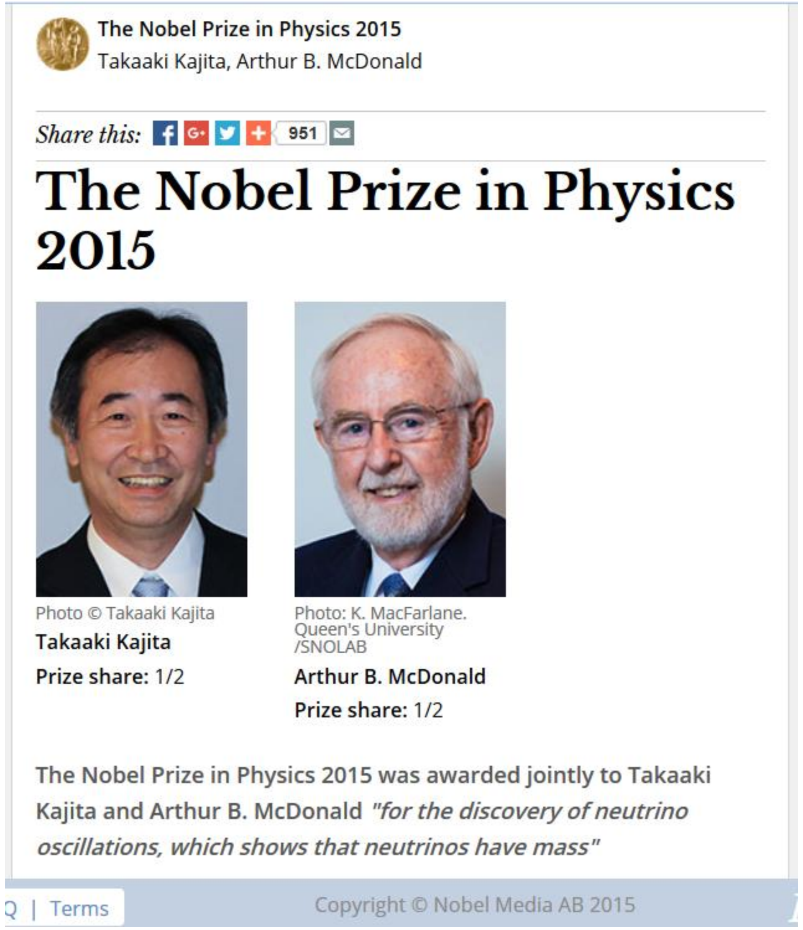
Selected questions in Neutrino Physics

Alain Blondel   Geneva and Paris-Sorbonne

Tuesday 17 January
How do we know there are three (and only three) families of light active neutrinos
How do we know neutrinos have negative helicity
(and are left-handed) ?
How do we know neutrinos have mass?
Why do neutrinos oscillate?

Wedensday 18 January
neutrino masses
kinematic measurement
cosmological constraints
Can neutrino masses be different from those of other fermions?
How can we discover neutrinos Majorana mass term?
Heavy Neutrinos at colliders
(If time permits: is there a eV-scale sterile neutrino?)
Why neutrinos are central in pushing the limits of the 'Standard Model'



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?

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

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 4 different methods:

-- kinematic method (the most «direct» and most difficult)
-- effect of neutrino mass on the early universe

And if neutrinos have a Majorana mass term:
-- neutrinoless double beta decay
-- detect directly the heavy right-handed neutrinos (HNL)

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, ...

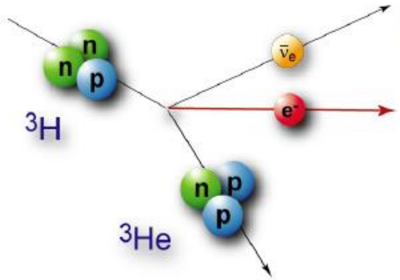
0νββ-decay: eff. Majorana mass

model-dependent (CP-phases)

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

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

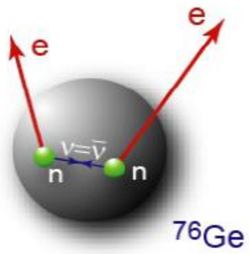
e.g.: GERDA, KamLAND-Zen, CUORE, EXO, Majorana, Nemo 3, ...



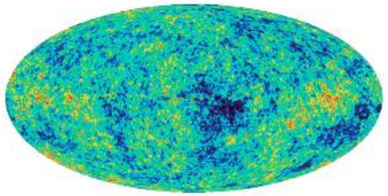
$\mathbf{m_\nu}$

neutrino mass measurements

$\mathbf{m_{\beta\beta}}$



$\mathbf{\Sigma m_i}$

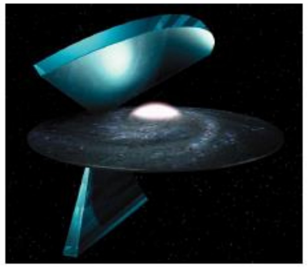


cosmology: ν hot dark matter Ω_ν

model dependent, analysis of CMB and structure formation data

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

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



Why several measurements ?

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 precision limited by nuclear matrix elements, but involves the phases and if successful demonstrates that neutrinos have a Majorana mass term

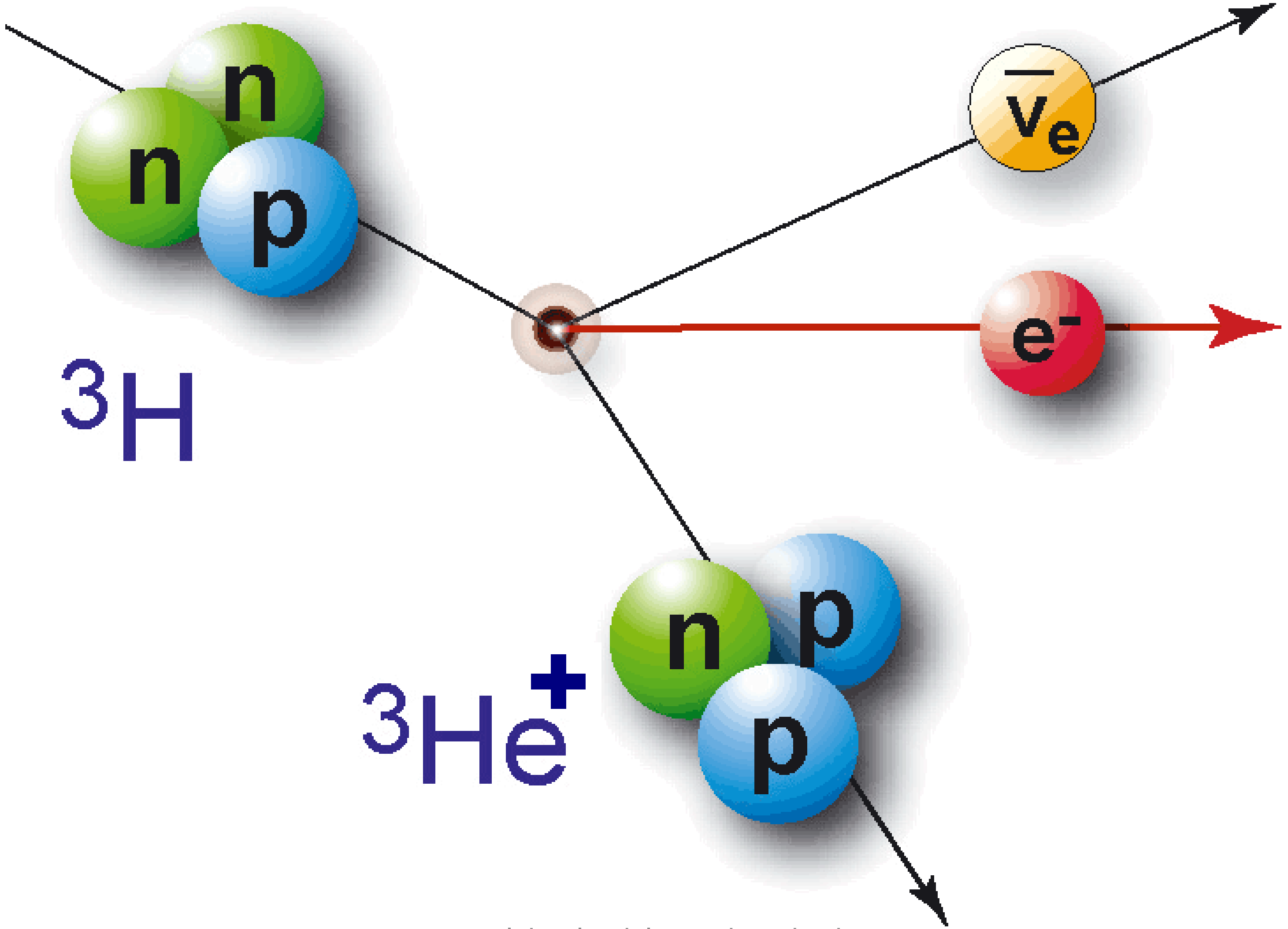
Kinematic measurement is model independent

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

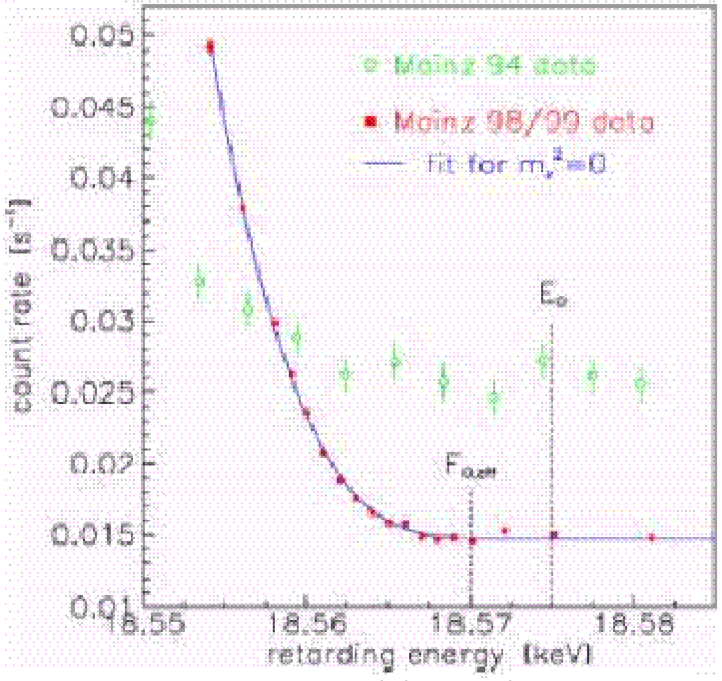
Particle physics: Probe theoretical models of neutrino mass generation, test of extension of the Standard model (See-saw Mechanism)

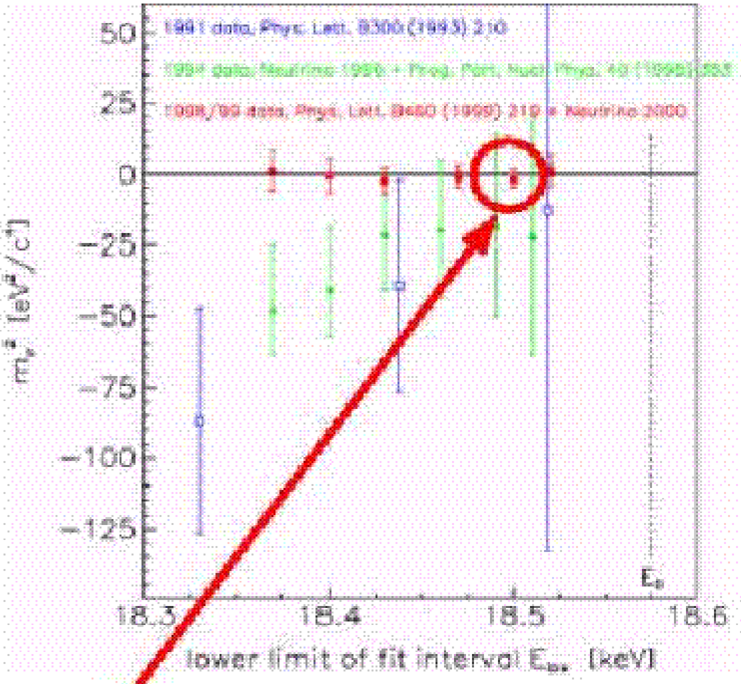
Electron antineutrino mass measurement in tritium β decay



Mainz data of 1998,1999

slide from my lectures in 2006





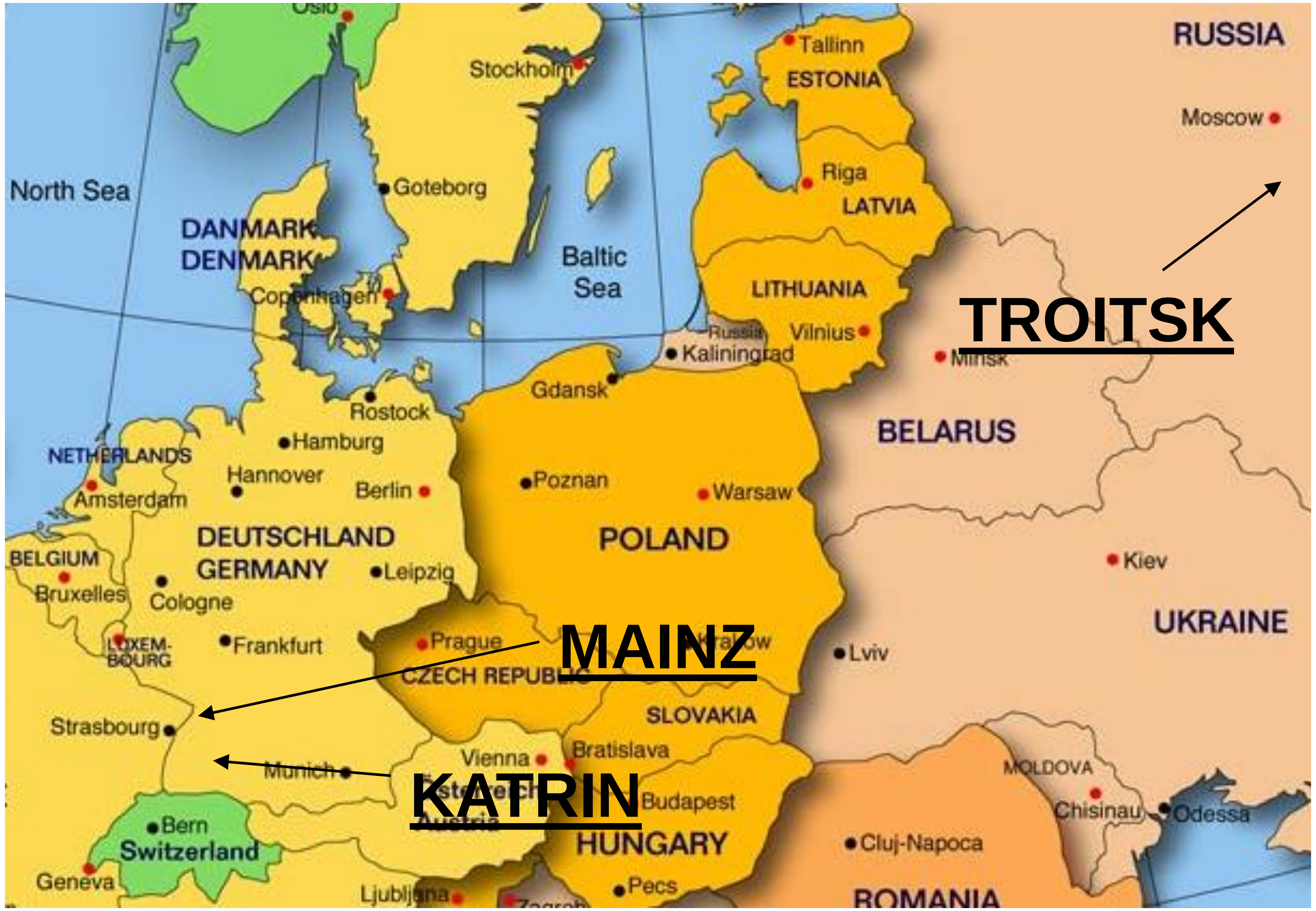
$m^2(\nu) = -1.6 \pm 2.5 \pm 2.1$ eV^2 $\quad$ (χ^2/d.o.f. = 125/121)

$\Rightarrow \quad m(\nu) < 2.2$ eV $\quad$ (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

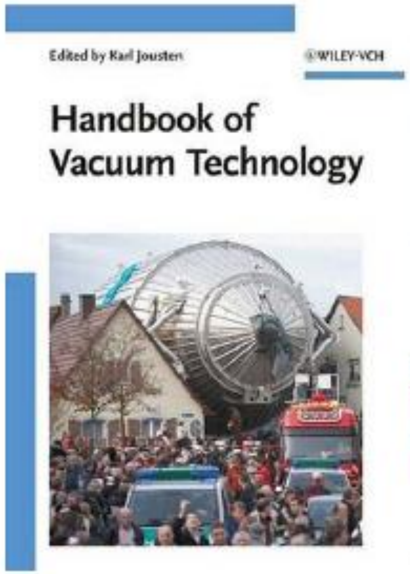
Electron antineutrino mass measurement in tritium β decay



coalition of two expert groups (Troitsk and Mainz, and many new collaborators) to combine efforts towards new experiment with more powerful source and more precise (larger) spectrometer

Physics run in 2019-2025!

spectrometer - transport



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

What is measured

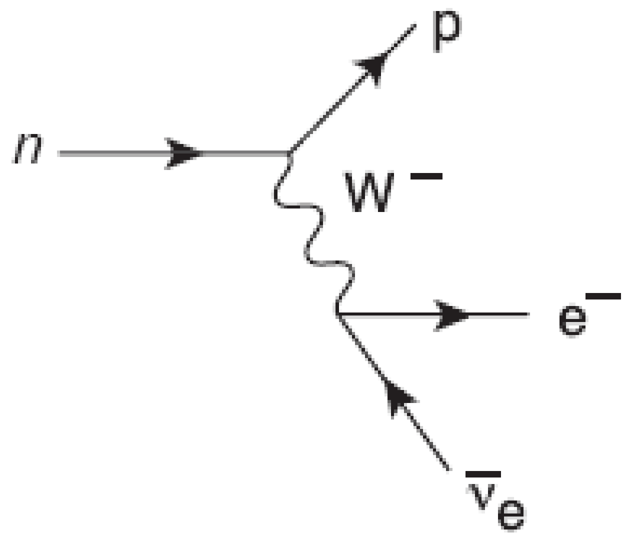
e- spectrum in β decay

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

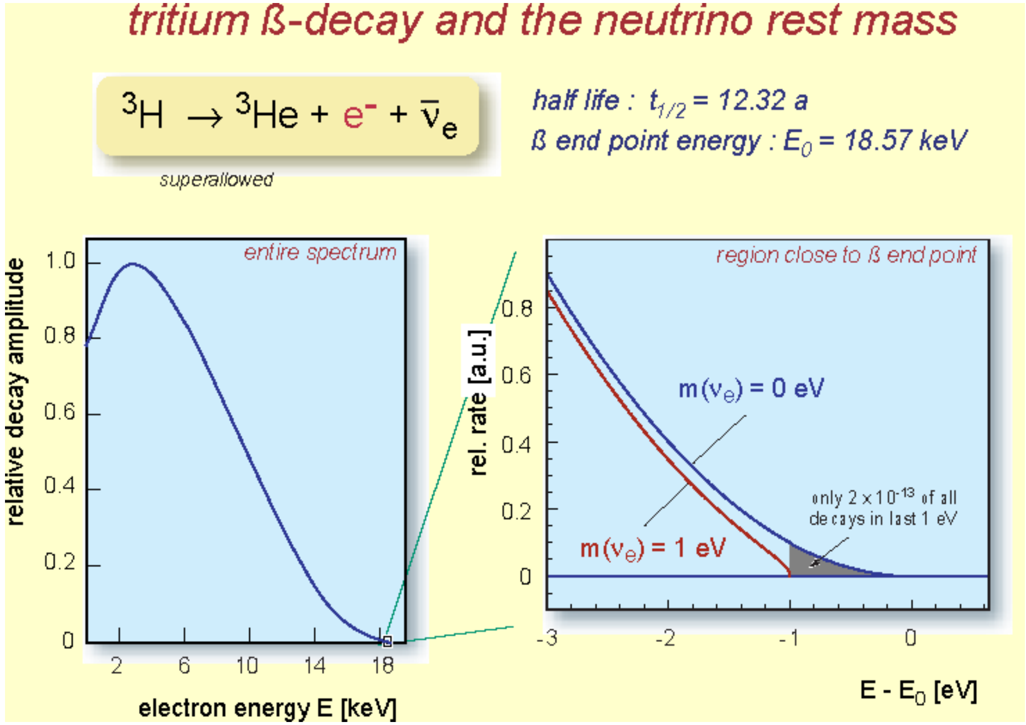
The only variable measured is **electrons kinetic energy**

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

$$m^2(\nu_e) = \sum_i |U_{ei}|^2 \cdot m^2(\nu_i)$$



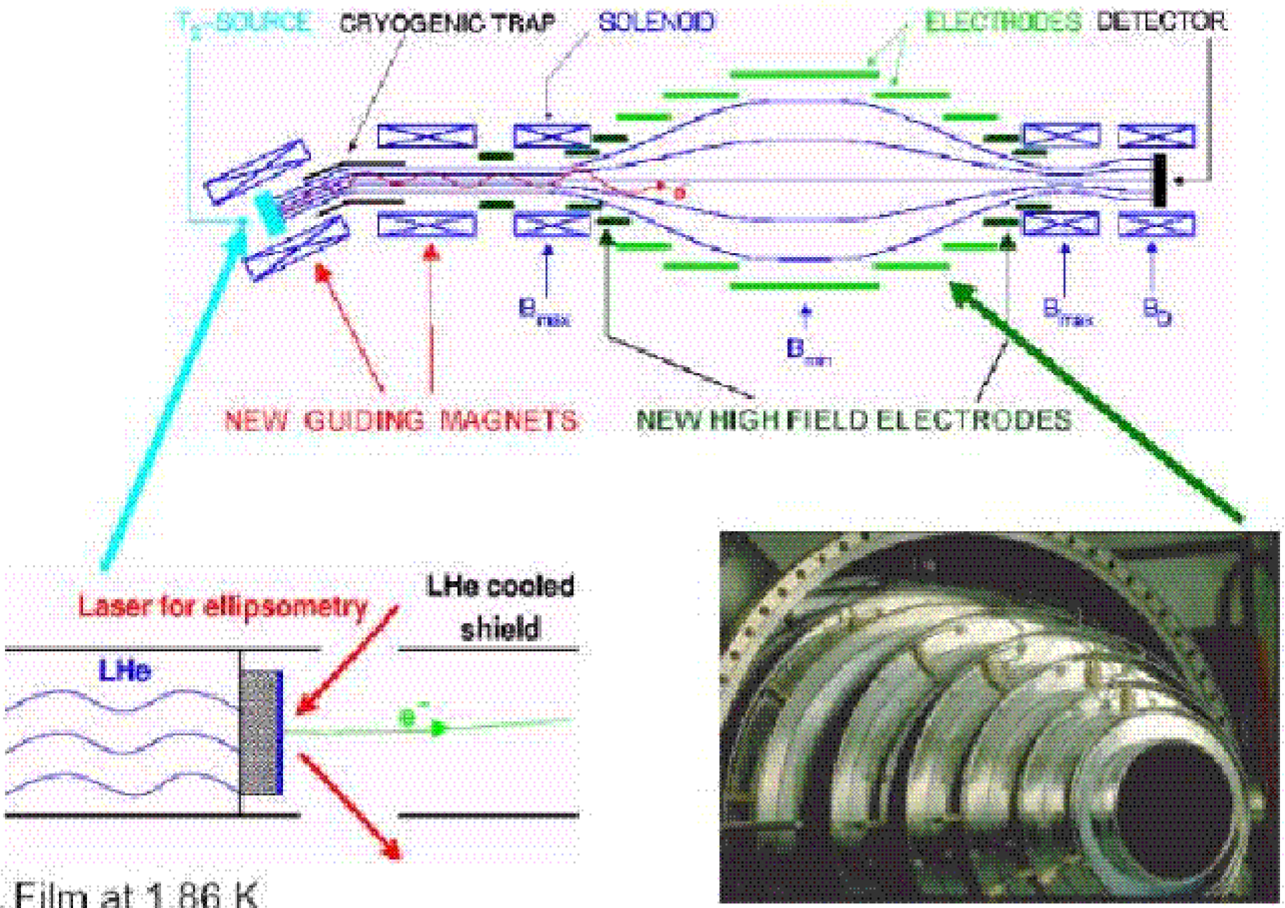
Tritium β decay is chosen



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

- Tritium and ^{187}Re have the lowest possible E_0, but tritium is preferred
- Much higher tritium decay rate, ^{187}Re decay rate is $2.46\text{x}10^{-10}$ times smaller
- Less inelastic scattering in the source
- Simpler excitation states in daughter Helium

Mainz Neutrino Mass Experiment since 1997



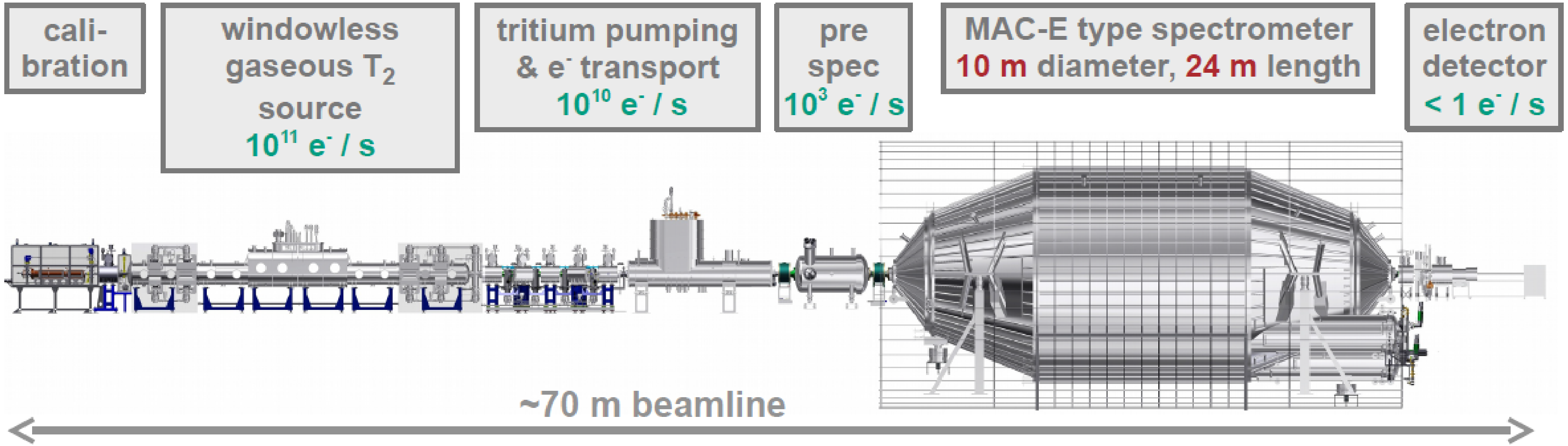
- T_2 Film at 1.86 K
- quench-condensed on graphite (HOPG)
- 45 nm thick (≈130ML), area 2cm²
- Thickness determination by ellipsometry

Mainz
ν group
2001:

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

* → FZ Karlsruhe
** → Univ. Bonn

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

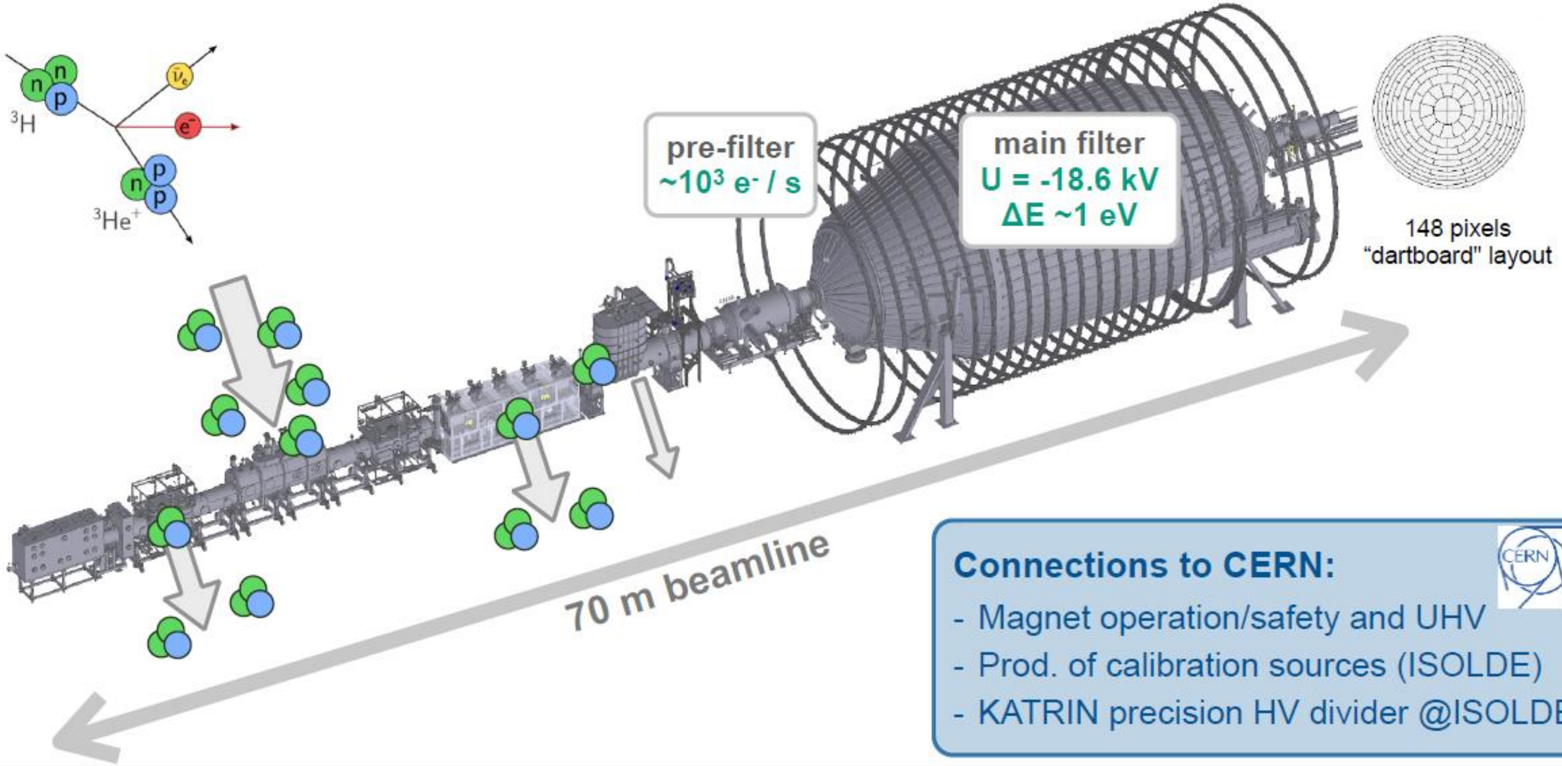
→ ultra-high energy resolution

Sensitivity on $m(\nu_e)$:
2 eV → 200 meV

Working principle of KATRIN

KIT Karlsruhe Institute of Technology

windowless gaseous T_2 source 10^{11} e^- / s	tritium pumping & e^- transport T_2 flow reduction $>10^{14}$	high-pass energy filters MAC-E filter	counting detector < 1 e^- / s



Connections to CERN:

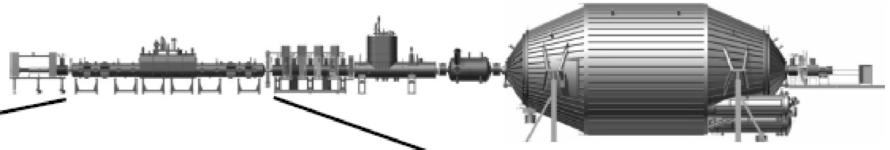
- Magnet operation/safety and UHV
- Prod. of calibration sources (ISOLDE)
- KATRIN precision HV divider @ISOLDE

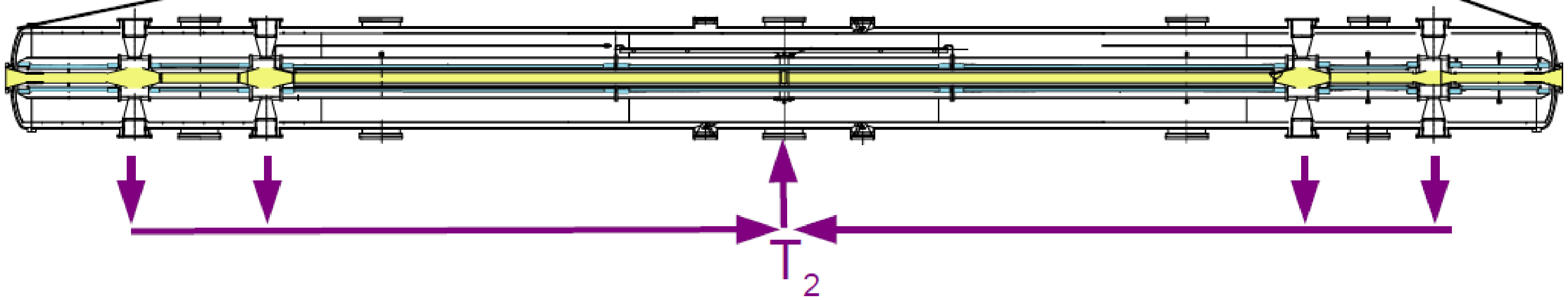
10 Full system description & commissioning paper: 2103.04755 K. Valerius | Probing the neutrino mass scale

WWU MÜNSTER

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





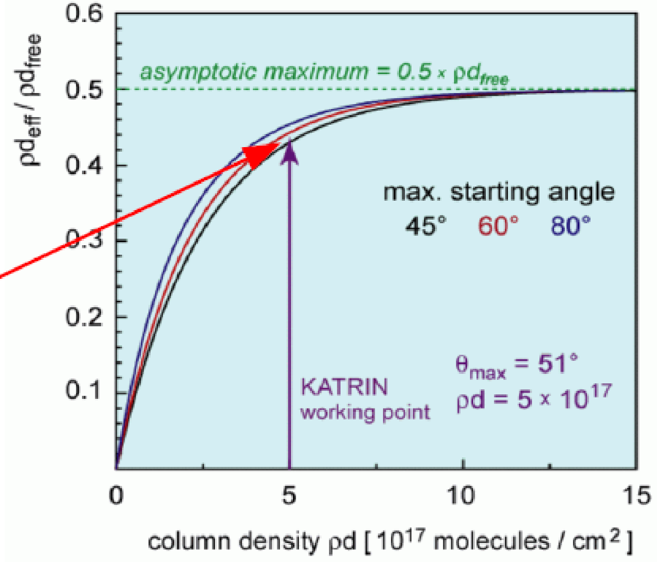
WGTS: tube in long superconducting solenoids
⌀ 9cm, length: 10m, T = (30 ± 0.03) K

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

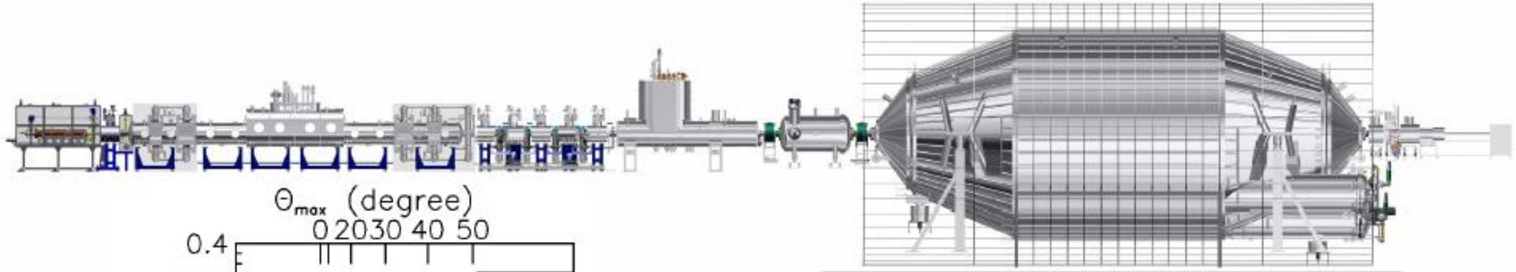
T_2 purity f_T by laser Raman spectr.

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

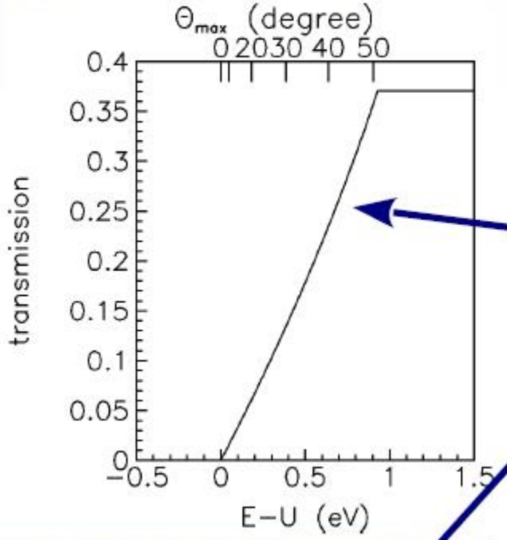
check column density by e-gun



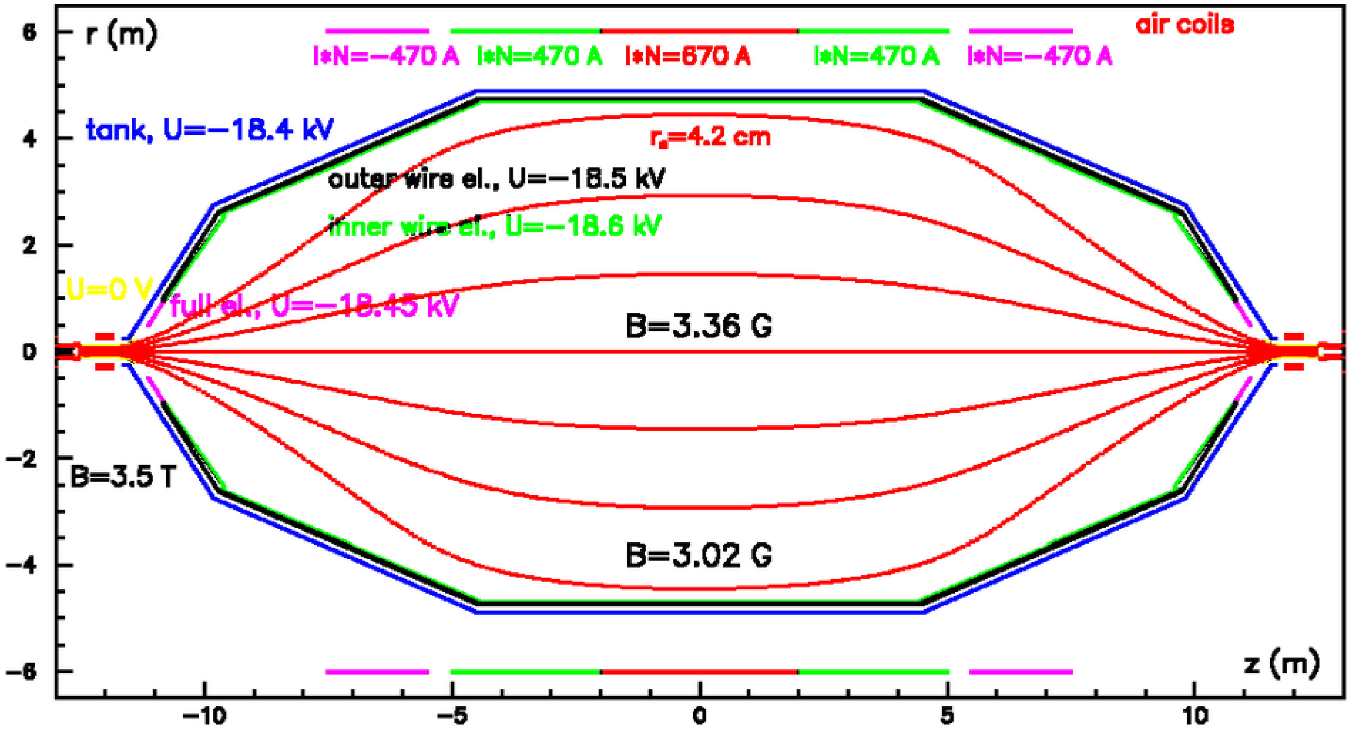
The KATRIN Main Spectrometer: an integrating high resolution MAC-E-Filter



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

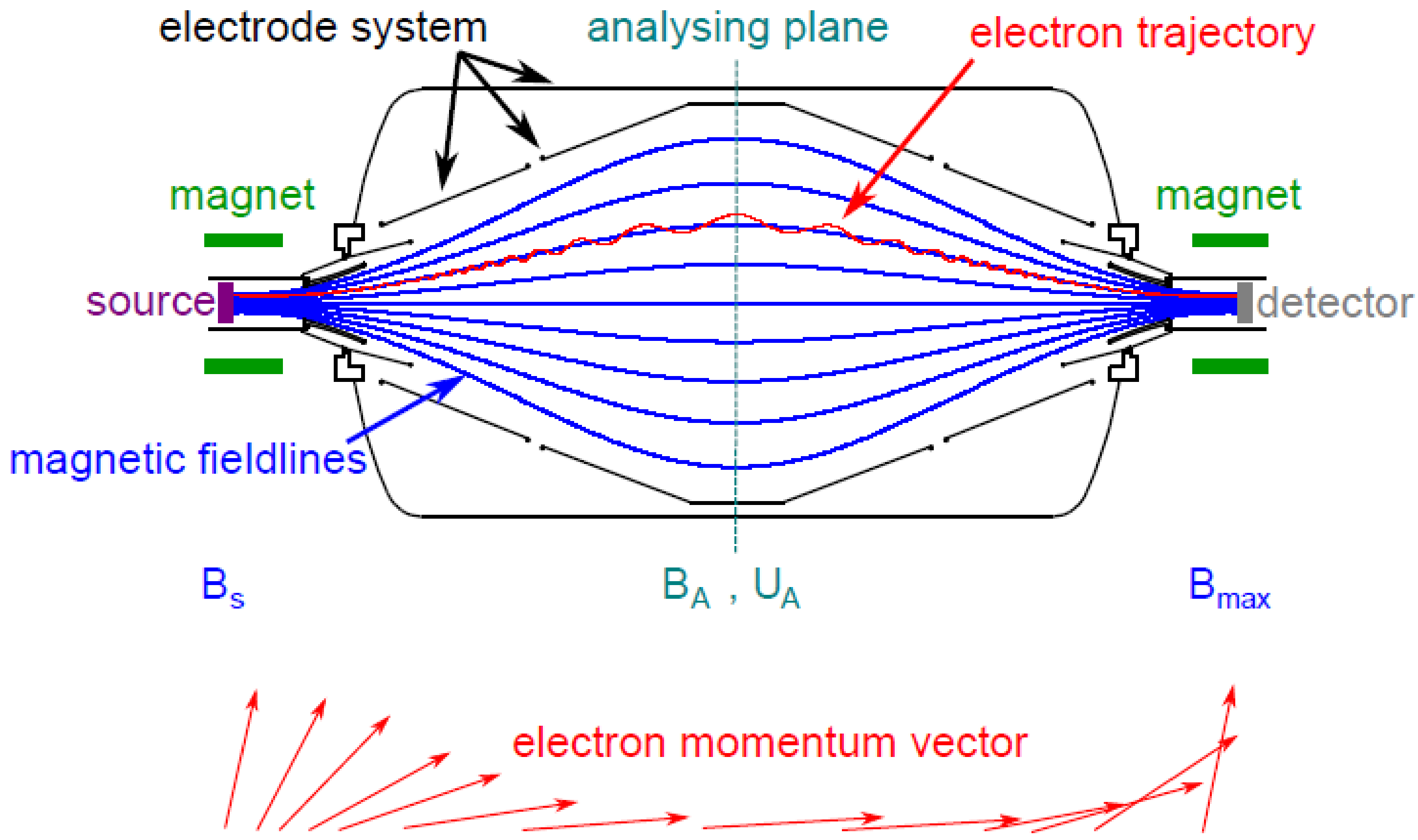


: Electromagnetic design of the KATRIN main spectrometer with two-layer wire electrodes

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)

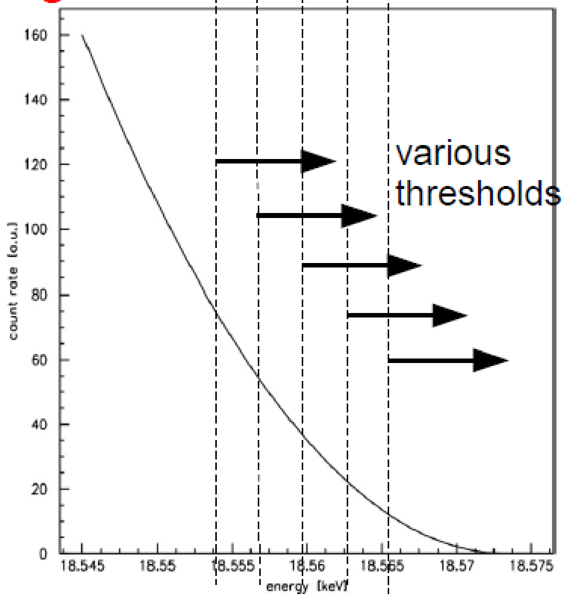
Magnetic Adiabatic Collimation & Electrostatic filter

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



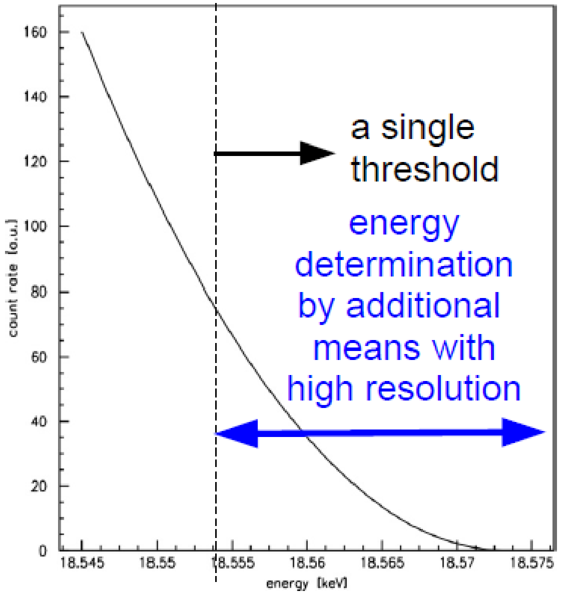
Gain of additional differential method
avoiding loss of statistics by many filter settings

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

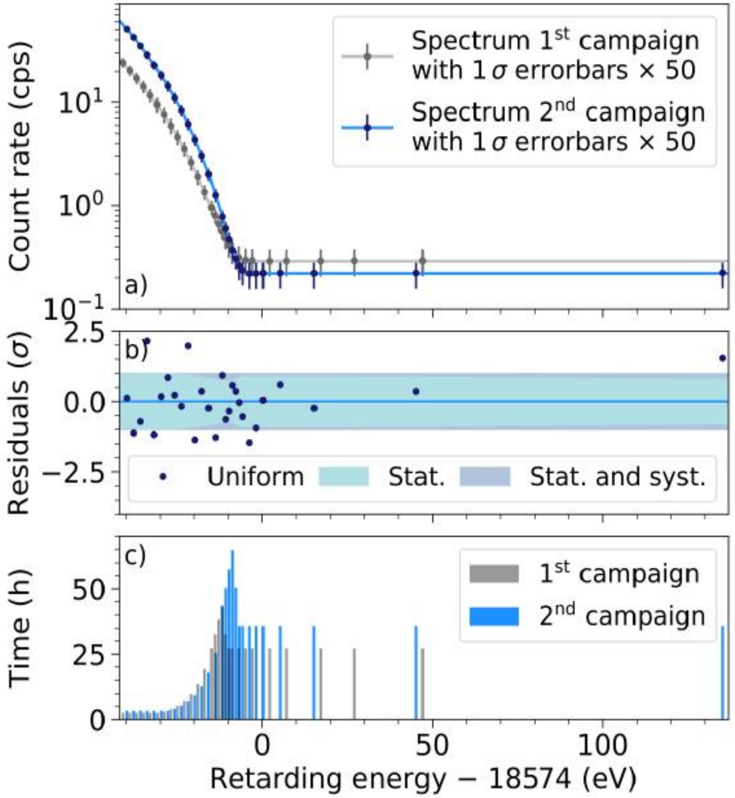
→ Differential method: expect naively statistical improvement in m_ν^2 of up to a factor $\sqrt{40}$ w.r.t. standard KATRIN,

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

Latest ν −mass results



First campaign (spring 2019):

✓ total statistics: 2 million events

✓ best fit: $m_\nu^2 = \left(-1.0^{+0.9}_{-1.1}\right)$ eV² (stat. dom.)

✓ limit: $m_\nu < 1.1$ eV (90% CL)

Second campaign (autumn 2019):

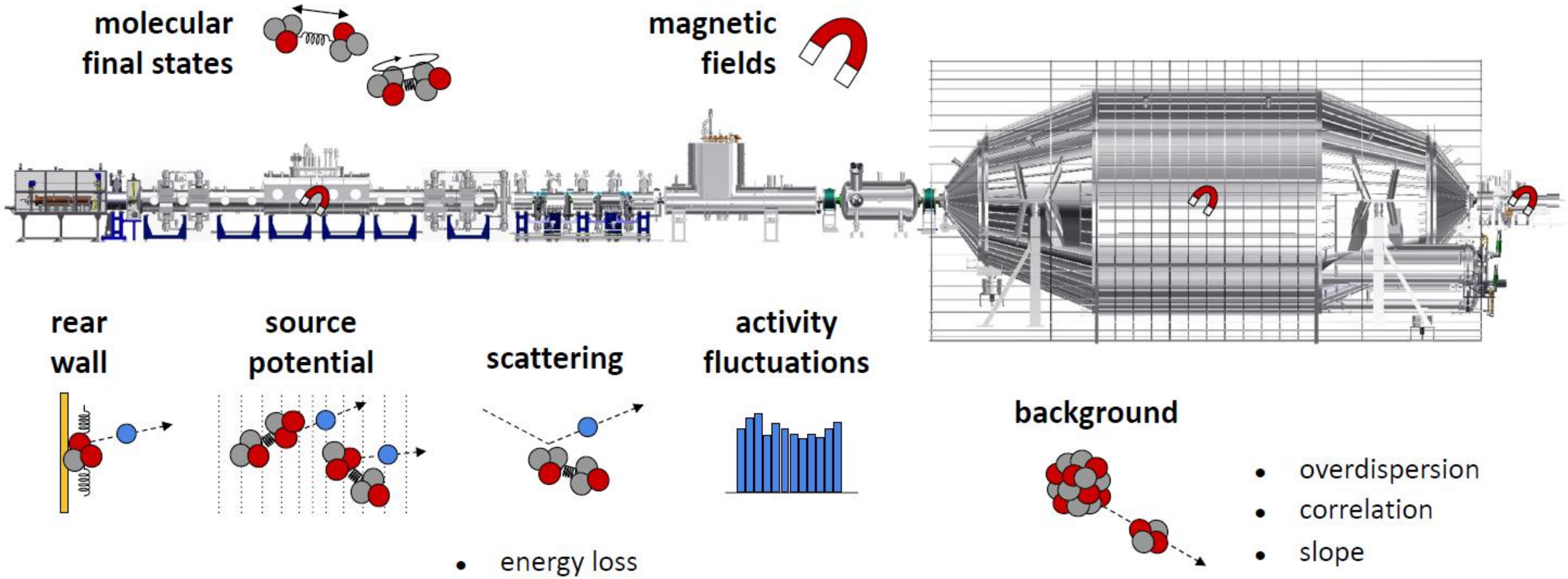
✓ total statistics: 4.3 million events

✓ best fit: $m_\nu^2 = \left(0.26^{+0.34}_{-0.34}\right)$ eV² (stat. dom.)

✓ limit: $m_\nu < 0.9$ eV (90% CL)

Combined result: $m_\nu < 0.8$ eV (90% CL)

Systematics uncertainties overview



- energy loss
- column density

- overdispersion
- correlation
- slope

Thierry Lasserre - Neutrino 2022

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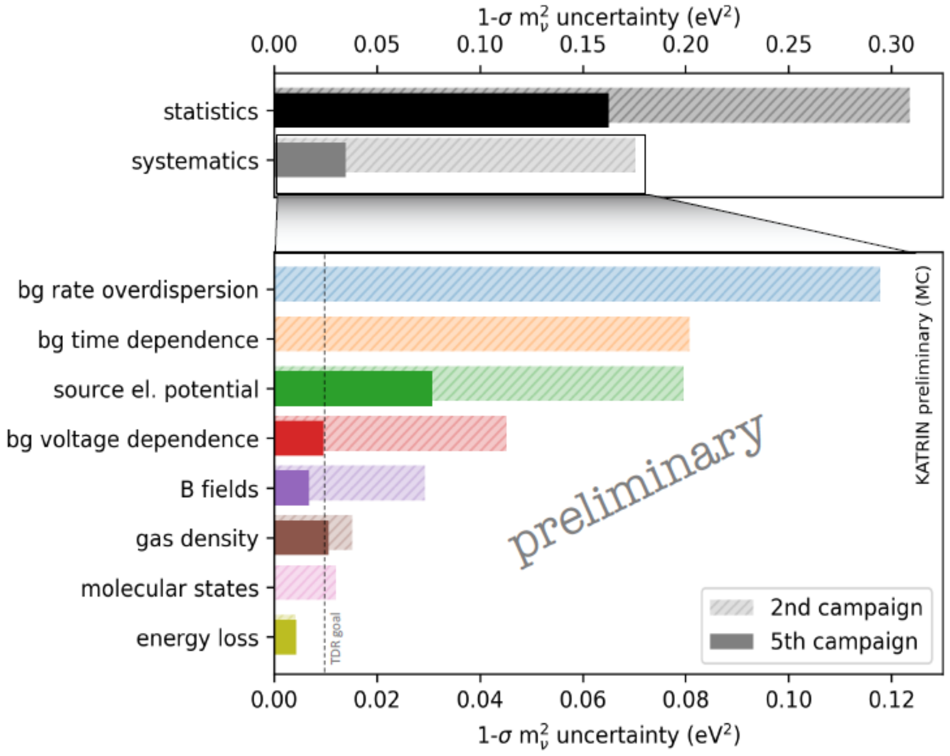
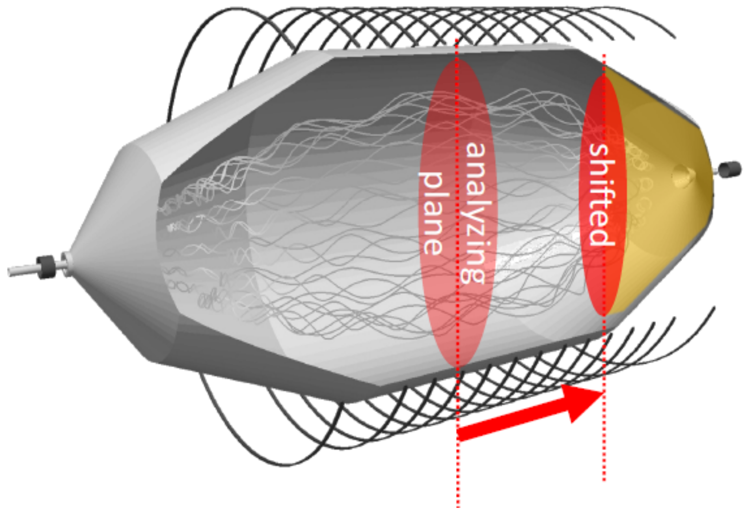
Improvements achieved by 2022



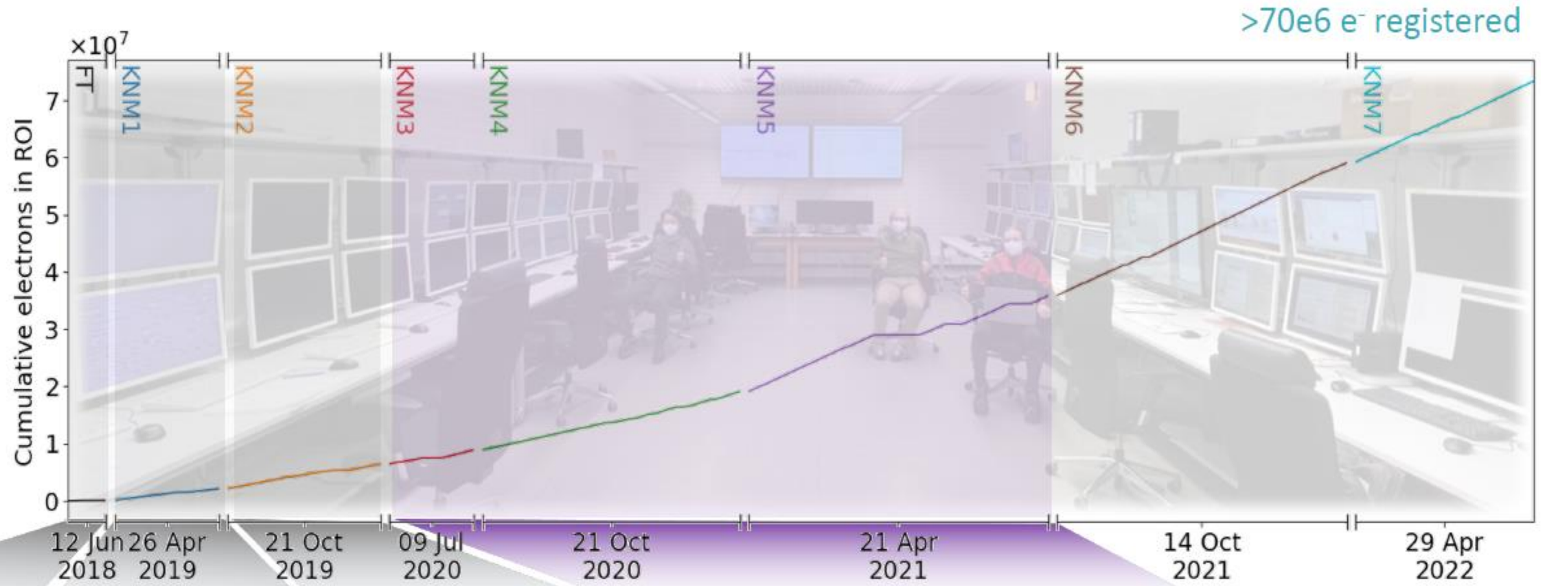
Major improvements:

✓ background reduction (÷2) via new EM field layout
A. Lokhov et al, EPJC 82, 258 (2022)

✓ 10 GBq ^{83}Rb/^{83m}Kr calibration (ν −mass scan conditions)
J. Sentkerestiová et al, JINST 13 (2018)



Outlook – 2022/2023



- commissioning
- only 0.5% tritium

EPJ C 80, 264 (2020)

- 1^{st} campaign

  $2e6\ e^-$ in ROI
- $m_\nu < 1.1$ eV

PRL. 123, 221802 (2019)

PRD. D 104, 012005 (2021)

- $1^{st} + 2^{nd}$ campaigns
- $6e6\ e^-$ in ROI
- $m_\nu < 0.8$ eV

Nat. Phys. **18**, 160–166 (2022)

- next data unblinding in summer 2022
- 1^{st}, 2^{nd}, 3^{rd}, 4^{th}, 5^{th} campaigns
- ~30e6 e^- in ROI

→target : 0.2meV by 2025

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Neutrinos and Cosmology

NB I am not a specialist, questions to Neronov!

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

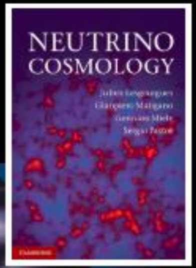
controls the size of the effects

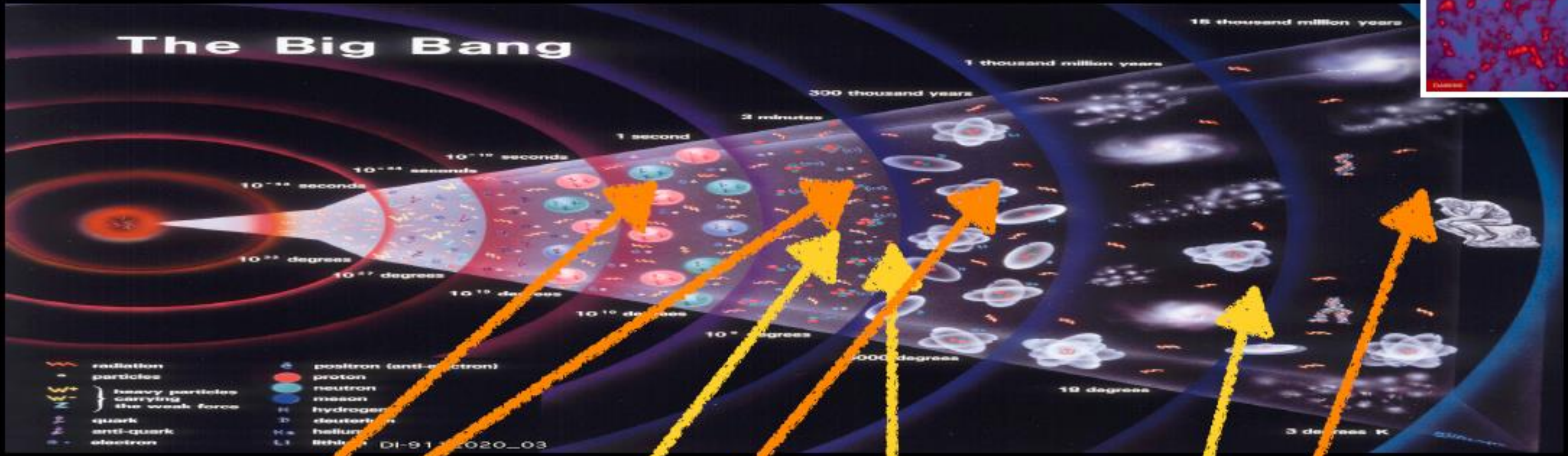
Mass of neutrinos

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)

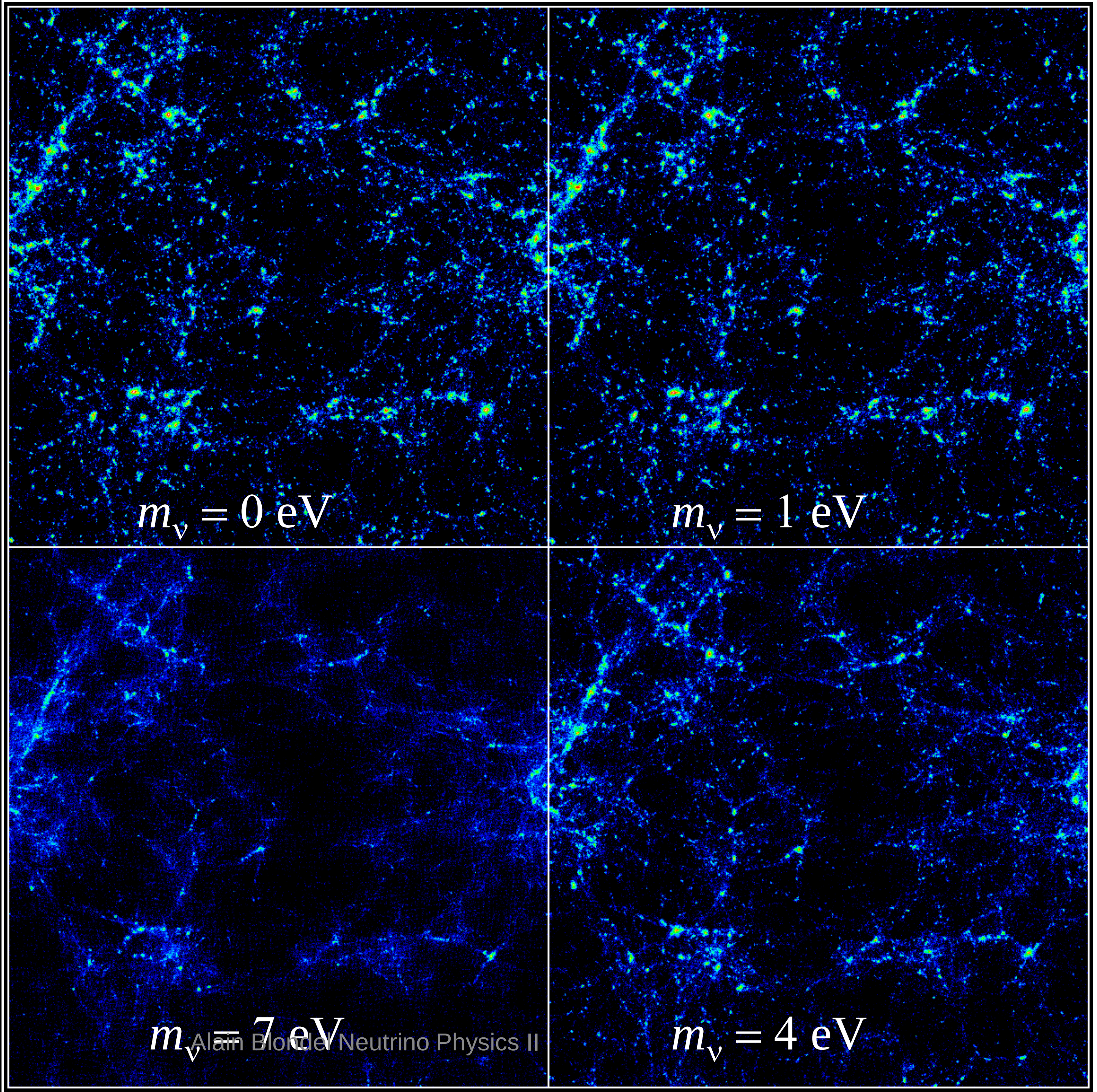
neutrino slow down early dark matter clustering

neutrino propagation and dispersion velocity

neutrino slow down late ordinary/dark matter clustering

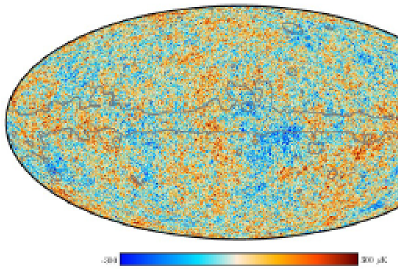
Halzen

adding hot neutrino dark matter erases small structure

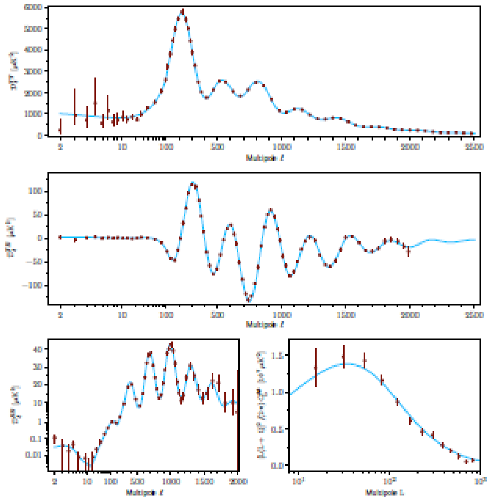


Cosmological observables

CMB temperature/polarisation maps



CMB temp./polar. spectrum



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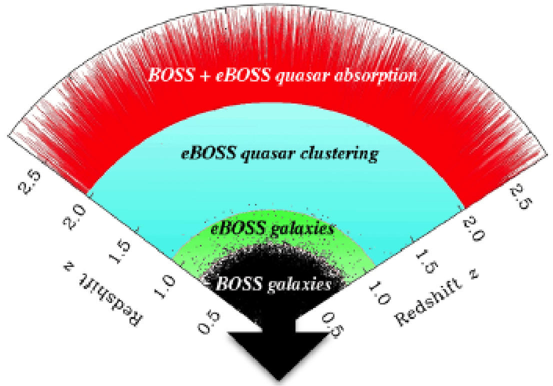
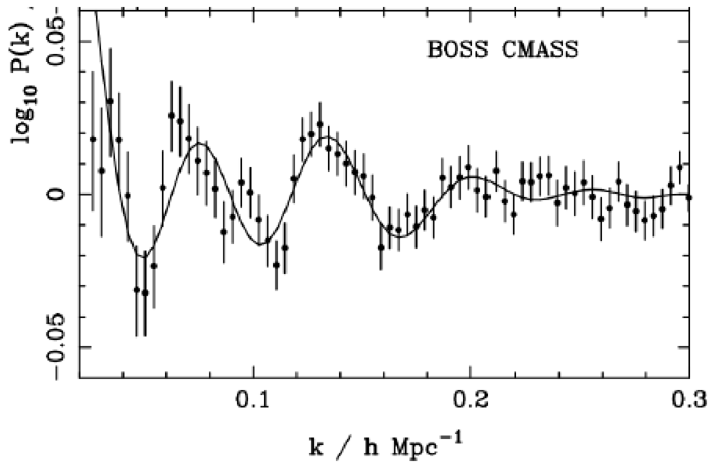
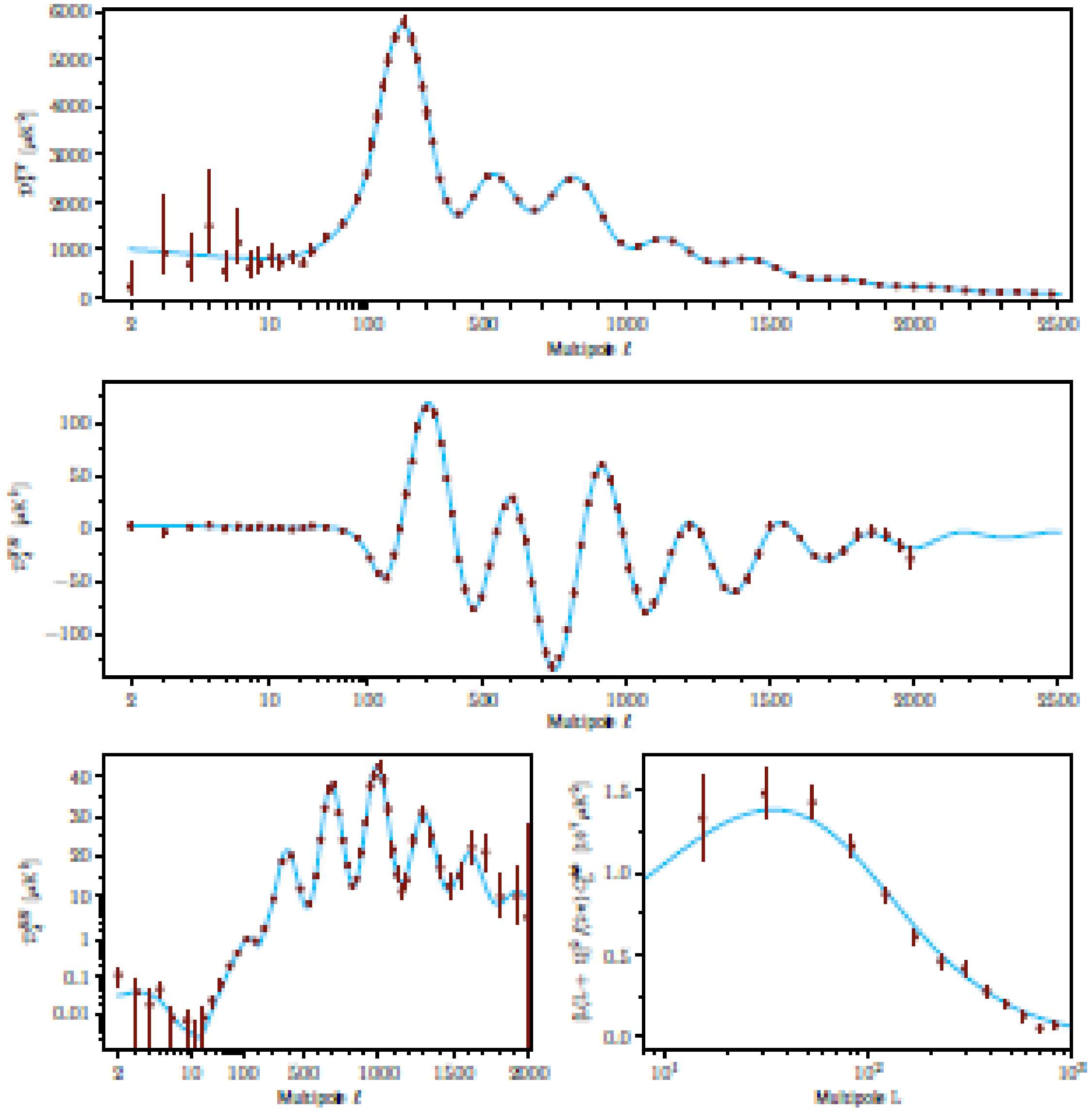
Galaxy distribution and lensed shapes



LSS (matter) power spectrum

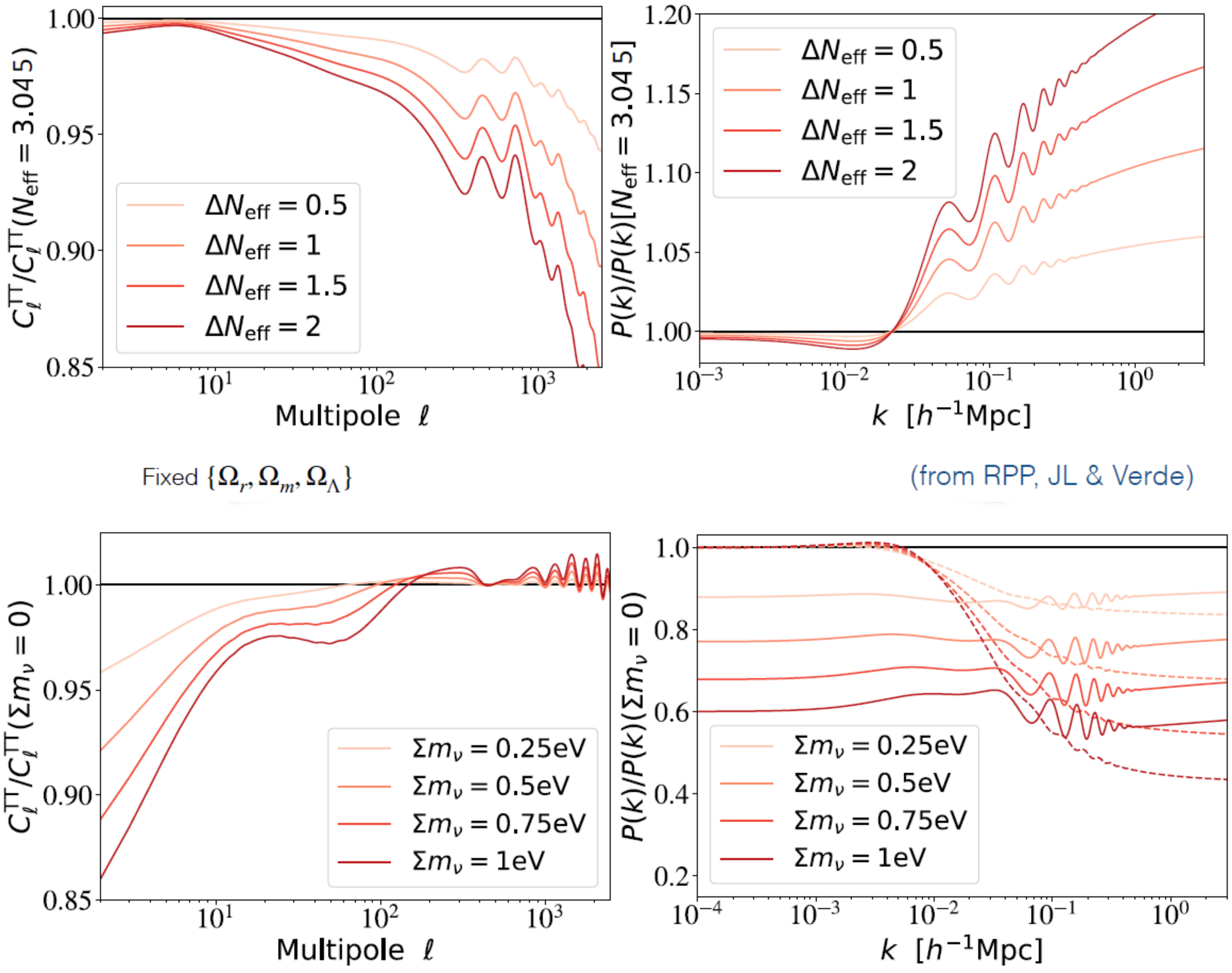


CMB temp./polar. spectrum



5 mber f

Impact of the Number of « neutrino » degrees of freedom N_{eff}



Impact of the sum of neutrino masses

$$N_{\mathrm{eff}} = \frac{\text{(energy density of neutrinos + possible other light/massless relics)}}{\text{(energy density of one neutrino family in instantaneous decoupling limit)}}$$

$N_{\mathrm{eff}} \simeq 3$ in absence of extra relics (light sterile νs, axions, dark radiation)

Measurement of N_{eff}

(from RPP, JL & Verde)

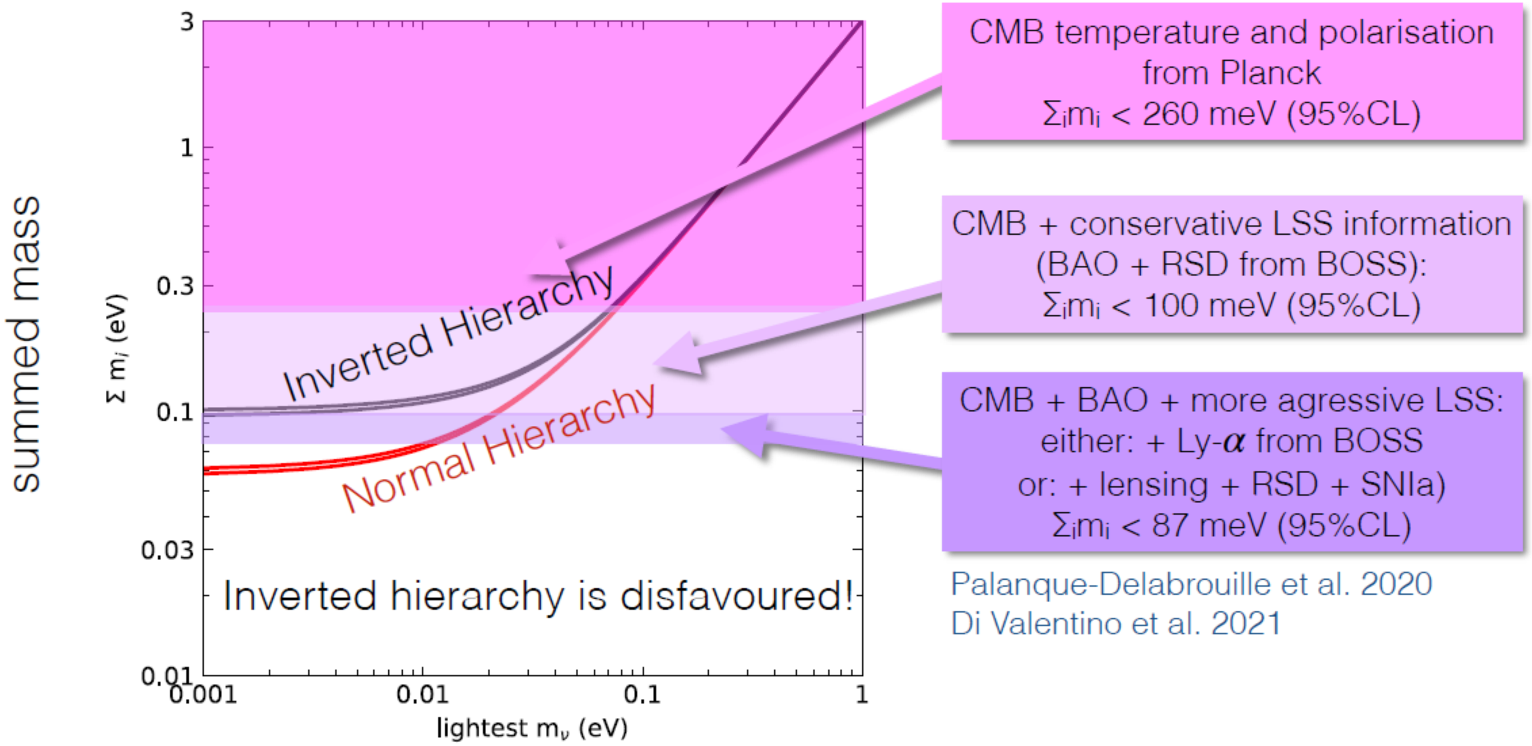
	Model	95%CL	Ref.
CMB alone			
Pl18[TT,TE,EE+lowE]	ΛCDM+N_{eff}	$2.92^{+0.36}_{-0.37}$	[22]
CMB + background evolution + LSS			
Pl18[TT,TE,EE+lowE+lensing] + BAO	ΛCDM+N_{eff}	$2.99^{+0.34}_{-0.33}$	[22]
" + BAO + R21	ΛCDM+N_{eff}	3.34 ± 0.14 (68%CL)	[11]
Pl18[TT,TE,EE+lowE+lensing] + BAO	" +5-params.	2.85 ± 0.23 (68%CL)	[23]

NB theoretical number is N_{eff}=3.044

NO EVIDENCE FOR ADDITIONAL light sterile neutrino (up to ~keV)

Bounds on Σm_ν

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



Palanque-Delabrouille et al. 2020
Di Valentino et al. 2021

Generally these results depend on assumptions that are not as precisely verified as the Standard Model of particle physics! Nevertheless they have improved considerably in the last 10 years.

Neutrinos have mass and mix

This is NOT the Standard Model

why can’t we ‘just’ add masses to neutrinos?

Fermion number conservation

fermion number violation is the first Sakharov condition for the **Baryon Asymmetry of the Universe**
Baryogenesis
or Leptogenesis + sphalerons
Also requires
-2- CP violation and
-3- out-of-equilibrium universe (Big Bang)

Is *not* in itself a law or a symmetry of the Standard Model

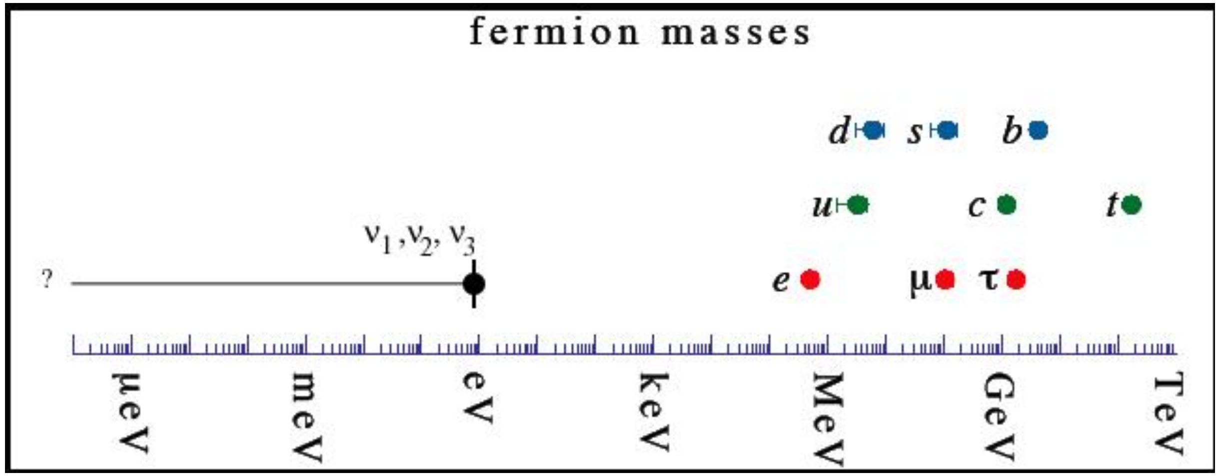
For charged fermions (e/mu/tau and the quarks) it is not possible to transform a fermion into an antifermion **because of charge conservation**

For neutrinos, which are neutral, the SM assumes they are massless.
neutrino is left-handed (identical if massless to negative helicity)
and the antineutrino has positive helicity
neutrino <-> antineutrino transition is forbidden by **angular momentum conservation**

This results in practice in <u>apparent conservation of fermion number</u>

The existence of massive neutrinos allows for spin flip and thus in principle a neutrino-antineutrino transition
« Majorana mass term »
since a left handed field has a component of the opposite helicity (and vice versa)
$\nu_L \approx \nu_- + \nu_+ \, m/E$ (mass is what allows to flip the helicity)
for very small mass and light neutrinos this is very, very small: for m=50meV and P =30 MeV ➔ $(m/E)^2 = 10^{-18}$

This can be observed in neutrino less double beta decay



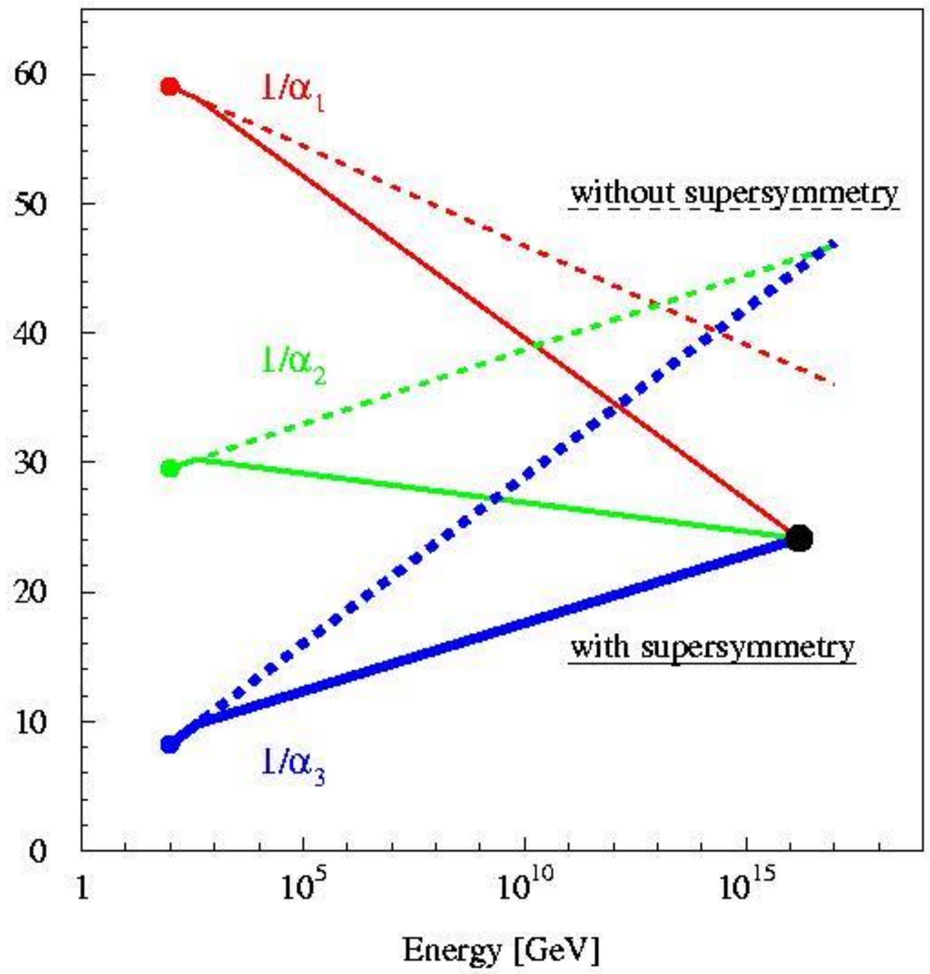
The mass spectrum of the elementary particles. Neutrinos are 10^{12} times lighter than other elementary fermions. The hierarchy of this spectrum remains a puzzle of particle physics.

Most attractive wisdom: via the see-saw mwchanism, the neutrinos are very light because they are low-lying statesin a split doublet with heavy neutrinos of unknown mass scale

Traditional wisdom uses Dirac mass of the top quark

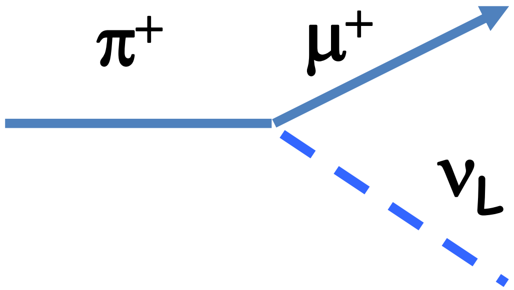
$m\,M = \langle v \rangle^2$ with $\langle v \rangle \approx m_{top} = 174$ GeV ➔ for $m_{\nu} = O(10^{-2})$ eV $\Rightarrow M \sim 10^{15}$ GeV

However it could just also be similar to the electron mass or even a few keV in which case the Majorana mass could be at or below the Electroweak scale.

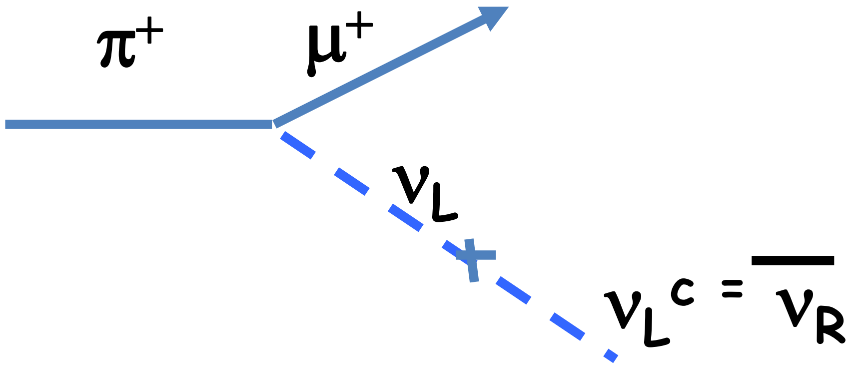


One often considers that $M_R \sim M_{GUT} \sim 10^{10}$ to 10^{15} GeV

Pion decay with massive neutrinos



$+$



1

$(m_\nu /E)^2$

<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

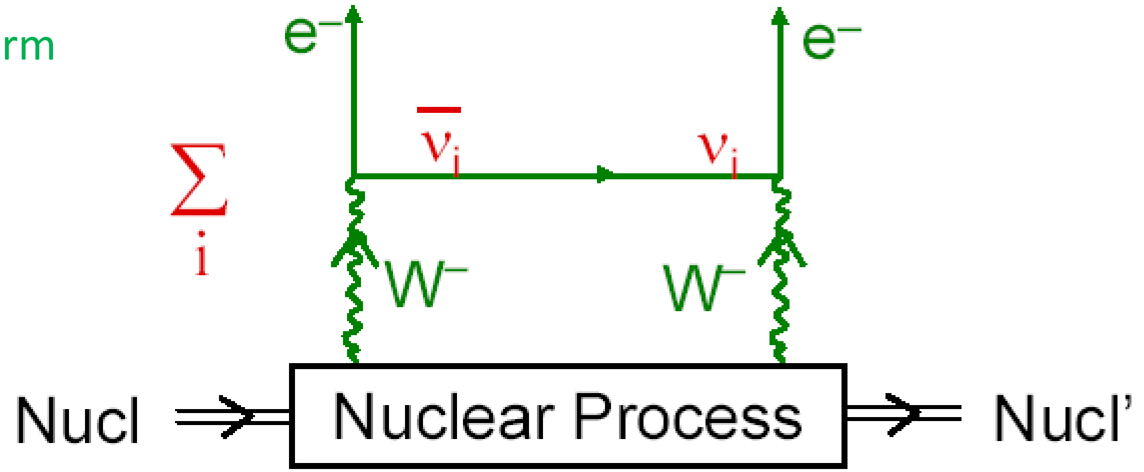
$(.05/30\ 10^6)^2 = 10^{-18}$

pure Dirac or Majorana are not observable this way, heavy RH(sterile) possible

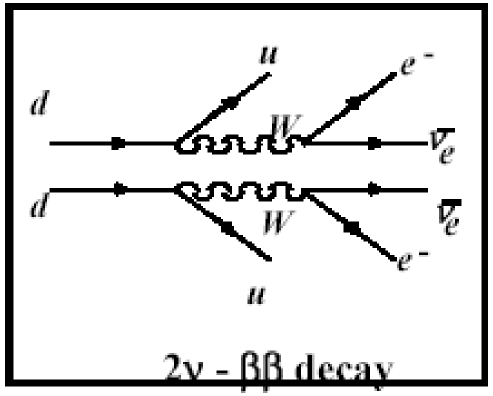
The Idea That Can Work —

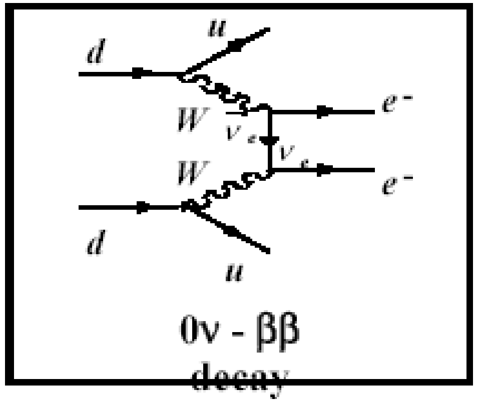
Neutrinoless Double Beta Decay [$0\nu\beta\beta$]

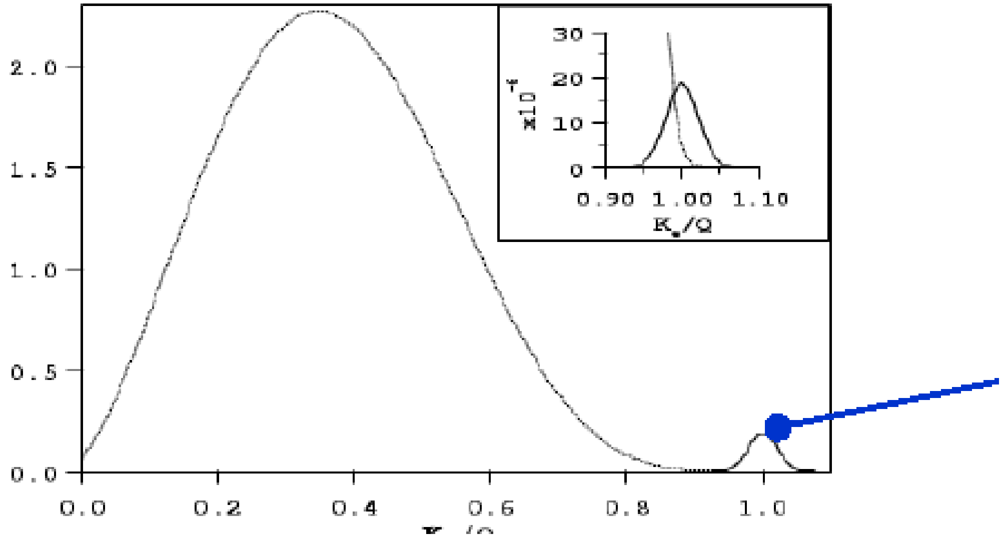
virtual process allows spin flip
if neutrinos have Majorana mass term



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



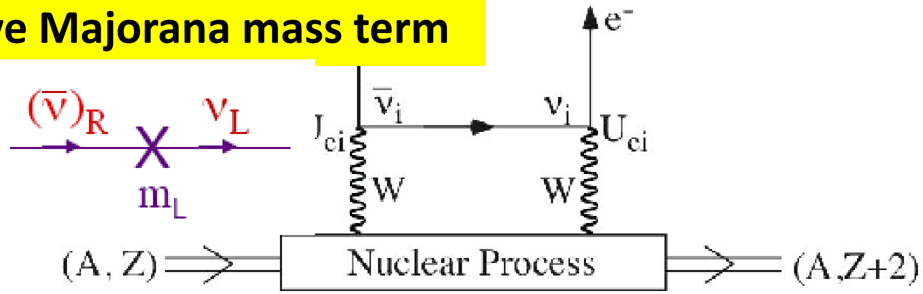




Two neutrino ββ decay has been detected in ten nuclei also into exited states

Neutrinoless Double Beta Decay (0νββ)

- Hypothetical ββ decay mode allowed if neutrinos are Majoran particles, **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: $m_{\beta\beta} \equiv \left|\sum_{i=1}^{3} U_{ei}^2 m_i\right|$

the nuclear matrix element introduces large uncertainties

-- Global program of calculations
-- and auxiliary measurements

-- importance of search on as many possible isotopes as possible

- $M^{0\nu}$ 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:

• ν_j- Dirac:	$\frac{1}{2}(n-1)(n-2)$	0	1	3
• ν_j- Majorana:	$\frac{1}{2}n(n-1)$	1	3	6

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

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

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

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

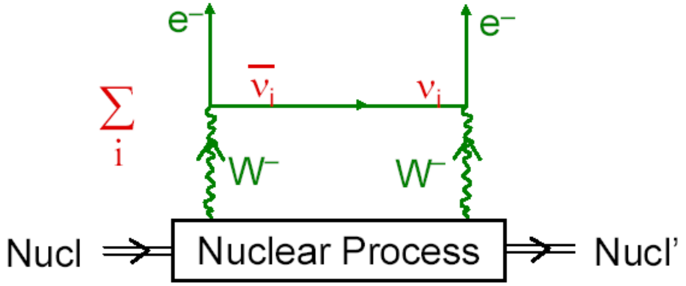
$A(\beta\beta)_{0\nu} \sim <m>$ M(A,Z), M(A,Z) - NME,

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

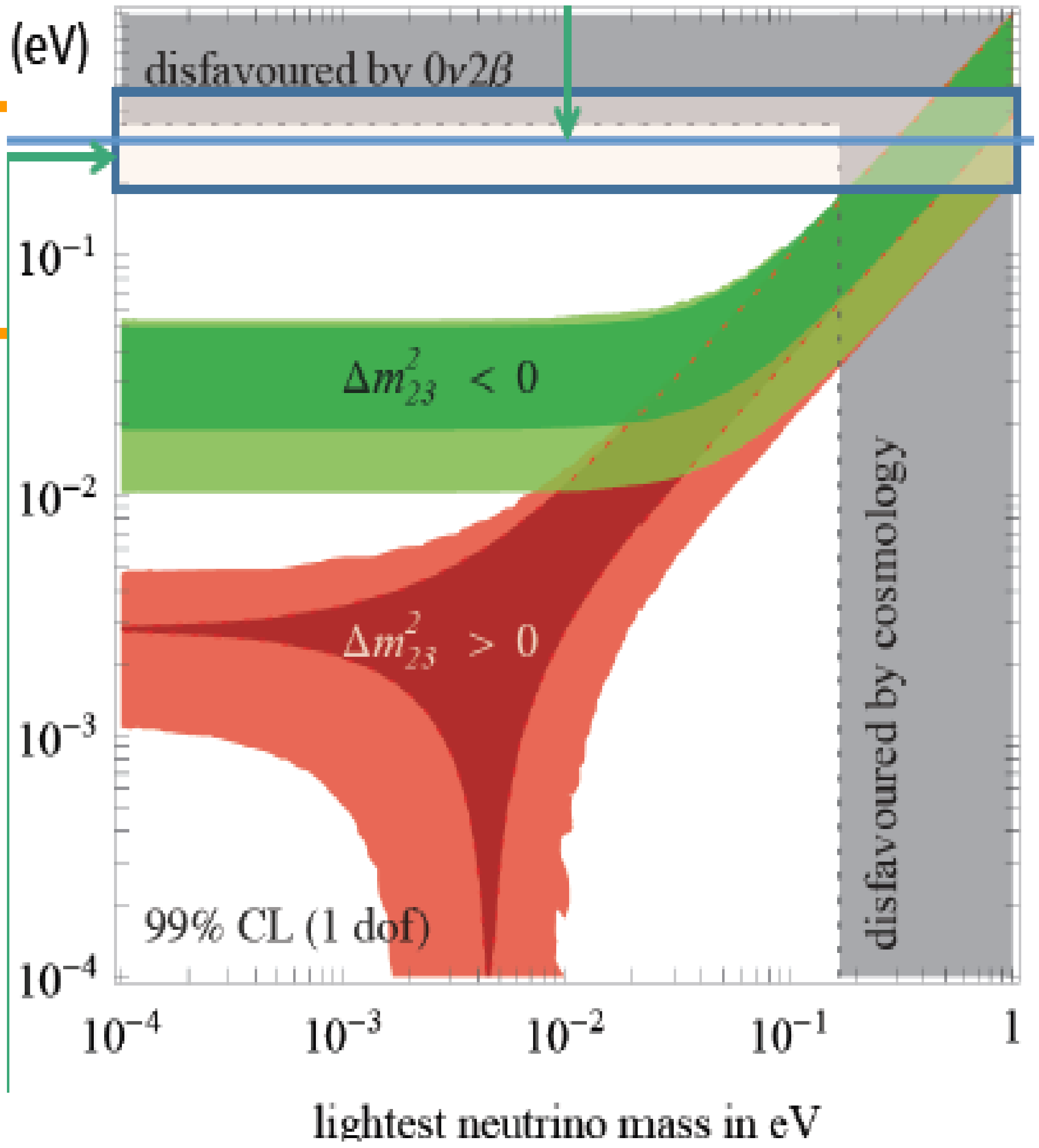
what 0νββ measures is <m> :

$$A(\beta\beta)_{0\nu} \sim \langle m \rangle \; M(A,Z), \qquad M(A,Z) \text{ - NME},$$

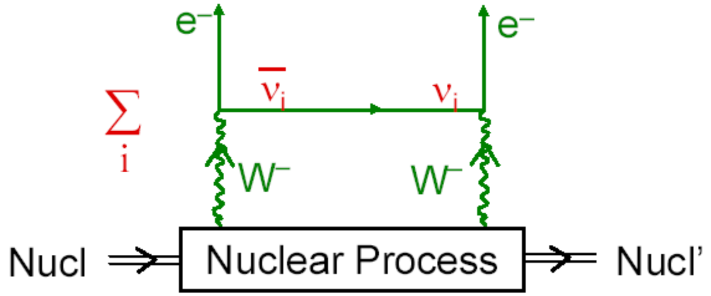
$$|\langle m \rangle| = \left| m_1 |U_{e1}|^2 + m_2 |U_{e2}|^2 \, e^{i\alpha_{21}} + m_3 |U_{e3}|^2 \, e^{i\alpha_{31}} \right|,$$



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 which interacts with the W



reaching limits below ~25 meV would allow strong indication on mass ordering of neutrinos



$(G_F)^4$

Experimental approach

Geochemical experiments

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

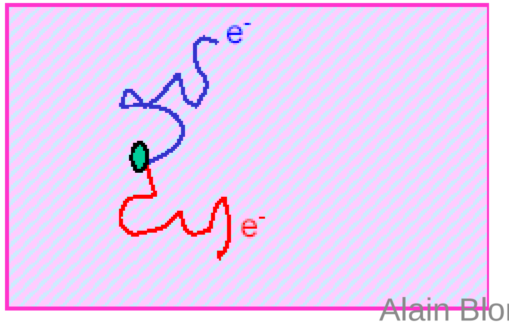
Radiochemical experiments

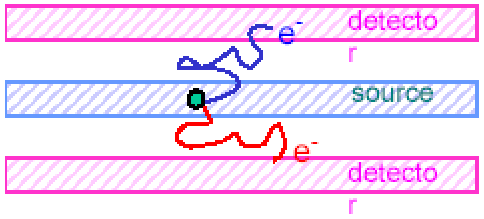
$^{238}U => {}^{238}Pu$ (non confirmed)

Direct experiments

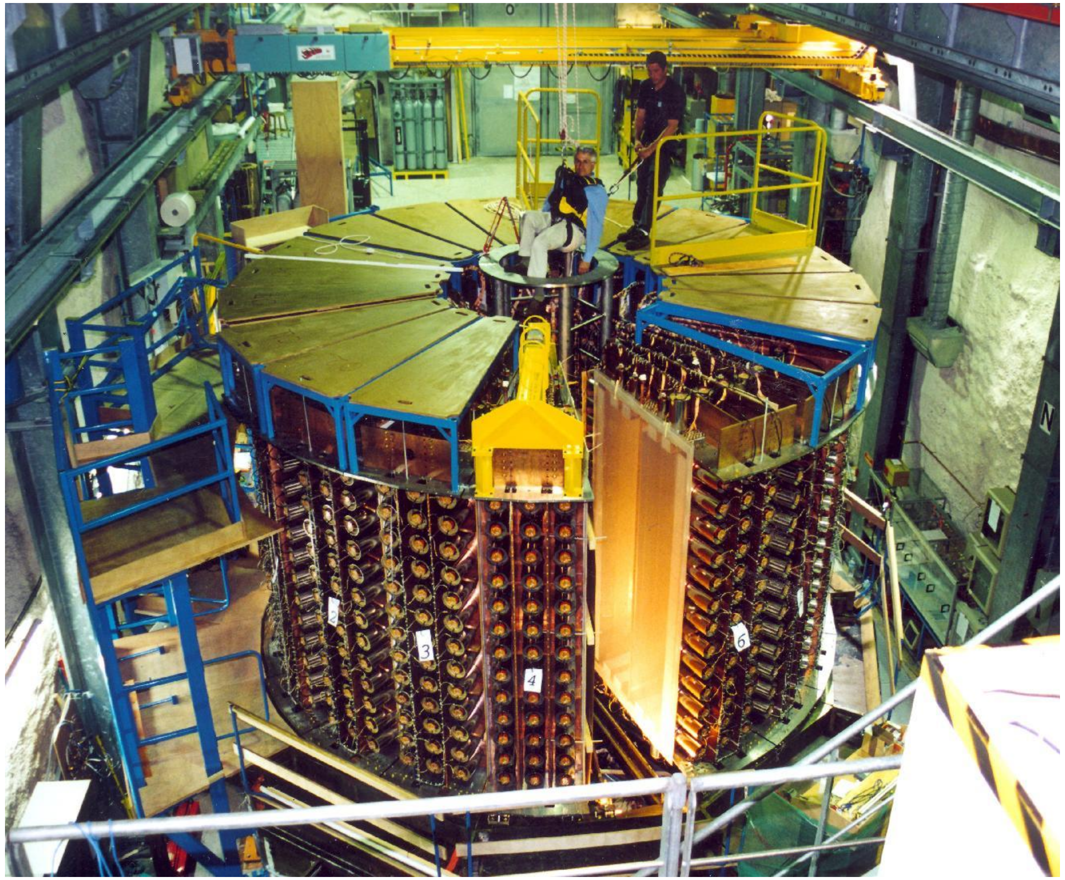
Source = detector (calorimetric)

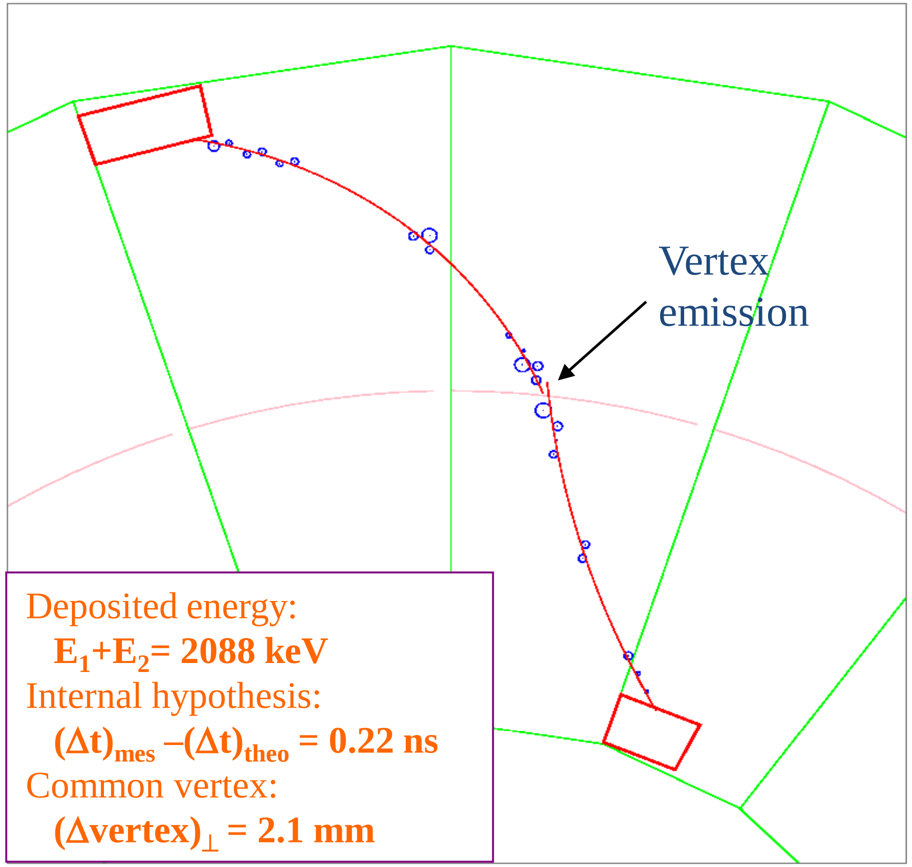
Source ≠ detector





Source ≠ Detector





NEMO

Criteria to select ββ events:

- 2 tracks with charge < 0
- 2 PMT, each > 200 keV
- PMT-Track association
- Common vertex

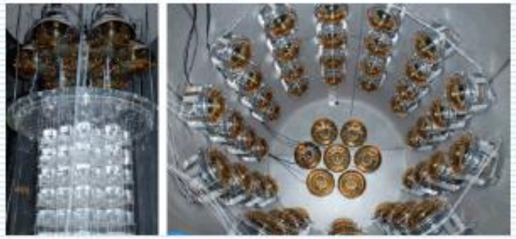
- Internal hypothesis (external event rejection)
- No other isolated PMT (γ rejection)
- No delayed track (^{214}Bi rejection)

«typical» 2νββ evenement

$0\nu\beta\beta$ decay isotopes and experiments

Candidates	$Q_{\beta\beta}$(MeV)	N.A. (%)
$^{48}Ca \rightarrow ^{48}Ti$	4.268	0.187
$^{76}Ge \rightarrow ^{76}Se$	2.039	7.8
$^{82}Se \rightarrow ^{82}Kr$	2.998	8.8
$^{96}Zr \rightarrow ^{96}Mo$	3.356	2.8
$^{100}Mo \rightarrow ^{100}Ru$	3.034	9.7
$^{110}Pd \rightarrow ^{110}Cd$	2.017	11.7
$^{116}Cd \rightarrow ^{116}Sn$	2.813	7.5
$^{124}Sn \rightarrow ^{124}Te$	2.293	5.8
$^{130}Te \rightarrow ^{130}Xe$	2.528	34.1
$^{136}Xe \rightarrow ^{136}Ba$	2.458	8.9
$^{150}Nd \rightarrow ^{150}Sm$	3.371	5.6

【Current CANDLES detector】

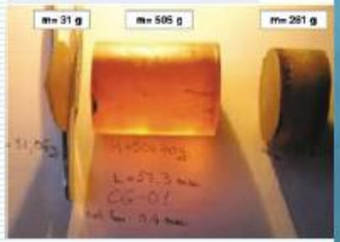


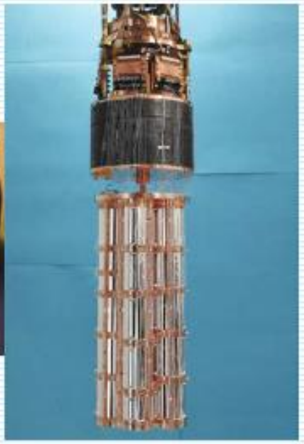
CANDLE
CaF scintillating crystal

SuperNEMO
Se source foil

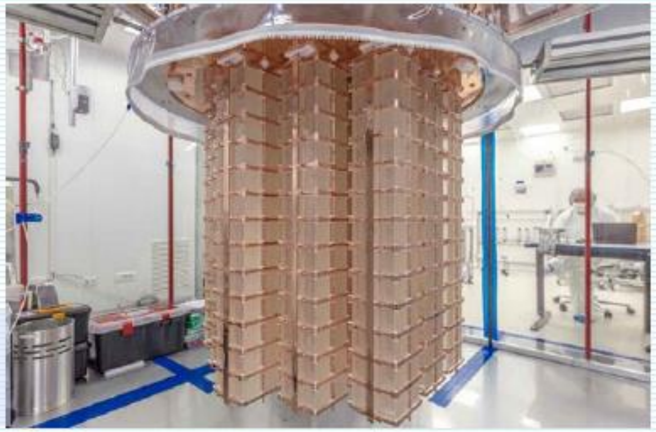
GERDA, MAJORANA
Ge crystal

CUPID-0
ZnSe scintillating crystal

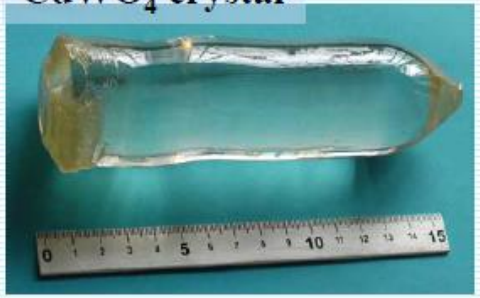




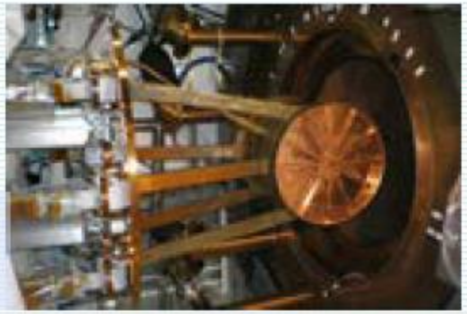
CUORE
TeO_2 crystal



Aurora
$CdWO_4$ crystal



EXO, KamLAND-Zen
Liquid Xe



Amore
$CaMoO_4$ crystal

Leading limits in each $0\nu\beta\beta$ isotope

A monoenergetic peak at the Q-value is searched for.
Need a large amount of decay isotope and low radioactive environment

Experiment	Isotope	Exposure [kg yr]	$T^{0\nu}_{1/2}[10^{25}$ yr]	$m_{\beta\beta}$ [meV]
Gerda	^{76}Ge	127.2	18	79-180
Majorana	^{76}Ge	26	2.7	200-433
CUPID-0	^{82}Se	5.29	0.47	276-570
NEMO3	^{100}Mo	34.3	0.15	620-1000
CUPID-Mo	^{100}Mo	2.71	0.18	280-490
Amore	^{100}Mo	111	0.095	1200-2100
CUORE	^{130}Te	1038.4	2.2	90-305
EXO-200	^{136}Xe	234.1	3.5	93-286
KamLAND-Zen	^{136}Xe	970	23	36-156

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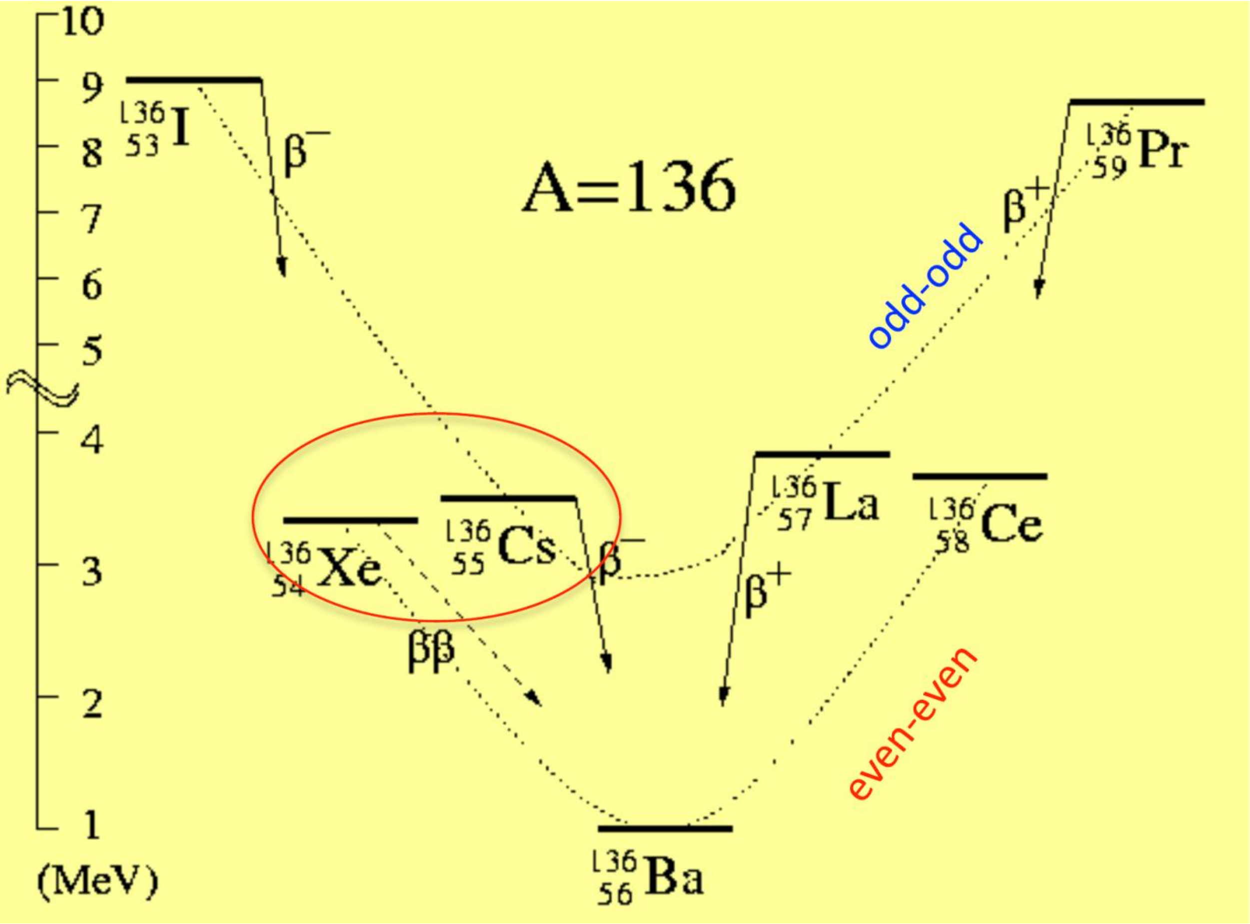
^{136}XENON

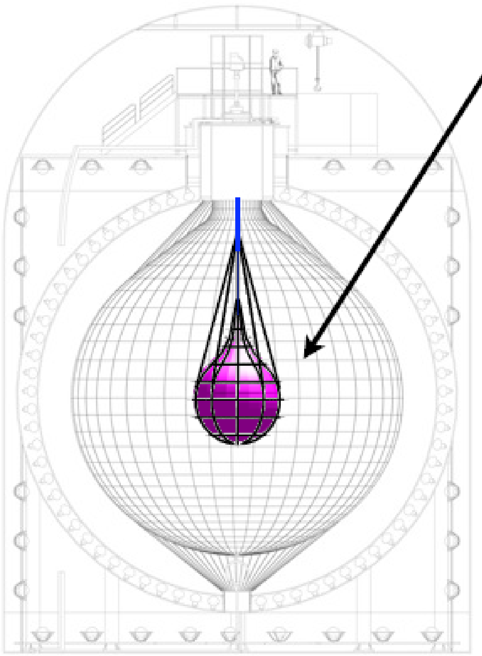


Q-value 2457.9±0.4keV

KamLAND-Zen

the old Kamioka
Nucleon Decay Experiment
KamiokaNDE

→ KamLAND (nuclear reactor neutrinos)
→ Zen (like Xenon)



- 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	$90.93\pm0.05\%$ ^{136}Xe $8.89\pm0.01\%$ ^{134}Xe	2.5% by weight

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

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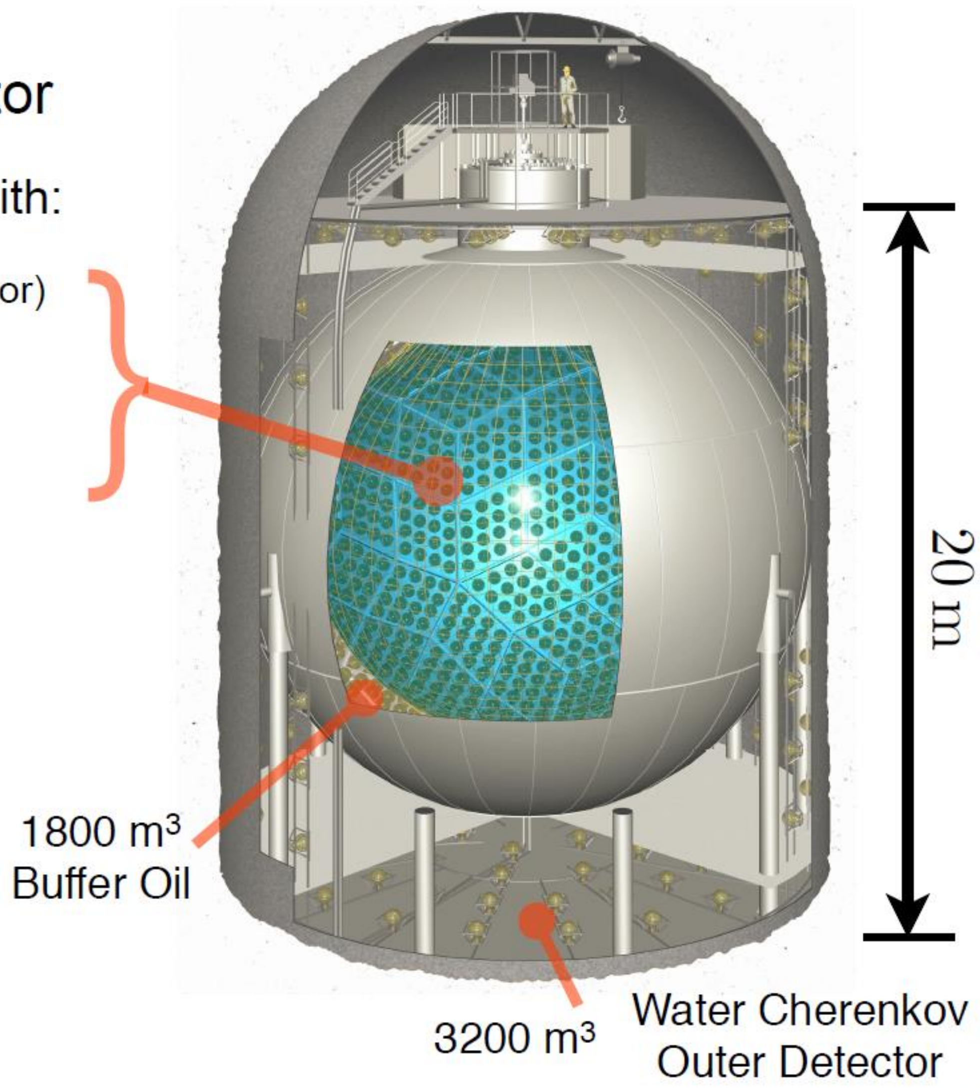
KamLAND(-Zen) detector

- 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



Patrick Decowski/Nikhef

7

KamLAND(-Zen) detector

- 1 kton Scintillation Detector
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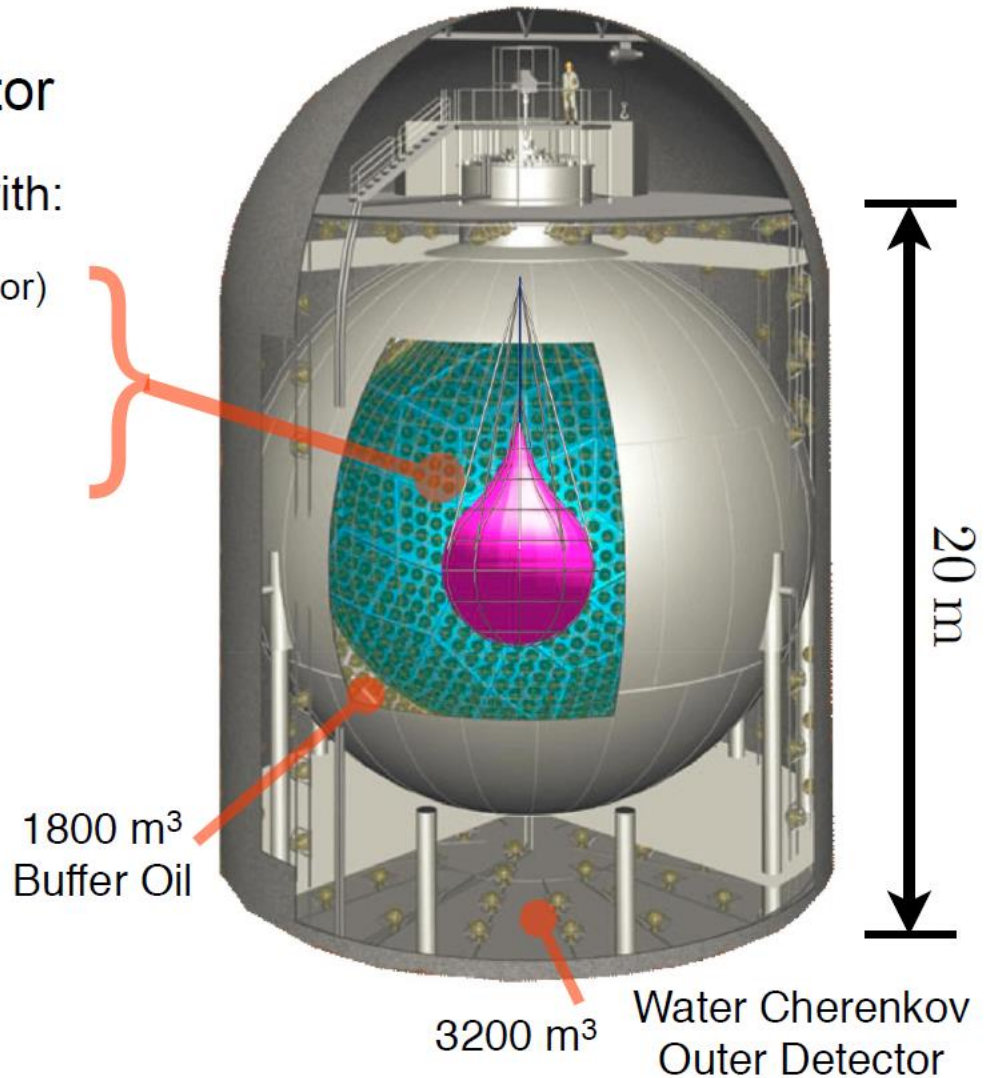

Patrick Decowski/Nikhef

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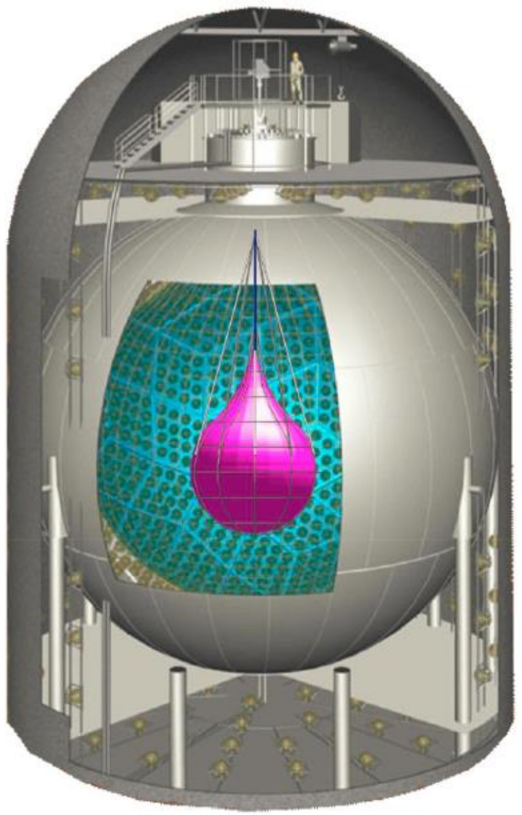
KamLAND-Zen advantages & disadvantages

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

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



Patrick Decowski/Nikhef

KamLAND-Zen Timeline

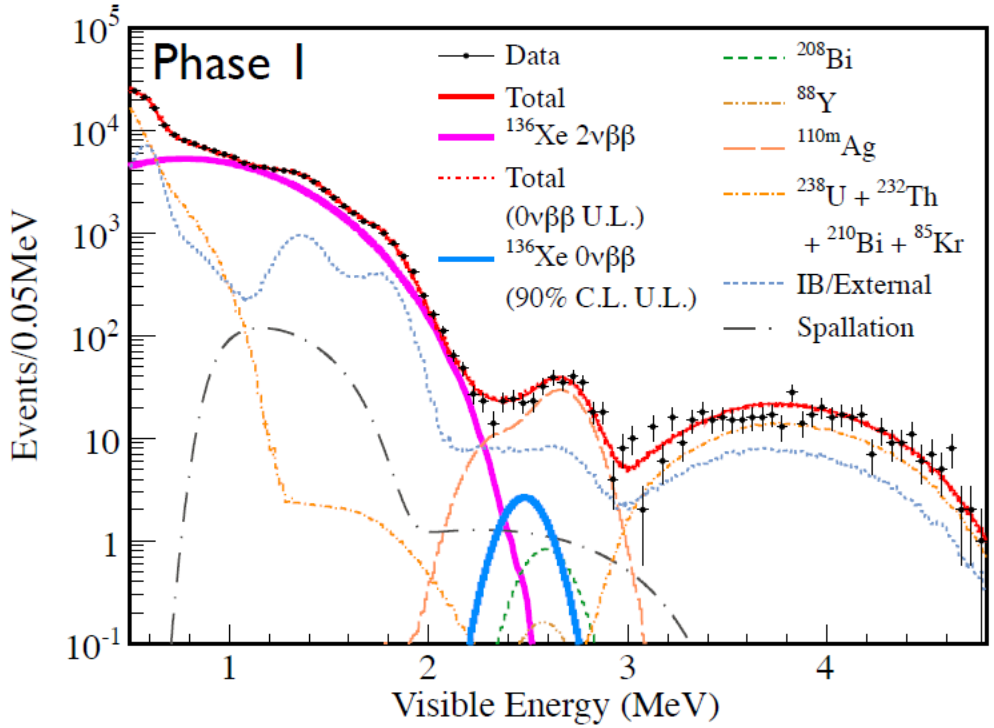
2011	2012	2013	2014	2015

Phase I

Sept '11:Start — 90 kg-yr

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

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



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

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

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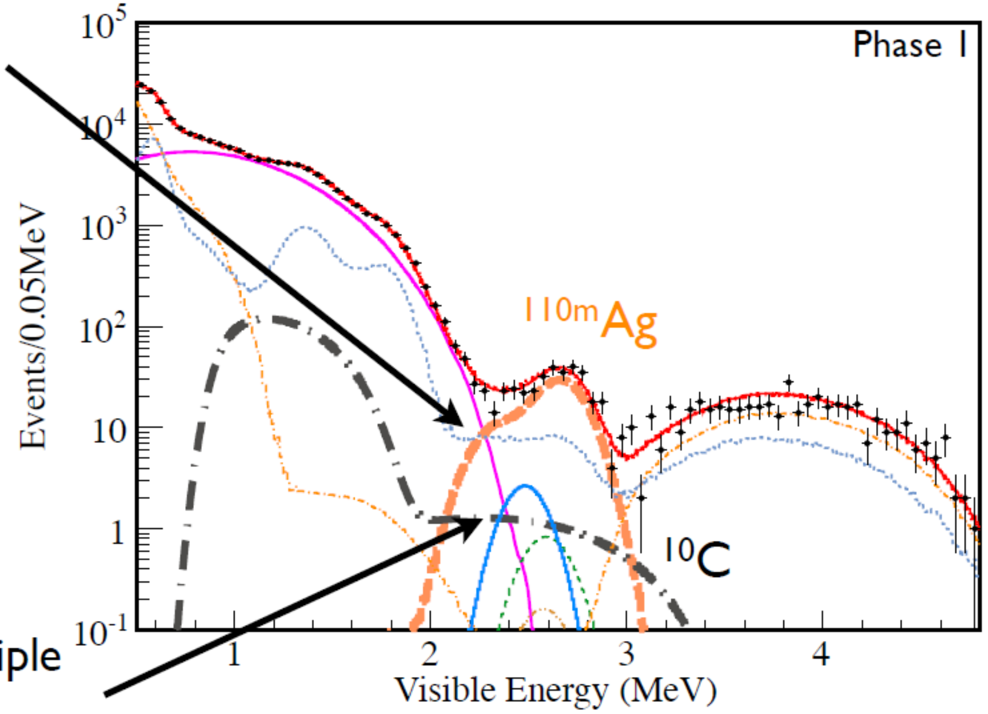
Phase I to Phase II Improvements

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

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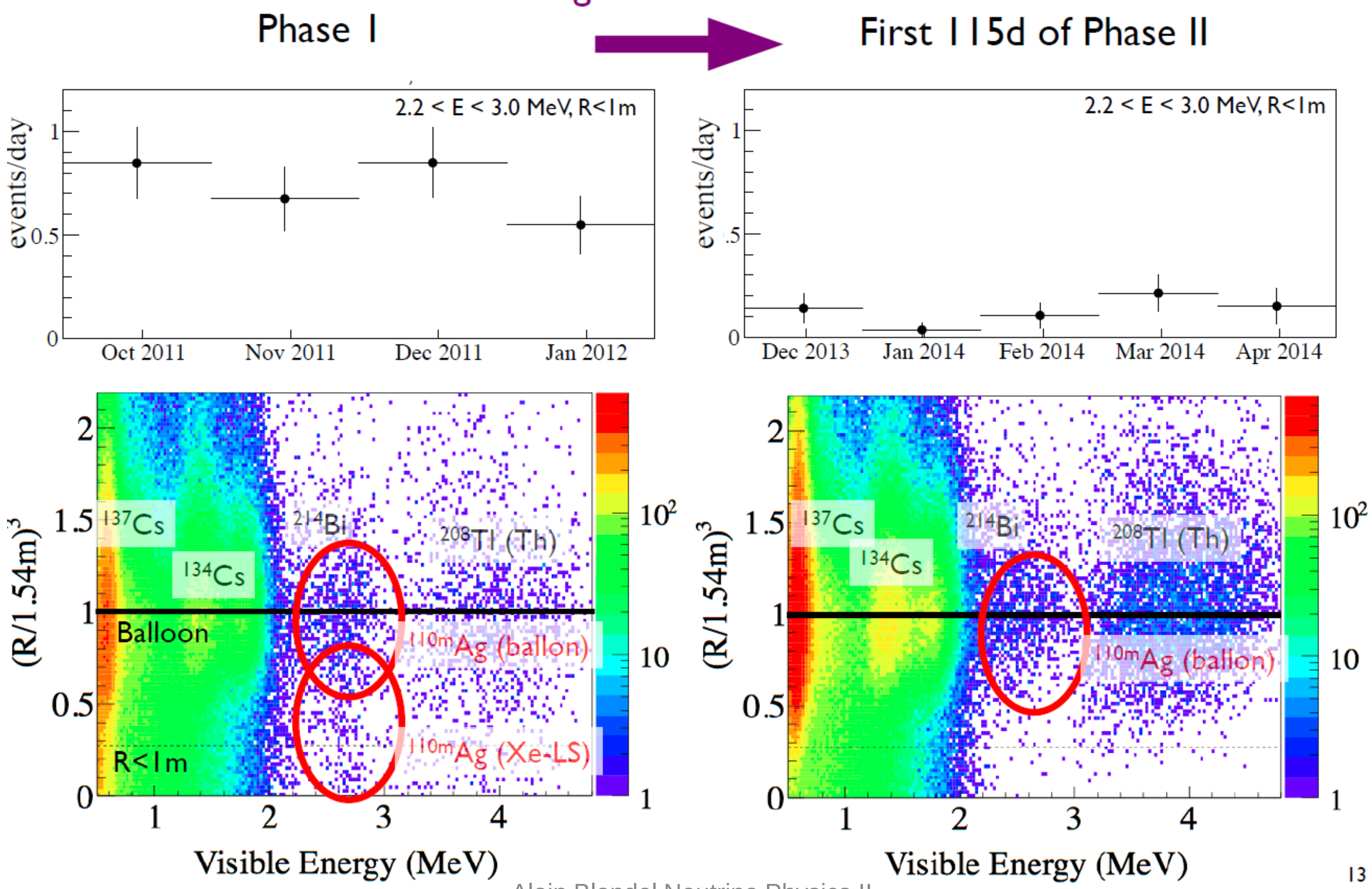
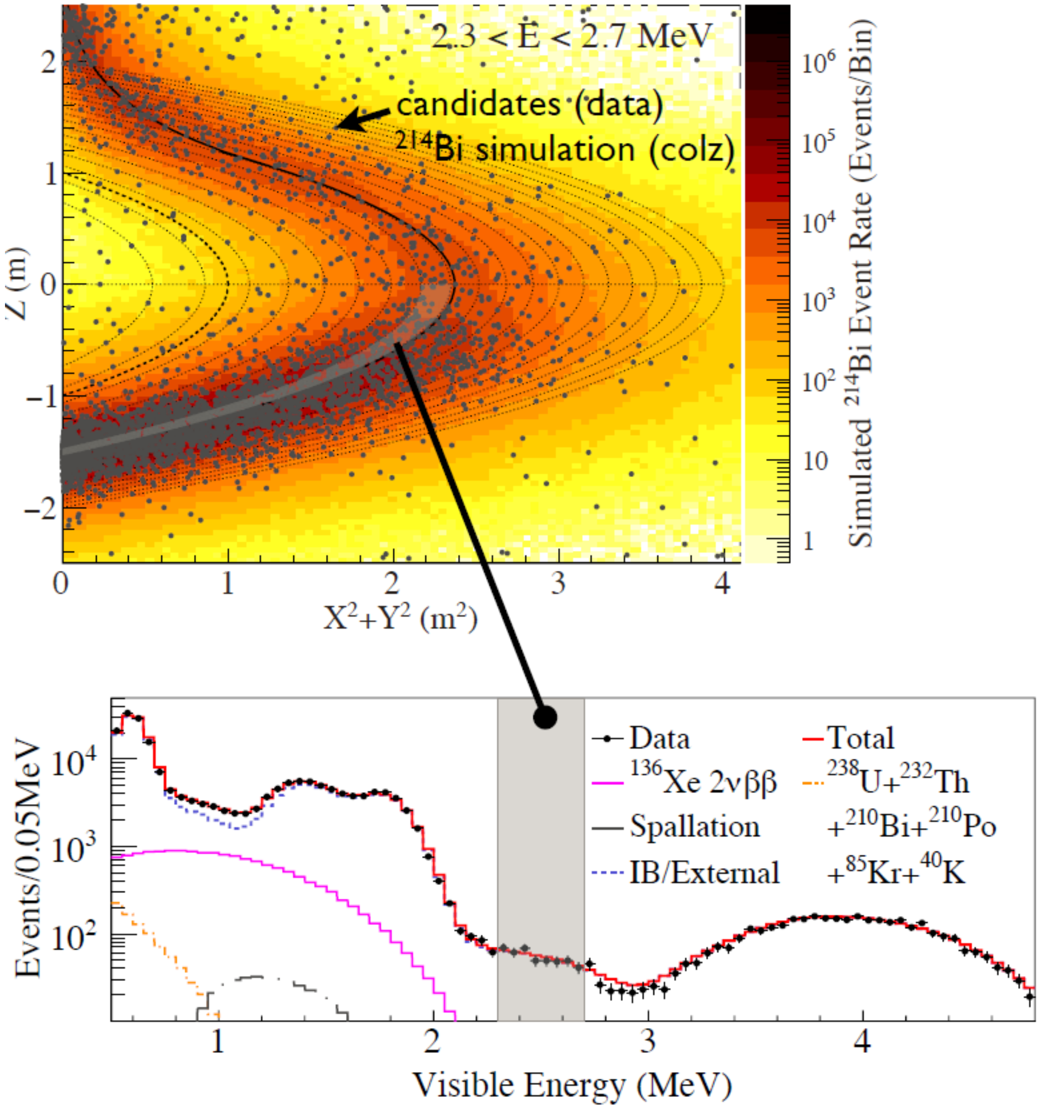
^{110m}Ag Background Reduction

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



KLZ-400 Phase 2 Data



Event Selection:

i) $R < 2m$

ii) $\Delta T > 2ms$ 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

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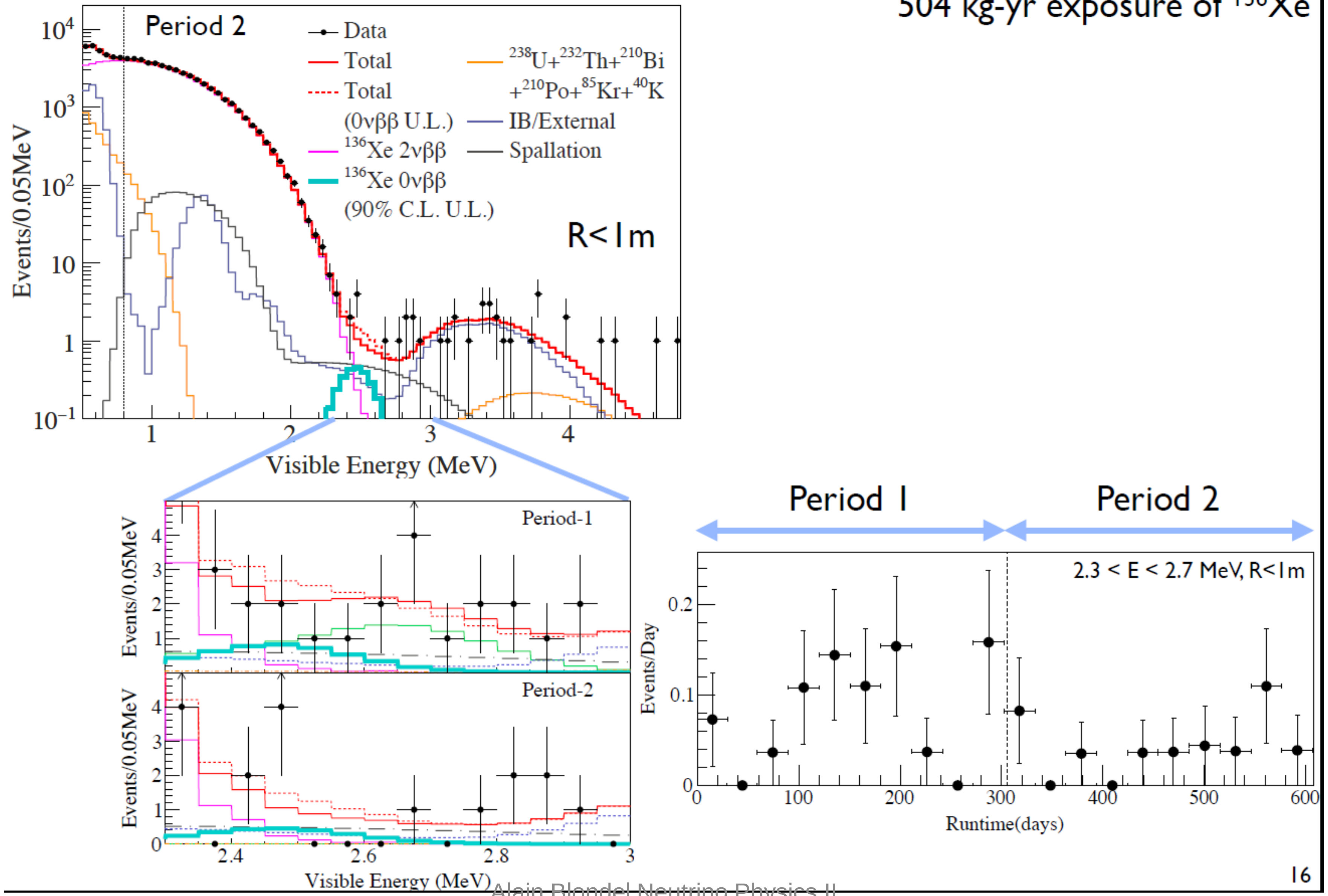
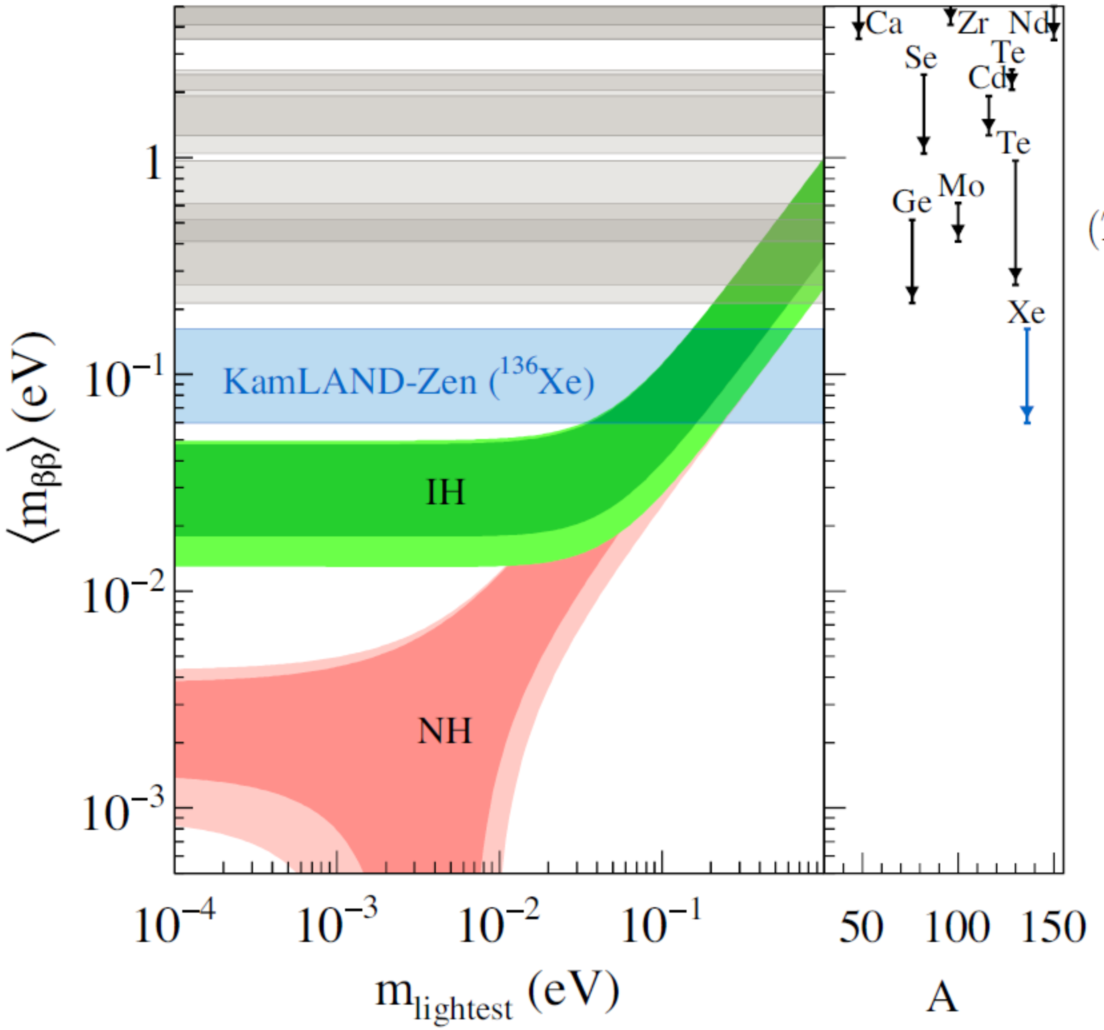
Results for Phase-2

504 kg-yr exposure of ^{136}Xe



Effective Neutrino Mass

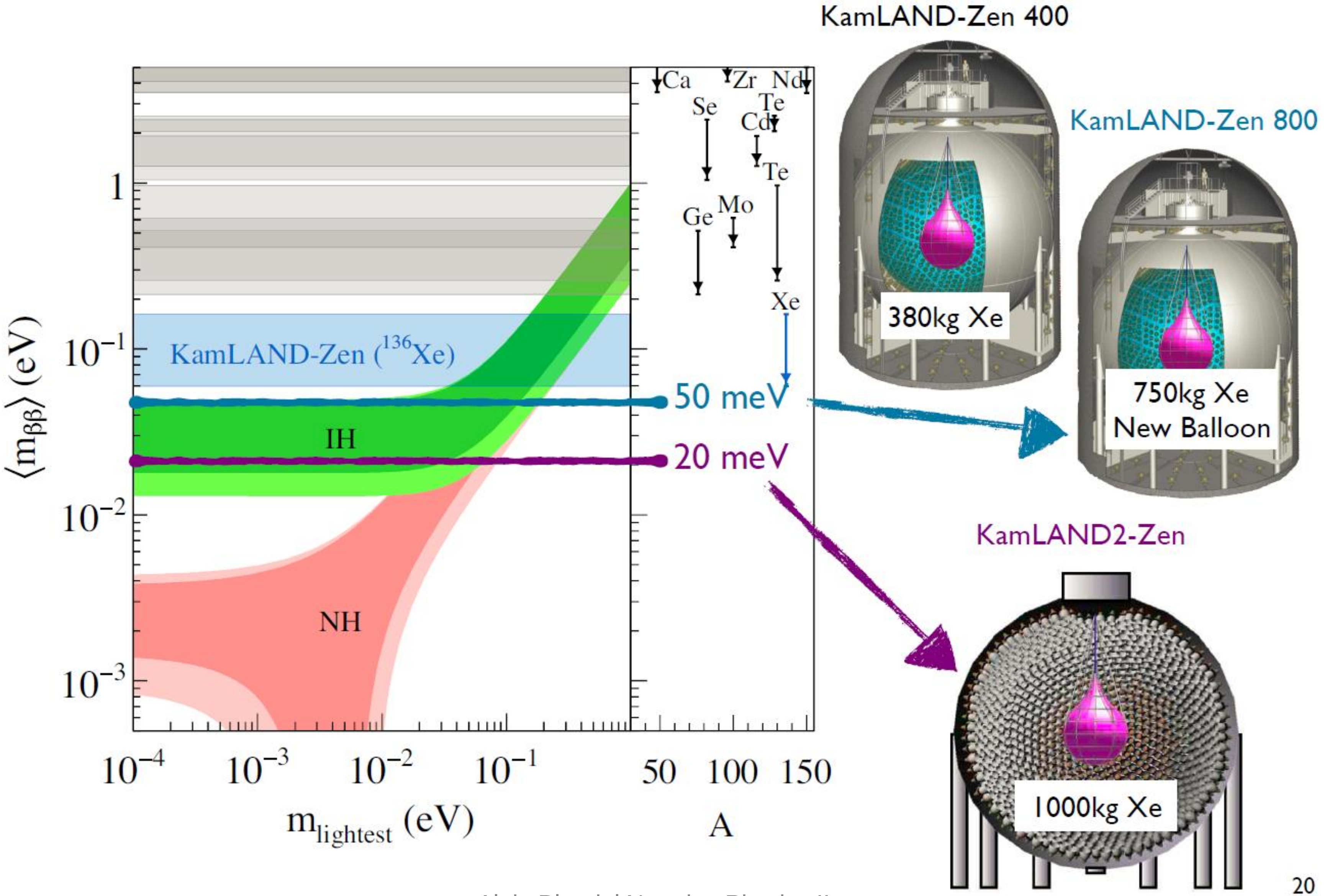


$$(T^{0\nu}_{1/2})^{-1} = G_{0\nu}(Q,Z)|M_{0\nu}|^2\langle m_{\beta\beta}\rangle^2$$

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

KamLAND-Zen Coll, Phys. Rev. Lett. 117, 082503 (2016); arXiv:1605.02889 19

Future Goals



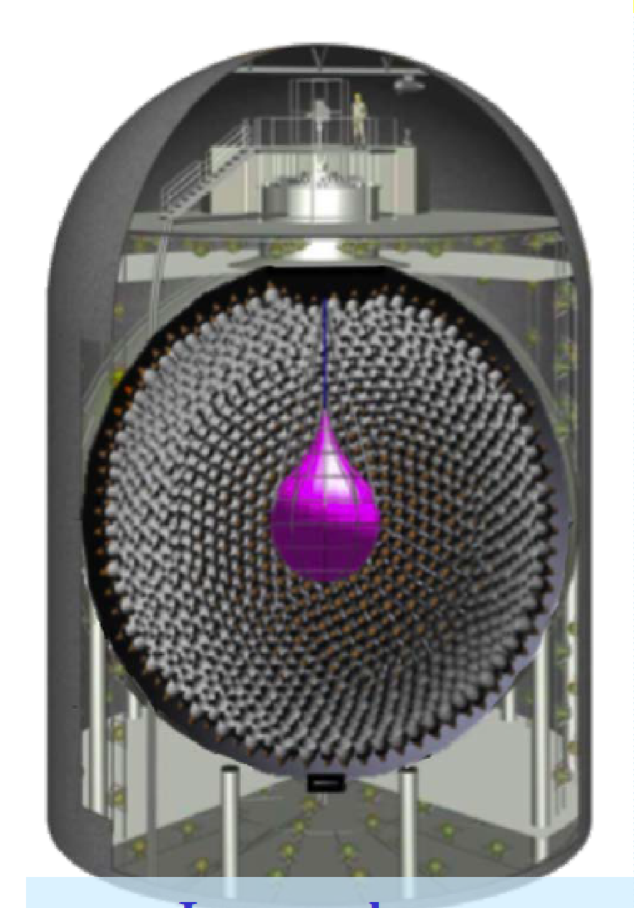
KamLAND-Zen
1 ton-class ^{136}Xe 0νββ experiment reaching IH region

KamLAND-Zen 400 and KamLAND-Zen 800 combined results

Limit: $T^{0\nu}_{1/2} > 2.3 \times 10^{26}$ year (90%C.L.), $m_{\beta\beta} < 36$–156 meV

(g_A=1.27, NME = 1.11-4.77 are assumed)

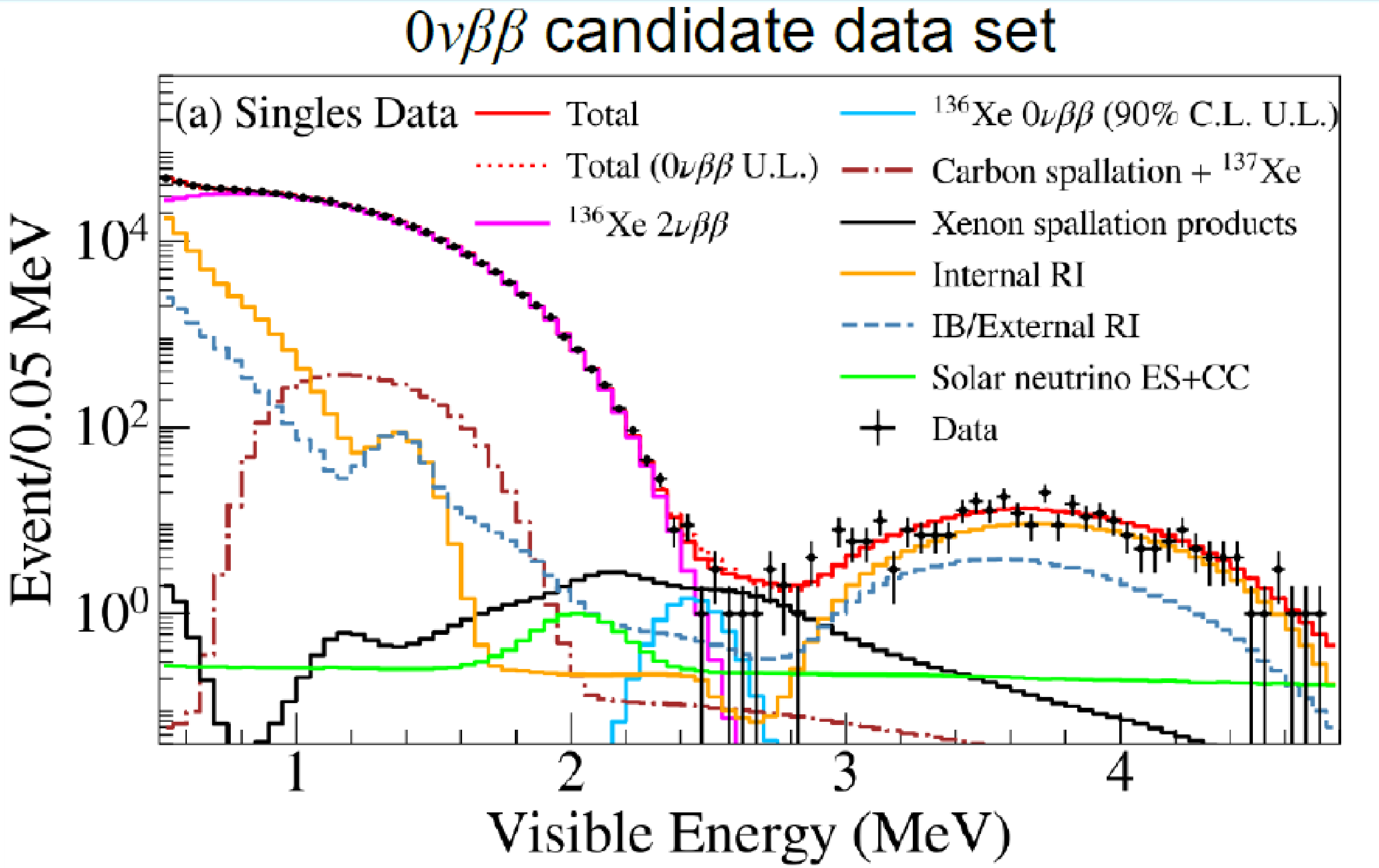
Currently, the most strict 0νββ limit



Large volume liquid scintillator detector

LS: 30.5 m^3, ^{136}Xe: 677 kg

6/3/2022



GERDA motivations

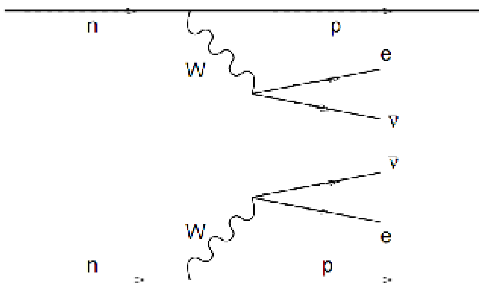
The GERmanium Detector Array experiment is an ultra-low background experiment designed to search for ^{76}Ge $0\nu\beta\beta$ decay.

$2\nu\beta\beta$

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

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

Observed.



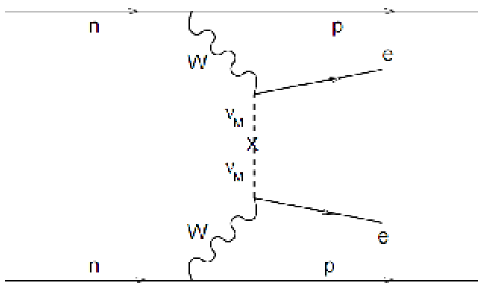
$0\nu\beta\beta$

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

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

Observed?

Light Majorana neutrino exchange



$Q = M_i - M_f - 2m_e$

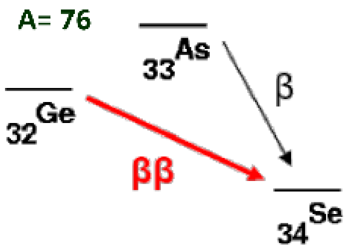
$$(T^{0\nu}_{1/2})^{-1} = G^{0\nu}\,|M^{0\nu}|^2 \frac{m^2_{\beta\beta}}{m^2_e}$$

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

$\equiv$ 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

$T^{0\nu}_{1/2} = 1.19(0.69 - 4.18)$

$\times 10^{25}$ yr (3σ range)

Phys. Lett. B 586, 198 (2004)

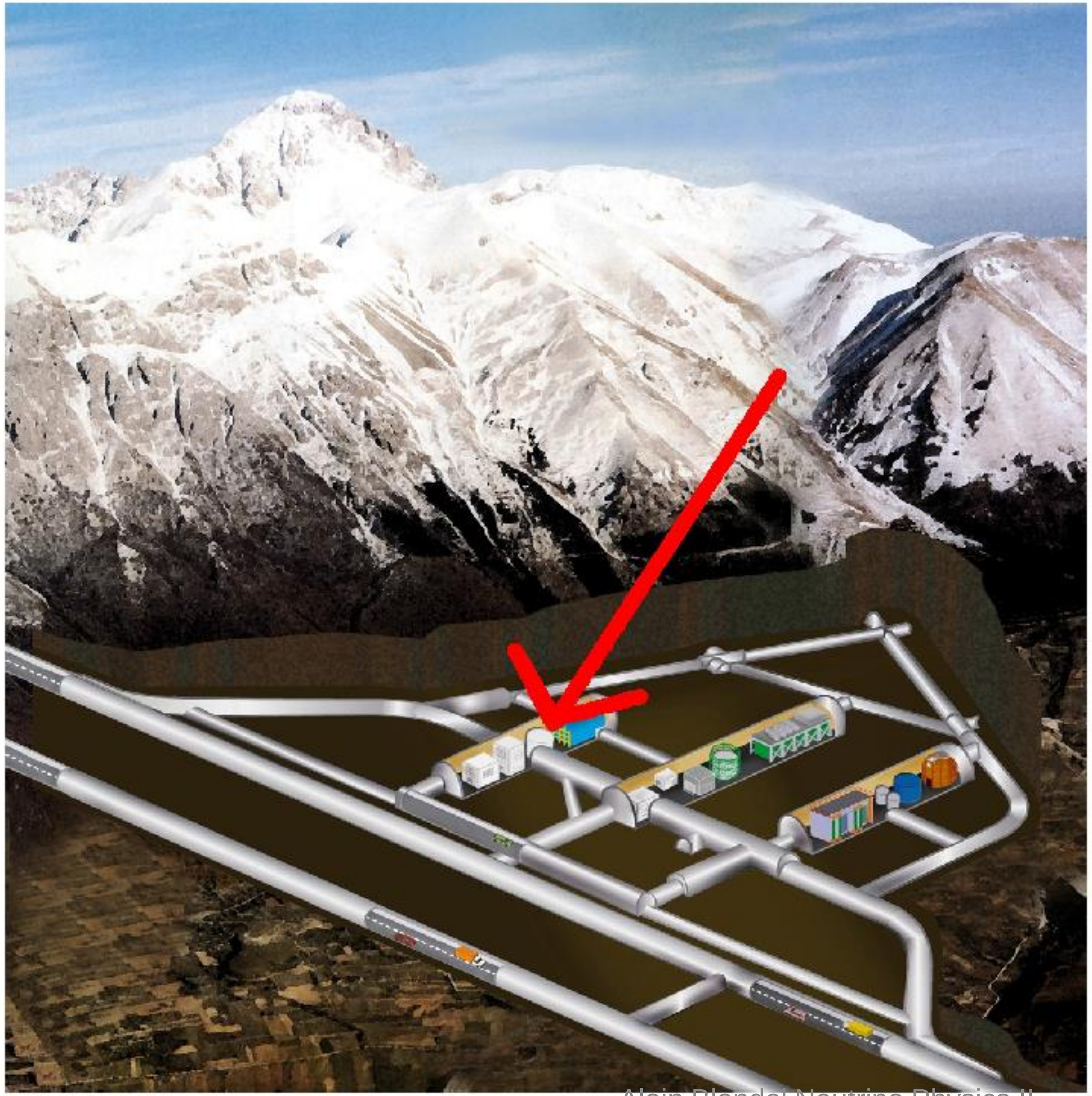
$T^{0\nu}_{1/2} = 2.23^{+0.44}_{-0.31} \times 10^{25}$ yr

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

GERDA first goal:
check the HdM claim

2/20

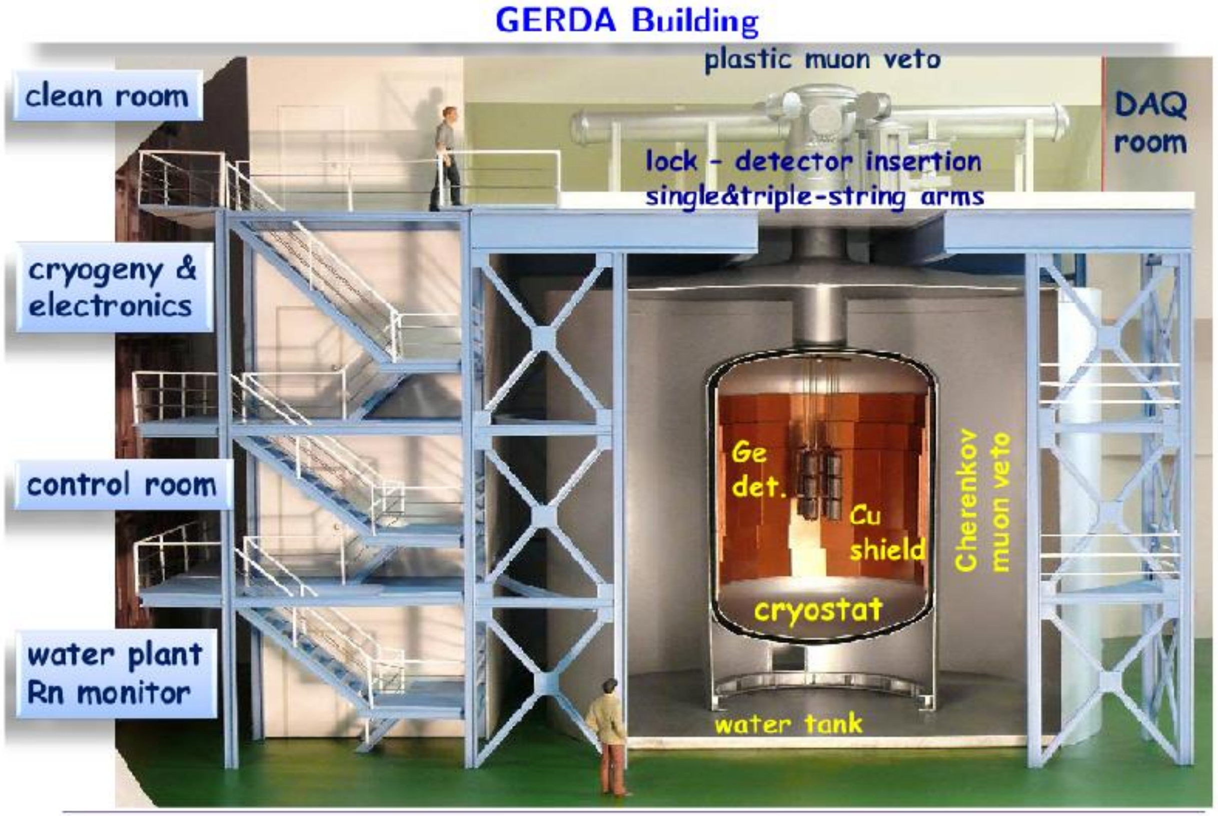
GERDA @ LNGS



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 ~ 64 m^3

T= 88.8 K

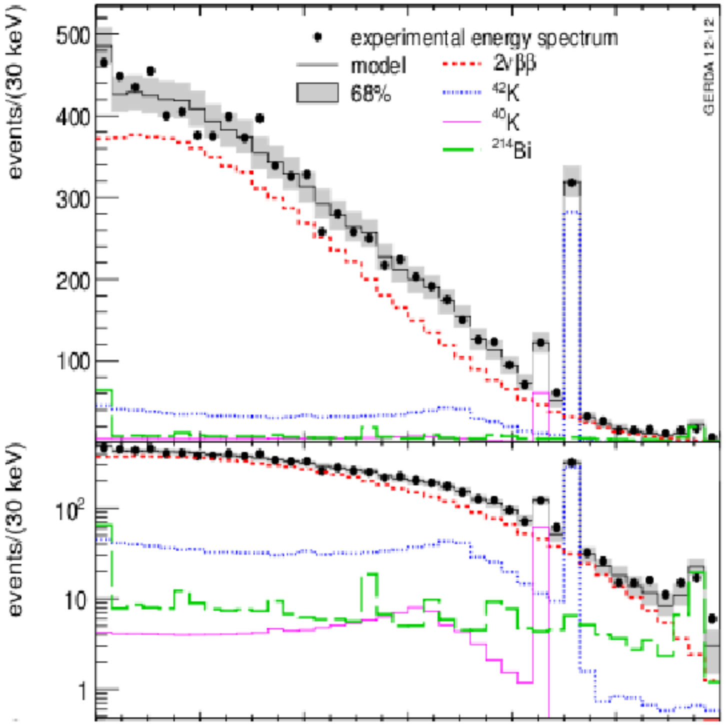
Naked detectors in LAr!

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

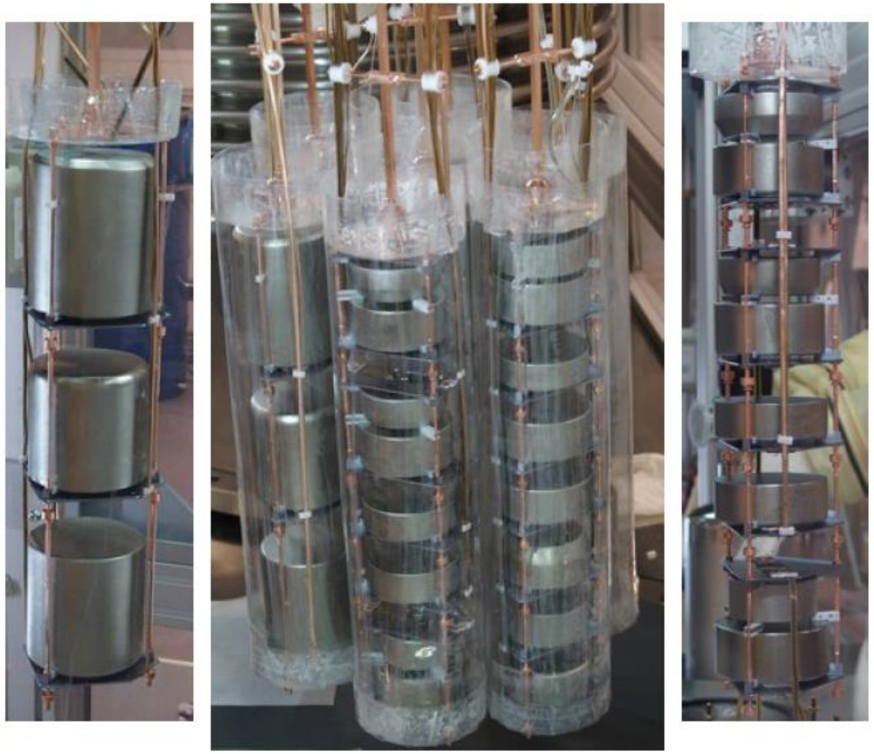
Fit range: 600-1800 keV
Exposure: 5.04 kg·yr

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

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

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

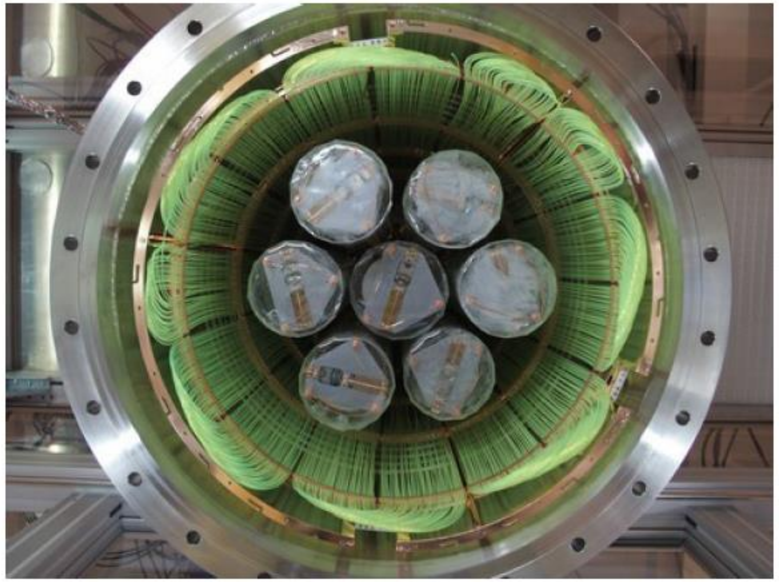
Start of GERDA Phase II



Coaxial layout of detectors

Full Integration of Phase II Array finished in December 2015

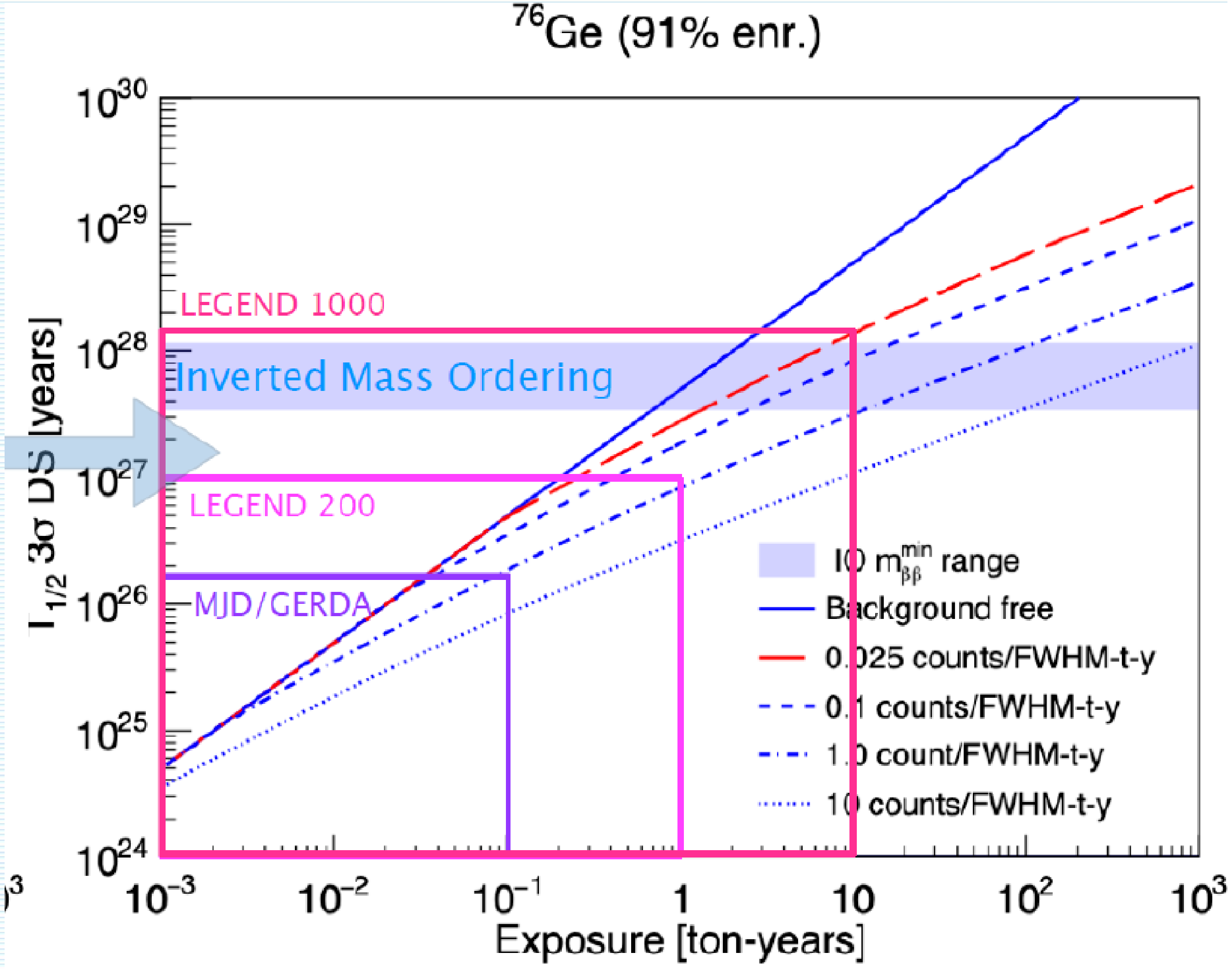
- all Ge and LAr detector channels working



LEGEND
1 ton-class ^{76}Ge $0\nu\beta\beta$ experiment

LEGEND-200

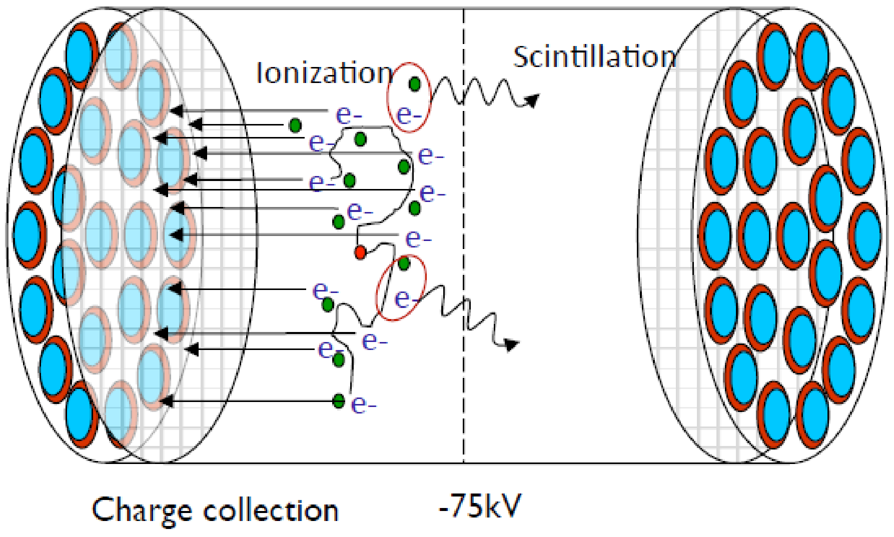
- Builds on the past successes of the MAJORANA DEMONSTRATOR and GERDA
- Low-risk approach to meeting background and sensitivity goals
- LEGEND-200: start data taking in 2022



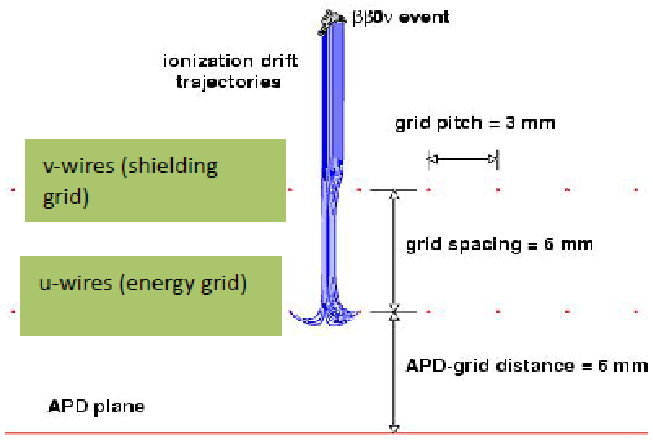
LEGEND-1000 is a next-generation Experiment aiming for unambiguous discovery of $0\nu\beta\beta$ with 10^{28} years of sensitivity targeting 10 years of exposure

- in Conceptual Design phase
- 20x reduction to LEGEND-200 background goal
- Next-generation R&D efforts including Germanium Machine learning in progress

EXO-200 Time Projection Chamber (TPC) Basics



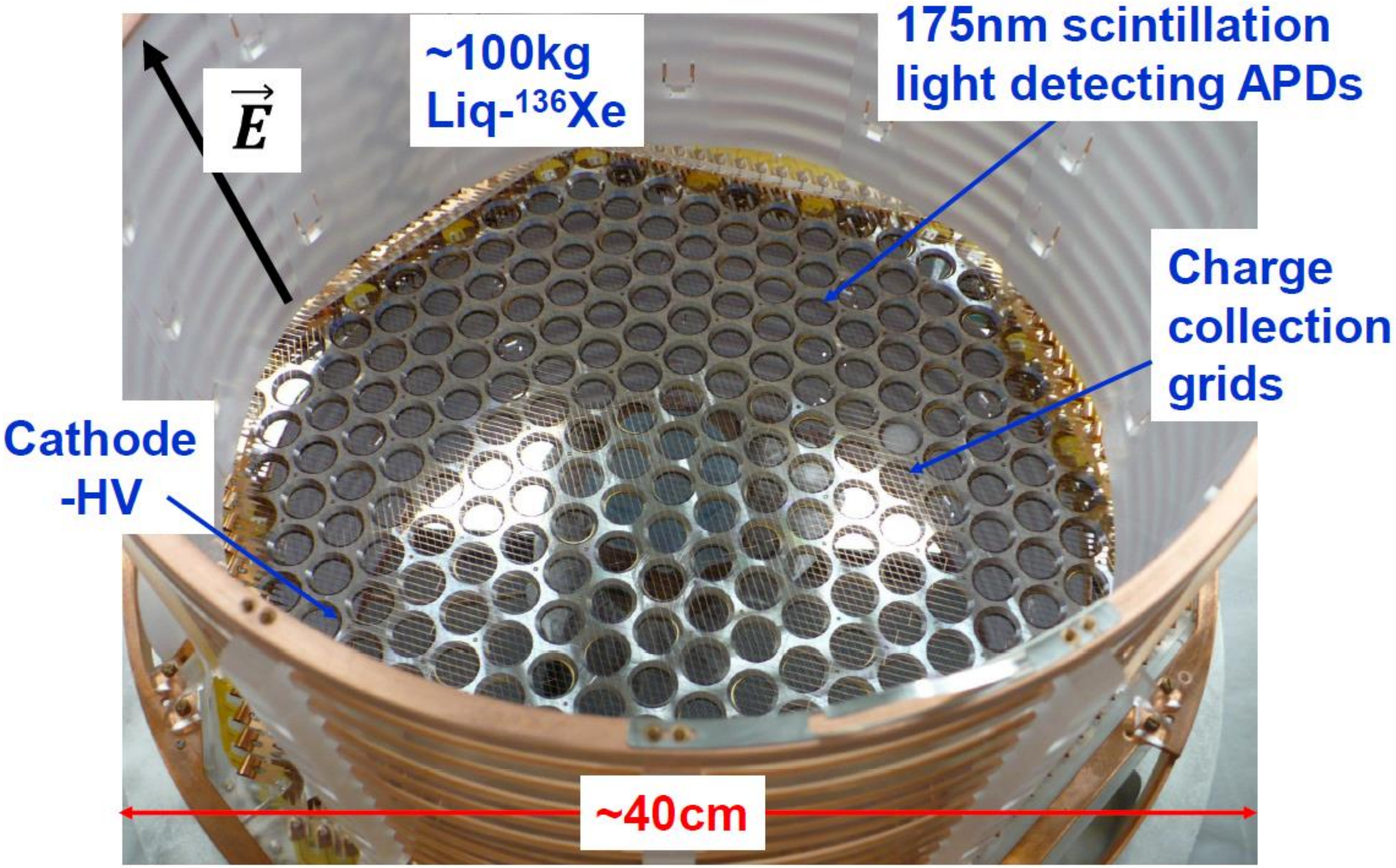
TPC Schematics



Simulation of Charge Drift

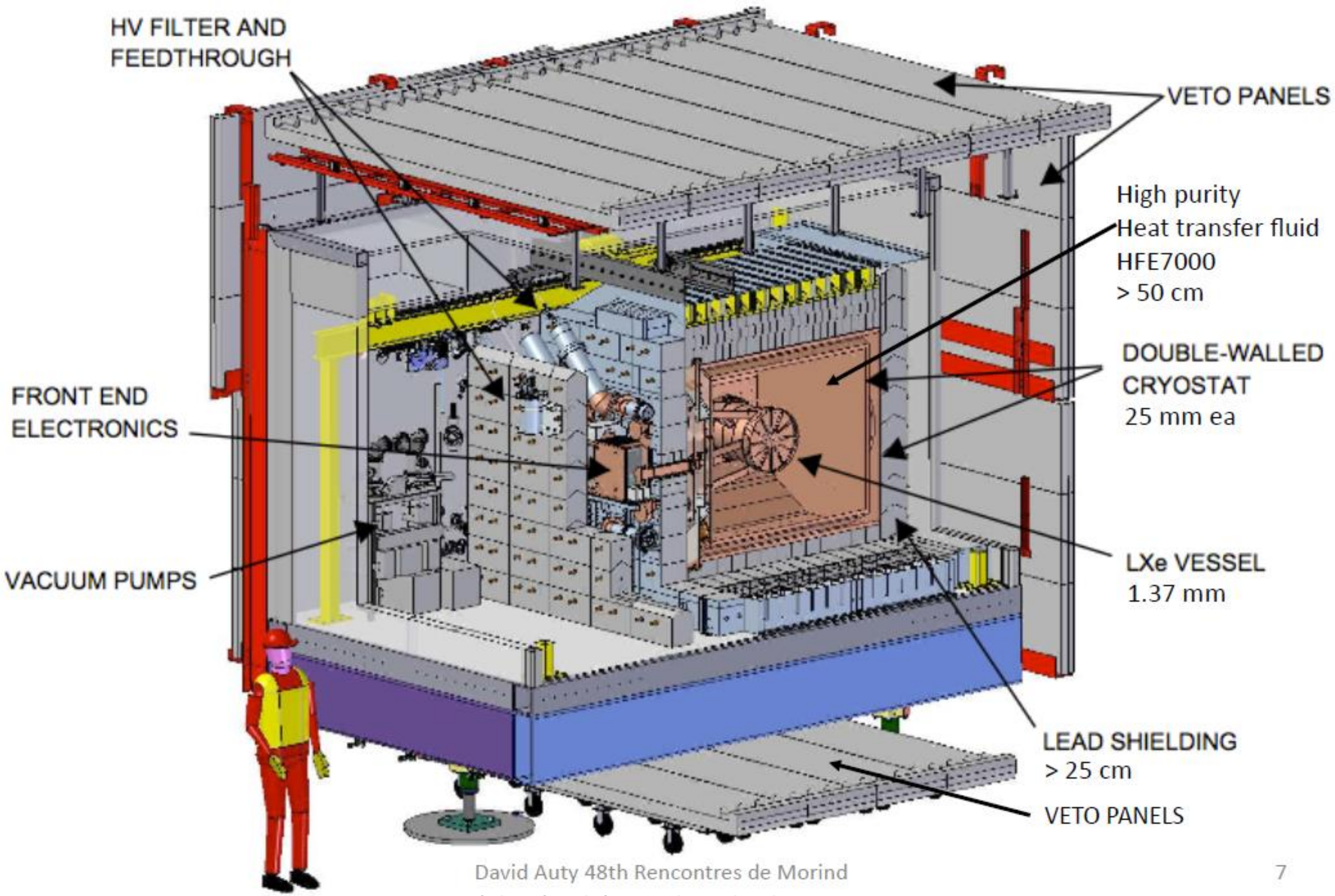
- Two TPC modules with common cathode in the middle.
- APD array observes prompt scintillation for drift time measurement.
    - From which the Z-position can be calculated
- V-position given by induction signal on shielding grid.
- U-position and energy given by charge collection grid.

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



Neutrino 2018, Jun 2018 EXO-200 and nEXO - Gratta 6

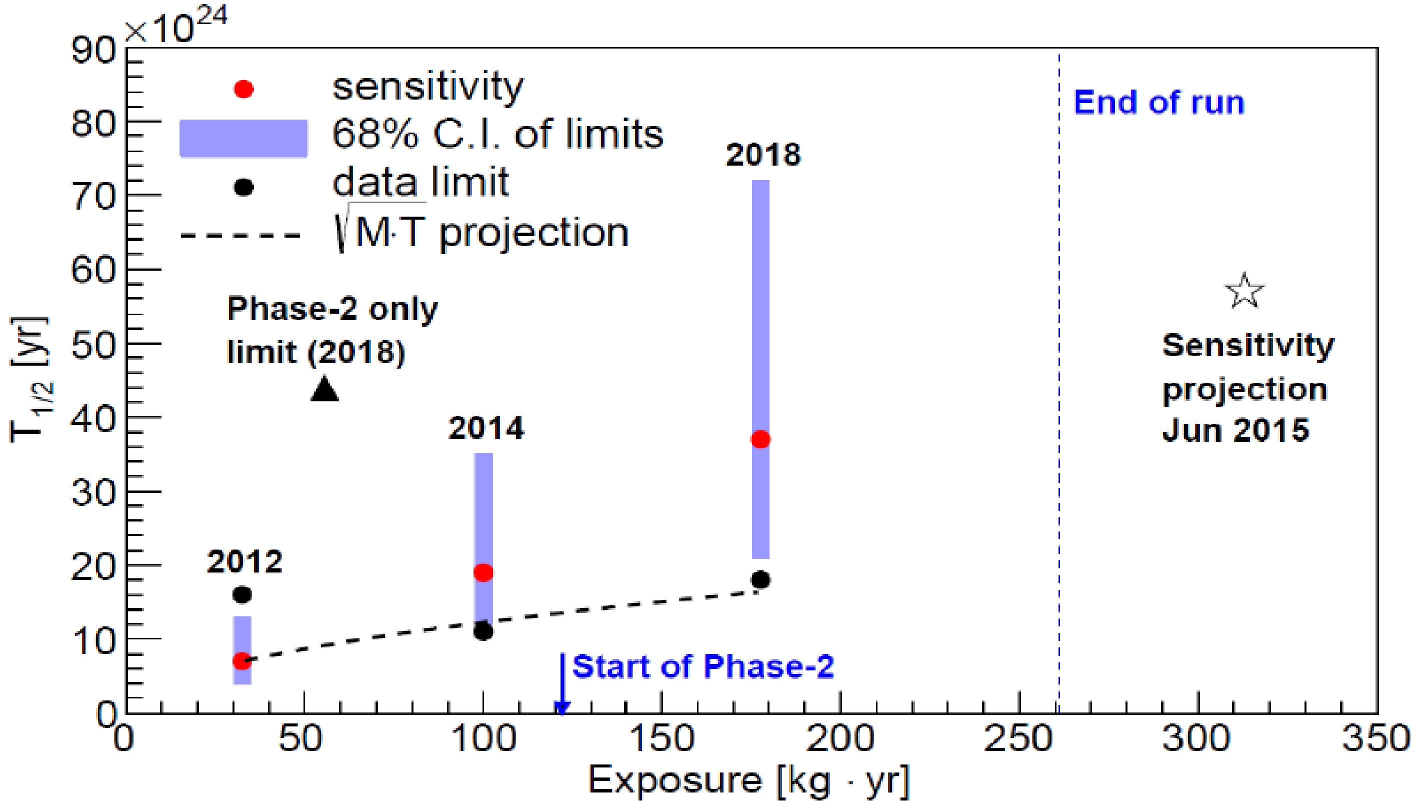
The EXO-200 Detector



David Auty 48th Rencontres de Morind 7

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)

Leading limits in each $0\nu\beta\beta$ isotope

A monoenergetic peak at the Q-value is searched for.
Need a large amount of decay isotope and low radioactive environment

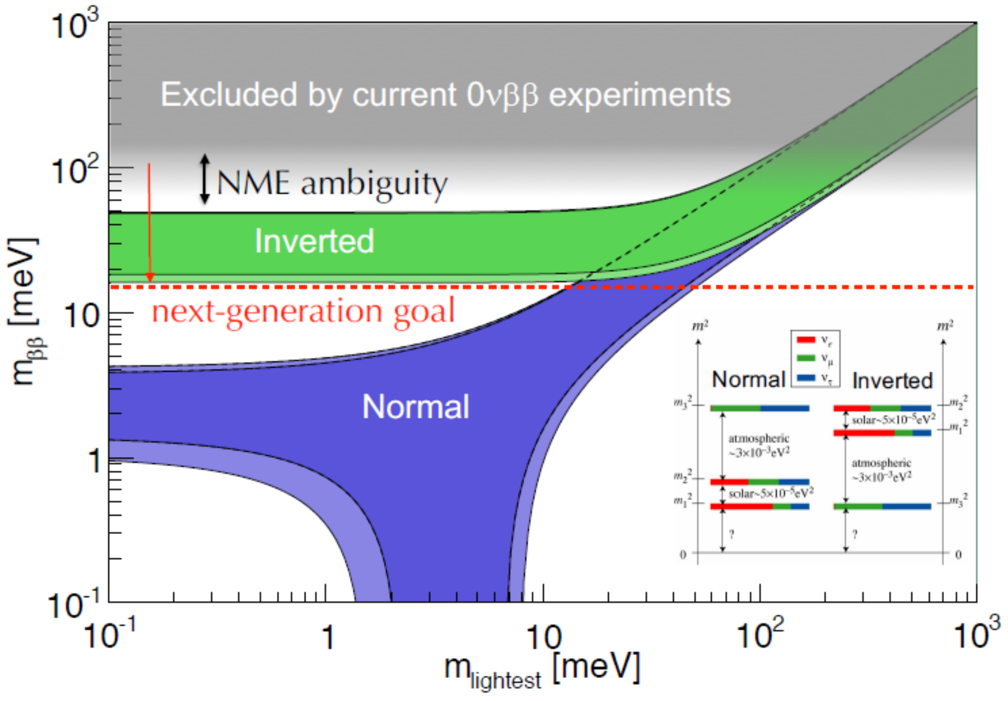
Experiment	Isotope	Exposure [kg yr]	$T^{0\nu}_{1/2}[10^{25}$ yr]	$m_{\beta\beta}$ [meV]
Gerda	^{76}Ge	127.2	18	79-180
Majorana	^{76}Ge	26	2.7	200-433
CUPID-0	^{82}Se	5.29	0.47	276-570
NEMO3	^{100}Mo	34.3	0.15	620-1000
CUPID-Mo	^{100}Mo	2.71	0.18	280-490
Amore	^{100}Mo	111	0.095	1200-2100
CUORE	^{130}Te	1038.4	2.2	90-305
EXO-200	^{136}Xe	234.1	3.5	93-286
KamLAND-Zen	^{136}Xe	970	23	36-156

10

Current Limits and Future Goals

- Present best limits:
  - ^{136}Xe (KamLAND-Zen): $T_{1/2} > 10^{26}$ yrs
  - ^{76}Ge (GERDA): $T_{1/2} > 10^{26}$ yrs
  - ^{130}Te (CUORE): $T_{1/2} > 3\text{x}10^{25}$ yrs
- Future goal:
  ~2 OoM improvement in $T_{1/2}$
  - Covers IO
  - Up to 50% of NO
  - Factor of ~few in Λ
  - An aggressive experimental goal

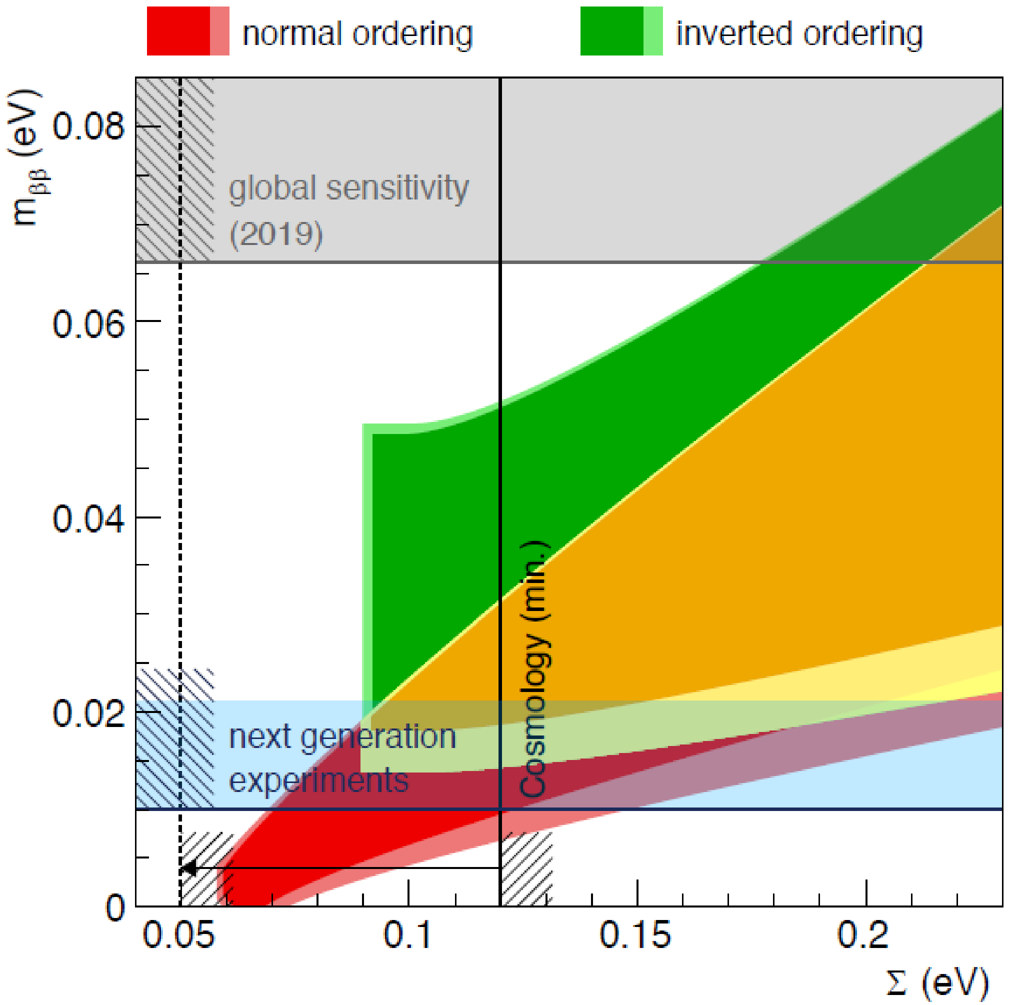
$$\frac{1}{T_{1/2}} = G_{01}\, g_A^4 \left(M^{0\nu} + \frac{g_\nu^{\mathrm{NN}}\, m_\pi^2}{g_A^2} M_{\mathrm{cont}}^{0\nu} \right)^2 \frac{m_{\beta\beta}^2}{m_e^2}$$



J. Detwiler 4

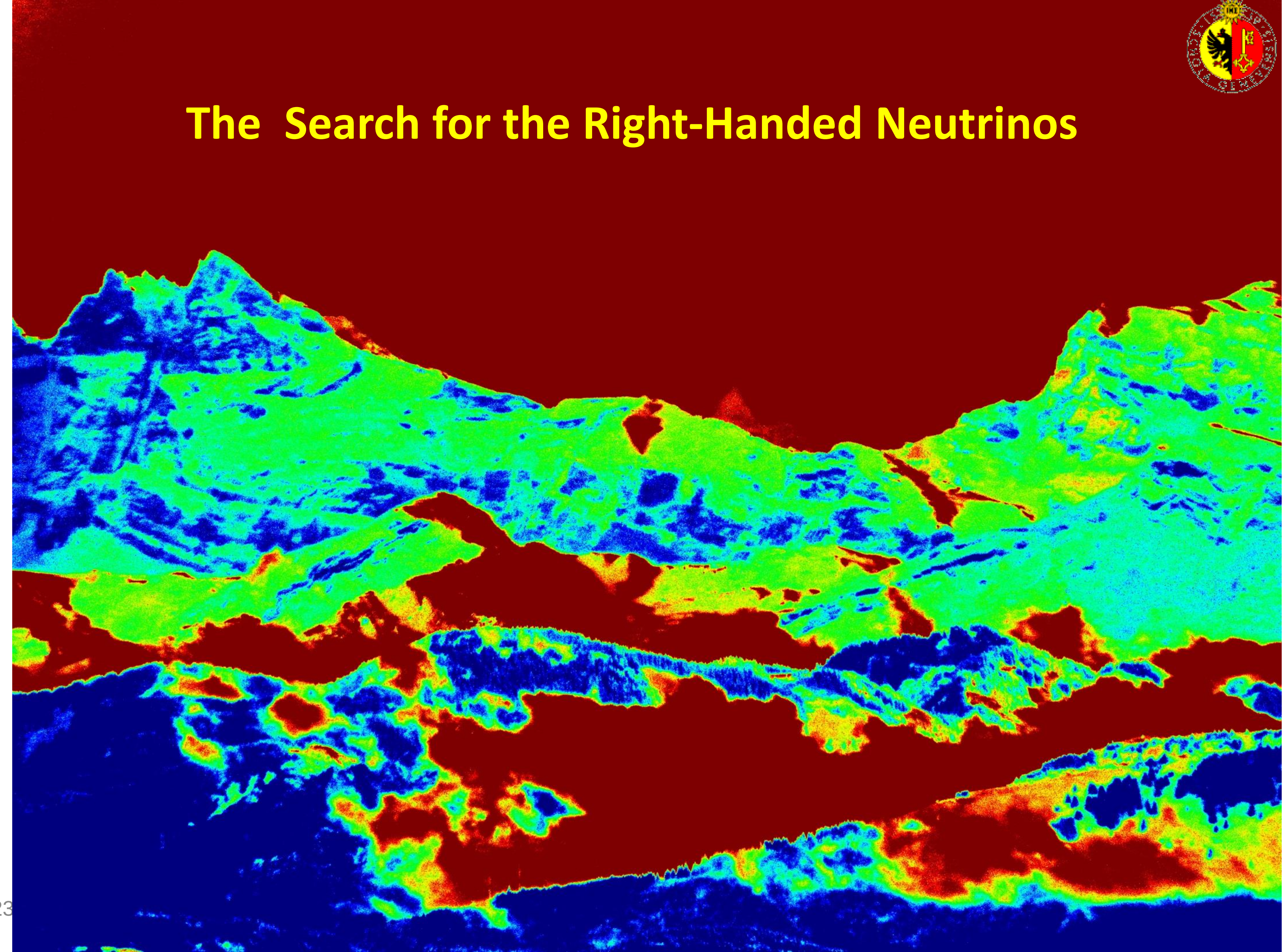
Summary & Outlook

- Major progress for preparation of **ton-scale** experiments over last two years
- Experiment design for **discovery** (not limit setting)
- Will fully explore **IO** and large part of **NO**
- Several DBD isotopes and techniques required, given **NME uncertainties**
- Formidable **experimental challenges** to acquire ton yr exposure quasi **background free – or compensate with huge mass (Te)**
- North-American – European **convergence on portfolio** of experiments contingent on funding: current front-runners are LEGEND-1000, nEXO and CUPID; breakthrough R&D on Ba-tagging
- Asia: KL2Z, Amore, PandaX, JUNO
- **Availability of DBD isotopes** from Western supplier
- How to go to **bottom of NO**? Assess **performance** of ton-scale experiments first. All have the potential to **increase exposure** and reduce further **backgrounds**



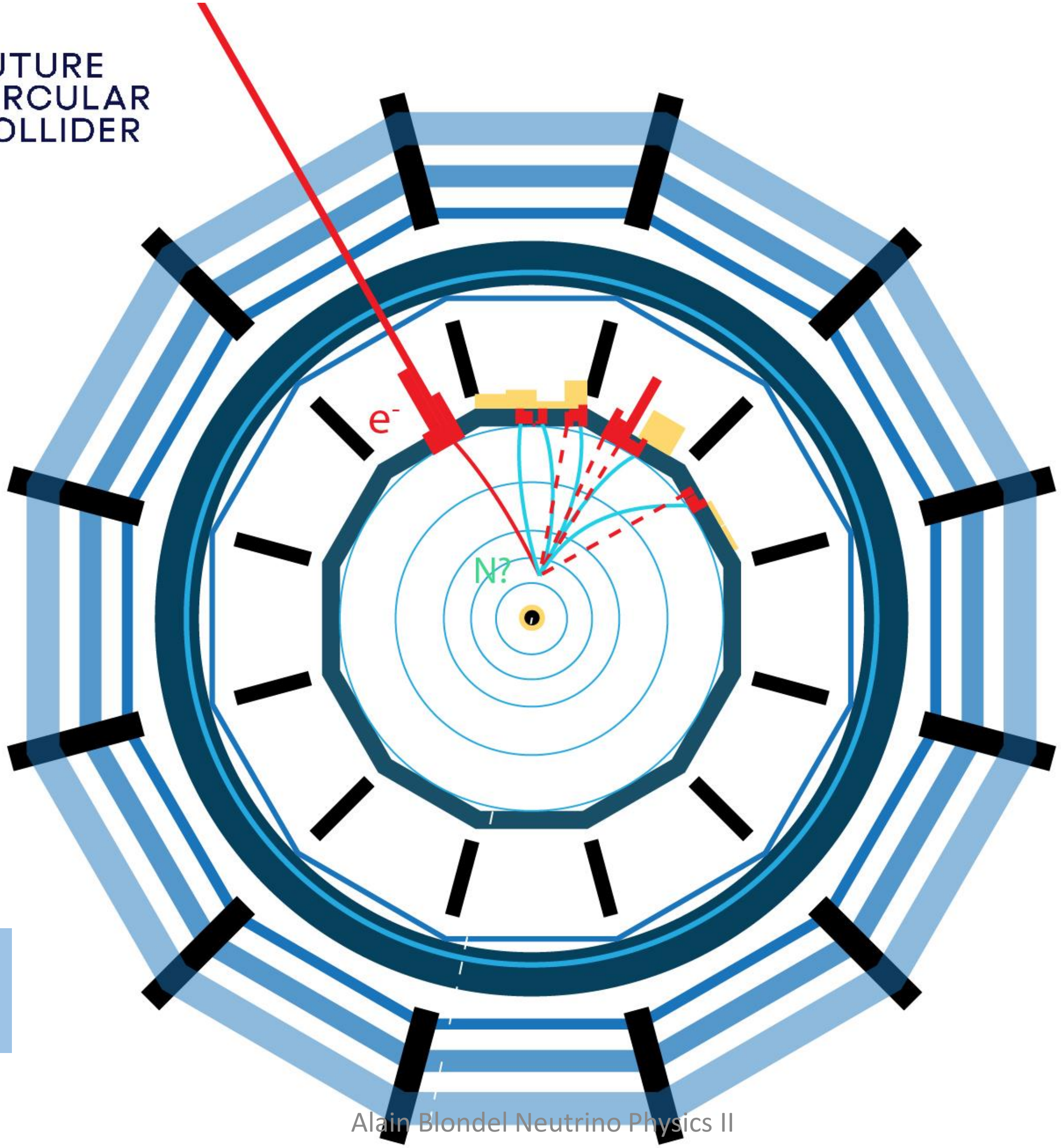
Stephan Schoenert, Neutrino 2022

The Search for the Right-Handed Neutrinos



Heavy Neutral Leptons and Fermion number violation

FUTURE CIRCULAR COLLIDER



courtesy
Panos Charitos

Fermion number conservation

fermion number violation is the first Sakharov condition for the
Baryon Asymmetry of the Universe
Baryogenesis or Leptogenesis + sphalerons
Also requires
-- CP violation and
-- out of equilibrium universe (Big Bang OK

Is *not* in itself a law or a symmetry of the Standard Model

For charged fermions (e/mu/tau and the quarks) it is not possible to transform a
because of charge conservation

For neutrinos, which are neutral, the SM assumes they are massless.
neutrino is left-handed (identical if massless to negative helicity)
and the antineutrino has positive helicity
neutrino <-> antineutrino transition is forbidden by **angular momentum conservation**

This results in practice in <u>apparent conservation of fermion number</u>

The existence of massive neutrinos allows for spin flip and thus in principle a neutrino-antineutrino transition.
since a left handed field has a component of the opposite helicity (and vice versa)
$\nu_L \approx \nu_- + \nu_+ \, m/E$ (mass is what allows to flip the helicity)

for very small mass and light neutrinos this is very, very small: for m=50meV and P =30 MeV ➔ $(m/E)^2 = 10^{-18}$

This can be observed in neutrino less double beta decay or by searching directly for the right-handed neutrinos!

Motivation and Communication

A matter of name:

Sterile neutrinos ``ν_4" (and *NO* it is *not* a fourth family of neutrino!)
Heavy Neutral Leptons
Right-Handed Neutrinos
Heavy Majorana neutrinos

are all the same!

Generically we are talking of the new degree of freedom that arises for each family of light neutrinos that is massive.
Massive neutrino → two helicity states, which can be projected on
Electroweak Left-handed ($\nu_L = \nu_- + m/E\ \nu_+$) and Right-Handed ($\nu_R = \nu_+ + m/E\ \nu_-$) states.

At least two are needed to account for observed three family neutrino oscillations, three more 'natural'

Most models of neutrino mass generation, and certainly the simplest and most natural ones,
involve right-handed neutrinos

Of course it is possible to generate heavy neutral leptons in different, ad-hoc ways.

Recent heavy neutrino analyses at the LHC

- Probing heavy Majorana neutrinos & Weinberg operator via $pp \to \mu^{\pm}\mu^{\pm}jj$
  - EXO-21-003
- Search for type-III seesaw heavy leptons
  - arXiv:2202.02039 ATLAS EXPERIMENT, arXiv:2202.08676
- Heavy Composite Majorana Neutrino
  - EXO-20-011
- Left-Right Symmetry model
  - JHEP 04 (2022) 047, EXO-20-006
- Long-lived heavy neutral leptons with displaced vertices
  - arXiv:2204.11988 ATLAS EXPERIMENT, arXiv:2201.05578

Heavy Neutral Leptons -- recent litterature

The Present and Future Status of Heavy Neutral Leptons

Asli M. Abdullahi, Pablo Barham Alzas, Brian Batell, Alexey Boyarsky, Saneli Carbajal, Animesh Chatterjee, Jose I. Crespo-Anadon, Frank F. Deppisch, Albert De Roeck, Marco Drewes, Alberto Martin Gago, Rebeca Gonzalez Suarez, Evgueni Goudzovski, Athanasios Hatzikoutelis, Marco Hufnagel, Philip Ilten, Alexander Izmaylov, Kevin J. Kelly, Juraj Klaric, Joachim Kopp, Suchita Kulkarni, Mathieu Lamoureux, Gaia Lanfranchi, Jacobo Lopez-Pavon, Oleksii Mikulenko, Michael Mooney, Miha Nemevsek, Maksym Ovchynnikov, Silvia Pascoli, Ryan Plestid, Mohamed Rashad Darwish, Federico Leo Redi, Oleg Ruchayskiy, Richard Ruiz, Mikhail Shaposhnikov, Ian M. Shoemaker, Robert Shrock, Alex Sousa, Nick Van Remortel, Vsevolod Syvolap, Volodymyr Takhistov, Jean-Loup Tastet, Inar Timiryasov, Aaron C. Vincent, Jaehoon Yu

The existence of non-zero neutrino masses points to the likely existence of multiple SM neutral fermions. When such states are heavy enough that they cannot be produced in oscillations, they are referred to as Heavy Neutral Leptons (HNLs). In this white paper we discuss the present experimental status of HNLs including colliders, beta decay, accelerators, as well as astrophysical and cosmological impacts. We discuss the importance of continuing to search for HNLs, and its potential impact on our understanding on key fundamental questions, and additionally we outline the future prospects for next-generation future experiments or upcoming accelerator run scenarios.

Comments: 82 pages, 34 figures. Contribution to Snowmass 2021
Subjects: **High Energy Physics - Phenomenology (hep-ph)**; High Energy Physics - E
Cite as: arXiv:2203.08039 **[hep-ph]**
(or arXiv:2203.08039v1 **[hep-ph]** for this version)
https://doi.org/10.48550/arXiv.2203.08039

High Energy Physics - Experiment

[Submitted on 10 Mar 2022 (v1), last revised 11 Mar 2022 (this version, v2)]

Searches for Long-Lived Particles at the Future FCC-ee

J. Alimena, P. Azzi, M. Bauer, A. Blondel, M. Drewes, R. Gonzalez Suarez, J. Klaric, S. Kulkarni, M. Neubert, C. Rizzi, R. Ruiz, L. Rygaard, A. Sfyrla, T. Sharma, A. Thamm, C. B. Verhaaren

The electron-positron stage of the Future Circular Collider, FCC-ee, is a frontier factory for Higgs, top, electroweak, and flavour physics. It is designed to operate in a 100 km circular tunnel built at CERN, and will serve as the first step towards $\geq$ 100 TeV proton-proton collisions. In addition to an essential and unique Higgs program, it offers powerful opportunities to discover direct or indirect evidence of physics beyond the Standard Model.
Direct searches for long-lived particles at FCC-ee could be particularly fertile in the high-luminosity Z run, where 5×10^{12} Z bosons are anticipated to be produced for the configuration with two interaction points. The high statistics of Higgs bosons, W bosons and top quarks in very clean experimental conditions could offer additional opportunities at other collision energies. Three physics cases producing long-lived signatures at FCC-ee are highlighted and studied in this paper: heavy neutral leptons (HNLs), axion-like particles (ALPs), and exotic decays of the Higgs boson. These searches motivate out-of-the-box optimization of experimental conditions and analysis techniques, that could lead to improvements in other physics searches.

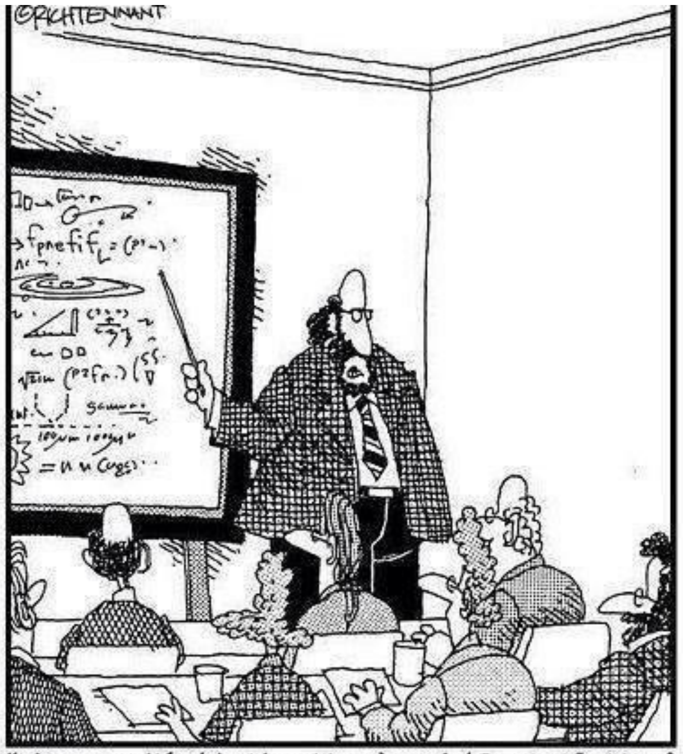
Comments: Contribution to Snowmass 2021
Subjects: **High Energy Physics - Experiment (hep-ex)**; High Energy Physics - Phenomenology (hep-ph); High Energy Physics - Theory (hep-th)
Cite as: arXiv:2203.05502 **[hep-ex]**
(or arXiv:2203.05502v2 **[hep-ex]** for this version)
https://doi.org/10.48550/arXiv.2203.05502

777 references!

my SM training in 1976

Electroweak eigenstates

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

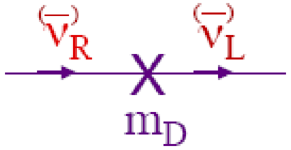
can't produce them
can't detect them
-- so why bother? –
Also called 'sterile'

NB unlike for ν_L, nothing distinguishes the particle and antiparticle of ν_R which is a singlet (no 'charge')
→ naturally a Majorana particle

Neutrino masses occur via processes which are intimately related to the Higgs boson
➔ what are the couplings of the H(125) to neutrinos?

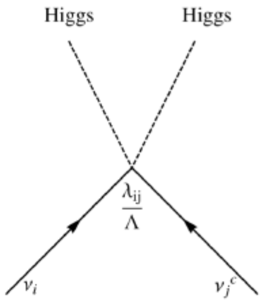
Adding neutrino masses to the Standard model 'simply' by adding a Dirac mass ➔ right-handed neutrino

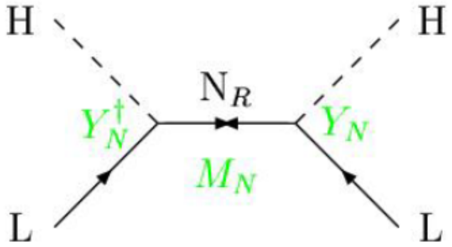
$m_D \overline{\nu_L} \nu_R$



m_D is the Higgs **Yukawa coupling** (like everybody else). Then the right handed neutrinos are perfectly sterile, (**except** that they couple to both the Higgs boson and gravitation).
Things become more interesting: **a Majorana mass term** arises. So-called **Weinberg Operator** (only Dim5 operator in EFT) and involves the Higgs boson and the neutrino Yukawa coupling

Origin of neutrino mass:





Pilar Hernandez, Granada 2019-05

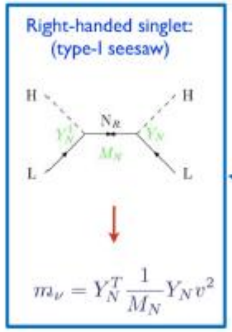
Majorana mass term is extremely interesting as this is the **particle-to-antiparticle transition** that we want in order to explain **the Baryon asymmetry of the Universe** (+ CP violation in e.g. neutrinos)

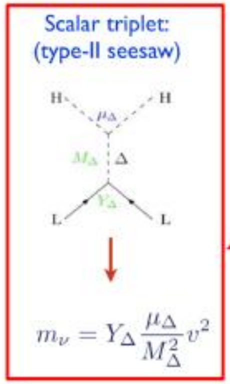
$$M_R \, \overline{\nu_R{}^c} \, \nu_R$$

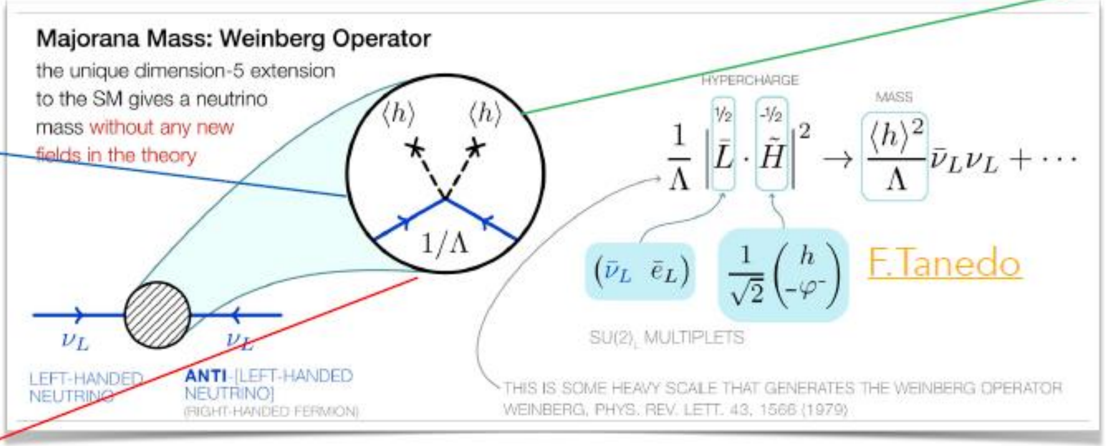
Seesaw Model

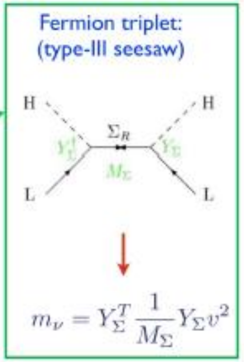
The minimal neutrino Standard Model
is type I see-saw (just complete with RH ν's)

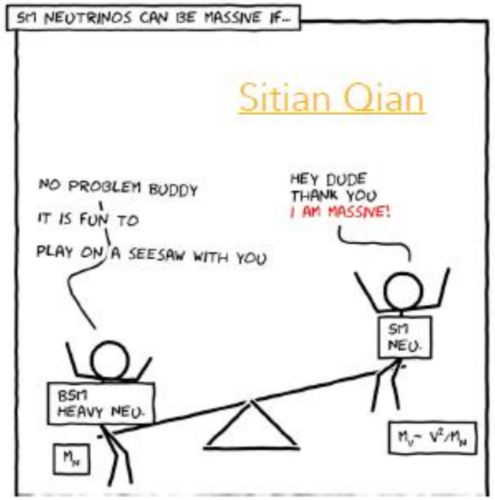
- Opening the black box of Weinberg Operator requires a "**seesaw**"
  - Only three different kinds of realization at Born-level are allowed











- Heavier BSM particles lead to lighter SM neutrinos

Mass eigenstates

See-saw type I :

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

$M_R \neq 0$
$m_D \neq 0$
Dirac + Majorana 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	$\bar{\nu}$	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)

Manifestations of right handed neutrinos

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

$\nu = \nu_L \cos\theta - N^c_R \sin\theta$

$N = N_R \cos\theta + \nu_L{}^c \sin\theta$

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

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 ('eV sterile neutrino' (LSND/miniBooNE/reactor anomalies etc... but ruled out since PLANCK mission MINOS/ICECUBE/DAYABAY/microBooNE. Search still ongoing in broader region)

-- if in keV region (dark matter), monochromatic photons from galaxies with $E=m_N/2$, KATRIN

-- 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

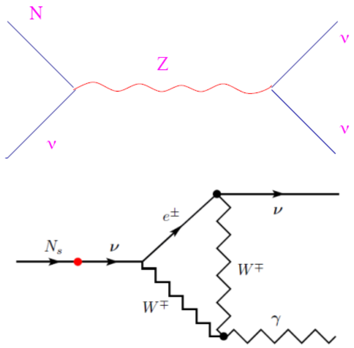
➔ violation of unitarity and lepton universality in Z, W or τ decays

-- etc... etc...

-- Couplings are very small ($|U|^2 = m_\nu / m_N$) for one family. For three families they can be somewhat larger **but most interesting region is near the one-family see-saw limit.**

Direct Search Processes (I)

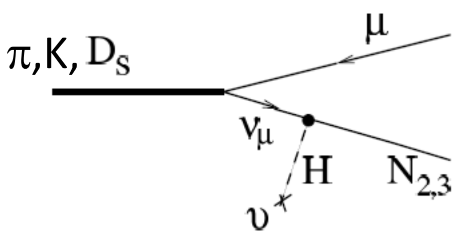
m_N Below m_e:
$N \rightarrow 3\nu$; $N \rightarrow \nu\gamma$ w $E_\gamma = m_N/2$

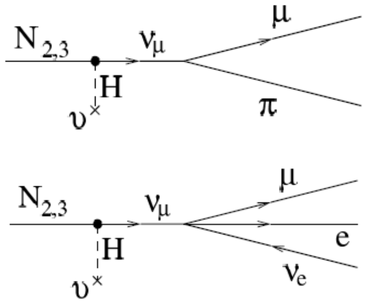


$$\tau_{N_1} = 10^{14}\,\text{years}\left(\frac{10\ \text{keV}}{M_N}\right)^5\left(\frac{10^{-8}}{\theta_1^2}\right)$$

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,D neutrino beams) examples:





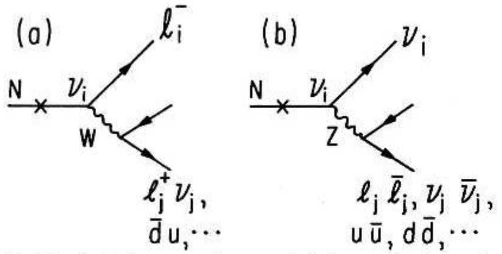


FIG. 2. Typical decays of a neutral heavy lepton via (a) charged current and (b) neutral current. Here the lepton l_i

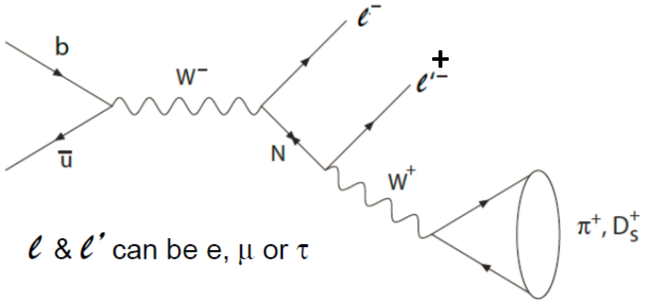
$$L \approx \frac{3}{|U|^2\ (m_{\nu_m}(\mathrm{GeV}/c^2))^6} \times \frac{P_\nu}{45GeV/c}$$

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

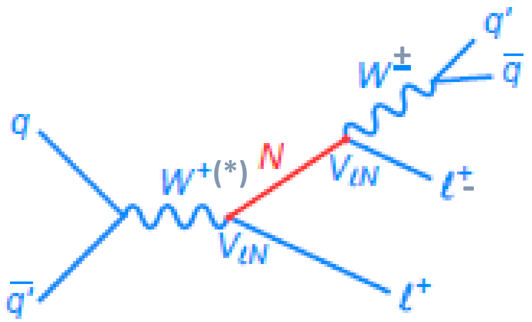
Processes (II)

Search for heavy right-handed neutrinos in collider experiments.

B factories



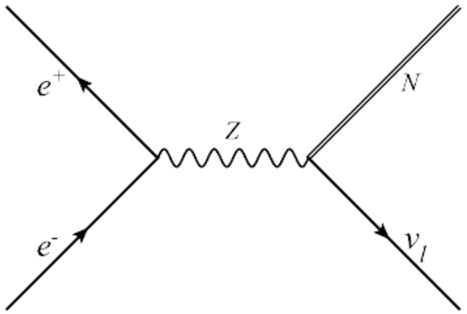
Hadron colliders



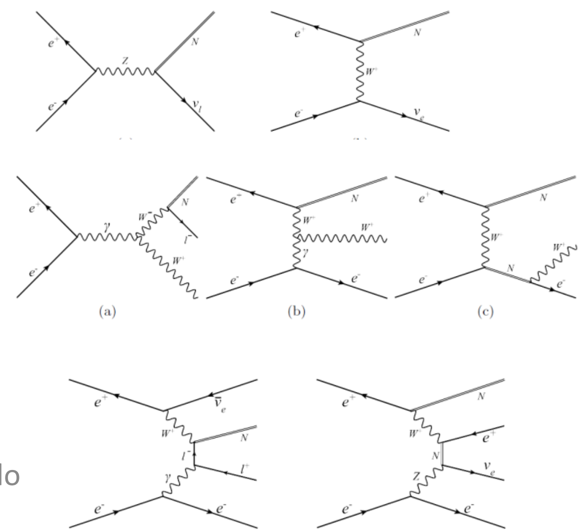
or $l^{\pm}\nu$

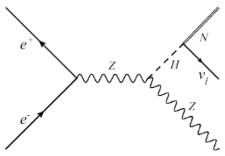
Z factory (FCC-ee, Tera-Z)

arXiv:1411.5230

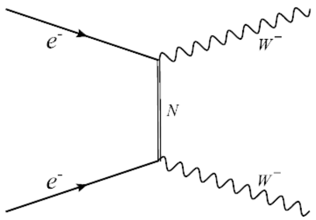


HE Lepton Collider (LEP2, CEPC, CLIC, FCC-ee, ILC, μμ)

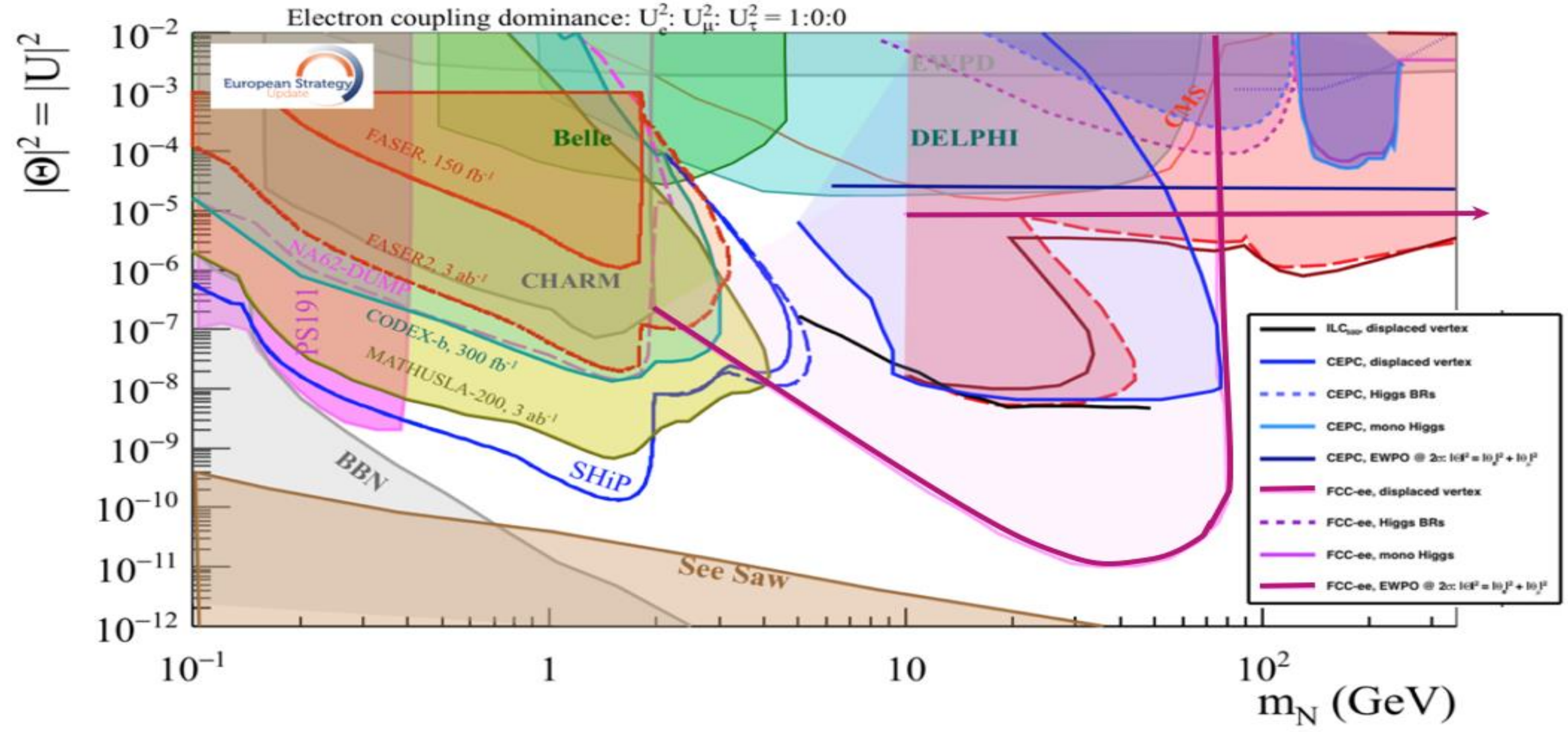




E. $e^-e^- \to W^-W^-$



This picture from ESPP(2019) is relevant to Neutrino, Rare processes and High Energy Frontiers.
FCC-ee (Z) is the most sensitive in the high mass (up to m_W)



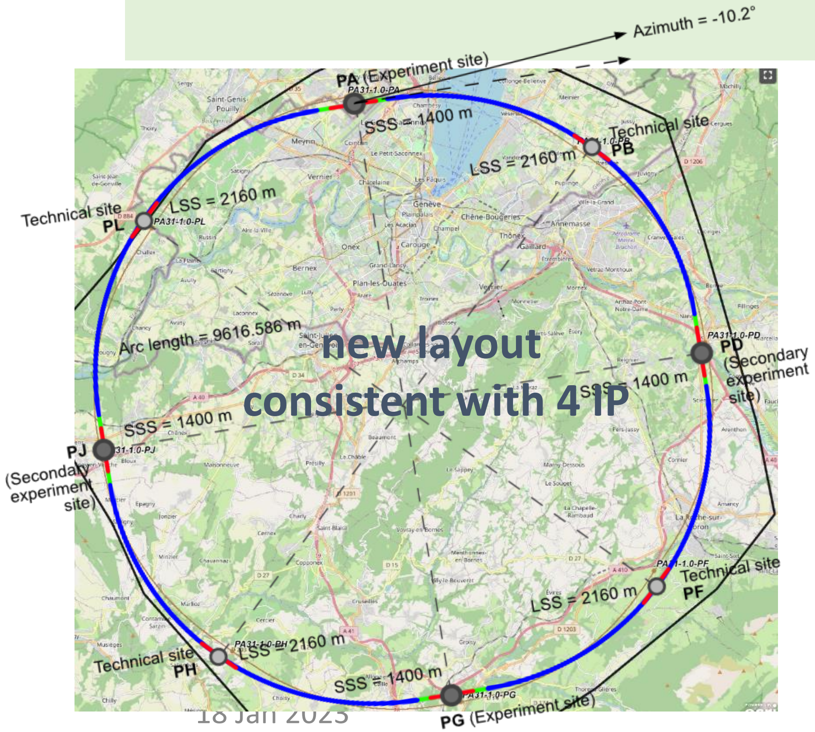
-- the purple line shows the 95% CL limit if no HNL is observed. (here for 10^{12} Z),
-- the horizontal line represents the sensitivity to **mixing of neutrinos** to the dark sector, using EWPOs (G_F vs $\sin^2\theta_W^{eff}$ and m_Z, m_W, tau decays) which extends sensitivity from 10^{-3} (now) to 10^{-5} (FCC) mixing all the way to very high HNL masses (500-1000 TeV at least). arxiv:2011.04725

The Future Circular Collider integrated program at CERN

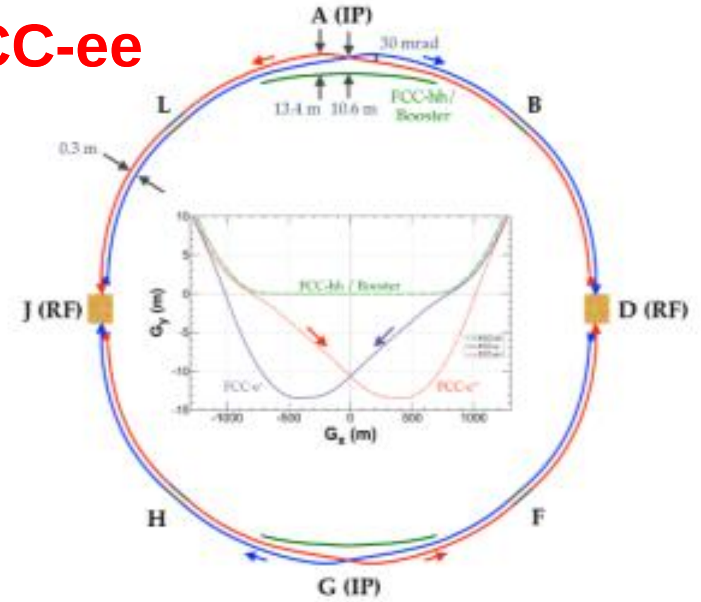
Comprehensive cost-effective program inspired by successful LEP – LHC success story

- **Stage 1: FCC-ee (Z, W, H, tt) as first generation Higgs EW and top factory at highest luminosities.**
- **Stage 2: FCC-hh (~100 TeV) as natural continuation at energy frontier, with ion and eh options.**
- **Maximizes physics output with strong complementarity**
- Integrating an ambitious high-field magnet R&D program
- Common civil engineering and technical infrastructures, building on and reusing CERN's existing infrastructure.
- Start construction early 2030's, start data taking shortly after HL-LHC completion
- **FCC-INT project plan is fully integrated with HL-LHC exploitation ➔ seamless continuation of HEP**
- **Feasibility study approved and funded at CERN (100MCHF/5yrs) + magnet R&D (120 MCHF/6yrs)**

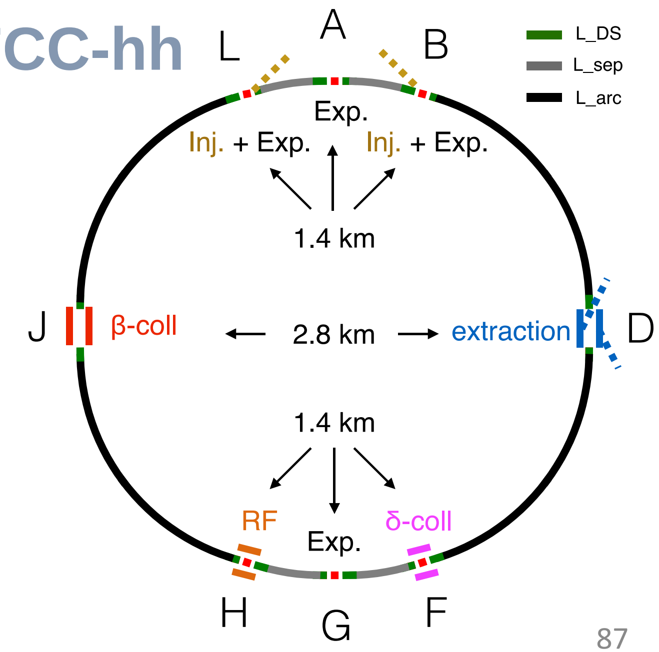
***** GLOBAL COLLABORATION *****



FCC-ee

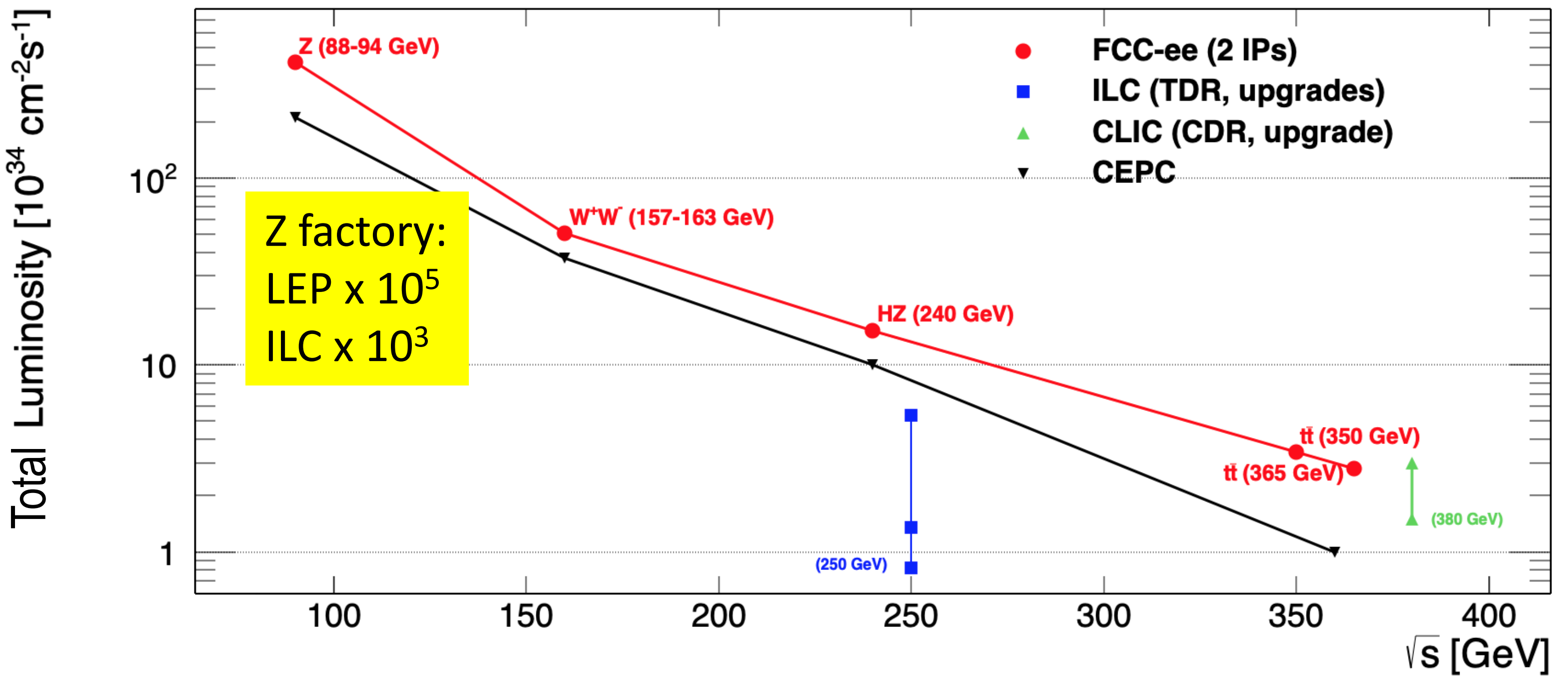


FCC-hh



FCC-ee

Great energy range for the heavy particles of the Standard Model



notes:

-- 4IP increases Total Lumi by 1.7

-- 2IP assumed in all numbers below

-- order and duration of Z/WW/ZH can be decided at a later stage

-- ee→ H must be after both Z and ZH and before tt

see back-ups for facility comparisons

Event statistics (2IP) for a 15 years data taking plan

					E_{CM} errors:
Z peak	**E_{cm} : 91 GeV**	4yrs	**5 10^{12} e+e- → Z**	**LEP x 10^5**	<100 keV
WW threshold	**$E_{cm} \geq 161$ GeV**	2yrs	**>10^8 e+e- → WW**	**LEP x 2.10^3**	<300 keV
ZH maximum	**E_{cm} : 240 GeV**	3yrs	**> 10^6 e+e- → ZH**	**Never done**	1 MeV
s-channel H	***E_{cm} : m_H***	*(3yrs?)*	***O(5000) e+e- → H***	***Never done***	<< 1 MeV
$t\bar{t}$	**E_{cm} : ≥ 350 GeV**	5yrs	**10^6 e+e- → $t\bar{t}$**	**Never done**	2 MeV

HNL RH 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 antineutrino and add contributions of 3 neutrino species **(➔ $\Sigma_{\lambda=e,\mu,\tau} |U_\lambda|^2$)**

Decay

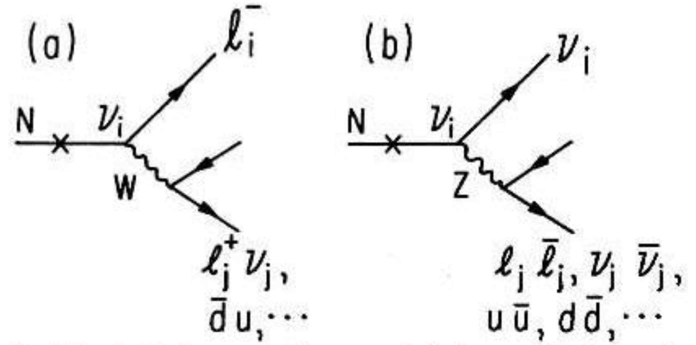


FIG. 2. Typical decays of a neutral heavy lepton via (a) charged current and (b) neutral current. Here the lepton l_i denotes e, μ, or τ.

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)*

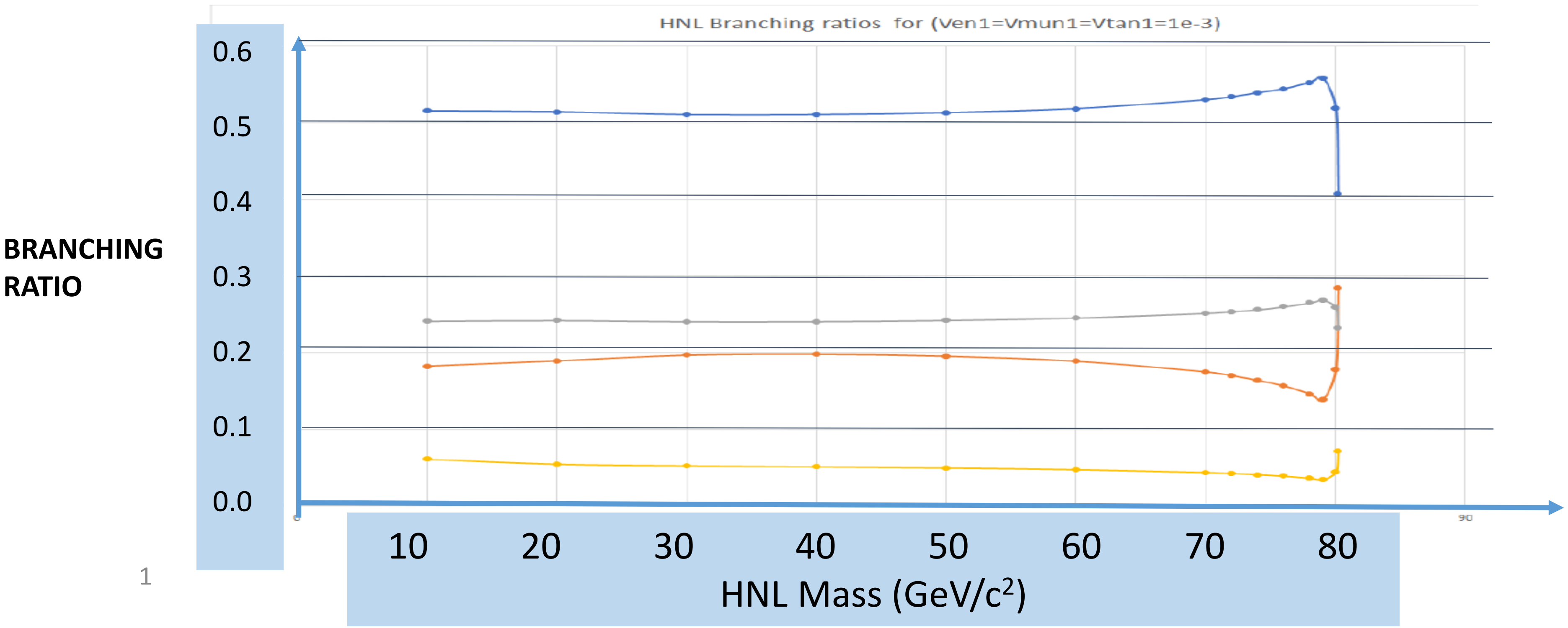
Long life time → detached vertex for M_N~<M_Z

Production of HNL at FCC-ee

We experimentally assume HNL production one at a time. (there could be up to three)

This is an approximation of the more favored situation where two or three almost degenerate HNLs are produced, possibly generating a phenomenology akin to e.g. K_L and K_S or (K <-> $\bar{K}$) system with oscillations and other lifetime effects.
This is extraordinarily interesting and should be studied in the future. (see Antusch, last slide)

In the simplified, <u>one-N-at-a-time</u> assumption the particle has one mass, one cross-section and one decay width/life time. and four decay modes N→ eW*, μW*, τW* (CC decays) and N→ νZ* (NC decay)-- two or more charged tracks except N->ννν



Tanishq Sharma

N→ λ W*→ qq
N→ ν Z* → qq
N→ λ⁺λ(')⁻ ν
N→ λ W*→λ'ν and
N→ ν Z*→ λ λ)
N→ ν νν

Decay length LLP vs Prompt analysis in FCC-ee EXTREMELY CLEAN CONDITIONS

in a wide range of mass and small enough couplings we have **a long lived signature**
then things are nice and easy, because it is essentially background free.
NB in this case one event would be enough to establish discovery (this needs to be carefully demonstrated(!)
taking into account the exact location of the cavern and the details of analysis (detector readout etc..)

-- The LLP signal would be required to have *no* particle originating from the main vertex.
a distance from the vertex of 400 microns would be sufficient to eliminate the prompt background.

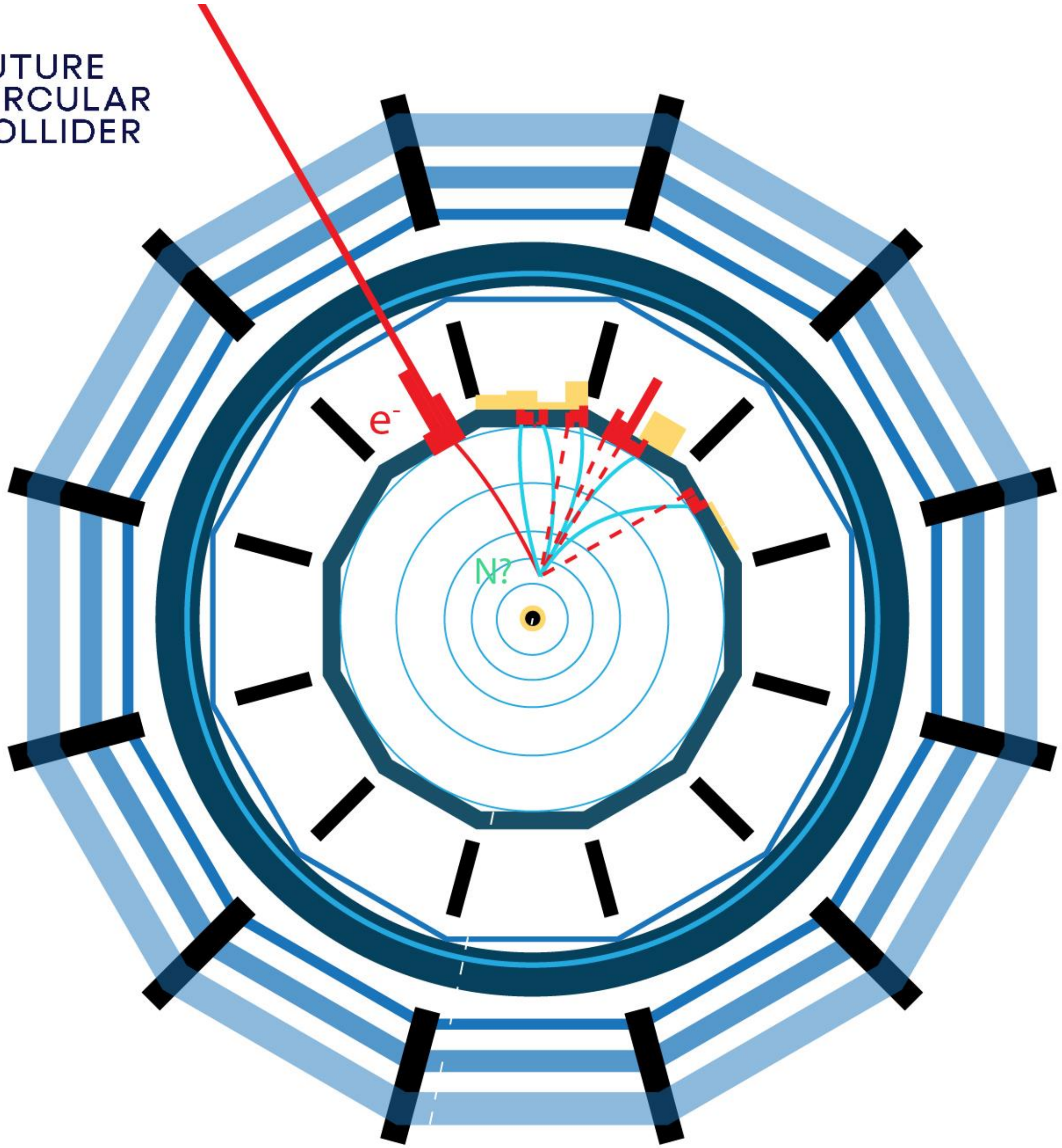
For higher masses and couplings we have a **prompt analysis**. **The boundary** depends critically on the ability
to separate the prompt signal from the irreducible backgrounds $Z \to W^*W^*$ and $Z \to Z^*Z^*$ including e.g. tau decays (or not).
(S. Bay-Nilsen Master Thesis)

vs EWPO

For large mixing angles, irrespectively of the HNL mass, a limit exists from precision measurements
of G_F (muon life time) , vs m_W and $\sin^2\theta_W^{eff}$ $\to$ constraints ν_μ and ν_e mixing with HNL.

in the FCC-ee ν_τ mixing can be constrained by measuring of G_F from tau life time in 1.5 10^{11} tau pairs.

FUTURE CIRCULAR COLLIDER



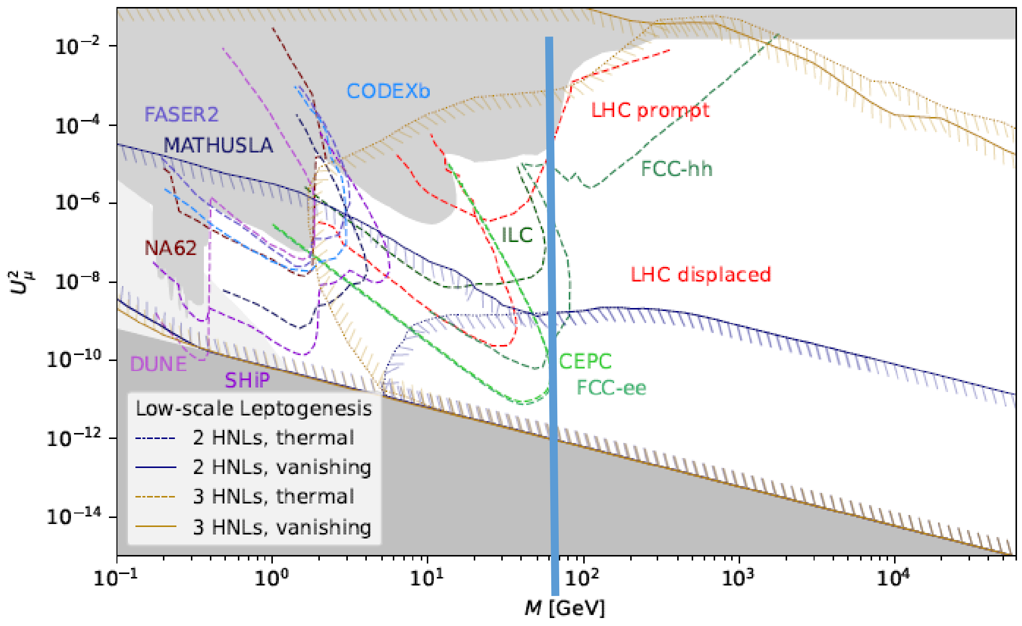


Figure 3: *Bold green line:* Sensitivity of displaced vertex searches at FCC-ee with 5×10^{12} Z bosons corresponding to 4 observed HNL decays, assuming no background and 75% reconstructed HNL decays with a displacement between 400μm and 1.22m. For comparison, we show what CepC can achieve with 4.2×10^{12} Z bosons for the same parameters. *Bold turquoise line:* Gain in sensitivity if the maximal observable displacement is increased to 5m with a HECATE-like detector [77]. *Dark gray:* Lower bound on the total HNL mixing from the requirement to explain the light neutrino oscillation data [72]. *Medium gray:* Constraints on the mixing $|V_{\mu i}|^2$ of HNLs from past experiments [78–88], obtained under the assumption $|V_{\ell N}|^2 = \delta_{\ell\mu} U_\mu^2$. *Light gray:* Lower bound on U_μ^2 from BBN [89,90]. *Hashed orange and violet lines:* Regions in which the observed baryon asymmetry of the universe can be explained with two [91, 92] or three [93] HNL flavours and different initial conditions, as explained in the legend. *Other colourful lines:* Estimated sensitivities of the LHC main detectors (taken from [94–96]) and NA62 [65] as well as the sensitivities of selected planned or proposed experiments (DUNE [97], FASER2 [98], SHiP [99, 100], MATHUSLA [101], Codex-b [102]) as well as FCC-hh [75].

this correctly says 'sensitivity with displaced vertex search'

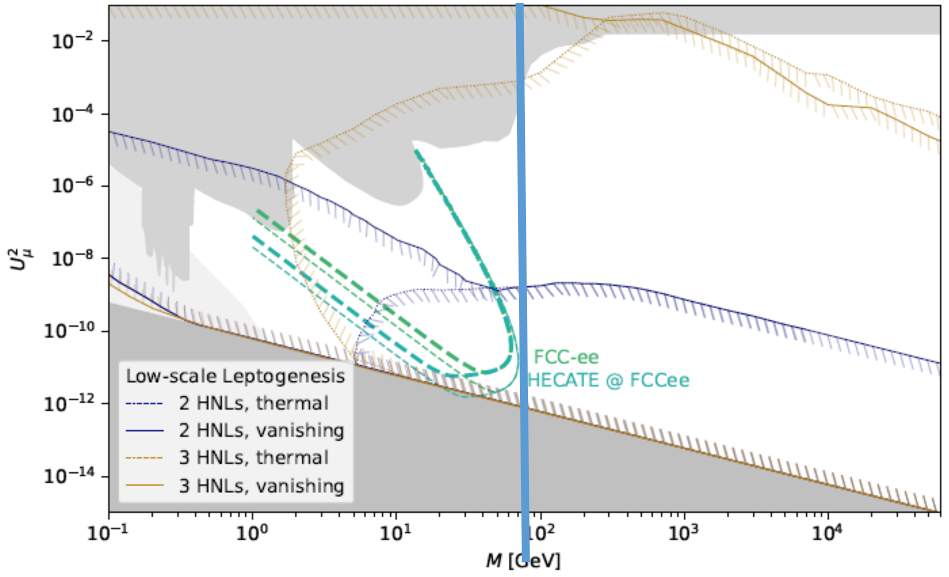


Figure 4: In this figure, similar to Fig. 3, the contours for 4 events (bold lines) and 1 event (non-bold lines) are shown for FCC-ee with a 1.2 m radius setup for the displaced vertex analysis only. In addition, the curves are also shown for a putative 5 m radius volume as in the HECATE [77] set-up, increasing the sensitivity for low mass and small coupling part of the parameter space.

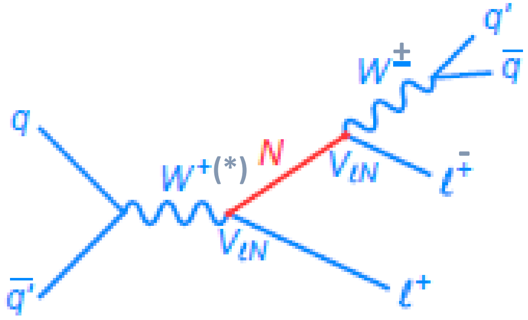
NEW: show 4 event and 1 event curves for $5 10^{12}$ Z

4 events corresponds to, having not seen anything, excluding the regions where you would have 95% chance of seeing something if its there.
limit-setting oriented.
1 event corresponds to no background situation where you would have 63% chance of seeing one event.
discovery oriented

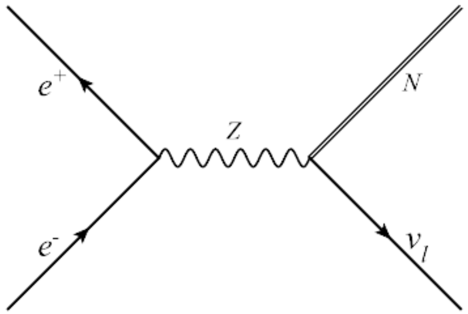
Dirac vs Majorana(I) observation of fermion number violation.

It has been emphasized by Mccullough that there exist ways to create models of Dirac HNL-like particles and that **the discovery of a RH-ν requires the observation of the Majorana nature of the particle.**

This is straight forward for HNL from τ **D, B decays or W decays (CC decay)** →
IF sign of both initial lepton and final state lepton is observed



For Z factory (NC) it is not so obvious:→
cannot see the initial neutrino
Recent breakthrough!



Several methods:

0. if long lived decay → life time measurement.
1. Forwards backward asymmetry relic of the Z parity violating couplings. Dirac keeps it, Majorana washes it out.
   ➔ uses N→ λqq decay and requires lepton charge reconstruction.
2. Polarization (also relic of Z parity violation) of HNL leads to harder lepton spectrum for Dirac than for Majorana
   ➔ uses N→ λqq and requires lepton momentum reconstruction (but not the charge)
   NB analysis sensitive to detail W* mass distribution, esp. for small masse W* (in tau & D mass region and below)
3. W/Z diagram interference (Petcov) for N→ λλν Very elegant but less statistics and less easy

These methods 1,2,3 work for the prompt analysis as well as for the LLP analysis within presumably a smaller radius.

Dirac vs Majorana

the lifetime is reduced by a factor 2 for a Majorana vs Dirac particle

it is nicely visible in the plots prepared by T. Sharma *-->

C_{MD}= 1(Dirac), 2(Majorana)

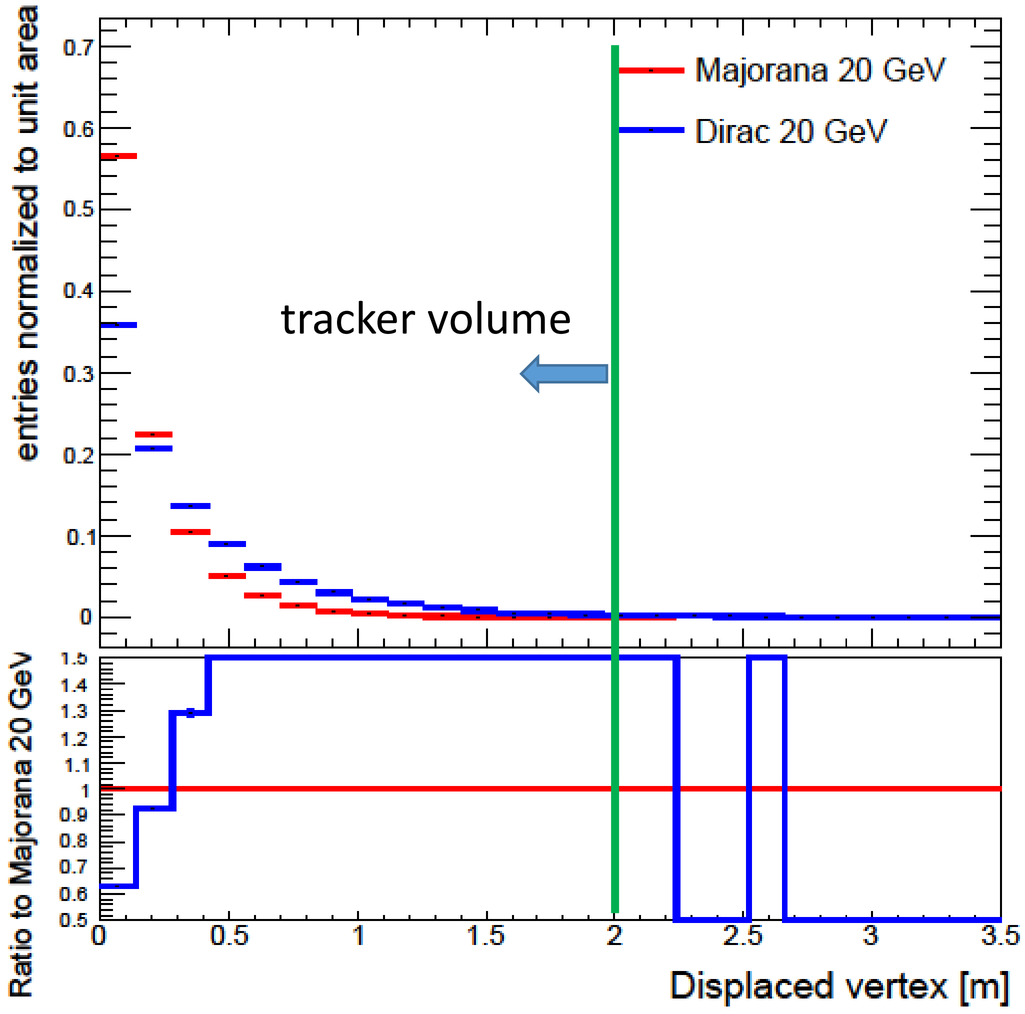
$$\mathrm{BR}(Z \to \nu N) = \frac{2}{3}|U_N|^2 \ \mathrm{BR}(Z \to \mathrm{invisible}) \ \left(1 + \frac{{m_N}^2}{2{m_Z}^2}\right)\left(1 - \frac{{m_N}^2}{{m_Z}^2}\right),$$

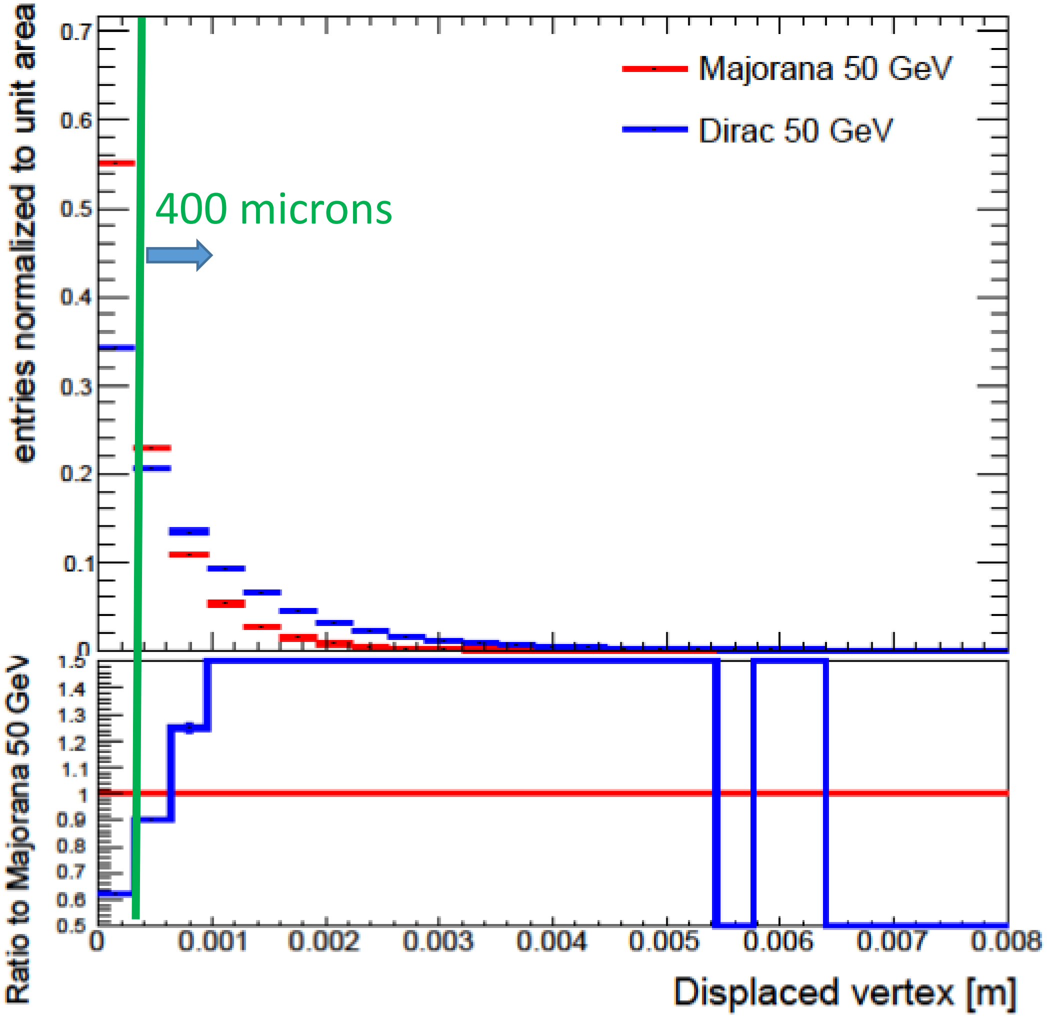
$$\Gamma_N = \frac{1}{c\tau_N} \simeq C_0 C_{MD} |U_N|^2 \ \left(\frac{m_N}{50\mathrm{GeV}}\right)^5 \times \left(\frac{3.10^9}{1 \ \mathrm{cm}}\right)$$

$$|U_N|^2 \equiv \sum_{\ell=e,\mu,\tau} |U_{\ell N}|^2$$

➔ **At the Z** the production cross-section and the decay rate depend on the same combination of mixing angles!

Of course this can only be used **if** we can measure the lifetime, however at larger mixing angle the other methods can be used.





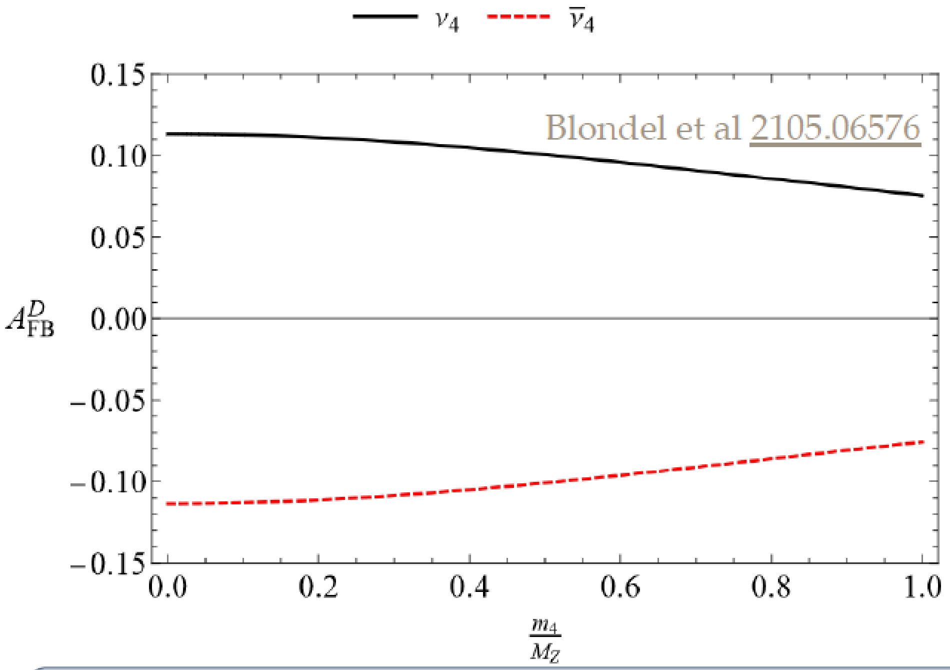
decay length for mixing angle $|U|^2=10^{-6}$ in N→ e+e- ν mode (10^4 events)

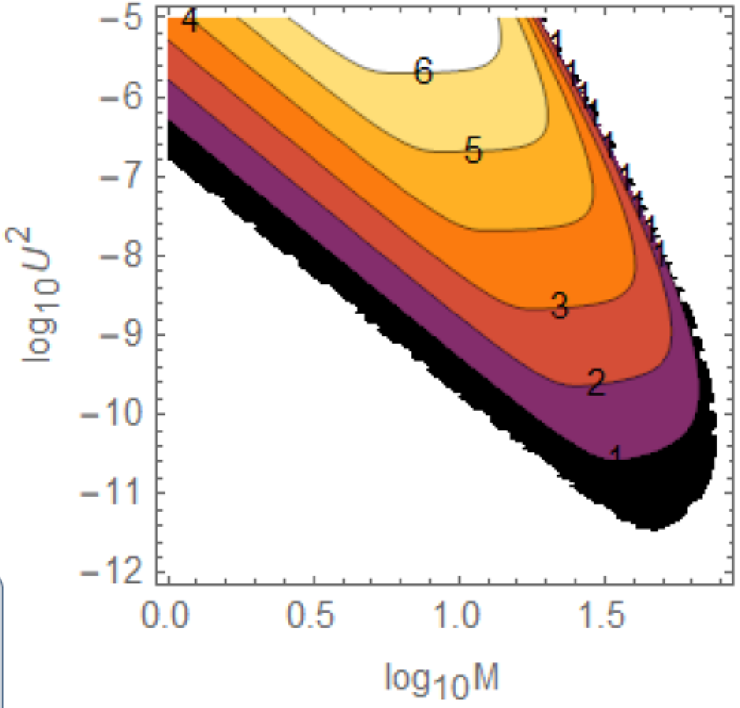
Forward-Backward Asymmetry

$$A_{\mathrm{FB}} = \frac{1}{\sigma}\left[\int_0^1 \frac{d\sigma}{d\cos\theta} d\cos\theta - \int_{-1}^0 \frac{d\sigma}{d\cos\theta} d\cos\theta\right]$$

$$A^D_{\mathrm{FB}}(\nu_4) = \frac{3}{2}\frac{M_Z^2}{(2M_Z^2+m_4^2)}\frac{(g_L^2-g_R^2)}{(g_L^2+g_R^2)},$$

$$A^D_{\mathrm{FB}}(\bar\nu_4) = \frac{3}{2}\frac{M_Z^2}{(2M_Z^2+m_4^2)}\frac{(g_R^2-g_L^2)}{(g_L^2+g_R^2)}$$

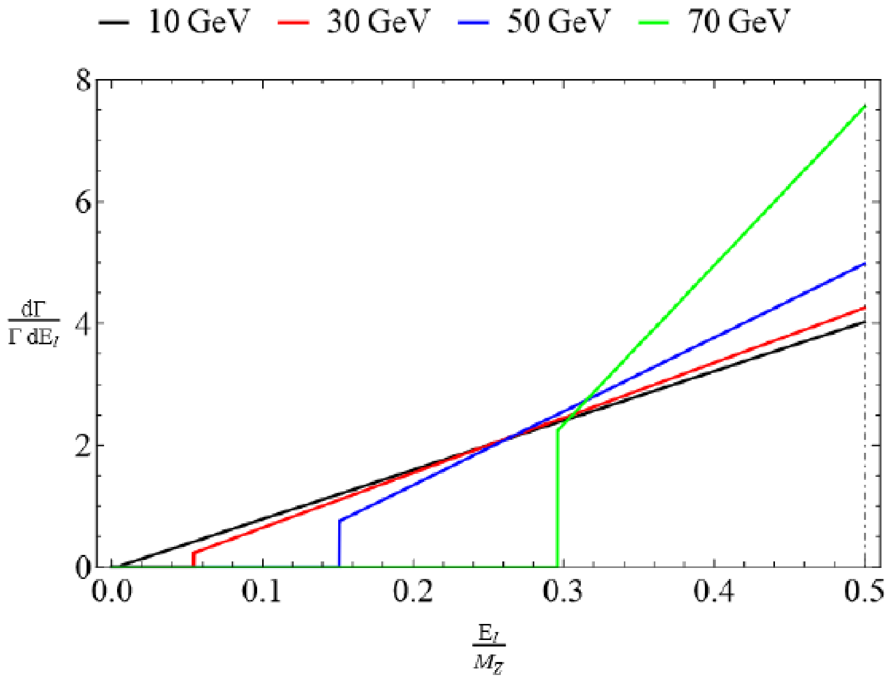


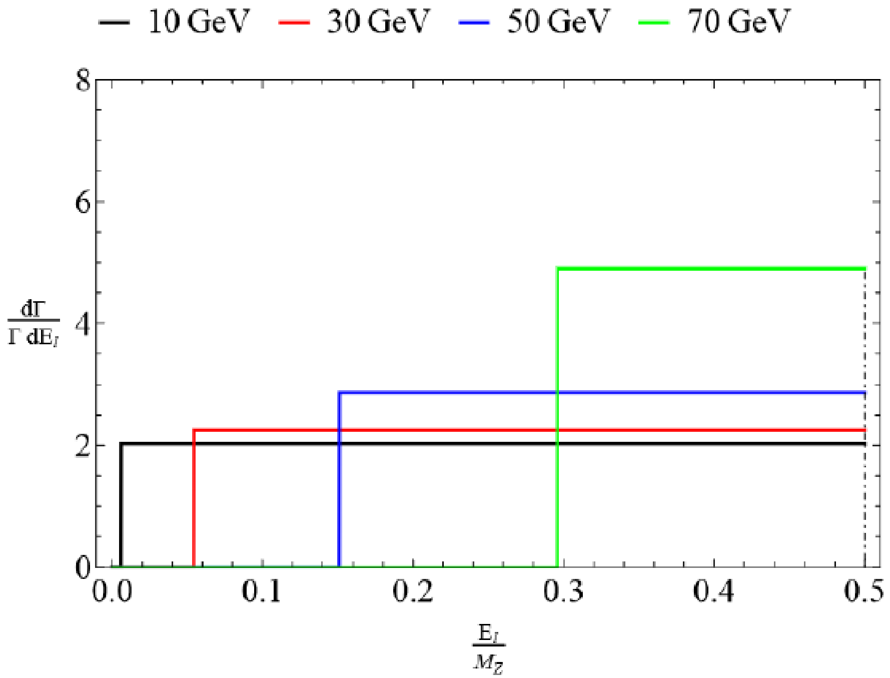


Drewes, ICHEP

- Forward-backward asymmetry ~10%
- Needs hundreds of events for 2σ exclusion
- Estimate: doable for $U^2 > 10^{-9}$ at FCC-ee

Polarisation Impact on Lepton Spectrum





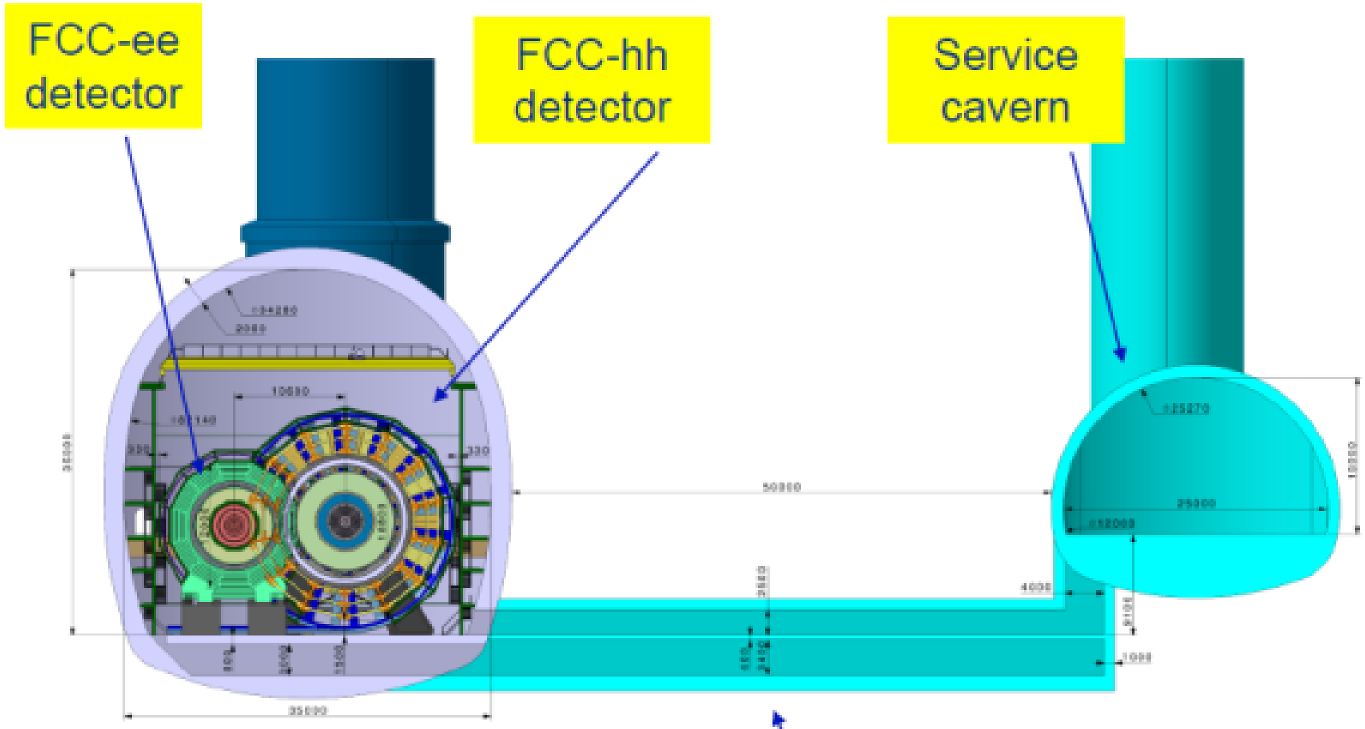
- **Dirac** N and anti-N *individually* are highly polarised, can only decay into lepton or anti-lepton, respectively
- **Majorana** N are only mildly polarised and decay into leptons of either charge
- Lepton spectrum in HNL decay depends on polariations, e.g. decay into pion+lepton:

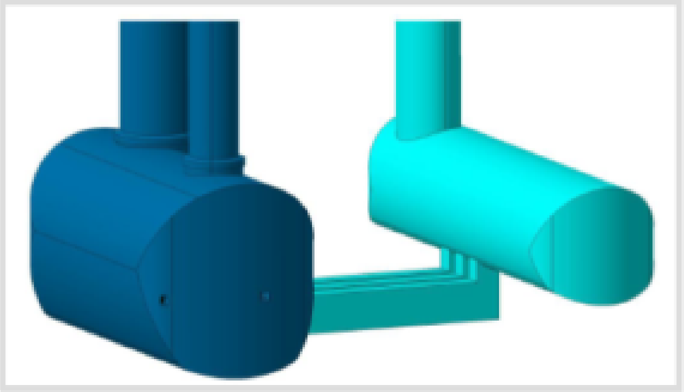
$$\frac{1}{\Gamma(\ell^{\pm})}\frac{d\Gamma(\ell^{\pm})}{dE_\ell} = \frac{4}{\left(1-\frac{M^2}{m_Z^2}\right)^2}\left[\frac{(1\mp P)}{2} - \frac{M^2}{m_Z^2}\frac{(1\pm P)}{2} \pm 2P\frac{E_\ell}{m_Z}\right]$$

Blondel et al 2105.06576

Common experimental points (A, G)

Distance between detector cavern and service cavern 50 m.
Strayfield of unshielded detector solenoid < 5mT.





Preliminary design of access and cable paths

HECATE DETECTOR TO FILL THE WHOLE CAVERN with e.g. RPC or Scintillator modules.

Future Circular Collider Study
Michael Benedikt
Physics at FCC, 4 March 2019

4

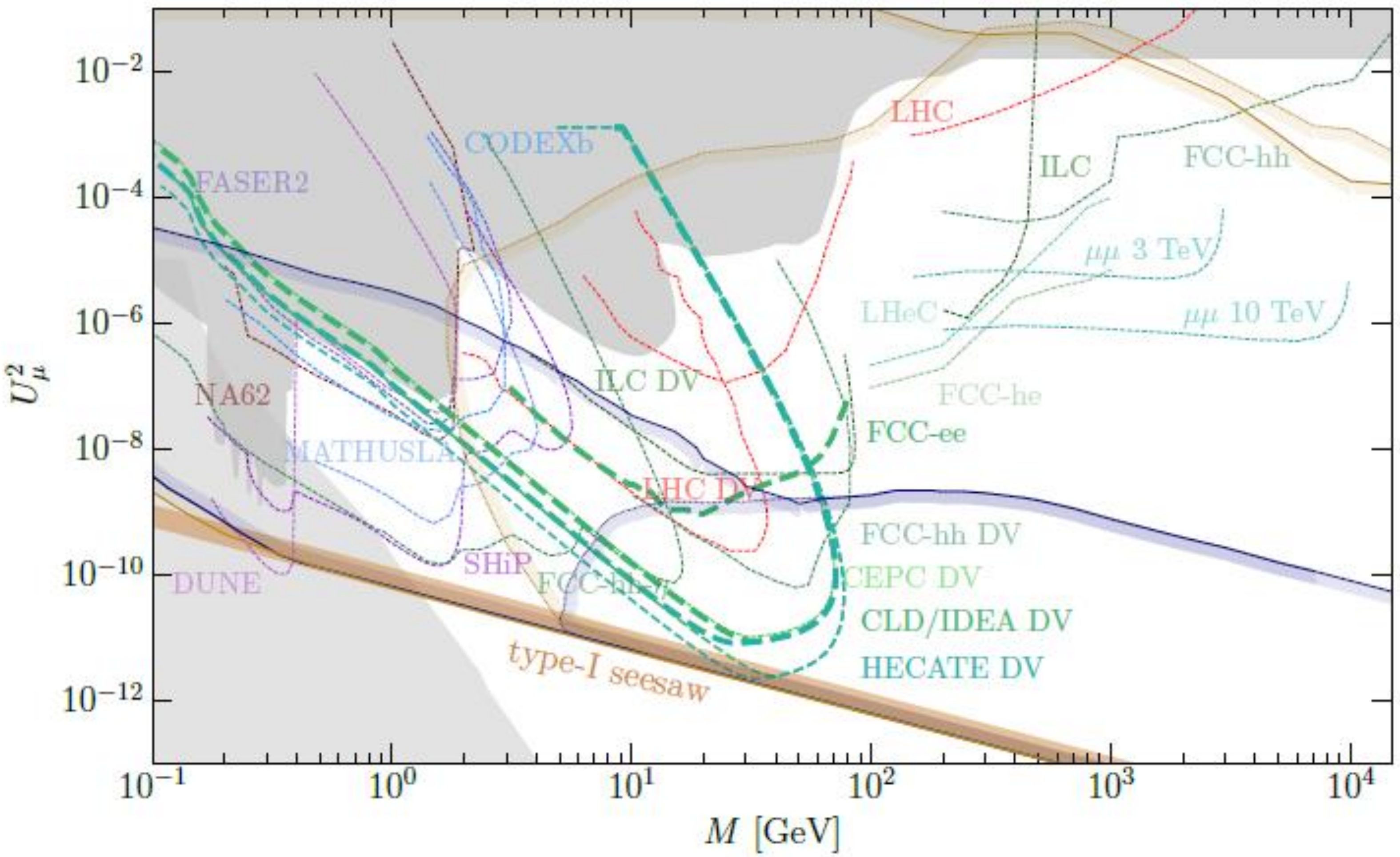
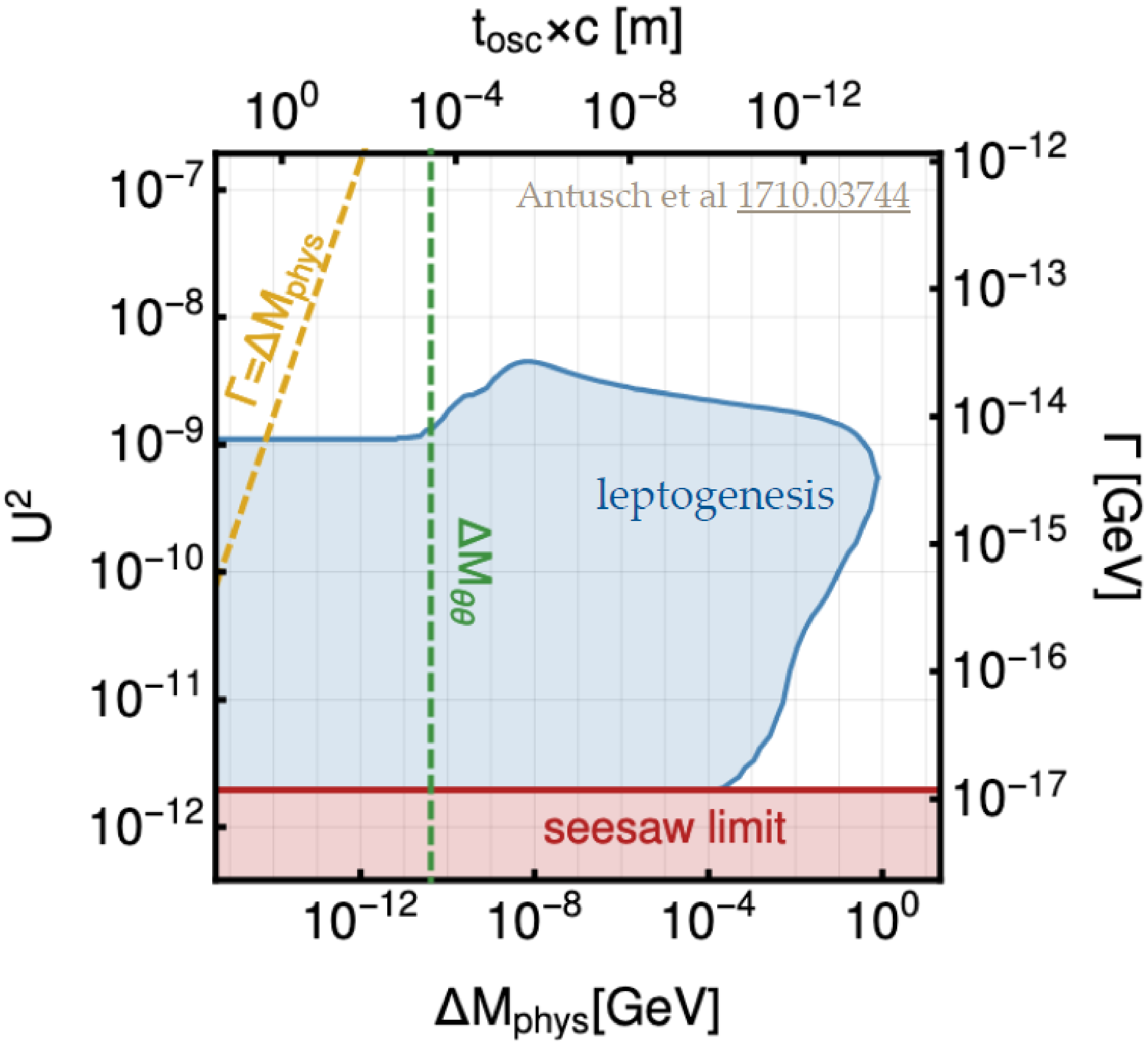
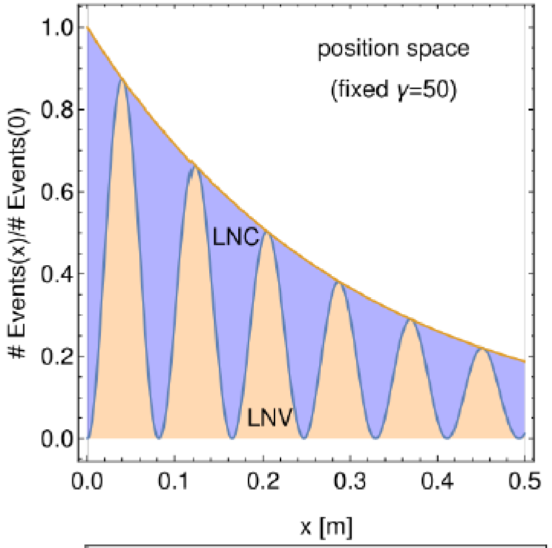


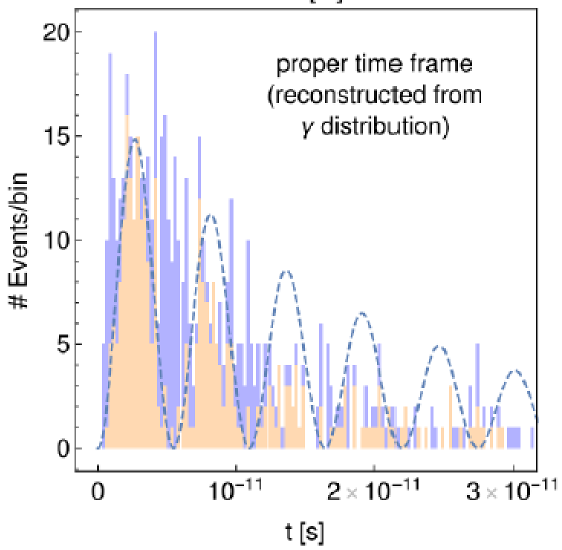
Figure 2: Comparison of the parameter regions in which four events (bold lines) and one event (non-bold lines) are expected in the IDEA/CLD detector or HECATE, with the same conventions and assumptions as in Fig. 2.

case with two interfering HNL produced → on site observation of leptogenesis!

Testing Leptogenesis







Conclusions

0. as emphasized in 2021 NUFACT, the FCC-ee is a heavy neutrino factory.

1. We cannot overstate the importance of the HNL search – although large chance to be in vain
   the probability to appear below the W mass covers a fair fraction of the EW scale see-saw models.
   Directly related to the Higgs Yukawa coupling and extremely straightforward.

2. Right-handed neutrinos contain a very attractive solution to both the neutrino masses and the matter dominance in the Universe.
   -- it is also beautiful by its simplicity.

3. analysis contains many unpicked low-lying fruits and we keep finding new tricks.

JOIN US!

A bit of phenomenology

decay modes

-- ~50-55 % is made of N→ λ W*→ qq λ= e, μ, τ, each propto $|U_\lambda|^2$

-- ~22-28 % is made of N→ $\lambda\lambda$v (N→ λ W*→λ'v and N→ v Z*→ λ λ)

-- ~6% is made of N→ v v v (no chance)

-- ~18-20% is made of N→ v Z*→ qq

exact numbers vary with HNL mass (difference btw W and Z propagator)

-- > 50-55% has no missing energy in the decay (except for tau decay)
***and* is sign/helicity tagged (as coming from W decay).**

-- not to forget: the NC/CC ratio is independent of the individual $|U_\lambda|^2$ λ= e, μ, τ
« Neutral Current » topology can be enhanced in the HNL decays into a lighter HNL

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**

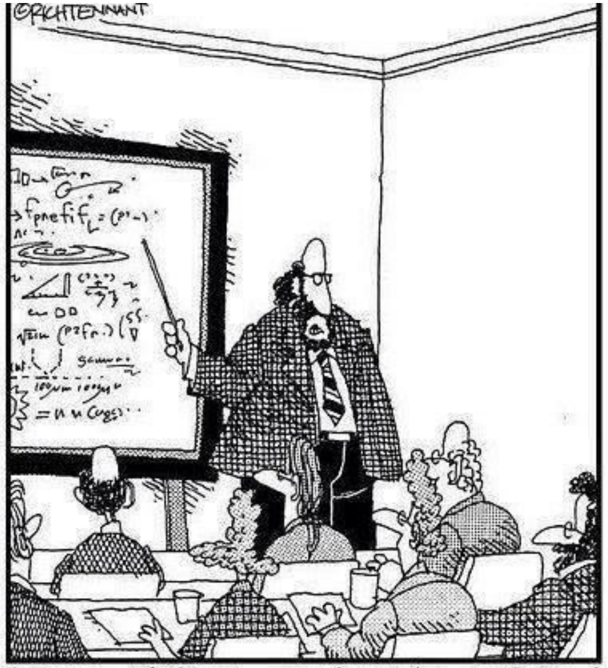
Electroweak eigenstates

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

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? –

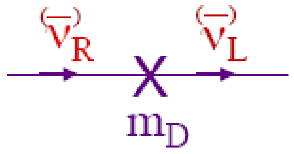
Also called 'sterile'



" 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."

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

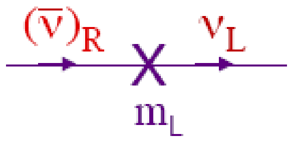
$m_D \nu_L \overline{\nu_R}$ $\quad m_D \overline{\nu_L} \nu_R$



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 :

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

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

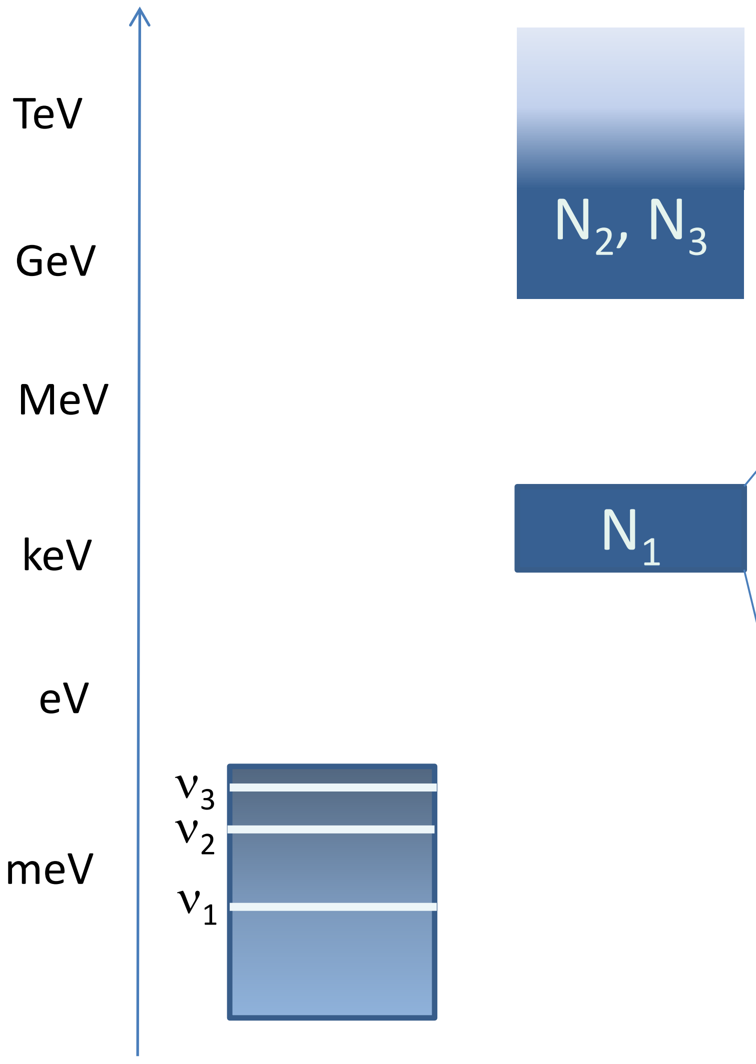
	ν	N	$\bar{\nu}$	$\bar{N}$
I_{weak}=	½	0	½	0

4 states , 2 mass levels

m_1 have ~I=1/2 (~active)
m_2 have ~I=0 (~sterile)

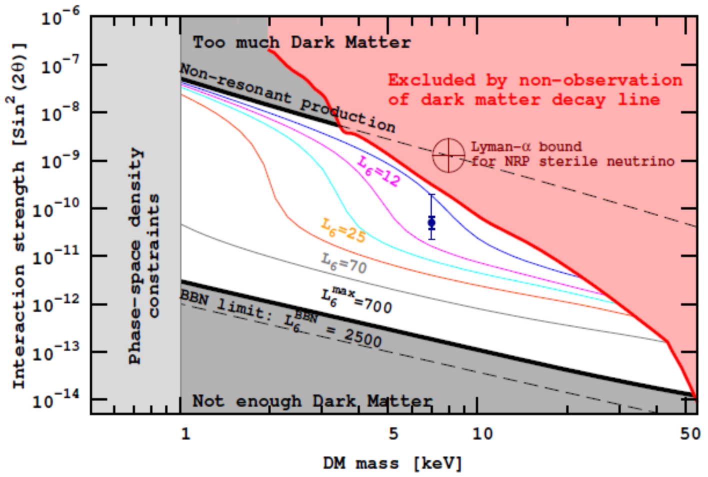
There even exists a scenario that explains everything: the νMSM

Shaposhnikov et al

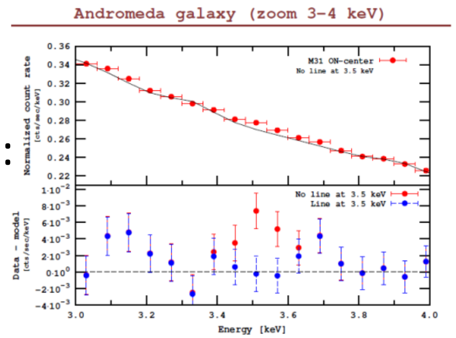


can generate Baryon Asymmetry of Universe
if $m_{N2,N3} > 140$ MeV

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 :
$\theta \approx (m_D/M)$
$\boldsymbol{m_\nu} \approx \frac{\boldsymbol{m_D}^2}{\boldsymbol{M}}$
$m_N \approx M$
$|U|^2 \propto \theta^2 \approx \boldsymbol{m_\nu} / m_N$

$$\boldsymbol{\nu} = \boldsymbol{\nu L} \cos\theta - \boldsymbol{N^c}_{\boldsymbol{R}} \ \mathbf{sin}\theta$$

$$\boldsymbol{N} = \boldsymbol{N_R} \cos\theta + \boldsymbol{\nu_L}^{c} \sin\theta$$

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

what is produced in W, Z decays is:

$$\boldsymbol{\nu_L} = \boldsymbol{\nu} \cos\theta + \boldsymbol{N} \ \sin\theta$$

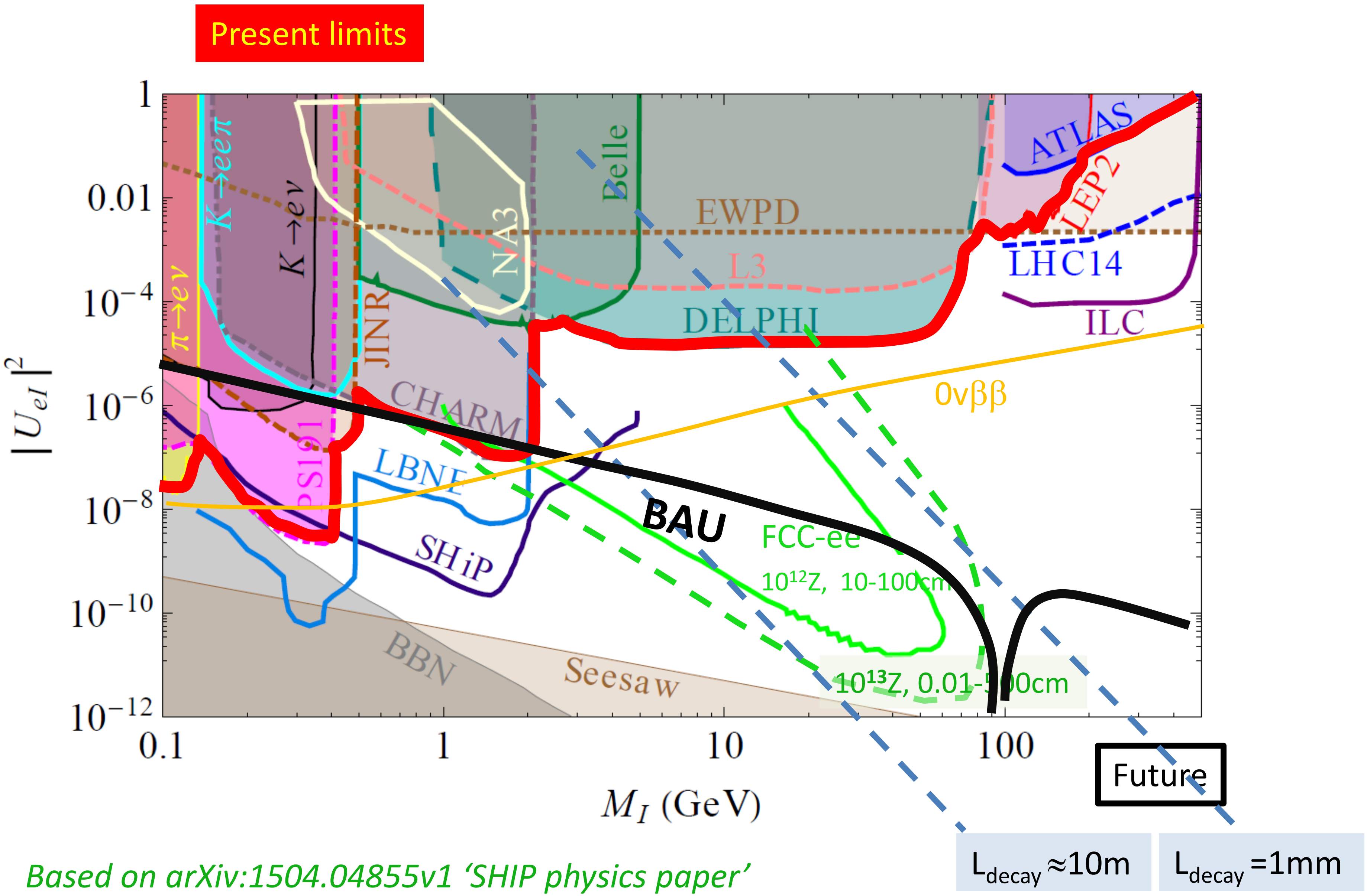
-- mixing with active neutrinos leads to various observable consequences
- -- if very light (eV) , possible effect on neutrino oscillations (see talks later today)
- -- if in keV region (dark matter), monochromatic photons from galaxies with $E=m_N/2$

-- 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 ($\boldsymbol{m_\nu} / m_N$) *(but who knows?)* **and generally seem out of reach at high energy colliders.**

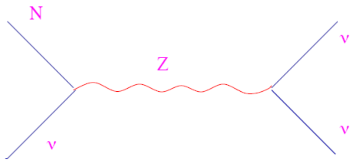


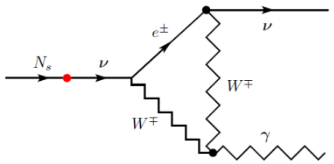
Based on arXiv:1504.04855v1 'SHIP physics paper'
And Pilar Hernandez, HEP-EPS Vienna

Search Processes (I)

m_N Below m_π:

$N \rightarrow 3\nu$; $N \rightarrow \nu\gamma$ w $E_\gamma = m_N/2$

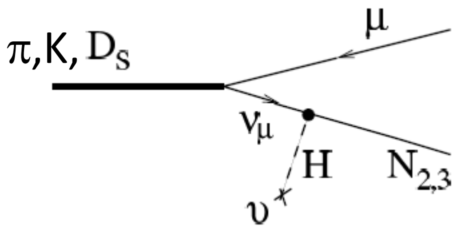


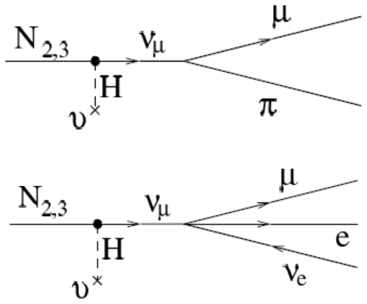


$$\tau_{N_1} = 10^{14}\,\text{years}\left(\frac{10\ \text{keV}}{M_N}\right)^5\left(\frac{10^{-8}}{\theta_1^2}\right)$$

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:





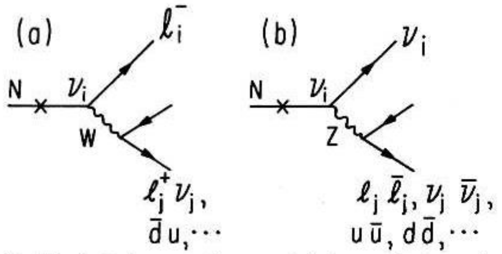


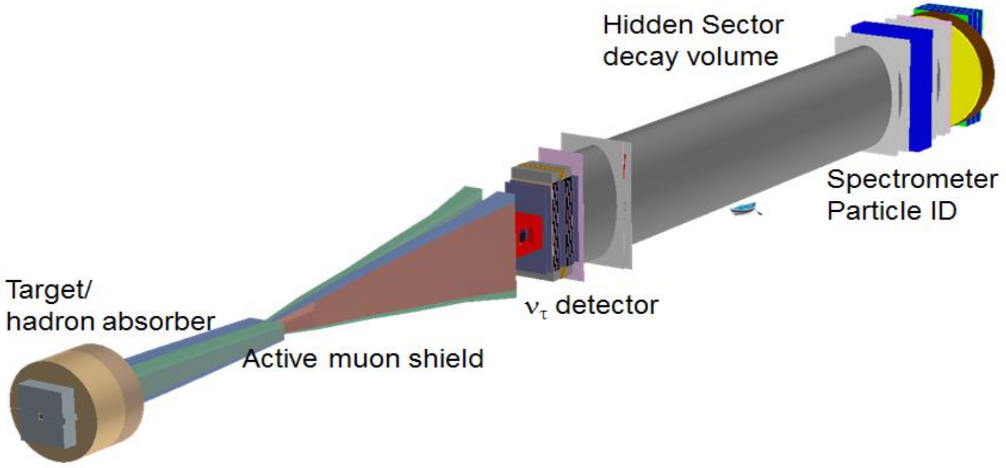
FIG. 2. Typical decays of a neutral heavy lepton via (a) charged current and (b) neutral current. Here the lepton l_i

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

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

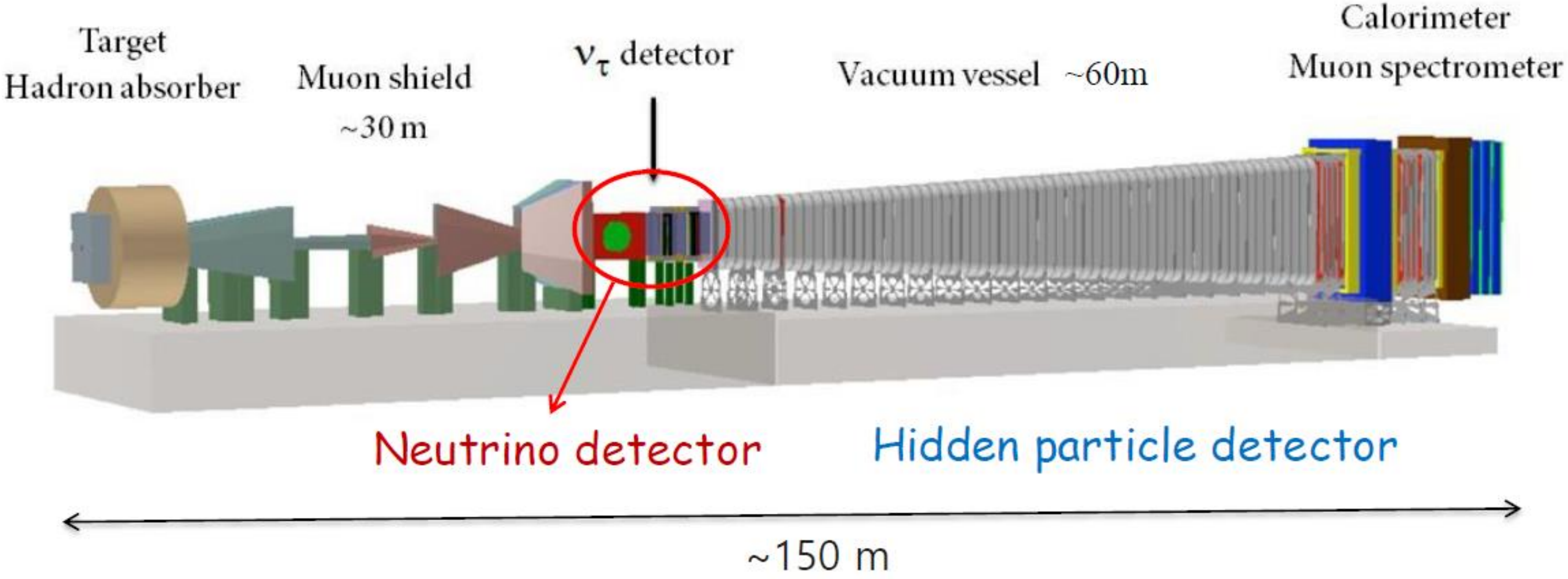


arXiv:1504.04855
arXiv:1504.04956

SHiP Detector

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

PID
Energy measure

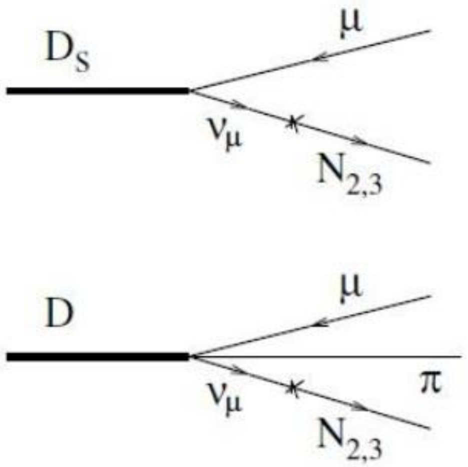


Hadron absorber
eliminate
2ry mesons
~ 5m Fe

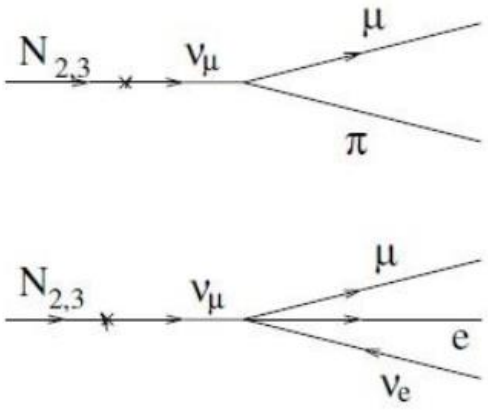
Nuclear Emulsion
Tau-neutrino physics
LDM search

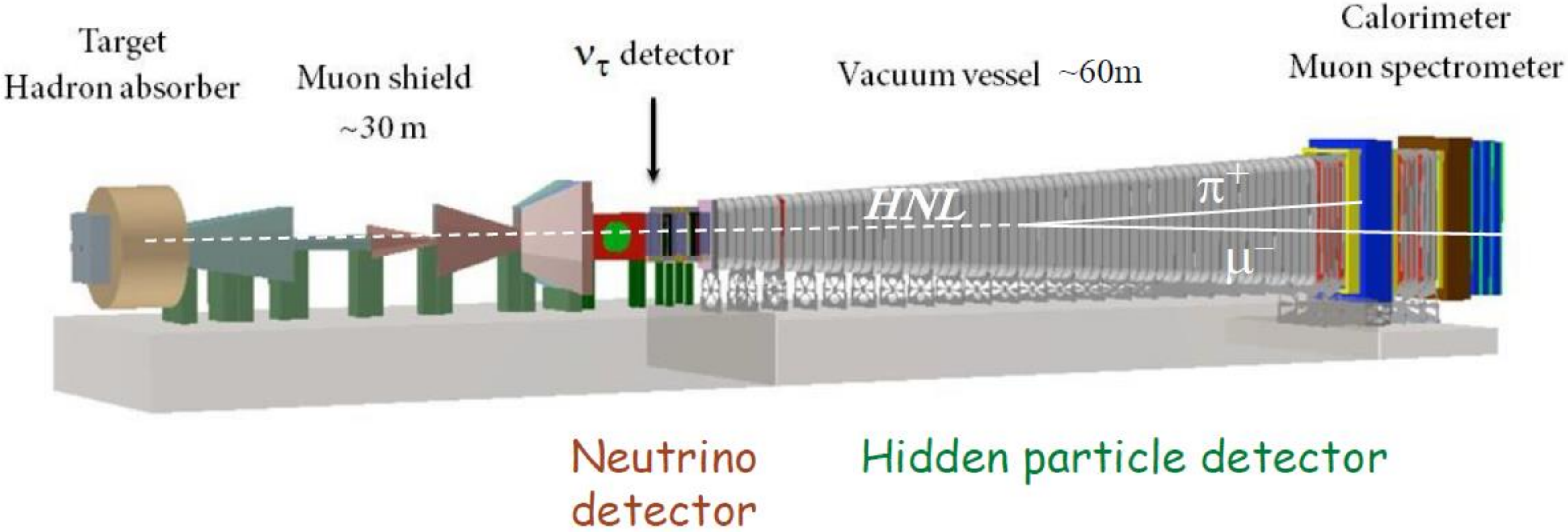
Vacuum decay vessel
~60 m long evacuated decay vessel surrounded by liquid scintillator veto system

HNL production



HNL decay





HNL sensitivity

Cosmologically interesting region at low couplings

- **m_{HNL} < m_b**

  SHiP will have much better sensitivity than LHCb or Belle2

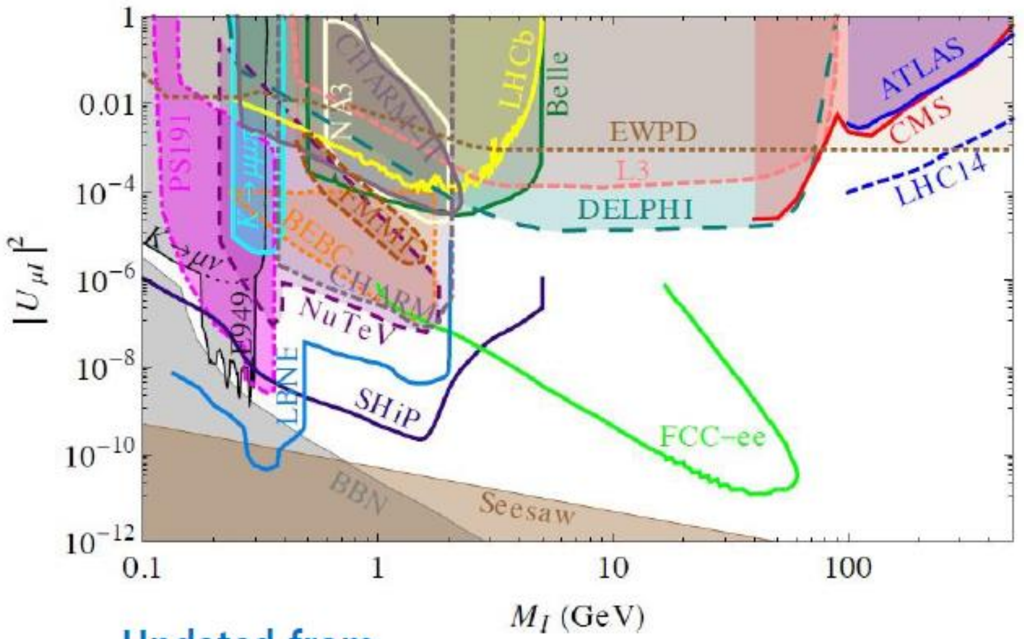
- **m_b < m_{HNL} < m_Z**

  FCC-ee, improvements expected from ATLAS/CMS

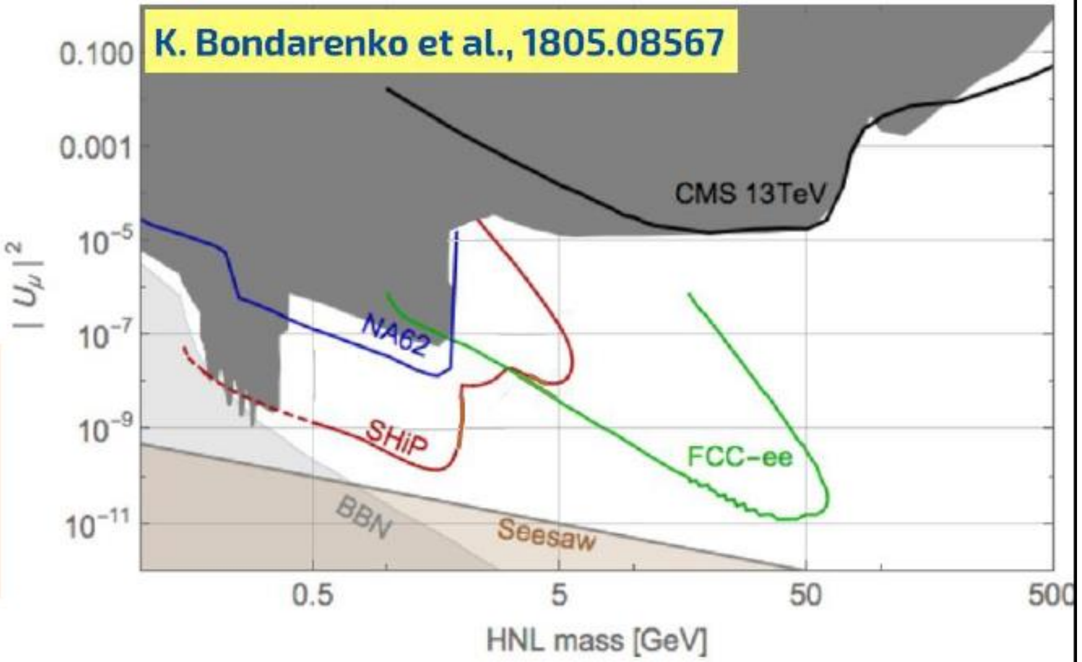
- **m_{HNL} > m_Z**

  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.



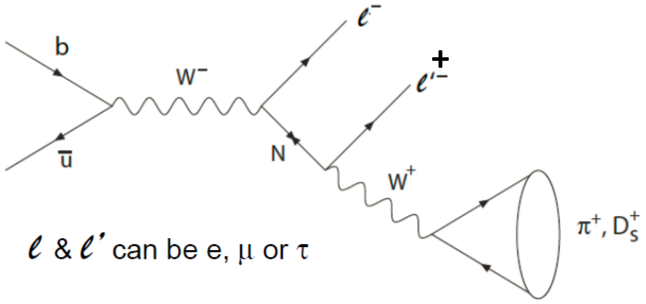
Updated from



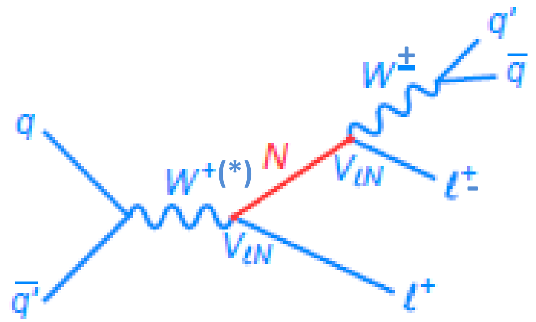
Processes (II)

Search for heavy right-handed neutrinos in collider experiments.

B factories

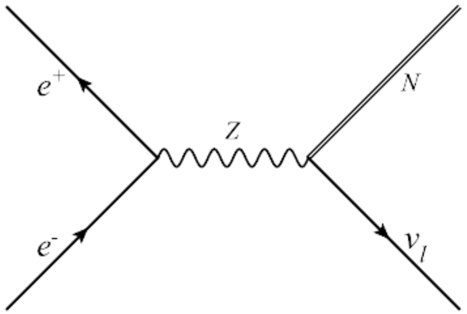


Hadron colliders

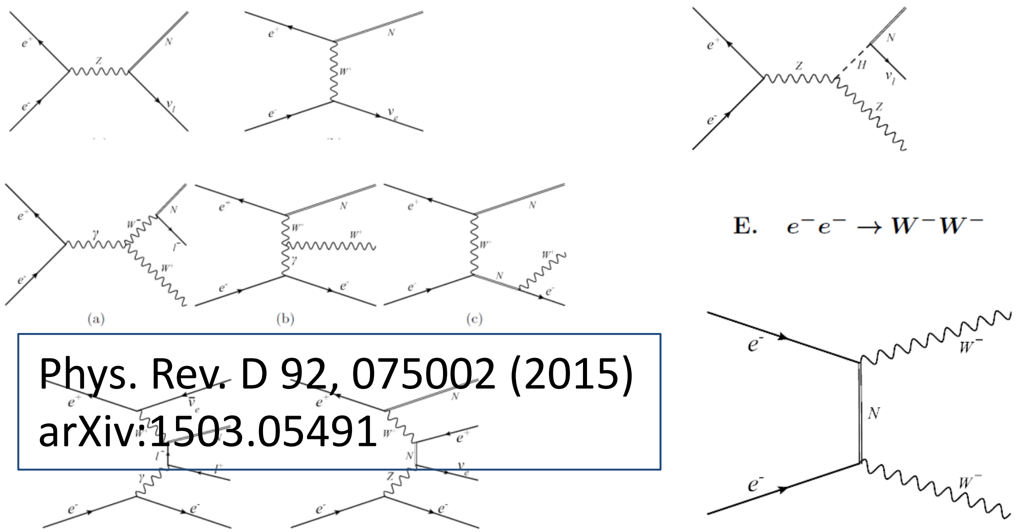


Z factory (FCC-ee, Tera-Z)

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

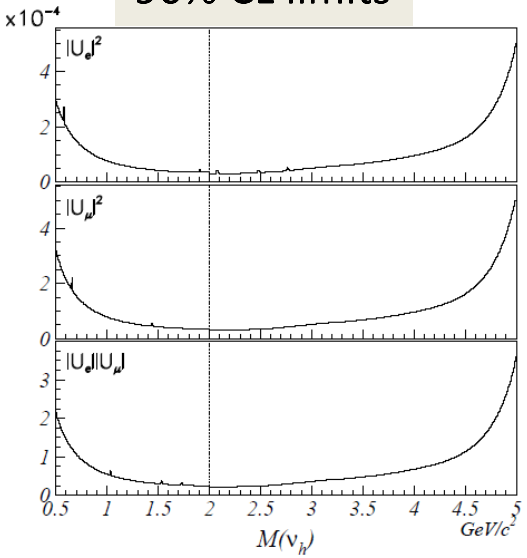
-- **BELLE** *Phys. Rev. D. 87, 071102 (2013), arXiv:1301.1105*

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

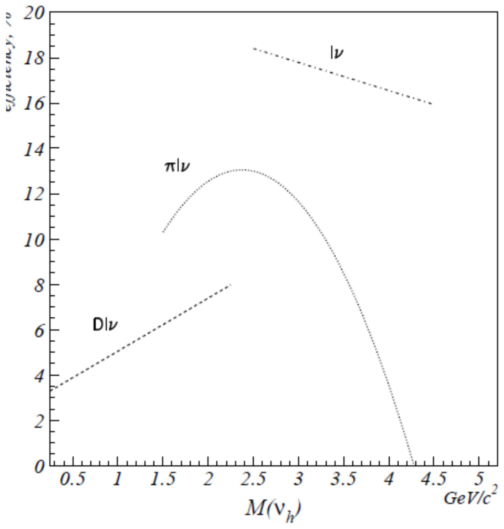
Search for ℓ_2 +($\ell_1\pi$), where ℓ_1 and π have **opposite charge and displaced vertex** for M(ν_h) =1GeV/c2 and $|U_e|^2 = |U_\mu|^2 = 10^{-4}$ the flight length is $c\tau \simeq$ 20m.

➔ 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

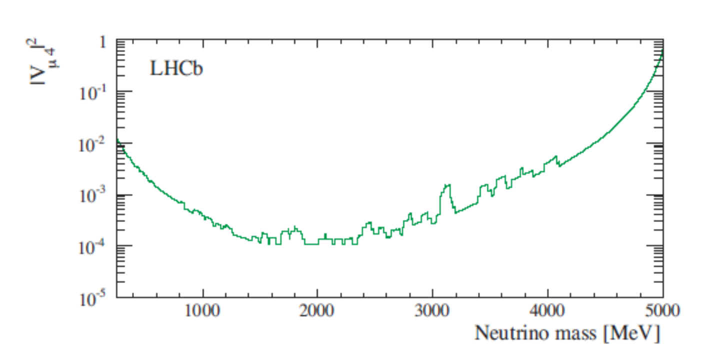


Efficiency for the search



LHCb collaboration,
PRL 112, 131802 (2014)

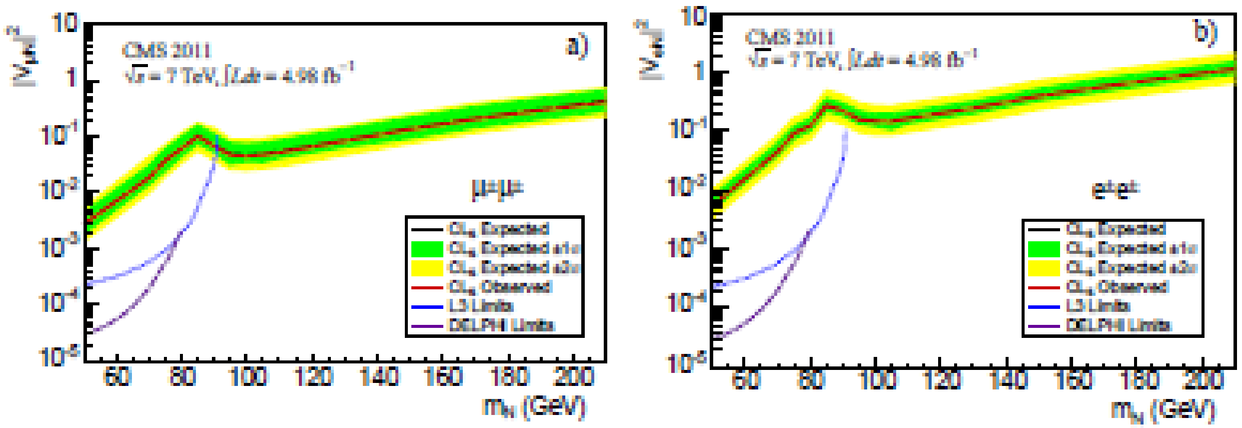
$\mathcal{B}(B^- \to \pi^+\mu^-\mu^-) < 4.0 \times 10^{-9}$ at 95%

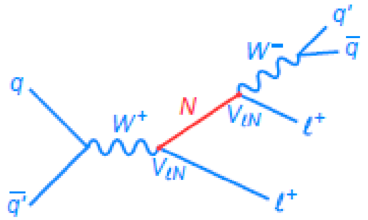


Scope for 10-100x improvement at SuperKEKb

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

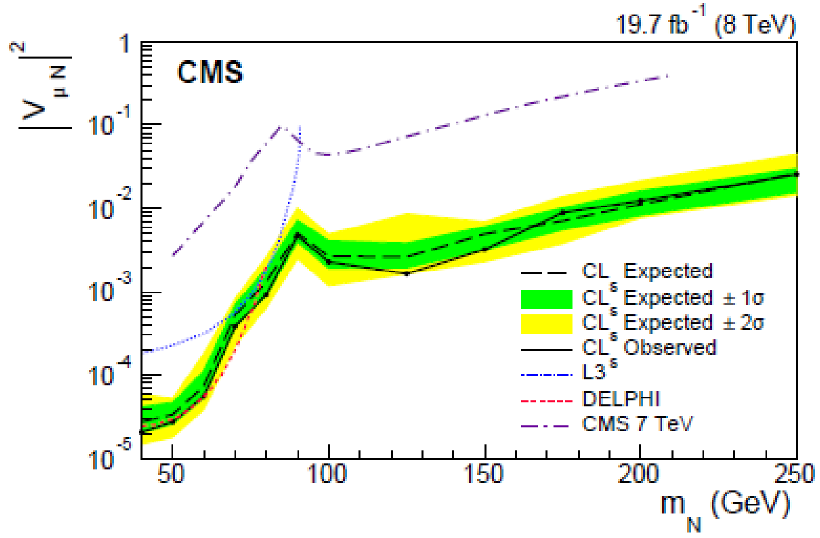
CMS search for same sign muon pairs or electron pairs at the LHC





CMS arXiv:1207.6079.

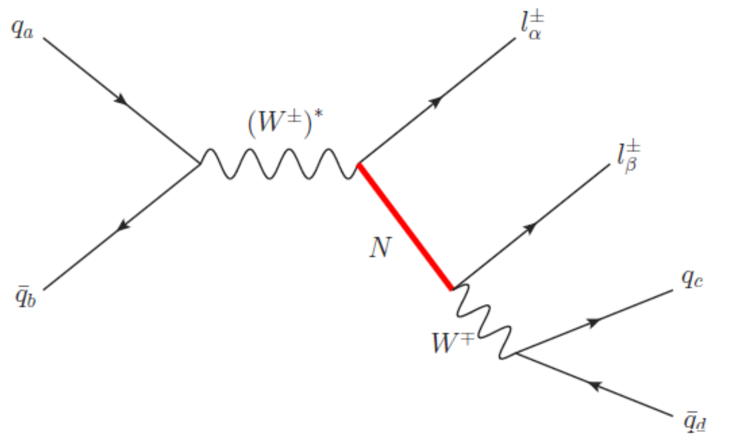
arXiv:1501.05566



Begin to match/superseed the DELPHI limit.

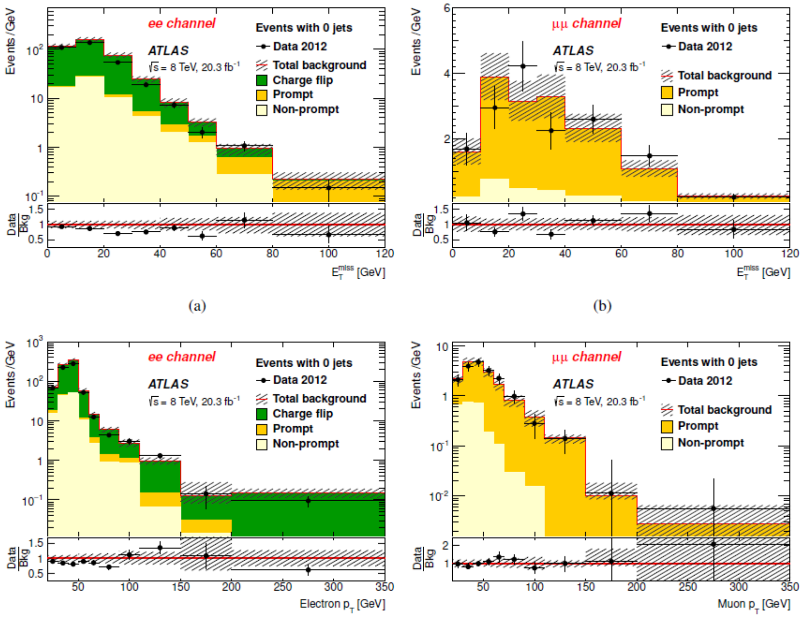
limits at $|U|^2 \sim 10^{-2-5}$ level

ATLAS search for Heavy Neutrinos at LHC *JHEP07(2015)162 arXiv:1506.06020*



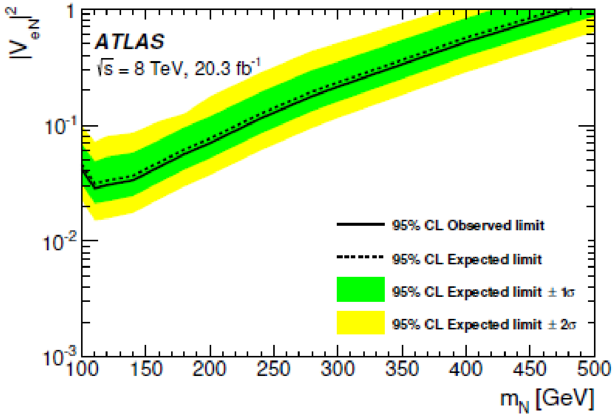
e^-e^-, e^+e^+, $\mu^-\mu^-$, $\mu^+\mu^+$ final states
(like sign, like flavour leptons)
Concentrates on m_N>100 GeV
'because <100 GeV excluded by LEP'

Charge flip significant bkgd for ee channel

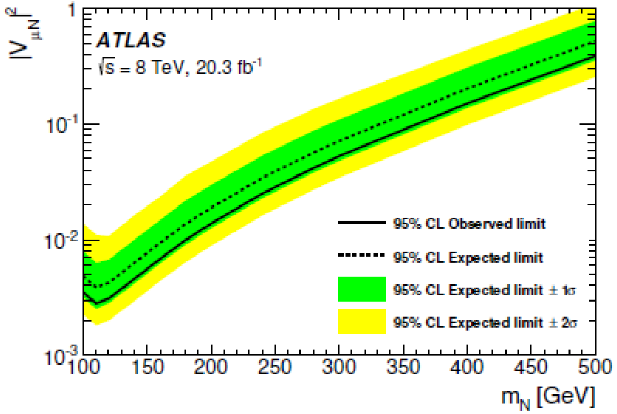


(a) (b)

(c) (d)



(b)



LHC prospects

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

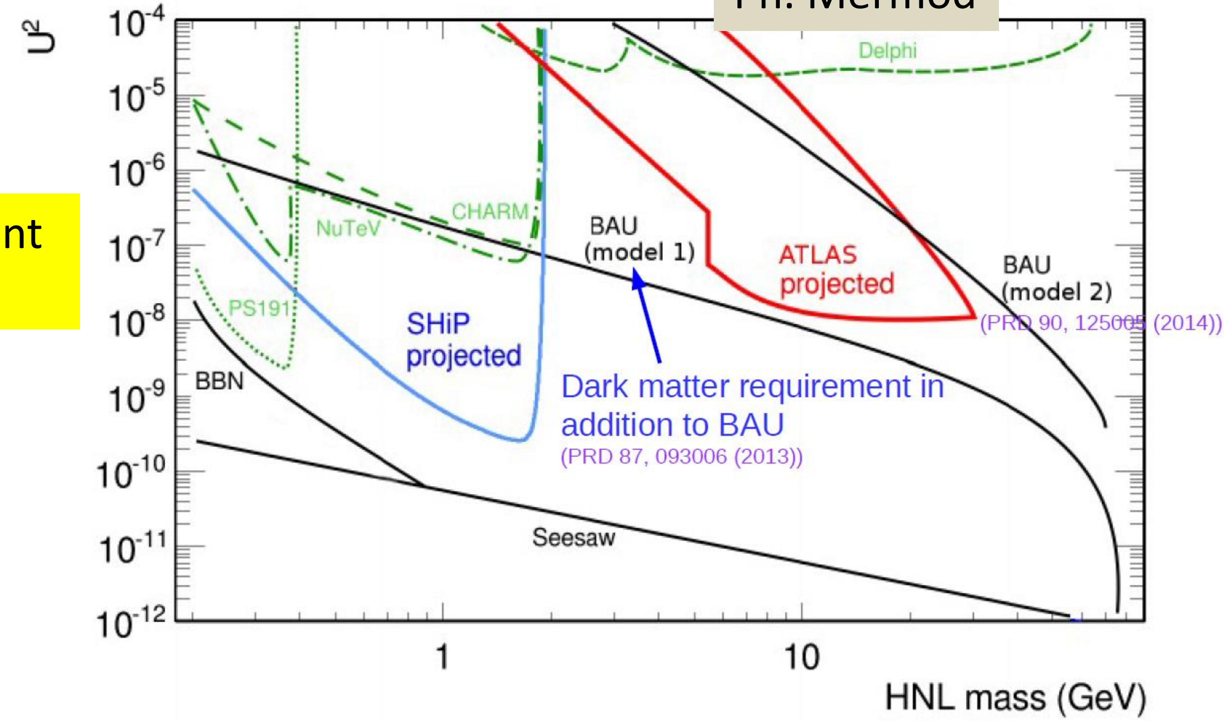
Signals of RH neutrinos with mass $\leq m_W$ could be visible if mixing angle $O(10^{-7,8})$

The keys for that region of phase space

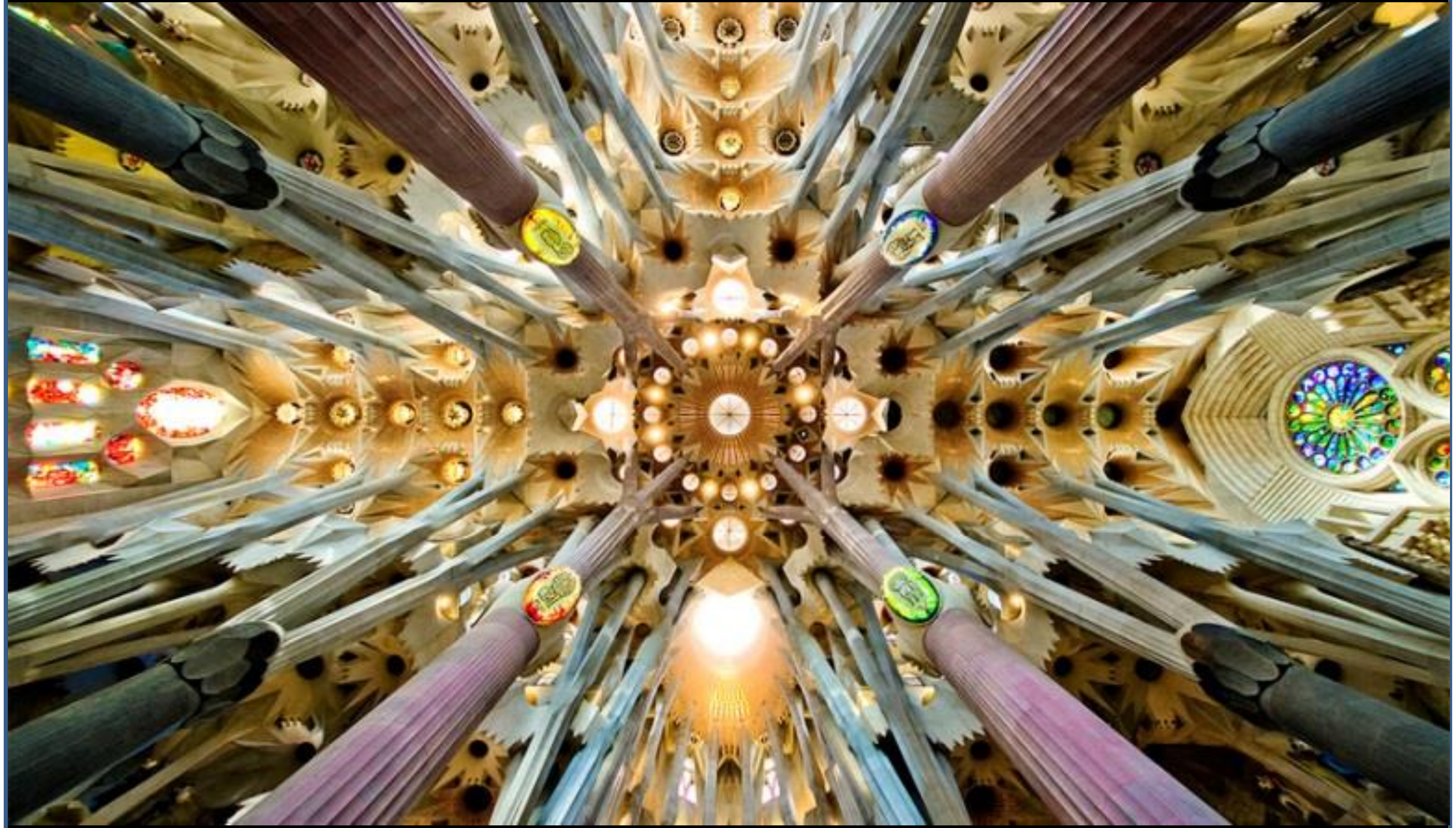
-- require **displaced vertex**
-- allow leptons of different charge and flavour
-- constrain to W mass.

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*

- ***Ultimate goal:*** **$\geq$16 T magnets**
  ***$\geq$100 TeV pp*-collider (*FCC-hh*)**

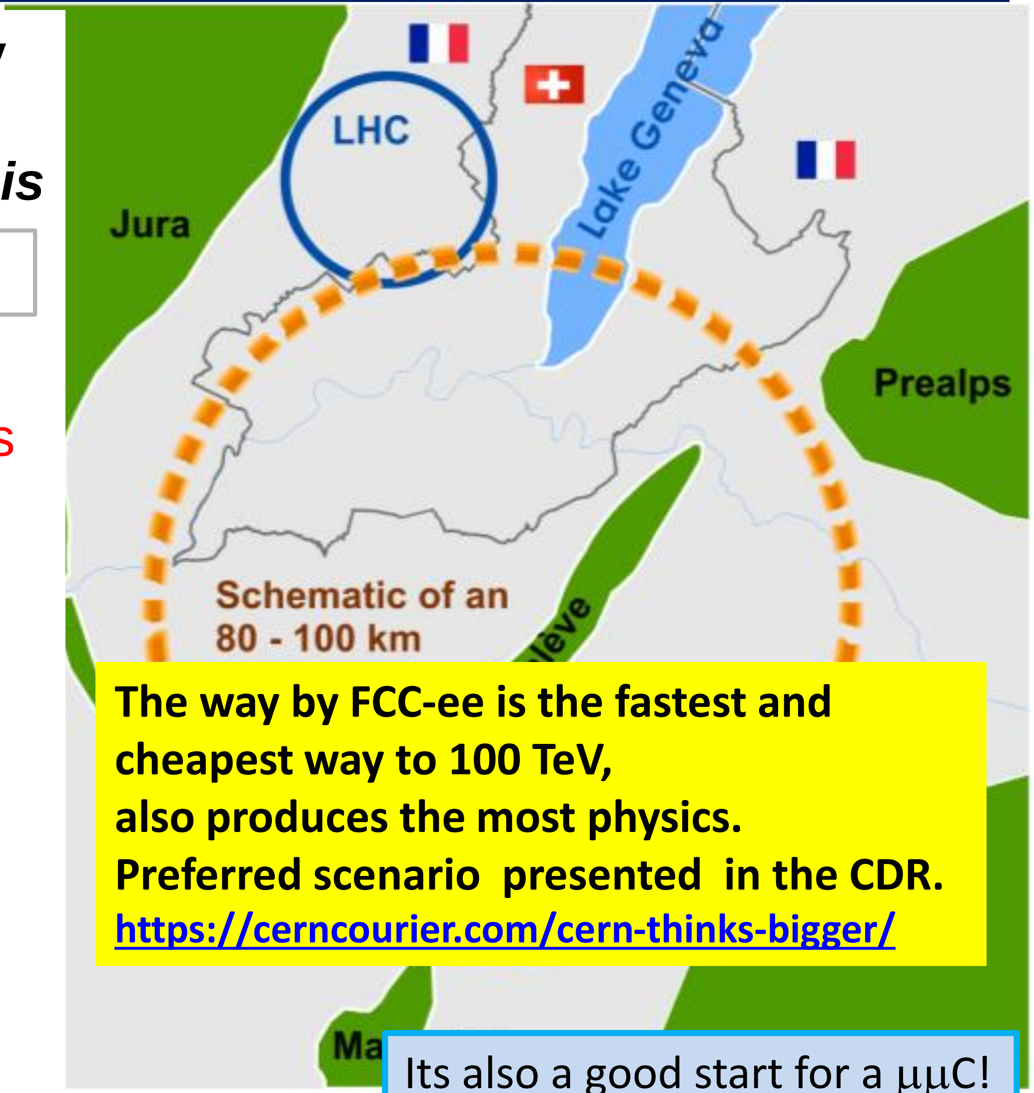
→ defining infrastructure requirements

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

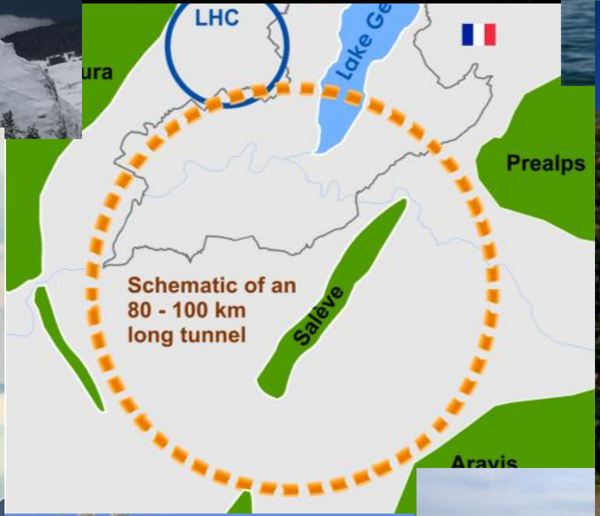
Possible addition:

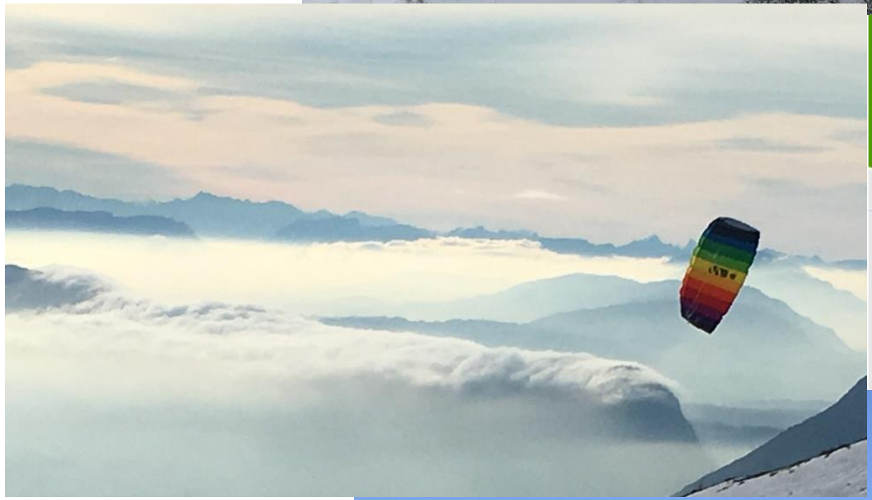
- ***p-e* (*FCC-he*) option**

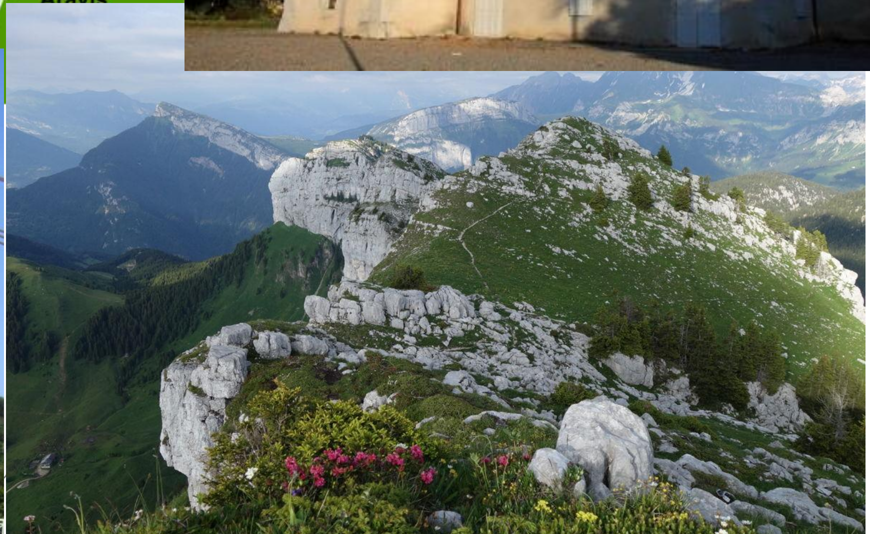


**The way by FCC-ee is the fastest and cheapest way to 100 TeV,
also produces the most physics.
Preferred scenario presented in the CDR.
https://cerncourier.com/cern-thinks-bigger/**

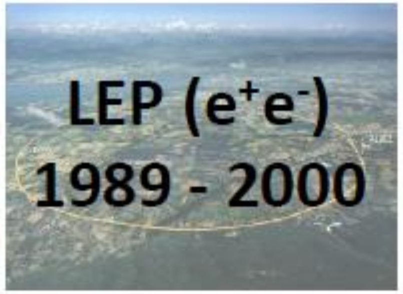
Its also a good start for a μμC!

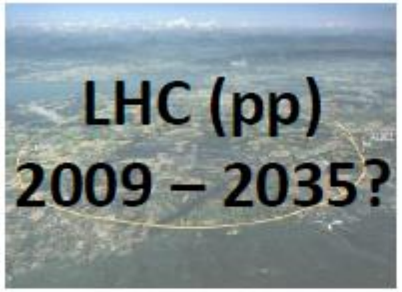

LHC
Prealps
Schematic of an
80 - 100 km
long tunnel
Saleve
Aravis





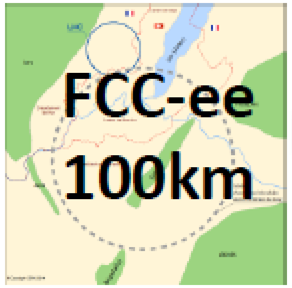
- 27km tunnel

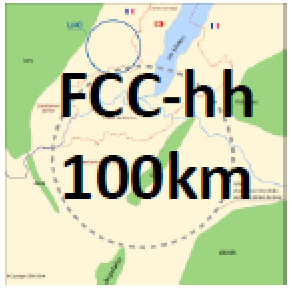




M. Aleksa

- 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

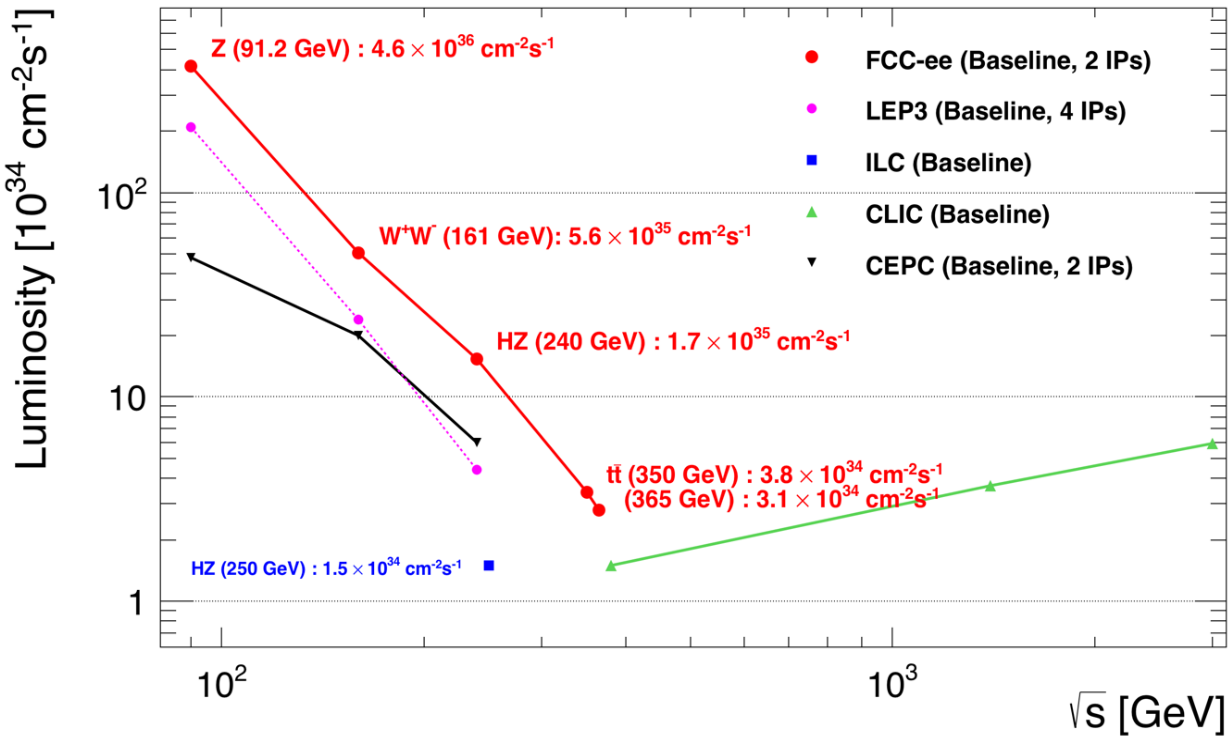
A public presentation of the main results was given on 4-5 March

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

what follows is based on slides presented at the meeting

FCC-ee

Z WW HZ tt



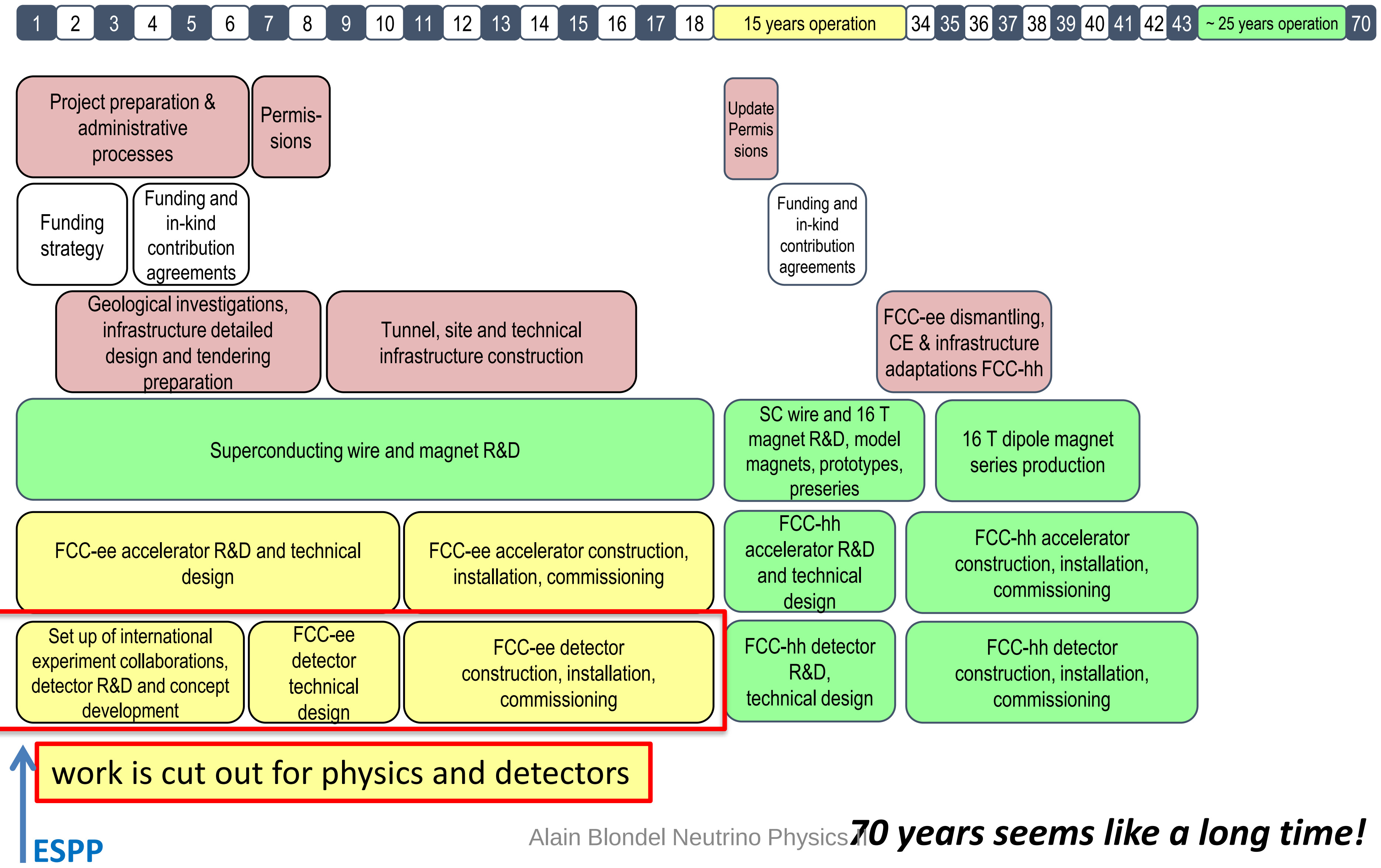
Event statistics :

E_{CM} errors:

Z peak	**E_{cm} : 91 GeV**	**$5\ 10^{12}$**	**e+e- → Z**	**LEP x 10^5**	100 keV
WW threshold	**E_{cm} : 161 GeV**	**10^8**	**e+e- → WW**	**LEP x 2.10^3**	300 keV
ZH threshold	**E_{cm} : 240 GeV**	**10^6**	**e+e- → ZH**	**Never done**	2 MeV
$t\bar{t}$ threshold	**E_{cm} : 350 GeV**	**10^6**	**e+e- → $t\bar{t}$**	**Never done**	5 MeV

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

FCC integrated project technical timeline



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:

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

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

Decay

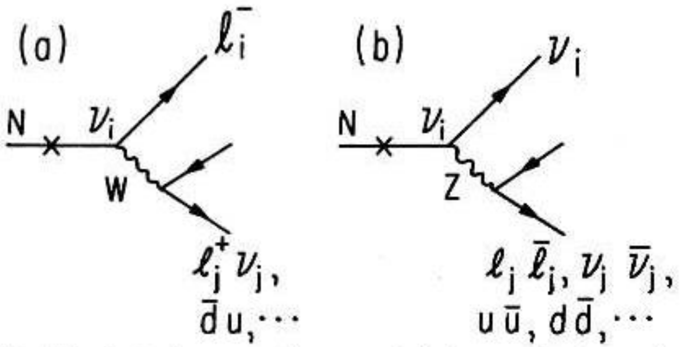


FIG. 2. Typical decays of a neutral heavy lepton via (a) charged current and (b) neutral current. Here the lepton l_i denotes e, μ, or τ.

Decay length:

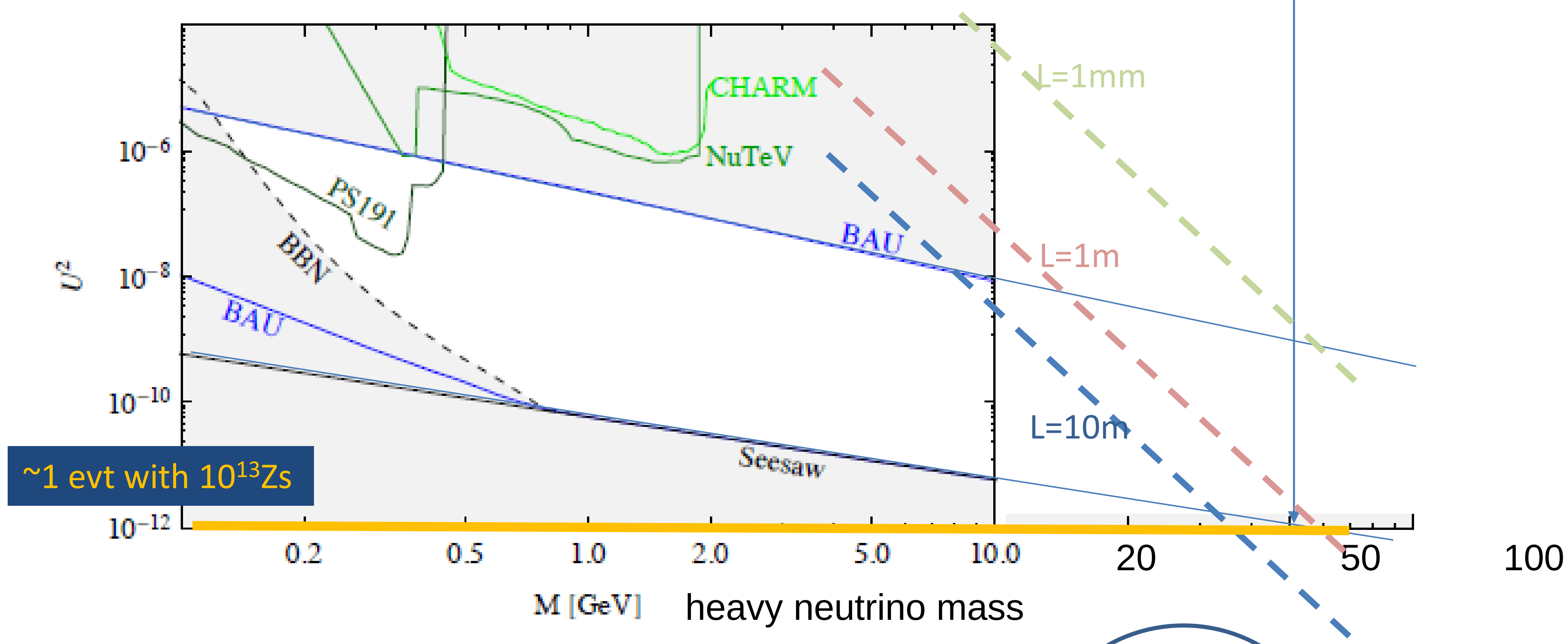
$$L \approx \frac{3 \text{ cm}}{|U|^2 \left(m_{\nu_m}(\mathrm{GeV}/c^2)\right)^6}$$

NB CC decay always leads to $\geq$ 2 charged tracks

Backgrounds : four fermion: e+e- → $W^{*+} W^{*-}$ e+e- → $Z^*(\nu\nu)$ + $(Z/\gamma)^*$

Decay length

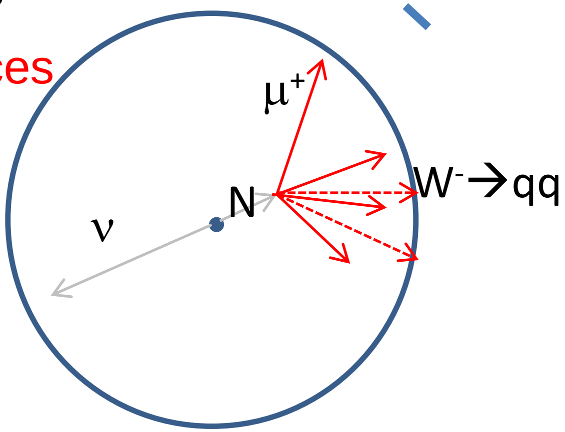
Interesting region
$|U|^2 \sim 10^{-9}$ to 10^{-12} @ 50 GeV



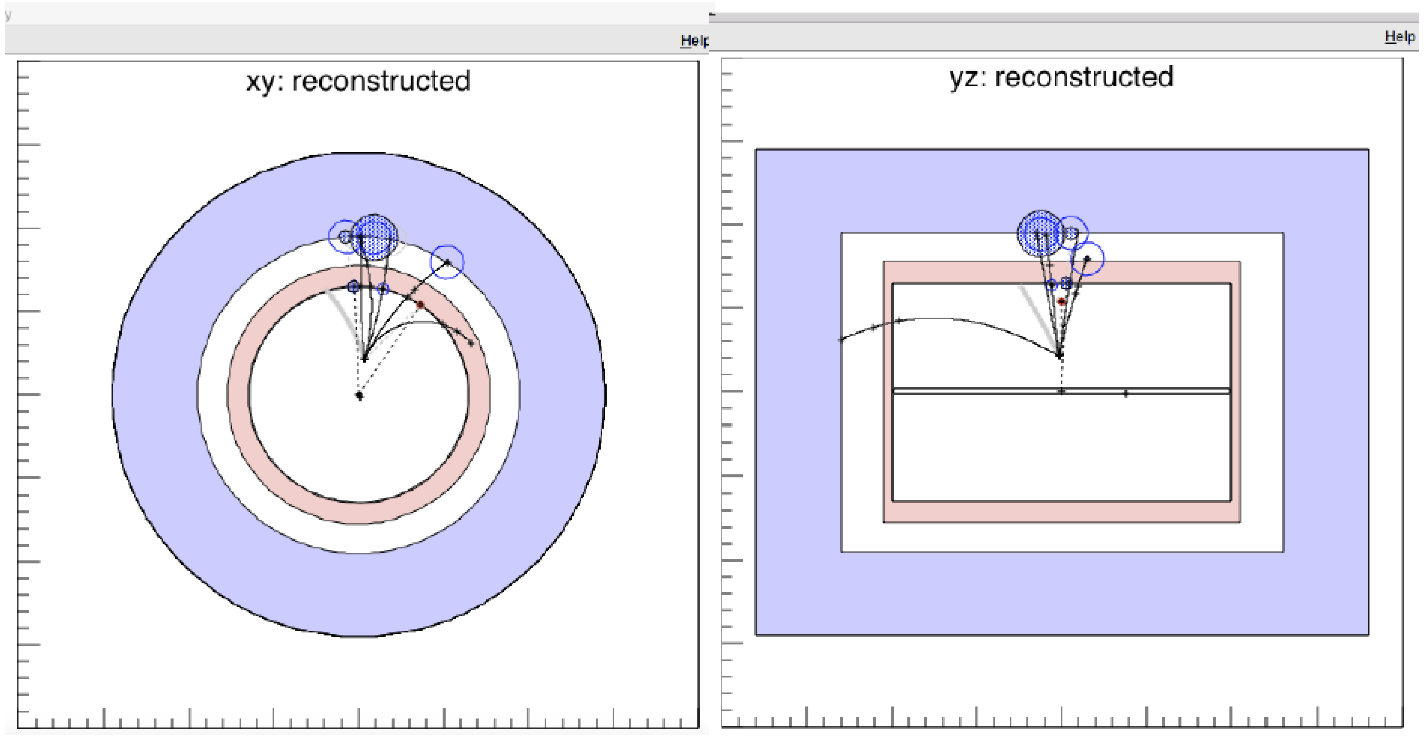
a large part of the interesting region will lead to detached vertices

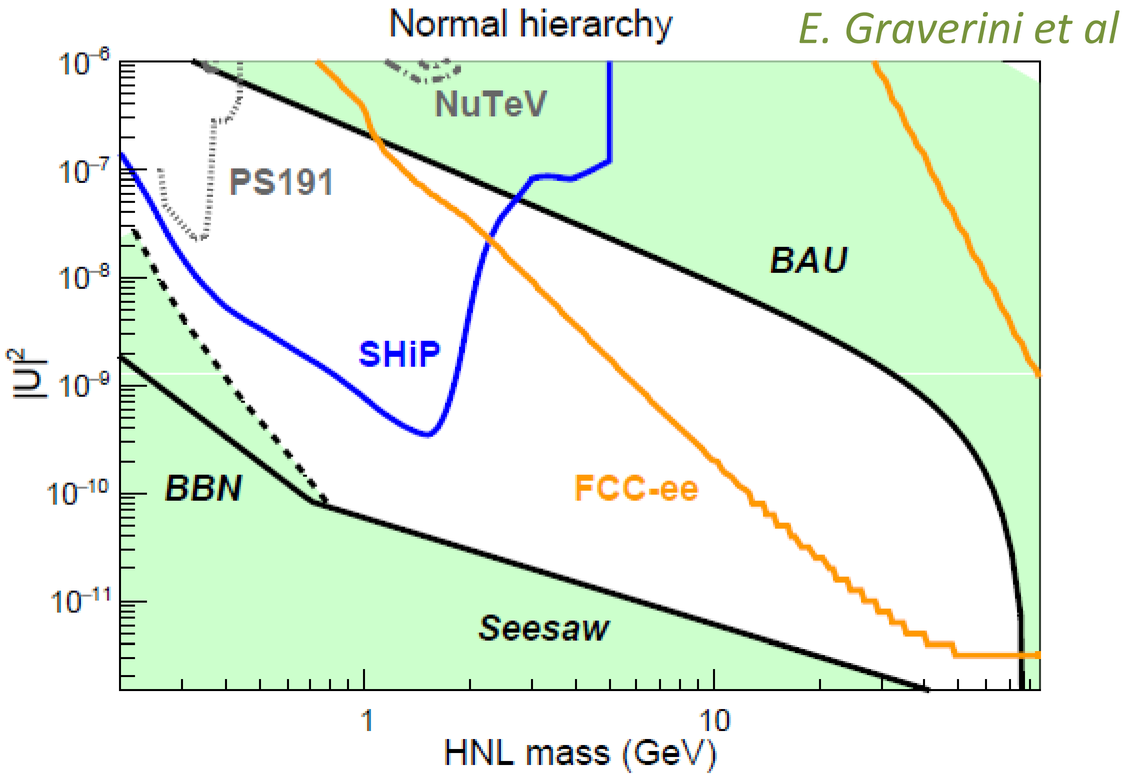
... ➔very strong reduction of background!

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

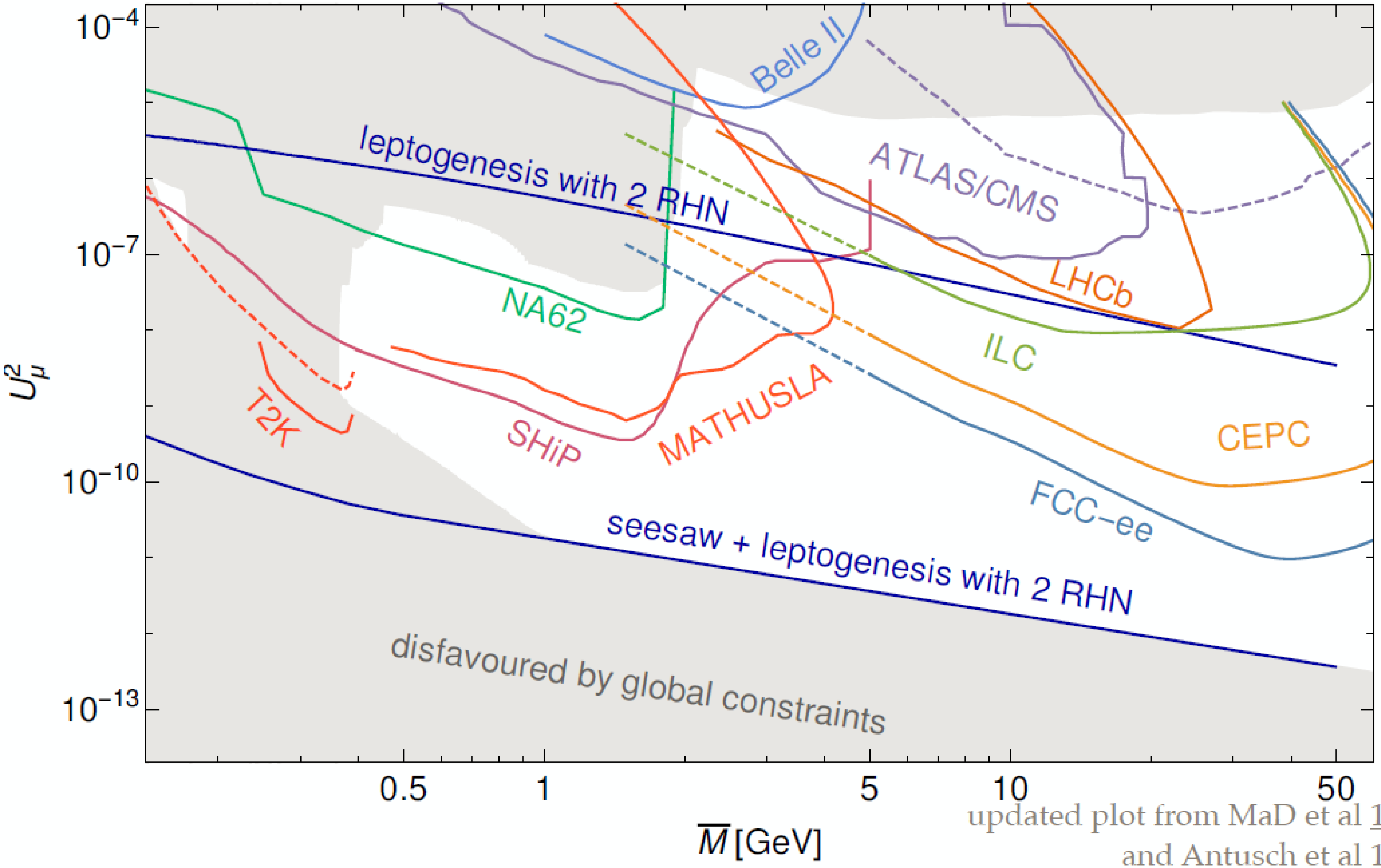




(a) Decay length 500 μm to 2 m

with 5 10^{12} Z

Constraints and Future Searches

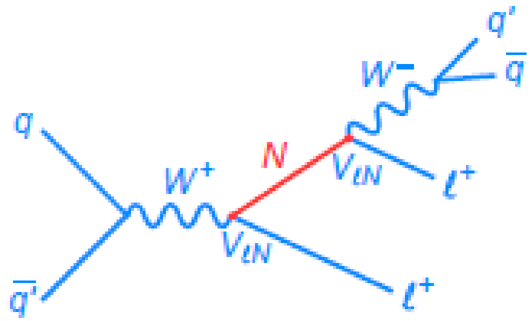


updated plot from MaD et al 1609.09069
and Antusch et al 1710.03744
cf. also Cai et al 1711.02180

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.

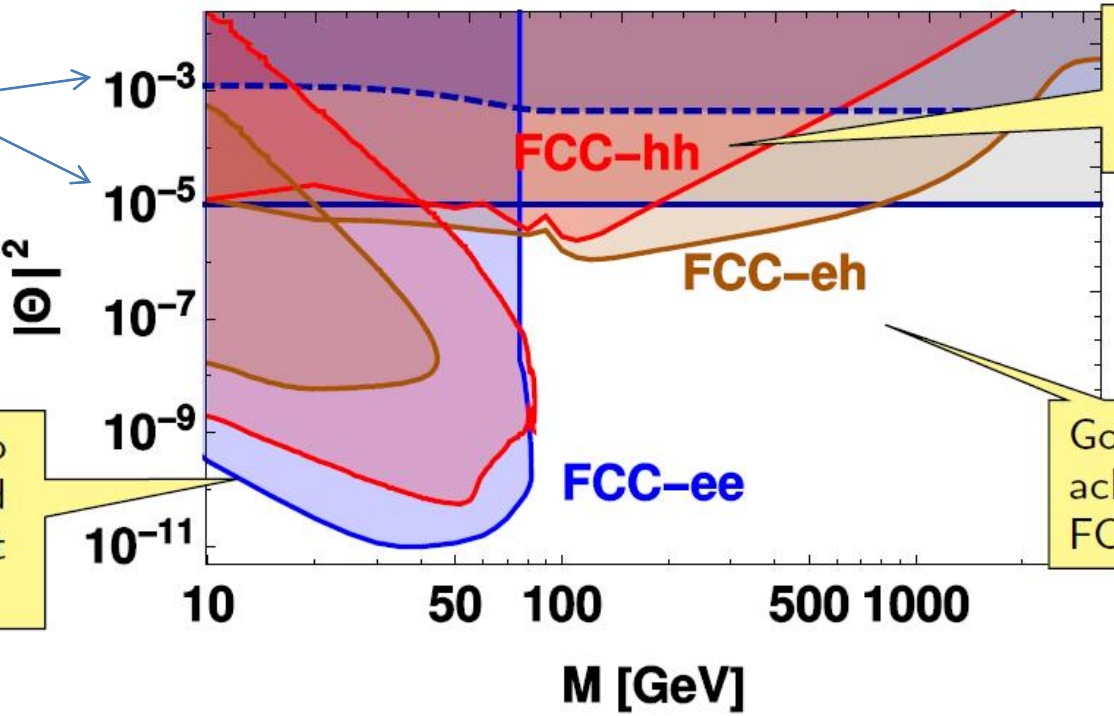
VERY interesting...

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



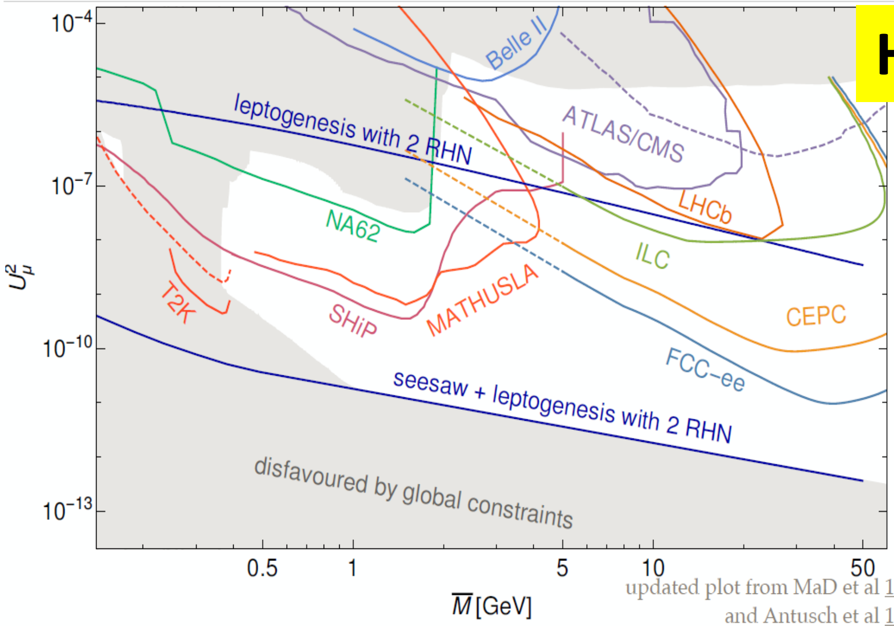
FCC-hh able to test all flavour combinations.

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

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

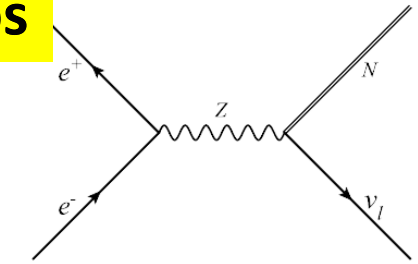
detailed study required for all FCCs – especially FCC-hh to understand feasibility at all

Heavy neutrinos



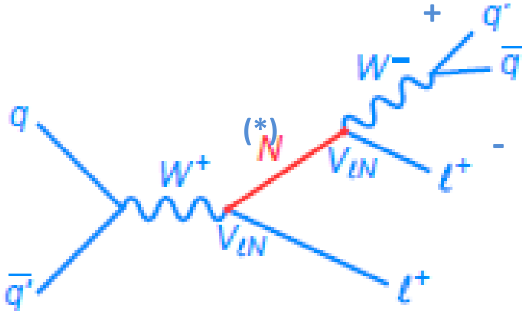
updated plot from MaD et al 1609.09069
and Antusch et al 1710.03744
cf. also Cai et al 1711.02180

FCC-ee Z



or $l^{\pm}\nu$

FCC-hh



FCC-ee

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

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

FCC-hh

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

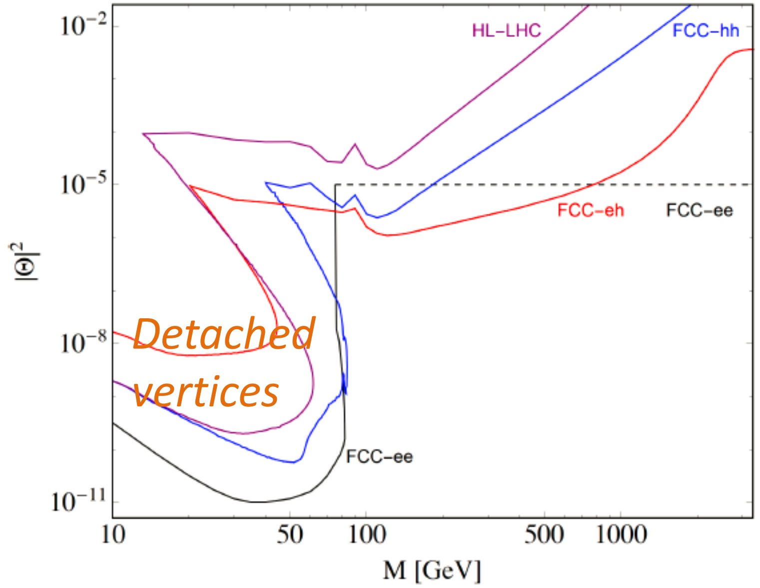
with initial and final lepton charge and flavour

FCC e-p

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

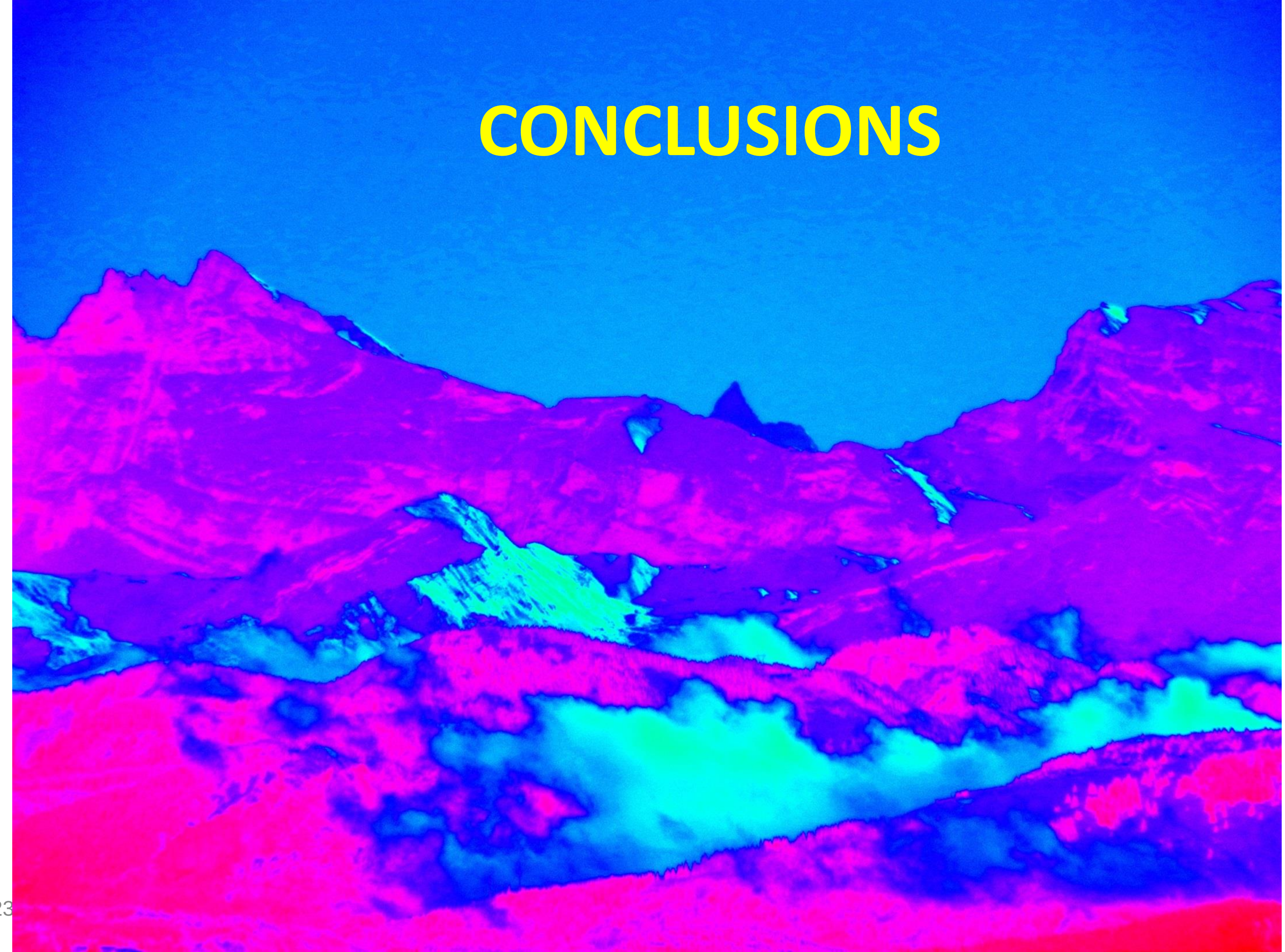
<u>Complementarity:</u>

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 $0\nu\beta\beta\beta$**
- **-- collider experiments**
- **-- astrophysical and cosmological experiments**