Neutrino Physics – a theoretical Perspective

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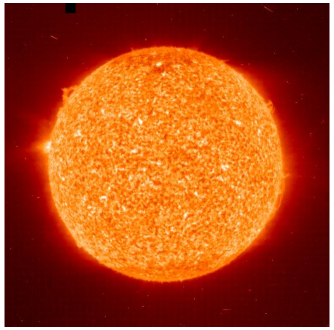
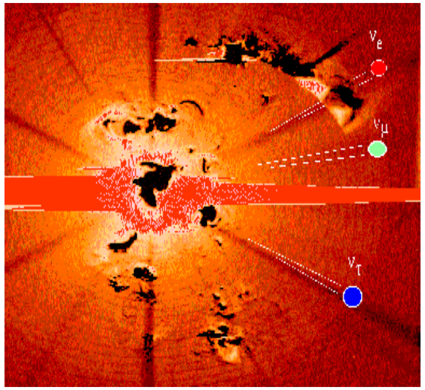
Max Planck Institute for Physics: 100 Year Anniversary, Oct. 10-12, 2017

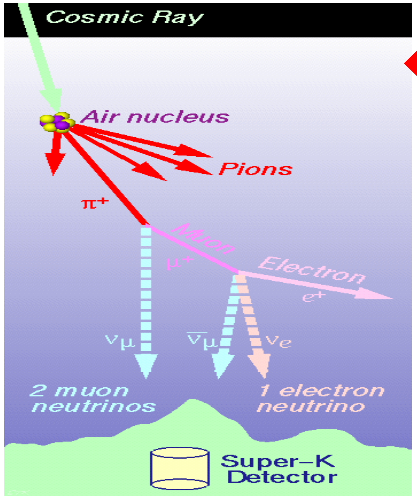
Neutrino Sources



←Sun



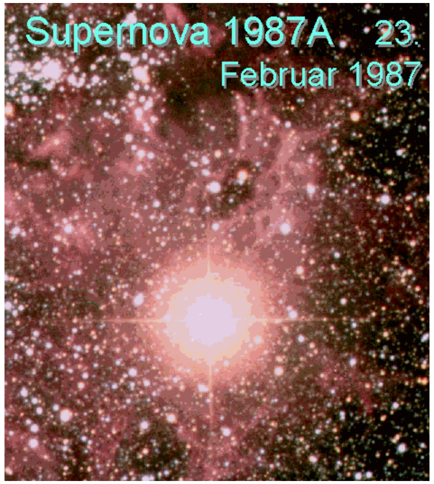
←Cosmology



←Atmosphere

←Earth

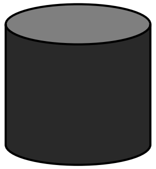
Astronomy: →
Supernovae
GRBs
UHE ν's



Reactors→

Accelerators→

β-Sources→

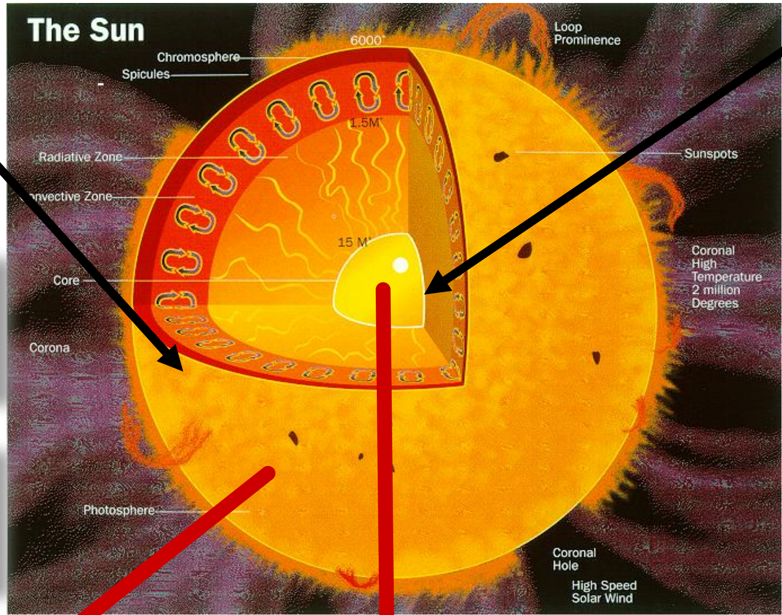


ν's as Messangers: Two Pictures of the Sun

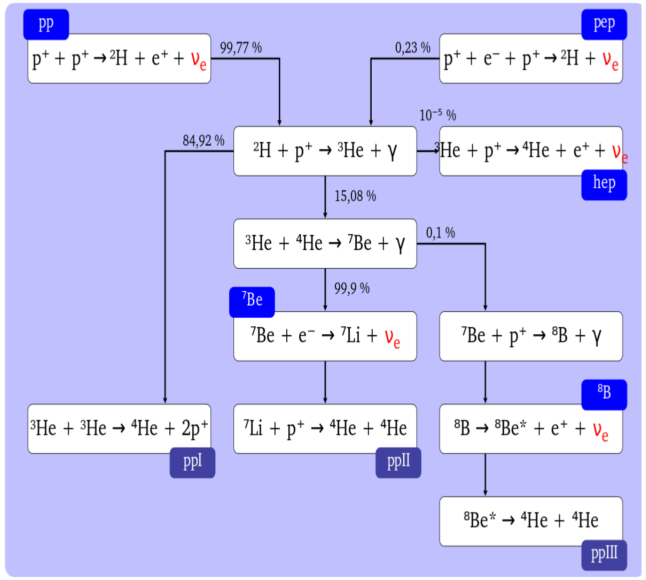
Surface:6000° K

Energy→ surface:
< 170.000 years >

Neutrinos → surface:
2.3 seconds

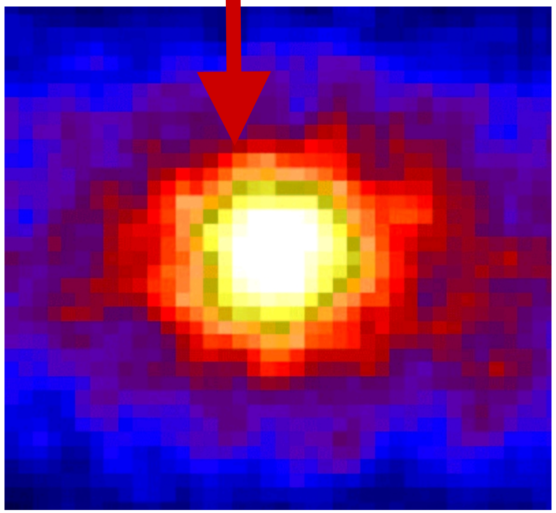


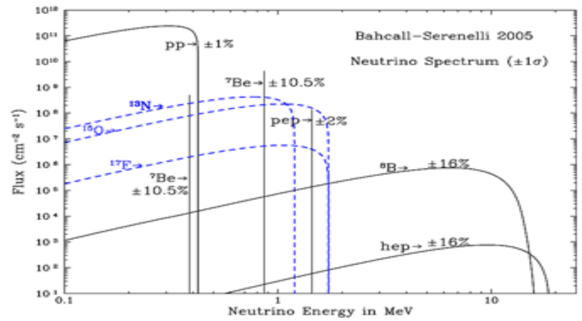
Fusion processes:
15 million degrees



light

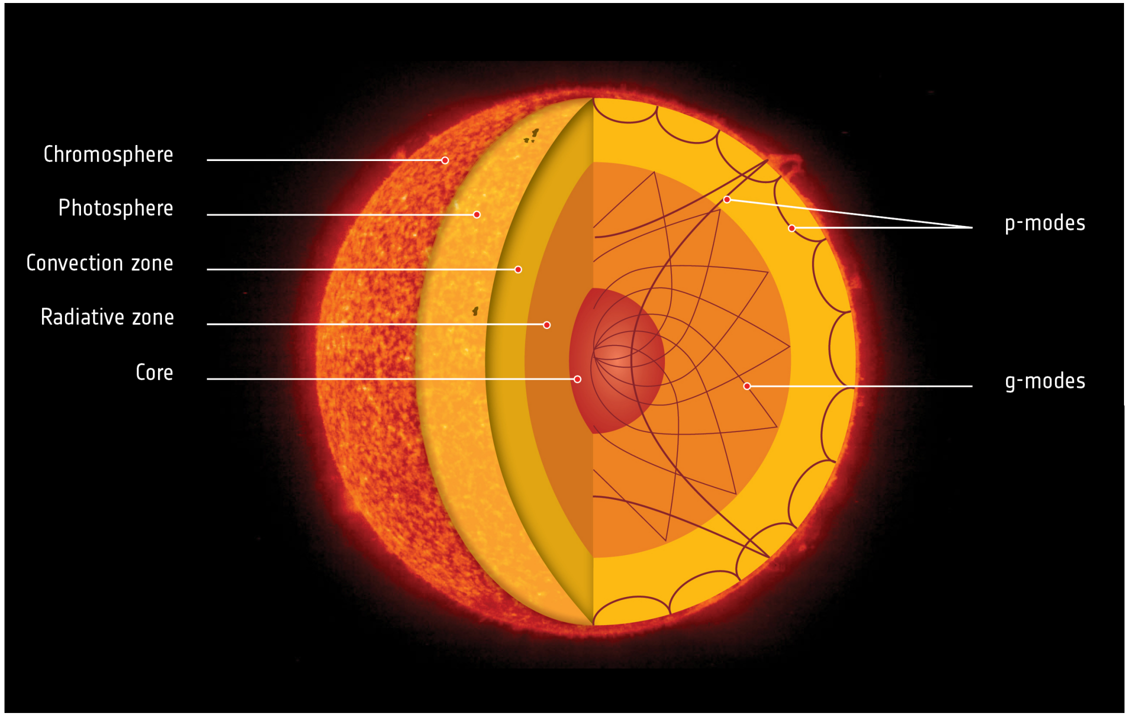
neutrinos

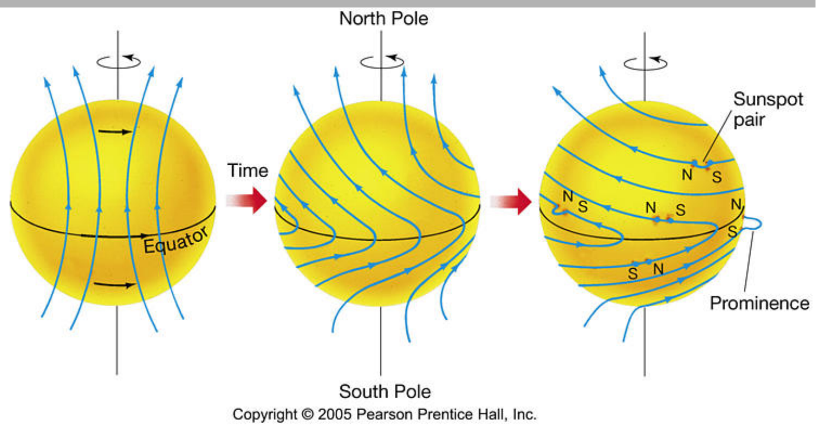


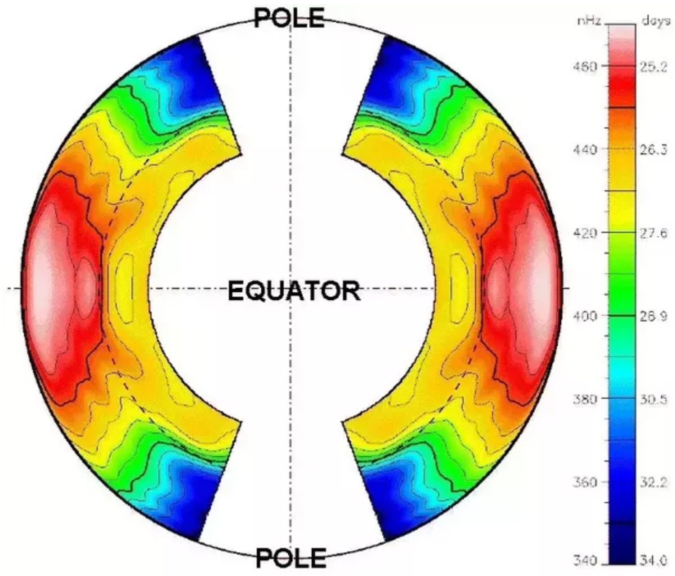


→ Important contributions to the understanding of the sun (a star)

SOHO Surprise: Rapidly Rotating Solar Core







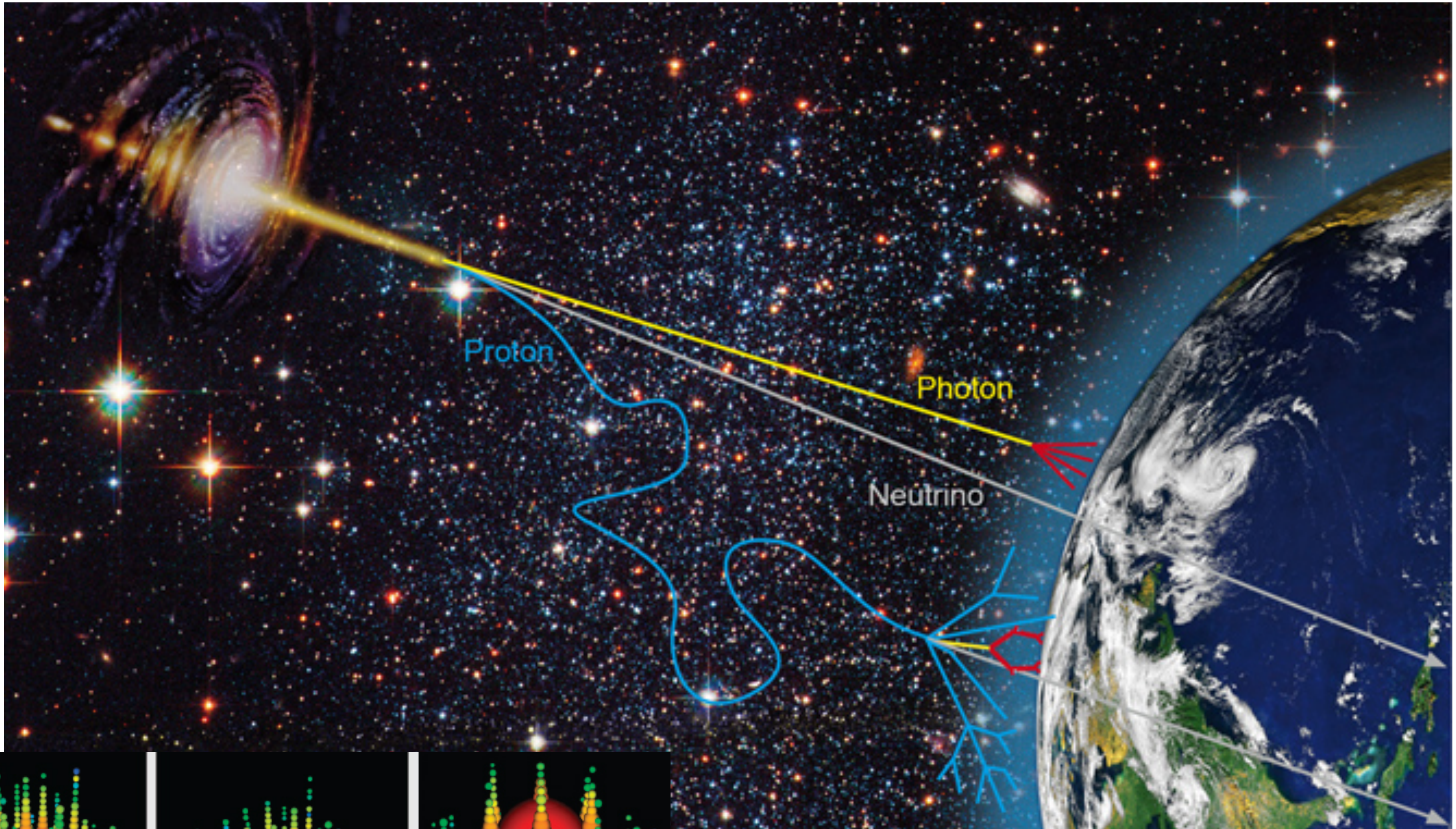
<u>SOHO - g-mode pressure waves:</u>

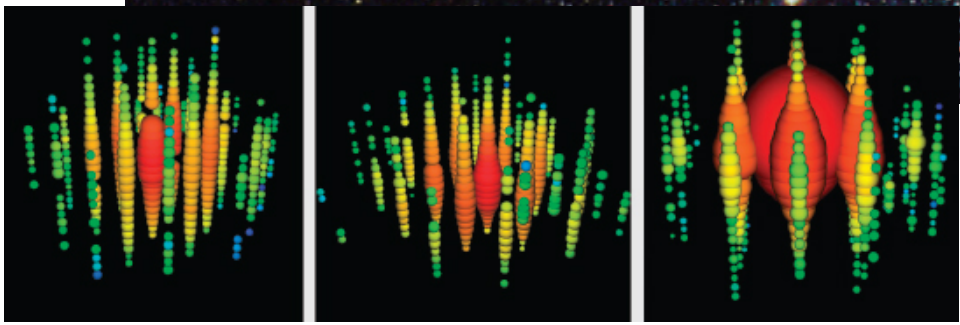
Differential rotation grows inside the sun: factor ~4

<u>Will have impact on Standard Solar Model:</u>

- energy transport
- metallicity (may resolve problems or make them bigger)

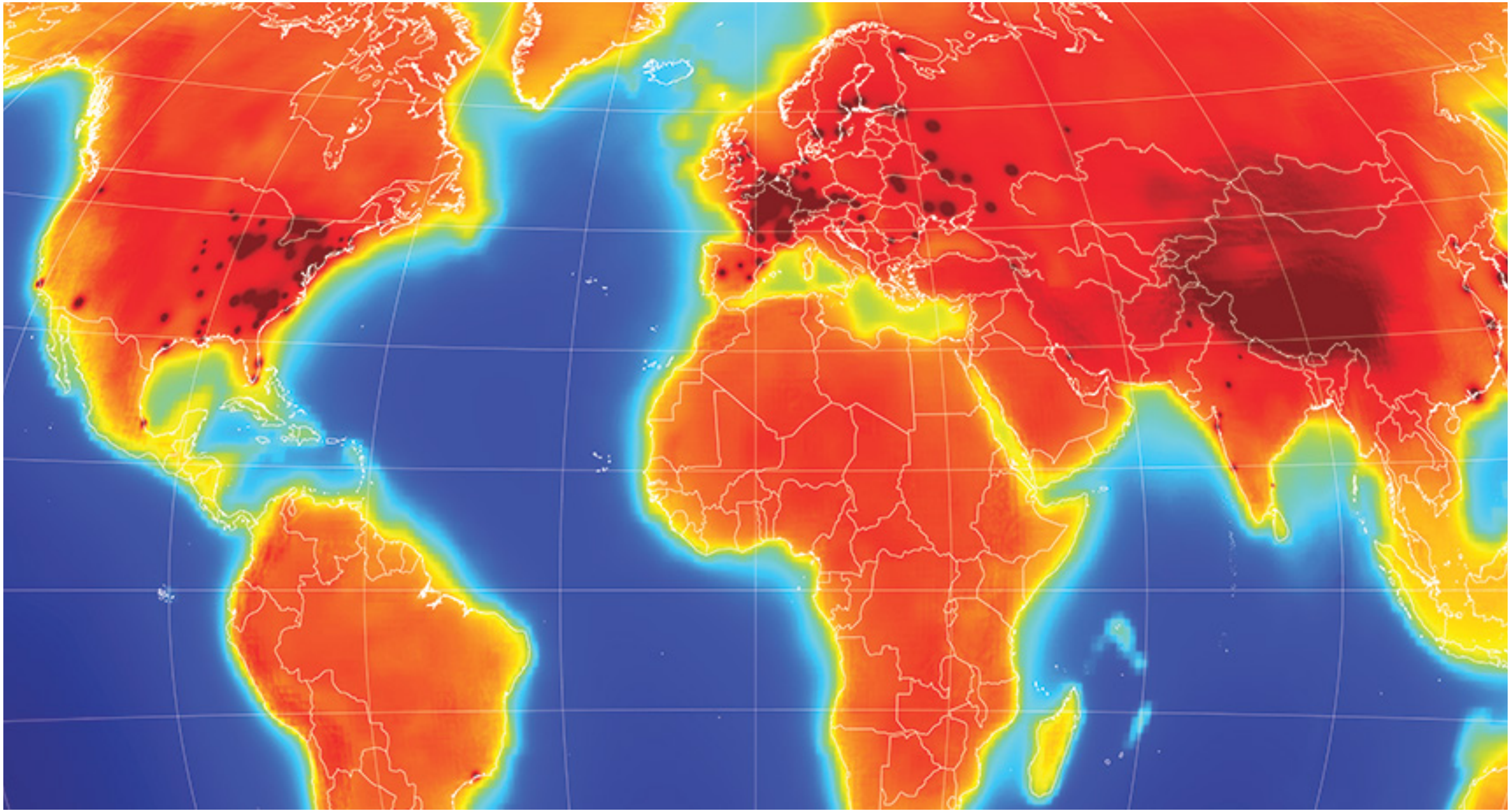
Neutrino Astronomy





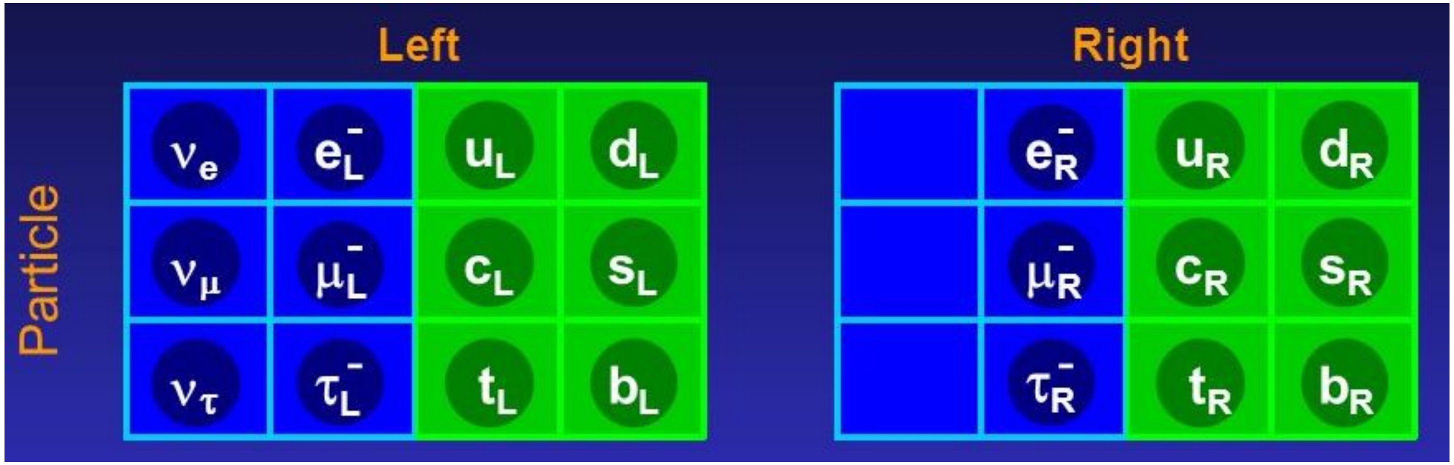
IceCube: exciting results
no identified point sources yet – maybe soon…
see talks by E. Resconi and K. Mannheim

Neutrino Picture of the Earth

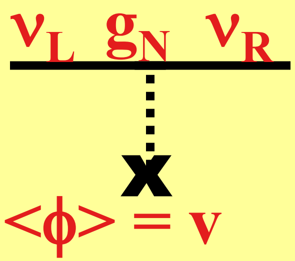


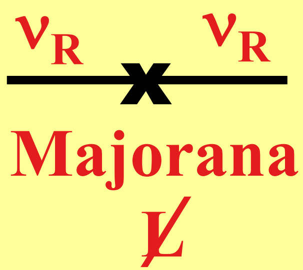
geo-neutrinos – an interesting subject, but no time
reactor-neutrinos – later in the talk

Bottom-up: Add Neutrino Masses to the SM



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





$$\begin{pmatrix}\overline{\nu}_L & \overline{\nu}^c_R\end{pmatrix}\begin{pmatrix}0 & m_D \\ m_D & M_R\end{pmatrix}\begin{pmatrix}\nu^c_L \\ \nu_R\end{pmatrix}$$

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

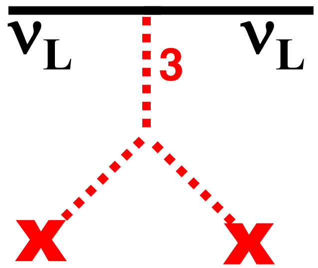
+9+ new ingredients: ➔ SM+
1) Majorana mass = scales
2) lepton number violation

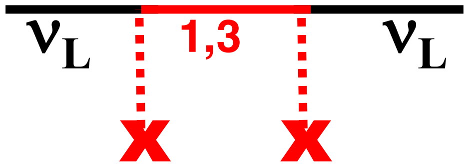
6x6 block mass matrix
block diagonalization
M_R heavy ➔ 3 light ν's

Other Possibilities

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

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

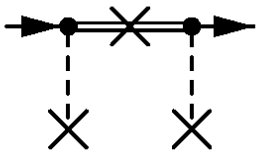




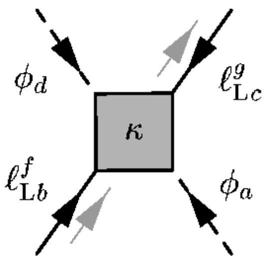
Both ν_R and new singlets / triplets:

➔ see-saw type II, III $m_\nu = M_L - m_D M_R^{-1} m_D^T$

Higher dimensional operators: d=5, …



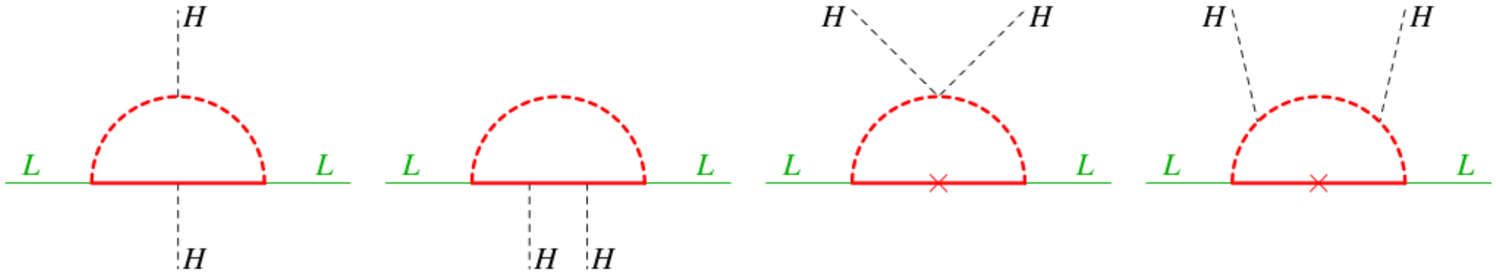
$\Rightarrow$



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

➔ $M_L L\overline{L}^c$

Radiative neutrino mass generation



Add: more neutrinos, SUSY, extra dimensions, …

➔ huge number of papers on neutrino masses...
... but we know only two Δm^2... (plus mass & unitarity bounds)

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

even for ν_R ➔ BSM physics
often connections to LFV, LHC, DM

3 Light massive Neutrinos (...assumed)

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

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

Known:

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

questions:

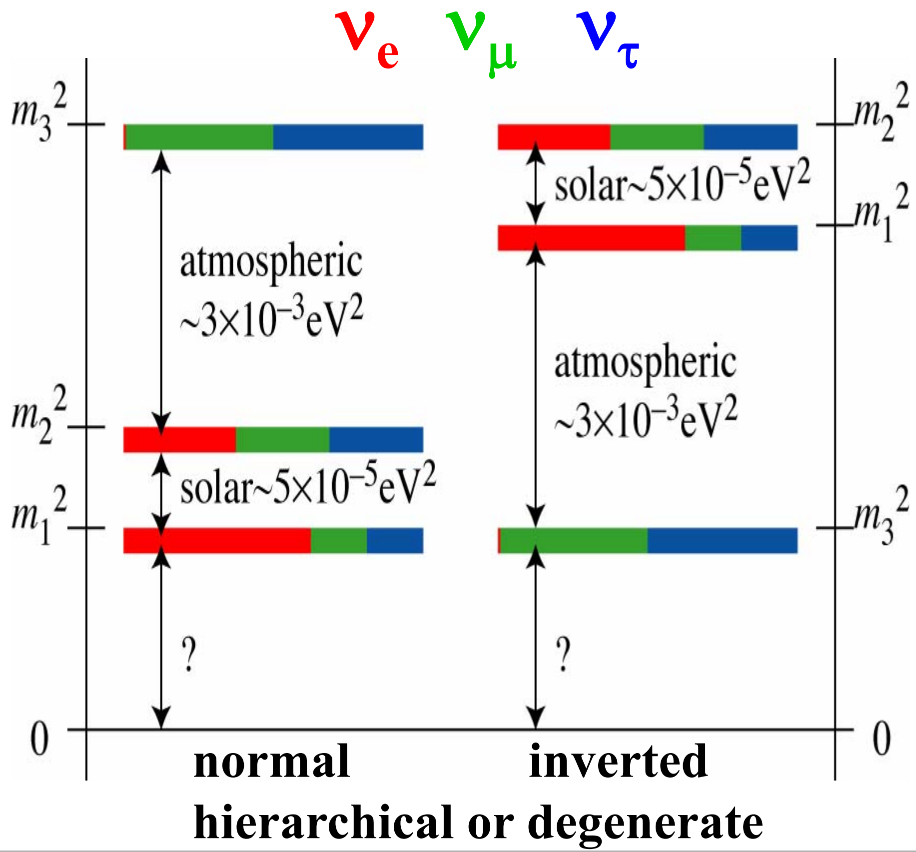
➔ Dirac ≃ SM / Majorana = BSM

➔ 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:

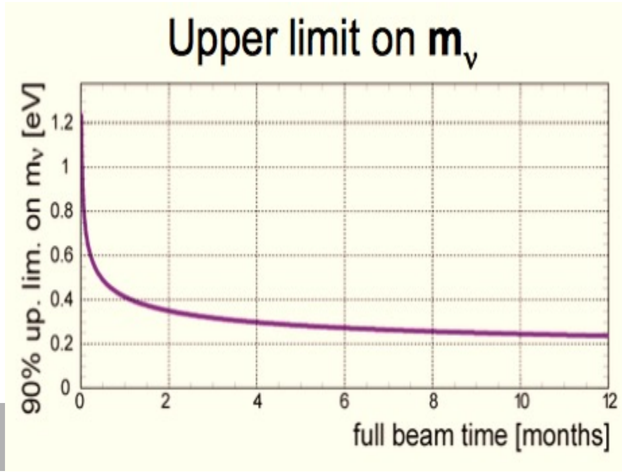
Tritium decay: Mainz and Troitsk experiments: $m_1 < 2.2$ eV

Limits from cosmology: 0.17-0.25 eV

Future:

KATRIN ➔ will start measurements soon ➔ 0.2eV

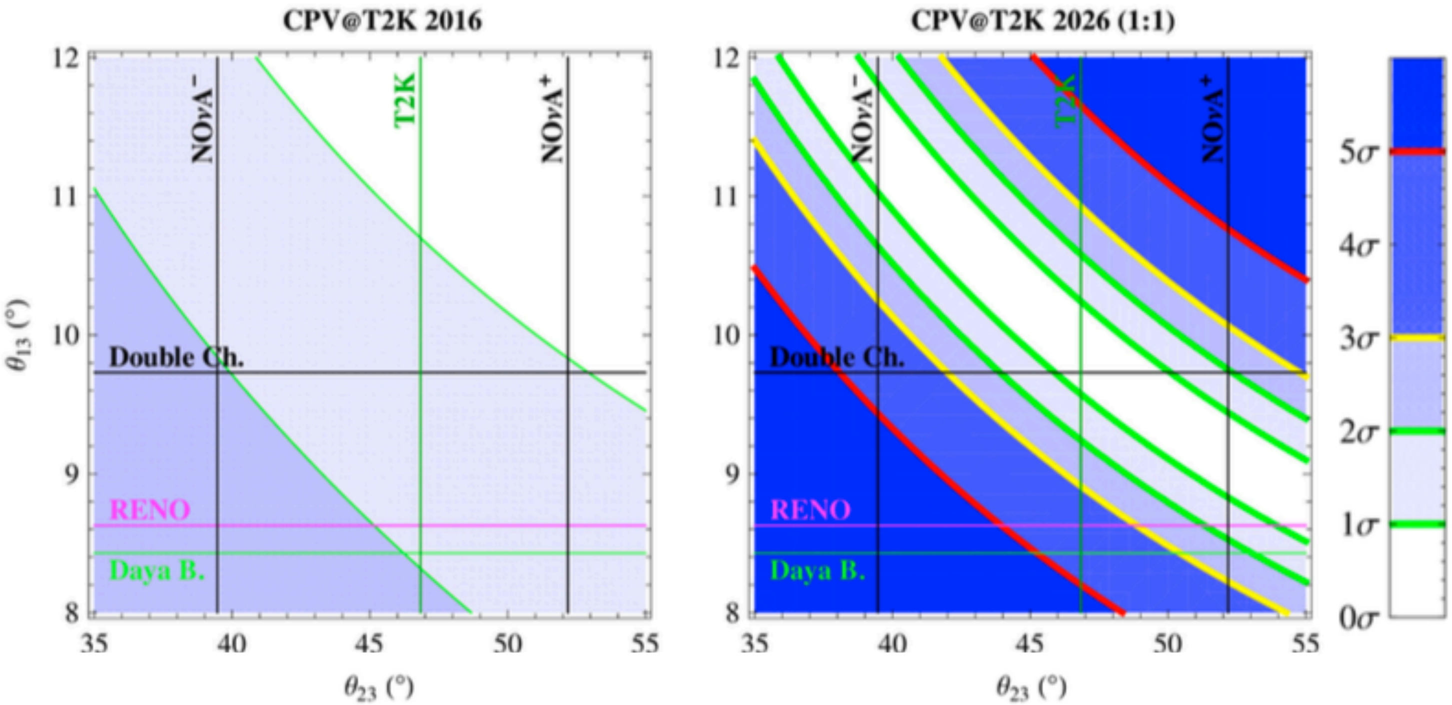
ECHO, Project8, …



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 $\delta_{CP} = 76 \pm 1^\circ$

The Value of Precision 3 Flavour ν Physics

$$|V_{\rm CKM}| \sim \begin{pmatrix} 1 & 0.2 & 0.004 \\ 0.2 & 1 & 0.04 \\ 0.008 & 0.04 & 1 \end{pmatrix}$$

$$|U_{\rm PMNS}| \sim \begin{pmatrix} 0.8 & 0.5 & 0.1 \\ 0.5 & 0.6 & 0.7 \\ 0.3 & 0.6 & 0.7 \end{pmatrix}$$

- **Remember: Many theoretical options…**
- **Precise measurements test mass models**
  e.g. based on flavour symmetries
  ←→ many models...
  exclude some or learn something generic?
- **Majorana masses ←→ leptogenesis = explanation of BAU**
  ←→ related to heavy Majorana CP phases
  ←→ detection of δ_{CP} phase makes this more plausible
  BUT: Don‘t forget it is only the light Dirac-like phase
  AND: Leptogenesis works also for Dirac neutrinos
- **Neutrinos are a 0.6% HDM component**
  ←→ cosmological structure formation ←→ DM in the universe
- **Precision may open the door for more new physics**
  ←→ test of 3 flavour unitarity, over-constraining, ...

Sterile Neutrinos: Mass Spectra (for ν_R)

3x3 matrix

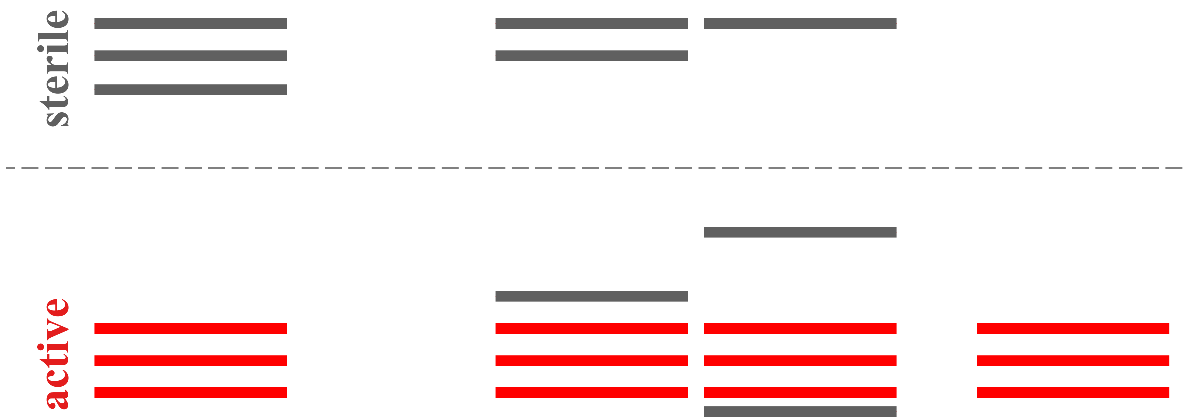
3   0 … N   3xN   NxN

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

- N per se arbitrary
- M_L, m_D, M_R could have almost any form / values:
  - zeros (symmetries)
  - 0 + 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 $\simeq$

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

Antusch, Fischer

➔ at most small admixtures of sterile neutrinos

Weak indications for sterile neutrinos:

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

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

E. Aver, K. Olive, E. Skillman, Y. Izotov, T. Thuan, …

Astrophysics: keV-ish sterile neutrinos could explain pulsar kicks

Kusenko, Segre, Mocioiu, Pascoli, Fuller et al., Biermann & Kusenko, Stasielak et al., Loewenstein et al., Dodelson, Widrow, Dolgov, …

BUT: Tensions with cosmology…

How to compare 2σ in cosmology with 2σ in particle physics?

$$N_{\rm eff} = 3.32 \pm 0.27 \ (68\% CL)$$

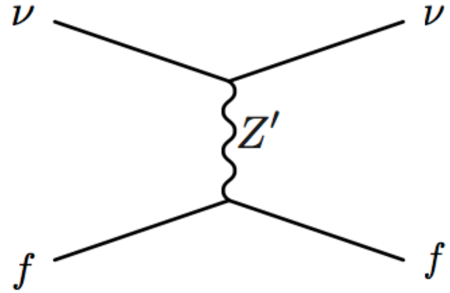
$$\sum m_\nu < 0.28 \text{ eV} \ (95\% CL)$$

Certainly not all evidences true, but one would be enough:

VERY IMPORTANT ➔ experiments see talk by T. Lasserre

Searches for new Physics: NSI's

NSI's ←→ new physics at high scales which is integrated out
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

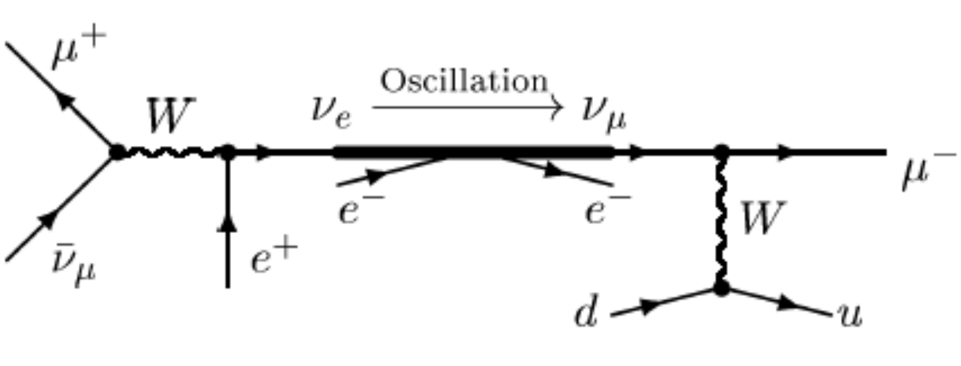
$$|\epsilon| \simeq \frac{M_W^2}{M_{NSI}^2}$$

➔ tests high energy scales: ε = 0.01 ←→ TeV

Grossman, Bergmann+Grossman, Ota+Sato, Honda et al., Friedland+Lunardini, Blennlow+Ohlsson+Skrotzki, Huber+Valle, Huber+Schwetz+Valle, Campanelli+Romanino, Bueno et al., Kopp+ML+Ota, …

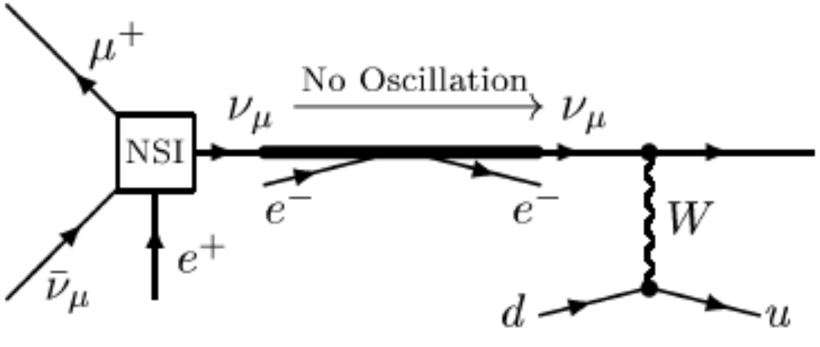
NSIs interfere with Oscillations

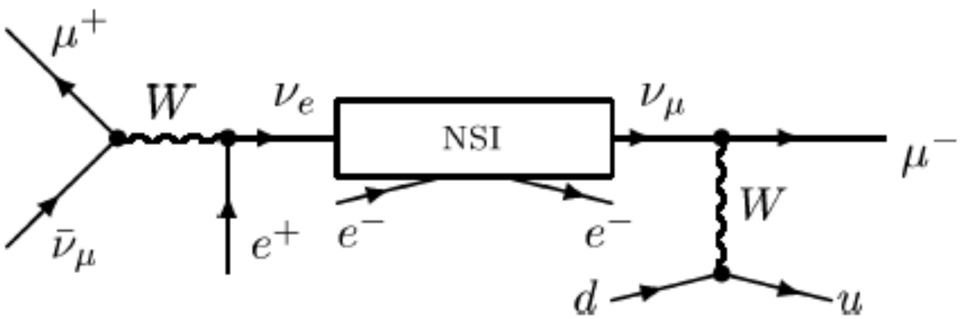
the “golden” oscillation channel

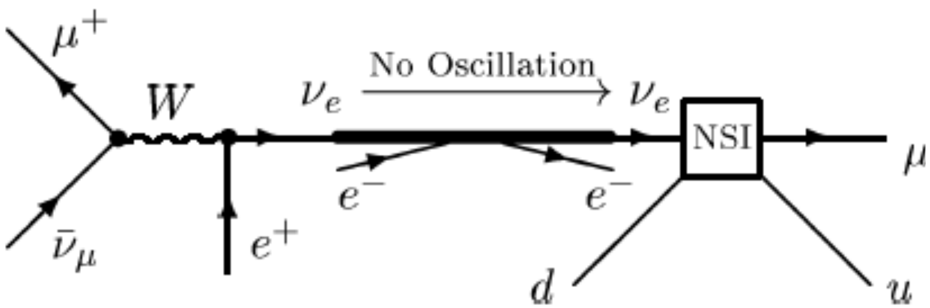


(a)

NSI contributions to the “golden” channel

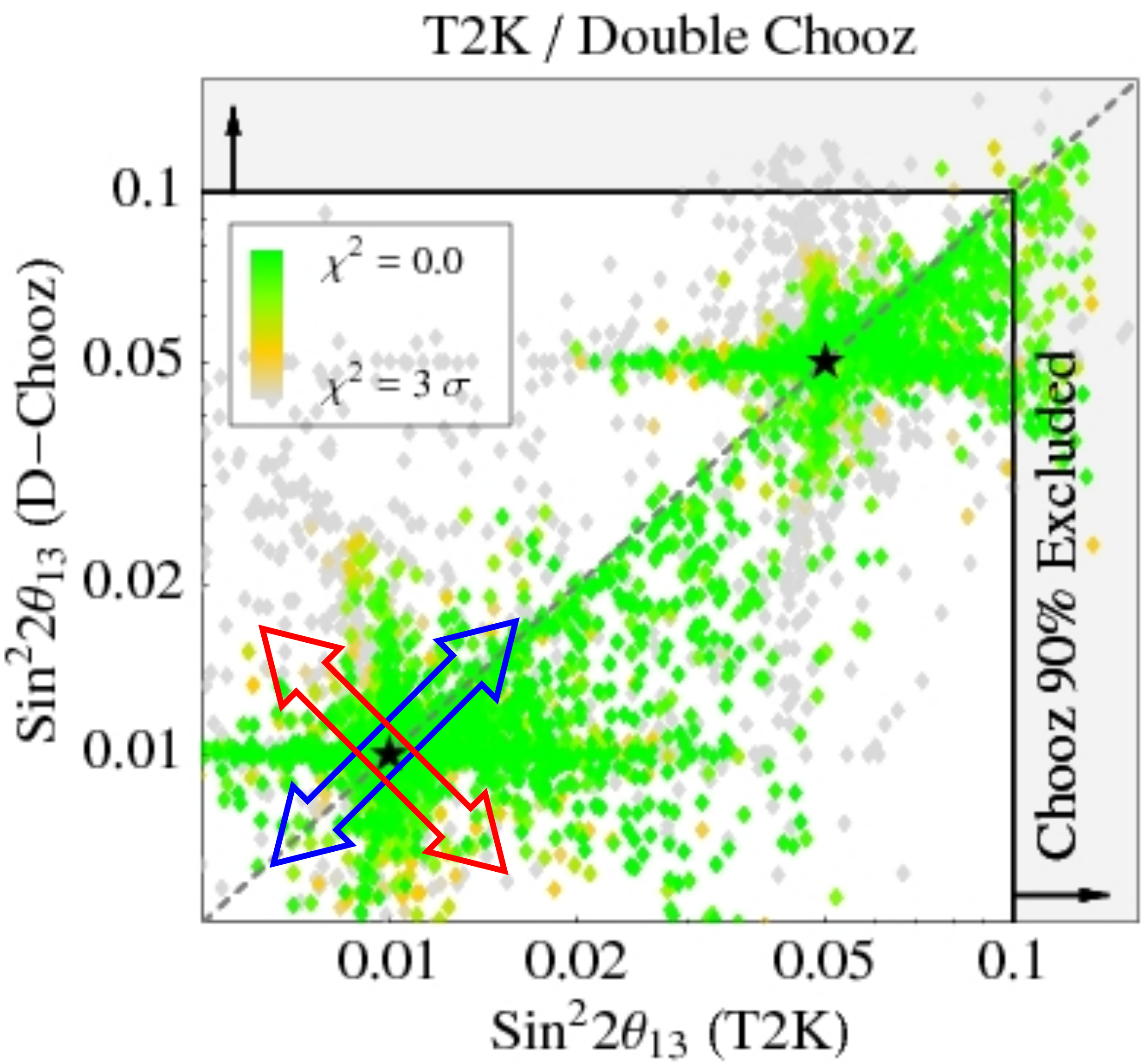






interference in oscillations ~ε ⇔ FCNC effects ~ε^2

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

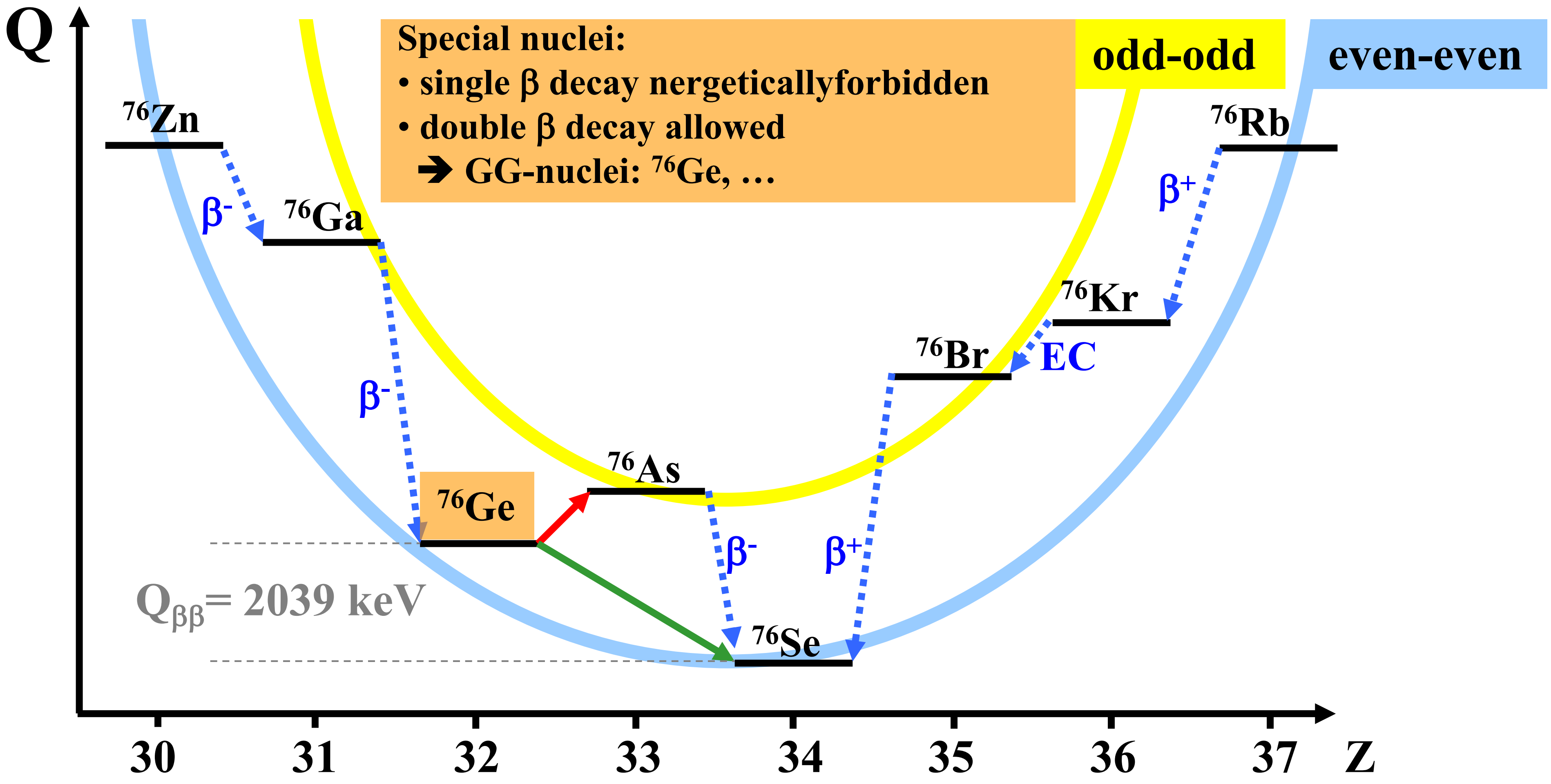
Kopp, ML, Ota

Double Beta Decay

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

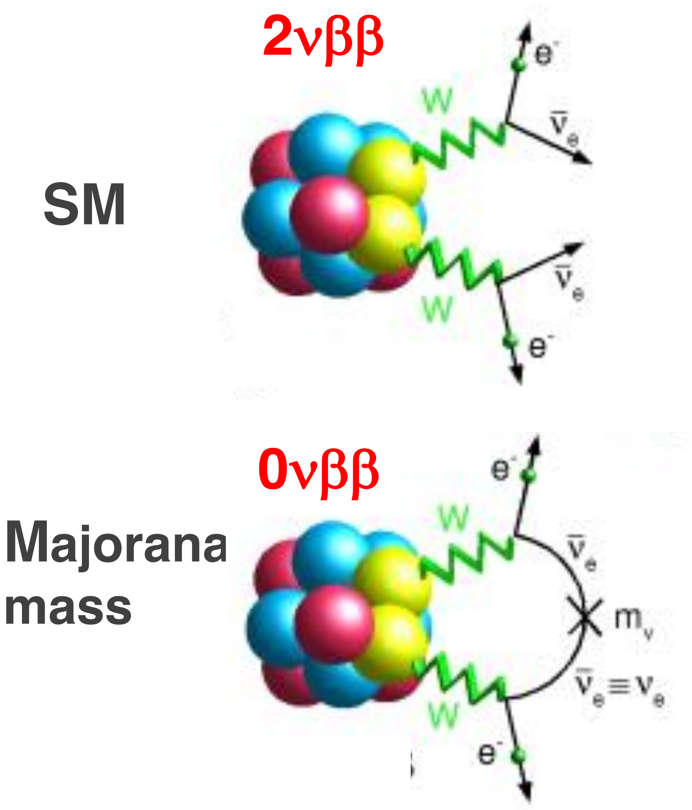
BUT: Be careful about the inverted reasoning!

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…

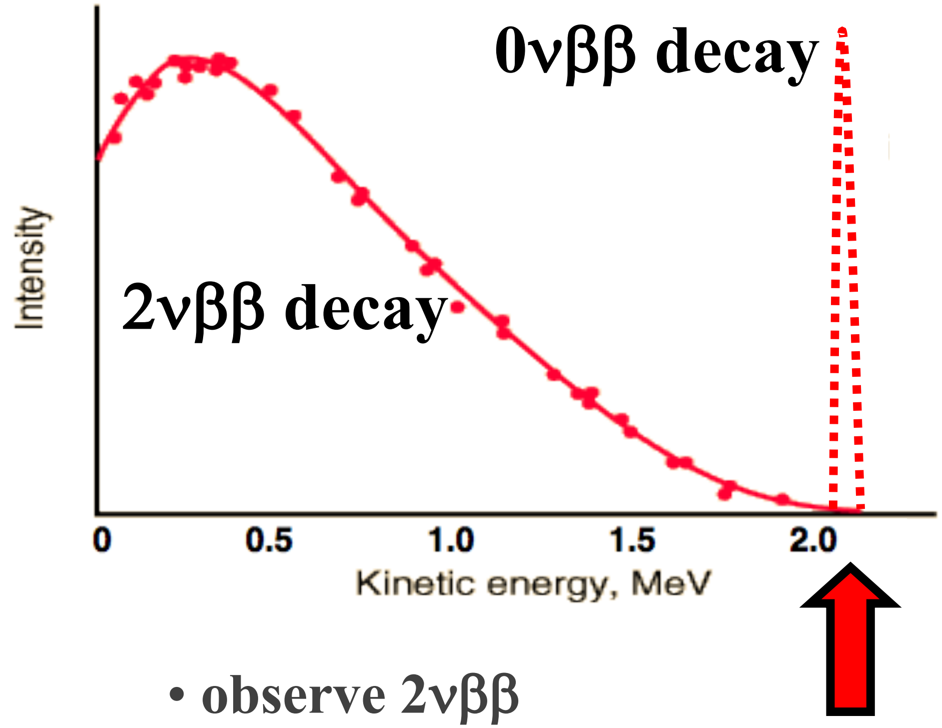
The Standard Picture of Double Beta Decay



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

2νββ decay seen for diff. isotopes (Kirsten,…)

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



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

➔ signal = Majorana mass

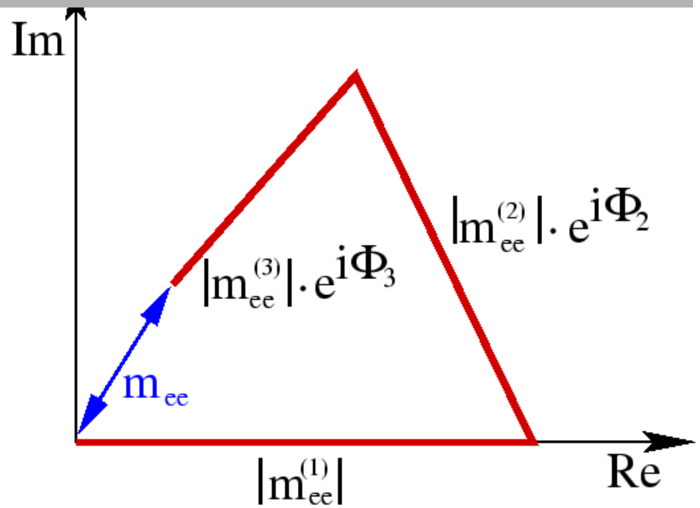
$$1/\tau = G(Q,Z)\, |M_{nucl}|^2 \langle m_{ee}\rangle^2$$

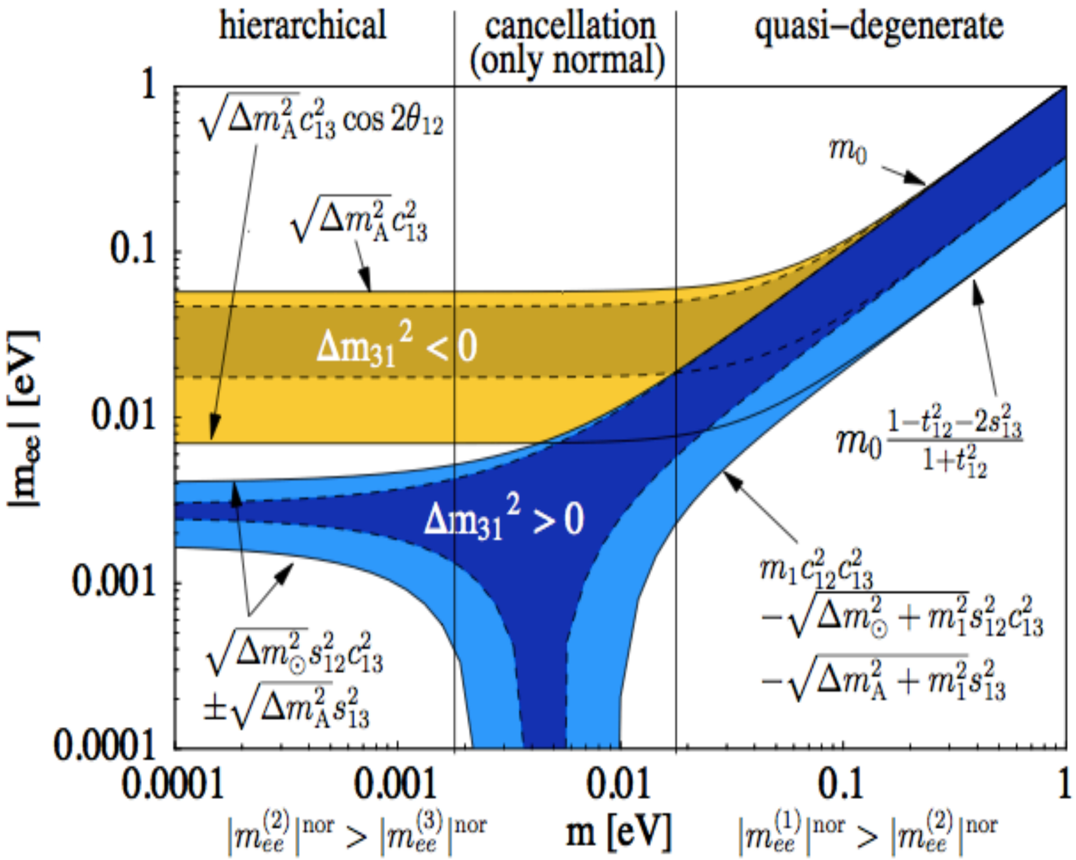
NMEs have uncertainties…

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:

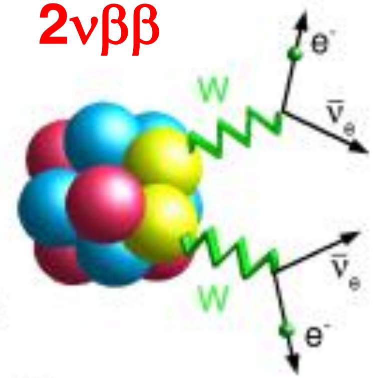
- cosmology: m < 0.2-0.3 eV
- 0νββ: m_{ee} < 0.1-0.3 eV
- NMEs ➔ unavoidable theory errors
- known Δm^2 from oscillations
  - ➔ yellow/blue areas
  - ➔ improved sensitivity is very promising!

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

More general: L Violating Processes

SM

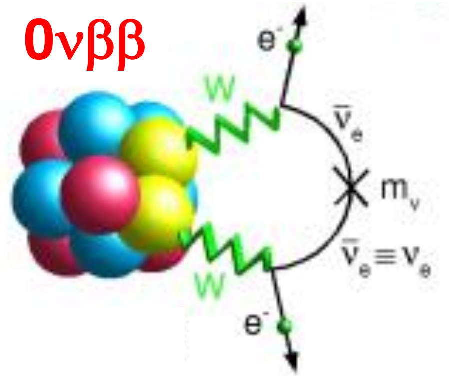
2νββ



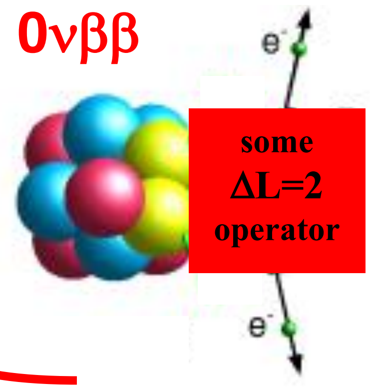
BSM

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

0νββ

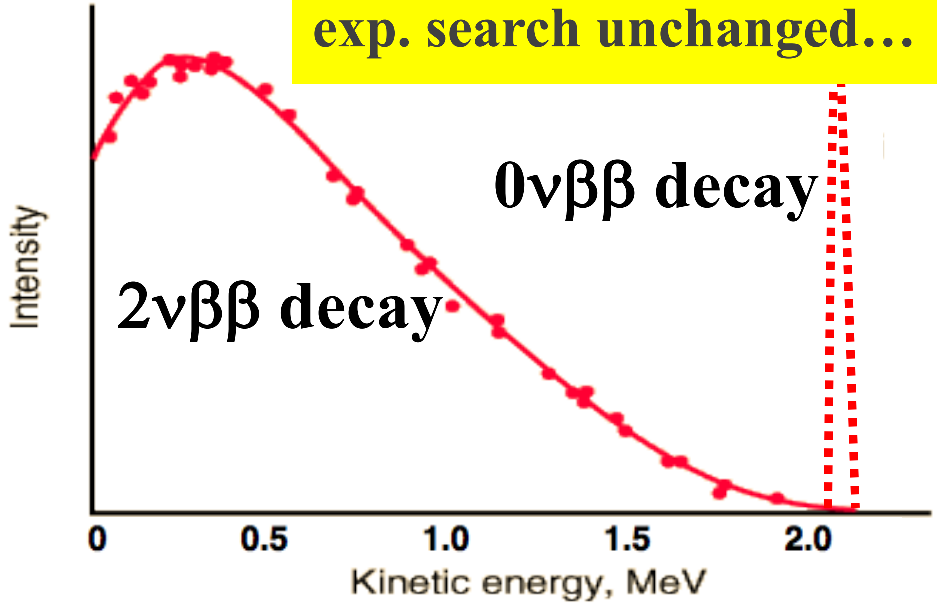


0νββ

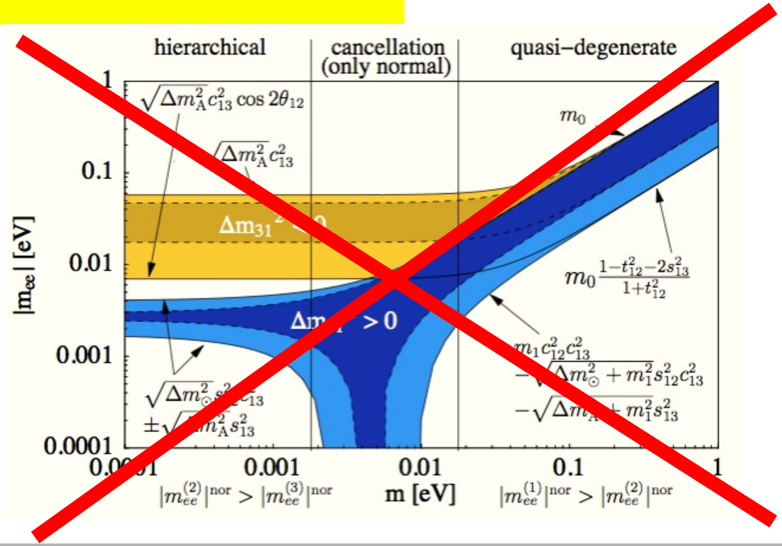


some ΔL=2 operator

exp. search unchanged…

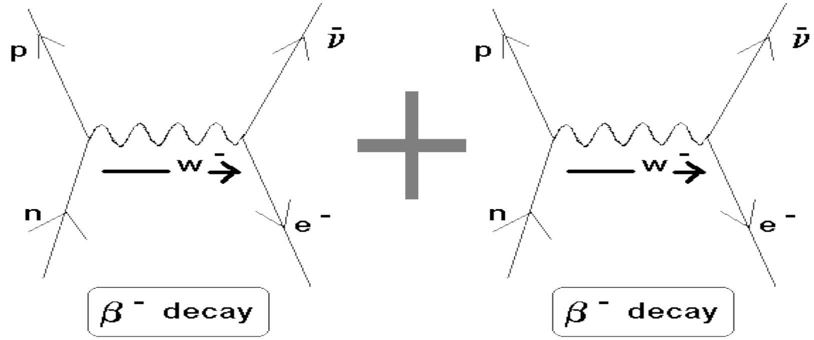


…interpretation changes:



Other Double Beta Decay Processes

Standard Model:

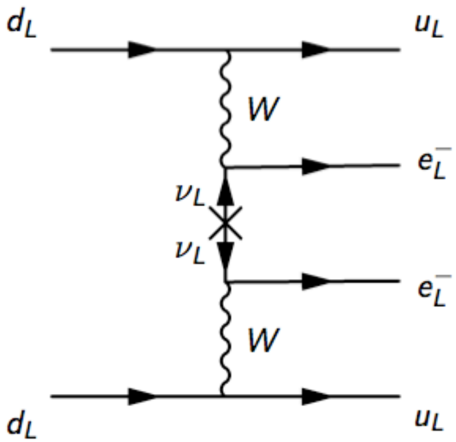


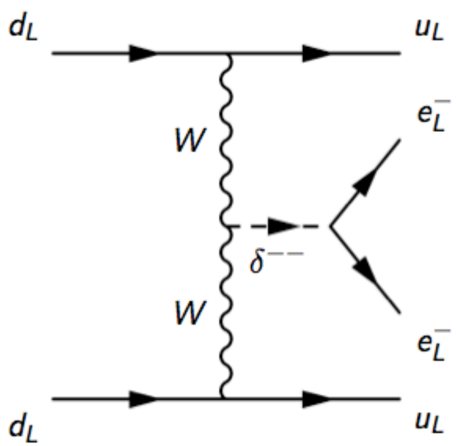
➔ 2 electrons + 2 neutrinos

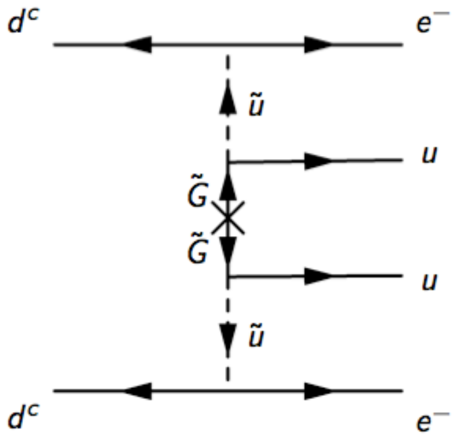
2νββ

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

0νββ







…

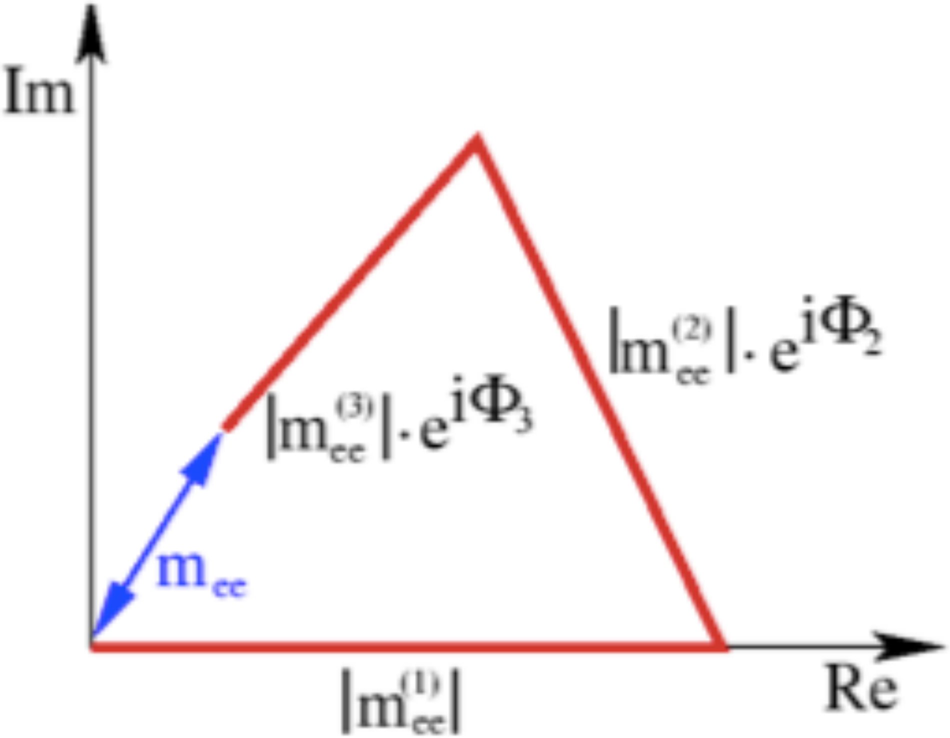
Majorana neutrino masses ←→ Dirac?

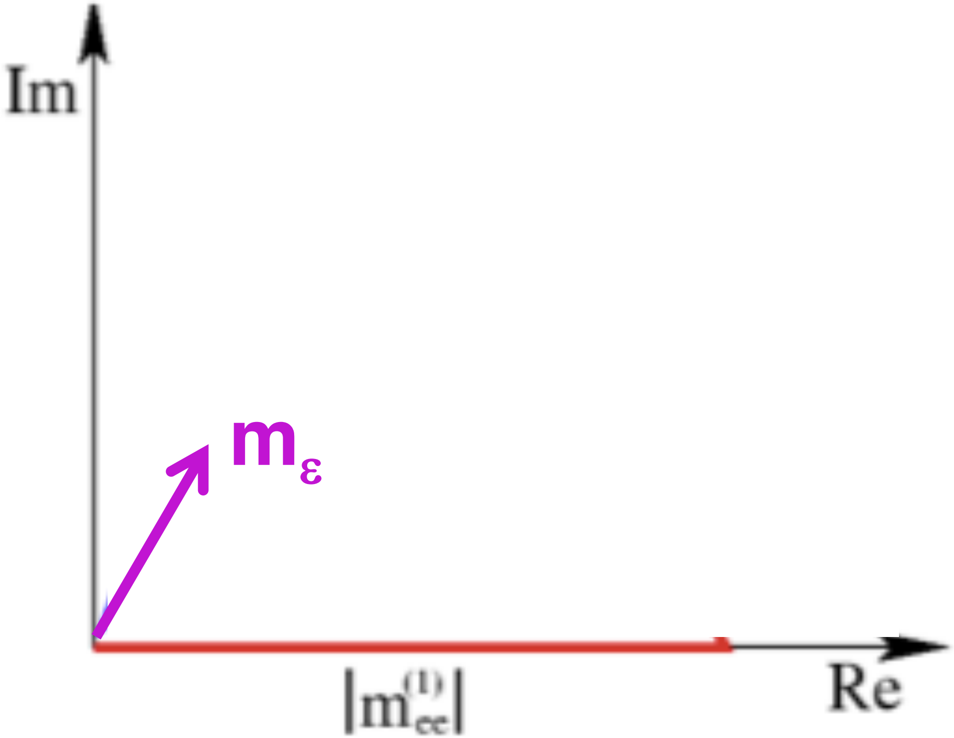
SM + Higgs triplet

SUSY

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

Extreme Cases

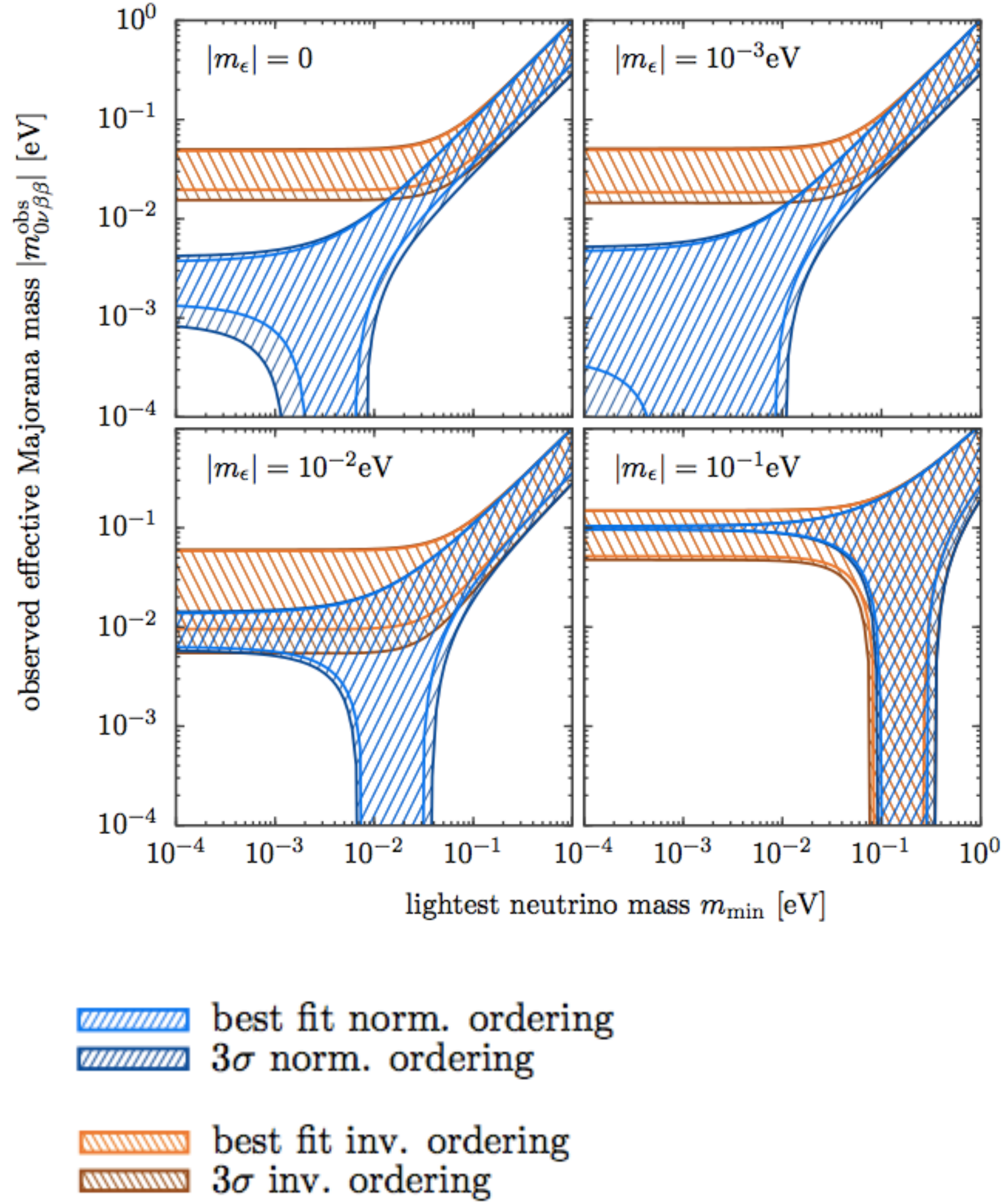


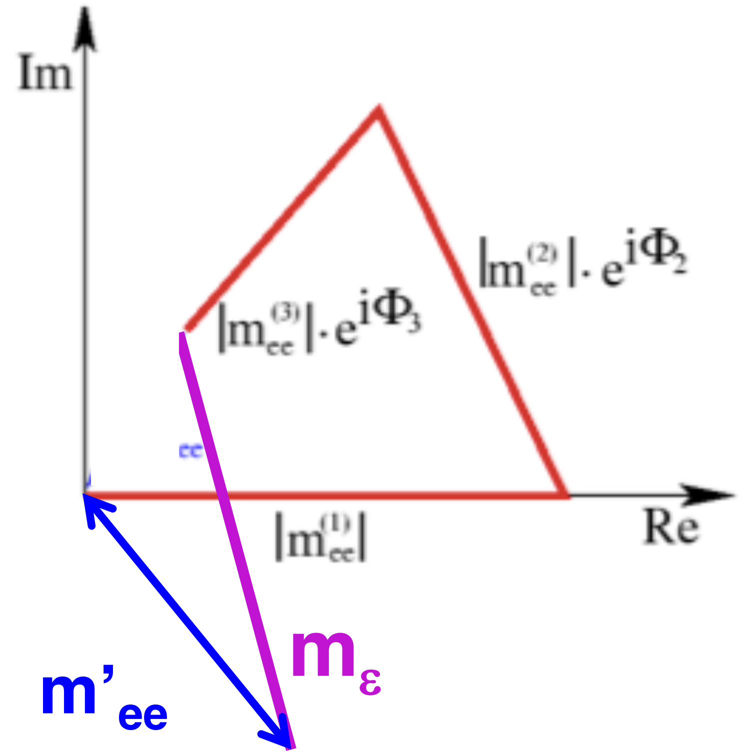


m_{ee} **from Majorana neutrinos only and no other $\Delta L=2$ physics**

m_{ε} **from other $\Delta L=2$ physics with Dirac neutrino masses**

and anything in-between





interferences

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

→ shifts of masses, mixings and CP phases

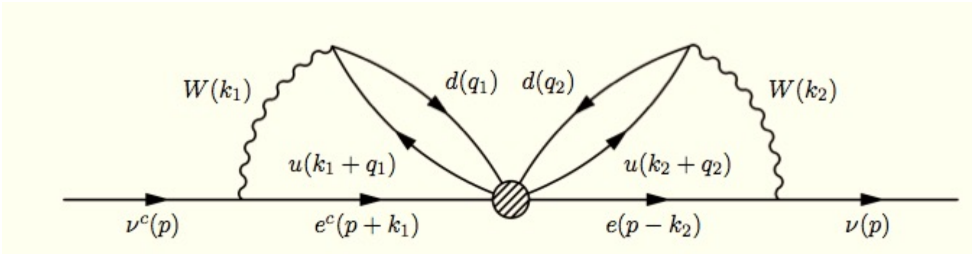
→ destroys ability to extract Majorana phases

→ 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



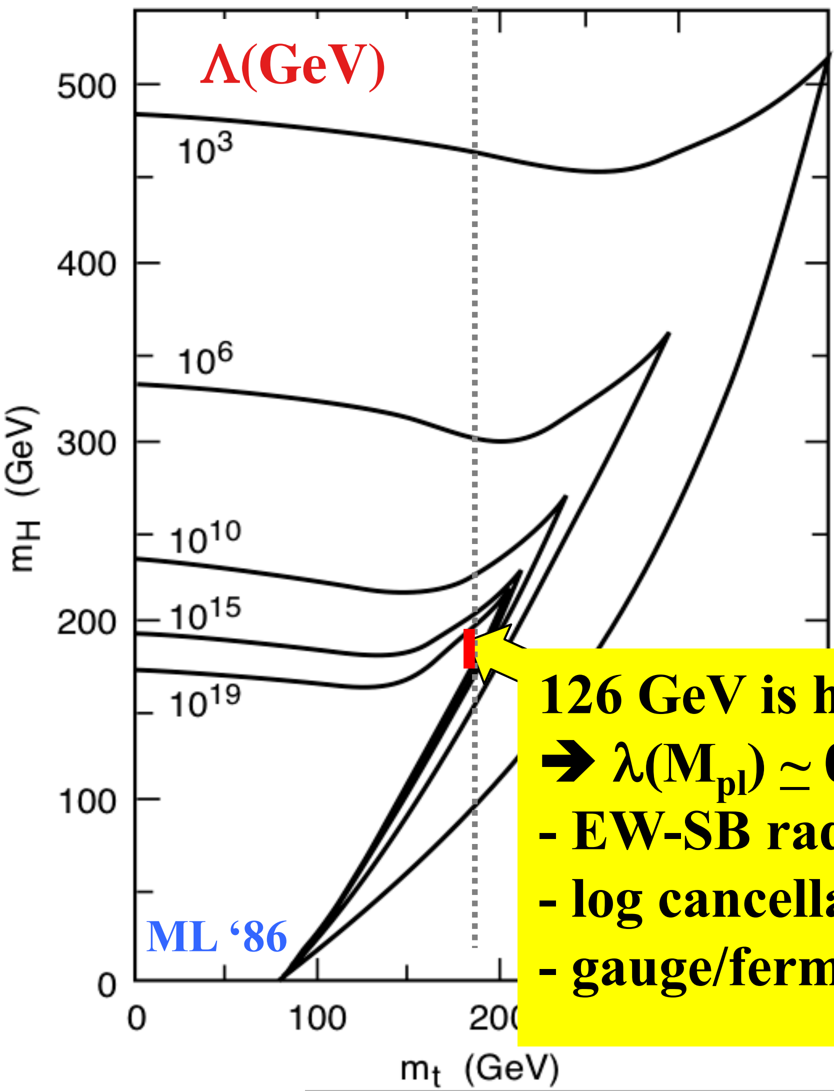
Dürr, ML, Merle
4 loops ➔ enforce $\delta m_\nu = 10^{-25}$ eV ➔ very tiny (academic interest)
➔ cannot explain observed ν masses and splitting's

Extreme possibility:
- 0νββ = L violation = other BSM physics
- neutrino masses = Dirac (plus very tiny Majorana corrections)
+ Dirac leptogenesis, + ...

New Ideas for Electro-Weak Symmetry Breaking

➔ SM is a renormalizable QFT like QED w/o hierarchy problem

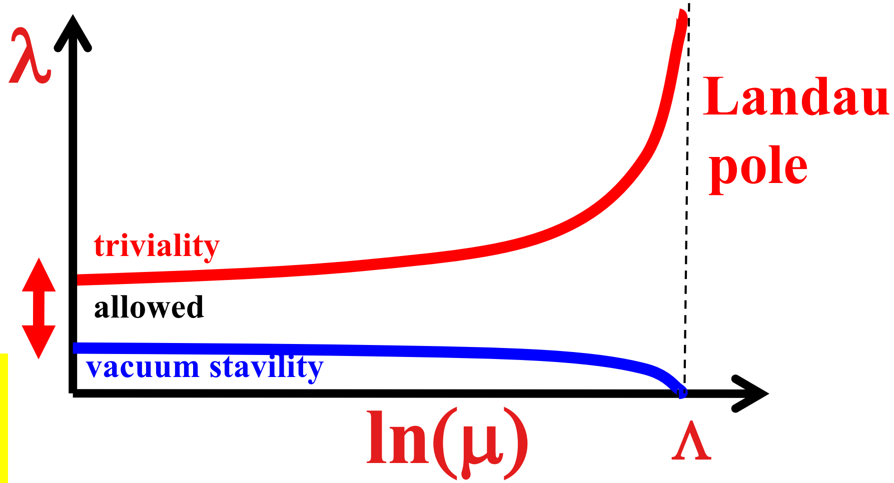
➔ Cutoff "Λ" has no meaning ➔ triviality, vacuum stability



126 GeV is here!
➔ $\lambda(M_{pl}) \simeq 0$
- EW-SB radiative
- log cancellations
- gauge/fermion/scalar

126 GeV < m_H < 174 GeV

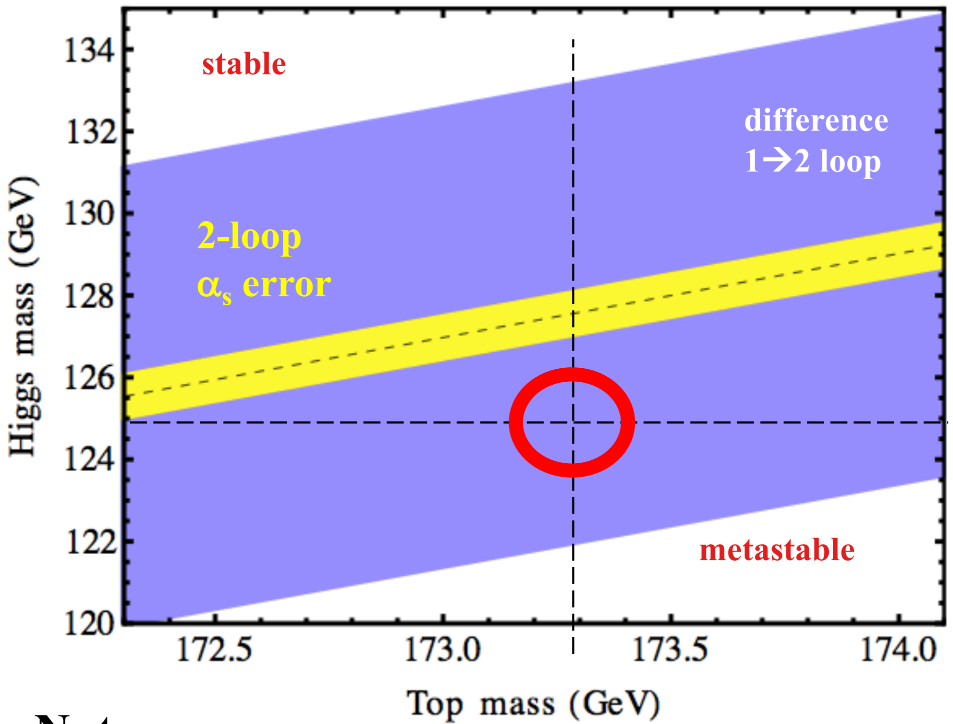
SM does not exist w/o embeding
- U(1) copling , Higgs self-coupling



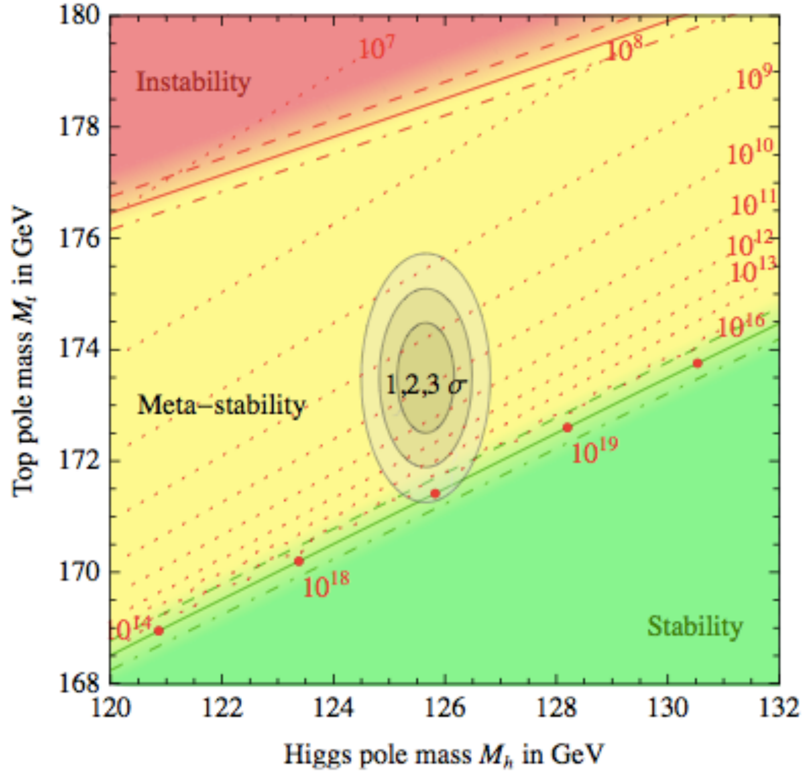
➔ RGE arguments seem to work
➔ we need some embedding
⇔ no BSM physics observed!
just a SM Higgs…

Is the Higgs Potential at M_{Planck} flat?

Holthausen, ML, Lim (2011)



Buttazzo, Degrassi, Giardino, Giudice, Sala, Salvio, Strumia



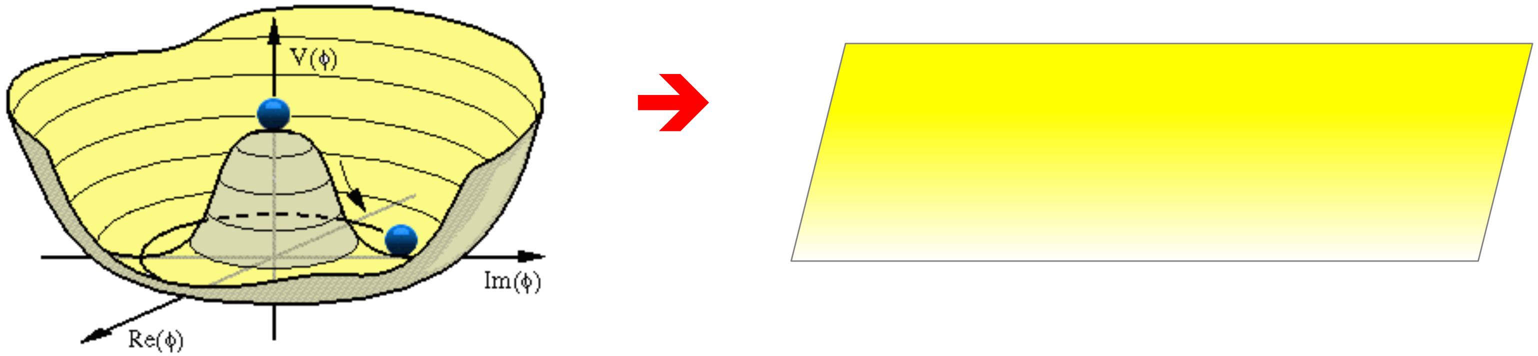
Notes:

- remarkable relation between weak scale, m_t, couplings and M_{Planck} ←→ precision
- strong cancellations between Higgs and top loops
  → very sensitive to exact value and error of m_H, m_t, $\alpha_s = 0.1184(7)$ → currently 1.8σ in m_t
- other physics: DM, m_ν … axions, …Planck scale thresholds… SM+ ←→ $\lambda = 0$

→ top mass errors: data ←→ LO-MC → translation of m_{pole} → MS bar
→ be cautious about claiming that metastability is established
→ and we need to include DM, neutrino masses, …

Is there a Message?

- $\lambda(M_{Planck}) \simeq 0$? ➔ flat potential at M_{planck}
  ➔ flat Mexican hat (<1%) at the Planck scale – why?
  Unrelated: M_{planck}, M_{weak}, gauge, Higgs and Yukawa couplings



- if in addition $\mu^2 = 0$ ➔ $V(M_{Planck}) \simeq 0$?

<u>(Remember:</u> μ is the only single scale of the SM)

- note also that $\lambda(M_{Planck}) \simeq 0$ implies big log cancellations

conformal (or shift) symmetry as solution to the HP

➔ combined conformal & EW symmetry breaking

➔ realizations ➔ implications for neutrino masses and DM

Conformal Symmetry & Neutrino Masses

ML, Schmidt and J.Smirnov

- No explicit scale ➔ no explicit (Dirac or Majorana) mass term
  ➔ only Yukawa couplings ⊗ generic scales
- this links two very special features of SM: one scale – L number

- Enlarge the Standard Model field spectrum
  like in 0706.1829 - Foot, Kobakhidze, McDonald, 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

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

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

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

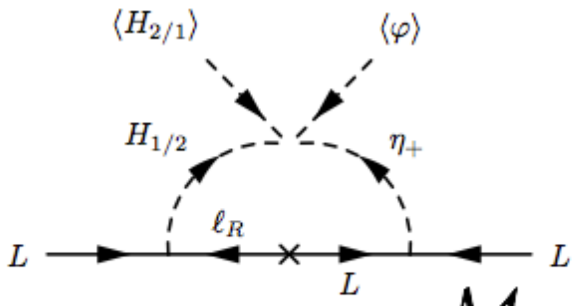
➔ generically expect a TeV seesaw

BUT: y_M might be tiny

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

➔ suppressed 0νββ

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

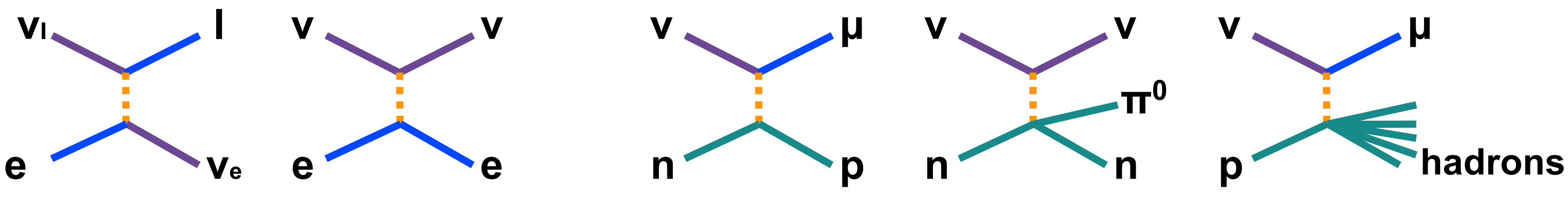
The punch line:
all usual neutrino mass terms can be generated

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

A new Tool: Coherent Neutrino Scattering

The Standard Model has six different interactions of neutrinos with matter:

- **5 have already been detected**



inverse muon (tau) decay

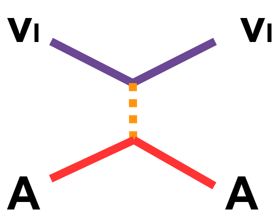
elastic electron scattering

(quasi) - elastic nucleon scattering

nuclear excitation and resonant production

Deep inelastic scattering and jet production

- **1 has so far not been detected:**



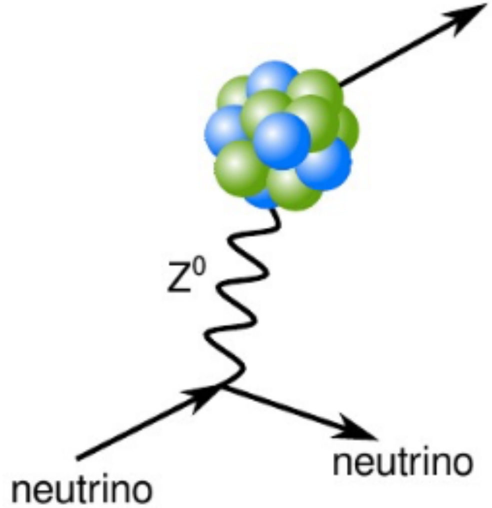
Coherent neutrino-nucleus scattering: CνS

➔ **conceptually important**
➔ **useful method to test new physics**

A. Drukier, Leo Stodolsky, Phys.Rev. D30 (1984) 2295 (1984), DOI: 10.1103/PhysRevD.30.2295

Coherent Neutrino Scattering

Z-exchange of a neutrino with nucleus
→ nucleus recoils as a whole
→ coherent up to E_ν~ 50 MeV



$$Q_w = N - (1 - 4\sin^2\theta_w)Z$$

$$\frac{d\sigma(E_\nu, T)}{dT} = \frac{G_f^2}{4\pi} Q_w^2 M \left(1 - \frac{MT}{2E_\nu^2}\right) F(Q^2)^2$$

~ N^2

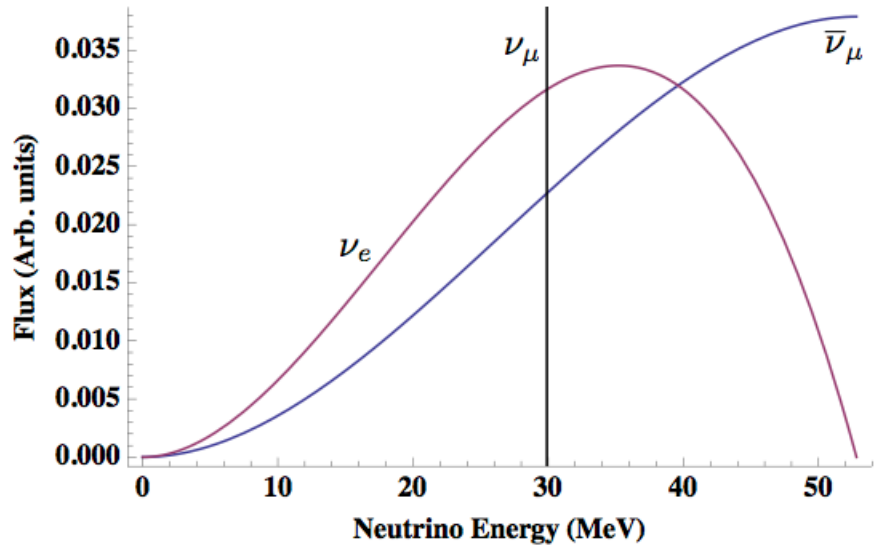
N ≃ 40 → N^2 = 1600 → detector mass 10t → few kg

Important: Coherence length ~ 1/E
→ need neutrinos below O(50) MeV for typical nuclei
→ low energy E_ν ←→ lower cross sections ←→ flux!

Two main Paths

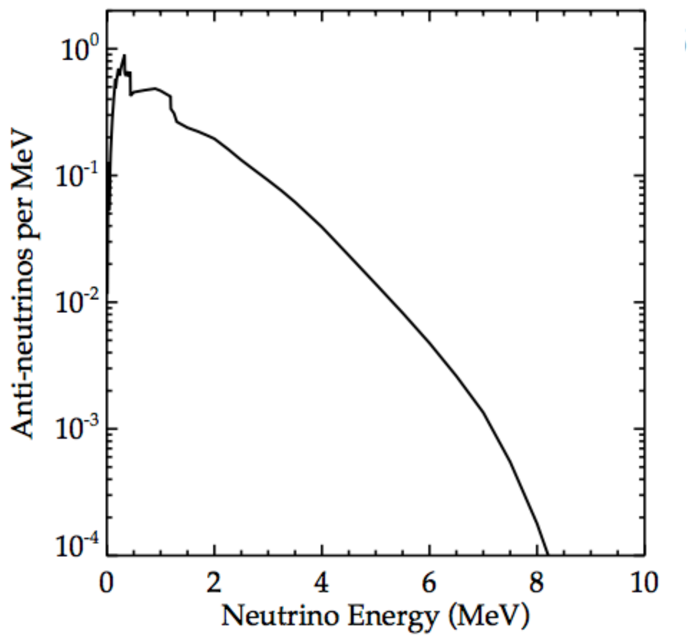
Accelerators:

π-decay-at-rest (DAR) ν source
Different flavors produced
relatively high recoil energies
➔ close to de-coherence



Reactors:

Lower ν energies than accelerators
Lower cross section
Different flavor content
implications for probes of new physics



Vogel et al. 1981, Kopeikin 2012

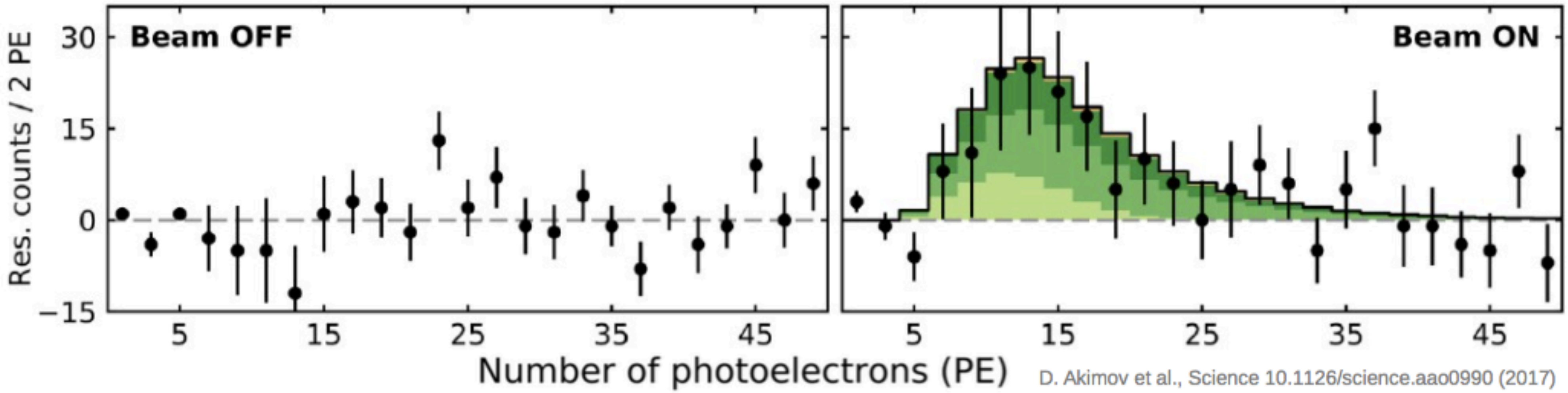
First Observation of CvS

COHERENT experiment (stopped π beam 30-50 MeV neutrinos)

- 4 different detector technologies
  - 14 kg of **CsI** scintillating crystals
  - 35 kg single phase LAr detector
  - 185 kg NaI scintillating crystal
  - 10 kg HPGe PPC detectors
- SNS source with $\bar{\nu}$ flux of $4.3 \cdot 10^7$ $\nu/cm^2/s$ @ 20m

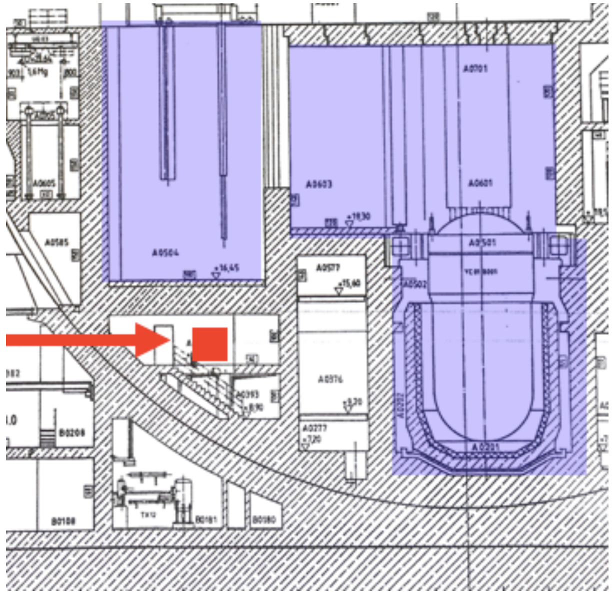
First COHERENT result July 2017

- 15 month of live-time accumulated with CsI[Na]
- 6.7 σ significance for excess in events, with 1 σ consistency with the SM prediction



D. Akimov et al., Science 10.1126/science.aao0990 (2017)

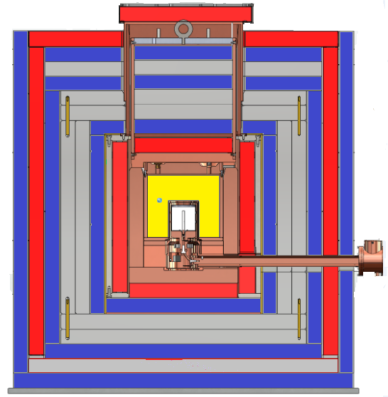
CONUS @MPIK



Coherent ν scattering: improvements

1) The world‘s most intense neutrino source:

3.9GW$_{th}$ reactor (Brokdorf, Germany) @ d=17m
➔ ν flux: 10^{14}/cm^2/s ←➔ ca. 200 kW/m^2 in neutrinos
very high duty cycle; access during operation
on-site PTB measurements of n flux (Bonner spheres)



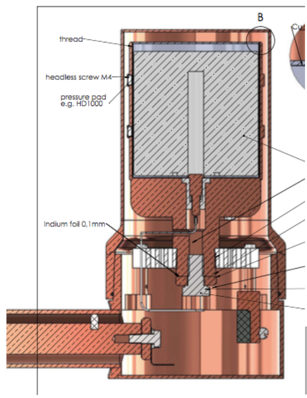
2) GIOVE-type active shielding ➔ „virtual depth“

shield + reactor (more concrete, water)
➔ corresponds effectively to few hundred m.w.e.

3) Newest low backgd. low threshold Ge detectors

BEGe R&D @MPIK: Asterix & Obelix....
4x kg-size SAGe, PT-cooler, pulsar resol. 70-85 eV, $E_{th} \simeq 240$ eV

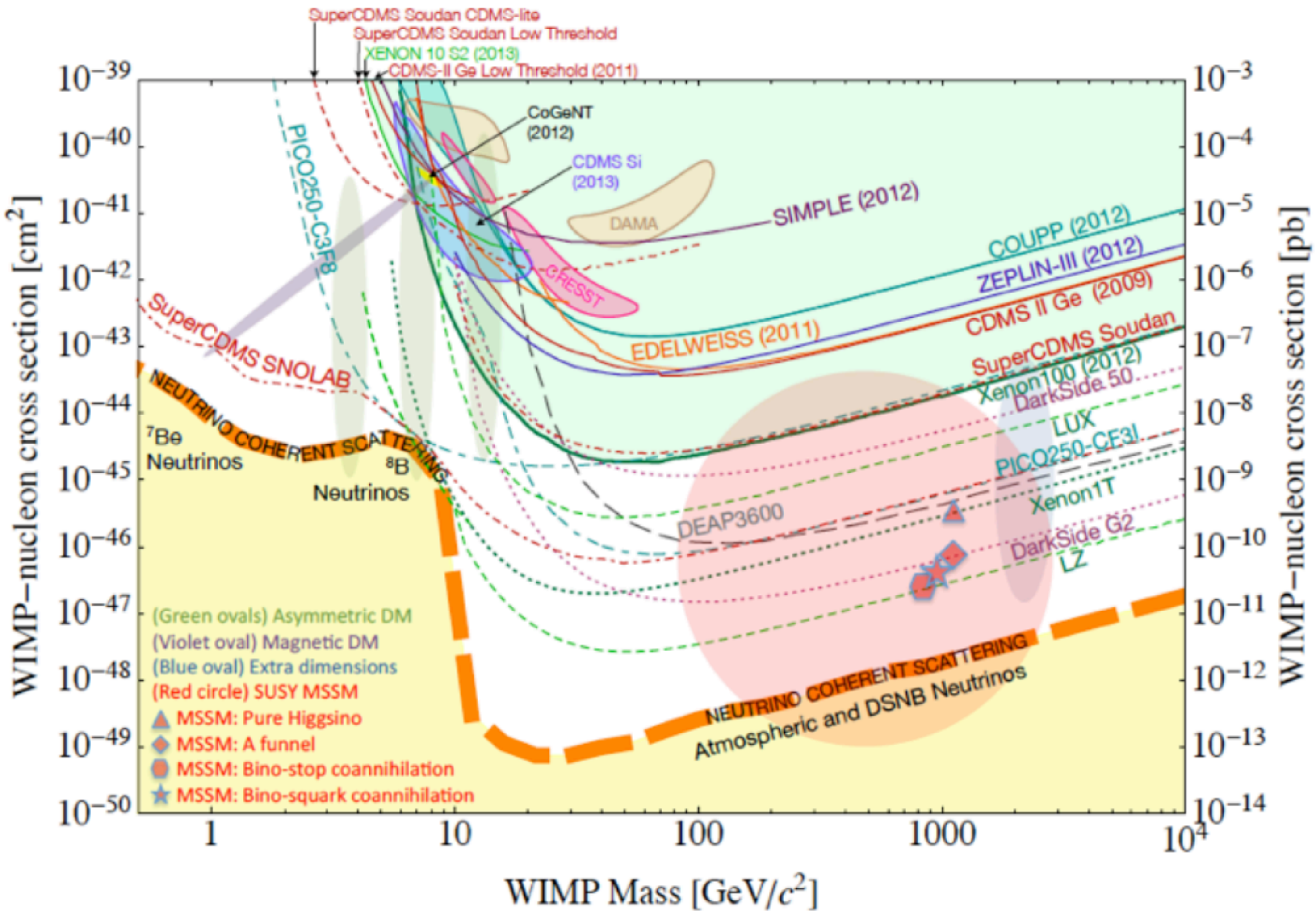
➔ E_ν up to 8 MeV → fully coherent
➔ 4kg detector with ~ 300 eV threshold
data taking 2017 ➔ high event rate



Why is CνS interesting

DM connection:

1) DM experiments <u>assume</u> coherent DM scattering → test of CνS
2) Neutrino floor of direct DM experiments *IS* due to CνS



Why is CvS interesting

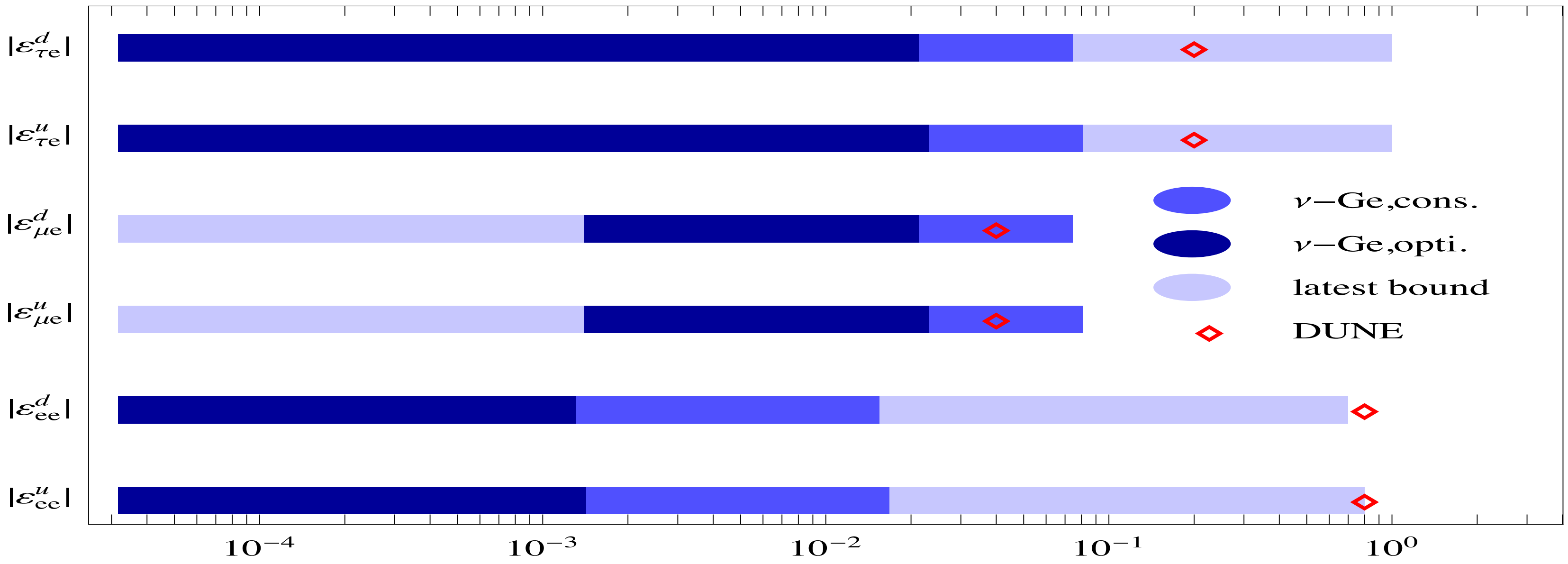
Upscaling 4kg ➔ 100kg (not that big or more complicated...)

3) neutrino magnetic moments - BSM: SUSY, extra dimensions, …

4) sterile neutrino searches

5) nuclear form factors

6) NSI's – 100kg, 5y operation @ 4GW   ML, Rodejohann, Xu



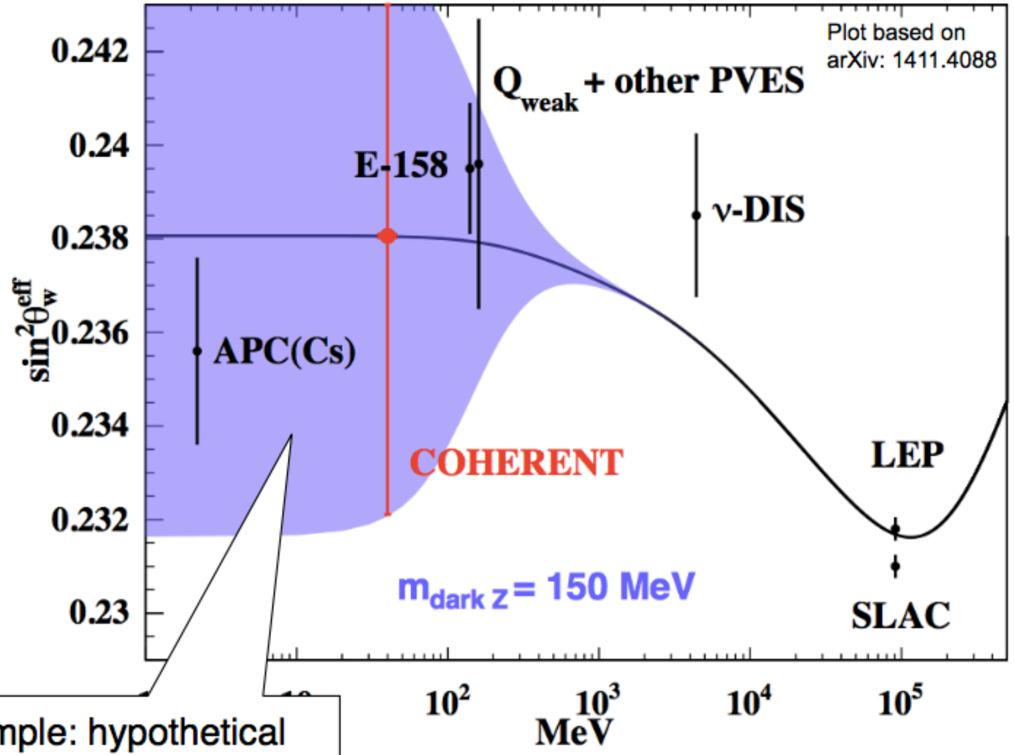
~10 TeV   ~TeV

7) nuclear safeguarding and reactor monitiring (ν technology)

Precise Measurement of $\sin^2\theta_W$ at low E

Clean SM prediction for the rate ➔ measure $\sin^2\theta_W$eff ; **deviation probes new physics**

$$\sigma \sim \frac{G_f^2 E^2}{4\pi}(N - (1 - 4\sin^2\theta_W)Z)^2$$



Example: hypothetical dark Z mediator (explanation for g-2 anomaly)

BSMsens =
10^{-3} ➔ $\Delta\sin^2\theta_W = 0.006$
10^{-4} ➔ $\Delta\sin^2\theta_W = 0.0006$

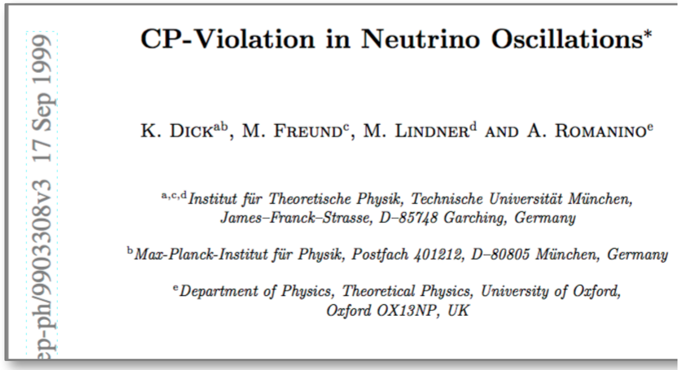
CEvNS sensitivity is @ low Q; need sub-percent precision to compete w/ electron scattering & APV, but **new channel**

slide adopted from K. Scholberg

Summary

From Pauli (will never be seen…) to today (high statistics exp.)
➔ neutrino physics was and is a very hot field!

- **3 active neutrinos**
  → routine → precision → mass hierachy and CPV


ep-ph/9903308v3 17 Sep 1999

CP-Violation in Neutrino Oscillations*

K. Dick[ab], M. Freund[c], M. Lindner[d] and A. Romanino[e]

[a,c,d] *Institut für Theoretische Physik, Technische Universität München, James–Franck–Strasse, D–85748 Garching, Germany*

[b] *Max-Planck-Institut für Physik, Postfach 401212, D–80805 München, Germany*

[e] *Department of Physics, Theoretical Physics, University of Oxford, Oxford OX13NP, UK*

- **Further exciting fundamental topics**
  - absolute neutrino mass
  - L violation and 0νββ
    - very new physics & interesting connections to other physics: LHC, LFV
  - do sterile neutrinos exist?
    - keV ν's as warm dark matter, eV evidences, TeV & EW fits, …
  - connections to EW symmetry breaking, DM
    - Higgs portals, …

- **Neutrinos are unique probes into many sources**

Neutrinos are always good for BSM surprises…!

Congratulations from all your colleagues at the

Max-Planck-Institut für Kernphysik in Heidelberg