Cosmological constraints on new physics in $0\nu\beta\beta$

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https://xunjiexu.github.io/

珠海 2023.05.21 https://indico.ihep.ac.cn/event/18834

Neutrinoless double beta decay ($0\nu\beta\beta$): What is it?

- Beta decay:

$$n \rightarrow p + e^- + \overline{\nu_e}$$

$$(A, Z) \rightarrow (A, Z + 1) + e^- + \overline{\nu_e}$$

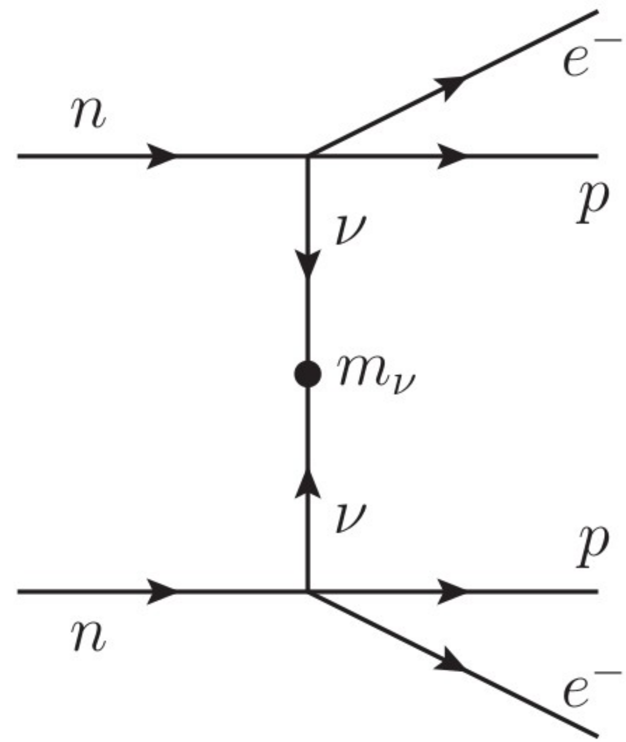
- Double beta decay:

$$(A, Z) \rightarrow (A, Z + 2) + 2e^- + 2\overline{\nu_e}$$

- Neutrinoless double beta decay:

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

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



... the most promising experimental approach to probe $\nu \in$ M/D

Experimental status

1902.04097

Isotope	$T^{0\nu}_{1/2}$ ($\times 10^{25}$ y)	$\langle m_{\beta\beta} \rangle$ (eV)	Experiment
^{48}Ca	$> 5.8 \times 10^{-3}$	$< 3.5 - 22$	ELEGANT-IV
^{76}Ge	> 8.0	$< 0.12 - 0.26$	GERDA
	> 1.9	$< 0.24 - 0.52$	MAJORANA
^{82}Se	$> 3.6 \times 10^{-2}$	$< 0.89 - 2.43$	NEMO-3
^{96}Zr	$> 9.2 \times 10^{-4}$	$< 7.2 - 19.5$	NEMO-3
^{100}Mo	$> 1.1 \times 10^{-1}$	$< 0.33 - 0.62$	NEMO-3
^{116}Cd	$> 1.0 \times 10^{-2}$	$< 1.4 - 2.5$	NEMO-3
^{128}Te	$> 1.1 \times 10^{-2}$	—	—
^{130}Te	> 1.5	$< 0.11 - 0.52$	CUORE
^{136}Xe	> 10.7	$< 0.061 - 0.165$	KamLAND-
	> 1.8	$< 0.15 - 0.40$	EXO-200
^{150}Nd	$> 2.0 \times 10^{-3}$	$< 1.6 - 5.3$	NEMO-3

2002.07182

	SuperNEMO	–		10	
^{96}Zr	NEMO–3	9.2×10^{-4}	[3]		
^{100}Mo	NEMO–3	1.1×10^{-1}	[8]		
	CUPID–1T	–		9.2×10^2	
	AMoRE	9.5×10^{-3}	[26]	5.0×10	
^{116}Cd	NEMO–3	[illegible] $\times 10^{-2}$	[13]		
^{128}Te	–	1.1×10^{-2}	[1]	–	
^{130}Te	CUORE	3.2	[21]	9.0	
	SNO+	–		1.0×10^2	
^{136}Xe	KamLAND-Zen	10.7	[10]	2.0×10^2	
	EXO–200	3.5	[27]	10^3	[34]
	NEXT	–		2.0×10^2	[35]
	PandaX	–		1.0×10^2	[36]
^{150}Nd	NEMO–3	2.0×10^{-3}	[12]		

1705.02996

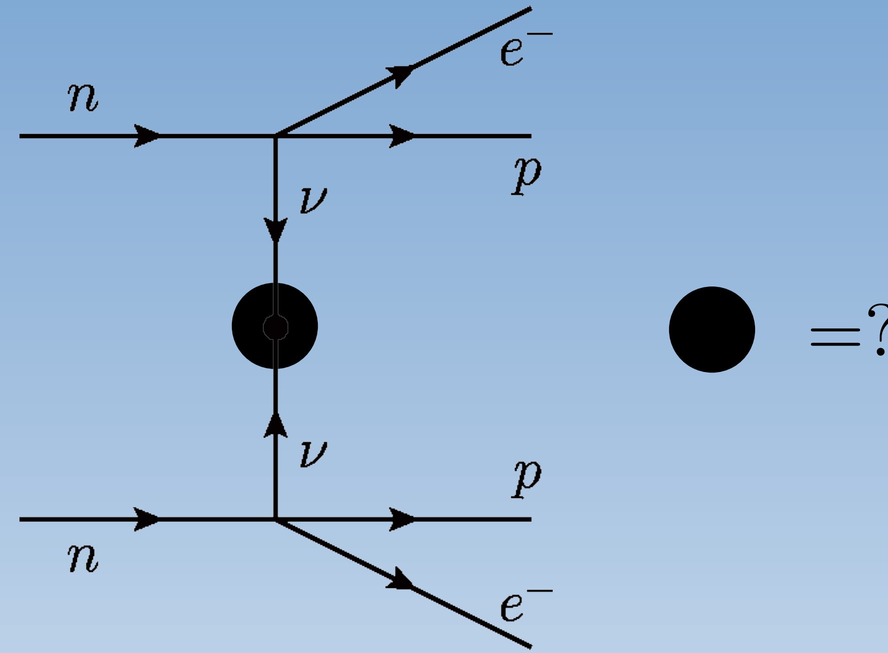
Experiment	Iso.	Iso. Mass [kg$_{iso}$]	3σ disc. sens. $\hat{T}_{1/2}$ [yr]	$\hat{m}_{\beta\beta}$ [meV]
LEGEND 200 [62, 63]	^{76}Ge	175	$8.4 \cdot 10^{26}$	40–73
LEGEND 1k [62, 63]	^{76}Ge	873	$4.5 \cdot 10^{27}$	17–31
SuperNEMO [69, 70]	^{82}Se	100	$6.1 \cdot 10^{25}$	82–138
CUPID [59, 60, 71]	^{82}Se	336	$1.8 \cdot 10^{27}$	15–25
CUORE [53, 54]	^{130}Te	206	$5.4 \cdot 10^{25}$	66–164
CUPID [59, 60, 71]	^{130}Te	543	$2.1 \cdot 10^{27}$	11–26
SNO+ Phase I [67, 72]	^{130}Te	[illegible]	$1.1 \cdot 10^{26}$	46–115
SNO+ Phase II [68]	^{130}Te	7960	$4.8 \cdot 10^{26}$	22–54
KamLAND-Zen 800 [61]	^{136}Xe	750	$1.6 \cdot 10^{26}$	47–108
KamLAND2-Zen [61]	^{136}Xe	1000	$8.0 \cdot 10^{26}$	21–49
nEXO [73]	^{136}Xe	4507	$4.1 \cdot 10^{27}$	9–22
NEXT 100 [65, 74]	^{136}Xe	91	$5.3 \cdot 10^{25}$	82–189
NEXT 1.5k [75]	^{136}Xe	1367	$7.9 \cdot 10^{26}$	21–49
PandaX-III 200 [66]	^{136}Xe	180	$8.3 \cdot 10^{25}$	65–150
PandaX-III 1k [66]	^{136}Xe	901	$9.0 \cdot 10^{26}$	20–46

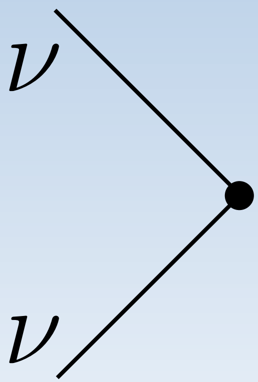
… substantially improved sensitivity

Future ...

... can we see signals from

- nonzero $m_{\beta\beta}$?
- more new physics?

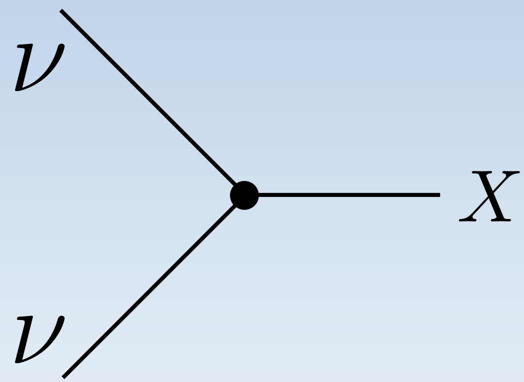




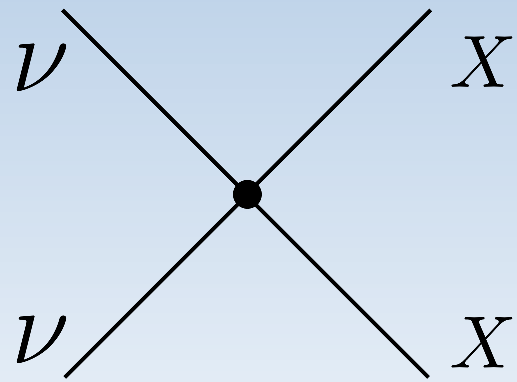
just mass? ... No!

e.g. $m_D^2/(\not{p} - m_R) \neq m_\nu$

ν self-energy $\neq$ mass†



Majoron emission†



Dirac neutrinos

Dark matter

ν self-int.

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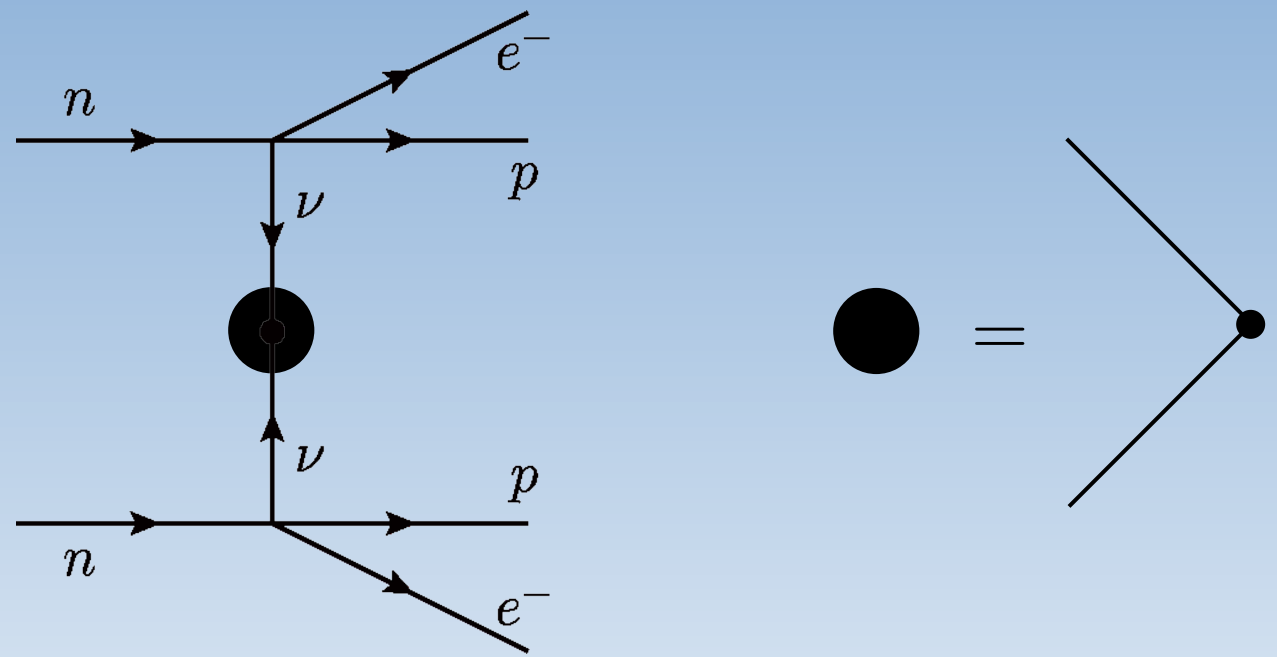
† see e.g. 1907.12478, 1811.00031, 1808.08158, ...

Cosmological constraints



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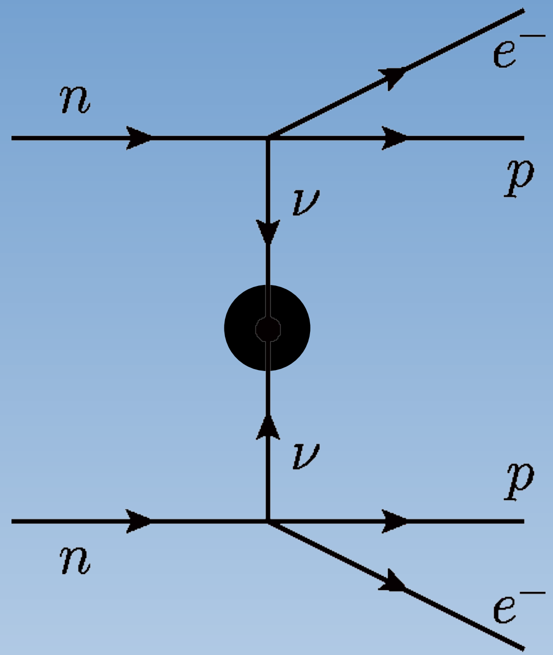
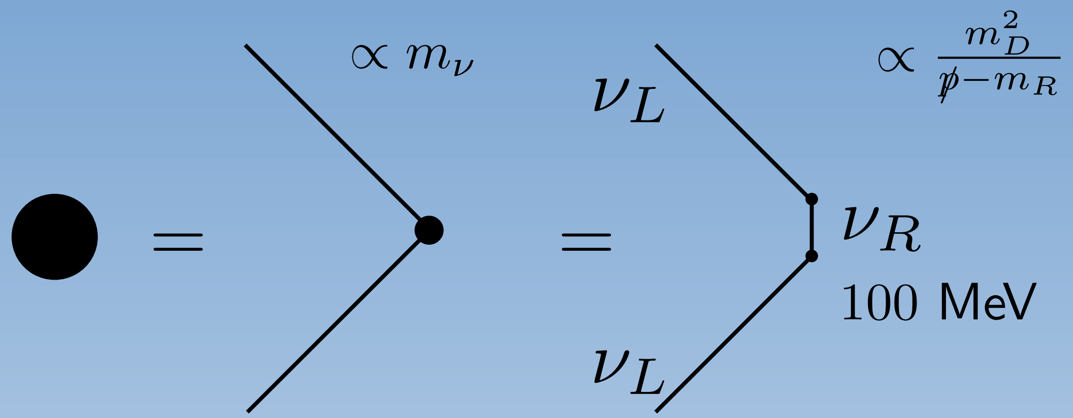


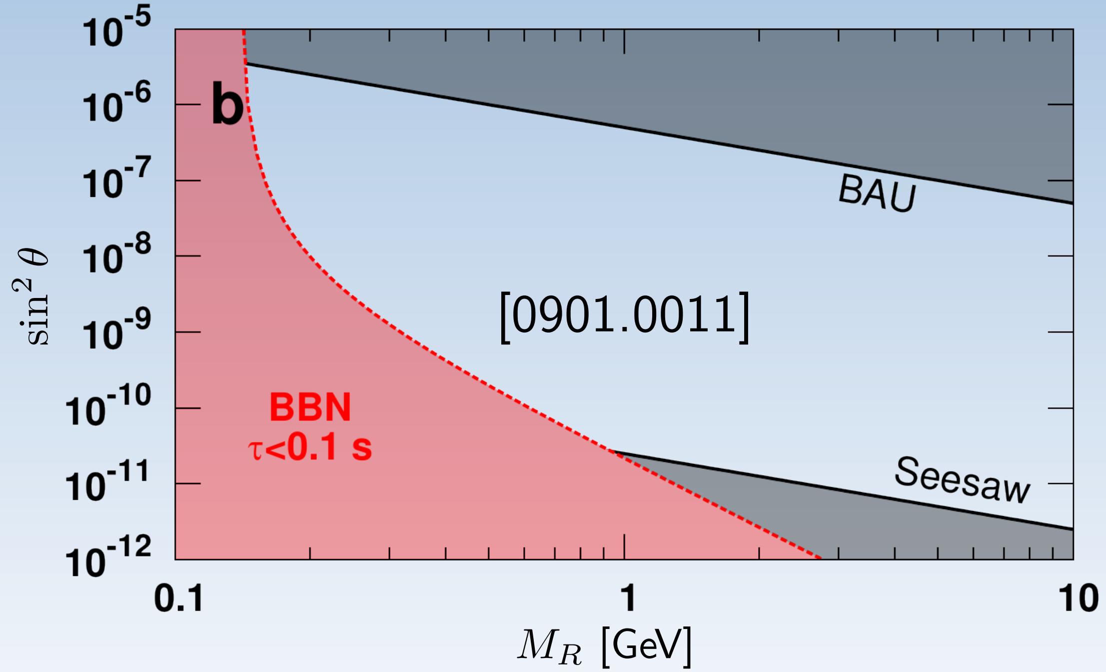


see Yufeng Li's talk

Strong bounds from BBN:

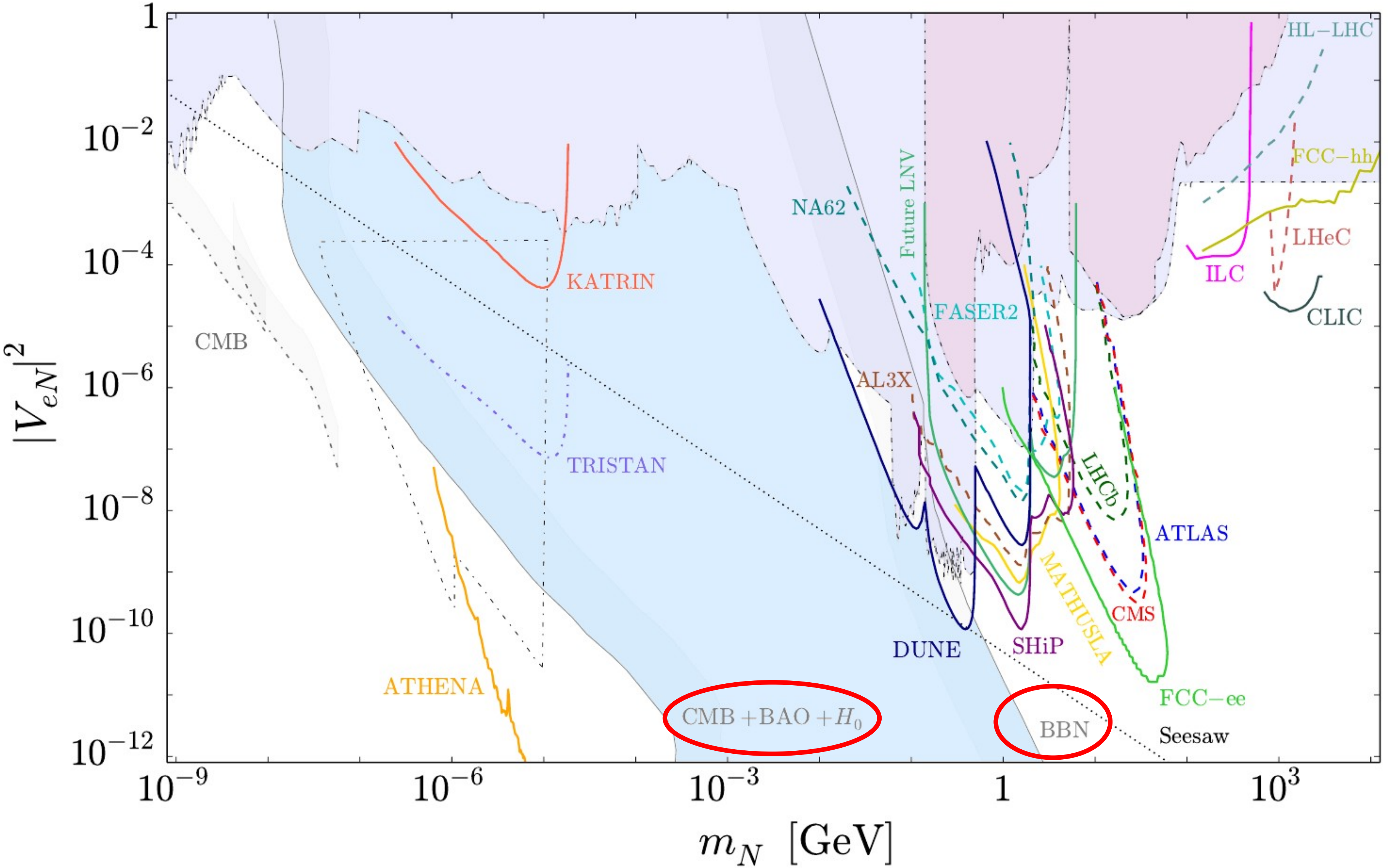
- High-T, $\nu_L \to \nu_R$
  - via osc.
- Low-T, ν_R decay
  - lifetime too long

… even seesaw excluded!

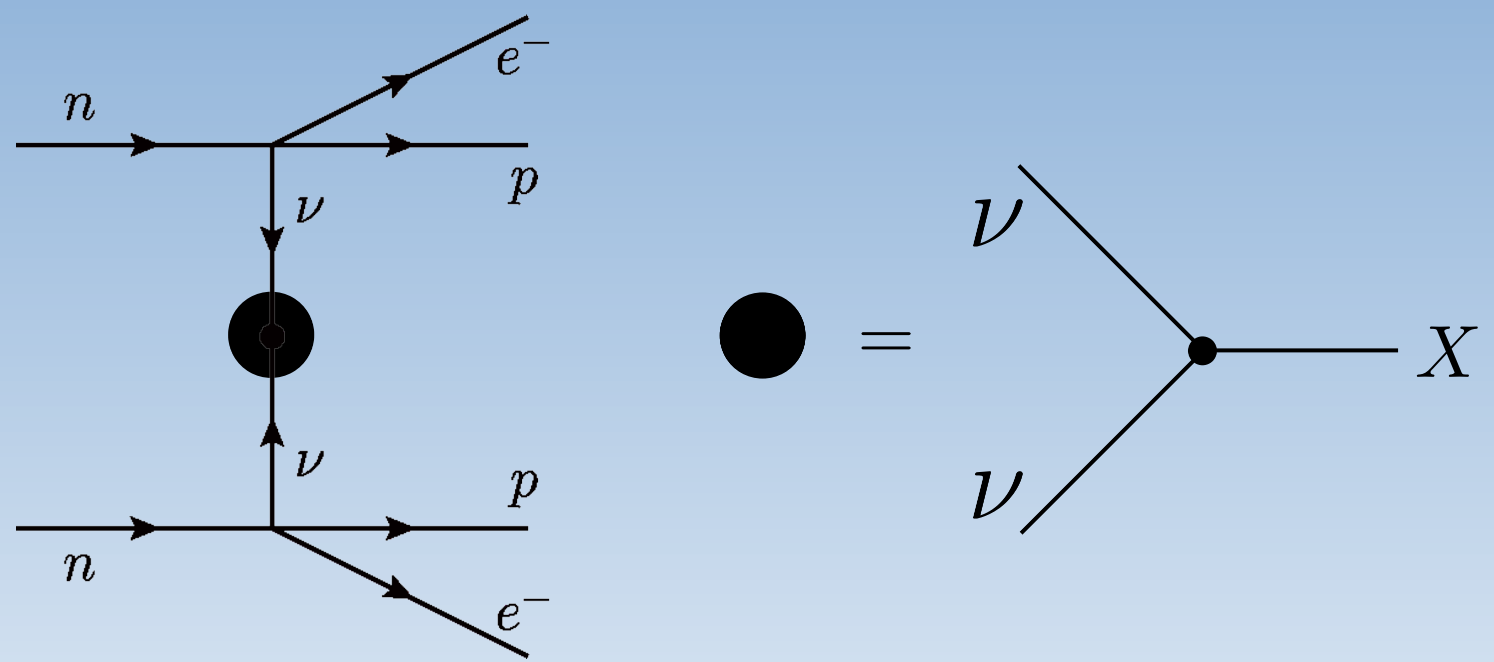


Boyarsky, Ruchayskiy, Shaposhnikov

How strong are cosmological bounds on massive ν_R?



Bolton, Deppisch, et al 1912.03058



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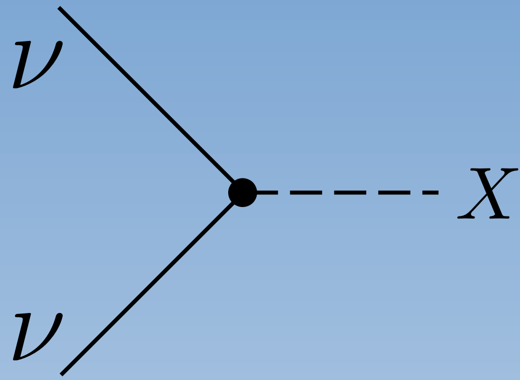
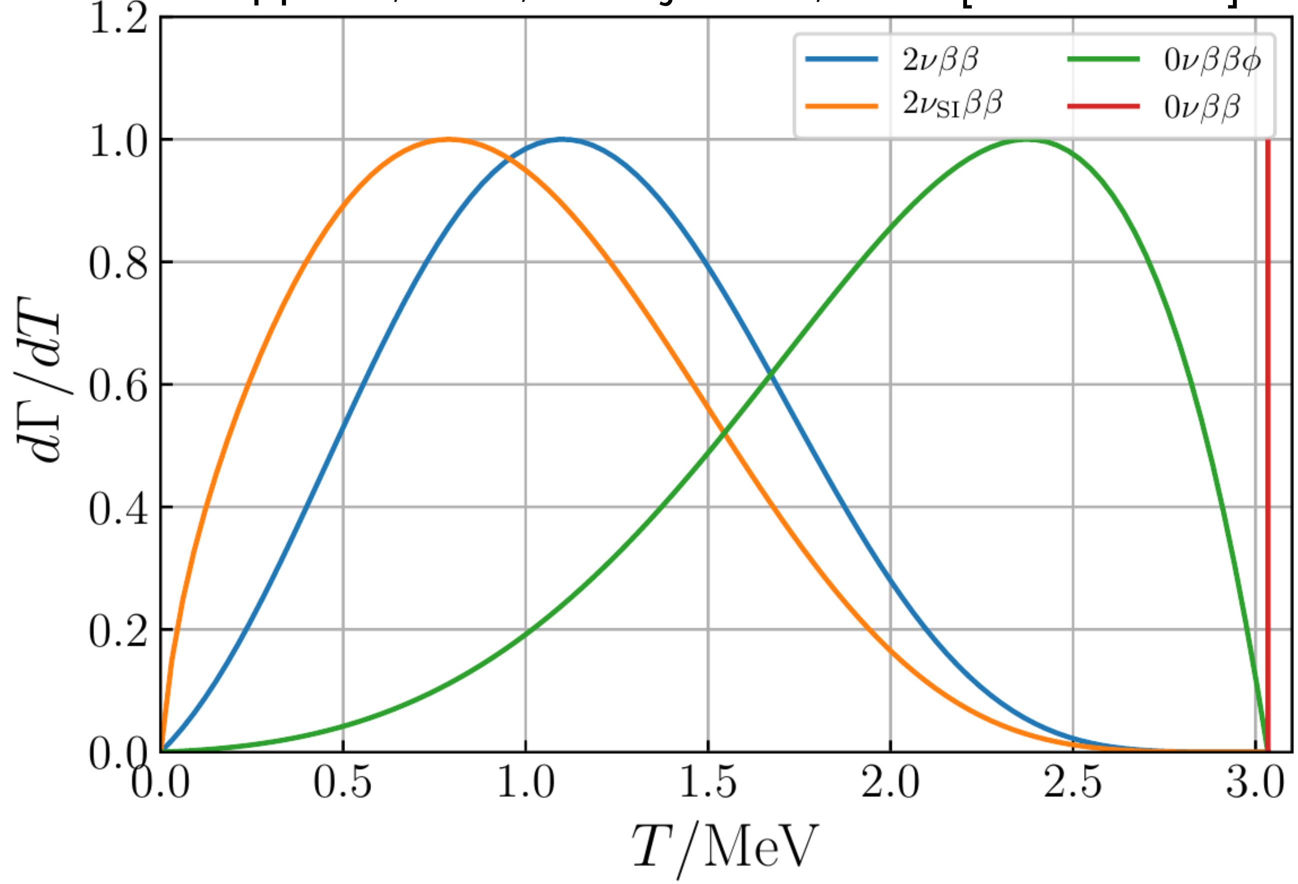
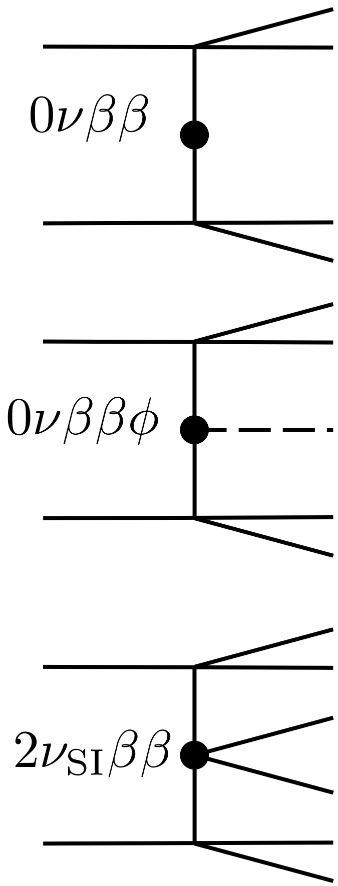
X

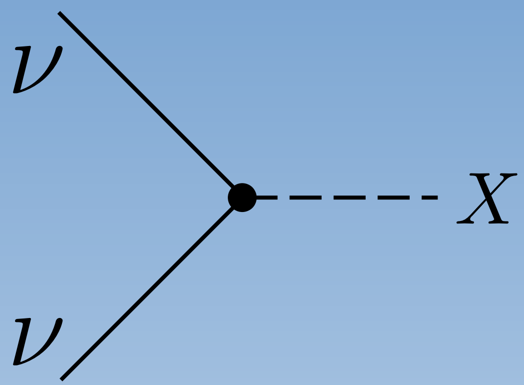


X has to be a boson. Usually it is a LNV scalar, known as the *Majoron*

Deppisch, Graf, Rodejohann, XJX [2004.11919]







First searched by KamLAND-Zen

KamLAND-Zen Result:

$$y < (0.8 - 1.6) \times 10^{-5}$$

RAPID COMMUNICATIONS

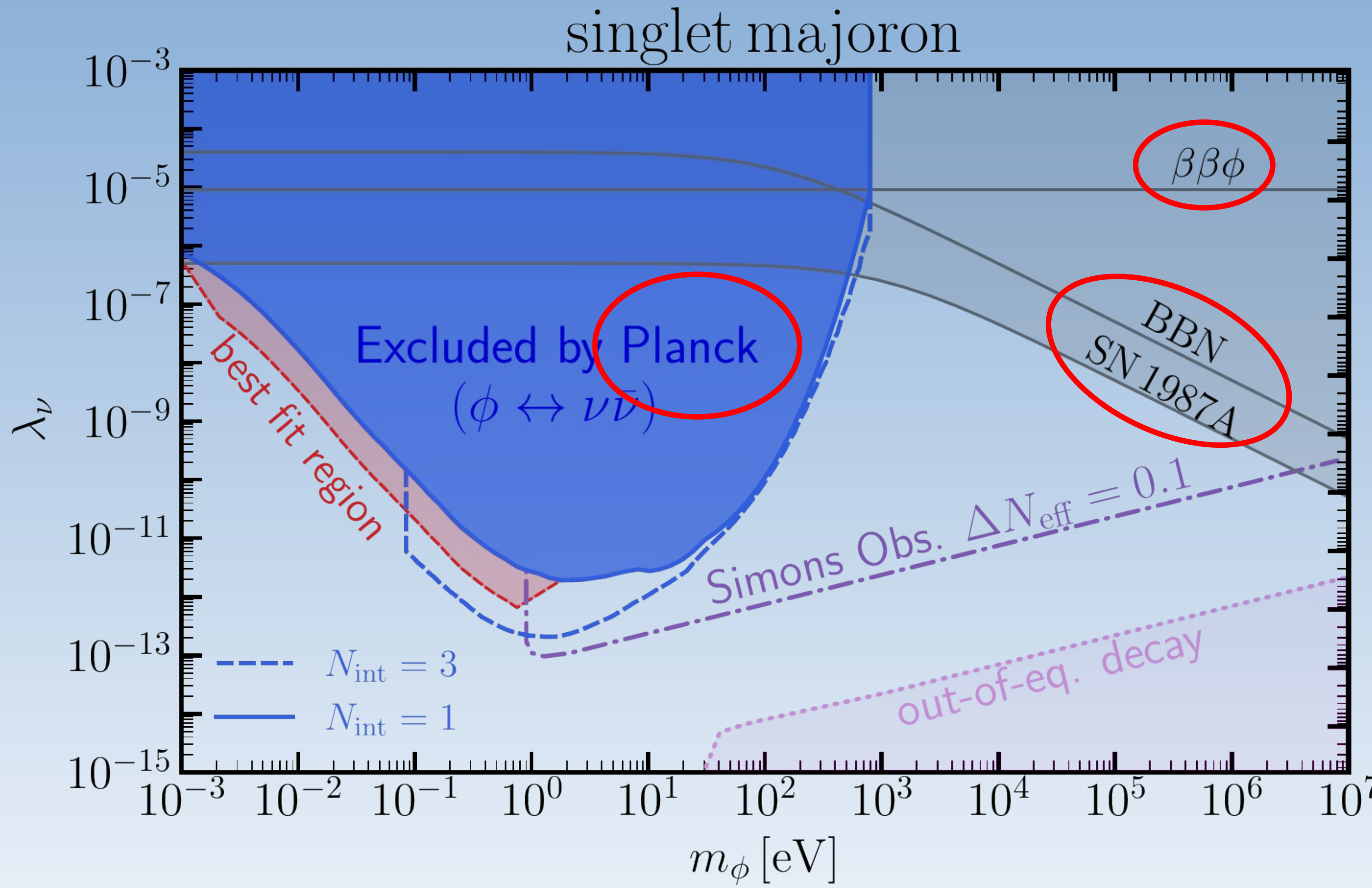
PHYSICAL REVIEW C **86**, 021601(R) (2012)

Limits on Majoron-emitting double-β decays of ^{136}Xe in the KamLAND-Zen experiment

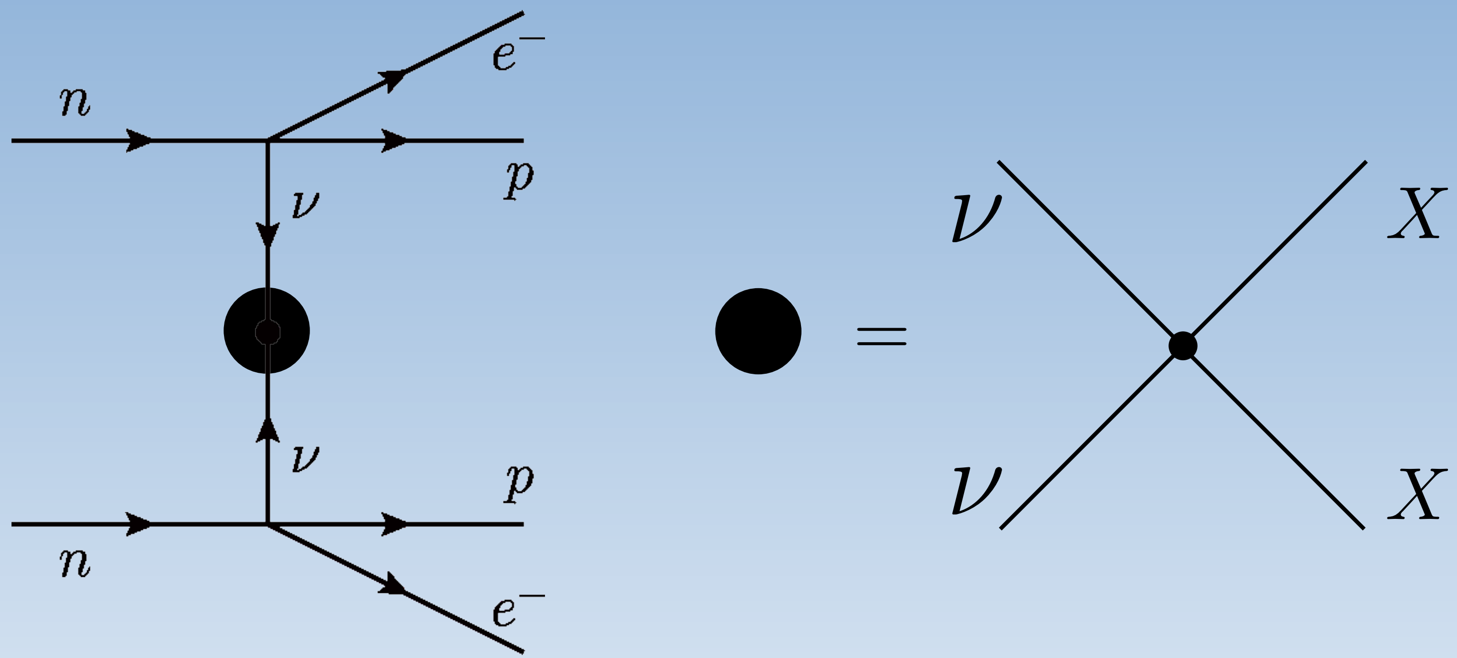
A. Gando,[1] Y. Gando,[1] H. Hanakago,[1] H. Ikeda,[1] K. Inoue,[1,2] R. Kato,[1] M. Koga,[1,2] S. Matsuda,[1] T. Mitsui,[1] T. Nakada,[1] K. Nakamura,[1,2] A. Obata,[1] A. Oki,[1] Y. Ono,[1] I. Shimizu,[1] J. Shirai,[1] A. Suzuki,[1] Y. Takemoto,[1] K. Tamae,[1] K. Ueshima,[1] H. Watanabe,[1] B. D. Xu,[1] S. Yamada,[1] H. Yoshida,[1] A. Kozlov,[2] S. Yoshida,[3] T. I. Banks,[4] J. A. Detwiler,[4] S. J. Freedman,[2,4] B. K. Fujikawa,[2,4] K. Han,[4] T. O'Donnell,[4] B. E. Berger,[5] Y. Efremenko,[2,6] H. J. Karwowski,[7] D. M. Markoff,[7] W. Tornow,[7] S. Enomoto,[2,8] and M. P. Decowski[2,9]
(KamLAND-Zen Collaboration)

Other $0\nu\beta\beta$ exp. also searched for this:

- CUPID-0[2209.09490], GERDA [2209.01671], EXO-200 [1409.6829], ...
- Results: $\sim$ the same order of magnitude



Sandner, Escudero, Witte [2305.01692]



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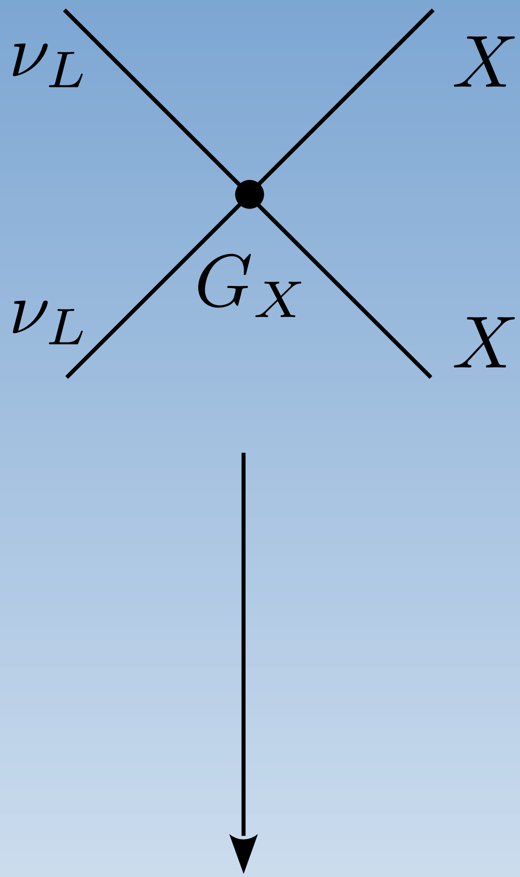
$=$
ν
X
ν
X

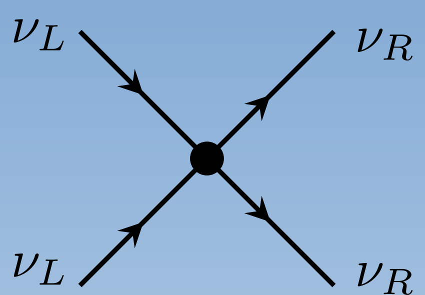


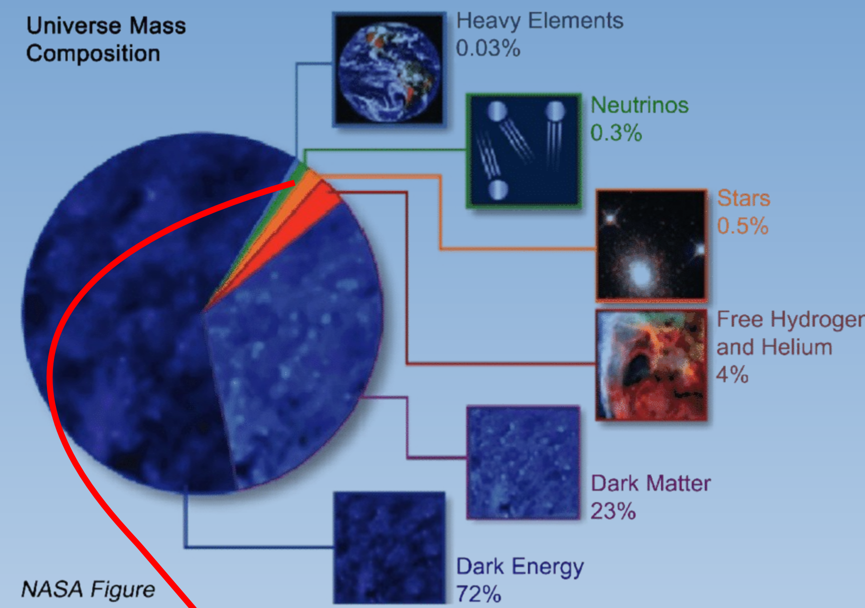
X could be:

- ν_R (Dirac neutrinos)
- DM
- ν_L (ν self-int.)

A very generic question: How large is G_X?

Let's start with Dirac neutrinos ...





- Dirac neutrinos $\Rightarrow$ (almost) massless $\nu_R \Rightarrow$ change $N_{\rm eff}$
- If in equilibrium, each ν_L or $\nu_R \rightarrow N_{\rm eff} + 1$
- SM predicts $N_{\rm eff} \approx 3$

SM prediction[†]

$$N_{\rm eff} = 3.0440 \pm 0.0002$$

Planck 2018

$$N_{\rm eff} = 2.99 \pm 0.17$$

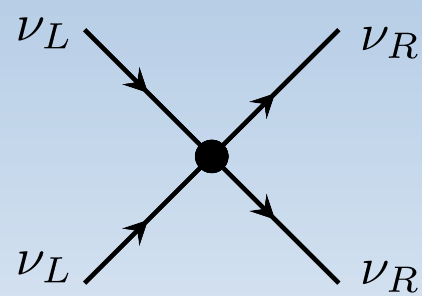
- ... so light ν_R interacting with SM would be severely constrained.

† Yvonne Y. Y. Wong *et al* [2012.02726]

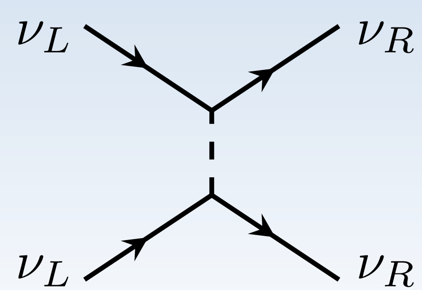
... depends on whether ν_R thermalizes or not

- Contact interaction always $\rightarrow$ ν_R thermalizes $\rightarrow$ freeze-out
- Non-contact interactions $\rightarrow$ could be freeze-in

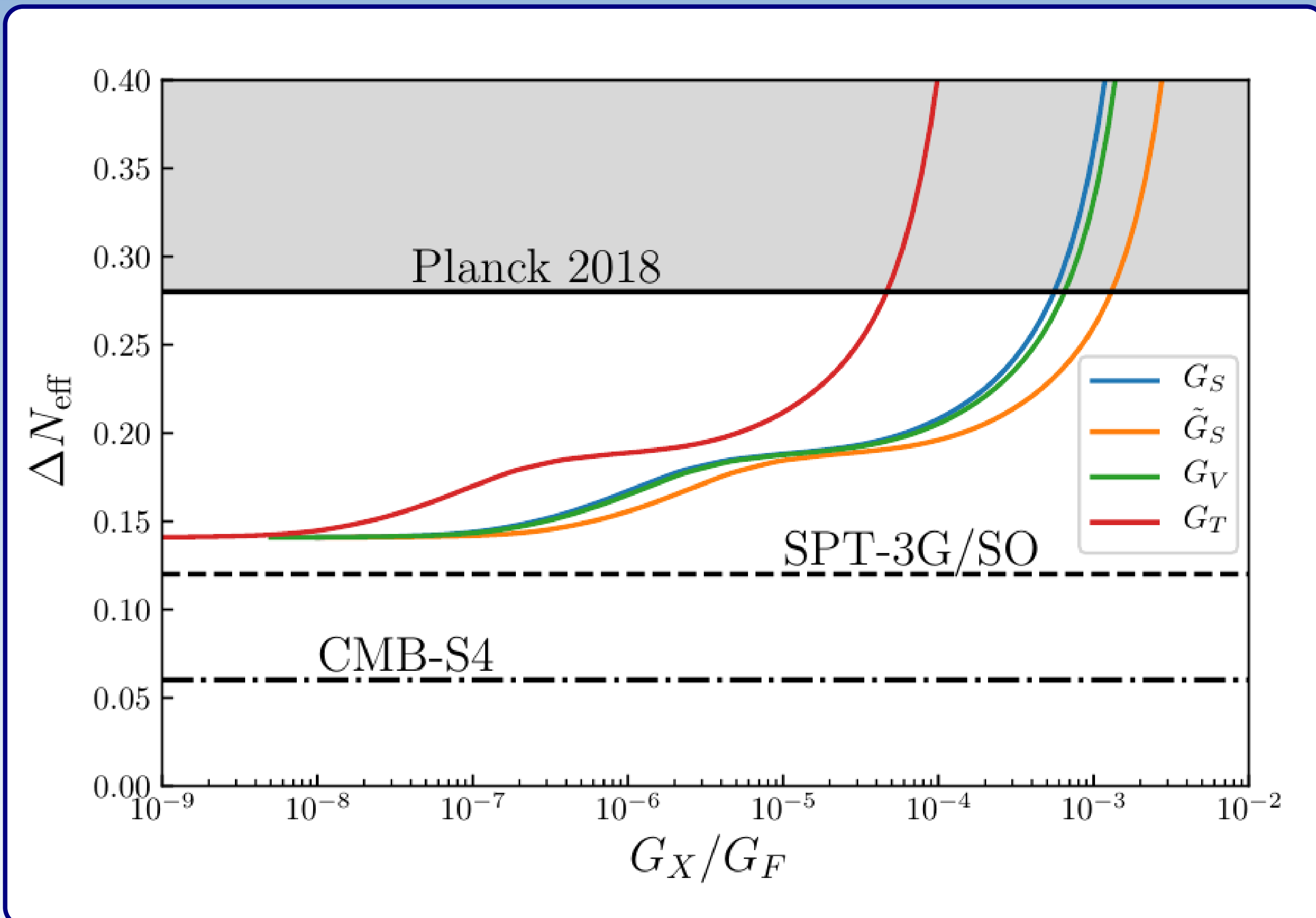
Dirac neutrinos and $N_{\rm eff}$
X. Luo, W. Rodejohann, X. Xu, JCAP, 2005.01629

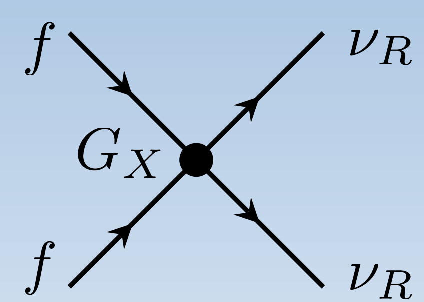


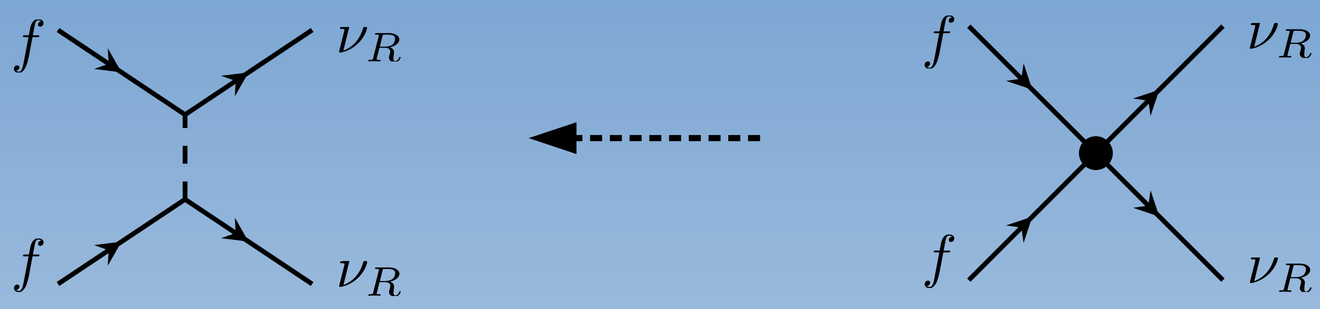
Dirac neutrinos and $N_{\rm eff}$: Part II. The freeze-in case
X. Luo, W. Rodejohann, X. Xu, JCAP, 2011.13059



Current: $10^{-5} \sim 10^{-3} G_F$ excluded $\Rightarrow$ probing 50 TeV physics
Future: ∞ TeV ???







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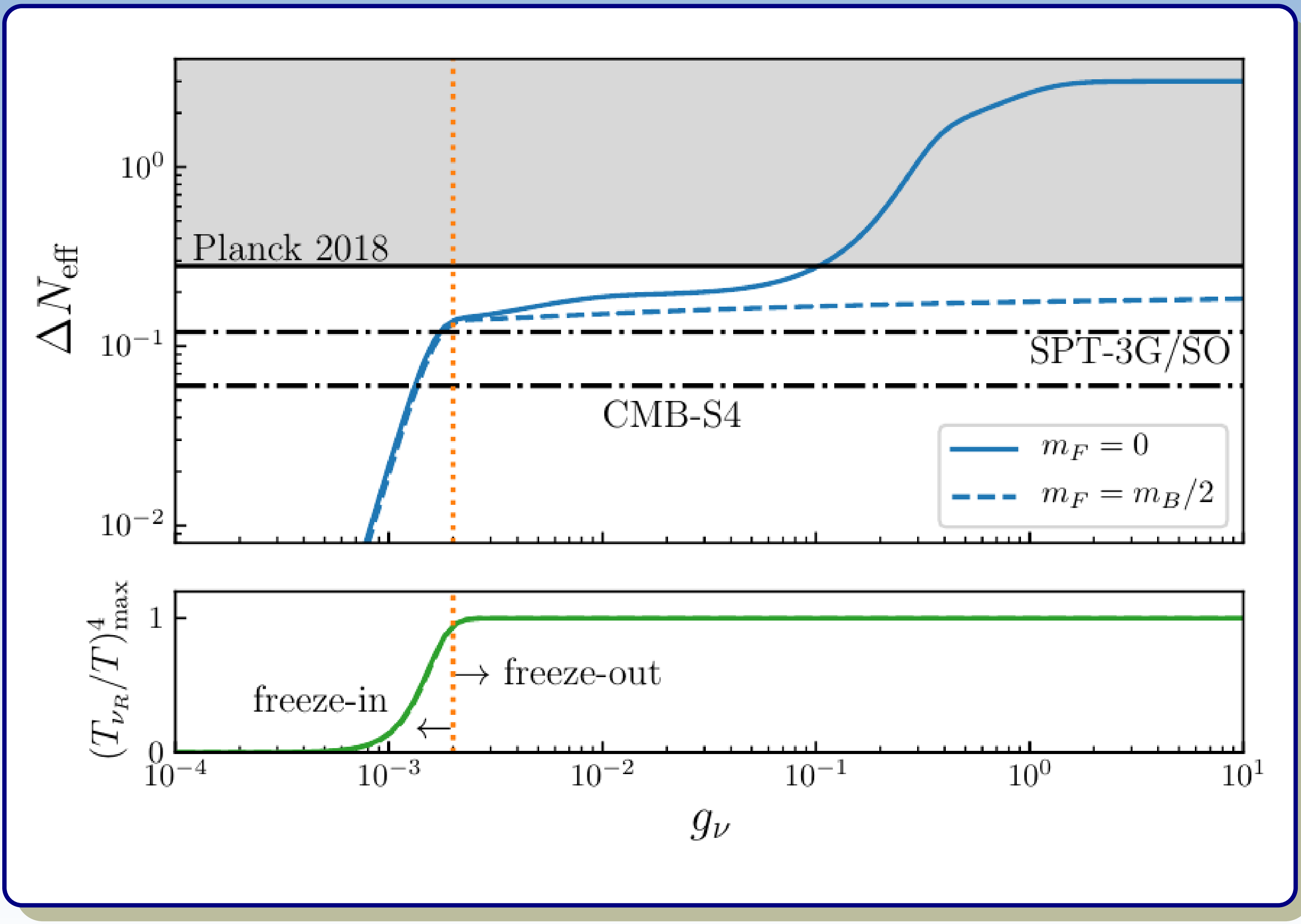
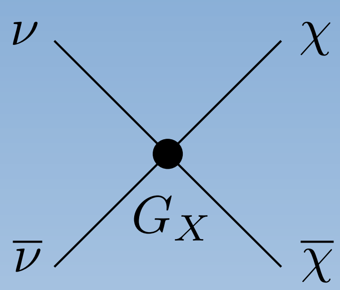


$\Delta N_{\rm eff}$
10^0
10^{-1}
10^{-2}
Planck 2018
SPT-3G/SO
CMB-S4
$m_F = 0$
$m_F = m_B/2$
$(T_{\nu_R}/T)^4_{\rm max}$
1
0
freeze-in
$\leftarrow$
$\rightarrow$ freeze-out
10^{-4}
10^{-3}
10^{-2}
10^{-1}
10^0
10^1
g_ν

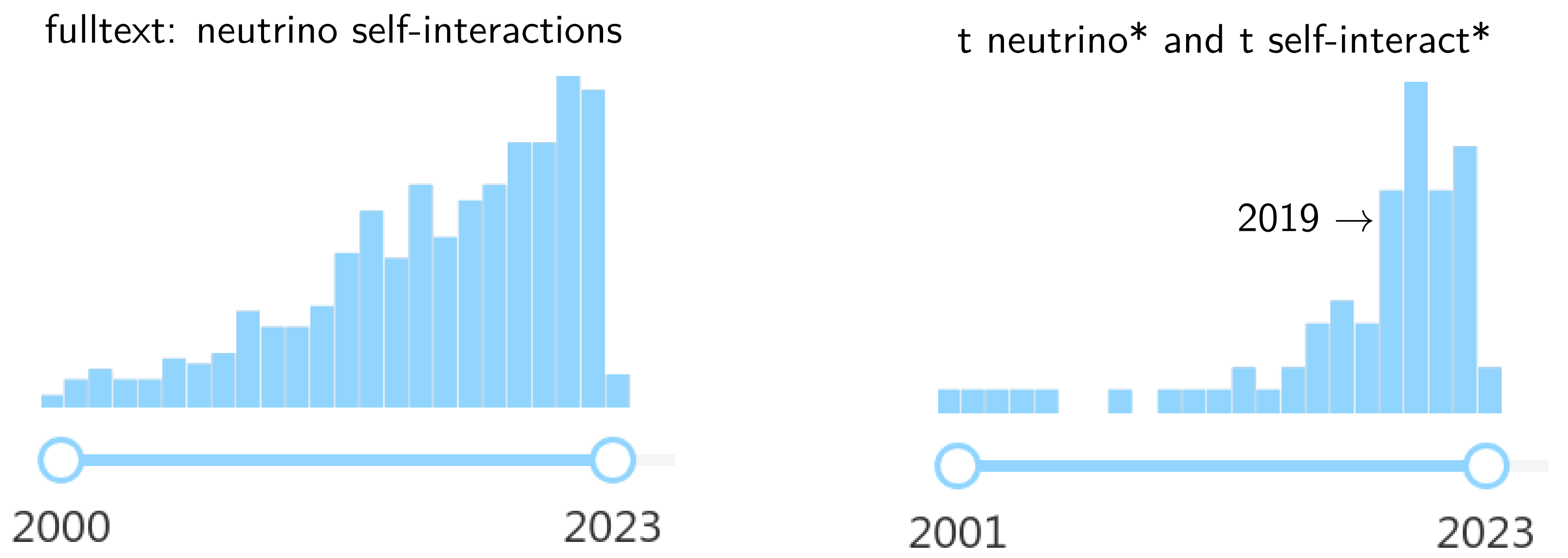
ν-DM interactions



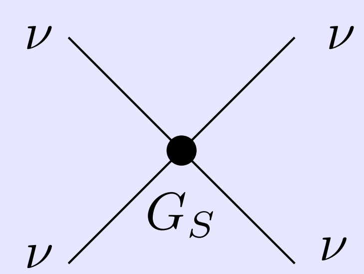
- Contact interaction always $\rightarrow$ DM χ thermalizes $\rightarrow$ freeze-out
- How large is G_X?
  - $\Omega_{\rm DM}h^2 = 0.12 \rightarrow G_X \sim G_F \times 10^2 {\rm GeV}/m_\chi$
- observational consequences from today's DM annihilation
  - monochromatic ν from $\chi\overline{\chi} \rightarrow \nu\overline{\nu}$, sounds great (IceCube, Super-K, ...)
    - but, in general, ☹ [Aisati, Garcia-Cely, *et al*]*
    - Interesting exception: PTOLEMY, keV ν [Hufnagel, Xu]*
  - 1-loop: $\chi\overline{\chi} \rightarrow \nu\overline{\nu} \rightarrow \ell\overline{\ell}$ [M. Blennow, E. Fernandez-Martinez, *et al*]*

* 1706.06600, 2110.09883, 1903.00006

Rising interest, why?



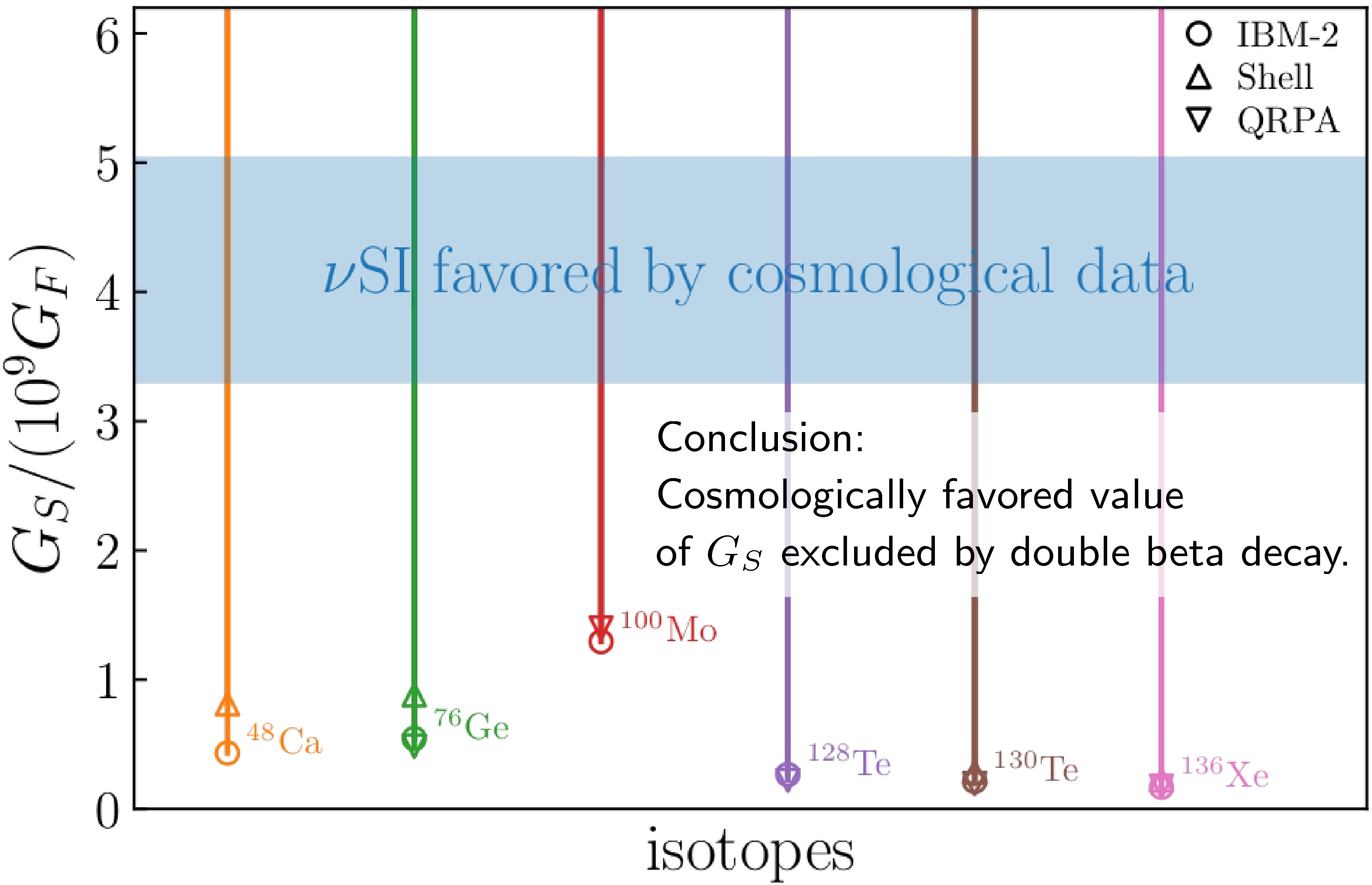
- partially due to the cosmological H_0 tension*
- … claimed $G_S = 10^{7\sim9} G_F$ could solve the H_0 tension
- $0(2)\nu\beta\beta$ can say something …



* Kreisch *et al* 1902.00534; Brinckmann *et al* 2012.11830; …

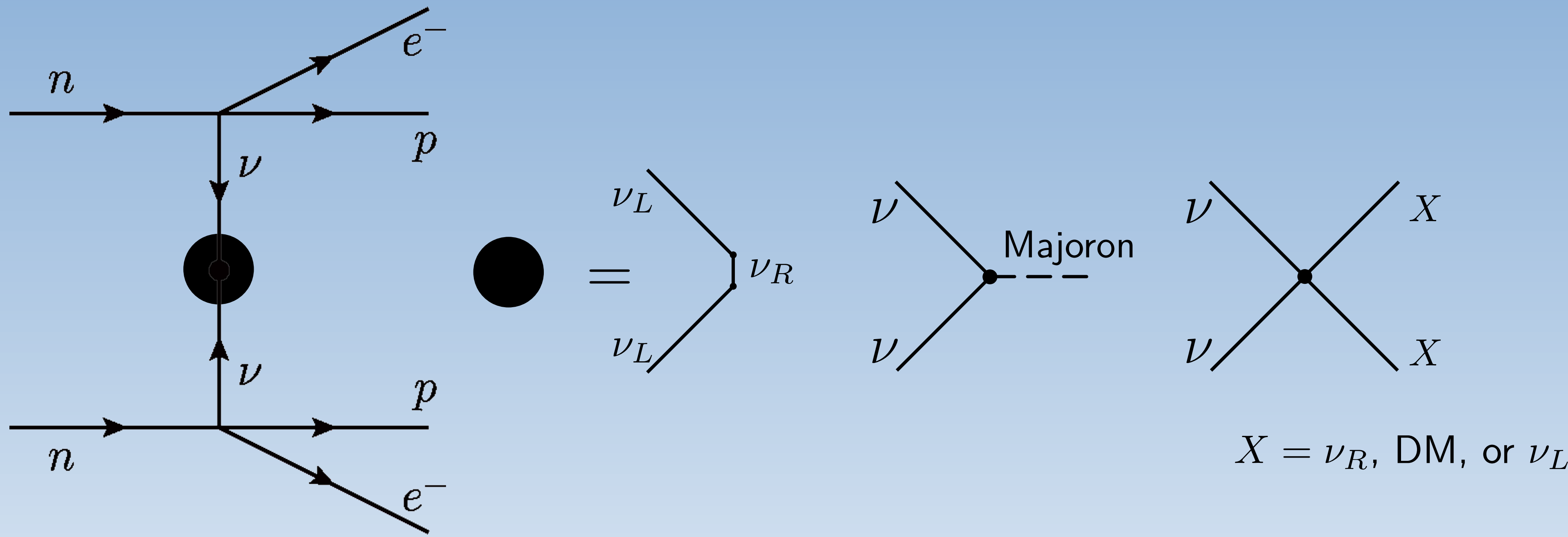
Cosmological constraints are not always better than $\beta\beta$ decay
— Here is an example.

Deppisch, Graf, Rodejohann, XJX [2004.11919]



Conclusion:
Cosmologically favored value of G_S excluded by double beta decay.

New physics to look for in $0\nu\beta\beta$:



Cosmological constrains:

- Usually stronger than $0\nu\beta\beta$
- some exceptions, ...

Conclusions: complementarity between cosmology and $0\nu\beta\beta$!

Backup