

New physics in rare decays

Toshi Ota, IFT Madrid



Contents

New Physics (NP) associated with the measurements of neutrinos in the next decades.

1. NP in $0\nu 2b$ If we will face a conflict in ν SM...
2. Nucleon decays at large ν detectors

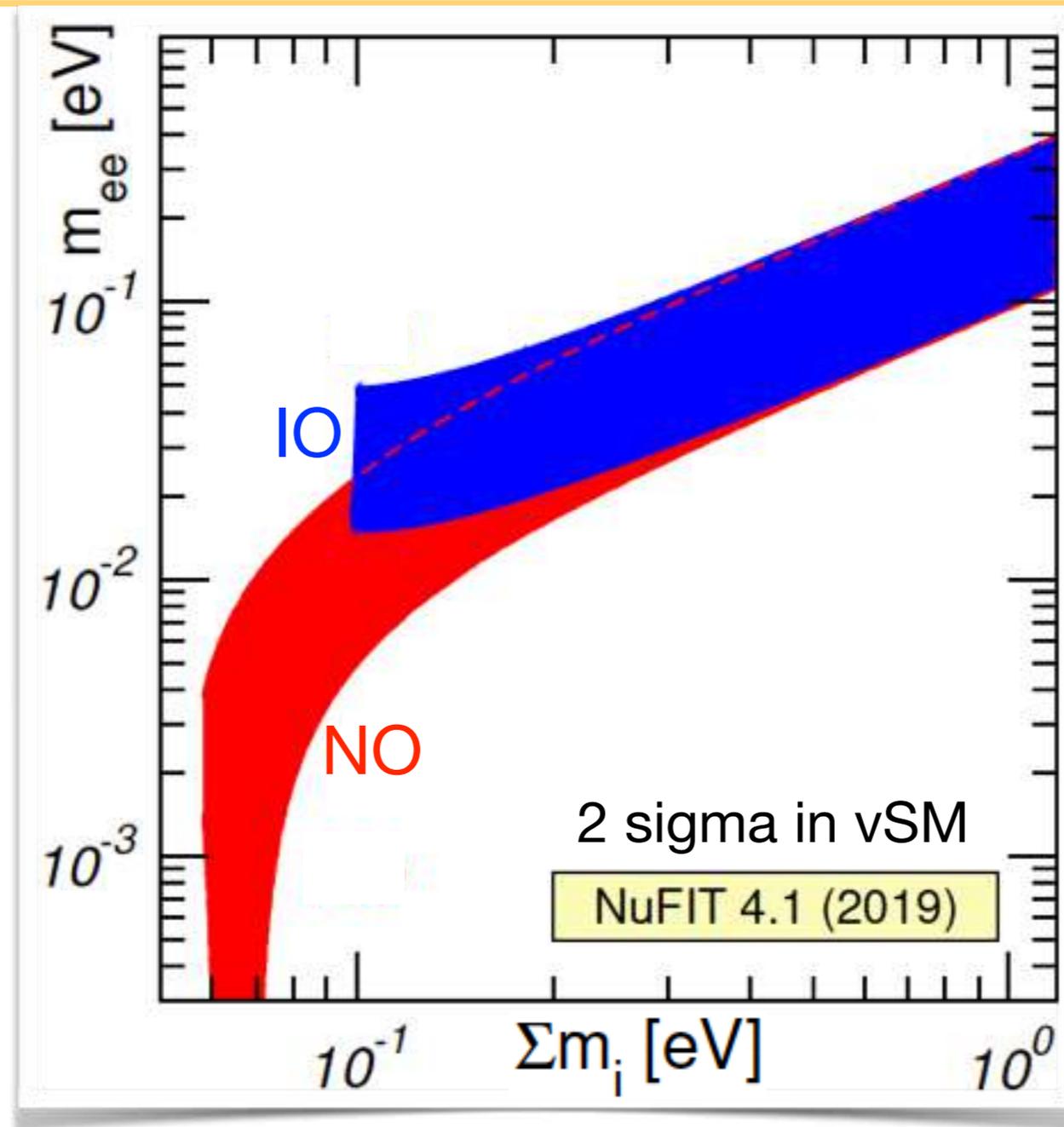
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New Physics (NP) associated with the measurements of neutrinos in the next decades.

1. NP in $0\nu 2\beta$ If we will face a conflict in ν SM...
2. Nucleon decays at large ν detectors
3. Do we need more ν exp? - Stress test of ν SM

#1.
Cornering the parameters of the vSM

Playground of the ν SM(+ Λ CDM)



Playground of the ν SM(+ Λ CDM)

cf. Tab.2 in 1902.04097

Tab.3 in 1901.11342

0v2b

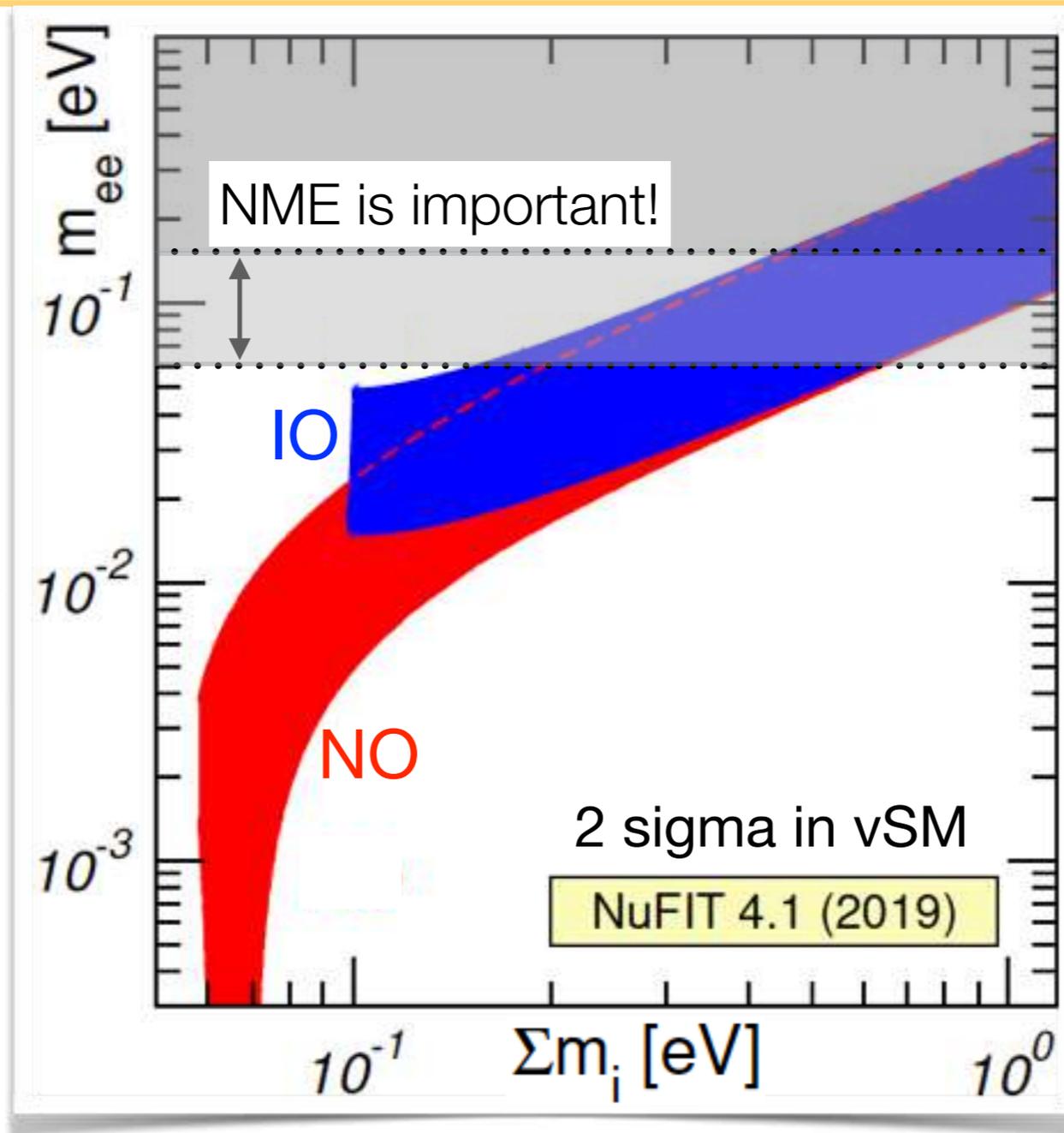
CUORE

EXO-200

GERDA

Kam.-Zen

more



Playground of the ν SM(+ Λ CDM)

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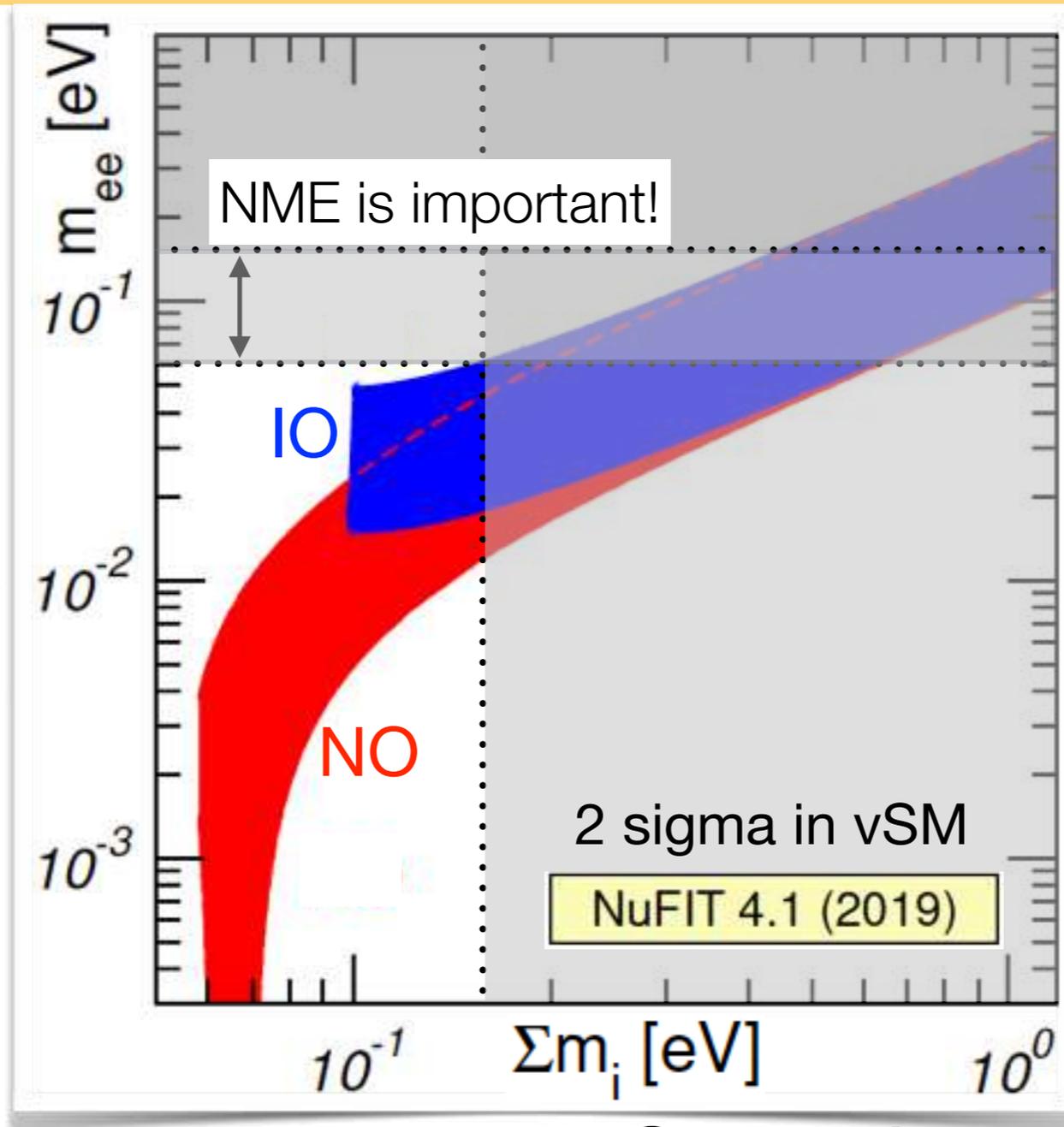
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Cosmology

Λ CDM + Σm_ν (+ N_{eff})

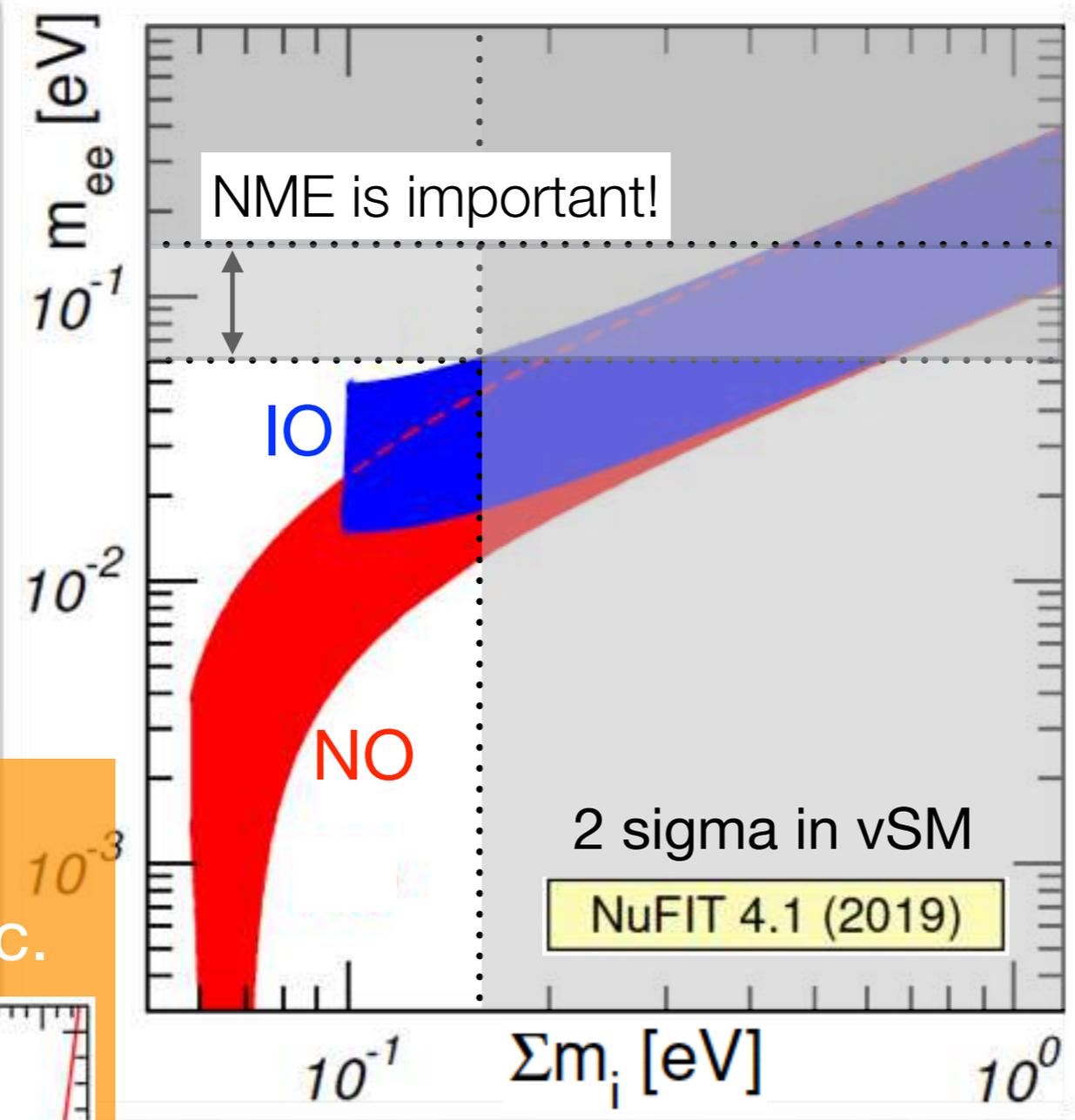
CMB+LSS+BAO+...

cf. Tab.2 in 1907.12598 Tab.25.2 PDG review

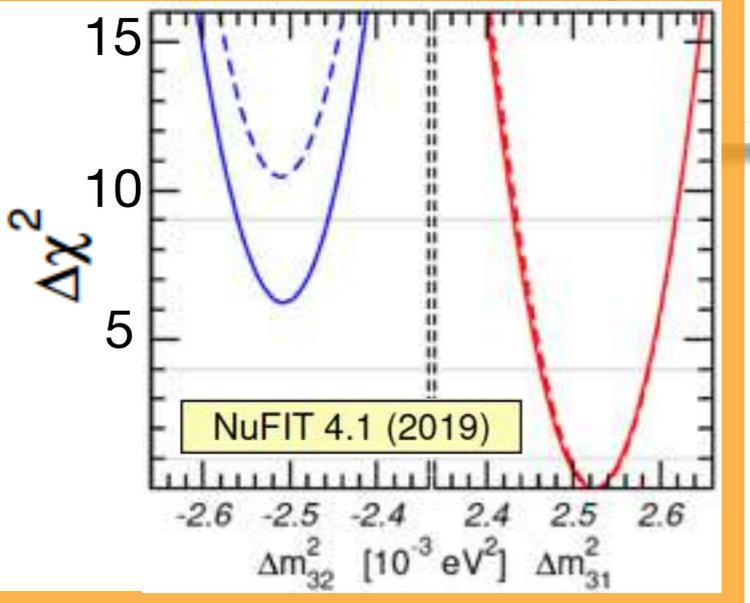
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0v2b
 CUORE
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 more



ν OSC.
 MINOS, NOvA
 T2K, (atm.) + reac.



Cosmology
 Λ CDM + Σm_ν (+ N_{eff})
 CMB+LSS+BAO+...

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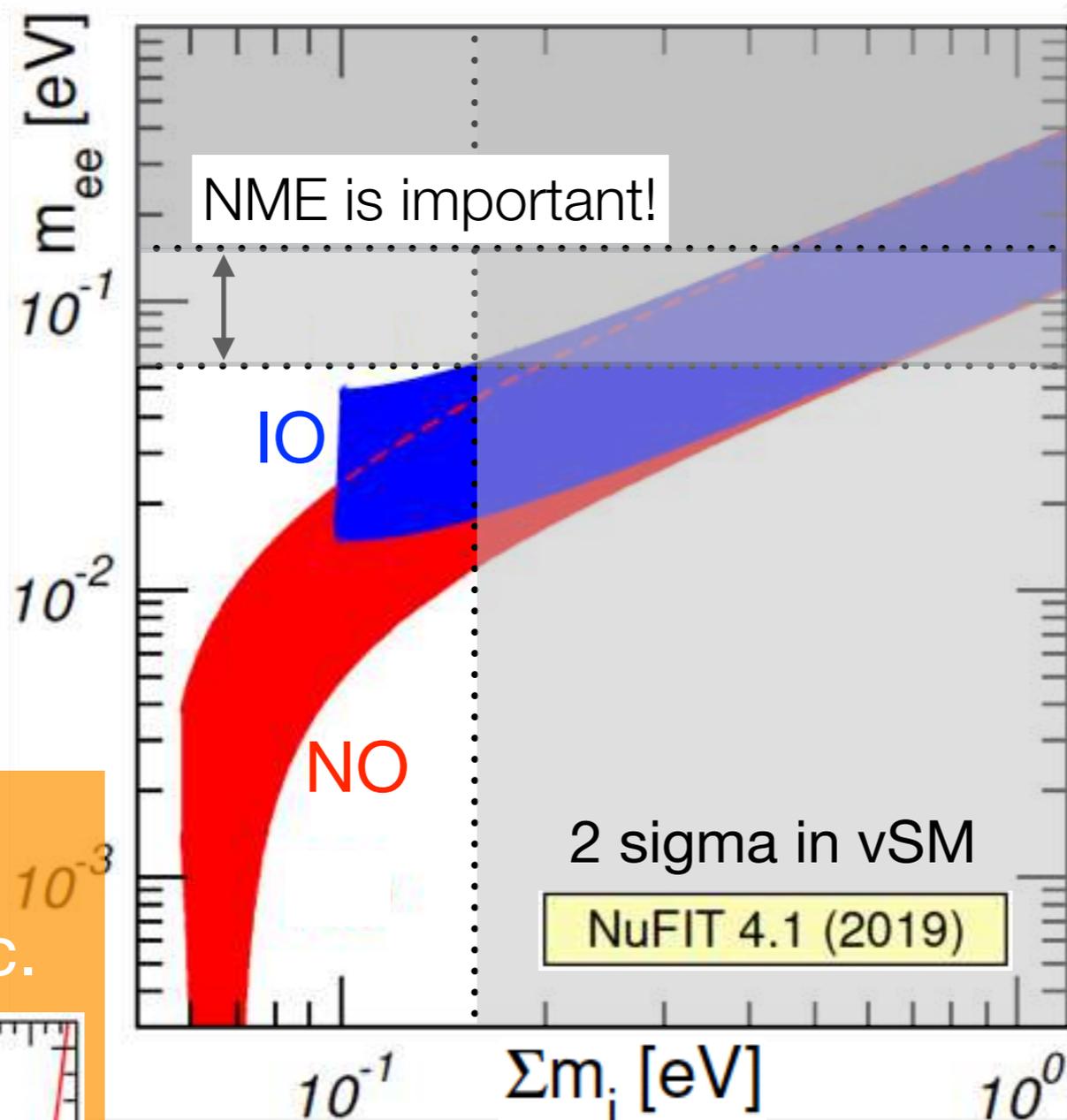
Playground of the ν SM(+ Λ CDM)

Please excuse me for the incomplete list.

cf. Tab.2 in 1902.04097
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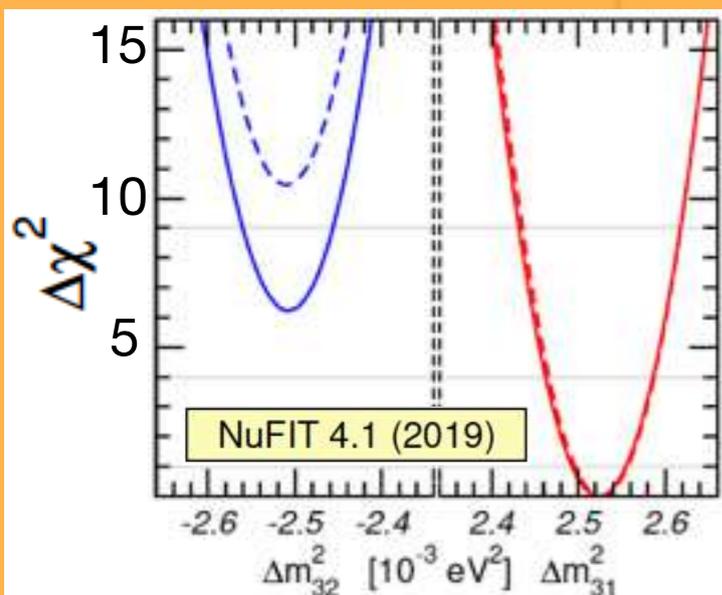
0v2b

CUORE
EXO-200
GERDA
Kam.-Zen
more



ν OSC.

MINOS, NOvA
T2K, (atm.) + reac.



- 2019 KATRIN 1st result
- 2020(-2030) **LSST**
LSS, BAO nearby
- 2021(-2026) **LEGEND-200**
 $m_{\beta\beta} = 0.034 - 0.09\text{eV}$
- JUNO**
LHC run-3 (L=300/fb)
- 2022(-2028) **Euclid**
 $z \sim 2$
- 2024- HL-LHC (L=3k/fb)
- 2026(-2036) **DUNE, HK**
- 2027- **SKA**
Cosmic dawn $z \sim 10$
- 2030?- **LEGEND-1000**
 $m_{\beta\beta} = 0.011 - 0.028\text{eV}$

Cosmology

Λ CDM + Σm_ν (+ N_{eff})

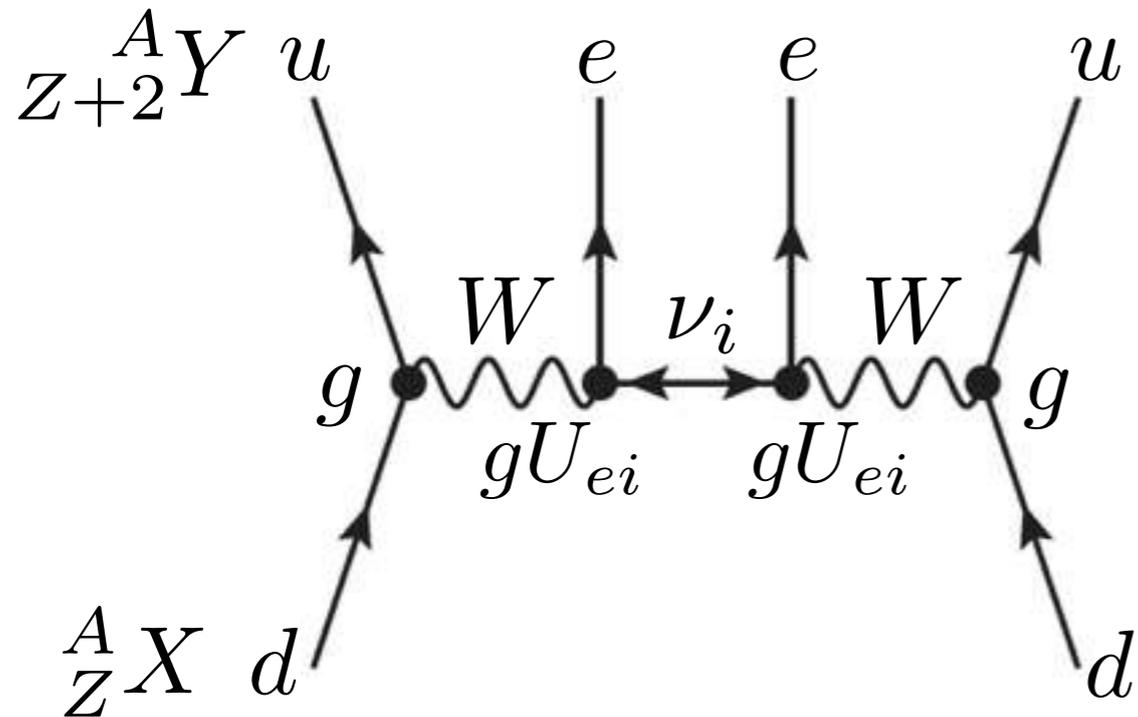
CMB+LSS+BAO+...

cf. Tab.2 in 1907.12598 Tab.25.2 PDG review

If we will face a conflict...?

...New Physics in $0\nu 2\beta$?

e.g., LBL&Cosmo: NH, $0\nu 2\beta$: Discovered at $m_{\beta\beta} \simeq 0.05$ eV

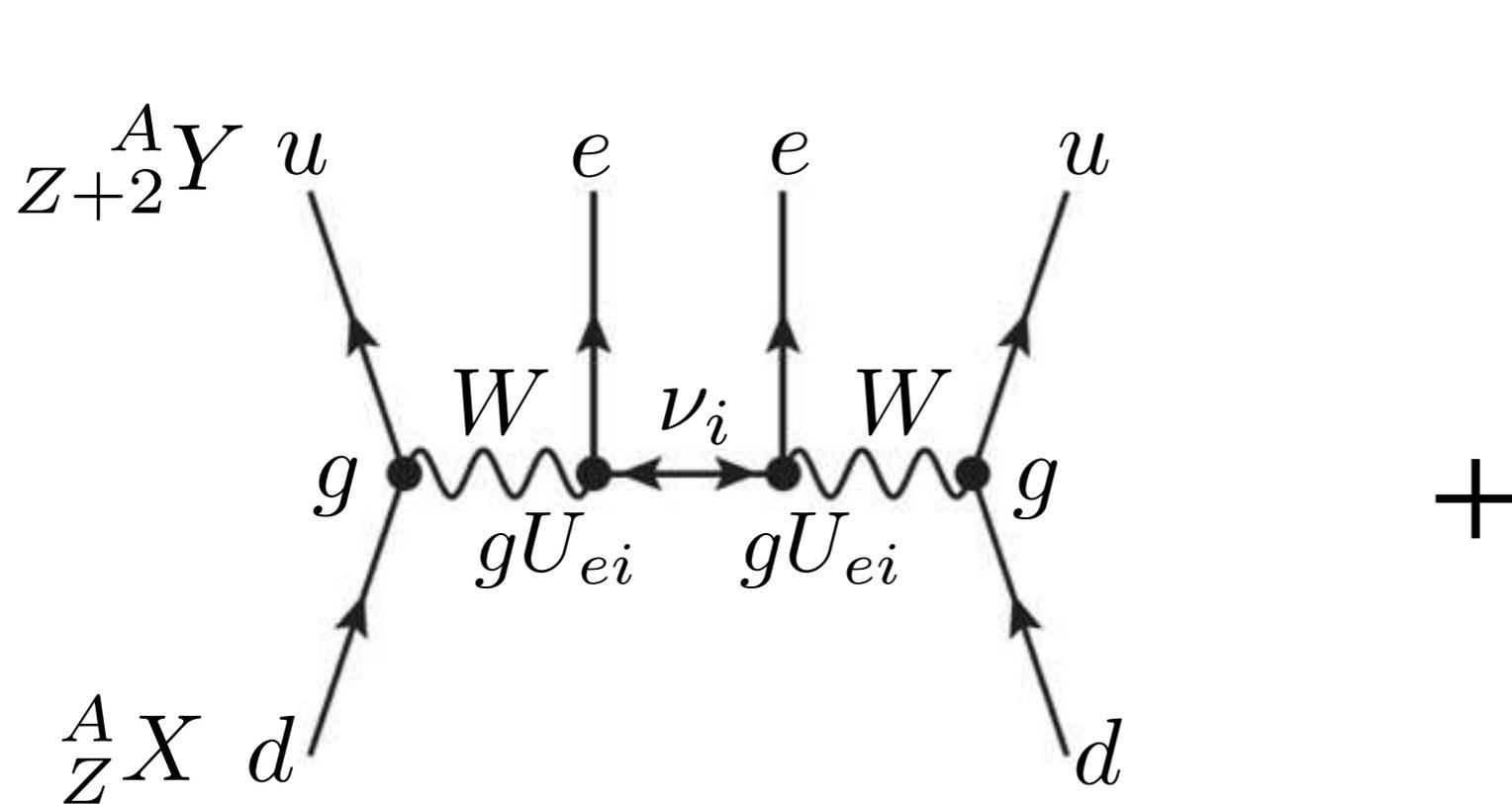


$$\mathcal{L}_{\nu\text{SM}} \sim G_F^2 \frac{m_{\beta\beta}}{p^2} \bar{u}\bar{u}d\bar{d}e\bar{e} \quad p \simeq 0.1[\text{GeV}]$$

Standard contribution

...New Physics in $0\nu 2\beta$?

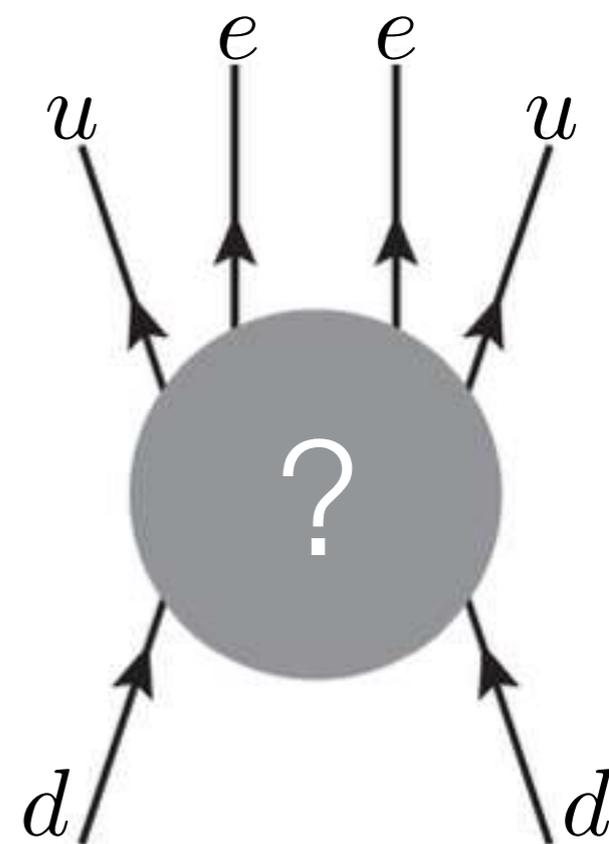
e.g., LBL&Cosmo: NH, $0\nu 2\beta$: Discovered at $m_{\beta\beta} \simeq 0.05$ eV



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Standard contribution

+

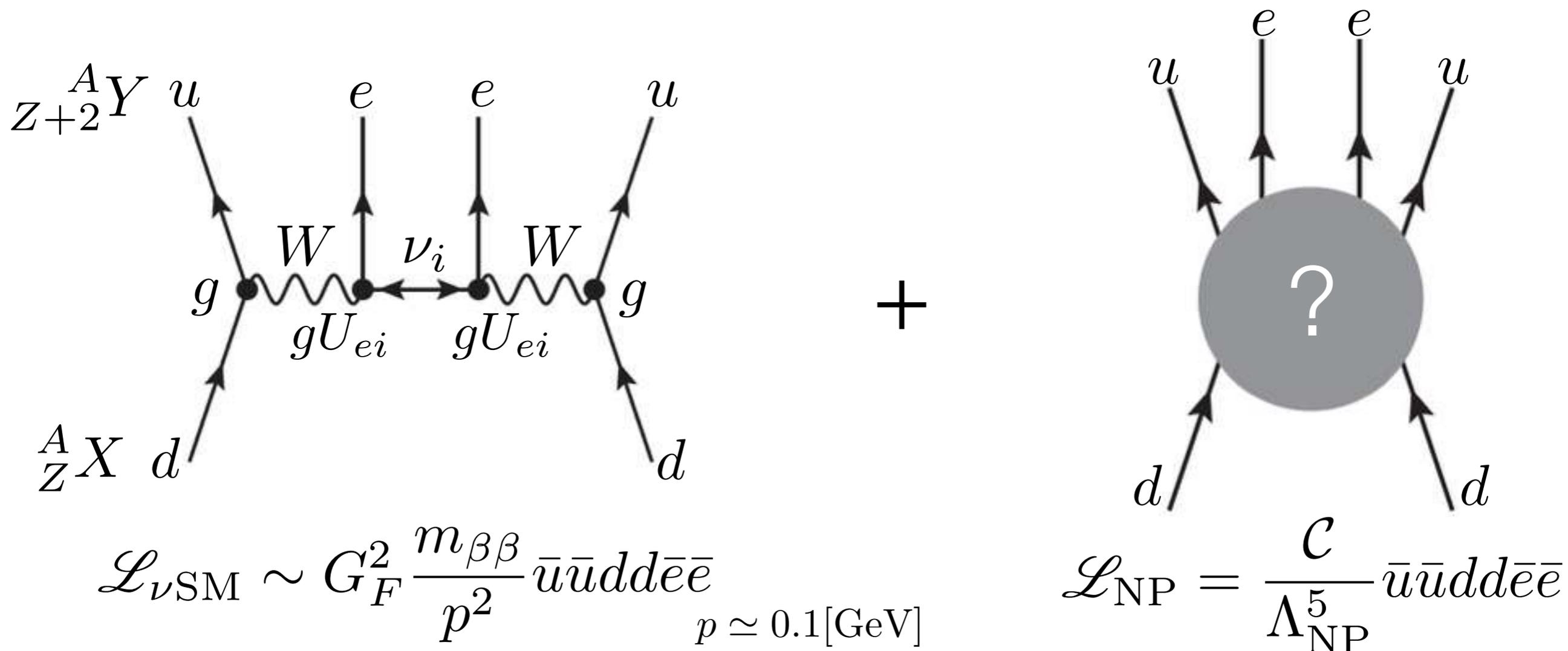


$$\mathcal{L}_{\text{NP}} = \frac{\mathcal{C}}{\Lambda_{\text{NP}}^5} \bar{u}\bar{u}d\bar{d}e\bar{e}$$

New Physics contribution

...New Physics in 0ν2β?

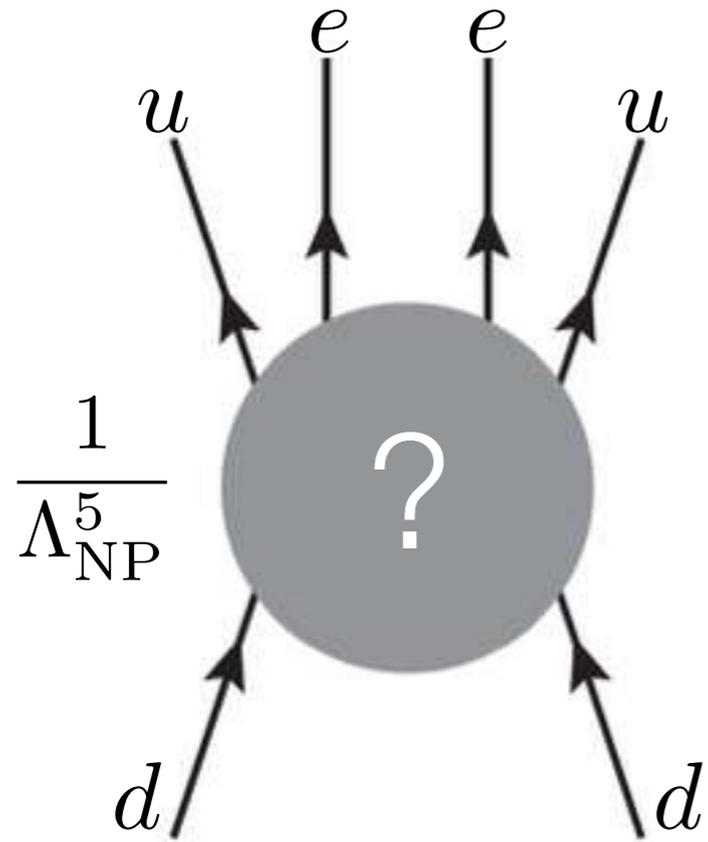
e.g., LBL&Cosmo: NH, 0ν2β: Discovered at $m_{\beta\beta} \simeq 0.05 \text{ eV}$



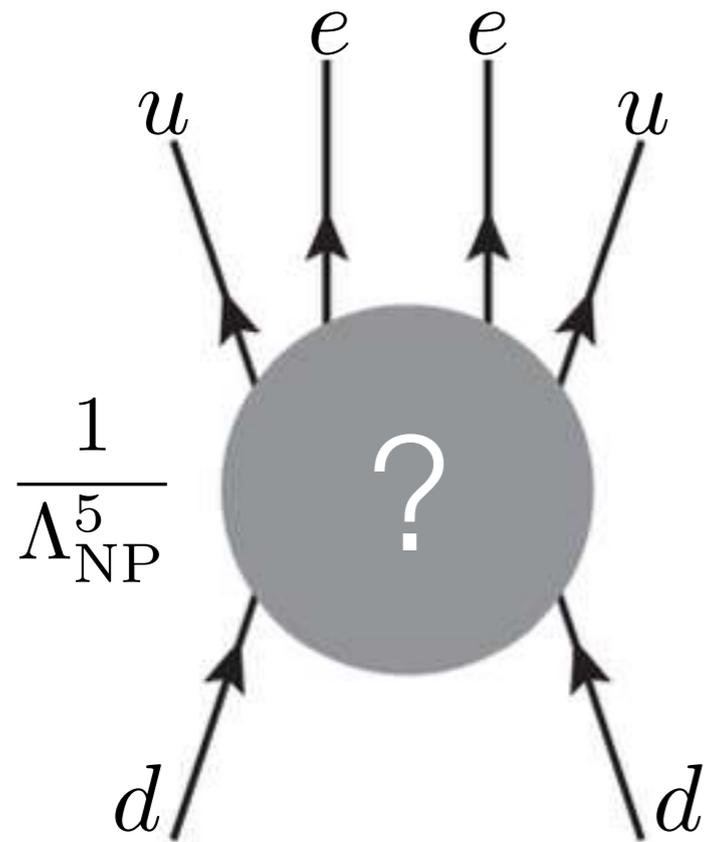
Sensitivity to $m_{\beta\beta}$ = Sensitivity to NP at the scale Λ_{NP}

$$G_F^2 \frac{|m_{\beta\beta}|_{\text{exp.}}}{p^2} \stackrel{!}{=} \frac{\mathcal{C}}{\Lambda_{\text{NP}}^5} \quad \boxed{\mathcal{C}=1} \Rightarrow \Lambda_{\text{NP}} = 4 \text{ TeV} \left[\frac{0.05 \text{ eV}}{|m_{\beta\beta}|_{\text{exp.}}} \right]^{1/5}$$

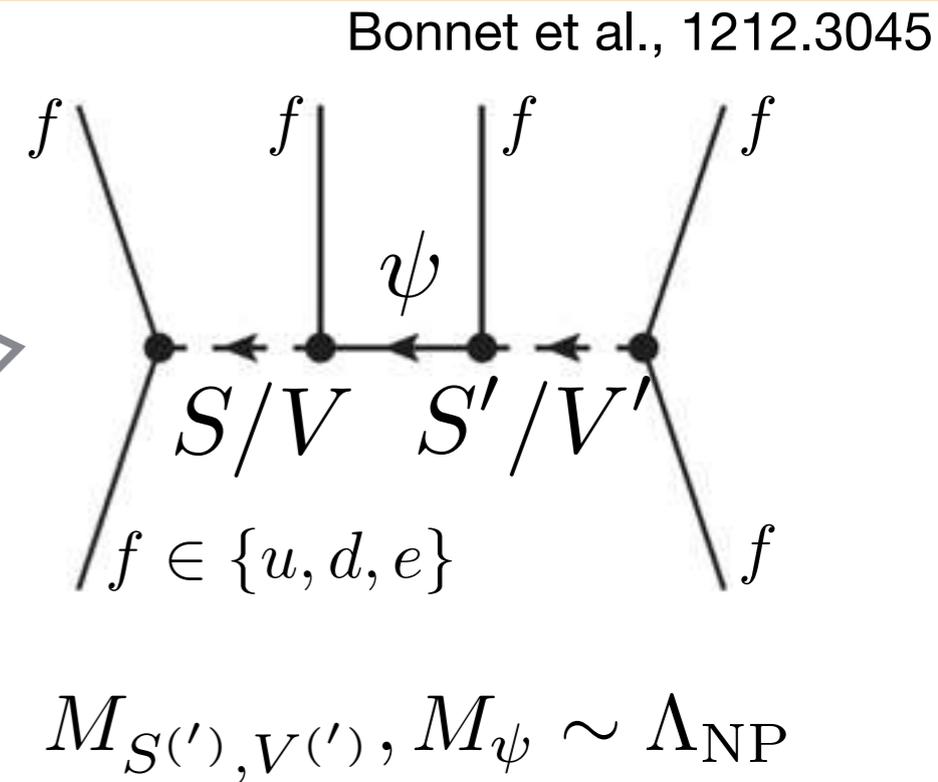
What are the effective ops made of?



What are the effective ops made of?



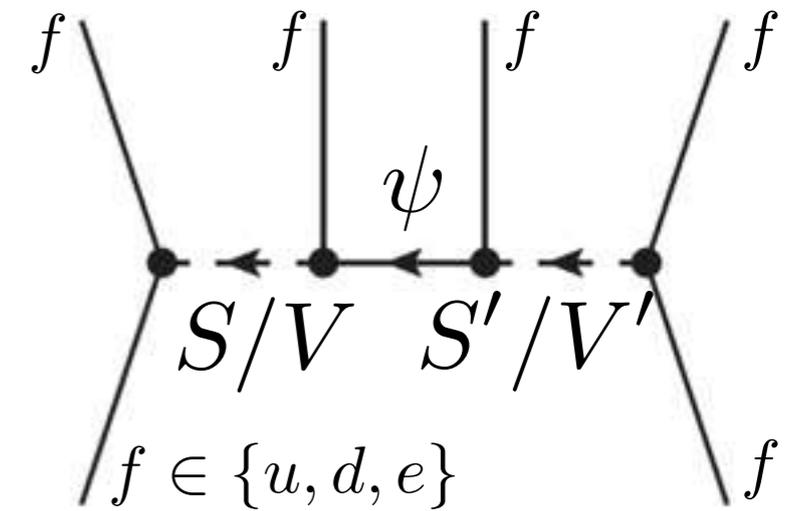
Decompose...
@tree



What are the effective ops made of?

#	Decomposition	Long Range?	Mediator ($U(1)_{em}, SU(3)_c$)			Models/Refs./Comments
			S or V_ρ	ψ	S' or V'_ρ	
1-i	$(\bar{u}d)(\bar{e})(\bar{e})(\bar{u}d)$	(a)	(+1, 1)	(0, 1)	(-1, 1)	Mass mechan., RPV [58–60], LR-symmetric models [39], Mass mechanism with ν_S [61], TeV scale seesaw, e.g., [62, 63] [64]
1-ii-a	$(\bar{u}d)(\bar{u})(d)(\bar{e}\bar{e})$		(+1, 8)	(0, 8)	(-1, 8)	
			(+1, 1)	(+5/3, 3)	(+2, 1)	
1-ii-b	$(\bar{u}d)(d)(\bar{u})(\bar{e}\bar{e})$		(+1, 8)	(+5/3, 3)	(+2, 1)	
			(+1, 1)	(+4/3, $\bar{3}$)	(+2, 1)	
			(+1, 8)	(+4/3, $\bar{3}$)	(+2, 1)	
2-i-a	$(\bar{u}d)(d)(\bar{e})(\bar{u}\bar{e})$		(+1, 1)	(+4/3, $\bar{3}$)	(+1/3, 3)	RPV [58–60], LQ [65, 66]
			(+1, 8)	(+4/3, $\bar{3}$)	(+1/3, $\bar{3}$)	
2-i-b	$(\bar{u}d)(\bar{e})(d)(\bar{u}\bar{e})$	(b)	(+1, 1)	(0, 1)	(+1/3, $\bar{3}$)	RPV [58–60], LQ [65, 66]
			(+1, 8)	(0, 8)	(+1/3, $\bar{3}$)	
2-ii-a	$(\bar{u}d)(\bar{u})(\bar{e})(d\bar{e})$		(+1, 1)	(+5/3, 3)	(+2/3, 3)	RPV [58–60], LQ [65, 66]
			(+1, 8)	(+5/3, 3)	(+2/3, 3)	
2-ii-b	$(\bar{u}d)(\bar{e})(\bar{u})(d\bar{e})$	(b)	(+1, 1)	(0, 1)	(+2/3, 3)	RPV [58–60], LQ [65, 66]
			(+1, 8)	(0, 8)	(+2/3, 3)	
2-iii-a	$(d\bar{e})(\bar{u})(d)(\bar{u}\bar{e})$	(c)	(-2/3, $\bar{3}$)	(0, 1)	(+1/3, $\bar{3}$)	RPV [58–60]
			(-2/3, $\bar{3}$)	(0, 8)	(+1/3, $\bar{3}$)	RPV [58–60]
2-iii-b	$(d\bar{e})(d)(\bar{u})(\bar{u}\bar{e})$		(-2/3, $\bar{3}$)	(-1/3, 3)	(+1/3, $\bar{3}$)	
			(-2/3, $\bar{3}$)	(-1/3, $\bar{6}$)	(+1/3, $\bar{3}$)	
3-i	$(\bar{u}\bar{u})(\bar{e})(\bar{e})(dd)$		(+4/3, 3)	(+1/3, 3)	(-2/3, 3)	only with V_ρ and V'_ρ
			(+4/3, 6)	(+1/3, 6)	(-2/3, 6)	
3-ii	$(\bar{u}\bar{u})(d)(d)(\bar{e}\bar{e})$		(+4/3, $\bar{3}$)	(+5/3, 3)	(+2, 1)	only with V_ρ
			(+4/3, 6)	(+5/3, 3)	(+2, 1)	
3-iii	$(dd)(\bar{u})(\bar{u})(\bar{e}\bar{e})$		(+2/3, 3)	(+4/3, $\bar{3}$)	(+2, 1)	only with V_ρ
			(+2/3, $\bar{6}$)	(+4/3, $\bar{3}$)	(+2, 1)	
4-i	$(d\bar{e})(\bar{u})(\bar{u})(d\bar{e})$	(c)	(-2/3, 3)	(0, 1)	(+2/3, 3)	RPV [58–60]
			(-2/3, $\bar{3}$)	(0, 8)	(+2/3, 3)	RPV [58–60]
4-ii-a	$(\bar{u}\bar{u})(d)(\bar{e})(d\bar{e})$		(+4/3, $\bar{3}$)	(+5/3, 3)	(+2/3, 3)	only with V_ρ
			(+4/3, 6)	(+5/3, 3)	(+2/3, 3)	see Sec. 4 (this work)
4-ii-b	$(\bar{u}\bar{u})(\bar{e})(d)(d\bar{e})$		(+4/3, $\bar{3}$)	(+1/3, $\bar{3}$)	(+2/3, 3)	only with V_ρ
			(+4/3, 6)	(+1/3, 6)	(+2/3, 3)	
5-i	$(\bar{u}\bar{e})(d)(d)(\bar{u}\bar{e})$	(c)	(-1/3, 3)	(0, 1)	(+1/3, 3)	RPV [58–60]
			(-1/3, 3)	(0, 8)	(+1/3, $\bar{3}$)	RPV [58–60]
5-ii-a	$(\bar{u}\bar{e})(\bar{u})(\bar{e})(dd)$		(-1/3, 3)	(+1/3, $\bar{3}$)	(-2/3, 3)	only with V'_ρ
			(-1/3, 3)	(+1/3, 6)	(-2/3, 6)	
5-ii-b	$(\bar{u}\bar{e})(\bar{e})(\bar{u})(dd)$		(-1/3, 3)	(-4/3, 3)	(-2/3, $\bar{3}$)	only with V'_ρ
			(-1/3, 3)	(-4/3, 3)	(-2/3, 6)	

Bonnet et al., 1212.3045



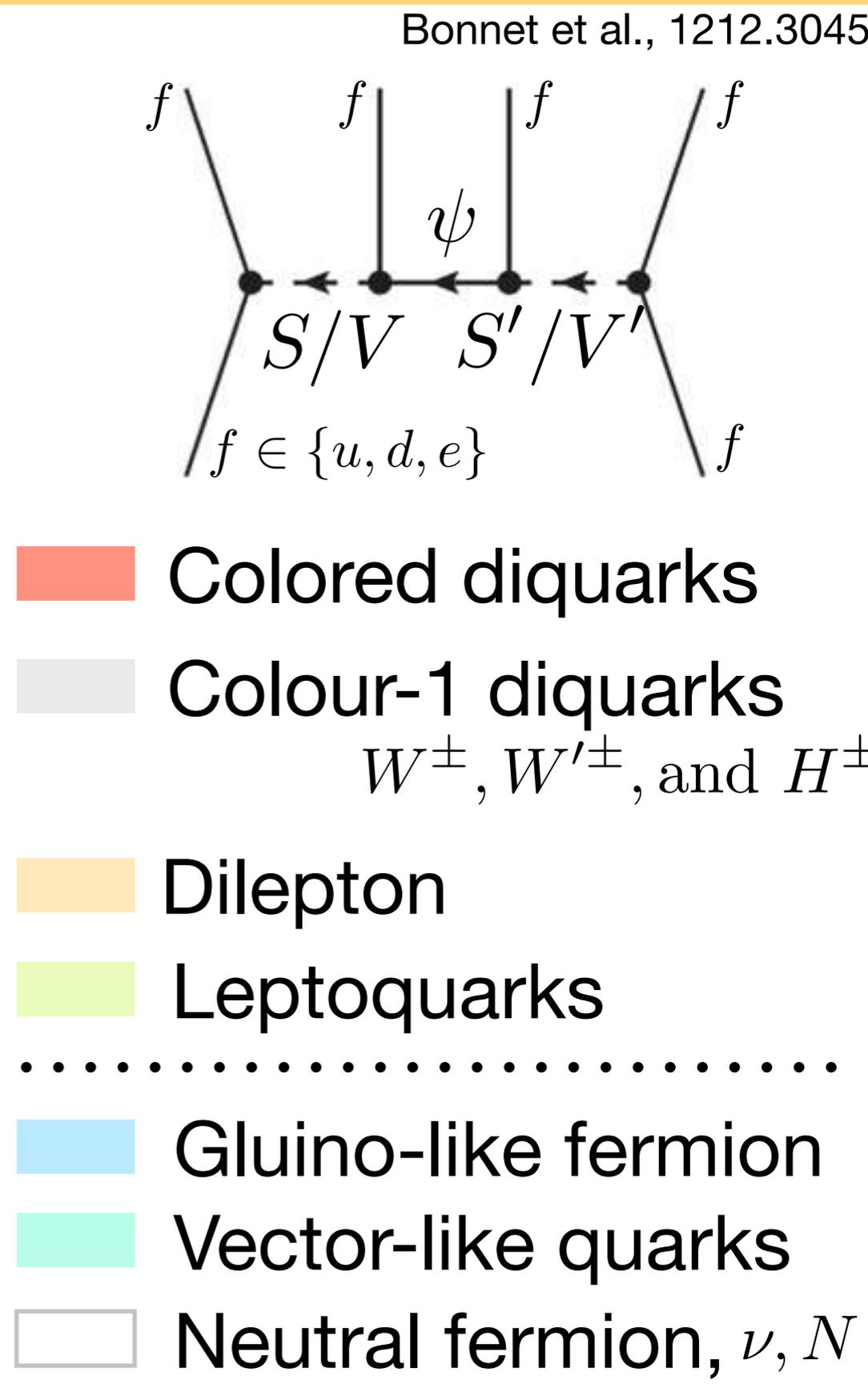
$$M_{S('), V('), M_\psi} \sim \Lambda_{\text{NP}}$$

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2-i-b	$(\bar{u}d)(\bar{e})(d)(\bar{u}\bar{e})$	(b)	(+1, 1)	(+4/3, $\bar{3}$)	(+2, 1)	RPV [58–60], LQ [65, 66]
2-ii-a	$(\bar{u}d)(\bar{u})(\bar{e})(d\bar{e})$		(+1, 8)	(+4/3, $\bar{3}$)	(+2, 1)	
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3-i	$(\bar{u}\bar{u})(\bar{e})(\bar{e})(dd)$		(-2/3, $\bar{3}$)	(0, 8)	(+1/3, $\bar{3}$)	only with V_ρ and V'_ρ
3-ii	$(\bar{u}\bar{u})(d)(d)(\bar{e}\bar{e})$		(+4/3, 3)	(+1/3, 6)	(-2/3, 6)	only with V_ρ
3-iii	$(dd)(\bar{u})(\bar{u})(\bar{e}\bar{e})$		(+4/3, $\bar{3}$)	(+5/3, 3)	(+2, 1)	only with V_ρ
4-i	$(d\bar{e})(\bar{u})(\bar{u})(d\bar{e})$	(c)	(+4/3, 6)	(+5/3, 3)	(+2, 1)	only with V_ρ
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			(+4/3, 6)	(+1/3, 6)	(+2/3, 3)	
			(-1/3, 3)	(0, 1)	(+1/3, 3)	RPV [58–60]
			(-1/3, 3)	(0, 8)	(+1/3, $\bar{3}$)	RPV [58–60]
			(-1/3, 3)	(+1/3, 3)	(-2/3, 3)	only with V'_ρ
			(-1/3, 3)	(+1/3, 6)	(-2/3, 6)	
			(-1/3, 3)	(-4/3, 3)	(-2/3, $\bar{3}$)	only with V'_ρ
			(-1/3, 3)	(-4/3, 3)	(-2/3, 6)	

bosons

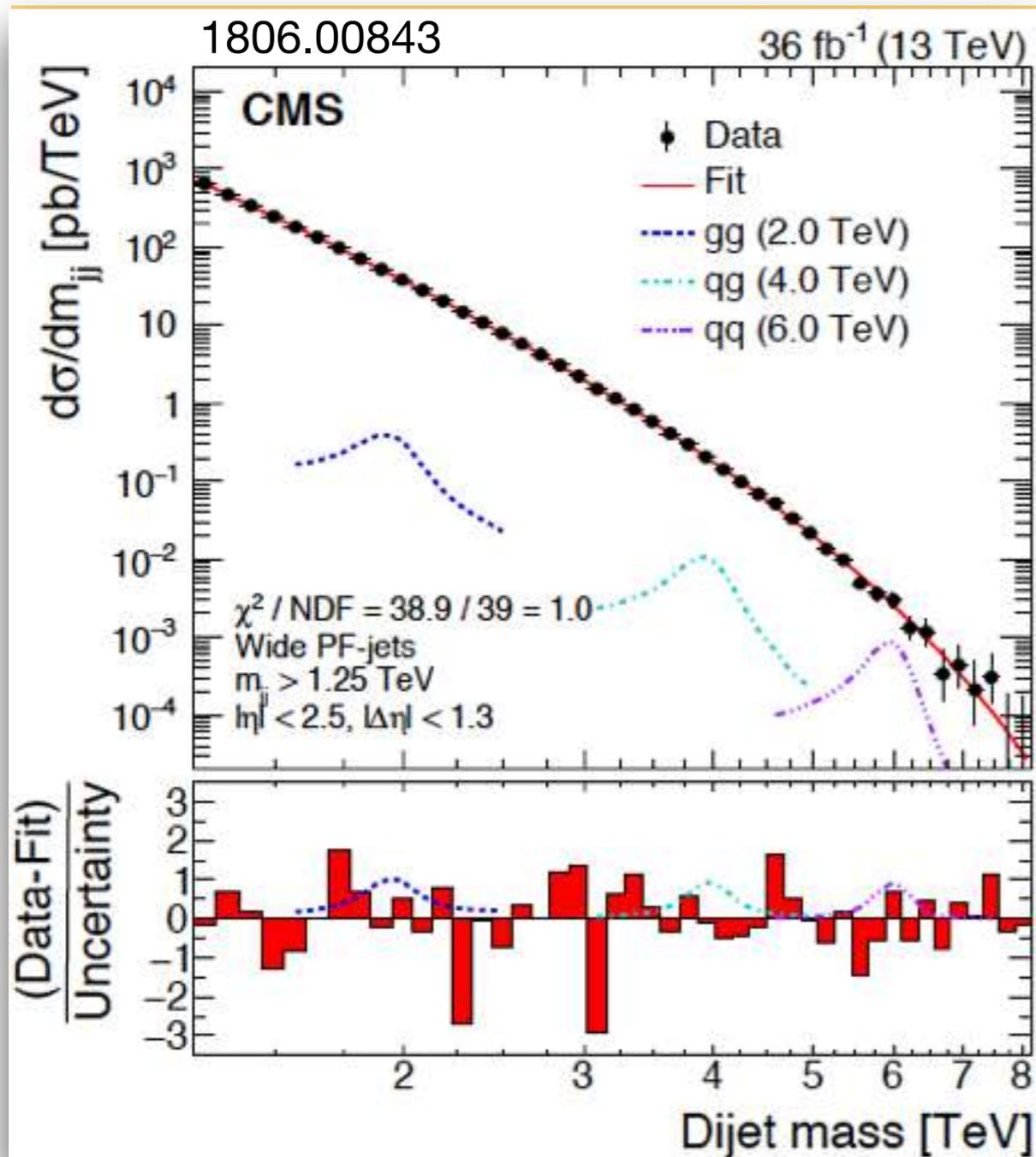
fermions



Searches for the mediators at LHC

Diquarks

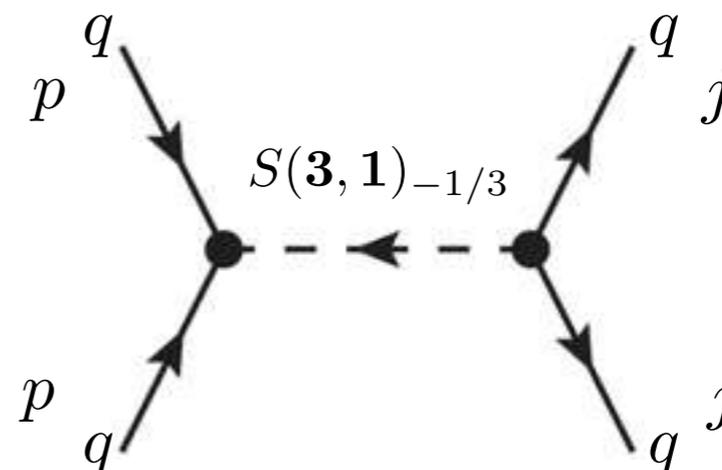
cf. Han et al., 1010.4309



Production: qqS int.

e.g., QQS & $u_R d_R S$ — E_6 GUT inspired
Coupling with the size of the EM int.

Signal: Resonance in M_{jj}



* Same for the Colour-1 one $\bar{u}\gamma^\rho d W_\rho'^+$
(with the SM W-like coupling)

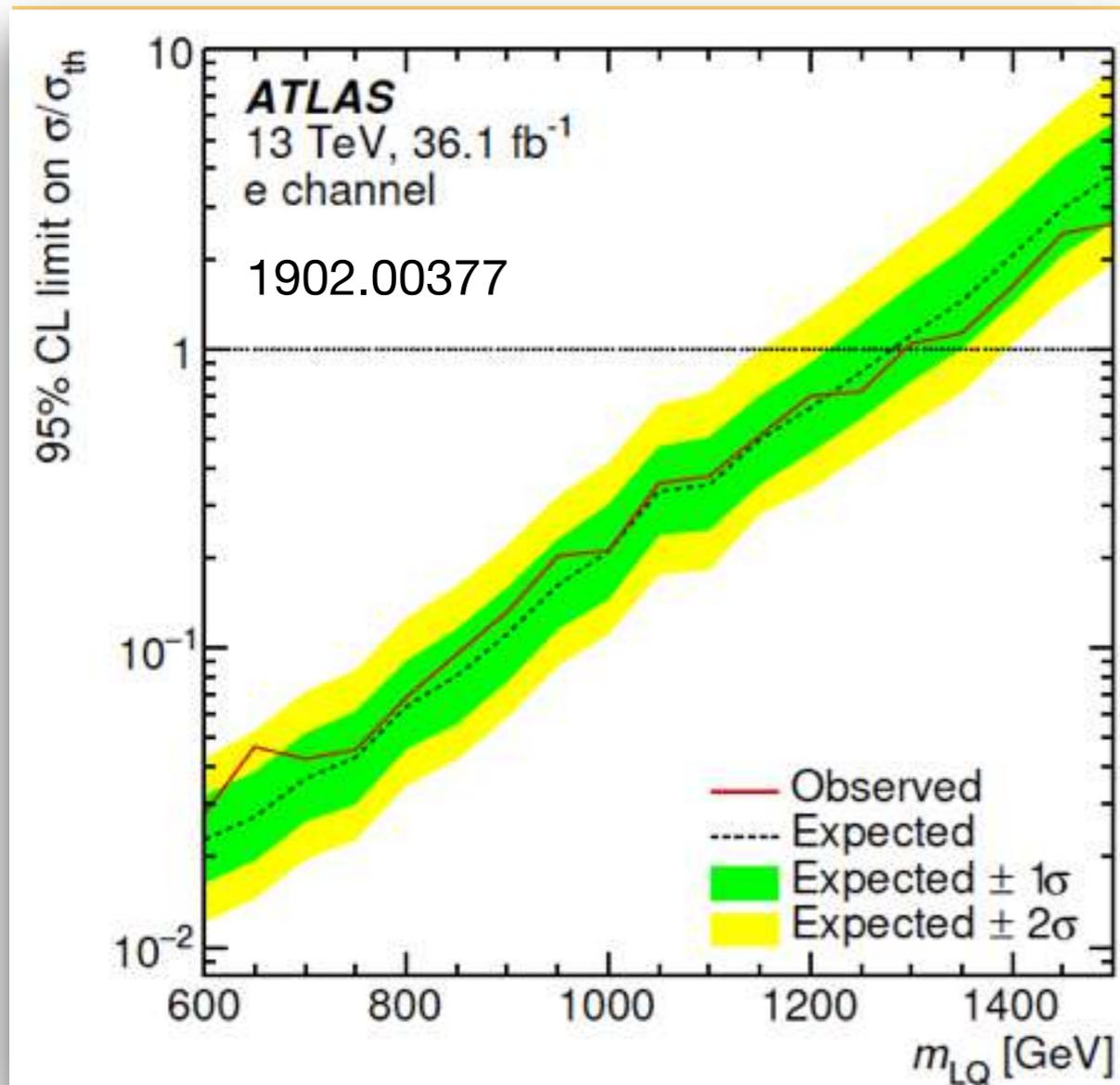
Bound: $M_S > 7.2\text{TeV}$ $M_{W'} > 3.3\text{TeV}$

Sensitivity at 0v2b exps. (with $c = 1$)

$$\Lambda_{\text{NP}} = 4 \text{ TeV} \left[\frac{0.05\text{eV}}{|m_{\beta\beta}|_{\text{exp.}}} \right]^{1/5} \quad \text{comparable to the LHC's.}$$

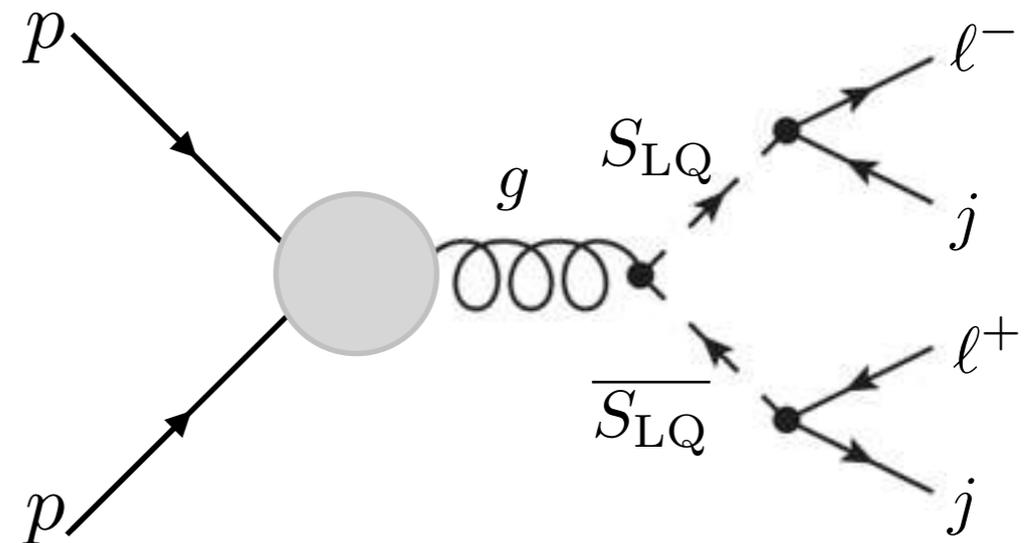
Leptoquarks

cf. Buchmueller Rueckl Wyler (1987)
Belyayev et al., hep-ph/0502067



Production: Strong interaction
Pair-production with g

Signal: $g \rightarrow S_{LQ} S_{LQ}^* \rightarrow 2j2\ell$



Bound: $M_{S_{LQ}} > 1.25\text{TeV}$
for the 1st gen. scalar LQ

* $\text{Br}(S_{LQ} \rightarrow q\ell) = 0.5$ is assumed

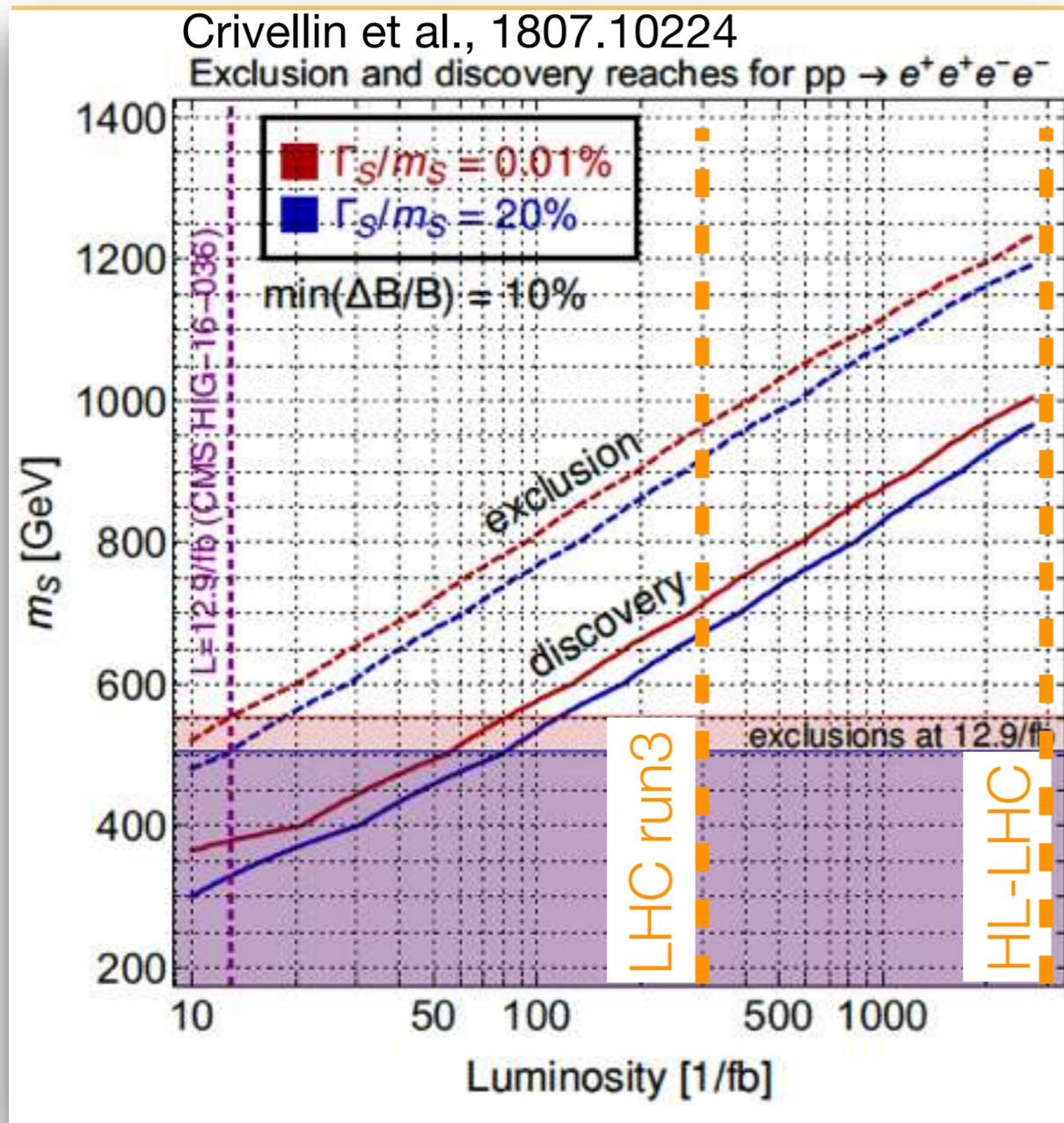
To bound LQs with $M_{LQ} > 2\text{TeV}$

Pair-production suffers from the phase space suppression.

Single production $gq \rightarrow q^* \rightarrow S_{LQ} + \ell$ at HL-LHC $\sigma_{\text{single}} < 10^{-1}\text{fb}$

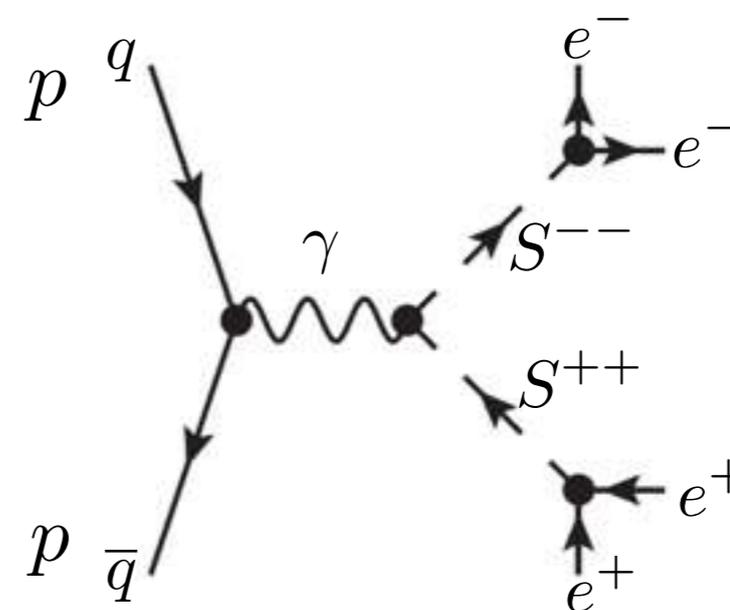
Dilepton aka Doubly charged boson

cf. Han et al. 0706.0441



Production: EM Drell-Yan

Signal: $pp \rightarrow 4e$, resonance in M_{ee}



There is a dilepton search at ATLAS [1903.06248]. However, it assumed that the dilepton also couples to quarks: $q\bar{q} \rightarrow S \rightarrow ee$ We have only $q\psi S$

Future prospects of the searches for heavier dileptons

To produce a pair of them, we need high $\sqrt{s} = \text{HE-LHC}$

$M_S > 8\text{TeV}$ (with $O(1)$ coupling) @ ILC-250 (through Bhabha scattering) Crivellin et al., 1807.10224

Coloured fermions

Colour-8 fermion (gluino-like)

cf. Octet boson@LHC, Chen et al., 1410.8113

Production: Pair-produced through g

Signal: $\psi(\mathbf{8}) \rightarrow qS_{LQ} \rightarrow q\bar{q}\ell$ 2j+a lepton

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cf. Octet boson@LHC, Chen et al., 1410.8113

Production: Pair-produced through g

Signal: $\psi(\mathbf{8}) \rightarrow q S_{LQ} \rightarrow q \bar{q} \ell$ 2j+a lepton

Gluino in SUSY $\tilde{g} \rightarrow q \tilde{q}^* \rightarrow q \bar{q} \chi_1^0$ 2j+Missing E

Gluino in RpV SUSY $\psi(\mathbf{8}) \rightarrow qqq$ 3j ATLAS, 1804.03568

$pp \rightarrow \psi(\mathbf{8}) \bar{\psi}(\mathbf{8}) \rightarrow 2q 2\bar{q} \ell^+ \ell^-$ Carquin et al., 1904.07257

LHC run-III will set the bound at $M_\psi > 2.5\text{TeV}$

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Gluino in RpV SUSY $\psi(\mathbf{8}) \rightarrow qqq$ 3j ATLAS, 1804.03568

$pp \rightarrow \psi(\mathbf{8})\bar{\psi}(\mathbf{8}) \rightarrow 2q2\bar{q}\ell^+\ell^-$ Carquin et al., 1904.07257

LHC run-III will set the bound at $M_\psi > 2.5\text{TeV}$

.....

Colour-3 fermion (vector-like quark)

* Search for 6 should be essentially the same

Production: Pair-produced through g

Signal: Depends on the int. VLQs have

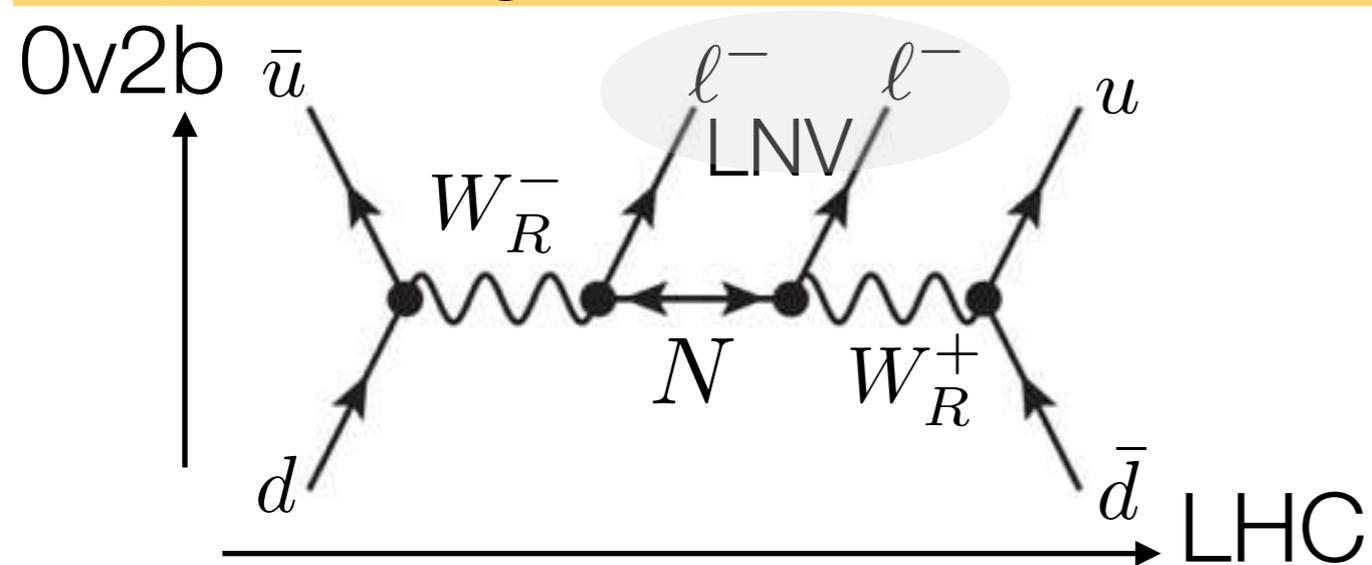
e.g., $\psi(\mathbf{3}) \rightarrow uS \rightarrow uue$

Typically the bounds are around $\sim 1\text{ TeV}$ cf. Nikiforou, 1808.04695

Neutral fermions

SM ν , sterile ν , heavy right-handed ν , etc...

Typical signal for TeV N is $pp \rightarrow \ell\ell jj$ through the EW Drell-Yan



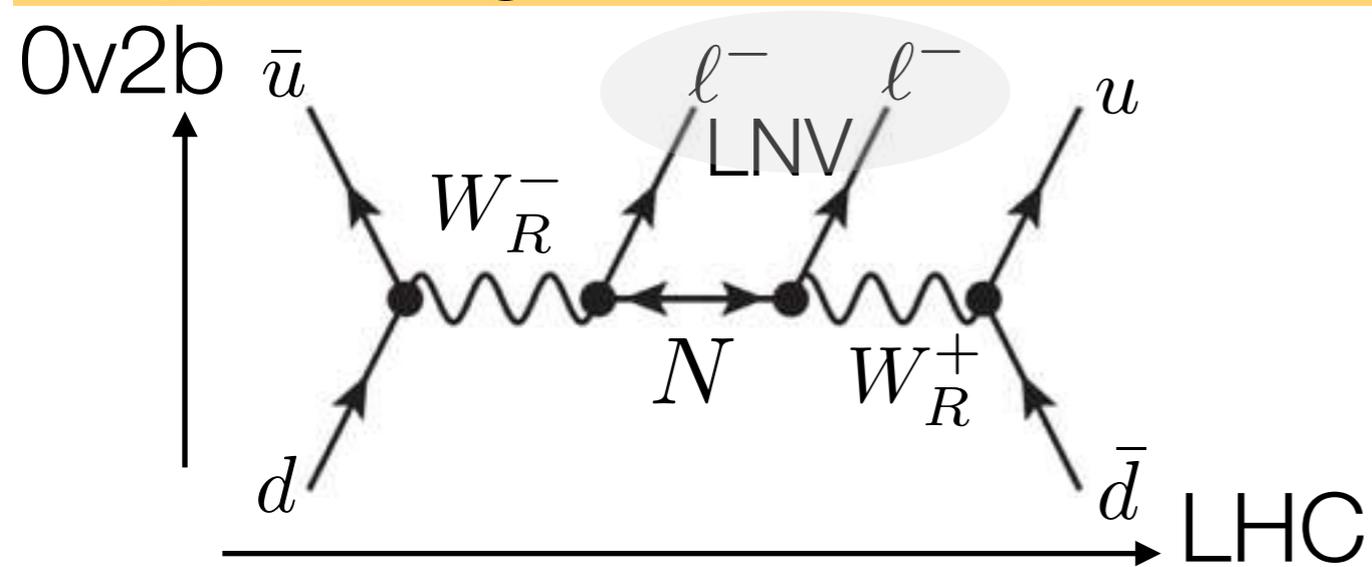
$\ell^\pm \ell^\pm$ Direct test of LNV
contribution to 0v2b

LHC bounds depend
on the “ingredients”

Neutral fermions

SM ν , sterile ν , heavy right-handed ν , etc...

Typical signal for TeV N is $pp \rightarrow \ell\ell jj$ through the EW Drell-Yan

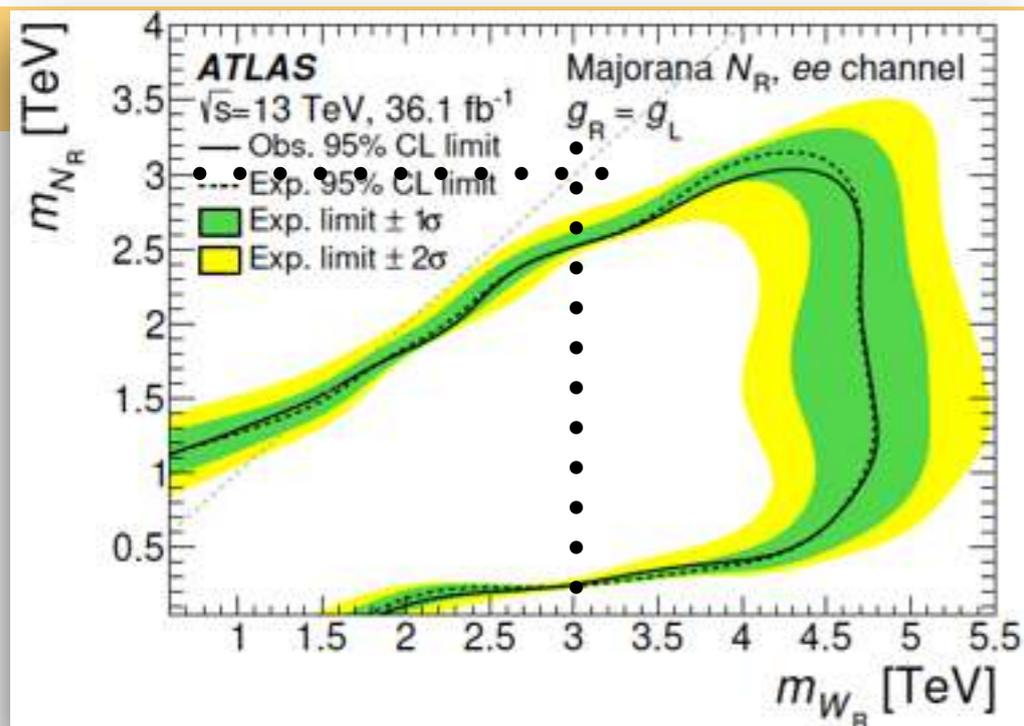


$\ell^\pm \ell^\pm$ Direct test of LNV contribution to $0\nu 2b$

LHC bounds depend on the “ingredients”

W_R-N-W_R inspired by LR sym.

WR-N-WR, CMS 1803.11116, ATLAS 1809.11105.



$W_R = \text{colour-1 diquark } M_{W_R} \gtrsim 4 \text{ TeV}$

$0\nu 2b$ amp. mediated by W_R-N-W_R

$$\mathcal{A}_{0\nu 2\beta}^{W_R N W_R} = 2 \cdot 10^{-20} [\text{GeV}^{-5}] \left[\frac{3 \text{ TeV}}{M_{W_R}} \right]^4 \left[\frac{3 \text{ TeV}}{M_N} \right]$$

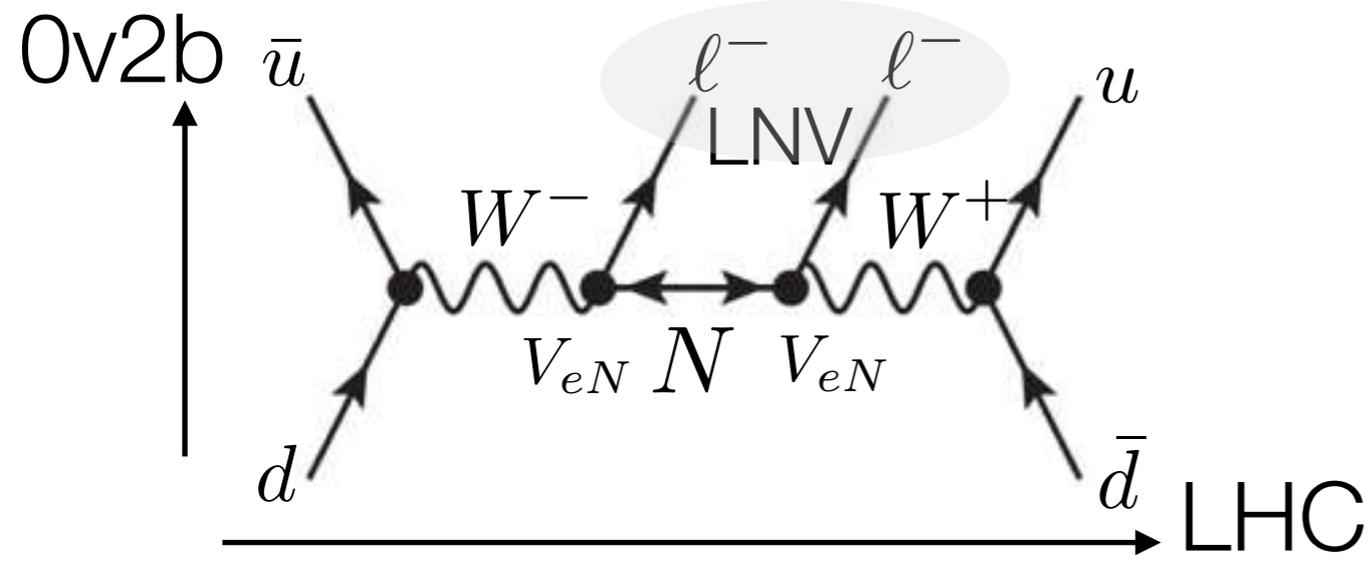
comparable with

$$\mathcal{A}_{0\nu 2\beta}^{\text{SM}} = 6.8 \cdot 10^{-19} [\text{GeV}^{-5}] \left[\frac{m_{\beta\beta}}{0.05 \text{ eV}} \right]$$

Neutral fermions

SM ν , sterile ν , heavy right-handed ν , etc...

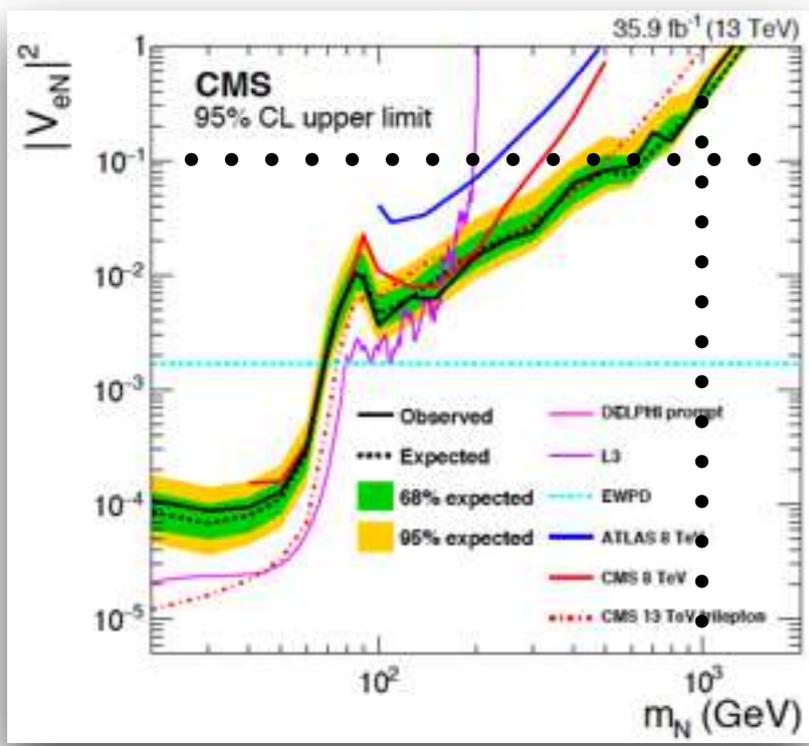
Typical signal for TeV N is $pp \rightarrow \ell\ell jj$ through the EW Drell-Yan



$\ell^\pm \ell^\pm$ Direct test of LNV contribution to $0\nu 2b$

LHC bounds depend on the “ingredients”

$W-N-W$ inspired by e.g., TeV seesaw W-N-W, CMS 1806.10905



Bound is much weaker than W_R-N-W_R

$$\mathcal{A}_{0\nu 2\beta}^{WN} = 10^{-14} [\text{GeV}^{-5}] \left[\frac{V_{eN}^2}{0.1} \right] \left[\frac{1\text{TeV}}{M_N} \right]$$

If LHC sees this N , $0\nu 2b$ has already seen it.
cf. e.g., Blennow et al., 1005.3240

$$\mathcal{A}_{0\nu 2\beta}^{\text{SM}} = 6.8 \cdot 10^{-19} [\text{GeV}^{-5}] \left[\frac{m_{\beta\beta}}{0.05\text{eV}} \right]$$

Short summary for NP in $0\nu 2b$

A conflict among $0\nu 2b$, oscillation, and cosmology in future may suggest NP beyond vSM.

$0\nu 2b$ experiments are sensitive not only to Majorana neutrino mass, but also to NP at TeV.

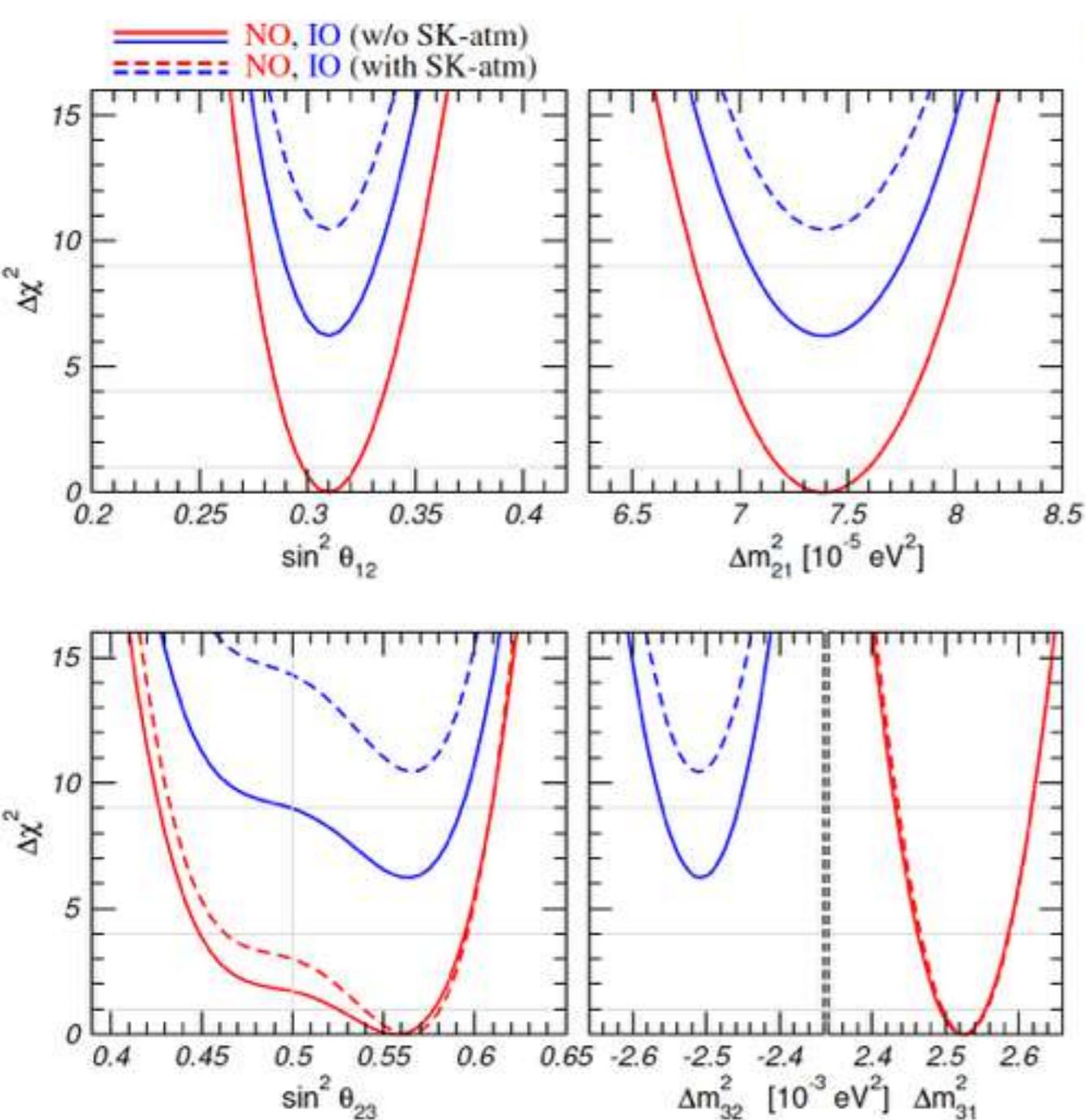
The searches for the mediators are on-going at LHC.

#2.

We will have large “neutrino”
detectors in the next decade...

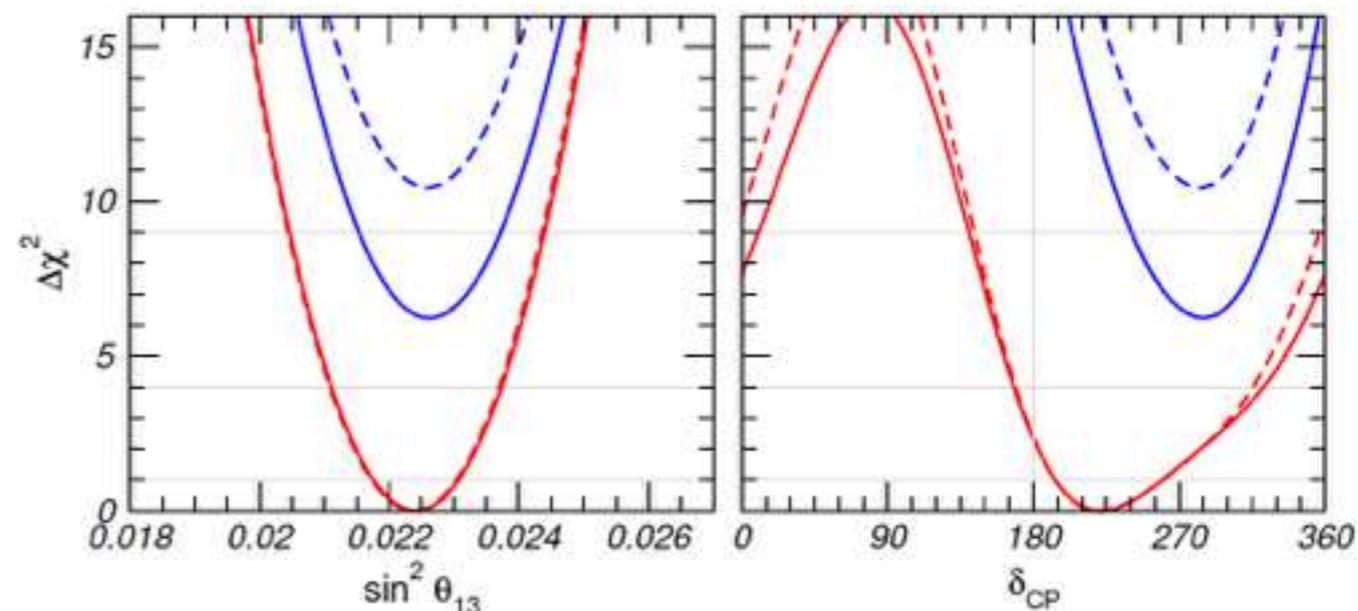
Current status of the ν osc. expts

Neutrino physics is shifting from Discovery phase to Precision era



NuFIT 4.1 (2019)

Esteban et al., 1811.05487



We will know

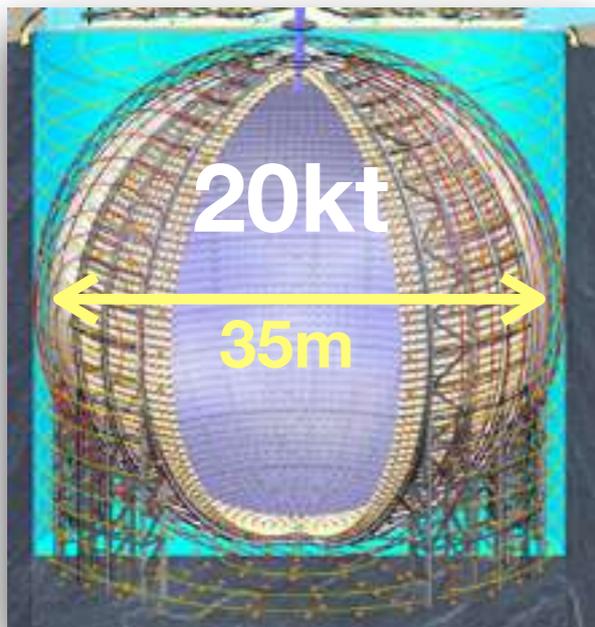
CP violating phase

Mass hierarchy

Octant of θ_{23}

More precision = More statistics = Large volume detectors

Large volume “neutrino” detectors



20 kt liquid scintillator
(35kt water Cherenkov veto)

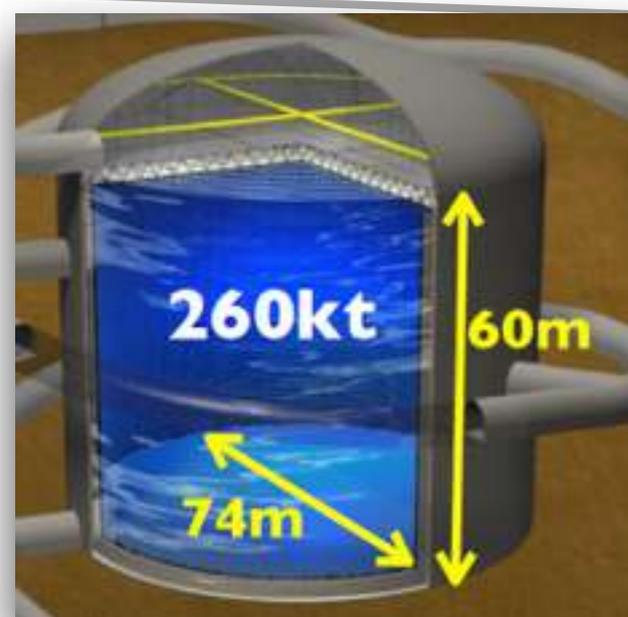
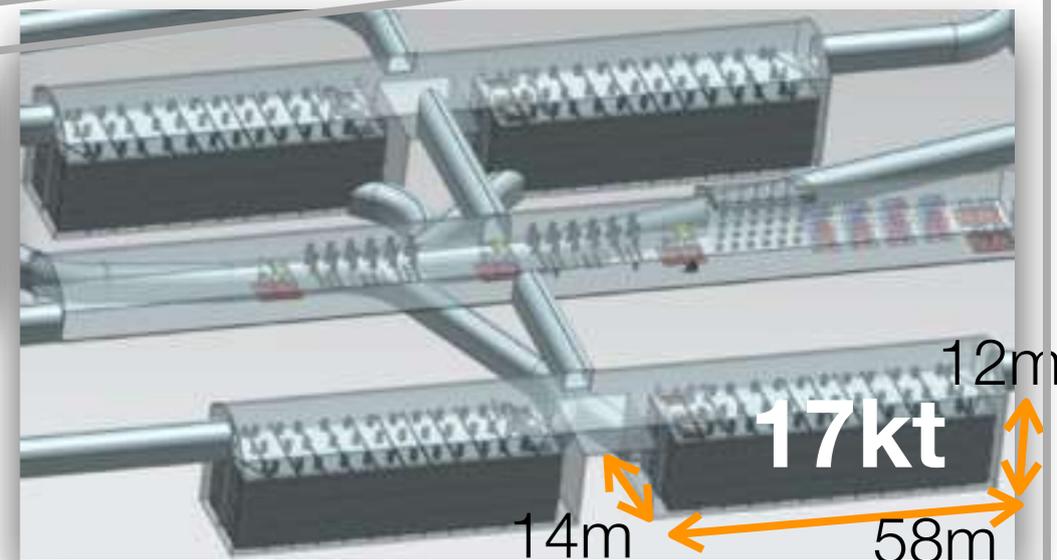
$$\frac{\Delta m_{\text{sol.}}^2 L}{4E} \sim \frac{\pi}{2}$$

Start taking data in 2021

Liquid Ar TPC



4 × 17 kt (Fiducial 10 kt) modules
Installation of the 1st module in 2025



260 kt (Fiducial 190 kt)
Water Cherenkov
Expected to start in 2026
MEXT: green-light to the construction

$$\frac{\Delta m_{\text{atm.}}^2 L}{4E} \sim \frac{\pi}{2}$$

Proposal:
2nd detector in Korea

Large volume “neutrino” detectors



European Spallation Source ν SuperBeam

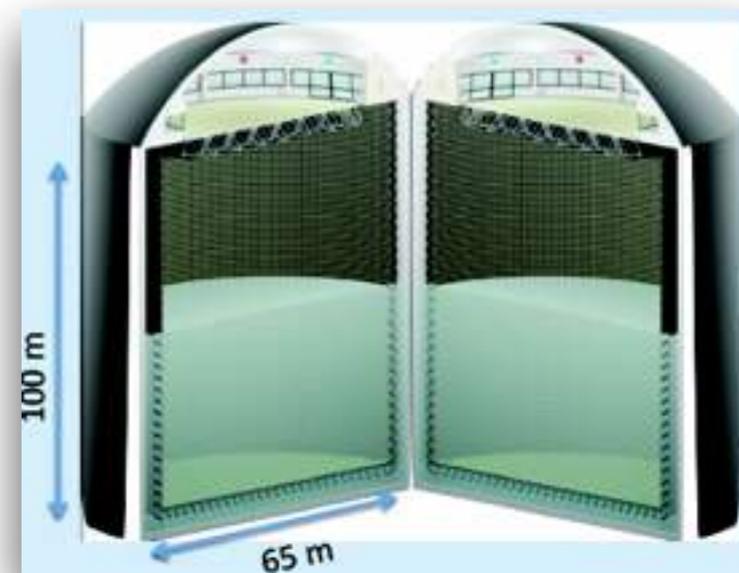
<https://essnusb.eu>

MEMPHYHS (MEga-ton Mass PHYSics) proposal

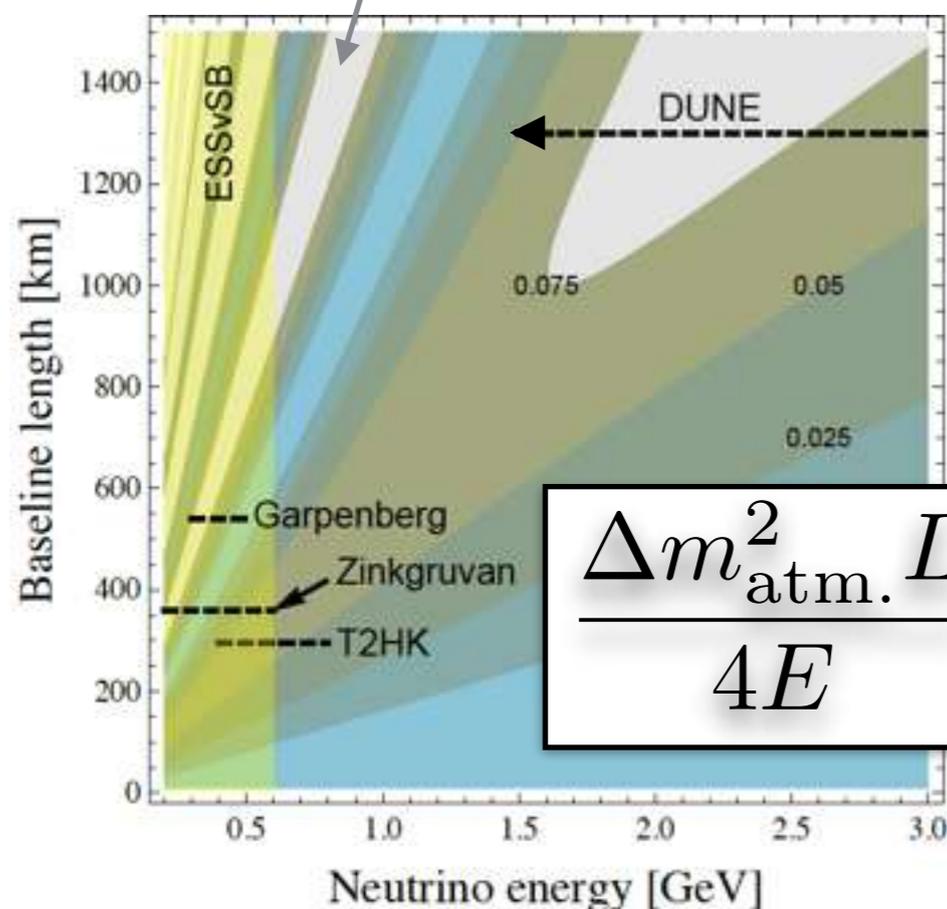
LAGUNA, hep-ex/0607026

0.5 Mt (fiducial) WC

(240k 8”PMTs, 30% photo cover.)



2nd osc. maximum



$$\frac{\Delta m_{\text{atm.}}^2 L}{4E} \sim \frac{3\pi}{2}$$

cf. Talk by Dracos @ICHEP 2018

ESS@Lund, Sweden in Apr. 2019



1st proton-on-target in 2023

Kamioka-NDE カミオカンデ

Neutrino Detection Experiment

Nucleon Decay Experiment

Why NDE? - GUT!

Why GUTs? — $q_p + q_e = 0$

Why NDE? - GUT!

Why GUTs? — $q_p + q_e = 0$

— Quarks and leptons in a box

$$\mathbf{10} \ni \{u_R^c, Q, e_R^c\}$$

$$\bar{\mathbf{5}} \ni \{d_R^c, L\}$$

Georgi Glashow (1974)

N BARYONS
 $(S = 0, I = 1/2)$

$p, N^+ = uud; \quad n, N^0 = udd$

p

$$I(J^P) = \frac{1}{2}(\frac{1}{2}^+)$$

Mass $m = 1.00727646688 \pm 0.00000000009$ u

Mass $m = 938.272081 \pm 0.000006$ MeV [a]

$|m_p - m_{\bar{p}}|/m_p < 7 \times 10^{-10}$, CL = 90% [b]

$|\frac{q_{\bar{p}}}{m_{\bar{p}}}|/(\frac{q_p}{m_p}) = 1.00000000000 \pm 0.00000000007$

$|q_p + q_{\bar{p}}|/e < 7 \times 10^{-10}$, CL = 90% [b]

$|q_p + q_e|/e < 1 \times 10^{-21}$ [c]

Magnetic moment $\mu = 2.1928473446 \pm 0.0000000008 \mu_N$

$(\mu_p - \mu_{\bar{p}})/\mu = (0.3 \pm 0.8) \times 10^{-6}$

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Citation: M. Tanabashi et al. (Particle Data Group), Phys. Rev. D 98, 030001 (2018)

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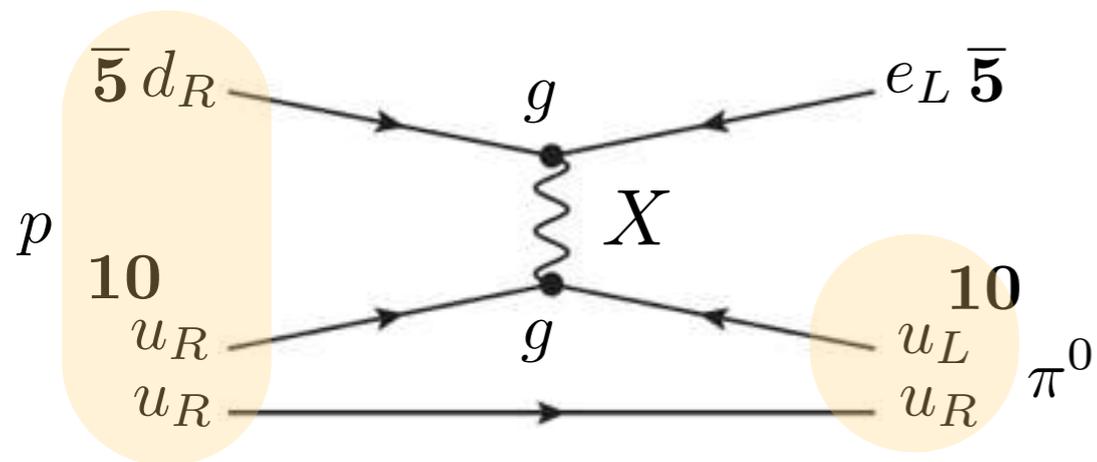
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(...) / ... = (0.2 + 0.8) x 10^-6

Grand unifications in general suggest...

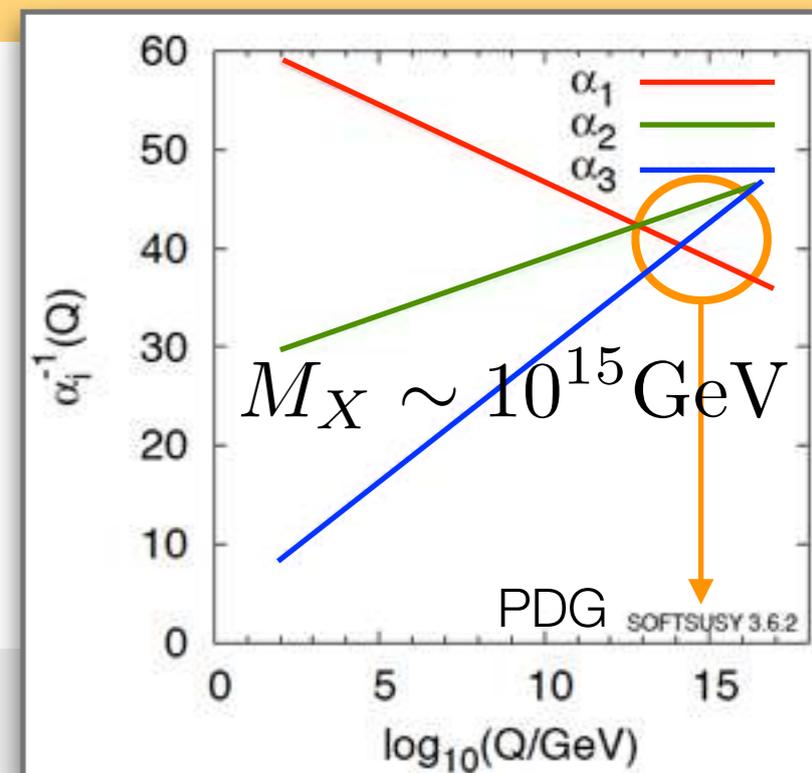


Georgi Quinn Weinberg (1974)

Lifetime is roughly...

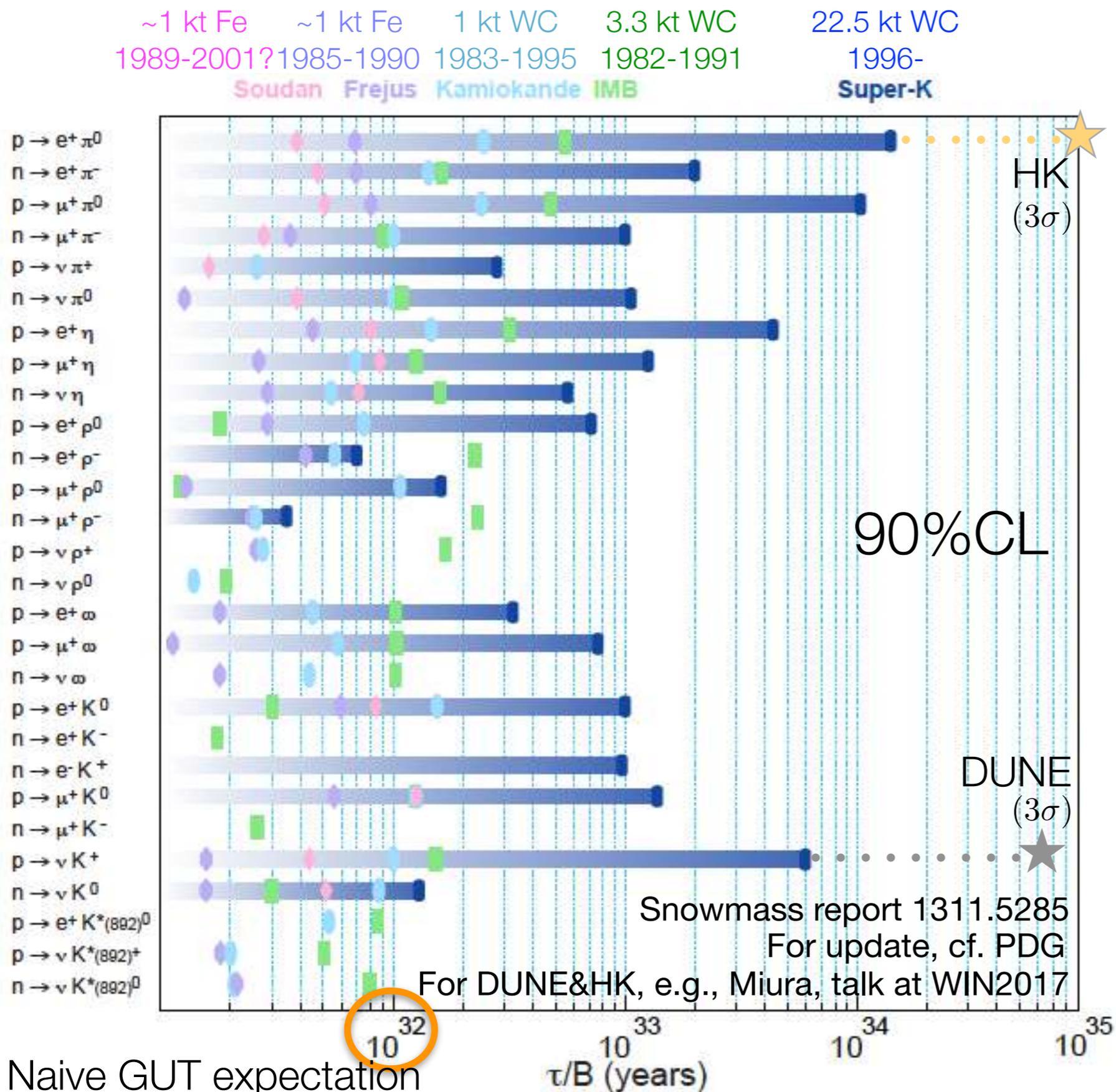
$$\frac{1}{\tau_p} \sim m_p^5 \left| \frac{g^2}{M_X^2} \right|^2$$

$$\tau(p \rightarrow \pi^0 e^+) \sim \mathcal{O}(10^{32}) \text{ yrs}$$



which is reachable with an O(1) kt detector in a year — NDEs

Past, Now and Future of NDEs



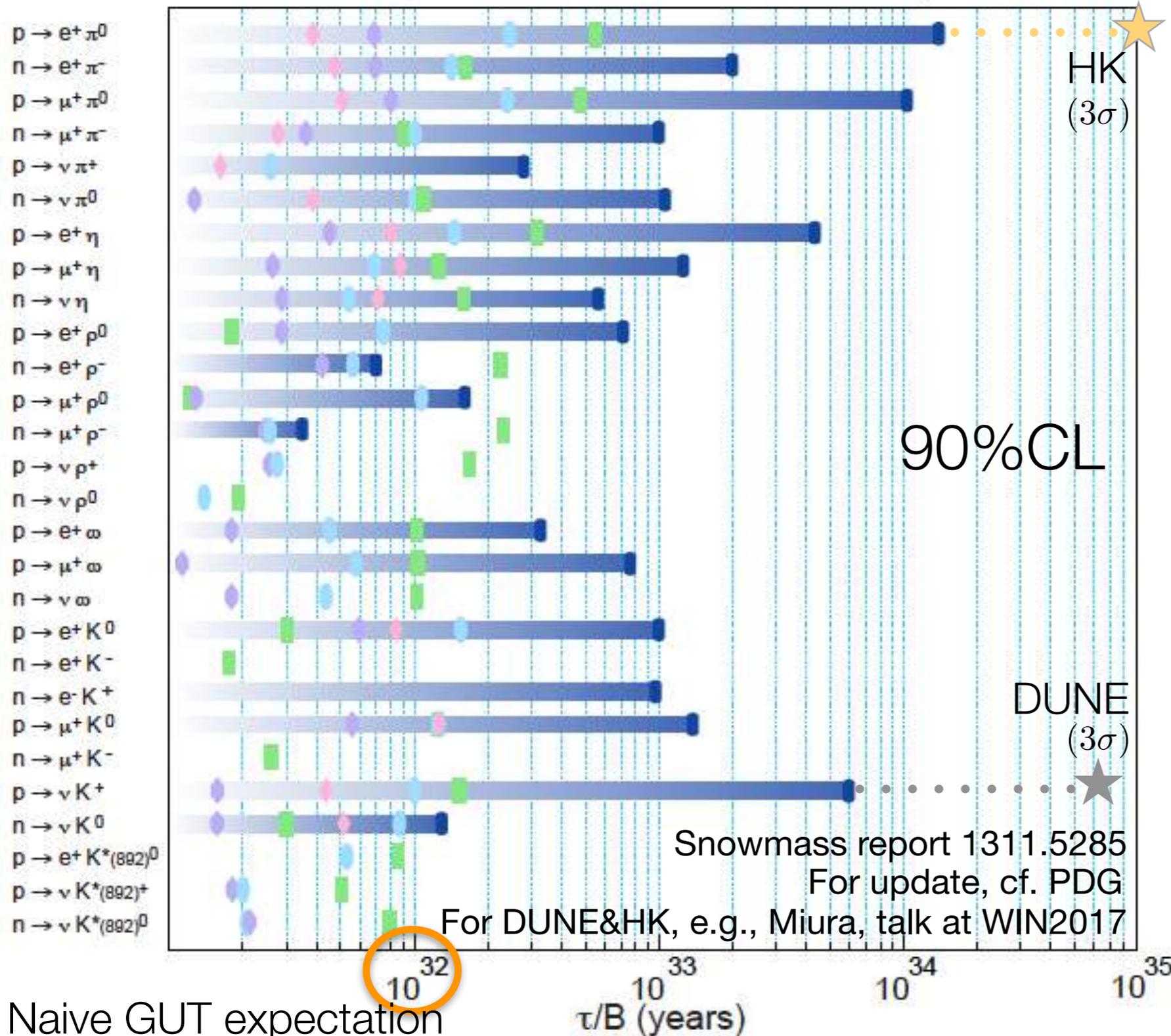
Past, Now and Future of NDEs

~1 kt Fe 1989-2001? Soudan
 ~1 kt Fe 1985-1990 Frejus
 1 kt WC 1983-1995 Kamiokande
 3.3 kt WC 1982-1991 IMB
 22.5 kt WC 1996- Super-K

GUT \rightarrow Proton decay

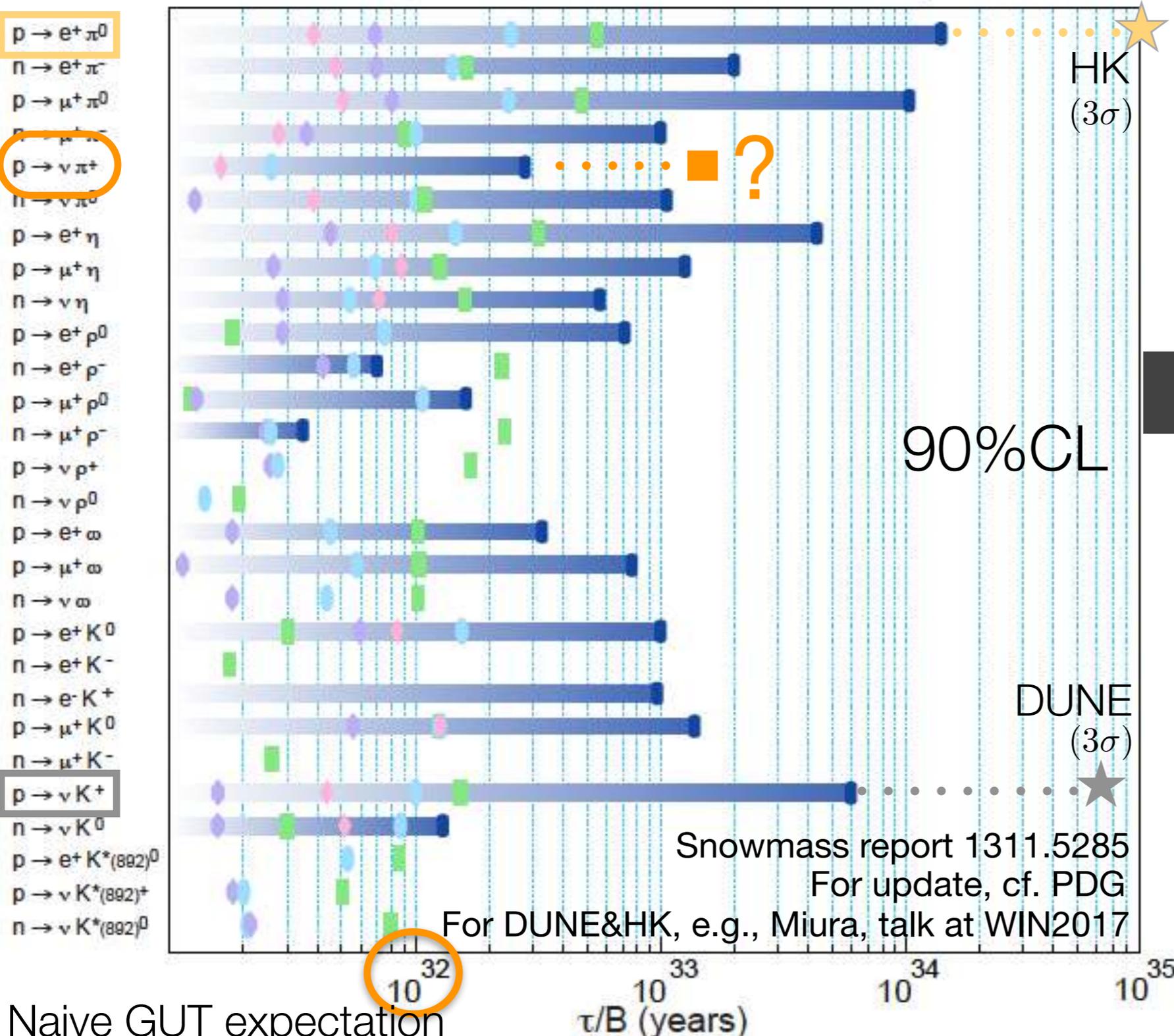
Proton decay \rightarrow GUT?

Review the possibilities w. a bottom up app.



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GUT → Proton decay

Proton decay → GUT?

Review the possibilities w. a bottom up app.

Benchmark modes

$$p \rightarrow \pi^0 + e^+$$

for GUT

$$p \rightarrow K^+ + \bar{\nu}$$

for SUSY-GUT

Can the other modes tell us something?

Bottom up approach - SMEFT

At $d=4$, SM conserves B and L (at the perturbative level)

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At $d=5$, SMEFT accommodates Majorana masses for neutrinos

$$\mathcal{L}_5 = \frac{c}{\Lambda} (\overline{L^c} i\tau^2 H)(H i\tau^2 L) + \text{H.c.} \quad \Delta L = 2 \quad \text{Weinberg (1979)}$$

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At $d=6$, SMEFT can violate B+L (but conserves B-L)

$$\mathcal{L}_6 \supset \frac{1}{\Lambda^2} \sum_i C_i \mathcal{O}_i + \text{H.c.}$$

Four-Fermi ops. with
3 quarks & 1 lepton
 $\Delta B = 1 \quad \Delta L = 1$

$$\begin{aligned} \mathcal{O}_1 &= \epsilon^{IJK} (\overline{d_R^c}^I u_{RJ}) (\overline{Q^c}^K i\tau^2 L) \\ \mathcal{O}_2 &= \epsilon^{IJK} (\overline{Q^c}^I i\tau^2 Q_J) (\overline{u_R^c}^K e_R) \\ \mathcal{O}_3 &= \epsilon^{IJK} (\overline{Q^c}^I i\tau^2 Q_J) (\overline{Q^c}^K i\tau^2 L) \\ \mathcal{O}_4 &= \epsilon^{IJK} (\overline{Q^c}^I i\tau^2 \tau^a Q_J) (\overline{Q^c}^K i\tau^2 \tau^a L) \\ \mathcal{O}_5 &= \epsilon^{IJK} (\overline{d_R^c}^I u_{RJ}) (\overline{u_R^c}^K e_R) \end{aligned}$$

Weinberg (1979), Wilczek&Zee (1979), Abbott&Wise (1980)

They lead to 2-body proton decays, $p \rightarrow \text{meson} + \text{anti-lepton}$

For nucleon decays with $d>6$ ops: Heeck&Takhistov 1910.07647, Hambye&Heeck 1712.04871,

Fonseca et al., 1802.04814, and talk by Hirsch in this workshop

What can we learn from the eff.ops?

If we will find $p \rightarrow \pi^+ + \text{missing}$ at the next NDEs... $\tau_p \sim 10^{33} \text{ yrs}$

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but...

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————— B+L is violated only with the 3rd gen. lepton.
- A hint to the flavor structure

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or

$$p \rightarrow \pi^+ + \bar{\nu}_s$$

———— No charged lepton counterpart

SM singlet fermion, aka Sterile neutrino/Right-handed neutrino

A model for $p \rightarrow \pi^+ + \overline{N}$

There are two additional effective operators with N

$$\mathcal{O}_{N1} = (QQ)(d_R N)$$

$$\mathcal{O}_{N2} = (u_R d_R)(d_R N)$$

cf. e.g., Alonso et al.,
1405.0486

Light N has rich phenomenology

A model for $p \rightarrow \pi^+ + \bar{N}$

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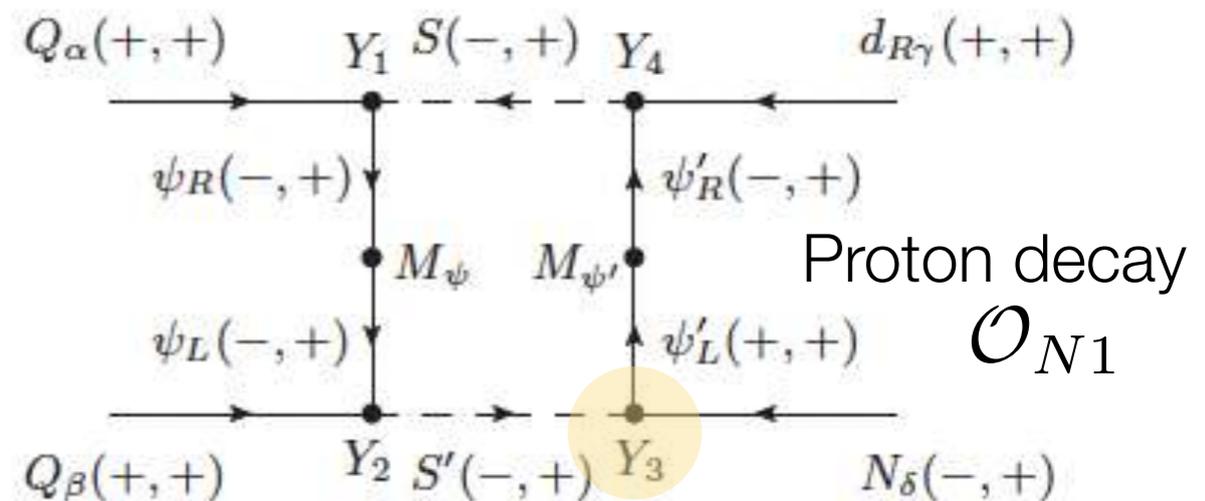
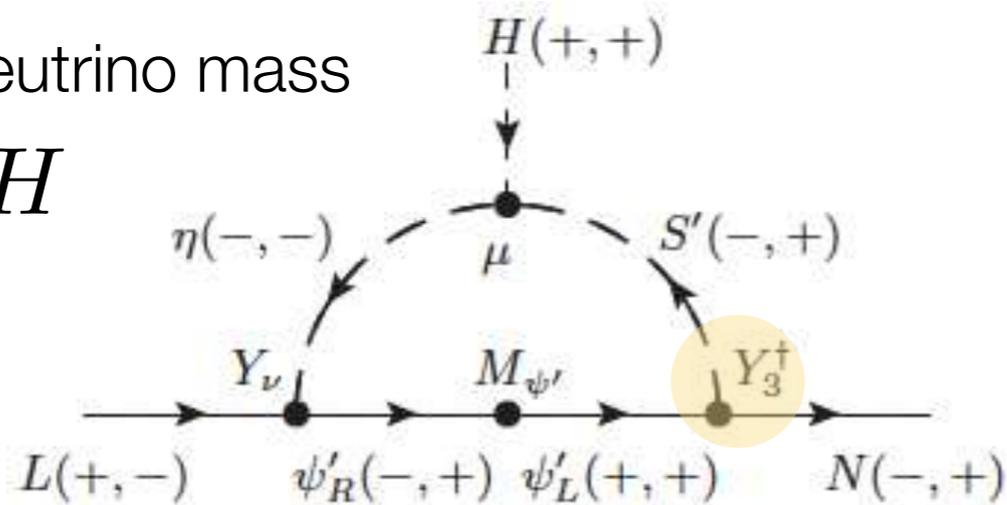
Light N has rich phenomenology

Smallness of neutrino masses \longleftrightarrow Longevity of protons

Helo et al.,
1803.00035

Dirac neutrino mass

$$\bar{N} L H$$



with 2 vector-like fermions and 3 scalars

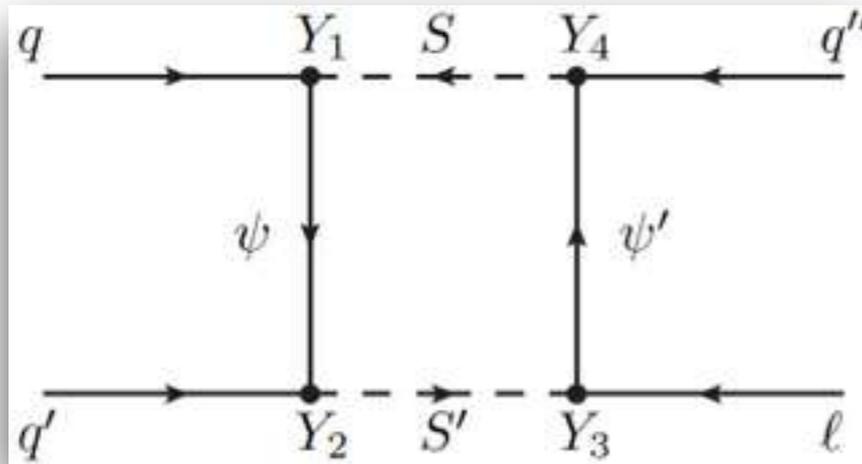
$$\psi'(\mathbf{1}, \mathbf{1})_0 \quad \psi(\bar{\mathbf{3}}, \mathbf{2})_{-1/6} \quad \eta(\mathbf{1}, \mathbf{2})_{+1/2} \quad S'(\mathbf{1}, \mathbf{1})_0 \quad S(\mathbf{3}, \mathbf{1})_{-1/3}$$

With $M, \mu \sim \text{TeV}$, the size of the couplings Y s are roughly $\mathcal{O}(10^{-5})$
for $m_\nu \sim \mathcal{O}(0.1) \text{ eV}$ $\tau_p \sim \mathcal{O}(10^{32}) \text{ yrs}$

Models for p-decay at 1-loop

* Tree = Leptoquarks

Decompose the eff. ops into...

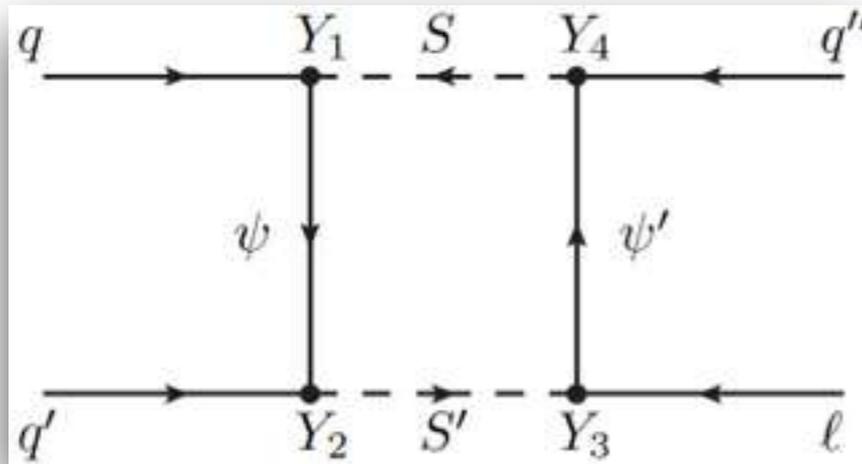


Helo et al.,
1904.00036

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Helo et al.,
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Charges of
 ψ S ψ' S'

Common for all \mathcal{O} s

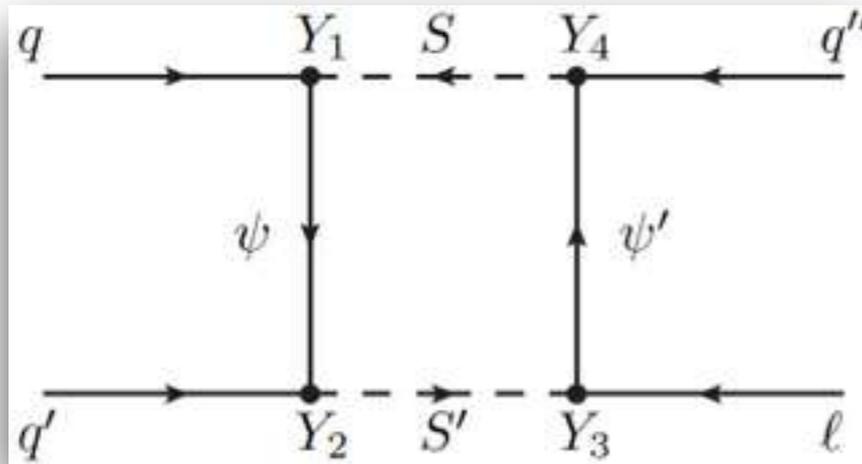
	Mediators				$SU(3)$ coeff.
	ψ	S	ψ'	S'	
#1	1	$\bar{3}$	3	3	-1
#2	3	1	$\bar{3}$	$\bar{3}$	1
#3	3	8	$\bar{3}$	$\bar{3}$	$-\frac{8}{3}$
#4	3	8	6	6	4
#5	$\bar{3}$	3	1	1	1
#6	$\bar{3}$	3	8	8	$-\frac{8}{3}$
#7	$\bar{3}$	$\bar{6}$	8	8	-4
#8	6	3	8	8	4
#9	$\bar{6}$	8	$\bar{3}$	$\bar{3}$	-4
#10	8	$\bar{3}$	3	3	$\frac{8}{3}$
#11	8	$\bar{3}$	$\bar{6}$	$\bar{6}$	-4
#12	8	6	3	3	4

Choices for the $SU(3)$ colour

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Helo et al.,
1904.00036

$(qq')(q''l)$

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Choices for the $SU(2) \times U(1)$

For $\mathcal{O}_1 = [d_R u_R][QL]$

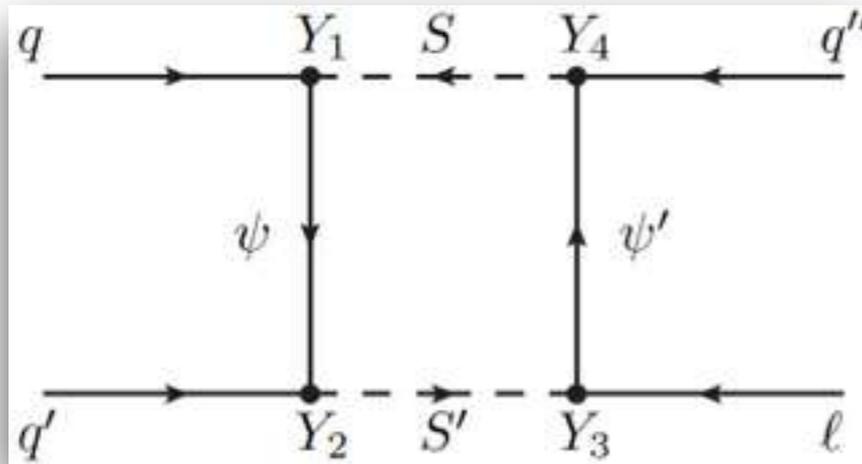
\mathcal{O}_1	Mediators $SU(2)_{U(1)}$				$SU(2)$ coeff.	Fierz \times Loop factors	$SU(3)$ sign
Decom.	ψ	S	ψ'	S'			
$(du)(QL)$	1_α	$1_{\alpha+\frac{1}{3}}$	$2_{\alpha+\frac{1}{6}}$	$1_{\alpha+\frac{2}{3}}$	1	$M_\psi M_{\psi'} I_4$	+
	2	2	1	2	-1		
	2	2	3	2	-3		
	3	3	2	3	3		
$(ud)(QL)$	1_α	$1_{\alpha-\frac{2}{3}}$	$2_{\alpha-\frac{5}{6}}$	$1_{\alpha-\frac{1}{3}}$	1	$M_\psi M_{\psi'} I_4$	-
	2	2	1	2	-1		
	2	2	3	2	-3		
	3	3	2	3	3		
$(dQ)(uL)$	1_α	$1_{\alpha+\frac{1}{3}}$	$1_{\alpha-\frac{1}{3}}$	$2_{\alpha+\frac{1}{6}}$	-1	$-\frac{1}{2} J_4$	-
	2	2	2	1	-1		
	2	2	2	3	3		
	3	3	3	2	-3		
$(Qd)(uL)$	1_α	$2_{\alpha-\frac{1}{6}}$	$2_{\alpha-\frac{5}{6}}$	$1_{\alpha-\frac{1}{3}}$	1	$\frac{1}{2} J_4$	+
	2	1	1	2	-1		
	2	3	3	2	-3		
	3	2	2	3	3		
$(uQ)(dL)$	1_α	$1_{\alpha-\frac{2}{3}}$	$1_{\alpha-\frac{1}{3}}$	$2_{\alpha+\frac{1}{6}}$	-1	$-\frac{1}{2} J_4$	+
	2	2	2	1	-1		
	2	2	2	3	3		
	3	3	3	2	-3		
$(Qu)(dL)$	1_α	$2_{\alpha-\frac{1}{6}}$	$2_{\alpha+\frac{1}{6}}$	$1_{\alpha+\frac{2}{3}}$	1	$\frac{1}{2} J_4$	-
	2	1	1	2	-1		
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Choices for the $SU(2) \times U(1)$

For $\mathcal{O}_1 = [d_R u_R][QL]$

\mathcal{O}_1	Mediators $SU(2)_{U(1)}$				$SU(2)$ coeff.	Fierz \times Loop factors	$SU(3)$ sign
Decom.	ψ	S	ψ'	S'			
$(du)(QL)$	1_α	$1_{\alpha+\frac{1}{3}}$	$2_{\alpha+\frac{1}{6}}$	$1_{\alpha+\frac{2}{3}}$	1	$M_\psi M_{\psi'} I_4$	+
	2	2	1	2	-1		
	2	2	3	2	-3		
	3	3	2	3	3		
$(ud)(QL)$	1_α	$1_{\alpha-\frac{2}{3}}$	$2_{\alpha-\frac{5}{6}}$	$1_{\alpha-\frac{1}{3}}$	1	$M_\psi M_{\psi'} I_4$	-
	2	2	1	2	-1		
	2	2	3	2	-3		
	3	3	2	3	3		
$(dQ)(uL)$	1_α	$1_{\alpha+\frac{1}{3}}$	$1_{\alpha-\frac{1}{3}}$	$2_{\alpha+\frac{1}{6}}$	-1	$-\frac{1}{2} J_4$	-
	2	2	2	1	-1		
	2	2	2	3	3		
	3	3	3	2	-3		
$(Qd)(uL)$	1_α	$2_{\alpha-\frac{1}{6}}$	$2_{\alpha-\frac{5}{6}}$	$1_{\alpha-\frac{1}{3}}$	1	$\frac{1}{2} J_4$	+
	2	1	1	2	-1		
	2	3	3	2	-3		
	3	2	2	3	3		
$(uQ)(dL)$	1_α	$1_{\alpha-\frac{2}{3}}$	$1_{\alpha-\frac{1}{3}}$	$2_{\alpha+\frac{1}{6}}$	-1	$-\frac{1}{2} J_4$	+
	2	2	2	1	-1		
	2	2	2	3	3		
	3	3	3	2	-3		
$(Qu)(dL)$	1_α	$2_{\alpha-\frac{1}{6}}$	$2_{\alpha+\frac{1}{6}}$	$1_{\alpha+\frac{2}{3}}$	1	$\frac{1}{2} J_4$	-
	2	1	1	2	-1		
	2	3	3	2	-3		
	3	2	2	3	3		

Choices for the $SU(3)$ colour

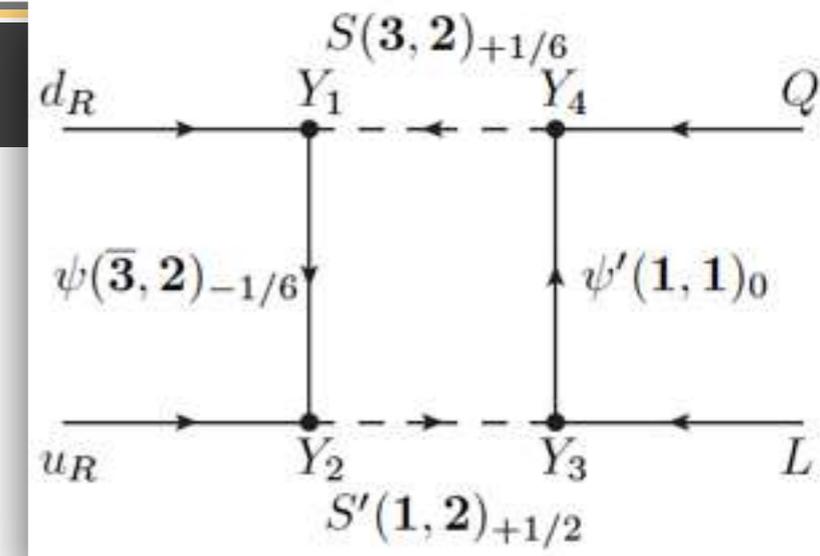
Inspired by Scotogenic model

Ma (2006)

radiative $m_\nu + \text{DM}$

Proton decays $p \rightarrow \pi^0 \ell^+ / \pi^+ \bar{\nu}_\ell$

$$\tau_p \sim 10^{34} [\text{yrs}] \left[\frac{\bar{M}}{1 \text{TeV}} \right]^4 \left[\frac{3 \cdot 10^{-6}}{\bar{Y}} \right]^8$$



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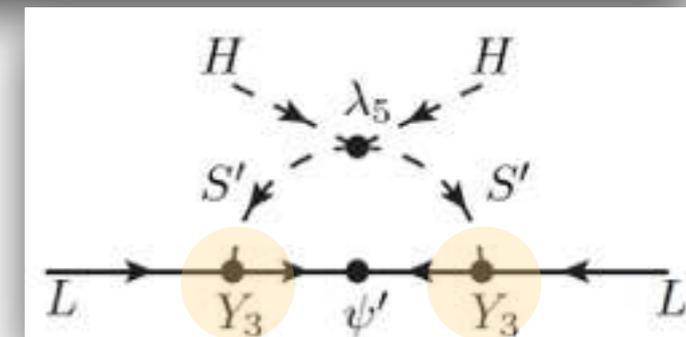
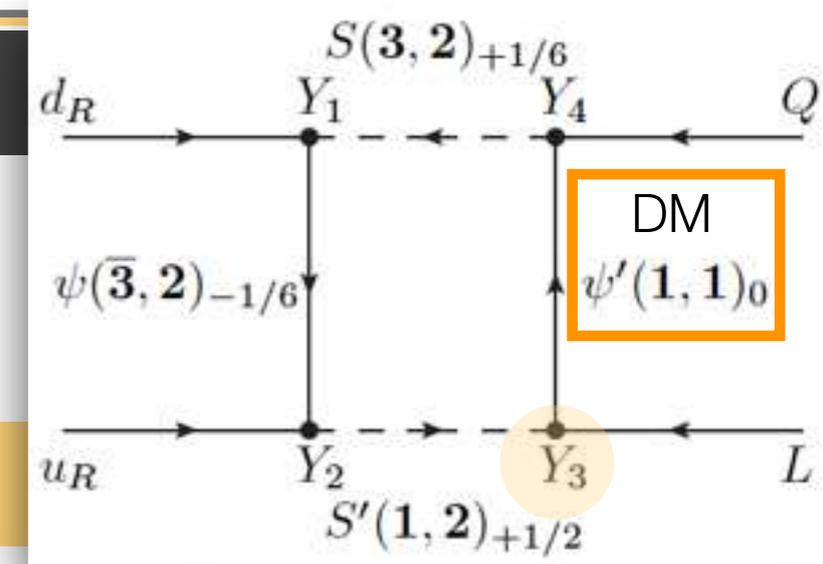
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m_ν a la scotogenic models $\overline{M} \sim \text{TeV}$

$$Y_3 \sim 10^{-5} \text{ for } \lambda_5 \sim 1$$

$Y_3 < \mathcal{O}(10^{-2})$ from the cLFV bounds



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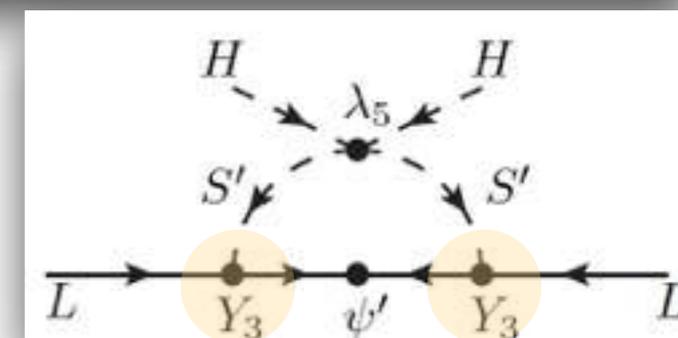
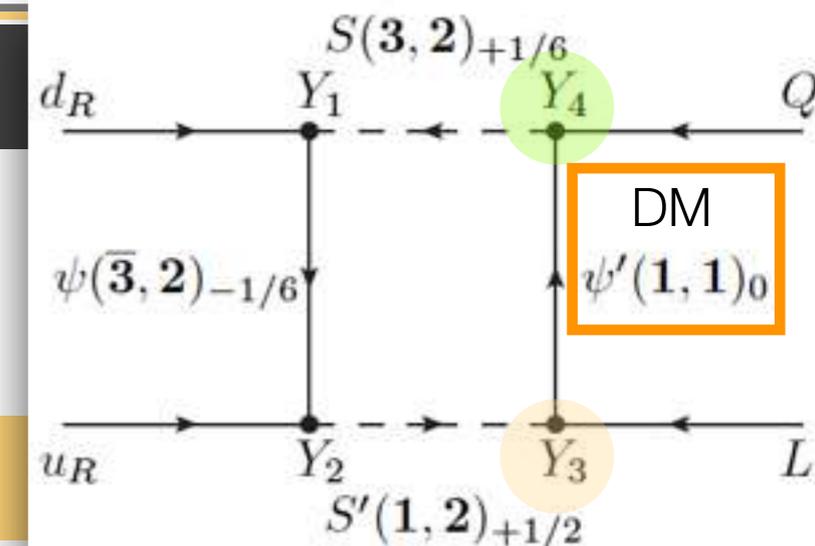
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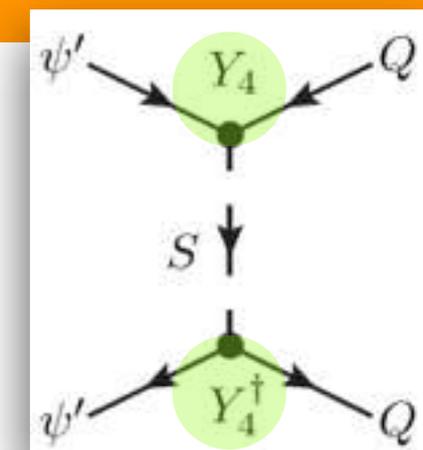
$Y_3 < \mathcal{O}(10^{-2})$ from the cLFV bounds



To reproduce the correct DM relic density

$$\text{Freeze-out DM: } \Omega_{\text{DM}} h^2 \sim 0.1 \left[\frac{2 \cdot 10^{-26} [\text{cm}^3/\text{s}]}{\langle \sigma v \rangle} \right]$$

$$\sum_{q=u,d} \langle \sigma(\psi' \psi' \rightarrow q \bar{q}) v \rangle \simeq 2 \cdot 10^{-26} [\text{cm}^3/\text{s}] \left[\frac{Y_4}{1.0} \right]^4 \left[\frac{\text{TeV}}{M} \right]^2$$



Inspired by Scotogenic model

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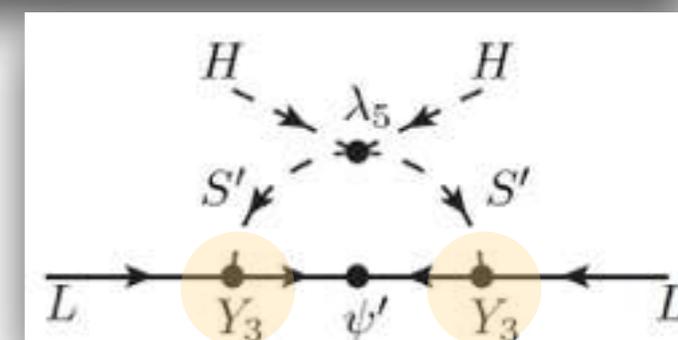
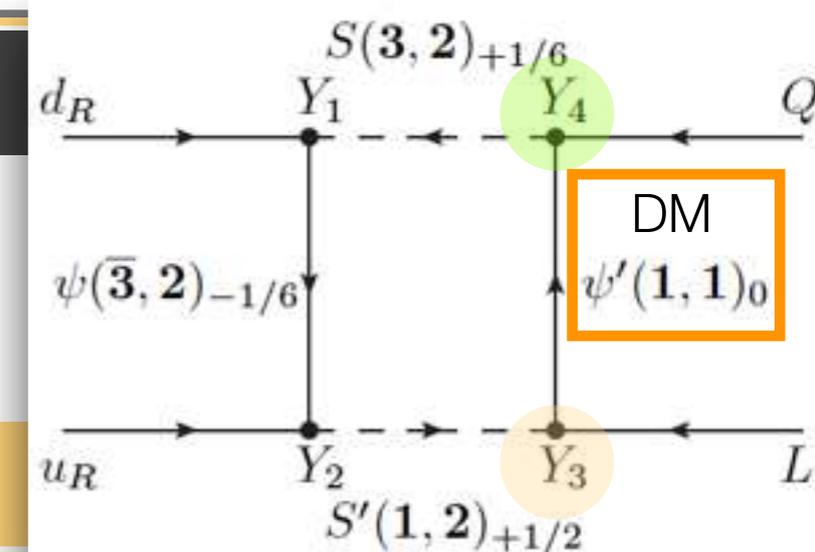
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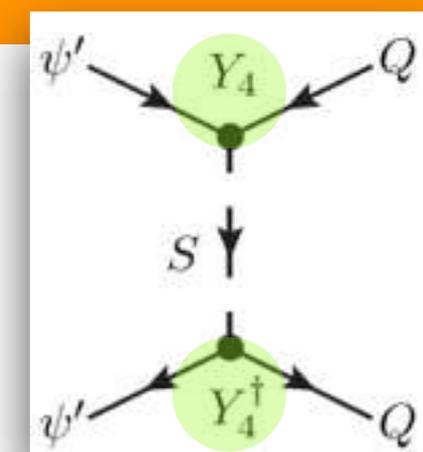
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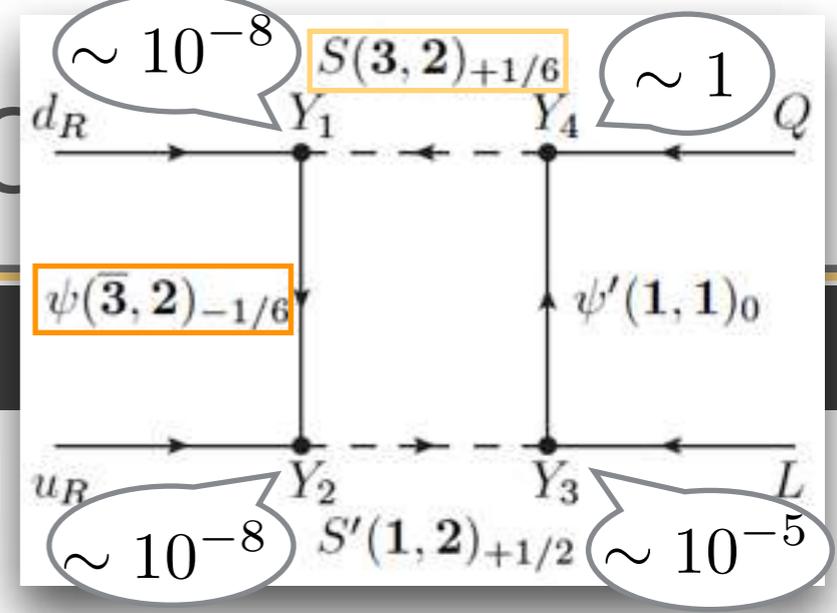


$$Y_3 \sim 10^{-5} \text{ \& } Y_4 \sim 1 \quad \tau_p \sim 10^{-34} \text{ yrs} \quad Y_{1,2} \sim 10^{-8}$$

Inspired by Scotogenic mod

LHC searches for the mediator fields

Colored ones are expected to be constrained



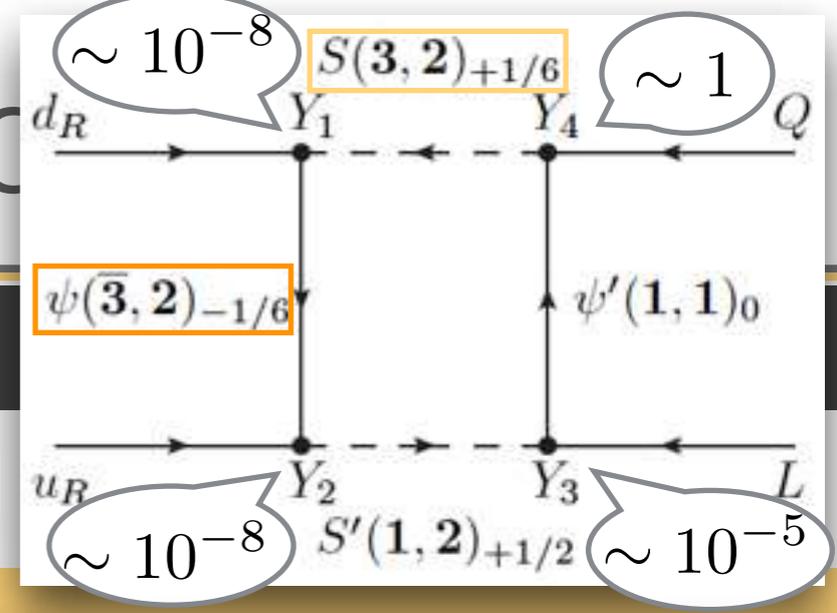
Inspired by Scotogenic mod

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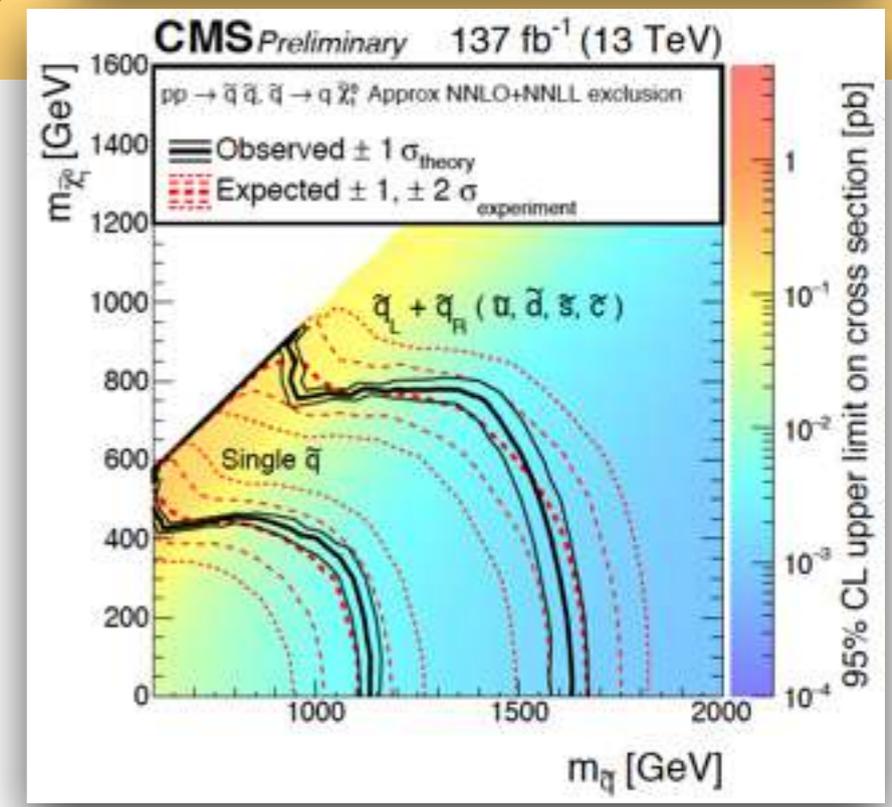
“Squark” search @LHC

CMS-SUS-19-006
@ EPS 2019



$$S \xrightarrow{Y_4} Q\psi' = \text{jet} + \text{missing}$$

No bound for $M_{\psi'} \gtrsim 1 \text{ TeV}$



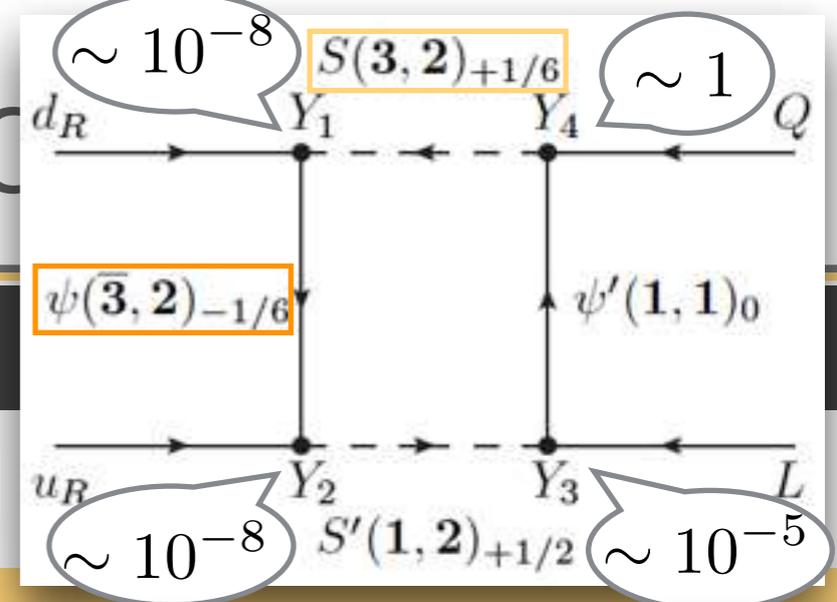
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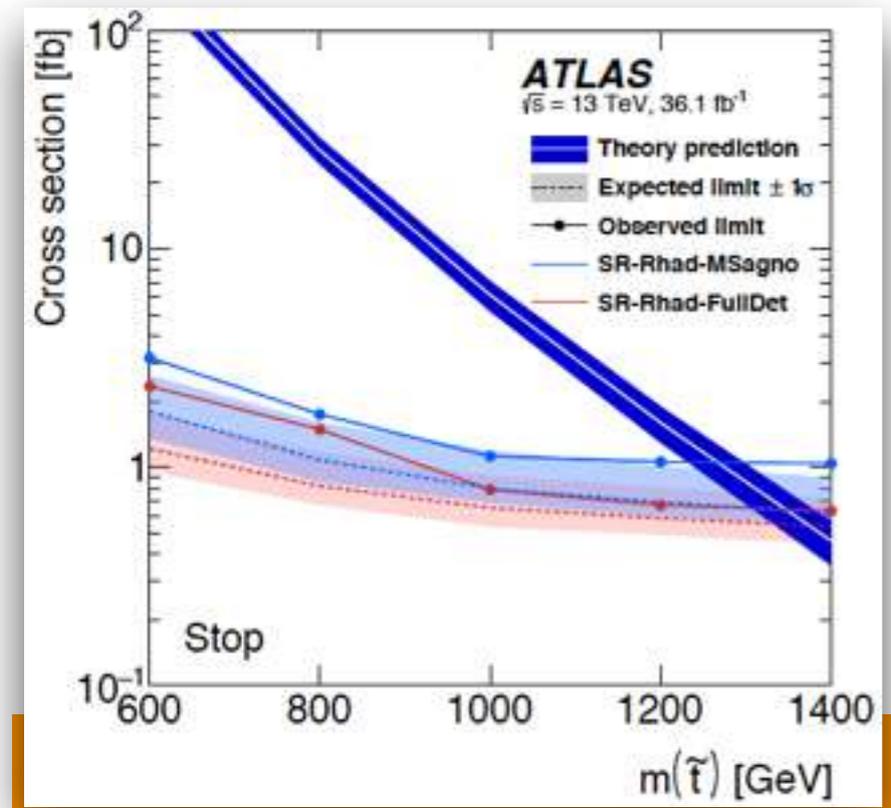
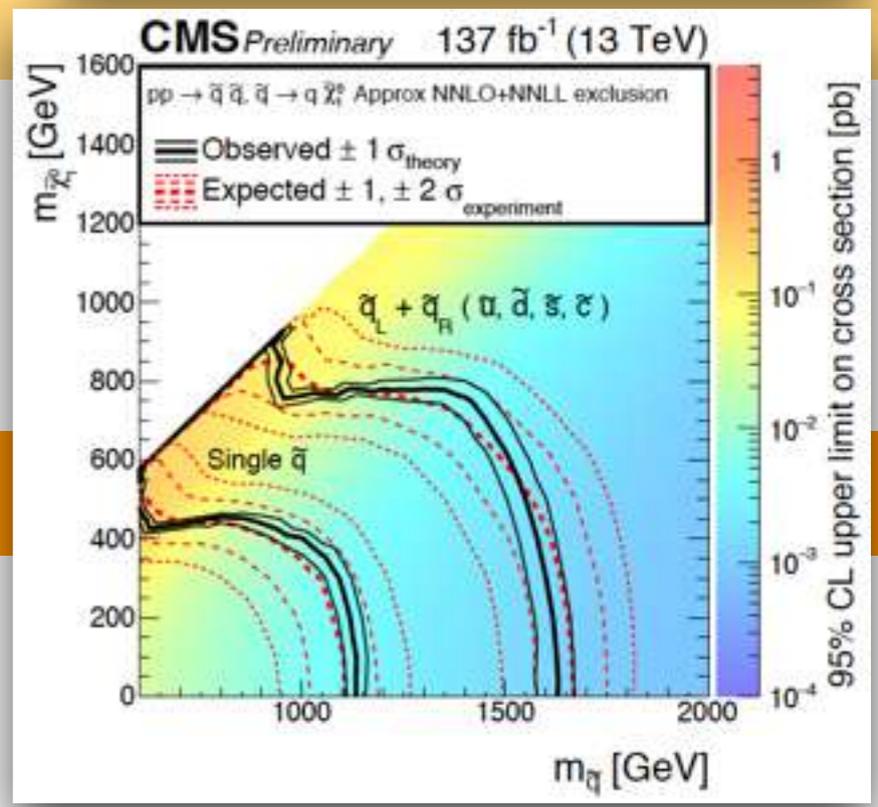
CMS-SUS-19-006
@ EPS 2019



$$S \xrightarrow{Y_4} Q\psi' = \text{jet} + \text{missing}$$

No bound for $M_{\psi'} \gtrsim 1 \text{ TeV}$

Long-lived colored & charged particle 1902.01636



$$\bar{\psi} \rightarrow d_R Q \psi'$$

$$= 2 \text{ jets} + \text{missing}$$

but with $\tau_{\psi} > 10 \text{ s}$ for $Y \sim 10^{-6}$ — LLP

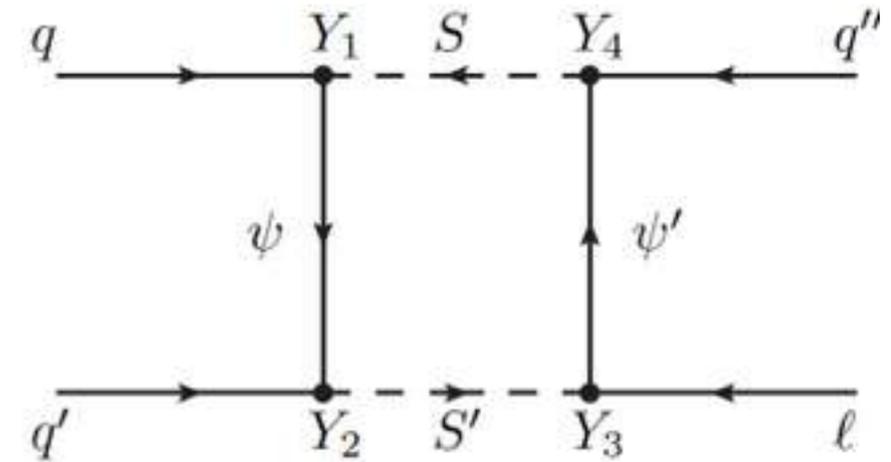
Energy loss at the calorimeter layer

“Heavy ionizing track (R-hadron)”

How to use the tables

Fundamental Lagrangian: Yukawa interactions

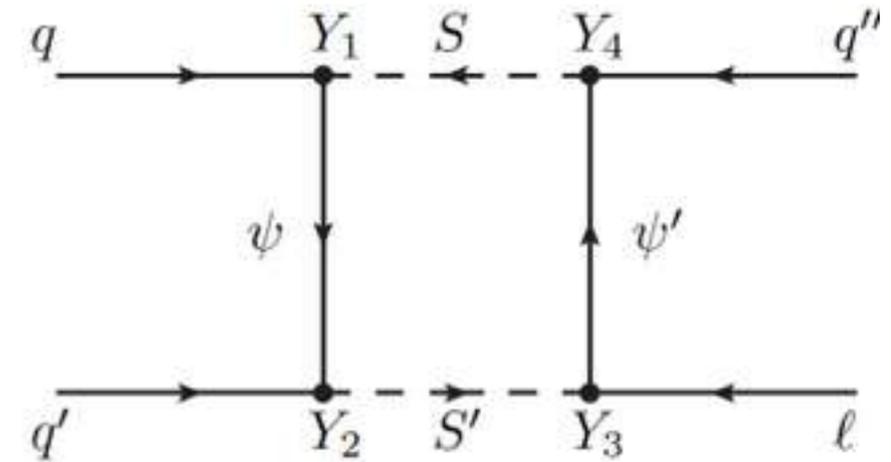
$$\mathcal{L} \supset Y_1 \bar{q}^c \psi^c S + Y_2 \bar{\psi}^c q' S'^{\dagger} \\ + Y_3 \bar{\psi}' \ell S' + Y_4 \bar{q}''^c \psi' S'^{\dagger} + \text{H.c.}$$



How to use the tables

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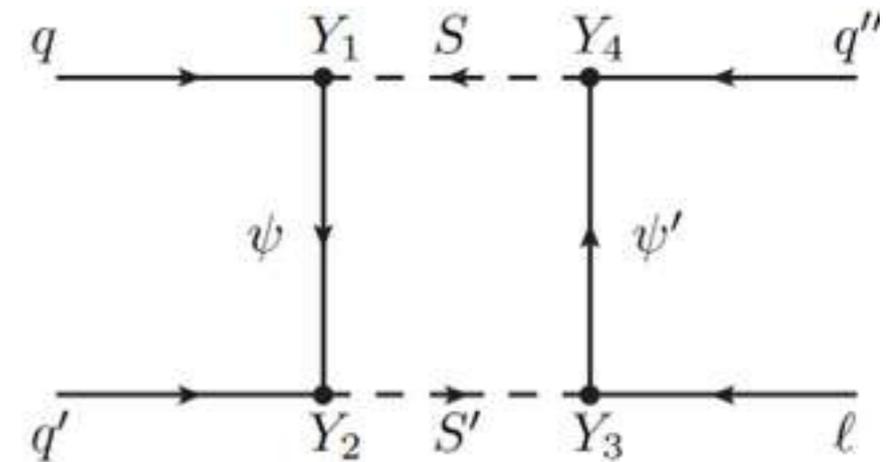
Derive the effective Lagrangians for proton decays...

$$\mathcal{L}_{\text{eff}} = [Y_1 \bar{q}^c \psi^c S] [Y_2 \bar{\psi}^c q' S'^{\dagger}] [Y_4 \bar{q}'''^c \psi' S^{\dagger}] [Y_3 \bar{\psi}' \ell S']$$

How to use the tables

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Tables

Helo et al.,
1904.00036

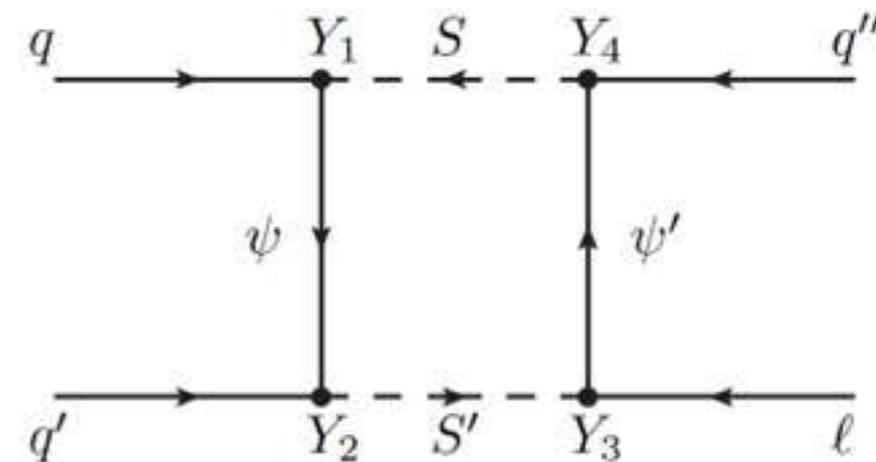
Yukawas time “factors”, “coeffs.” and “signs” due to...

Group theoretical calc., Loop integrals, Fierz transformations

How to use the tables

Fundamental Lagrangian: Yukawa interactions

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e.g., Aoki et al., 1705.01338
Hadron matrix element given from lattice calc.

$$= \text{coeff.} \times \mathcal{O}(s) \text{ eff. ops}$$

Tables

Helo et al.,
1904.00036

Proton
lifetime

$$\Gamma_p = \frac{m_p}{32\pi} \left[1 - \frac{m_M^2}{m_p^2} \right]^2 |W \times \text{coeff.}|^2$$

Yukawas time “factors”, “coeffs.” and “signs” due to...

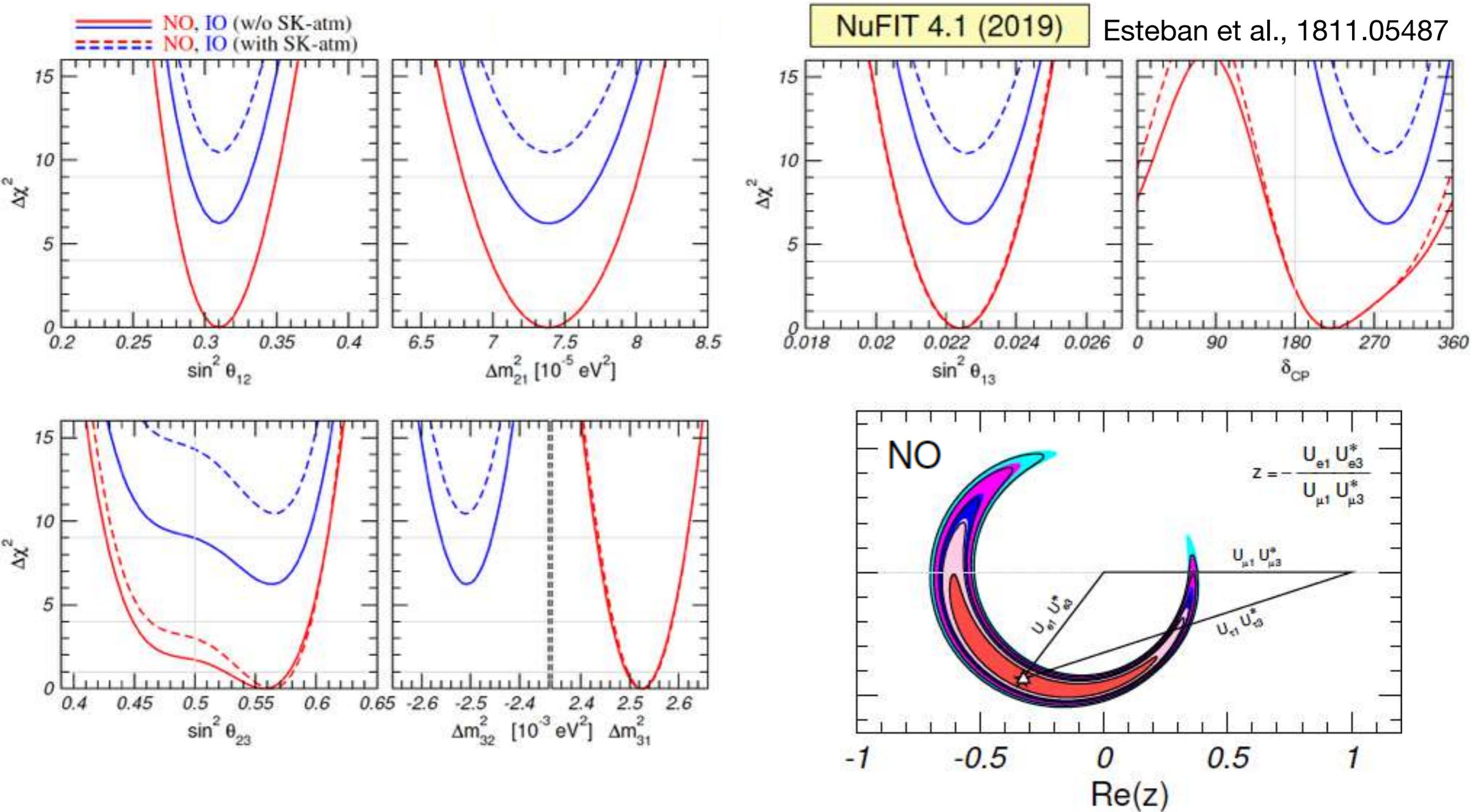
Group theoretical calc., Loop integrals, Fierz transformations

Let me talk on a topic we have just started discussion recently

Do we need yet another
 ν experiment after DUNE, T2HK...?

5 more slides

We know about neutrino very well...



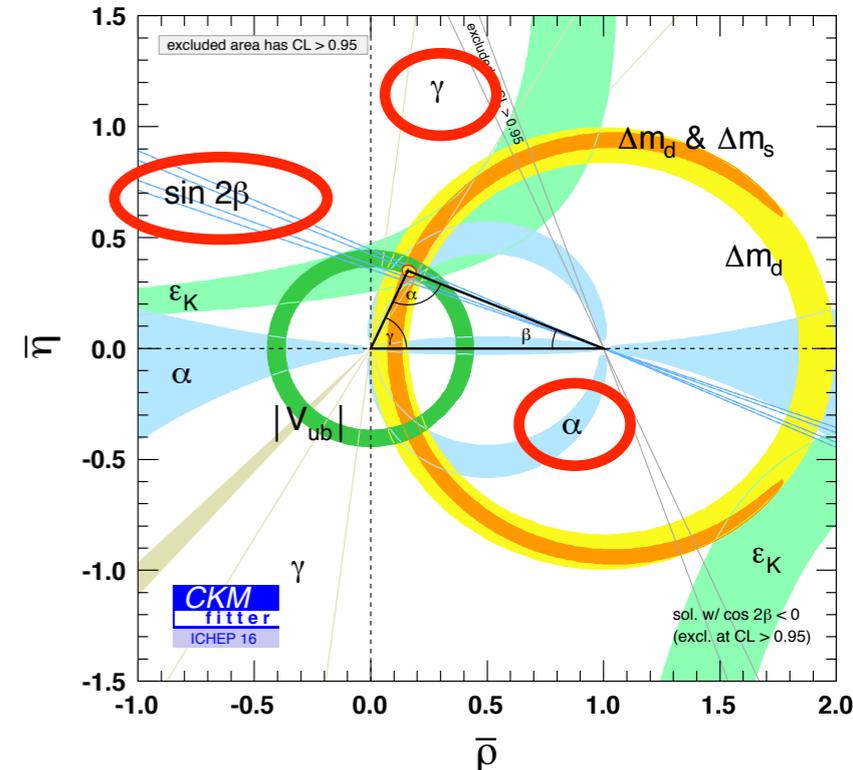
Parameterize the unitary PMNS with θ'_s and δ_{CP} and fit them to the experimental measurements.

Test of CKM

e.g., Triangle of the B meson system

$$A_{\bar{B}^0 \rightarrow f}^{CP} = -\zeta_f \sin(2\Phi) \sin(\Delta M_{B^0} t)$$

Coefficient \times Osc. in time



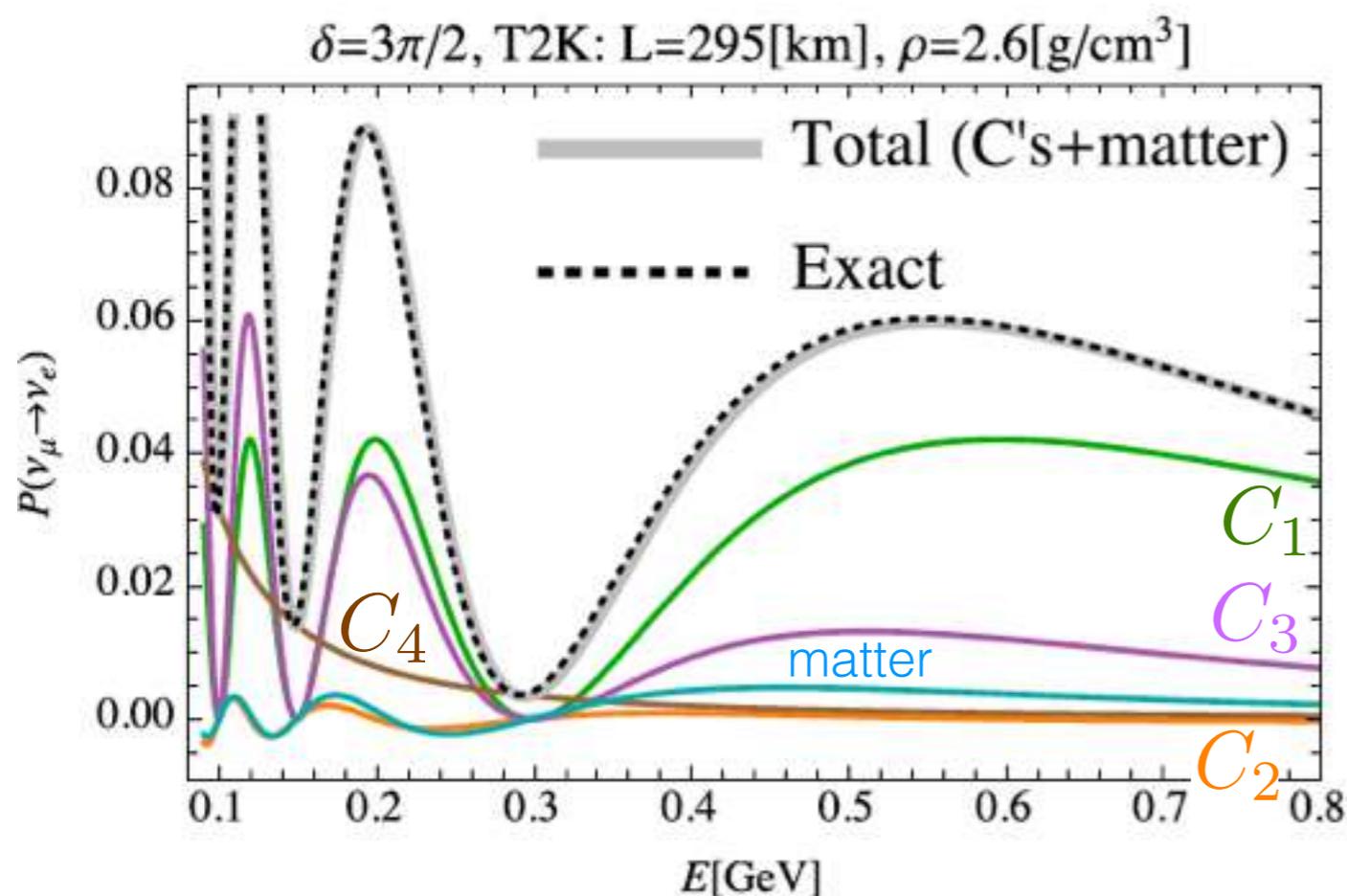
Mode	ζ_f	$-\sin(2\Phi)$	Angle in the unitarity triangle
$B_d^0 \rightarrow J/\psi K_S$ $b \rightarrow c$	-	$\text{Im} [V_{td}/V_{td}^*]$	β
$B_d^0 \rightarrow \pi^+ \pi^-$ $b \rightarrow u$	+	$\text{Im} [(V_{td}/V_{td}^*)(V_{ub}/V_{ub}^*)]$	α
$B_s^0 \rightarrow \rho^0 K_S$ $b \rightarrow u$	-	$\text{Im}[V_{ub}/V_{ub}^*]$	γ

The independent observations of the 3 modes determine the 3 angles of a CKM triangle independently.

Consistency test: Sum of the angles $\stackrel{?}{=} \pi$

Can we do the same type of test in lepton sector?

Same type of test in PMNS...



$$\begin{aligned}
 P_{\nu_\mu \rightarrow \nu_e}^{\text{vac.}} = & C_1 \sin^2 \frac{\Delta m_{31}^2 L}{4E} \\
 & + C_2 \left[\frac{\Delta m_{21}^2 L}{4E} \right] \sin \frac{\Delta m_{31}^2 L}{2E} \\
 & + C_3 \left[\frac{\Delta m_{21}^2 L}{4E} \right] \sin^2 \frac{\Delta m_{31}^2 L}{4E} \\
 & + C_4 \left[\frac{\Delta m_{21}^2 L}{4E} \right]^2
 \end{aligned}$$

Suppose we can do the “spectroscopy” of the osc. probability and measure the coeff.s “independently”, we can test the consistency of the unitarity triangle!

4 independent information:

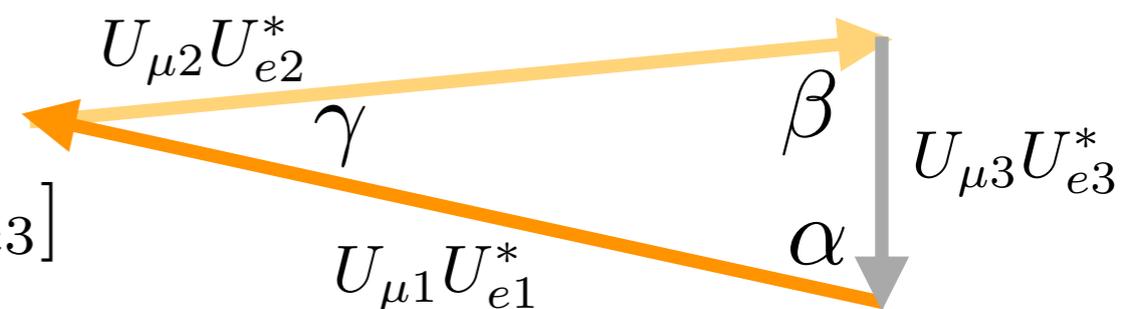
With 3 info (e.g., 2 sides and 1 angle in between), one can fix a triangle. Then, with the one left, one can test the consistency.

Same type of test in PMNS...

If PMNS is unitary

$$C_1 = 4|U_{\mu 3}U_{e 3}^*|^2 \quad C_2 = 4\text{Re}[U_{\mu 2}U_{e 2}^*U_{\mu 3}^*U_{e 3}]$$

$$C_4 = 4|U_{\mu 2}U_{e 2}^*|^2 \quad C_3 = 8\text{Im}[U_{\mu 2}U_{e 2}^*U_{\mu 3}^*U_{e 3}]$$



By checking $4C_1C_4 \stackrel{?}{=} 4C_2^2 + C_3^2$ one can “test” the consistency which corresponds to $\cos^2 \beta + \sin^2 \beta \stackrel{?}{=} 1$ Sato hep-ph/0008056

We can know an angle in the triangle as $C_3/C_2 = -2 \tan \beta$.

Test of CPV: $\tan \beta \neq 0 \implies \beta \neq \{0, \pi\}$. $\delta_{\text{CP}} \neq \{0, \pi\}$ in the standard fit.

triangle does not collapse

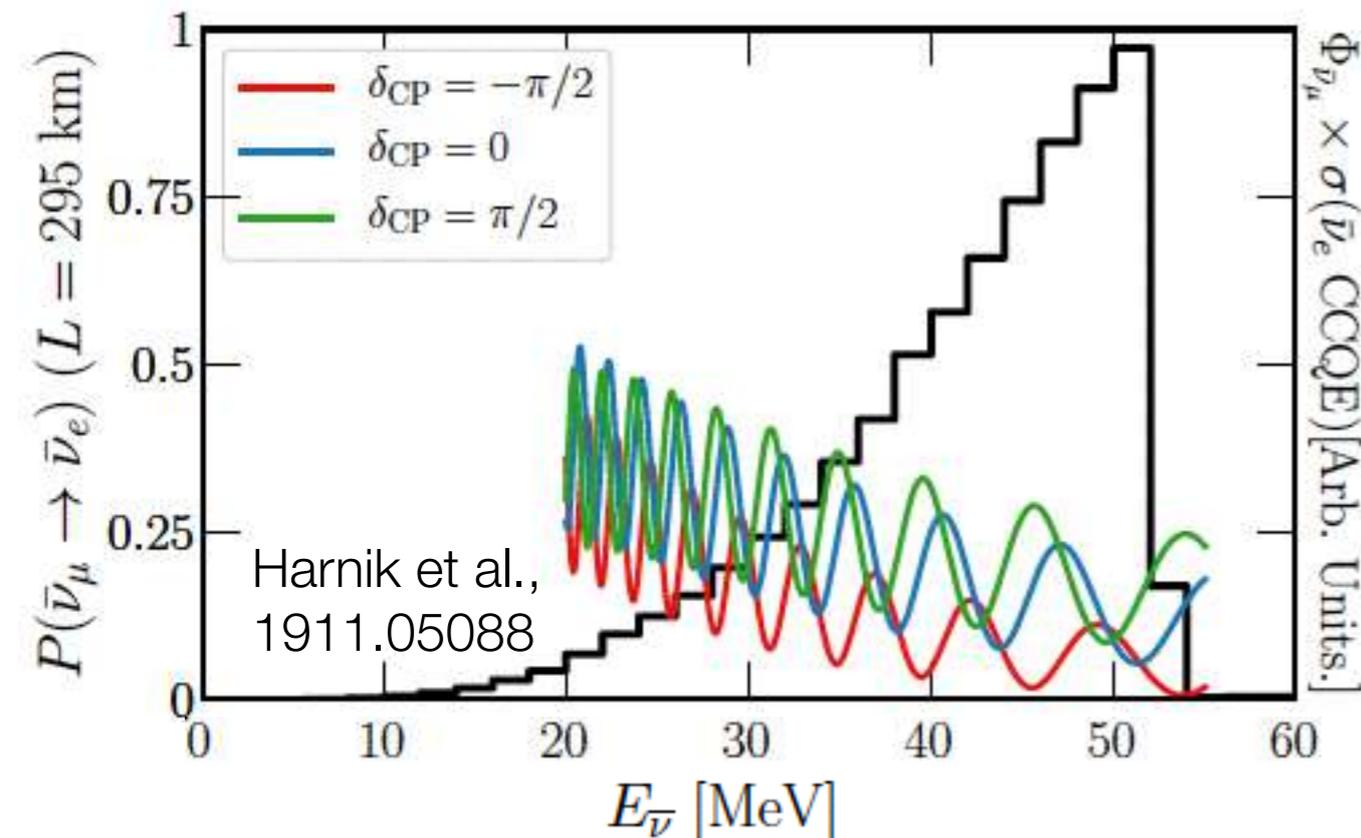
But it is still not the same as the test in CKM $\alpha + \beta + \gamma \stackrel{?}{=} \pi$

For that, surely, we need yet another ν experiment.

The neutrino experiment industry will not die.

Can we measure the other angles?

e.g., the appearance channel with a longer baseline



Appearance channel at a muon Decay-At-Rest experiment with the T2K baseline.

The averaged probability is still sensitive to CP!

No need to see the wiggles.

In the region where the oscillation driven by the atmos. is averaged out, the probability is written as

$$P_{\bar{\nu}_\mu \rightarrow \bar{\nu}_e}^{\text{aver.}} = C'_0 + C'_1 \cos \frac{\Delta m_{21}^2 L}{2E} - C'_2 \sin \frac{\Delta m_{21}^2 L}{2E}$$

which is actually sensitive to the angle γ as $\tan \gamma = -C'_2 / C'_1$.

Wrap-up

The standard 3-generation framework will be challenged by precision experiments in the next decade.

Conflict among $0\nu 2b$, osc, and cosmology

NP contributions to $0\nu 2b$

or we miss something in our understanding of the evolution of the Universe

Complementary with LHC searches for exotics

for precision measurements of ν

Nucleon decays at large volume ν detectors

Bottom up approach - List also non-GUT possibilities

$p \rightarrow \pi^+ + \text{missing}$ may be a hint on sterile ν

Unitarity triangle test in the lepton sector

We have just started the discussion...

Backup

SM singlet fermion N

$$\mathcal{L} = \mathcal{L}_{\text{SM}} + Y_\nu \bar{N} L i\tau^2 H + \frac{1}{2} M_N \bar{N}^c N + \text{H.c.} \quad \#L(N) = +1$$

#L is violated in a high scale, e.g., the scale of $\text{SO}(10) \rightarrow \text{SU}(5)$

Seesaw mechanism for tiny Majorana masses for ν_L

$N = \nu_s^c$ can appear in the low scale with a Majorana mass...

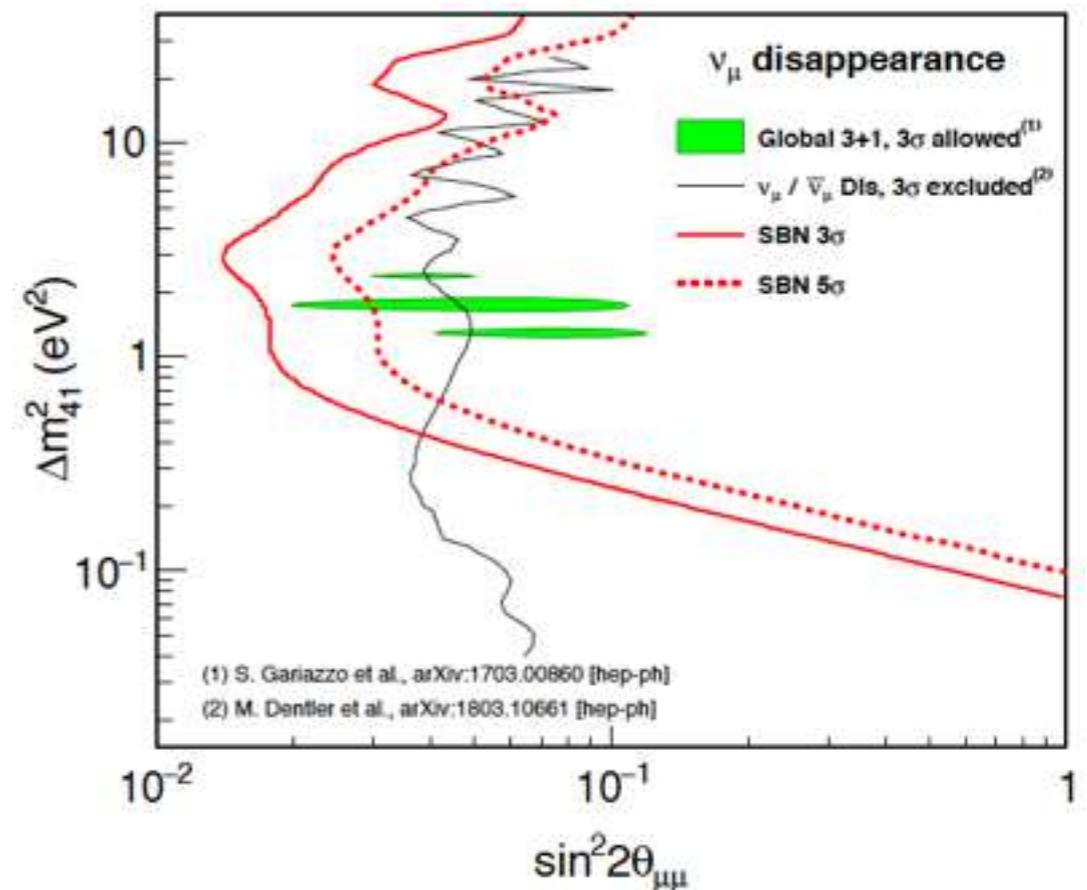
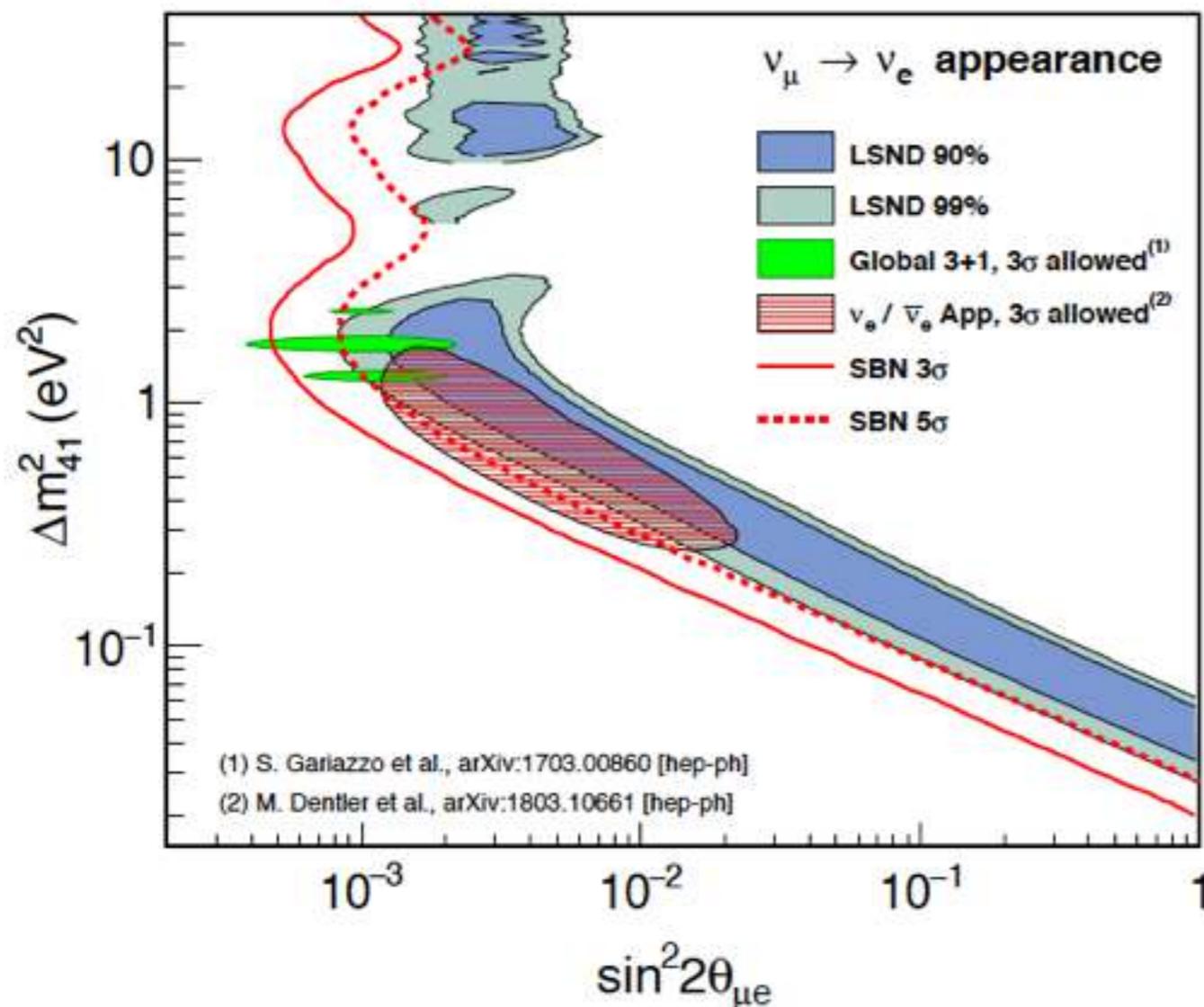
$$\begin{aligned} \mathcal{L} &= \mathcal{L}_{\text{SM}} + \frac{1}{2} m_\nu \bar{\nu}_L^c \nu_L + Y_{\nu_s} \bar{\nu}_s^c \nu_L \langle H^0 \rangle + \frac{1}{2} m_{\nu_s} \bar{\nu}_s^c \nu_s + \text{H.c.} \\ &= \mathcal{L}_{\text{SM}} + \frac{1}{2} \begin{pmatrix} \bar{\nu}_L^c & \bar{\nu}_s^c \end{pmatrix} \begin{pmatrix} m_\nu & Y_{\nu_s} \langle H^0 \rangle \\ Y_{\nu_s}^\top \langle H^0 \rangle & m_{\nu_s} \end{pmatrix} \begin{pmatrix} \nu_L \\ \nu_s \end{pmatrix} + \text{H.c.} \\ &= \mathcal{L}_{\text{SM}} + \frac{1}{2} \bar{\nu}_L^c \alpha (U^*)^\alpha_i m_i (U^\dagger)_i^\beta \nu_{L\beta} + \text{H.c.} \quad \begin{array}{l} \alpha, \beta \in \{e, \mu, \tau, s\} \\ i = 1 - 4 \end{array} \end{aligned}$$

Some anomalous results of ν osc. support ν_s with

$$m_4 \sim 1[\text{eV}] \quad \text{and} \quad |U_{e4}| |U_{\mu 4}| \sim 0.05 \quad \dots \text{and some do not.}$$

or #L is exact, $M_N = 0$. - Dirac neutrino mass with $N = \nu_R$

Sterile ν search

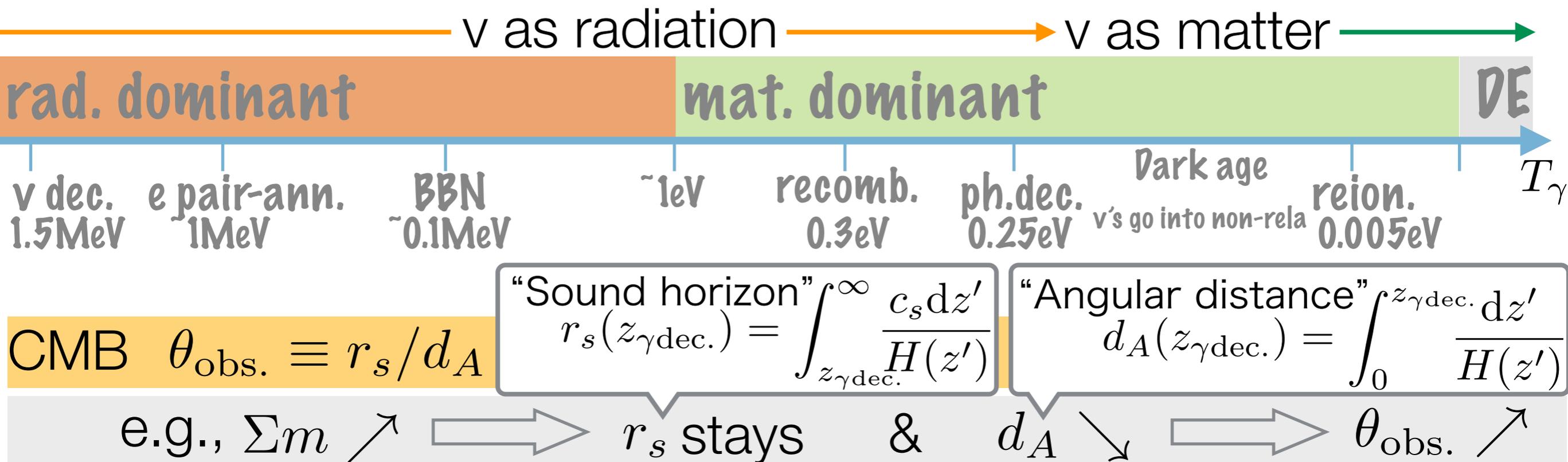


Machado et al., 1903.04608

- **LSND:** Stopped pion source with a detector optimized to probe $\bar{\nu}_e$ via inverse beta decay. A 3.8σ excess of events over backgrounds was observed, compatible with $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ oscillations with $L/E \approx 1 \text{ m/MeV}$ (19).
- **MiniBooNE:** Accelerator neutrino source with the capability of producing a dominant ν_μ or $\bar{\nu}_\mu$ beam. Excesses of ν_e ($\bar{\nu}_e$) events in ν_μ ($\bar{\nu}_\mu$) mode were observed over backgrounds, amounting to a 4.5σ (2.8σ) discrepancy from expectations. The observed excesses are found to be compatible with LSND within a sterile neutrino framework (6).

An additional contribution to Σm_ν causes problems in cosmology...

Bound to Σm_ν from cosmology



LSS Free streaming of ν disturbs the structure formation.

The structures with the scale smaller than a particular size are suppressed.

BAO Standard ruler $r_s(z_{\gamma\text{dec.}})$

in galaxy ($z < 2$) LyA ($z \sim 3$)

21cm ($10 < z < 20$)

Schoenberg et al., 1907.11594
Tension btw galaxy+LyA&SN

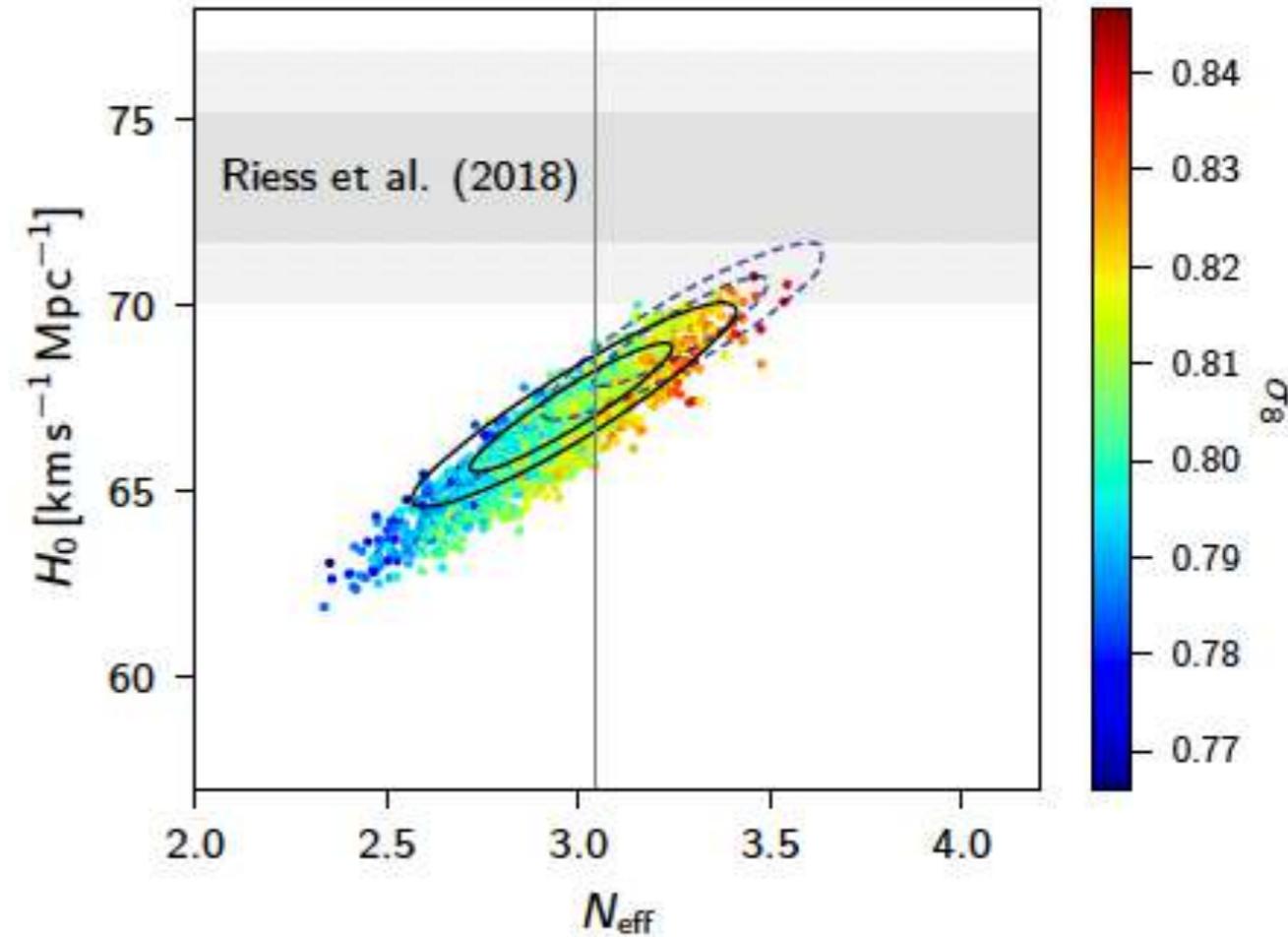
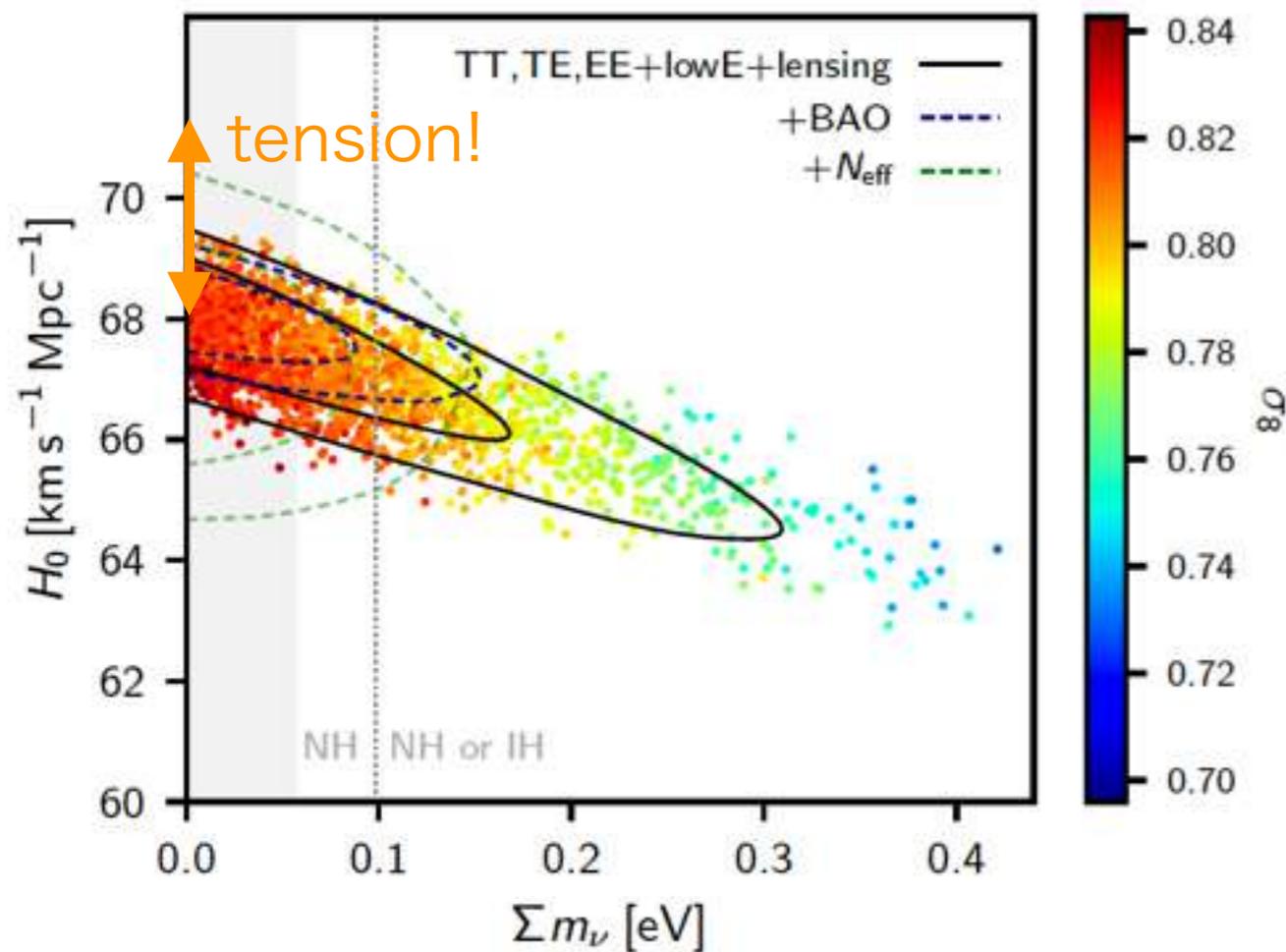
H0 tension - Possibly something is missing in LambdaCDM?

cf. Bernal et al., 1607.05617,
Jee et al., 1909.06712.

Incl. of “something” may change the bound...

H0 tension and neutrino parameters

Planck collaboration, 1807.06209



$\Sigma m \nearrow \longrightarrow H_0 \searrow$ ————— H0 tension gets higher

→ Inclusion of the H0 measurement with SNs

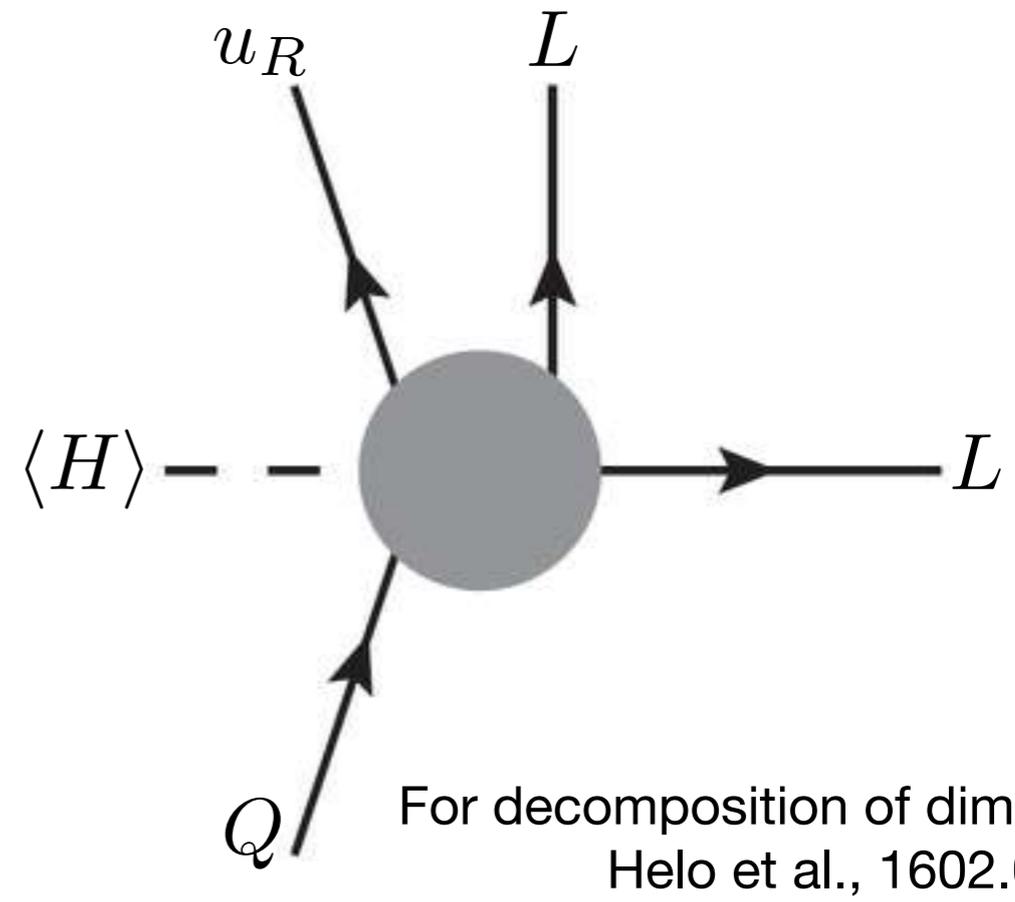
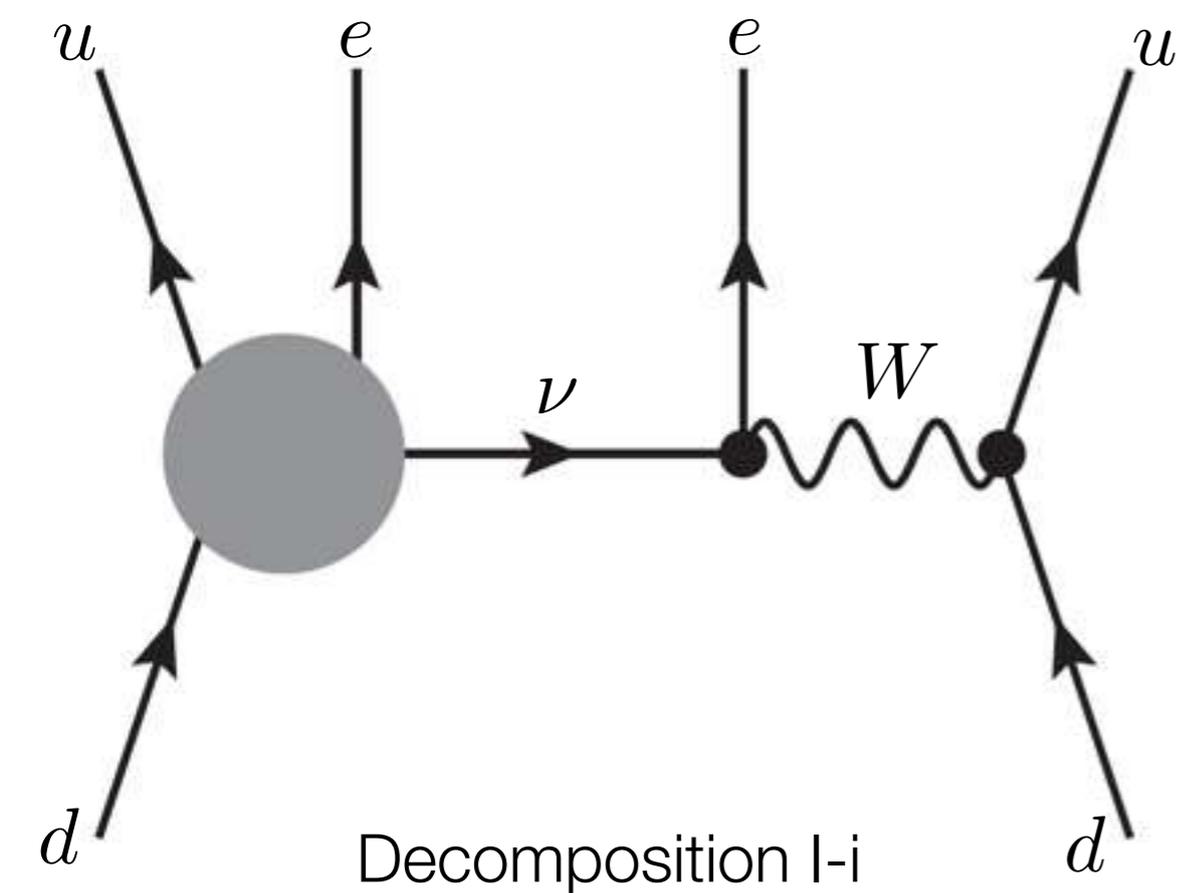
→ Σm bound stronger

Extra radiation d.o.f. (N_{eff}) relaxes the H0 tension.

Long-range contribution to $0\nu 2b$

No suppression with $m_{\beta\beta}$

Based on LNV dim.=7 operator

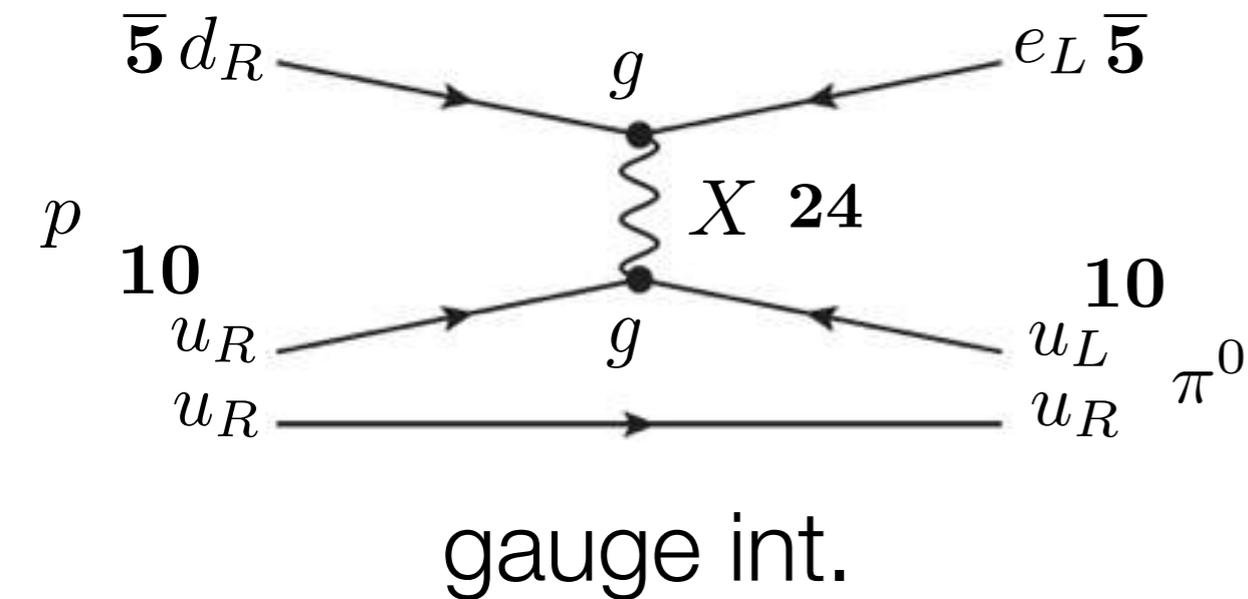


$$\mathcal{L}_{\text{Long-range}} = \frac{\mathcal{C}}{\Lambda_{\text{NP}}^3} G_F \frac{1}{p} \quad \xrightarrow{\mathcal{L}_{\text{Long-range}} \stackrel{!}{=} \mathcal{L}_{\nu\text{SM}}} \quad \Lambda_{\text{NP}} = 56 [\text{TeV}] \left[\frac{0.05 \text{eV}}{m_{\beta\beta}} \right]^{1/3}$$

$0\nu 2b$ expts are sensitive to NP at $O(10)$ TeV.

Proton decays in GUT&SUSY-GUT

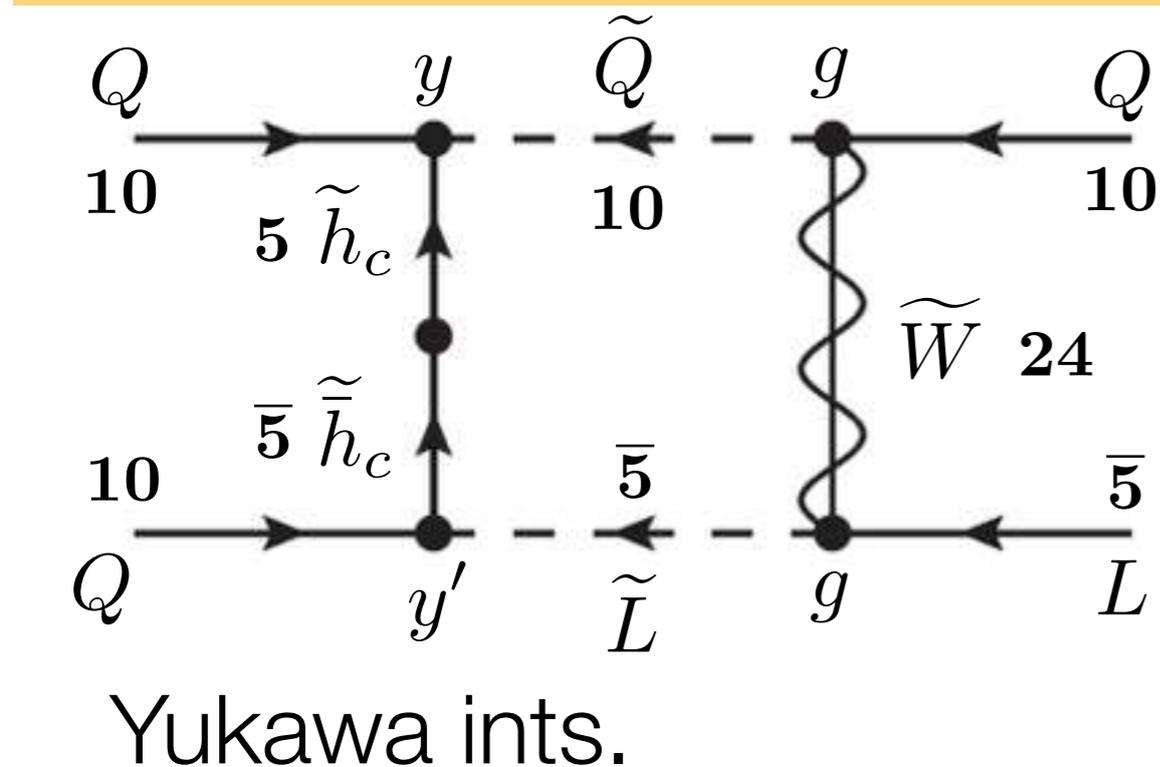
GUT: Dim.6 mediated by a GUT gauge boson



$$g = 0.1 \quad M_{\text{GUT}} = 10^{15} \text{ GeV}$$

$$\tau_p \sim \frac{1}{m_p^5 \left| \frac{g^2}{M_{\text{GUT}}^2} \right|^2} = 3 \cdot 10^{32} [\text{yrs}]$$

SUSY-GUT: Dim.5 mediated by a coloured higgsino + Dressing

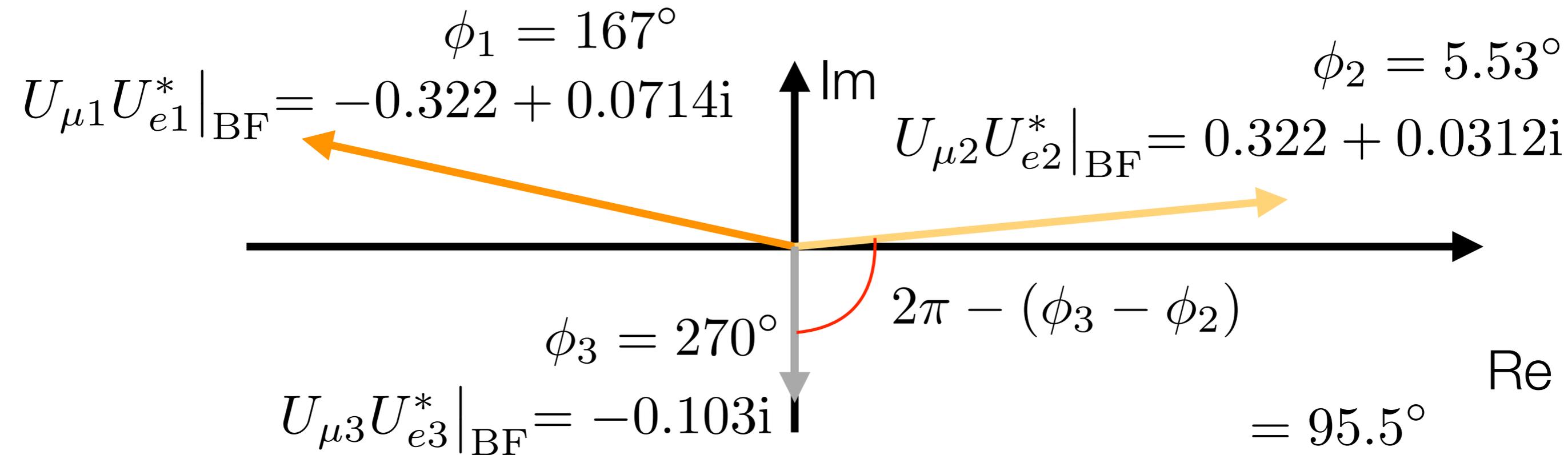


$$g = 0.1 \quad y = y' = 10^{-4}$$

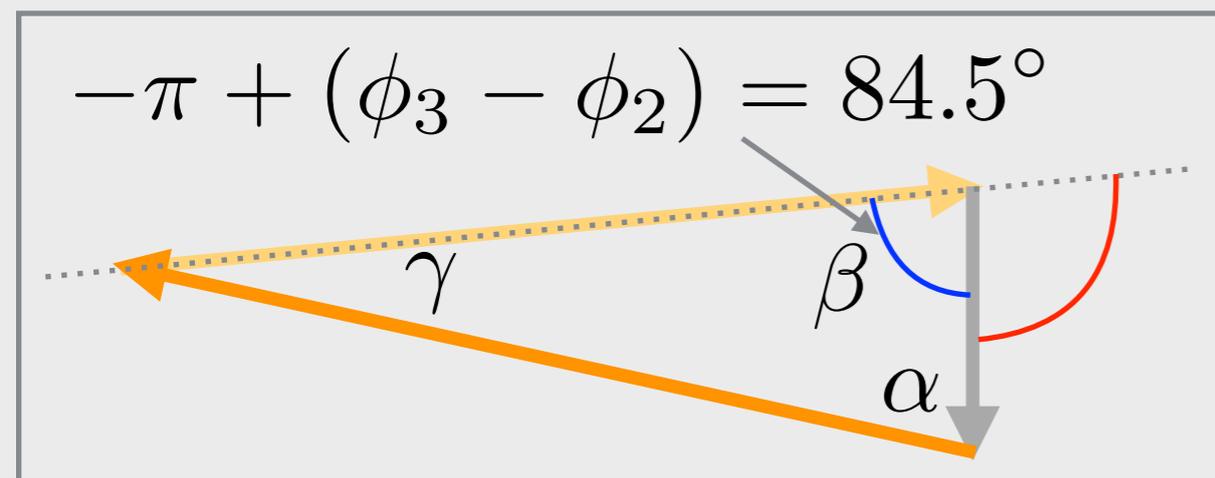
$$M_{\text{SUSY}} = 1 \text{ TeV} \quad M_{\text{GUT}} = 10^{16} \text{ GeV}$$

$$\tau_p \sim \frac{1}{m_p^5 \left| \frac{1}{16\pi^2} \frac{g^2 y y'}{M_{\text{GUT}} M_{\text{SUSY}}} \right|^2} = 7 \cdot 10^{30} [\text{yrs}]$$

Coefficients & angles



To measure the $\cos \delta$ term



is to know $\cos \beta$ of the triangle

$$\text{Re}[U_{\mu 2} U_{e 2}^* (U_{\mu 3} U_{e 3}^*)^*]$$

coef. of the $\cos \delta$ term

$$= |U_{\mu 2} U_{e 2}^*| |U_{\mu 3} U_{e 3}^*| \cos(\phi_2 - \phi_3)$$

$$= |U_{\mu 2} U_{e 2}^*| |U_{\mu 3} U_{e 3}^*| \cos(\phi_3 - \phi_2)$$

$$= -|U_{\mu 2} U_{e 2}^*| |U_{\mu 3} U_{e 3}^*| \cos(\pi - (\phi_3 - \phi_2))$$

$$= -|U_{\mu 2} U_{e 2}^*| |U_{\mu 3} U_{e 3}^*| \cos(-\pi + (\phi_3 - \phi_2))$$

$$= -|U_{\mu 2} U_{e 2}^*| |U_{\mu 3} U_{e 3}^*| \cos \beta$$

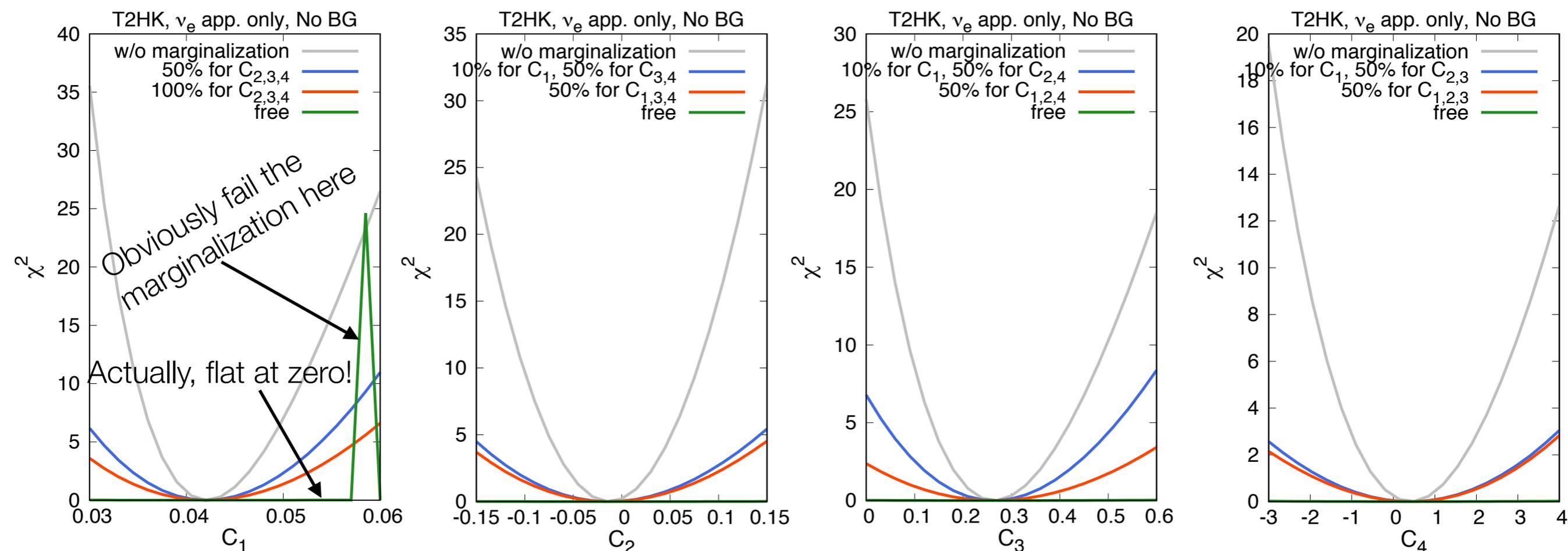
Expansion w. Δm_{31}^2 , or w. Δm_{32}^2

$$\begin{aligned}
 P_{\nu_\mu \rightarrow \nu_e} &= 4|U_{\mu 3}|^2 |U_{e 3}|^2 \sin^2 \frac{\Delta m_{31}^2 L}{4E} \\
 &+ 4\text{Re}[U_{\mu 2} U_{e 2}^* U_{\mu 3}^* U_{e 3}] \frac{\Delta m_{21}^2 L}{4E} \sin \frac{\Delta m_{31}^2 L}{2E} \\
 &+ 8\text{Im}[U_{\mu 2} U_{e 2}^* U_{\mu 3}^* U_{e 3}] \frac{\Delta m_{21}^2 L}{4E} \sin^2 \frac{\Delta m_{31}^2 L}{4E} \\
 &+ 4|U_{\mu 2}|^2 |U_{e 2}|^2 \left[\frac{\Delta m_{21}^2 L}{4E} \right]^2 + \mathcal{O}(|U_{e 3}|^2 \Delta m_{21}^2)
 \end{aligned}$$

$$\begin{aligned}
 &= 4|U_{\mu 3}|^2 |U_{e 3}|^2 \sin^2 \frac{\Delta m_{32}^2 L}{4E} \\
 &- 4\text{Re}[U_{\mu 1} U_{e 1}^* U_{\mu 3}^* U_{e 3}] \frac{\Delta m_{21}^2 L}{4E} \sin \frac{\Delta m_{32}^2 L}{2E} \\
 &- 8\text{Im}[U_{\mu 1} U_{e 1}^* U_{\mu 3}^* U_{e 3}] \frac{\Delta m_{21}^2 L}{4E} \sin^2 \frac{\Delta m_{32}^2 L}{4E} \\
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 \end{aligned}$$

Test fit of $C_1 - C_4$ with T2HK

w. the GLoBES software



5% error for Δm_{21}^2 , 3% for Δm_{31}^2 , and 5% for the matter density.

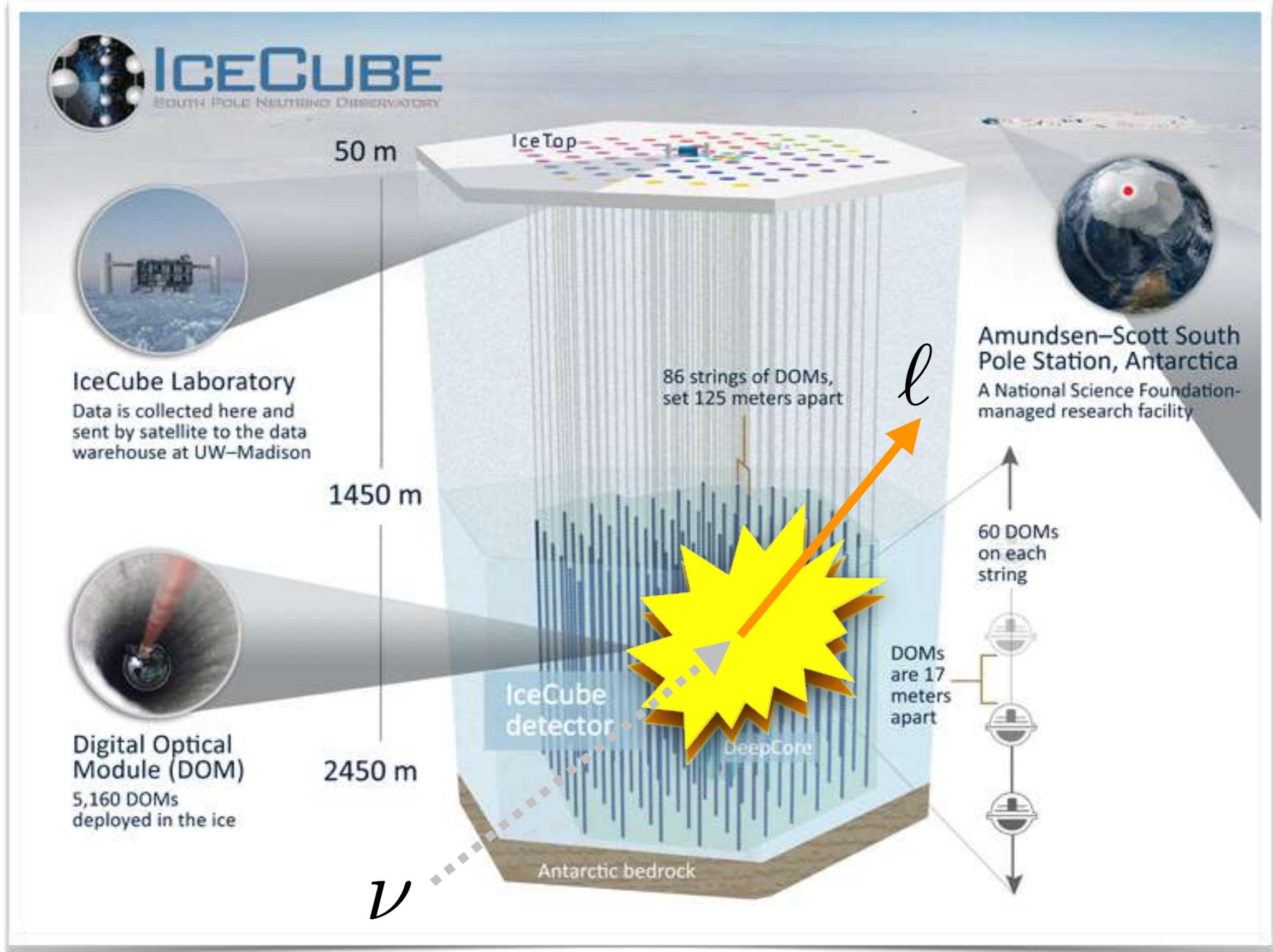
As expected, T2HK cannot determine C_4 ; We need 2nd max.

$C_3/C_2 = -2 \tan \beta$: We can directly know an angle of the triangle!

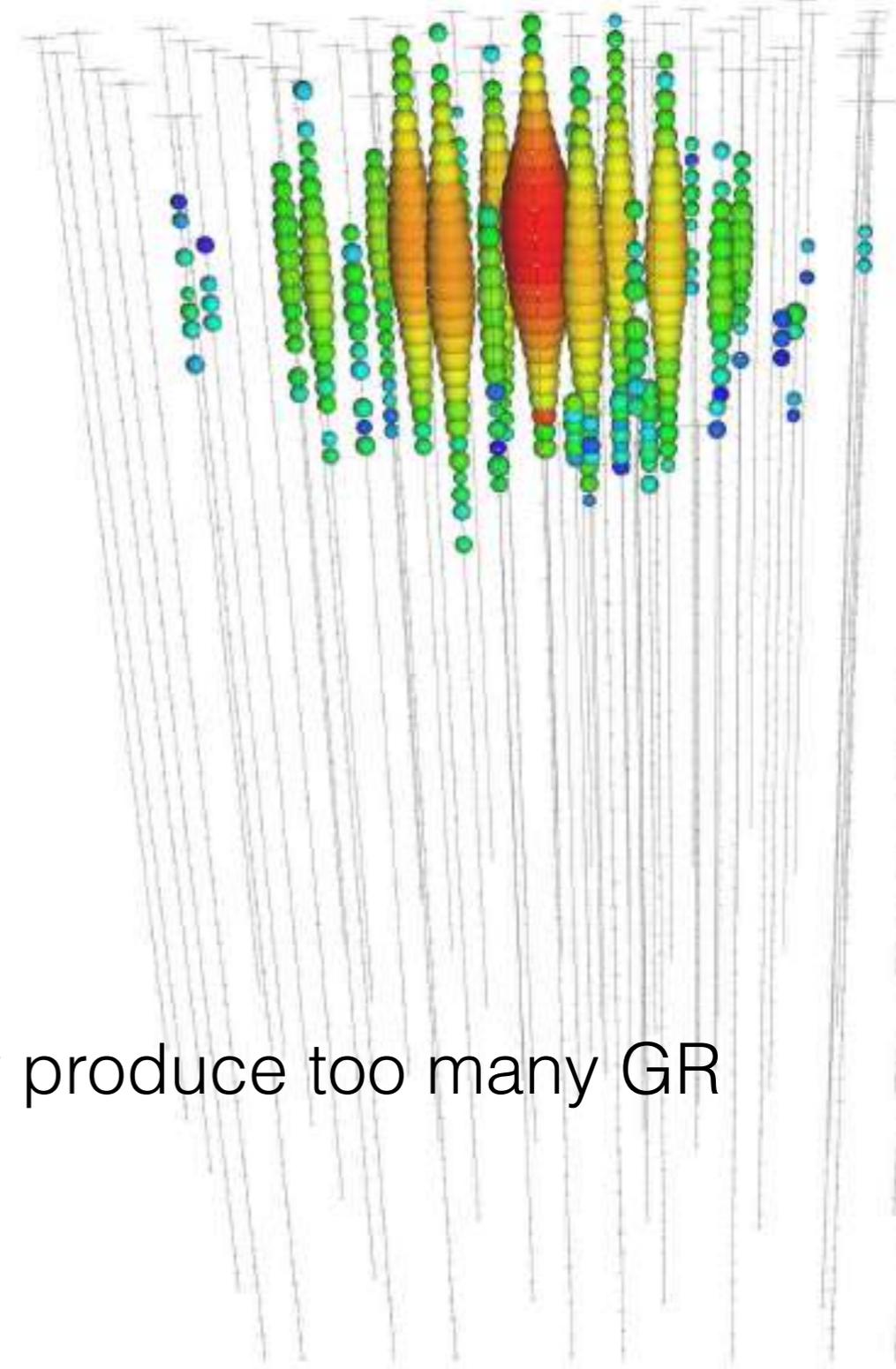
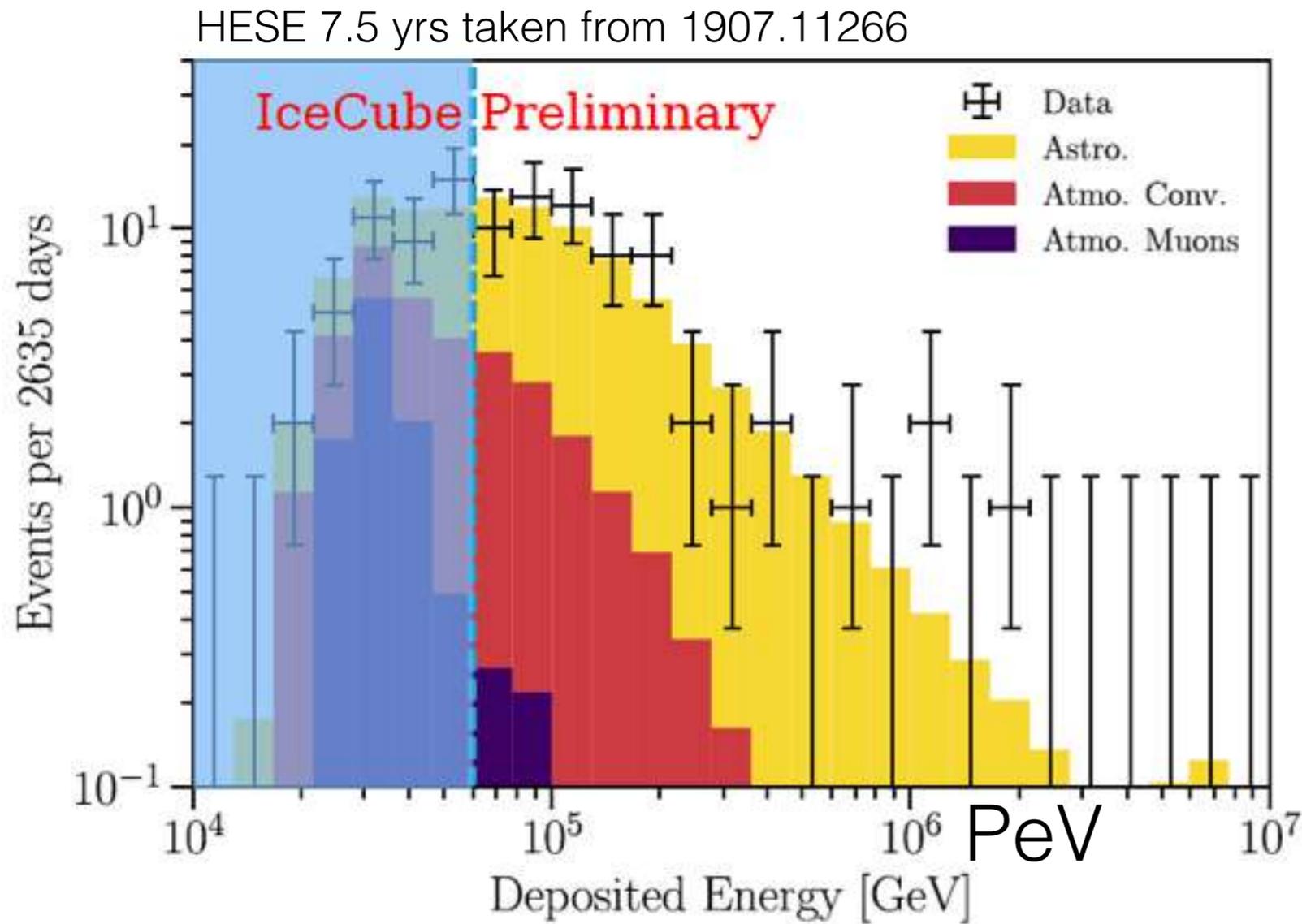
If this is 0, $\beta = 0$ or π , i.e., the triangle is collapsed=CP conserve.

Cosmic neutrinos as a probe to NP

Cosmic neutrinos at IceCube

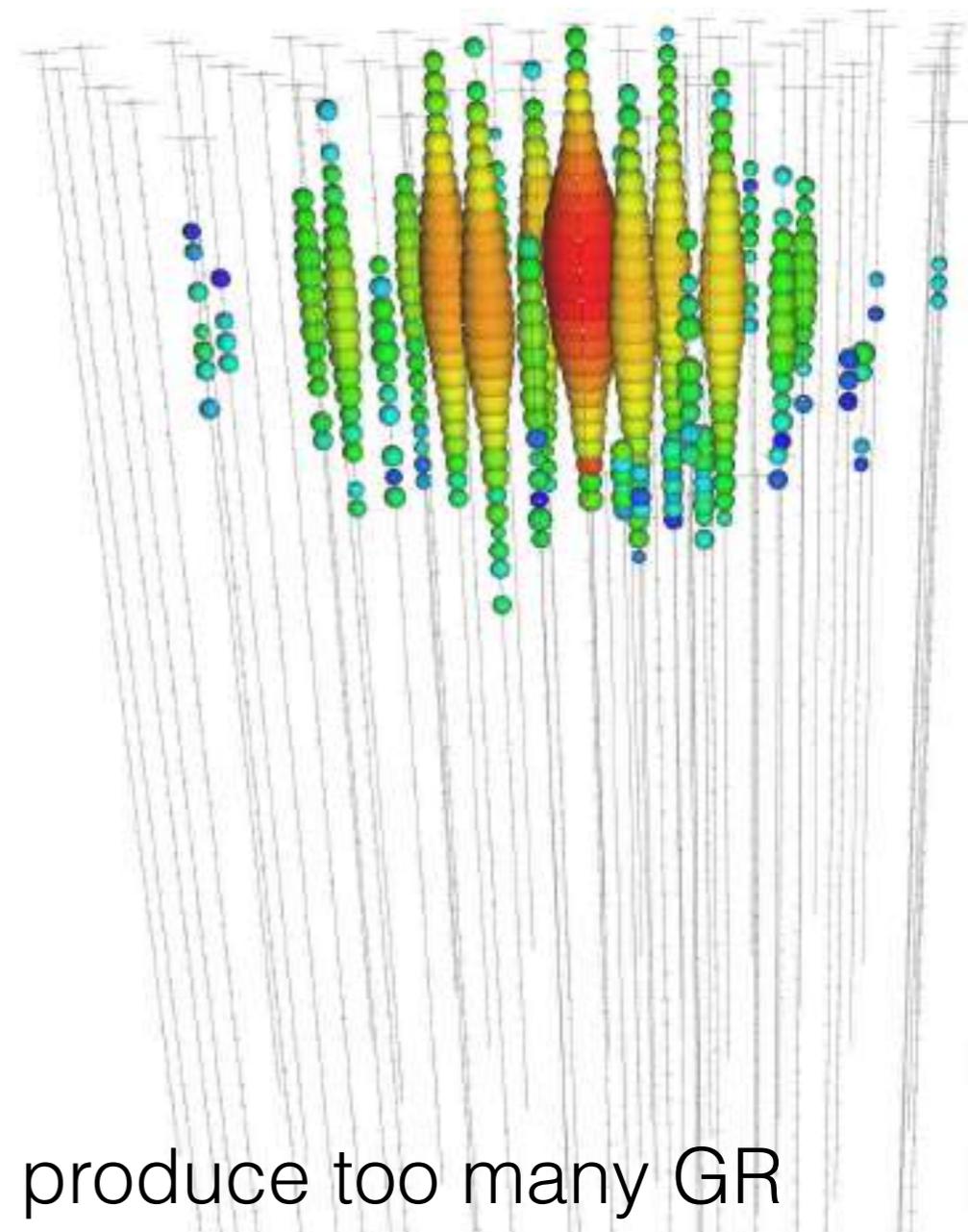
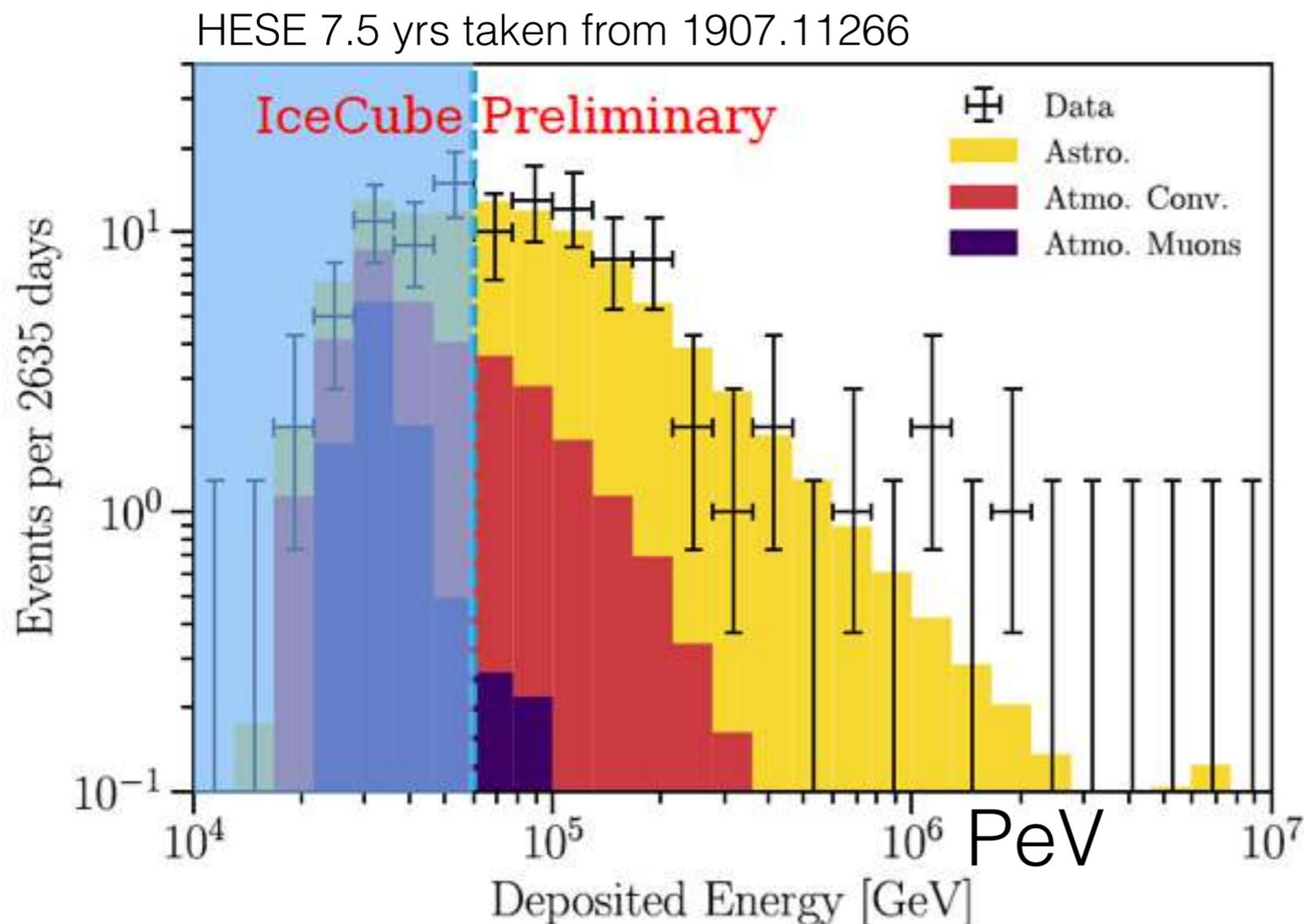


Spectrum - A new playground for NP



Best-fit single power law ~ 2.8 which may produce too many GR

Spectrum - A new playground for NP



Best-fit single power law ~ 2.8 which may produce too many GR
Characteristic structures can be a hint on New Physics

1. Decay of PeV DM as the source,
2. Resonance with a TeV LQ at the detection,
3. Leptonic force mediated by a MeV field in the propagation

Where do they come from?

It is still a mystery - but we are getting some hints recently...

No correlation to the galaxy → Extra galactic origin

v's travel more than $O(1)$ Mpc-Gpc!

Milkyway galaxy ~30 kpc in diameter

SN1987A 51.4 kpc

Local group of galaxies ~3 Mpc

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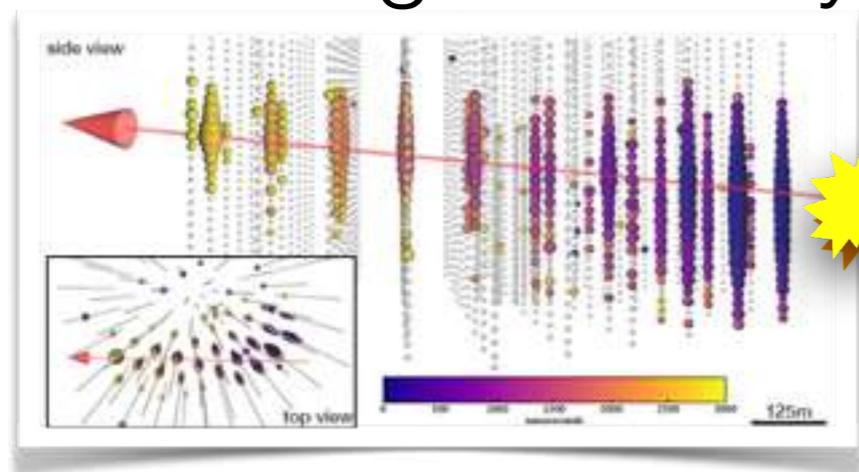
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IceCube170922A event

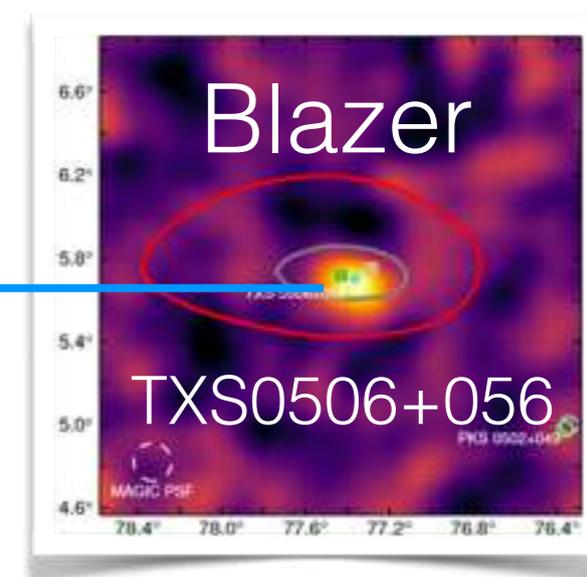
1807.08816

ν from a gamma ray source, TXS0506+056



ν_{μ} with $E \sim 290 \text{ TeV}$

traveled "1.75 Gpc"



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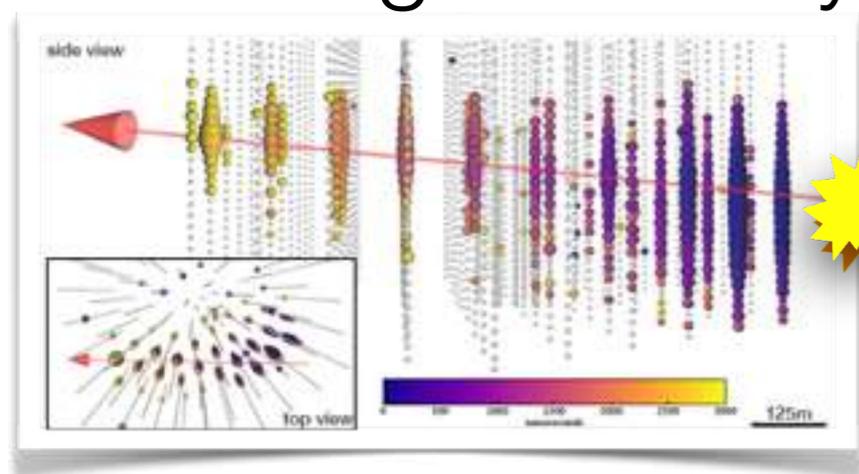
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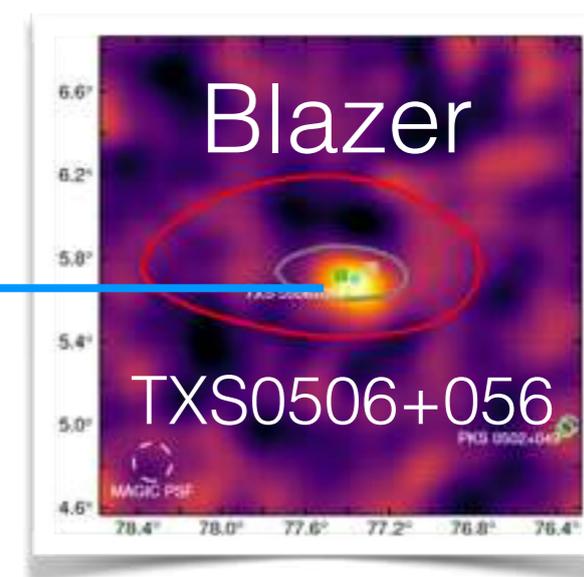
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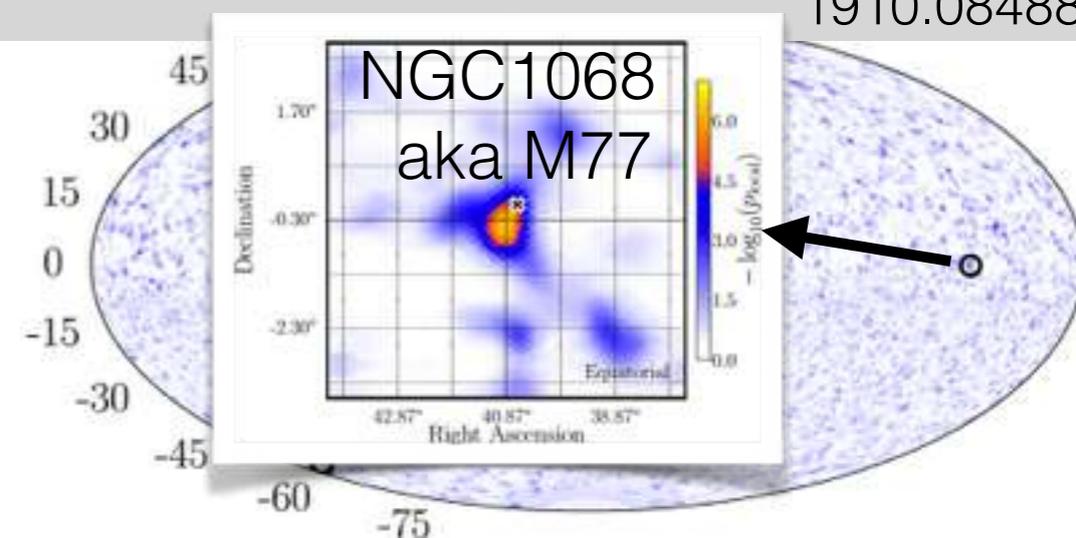
traveled "1.75 Gpc"



A hint? Sky map of ν_{μ} s with $E > 1$ TeV

1910.08488

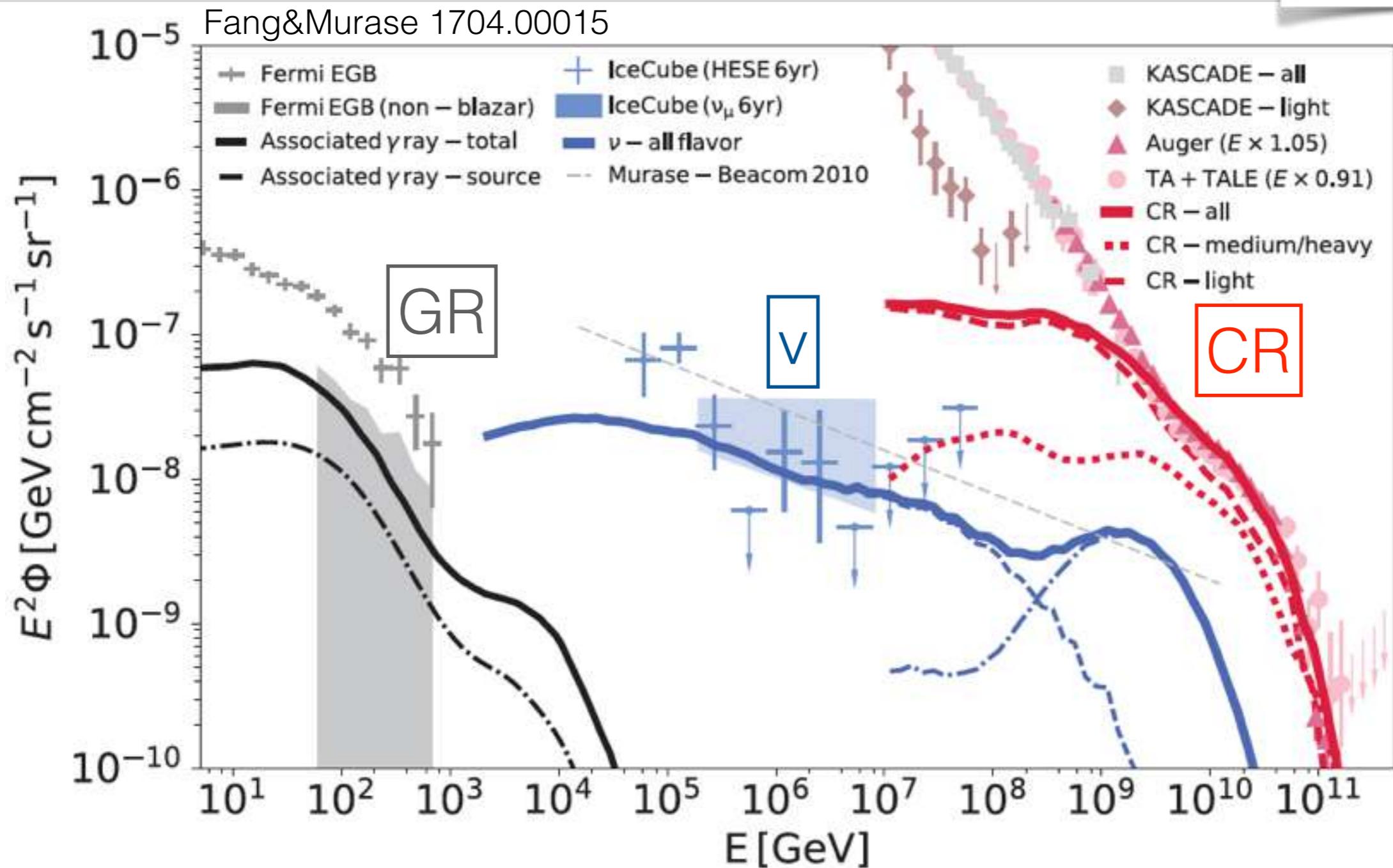
One of the hot spots corresponds to NGC1068, which is a nearby SMBH, 14.4 Mpc away.



Multi-messenger astrophysics



Spectra of UHECR, HEV, and GR from BH jets

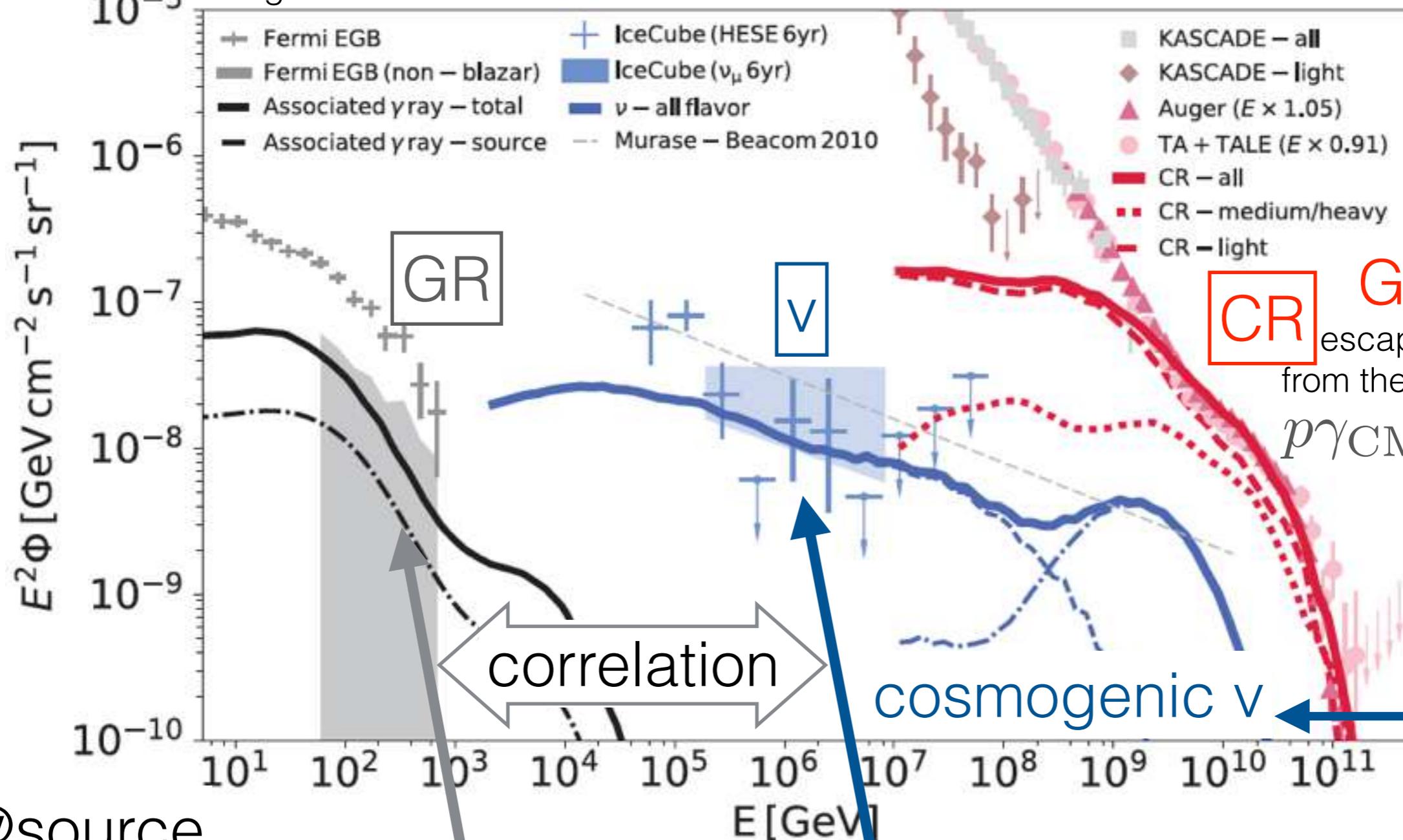


Multi-messenger astrophysics

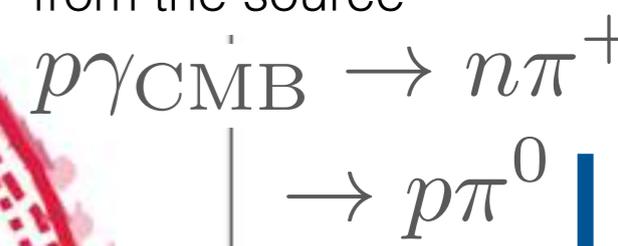


Spectra of **UHECR**, **HEv**, and **GR** from BH jets

Fang&Murase 1704.00015

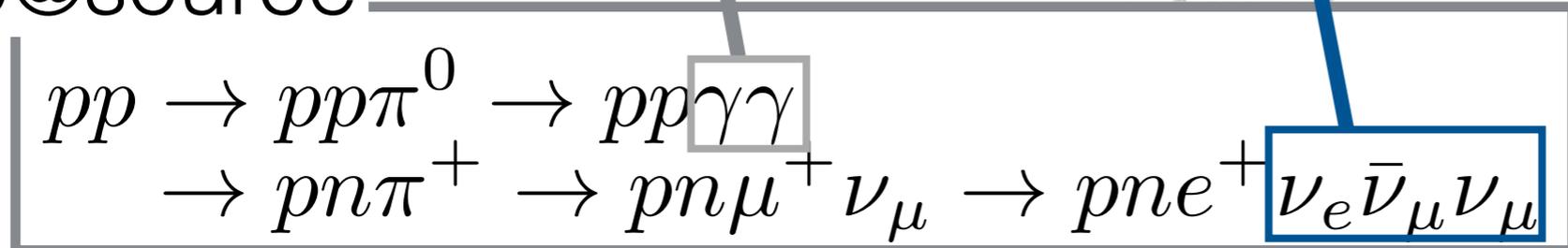


CR GZK cutoff
escape from the source



cosmogenic ν

p@source

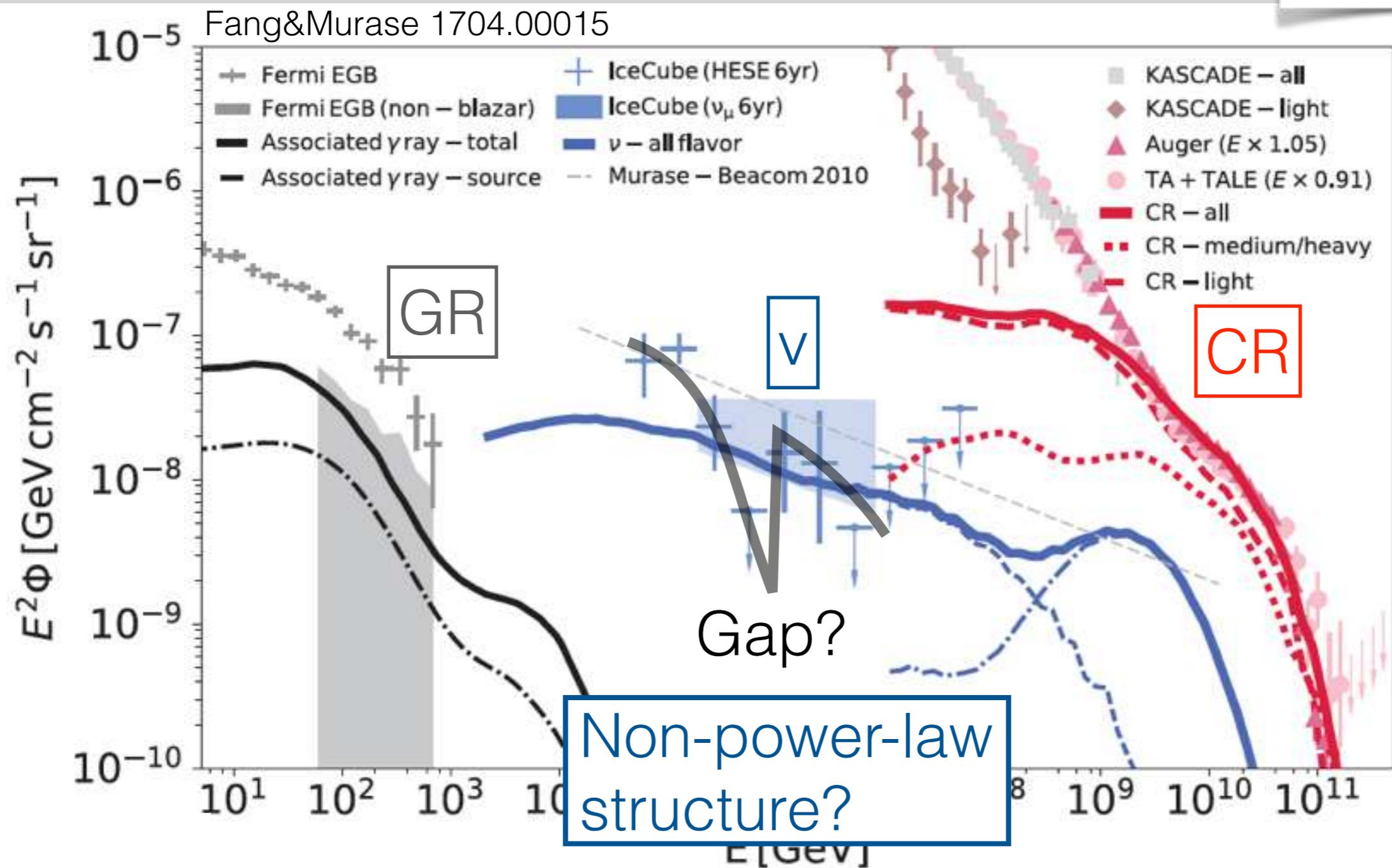


GR ← EM cascade

Multi-messenger astrophysics



Spectra of UHECR, HEV, and GR from BH jets



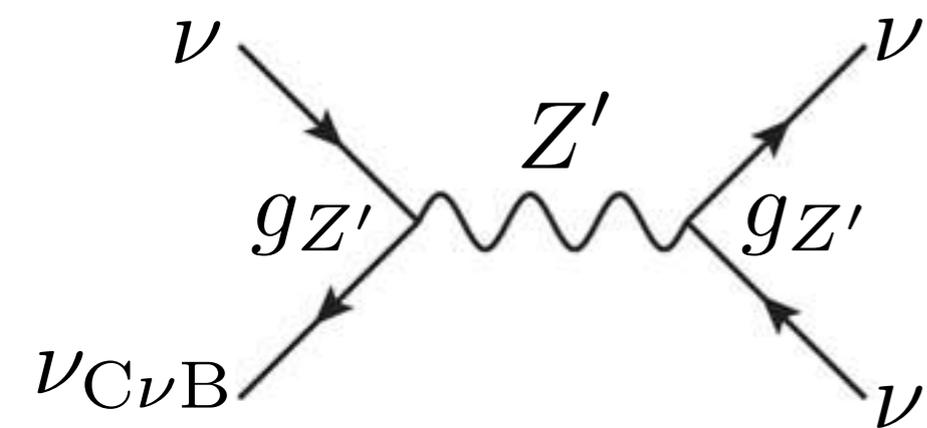
New leptonic force
for the IceCube spectrum

“Structures” in the spectrum?

New leptonic force as an idea for the gap(s) in the spectrum

Resonant scattering with $C\nu B$

Neutrinos with a particular energy loses its energy in their propagation.



Model: gauged $U(1)_{L_\mu - L_\tau}$

$$\mathcal{L} = g_{Z'} Q_\alpha \left[\overline{L}_\alpha \gamma^\rho L_\alpha + \overline{\ell}_{R\alpha} \gamma^\rho \ell_{R\alpha} \right] Z'_\rho$$

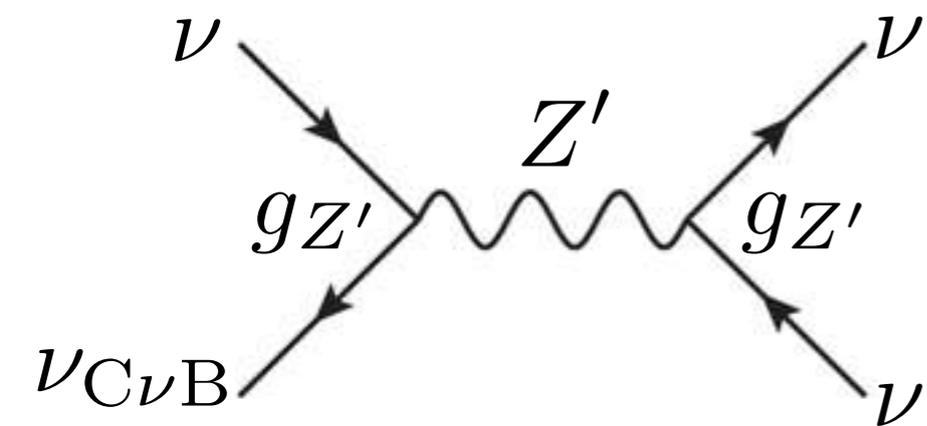
with the charge $Q_{e,\mu,\tau} = \{0, +1, -1\}$

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#1. Gap @ \sim PeV: ν with $E_\nu \sim$ PeV make the resonant scattering

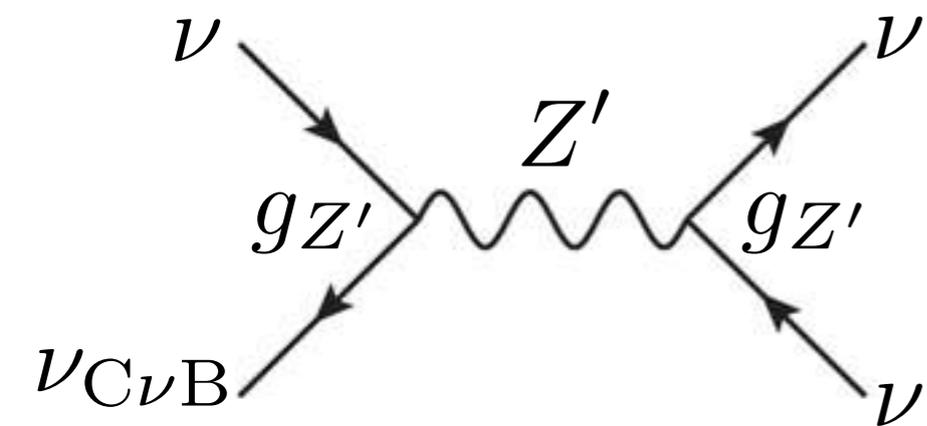
$$s = 2E_\nu m_\nu \stackrel{!}{=} M_{Z'}^2, \text{ with } m_\nu \sim \mathcal{O}(0.1)\text{eV} \implies M_{Z'} \sim \text{MeV}$$

in the limit of CvB-at-rest

“Structures” in the spectrum?

New leptonic force as an idea for the gap(s) in the spectrum

Resonant scattering with CvB Neutrinos with a particular energy loses its energy in their propagation.



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#1. Gap @ ~PeV: ν with $E_\nu \sim \text{PeV}$ make the resonant scattering

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in the limit of CvB-at-rest

#2. ν scatters at least once in its travel ~Gpc

Mean free path $\lambda = 1/(n_{\text{CvB}} \sigma_{\text{@res}}) \stackrel{!}{\lesssim} \mathcal{O}(1)\text{Gpc}$

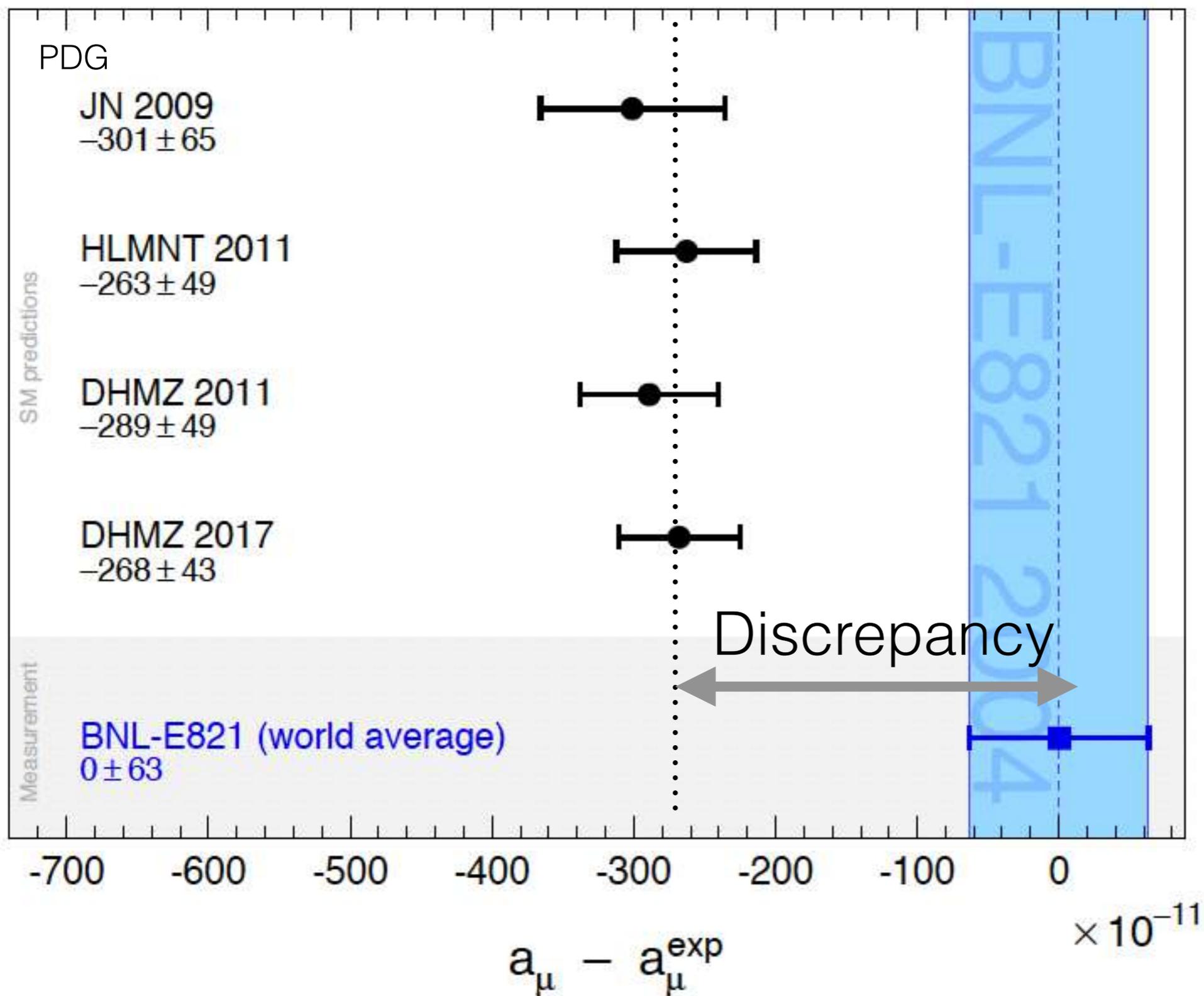
$$n_{\text{CvB}} = 56.8 [\text{/cm}^3]$$

for each d.o.f

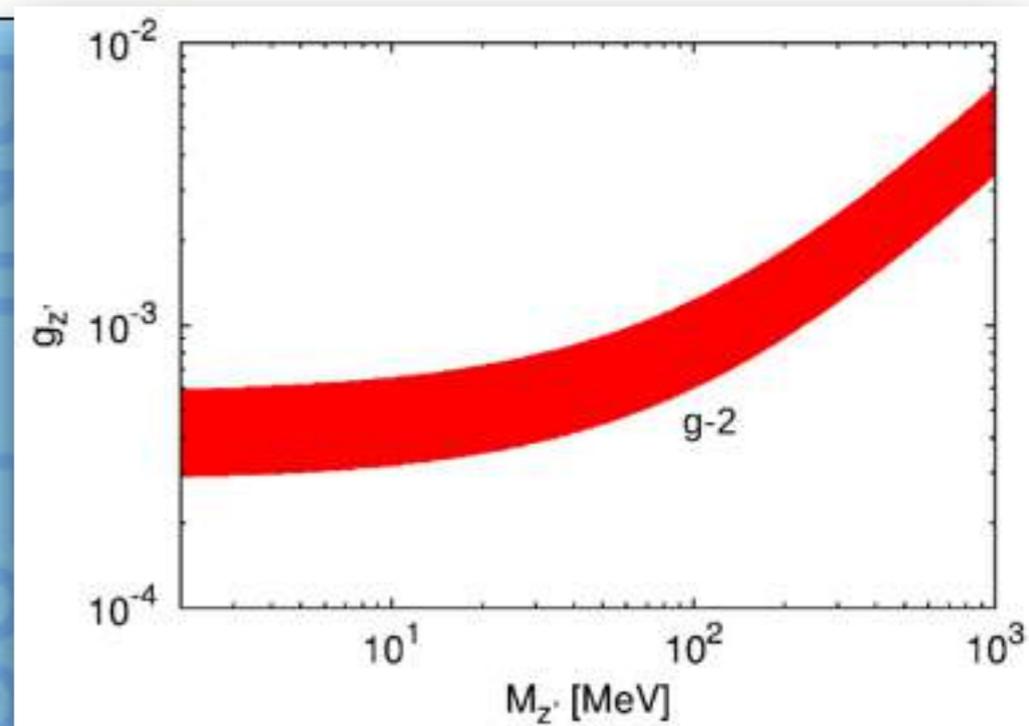
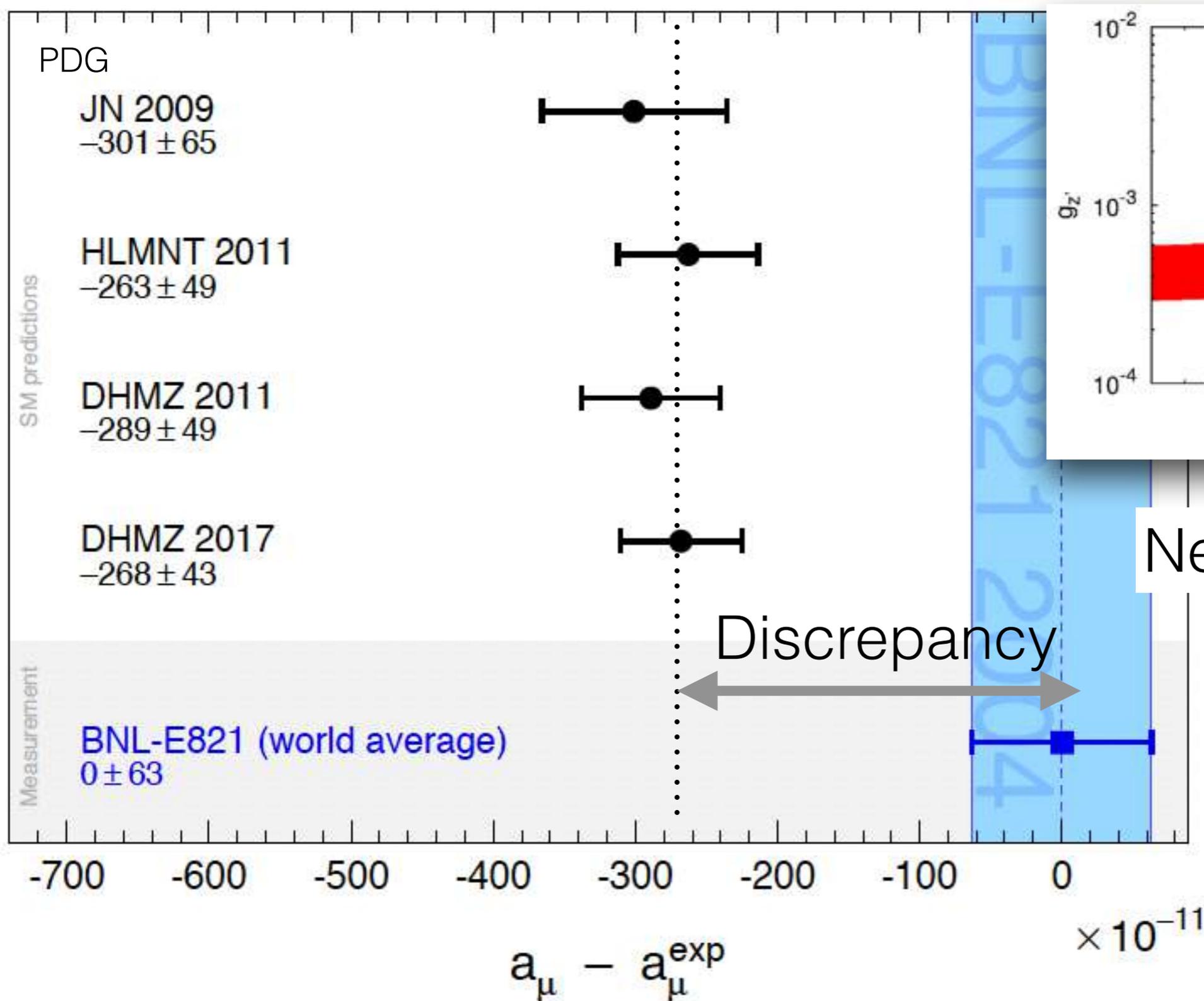
$$\sigma_{\text{@res}} \gtrsim \mathcal{O}(10^{-30})\text{cm}^2 \implies g_{Z'} \gtrsim 10^{-4}$$

The new leptonic force is also good
for the other observables...

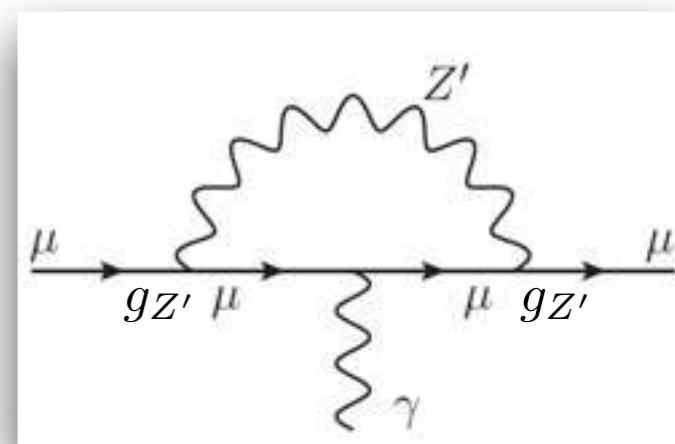
Muon $g-2$ - Long-standing 3 sigma



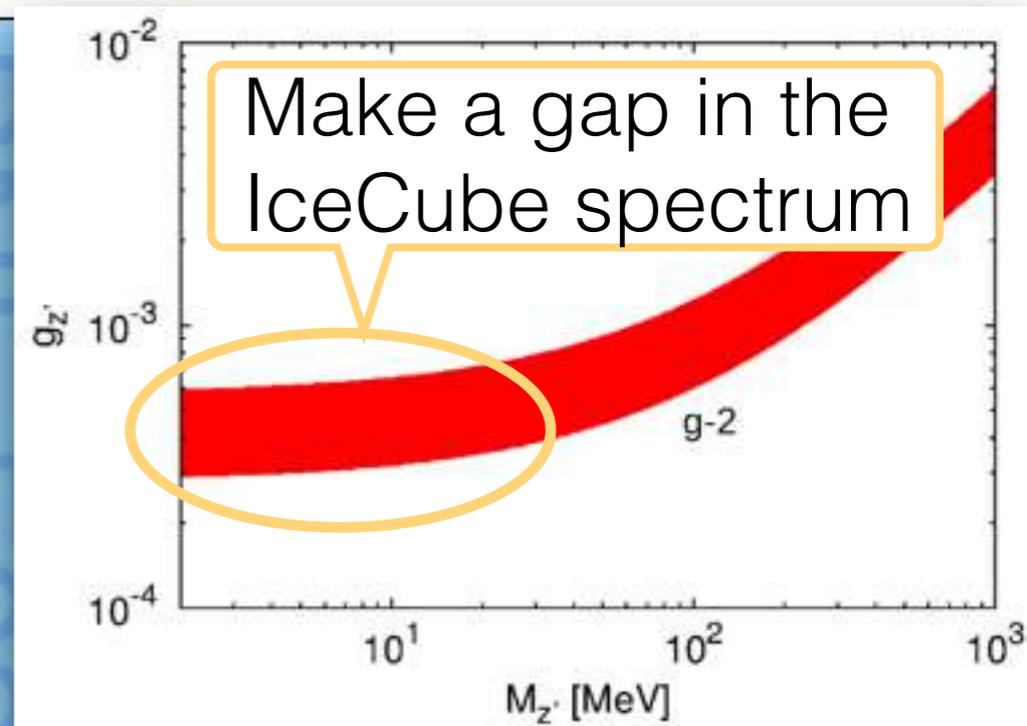
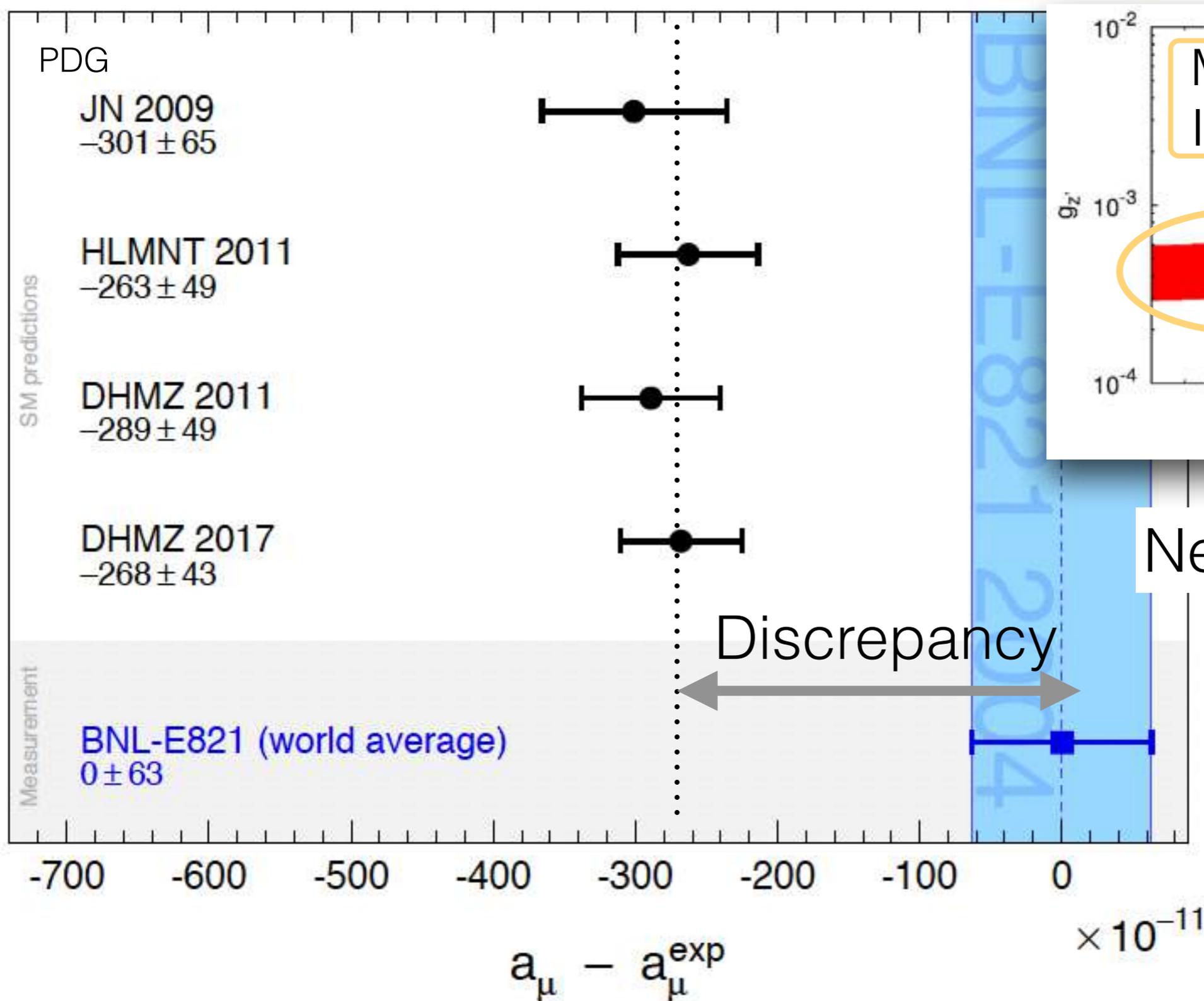
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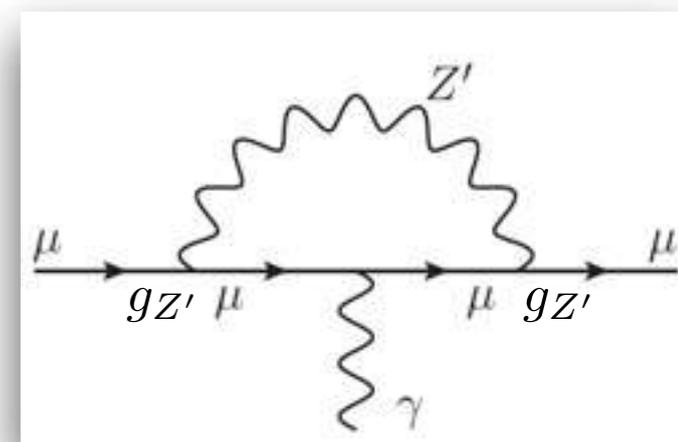
New Leptonic force?



Muon $g-2$ - Long-standing 3 sigma



New Leptonic force?



We are waiting for the release from Fermilab $g-2$ exp.

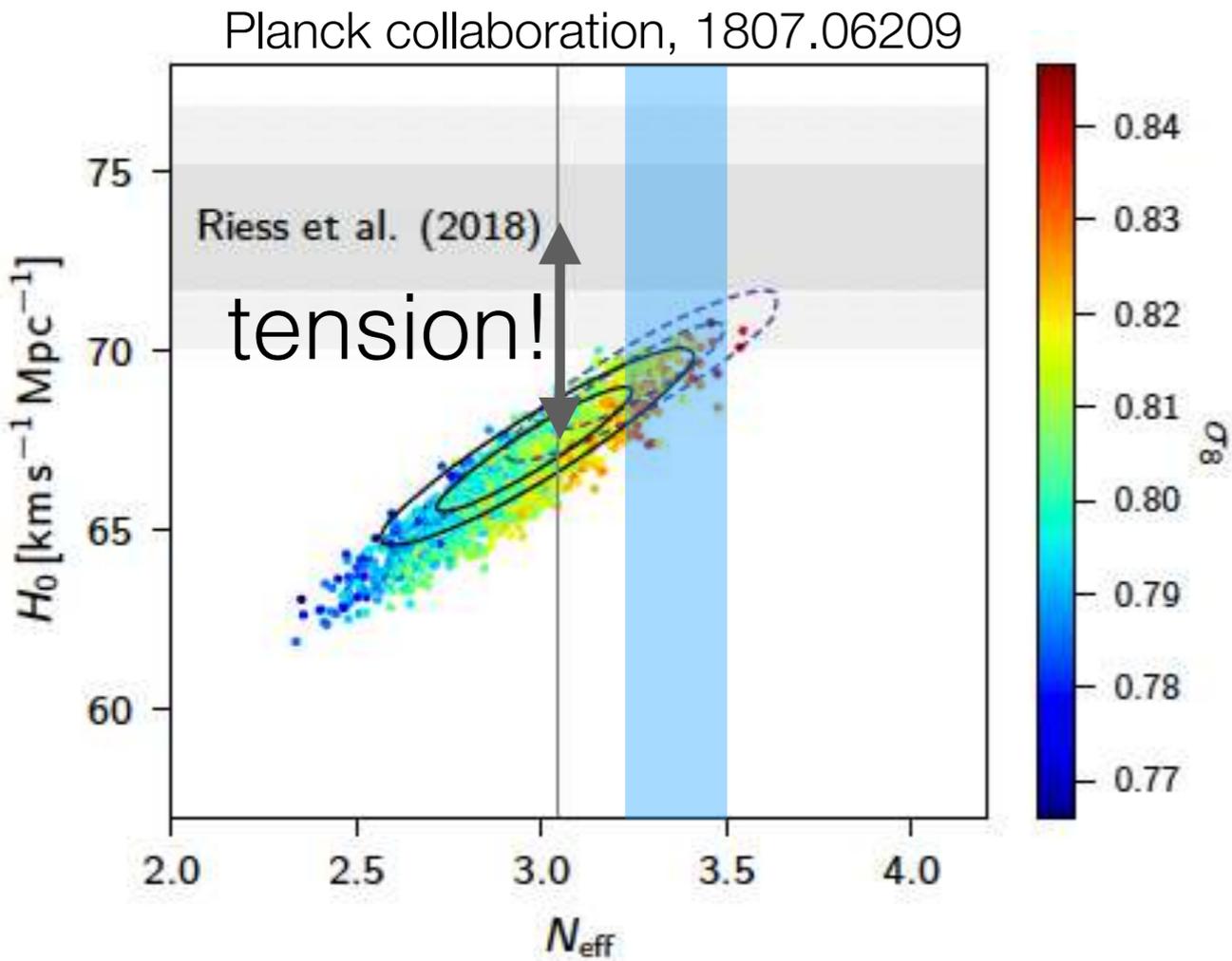
H0 tension - NP beyond Λ CDM?

Neff-H0 correlation in the CMB observation

$$\text{CMB } \theta_{\text{obs.}} \equiv r_s / d_A$$

“Sound horizon”
 $r_s(z_{\gamma\text{dec.}}) = \int_{z_{\gamma\text{dec.}}}^{\infty} \frac{c_s dz'}{H(z')}$

“Angular distance”
 $d_A(z_{\gamma\text{dec.}}) = \int_0^{z_{\gamma\text{dec.}}} \frac{dz'}{H(z')}$



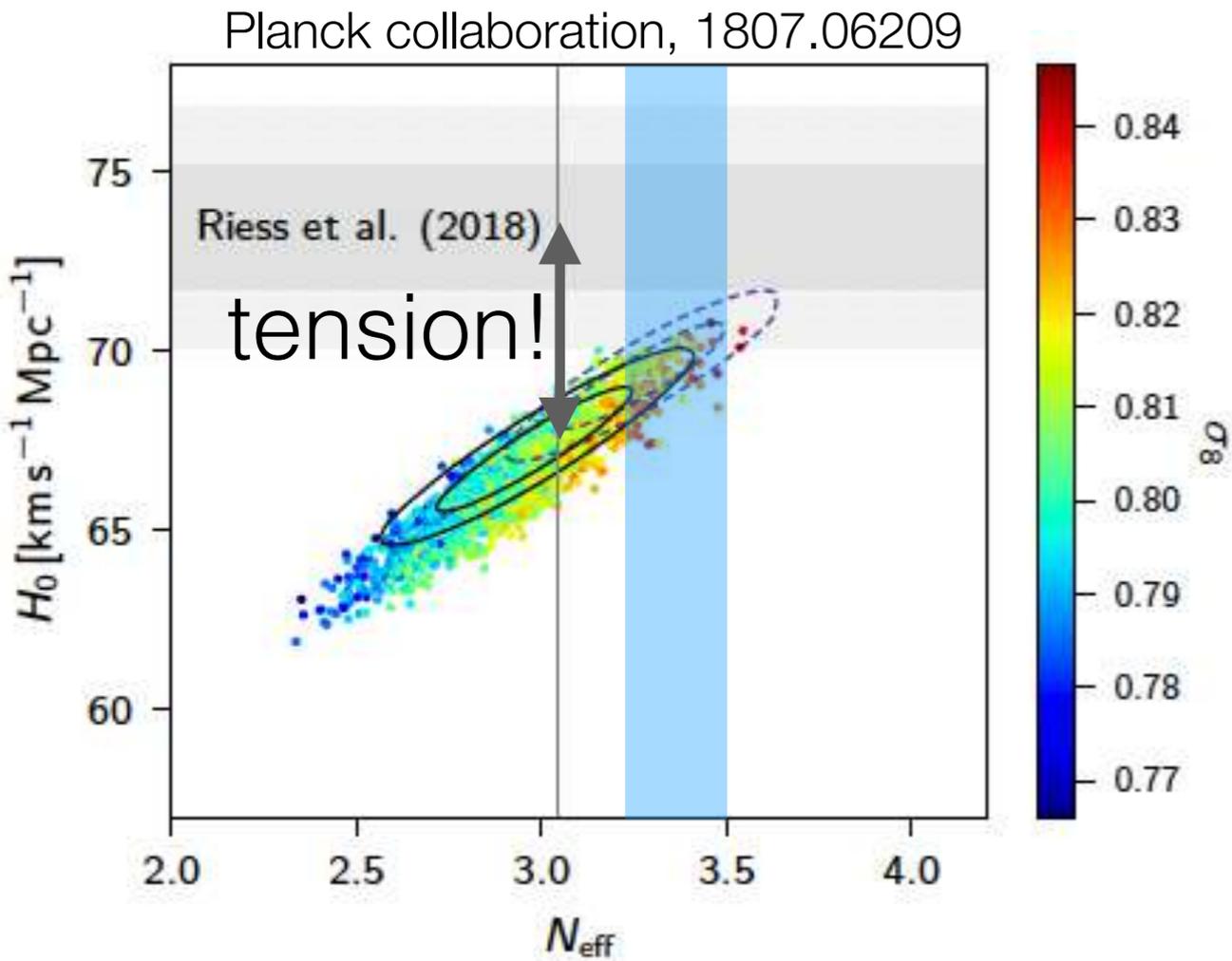
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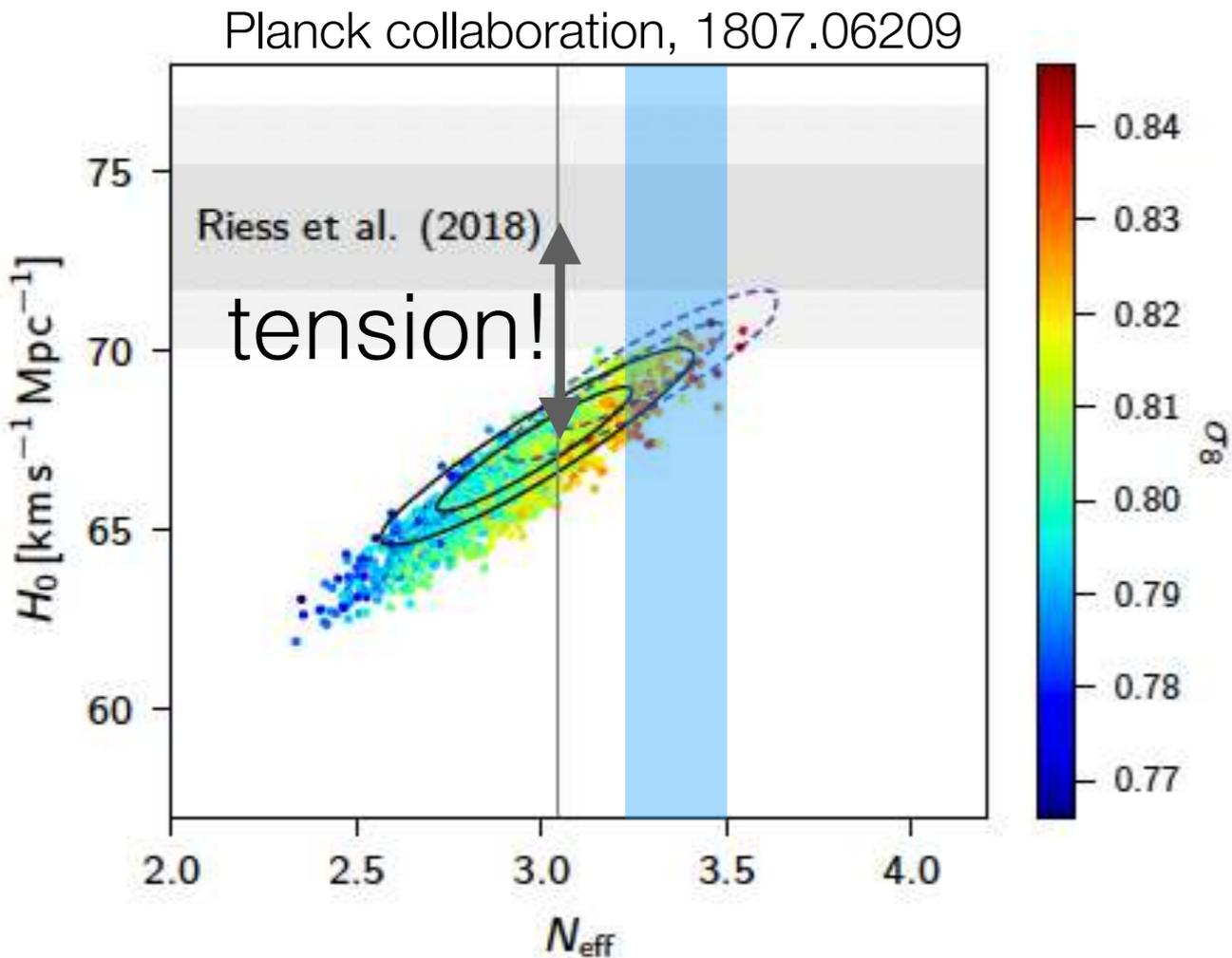
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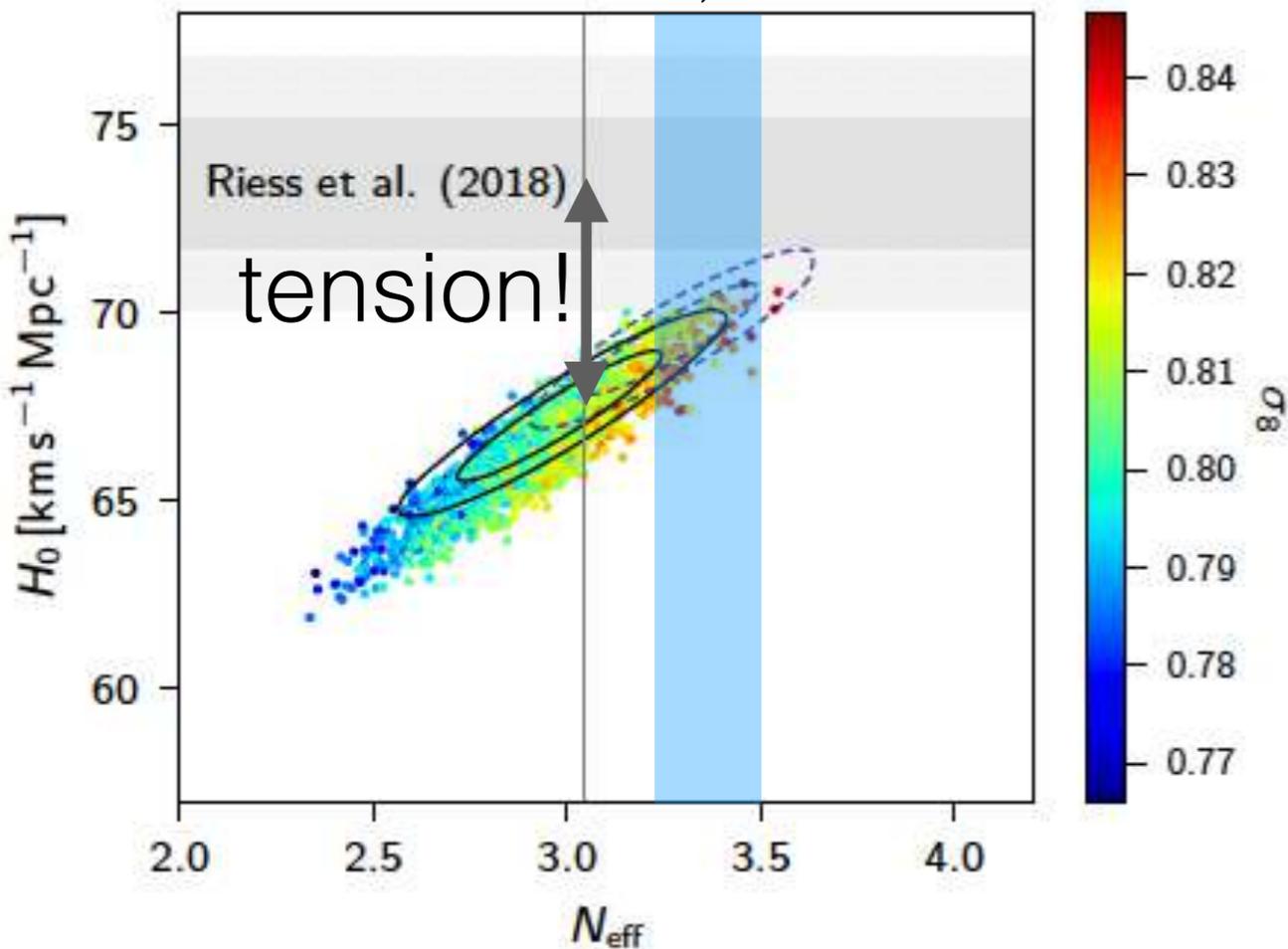
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\Rightarrow late time $H \nearrow$

Planck collaboration, 1807.06209



H0 tension - NP beyond Λ CDM?

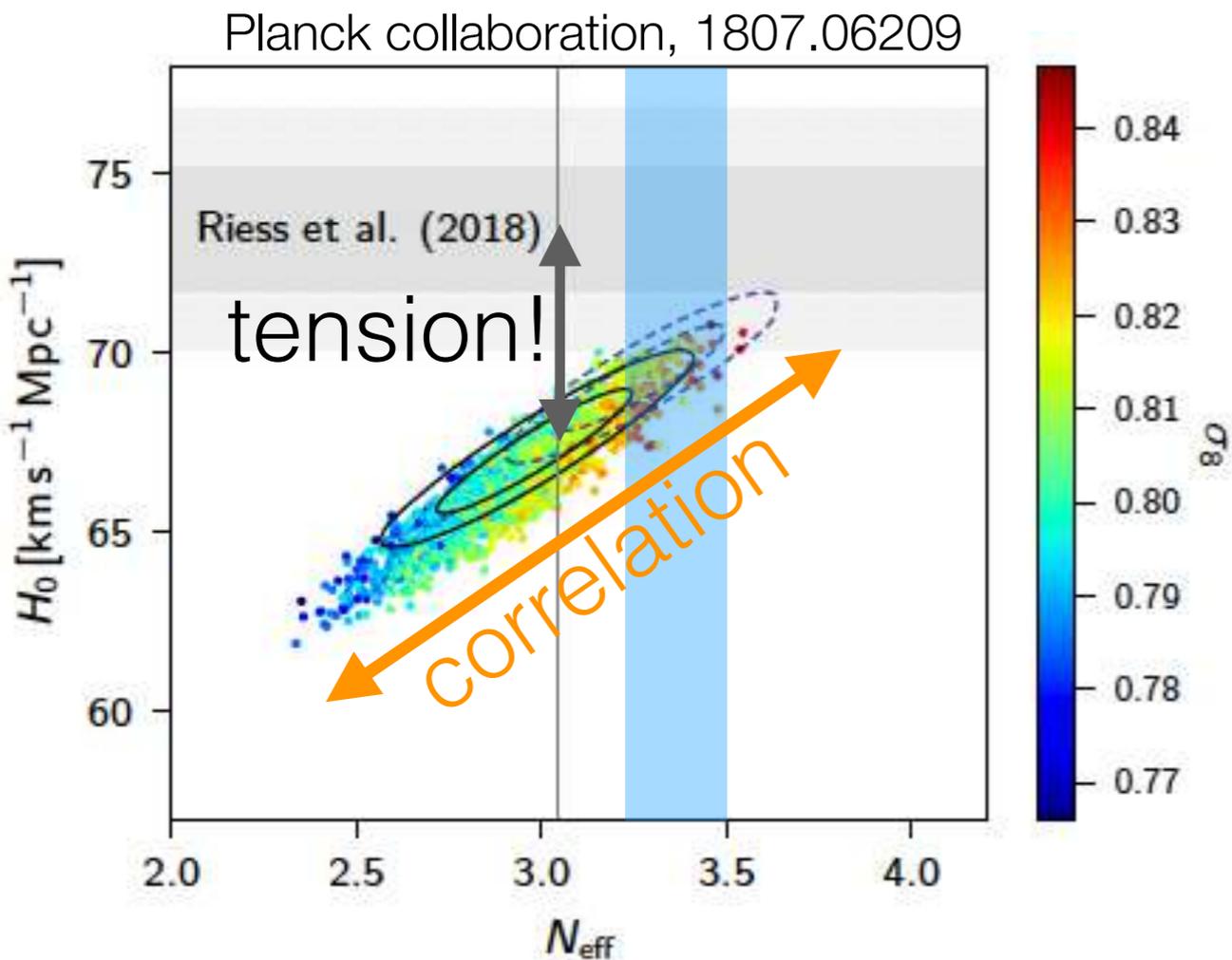
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CMB $\theta_{\text{obs.}} \equiv r_s / d_A$ **Neff** $\nearrow \Rightarrow r_s \searrow$ & keep $\theta_{\text{obs.}} \Rightarrow d_A \searrow$

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\Rightarrow **latetime H** \nearrow



The decay of Z' heats ν 's

$\Rightarrow T_\nu \nearrow \Rightarrow \text{Neff} \nearrow \Rightarrow \text{Relax the tension}$

H0 tension - NP beyond Λ CDM?

Neff-H0 correlation in the CMB observation

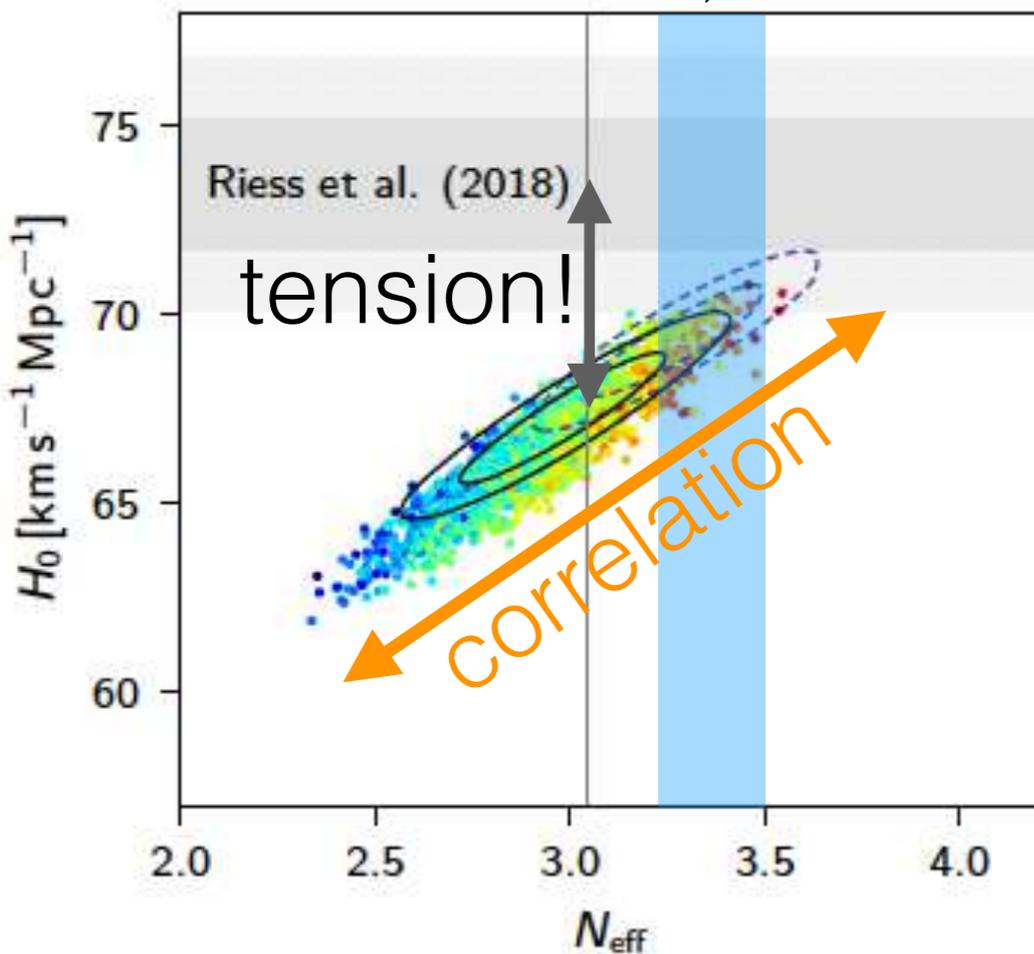
CMB $\theta_{\text{obs.}} \equiv r_s / d_A$ $\xrightarrow{\text{Neff} \nearrow} r_s \searrow$ & keep $\theta_{\text{obs.}} \Rightarrow d_A \searrow$

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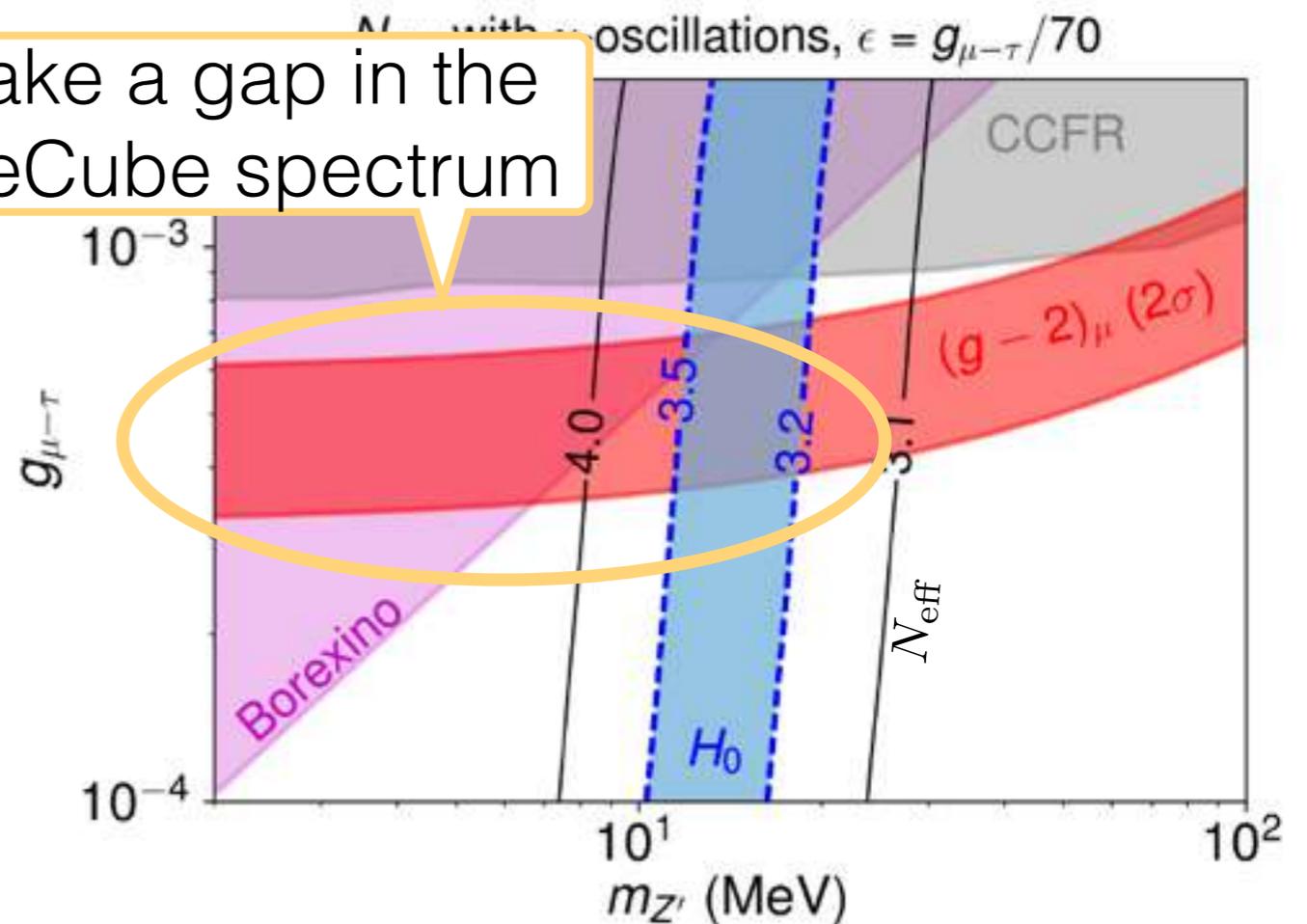
\Rightarrow latetime H \nearrow

Planck collaboration, 1807.06209



Escudero et al., 1901.02010

Make a gap in the IceCube spectrum

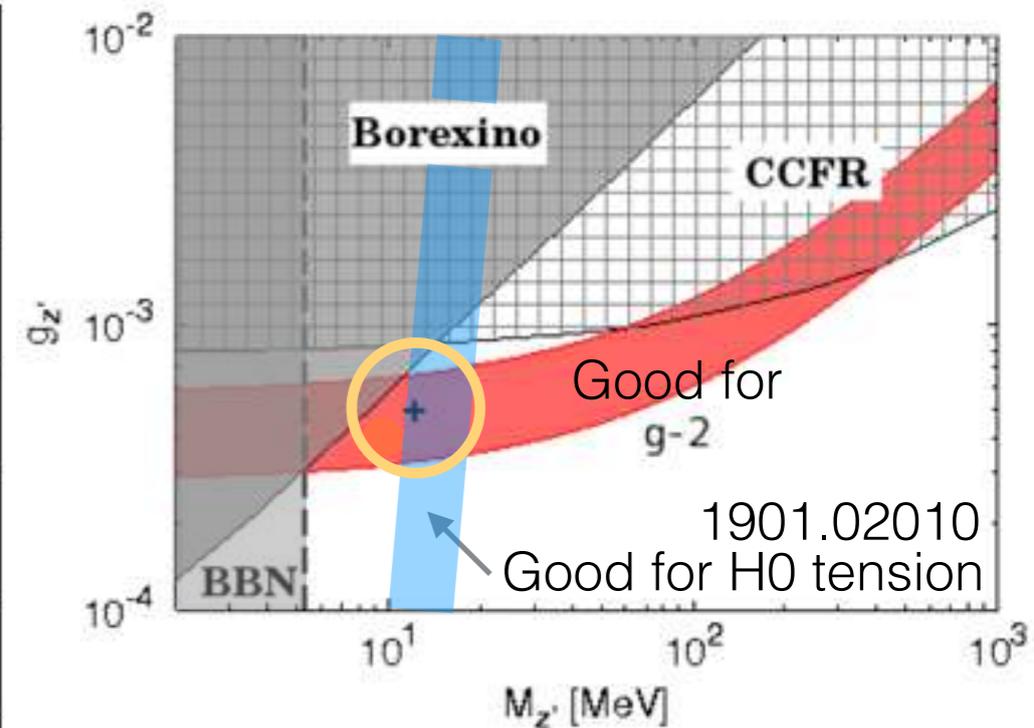
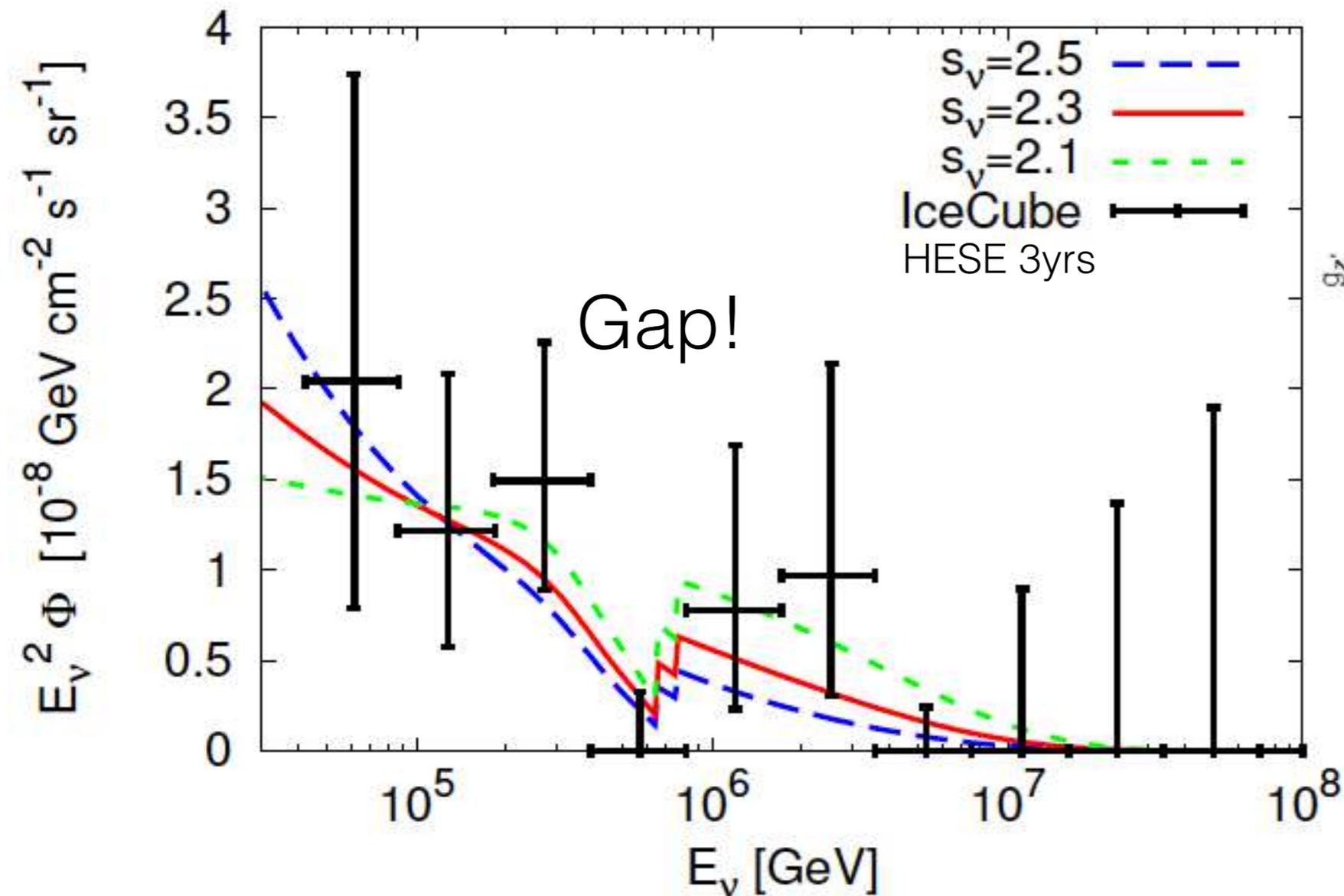


The annihilation of Z' heats ν 's

$\Rightarrow T_\nu \nearrow \Rightarrow \text{Neff} \nearrow \Rightarrow$ Relax the tension

Impact on the IceCube spectrum

Numerical result Araki et al., 1508.07471&1409.4180

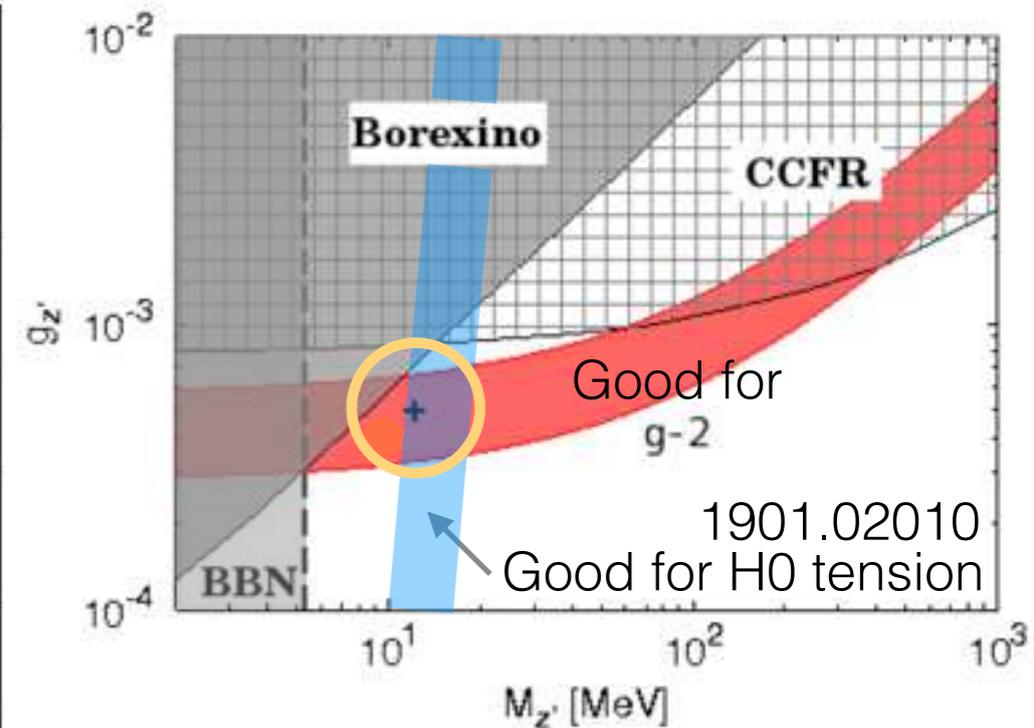
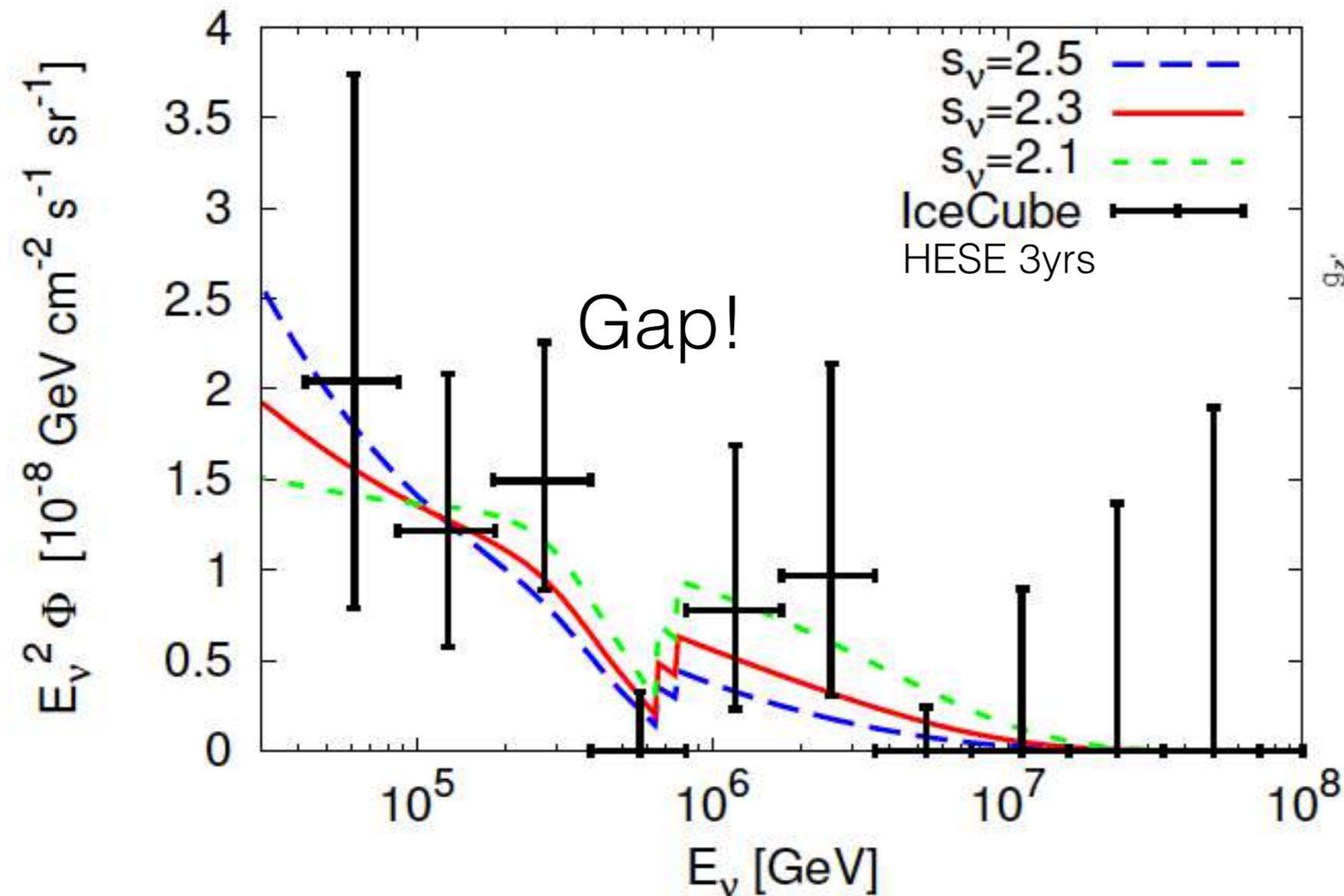


*Here the ν source distribution is assumed to follow the SFR.

A hard spectrum with a gap can fit to the data - good for GR

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A hard spectrum with a gap can fit to the data - good for GR

Araki et al., 1702.01497. Ballett et al., 1807.10973, Altmannshofer et al., 1902.06765

Future test of the leptonic Z' : @Belle II, Trident@DUNE near detector etc... Ultimate test - Muon beam dump Gninenko et al., 1412.1400