Neutrinoeigenschaften

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AT-Physik in D

30/09/14

MAX-PLANCK-INSTITUT FÜR KERNPHYSIK

MANITOP

Massive Neutrinos: Investigating their Theoretical Origin and Phenomenology

MAX-PLANCK-GESELLSCHAFT

Heisenberg-Programm

Neutrinoeigenschaften in Kürze

- massiv
- mischen
- wahrscheinlich Majorana

Standardmodel

addiere m_ν zu

Spezies	$\#$	$\sum$
Quarks	10	10
Leptonen	3	13
Ladung	3	16
Higgs	2	18
starke CP	1	19

Standardmodel

addiere m_ν

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$\longrightarrow$

Spezies	$\#$	$\sum$
Quarks	10	10
Leptonen	12 (10)	22 (20)
Ladung	3	25 (23)
Higgs	2	27 (25)
starke CP	1	28 (26)

Standardmodel*

addiere m_ν

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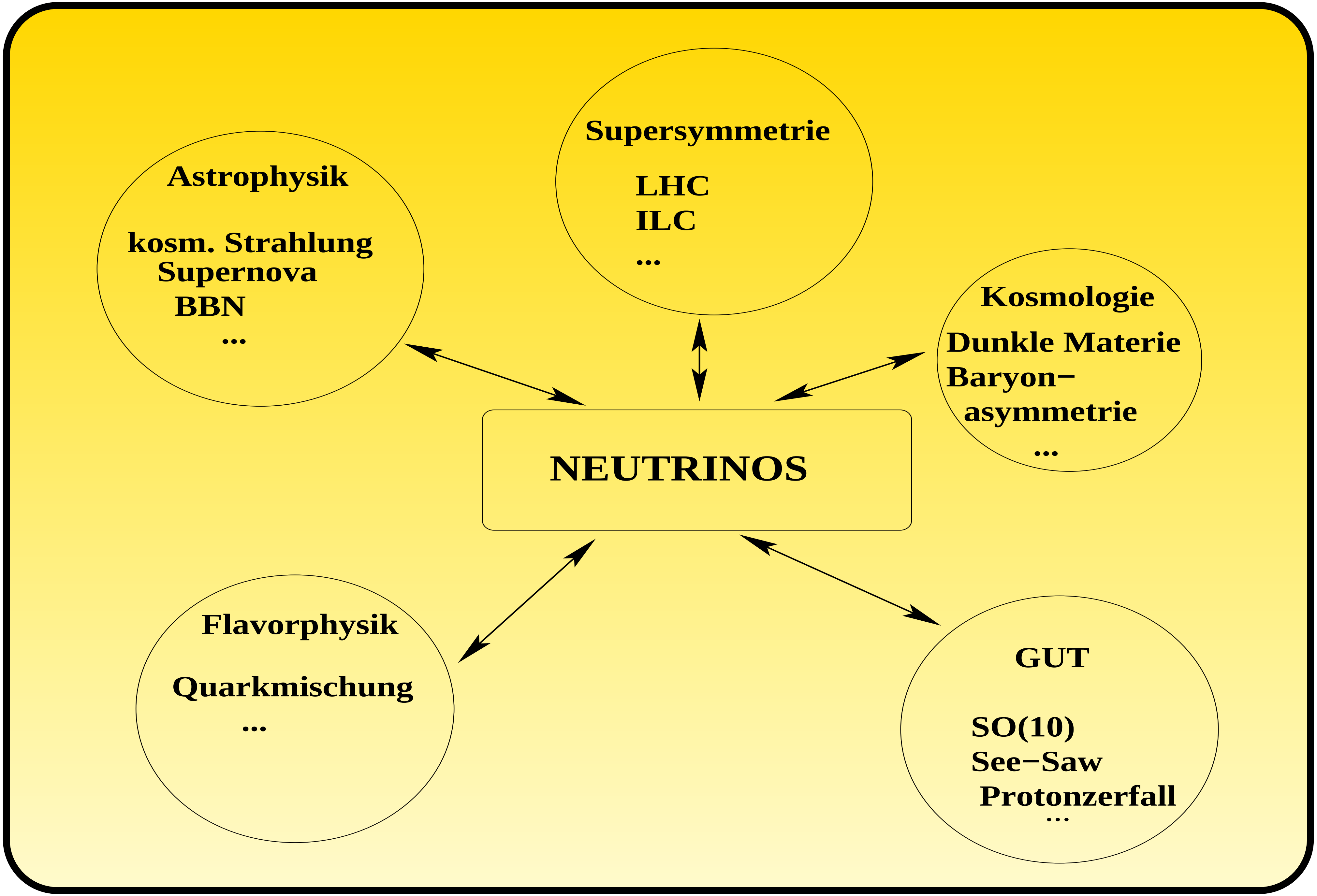
- **plus neue Energieskala**
- **plus neue SM Darstellung**
- **plus neue Konzepte**
- **plus**. . .


Supersymmetrie
LHC
ILC
...
Astrophysik
kosm. Strahlung
Supernova
BBN
...
Kosmologie
Dunkle Materie
Baryon−
asymmetrie
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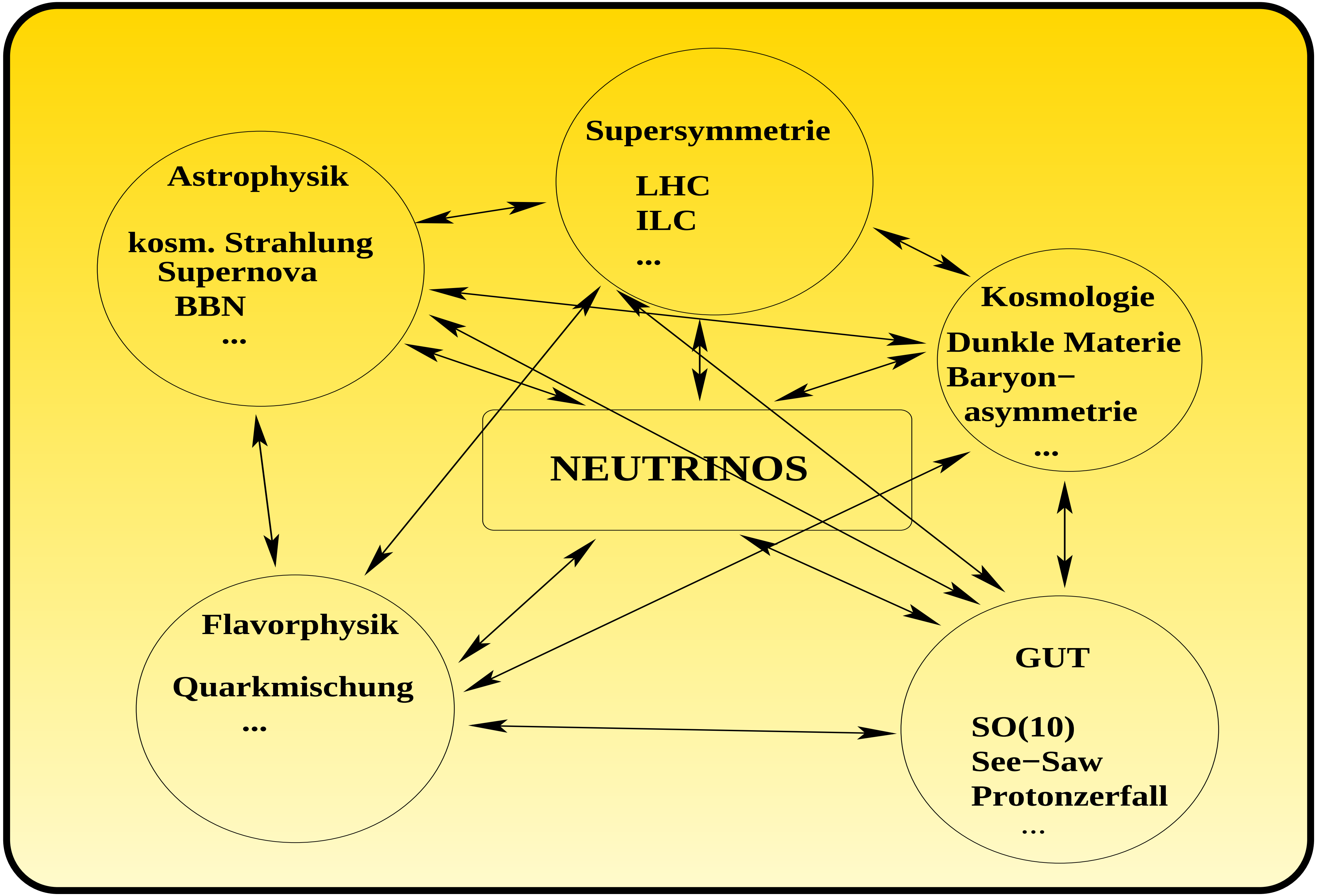
NEUTRINOS
Flavorphysik
Quarkmischung
...
GUT
SO(10)
See−Saw
Protonzerfall
...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Neutrinoparameter bei niedriger Energie

$$\mathcal{L} = \frac{1}{2}\,\nu^T\, m_\nu\, \nu \quad \text{mit} \quad m_\nu = U\,\mathrm{diag}(m_1, m_2, m_3)\, U^T$$

und PMNS Matrix

$$U = \begin{pmatrix} c_{12}\, c_{13} & s_{12}\, c_{13} & s_{13}\, e^{-i\delta} \\ -s_{12}\, c_{23} - c_{12}\, s_{23}\, s_{13}\, e^{i\delta} & c_{12}\, c_{23} - s_{12}\, s_{23}\, s_{13}\, e^{i\delta} & s_{23}\, c_{13} \\ s_{12}\, s_{23} - c_{12}\, c_{23}\, s_{13}\, e^{i\delta} & -c_{12}\, s_{23} - s_{12}\, c_{23}\, s_{13}\, e^{i\delta} & c_{23}\, c_{13} \end{pmatrix} P$$

mit $P = \mathrm{diag}(e^{i\alpha}, e^{i\beta}, 1)$ ($\leftrightarrow$ Majorana, Leptonzahlverletzung)

$\Rightarrow$ 3 Winkel, 3 Phasen, 3 Massen

3 Aufgaben

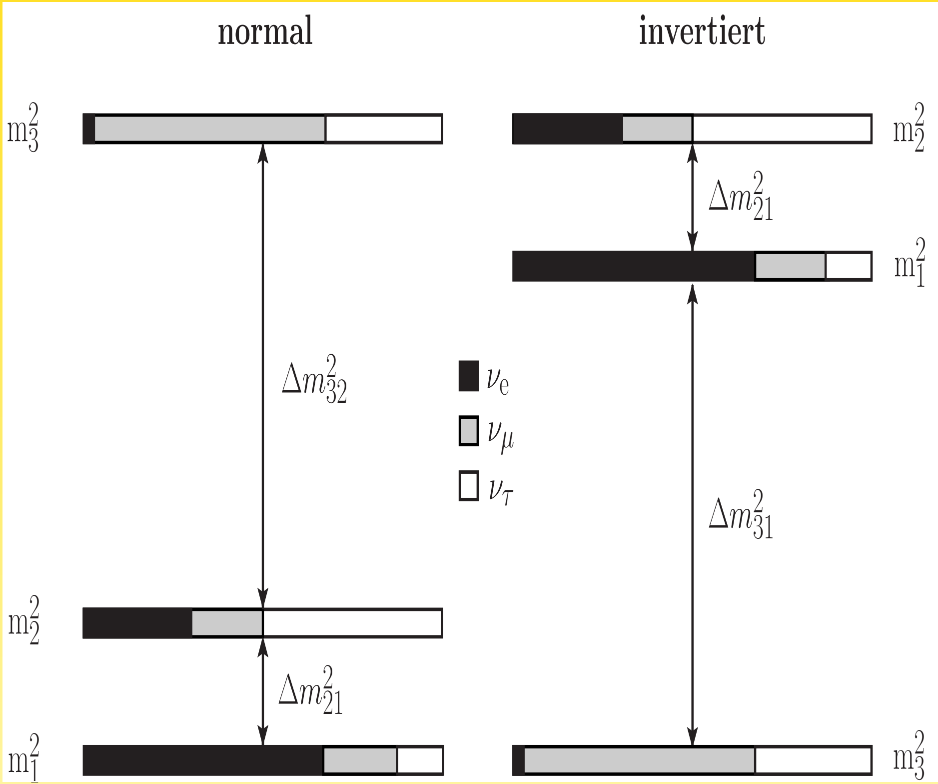
- Parameter bestimmen
- Parameter erklären
- Überprüfen ob minimale Beschreibung ("3 Majorana-Neutrino Paradigma") korrekt ist

Status 2014

9 physikalische Parameter in m_ν

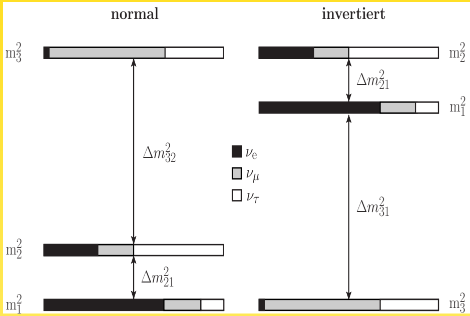
- θ_{12} und $m_2^2 - m_1^2$
- θ_{23} und $|m_3^2 - m_2^2|$
- θ_{13}
- m_1, m_2, m_3
- sgn$(m_3^2 - m_2^2)$
- Dirac-Phase δ
- Majorana-Phasen α und β

Massenskala und -ordnung



Skala und normal/invertiert fundamentaler Input für Modellbauer!

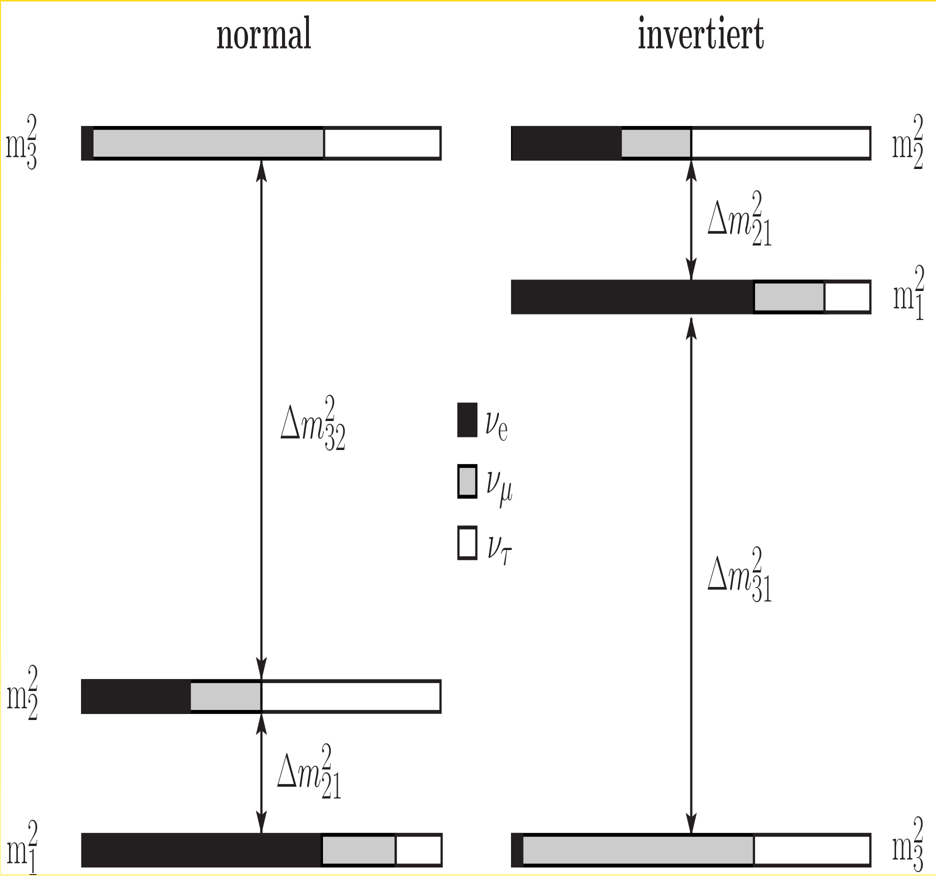
Massenskala und -ordnung

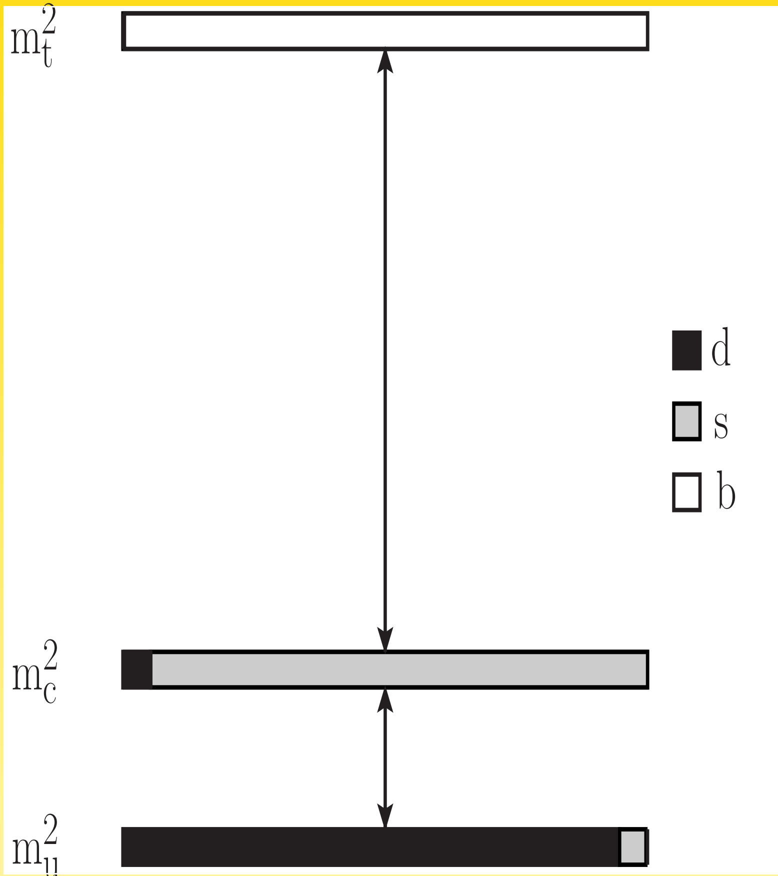


$$(m_\nu)_{\rm NH} \sim \begin{pmatrix} \epsilon^2 & \epsilon & \epsilon \\ \epsilon & 1 & 1 \\ \epsilon & 1 & 1 \end{pmatrix} \quad \text{versus} \quad (m_\nu)_{\rm IH} \sim \begin{pmatrix} 1 & 1 & 1 \\ 1 & 1 & 1 \\ 1 & 1 & 1 \end{pmatrix}$$

Allgemein: $m_\nu \propto 1/\Lambda_{\rm NP}$

Skala und normal/invertiert fundamentaler Input für Modellbauer!





Warum so verschieden?? $\leftrightarrow$ Flavoursymmetrien!

Neutrinomasse

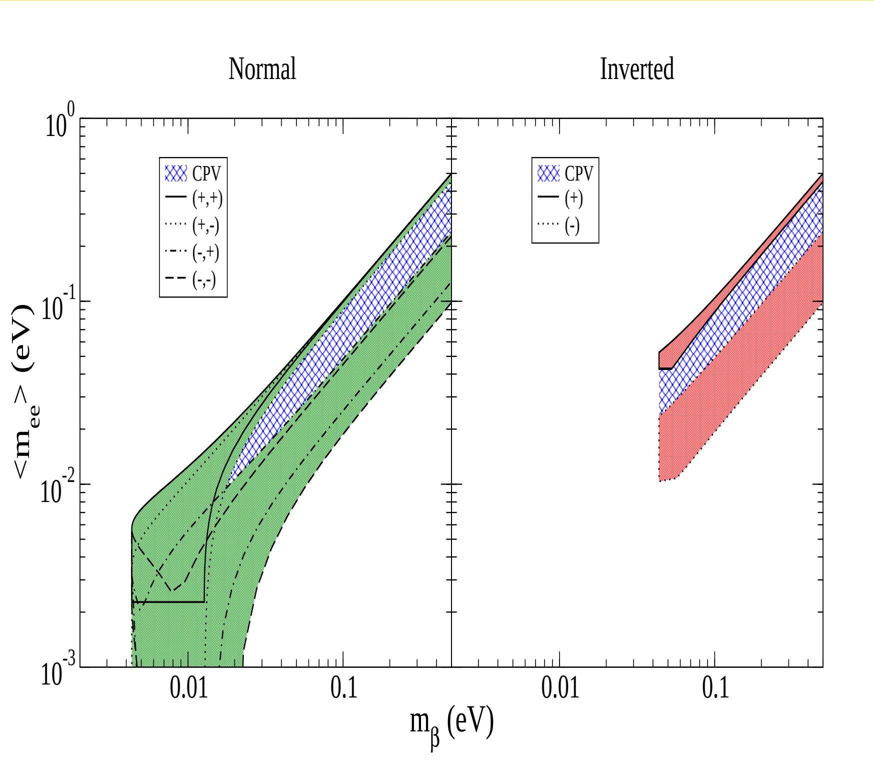
$$m(\text{schwerste}) \gtrsim \sqrt{|m_3^2 - m_1^2|} \simeq 0.05 \text{ eV}$$

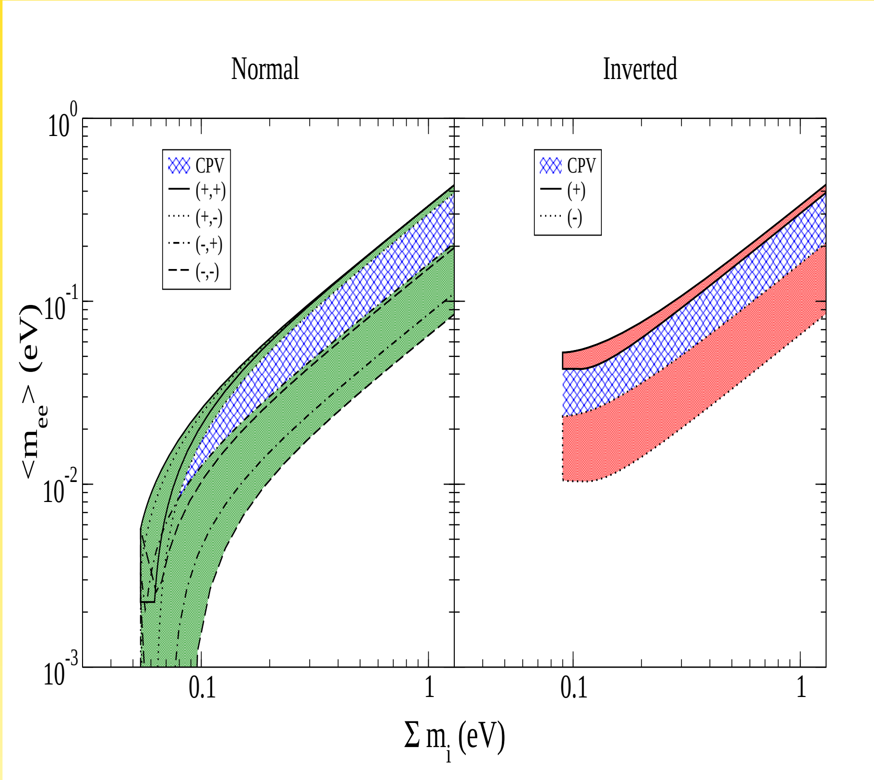
3 **komplementäre** Methoden zur Messung:

Methode	Observable	geg. [eV]	nah/fern [eV]	pro	con
Kurie	$\sqrt{\sum \lvert U_{ei}\rvert^2 m_i^2}$	2.3	$0.2/0.1$	model-unabh.; theo. sauber	final?; schwächstes
Kosmo.	$\sum m_i$	0.7	$0.3/0.05$	bestes; NH/IH	Systematik; model-abh.
$0\nu\beta\beta$	$\lvert \sum U_{ei}^2 m_i \rvert$	0.3	$0.1/0.05$	fundamental; NH/IH	model-abh.; theo. schmutzig

Alle 3 unverzichtbar!

Komplementarität!





$|m_{ee}| = |U_{ei}^2\, m_i|$, $m_\beta = \sqrt{|U_{ei}|^2\, m_i^2}$ und $\Sigma = \sum m_i$

Massenskala

$$\begin{pmatrix} u \\ d \end{pmatrix} \text{ mit } m_u \simeq m_d \qquad \text{versus} \qquad \begin{pmatrix} \nu_e \\ e \end{pmatrix} \text{ mit } m_\nu \simeq 10^{-6}\, m_e$$

warum m_ν winzig? $\Rightarrow$ Seesaw-Mechanismus

Ursprung kleiner Neutrinomassen: Seesaw-Mechanismus

Einfachstes Konzept[a] führt drei neue Aspekte ein:

- fermionische Singlets $N_R \sim (1,0)$
- neue Energieskala M_R ($\propto 1/m_\nu$)
- Leptonzahlverletzung

$$m_\nu = m_D^2/M_R = m_{\rm SM}\,\epsilon \text{ mit } \epsilon = m_{\rm SM}/M_R$$

[a] Vorhersage von $SO(10)$ Modellen!

Tests des Seesaw?

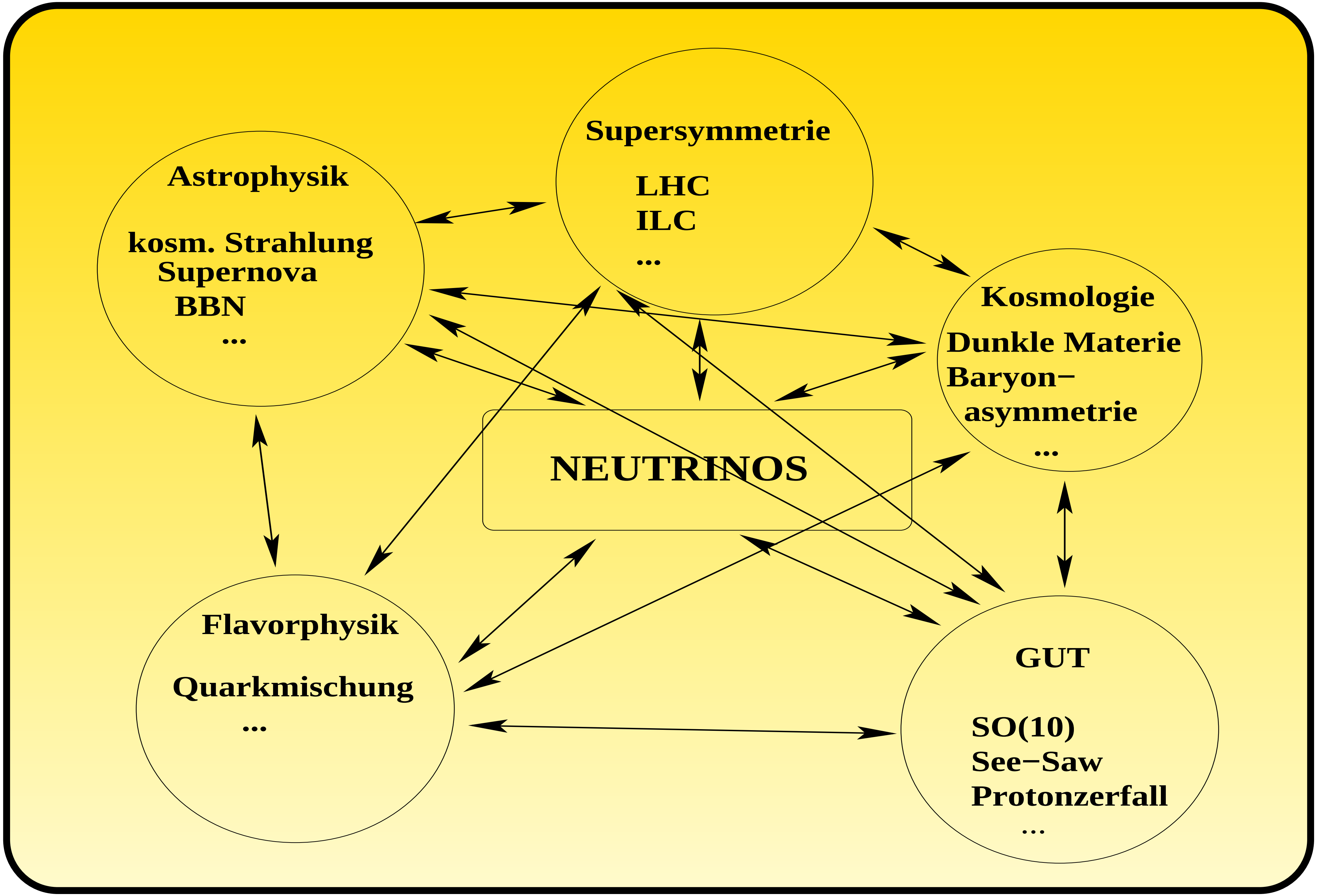
naiv, $M_R = m_D^2/m_\nu = v^2/\sqrt{\Delta m_\mathrm{A}^2} \sim 10^{15}$ GeV...

Seesaw-Portal: $\bar{L}\,\Phi\,N_R \longrightarrow m_D$:

Vertex aus Lepton-Doublet L, Higgs Φ, Singlet N_R!

- $N_R \to L\,\Phi$: Leptogenese
- $L_\alpha \to N_R\,\Phi \to L_\beta$: Leptonflavorverletzung
- $\Phi \to N_R\,L \to \Phi$: Vakuumstabilität

(plus neutrinoloser doppelter Betazerfall)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Pfade zu Neutrinomassen

	Inhalt	**Quantenzahl Messenger**	$\mathcal{L}$	m_ν	**Skala**
"**SM**" (Dirac-Masse)	**RH** ν	$N_R \sim (1,0)$	$h\overline{N_R}\Phi L$	hv	$h = \mathcal{O}(10^{-12})$
"**effektiv**" (dim 5 Operator)	**neue Skala + LZV**	**–**	$h\,\overline{L^c}\,\Phi\,\Phi\,L$	$\frac{h\,v^2}{\Lambda}$	$\Lambda = 10^{14}$ **GeV**
"**direkt**" (type II seesaw)	**Higgs-Triplet + LZV**	$\Delta \sim (3,2)$	$h\overline{L^c}\Delta L + \mu\Phi\Phi\Delta$	hv_T	$\Lambda = \frac{1}{h\mu}M_\Delta^2$
"**indirekt 1**" (type I seesaw)	**RH** ν **+ LZV**	$N_R \sim (1,0)$	$h\overline{N_R}\Phi L + \overline{N_R}M_R N_R^c$	$\frac{(hv)^2}{M_R}$	$\Lambda = \frac{1}{h}M_R$
"**indirekt 2**" (type III seesaw)	**Fermion-Triplets + LZV**	$\Sigma \sim (3,0)$	$h\overline{\Sigma}\,L\Phi + \mathrm{Tr}\overline{\Sigma}M_\Sigma\Sigma$	$\frac{(hv)^2}{M_\Sigma}$	$\Lambda = \frac{1}{h}M_\Sigma$

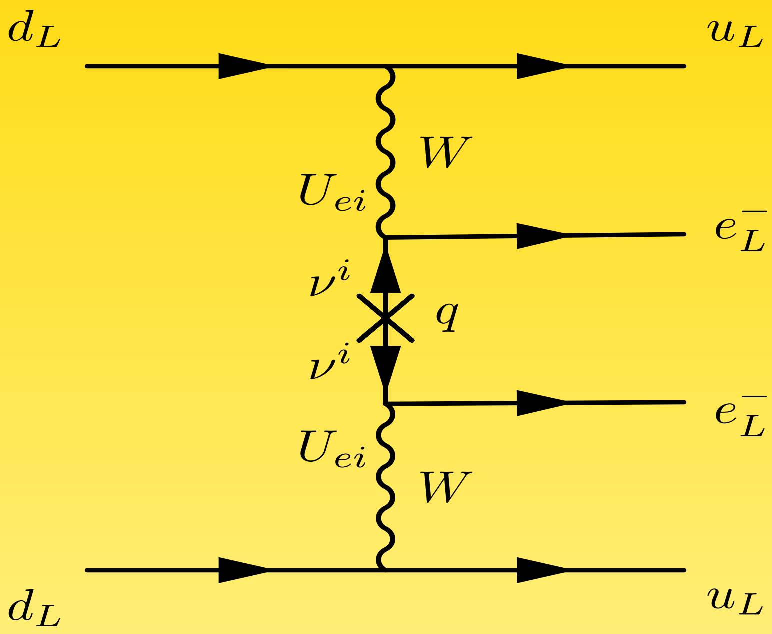
plus Seesaw-Varianten (linear, double, inverse,. . .)

plus radiative Mechanismen

plus zusätzliche Raumdimensionen

plusplusplus

Konsequenz fast aller Mechanismen: Leptonzahlverletzung



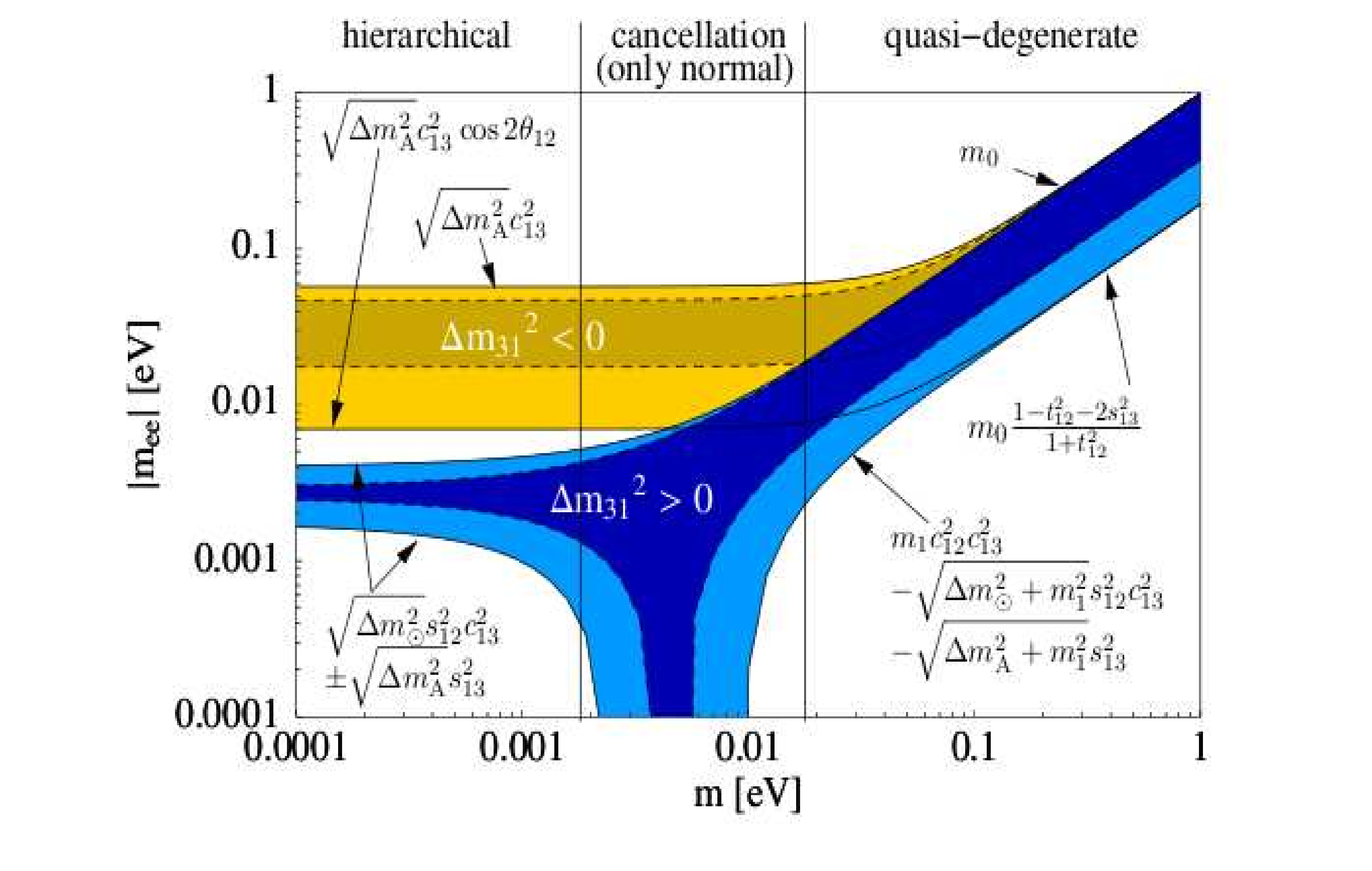
Neutrinoloser doppelter Betazerfall $(A,Z) \to (A,Z+2) + 2\,e^-$

$$\boxed{|m_{ee}| \equiv \left|\sum U_{ei}^2\, m_i\right| = \left||U_{e1}|^2\, m_1 + |U_{e2}|^2\, m_2\, e^{2i\alpha} + |U_{e3}|^2\, m_3\, e^{2i\beta}\right|}$$

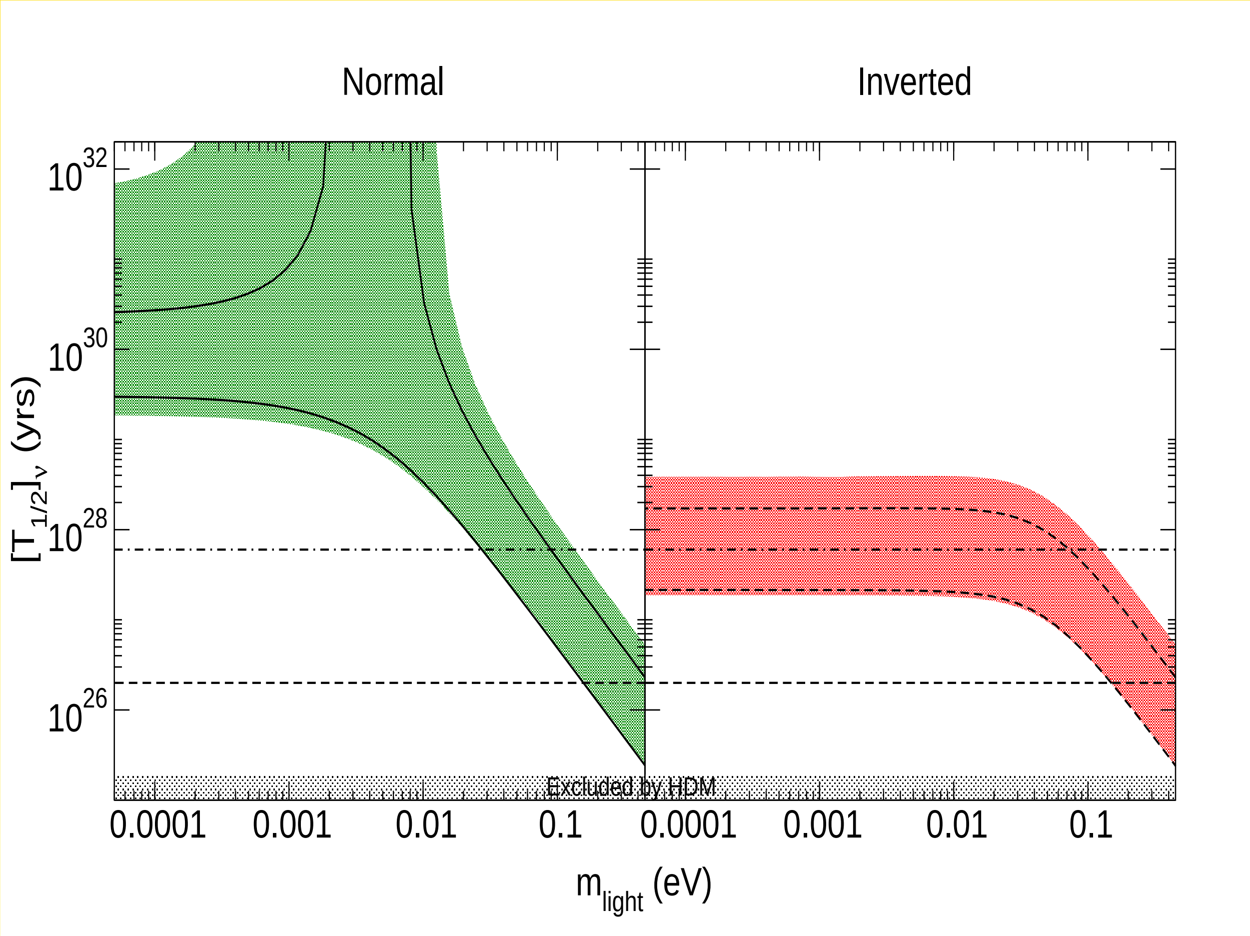
$$\boxed{= f\left(\theta_{12}, |U_{e3}|, m_i, \mathrm{sgn}(\Delta m_{\mathrm{A}}^2), \alpha, \beta\right)}$$

7 von 9 Parametern!

Statt des üblichen Plots. . .



. . .Lebensdauer vs. kleinste Masse

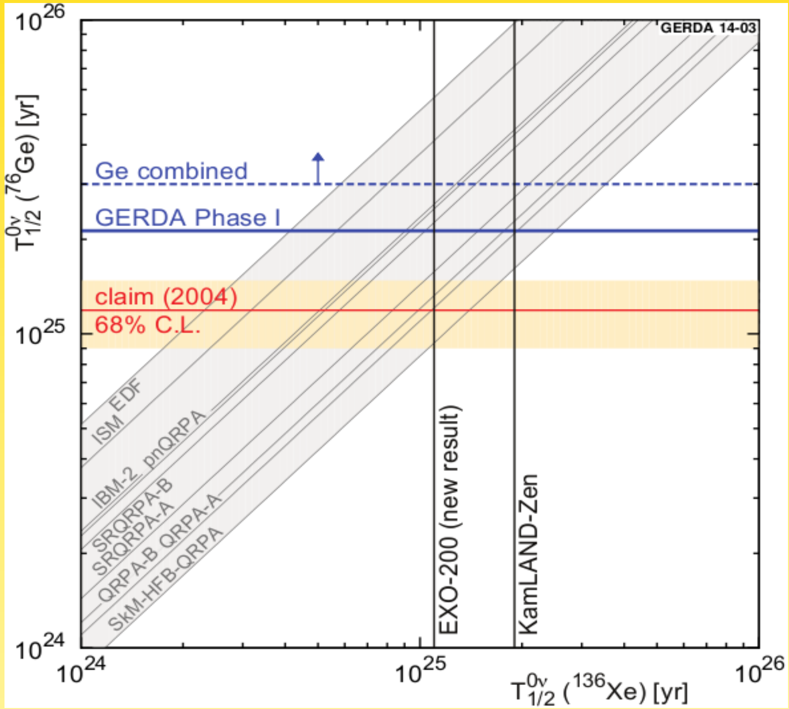


Laufende, bald startende Experimente

HDM-Limit von 2001 erst 2012/13 verbessert...

Name	Isotop	Quelle = Detektor; kalorimetrisch mit			Quelle ≠ Detektor
		ΔE hoch	ΔE niedr.	Topologie	Topologie
AMoRE	^{100}Mo	✓	–	–	–
CANDLES	^{48}Ca	–	✓	–	–
COBRA	^{116}Cd (und ^{130}Te)	–	–	✓	–
CUORE	^{130}Te	✓	–	–	–
DCBA/MTD	^{82}Se / ^{150}Nd	–	–	–	✓
EXO	^{136}Xe	–	–	✓	–
GERDA	^{76}Ge	✓	–	–	–
IHE	^{82}Se / ^{100}Mo / ^{116}Cd / ^{130}Te	✓	–	–	–
KamLAND-Zen	^{136}Xe	–	✓	–	–
LUCIFER	^{82}Se / ^{100}Mo / ^{130}Te	✓	–	–	–
LUMINEU	^{100}Mo	✓	–	–	–
MAJORANA	^{76}Ge	✓	–	–	–
MOON	^{82}Se / ^{100}Mo / ^{150}Nd	–	–	–	✓
NEXT	^{136}Xe	–	–	✓	–
SNO+	^{130}Te	–	✓	–	–
SuperNEMO	^{82}Se / ^{150}Nd	–	–	–	✓
XMASS	^{136}Xe	–	✓	–	–

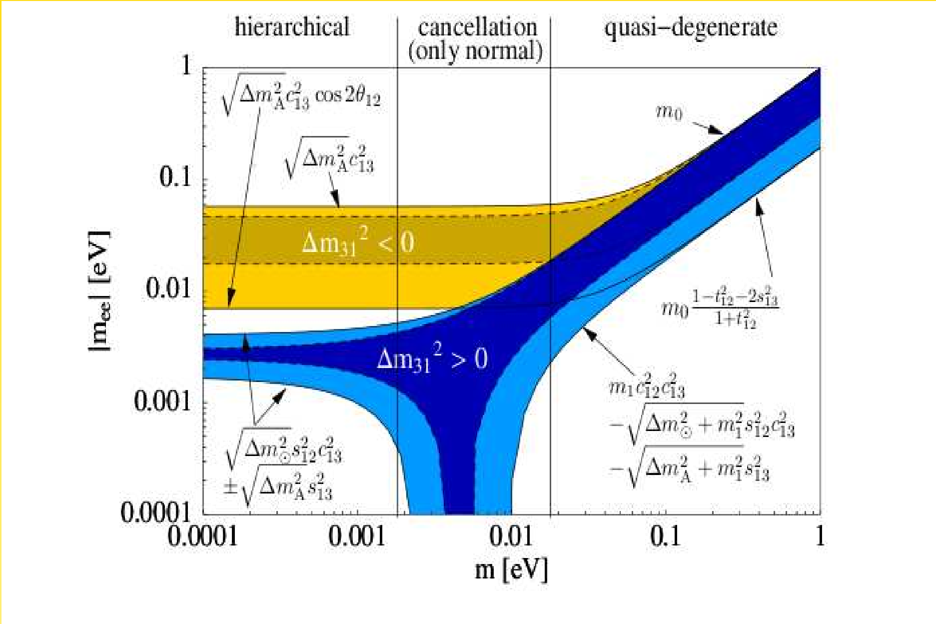
NME	^{76}Ge		^{136}Xe	
	GERDA	comb	KLZ	comb
EDF(U)	**0.32**	**0.27**	**0.13**	–
ISM(U)	**0.52**	**0.44**	**0.24**	–
IBM-2	**0.27**	**0.23**	**0.16**	–
pnQRPA(U)	**0.28**	**0.24**	**0.17**	–
SRQRPA-B	**0.25**	**0.21**	**0.15**	–
SRQRPA-A	**0.31**	**0.26**	**0.23**	–
QRPA-A	*0.28*	*0.24*	*0.25*	–
SkM-HFB-QRPA	*0.29*	*0.24*	*0.28*	–



GERDA, Schwingenheuer

Bhupal Dev, Goswami, Mitra,
W.R., Phys. Rev. **D88**

Invertierte Ordnung

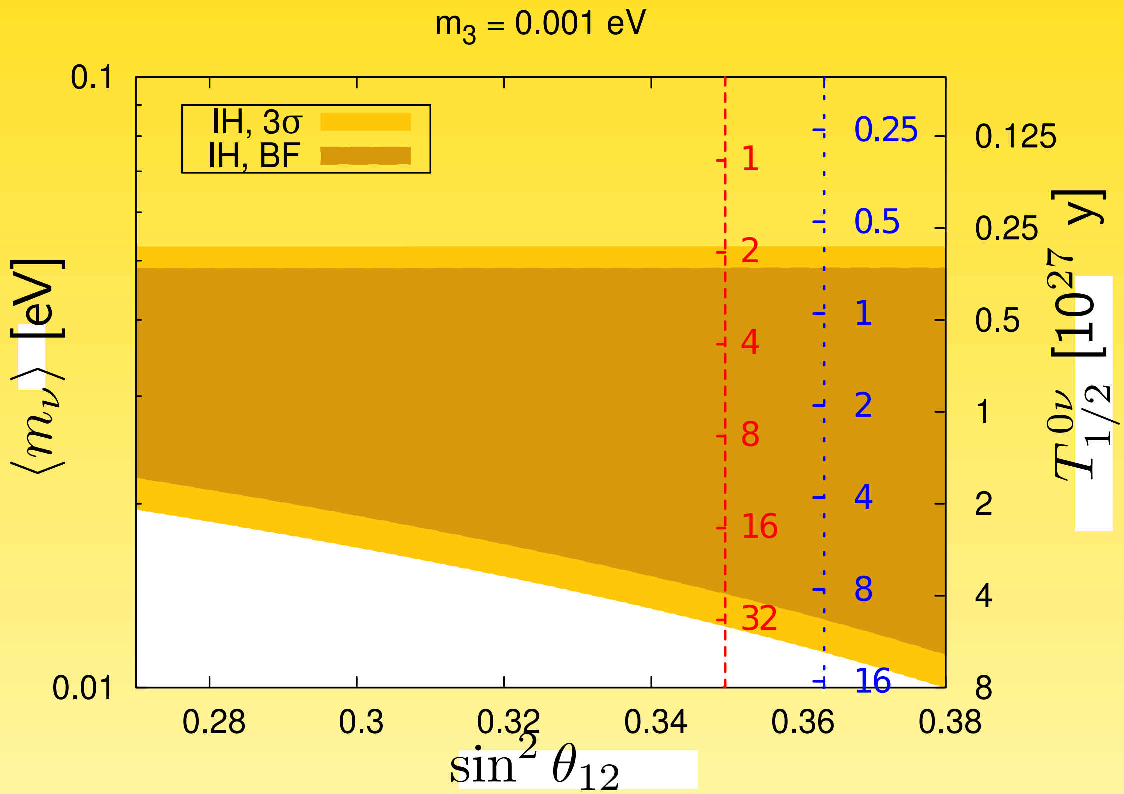


wichtige Skala:

$$|m_{ee}|^{\mathsf{IH}}_{\mathsf{min}} \simeq c^2_{13} \sqrt{\Delta m^2_{\mathrm{A}}} \cos 2\theta_{12}$$

kennen wir $|m_{ee}|^{\mathsf{IH}}_{\mathsf{min}}$ gut genug?

Invertierte Ordnung



Dueck, W.R., Zuber, PRD **83**

Invertierte Ordnung ausschließen

$$|m_{ee}|^{\rm IH}_{\rm min} = \left(1 - |U_{e3}|^2\right) \sqrt{|\Delta m^2_{\rm A}|} \left(1 - 2\sin^2\theta_{12}\right)$$
$$= (0.01 \ldots 0.02)~\rm eV$$

$\Rightarrow$ 3σ-Bereich von $\sin^2\theta_{12}$ gibt Faktor ~ 2 Unsicherheit für $|m_{ee}|^{\rm IH}_{\rm min}$

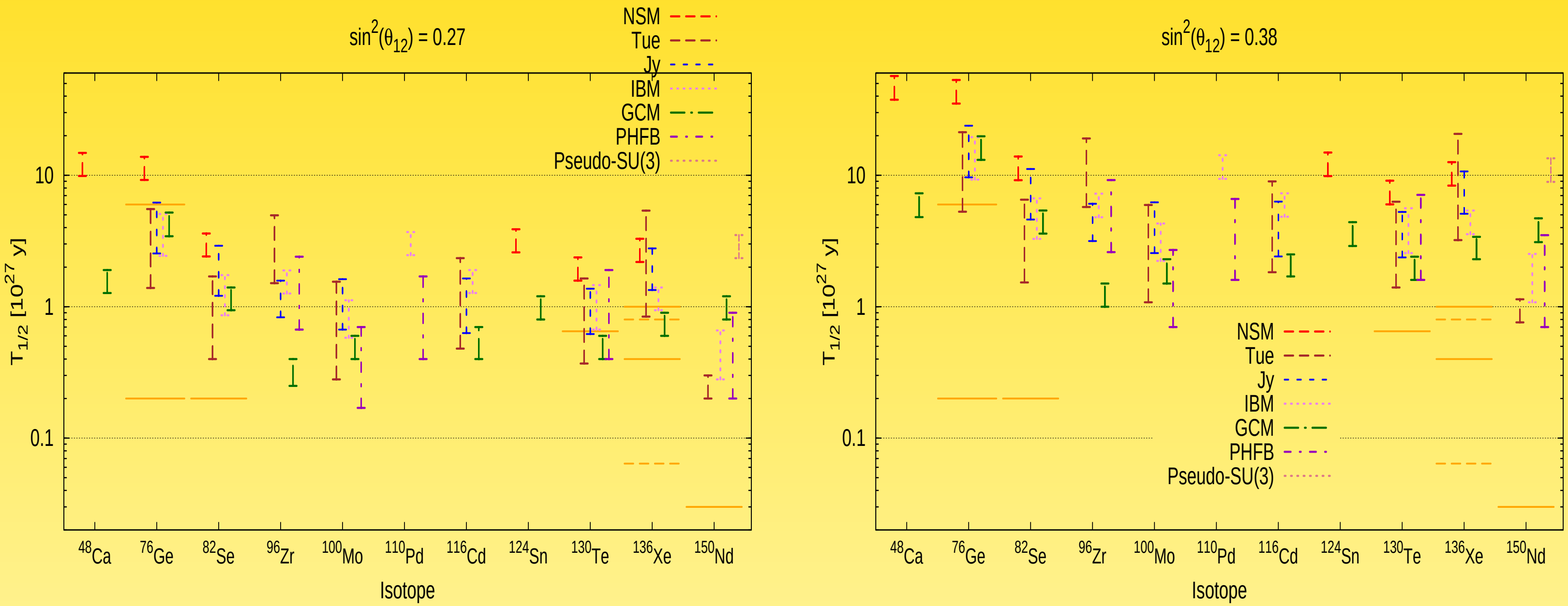
$$(T^{0\nu}_{1/2})^{-1} \propto |m_{ee}|^2 \propto \sqrt{\frac{M\,t}{B\,\Delta E}}$$

$\Rightarrow$ Faktor ~ 16 für $M \times t \times B \times \Delta E$

$\Rightarrow$ Präzisionsmessung von θ_{12} nötig (e.g. JUNO)

Dueck, W.R., Zuber, PRD **83**

Invertierte Ordnung ausschließen



$\sin^2\theta_{12} = 0.27$ $\qquad\qquad$ $\sin^2\theta_{12} = 0.38$

Matrixelemente **und θ_{12}!!**

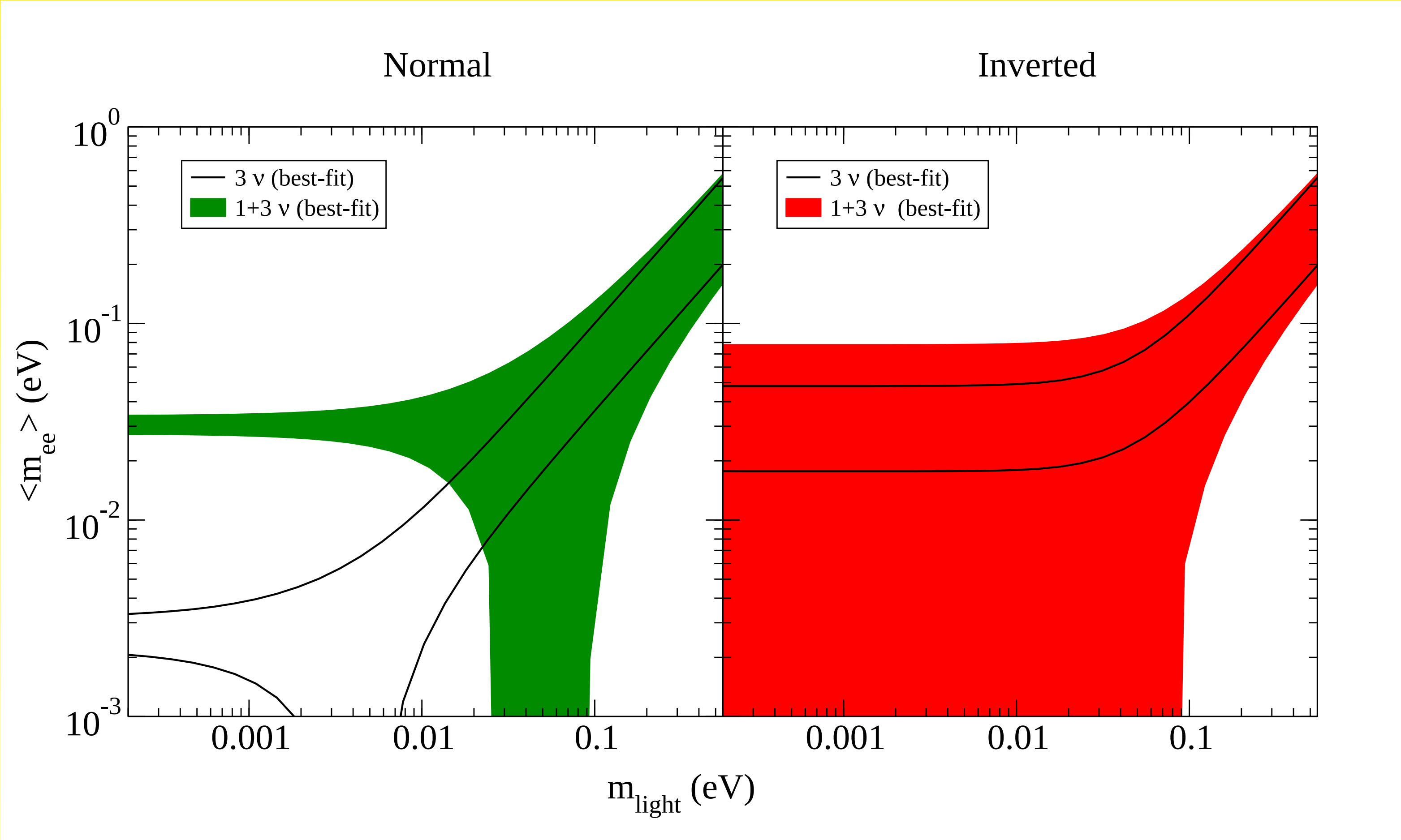
Vorhersagen von Grand Unified Theories

Modell	Fit	$\lvert m_{ee}\rvert$ [meV]	m_0 [meV]	M_3 [GeV]	χ^2
$10_H + \overline{126}_H$	NH	0.49	2.40	3.6×10^{12}	23.0
$10_H + \overline{126}_H$ + SS	NH	0.44	6.83	1.1×10^{12}	3.29
$10_H + \overline{126}_H + 120_H$	NH	2.87	1.54	9.9×10^{14}	11.2
$10_H + \overline{126}_H + 120_H$ + SS	NH	0.78	3.17	4.2×10^{13}	6.9×10^{-6}
$10_H + \overline{126}_H + 120_H$	IH	35.52	30.2	1.1×10^{13}	13.3
$10_H + \overline{126}_H + 120_H$ + SS	IH	24.22	12.0	1.2×10^{13}	0.6

Dueck, W.R., JHEP **1309**

Falls sterile Neutrinos. . .

$|m_{ee}| = 0$ für IH und $|m_{ee}| \neq 0$ für NH!



Barry, W.R., Zhang, JHEP **1107**

Interpretation des Doppelbetazerfalls

- **Standardinterpretation:**

  Neutrinoloser doppelter Betazerfall wird von leichten massiven Majorana-Neutrinos erzeugt

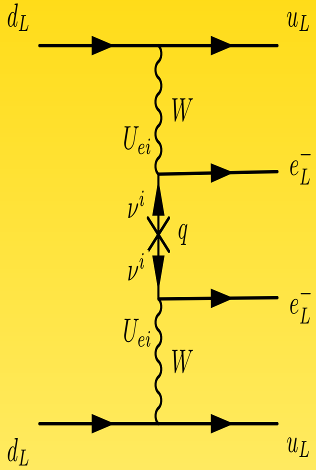
- **Nicht-Standardinterpretationen:**

  Neutrinoloser doppelter Betazerfall wird **nicht** von leichten massiven Majorana-Neutrinos erzeugt

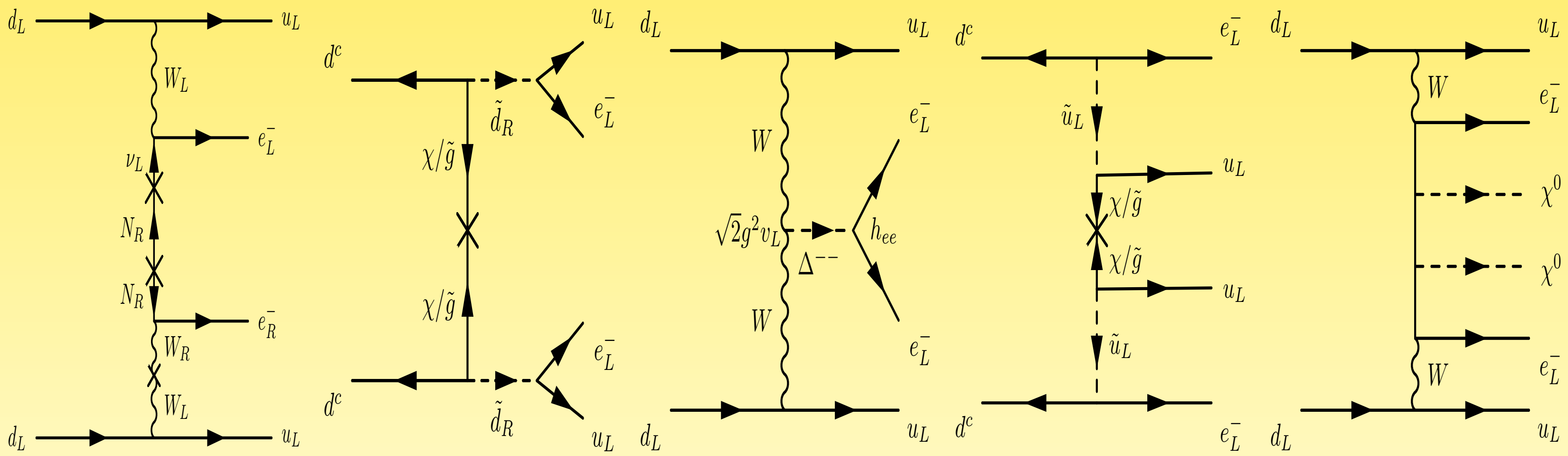
W.R., Int. J. Mod. Phys. **E20**, 1833-1930 (2011)

$0\nu\beta\beta$-Experimente sind keine reinen Neutrinoexperimente!

- **Standardinterpretation:**



- **Nicht-Standardinterpretationen:**

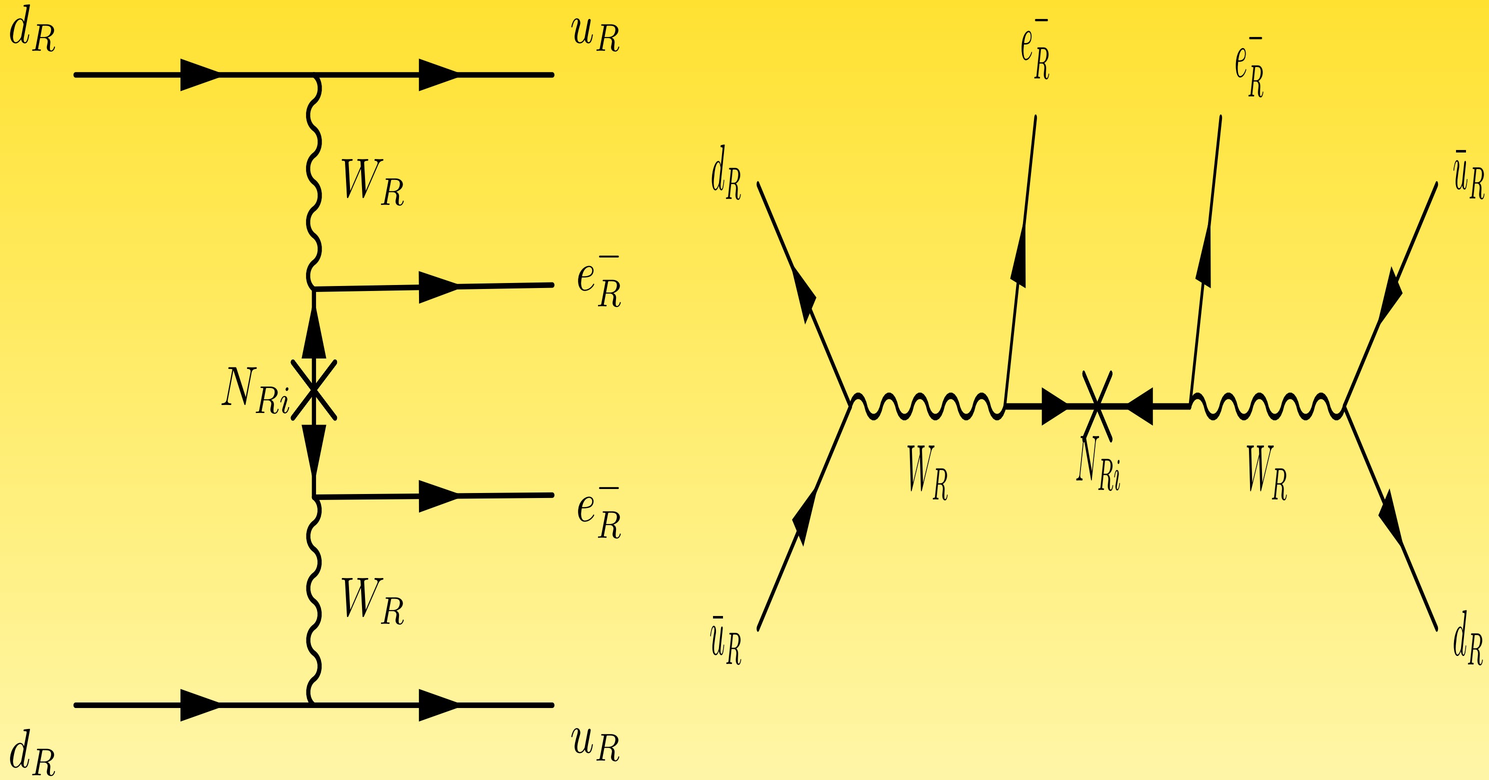


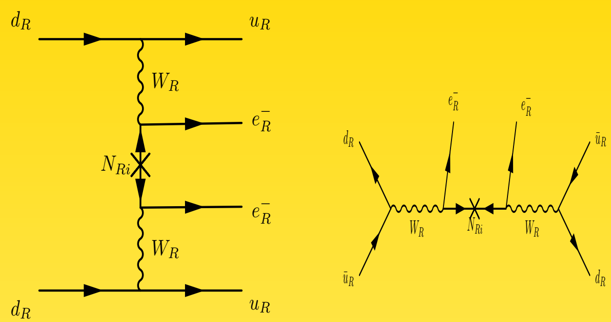
Nützlicher Zufall: $T_{1/2}^{0\nu}(1\ \mathrm{eV}) = T_{1/2}^{0\nu}(1\ \mathrm{TeV})$

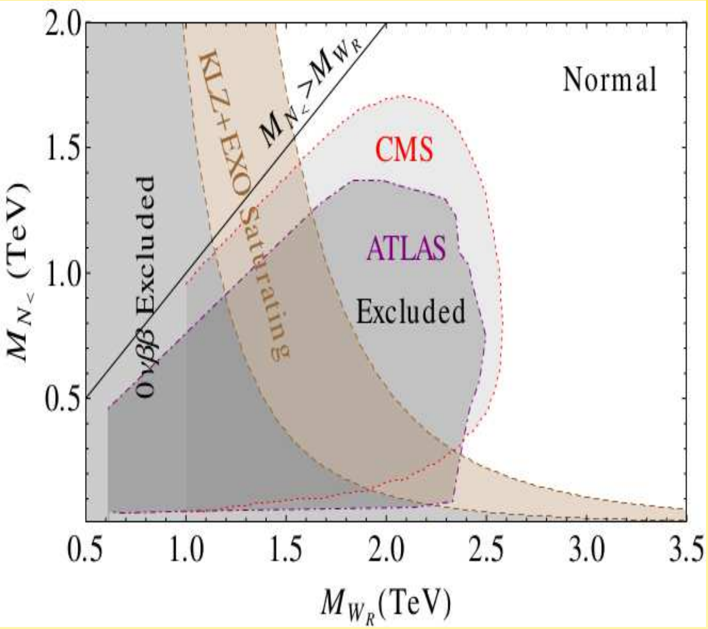
- RPV Supersymmetrie
- links-rechts symmetrische Modelle
- schwere Neutrinos
- Color-octets
- Leptoquarks
- effektive Operatoren
- Extra Dimensionen
- ...

$\Rightarrow$ Lösung des inversen Problems...

LHV vs. $0\nu\beta\beta$

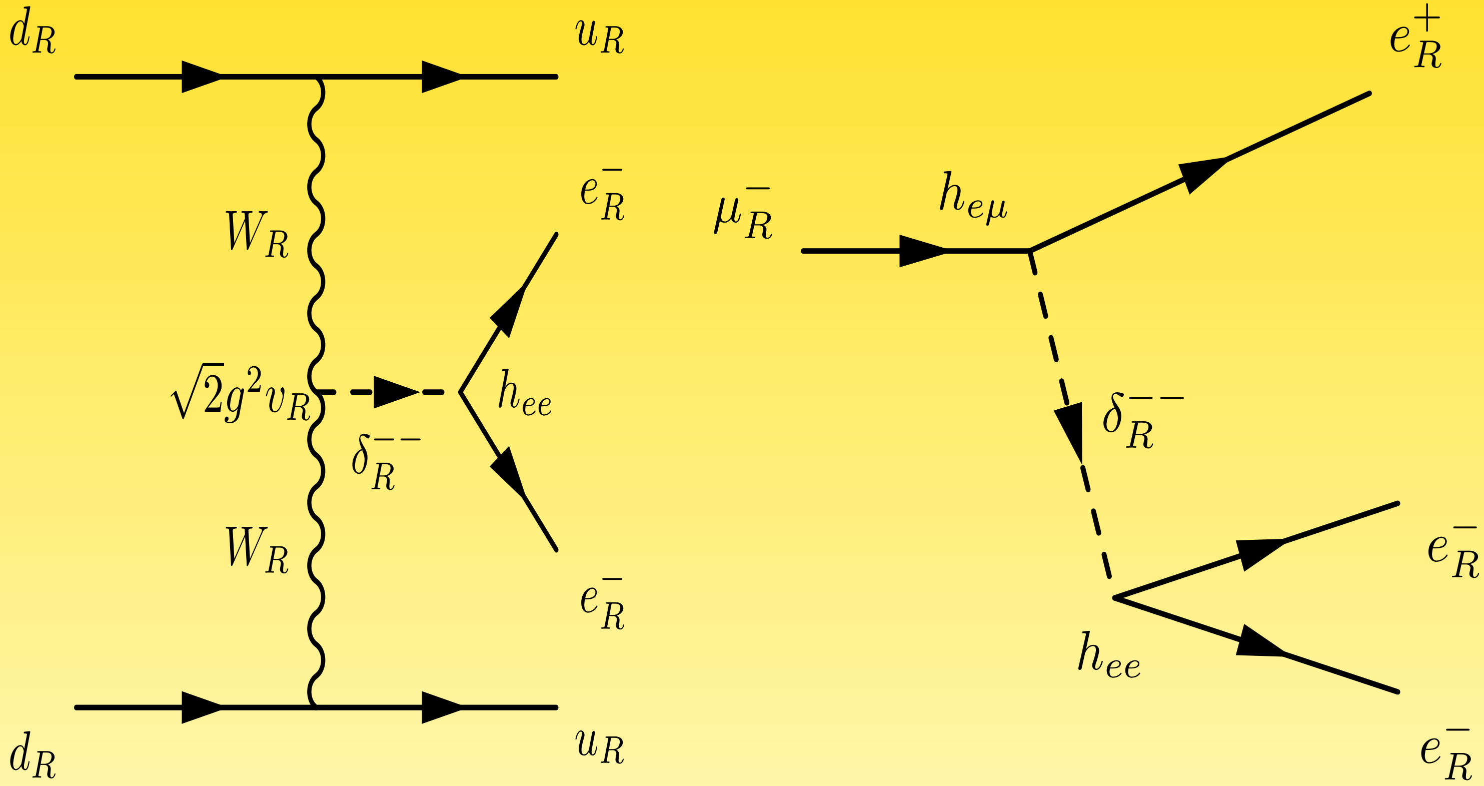






Bhupal Dev, Goswami, Mitra, W.R., Phys. Rev. **D88**

Leptonflavorverletzung



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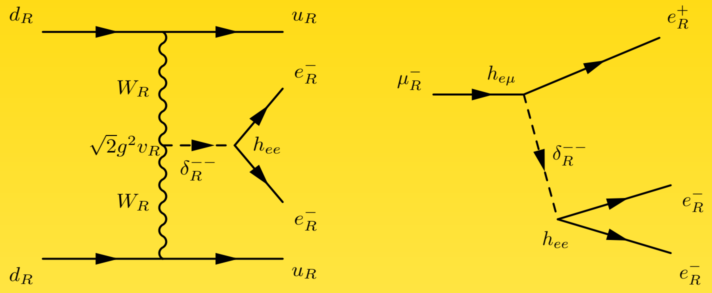
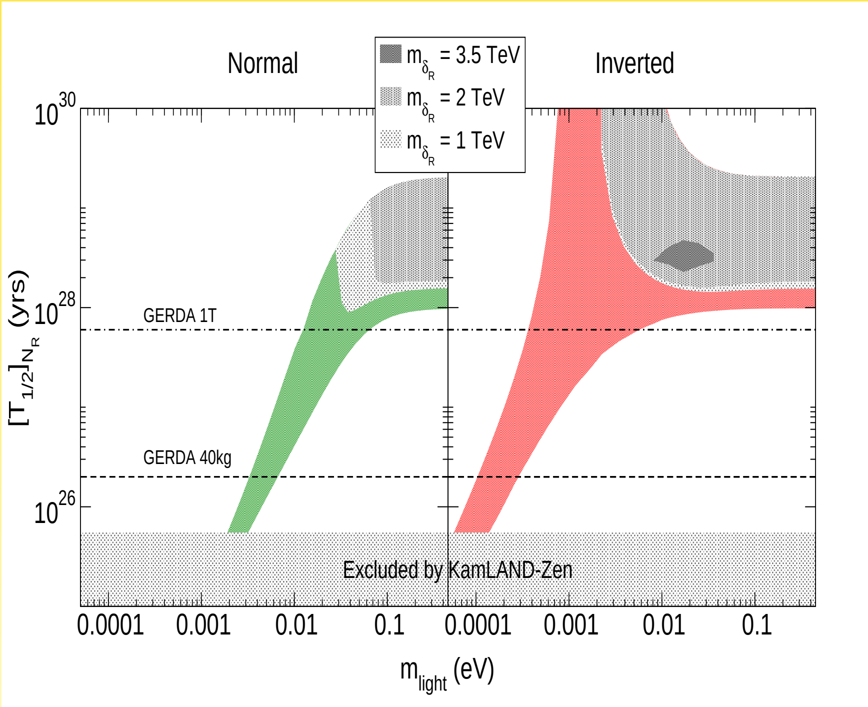
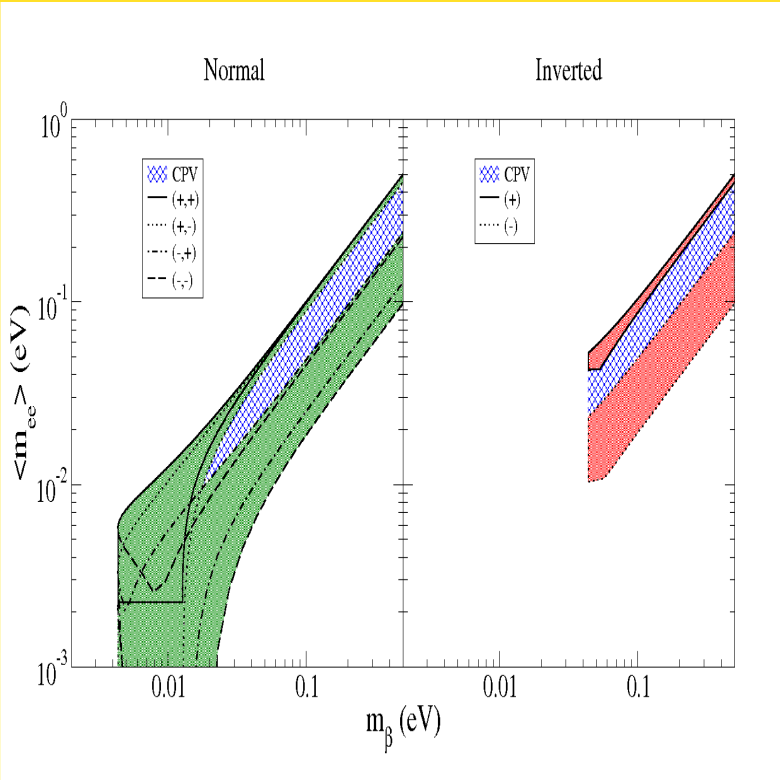
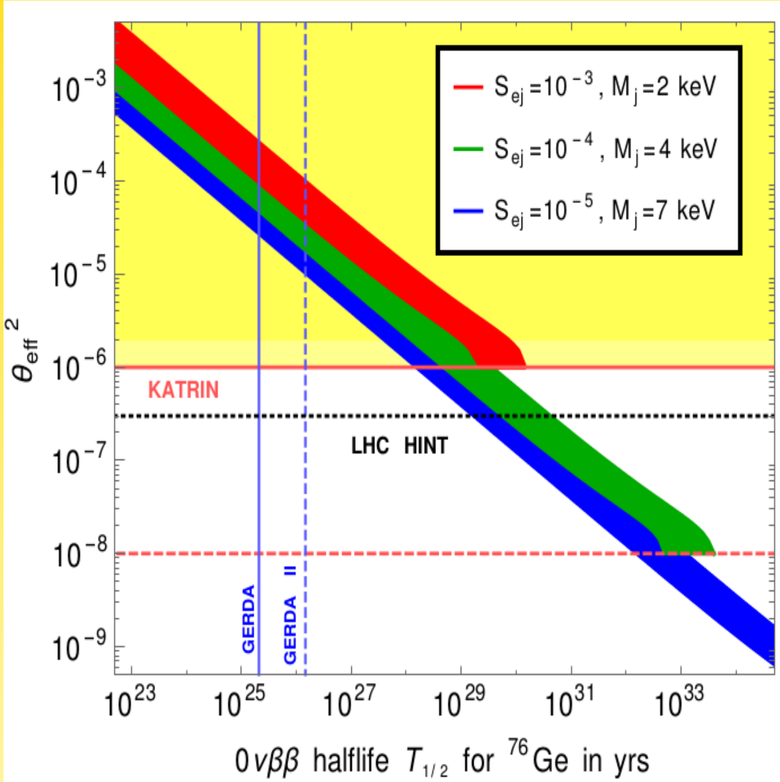




Barry, W.R., JHEP **1309**

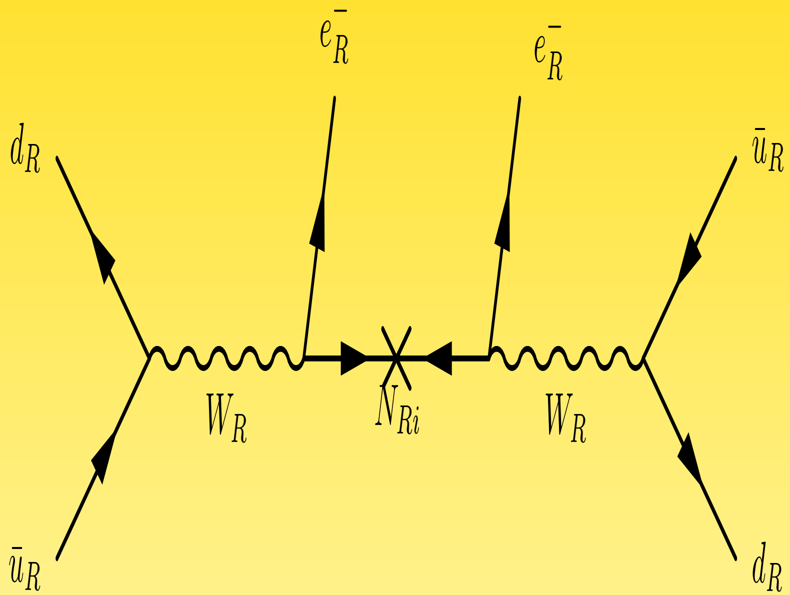
Auch hier Zusammenhang zu (modifizierter) KATRIN?

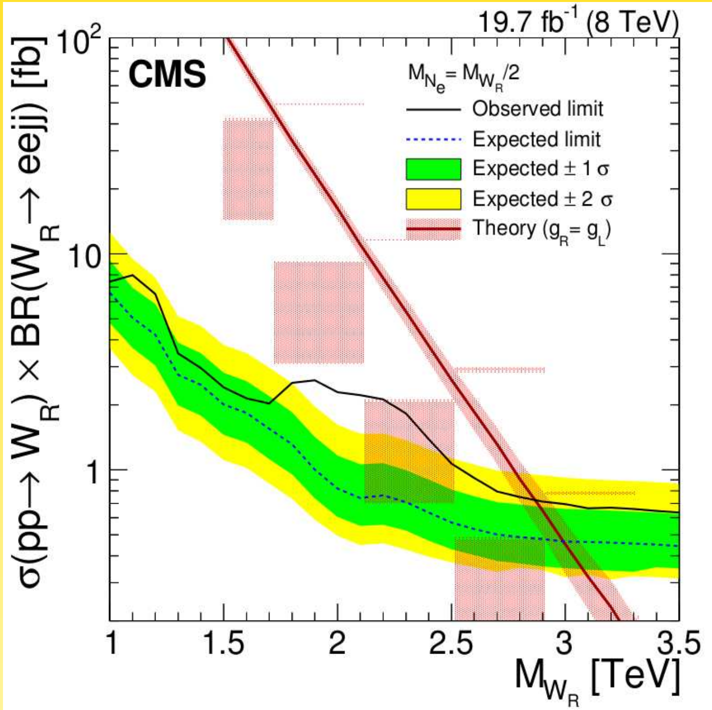




Barry, Heeck, W.R., 1404.5955

Neues aus dem Sommerloch: ein LHC-Signal in $eejj$? (1407.3683)

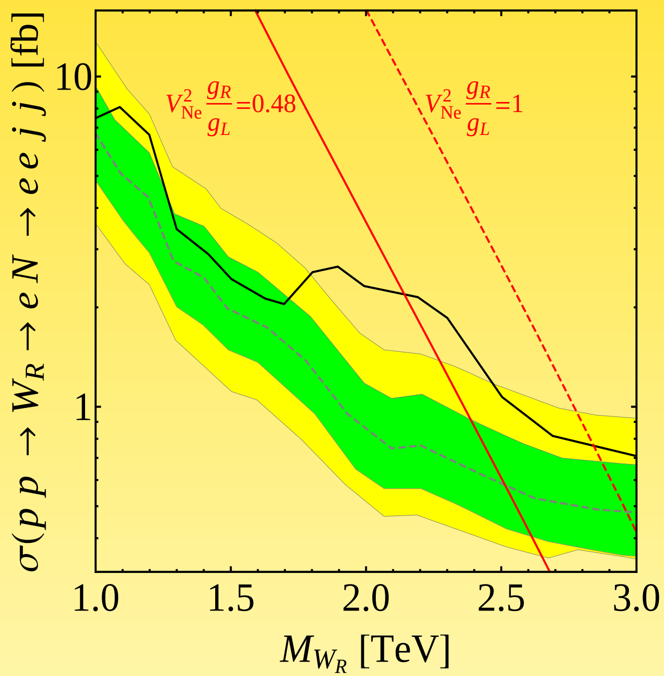


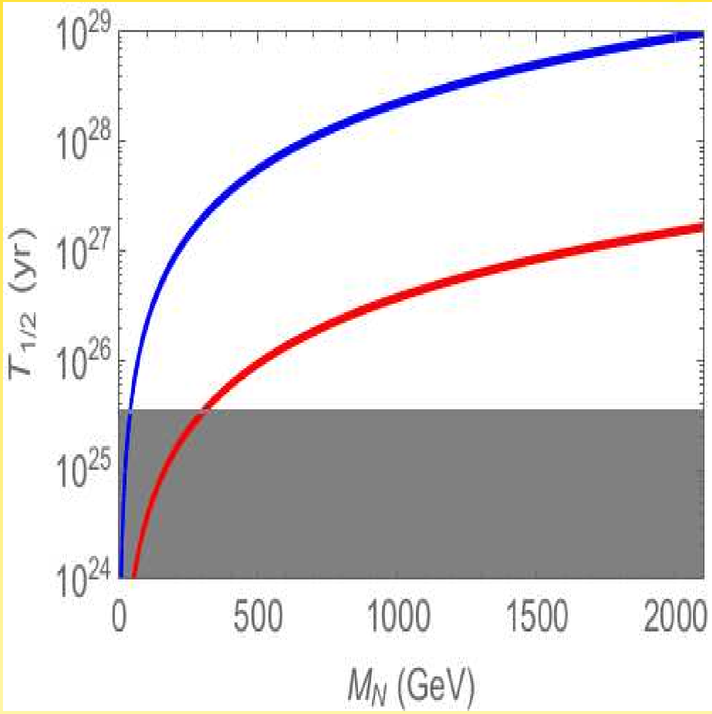


lokale 2.8σ bei $M_{W_R} = 2.1$ TeV, nur im ee-Kanal

Interpretation I: LRSM

Möglich mit modifizierter links-rechts Symmetrie, $g_R = 0.6\, g_L$ (Skalarfelder der $SU(2)_L$ haben verschiedene Masse als Skalarfelder der $SU(2)_R$)

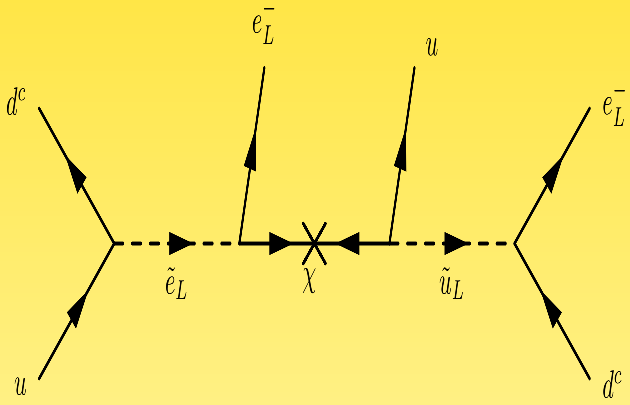


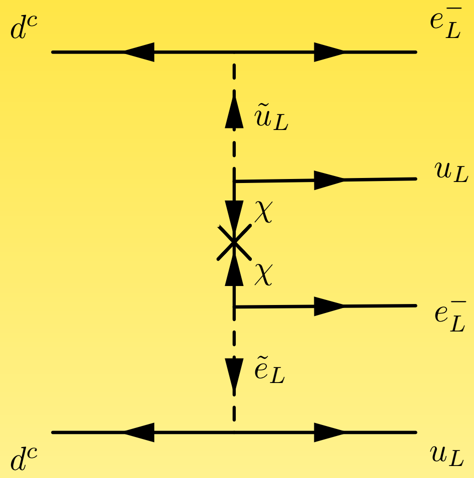


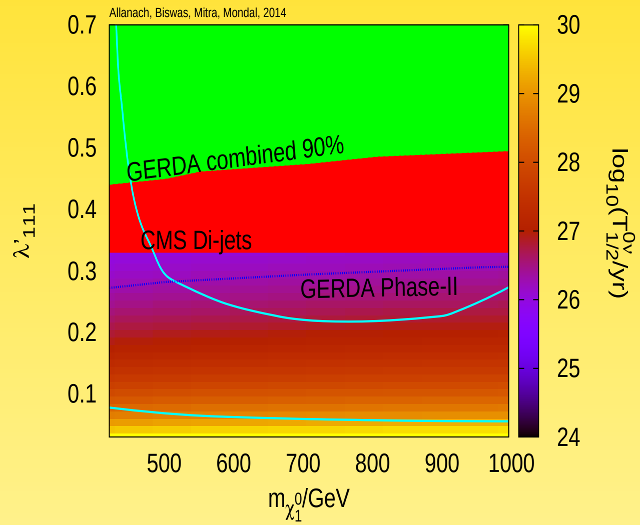
Deppisch *et al.*, 1407.5384

Bhupal Dev, W.R.

Interpretation II: RPV







Allanach *et al.*, 1408.5439

Zusammenfassung

Chi l'ha visto?

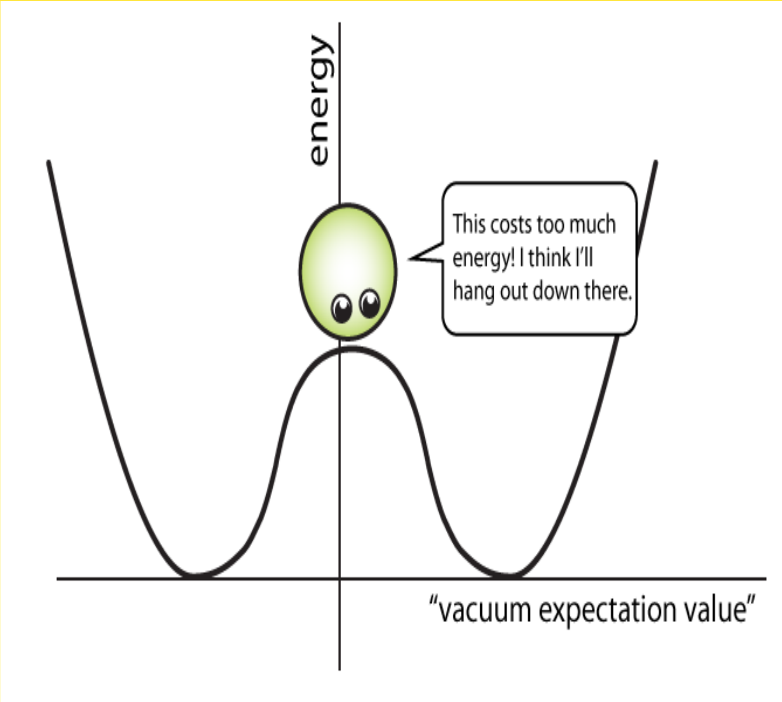
Ettore Majorana, ordinario di fisica teorica all' Università di Napoli, è misteriosamente scomparso dagli ultimi di marzo. Di anni 31, alto metri 1,70, snello, con capelli neri, occhi scuri, una lunga cicatrice sul dorso di una mano. Chi ne sapesse qualcosa è pregato di scrivere al R. P. E. Marianecci, Viale Regina Margherita 66 - Roma.

Phänomenologie schwerer Singlets: Higgs

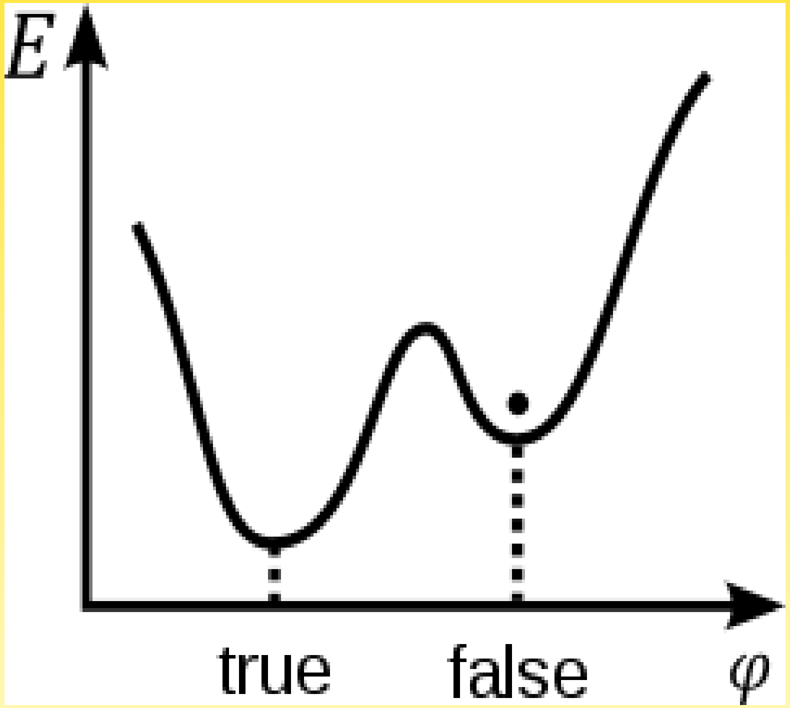
Higgs-Potenzial ist flach $\Rightarrow$ Korrekturen gefährlich

$$\dot{\lambda} \propto -24\,\mathrm{Tr}\left(Y_u^\dagger Y_u\right)^2 \propto m_t^4 \quad \Rightarrow \textbf{Vakuumstabilität}$$

(`Holthausen, Lim, Lindner; Bezrukov` *et al.*; `Degrassi` *et al.*; `Masina`)



$\longrightarrow$



(Vakuum vermutlich metastabil)

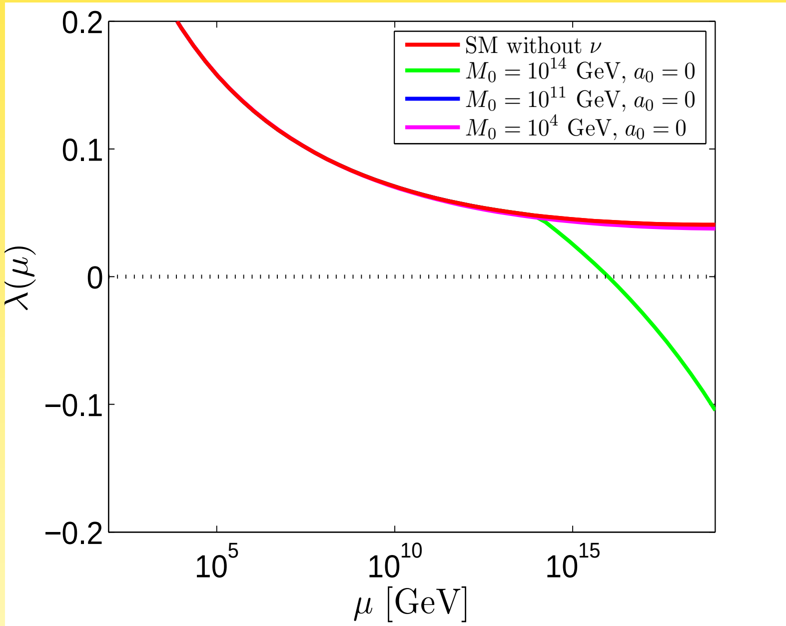
Phänomenologie schwerer Singlets: Higgs

Dirac-Beitrag $\bar{L}\,\Phi\,N_R$ zu λ:

$$\dot{\lambda} \propto -8\,m_D^4$$

`Casas` *et al.*; `Strumia` *et al.*; `W.R., Zhang`

Zerstört Vakuumstabilität



(auch für TeV-Neutrinos die an Beschleunigern produzierbar sind)

Sterile Neutrinos

immer noch viele Hinweise auf (sub-)eV sterile Neutrinos (LSND, MiniBooNE, Gallium, Reaktor, etc.)

Falls diese sterile Neutrinos existieren...

- ...ändern sich die Massenobservablen und ihre Korrelationen
- ...müssen wir Flavorsymmetriemodelle überdenken
- ...müssen wir Seesaw-Modelle überdenken
- ...könnte Standard-Kosmologie falsch sein
- ...etc.

teilweise ebenso für keV sterile Neutrinos ($\leftrightarrow$ WDM)

Warum sollten wir Leptonzahlerhaltung testen?

- L und B *zufällig* im SM erhalten
- effektive Theorie: $\mathcal{L} = \mathcal{L}_{\rm SM} + \frac{1}{\Lambda}\,\mathcal{L}_{\rm LZV} + \frac{1}{\Lambda^2}\,\mathcal{L}_{\rm LFV,\,BZV} + \ldots$
- Baryogenese: B verletzt
- B, L oft in GUTs zusammenhängend
- GUTs haben Seesaw und Majorana-Neutrinos
- (chirale Anomalien: $\partial_\mu J^\mu_{B,L} = c\, G_{\mu\nu}\, \tilde{G}^{\mu\nu} \neq 0$ mit $J^B_\mu = \sum \overline{q_i}\,\gamma_\mu\, q_i$ und $J^L_\mu = \sum \overline{\ell_i}\,\gamma_\mu\,\ell_i$)

$\Rightarrow$ Leptonzahlverletzung genau so wichtig wie Baryonzahlverletzung

(0$\nu\beta\beta$ ist viel mehr als ein Neutrinoexperiment)

Vorhersagen von Grand Unified Theories

Yukawa-Struktur von $SO(10)$ Modellen hängt von Higgs-Darstellungen ab

10_H ($\leftrightarrow H$), $\overline{126}_H$ ($\leftrightarrow F$), 120_H ($\leftrightarrow G$)

Gibt Relationen zwischen Massenmatrizen:

$$
\begin{aligned}
m_{\text{up}} &\propto r(H + sF + it_u\, G) \\
m_{\text{down}} &\propto H + F + iG \\
m_D &\propto r(H - 3sF + it_D\, G) \\
m_\ell &\propto H - 3F + it_l\, G \\
M_R &\propto r_R^{-1} F
\end{aligned}
$$

$\leftrightarrow$ Fit mit RG, Higgs, θ_{13}

Dueck, W.R., JHEP **1309**

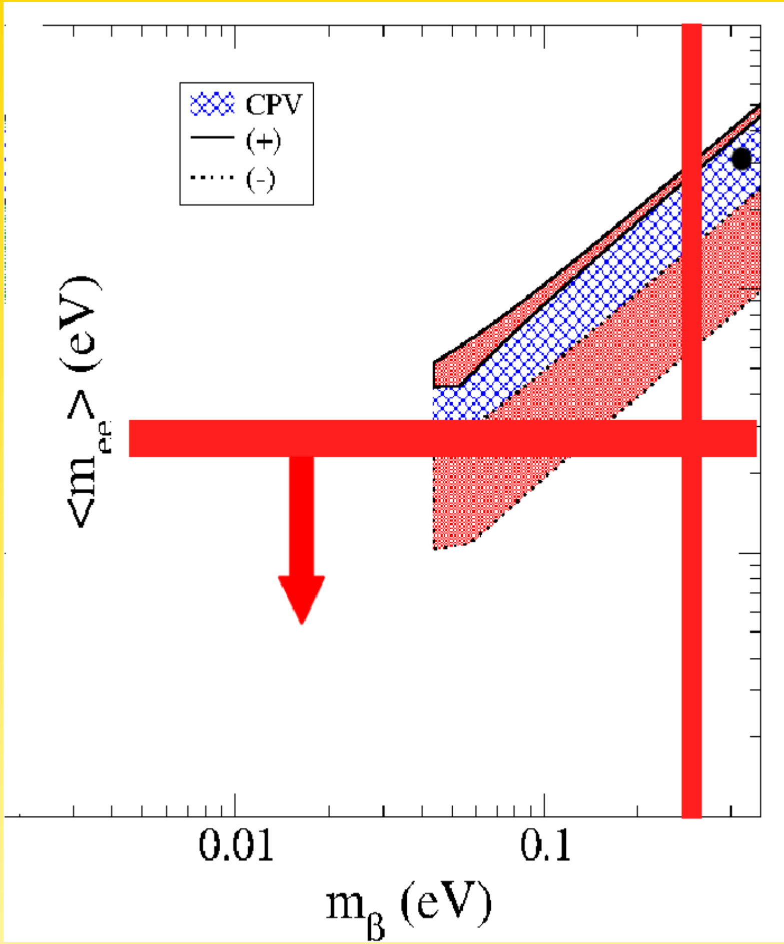
PMNS-Matrix:

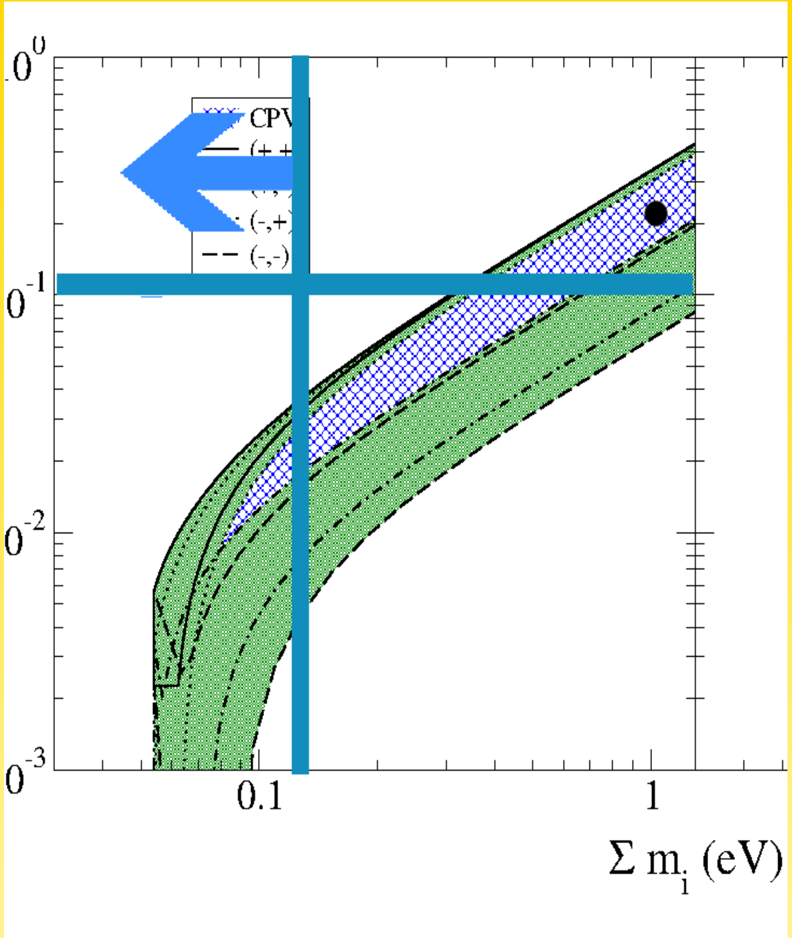
$$|U| = \begin{pmatrix} 0.801\ldots0.845 & 0.514\ldots0.580 & 0.137\ldots0.158 \\ 0.225\ldots0.517 & 0.441\ldots0.699 & 0.614\ldots0.793 \\ 0.246\ldots0.529 & 0.464\ldots0.713 & 0.590\ldots0.776 \end{pmatrix}$$

CKM-Matrix:

$$|V| = \begin{pmatrix} 0.97427 \pm 0.00015 & 0.22534 \pm 0.00065 & 0.00351^{+0.00015}_{-0.00014} \\ 0.22520 \pm 0.00065 & 0.97344^{+0.00016}_{-0.00016} & 0.0412^{+0.0011}_{-0.0005} \\ 0.00867^{+0.00029}_{-0.00031} & 0.0404^{+0.0011}_{-0.0005} & 0.999146^{+0.000021}_{-0.000046} \end{pmatrix}$$

Warum so verschieden?? $\leftrightarrow$ Flavoursymmetrien!





CP-Verletzung!

Dirac-Neutrinos!

Etwas anderes erzeugt $0\nu\beta\beta$!

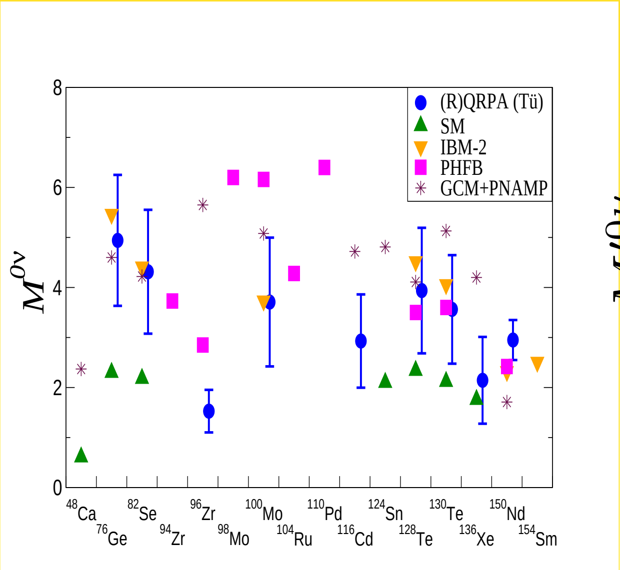
Komplementarität!

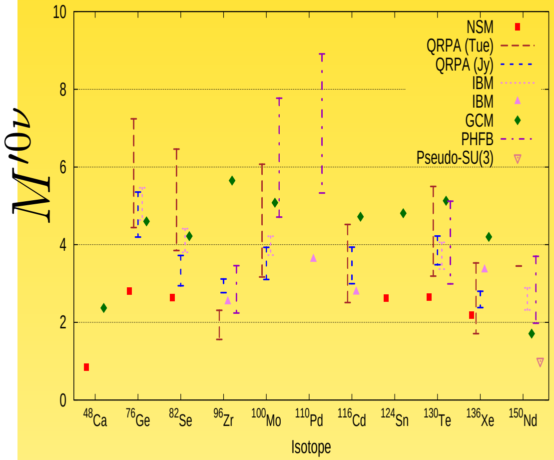
- sind in Ära der Komplementarität:
  - Kosmologie-Limits schließen aus dass leichte Neutrinos $0\nu\beta\beta$-Limits erfüllen
  - $0\nu\beta\beta$-Limits schließen aus dass leichte Neutrinos Mainz/Troitsk-Limit erfüllen
- interessante Möglichkeiten falls Inkonsistenzen auftauchen...

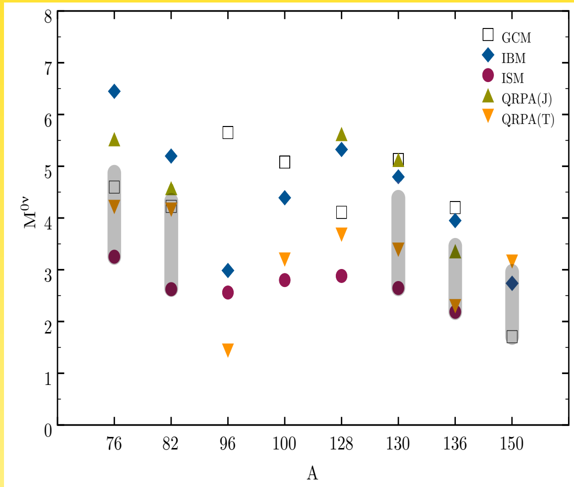
Komplementarität und Nicht-Standardphysik

- Kosmologie $\neq \Lambda$CDM
  - Pan-STARRS1 Survey (1310.3828): $\omega_{\rm DE} = -1.142^{+0.076}_{-0.065}$: Σ-Limit schwächer
  - BICEP-2 vs. Planck: $N_{\rm eff} = 4$ bevorzugt, m_s wird kleiner (1403.7028, 1403.8049, 1404.1794)
  - σ_8 von Planck vs. lokales σ_8: $\Sigma = 0.5 \pm 0.2$ eV (1403.4852)
- keine Neutrinos in $0\nu\beta\beta$
- KATRIN: RH Ströme, extra Dimensionen, tachyonische Neutrinos,...

Von Lebensdauer zu Teilchenphysik: Kernmatrixelemente







Xe-Limit ist besser als Ge-Limit wenn:

$$T_{\mathrm{Xe}} > T_{\mathrm{Ge}} \frac{G_{\mathrm{Ge}}}{G_{\mathrm{Xe}}} \left| \frac{\mathcal{M}_{\mathrm{Ge}}}{\mathcal{M}_{\mathrm{Xe}}} \right|^2 \text{ yrs}$$

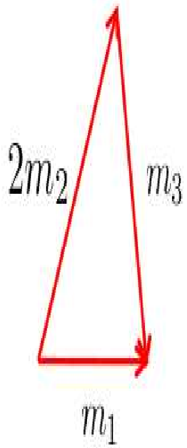
The Zoo (of A_4 models)

Type	L_i	ℓ_i^c	ν_i^c	Δ	References
A1				-	[1–14] [15]$^{\#}$
A2	$\underline{3}$	$\underline{1}, \underline{1}', \underline{1}''$	-	$\underline{1}, \underline{1}', \underline{1}'', \underline{3}$	[16–18]
A3				$\underline{1}, \underline{3}$	[19]
B1	$\underline{3}$	$\underline{1}, \underline{1}', \underline{1}''$	$\underline{3}$	-	[4, 20–27]$^{\#}$ [28–30]* [31–45]
B2				$\underline{1}, \underline{3}$	[46]$^{\#}$
C1				-	[2, 47, 48]
C2	$\underline{3}$	$\underline{3}$	-	$\underline{1}$	[49, 50] [51]$^{\#}$
C3				$\underline{1}, \underline{3}$	[52]
C4				$\underline{1}, \underline{1}', \underline{1}'', \underline{3}$	[53]
D1				-	[54, 55]$^{\#}$ [56, 57]* [58]
D2	$\underline{3}$	$\underline{3}$	$\underline{3}$	$\underline{1}$	[59] [60]*
D3				$\underline{1}'$	[61]*
D4				$\underline{1}', \underline{3}$	[62]*
E	$\underline{3}$	$\underline{3}$	$\underline{1}, \underline{1}', \underline{1}''$	-	[63, 64]
F	$\underline{1}, \underline{1}', \underline{1}''$	$\underline{3}$	$\underline{3}$	$\underline{1}$ or $\underline{1}'$	[65]
G	$\underline{3}$	$\underline{1}, \underline{1}', \underline{1}''$	$\underline{1}, \underline{1}', \underline{1}''$	-	[66]
H	$\underline{3}$	$\underline{1}, \underline{1}, \underline{1}$	-	-	[67]
I	$\underline{3}$	$\underline{1}, \underline{1}, \underline{1}$	$\underline{1}, \underline{1}, \underline{1}$	-	[68]*
J	$\underline{3}$	$\underline{1}, \underline{1}, \underline{1}$	$\underline{3}$	-	[12, 39, 69, 70]
K	$\underline{3}$	$\underline{1}, \underline{1}, \underline{1}$	$\underline{1}, \underline{1}$	$\underline{1}$	[71]*
L	$\underline{3}$	$\underline{1}, \underline{1}, \underline{1}$	$\underline{1}$	-	[72]*
M	$\underline{1}, \underline{1}', \underline{1}''$	$\underline{1}, \underline{1}'', \underline{1}'$	$\underline{3}, \underline{1}$	-	[73, 74]
N	$\underline{1}, \underline{1}', \underline{1}''$	$\underline{1}, \underline{1}'', \underline{1}'$	$\underline{3}, \underline{1}', \underline{1}''$	-	[75]

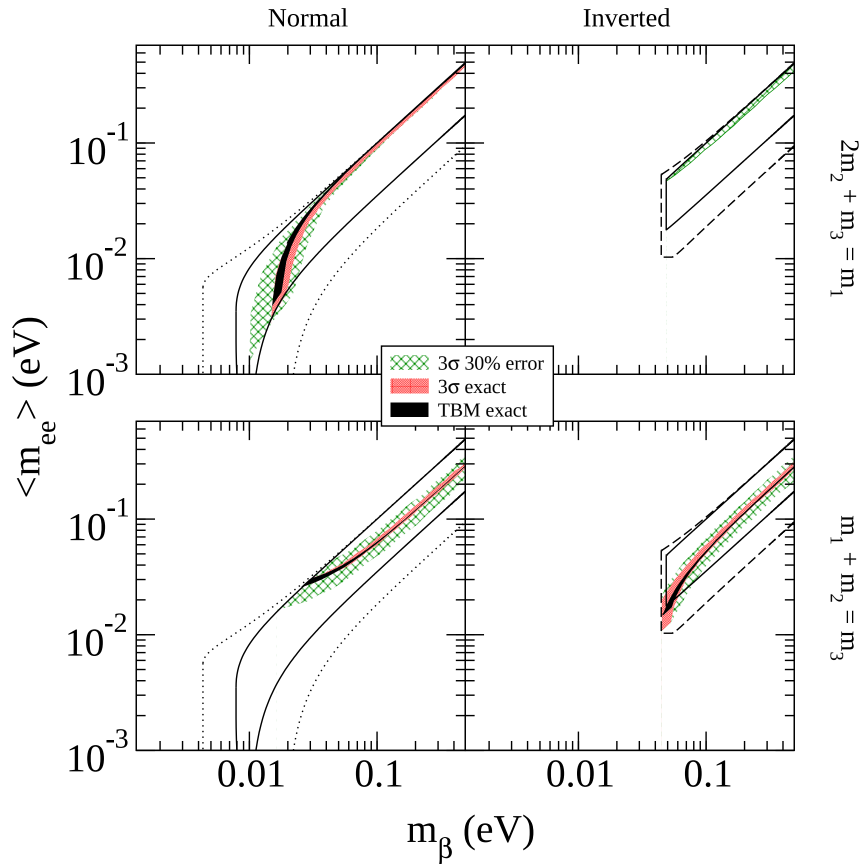
Barry, W.R., PRD **81**, 093002 (2010)

all give the same mixing scheme...

Neutrino mass sum-rules



Sum-rule	Flavour symmetry
$2m_2 + m_3 = m_1$	$A_4, T', (S_4)$
$m_1 + m_2 = m_3$	$S_4, (A_4)$
$\frac{2}{m_2} + \frac{1}{m_3} = \frac{1}{m_1}$	A_4, T'
$\frac{1}{m_1} + \frac{1}{m_2} = \frac{1}{m_3}$	S_4



constrains masses and Majorana phases

Barry, W.R., NPB **842**

Seesaw-Formalismus

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

6×6 Matrix, diagonalisiert mit

$$\mathcal{U}_\nu \simeq \begin{pmatrix} 1 - \frac{1}{2}BB^\dagger & B \\ -B^\dagger & 1 - \frac{1}{2}B^\dagger B \end{pmatrix} \begin{pmatrix} U & 0 \\ 0 & V_R \end{pmatrix} \quad \text{mit } B = m_D M_R^{-1}$$

leichte Neutrinos (mischen nicht-unitär):

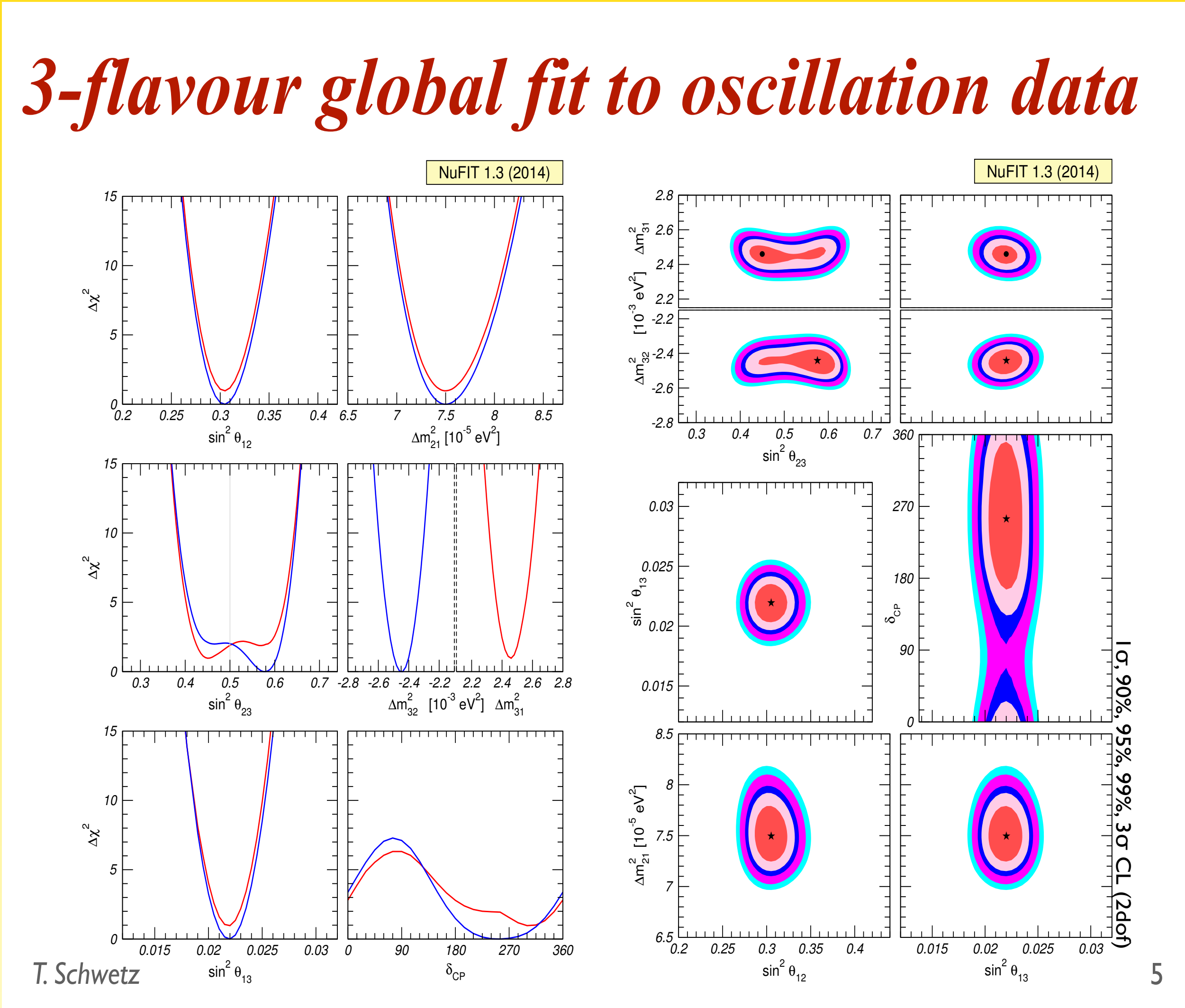
$$m_\nu = -m_D\, M_R^{-1}\, m_D^T = U\, \mathrm{diag}(m_1, m_2, m_3)\, U^T$$

schwere Neutrinos:

$$M_R = V_R\, \mathrm{diag}(M_1, M_2, M_3)\, V_R^T$$

(N_R sind *sterile Neutrinos*)

Status globaler Fits (`Maltoni` *et al.*, `post Nu2014`)

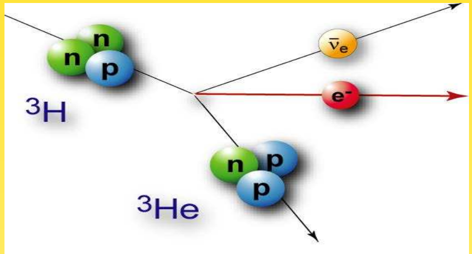


Ergebnisse der Fits

		Fogli et al.	*Maltoni et al.*	*Valle et al.*
$\sin^2\theta_{23}$	nor	0.437	0.452	0.567
	inv	0.455	0.579	0.573
$\delta/^\circ$	nor	250	306	266
	inv	236	254	266

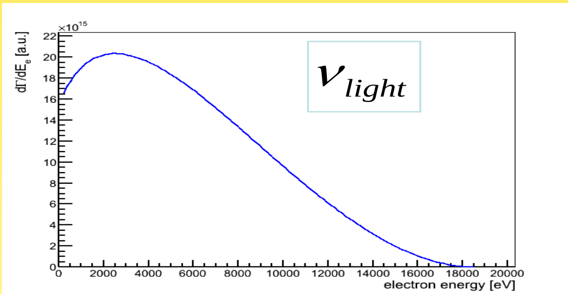
- Oktant von θ_{23}: T2K misst signifikante $P_{\mu e} \propto \sin^2\theta_{13}\,\sin^2\theta_{23} + \mathrm{Materie}, \delta$, aber stark von Details atm. nus abhängig (sub-GeV e-Exzess)
- $\delta \simeq \frac{3}{2}\pi$: Korrelation von θ_{13} aus LBL und KL; 1σ-Bereich ist $\sin\delta \in [-1, 0]$
- CP Verletzung ist bei $\lesssim 1.5\sigma$, korreliert mit θ_{23}
- Keine signifikante Präferenz bei Normal vs. Invertiert

Imprint of keV neutrinos on ß-spectrum

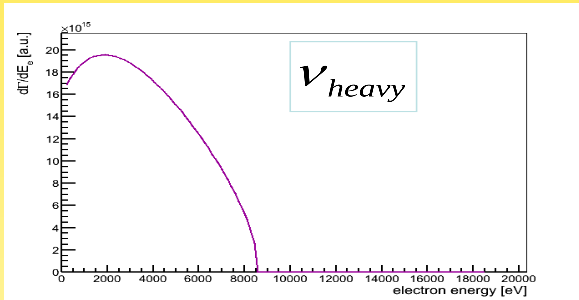


$$\begin{pmatrix} \nu_e \\ \nu_s \end{pmatrix} = \begin{pmatrix} \cos\theta & -\sin\theta \\ \sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} \nu_{light} \\ \nu_{heavy} \end{pmatrix}$$

$\cos^2(\theta)$



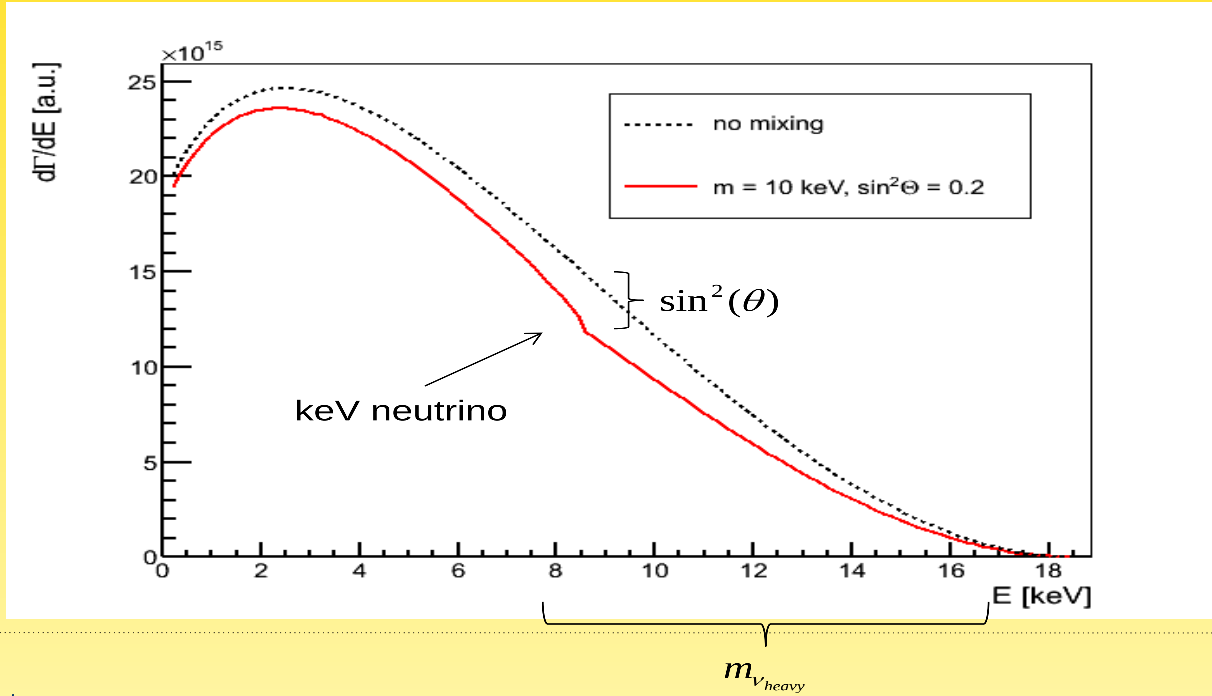
$+ \sin^2(\theta)$



Susanne Mertens 12 BERKELEY LAB

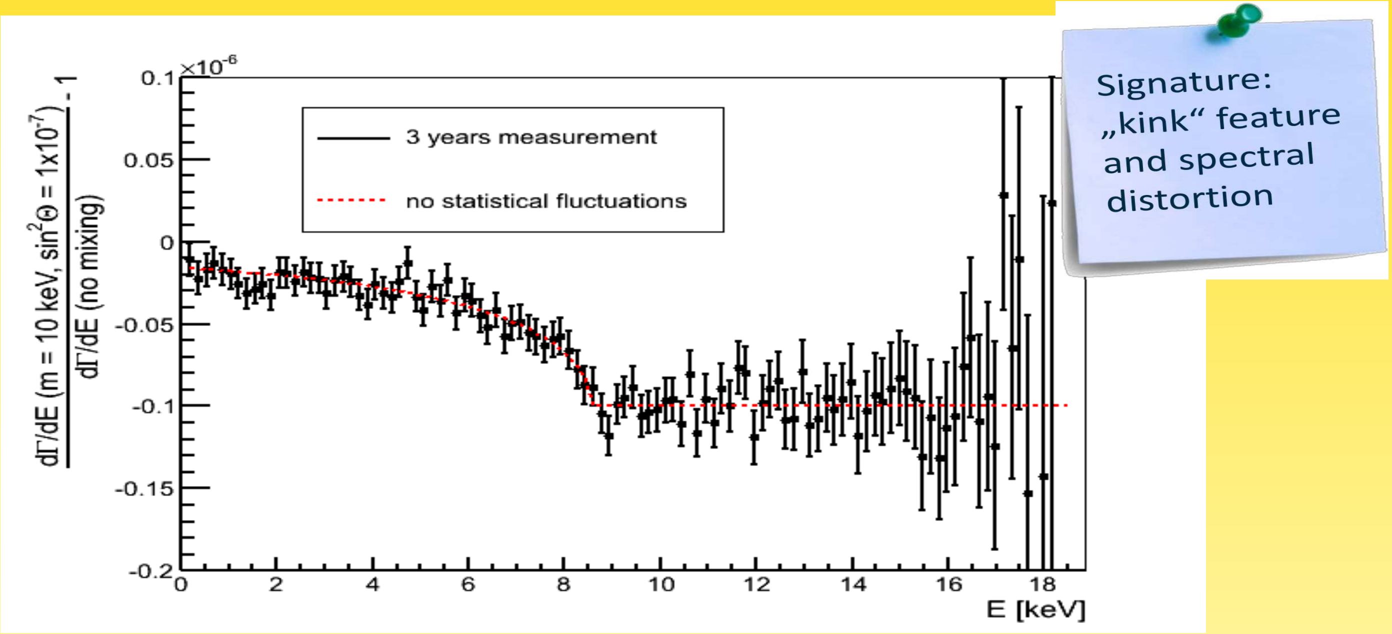
Mertens *et al.*, 1409.0920

Imprint of keV neutrinos on ß-spectrum

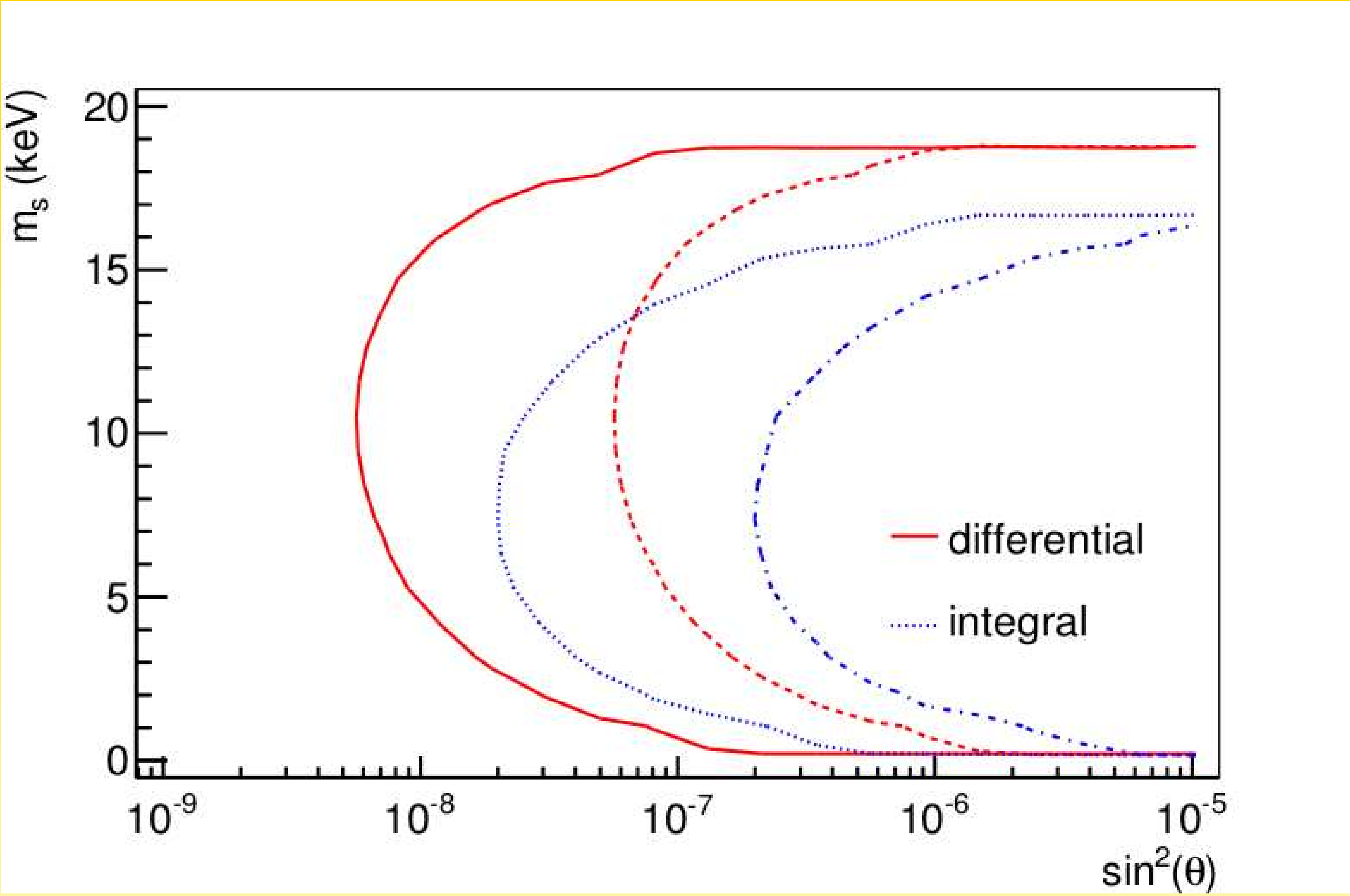


Mertens *et al.*, 1409.0920

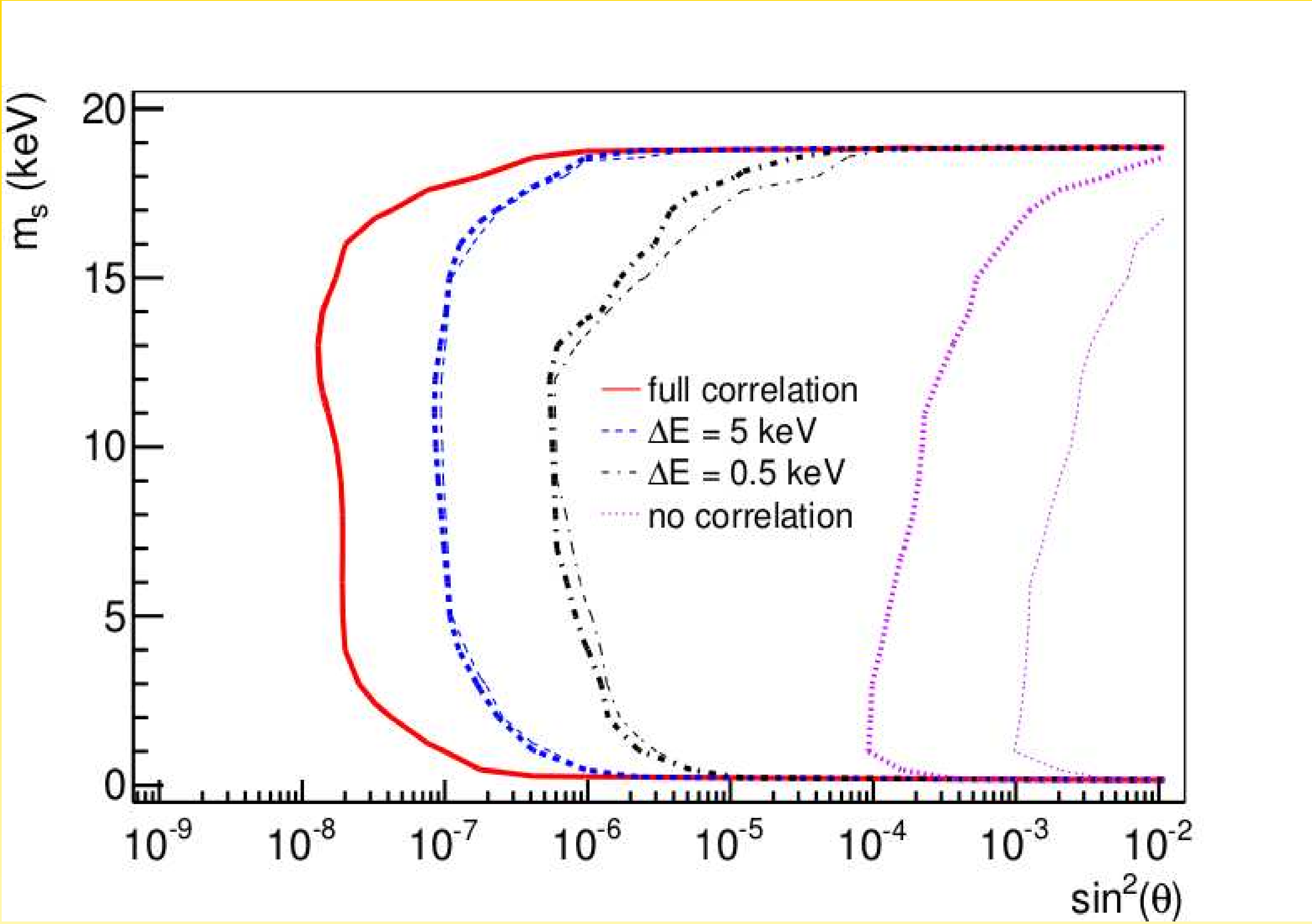
Imprint of keV neutrinos on ß-spectrum



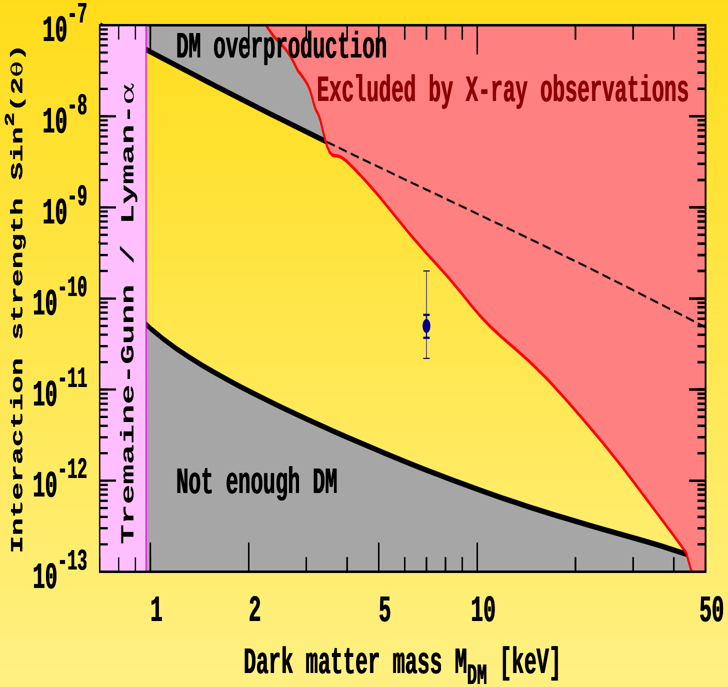
Mertens *et al.*, 1409.0920



(i) energy resolving detector (differential) or (ii) counting detector (integral) or (iii) time-of-flight

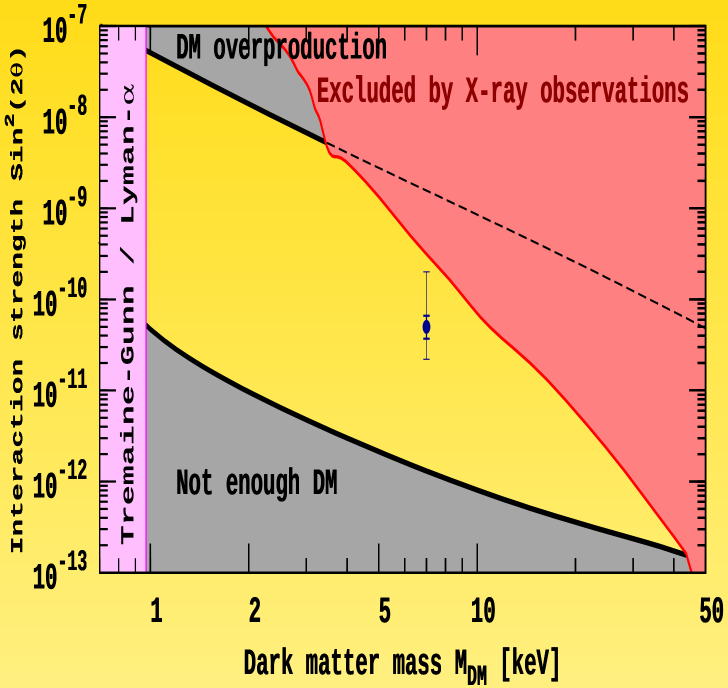


$\Rightarrow$ mixing down to 10^{-7} in reach!?



$\Rightarrow$ mixing down to 10^{-7} in reach!?

hard for KATRIN to see something. . .

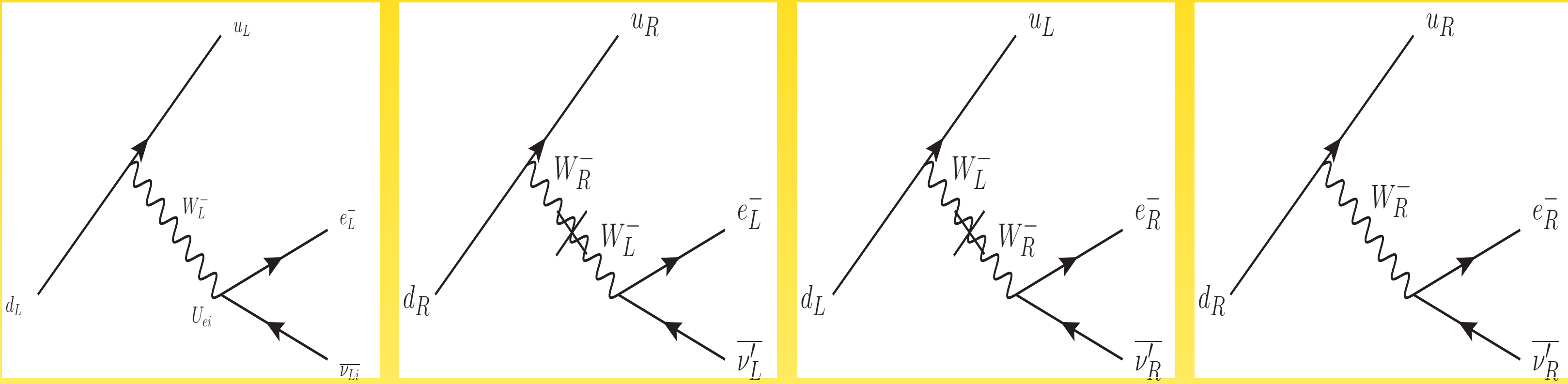


$\Rightarrow$ mixing down to 10^{-7} in reach!?

hard for KATRIN to see something...

...can increase signal with additional interactions, e.g. right-handed currents

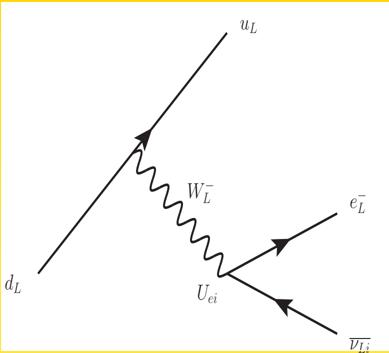
KATRIN and right-handed currents

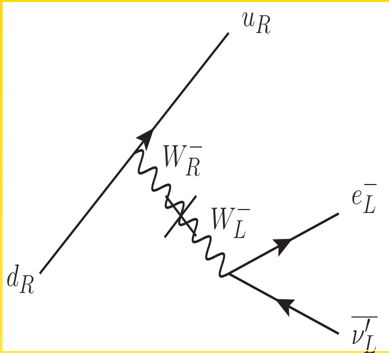


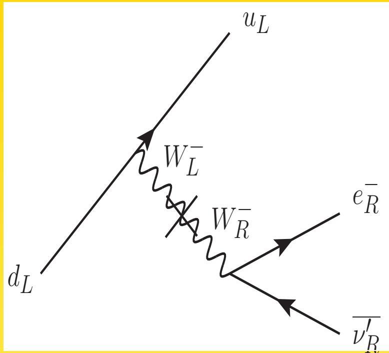
- left-handed contribution
- right-handed contribution
- interference contribution (`Bonn` *et al.*)

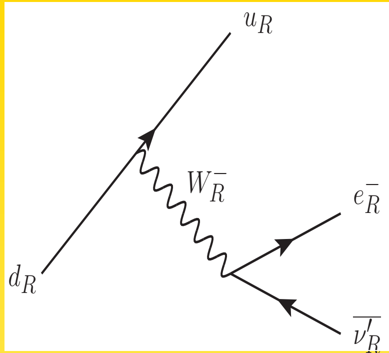
Neutrino masses up to $m = 18.6$ keV testable

(`Mertens` *et al.*; `deVega` *et al.*)









$$\left(\frac{\mathrm{d}\Gamma}{\mathrm{d}E}\right)_{LL} = K'(E+m_e)p_e X[1+2C\tan\xi]$$
$$\times\left[|U_{ei}|^2\sqrt{X^2-m_i^2}\,\Theta(X-m_i)+|S_{ei}|^2\sqrt{X^2-M_i^2}\,\Theta(X-M_i)\right]$$

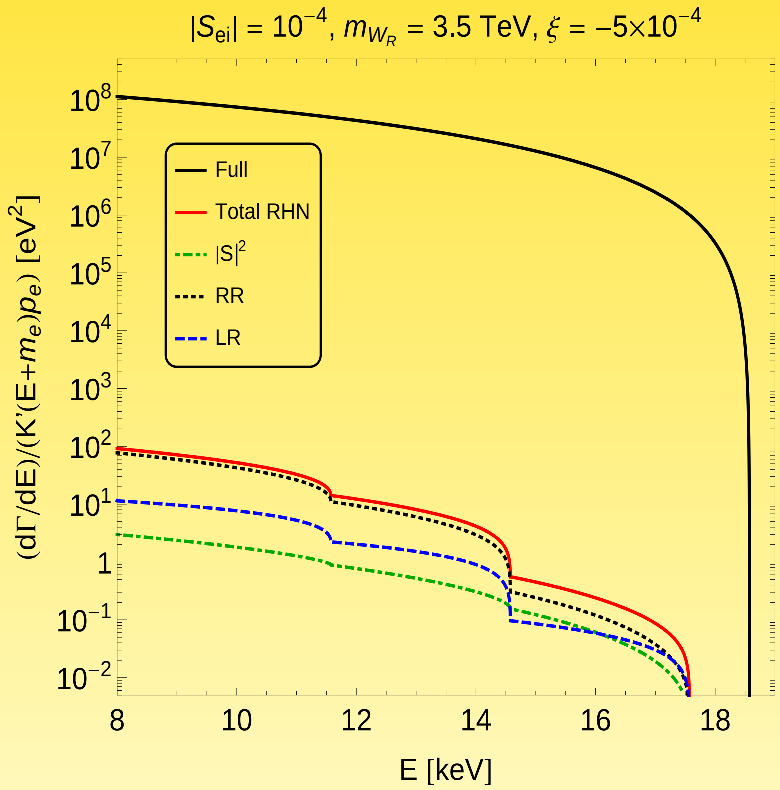
$$\left(\frac{\mathrm{d}\Gamma}{\mathrm{d}E}\right)_{RR} \simeq K'(E+m_e)p_e X\left[\frac{m_{W_L}^4}{m_{W_R}^4}+\tan^2\xi+2C\frac{m_{W_L}^2}{m_{W_R}^2}\tan\xi\right]$$
$$\times|V_{ei}|^2\sqrt{X^2-M_i^2}\,\Theta(X-M_i)$$

$$\left(\frac{\mathrm{d}\Gamma}{\mathrm{d}E}\right)_{LR} = -2K'm_e p_e \mathrm{Re}\left\{\left[\left(\frac{m_{W_L}}{m_{W_R}}\right)^2+C\tan\xi\right]\right.$$
$$\left.\times\left[U_{ei}T_{ei}m_i\sqrt{X^2-m_i^2}\,\Theta(X-m_i)+S_{ei}V_{ei}M_i\sqrt{X^2-M_i^2}\,\Theta(X-M_i)\right]\right\}$$

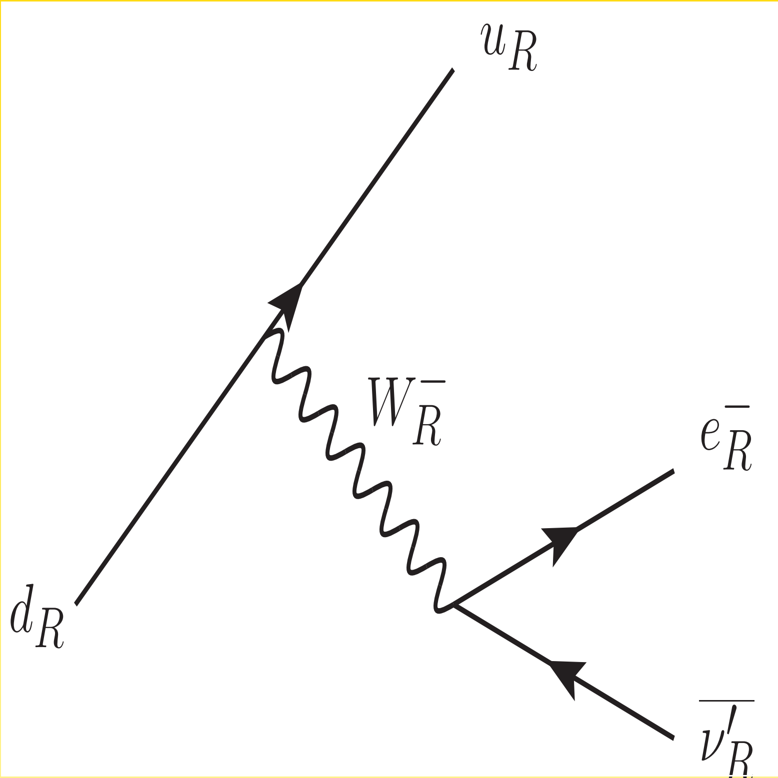
with $X = E_0 - E$

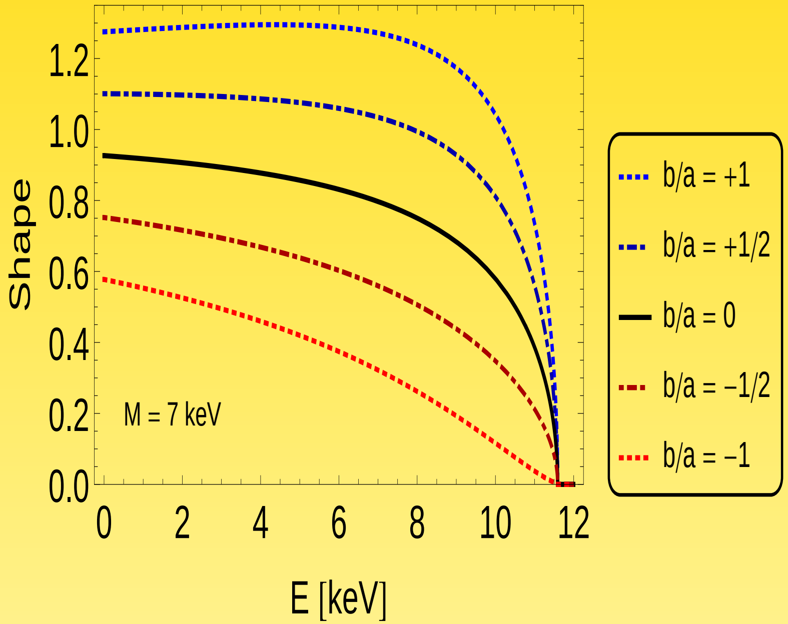
in total one has

$$\frac{\mathrm{d}\Gamma}{\mathrm{d}E} = \left(\frac{\mathrm{d}\Gamma}{\mathrm{d}E}\right)_{LL} + \left(\frac{\mathrm{d}\Gamma}{\mathrm{d}E}\right)_{RR} + \left(\frac{\mathrm{d}\Gamma}{\mathrm{d}E}\right)_{LR}$$



Focus for simplicity on





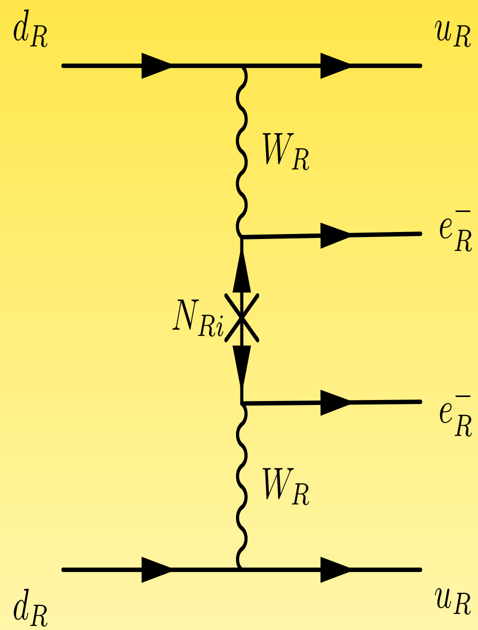
and assume keV neutrino with RH current

$$\frac{\mathrm{d}\Gamma/\mathrm{d}E - (\mathrm{d}\Gamma/\mathrm{d}E)_{\mathrm{std}}}{(\mathrm{d}\Gamma/\mathrm{d}E)_{\mathrm{std}}} \simeq \left(a + b\frac{M}{E_0 - E}\right)\sqrt{1 - \frac{M^2}{(E_0 - E)^2}}\,\Theta(E_0 - E - M)$$

neglect interference term b:

$$\theta_{\rm eff}^2 \simeq |S_{ej}|^2 + 1.1\times 10^{-6}\,|V_{ej}|^2 \left(\frac{2.5\,\rm TeV}{m_{W_R}}\right)^4$$

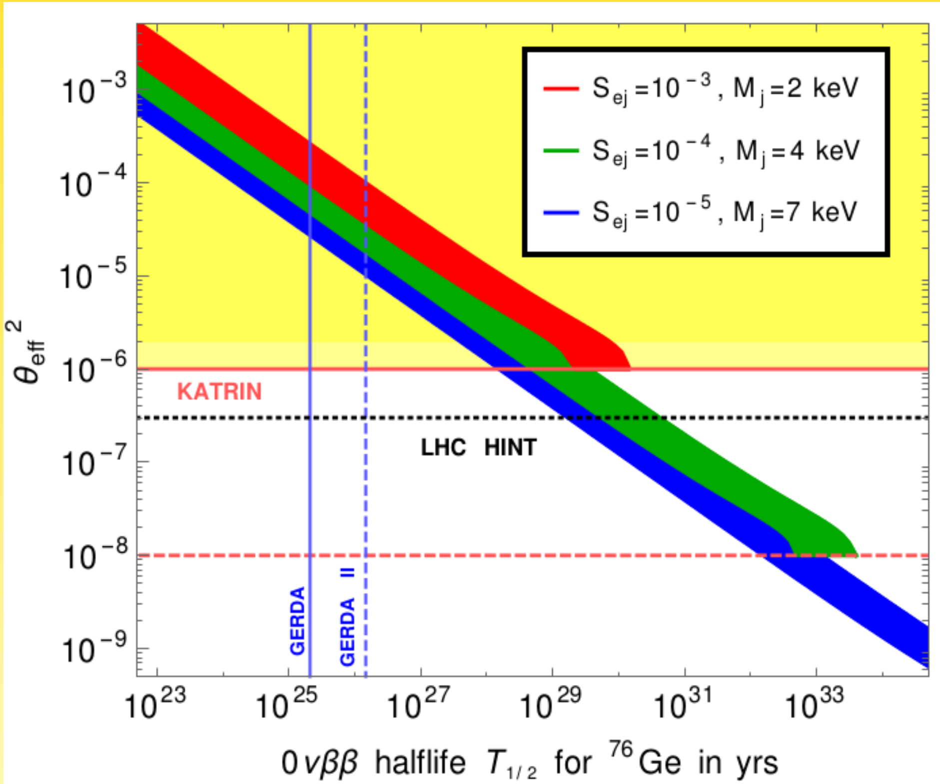
and note that M does $0\nu\beta\beta$ with amplitude $\propto |V_{ej}|^2\,(m_W/m_{W_R})^4\,M/q^2$



$\Rightarrow$ connection to $0\nu\beta\beta$ constraints!

connection to $0\nu\beta\beta$ constraints:

$$\theta_{\rm eff}^2 = |S_{ej}|^2 + \frac{m_e}{M_j}\left[|\mathcal{M}_\nu^{0\nu}|^{-2}\left(G_{01}^{0\nu}\right)^{-1}\left(T_{1/2}^{0\nu}\right)^{-1} - |S_{ej}^2 M_j/m_e|^2\right]^{\frac{1}{2}}$$



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How the additional interactions save the day

- double beta decay without RHC: $\theta^2 M = 7 \times 10^{-10}\,\mathrm{keV} = 70\,\mu\mathrm{eV}$
- double beta decay with RHC: $(m_{W_L}/m_{W_R})^4\,|V_{ei}|^2 M = 8\,\mathrm{meV}$
- decay: $\dfrac{\Gamma_{\mathrm{RHC}}(N_j \to \bar{\nu}\gamma)}{\Gamma_{\mathrm{SM}}(N_j \to \nu\gamma)} \simeq \dfrac{m_{W_L}^4\,|S_{ei}|^2}{m_{W_R}^4\,|T_{ei}|^2} \simeq \dfrac{m_{W_L}^4}{m_{W_R}^4}$
- beta decay: $\theta_{\mathrm{eff}}^2 \simeq |S_{ej}|^2 + 1.1 \times 10^{-6}\,|V_{ej}|^2 \left(\frac{2.5\,\mathrm{TeV}}{m_{W_R}}\right)^4 > |S_{ej}|^2$

Implizieren Dirac-Neutrinos Leptonzahlerhaltung?

Model basierend auf $B - L$, gebrochen um 4 Einheiten

$\Rightarrow$ Neutrinos sind Dirac, $\Delta L = 2$ verboten, aber $\Delta L = 4$ erlaubt...

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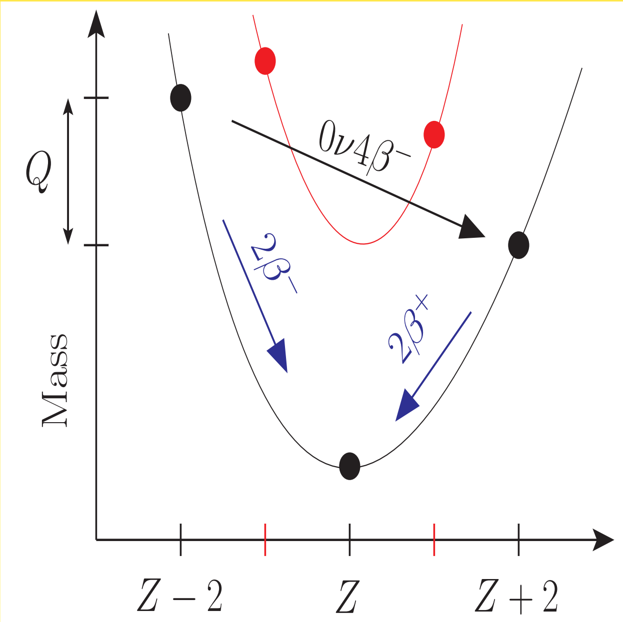
Implizieren Dirac-Neutrinos Leptonzahlerhaltung?

Model basierend auf $B - L$, gebrochen um 4 Einheiten

$\Rightarrow$ Neutrinos sind Dirac, $\Delta L = 2$ verboten, aber $\Delta L = 4$ erlaubt...

$\Rightarrow$ Observable: neutrinoloser vierfacher Betazerfall $(A, Z) \to (A, Z+4) + 4\,e^-$



	$Q_{0\nu 4\beta}$	Zerfälle	NA
${}^{96}_{40}\mathrm{Zr} \to {}^{96}_{44}\mathrm{Ru}$	0.629	$\tau^{2\nu 2\beta}_{1/2} \simeq 2 \times 10^{19}$	2.8
${}^{136}_{54}\mathrm{Xe} \to {}^{136}_{58}\mathrm{Ce}$	0.044	$\tau^{2\nu 2\beta}_{1/2} \simeq 2 \times 10^{21}$	8.9
${}^{150}_{60}\mathrm{Nd} \to {}^{150}_{64}\mathrm{Gd}$	2.079	$\tau^{2\nu 2\beta}_{1/2} \simeq 7 \times 10^{18}$	5.6

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