Neutrino Masses

Manfred Lindner

MAX-PLANCK-INSTITUT FÜR KERNPHYSIK HEIDELBERG

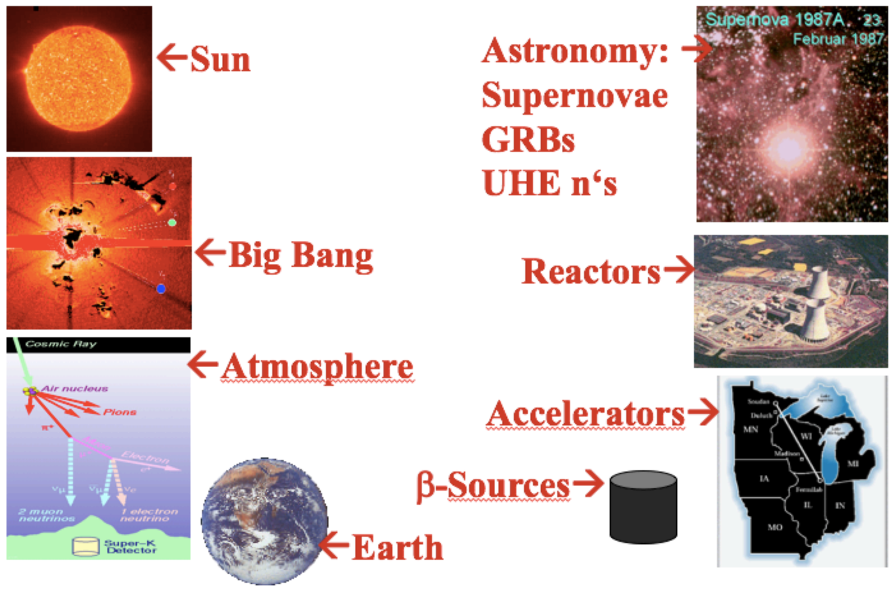
tifr

25th INTERNATIONAL CONFERENCE ON SUPERSYMMETRY AND THE UNIFICATION OF FUNDAMENTAL INTERACTIONS (SUSY17)

TATA INSTITUTE OF FUNDAMENTAL RESEARCH, MUMBAI

DECEMBER 11 - 15, 2017

- **Many interesting aspects of neutrino masses**
  - requires some new physics (how minimal / extended?)
  - lever arm to other new physics (neutrino portals)
  - why three generations?
  - precise flavour information ←→ understand masses & mixings
  - may be related to other topics/problems (BAU, DM, ...)
  - UV completion and gauge unification
  - ...
- **AND: learn about ν sources ... ➔**



All-time INSPIRE statistics
- Higgs: 17,437
- top: 7,933
- WIMP: 990
- supersymmetry + SUSY: 13,766
- neutrino: 37,267

Directions in Neutrino Physics

3 active ν's only: precise masses and mixings

- oscillations
- absolute mass ⇔ how precise should we know?
- Dirac or Majorana

more than 3 neutrinos

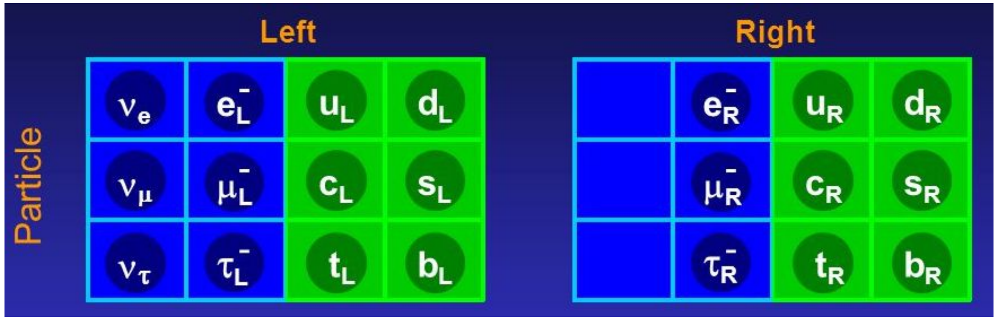
- sterile neutrinos
- L-violation ⇔ any one of them a major discovery!
- NSIs
- large magnetic moments
- …

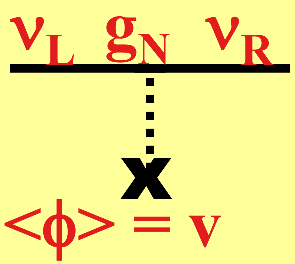
3f ➔ precision: θ_{ij} , m_1, Δm_{ij}^2, MH, CP

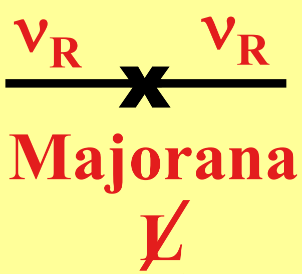
beyond 3f: over-constraining, 0νββ, NSI's, mag. moments, coherent scattering, ...

Bottom-up: Minimal Neutrino Masses

Simplest & suggestive possibility:
add 3 right handed singlets (1_L)







$$\begin{pmatrix}\bar{\nu}_L & \bar{\nu}_R^{c}\end{pmatrix}\begin{pmatrix}0 & m_D \\ m_D & M_R\end{pmatrix}\begin{pmatrix}\nu_L^{c} \\ \nu_R\end{pmatrix}$$

like quarks and charged leptons → Dirac mass terms (including NMS mixing)

9 param. and new ingredients:
1) Majorana mass = scales
2) lepton number violation

6x6 block mass matrix block diagonalization M_R heavy → 3 light ν's

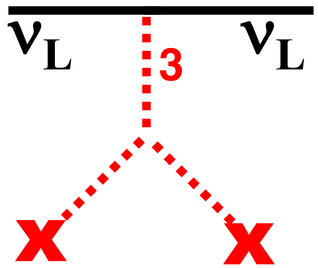
Beyond the SM: SM+ see-saw

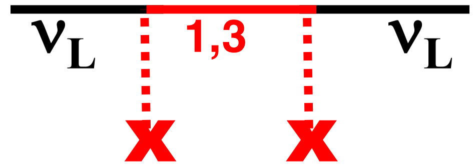
- **L-violation: A henn & egg problem for embeddings**
- **Why N=3 right singlets ν_R? – other number possible**

Other Possibilities

add scalar triplets (3_L) or add fermionic (1_L) or (3_L)

➔left-handed Majorana mass term: $M_L LL^c$



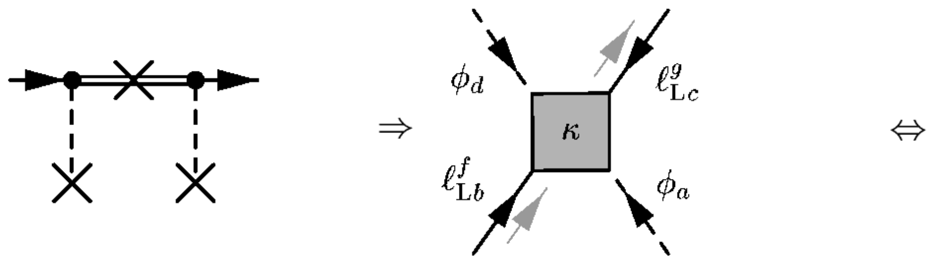


Both ν_R and new singlets / triplets:

➔ see-saw type II, III

$$m_\nu = M_L - m_D M_R^{-1} m_D^T$$

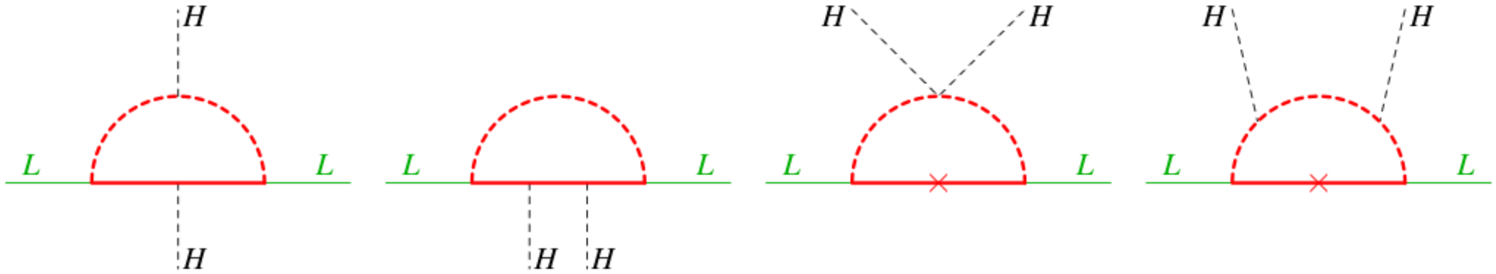
Higher dimensional operators: d=5, …



$$\mathcal{L}_{mass} = \kappa \cdot \overline{\nu}_L^C \nu_L \Phi^T \Phi$$

➔ $M_L L\overline{L}^c$

Radiative neutrino mass generation



Many more: combine with LR, SUSY, extra d, …

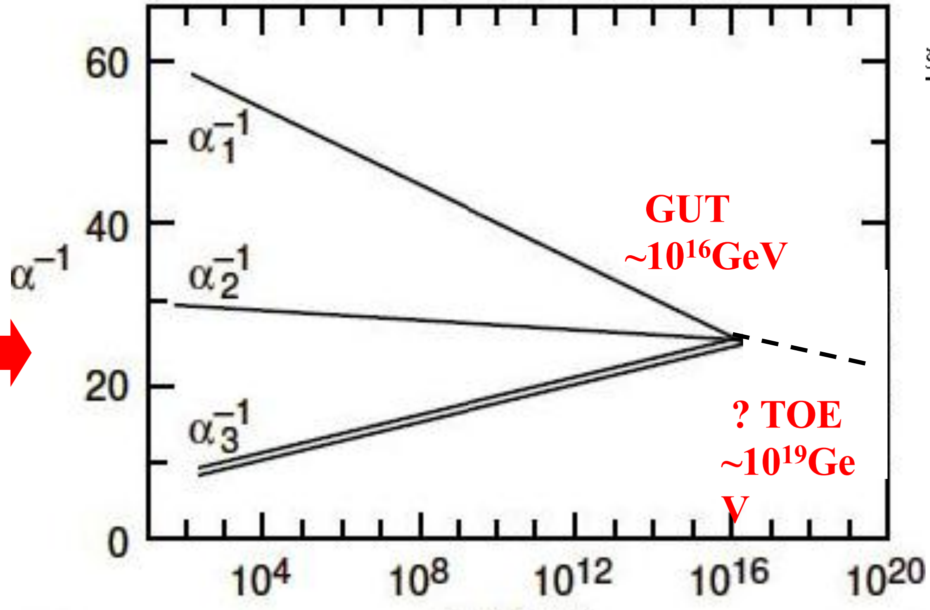
→ **huge number of possibilities...**
... but we know only two Δm^2... (plus mass & unitarity bounds)

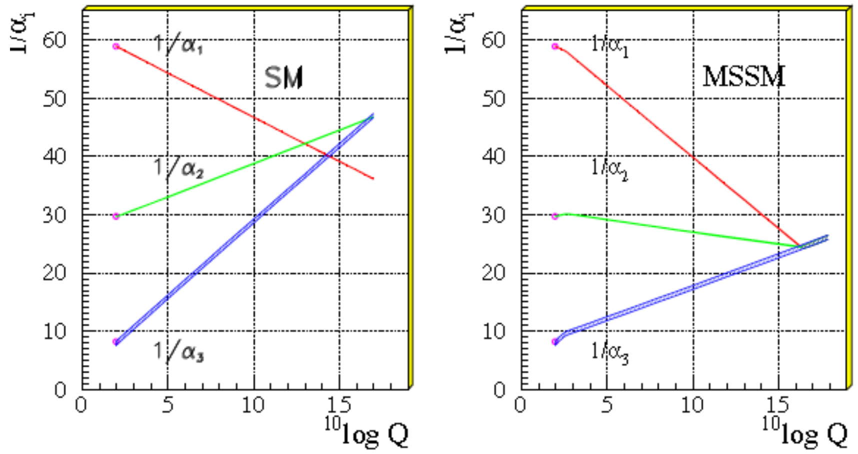
→ **which new scale? high scale (GUT, L-viol.) or low (TeV see-saw)**

→ **neutrino masses can/may solve two of the SM problems:**
- **leptogenesis as explanation of BAU**
- **keV sterile neutrinos as excellent warm dark matter candidate**

→ **often connections to LFV, LHC, precision observables, DM**

Extrapolation to highest Energies





gauge bosons ➔

Higgs ➔ gauge hierarchy problem: $\delta m_H^2 \sim \Lambda^2$

quarks leptons ➔ flavour problem: 3 generations
many parameters (m_i ,mixings)
unification into GUTs

$m_\nu=(m^D)^T M_R^{-1} m_D$

- SM particles fit nicely into GUT representations
- charge quantization
  ➔ points to unification
  ➔ proton decay…

Λ_{GUT} – see-saw scale?

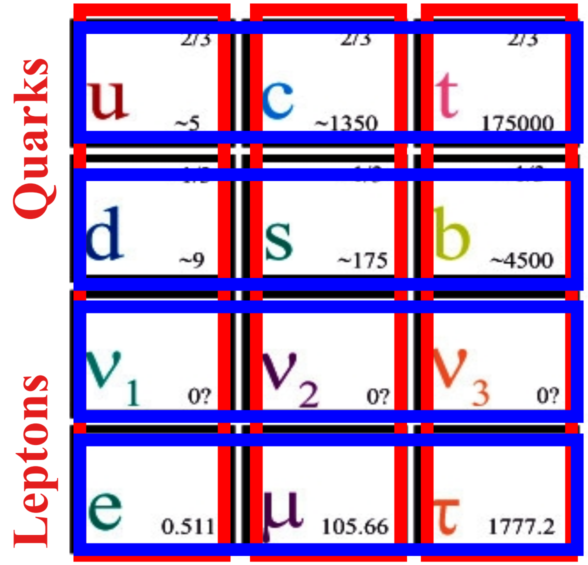
precision➔SUSY @TeV

incomplete: m_ν, DM

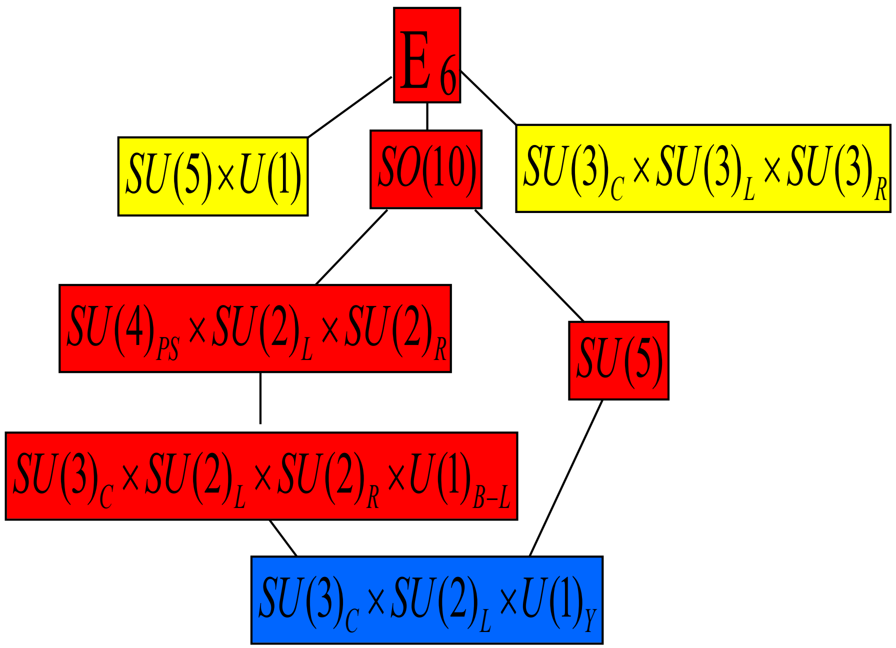
The larger Picture

Gauge unification suggests GUTs

- unified gauge group
- unified particle multiplets ←→ ν_R
  - ➔ Q,L Yukawa couplings connected
  - ➔ proton decay , …
- generations are just copies



1. 2. 3. generation



generations ←→ symmetries

- 3 generations → representation

- regularities in q&l parameters

➔ flavour symmetries:

A4, S3, D5, ...

➔ very many possibilities & publications...

3 Light massive Neutrinos (...assumed)

Mass & mixing parameters: m_1 , Δm^2_{21}, $|\Delta m^2_{31}|$, sign(Δm^2_{31})

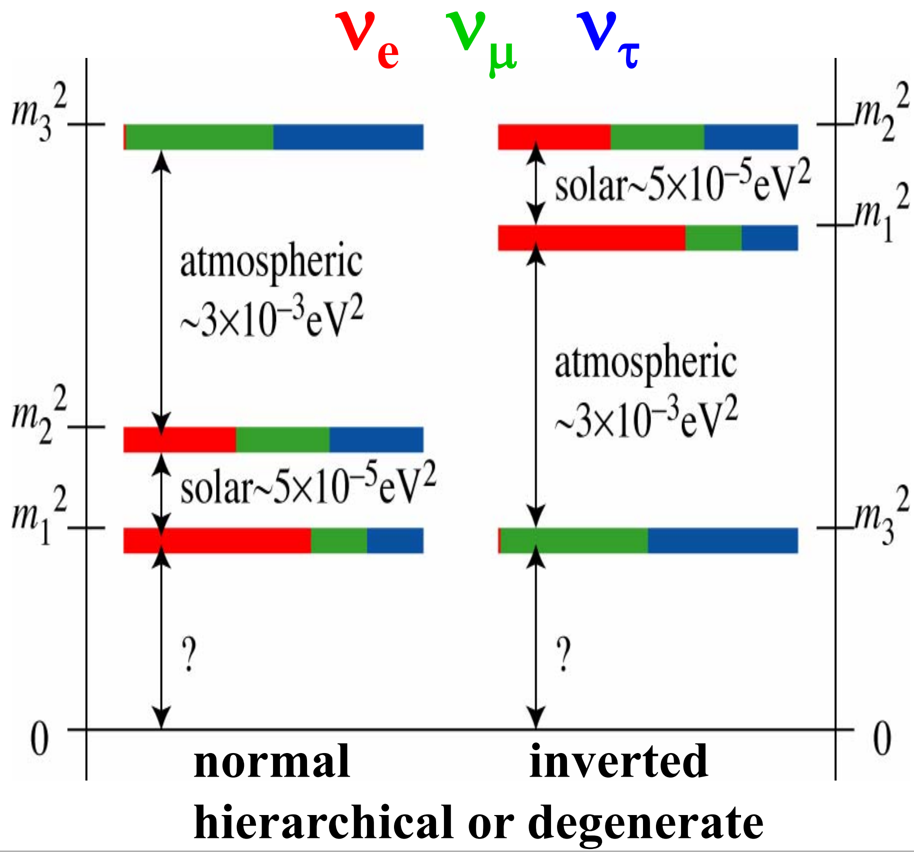
$$U = \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta} & c_{23}c_{13} \end{pmatrix} \text{diag}(e^{i\alpha}, e^{i\beta}, 1)$$

Known:

- two Δm^2, three mixing angles
- bounds on m_1
- weak indications for δ_{CP} and MH

questions:

➔ Dirac ~ SM / Majorana = BSM
➔ mass scale: m_1
➔ mass ordering: sgn(Δm^2_{31})
➔ is θ_{23} maximal?
➔ CP violation



The Status of Neutrino Parameters (assume 3 flavours)

See e.g. Esteban, Gonzalez-Garcia, Maltoni, Martinez-Soler, Schwetz

	Normal Ordering (best fit)		Inverted Ordering ($\Delta\chi^2 = 0.83$)		Any Ordering
	bfp $\pm 1\sigma$	3σ range	bfp $\pm 1\sigma$	3σ range	3σ range
$\sin^2\theta_{12}$	$0.306^{+0.012}_{-0.012}$	$0.271 \to 0.345$	$0.306^{+0.012}_{-0.012}$	$0.271 \to 0.345$	$0.271 \to 0.345$
$\theta_{12}/^\circ$	$33.56^{+0.77}_{-0.75}$	$31.38 \to 35.99$	$33.56^{+0.77}_{-0.75}$	$31.38 \to 35.99$	$31.38 \to 35.99$
$\sin^2\theta_{23}$	$0.441^{+0.027}_{-0.021}$	$0.385 \to 0.635$	$0.587^{+0.020}_{-0.024}$	$0.393 \to 0.640$	$0.385 \to 0.638$
$\theta_{23}/^\circ$	$41.6^{+1.5}_{-1.2}$	$38.4 \to 52.8$	$50.0^{+1.1}_{-1.4}$	$38.8 \to 53.1$	$38.4 \to 53.0$
$\sin^2\theta_{13}$	$0.02166^{+0.00075}_{-0.00075}$	$0.01934 \to 0.02392$	$0.02179^{+0.00076}_{-0.00076}$	$0.01953 \to 0.02408$	$0.01934 \to 0.02397$
$\theta_{13}/^\circ$	$8.46^{+0.15}_{-0.15}$	$7.99 \to 8.90$	$8.49^{+0.15}_{-0.15}$	$8.03 \to 8.93$	$7.99 \to 8.91$
$\delta_{CP}/^\circ$	261^{+51}_{-59}	$0 \to 360$	277^{+40}_{-46}	$145 \to 391$	$0 \to 360$
$\frac{\Delta m^2_{21}}{10^{-5}\ \text{eV}^2}$	$7.50^{+0.19}_{-0.17}$	$7.03 \to 8.09$	$7.50^{+0.19}_{-0.17}$	$7.03 \to 8.09$	$7.03 \to 8.09$
$\frac{\Delta m^2_{3\ell}}{10^{-3}\ \text{eV}^2}$	$+2.524^{+0.039}_{-0.040}$	$+2.407 \to +2.643$	$-2.514^{+0.038}_{-0.041}$	$-2.635 \to -2.399$	$\begin{bmatrix} +2.407 \to +2.643 \\ -2.629 \to -2.405 \end{bmatrix}$

Absolute mass limits:

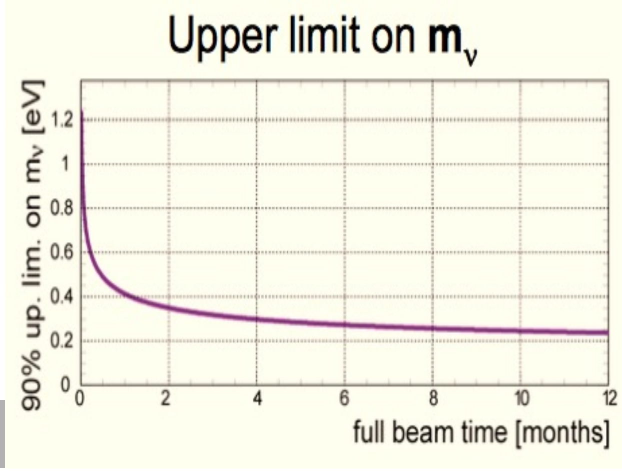
Tritium decay: Mainz and Troitsk experiments: $m_1 < 2.2$ eV

Cosmology: 0.17-0.25 eV

Future:

KATRIN ➔ will start measurements soon ➔ 0.2eV

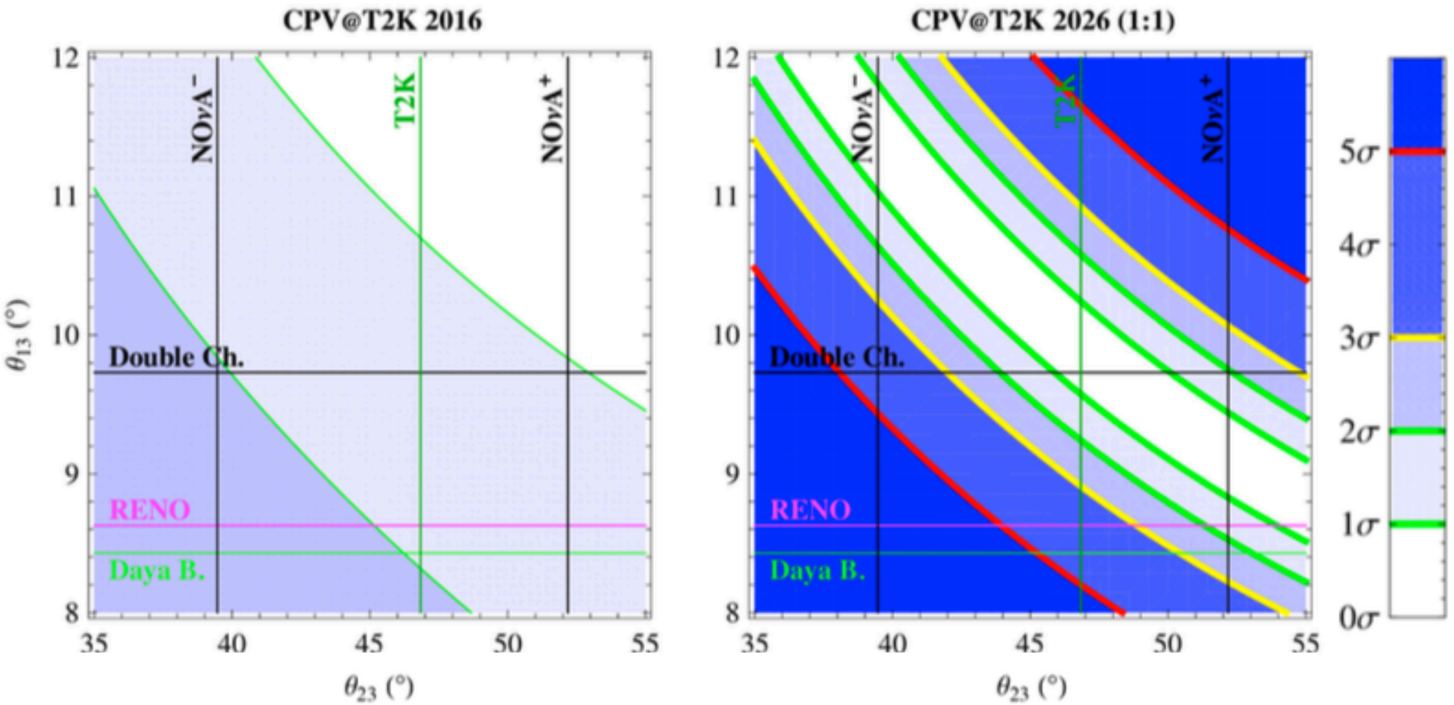
ECHO, Project8, …



The future of three Neutrino Oscillations

Precision oscillation physics now and in the next years

Now: **Reactors: Double Chooz, Daya Bay, RENO + Beams: T2K, NOνA**



1709.10252
Rodejohann, ML, Xu

➔ global fits...: better θ_{ij} and certain significance for δ_{CP} (no mass hierarchy)

Future: JUNO, T2HK, DUNE, PINGU, ORCA, …

Precision ←→ how much do we learn about flavour, fermion masses, …?
Depends on obtained precision and values: E.g. $\delta_{CP} = 0 \pm 1^\circ$ or $\delta_{CP} = 76 \pm 1^\circ$

Extended Scenarios: E.g. N times ν_R

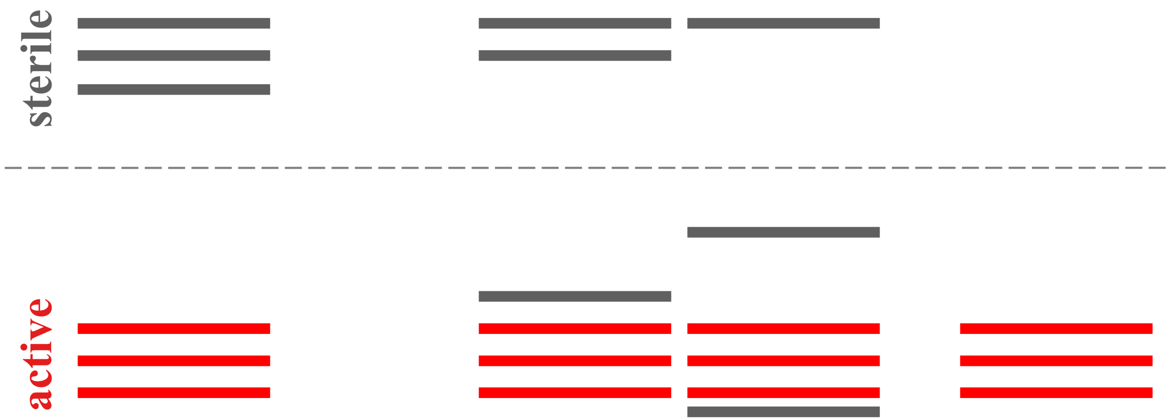
3 — 0 … N — 3x3 matrix — 3xN — NxN

$$\begin{pmatrix} \bar{\nu}_L & \bar{\nu}^c_R \end{pmatrix} \begin{pmatrix} M_L & m_D \\ m_D & M_R \end{pmatrix} \begin{pmatrix} \nu^c_L \\ \nu_R \end{pmatrix}$$

- N per se arbitrary
- M_L, m_D, M_R could have almost any form / values:
  - zeros (symmetries)
  - tiny corrections
  - scales: M_W, M_{GUT}, …

➔ diagonalization: 3+N EV

M_L=0, m_D=O(GeV) M_R=high: see-saw	M_R singular singular-SS	M_L=M_R=0 Dirac



data: 3x3 PMNS matrix almost unitary (few %)

UPMNS ≃

$$\begin{pmatrix} \begin{pmatrix} 0.8 & 0.5 & 0.1 \\ 0.5 & 0.6 & 0.7 \\ 0.3 & 0.6 & 0.7 \end{pmatrix} & \begin{pmatrix} O(\varepsilon) \end{pmatrix} \\ \begin{pmatrix} O(\varepsilon) \end{pmatrix} & \begin{pmatrix} O(1) \end{pmatrix} \end{pmatrix}$$

Antusch, Fischer

…at most small admixtures of sterile neutrinos
➔ weak hints for sterile neutrinos:

Particle Physics: LSND,Gallium, MiniBooNE, reactor anomaly,…

BBN: Extra ν's possible: $N_\nu \simeq 3.7 \pm 1$

Astrophysics: keV-ish sterile neutrinos could explain pulsar kicks

BUT: Tensions with cosmology…

How to compare 2σ in cosmology with 2σ
in particle physics? H from Planck and others…

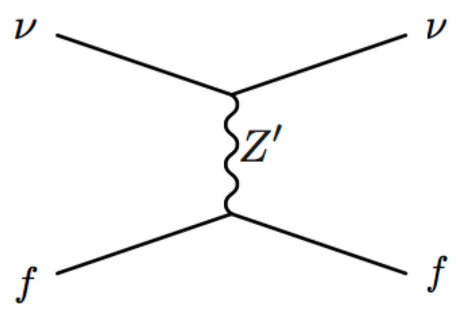
$$N_{\rm eff} = 3.32 \pm 0.27 \ (68\% CL)$$
$$\sum m_\nu < 0.28 \ {\rm eV} \ (95\% CL)$$

Certainly most hints are not true, but one would be enough:

- ➔ **various IMPORTANT experiments results next year ➔ exciting times…**
- ➔ **sterile neutrinos remain an option even if nothing found!**

Searches for new Physics: NSI's

NSI's ←→ new physics at high scales which are integrated out: "ν portal"
Z', new scalars, … ➔ ε_{ij}



$$\mathcal{L}_{NSI} \simeq \epsilon_{\alpha\beta} 2\sqrt{2} G_F (\bar{\nu}_{L\beta}\, \gamma^{\rho}\, \nu_{L\alpha})(\bar{f}_L \gamma_{\rho} f_L)$$

$$\frac{d\sigma}{dT}(E_\nu, T) = \frac{G_F^2 M}{\pi}\left(1 - \frac{MT}{2E_\nu^2}\right) \times \left\{\left[Z(g_V^p + 2\varepsilon_{ee}^{uV} + \varepsilon_{ee}^{dV}) + N(g_V^n + \varepsilon_{ee}^{uV} + 2\varepsilon_{ee}^{dV})\right]^2 + \sum_{\alpha=\mu,\tau}\left[Z(2\varepsilon_{\alpha e}^{uV} + \varepsilon_{\alpha e}^{dV}) + N(\varepsilon_{\alpha e}^{uV} + 2\varepsilon_{\alpha e}^{dV})\right]^2\right\}$$

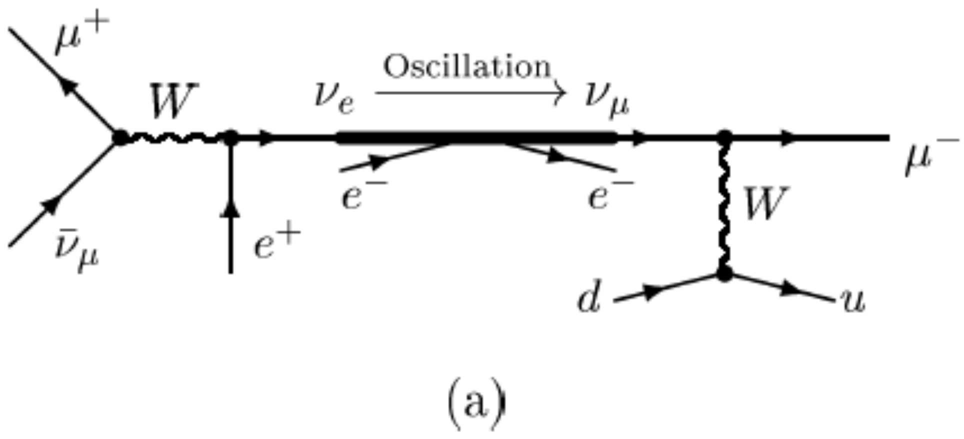
Barranco et al. 2005

$$|\epsilon| \simeq \frac{M_W^2}{M_{NSI}^2}$$

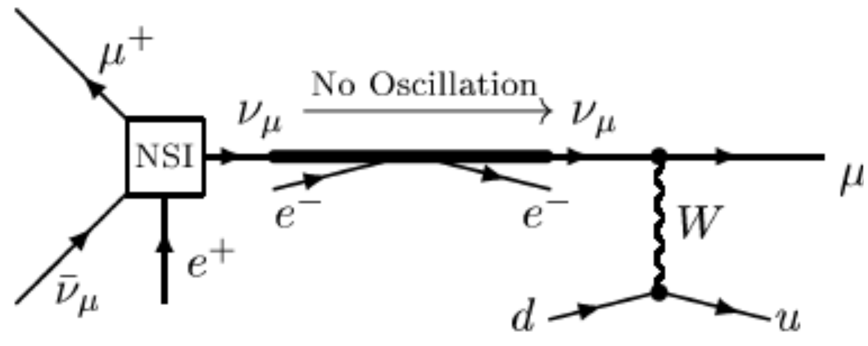
Measure ε = 0.01 ←→ TeV scales
➔ competitive method to test TeV physics

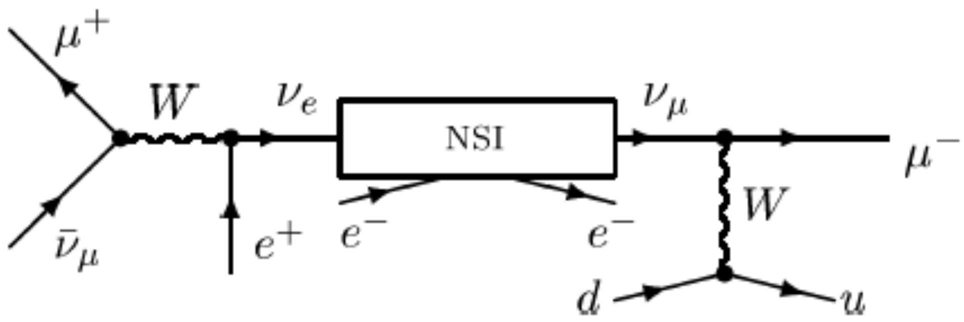
NSIs interfere with Oscillations

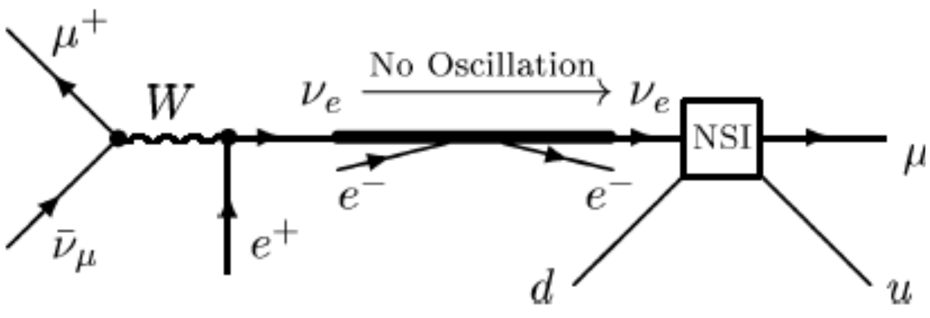
the "golden" oscillation channel



NSI contributions to the "golden" channel

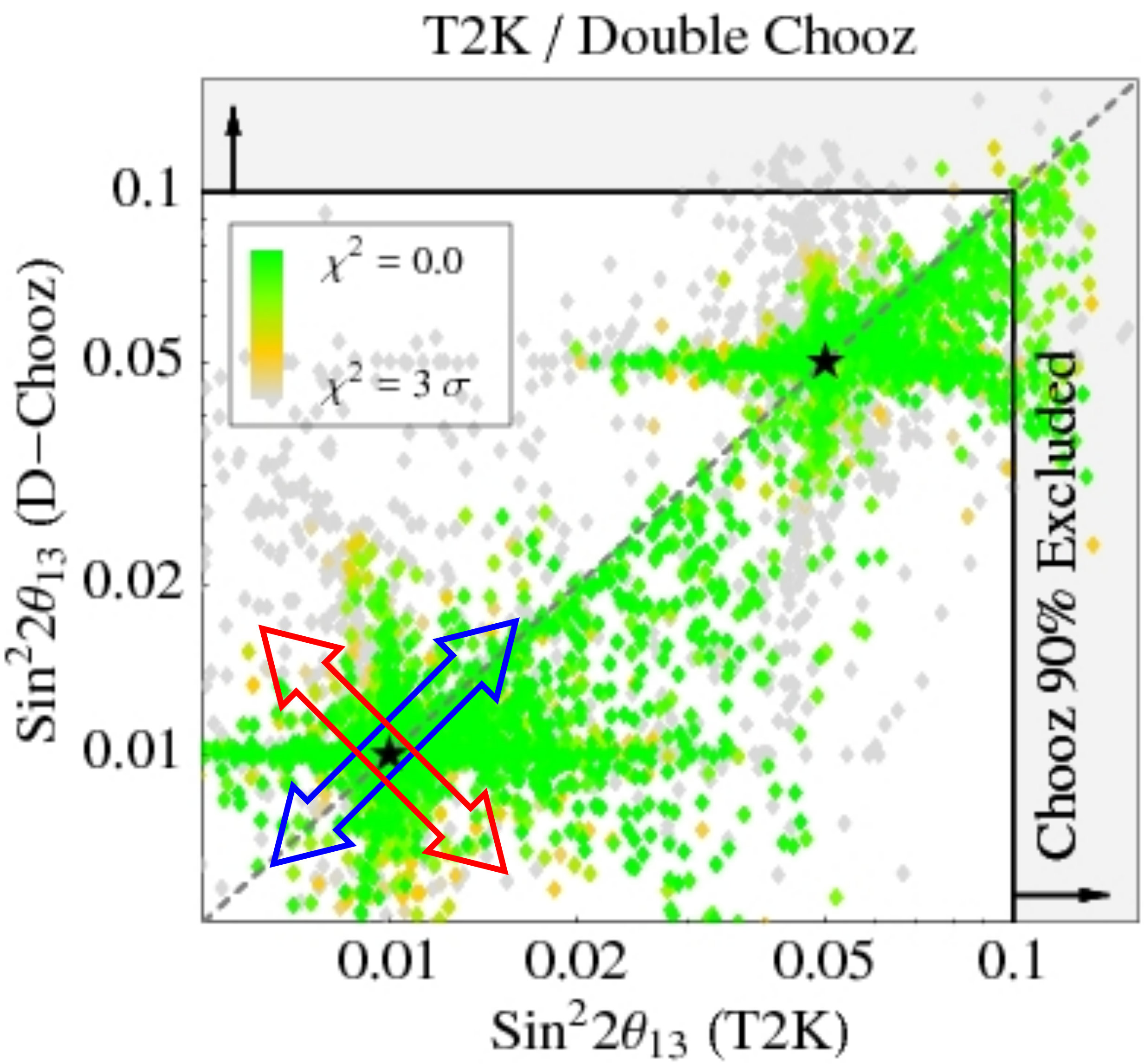






interference in oscillations ~ε ⇔ FCNC effects ~ε²

NSI: Offset and Mismatch in θ_{13}



Redundant measurements:

Double Chooz + T2K

***=assumed 'true' values of θ_{13}**

scatter-plot: ε values random

- below existing bounds

- random phases

NSIs can lead to:

- offset

- mismatch

➔ redundancy

➔ interesting potential of over-constraining

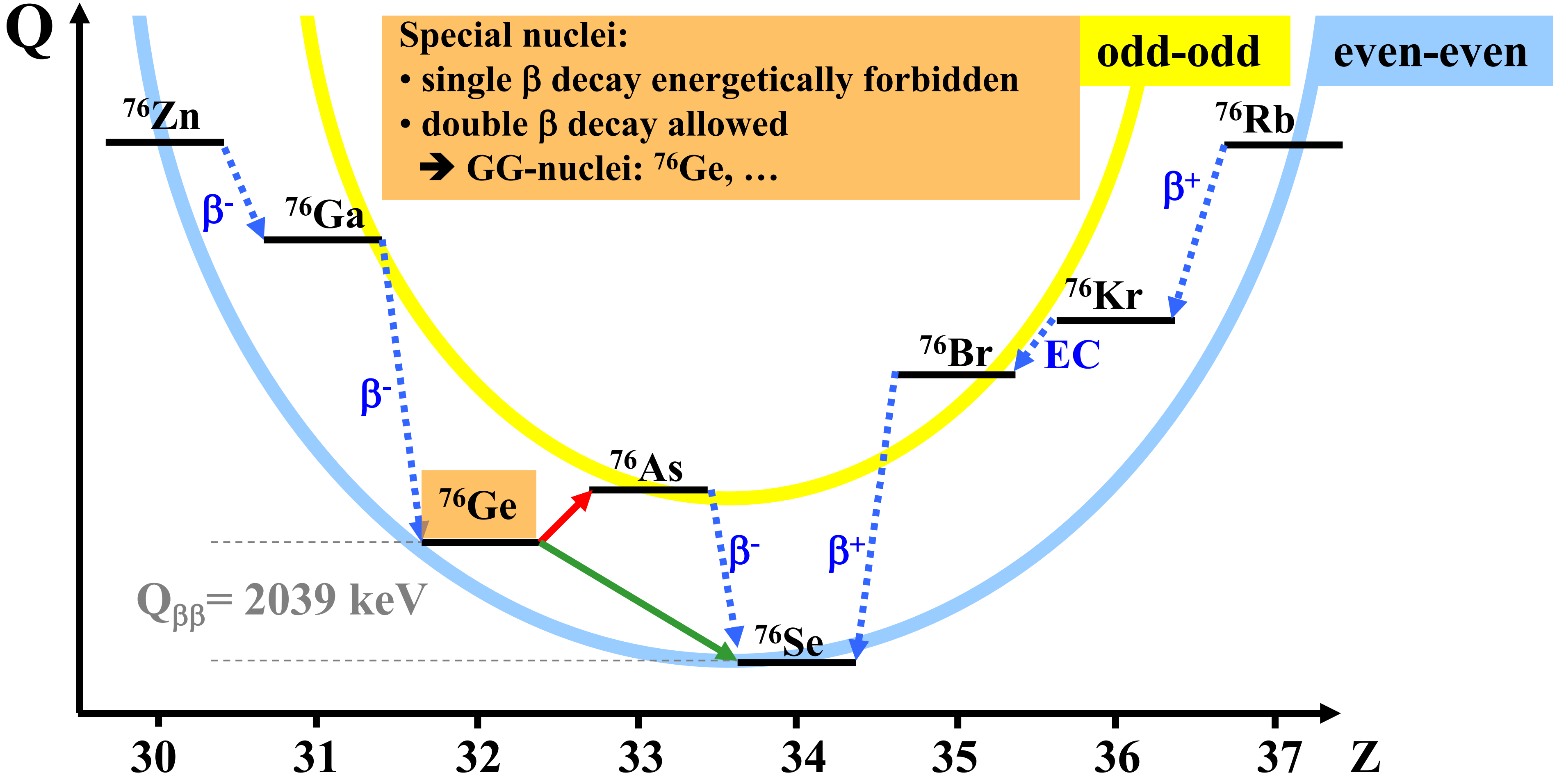
Kopp, ML, Ota

Double Beta Decay

If neutrinos have Majorana masses
➔ Lepton Number Violation
➔ Neutrinoless Double Beta Decay

BUT: Be careful about the inverted reasoning!

Double β-Decay & Mass Parabolas



Important: Isotopes with forbidden single β decay

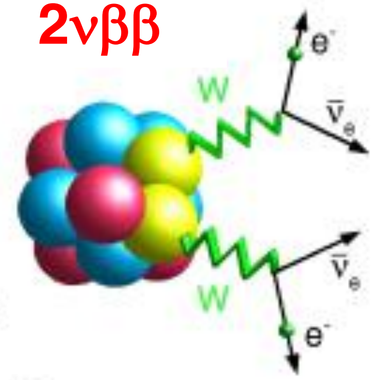
^{76}Ge: Only double β decay ➔ SM: 2ν+2e$^-$ *OR* 2e$^-$

Further double beta isotopes…

The Standard Picture of Double Beta Decay

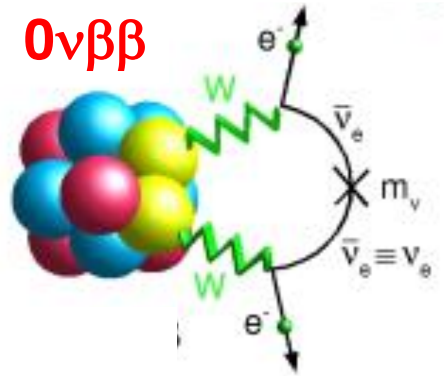
$2\nu\beta\beta$

SM



$0\nu\beta\beta$

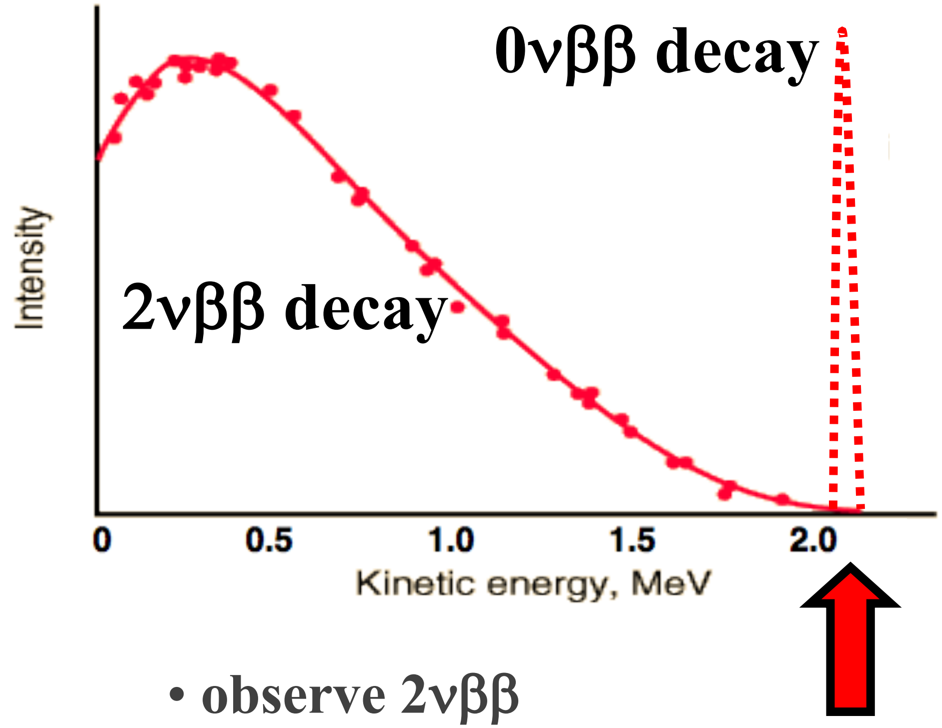
Majorana mass



$T^{1/2} > O(10^{25}y)$

$2\nu\beta\beta$ decay seen for diff. isotopes (Kirsten,…)

$T^{1/2} = O(10^{18} - 10^{21}$ years) ➔ up to $10^{11} \otimes T_{Universe}$



- observe $2\nu\beta\beta$
- look for $0\nu\beta\beta$ signal at $Q_{\beta\beta}$
- large amount of $0\nu\beta\beta$ nuclei
- extreme low backgrounds!

➔ signal = Majorana mass

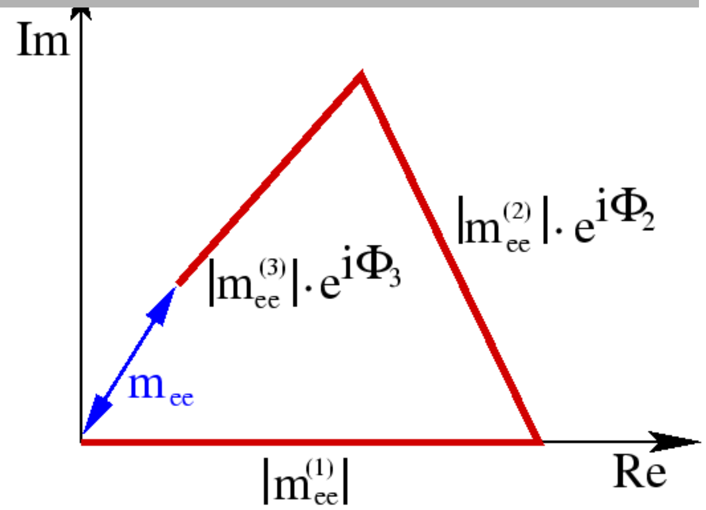
$$1/\tau = G(Q,Z)\ |M_{nucl}|^2 <m_{ee}>^2$$

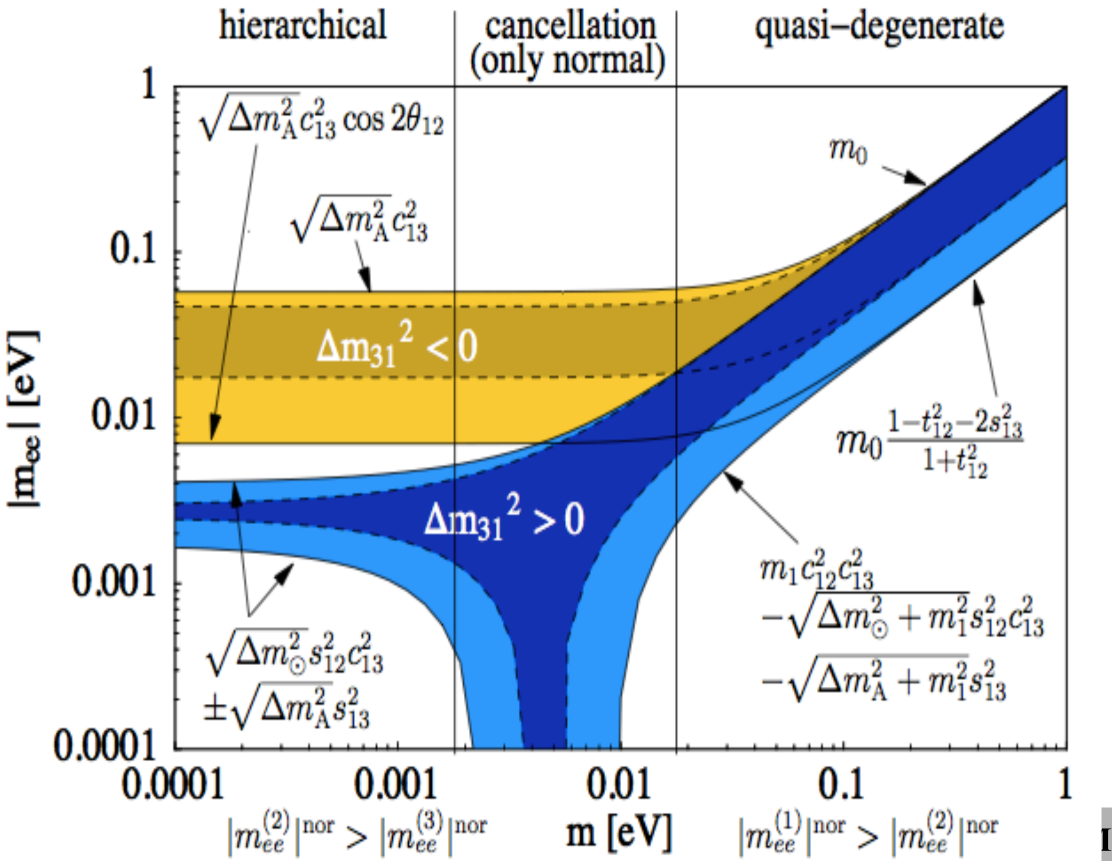
NMEs have uncertainties…

m_{ee}: The Effective Neutrino Mass

$$m_{ee} = |m_{ee}^{(1)}| + |m_{ee}^{(2)}| \cdot e^{i\Phi_2} + |m_{ee}^{(3)}| \cdot e^{i\Phi_3}$$

$$\begin{aligned} |m_{ee}^{(1)}| &= |U_{e1}|^2 m_1 \\ |m_{ee}^{(2)}| &= |U_{e2}|^2 \sqrt{m_1^2 + \Delta m_{21}^2} \\ |m_{ee}^{(3)}| &= |U_{e3}|^2 \sqrt{m_1^2 + \Delta m_{31}^2} \end{aligned}$$





Comments:

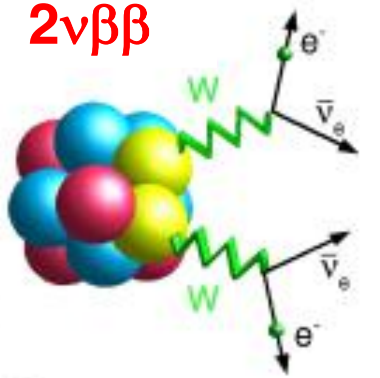
- cosmology: m < 0.2-0.3 eV
- 0νββ: m_{ee} < 0.1-0.3 eV
- NMEs ➔ unavoidable theory errors
- known Δm^2 from oscillations
  - ➔ yellow/blue areas
  - ➔ improved sensitivity is very promising!

- **warnings**:
  - assumes no *other* ΔL=2 physics
  - assumes no sterile neutrinos, ...

More general: L Violating Processes

2νββ

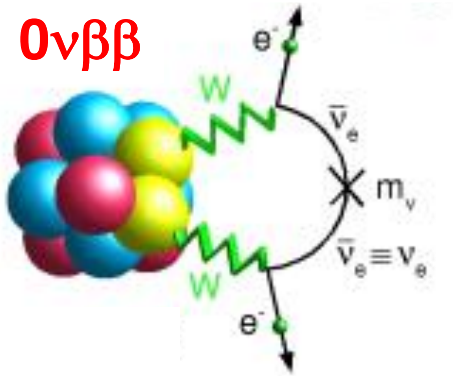
SM



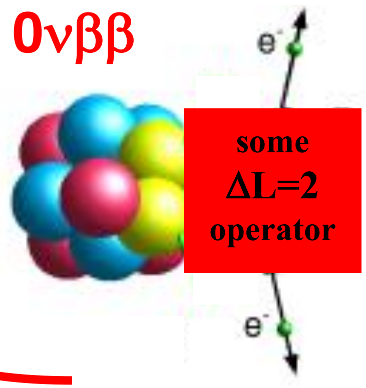
BSM

$T^{1/2} > O(10^{25}y)$

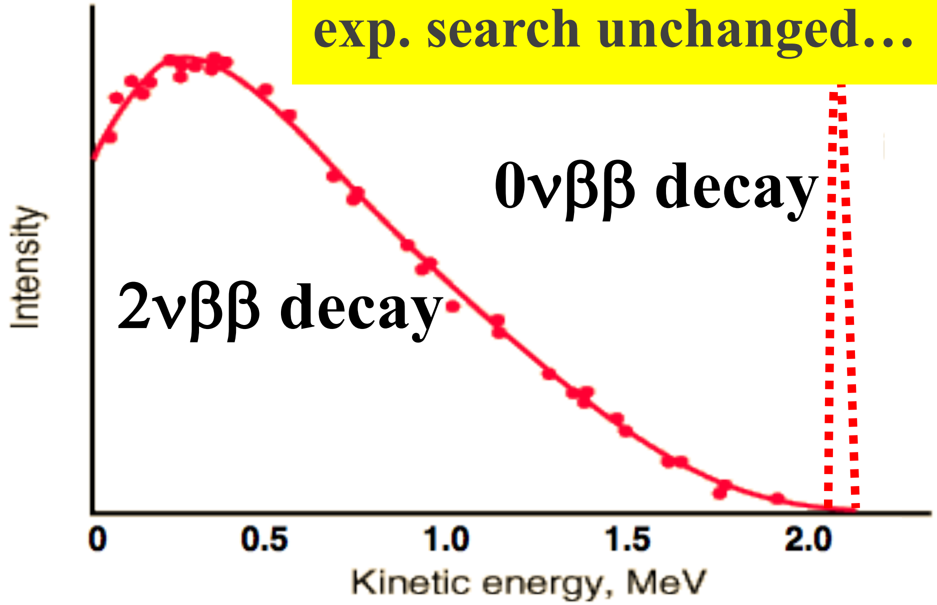
0νββ



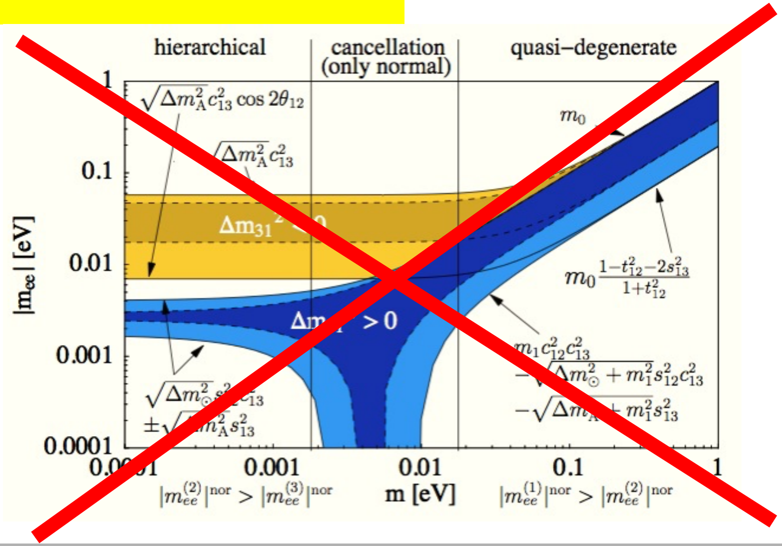
0νββ



exp. search unchanged…

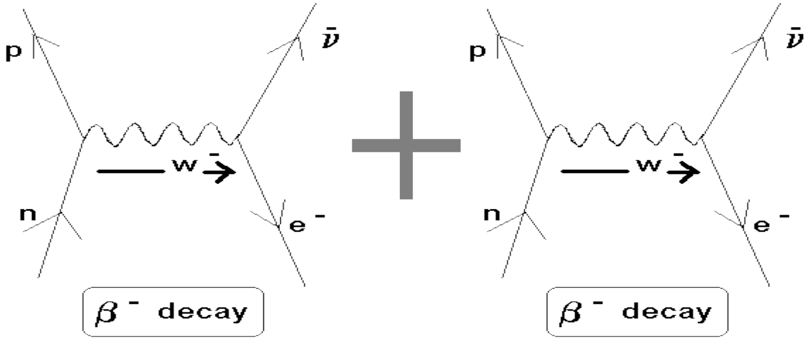


…interpretation changes:



Other Double Beta Decay Processes

Standard Model:

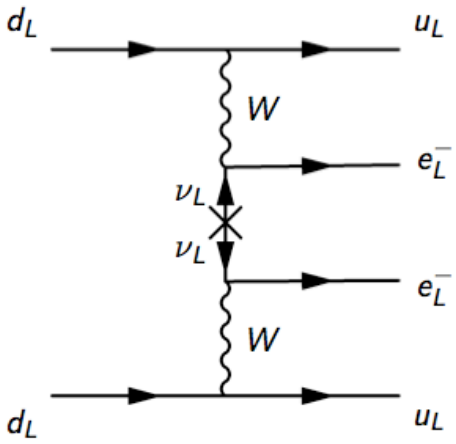


➔ 2 electrons + 2 neutrinos

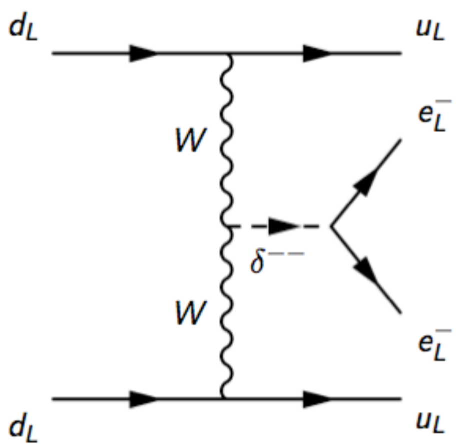
2νββ

Majorana ν-masses or other ΔL=2 physics: ➔ 2 electrons

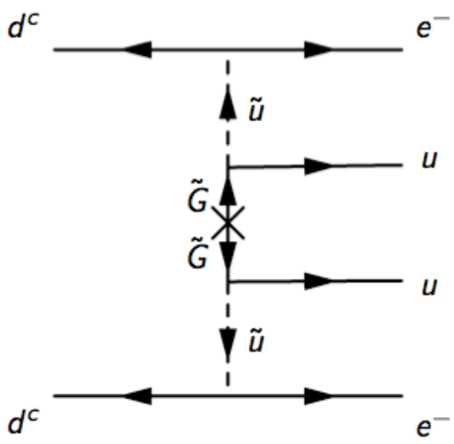
0νββ



Majorana neutrino masses ←→ Dirac?



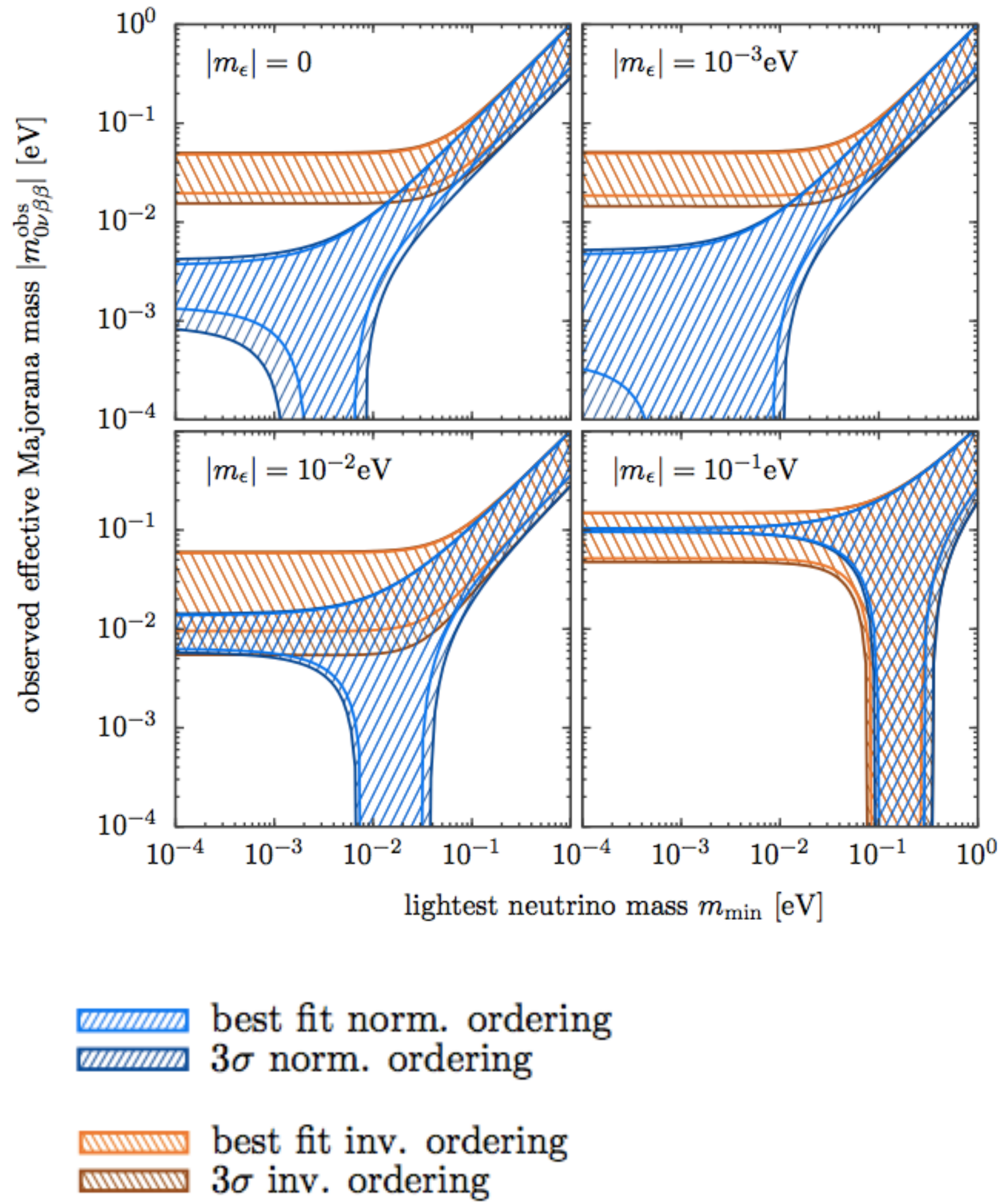
SM + Higgs triplet

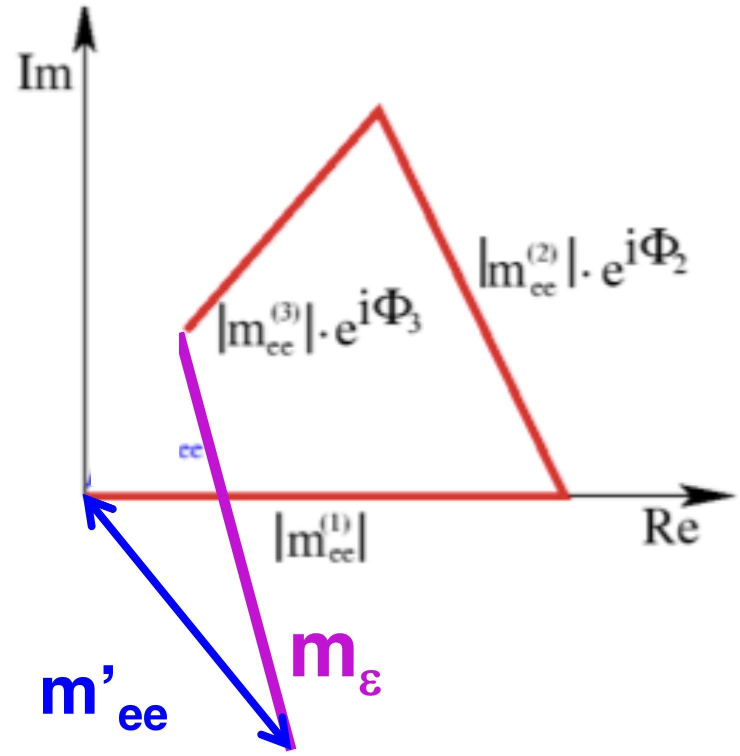


SUSY

…

important connections to LHC and LFV …
sub eV Majorana mass ←→ TeV scale physics





interferences

growing m_ε for fixed $0\nu\beta\beta$

→ shifts of masses, mixings and CP phases

→ destroys ability to extract Majorana phases

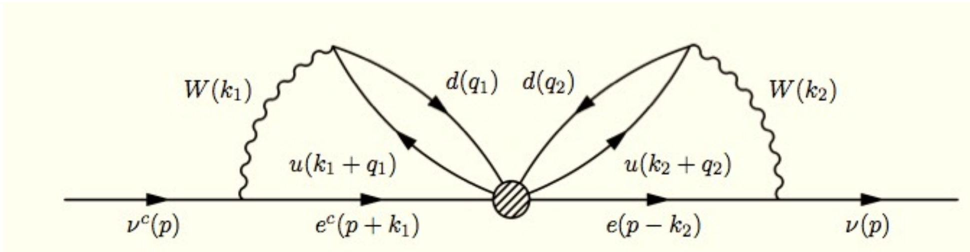
→ sensitivity to TeV

Does 0νββ Decay imply Majorana Masses?

- Schechter-Valle Theorem ➔ **is misleading**

  Any ΔL=2 operator which mediates the decay induces via loops Majorana mass terms ➔ unavoidable: Majorana neutrinos…!?

0νββ➔ some ΔL=2 operator



Dürr, ML, Merle

4 loops ➔ enforce $\delta m_\nu = 10^{-25}$ eV ➔ very tiny (academic interest)

➔ cannot explain observed ν masses and splitting's

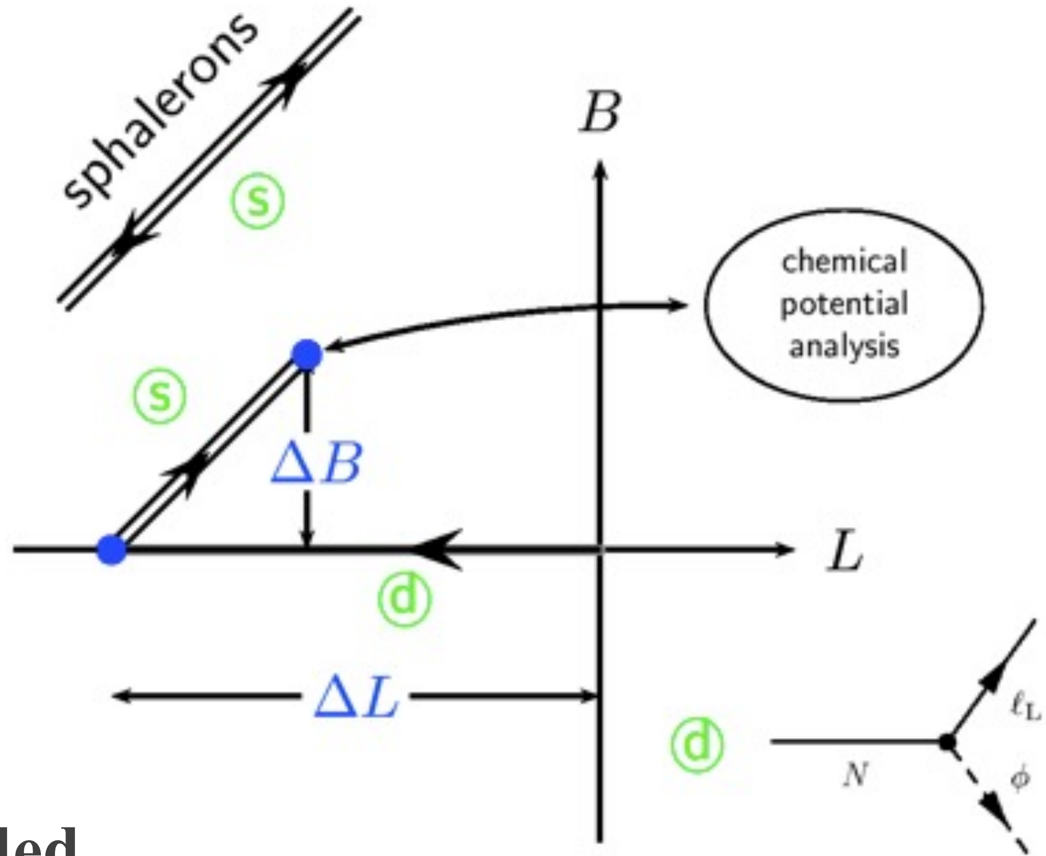
Extreme possibility:

- 0νββ = L violation = other BSM physics
- neutrino masses = Dirac (plus very tiny Majorana corrections)

+ Dirac leptogenesis, + ...

Leptogenesis

sphalerons (s)
- **violate B+L**
- **preserve B-L**

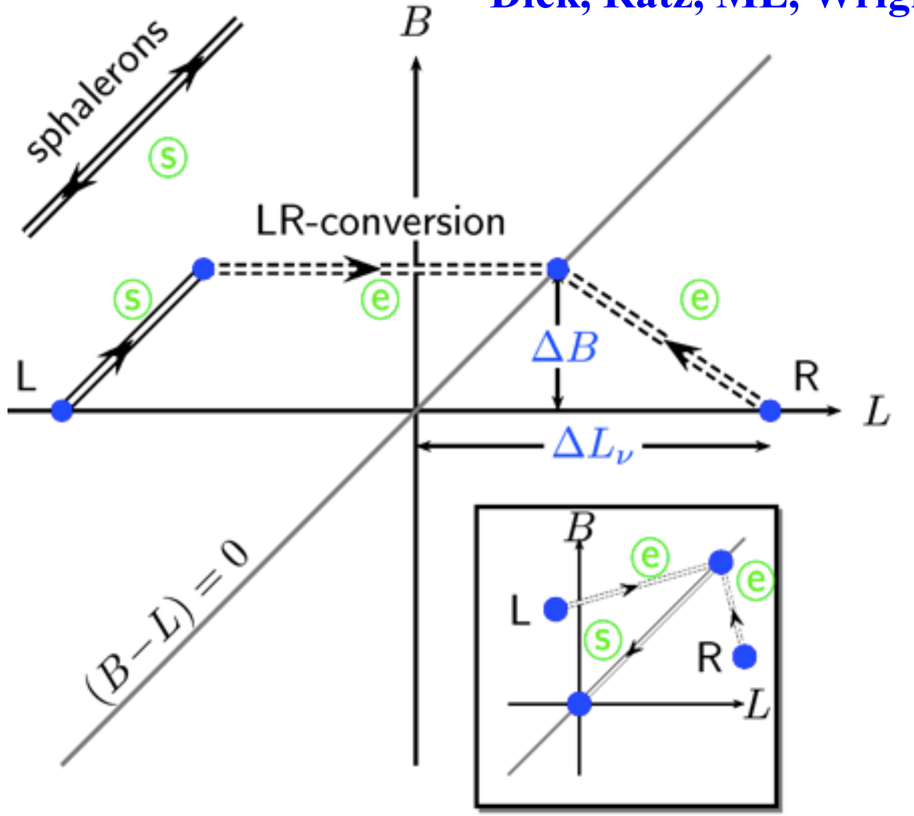


standard leptogenesis:
- **decays of heavy right-handed neutrinos (d) produces ΔL**
- **sphalerons (s) convert ΔL partially into ΔB**

➔ BAU explained by Majorana ν's (L-violation)

Dirac Leptogenesis

Dick, Ratz, ML, Wright



Sphalerons violate L
➔ enough to create BAU?

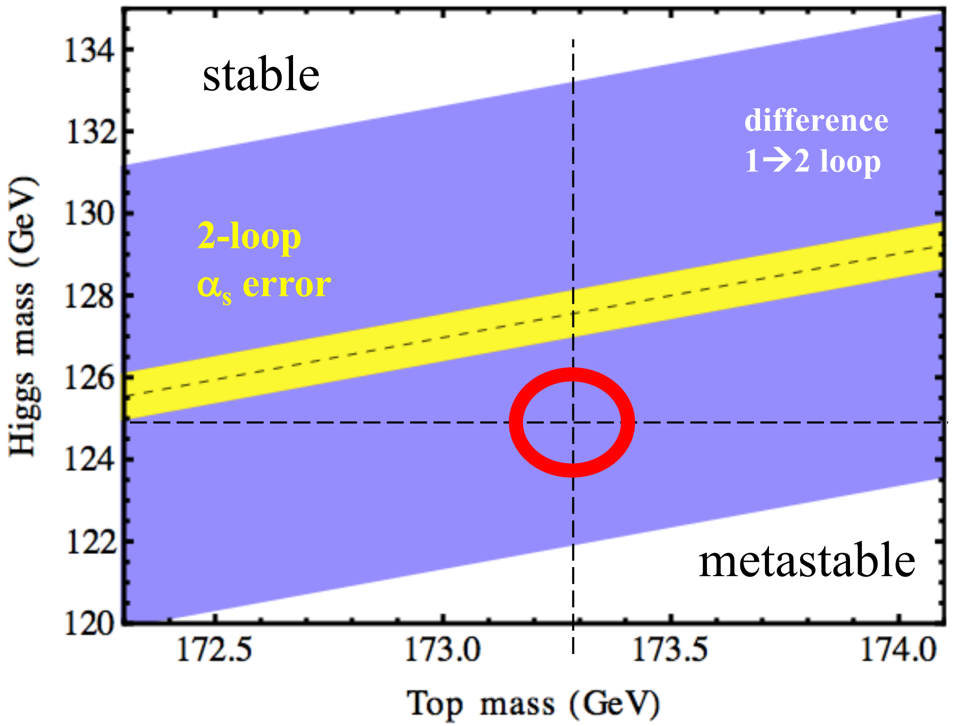
Big Bang produces ν_L, ν_R

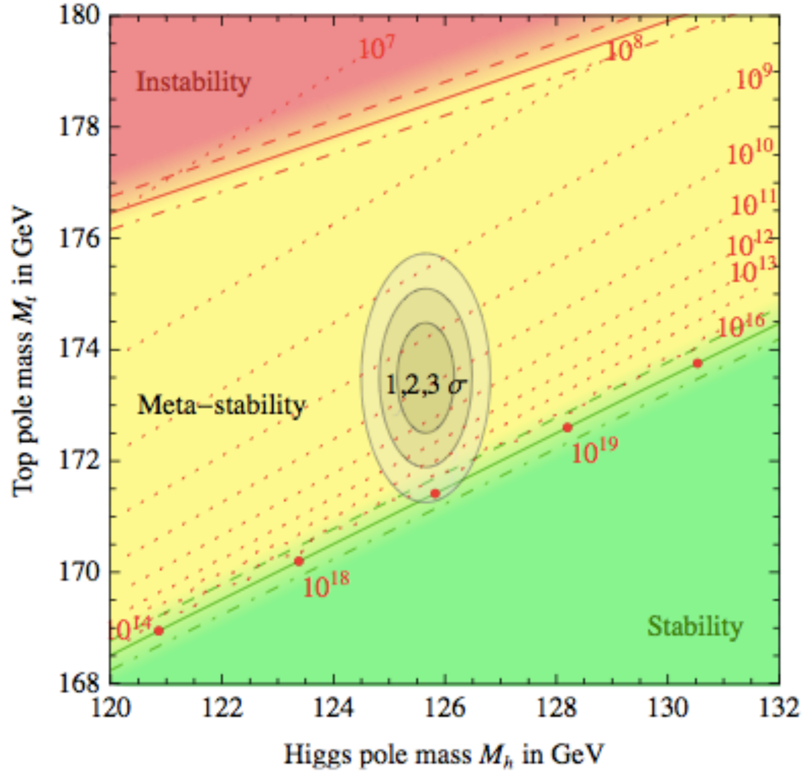
Dirac neutrinos: tiny Yukawa couplings
➔ R-L conversion takes longer than sphaleron epoch
➔ study ν_L, ν_R separately
➔ spahlerons affect only ν_L component
➔ later combine with ν_R
➔ explains BAU for neutrino masses below O(10) keV

leptogenesis works equally well for Dirac neutrinos!

Is the Higgs Potential at M_{Planck} flat?

Holthausen, ML, Lim (2011) **Buttazzo, Degrassi, Giardino, Giudice, Sala, Salvio, Strumia**





Experimental values point to metastability. Is it fully established?

➔ we need to include DM, neutrino masses, …? are all errors (EX+TH) fully included?

➔ be cautious about claiming that metastability is established

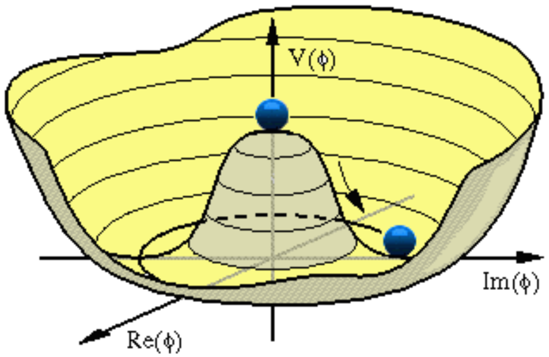
➔ An important aspect:

- a remarkable relation between weak scale, m_t, couplings and M_{Planck} ←→ precision
- remarkable interplay between gauge, Higgs and top loops (log divergences – not Λ^2)

Is there a Message?

- $\lambda(M_{Planck}) \simeq 0$? ➔ remarkable log cancellations
  M_{planck}, M_{weak}, gauge, Higgs & Yukawa couplings are unrelated

- remember: μ is the only single scale of the SM ➔ special role
  ➔ if in addition $\mu^2 = 0$ ➔ $V(M_{Planck}) \simeq 0$
  ➔ flat Mexican hat (<1%) at the Planck scale!



➔

➔ conformal (or shift) symmetry as solution to the HP

➔ combined conformal & EW symmetry breaking
- conceptual issues
- realizations

Generic Questions

- **Isn't the Planck-scale spoiling things (explicit scale, cut-off, …)?**
  ➔ renormalizable QFTs (SM) don't have cut-offs
  - explicit scales in embeddings act like a cut-off
  - important: no cutoff if the emebedding has no explicit scale

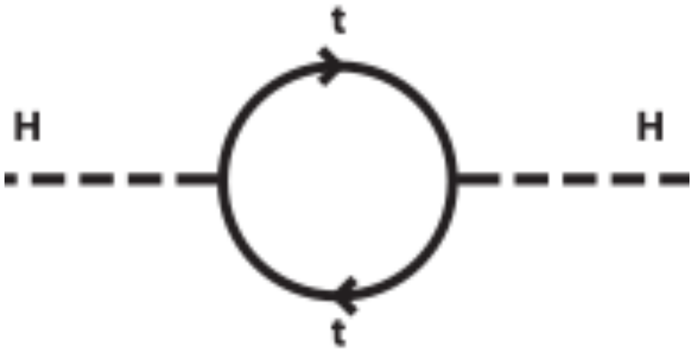
  ➔ non-linear realization of conformal symmetry… ➔ ~conformal gravity…
  ➔ protected by conformal symmetry up to conformal anomaly
  ➔ some mechanism that generates M_{Planck} by dimensional transmutation
  ➔ working assumption: M_{Planck} somehow generated in a conformal setting

- **Are M_{planck} and M_{weak} connected?**
  ➔ maybe …
  ➔ here assumed to be an independently generated scales

- **UV: ultimate solution should be asymptotically safe ➔ UV-FPs…**

- **Conceptual change for scale setting:**
  So far a rollover of scale generation: SM ➔ BSM ➔ GUT ➔ gravity (M_{Planck})
  here: only relative scales – absolute scale is meaningless

Non-linear Realization of Conformal Symmetry



If conformal symmetry is realized in a non-linear way:

➔ protection by conformal symmetry

➔ only log sensitivity

←→ conformal anomaly

←→ β-functions

- **Avoids hierarchy problem, even though there is the the conformal anomaly - only logs ←→ β-functions**
- **Dimensional transmutation by log running like in QCD**
  ➔ scalar QCD: scalars can condense and set scales like fermions
  ➔ also for massless scalar QCD: **scale generation; no hierarchy**

Why the minimalistic SM does not work

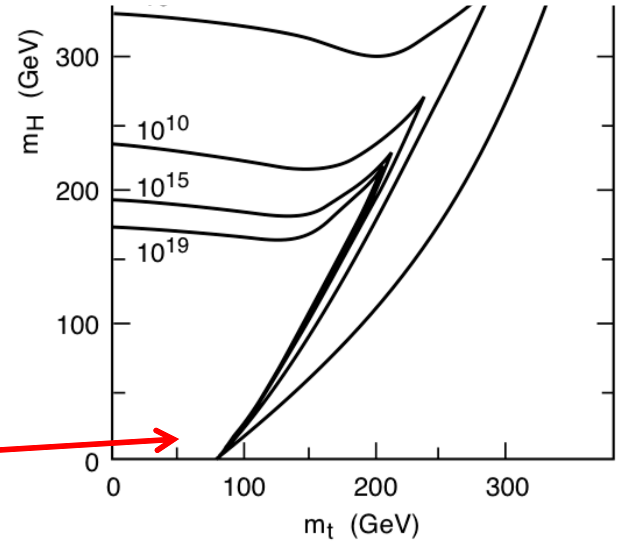
Minimalistic version: → "SM-"

SM + with $\mu = 0$ ←→ CS

Coleman Weinberg: effective potential

→ CS breaking (dimensional transmutation)

→ induces for $m_t < 79$ GeV
a Higgs mass $m_H = 8.9$ GeV

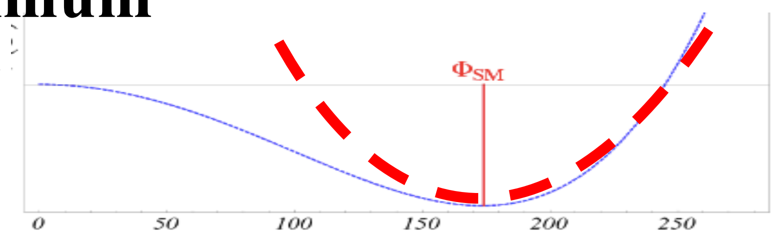


This would conceptually realize the idea, but:

Higgs too light and the idea does not work for $m_t > 79$ GeV

Reason for $m_H \ll v$: V_{eff} flat around minimum

←→ $m_H \sim$ radiative loop factor $\sim 1/16\pi^2$



AND: We need neutrino masses, dark matter, …

Realizing the Idea via Higgs Portals

- SM scalar Φ plus some new scalar φ (or more scalars)
- CS → no scalar mass terms
- the scalar portal $\lambda_{mix}(\varphi^+\varphi)(\Phi^+\Phi)$ must exist

→ a condensate of $<\varphi^+\varphi>$ produces $\lambda_{mix}<\varphi^+\varphi>(\Phi^+\Phi) = \mu^2(\Phi^+\Phi)$
→ effective mass term for Φ

- CS anomalous … → breaking → only ln(Λ)

→ implies a TeV-ish condensate for φ to obtain $<\Phi> = 246$ GeV

- Model building possibilities / phenomenological aspects:
  - φ could be an effective field of some hidden sector DSB
  - further particles could exist in hidden sector; e.g. confining…
  - extra hidden U(1) potentially problematic ←→ U(1) mixing
  - avoid Yukawas which couple visible and hidden sector

→ phenomenology safe due to Higgs portal, but there is TeV-ish new physics!

Realizing the Idea: Specific Realizations

SM + extra singlet: Φ, φ

Nicolai, Meissner, Farzinnia, He, Ren, Foot, Kobakhidze, Volkas, …

SM + extra SU(N) with new N-plet in a hidden sector

Ko, Carone, Ramos, Holthausen, Kubo, Lim, ML, (Hambye, Strumia) , …

SM embedded into larger symmetry (CW-type LR)

Holthausen, ML, M. Schmidt

SM + QCD colored scalar which condenses at TeV scale

Kubo, Lim, ML

Since the SM-only version does not work ➔ observable effects:

- Higgs coupling to other scalars (singlet, hidden sector, …)
- dark matter candidates ←→ hidden sectors & Higgs portals
- consequences for neutrino masses

Conformal Symmetry & Neutrino Masses

ML, S. Schmidt and J.Smirnov

- No explicit scale → no explicit (Dirac or Majorana) mass term
  → only Yukawa couplings ⊗ generic scales

- Enlarge the Standard Model field spectrum
  like in 0706.1829 - R. Foot, A. Kobakhidze, K.L. McDonald, R. Volkas
- Consider direct product groups: SM ⊗ HS

- Two scales: CS breaking scale at O(TeV) + induced EW scale

Important consequence for fermion mass terms:

→ spectrum of Yukawa couplings ⊗ TeV or EW scale
→ interesting consequences ←→ Majorana mass terms are no longer expected at the generic L-breaking scale → anywhere
→ alternative: only Dirac mass terms…

Examples

$$\mathcal{M} = \begin{pmatrix} 0 & y_D\langle H\rangle \\ y_D^T\langle H\rangle & y_M\langle\phi\rangle \end{pmatrix}$$

Yukawa seesaw:

SM + ν_R + singlet

$$\langle\phi\rangle \approx \text{TeV}$$

$$\langle H\rangle \approx 1/4\,\text{TeV}$$

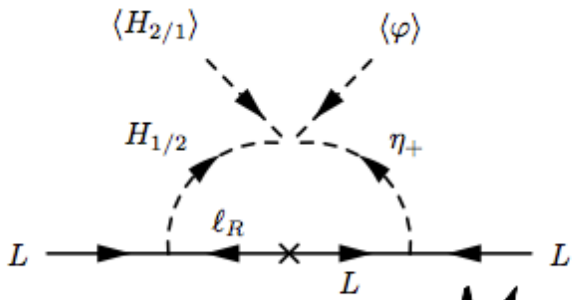
➔ generically expect a TeV seesaw

BUT: y_M can be tiny

➔ wide range of sterile masses ➔ including pseudo-Dirac case

➔ suppressed $0\nu\beta\beta$

Radiative masses



$$\mathcal{M} = m_L \quad \text{or}$$

$$\mathcal{M} = \begin{pmatrix} \mu_1 & y_D\langle H\rangle \\ y_D^T\langle H\rangle & \mu_2 \end{pmatrix}$$

➔ pseudo-Dirac case

The punch line:
all usual neutrino mass terms can be generated

→ suitable scalars
→ no explicit masses
all via Yukawa couplings
→ different numerical expectations

Another Example: Inverse Seesaw

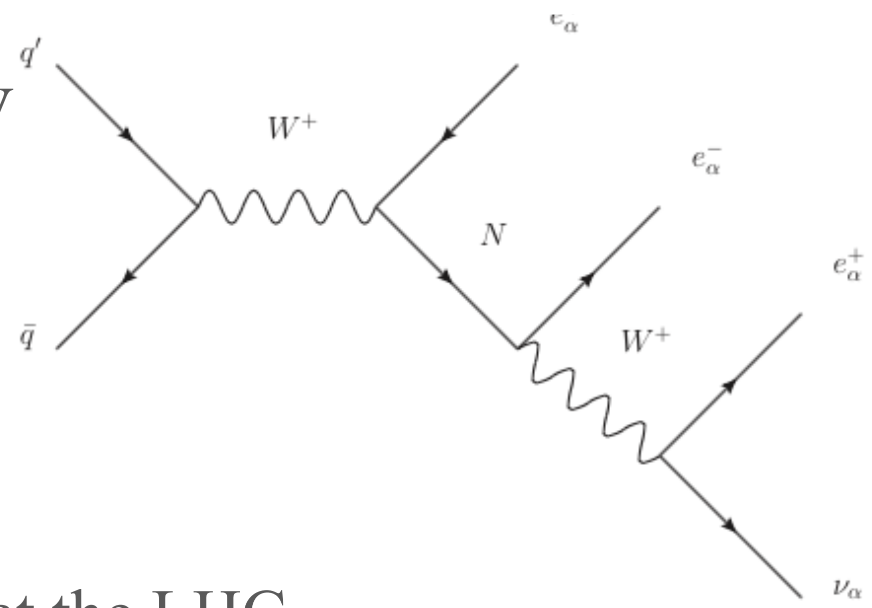
$SU(3)_c \times SU(2)_L \times U(1)_Y \times U(1)_X$

Humbert, ML, J. Smirnov

	H	ϕ_1	ϕ_2	L	ν_R	N_R	N_L
$U(1)_X$	0	1	2	0	0	1	1
Lepton Number	0	0	0	1	1	0	0
$U(1)_Y$	1	0	0	-1	0	0	0
$SU(2)_L$	2	1	1	2	1	1	1

$$\mathcal{M} = \begin{pmatrix} 0 & y_D\langle H\rangle & 0 & 0 \\ y_D\langle H\rangle & 0 & y_1\langle\phi_1\rangle & \tilde{y}_1\langle\phi_1\rangle \\ 0 & y_1\langle\phi_1\rangle & y_2\langle\phi_2\rangle & 0 \\ 0 & \tilde{y}_1\langle\phi_1\rangle & 0 & \tilde{y}_2\langle\phi_2\rangle \end{pmatrix}$$

- ➔ light eV "active" neutrino(s)
- ➔ two pseudo-Dirac neutrinos; m~TeV
- ➔ sterile state with μ ≈ keV



- ➔tiny non-unitarty of PMNS matrix
- ➔tiny lepton universality violation
- ➔suppressed 0νββ decay ←!
- ➔lepton flavour violation
- ➔tri-lepton production could show up at the LHC
- ➔keV neutrinos as warm dark matter ➔

Conclusions

- Neutrino physics **was, is and will remain a hot field**

- Many **important insights** into
  - fundamental interactions
  - sources
  - important consequences: baryon asymmetry of the Universe

- **3 neutrino flavours ➔ precision area**
  - reactor neutrinos
  - neutrino beams (NOνA, T2K, T2HK, DUNE, ...)

  ➔ origin of fermion masses?

- **More than 3 neutrinos**
  - Majorana masses, L-violation, sterile ν's, NSIs, large mag. moments, ...

  ➔ **any one of them would be a major discovery**

- New paths: **Coherent neutrino scattering as a new tool...**

NEVTRINO 2018

XXVIII INTERNATIONAL CONFERENCE ON NEUTRINO PHYSICS AND ASTROPHYSICS

4–9 June
Heidelberg

TOPICS

- Neutrino Oscillations and Mass Measurements
- Accelerator Neutrinos
- Reactor Neutrinos
- Solar Neutrinos
- Atmospheric Neutrinos
- Neutrinoless Double Beta Decay
- Leptonic CP-violation
- Coherent Scattering
- Neutrino Interactions
- Sterile Neutrinos
- Connections to Dark Matter and BSM Physics
- Theory of Masses and Mixings
- Astrophysical Neutrinos
- Neutrino Cosmology
- Supernova Neutrinos
- Geoneutrinos
- Future Projects

International Advisory Committee

A.S. Barabash (Moscow)
L. Baudis (Zürich)
J.F. Beacom (Ohio)
S.J. Brice (Fermilab)
J. Cao (IHEP)
P. Coyle (Marseille)
S. Davidson (Lyon)
A. Dighe (TIFR)
S. Dodelson (CMU)
A.D. Dolgov (Novosibirsk)
Y. Farzan (IPM)
R.Z. Funchal (São Paulo)
M. Goodman (ANL)
G. Gratta (Stanford)
T. Hambye (Bruxelles)
Y. Hayato (Kamioka)
S.-B. Kim (Seoul)
Y. Kuno (Osaka)
M. Mezzetto (INFN)
A. Pilaftsis (Manchester)
G.G. Raffelt (MPP)
M.C. Sanchez (ISU)
K. Scholberg (Duke)
S.-H. Seo (Seoul)
N.J.T. Smith (SNOLAB)
H. Tanaka (Toronto)
L. Verde (Barcelona)
F. Vissani (INFN & GSSI)
Y. Wang (IHEP)
T.J. Weiler (Vanderbilt)
C. Weinheimer (Münster)
J.F. Wilkerson (UNC)
Y.Y.Y. Wong (UNSW)

Scan to discover!

Local Organising Committee

E. Akhmedov (MPIK)
A. Bernreiser (MPIK)
C. Buck (MPIK)
G. Drexlin (KIT, co-chair)
K. Eitel (KIT)
K. Fischer (KIT)
M. Lindner (MPIK, chair)
T. Marrodán Undagoitia (MPIK)
W. Rodejohann (MPIK)
S. Schoppmann (MPIK)
T. Schwetz-Mangold (KIT)
H. Simgen (MPIK)
A.Y. Smirnov (MPIK)
M. Steidl (KIT)
K. Valerius (KIT)

MAX-PLANCK-INSTITUT FÜR KERNPHYSIK HEIDELBERG

KIT Karlsruhe Institute of Technology

PHOTO: SEBASTIAN TRANDAFIR/SKYLINE-PANORAMA, GRAPHIC DESIGN: HELENA ALMAZÁN

https://www.mpi-hd.mpg.de/nu2018/