DARK MATTER THEORY / MODELS: AN OVERVIEW

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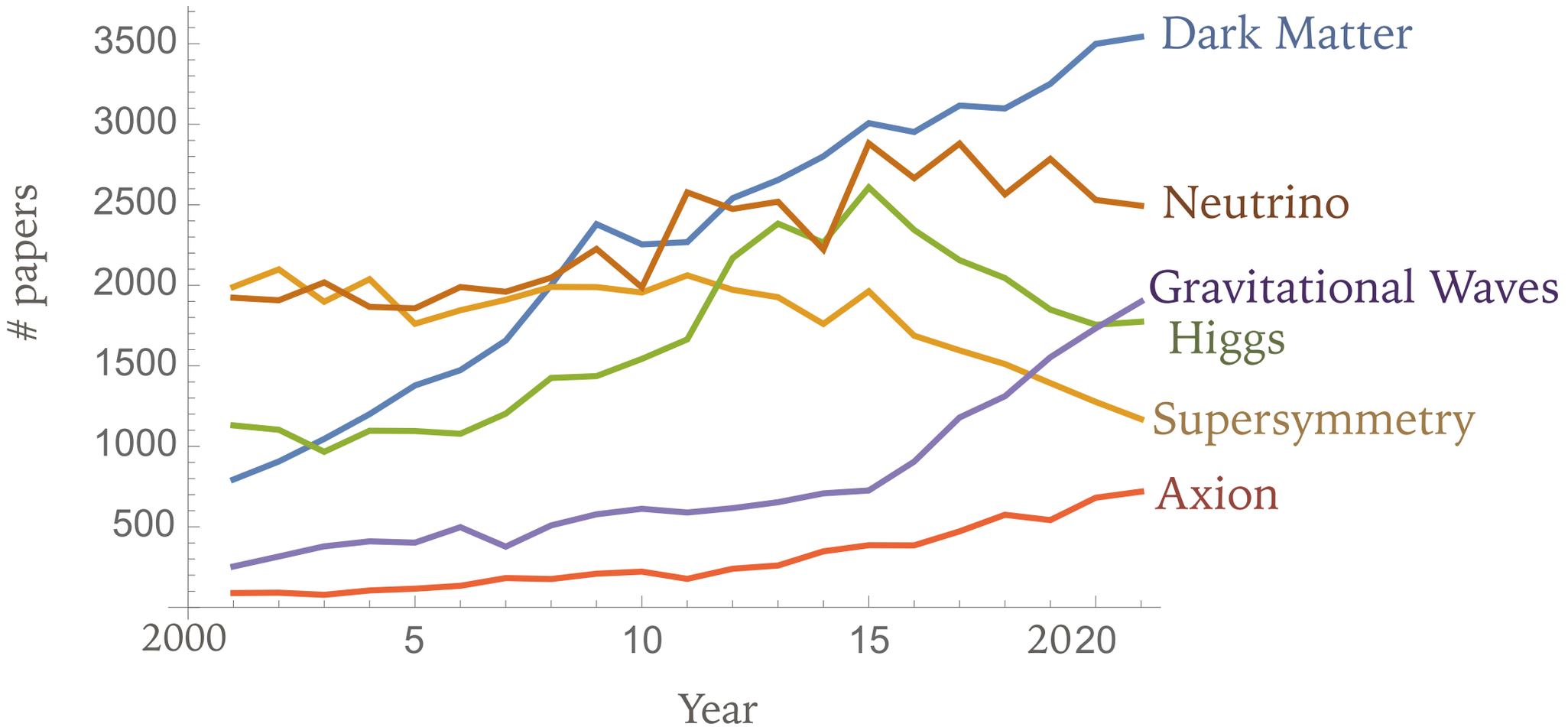
SECOND EUCAPT SYMPOSIUM

(Image Credit: Shutterstock)

DARK MATTER CONTINUES TO REMAIN ONE OF THE MOST ACTIVE RESEARCH TOPICS IN HIGH ENERGY PHYSICS

(as of 23/05/2022)



DARK MATTER CONTINUES TO REMAIN ONE OF THE MOST ACTIVE RESEARCH TOPICS IN HIGH ENERGY PHYSICS

Undergone **significant paradigm changes** in the past decade, driven both by our **evolving understanding of the underlying theoretical structure of nature** and by **new experimental developments**

CONTINUES TO BE A RICH DIRECTION FOR NEW IDEAS AND POSSIBILITIES!

FOUNDATIONS OF DARK MATTER MODELS

Needs theory motivation

Tie its existence to a possible solution to one of the “eternal” questions

- Hierarchy Problem
- Baryon asymmetry
- Neutrino Masses
- Strong CP problem
- Inflation
- Flavor Puzzle

BUILDING A DARK MATTER MODEL: THE ART OF SMALL NUMBERS

- Small abundance: $\frac{n_{DM}}{n_\gamma} \approx 10^{-9}$
- (however, $\Omega_{DM} \approx 5\Omega_{baryons}$)

Strongest hint we have that DM and SM are somehow related!

- "small" interaction cross sections
  (with SM as well as with self; constrained by many observations)
  especially important for nonthermal DM models
- Small decay width (stable over cosmological timescales)
  challenging for decaying DM models
- Small free-streaming lengths ("cold")

BUILDING A DARK MATTER MODEL: THE ART OF SMALL NUMBERS

We have been following this blueprint **over the decades with great success**…but **our understanding of the nature of these problems**, as well as our **ability to test them experimentally**, is **continuously changing**.

Our dark matter models must change too!

- Small free-streaming lengths (“cold”)

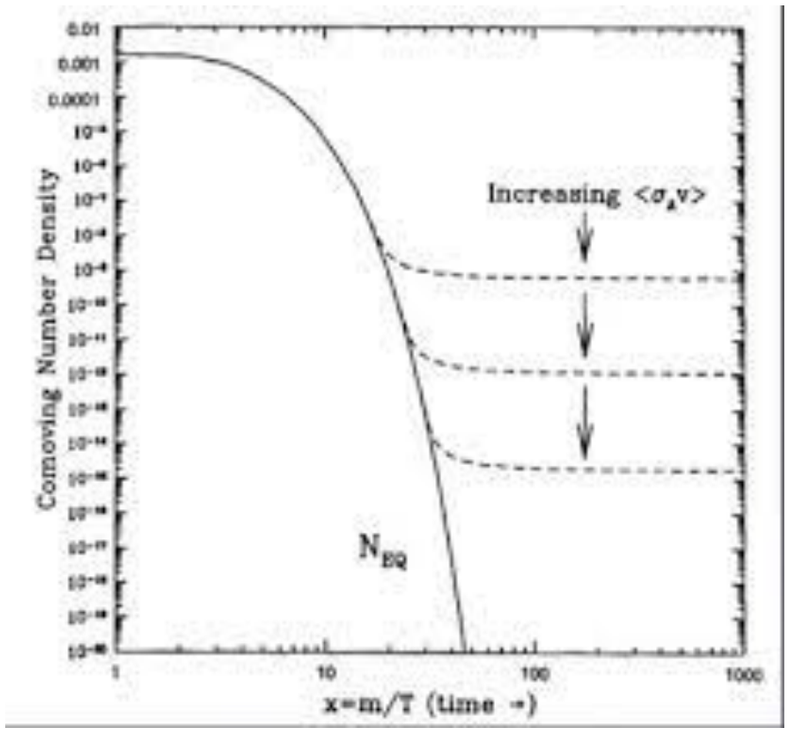
DARK MATTER THEORY TALK, TYPICAL OPENING SLIDE

~10 YEARS AGO

"WE HAVE A VERY GOOD IDEA"

WIMP MIRACLE!

Weak scale mass+cross section
→ correct relic density

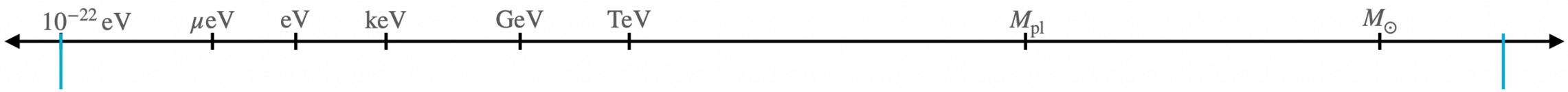


Followed by: details of a BSM model at the weak scale that includes a dark matter candidate, predictions of indirect and direct detection signals

DARK MATTER THEORY TALK, TYPICAL OPENING SLIDE

~TODAY

"WE HAVE NO IDEA!"



Allowed dark matter parameter space spans **several orders of magnitude in mass, not even close to being probed** by experiments

Followed by: focus on a specific mass range, discussion of viable dark matter model(s) in the regime that can be probed in new ways

WIMPS ⟷ ANARCHY

Optimism

Theory motivated

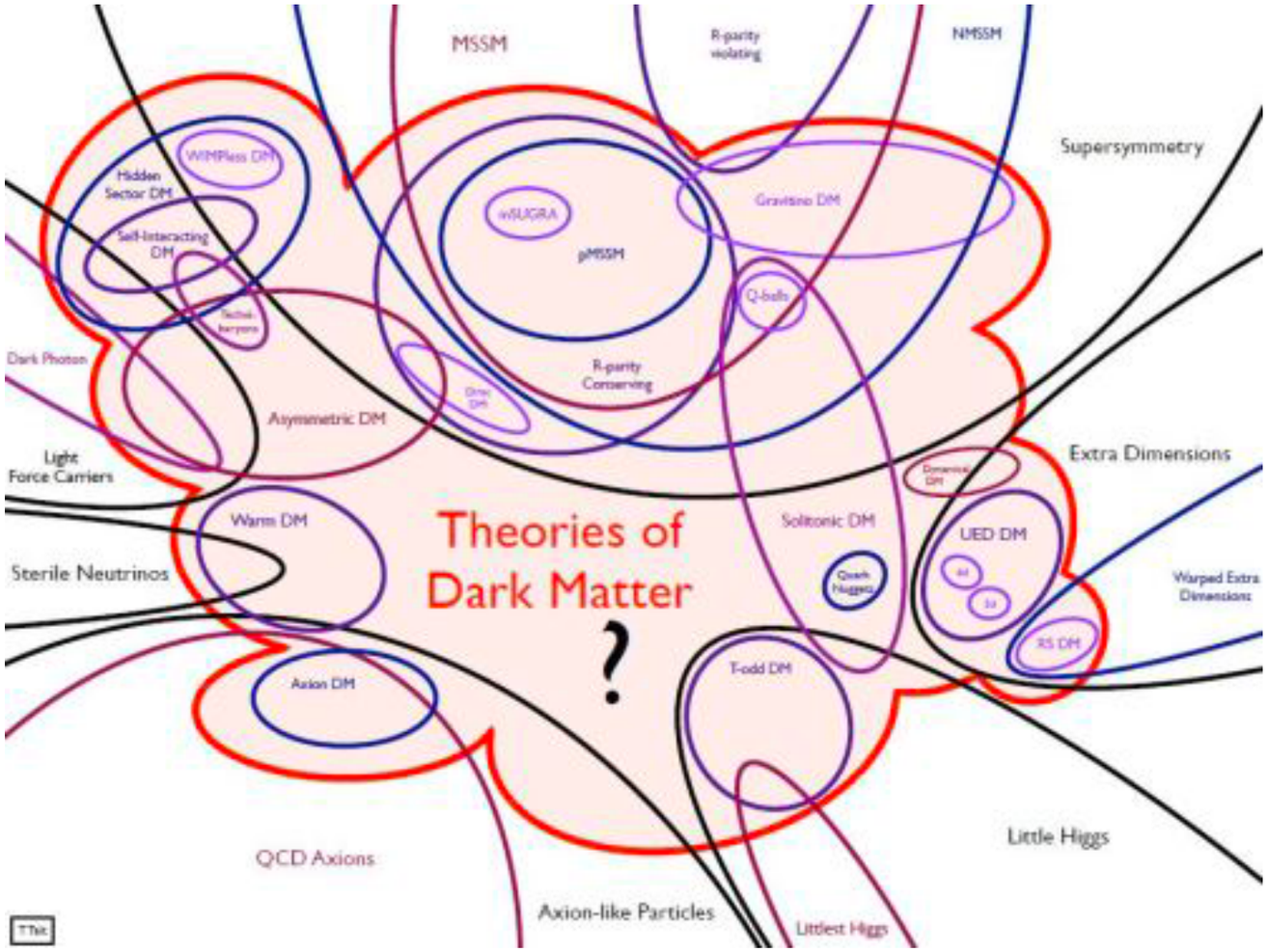
Looking under the lamppost

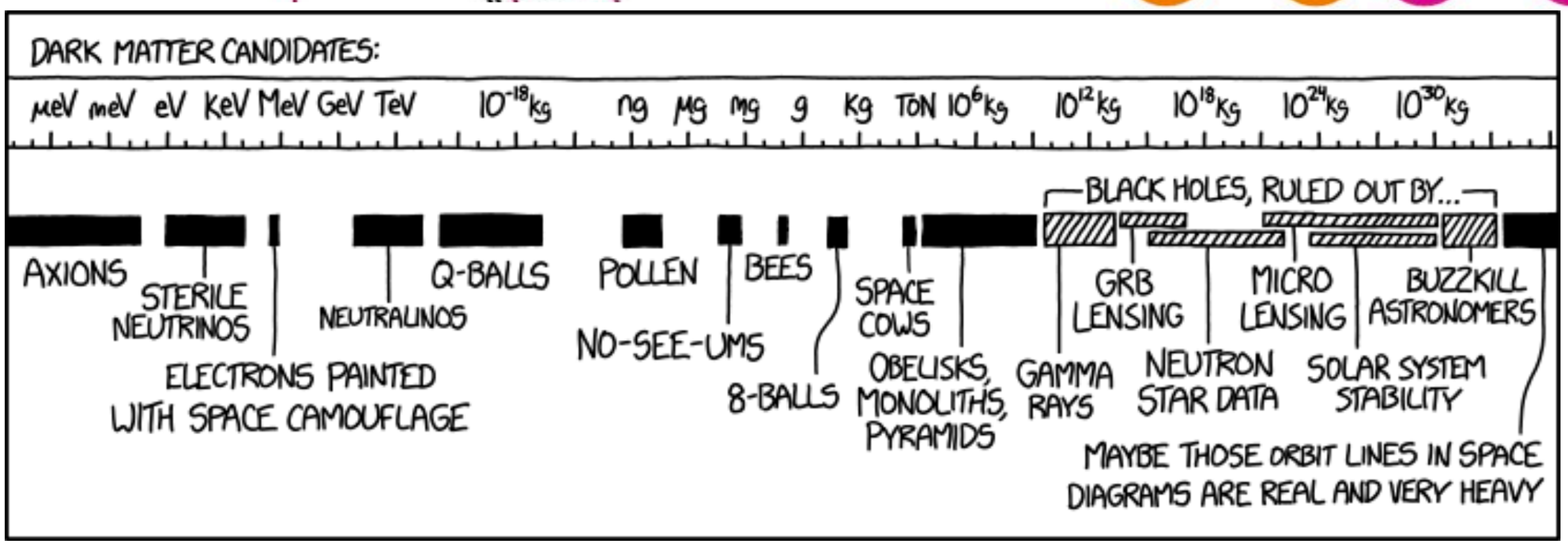
Stuck with old ideas

"Signal" building

Cynicism

DARK MATTER : NO SHORTAGE OF CANDIDATES!





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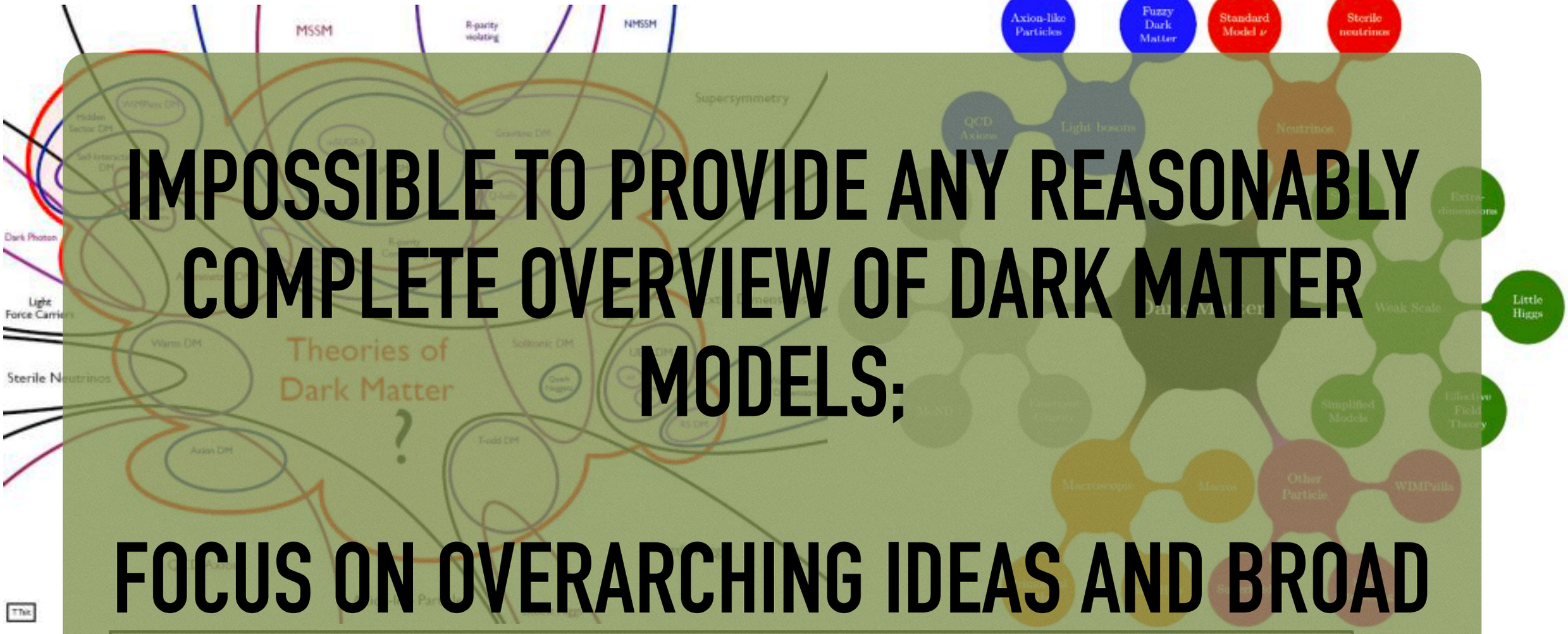
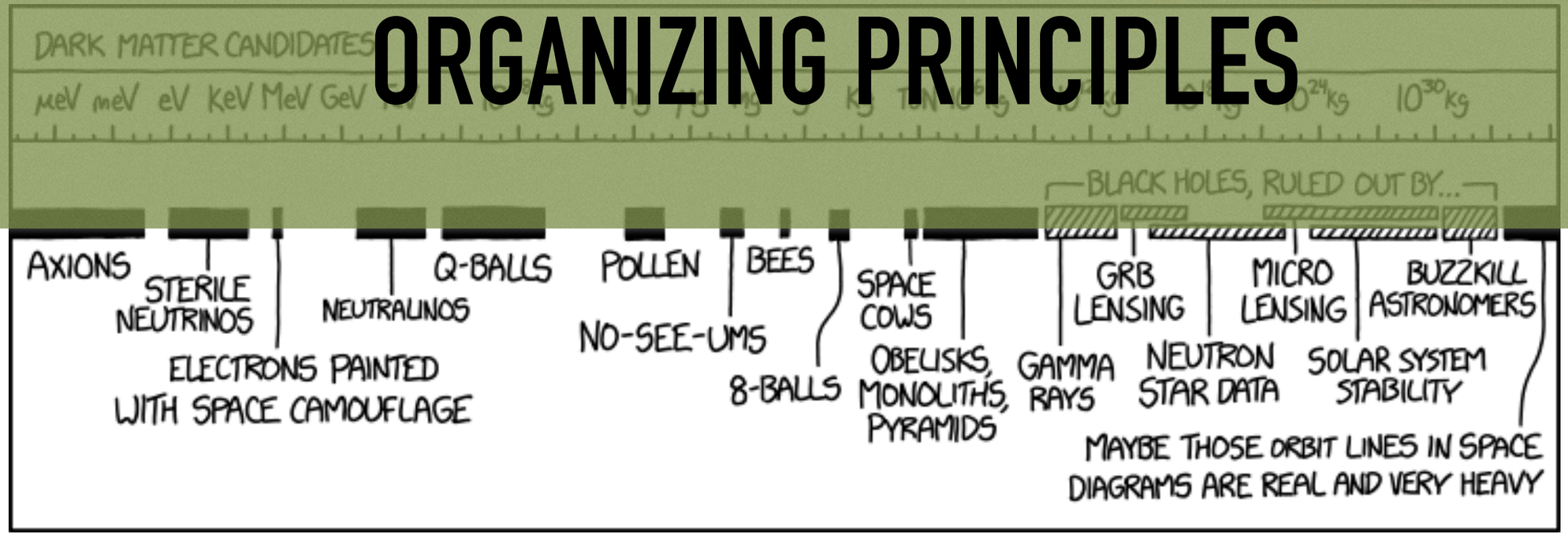


IMPOSSIBLE TO PROVIDE ANY REASONABLY COMPLETE OVERVIEW OF DARK MATTER MODELS;

FOCUS ON OVERARCHING IDEAS AND BROAD ORGANIZING PRINCIPLES



ORGANIZE BY DARK MATTER MASS

see Prateek Agrawal's overview talk
"Model building aspects of dark matter"
First EuCAPT Symposium

de-Broglie wavelength fits within dwarf galaxies

DM mass < halo mass

QCD Axion
ALPs

WIMPs
(e.g. neutralino DM)

Primordial
Black Holes

Many recent, excellent whitepapers from the Snowmass 2022 study

2203.14923 [hep-ex]

2203.14915 [hep-ex]

2203.06680 [hep-ph]

2203.06508 [hep-ph]

2203.08967 [hep-ph]

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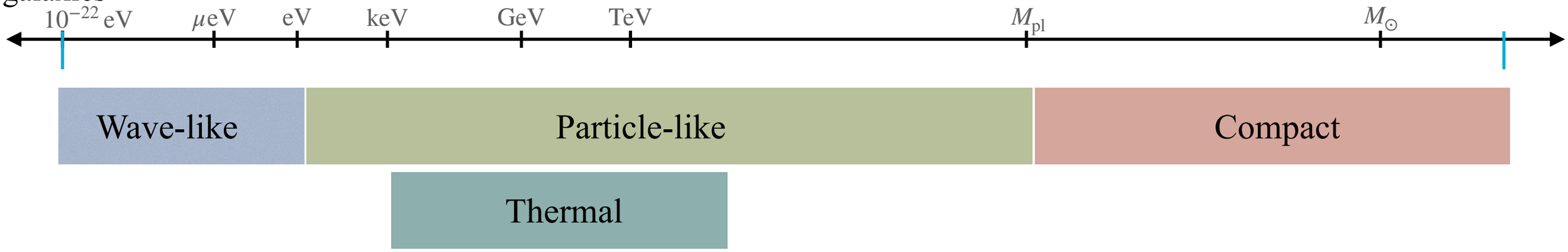

However, important to keep in mind that not all dark matter candidates are amenable to this organizational scheme!

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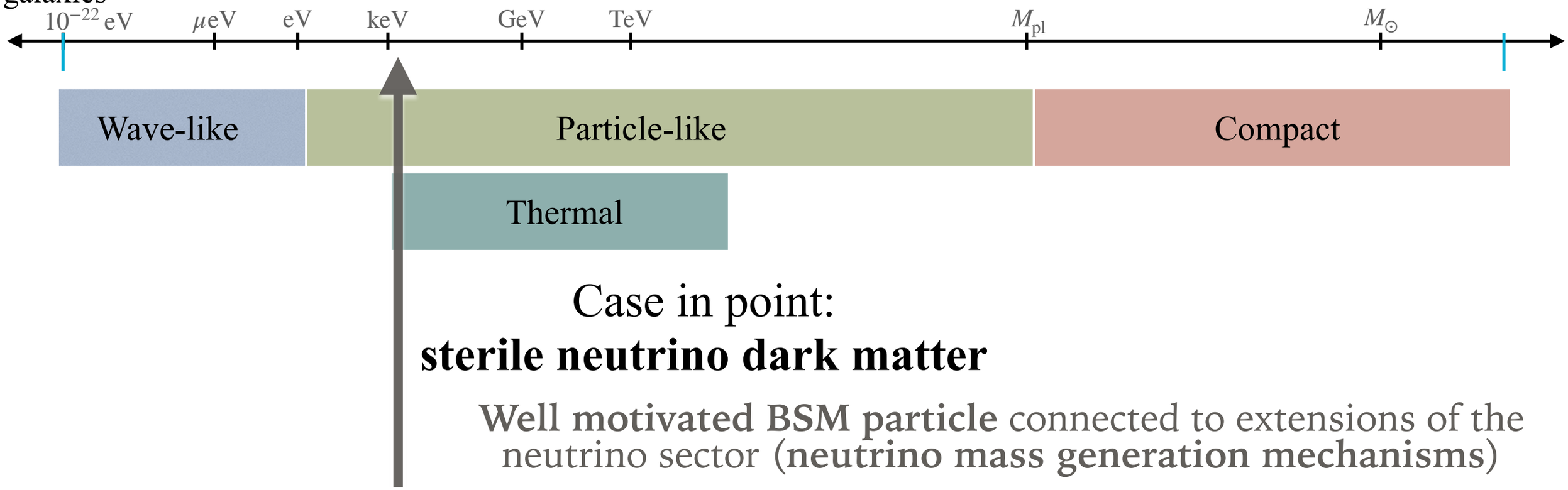

Case in point:

sterile neutrino dark matter

Well motivated BSM particle connected to extensions of the neutrino sector (**neutrino mass generation mechanisms**)

Originally envisioned to be **at keV scale**, where its **mixing with SM neutrinos** gives an appropriately long lifetime as well as the correct relic abundance **(Dodelson-Widrow (DW) mechanism)**.

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Sterile neutrino dark matter produced via **DW is now ruled out by observations!** However, **BSM extensions of the neutrino sector** feature other heavier particles, which can **produce sterile neutrino DM via other mechanisms** (e.g. freeze-in). **Consistent over a much larger mass window!**

WHAT MOTIVATES NEW WORK IN DARK MATTER THEORY?

- **THEORY**

Improved understanding of the underlying structure of nature, as a result of new ideas and insights, and constraints from experiments

EXAMPLE: SUSY WIMP in a hidden sector (with RPV)

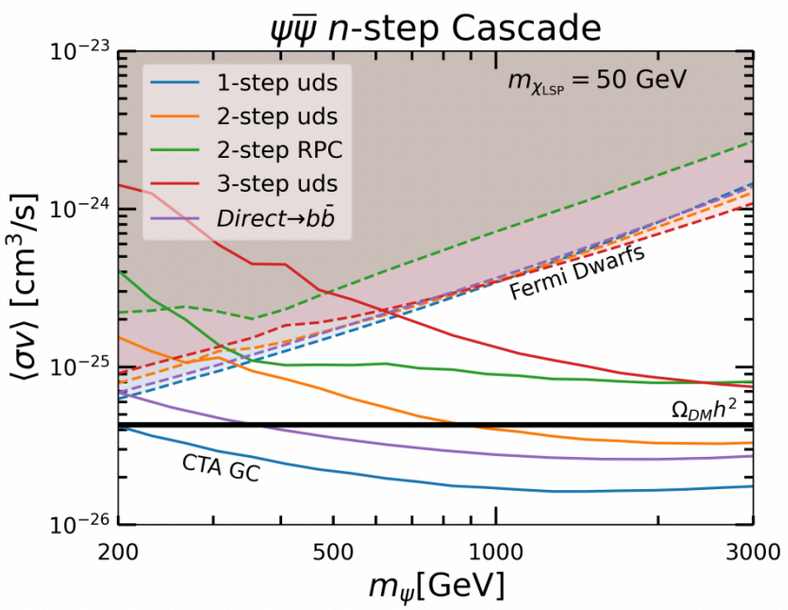
(Barnes, Johnson, Pierce, Shakya, 2003.13744 [hep-ph] 2106.09740 [hep-ph])

Can get WIMP DM in a generic hidden sector…but why weak scale??

LHC results and Higgs mass suggest that superpartners are not at the weak scale, but much heavier (~10 TeV), weak scale seems to an accident rather than a fundamental scale of nature

Gravity mediated SUSY breaking relates the two sectors at some high UV scale, can run to different scales in the IR

WIMP "miracle" in the hidden sector; sharp predictions for indirect detection, coming from multi-layered cascade decays



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- **EXPERIMENTS**

Advent of new experimental programs enable us to probe a new class of dark matter models; requires us to understand theoretically viable models in that parameter space

Recent examples:

dark sectors (high intensity, beam dump type experiments)

Neutrino experiments

ALP searches

Light dark matter with superconductors

Gravitational Waves

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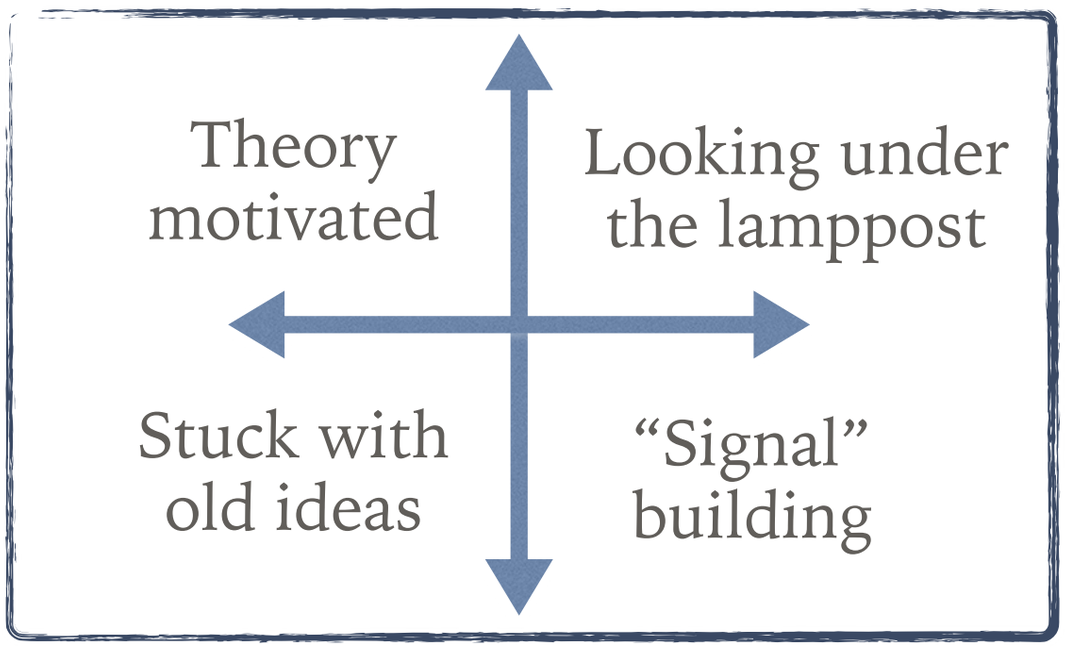
- **ANOMALIES**

Unexpected measurements that invite us to understand the viability of dark matter as a source of the signal

Recent examples: Galactic center excess (indirect detection), Xenon 1T (direct detection), muon g-2 (flavor), Hubble tension (cosmology)

SUMMARY



- Dark Matter Theory/Models: As rich and vibrant as ever!
- Our ideas of nature, and dark matter, have undergone significant paradigm changes in recent times
- Requires a balance between theory and experimental focus, between extreme specialisation and extreme anarchy
- New progress will be driven by a combination of theoretical insights, experimental advances, and anomalies