BSM and Dark Sectors Across the Board

April 6th 2022

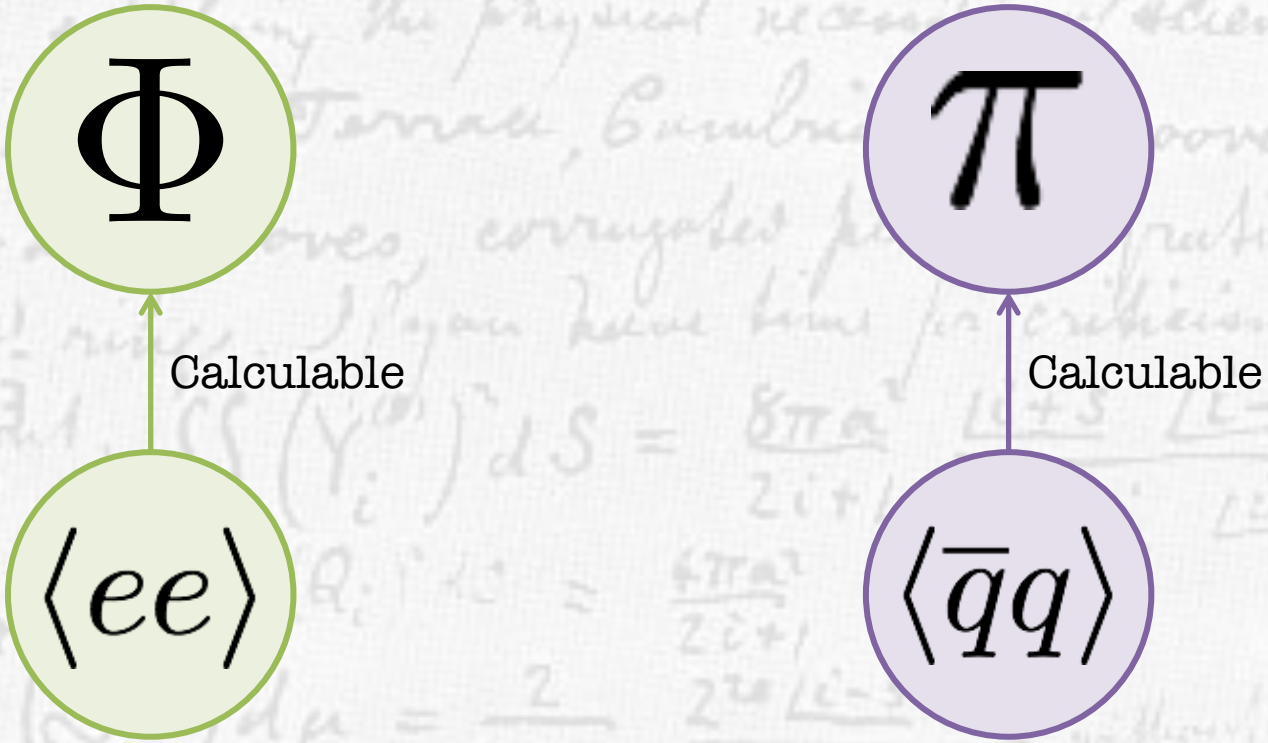
IOP Annual Meeting

Matthew McCullough

BSM – News from the Electroweak Scale

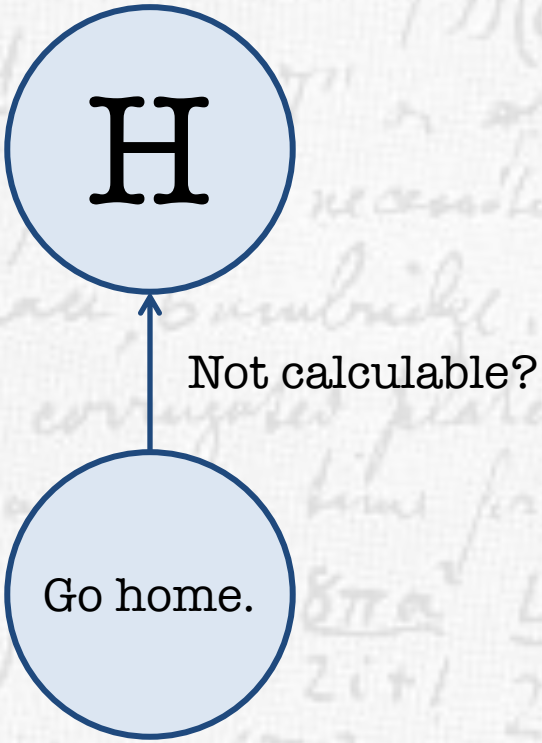
Backdrop

Every scalar we encountered until now has properties (mass, vev, etc) that are calculable within some more fundamental theory:



Backdrop

What about the Higgs?



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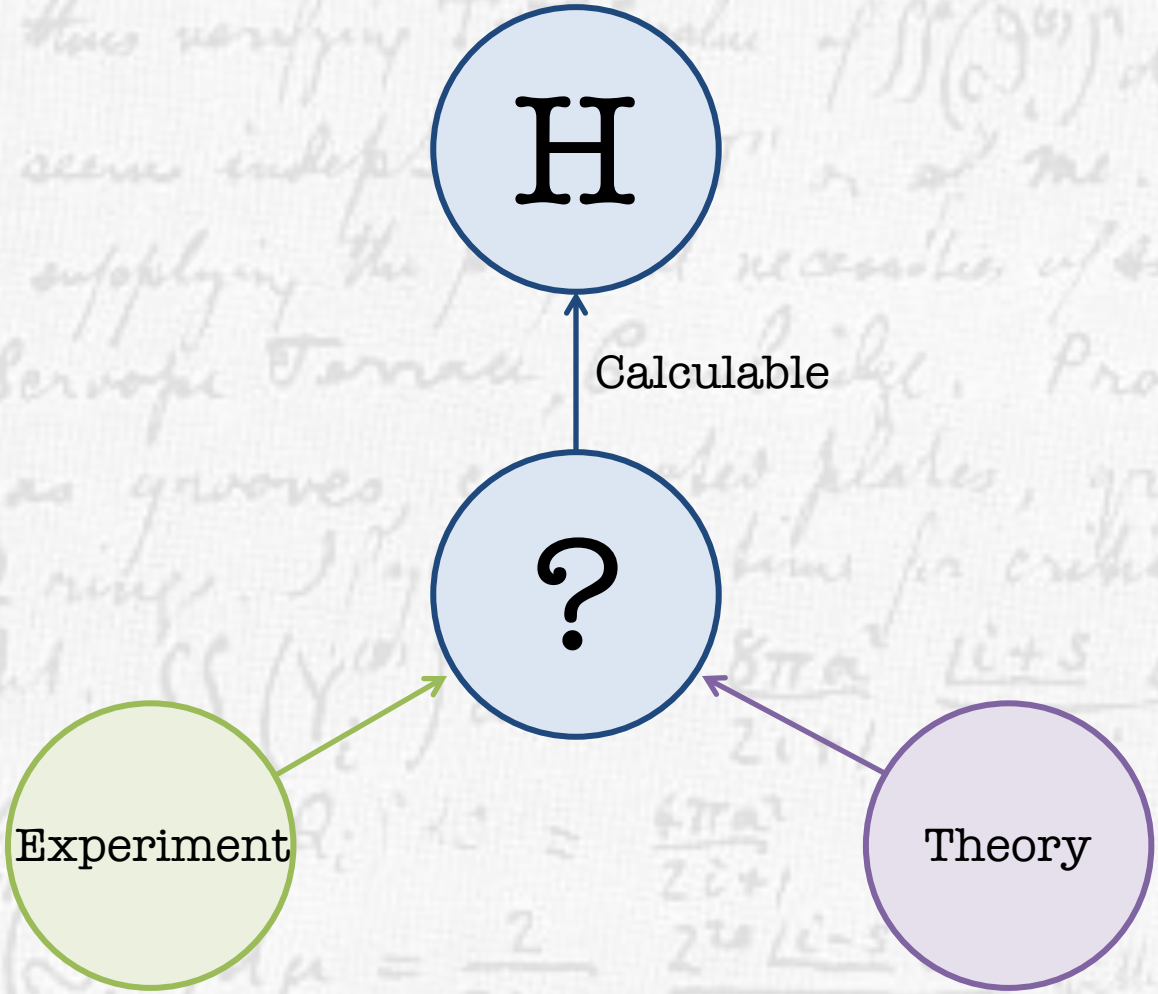

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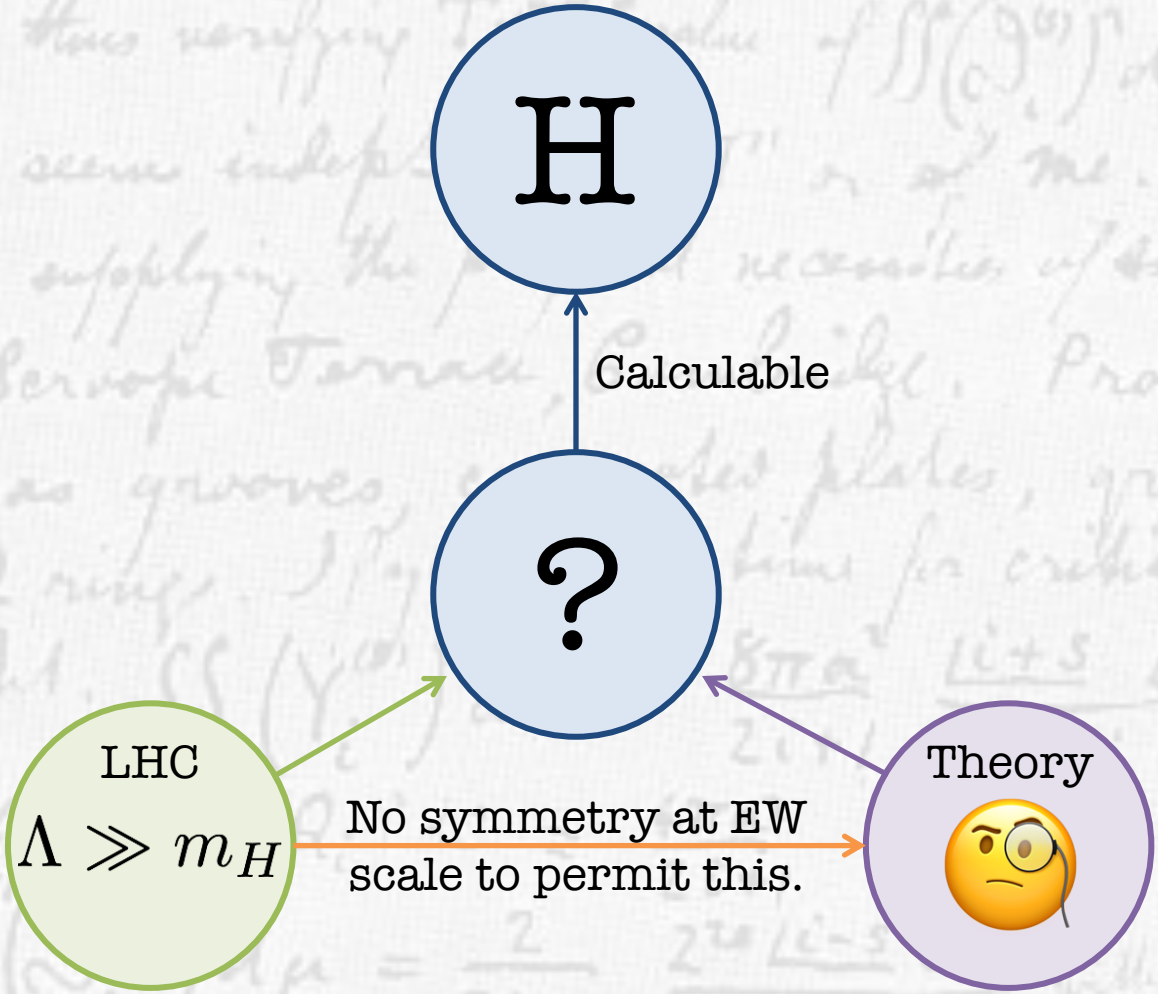


Hierarchy Problem

Many* approaches follow three basic paradigms...

Symmetry.

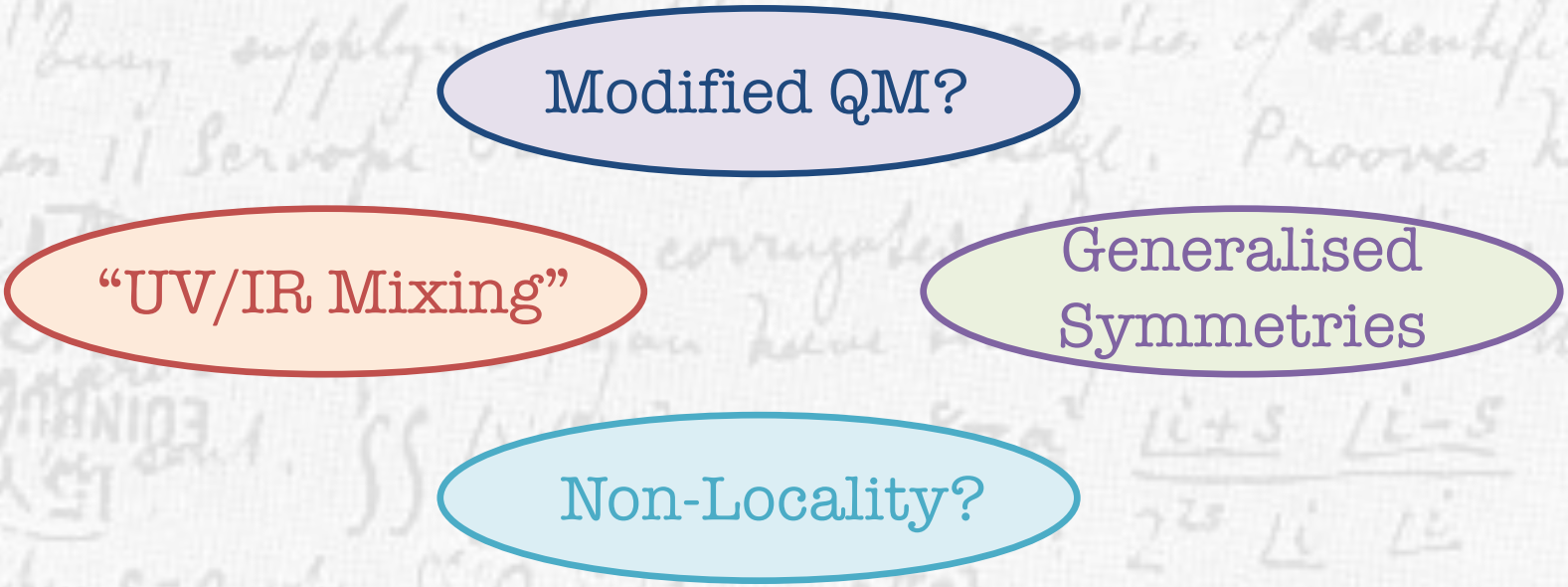
Beyond QFT.

Dynamics.

...all of which have seen significant progress in recent years.

Beyond QFT

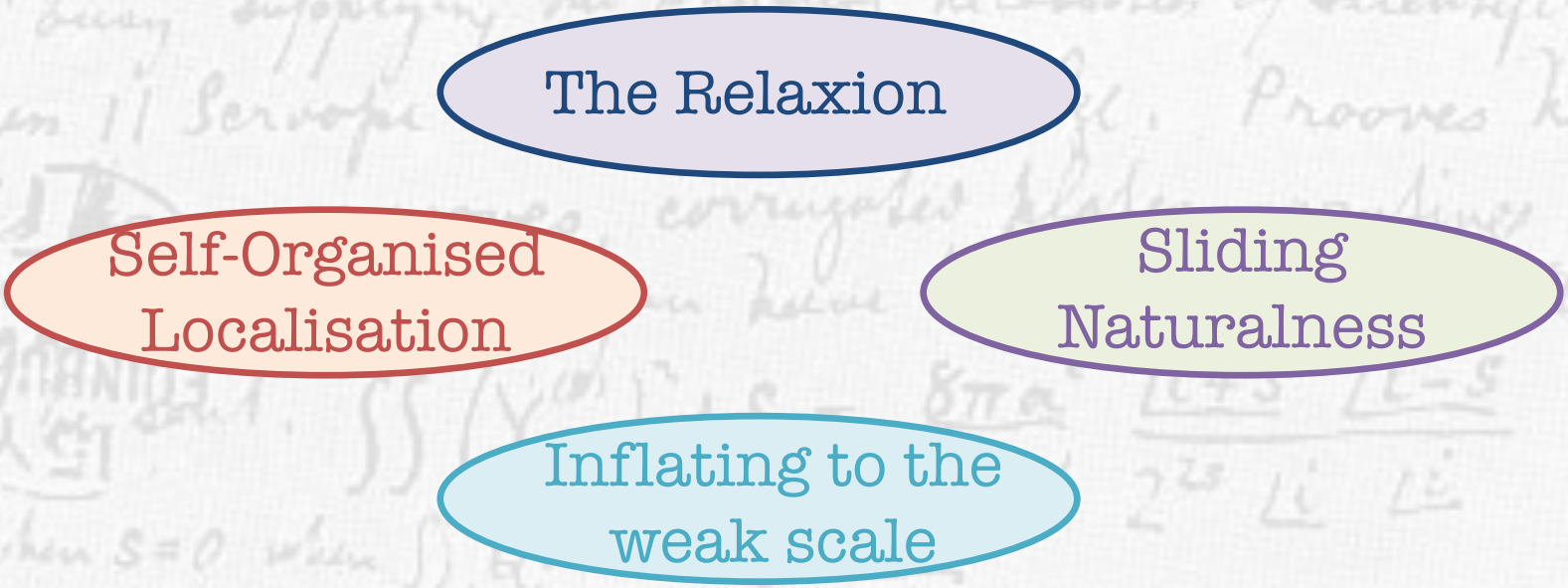
It's possible that QFT is wrong, or we don't understand it fully, and so view missing something. Gravity gives clues potentially.



Great free magazine article. Search for "Quanta Magazine Isabel Garcia Garcia".

Dynamics

There has been an explosion of ideas connecting early universe cosmology to the hierarchies of scales in physics. Including:

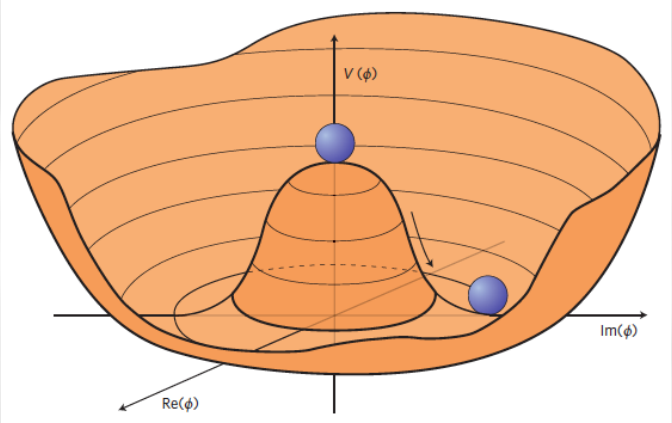


However, irreducible experimental signatures are few and far between...

But symmetry is not dead!

A Pion-like Higgs?

Consider pions. The reason they are so much lighter than the QCD scale is that they arise from spontaneous global symmetry breaking (Goldstone's Theorem):



Mass comes from terms that explicitly break the global symmetry, notably quark masses.

How far can we generalise this?

A Pion-like Higgs?

Durieux, MM, Salvioni 2021

To generate a pion-like Higgs potential assume some small explicit global symmetry-breaking "spurion" in a symmetric irrep with "n" indices:

$$V_\epsilon = \frac{\lambda}{f^{n-4}} \epsilon_{a_1,a_2,\ldots,a_n} \phi^{a_1} \phi^{a_2} \ldots \phi^{a_n}$$

This potential is not fine-tuned. Since an irrep is traceless the lowest dimension operator allowed is this and all others at:

$$\mathcal{O}(\epsilon^2, \epsilon^3, ..)$$

A Pion-like Higgs?

Durieux, MM, Salvioni 2021

Writing usual parameterisation for pion-like Higgs:

$$\phi = \frac{1}{\Pi} \sin \frac{\Pi}{f} \begin{pmatrix} \Pi_1 \\ \Pi_2 \\ \vdots \\ \Pi_N \\ \Pi \cot \frac{\Pi}{f} \end{pmatrix}, \qquad \text{with} \quad \Pi = \sqrt{\boldsymbol{\Pi} \cdot \boldsymbol{\Pi}}$$

We find:

$$V = \epsilon m_\rho^2 f^2 \, G_n^{(N-1)/2}(\cos \Pi / f)$$

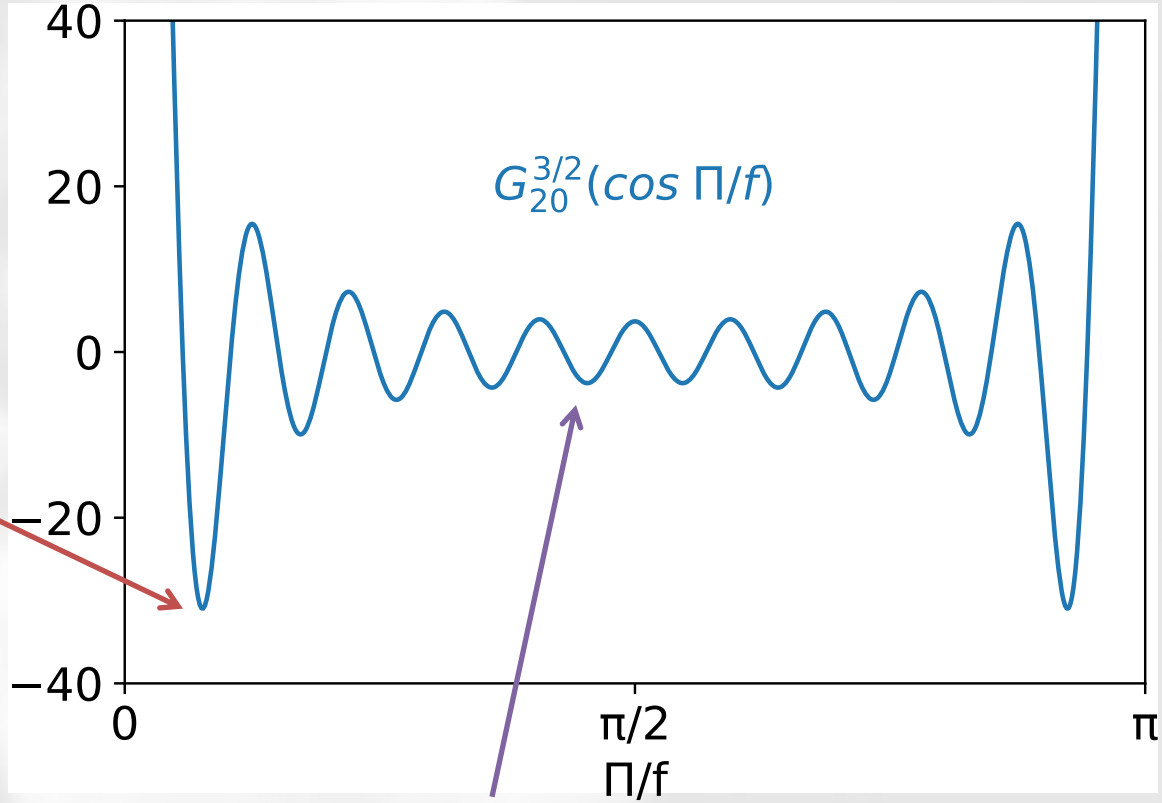
This is a Gegenbauer polynomial!

Getting to know Gegenbauer

The Gegenbauer potential looks like:

Global minimum at naturally small field values:

$$\frac{\langle \Pi \rangle}{f} \approx \frac{j_{\lambda+1/2,1}}{n+\lambda} \approx \frac{5.1}{n}$$



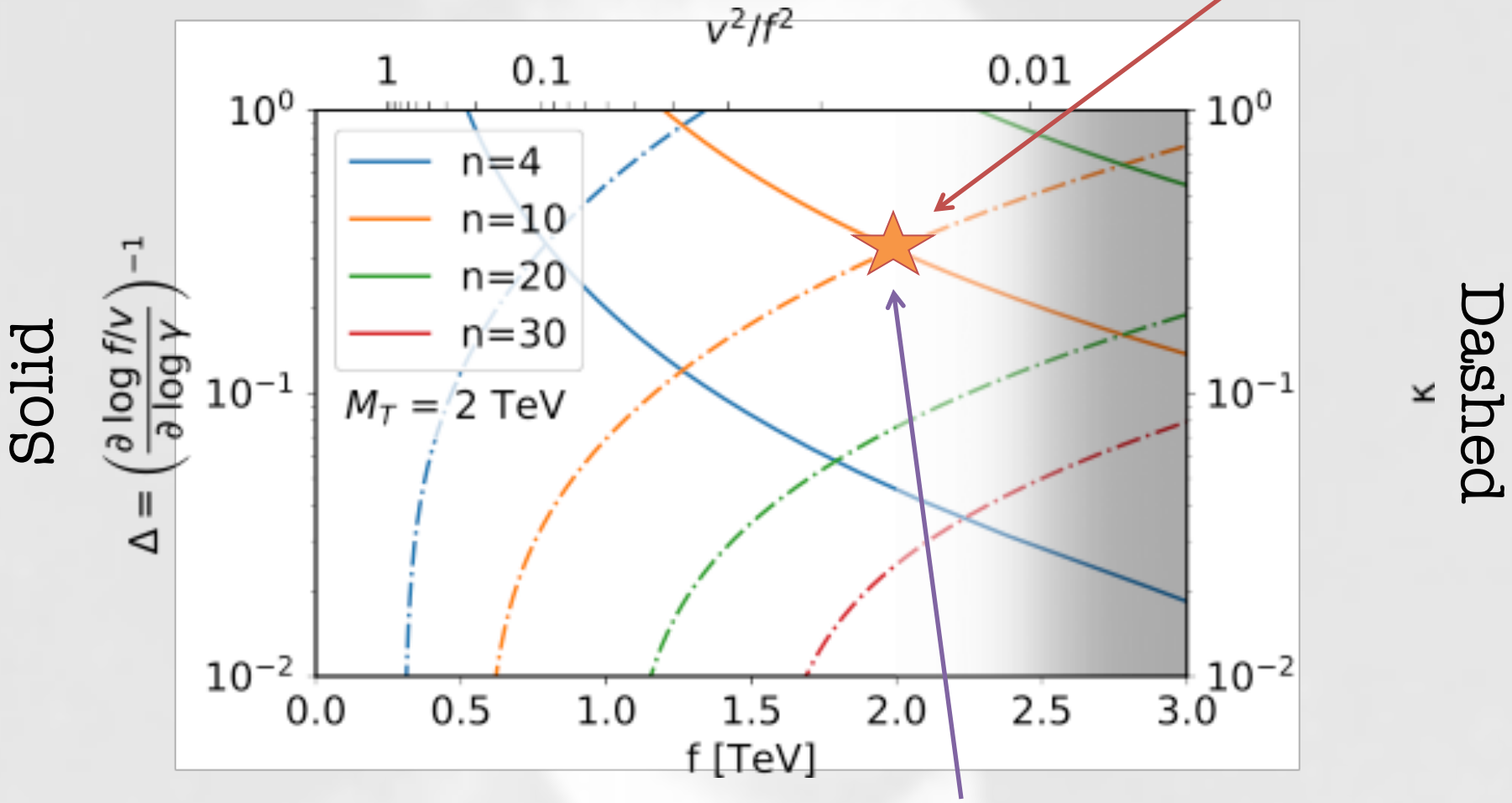
Approximately periodic:

$$G_n^\lambda\left(\cos\frac{\Pi}{f}\right) \xrightarrow{n\gg 1} \frac{J_{\lambda-1/2}\left((n+\lambda)\frac{\Pi}{f}\right)}{\Pi^{\lambda-1/2}} \xrightarrow{\frac{\Pi}{f}\gg\frac{1}{n}} \frac{\cos\left((n+\lambda)\frac{\Pi}{f}-\lambda\frac{\pi}{2}\right)}{\Pi^\lambda}$$

Fine-Tuning

Quantitatively:

Total tuning less than 10%.

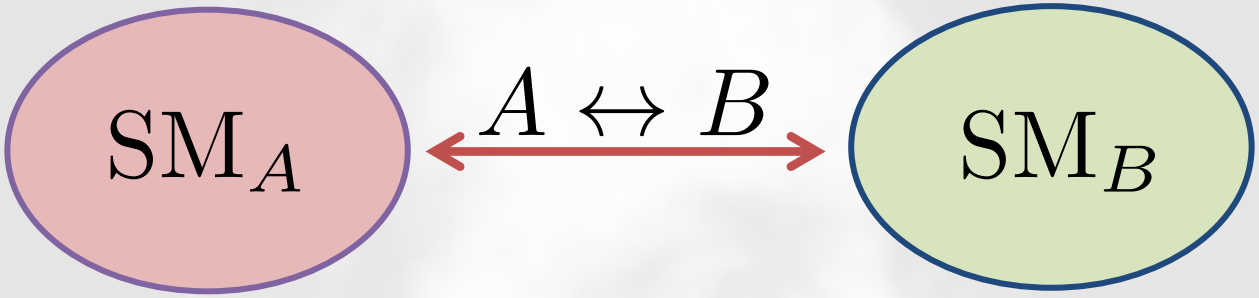


Higgs couplings SM-like at 1% level!

Twin Higgs

Chacko, Goh, Harnik 2005

Take two identical copies of the Standard Model:

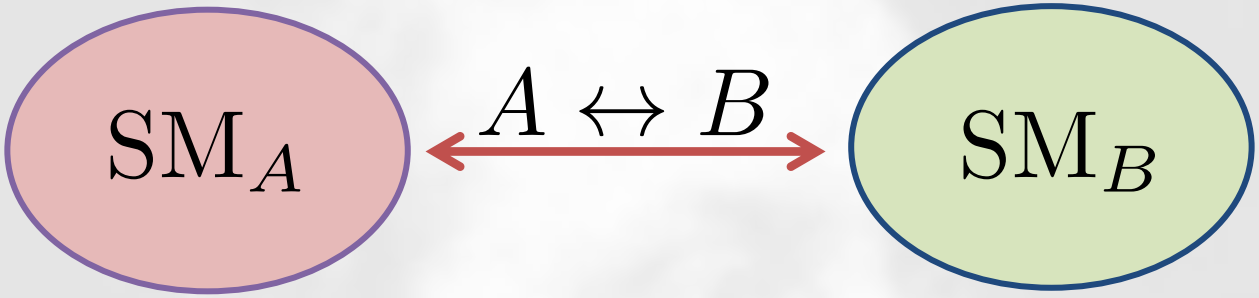


Everything twinned.

Twin Higgs

Chacko, Goh, Harnik 2005

- Take two identical copies of the Standard Model:



- Enhance symmetry structure to global SO(8):

Desired quartic dictated by accidental symmetry:

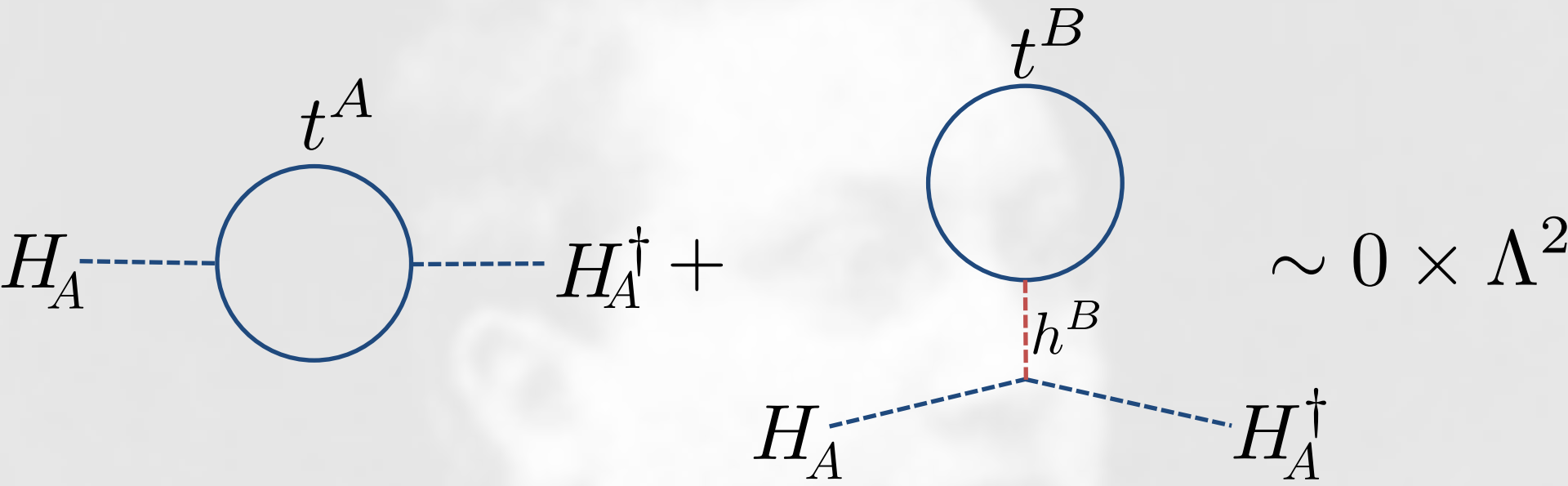
$$V_{\mathrm{Higgs}} = \lambda \left(|H_A|^2 + |H_B|^2 \right)^2 - \Lambda^2 \left(|H_A|^2 + |H_B|^2 \right)$$

Exchange enforces equal quadratic corrections for each Higgs. Thus masses still respect SO(8) symmetry.

Twin Higgs

Chacko, Goh, Harnik 2005

In outdated "quadratic divergences" parlay:



Quadratic divergences from SM top quark loops cancelled by loops of "Twin" top quarks.

Cancellation persists for all Twin particles: Twin W-bosons, Twin gluons, etc.

Twin Higgs

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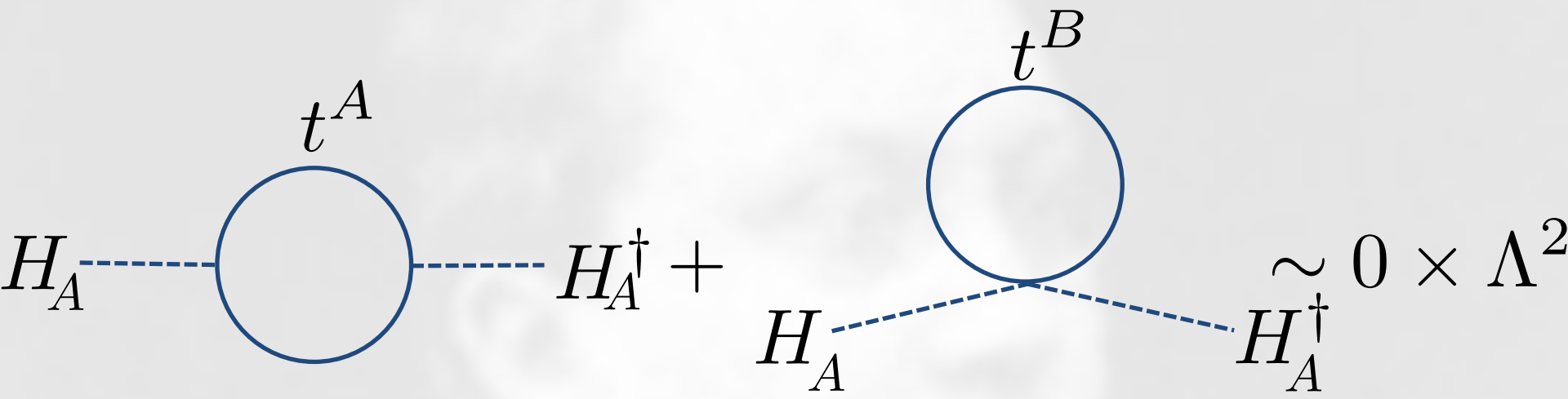

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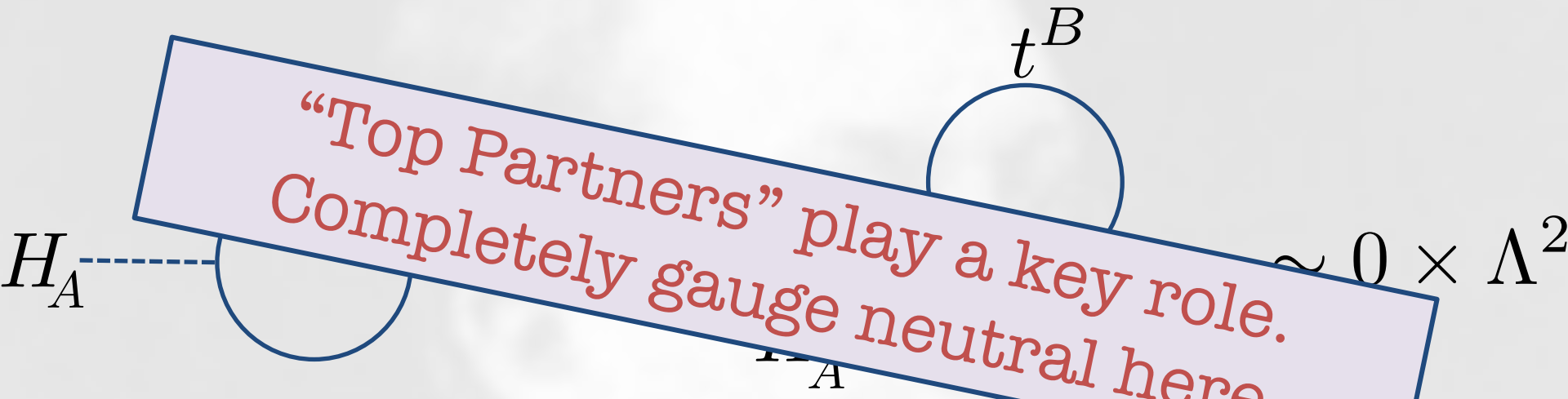

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Gegenbauer's Twin

Durieux, MM, Salvioni 2022

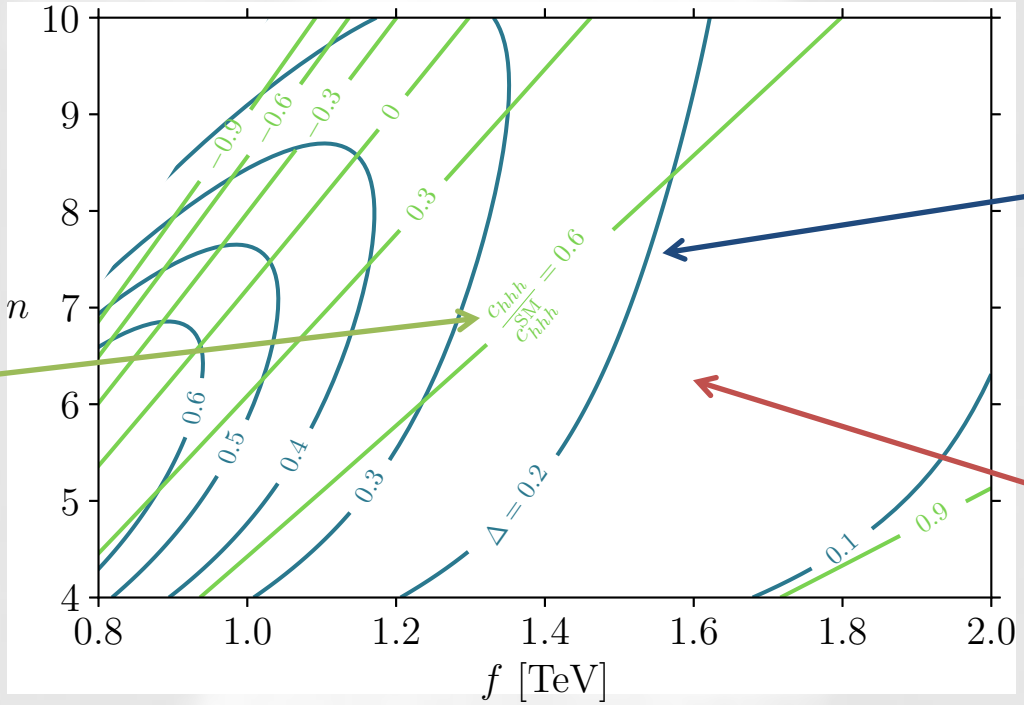
Gegenbauer contribution allows to naturally have a small weak scale...

Twin Higgs models, however, address the top sector part of the tuning...

Gegenbauer's Twin

Durieux, MM, Salvioni 2022

While the single-Higgs coupling corrections are small, Higgs trilinear receives big corrections:



Contours of self-coupling Relative to SM prediction.

Tuning contours.

Universal 1% modification of single-Higgs couplings.

This is a smoking-gun signal of Gegenbauer's Twin and could be detected at the HL-LHC.

Mini-Summary

The hierarchy problem is still there.

New ideas are being proposed all the time.

We must measure all of the properties of the Higgs boson.

Mini-Summary

The hierarchy problem is still there.

I have focussed in one topic in detail, at the price of omitting a great deal else going on, flavour, neutrinos, etc.

We must measure all of the properties of the Higgs boson.

BSM – News from the dark side

Dark Sectors

Evidence for dark matter is now overwhelming

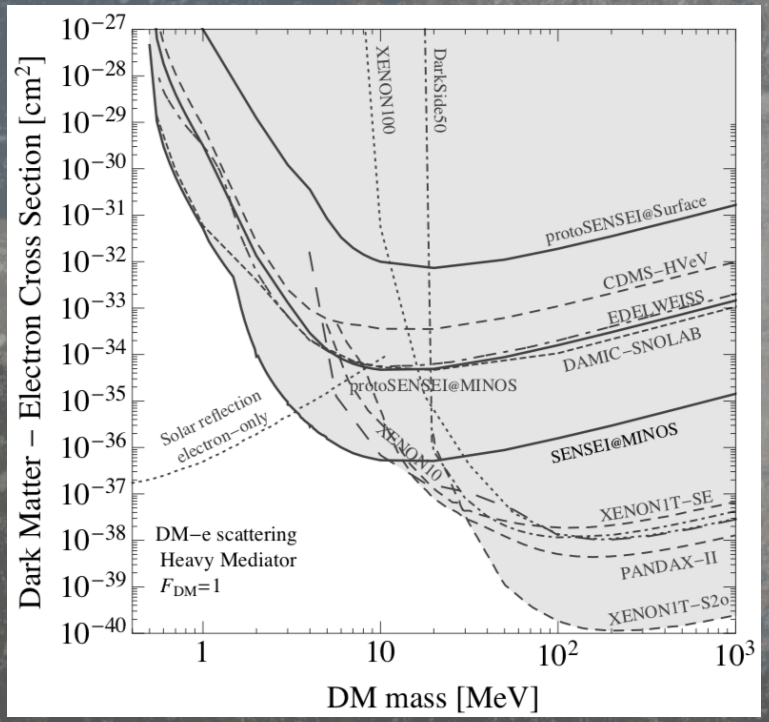
- Rotation curves
- CMB
- Large scale structure
- Velocity dispersions
- Gravitational lensing (Bullet Cluster)
- ....

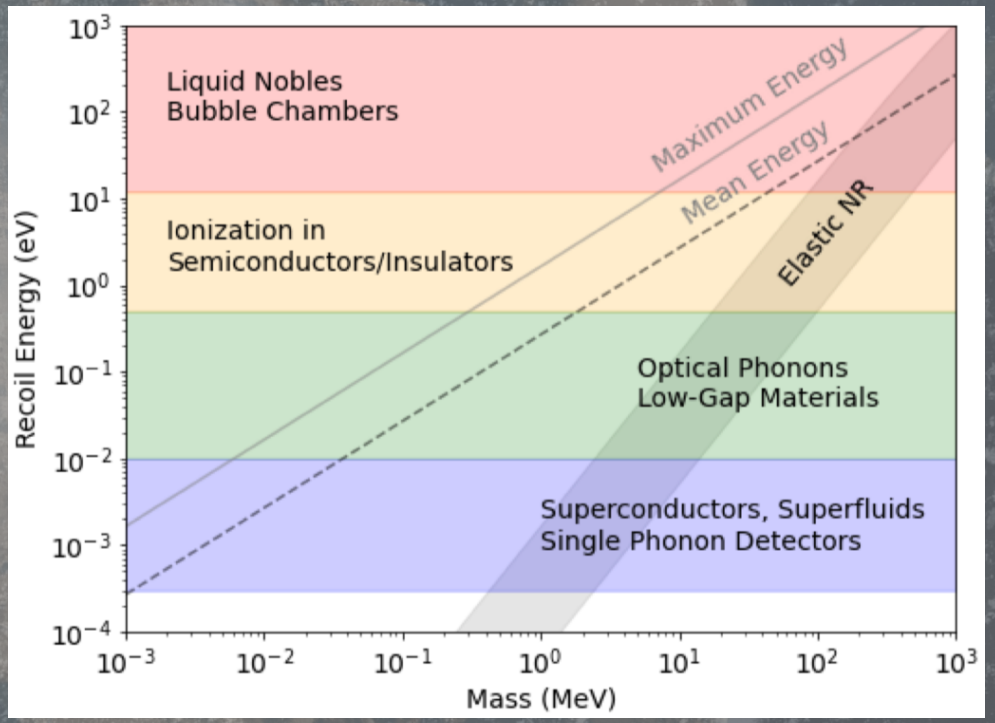
Yet we have no clue what it is at the particle level!

Feeling in the Dark

Snowmass Cosmic 2022

Recent years have seen an explosion in novel ideas for exploration in direct dark matter detection.





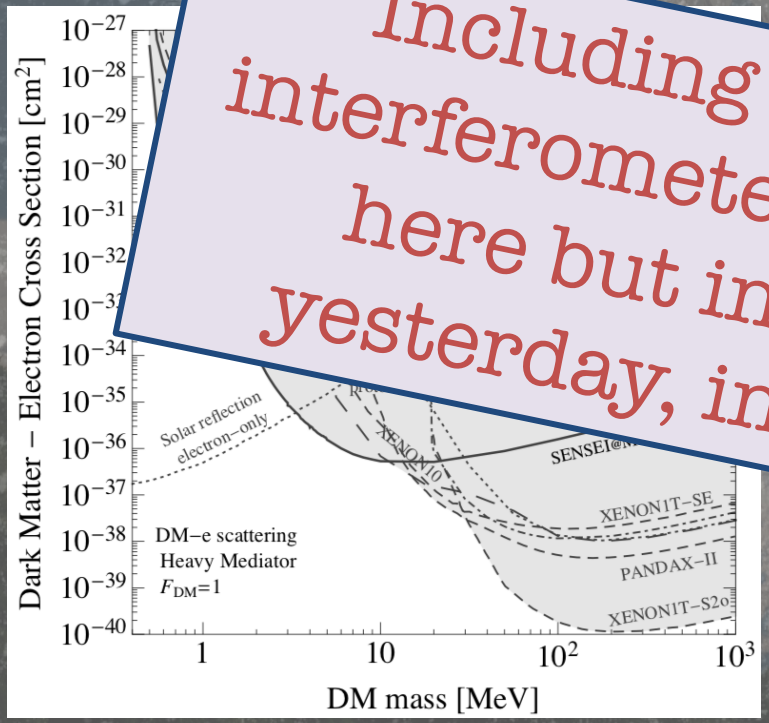
Have already fed into current limits (left) and are suggesting new materials for future (right).

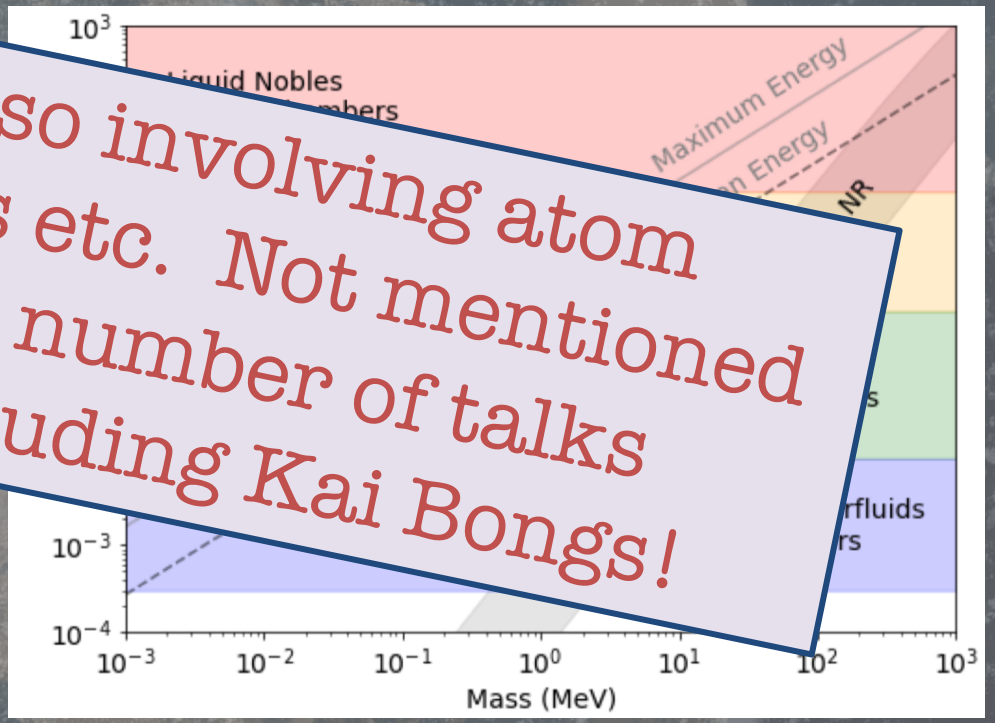
Feeling in the Dark

Snowmass Cosmic 2022

Recent years have seen an explosion in novel ideas for exploration in direct dark matter detection.

Including also involving atom interferometers etc. Not mentioned here but in a number of talks yesterday, including Kai Bongs!



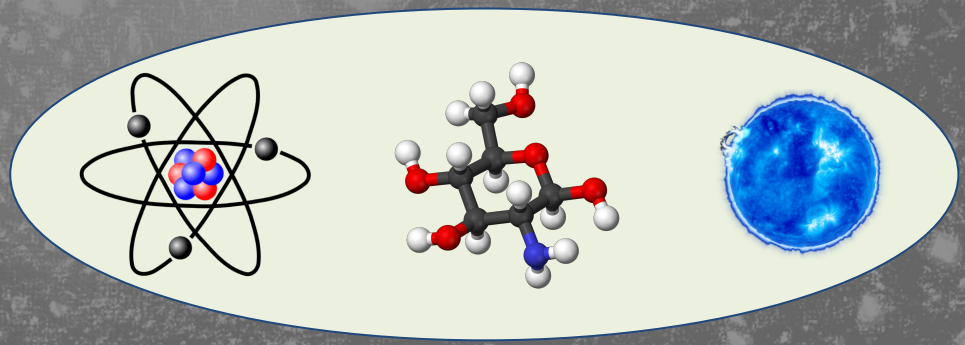


Have already fed into current limits (left) and are suggesting new materials for future (right).

Only 18% of all matter in Universe is visible.

e u d Z h
μ c s g
τ t b γ W

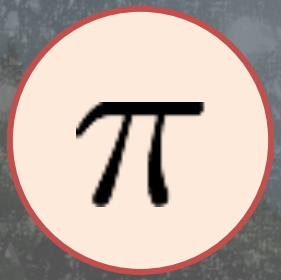
Within that 18% we observe extraordinary complexity.

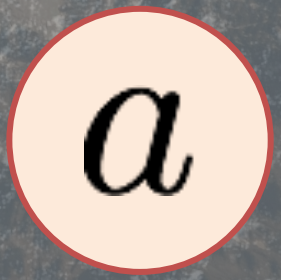


Similarly, it may be the light mediators, or other states, that open the window to the dark sector.

Windows

The standard model provides two examples of neutral bosons which can comfortably be light and have arbitrarily weak interactions:





Standard Model

Dark Sector

Feeling in the Dark

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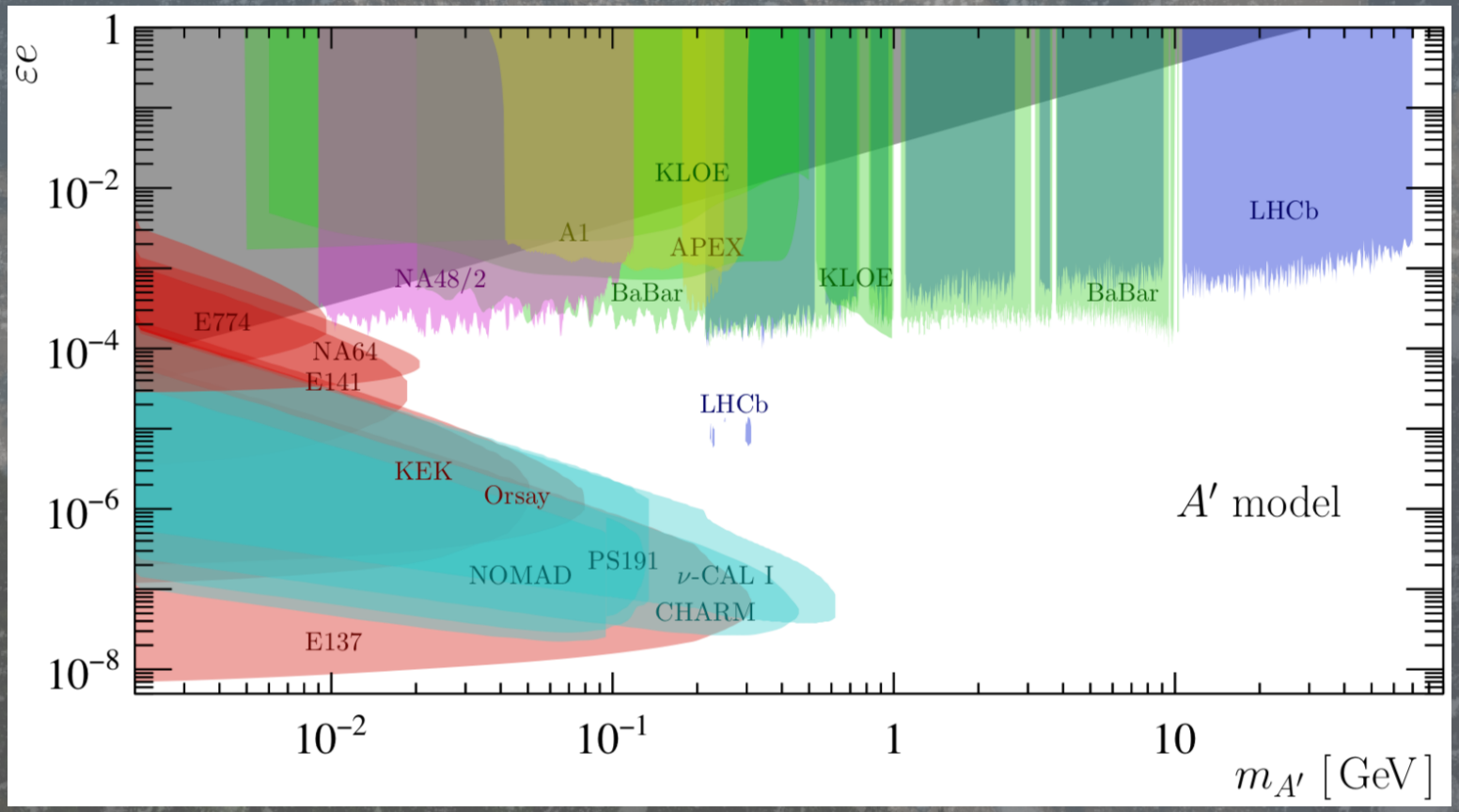
Ideas for probing dark sector species have also seen blossoming of possibilities.



From rare flavour processes to fixed target.

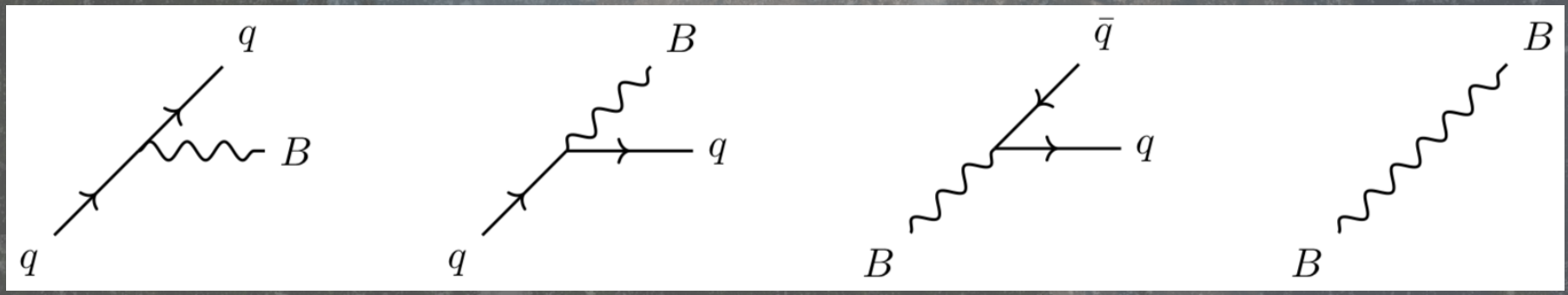
Dark Boson

MM, Moore, Ubiali, 2022

Consider a dark boson coupled to quarks:

$$\mathcal{L}_{\text{int}} = \frac{1}{3} g_B \bar{q} \not{B} q$$

This dark photon will have its own pdf, due to splitting etc:



Dark Boson

MM, Moore, Ubiali, 2022

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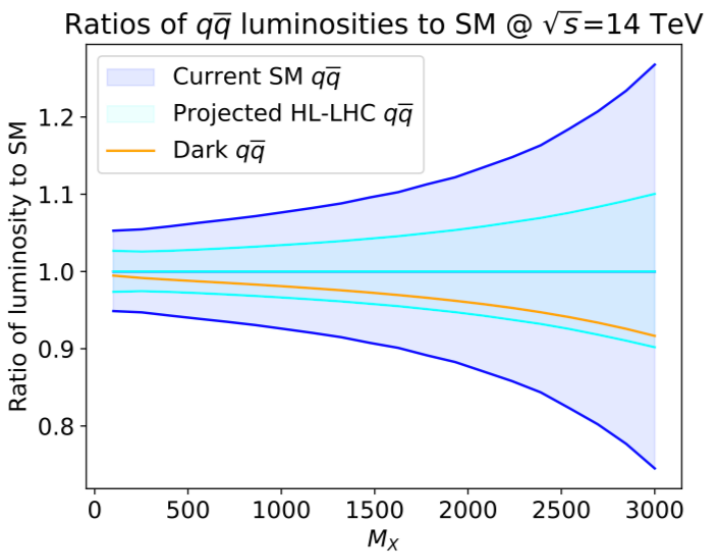
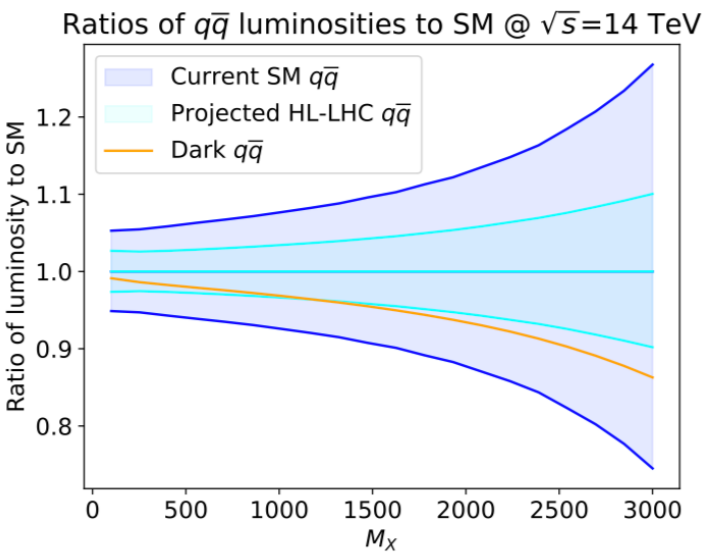
Which will in turn modify the quark pdfs as well:



(c) $m_B = 5$ GeV, $\alpha_B = 3 \times 10^{-3}$



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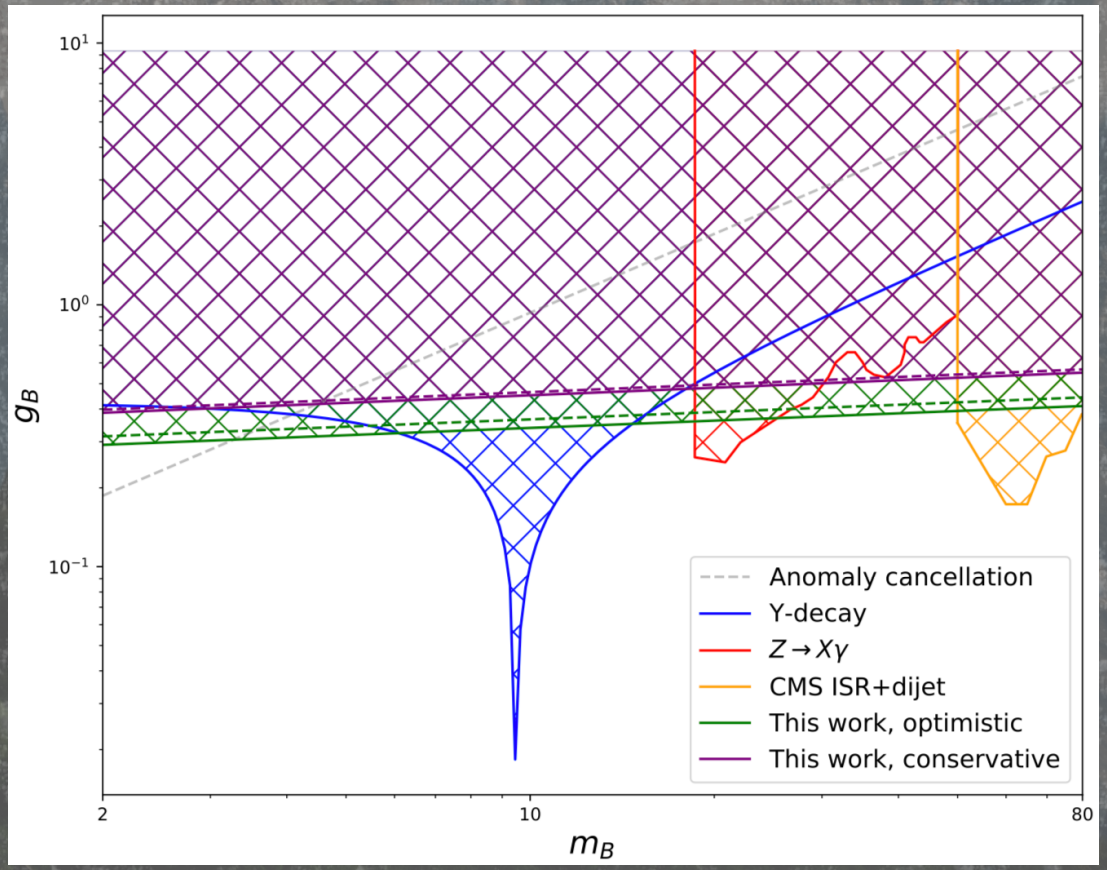
High-precision Drell-Yann can constrain the dark boson parameter space in a complementary manner to alternative probes.



Dark Boson

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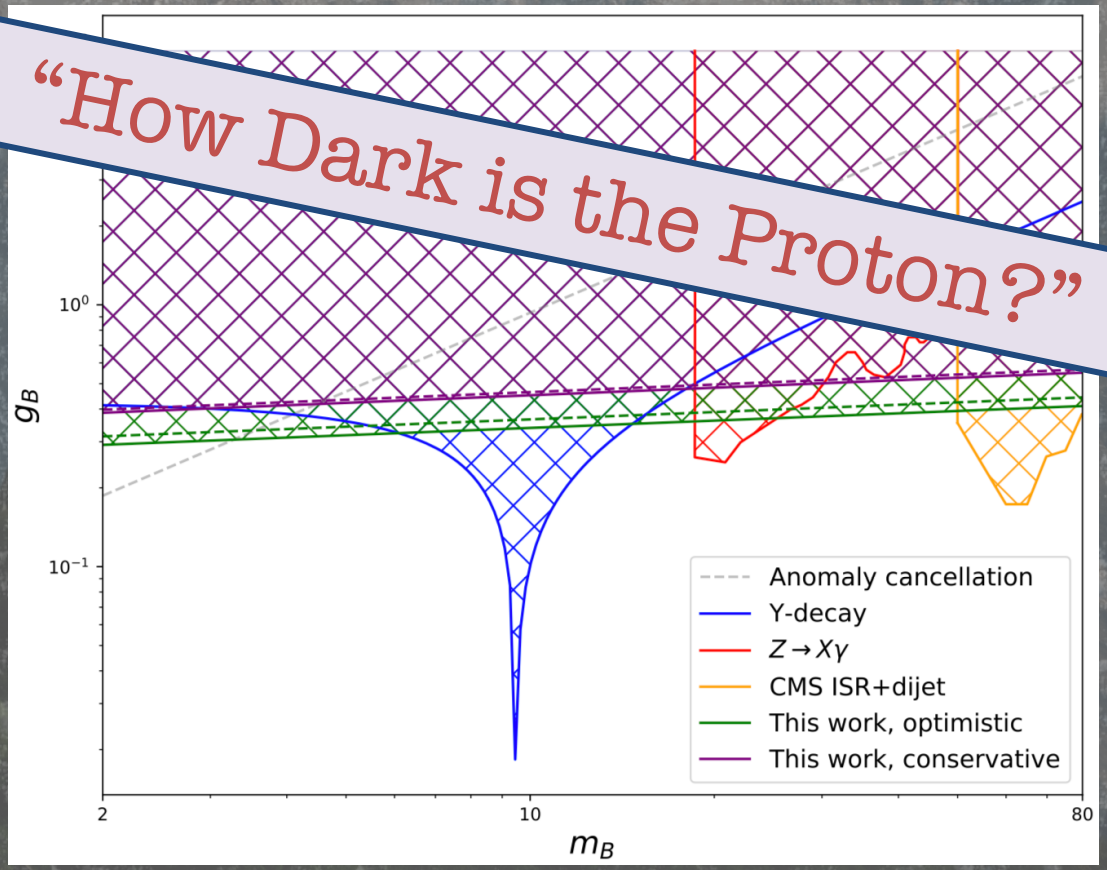
"How Dark is the Proton?"



Summary

BSM, across the board, is very much alive and kicking. Progress is rapid and exciting. New ideas abound.

Vast swathes of unexplored territory remain at the EW scale. Absolutely imperative we study everything about the Higgs. We don't know if it is Standard Model-like or not yet.

Theoretical view of the dark sector landscape is maturing and increasingly humble. This has ignited numerous new experimental ideas.