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Big Questions in Cosmology

Tracy Slatyer

The Future of High Energy Physics: A New Generation, A New Vision
Aspen Center for Physics
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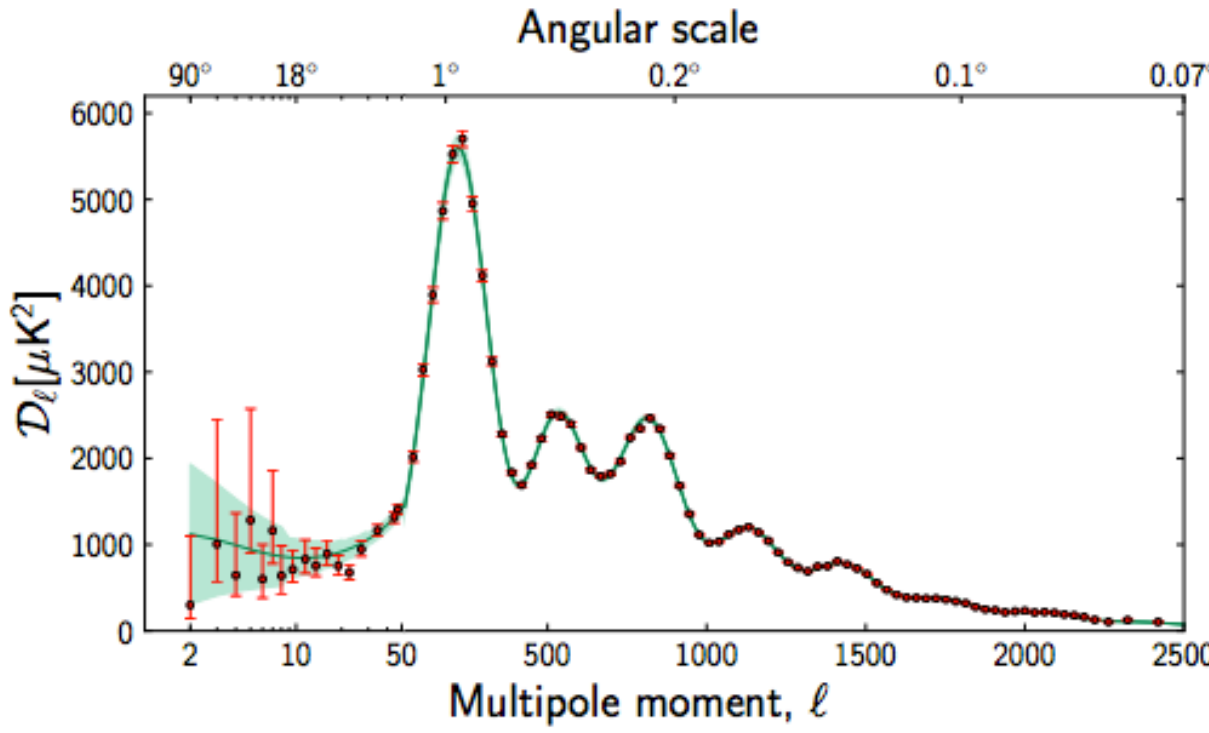
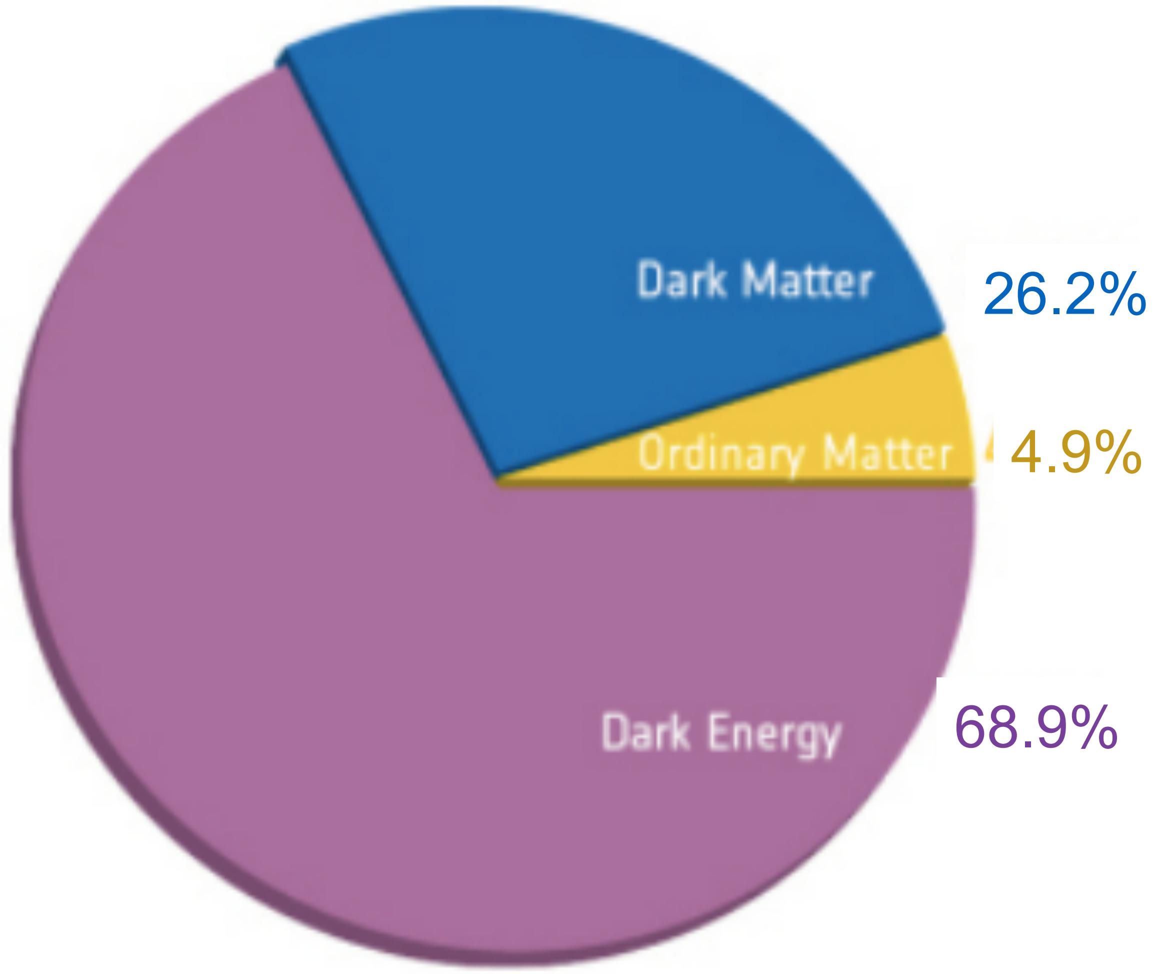
U.S. DEPARTMENT OF ENERGY | Office of Science

ΛCDM cosmology



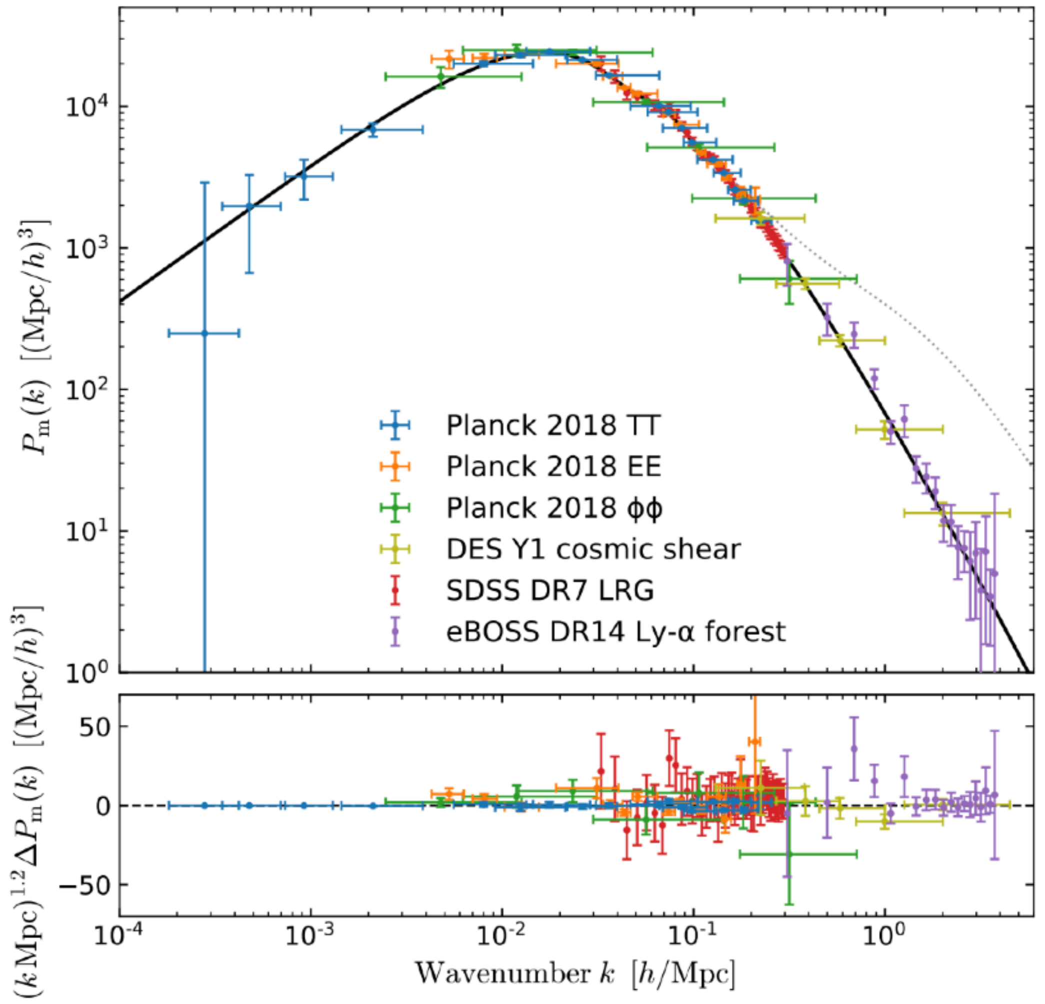
Credit: ESA and the Planck Collaboration

- Six-parameter model has provided a spectacularly successful description of the universe across a broad range of redshifts and scales. Linear and mildly non-linear scales allow for high-precision theoretical predictions, at small/nonlinear scales we rely on sophisticated simulations.
- Requires two new components: dark energy (Λ) and cold dark matter (CDM).
- Big-picture theoretical puzzles include:
  - origin and nature of dark energy and dark matter
  - origin of ordinary matter / baryogenesis
  - physics of the very early universe / inflation

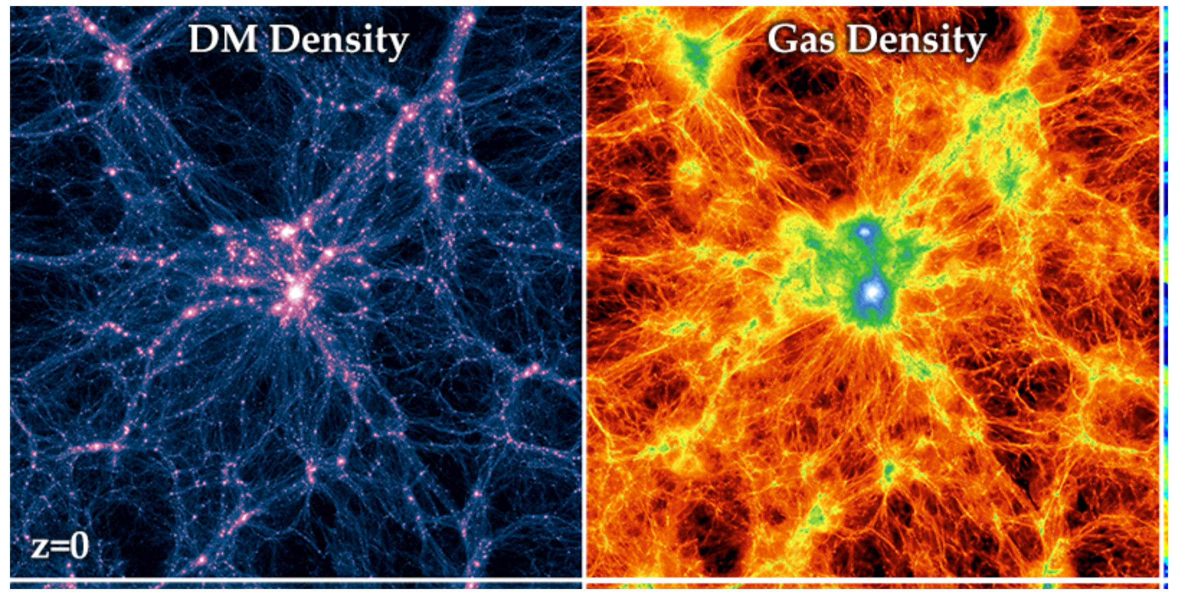


- Also some hints of divergences from ΛCDM
  - Most well-established is the Hubble tension, discrepancy between early- and late-time measurements of H_0
  - Others include the S_8 tension, (debated) hints of modified dark matter physics at small scales, the puzzle of early supermassive black holes, various excesses in indirect detection, etc…

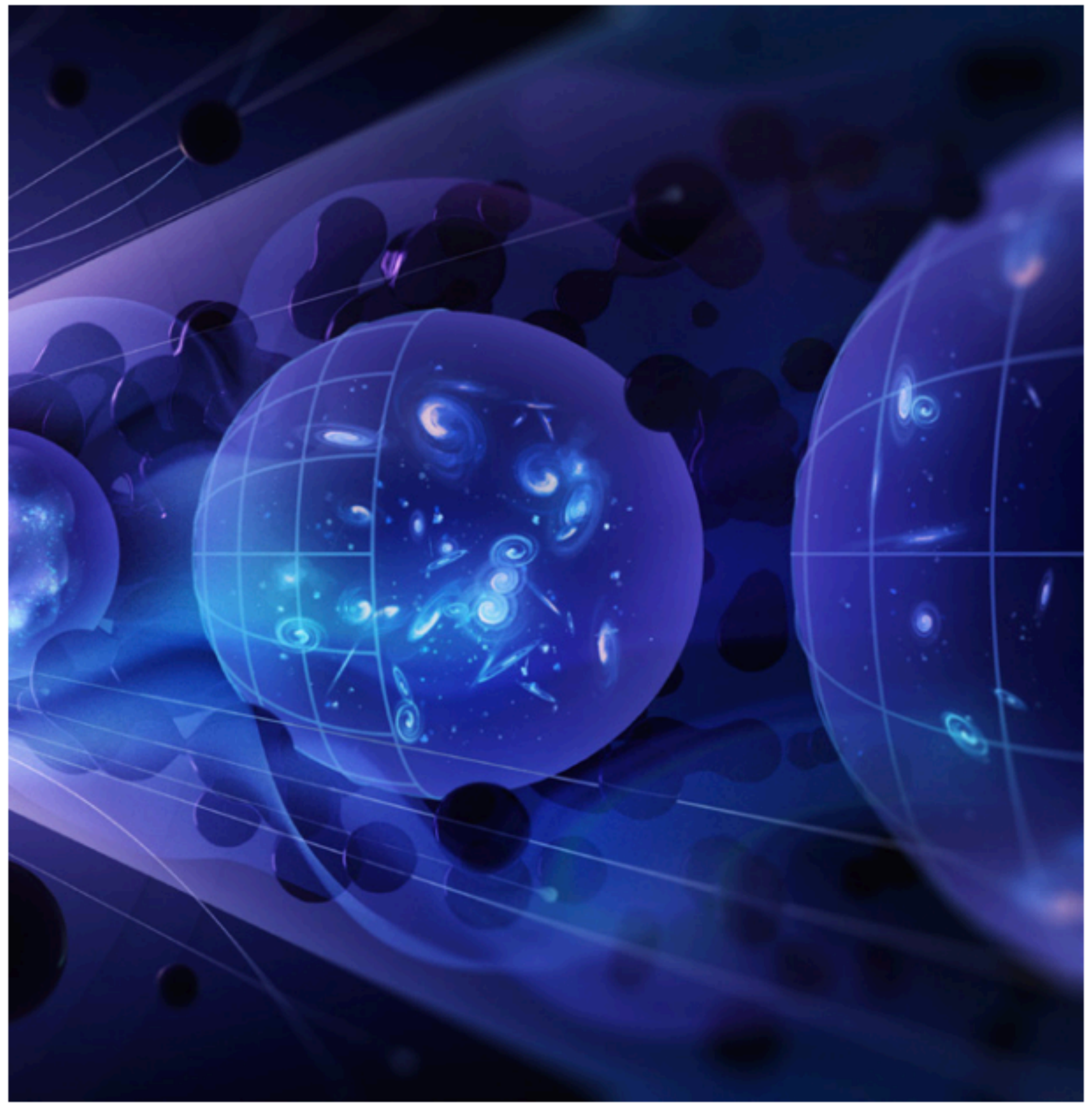
Chabanier et al 1905.08103



Illustris collaboration



Big Questions from P5



Illuminate the Hidden Universe

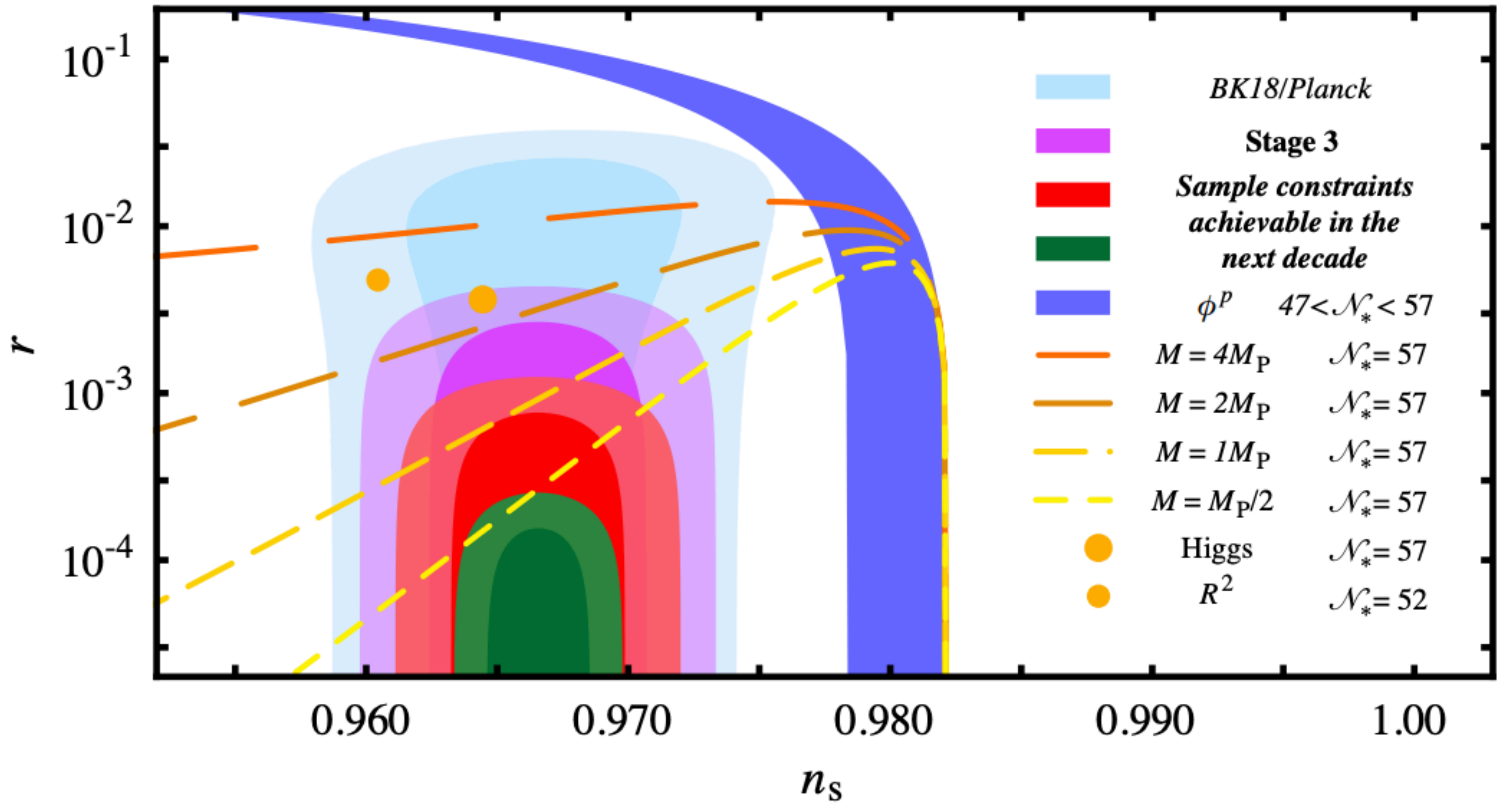
Determine the Nature of Dark Matter

Understand What Drives Cosmic Evolution

- What drives cosmic evolution?
  - How is the inflationary paradigm realized in nature? What is the energy scale of inflation?
  - What is the nature of dark energy? Does w differ from -1 or evolve with time? Why is Λ so small?
  - Can we discover or constrain deviations from the classic ΛCDM evolution, e.g. the presence of additional light degrees of freedom, an early epoch of matter domination, or early dark energy?
- What can we learn about the neutrino sector?
- Are anomalies (like the Hubble tension) telling us something important about cosmology/physics?
- Can new windows on the first stars/galaxies (e.g. JWST) shed light on fundamental physics questions? (see e.g. talk by Alex Kusenko re supermassive black holes) How about precision tests of the cosmic background radiation spectrum? (see talk by Ritoban Basu Thakur)

What can we learn about inflation?

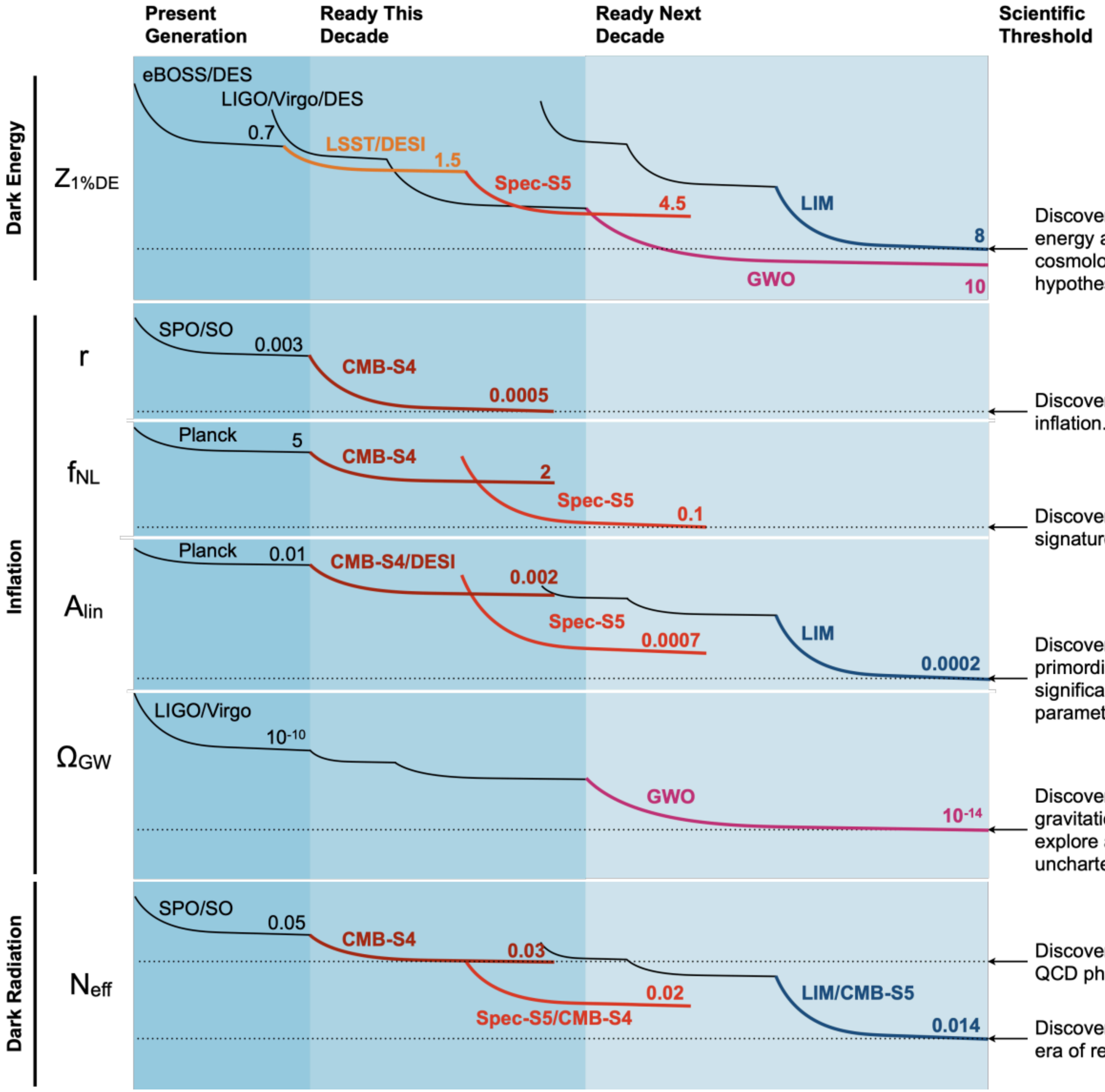
- Inflationary paradigm: exponential expansion in the very early universe. Quantum fluctuations during inflation source subsequent inhomogeneities in matter/radiation, with a close-to-scale-invariant power-law-like power spectrum.
- Scalar amplitude A_s and spectral tilt n_s of the primordial power spectrum of density perturbations are already well-measured by the cosmic microwave background (CMB).



Pimentel et al 2203.08128

- Many other observables that we can use to test this paradigm and distinguish inflationary models:
  - Primordial gravitational waves / tensor fluctuations sourced during inflation - imprint B-mode polarization in CMB (parameterized by tensor-to-scalar ratio r)
  - Non-trivial interaction dynamics during inflation would give rise to deviations from Gaussian random field (typically parameterized by f_{NL})
  - Relevant new energy scales during inflation could imprint scale-dependent deviations from simple power-law behavior on power spectrum

Tools to probe the expansion history



Discover time evolution of dark energy and test the cosmological constant hypothesis.

Discover the natural models of inflation.

Discover the non-Gaussianity signature of multi-field inflation.

Discover features in the primordial spectrum; explore a significant portion of uncharted parameter space.

Discover the cosmic gravitational wave background; explore a significant portion of uncharted parameter space.

Discover new relics up to the QCD phase transition era.

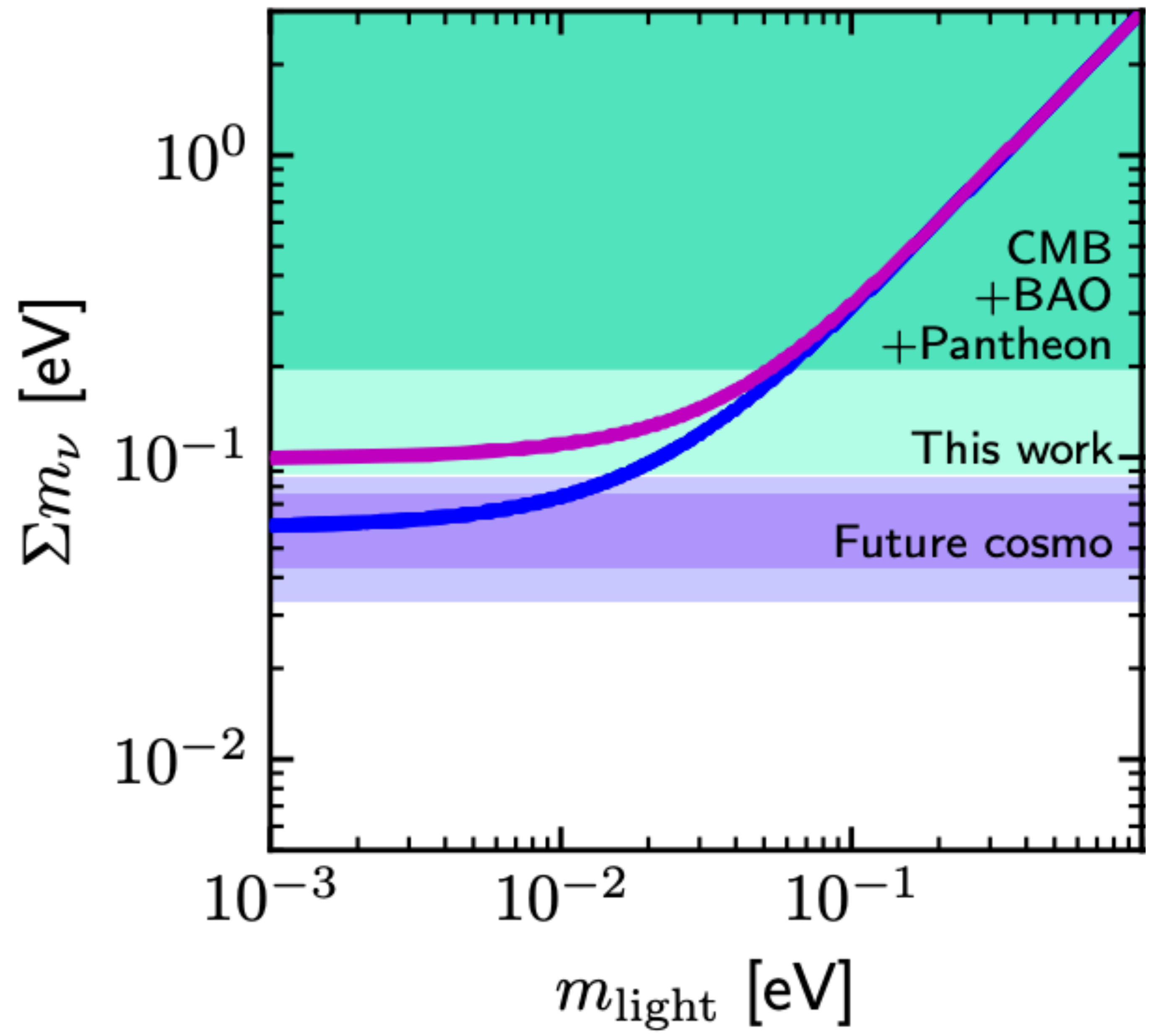
Discover new relics up to the era of reheating.

Chou et al, Cosmic Frontier report, 2211.09978

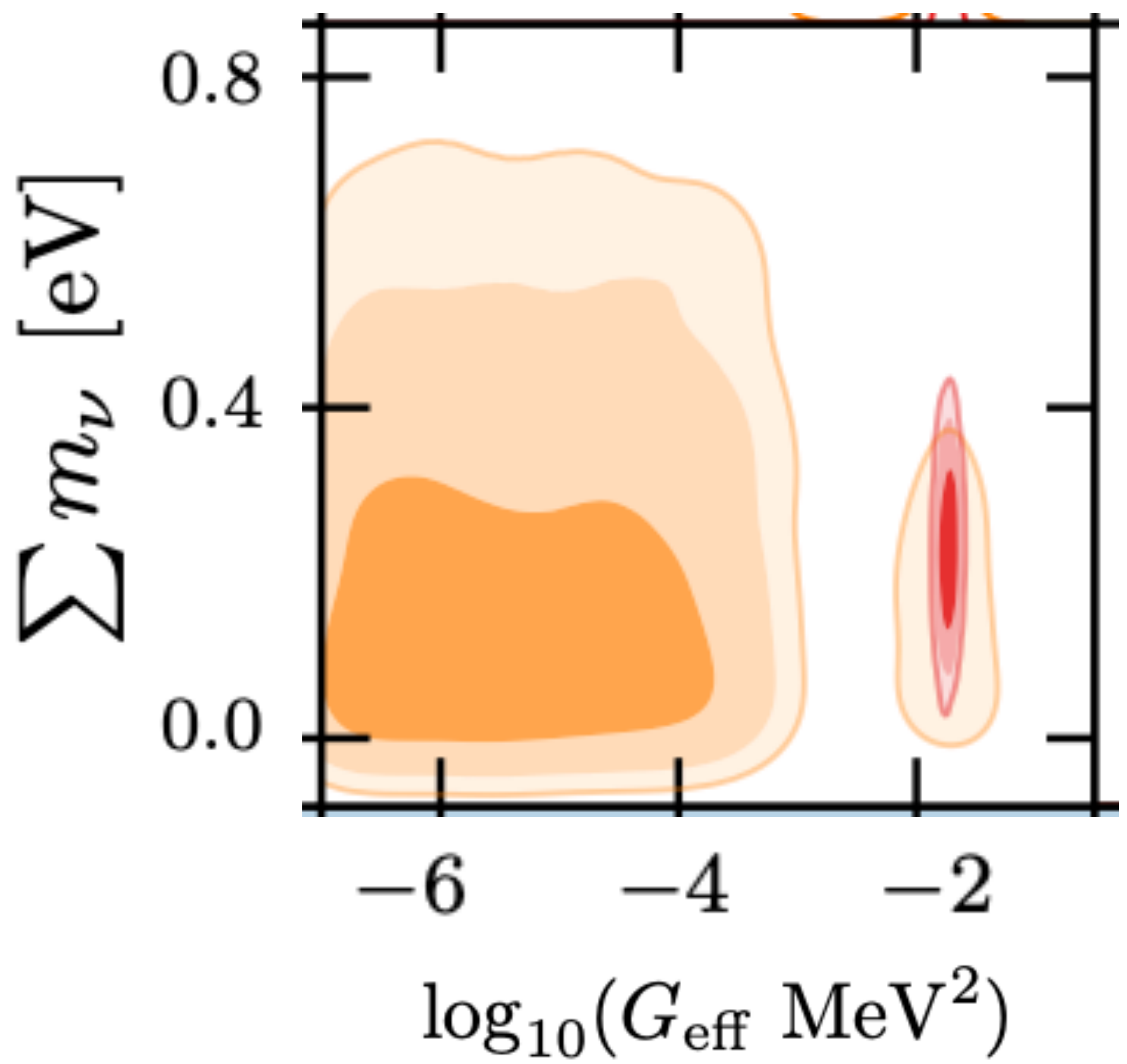
- Much of precision cosmology focuses on measuring in detail fluctuations in the radiation and matter distribution
  - CMB is traditional high-precision probe, we observe the sky in 2D (see talk by Ritoban Basu Thakur for much more detail!)
  - Galaxy surveys measure large-scale structure (LSS), provide 3D data and hence more modes
  - Further in the future, line-intensity mapping could provide an additional 3D probe that will cover a wider range of redshifts
- Gives access to inflation observables + modifications to expansion history more generally, including dark energy / new light relics
- Theoretical modeling beyond linear regime poses ongoing challenges (but significant recent progress)
- Direct searches for gravitational waves provide complementary tests of inflation and dark energy, and could search for phase transitions, cosmic strings, early matter domination, etc (see talk by Jan Schütte-Engel)

What can we learn about neutrinos?

- Sum of neutrino masses has scale-dependent effect on growth of density fluctuations.
- Sum currently constrained to be <90 meV in ΛCDM by combined cosmological measurements [di Valentino et al 2106.15267]
- Based on neutrino oscillation data, expect minimum value for the sum to be 60 meV for the normal hierarchy, 100 meV for the inverted hierarchy - already some tension for inverted hierarchy.
- Future CMB and LSS bounds are forecast to reduce error bars to the O(10) meV level - should detect non-zero value.
- If neutrinos have self-interactions, or interactions with the dark matter, this could delay the onset of free-streaming - has been suggested as a possible way to alleviate cosmological tensions.
- Recent claim by He et al 2309.03956 that an appreciable neutrino self-interaction (corresponding to a 10 MeV mass scale) is favored at >5σ by CMB+LSS data - also favors a non-zero sum of neutrino masses. Driven by power spectrum from Lyman-alpha, which prefers a slight additional tilt [Hooper et al 2110.04024] - other models that induce a scale-dependent modification to the matter power spectrum may also work.



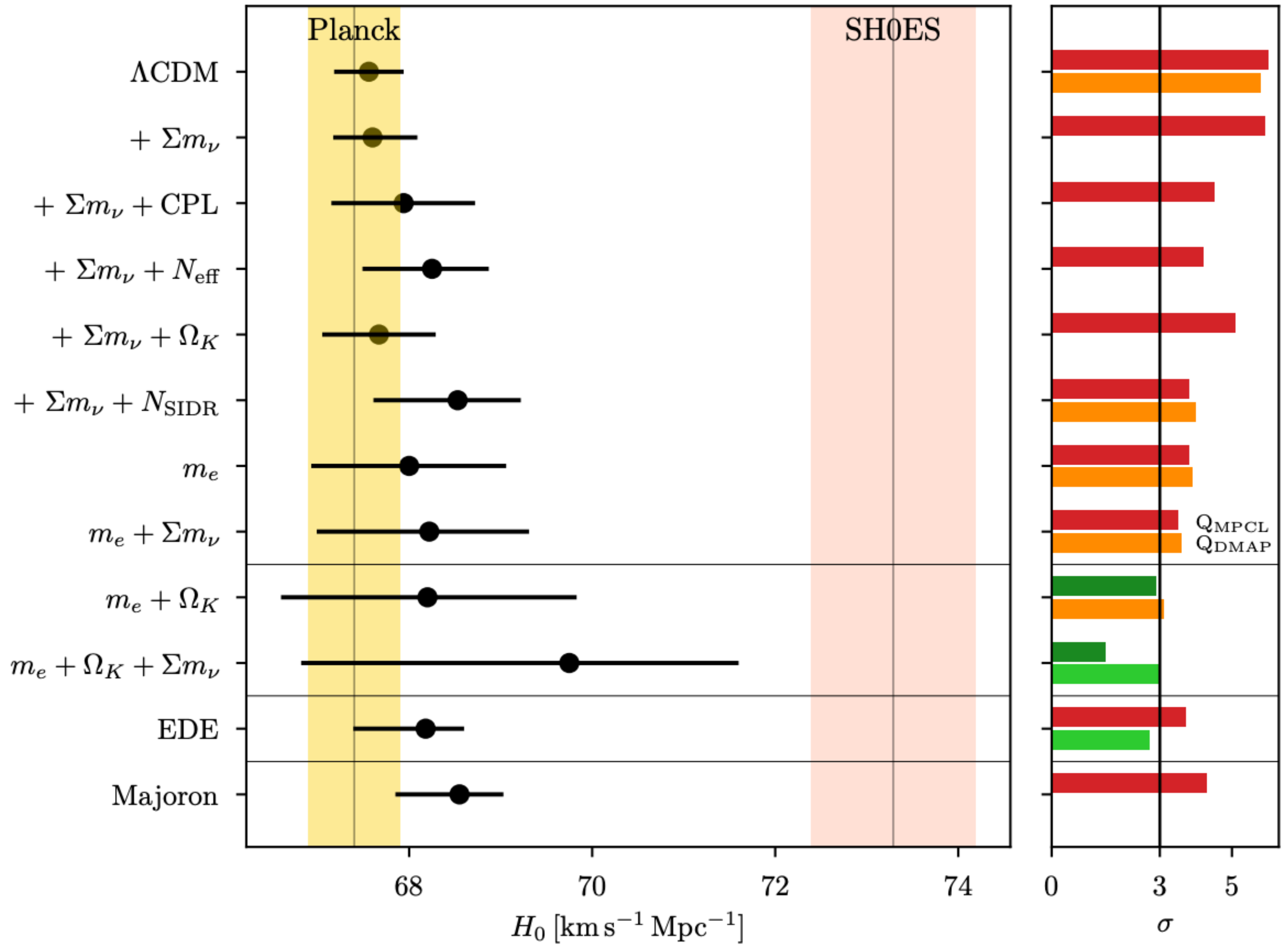
di Valentino et al 2106.15267



He et al 2309.03956

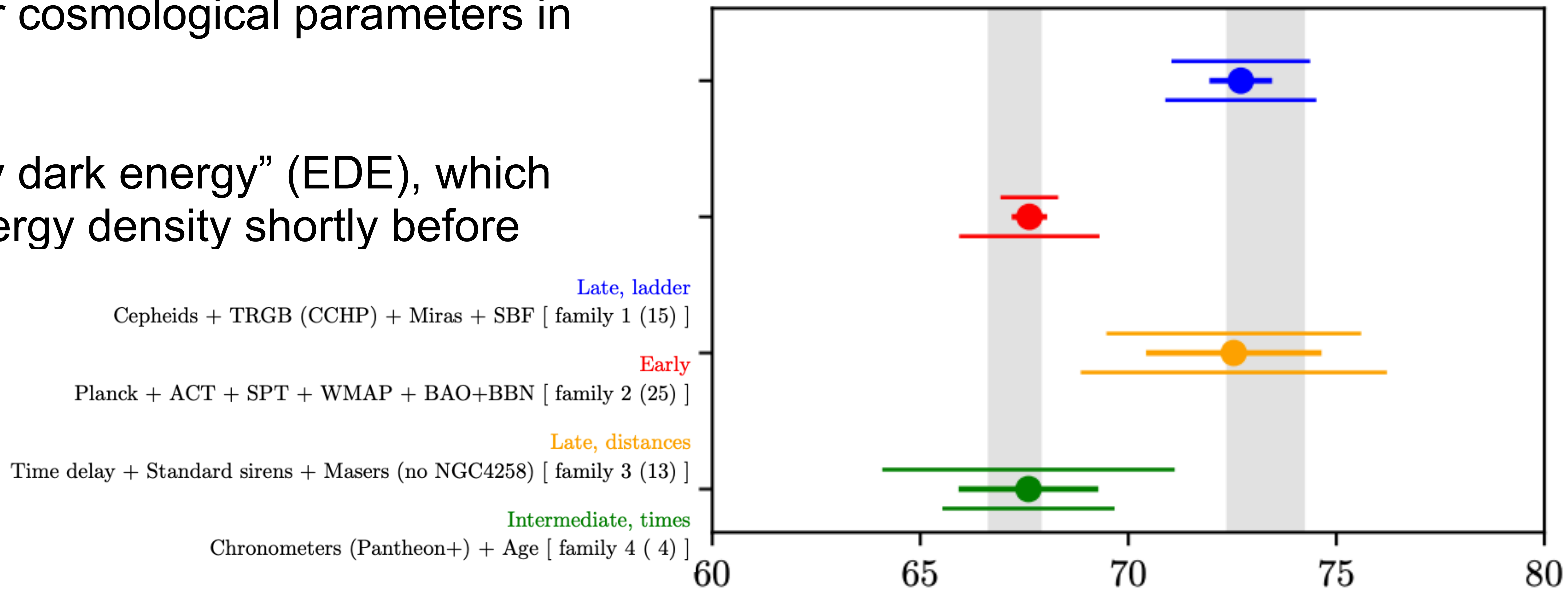
The Hubble tension

- Long-standing tension between the Hubble parameter H_0 inferred from (1) local measurements using luminosity of type-1a supernovae, and (2) angular scale of the sound horizon (or the horizon at matter-radiation equality).
- Intensive efforts have failed to find a compelling systematics-based explanation.
- See Verde et al 2311.13305 for a review of the problem and nice classification of the various different measurements.
- All possible solutions must grapple with a plethora of existing post-recombination cosmological data. Modifications to the pre-recombination history are less constrained but still tend to modify the other cosmological parameters in testable ways.
- For example, one widely-discussed solution is “early dark energy” (EDE), which posits a new component making up ~10% of the energy density shortly before recombination, which then decays away rapidly
- The canonical EDE solution is associated with increases in $\Omega_c h^2$, n_s and A_s; weak-lensing data severely constrain this scenario [McDonough et al 2310.19899, Efstathiou et al 2311.00524]

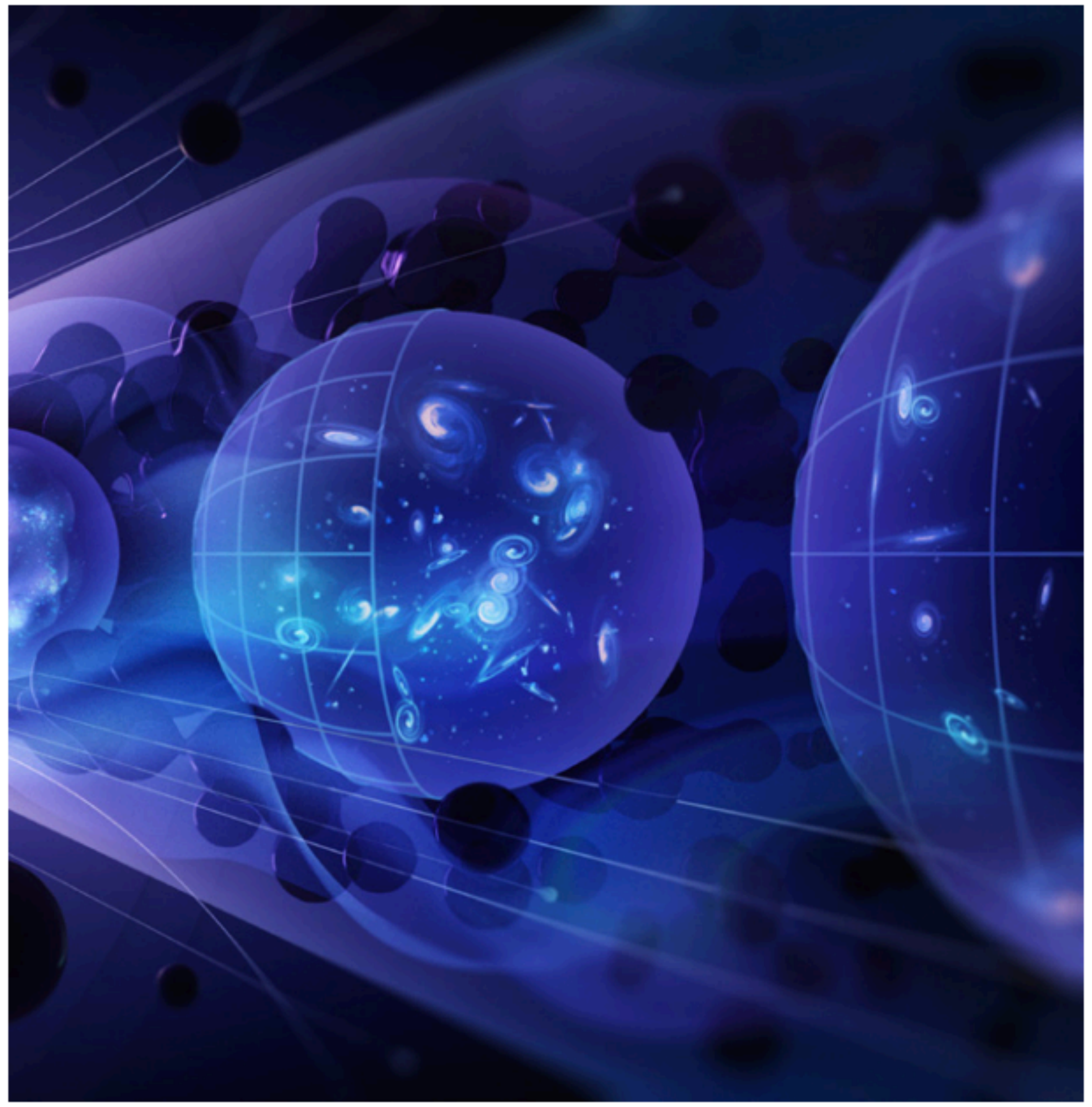


Recent review of possible solutions by Khalife et al 2312.09814

Summary of measurements by Verde et al 2311.13305



Big Questions from P5



Illuminate the Hidden Universe

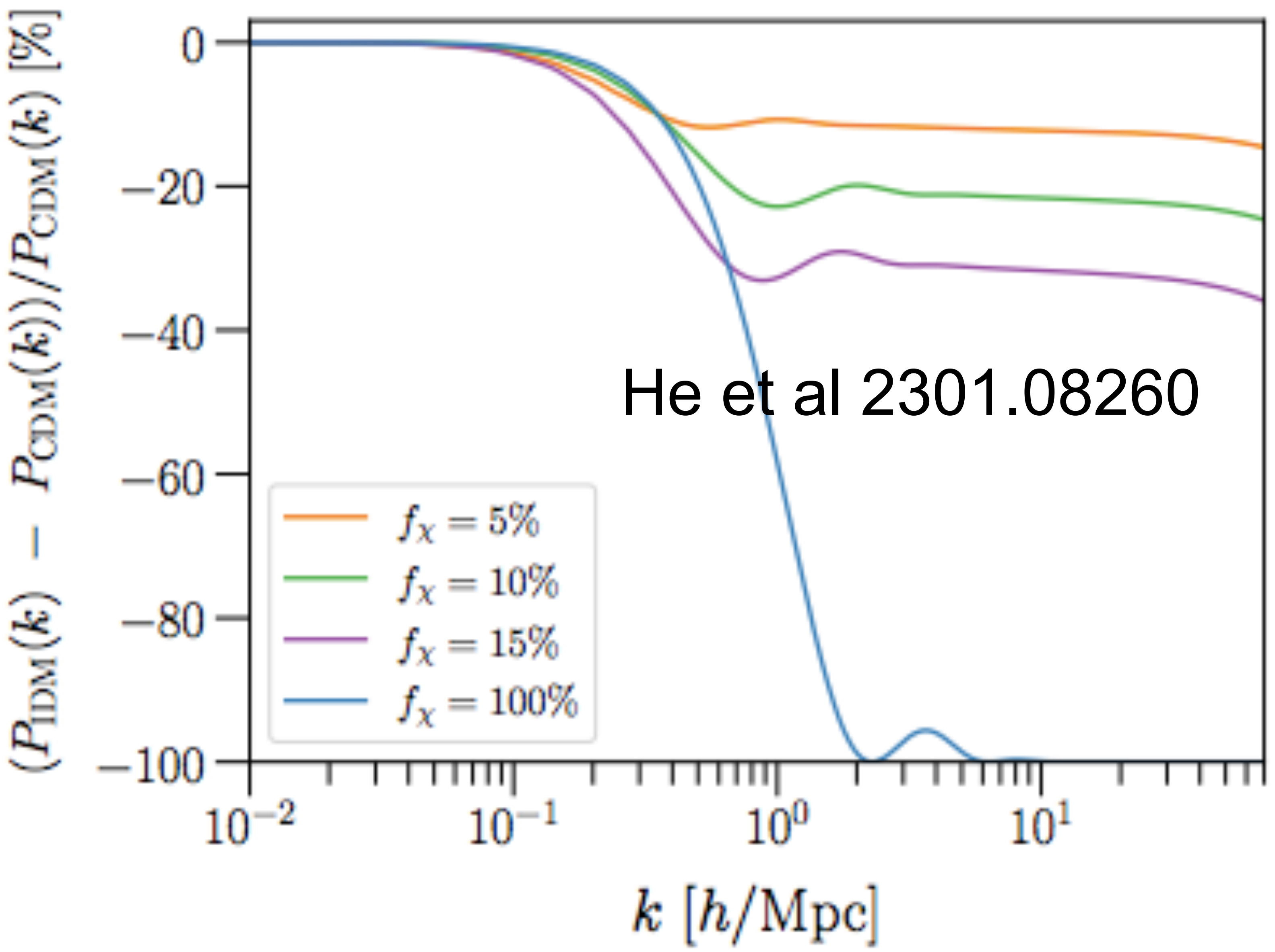
Determine the Nature of Dark Matter

Understand What Drives Cosmic Evolution

- What is the nature of dark matter?
  - How is dark matter distributed in our universe? What information can we extract from this distribution?
  - Is dark matter itself a new particle? Is it single-component or multi-component?
  - Does dark matter interact with known particles, or with itself, other than through gravity?
  - How was the observed abundance of dark matter produced?
  - To what degree can we robustly/model-independently exclude certain properties for the dark matter?
  - How solid are the motivations for classic DM scenarios, e.g. should we worry about the axion quality problem?
  - Are anomalies telling us something important about DM?

How is dark matter distributed and what can it tell us?

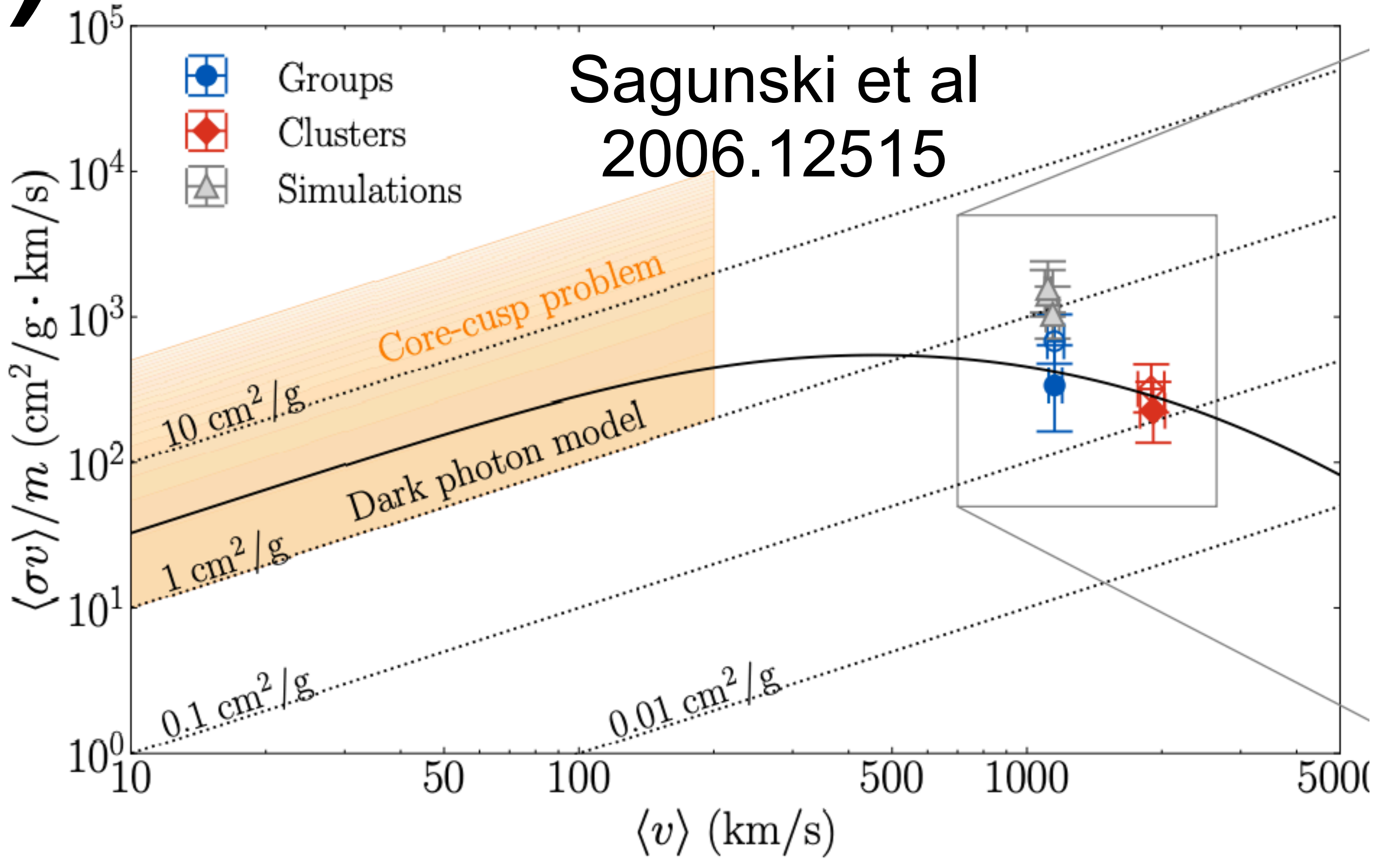
- Key objective: map how DM is distributed through the cosmos (in both space and time), via its gravitational effects. Deviations from standard expectations (collisionless+cold) can shed light on many aspects of DM physics.
- CMB+LSS data give a beautifully concordant picture on large scales, constrain few-percent-level changes to DM content of the universe post-recombination [e.g. Ilic et al 2004.09572, Simon et al 2203.07440].
  $N_{\rm eff}$ bounds also test the presence of new light degrees of freedom (to ~ 10 MeV using BBN) including dark matter [e.g. An et al '22].
- One generic modification (occurs in many model classes) is to suppress power below some characteristic scale:
  - Fuzzy DM (low mass): $\lambda_{\rm DB} = 2\pi/mv \approx (10^{-3}/v)(10^{-25}\text{eV}/m)0.4\text{Mpc}$
  - Warm DM (high velocity): $\lambda_{\rm fs}^{\rm eff} \approx (m/1\text{keV})^{-1.11}0.07\text{Mpc}$ (thermal DM)
  - DM interacting with SM: $k_{\rm cutoff}$ set by modes entering horizon when momentum transfer rate is comparable to Hubble parameter H
- In all these cases, suppression is most dramatic in the smallest-scale structures we can observe; currently ~$10^{7\text{-}8}$ solar masses, probed by stellar streams, Ly-alpha, strong lensing, MW satellites (see e.g. Bechtol et al 2203.07354 for a review)
- If only a fraction of the DM experiences these effects (or if effects have a non-trivial scale dependence), best tests can involve precision (CMB+LSS) probes of larger scales



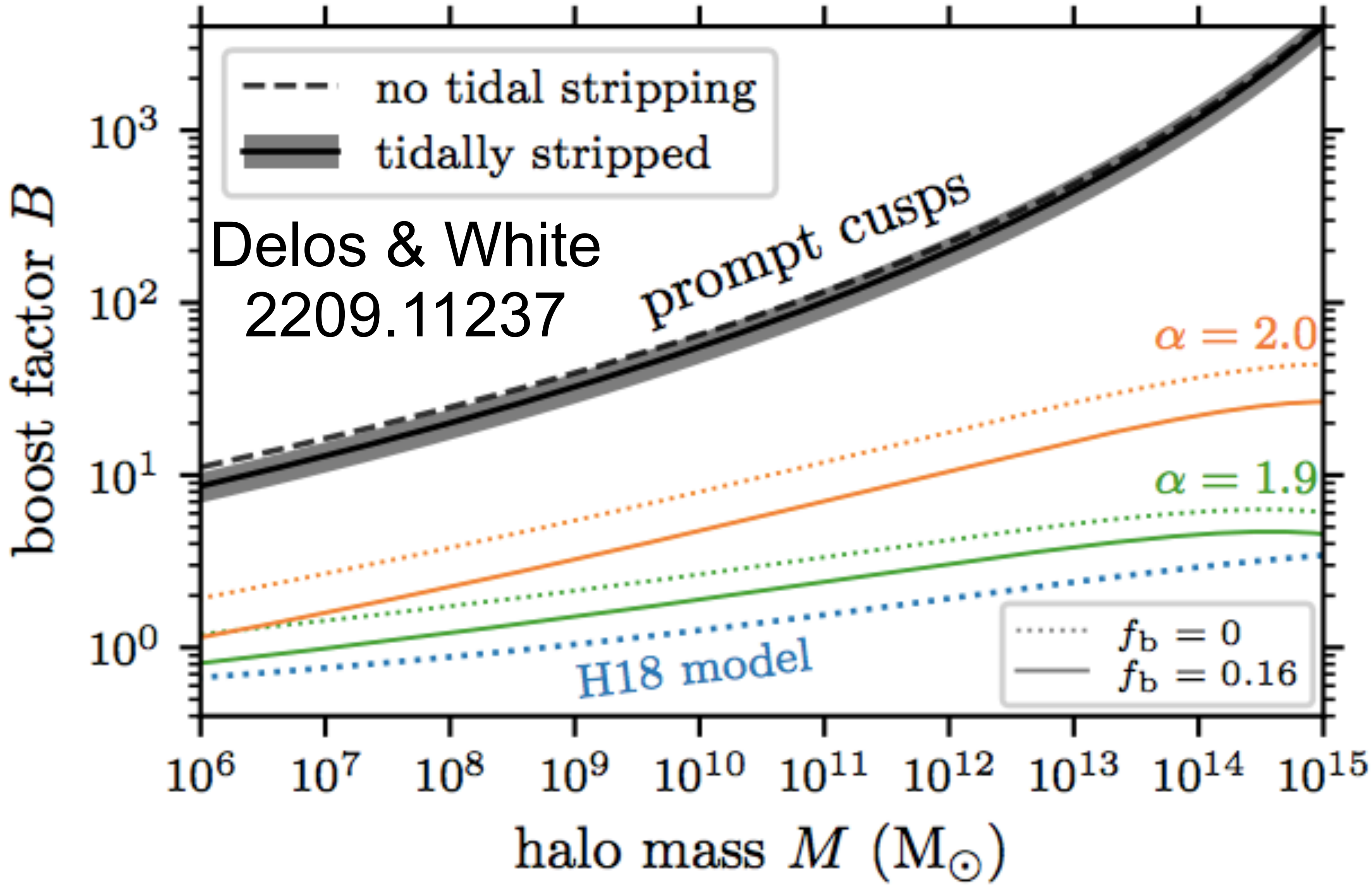
He et al 2301.08260

How is dark matter distributed and what can it tell us? (II)

- Studies of DM on small/highly non-linear scales typically require in-depth simulations and modeling of baryonic physics
- Much recent observational progress on measuring DM density and velocity distributions in Milky Way and other galaxies [e.g. Bechtol et al 2203.07354 (Snowmass) and references therein]
- Studies of DM within galaxy clusters/groups provide stringent upper bounds on DM-DM interactions [e.g. Bondarenko et al 2006.06623, Sagunski et al 2006.12515, Andrade et al 2012.06611] - but at low velocities a wide variety of cross sections still appear allowed [e.g. review by Adhikari et al 2207.10638 and references therein]
- Open question (for classic CDM): how does the smallest-scale substructure behave?
- Some simulations + analytic arguments [e.g. Delos & White 2207.05082] suggest very dense, early-forming halos survive as high-density “prompt cusps” to late times
- Not clear to me if the community modeling DM structure formation has converged on this yet [see e.g. Ishiyama & Ando 1907.03642, Ondaro-Mallea et al 2309.05707] - challenge for theorists/simulators - but if true, important for indirect detection



Sagunski et al 2006.12515



Delos & White 2209.11237

The search for non-gravitational interactions

- Gravitational probes provide some powerful observational no-go theorems (on DM mass $\lesssim 10^{-19}$ eV, speed during structure formation, spin for sub-keV DM via Pauli exclusion principle)

- However, many possible DM scenarios cannot be plausibly distinguished (any time in the foreseeable future) by their distribution (and hence by gravitational probes of their distribution)

- Motivates a large multi-faceted experimental program, spanning all Frontiers, to search for non-gravitational signatures of DM (see talks by Nancy Aggarwal, Stefania Gori, Rakshya Khatiwada, Noah Kurinsky, Hugh Lippincott, Reina Murayama, Katherine Pachal).

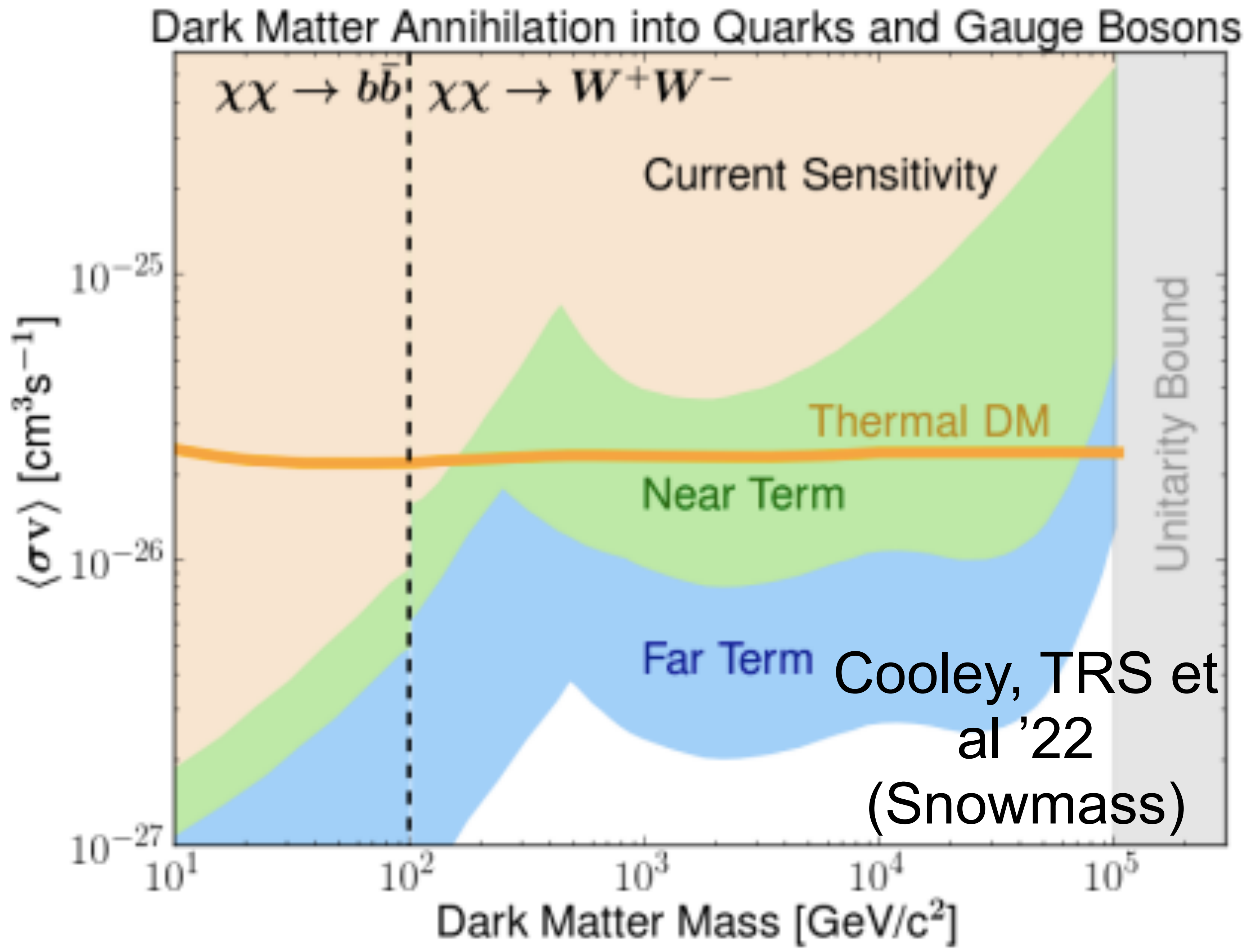
- Astrophysical/cosmological data also provide powerful probes of such interactions, accessing distance/time/energy scales not available on Earth.

- One example I like: cosmos can act as a calorimeter for energy transfer between dark and visible particles (modifying perturbations but also ionization/temperature history). Precision probes of the CMB spectrum (see next talk!) could broadly probe modifications to standard history below T~1 keV.

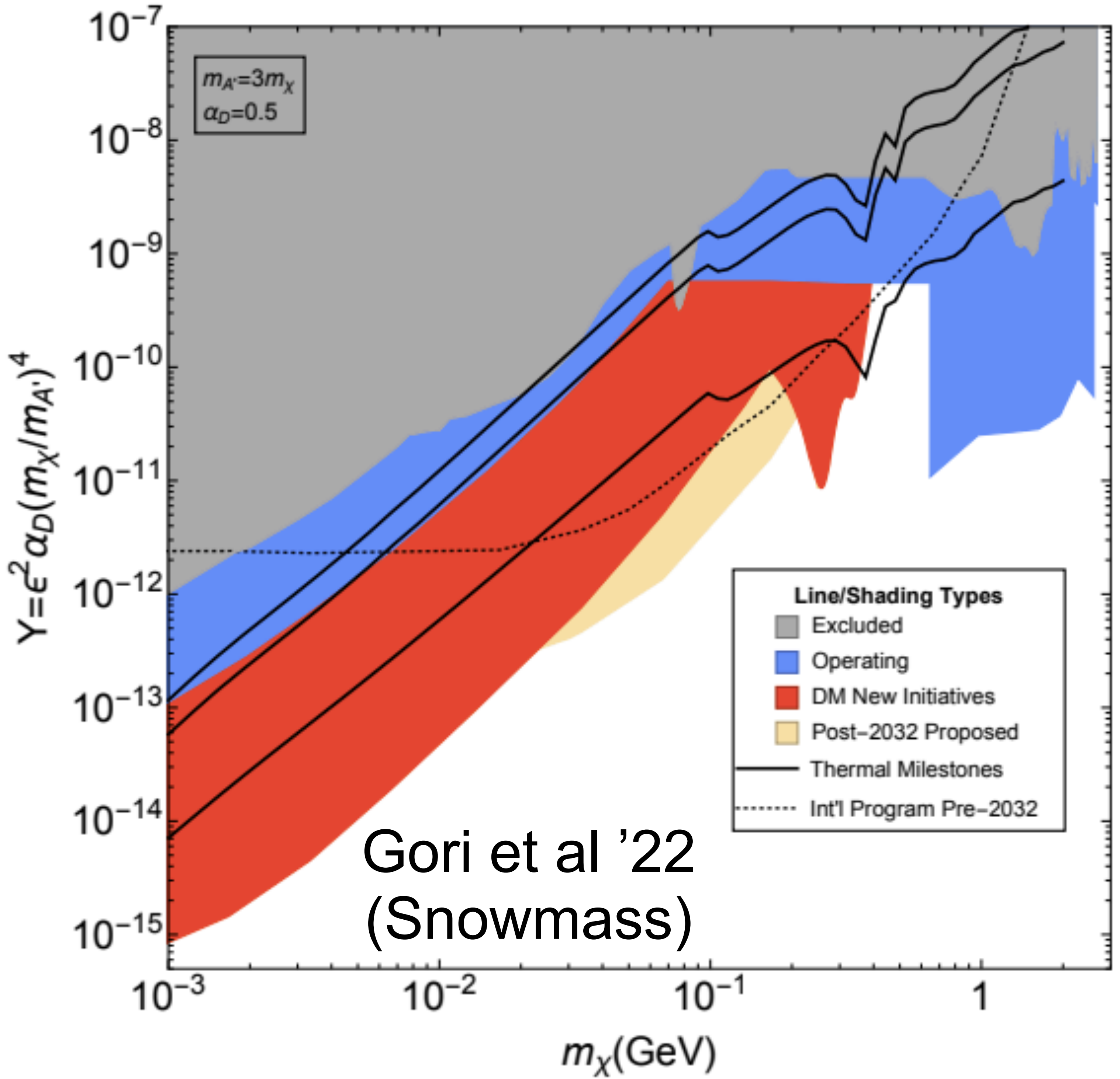
- A broad question: given the plethora of possible DM models consistent with standard cosmology, are there **top-down guiding principles** we can/should use to favor some scenarios over others? If so what are they?

Can we robustly test DM production mechanisms?

- One popular criterion: is there a simple/natural explanation for the DM abundance?
- Lack of a production mechanism may disfavor models - e.g. dark photon dark matter is a frequent benchmark for light vector DM, but East & Huang 2206.12432 pointed out that many production scenarios lead to vortices that drain energy out of the DM field
- A favorite benchmark: thermal relic mechanism (DM abundance set by early-universe annihilation) suggests $\langle\sigma v\rangle \approx 2 \times 10^{-26}$cm^3/s, works for ~MeV-100 TeV DM.
- Indirect-detection searches currently have sensitivity to this cross section up to DM masses of 10s-100s GeV, for all SM final states except neutrinos.
- Future large ground-based gamma-ray experiments (CTA, SWGO) have the potential to reach this cross section for 10-100 TeV DM - first test over ~the full mass range
- The main loophole is that the effective annihilation cross section today may differ from that in the early universe (due to e.g. p-wave suppression, asymmetry, coannihilation)
- At lower masses (sub-GeV), indirect detection constraints already require such a suppression, but accelerator searches can test the thermal freezeout mechanism by recreating the energy scale of the early universe (see talk by Stefania Gori)



Cooley, TRS et al ’22 (Snowmass)



Gori et al ’22 (Snowmass)

Does dark matter need to be a new particle?

- Classic counterexample is primordial black holes (see talk by Alexander Kusenko) - viable DM candidate if they can be produced copiously in the early universe.

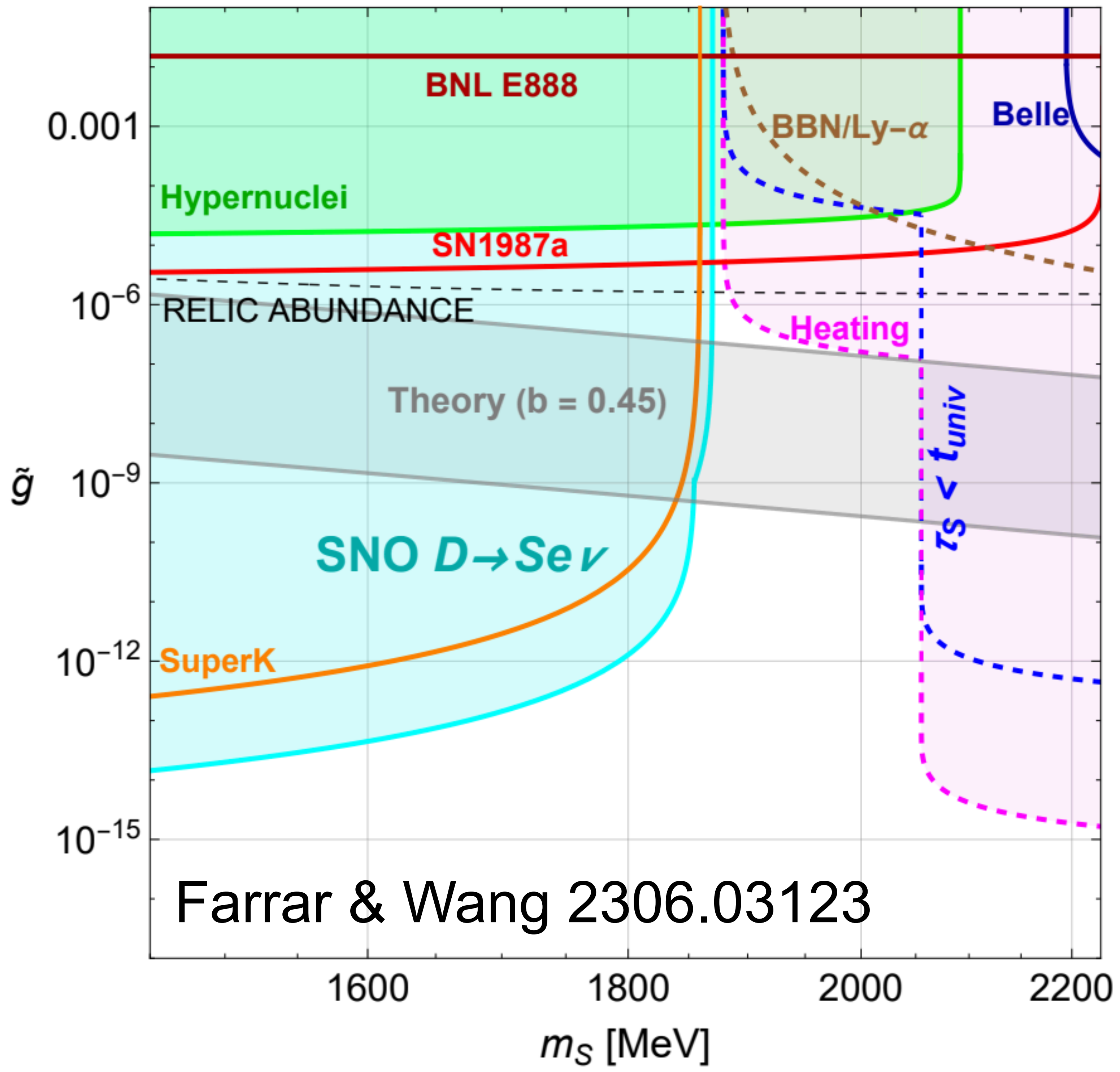
- There is an open window for all DM to be PBHs for PBH masses M~10^{17}-10^{23}g; recent papers argue that the standard evaporation calculation may be incorrect after half the PBH mass has evaporated — if evaporation is strongly quenched, could open a new window for very light PBHs (below 10^9 g) [Alexandre et al 2402.14069, Thoss et al 2402.17823].

- There has also been some interest in the possibility that dark matter could be an exotic bound state of SM particles

- Bob Jaffe suggested in 1977 that a color-singlet, flavor-singlet uuddss state could be a (meta)stable bound state. Glennys Farrar (1708.08951) suggested that this state could constitute a DM candidate, and labeled it “sexaquark” (S).

- Viability as a candidate for the bulk of the DM requires that the interactions of S with a baryon pair (Sbb) are highly suppressed - otherwise S is efficiently depleted in the early universe [Kolb & Turner 1809.06003]

- Also requires a fairly specific mass range, ~1.8-2 GeV, to allow a sufficiently long lifetime + avoid other stringent bounds



Farrar & Wang 2306.03123

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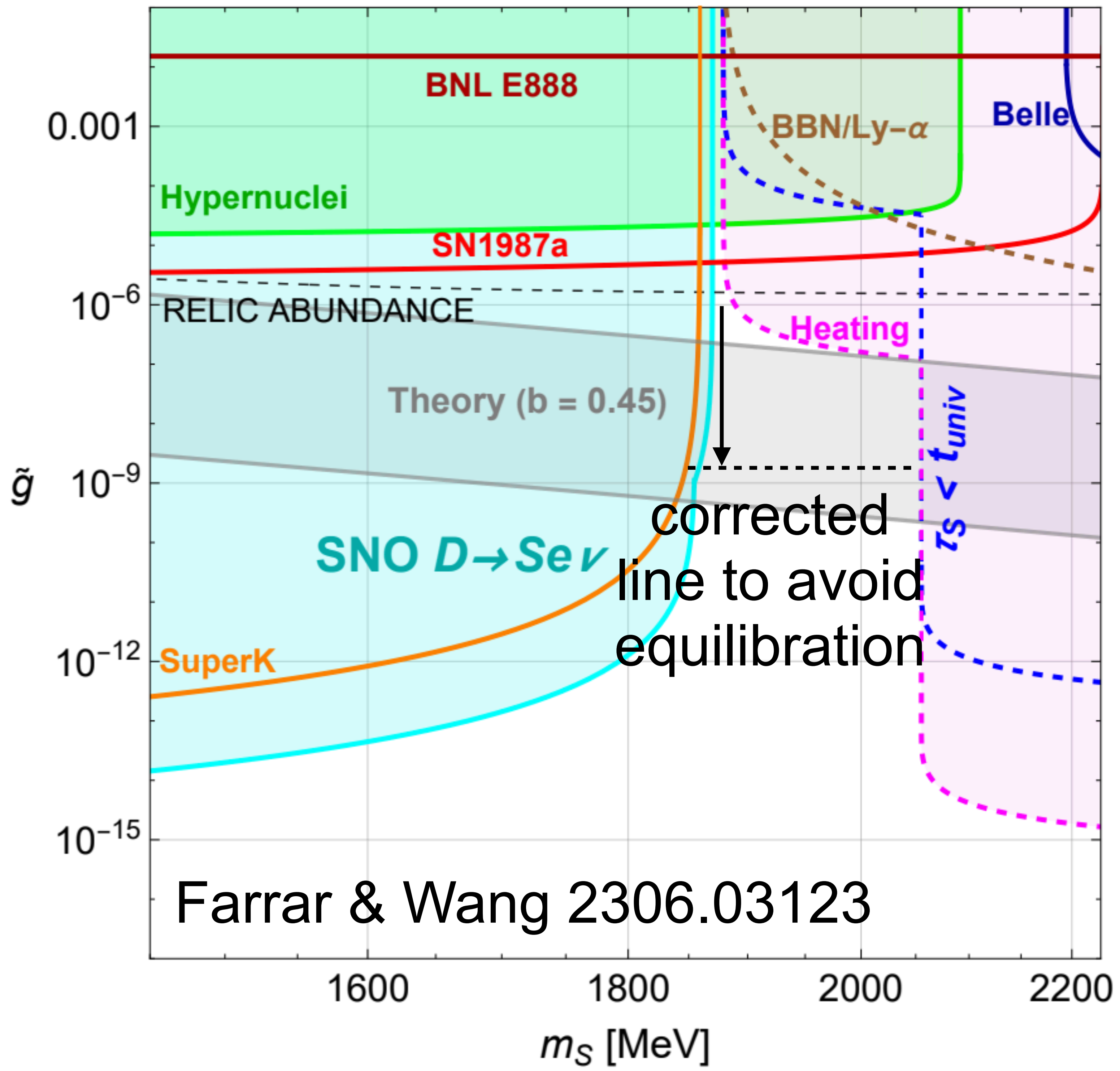


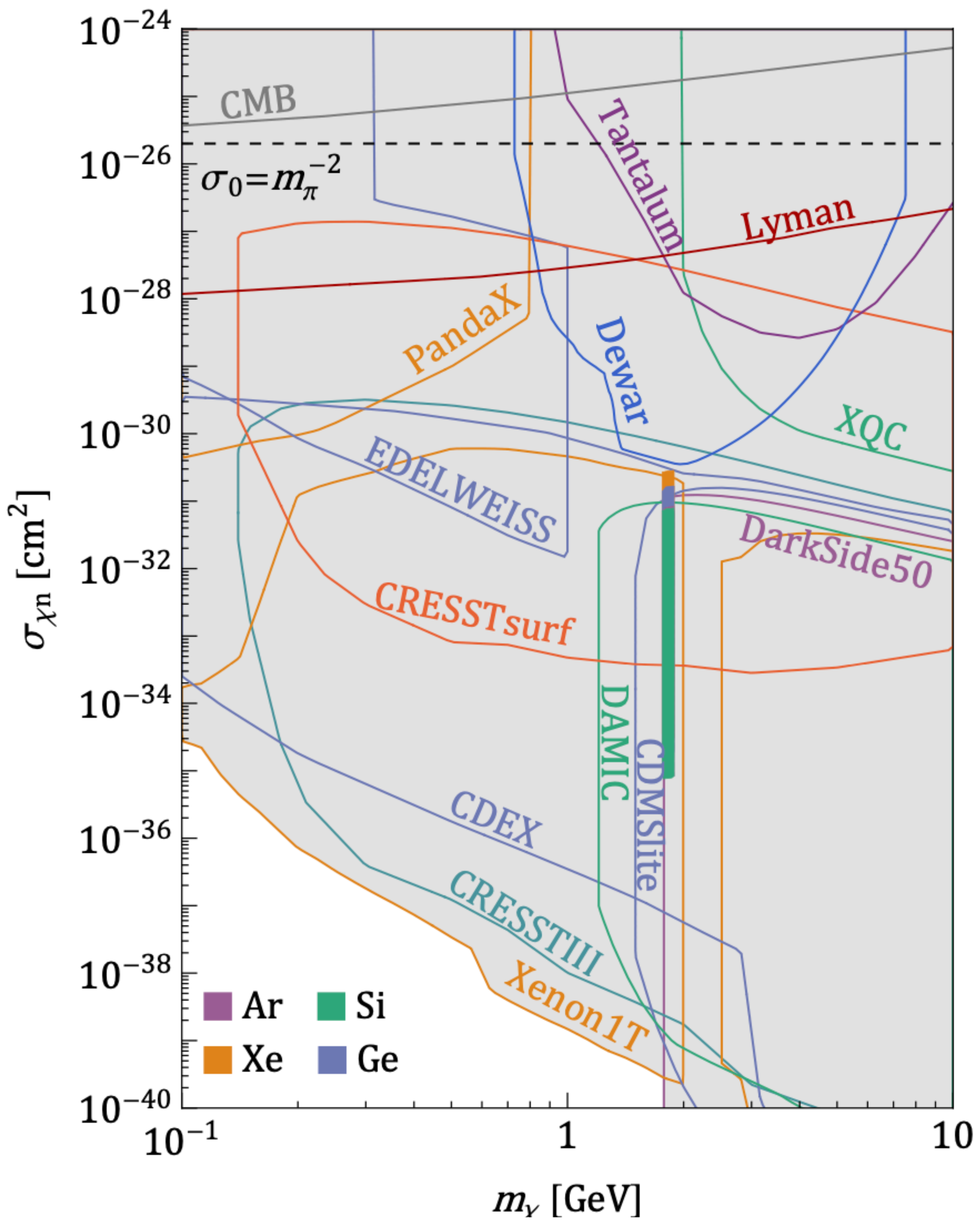
corrected line to avoid equilibration

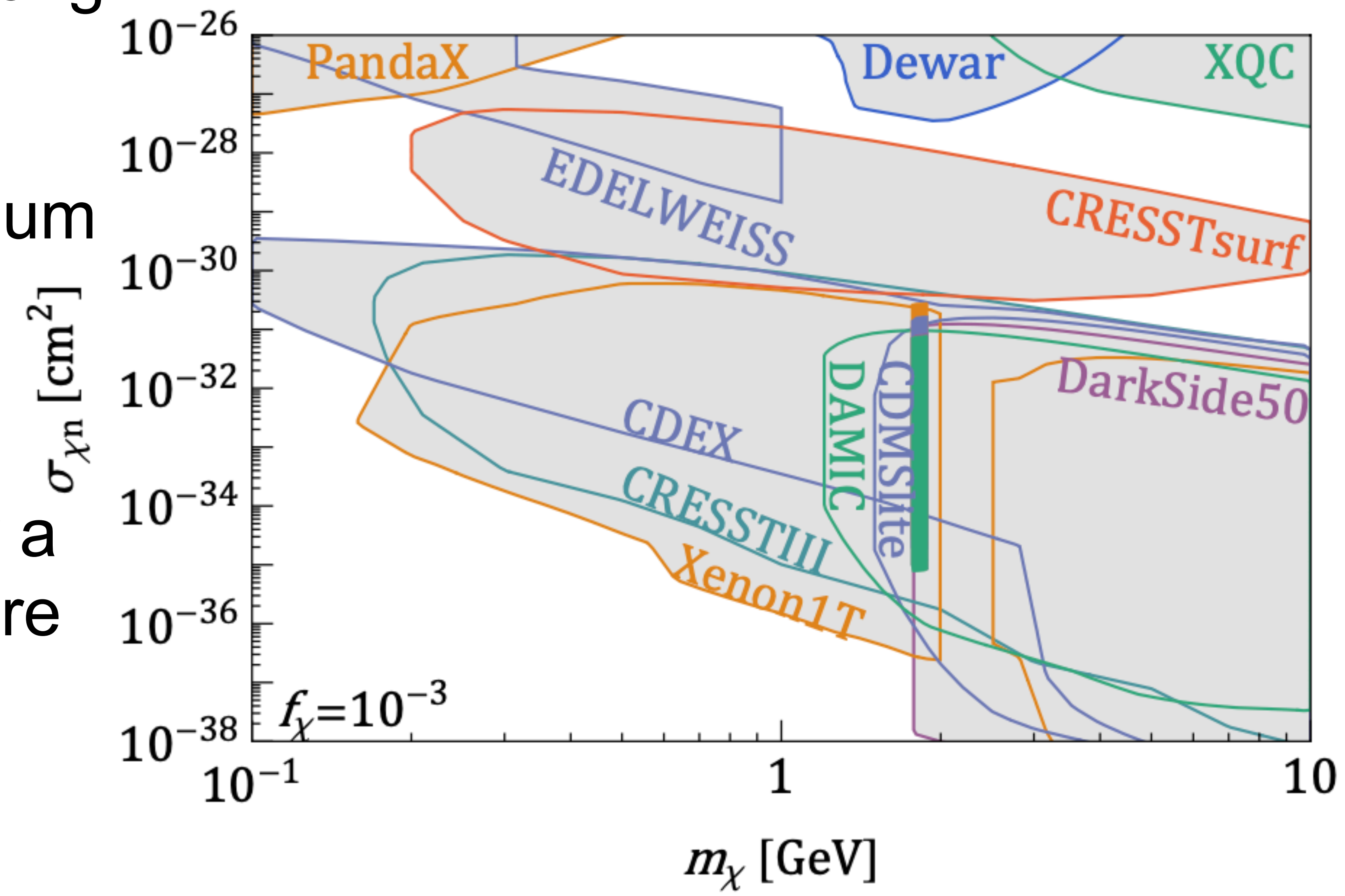
Farrar & Wang 2306.03123

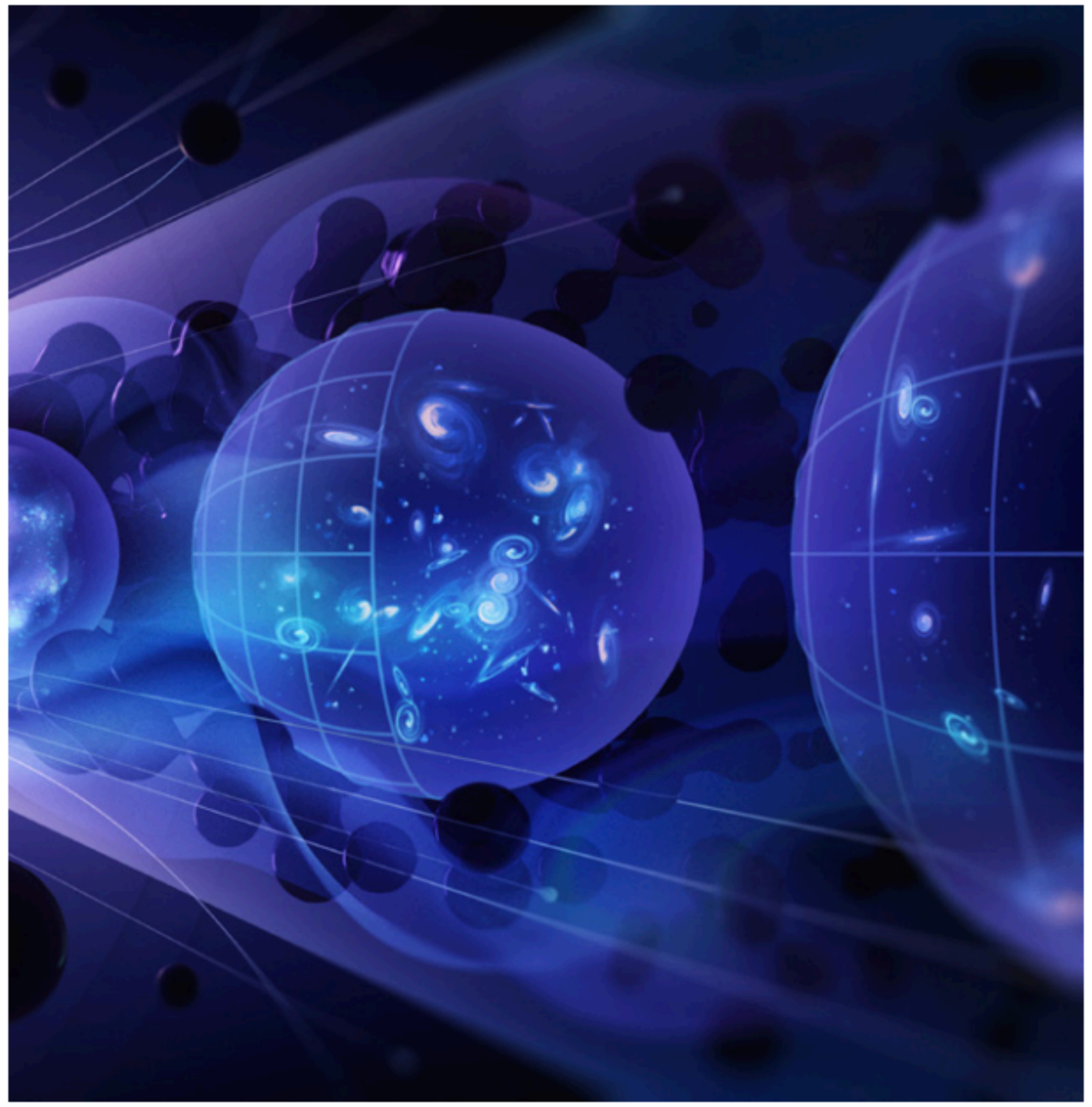
Testing the sexaquark DM hypothesis

- With PhD student Marianne Moore I recently explored the viability of the sexaquark as a DM candidate if we just assume these conditions can be satisfied [2403.03972]

- Gave two independent arguments that the sexaquark should still not be more than ~0.1% of the total DM
    - Direct detection bounds in this mass range appear to exclude even the expected electromagnetic cross section (even for a very compact sexaquark), for a component more than 0.1% of the DM (at 0.1% some parameter space opens up)
    - Achieving an abundance of 100% of the DM in the early universe requires both a very strong suppression of the effective Sbb vertex (~10^{-8}-10^{-9} in the effective coupling) and either:
        - Yield of net sexaquark number from the quark-hadron transition exceeding the equilibrium expectation by 3+ orders of magnitude (equilibrium expectation at this transition gives ~0.1% of the DM), or
        - Significant contribution to the DM density from antisexaquarks, which would then imply a very striking signal in SuperKamiokande unless the Sbb vertex is suppressed even more severely, by a factor of 10^{-12}-10^{-19}.







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Summary

- ΛCDM seems to work very well to describe a broad range of scales and redshifts - but only an effective description as we do not understand dark energy/matter
- CMB + (to an increasing degree) LSS allow for precision measurements of fluctuations, with prospects for significant near-future advances in sensitivity to inflation, subsequent cosmic evolution, and neutrino physics
- The Hubble tension may be the first example of a failure of ΛCDM that is now detectable because of the precision of our observations
- With regard to dark matter, there is an enormous range of possible masses and interaction strengths for DM, and there are viable theoretical scenarios populating the full range.
- We know the cosmological abundance (precisely), phase space distribution (in part), upper limits on interactions, lower limit on lifetime, and upper + lower bounds on the mass (very widely separated!) - but many fundamental questions remain open.
- In the next decade, we have the capability to delve deep into open parameter space for long-standing scenarios with independent theoretical motivations, in particular classic WIMPs and the QCD axion. But no guarantees - aim to search wide and map out the properties of DM as broadly as possible.

BACKUP SLIDES

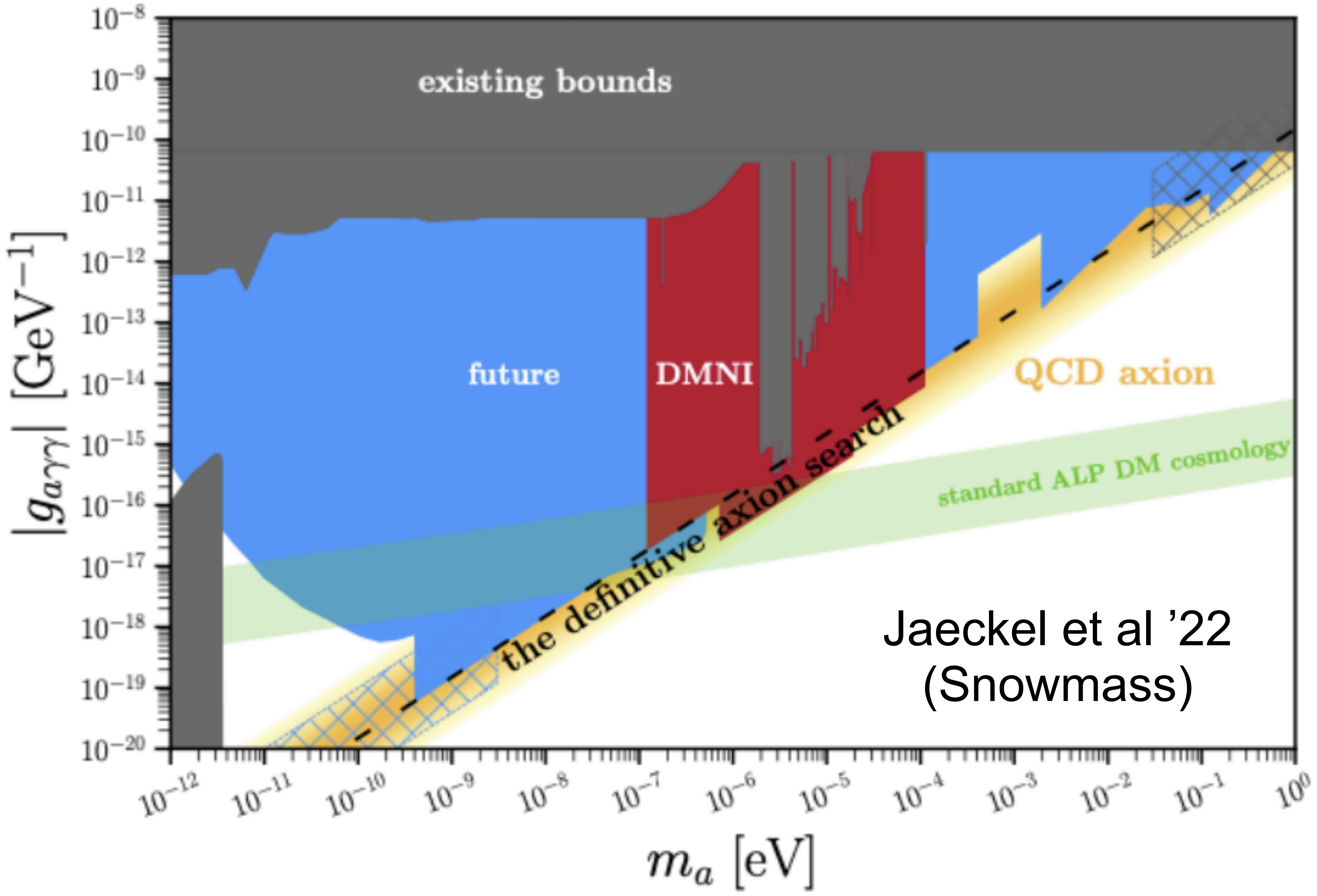
Can we test the axion solution to the strong CP problem?

- QCD axion is motivated by the strong CP problem; interaction strength with Standard Model then determined by axion mass (yellow band)

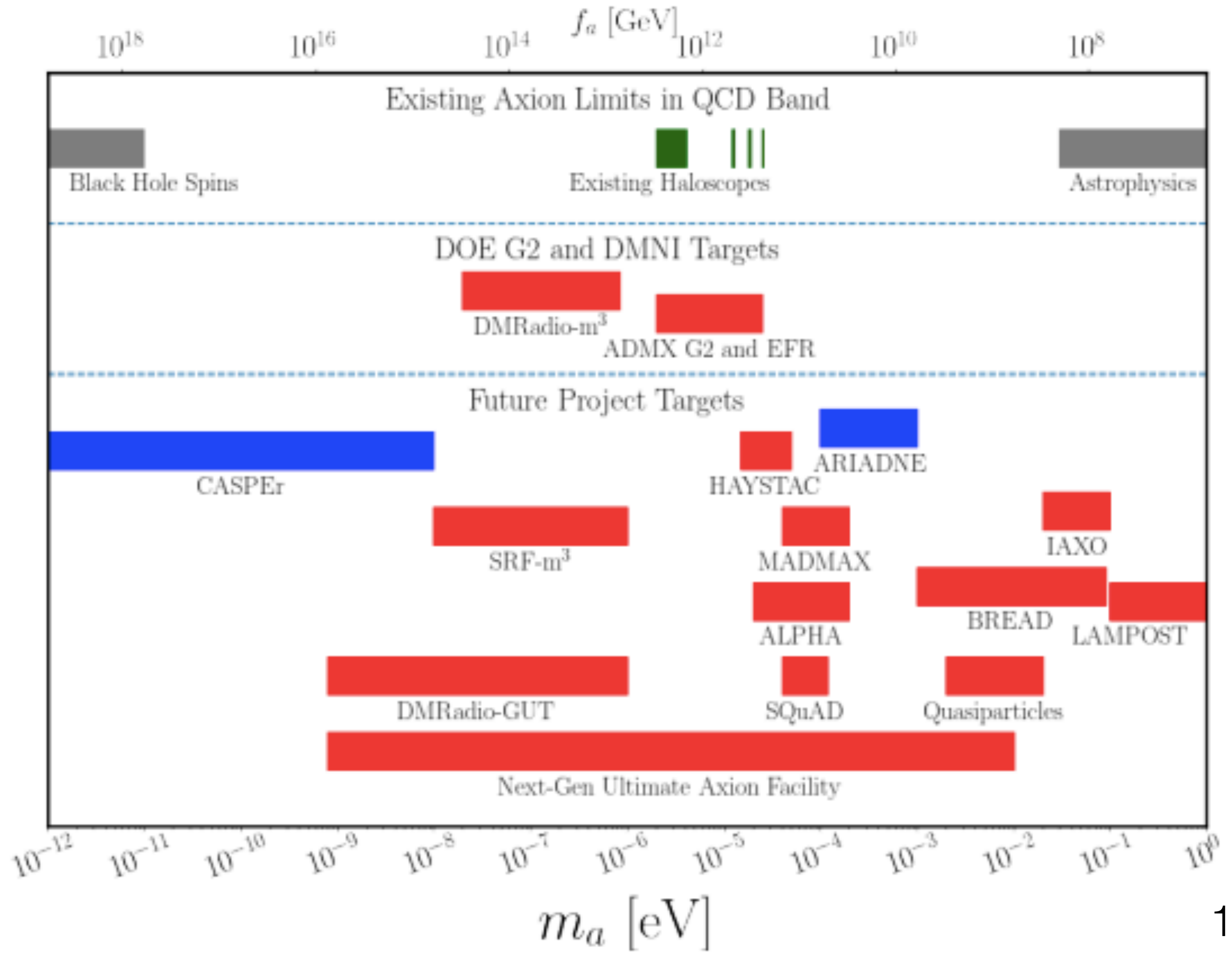
- Recent experimental advances mean that for the first time we have the possibility of testing the QCD axion band across much/ most of the available mass range

- There are still open questions about axion production. For "post-inflation axion", abundance calculation is challenging due to impact of axion string network; current latest estimate is correct abundance obtained for 40-180 μeV axions [Buschmann et al 2108.05368, see also Gorghetto et al 2007.04990]

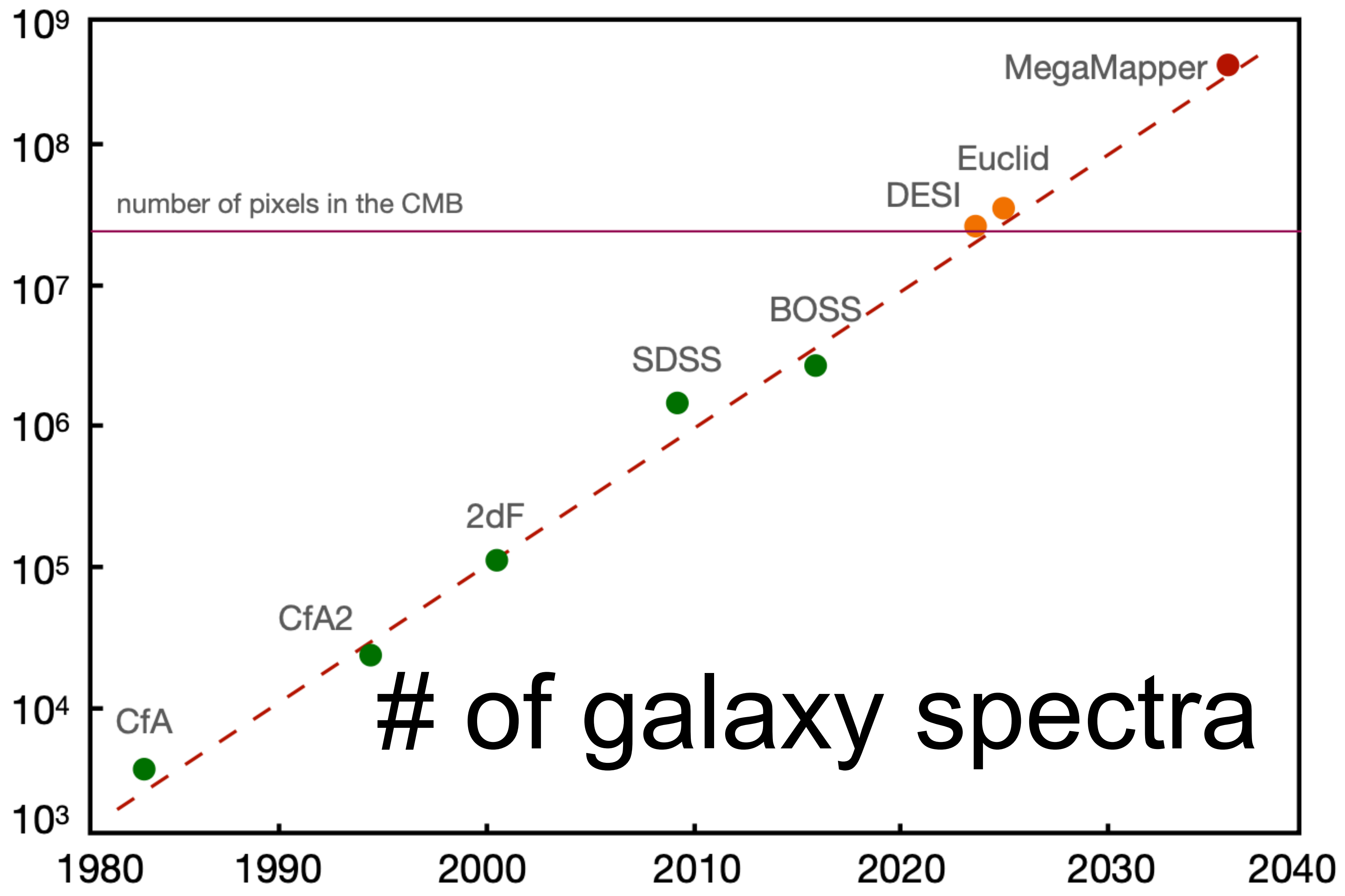
- Another open theoretical question relates to the axion quality problem, i.e. how to ensure that Planck-suppressed operators do not spoil the solution of the strong CP problem [e.g. Hook et al 1812.02669 and references therein, Lu et al 2312.07650]



Jaeckel et al ’22
(Snowmass)

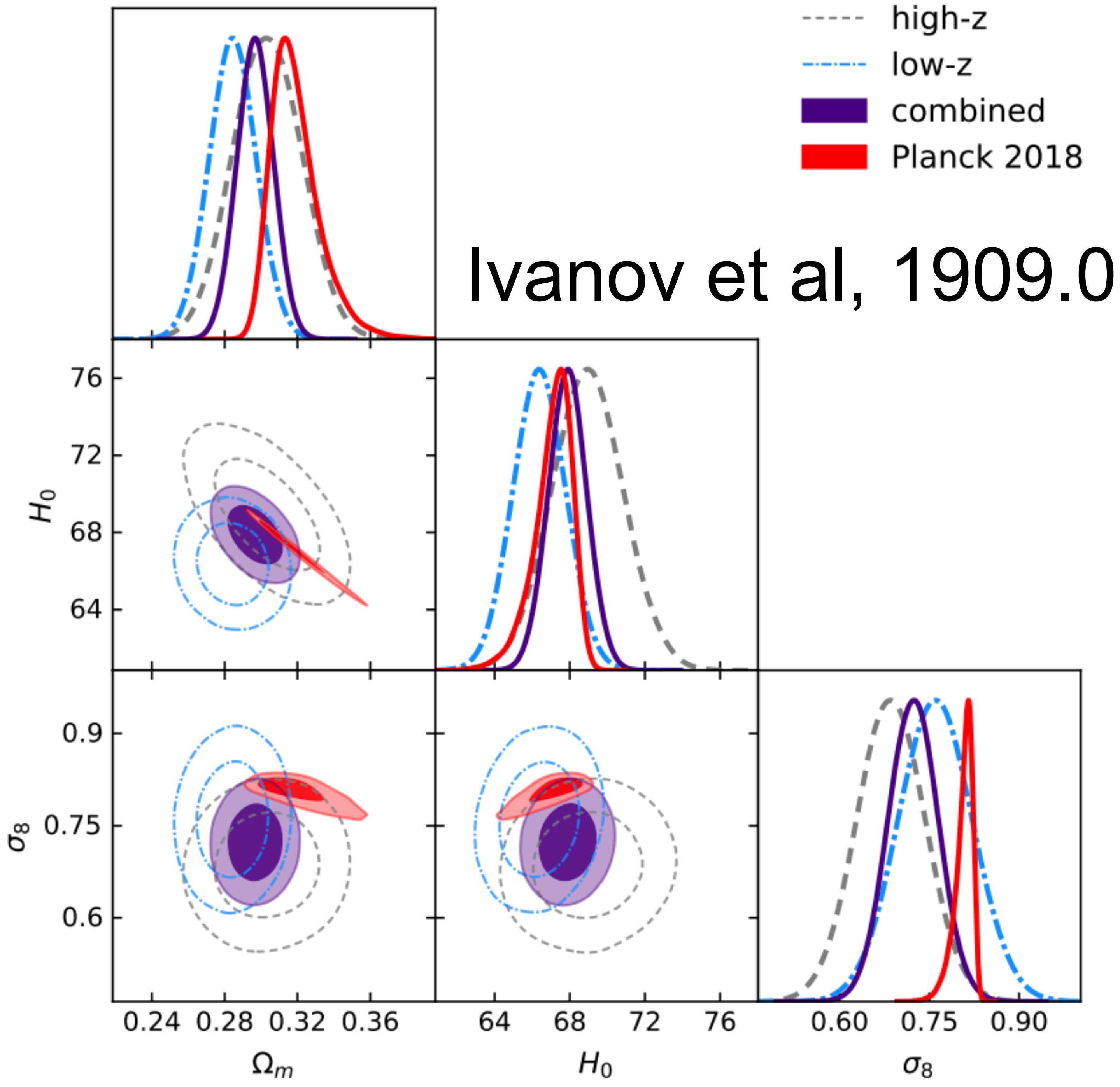


How can we make full use of LSS datasets?



Simonovic, CERN colloquium, 2021

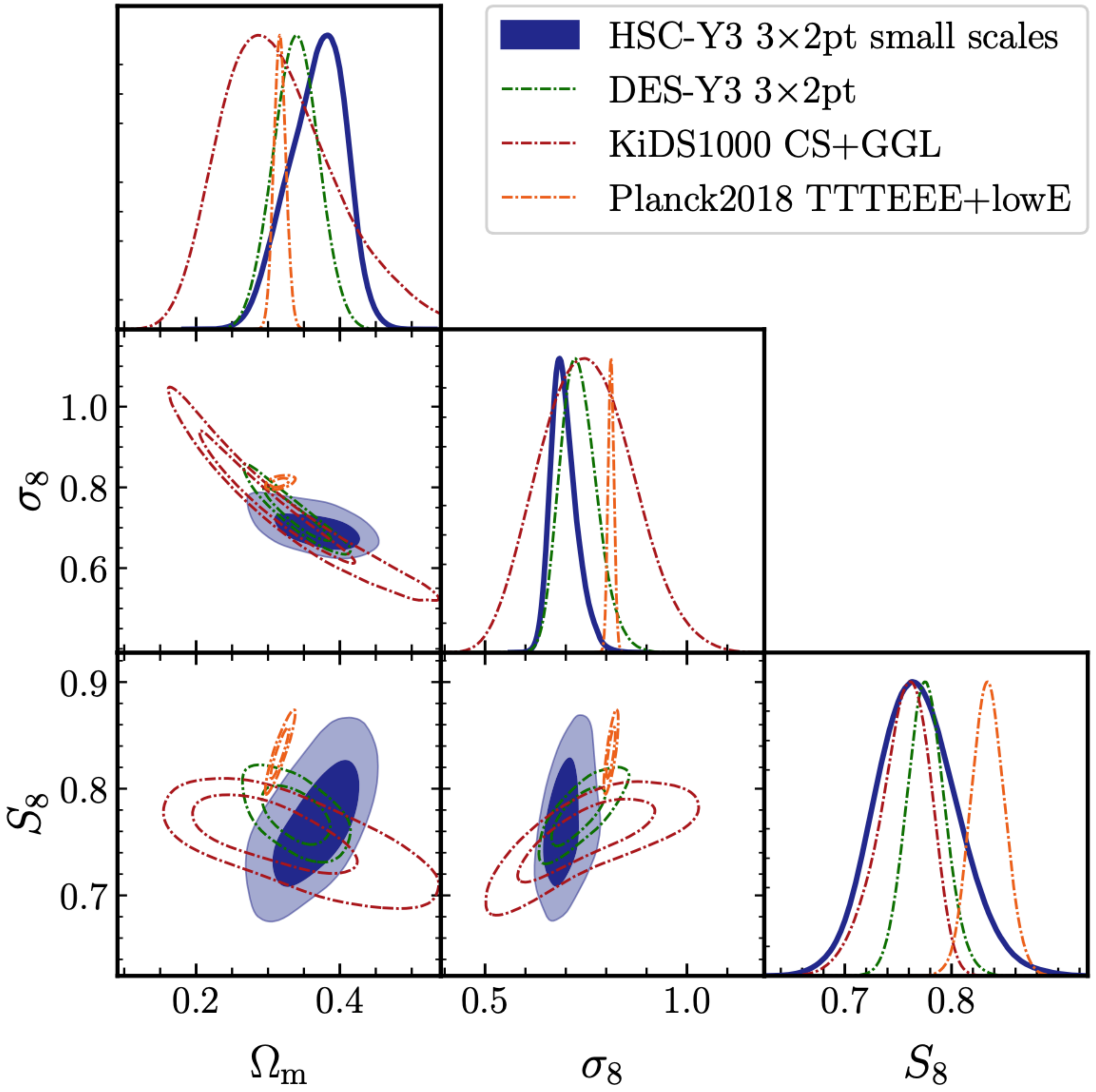
- In the past few years there has been a great deal of progress in using EFT-based perturbative methods to improve theoretical predictions for large-scale structure (LSS) [see e.g. review by Ivanov 2212.08488]
- Error bars on cosmological parameters from previous galaxy surveys are already competitive with CMB constraints [e.g. d'Amico et al 1909.05271, Ivanov et al 1909.05277], as are tests for non-Gaussianity
- Active work to go beyond summary statistics such as the power spectrum and infer cosmological parameters directly from the galaxy field [e.g. using simulation-based inference, Lemos et al 2310.15256]
- It is also possible to combine perturbative EFT methods with simulation-based priors on the parameters describing small-scale galaxy formation physics [e.g. Ivanov et al 2402.13310]



Ivanov et al, 1909.05277

The S_8 tension

- S_8 parameter (or σ_8; $S_8 \equiv \sqrt{\Omega_m/0.3}\,\sigma_8$) describes clustering of matter at 8 h^{-1} Mpc scale
- Persistent tension between the S_8 parameter inferred from the CMB vs from weak gravitational lensing
- Much less statistically significant than the Hubble tension (2-3 sigma depending on which datasets are considered)
- Can be influenced by various beyond-CDM effects that would modify matter clustering - e.g. interactions of dark matter and/or neutrinos, a subcomponent of dark matter that has suppressed structure on small scales, etc



Miyatake et al 2304.00704

Is JWST in tension with ΛCDM?

- James Webb Space Telescope has detected numerous massive luminous galaxies at high redshift - ongoing discussion on consistency with ΛCDM simulations [e.g. Sabti et al 2305.07049, Wang et al 2307.12487, Xiao et al 2309.02492]. My understanding is there is currently no strong evidence for tensions that could be resolved by adjusting the cosmology.
- Has provided some new insights into an older tension: how did supermassive black holes form so early?
- Standard picture for how to make supermassive black holes: collapse of first generation of stars (Pop-III) produces black holes which then grow by (Eddington-limited) accretion
- Plausible formation times for Pop-III stars + accretion at Eddington limit do not allow for quasars as large + early as observed
- JWST has strengthened this tension by identifying very large, very early black holes; e.g. a Chandra-JWST detection of a quasar in a z~10.1 galaxy, with estimated BH mass $4\text{x}10^7$ solar masses [Bogdan et al 2305.15458, Natarajan et al 2308.02654]
- Suggests either enhanced BH growth or the formation of large BH seeds to begin with, or both - there are possibilities for new physics to contribute to either [e.g. Pandey et al 1801.06649, Friedlander et al 2212.11100], although it is not yet clear if standard astrophysics is insufficient (e.g. Mayer et al 2304.02066 simulates the direct formation of large black holes from mergers between massive galaxies)

Testing modifications to late-time cosmic evolution

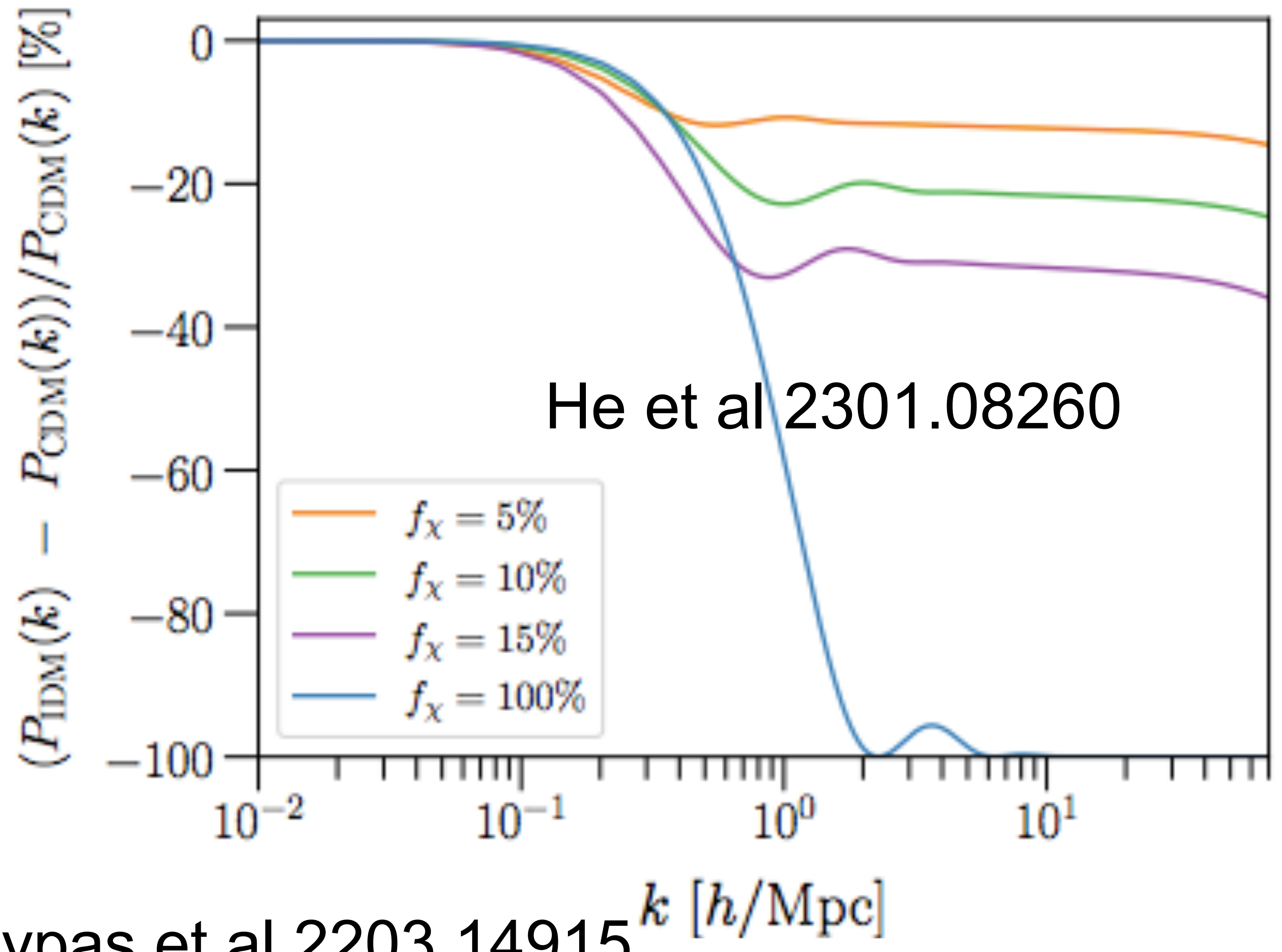
- Modifications to the expansion history at or after recombination can be tested using the CMB, large-scale structure (LSS), and direct measurements of the expansion rate (e.g. with supernovae)

- These datasets can be used to constrain the properties of dark energy, test for modifications to the dark matter equation of state, or test for new relativistic or near-relativistic relics contributing to the energy density [e.g. Xu et al 2107.09664]

- Gravitational waves could probe cosmological phase transitions [e.g. Kosowsky et al '92] or the presence of an early epoch of matter domination [e.g. Assadullahi et al 0901.0989]

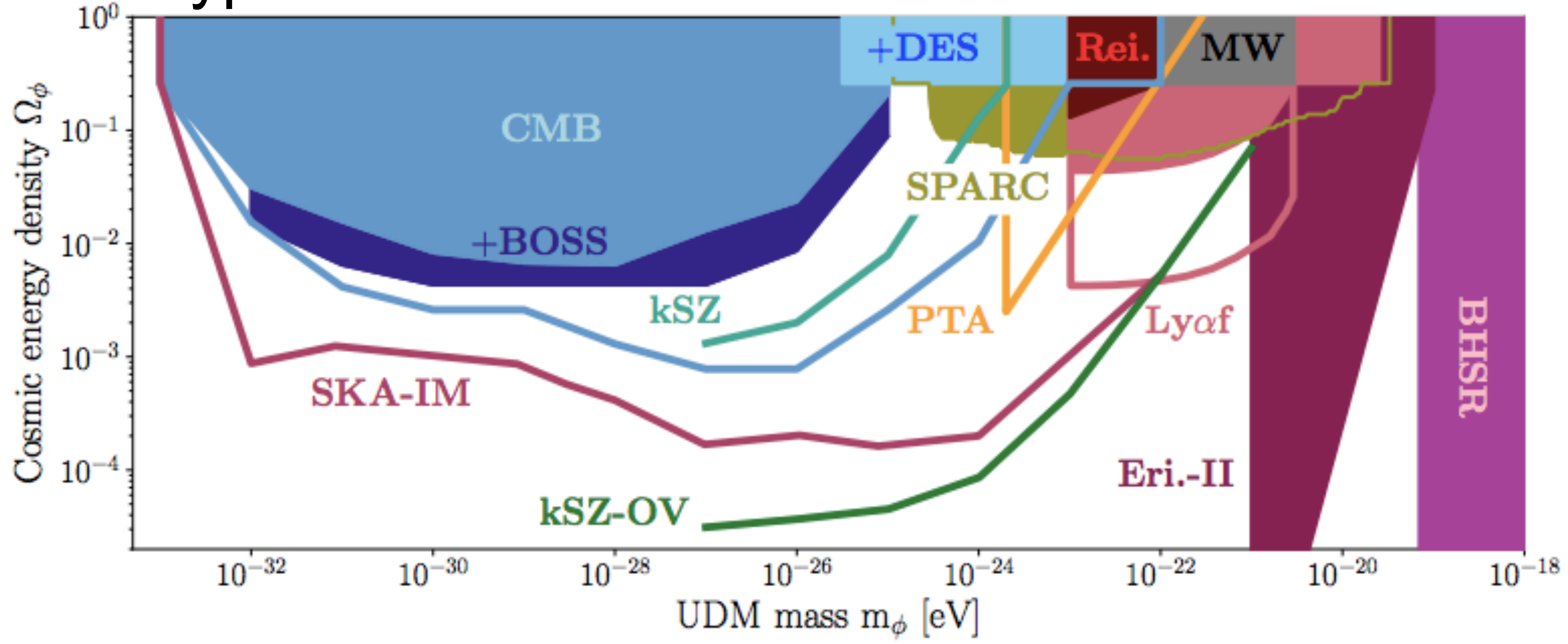
The smallest DM halos

- Open question: what are the smallest bound DM structures in the universe, and what is their internal structure? Probes many types of physics:
  - Sufficiently light DM would have macroscopic de Broglie wavelengths - “fuzzy DM”
  - Free streaming of fast-moving DM in the early universe would erase small halos; if DM was once efficiently heated by interactions with SM, too-light DM would be fast-moving (like neutrinos)
  - DM interaction strengths (with itself and baryons) at low velocities [e.g. Nadler et al ’19, Bondarenko et al ’21, Andrade et al ’21], modifies structure formation
  - If all DM experiences an effect that damps structure on small scales, gives cutoff in power spectrum of matter fluctuations - improve sensitivity by looking at smallest halos
  - If only a small fraction of DM is affected, there could instead be a plateau in the power spectrum (favorable for mild S_8 tension between CMB and gravitational lensing) - good use case for high-precision measurements, including at larger scales



He et al 2301.08260

Antypas et al 2203.14915

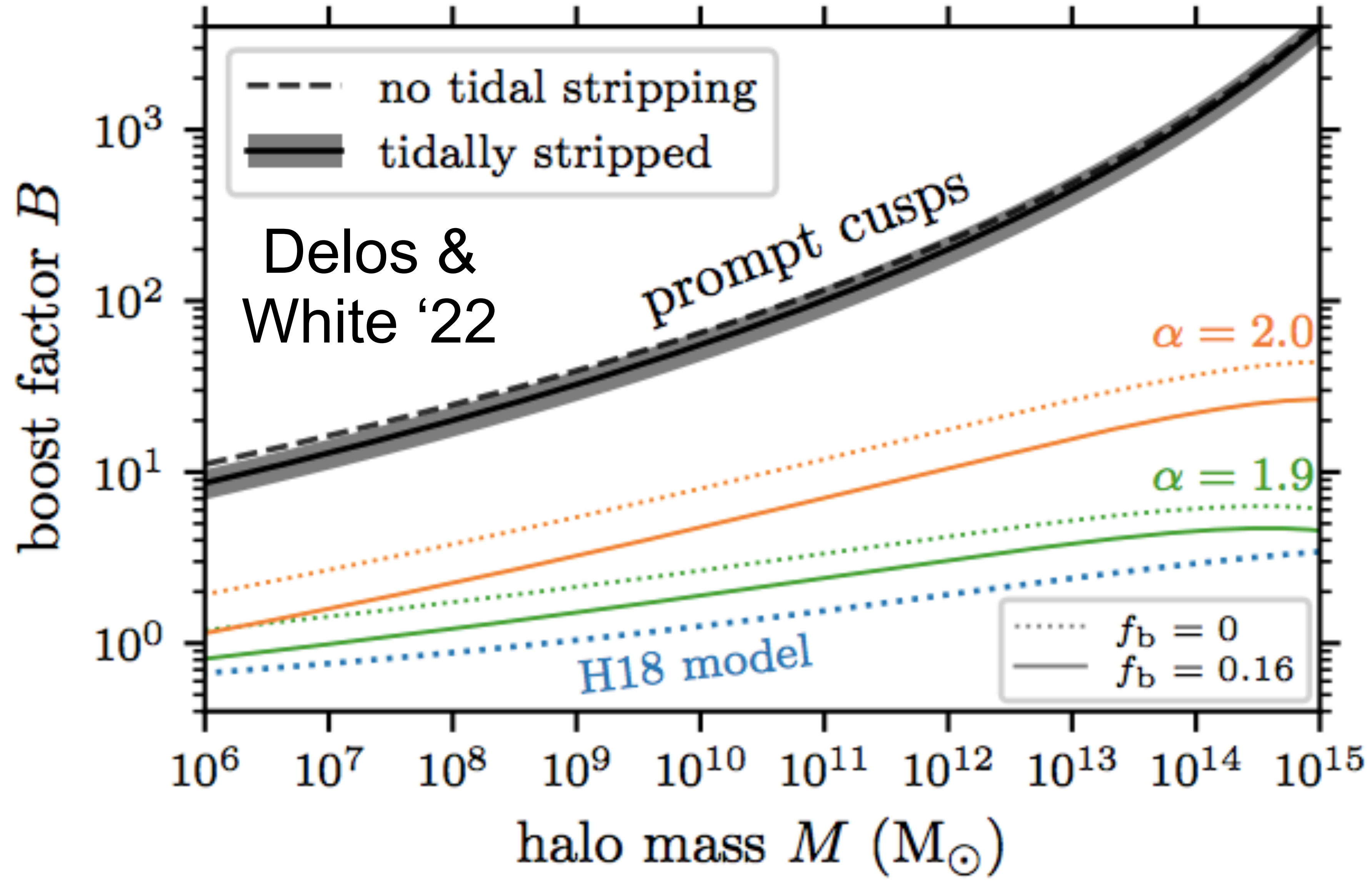


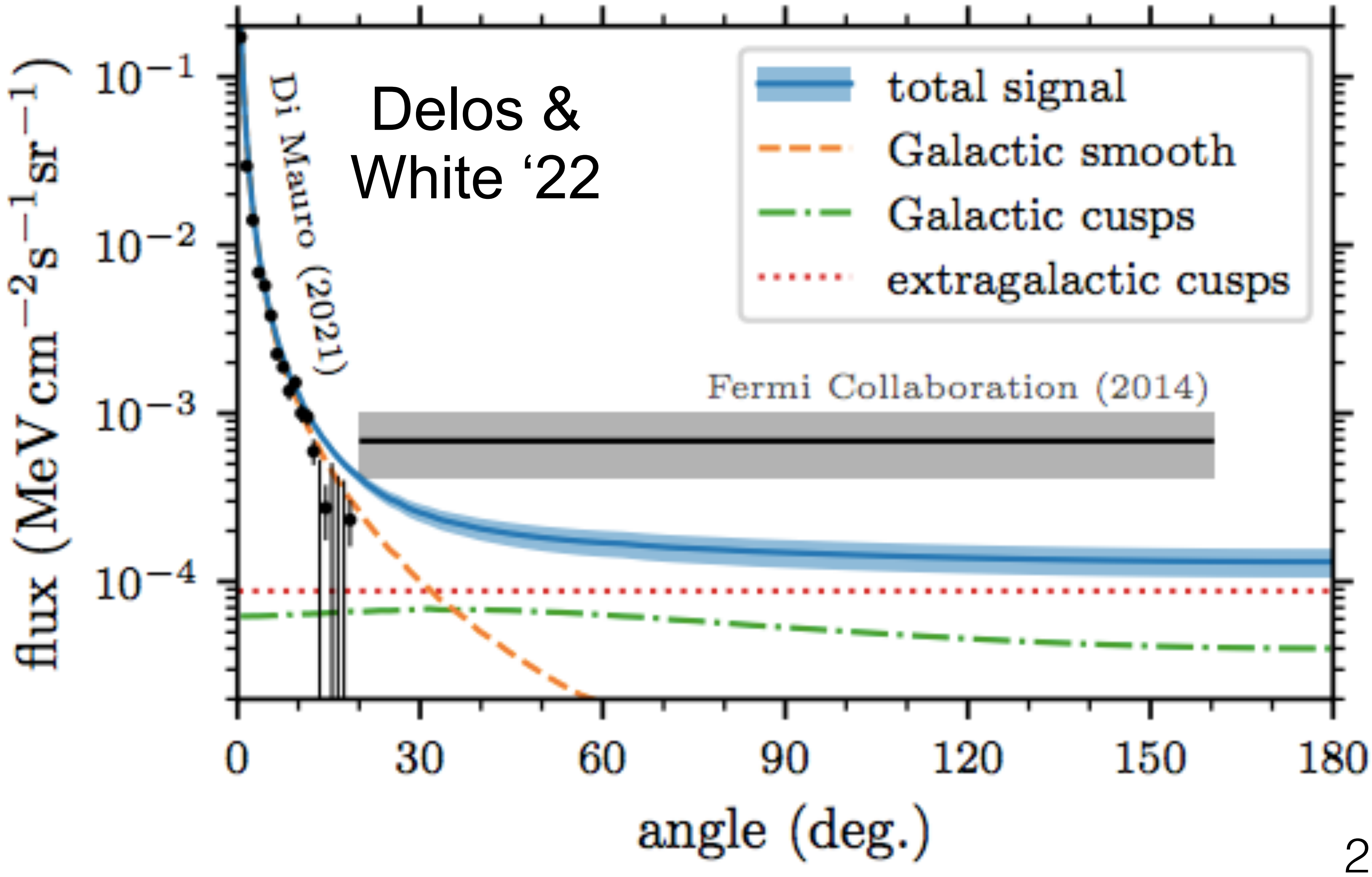
(see also Shevchuk et al 2308.14640)

- Multiple approaches to mapping the smallest currently-observable halos (~$10^{7\text{-}8}$ solar masses): Lyman-α forest (probes matter clumpiness at redshift~2-6) [e.g. Armengaud et al ’17, Irsic et al ’17, Nori et al ’19], fluctuations in the density of stellar streams (perturbed by DM subhalos) [e.g. Banik et al ’21], strong gravitational lensing of quasars [e.g. Hsueh et al ’19, Gilman et al ’19, Nadler et al ’21], observations of faint Milky Way satellite galaxies [e.g. Nadler et al ’19, ’21]

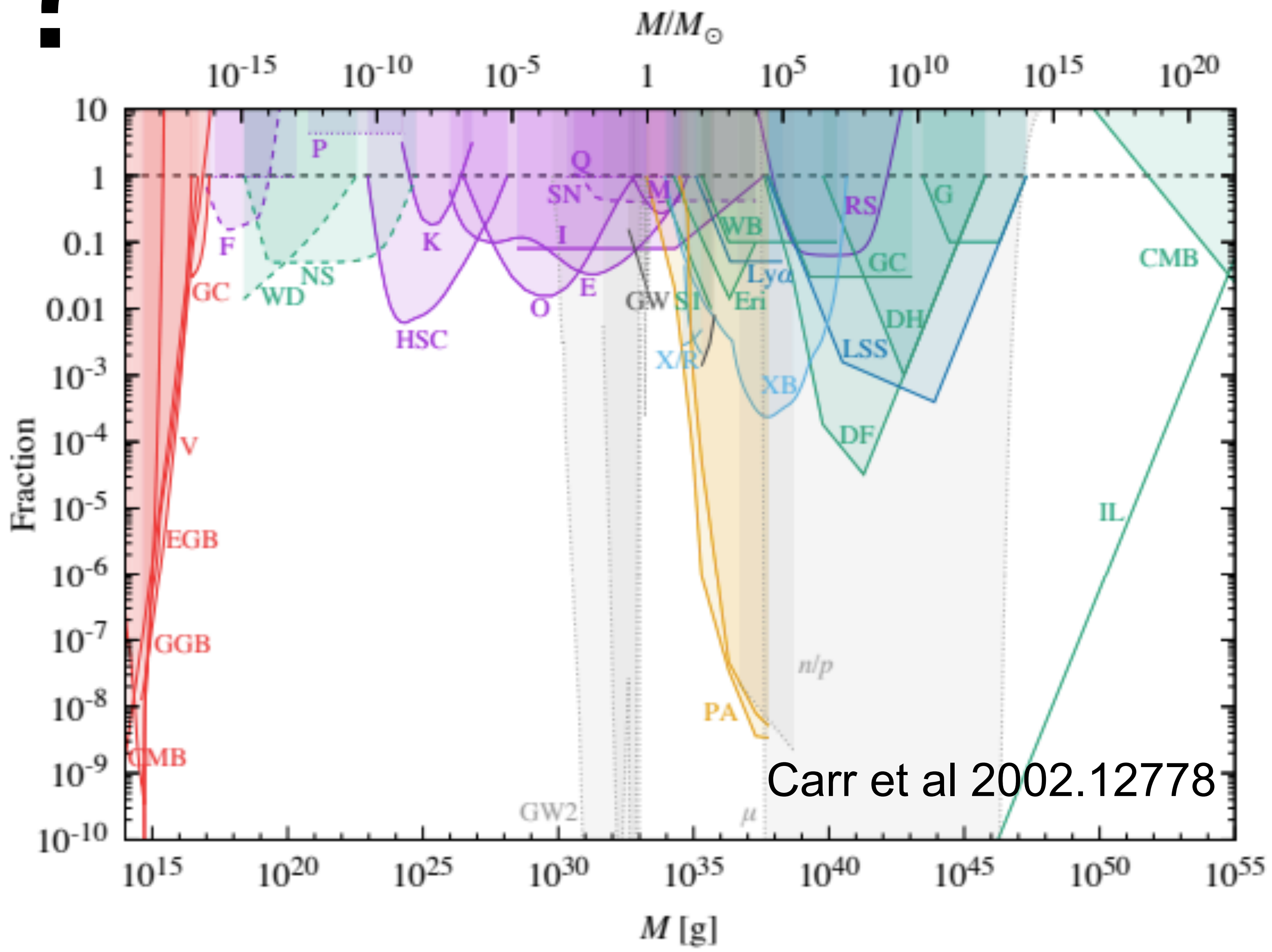
Prompt cusps?

- In pure CDM, some simulations & analytic arguments [e.g. Delos & White ’22] suggest:
    - when dark matter halos first collapse in the early universe, their inner density profiles scale roughly as $r^{-1.5}$ (r=distance from halo center)
    - while halos grow through mergers and accretion, and develop a more standard density profile, the original "prompt cusps” survive as dense clumps within the larger halos
- Not clear to me if the community modeling DM structure formation has converged on this yet [see e.g. Ishiyama & Ando ’20, Delos & White ’22, Ondaro-Mallea et al ’23] - challenge for theorists/simulators
- But if true, it would strongly enhance DM annihilation signals / strengthen indirect-detection bounds, as cusps are very dense
- Expect cusps to be disrupted in regions of high baryonic density by encounters with stars - could enhance e.g. isotropic gamma-ray background signals vs Galactic Center signals





Does dark matter need to be a new particle?



Carr et al 2002.12778

- Classic counterexample is primordial black holes - viable DM candidate if they can be produced copiously in the early universe.
- There is an open window for all DM to be PBHs for PBH masses $M\sim10^{17}$-10^{23}g
- At the low end of this window, PBHs slowly evaporate via Hawking radiation
- Recent papers argue that evaporation calculation may be incorrect after half the PBH mass has evaporated — if evaporation is strongly quenched, could open a new window for very light PBHs.
- Future space-based gamma-ray experiments focused on the MeV-GeV band have the potential to extend the mass reach by about an order of magnitude [Coogan et al ’21, Ray et al ’21].
- Production of PBHs during inflation has been studied by many groups [e.g. Geller et al ’22], but still large theoretical uncertainties (especially in tails of mass distribution) - also debate on whether perturbative calculation is under control [e.g. Kristiano & Yokoyama ’23, Riotto '23]

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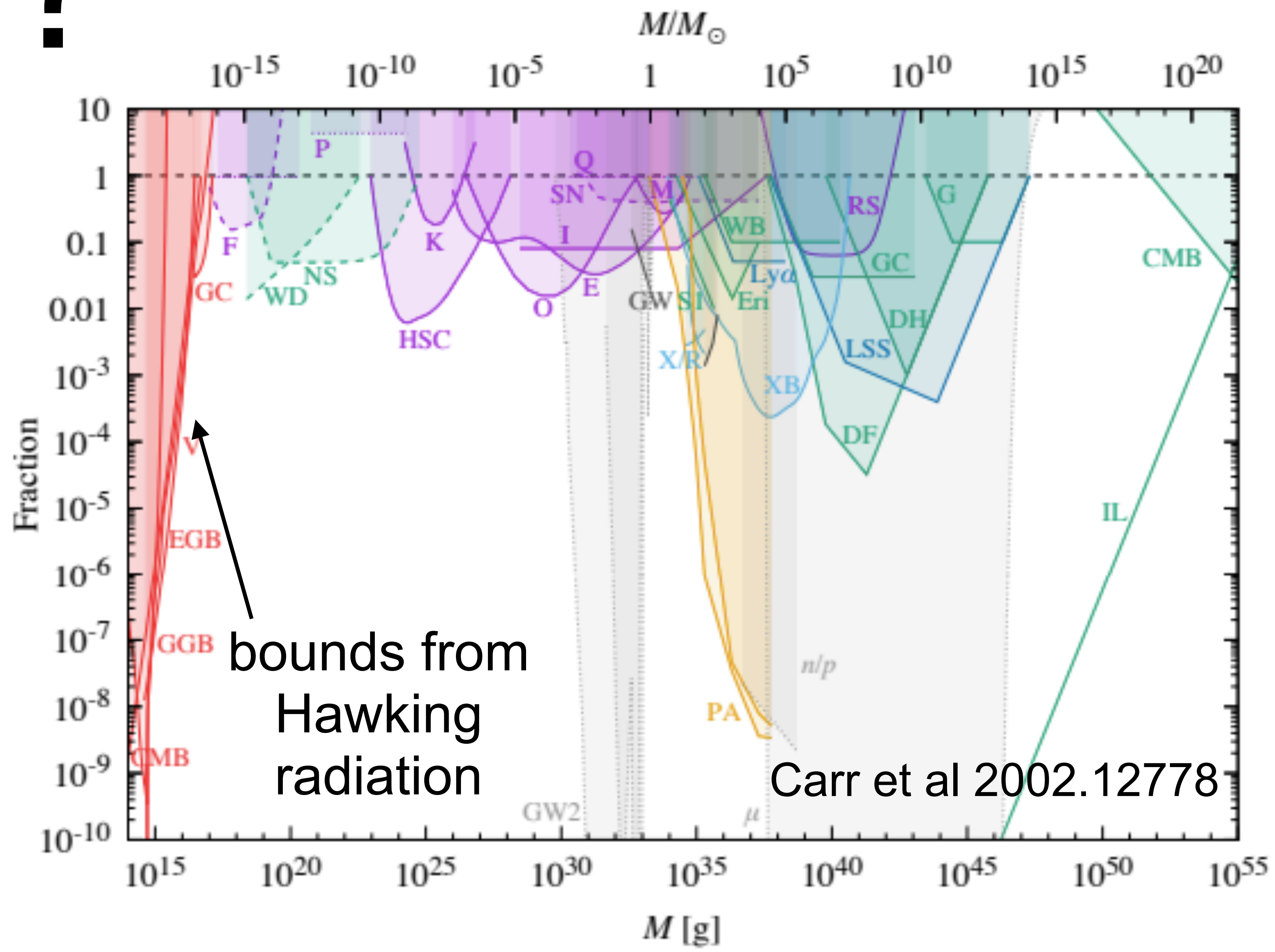

bounds from Hawking radiation

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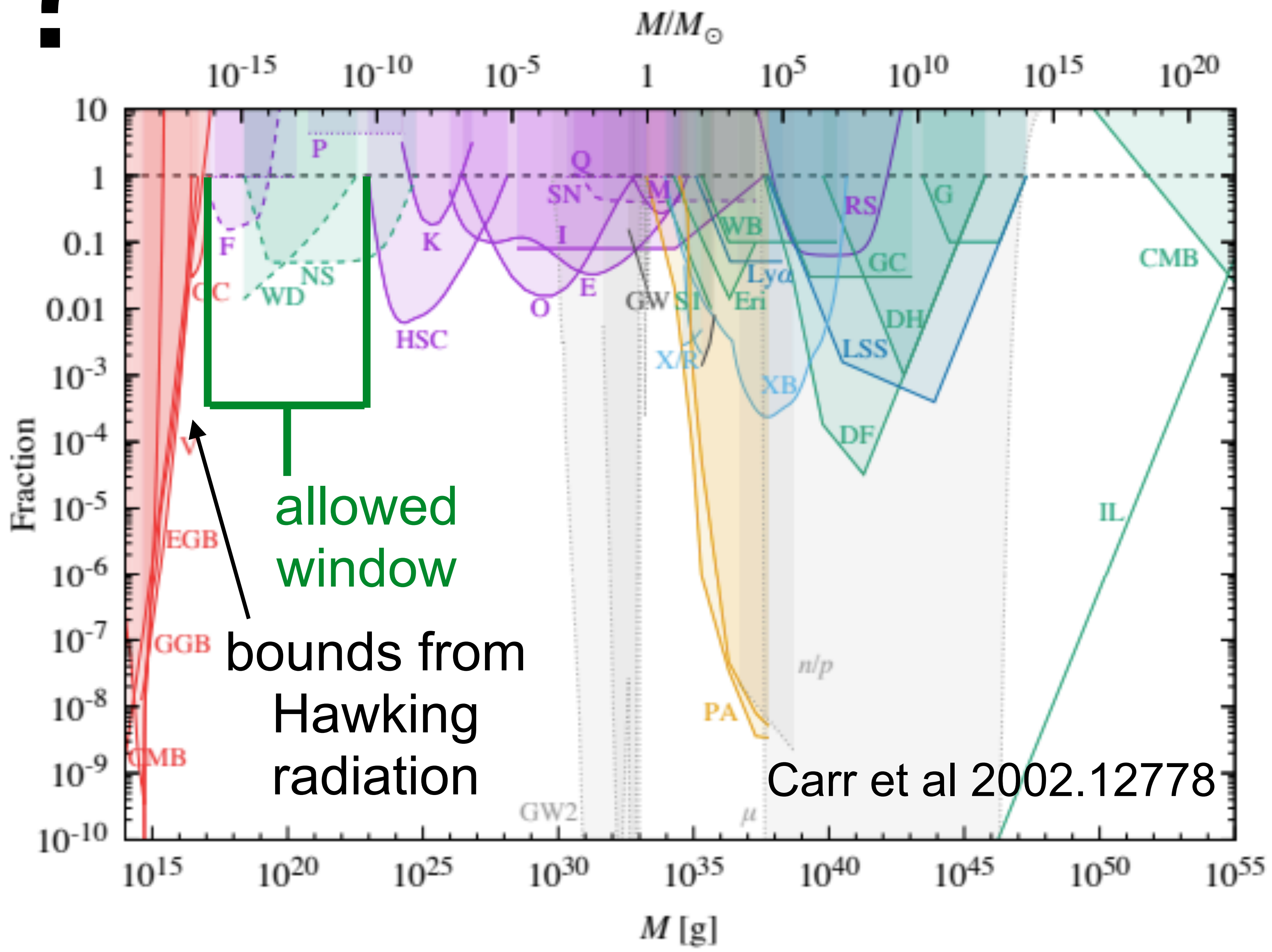

allowed window

bounds from Hawking radiation

Carr et al 2002.12778

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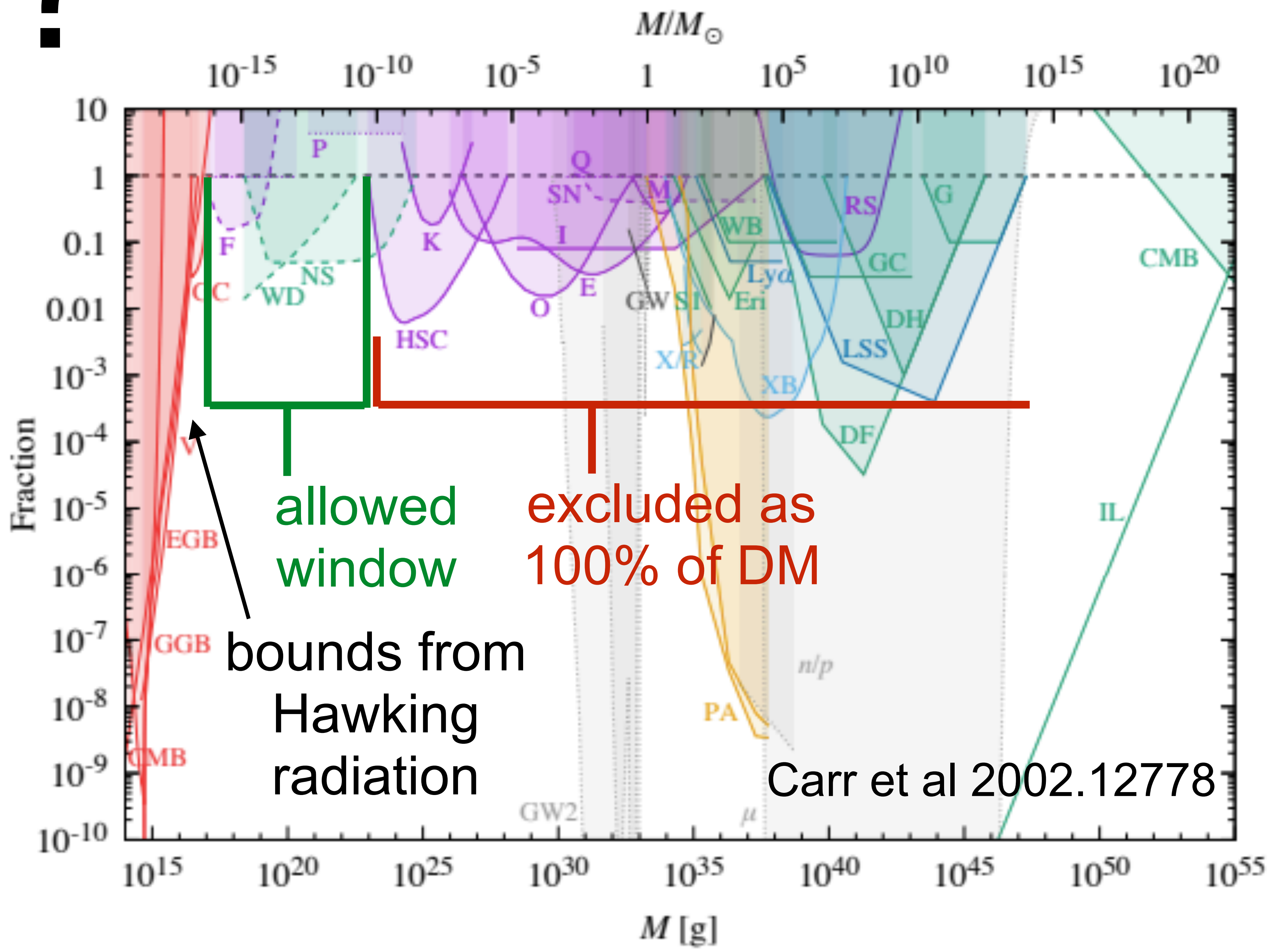

allowed window

excluded as 100% of DM

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Carr et al 2002.12778

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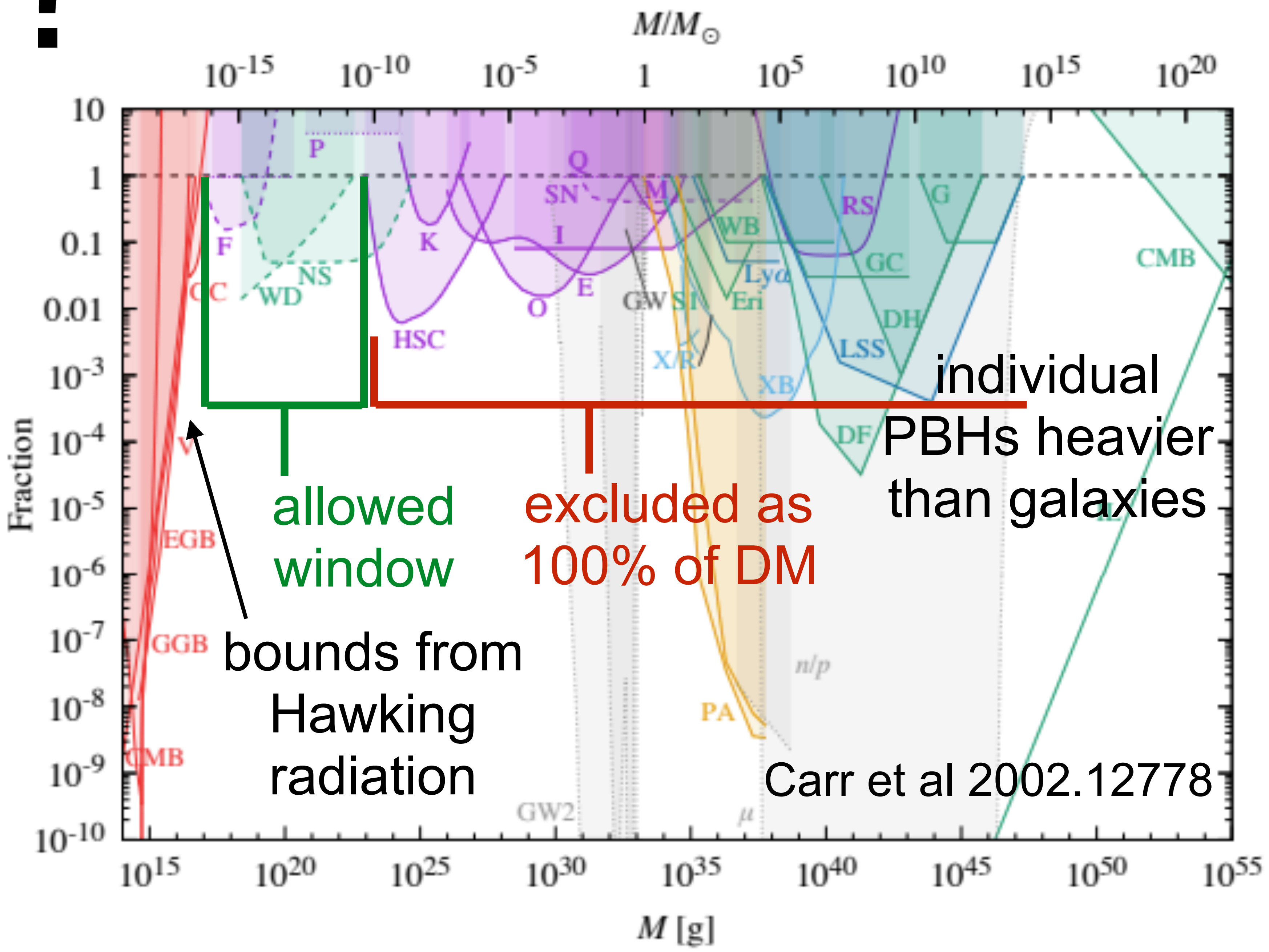

allowed window

excluded as 100% of DM

individual PBHs heavier than galaxies

bounds from Hawking radiation

Carr et al 2002.12778

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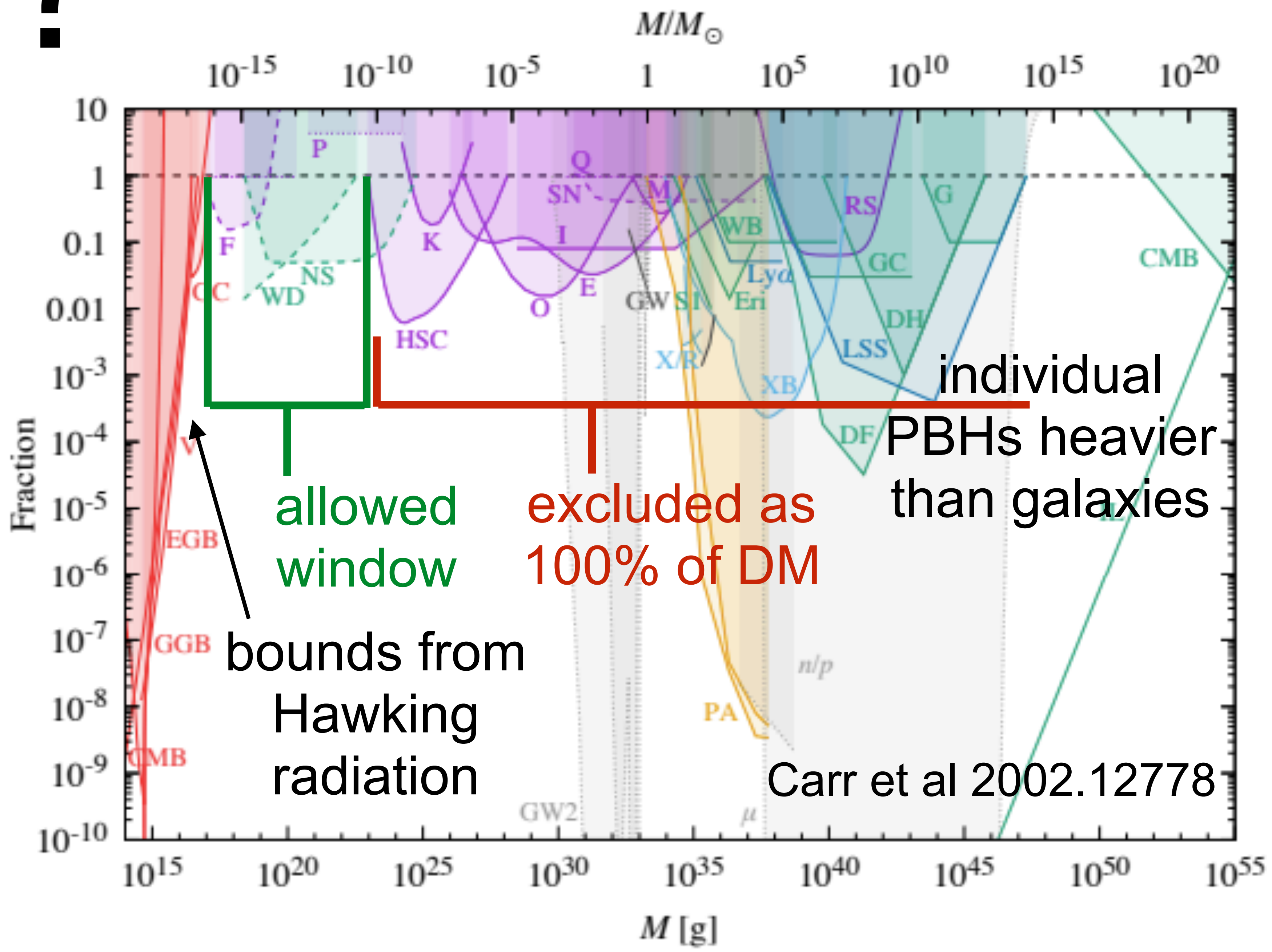

allowed window

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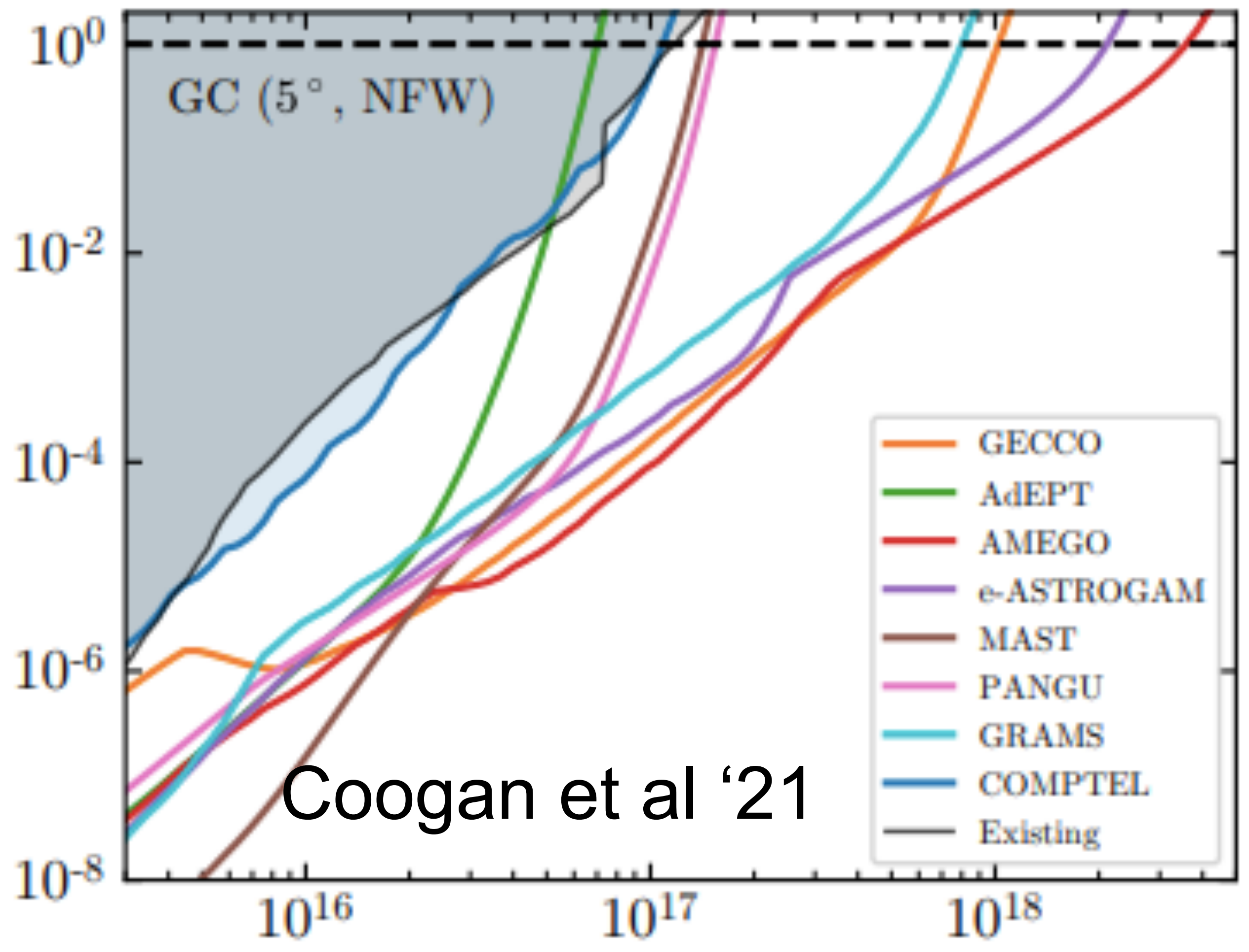
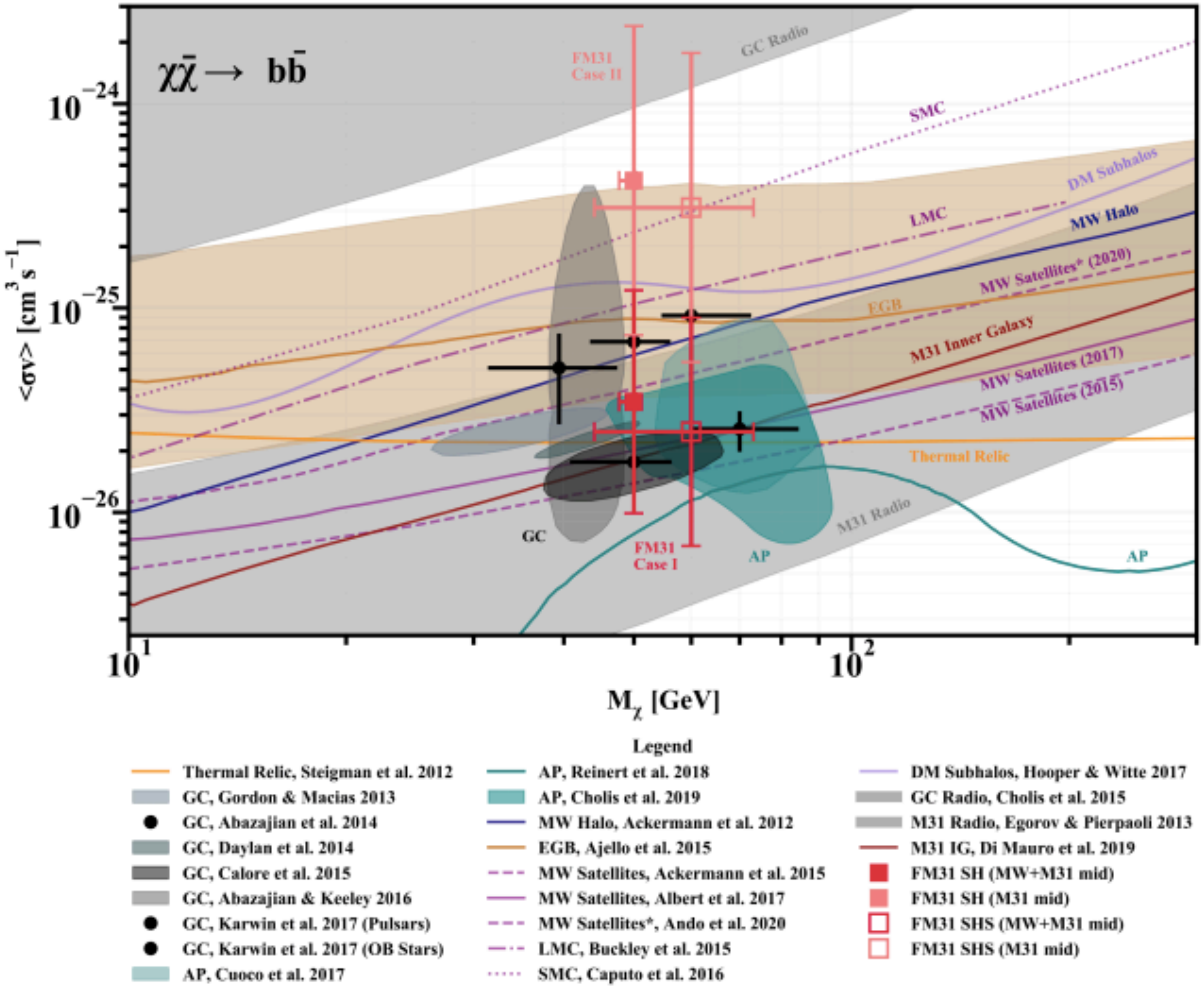


Coogan et al '21

DM counterpart signals for GCE?

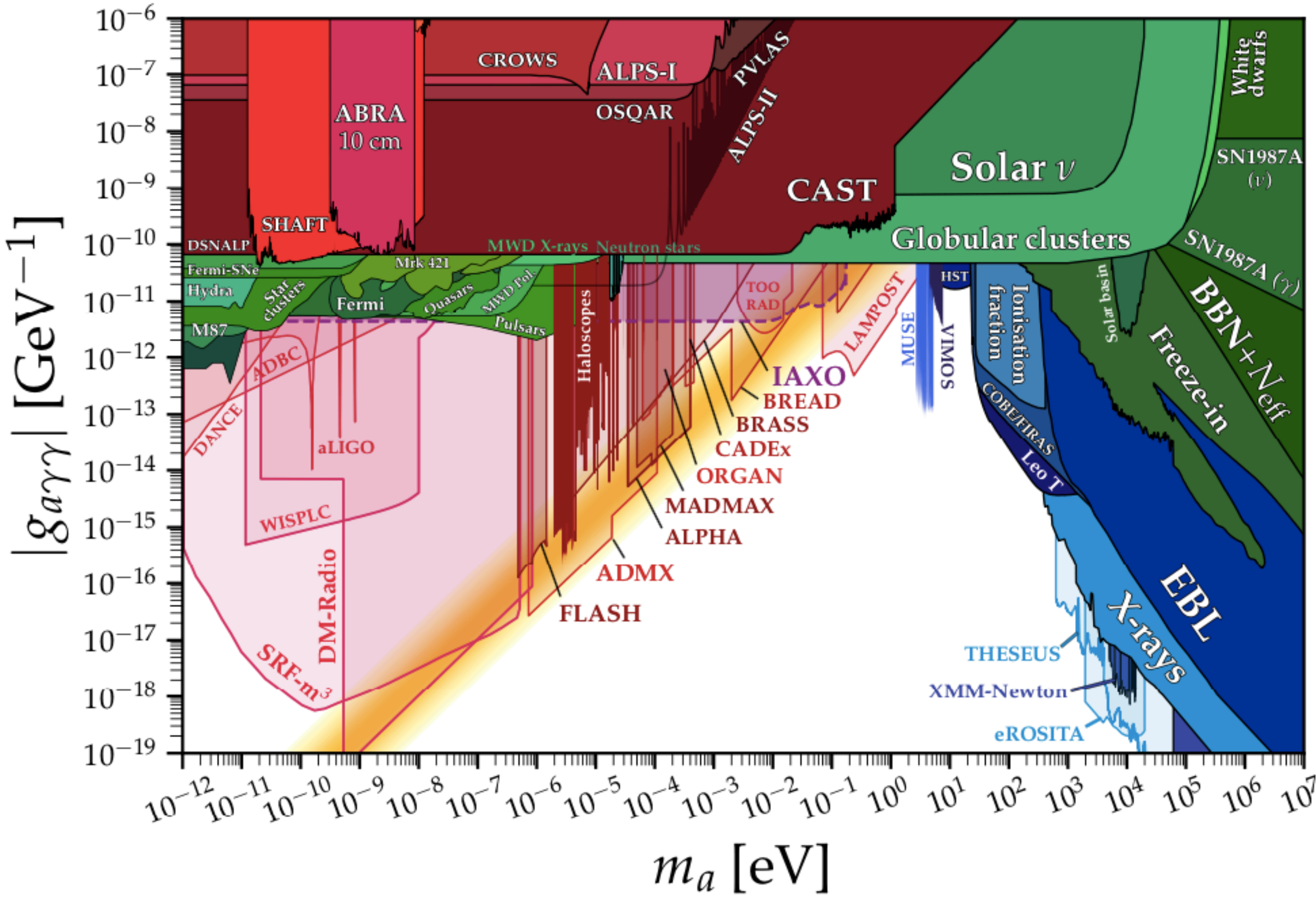
- Sensitivity of dwarf galaxy observations is not quite good enough to cleanly exclude DM interpretation [Alvarez et al ’20, McDaniel et al '23]
- There is a claimed excess in antiprotons at roughly the right energy, but more recent studies find it is not significant (<1 sigma) [see e.g. Heisig et al '20, Boudaud et al ’19, Cui et al ’17, Cuoco et al ’17]
- Recent claims of possible Andromeda counterparts in gamma-rays [Karwin et al ’19, ’21, Burns et al ’21] and radio [Chan et al ’21]
- GAPS (Japan-US collaboration, tested at KEK) may have sensitivity to see counterpart antideuteron signal [e.g. von Doetinchem et al ’20] - long-duration balloon flight planned for 2024-25 Antarctic summer

Karwin et al ‘21



The QCD axion

- “Strong CP problem”: parameter θ describes amount of CP violation in strong interactions, naively expected to be O(1), but experimentally $\theta \lesssim 10^{-10}$
- Axion solution: replace θ with a dynamical field that evolves toward a minimum of its potential
- This field has an associated energy density and could act as cold DM
- Interaction strength with Standard Model determined by axion mass - picks out favored region of parameter space (yellow band)
- Potentially tiny couplings, but many new ideas for how to search for it (often enabled by great advances in quantum sensors), achievable on 10-year timescale



Ciaran o’Hare
https://github.com/cajohare/AxionLimits

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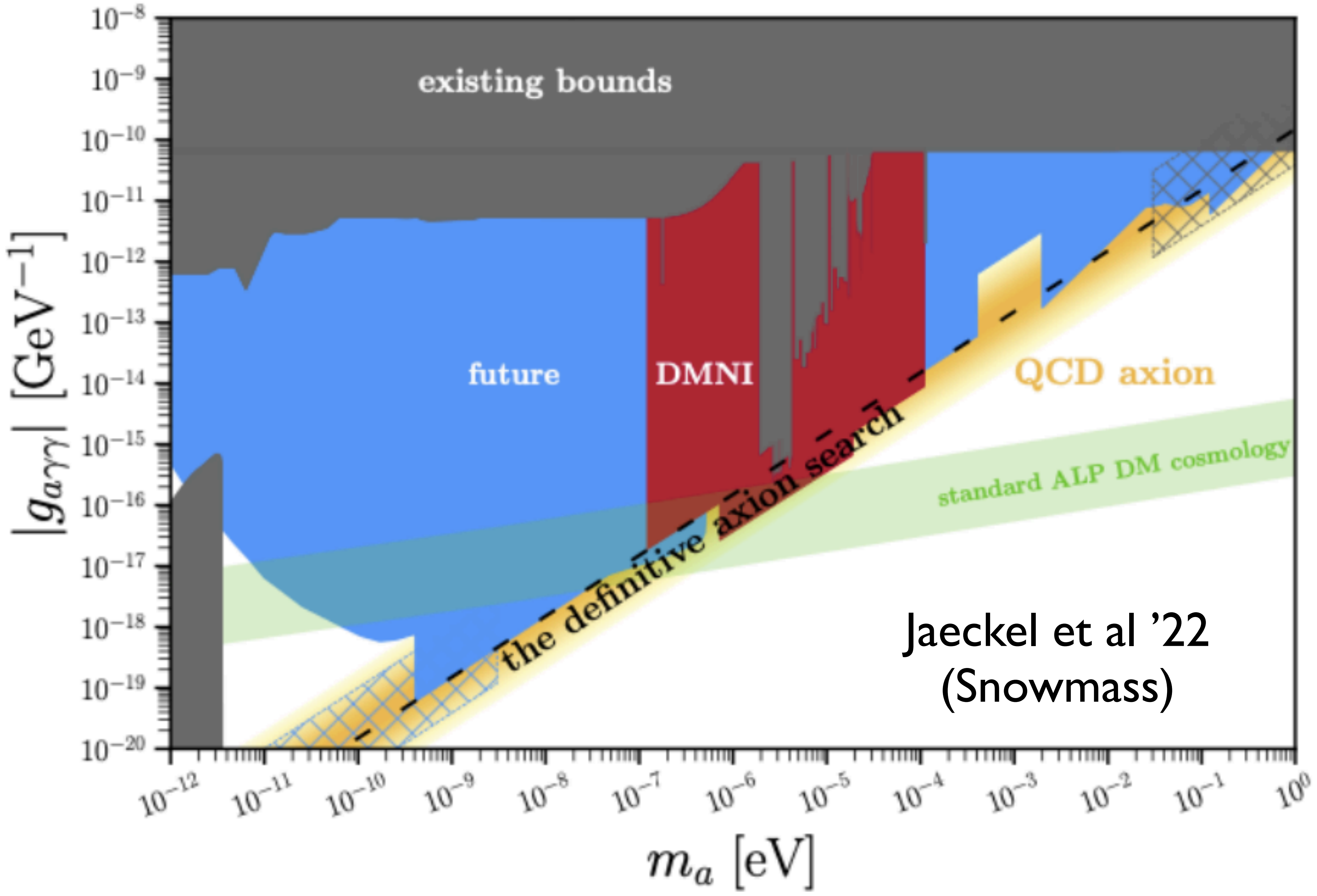
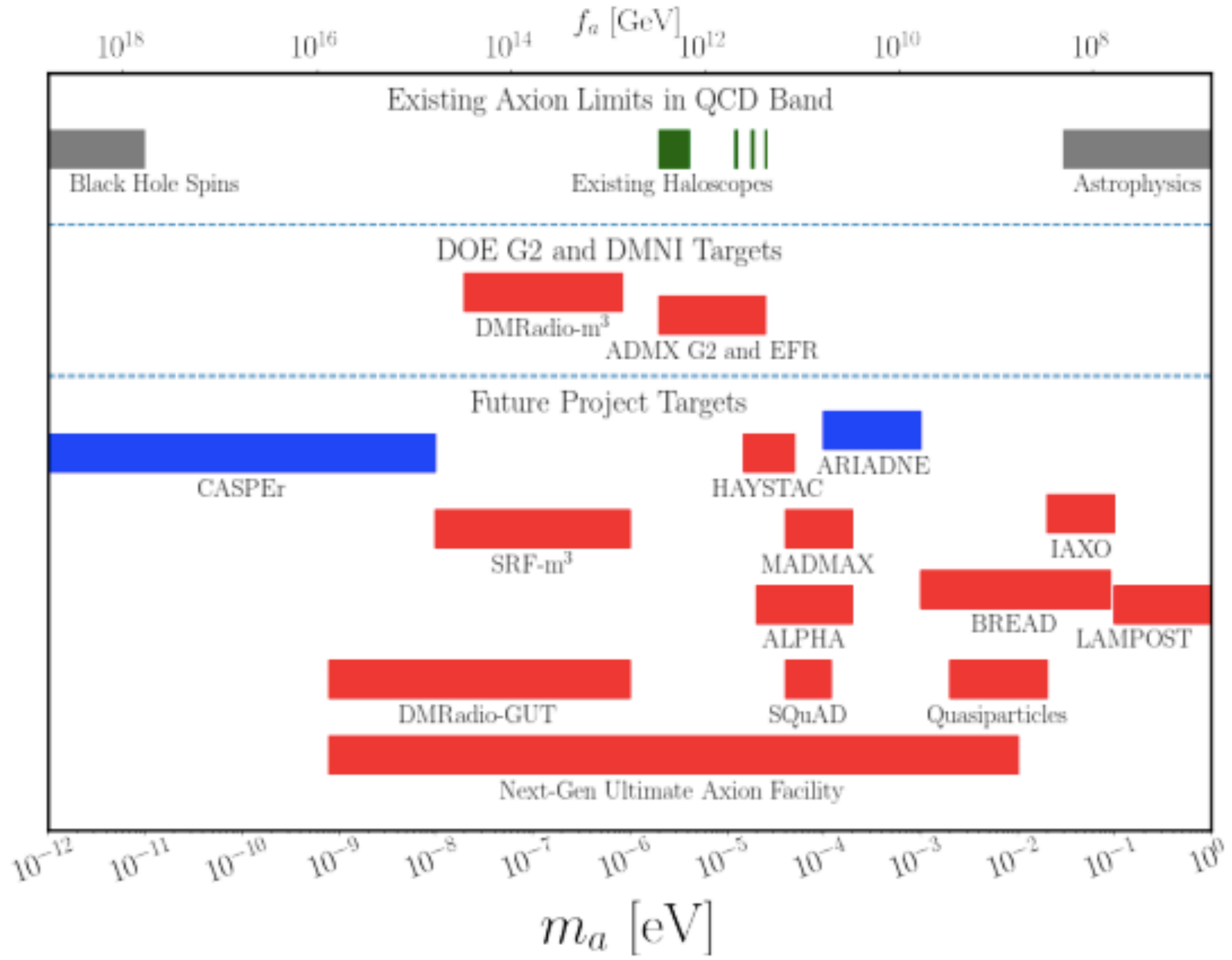
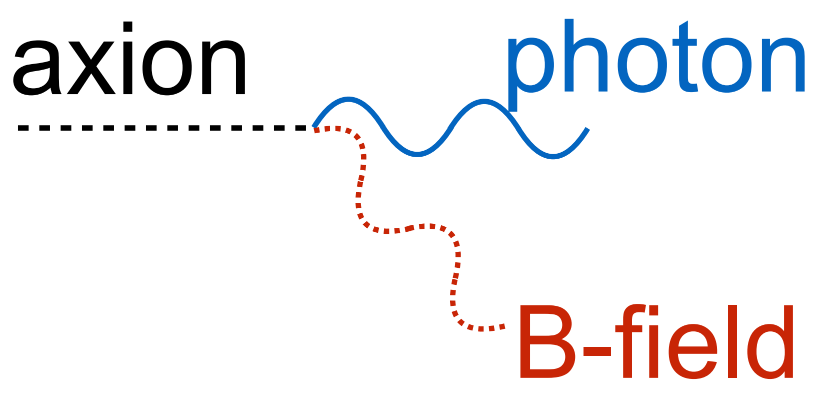


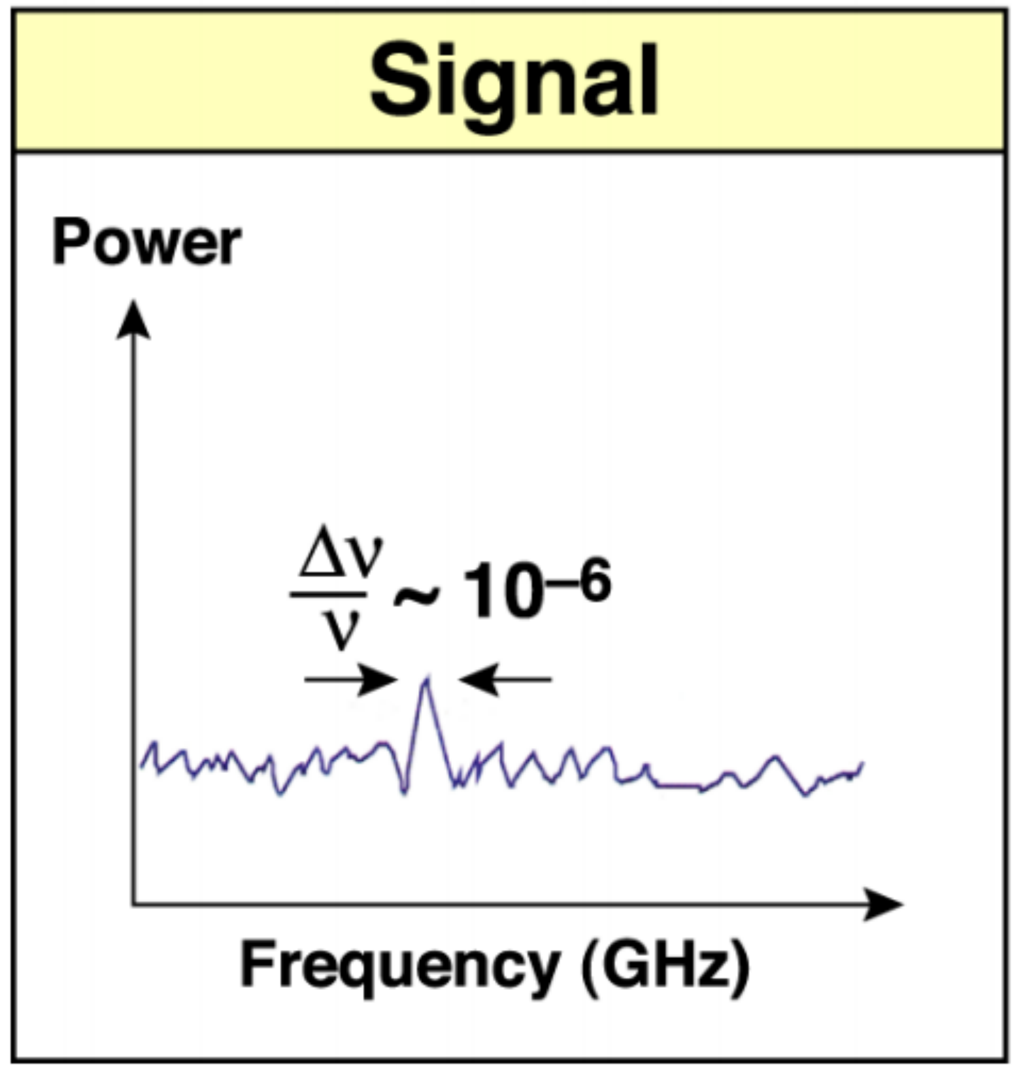
Jaeckel et al ’22
(Snowmass)

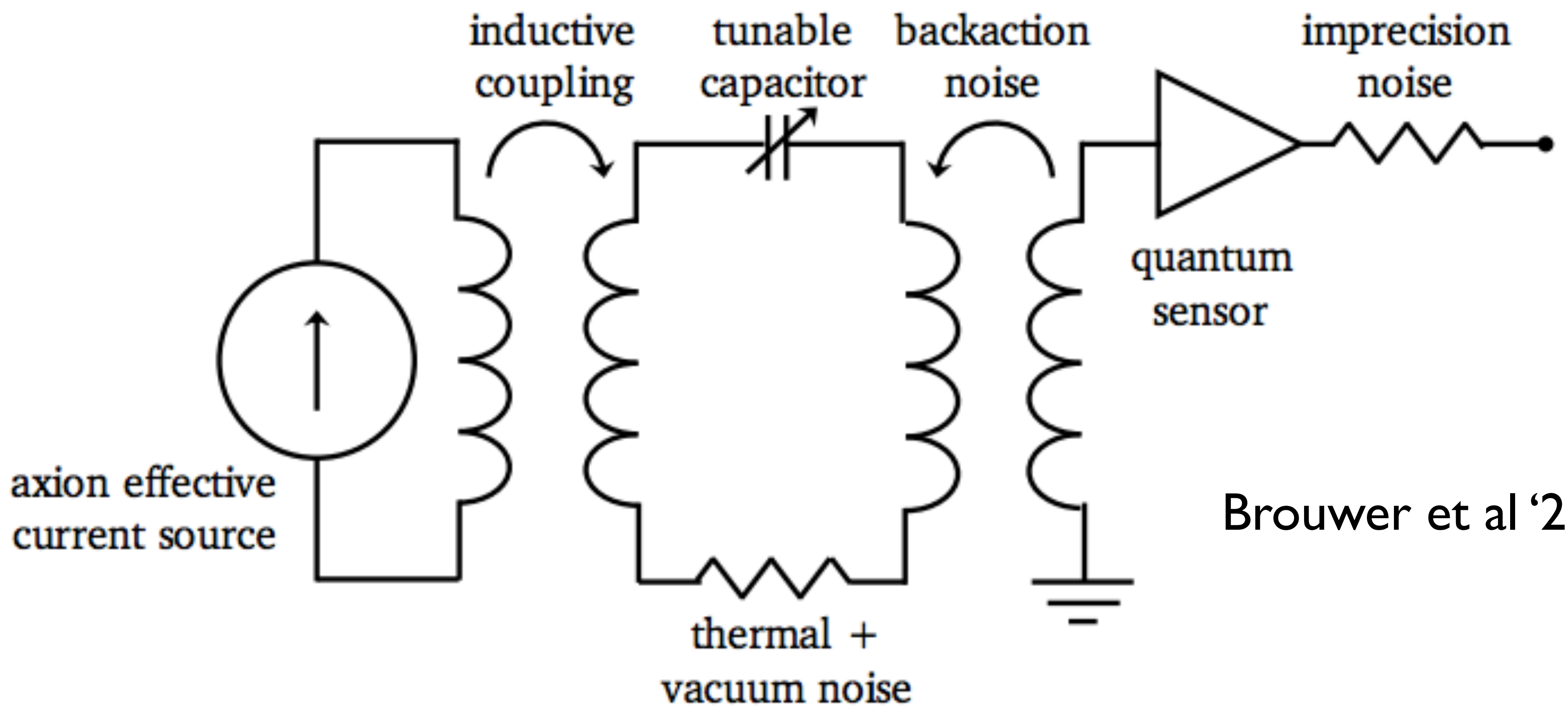


Searching for the QCD axion



- QCD axions (and axion-like particles - same type of coupling but don't solve strong CP) can oscillate into photons in the presence of a B-field. This opens up many searches, e.g.:
  - ADMX experiment: look for frequency-dependent increase in power due to resonant axion-photon conversion in a resonant cavity
  - Proposed DMRadio experiment: treat axion field as a perturbation to Maxwell's equations, induce a small oscillating effective current, enhance signal with resonant LC circuit
- Recent studies note that axion experiments can be adapted to do searches for high-frequency gravitational waves [Domcke et al '22]
- Axions could also have many interesting astrophysical/cosmological signals - e.g. allowing propagation of very high-energy photons from distant extragalactic sources, generating GW signals through binding to BHs, producing "echos" of light from supernovae, etc (see talks by Noriko Yamasake, Yuji Chinone)

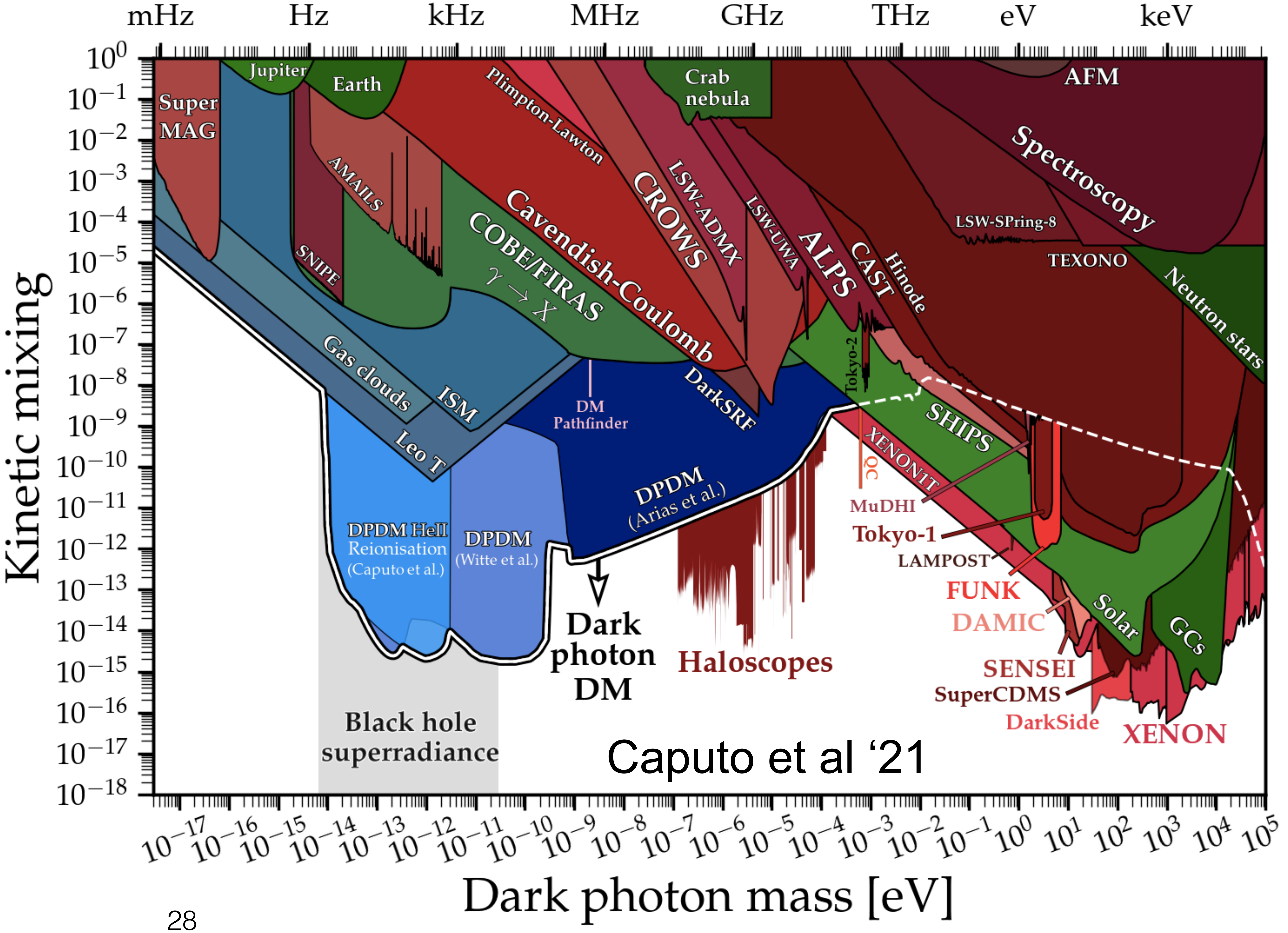




Brouwer et al '22

Dark photon dark matter

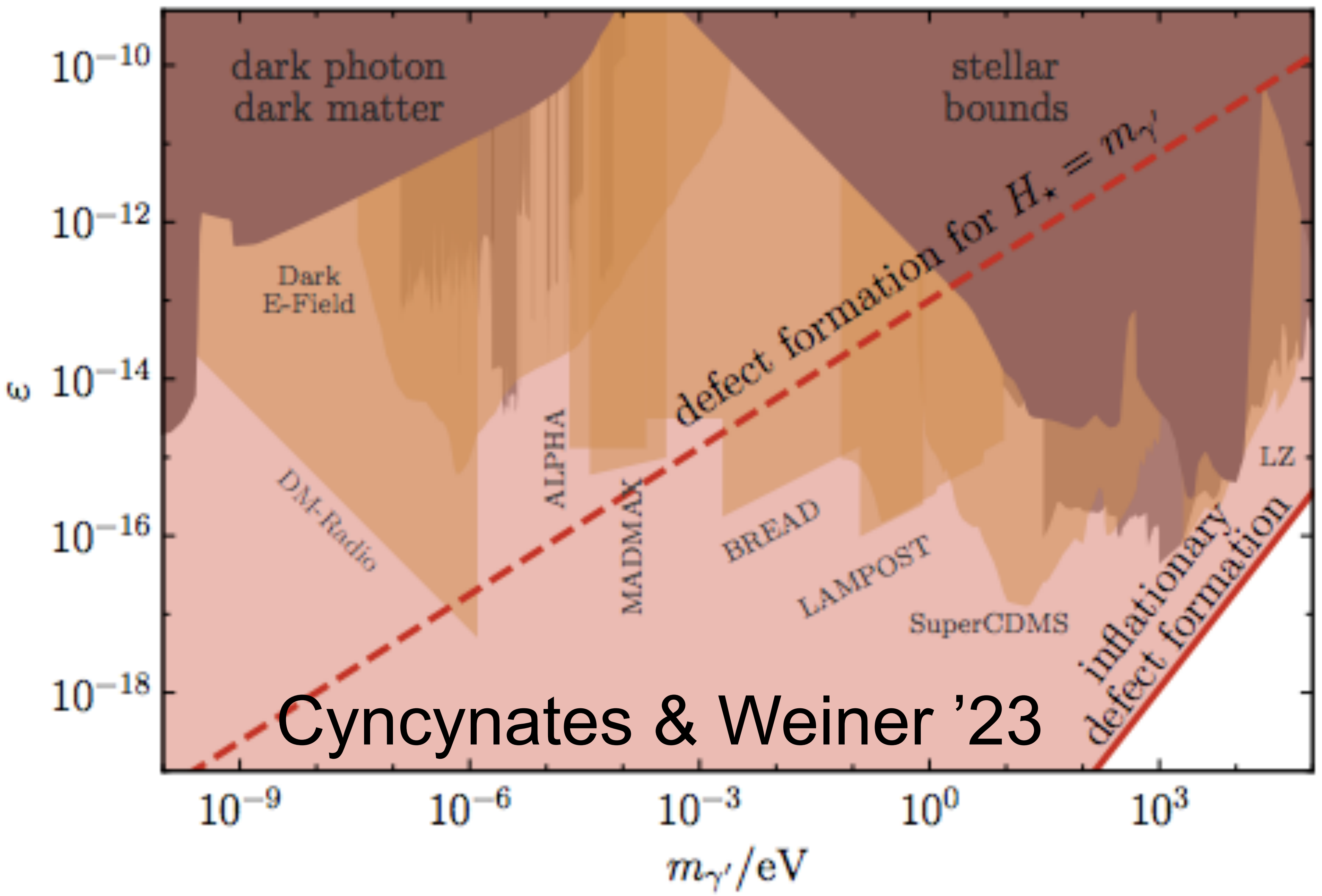
- Axion is a (pseudo)scalar - what about vector DM?
- Commonly-studied benchmark is the “dark photon”, gauge boson of new dark U(1) symmetry (typically broken so the dark photon has a mass)
- Can mix with the SM photon via dimension-4 kinetic mixing term in the Lagrangian,
$$\Delta\mathscr{L} = \frac{\epsilon}{4} F_D^{\mu\nu} F_{\mu\nu}$$
- Many axion searches can also be adapted to dark photons, searching for DM-photon conversion - dark photon case does not require magnetic field
- Requires low mass + small mixing ϵ for stability on cosmological timescales
- Also studied extensively as a benchmark in cases where dark photon is not itself the DM (usually it is unstable), but couples to both DM and SM



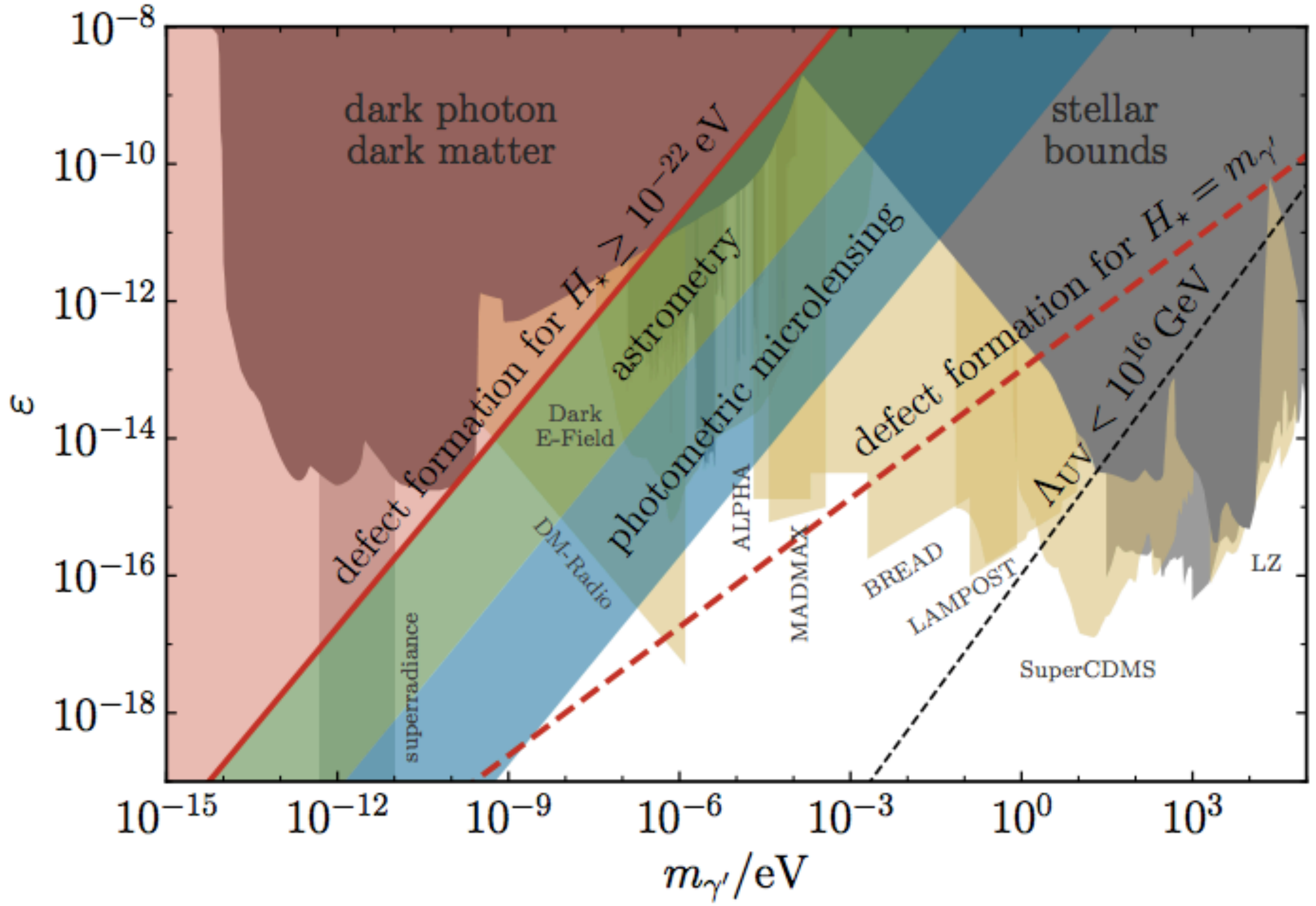
Caputo et al ‘21

Can dark photons be the DM?

- There is a non-trivial question of how to produce the correct abundance for dark photon dark matter - early attempts e.g. mimicking misalignment for axions were difficult to make consistent
- In many dark photon models, expect vortices to form due to interactions between dark photon and dark Higgs that gives it mass - these drain energy out of the dark matter field [East & Huang '22]
- Active ongoing work to build models that evade these vortex formation bounds [e.g. Cyncynates & Weiner '23]
- There are conjectures about quantum gravity that would imply a lower bound on the dark photon mass around the meV scale in at least some scenarios [see e.g. Reece '19, Craig & Garcia '18]

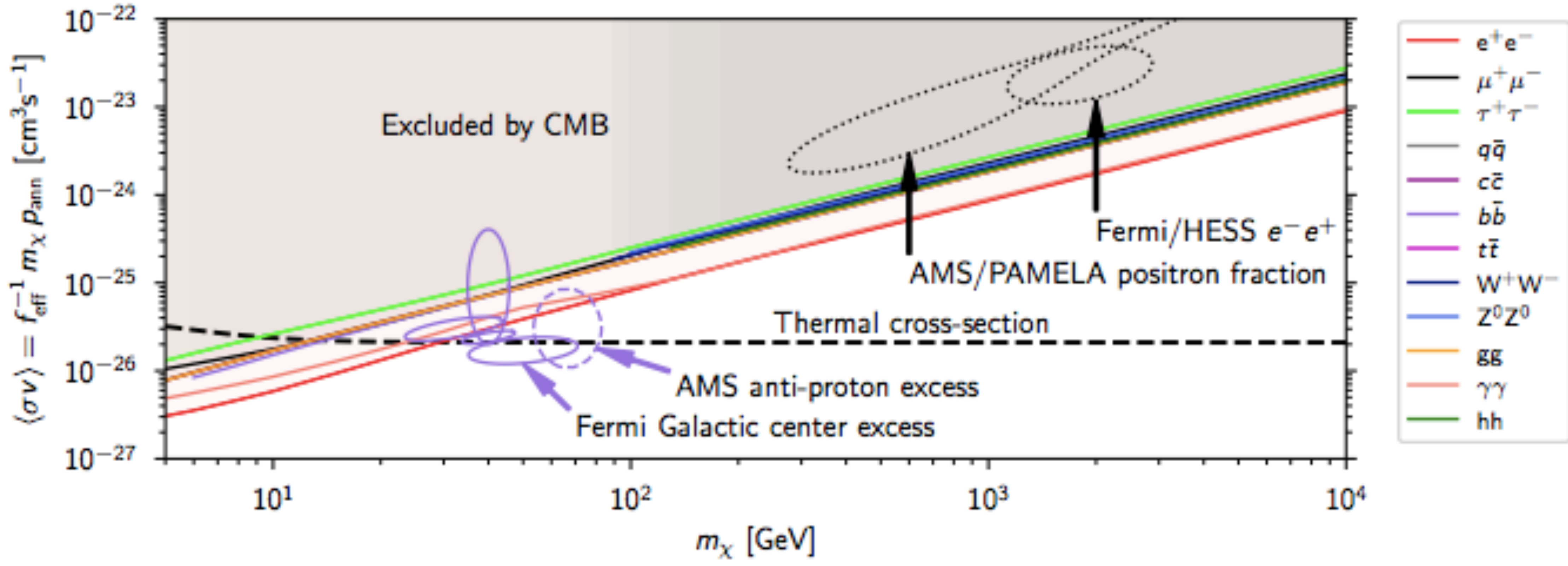


Cyncynates & Weiner '23

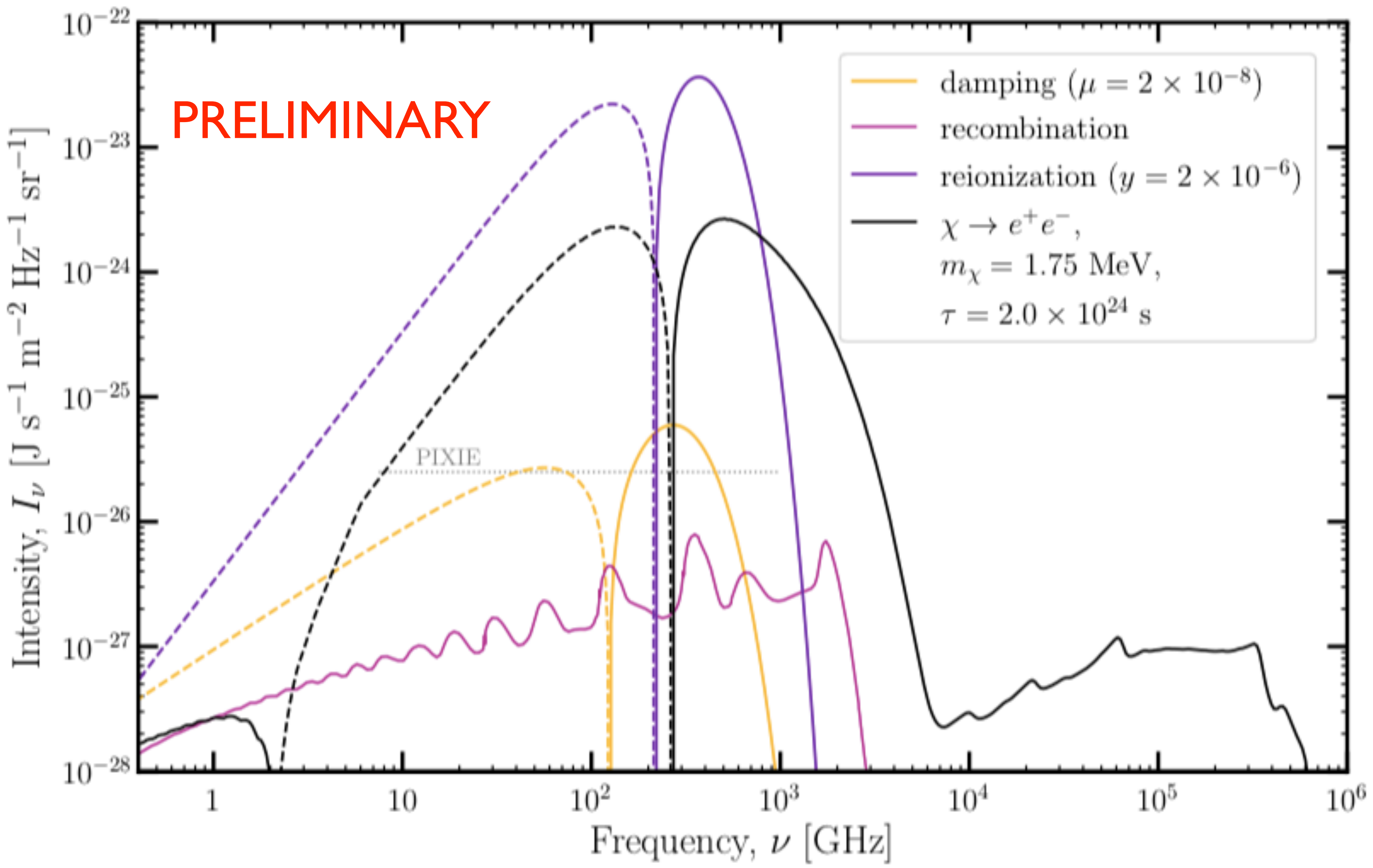


The cosmos as calorimeter

- Even a tiny fraction of dark matter interacting through non-gravitational channels could cause a slow and steady trickle of energy between the dark and visible particles - modifying the history of our universe in striking ways
- Extra ionization from such energy injection leads to stringent constraints on annihilation/decay of light DM from CMB anisotropies
- Focus so far on anisotropies, not blackbody spectrum - but future instruments could improve on current sensitivity to spectral distortions by 3+ orders of magnitude
- Observations of primordial 21cm radiation could open an entirely new observational window on the early universe (major target of current/future telescopes EDGES, LOFAR, MWA, PAPER, SARAS, SCI-HI, DARE, HERA, LEDA, PRIZM, SKA)
- My group is working to improve on forecasts in these observables and more - talk to me if interested!



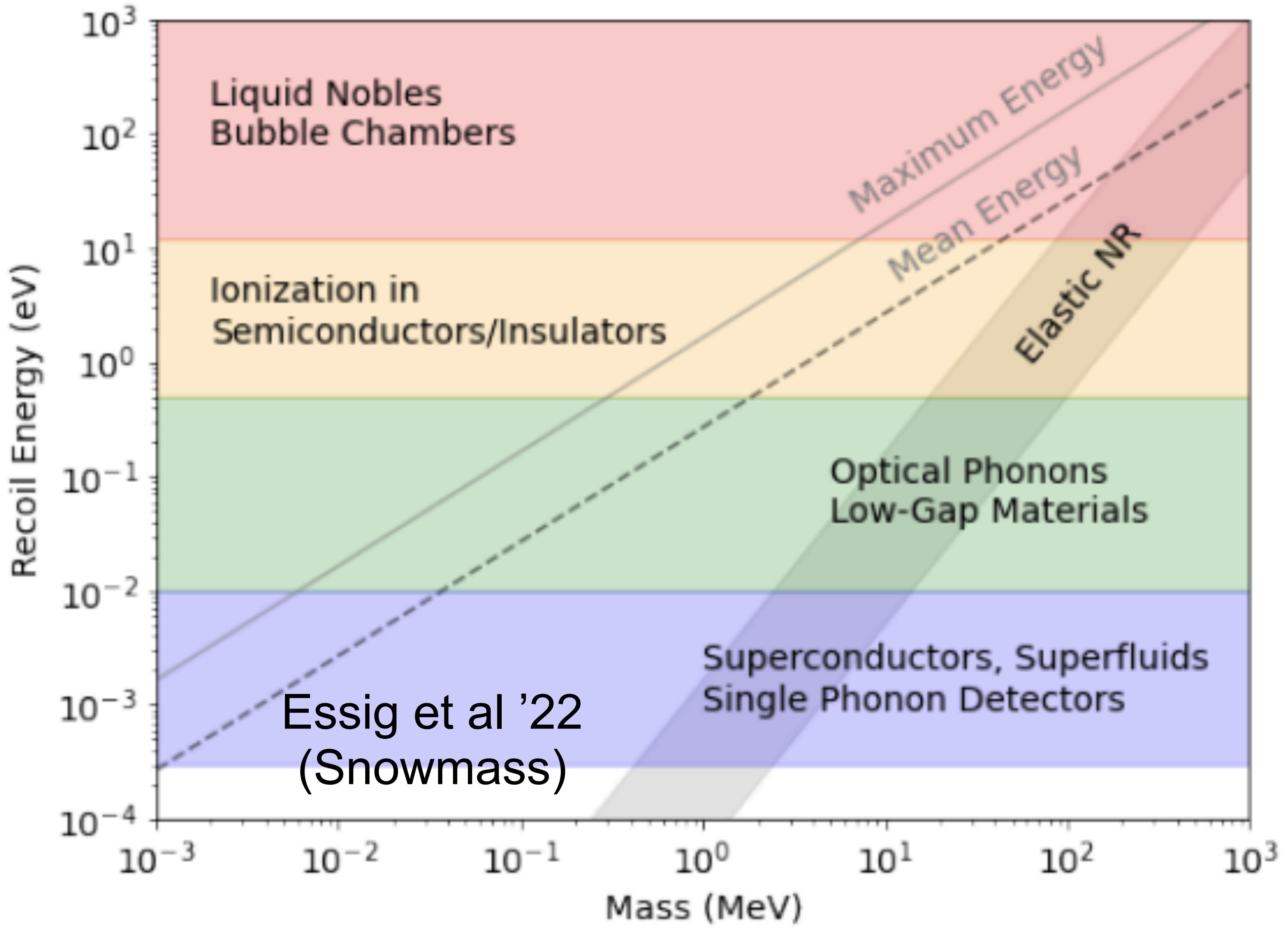
Planck Collaboration ’18



Low-mass thermal DM

- There is a great deal of current interest in the MeV-GeV mass band
  - Simple dynamical explanations for DM abundance (thermal freezeout, freeze-in, and many variations)
  - Generally requires new mediators connecting DM and the Standard Model - "dark sectors”, new "dark forces”.
  - Constrained by indirect detection - picks out classes of models with small/absent annihilation signals

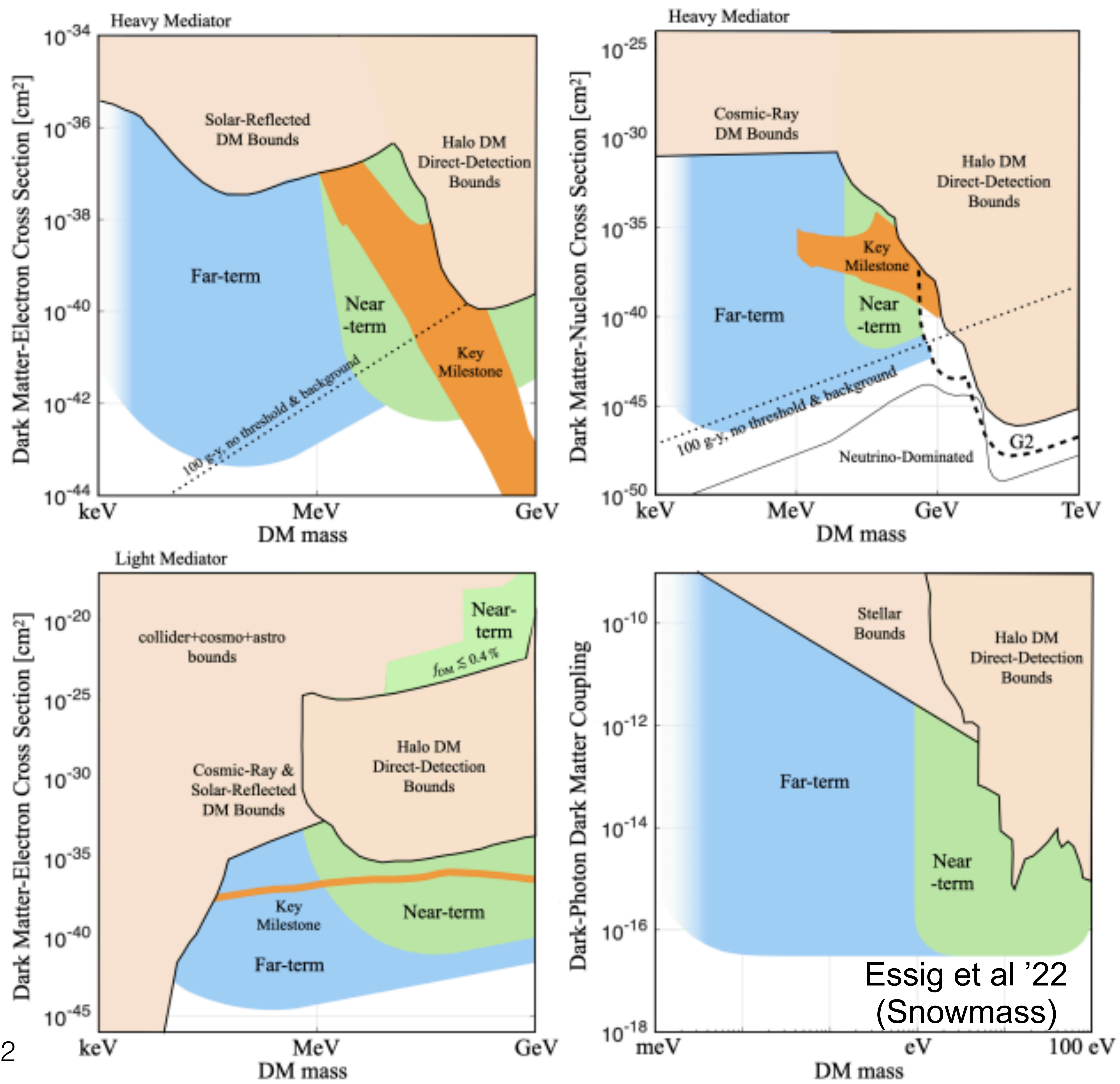
- Classic direct detection experiments lose sensitivity for DM masses below 1-10 GeV - kinematic mismatch between DM and atomic nuclei leads to tiny energy recoils
  - However, secondary photons/electrons produced in conjunction with nucleus-DM scattering, via bremsstrahlung or the “Migdal effect”, can be detectable [e.g. Kouvaris et al ’17, Ibe et al ’18, Bell et al '20]
- Can gain by looking at electron recoils (better kinematics for MeV-scale DM)
- Very active research program underway to work out possibly observable signatures of tiny energy depositions, often using special features of carefully-chosen target materials, e.g. tiny bandgaps (see Essig et al ’22 (Snowmass) for a review)



Essig et al ’22 (Snowmass)

Example: SENSEI

- Employs ultra-low-noise silicon Skipper-Charge-Coupled-Devices (Skipper-CCDs)
- Silicon band gap ~ 1.2 eV
- Recent advances allow measurements of charge in each pixel (over millions of pixels) with sub-electron noise
- Search for single electron excitations across band gap, allowing testing of:
  - DM-electron scattering down to m~500 keV (recoil energy ~ 1 eV)
  - DM-nucleus scattering down to m~1 MeV (via Migdal effect)
  - DM absorption on electrons down to m~1 eV

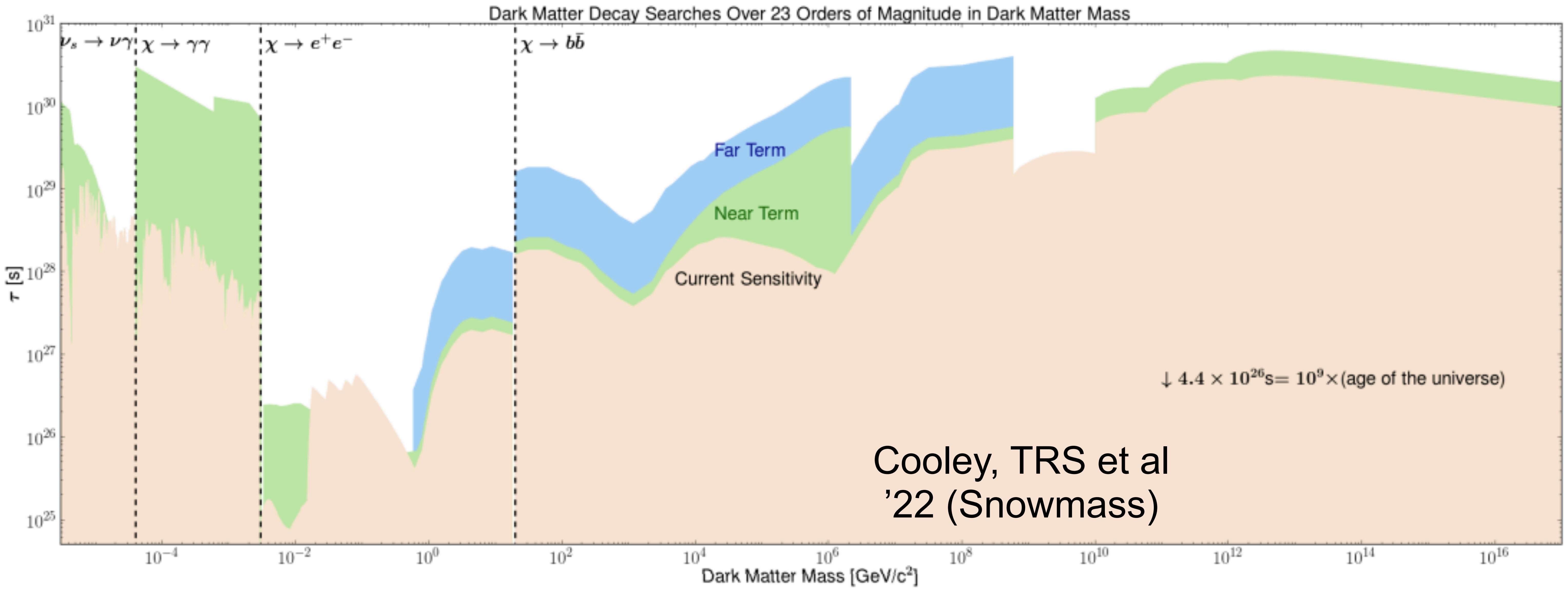


Essig et al '22 (Snowmass)

Ultraheavy DM

- DM above 100 TeV - PeV can be produced non-thermally, or via thermal freezeout if standard assumptions are violated:
  - modified cosmology: large entropy injections, first-order phase transition in the dark sector [e.g. Asadi, TRS et al ’21], etc
  - formation of many-particle bound states [e.g. Coskuner et al ’19, Bai et al ‘19] - can lead to macroscopic DM candidates
- Macroscopic DM could have striking signatures in direct-detection experiments, large neutrino detectors [e.g. Bai et al ’20]
- Very tiny interactions may be detectable with ultra-high-precision mechanical sensors [e.g. Carney et al ’20, ’21]

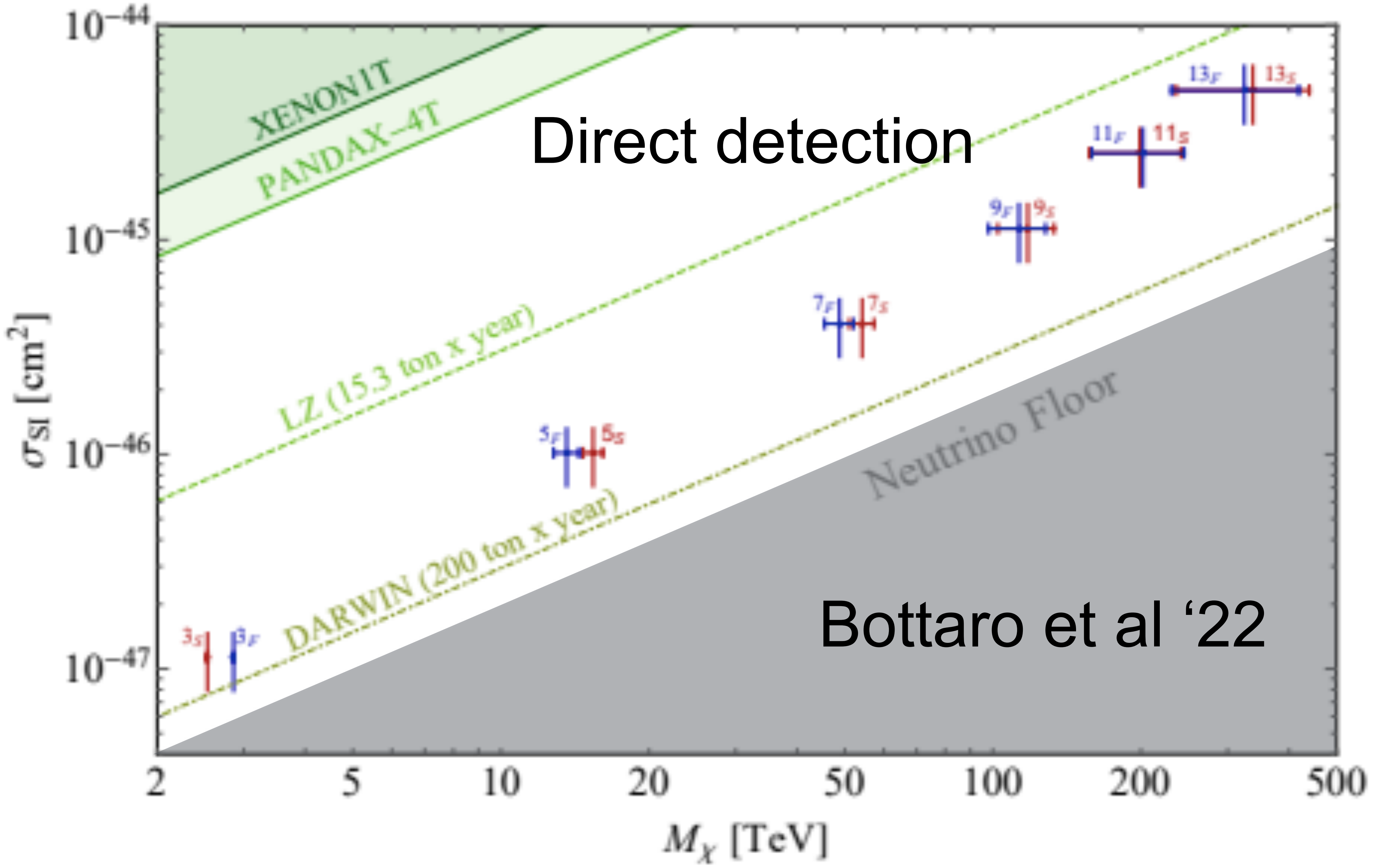
- Searches for decay products severely constrain the DM lifetime (for visible decays)
- Must be 8+ orders of magnitude longer than the age of the universe over 20+ orders of magnitude in mass
- Primordial black holes provide an existence proof of very heavy, decaying DM up to ~10^{23} g (see talk by Stefano Profumo)



Cooley, TRS et al ’22 (Snowmass)

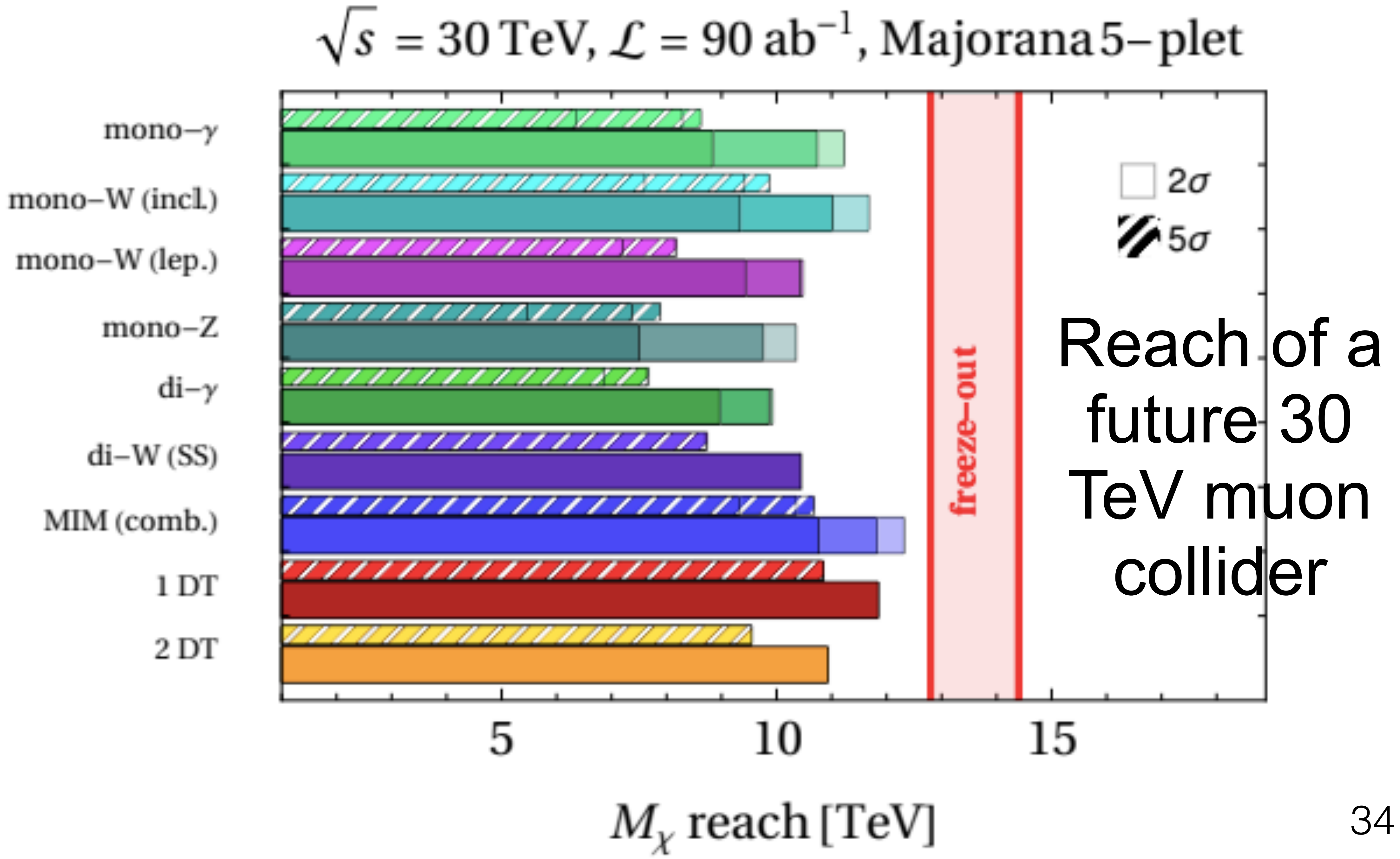
Electroweak DM

- Some of the simplest classic WIMP models remain unconstrained - DM could still interact through the W and Z bosons of the Standard Model
- Example: in "minimal DM” [Cirelli et al ’05] scenarios, DM is part of a SU(2)$_W$ multiplet; doublet and triplet examples appear in supersymmetry as partners of the gauge and Higgs bosons
- Requires relatively heavy masses (TeV+) to obtain the relic density - difficult to probe at colliders
- Careful effective-field-theory calculations of direct detection signal: close to neutrino floor (odd representations) or below it (even representations)
- What about indirect detection?



Direct detection

Bottaro et al ‘22



Reach of a future 30 TeV muon collider

Resolving puzzles in the data

- Over the years we have seen a number of puzzling signal candidates in direct and (especially) indirect detection

- Conclusively resolving these excesses may require new analysis techniques and/or new datasets - whether or not they are telling us about DM, they are something we need to understand

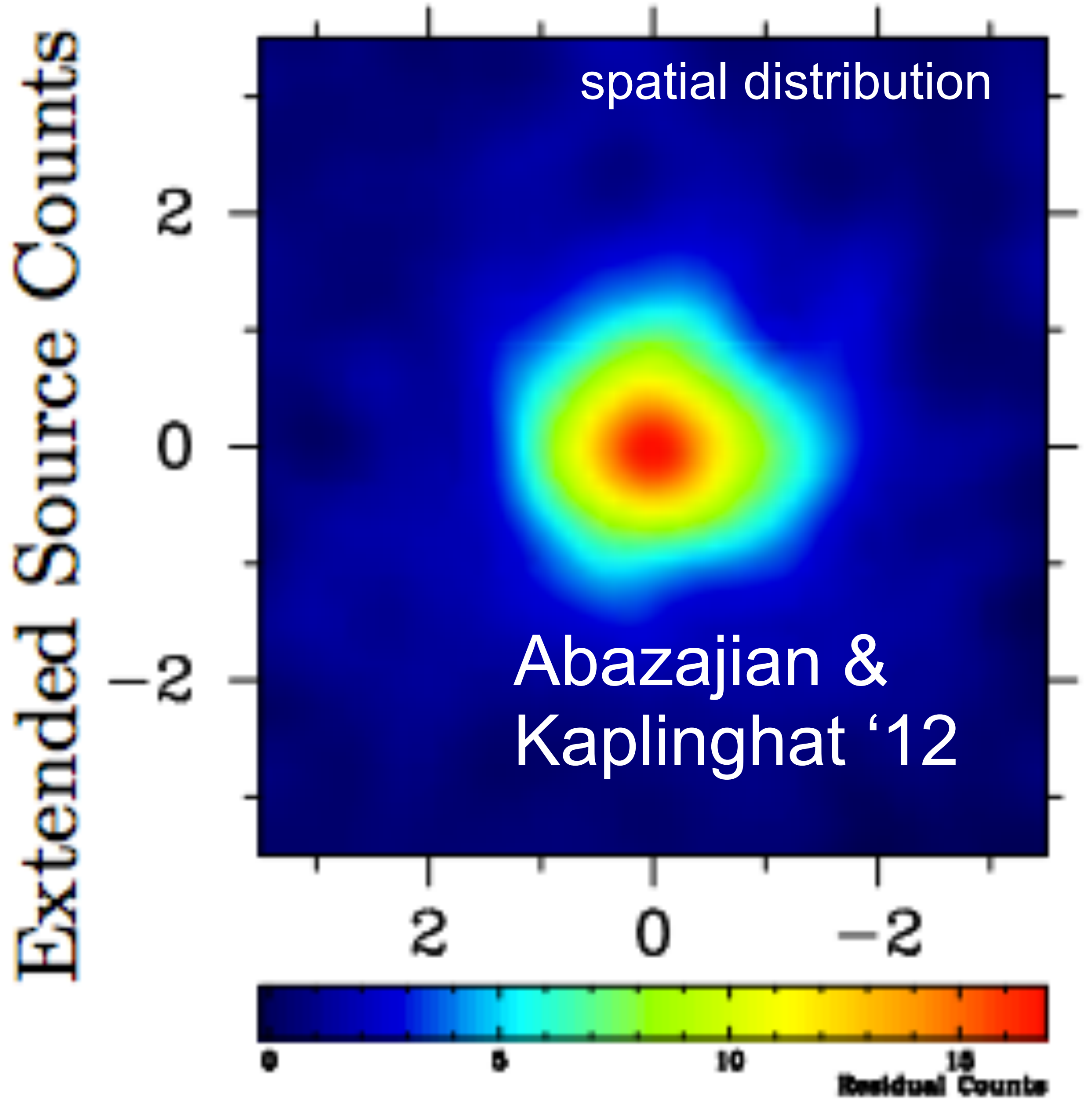
- One that has gotten a lot of attention is the Galactic Center Excess (GCE), as a possible signal of DM annihilation.

  - Excess of gamma-ray photons, peak energy ~1-3 GeV, in the region within ~10 degrees of the Galactic Center

  - Discovered by Goodenough & Hooper '09, confirmed by Fermi Collaboration in analysis of Ajello et al '16 (and many other groups in interim).

  - Simplest DM explanation: thermal relic DM at a mass of O(10-100) GeV

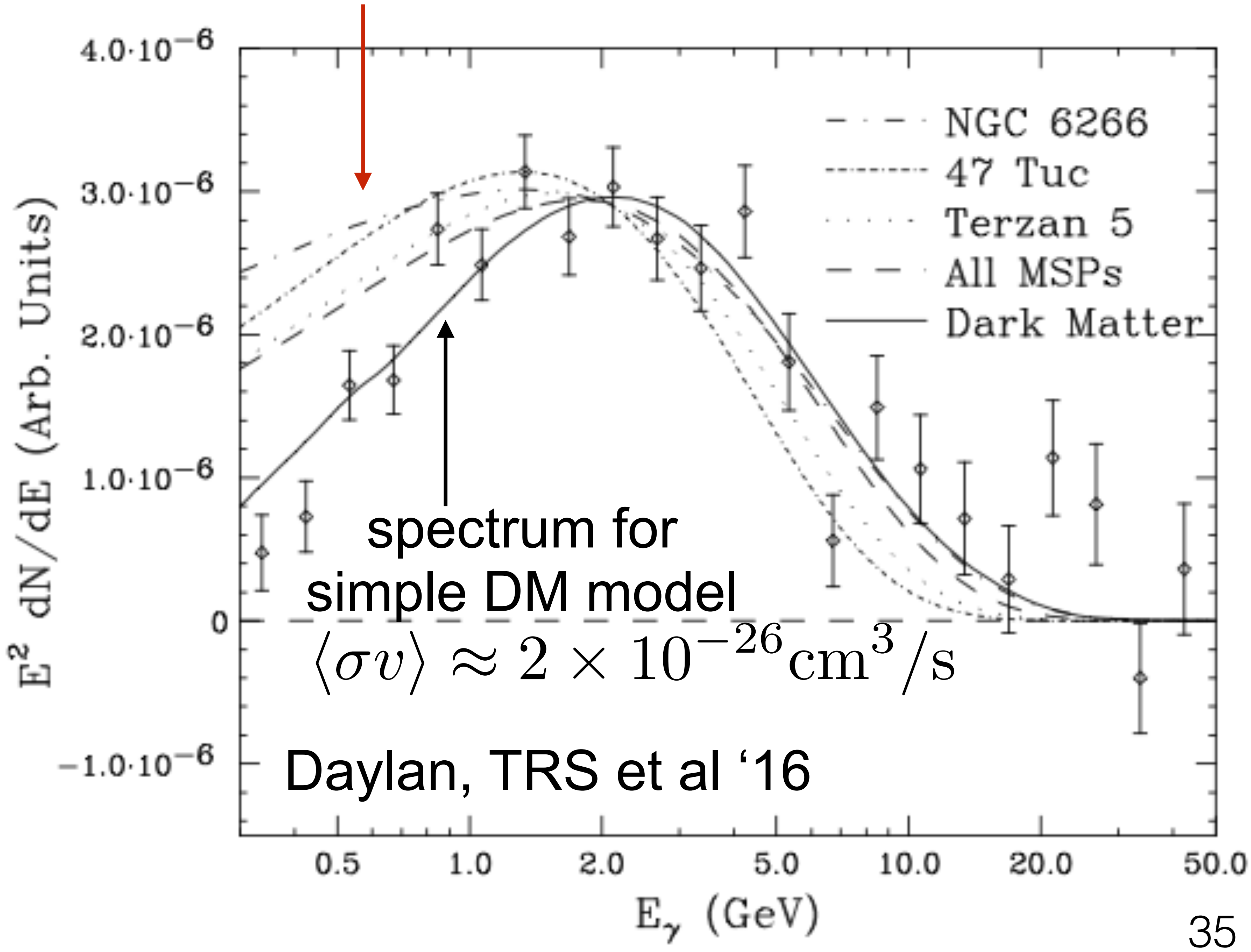
  - Leading non-DM explanation: population of pulsars (spinning neutron stars) below Fermi's point-source detection threshold



spatial distribution

Abazajian & Kaplinghat '12

observed spectra for pulsar populations



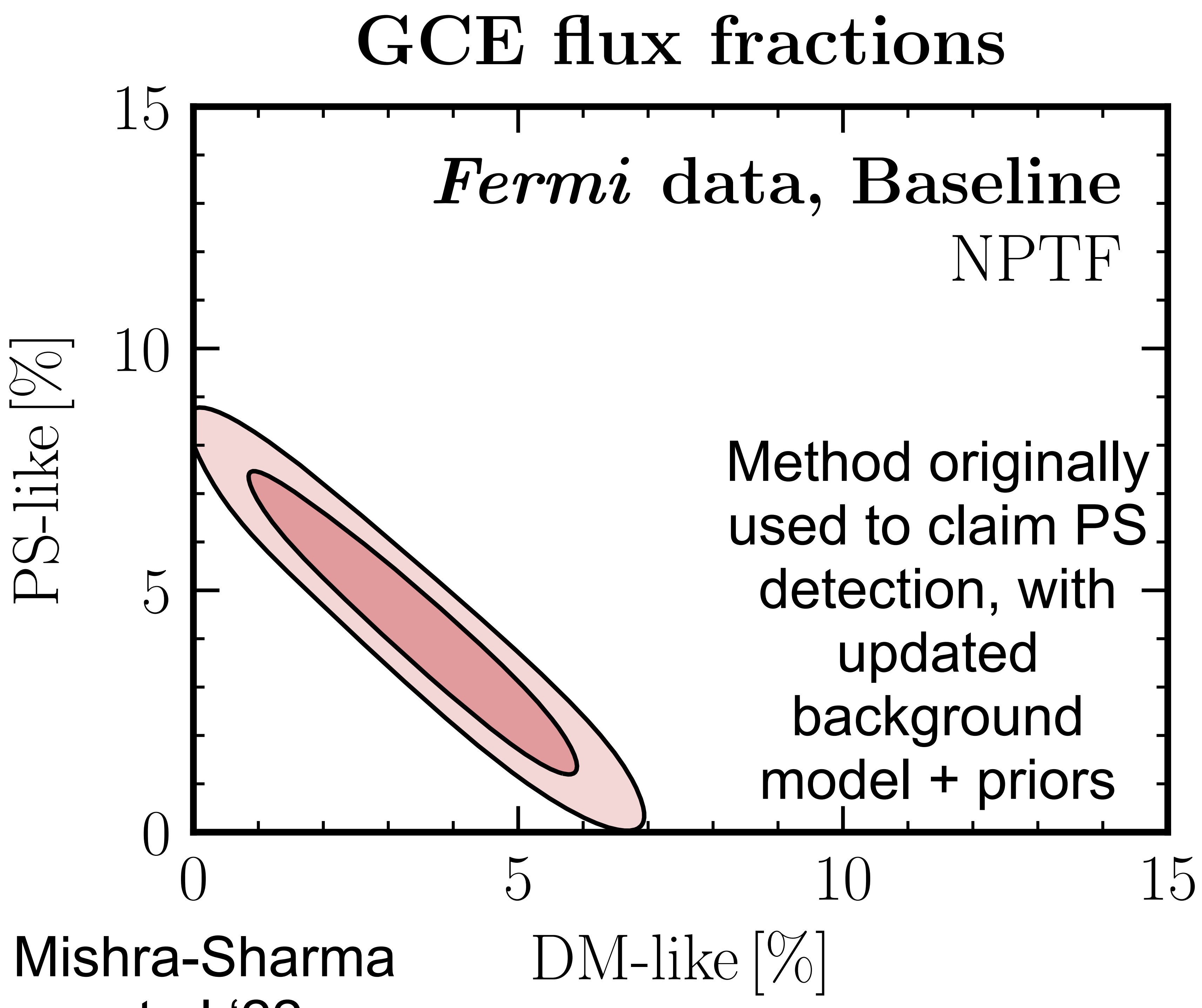
spectrum for simple DM model

$\langle \sigma v \rangle \approx 2 \times 10^{-26} \mathrm{cm}^3/\mathrm{s}$

Daylan, TRS et al '16

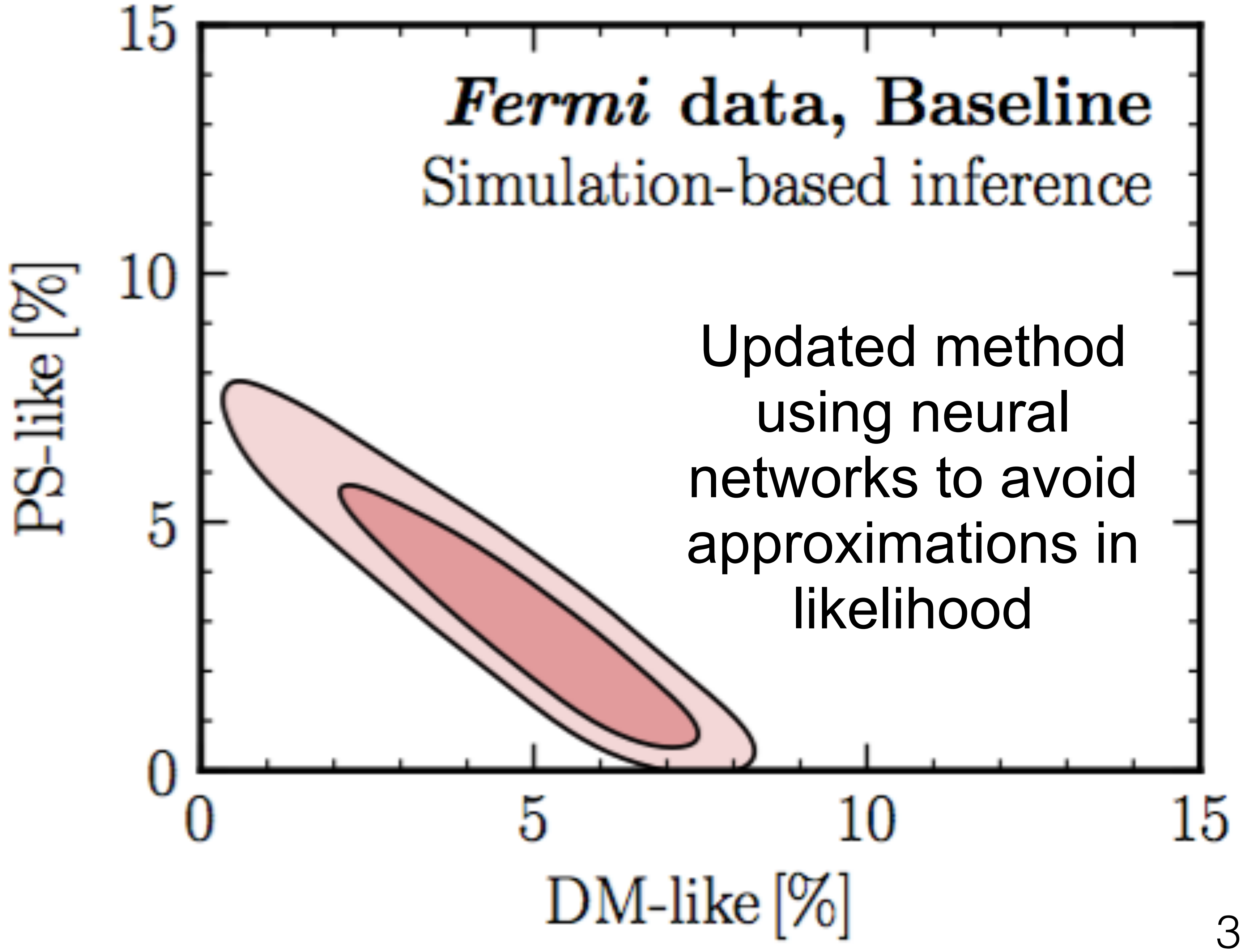
Is the GCE pulsars?

- Masking known point sources (4FGL) does not meaningfully impact the GCE [e.g. Zhong et al ’20]
- Could GCE be sourced by a new unresolved source population?
- Looking for point sources: wavelet transform, template fitting with modified likelihood to capture point source populations (non-Poissonian template fitting = NPTF)
- Earlier apparent evidence [Lee et al ’16, Bartels et al '16] that we had actually detected GCE sources in gamma rays was exaggerated by a systematic bias [Leane & TRS ’19, ’20; Buschmann et al ’20] or confusion with non-GCE sources [Zhong et al ’20].
- Methods that detect unresolved sources in this region [e.g. Calore et al ’21] do not necessarily answer whether they are GCE-associated.
- Recent studies using simulation-based inference to try to identify a GCE source population see a hint of a PS contribution, but significance is not high
  - List et al ‘20, ‘21 (neural-network-based histogram regression): GCE <66% diffuse at 95% confidence
  - Mishra-Sharma & Cranmer ‘21 (normalizing flows): PS fraction of 38^{+9}_{-19}%.



Method originally used to claim PS detection, with updated background model + priors

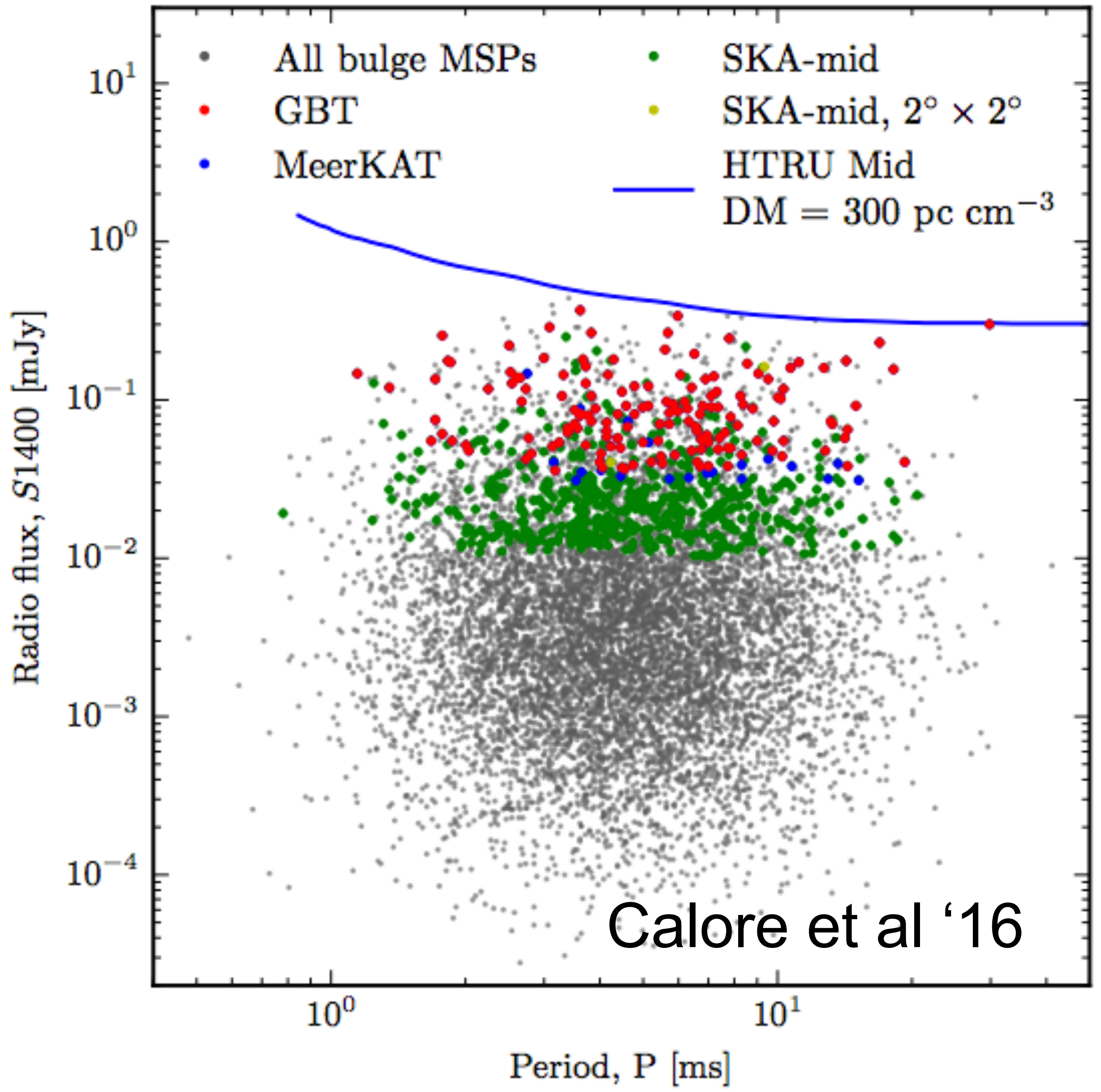
Mishra-Sharma et al ‘22



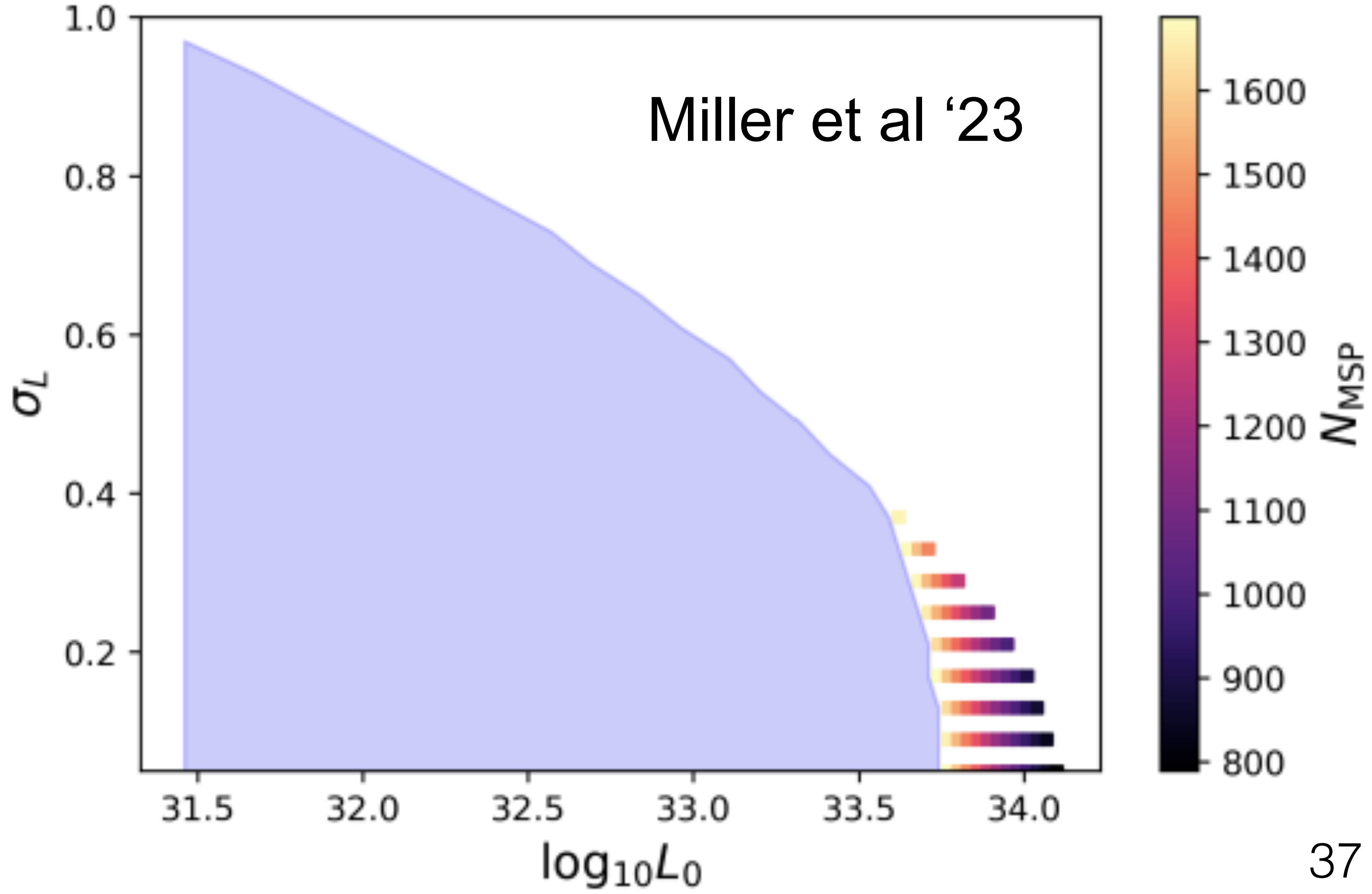
Updated method using neural networks to avoid approximations in likelihood

Could the GCE be pulsars?

- In my view pulsars are a perfectly viable hypothesis but not yet confirmed - the data do not rule out a smooth/diffuse signal
- There are simple pulsar luminosity functions (motivated by data and/or modeling) that would match the GCE with O(10^{4-5}) total sources and very few detected high-significance sources [Dinsmore & TRS '22]
- Typically pulsars also emit in radio and X-ray (better angular resolution + more counts)
  - In radio, MeerKAT telescope could see 10s of pulsars from this population, SKA hundreds [Calore et al '16] - currently taking/analyzing data
  - Berteaud et al '21 identifies X-ray sources for multiwavelength followup using Chandra data.
  - Possible high-energy counterpart from TeV halos around pulsars [Keith et al '23]
- Pulsar population could also produce GW signal [Calore et al '19, Miller et al '23] - most sensitive to case with many faint pulsars, complementary to searches with light.



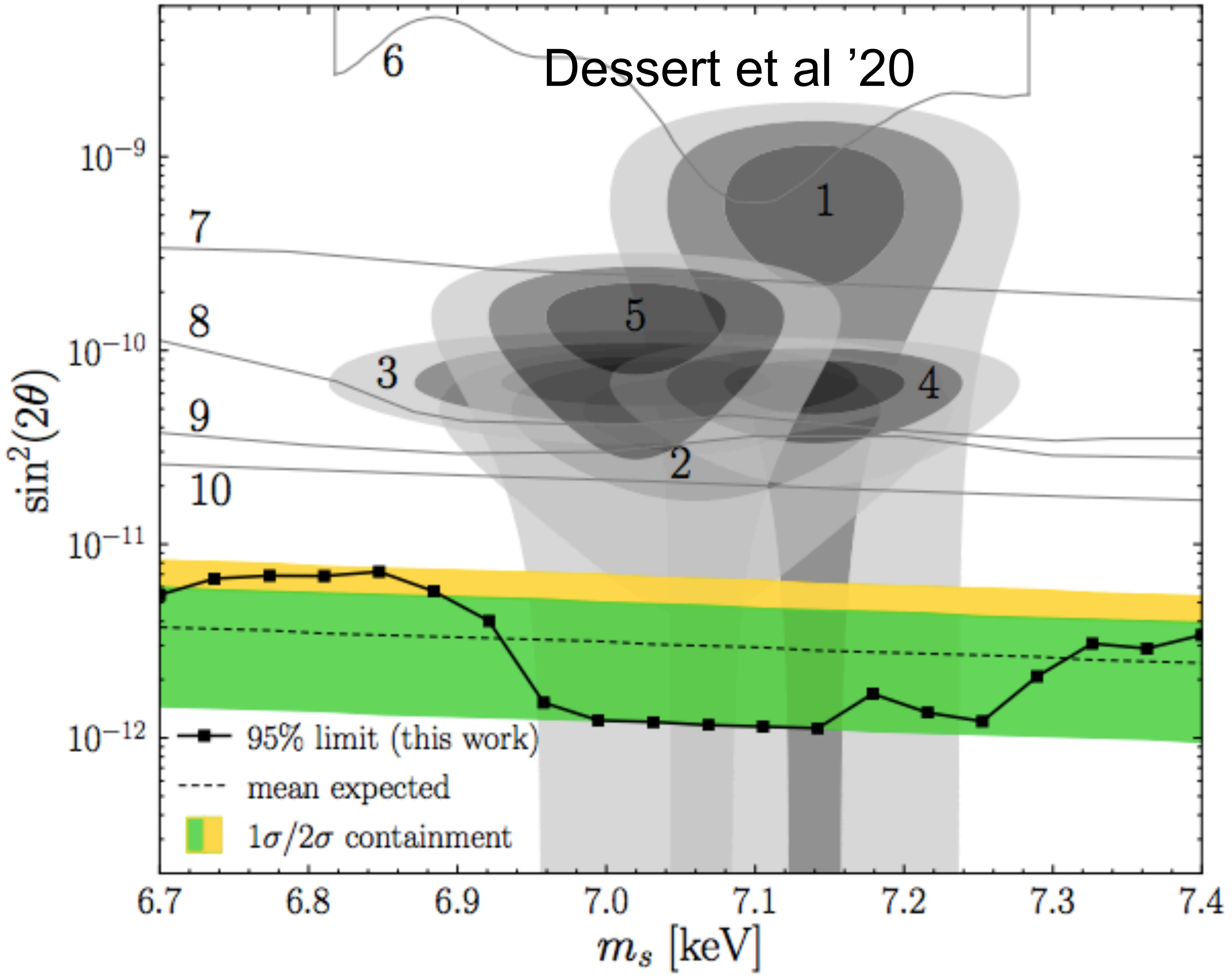
Calore et al '16

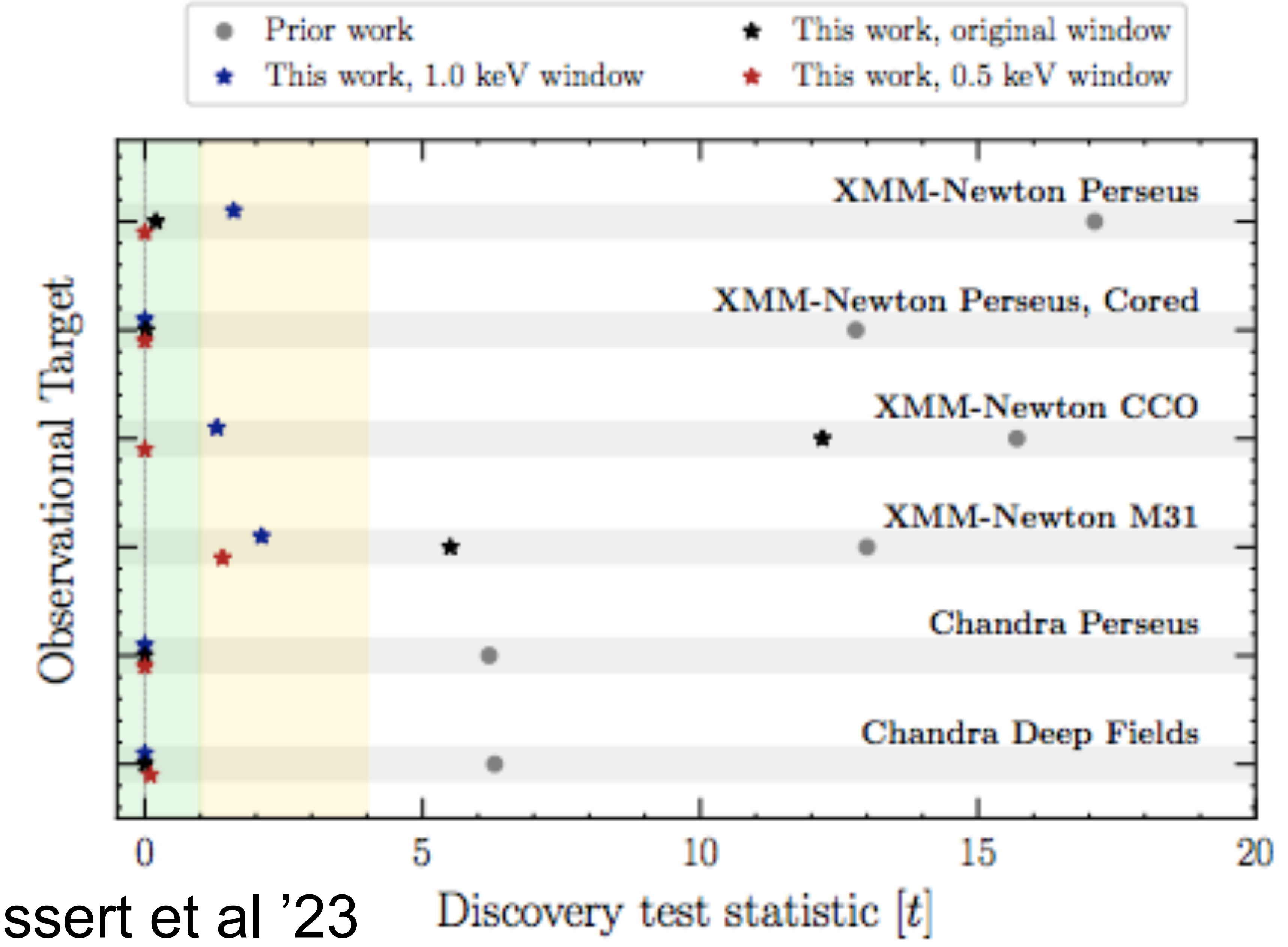


Miller et al '23

The 3.5 keV line

- Claims of observations originally in stacked galaxy clusters [Bulbul et al ’14, Boyarsky et al ’14], subsequently in other regions. Individual claimed signals are modestly significant (~4σ).
- Simplest DM explanation: 7 keV sterile neutrino decaying into neutrino+photon. (Other explanations involving annihilation, oscillations etc are possible.) In tension with null results in other searches (e.g. Dessert et al '20).
- Possible non-DM contributions: atomic lines (from K, Cl, Ar, possibly others), charge-exchange reactions between heavy nuclei and neutral gas [e.g. Shah et al ’16].
- However, recent analysis claims the signals are not present at the claimed level of significance - suggests original claims may be due to a failure to find the correct likelihood maximum [Dessert et al 2309.03254]
- Future X-ray experiments (eXTP, XRISM, Micro-X, possibly eROSITA) should have the sensitivity to see the signal if it exists; XRISM could possibly resolve the linewidth





Dessert et al ’23