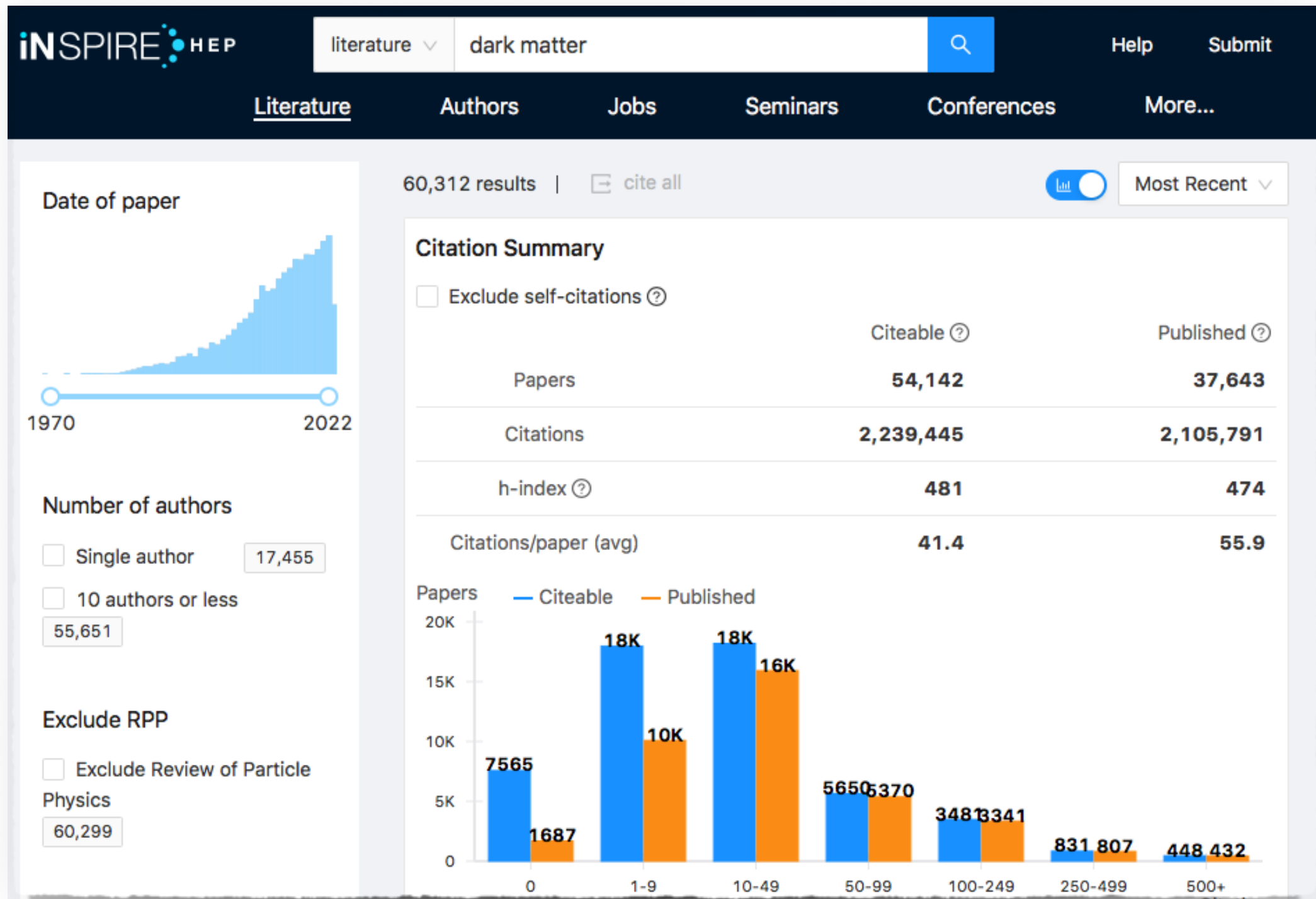


A visualization of the cosmic web, showing a complex network of filaments and clusters of galaxies. The filaments are composed of numerous small, distant galaxies, while the clusters are denser regions of galaxies. The colors range from deep purple and blue to bright yellow and orange, indicating different temperatures or densities of the matter.

A DARK MATTER PERSPECTIVE FROM THE THEORY FRONTIER

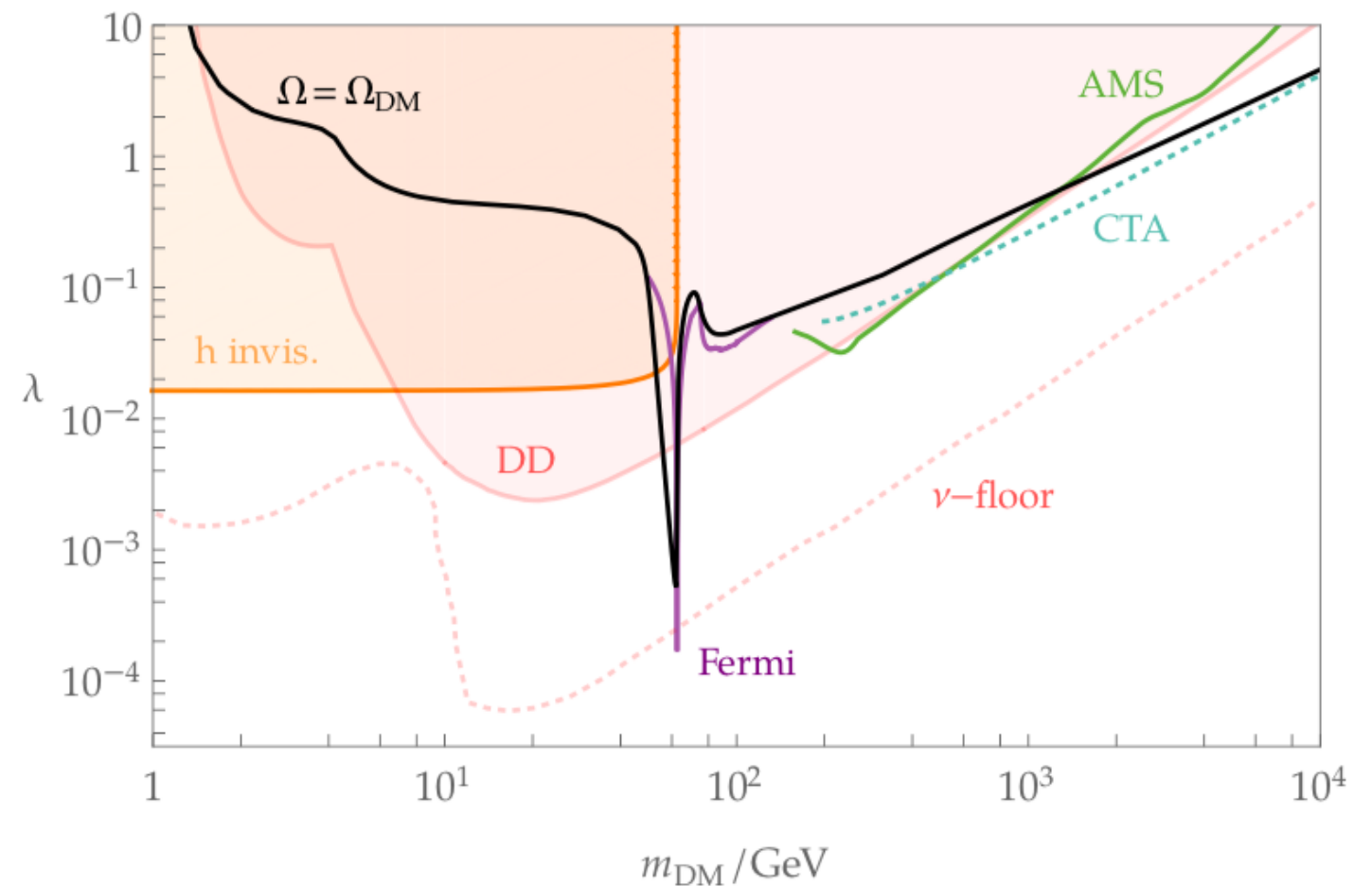
Jessie Shelton
DM Complementarity, Snowmass Community Summer Study, Seattle
July 19, 2022

“THINGS WE HAVEN'T THOUGHT OF YET”



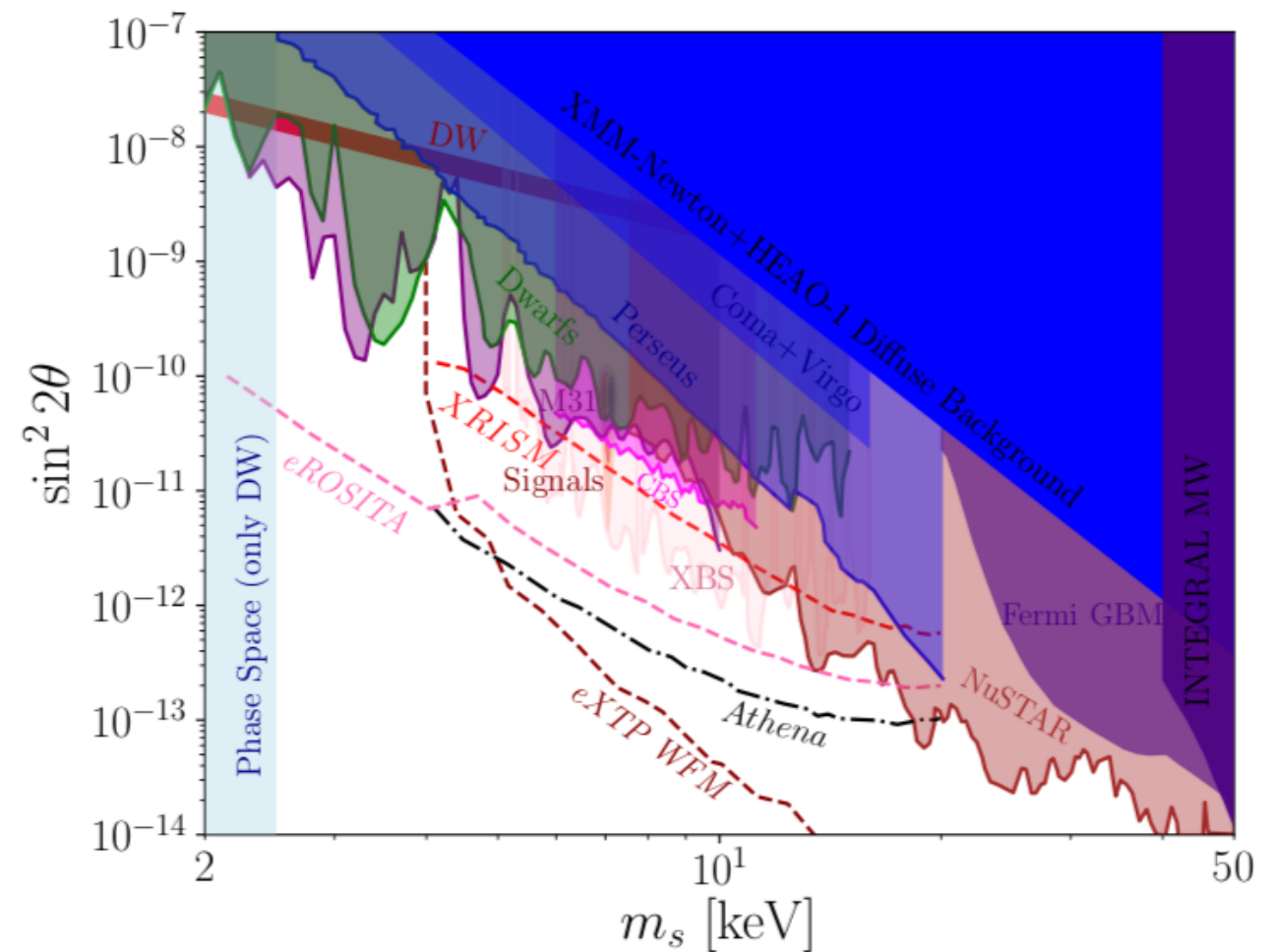
MINIMALISM IN MODELS OF DARK MATTER

- Dark matter models:
 - WIMPs
 - Higgs portal singlet
 - electroweakinos
 - Sterile neutrinos
 - QCD axion



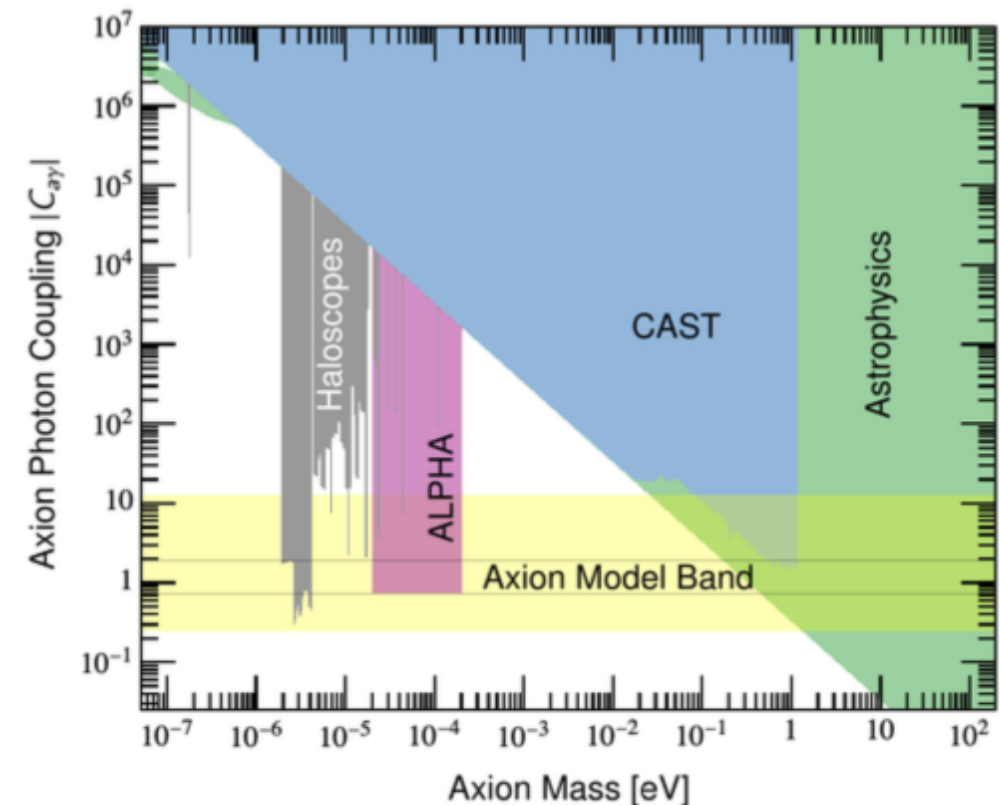
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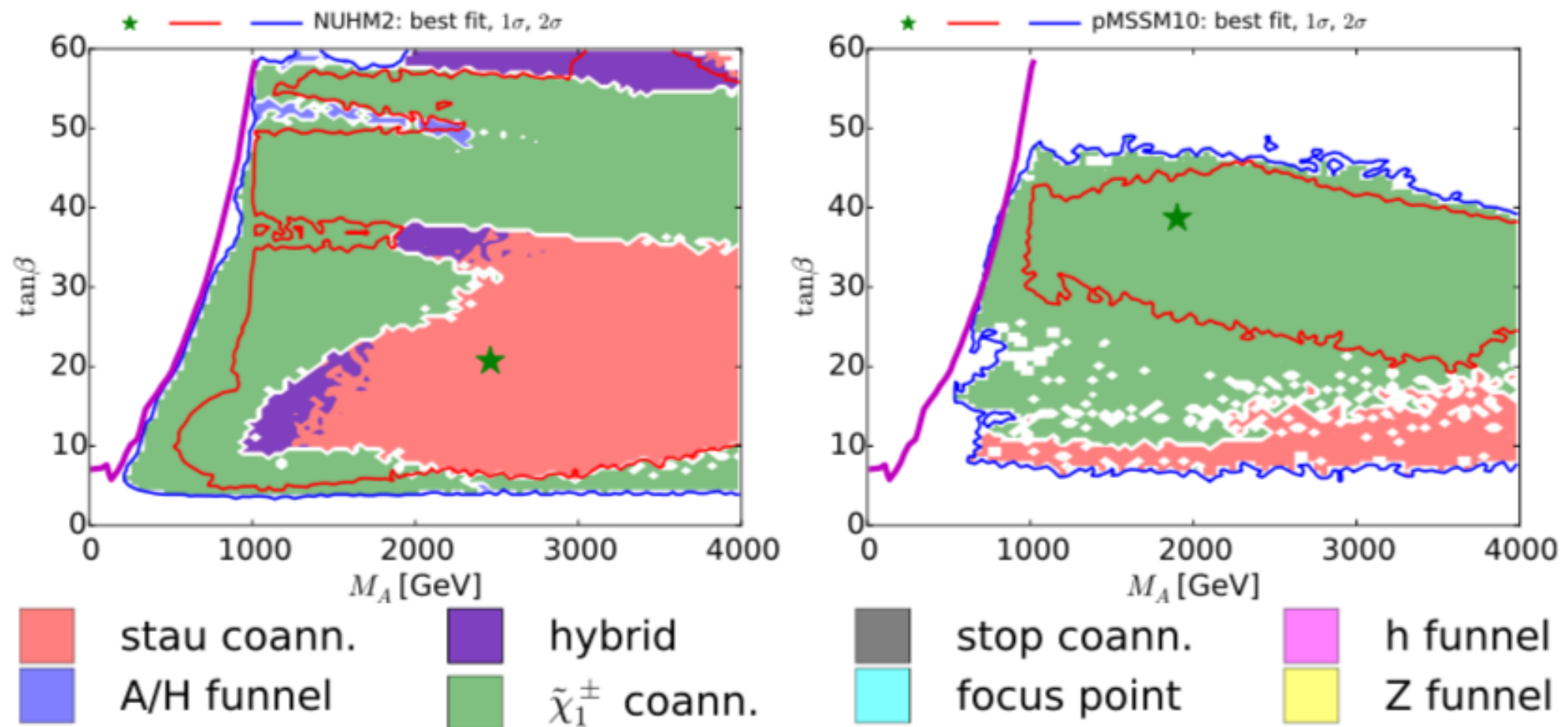
MINIMALISM IN MODELS OF DARK MATTER

- Dark matter models:
 - WIMPs
 - Higgs portal singlet
 - electroweakinos
 - Sterile neutrinos
 - QCD axion
 - nonperturbative cosmic history or extra parameter
 - terrestrial signals depend on UV completion



MINIMALISM IN MODELS OF DARK MATTER

- Less minimal models can realize a much wider range of thermal histories
- Not a recent observation:



- qualitatively change expected signatures of DM

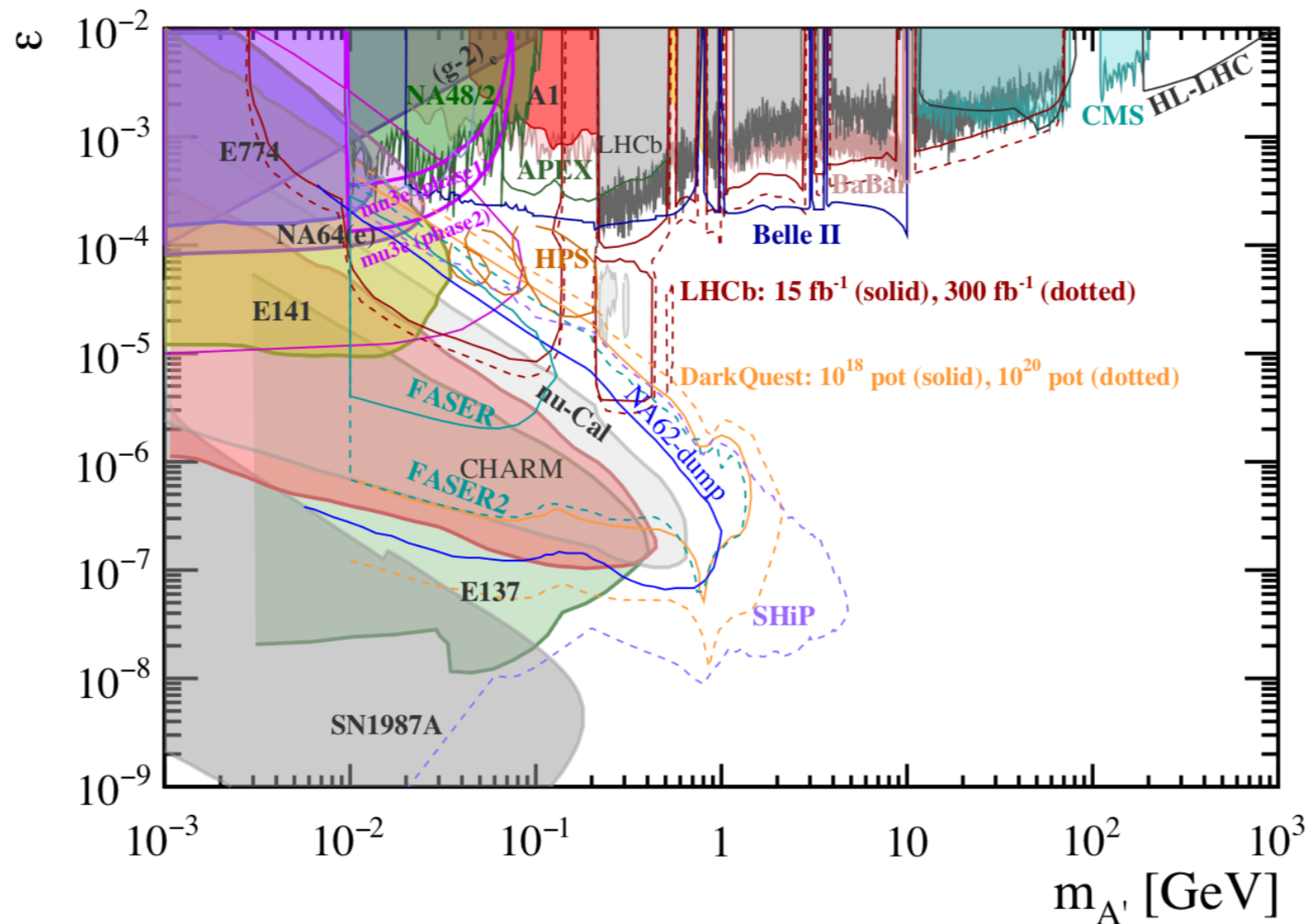
SIGNIFICANTLY BROADER RANGE OF DM SIGNATURES

- Recent years have seen a (re)flowering of DM models, particularly with BSM mediators:
 - broadens range of possible thermal histories, for instance:
 - interplay of multiple processes during freezeout
 - relic abundances set by elastic scattering with SM
 - cannibalism
 - light mediators qualitatively alter expectations in different experimental probes
 - direct detection
 - indirect detection, collider searches

[for more, see the summary in Asadi et al, this snowmass]

SIGNIFICANTLY BROADER RANGE OF DM SIGNATURES

► Direct light mediator searches:



+ stellar cooling, BBN,
CMB

CONFINING DARK SECTORS

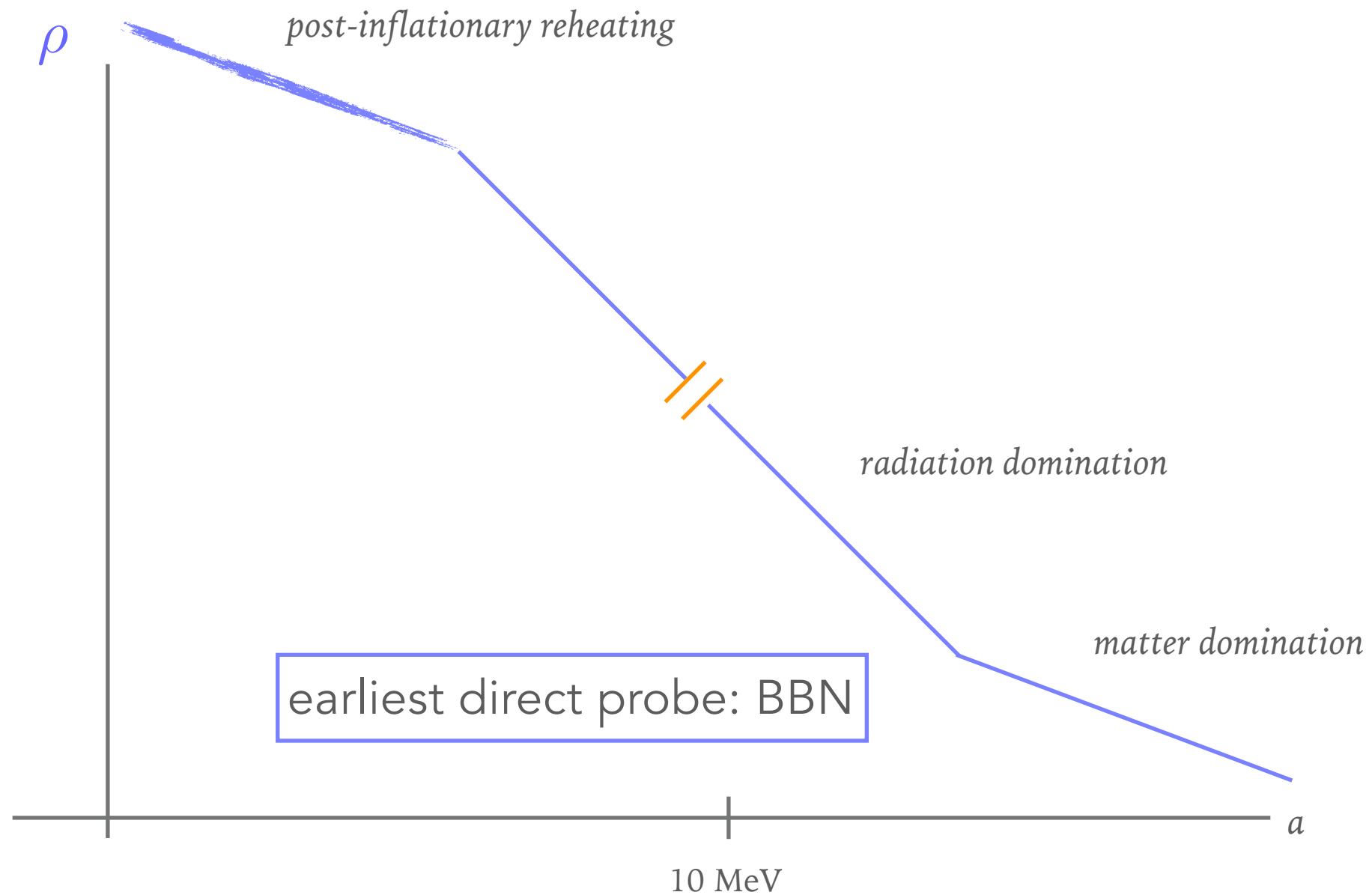
- It is “easy” to write down theories that realize multiple (meta)stable relics within a rich spectrum:

$$\mathcal{L} = \sum_i \bar{\psi}_i (iD_\mu \gamma^\mu - m_i) \psi_i + G_{\mu\nu}^a G^{a\mu\nu}$$

- motivates nearly-degenerate multiplets with nontrivial self-interactions
- motivates species with hierarchies of lifetimes
- what is hard is making precise predictions in theories with nonperturbative dynamics
- How “natural” are hidden sector theories?

THE STANDARD COSMOLOGY

► Standard cosmology:



BEYOND THE STANDARD COSMOLOGY

- Early departures from radiation domination naturally predicted in theories with
 - moduli
 - metastable thermal relics
- Substantial entropy injection can qualitatively alter relationship between DM cosmic abundance and couplings to matter
 - Higgs portal: re-opens minimal singlet model space
 - Freeze-in: can put production within reach of terrestrial detectors, eg. LHC

OUT-OF-EQUILIBRIUM IS NO LONGER OUT OF REACH

- Experimentally, starting to probe such small couplings that equilibrium cannot always be taken for granted:
 - freeze-in DM
 - Higgs portal on-resonance: kinetic equilibrium
 - light-mediator secluded annihilation (especially, dark photon-mediated direct detection)
 - **UV-sensitive**: must be mindful of self-consistency of models!
 - Rich range of cosmological signatures

NIGHTMARE SCENARIOS

- It is depressingly easy to write down simple DM models where terrestrial signals will always be out of reach
- This **does not mean** we should give up looking for terrestrial signals
- This **does mean** astrophysical and cosmological probes of dark particle physics are a vital part of the DM discovery program
 - Here also nonminimal scenarios can lead to rich signatures

SOME FINAL TAKEAWAYS

- Minimalism so far has not been the best guide to the particle physics of our universe
- It of course remains key to understand relation of DM to other open questions in the SM, but (my personal view) revolution in experimental knowledge means critical to look to data for clues
- Cosmological tests of dark matter physics are a key ingredient in a comprehensive search strategy
- Theoretical work is critical to develop new models, new signatures and relate signals across frontiers. Close and ongoing collaboration between theorists, observers, and experimentalists will be vital to develop a full picture of DM