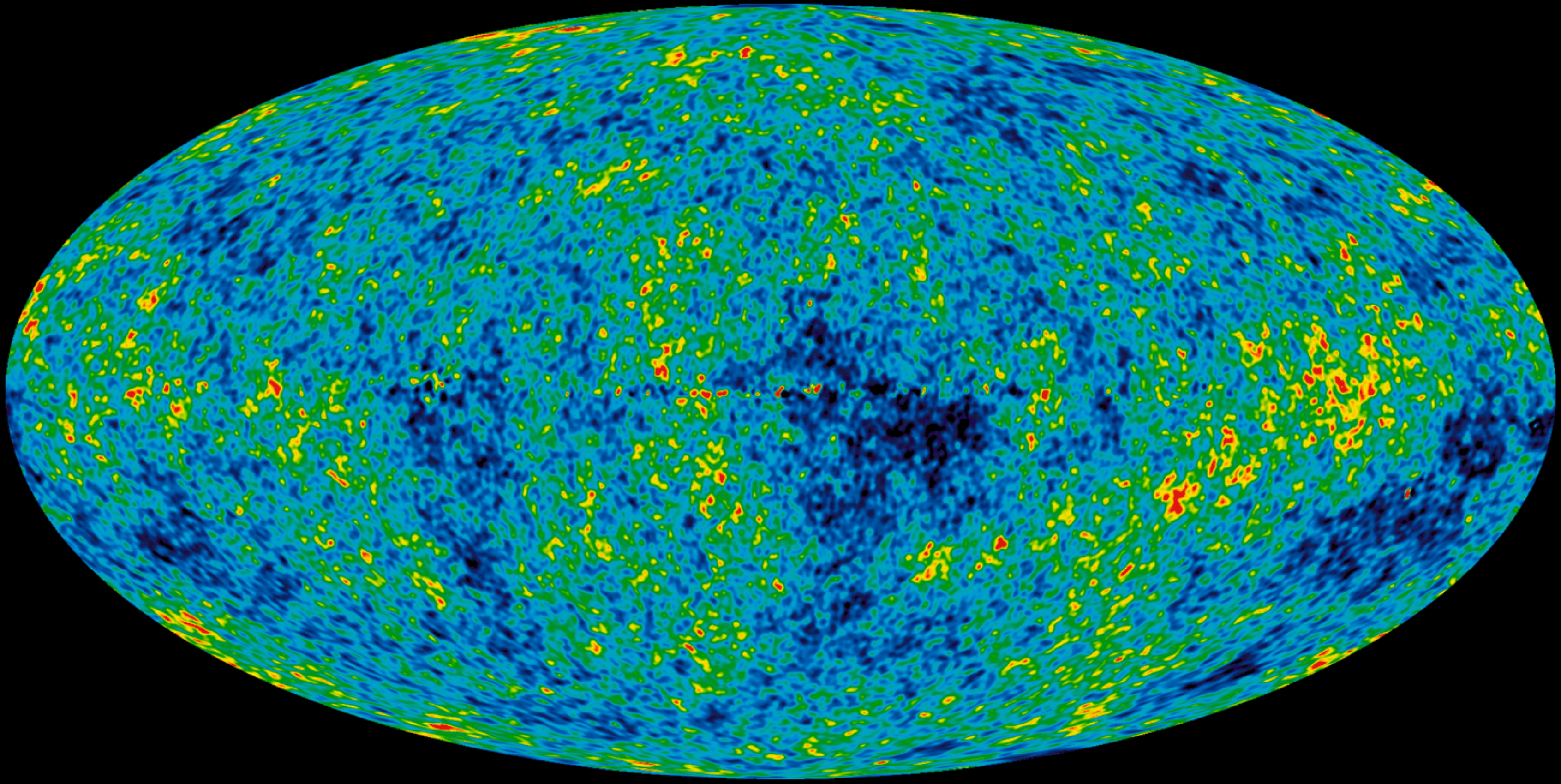


−23 < M_r < −22
−22 < M_r < −21
−22 < M_r < −21
−20 < M_r < −19
−19 < M_r < −18
−18 < M_r < −17
−17 < M_r < −16
500
0
-500
Comoving y [h⁻¹ Mpc]
-500
0
500
Comoving x [h⁻¹ Mpc] (towards ra=0)

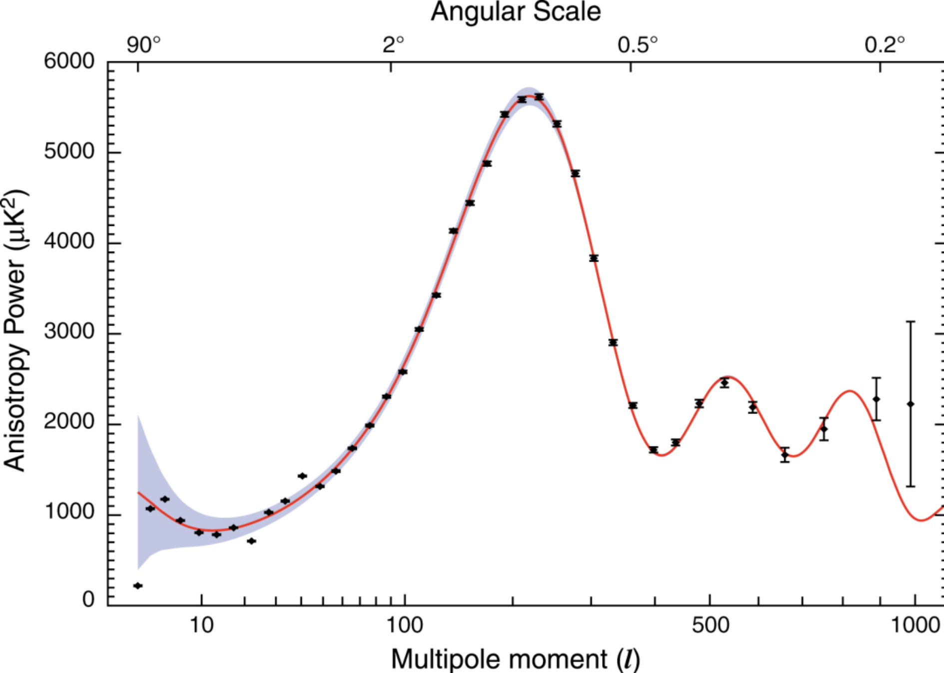
Halzen

adding hot neutrino dark matter erases small structure





http://map.gsfc.nasa.gov/



see e.g.
http://www.nu.to.infn.it/Neutrino_Cosmology/

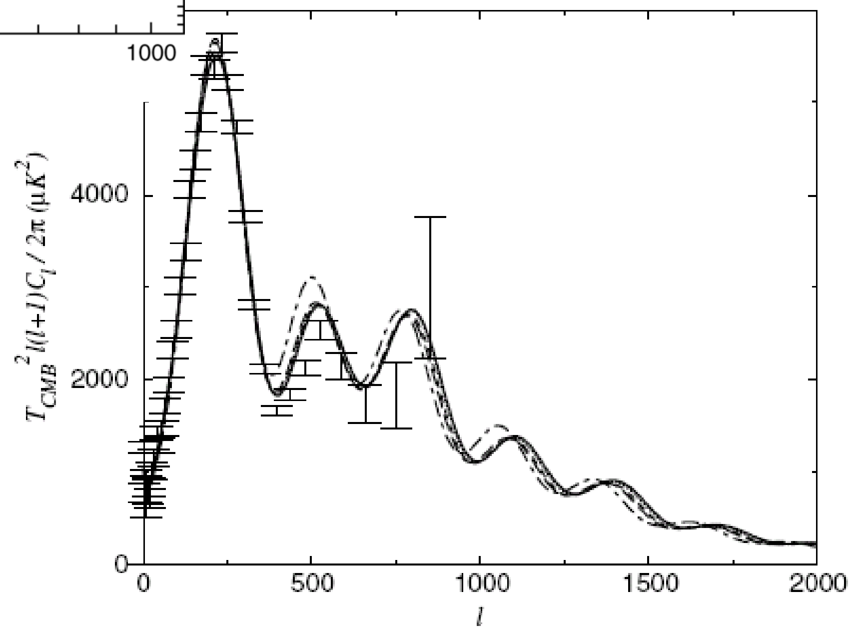
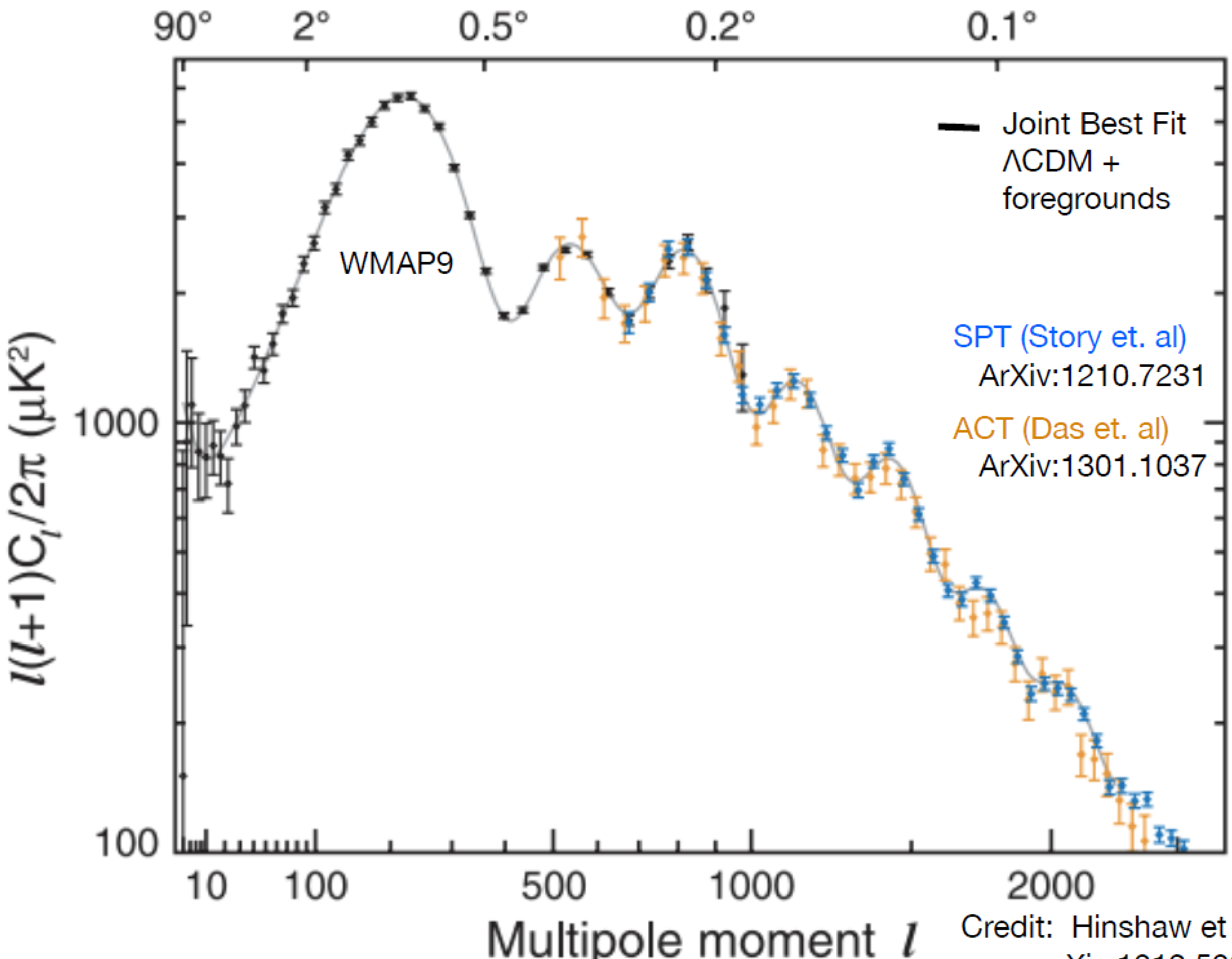
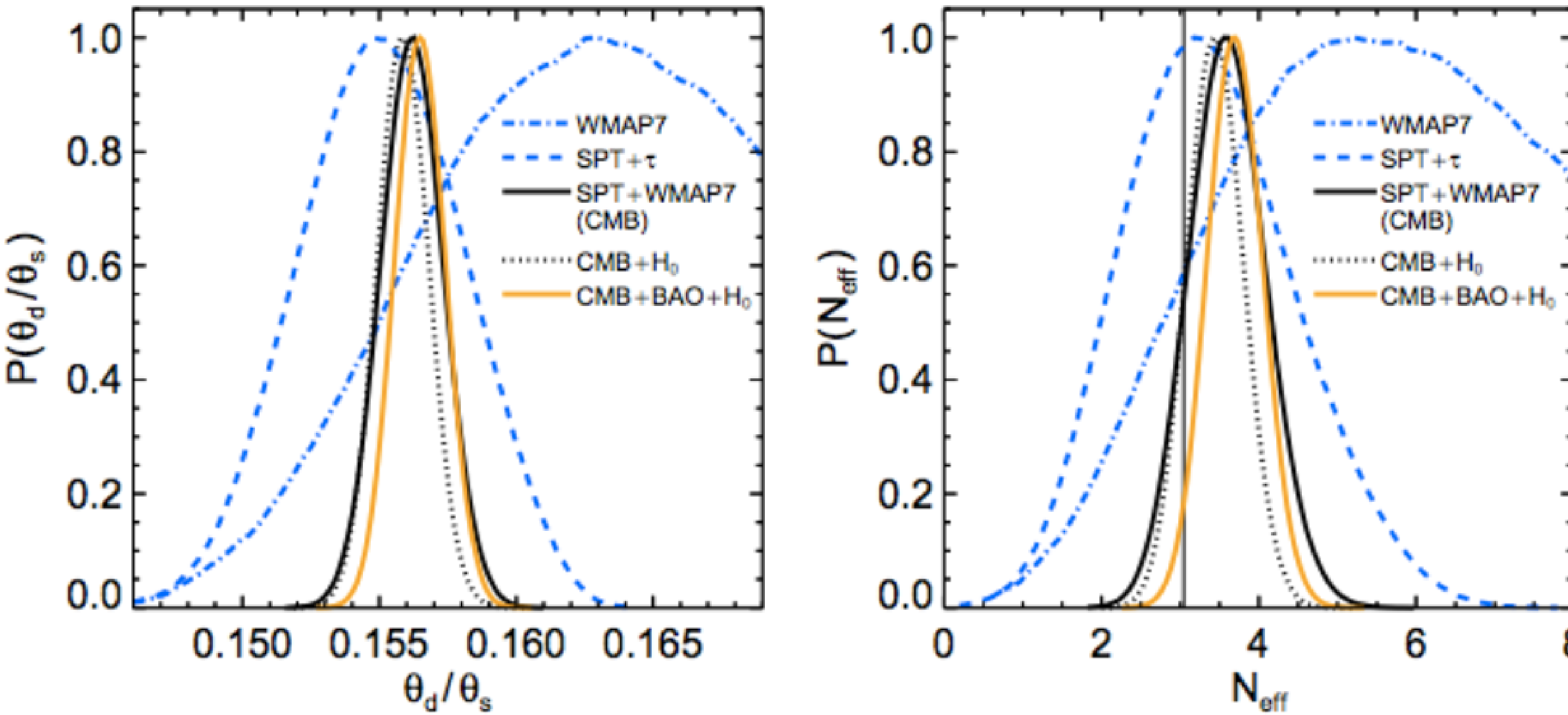


Figure 4. CMB power spectra for neutrino mass per flavour $m_\nu = 0$ (———), $m_\nu = 0.1$ (..........), $m_\nu = 0.3$ (- - - - -), $m_\nu = 0.5$ (– – – – –), and $m_\nu = 3$ eV (·–·–·–·–·). The other parameters are fixed at $\Omega_m = 0.3$, $\Omega_b = 0.04$ and $h = 0.7$. The vertical bars are the WMAP power spectrum data points.



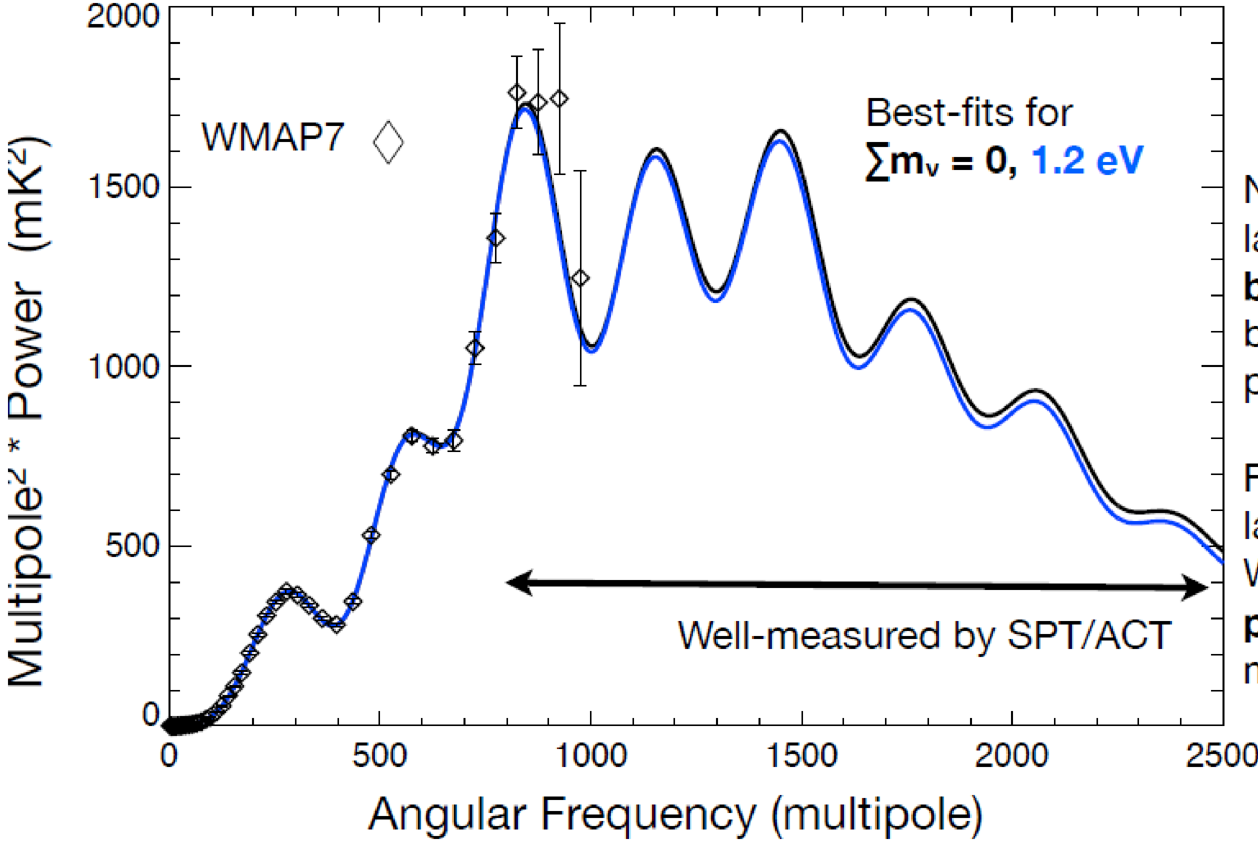
Credit: Hinshaw et al.
arXiv:1212.5226

Number of Neutrino-like Species (N_{eff})



- N_{eff} = 3.62 ± 0.48 (SPT+WMAP7)
- N_{eff} = 3.71 ± 0.35 (SPT+WMAP7+H_0+BAO) (1.9 σ higher than 3.046)
- N_{eff} = 2.97 ± 0.56 (ACT+WMAP7)
- N_{eff} = 3.50 ± 0.42 (ACT+WMAP7+H_0+BAO)

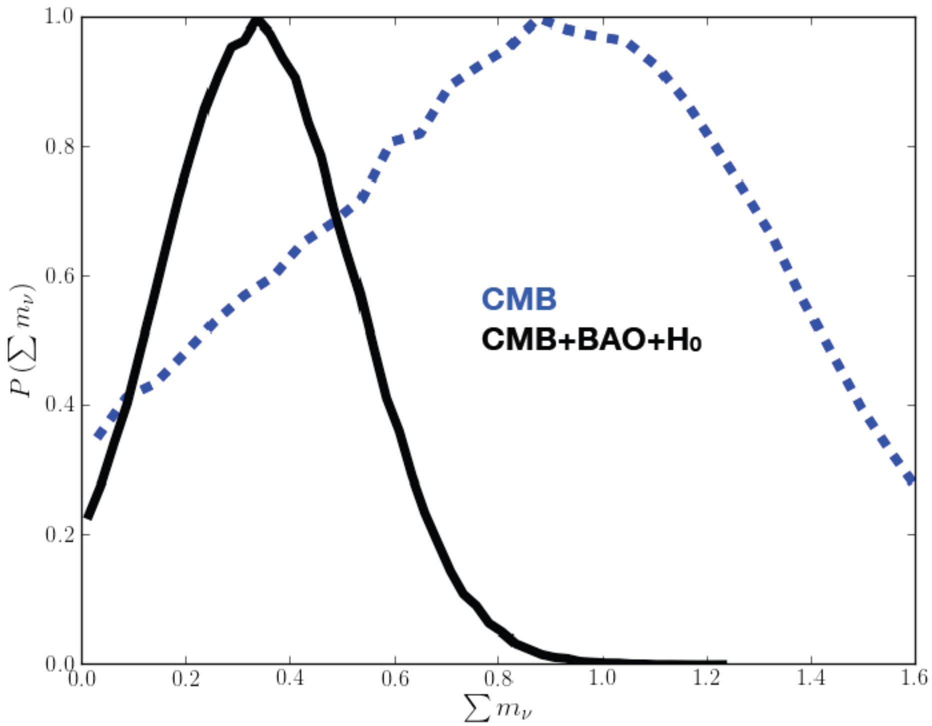
Massive neutrinos from the CMB



Neutrino mass affects largest scales, but **can be compensated for** by changing other parameters

Fixing the power at large scales to match WMAP gives **lower power** at small scales measured by **SPT/ACT**

Mass constraints from the CMB



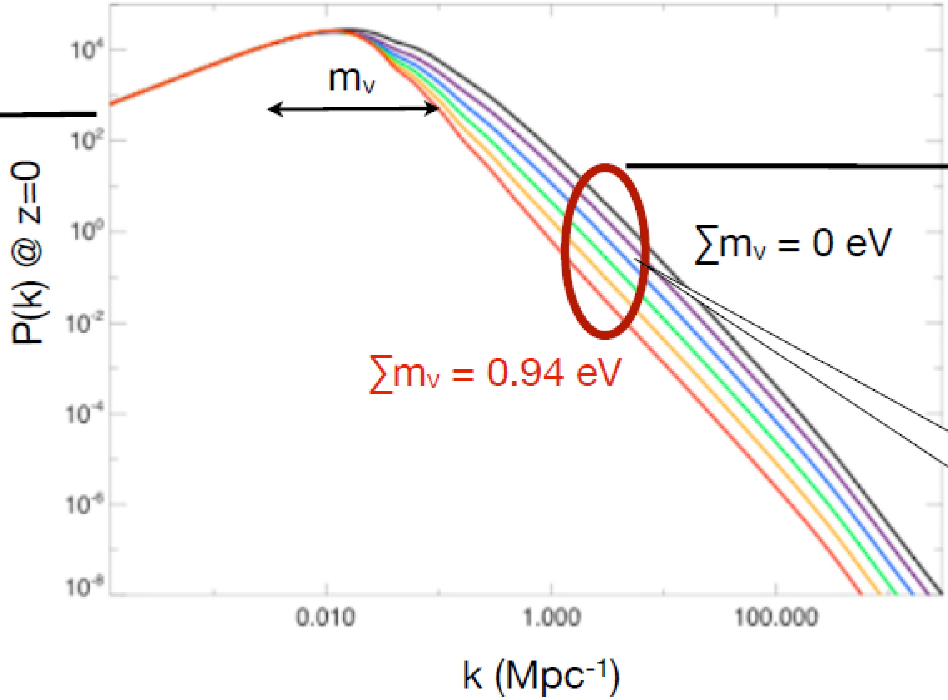
BAO and **H_0** measurements provide low-redshift information on the hubble rate at recent times

CMB is consistent at < 2 σ with massless neutrinos--**not very satisfying!**

As seen by structure growth

0.1 eV changes cluster abundance by **25%**

Large scales:
Faster expansion & clustering cancel (no net change)

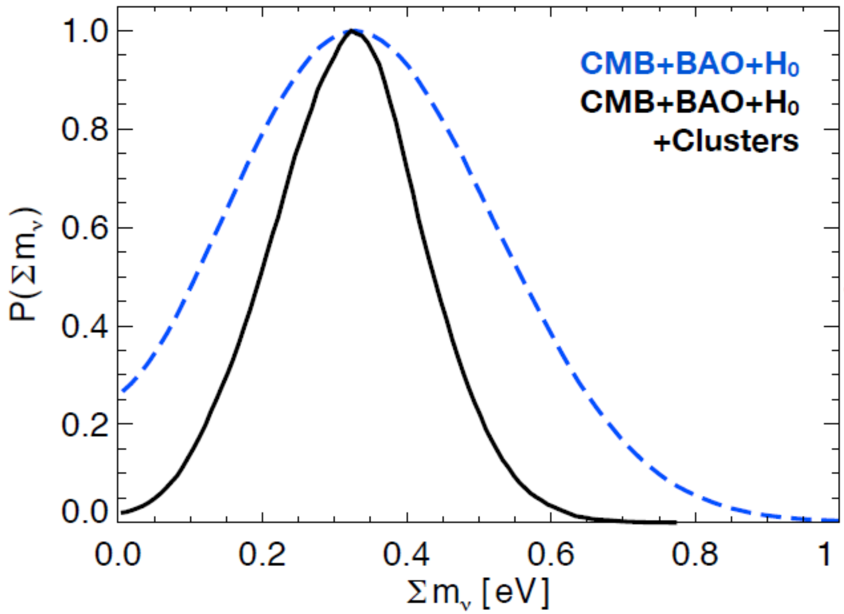


Small scales:
Faster expansion suppresses structure

Determines the number and mass of clusters

Hou, Reichardt et al., arXiv:1212.6267

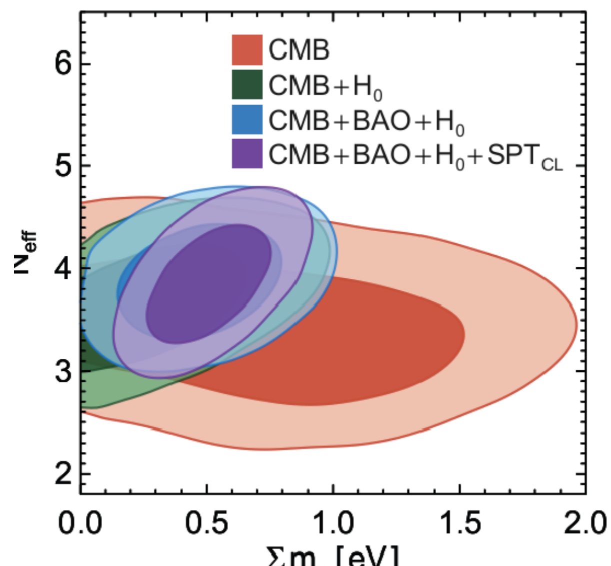
Hints of massive neutrinos



Including everything:
$\sum m_\nu = 0.32 \pm 0.11$ eV
3σ preference for $\sum m_\nu > 0$

Extra massive neutrinos

Altogether not very significant
… and model-dependent.
Shows sensitivity of our universe
to the minute properties of neutrinos



CMB + low redshift geometry:

$$N_{eff} = 3.89 \pm 0.37$$

$$\sum m_\nu = (480 \pm 210)\ \mathrm{meV}$$

CMB+low redshift geometry
+ Large Scale Structure:

$$N_{eff} = 3.86 \pm 0.37$$

$$\sum m_\nu = (510 \pm 150)\ \mathrm{meV}$$

More recent results

Neutrinos from cosmology, Graziano Rossi, Moriond 2016 EW
https://indico.in2p3.fr/event/12279/other-view?detailLevel=contribution&showSession=all&view=nicecompact&showDate=all

KEY RESULTS

INDIVIDUAL CONSTRAINTS ON $\sum m_\nu$ (95% CL)

$\sum \mathbf{m}_\nu < \mathbf{0.12}$ **eV** $\rightarrow$ CMB + Lyman-α + BAO

JOINT CONSTRAINTS ON $N_{\rm eff}$ AND $\sum m_\nu$ (95% CL)

$\mathbf{N}_{\rm eff} = \mathbf{2.88}^{+0.20}_{-0.20}$ & $\sum \mathbf{m}_\nu < \mathbf{0.14}$ **eV** $\rightarrow$ CMB + Lyman-α + BAO

1. Results on $\sum m_\nu$ tend to favor the *normal hierarchy scenario* for the masses of the active neutrino species

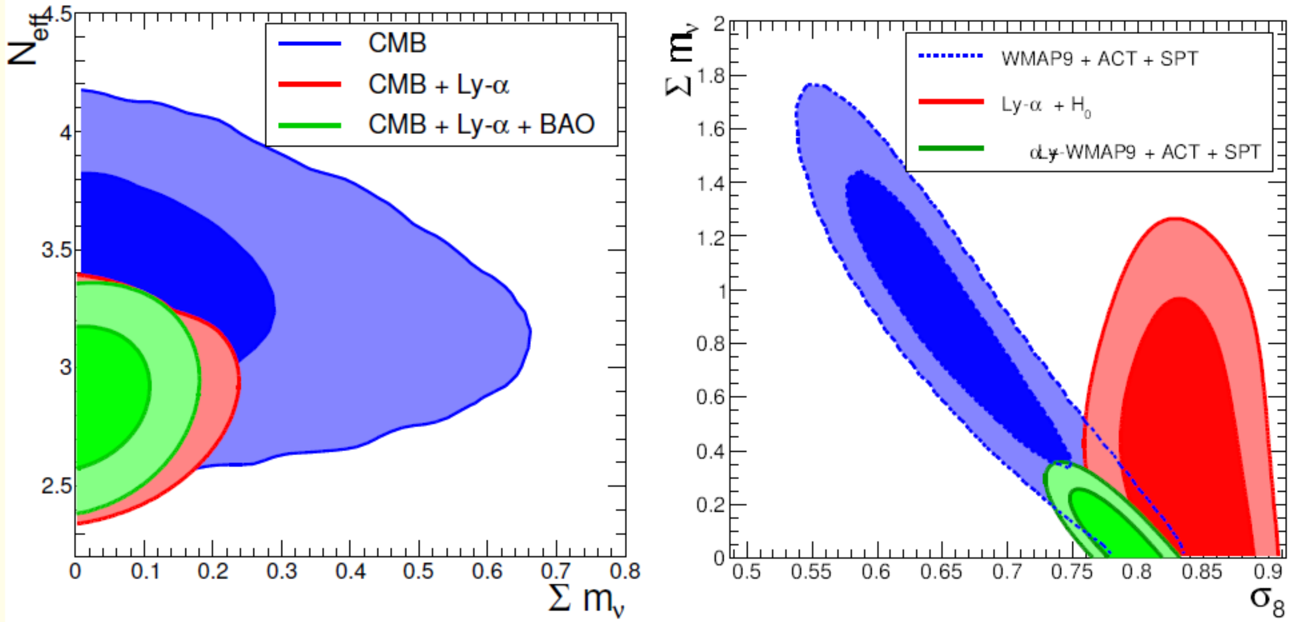
2. *Sterile neutrino* thermalized with active neutrinos *ruled out* at more than 5σ and $N_{\rm eff} = 0$ rejected at more than $14\sigma \rightarrow$ most robust evidence for the CNB from $N_{\rm eff} \sim 3$

COSMOLOGICAL PRIMER

COSMOLOGY & NEUTRINOS

SYNERGIES & PROSPECTS

Final Joint Constraints



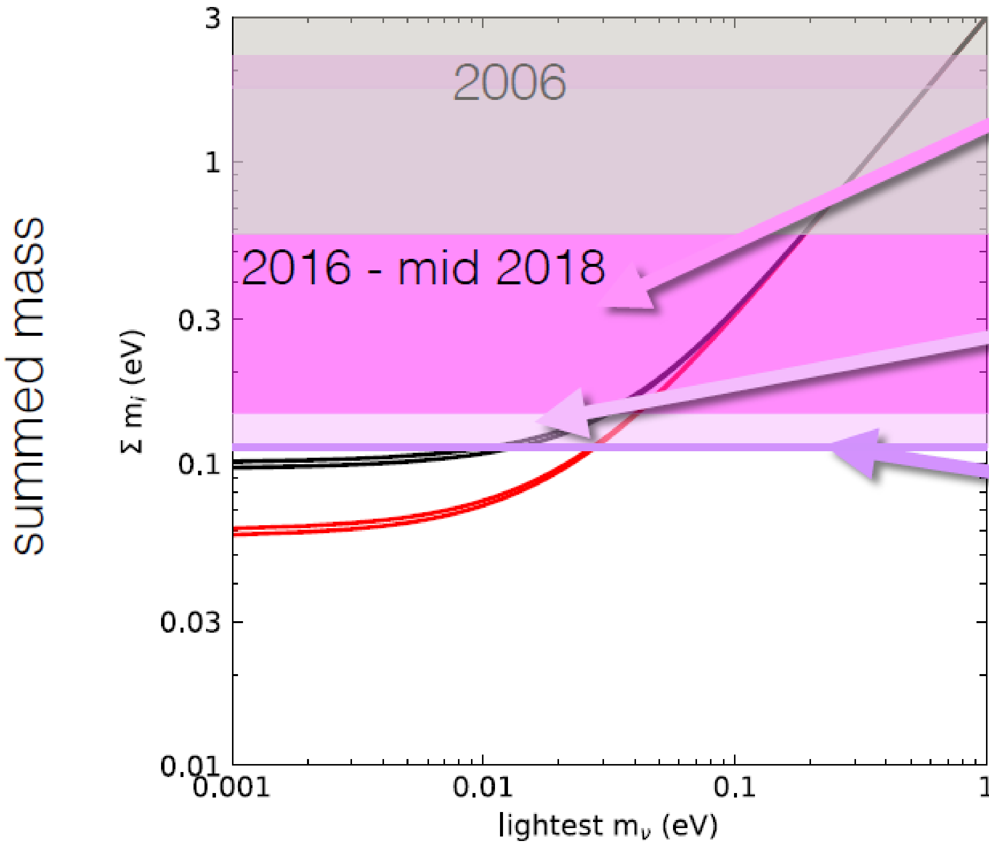
Rossi et al. (2015)

- $N_{\mathrm{eff}} = 2.91^{+0.21}_{-0.22}$ and $\sum m_\nu < 0.15$ eV (all at 95% CL) $\rightarrow$ CMB + Lyman-α
- $N_{\mathrm{eff}} = 2.88^{+0.20}_{-0.20}$ and $\sum m_\nu < 0.14$ eV (all at 95% CL) $\rightarrow$ CMB + Lyman-α + BAO

Getting close to the absolute limit of 0.05 eV!

Summed mass of active neutrinos

95%CL upper bounds on $\Sigma_i m_i$ for 7 parameters



CMB only: Planck,
w/o high-l polarisation and lensing…
$\Sigma_i m_i$ < 590 to 140 meV (95%CL)

CMB + conservative LSS :

- Planck 2016 {TT+SIMLow+lensing} + BAO:
  $\Sigma_i m_i$ < **170 meV** (95%CL)
- Planck 2016 {TTTEEE+SIMLow} + BAO:
  $\Sigma_i m_i$ < **120 meV** (95%CL)

- Planck 2015 + Lyman-α:
  $\Sigma_i m_i$ < **120 meV** (95%CL)

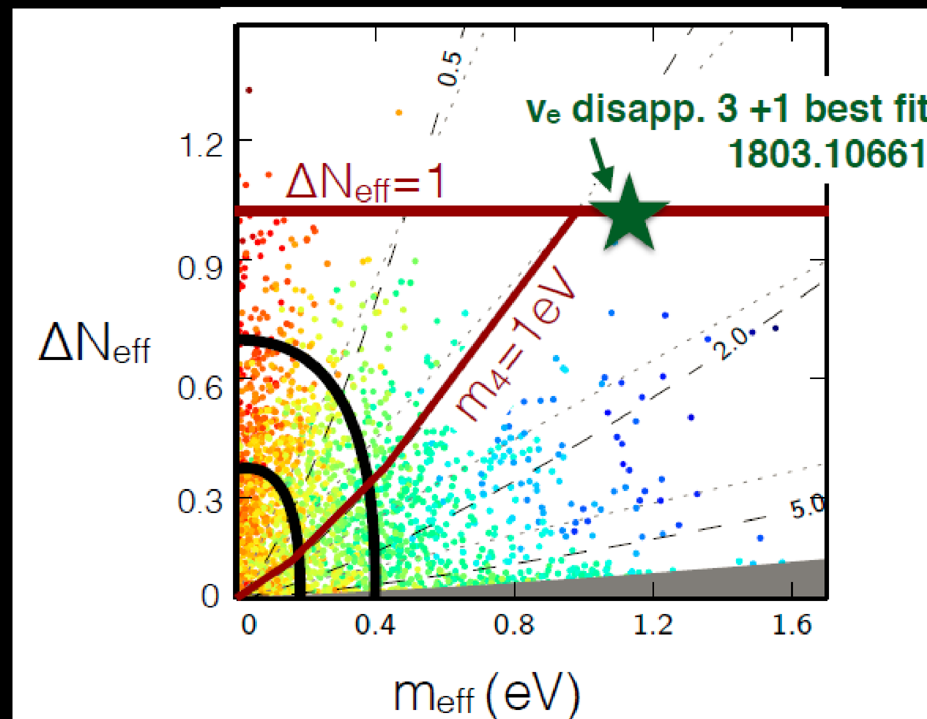
[Planck col.] 1605.02985; Cuesta et al. 2016;
Palanque-Delabrouille et al. 1506.05976;
Vagnozzi et al. 1701.08172;
PDG "Neutrino Cosmology" [JL & Verde]

… harder to avoid bounds with simple cosmological model extensions hese data are sensitive to the existence of additional sterile low mass neutrinos (as invoked to explain LSND and MiniBoone) and exclude them:

Extra relics (small mass case)

Current bounds on one early-decoupled or non-thermalized extra light species (e.g. ν_4 of 3+1 scenario, abusively called "sterile neutrino")

Effective density parameters	Planck 2015 (TT+lowP+lensing) + BAO
ΔN_{eff} (extra contribution to density *before* NR transition)	<0.7 (95%CL)
m_{eff} (extra contribution to density *after* NR transition)	< 400 meV (95%CL)

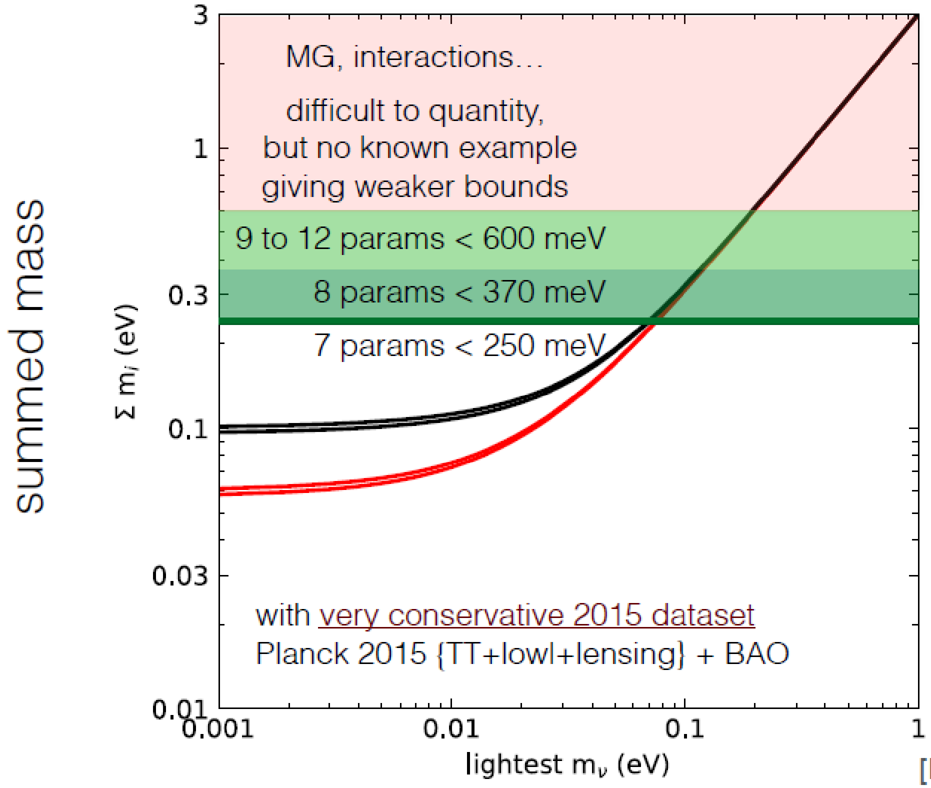


For Dodelson-Widrow neutrinos, physical mass $m = m_{eff}/\Delta N_{eff}$

However it should be stressed that new physics can seriously worsen the limits!

Robustness of mass bounds against cosmological model extensions

95%CL upper bounds on Σᵢmᵢ beyond 7 parameters



Usual suspects:

- extra massless relics
- extra light relics
- spatial curvature
- simplest dynamical DE
- primordial GWs
- primordial tilt running

Even more freedom in:

- modified Einstein Gravity
- interactions in DM sector
- ~~primordial perturbations~~

[Planck col.] 1502.01589; Di Valentino et al. 1507.06646

Neutrinos have mass and mix

This is NOT the Standard Model

why cant we just add masses to neutrinos?

Majorana neutrinos $\quad \nu_i = \bar{\nu}_i$

or

Dirac neutrinos? $\quad \nu_i \neq \bar{\nu}_i$

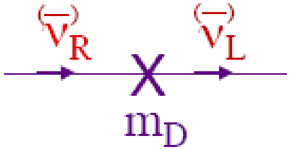
e+ ≠ e– since Charge(e+) = – Charge(e–).
But neutrinos may not carry any conserved charge-like
quantum number.
There is NO experimetal evidence or theoretical need for a conserved Lepton Number L as
L(ν) = L(l–) = –L(ν) = –L(l+) = 1

then, nothing distinguishes ν_i **from** $\bar{\nu}_i$

violation of fermion number…. !

Adding masses to the Stadard model neutrino 'simply' by adding a Dirac mass term

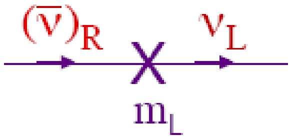
$$m_D \nu_L \overline{\nu_R} \qquad m_D \overline{\nu_L} \nu_R$$



implies adding a right-handed neutrino.

No SM symmetry prevents adding then a term like

$$m_M \overline{\nu_R^{\,c}} \, \nu_R$$



and this simply means that a neutrino turns into a antineutrino
(the charge conjugate of a right handed antineutrino is a left handed neutrino!)

this does not violate spin conservation since a left handed field has a component of the opposite helicity (and vice versa)

$$\nu_L \approx \nu_- + \nu_+ \, m/E$$

Neutrino mass with Dirac and Majorana mass terms:

$$\mathcal{L} = \frac{1}{2}(\bar{\nu}_L, \bar{N}_R^c) \begin{pmatrix} 0 & m_D \\ m_D^T & M_R \end{pmatrix} \begin{pmatrix} \nu_L^c \\ N_R \end{pmatrix}$$

$M_R \neq 0$
$m_D \neq 0$
Dirac + Majorana

$$\tan 2\theta = \frac{2\, m_D}{M_R - 0} \qquad \ll 1$$

$$m_\nu = \tfrac{1}{2}\left[(0 + M_R) - \sqrt{(0 - M_R)^2 + 4\, m_D^2}\right] \qquad \simeq -m_D^2/M_R$$

$$M = \tfrac{1}{2}\left[(0 + M_R) + \sqrt{(0 - M_R)^2 + 4\, m_D^2}\right] \qquad \simeq M_R$$

general formula — if $m_D \ll M_R$

$M_R = 0$
$m_D \neq 0$
Dirac only, (like e- vs e+):

$I_{weak}=$ ν_L ½, ν_R 0, $\bar{\nu}_R$ ½, $\bar{\nu}_L$ 0

4 states of equal masses
Some have I=1/2 (active)
Some have I=0 (sterile)

$M_R \neq 0$
$m_D = 0$
Majorana only

$I_{weak}=$ ν_L ½, $\bar{\nu}_R$ ½

2 states of equal masses
All have I=1/2 (active)

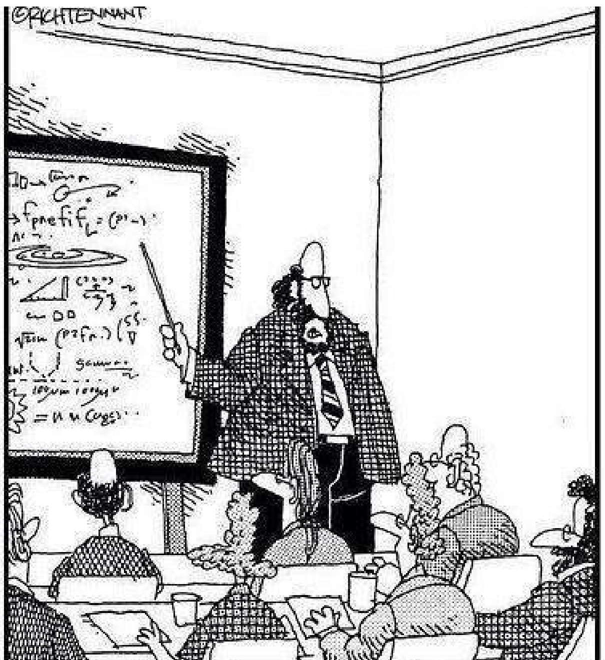
$M_R \neq 0$
$m_D \neq 0$
Dirac + Majorana

$I_{weak}=$ ν_L ½, N_R 0, $\bar{\nu}_R$ ½, $\bar{N}_L$ 0

4 states , 2 mass levels
m1 have I=1/2 (active)
m2 have I=0 (sterile)

Electroweak eigenstates

$\begin{pmatrix} e \\ \nu_e \end{pmatrix}_L$ $\begin{pmatrix} \mu \\ \nu_\mu \end{pmatrix}_L$ $\begin{pmatrix} \tau \\ \nu_\tau \end{pmatrix}_L$	$(e)_R$ $(\mu)_R$ $(\tau)_R$	Q= -1
	$(\nu_e)_R$ $(\nu_\mu)_R$ $(\nu_\tau)_R$	Q= 0
I = 1/2	I = 0	



"Along with 'Antimatter,' and 'Dark Matter,' we've recently discovered the existence of 'Doesn't Matter,' which appears to have no effect on the universe whatsoever."

Right handed neutrinos are singlets
no weak interaction
no EM interaction
no strong interaction

can't produce them
can't detect them
-- so why bother? –

Also called 'sterile'

$$\tan 2\theta = \frac{2\,m_D}{M_R - 0} \qquad \ll 1$$

$$m_\nu = \tfrac{1}{2}\left[(0+M_R) - \sqrt{(0-M_R)^2 + 4\,m_D^2}\right] \qquad \simeq -m_D^2/M_R$$

$$M = \tfrac{1}{2}\left[(0+M_R) + \sqrt{(0-M_R)^2 + 4\,m_D^2}\right] \qquad \simeq M_R$$

general formula — if $m_D \ll M_R$

m_D associated with EWSB, part of SM, bounded by $v/\sqrt{2} = 174$ GeV

M_R is SM singlet, does whatever it wants: $\Rightarrow M_R \gg m_D$

Note that this is not necessary
As one can have M anywhere…

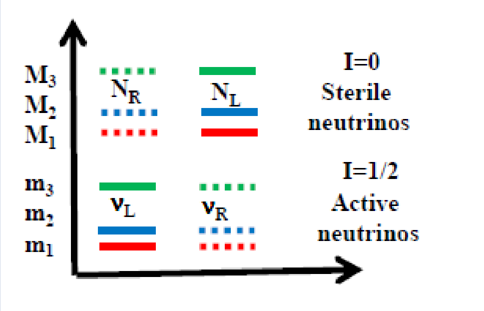
Hence, $\theta \simeq m_D/M_R \ll 1$

$\nu = \nu_L \cos\theta - N_R^c \sin\theta \simeq \nu_L$ with mass $m_\nu \simeq -m_D^2/M_R$

$N = N_R \cos\theta + \nu_L^c \sin\theta \simeq N_R$ with mass $M \simeq M_R$

one family see-saw :
$\theta \approx (m_D/M)$
$m_\nu \approx \frac{m_D^2}{M}$
$m_N \approx M$ ➔ $|U|^2 \propto \theta^2 \approx m_\nu / m_N$

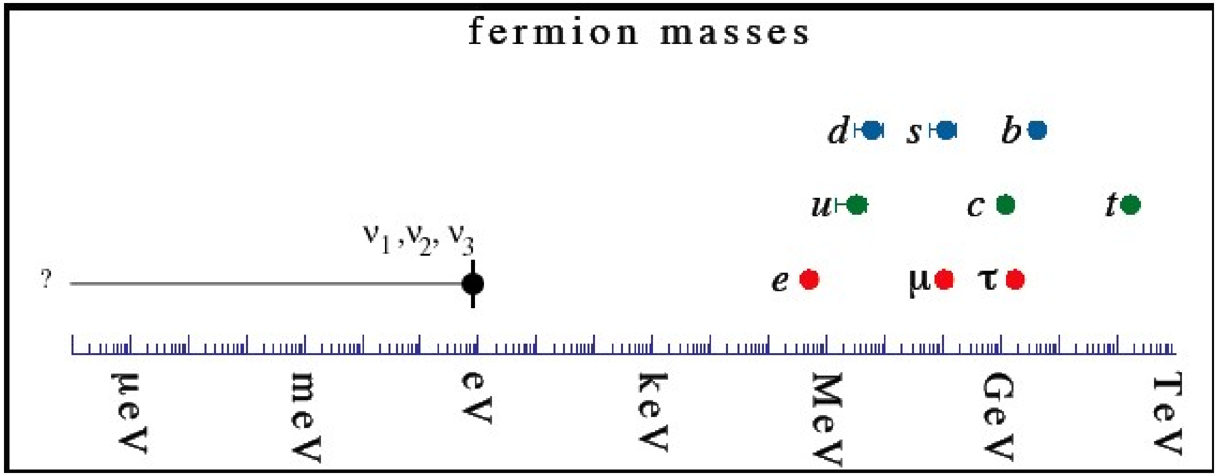
Neutrinos : the New Physics there is… and a lot of it!

SM	Dirac mass term only	Majorana mass term only	Dirac AND Majorana Mass terms
ν_L $\bar{\nu}_R$ I= ½ ½	ν_L ν_R $\bar{\nu}_R$ $\bar{\nu}_L$ ½ 0 ½ 0	ν_L ‘ $\bar{\nu}_R$ ‘ ½ ½	
X 3 Families	X 3 Families	X 3 Families	X 3 Families
6 massless states **wrong**	3 masses 12 states 3 active neutrinos 3 active antinu’s **6 sterile neutrinos…** 3 mixing angles 1 CP violating phase **0νββ = 0**	3 masses 6 active states **No steriles** 3 mixing angles 3 CP violating phases **0νββ ≠ 0**	6 masses 12 states 6 active states **6 sterile neutrinos…** More mixing angles and CPV phases **0νββ ≠ 0** → Leptogenesis and Dark matter

Mass hierarchies are all unknown except $m_1 < m_2$

Preferred scenario has both Dirac and Majorana terms …

… many physics possibilities and experimental challenges

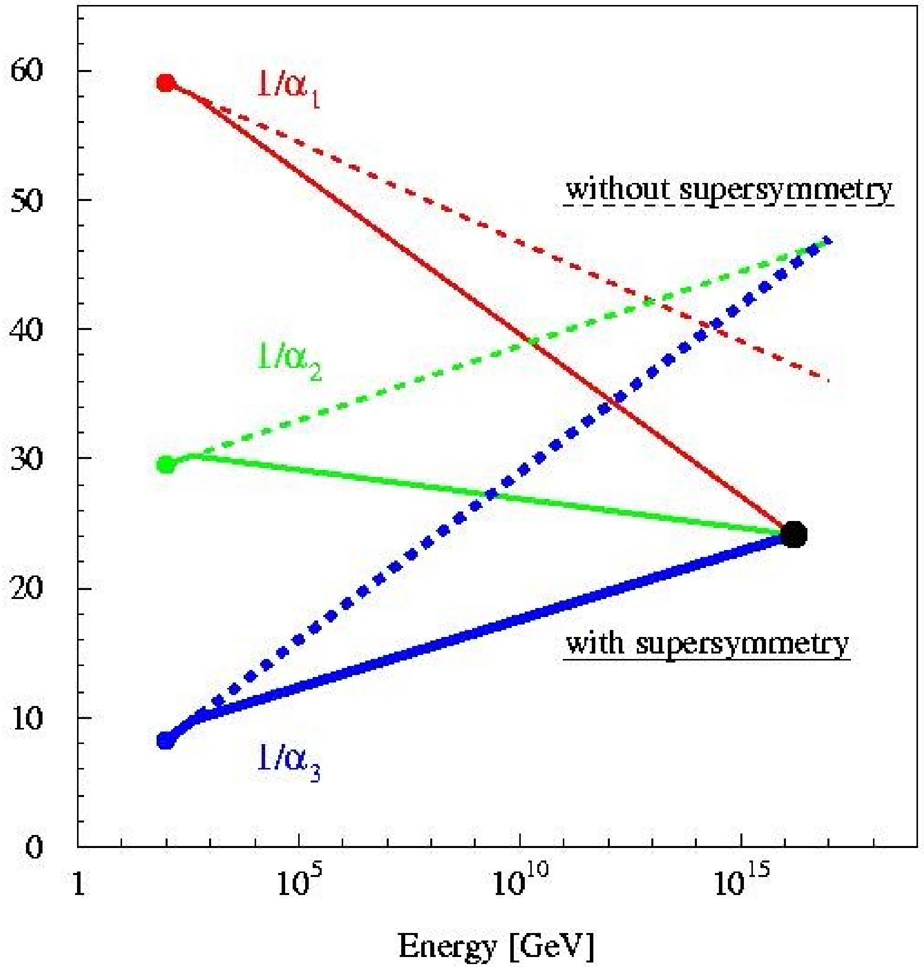


The mass spectrum of the elementary particles. Neutrinos are 10^{12} times lighter than other elementary fermions. The hierarchy of this spectrum remains a puzzle of particle physics.

Most attractive wisdom: via the see-saw mwchanism,
the neutrinos are very light because they are low-lying states
in a split doublet with heavy neutrinos of mass scale interestingly
similar to the grand unification scale.

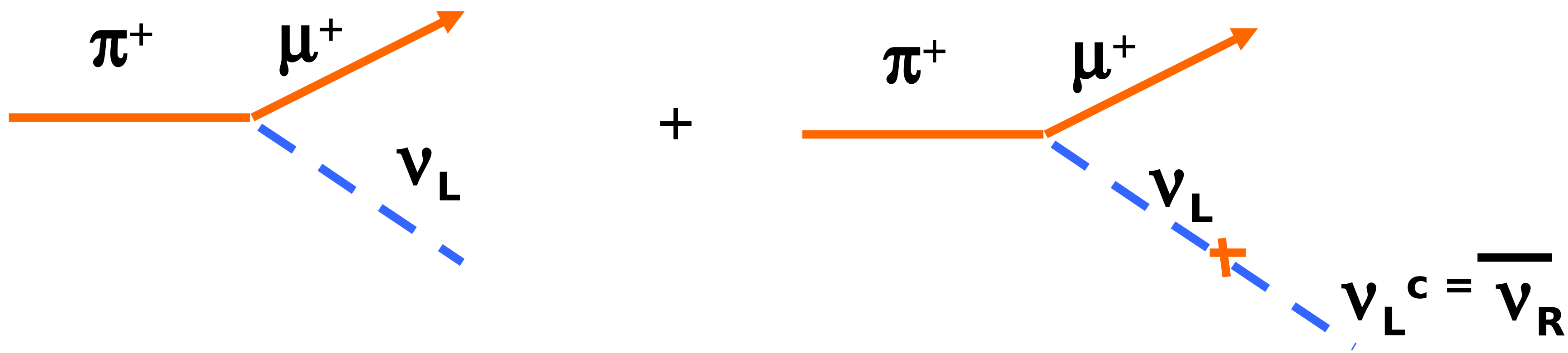
$m\,M = \langle v \rangle^2$ with $\langle v \rangle \sim= m_{top} = 174$ GeV

 for $m_{\nu} = O(10^{-2})$ eV $\Rightarrow M \sim 10^{15}$ GeV



One often considers that $M_R \sim M_{GUT} \sim 10^{10}$ to 10^{15} GeV

Pion decay with massive neutrinos



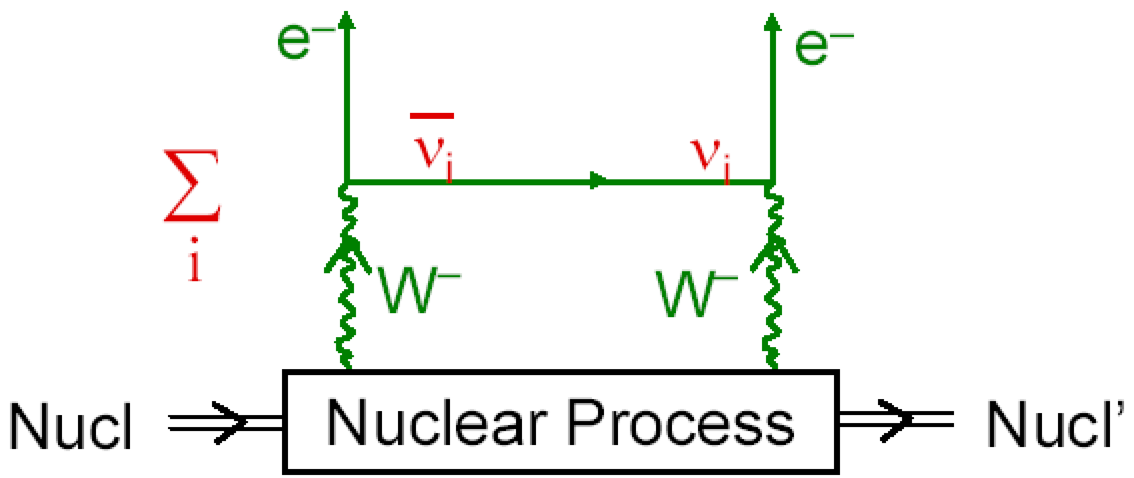
1 $\qquad$ $(m_\nu /E)^2$

<u>in case of pure Dirac:</u>
transition to sterile right handed neutrinos
<u>in case of pure Majorana:</u>
transition to anti-neutrino
<u>in case of see-saw:</u>
if possible, transition to heavy RH neutrino

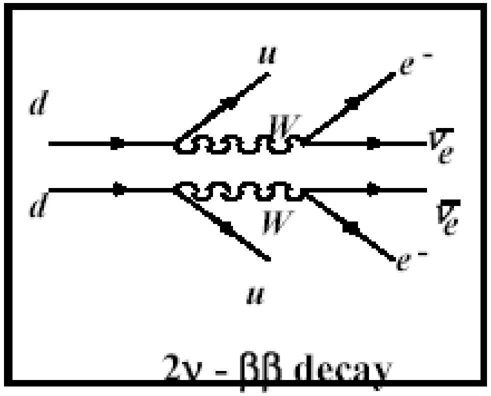
$(.05/30\ 10^6)^2 = 10^{-18}$

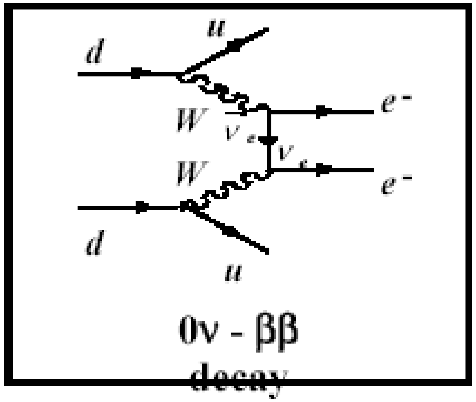
no problem

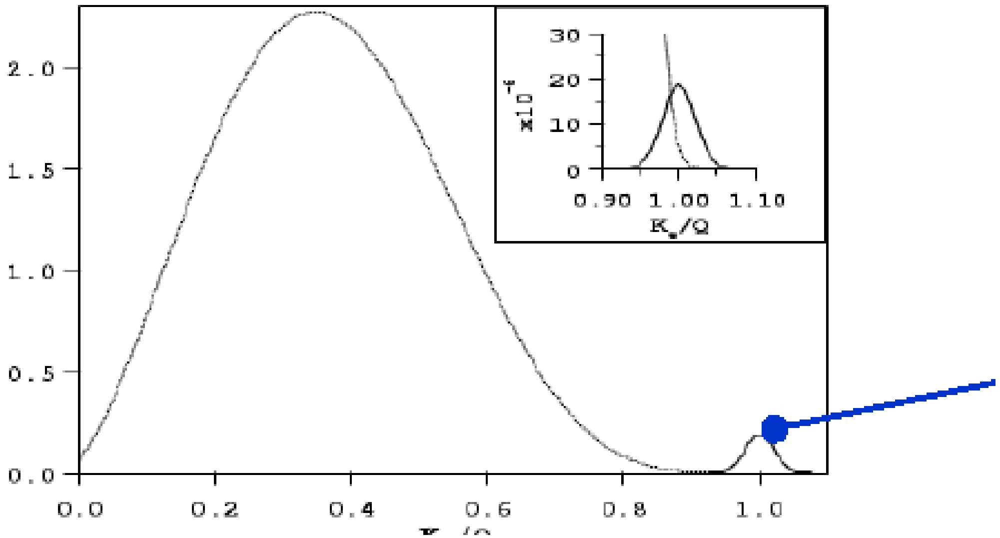
The Idea That Can Work — Neutrinoless Double Beta Decay [$0\nu\beta\beta$]



By avoiding competition, this process can cope with the small neutrino masses.





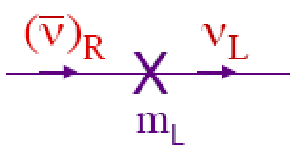


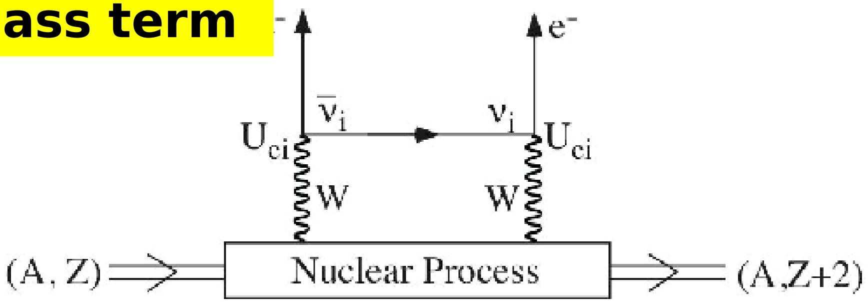
Two neutrino ββ decay has been detected in ten nuclei also into exited states

Neutrinoless Double Beta Decay (0νββ)

- Hypothetical ββ decay mode allowed if neutrinos

have Majorana mass term





Phase space factor

Nuclear matrix element

$$\frac{1}{T_{1/2}^{0\nu}} = G^{0\nu}|M^{0\nu}|^2|\langle m_{\beta\beta}\rangle|^2$$

Decay half-life

Effective Majorana neutrino mass: $m_{\beta\beta} \equiv \left|\sum_{i=1}^{3} U_{ei}^2\, m_i\right|$

- $M^{0\nu}$ is not known, must be estimated theoretically, estimates vary by factor of ~2 depending on method
- For $m_{\beta\beta}$ = 50 meV estimated half lives 10^{25} - 10^{27} years ! depending on the nuclear system

Three Neutrino Mixing

$$\nu_{l\mathrm{L}} = \sum_{j=1}^{3} U_{lj}\, \nu_{j\mathrm{L}}\ .$$

U is the Pontecorvo-Maki-Nakagawa-Sakata (PMNS) neutrino mixing matrix,

$$U = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix}$$

- U - $n \times n$ unitary:

		n	2	3	4
mixing angles:		$\frac{1}{2}n(n-1)$	1	3	6
CP-violating phases:					
• $\nu_j -$ Dirac:		$\frac{1}{2}(n-1)(n-2)$	0	1	3
• $\nu_j -$ Majorana:		$\frac{1}{2}n(n-1)$	1	3	6

$n = 3$: 1 Dirac and
2 additional CP-violating phases, Majorana phases

$$U = V \begin{pmatrix} 1 & 0 & 0 \\ 0 & e^{i\frac{\alpha_{21}}{2}} & 0 \\ 0 & 0 & e^{i\frac{\alpha_{31}}{2}} \end{pmatrix} \qquad (4)$$

$$V = \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta} & s_{23}c_{13}e^{i\delta} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta} & c_{23}c_{13}e^{i\delta} \end{pmatrix} \qquad (5)$$

$A(\beta\beta)_{0\nu} \sim \, <m>$ M(A,Z), M(A,Z) - NME,

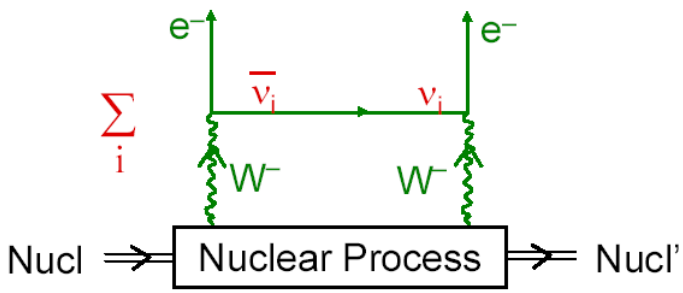
$$|<m>| = \left| m_1 |U_{e1}|^2 + m_2 |U_{e2}|^2\, e^{i\alpha_{21}} + m_3 |U_{e3}|^2\, e^{i\alpha_{31}} \right|,$$

S.M. Bilenky, J. Hosek, S.T.P.,1980;
J. Schechter, J.W.F. Valle,1980;
M. Doi, T. Kotani, E. Takasugi,1981

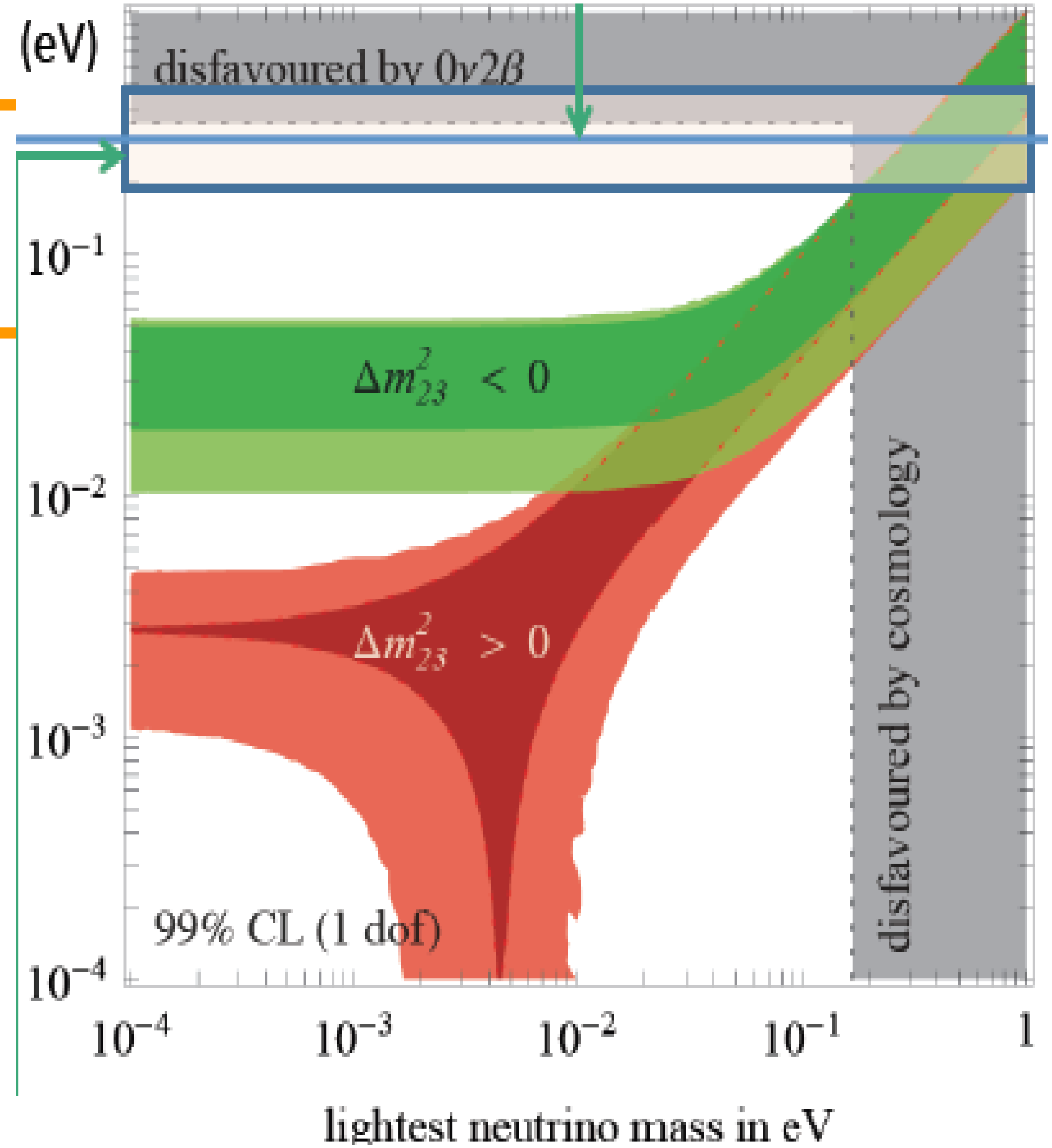
what 0νββ measures is <m> :

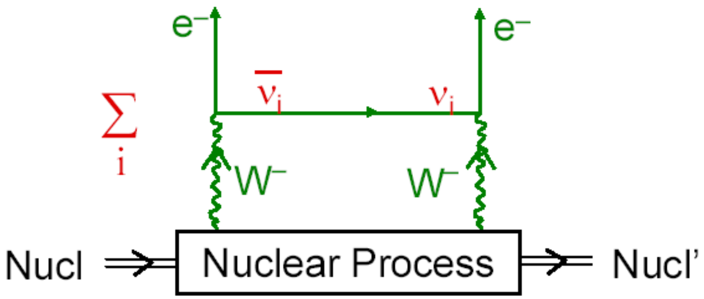
$$A(\beta\beta)_{0\nu} \sim <m>\ \mathrm{M(A,Z)}, \qquad \mathrm{M(A,Z)\ -\ NME},$$

$$|<m>| = |m_1|U_{e1}|^2 + m_2|U_{e2}|^2\, e^{i\alpha_{21}} + m_3|U_{e3}|^2\, e^{i\alpha_{31}}|,$$



m_1 m_2 m_3 are physical masses of active neutrinos (I=1/2) which in this case are just the same as in oscillation experiments,
and <u>which interacts with the W</u>





$(G_F)^4$

Experimental approach

Geochemical experiments

$^{82}Se \Rightarrow {}^{82}Kr$, $^{96}Zr \Rightarrow {}^{96}Mo$ (?) , $^{128}Te \Rightarrow {}^{128}Xe$ (non confirmed), $^{130}Te \Rightarrow {}^{130}Te$

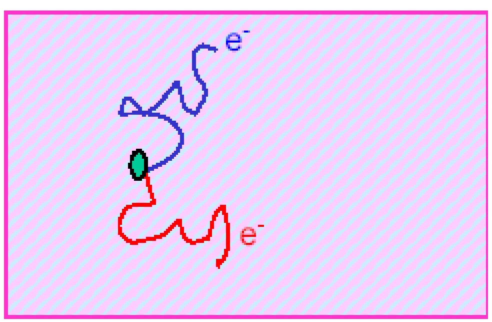
Radiochemical experiments

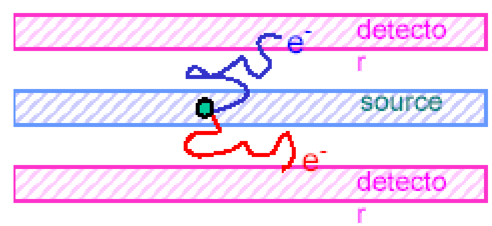
$^{238}U \Rightarrow {}^{238}Pu$ (non confirmed)

Direct experiments

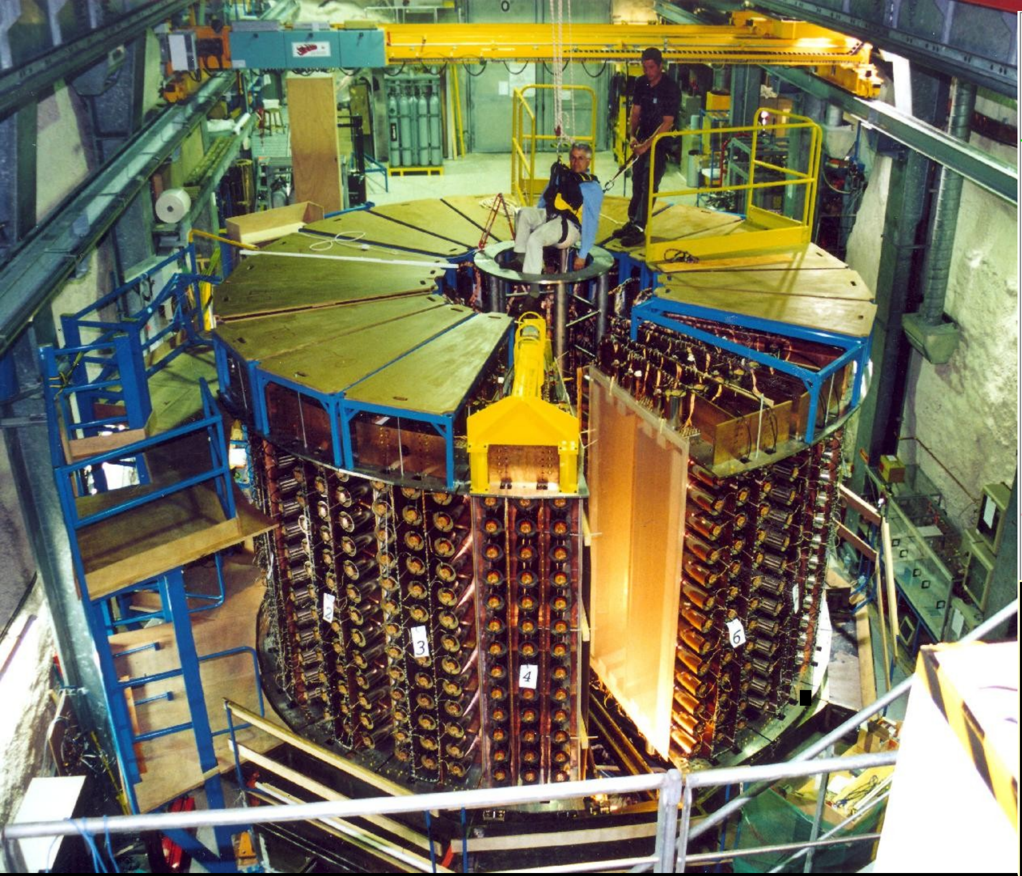
Source = detector (calorimetric)

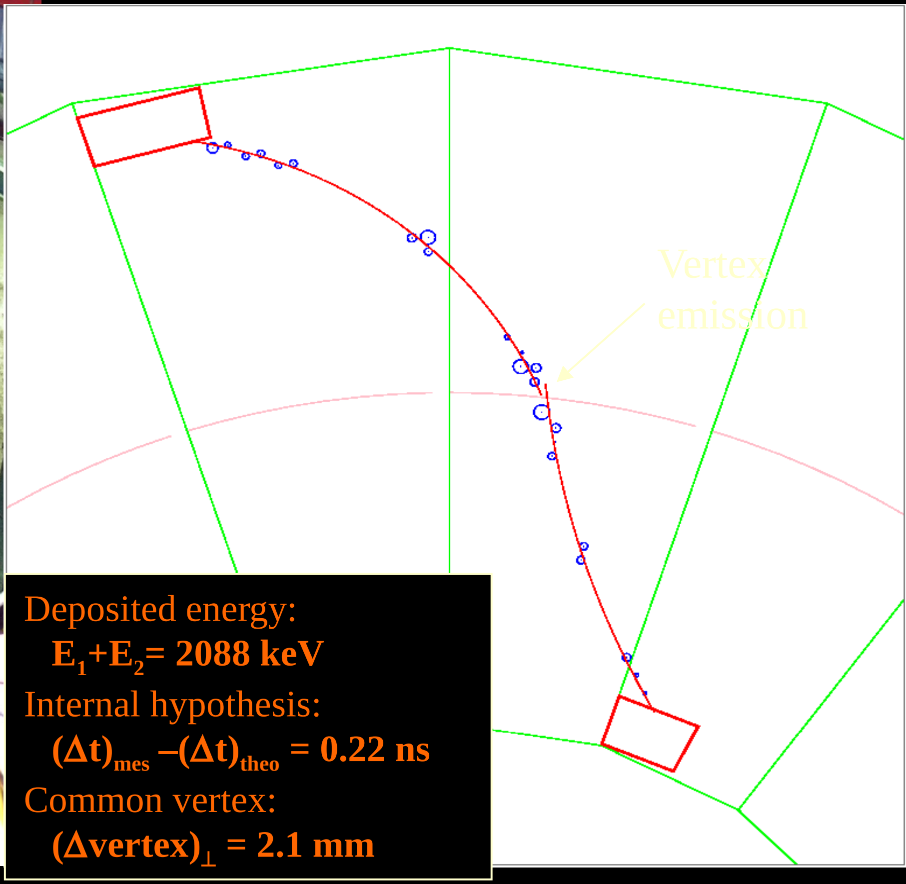
Source ≠ detector





Source ≠
Detector





NEMO

Criteria to select ββ events:

- 2 tracks with charge < 0
- 2 PMT, each > 200 keV
- PMT-Track association
- Common vertex
- Internal hypothesis (external event rejection)
- No other isolated PMT (γ rejection)
- No delayed track (^{214}Bi rejection)

typical 2νββ evenement

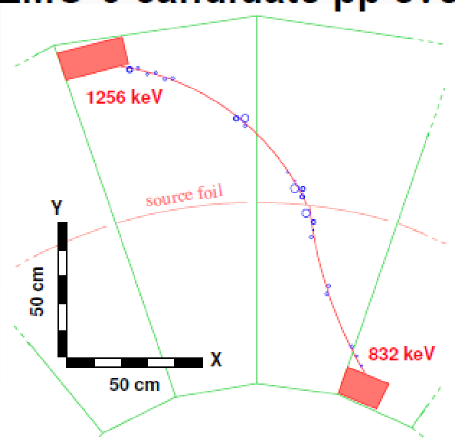
Candidate Isotope	Experiment
^{48}Ca	Candles
^{76}Ge	**Gerda**, Majorana
^{82}Se	SuperNemo,Lucifer
^{130}Te	**CUORE**
^{136}Xe	**EXO**, NEXT, **KamLAND-Zen**
^{150}Nd	SNO+

Where they show what they can do:

Best results from 2νββ

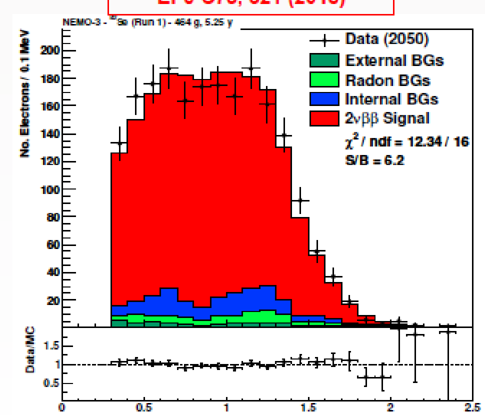
Isotope	$T_{1/2}$ (10^{19} yrs)	Experiment
^{48}Ca	6.4 ± 1.2	NEMO-3
^{76}Ge	192.6 ± 9.4	GERDA
^{82}Se	9.4 ± 0.6	NEMO-3
^{96}Zr	2.35 ± 0.21	NEMO-3
^{100}Mo	0.68 ± 0.05	NEMO-3
^{116}Cd	2.74 ± 0.18	NEMO-3/Aurora
^{130}Te	79 ± 2	CUORE
^{136}Xe	216.5 ± 6.1	EXO-200
^{150}Nd	0.93 ± 0.06	NEMO-3

NEMO-3 candidate ββ event



- Probe nuclear models
  - SSD vs HSD
- Possible experimental access to g_A
- Ultimate background characterisation
- Sensitive to exotic new physics
  - (LNV with Majoron, Lorentz violation, boson neutrinos, G_F variation etc)

EPJ C78, 821 (2018)



And what we are really interested in: As of Oct 2018

Best results from 0νββ

$$T^{0\nu}_{1/2}(90\%\ \text{C.L.}) = 2.54\times10^{26}\,\text{y}\left(\frac{\varepsilon\times a}{W}\right)\sqrt{\frac{M\times t}{b\times\Delta E}}$$

Isotope, mass	$Q_{\beta\beta}$, keV	b x ΔE x M, counts/yr	$T_{1/2}$, yr	$\langle m_\nu \rangle$, eV	Experiment, technique
^{76}Ge, 40kg	**2039**	**0.07**	**> 0.9 x 10^{26}**	**< 0.11-0.25**	**GERDA, HPGe**
^{82}Se, 5kg	2998	0.4	> 2.4 x 10^{24}	< 0.38-0.77	CUPID-0, scintillating bolometers
^{100}Mo, 7kg	3034	1.5	> 1.1 x 10^{24}	< 0.33-0.62	NEMO-3, tracko-calo
^{130}Te, 200kg	2528	21	> 1.5 x 10^{25}	< 0.13-0.50	CUORE, bolometers
^{136}Xe, 380kg	**2458**	**1**	**> 1.07 x 10^{26}**	**< 0.06-0.16**	**KamLAND-Zen, doped LS**

Different techniques reach similar sensitivity with different isotope mass

GERDA motivations

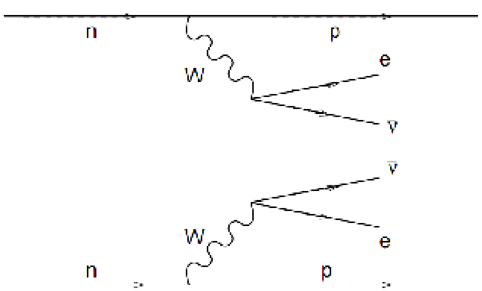
The GERmanium Detector Array experiment is an ultra-low background experiment designed to search for ^{76}Ge $0\nu\beta\beta$ decay.

$2\nu\beta\beta$

$$(Z,A) \rightarrow (Z+2,A) + 2e^- + 2\overline{\nu}_e$$

$\Delta L = 0 \Longrightarrow$ Predicted by s.m.

Observed.



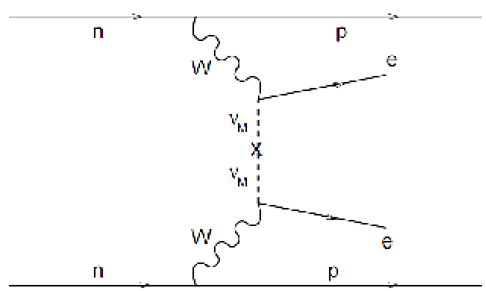
$0\nu\beta\beta$

$$(Z,A) \rightarrow (Z+2,A) + 2e^-$$

$\Delta L = 2 \Longrightarrow$ Physics beyond s.m.

Observed?

Light Majorana neutrino exchange



$$Q = M_i - M_f - 2m_e$$

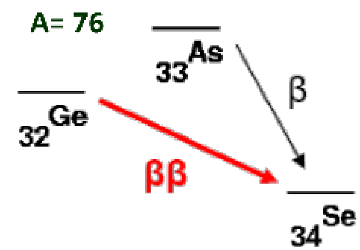
$$(T^{0\nu}_{1/2})^{-1} = G^{0\nu}|M^{0\nu}|^2 \frac{m^2_{\beta\beta}}{m^2_e}$$

$$m_{\beta\beta} \equiv |\sum_{i=1}^{3} U^2_{ei} m_i|$$

$\equiv$ effective Majorana mass

information on the absolute mass scale!

Schechter-Valle: $0\nu\beta\beta \Longrightarrow$ Majorana ν



$Q_{\beta\beta} = 2039$ keV

Part of Heidelberg-Moscow Collaboration claimed evidence for $0\nu\beta\beta$ observation of ^{76}Ge

$$T^{0\nu}_{1/2} = 1.19(0.69 - 4.18) \times 10^{25} \text{ yr } (3\sigma \text{ range})$$

Phys. Lett. B 586, 198 (2004)

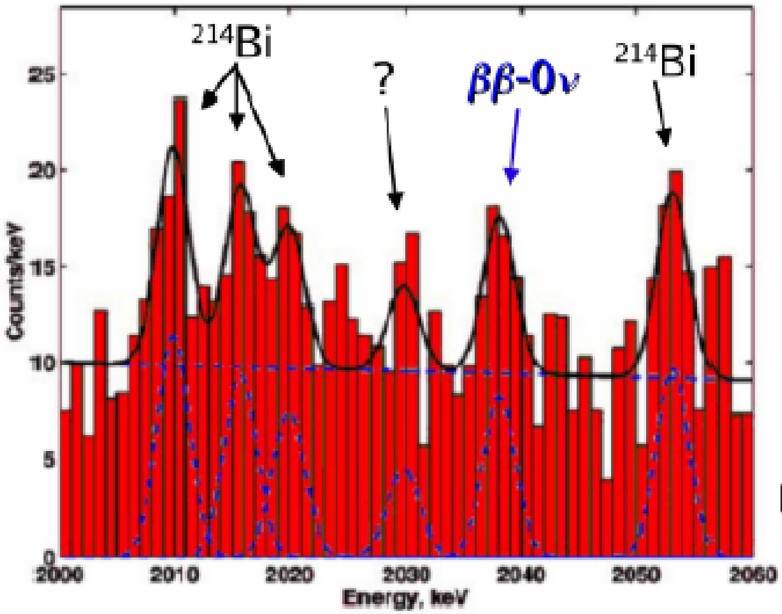
$$T^{0\nu}_{1/2} = 2.23^{+0.44}_{-0.31} \times 10^{25} \text{ yr}$$

Mod.Phys.Lett.A21:1547-1566,2006)

GERDA first goal:
check the HdM claim

Heidelberg-Moscow exp.: evidence for $\beta\beta$-0ν of ^{76}Ge

- best exploitation of the Ge detector technique proposed by E. Fiorini in 1960
  - longest running experiment (13 years) with largest exposure (71.7 kg×y)
  - Status-of-the-art for low background techniques and for enriched Ge detectors
  - reference for all last generation $\beta\beta$-0ν experiments



1990 – 2003 data, all 5 detectors

exposure = 71.7 kg×y

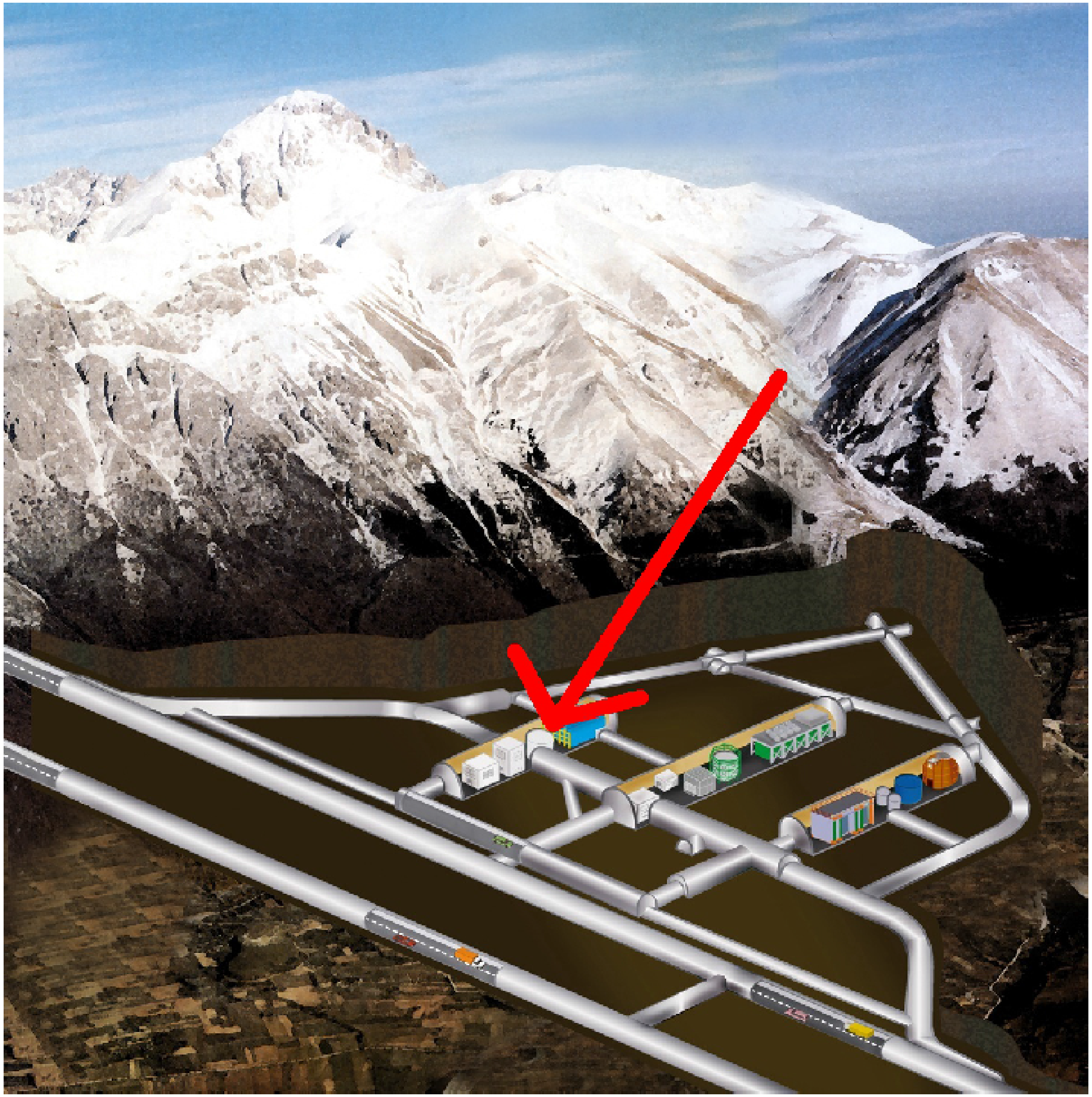
$\tau_{1/2}^{0\nu}$ **= 1.2×10^{25} years**

$\langle m_\nu \rangle$ **= 0.44 eV**

H.V.Klapdor-Kleingrothaus *et al.*, Phys. Lett. B 586 (2004) 198

- still, community **does not fully accept the result**, because:
  - signal is indeed **too faint** (4 σ) to be *blindly* accepted: people still find some weak points in the published analysis
  - presence of **not understood peaks** around the signal and with *similar* significance
  - impossibility to check an **energy window larger** than the published one
- **nevertheless any future $\beta\beta$-0ν experiment will have to cope with this result**

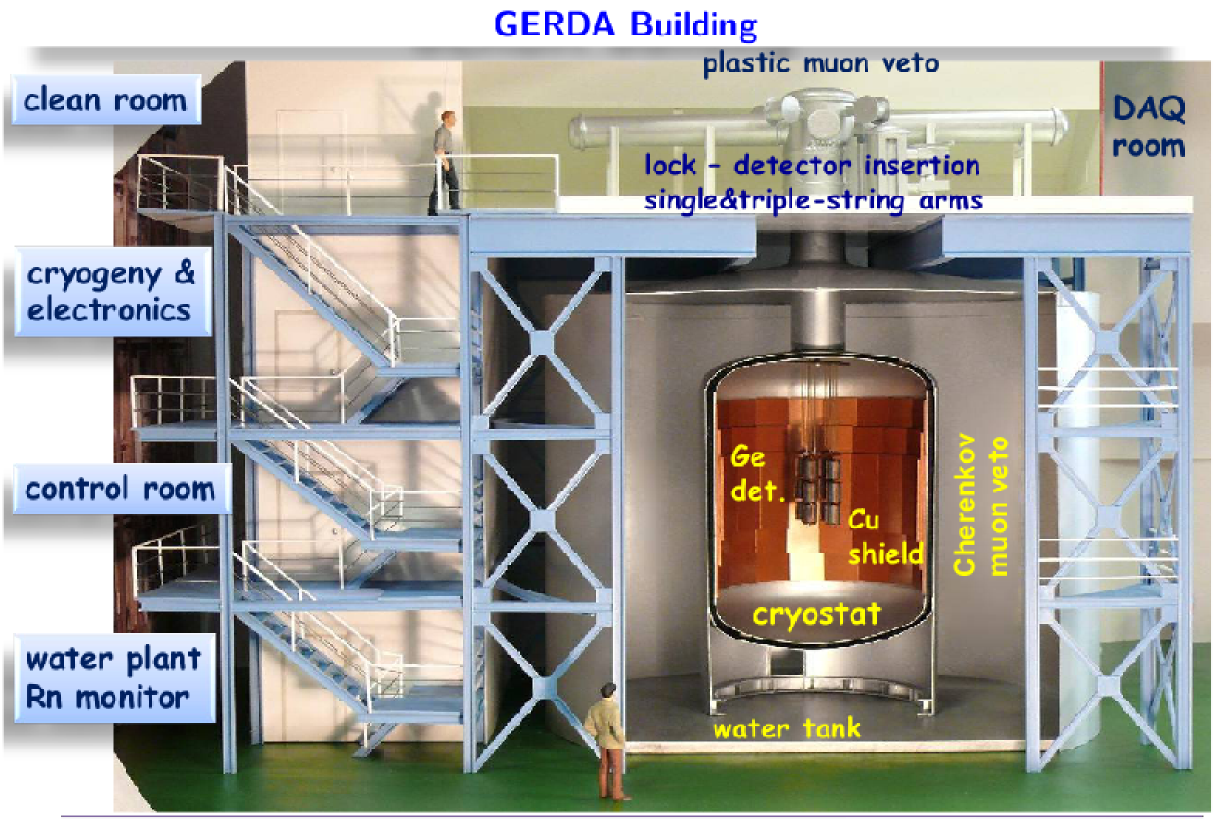
GERDA @ LNGS



The GERDA experiment is hosted in the Hall A of the Gran Sasso Laboratory (INFN)

1400 m of rock
3800 m.w.e.
Suppression of μ-flux$> 10^6$

The GERDA setup



Water tank

$\varnothing = 10$ m

$h = 8.9$ m

$V\ water = 590\ m^3$

The water tank acts as an active Cherenkov veto

Cryostat

$\varnothing = 4$ m

H= 5.88 m

Filled by LAr

LAr

Volume $\sim 64\ m^3$

T= 88.8 K

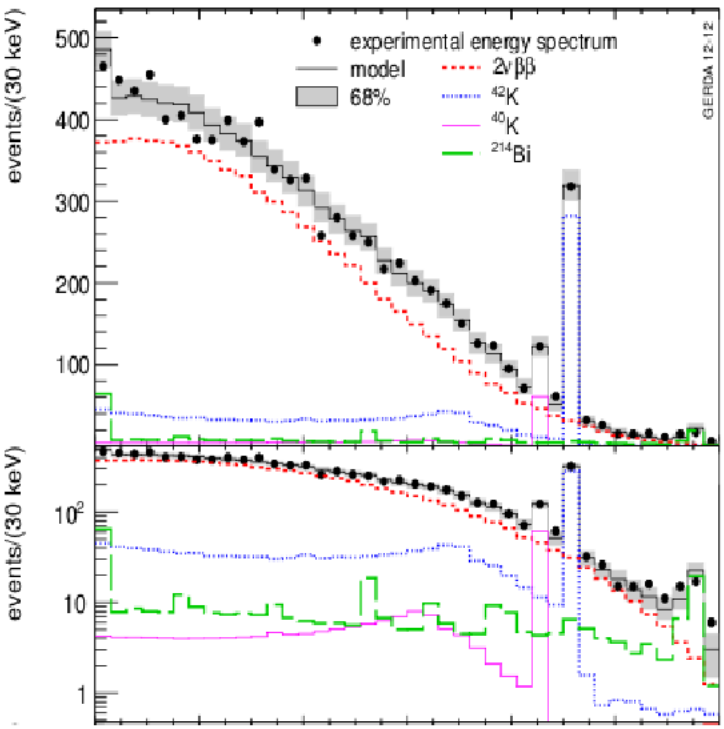
Naked detectors in LAr!

LAr $\rightarrow$ Passive shielding, Cooling, Active veto detecting scintillation light (Phase II)

Detectors are organized in strings - Low mass holders

The current lock system supports 2 arms = 3+1 strings of detectors.

^{76}Ge $2\nu\beta\beta$ half-life



Binned maximum likelihood

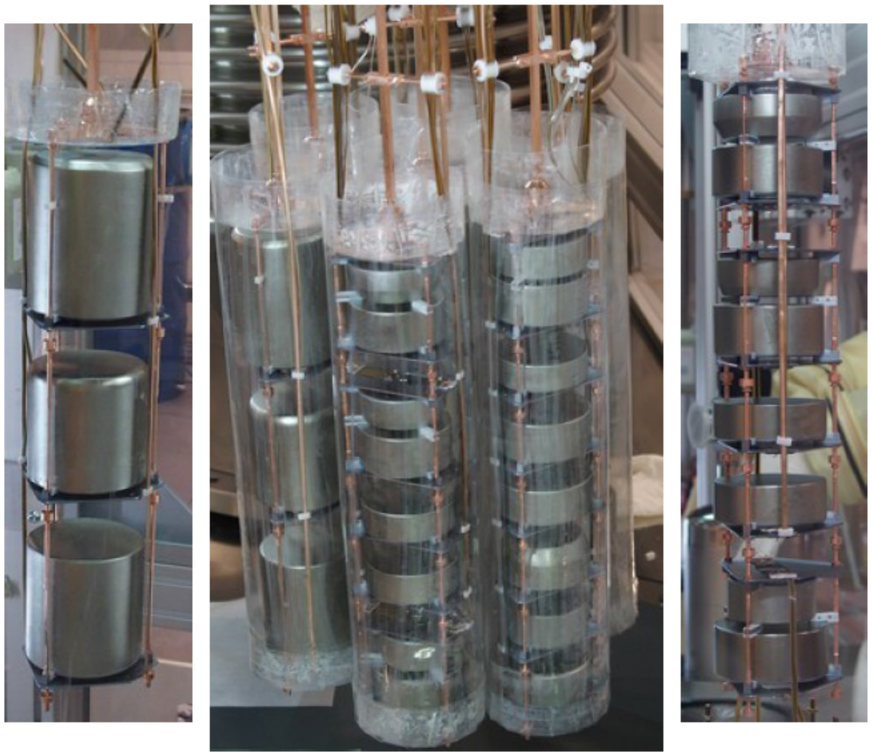
Fit range: 600-1800 keV
Exposure: 5.04 kg·yr

Best fit:
$2\nu\beta\beta$ 80%
^{42}K 14%
^{214}Bi 4%
^{40}K 2%

Integrating over all the nuisance parameters:
$T^{2\nu}_{1/2} = (1.84^{+0.09}_{-0.08}\ {}^{+0.11\ \mathrm{syst}}_{-0.06\ \mathrm{syst}}) \times 10^{21}$ yr

The GERDA Collaboration
J.Phys.G 40 (2013) 035110

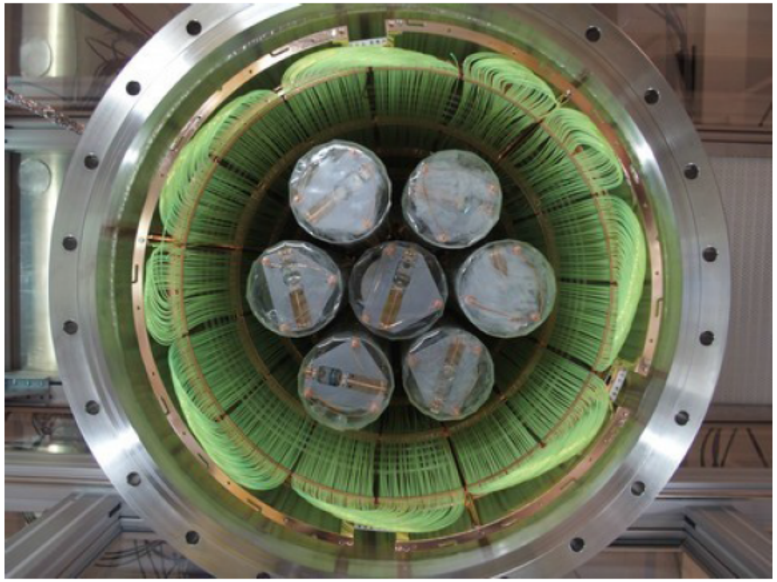
Start of GERDA Phase II



Coaxial layout of detectors

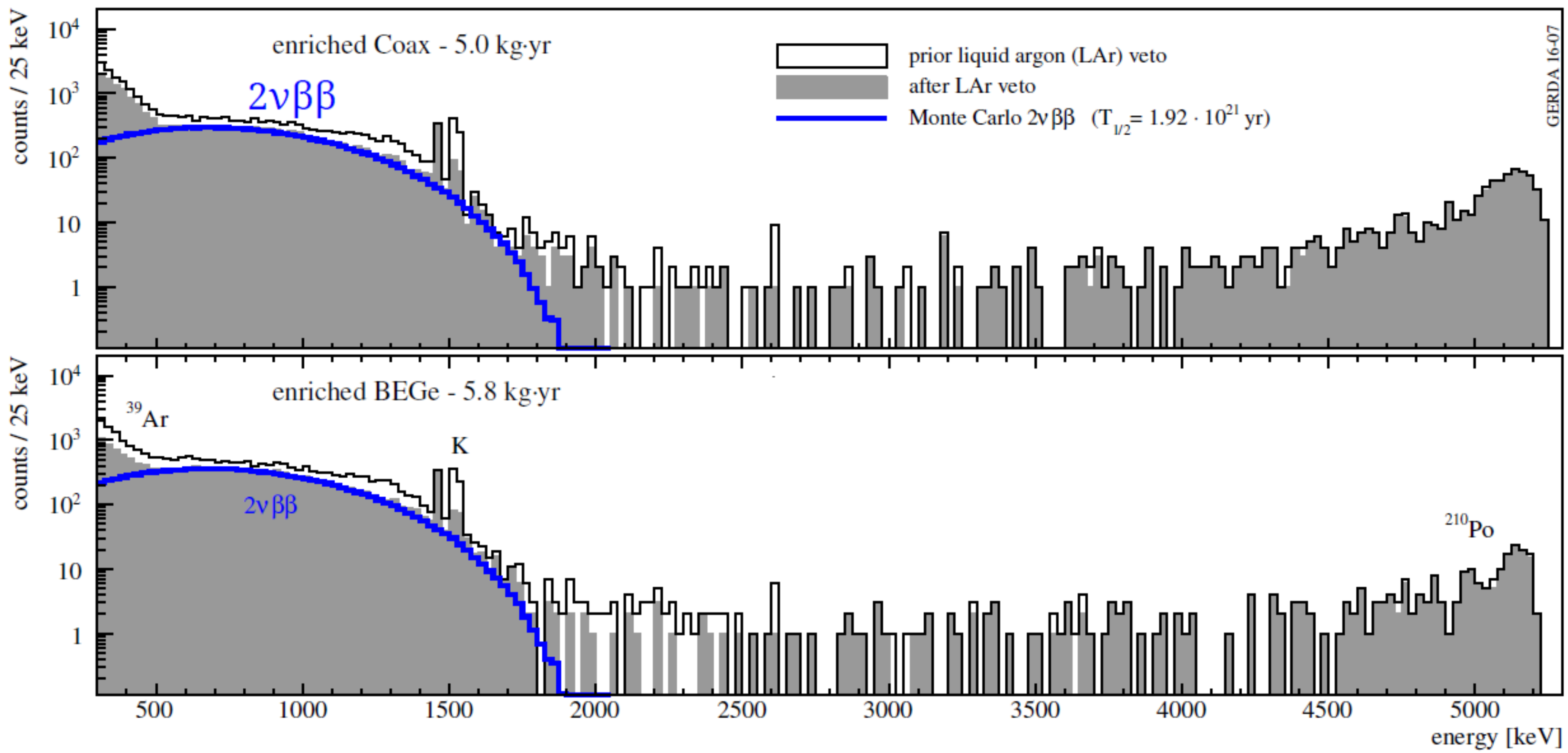
Full Integration of Phase II Array finished in December 2015

- all Ge and LAr detector channels working



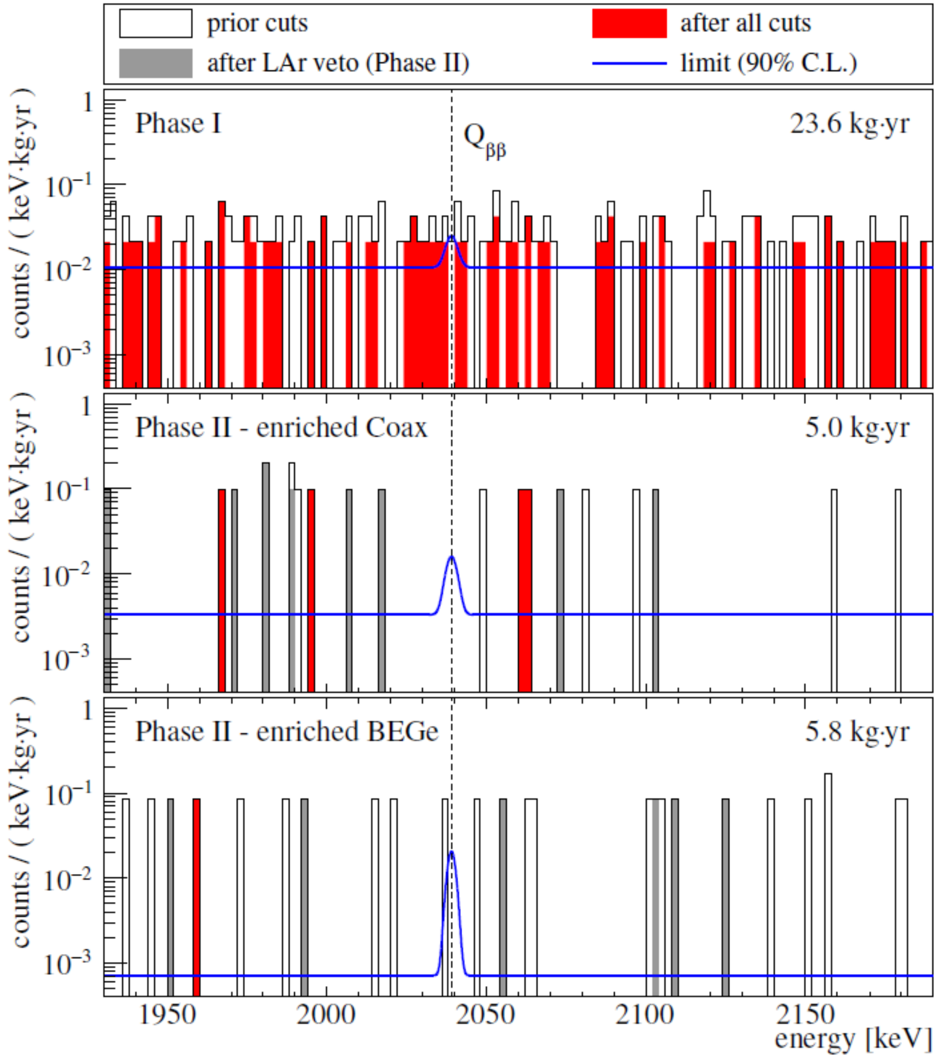
Performance of the LAr Veto

- $2\nu\beta\beta$:bck = 96:4 (1.0-1.3 MeV)



$2\nu\beta\beta$ MC with $T_{1/2} = 1.9 \cdot 10^{21}$ yr from Phase I EPJC 75 (2015) 416

Spectrum at $Q_{\beta\beta}$



Extended unbinned profile likehood:

- flat background in 1930-2190 keV
- signal = Gaussian with mean at $Q_{\beta\beta}$ and standard deviation σ_E
- 7 parameters: 6 BI + common $T_{1/2}$

- best fit for $N_{0\nu} = 0$
- lower limit $T^{0\nu}_{1/2} > 5.3 \cdot 10^{25}$ yr [+] with $T^{0\nu}_{1/2}$ sensitivity $4.0 \cdot 10^{25}$ yr (90 % C.L.)

[+]Frequentist approach after Cowan et al., EPJC 71 (2011) 1554

Conclusions

- GERDA sets a new limit on the half-life of $0\nu\beta\beta$ decay of ^{76}Ge

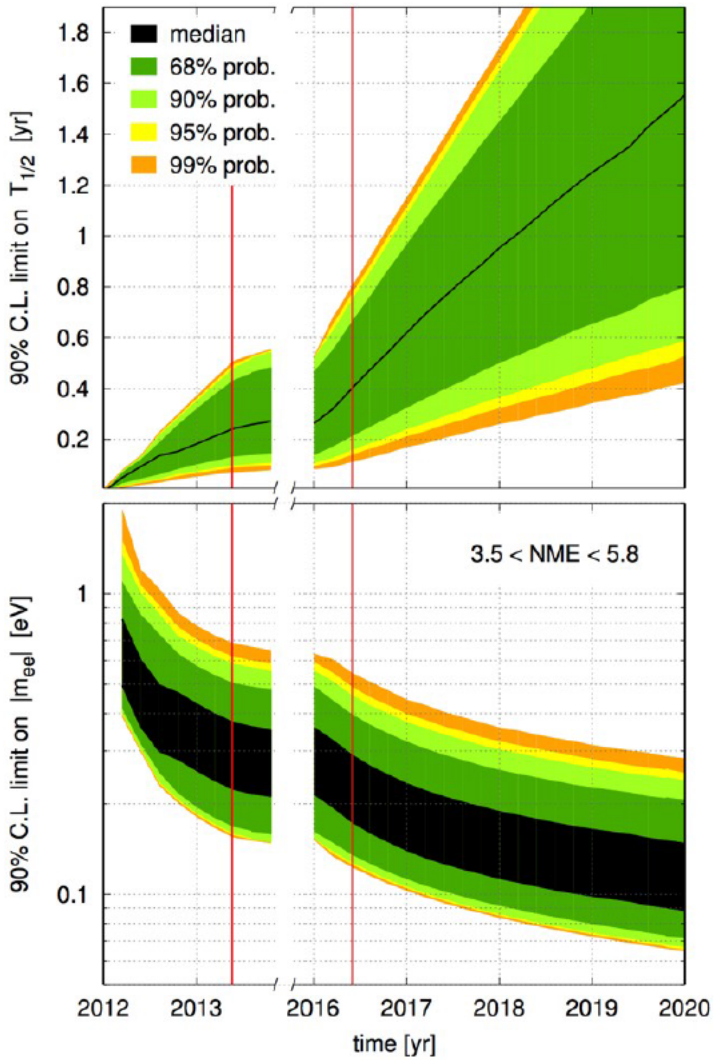
$$T^{0\nu}_{1/2} > 5.3 \cdot 10^{25}\, yr\, @\, 90\, C.L.$$

$$m_{\beta\beta} < (150 - 330)\, meV$$

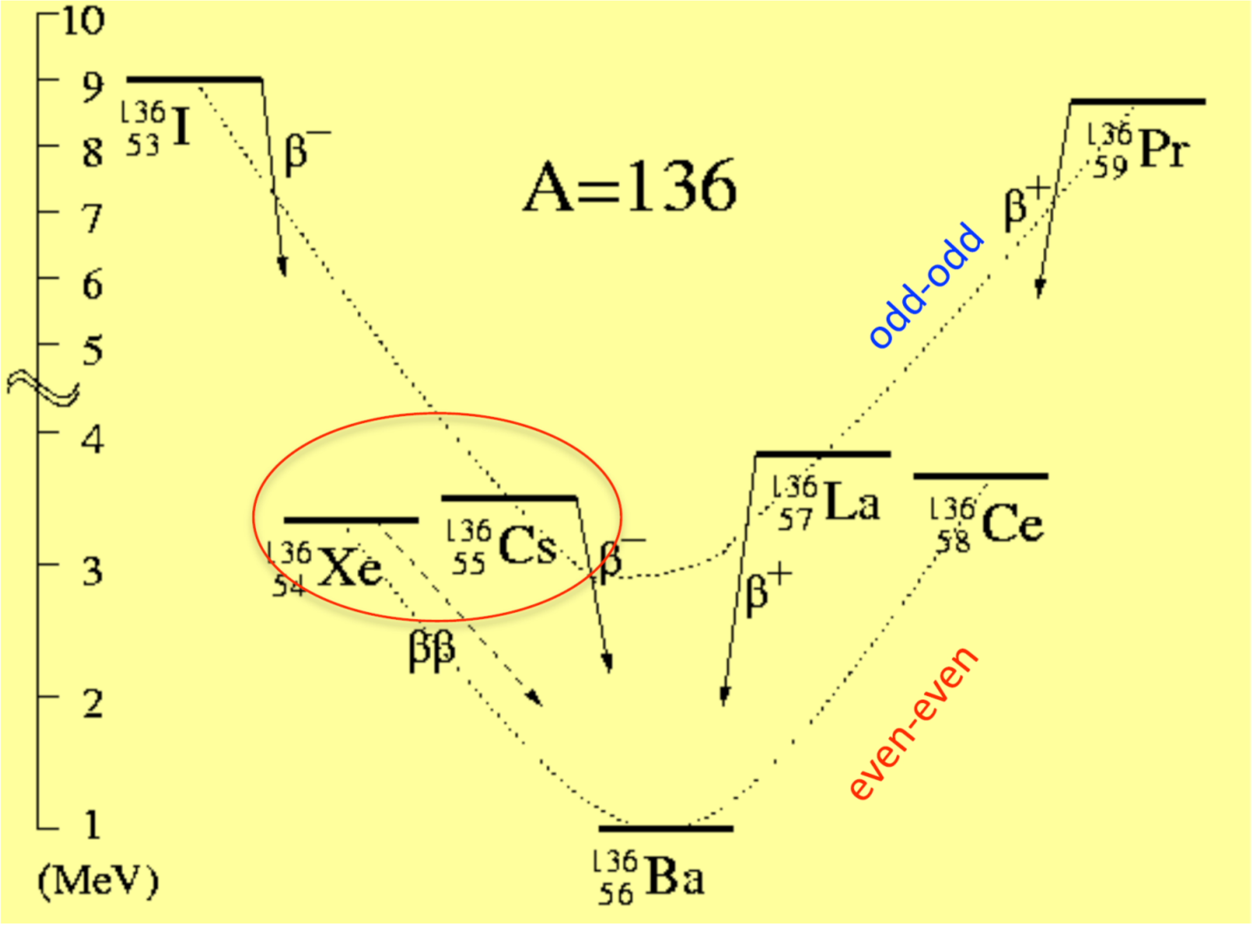
- best energy resolution:
  FWHM = 3.0 keV (4.0 keV) BEGe (Coax) at $Q_{\beta\beta}$
- flat background in ROI
- lowest background at $Q_{\beta\beta}$:
  10^{-3} counts/ (keV·kg·yr)

  will stay background-free within 100 kg·yr

  → important ingredients for discovery

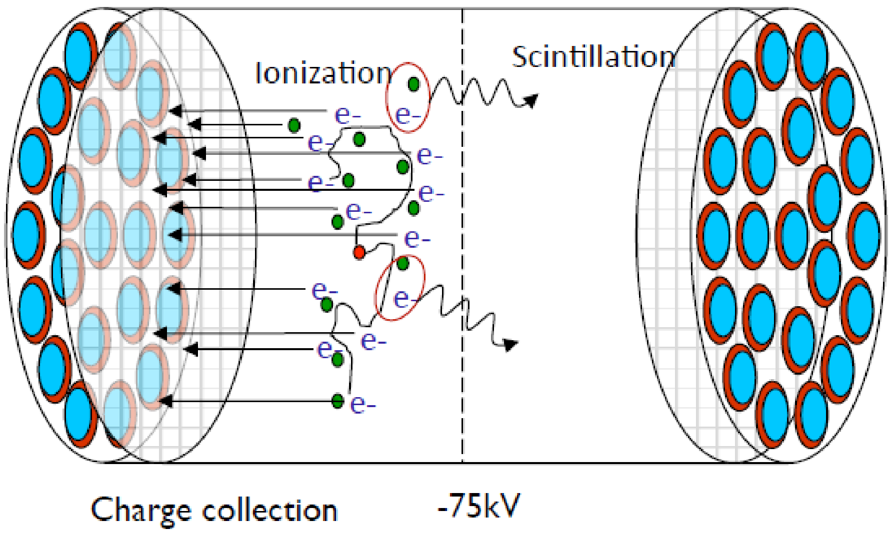


^{136}XENON

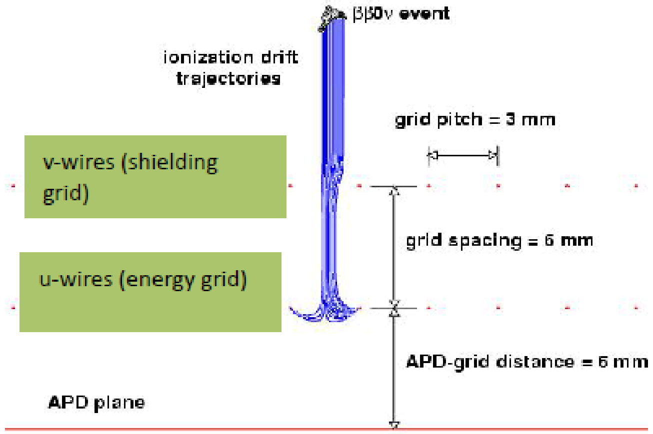


Q-value 2457.9±0.4keV

EXO-200 Time Projection Chamber (TPC) Basics



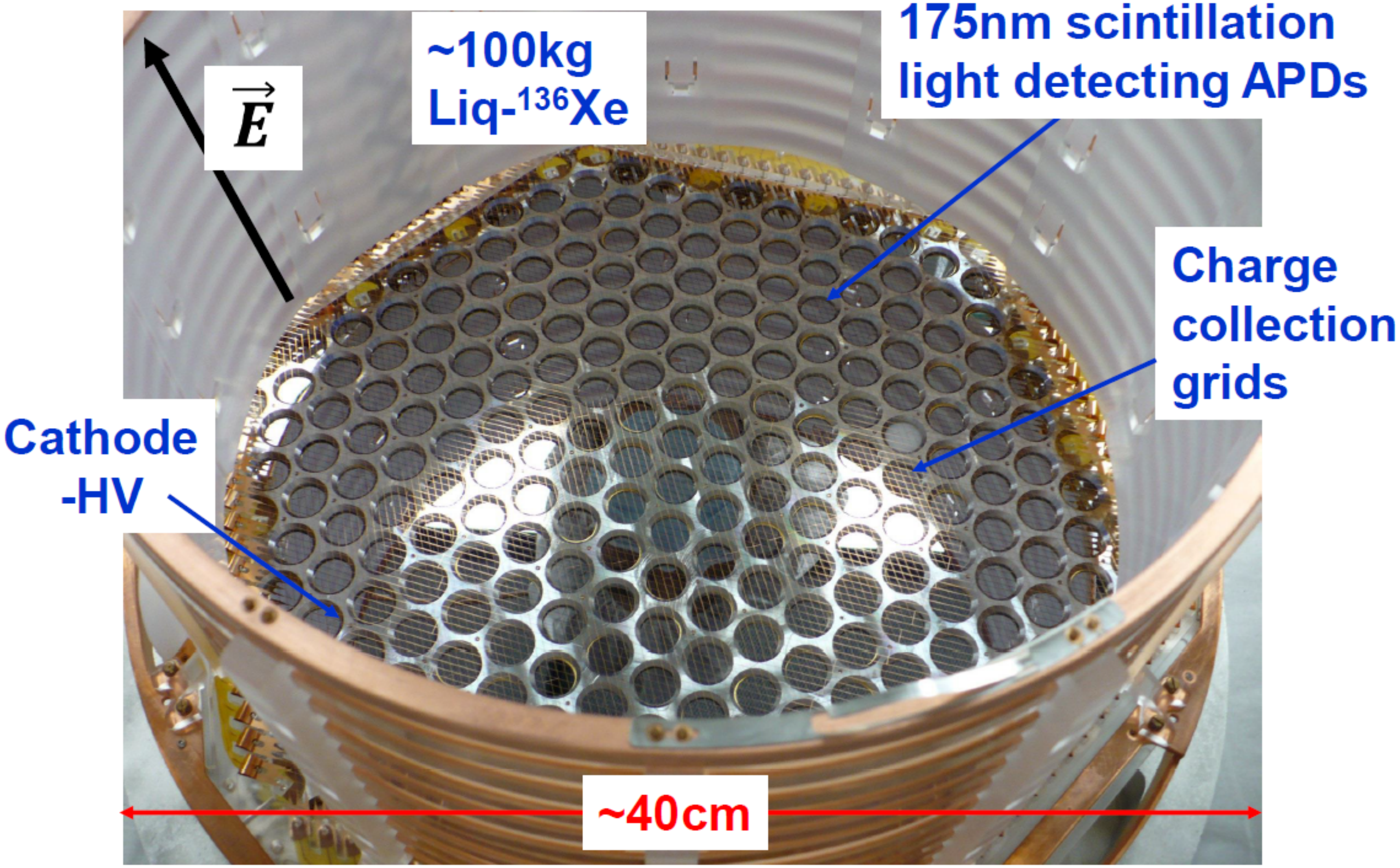
TPC Schematics



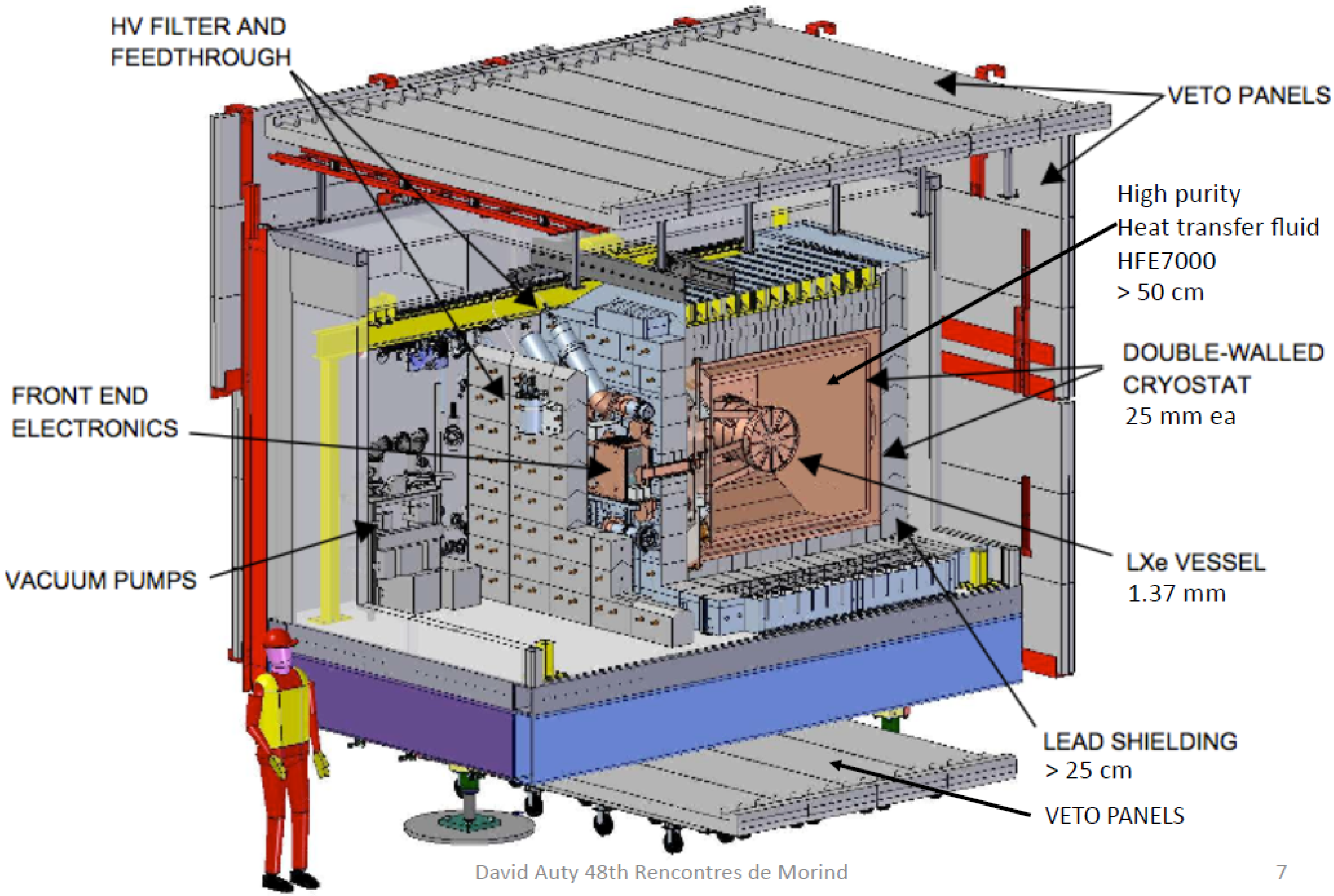
Simulation of Charge Drift

- Two TPC modules with common cathode in the middle.
- APD array observes prompt scintillation for drift time measurement.
  - From which the Z-position can be calculated
- V-position given by induction signal on shielding grid.
- U-position and energy given by charge collection grid.

The EXO-200 liquid ^{136}Xe Time Projection Chamber

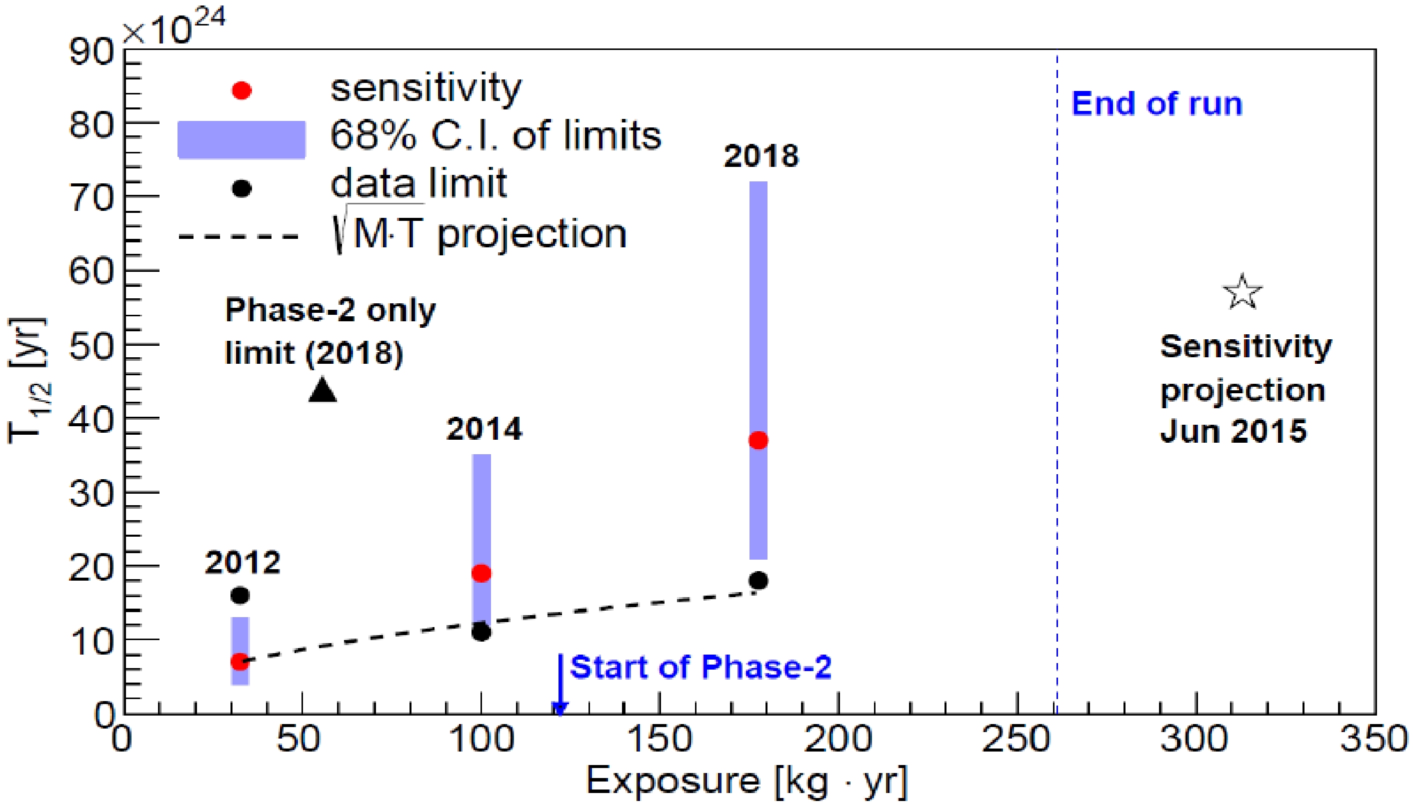


The EXO-200 Detector



A brief history of EXO-200 results

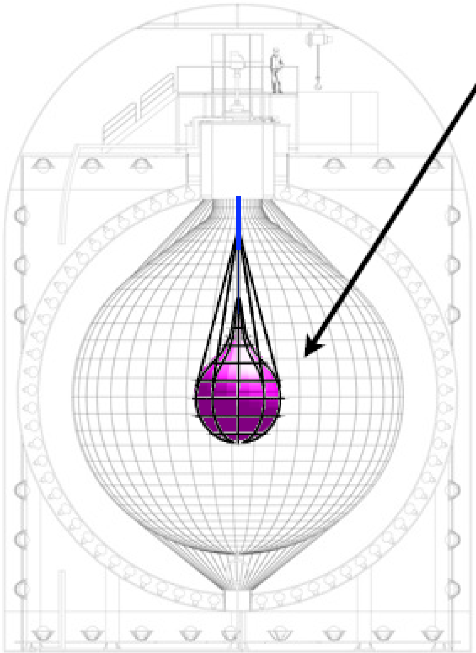
	Sensitivity (yr)	90% CL Limit (yr)	$<m_{\beta\beta}>$ (meV)
PRL 109, 032505 (2012)	0.7×10^{25}	1.6×10^{25}	
Nature 510, 229 (2014)	1.9×10^{25}	1.1×10^{25}	
PRL 120 072701 (2018)	3.8×10^{25}	1.8×10^{25}	147-398



The sensitivity is the correct way to estimate the capability of an experiment, because it contains all the information that can be / is used.

If one wants to use the incomplete picture of a single parameter, then the "background index" is ~ (0.11±0.01) / (kg·yr·FWHM)

KamLAND-Zen



- Mini-balloon ∅=3.08 m installed into center of KamLAND LS, 25μm thick nylon film

^{238}U	2×10^{-12}g/g
^{232}Th	5×10^{-12}g/g
^{40}K	6×10^{-12}g/g
Xe leakage	<0.26kg/yr

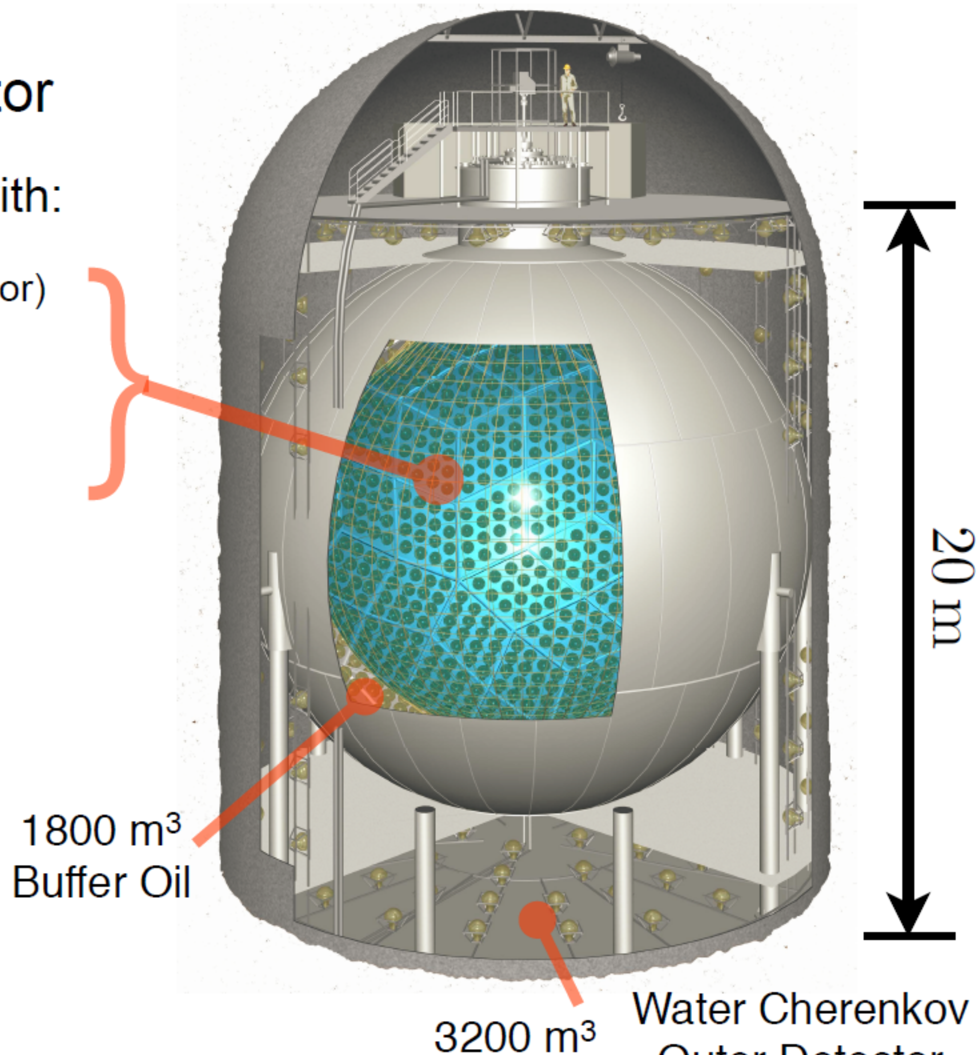
- Filled with 13 tons of Xe-loaded LS (300kg of ^{136}Xe) :

Component	Chemical formula	Fraction
Decane	$C_{10}H_{26}$	82%(by volume)
Pseudocumene	C_9H_{12}	18%(by volume)
PPO	$C_{15}H_{11}NO$	2.7 g/l
Dissolved Xe	90.93±0.05% ^{136}Xe 8.89±0.01% ^{134}Xe	2.5% by weight

- KL-Zen is only ~1% of KamLAND volume, reactor, geoneutrino, supernova watch etc continue in remaining KamLAND LS

KamLAND(-Zen) detector

- 1 kton Scintillation Detector
  - 6.5m radius balloon filled with:
    - 20% Pseudocumene (scintillator)
    - 80% Dodecane (oil)
    - PPO
- 34% PMT coverage
  - ~1300 17” fast PMTs
  - ~550 20” large PMTs
- Water Cherenkov veto
- Operational since 2002



KamLAND(-Zen) detector

- 1 kton Scintillation Detector
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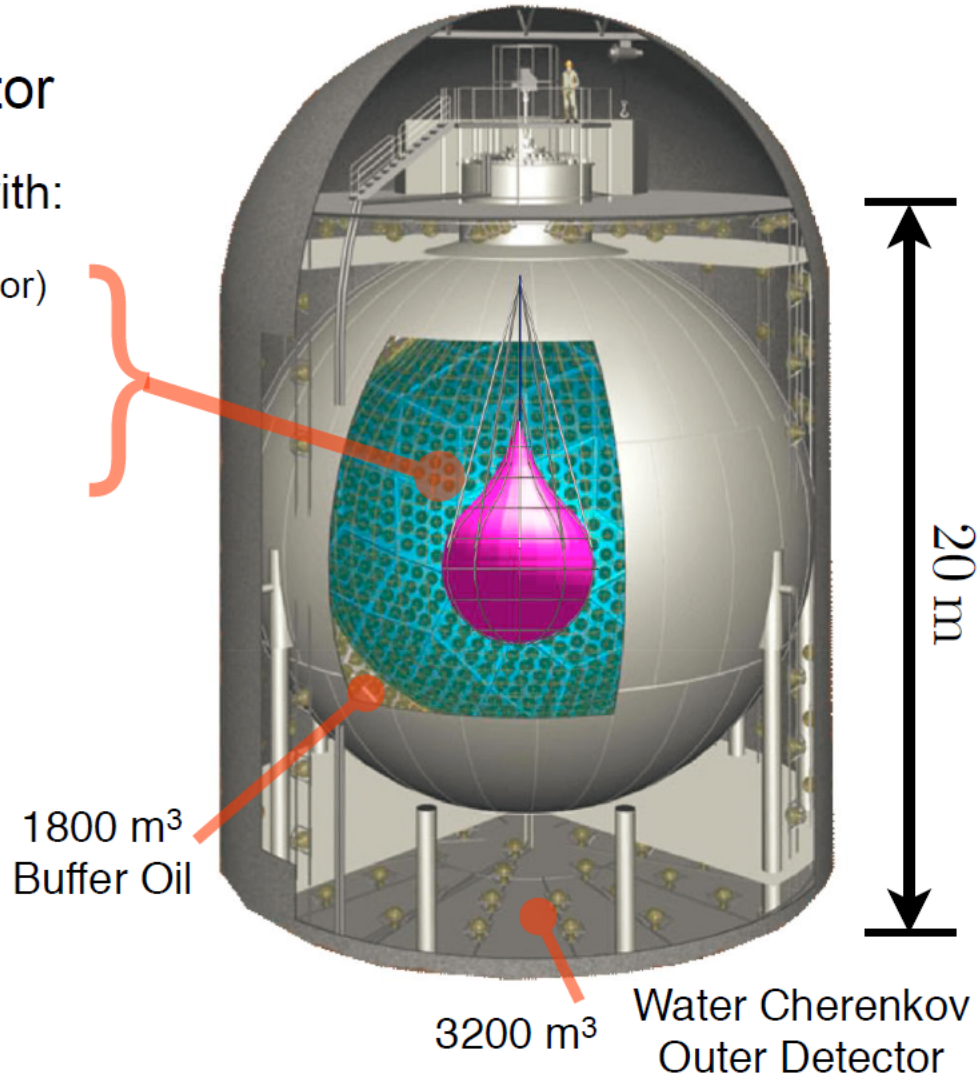
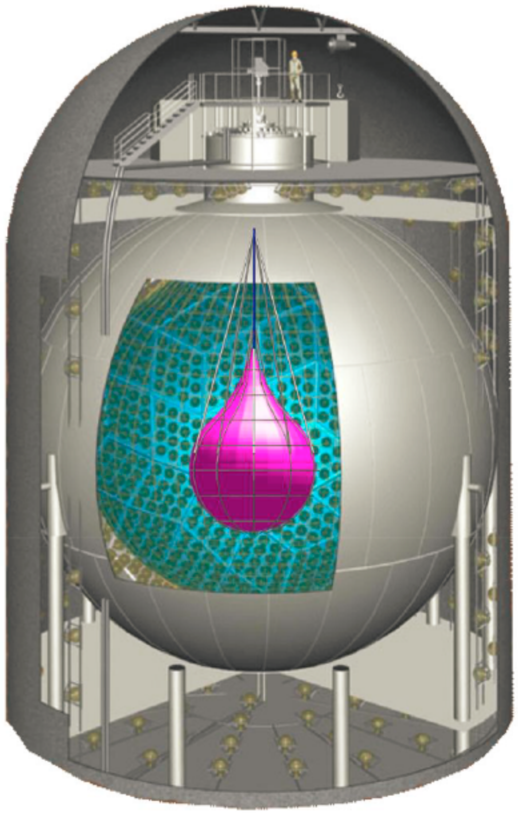


Patrick Decowski/Nikhef

KamLAND-Zen advantages & disadvantages

- +Well-understood detector
- +Highly pure, self-shielding environment
- +Large ββ source mass, scalable
- -Relatively poor energy resolution
- -No particle identification

$$T_{1/2}^{0\nu} \propto \epsilon \frac{a}{A} \sqrt{\frac{Mt}{b\Delta E}}$$



KamLAND-Zen Timeline

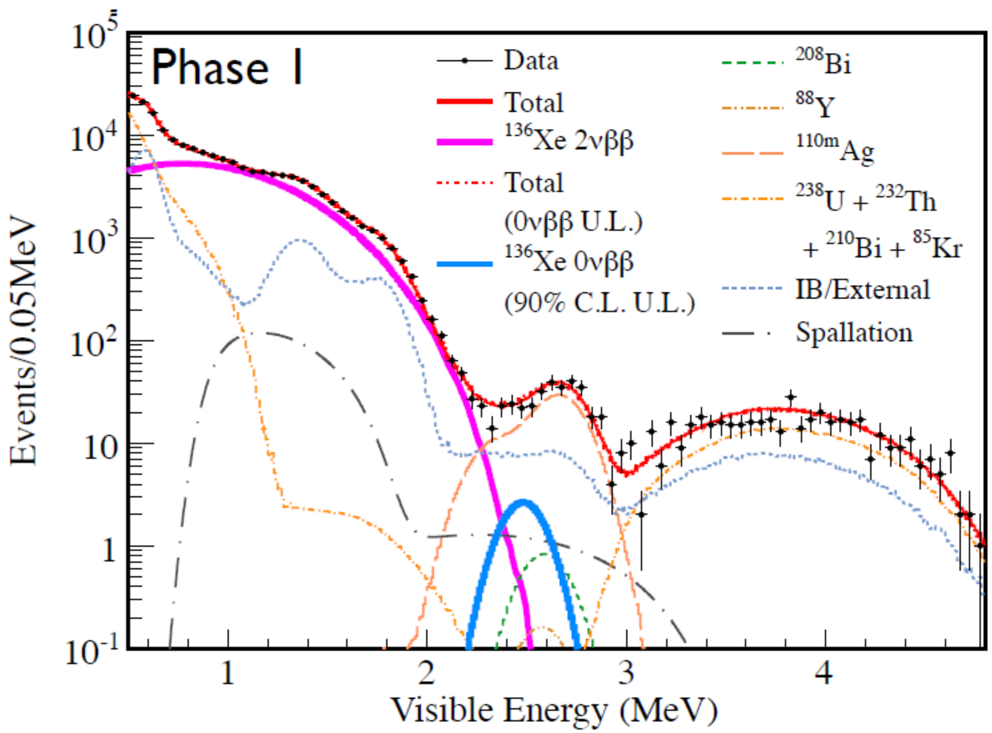
2011	2012	2013	2014	2015

Phase I

Sept '11:Start   90 kg-yr

$$T^{2\nu}_{1/2} = 2.30 \pm 0.02\,(\text{stat}) \pm 0.12\,(\text{sys}) \times 10^{21}\ \text{yr}$$

$T^{0\nu}_{1/2} > 1.9 \times 10^{25}$ yr (90% CL)



^{110m}Ag due to Fukushima-I nuclear fallout

KamLAND-Zen Collaboration, Phys.Rev.Lett. 110 (2013) 062502

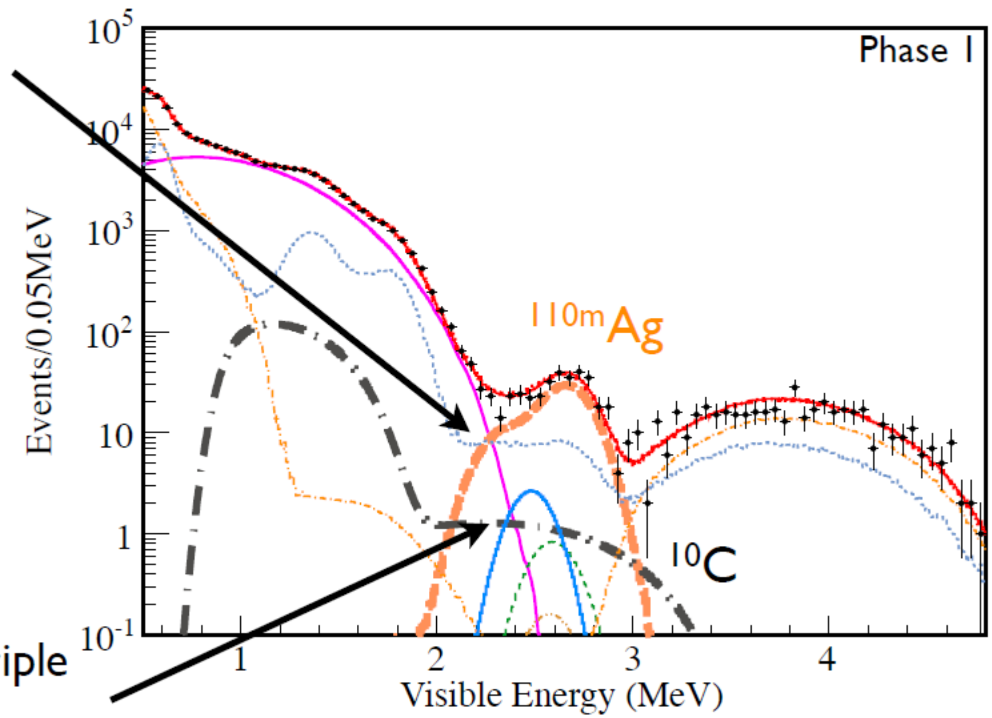
Phase I to Phase II Improvements

2011	2012	2013	2014	2015

Phase I | No Xe in MiniBalloon | Phase II

Sept '11:Start 90 kg-yr purification **504 kg-yr**

- Remove radioactive impurities with Xe-LS purification
  - long distillation campaign + new LS
- Increase the amount of Xe
  - 320kg → 383kg (+20%)
- Spallation cut after muon → ^{10}C rejection
  - muon-neutron-^{10}C (τ=27.8s) triple coincidence

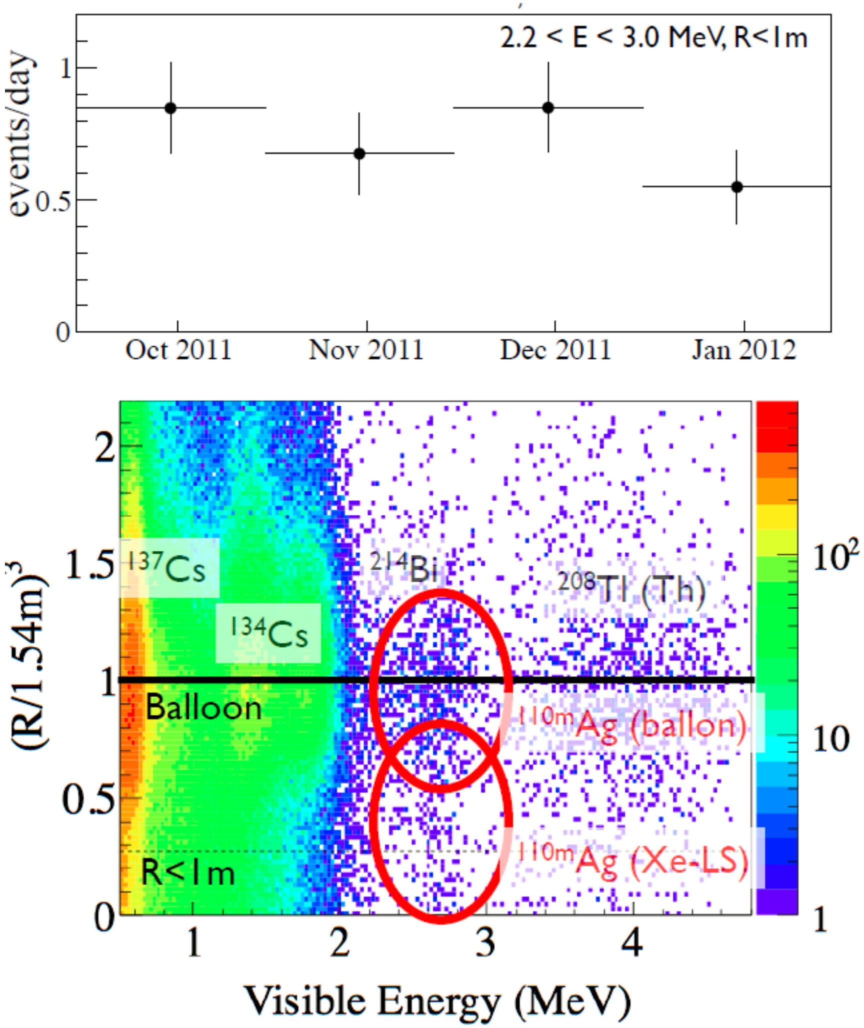


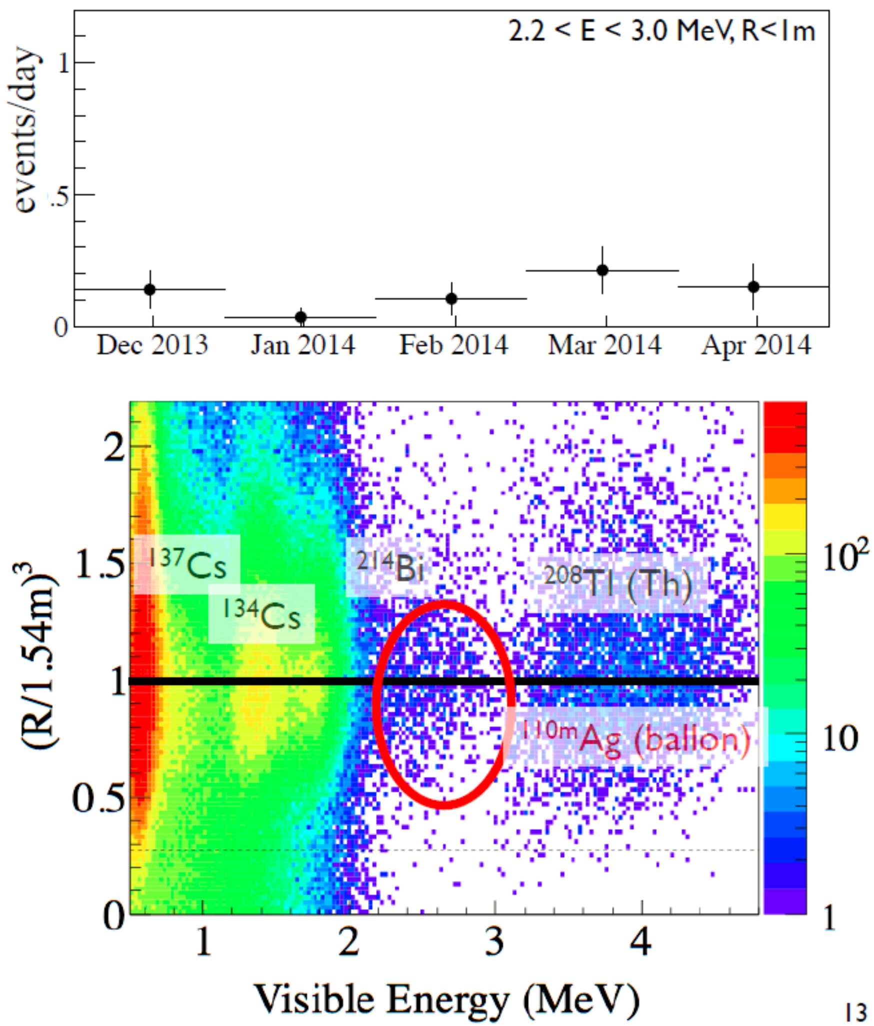
Patrick Decowski/Nikhef

^{110m}Ag Background Reduction

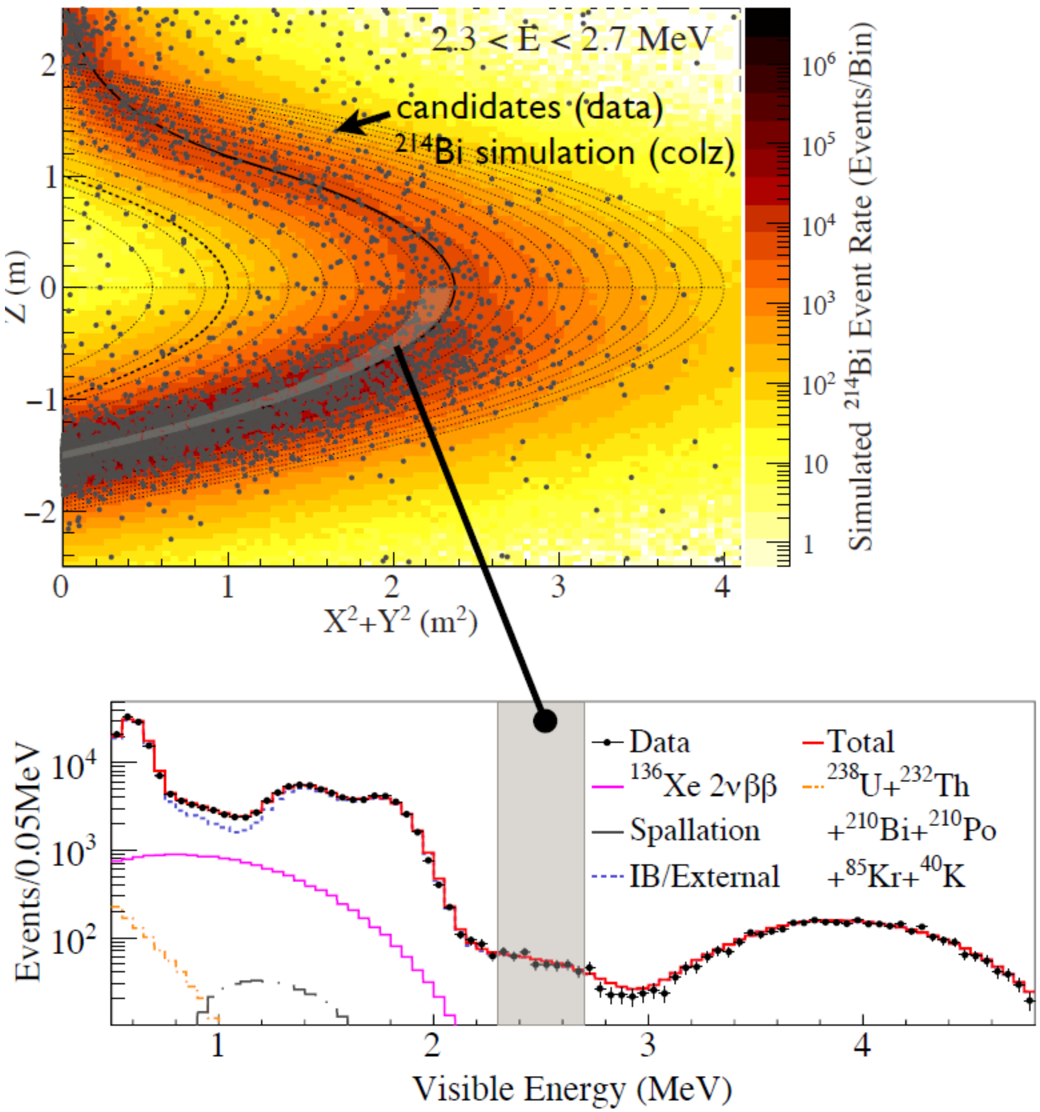
^{110m}Ag BG reduced < 1/10

Phase I → First 115d of Phase II





KLZ-400 Phase 2 Data



Event Selection:

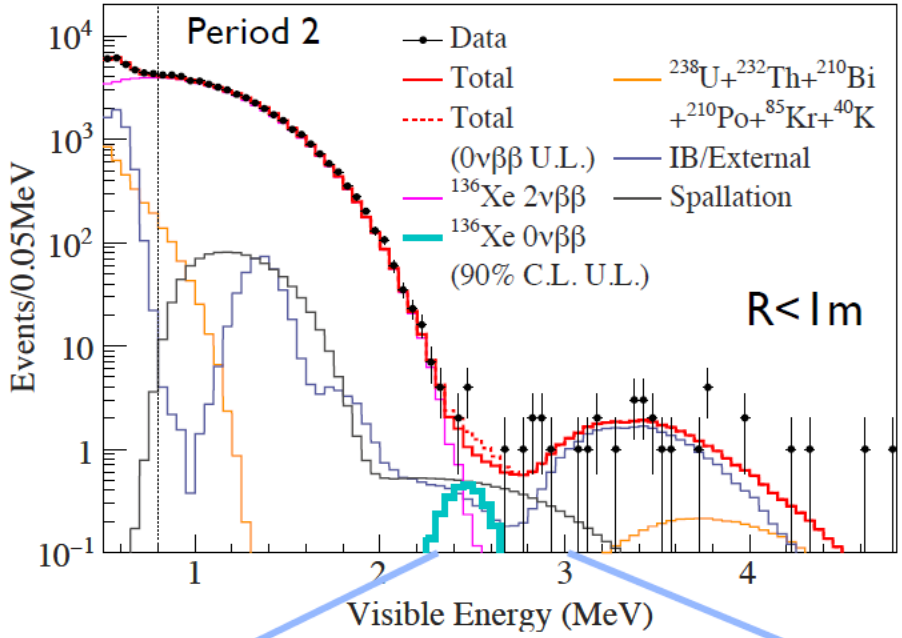
i) R < 2m
ii) ΔT > 2ms after muons
iii) no ^{214}Bi-^{214}Po (τ=237μs)
iv) no ^{212}Bi-^{212}Po (τ=0.4μs)
v) no reactor neutrinos

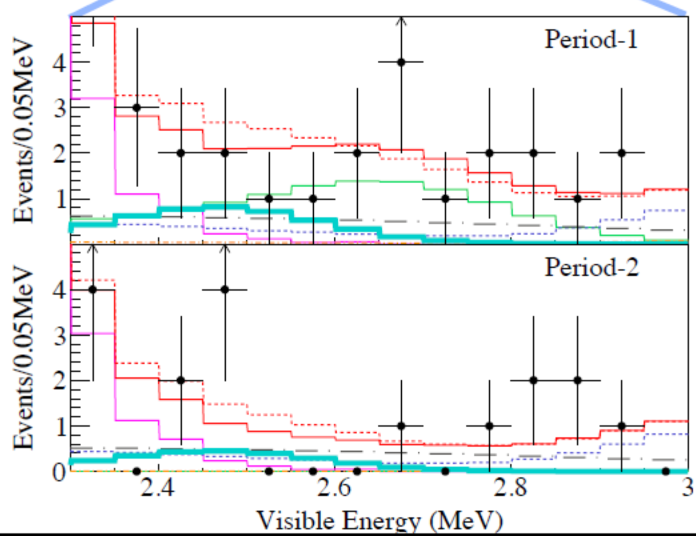
We use 40 equal-volume bins to account for varying BG: Simultaneous spectral fit in all volume bins

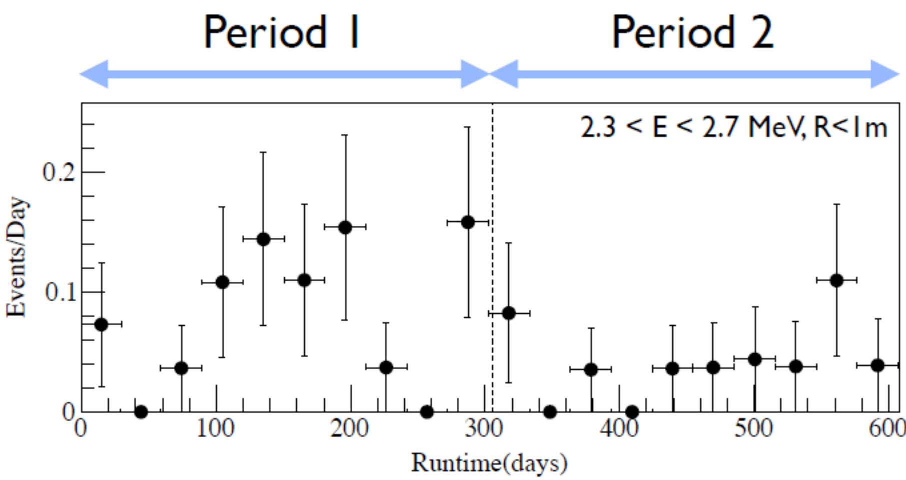
KamLAND-Zen Coll, Phys. Rev. Lett. 117, 082503 (2016); arXiv:1605.02889

Results for Phase-2

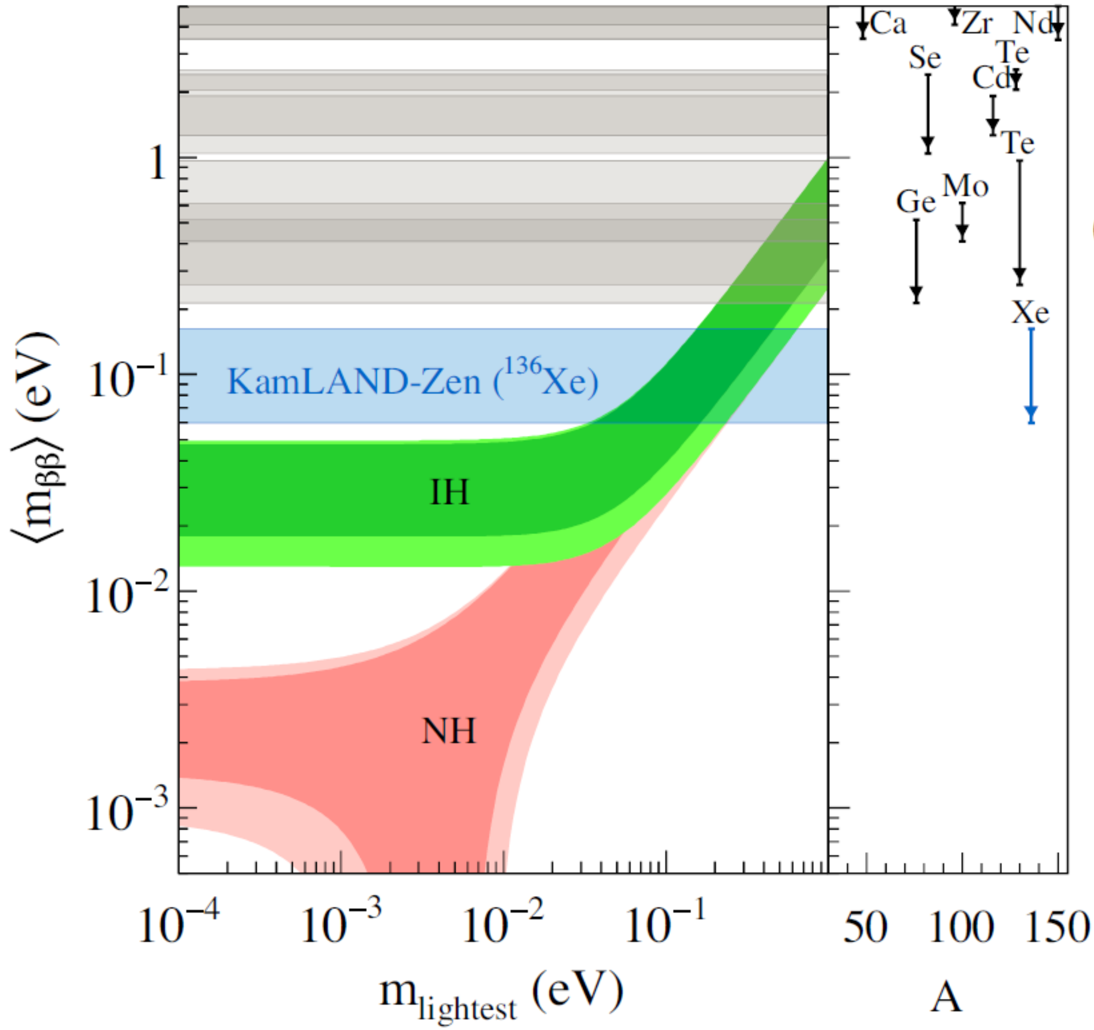
504 kg-yr exposure of ^{136}Xe







Effective Neutrino Mass

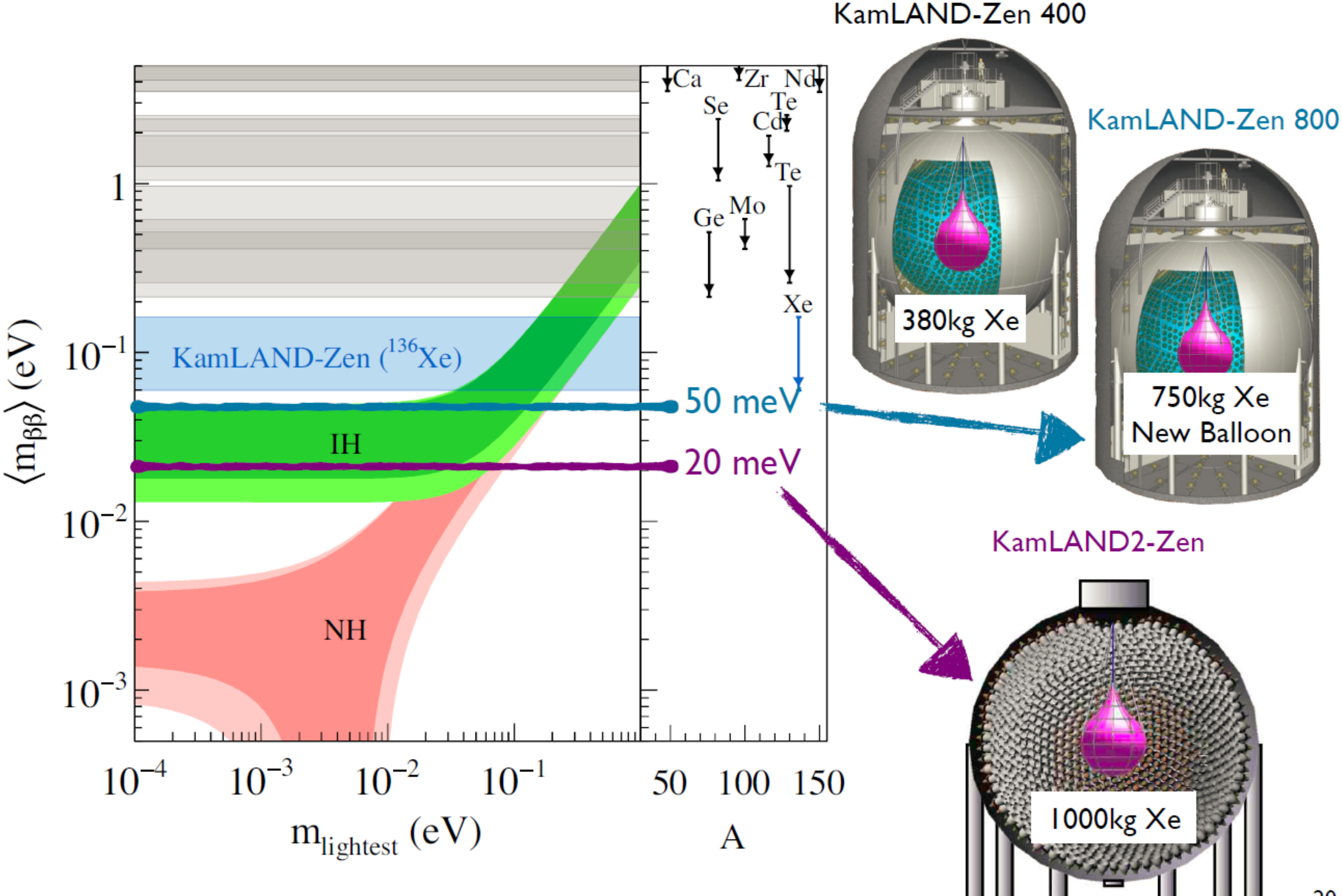


$$(T^{0\nu}_{1/2})^{-1} = G_{0\nu}(Q,Z)|M_{0\nu}|^2\langle m_{\beta\beta}\rangle^2$$

$\langle m_{\beta\beta}\rangle$ < 61 - 165 meV

KamLAND-Zen Coll, Phys. Rev. Lett. 117, 082503 (2016); arXiv:1605.02889

Future Goals



And what we are really interested in: As of Oct 2018

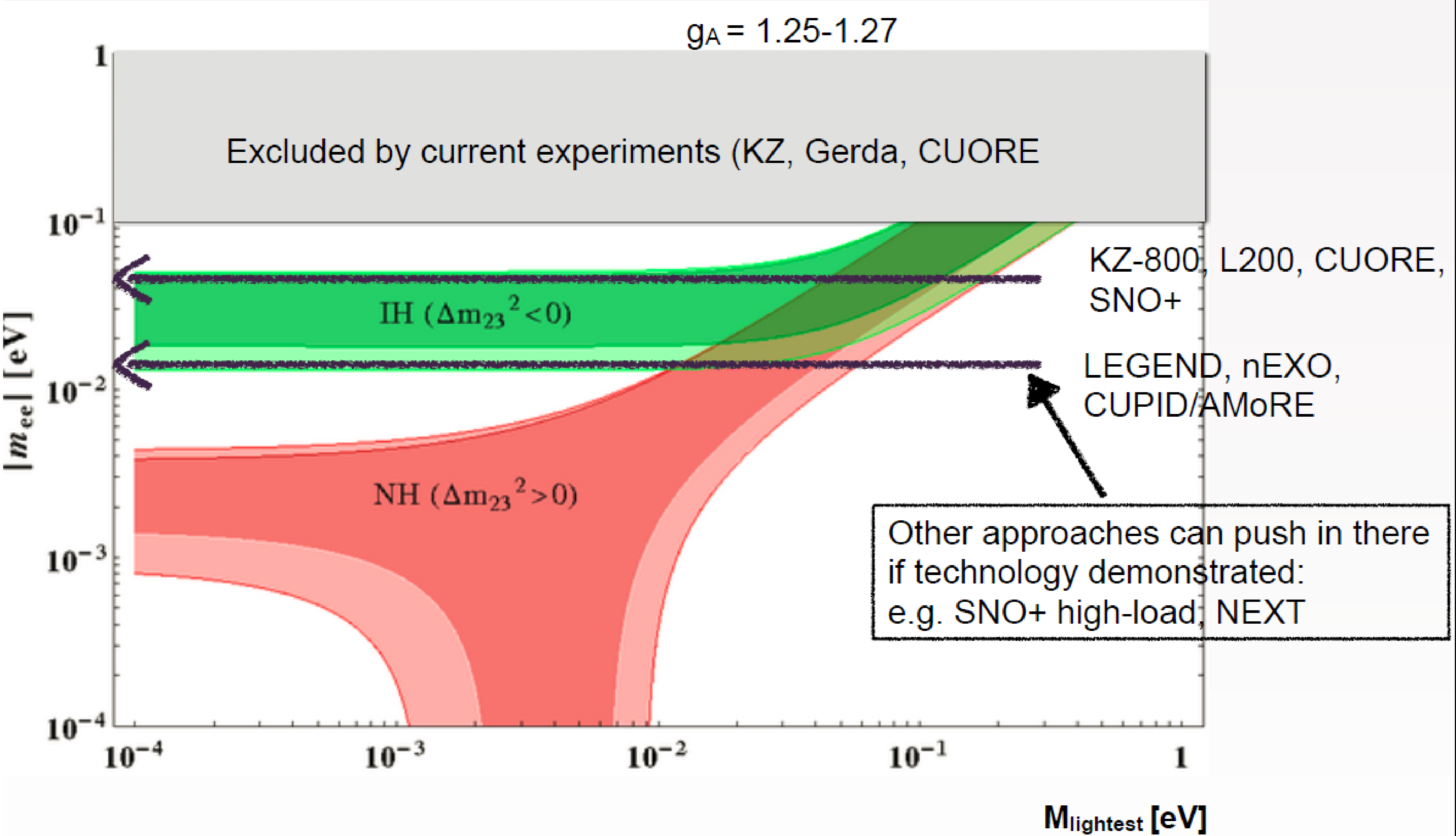
Best results from $0\nu\beta\beta$

$$T^{0\nu}_{1/2}\,(90\%\ \text{C.L.}) = 2.54\times 10^{26}\,\text{y}\left(\frac{\varepsilon\times a}{W}\right)\sqrt{\frac{M\times t}{b\times \Delta E}}$$

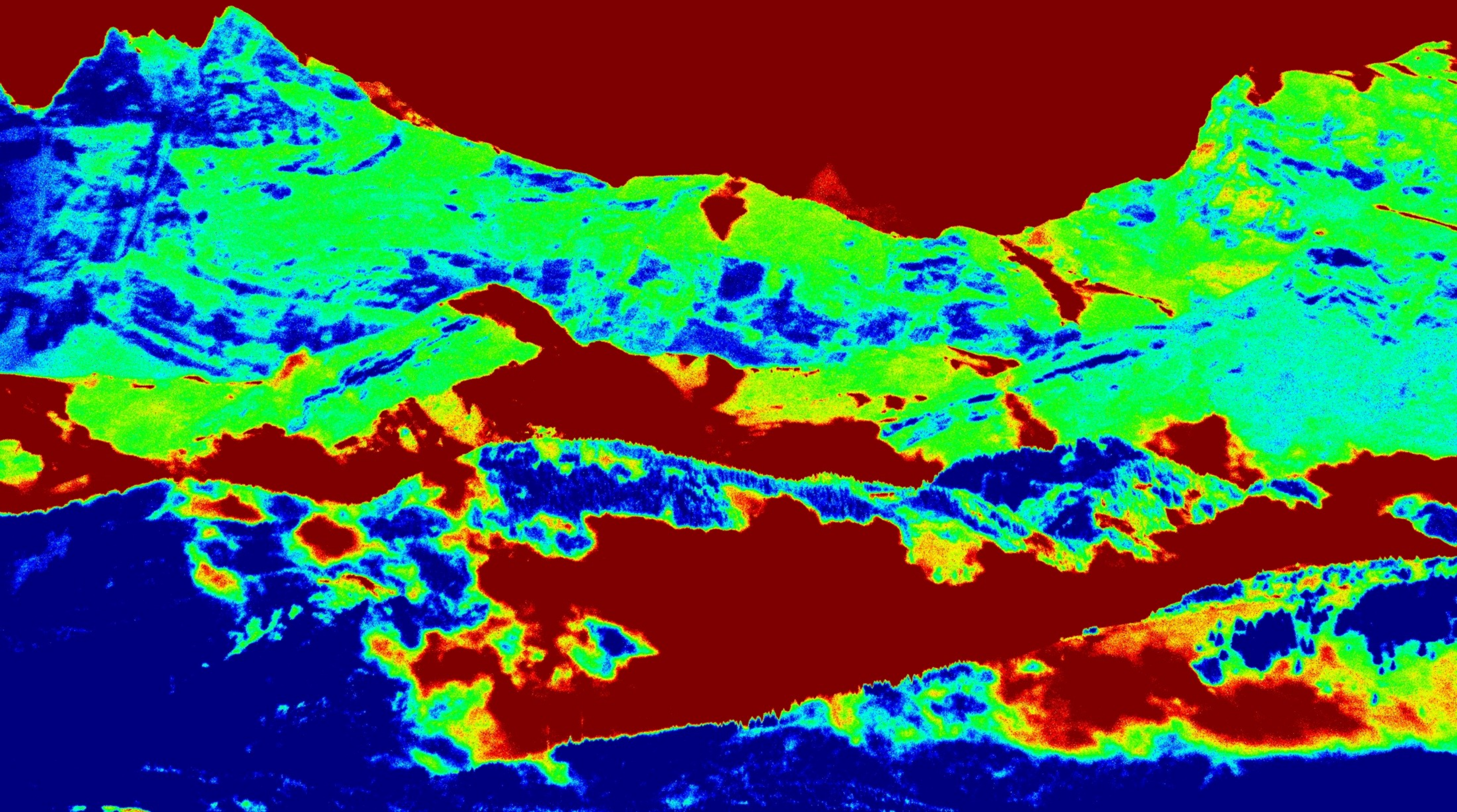
Isotope, mass	$Q_{\beta\beta}$, keV	b x ΔE x M, counts/yr	$T_{1/2}$, yr	$\langle m_\nu \rangle$, eV	Experiment, technique
^{76}Ge, 40kg	**2039**	**0.07**	**> 0.9 x 10^{26}**	**< 0.11-0.25**	**GERDA, HPGe**
^{82}Se, 5kg	2998	0.4	> 2.4 x 10^{24}	< 0.38-0.77	CUPID-0, scintillating bolometers
^{100}Mo, 7kg	3034	1.5	> 1.1 x 10^{24}	< 0.33-0.62	NEMO-3, tracko-calo
^{130}Te, 200kg	2528	21	> 1.5 x 10^{25}	< 0.13-0.50	CUORE, bolometers
^{136}Xe, 380kg	**2458**	**1**	**> 1.07 x 10^{26}**	**< 0.06-0.16**	**KamLAND-Zen, doped LS**

Different techniques reach similar sensitivity with different isotope mass

Current Results and Next Generation prospects



The Search for the Right-Handed Neutrinos



The Nobel Prize in Physics 2015
Takaaki Kajita, Arthur B. McDonald

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The Nobel Prize in Physics 2015

Photo © Takaaki Kajita

Takaaki Kajita

Prize share: 1/2

Photo: K. MacFarlane. Queen's University /SNOLAB

Arthur B. McDonald

Prize share: 1/2

The Nobel Prize in Physics 2015 was awarded jointly to Takaaki Kajita and Arthur B. McDonald *"for the discovery of neutrino oscillations, which shows that neutrinos have mass"*

Q | Terms

The discovery that neutrino flavours transform (Neutrino Oscillations) was a long process initiated in 1968 and completed in 1998-2001.
➔ **Neutrinos have mass !**

There is no unique way to incorporate this in the Standard Model
It almost certainly implies the existence of
-- new mass-generation mechanism
-- new phenomena such as right-handed neutrinos

➔ possible explanations for the baryon asymmetry of the universe and for dark matter

Neutrino masses? Mixings? Ordering?
Majorana mass term? CP violation
eV, keV, GeV, TeV, …, ZeV RH neutrinos?

Baryon asymmetry of Universe requires
-- CP violation
neutrinos
-- fermion number violation
-- non-equilibrium

This opens a deep field of research for many many years.

Baryon asymmetry of Universe requires:

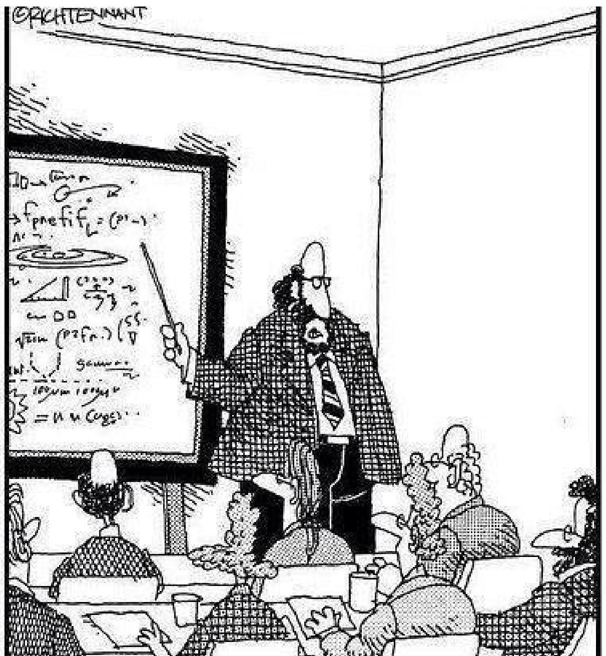
-- CP violation **3 families of neutrinos**

-- fermion number violation **Majorana mass term**

-- non-equilibrium **The Big Bang + heavy neutrino decay**

Electroweak eigenstates

I = 1/2	I = 0	
$\begin{pmatrix} e \\ \nu_e \end{pmatrix}_L \begin{pmatrix} \mu \\ \nu_\mu \end{pmatrix}_L \begin{pmatrix} \tau \\ \nu_\tau \end{pmatrix}_L$	$(e)_R \; (\mu)_R \; (\tau)_R$	Q= -1
	$(\nu_e)_R \; (\nu_\mu)_R \; (\nu_\tau)_R$	Q= 0



"Along with 'Antimatter,' and 'Dark Matter,' we've recently discovered the existence of 'Doesn't Matter,' which appears to have no effect on the universe whatsoever."

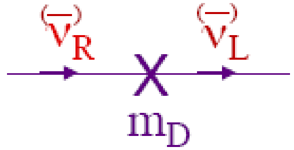
Right handed neutrinos are singlets
no weak interaction
no EM interaction
no strong interaction

can't produce them
can't detect them
-- so why bother? –

Also called 'sterile'

Adding masses to the Standard model neutrino 'simply' by adding a Dirac mass term (Yukawa coupling)

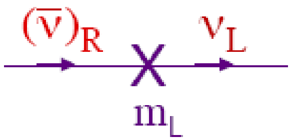
$$m_D \nu_L \overline{\nu_R}$$ $$m_D \overline{\nu_L}\, \nu_R$$



implies adding a right-handed neutrino (new particle)

<u>No SM symmetry </u>prevents adding then a term like

$$m_M \overline{\nu_R^{\ c}}\, \nu_R$$



and this simply means that a neutrino turns into a antineutrino

It is perfectly conceivable (‘natural’?) that both terms are present.

Dirac mass term + Majorana mass term ‘see-saw’

B. Kayser, the physics of massive neutrinos (1989)

Mass eigenstates

See-saw type I :

$$\mathcal{L} = \frac{1}{2}(\bar{\nu}_L,\ \bar{N}^c_R) \begin{pmatrix} 0 & m_D \\ m_D^T & M_R \end{pmatrix} \begin{pmatrix} \nu^c_L \\ N_R \end{pmatrix}$$

$M_R \neq 0$
$m_D \neq 0$
Dirac + Majorana mass terms

$$\tan 2\theta = \frac{2\, m_D}{M_R - 0} \qquad \ll 1$$

$$m_\nu = \tfrac{1}{2}\left[(0 + M_R) - \sqrt{(0 - M_R)^2 + 4\, m_D^2}\right] \qquad \simeq -m_D^2/M_R$$

$$M = \tfrac{1}{2}\left[(0 + M_R) + \sqrt{(0 - M_R)^2 + 4\, m_D^2}\right] \qquad \simeq M_R$$

general formula — if $m_D \ll M_R$

$M_R = 0$
$m_D \neq 0$
Dirac only, (like e- vs e+):

m ↑

	ν_L	ν_R	$\bar{\nu}_L$	$\bar{\nu}_R$
I_{weak}=	½	0	½	0

4 states of equal masses
Some have I=1/2 (active)
Some have I=0 (sterile)

$M_R \neq 0$
$m_D = 0$
Majorana only

m ↑

	ν_L	$\bar{\nu}_R$
I_{weak}=	½	½

2 states of equal masses
All have I=1/2 (active)

$M_R > m_D \neq 0$ — see-saw

Dirac + Majorana

m ↑

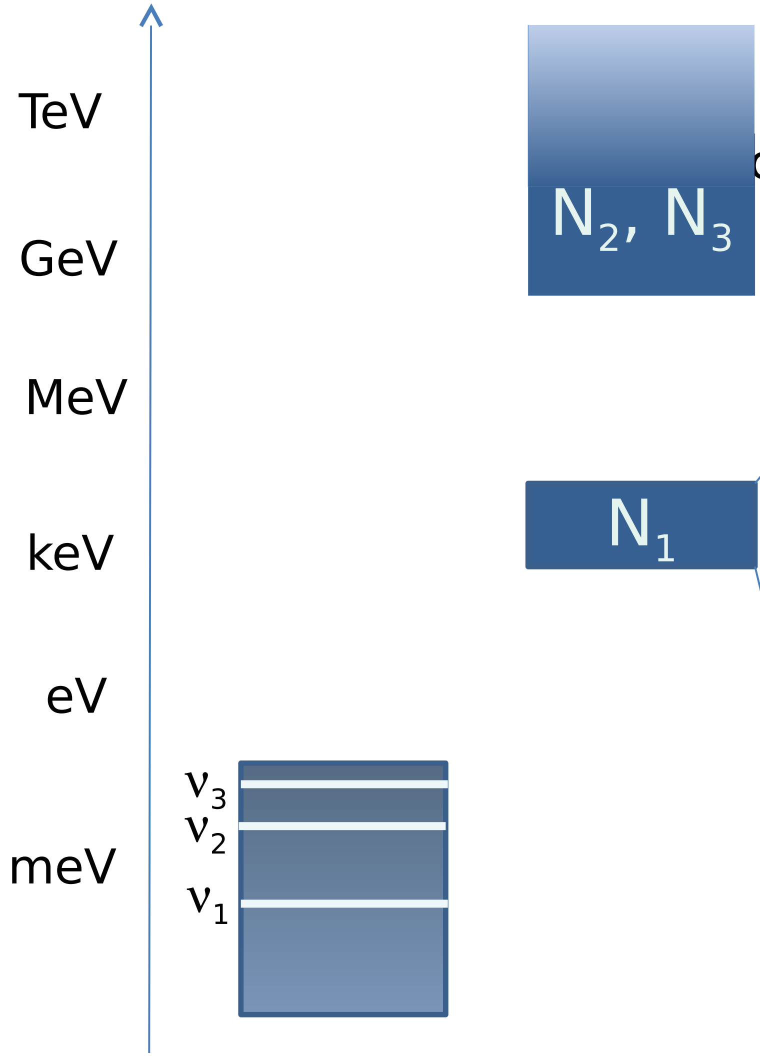
dominantly:

	ν	N	$\bar{\nu}$	$\bar{N}$
I_{weak}=	½	0	½	0

4 states , 2 mass levels
m_1 have ~I=1/2 (~active)
m_2 have ~I=0 (~sterile)

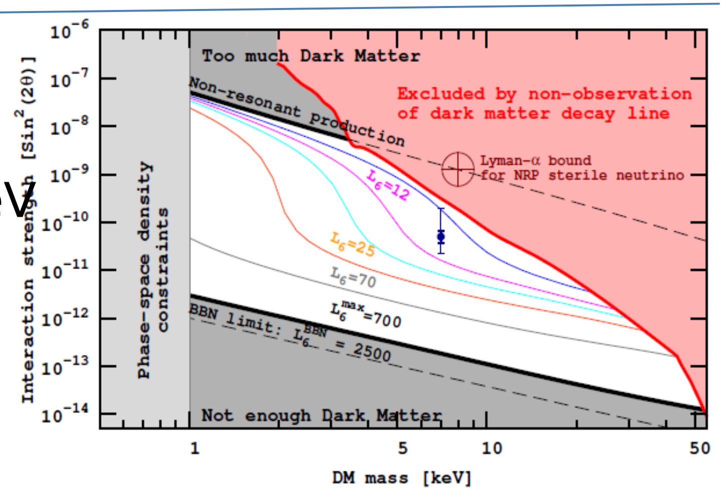
There even exists a scenario that explains everything: the νMSM

Shaposhnikov et al

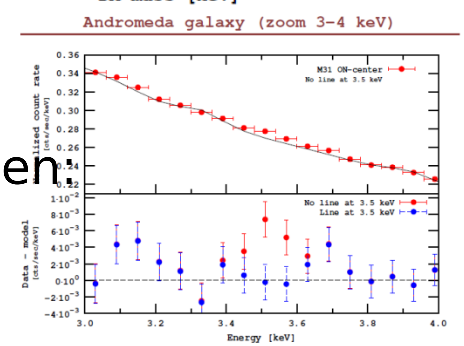


can generate Baryon Asymmetry of Universe if $m_{N2,N3}$ > 140 MeV

constrained:
mass: 1-50 keV
mixing : 10^{-7} to 10^{-13}
decay time: $\tau_{N1} > \tau_{Universe}$



$N_1 \rightarrow \nu\ \gamma$
may have been seen:
arxiv:1402:2301
arxiv:1402.4119



Manifestations of heavy right handed neutrinos

***one* family see-saw :**
$\theta \approx (m_D/M)$
$m_\nu \approx \frac{m_D^2}{M}$
$m_N \approx M$
$|U|^2 \propto \theta^2 \approx m_\nu / m_N$

$|U|^2 \propto \theta^2 \approx / m_N$

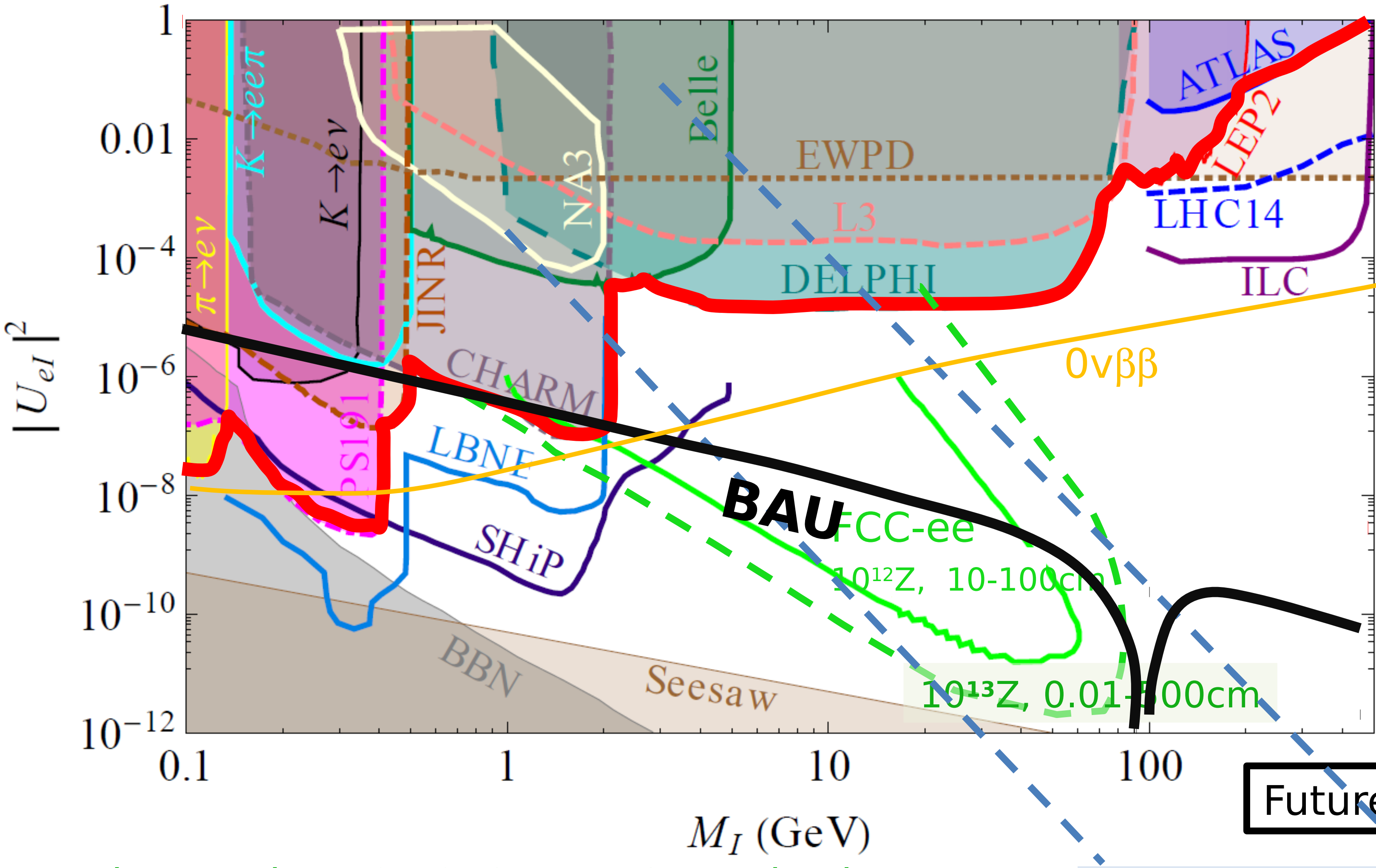
cosθ - θ
$$\nu = \nu_L \cos\theta - N^c{}_R \sin\theta$$
c sinθ
$$N = N_R \cos\theta + \nu_L{}^c \sin\theta$$

what is produced in W, Z decays is:
$$\nu_L = \nu \cos\theta + N \sin\theta$$
cosθ + θ

ν = light mass eigenstate
N = heavy mass eigenstate
$\neq \nu_L$, active neutrino which couples to weak inter. and $\neq N_R$, which does'nt.

-- mixing with active neutrinos leads to various observable consequences
-- if very light (eV) , possible effect on neutrino oscillations (see talks later today)
-- if in keV region (dark matter), monochromatic photons from galaxies with $E=m_N/2$
-- possibly measurable effects at High Energy
If N is heavy it will decay in the detector (not invisible)
→ PMNS matrix unitarity violation and deficit in Z «invisible» width
→ Higgs, Z, W visible exotic decays H→ $\nu_i \bar{N}_i$ and Z→ $\nu_i \bar{N}_i$, W-> $l_i \bar{N}_i$
→ also in K, charm and b decays via W*-> $l_i^\pm \bar{N}$, N → $l_j^\pm$
with any of six sign and lepton flavour combination
→ violation of unitarity and lepton universality in Z, W or τ decays
-- etc... etc...
-- Couplings are very small (m_ν / m_N) *(but who knows?)* **and generally seem out of reach at high energy colliders.**

Present limits



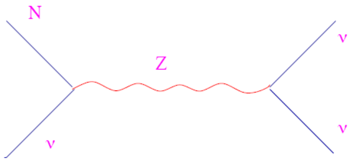
Future

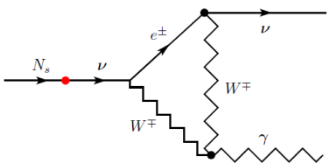
$L_{decay} \approx 10$m $L_{decay} = 1$mm

Based on arXiv:1504.04855v1 'SHIP physics paper'
And Pilar Hernandez, HEP-EPS Vienna

Search Processes (I)

m_N Below m_π:
N→ 3ν; N→ νγ w $E_\gamma = m_N/2$

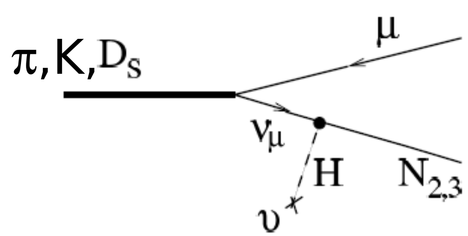


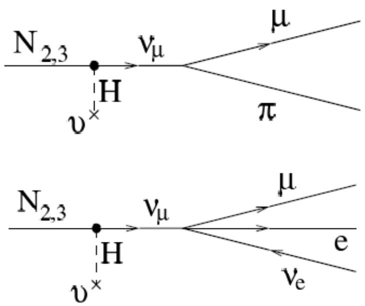


$$\tau_{N_1} = 10^{14}\,\text{years}\left(\frac{10\ \text{keV}}{M_N}\right)^5\left(\frac{10^{-8}}{\theta_1^2}\right)$$

Long life, **dark matter candidate**
Equilibrium with neutrinos produced in the stars
→ Search for gamma emission line (such as 3.5 keV line)
Drewes et al; arXiv:1602.04816v1

Meson decay (π,K: neutrino beams) examples:





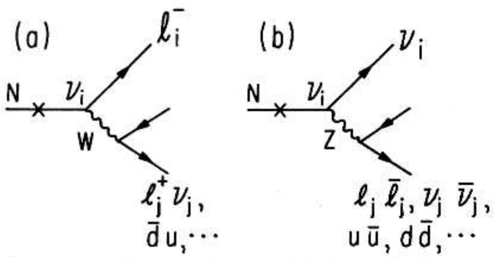


FIG. 2. Typical decays of a neutral heavy lepton via (a) charged current and (b) neutral current. Here the lepton l_i

$$L \approx \frac{3}{|U|^2\ (m_{\nu_m}(\text{GeV}/c^2))^6} \times \frac{P_\nu}{45 GeV/c}$$

Decay via W gives at least two charged particles, and amounts to ~60% of decays.
Searches for long lived decays in neutrino beams PS191, NuTeV, CHARM; SHIP and DUNE proposals

Experiment	PS191	NuTeV	CHARM	SHiP
Proton energy (GeV)	19.2	800	400	400
Protons on target ($\cdot 10^{19}$)	0.86	0.25	0.24	20
Decay volume (m^3)	360	1100	315	1780
Decay volume pressure (bar)	1 (He)	1 (He)	1 (air)	10^{-6} (air)
Distance to target (m)	128	1400	480	80-90
Off beam axis (mrad)	40	0	10	0

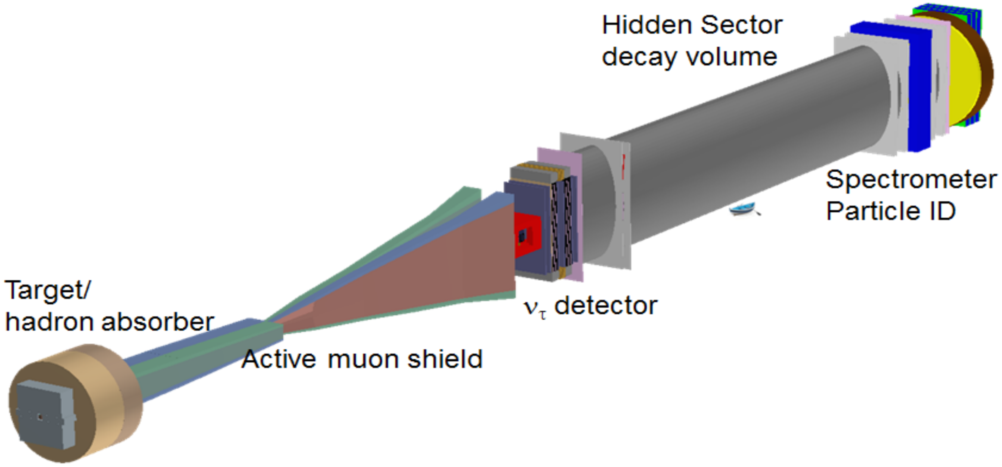
Next generation heavy neutrino search experiment SHIP

-- focuses on neutrinos from charm to cover 0.5 – 2 GeV region

-- uses beam dump to reduce background from neutrino interactions from pions and Kaons and bring the detector as close as possible to source.

-- increase of beam intensity and decay volume

status: proposal, physics report and technical report exist. R&D phase approved at CERN

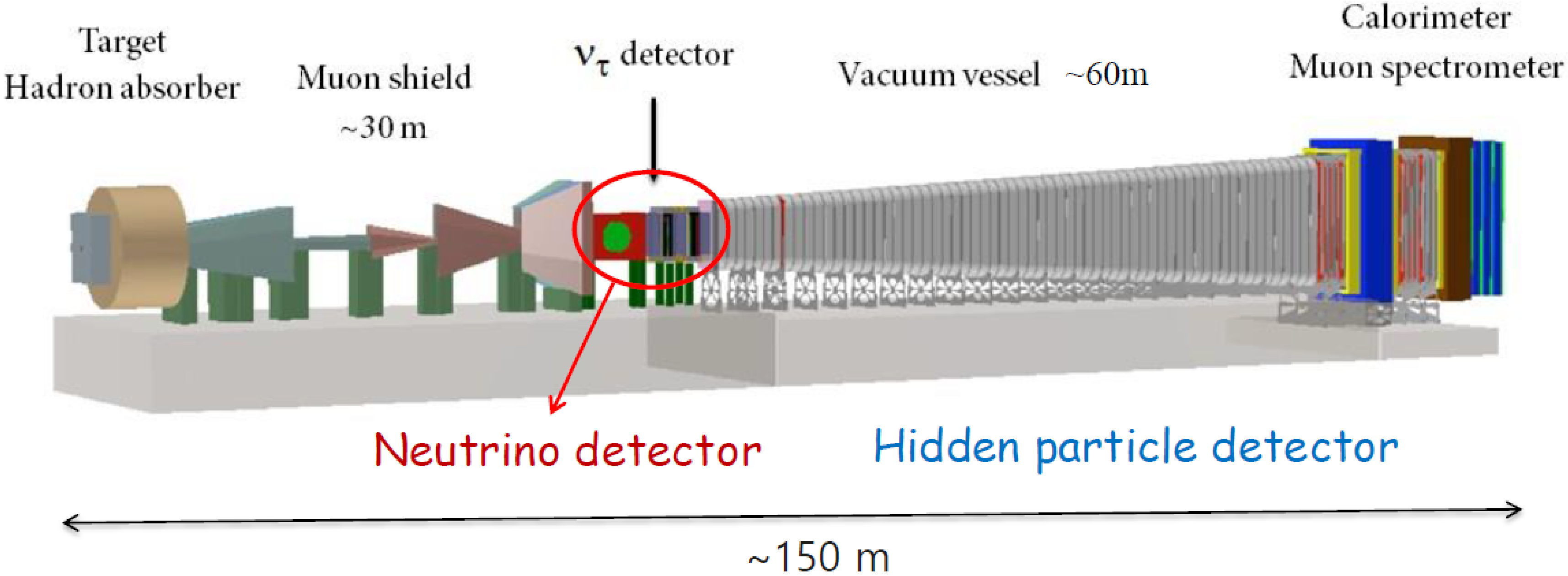


arXiv:1504.04855
arXiv:1504.04956

SHiP Detector

Active muon shield
deflect muons from 2ry meson decay
~ 35m long, 1.7 T magnet

PID
Energy measure

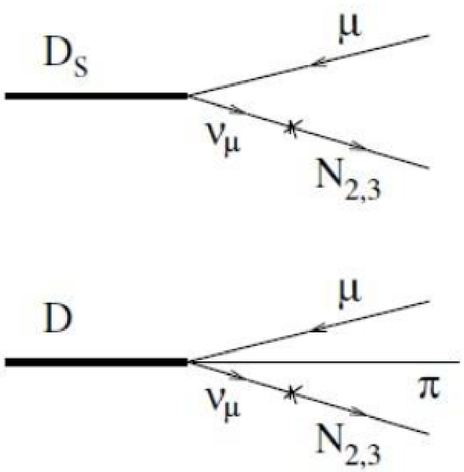


Hadron absorber
eliminate
2ry mesons
~ 5m Fe

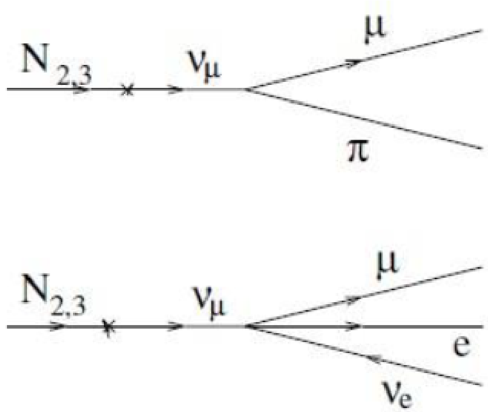
Nuclear Emulsion
Tau-neutrino physics
LDM search

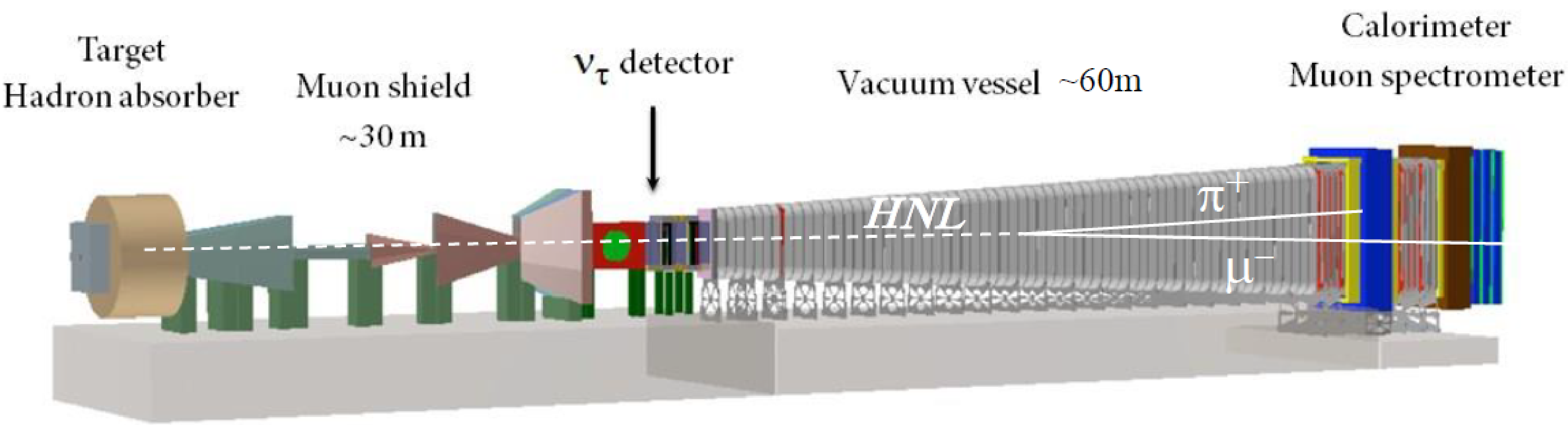
Vacuum decay vessel
~60 m long evacuated decay vessel surrounded by liquid scintillator veto system

HNL production



HNL decay





Neutrino detector

Hidden particle detector

HNL sensitivity

Cosmologically interesting region at low couplings

- **m_{HNL} < m_b**

  SHiP will have much better sensitivity than LHCb or Belle2

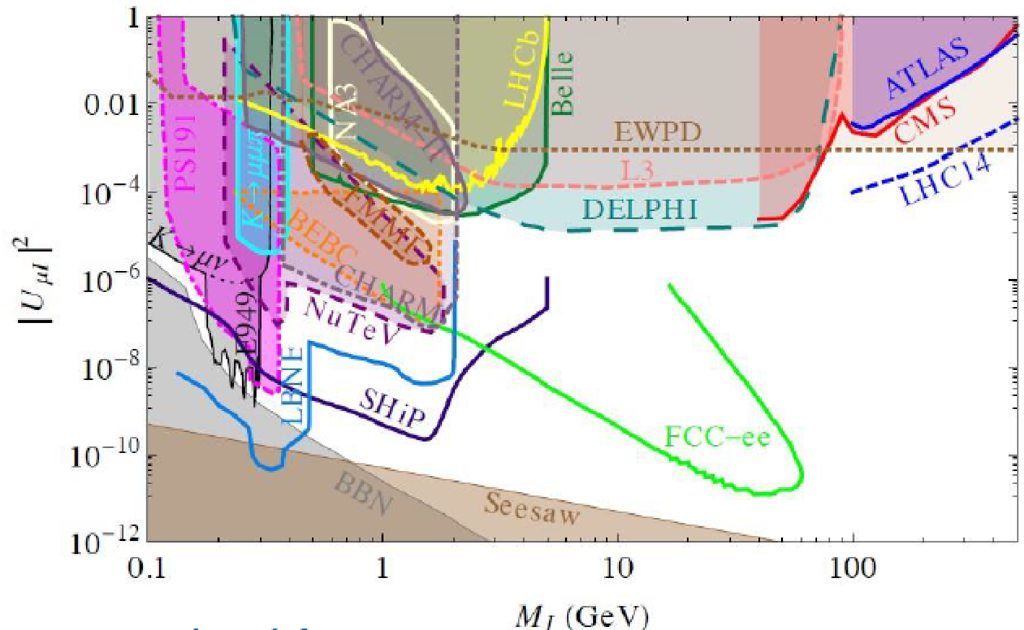
- **m_b < m_{HNL} < m_Z**

  FCC-ee, improvements expected from ATLAS/CMS

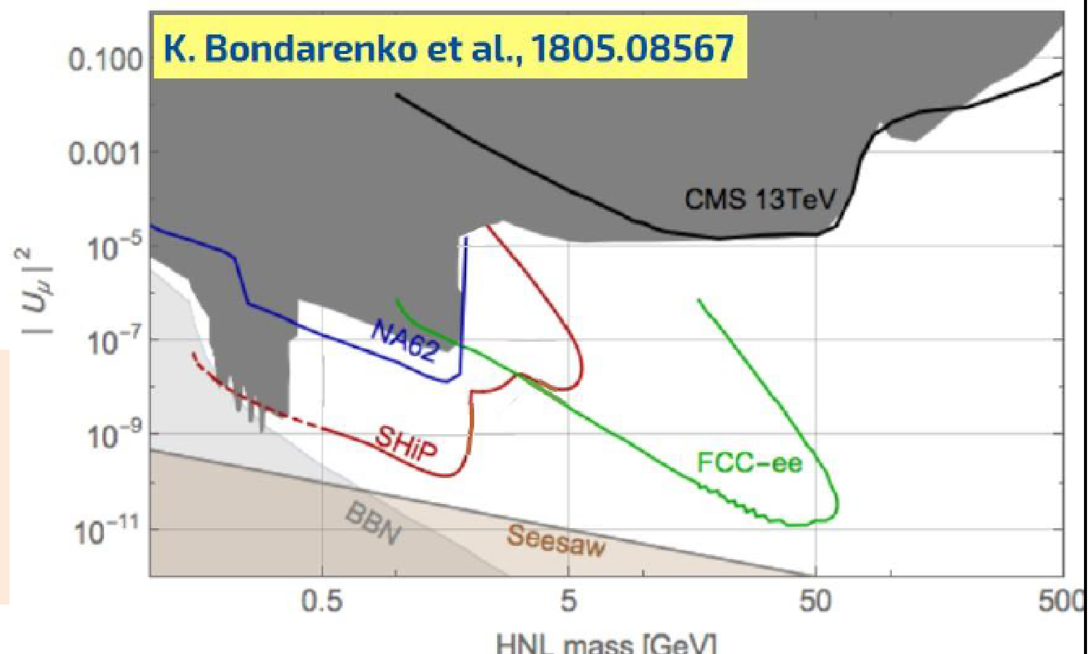
- **m_{HNL} > m_Z**

  targeted by ATLAS/CMS at HL-LHC

At **m_{HNL} = 1 GeV** and **$U^2 = 10^{-8}$** (50 x lower than present limit), SHiP will see more than **1,000** fully reconstructed events.



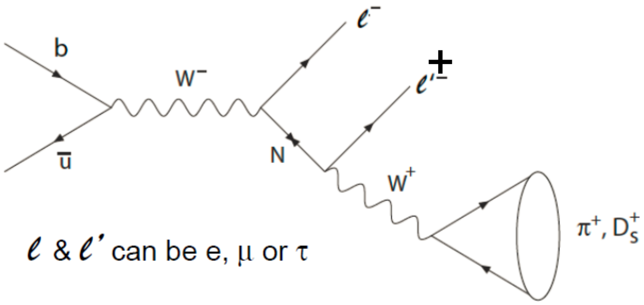
Updated from K. Bondarenko et al., 1805.08567



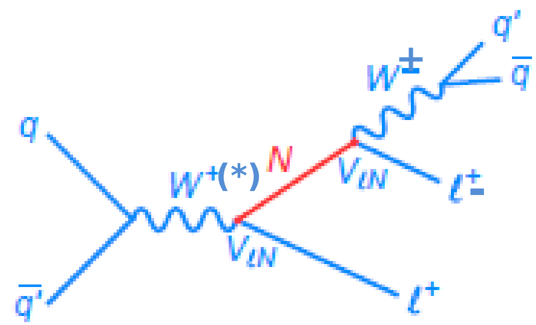
Processes (II)

Search for heavy right-handed neutrinos in collider experiments.

B factories

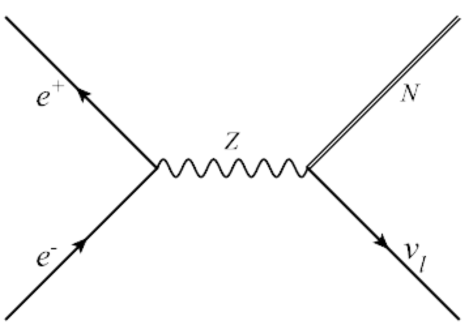


Hadron colliders

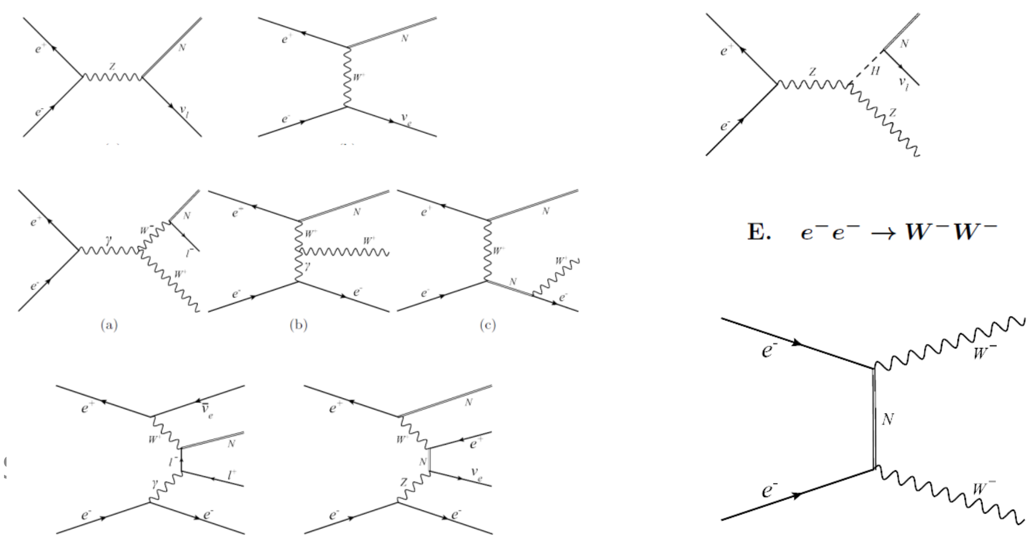


Z factory (FCC-ee, Tera-Z)

arXiv:1411.5230



HE Lepton Collider (LEP2, CEPC, CLIC, FCC-ee, ILC, μμ)



Phys. Rev. D 92, 075002 (2015)
arXiv:1503.05491

Searches for heavy neutrinos ν_h in B decays

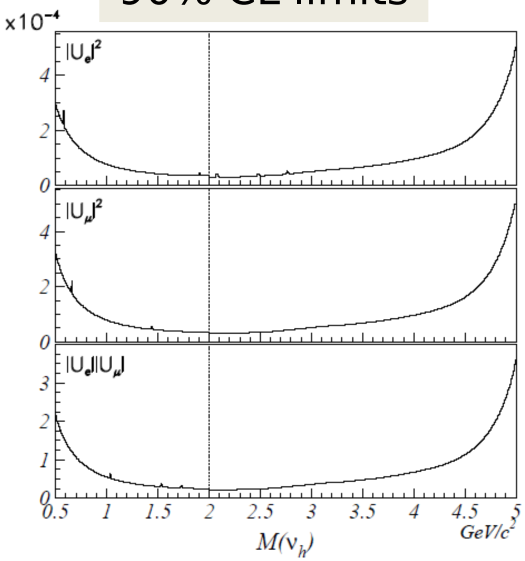
-- BELLE *Phys. Rev. D. 87, 071102 (2013), arXiv:1301.1105*

7.8 10^8 B mesons at Y_{4s}!

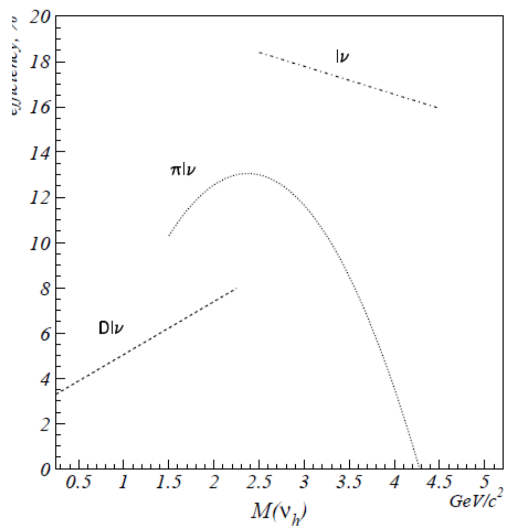
Search for $\ell_2 + (\ell_1\pi)$, where ℓ_1 and π have **opposite charge and displaced vertex**
for $M(\nu_h)$ =1GeV/c2 and $|U_e|^2 = |U_\mu|^2 = 10^{-4}$ the flight length is $c\tau \simeq 20$m.

 charge and flavour of $\boldsymbol{\ell_2\ell_1}$ can be **any combination of e, μ, + or -** because the heavy neutrino is assumed to be Majorana. (If Dirac fermion, -> opposite charges only).
A few signal events, no 'peak'.

90% CL limits

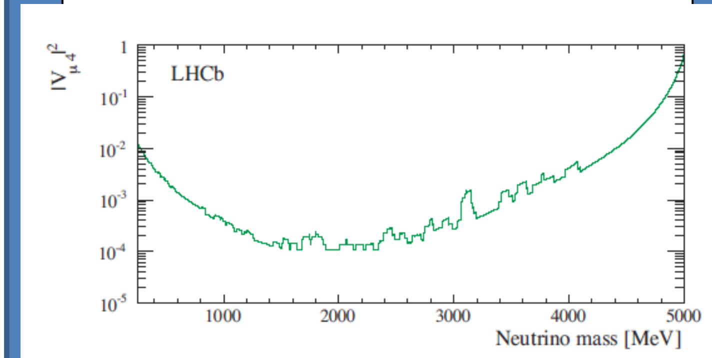


Efficiency for the search



LHCb collaboration,
PRL 112, 131802 (2014)

$\mathcal{B}(B^- \to \pi^+\mu^-\mu^-) < 4.0 \times 10^{-9}$ at 95%

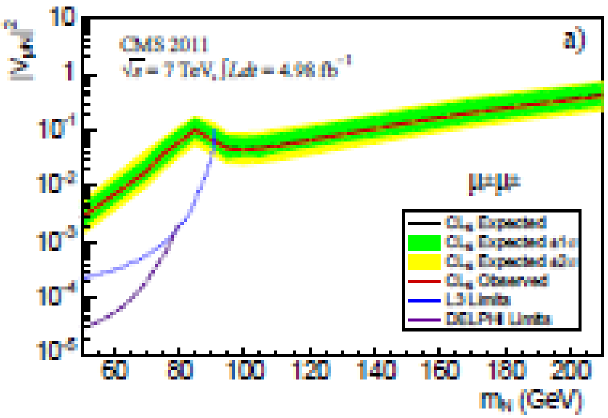


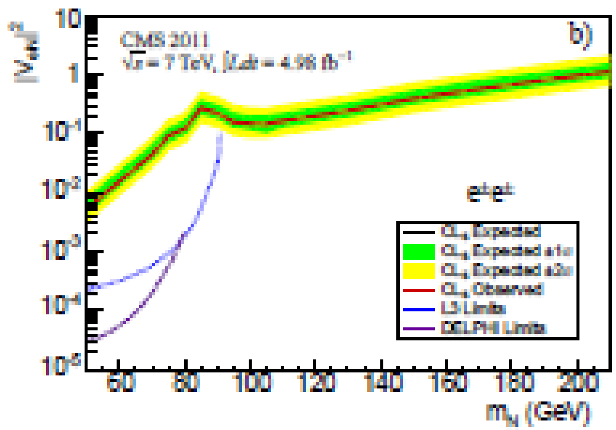
Scope for 10-100x improvement at SuperKEKb

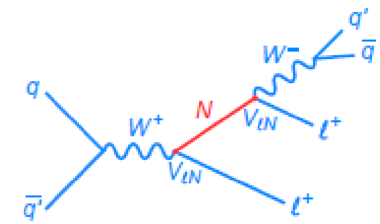
Scope for much improvement at 13TeV&HL-LHC!

CMS search for same sign muon pairs or electron pairs at the LHC

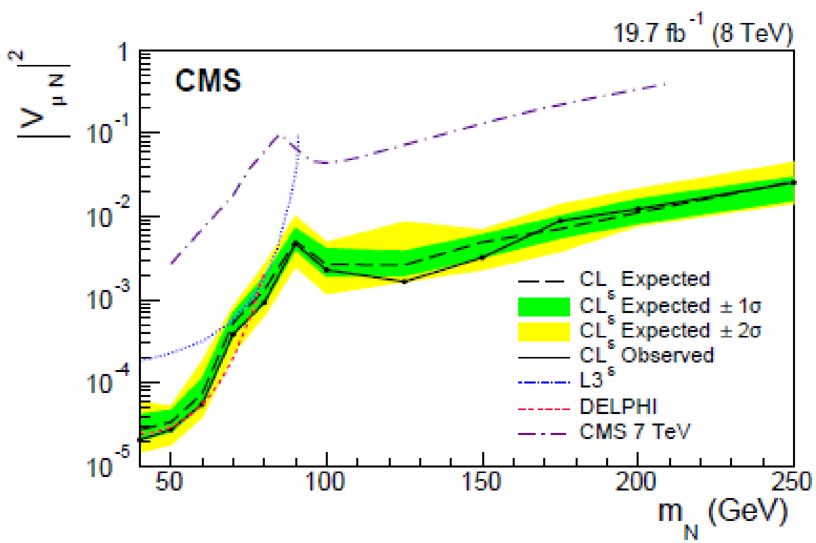
CMS







CMS arXiv:1207.6079.
arXiv:1501.05566

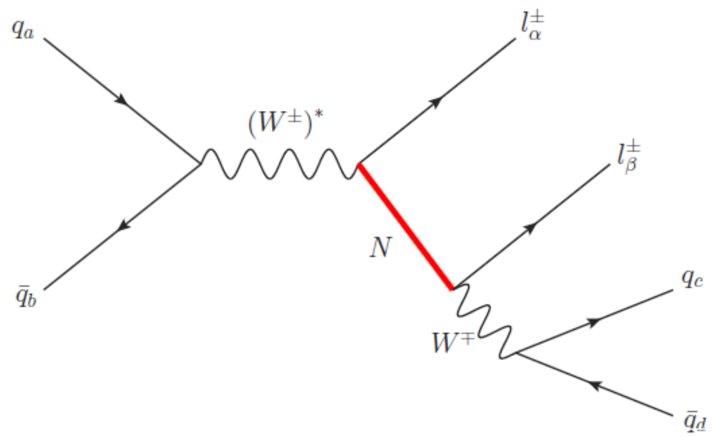


Begin to match/superseed the DELPHI limit.

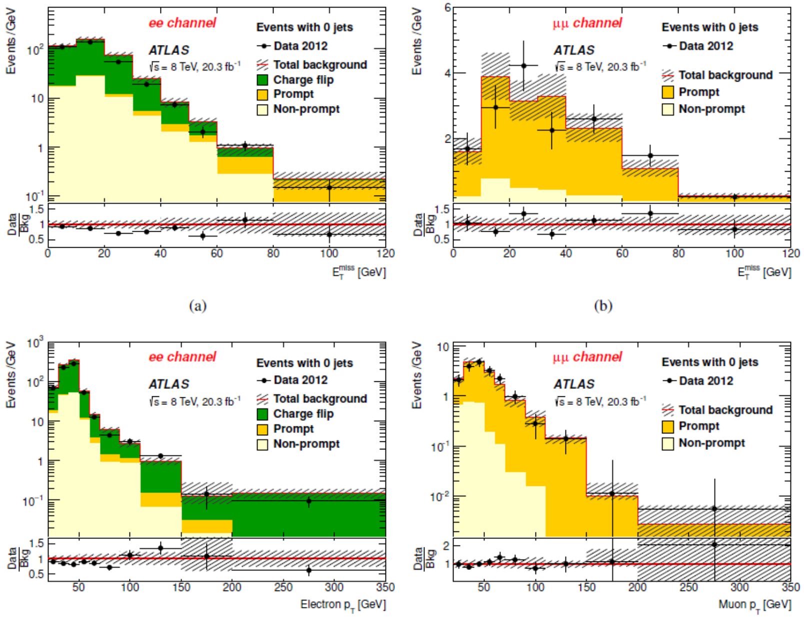
limits at $|U|^2 \sim 10^{-2-5}$ level

ATLAS search for Heavy Neutrinos at LHC

JHEP07(2015)162 arXiv:1506.06020

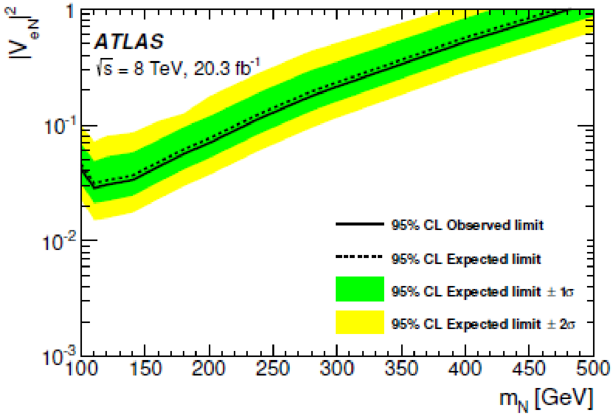


e^-e^-, e^+e^+, $\mu^-\mu^-$, $\mu^+\mu^+$ final states
(like sign, like flavour leptons)
Concentrates on m_N>100 GeV
'because <100 GeV excluded by LEP'
Charge flip significant bkgd for ee channel

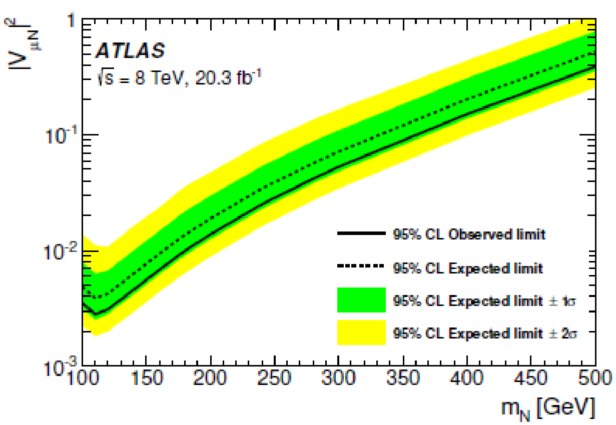


(a) (b)

(c) (d)



(b)



LHC prospects

~10^9 νs from W decays in ATLAS and CMS with 25 fb^{-1} @8 TeV

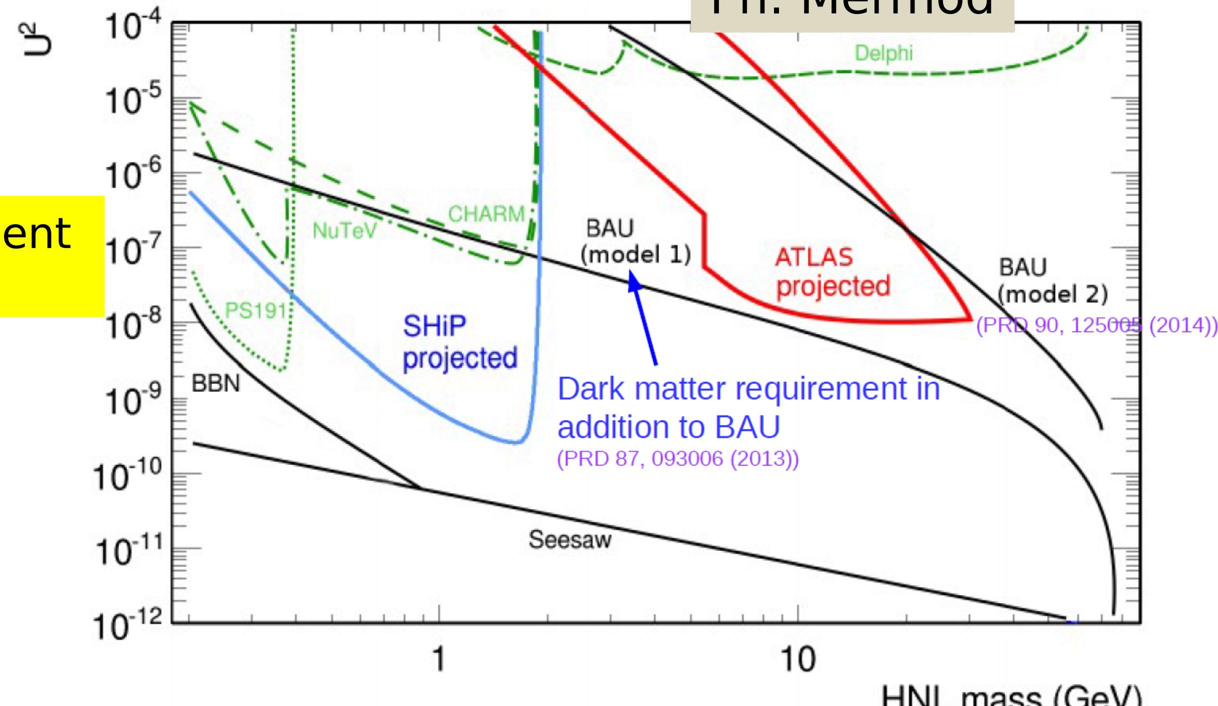
Signals of RH neutrinos with mass ≤ m_W could be visible if mixing angle $O(10^{-7,8})$

The keys for that region of phase space

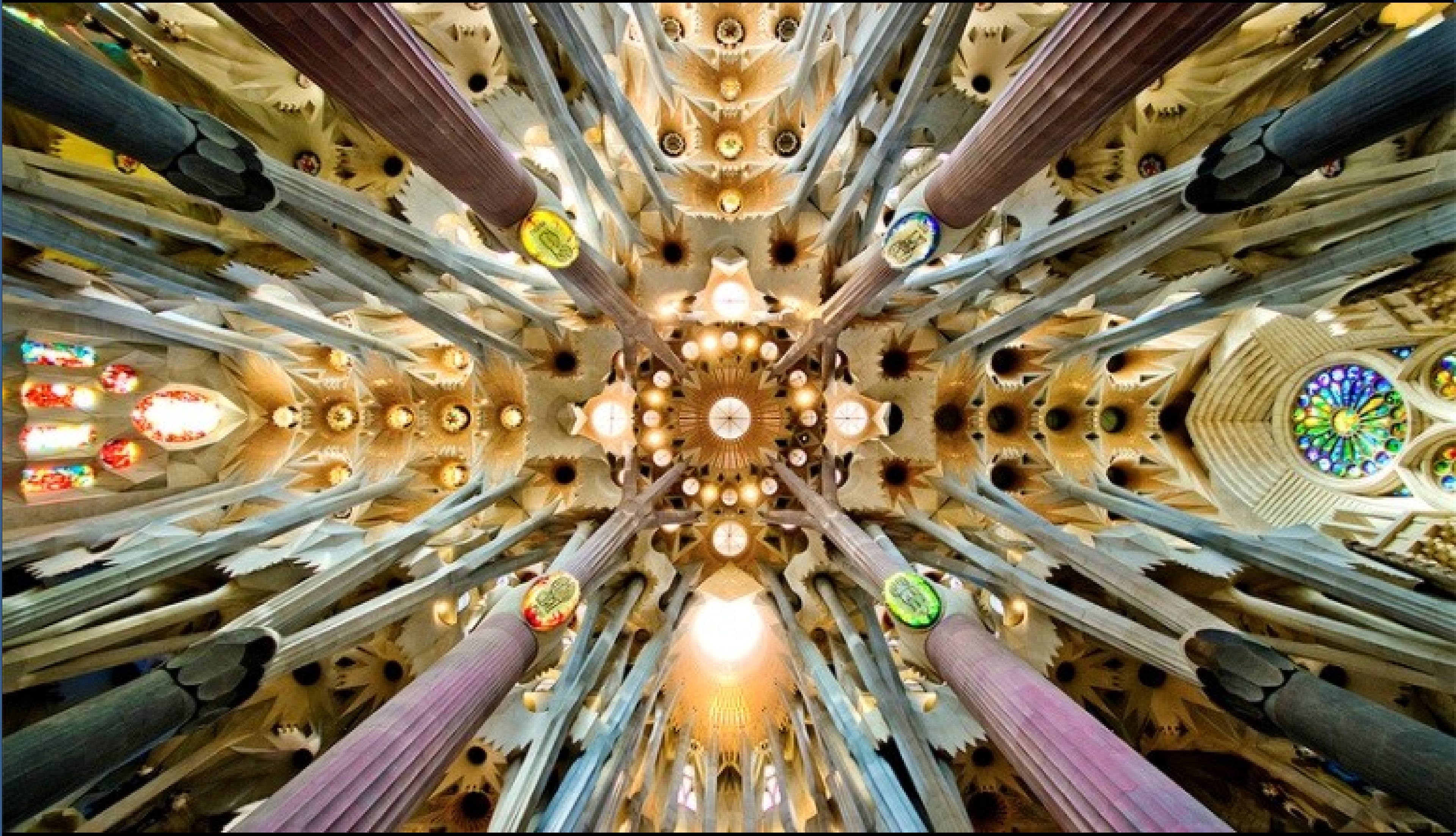
-- require **displaced vertex**
-- allow leptons of different charge and flavour
-- constrain to W mass.

Ph. Mermod

Hope for considerable improvement in W decays at LHC!



Heavy Neutrino searches at Future Circular Colliders



Alain Blondel, University of Geneva

The Future Circular Colliders
CDR and cost review Q4 2018 for ESU

International collaboration to Study Colliders fitting in a new ~100 km infrastructure, fitting in the *Genevois*

≥16 T magnets

- ***Ultimate goal:***
  ***≥100 TeV pp*-collider (*FCC-hh*)**

 defining infrastructure requirements

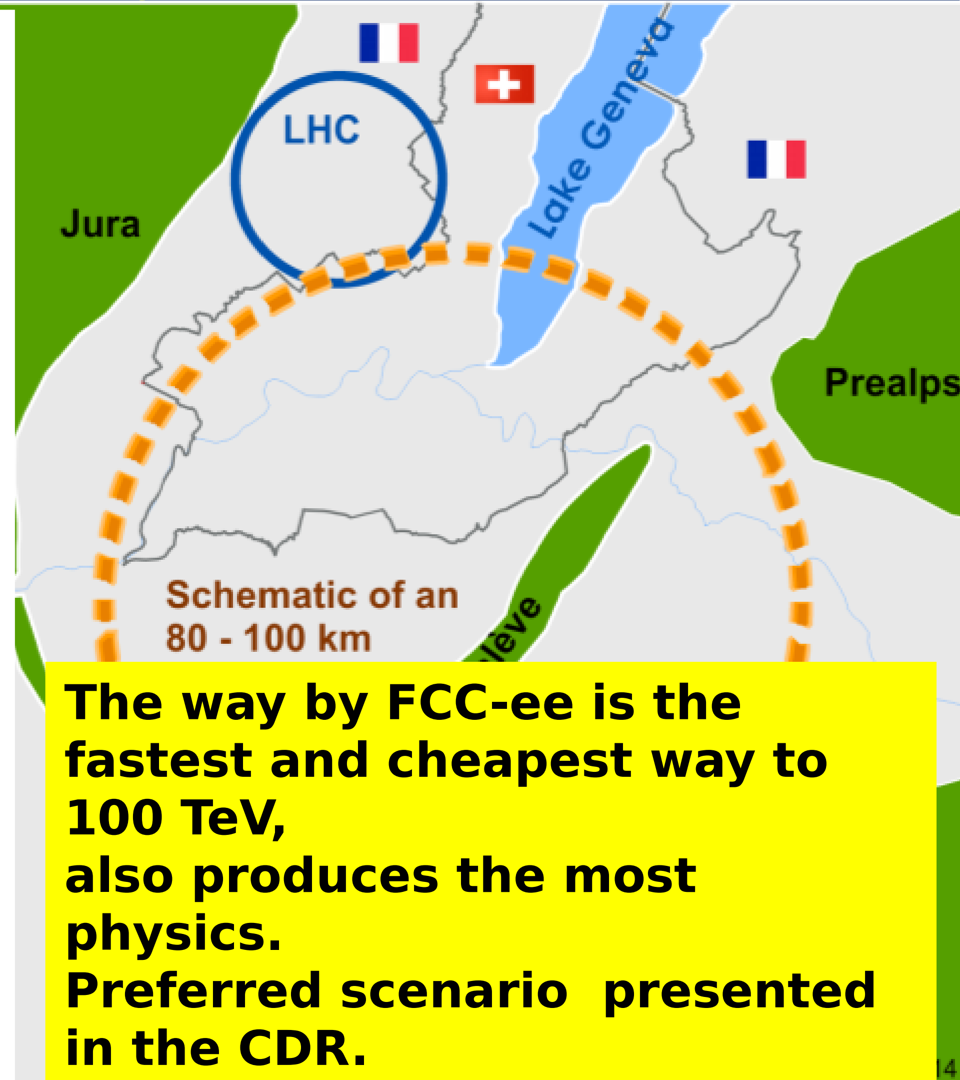
Two possible first steps:

- **e^+e^- collider (*FCC-ee*)**
  High Lumi, E_{CM} =90-400 GeV

- ***HE-LHC* 16T ⇒ 27 TeV**
  in LEP/LHC tunnel

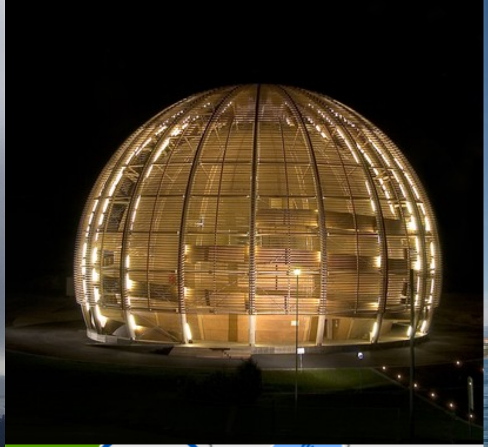
Possible addition:

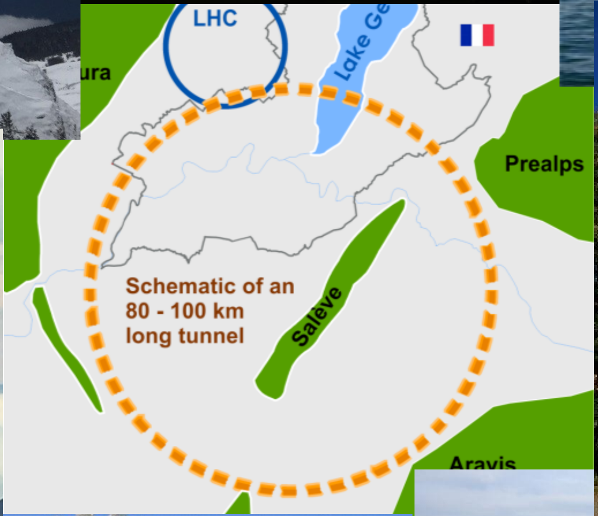
- ***p-e* (*FCC-he*) option**



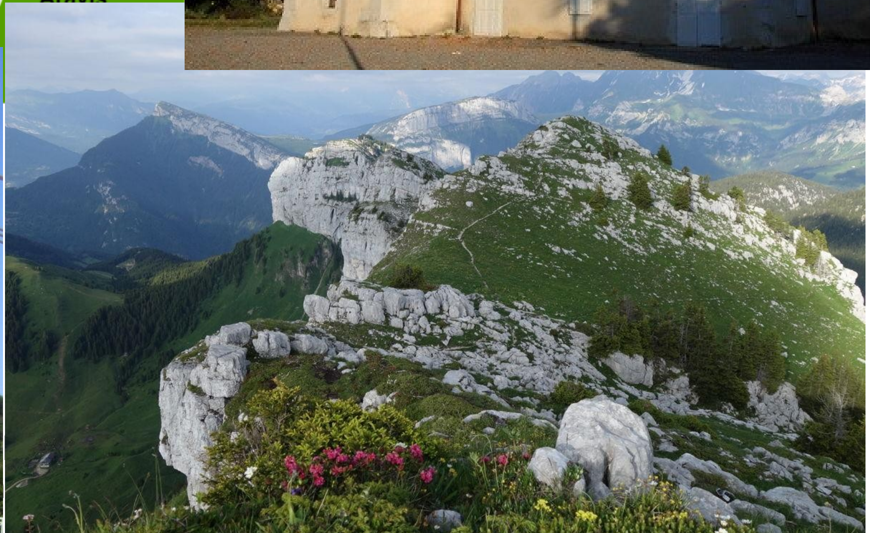
The way by FCC-ee is the fastest and cheapest way to 100 TeV,
also produces the most physics.
Preferred scenario presented in the CDR.
https://cerncourier.com/cern-thinks-bigger

Its also a good start for a μμ

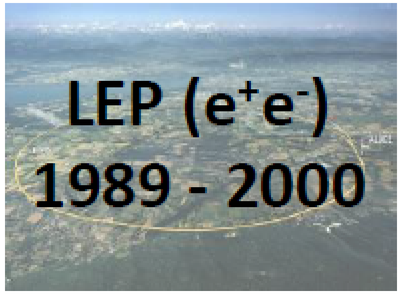



LHC
ura
Lake Ge
Prealps
Schematic of an
80 - 100 km
long tunnel
Salève
Aravis


PONT DE

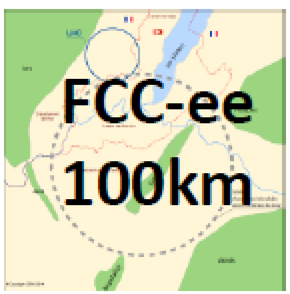


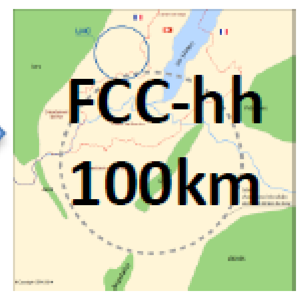
- 27km tunnel



M. Aleksa

- The next step: 100km tunnel





a 10-20 TeV muon collider using the 45 GeV stored e+ as LEMMA SOURCE?

FCC data taking starts at the end of HL-LHC

The Conceptual Design Report for the FCC was published 15 January 2019

Vol1 Physics

Vol2 FCC-ee

Vol3 FCC-hh and eh

Vol4 HE-LHC

https://fcc-cdr.web.cern.ch/

where can also be found the contributions to the European Strategy

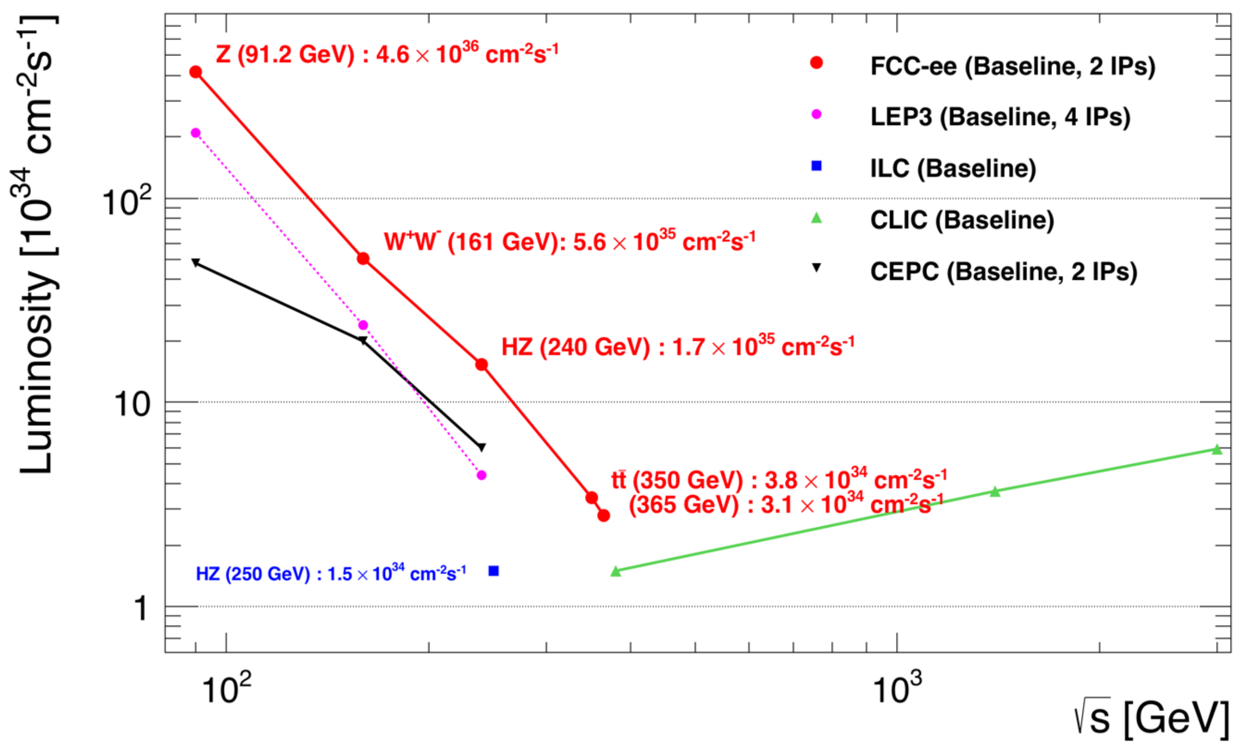
A public presentation of the main results was given on 4-5 March

https://indico.cern.ch/event/789349/

what follows is based on slides presented at the meeting

Z WW HZ tt

FCC-ee



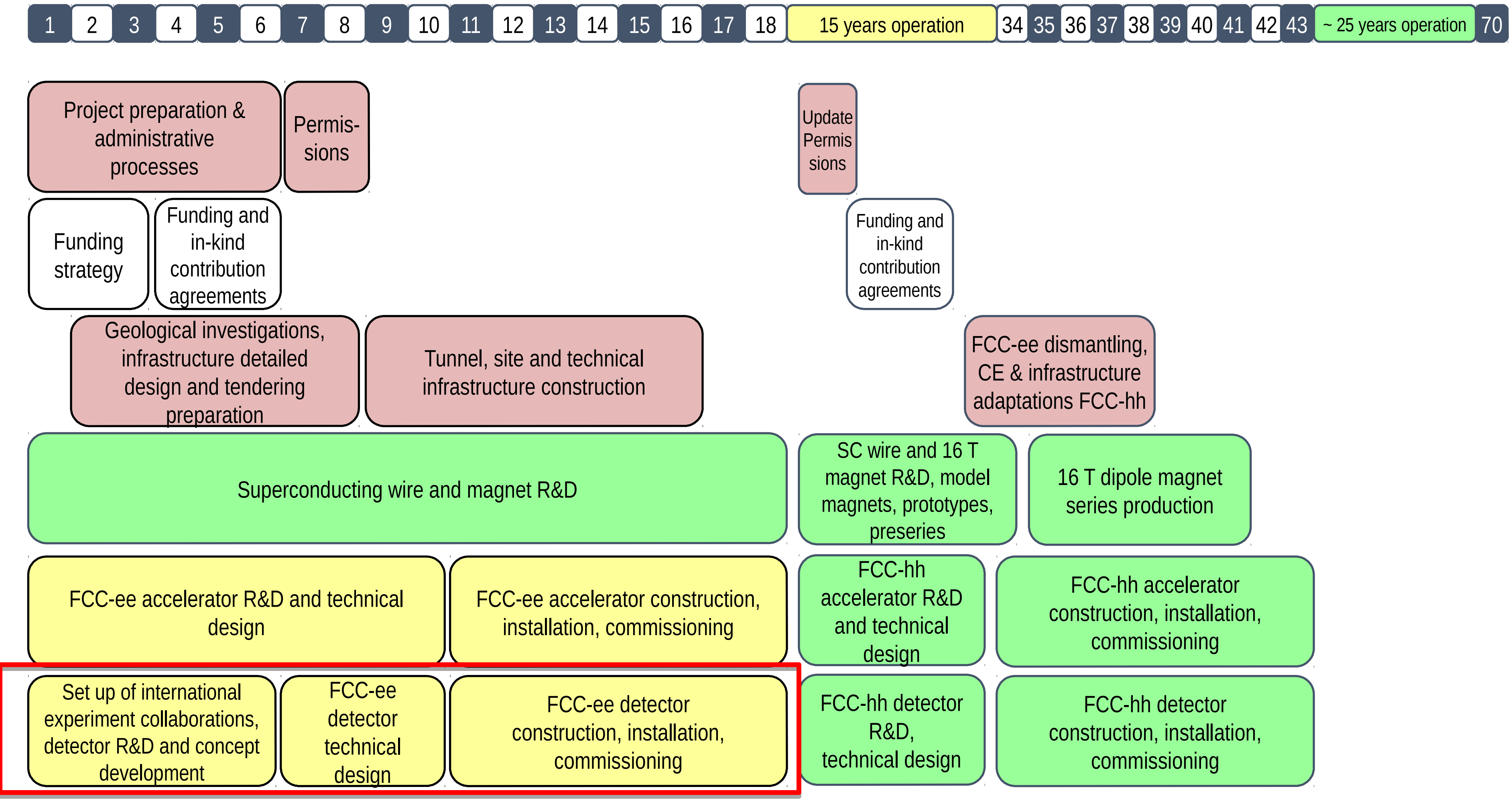
Event statistics :

Z peak	**E_{cm} : 91 GeV**	**5 10^{12} e+e- Z**
WW threshold	**E_{cm} : 161 GeV**	**10^{8} e+e- WW**
ZH threshold	**E_{cm} : 240 GeV**	**10^{6} e+e- ZH**
$\bar{t}t$ threshold	**E_{cm} : 350 GeV**	**10^{6} e+e- $\bar{t}t$**

	E_{CM} errors:
LEP x 10^{5}	100 keV
LEP x 2.10^{3}	300 keV
Never done	2 MeV
Never done	5 MeV

Great energy range for the heavy particles of the Standard Model.

FCC integrated project technical timeline



work is cut out for physics and detectors

ESPP

70 years seems like a long time!

(indirect) Effect of right handed neutrinos on EW precision observables

The relationship $|U|^2 \propto \theta^2 \approx m_\nu / m_N$ is valid for one family see-saw.
For two or three families the mixing can be larger (*Shaposhnikov*)
Antush and Fisher have shown that a slight # in Majorana mass can generate larger mixing between the left- and right-handed neutrinos. ***Worth exploring.***

«$\nu_L = \nu \cos\theta + N \sin\theta$» → $(\cos\theta)^2$ becomes parametrized as $1+\varepsilon_{\alpha\beta}$ ($\varepsilon_{\alpha\alpha}$ is negative)
the coupling to light 'normal' neutrinos is typically reduced.
In the G_F, M_Z α_{QED} scheme, G_F (extracted from $\mu \to e \nu_e \nu_\mu$) and *g* should be ***increased***
This leads to *correlated* variations of all predictions upon e or mu neutrino mixing.
The 'number of neutrinos' and tau decays are specifically sensitive to the tau-neutrino mixing.

Prediction in MUV	Prediction in the SM	Experiment
$[R_\ell]_{\rm SM}\,(1-0.15(\varepsilon_{ee}+\varepsilon_{\mu\mu}))$	20.744(11)	20.767(25)
$[R_b]_{\rm SM}\,(1+0.03(\varepsilon_{ee}+\varepsilon_{\mu\mu}))$	0.21577(4)	0.21629(66)
$[R_c]_{\rm SM}\,(1-0.06(\varepsilon_{ee}+\varepsilon_{\mu\mu}))$	0.17226(6)	0.1721(30)
$[\sigma^0_{had}]_{\rm SM}\,(1-0.25(\varepsilon_{ee}+\varepsilon_{\mu\mu})-0.27\varepsilon_\tau)$	41.470(15) nb	41.541(37) nb
$[R_{inv}]_{\rm SM}\,(1+0.75(\varepsilon_{ee}+\varepsilon_{\mu\mu})+0.67\varepsilon_\tau)$	5.9723(10)	5.942(16)
$[M_W]_{\rm SM}(1-0.11(\varepsilon_{ee}+\varepsilon_{\mu\mu}))$	80.359(11) GeV	80.385(15) GeV
$[\Gamma_{\rm lept}]_{\rm SM}(1-0.59(\varepsilon_{ee}+\varepsilon_{\mu\mu}))$	83.966(12) MeV	83.984(86) MeV
$[(s^{\ell,{\rm lep}}_{W,{\rm eff}})^2]_{\rm SM}(1+0.71(\varepsilon_{ee}+\varepsilon_{\mu\mu}))$	0.23150(1)	0.23113(21)
$[(s^{\ell,{\rm had}}_{W,{\rm eff}})^2]_{\rm SM}(1+0.71(\varepsilon_{ee}+\varepsilon_{\mu\mu}))$	0.23150(1)	0.23222(27)

Table 1: Experimental results and SM predictions for the EWPO, and the modification in the MUV scheme, to first order in the parameters $\varepsilon_{\alpha\beta}$. The theoretical predictions and experimental values are taken from Ref. [16]. The values of $(s^{\ell,{\rm lep}}_{W,{\rm eff}})^2$ and $(s^{\ell,{\rm had}}_{W,{\rm eff}})^2$ are taken from Ref. [17].

NB this is not decoupling

DIRECT Heavy Neutrino production in Z decays

Production:

$$BR\left(Z^0 \to \nu_m \overline{\nu}\right) = BR\left(Z^0 \to \nu\overline{\nu}\right)\,|U|^2\,\left(1 - \frac{m_{\nu_m}^2}{{m_{Z^0}}^2}\right)^2\left(1 + \frac{1}{2}\frac{m_{\nu_m}^2}{{m_{Z^0}}^2}\right)$$

multiply by 2 for anti neutrino and add contributions of 3 neutrino species (with different $|U|^2$)

Decay

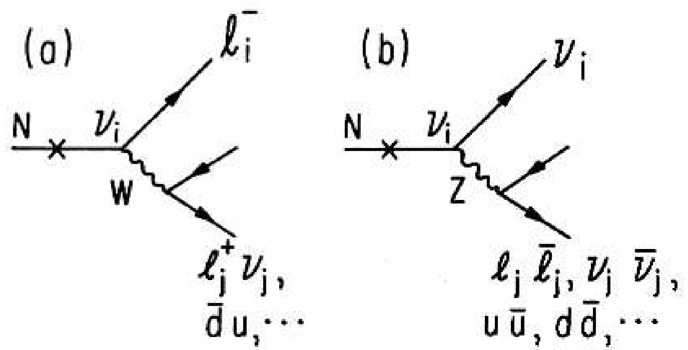


FIG. 2. Typical decays of a neutral heavy lepton via (a) charged current and (b) neutral current. Here the lepton l_i denotes e, μ, or τ.

Decay length:

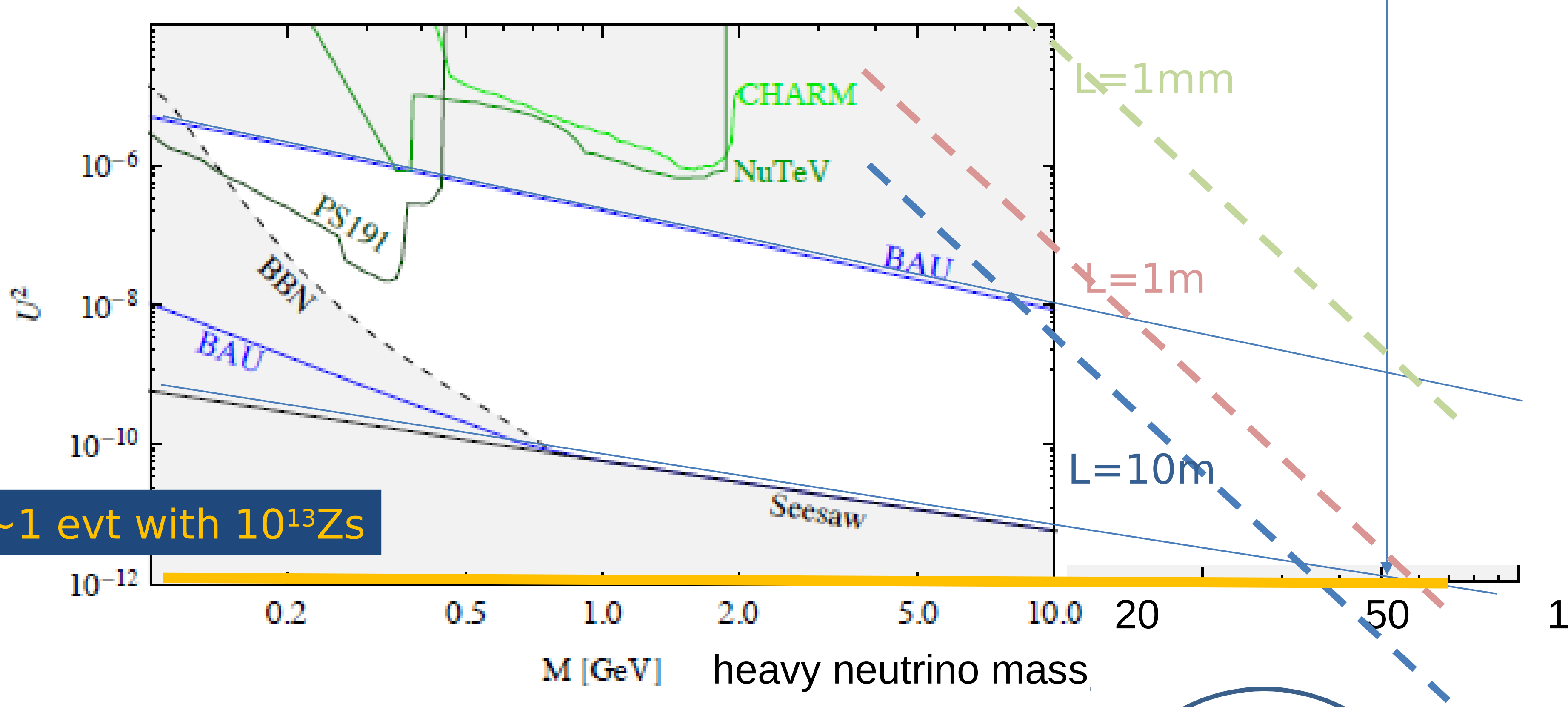
$$L \approx \frac{3\ \text{cm}}{|U|^2\,\left(m_{\nu_m}(\mathrm{GeV}/c^2)\right)^6}$$

NB CC decay always leads to ≥ 2 charged tracks

Backgrounds : four fermion: e+e- → W^{*+} W^{*-} e+e- → Z*(νν) + (Z/γ)*

Decay length

Interesting region
$|U|^2 \sim 10^{-9}$ to 10^{-12} @ 50 GeV

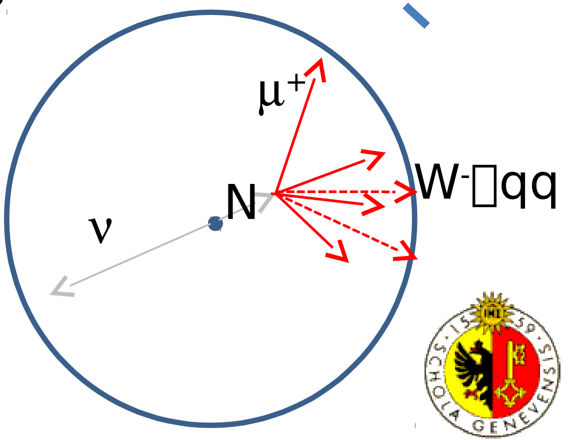


~1 evt with 10^{13}Zs

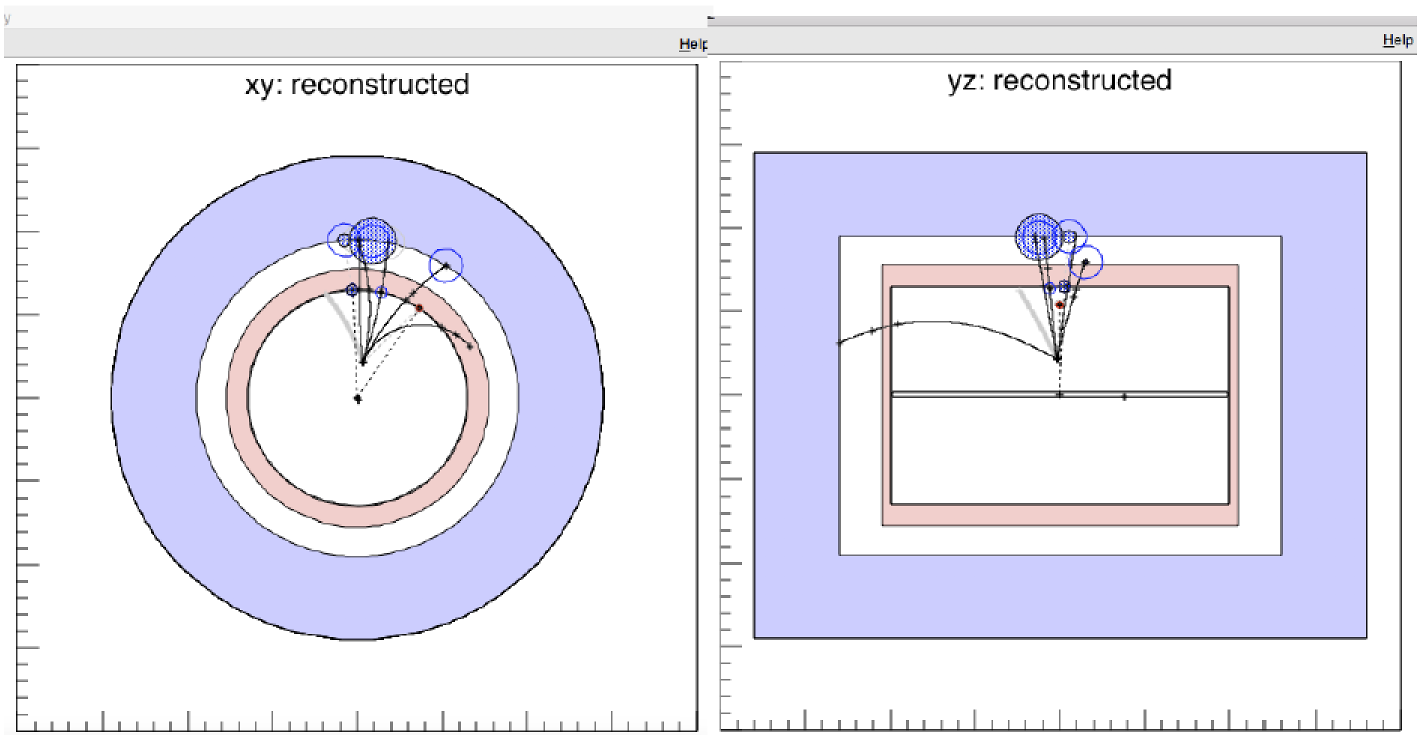
a large part of the interesting region will lead to detached vertices

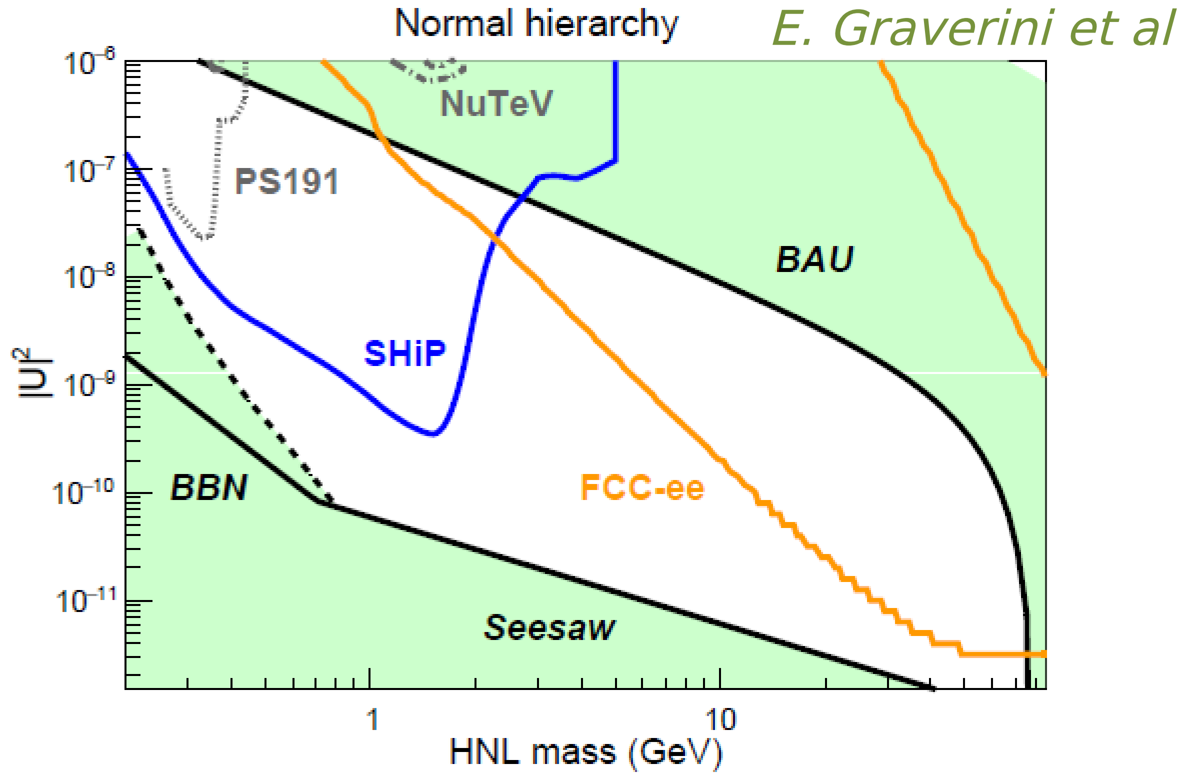
... very strong reduction of background!

Exact reach domain will depend on detector size
and details of displaced vertex efficiency & background



Simulation of heavy neutrino decay in a FCC-ee detector

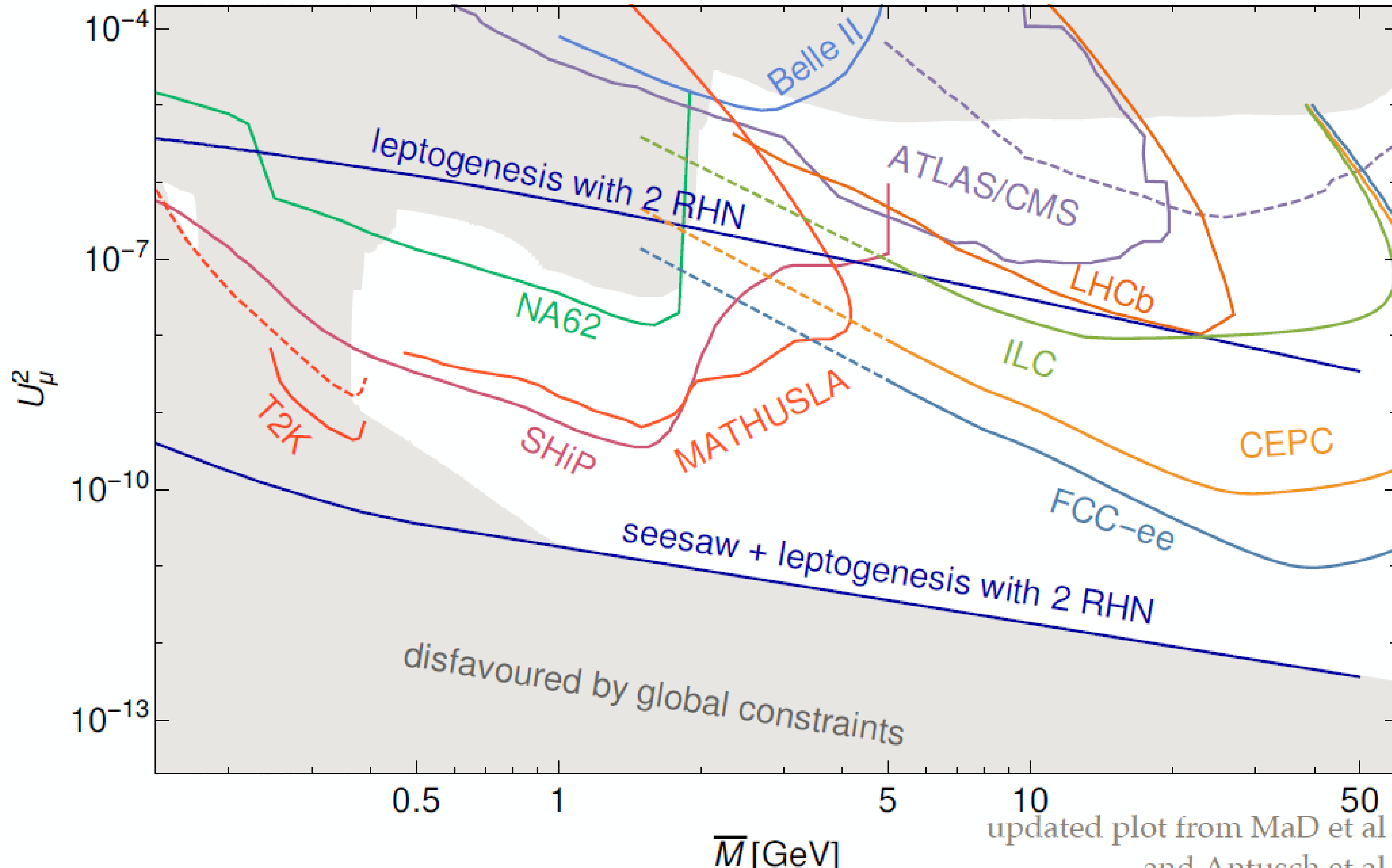




(a) Decay length 500 μm to 2 m

with 5 10^{12} Z

Constraints and Future Searches

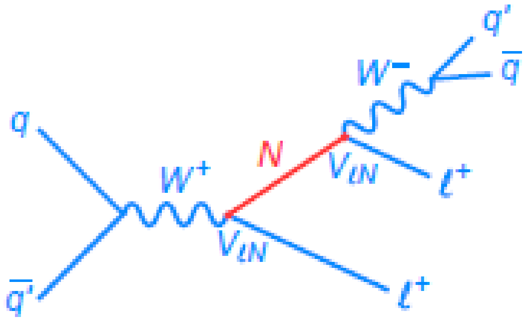


updated plot from MaD et al 1609.09069
and Antusch et al 1710.03744
cf. also Cai et al 1711.02180

Marco Drewes, should be upgraded for full FCC-ee statistics

FCC-hh

We have seen that the Z factory offers a clean method
for detection of Heavy Right-Handed neutrinos
Ws are less abundant at the lepton colliders



At the 100 TeV pp W is the dominant particle,
Expect 10^{13} real W's.

There is a lot of /pile-up/backgrounds/lifetime/trigger issues which need to be investigated.
BUT.... in the regime of long lived HNLs the simultaneous presence of
-- the initial lepton from W decays
-- the detached vertex with kinematically constrained decay
allows for a significant background reduction.

But it allows also a characterization both in flavour and charge of the produced neutrino, thus information of the flavour sensitive mixing angles and a test of the fermion violating nature of the intermediate (Majorana) particle.

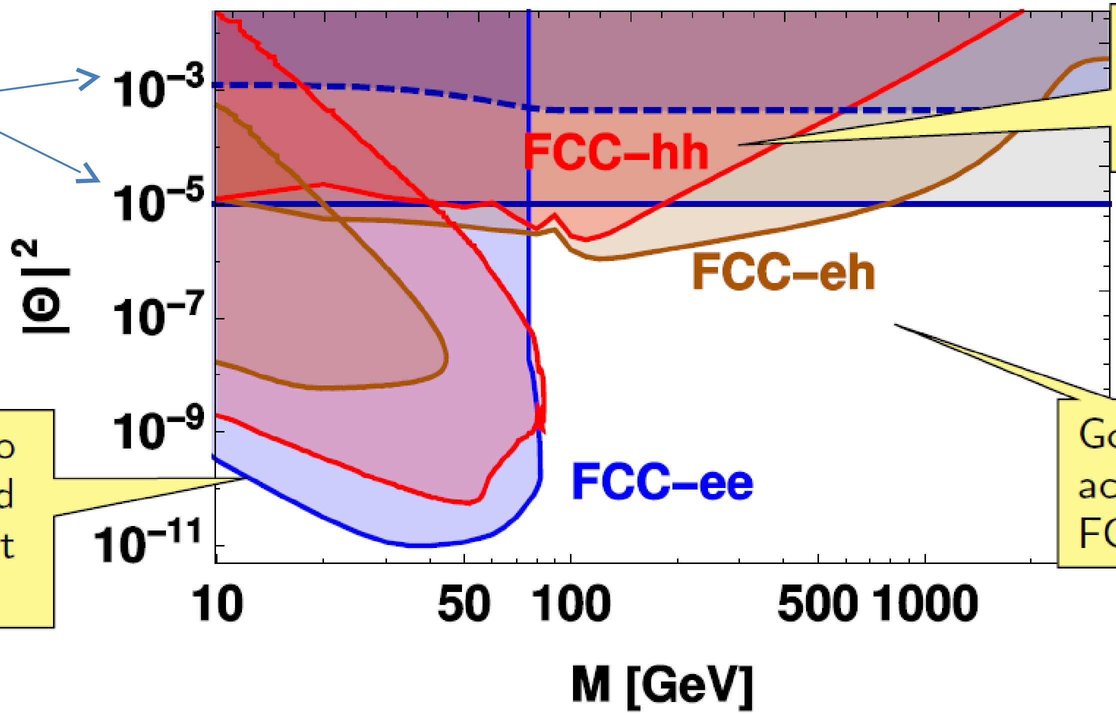
VERY interesting...

Summary

Another example of Synergy and complementarity while ee covers a large part of space very cleanly , its either ‘white’ in lepton flavour or the result of EWPOs etc Observation at FCC –hh or eh would test flavour mixing matrix!

- Systematic assessment of heavy neutrino signatures at colliders.
- First looks at FCC-hh and FCC-eh sensitivities.
- Golden channels:
  - **FCC-hh:** LFV signatures and displaced vertex search
  - **FCC-eh:** LFV signatures and displaced vertex search
  - **FCC-ee:** Indirect search via EWPO and displaced vertex search

EWPO sensitivity up to very high mass scales



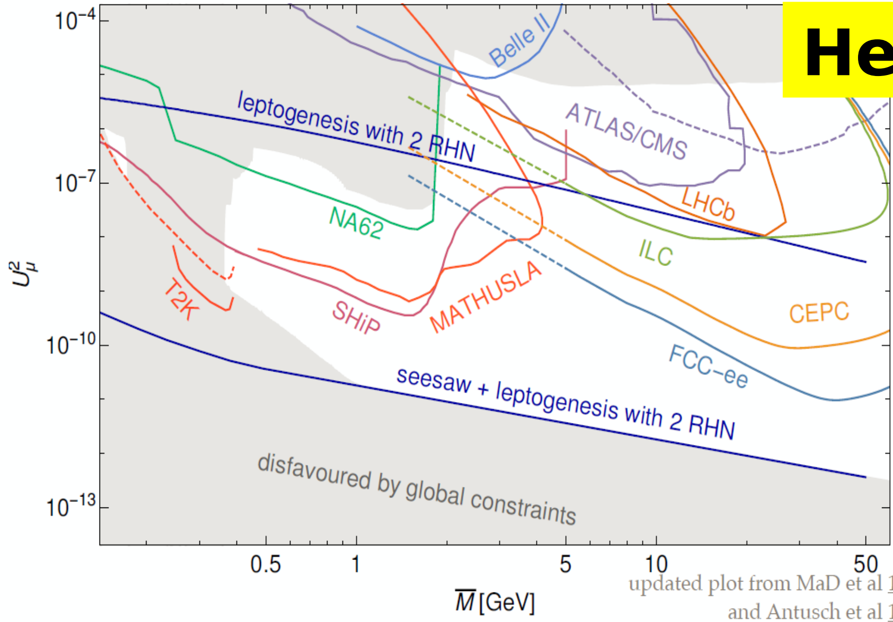
FCC-hh able to test all flavour combinations.

Best sensitivity to $|\theta|^2$ from displaced vertex searches at the FCC-ee.

Good sensitivity reach from FCC-hh & FCC-eh.

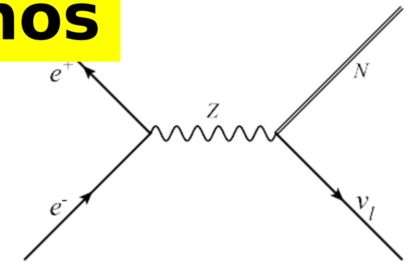
detailed study required for all FCCs – especially FCC-hh to understand

Heavy neutrinos

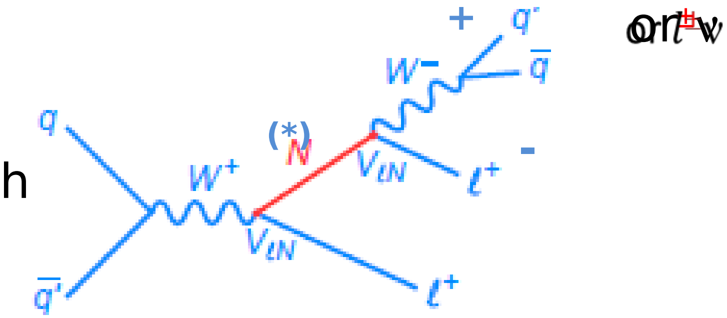


updated plot from MaD et al 1609.09069
and Antusch et al 1710.03744
cf. also Cai et al 1711.02180

FCC-ee Z



FCC-hh



FCC-ee

-- EWPO : sensitivity 10^{-5} up to very high masses

-- high sensitivity to single N(→ $l_2^{\pm}$W) in Z decay

FCC-hh

-- production in W-> $l_1^{\pm}$ + N(→ $l_2^{\pm}$W)

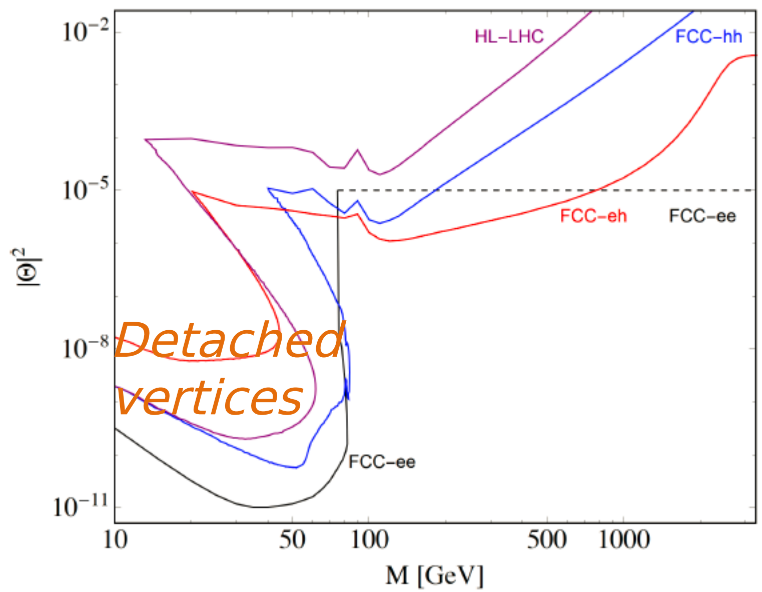
with initial and final lepton charge and flavour

FCC e-p

-- production in CC e$^{\pm}$ p → X N(→ $l^{\pm}$W) high mass

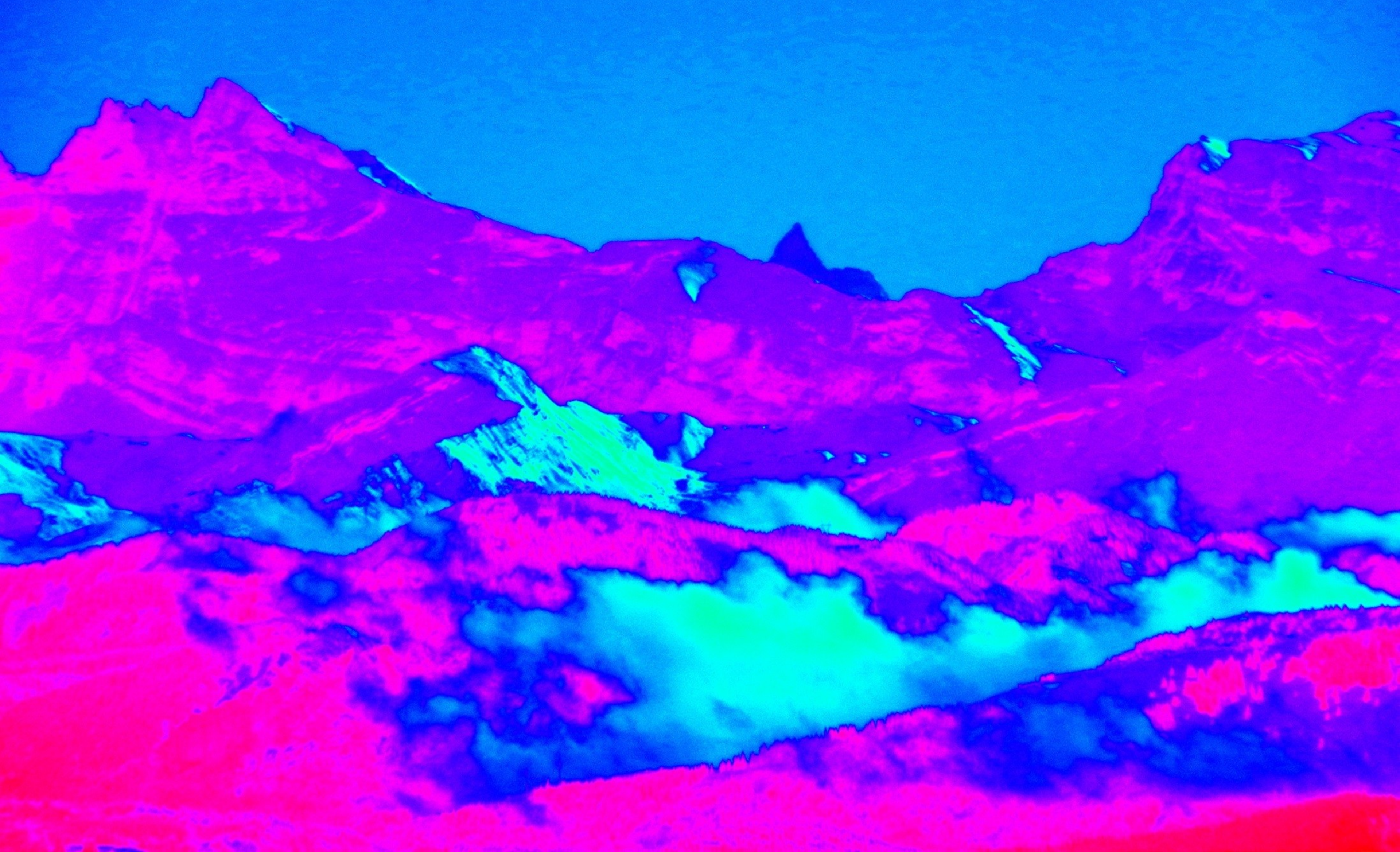
<u>Complementarity:</u>

discovery + studies of FNV and LFV!



The capability to probe massive neutrino mechanisms for generating the matter-antimatter asymmetry in the Universe should be a central consideration in the selection and design of future colliders. *(from the neutrino town meeting report to the ESPP)*

CONCLUSIONS



CONCLUSION ON NEUTRINOS

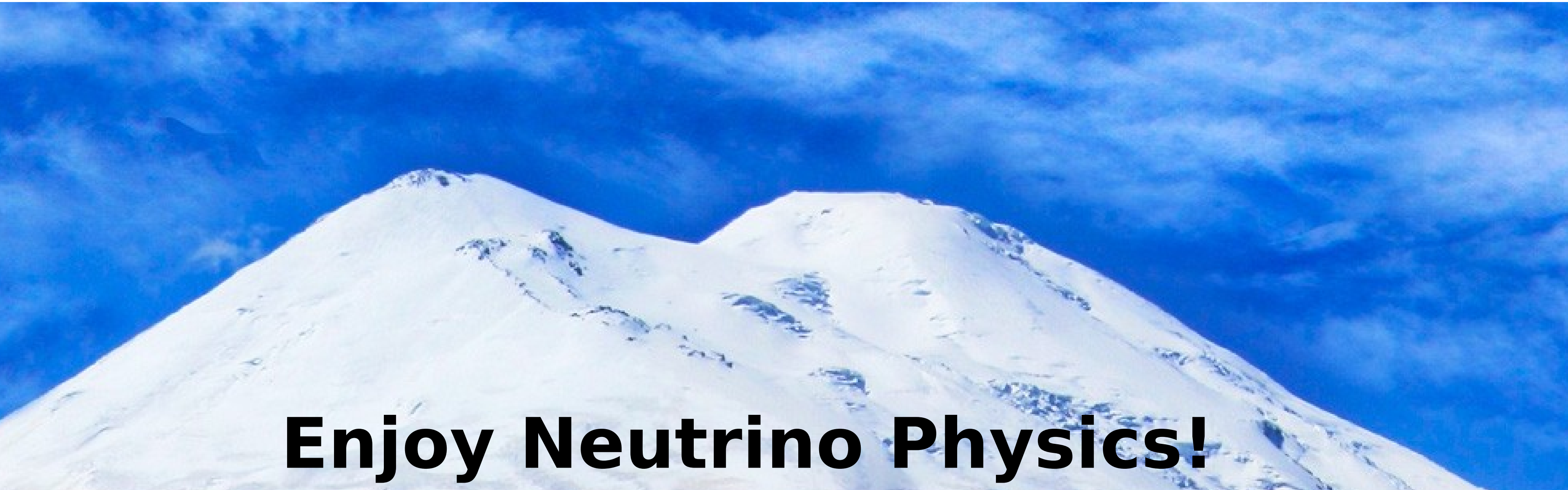
Neutrinos are the only place in particle physics where 'Beyond the Standard Model' has been observed, through the phenomenon of neutrino oscillations.

Neutrino oscillations: a quantum phenomenon which occurs because neutrinos have extremely small masses and mass splittings, which in itself is extremely surprising.

The leading possible explanation is the existence of right handed neutrinos with higher masses induced by the existence of a *Majorana mass term.*

This *may* provide an explanation for other unexplained experimental facts
- dark matter
- the baryon asymmetry of the universe

This is an exciting field with many experimental possibilities using complementary
-- neutrino beam experiments
-- nuclear physics experiments
-- collider experiments
-- astrophysical and cosmological experiments


Enjoy Neutrino Physics!