Where Next in the Search for Dark Matter?

Tracy Slatyer

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U.S. DEPARTMENT OF ENERGY | Office of Science

What is dark matter?

We know it:

Credit: NASA/CXC/M.Weiss

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  Matter = has mass, gravitates, cosmologically behaves like pressureless dust

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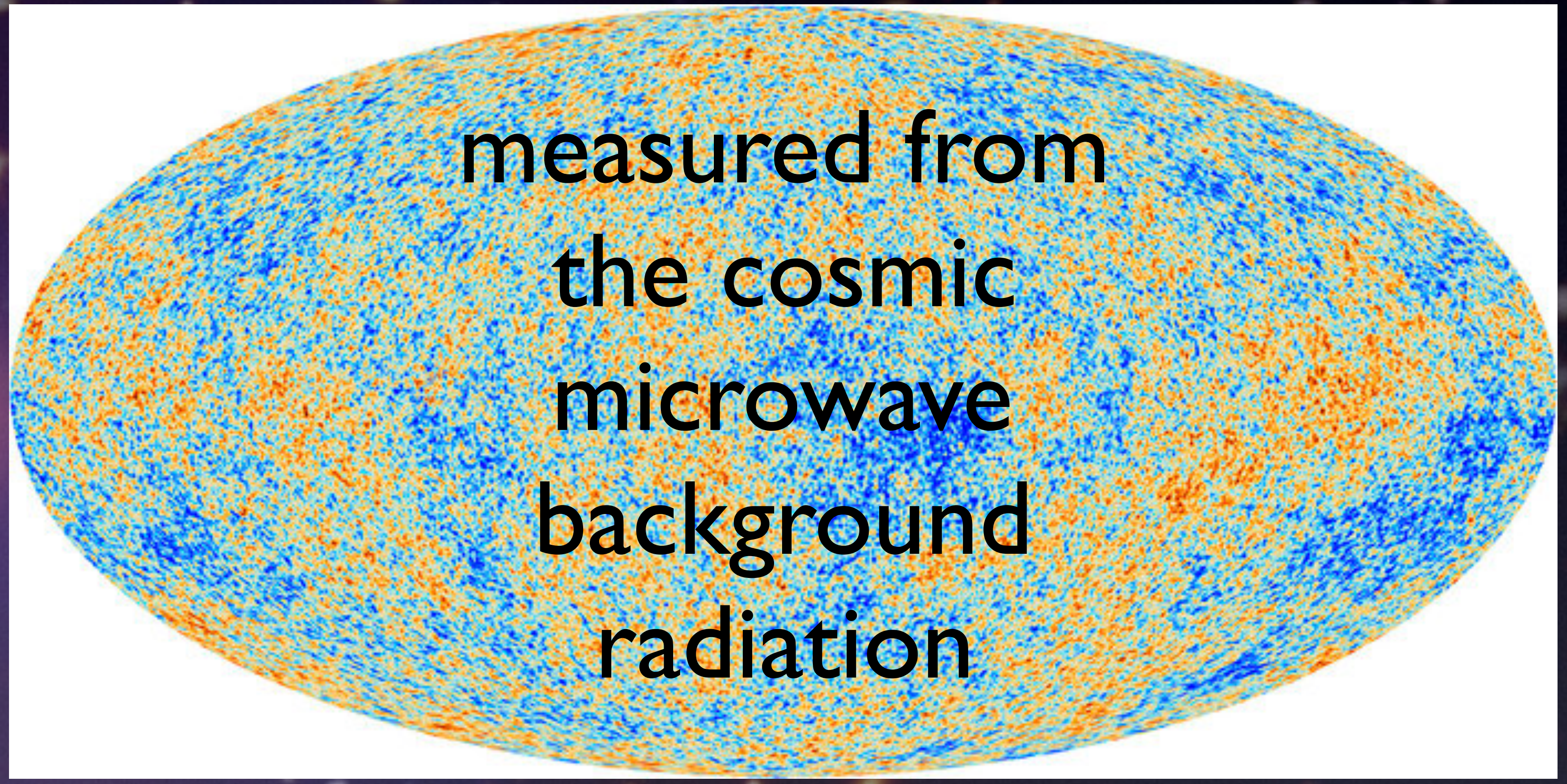

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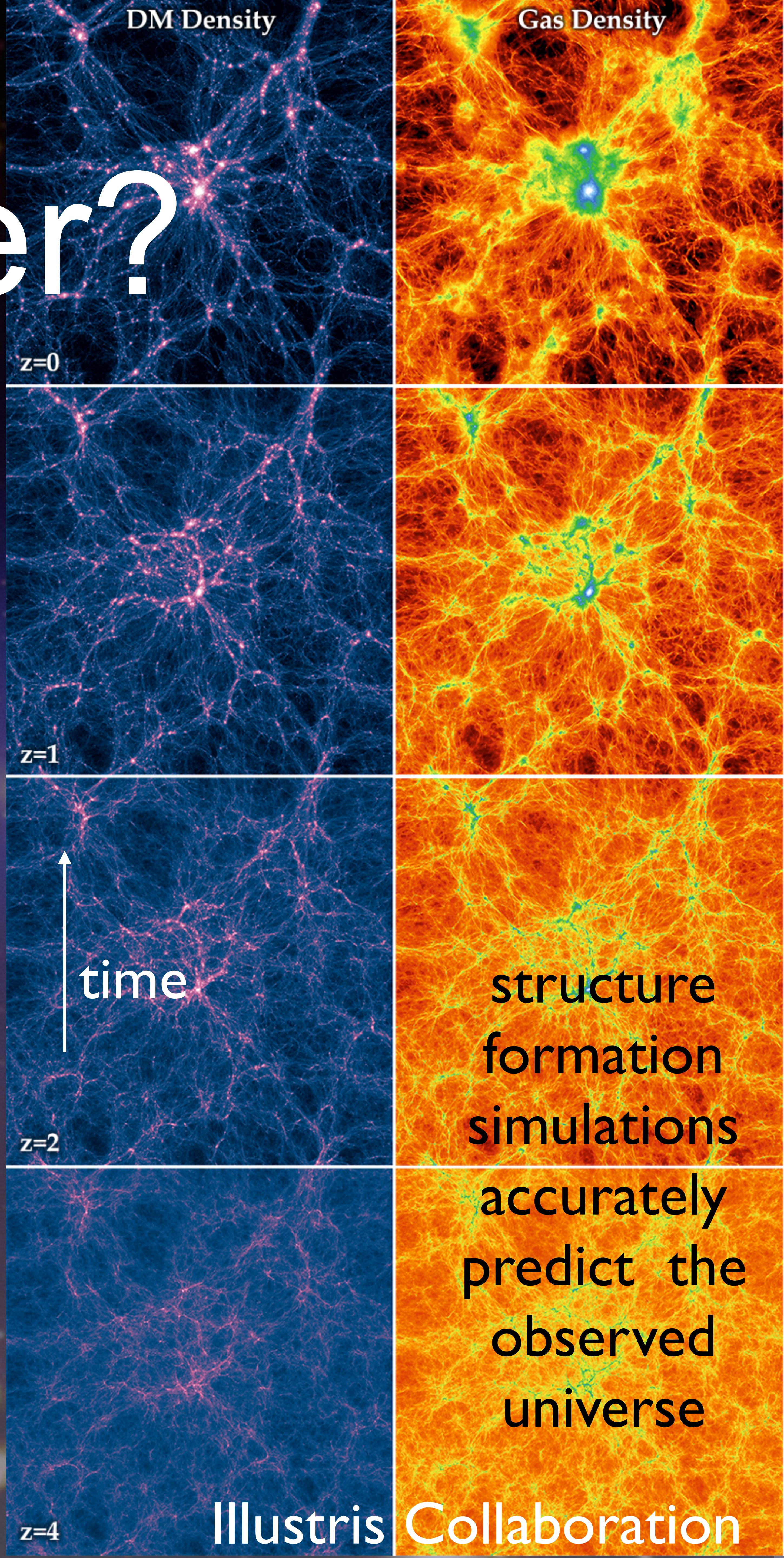

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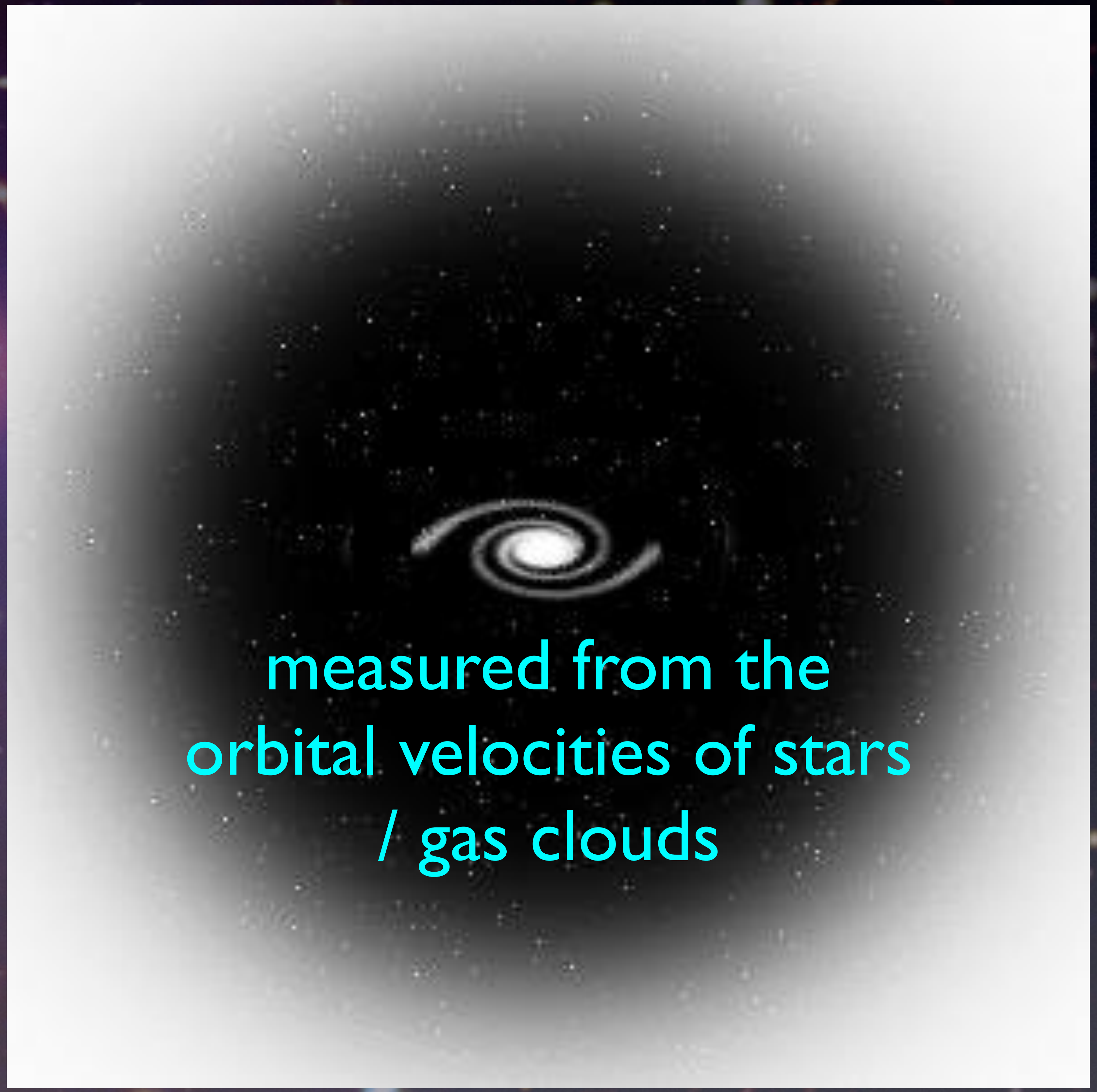

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- Interacts with other particles weakly or not at all (except by gravity). null results of existing searches

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Open questions:

- WHAT IS IT?

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What is dark matter?

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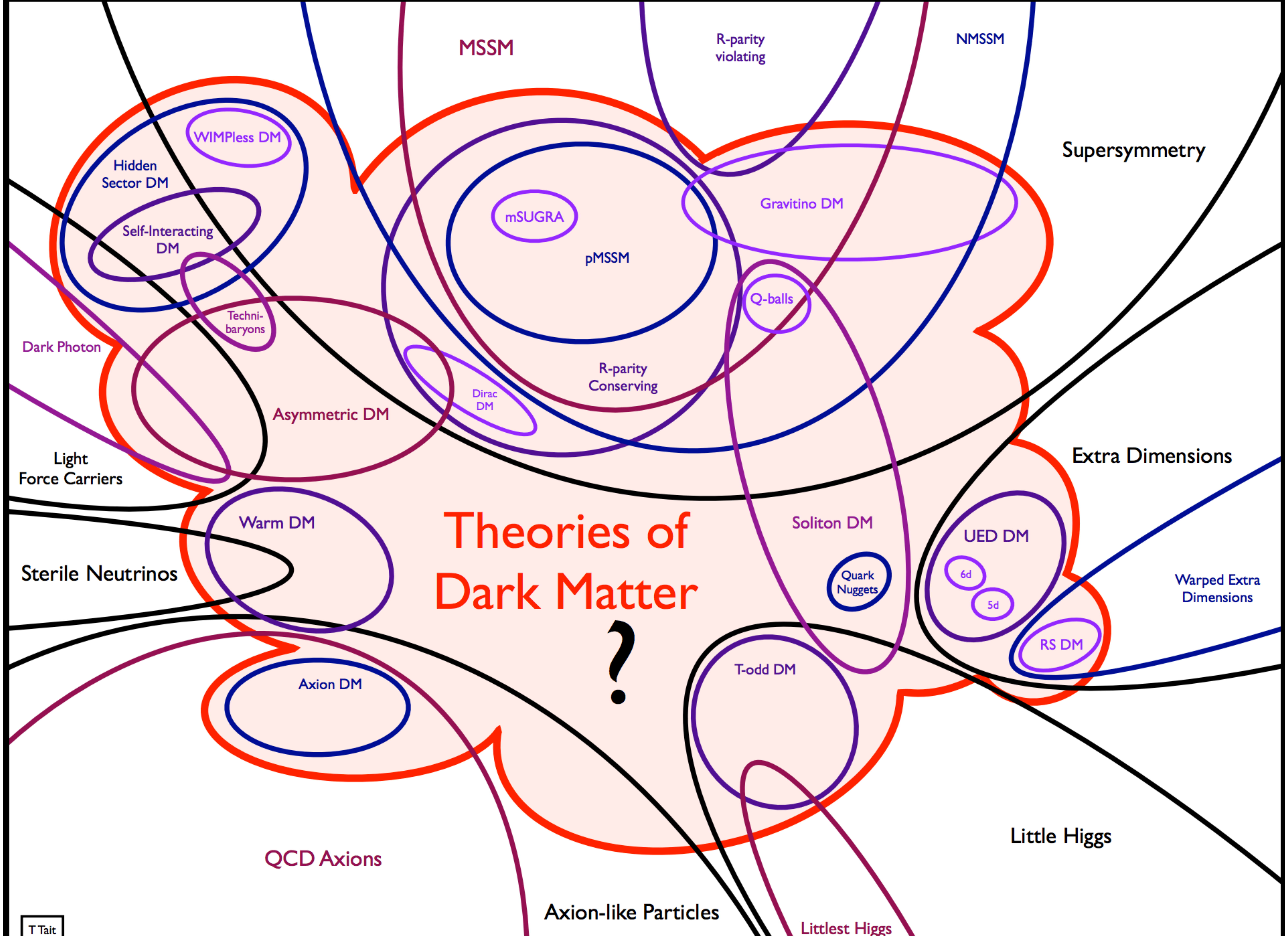
- Within the Standard Model, neutrinos are stable and neutral, but are too fast-moving to form structure as observed

Open questions:

- What it's made from.
- Is it one particle, or more than one, or not a particle (e.g. primordial black holes)?
- How it interacts with other particles.
- Whether it's absolutely stable, or decays slowly over time.
- Why its abundance is what it is.
- If/how it's connected to other deep problems in particle physics.
- And more…

Credit: NASA/CXC/M.Weiss



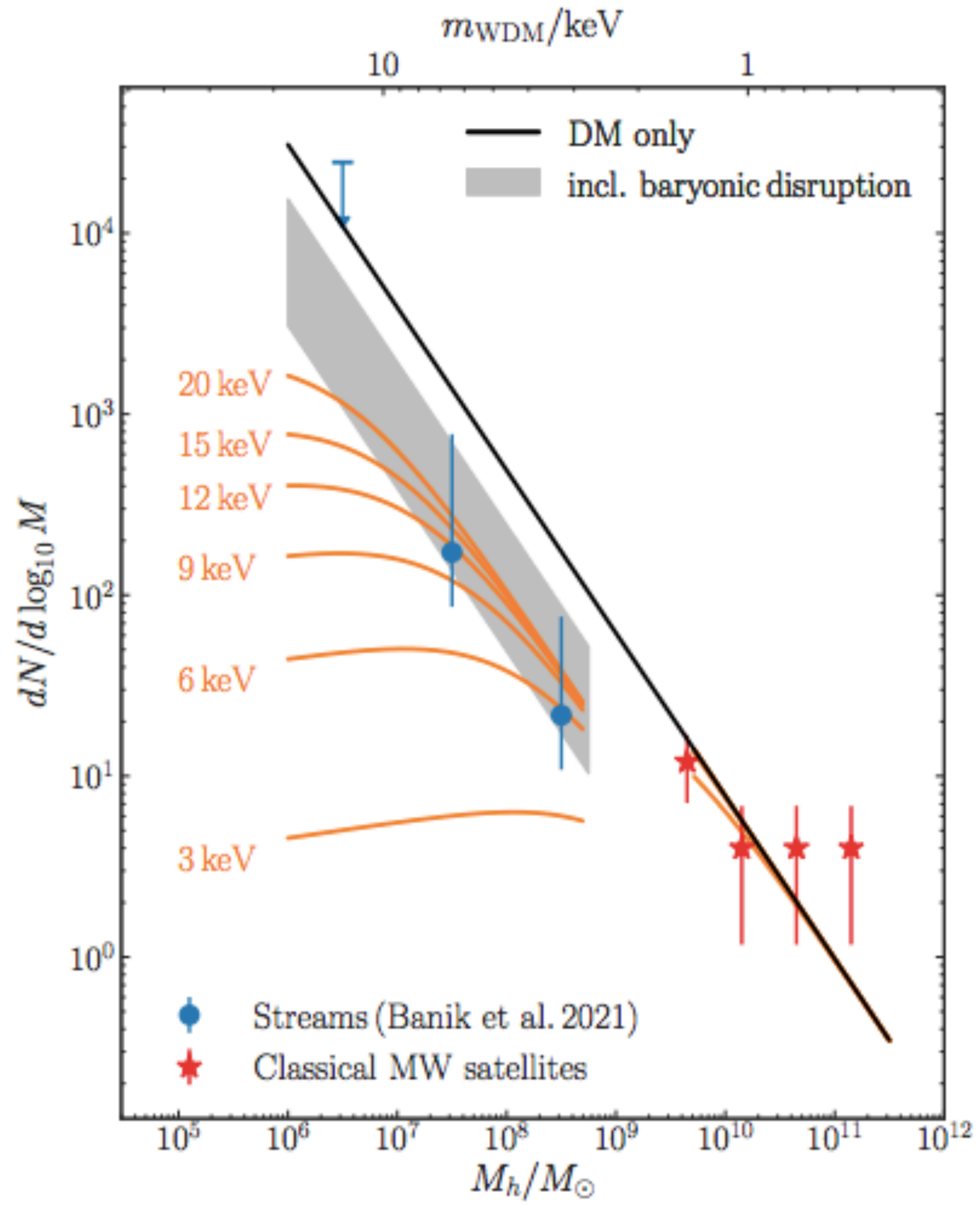
Taken from talk by Tim Tait, Snowmass July 2013

What more can we learn from purely gravitational probes of DM?

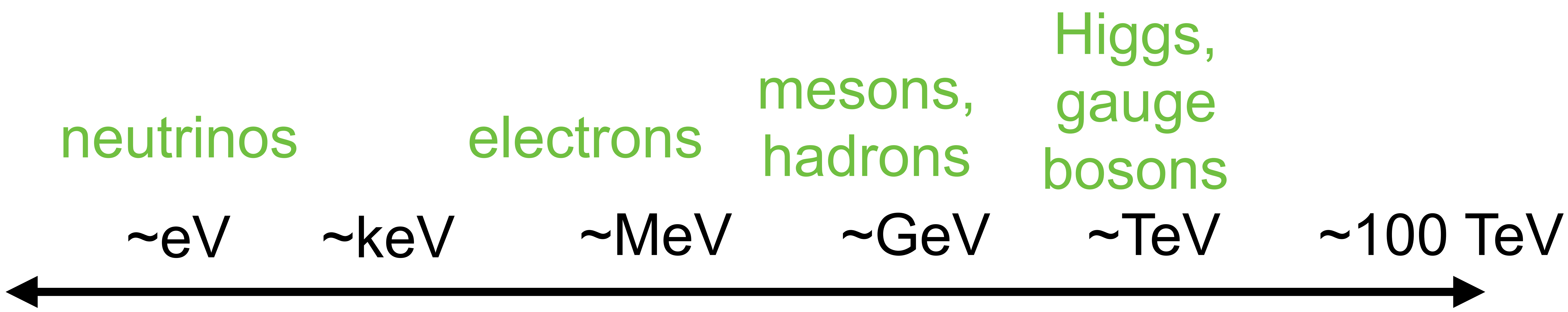
- Key idea: map how DM is distributed through the cosmos (in both space and time), via gravitational effects on stars/galaxies/gas clouds/etc, gravitational lensing, cosmic microwave background (CMB) radiation, etc

- One 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]

- 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 MW satellite galaxies [e.g. Nadler et al ’19, ’21]



What is the DM mass?



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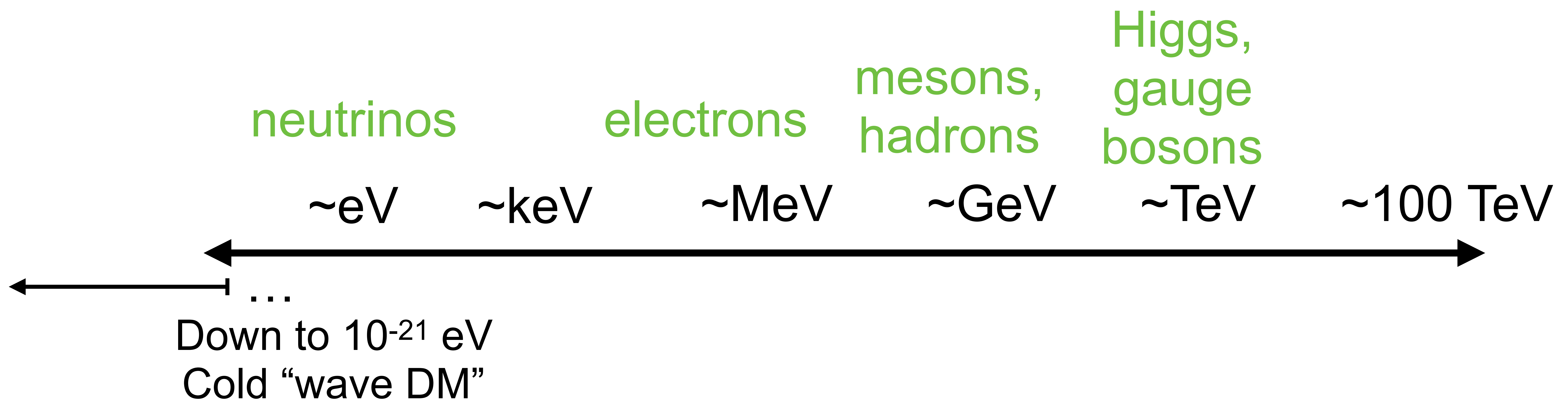

What is the DM mass?

neutrinos | electrons | mesons, hadrons | Higgs, gauge bosons

~eV ~keV ~MeV ~GeV ~TeV ~100 TeV

…

Down to 10^{-21} eV
Cold “wave DM”

bosonic (Tremaine-Gunn bound / Pauli exclusion)

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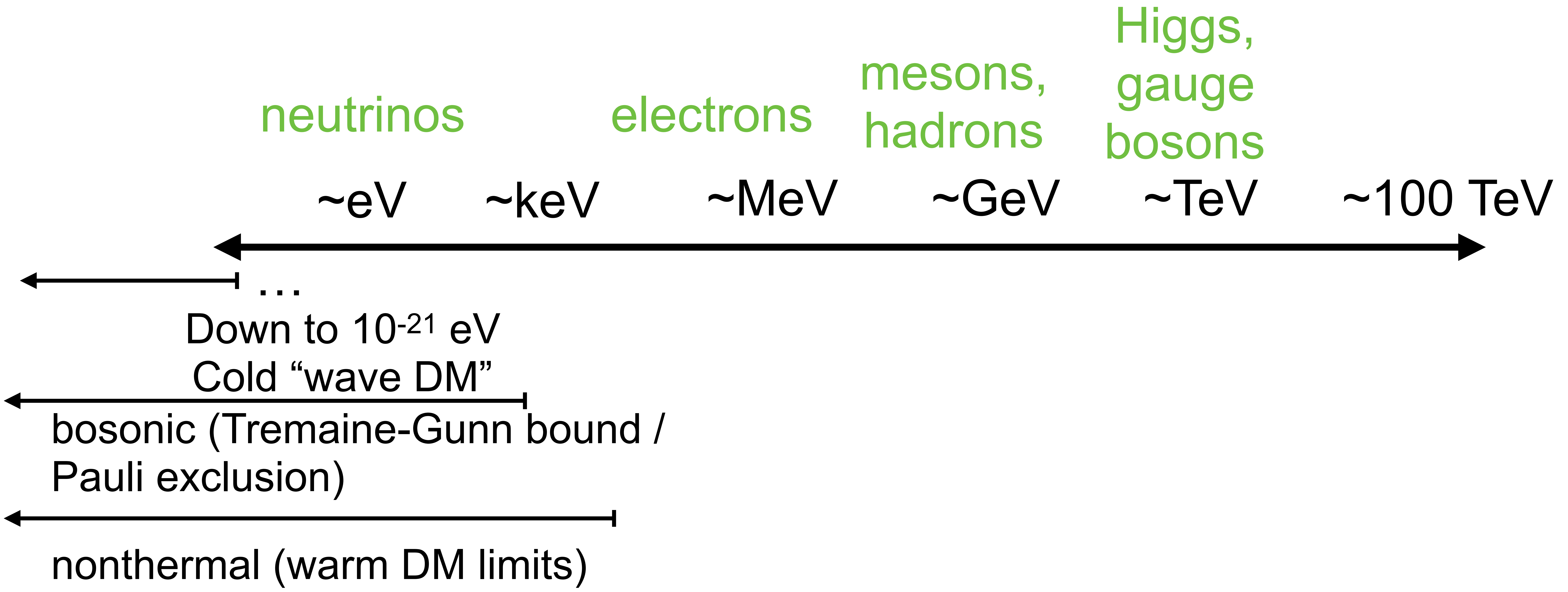

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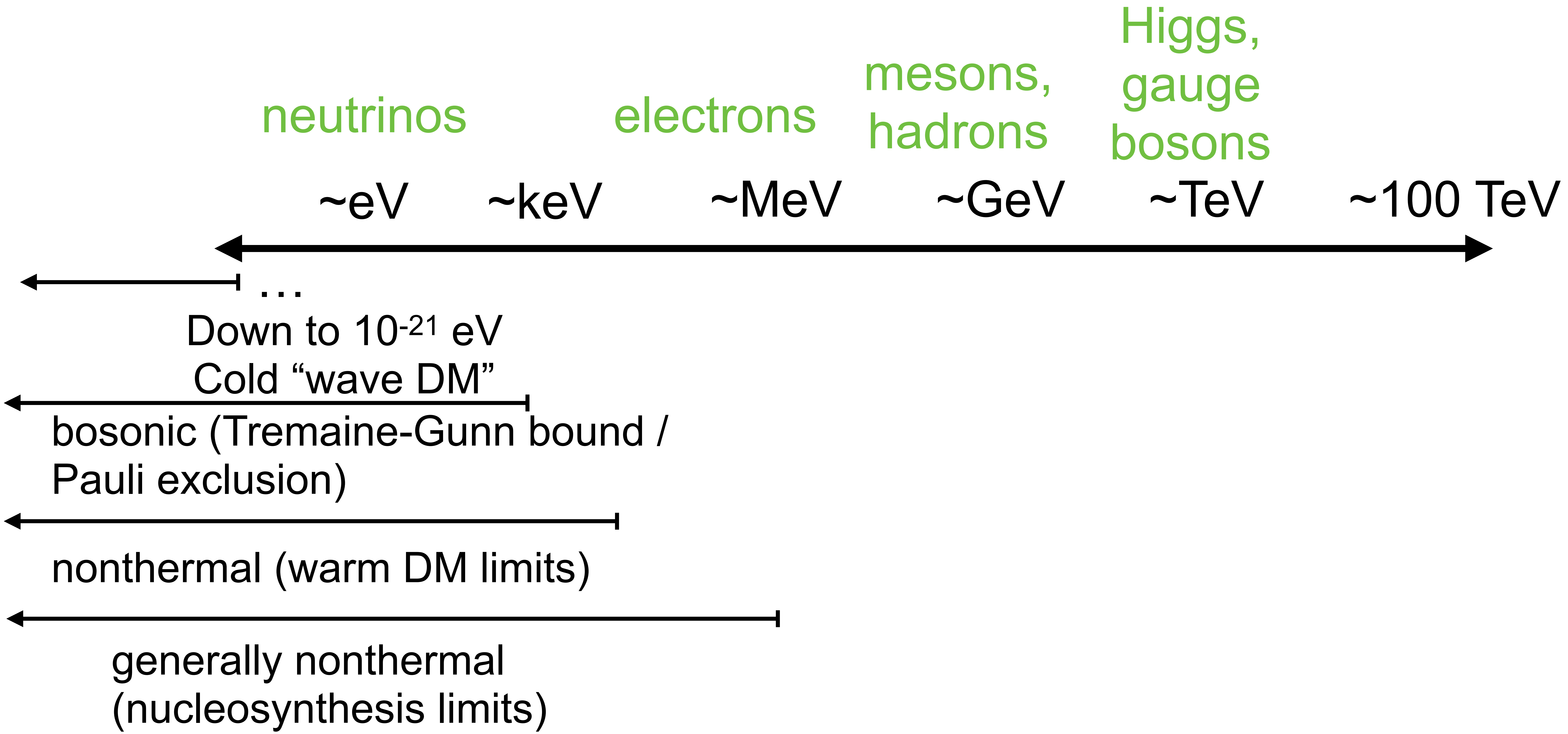

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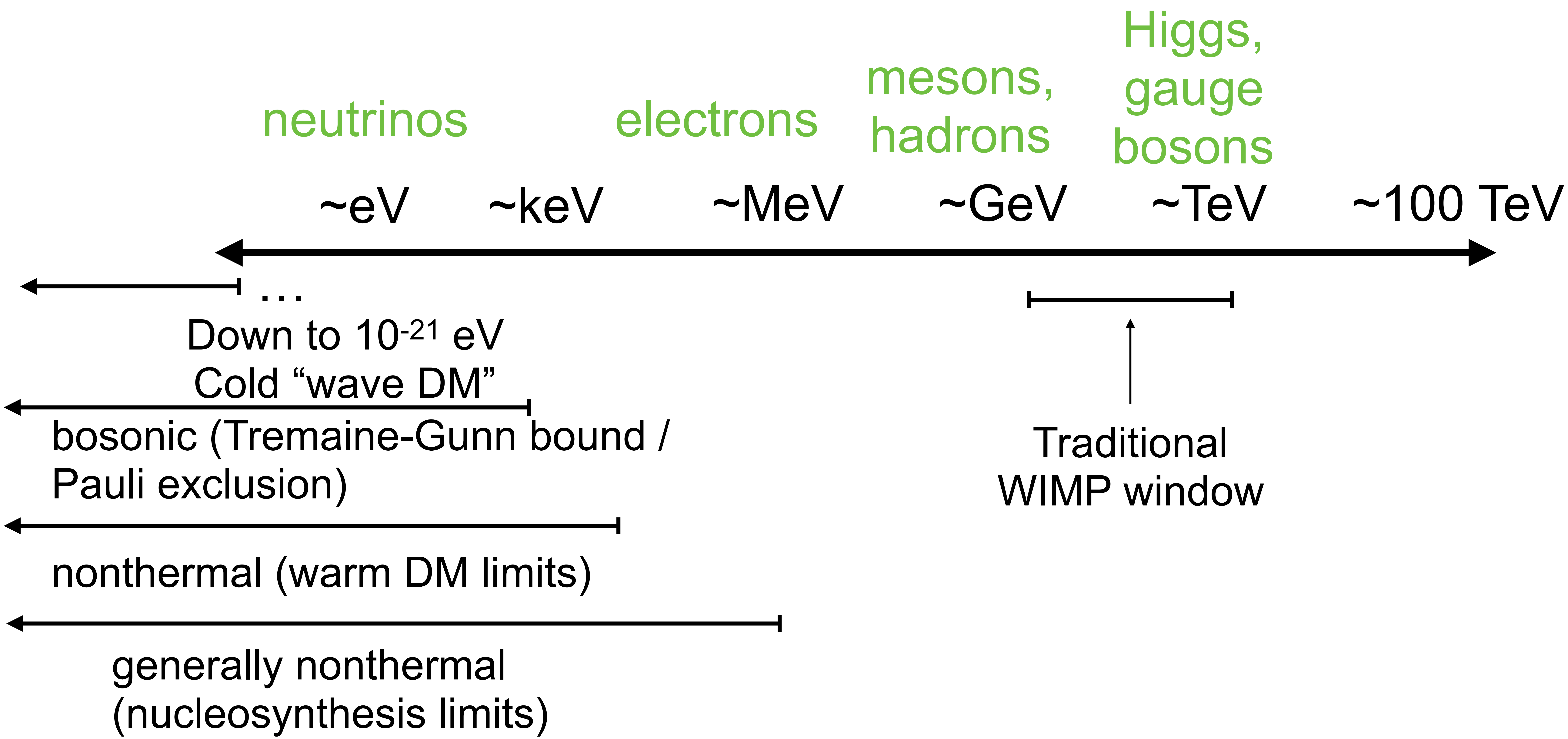

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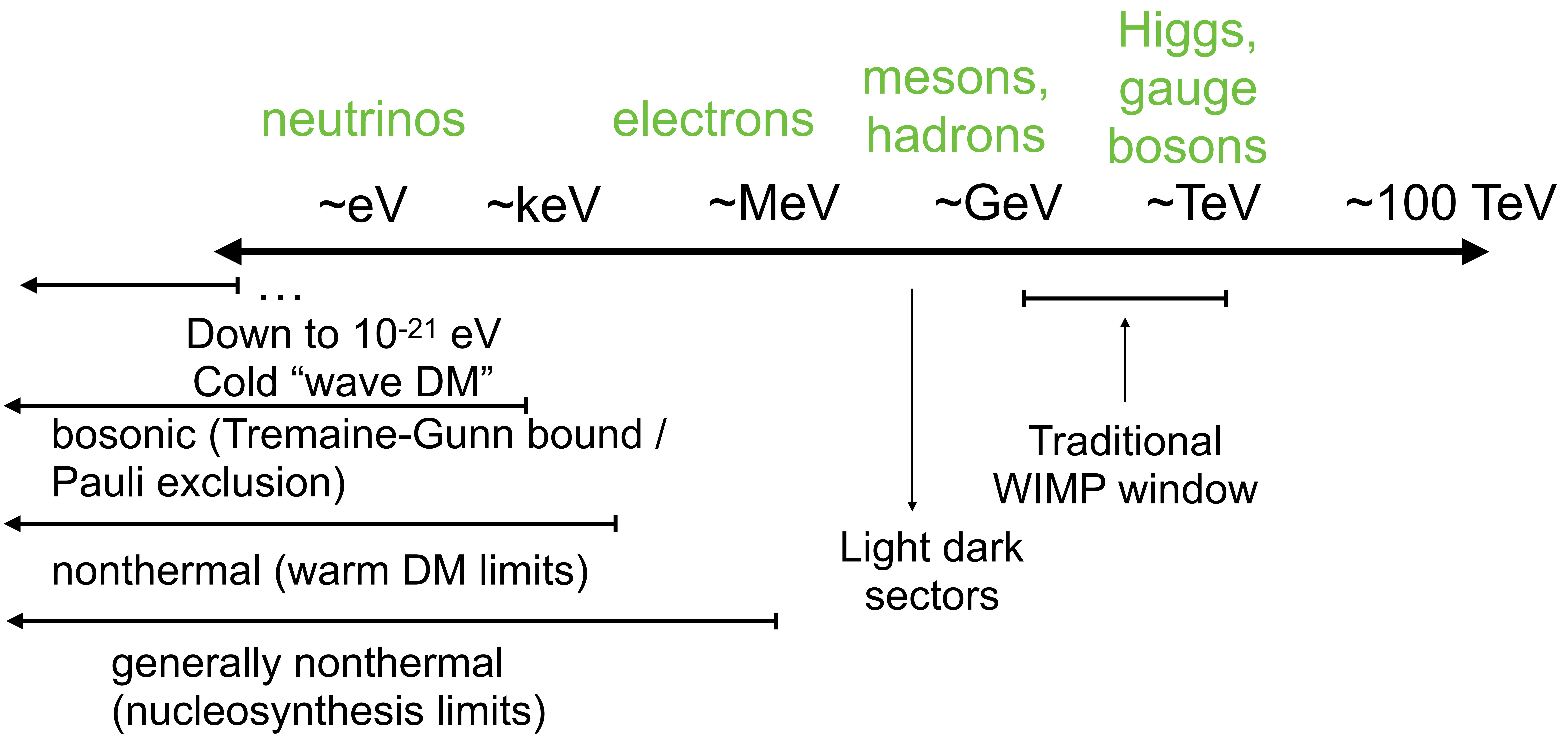

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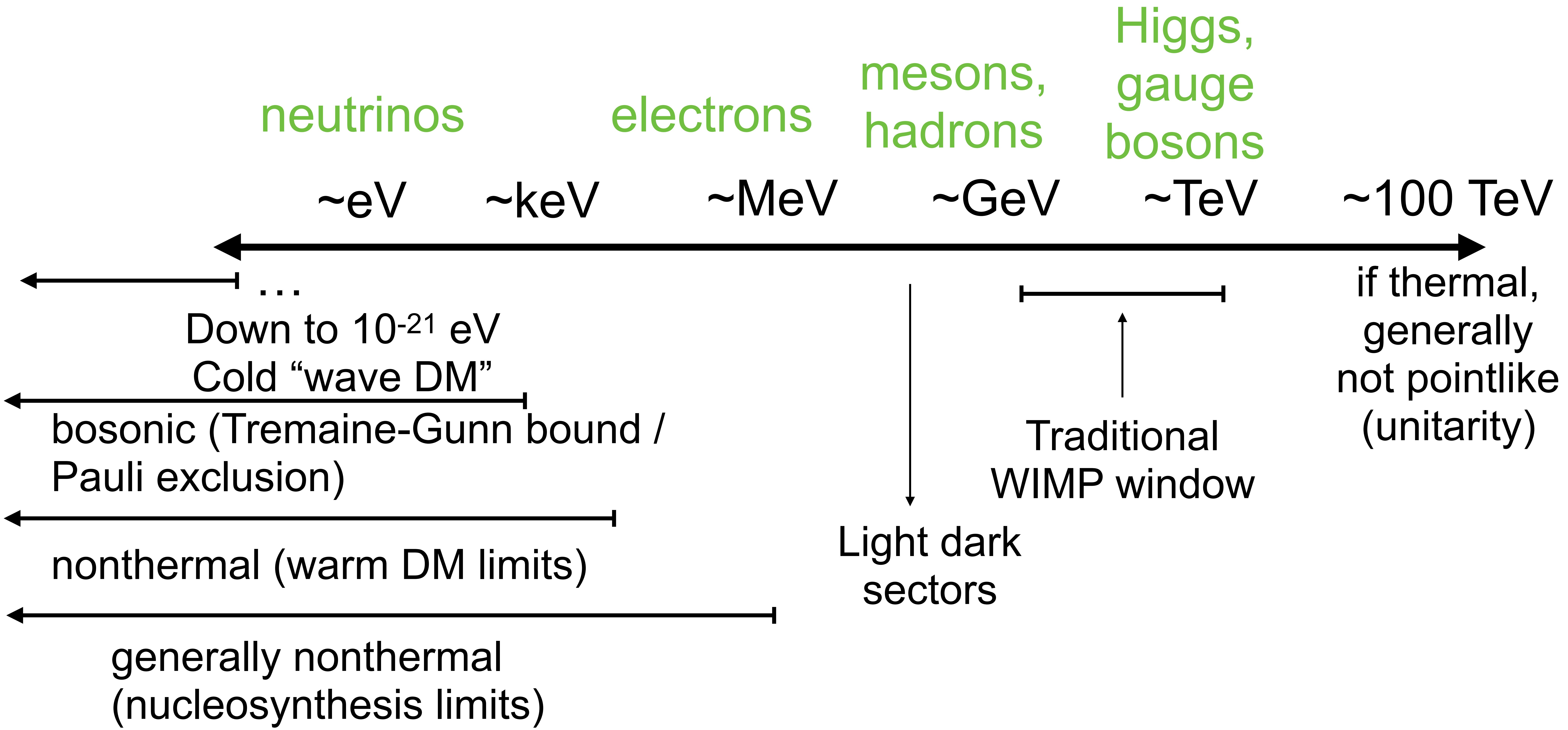

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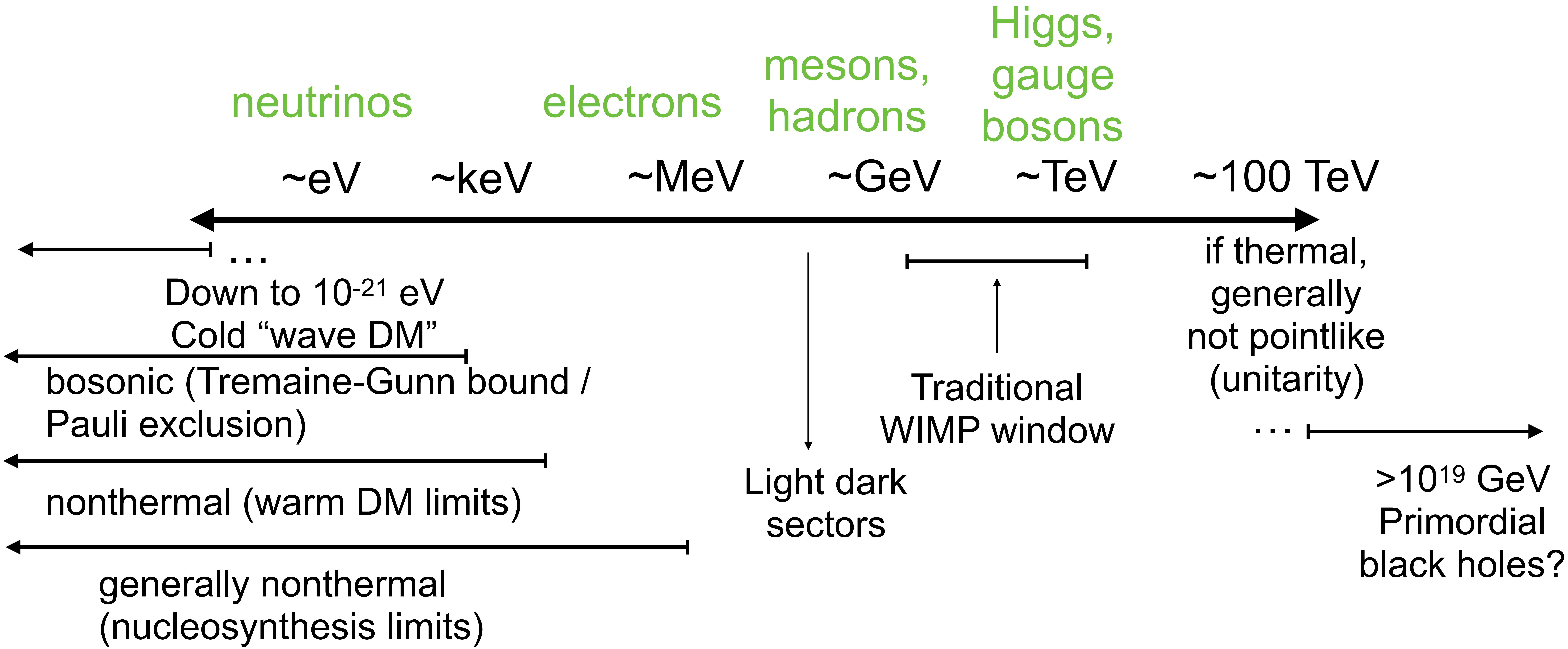
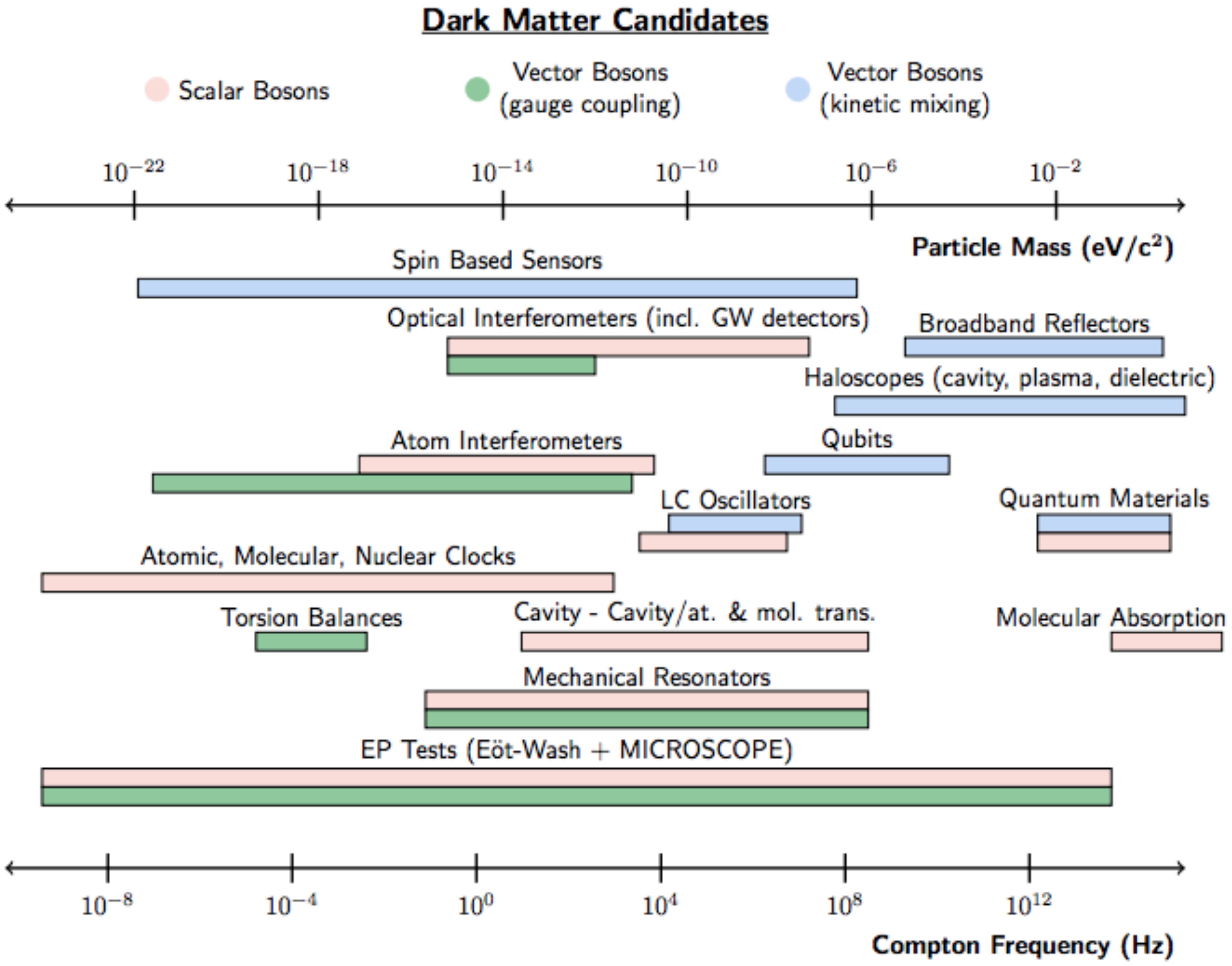


Ultralight/wave-like DM

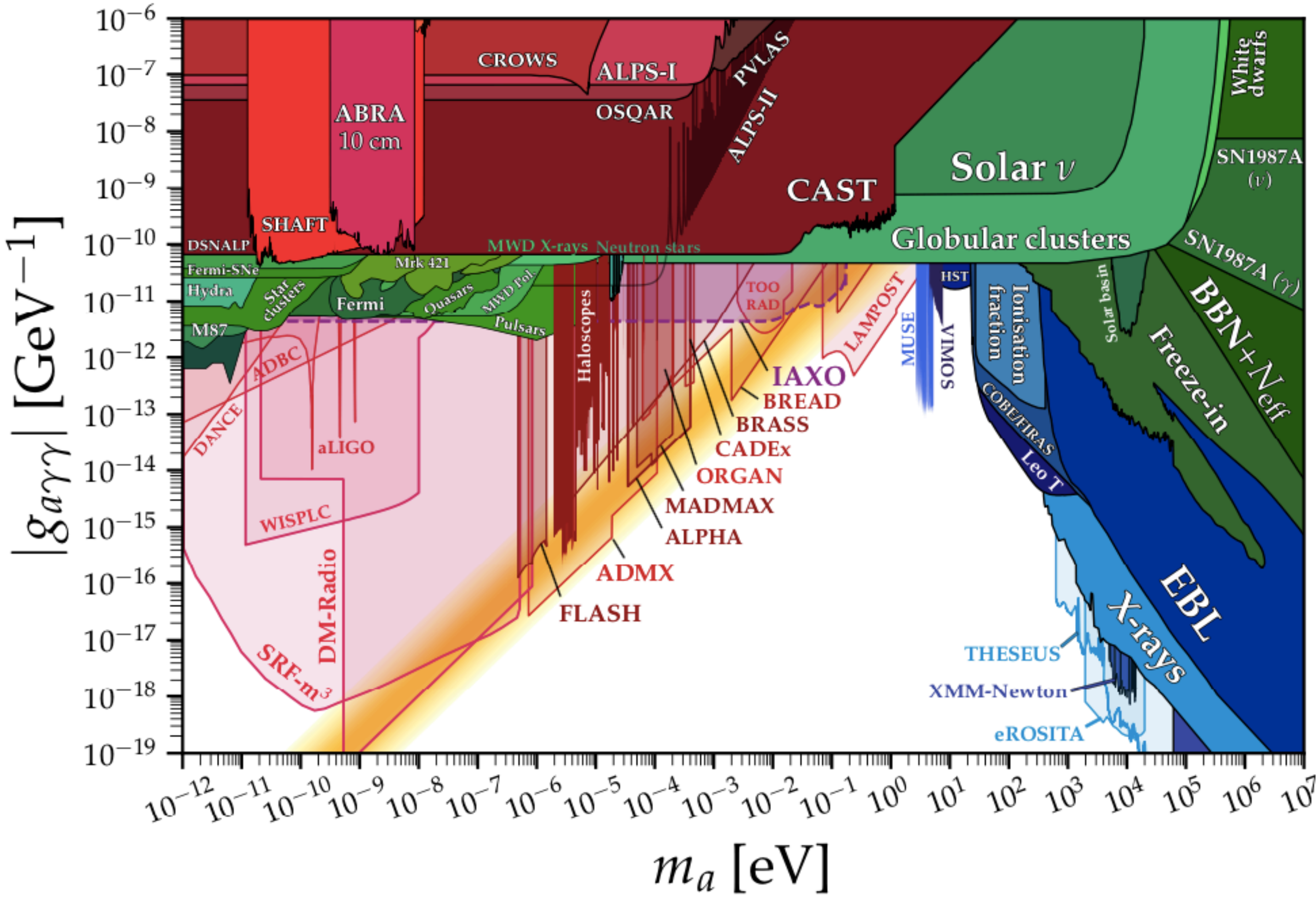
- For DM masses between 10^{-21} eV and ~1 keV, DM must be bosonic and avoid thermal contact with the Standard Model (= very weak interactions)
- At meV scales and below, wavelength is often macroscopic compared to terrestrial experiments
- Canonical example of DM in this range: QCD axion
- But DM could also be a new ultralight scalar/vector more generally - many ideas for tests for such particles



See Jaeckel et al '22 (Snowmass)
and references therein

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 (Sydney)
https://github.com/cajohare/AxionLimits

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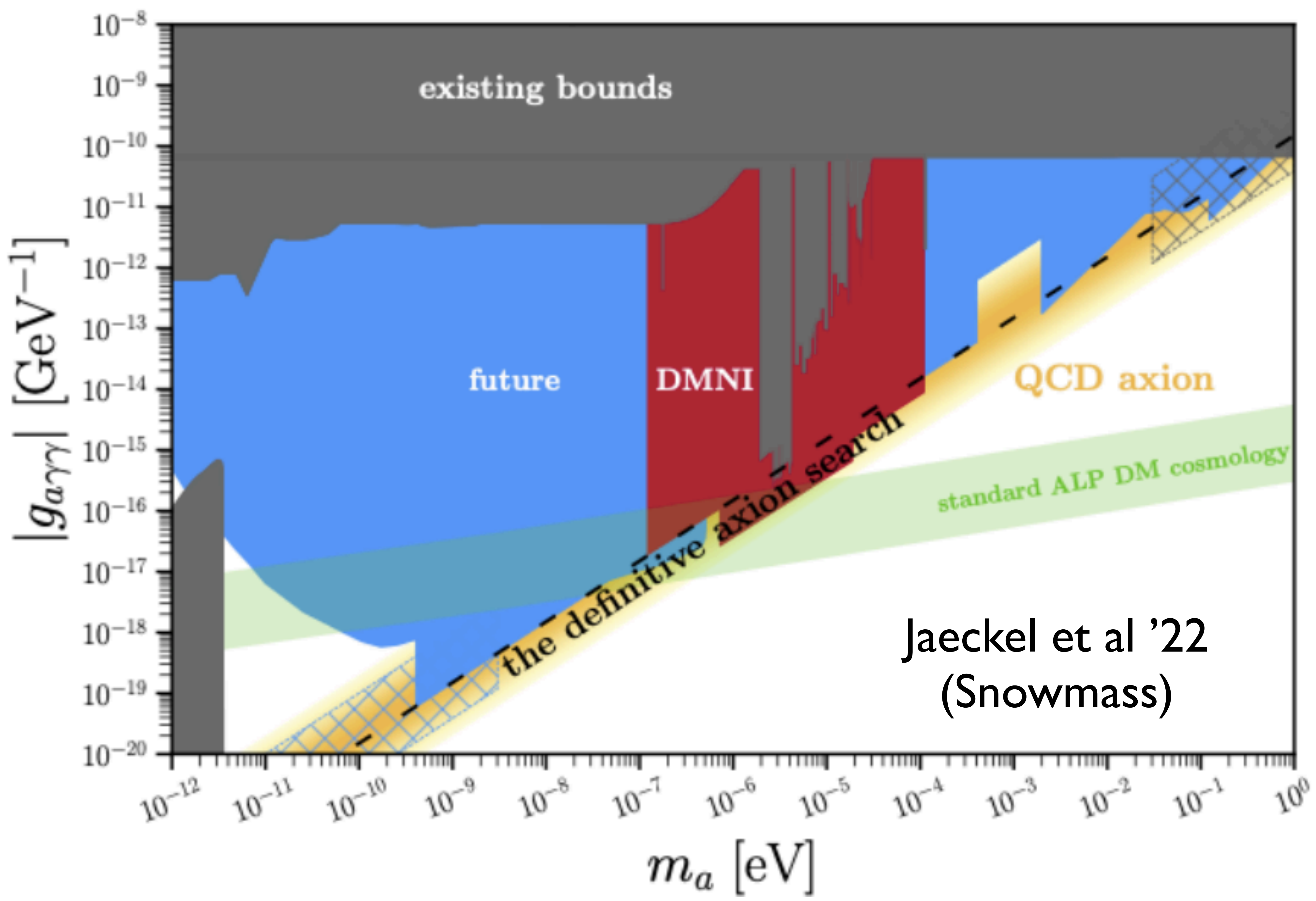
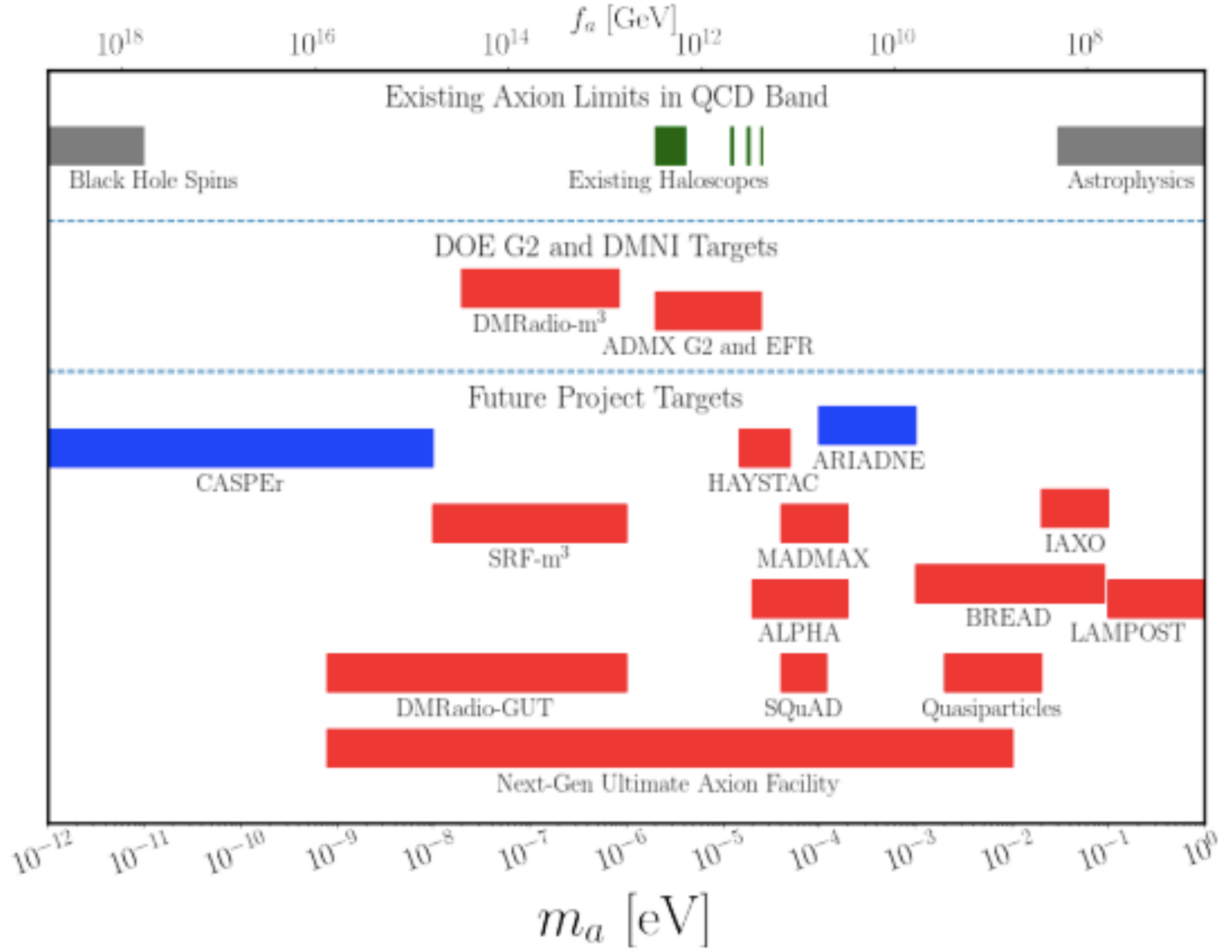
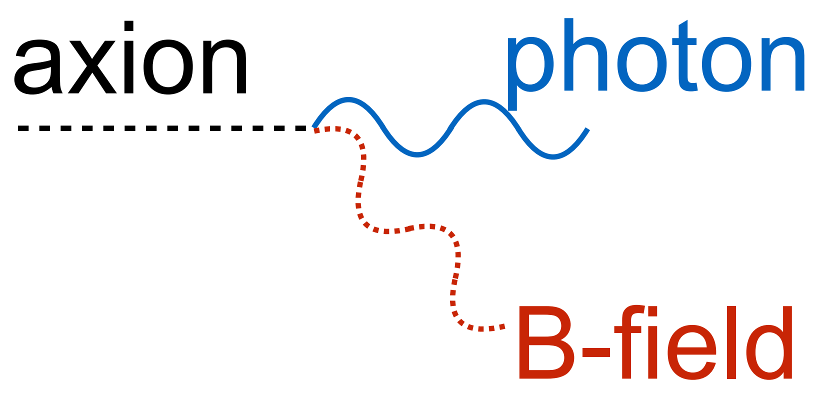
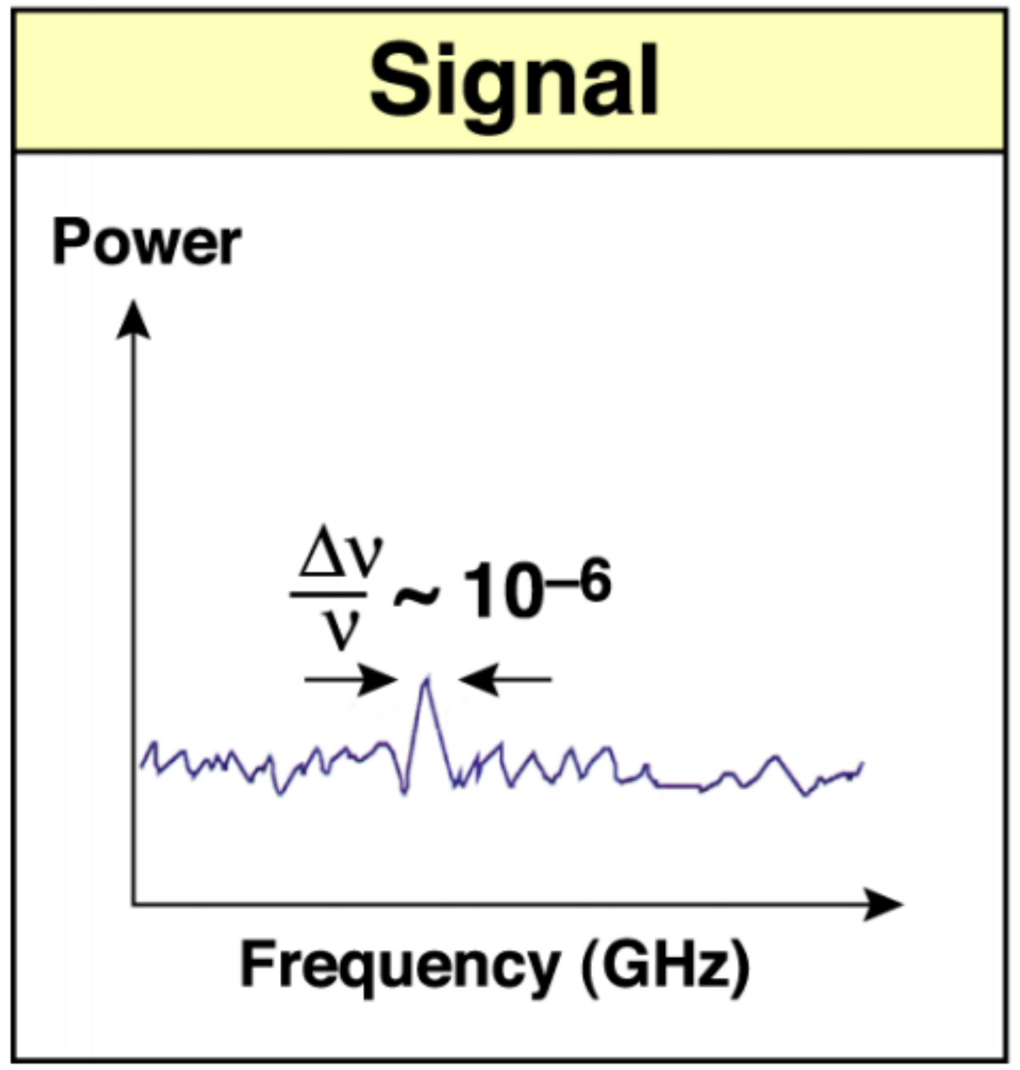


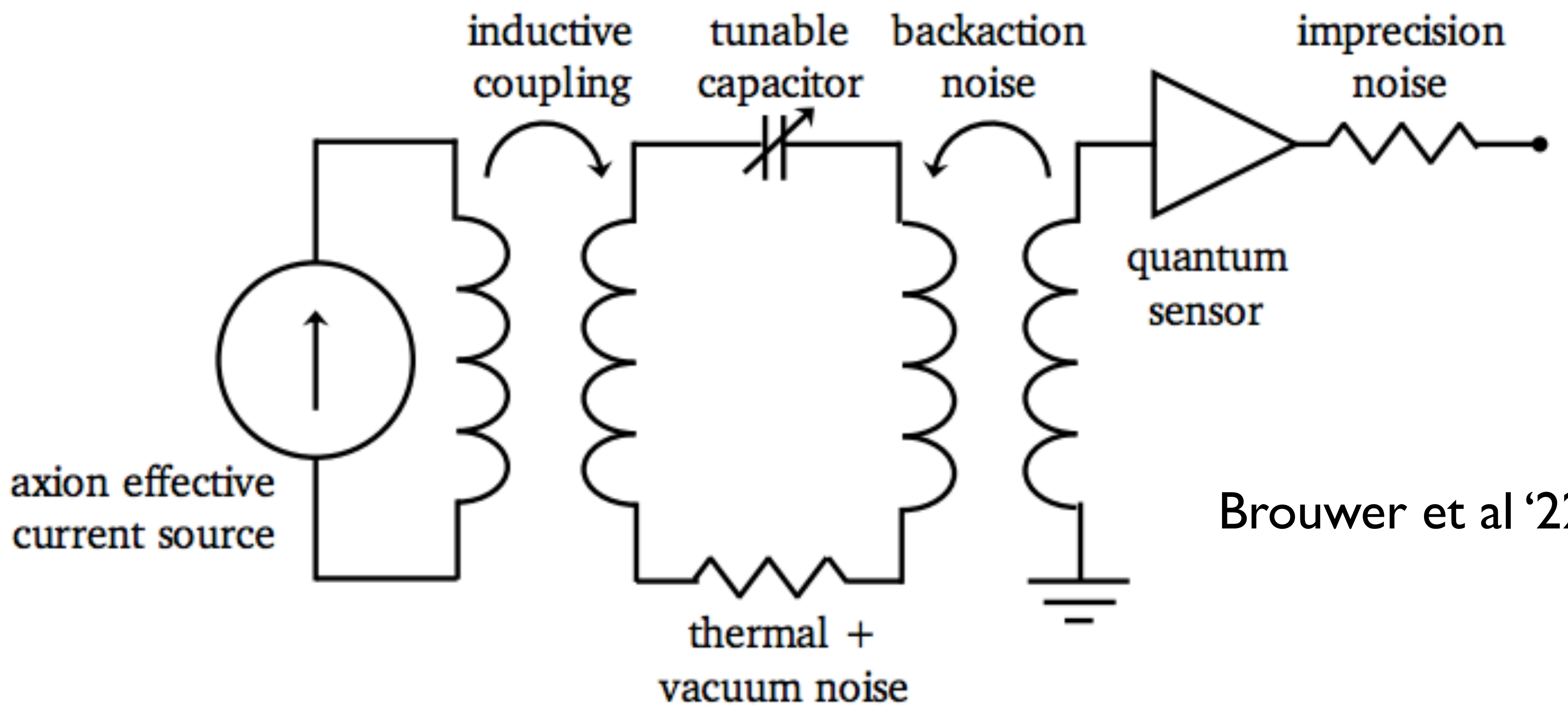


Searching for the QCD axion



- QCD axions (and axion-like particles) 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
- Axions could also have many interesting astrophysical 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





Brouwer et al '22

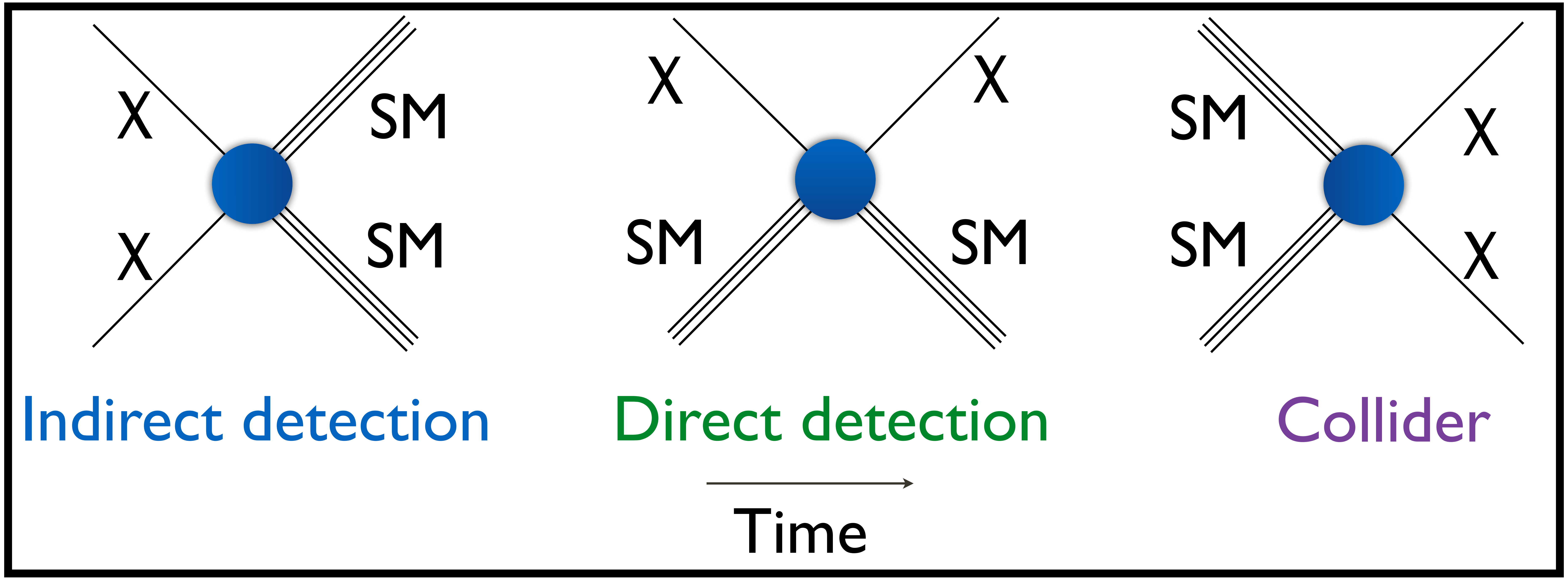
The thermal window

- For MeV+ DM, the DM could potentially be thermally coupled to the Standard Model
- One key question for all DM scenarios is "where did the DM abundance come from?"
- One hypothesis: DM was in equilibrium with SM in early universe + density was depleted through annihilations, DM DM → SM SM
- Observed present-day density → annihilation rate:

$$\langle \sigma v \rangle \approx 2 \times 10^{-26} \mathrm{cm}^3/s \approx \frac{1}{(25\mathrm{TeV})^2} \sim \frac{1}{m_{\mathrm{Pl}} T_{\mathrm{eq}}}$$

- Correct cross section for weakly-interacting particles with weak-scale masses - Weakly Interacting Massive Particle (WIMP) “miracle”
- Mechanism works for DM masses up to ~100 TeV - for heavier DM the required annihilation rate becomes impossible to attain (in standard cosmology), exceeding a generic upper bound from unitarity
- This mechanism implies significant DM-SM interactions, including a target annihilation cross section

Classic WIMP searches



- Indirect detection: look for Standard Model particles - electrons/positrons, photons, neutrinos, protons/antiprotons - produced when dark matter particles collide or decay.

- Direct detection: look for atomic nuclei "jumping" when struck by dark matter particles, using sensitive underground detectors.

- Accelerators: produce dark matter particles in high-energy collisions, look at visible particles produced in the same collisions, check for apparent violation of energy/momentum conservation.

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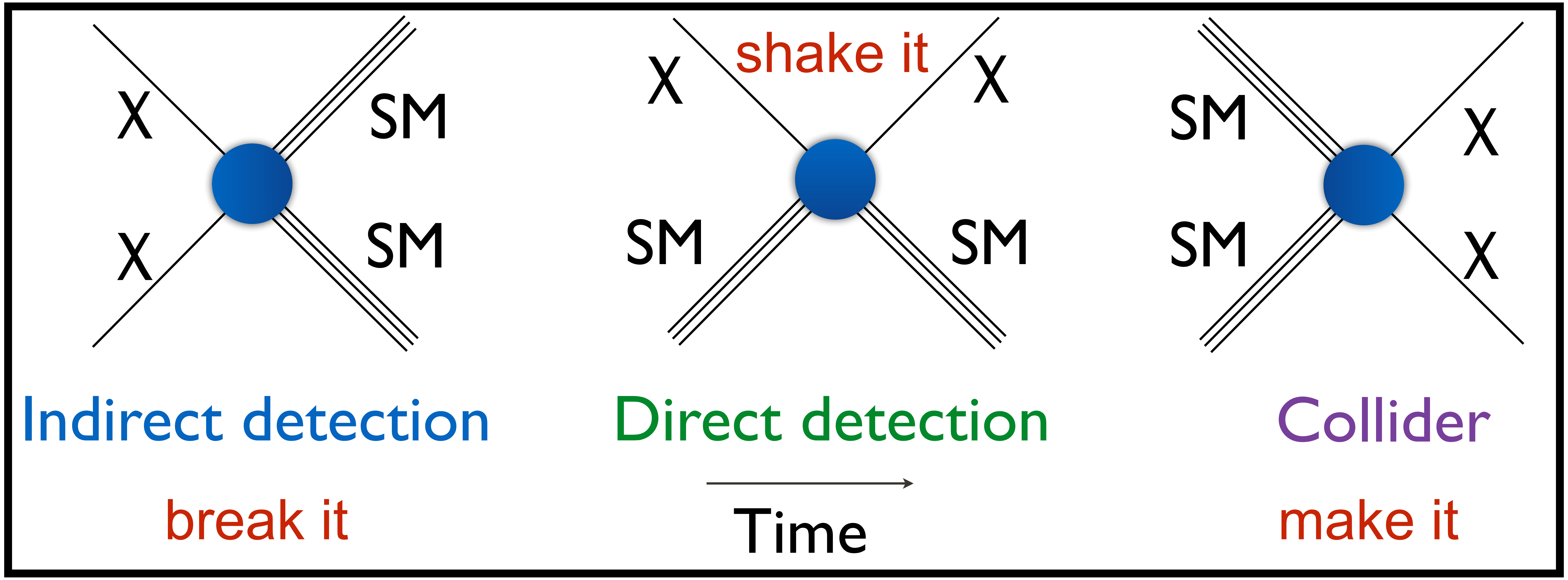

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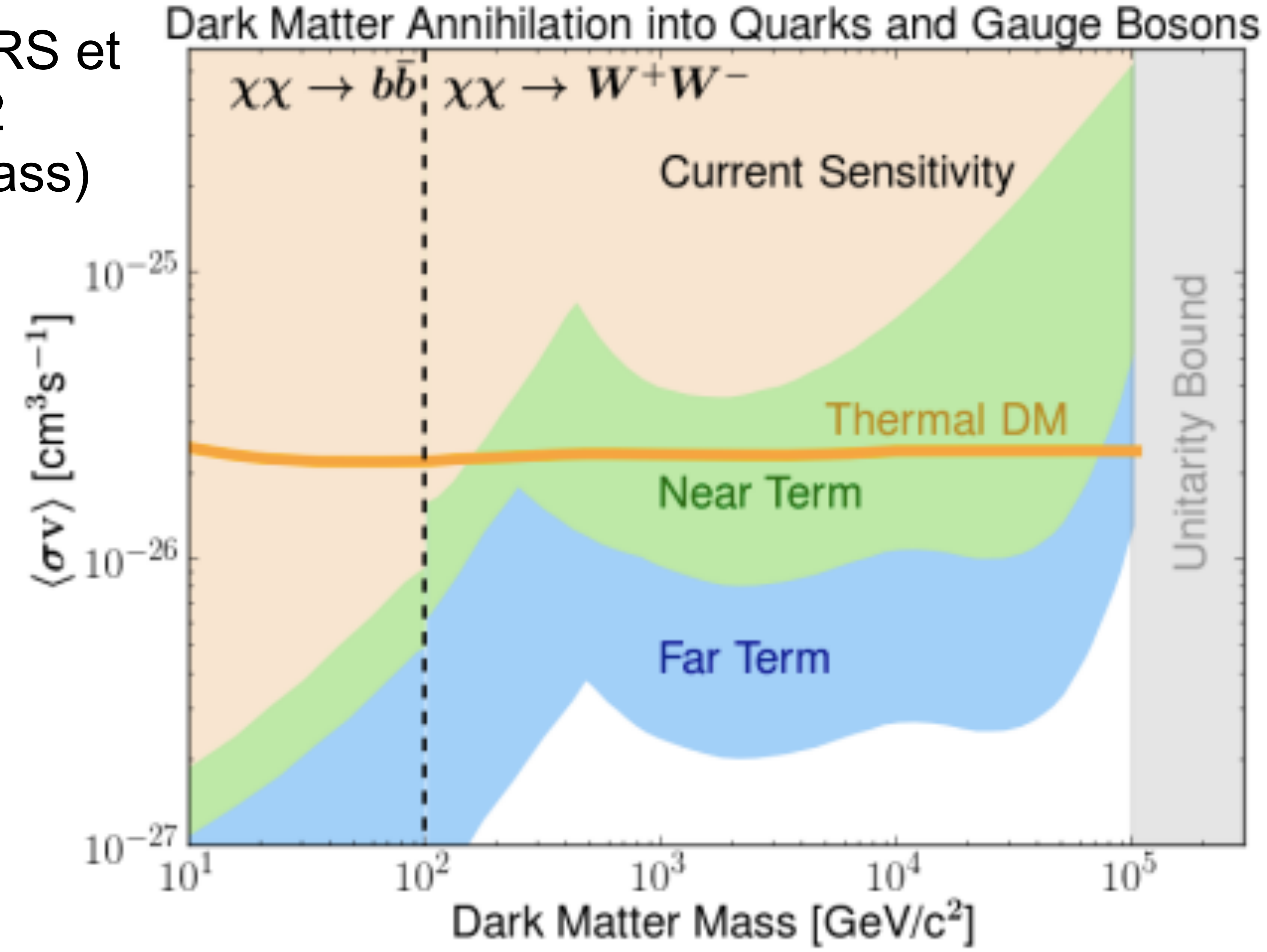
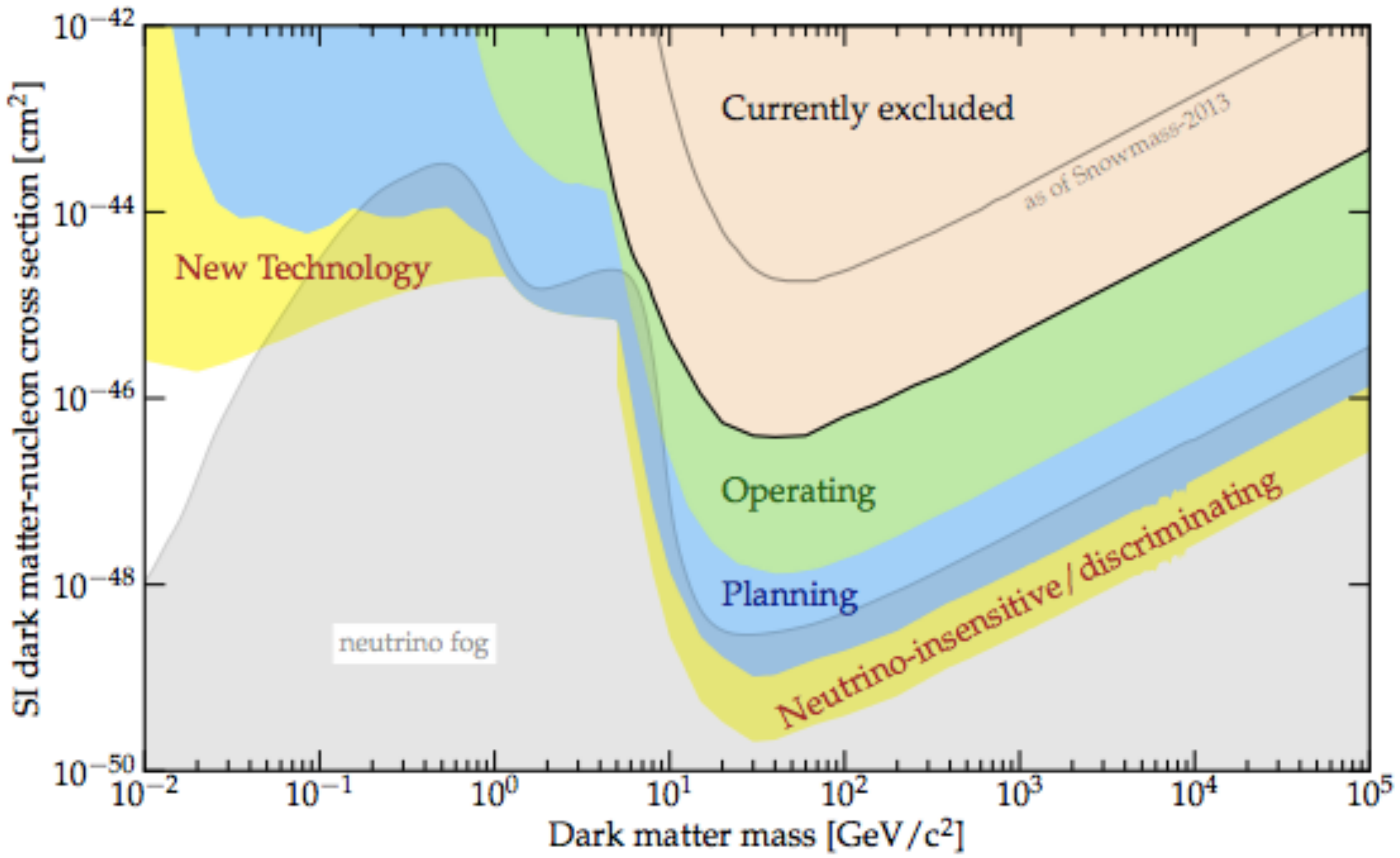
Limits on WIMPs

Cooley, TRS et al '22 (Snowmass)

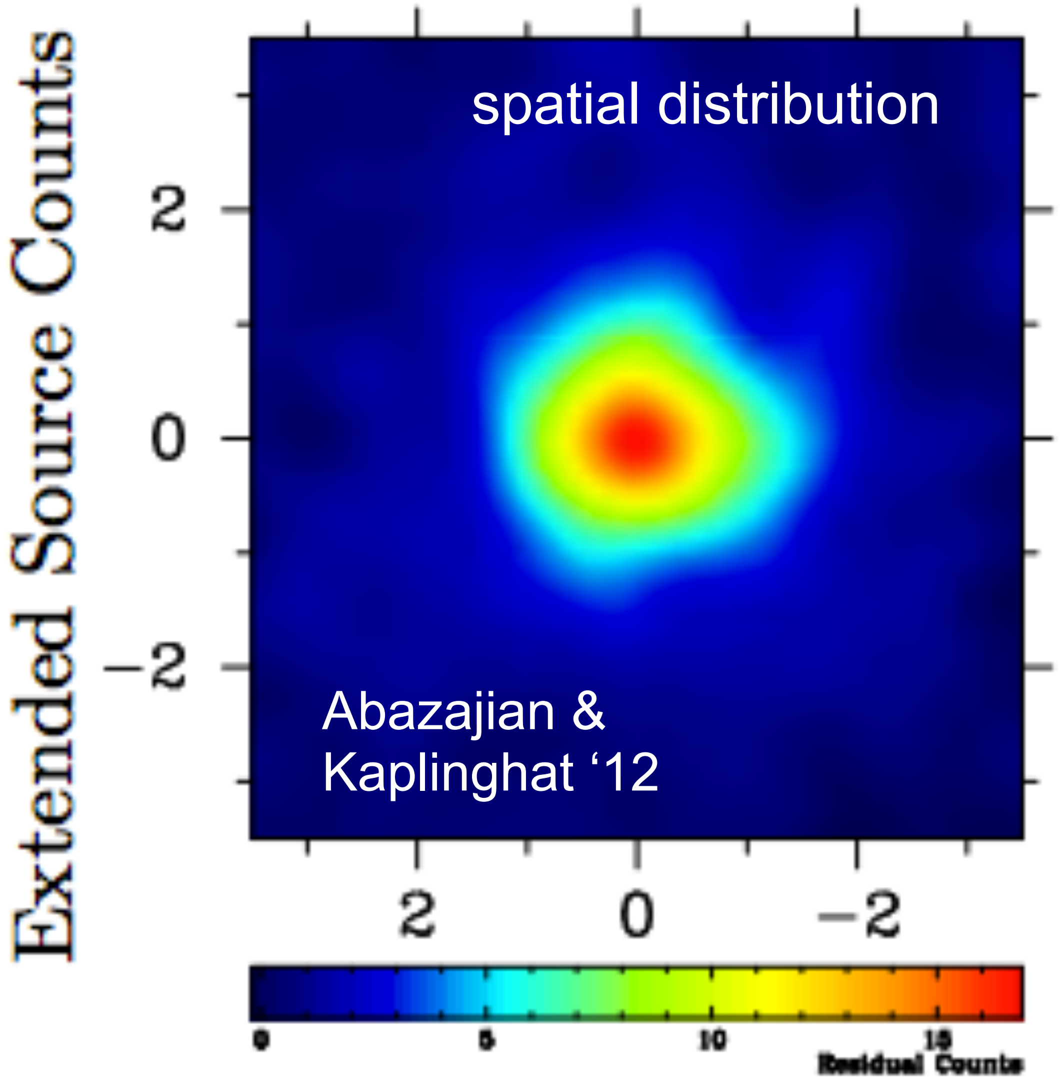


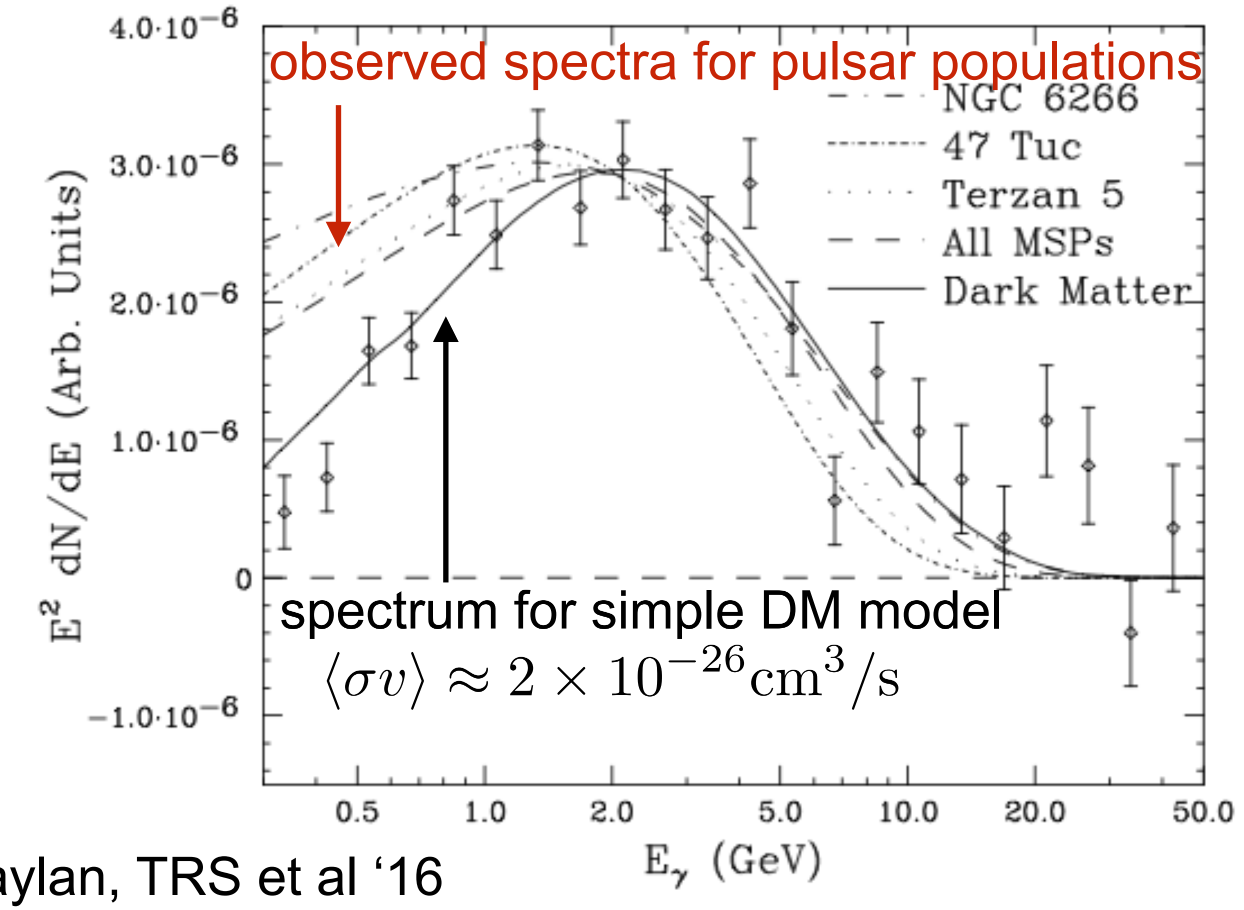
- There are stringent limits from all these searches - no robust detections yet.
- Limits from the CMB, gamma-ray and cosmic-ray experiments probe the thermal relic cross section up to DM masses of 10s-100s GeV, for all SM final states except neutrinos.
- Future experiments have the possibility of reaching this cross section for 10-100 TeV DM.
  - Large ground-based gamma-ray telescopes (CTA, SWGO) are needed to reach the thermal relic benchmark cross-section
  - Southern hemisphere locations are essential to observe the Galactic Center where DM density is expected to peak
- Direct-detection experiments with liquid noble gases set very powerful bounds on the DM-baryon scattering cross section for 10+ GeV DM.
  Next generation targeting the neutrino fog where solar neutrinos become a dominant background [e.g. O'Hare '21].
- Directional detection experiments such as Cygnus could help confirm a signal or reject neutrino backgrounds



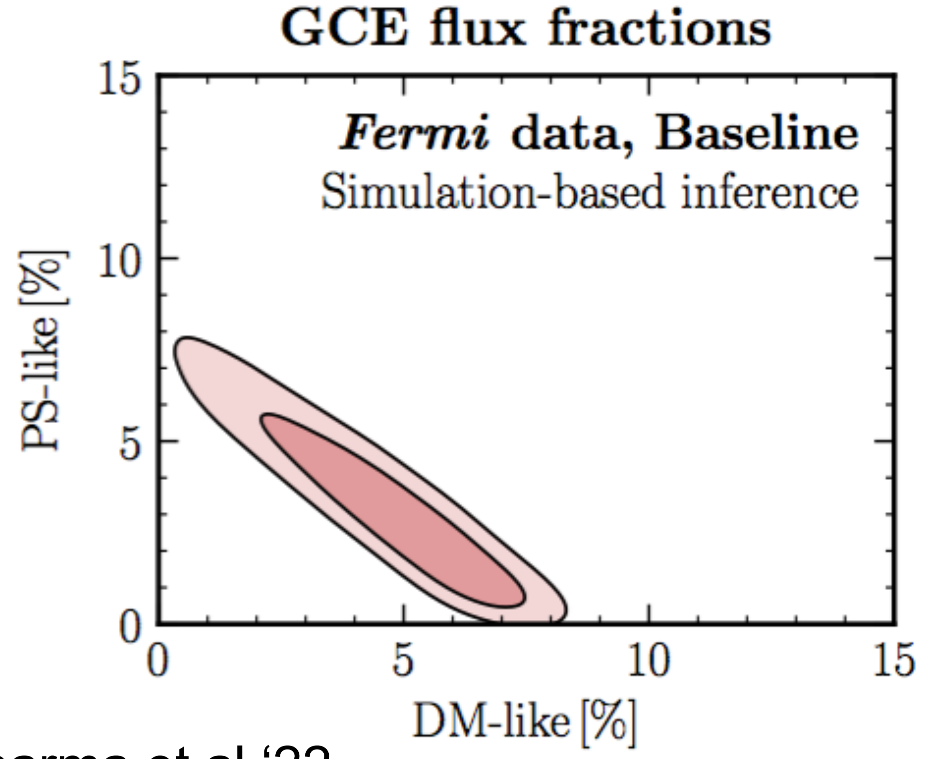
Resolving puzzles in the data

- Over the years we have seen a number of puzzling signal candidates in direct and (especially) indirect detection
- SABRE is a direct-detection experiment seeking to directly test one such long-standing excess, reported by the DAMA/LIBRA experiment
- Another that has gotten a lot of attention is the Galactic Center Excess (GCE), as a possible signal of DM annihilation. Also plausibly explained by a new population of millisecond pulsars, but (in my view) not definitively proved:
  - I showed with Rebecca Leane that earlier apparent evidence that we had actually detected the pulsars in gamma rays was exaggerated by a systematic bias - updated analyses show little evidence for point sources in the excess
  - key properties (that we would like to use to distinguish hypotheses) appear quite sensitive to uncertainties in the background modeling
- Conclusively resolving these (and similar) excesses may require new analysis techniques and/or new datasets (e.g. SKA may find the GCE pulsars for us!) - whether or not they are telling us about DM, they are something we need to understand





Daylan, TRS et al '16

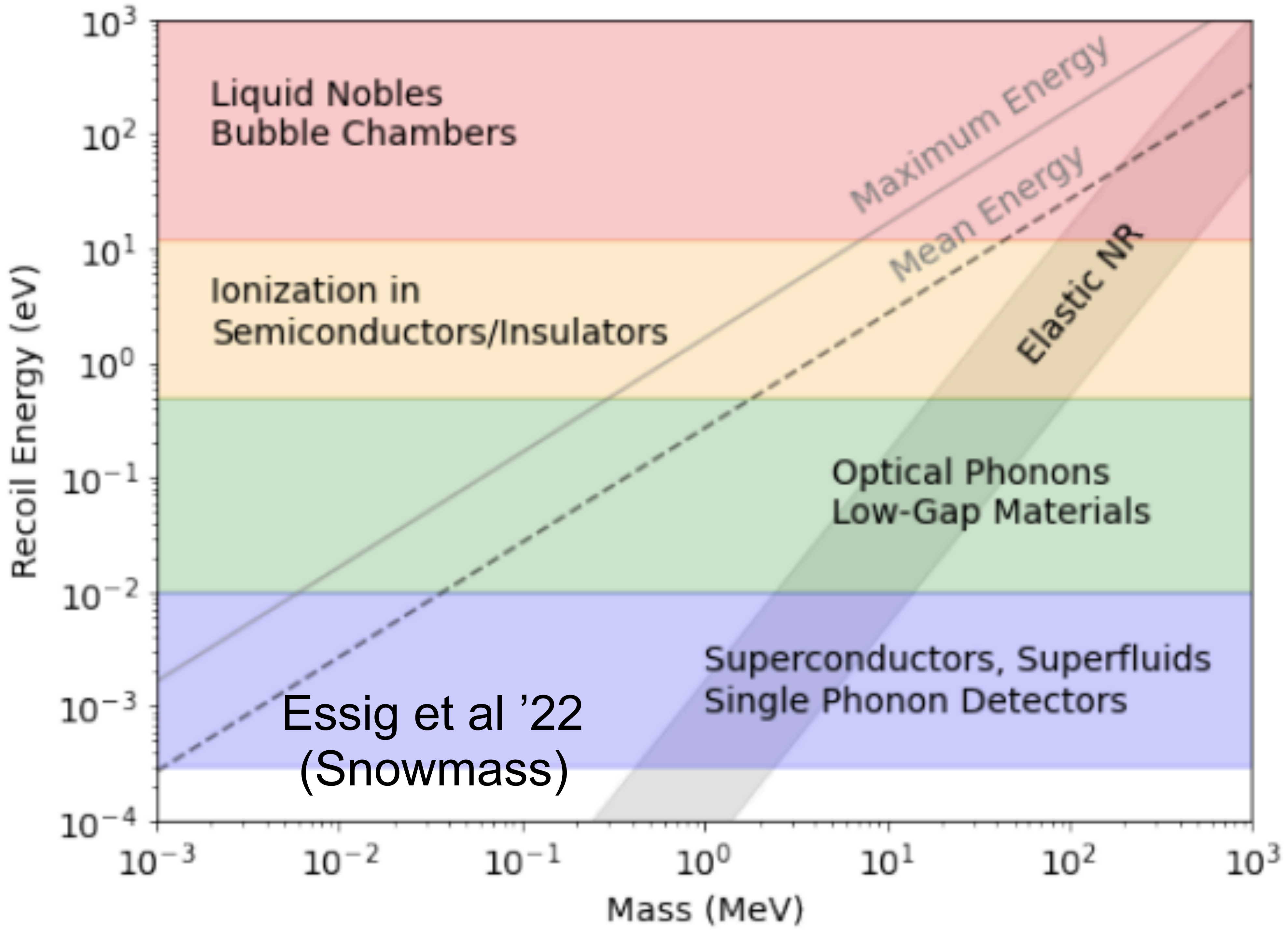


Mishra-Sharma et al '22

Low-mass thermal DM

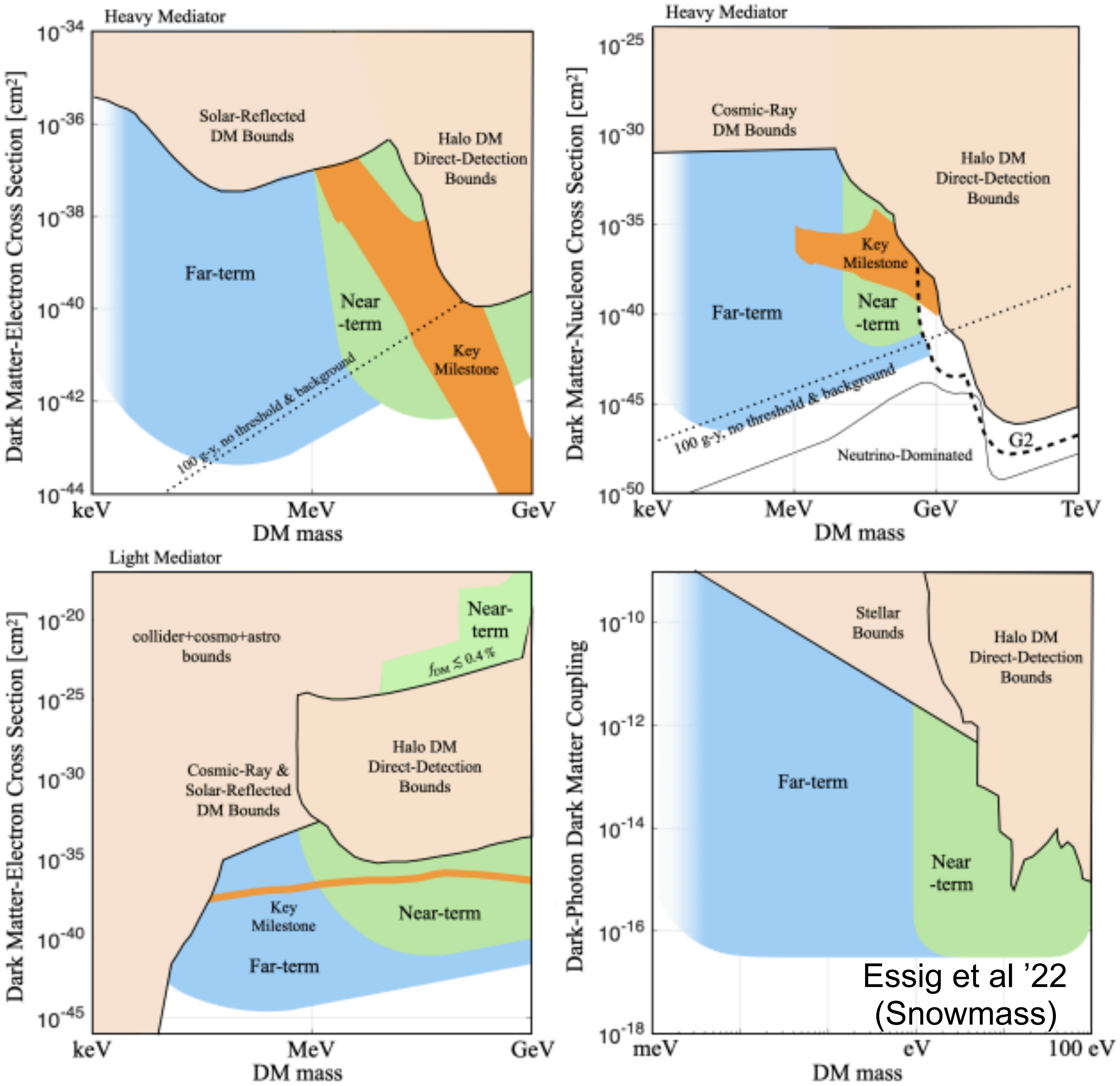
- There is a great deal of current interest in the MeV-GeV mass band
  - Simple dynamical explanations for DM abundance (thermal freezeout, freeze-in, and many variations)
  - Generally requires new mediators connecting DM and the Standard Model - "dark sectors", new "dark forces".
  - Constrained by 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)



Example: SENSEI

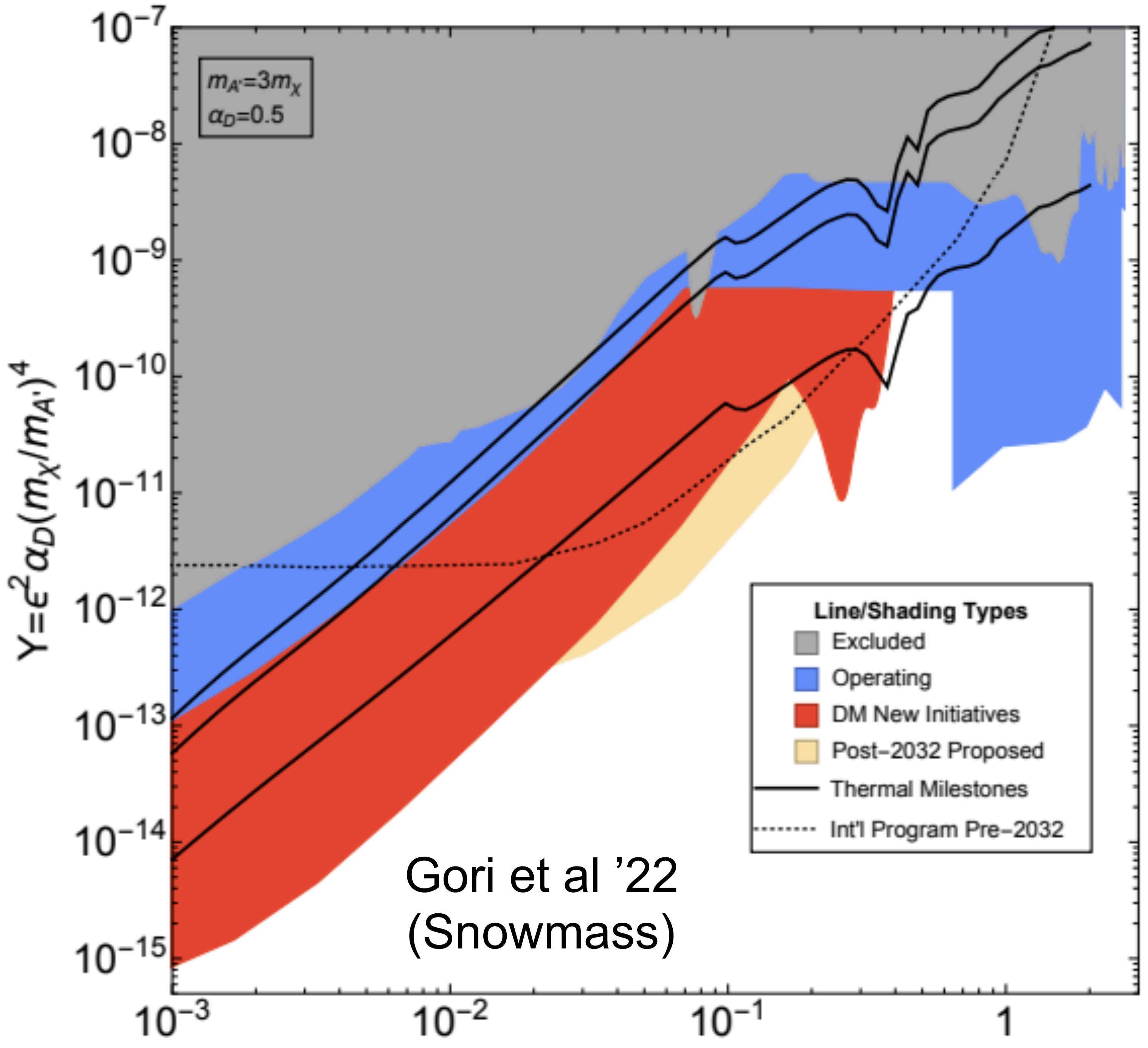
- Employs ultra-low-noise silicon Skipper-Charge-Coupled-Devices (Skipper-CCDs)
- Silicon band gap ~ 1.2 eV
- Recent advances allow measurements of charge in each pixel (over millions of pixels) with sub-electron noise
- Search for single electron excitations across band gap, allowing testing of:
  - 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

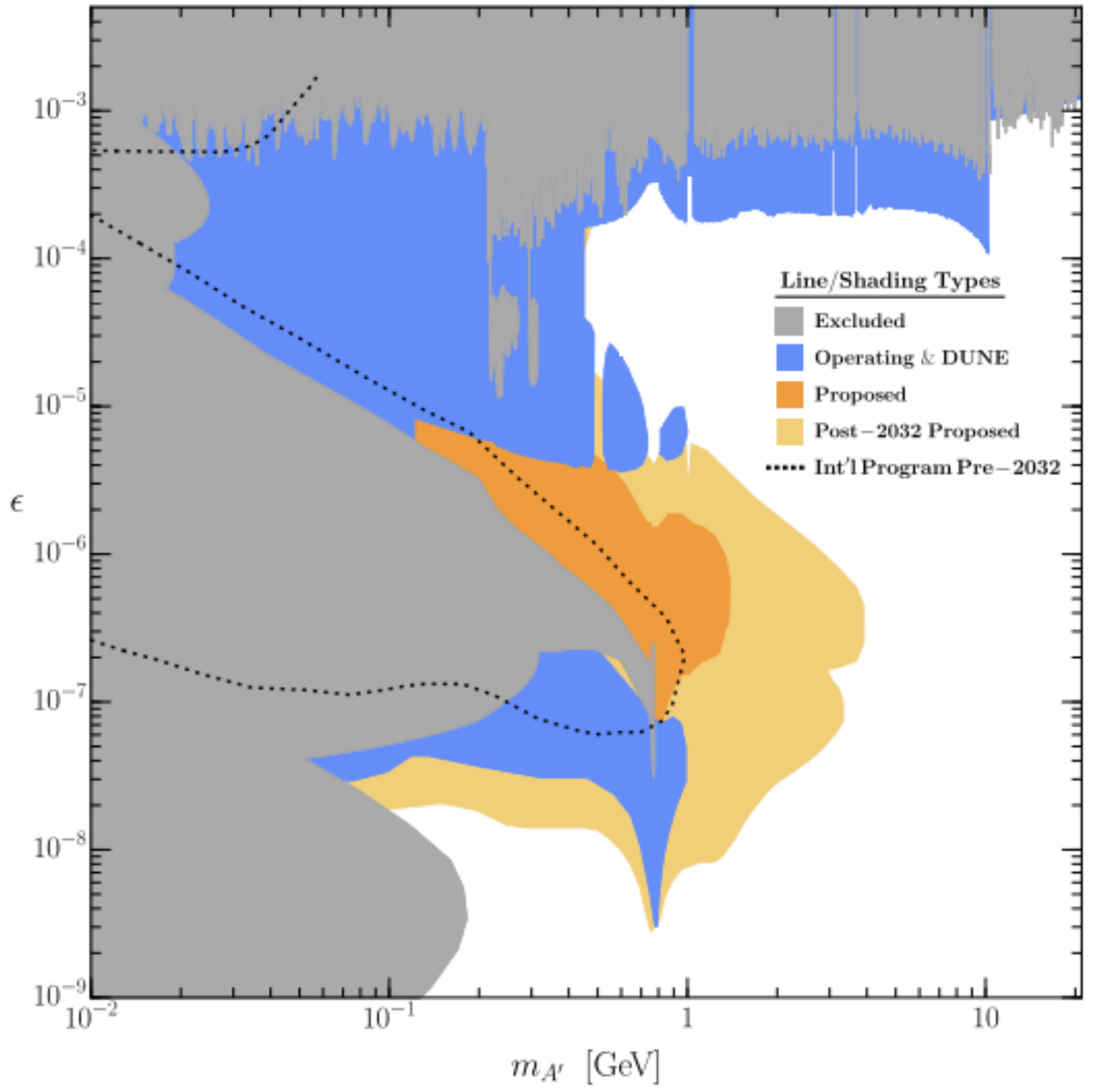


Essig et al ’22 (Snowmass)

Accelerator searches for light DM / dark sectors

- One set of targets: thermal freezeout models
  - Direct/indirect detection largely measure DM interactions in the present-day halo, v ~ 10^{-3}
  - Accelerators allow reproduction of conditions in the freezeout epoch (relativistic or near-relativistic DM)
- Another set of targets: mediators between "dark sector” and Standard Model
  - Implies new particles directly coupled to Standard Model - can search for their production and decay, may be our first clue to dark sector
  - Small couplings = long lifetimes. We can use existing accelerators (including the LHC) as a source of long-lived particles, + search for their displaced decays with additional detectors (e.g. FASER, CODEX-b, MATHUSLA)

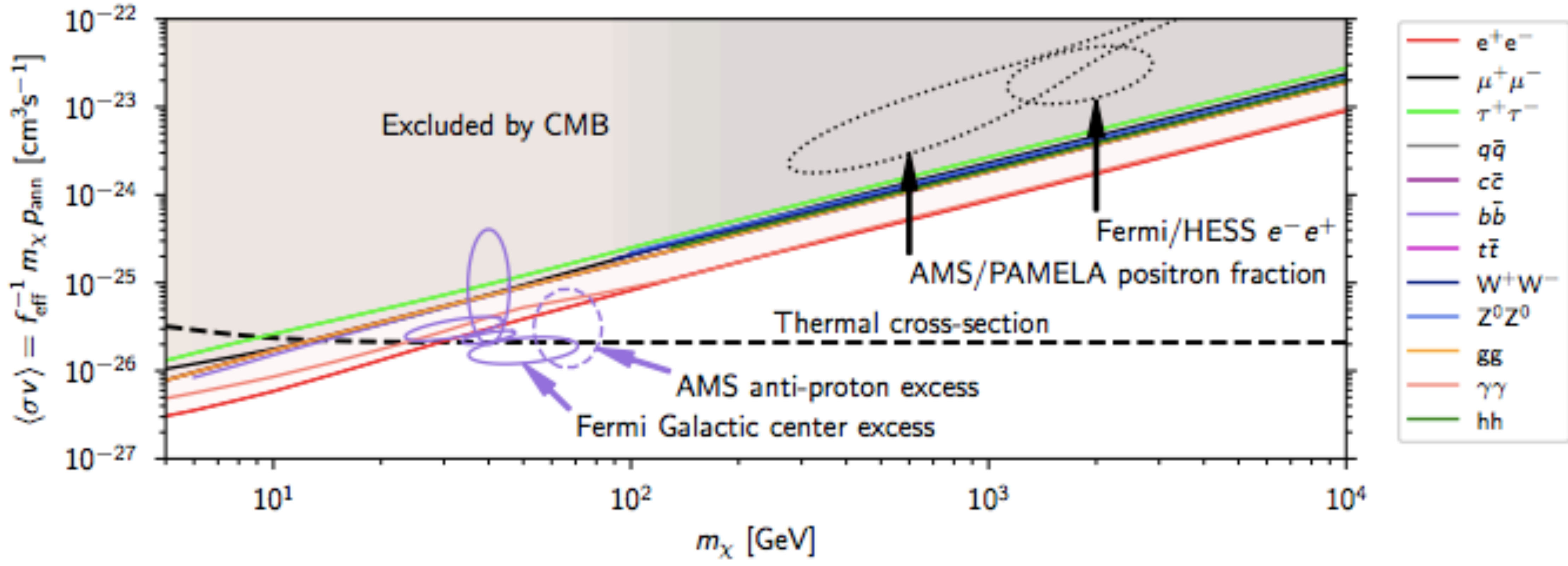


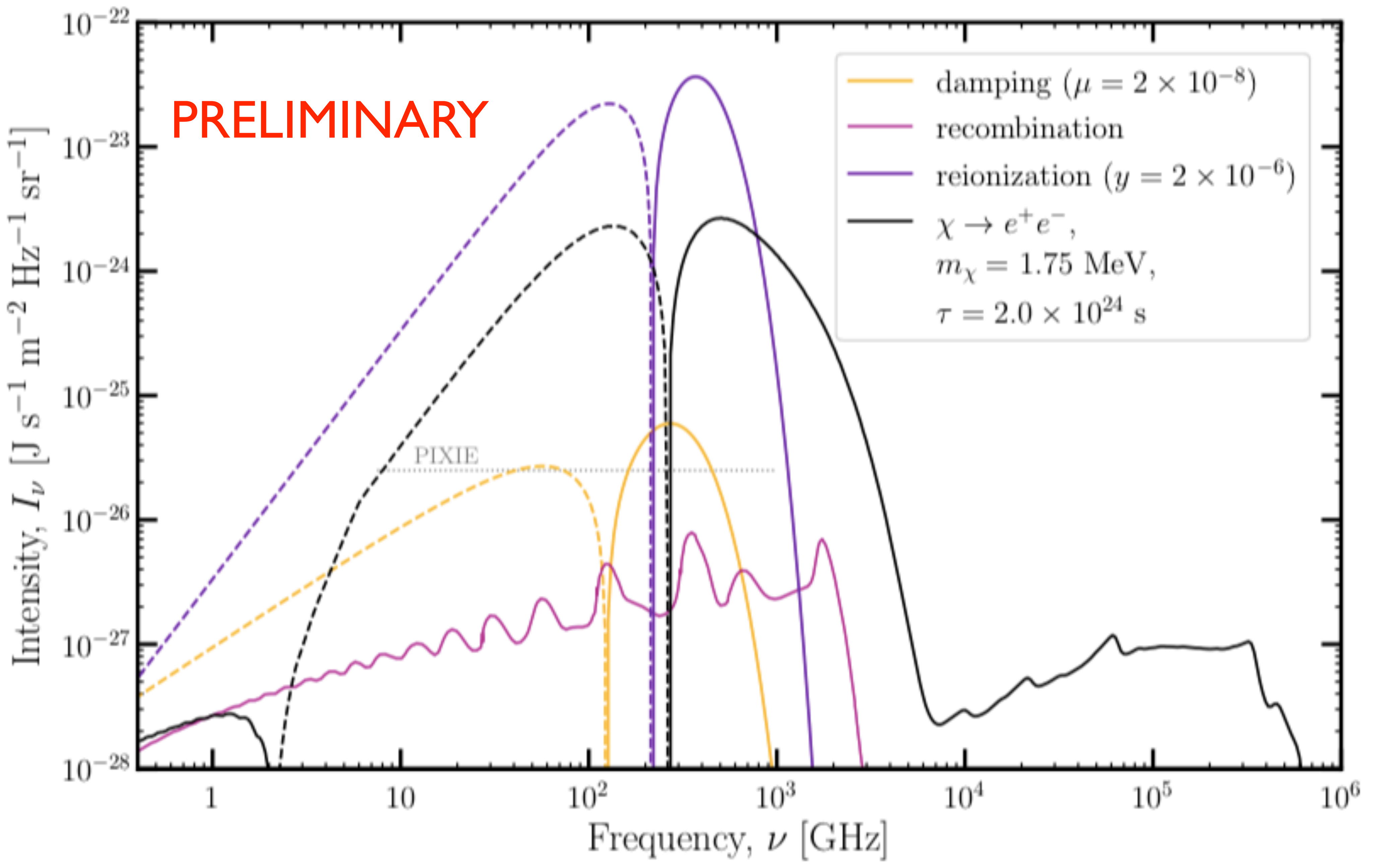


The cosmos as calorimeter

- 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

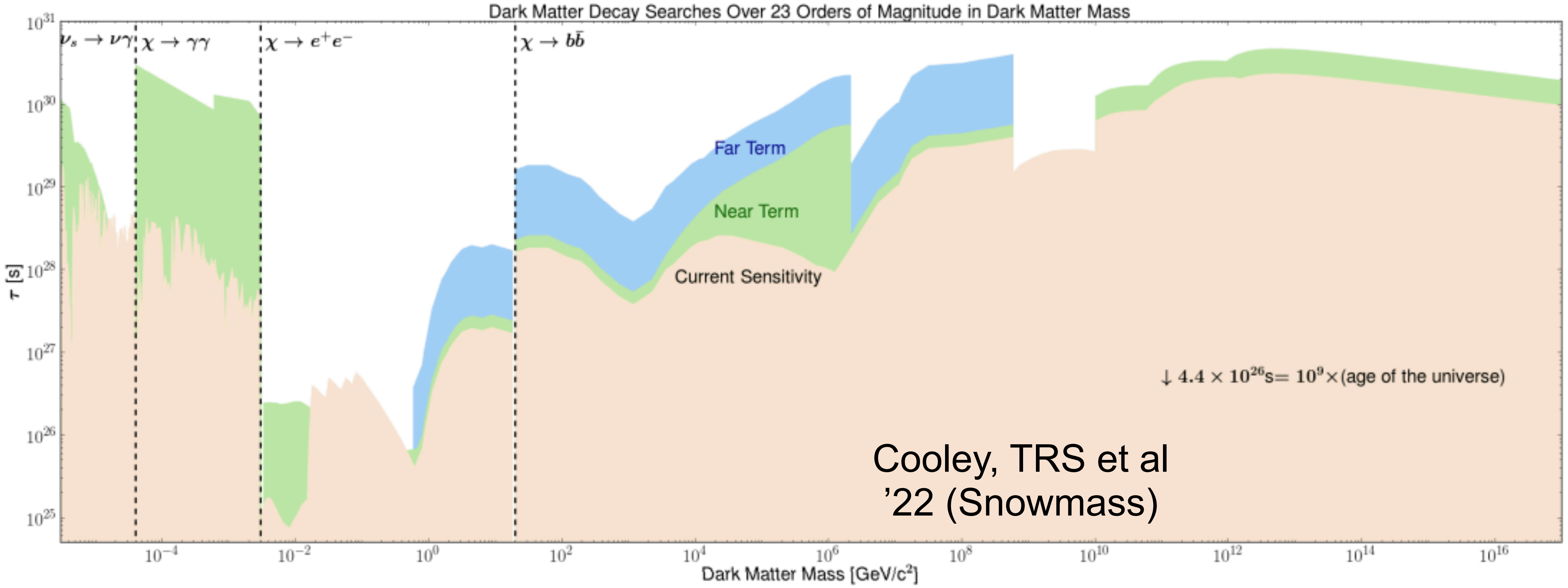




Above the thermal window: ultraheavy DM

- DM above 100 TeV - PeV masses can be produced non-thermally, or via thermal freezeout if standard assumptions are violated:
  - modified cosmology: large entropy injections, or a first-order phase transition in the dark sector [e.g. Asadi, TRS et al '21]
  - formation of many-particle bound states after freezeout [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]

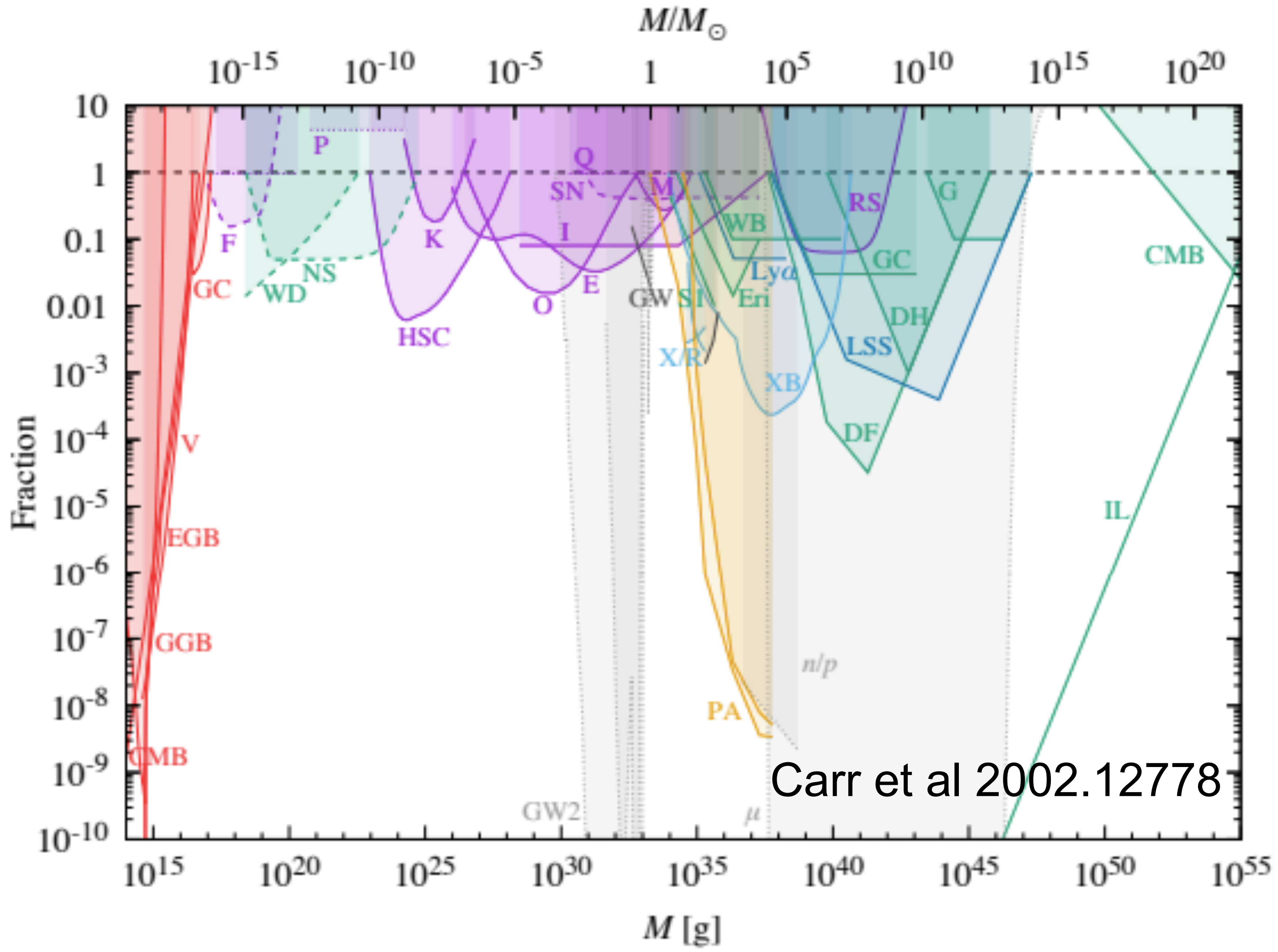
- Searches for decay products severely constrain the DM lifetime (for visible decays)
- Must be 8+ orders of magnitude longer than the age of the universe over 20+ orders of magnitude in mass



Cooley, TRS et al '22 (Snowmass)

Primordial black holes (PBHs) as DM

- Primordial black holes are a viable DM candidate if they can be produced copiously during the universe's first instants
- There is an open window for all DM to be PBHs for PBH masses $M \sim 10^{17}$-10^{23}g
- At the low end of this window, PBHs slowly evaporate via Hawking radiation
- 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].



Carr et al 2002.12778

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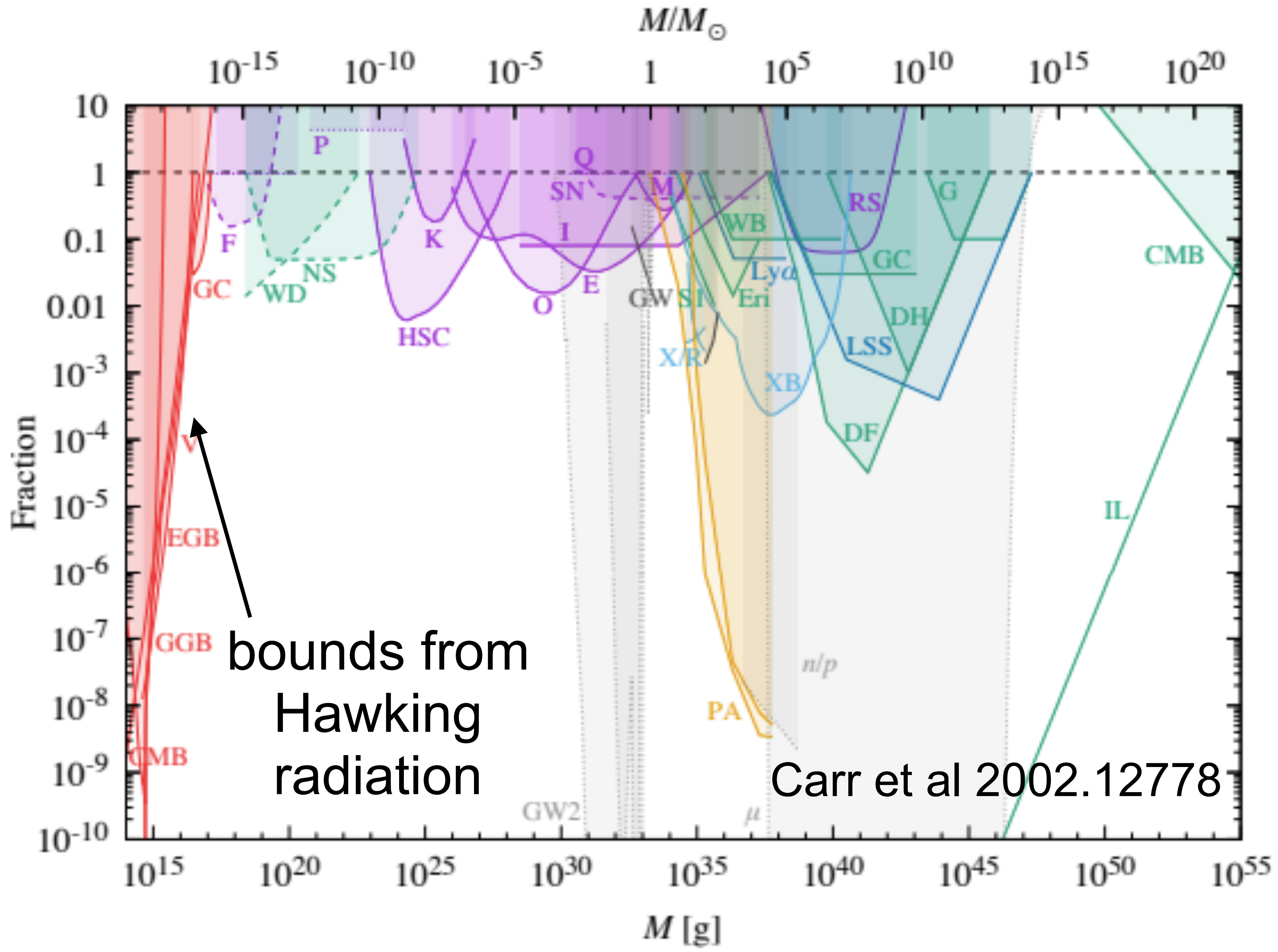

Primordial black holes (PBHs) as DM

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- There is an open window for all DM to be PBHs for PBH masses $M \sim 10^{17}$-10^{23}g

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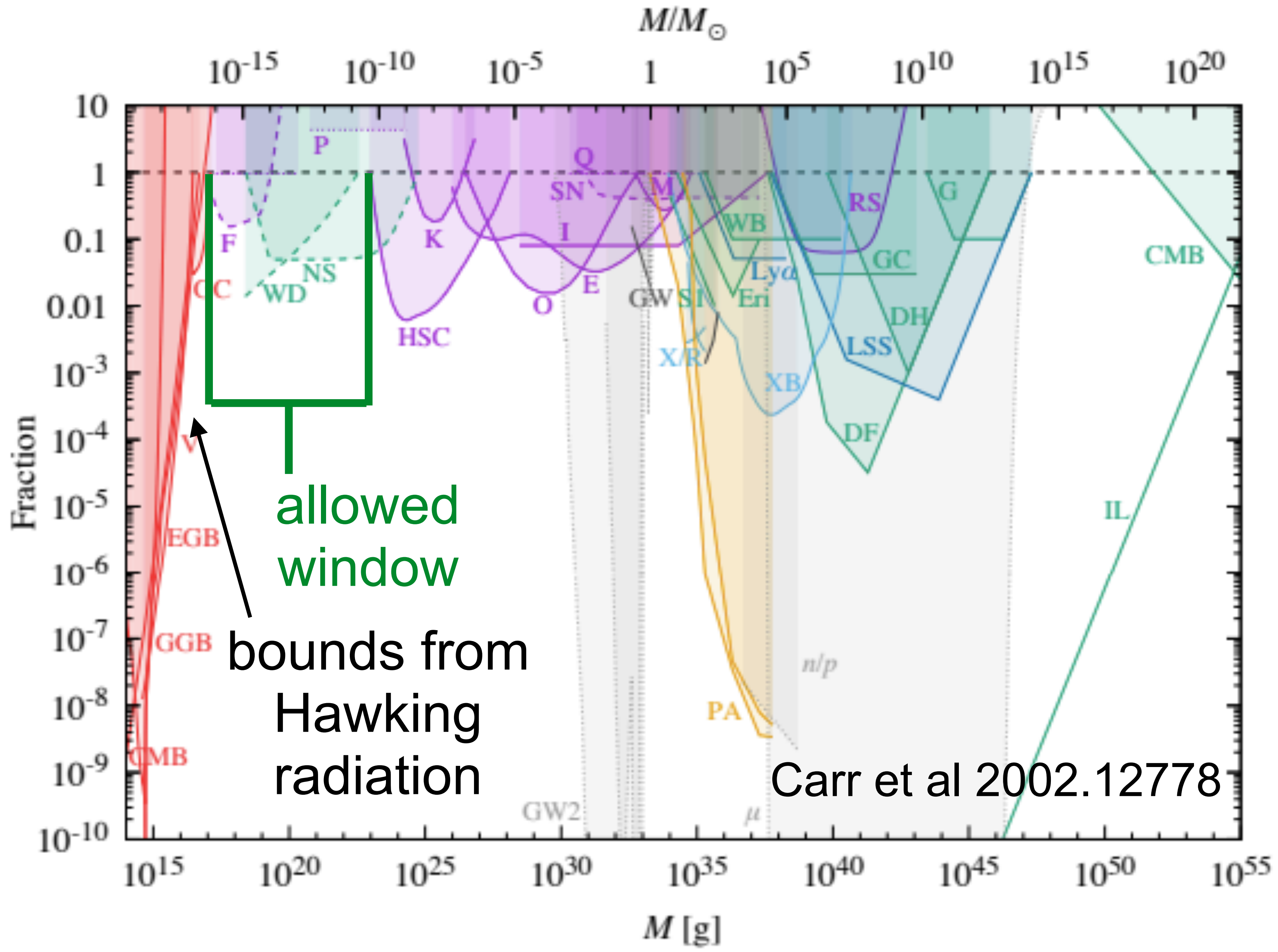

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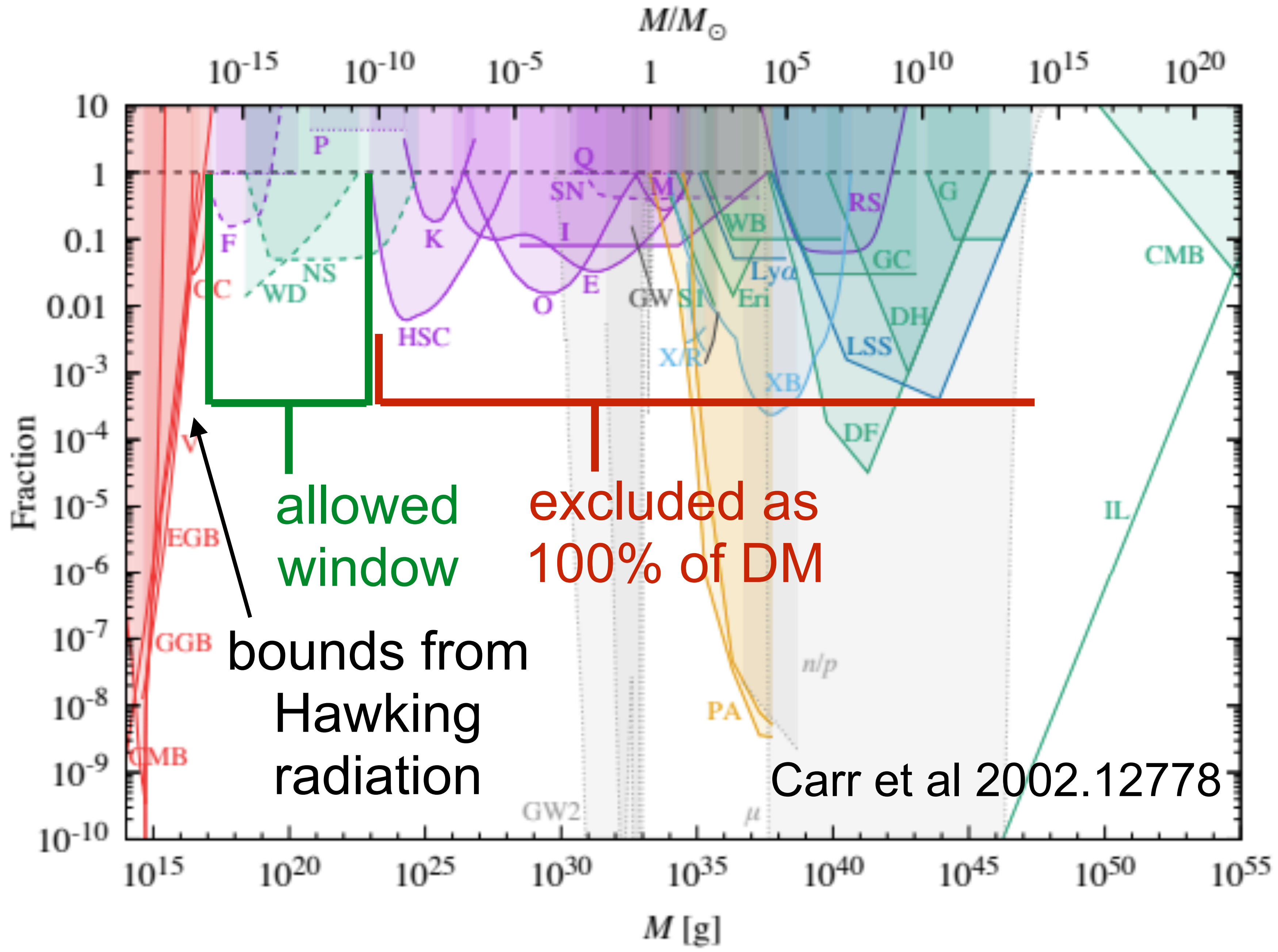

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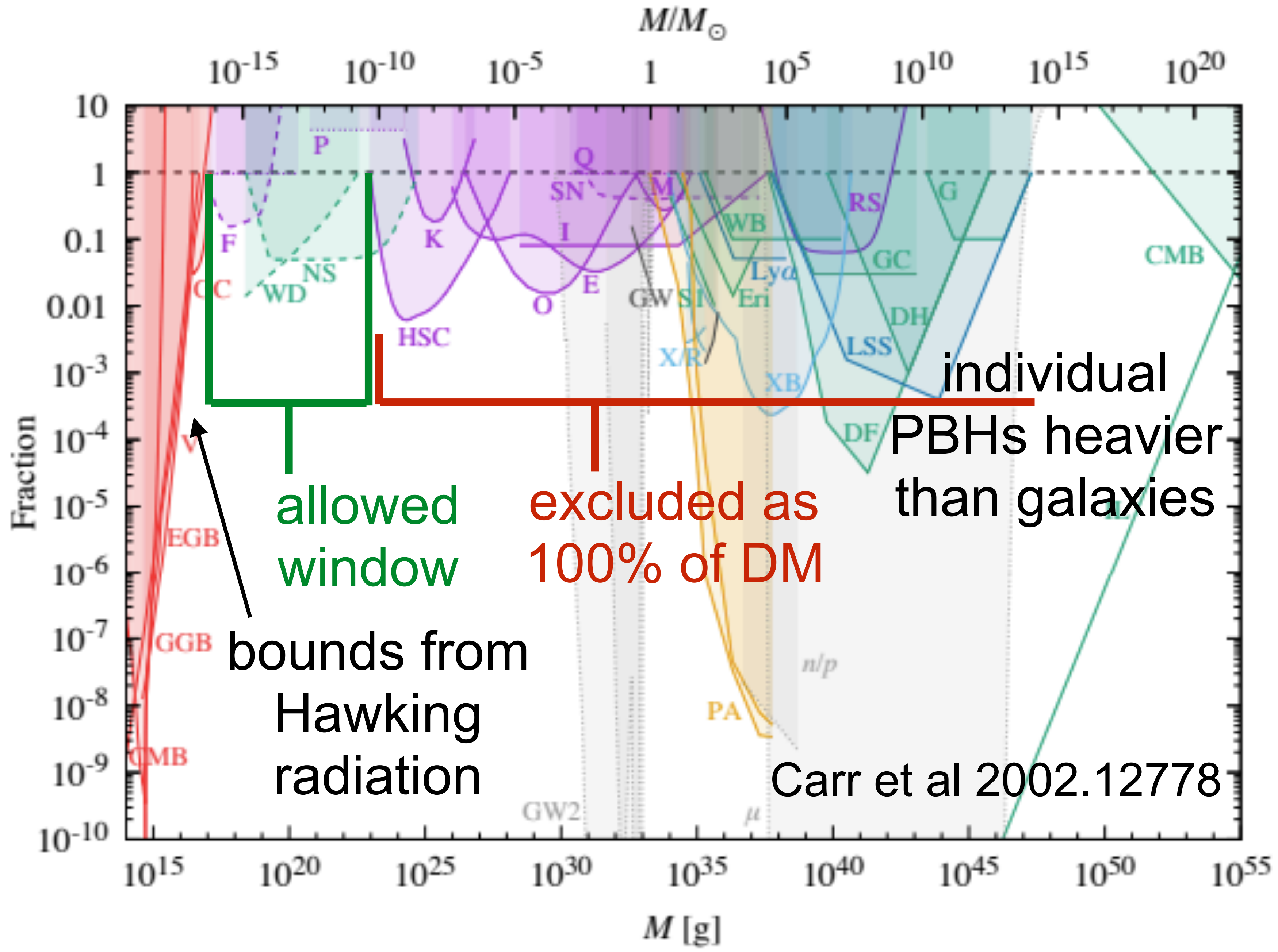

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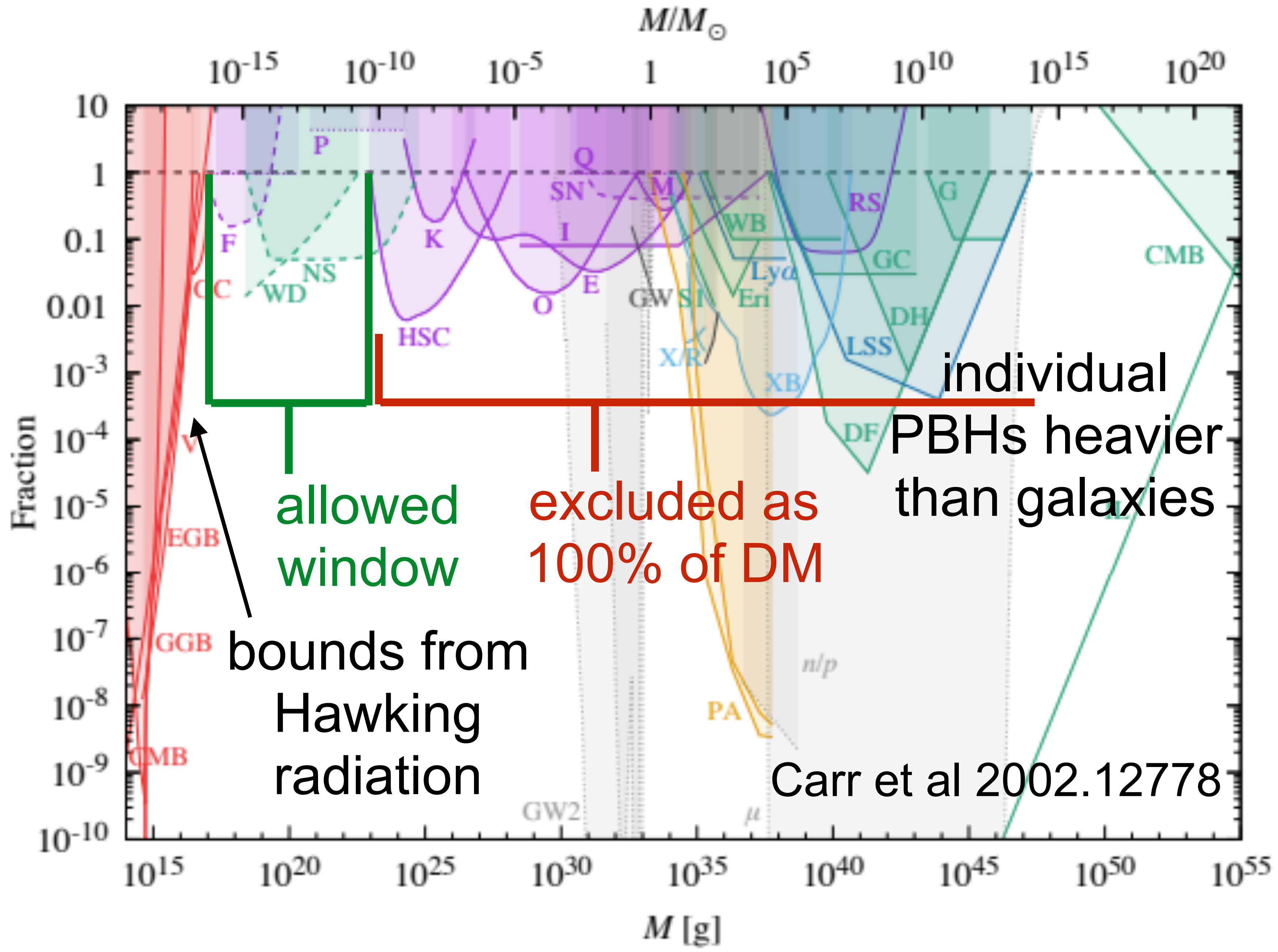
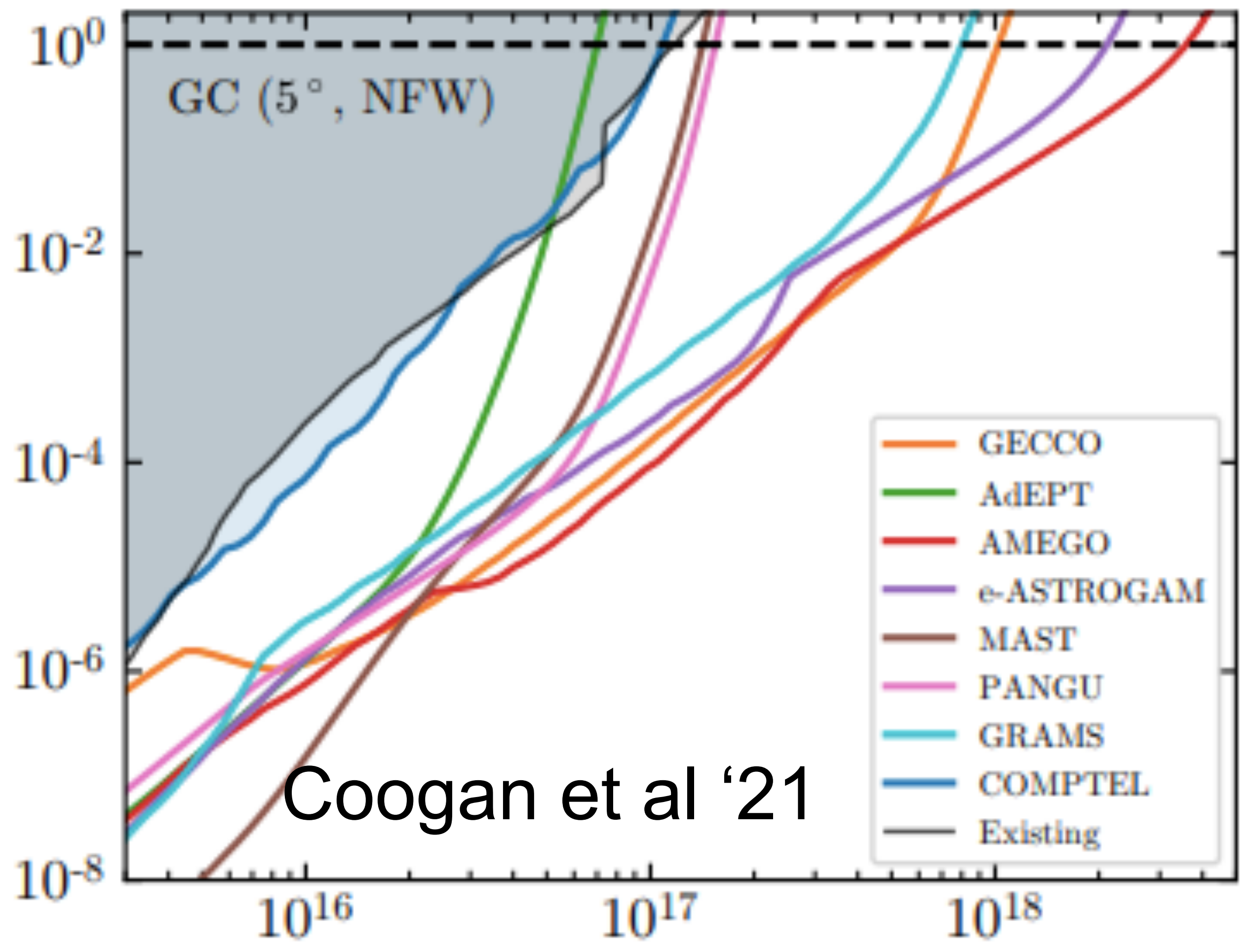




Summary

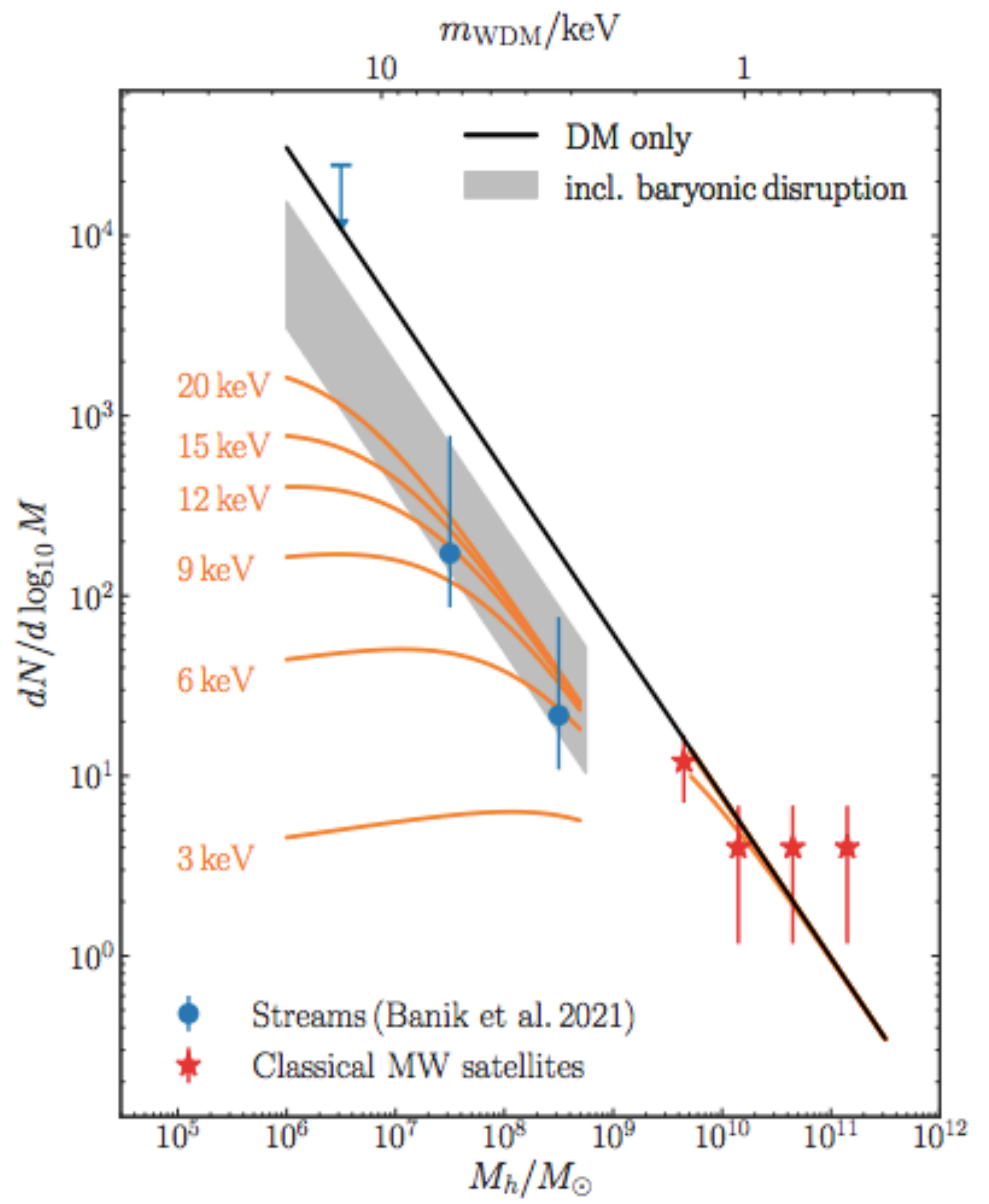
- The nature of DM is one of the central puzzles of fundamental physics.
- Knowns: cosmological abundance (precisely), phase space distribution (in part), upper limits on interactions, lower limit on lifetime, upper + lower bounds on mass (very widely separated!)
- Unknowns: values of mass, lifetime, non-gravitational interactions (if any); origin of abundance; one or multiple species; and many more…
- There is an enormous range of possible masses and interaction strengths for DM, and there are viable theoretical scenarios populating the full range.
- 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.
- Simultaneously the field is pursuing a broad program of searches to explore the full range of possibilities, including new direct-detection techniques with sensitivity to tiny energy depositions, and cosmic probes that can test the properties of DM even if it has no non-gravitational interactions with the Standard Model.

BACKUP SLIDES

How light / fast can DM be?

- Open question: what are the smallest bound DM structures in the universe, and what is their internal structure?

- The answer to this question tests many aspects of DM physics:
  - Sufficiently light DM would have macroscopic de Broglie wavelengths - “fuzzy DM” - that could be imprinted on the structure of small halos
  - Free streaming of fast-moving DM in the early universe would erase small halos; if DM was once in thermal contact with photons, too-light DM would be fast-moving (like neutrinos)
  - DM interaction strengths at low velocities
- 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 MW satellite galaxies [e.g. Nadler et al ’19, ’21]



What more can we learn from purely gravitational probes of DM?

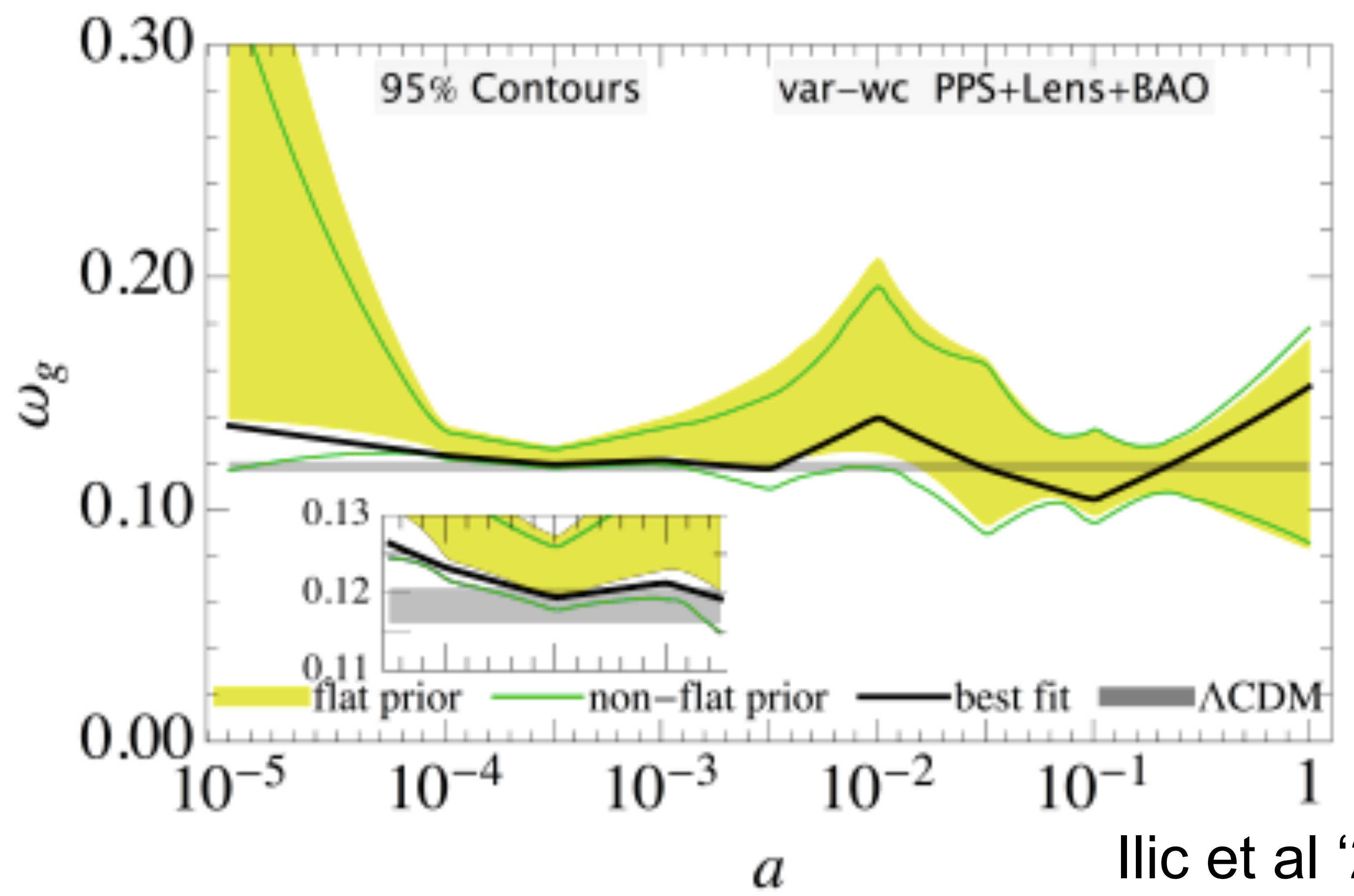
- Key idea: map how DM is distributed through the cosmos (in both space and time), via gravitational effects on stars/galaxies/gas clouds/etc, gravitational lensing, cosmic microwave background (CMB) radiation, etc

- Much recent progress on measuring DM density and velocity distributions in Milky Way and other galaxies, in particular using stellar data from Gaia [e.g. Bechtol et al ’22 (Snowmass) and references therein]

- Galaxy studies provide upper bounds on DM-DM interactions [e.g. Bondarenko et al ’21, Andrade et al ’21] and DM-SM interactions [e.g. Nadler et al ’19], as well as constraining the speed/mass of DM (next slide)

- Cosmology gives limits on how the DM content of the universe has changed over time, using observations of the CMB and large-scale structure [e.g. Poulin et al ’16, Ilic et al ’21]

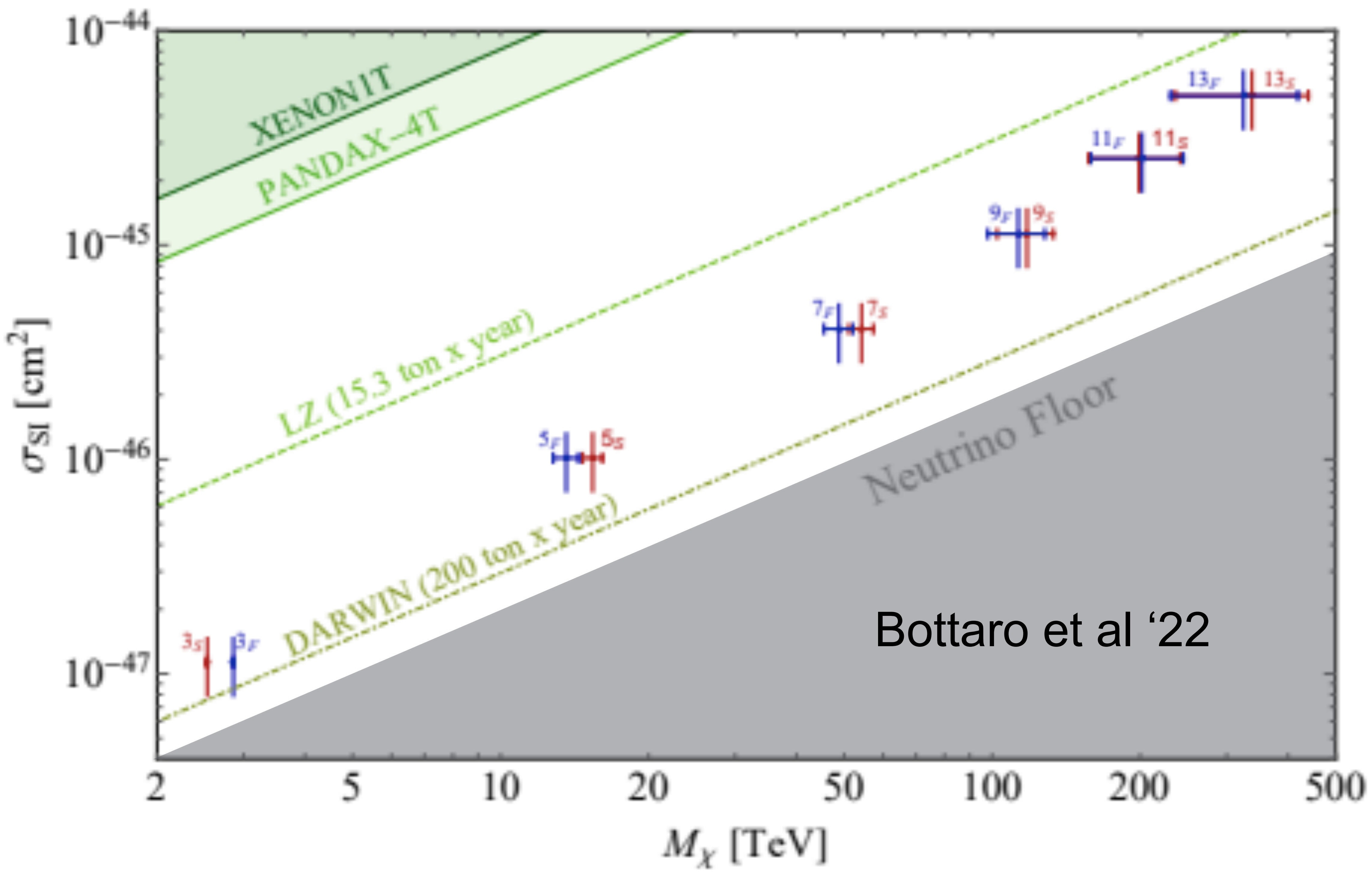
- Measurements of the abundances of light nuclei also constrain the radiation content (N_{eff}) at the time of nucleosynthesis - constrain light DM and other new particles [e.g. An et al ’22]



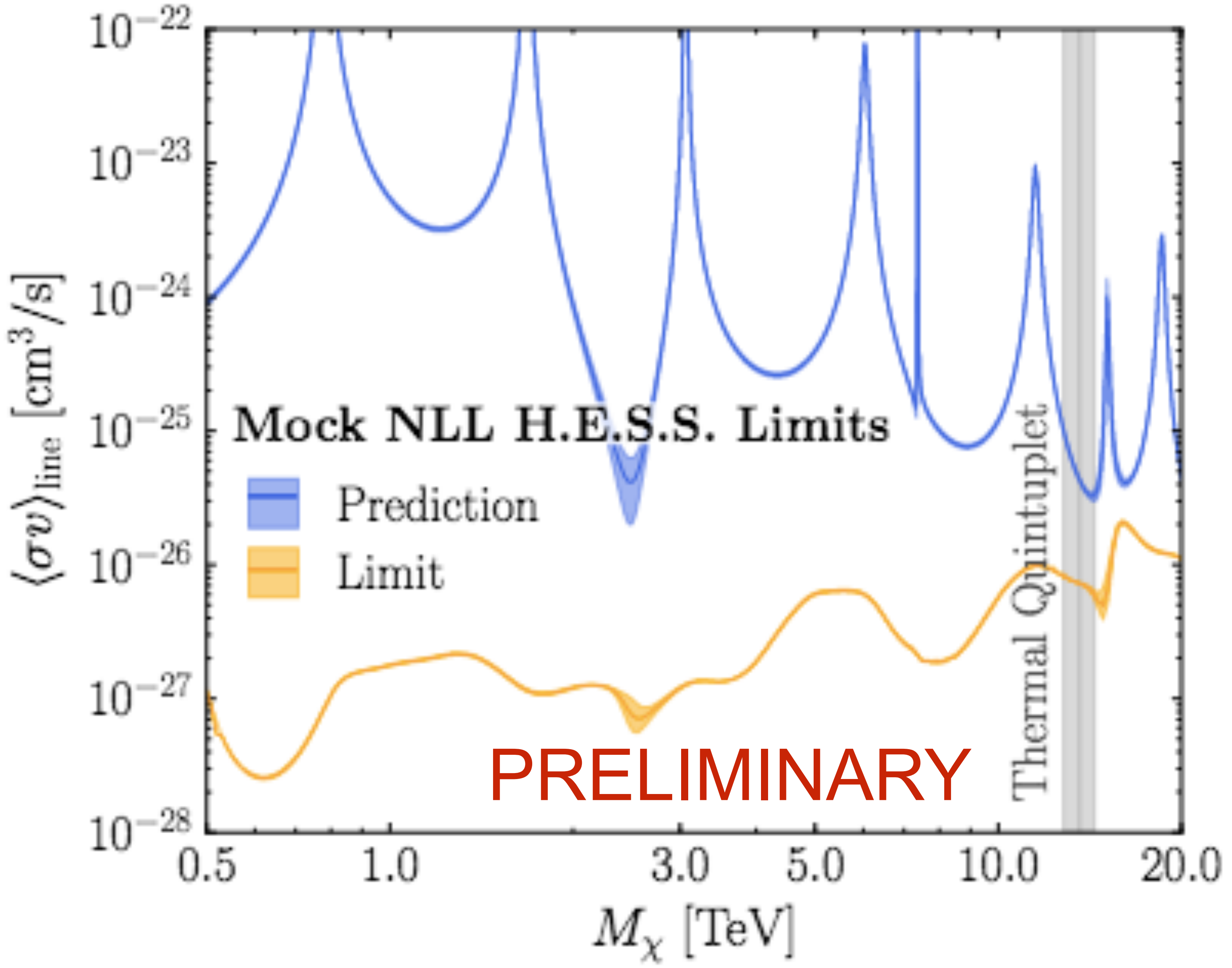
Ilic et al ‘21

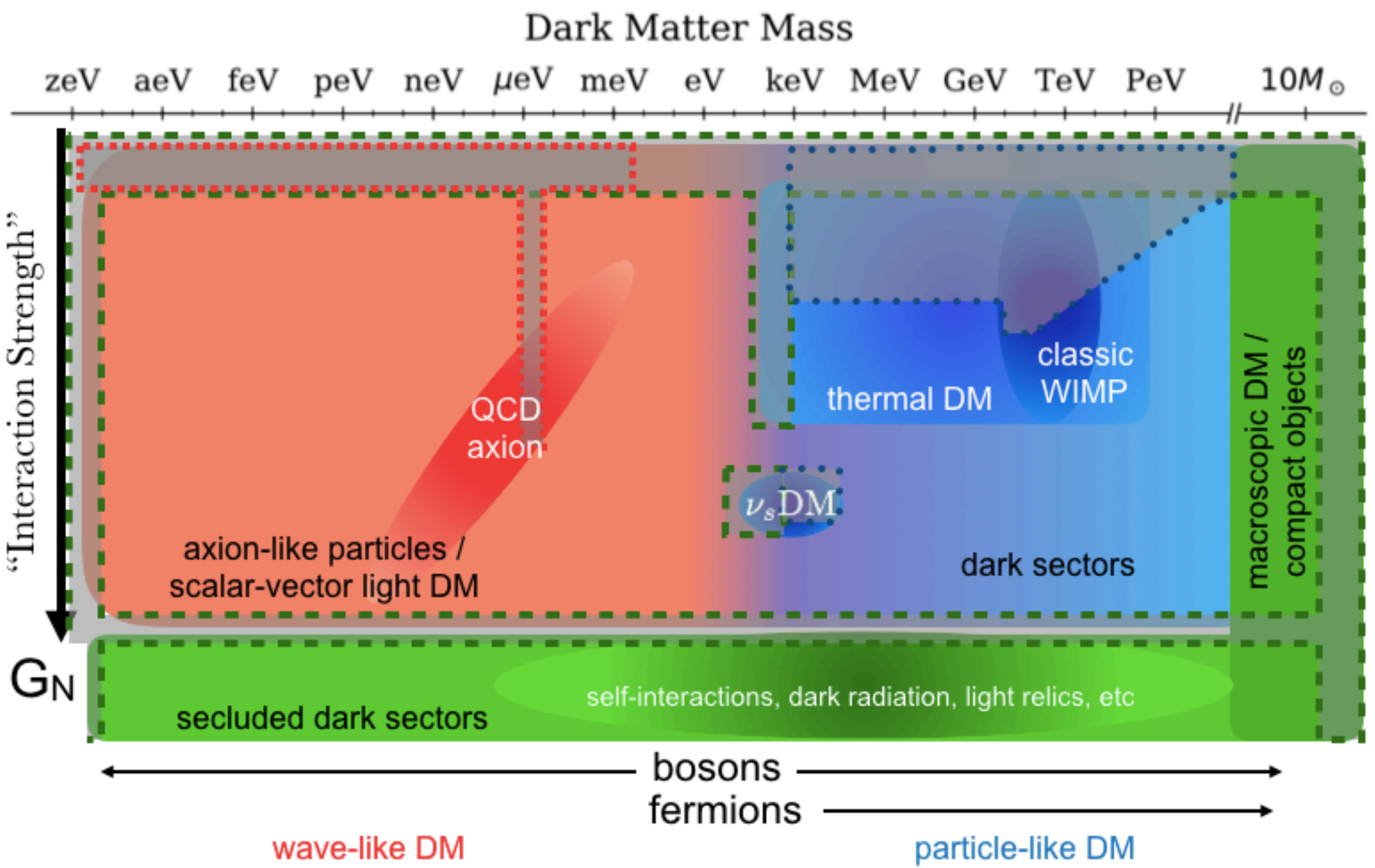
Electroweak DM

- At the same time, some of the simplest classic WIMP models remain unconstrained - DM could still interact through the W and Z bosons of the Standard Model
- 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
- Direct detection signal is close to neutrino floor (testable in next-gen experiments for most representations)
- Precise theory predictions for heavy electroweakinos require careful effective field theory analysis [e.g. Baumgart, TRS et al '19, Beneke et al '20, Beneke et al '22]
- But potentially detectable in gamma rays with current/future telescopes, or with future colliders [e.g. Canepa et al '20, Capdevilla et al '21]
- Beyond "minimal DM" cases, also a much broader landscape of models, including in supersymmetry (see e.g. Tuesday talk by Csaba Balazs).

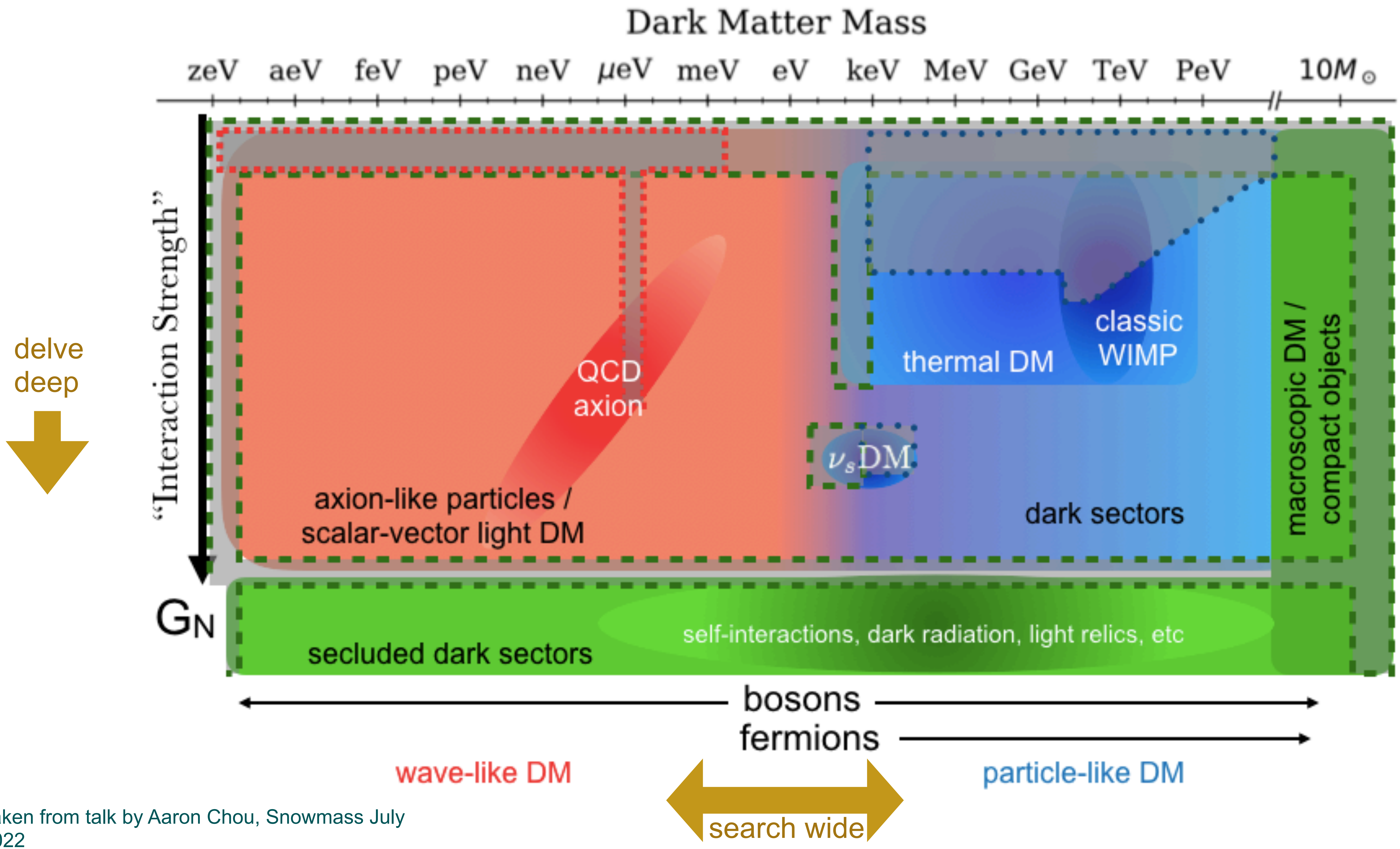


Estimated quintuplet sensitivity from HESS





Taken from talk by Aaron Chou, Snowmass July 2022



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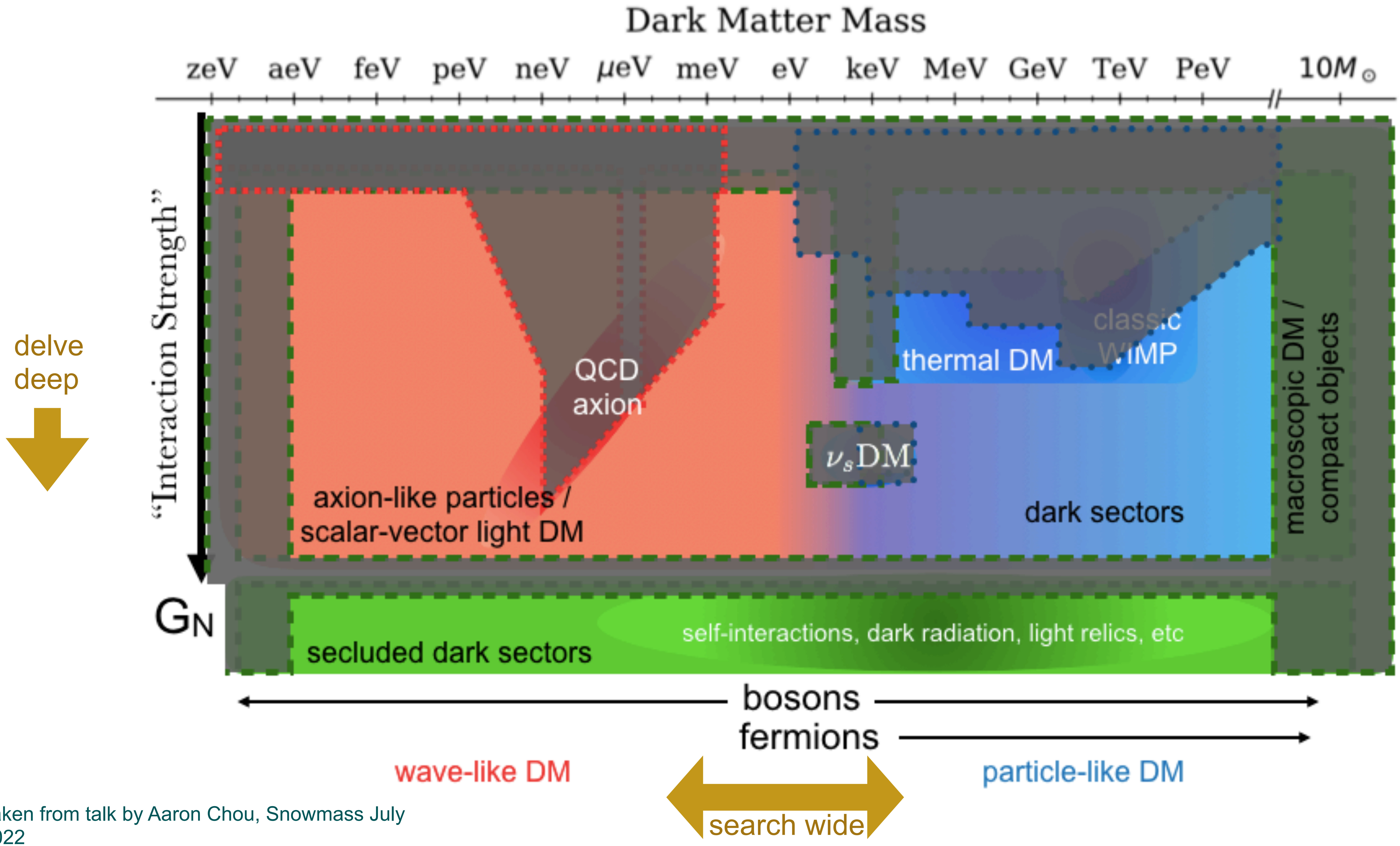

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