

Seminário DF - UFJF

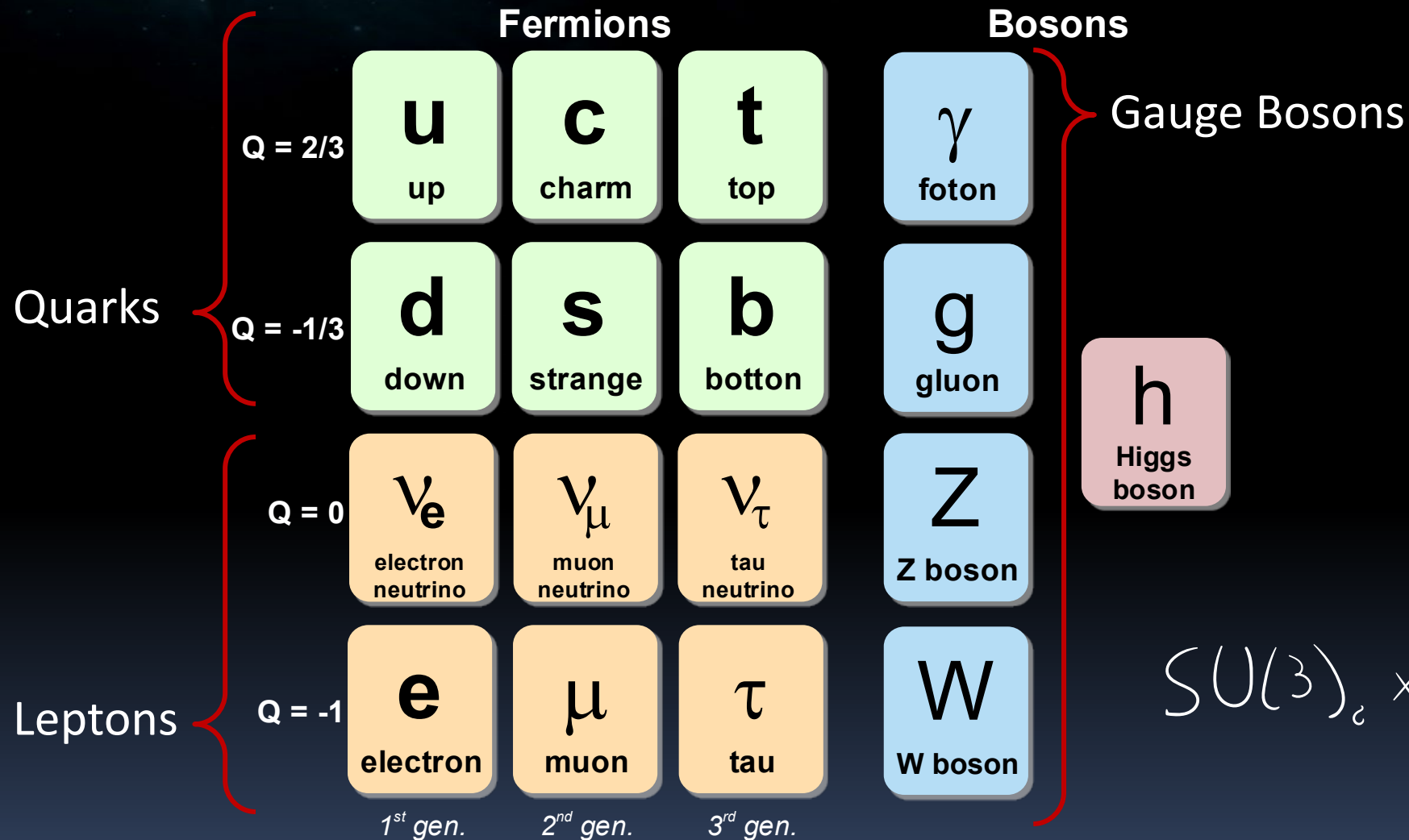
Como anda a Física de Partículas (e para onde vai?)

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IFT - UNESP
INSTITUTO DE FÍSICA TEÓRICA

The Standard Model



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

The Standard Model Works!

Symmetry + Symmetry Breaking pattern

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

$$g_s \quad g \quad g' \quad g_s \quad e, \theta_w$$

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 bottom	e electron	μ muon	τ tau	

γ
foton

g
gluon

Z
Z boson

W
W boson

The Standard Model Works!

$$\begin{aligned}
 & ig s_w M A_\mu (W_\mu^+ \phi^- - W_\mu^- \phi^+) - ig \frac{s_w}{2c_w} Z_\mu^0 (\phi^+ \partial_\mu \phi^- - \phi^- \partial_\mu \phi^+) + \\
 & ig s_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^0 Z_\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^0 A_\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 + ig s_w A_\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 - \\
 \end{aligned}$$

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 $\pm$ 0.24 GeV

Equivalent to Yukawa couplings, 13 parameters!

Higgs potential: v & m_H



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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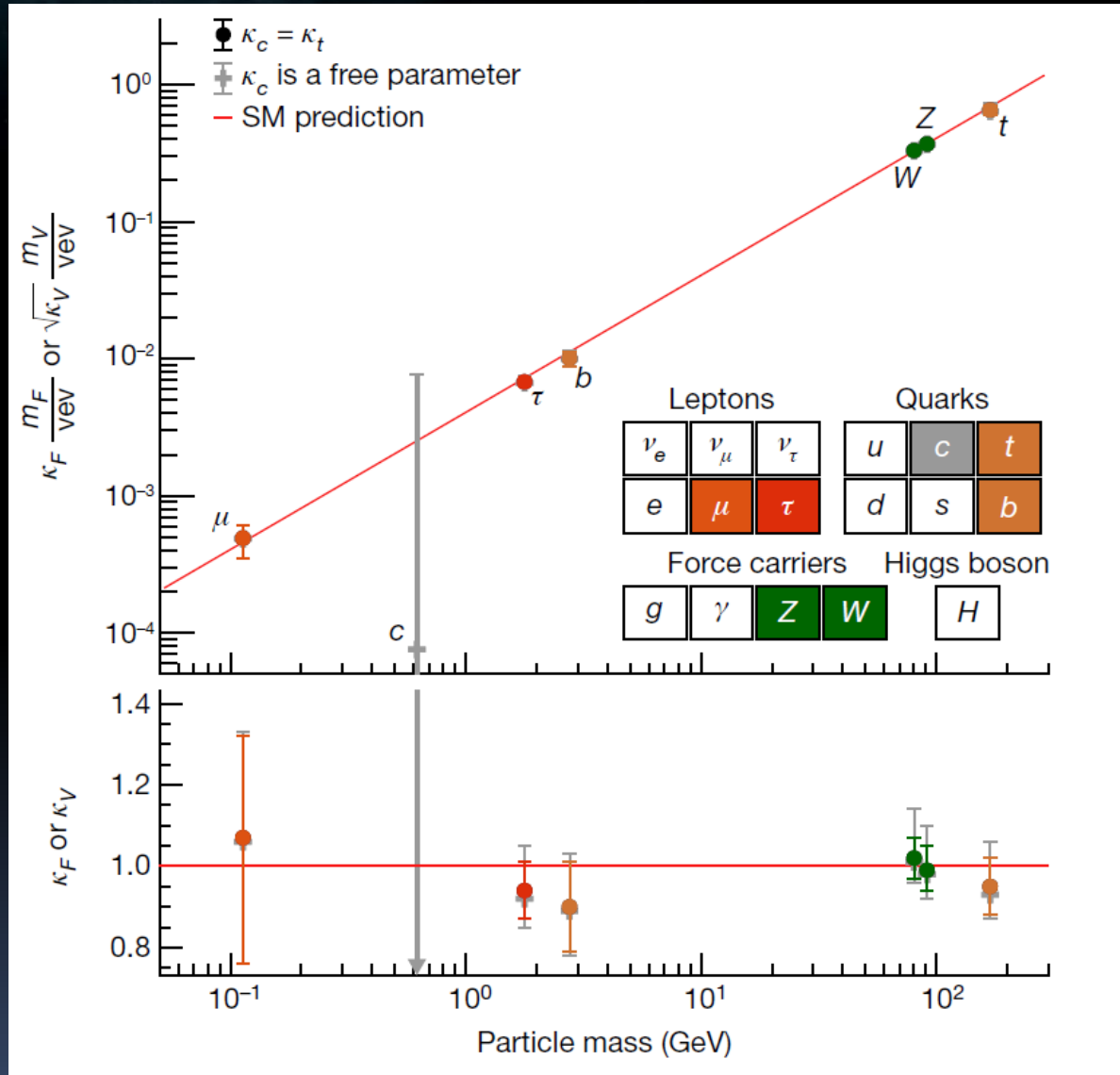
Takeaway message:

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)

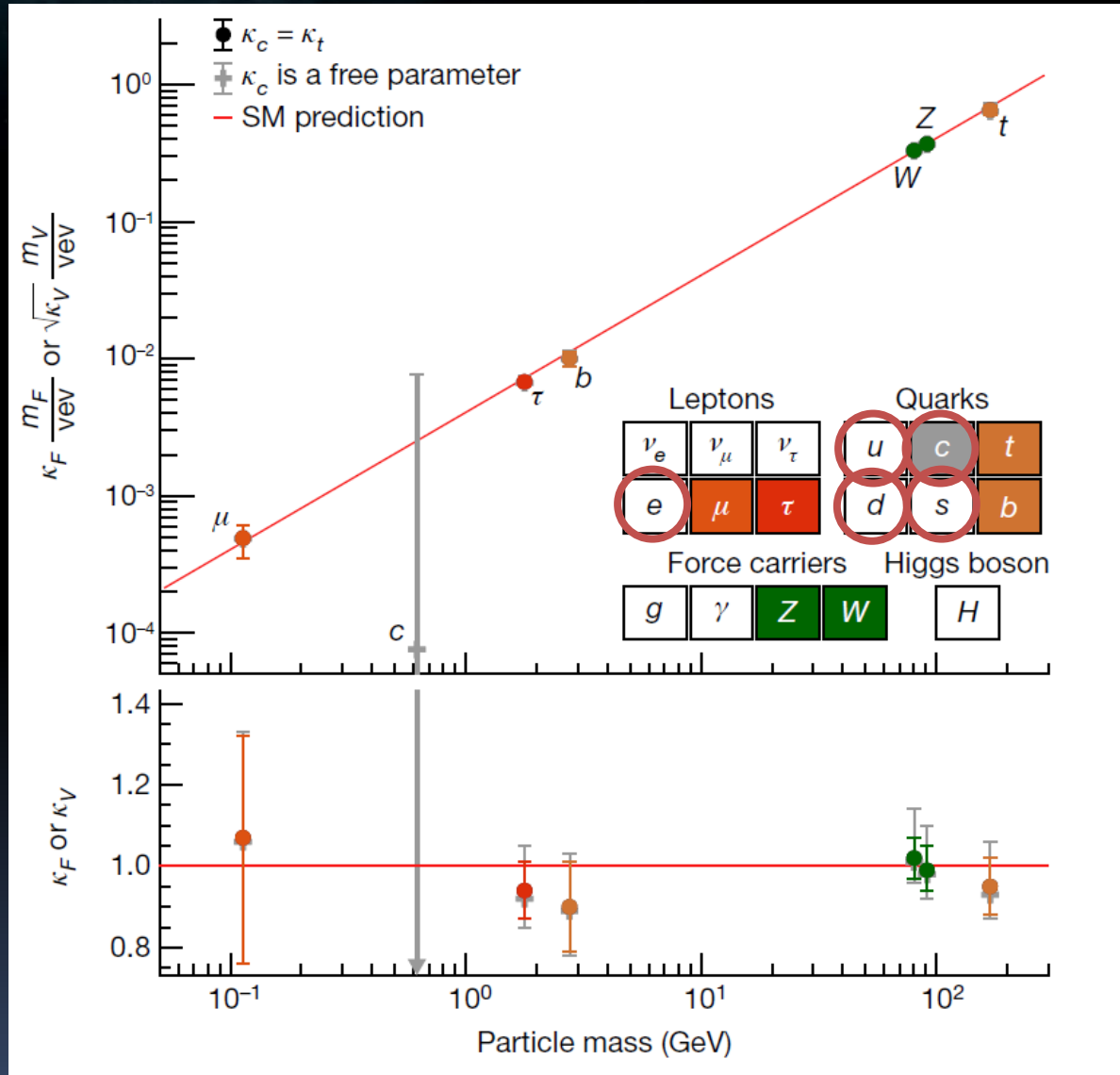
The Standard Model (recent tests)



(Run 2 $\sim 139 \text{ fb}^{-1}$)

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

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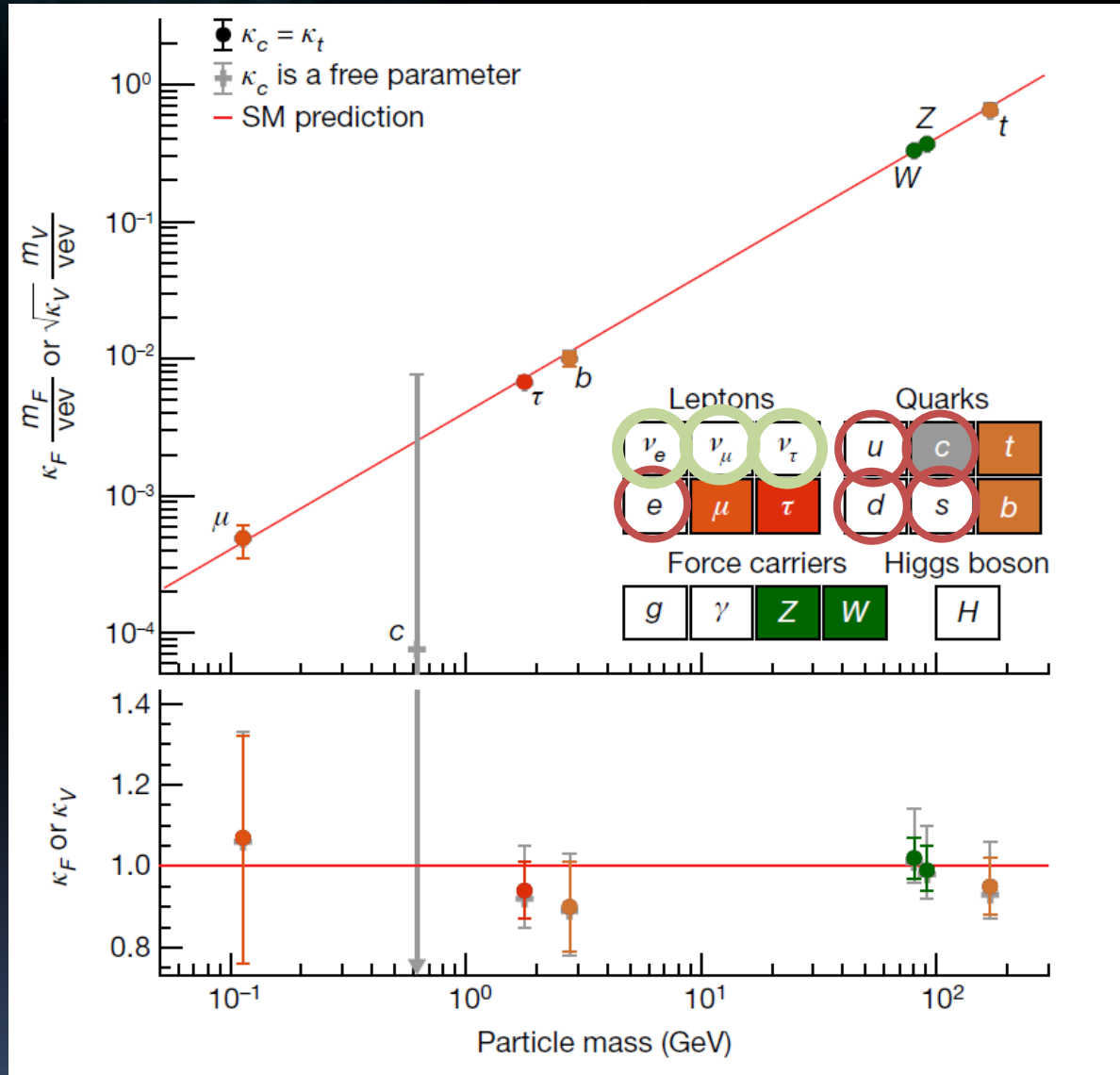
Untested!



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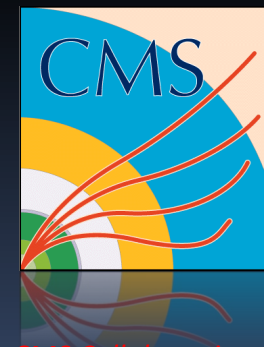
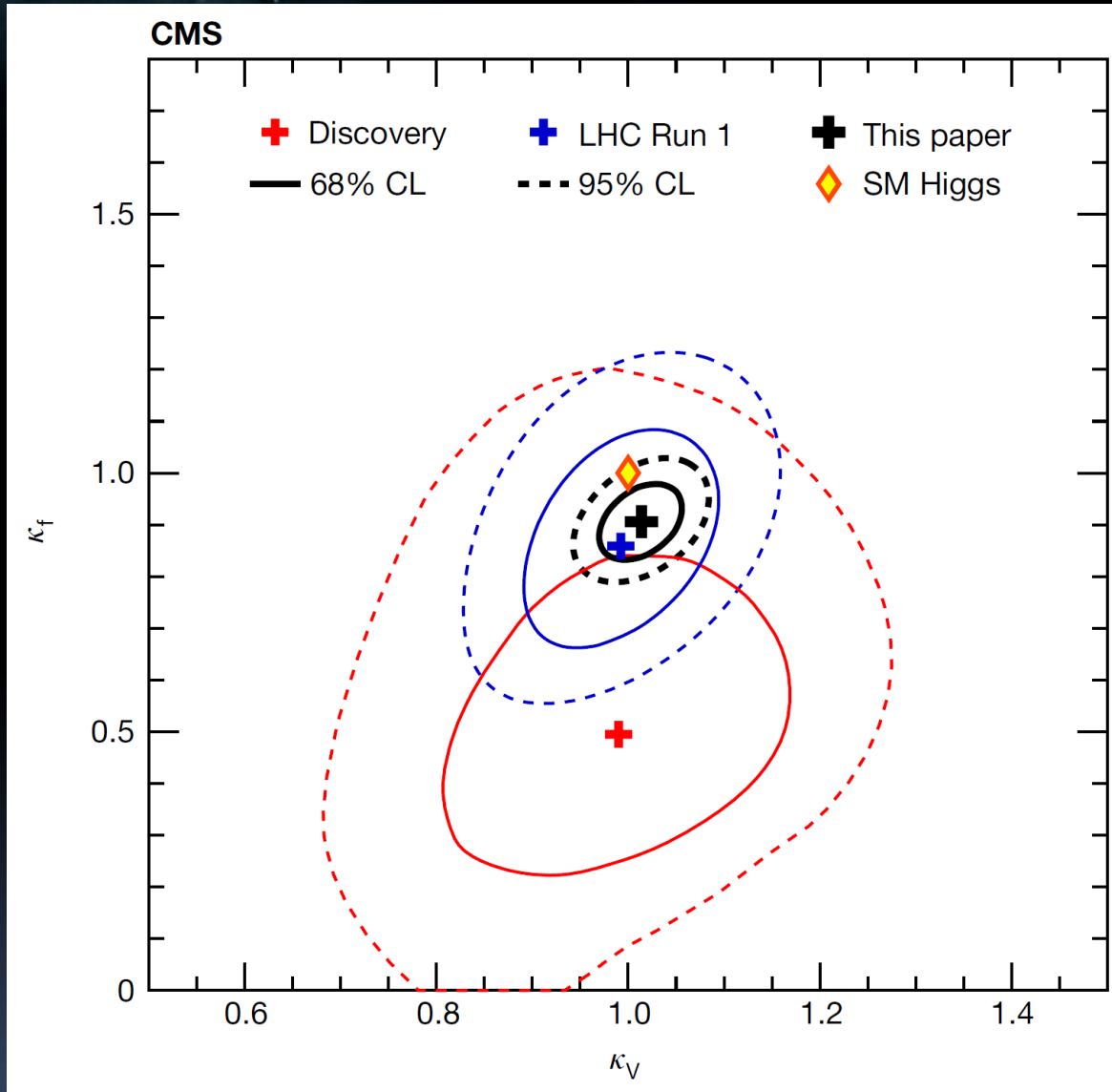
Untested!
Who knows?!



(Run 2 ~ 139 fb⁻¹)

ATLAS Collaboration, *Nature* 607 (2022) 7917, 52-59,
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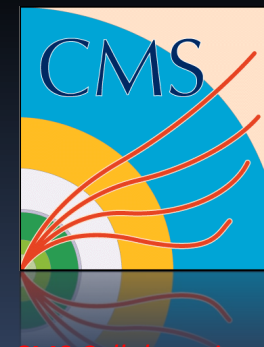
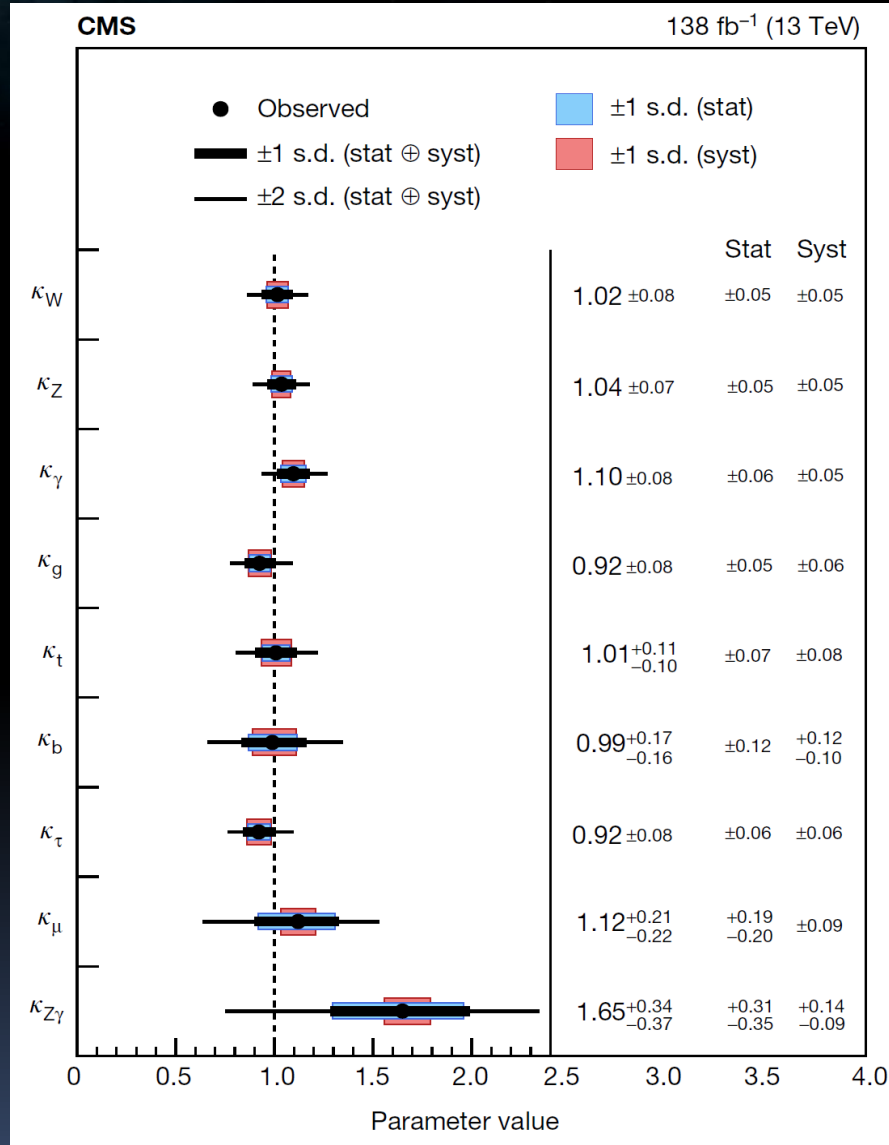
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CMS Collaboration, *Nature* 607 (2022) 7917, 60-68

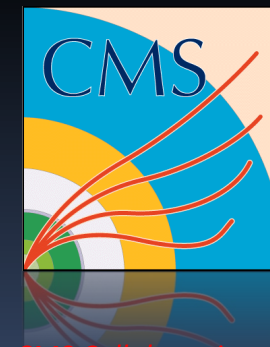
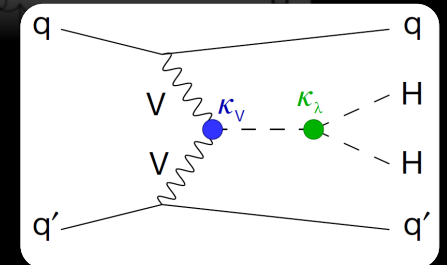
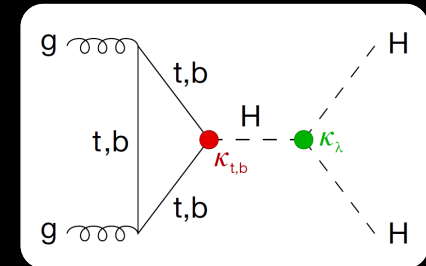
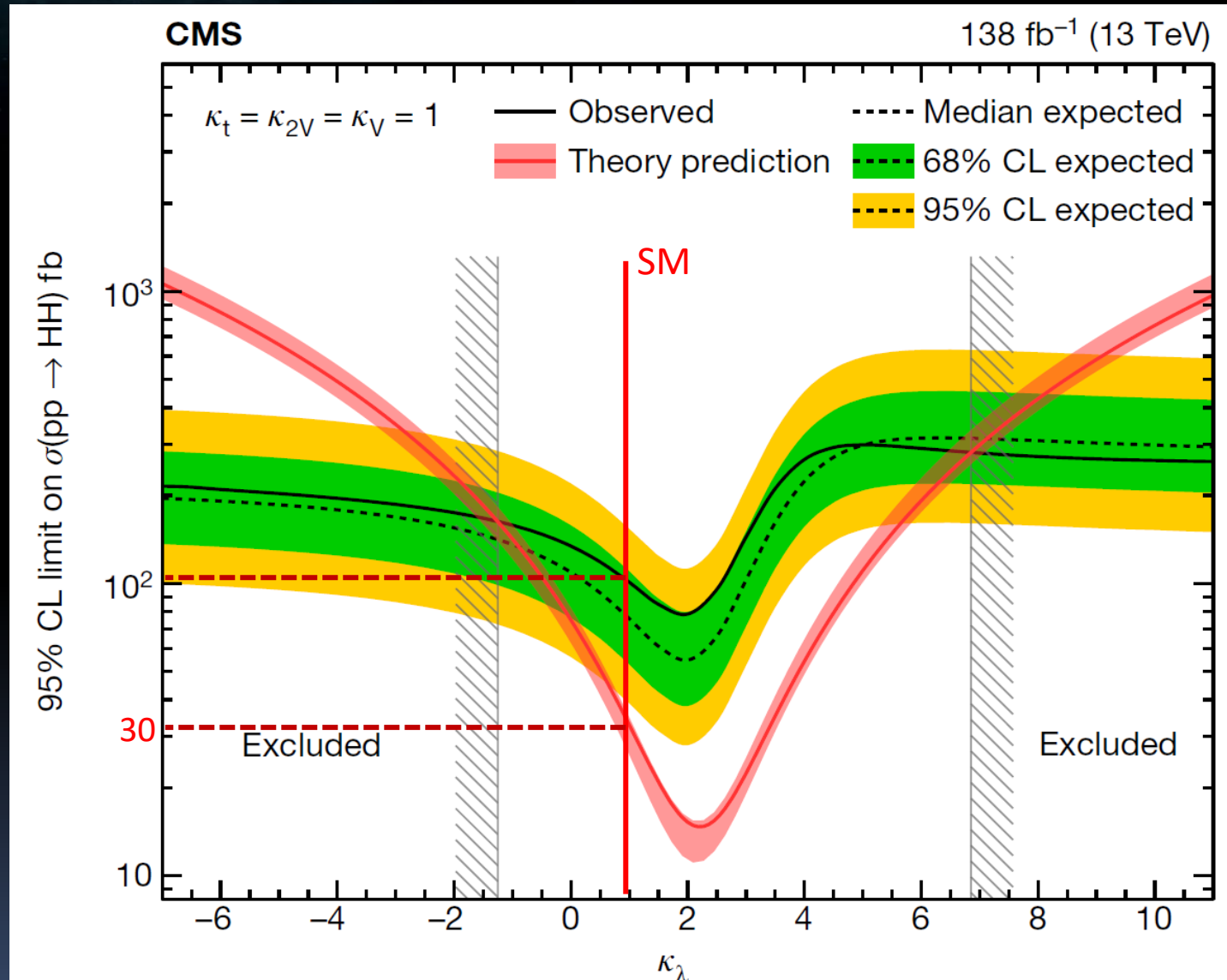
The Standard Model (recent tests)



(Run 2 ~ 138 fb⁻¹)

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

The Higgs Potential remains untested!



(Run 2 ~ 138 fb⁻¹)

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

The SM is not finalized!

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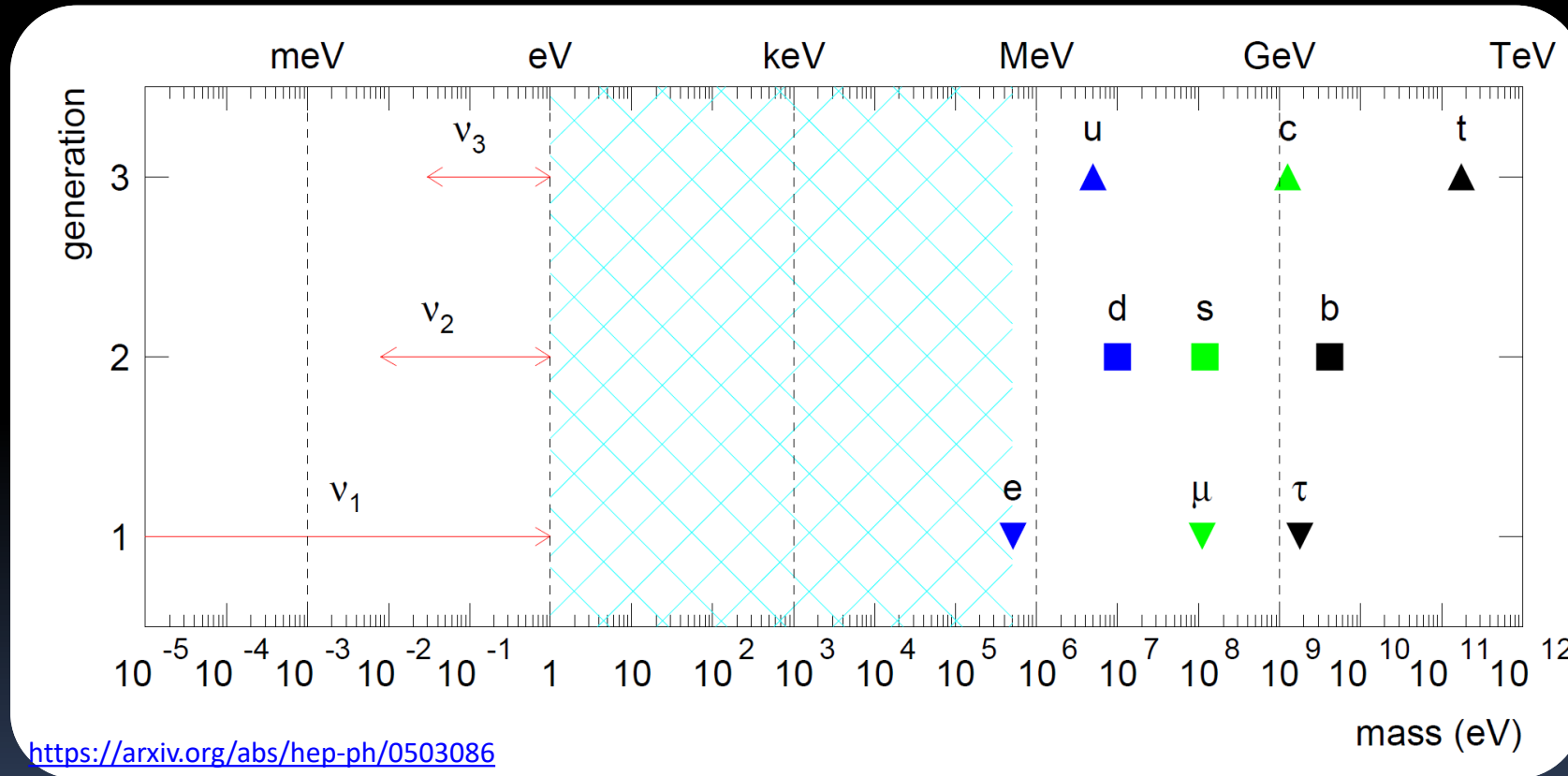
For all other fermions: $\frac{v}{\sqrt{2}} y_\psi \bar{\psi}_L \psi_R$ **but** we never observed a right handed neutrino

Massless spin $\frac{1}{2}$ $\longrightarrow$ Massive spin $\frac{1}{2}$

Takeaway message: New DoF NEEDED!

The SM is not finalized!

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



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

The SM is not finalized!

“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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- No color, no charge, no hypercharge, no isospin!
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Only novelty: Dirac Neutrinos $\longleftrightarrow$ Lepton Number Conservation becomes “fundamental”!

“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:

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

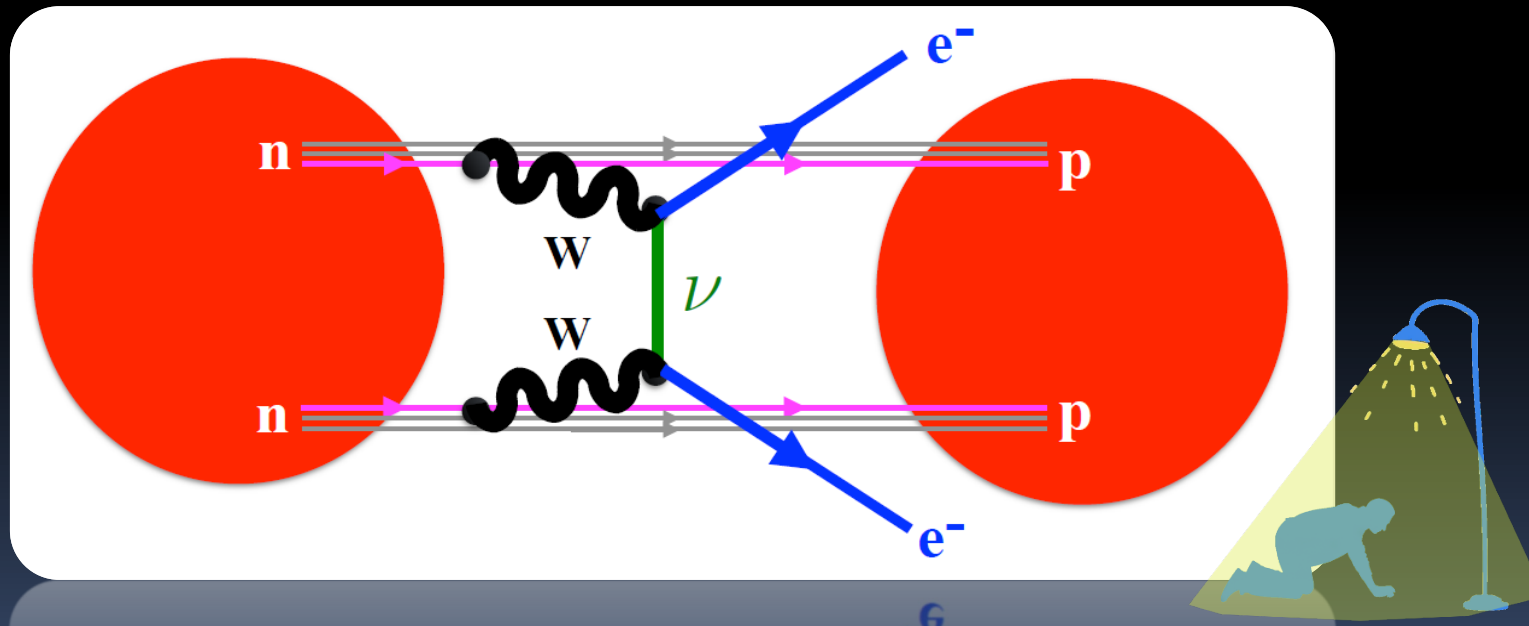
$$\mathcal{L}_5 = \frac{c_5}{\Lambda} \left(\tilde{H}^\dagger L_{f1} \right)^T C \left(\tilde{H}^\dagger L_{f2} \right)$$

New physics at (high) scale Λ

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

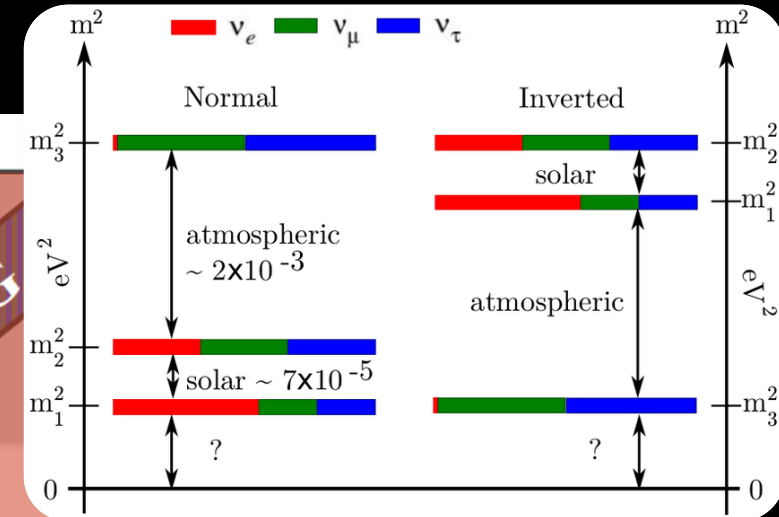
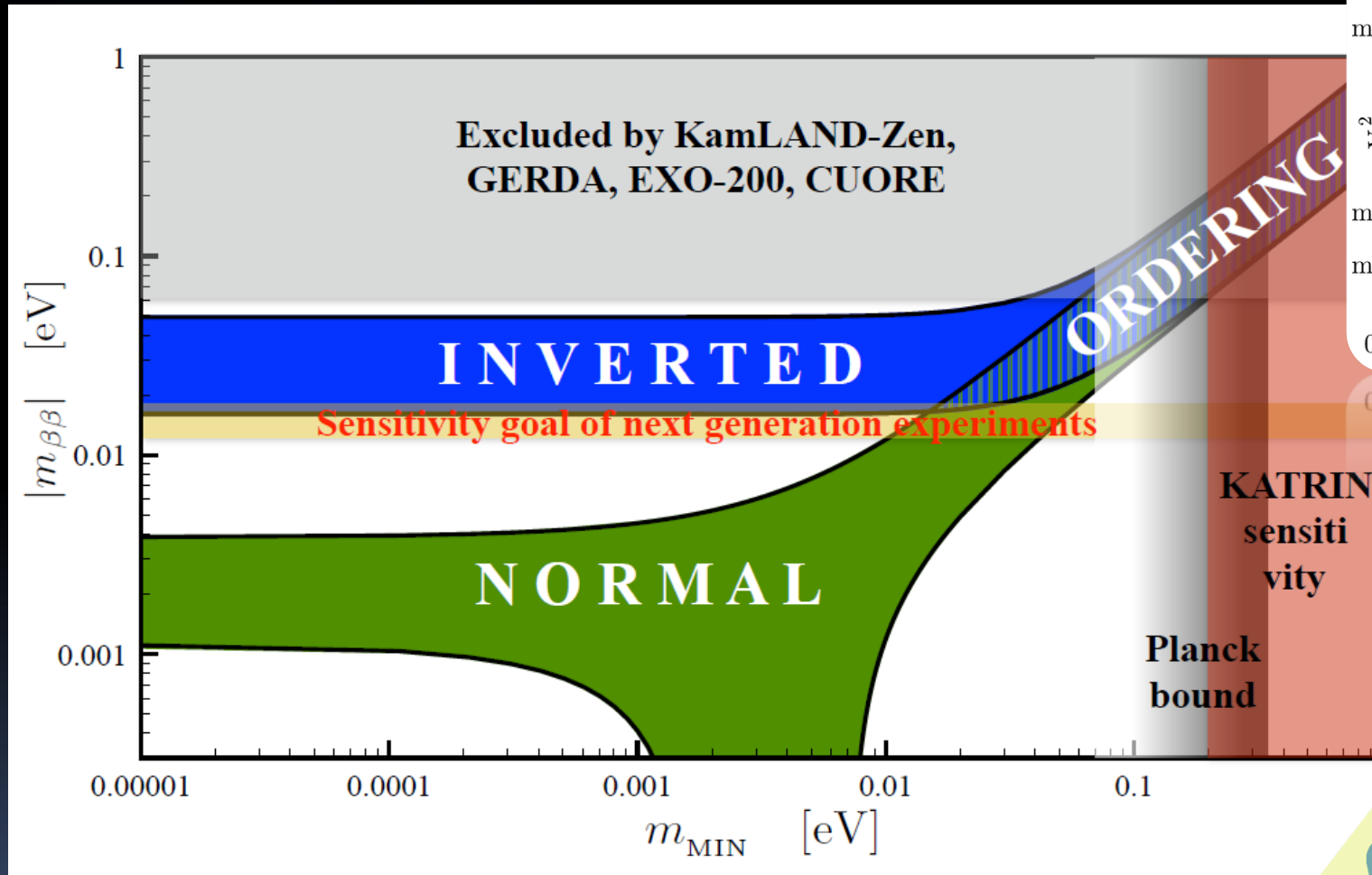
Lepton number violation!

Double Beta Decay APPEC Committee Report, arXiv:1910.04688



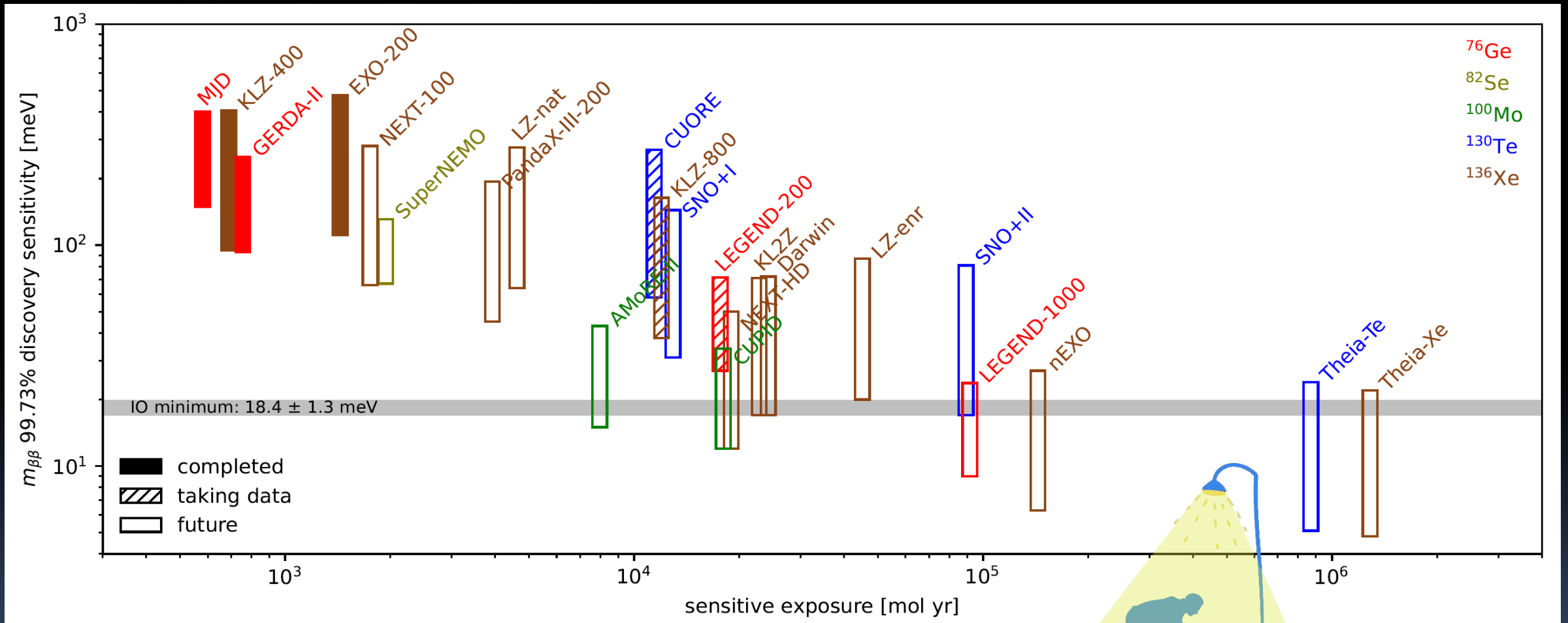
The SM is not finalized!

Lepton number violation!



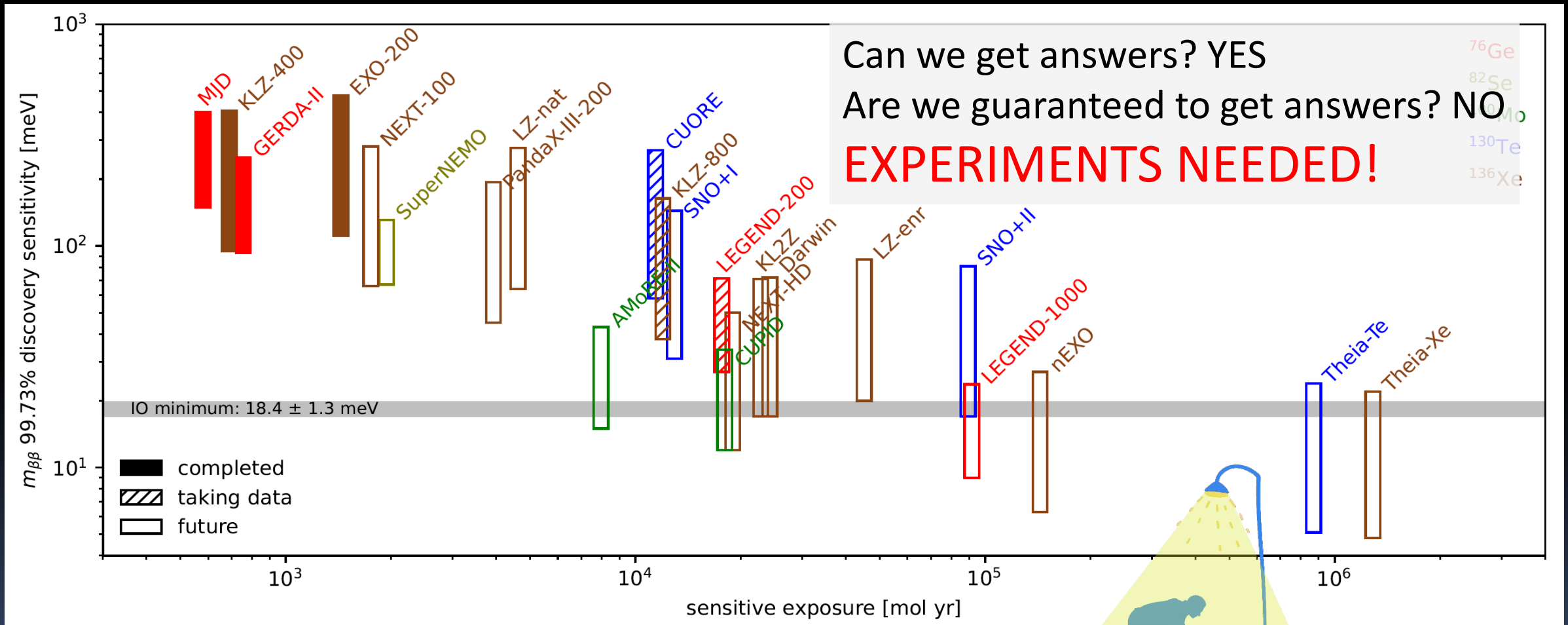
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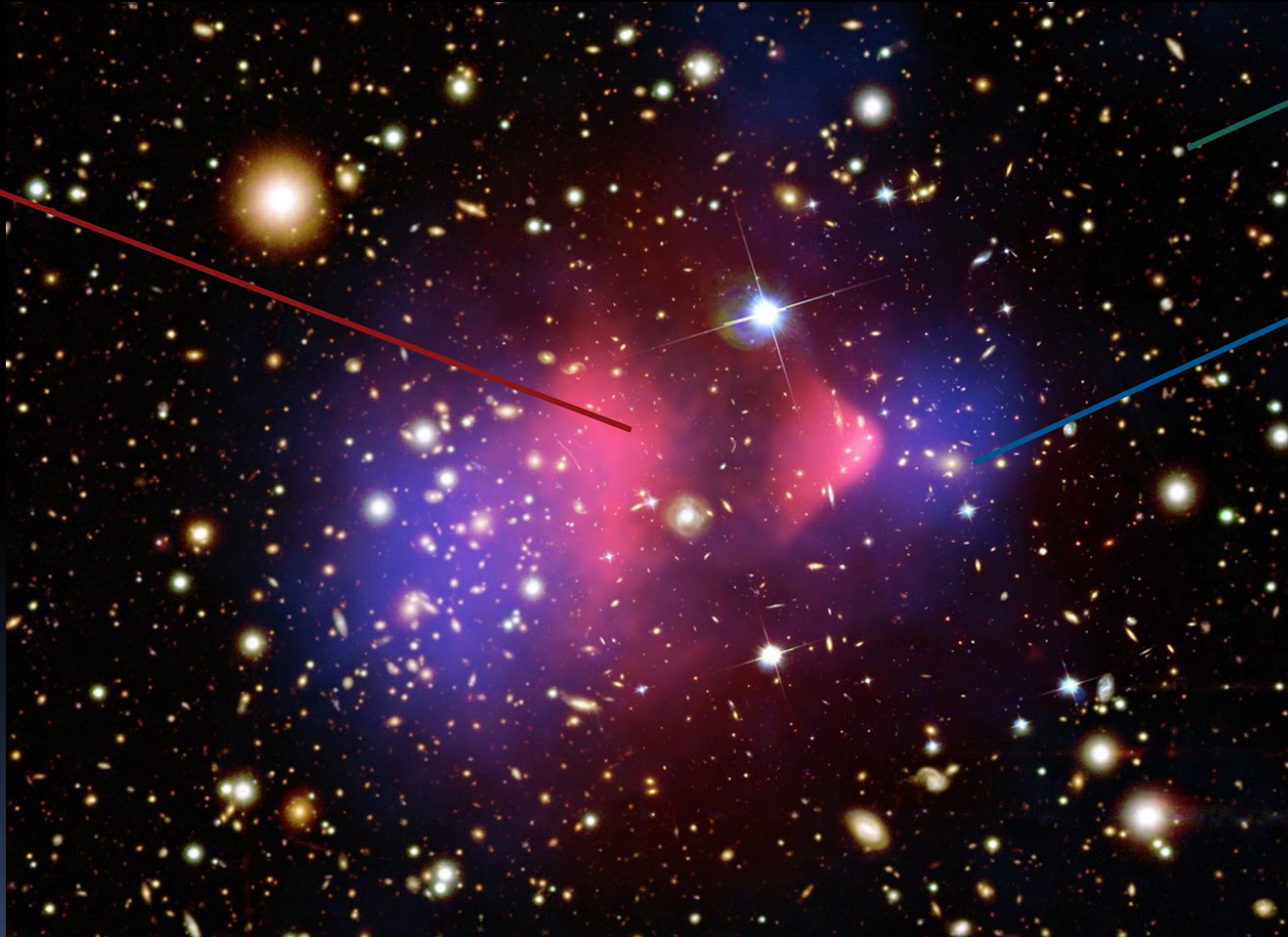
There is Dark Matter (Problem? Probably yes.)

The SM is not finalized!

There is Dark Matter (Problem? Probably yes.)

Can it be... Modified Gravity?

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



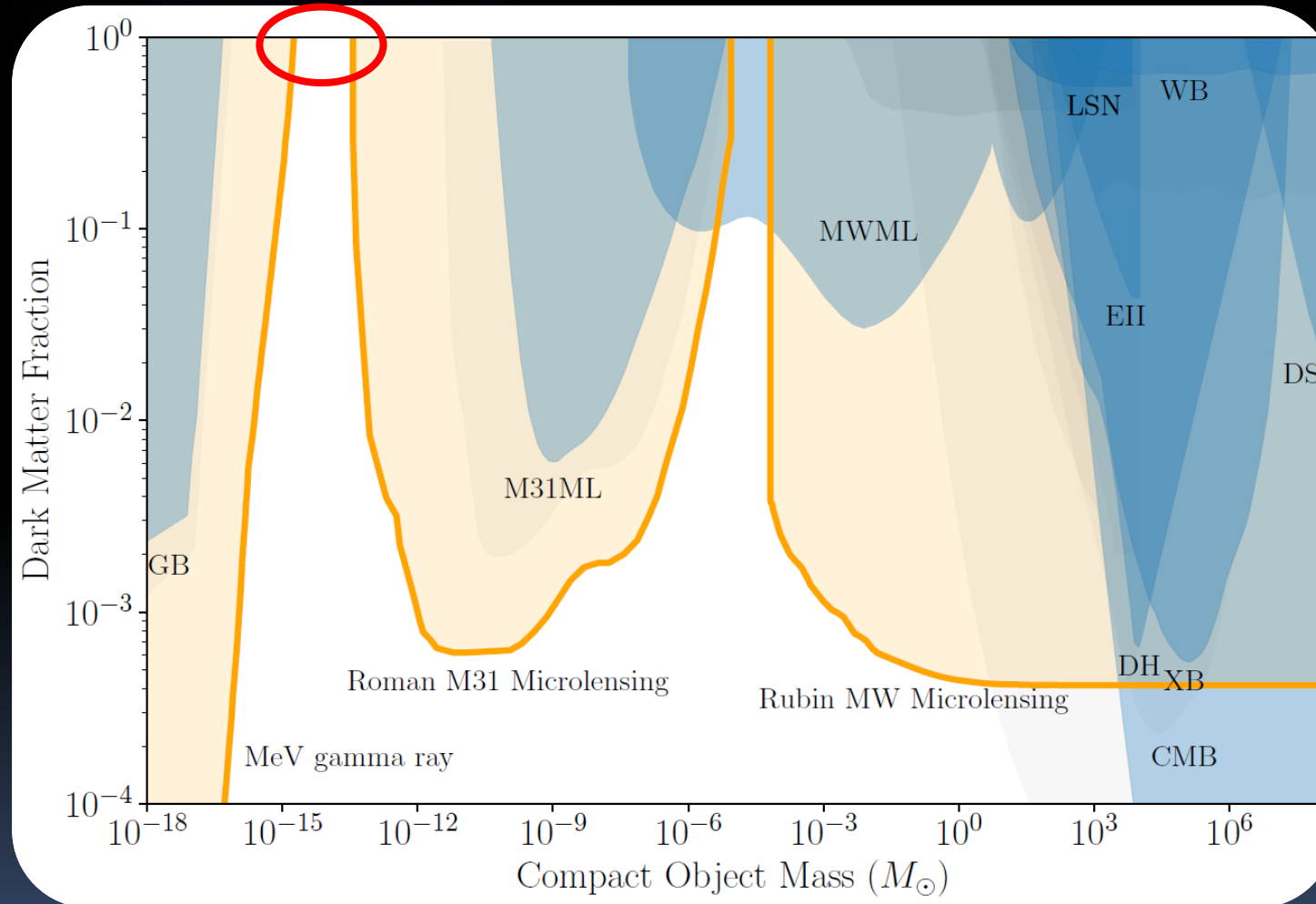
Visible Galaxies

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

The SM is not finalized!

There is Dark Matter (Problem? Probably yes.)

Can it be... Compact Objects?



Primordial **B**lack **H**oles still not directly excluded.

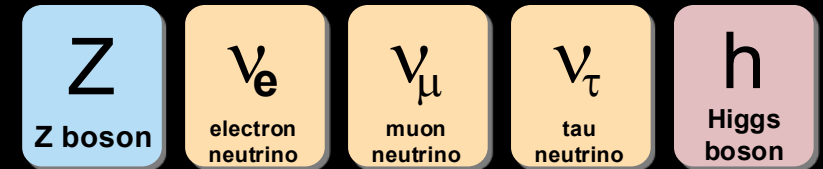
(theoretical issues with production are unresolved)

The SM is not finalized!

There is Dark Matter (Problem? Probably yes.)

Can it be... Some SM particle?

No electrical charge or strong interactions (QED or QCD)

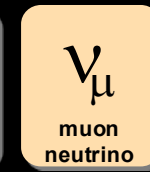


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Stable in cosmological time scales

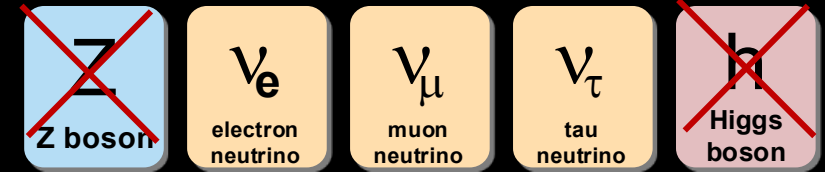


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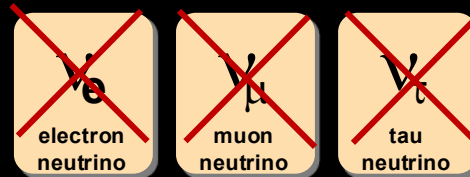
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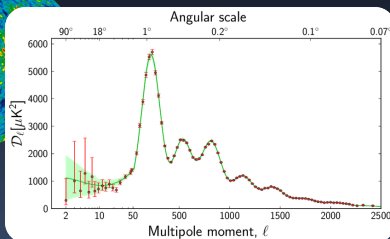
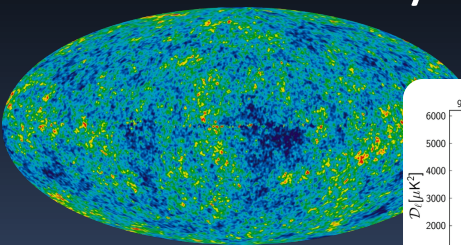
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Stable in cosmological time scales



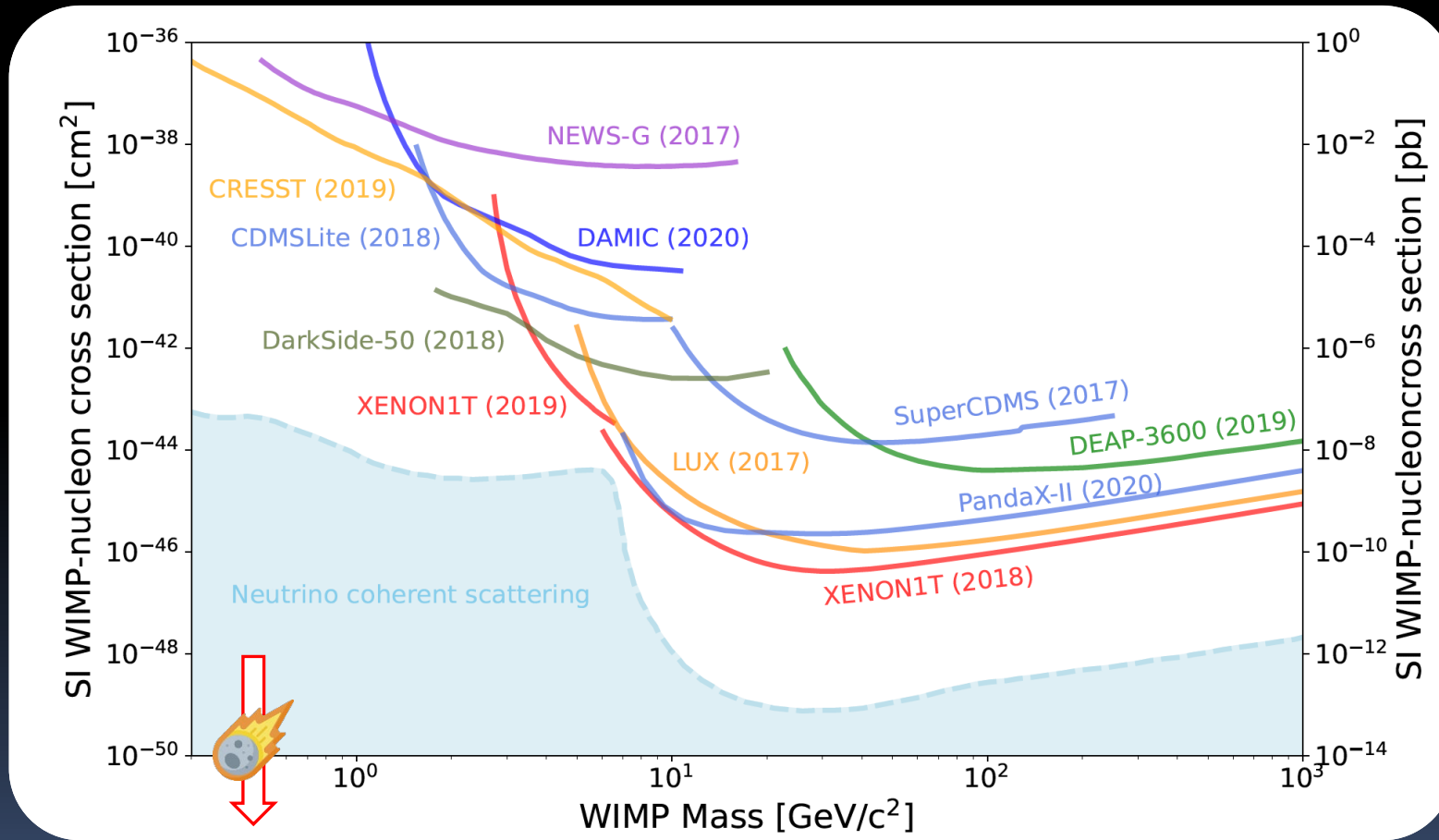
Cold Dark Matter ($\approx$ GeV)
... or maybe “Warm” ($\approx$ keV)



No candidates for DM in the SM!

The SM is not finalized!

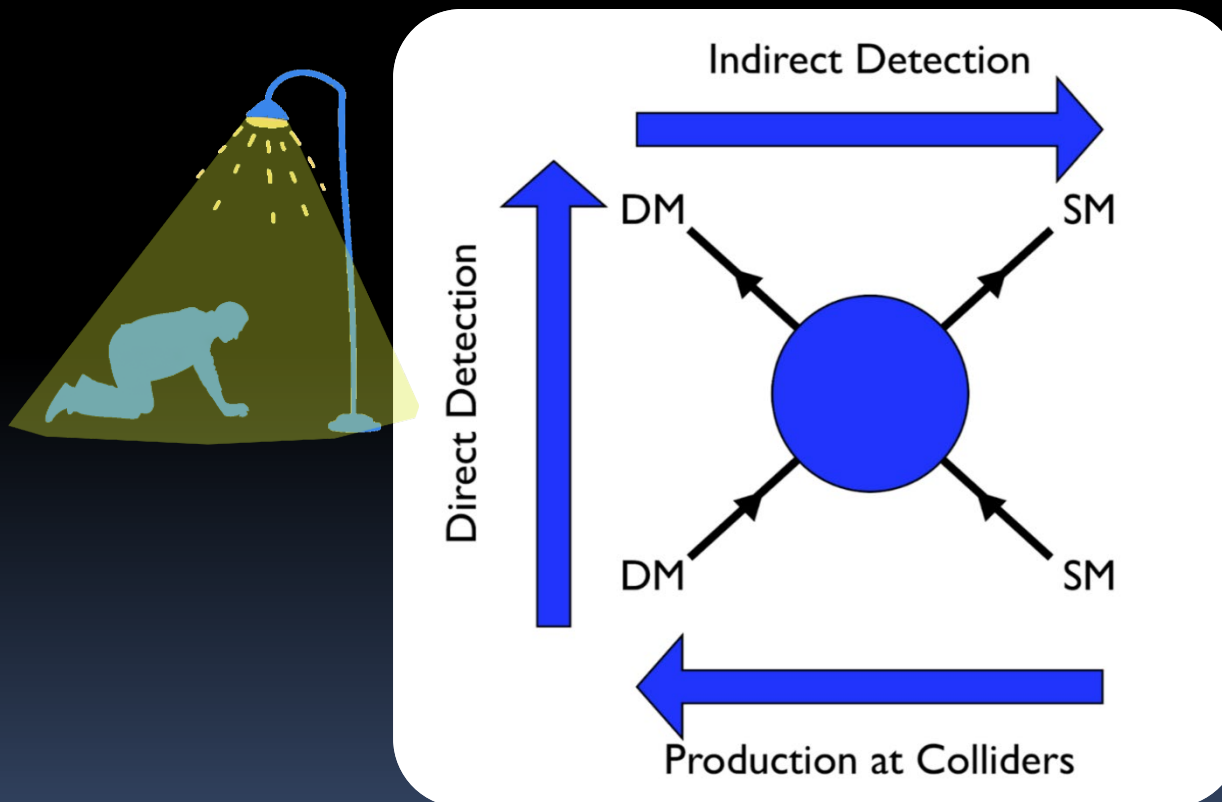
“Bad” solution: **Any** new particle with sufficiently weak interactions w/ SM
(i.e. weaker than “weak” – only gravitational int. is guaranteed)



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

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.);





ULTRALIGHT DARK MATTER

Mass range
 $\sim 10^{-22}$ eV to $\sim 10^{-6}$ eV

Experiments
CASPER, MAGIS-100

AXIONS

Mass range
 $\sim 10^{-6}$ eV to $\sim 10^{-3}$ eV

Experiments
ADMX, MADMAX,
QUAX, CAPP-8TB

What Could Dark Matter Be?

Mass, in electron volts (eV)

PRIMORDIAL BLACK HOLES

Mass range
 ~ 1 to ~ 30
solar masses

Experiments
LIGO/Virgo

WIMPs

Mass range
 ~ 1 GeV to ~ 1 TeV

Experiments
XENONnT,
PandaX-4T,
LZ, CRESST, DAMA,
COSINE-100

SUB-GeV DARK MATTER

Mass range
 ~ 1 keV to ~ 1 GeV

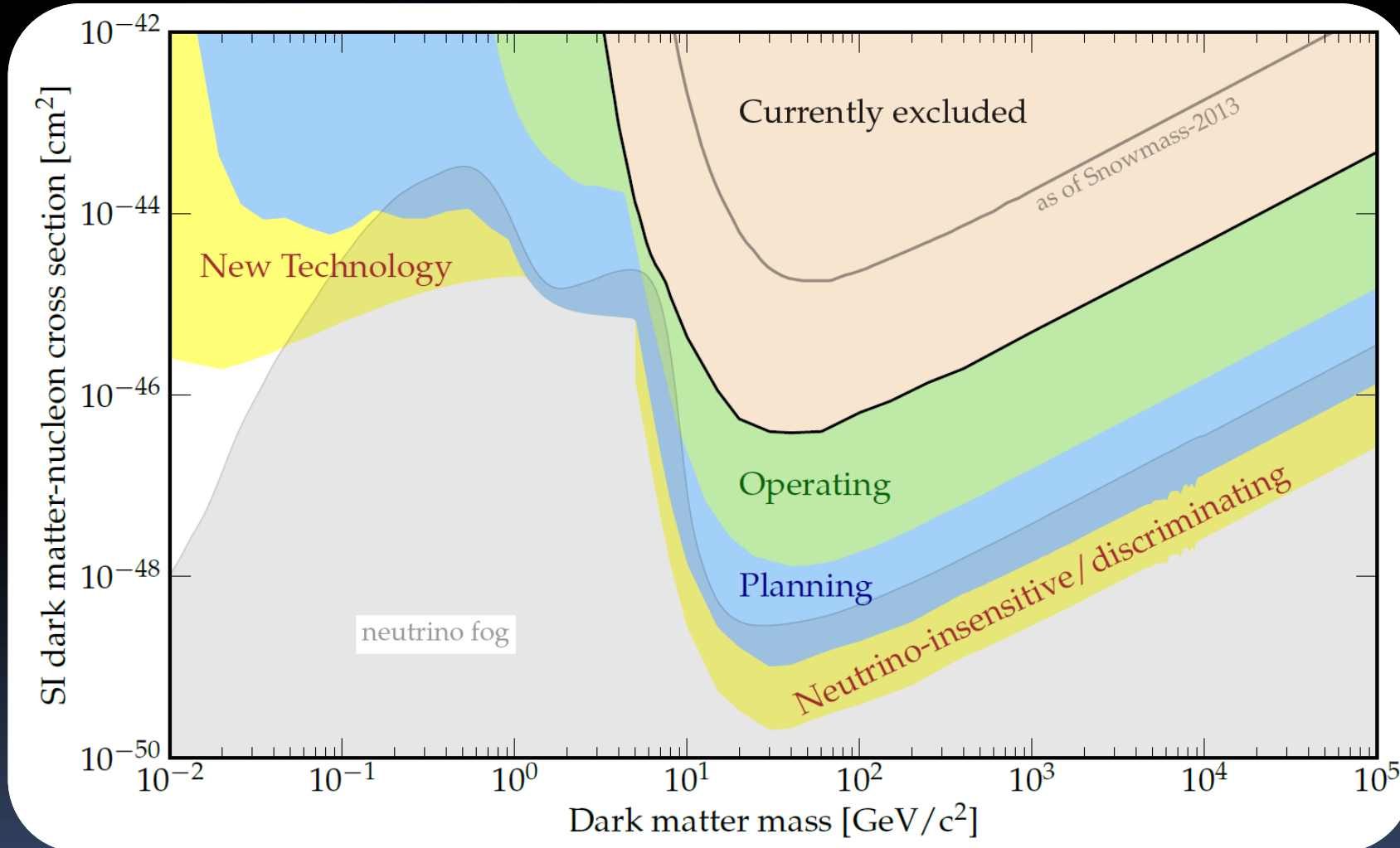
Experiments
SENSEI, TESSERACT

Electron mass

Proton mass

The SM is not finalized!

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



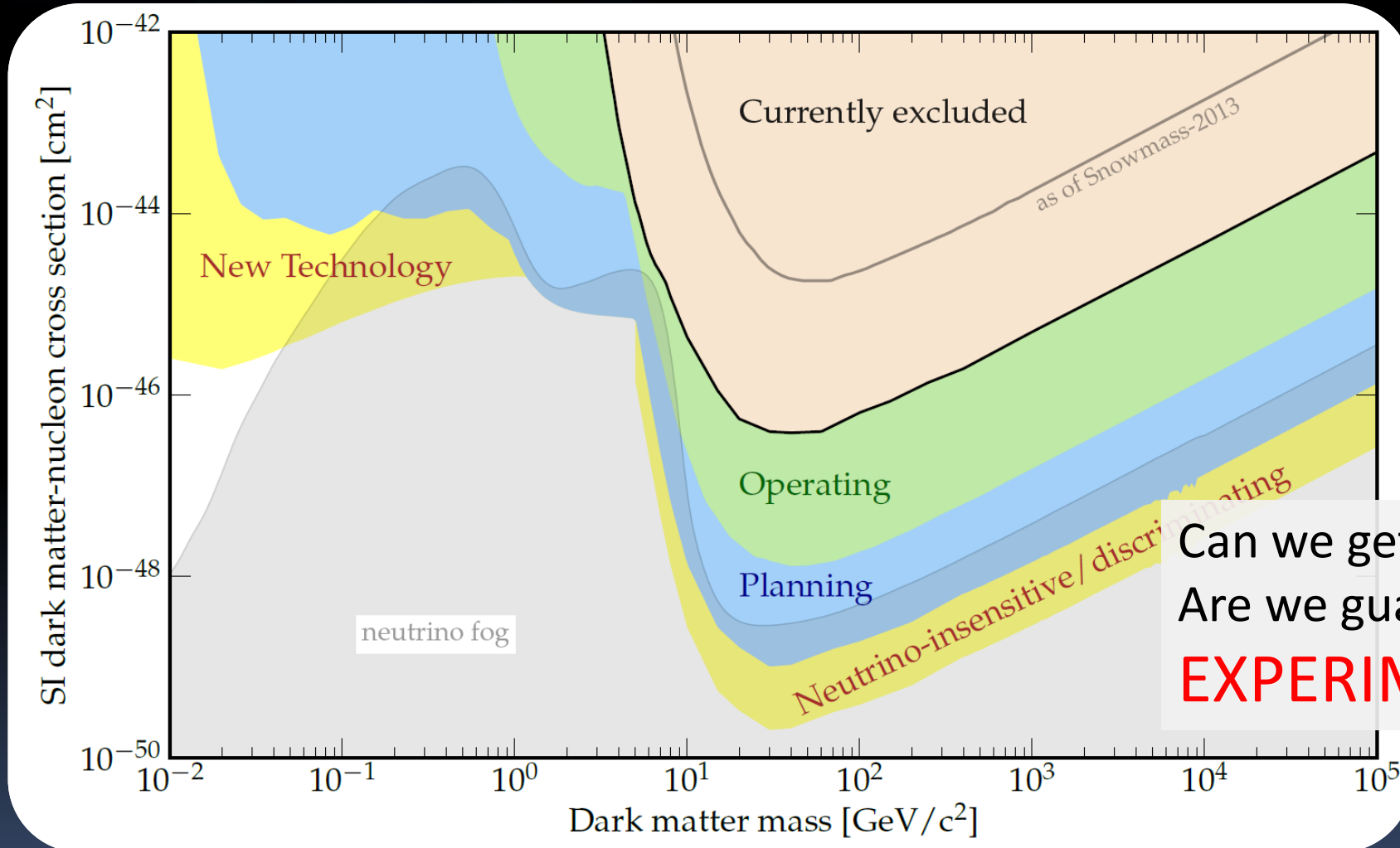
Operating: LZ, XENONnT, PandaX-4T, SuperCDMS SNOLAB, SBC

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



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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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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*)

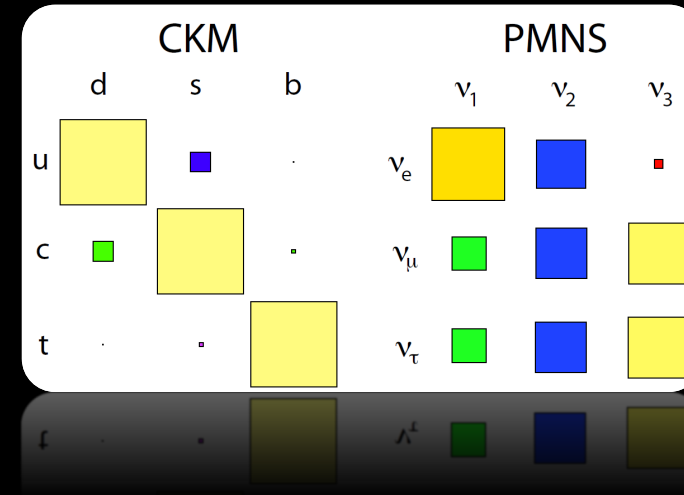
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S. Stone, arXiv:1212.6374

- Physics of Flavor / Family structure

(*Froggatt-Nielsen, Warped Extra Dimensions, 3-3-1, Partial Compositeness, Radiative Masses*)

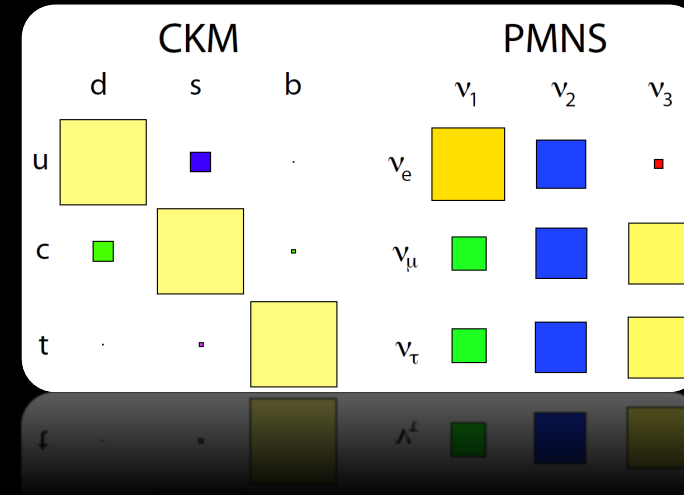


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(*Froggatt-Nielsen, Warped Extra Dimensions, 3-3-1, Partial Compositeness, Radiative Masses*)
- Fine tunings:
 - Strong CP Problem (*Axions Mainly*)
 - Cosmological Constant



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	CKM				PMNS		
	d	s	b		ν_1	ν_2	ν_3
u				ν_e			
c				ν_μ			
t				ν_τ			

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- Hierarchy between Electroweak scale and the SM cut-off

	CKM				PMNS		
	d	s	b		ν_1	ν_2	ν_3
u				ν_e			
c				ν_μ			
t				ν_τ			

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:

$$\mathcal{L} = \frac{1}{2} \partial^\mu \phi \partial_\mu \phi - \frac{m^2}{2} \phi^2 + \bar{\Psi} (i \not{\partial} - M) \Psi - y \phi \bar{\Psi} \Psi$$

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

Tip: $m \ll M$ is not enough!

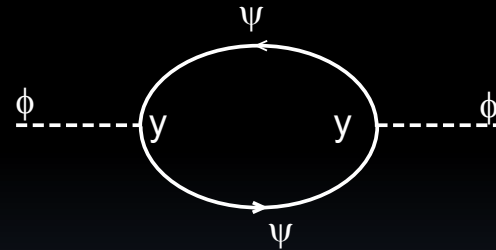
Hierarchy and Scalar masses, a toy model

A scalar, a fermion and 3 parameters:

$$\mathcal{L} = \frac{1}{2} \partial^\mu \phi \partial_\mu \phi - \frac{m^2}{2} \phi^2 + \bar{\Psi} (i \not{\partial} - M) \Psi - y \phi \bar{\Psi} \Psi$$

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

Integrate out the fermion:



the cut-off for
this EFT

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

m_{phys}^2

Hierarchy and Scalar masses, a toy model

Low mass scalar:

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

$$m_{\text{PHZS}}^2 \ll M^2 \longleftrightarrow m^2 \sim \gamma^2 M^2 \quad \text{which we understand IF there is a symmetry demanding it}$$

Hierarchy and Scalar masses, a toy model

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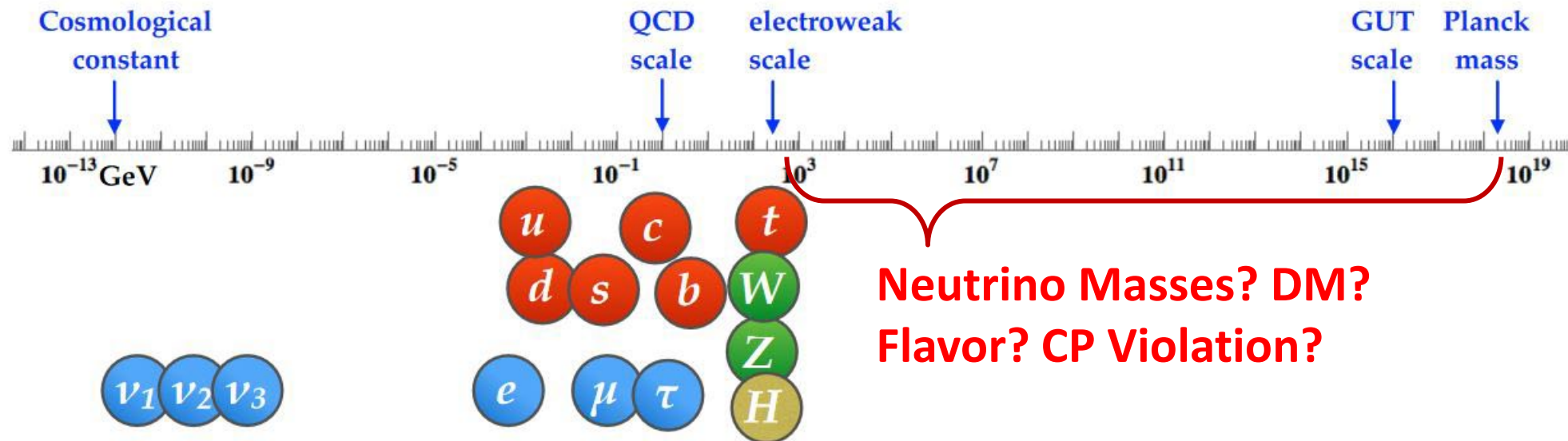
$m_{\text{PHYS}}^2 \ll M^2 \longleftrightarrow m^2 \sim \gamma^2 M^2$ which we understand **IF** there is a symmetry demanding it

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



The SM is not understood!

The “Big Desert” hypothesis:

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

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

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

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

Fine tuning of 10^{-30}

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

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NOT INCREDIBLY FAVORED RIGHT NOW
(but see fine print)

The SM is not understood!

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

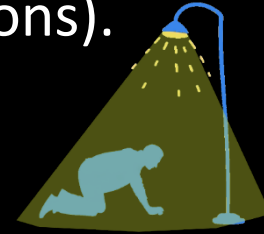


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“Good” solution: Cancel loop corrections (SUSY), bring the cut-off down (composite Higgs as a pNGB) or some dynamical mechanism for the Higgs VEV (Relaxions).

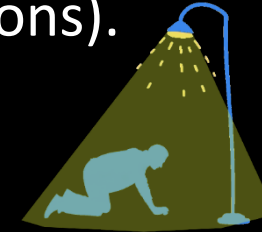


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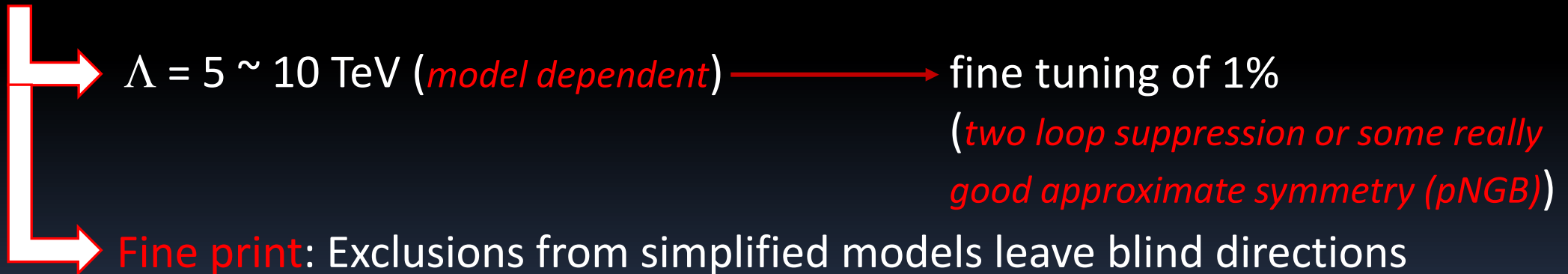
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No sign of new Physics around 1 TeV!

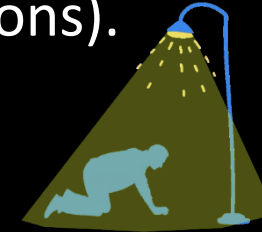


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No sign of new Physics around 1 TeV!



$\Lambda = 5 \sim 10 \text{ TeV}$ (*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

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

The Energy/Luminosity frontiers

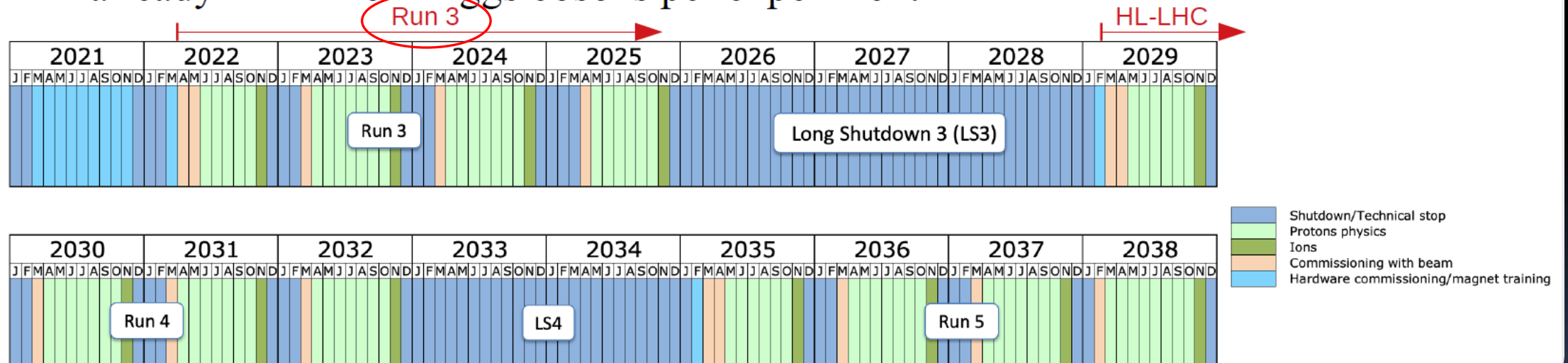
HL-LHC: 3000 fb^{-1}



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

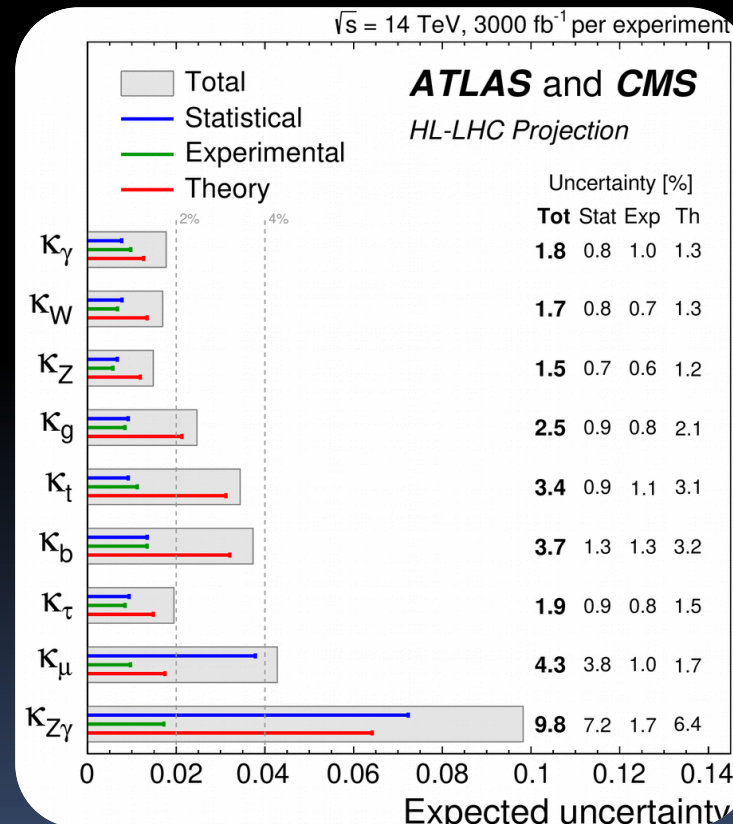


The Energy/Luminosity frontiers

HL-LHC: 3000 fb⁻¹

Goals: Higgs mass ($\sigma \sim 10\text{-}20$ MeV, 0.01%), Higgs Width ($\sigma \sim 20\%$)

Higgs couplings:



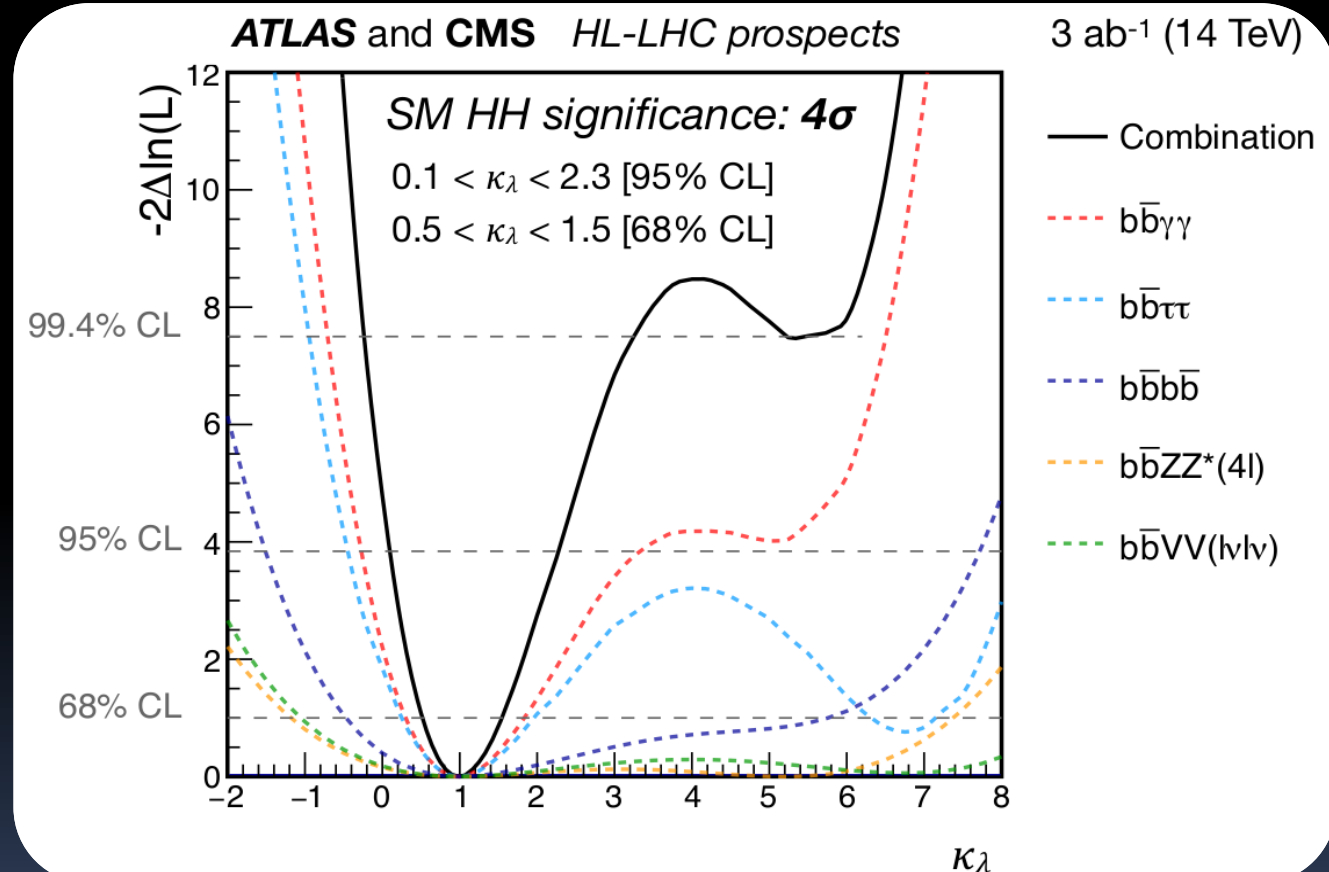
*E. Petit on behalf of
ATLAS & CMS, Prospects for Higgs Physics at the (HL-)LHC*



The Energy/Luminosity frontiers

HL-LHC: 3000 fb⁻¹

Goals: Trilinear Higgs Coupling:



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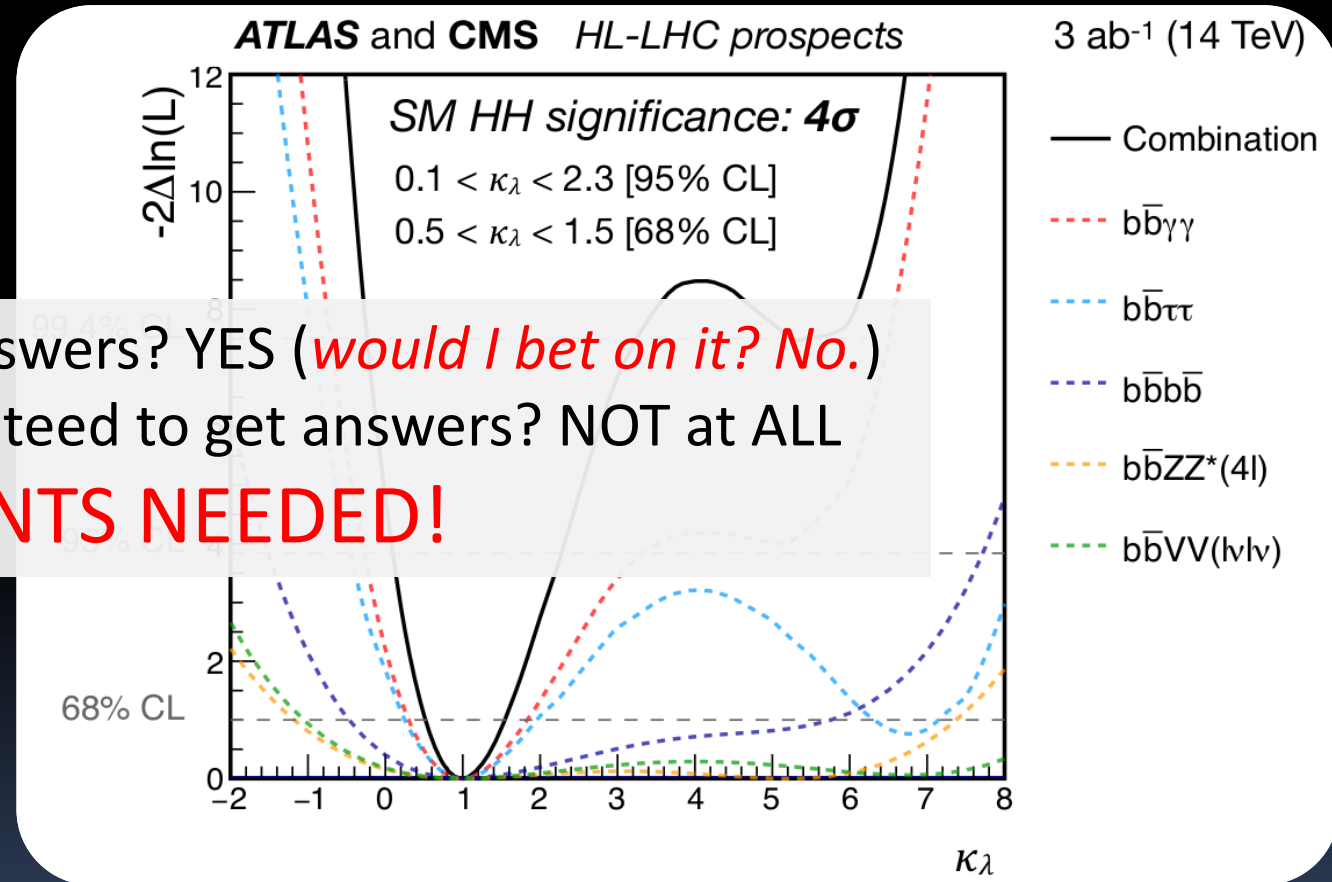


The Energy/Luminosity frontiers

HL-LHC: 3000 fb⁻¹

Goals: Trilinear Higgs Coupling:

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*

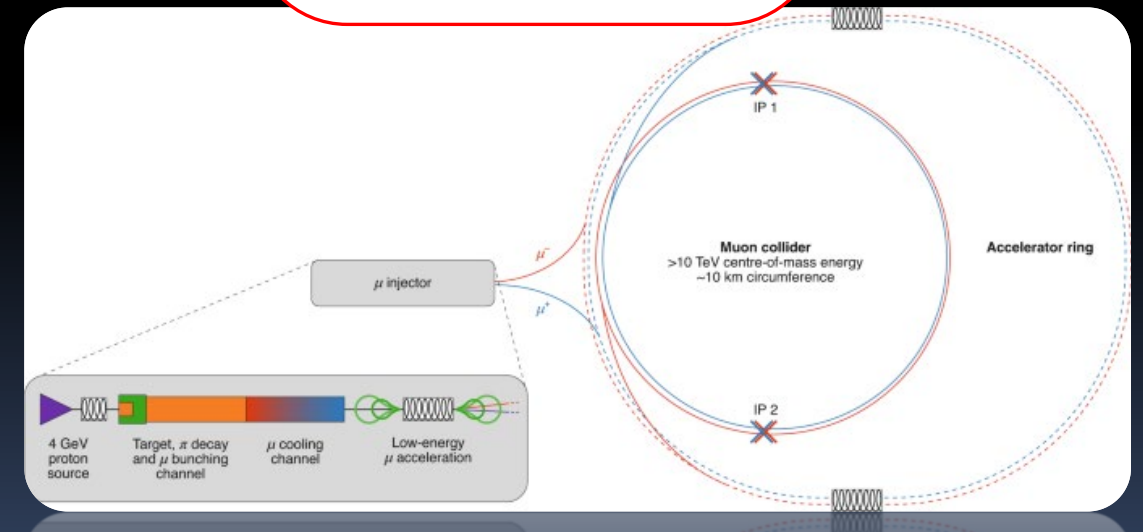
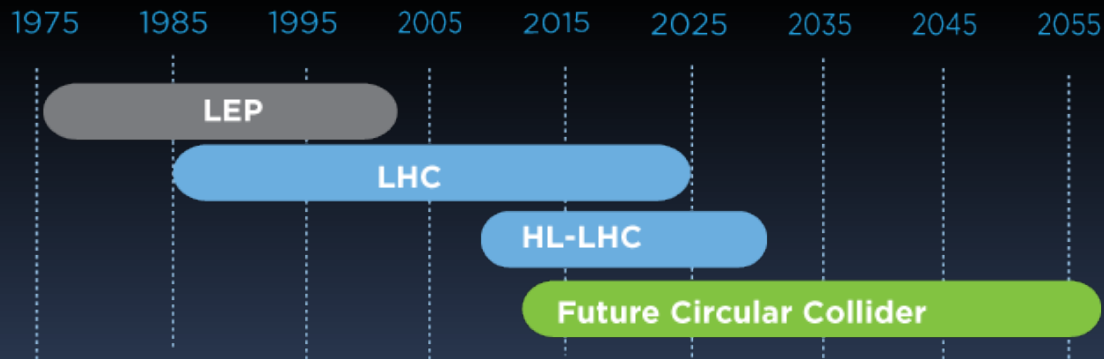


The Energy/Luminosity frontiers

Future Colliders:

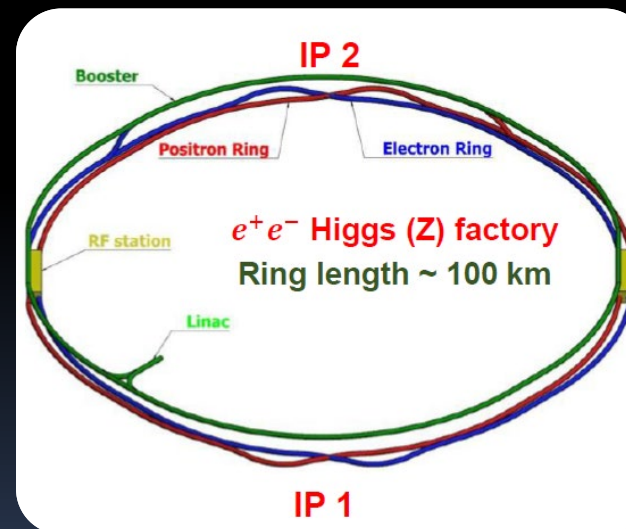


100 TeV (pp),
90-350 GeV (e^+e^-)



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)



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?

Now we are entering a new “Exploration Phase”

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



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!**



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, NⁿLO 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!



