IFT Colloquium

Opportunities and Challenges in Particle Physics: a personal view

Ricardo D'Elia Matheus

The Standard Model

		Fermions			Bosons	
Quarks	Q = 2/3	u up	c charm	t top	γ foton	Gauge Bosons
	Q = -1/3	d down	s strange	b botton	g gluon	h Higgs boson
Leptons	Q = 0	ν_e electron neutrino	ν_μ muon neutrino	ν_τ tau neutrino	Z Z boson	
	Q = -1	e electron	μ muon	τ tau	W W boson	
		1^{st} gen.	2^{nd} gen.	3^{rd} gen.		

$$SU(3)_c \times SU(2)_L \times U(1)_Y$$

The Standard Model Works!

Symmetry + Symmetry Breaking pattern

$$SU(3)_c \times SU(2)_L \times U(1)_Y \longrightarrow SU(3)_c \times U(1)_{EM}$$

$$g_s \qquad g \qquad g' \qquad\qquad g_s \qquad e,\ \theta_W$$

Non trivial predictions!

"Matter" content (DoF actually present)

u up	c charm	t top	ν_e electron neutrino	ν_μ muon neutrino	ν_τ tau neutrino	h Higgs boson
d down	s strange	b botton	e electron	μ muon	τ tau	

γ foton
g gluon
Z Z boson
W W boson

The Standard Model Works!

$$igs_w M A_\mu (W_\mu^+\phi^- - W_\mu^-\phi^+) - ig\frac{1-2c_w^2}{2c_w} Z_\mu^0(\phi^+\partial_\mu\phi^- - \phi^-\partial_\mu\phi^+) +$$
$$igs_w A_\mu(\phi^+\partial_\mu\phi^- - \phi^-\partial_\mu\phi^+) - \frac{1}{4} g^2 W_\mu^+W_\mu^-[H^2+(\phi^0)^2+2\phi^+\phi^-] -$$
$$\frac{1}{4} g^2\frac{1}{c_w^2}Z_\mu^0Z_\mu^0[H^2+(\phi^0)^2+2(2s_w^2-1)^2\phi^+\phi^-] - \frac{1}{2} g^2\frac{s_w^2}{c_w}Z_\mu^0\phi^0(W_\mu^+\phi^- +$$
$$W_\mu^-\phi^+) - \frac{1}{2} ig^2\frac{s_w^2}{c_w}Z_\mu^0 H(W_\mu^+\phi^- - W_\mu^-\phi^+) + \frac{1}{2} g^2 s_w A_\mu\phi^0(W_\mu^+\phi^- +$$
$$W_\mu^-\phi^+) + \frac{1}{2} ig^2 s_w A_\mu H(W_\mu^+\phi^- - W_\mu^-\phi^+) - g^2\frac{s_w}{c_w}(2c_w^2-1)Z_\mu^0A_\mu\phi^+\phi^- -$$
$$g^1 s_w^2 A_\mu A_\mu\phi^+\phi^- - \bar{e}^\lambda(\gamma\partial+m_e^\lambda)e^\lambda - \bar{\nu}^\lambda\gamma\partial\nu^\lambda - \bar{u}_j^\lambda(\gamma\partial+m_u^\lambda)u_j^\lambda -$$
$$\bar{d}_j^\lambda(\gamma\partial+m_d^\lambda)d_j^\lambda + igs_wA_\mu[-(\bar{e}^\lambda\gamma^\mu e^\lambda)+\frac{2}{3}(\bar{u}_j^\lambda\gamma^\mu u_j^\lambda)-\frac{1}{3}(\bar{d}_j^\lambda\gamma^\mu d_j^\lambda)] +$$
$$\frac{ig}{4c_w}Z_\mu^0[(\bar{\nu}^\lambda\gamma^\mu(1+\gamma^5)\nu^\lambda)+(\bar{e}^\lambda\gamma^\mu(4s_w^2-1-\gamma^5)e^\lambda)+(\bar{u}_j^\lambda\gamma^\mu(\frac{4}{3} s_w^2 -$$
$$1-\gamma^5)u_j^\lambda)+(\bar{d}_j^\lambda\gamma^\mu(1-\frac{8}{3} s_w^2-\gamma^5)d_j^\lambda)] + \frac{ig}{2\sqrt{2}}W_\mu^+[(\bar{\nu}^\lambda\gamma^\mu(1+\gamma^5)e^\lambda)+$$
$$(\bar{u}_j^\lambda\gamma^\mu(1+\gamma^5)C_{\lambda\kappa}d_j^\kappa)] + \frac{ig}{2\sqrt{2}}W_\mu^-[(\bar{e}^\lambda\gamma^\mu(1+\gamma^5)\nu^\lambda)+(\bar{d}_j^\kappa C_{\lambda\kappa}^\dagger\gamma^\mu(1+$$
$$\gamma^5)u_j^\lambda)] + \frac{ig}{2\sqrt{2}}\frac{m_e^\lambda}{M}[-\phi^+(\bar{\nu}^\lambda(1-\gamma^5)e^\lambda)+\phi^-(\bar{e}^\lambda(1+\gamma^5)\nu^\lambda)] -$$
$$\frac{g}{2}\frac{m_e^\lambda}{M}[H(\bar{e}^\lambda e^\lambda)+i\phi^0(\bar{e}^\lambda\gamma^5 e^\lambda)] + \frac{ig}{2M\sqrt{2}}\phi^+[-m_d^\kappa(\bar{u}_j^\lambda C_{\lambda\kappa}(1-\gamma^5)d_j^\kappa)+$$
$$m_u^\lambda(\bar{u}_j^\lambda C_{\lambda\kappa}(1+\gamma^5)d_j^\kappa] + \frac{ig}{2M\sqrt{2}}\phi^-[m_d^\lambda(\bar{d}_j^\lambda C_{\lambda\kappa}^\dagger(1+\gamma^5)u_j^\kappa) - m_u^\kappa(\bar{d}_j^\lambda C_{\lambda\kappa}^\dagger(1-$$

Many different operators!

19 parameters!

Every test so far confirms it

The Standard Model Works!

m_e	Electron mass	511 keV
m_μ	Muon mass	105.7 MeV
m_t	Tau mass	1.78 GeV
m_u	Up quark mass	1.9 MeV
m_d	Down quark mass	4.4 MeV
m_s	Strange quark mass	87 MeV
m_c	Charm quark mass	1.32 GeV
m_b	Bottom quark mass	4.24 GeV
m_t	Top quark mass	173.5 GeV
θ_{12}	CKM 12-mixing angle	13.1°
θ_{23}	CKM 23-mixing angle	2.4°
θ_{13}	CKM 13-mixing angle	0.2°
δ	CKM CP violation Phase	0.995
g'	U(1) gauge coupling	0.357
g	SU(2) gauge coupling	0.652
g_s	SU(3) gauge coupling	1.221
θ_{QCD}	QCD vacuum angle	~ 0
v	Higgs vacuum expectation value	246 GeV
m_H	Higgs mass	125.09 ± 0.24 GeV

Equivalent to Yukawa couplings, 13 parameters!

Higgs potential: v & mH

15 out of 19 parameters in the model are HIGGS PHYSICS!

(and we still don't call "Higgs Exchange" a 5th force)

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Takeaway message:

Understanding the Higgs = Understanding the SM

BSM aside:

(If you include neutrinos as Dirac fermions, you get an extra 7 parameters, all equivalent to Yukawa couplings)

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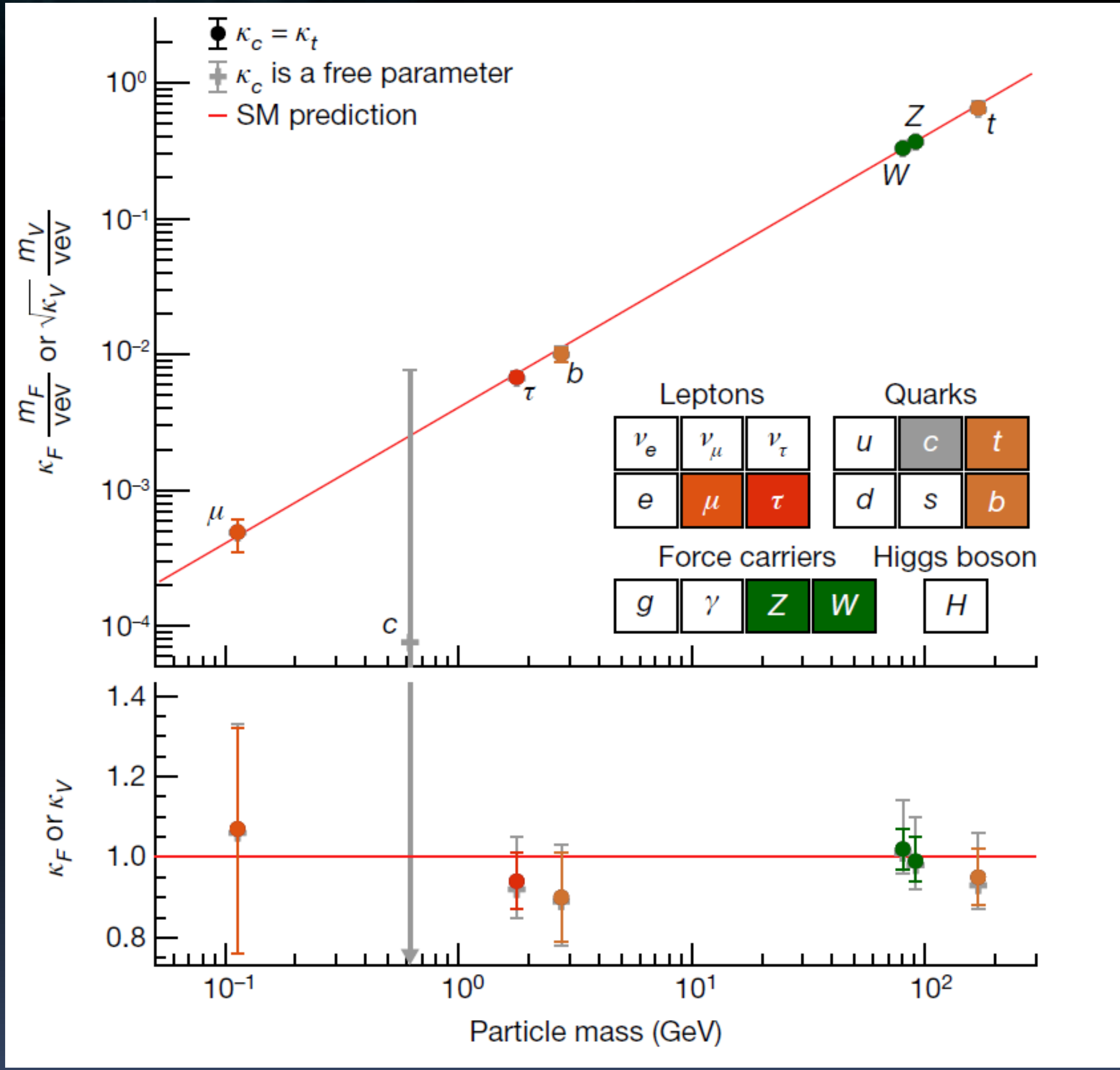
The Standard Model (recent tests)



(Run 2 ~ 139 fb^{-1})

ATLAS Collaboration, Nature 607 (2022) 7917, 52-59,
Nature 612 (2022) 7941, E24 (erratum)

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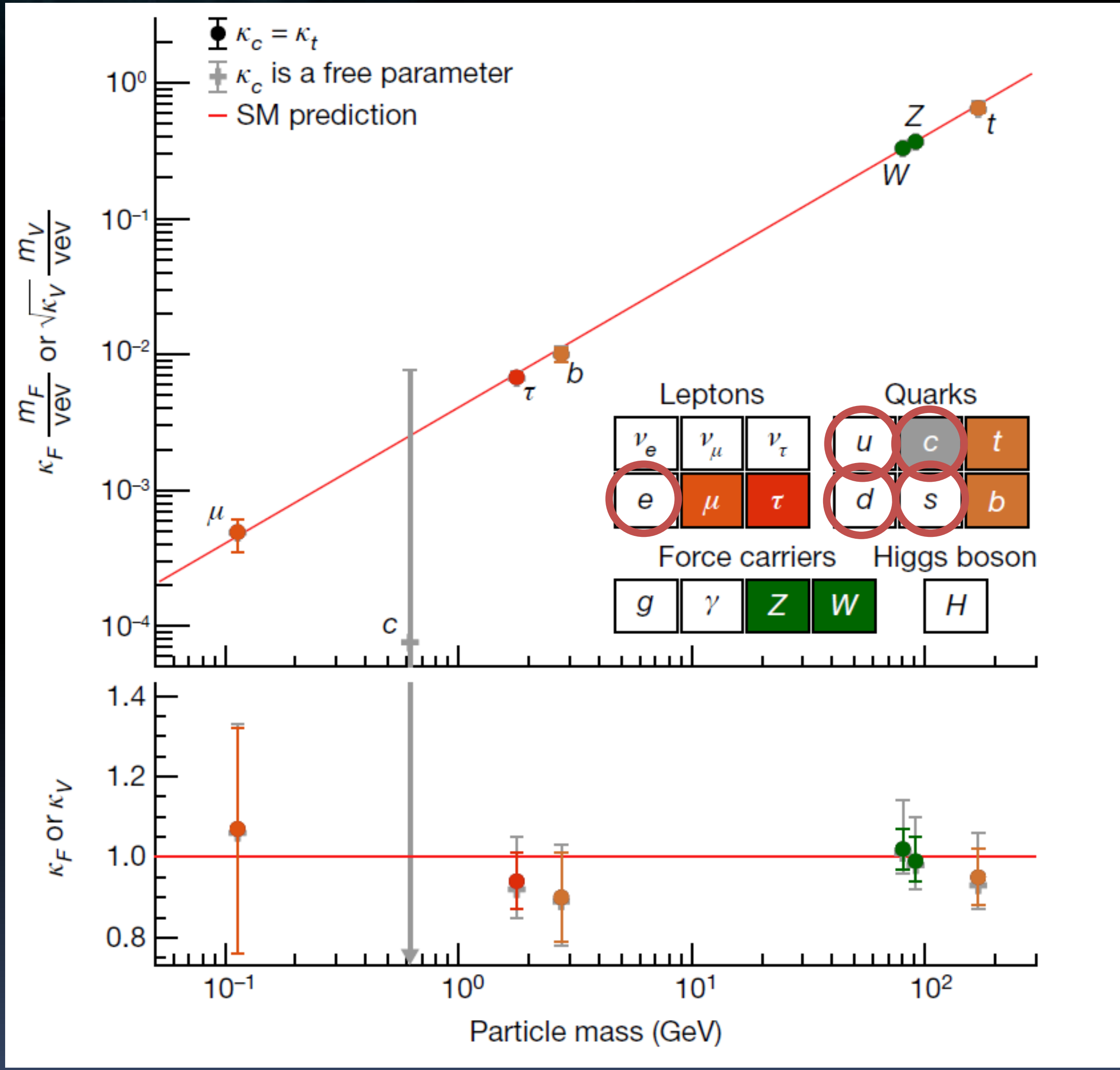

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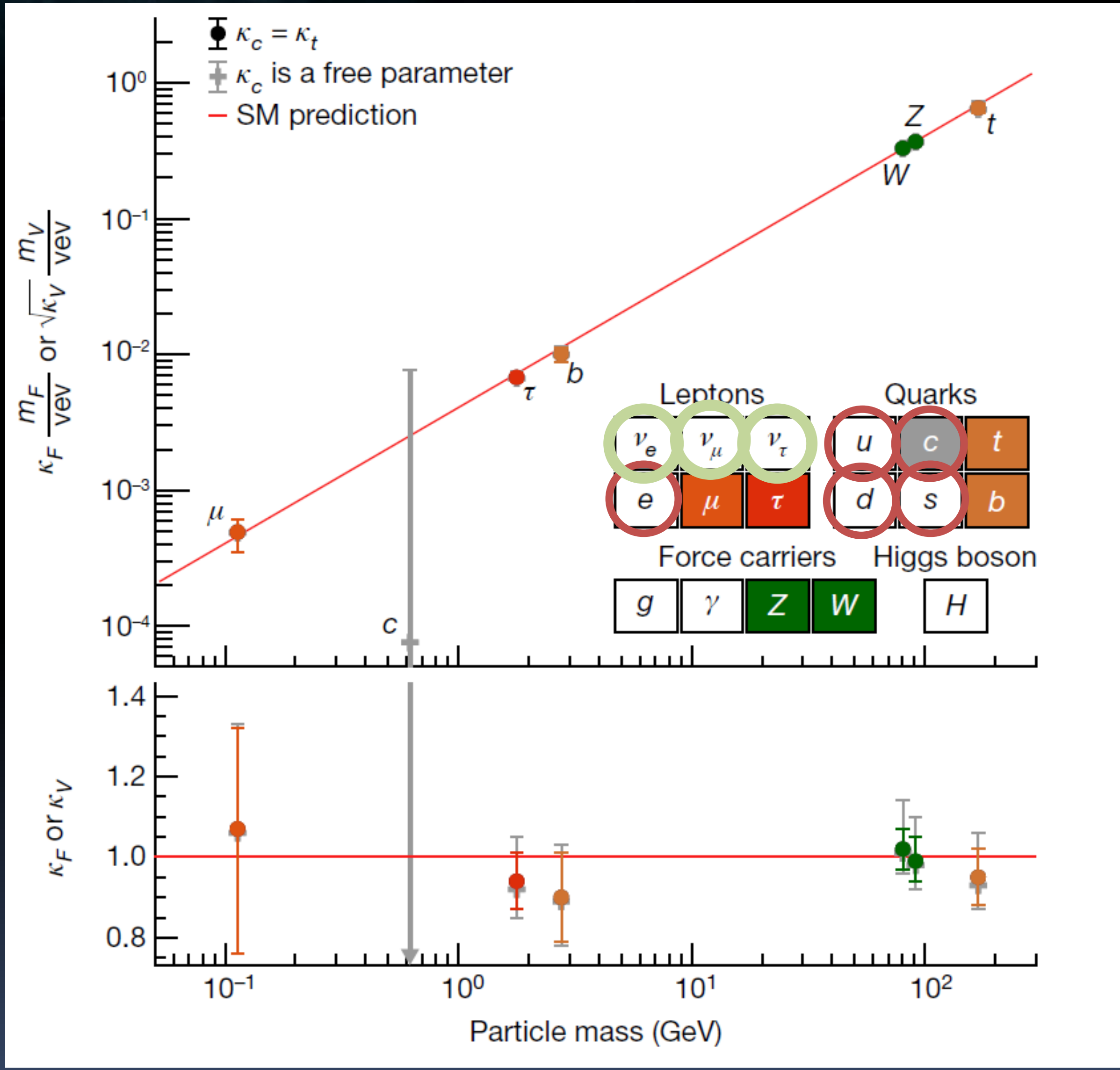

Untested!

Who knows?!

(Run 2 ~ 139 fb^{-1})

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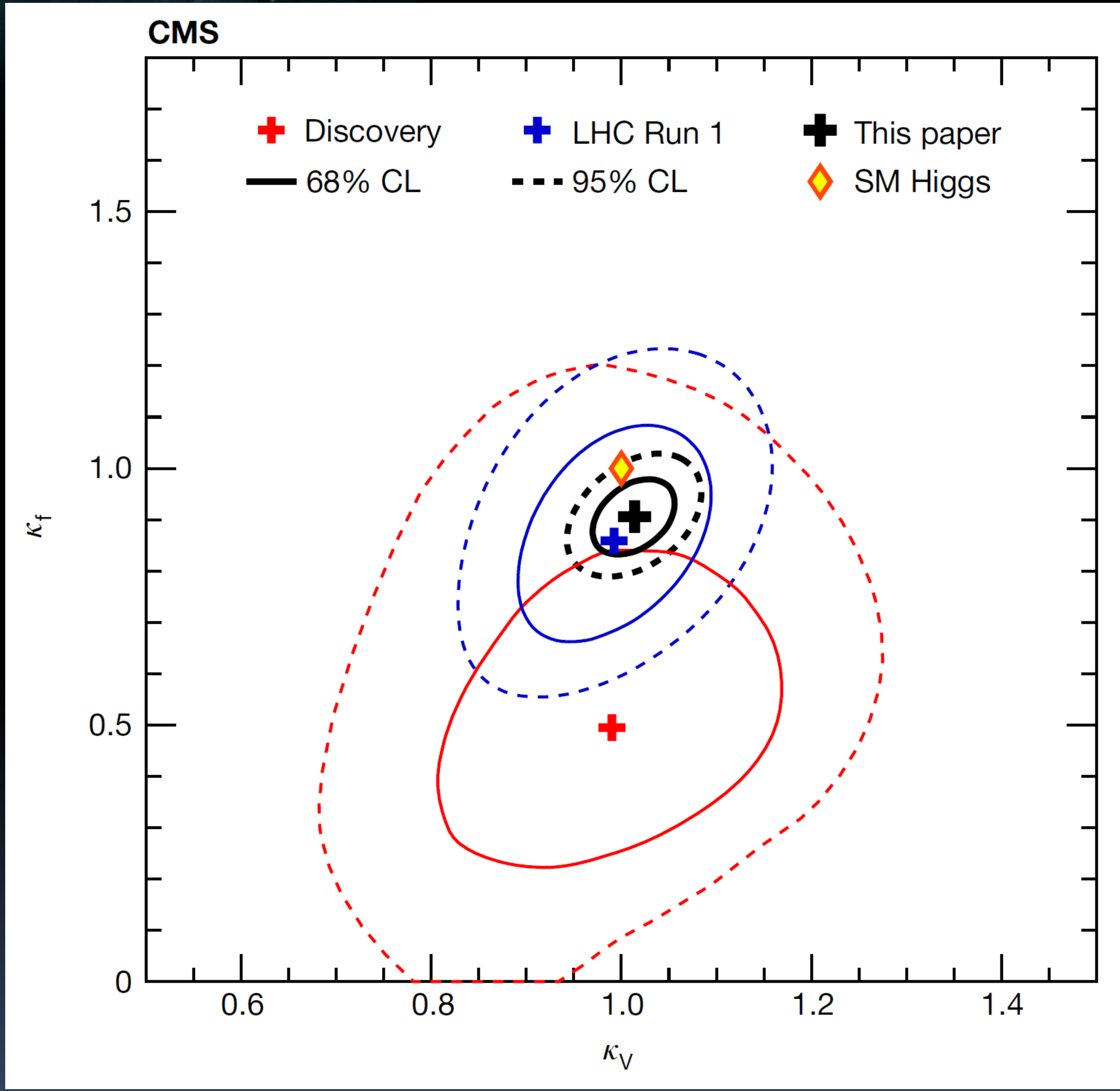

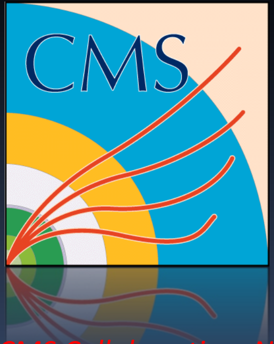

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CMS Collaboration, Nature 607 (2022) 7917, 60-68

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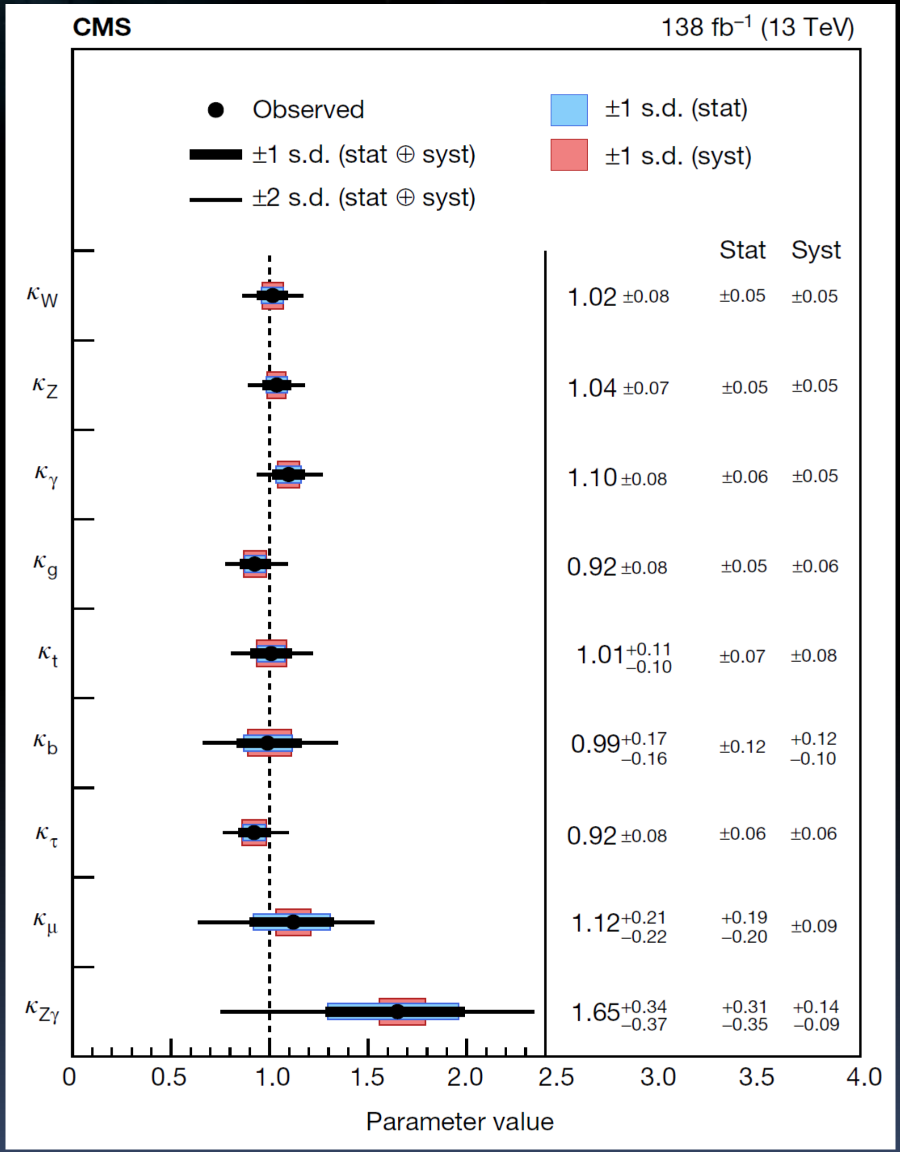

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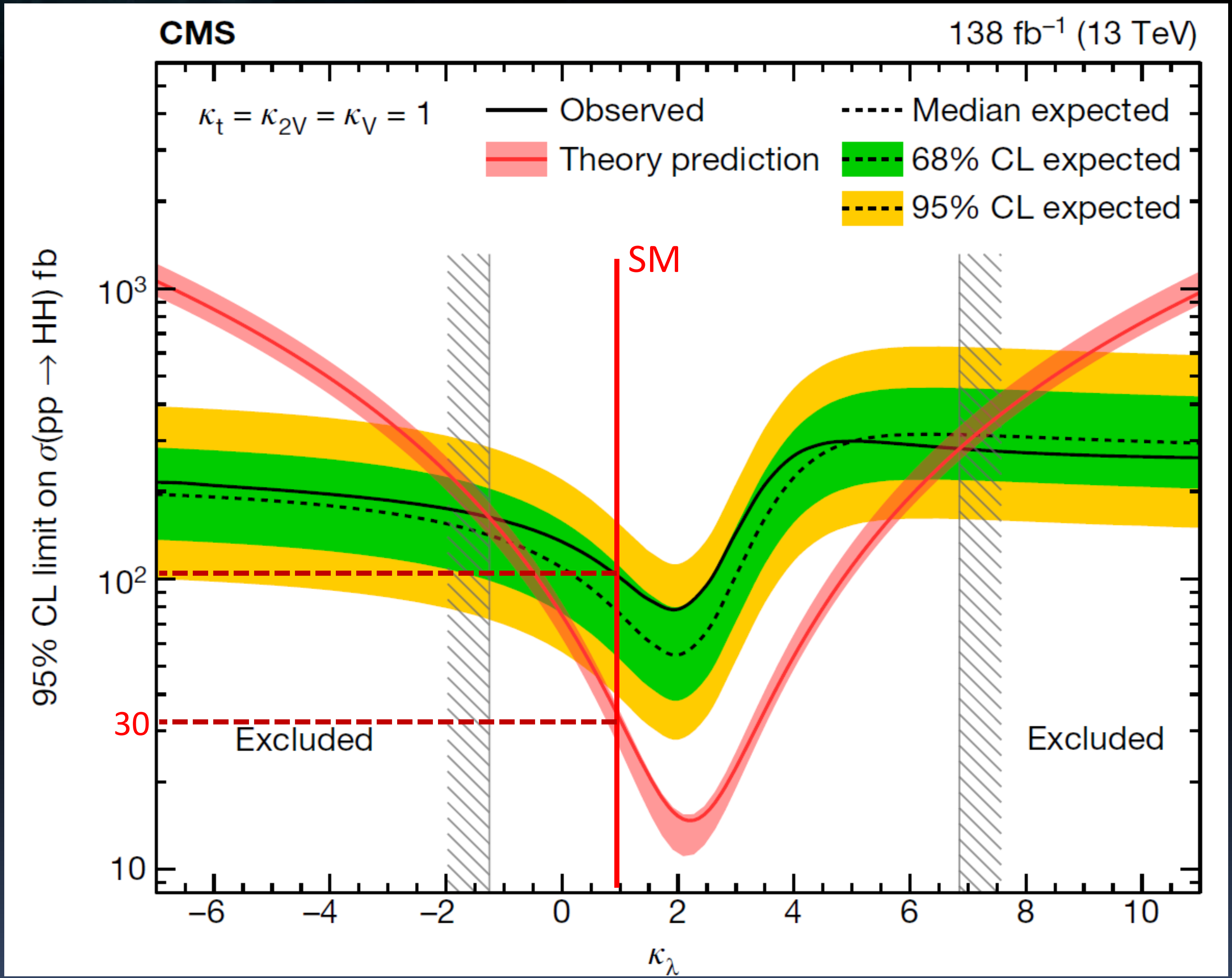
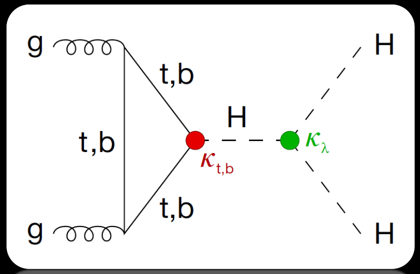
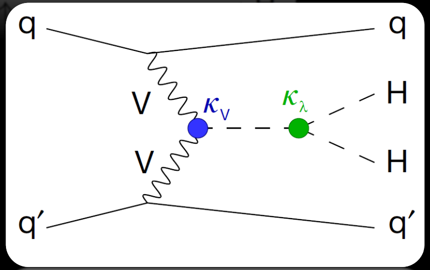
The Higgs Potential remains untested!







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The SM is not finalized!

Neutrinos have Masses (Problem!)

Neutrino Oscillations imply masses for the neutrinos (sub eV)

For all other fermions: $\frac{v}{\sqrt{2}} y_\psi \bar{\psi}_L \psi_R$ but we never observed a right handed neutrino

→ This DoF was never included in the SM

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Massless spin ½ → Massive spin ½

Takeaway message: New DoF NEEDED!

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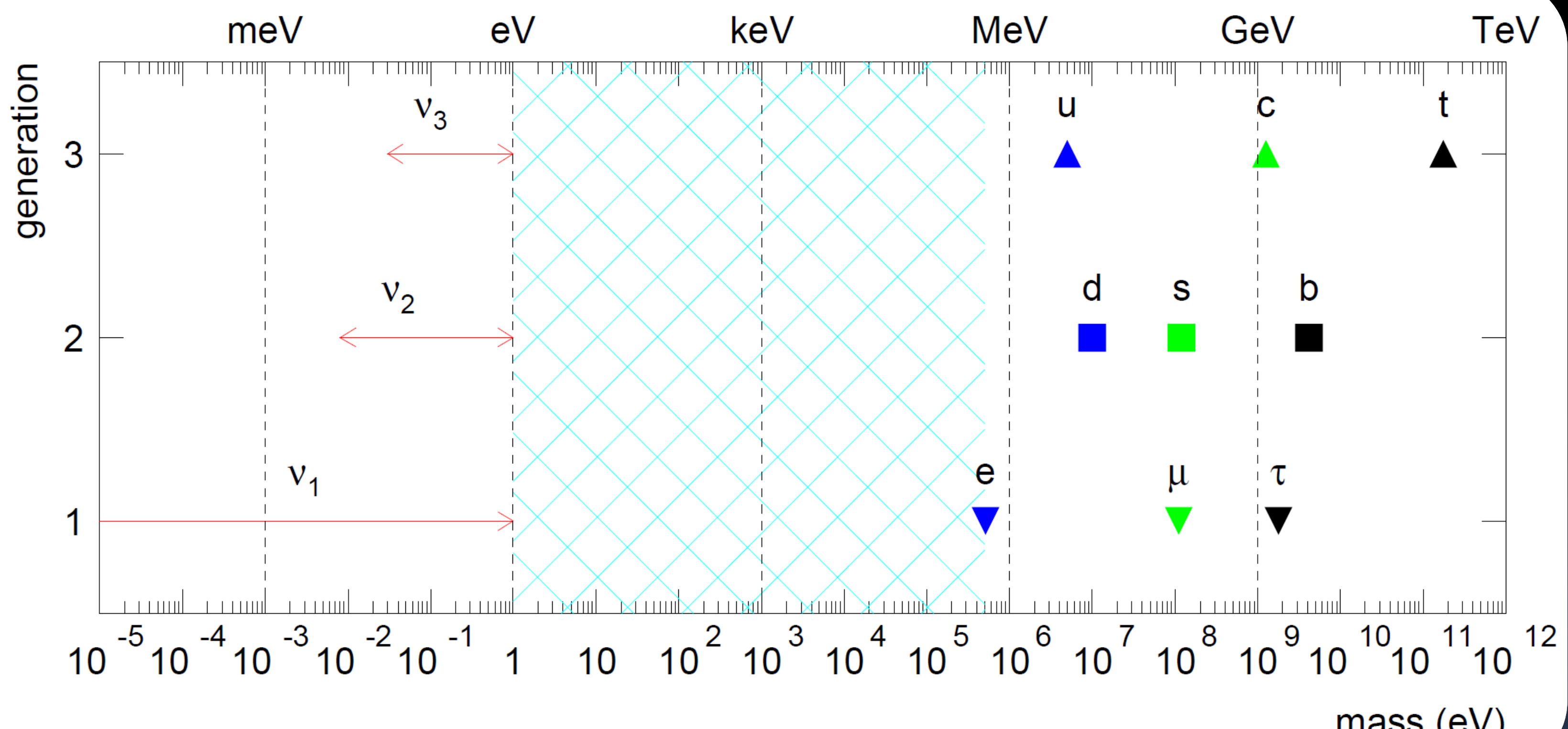
"Bad" (*and quite unsurprising*) solution: Right Handed Neutrino & Dirac Neutrinos



https://arxiv.org/abs/hep-ph/0503086

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"Bad" (*and quite unsurprising*) solution: Right Handed Neutrino & Dirac Neutrinos

- No color, no charge, no hypercharge, no isospin!
- Only interactions: gravitational and Yukawa (10^{-12})

Only novelty: Dirac Neutrinos ⟺ Lepton Number Conservation becomes "fundamental"!

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"Good" solutions: possible near term observations

→ Masses from a new scalar; extra dimensions (KK modes);
The many types of see-saw (imply Majorana Fermions).

The SM is not finalized!

The "cool kid" of mass models:

$$\mathcal{L}_5 = \frac{c_5}{\Lambda}\left(\tilde{H}^\dagger L_{f_1}\right)^T C \left(\tilde{H}^\dagger L_{f_2}\right)$$

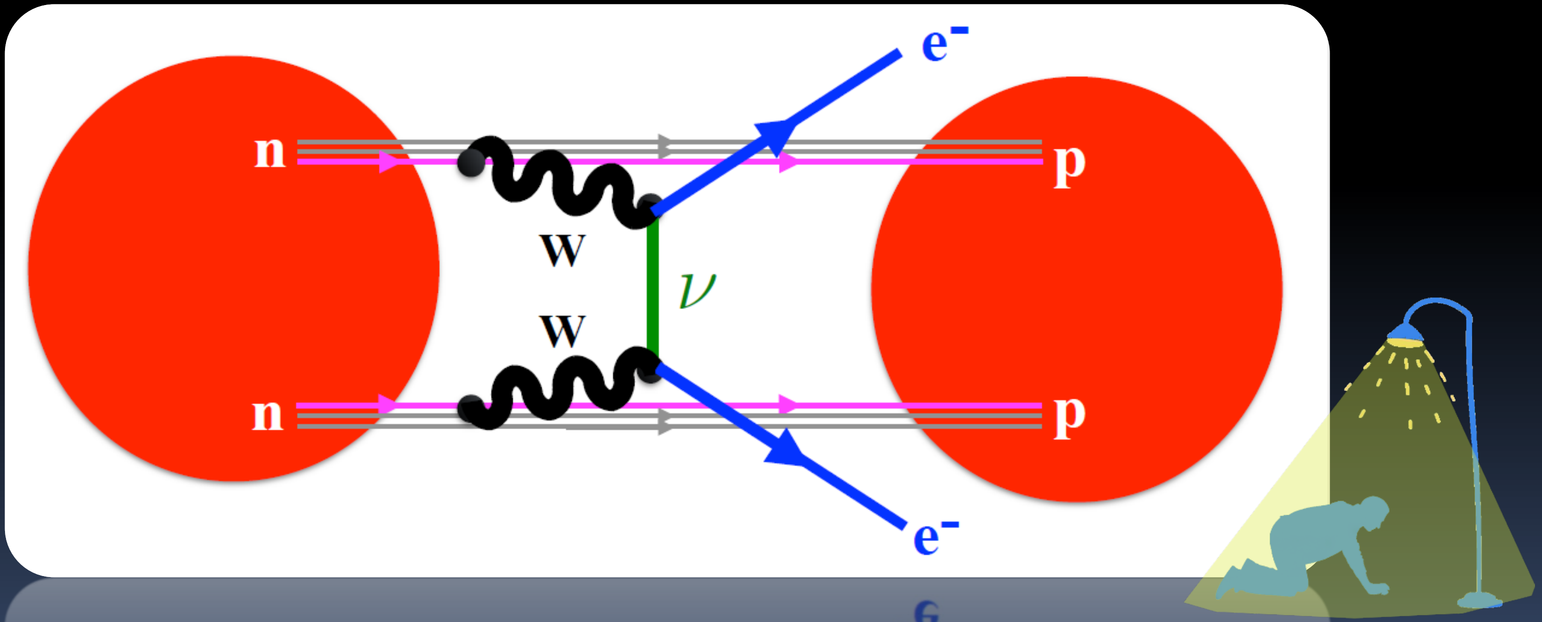
$\tilde{H}_i = \epsilon_{ij}(H_j)^*$

New physics at (high) scale Λ

$c_5 \sim 1$, $\Lambda \sim 10^{14}$ GeV

Lepton number violation!

Double Beta Decay APPEC Committee Report, arXiv:1910.04688



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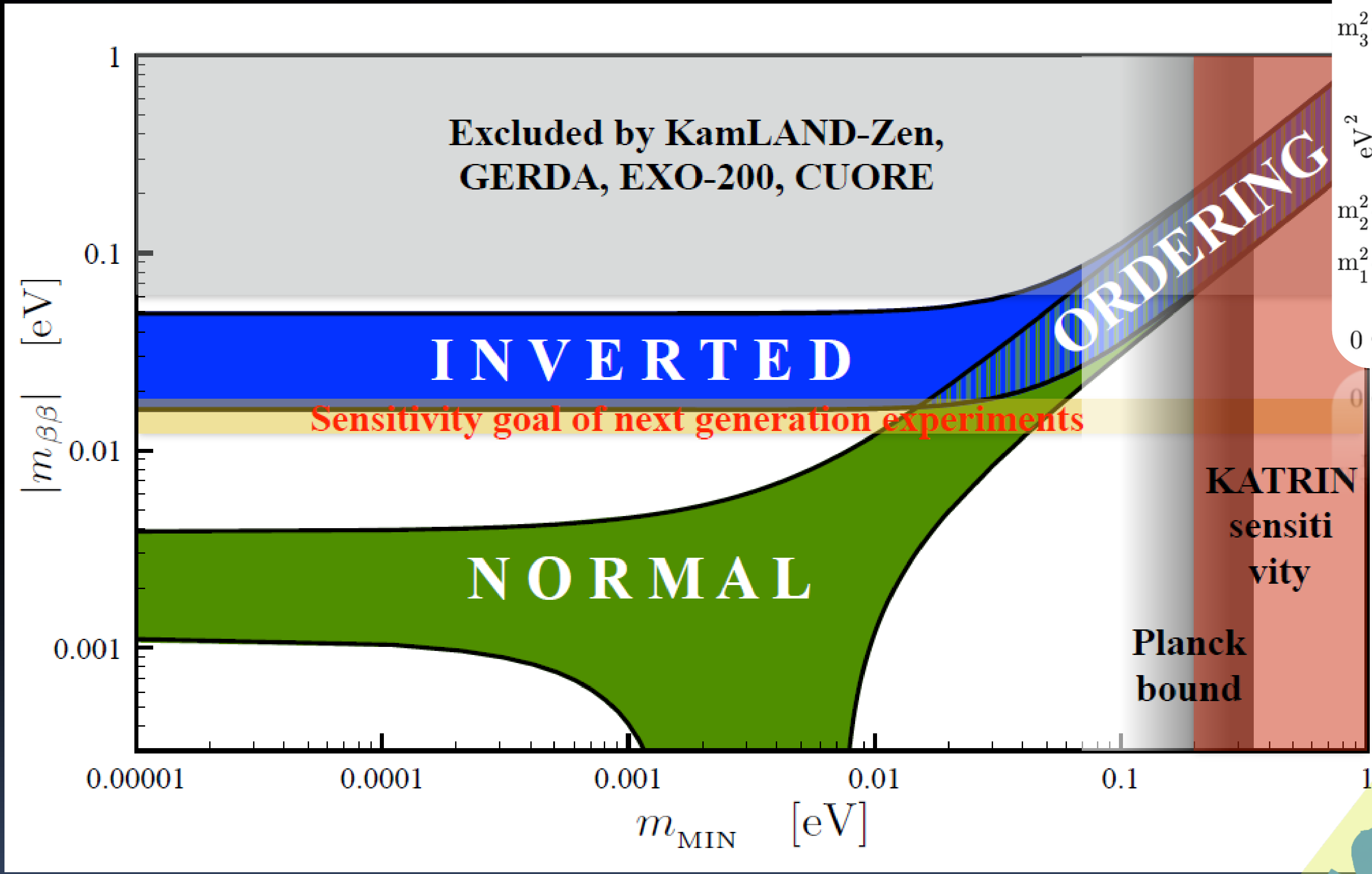

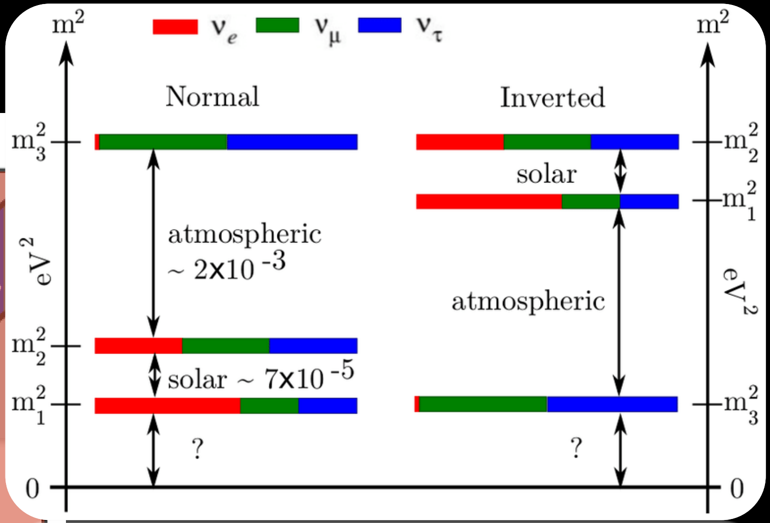

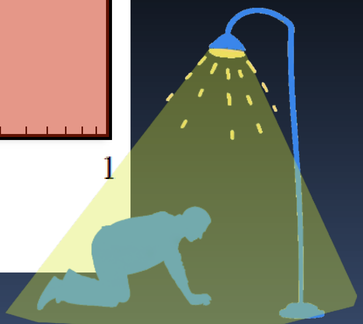

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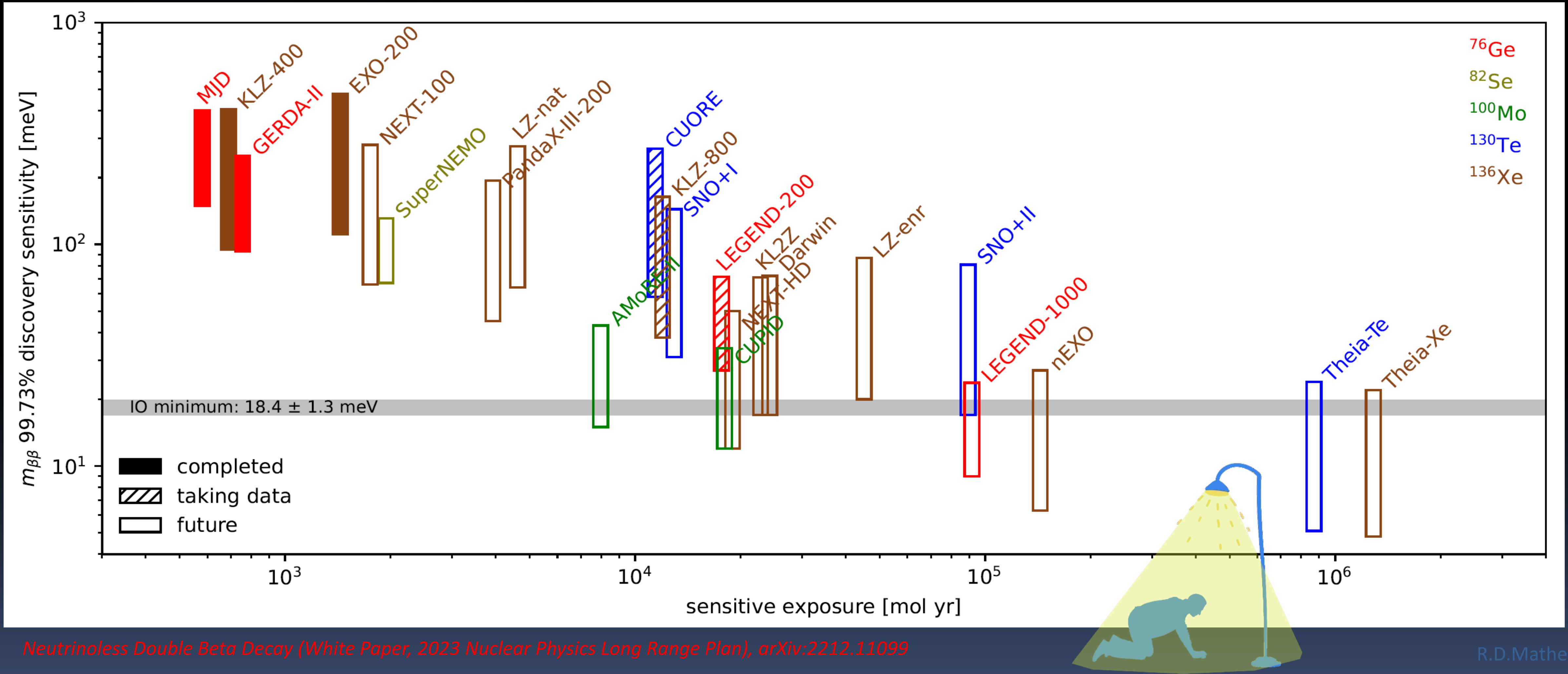

Neutrinoless Double Beta Decay (White Paper, 2023 Nuclear Physics Long Range Plan), arXiv:2212.11099

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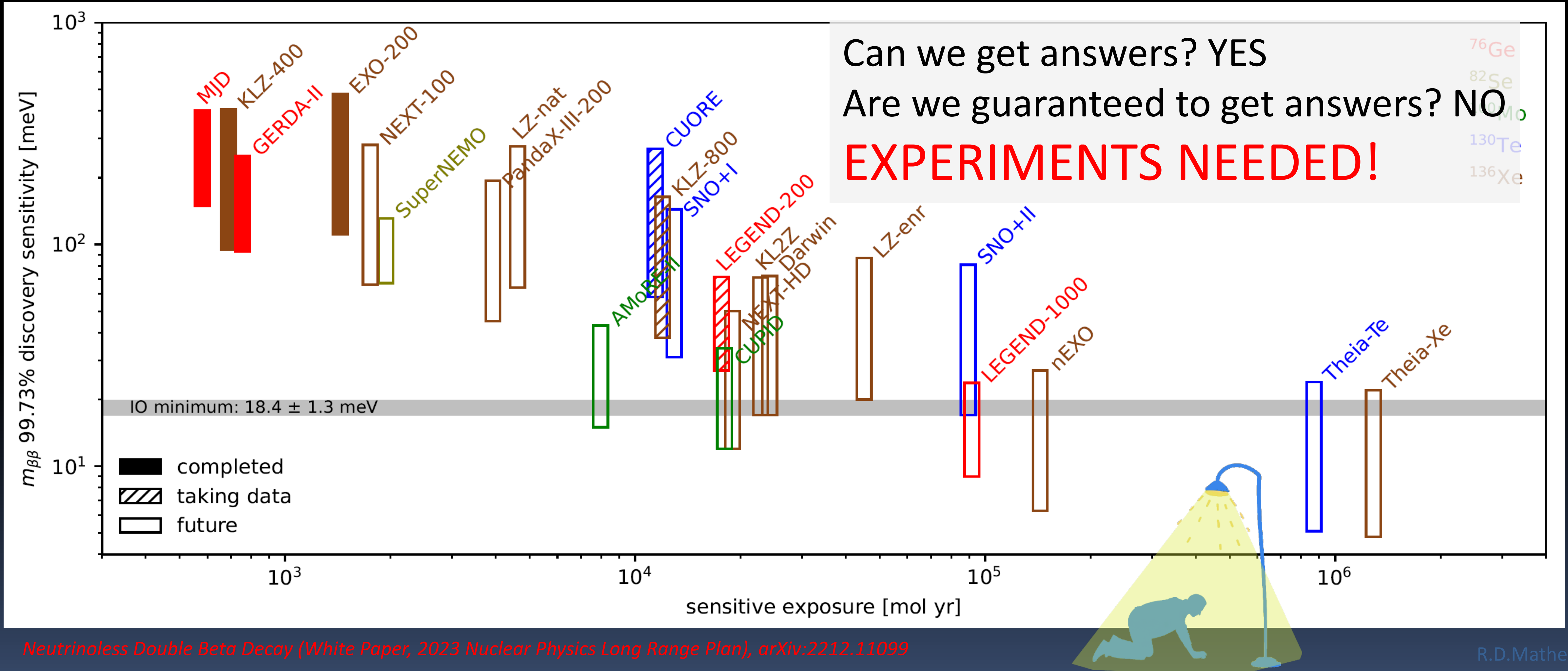

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The SM is not finalized!

There is Dark Matter (Problem? Probably yes.)

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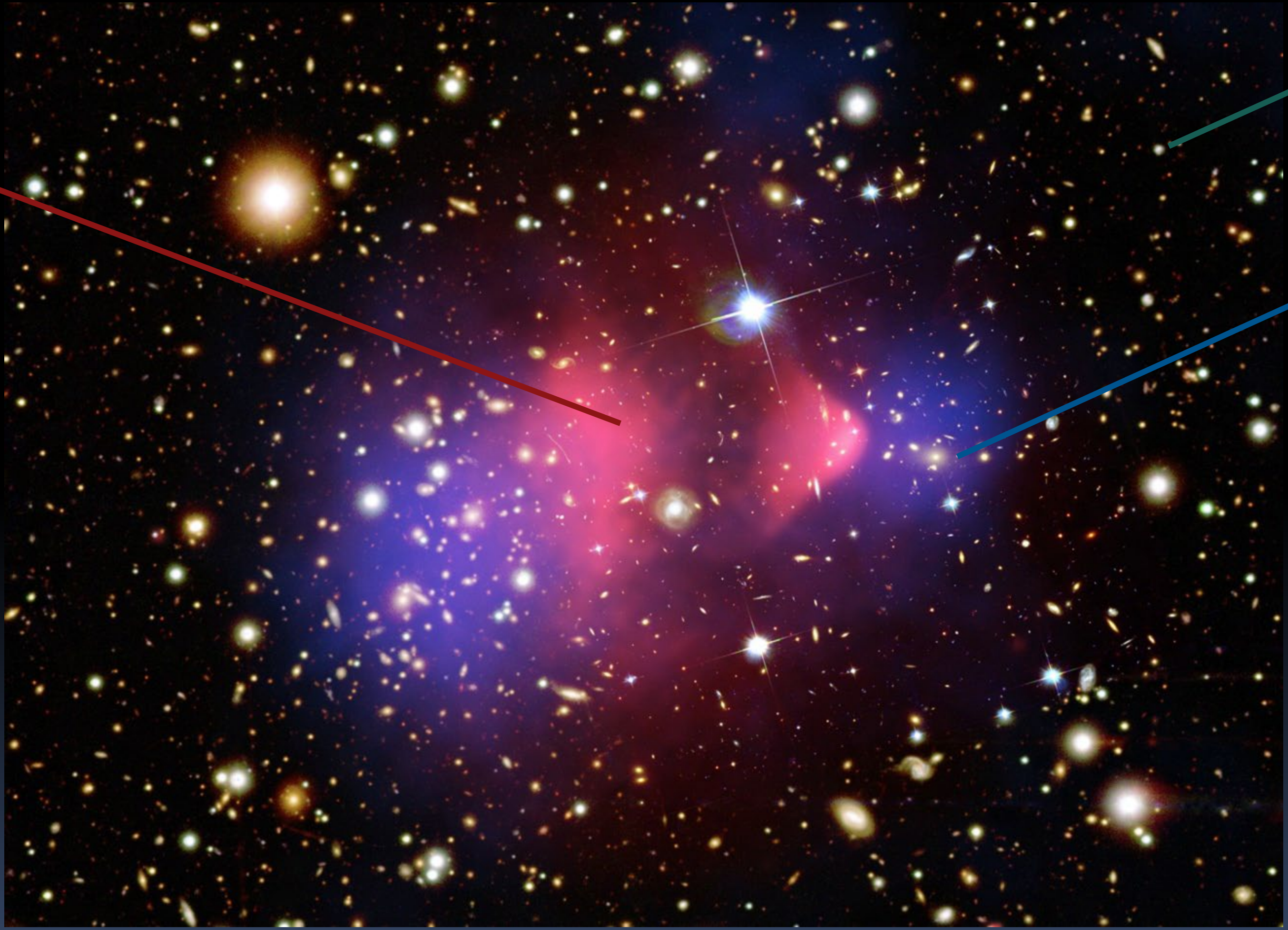
Can it be... Modified Gravity?

Gas shinning in X-Rays (that is where most of the baryonic matter is)



Source: Chandra X-Ray Observatory

Visible Galaxies

This is where the gravitational well is deeper (according to lensing). We believe this to be the distribution of Dark Matter

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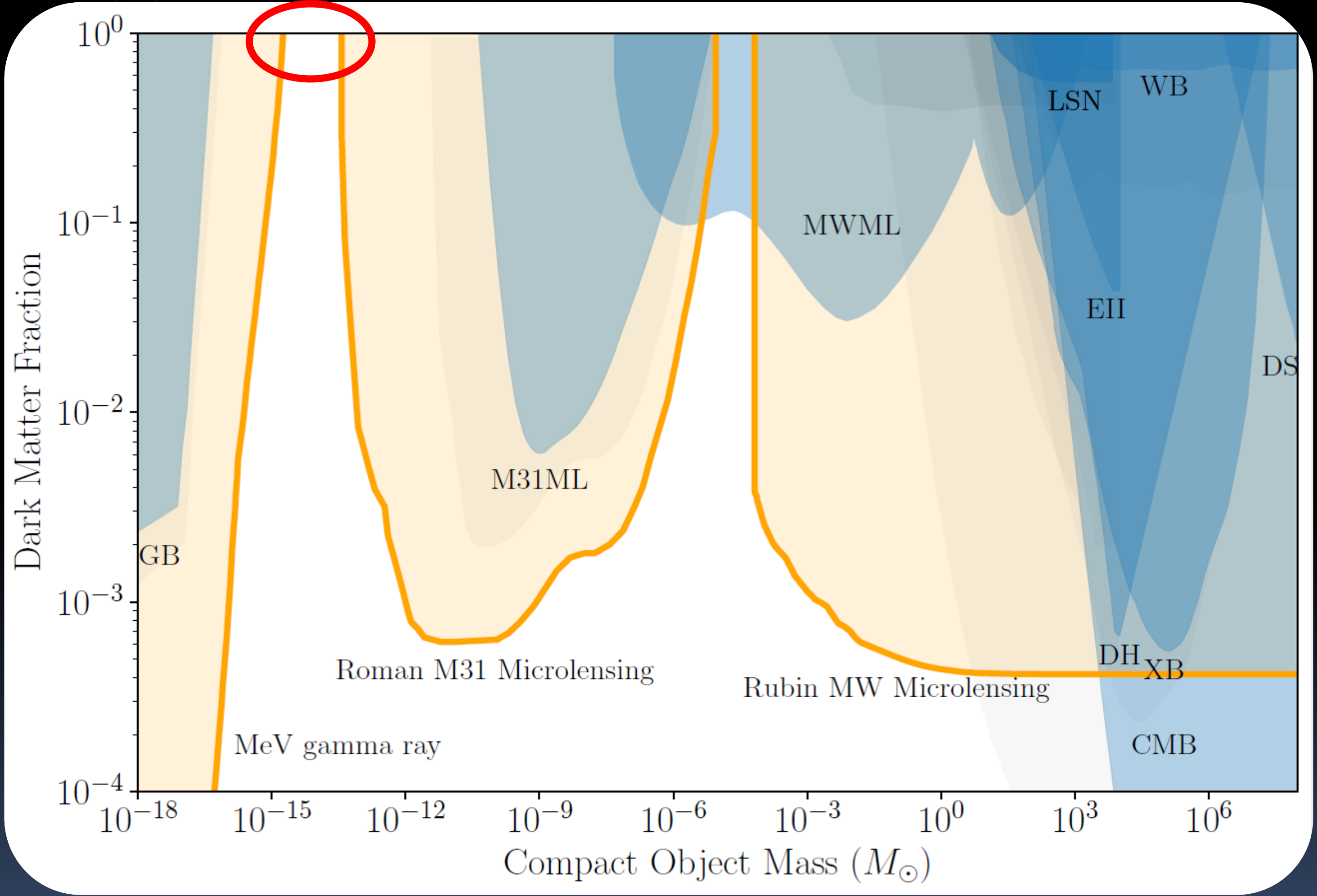

Can it be… Compact Objects?

Primordial Black Holes still not directly excluded.

(theoretical issues with production are unresolved)

Snowmass2021 Cosmic Frontier White Paper: Primordial black hole dark matter, Physics of the Dark Universe, Volume 41, August 2023, 101231, arXiv: 2203.08967

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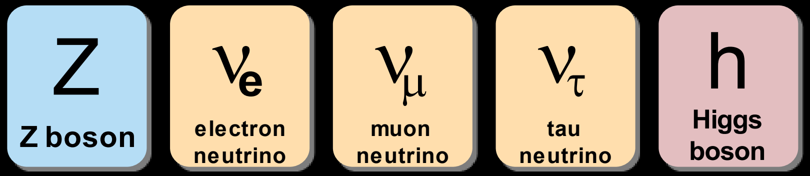
There is Dark Matter (Problem? Probably yes.)

Can it be... Some SM particle?

No electrical charge or strong interactions (QED or QCD)



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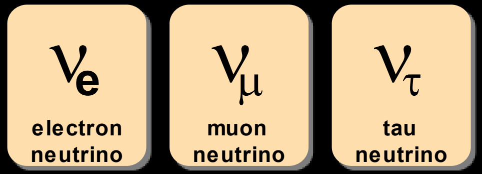
Stable in cosmological time scales



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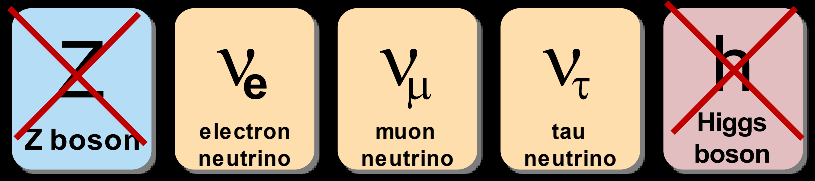
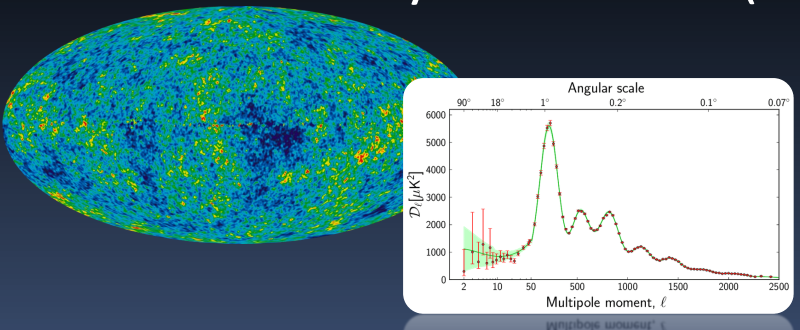


Stable in cosmological time scales

Cold Dark Matter (≈ GeV)

... or maybe "Warm" (≈ keV)



No candidates for DM in the SM!

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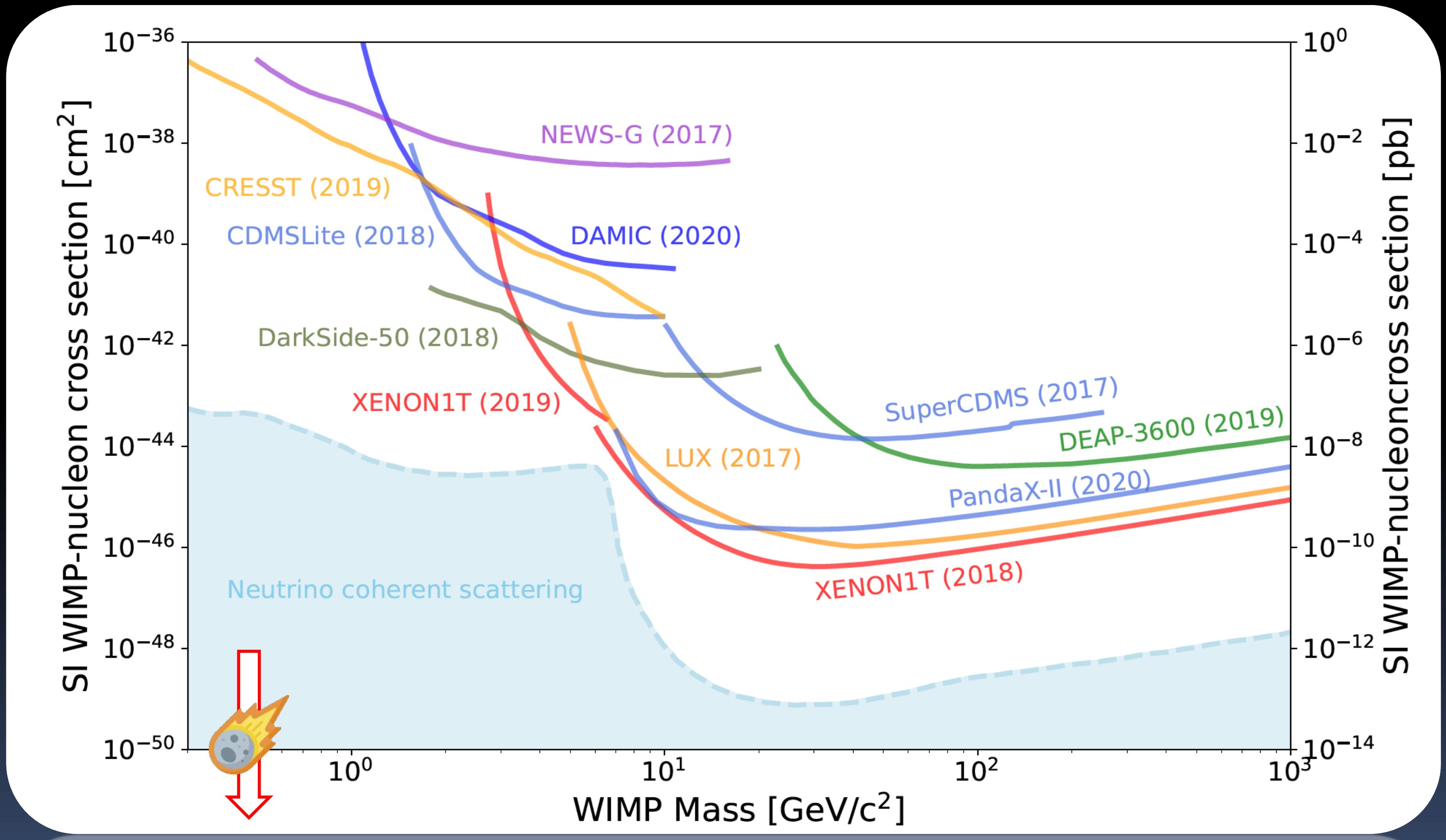
The SM is not finalized!

"Bad" solution: **Any** new particle with sufficiently weak interactions w/ SM (*i.e. weaker than "weak" – only gravitational int. is guaranteed*)



R.L. Workman et al. (Particle Data Group), Prog. Theor. Exp. Phys. 2022, 083C01 (2022) and 2023 update

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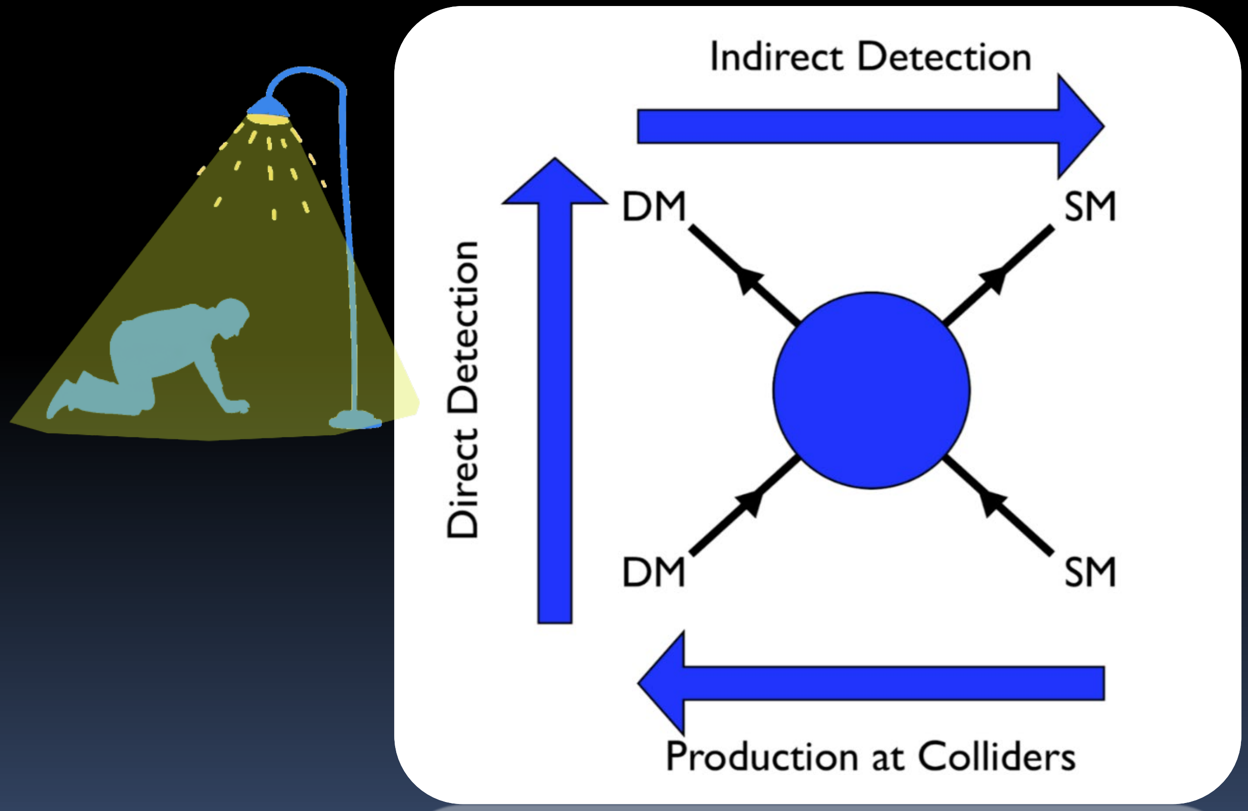
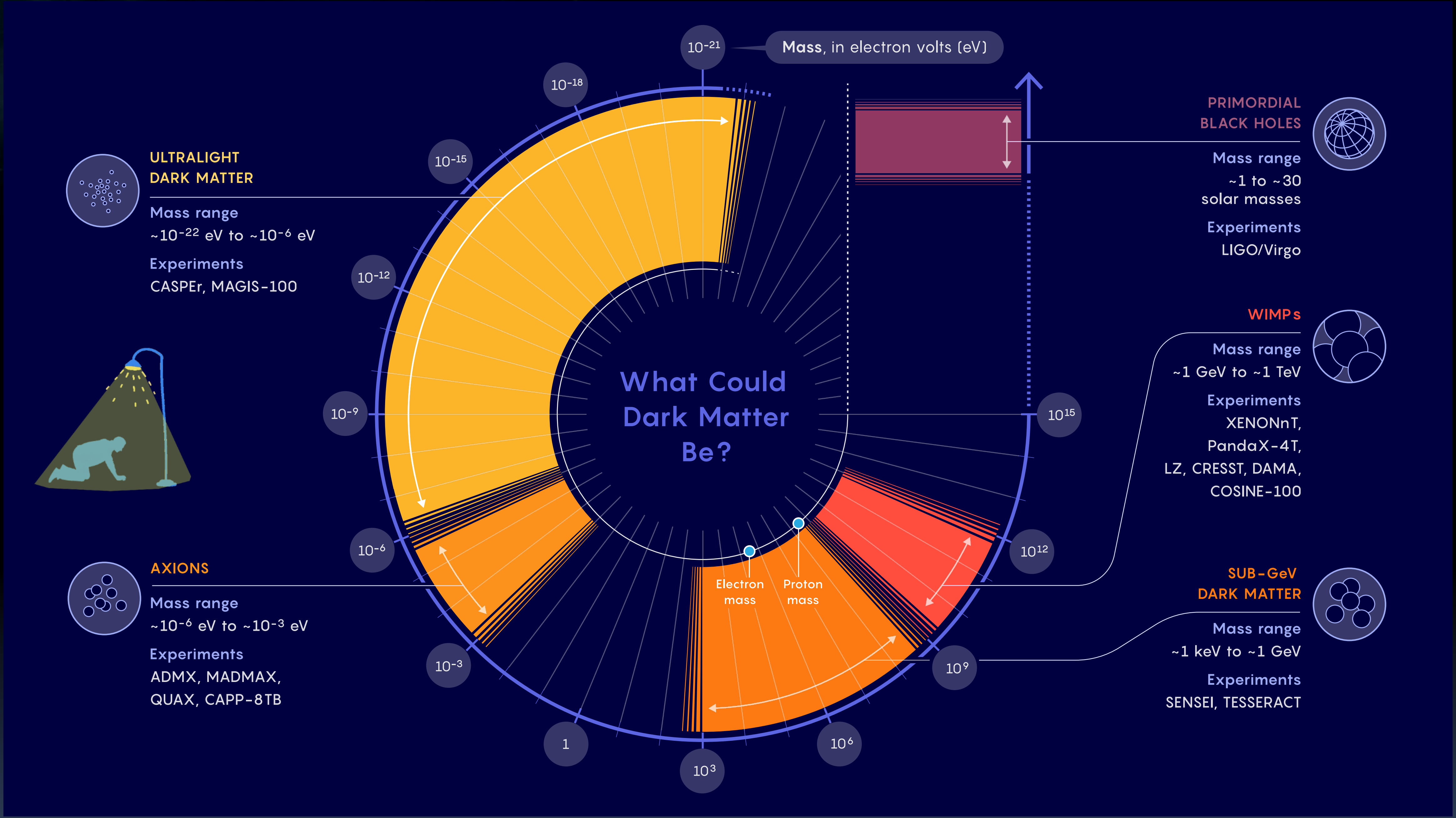
The SM is not finalized!

“Good” solutions: WIMPs (from many models: MSSM, Higgs or Z portals, Extra Dim., Composite Higgs, Little Higgs, …); Axions and ALP; Dark Photons; Sterile Neutrinos; Complicated Dark Sectors (Mirror DM et al.);





Samuel Velasco/Quanta Magazine

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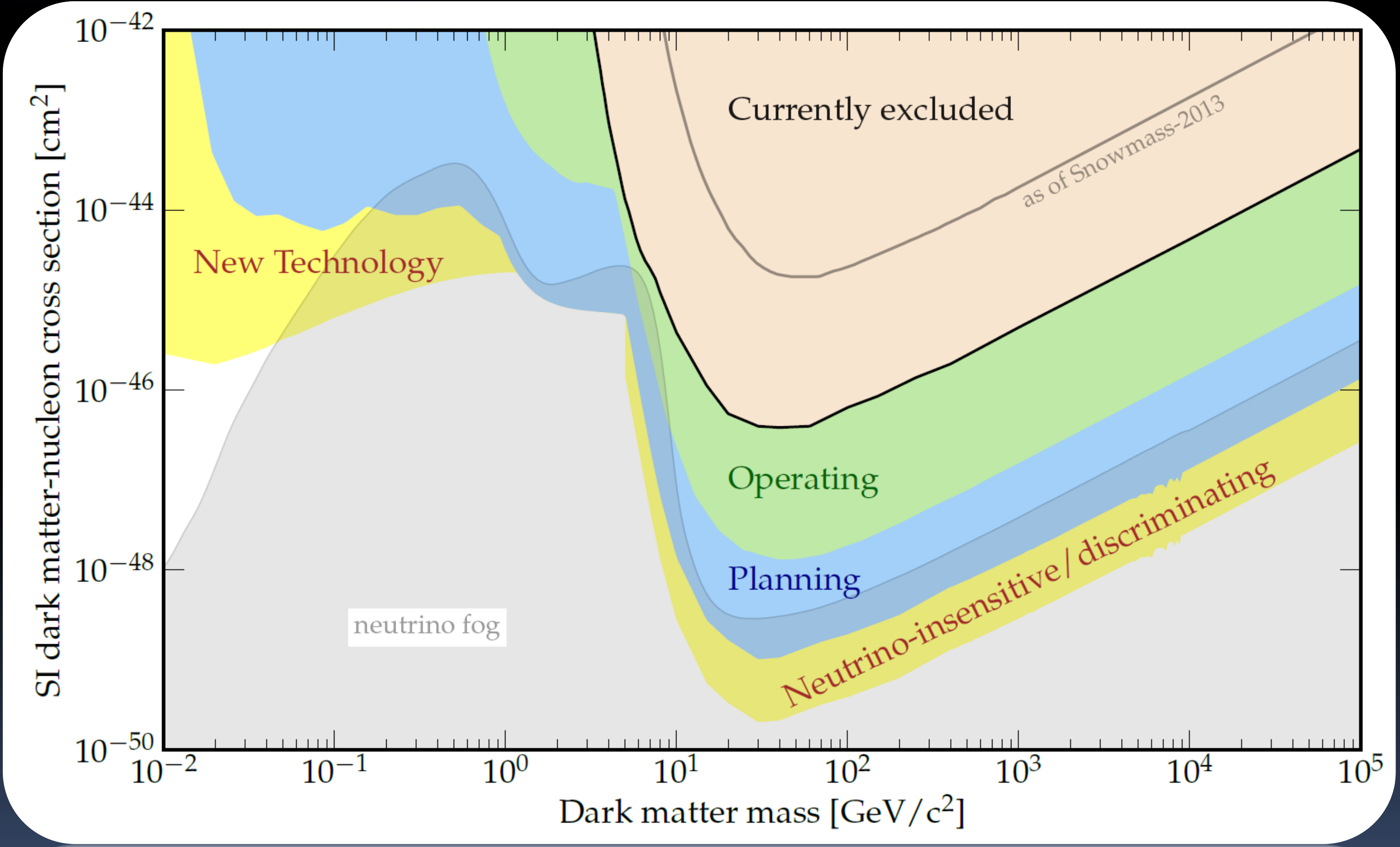
Report of the Topical Group on Particle Dark Matter for Snowmass 2021, arXiv:2209.07426



Operating: LZ, XENONnT, PandaX-4T, SuperCDMS SNOLAB, SBC

Planned (up to 2035): SuperCDMS, DarkSide-LowMass, SBC, 1000 ton-year liquid xenon, ARGO

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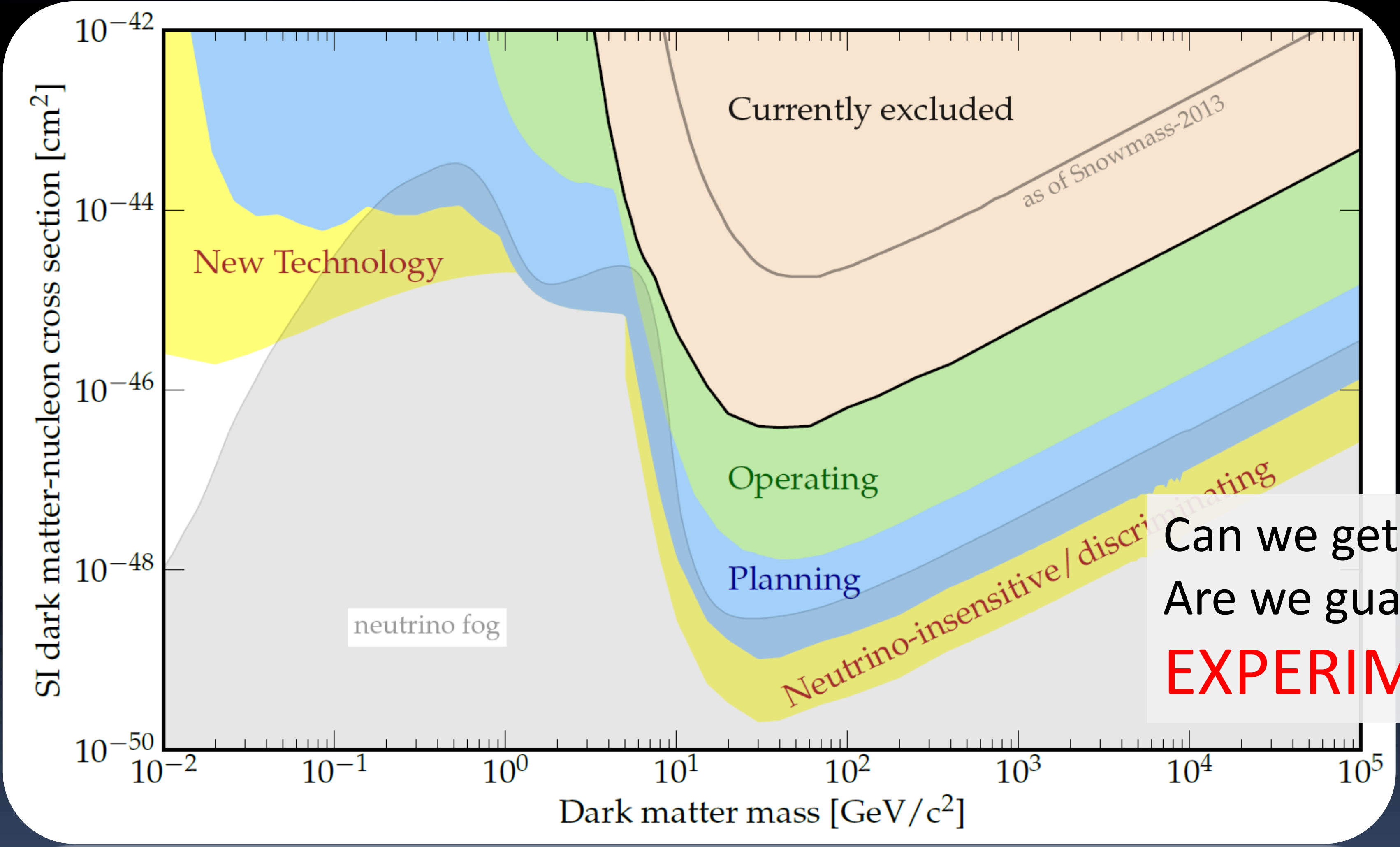

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Can we get answers? YES

Are we guaranteed to get answers? NO

EXPERIMENTS NEEDED!

The SM is not finalized!

Other “missing” phenomena:

- Baryogenesis: not enough CP, SM lacks a strong phase transition
  (*many solutions, including many of the previous ones; simplest one: 2HDM*)

- Quantum Gravity? Gravitons? (*not that many solutions…*)

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- Quantum Gravity? Gravitons? (*not that many solutions…*)

Can we get EXPERIMENTAL answers? Not so soon…

The SM is not understood!

Despite the good fit, we would like deeper explanations to quite a few points:

- Non-Perturbative QCD and Confinement
  (*see Gastão colloquium on YouTube*)

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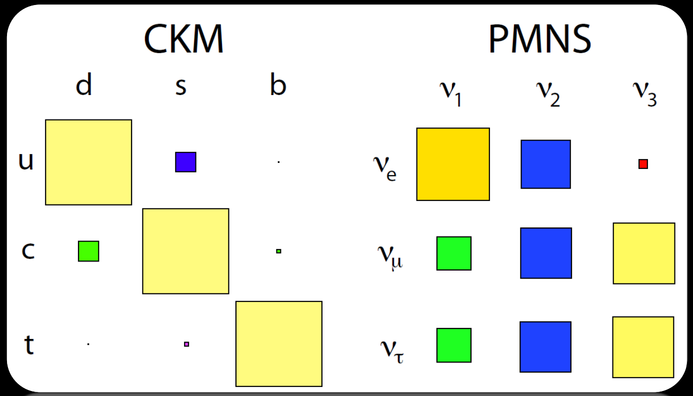
S. Stone, arXiv:1212.6374



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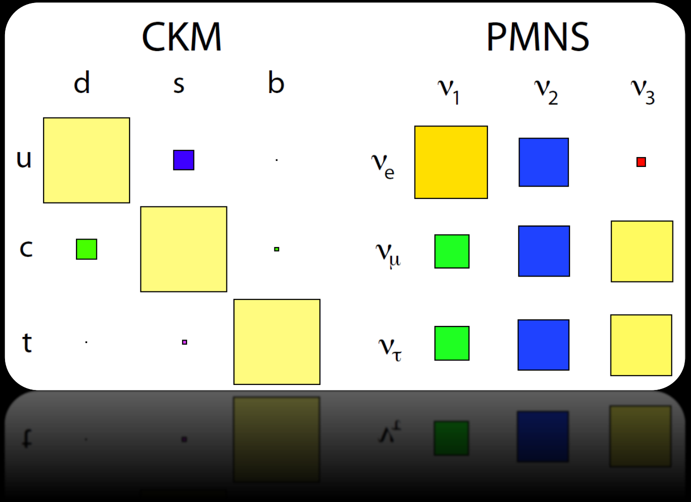

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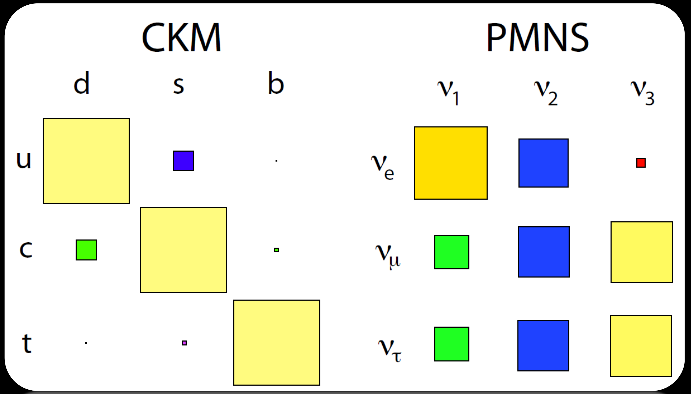

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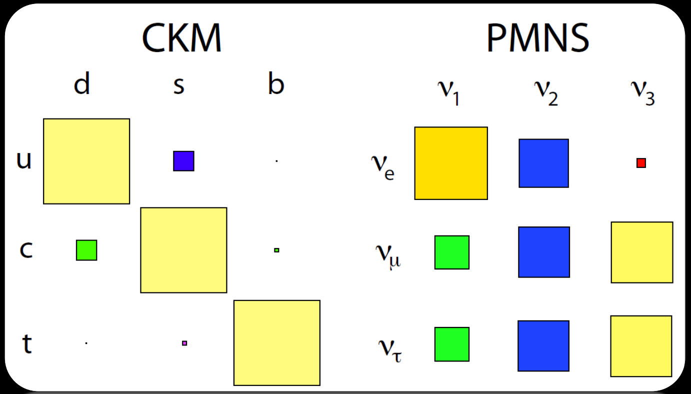

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- Fine tunings:
  - Strong CP Problem (*Axions Mainly*)
  - Cosmological Constant
  - Hierarchy between Electroweak scale and the SM cut-off

Can we get answers? YES
Are we guaranteed to get answers? NO
EXPERIMENTS NEEDED!

Can we get EXPERIMENTAL answers? Not so soon…

Hierarchy and Scalar masses, a toy model

A scalar, a fermion and 3 parameters:

$$\mathcal{L} = \frac{1}{2}\partial^\mu\phi\,\partial_\mu\phi - \frac{m^2}{2}\phi^2 + \bar{\psi}(i\partial\!\!\!/ - M)\psi - y\phi\bar{\psi}\psi$$

Under which conditions (m, M and y) can I have a scalar much lighter than the fermion?

Tip: m << M is not enough!

Hierarchy and Scalar masses, a toy model

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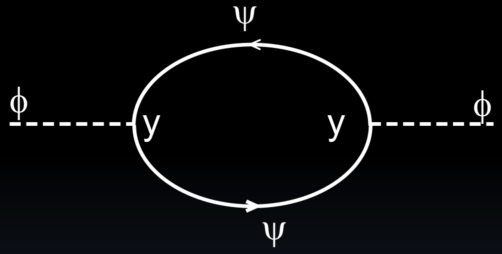
Integrate out the fermion:



$$\mathcal{L} = \frac{1}{2}\left(1 - \frac{y}{8\pi^2}\right)\partial^\mu \phi\, \partial_\mu \phi - \frac{1}{2}\underbrace{\left(m^2 - \frac{3y^2 \overbrace{M^2}}{4\pi^2}\right)}_{m^2_{PHYS}}\phi^2 + \ldots$$

the cut-off for this EFT (M^2)

Hierarchy and Scalar masses, a toy model

Low mass scalar: $$\mathcal{L} = \frac{1}{2}\left(1 - \frac{y}{8\pi^2}\right)\partial^\mu\phi\,\partial_\mu\phi - \frac{1}{2}\left(m^2 - \frac{3y^2M^2}{4\pi^2}\right)\phi^2 + \dots$$

$$m^2_{PHYS} \ll M^2 \longleftrightarrow m^2 \sim y^2 M^2$$

which we understand **IF** there is a symmetry demanding it

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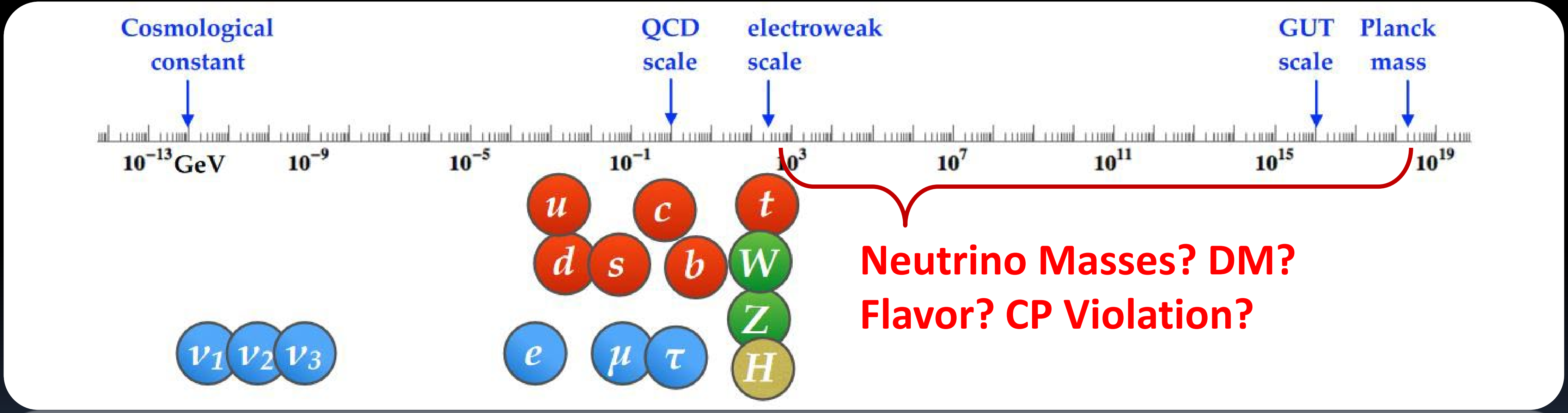
The (minute) details of the UV theory set the IR theory: **UV Sensitivity**

(*Should we call this a UV/IR mixing? Note that it does not imply the breakdown of EFT, QFT or reductionism. Just the separation of scales is breaking down.*)

The SM is not understood!

The Higgs is sensitive to ANY new scales above the electroweak scale



R.D.Matheus

The SM is not understood!

The "Big Desert" hypothesis:

$$m_h \sim \sqrt{-\kappa + \frac{\Lambda^2}{16\pi^2}}$$

$$\Lambda \sim 10^{18}\ \text{GeV} \quad (M_p)$$

$$m_h \sim \sqrt{-\kappa + 10^{34}}\ \text{GeV}$$

$$m_h^{exp} \approx 125\ \text{GeV}$$

Fine tuning of 10^{-30}

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The "LHC will solve it" hypothesis (a.k.a. "Natural solution"):

$$m_h \sim \sqrt{-\kappa + \frac{\Lambda^2}{16\pi^2}}$$

$$\Lambda \sim 10^{3}\ \text{GeV}$$

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$\kappa = O(10^4)$, no fine tuning!

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$\kappa = O(10^4)$, no fine tuning!

NOT INCREDIBLY FAVORED RIGHT NOW

(but see fine print)

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"Bad" solution: It is really solved in some far away UV (~~separation of scales~~)

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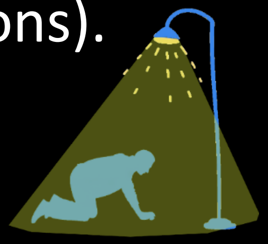
"Good" solution: Cancel loop corrections (SUSY), bring the cut-off down (composite Higgs as a pNGB) or some dynamical mechanism for the Higgs VEV (Relaxions).



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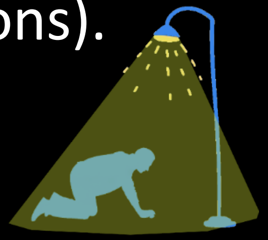

 No sign of new Physics around 1 TeV!

- Λ = 5 ~ 10 TeV (*model dependent*) → fine tuning of 1% (*two loop suppression or some really good approximate symmetry (pNGB)*)
- Fine print: Exclusions from simplified models leave blind directions

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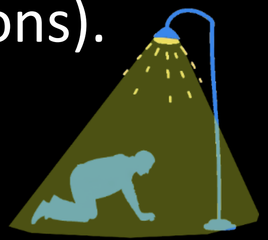

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Global fits SMEFT/HEFT are BETTER!
(and underway)

R.D.Matheus

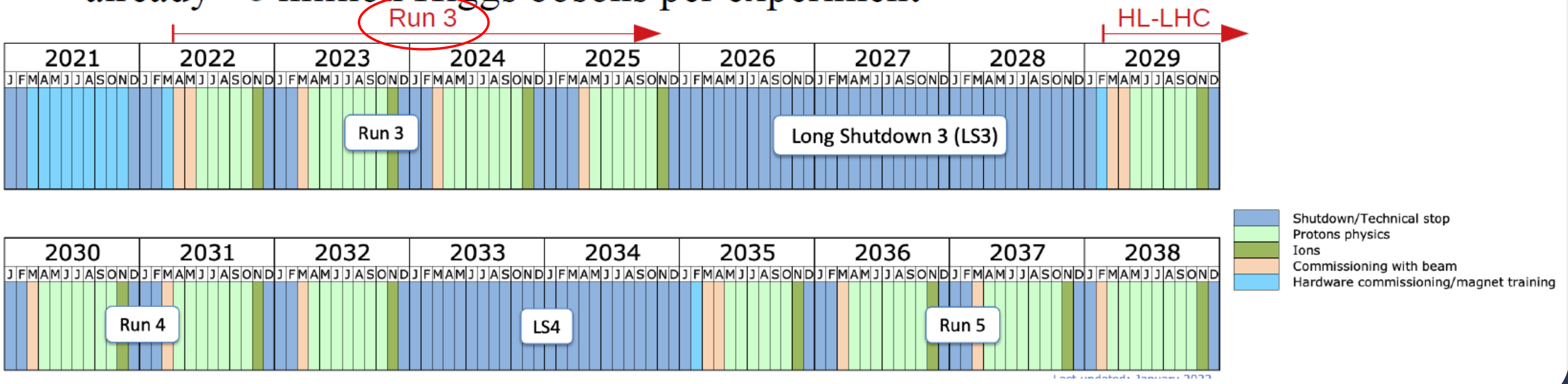
The Energy/Luminosity frontiers

HL-LHC: 3000 fb^{-1}

Aprox. 350 fb^{-1}

E. Petit on behalf of ATLAS & CMS, Prospects for Higgs Physics at the (HL-)LHC

- Only 5% of total LHC dataset delivered
  - already ~8 million Higgs bosons per experiment

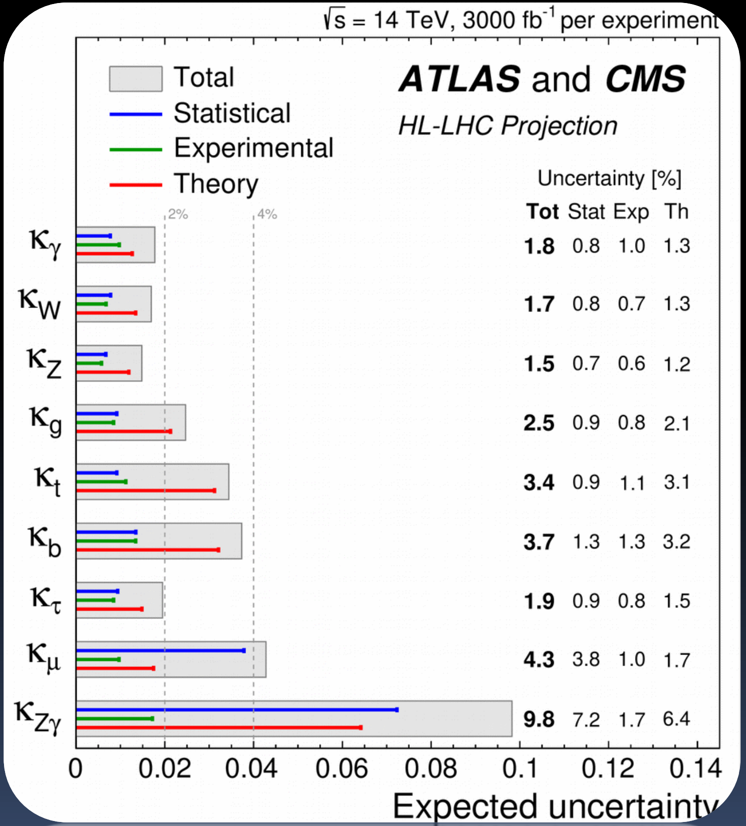


The Energy/Luminosity frontiers

HL-LHC: 3000 fb^{-1}

Goals: Higgs mass (σ ~ 10-20 MeV, 0.01%), Higgs Width (σ ~ 20%)

Higgs couplings:

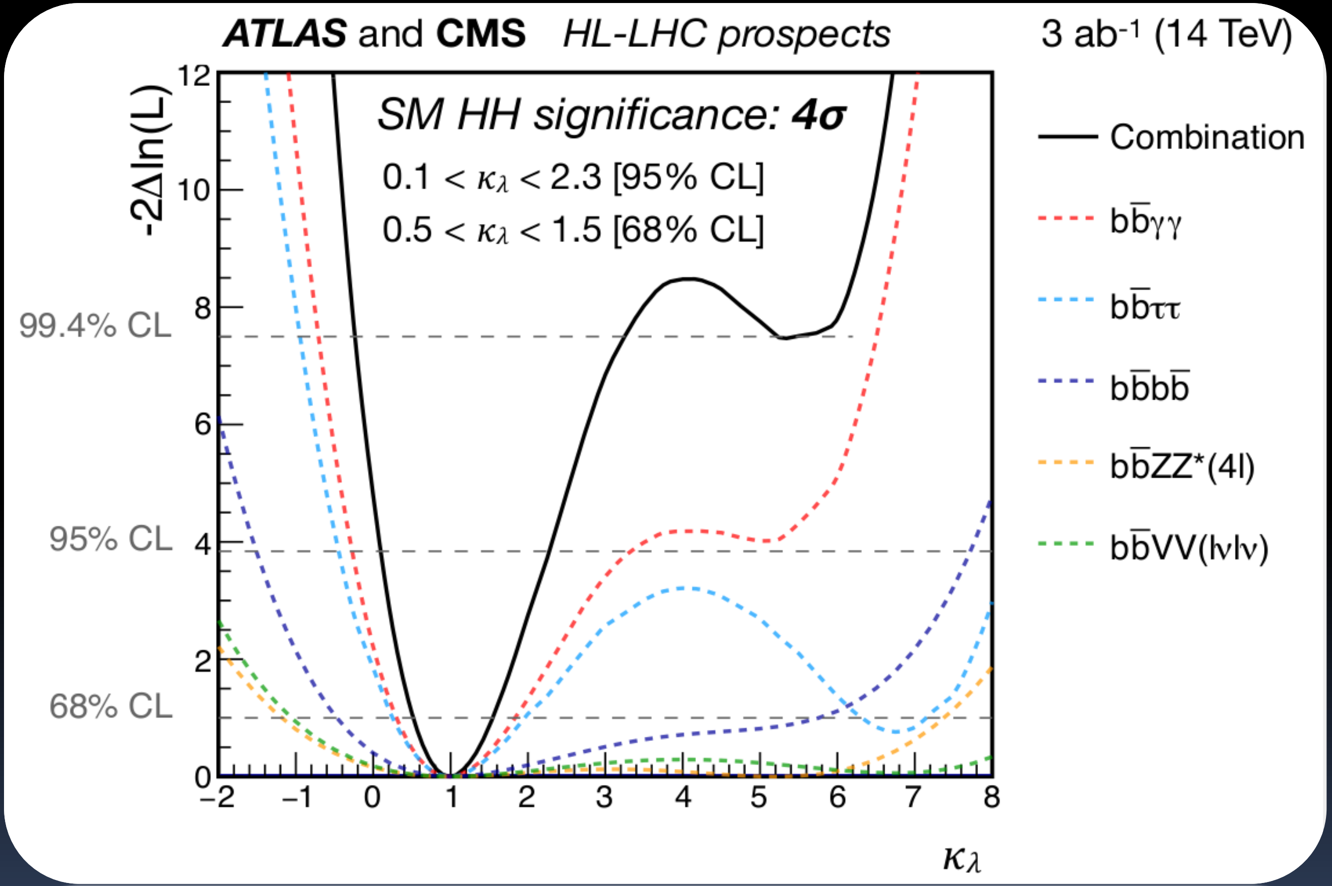


E. Petit on behalf of
ATLAS & CMS, Prospects for Higgs Physics at the (HL-)LHC

The Energy/Luminosity frontiers

HL-LHC: 3000 fb^{-1}

Goals: Trilinear Higgs Coupling:



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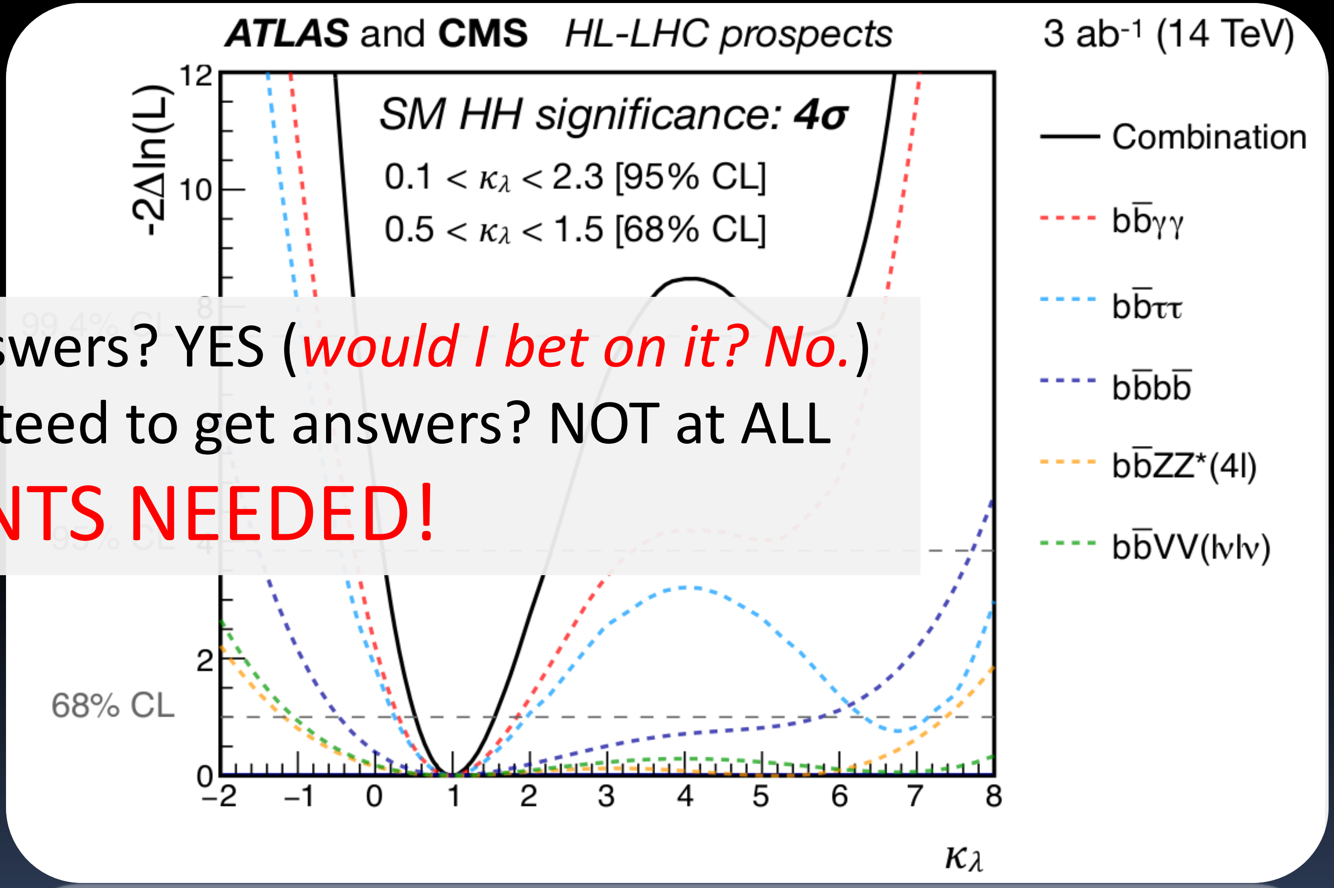


Can we get answers? YES (*would I bet on it? No.*)

Are we guaranteed to get answers? NOT at ALL

EXPERIMENTS NEEDED!

E. Petit on behalf of
ATLAS & CMS, Prospects for Higgs Physics at the (HL-)LHC

R.D.Matheus

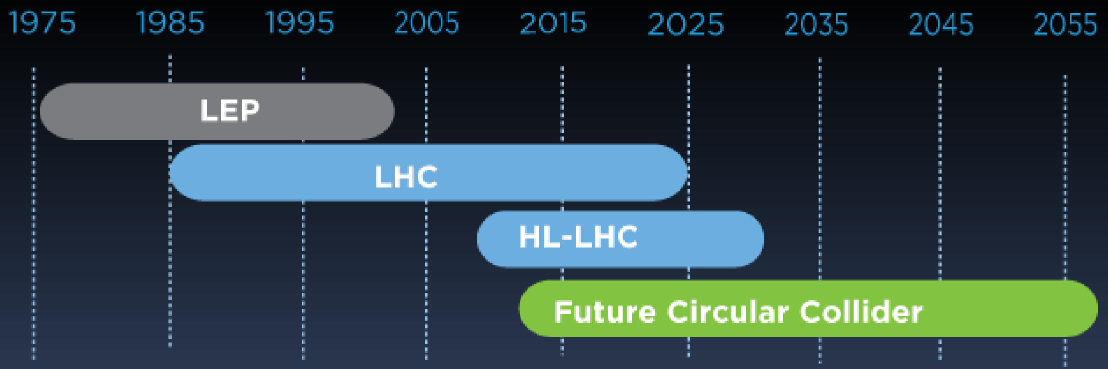
The Energy/Luminosity frontiers

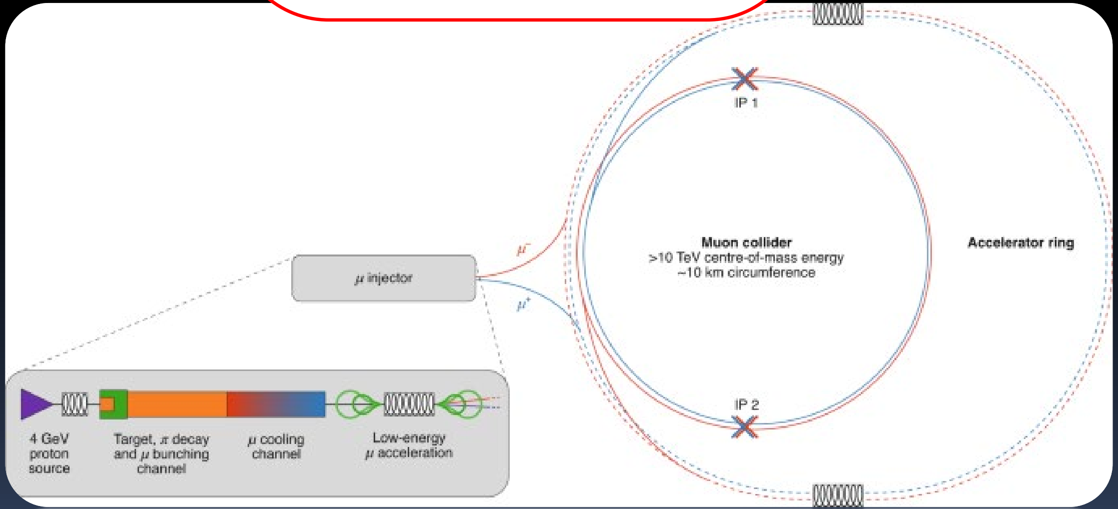
Future Colliders:

FCC
hh ee he

100 TeV (pp),
90-350 GeV (e^+e^-)

International
MUON Collider
Collaboration

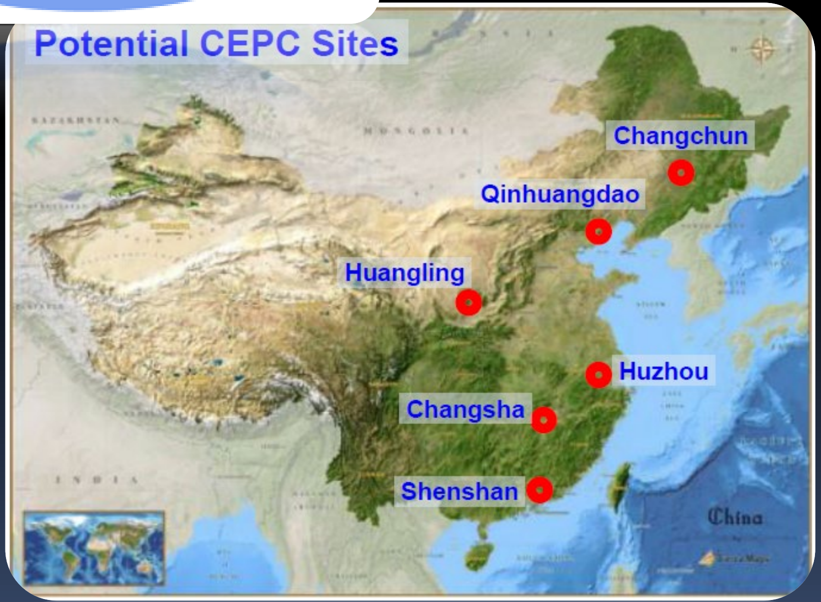


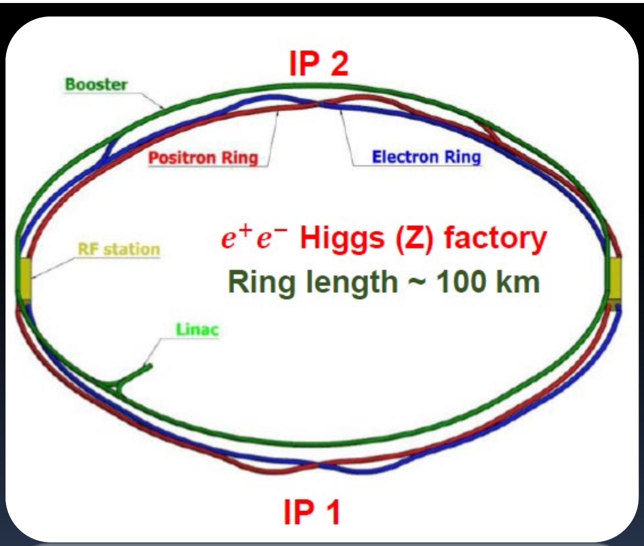


The Energy/Luminosity frontiers

Future Colliders:

XinChou Lou, CEPC Status and Progress (2022)





240 GeV (e^+e^-)
(maybe 360 GeV)

The Energy/Luminosity frontiers

Can we get answers? YES

Are we guaranteed to get answers? NO

EXPERIMENTS NEEDED!

The Future of Particle Physics

Takeaway message:

EXPERIMENTS NEEDED!

The Future of Particle Physics

What should I *(the student)* do?

We are watching a paradigm change:

- Not of Particle Physics or QFT (*no serious evidence for failure of that yet*)
- But of the way we do Particle Physics!

The Future of Particle Physics

What should I *(the student)* do?

For many decades we were in a "Confirmation Phase" of the SM

- After a few "chance discoveries" (exploratory science)
  - Proton (1919)
  - Beta decay spectrum (1927)
  - Neutron (1932)
  - Muon (1936)
  - Kaon (1947)
- We were able to predict the electroweak sector!

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- We were able to predict the electroweak sector!

Lucky, lucky!

- Weak interactions break symmetries (preserved by QED and QCD)

~~P~~ ~~CP~~ ~~Flavor~~

LO contributions given by operators generated at the ~100 GeV scale.
Measurable at much lower energies!

The Future of Particle Physics

What should I *(the student)* do?

Now we are entering a new “Exploration Phase”

The Future of Particle Physics

What should I *(the student)* do?

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- We need to look everywhere (*toolset of models helps*)

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- If you are a experimentalist: keep up the good work!

The Future of Particle Physics

What should I *(the student)* do?

Now we are entering a new "Exploration Phase"

- We need to look everywhere (*toolset of models helps*)
- If you are a experimentalist: keep up the good work!
- If you are a theoretician: get closer to (*not farther from*) experiments
  - Measurement proposals, background estimations, N^nLO calculations and model independent fits are all needed!
  - Overcommitting to your favorite model or building new ever-increasingly "parameter rich" models is not a good strategy

Thanks for the Attention!