Neutrino Physics: Overview and Directions

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The SM – a Synergy of Concepts

d=4 QFTs:

QED ➔	QCD ➔	SM
$U(1)_{em}$	$SU(3)_C$	$SU(3)_C \times SU(2)_L \times U(1)_Y$

electrodynamics
relativity } QED

strong force → QCD

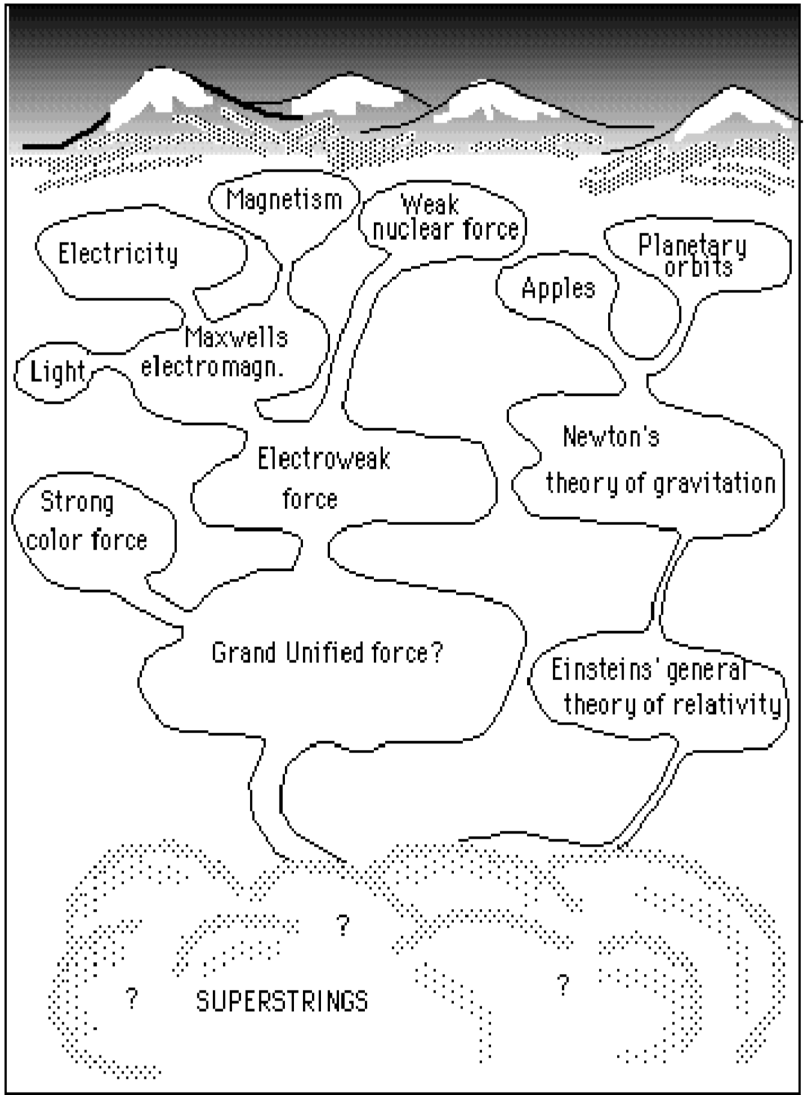
weak decays + Higgs mech., χ-ral
+ neutrino masses
+ dark matter ⬅➔?
+ DE ?

AND: gravity

territory of speculations:
SM ➔ extra reps? LR?
TC? SUSY? GUTs? TOE?
extra dim.? strings?

weak scale <<<< M_{Planck}

Reasons to go Beyond the Standard Model



Theoretical:

! SM does not exist without cutoff
(triviality, vacuum stability)
? Gauge hierarchy problem
? Origin of generations / flavour
? Gauge unification, charge quantization
! Strong CP problem
? Unification with gravity
? Global symmetries & GR anomalies

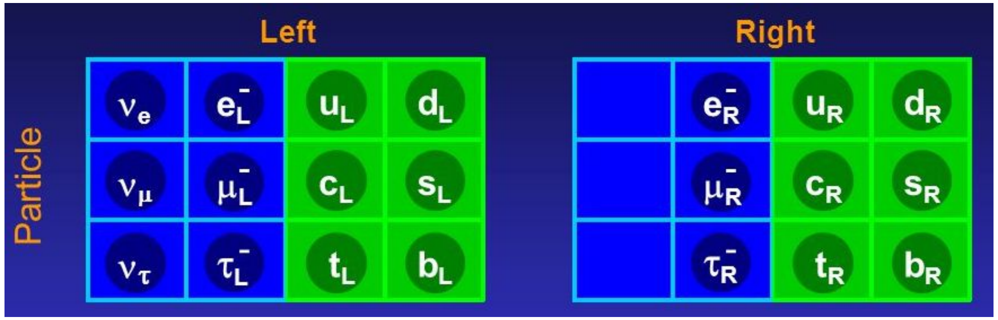
Experimental facts:

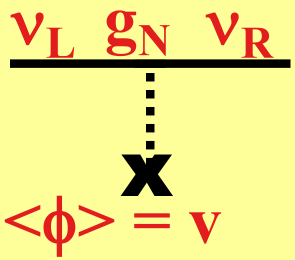
? Electro weak scale << Planck scale
? Gauge couplings almost unify
? Flavour: Patterns of masses & mixings
? Dark Energy
! Dark Matter
! Baryon asymmetry of the Universe
! Neutrinos masses & large mixings

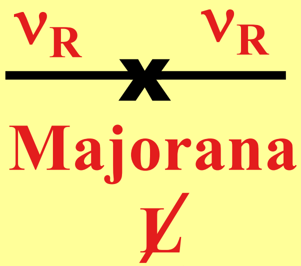
➔ **how solid are these reasons!? How does neutrino physics fit in?**

Bottom-up: Minimal Neutrino Masses

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







$\rightarrow$

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

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

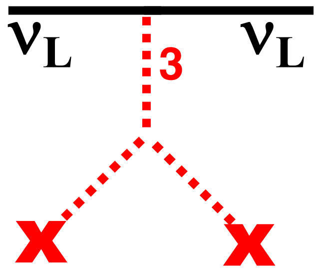
Beyond the SM: SM+ see-saw

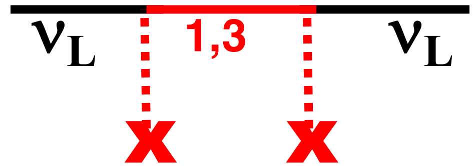
- **L-violation: A henn & egg problem for embeddings**
- **Why N=3 right singlets ν_R? – other number possible**

Other Possibilities

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

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

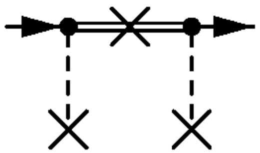




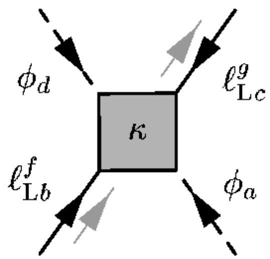
Both ν_R and new singlets / triplets:

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

Higher dimensional operators: d=5, …



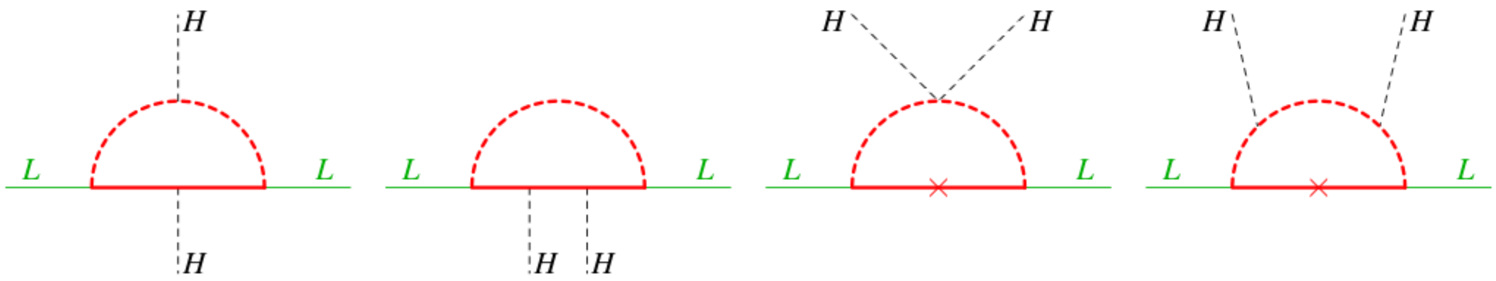
$\Rightarrow$



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

➔ $M_L L \overline{L}^c$

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

3 Light 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:

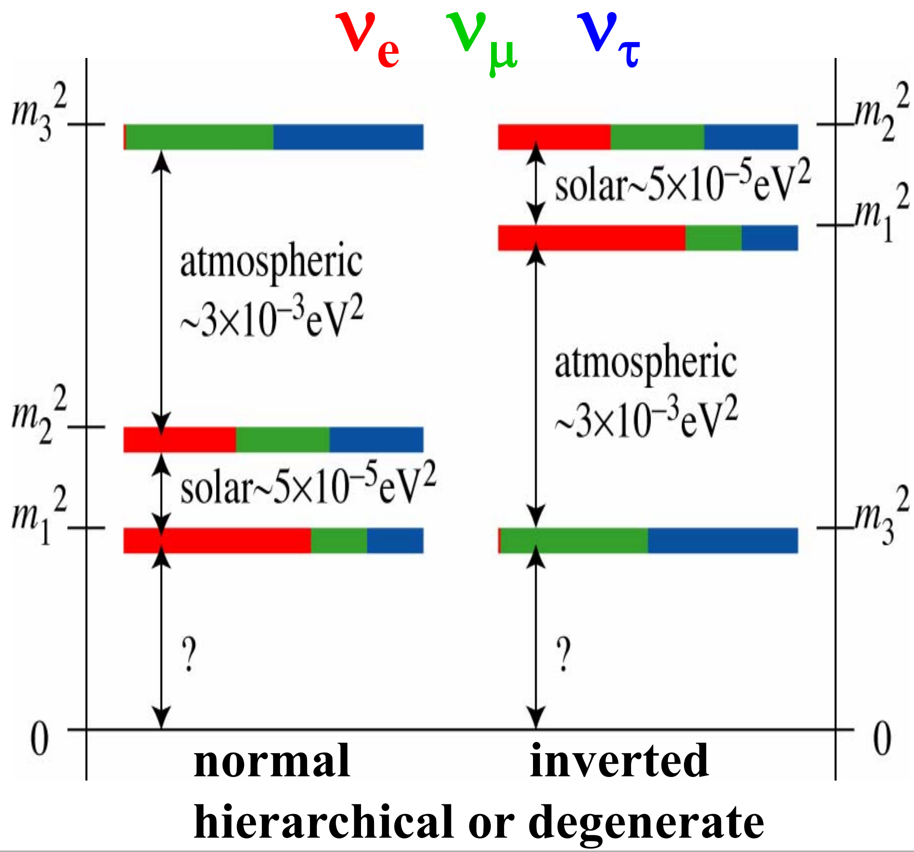
➔ Dirac ≃ SM / Majorana = BSM

➔ mass scale: m_1

➔ mass ordering: sgn(Δm^2_{31})

➔ is θ_{23} maximal?

➔ CP violation



The Status of Neutrino Parameters (3f)

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}	$145 \to 391$	$0 \to 360$
$\frac{\Delta m^2_{21}}{10^{-5}\ \text{eV}^2}$	$7.50^{+0.19}_{-0.17}$	$7.03 \to 8.09$	$7.50^{+0.19}_{-0.17}$	$7.03 \to 8.09$	$7.03 \to 8.09$
$\frac{\Delta m^2_{3\ell}}{10^{-3}\ \text{eV}^2}$	$+2.524^{+0.039}_{-0.040}$	$+2.407 \to +2.643$	$-2.514^{+0.038}_{-0.041}$	$-2.635 \to -2.399$	$\begin{bmatrix} +2.407 \to +2.643 \\ -2.629 \to -2.405 \end{bmatrix}$

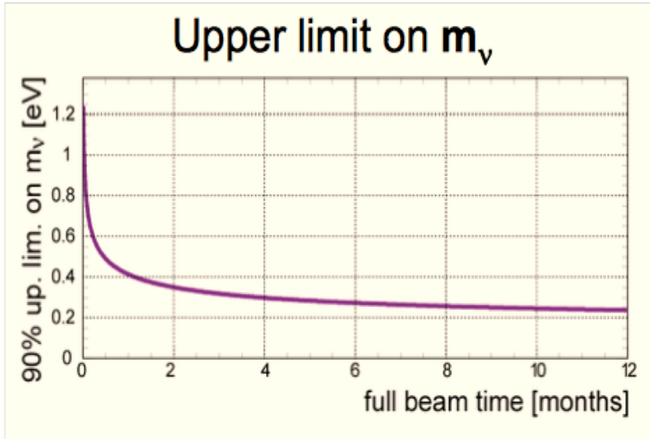
UPDATE REQUIRED

Absolute mass limits from Mainz and Troitsk: $m_1 < 2.2$ eV
Limits from cosmology: 0.15-0.2 eV

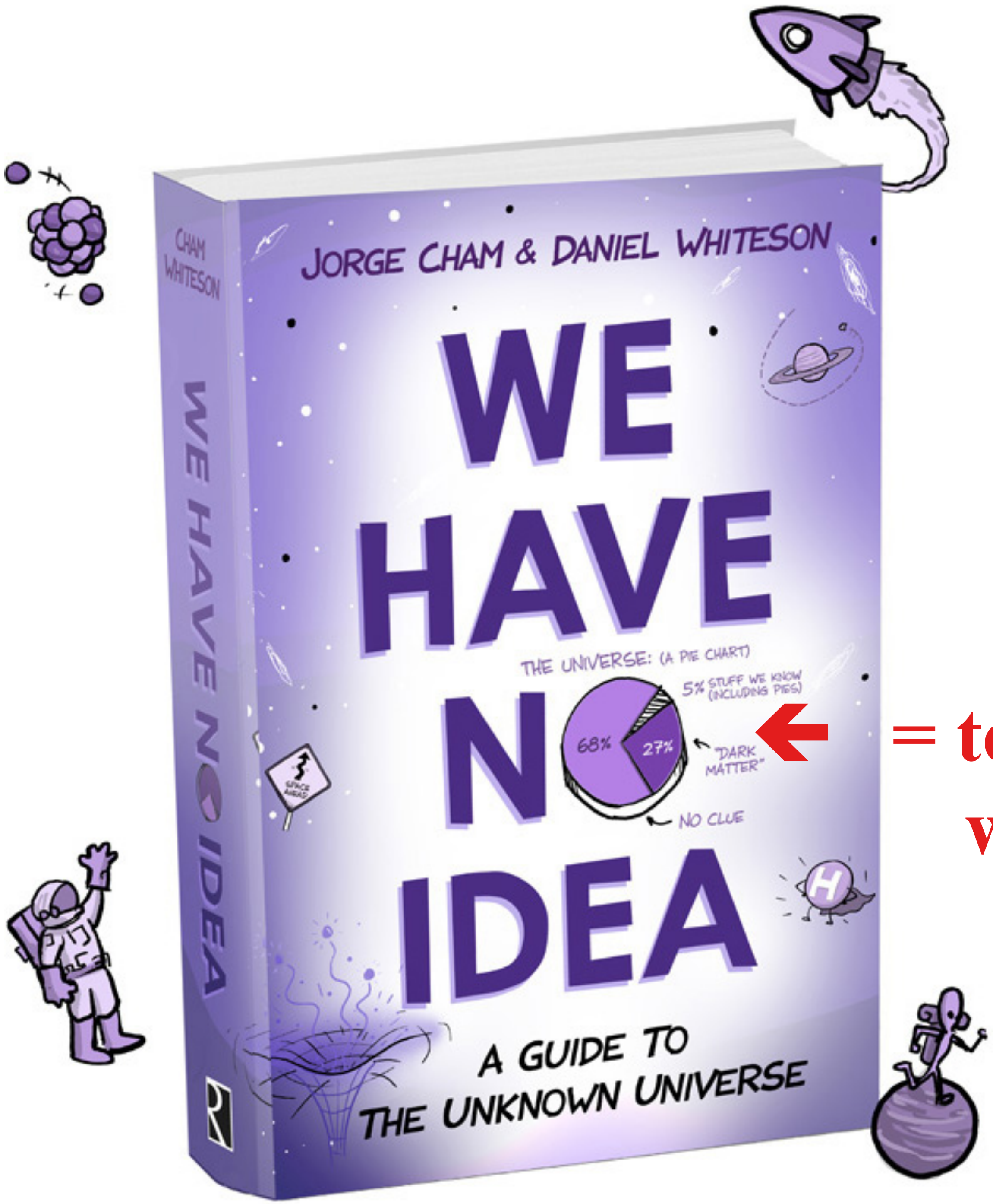
KATRIN: started operation ➔ 0.2eV ; Project8, …

Important:

- Active ν unitarity already tested > 95%
- origin of ν masses unknown



➔ Talks by E. Martinez, T. Schwetz, Ch. Weinheimer and others



= too many ideas
we need more data!

Directions in Neutrino Physics

Scenario A) 3 massive ν's only: determine masses and mixings

- oscillations
- absolute mass ←→ how precise should we be?
- Dirac or Majorana — killing models versus deeper insights

Scenario B) more than 3 neutrinos

- sterile neutrinos
- L-violation ←→ any one of them is a major discovery!
- NSIs — high risk projects
- large magnetic moments
- magnetic moments, …

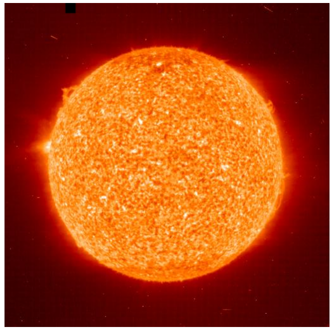
1) precision oscillations: θ_{ij} , Δm_{ij}^2, **MH, CP,** over-constraining

2) other: m_1, $0\nu\beta\beta$, sterile searches, NSIs, coherent scattering, ...

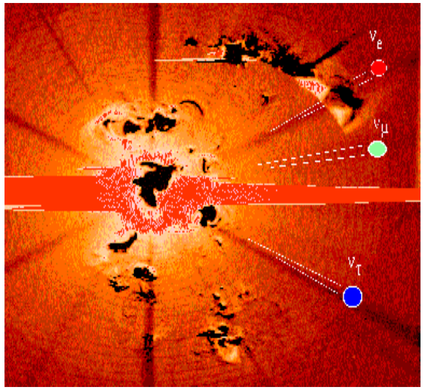
3 main physics directions:

- learn about sources
- precise flavour information ←→ origin of masses/flavour?
- lever arm (direct or indirect) to other new physics (e.g. proton decay)

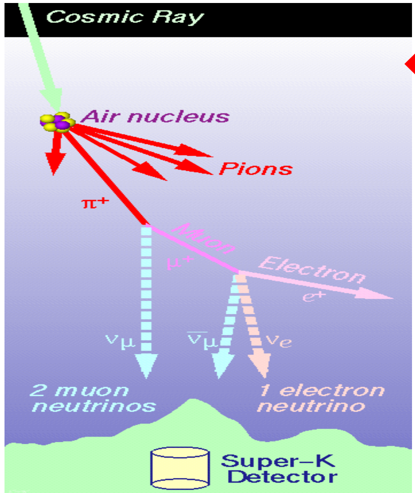
Neutrino Sources and Topics (fixed / man made)



←Sun



←Cosmology



←Atmosphere

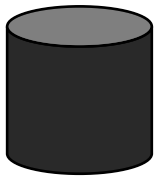
←Earth

Astronomy: →
Supernovae
SNRs, GRBs
UHE ν's

Reactors→

Accelerators→

β-Sources→



The Value of Precision 3 Flavour ν Physics

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

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

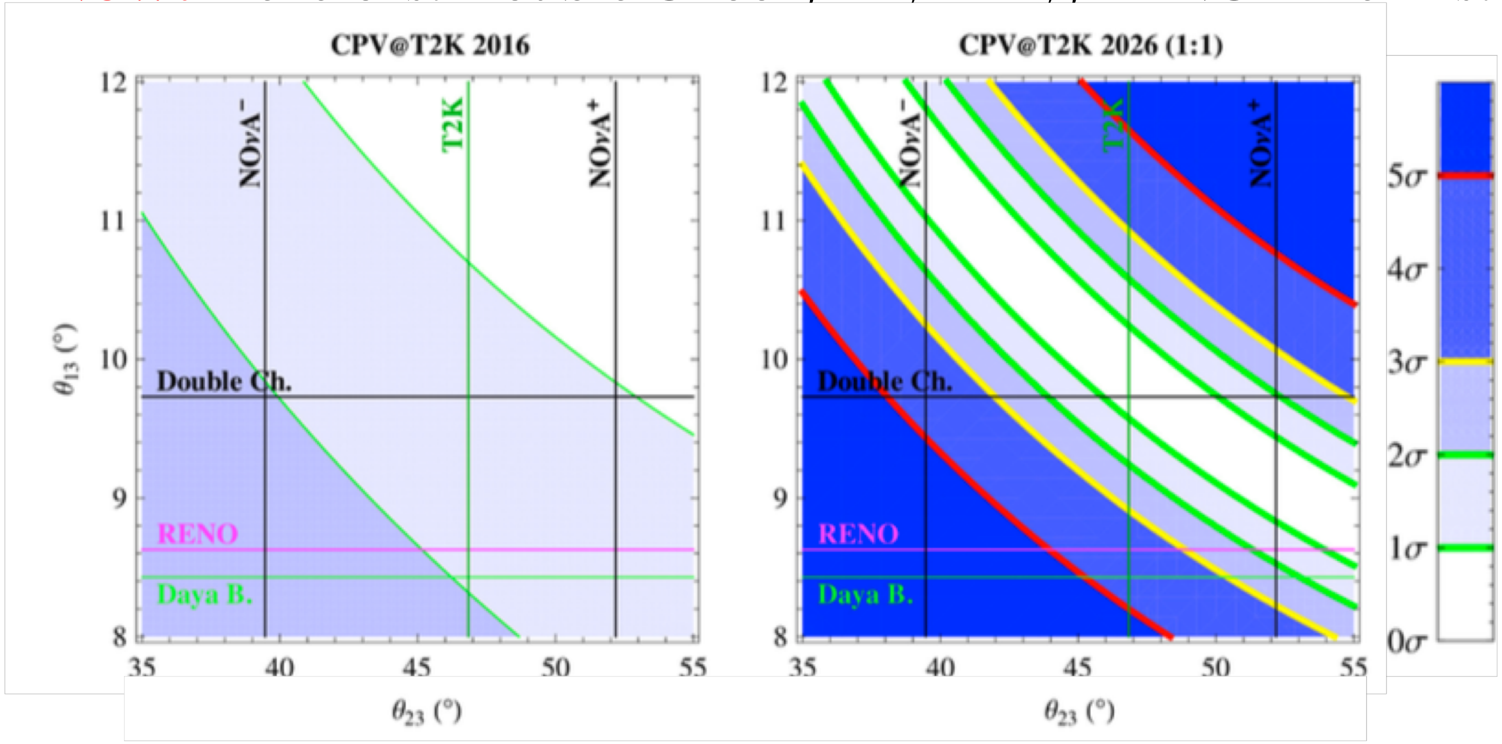
- **Remember: Many theoretical options…**
- **Precise measurements test mass models**
  e.g. based on flavour symmetries
  ←→ many models... will we learn something generic?
- **Majorana masses ←→ best explanation of BAU**
  ←→ related to heavy Majorana CP phases
  ←→ detection of δ_{CP} phase makes this more plausible

  BUT: Don't forget it is only the light Dirac-like phase
  ... and BAU without Majorana (phase transitions, ... , D-leptogenesis)
- **Neutrinos are a 0.6% HDM component**
  ←→ cosmological structure formation
- **Precision may open the door for more new physics**
  ←→ test of 3 flavour unitarity, overconstraining, ...

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



Rodejohann, ML, Xu others…

➔ global fits...: better θ_{ij} and certain significance for δ_{CP}

➔ Mass hierarchy: latest NoVA+T2K+cosmology ➔ >3σ for normal hierarchy

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

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

Beyond three Neutrinos

Sterile Neutrino Hints & Searches

Project	neutrino	source	E (MeV)	L (m)	status
SAGE [166]	ν_e	^{51}Cr	0.75	$\lesssim 1$	in preparation
CeSOX [167, 168]	$\bar{\nu}_e$	^{144}Ce	1.8 – 3	5 – 12	in preparation
CrSOX [167]	ν_e	^{51}Cr	0.75	5 – 12	proposal
Daya Bay [169, 170]	$\bar{\nu}_e$	^{144}Ce	1.8 – 3	1.5 – 8	proposal
JUNO [171]	$\bar{\nu}_e$	^{144}Ce	1.8 – 3	$\lesssim 32$	proposal
LENS [172]	$\nu_e, \bar{\nu}_e$	^{51}Cr, ^{6}He	0.75, $\lesssim 3.5$	$\lesssim 3$	abandoned
CeLAND [173]	$\bar{\nu}_e$	^{144}Ce	1.8 – 3	$\lesssim 6$	abandoned
LENA [174]	ν_e	^{51}Cr, ^{37}Ar	0.75, 0.81	$\lesssim 90$	abandoned

Source experiments

Project	P_{th} (MW)	M_{target} (tons)	L (m)	Depth (m.w.e.)	status
Nucifer (FRA) [175]	70	0.8	7	13	operating
Stereo (FRA) [176]	57	1.75	9 – 12	18	~~in preparation~~ → running
DANSS (RUS) [177]	3000	0.9	10 – 12	50	~~in preparation~~ → running
SoLid (BEL) [178]	45 – 80	3	6 – 8	10	in preparation
PROSPECT (USA) [179]	85	3, 10	7 – 12, 15 – 19	few	in preparation
NEOS (KOR) [180]	16400	1	25	10 – 23	~~in preparation~~ → result, withdrawn → updated
Neutrino-4 (RUS) [181]	100	1.5	6 – 11	10	proposal
Poseidon (RUS) [182]	100	3	5 – 8	15	proposal
Hanaro (KOR) [183]	30	0.5	6	few	proposal
CARR (CHN) [184]	60	~ 1	7, 11	few	proposal

Reactor experiments

tensions with cosmology…
→ N_{eff} = 3.x < ~ 4
BBN...

Nevertheless:
→ lab tests important

Also important:
→ keV sterile ν =WDM..

Giunti 1512.04758

→searches for eV & keV sterile ν's … → T. Lasserre, V. Antonelli, A. Boiarskyi

Could TeV sterile Neutrinos make Sense?

- **Good theoretical reasons for any sterile neutrino mass**
- **Assume Lagrangian with type I see-saw ←→ parameter relations**
- **Global fit to all data: LFV, LHC, EWPO and active neutrinos and consider 3 tyical mass spectra**

$$\sin^2\theta_{12} = 0.30 \pm 0.013\,,$$
$$\sin^2\theta_{23} = 0.41^{+0.037}_{-0.025}\,,$$
$$\sin^2\theta_{13} = 0.023 \pm 0.0023\,,$$
$$\delta_{CP} = 300^{+66}_{-138}\,,$$

	NH	IH	QD
m_1 (eV)	~ 0	$4.85 \cdot 10^{-2}$	~ 0.1
m_2 (eV)	$8.660 \cdot 10^{-3}$	$4.93 \cdot 10^{-2}$	~ 0.1
m_3 (eV)	$4.97 \cdot 10^{-2}$	~ 0	~ 0.1

- **Deviations from 3f unitarity:**

$$\epsilon_\alpha \equiv \sum_{i\geq 4} |\mathrm{U}_{\alpha i}|^2$$

$$\epsilon_e - \epsilon_\mu = 0.0022 \pm 0.0025$$
$$\epsilon_\mu - \epsilon_\tau = 0.0017 \pm 0.0038$$
$$\epsilon_e - \epsilon_\tau = 0.0039 \pm 0.0040$$

- **Quality of fit:**

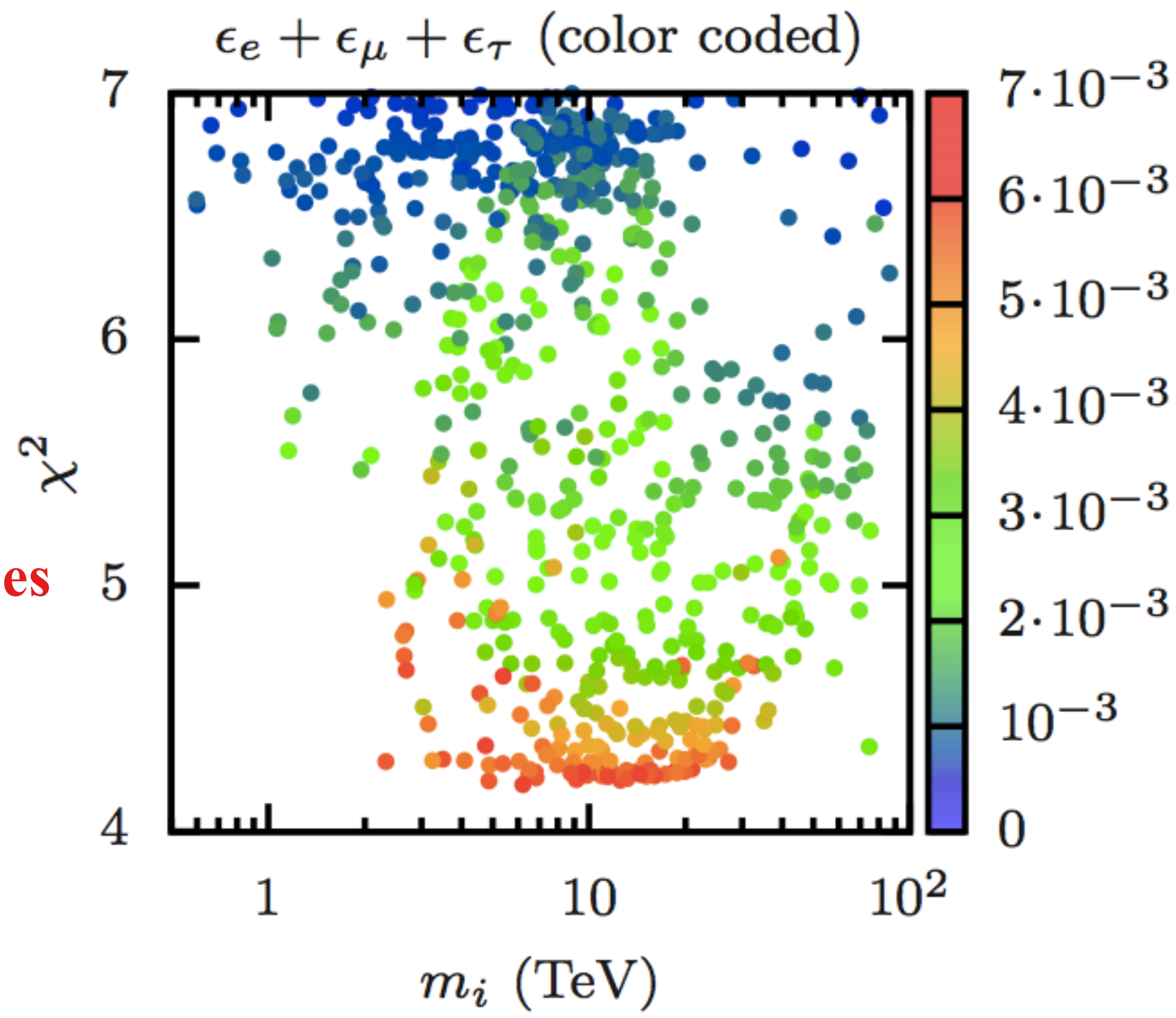
$$\chi^2_{\mathrm{EWPO}} = \sum_i \frac{(O_i - O_{i,\mathrm{SM}})^2}{(\delta O_i)^2 + (\delta O_{i,\mathrm{SM}})^2}$$

Akhmedov, Kartavtsev, ML, Michaels and J. Smirnov

Example

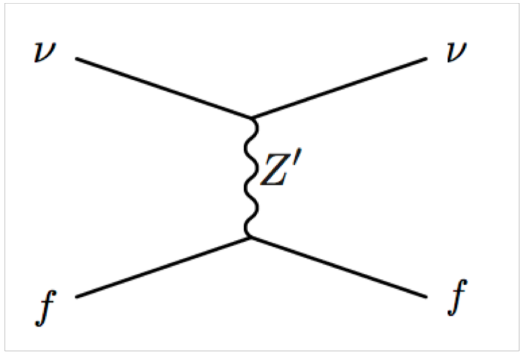
NH, $\varepsilon_e + \varepsilon_\mu + \varepsilon_\tau$ as a function of the lightest heavy neutrino mass for 4dof

sterile ν's improve fit for multi-TeV-ish masses



Searches for new Physics: NSI's

NSI's ←→ new physics at high scales
Which are 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

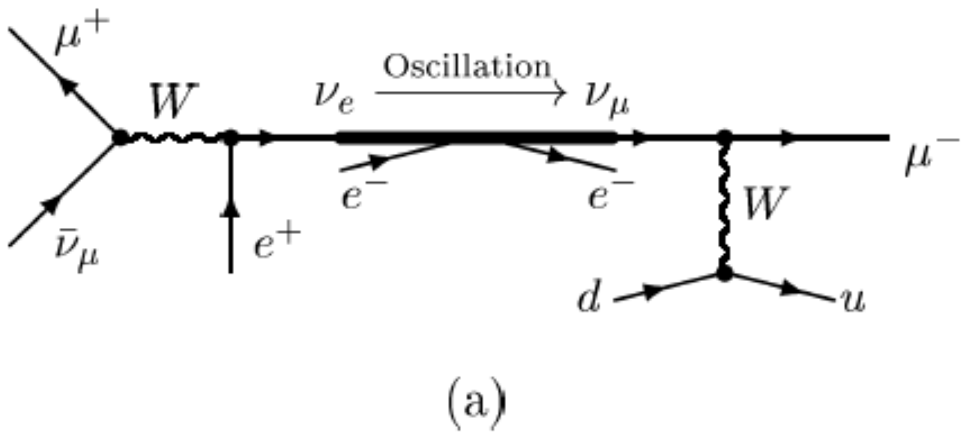
$$|\epsilon| \simeq \frac{M_W^2}{M_{NSI}^2}$$

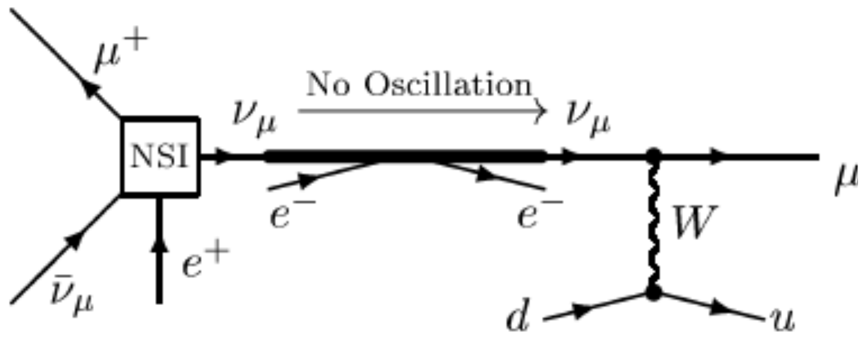
➔ Competitive method to test TeV scales
ε = 0.01 ←→ TeV scales

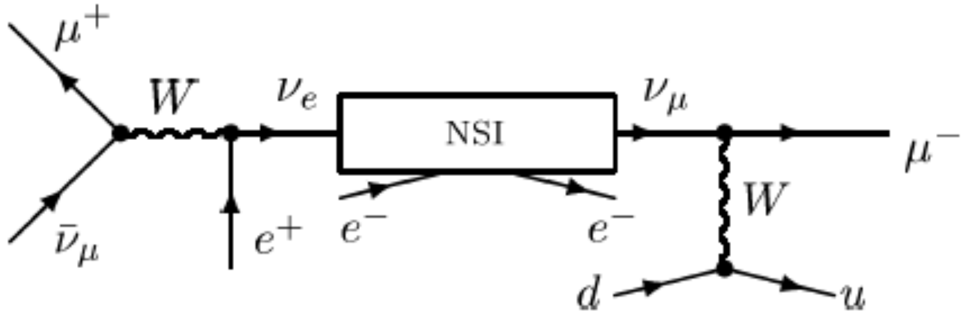
NSIs interfere with Oscillations

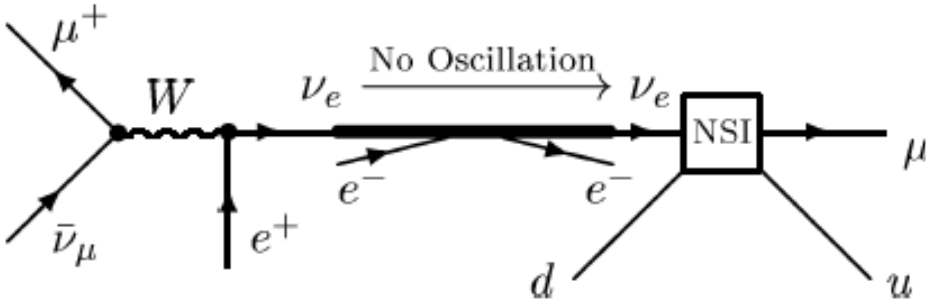
the "golden" oscillation channel

NSI contributions to the "golden" channel



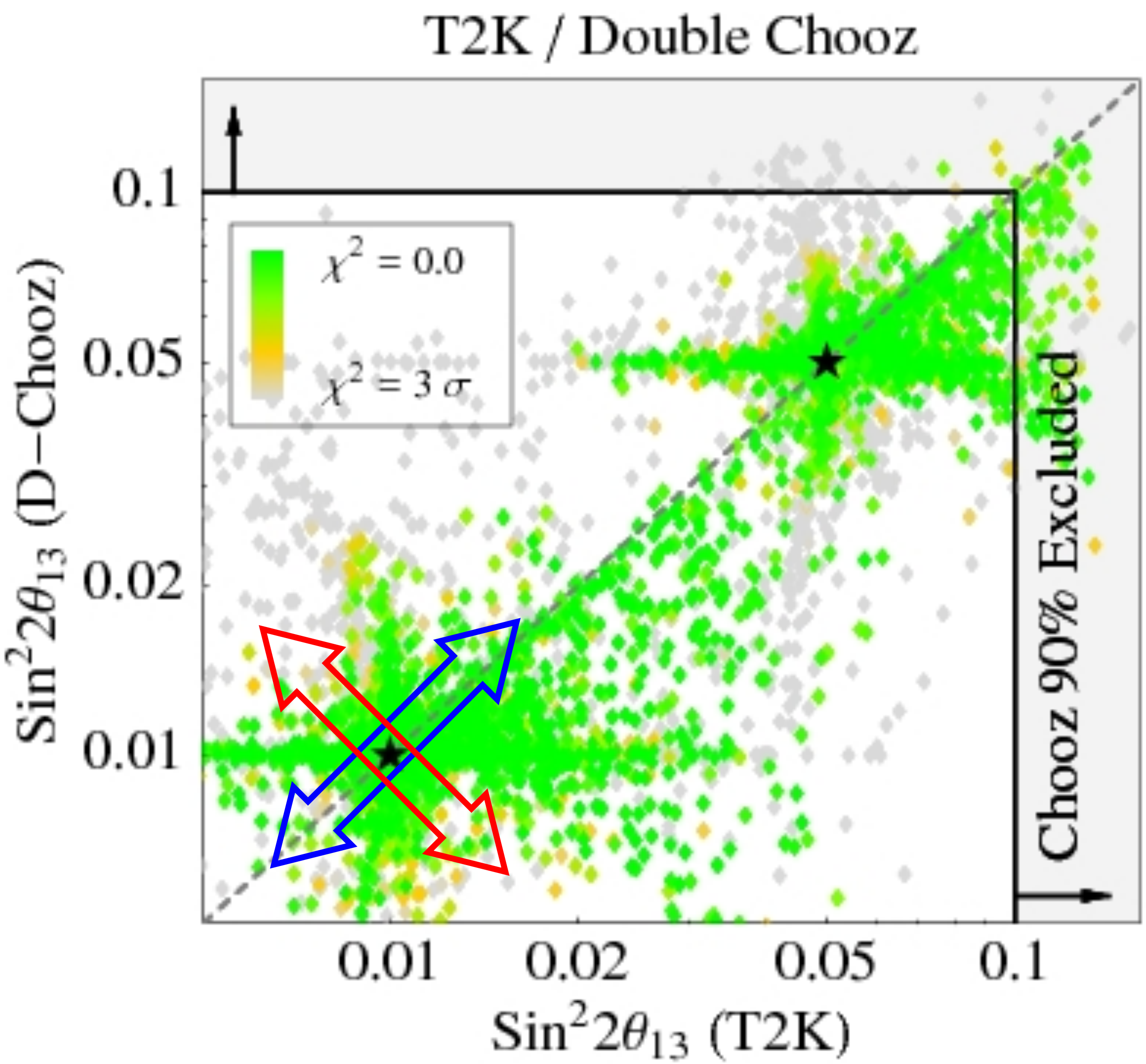






interference in oscillations ~ε ⇔ FCNC effects ~ε^2

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**

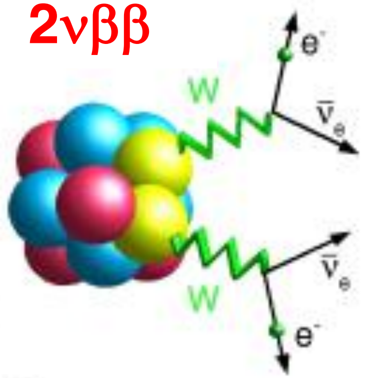
➔ **interesting potential**

Kopp, ML, Ota

The 3ν Picture of 0νββ Decay

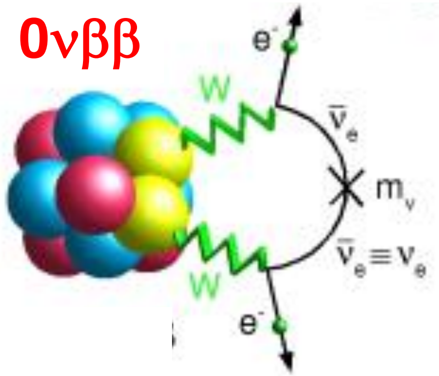
2νββ

SM



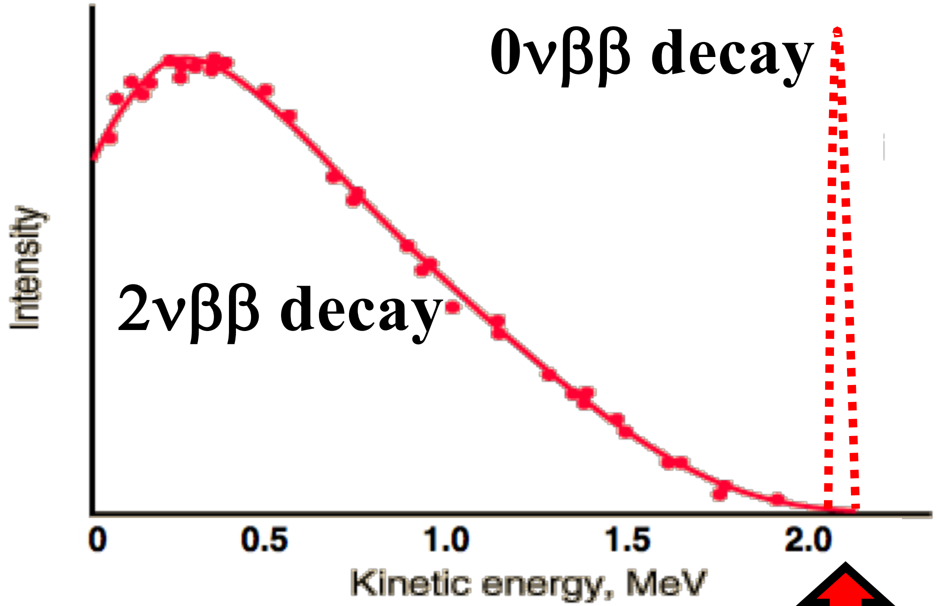
0νββ

Majorana mass



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

2νββ decay seen for diff. isotopes (Kirsten,…)
$T^{1/2} = O(10^{18} - 10^{21}$ years) ➔ up to 10^{11} ⊗ $T_{Universe}$



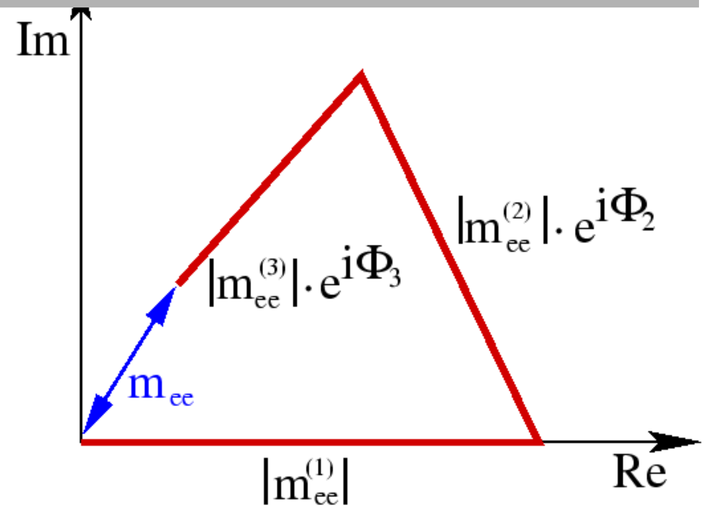
- observe 2νββ
- look for 0νββ signal at $Q_{\beta\beta}$
- large amount of ^{76}Ge nuclei
- extreme low backgrounds!

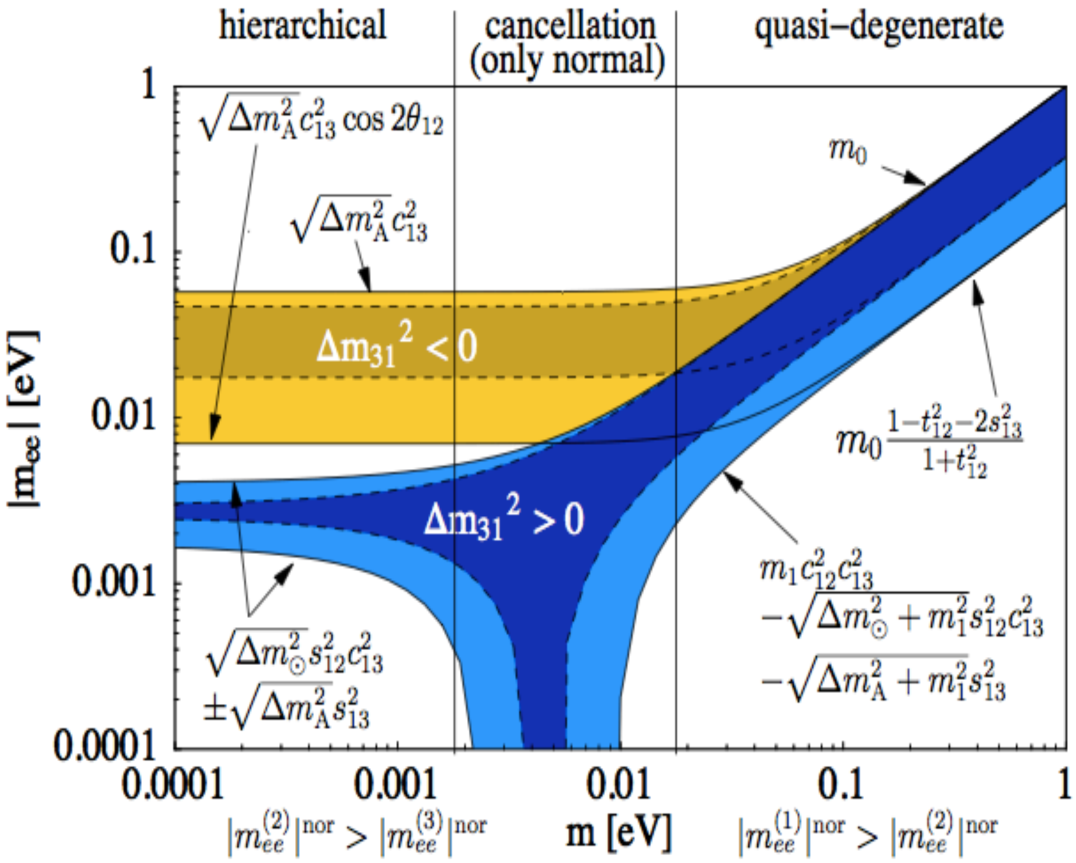
➔ signal = Majorana mass

m_{ee}: The Effective Neutrino Mass

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

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





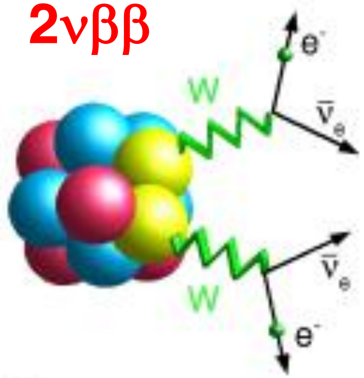
Comments:
- cosmology: m < 0.2-0.3 eV
- $0\nu\beta\beta$: m_{ee} < 0.1-0.3 eV
- NMEs ➔ unavoidable theory errors
- known Δm^2 from oscillations
  - ➔ yellow/blue areas
  - ➔ improved sensitivity is very promising!

- **warnings**:
  - assumes no *other* $\Delta L=2$ physics
  - assumes no sterile neutrinos, ...

More general: L Violating Processes

SM

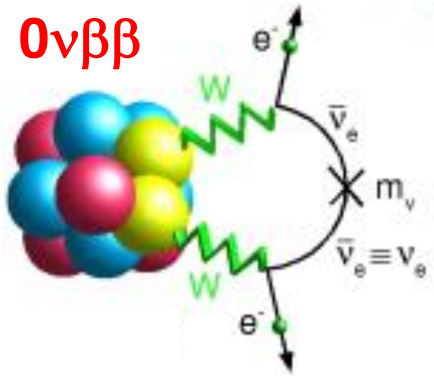
2νββ



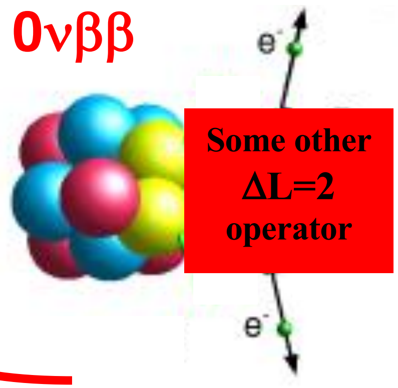
BSM

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

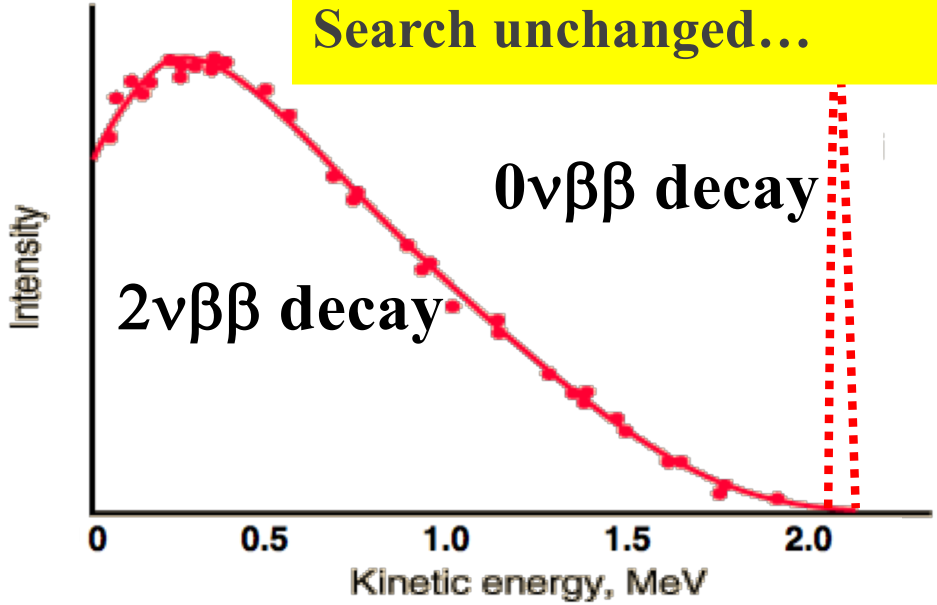
0νββ



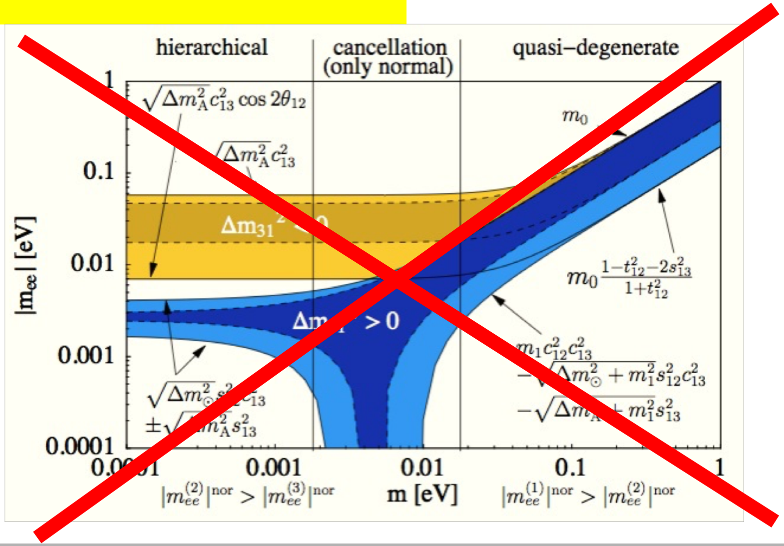
0νββ



Search unchanged…

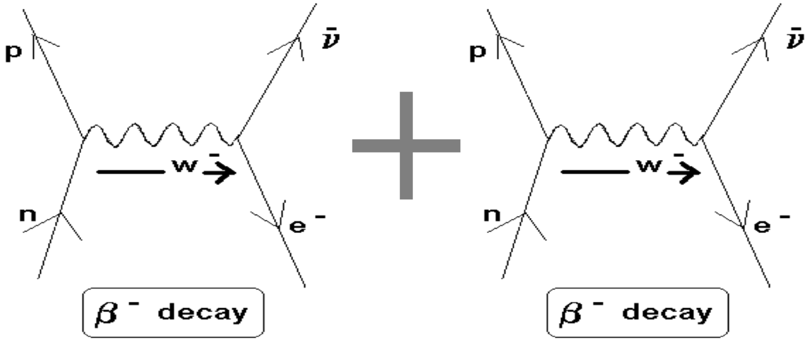


…interpretation changes:



Other Double Beta Decay Processes

Standard Model:

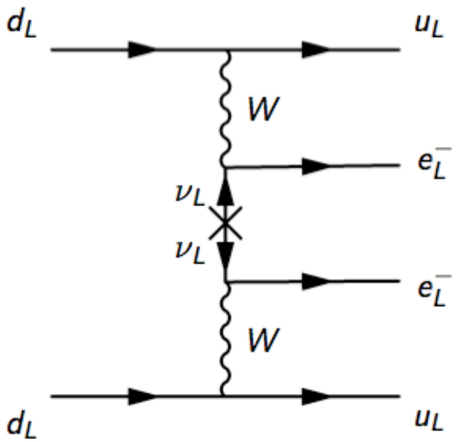


➔ 2 electrons + 2 neutrinos

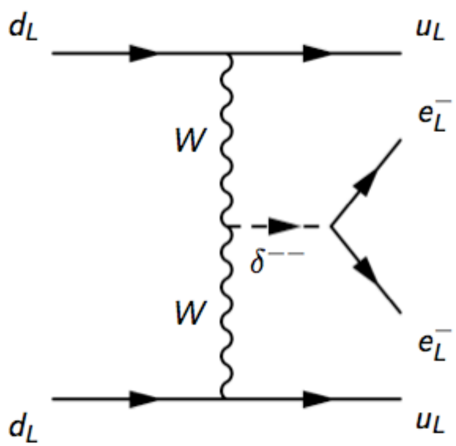
$2\nu\beta\beta$

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

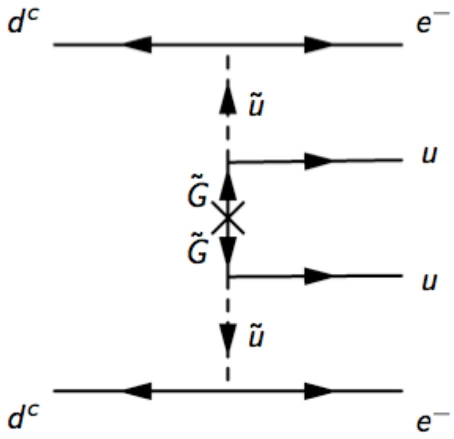
$0\nu\beta\beta$



Majorana neutrino masses ←→ Dirac?



SM + Higgs triplet

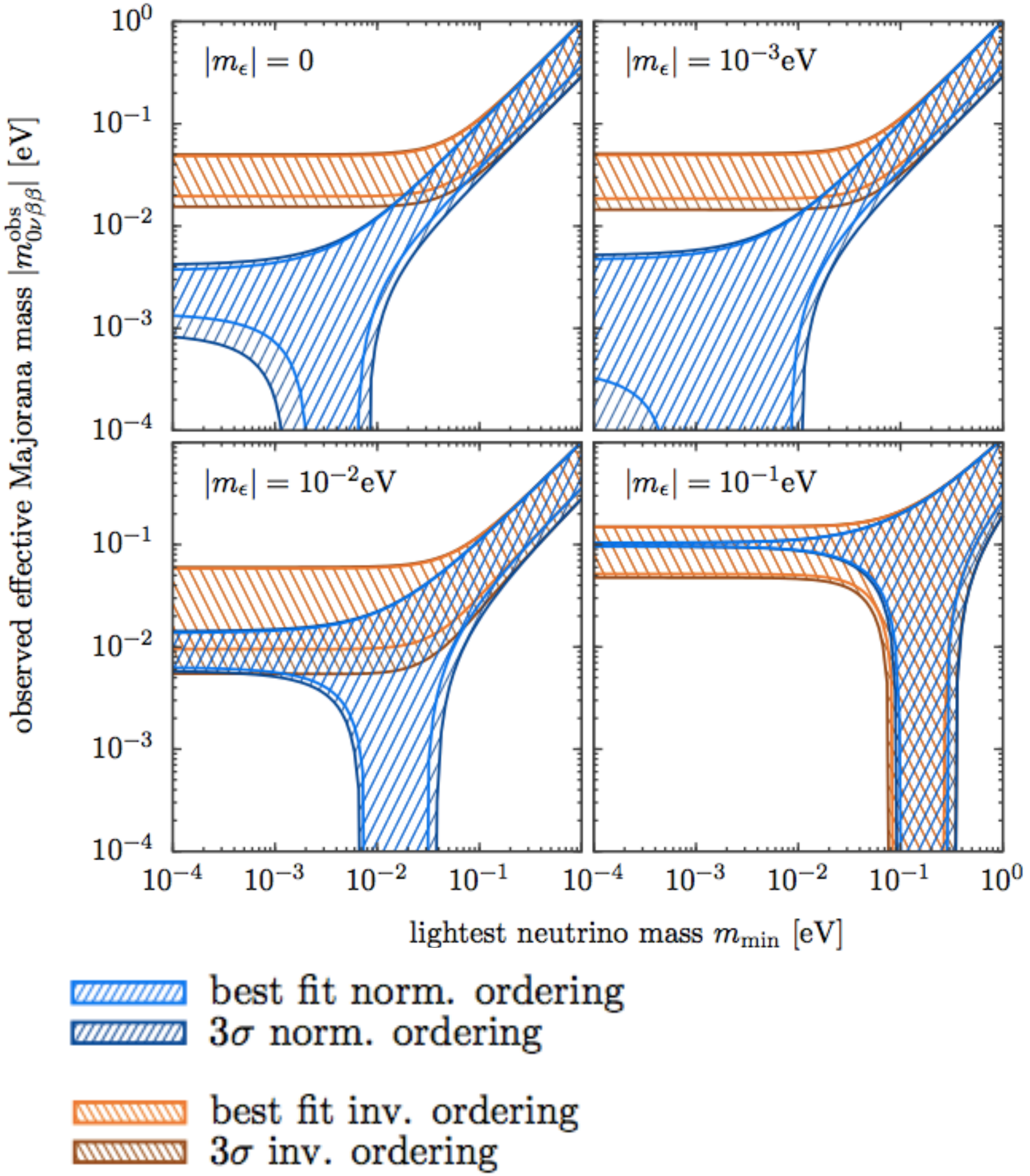


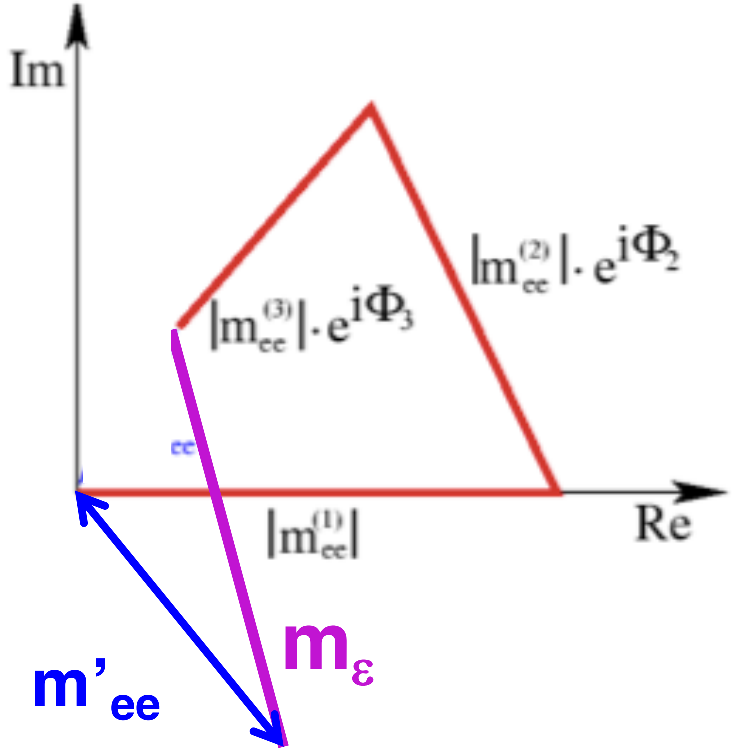
SUSY

…

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

Majorana or other Physics or Interferences





interferences

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

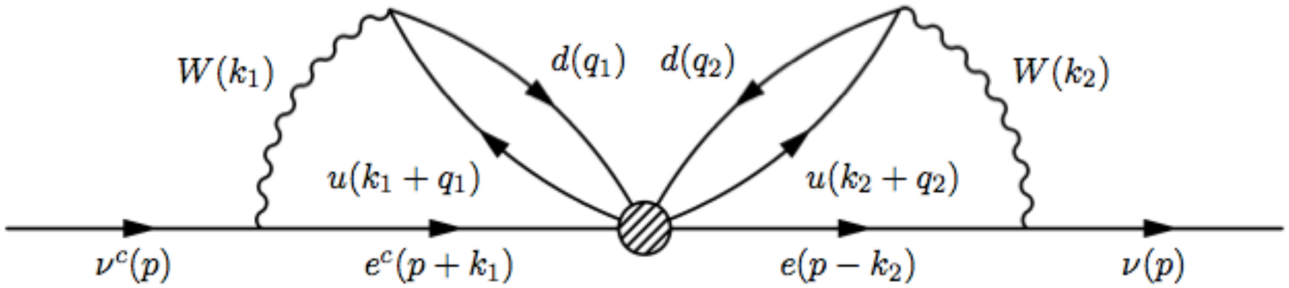
→ shifts of masses, mixings and CP phases

→ destroys ability to extract Majorana phases

→ sensitivity to TeV physics

The Schechter-Valle Theorem induced Mass

- any $\Delta L=2$ operator which leads to $0\nu\beta\beta$ decay induces via loops a Majoarana mass
- assume a $0\nu\beta\beta$ signal ➔ how big is the induced mass?



Dürr, ML, Merle

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

➔ cannot explain observed ν masses and splittings

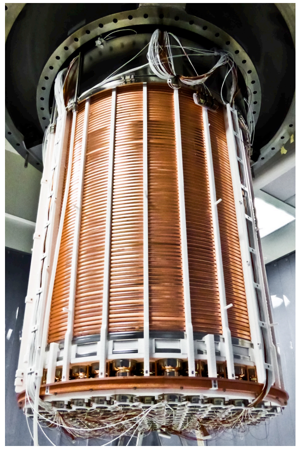
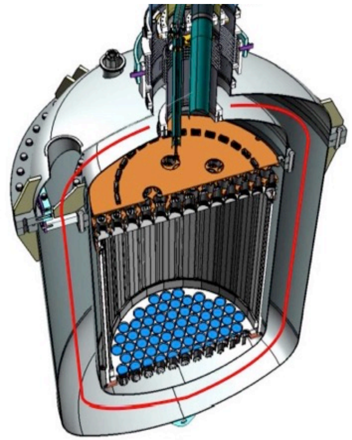
➔ explicit Dirac neutrino mass operators required

Extreme possibility:

- $0\nu\beta\beta$ = L violation = other BSM physics
- neutrino masses = Dirac (plus very tiny correction)

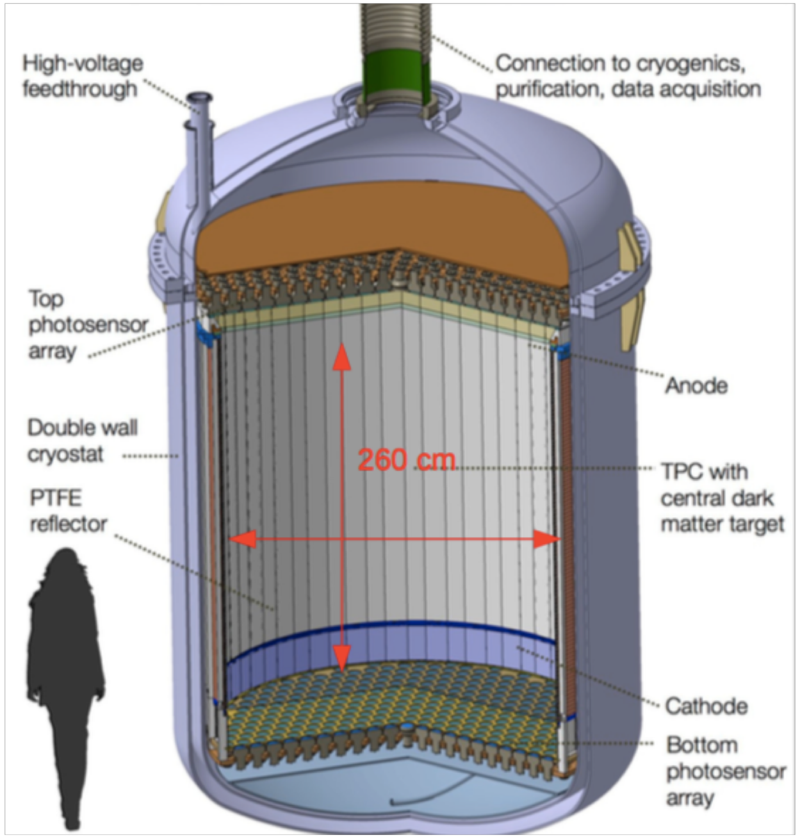
The XENON Dark Matter Program

The XENON program at Gran Sasso, Italy (3600 mwe)

	XENON10	XENON100	XENON1T	XENONnT
				
Period	**2005-2007**	**2008-2016**	**2012-2018** →	**2019-2023**
Total mass	25 kg	161 kg	3200 kg	~8000 kg
Drift length	15 cm	30 cm	100 cm	150 cm
Status	Completed (2007)	Completed (2016)	Running	Construction
σ_{SI} limit (@50 GeV/c^2)	8.8×10^{-44} cm^2	1.1×10^{-45} cm^2	1.6×10^{-47} cm^2 (2018)	1.6×10^{-48} cm^2 (2023)

XENONnT being prepared while XENON1T runs → switching gears

Beyond that: DARWIN



- **Baseline: 50t LXE**
- **40t LXe TPC, aim at 200 t*yr**
- **TPC dimension 2.6m x 2.6m**
- ~1800 * 3" PMTs (or ~1000 4" PMTs)
- Low-background cryostat
- Water Cherenkov shield (~14m diameter)
- Possible location LNGS
- aim at sensitivity of a few 10^{-49} cm^2, limited by irreducible ν-backgrounds
- R&D and initial design now
- **Timescale: after XENONnT**
- **Cost effective:**
  - use existing Xe gas; buy more & re-sell
  - no enrichment (faster & much cheaper)

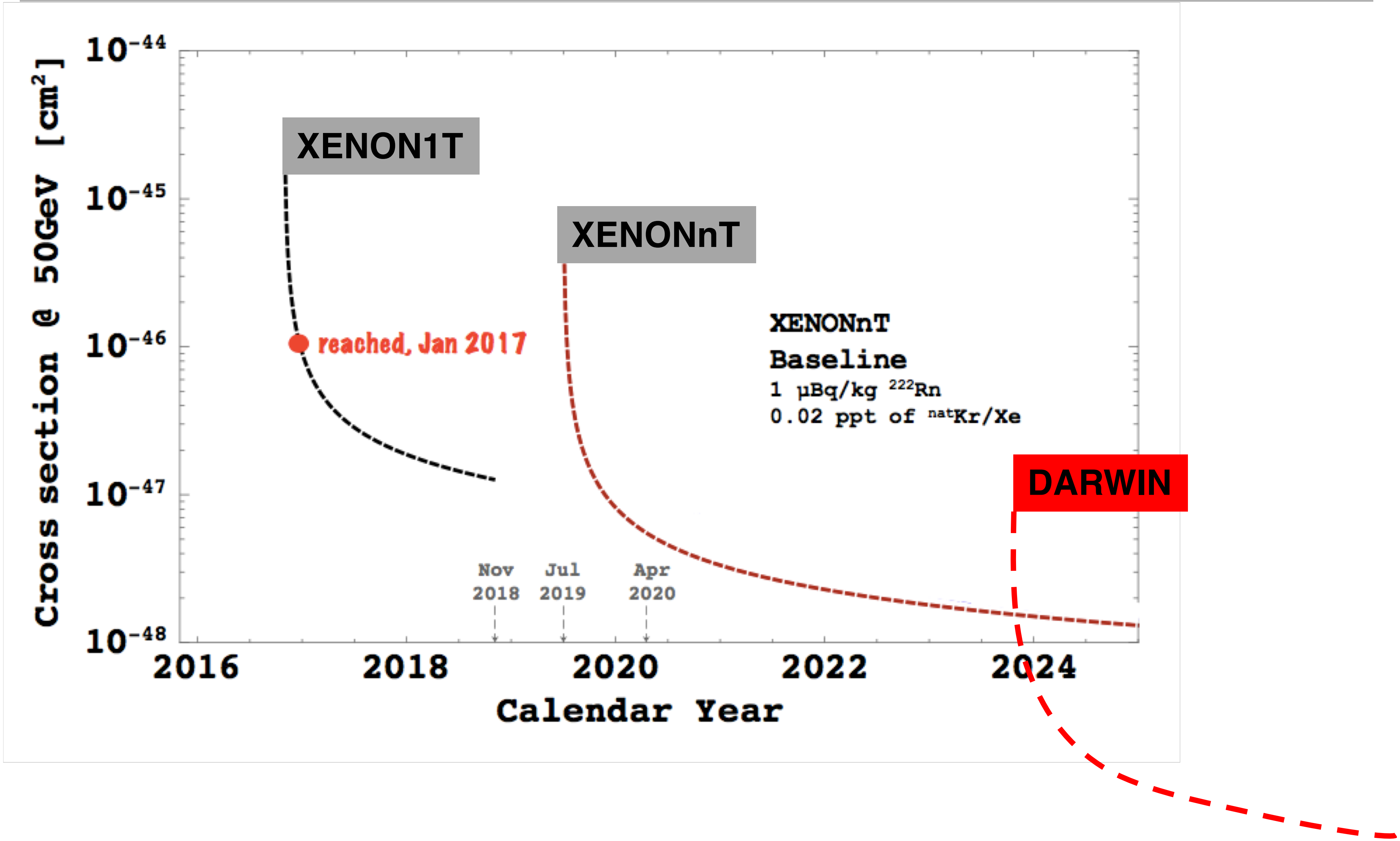
JCAP 11, 017 (2016)

www.darwin-observatory.org

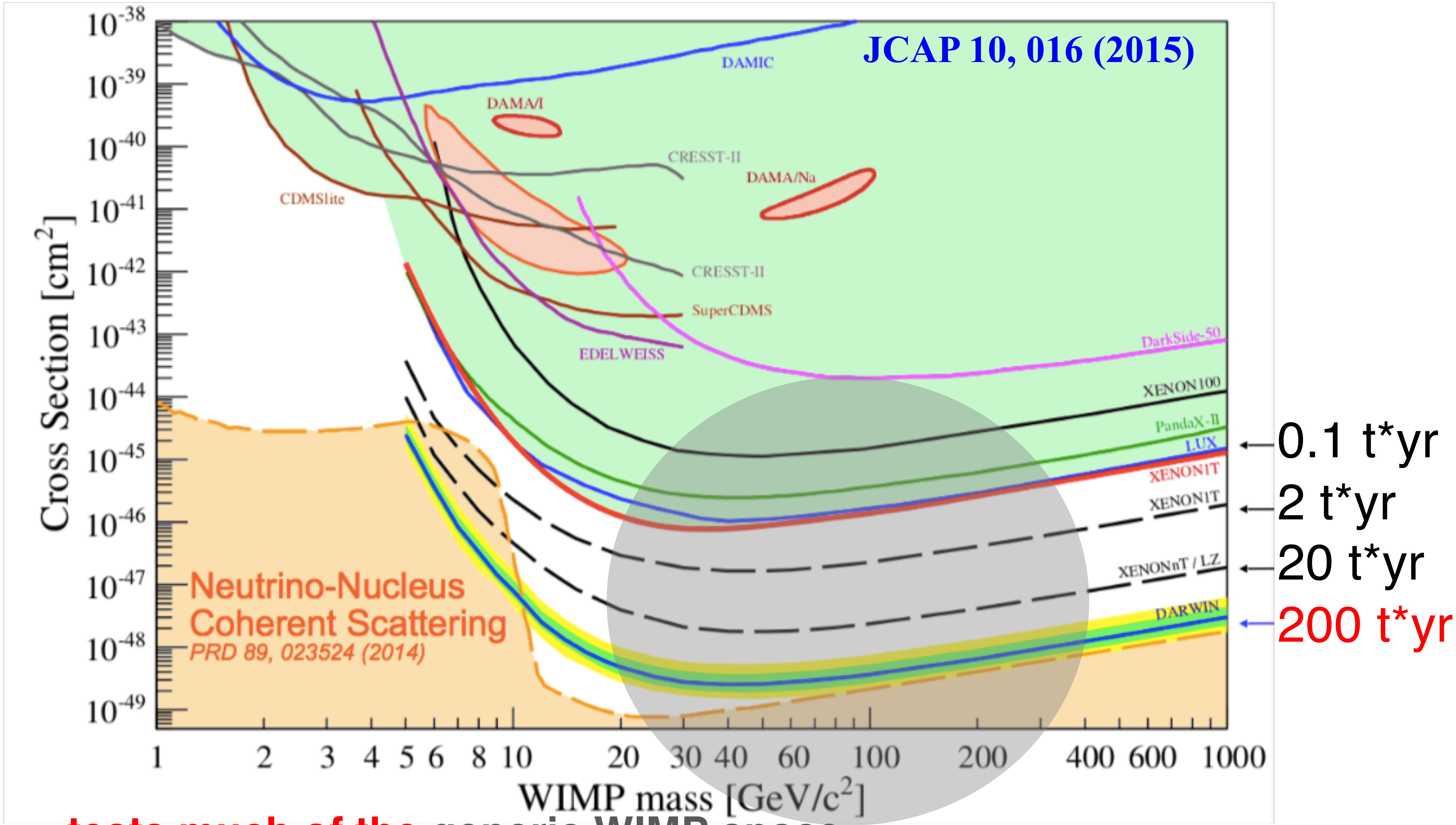
DARWIN

27 institutes from EU, US, ...

Pushing the WIMP Sensitivity



Spin Independent (SI) WIMP Interaction



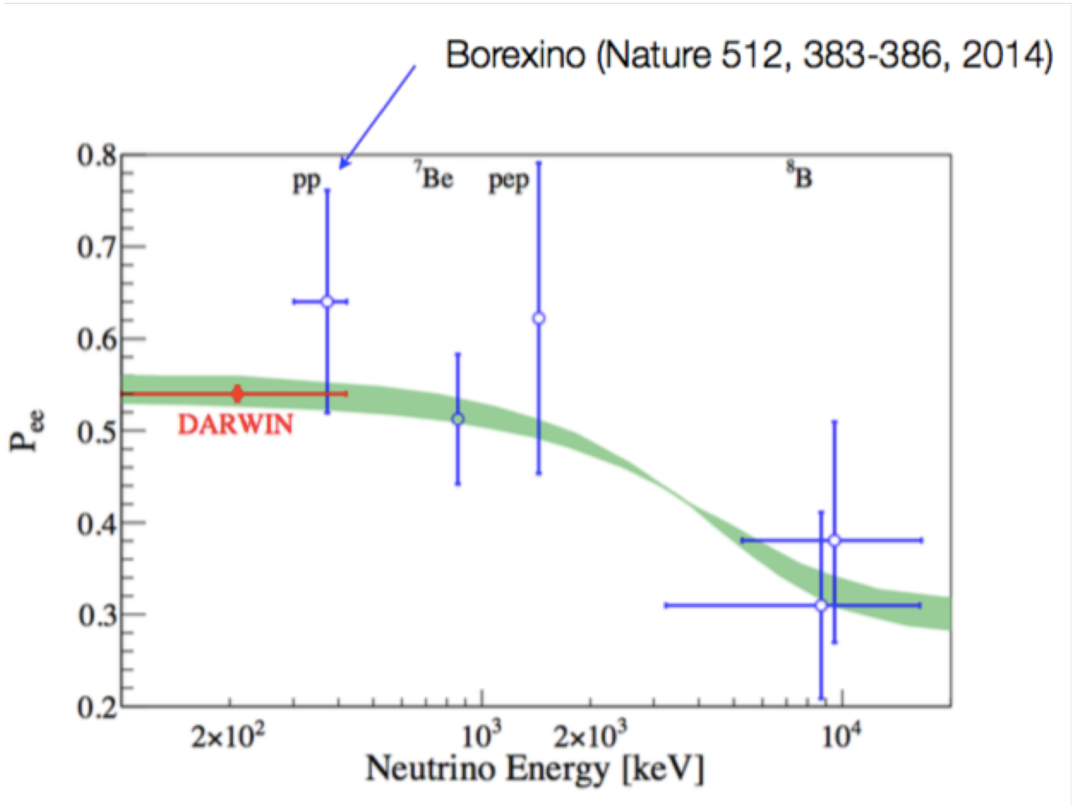
- tests much of the generic WIMP space
- a declining WIMP case w/o discovery?

➔ solar neutrino signal & CNNS with 200 t*yr

Neutrino Physics with DARWIN

➔ **Coherent Neutrino-Nucleus Scattering (CNNS)**
200 t*yr ➔ ca. 200 (25) events for > 3 (4) keV_{NR}

➔ **Low energy solar neutrino signal: pp, ^{7}Be** **JCAP 01, 044 (2014)**
~1% statistical uncertainty for 100 t*yr ➔ solar models & ν properties



real-time measurement of the solar neutrino flux:
→ 7.2 events/day from pp
→ 0.9 events/day from 7Be

➔ **Supernova neutrinos:**
→ 5σ sensitivity for a 27M⊙ SN progenitor at 10 kpc (~700 events)
→ flavor-insensitive neutrino energy measurement **Phys. Rev. D 94 (2016)**

$0\nu\beta\beta$ with ^{136}Xe

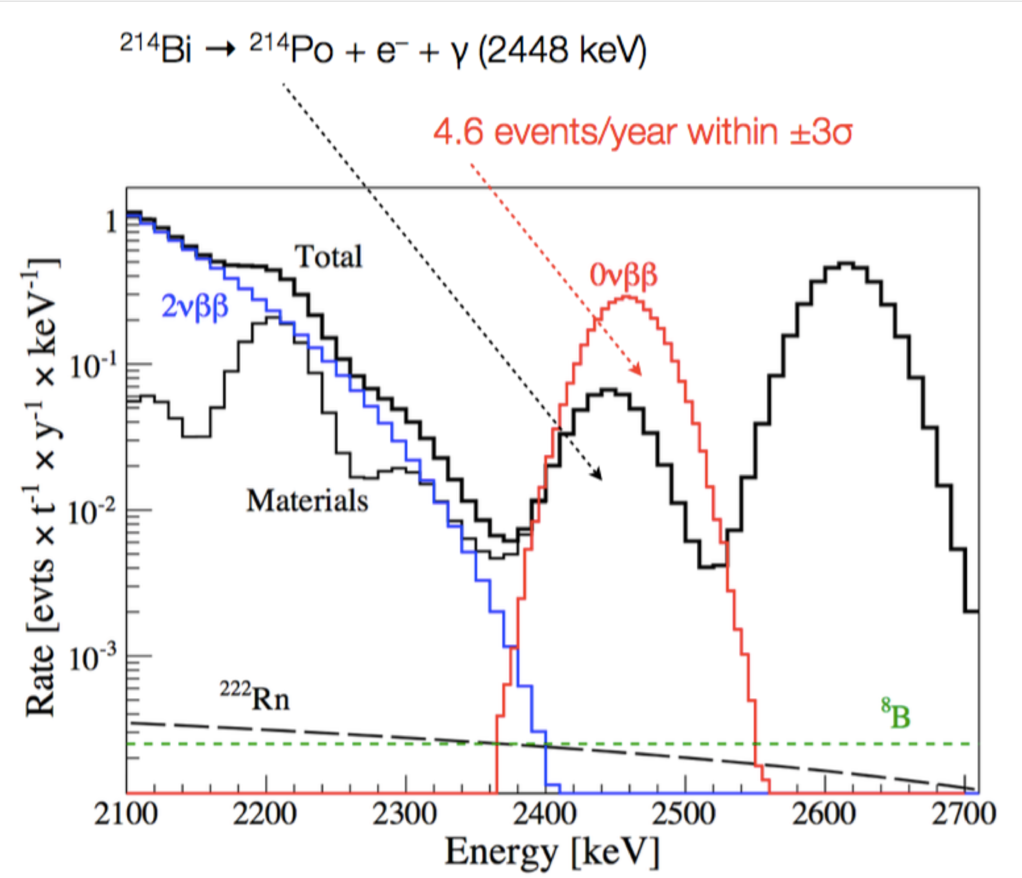
8.9% natural abundance

➔ 3.5 t ^{136}Xe in 40t without enrichment!

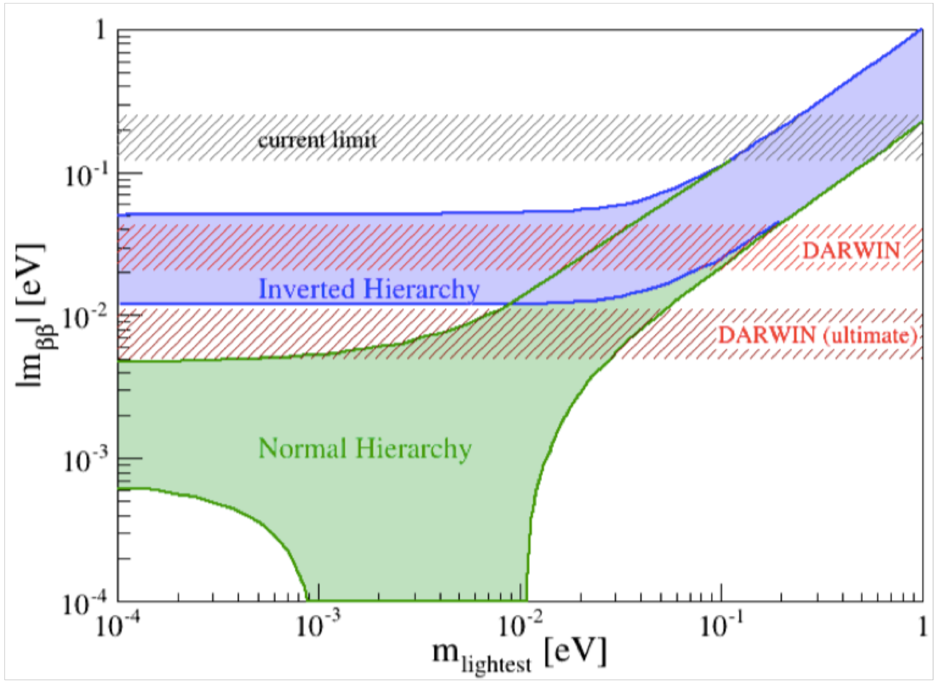
$Q_{\beta\beta}$ = (2458.7 ± 0.6) keV

Assume:

- 6t fiducial
- energy resolution at $Q_{\beta\beta} \simeq 1\%$



JCAP 01, 044 (2014)



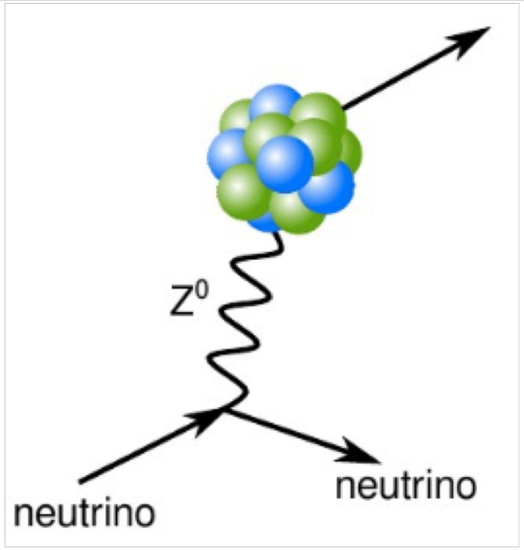
Sensitivity @ 95% CL:

· 140 t*yr → $T_{1/2} > 8.5 \times 10^{27}$ yr

IMPORTANT: **DARWIN might become a powerful, cost effective and time-wise competitive $0\nu\beta\beta$ experiment (no enrichment!)**

A new Tool: Coherent Neutrino Scattering

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



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

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

N $\simeq$ 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 ←→ maximal flux!

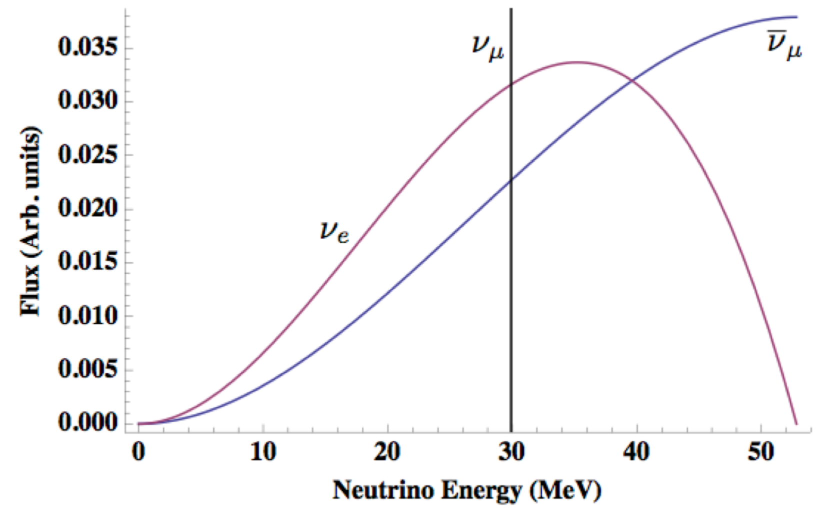
Two Paths

Low energy ν's from accelerators:

- π-decay-at-rest (DAR) ν source
- different flavors produced
- relatively high recoil energies

➔ close to de-coherence

➔ 1st observation of CEνNS by COHERENT in 2017

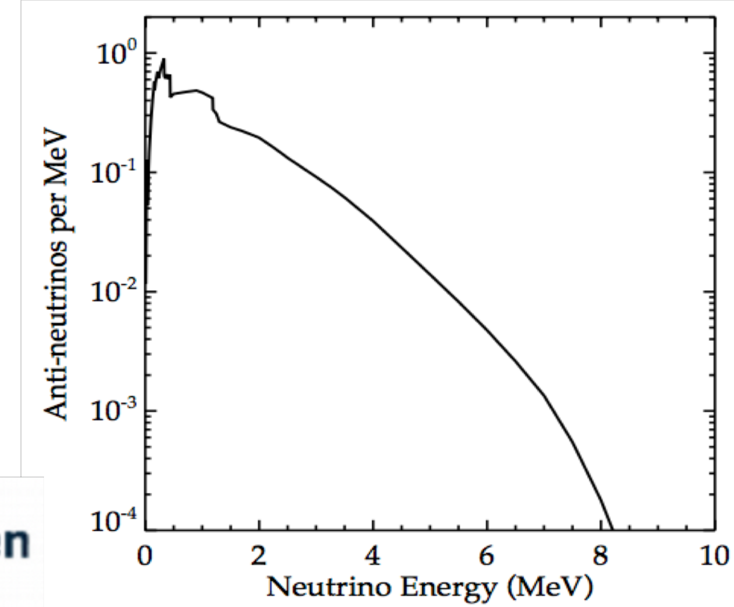


Anderson et al., 1201.3805

Reactors:

- lower ν energies than accelerators
- lower cross section – higher flux
- different flavor content implications for probes of new physics

➔ CONUS in 2018



81, Kopeikin 2012

CONUS

MAX-PLANCK-INSTITUT FÜR KERNPHYSIK HEIDELBERG

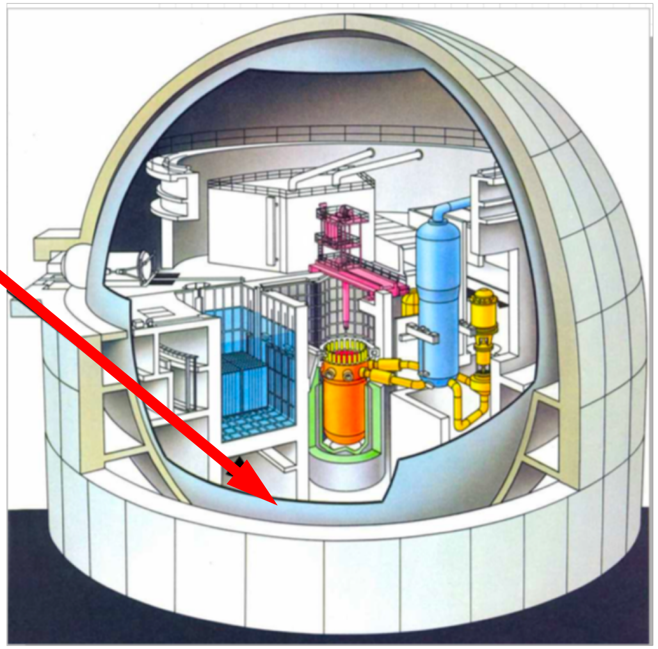
Preussen Elektra

The CONUS Experiment

Brokdorf (Germany) nuclear power plant:

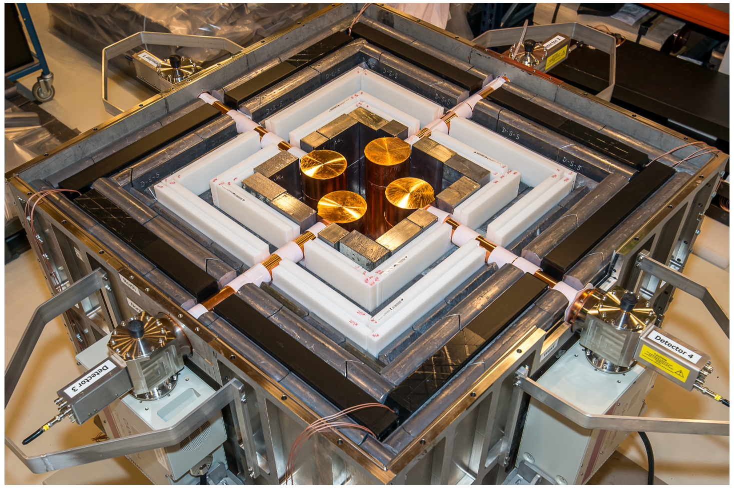
thermal power 3.9 GW_{th} detector @ d=17m

➔ ν flux: 2.4 x $10^{13}/cm^2/s$; very high duty cycle
access during reactor operation



➔ extreme neutrino flux
E_ν up to ~ 8 MeV → fully coherent

- overburden 45 m.w.e
- active shielding ("virtual depth")
- 4x 1kg ultra low threshold Ge-detectors
- electro-cooling with PTR's
- reactor ON/OFF measurements



← about 1m →

NEUTRINO 2018 in June:

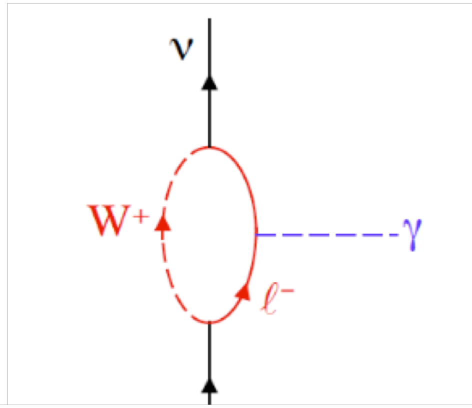
➔ 2.4σ after only one month of data taking

➔ meanwhile 5 months ➔ to appear soon

➔ various plans for next generation experiments

100kg Upscaling: ν Magnetic Moments

Magnetic moment for minimal ν masses are very tiny:



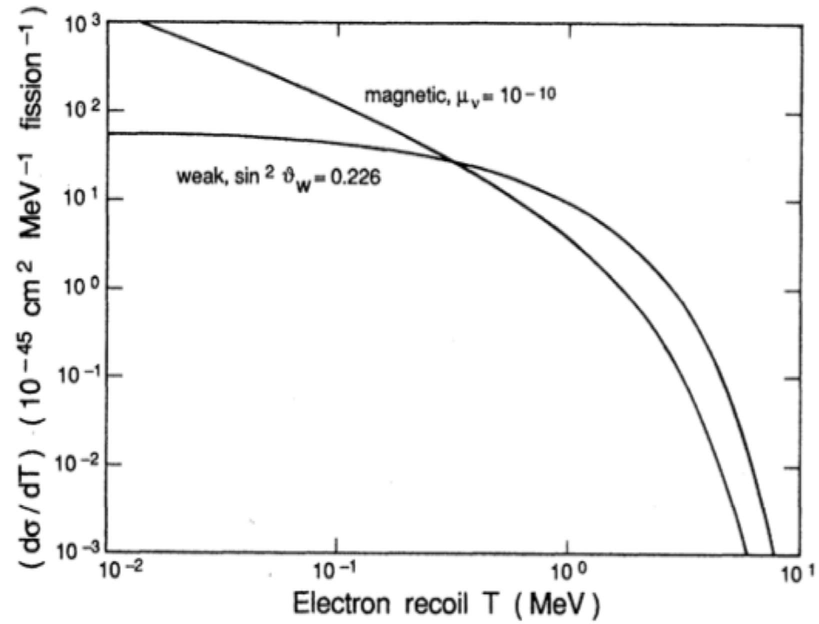
Dirac: $$\mu^D_{kk} \simeq 3.2 * 10^{-19} \left(\frac{m_k}{\mathrm{eV}}\right) \mu_B$$

Majorana: $$\mu^M_{ll'} \lesssim 4 * 10^{-9} \mu_B \left(\frac{M^M_{ll'}}{\mathrm{eV}}\right) \left(\frac{\mathrm{TeV}}{\Lambda}\right)^2 \left|\frac{m_\tau^2}{m_l^2 - m_{l'}^2}\right|$$

➔ **detectable enhancements via new physics:** **SUSY, extra dimensions, …**

Best limits so far:
e-scattering (GEMMA) and astrophysics:

$$\mu_\nu < 3 \times 10^{-11} \mu_b$$



Scattering on protons coherently enhanced:

➔ **detectable at low E (Vogel & Engel 1989)**

➔ **100kg *5y = 500 kg-year + low threshold**

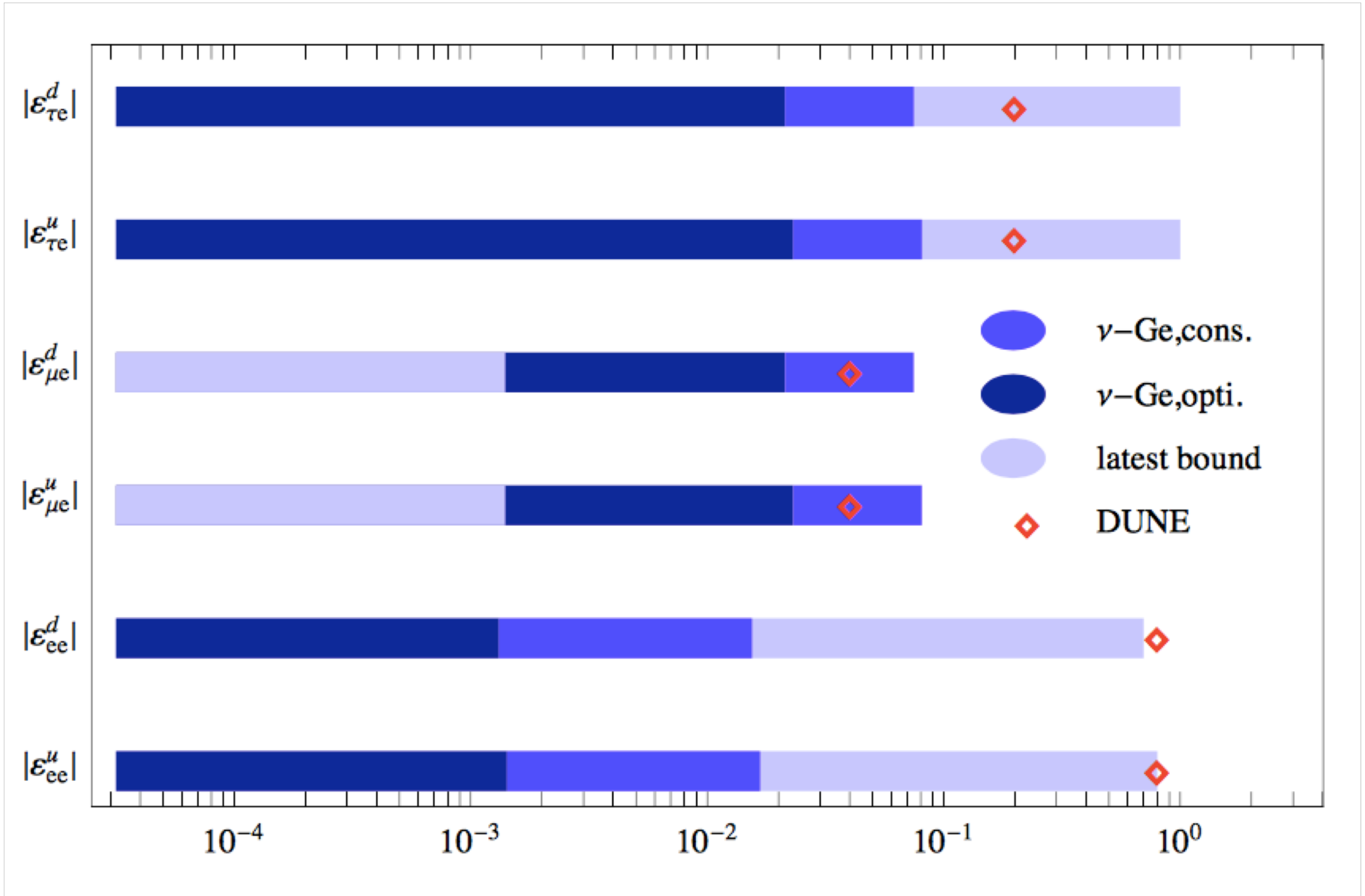
➔ **at least an order of magnitude improvement**

$$\left.\frac{d\sigma}{dT_{\mathrm{R}}}\right|_{\mu_\nu} = \frac{\pi\alpha^2\mu_\nu^2}{m_e^2}\left[\frac{1 - T_{\mathrm{R}}/E_\nu}{T_{\mathrm{R}}} + \frac{T_{\mathrm{R}}}{4E_\nu^2}\right]$$

NSI-Potential of O(100kg) Detector

100kg detector, 5 years operation @ 4GW

ML, W. Rodejohann, X.Xu



~10 TeV **~TeV**

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

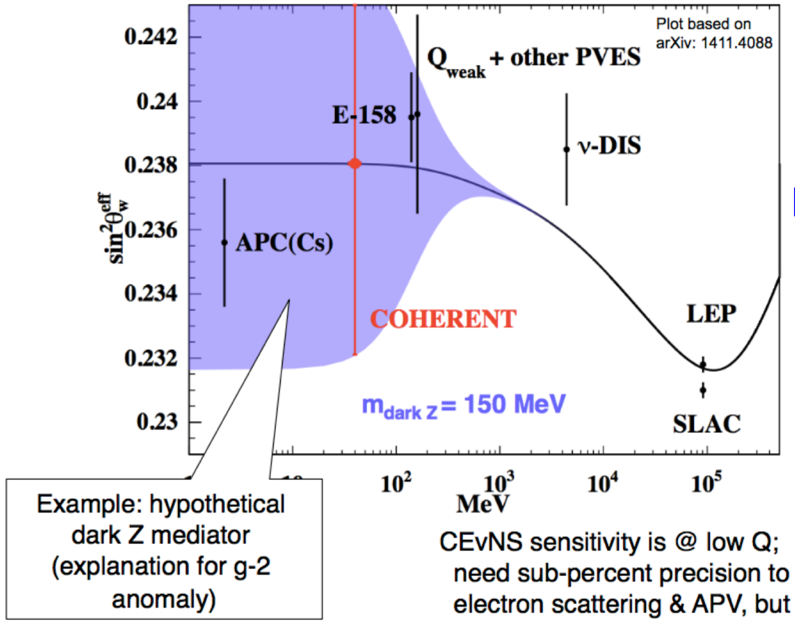
Clean SM prediction for the rate ➔ measure $\sin^2\theta_W$eff ; **deviation probes new physics**

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

BSM sensitivity ←→ precision

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**

K. Scholberg

Other topics:

- Explore coherent scattering ←→direct DM experiments
- Sterile neutrino searches (if still alive…)
- Nuclear form factors in neutrino light
- Nuclear safe-guarding
- …

Summary

- Neutrino physics **was, is and will remain a hot field**
- Many **important insights** into
  - sources
  - fundamental interactions
- **3 neutrino flavours ➔ precision area**
  - reactor neutrinos
  - neutrino beams (NOνA, T2K, T2HK, DUNE, ...)

  ➔ origin of fermion masses? How precise can we get and is that enough?
- **More than 3 neutrinos**
  - Majorana masses, L-violation, sterile ν's, NSIs, large mag. moments, direct dark matter searches, proton decay, n-$\underline{n}$ oscillations, ...

  ➔ **any one of them would be a major discovery**
- New: **Coherent neutrino scattering, a new & fast moving direction**
- **Road maps: Many paths with unknowns ➔ a good mix of vehicles**