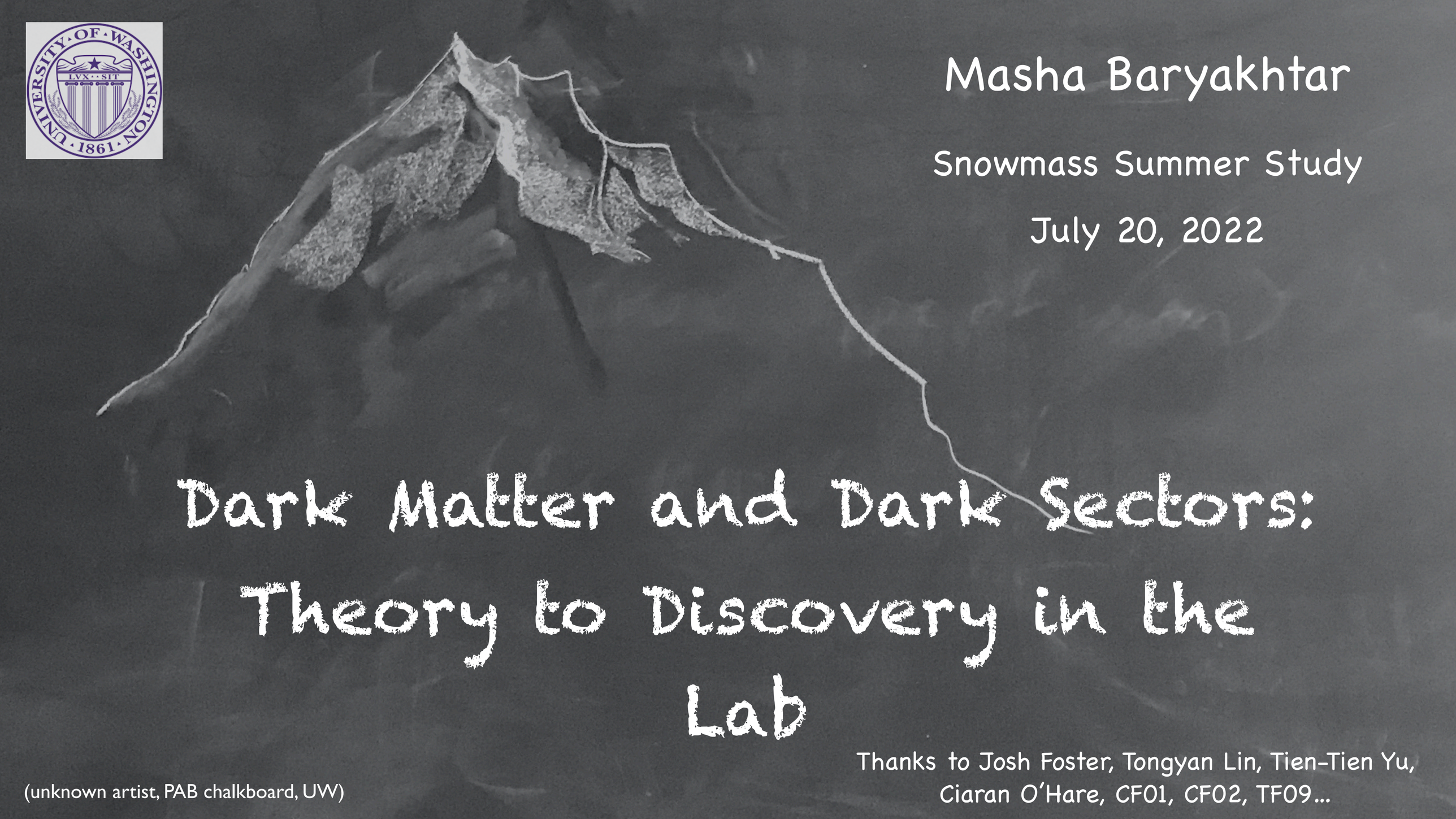


Masha Baryakhtar

Snowmass Summer Study

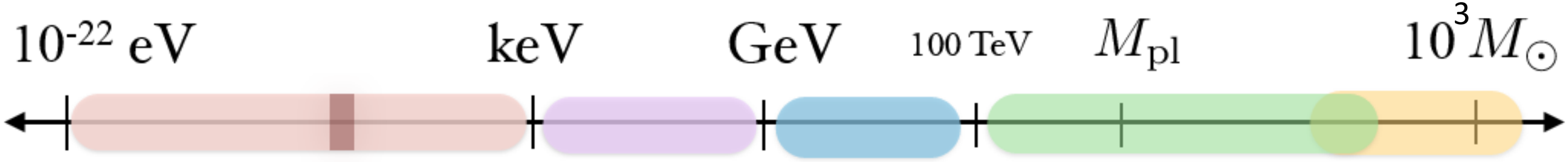
July 20, 2022

Dark Matter and Dark Sectors: Theory to Discovery in the Lab

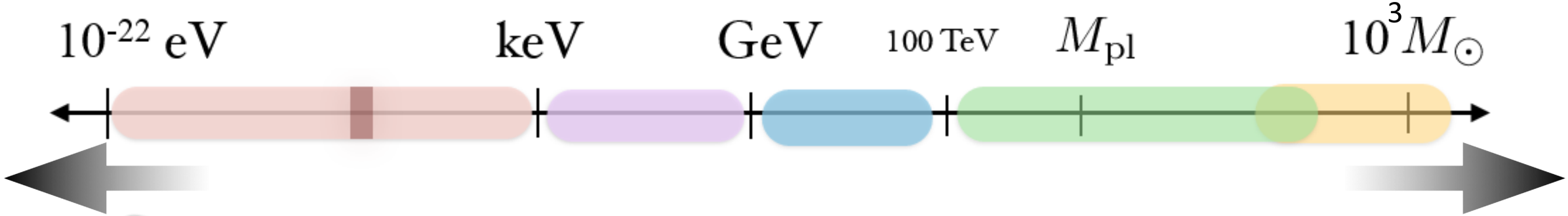
Thanks to Josh Foster, Tongyan Lin, Tien-Tien Yu, Ciaran O'Hare, CF01, CF02, TF09...

(unknown artist, PAB chalkboard, UW)

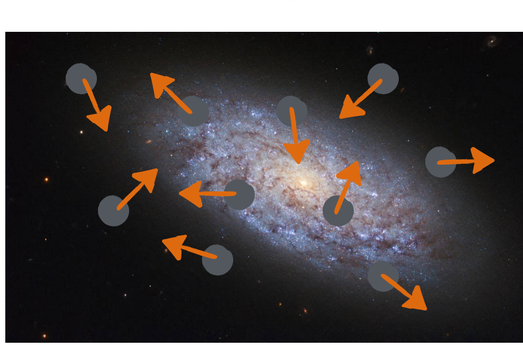
Dark Matter



Dark Matter



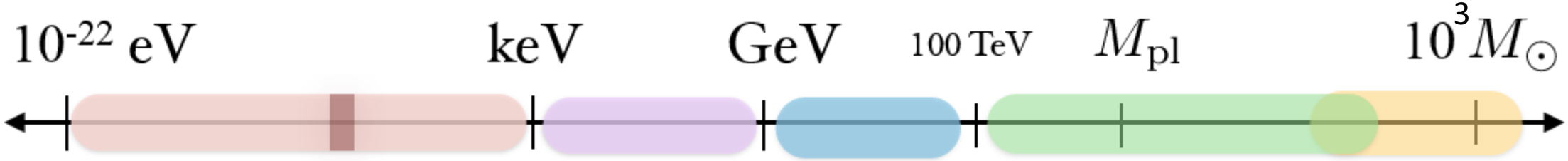
too fuzzy



too granular

Credits: NASA's Goddard Space Flight Center/Jenny Hottle

Dark Matter



~90 orders of magnitude!

Theoretical Directions

- Theory development*
- Production mechanism
- Can it be constrained or detected astrophysically
- How do we detect and study it in the lab?

*bonus points for solving outstanding problems

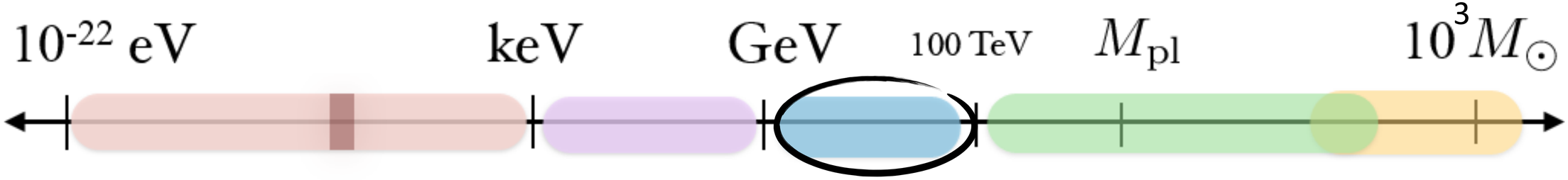
Theoretical Directions

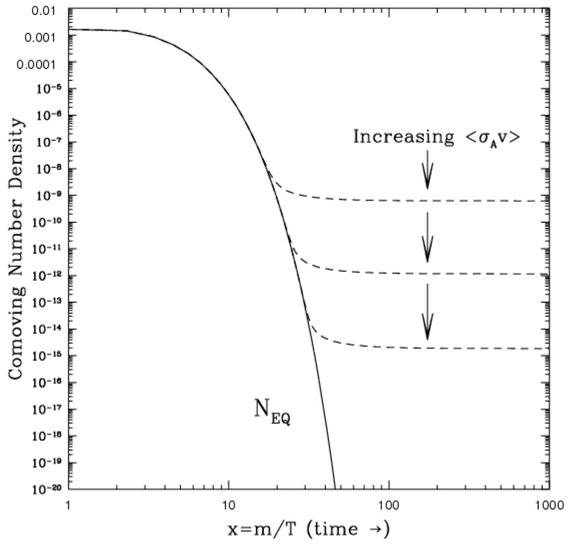
- Theory development*
- Production mechanism
- Can it be constrained or detected astrophysically
- How do we detect and study it in the lab?

see Josh Foster's talk in this session!

*bonus points for solving outstanding problems

Theorists Searching for New Physics



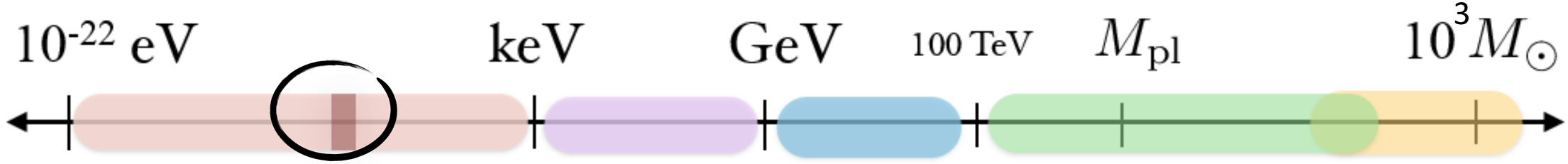


Jungman, Kamionkowski & Griest (1996)

Weakly Interacting Massive Particles

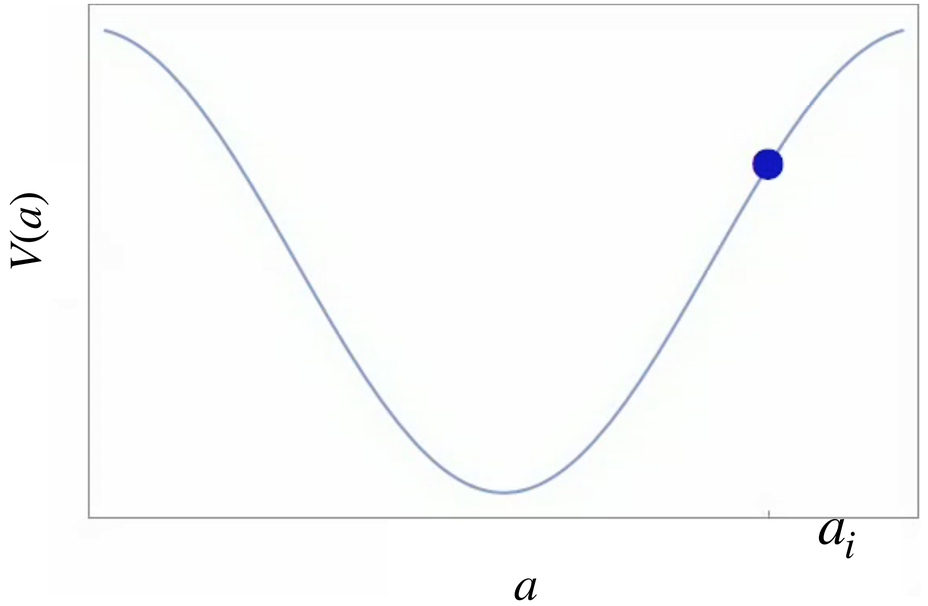
- ☑ Predicted in supersymmetric theories that hope to solve the hierarchy problem
- ☑ Correct cosmological abundance through thermal equilibrium through Standard Model interactions and freeze-out

Theorists Searching for New Physics



QCD axion

- ☑ Predicted in Peccei-Quinn mechanism to address the Strong-CP problem
- ☑ Correct cosmological abundance through inflationary misalignment mechanism



$$\ddot{a} + 3H\dot{a} + m^2 a = 0$$

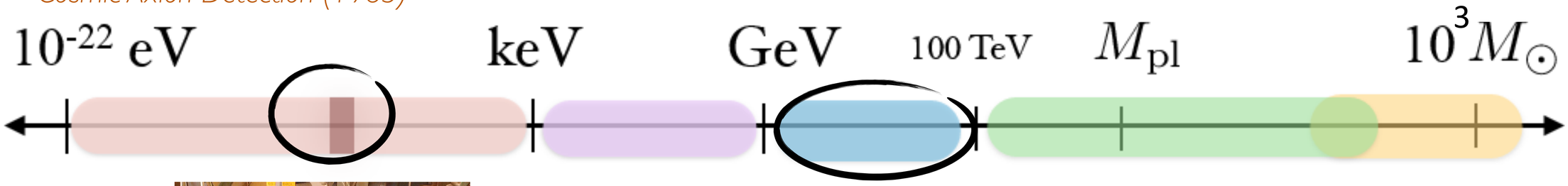
Preskill, Wise, Wilczek (1983)
Dine, Fischler (1982)
Abbott, Sikivie (1982)

Theorists Searching for New Physics

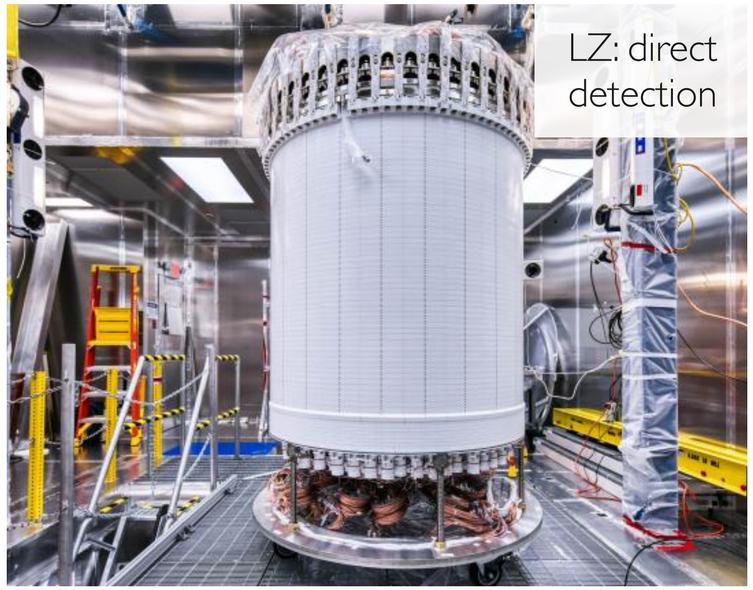
Sikivie: *Experimental Tests of the "Invisible" Axion (1983)*

Krauss, Moody, Wilczek, Morris: *Calculations for Cosmic Axion Detection (1985)*

Goodman, Witten *Detectability of Certain Dark Matter Candidates (1984)*

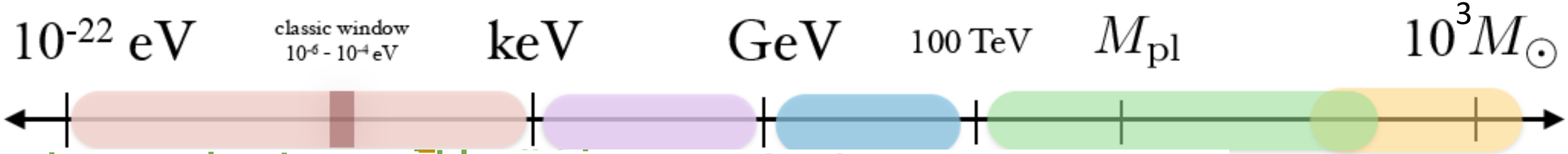


ADMX: cosmic axion searches



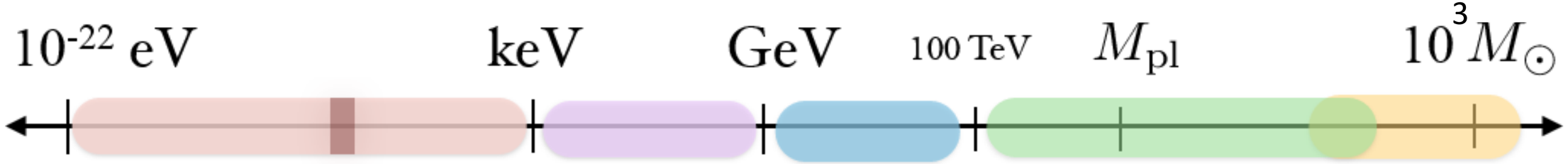
LZ: direct detection

Dark Matter in the Last Decade: Explosion of ideas



1. Directional detection of WIMPs with NV center spectroscopy
Rajendran, Zobrist, Sushkov, Walsworth, Lukin
2. Quantum sim/optimization for WIMP nuclear-recoil response
3. LHe and GaAs for calorimetry for hidden-sector DM
Knapen, Lin, Pyle, Zurek
4. Nanowire single-photon detectors for hidden photons **MB**, Huang, Lasenby
5. Qubits and Rydberg atoms for QCD axions Arvanitaki, Dimopoulos, Van Tilburg
6. Qubits and ultrahigh-Q cavities for hidden photons Graham, Mardon, Rajendran, Zhao
7. Photon upconverters for QCD axions (needed for nuclear spins and lumped resonators)
8. Lumped resonators for QCD axions Kahn, Safdi, Thaler; Chaudhuri, Graham, Irwin, Mardon, Rajendran, Zhao
9. Nuclear spins for QCD axions Budker, Graham, Ledbetter, Rajendran, Sushkov
10. Clocks / cold atoms for scalar dark matter
Arvanitaki, Huang, Van Tilburg

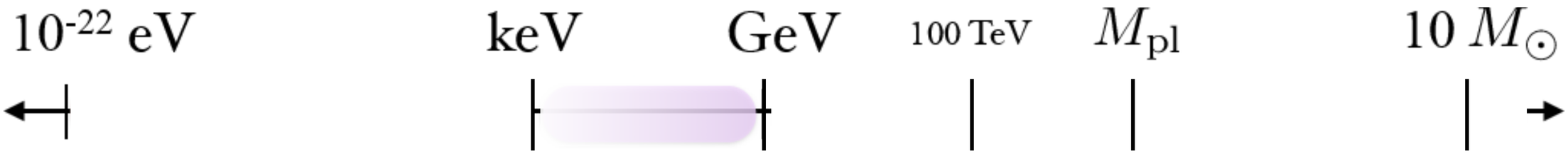
Dark Matter in the Last Decade: Some Examples



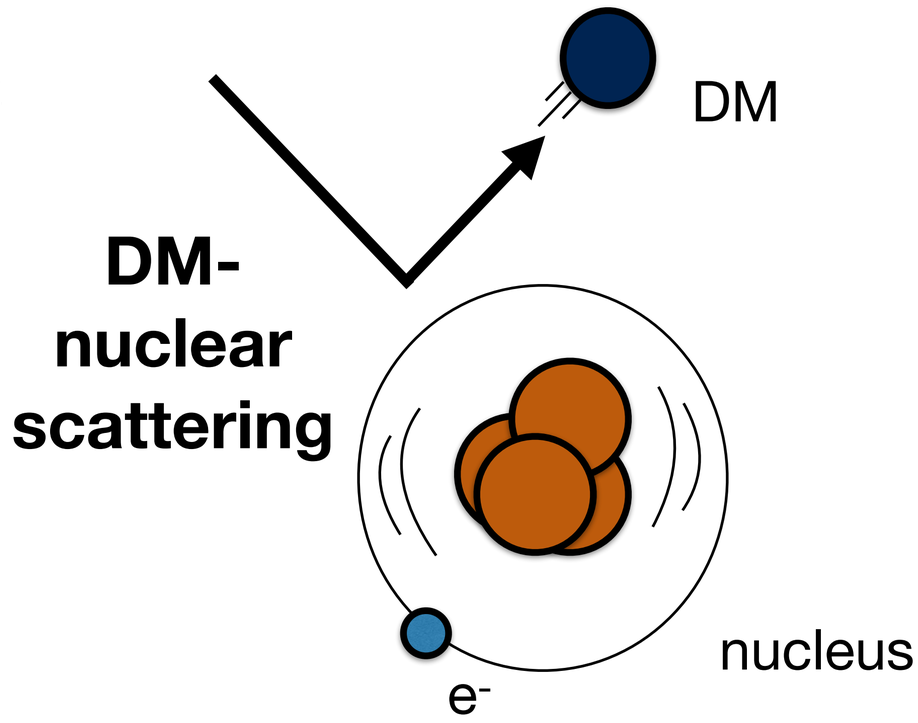
(2,3) axions coupled to photons

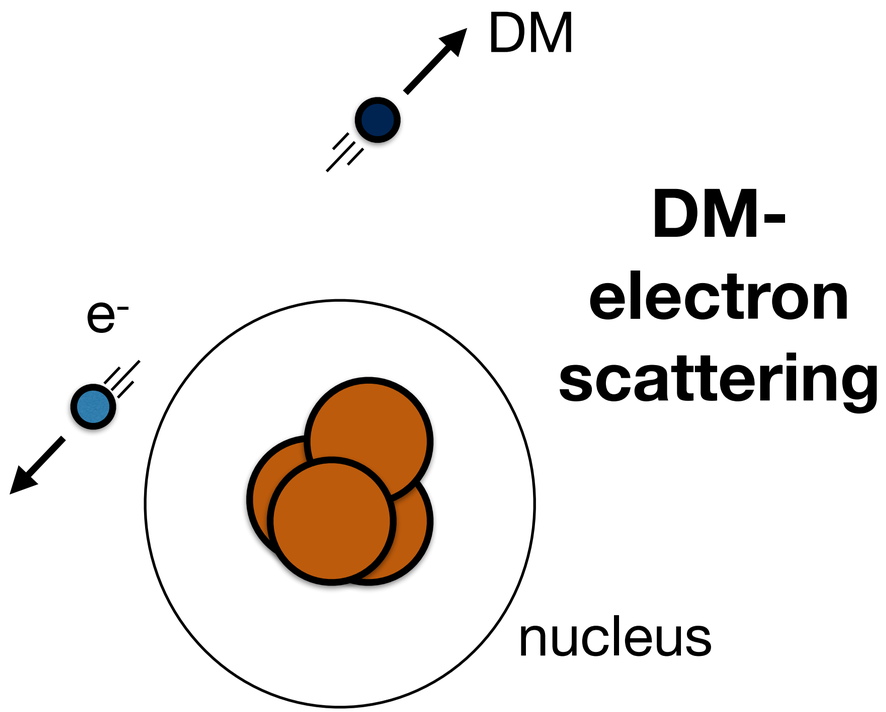
(1) dark photon-mediated light dark

Dark Photon Mediated Light Dark Matter



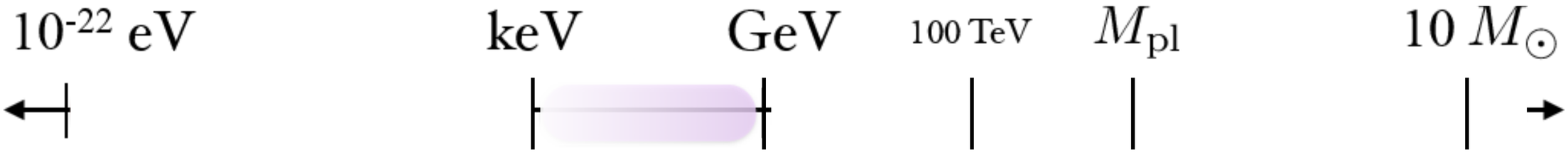
- ☑ New light sector produced through freeze-in or freeze-out
- ☑ Interactions with standard model mediated by a dark photon



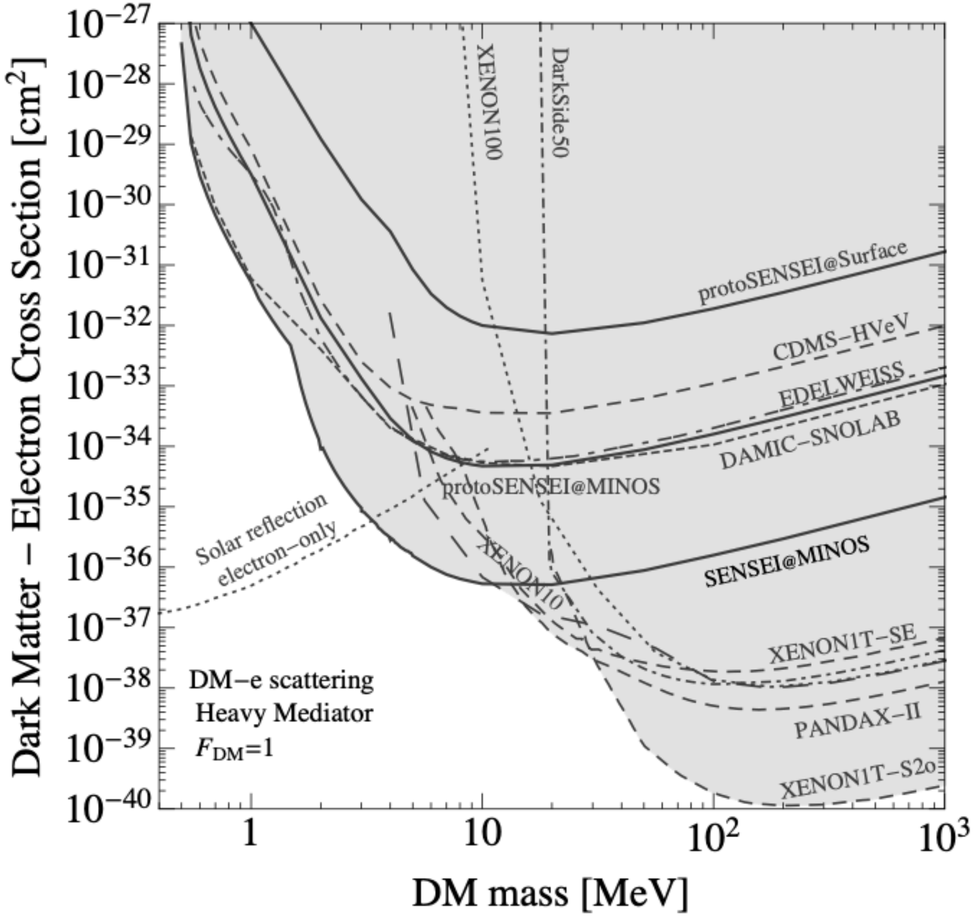


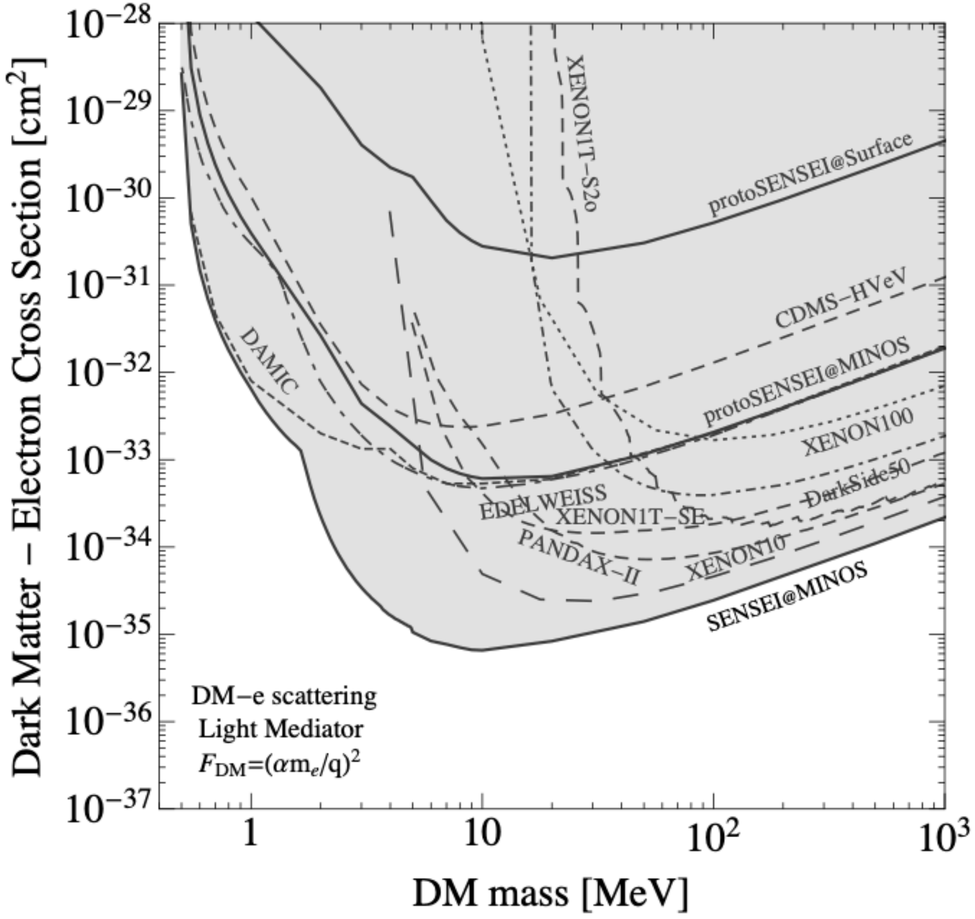
graphics by Tien-Tien Yu

Dark Photon Mediated Light Dark Matter

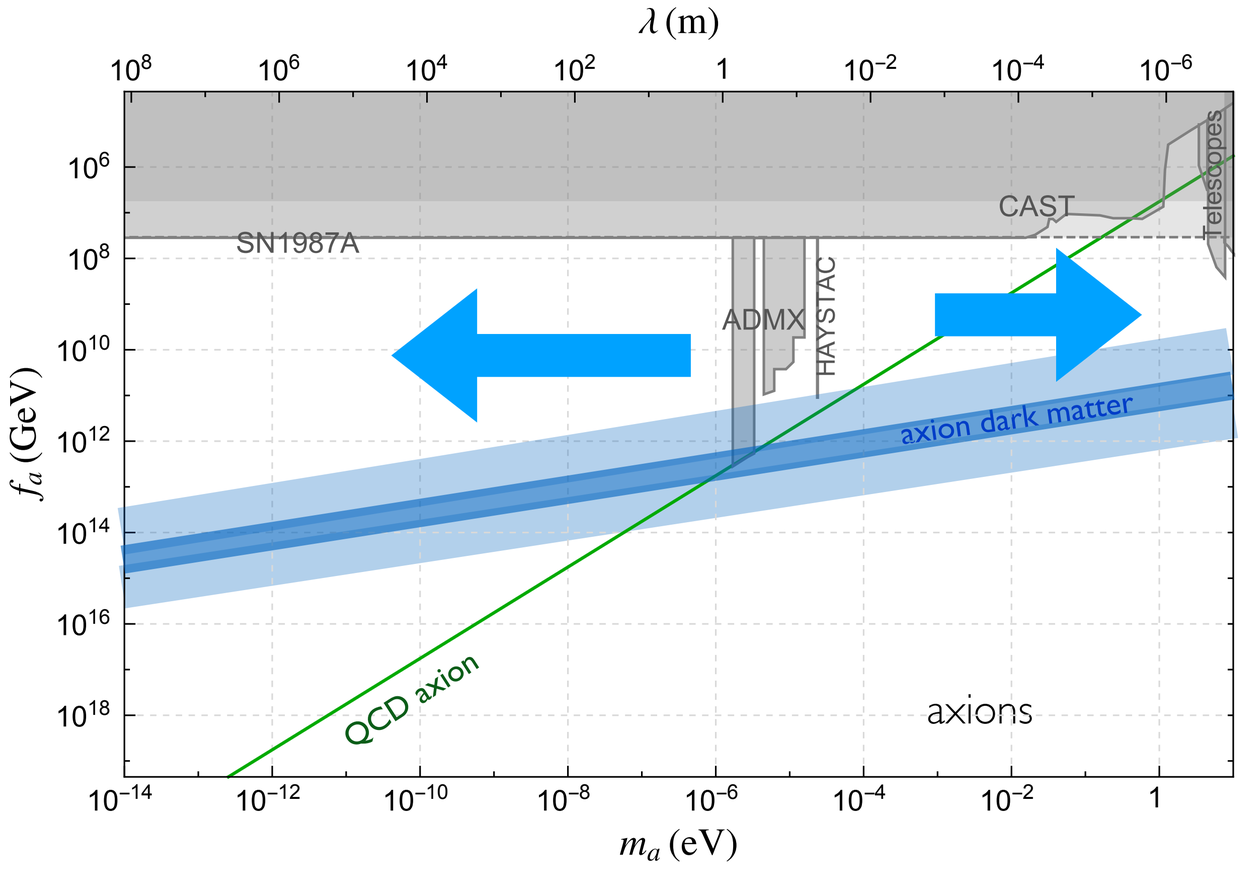


[arXiv:2203.08297]



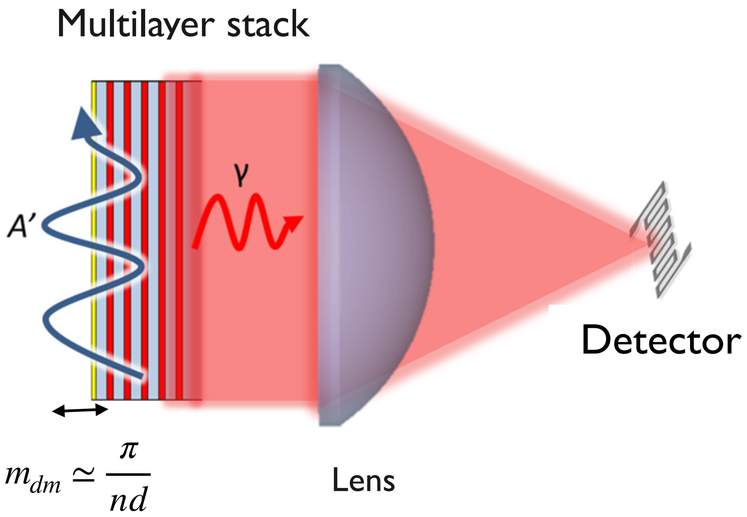


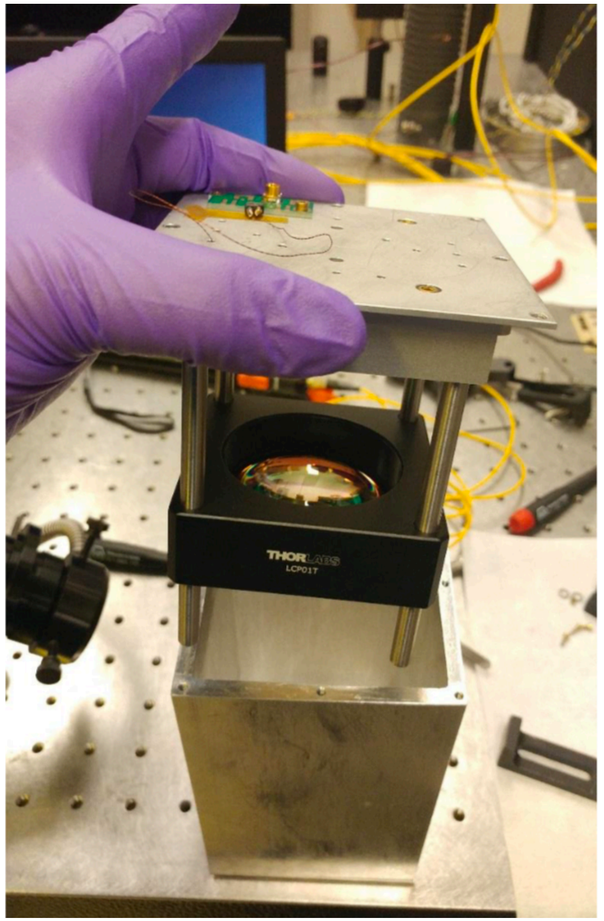
Axions interacting with Photons



- ☑ Axions produced through misalignment and/or emission from cosmic strings
- ☑ Generically couple to photons, contributing new source terms in Maxwell's equations
- ☑ Generic light axions motivated from UV theories like string theory

Heavier Axion Dark Matter



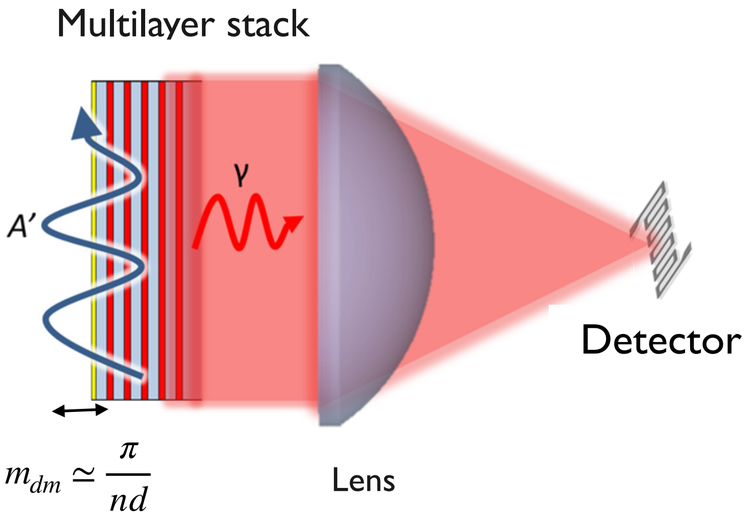


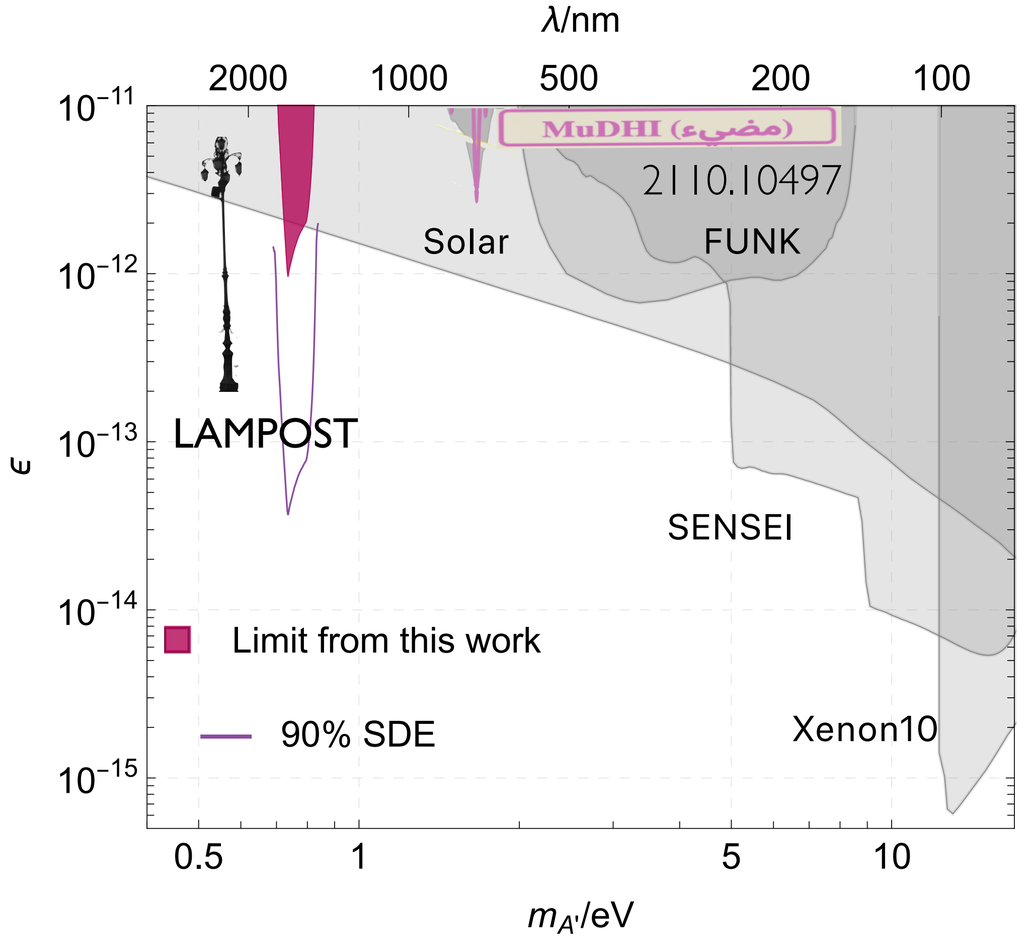
- photons relativistic while dark matter is almost at rest
- Use material lattice to introduce momentum scale in the problem

MADMAX collaboration
MB, J. Huang, R. Lasenby, PRD 2018
Chiles, Charaev, Lasenby, **MB**, Huang, Roshko, Burton, Colangelo, Van Tilburg, Arvanitaki, Nam, Berggren 2110.01582
Manenti, Mishra, Bruno, Di Giovanni, Millar, Morå, Roberts, Oikonomou, Sarnoff, Arneodo 2110.10497

Heavier Axion Dark Matter

10^{-22} eV — keV — GeV — 100 TeV — $M_{\rm pl}$ — $10\,M_\odot$





- Convert to photons, which are relativistic while dark matter is almost at rest
- Use material lattice to introduce momentum into the setup

MADMAX collaboration
MB, J. Huang, R. Lasenby, PRD 2018
Chiles, Charaev, Lasenby, **MB**, Huang, Roshko, Burton, Colangelo, Van Tilburg, Arvanitaki, Nam, Berggren 2110.01582
Manenti, Mishra, Bruno, Di Giovanni, Millar, Morå, Roberts, Oikonomou, Sarnoff, Arneodo 2110.10497

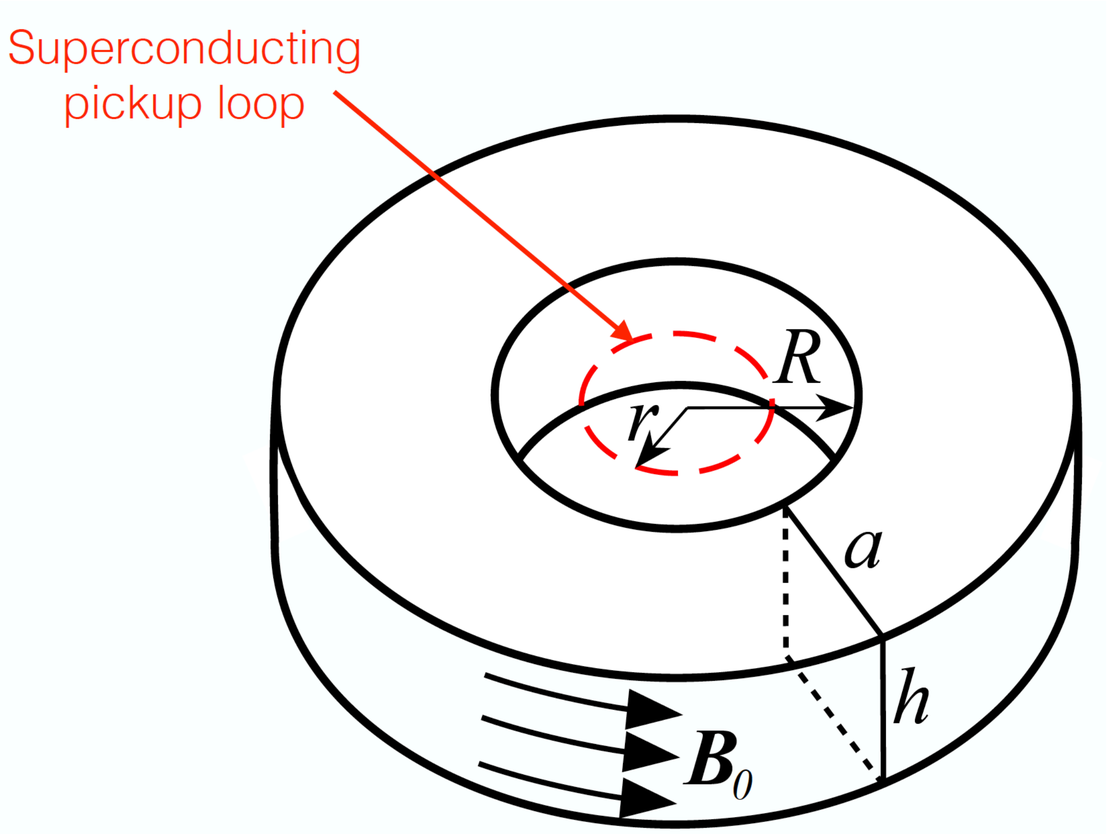
Lighter Axion Dark Matter

10^{-22} eV — keV — GeV — 100 TeV — $M_{\rm pl}$ — $10\,M_\odot$

- Axion field modifies Maxwell's equations

$$\nabla \times \mathbf{B} = \mathbf{J} + g_{a\gamma\gamma}\frac{\partial a}{\partial t}\mathbf{B}$$

- Time-varying effective current, induces time-varying magnetic flux
  - Measuring the flux = measuring the local axion field

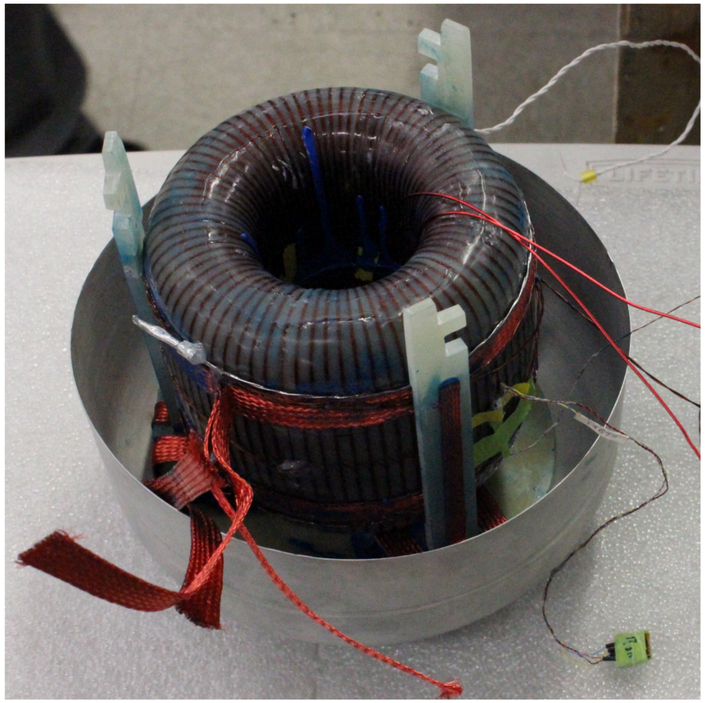


Y. Kahn, B.R. Safdi, J. Thaler, *Phys.Rev.Lett.* 117 (2016) 14, 141801

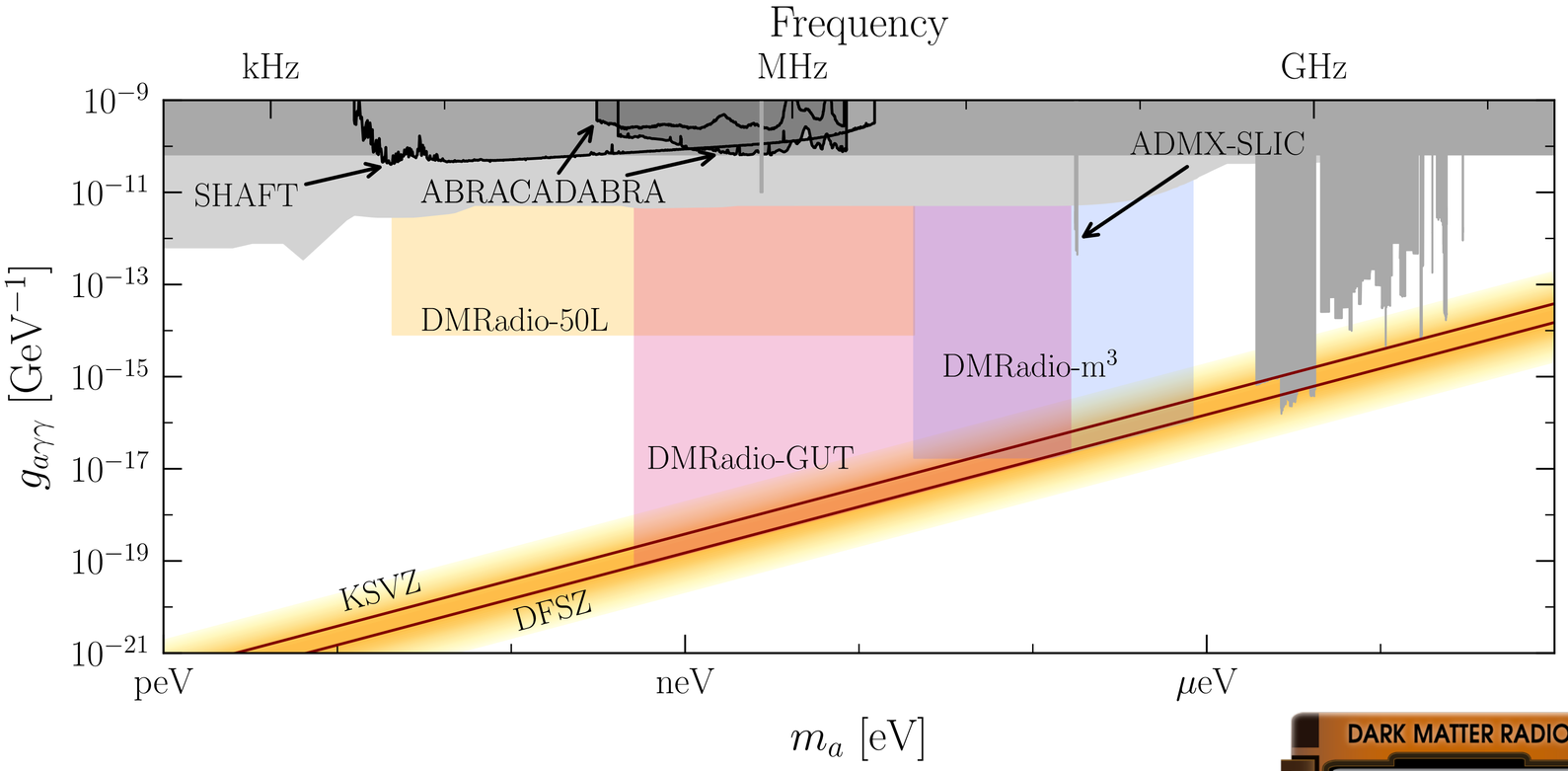
from Josh Foster

Lighter Axion Dark Matter

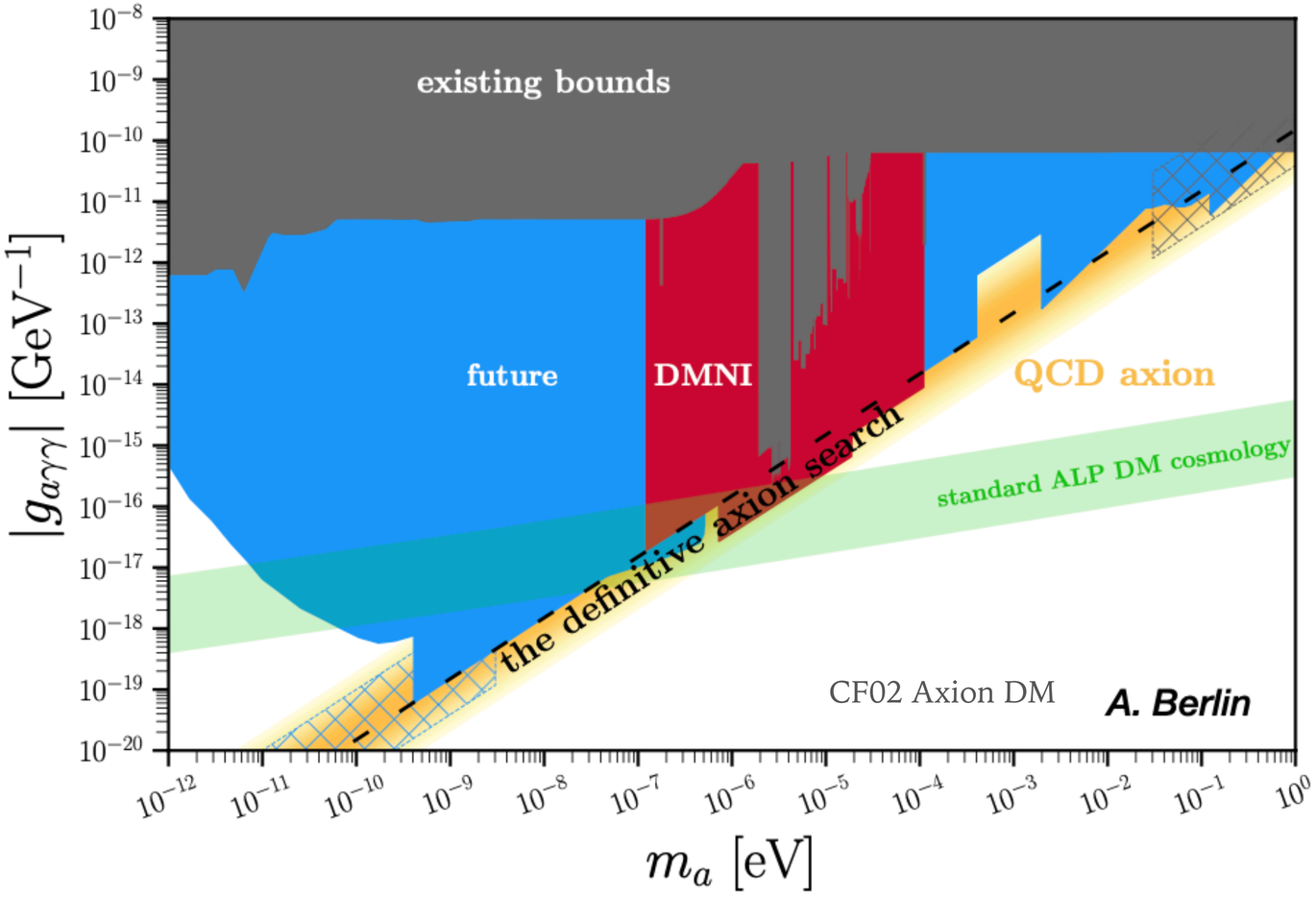
10^{-22} eV — keV — GeV — 100 TeV — $M_{\rm pl}$ — $10\,M_\odot$



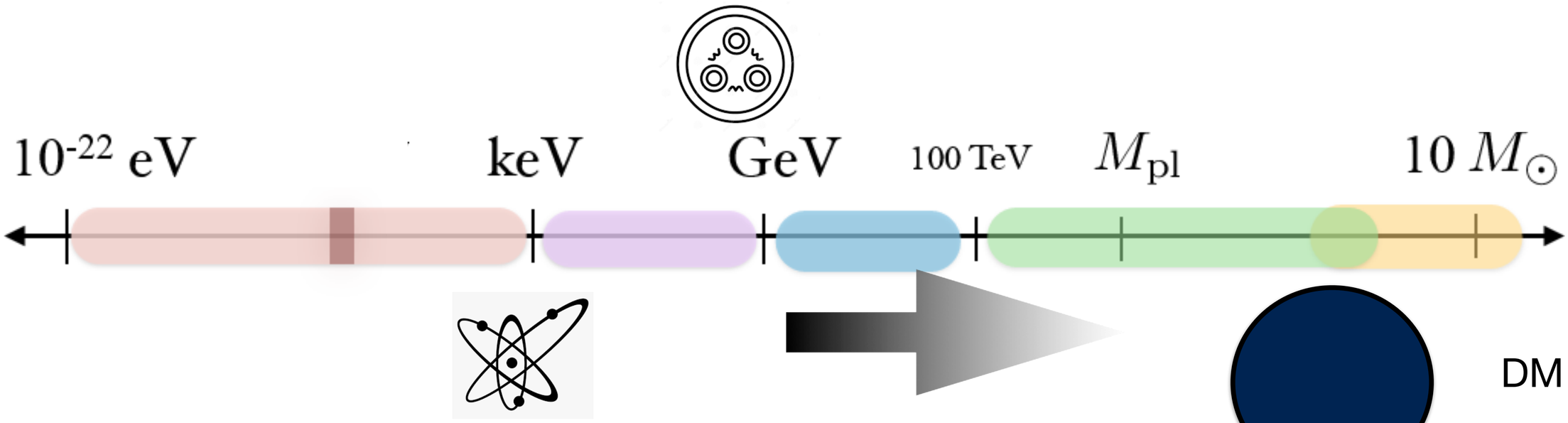
ABRA-10cm Prototype Detector
from Josh Foster

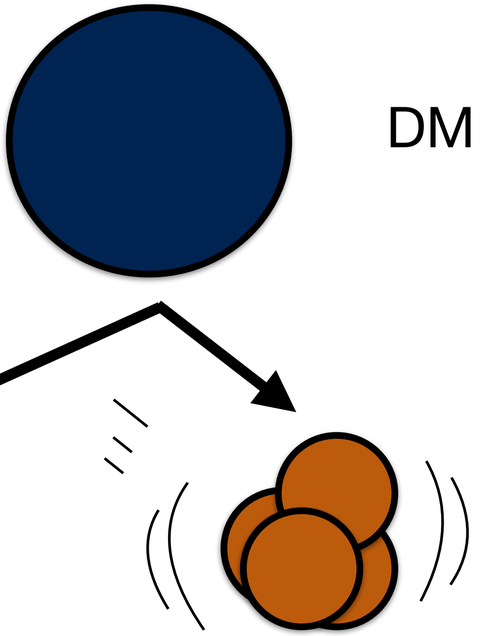


Axions interacting with Photons



Challenges and Opportunities at Low Masses

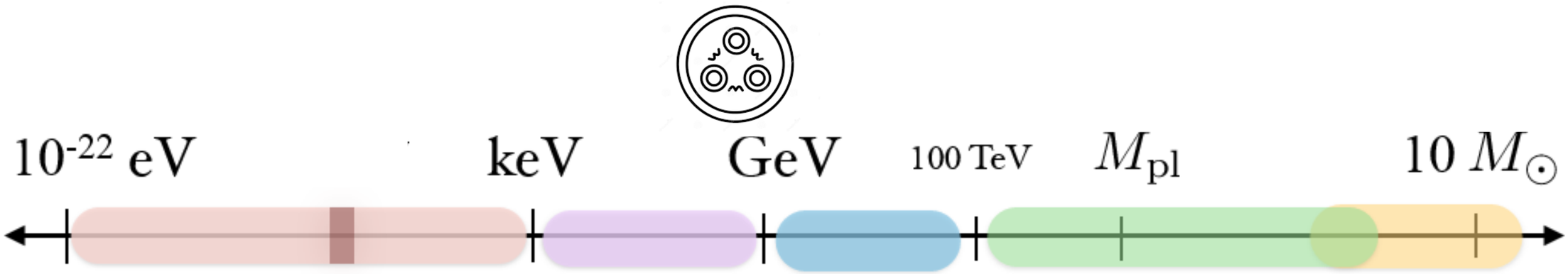




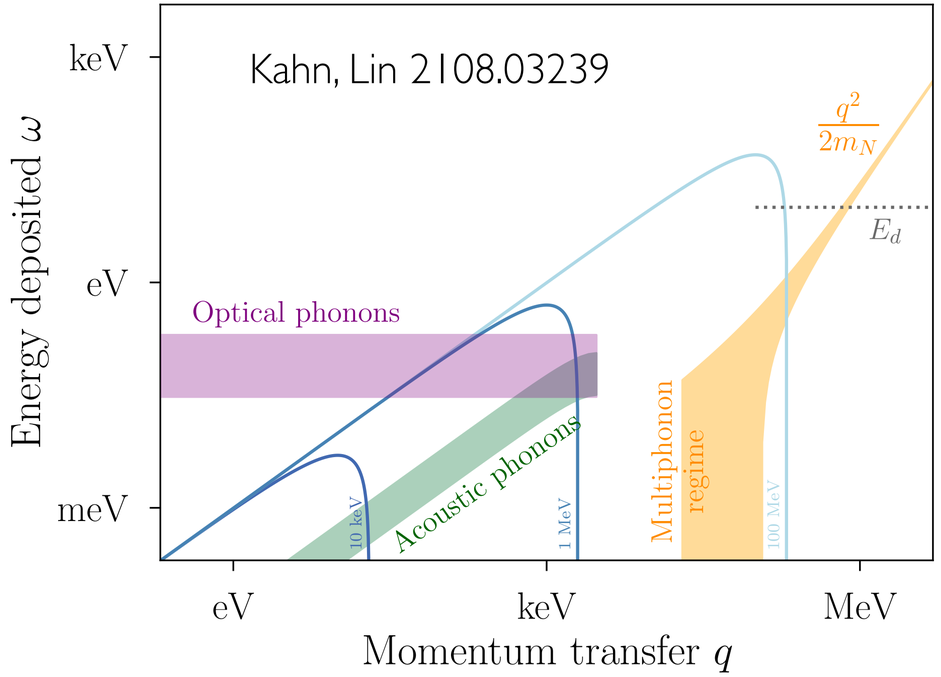
Scattering depends on underlying interaction with nuclei, kinematics largely identical

adapted from Tien-Tien Yu

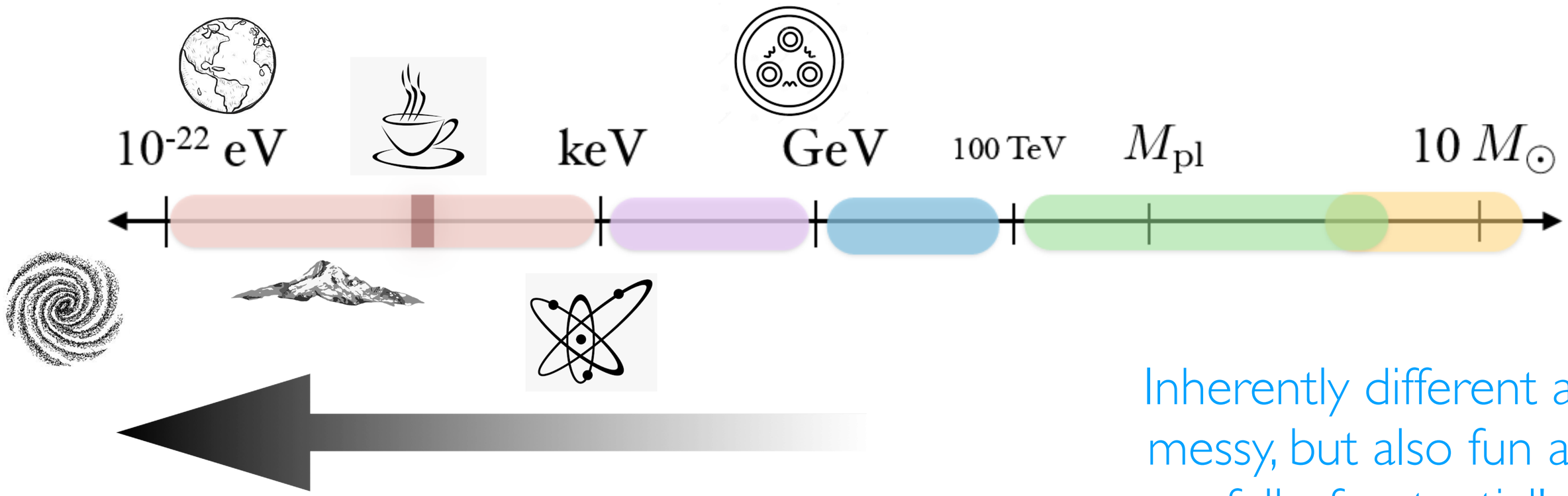
Challenges and Opportunities at Low Masses



Scattering (and absorption) depends on material composition and structure



Challenges and Opportunities at Low Masses



Inherently different and messy, but also fun and full of potential!

Dark matter energies and length scales become comparable to inter-atomic spacing, vibrational modes in materials, people, labs, planets…

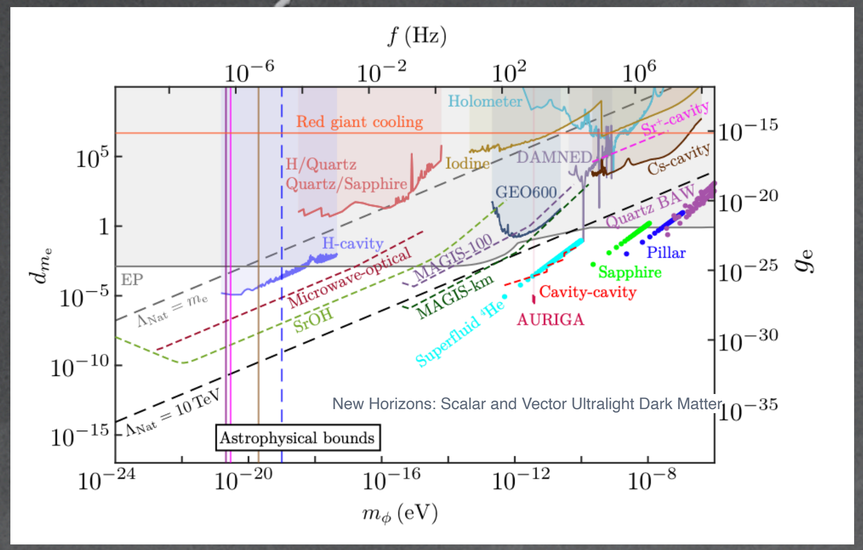
Dark Matter in the Next Decade:

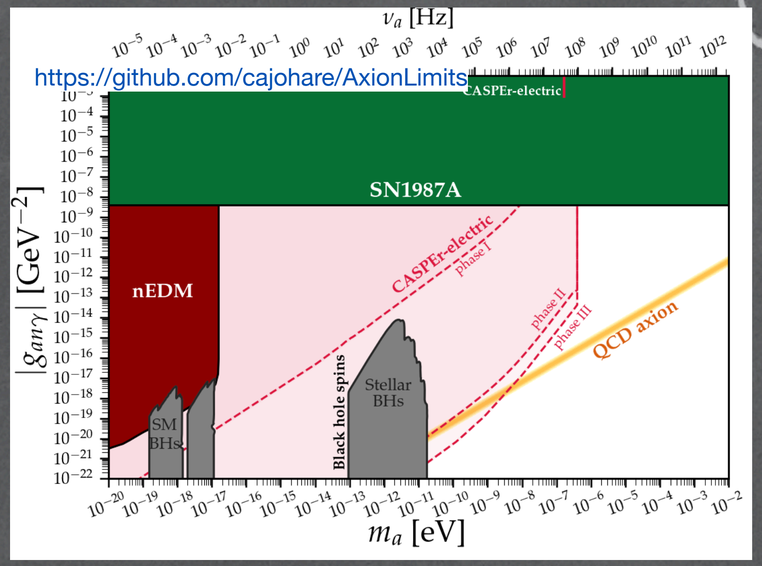
New Materials, New Thresholds, New Interactions

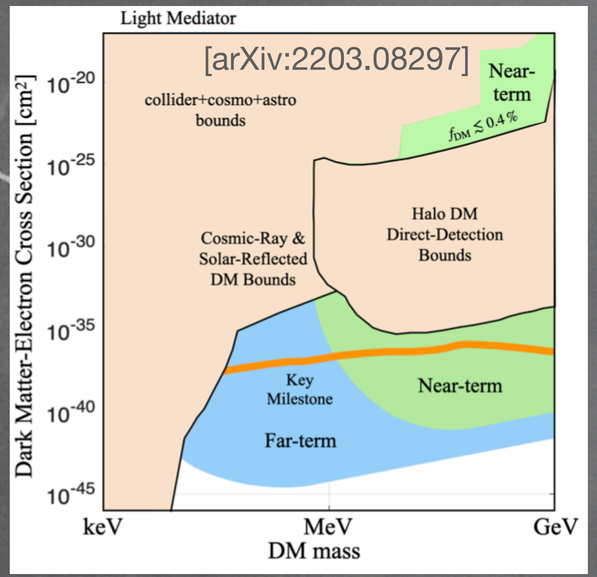
Ultralight scalar modifications of SM couplings

Axion interactions with electrons, nuclei, incl. `fundamental coupling'

Collective excitations in materials from light DM scattering



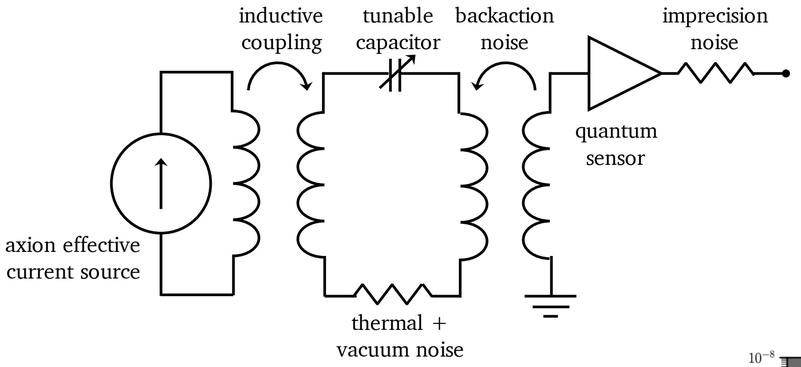


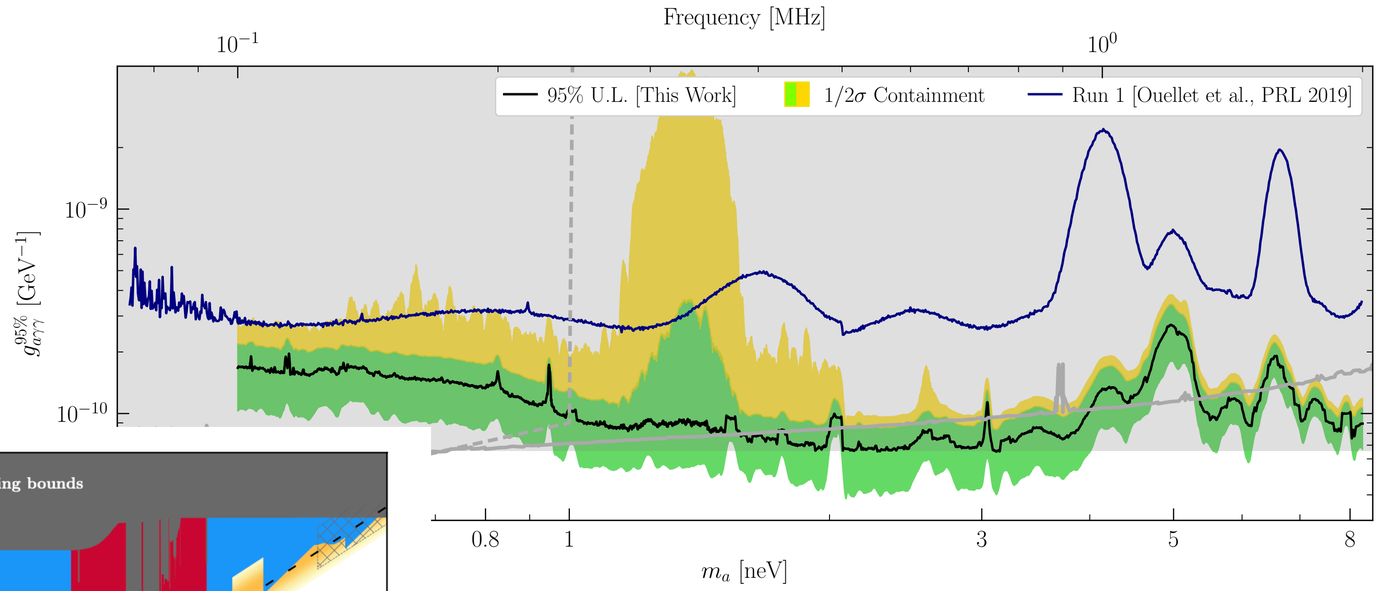


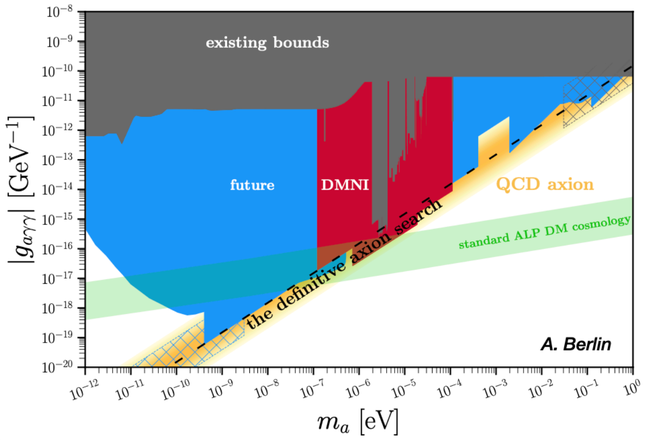
+new models and observables

Mount Rainier as seen from Paradise Meadow
NPS photo

AXION DIRECT DETECTION WITH ABRACADABRA







Ouellet, **JWF** et al., *Phys.Rev.Lett.* 122 (2019) 12, 121

Ouellet, **JWF** et al., *Phys.Rev.D* 99 (2019) 5, 052012

Salemi, **JWF** et al., arXiv:2102.06722 [hep-ex]