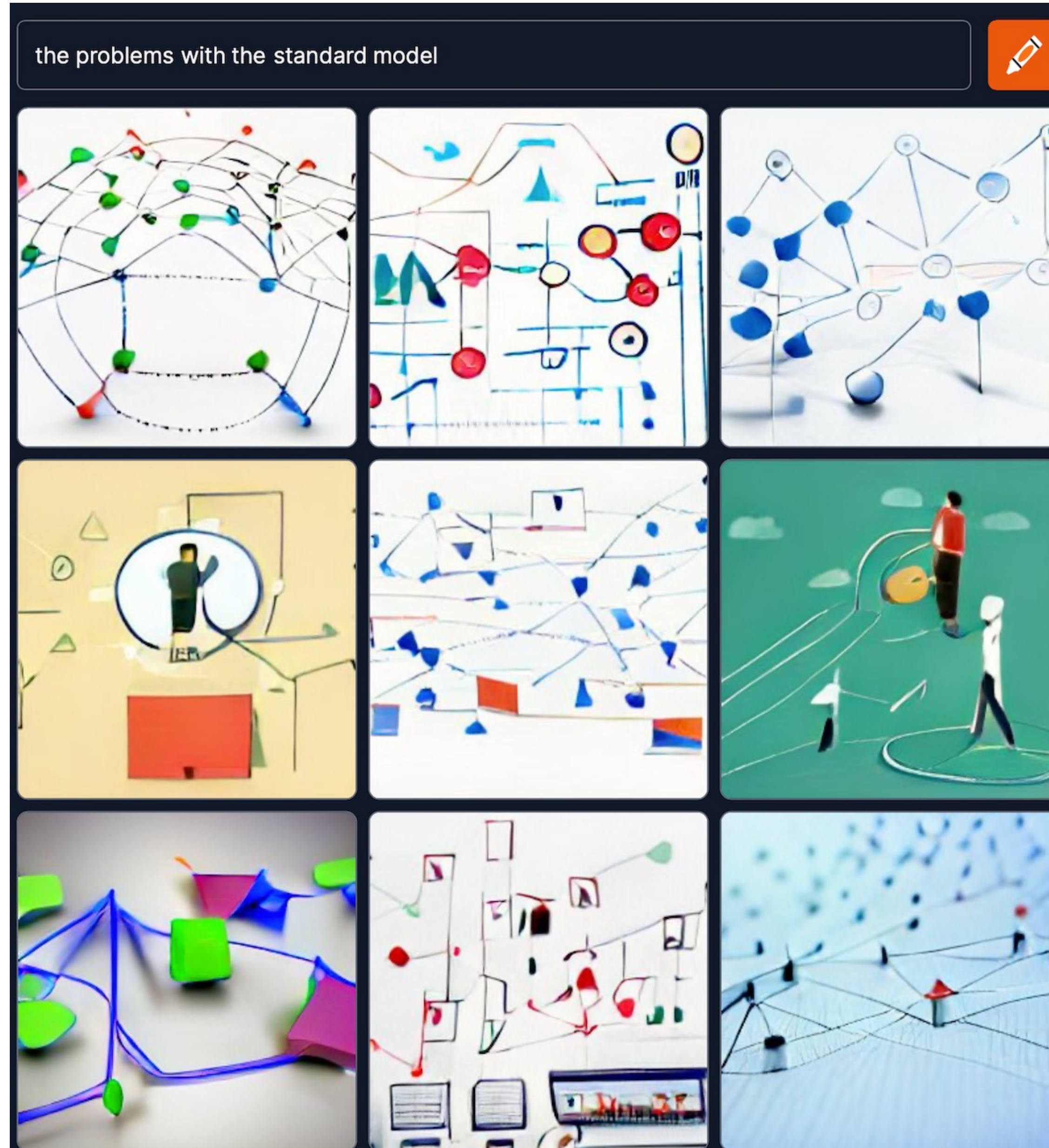
The Problems with the Standard Model

Kate Scholberg,
Duke University

SLAC Summer Institute
August 8, 2022

DALL-E-Mini output



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*an experimentalist viewpoint

DALL-E-Mini output

Disclaimers:

- I am leaving important things out!
- I may not know the answers to questions on specifics!

  ...you will hear more from experts at this school

Outline

The Standard Model: what is it?

Why do we love it?

Why are we angry with it?

What are we going to do about it?

Several examples of opportunities!

"The Standard Model": What Is It?

"The Standard Model": What Is It?

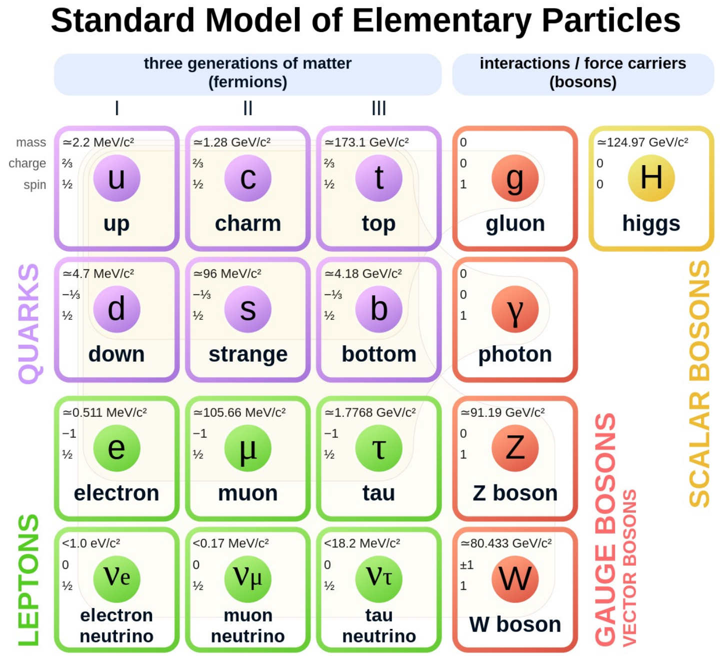
Let's turn to Wikipedia...

Standard Model

From Wikipedia, the free encyclopedia

This article is about a non-mathematical general overview of the Standard Model of particle physics. For a mathematical description, see Mathematical formulation of the Standard Model. For other uses, see Standard model (disambiguation).

The **Standard Model** of particle physics is the theory describing three of the four known fundamental forces (electromagnetic, weak and strong interactions, omitting gravity) in the universe and classifying all known elementary particles. It was developed in stages throughout the latter half of the 20th century, through the work of many scientists worldwide,[1] with the current formulation being finalized in the mid-1970s upon experimental confirmation of the existence of quarks. Since then, proof of the top quark (1995), the tau neutrino (2000), and the Higgs boson (2012) have added further credence to the Standard Model. In addition, the Standard Model has predicted various properties of weak neutral currents and the W and Z bosons with great accuracy.



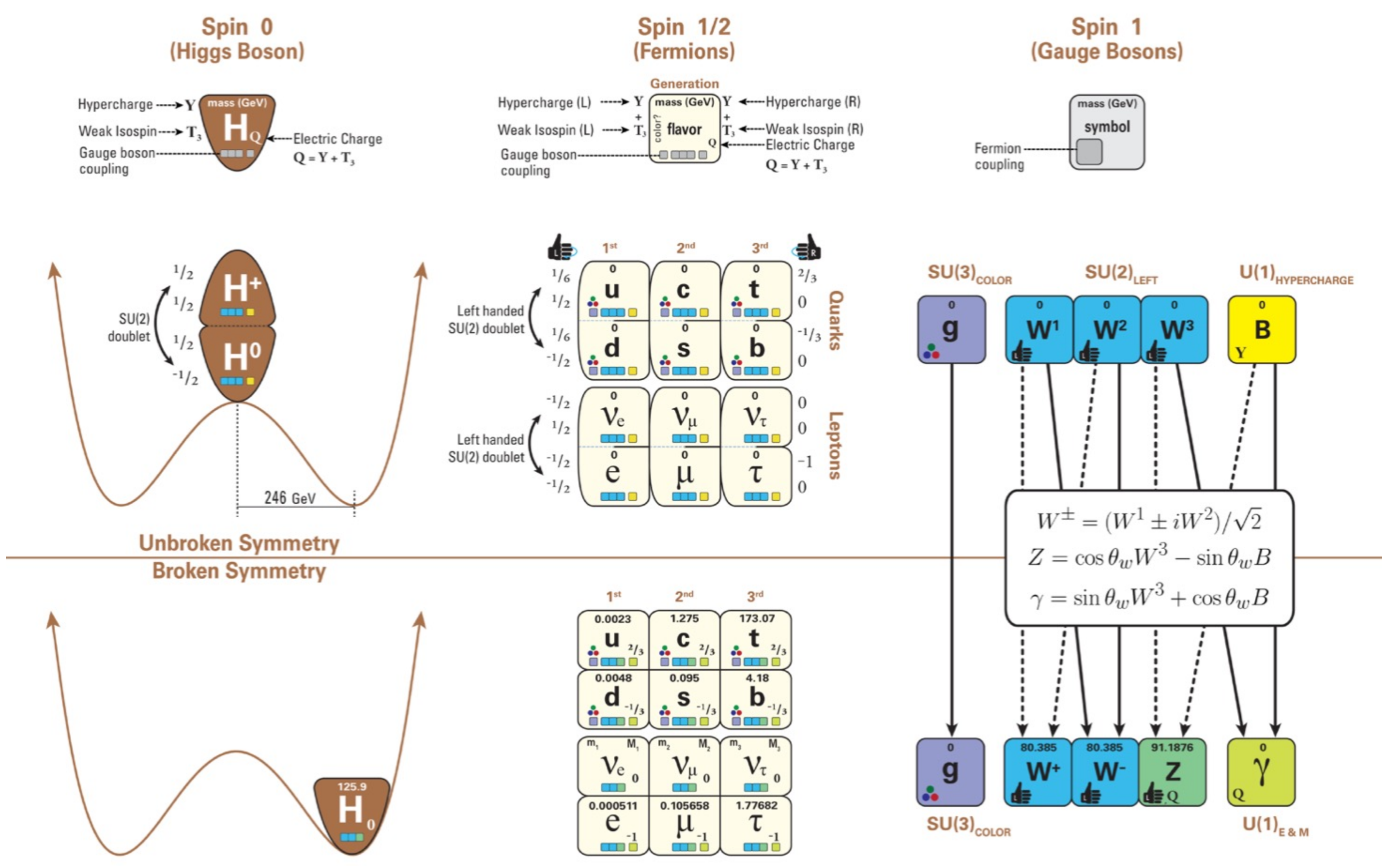
"The Standard Model": What Is It?

Mathematical formulation of the Standard Model

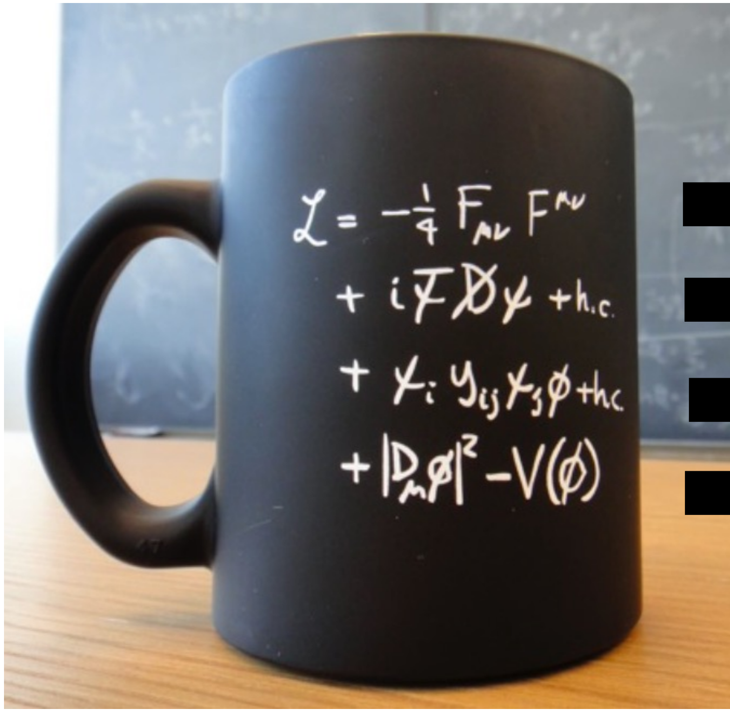
From Wikipedia, the free encyclopedia

This article describes the mathematics of the **Standard Model** of particle physics, a gauge quantum field theory containing the internal symmetries of the unitary product group $SU(3) \times SU(2) \times U(1)$. The theory is commonly viewed as describing the fundamental set of particles – the leptons, quarks, gauge bosons and the Higgs boson.

The Standard Model of Particle Physics



Lagrangian Formulation of the SM



- the forces
- how the forces act on particles
- how the particles get their masses
- lets the Higgs do its job

coffee mug version

The big picture idea that an experimentalist remembers from grad school:

- Write down *the* Lagrangian
- Apply the Euler-Lagrange equations
- Get the equations of motion of all the known particles (e.g. Dirac equation)
- Symmetries lead to gauge fields associated with interactions
- A scalar massive Higgs is needed for electroweak symmetry breaking, gives particles their masses
- There are 19 parameters determined by experiment

The Standard Model Lagrangian long version

gluons (color charge)

interactions between bosons (photons, $W^{\pm}$, Z, H)

interactions between matter and the weak force, and interactions with the Higgs

``ghosts" (artifacts in field theory formulation)

1

$$-\frac{1}{2}\partial_\nu g^a_\mu \partial_\nu g^a_\mu - g_s f^{abc}\partial_\mu g^a_\nu g^b_\mu g^c_\nu - \frac{1}{4}g^2_s f^{abc} f^{ade} g^b_\mu g^c_\nu g^d_\mu g^e_\nu +$$
$$\frac{1}{2}ig^2_s(\bar{q}^\sigma_i \gamma^\mu q^\sigma_j)g^a_\mu + \bar{G}^a\partial^2 G^a + g_s f^{abc}\partial_\mu \bar{G}^a G^b g^c_\mu$$

2

$$- \partial_\nu W^+_\mu \partial_\nu W^-_\mu -$$
$$M^2 W^+_\mu W^-_\mu - \frac{1}{2}\partial_\nu Z^0_\mu \partial_\nu Z^0_\mu - \frac{1}{2c^2_w}M^2 Z^0_\mu Z^0_\mu - \frac{1}{2}\partial_\mu A_\nu \partial_\mu A_\nu - \frac{1}{2}\partial_\mu H \partial_\mu H -$$
$$\frac{1}{2}m^2_h H^2 - \partial_\mu \phi^+ \partial_\mu \phi^- - M^2\phi^+\phi^- - \frac{1}{2}\partial_\mu\phi^0\partial_\mu\phi^0 - \frac{1}{2c^2_w}M\phi^0\phi^0 - \beta_h[\frac{2M^2}{g^2} +$$
$$\frac{2M}{g}H + \frac{1}{2}(H^2 + \phi^0\phi^0 + 2\phi^+\phi^-)] + \frac{2M^4}{g^2}\alpha_h - igc_w[\partial_\nu Z^0_\mu(W^+_\mu W^-_\nu -$$
$$W^+_\nu W^-_\mu) - Z^0_\nu(W^+_\mu\partial_\nu W^-_\mu - W^-_\mu\partial_\nu W^+_\mu) + Z^0_\mu(W^+_\nu\partial_\nu W^-_\mu -$$
$$W^-_\nu\partial_\nu W^+_\mu)] - igs_w[\partial_\nu A_\mu(W^+_\mu W^-_\nu - W^+_\nu W^-_\mu) - A_\nu(W^+_\mu\partial_\nu W^-_\mu -$$
$$W^-_\mu\partial_\nu W^+_\mu) + A_\mu(W^+_\nu\partial_\nu W^-_\mu - W^-_\nu\partial_\nu W^+_\mu)] - \frac{1}{2}g^2 W^+_\mu W^-_\mu W^+_\nu W^-_\nu +$$
$$\frac{1}{2}g^2 W^+_\mu W^-_\nu W^+_\mu W^-_\nu + g^2 c^2_w(Z^0_\mu W^+_\mu Z^0_\nu W^-_\nu - Z^0_\mu Z^0_\mu W^+_\nu W^-_\nu) +$$
$$g^2 s^2_w(A_\mu W^+_\mu A_\nu W^-_\nu - A_\mu A_\mu W^+_\nu W^-_\nu) + g^2 s_w c_w[A_\mu Z^0_\nu(W^+_\mu W^-_\nu -$$
$$W^+_\nu W^-_\mu) - 2A_\mu Z^0_\mu W^+_\nu W^-_\nu] - g\alpha[H^3 + H\phi^0\phi^0 + 2H\phi^+\phi^-] -$$
$$\frac{1}{8}g^2\alpha_h[H^4 + (\phi^0)^4 + 4(\phi^+\phi^-)^2 + 4(\phi^0)^2\phi^+\phi^- + 4H^2\phi^+\phi^- + 2(\phi^0)^2 H^2] -$$
$$gMW^+_\mu W^-_\mu H - \frac{1}{2}g\frac{M}{c^2_w}Z^0_\mu Z^0_\mu H - \frac{1}{2}ig[W^+_\mu(\phi^0\partial_\mu\phi^- - \phi^-\partial_\mu\phi^0) -$$
$$W^-_\mu(\phi^0\partial_\mu\phi^+ - \phi^+\partial_\mu\phi^0)] + \frac{1}{2}g[W^+_\mu(H\partial_\mu\phi^- - \phi^-\partial_\mu H) - W^-_\mu(H\partial_\mu\phi^+ -$$
$$\phi^+\partial_\mu H)] + \frac{1}{2}g\frac{1}{c_w}(Z^0_\mu(H\partial_\mu\phi^0 - \phi^0\partial_\mu H) - ig\frac{s^2_w}{c_w}MZ^0_\mu(W^+_\mu\phi^- - W^-_\mu\phi^+) +$$
$$igs_w MA_\mu(W^+_\mu\phi^- - W^-_\mu\phi^+) - ig\frac{1-2c^2_w}{2c_w}Z^0_\mu(\phi^+\partial_\mu\phi^- - \phi^-\partial_\mu\phi^+) +$$
$$igs_w A_\mu(\phi^+\partial_\mu\phi^- - \phi^-\partial_\mu\phi^+) - \frac{1}{4}g^2 W^+_\mu W^-_\mu[H^2 + (\phi^0)^2 + 2\phi^+\phi^-] -$$
$$\frac{1}{4}g^2\frac{1}{c^2_w}Z^0_\mu Z^0_\mu[H^2 + (\phi^0)^2 + 2(2s^2_w - 1)^2\phi^+\phi^-] - \frac{1}{2}g^2\frac{s^2_w}{c_w}Z^0_\mu\phi^0(W^+_\mu\phi^- +$$
$$W^-_\mu\phi^+) - \frac{1}{2}ig^2\frac{s^2_w}{c_w}Z^0_\mu H(W^+_\mu\phi^- - W^-_\mu\phi^+) + \frac{1}{2}g^2 s_w A_\mu\phi^0(W^+_\mu\phi^- +$$
$$W^-_\mu\phi^+) + \frac{1}{2}ig^2 s_w A_\mu H(W^+_\mu\phi^- - W^-_\mu\phi^+) - g^2\frac{s_w}{c_w}(2c^2_w - 1)Z^0_\mu A_\mu\phi^+\phi^- -$$
$$g^1 s^2_w A_\mu A_\mu\phi^+\phi^-$$

3

$$- \bar{e}^\lambda(\gamma\partial + m^\lambda_e)e^\lambda - \bar{\nu}^\lambda\gamma\partial\nu^\lambda - \bar{u}^\lambda_j(\gamma\partial + m^\lambda_u)u^\lambda_j -$$
$$\bar{d}^\lambda_j(\gamma\partial + m^\lambda_d)d^\lambda_j + igs_w A_\mu[-(\bar{e}^\lambda\gamma^\mu e^\lambda) + \frac{2}{3}(\bar{u}^\lambda_j\gamma^\mu u^\lambda_j) - \frac{1}{3}(\bar{d}^\lambda_j\gamma^\mu d^\lambda_j)] +$$
$$\frac{ig}{4c_w}Z^0_\mu[(\bar{\nu}^\lambda\gamma^\mu(1+\gamma^5)\nu^\lambda) + (\bar{e}^\lambda\gamma^\mu(4s^2_w - 1 - \gamma^5)e^\lambda) + (\bar{u}^\lambda_j\gamma^\mu(\frac{4}{3}s^2_w -$$
$$1 - \gamma^5)u^\lambda_j) + (\bar{d}^\lambda_j\gamma^\mu(1 - \frac{8}{3}s^2_w - \gamma^5)d^\lambda_j)] + \frac{ig}{2\sqrt{2}}W^+_\mu[(\bar{\nu}^\lambda\gamma^\mu(1+\gamma^5)e^\lambda) +$$
$$(\bar{u}^\lambda_j\gamma^\mu(1+\gamma^5)C_{\lambda\kappa}d^\kappa_j)] + \frac{ig}{2\sqrt{2}}W^-_\mu[(\bar{e}^\lambda\gamma^\mu(1+\gamma^5)\nu^\lambda) + (\bar{d}^\kappa_j C^\dagger_{\lambda\kappa}\gamma^\mu(1+$$
$$\gamma^5)u^\lambda_j)] +$$

4

$$\frac{ig}{2\sqrt{2}}\frac{m^\lambda_e}{M}[-\phi^+(\bar{\nu}^\lambda(1-\gamma^5)e^\lambda) + \phi^-(\bar{e}^\lambda(1+\gamma^5)\nu^\lambda)] -$$
$$\frac{g}{2}\frac{m^\lambda_e}{M}[H(\bar{e}^\lambda e^\lambda) + i\phi^0(\bar{e}^\lambda\gamma^5 e^\lambda)] + \frac{ig}{2M\sqrt{2}}\phi^+[-m^\kappa_d(\bar{u}^\lambda_j C_{\lambda\kappa}(1-\gamma^5)d^\kappa_j) +$$
$$m^\lambda_u(\bar{u}^\lambda_j C_{\lambda\kappa}(1+\gamma^5)d^\kappa_j] + \frac{ig}{2M\sqrt{2}}\phi^-[m^\lambda_d(\bar{d}^\lambda_j C^\dagger_{\lambda\kappa}(1+\gamma^5)u^\kappa_j) - m^\kappa_u(\bar{d}^\lambda_j C^\dagger_{\lambda\kappa}(1-$$
$$\gamma^5)u^\kappa_j] - \frac{g}{2}\frac{m^\lambda_u}{M}H(\bar{u}^\lambda_j u^\lambda_j) - \frac{g}{2}\frac{m^\lambda_d}{M}H(\bar{d}^\lambda_j d^\lambda_j) + \frac{ig}{2}\frac{m^\lambda_u}{M}\phi^0(\bar{u}^\lambda_j\gamma^5 u^\lambda_j) -$$
$$\frac{ig}{2}\frac{m^\lambda_d}{M}\phi^0(\bar{d}^\lambda_j\gamma^5 d^\lambda_j) +$$

5

$$\bar{X}^+(\partial^2 - M^2)X^+ + \bar{X}^-(\partial^2 - M^2)X^- + \bar{X}^0(\partial^2 -$$
$$\frac{M^2}{c^2_w})X^0 + \bar{Y}\partial^2 Y + igc_w W^+_\mu(\partial_\mu\bar{X}^0 X^- - \partial_\mu\bar{X}^+ X^0) + igs_w W^+_\mu(\partial_\mu\bar{Y}X^- -$$
$$\partial_\mu\bar{X}^+ Y) + igc_w W^-_\mu(\partial_\mu\bar{X}^- X^0 - \partial_\mu\bar{X}^0 X^+) + igs_w W^-_\mu(\partial_\mu\bar{X}^- Y -$$
$$\partial_\mu\bar{Y}X^+) + igc_w Z^0_\mu(\partial_\mu\bar{X}^+ X^+ - \partial_\mu\bar{X}^- X^-) + igs_w A_\mu(\partial_\mu\bar{X}^+ X^+ -$$
$$\partial_\mu\bar{X}^- X^-) - \frac{1}{2}gM[\bar{X}^+ X^+ H + \bar{X}^- X^- H + \frac{1}{c^2_w}\bar{X}^0 X^0 H] +$$
$$\frac{1-2c^2_w}{2c_w}igM[\bar{X}^+ X^0\phi^+ - \bar{X}^- X^0\phi^-] + \frac{1}{2c_w}igM[\bar{X}^0 X^-\phi^+ - \bar{X}^0 X^+\phi^-] +$$
$$igMs_w[\bar{X}^0 X^-\phi^+ - \bar{X}^0 X^+\phi^-] + \frac{1}{2}igM[\bar{X}^+ X^+\phi^0 - \bar{X}^- X^-\phi^0]$$

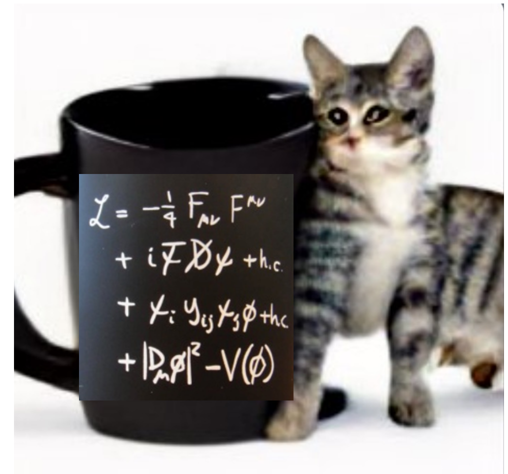
From *Symmetry* magazine

Parameters of the Standard Model				[hide]
Symbol	**Description**	**Renormalization scheme (point)**	**Value**	**Experimental uncertainty**
m_e	Electron mass		510.9989461(31) keV	
m_μ	Muon mass		105.6583745(24) MeV	
m_τ	Tau mass		1.77686(12) GeV	
m_u	Up quark mass	$\mu_{\overline{MS}}$ = 2 GeV	2.2 MeV	+0.5 -0.4 MeV
m_d	Down quark mass	$\mu_{\overline{MS}}$ = 2 GeV	4.7 MeV	+0.5 -0.3 MeV
m_s	Strange quark mass	$\mu_{\overline{MS}}$ = 2 GeV	95 MeV	+9 -3 MeV
m_c	Charm quark mass	$\mu_{\overline{MS}} = m_c$	1.275 GeV	+0.025 -0.035 GeV
m_b	Bottom quark mass	$\mu_{\overline{MS}} = m_b$	4.18 GeV	+0.04 –0.03 GeV
m_t	Top quark mass	On-shell scheme	173.0 GeV	±0.4 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-violating Phase		0.995	
g_1 or g'	U(1) gauge coupling	$\mu_{\overline{MS}} = m_Z$	0.357	
g_2 or g	SU(2) gauge coupling	$\mu_{\overline{MS}} = m_Z$	0.652	
g_3 or g_s	SU(3) gauge coupling	$\mu_{\overline{MS}} = m_Z$	1.221	
θ_{QCD}	QCD vacuum angle		~0	
v	Higgs vacuum expectation value		246.2196(2) GeV	
m_H	Higgs mass		125.18 GeV	±0.16 GeV

Wikipedia

Why Do We Love the Standard Model?

- mathematically self-consistent
- actually pretty concise
- based on symmetry principles



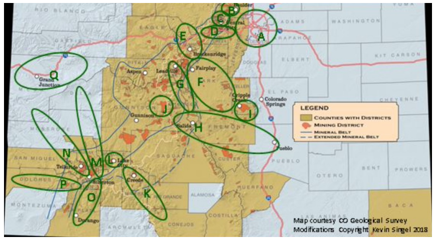
DALL-E-Mini "kitten next to black coffee mug"

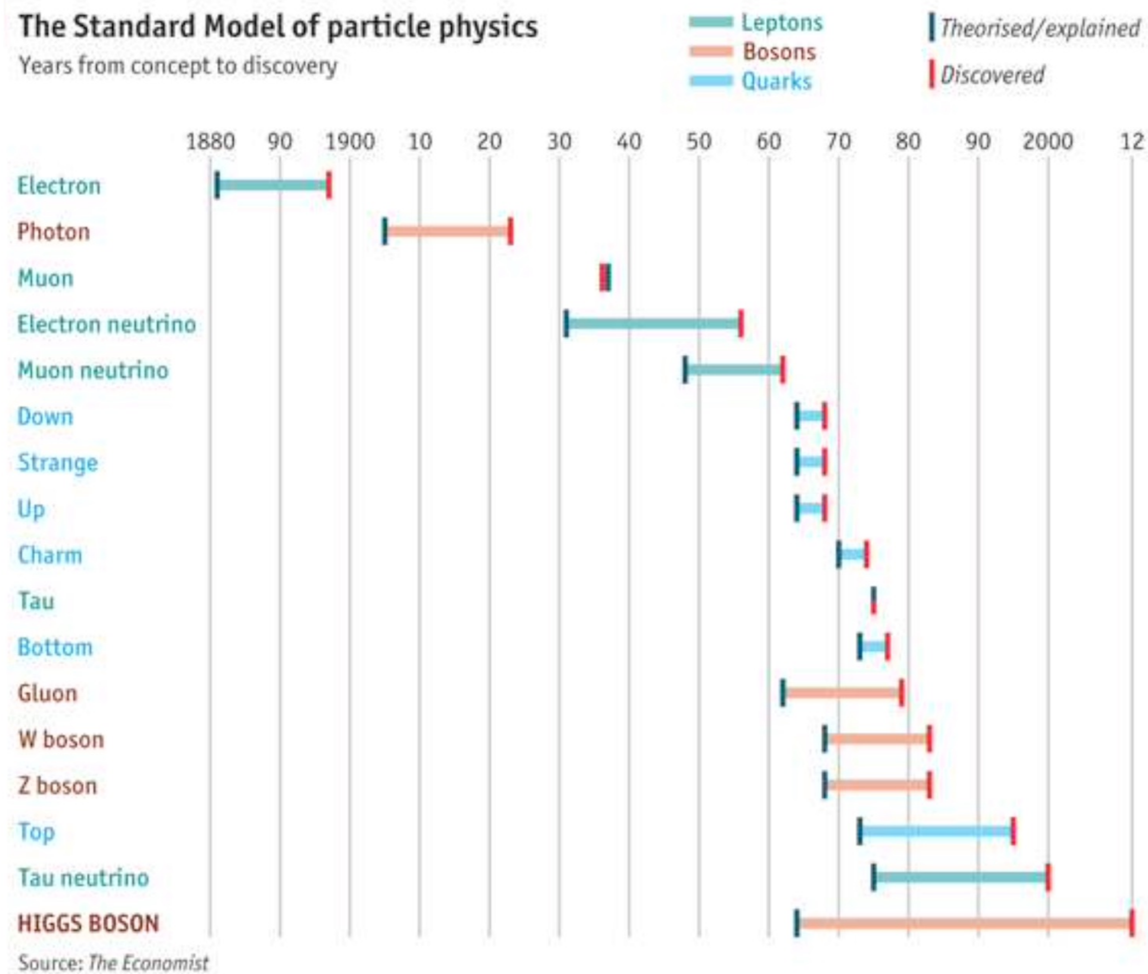
Next sentence of the Wikipedia article:

"....the Standard Model is believed to be theoretically self-consistent[note 1] and has demonstrated huge successes in providing experimental predictions "

It works *amazingly* well for describing a vast range of strong and electroweak phenomena!

Lots of warm fuzzy stories of predictions → discoveries

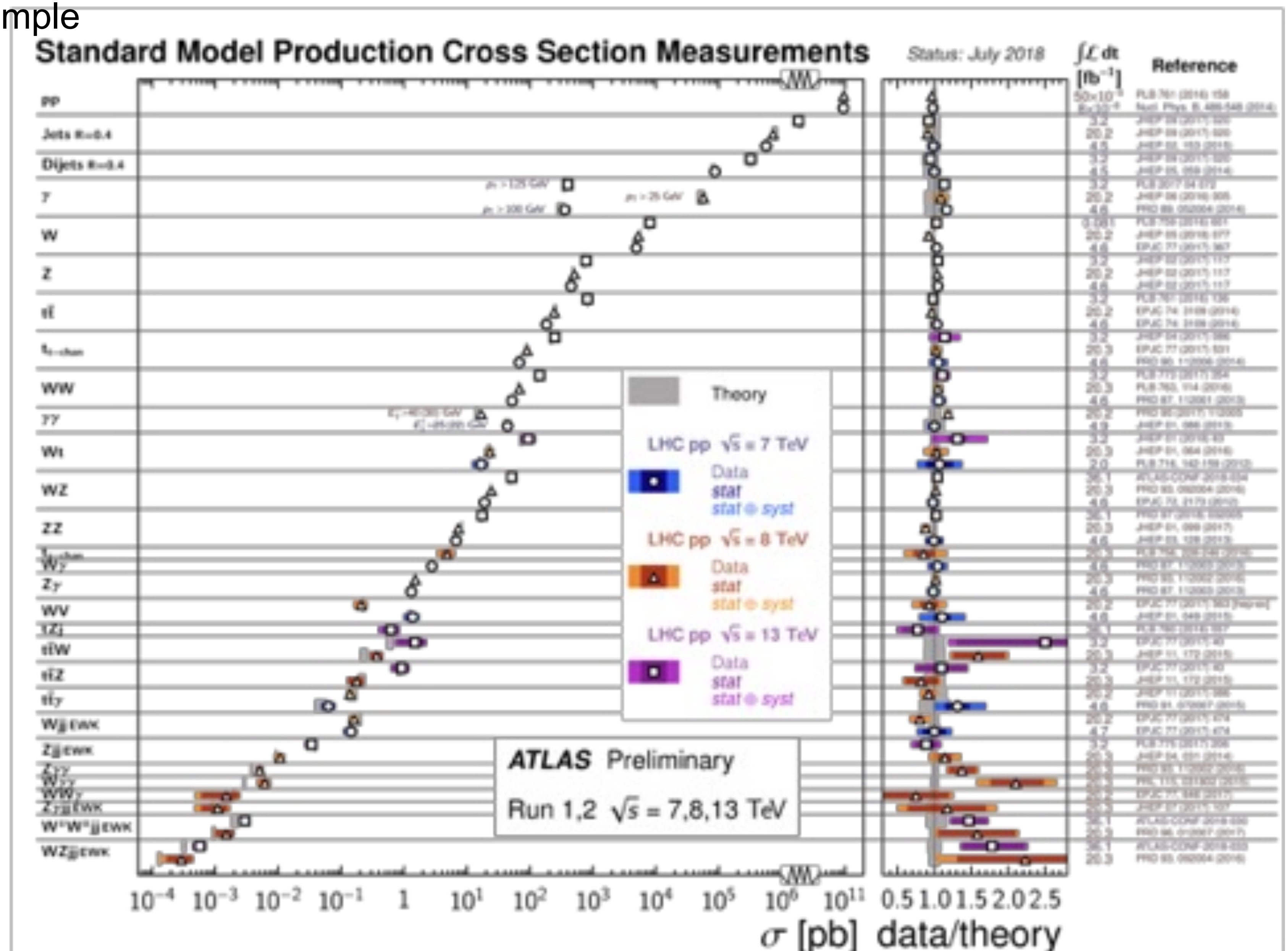




Jesse Thaler's talk at Snowmass CSS

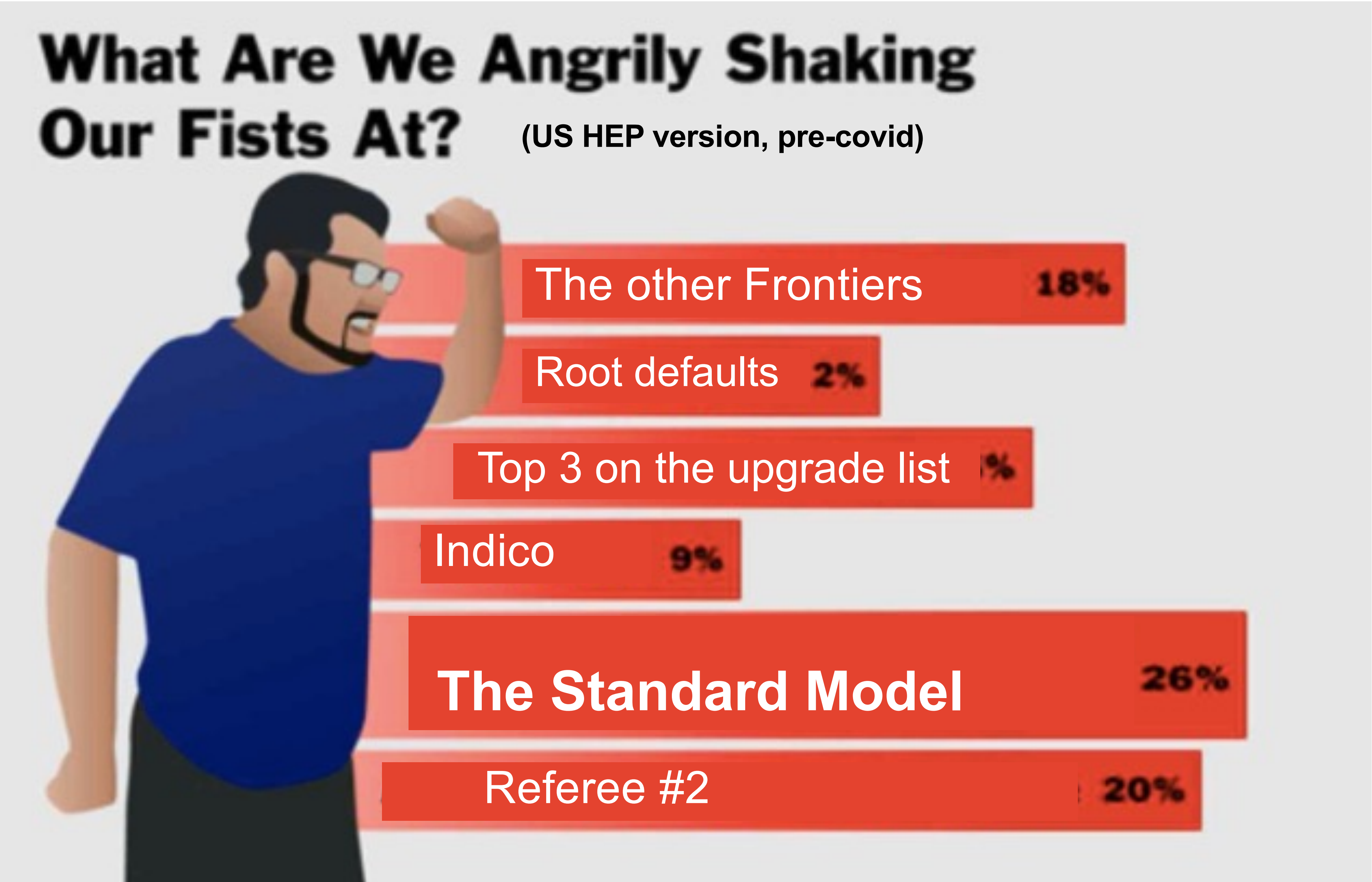
Fantastic agreement over huge range of production cross-section scales

Example



https://www.roma1.infn.it/exp/atlas/research/physics-analysis/standard-model/

But physicists are still grumpy...



Why are we angry with the Standard Model?

We're greedy for comprehensive simplicity!

<u>Categories of grumpiness*</u>...

- *Awkwardness:*
  it's not simple and
  aesthetically pleasing (enough)
  ... too fine-tuned...

- *Insufficiency:*
  it doesn't explain everything!
  ...doesn't cover vast categories
  observed phenomena

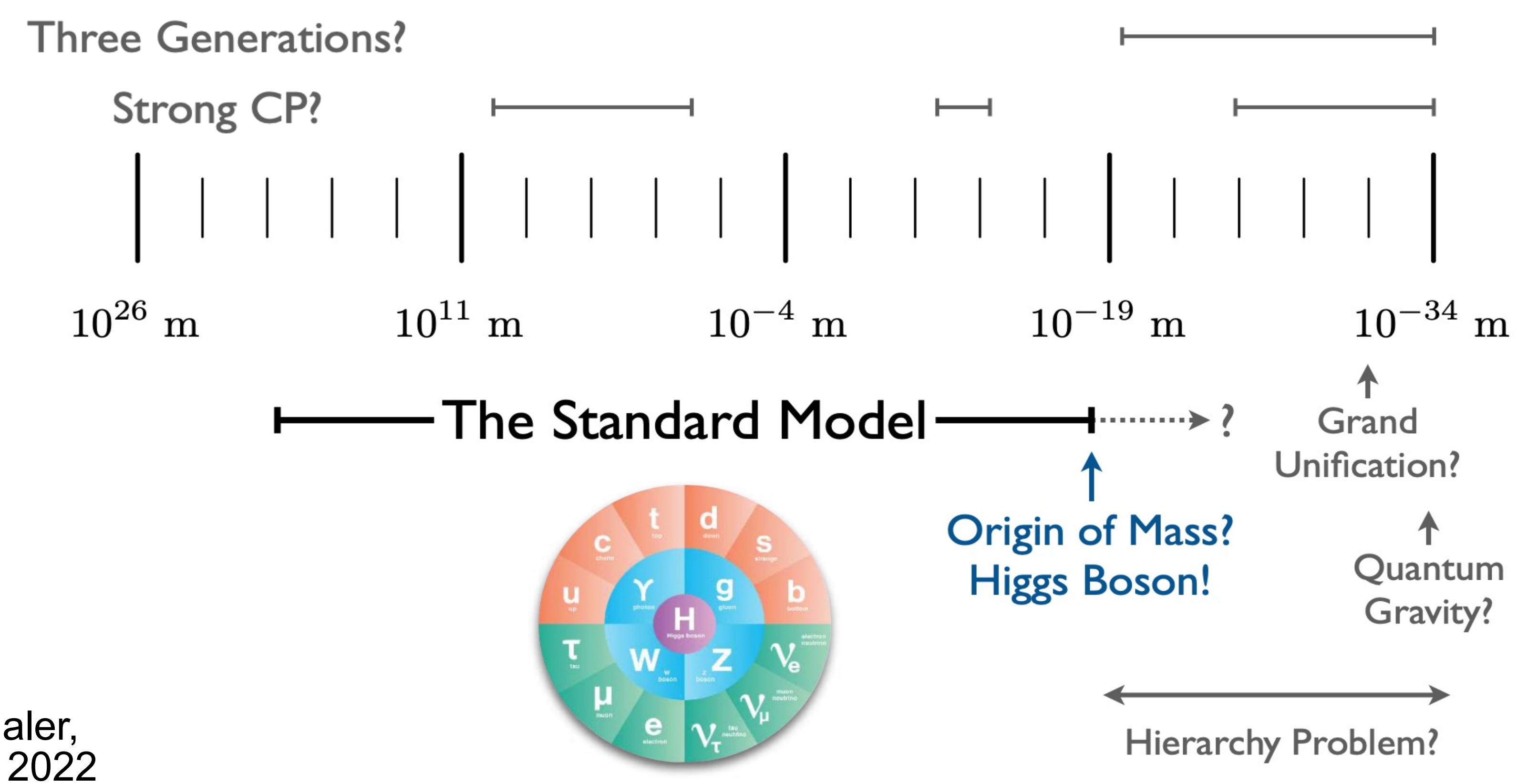
DALL-E-Mini
"a very ugly and
awkward old car"

DALL-E Mini
"too many clowns
in the clown car"
[the least creepy output]

*not completely distinct categories

Awkwardness/aesthetics issues...

- still quite a lot of parameters... where do they come from?
- why three families? what's the origin of flavor?
- "hierarchy problem"
- "strong CP problem"
  } fine-tuning issues
- energy scale where all forces are unified? [+gravity...]

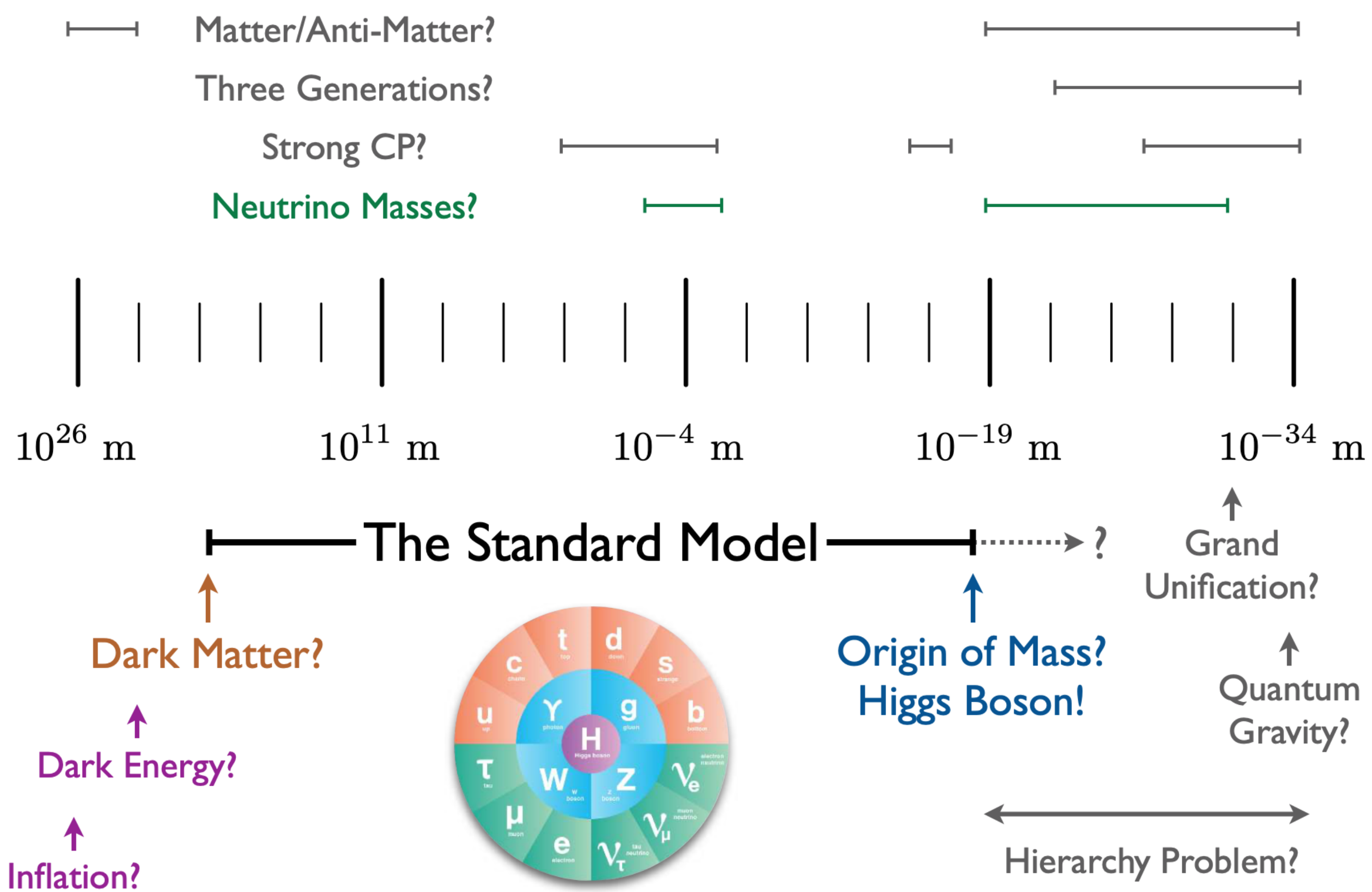


J. Thaler,
CSS 2022

There are some popular, testable solutions to some of these...

Major *observed* phenomena the SM fails to describe:

- neutrino mass and oscillations
- baryon asymmetry of the Universe
- dark matter
- dark energy
- acausal density fluctuations
- (quantum) gravity



J. Thaler, CSS 2022

Lots of ideas for these too!

...and yet... the SM has been irritatingly robust, so far*, against experimental tests in its domain of applicability**

DALL-E-Mini
"irritatingly robust
clown car"

*there are some chinks in the armor
**not a tautology... lots of testable BSM ideas in this domain

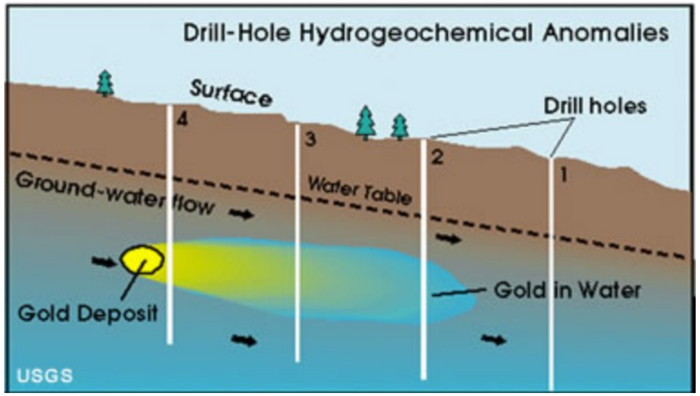
So, What are We Going to Do About This?

Think of the problem in terms of
puzzles and surprises!

BSM *has* to be there, somewhere...
we need to go prospecting for it!

Approaches

Keep looking!
improve the predictions and figure out the best places to look



Keep pushing on the precision!

Improve the tools!

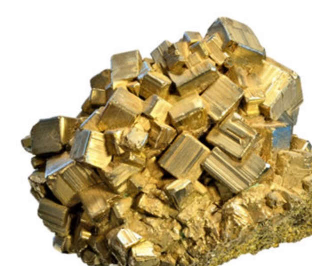
Pay Attention to Anomalies!

"Round about the accredited and orderly facts of every science there ever floats a sort of dust-cloud of exceptional observations, of occurrences minute and irregular and seldom met with, which it always proves more easy to ignore than to attend to... ***Anyone will renovate his science who will steadily look after the irregular phenomena, and when science is renewed, its new formulas often have more of the voice of the exceptions in them than of what were supposed to be the rules.****"*

William James, 19th century philosopher of science

Still true, but these days, we're all over the anomalies...

...need to watch out for fool's gold...



Now, some examples of exciting prospecting expeditions!

… [stealing heavily from Snowmass CSS!]

picking a few you'll hear about later in the school

- neutrinos
- dark matter
- Hubble tension
- flavor

Neutrino Mass and Oscillations

We know that neutrinos have mass because they change flavor

Flavor states related to mass states by a unitary mixing matrix

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} \mathrm{U}^*_{\mathrm{e}1} & \mathrm{U}^*_{\mathrm{e}2} & \mathrm{U}^*_{\mathrm{e}3} \\ \mathrm{U}^*_{\mu 1} & \mathrm{U}^*_{\mu 2} & \mathrm{U}^*_{\mu 3} \\ \mathrm{U}^*_{\tau 1} & \mathrm{U}^*_{\tau 2} & \mathrm{U}^*_{\tau 3} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

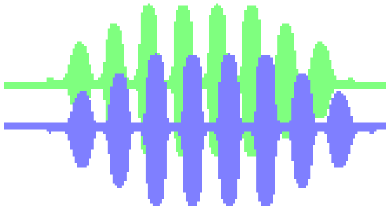
participate in weak interactions

unitary mixing matrix

eigenstates of free Hamiltonian

$$|\nu_f\rangle = \sum_{i=1}^{N} U^*_{fi} |\nu_i\rangle$$

If mixing matrix is not diagonal, get *flavor oscillations* as neutrinos propagate (essentially, interference between mass states)



The three-flavor neutrino paradigm

$$|\nu_f\rangle = \sum_{i=1}^{N} U_{fi}^{*} |\nu_i\rangle$$

Parameterize mixing matrix U as

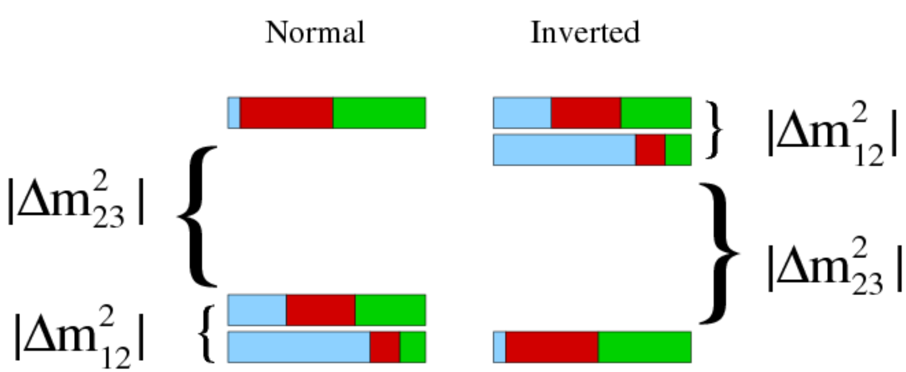
$$U = \begin{bmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{bmatrix} \begin{bmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{bmatrix} \begin{bmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

$$\times \begin{bmatrix} e^{i\alpha_1/2} & 0 & 0 \\ 0 & e^{i\alpha_2/2} & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

3 masses	m_1, m_2, m_3 (2 mass differences + absolute scale)
3 mixing angles	$\theta_{23}, \theta_{12}, \theta_{13}$
1 CP phase	δ
(2 Majorana phases)	α_1, α_2

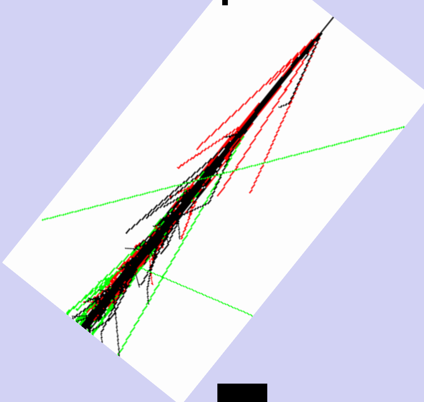
$$s_{ij} \equiv \sin\theta_{ij}, c_{ij} \equiv \cos\theta_{ij}$$

signs of the mass differences matter



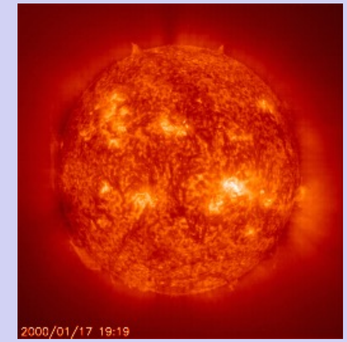
We now have clean flavor-transition signals in two 2-flavor sectors

atmospheric



signal with
“wild” neutrinos...

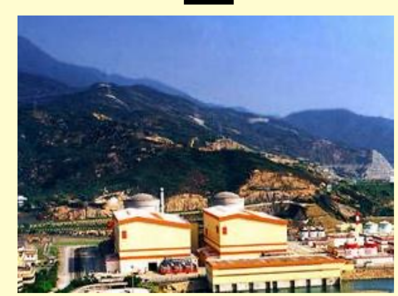
solar



$$
U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}
$$

beams

confirmed with
“tame” ones...



reactor

The three-flavor picture fits the data well

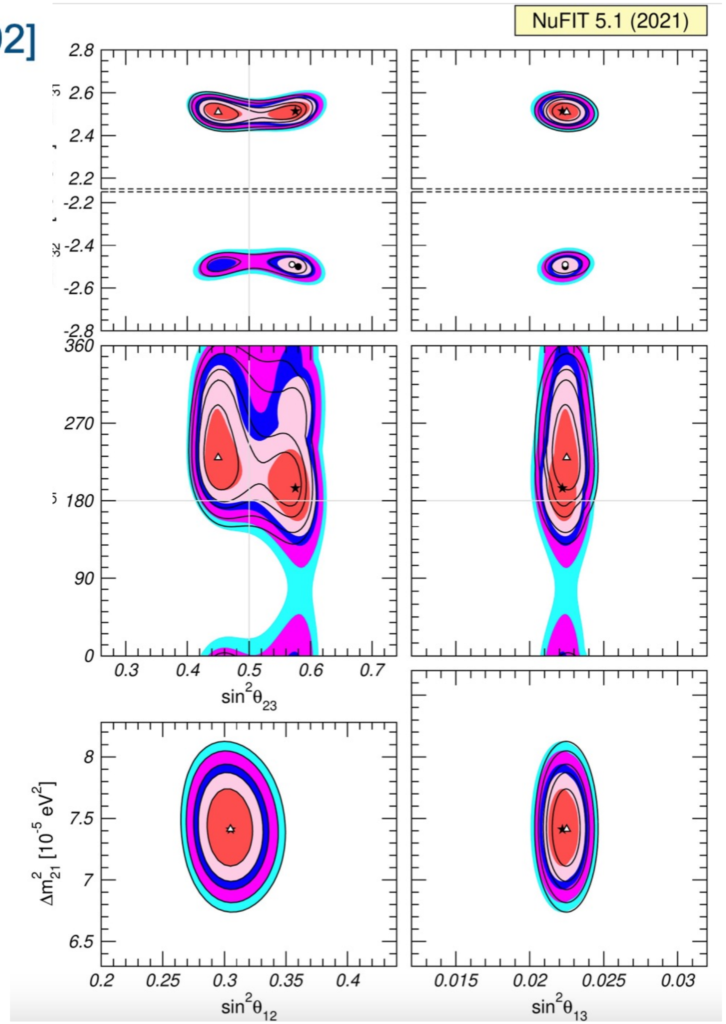
Global three-flavor fits to all data

Esteban, Gonzalez-Garcia, Maltoni, Schwetz, Zhou, JHEP'20 [2007.14792]

with SK atmospheric data

	Normal Ordering (best fit)		Inverted Ordering ($\Delta\chi^2 = 7.0$)	
	bfp $\pm 1\sigma$	3σ range	bfp $\pm 1\sigma$	3σ range
$\sin^2\theta_{12}$	$0.304^{+0.012}_{-0.012}$	$0.269 \to 0.343$	$0.304^{+0.013}_{-0.012}$	$0.269 \to 0.343$
$\theta_{12}/^\circ$	$33.45^{+0.77}_{-0.75}$	$31.27 \to 35.87$	$33.45^{+0.78}_{-0.75}$	$31.27 \to 35.87$
$\sin^2\theta_{23}$	$0.450^{+0.019}_{-0.016}$	$0.408 \to 0.603$	$0.570^{+0.016}_{-0.022}$	$0.410 \to 0.613$
$\theta_{23}/^\circ$	$42.1^{+1.1}_{-0.9}$	$39.7 \to 50.9$	$49.0^{+0.9}_{-1.3}$	$39.8 \to 51.6$
$\sin^2\theta_{13}$	$0.02246^{+0.00062}_{-0.00062}$	$0.02060 \to 0.02435$	$0.02241^{+0.00074}_{-0.00062}$	$0.02055 \to 0.02457$
$\theta_{13}/^\circ$	$8.62^{+0.12}_{-0.12}$	$8.25 \to 8.98$	$8.61^{+0.14}_{-0.12}$	$8.24 \to 9.02$
$\delta_{CP}/^\circ$	230^{+36}_{-25}	$144 \to 350$	278^{+22}_{-30}	$194 \to 345$
$\frac{\Delta m^2_{21}}{10^{-5}\ \mathrm{eV}^2}$	$7.42^{+0.21}_{-0.20}$	$6.82 \to 8.04$	$7.42^{+0.21}_{-0.20}$	$6.82 \to 8.04$
$\frac{\Delta m^2_{3\ell}}{10^{-3}\ \mathrm{eV}^2}$	$+2.510^{+0.027}_{-0.027}$	$+2.430 \to +2.593$	$-2.490^{+0.026}_{-0.028}$	$-2.574 \to -2.410$

$$\Delta m^2_{3\ell} \equiv \Delta m^2_{31} > 0 \text{ for NO and } \Delta m^2_{3\ell} \equiv \Delta m^2_{32} < 0 \text{ for IO.}$$



Esteban et al., arXiv:2007.14792, 10.1007/JHEP09(2020)178

What do we *not* know about the three-flavor paradigm?

Esteban, Gonzalez-Garcia, Maltoni, Schwetz, Zhou, JHEP'20 [2007.14792]

with SK atmospheric data

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Is θ_{23} non-negligibly greater or smaller than 45 deg?

What do we *not* know about the three-flavor paradigm?

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sign of Δm^2 unknown (ordering of masses)

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Esteban, Gonzalez-Garcia, Maltoni, Schwetz, Zhou, JHEP'20 [2007.14792]

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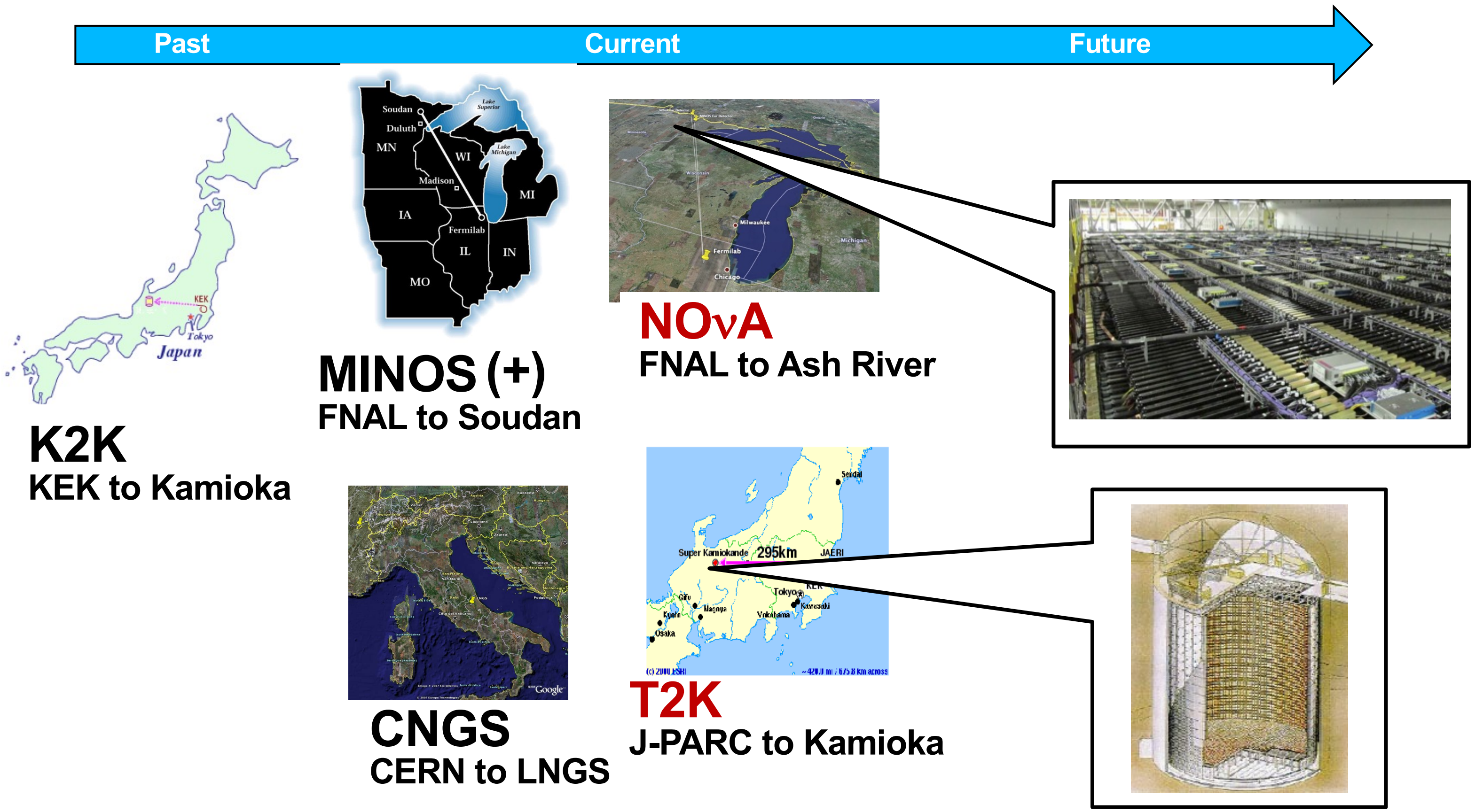
Is θ_{23} non-negligibly greater or smaller than 45 deg?

poor knowledge*

sign of Δm^2 unknown (ordering of masses)

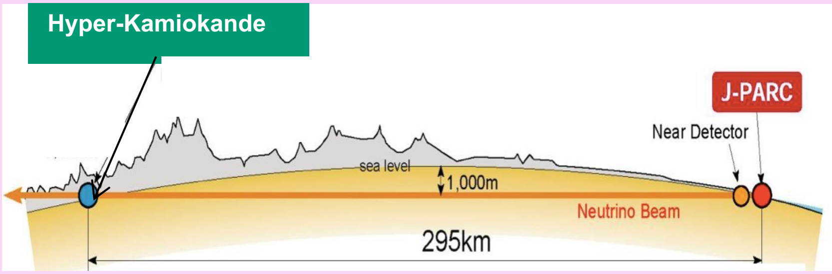
**maybe* related to baryon asymmetry of the Universe?

Long-baseline neutrino oscillation experiments
will address these questions

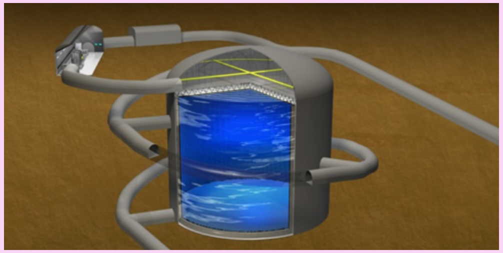


Next-generation long-baseline beam experiments

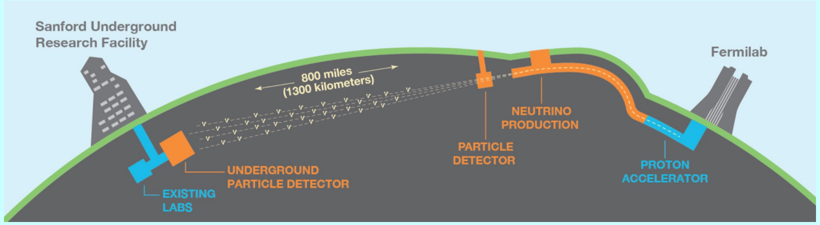
Hyper-Kamiokande



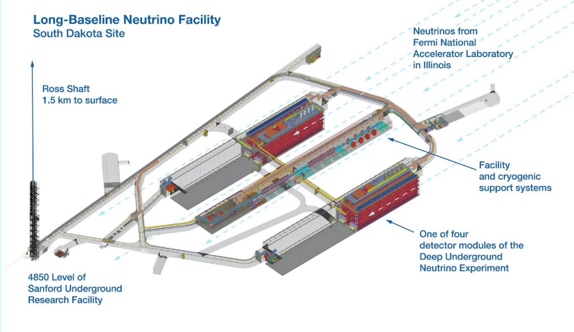
- 295-km baseline
- 260k (188k) ton mass water Cherenkov detector
- First data in 2027



DUNE/LBNF

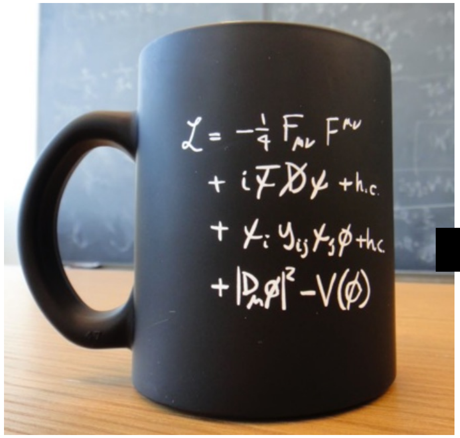


- 1300-km baseline
- 4 10-kton LArTPC modules
- 4850-ft depth
- Phase 2 "Module of Opportunity" for 3&4



Multi-purpose detectors, broad physics programs in both cases, including astrophysical neutrinos (over a range of energies)

Neutrino mass is zero in the SM...



not for neutrinos

From André de Gouvêa

Standard Model in One Slide, No Equations

The SM is a quantum field theory with the following defining characteristics:

- Gauge Group $(SU(3)_c \times SU(2)_{\rm L} \times U(1)_{\rm Y})$;
- Particle Content (fermions: Q, u, d, L, e, scalars: H).

Once this is specified, the SM is unambiguously determined:

- Most General Renormalizable Lagrangian;
- Measure All Free Parameters, and You Are Done! (after several decades of hard experimental work...)

If you follow these rules, neutrinos have no mass. Something has to give.

From André de Gouvêa

Neutrino Masses, EWSB, and a New Mass Scale of Nature

The LHC has revealed that the minimum SM prescription for electroweak symmetry breaking — the one Higgs double model — is at least approximately correct. What does that have to do with neutrinos?

The tiny neutrino masses point to three different possibilities.

1. Neutrinos talk to the Higgs boson very, very **weakly** (Dirac neutrinos);
2. Neutrinos talk to a **different Higgs** boson – there is a new source of electroweak symmetry breaking! (Majorana neutrinos);
3. Neutrino masses are small because there is **another source of mass** out there — a new energy scale indirectly responsible for the tiny neutrino masses, a la the seesaw mechanism (Majorana neutrinos).

Searches for $0\nu\beta\beta$ help tell (1) from (2) and (3), the LHC, charged-lepton flavor violation, *et al* may provide more information.

Need more experimental information!

Are neutrinos Majorana or Dirac?

$\nu = \bar{\nu}$ 2 states	$\nu \neq \bar{\nu}$ 4 states
$(\nu_L \leftarrow \text{CPT} \rightarrow \bar{\nu}_R)$	$(\nu_L \leftarrow \text{CPT} \rightarrow \bar{\nu}_R)$
$\updownarrow$ Lorentz	$\updownarrow$ Lorentz
$(\bar{\nu}_R \leftarrow \text{CPT} \rightarrow \nu_L)$	$(\nu_R \leftarrow \text{CPT} \rightarrow \bar{\nu}_L)$

Need to know this to know how to describe neutrino mass

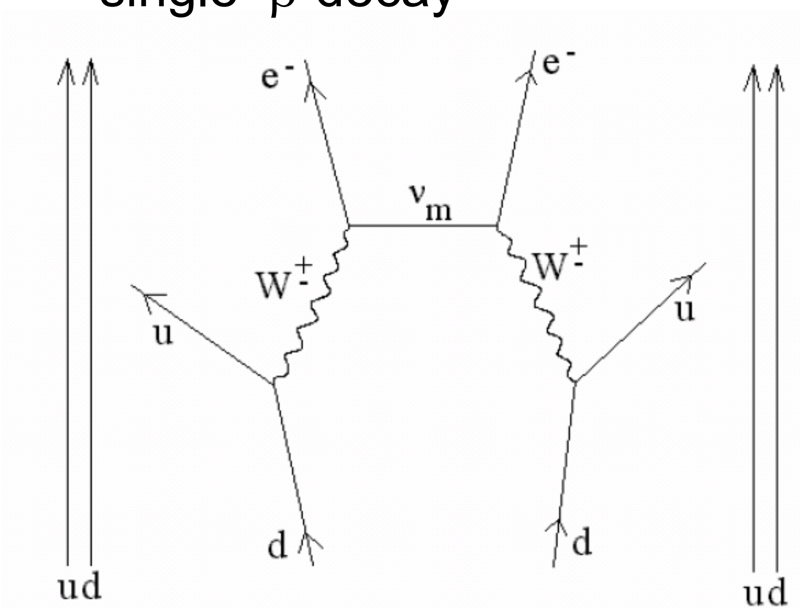
e.g. "see-saw" mechanism $\Rightarrow$ Majorana ν
... may be helpful also for leptogenesis...

How can we tell if neutrinos are Majorana or Dirac?

Best (only?) experimental strategy: look for

neutrinoless double beta decay

in isotopes for which it is energetically possible and which don't single β-decay



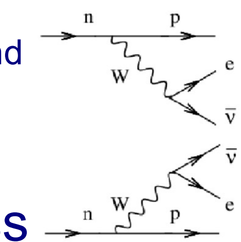
Only possible for Majorana ν

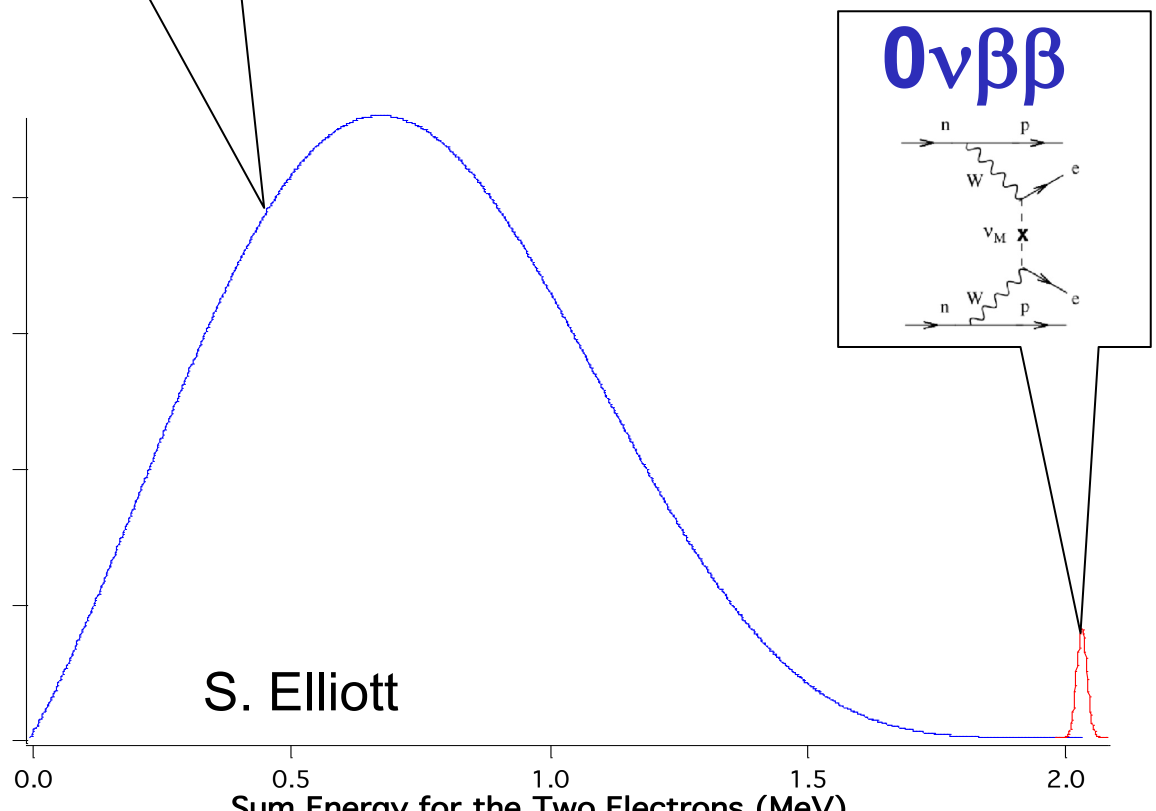
(...or exotic physics)

$$(T^{0\nu}_{1/2})^{-1} = G^{0\nu} \cdot |M^{0\nu}|^2 \cdot \langle m_{\beta\beta} \rangle^2$$

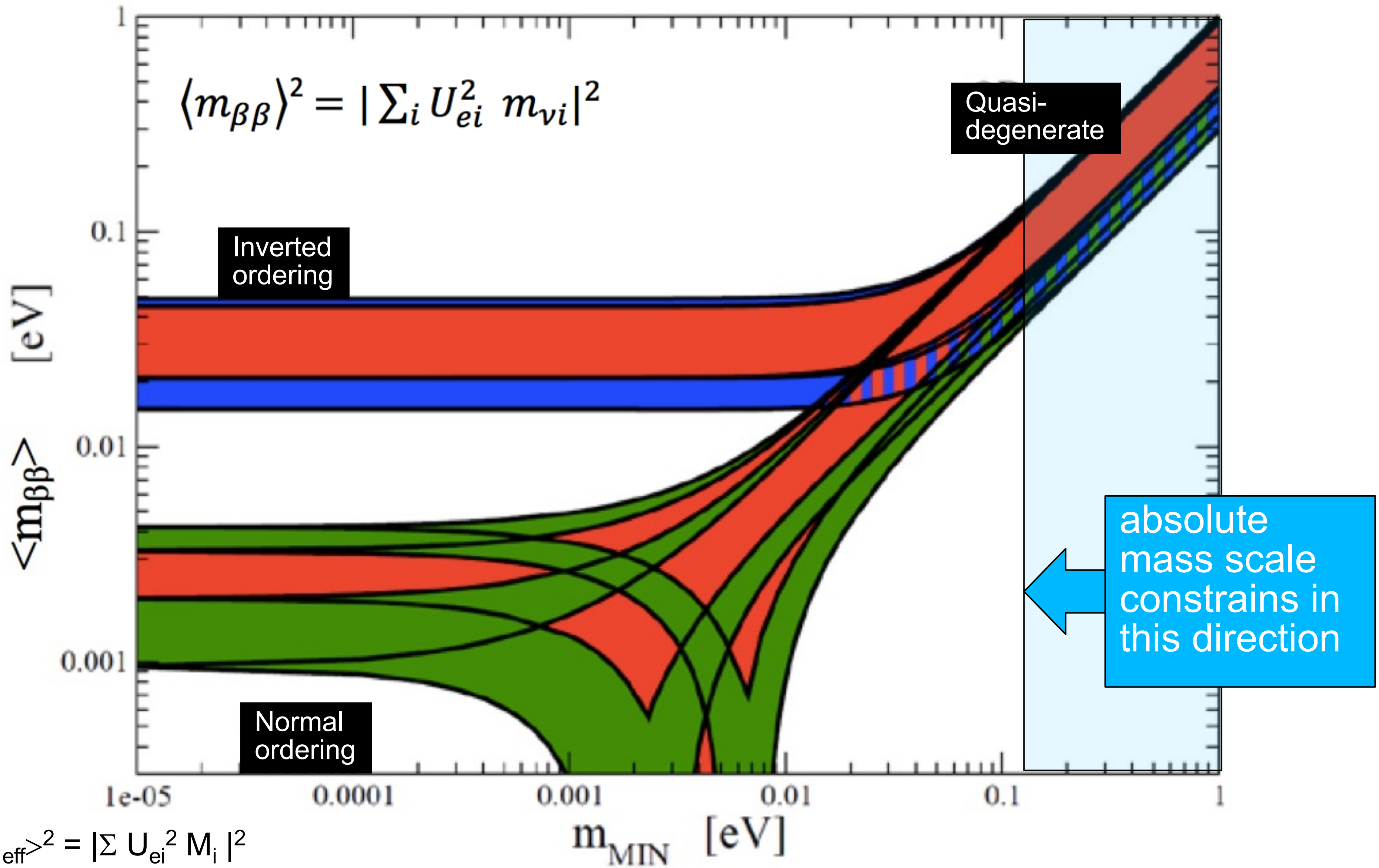
Observable: peak in the two-electron spectrum corresponding to ν-less final state

2νββ (SM 2nd order weak process)





The NLDBD T-Shirt Plot



$\langle M_{eff}\rangle^2 = |\Sigma\, U_{ei}^2\, M_i\,|^2$

***If* neutrinos are Majorana, experimental results must fall in the shaded regions**

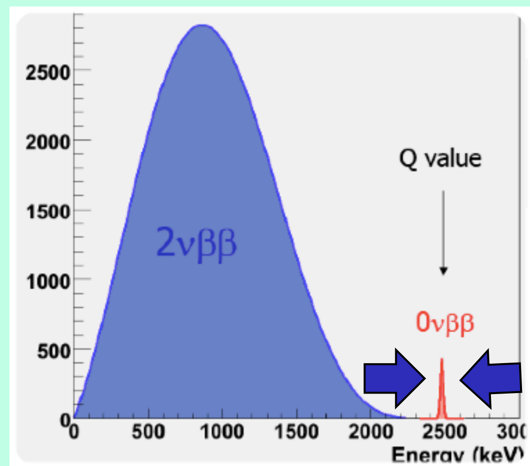
Extent of the regions determined by uncertainties on Majorana phases and mixing matrix elements

General NLDBD experiment strategies

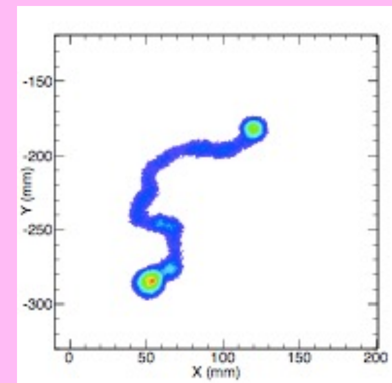
$$T_{1/2} > \frac{\ln 2 \ \varepsilon \cdot N_{source} \cdot T}{UL(B(T) \cdot \Delta E)}$$

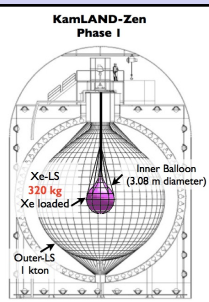
The "Brute Force" Approach

The "Peak-Squeezer" Approach

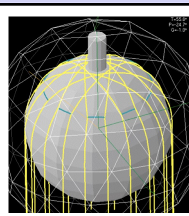


The "Final-State Judgement" Approach

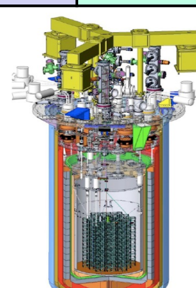




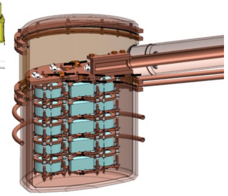
KamLAND-Zen (^{136}Xe)



SNO+ (^{130}Te)

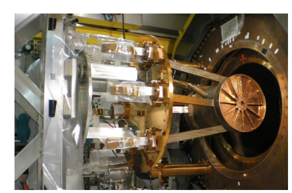


CUORICINO/ CUORE (^{130}Te)

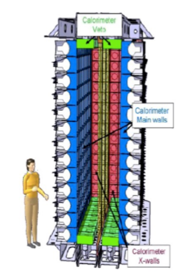


MAJORANA (^{76}Ge)

GERDA (^{76}Ge)



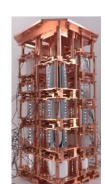
EXO (^{136}Xe)



NEMO/ SuperNEMO (various/^{82}Se)

CUPID (^{82}Se)

CUPID -Mo (^{100}Mo)



AMORE (^{100}Mo)

General NLDBD experiment strategies

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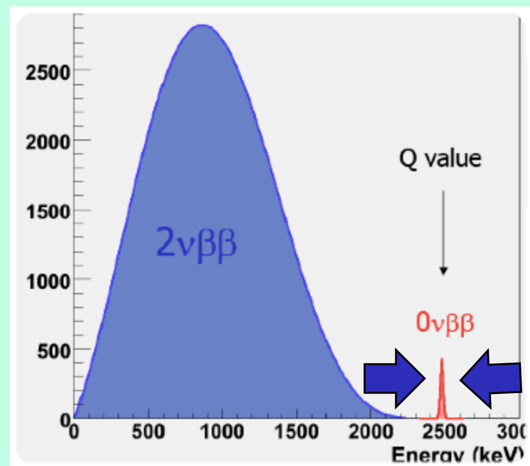
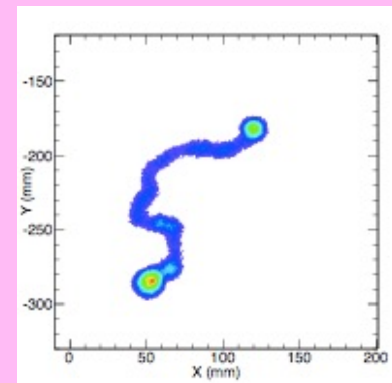
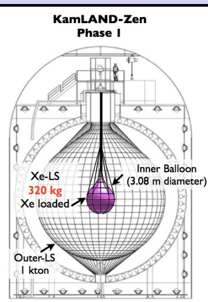
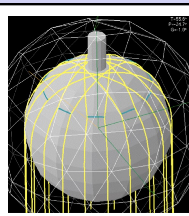
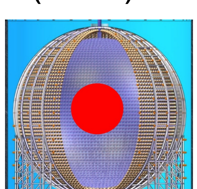
		



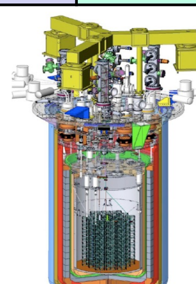
KamLAND-Zen (^{136}Xe)



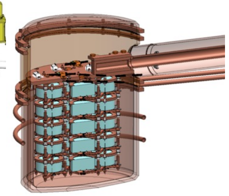
SNO+ (^{130}Te)



JUNO-ββ (^{136}Xe, ^{130}Te)



CUORICINO/ CUORE (^{130}Te)

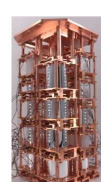


MAJORANA (^{76}Ge)

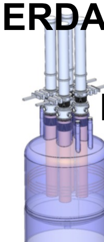
CUPID (^{82}Se)

CUPID -Mo (^{100}Mo)

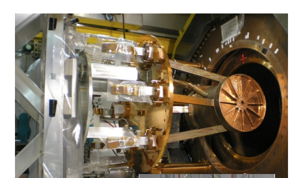
GERDA (^{76}Ge)

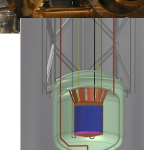


AMORE (^{100}Mo)

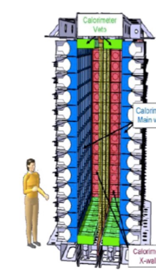


LEGEND (^{76}Ge)

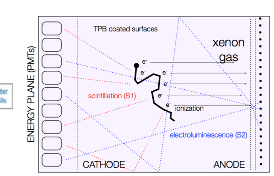




EXO /nEXO (^{136}Xe)



NEMO/ SuperNEMO (various/^{82}Se)

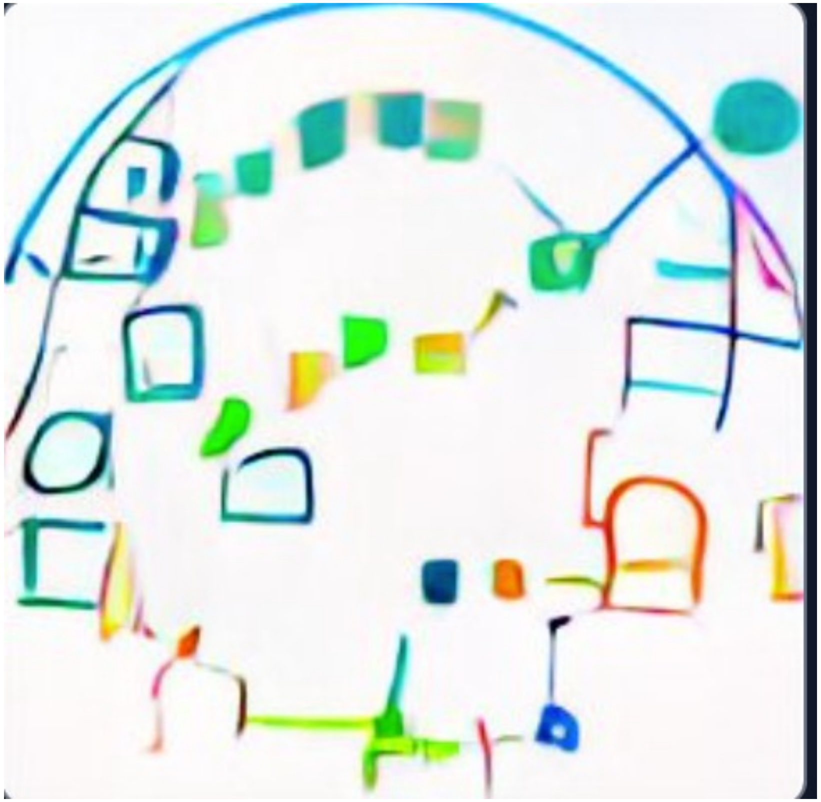


NEXT (^{136}Xe)

+more future ideas...

All this is in the context of the 3-flavor paradigm...

There are already some slightly uncomfortable data that **don’t fit this paradigm**...
(but don't really hang together in any consistent model)

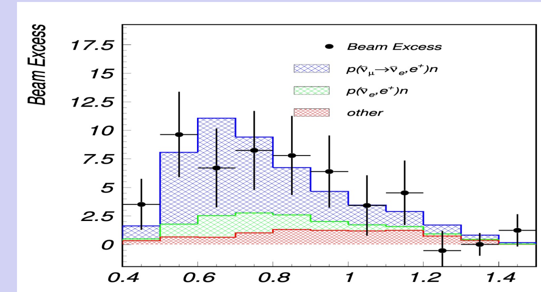


DALL-E-Mini
"uncomfortable data"

Anomalies in neutrino physics...

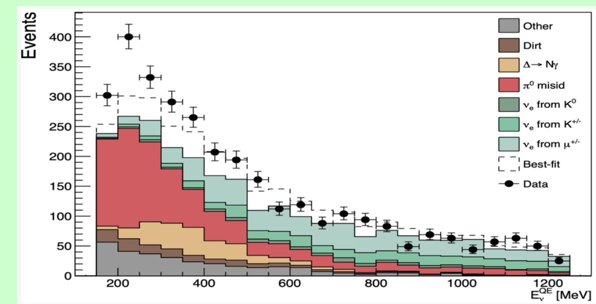
LSND @ LANL (~30 MeV, 30 m)

Excess of $\overline{\nu}_e$ interpreted as $\bar{\nu}_\mu \longrightarrow \bar{\nu}_e$



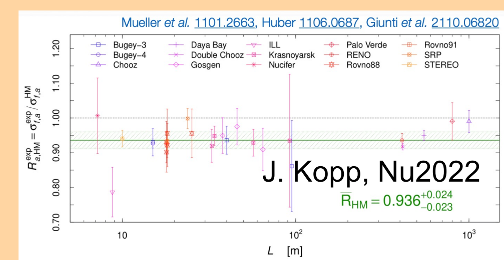
MiniBooNE @ FNAL ($\nu,\overline{\nu}$ ~1 GeV, 0.5 km)

- unexplained >3 σ excess for E < 475 MeV in neutrinos
  "low-energy excess" inconsistent w/ LSND oscillation
- no excess for E > 475 MeV in neutrinos
  (inconsistent w/ LSND oscillation)
- small excess for E < 475 MeV in antinus



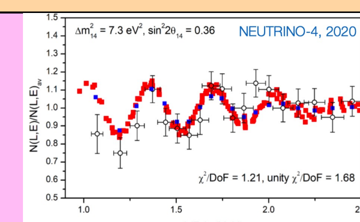
"Reactor flux anomaly"

deficit of reactor antinue absolute flux
wrt calculation [resolved?]



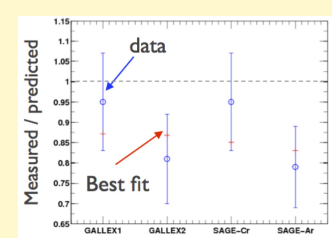
"Reactor spectral anomaly"

a wiggle, but in only one expt...



"Gallium anomaly"

~3σ deficit of nue flux from 51-Cr source in Ga



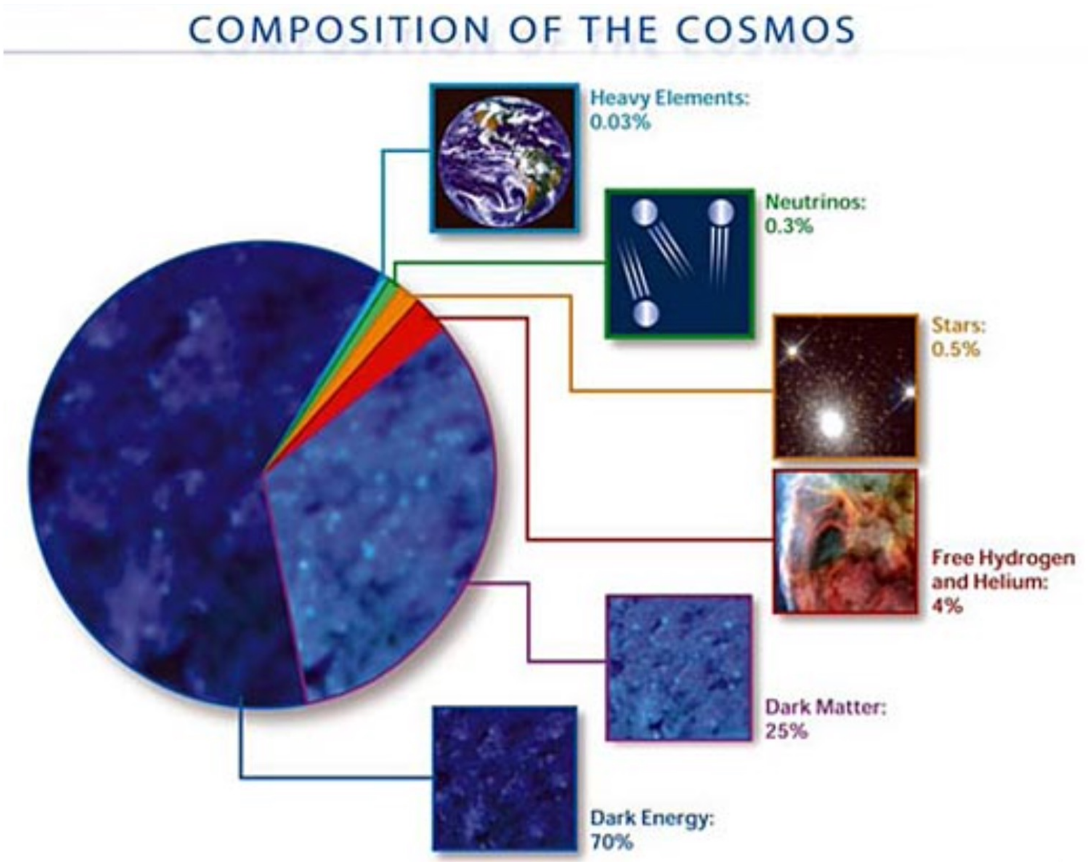
New states? Other new physics?

We should continue to listen
to the "voice of the exceptions"...

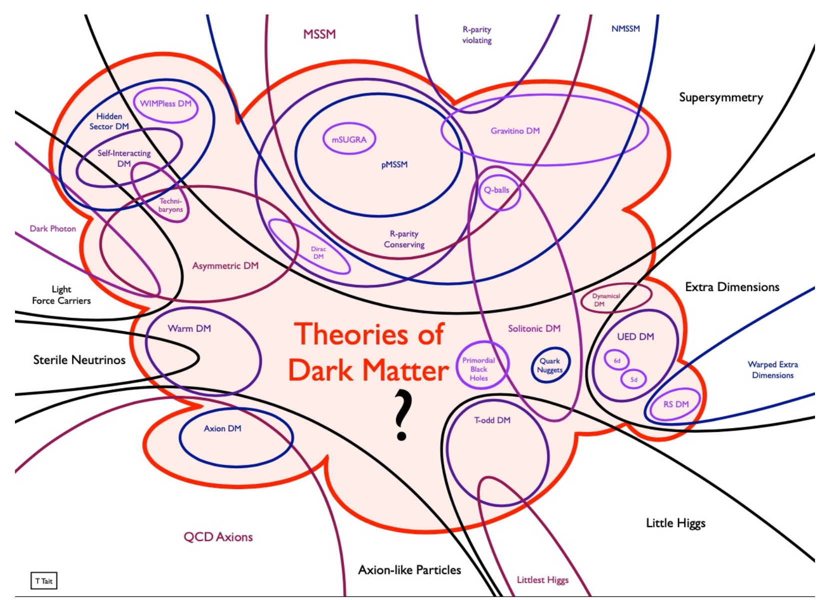
Nuggets or fool's gold?

Need more data...!

Next example... **Dark Matter**

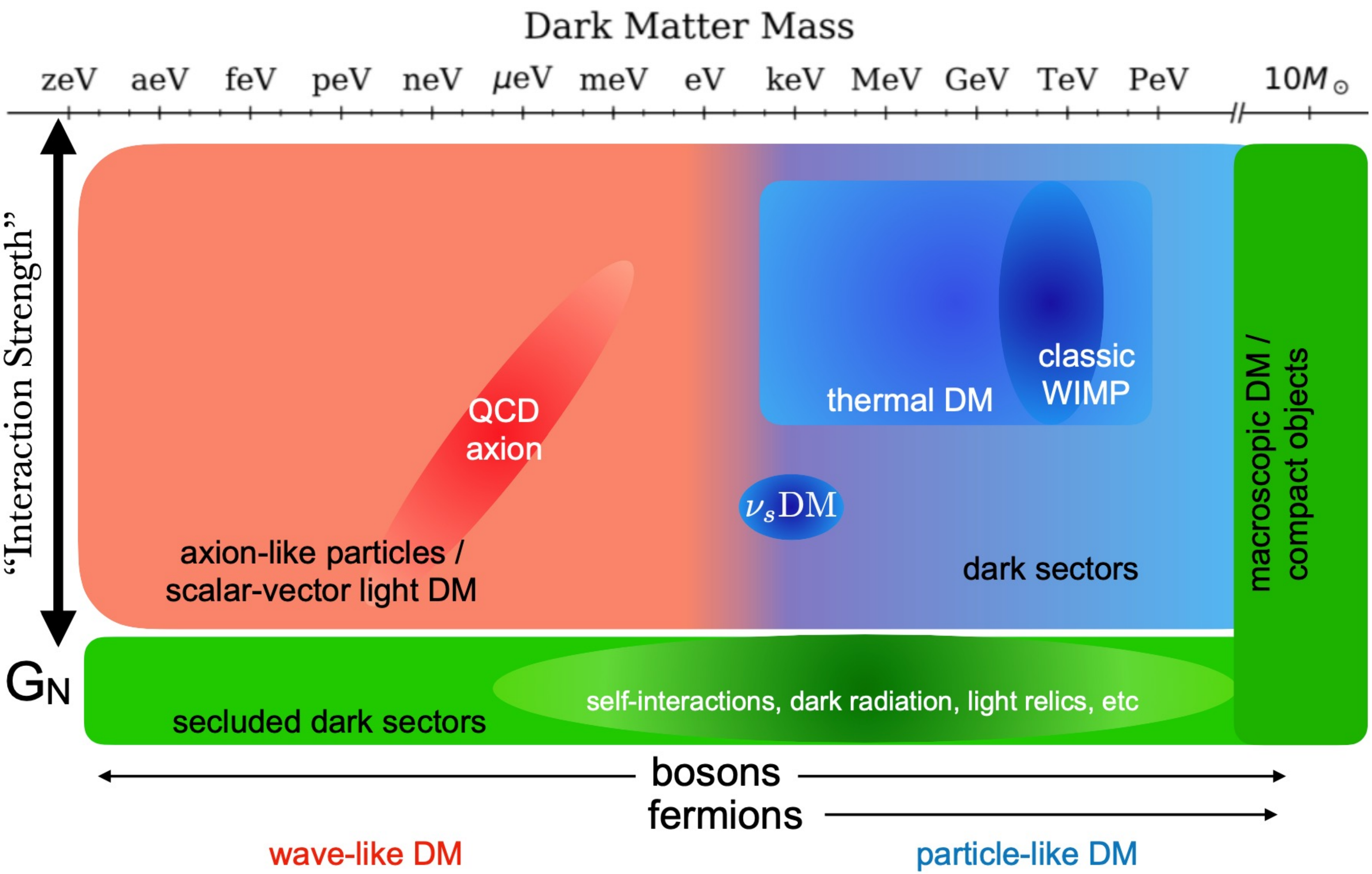


There is definitely extra stuff out there that interacts gravitationally... what is it?



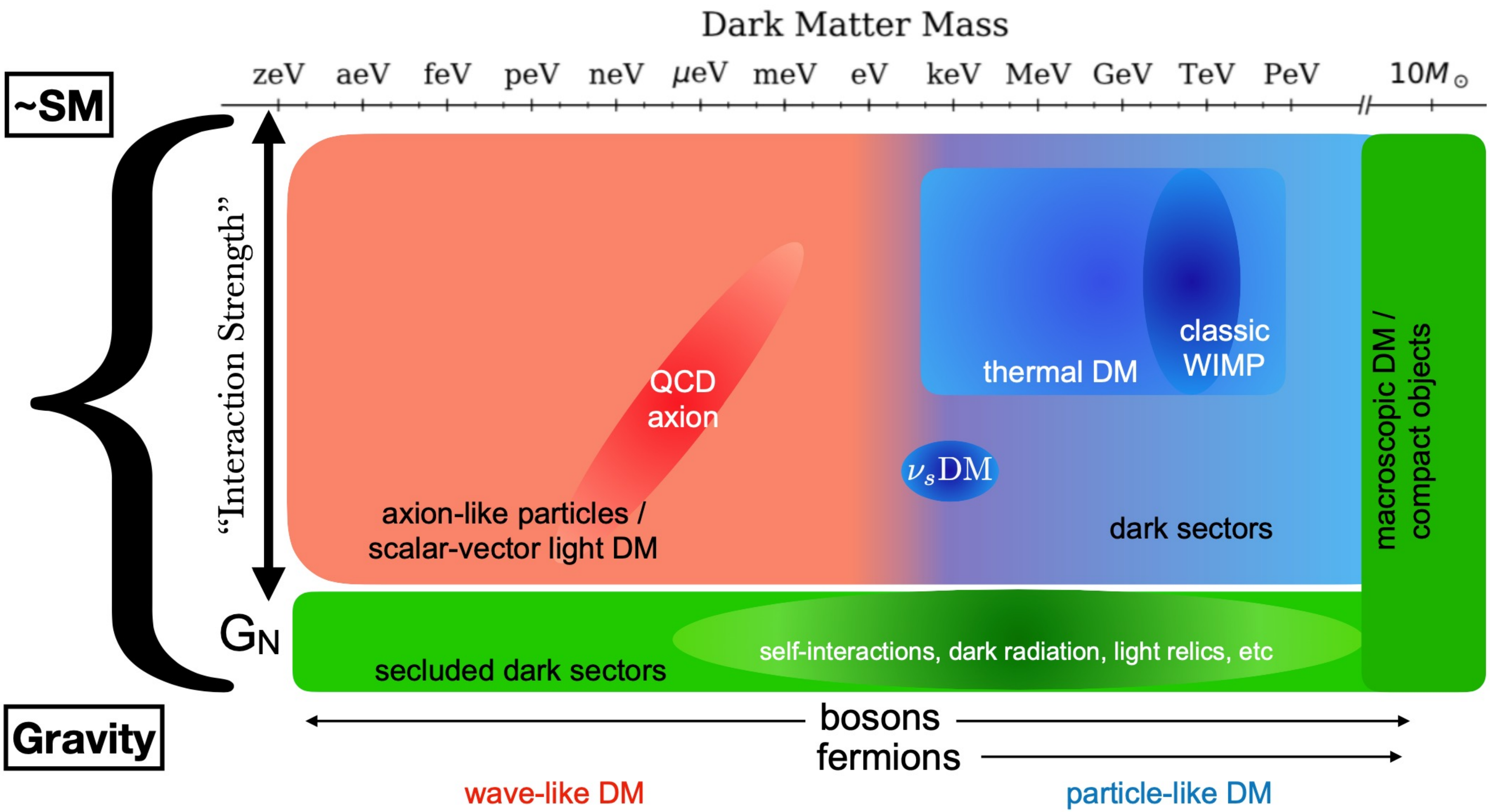
Many, many ideas for what this is...

Aaron Chou, CSS



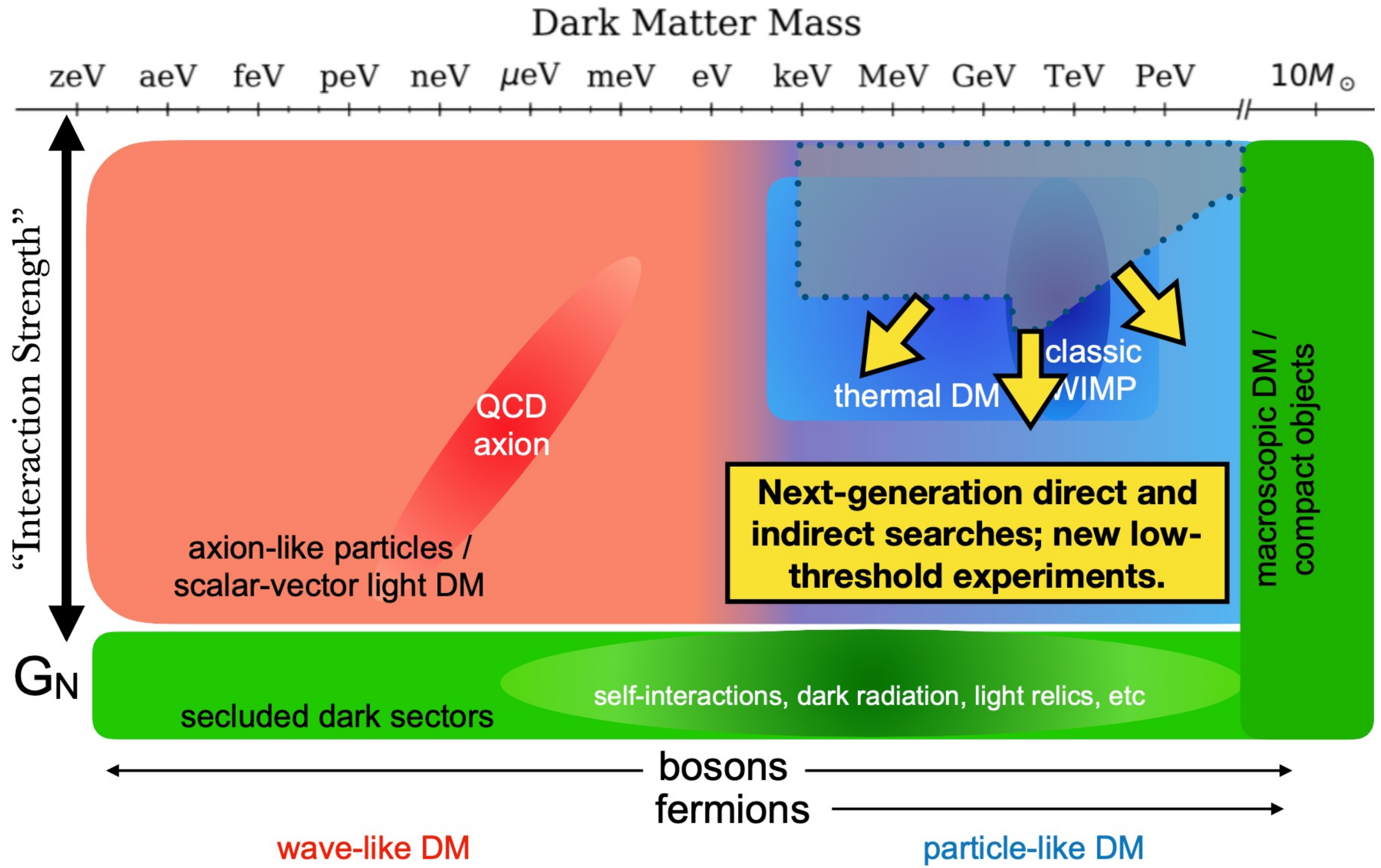
Aaron Chou, CSS

Possible interaction strengths range from the scale of the standard model to the scale of gravity



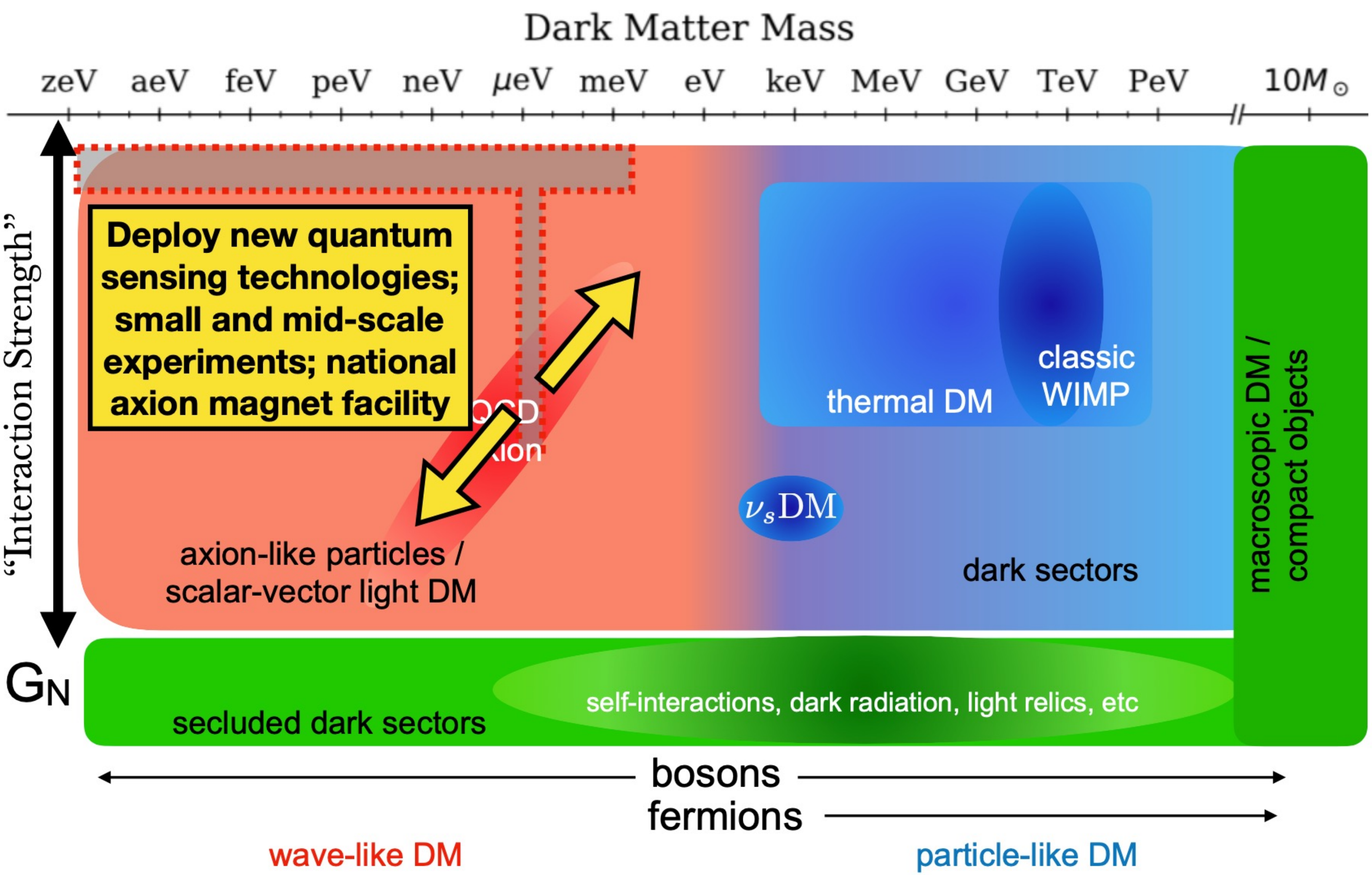
Aaron Chou, CSS

Above ~1 eV, use sensitive detectors to search for the scattering, absorption, decay, and annihilation of particle DM



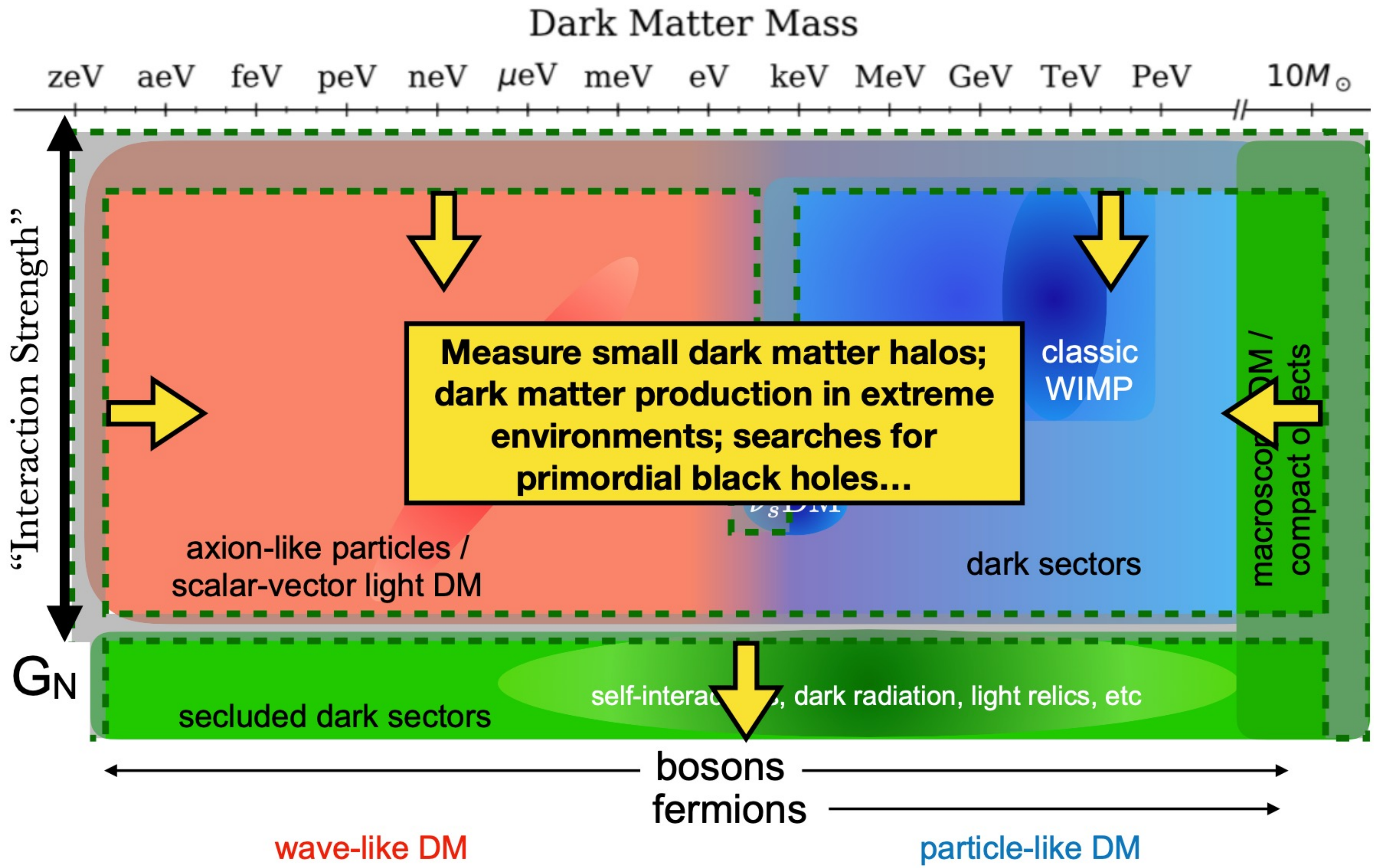
Aaron Chou, CSS

Below ~1 eV, use quantum sensing techniques to detect feeble forces exerted by wave-like DM.



Aaron Chou, CSS

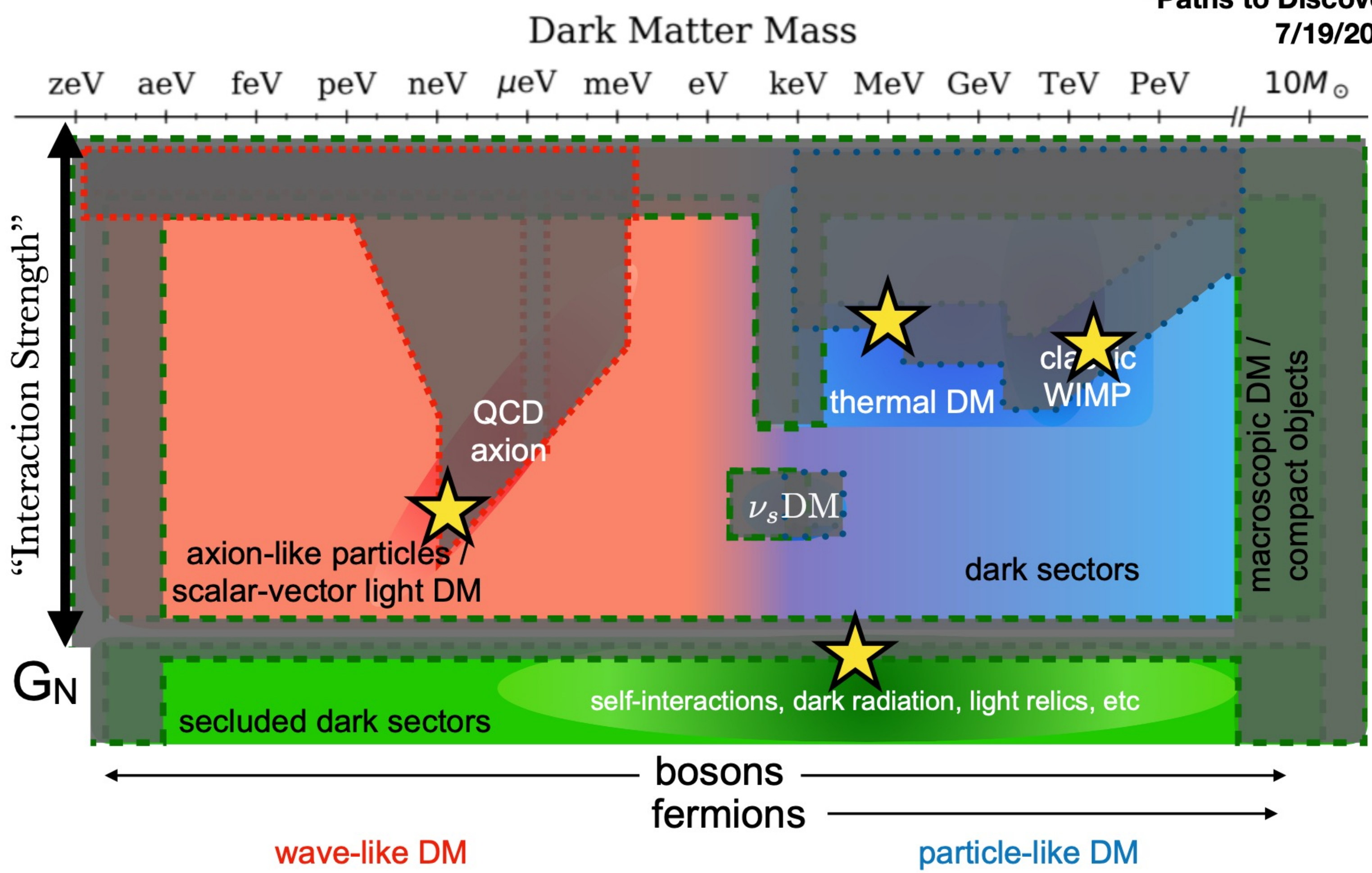
Cosmic probes from telescopes can detect DM interactions in extreme environments and through gravity alone.



Aaron Chou, CSS

Or multiple discoveries in a rich dark sector!!!

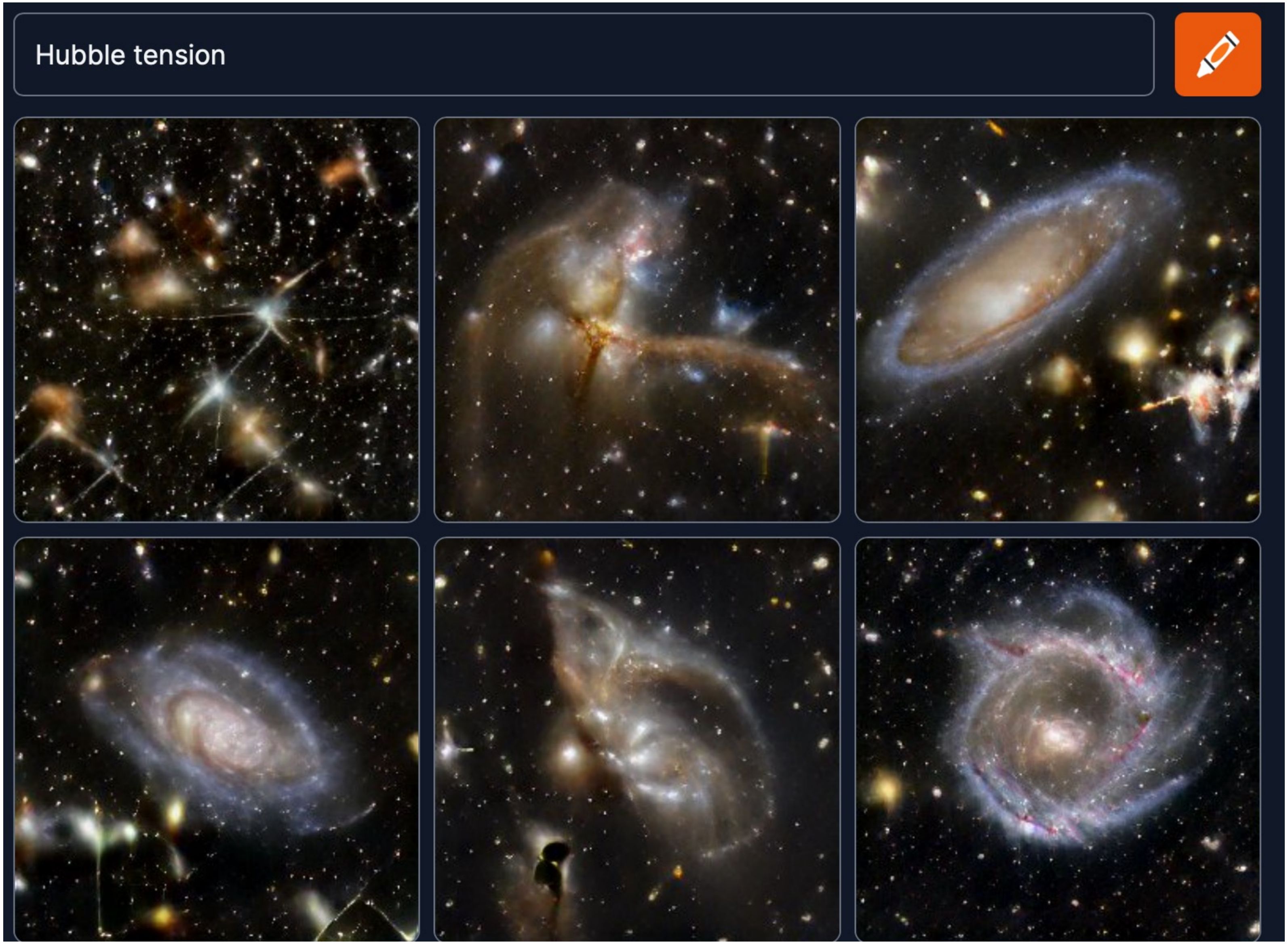
cf. Tracy Slatyer and Risa Wechsler's talks from "Paths to Discovery" Session 7/19/2022



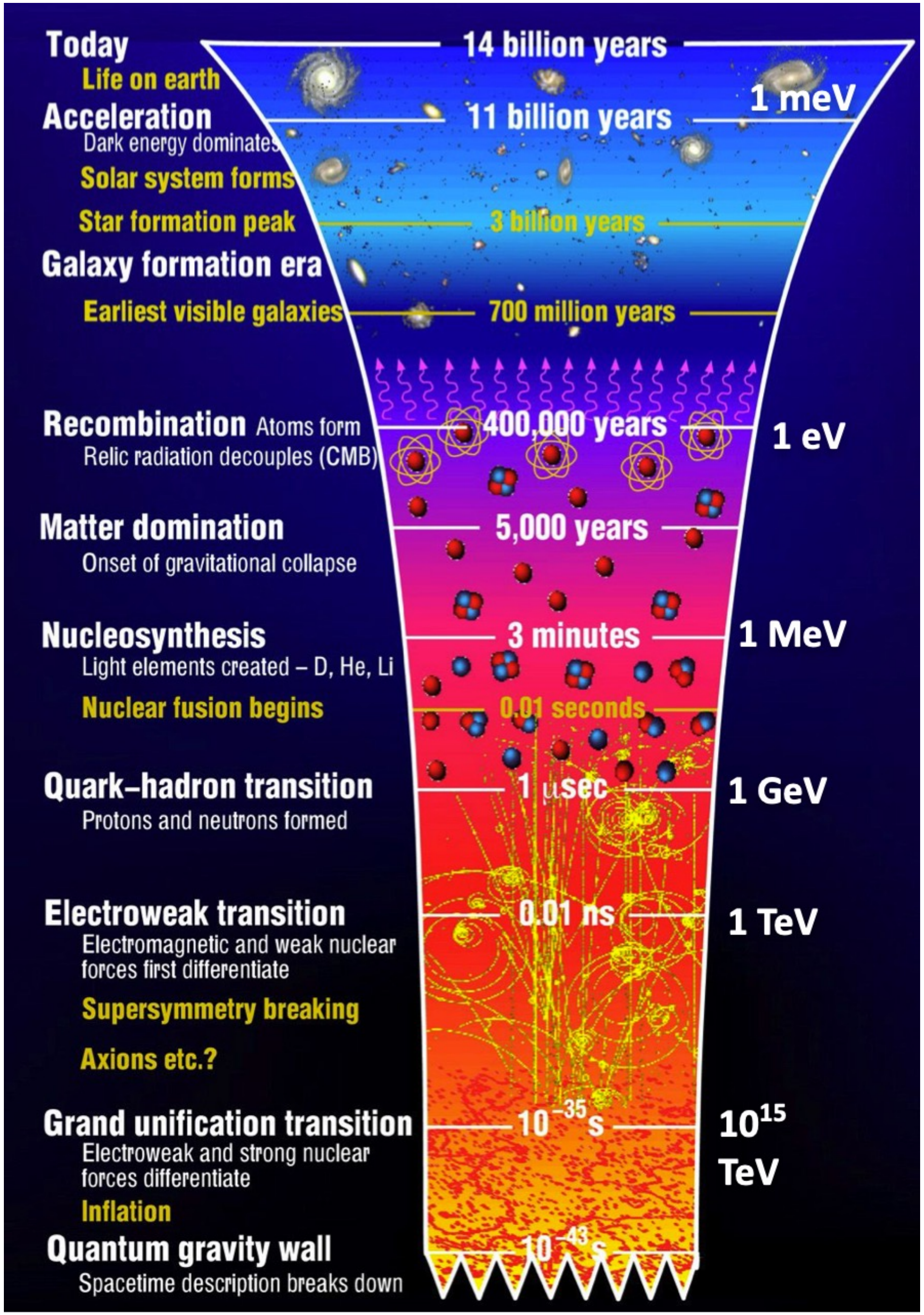
Delve Deep, Search Wide!

include complementary dark sector searches at colliders/beams!

Next example: **Hubble Tension**



A different "Standard Model" in cosmology



ΛCDM model

6 independent parameters
+ additional fixed parameters
+ GR

Observables:

- Cosmic microwave bg
- Large-scale structure
- Accelerating expansion (SNae,etc.)
- Abundances of light elements

Cosmologists are grumpy about this model too...

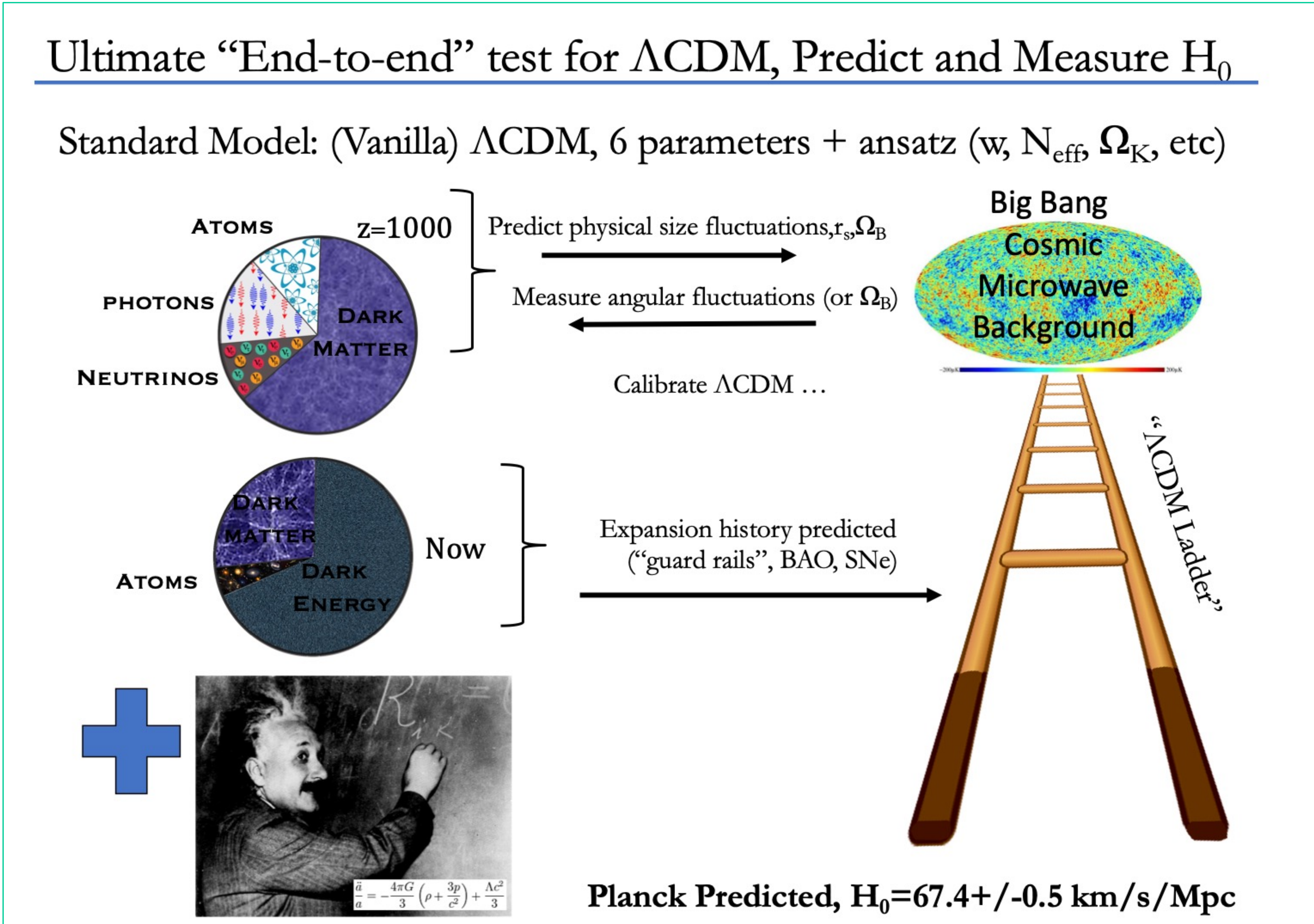
(for maybe different reasons?)

Planck Collaboration Cosmological parameters[85]

	Description	Symbol	Value-2015[86]	Value-2018[87]
Independent parameters	Physical baryon density parameter[a]	$\Omega_b h^2$	0.022 30 ±0.000 14	0.0224 ±0.0001
	Physical dark matter density parameter[a]	$\Omega_c h^2$	0.1188 ±0.0010	0.120 ±0.001
	Age of the universe	t_0	$13.799 \pm 0.021 \times 10^9$ years	$13.787 \pm 0.020 \times 10^9$ years[90]
	Scalar spectral index	n_s	0.9667 ±0.0040	0.965 ±0.004
	Curvature fluctuation amplitude, $k_0 = 0.002\ \mathrm{Mpc}^{-1}$	Δ_R^2	$2.441^{+0.088}_{-0.092} \times 10^{-9}$[91]	?
	Reionization optical depth	τ	0.066 ±0.012	0.054 ±0.007
Fixed parameters	Total density parameter[b]	Ω_{tot}	1	?
	Equation of state of dark energy	w	–1	$w_0 = -1.03 \pm 0.03$
	Tensor/scalar ratio	r	0	$r_{0.002} < 0.06$
	Running of spectral index	$dn_s/d\ln k$	0	?
	Sum of three neutrino masses	$\sum m_\nu$	0.06 eV/c^2[c][84]:40	0.12 eV/c^2
	Effective number of relativistic degrees of freedom	N_{eff}	3.046[d][84]:47	2.99 ±0.17
Calculated values	Hubble constant	H_0	67.74 ± 0.46 km s^{-1} Mpc^{-1}	67.4 ± 0.5 km s^{-1} Mpc^{-1}
	Baryon density parameter[b]	Ω_b	0.0486 ±0.0010[e]	?
	Dark matter density parameter[b]	Ω_c	0.2589 ±0.0057[f]	?
	Matter density parameter[b]	Ω_m	0.3089 ±0.0062	0.315 ±0.007
	Dark energy density parameter[b]	Ω_Λ	0.6911 ±0.0062	0.6847 ±0.0073
	Critical density	ρ_{crit}	$(8.62 \pm 0.12) \times 10^{-27}$ kg/m^3[g]	?
	The present root-mean-square matter fluctuation averaged over a sphere of radius $8h^{-1}$ Mpc	σ_8	0.8159 ±0.0086	0.811 ±0.006
	Redshift at decoupling	z_*	1 089.90 ±0.23	1 089.80 ±0.21
	Age at decoupling	t_*	377 700 ±3200 years[91]	?
	Redshift of reionization (with uniform prior)	z_{re}	$8.5^{+1.0}_{-1.1}$[92]	7.68 ±0.79

"Hubble Tension"

A. Riess, PPC2022



Cosmology Intertwined: A Review of the Particle Physics,
Astrophysics, and Cosmology Associated with the Cosmological Tensions and Anomalies
arXiv:2203.06142v3

CMB with Planck

CMB without Planck

No CMB, with BBN

CMB lensing

LSS t_{eq} standard ruler

SNIa- Cepheid

SNIa- TRGB

SNIa- Miras

SBF

SNII

Masers

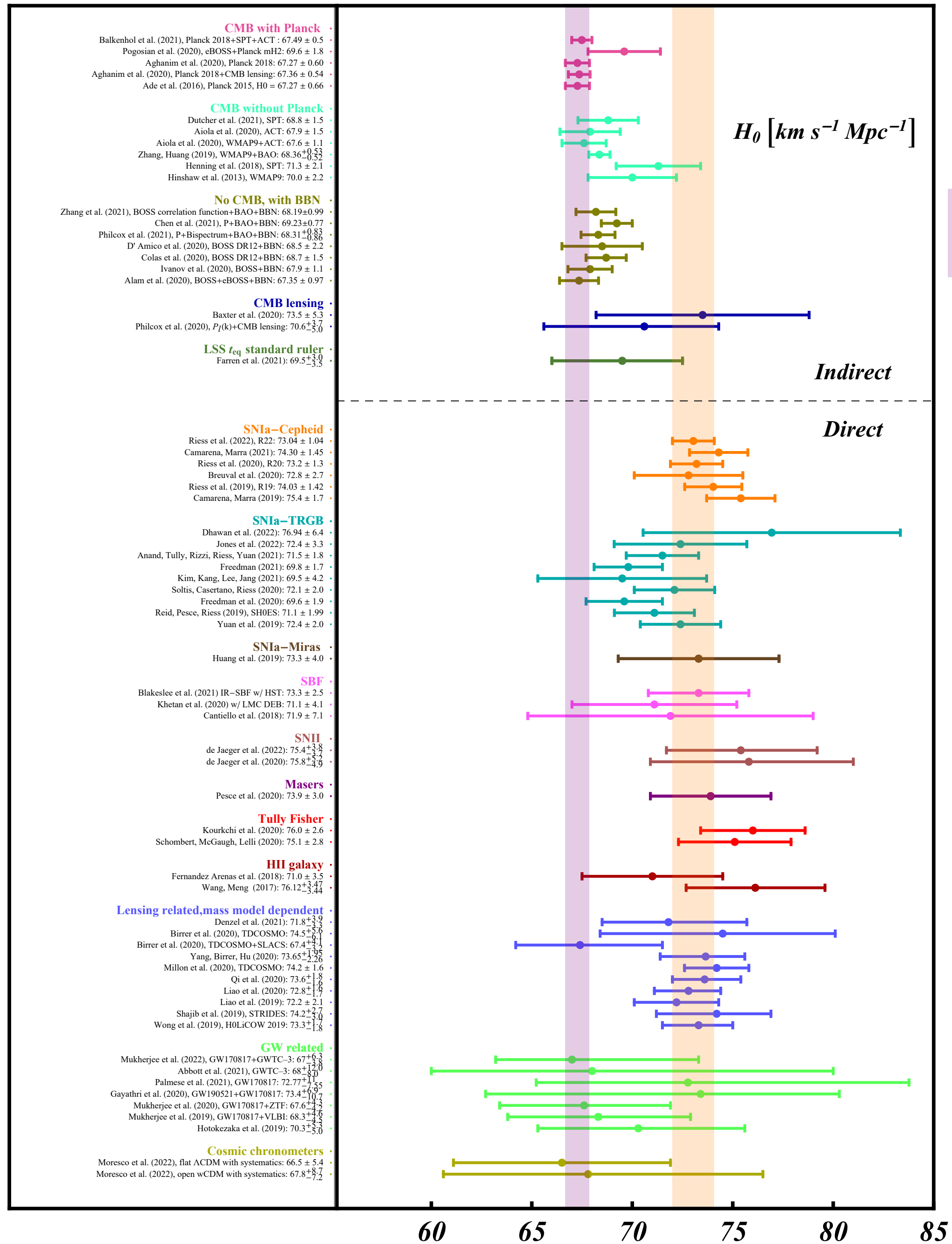
Tully Fisher

HII galaxy

Lensing related,
mass model dependent

GW related

Cosmic chronometers



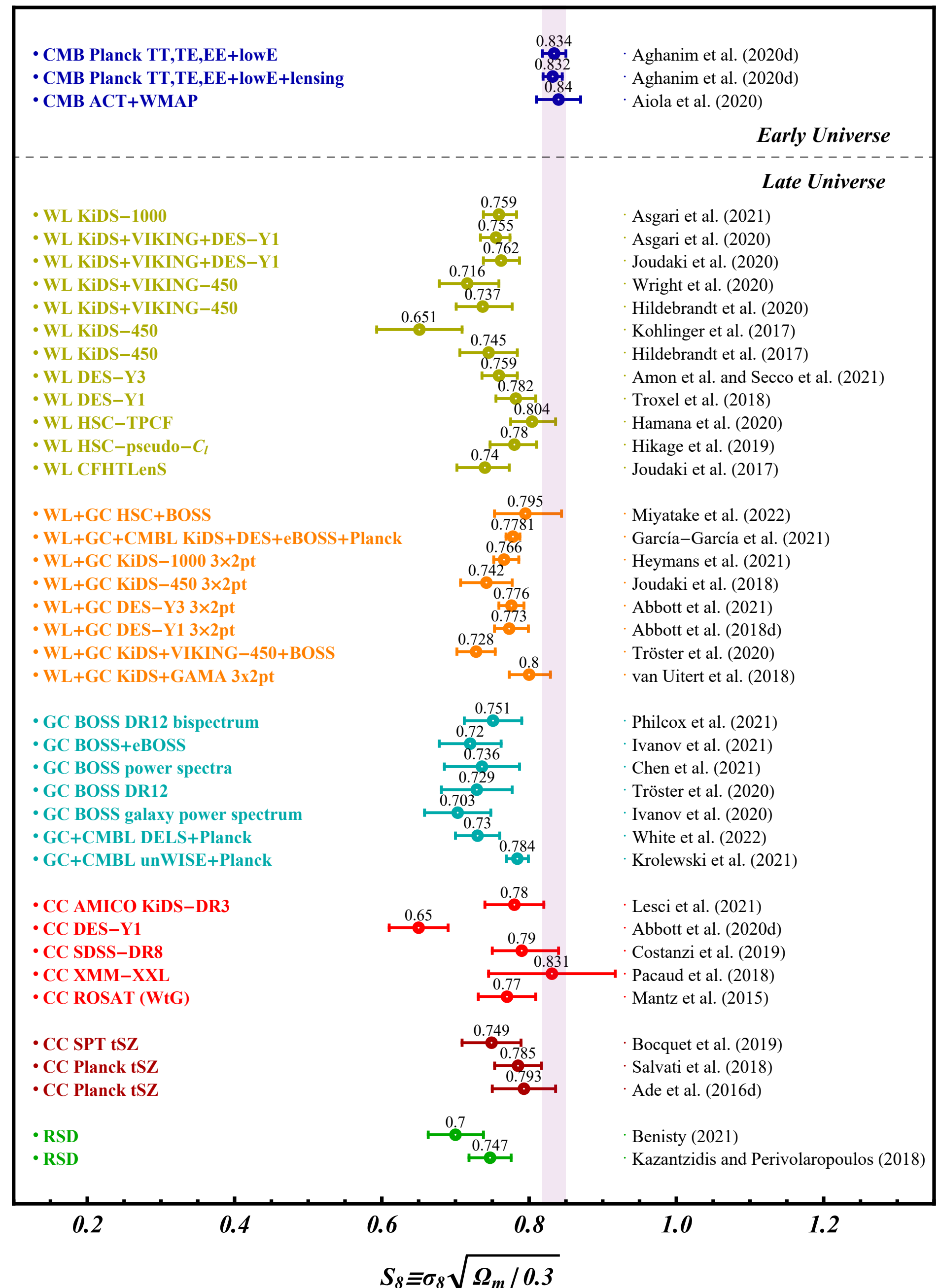
Indirect

Direct

Cosmology Intertwined: A Review of the Particle Physics,
Astrophysics, and Cosmology Associated with the Cosmological Tensions and Anomalies

arXiv:2203.06142v3

Also tension in S_8, parameter related to smoothness of the matter distribution



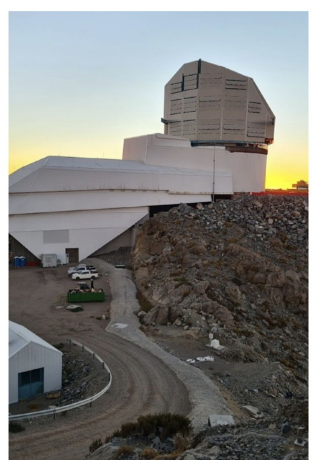
Clearly something is not working in cosmology...

- Systematics?
- Modified gravity?
- Different cosmological models?
- **BSM particle physics?**

Need more data!

Figuring out what dark matter is would help...
More info from new observatories


DESI


LSST


CMB-S4

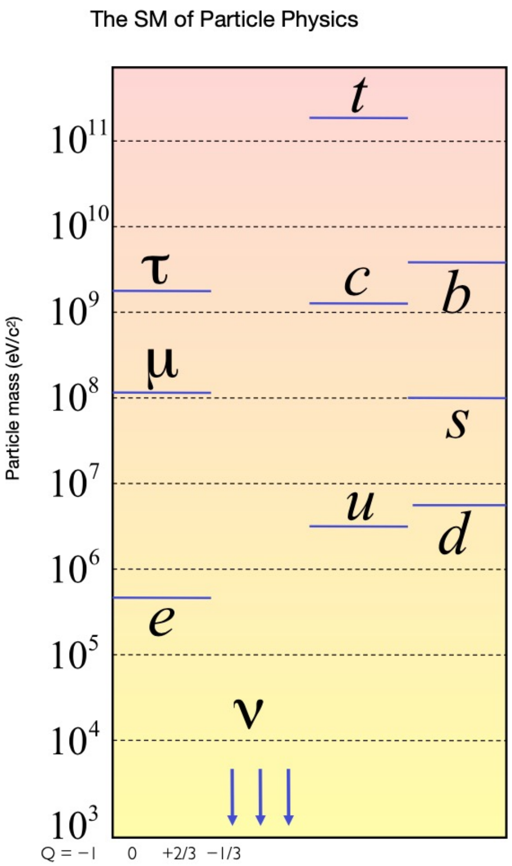

GWO

M. Soares-Santos, CSS

Last example: **flavor weirdness**

Flavour structure, V_{CKM}, V_{PMNS}, Masses

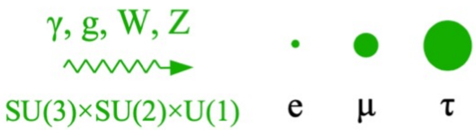
G. Isidori



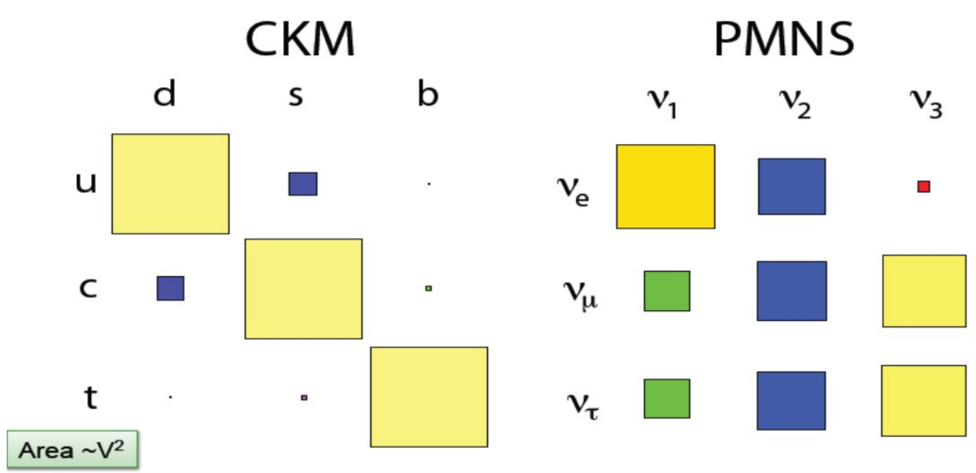
Suppose we could test matter only with long λ photons

We would conclude that these two particles are identical copies except for their mass

This is exactly the same argument we use to infer flavour universality in the SM



These three families of particles seem to be identical copies except for their mass



Why these values, are the two related, are they related to masses?

Phillip Urquijo, CSS

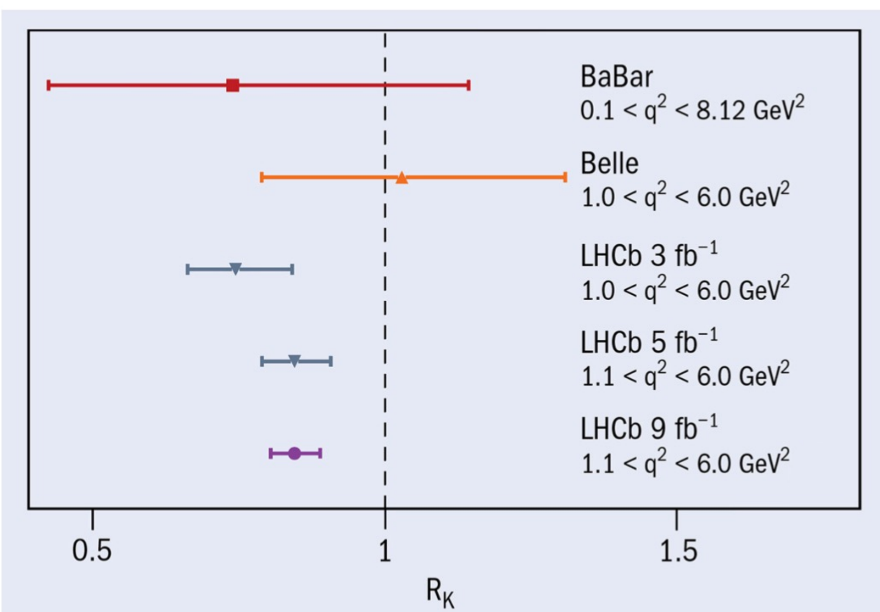
Many experiments going after flavor questions

LHC, B Mixing (LHCb, Belle II)	ATLAS, CMS, LHCb, Belle II	Belle II τ LFV τ V_{CKM}	BESIII, Belle II, LHCb	NA62, LHCb, KOTO	MEG Mu3e g-2
t	b	τ	c	s	μ

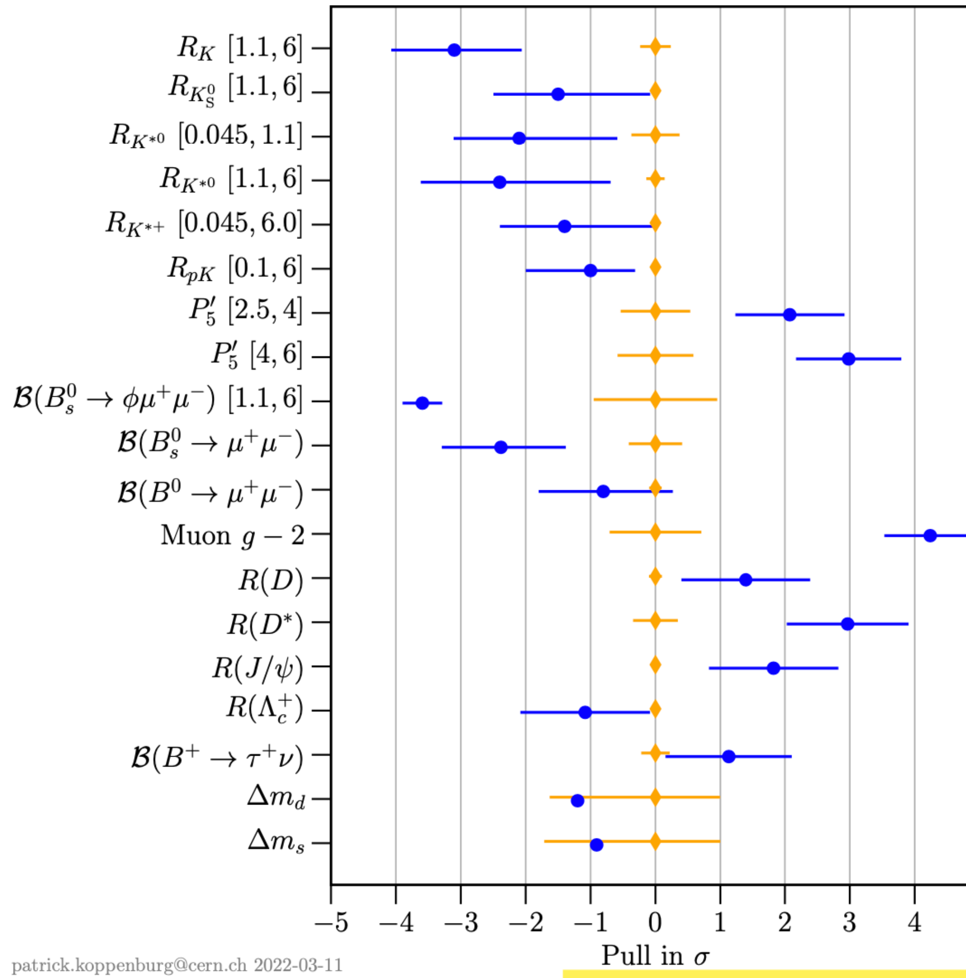
Phillip Urquijo, CSS

Anomalies in decays to leptons

- R_K probes the ratio of B-meson decays to muons vs electrons:
  $R_K = BR(B^+ \to K^+\mu^+\mu^-) / BR(B^+ \to K^+e^+e^-)$
- Hints that lepton flavor universality is violated: $R_K = 0.846^{+0.044}_{-0.041}$, 3.1σ
- Several other anomalies at the 2^+ σ level



https://cerncourier.com/a/new-data-strengthens-rk-flavour-anomaly/



See R. Coutinho's talk on Thursday

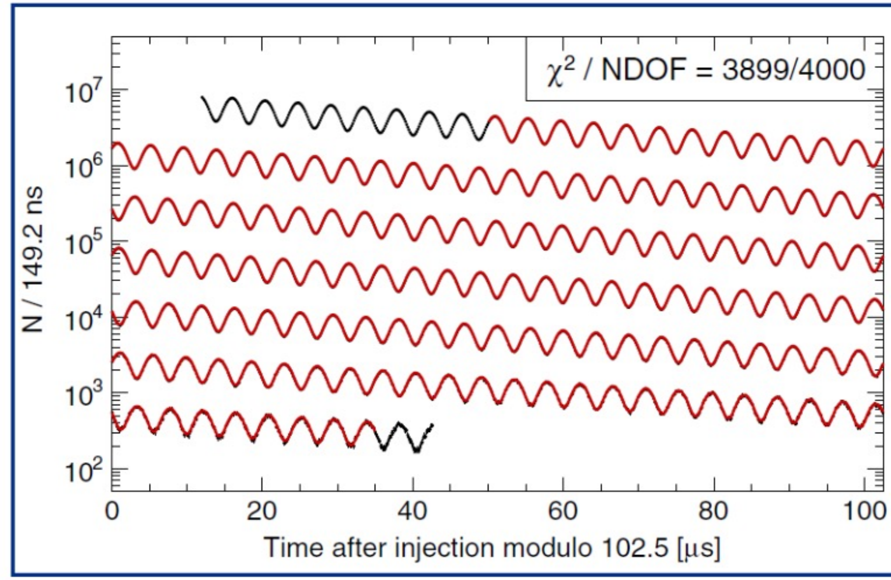
Phillip Urquijo, CSS

B. Kiburg

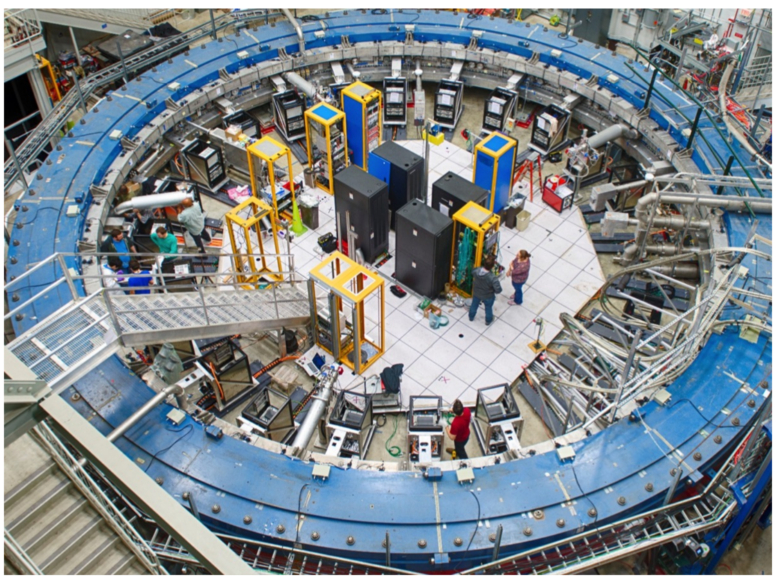
The muon g-2 anomaly

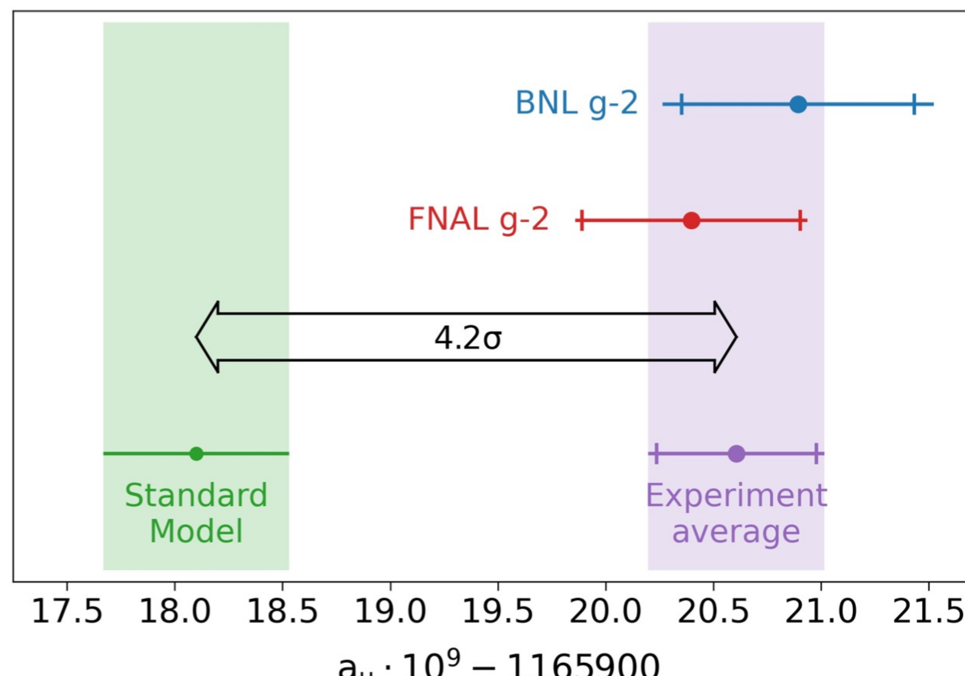
Count decays of
stored polarized muons,
compare to precise prediction

$$\omega_s - \omega_c \equiv \omega_a = \frac{eB}{m}\frac{g-2}{2} = \frac{eB}{m}a_\mu$$



B. Kiburg





Mistake somewhere?
New light boson that couples
preferentially to μ's? ...?

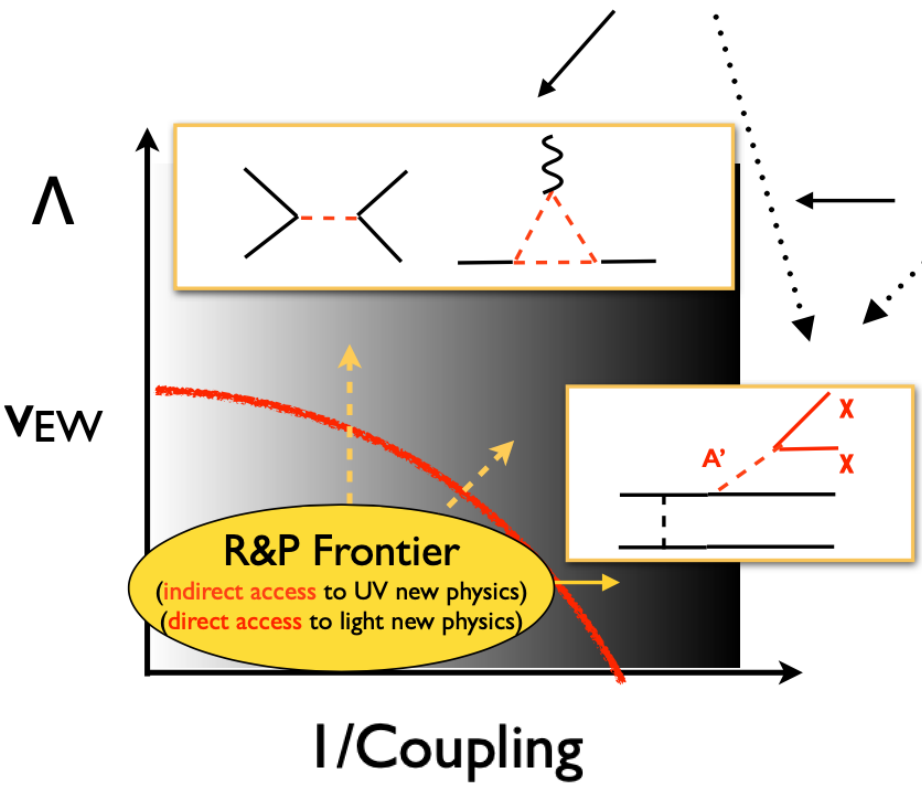
Lots more opportunities...

Vince Cirigliano, CSS

The "Rare & Precision" frontier

- Three classes of new physics probes

1. Searches for rare or SM-forbidden processes that probe (accidental) symmetries of the SM (B-L, $L_{e,\mu,\tau}$) or specific symmetry-violation patterns of the SM (CP, quark flavor)



2. Precision measurements of SM-allowed processes (theory input is crucial to claim discovery): lepton g-2, CC weak decays, …

3. Searches for dark sector particles and mediators ($\pi^+ \to ae\nu$, $\pi^+ \to eN$, $\mu \to ea$, …)

See Stefania Gori's Colloquium on 7/20

Strong overlap and synergy of HEP, NP, AMO

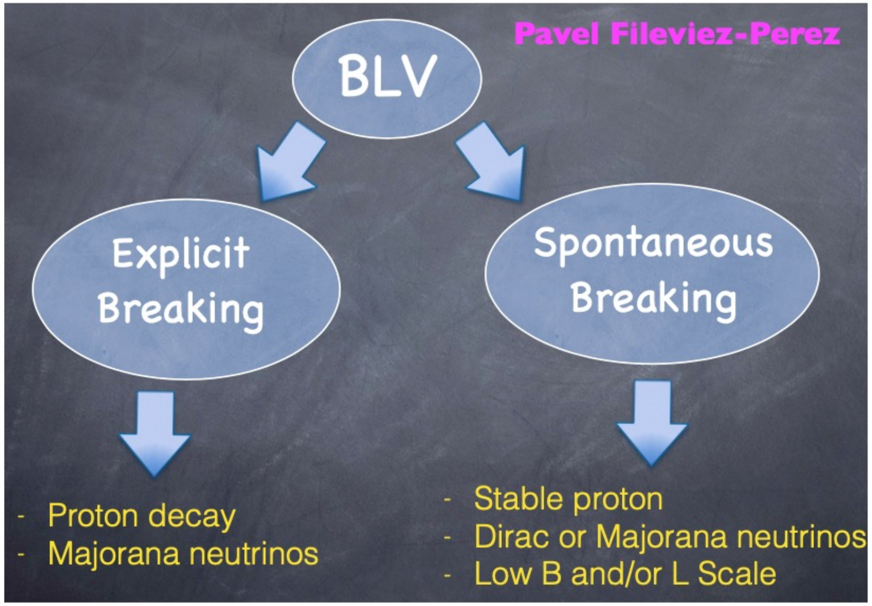
And more...

Baryon and Lepton Number

- B&L violation tied to the origin of baryon asymmetry and neutrino mass

- In explicit models, BLV realized through different mechanisms and at different scales:

- SU(5), SO(10) GUTs, (RPV) SUSY.
- Typically high scale



- B and/or L as gauge symmetries. Simplest Models have $\Delta B=3$ & dark matter candidate
- Pati-Salam models: $\Delta B=2$, $\Delta L=2$.
- Low-scale: new particles can be probed at colliders

- Experimental probes include: proton decay [SK,HK,JUNO, DUNE]; n-$\bar{n}$ oscillations [ORNL, ESS]; neutrinoless double beta decay ($0\nu\beta\beta$); BLV at colliders

Vince Cirigliano, CSS

And more...**Multi-Messenger Astrophysics**

Many, many detectors

ν

SuperK + gadolinium
JUNO
DUNE
Hyper-Kamiokande
KM3NeT
IceCube-Gen2
ARA, RNO-G

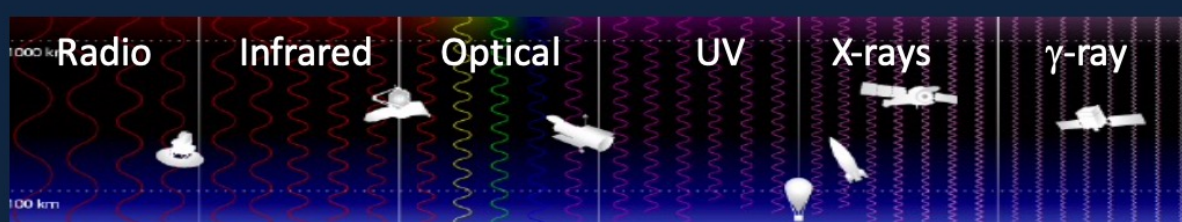
CR

LHAASO
PUEO
GRAND
TAMBO
POEMMA

GW

KAGRA
LIGO-India
LIGO Voyager
Cosmic Explorer
Einstein Telescope
LISA

γ



Radio	Infrared	Optical	UV	X-rays	γ-ray
LAST SKA	JWST	LSST TMT ELT		Athena	CTA SWGO

Shunsaku Horiuchi,
Snowmass Neutrino Colloquium

And don't forget the tools!

Ian Shipsey, CSS

Where will the answers come from?

Discoveries in particle physics

Based on an original slide by S.C.C. Ting

Facility	Original purpose, Expert Opinion	Discovery with Precision Instrument
P.S. CERN (1960)	π N interactions	Neutral Currents -> Z,W
AGS BNL (1960)	π N interactions	Two kinds of neutrinos Time reversal non-symmetry charm quark
FNAL Batavia (1970)	Neutrino Physics	bottom quark top quark
SLAC Spear (1970)	ep, QED	Partons, charm quark tau lepton
ISR CERN (1980)	pp	Increasing pp cross section
PETRA DESY (1980)	top quark	Gluon
Super Kamiokande (2000)	Proton Decay	Neutrino oscillations
Telescopes (2000)	SN Cosmology	Curvature of the universe Dark energy

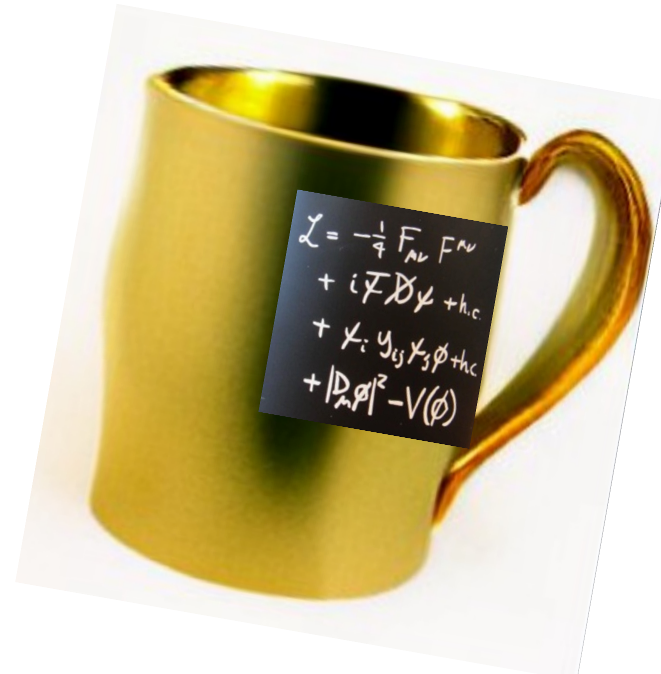
Ian Shipsey, CSS

They may be surprises!

How to find your golden opportunities?

Theorists:

- Think creatively!
- Develop new theoretical tools!
- Talk with experimentalists!



Experimentalists:

- Keep measuring!
- Develop new experimental tools!
- Talk with theorists!

Both:

- Keep exploring!
- Talk with non-particle-physicists!
- Keep your eyes open and ready for surprises!

Enjoy the school!