

*Some random, biased thoughts on*  
**Physics Beyond the Standard Model**

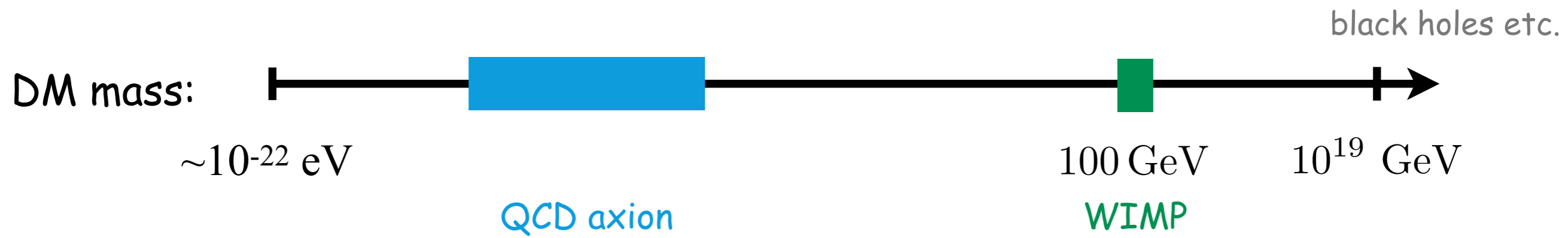
Peter W. Graham  
Stanford

# Beyond the Standard Model (SM)

The Standard Model is remarkably successful, but this only deepens the remaining mysteries:

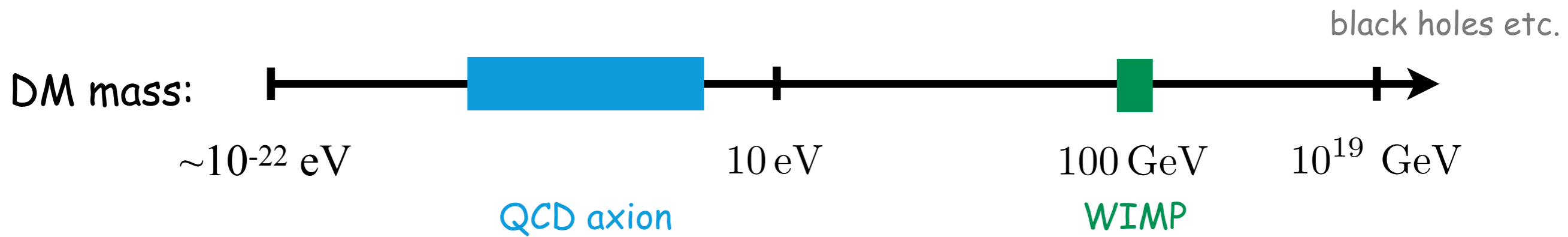
- Nature of dark matter
- Hierarchy problem = weak scale (mass of the Higgs) appears finely-tuned
- Strong CP problem = smallness of nucleon electric dipole moment is tuned
- Cosmological constant problem = smallness of the cosmological constant is fine-tuned
- Mechanism of baryogenesis
- Microphysics of inflation/reheating
- Explanation of flavor structure of SM
- High energy theory of quantum gravity

# Dark Matter



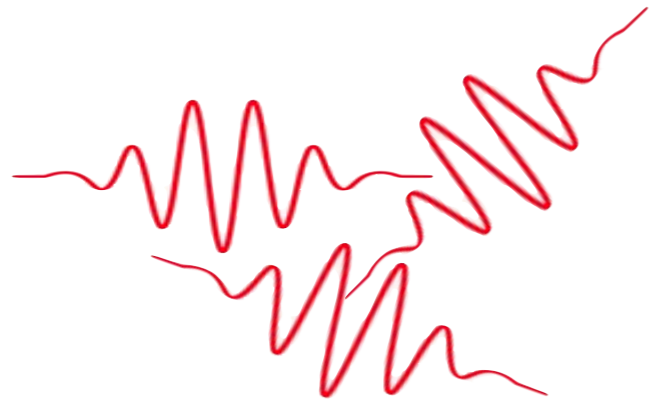
WIMPs and axions two of the best-motivated candidates  
But also huge DM parameter space should be explored

# Dark Matter Direct Detection



How can we search for DM over this wide range?

useful to picture as a "coherent" field or wave:

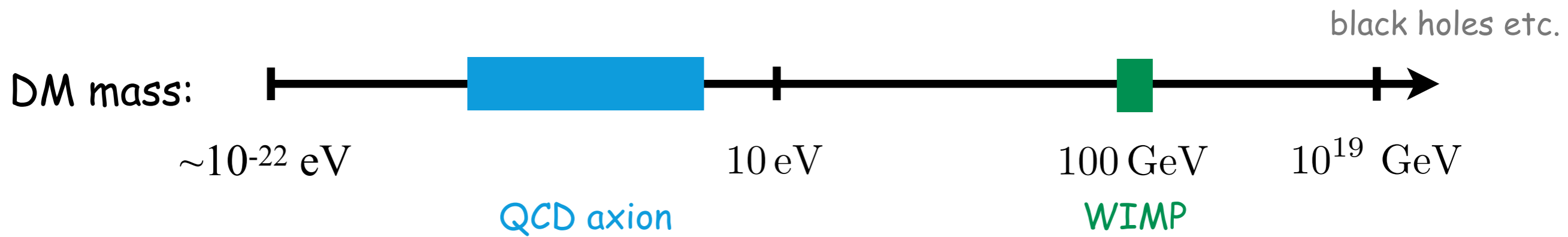


DM is "particle-like"



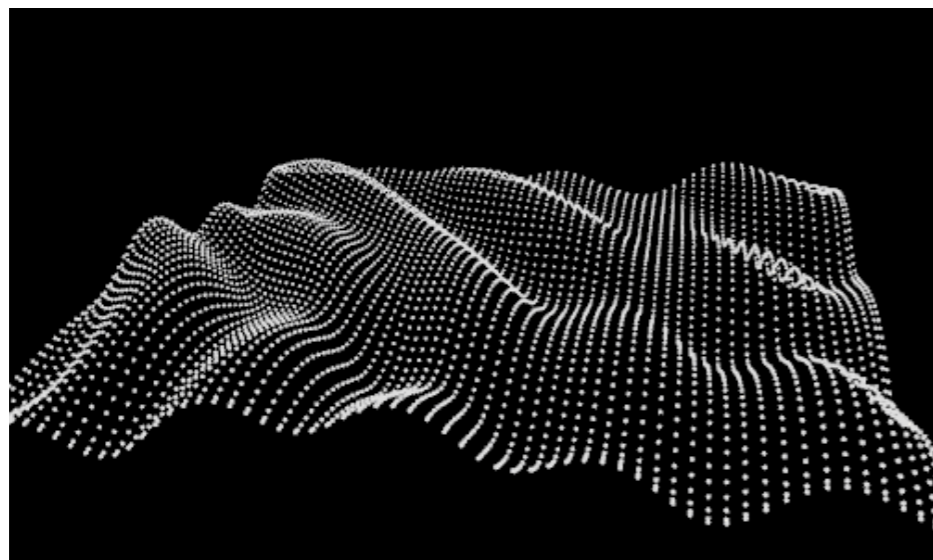
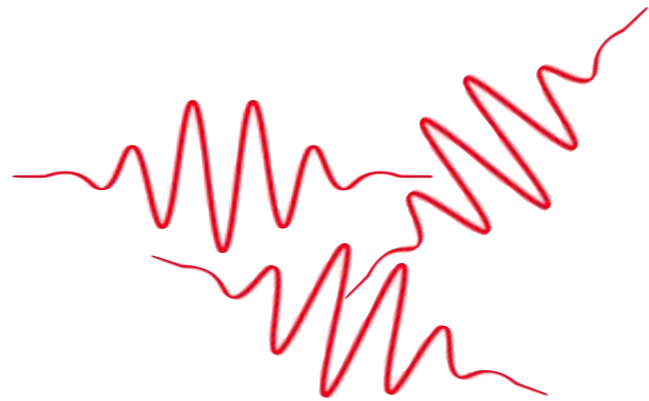
"particle detectors" best  
see energy deposition from hard  $2 \rightarrow 2$  scattering

# Dark Matter Direct Detection



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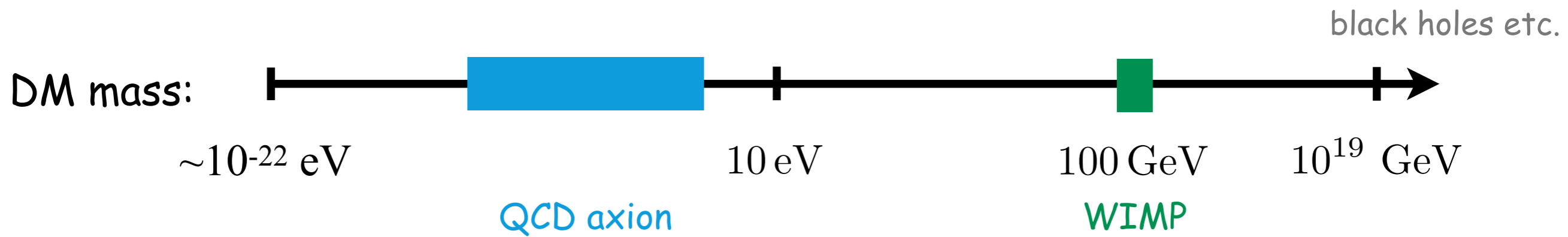
more like gravitational wave detection

DM is "particle-like"



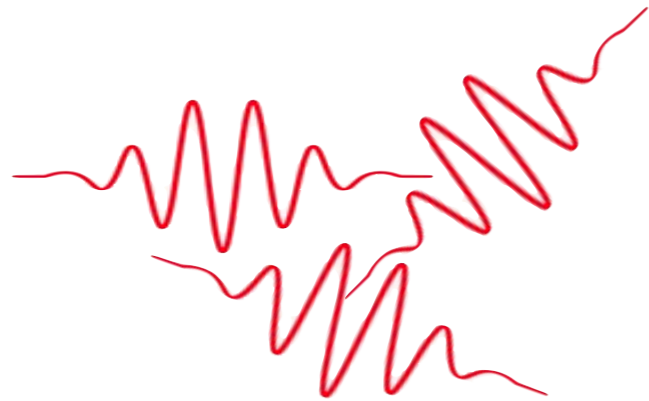
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# Dark Matter Direct Detection



How can we search for DM over this wide range?

useful to picture as a "coherent" field or wave:



Lower bounds on mass from large de Broglie wavelength effects - "quantum pressure"

e.g. DM won't fit in dwarf galaxies

e.g. wavelike effects  $\rightarrow$   $O(1)$  overdensities which heat stellar population in ultrafaint dwarfs

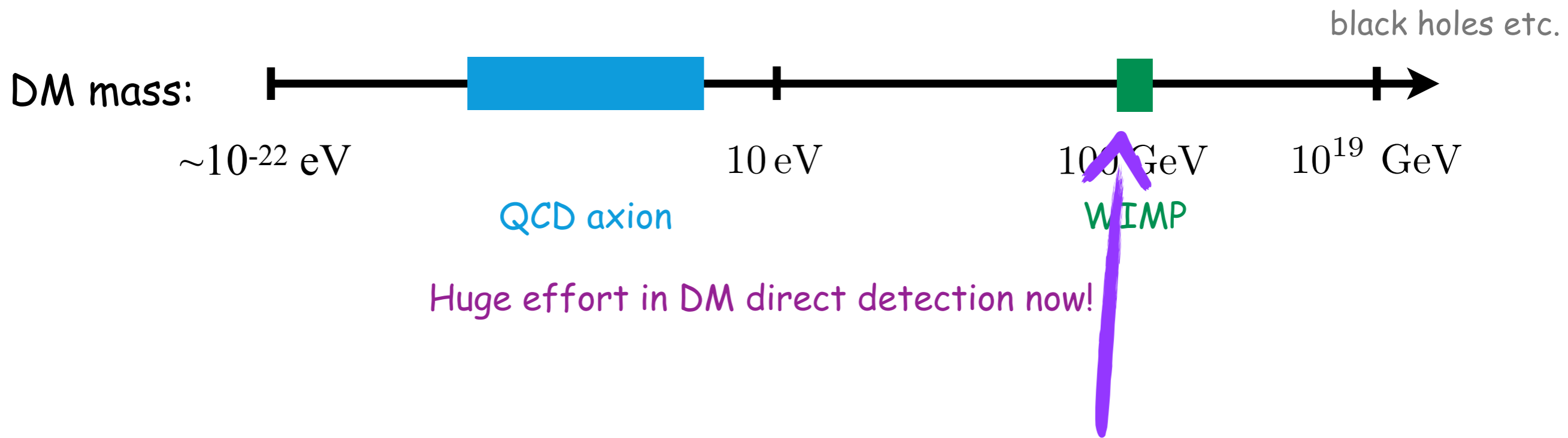
See e.g. Dalal & Kravtsov arXiv:2203.05750

DM is "particle-like"



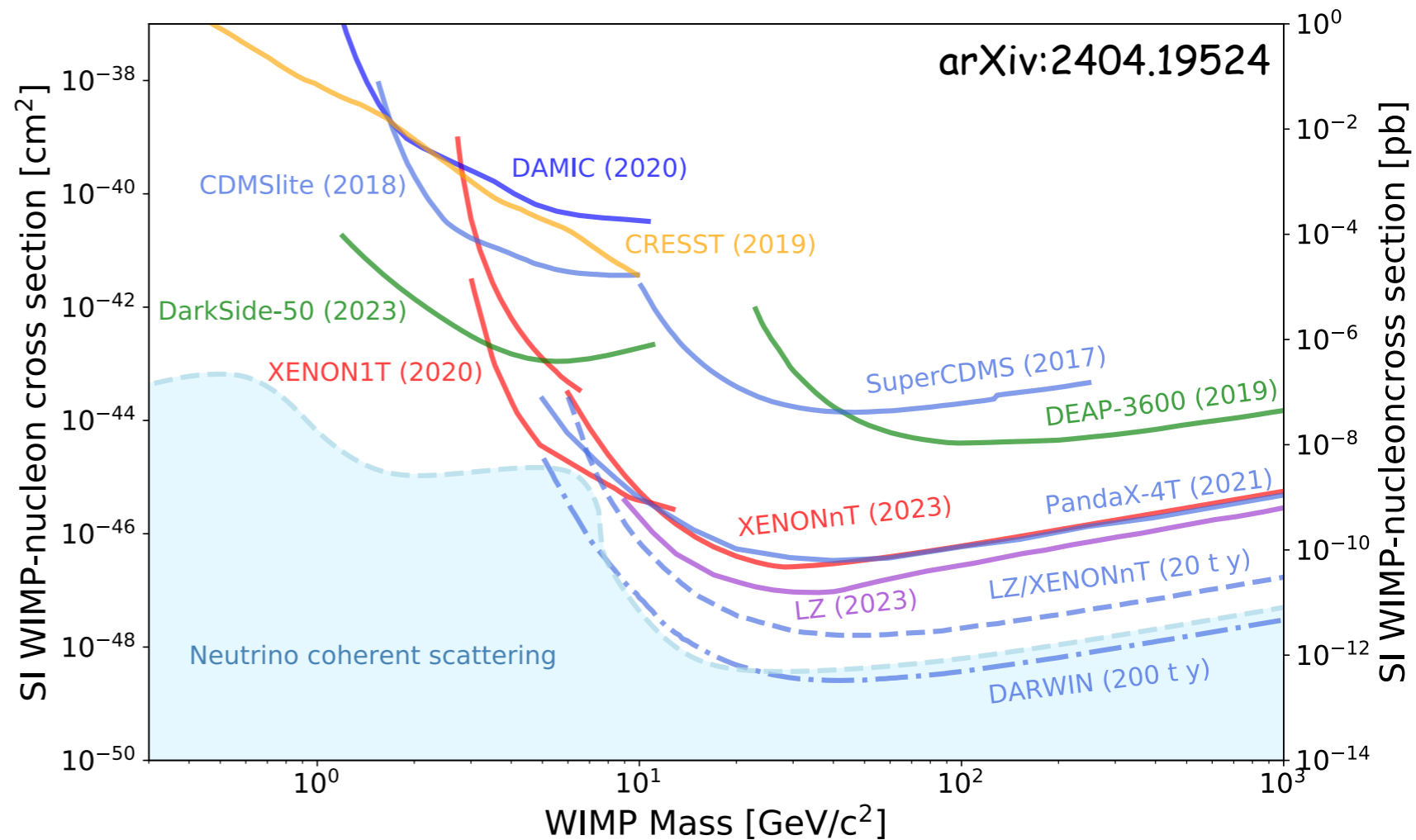
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# Dark Matter Direct Detection

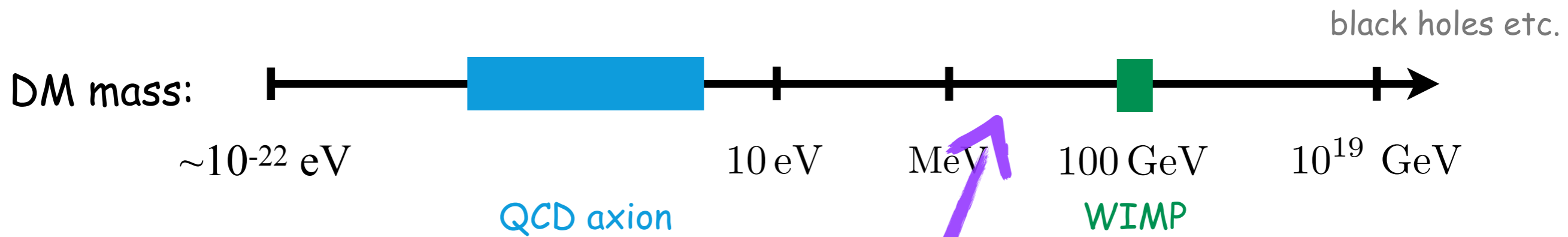


Classic WIMP search

DM scattering elastically off nucleons

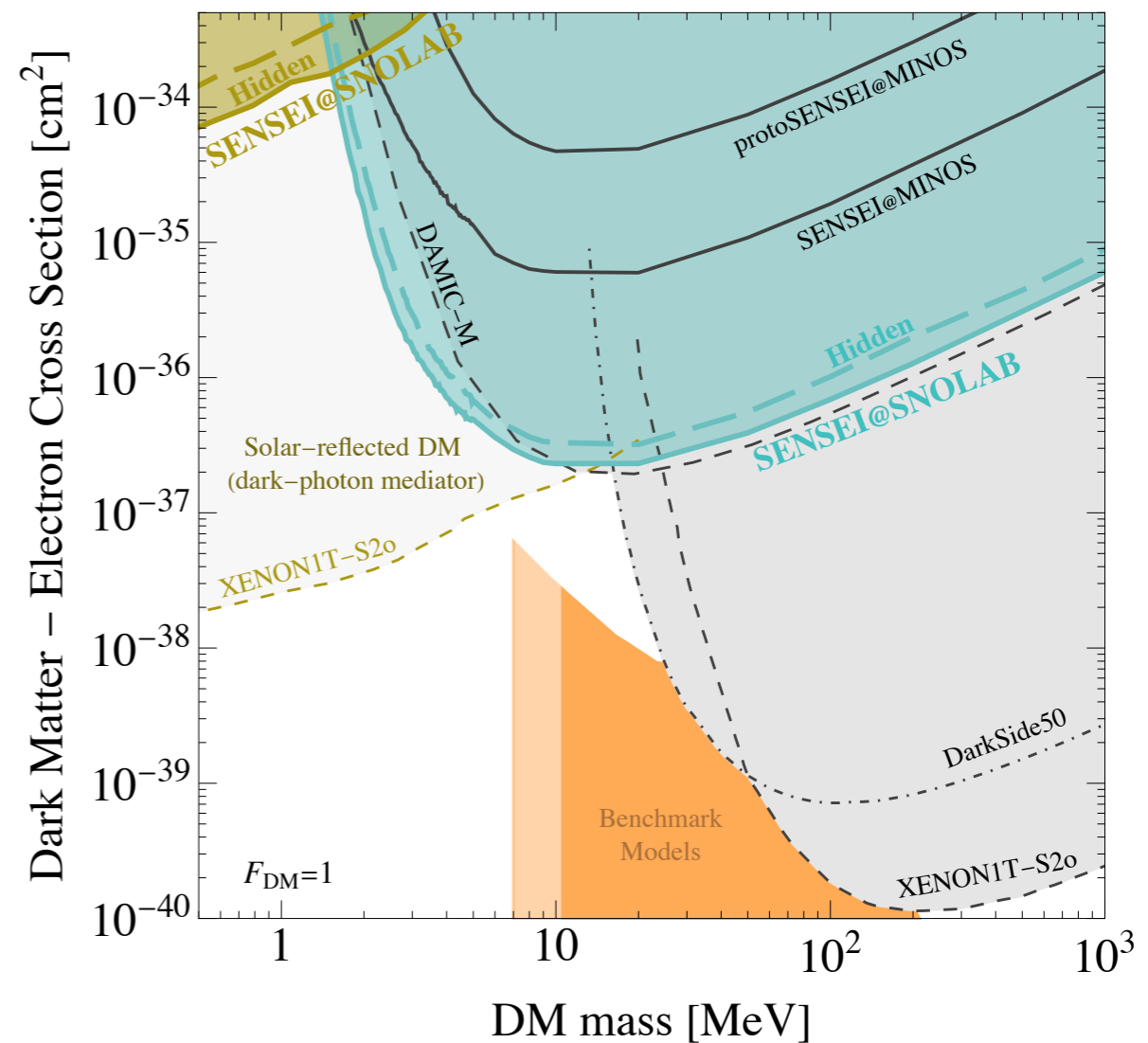
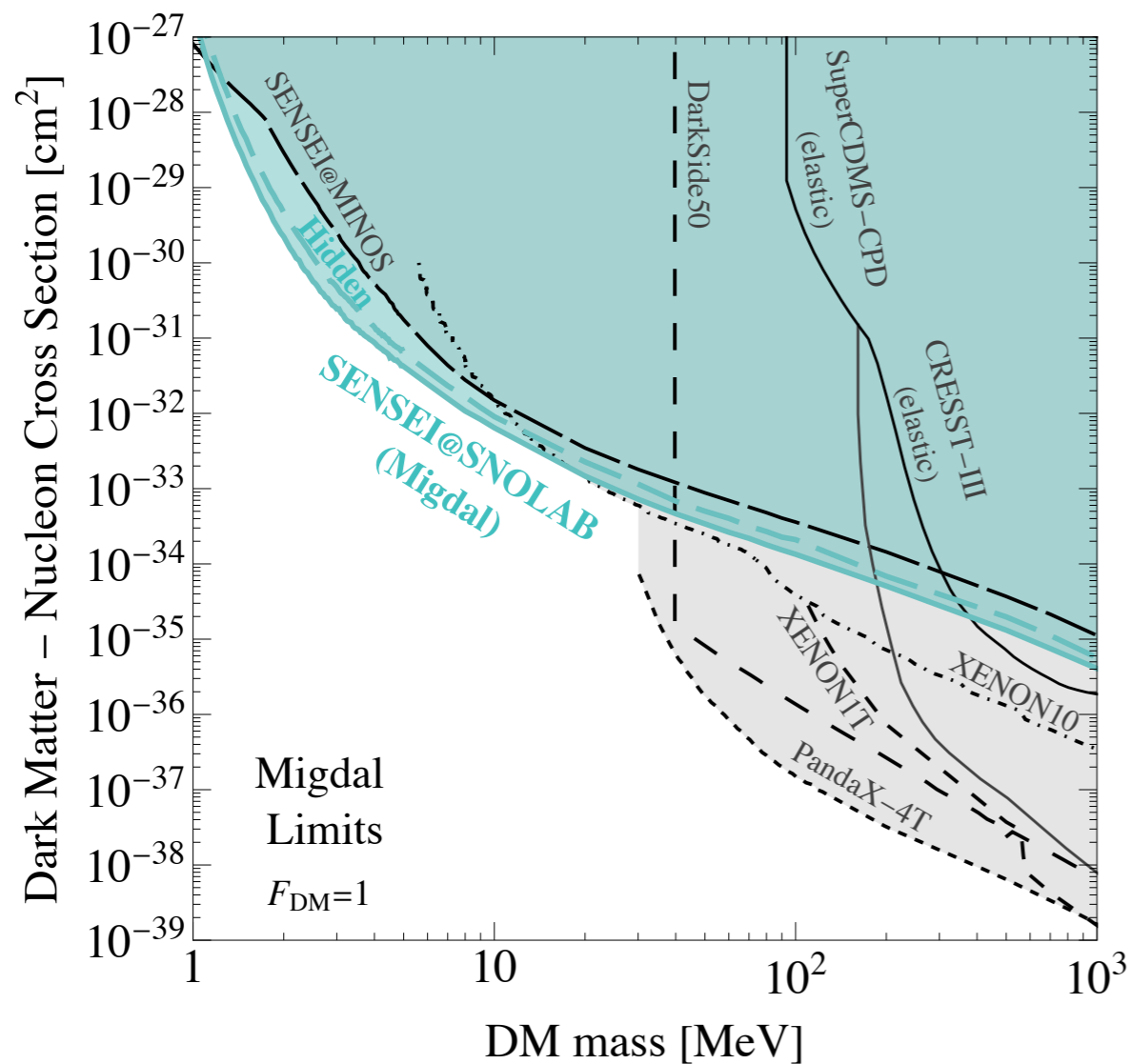


# Dark Matter Direct Detection



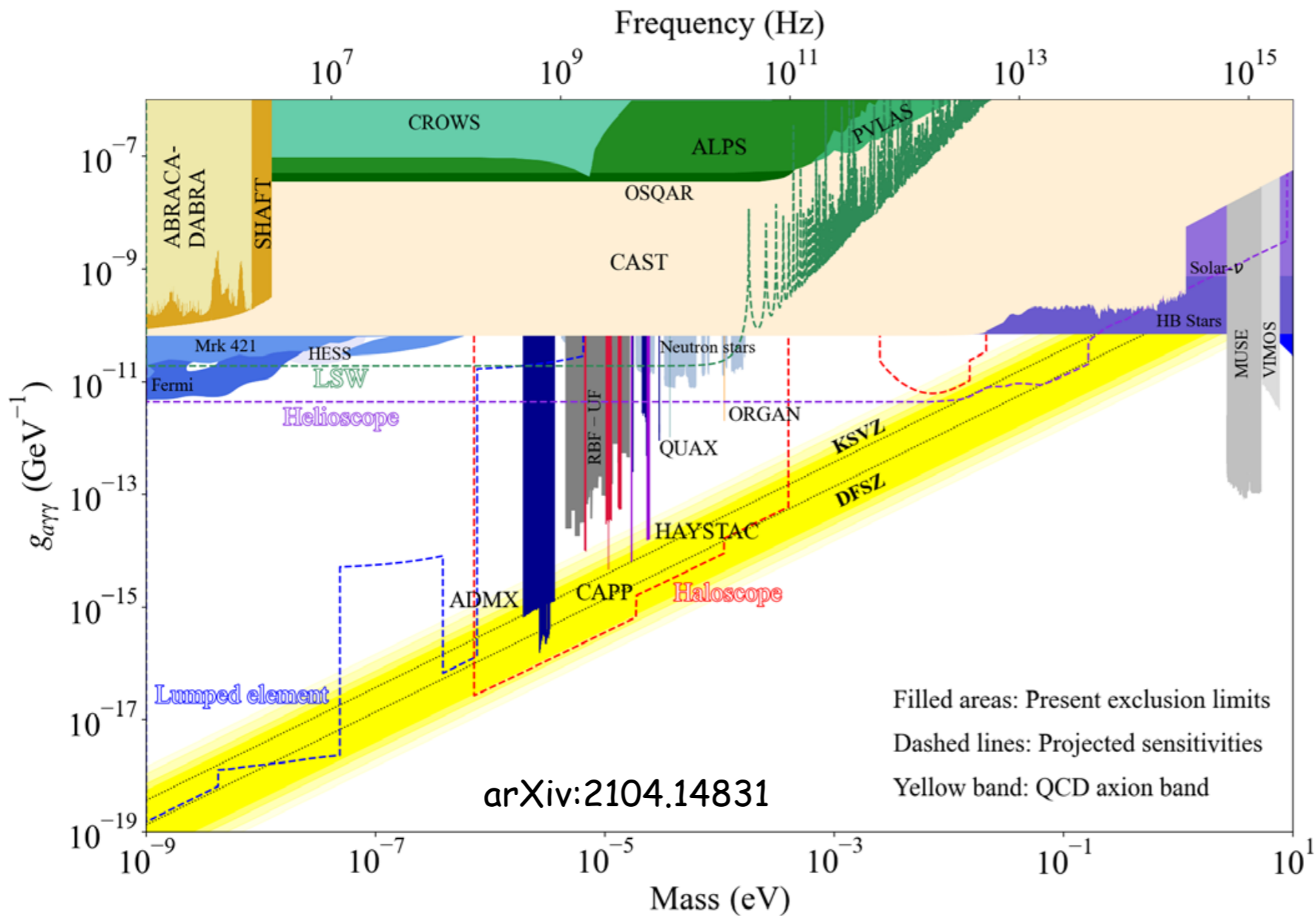
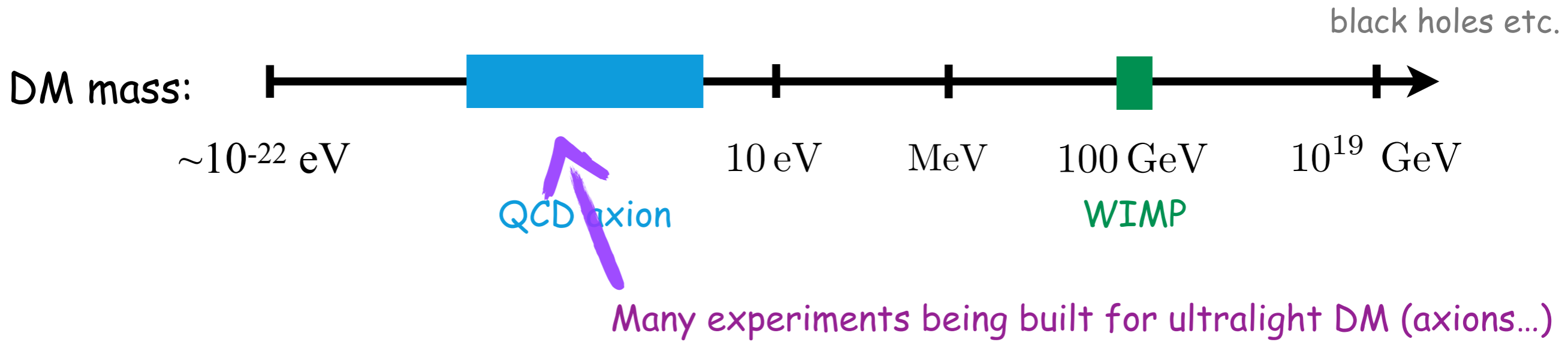
Many experiments pushing for "Light DM" (below GeV)

arXiv:2312.13342



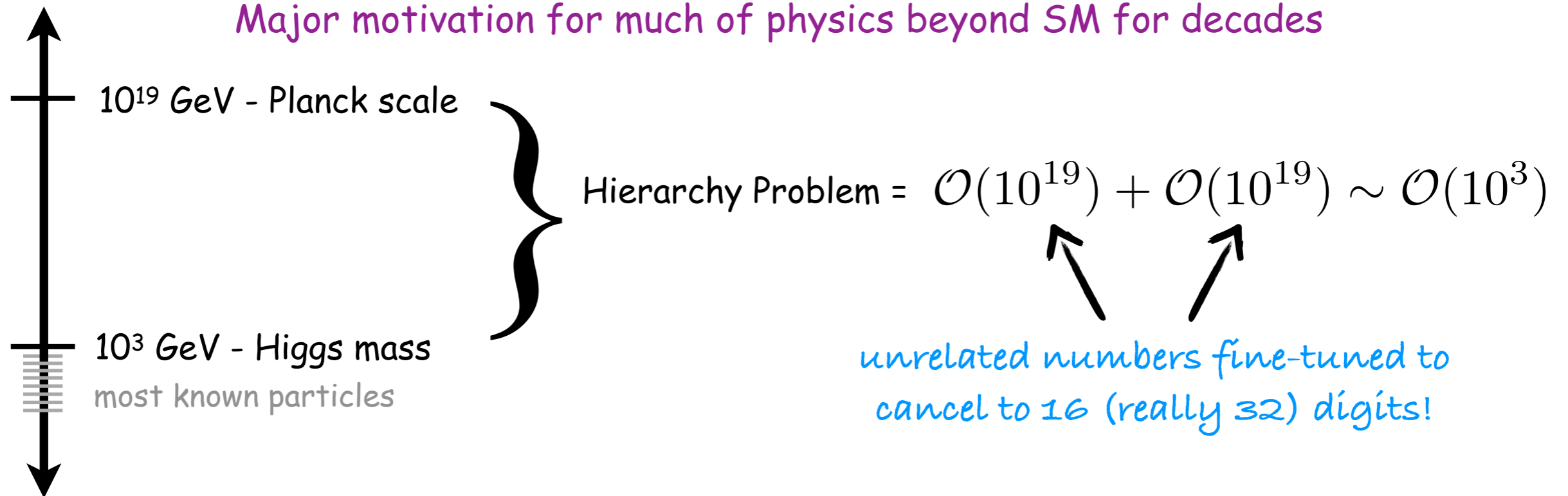


# Dark Matter Direct Detection



# The Hierarchy Problem

Major motivation for much of physics beyond SM for decades



Two classes of solutions:

## 1. Weak-scale solutions (e.g. supersymmetry, large extra dimensions, technicolor, little Higgs...)

- change calculation in theory to remove the large (quantum loop) contributions
- requires new particles at weak scale (cut off loops), can be relevant to cosmology (e.g. WIMPs)
- tension with LHC results

## 2. Cosmological solutions (e.g. relaxion) PRL 115 (2015) arXiv:1504.07551

- Dynamics in early universe causes weak scale to select this small value
- turn Higgs mass from fundamental constant into dynamical variable (like axion solution to strong CP)

## 3. Anthropics?

# New Ultralight Particles

## Hierarchy problem

- The cosmological solutions motivate a light, axion-like field

## Cosmological Constant problem

- No known working solutions
- However possibilities are similar: either new physics at  $CC$  scale ( $\sim$  meV, hard!)  
OR a cosmological solution (again needs an axion-like field)

## Strong CP problem

- QCD axion is simplest solution
- similarly is a “cosmological solution” the nucleon EDM is reduced during cosmology

All these “cosmological solutions” imply new ultralight particles e.g. axions

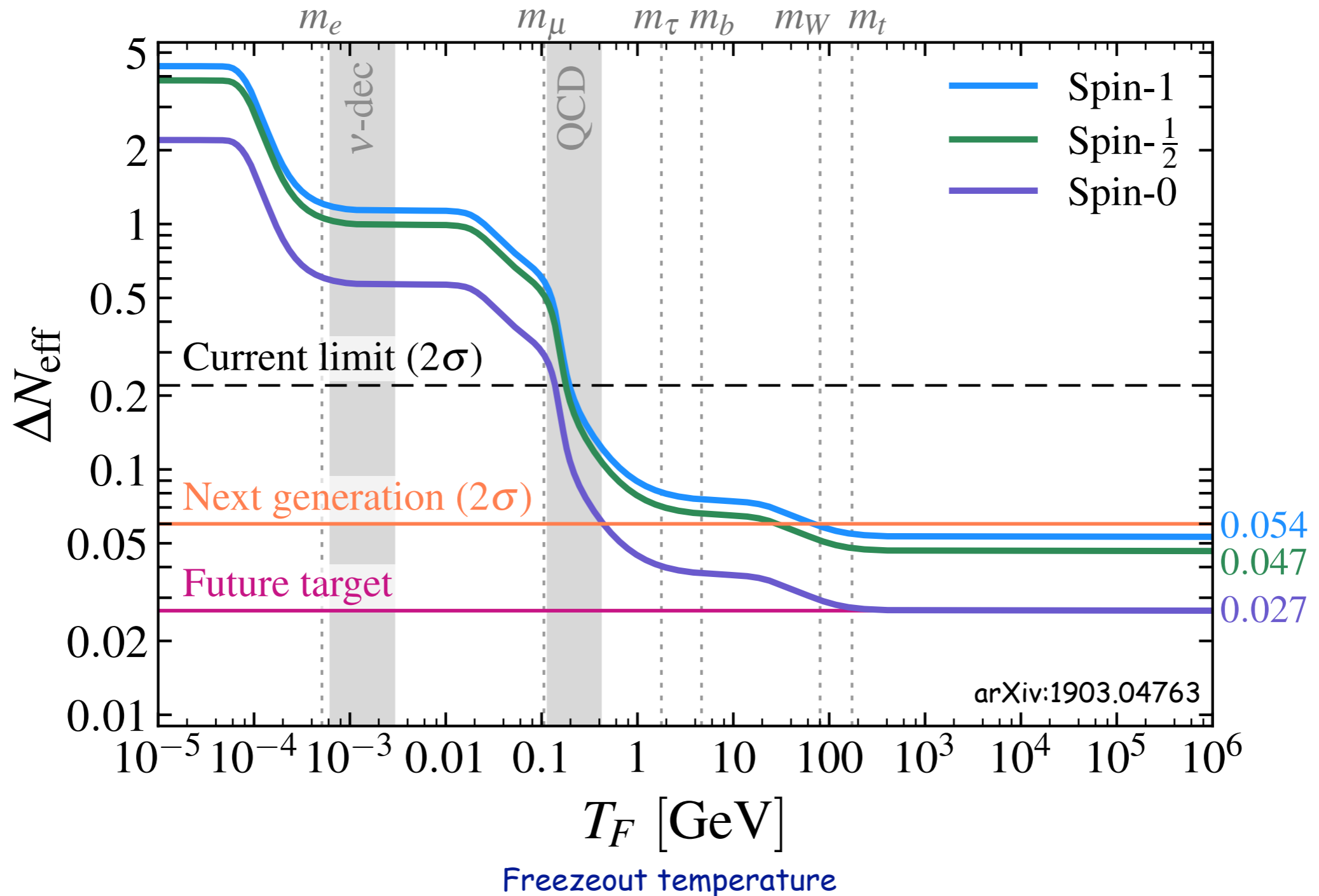
Not surprisingly, these can have many cosmological consequences

A few random examples  
relevant to cosmology

# $N_{\text{eff}}$ and Ultralight Particles

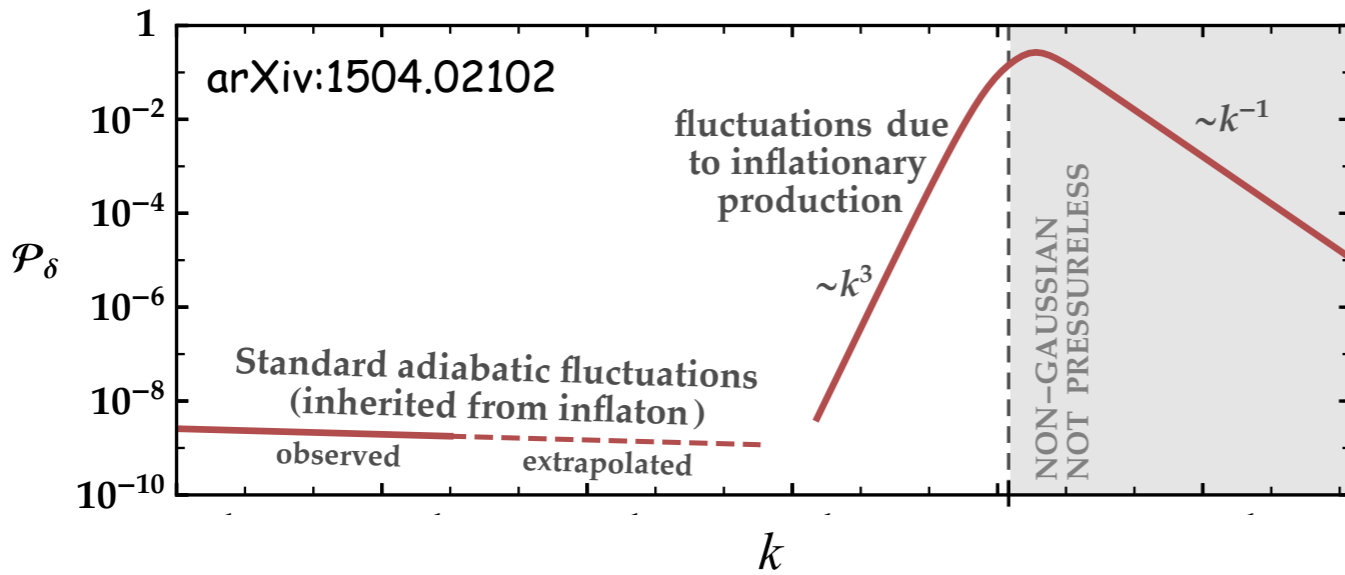
Ultralight particles (e.g. axions) could thermalize in early universe, then contribute to  $N_{\text{eff}}$

Baumann, Green, & Wallisch arXiv:1604.08614



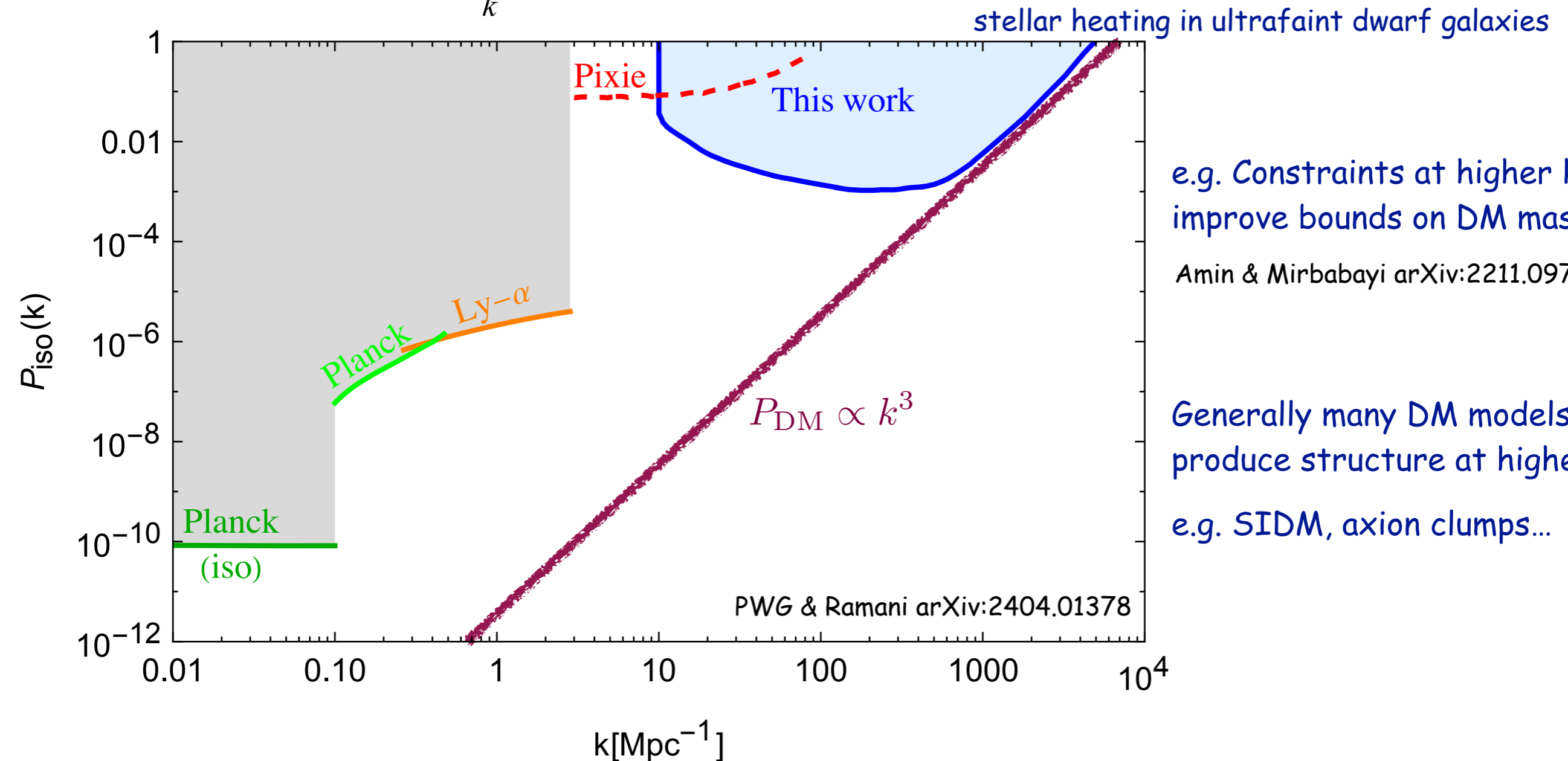
$N_{\text{eff}}$  measurements powerful way to search for many types of new physics

# Isocurvature Probe of Dark Matter Production



Many DM production mechanisms create peaked isocurvature spectrum with  $k^3$  tail

e.g. post-inflationary QCD axion, inflationary production of dark photon, PBH's...



e.g. Constraints at higher  $k$  improve bounds on DM mass

Amin & Mirbabayi arXiv:2211.09775

Generally many DM models can produce structure at higher  $k$

e.g. SIDM, axion clumps...

# New Forces on Dark Matter

Can there be a new long-range force on dark matter?

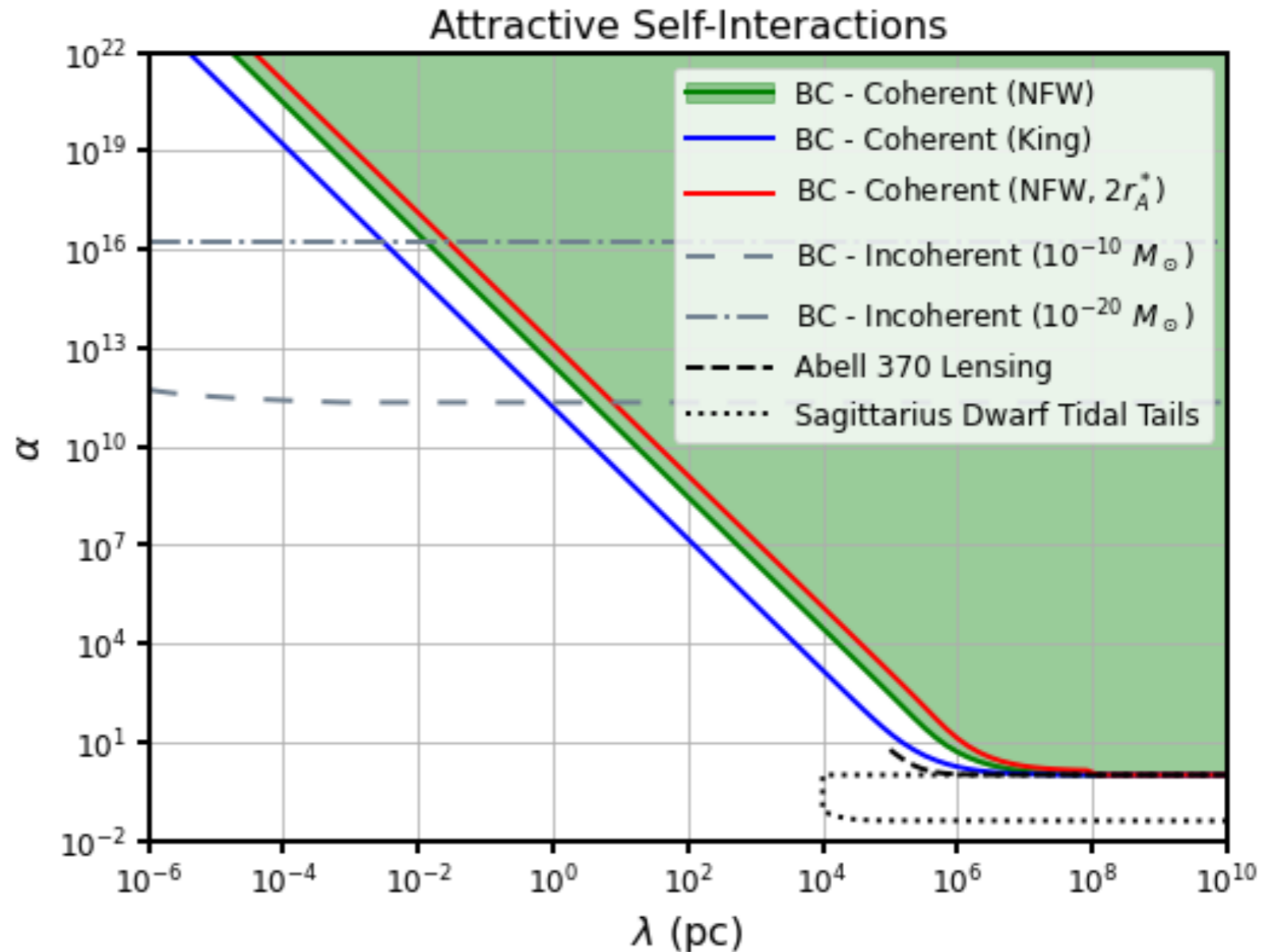
See e.g. Craig, Green, Meyers & Rajendran arXiv:2405.00836 motivated new long range force from DESI?

constrained by astrophysics

e.g. for attractive Yukawa

$$V = -\alpha G \frac{m_1 m_2}{r} e^{-r/\lambda}$$

Coherent scattering in Bullet Cluster constrains new force:



Cosmology (structure formation...) presumably limits such new forces as well