Dark Matter: Knowns and Unknowns

Tracy Slatyer

ICRC 2021
14 July 2021

U.S. DEPARTMENT OF ENERGY | Office of Science

Outline

- Review of long-standing evidence for DM
- Low-mass DM: limits on fuzzy DM and searches for light cold bosonic DM
- The thermal window: review of mass range, discussion of current constraints
- Very heavy DM and primordial black holes
- A brief update on some anomalies/excesses

What is dark matter?

We know it:

What is dark matter?

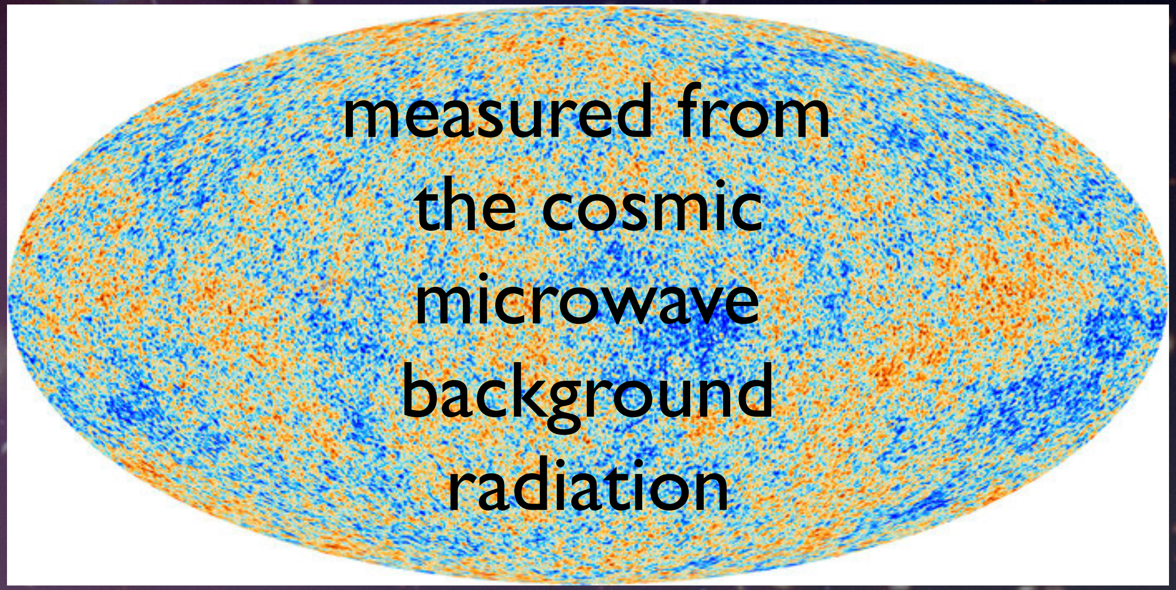
We know it:

- Doesn't scatter/emit/absorb light (really "transparent matter"!) but does have mass (and hence gravity).

What is dark matter?

We know it:

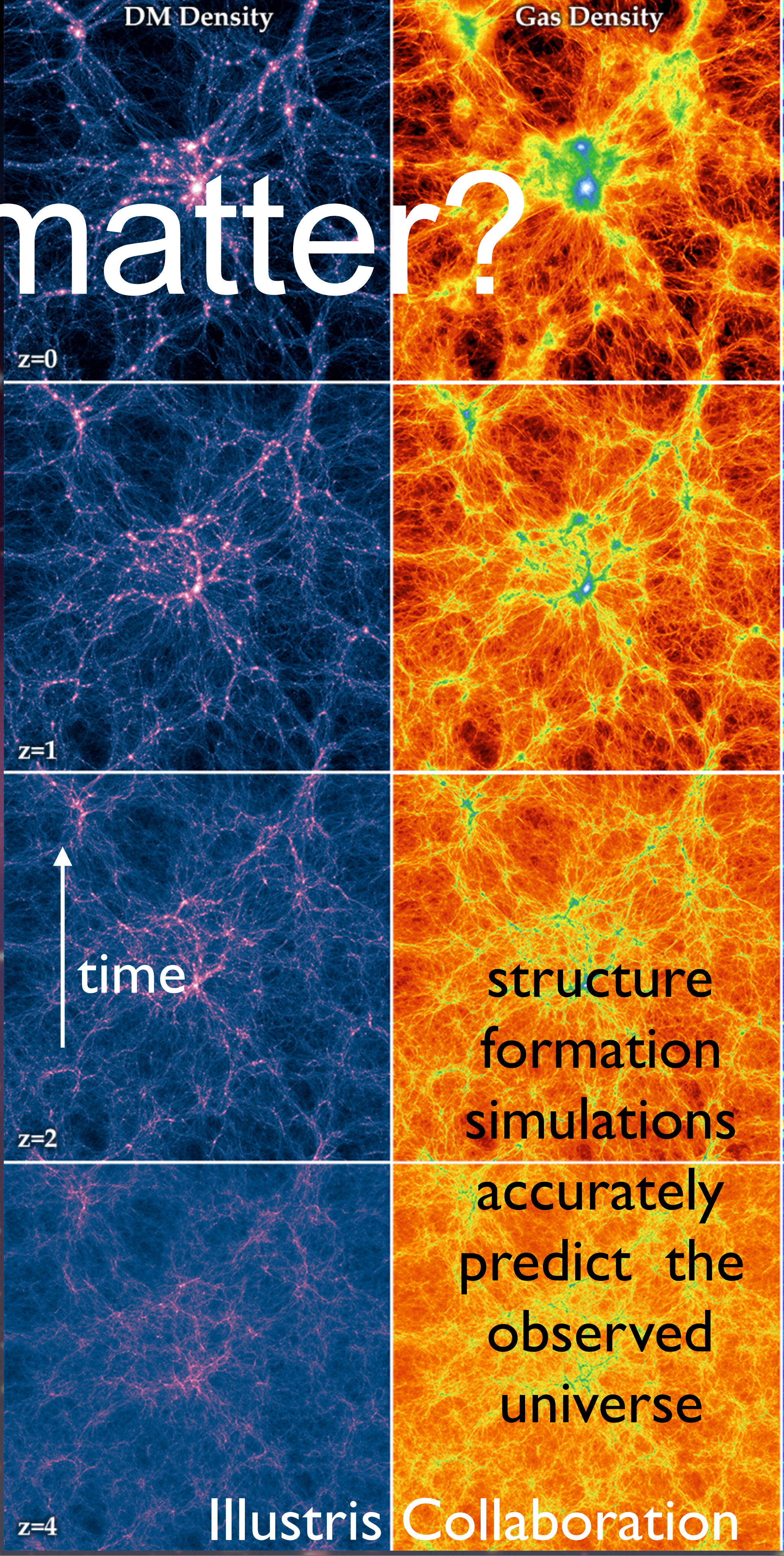
- Doesn't scatter/emit/absorb light (really "transparent matter"!) but does have mass (and hence gravity).
- Is ~84% of the matter in the universe.



What is dark matter?

We know it:

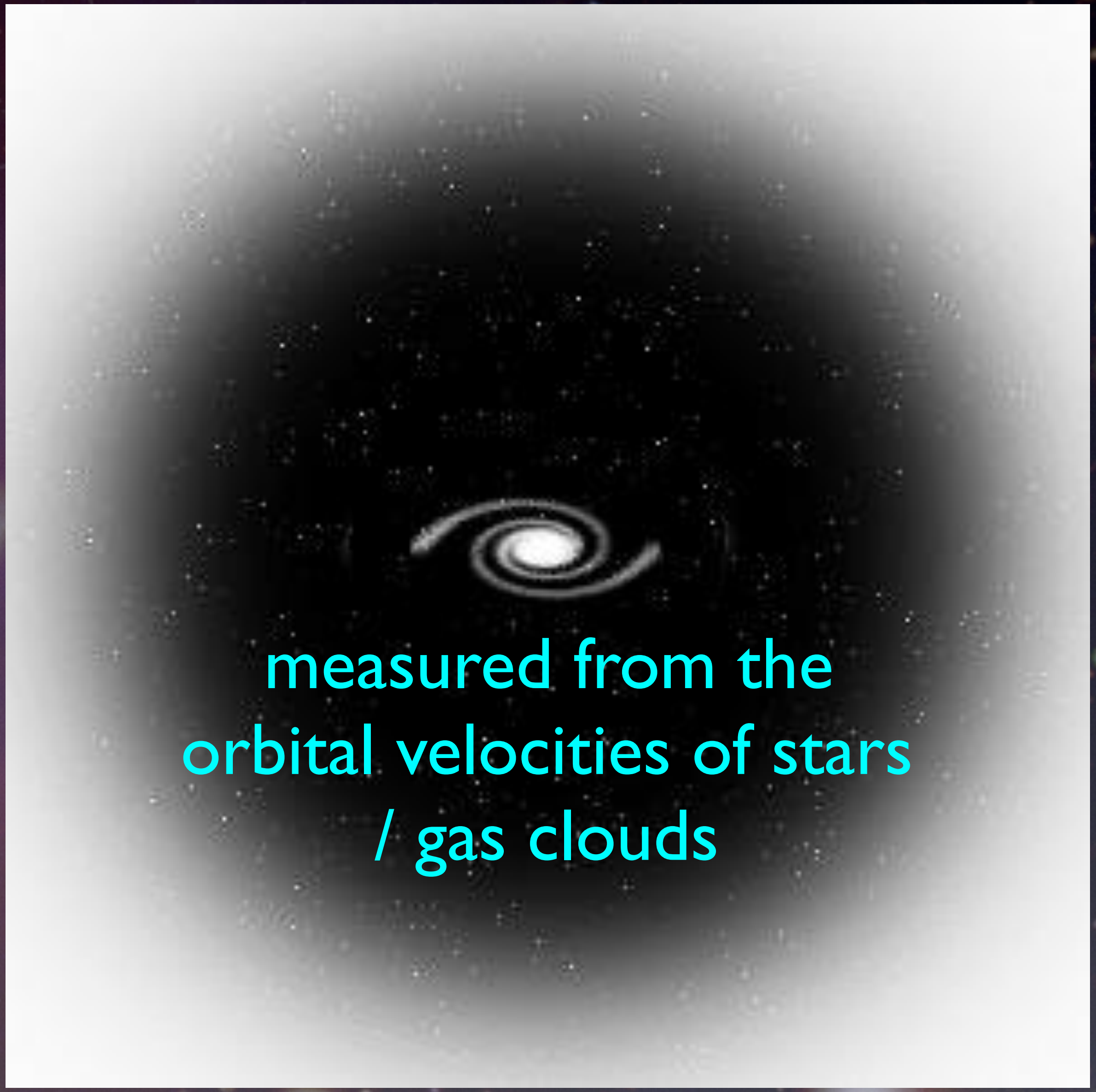
- Doesn't scatter/emit/absorb light (really "transparent matter"!) but does have mass (and hence gravity).
- Is ~84% of the matter in the universe.
- Forms the primordial "scaffolding" for the visible universe, which we can predict and map with increasing precision.



What is dark matter?

We know it:

- Doesn't scatter/emit/absorb light (really "transparent matter"!) but does have mass (and hence gravity).
- Is ~84% of the matter in the universe.
- Forms the primordial "scaffolding" for the visible universe, which we can predict and map with increasing precision.
- Forms large clouds or "halos" around galaxies.



What is dark matter?

We know it:

- Doesn't scatter/emit/absorb light (really "transparent matter"!) but does have mass (and hence gravity).
- Is ~84% of the matter in the universe.
- Forms the primordial "scaffolding" for the visible universe, which we can predict and map with increasing precision.
- Forms large clouds or "halos" around galaxies.
- Interacts with other particles weakly or not at all (except by gravity).

null results of
existing searches

What is dark matter?

We know it:

What is dark matter?

We know it:

- Consequently, cannot be explained solely within the Standard Model

What is dark matter?

We know it:

- Consequently, cannot be explained solely within the Standard Model

- Neutrinos are the best candidate, but are too fast-moving to form structure as observed

What is dark matter?

We know it:

- Consequently, cannot be explained solely within the Standard Model
- Neutrinos are the best candidate, but are too fast-moving to form structure as observed

Open questions

- WHAT IS IT?

What is dark matter?

We know it:

- Consequently, cannot be explained solely within the Standard Model
- Neutrinos are the best candidate, 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…

What more can we learn from purely gravitational probes?

- Estimate the density and velocity distribution of DM in the MW and beyond - much recent progress on this front using stellar data, especially from Gaia [e.g. Banik et al ’19, Bonaca et al ’19, Buch et al ’19, Posti et al ’19, Necib et al ’19, ’20] - mapping shape of DM halo, measuring local density, probing substructure, mapping out contributions to the velocity distribution

- Set bounds on the lifetime of DM from modifications to the cosmic microwave background radiation if the DM decays during/after recombination - no more than 3.8% of the DM can decay between recombination and the present day [Poulin et al ’16]

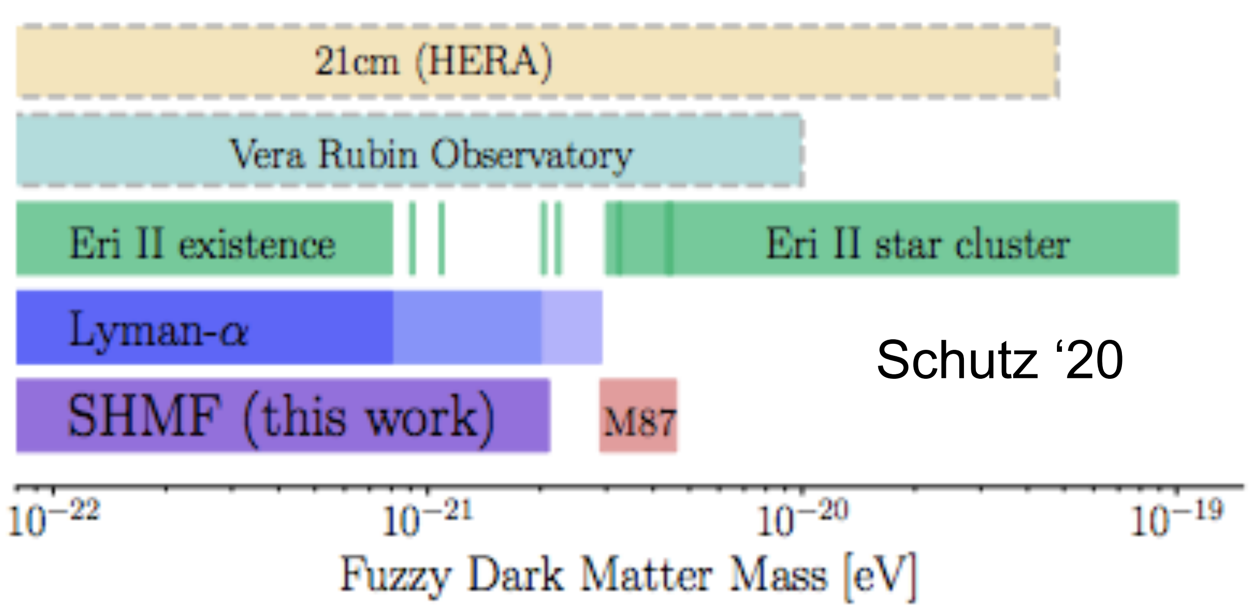
- Set upper bounds on DM-DM interactions [e.g. Bondarenko et al ’21, Andrade et al arXiv:2012.06611]

- Set limits on DM-SM interactions - although typically there are (much) stronger limits from searching for those interactions directly

- Set limits on the mass and velocity of individual DM particles

How light can DM be?

- Sufficiently light DM can have a wavelength large enough to modify observed sub-galactic structure - “fuzzy DM”
- The minimum DM mass is thus controlled by the smallest-scale DM structures we can observe
- Multiple approaches to mapping the smallest halos:
  - Lyman-α forest (probes matter clumpiness at z~2-6) [e.g. Armengaud et al ’17, Irsic et al ’17, Nori et al ’19]
  - Fluctuations in the linear density of stellar streams (perturbed by DM subhalos) [Banik et al ’19]
  - Strong gravitational lensing of quasars [Hsueh et al ’19, Gilman et al ’19]
  - Observations of faint MW satellite galaxies [e.g. Nadler et al ’19]
- Current limits on fuzzy DM:
  $m_{\rm DM} \gtrsim 2 - 3 \times 10^{-21}$eV [Schutz ’20]



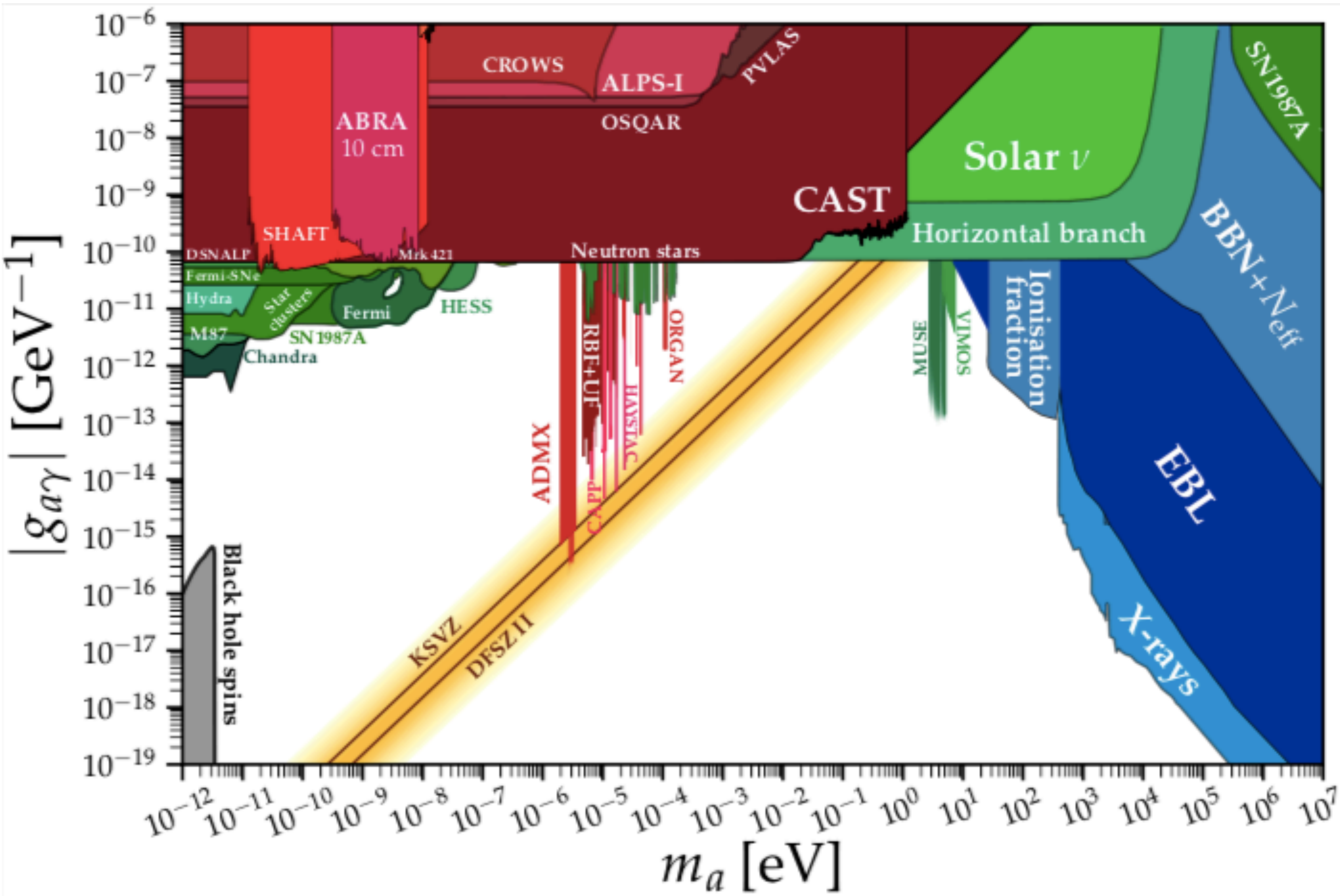
Schutz ‘20

How fast can DM be?

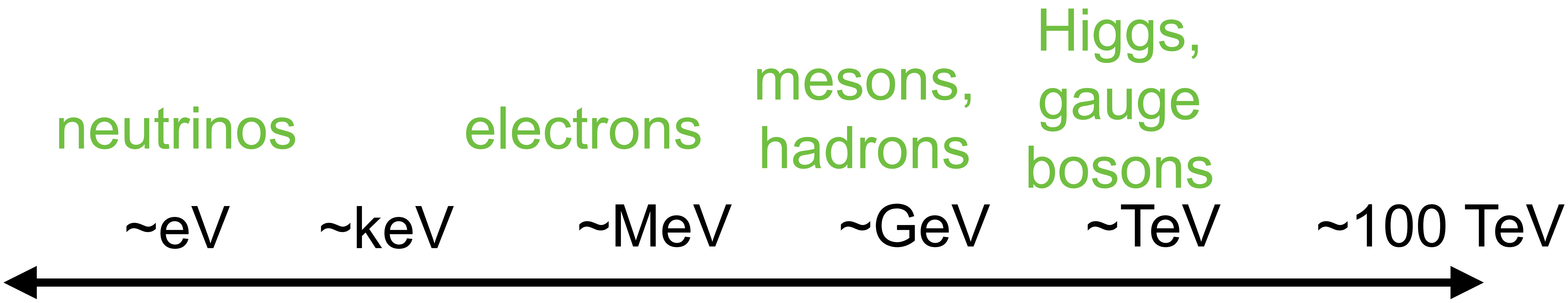
- The same observations of small halos tell us DM cannot be too fast-moving - a large free-streaming length would disrupt small-scale structure
- If DM is in thermal contact with the SM, heating from the thermal bath would ensure too-light DM is fast-moving during structure formation
- Current bounds exclude such "warm dark matter” candidates lighter than 3-6 keV (through the analyses described on the previous slide)
- Tremaine-Gunn bound: DM phase-space density in small galaxies requires sub-keV DM to be bosonic (fermions cannot attain a high enough density due to Pauli exclusion) [e.g. Boyarsky ’09]
- Thus light (<< keV) DM must be both non-thermal and bosonic - huge range of parameter space open down to 10^{-21} eV, classic example model is the axion.
- Relevant limits from dedicated axion-search experiments, direct detection, cosmology, astrophysics (e.g. observations of supernovae and neutron stars), etc

Axion limits

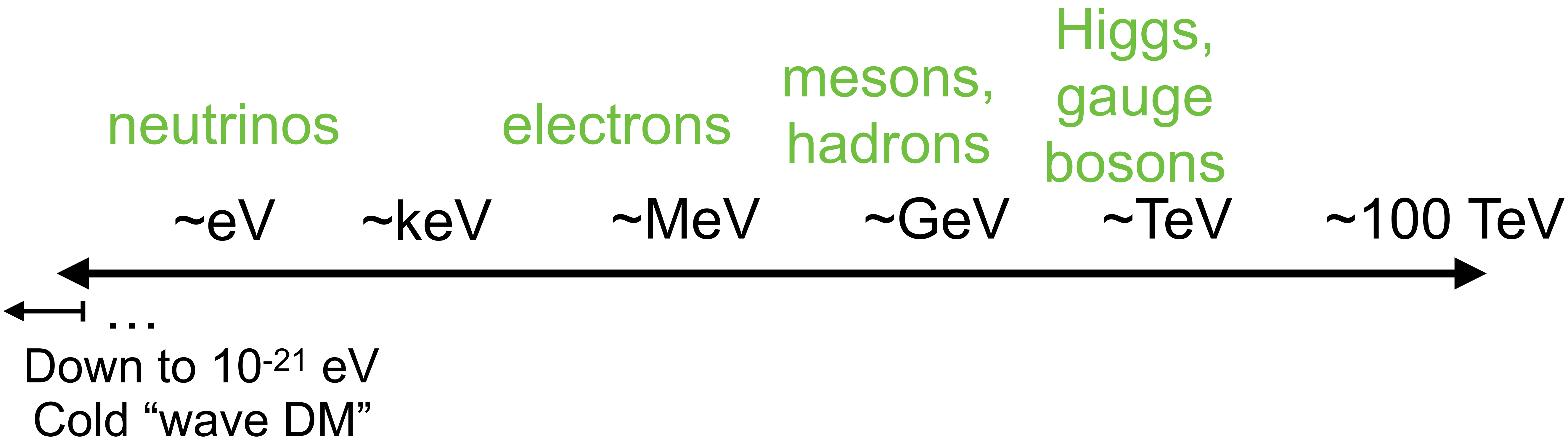
(credit https://cajohare.github.io/AxionLimits/)



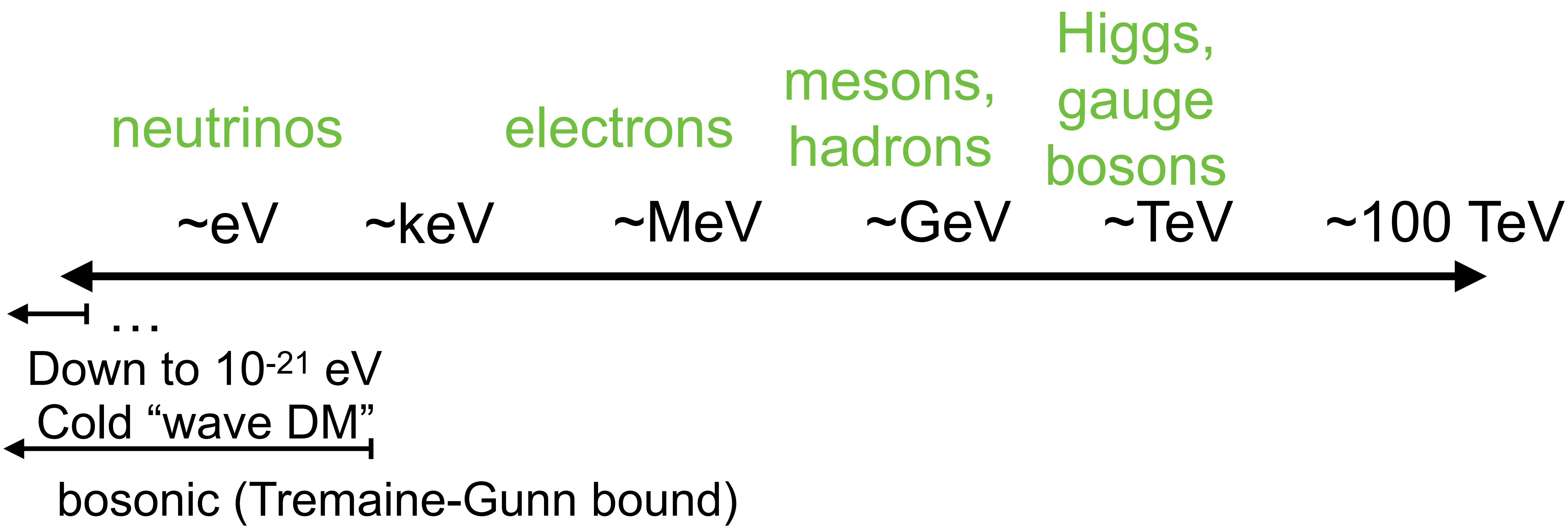
What is the DM mass?



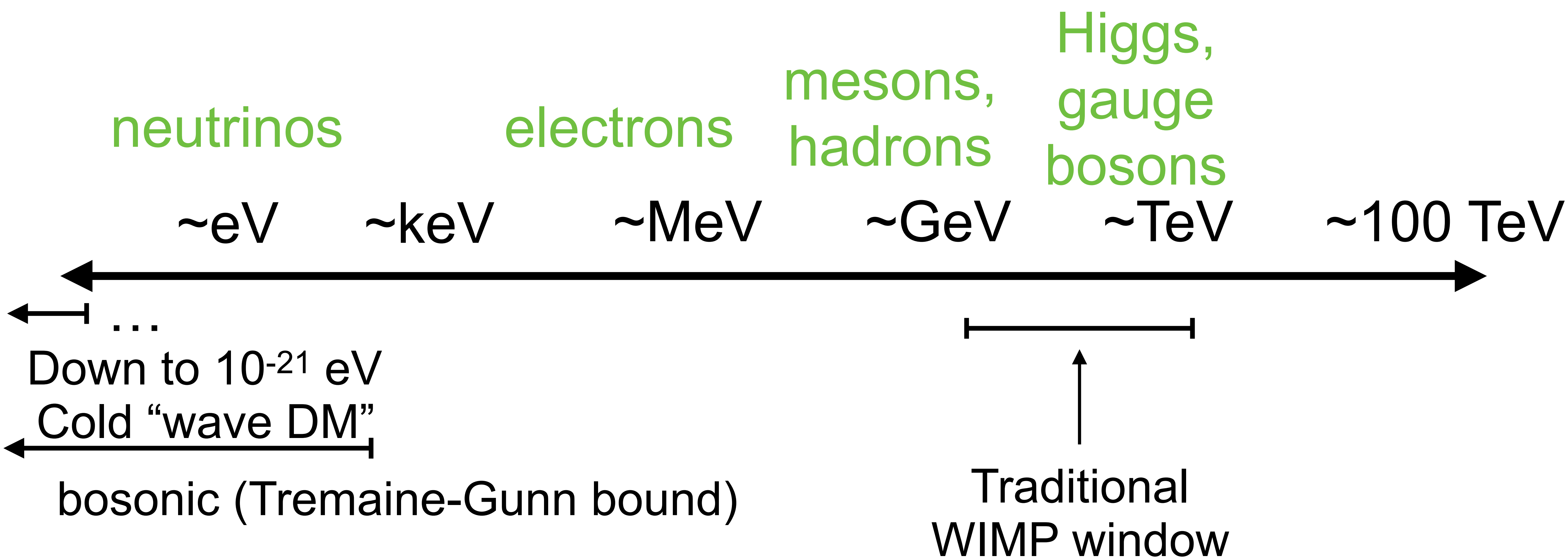
What is the DM mass?



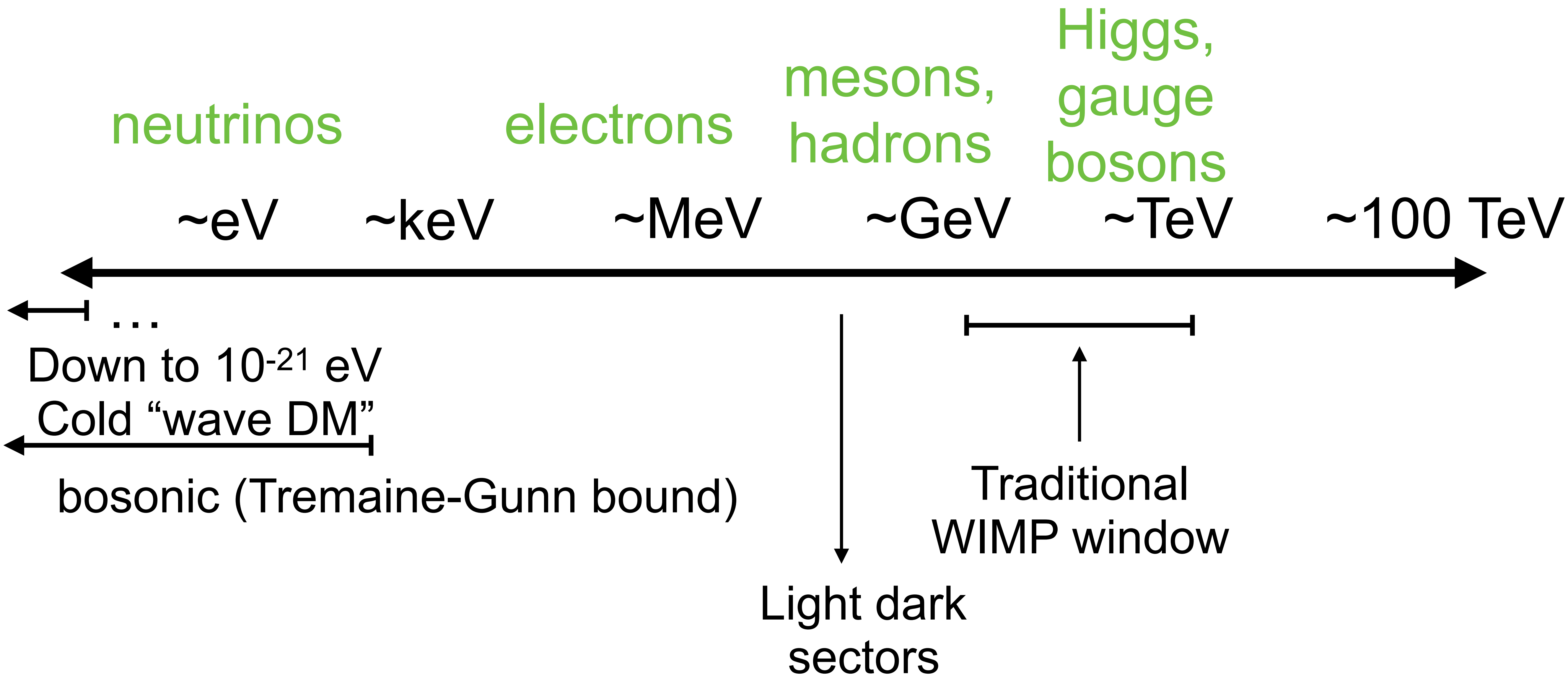
What is the DM mass?



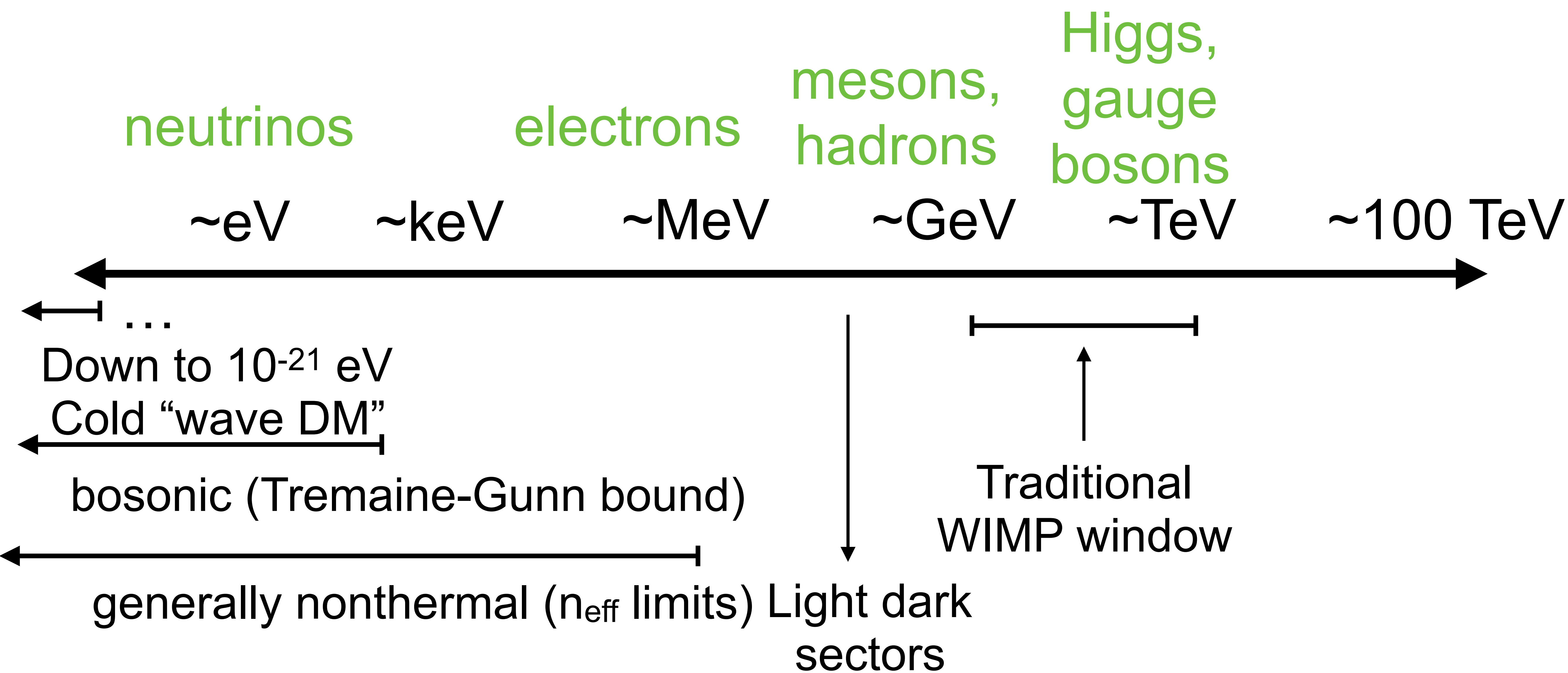
What is the DM mass?



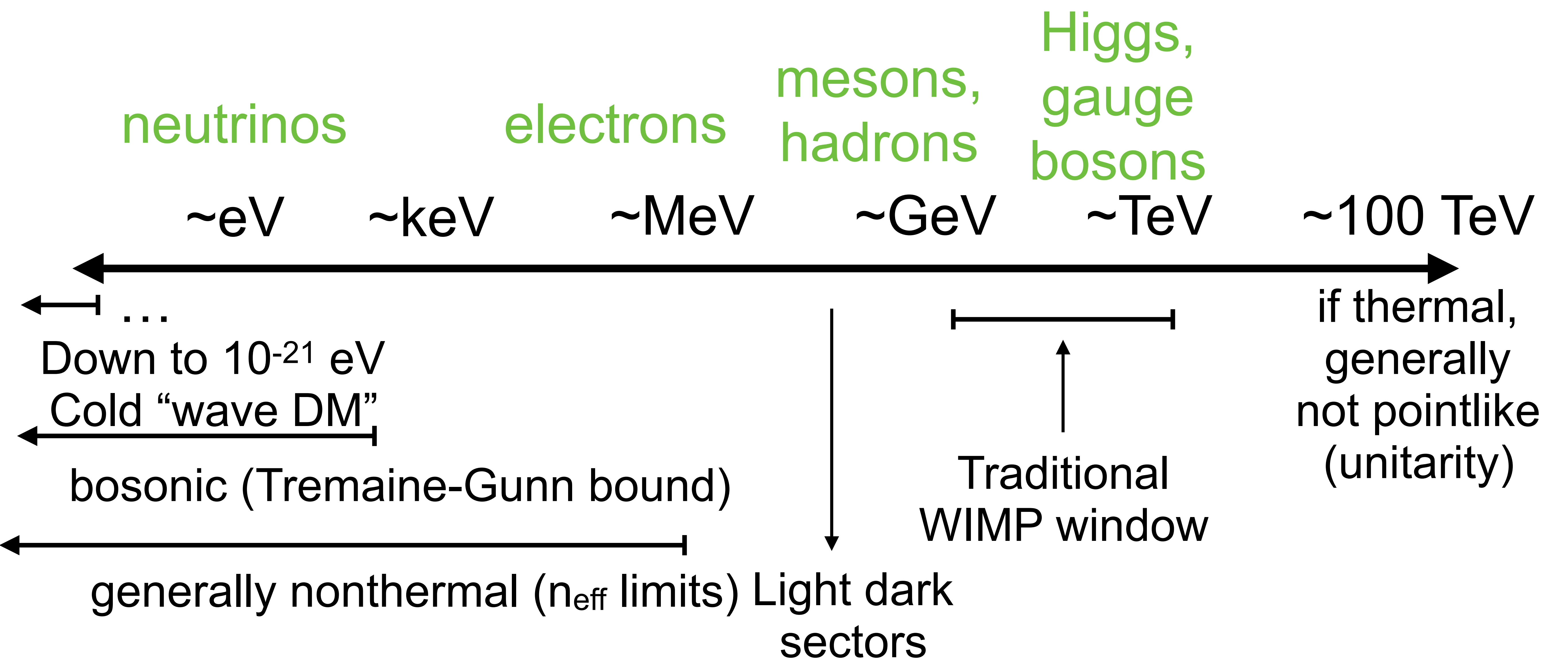
What is the DM mass?



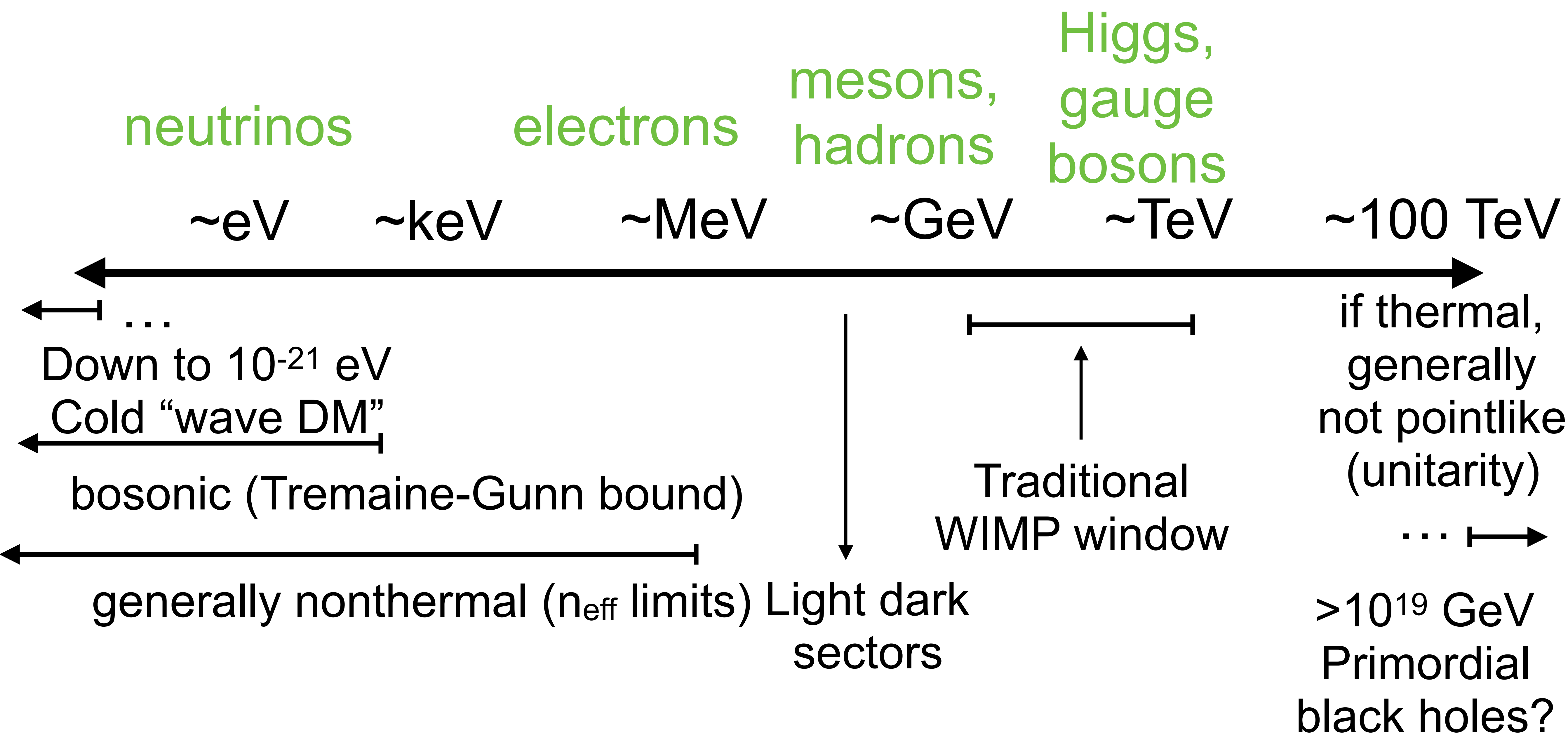
What is the DM mass?



What is the DM mass?



What is the DM mass?



The thermal window

- Where did the DM abundance come from?

- 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:

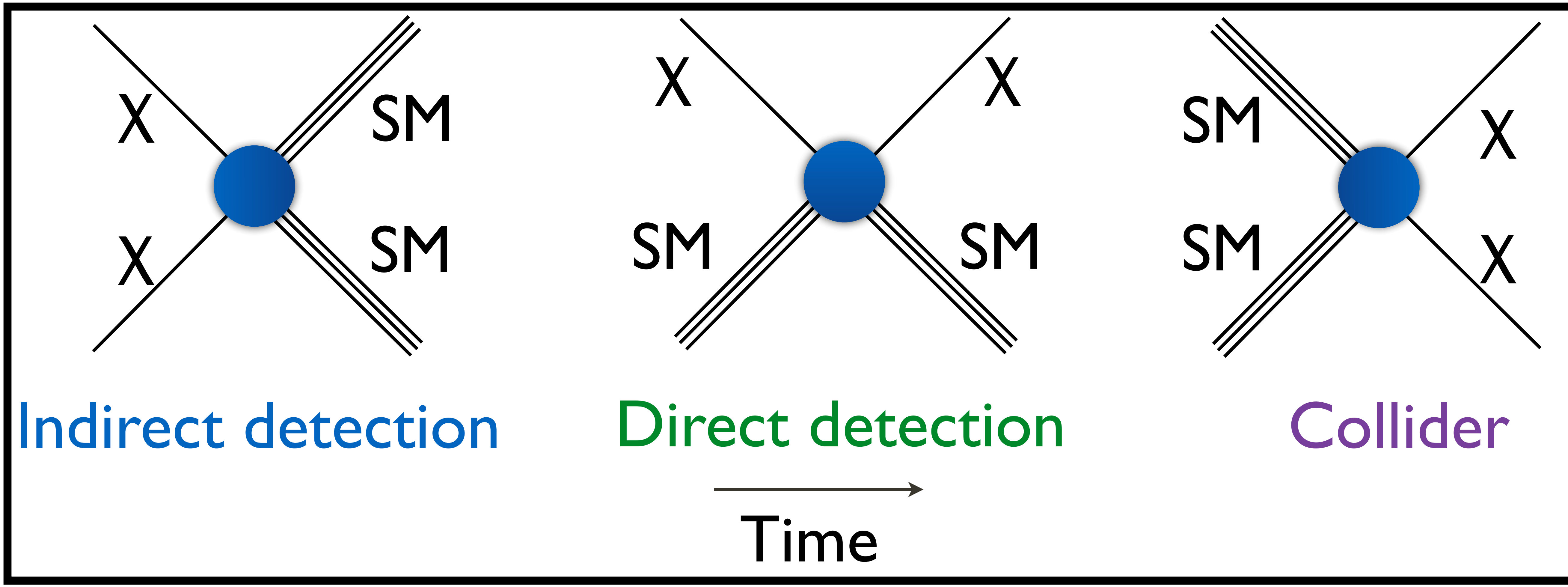
$$\langle \sigma v \rangle \approx 2 \times 10^{-26} \mathrm{cm}^3/s \approx \frac{1}{(25\mathrm{TeV})^2} \sim \frac{1}{m_{\mathrm{Pl}} T_{\mathrm{eq}}}$$

- 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 required annihilation rate becomes impossible to attain (in standard cosmology), exceeds upper limit from unitarity

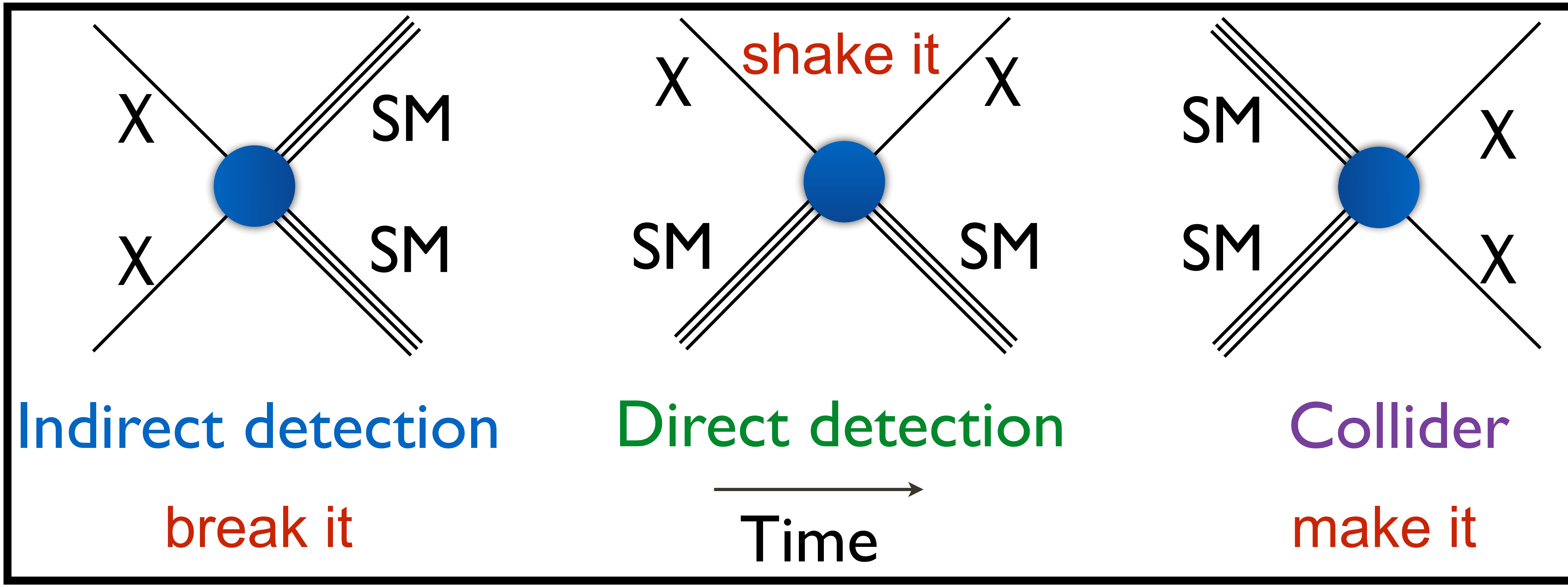
- Works for DM masses down to ~1 MeV, lighter DM usually modifies Big Bang nucleosynthesis → disrupts successful predictions for light-element abundances [e.g. Sabti et al '19]

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.
- Colliders: 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.

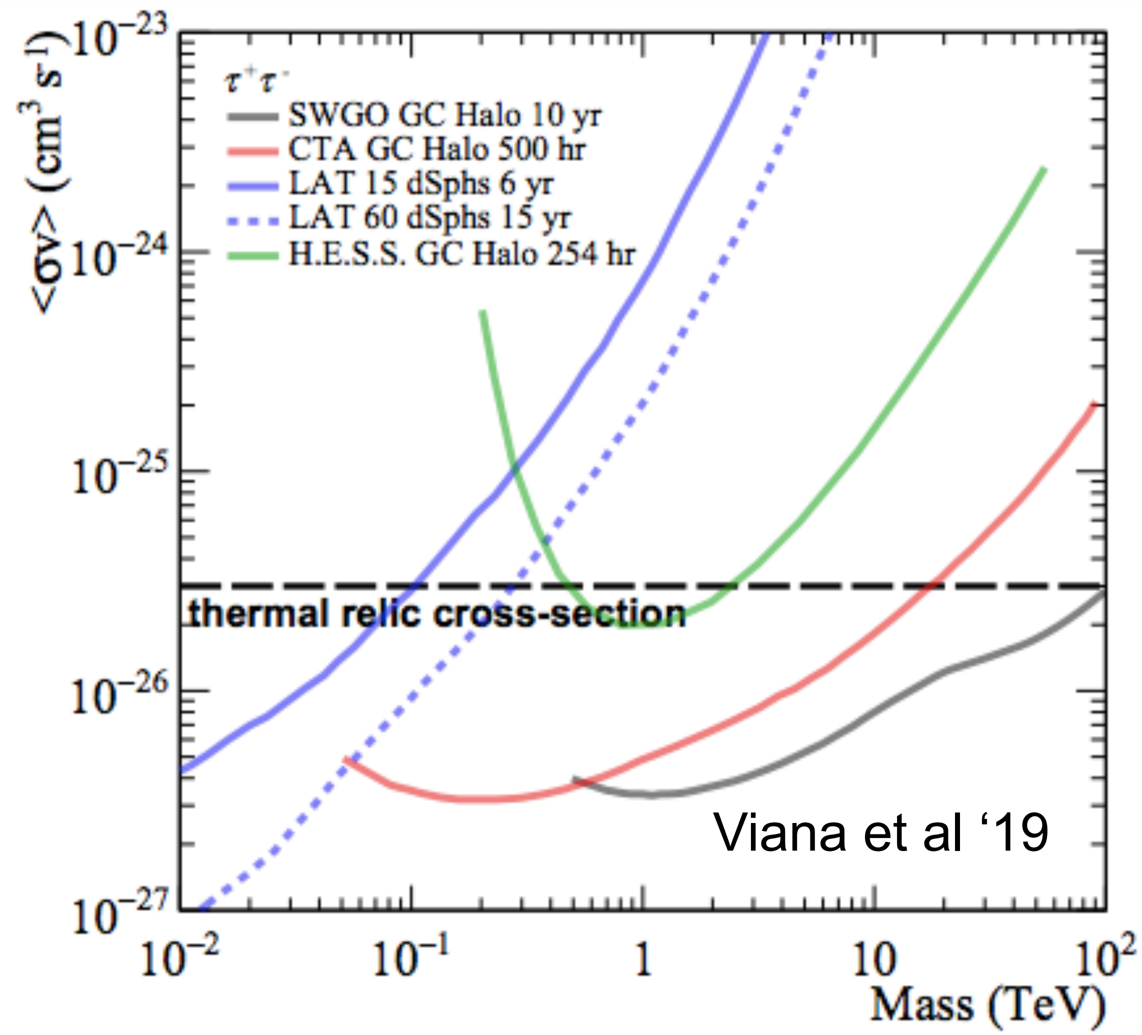
Classic WIMP searches

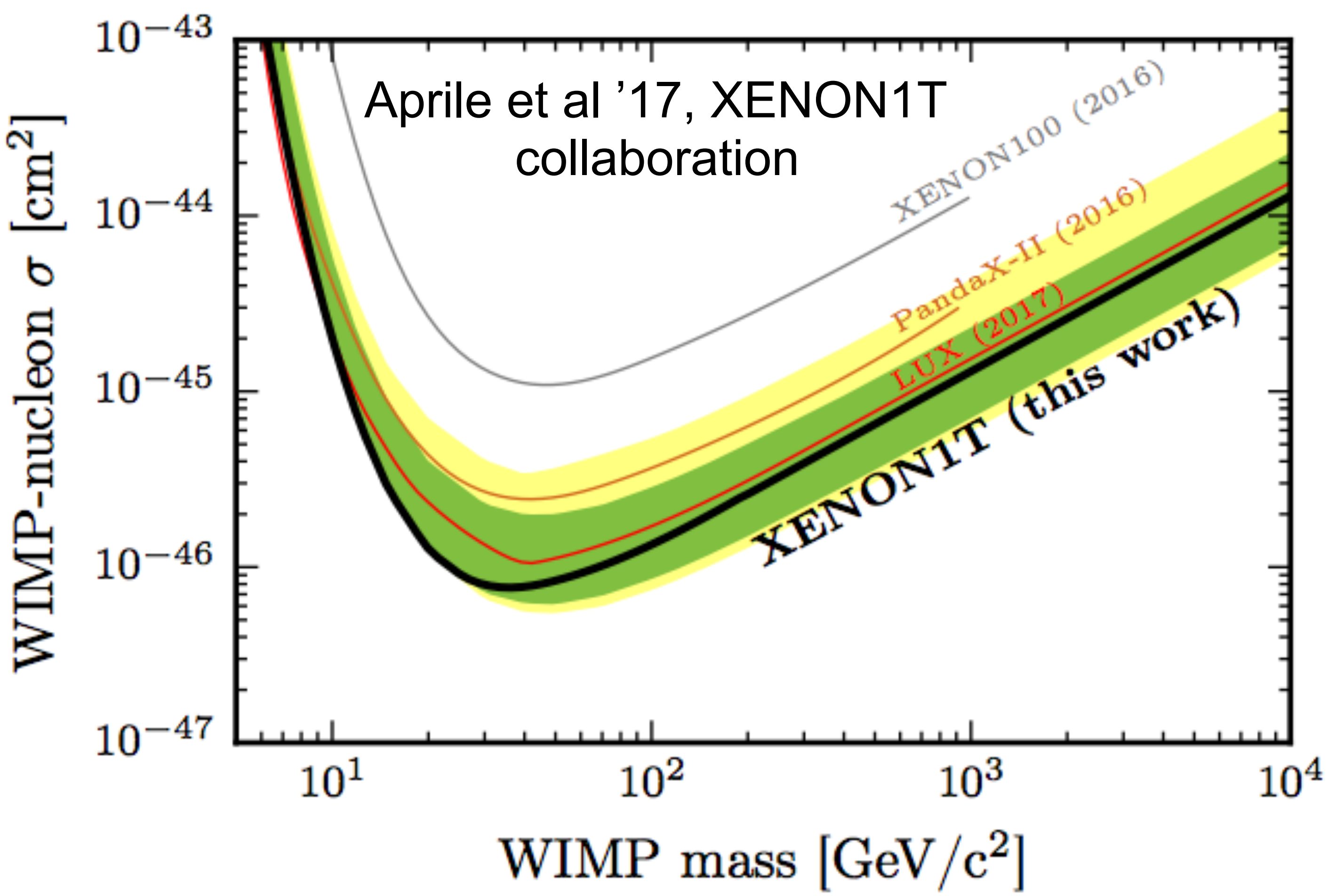


- Indirect detection: look for Standard Model particles - electrons/positrons, photons, neutrinos, protons/antiprotons - produced when dark matter particles collide or decay.
- Direct detection: look for atomic nuclei "jumping" when struck by dark matter particles, using sensitive underground detectors.
- Colliders: 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.

Limits on WIMPs

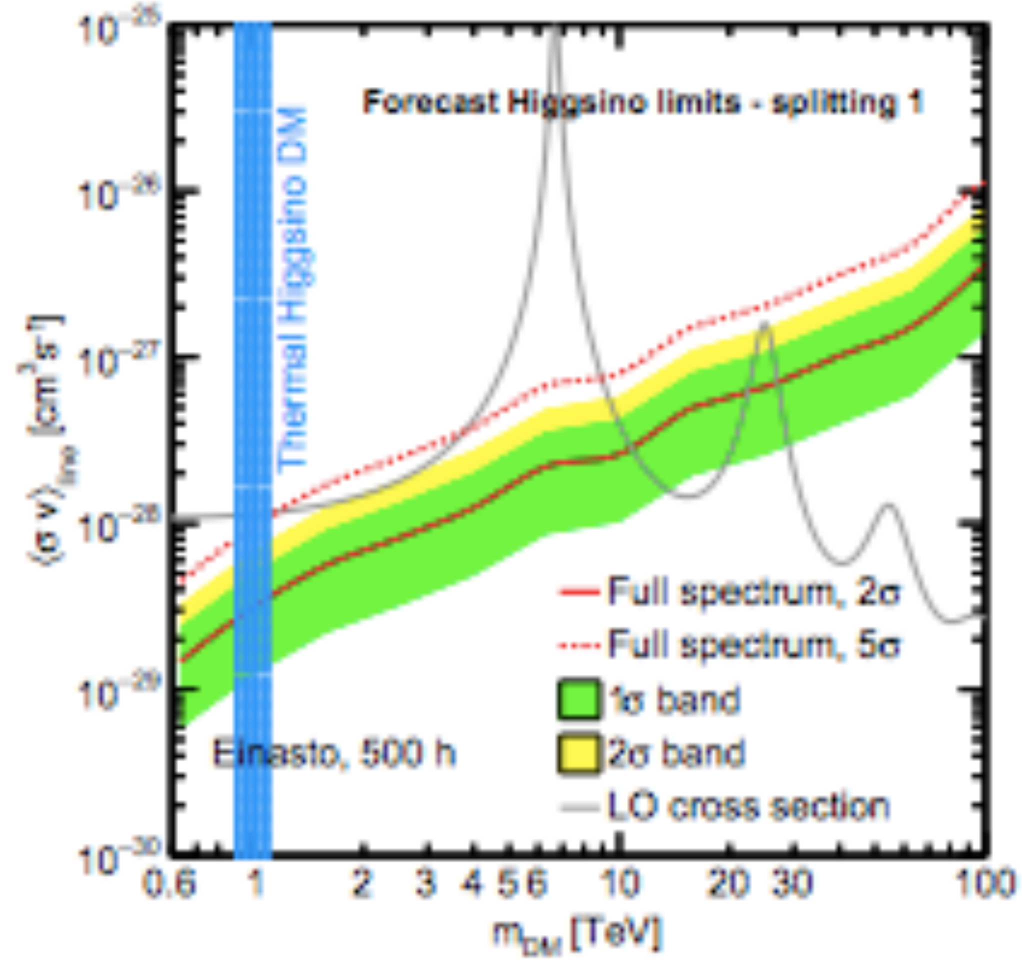
- There are stringent limits from all these searches - no robust detections yet.
- Limits from the CMB, gamma-ray and cosmic-ray experiments probe the thermal relic cross section up to DM masses of 10s-100s GeV, for all SM final states except neutrinos.
- Future experiments have the possibility of reaching this cross section for 10-100 TeV DM.
- Direct-detection experiments set very powerful bounds on the DM-baryon scattering cross section for 10+ GeV DM.



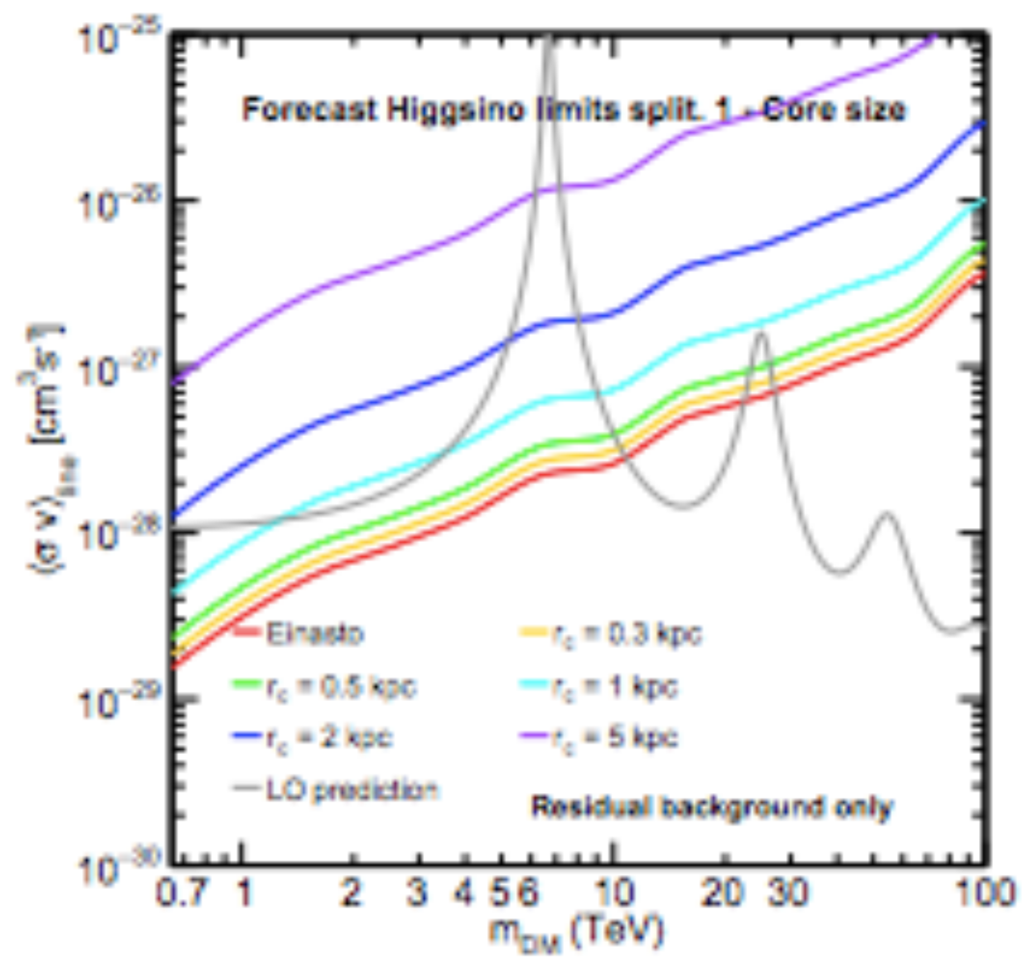


Electroweak DM

- At the same time, some of the simplest classic WIMP models remain unconstrained - DM could still interact through the W and Z bosons!
- One example is the <u>higgsino</u> - fermionic DM transforming as a $SU(2)_W$ doublet, appears in supersymmetry as the Higgs superpartner
- Obtains the correct relic density for m_{DM} ~ 1 TeV
- Direct detection signal is below neutrino floor; undetectable with current colliders
- Precise theory predictions for heavy electroweakinos require careful effective field theory analysis [e.g. Baumgart, TRS et al '19, Beneke et al '20]
- Potentially detectable in gamma rays with CTA, or with future colliders [e.g. Canepa et al '20, Capdevilla et al '21]



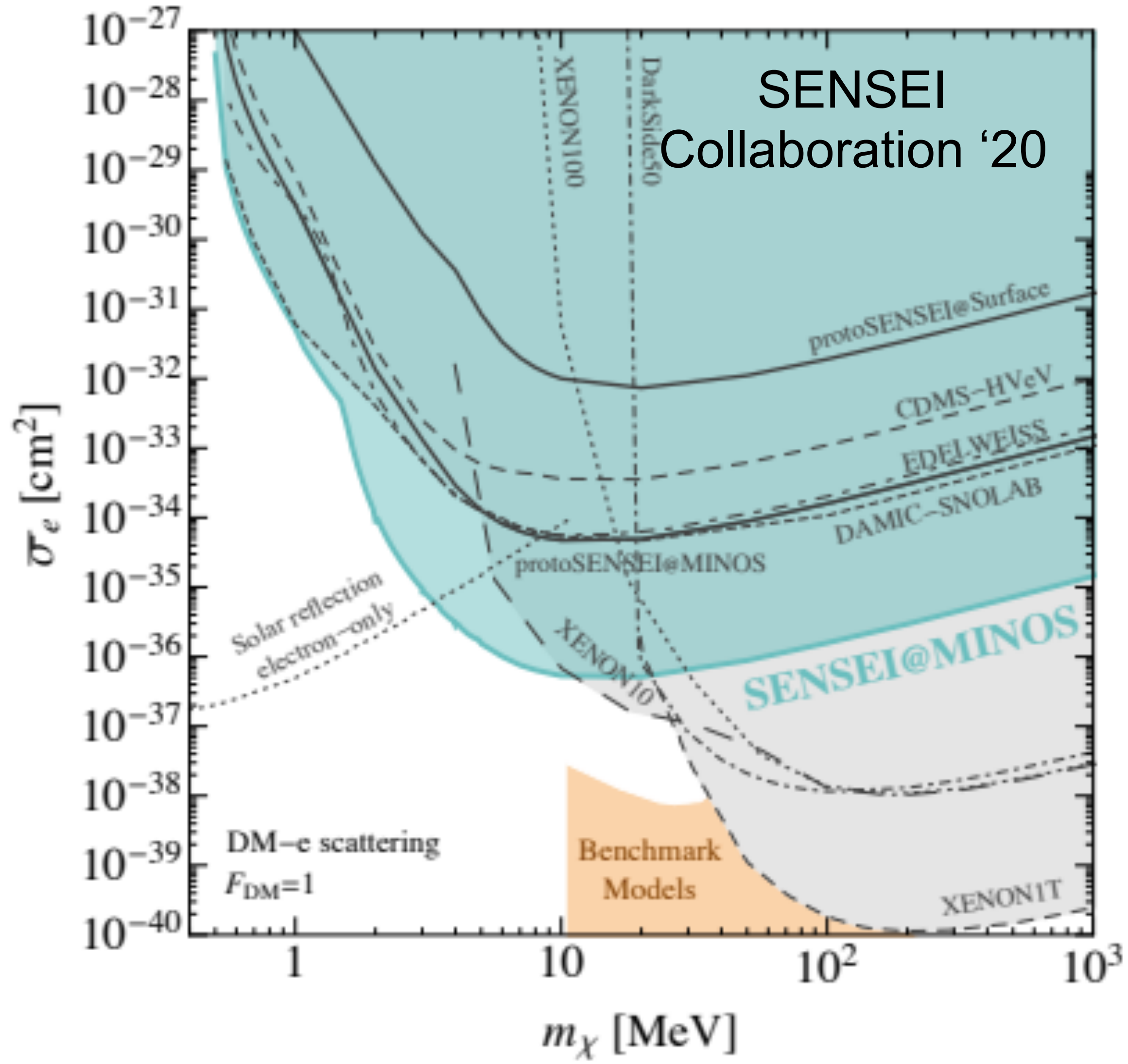
Rinchiuso, TRS et al '21

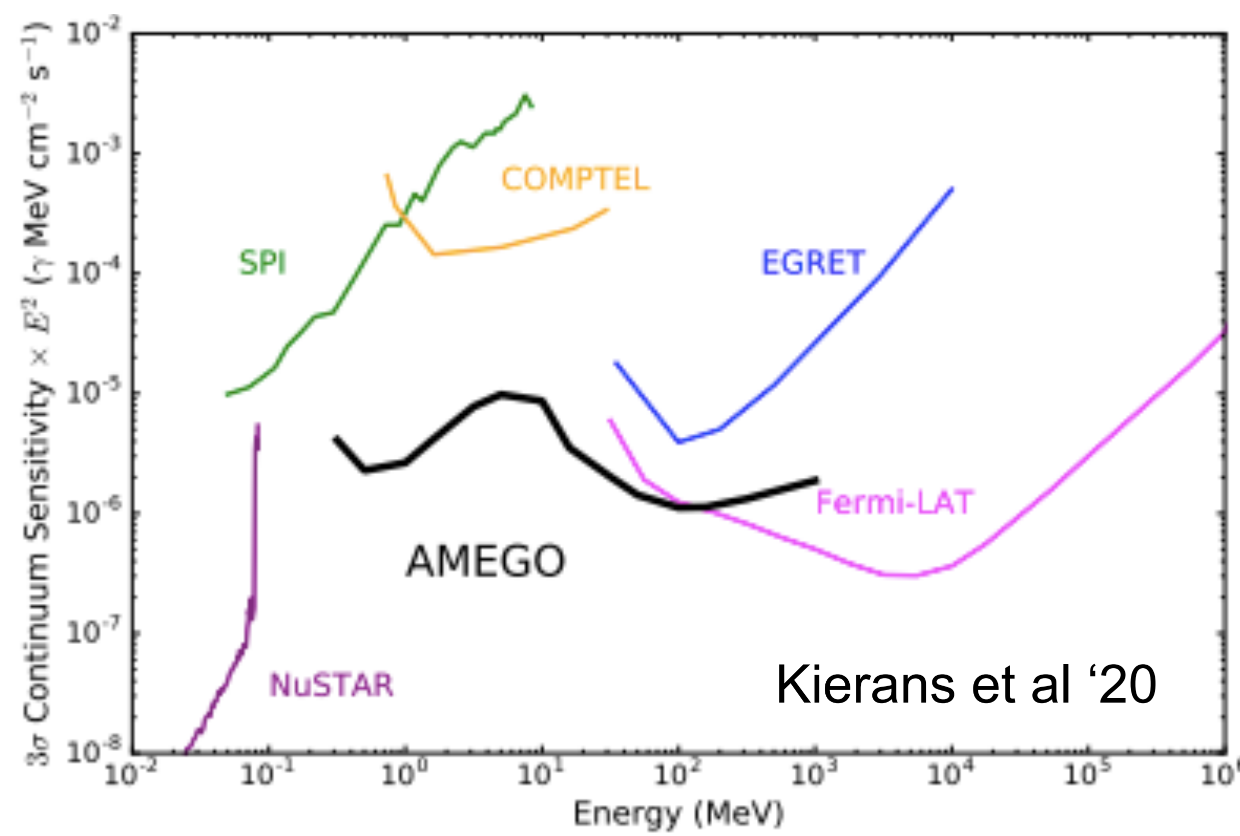


Low-mass thermal DM

- Classic direct detection experiments lose sensitivity for DM masses below 1-10 GeV, and accelerator-based searches often need to be redesigned
- Indirect limits remain very strong, but can be evaded if annihilation is suppressed (e.g. asymmetric DM, p-wave annihilation suppressed at low velocities, etc)
- MeV-GeV band is the focus of a huge amount of effort [e.g. Cosmic Visions report, Battaglieri et al '17] - many new direct-detection, accelerator-based searches
- In indirect detection, proposed missions such as AMEGO, GRAMS, GECCO, can cover the "MeV gap" in gamma-ray sensitivity

Example: constraints on DM-electron scattering





Above the thermal window: ultraheavy DM (theory)

- In the presence of a long-range force, contributions from bound state formation, high partial waves can saturate and extend the unitarity bound, up to ~PeV [e.g. von Harling & Petraki ’14, Smirnov & Beacom ’19]

- (Much) higher masses can be achievable for thermal relic DM when standard assumptions break down, e.g.:

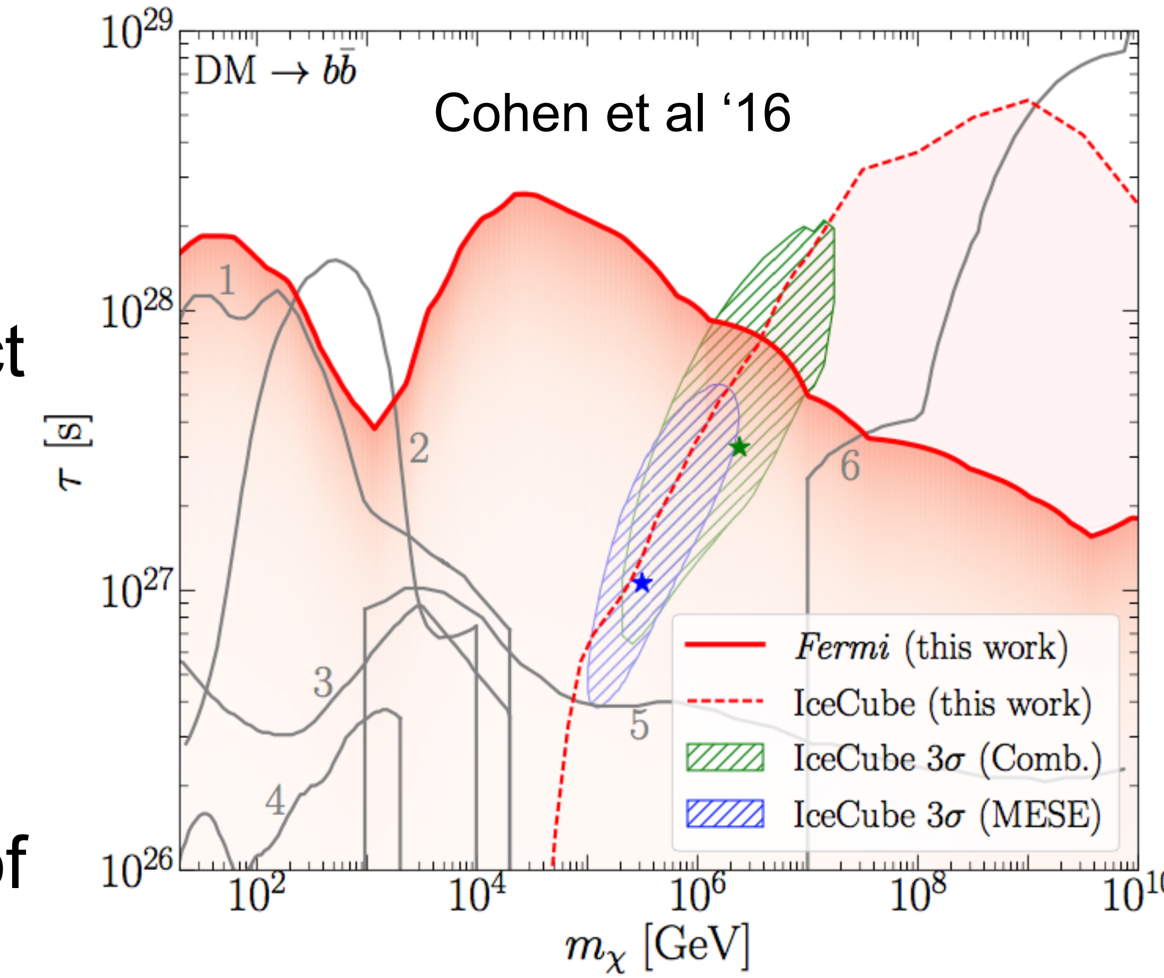
    - modified cosmology: large entropy injections, or a first-order phase transition in the dark sector [e.g. Asadi, TRS et al ’21]

    - formation of many-particle bound states after freezeout [e.g. Coskuner et al ’19, Bai et al ‘19] - can lead to macroscopic DM candidates

- Non-thermal production mechanisms (e.g. out-of-equilibrium decay of a heavier state) are also possible

Ultraheavy DM (observation)

- Very difficult to probe at colliders, but direct & indirect searches can have sensitivity
- Existing photon/neutrino observations constrain decaying DM up to very high masses (due to non-observation of lower-energy secondary particles), for lifetimes of $10^{27\text{-}28}$ s



- Observations of ultra-high-energy CRs and photons could also provide sensitivity to these heavy DM candidates [e.g. Berezinsky et al '97, Romero-Wolf et al '20, Anchordoqui et al '21]
- Macroscopic DM could have striking signatures in direct-detection experiments and large-volume 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]

Primordial black holes (PBHs) as dark matter

- General idea: black holes can be formed from inhomogeneities in the high-density early universe [see Carr et al 2002.12778 for a recent review containing more comprehensive references].

- Black holes are electrically neutral (or quickly become so) and interact primarily via gravity.

- Sufficiently heavy black holes have a lifetime >> age of the universe.

- Black holes would be heavy, non-relativistic "particles", and would play the cosmological role of DM provided they are formed well before matter-radiation equality - hence only primordial BHs are viable DM candidates, not those formed from stars.

- Perhaps the most plausible DM scenario that does not require DM to be comprised of new particles beyond the Standard Model (although probably requires a non-minimal inflation model or other BSM physics).

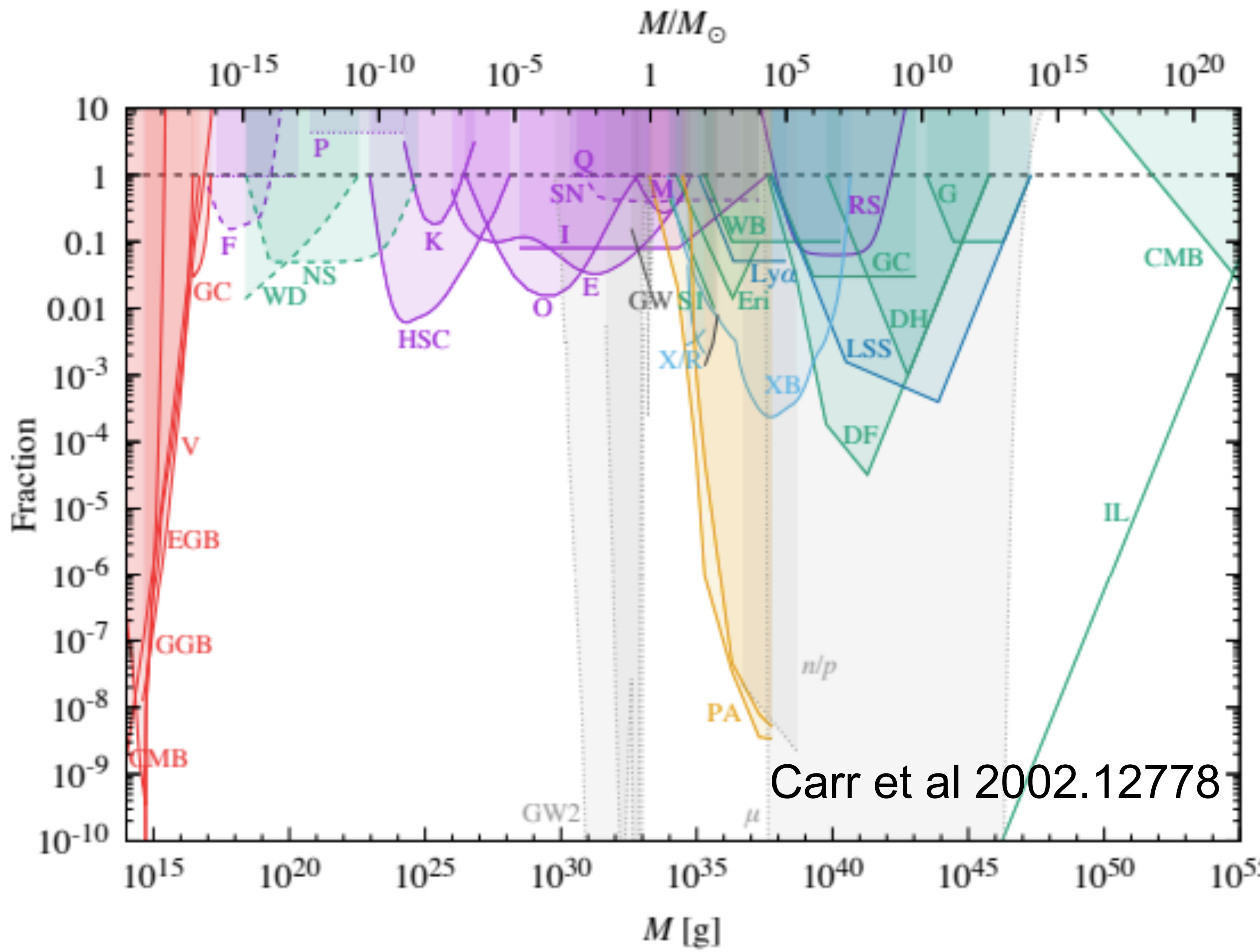
- PBHs are decaying DM - they slowly decay through Hawking radiation (with temperatures far less than the BH mass), PBHs in an observationally interesting mass range can produce X-ray and soft gamma-ray radiation.

Constraints on PBHs as DM

- Too-light PBHs evaporate via Hawking radiation - null searches for the radiation constrain lifetimes longer than the age of the universe

$$T_{\rm BH} = \frac{M_{\rm Pl}^2}{8\pi M} \qquad \tau \sim \frac{M^3}{M_{\rm Pl}^2}$$

- Over a wide mass range, PBHs can be probed with a combination of gravitational lensing + dynamical effects in astrophysical systems



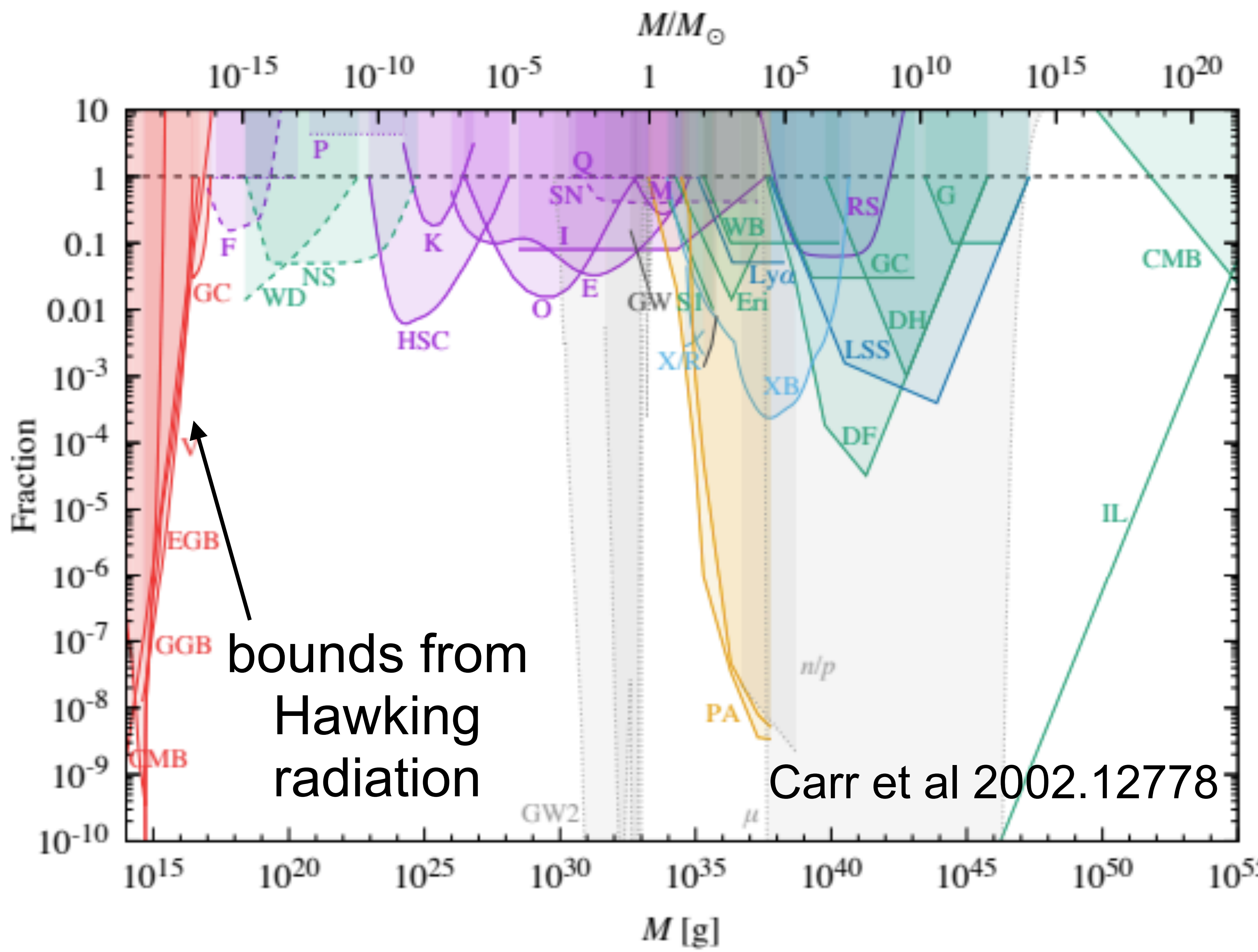
- Dashed lines = constraints have been proposed, but are not reliable or have been refuted
- There is an open window for f=1 (all DM=PBHs) from M~10^{17}-10^{23}g

Constraints on PBHs as DM

- Too-light PBHs evaporate via Hawking radiation - null searches for the radiation constrain lifetimes longer than the age of the universe

$$T_{\rm BH} = \frac{M_{\rm Pl}^2}{8\pi M} \qquad \tau \sim \frac{M^3}{M_{\rm Pl}^2}$$

- Over a wide mass range, PBHs can be probed with a combination of gravitational lensing + dynamical effects in astrophysical systems



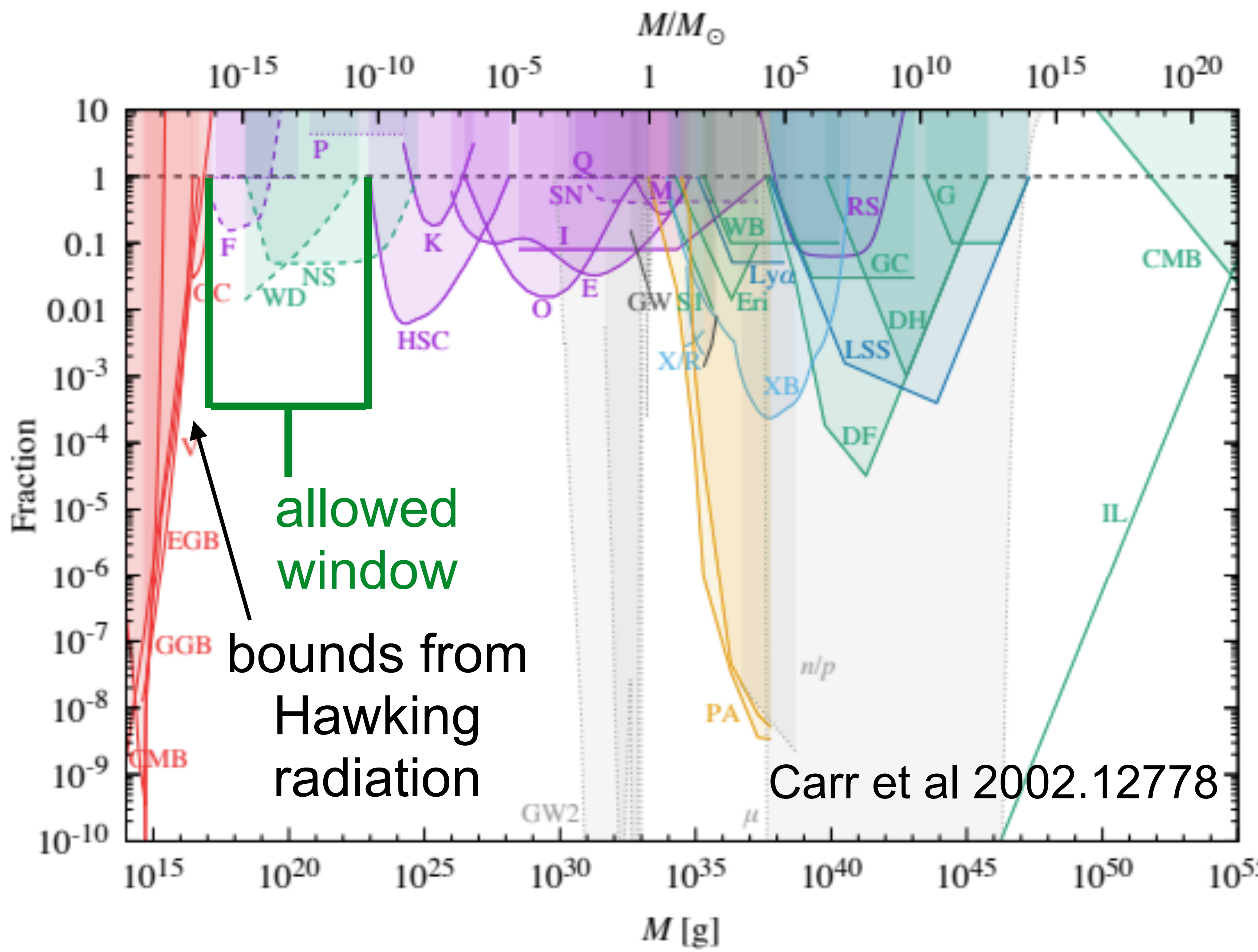
- Dashed lines = constraints have been proposed, but are not reliable or have been refuted
- There is an open window for f=1 (all DM=PBHs) from M~10^{17}-10^{23}g

Constraints on PBHs as DM

- Too-light PBHs evaporate via Hawking radiation - null searches for the radiation constrain lifetimes longer than the age of the universe

$$T_{\rm BH} = \frac{M_{\rm Pl}^2}{8\pi M} \qquad \tau \sim \frac{M^3}{M_{\rm Pl}^2}$$

- Over a wide mass range, PBHs can be probed with a combination of gravitational lensing + dynamical effects in astrophysical systems



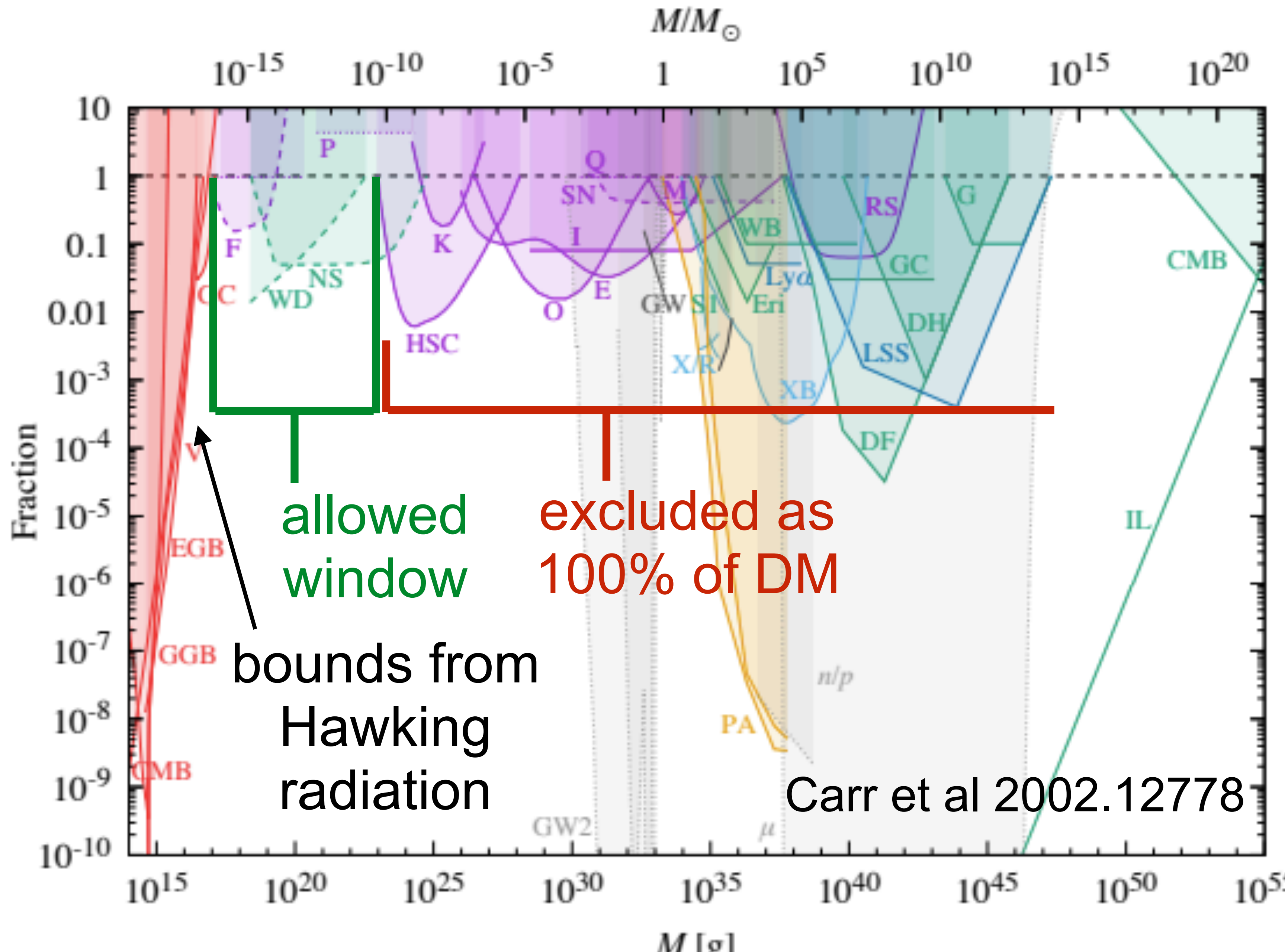
- Dashed lines = constraints have been proposed, but are not reliable or have been refuted
- There is an open window for f=1 (all DM=PBHs) from M~10^{17}-10^{23}g

Constraints on PBHs as DM

- Too-light PBHs evaporate via Hawking radiation - null searches for the radiation constrain lifetimes longer than the age of the universe

$$T_{\rm BH} = \frac{M_{\rm Pl}^2}{8\pi M} \qquad \tau \sim \frac{M^3}{M_{\rm Pl}^2}$$

- Over a wide mass range, PBHs can be probed with a combination of gravitational lensing + dynamical effects in astrophysical systems



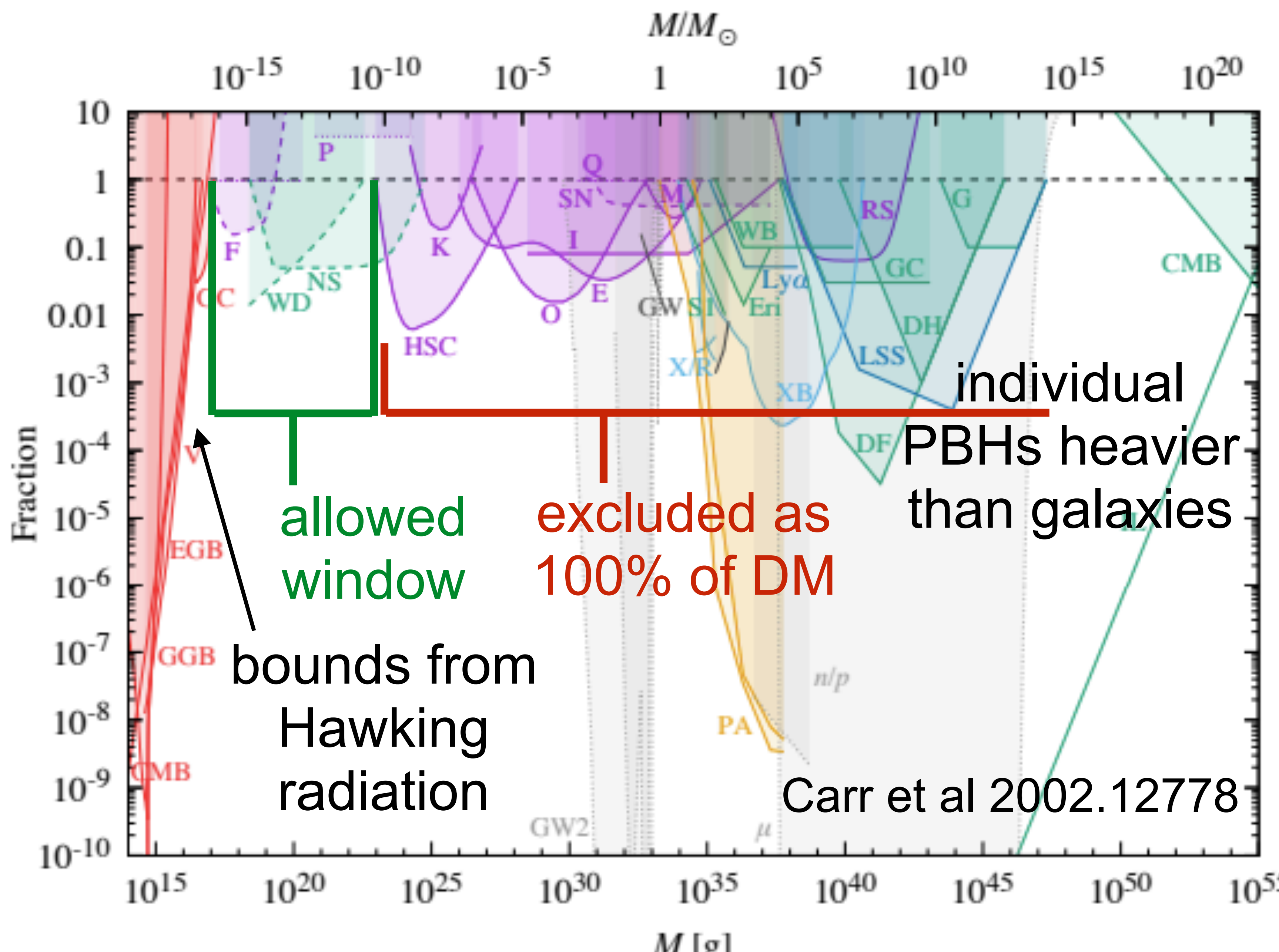
- Dashed lines = constraints have been proposed, but are not reliable or have been refuted
- There is an open window for f=1 (all DM=PBHs) from M~10^{17}-10^{23}g

Constraints on PBHs as DM

- Too-light PBHs evaporate via Hawking radiation - null searches for the radiation constrain lifetimes longer than the age of the universe

$$T_{\rm BH} = \frac{M_{\rm Pl}^2}{8\pi M} \qquad \tau \sim \frac{M^3}{M_{\rm Pl}^2}$$

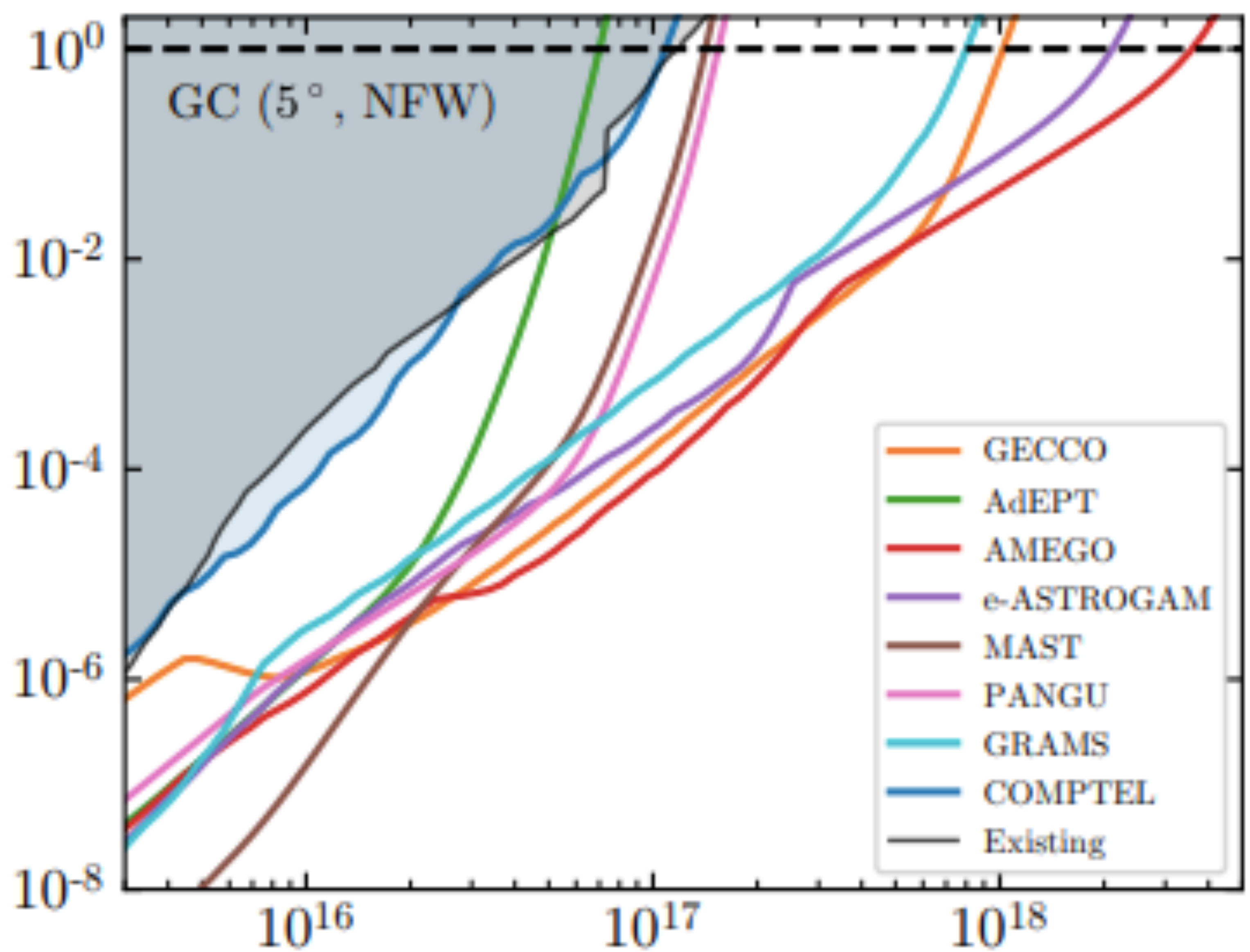
- Over a wide mass range, PBHs can be probed with a combination of gravitational lensing + dynamical effects in astrophysical systems



- Dashed lines = constraints have been proposed, but are not reliable or have been refuted
- There is an open window for f=1 (all DM=PBHs) from $M \sim 10^{17}$-10^{23}g

Gamma/X-ray signals from PBHs

- The lower end of this open window in mass, around 10^{17} g, is set by the non-observation of Hawking radiation from these PBHs
- Proposed MeV-band gamma-ray telescopes have the potential to extend the mass reach by around an order of magnitude [Coogan et al '21, Ray et al '21].
- The $10^{18\text{-}23}$ g band will be hard to probe this way - many interesting ideas based on lensing, astrophysical observables [e.g. Montero-Camacho et al '19, Jung et al '20].



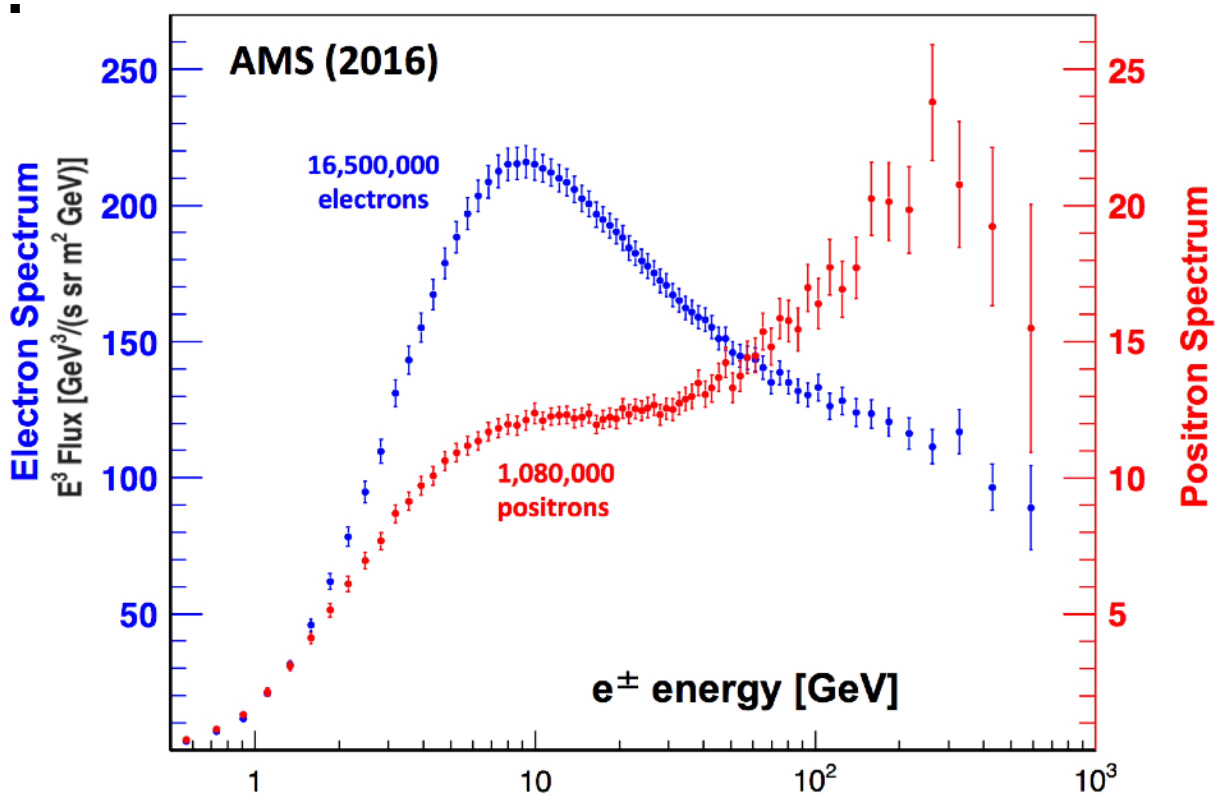
Coogan et al '21

Anomalies - clues or red herrings?

- Among all these ideas and searches for DM, in recent years there have been a number of hints of possible signals.
- Since this is ICRC, I will focus on signals in cosmic rays / high-energy astrophysics.
- There are other possible hints of new physics which may have to do with DM, such as the 4.2 sigma discrepancy between (non-lattice) theoretical prediction and measured value for muon g-2 [Abi et al '21]
  - Some example ideas (involving DM) are dark photons with semi-visible decays [Mohlabeng 1902.05075], lepton portal DM (DM couples directly to charged leptons) [Bai & Berger 2104.03301], minimal supersymmetry with a mostly-bino DM candidate [Cox et al 2104.03290], etc
  - However there are also many possible explanations not involving DM, and in the interests of time I will not say more here.

The positron excess

- PAMELA/AMS-02 positron excess:
  - Cosmic-ray positron flux is enhanced relative to electron flux between ~10 and several hundred GeV.
  - Highly statistically significant.

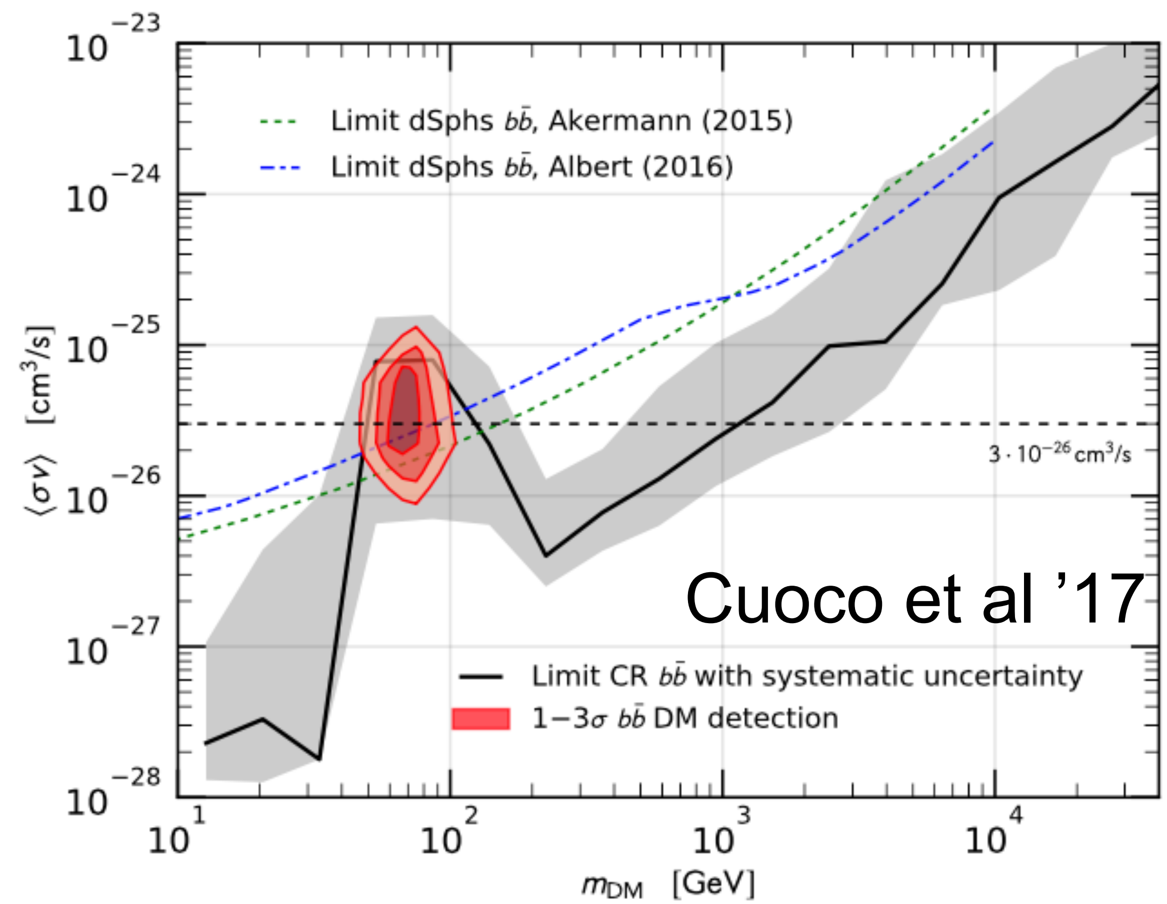


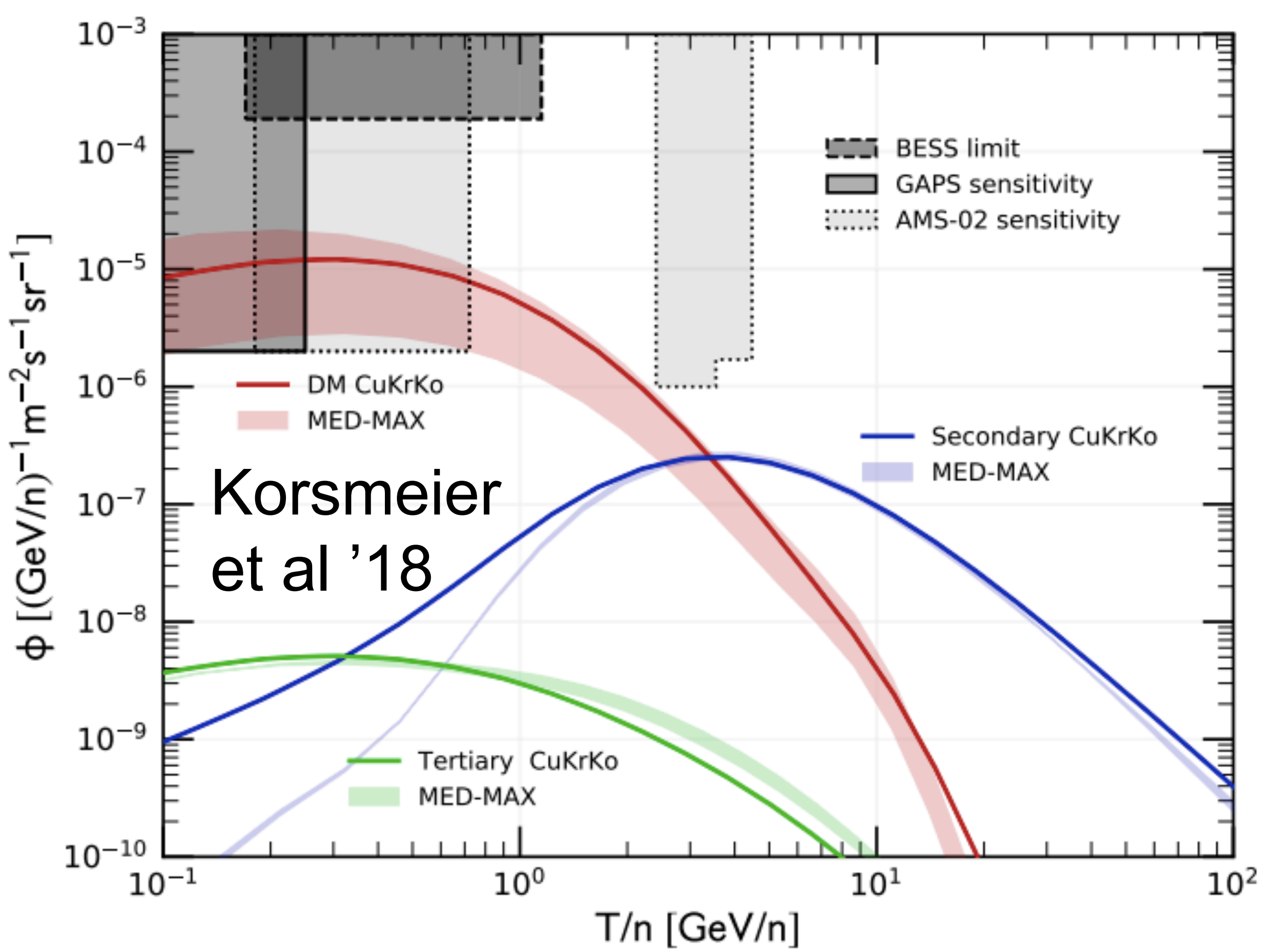
Sam Ting, 8 December 2016, CERN colloquium

- DM explanation: TeV-scale DM annihilating or decaying dominantly into leptons (if annihilation, requires rate >> thermal).
- Recent observations of nearby pulsars suggest they produce abundant TeV-scale positrons that likely explain the excess [e.g. Hooper et al ’17].

The antiproton excess

- AMS-02 observes a hint of an excess in ~10-20 GeV antiprotons, relative to background models
- Corresponds to a ~thermal cross section and ~40-130 GeV DM mass.
- Significance level is still highly debated [see Heisig et al '20, Boudaud et al '19, Cuoco et al '19, Cholis et al '19, Reinert & Winkler '18, Cui et al '17, Cuoco et al '17] - depends sensitively on model for correlations between bins.
- GAPS could potentially test similar parameter space in anti-deuterons [e.g. von Doetinchem et al '20].





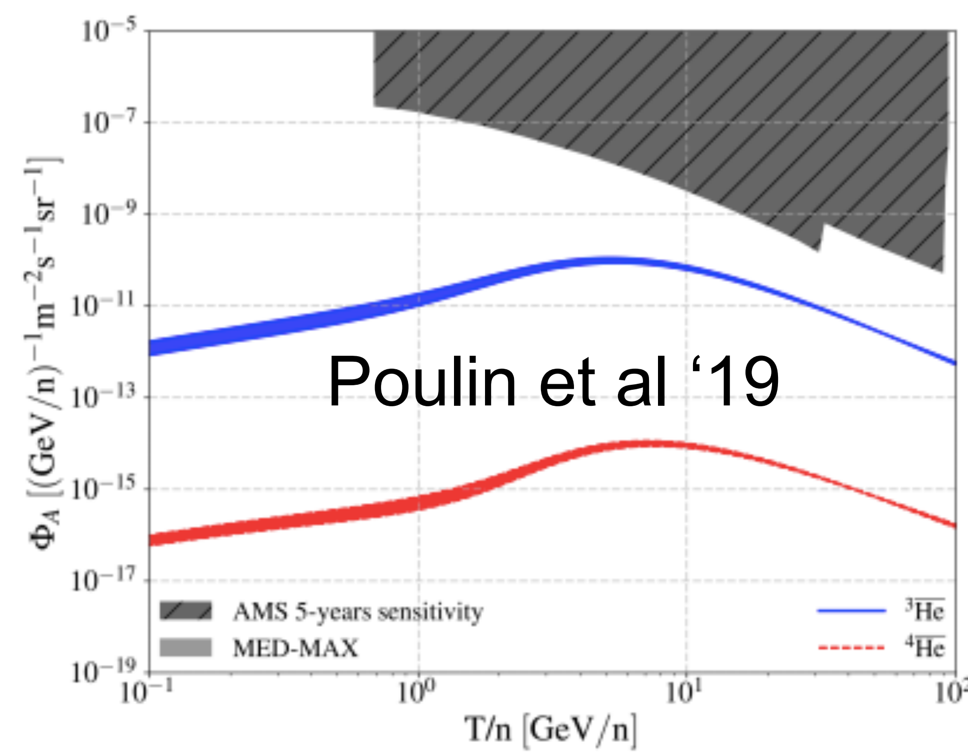
AMS-02 antihelium events

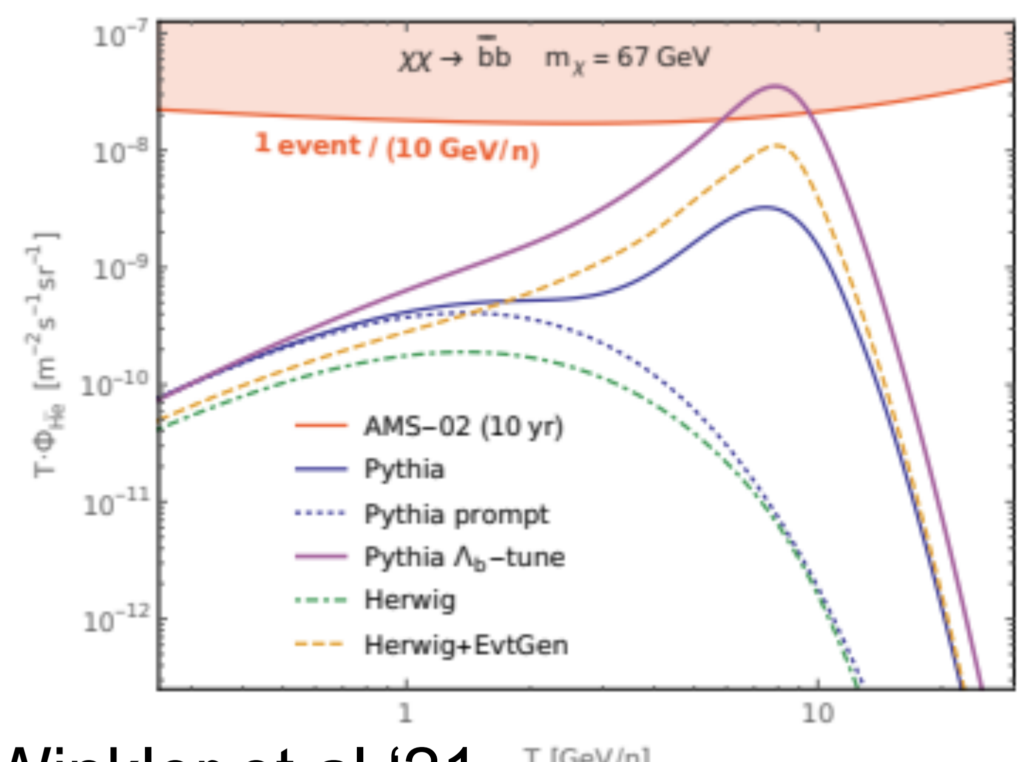
- AMS-02 Collaboration announced tentative possible detection of six apparent anti-He-3 events and two apparent anti-He-4 events ["AMS Days at La Palma, La Palma, Canary Islands, Spain," (2018)]

- Expected astrophysical background is tiny - but so is expected DM signal!

- One proposal is that clouds of antimatter or anti-stars could generate these events [Poulin et al '19]

- Alternatively, recent theoretical work suggested that the DM signal calculations might have missed an important process [Winkler & Linden '21], and production of $\bar{\Lambda}_b$-baryons which decay to antihelium could boost the signal

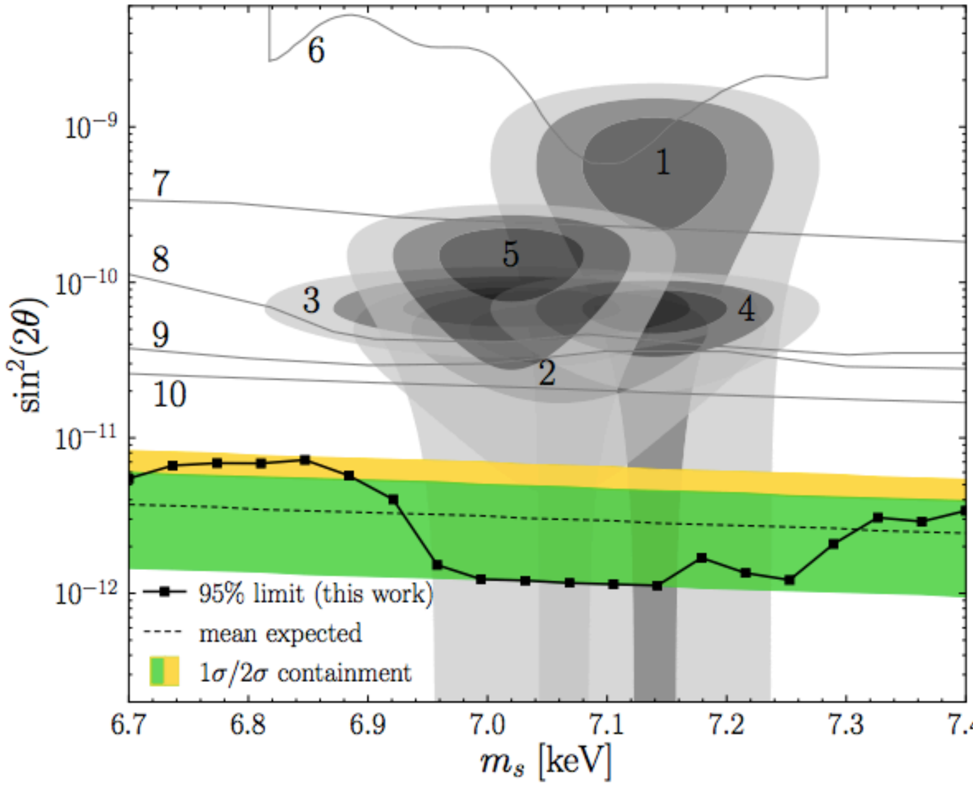




Winkler et al '21

The 3.5 keV line

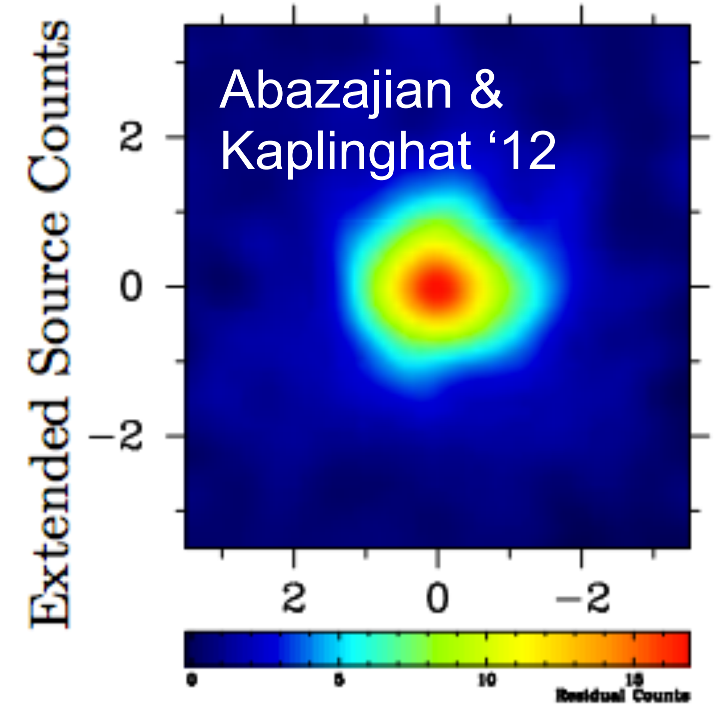
- Observed originally in stacked galaxy clusters [Bulbul et al '14, Boyarsky et al '14], subsequently in other regions. Individual signals are modestly significant (~4σ).
- Simplest DM explanation: 7 keV sterile neutrino decaying into neutrino+photon. (Other explanations involving annihilation, oscillations etc are possible.)
- 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].
- Simple decay explanation seems inconsistent with null results in other searches, in particular recent work by Dessert et al '20, https://github.com/bsafdi/BlankSkyfor3p5
- Active controversy over validity of upper limits [Abazajian 2004.06170, Boyarsky et al 2004.06601] - key points are flexibility of background model, energy range considered.
- Future X-ray experiments (eXTP, XRISM, Micro-X, possibly eROSITA) should have the sensitivity to see the signal, in some cases with improved energy resolution.

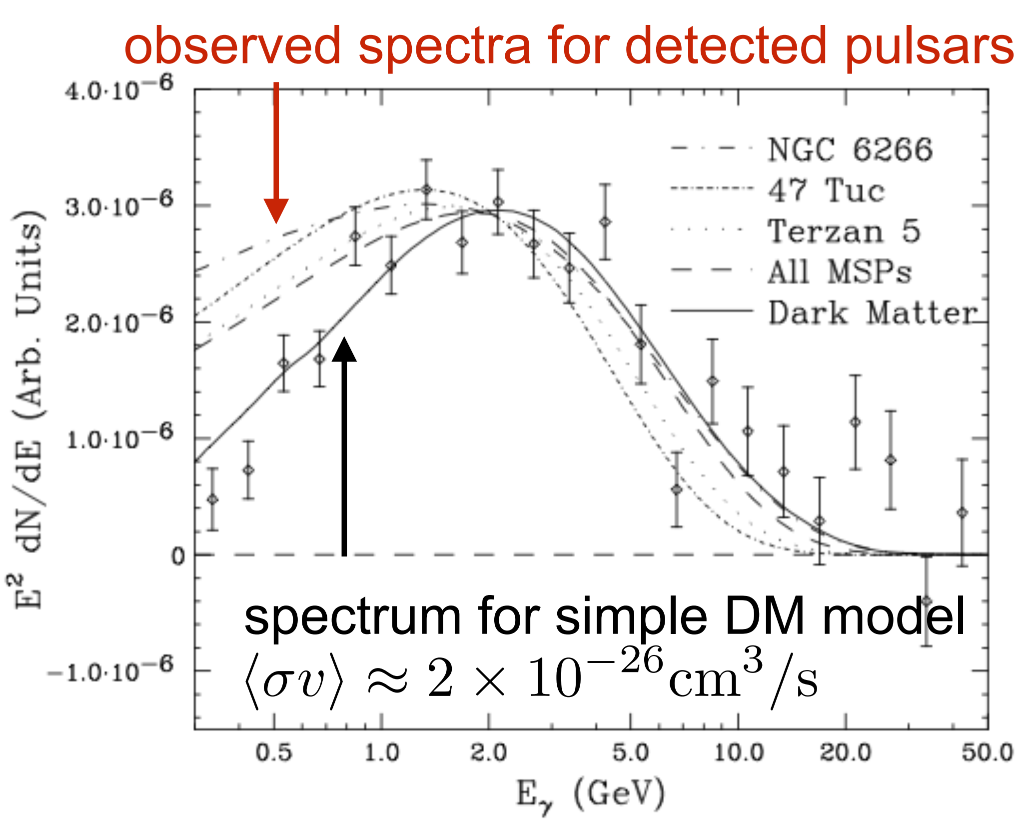


Dessert et al '20

The Galactic Center excess (GCE)

- 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 annihilating DM at a mass scale of O(10-100) GeV
- Leading non-DM explanation: population of pulsars below Fermi's point-source detection threshold





Daylan, TRS et al '16

A GCE status report

- Morphology: independent groups have found a stellar-bulge-like morphology is preferred over spherical symmetry [Macias et al ’18, Bartels et al ’18, Macias et al ’19]. This would suggest a stellar origin. However, this depends on the background/foreground modeling; di Mauro ’21 finds the opposite preference.

- Photon statistics: point sources or diffuse?

  - Several groups have found hints for faint point-source (PS) populations toward the inner Galaxy [Bartels et al ’16, Calore et al ’21] - comparison with the 4FGL catalog indicates most sources are not potential contributors to the GCE [Zhong et al ’20]

  - Other studies have claimed evidence for a GCE-distributed PS population [Lee, TRS et al ’16, Buschmann et al ’20], but follow-ups have shown these PSs may be spurious [Leane & TRS '19, ’20, List et al ’20]

- Detection of pulsars in other frequency bands could help resolve the issue in the next few years [e.g. Calore et al ’16, Berteaud et al ’20].

Summary

- Knowns: cosmological abundance (precisely), phase space distribution (steadily improving), upper limits on interactions, lower limit on lifetime, upper + lower bounds on mass (very widely separated!)
- Unknowns: values of mass, lifetime, non-gravitational interactions; cosmological history
- We have many scenarios for what DM could be, and many exciting ideas for how to test them, spanning the (enormous) range of possible masses and interaction strengths
- There are already a number of excesses/anomalies we don't fully understand - may be hints to DM, or (perhaps more likely) clues to new high-energy astrophysics

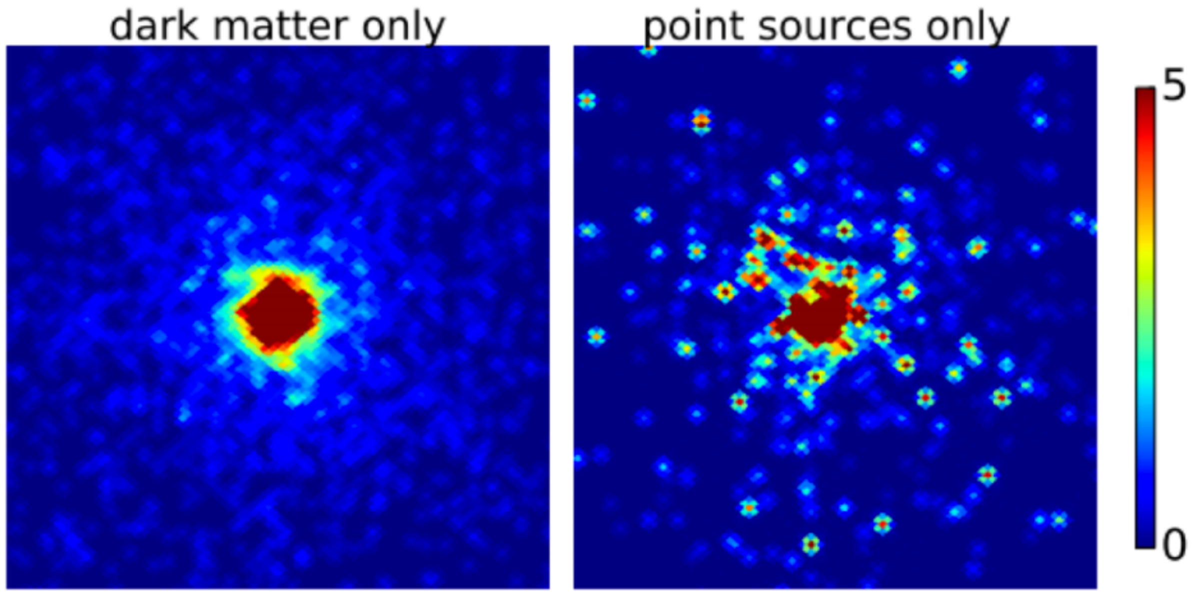
BACKUP SLIDES

Photon statistics

Lee, Lisanti, Safdi, TRS & Xue ’16

DM origin hypothesis

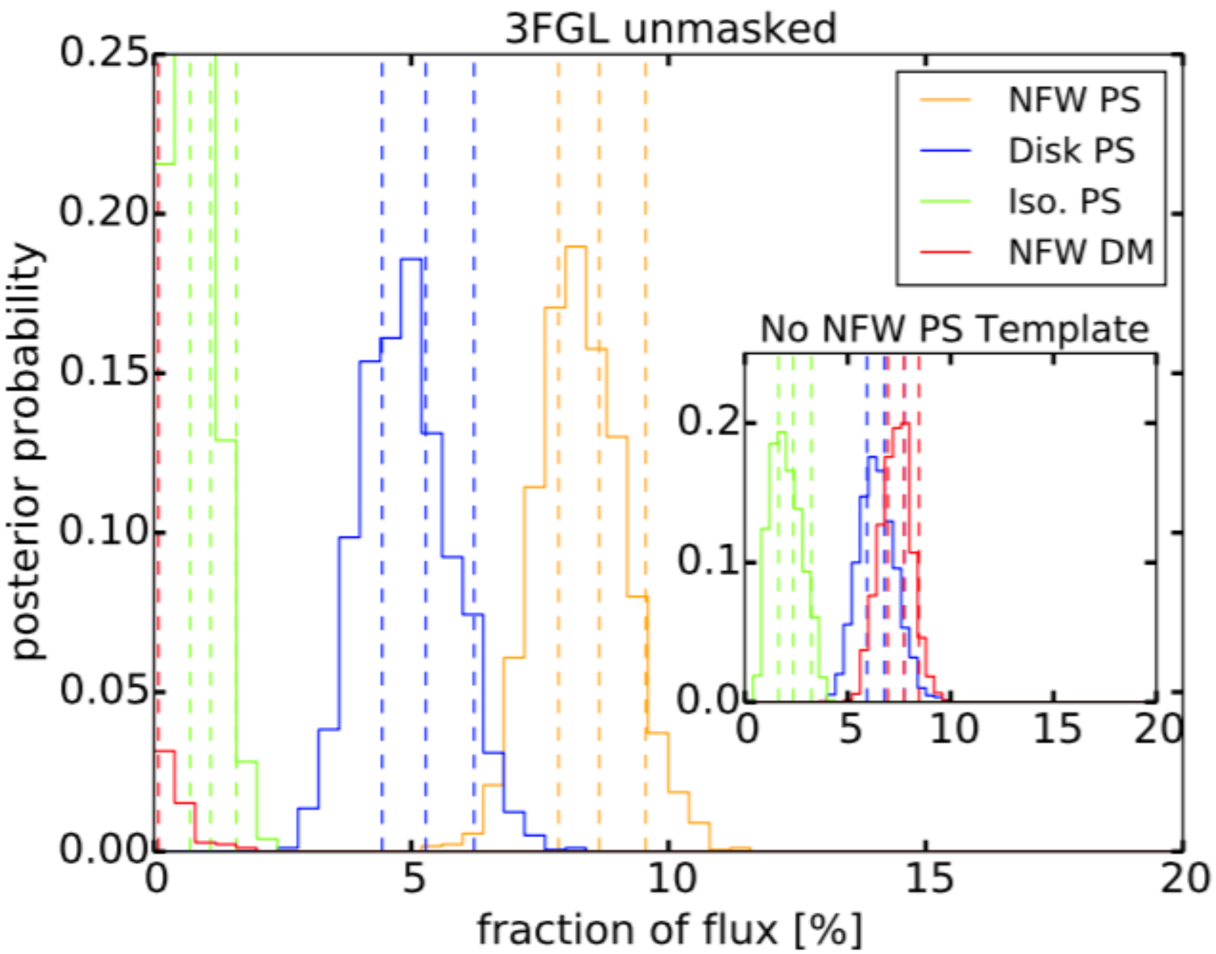
signal traces DM density squared, expected to be ~smooth near GC with subdominant small-scale structure



Pulsar origin hypothesis

signal originates from a collection of compact objects, each one a faint gamma-ray point source

- We may be able to distinguish between hypotheses by looking at clumpiness of the photons [e.g. Malyshev & Hogg ’11; Lee, Lisanti & Safdi ’15].
- If we are looking at dark matter (or another diffuse source, like an outflow), we expect a fairly smooth distribution - fluctuations described by Poisson statistics.
- In the pulsar case, we might instead see many “hot spots” scattered over a fainter background - non-Poissonian fluctuations, higher variance.
- Related analysis by Bartels et al ’16, using wavelet approach

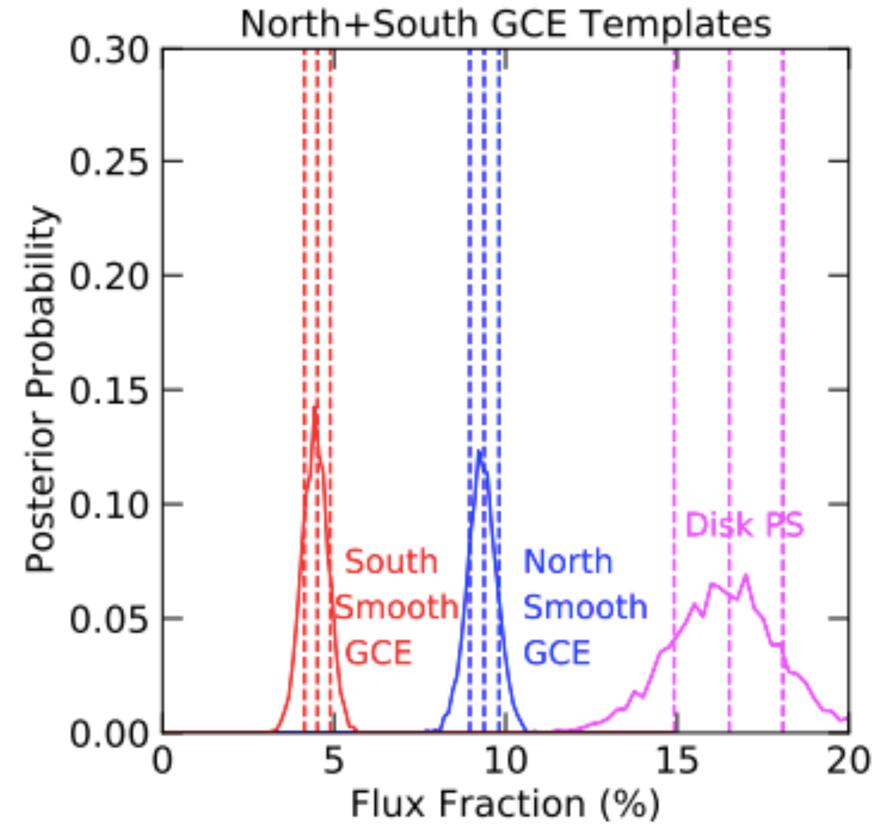


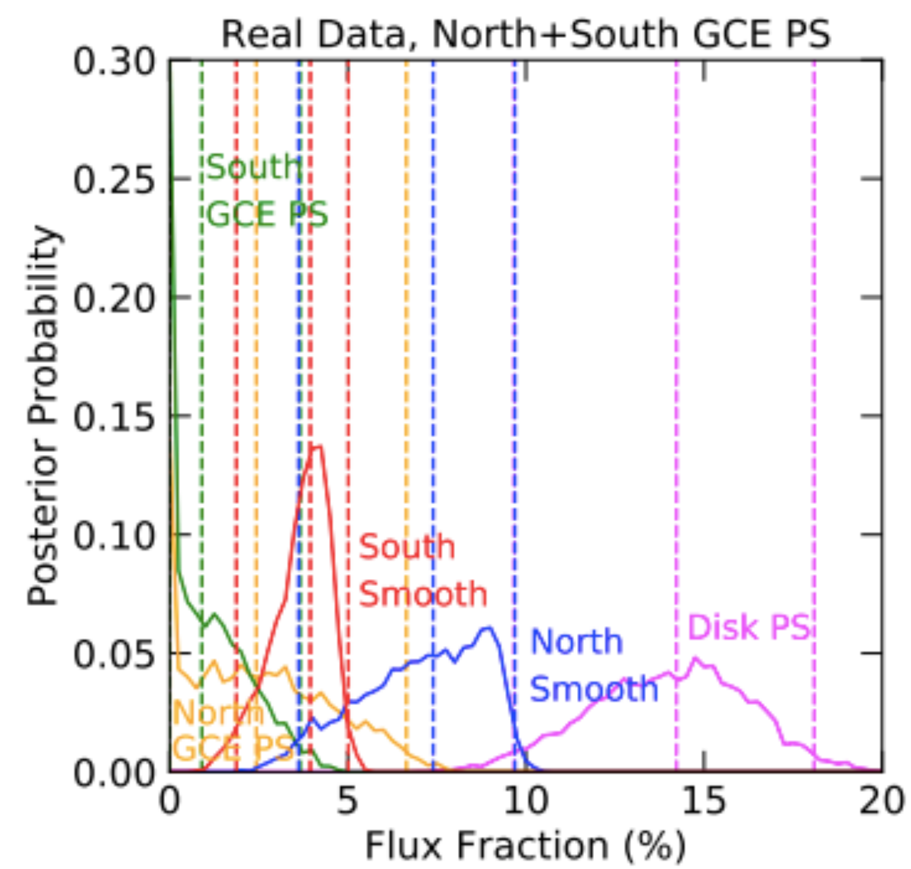
- Lee et al ‘16: fit shows a strong preference to assign all GCE flux to new PS population (Bayes factor in favor of model with PSs ~10^9, roughly analogous to 6σ)
- Suggests signal is composed of a relatively small number of just-below-threshold sources

- Leane & TRS ’19, Chang et al ’19, Buschmann et al ’20:
  - background models used in original analysis lead to significant bias against DM signal, reconstruct injected smooth signals as ensembles of point sources;
  - newer models can be created that do not have the same clear bias, evidence for PSs drops to Bayes factor $10^{3.4}$, analogous to 3-4σ
- Leane & TRS ’20a, b: even with perfect background models, an overly-rigid signal model can lead to a spurious preference for a PS population

Spurious point sources (data)

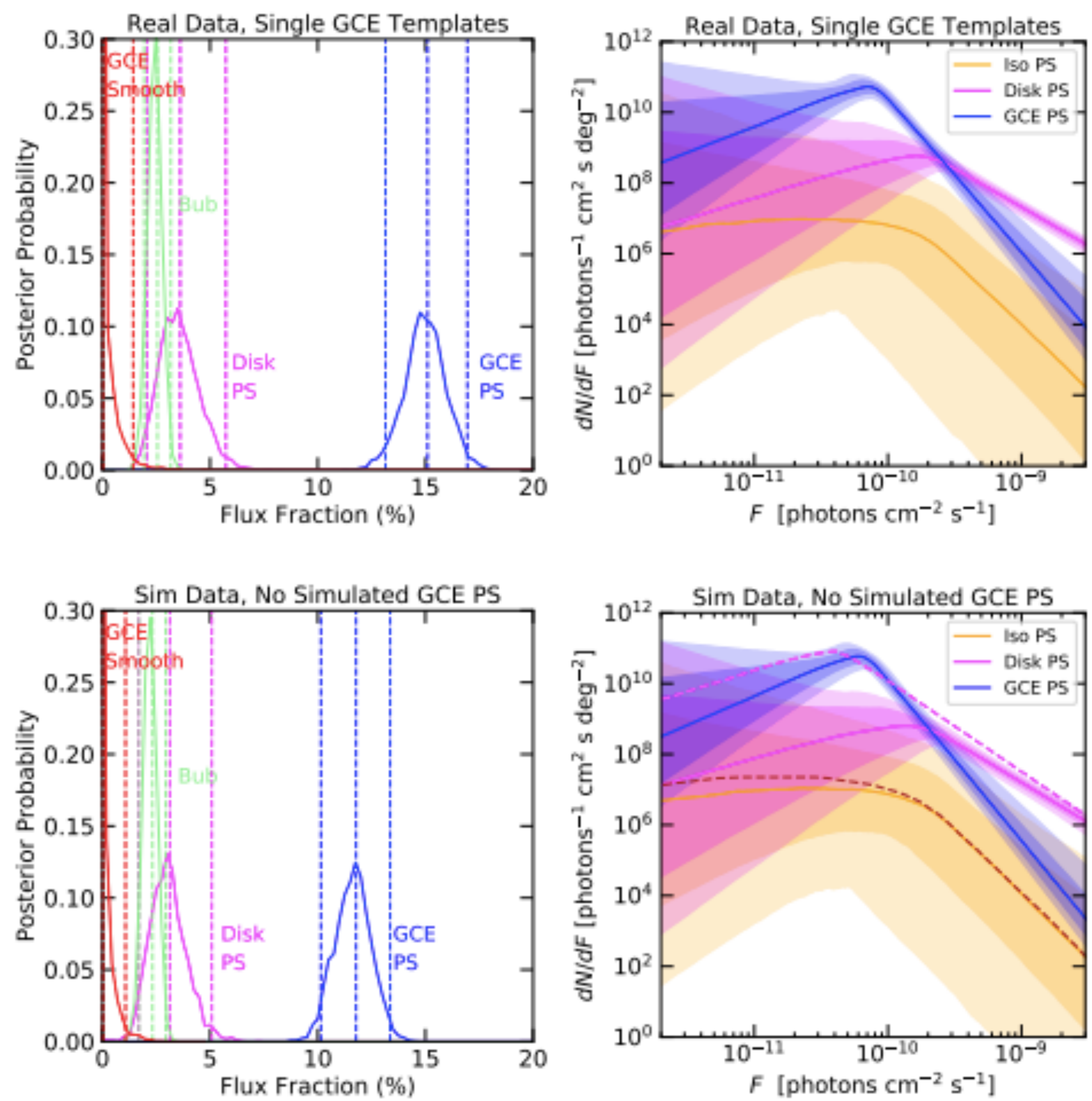
- We found this by accident - trying to test the spatial morphology of the GCE in more detail
- In the region of interest we used, when we split the GCE into 2+ spatial components, all evidence for GCE PSs went away (BF $> 10^{15} \rightarrow$ BF < 10 with one added d.o.f)
- Apparent preference for PSs is really just a preference for N/S asymmetry
- Occurs because bright PS populations inherently have a higher error bar on flux - easier to explain a “bad" signal template





Spurious point sources (simulations)

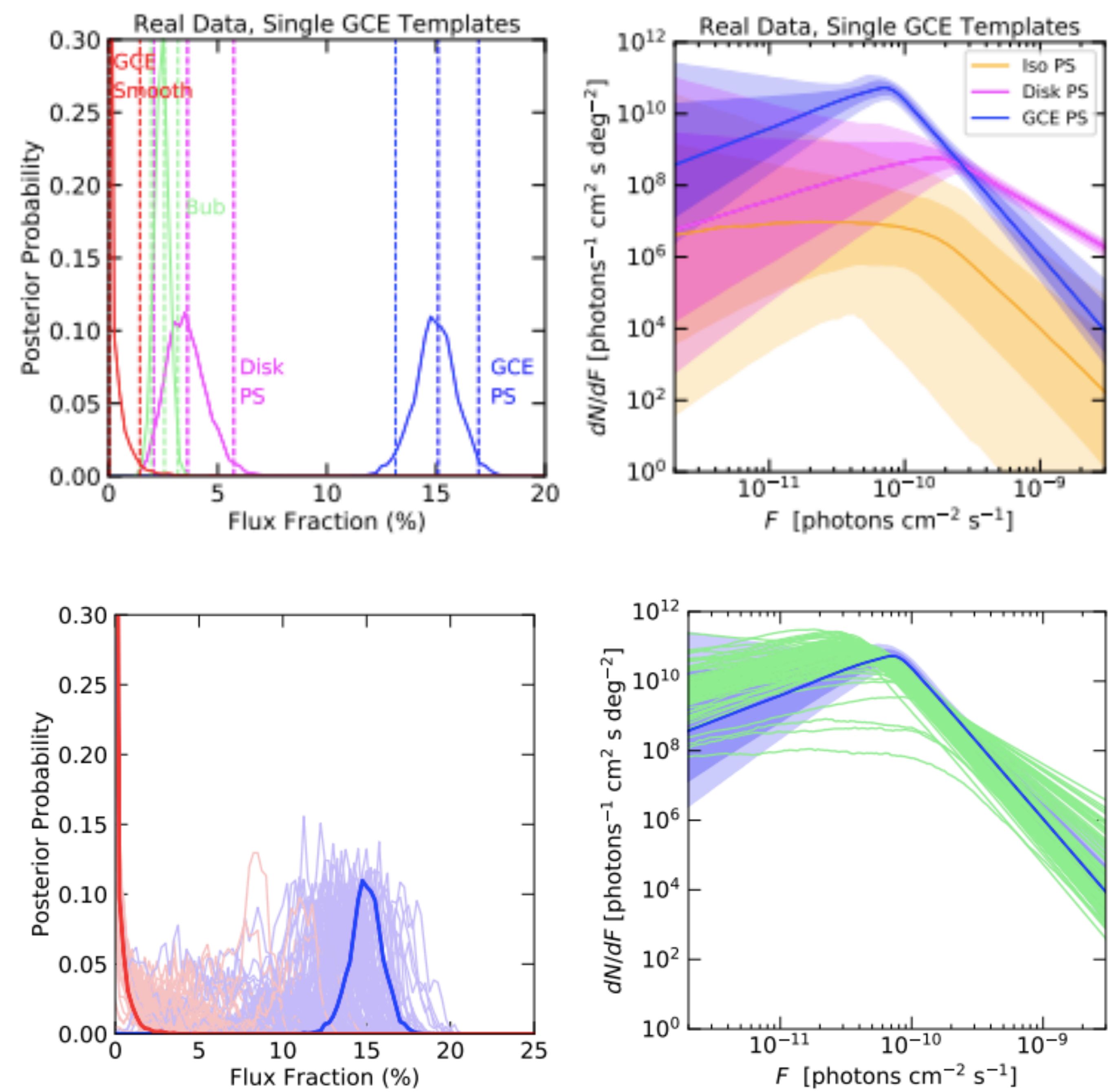
- Simulate smooth GCE with asymmetry, fit as linear combination of symmetric smooth template + symmetric PS template
- The observed behavior matches what we see (for the same fit) in the real data very closely, although in the simulations we know the PS population isn't real
- So perhaps the apparent PSs in the real data are spurious?



One example realization

Spurious point sources (simulations)

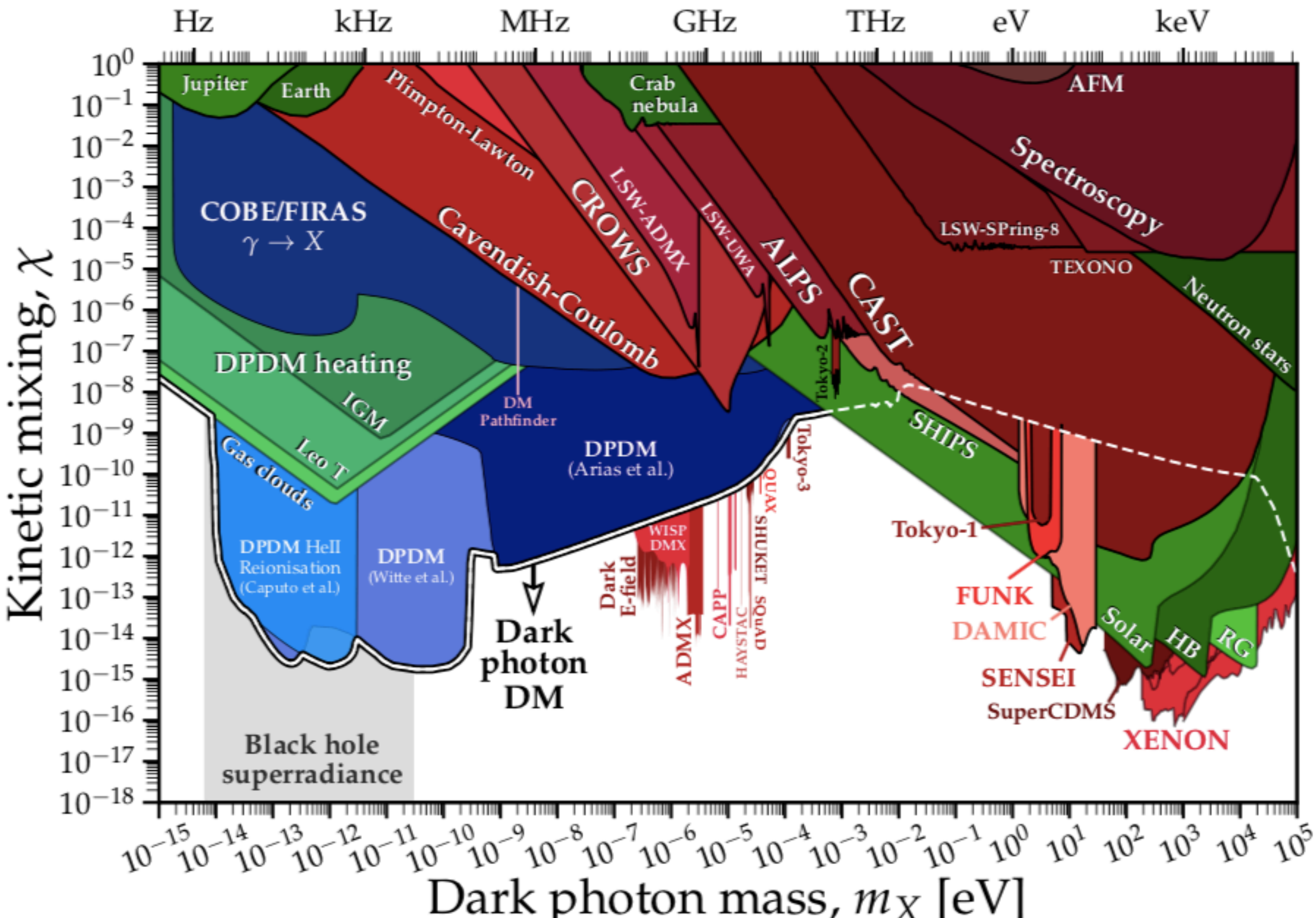
- Simulate smooth GCE with asymmetry, fit as linear combination of symmetric smooth template + symmetric PS template
- The observed behavior matches what we see (for the same fit) in the real data very closely, although in the simulations we know the PS population isn't real
- So perhaps the apparent PSs in the real data are spurious?



100 realizations

Dark photon limits

(credit https://cajohare.github.io/AxionLimits/)



The thermal freezeout scenario

- Suppose there is some interaction that interconverts between dark matter and SM particles and is efficient in the early universe

(1) $\chi\chi \leftrightarrow \mathrm{SM\,SM}$

- As the universe expands, it cools down; eventually its temperature drops below the dark matter mass.

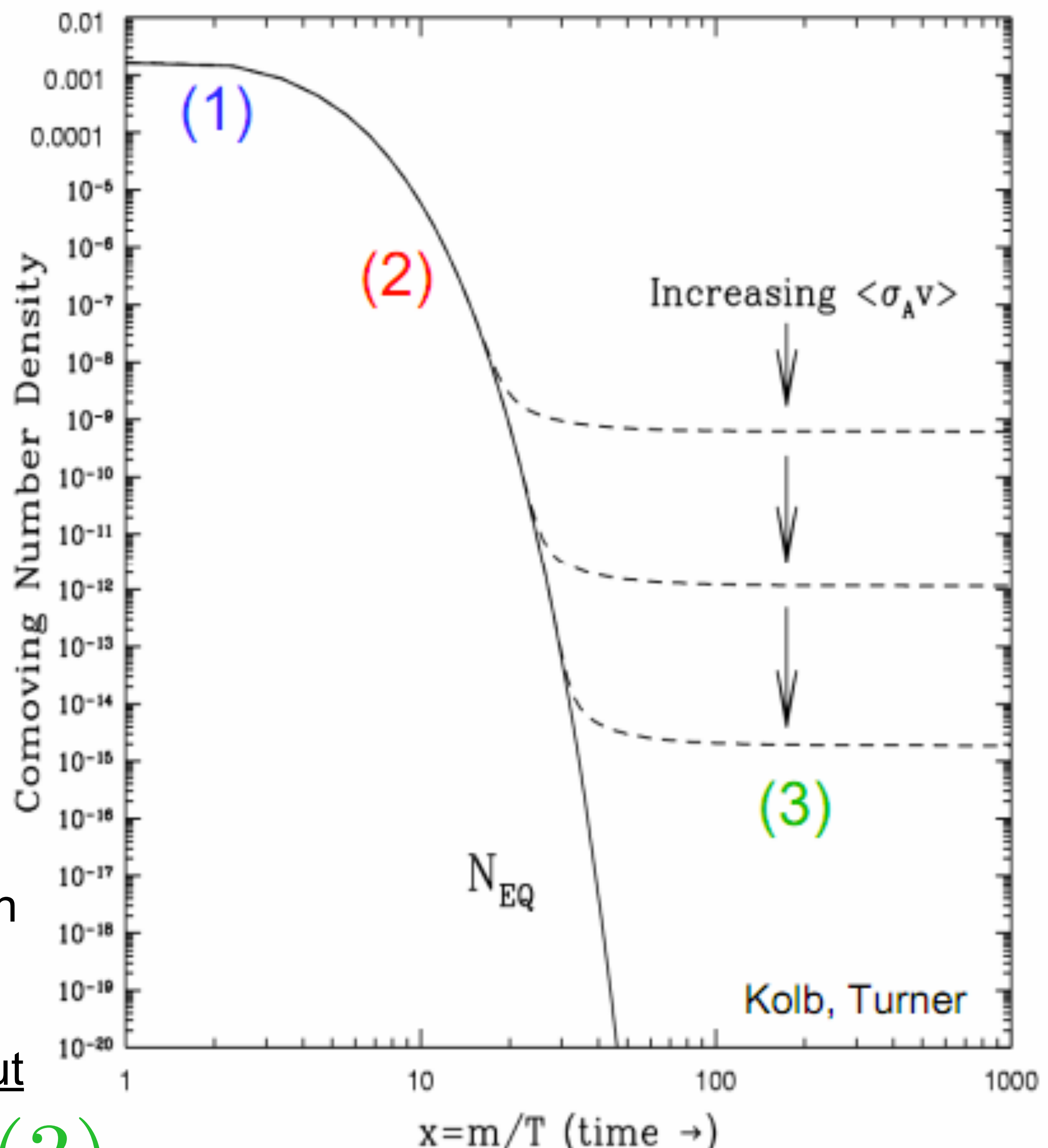
- At this stage, dark matter particles can efficiently annihilate to visible particles, but not the reverse:

(2) $\chi\chi \rightarrow \mathrm{SM\,SM} \not\rightarrow \chi\chi$

- Dark matter abundance falls exponentially - eventually cuts off when the timescale for collision becomes comparable to the expansion timescale

- At this point we say the annihilation has <u>frozen out</u> and the late-time dark matter abundance is fixed

(3)



The thermal freezeout scenario

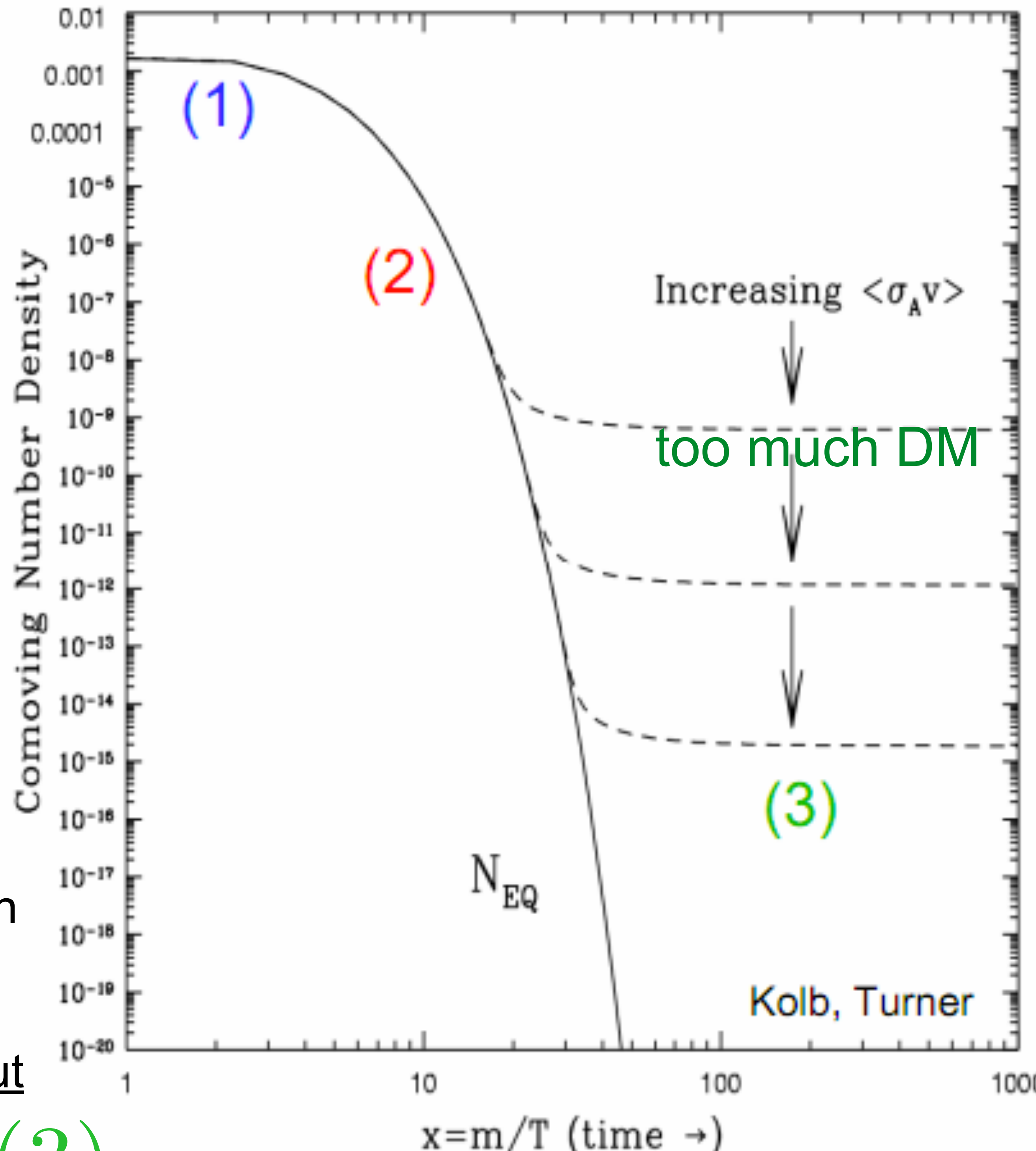
- Suppose there is some interaction that interconverts between dark matter and SM particles and is efficient in the early universe

(1) $\chi\chi \leftrightarrow \mathrm{SM\,SM}$

- As the universe expands, it cools down; eventually its temperature drops below the dark matter mass.
- At this stage, dark matter particles can efficiently annihilate to visible particles, but not the reverse:

(2) $\chi\chi \rightarrow \mathrm{SM\,SM} \not\rightarrow \chi\chi$

- Dark matter abundance falls exponentially - eventually cuts off when the timescale for collision becomes comparable to the expansion timescale
- At this point we say the annihilation has <u>frozen out</u> and the late-time dark matter abundance is fixed (3)



The thermal freezeout scenario

- Suppose there is some interaction that interconverts between dark matter and SM particles and is efficient in the early universe

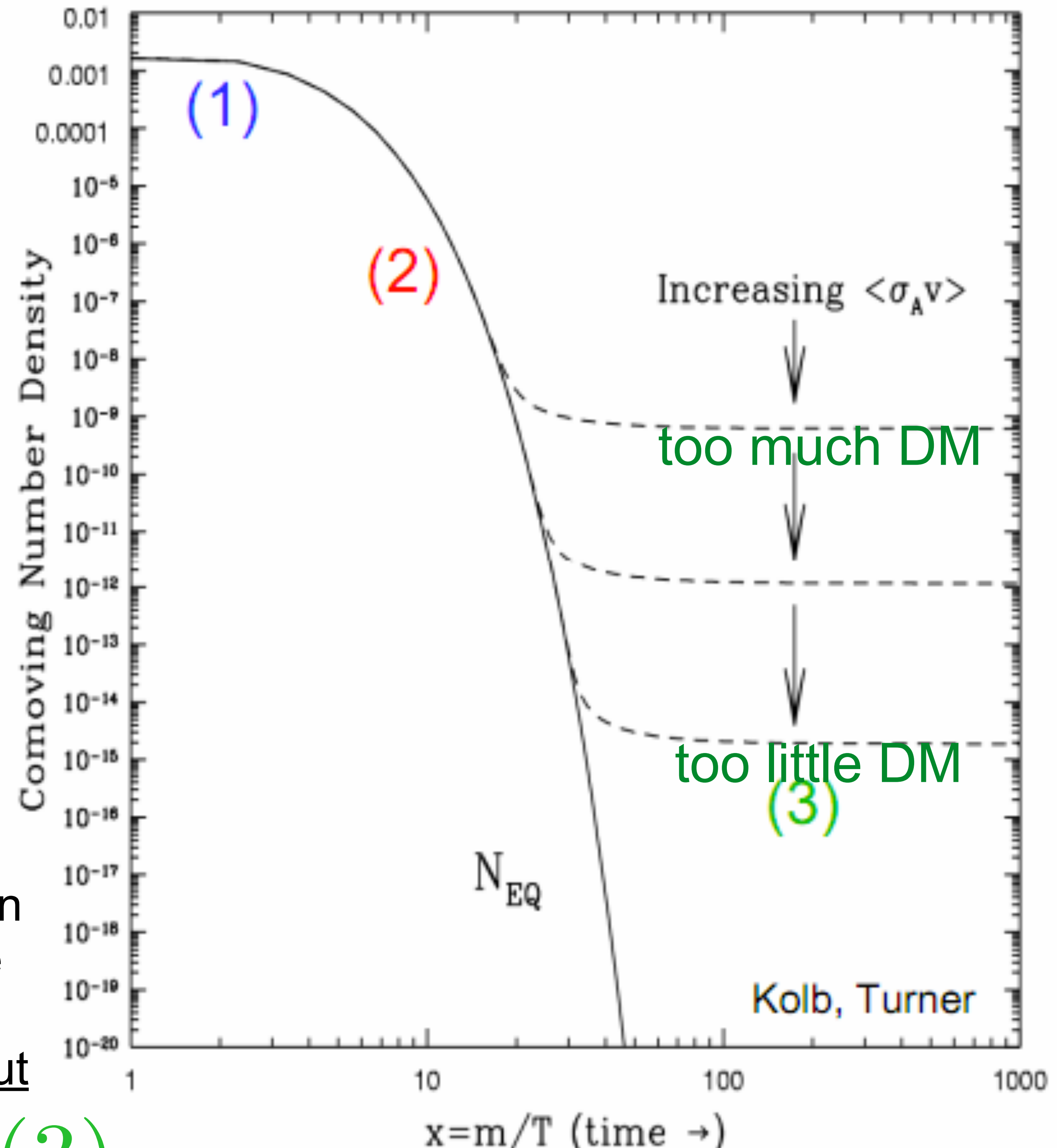
(1) $\chi\chi \leftrightarrow \mathrm{SM}\,\mathrm{SM}$

- As the universe expands, it cools down; eventually its temperature drops below the dark matter mass.
- At this stage, dark matter particles can efficiently annihilate to visible particles, but not the reverse:

(2) $\chi\chi \rightarrow \mathrm{SM}\,\mathrm{SM} \not\rightarrow \chi\chi$

- Dark matter abundance falls exponentially - eventually cuts off when the timescale for collision becomes comparable to the expansion timescale
- At this point we say the annihilation has <u>frozen out</u> and the late-time dark matter abundance is fixed

(3)



The thermal freezeout scenario

- Suppose there is some interaction that interconverts between dark matter and SM particles and is efficient in the early universe

(1) $\chi\chi \leftrightarrow \mathrm{SM}\,\mathrm{SM}$

- As the universe expands, it cools down; eventually its temperature drops below the dark matter mass.

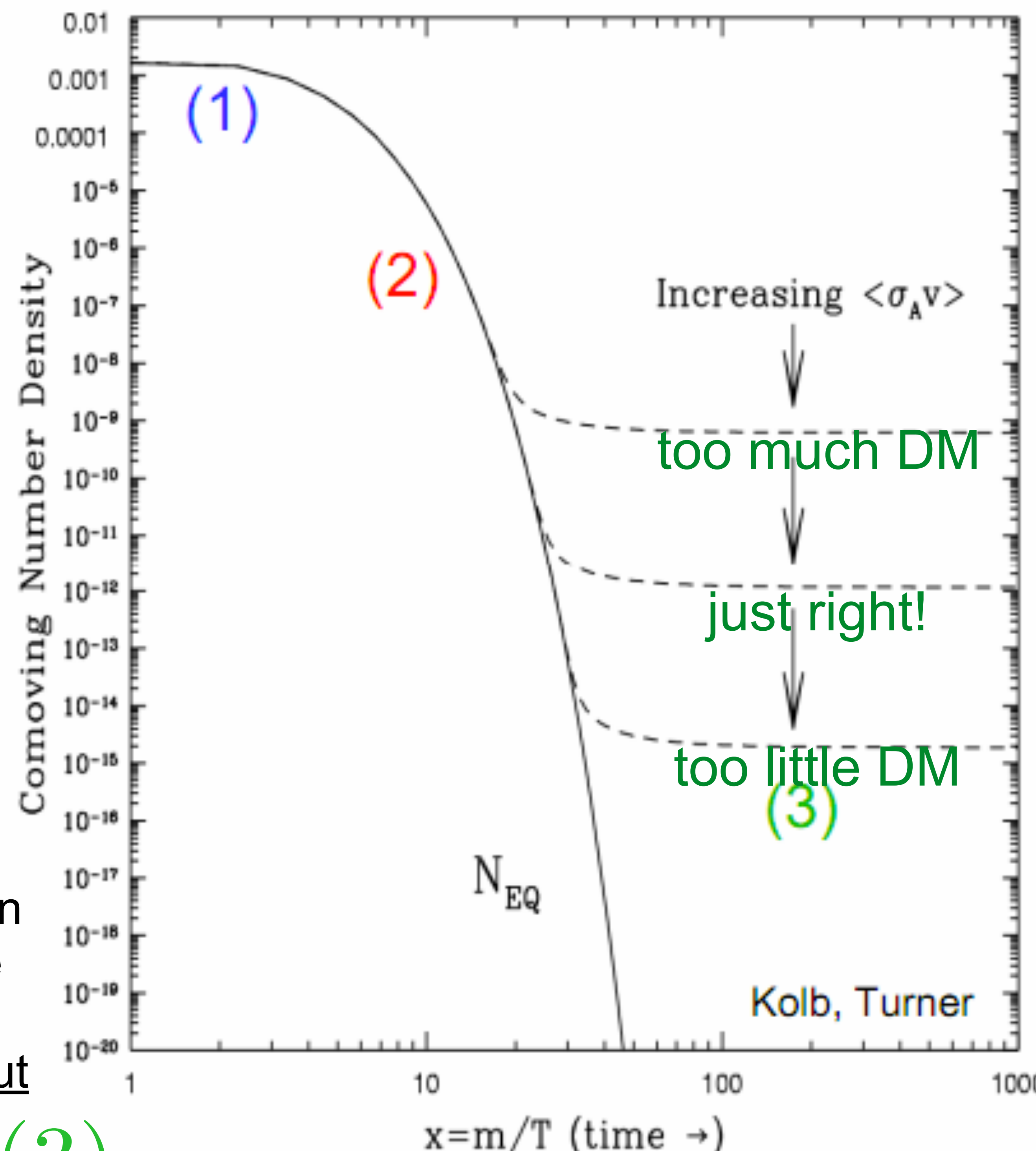
- At this stage, dark matter particles can efficiently annihilate to visible particles, but not the reverse:

(2) $\chi\chi \rightarrow \mathrm{SM}\,\mathrm{SM} \not\rightarrow \chi\chi$

- Dark matter abundance falls exponentially - eventually cuts off when the timescale for collision becomes comparable to the expansion timescale

- At this point we say the annihilation has <u>frozen out</u> and the late-time dark matter abundance is fixed

(3)



High-mass limit: unitarity

- In this scenario, the interaction strength controls the freezeout and hence the late-time ("relic") abundance of dark matter: stronger interactions = longer exponential decrease = lower abundance. Simple, compelling scenario to obtain the correct DM abundance (but not the only option!)

- From measuring the relic abundance we can predict the annihilation rate:

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

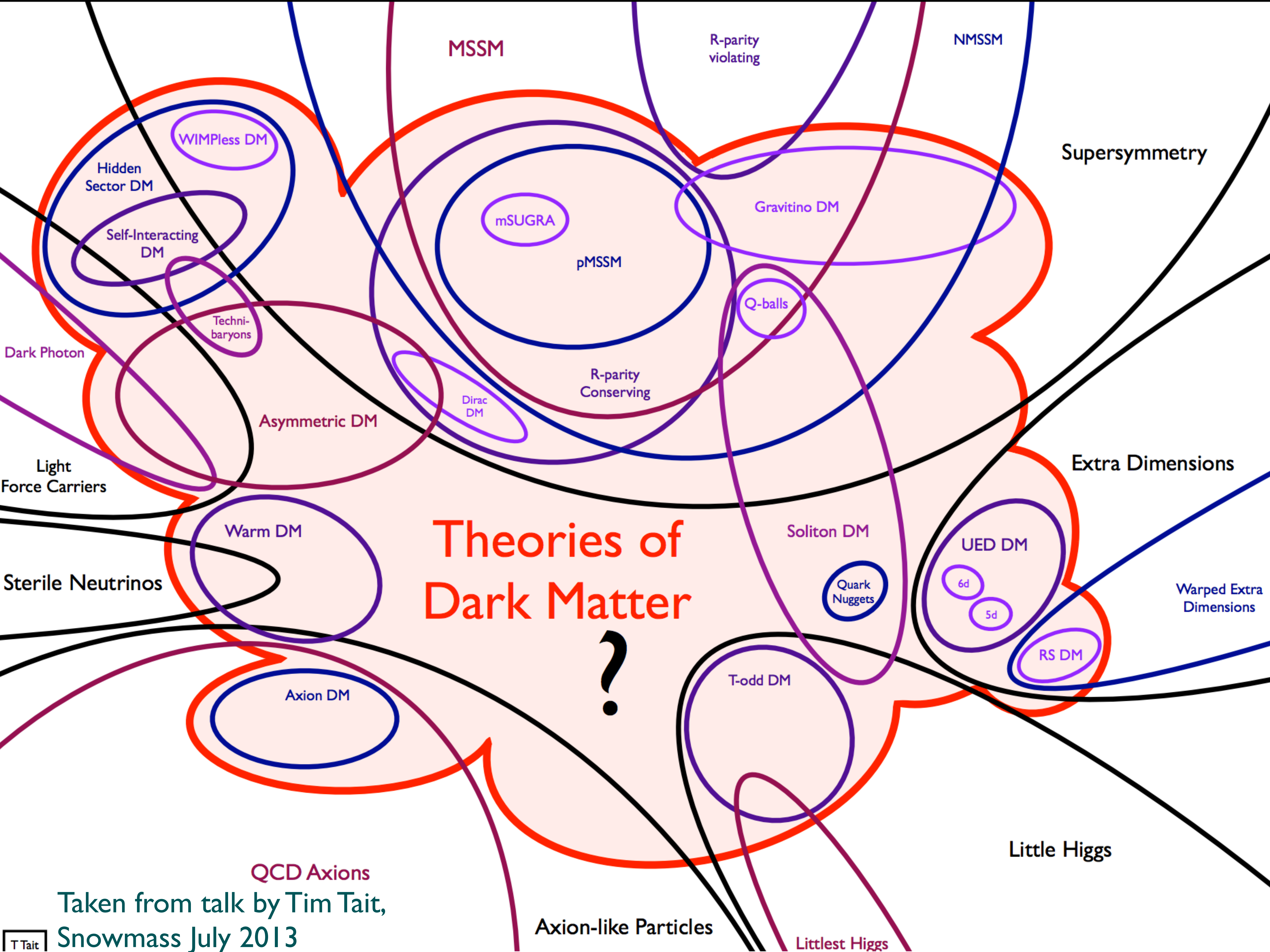
- In the limit of weak interactions, this suggests a characteristic mass scale around $M \sim \alpha_D \times 25\mathrm{TeV}$, if α_D is the relevant coupling

- In the limit of strong interactions, partial-wave unitarity still sets a mass-dependent upper bound on the cross section, which implies a maximum mass scale around 100 TeV:

$$\sigma = \sum_{l=0}^{\infty} \sigma_l, \quad \sigma_l = \frac{4\pi}{k^2}(2l+1)\sin^2\delta_l \leq (2l+1)\frac{4\pi}{k^2}$$

Low-mass limits & the "thermal window”

- Warm dark matter limits discussed earlier require masses above the keV scale
- For most models, there is a stronger bound from Big Bang Nucleosynthesis (BBN), our earliest direct probe of cosmic history - begins when the universe is O(1) s old, at temperatures ~ 1 MeV
- Thermally-coupled DM at the MeV scale or lower will generally perturb BBN via its effect on N_{eff}, # of relativistic degrees of freedom (changes expansion history) - either directly or through heating of photons/neutrinos via annihilations [see e.g. Sabti et al ‘19 for a recent analysis]
- Thus the thermal freezeout scenario applies most straightforwardly to DM with mass between 1 MeV and 100 TeV - “thermal window”
- If we can test the thermal relic cross section for DM masses across this window, we can probe (at least the simplest version of) this explanation for the origin of DM



Taken from talk by Tim Tait,
Snowmass July 2013