Higgs in the Swampland

Nathaniel Craig
UC Santa Barbara

×05
51
000151730
233

The Naturalness Strategy

Param	UV sensitivity	Natural if	NP	Scale	Natural?
"m_e"	$e^2\Lambda$	Λ ≲ 5 MeV	Positron	511 keV	✓
$m_{\pi\pm}^2$ - $m_{\pi 0}^2$	$\frac{3\alpha}{4\pi}\Lambda^2$	Λ ≲ 850 MeV	Rho	770 MeV	✓
m_{KL}-m_{KS}	$\frac{s_c^2 f_K^2 m_{K_L^0}}{24\pi^2 v^4}\Lambda^2$	Λ ≲ 2 GeV	Charm	1.2 GeV	✓
m_H^2	$-\frac{6y_t^2}{16\pi^2}\Lambda^2 + \ldots$	Λ ≲ 500 GeV	?	?	?

From the "naturalness strategy" to new physics

At this level, we expect

- New physics below the TeV scale…
- …coupling to the Higgs

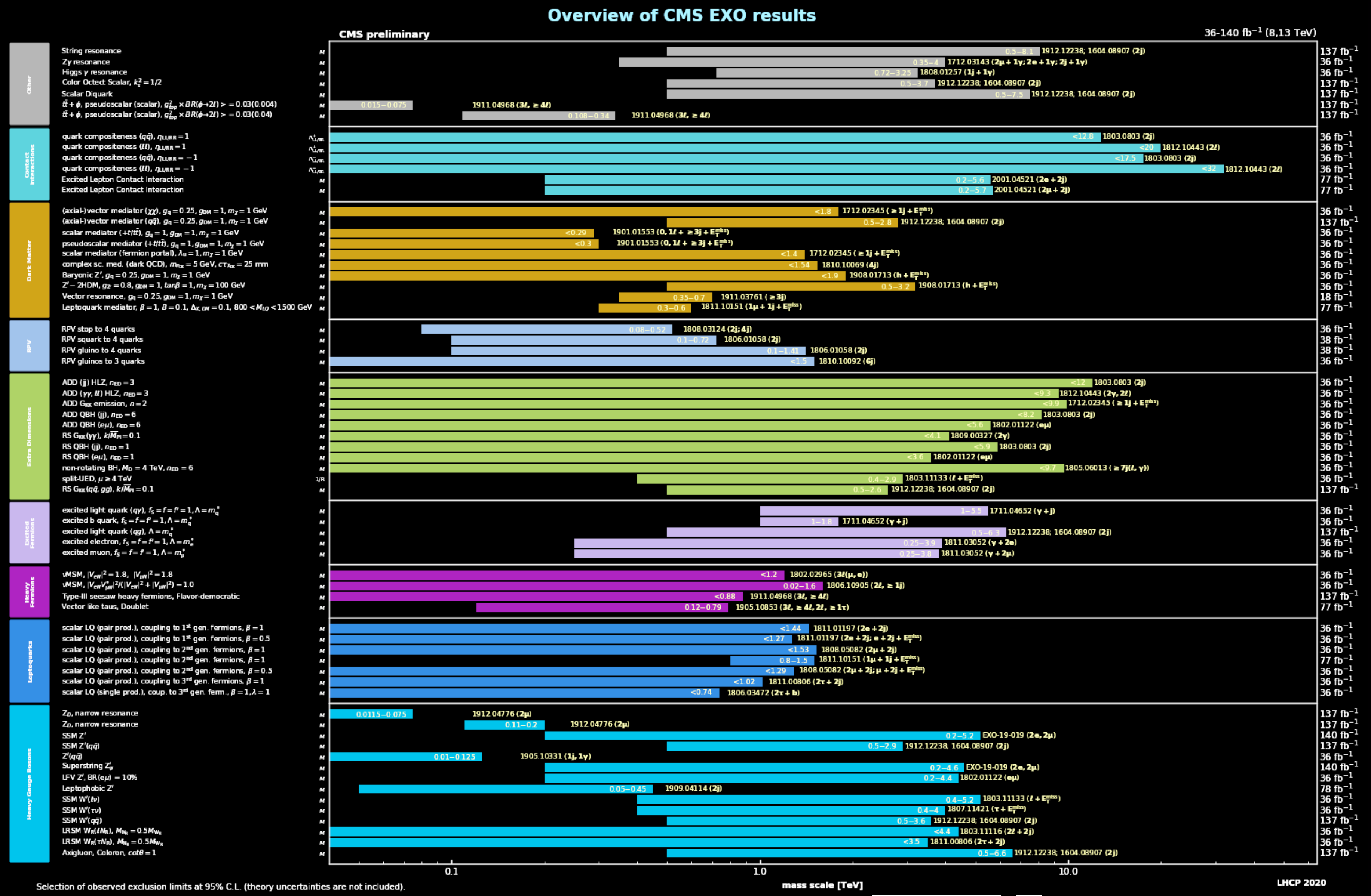
Strong motivation for BSM Higgs physics!
But maybe too broad to be useful…

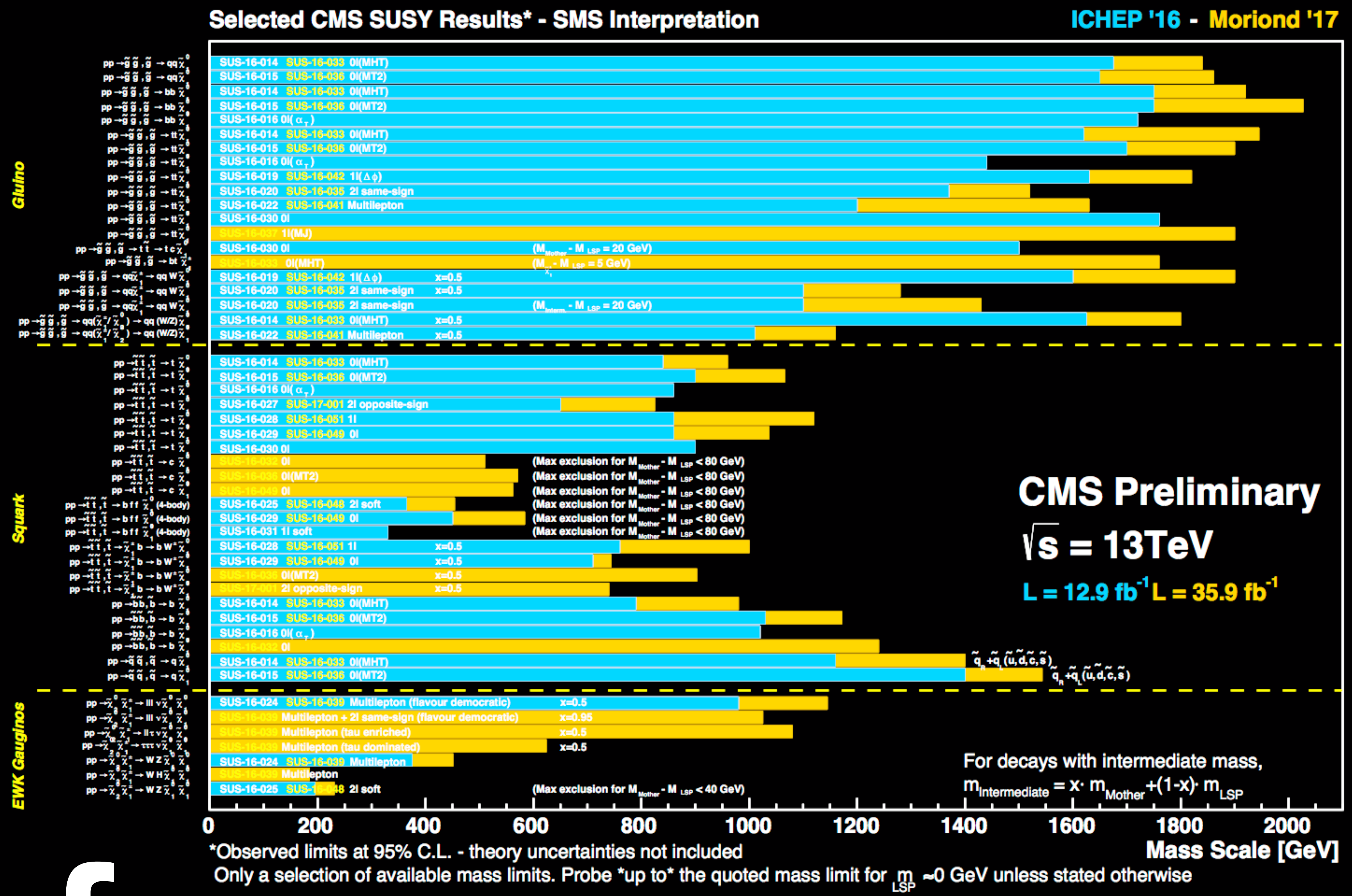
Implementation is up to us

We've refined this strategy using some rules of thumb, for example…

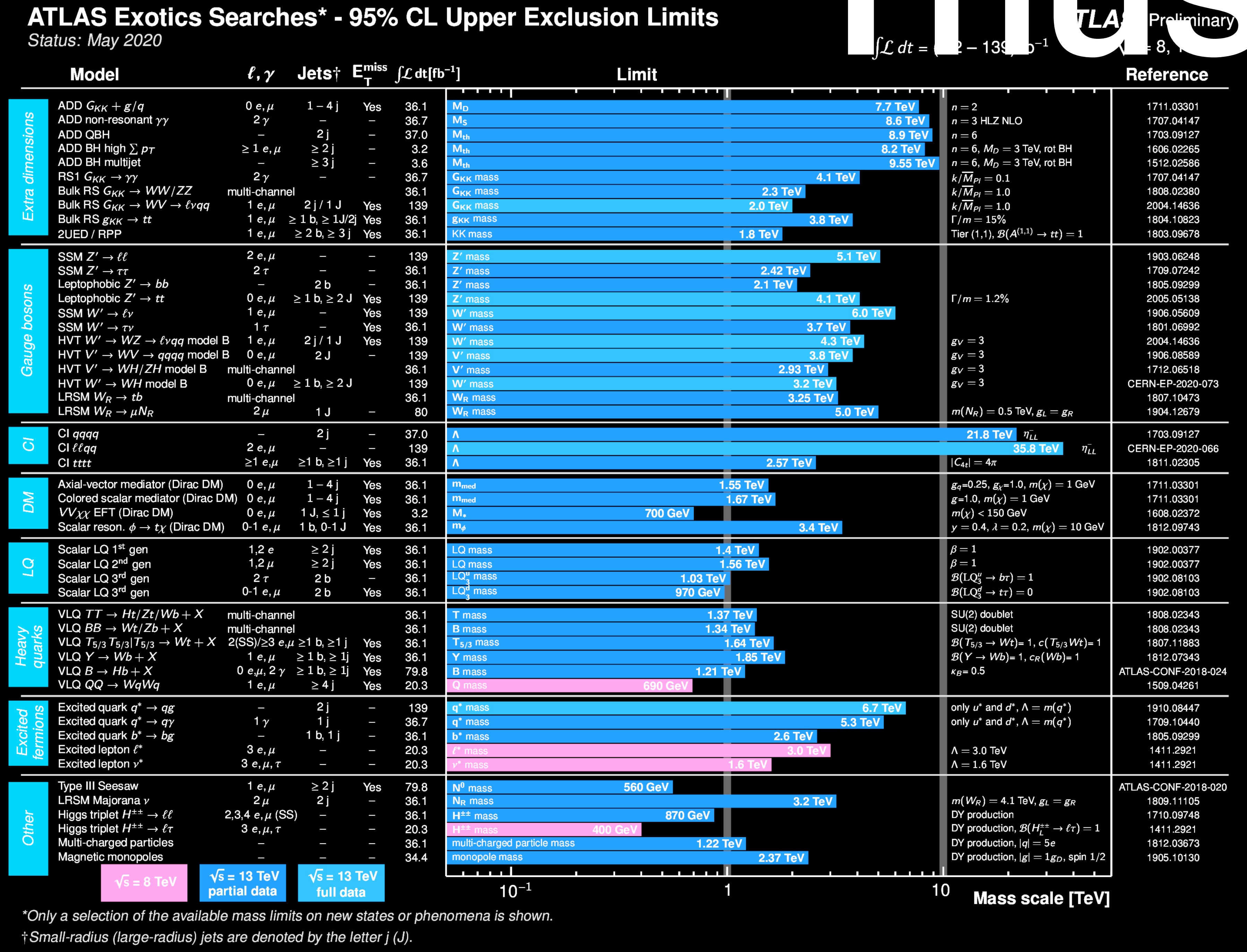
1. **The Standard Model coupled to gravity is a generic EFT.**
2. **The solutions to the hierarchy problem involve symmetries, low cutoffs, or anthropics.**
3. **Symmetries imply new particles charged under the SM.**

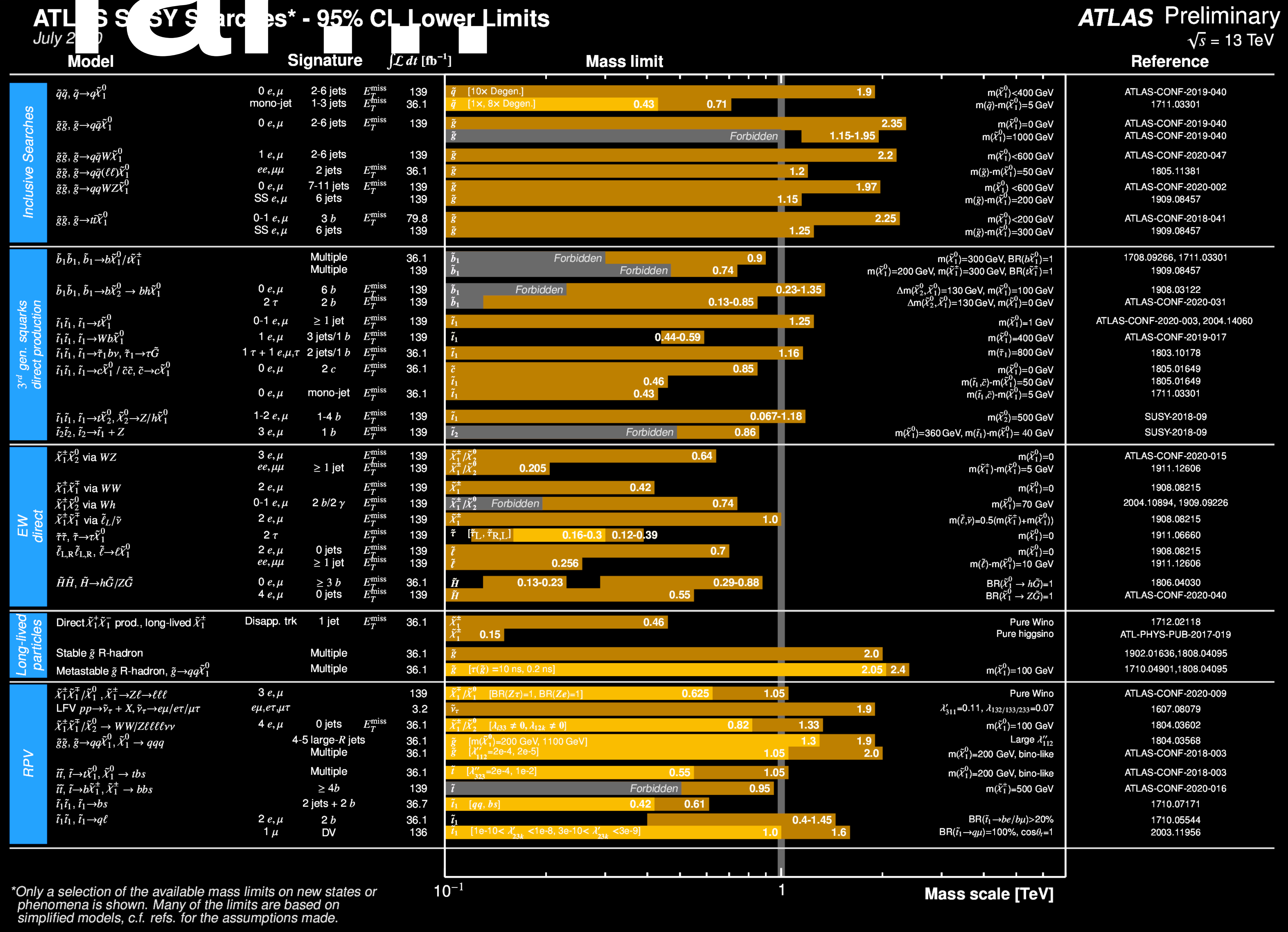
In turn, this tells us what kind of NP to expect: SUSY, CHM,…


Overview of CMS EXO results
CMS preliminary
36-140 fb⁻¹ (8,13 TeV)
Selection of observed exclusion limits at 95% C.L. (theory uncertainties are not included).
mass scale [TeV]
LHCP 2020

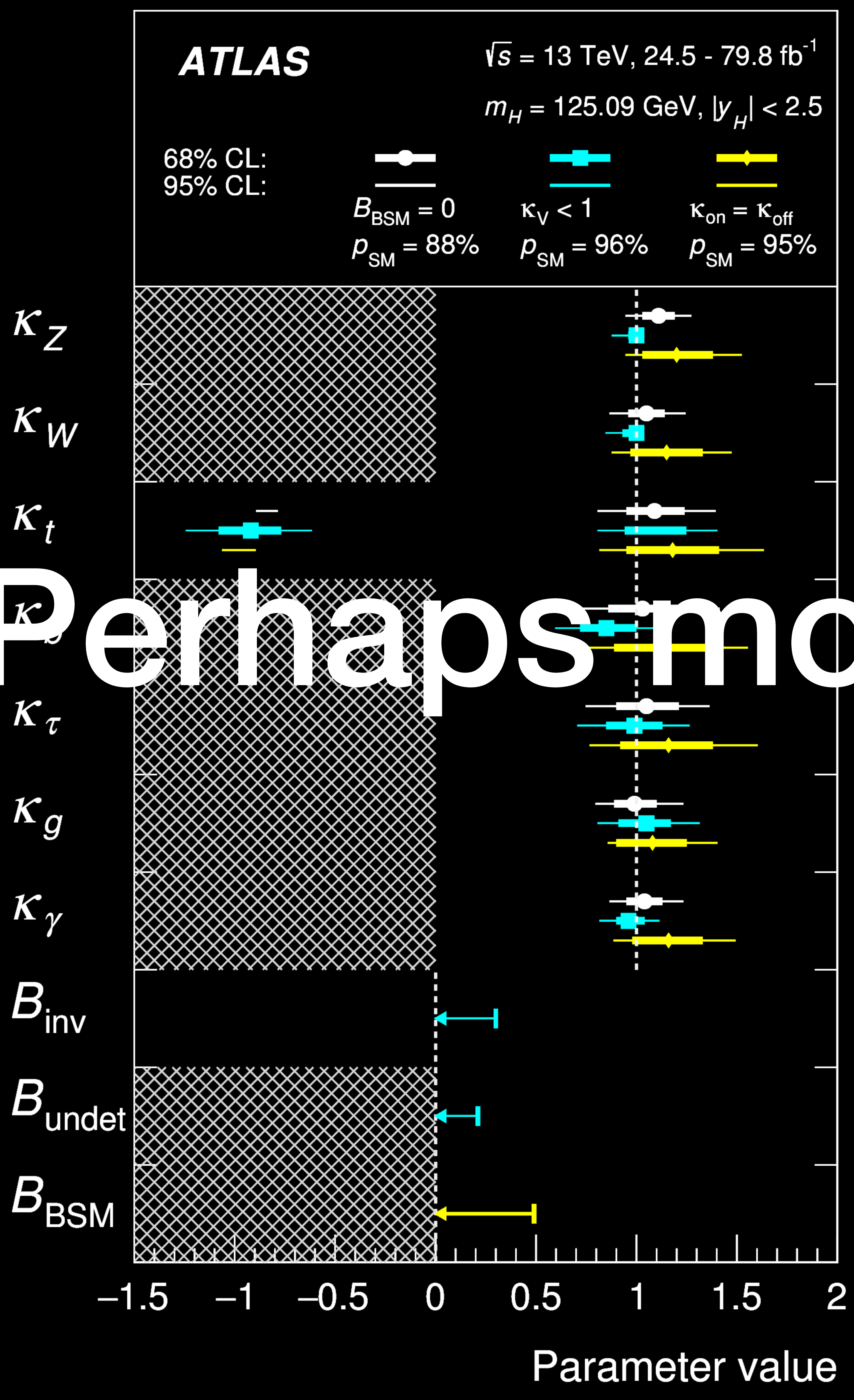

Selected CMS SUSY Results* - SMS Interpretation
ICHEP '16 - Moriond '17
Gluino
Squark
EWK Gauginos
CMS Preliminary
√s = 13TeV
L = 12.9 fb⁻¹ L = 35.9 fb⁻¹
For decays with intermediate mass,
m_Intermediate = x · m_Mother + (1-x) · m_LSP
Mass Scale [GeV]
*Observed limits at 95% C.L. - theory uncertainties not included
Only a selection of available mass limits. Probe *up to* the quoted mass limit for m_LSP ~0 GeV unless stated otherwise

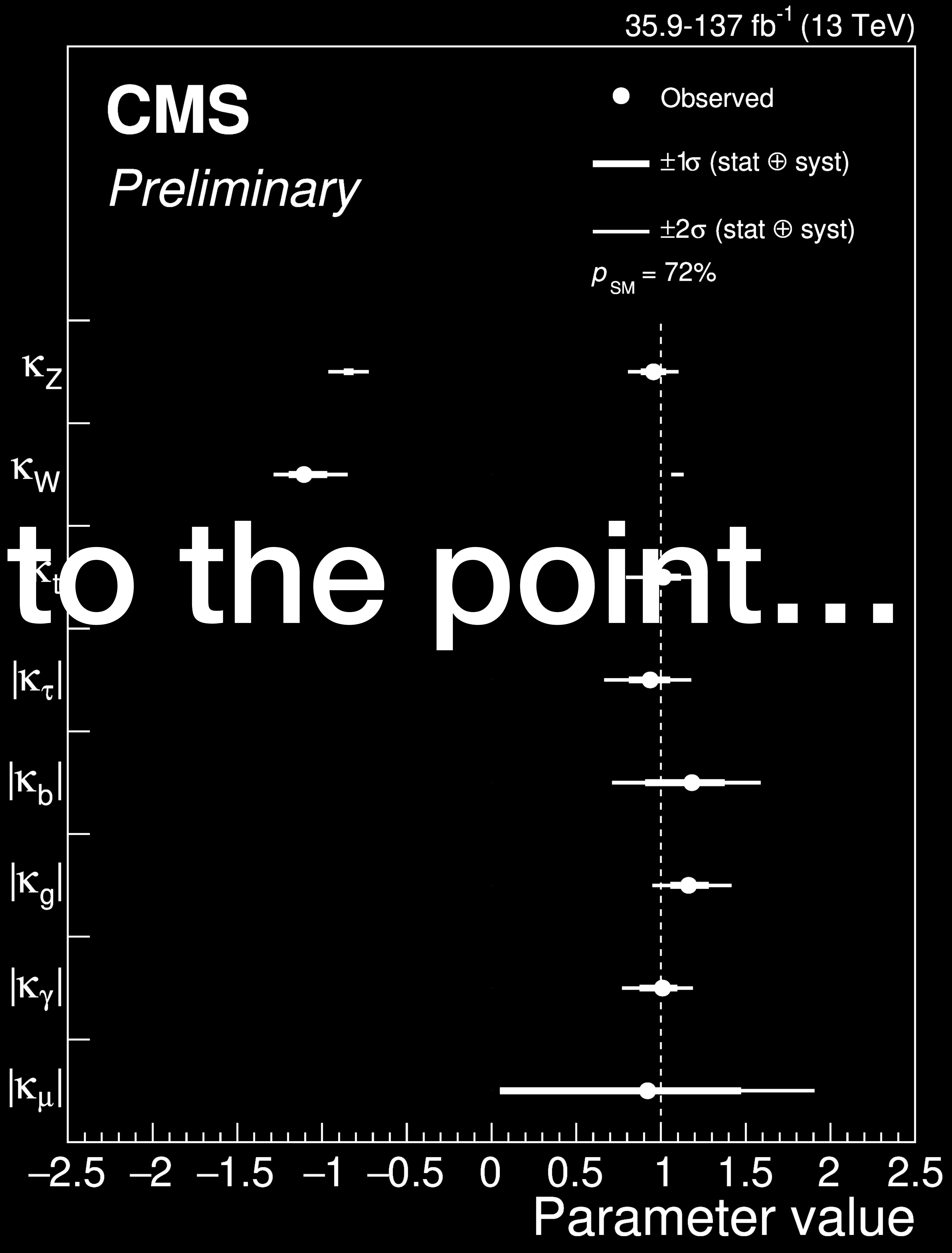
Thus far...


ATLAS Exotics Searches* - 95% CL Upper Exclusion Limits
Status: May 2020
ATLAS Preliminary
Model
Limit
Reference
Extra dimensions
Gauge bosons
CI
DM
LQ
Heavy quarks
Excited fermions
Other
√s = 8 TeV
√s = 13 TeV partial data
√s = 13 TeV full data
Mass scale [TeV]
*Only a selection of the available mass limits on new states or phenomena is shown.
†Small-radius (large-radius) jets are denoted by the letter j (J).


ATLAS SUSY Searches* - 95% CL Lower Limits
ATLAS Preliminary
√s = 13 TeV
Model
Signature
Mass limit
Reference
Inclusive Searches
EW direct
Long-lived particles
RPV
Mass scale [TeV]
*Only a selection of the available mass limits on new states or phenomena is shown. Many of the limits are based on simplified models, c.f. refs. for the assumptions made.

Perhaps more to the point…





On the wrong track?

What if some of the rules of thumb are wrong?

1. ~~The Standard Model coupled to gravity is a generic EFT.~~ → **TODAY**

2. ~~The solutions to the hierarchy problem involve symmetries, low cutoffs, or anthropics.~~

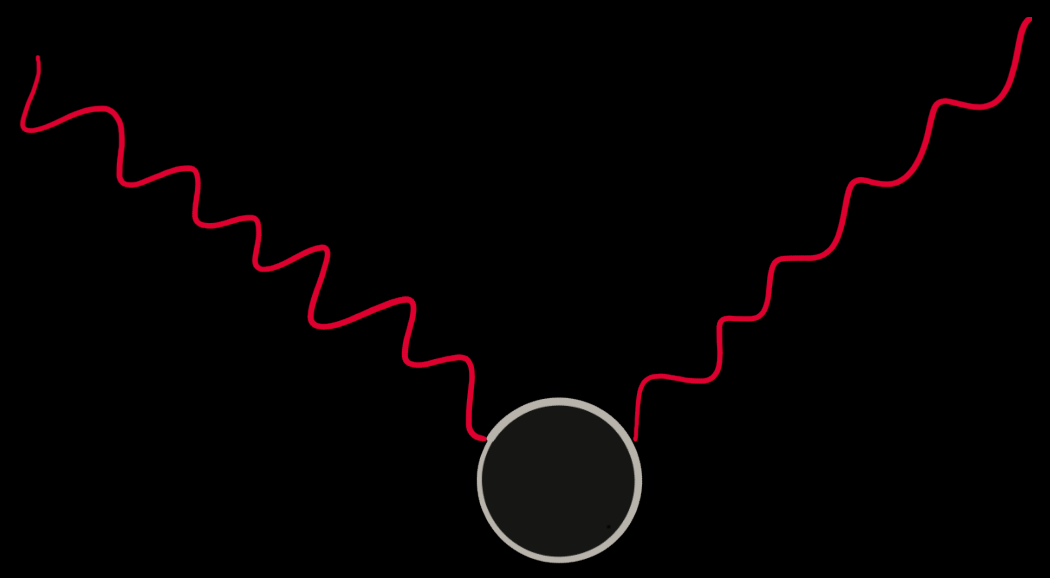
3. ~~Symmetries imply new particles charged under the SM.~~

Relaxion

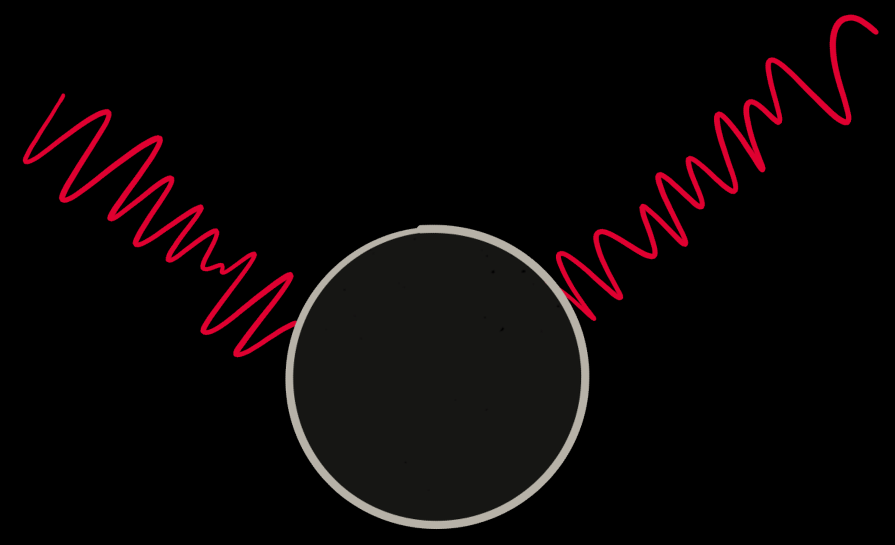
Twin Higgs, discrete symmetries, “neutral naturalness”, …

The End of EFT?

Parameter space of EFTs shaped by consistent coupling to gravity



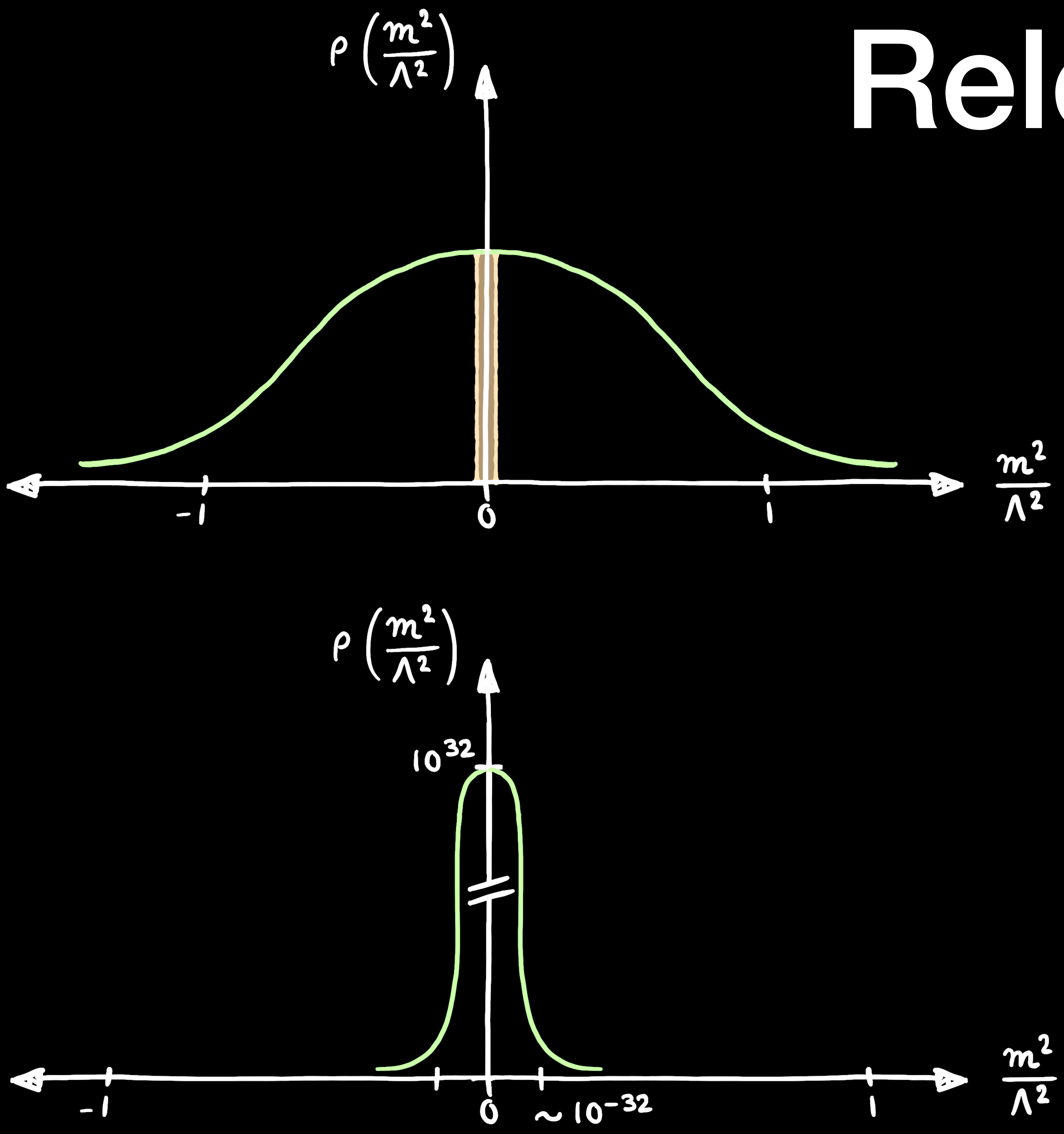
UV/IR mixing…



Various (conjectured) consequences:

- No global symmetries
- Charge quantization
- Completeness hypothesis
- No (meta)stable dS vacua
- Infinite states @ infinite distances
- “Gravity is the weakest force”

Relevance to BSM?



[Isabel Garcia Garcia, BSM Pandemic seminar 07/20]

Usual (EFT) logic of hierarchy problem: uncorrelated UV contributions give broad distribution of possible values of m_h up to cutoff; m_h well below cutoff "unlikely"

Usual (EFT) logic of hierarchy solution: lower the cutoff.

Alternately: consistency with gravity orchestrates correlations among UV parameters to satisfy bounds, changing the distribution.

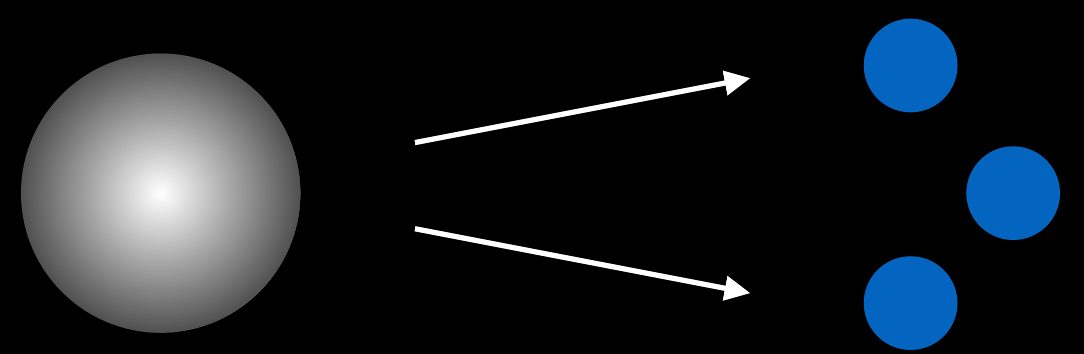
The Weak Gravity Conjecture

(Electric) weak gravity conjecture: an abelian gauge theory must contain a state of charge *q* and mass *m* satisfying

$$qg > \frac{m}{M_{\rm Pl}}$$

[Arkani-Hamed, Motl, Nicolis, Vafa ‘07]

“Justification”: consider BH of charge *Q*, mass *M* decaying to this particle



particles produced = Q/q

Energy conservation: $mQ/q < M$

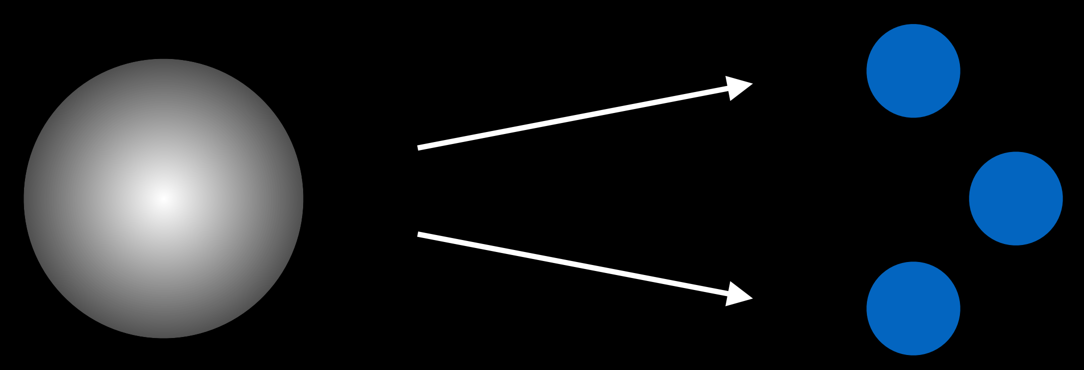
Then BH satisfies $Z = Q\, M_{Pl}/M < z = q\, M_{Pl}/m$

Extremal BH (Z=1) stable unless there exists a state with z > 1

⇒ $q > m/M_{Pl}$ to avoid stable black holes, remnants, in conflict w/ holography

Magnetic Weak Gravity Conjecture

Analogous argument for BHs carrying magnetic charge:



For monopole of size L,
decay of extremal BH implies

$$m_{\text{mon}} \sim \frac{(2\pi/g)^2}{L} \lesssim \frac{2\pi}{g} M_{\text{Pl}}$$

$$\Rightarrow \Lambda \equiv L^{-1} \lesssim g M_{\text{Pl}}$$

Note: cutoff need not imply appearance of quantum gravity,
only physics underlying monopole structure

A Family of Conjectures

Electric WGC: $m \leq (gq)M_{\text{Pl}}$
[Arkani-Hamed, Motl, Nicolis, Vafa '07]

Magnetic WGC: $\Lambda \lesssim gM_{\text{Pl}}$
[Arkani-Hamed, Motl, Nicolis, Vafa '07]

+Scalar WGC: $m \leq \sqrt{g^2q^2 - \mu^2}M_{\text{Pl}}$
[Palti '17]

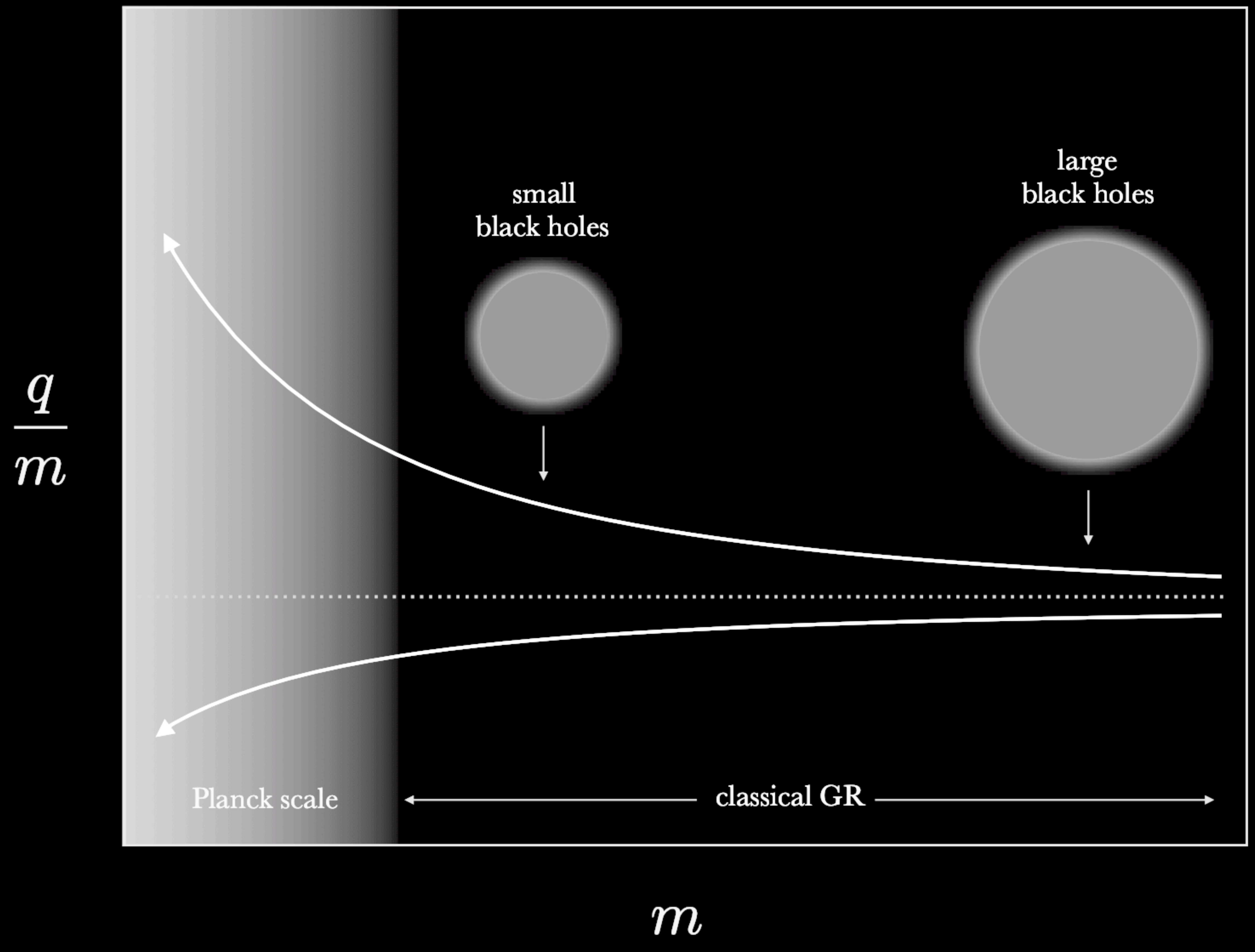
dS WGC: $m^2 \gtrsim gqM_{\text{Pl}}H$
[Montero, Van Riet, Venken '19]

Axion WGC: $f \leq (1/S)M_{\text{Pl}}$
[Arkani-Hamed, Motl, Nicolis, Vafa '07]

New hierarchies from EFT + gravity.

Irrelevance to BSM?

[Cheung, Liu, Remmen '18]



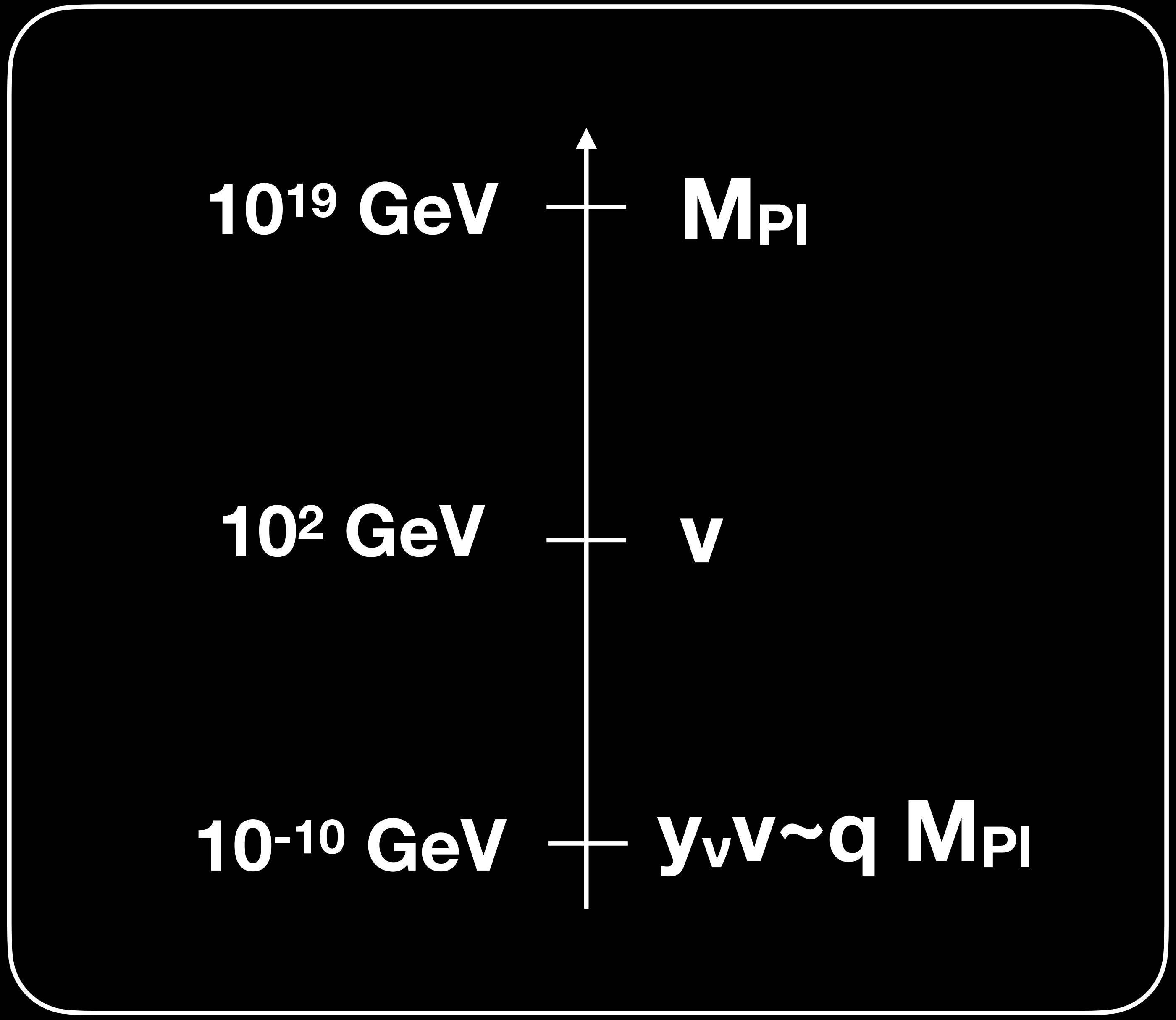
Higher-dimensional operators deform extremality curve in direction that allows larger extremal black holes to decay into smaller extremal black holes, "self-satisfying" WGC.

Could still expect arguments to hold for sub-Planckian states, in which case WGC still relevant to particle physics; status unclear.

Weak Gravity, Weak Scale?

[Cheung, Remmen '14]: If mass of WGC particle is UV sensitive, then for fixed UV-insensitive parameters, satisfying the WGC enforces fine-tuning. *(Or: would orchestrate correlations among UV contributions)*

Application to SM: charge SM fermions under weakly gauged (unbroken) $U(1)_{B-L}$ (bounds currently $q \lesssim 10^{-24}$). Cancel anomalies with RHN ν_R



Neutrino mass from EWSB

$$y_\nu H \bar{L} \nu_R \to m_\nu \sim y_\nu v$$

If lightest neutrino is WGC particle,

$m_\nu \sim 0.1$ eV, $q \gtrsim 10^{-29}$

For fixed y, q, satisfying WGC places an upper bound on v

See also: [Ibañez, Martin-Lozano, Valenzuela '17,…]

Weak Gravity, Weak Scale?

Things that could go wrong:

- WGC could be satisfied by states outside EFT
- Satisfying WGC could compel the appearance of a new light state that enforces apparent UV correlations (e.g. relaxion)
- Apparently UV-sensitive parameters might control apparently UV-insensitive ones (e.g. emergent gauge fields)

Thing that certainly goes wrong:

- Magnetic WGC implies cutoff of U(1) at $\Lambda \lesssim g M_{Pl}$

Weak Gravity, Weak Scale?

First order of business: can m, Λ be raised to the weak scale?

New $U(1)_X$ plus matter acquiring some mass from the Higgs. E.g…

[NC, Garcia Garcia, Koren '19]

	$SU(2)_L$	$U(1)_Y$	$U(1)_X$
L	$\square$	$+1/2$	$+1$
L^c	$\square$	$-1/2$	-1
N	-	0	$+1$
N^c	-	0	-1

$$-\mathcal{L} \supset \left\{ m_L L L^c + m_N N N^c + y H^\dagger L N^c + \tilde{y} H L^c N \right\} + \text{h.c.}$$

Best option: $m_N < m_L$, lightest mass eigenstate χ_1 is WGC particle

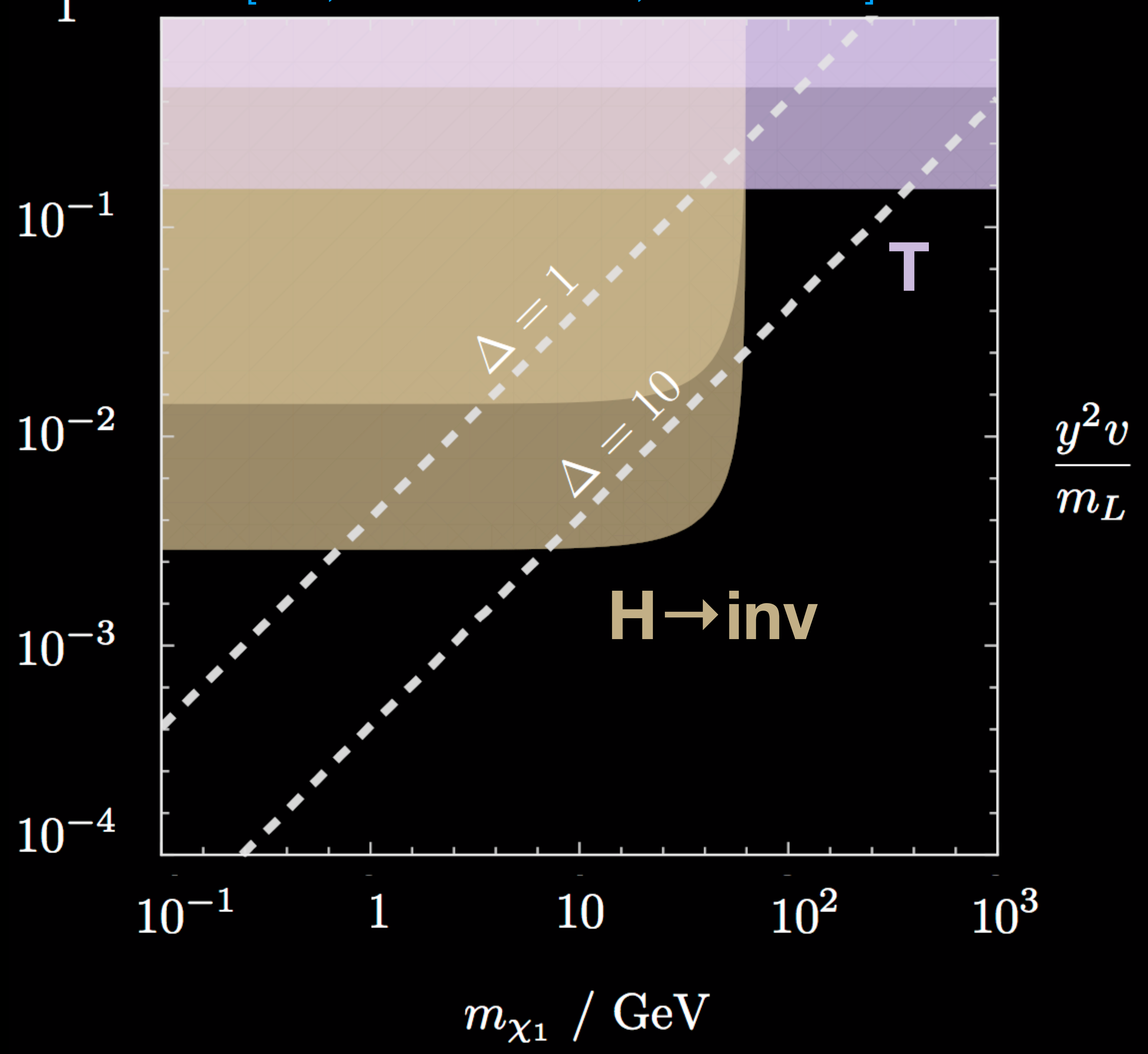
Then for fixed (technically natural) g, m_L, m_N, y,

$$v^2 \lesssim \frac{2}{y^2} \left(m_{\chi_1}^2 + m_{\chi_1}(m_L - m_N) - m_L m_N \right)$$

Weak Gravity, Weak Scale?

Still have a notion of sensitivity of the weak scale
to parameters involved in the bound

[NC, Garcia Garcia, Koren '19]



Quantify with e.g. $$\Delta_x \equiv \left| \frac{\partial \log v^2}{\partial \log x} \right|$$

Here $$\Delta_{\max} \sim \frac{m_N m_L}{y^2 v^2}$$

Not surprising: WGC particle should get "most of" its mass from EWSB.

Surprisingly predictive: look for new singlet fermions coupled to the Higgs at/below the weak scale.

DM story interesting…

Weak Gravity, Weak Scale?

Lightest particle charged under $U(1)_X$ is stable ⇒ **dark matter** candidate

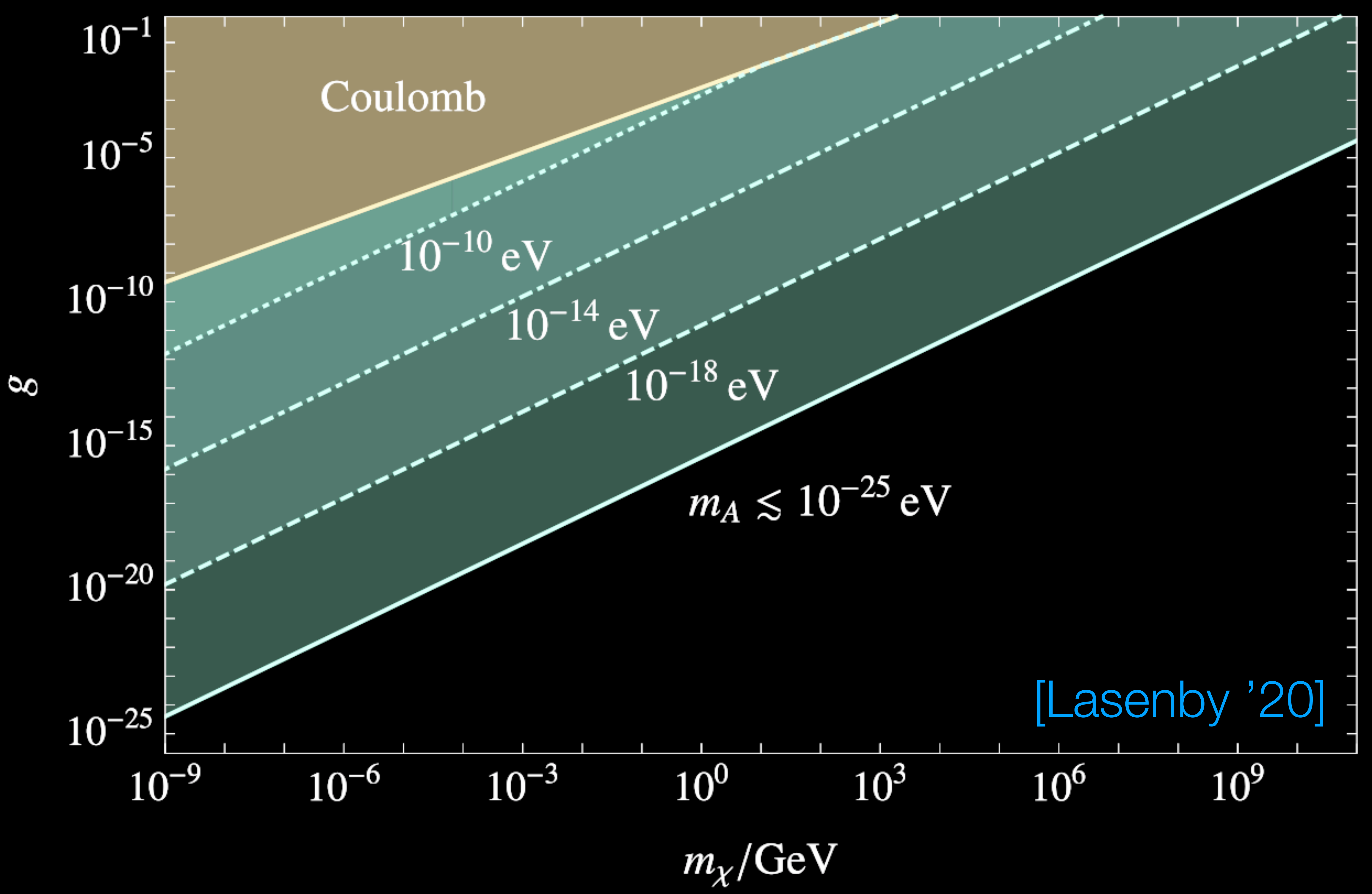
$U(1)_X$ gives a very weak, long-range force, too weak to influence individual collisions but relevant on scale of galaxy clusters

Galaxy cluster collisions can trigger plasma instabilities, making DM collisional on large scales [Ackerman, Buckley, Carroll, Kamionkowski ’08; Heikinheimo, Raidal et al ’15; Spethmann et al ’16]

Timescale of plasma fluctuations set by plasma frequency,

$$\omega_p = \sqrt{\frac{g^2\rho}{m^2}} \geq \frac{\sqrt{\rho}}{M_{\rm Pl}} \qquad \omega_p^{-1} \lesssim 10^{15}\,{\rm s} \times \left(\frac{0.04\,{\rm GeV\,cm^{-3}}}{\rho}\right)^{1/2}$$

C.f. $\tau \sim 1\,{\rm Gyr} \sim 10^{16}\,{\rm s}$ for galaxy cluster collisions



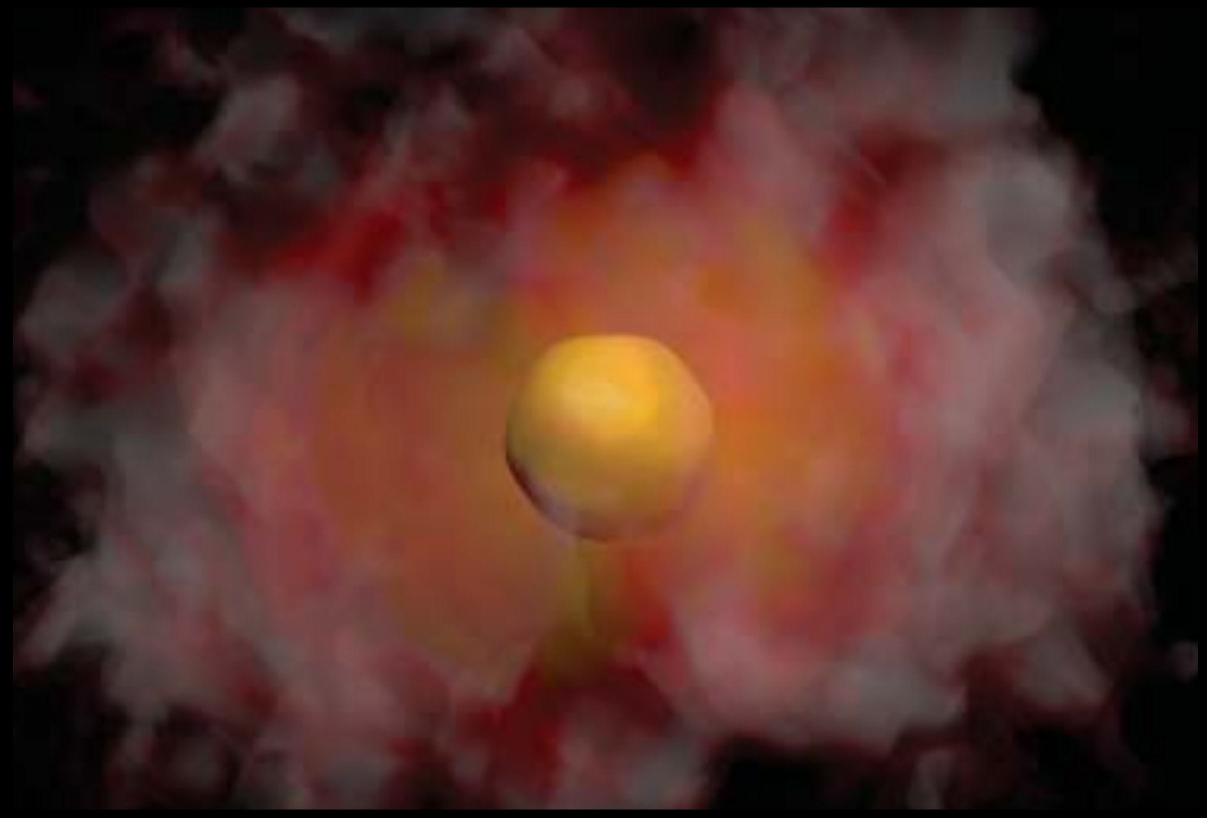
Weak Gravity, Weak Scale?

Second order of business: can the magnetic WGC scale be something less severe than the SM cutoff? Only confident that Λ ~ scale associated w/ structure of magnetic monopoles

E.g. t' Hooft-Polyakov monopoles $SU(2)_X \underset{\langle \mathrm{Adj} \rangle}{\rightarrow} U(1)_X$

$$``\Lambda" = m_W = g_2 f = 2gf \lesssim 2gM_{\mathrm{Pl}}$$

W's would trivialize bound from vanilla electric WGC, but not e.g. unit charge version (charge ±2 under $U(1)_X$)



Resolution of physics at Λ ~ weak scale implies additional exotic physics coupling directly or indirectly to the Higgs.

The de Sitter Conjecture

de Sitter Conjecture: Low energy effective scalar potential in any consistent theory of quantum gravity must satisfy

$$|\nabla V| \geq c \frac{V}{M_{\mathrm{Pl}}}$$

[Obied, Ooguri, Spodyneiko, Vafa '18]

Arguments from string theory examples, entropy of dS + distance conjecture
Challenging for inflation, suggests dark energy should be dynamical

[Denef, Hebecker, Wrase '18]: **Badly violated by SM Higgs boson + dynamical DE**

$$\frac{|\nabla V|}{V} \simeq \frac{|\nabla V_{\mathrm{quintessence}}|}{\Delta V_H} \sim \frac{10^{-120}}{10^{-65}} \frac{1}{M_{\mathrm{Pl}}} \sim \frac{10^{-55}}{M_{\mathrm{Pl}}}$$

Either quintessence field couples nontrivially to Higgs, or conjecture too strong…

The Refined dS Conjecture

Refined dS Conjecture: Low energy effecive scalar potential in any consistent theory of quantum gravity must satisfy either the dS Conjecture or

$$\min(\nabla_i \nabla_j V) \leq -c' \frac{V}{M_{\rm Pl}^2}$$

[Ooguri, Palti, Shiu, Vafa '18]

Consistent with SM Higgs, $$\frac{\min(\nabla_i \nabla_j V)}{V} \sim -\frac{10^{35}}{M_{\rm Pl}^2}$$

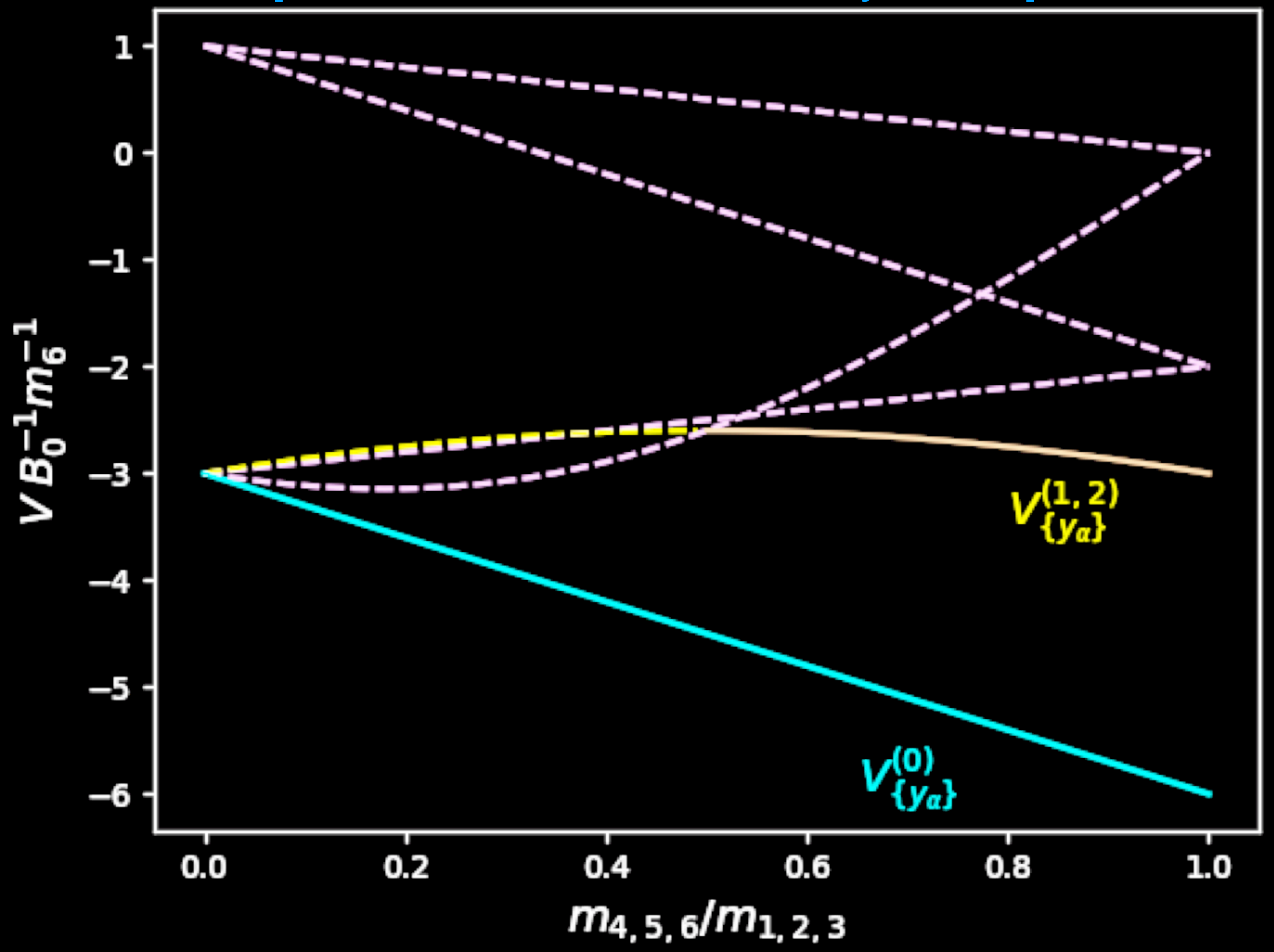
New wrinkle: **essentially forbids metastable vacua**, since satisfying RdSC in metastable minimum implies quintessence evolving too rapidly in our vacuum, reaching deep AdS state ("big crunch") within ~fraction of a Hubble time

See also: [Ibañez, Martin-Lozano, Valenzuela '17,…]

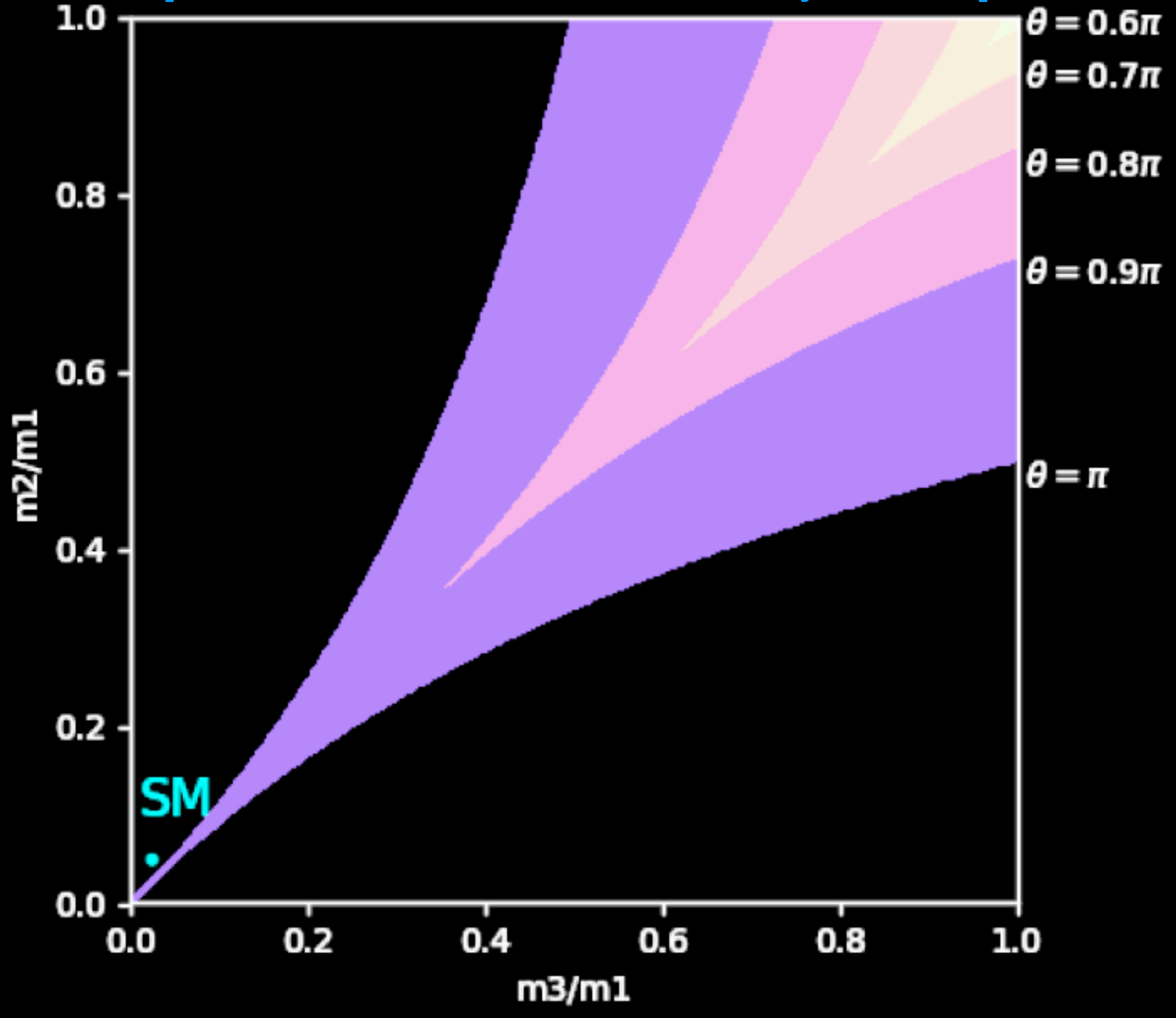
The SM and the RdSC

[March-Russell, Petrossian-Byrne ’20] RdSC relevant to SM flavor!
QCD has metastable vacua for certain values of yukawas, $\bar{\theta}$;
measured values consistent w/ RdSC

[March-Russell, Petrossian-Byrne ’20]



[March-Russell, Petrossian-Byrne ’20]

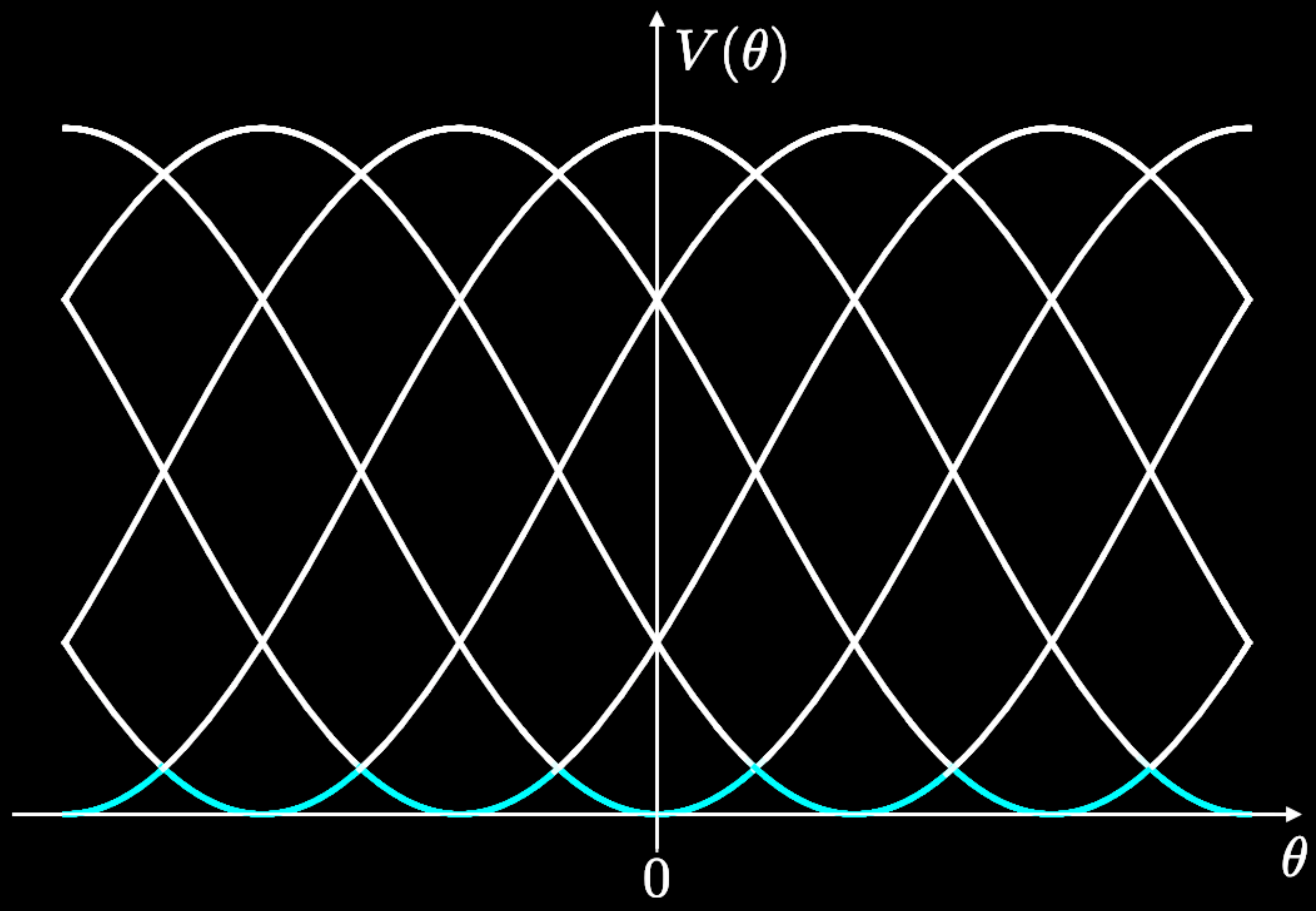


The Weak Scale & the RdSC

[March-Russell, Petrossian-Byrne '20] If pure SU(3) YM has metastable vacua, then for fixed yukawas the RdSC would bound the weak scale from above, $v \lesssim 50$ TeV.

[Witten '98, Shifman '98] Large-N YM should possess N-1 metastable vacua: reconciles 2π periodicity $V(\theta + 2\pi) = V(\theta)$ and large-N scaling $V(\theta) = N^2 f(\theta/N)$ for 2π periodic $f(x)$: potential is multi-branched, with each branch $2\pi N$ periodic, ground state 2π periodic due to level crossings

Status at small N unknown, no lattice studies or reliable semiclassics, would be lovely to find out!



[March-Russell, Petrossian-Byrne '20]

Conclusions

- Not sure (personally) how much more there is to say about Higgs & hierarchy problem following traditional EFT logic.

- If the naturalness strategy fails, it should be for good reason. Failure of EFT logic due to gravitational effects is compelling, albeit hard to quantify. Swampland conjectures provide tools applicable to low-energy theory.

- Surprising relevance to Higgs, SM, and its extensions, and visa versa.

- Applications to hierarchy problem convolve conjecture & supposition (e.g. applying WGC to EFT landscape at fixed dimensionless couplings), but follow familiar reasoning (anthropics) and have testable consequences.

- Early days, but stand to learn much more about BSM from Swampland Conjectures and visa versa…

Thank you!