Model building aspects of dark matter

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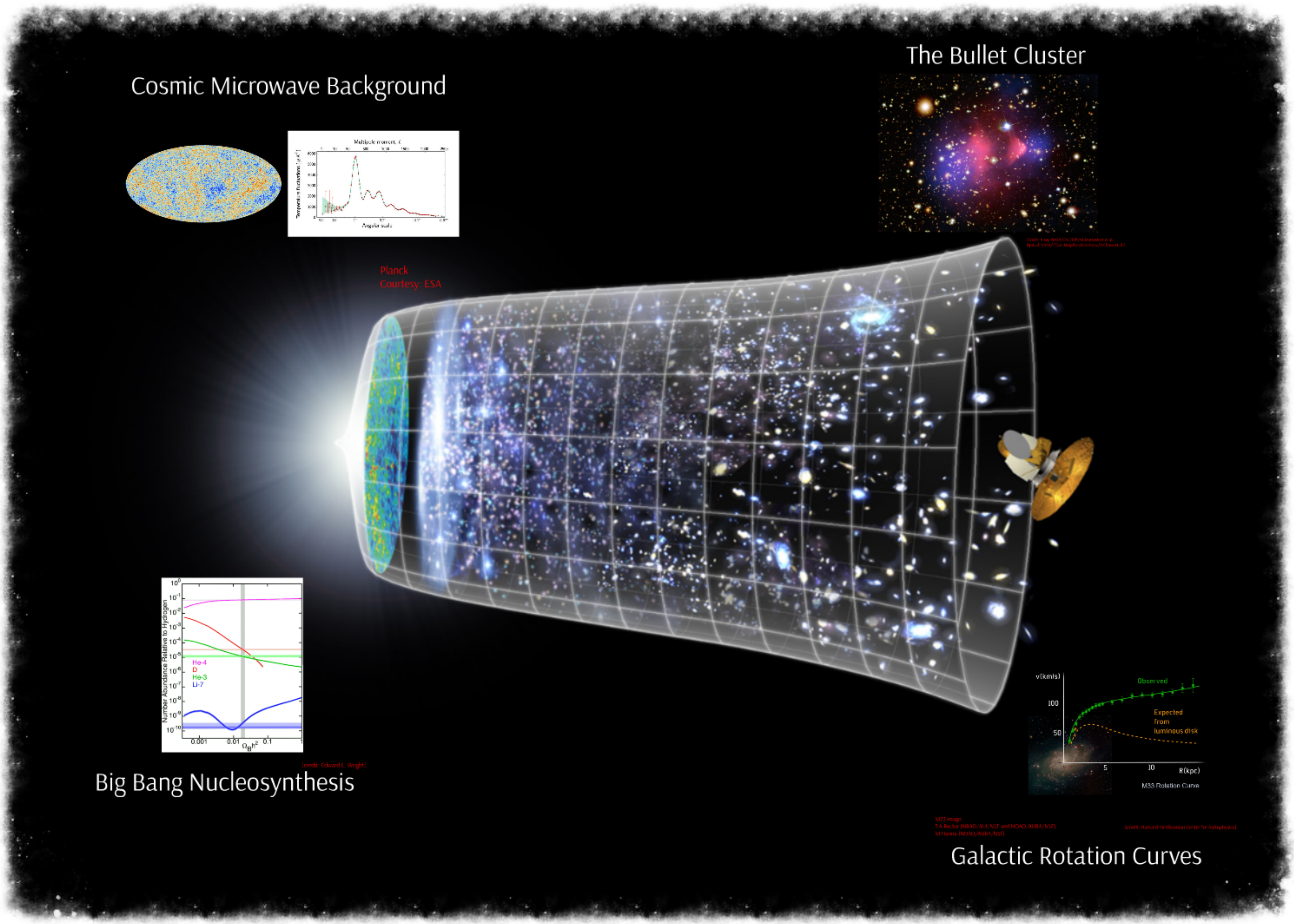
Dark Matter Exists



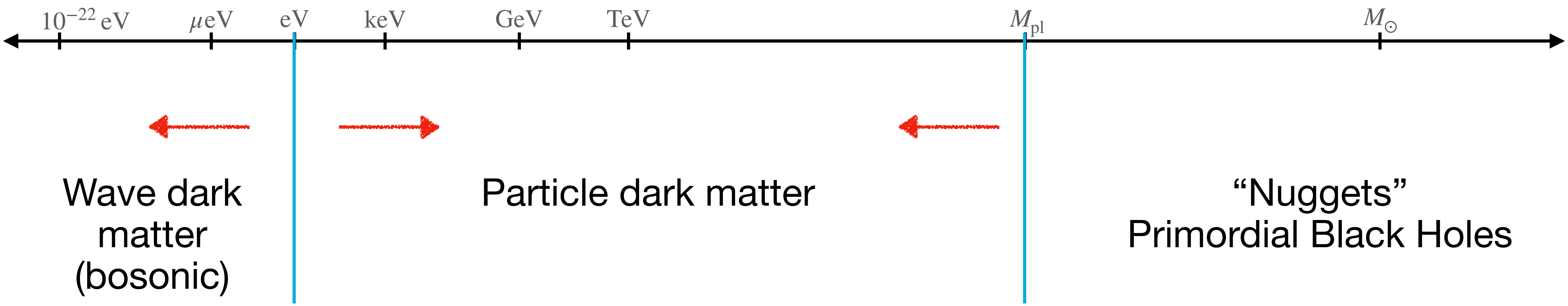
A vast parameter space, need organizing principles and models

Dark matter should fit inside dwarf galaxy haloes

$$\lambda_{\text{de Broglie}} \simeq \left(m_{\text{DM}} v_{\text{virial}}\right)^{-1} \lesssim 1\,\text{kpc}$$

$$v_{\text{virial}} \sim 10^{-3}$$

Dark matter mass < halo mass

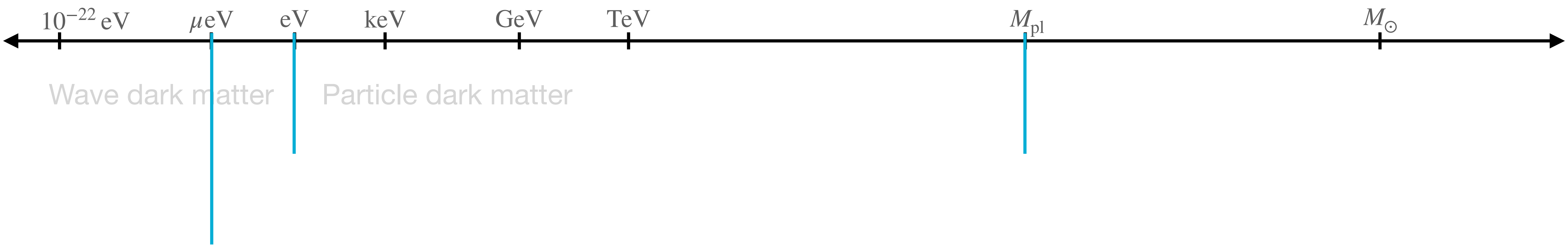


$$\text{Occupation number} \sim \frac{\rho_{\rm DM}}{m_{\rm DM}} \lambda^3_{\rm deBroglie} < 1$$

$$\rho_{\rm DM} \simeq \frac{\rm GeV}{\rm cm^3}$$

Related to the Tremaine-Gunn bound

Tremaine, Gunn
Phys. Rev. Lett. 42, 407 (1979)



QCD axion

A new light particle, motivated by the strong-CP problem

Excellent dark matter candidate
Coherent field oscillations ~ pressureless dust

Peccei, Quinn (1977)
Weinberg (1978)
Wilczek (1978)

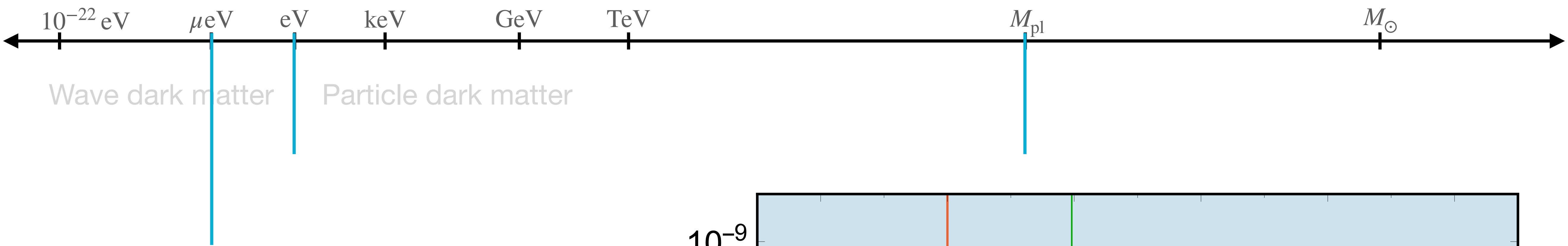
Relevant parameters: mass m_a and decay constant f_a

Role in strong-CP solution $\Rightarrow m_a \simeq \dfrac{\Lambda_{\rm QCD}^2}{f_a}$

Initial misalignment angle

Dark matter abundance $\Omega_{\rm DM} \simeq 0.1 \left(\dfrac{f_a}{10^{12}\,\text{GeV}} \right)^{7/6} \theta_i^2$

[Misalignment mechanism]

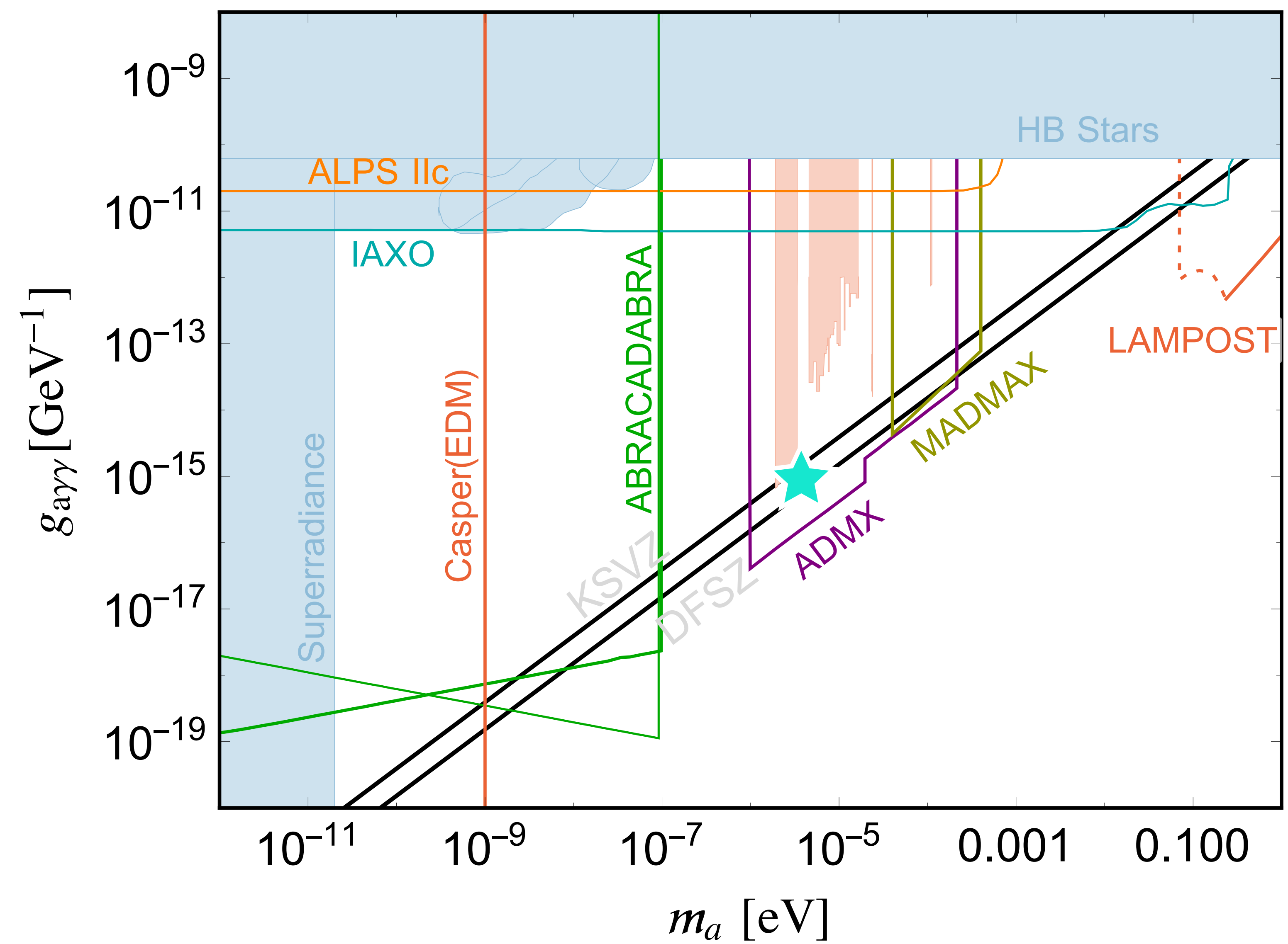


QCD axion

In simplest models

$$g_{a\gamma\gamma} \simeq \frac{\alpha_{\rm em}}{2\pi f_a}$$

Narrow target space for experiments



Model-building question:

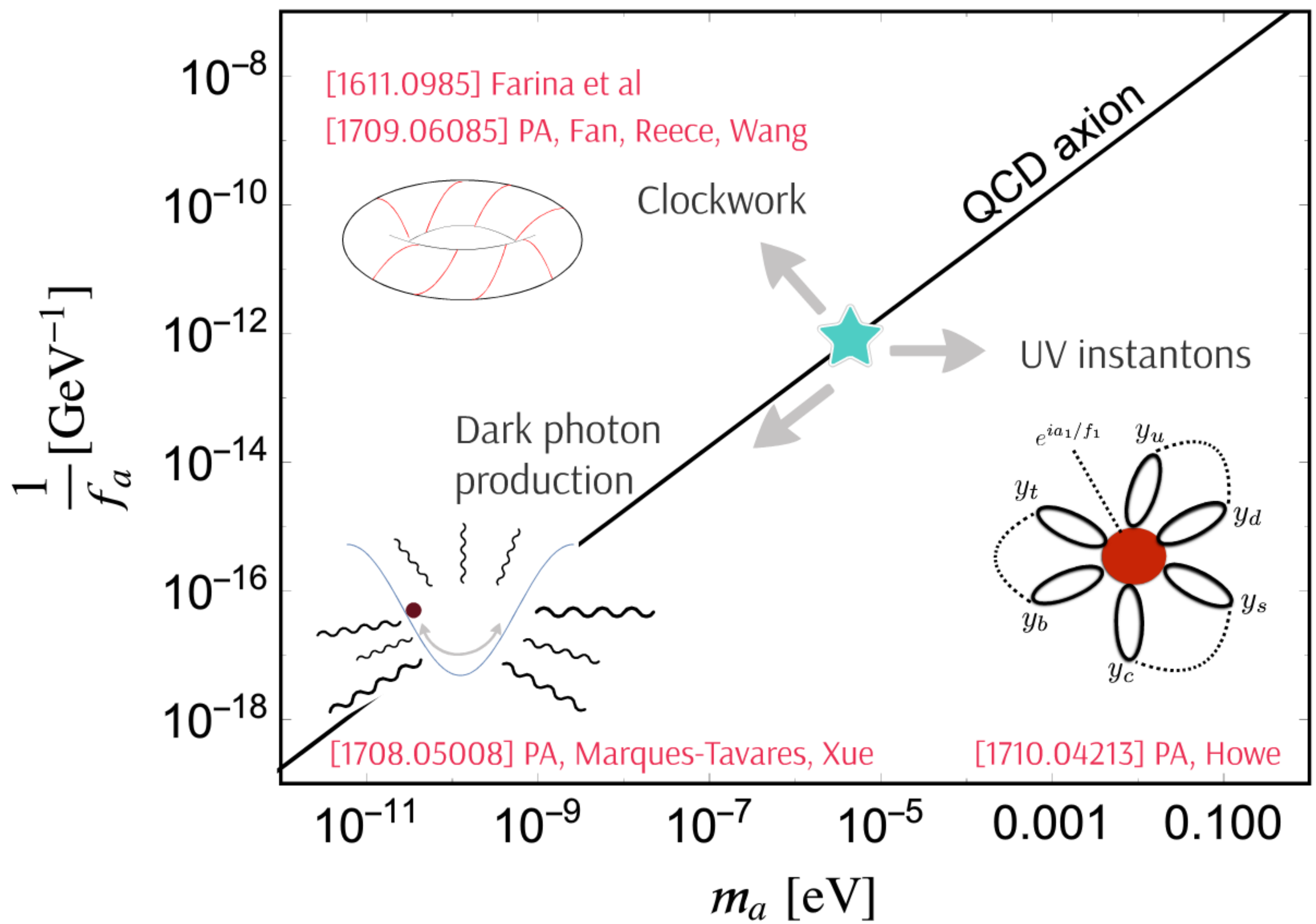
Are there mechanisms that extend this motivated parameter space?

QCD axion

Enhanced photon couplings

Large-f_a axions

Heavy QCD axions



Extended parameter space where axion solves strong-CP and constitutes the dark matter

General Wave-like Dark Matter Candidates

Axion-like Particles

Light pseudo-Nambu Goldstone particles, not solving the strong CP problem

Dark photon dark matter

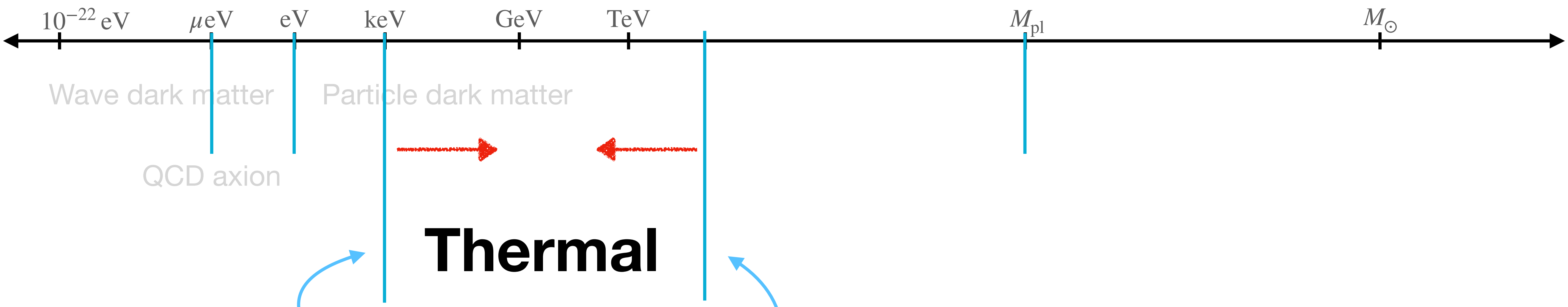
Spin-1 dark matter particles
Need a new mechanism for populating dark matter

PA, Kitajima, Reece, Sekiguchi, Takahashi [1810.07188]
Co, Pierce, Zhang, Zhao [1810.07196]
Bastero-Gil, Santiago, Ubaldi, Vega-Morales [1810.07208]
Dror, Harigaya, Narayan [1810.07195]
Long, Wang [1901.03312]

Fuzzy Dark Matter

Ultra-light dark matter, $m \simeq 10^{-21}\,\mathrm{eV}$
Motivated by small-scale structure problems in Cold Dark Matter

Hu, Barkana, Gruzinov [astro-ph/0003365]
Hui, Ostriker, Tremaine, Witten [1610.08297]



Cold Dark Matter

Kinetic decoupling early enough to not erase small scale structure

Unitarity Bound

Annihilation cross section for correct relic abundance would violate unitarity

Weakly Interacting Dark Matter Paradigm

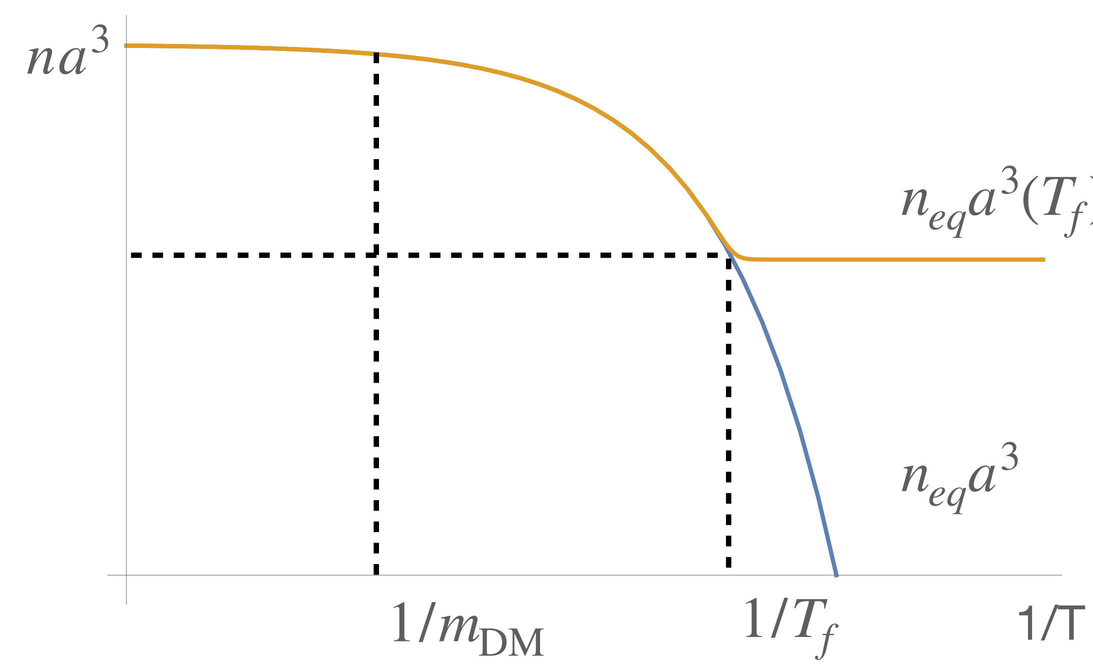
Freeze-out abundance is set by the annihilation cross-section

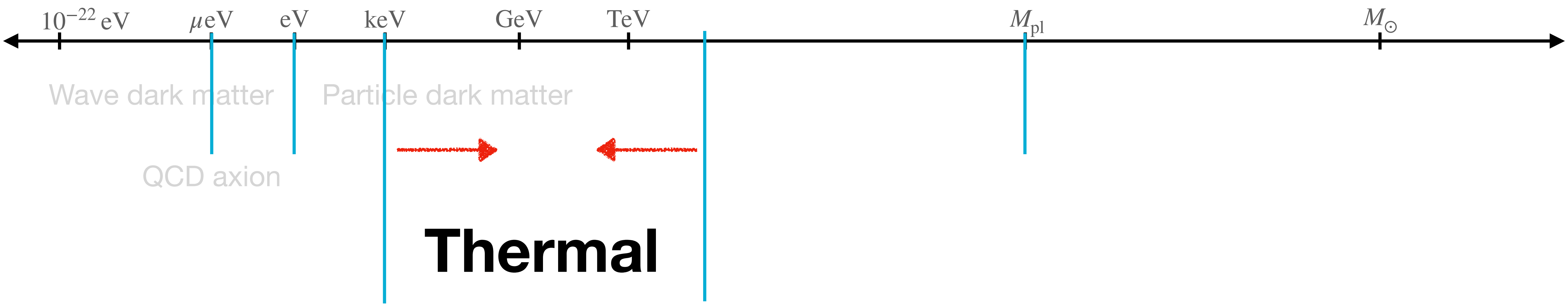
$$n_{eq}\langle\sigma v\rangle(T_f) \simeq H(T_f)$$

$$\langle\sigma v\rangle \simeq \frac{x_f}{T_{\rm eq}M_{\rm pl}} \sim \frac{\alpha_W^2}{\rm TeV^2}$$

$$x_f = \frac{m_{\rm DM}}{T_f} \sim 20$$

sensitive only logarithmically to parameters

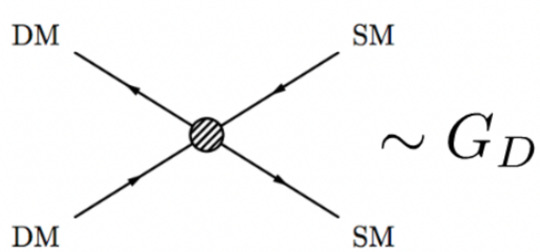


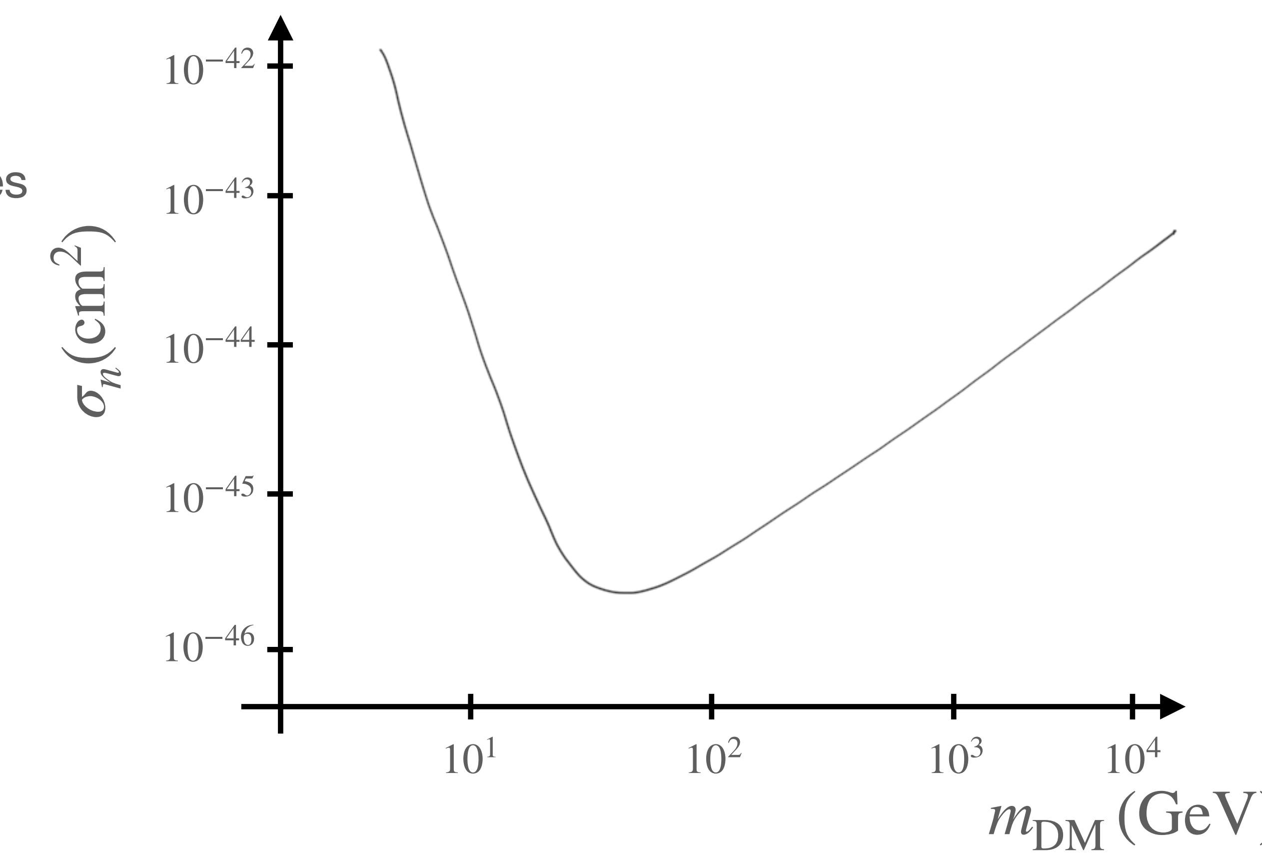


Weakly Interacting Dark Matter Paradigm

Implies detectability in various on-going experiments

Parametrize using simplified models / effective vertices

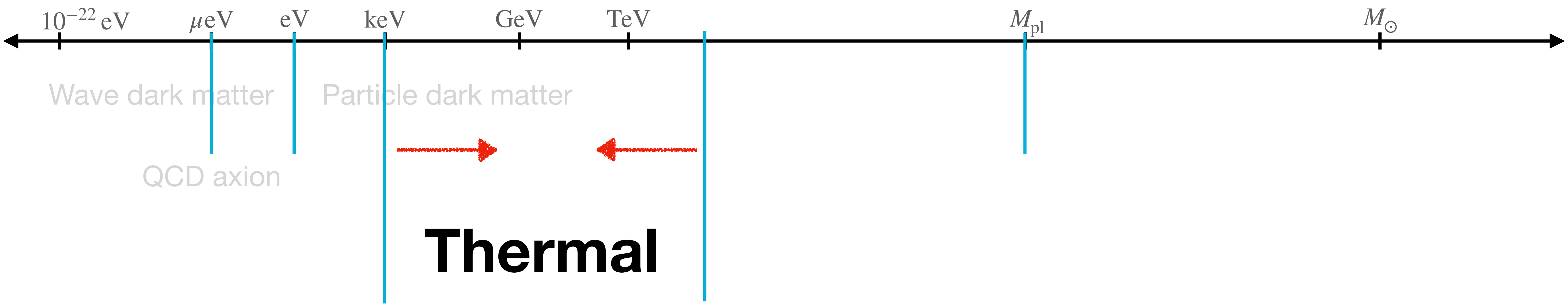




Simple estimate

$$\sigma_n \sim 10^{-42}\,\mathrm{cm}^2 \frac{G_D^2}{(1\,\mathrm{TeV})^{-4}}$$

Motivates model building and new experiments, sub-GeV dark matter



Weakly Interacting Dark Matter Paradigm

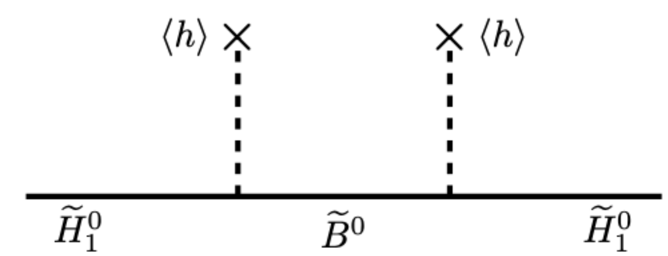
Connects with motivated models at the weak scale

Example: Higgsino dark matter as a simple electroweak target

Pseudo-Dirac limit almost pure Higgsinos with a small splitting

Direct detection is suppressed, close to neutrino floor

- Scattering at tree-level through the Higgs suppressed by $m_Z/M_{1,2}$
- Accidental cancellation of the loop-level scattering
- Spin-dependent couplings through Z also suppressed



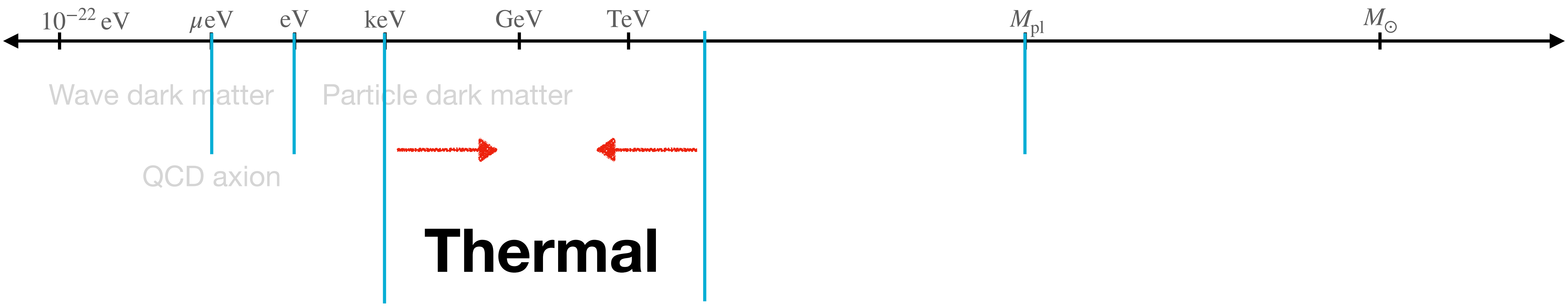
Halverson, Orlofsky, Pierce [1403.1592]
Mahbubani, Schwaller, Zurita [1703.05327]
Fukuda, Nagata, Otono, Shirai [1703.09675]

Future colliders can probe the pseudo-Dirac case with disappearing track searches

Indirect detection may be sensitive in the future, subject to astrophysical uncertainties

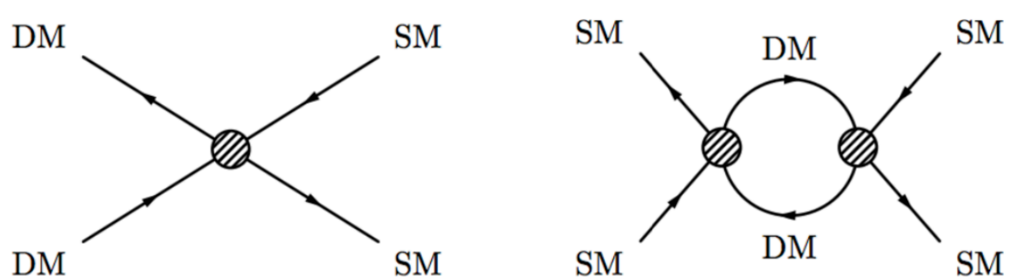
Capture in compact starts might be a promising avenue

Krall, Reece [1705.04843]



Weakly Interacting Dark Matter Paradigm

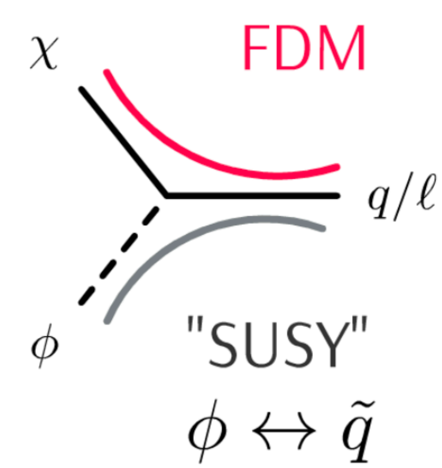
WIMP flavor problem



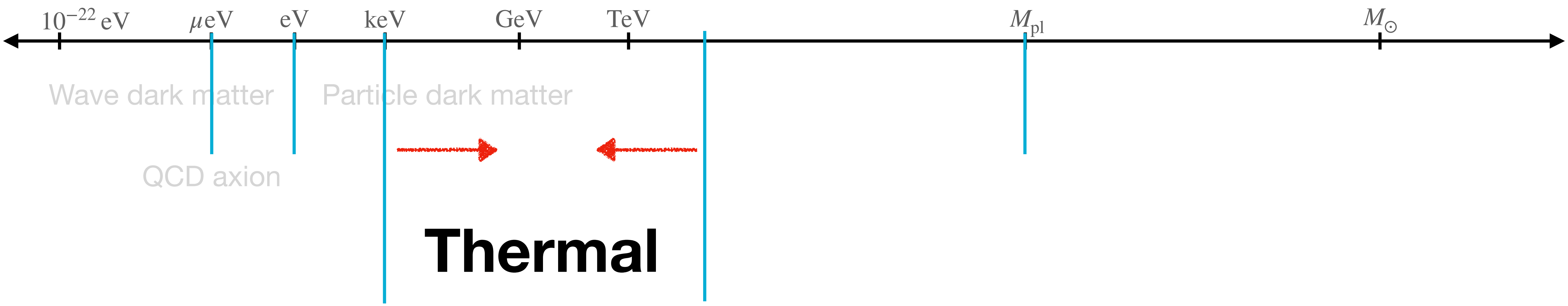
New weak scale interactions restricted by flavor constraints

Motivates model-building with flavor structure

Flavored Dark Matter

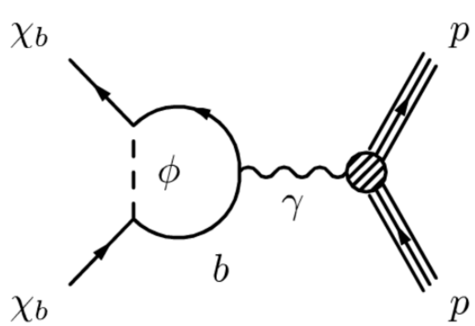


PA, Blanchet, Chacko. Kilic [1109.3516]
Kile and A. Soni [1104.5239]
Batell, Pradler, Spannowsky [1105.1781]



Weakly Interacting Dark Matter Paradigm

b-flavored dark matter can have loop suppressed direct detection



PA, Batell, Hooper, Lin [1404.1373]

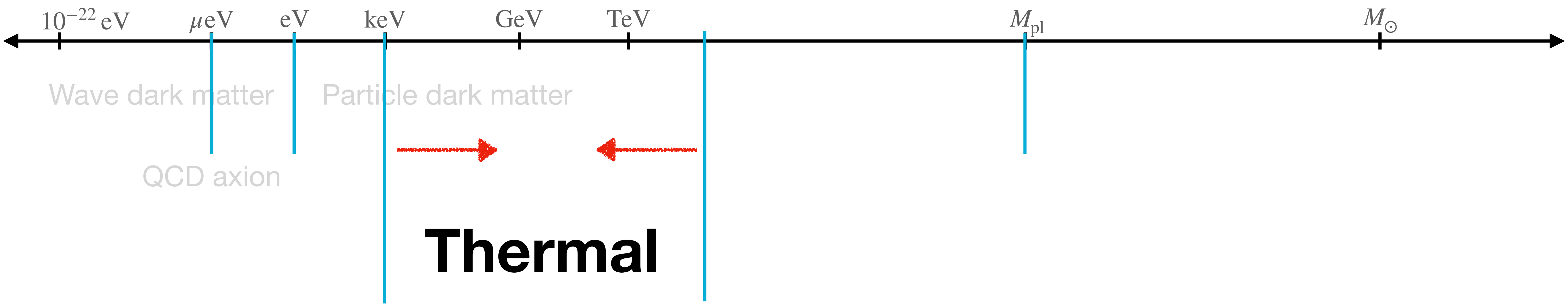
$$\sigma_n \sim 10^{-42}\,\mathrm{cm}^2 \left(\frac{\alpha}{4\pi}\right)^2 \frac{G_D^2}{(1\ \mathrm{TeV})^{-4}} \sim 10^{-46}\,\mathrm{cm}^2 \frac{G_D^2}{(1\ \mathrm{TeV})^{-4}}$$

Can explain the Galactic Center Excess of gamma-rays

Similar suppression for leptophilic dark matter

PA, Chacko, Verhaaren [1402.7369]

Can explain the anomaly in (g-2) of the muon



Beyond Freeze-out

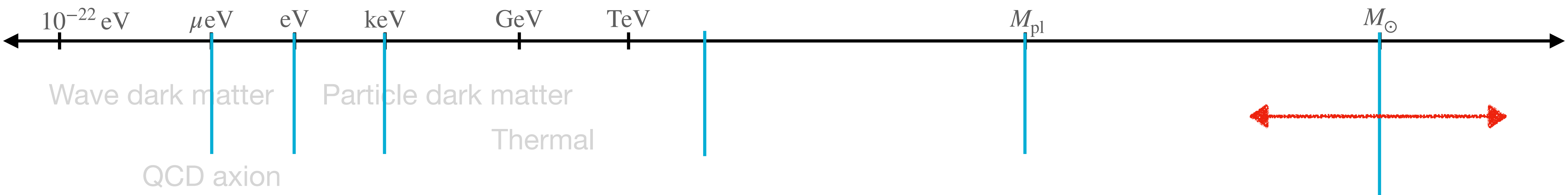
Freeze-in mechanism

Hall, Jedamzik, March-Russell, West [0911.1120]

Exceptions to the thermal relic abundance calculation

D'agnolo, Liu, Ruderman, Wang [2012.11766]
D'Agnolo, Pappadopulo, Ruderman [1906.09269]
Raffaele Tito D'Agnolo, Mondino, Ruderman, Wang [1803.02901]
D'Agnolo, Pappadopulo, Ruderman [1705.08450]

Opens up a broader mass and coupling space!

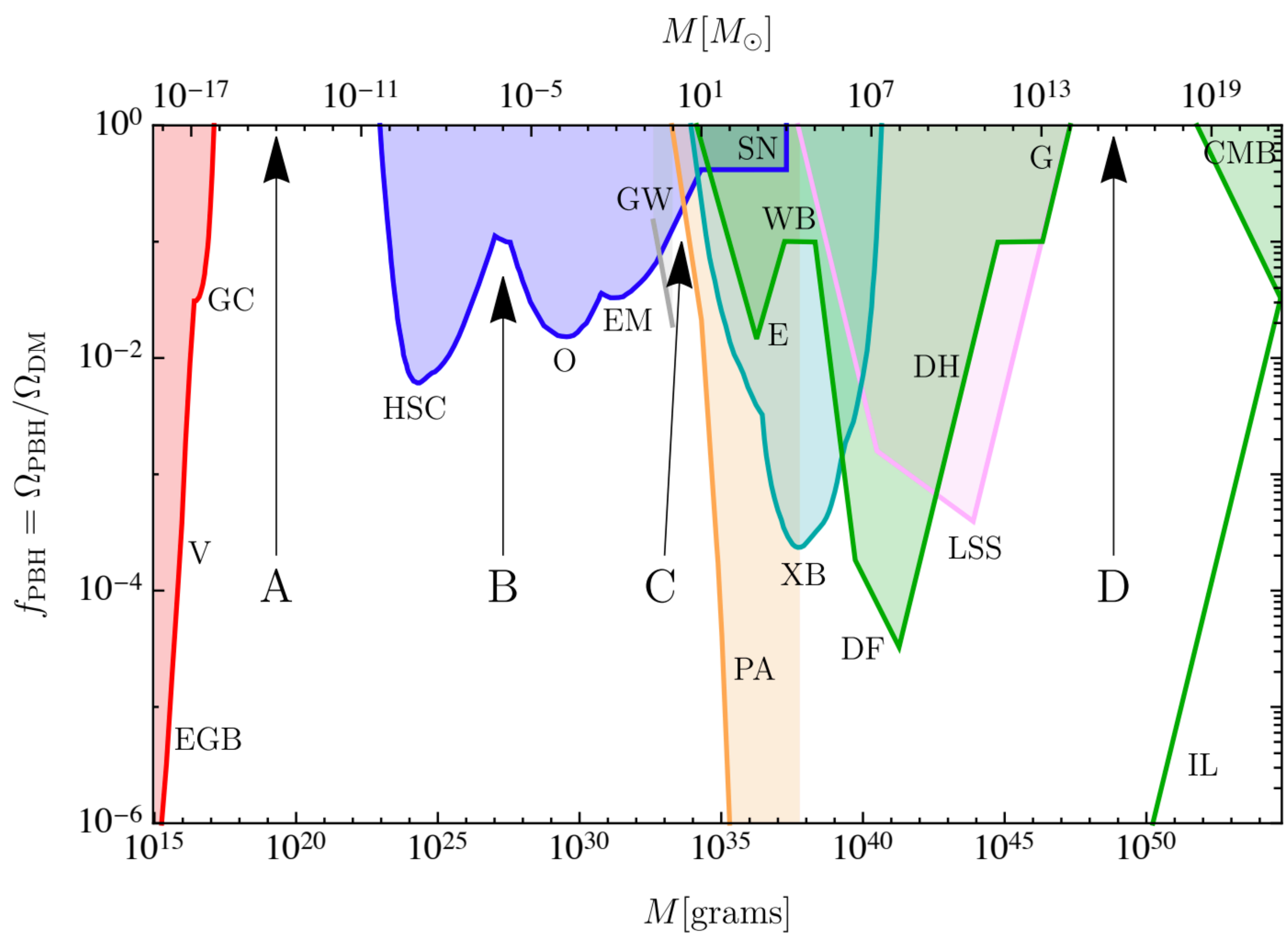


Primordial Black Holes

Multiple possible mechanisms for productions

- Primordial fluctuations
- Cosmic defect collapse
- Bubble collisions

Carr, Kuhnel [arXiv:2006.02838]



Can help produce superheavy dark matter

Lennon, March-Russell, Petrossian-Byrne, Tillim [1712.07664]

Summary

- The nature of dark matter is one of the biggest mysteries in fundamental physics, and concrete evidence of new physics beyond the Standard Model
- Models and mechanisms help organize the vast number of possibilities, highlighting experimental directions
- Experimental hints and anomalies provide quantitative inputs, sharpen existing models, and motivate new models
- New mechanisms can open up an extended parameter space for experiments
- The discovery of dark matter might rely crucially on this interface of model building directions and experiments