Dark Matter Puzzles from Indirect Searches

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Physics Colloquium
Georges Lemaitre Lecture Series
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U.S. DEPARTMENT OF ENERGY | Office of Science

Outline

- Introduction/review on the evidence for dark matter (DM)
- What we know about dark matter + open questions
- Examples of how indirect searches using astrophysical/cosmological data can probe DM physics:
  - low-mass thermal dark matter / dark sectors
  - electroweak dark matter
  - ultraheavy dark matter and primordial black holes
- A survey of current anomalies/excesses

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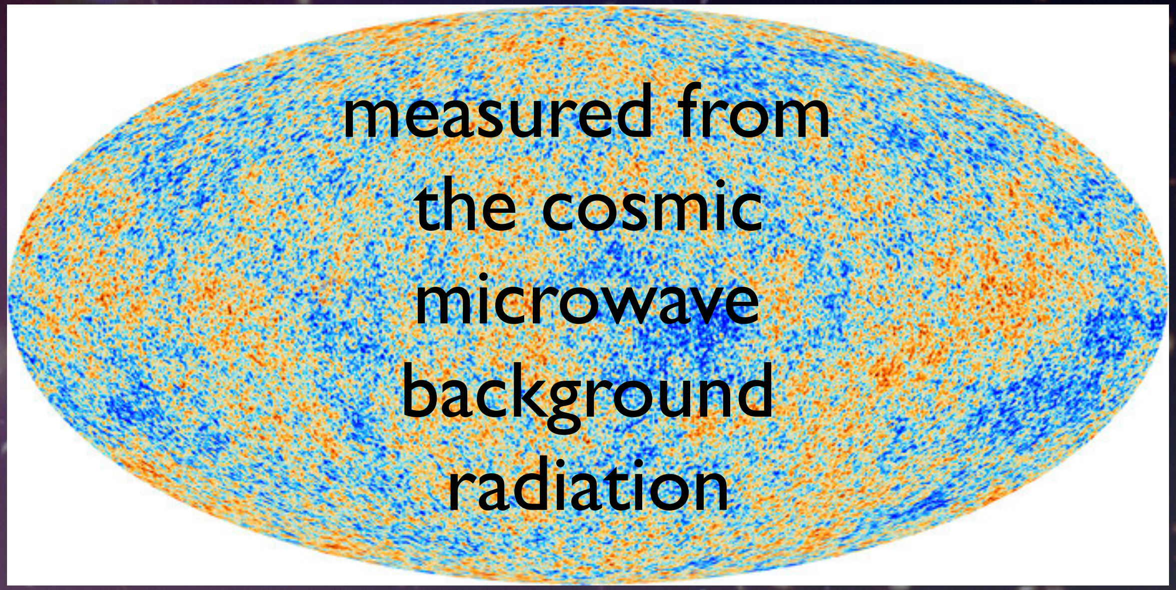

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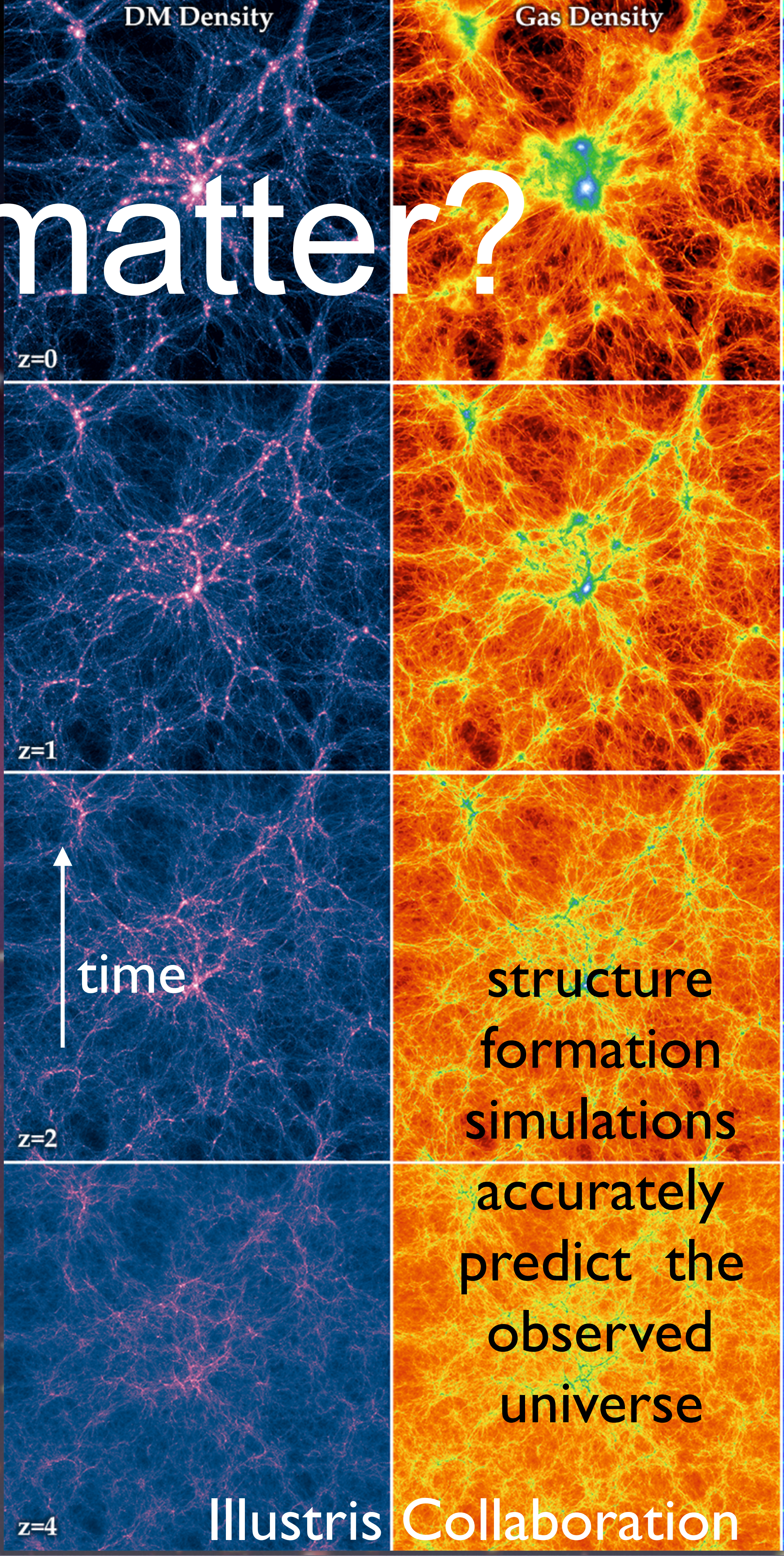

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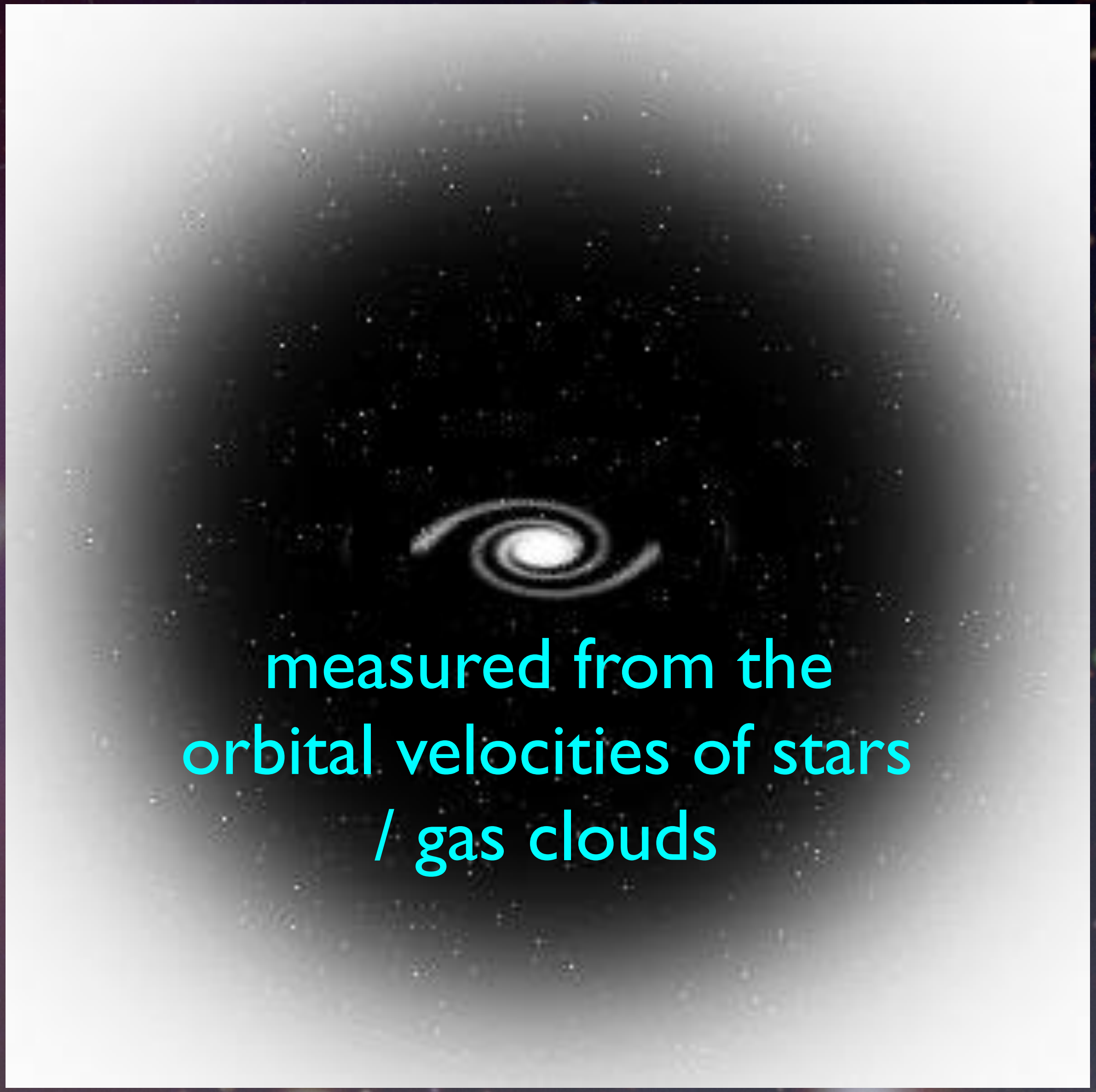

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- Forms large clouds or "halos" around galaxies.
- Interacts with other particles weakly or not at all (except by gravity).

null results of existing searches

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- WHAT IS IT?

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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]

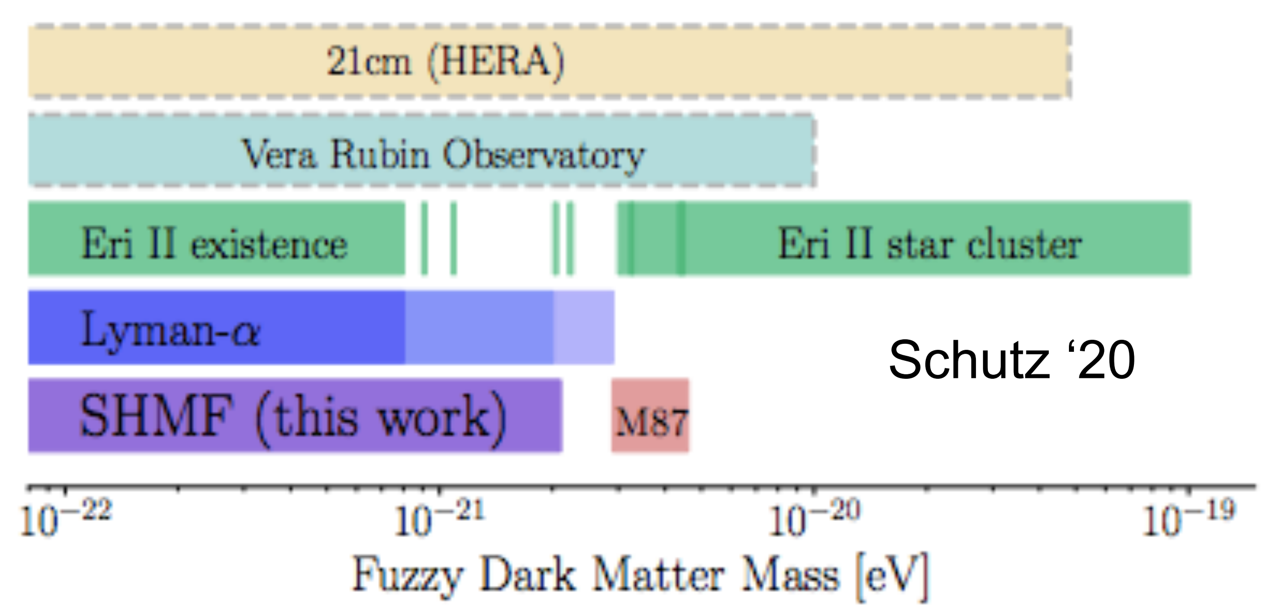
- Set upper bounds on DM-DM interactions [e.g. Bondarenko et al '21, Andrade et al arXiv:2012.06611]

- 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?

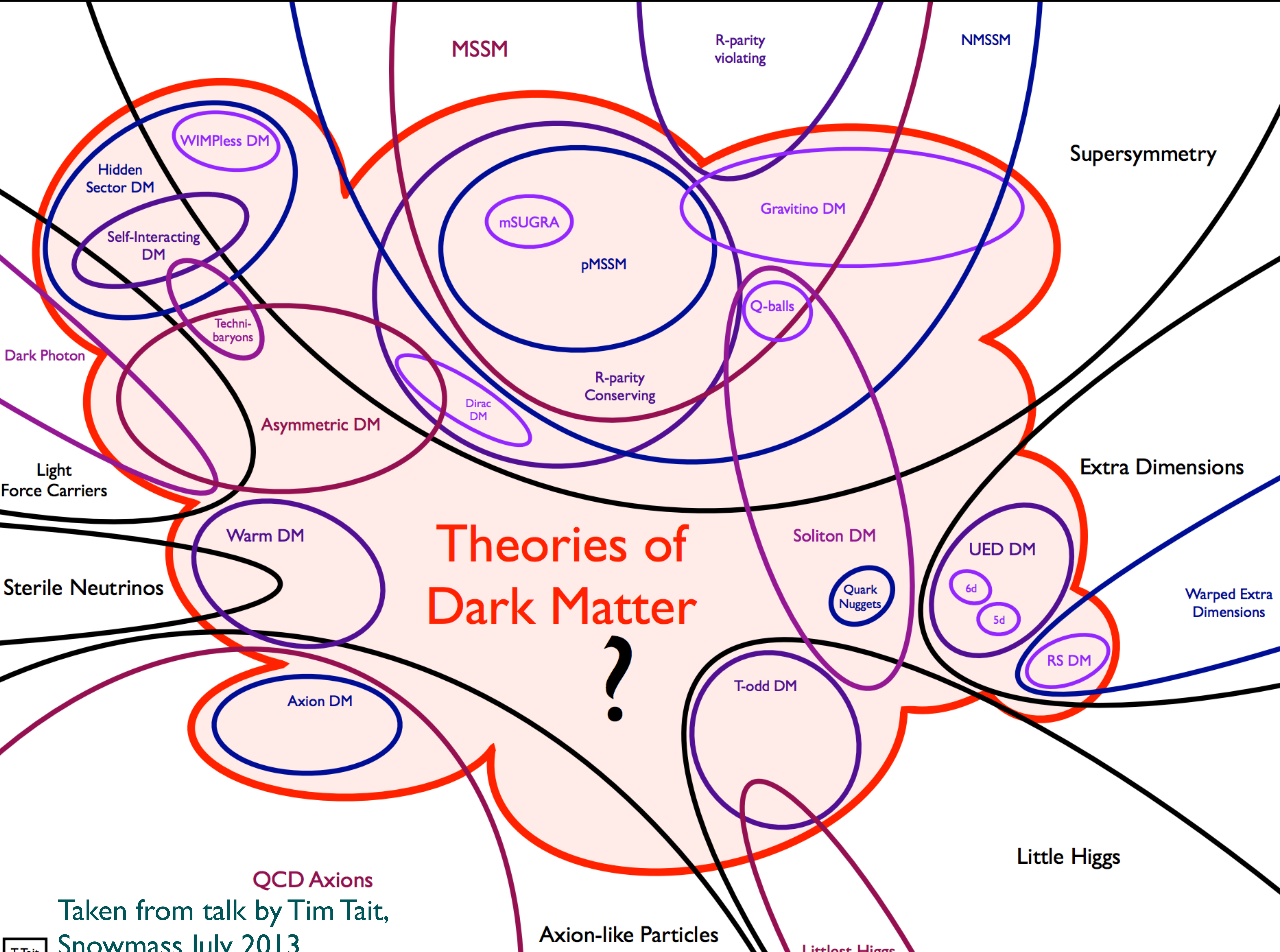
- Sufficiently light DM can have a wavelength large enough to modify observed sub-galactic structure - "fuzzy DM"
- The minimum DM mass is thus controlled by the smallest-scale DM structures we can observe
- Multiple approaches to mapping the smallest halos:
    - Lyman-α forest (probes matter clumpiness at redshifts 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 satellite galaxies of the Milky Way [e.g. Nadler et al '19]
- Current limits on fuzzy DM: $m_{\mathrm{DM}} \gtrsim 2-3\times10^{-21}$eV [Schutz '20]



Schutz '20

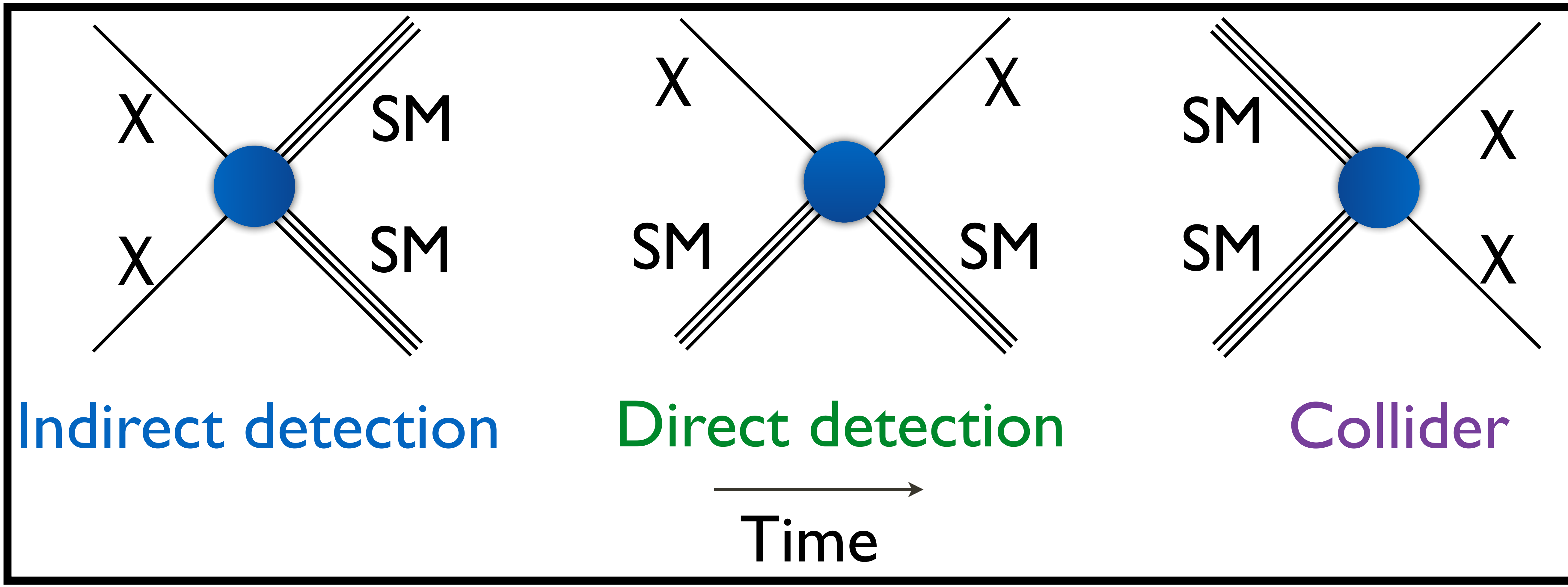
How fast can DM be?

- 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.



Taken from talk by Tim Tait,
Snowmass July 2013

Classic DM 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.

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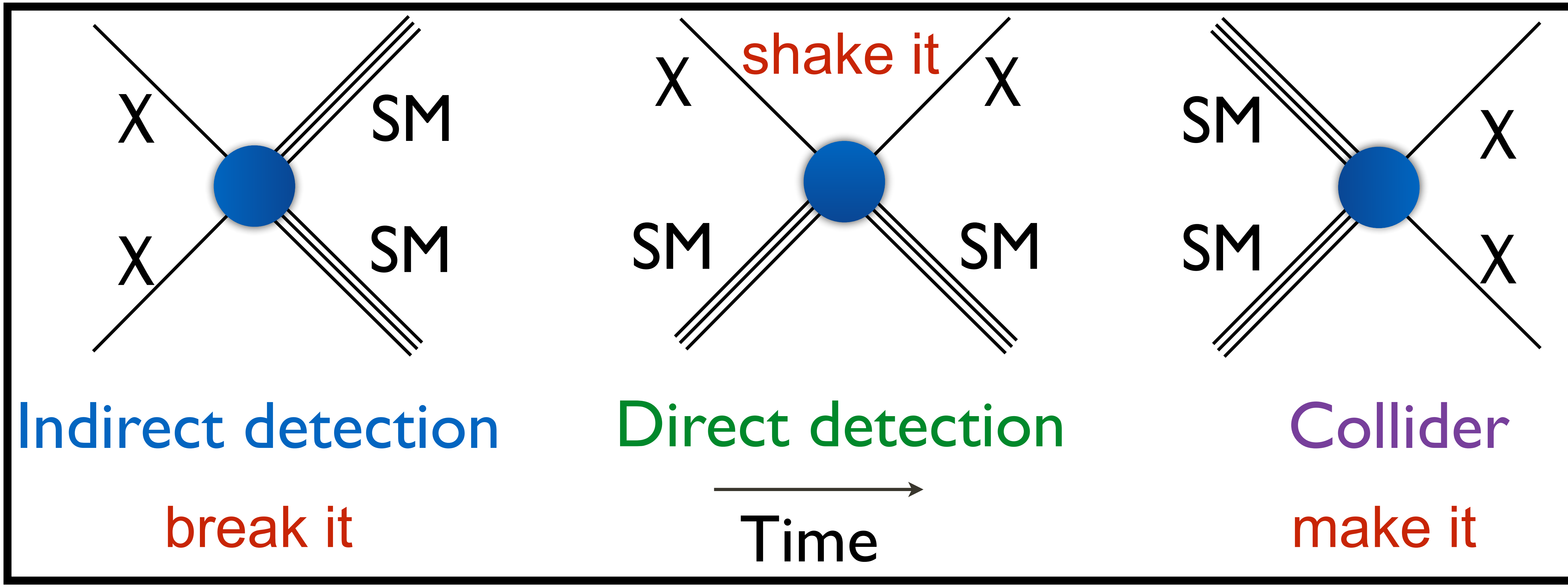

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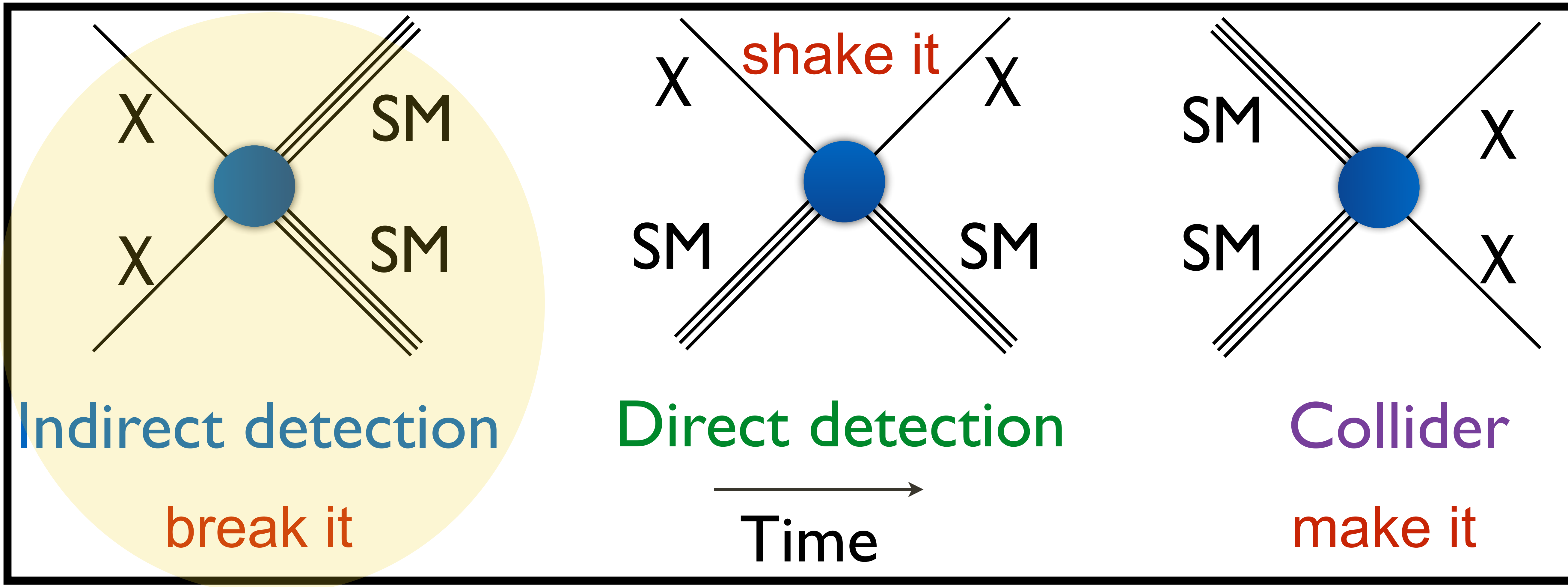

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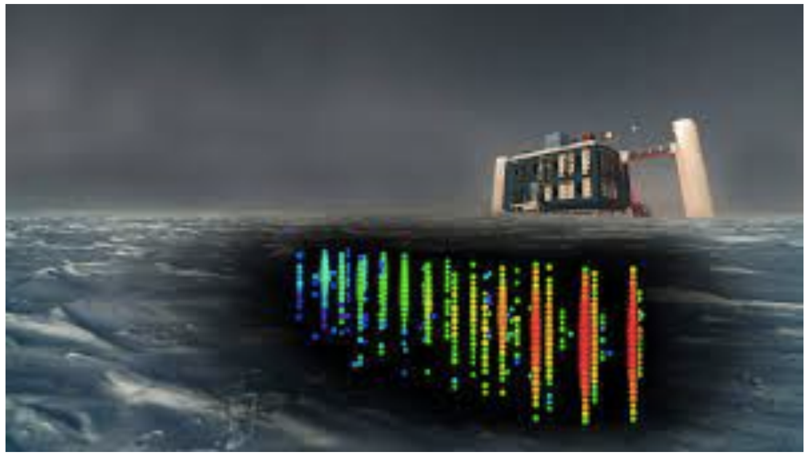
(some) Related work at UCLouvain

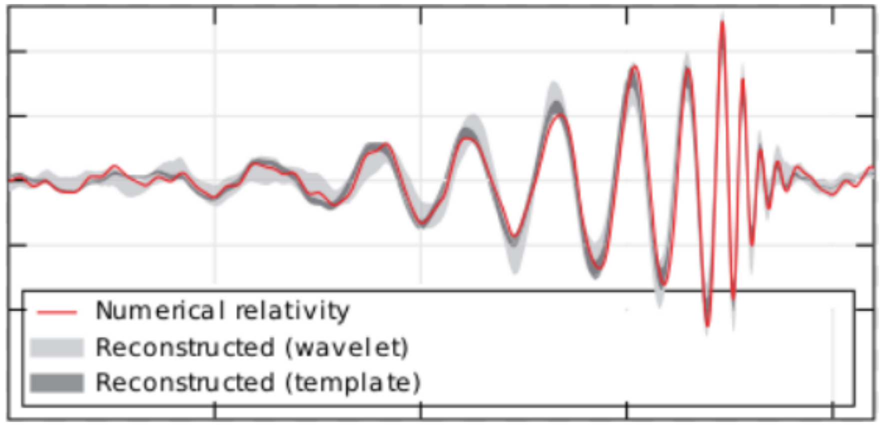


<u>Neutrino astronomy</u>
Gwenhaël De Wasseige

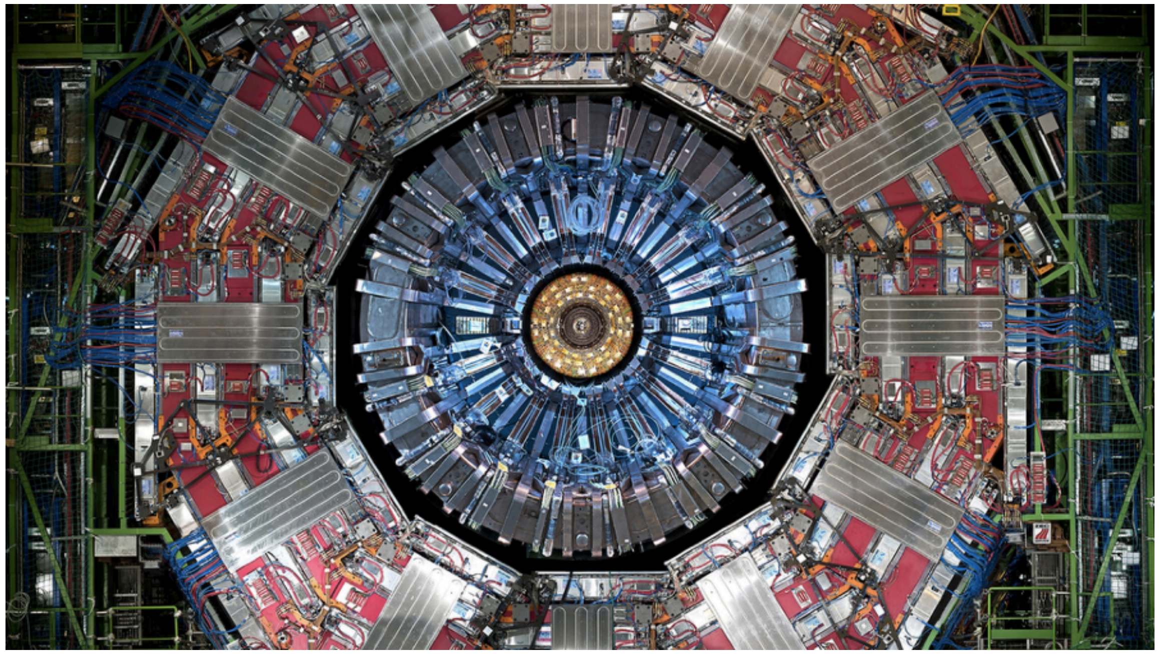
<u>Dark sector searches</u>
Eduardo Cortina Gil

<u>Collider physics</u>
Chiara Arina, Giacomo Bruno, Celine Degrande, Andrea Giammanco, Vincent Lemaitre, Fabio Maltoni

<u>Gravitational wave astronomy</u>
Giacomo Bruno, Joris van Heiningen



<u>Fundamental theory / cosmology</u>
Marco Drewes, Jean Marc Gerard, Jan Govaerts, Christophe Ringeval



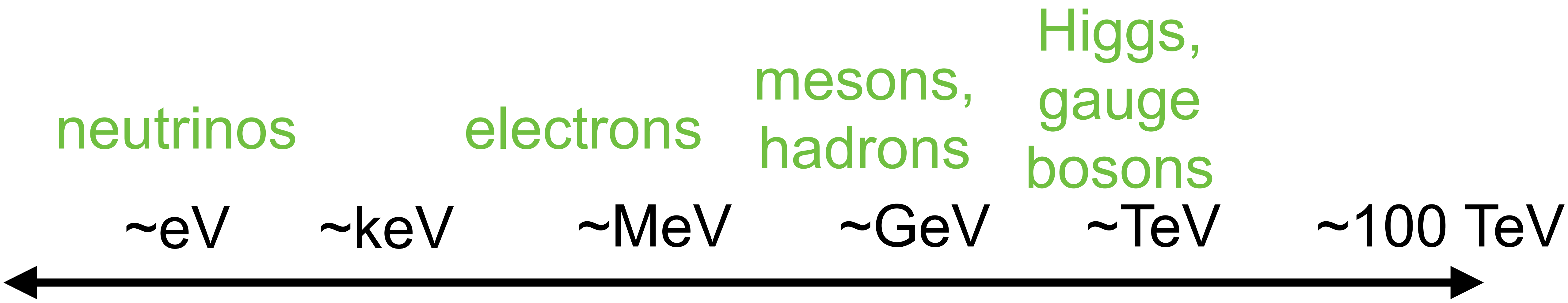
Some mechanisms for indirect signals of dark matter

- Annihilations / collisions between dark matter (DM) particles that produce visible particles
  - Has natural "thermal relic" benchmark cross section, if annihilation depletes early-universe DM abundance to its observed value:

$$\langle \sigma v \rangle \sim \frac{1}{m_{\mathrm{Planck}} T_{\mathrm{eq}}} \sim \frac{1}{(100\mathrm{TeV})^2} \approx 2 \times 10^{-26} \mathrm{cm}^3/\mathrm{s}$$

- Decay of DM into visible particles, directly or through intermediate states - lifetime must be >> age of universe
- Scattering of DM on visible particles leading to indirect signals
- Oscillation of DM into visible particles, and vice versa

Classification of DM by mass



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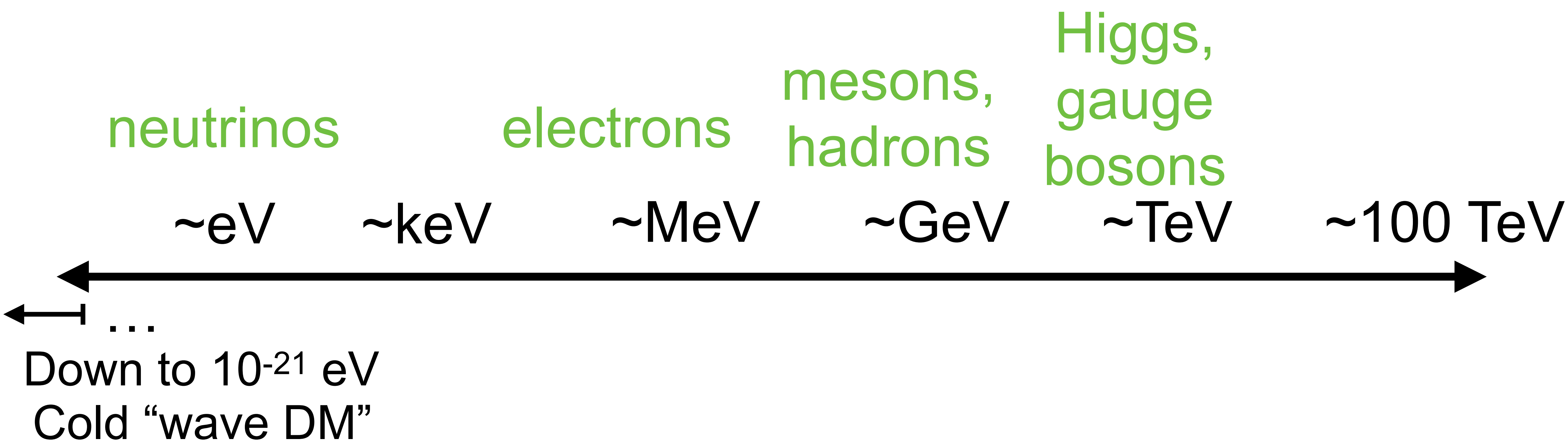

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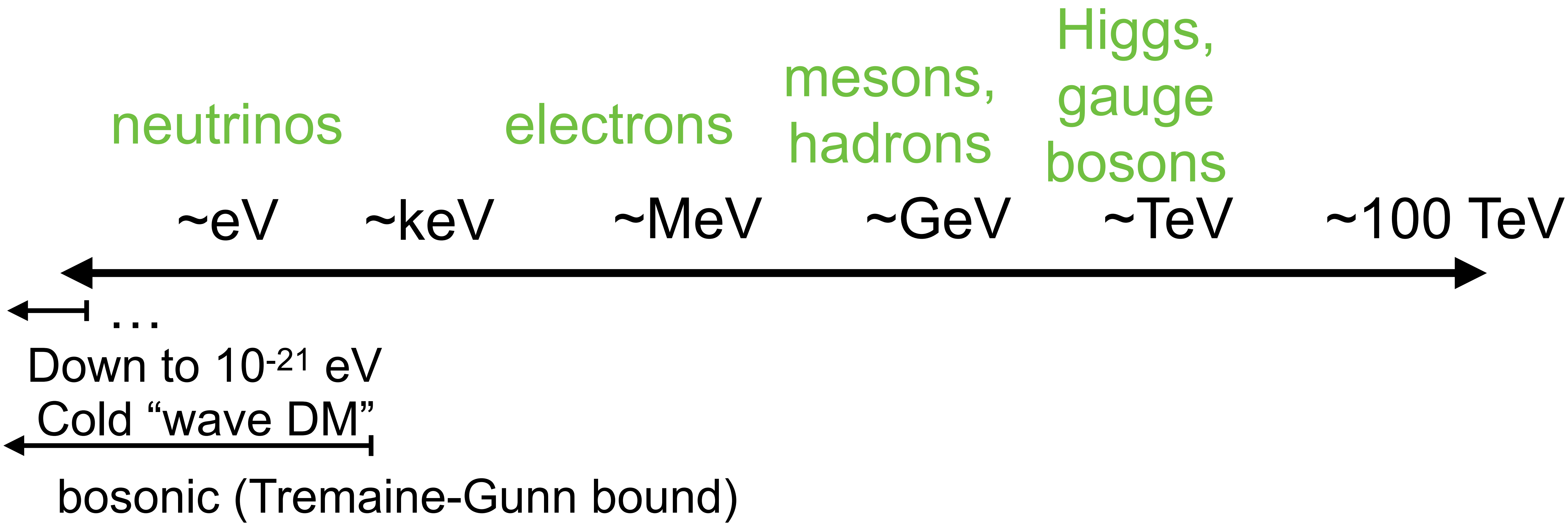

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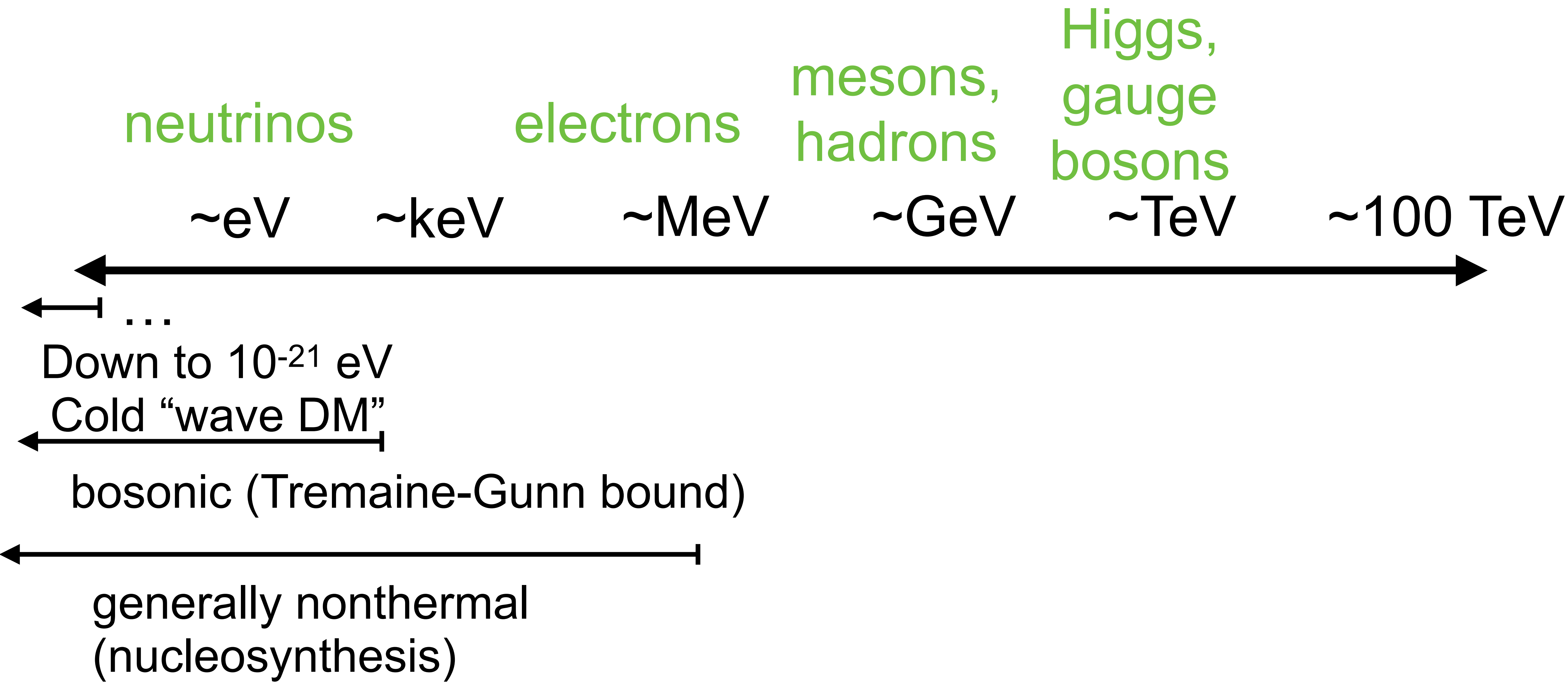

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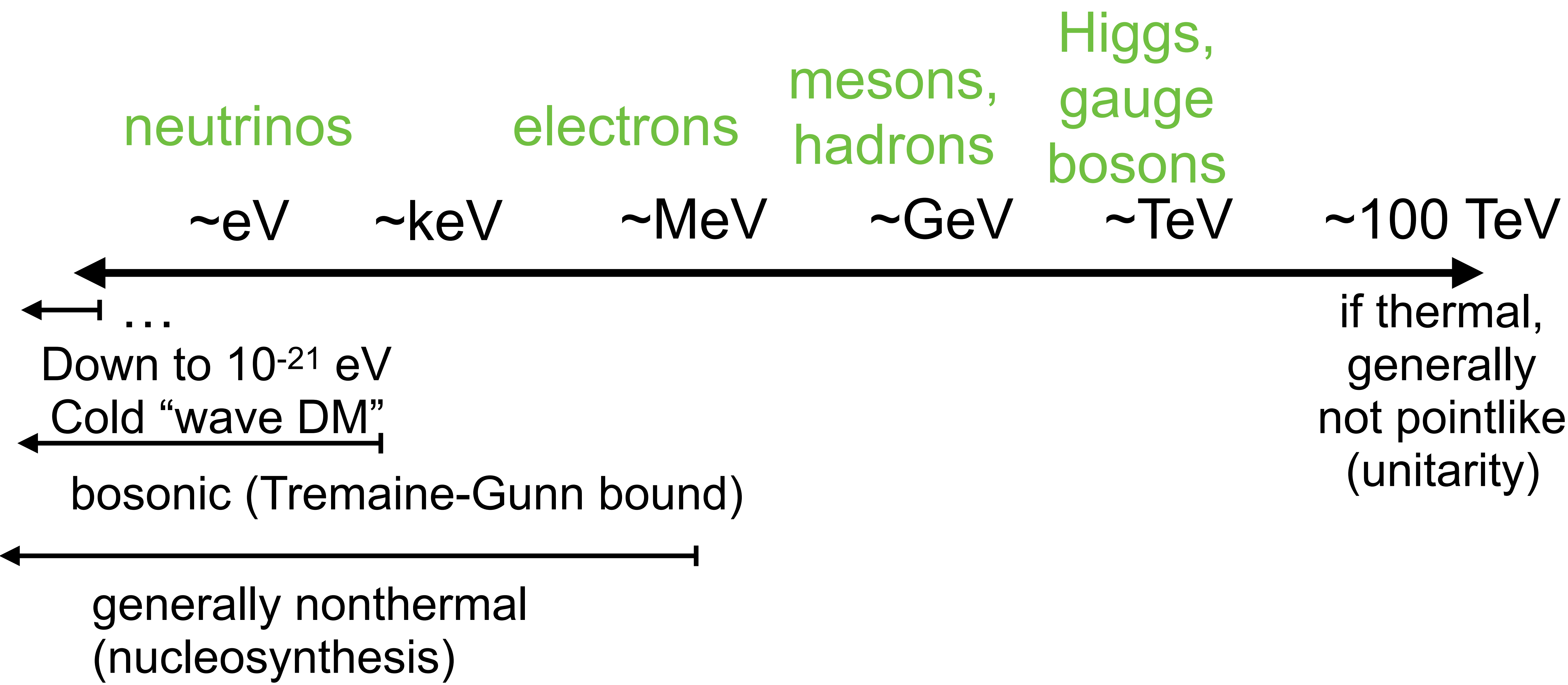

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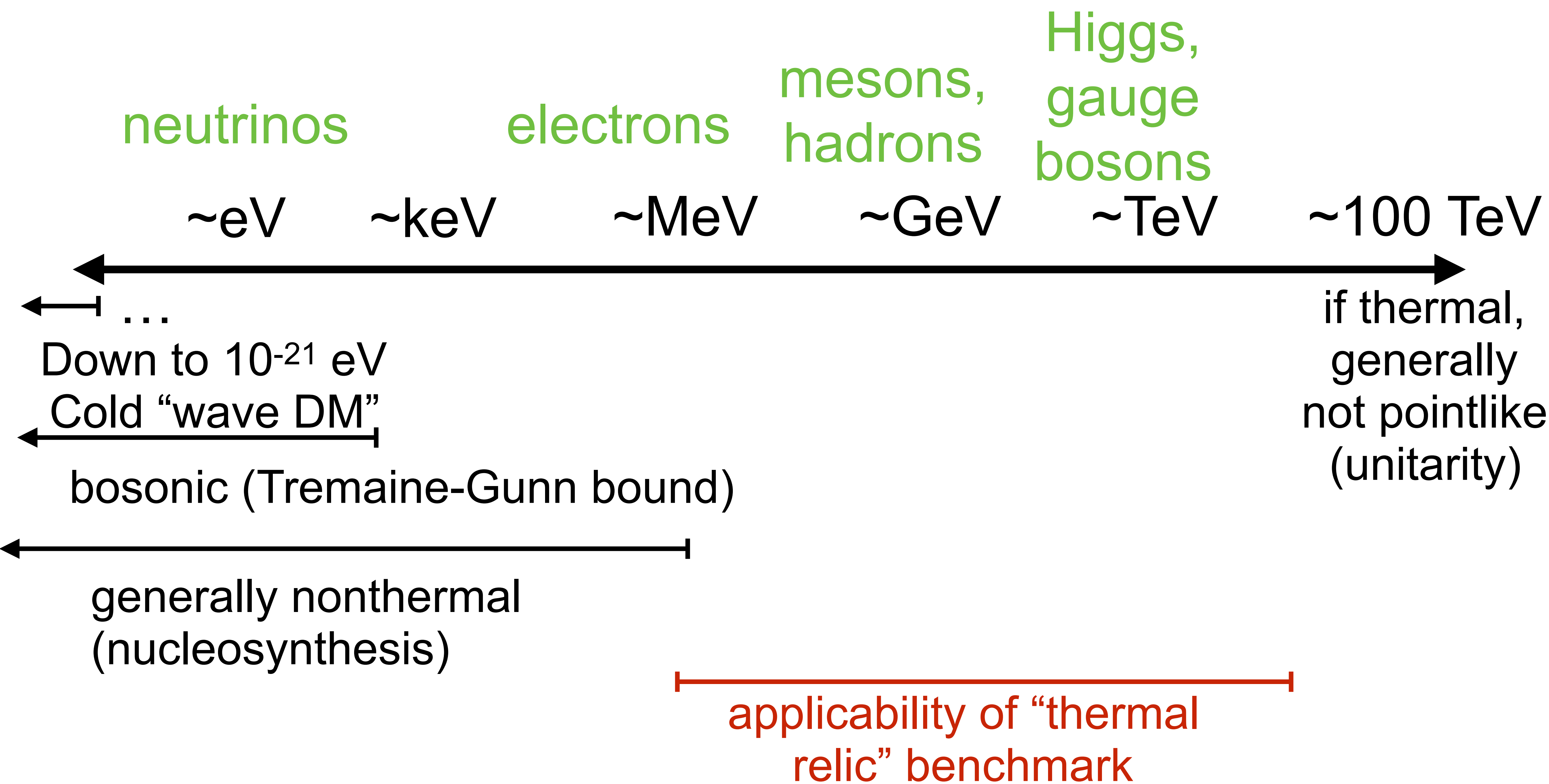

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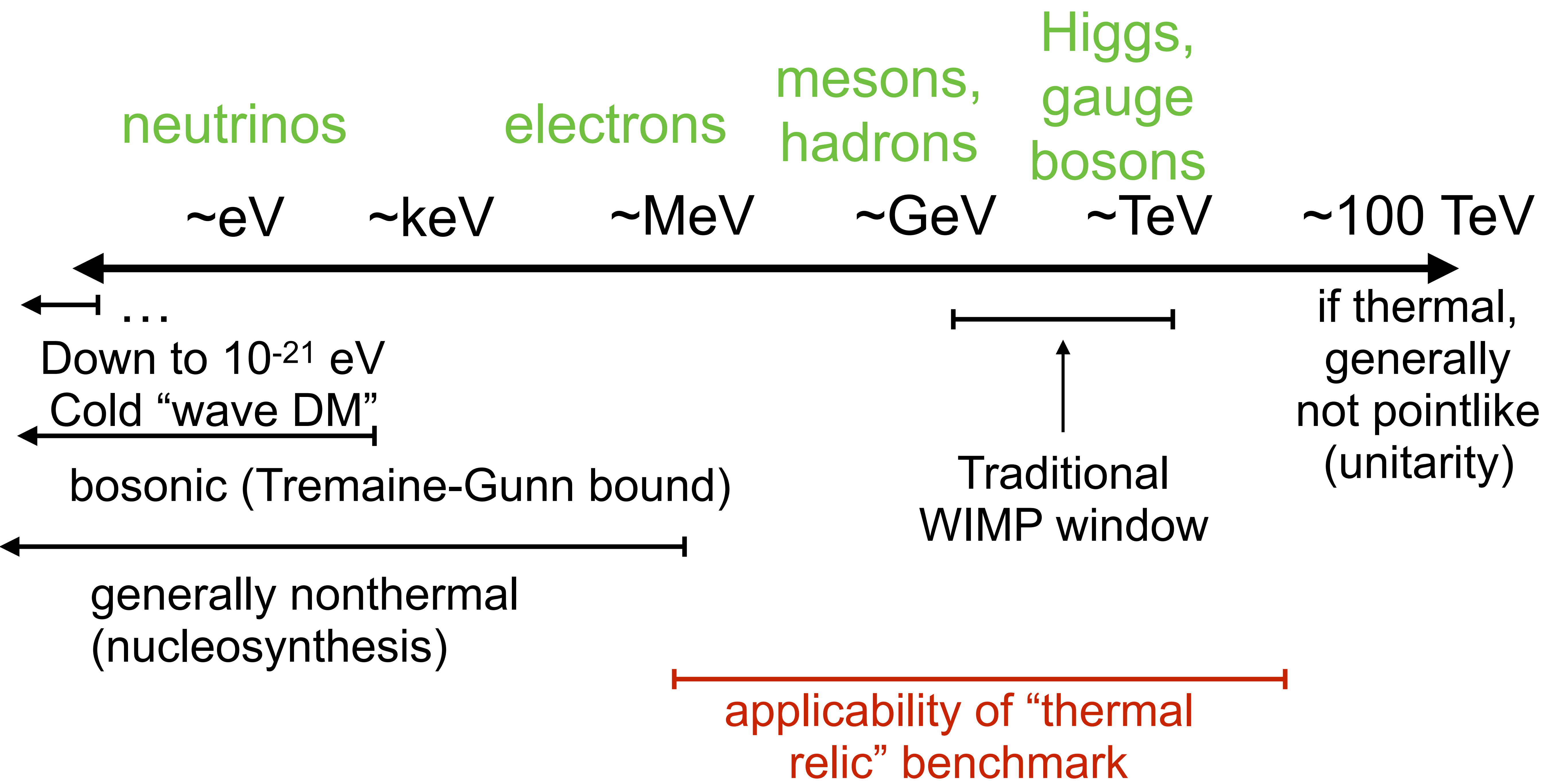

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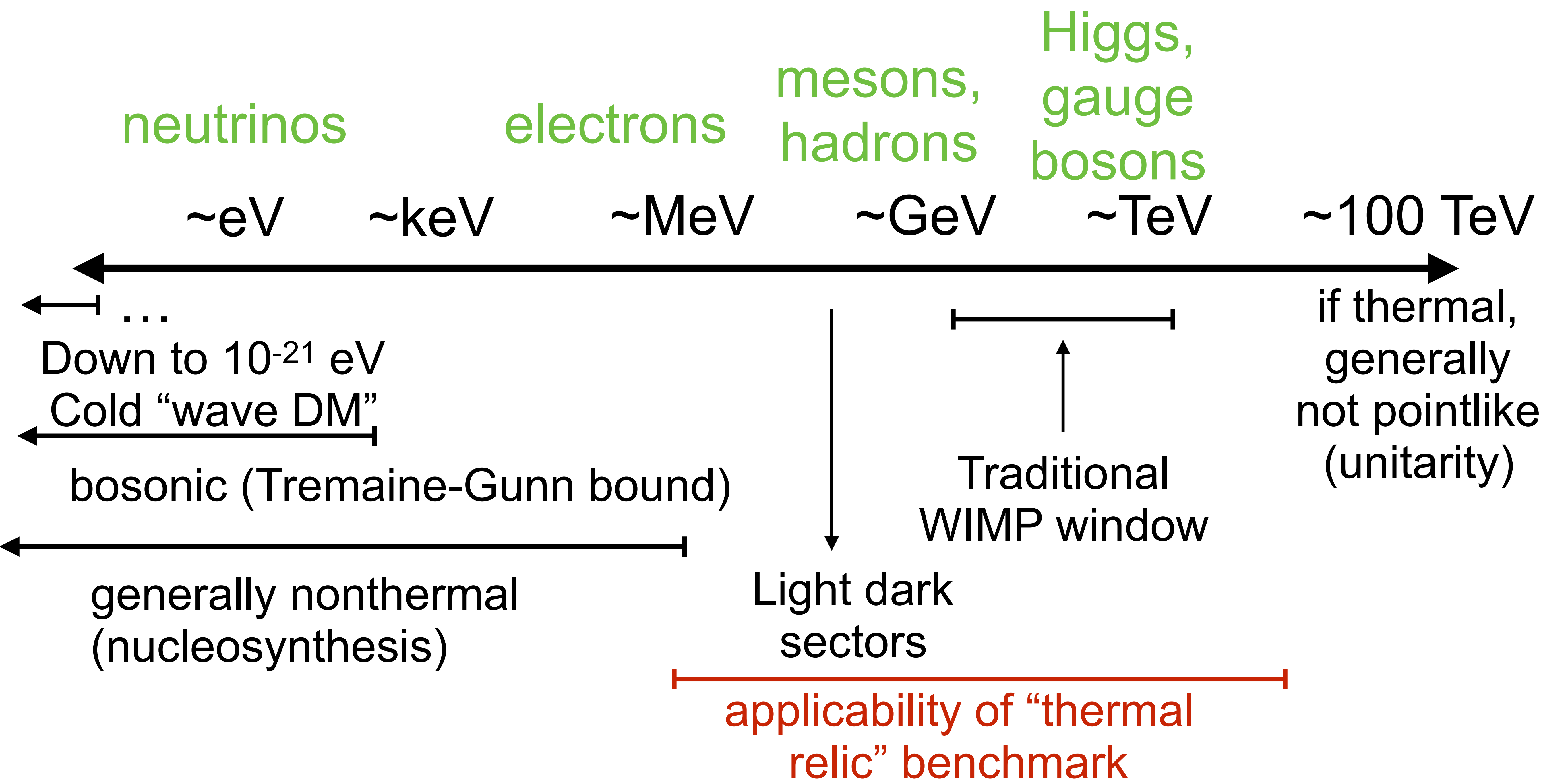

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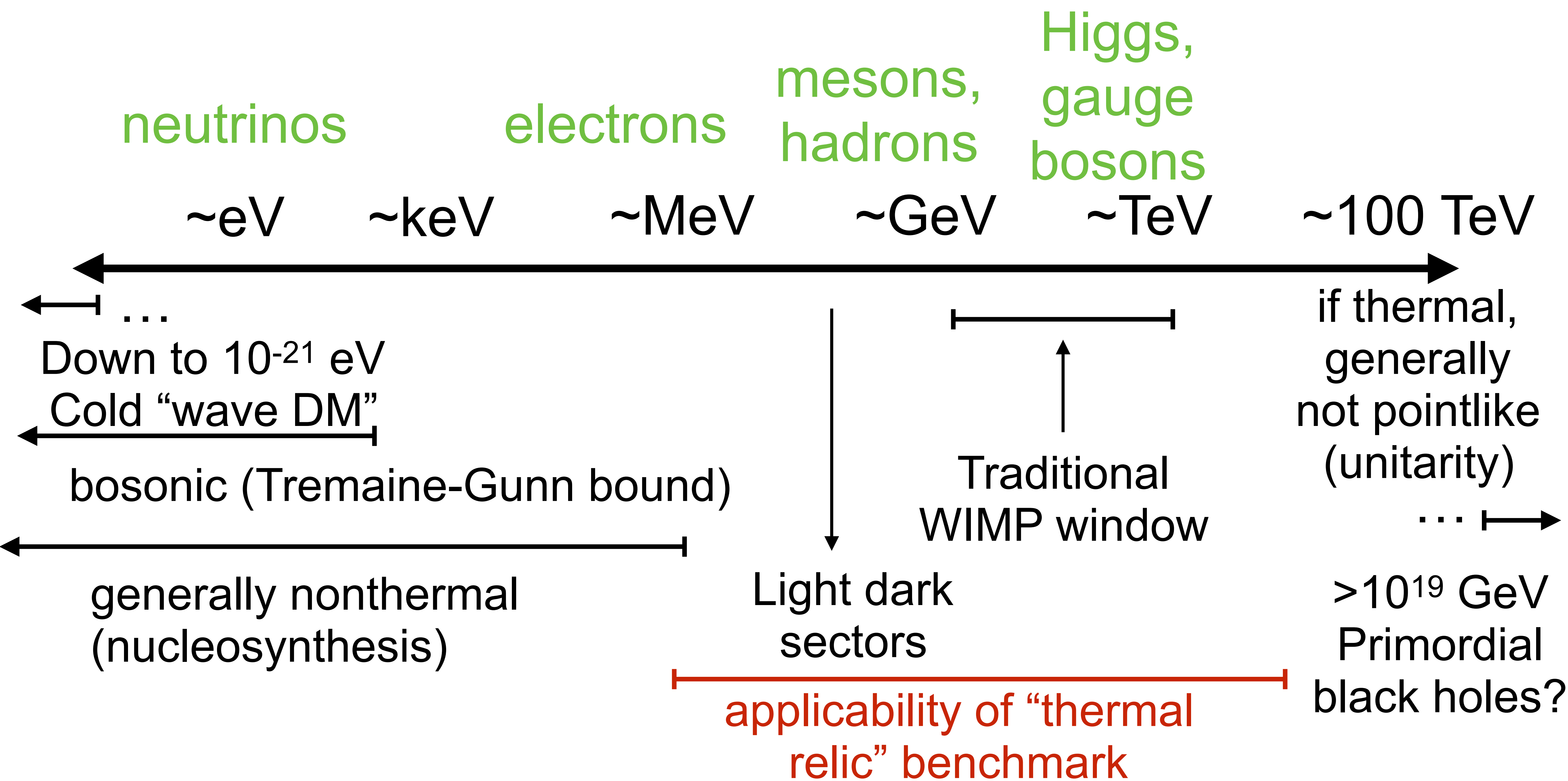
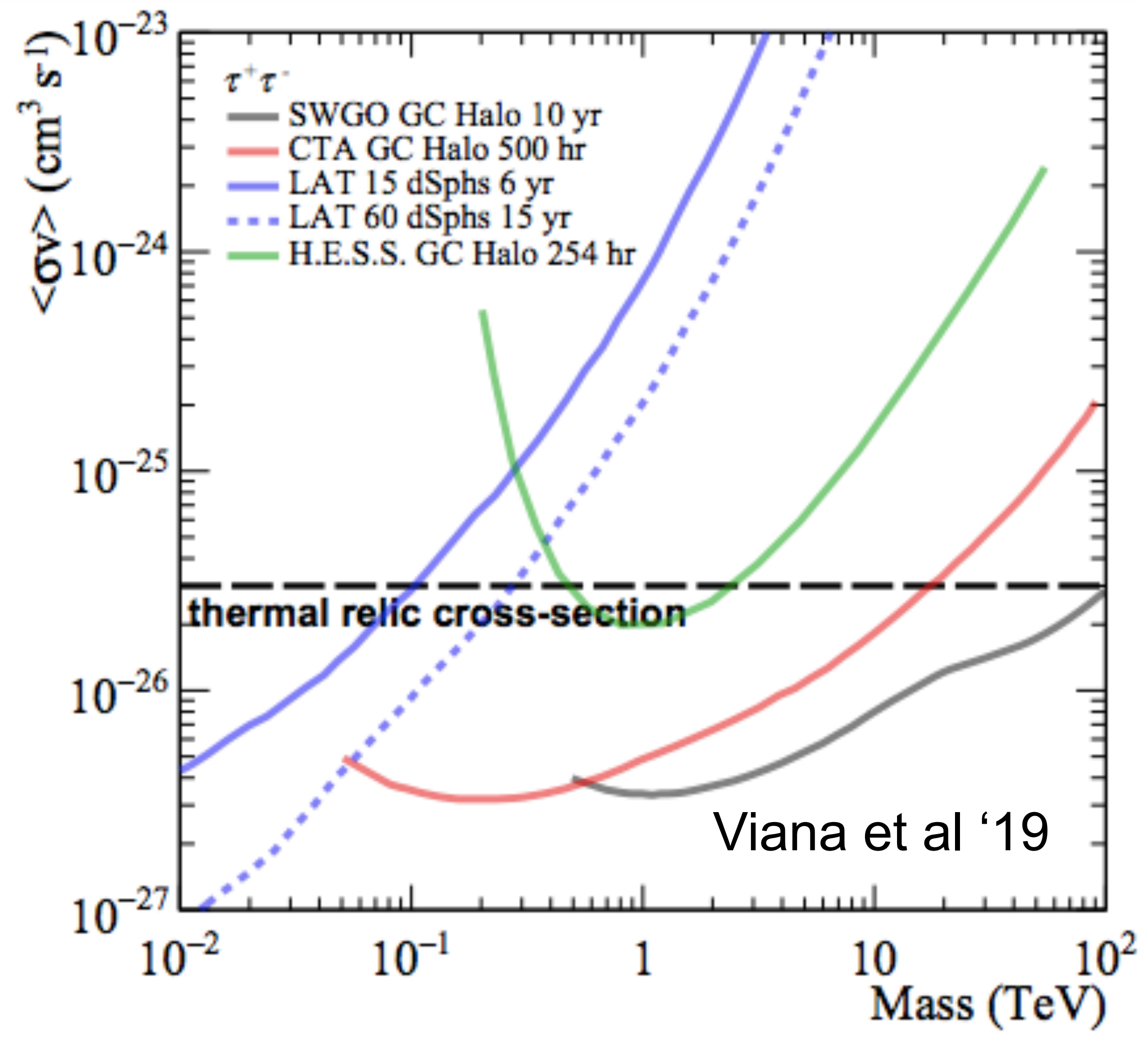
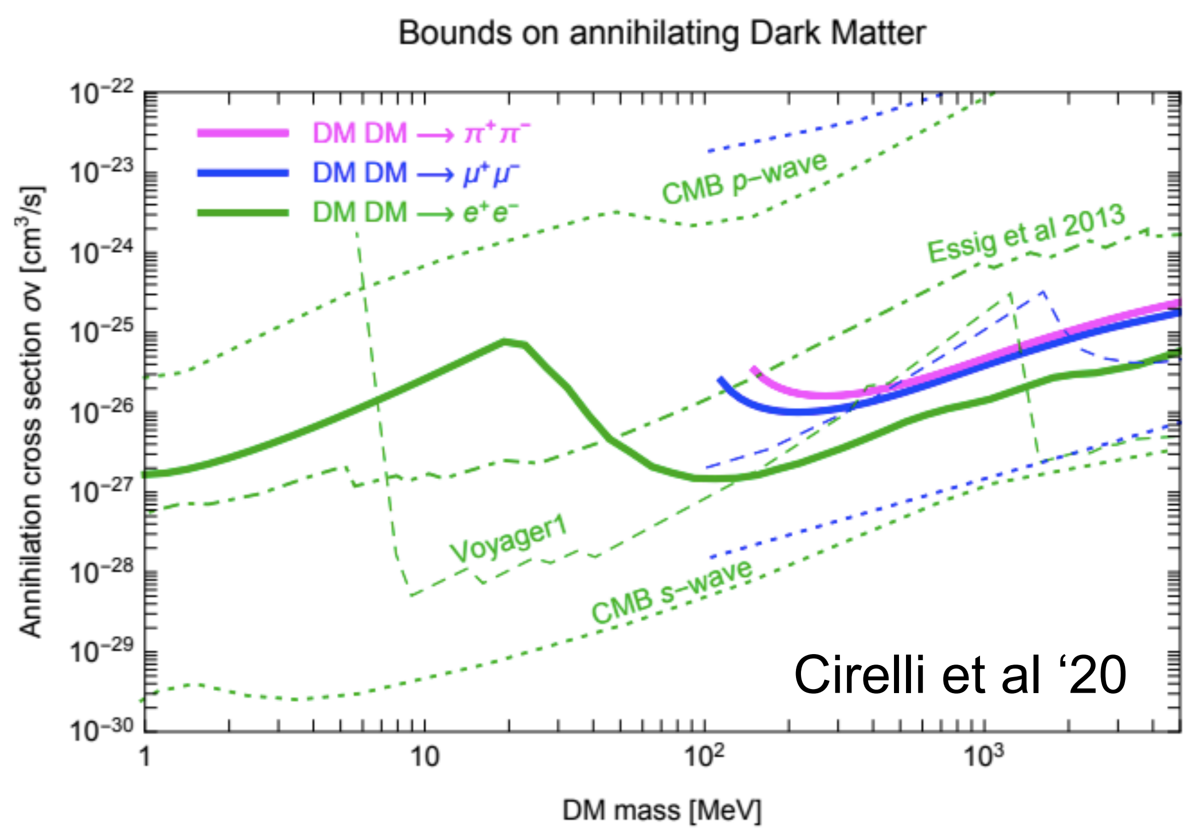


Current limits

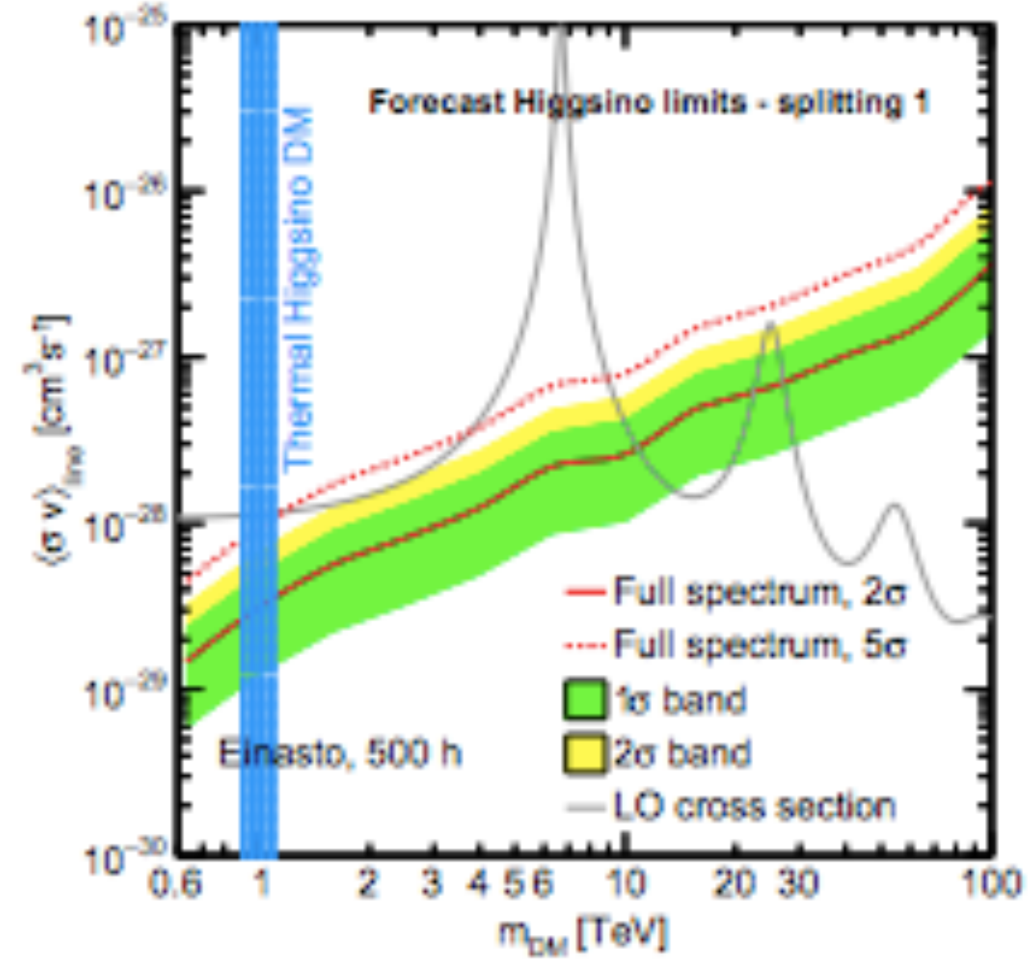
- There are stringent limits from indirect/direct/collider searches - no robust detections yet.
- Limits from the CMB, gamma-ray and cosmic-ray experiments probe the thermal relic cross section up to DM masses of 10s-100s GeV, for all SM final states except neutrinos.
- CMB bounds: energy injection from annihilation/decay could ionize hydrogen in the early universe, modifying the primordial radiation. [See Lecture 4]
- Gamma-ray/cosmic-ray/neutrino bounds: search directly for particles produced from DM annihilation/decay. [See Lecture 3]
- Future experiments have the possibility of reaching this cross section for 10-100 TeV DM.



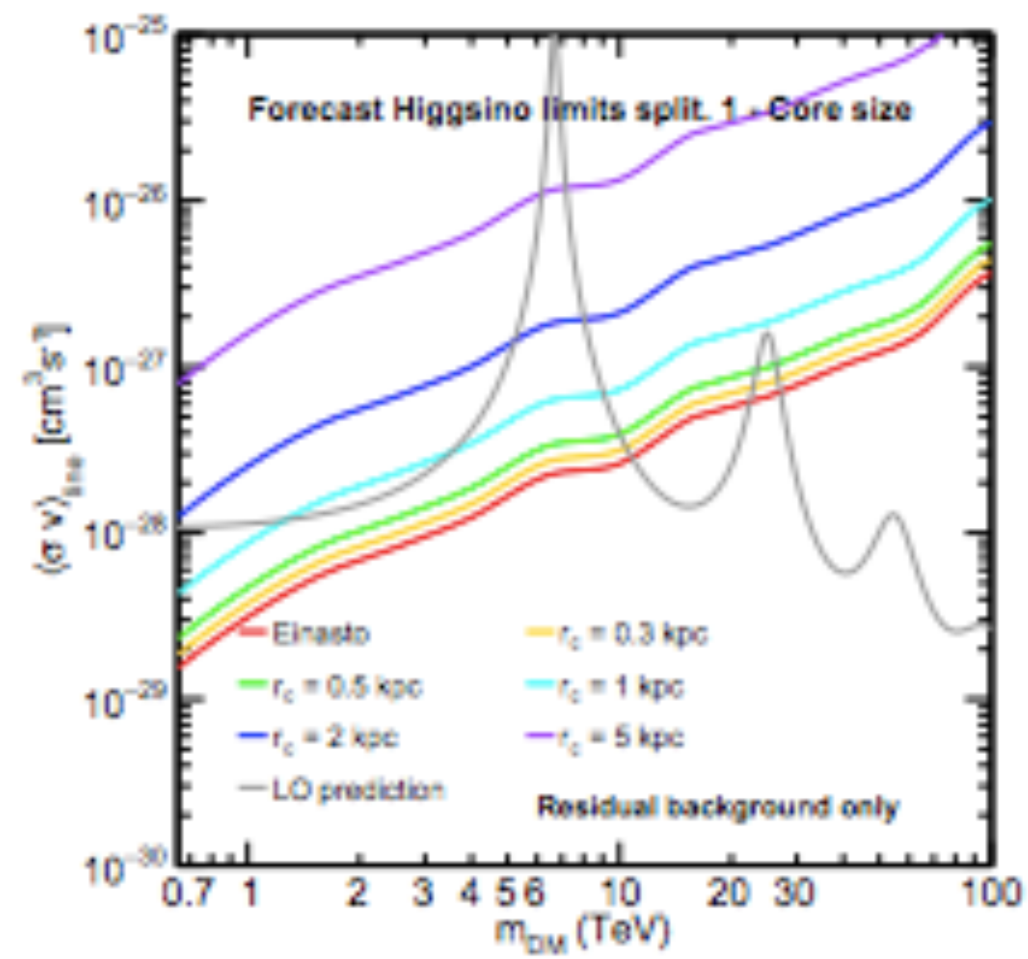


Electroweak DM

- 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 higgsino - fermionic DM interacting with W and Z bosons analogously to a Higgs boson
- 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 weakly-interacting DM 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]



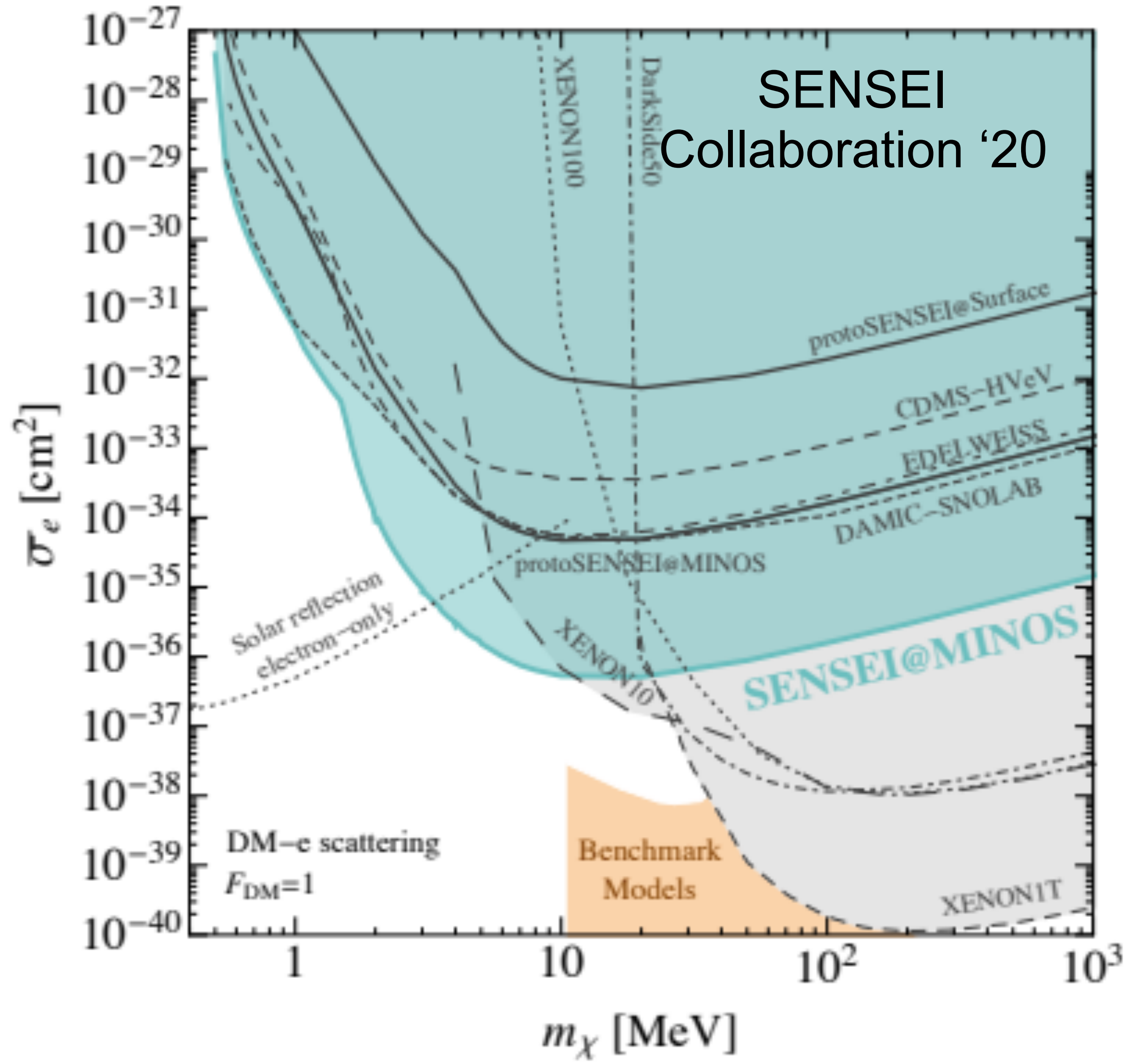
Rinchiuso, TRS et al '21

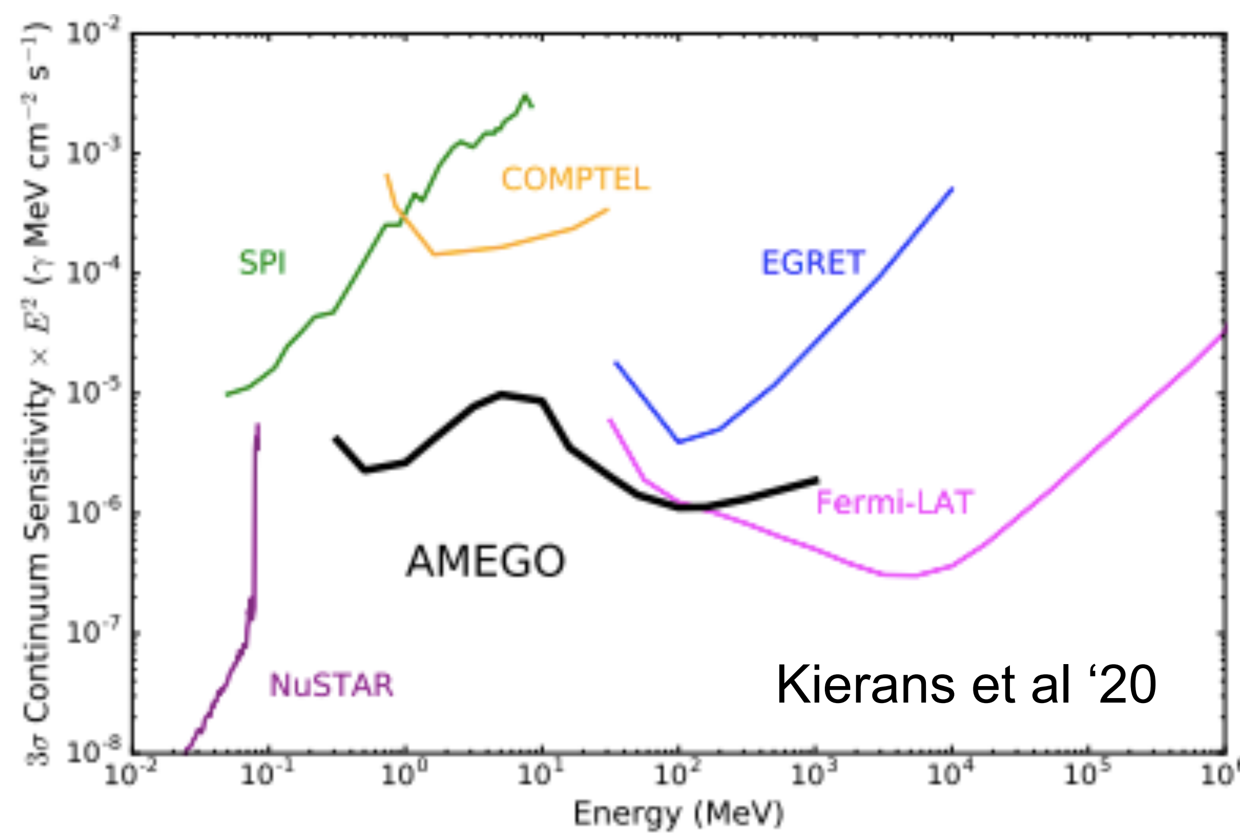


Low-mass thermal DM

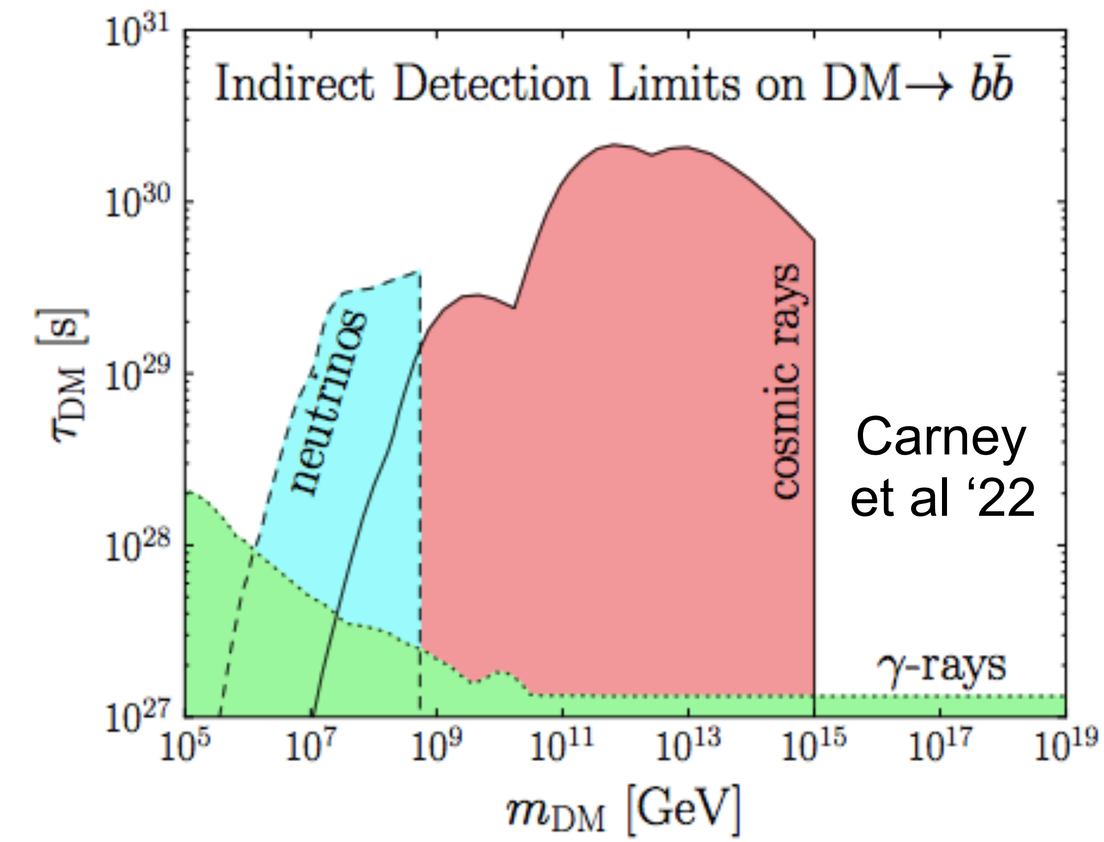
- MeV-GeV band is currently the focus of a huge amount of effort across indirect detection, direct detection, and colliders.
- Classic direct detection experiments lose sensitivity for DM masses below 1-10 GeV, and accelerator-based searches often need to be redesigned
- Indirect limits remain strong, but can be evaded if annihilation is suppressed
- There is also currently a “MeV gap” in gamma-ray sensitivity - proposed missions such as AMEGO, GRAMS, GECCO could cover this gap

Example: constraints on DM-electron scattering





Above the thermal window: ultraheavy DM



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

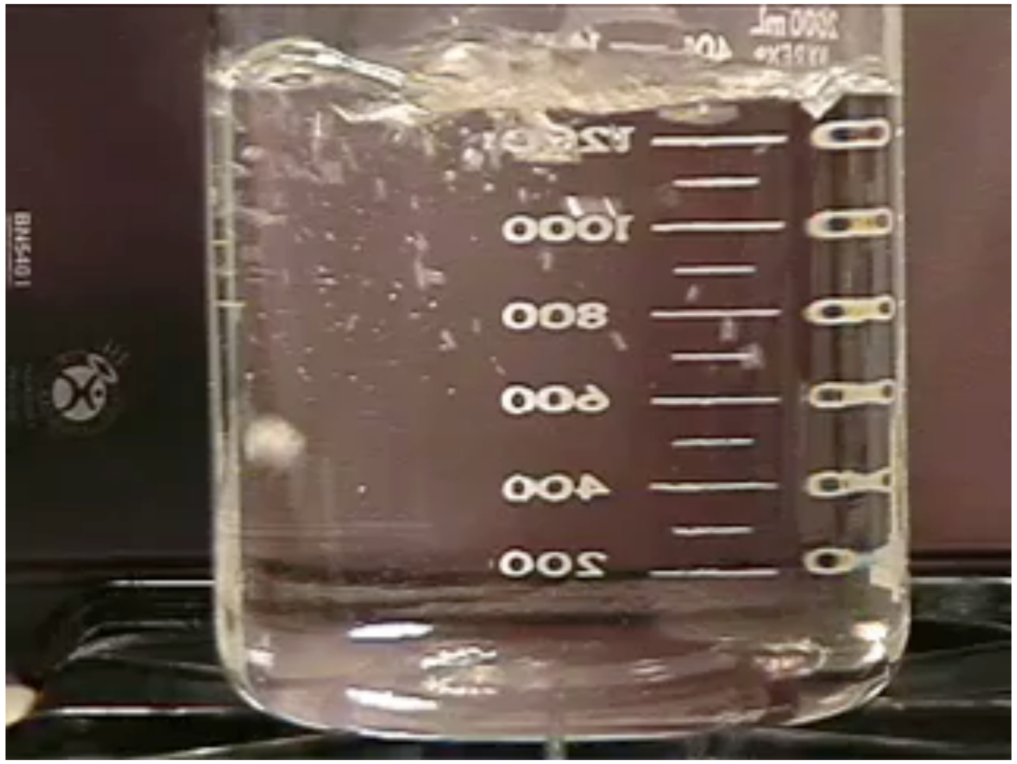
- (Much) higher masses can be achievable for thermal relic DM when standard assumptions break down, e.g. via modifications to cosmology such as a first-order phase transition in the dark sector [e.g. Asadi, TRS et al '21], or formation of many-particle bound states after freezeout [e.g. Coskuner et al '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

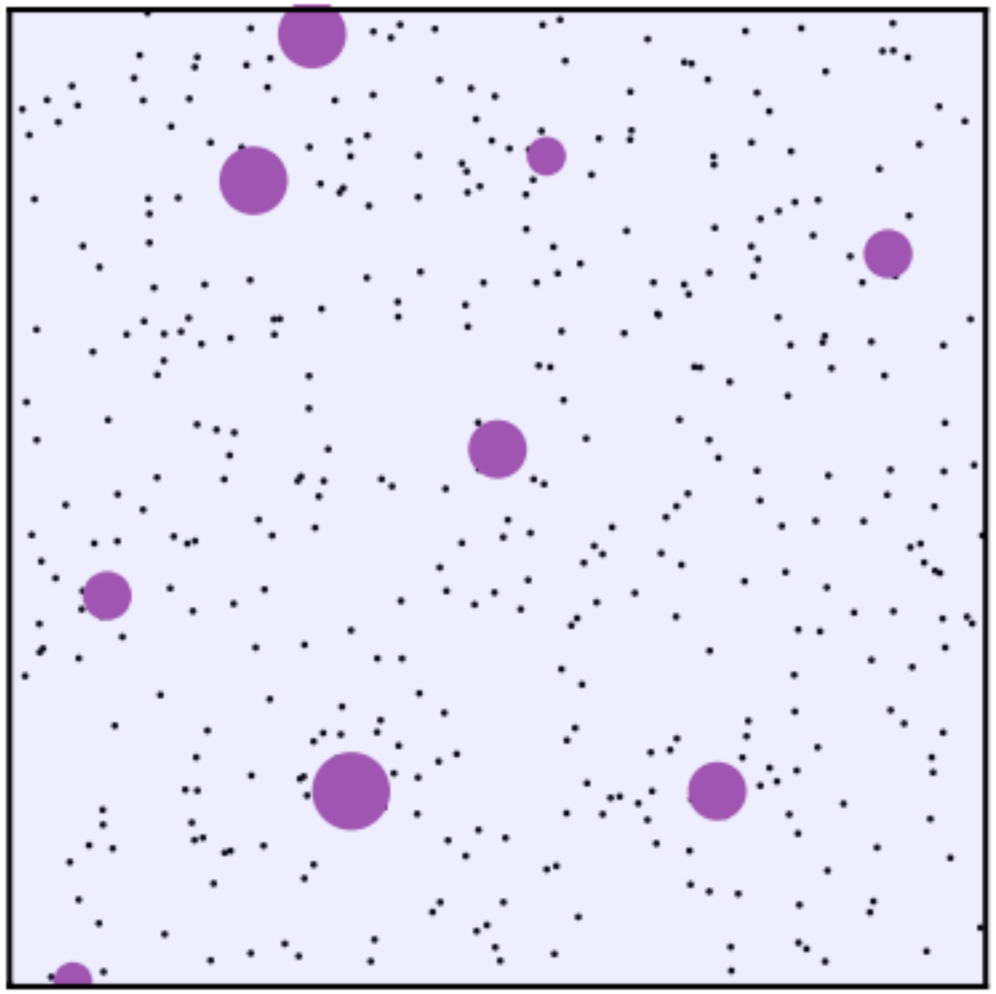
- Observations of ultra-high-energy CRs and photons could provide sensitivity to decays of ultraheavy DM candidates [e.g. Berezinsky et al '97, Romero-Wolf et al '20, Anchordoqui et al '21, Carney et al '22]

Heavy thermal DM from squeezeout

- If the dark matter has its own strong interactions, there can be a 1st-order phase transition in the "dark sector"
- Growing bubbles of the new phase compress the dark matter, increasing its annihilation rate [Asadi, TRS et al '21, 22]
- This can lead to the correct DM abundance for masses of 1000+ PeV



ISLE Physics, YouTube



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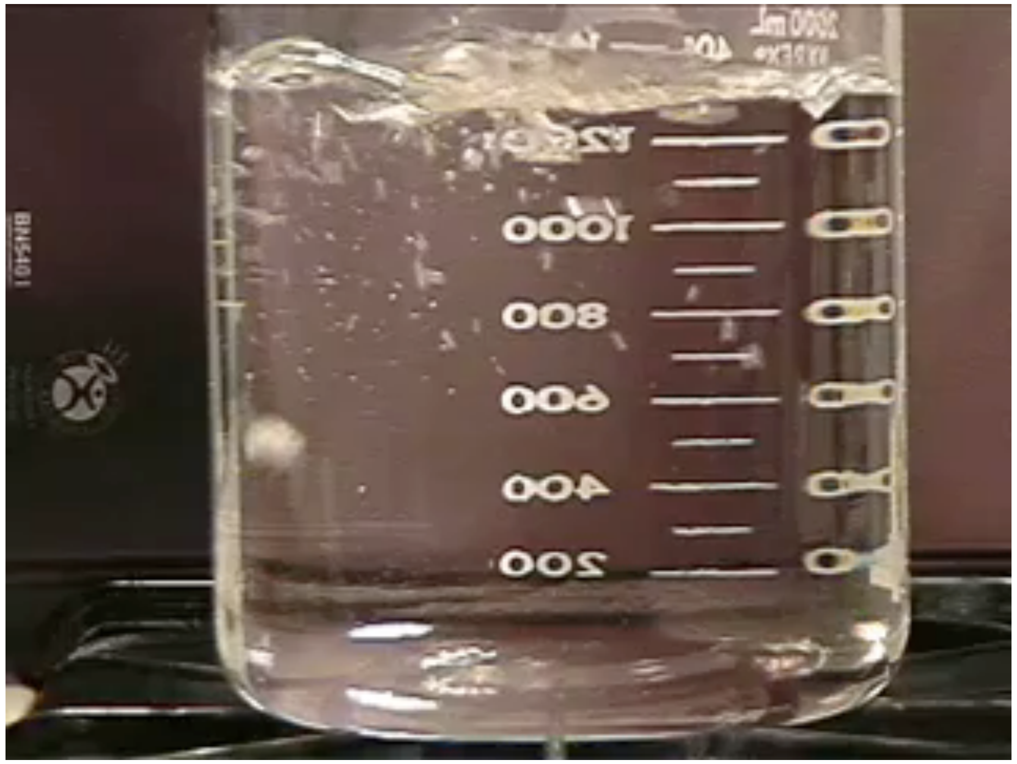

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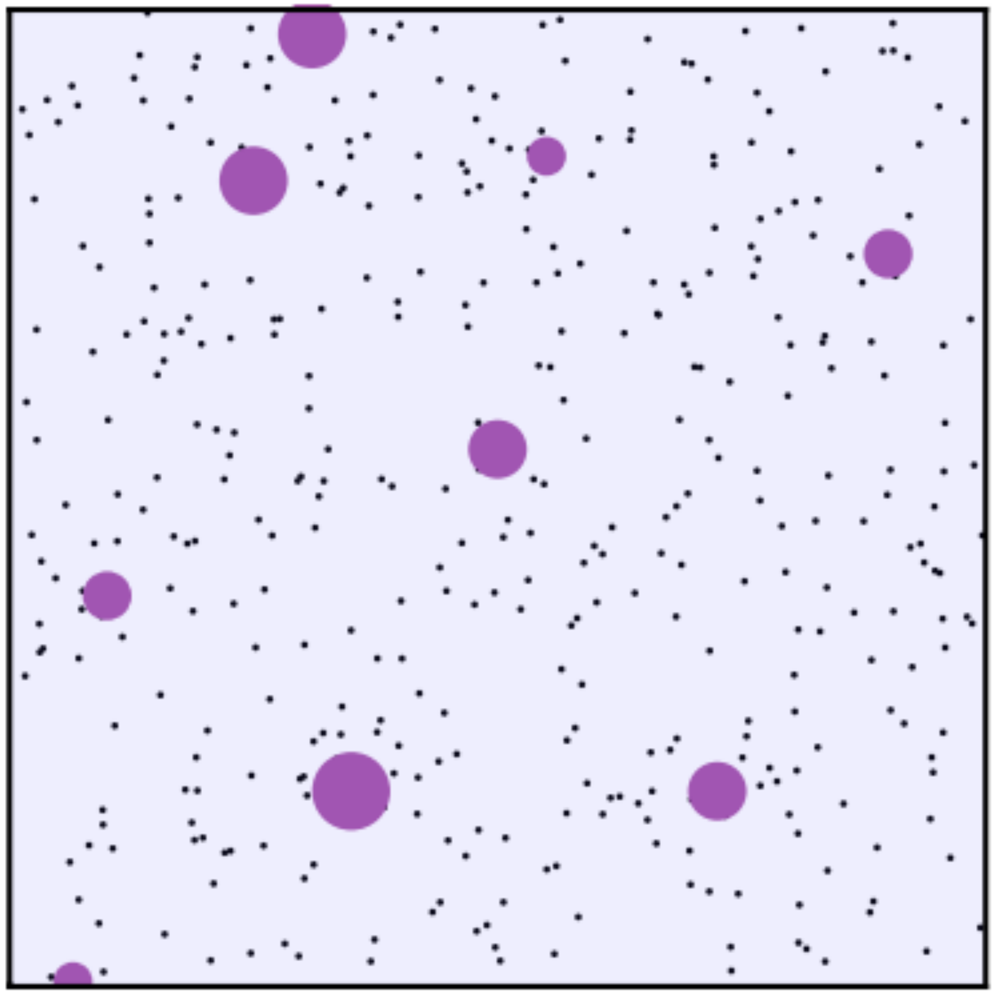

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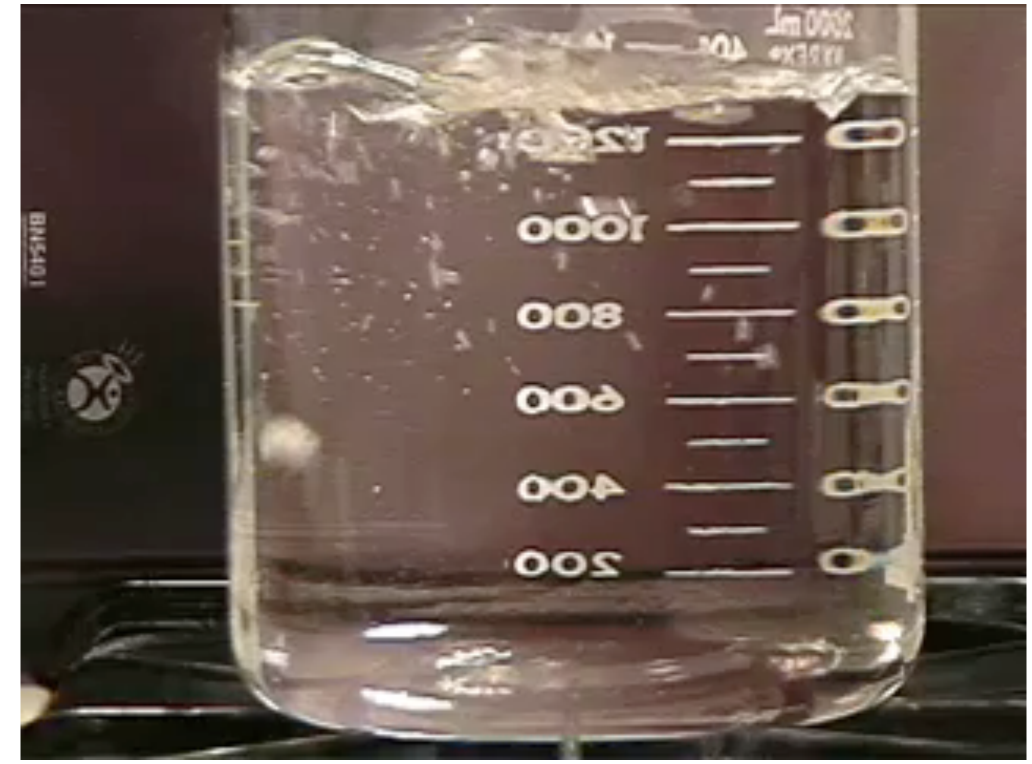

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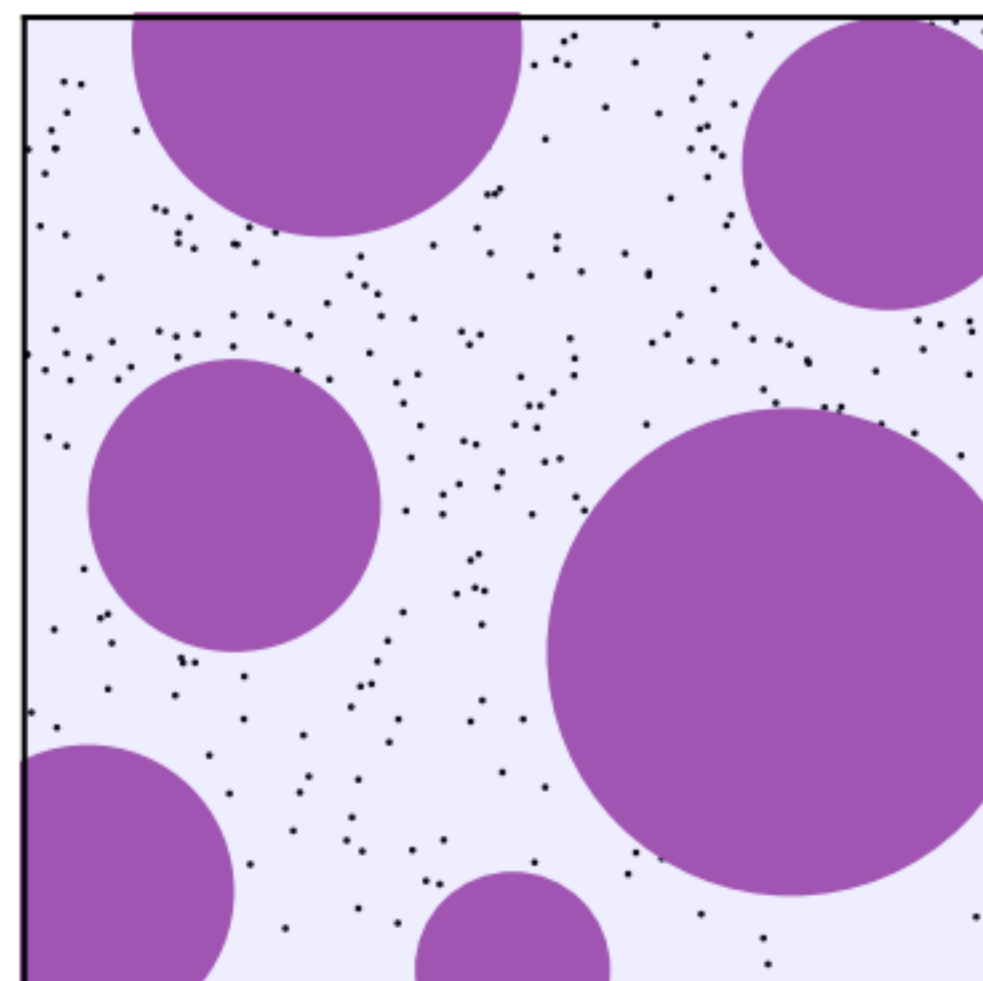

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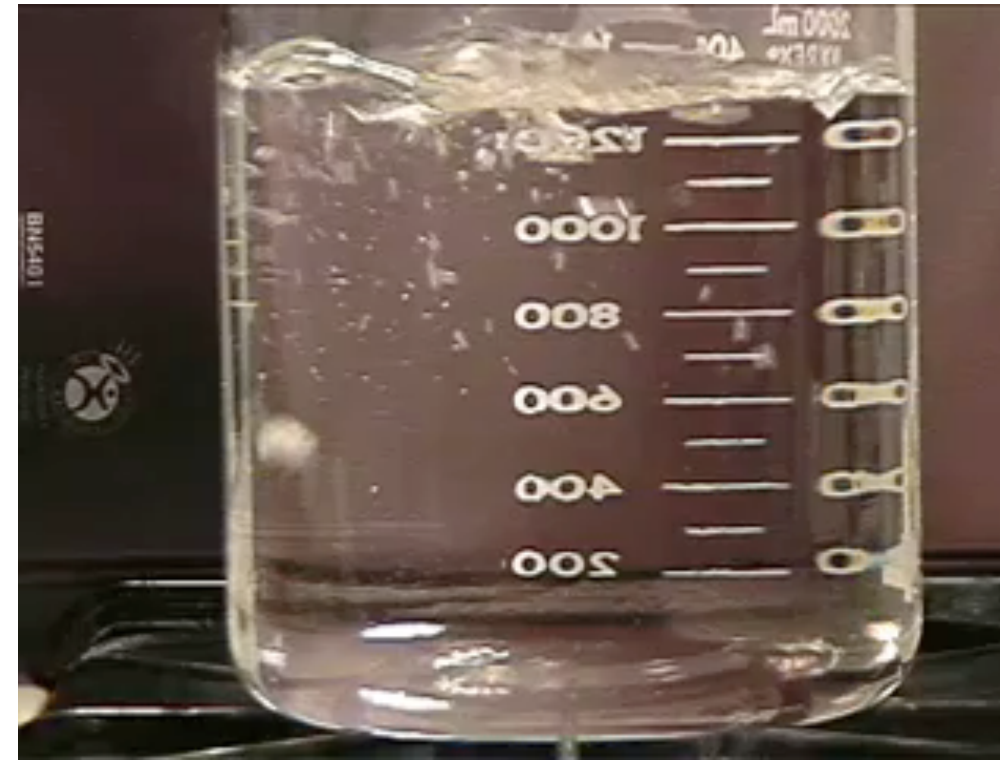

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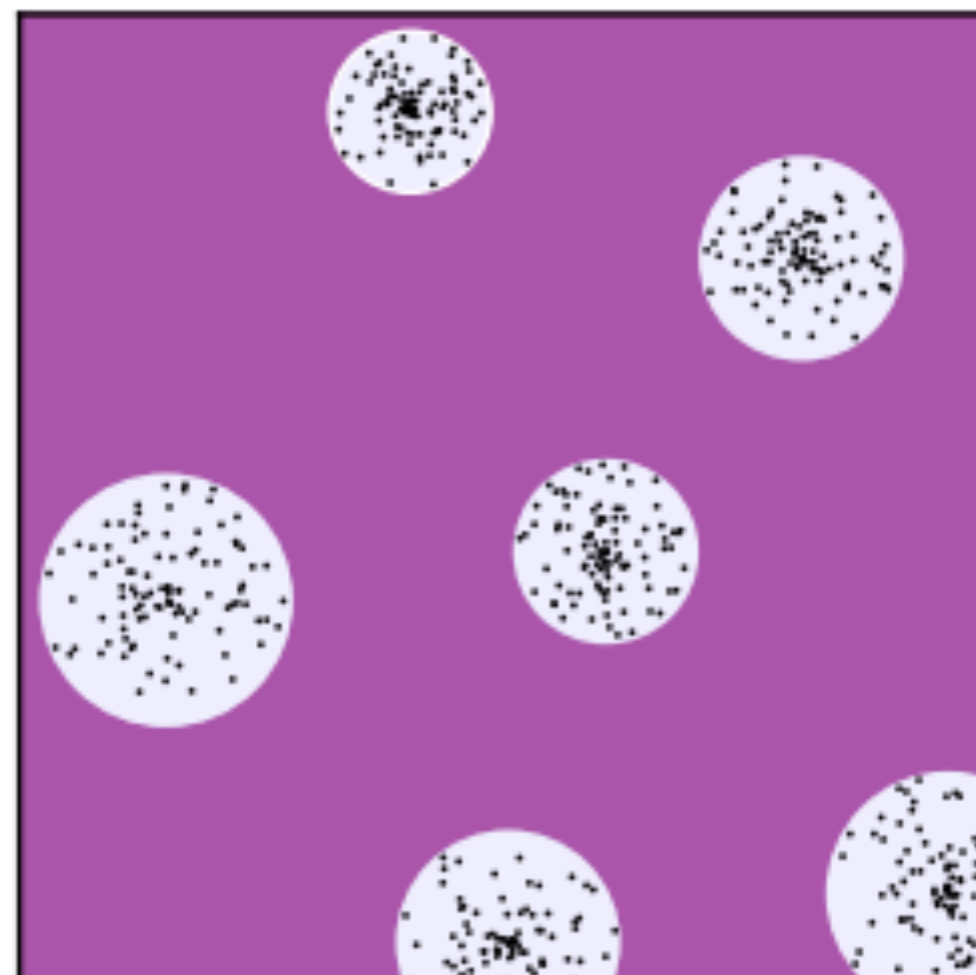

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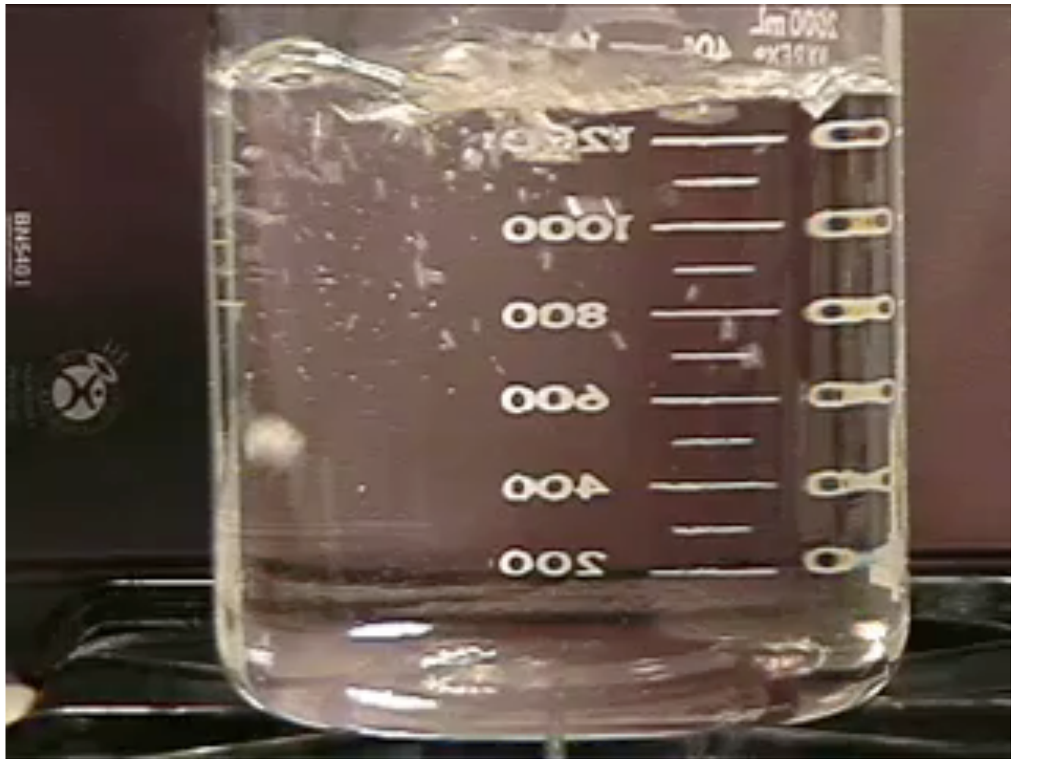

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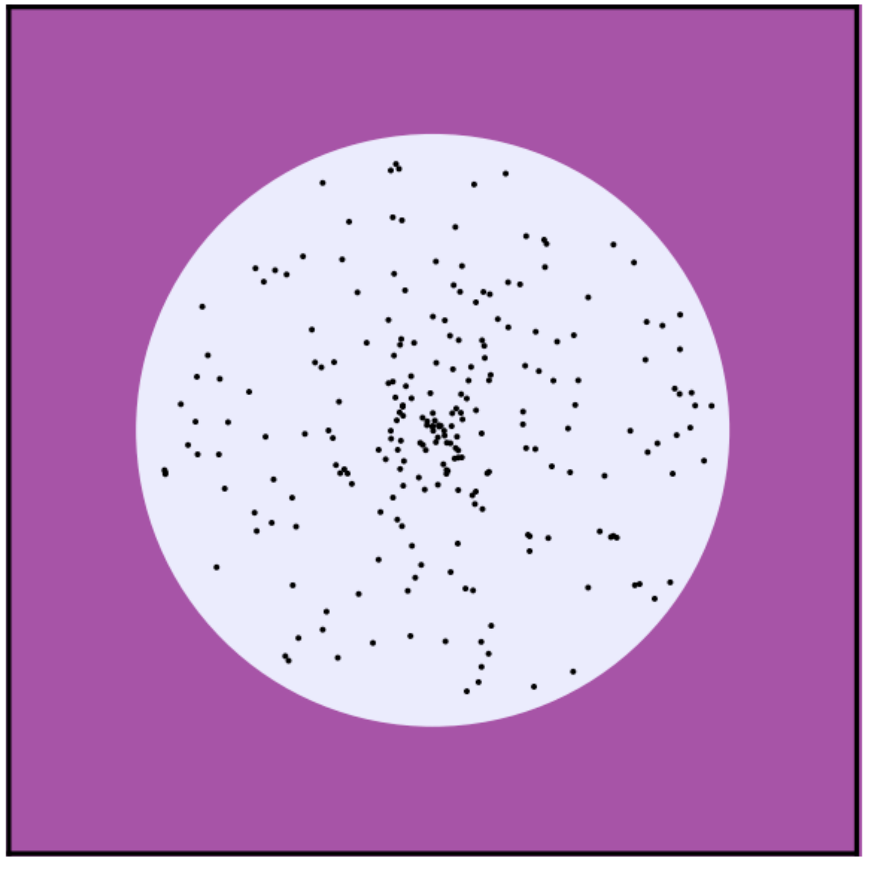

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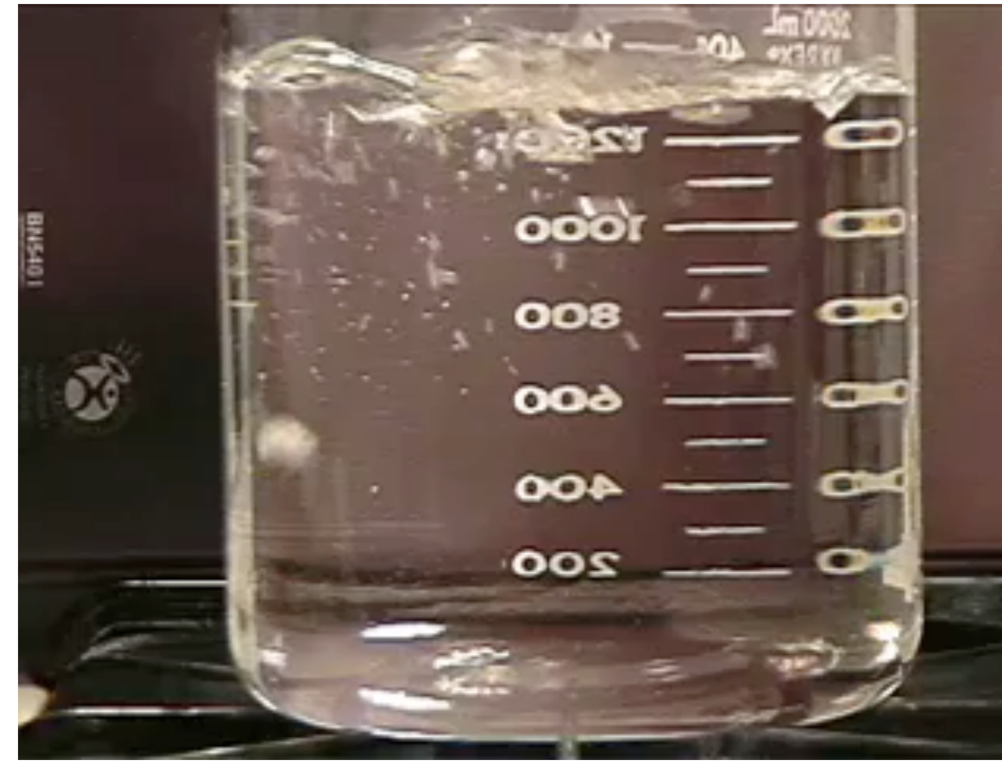

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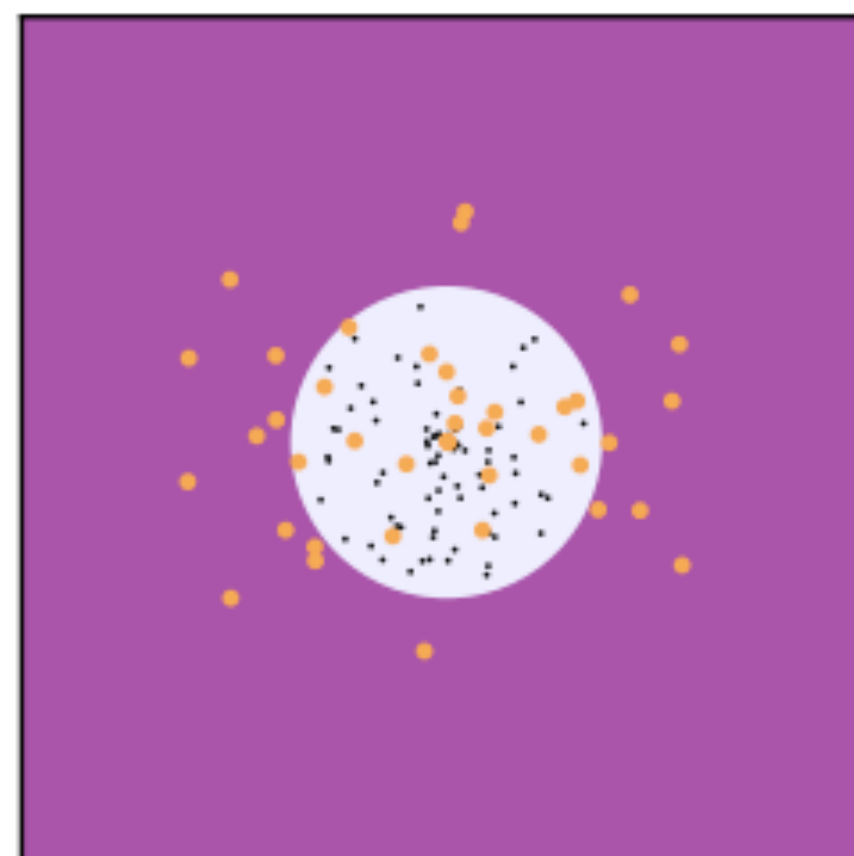

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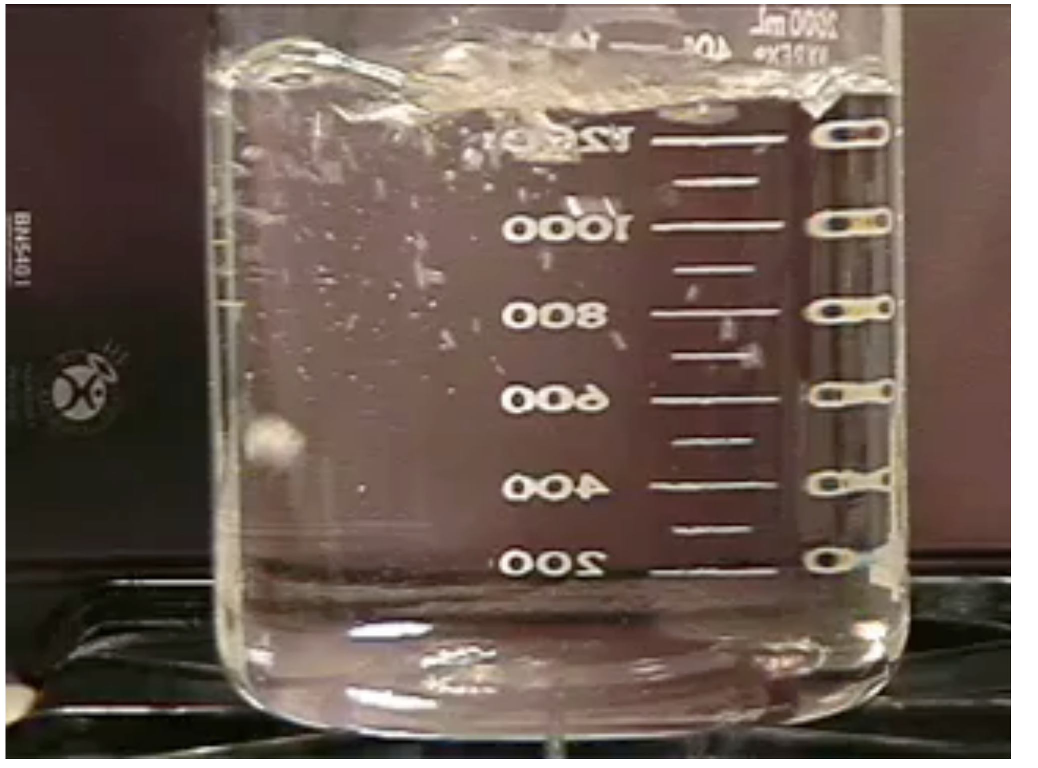

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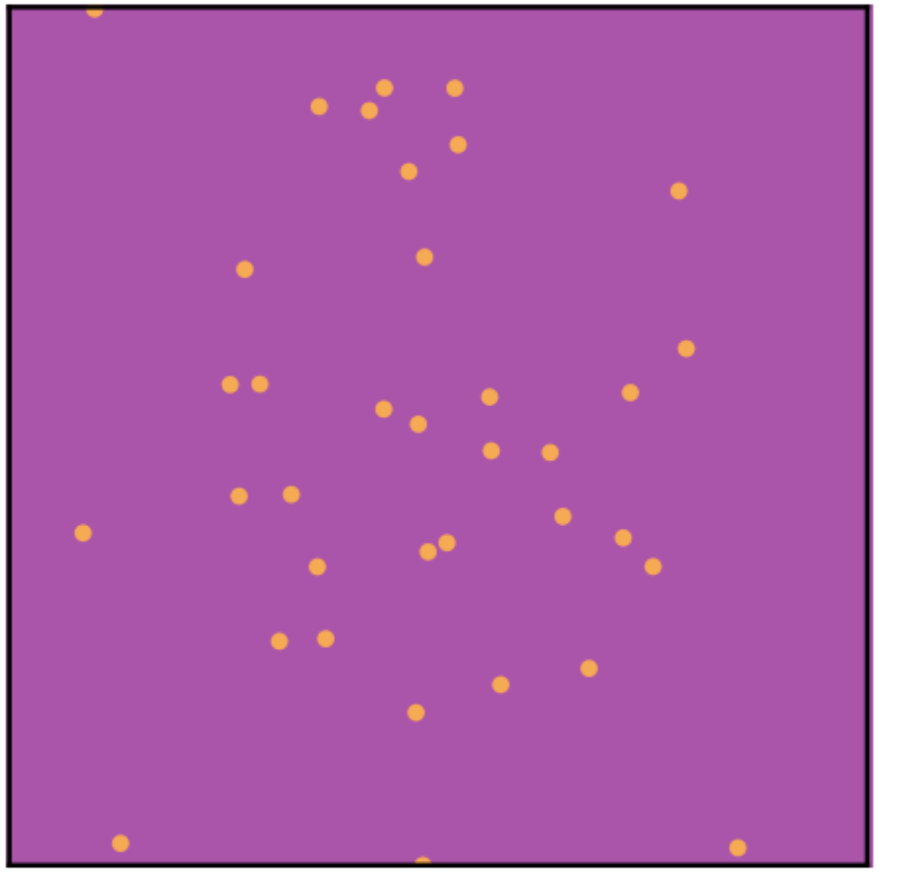
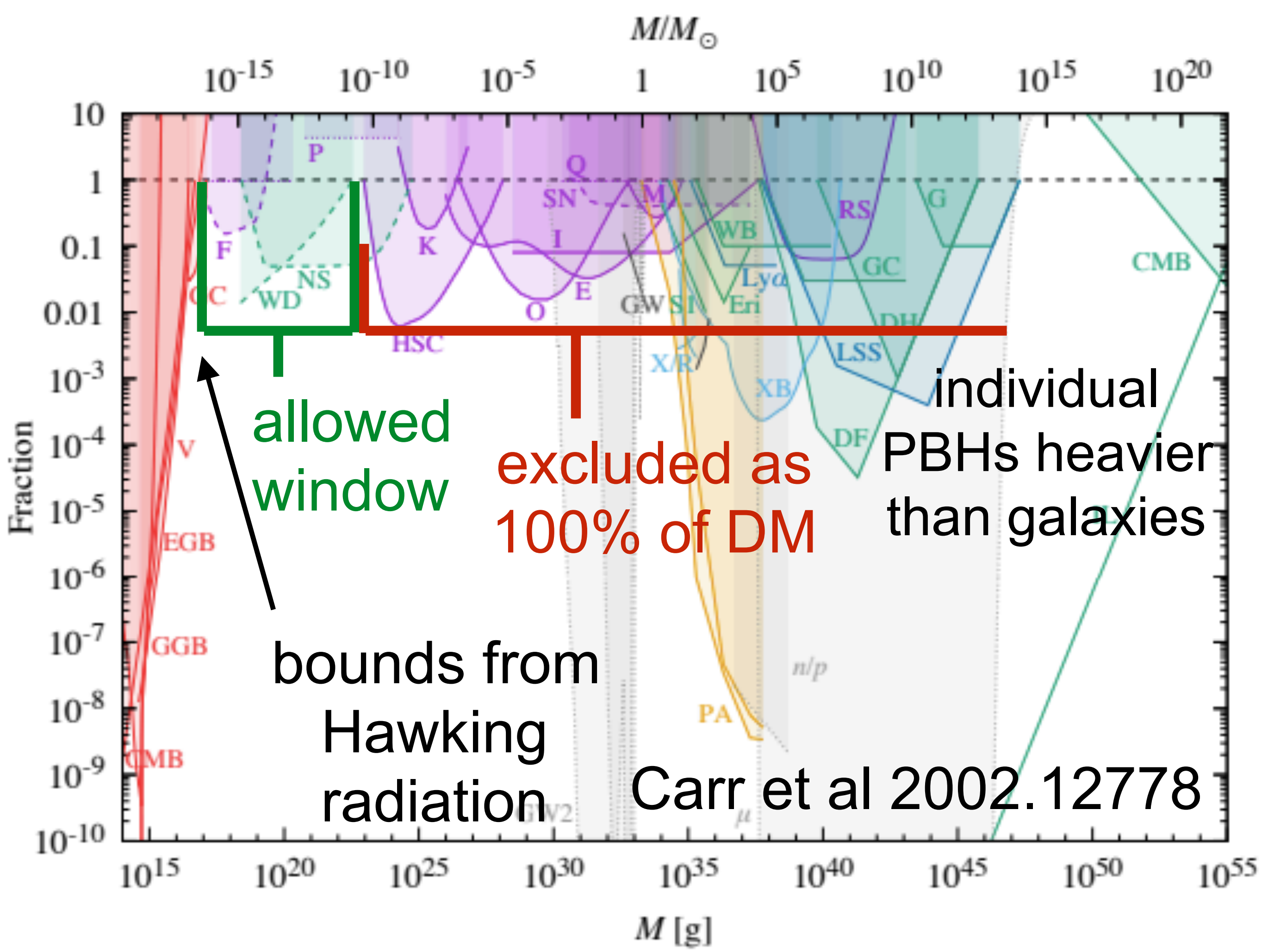
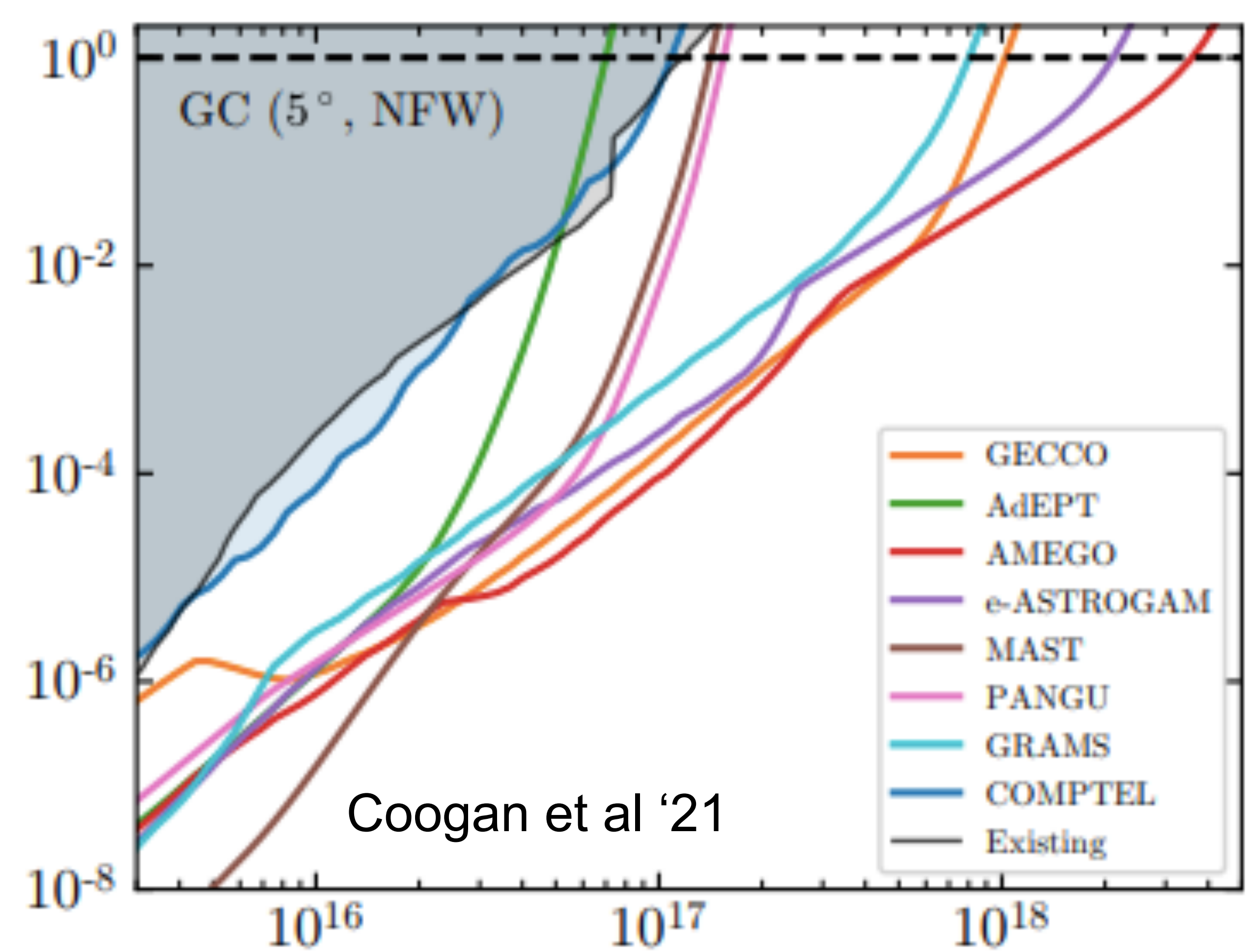


Primordial black holes

- Primordial black holes (PBHs) can also serve as a DM candidate if they lie in the right mass range - $10^{17\text{-}23}$ g PBHs appear viable to constitute 100% of the DM. Could be produced during inflation.
- PBHs are decaying DM - they slowly decay through Hawking radiation (with temperatures far less than the BH mass), PBHs around 10^{17} g would produce X-ray and soft gamma-ray radiation.
- The non-observation of this radiation sets the strongest current bounds on such PBHs - possible to improve the limit with future MeV-band observations, where a number of new telescopes have been proposed.



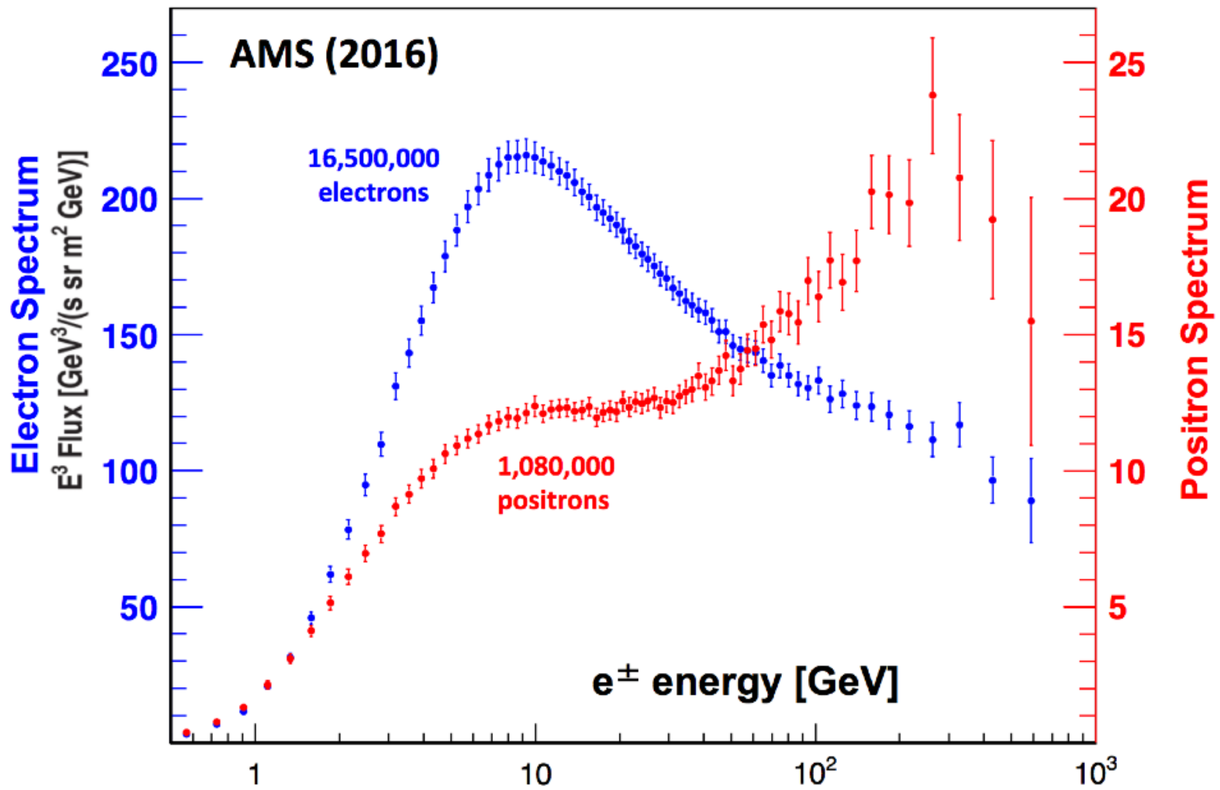


Some excesses/anomalies

- Annihilation/decay?
  - PAMELA/AMS-02 positron excess (needs O(TeV) DM with large cross section / short lifetime) [Aguilar et al (AMS-02) ’13; see also Hooper et al ’17]
  - AMS-02 ~10-20 GeV antiproton bump (needs O(10-100) GeV DM with thermal relic cross section) [Cui et al ’17, Cuoco et al ’17; see also Boudaud et al ’19, Cuoco et al ’19]
  - AMS-02 antihelium events (?? maybe annihilation?) [AMS Days at La Palma, La Palma, Canary Islands, Spain ’18; see also Poulin et al ’19, Winkler & Linden ’21]
  - 3.5 keV X-ray line detected in a range of systems (needs 7 keV decaying DM, e.g. sterile neutrino) [Bulbul et al ’14, Boyarsky et al ’14; see also Abazajian et al ’17, Dessert et al ‘20]
  - Galactic Center excess (GCE) seen in Fermi gamma-rays (needs O(10-100) GeV DM with thermal relic cross section) [Goodenough & Hooper ’09; see Wednesday’s lecture]
- Scattering? EDGES claimed observation of primordial 21cm signal with deep absorption trough (could potentially be explained by colder-than-expected early universe) [Bowman et al ’18; see also Hills et al ’18, Bradley et al ’19] - now in 2 sigma tension with SARAS 3 observations [Singh et al, Nature Astronomy ’22]

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.
  - Positron background expected to fall faster than electron background - suggests some new primary source of positrons



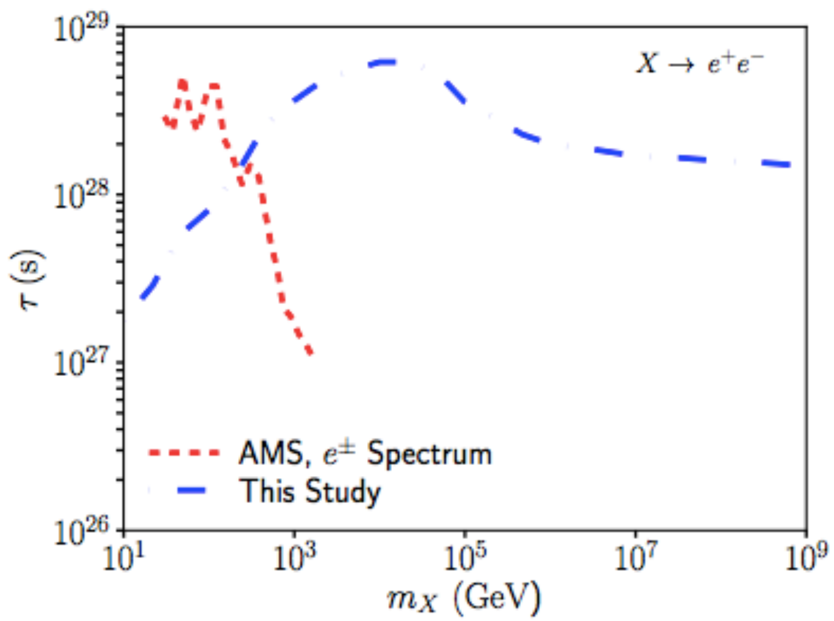
Sam Ting, 8 December 2016, CERN colloquium

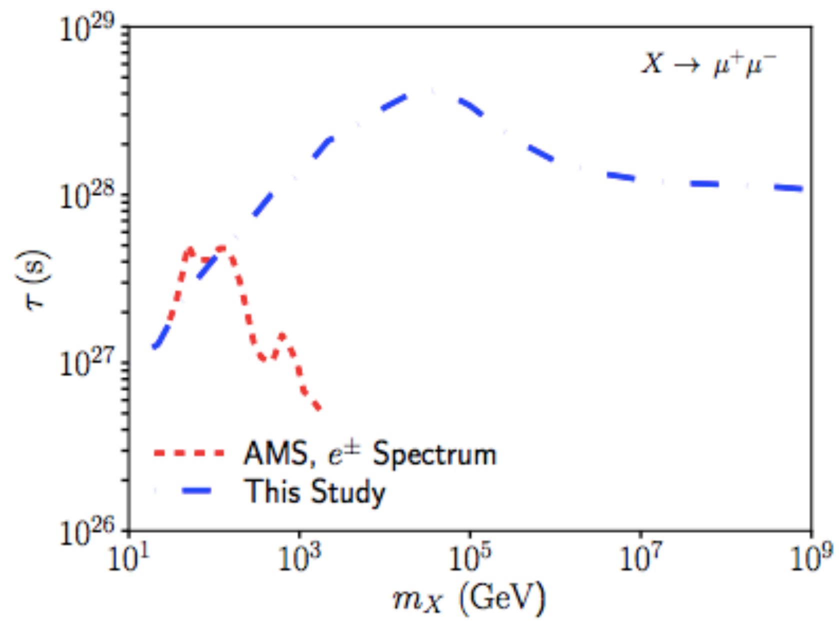
- DM explanation: TeV-scale DM annihilating or decaying dominantly into leptons
  - if annihilation, requires rate several orders of magnitude above thermal - can be natural due to e.g. Sommerfeld enhancement
  - need to suppress annihilation to quarks to avoid overproducing antiprotons - can be natural if DM is leptophilic or annihilates into sub-GeV mediators that then decay

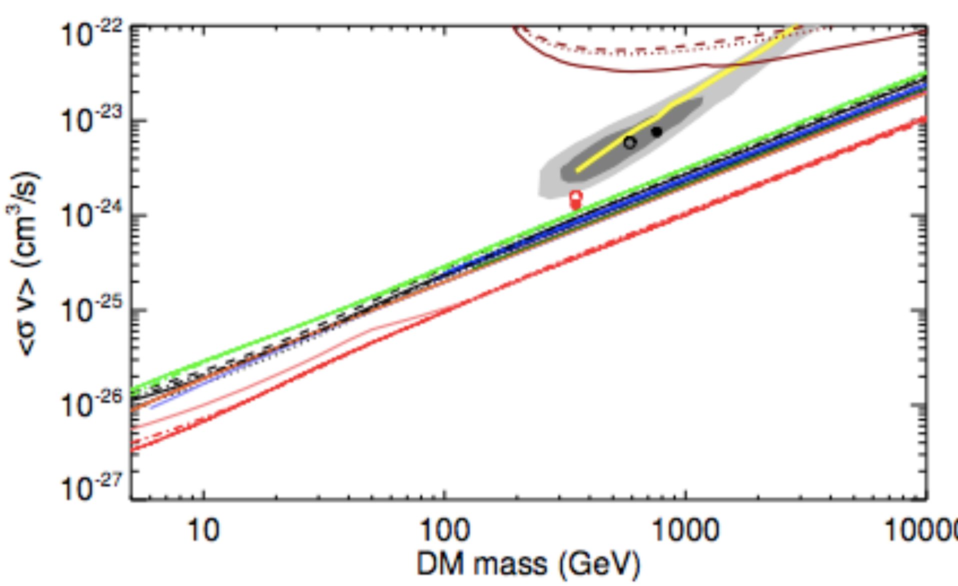
Challenges for the DM interpretation

- DM annihilation interpretation is challenging due to null results in CMB searches + gamma-ray searches - needs extra ingredients (e.g. large DM overdensity, either nearby or combined with annihilation to a long-lived particle, Kim et al 1702.02944 has an example)

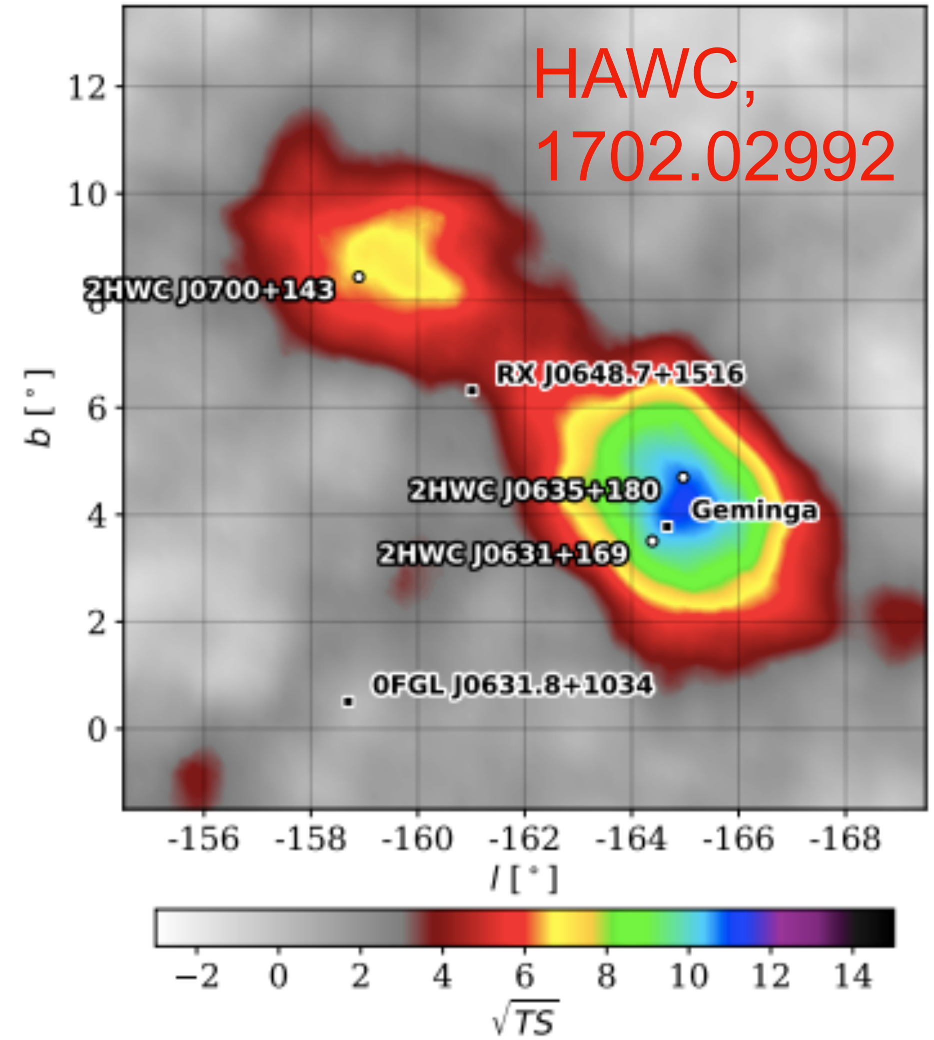
- DM decay interpretation may be easier to reconcile, but tight constraints from galaxy clusters, extragalactic gamma-ray background [e.g. Blanco & Hooper '19]



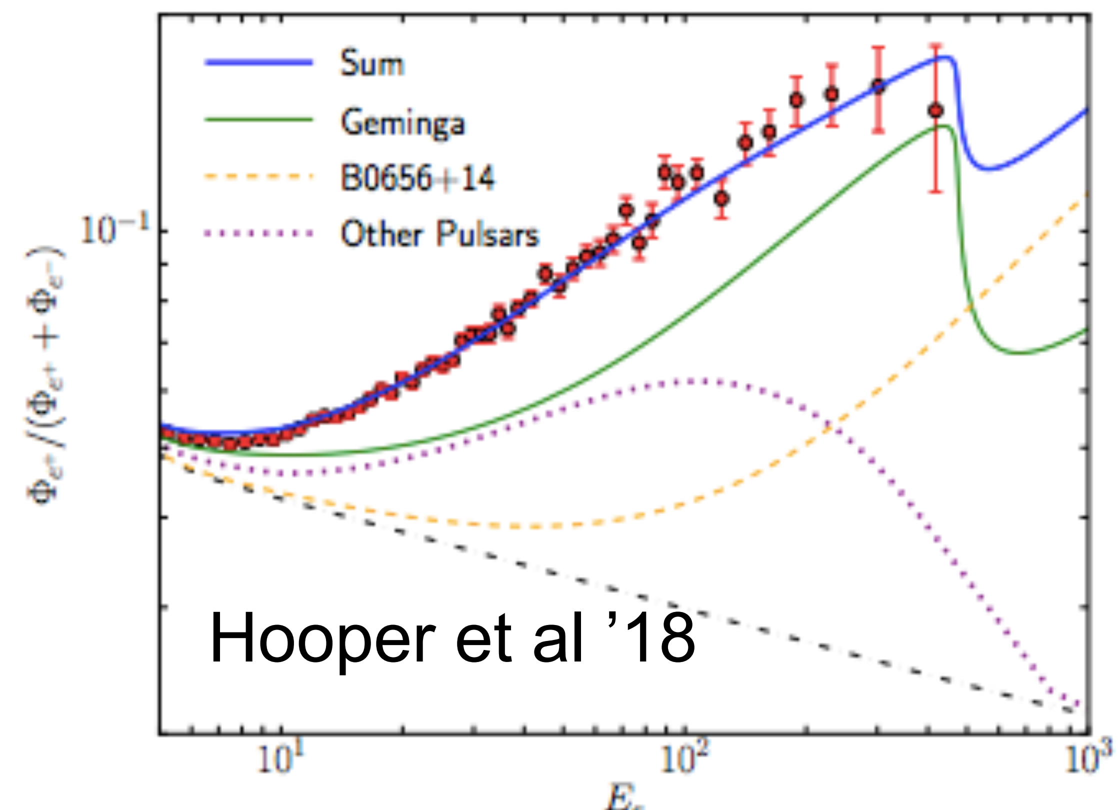




TeV pulsar halos



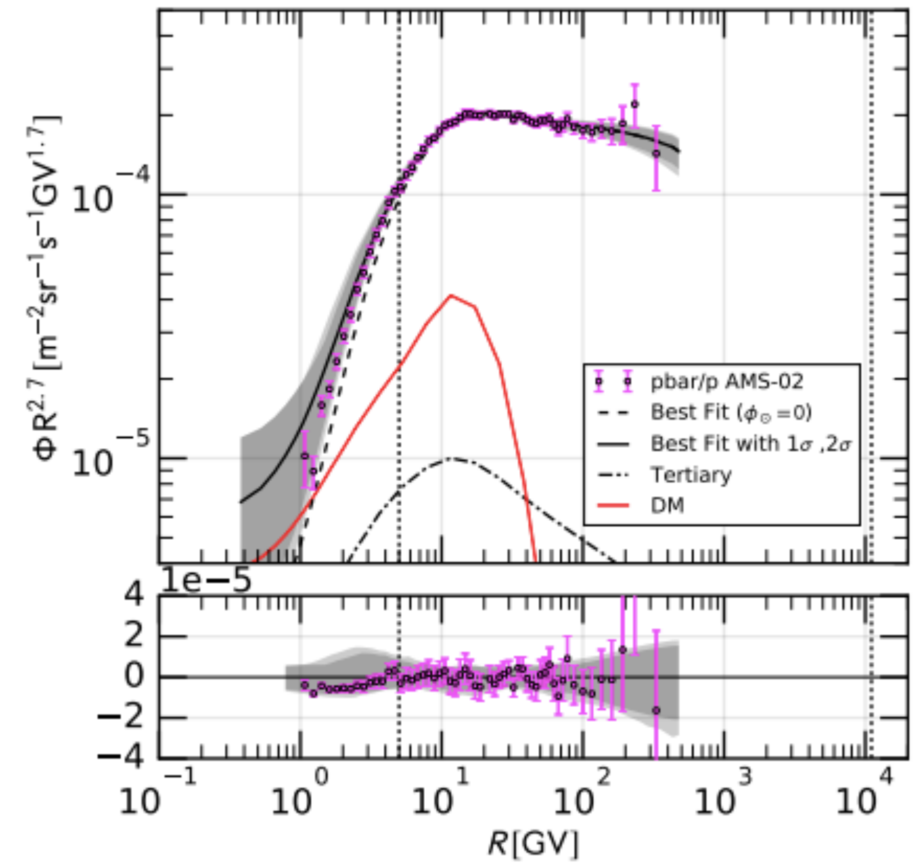
- Quite surprisingly, in 2017 the HAWC gamma-ray telescope discovered “TeV halos” of gamma-rays around nearby pulsars (Geminga, Monogem) - since IDed around other pulsars
- Surprising because the expectation is e^+e^- from the pulsars would spread out too far for HAWC to detect the emission
- Hypothesis is now that pulsars are producing TeV+ e^+e^- but diffusion around the pulsars is impeded [see e.g. Evoli et al ’18 for a model]
- Implies large fraction of spin-down power goes into e^+e^-, and no problem producing TeV+ e^+e^-

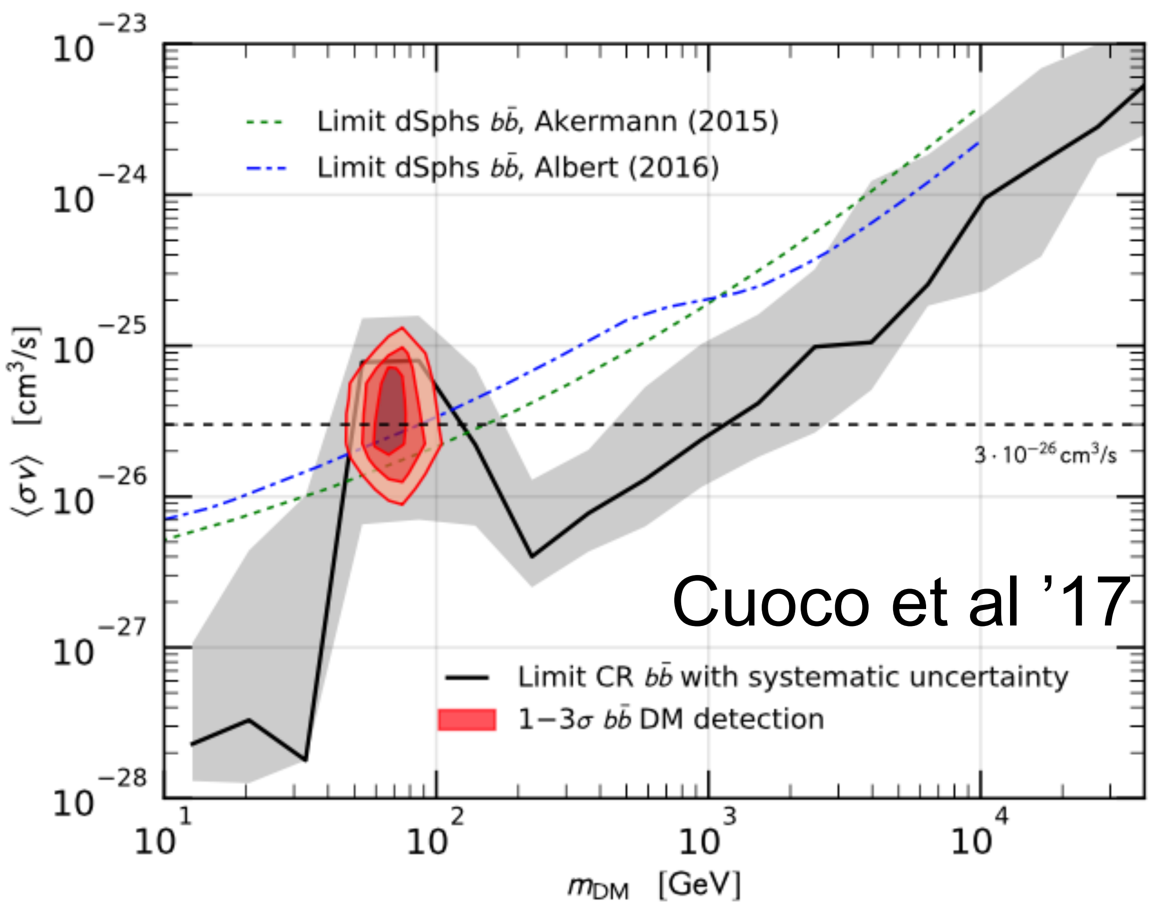


Note: this is a plausible model, not an a priori prediction

AMS-02 low-energy antiproton bump?

- Two independent groups claimed in 2017 that AMS-02 data reveal a modestly significant “bump” in ~10-20 GeV antiprotons [Cui et al ’17, Cuoco et al ’17]
- Corresponds to a ~thermal cross section and ~40-130 GeV DM mass.
- Not visually obvious and highly significant like positron signal - could be just a statistical fluctuation
- But interesting parameter space - would align well with Galactic Center Excess



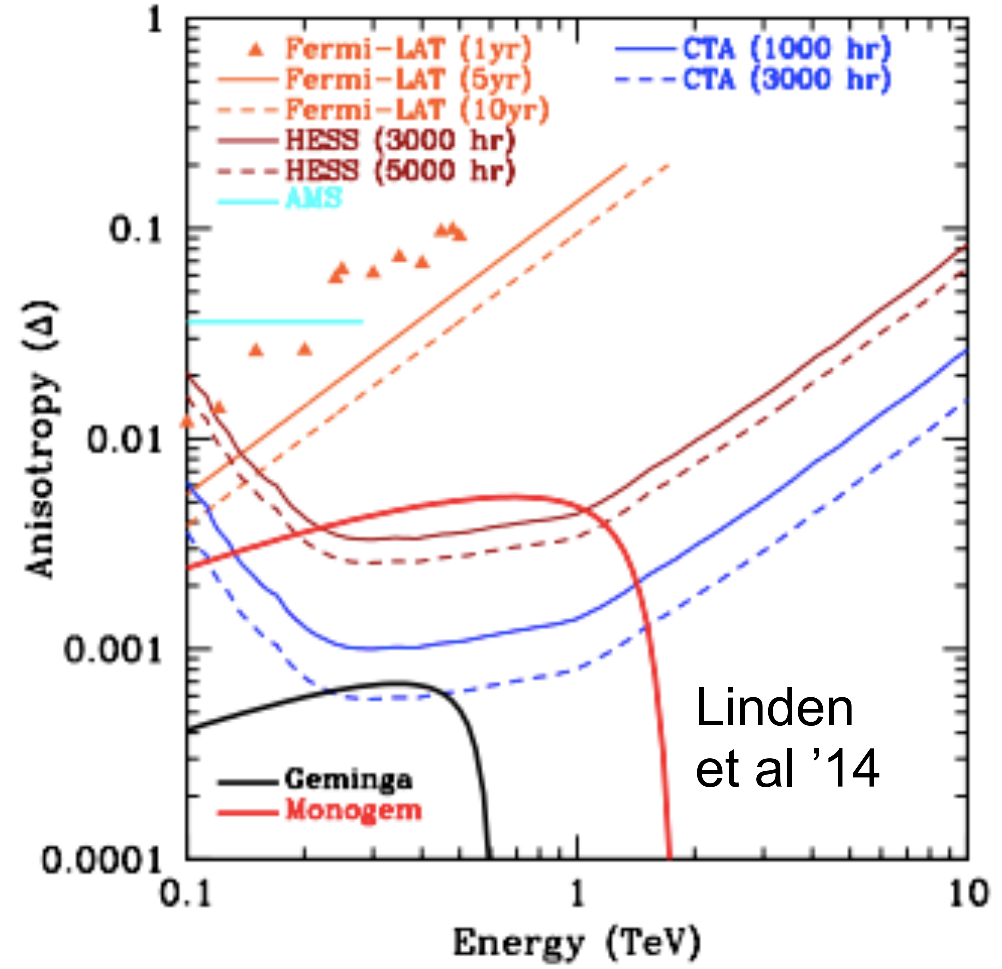


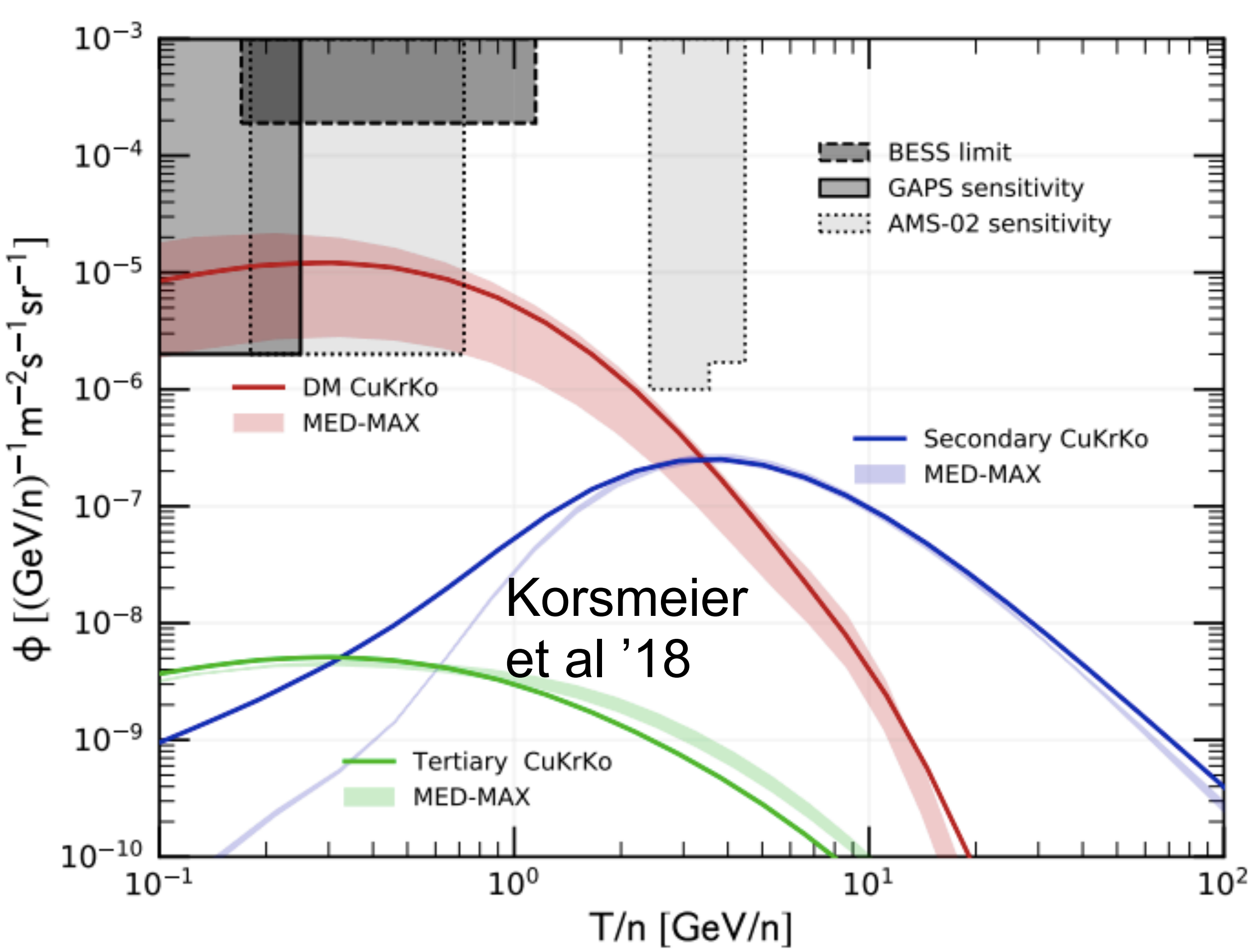
Trouble with correlations

- Boudaud et al '19 "AMS-02 antiprotons' consistency with a secondary astrophysical origin", claims full consistency with astrophysical origin when including an estimated covariance matrix for the data
  - "On the data side, a covariance matrix of errors directly provided by the AMS-02 collaboration would definitively be an important improvement to fully benefit from the precision achieved by AMS-02."
  - Similar results from Heisig et al '20, focus on systematic uncertainties in absorption cross-section of CRs within detector material
- Cuoco et al '19 "Scrutinizing the evidence for dark matter in cosmic-ray antiprotons" - claims over 5 sigma evidence when systematic error correlations are included using a data-driven method
  - "Our analysis demonstrates the importance of providing the covariance of the experimental data, which is needed to fully exploit their potential."
- Both papers attempt to model correlations between systematic errors at different energies, using AMS-02 data; they get completely different results for the significance of the signal

Where next for positrons and antiprotons?

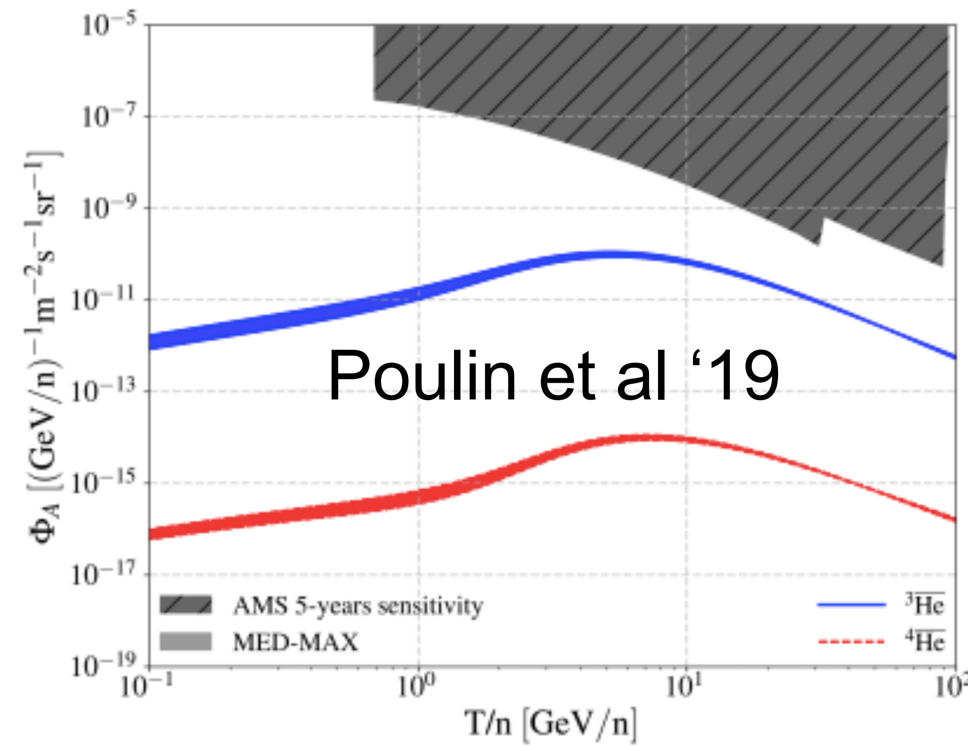
- Very active effort to find more TeV halos around pulsars & determine how common they are in the Galaxy
- Anisotropy in arrival direction is a possible probe, but scrambling of arrival directions by B-field makes detection challenging - may be testable using air Cherenkov telescopes [Linden et al '14]
- For antiprotons, there may still be work to do on the theory/analysis side, trying to nail down uncertainties in production cross-sections + error correlations
- GAPS is a balloon experiment expected to fly in the next few years (delayed due to covid)
- Could potentially test similar parameter space in anti-deuterons [e.g. von Doetinchem et al '20].

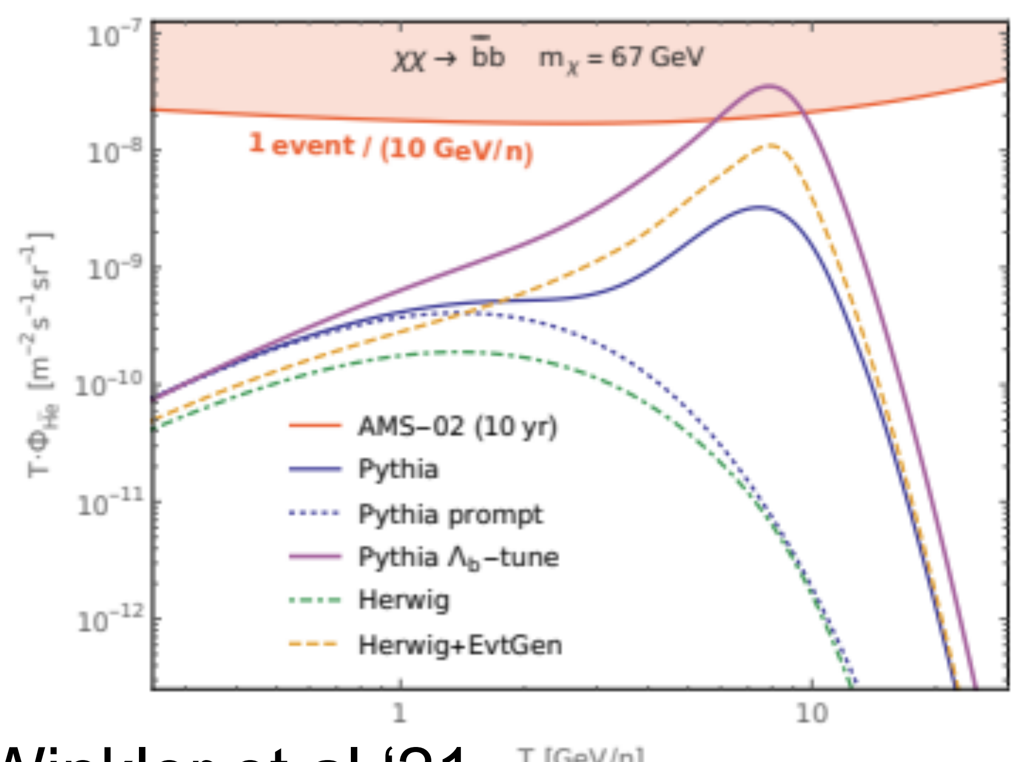




AMS-02 antihelium events

- 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





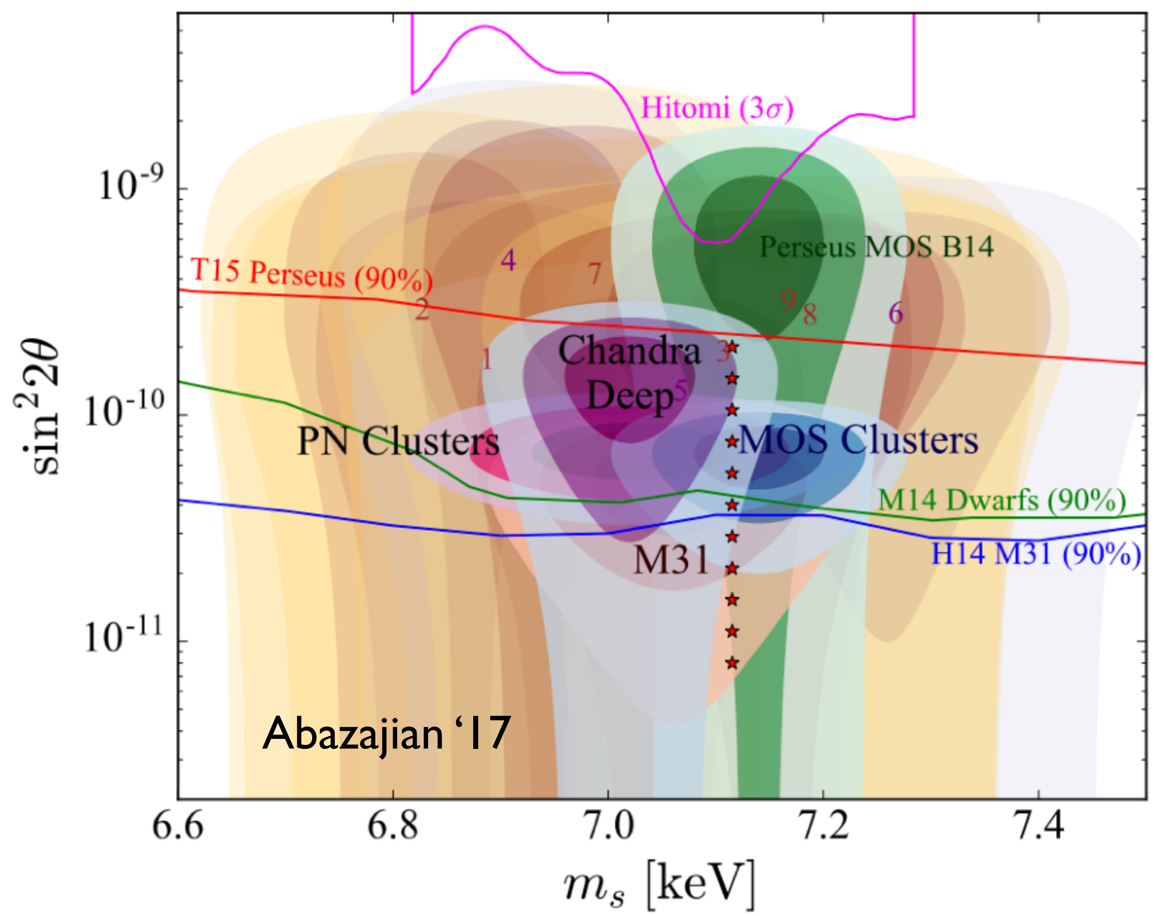
Winkler et al '21

The 3.5 keV line

- Apparent X-ray spectral 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.

- DM alternatives include exciting dark matter [Cline & Frey '14, Finkbeiner & Weiner '16] - DM has a metastable excited state that can be collisionally excited and then decay.

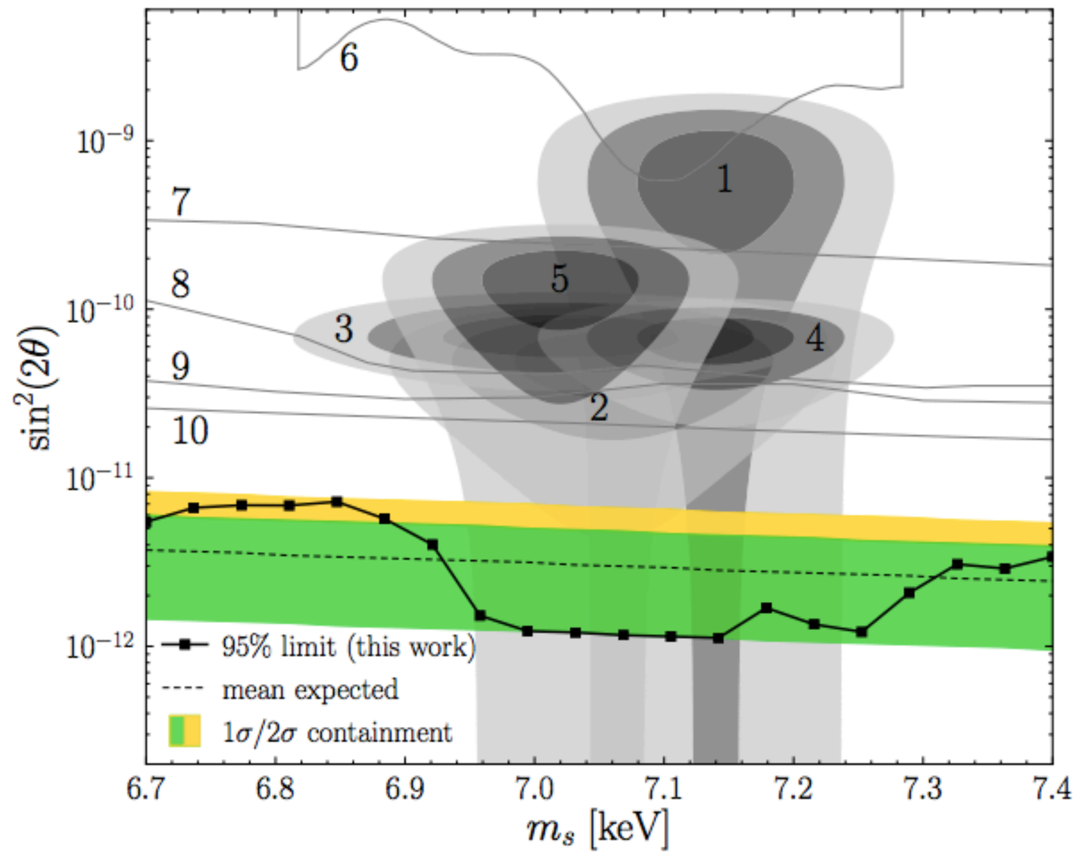


- Another possibility is conversion of an axion-like particle to an X-ray photon in the presence of magnetic fields [e.g. Conlon & Day '14] - can lead to widely varying signals from different systems [e.g. Alvarez et al '15].

- 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].

Challenges to the DM interpretation

- 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.

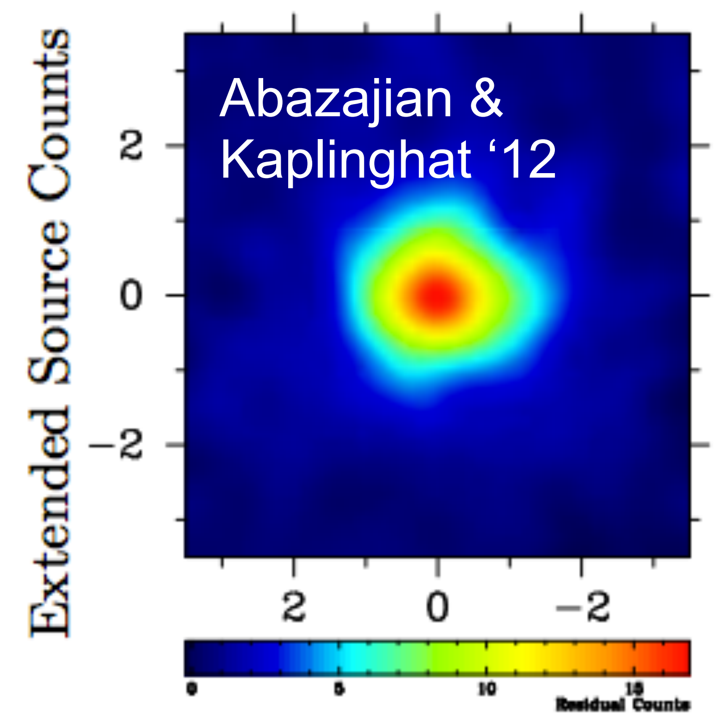


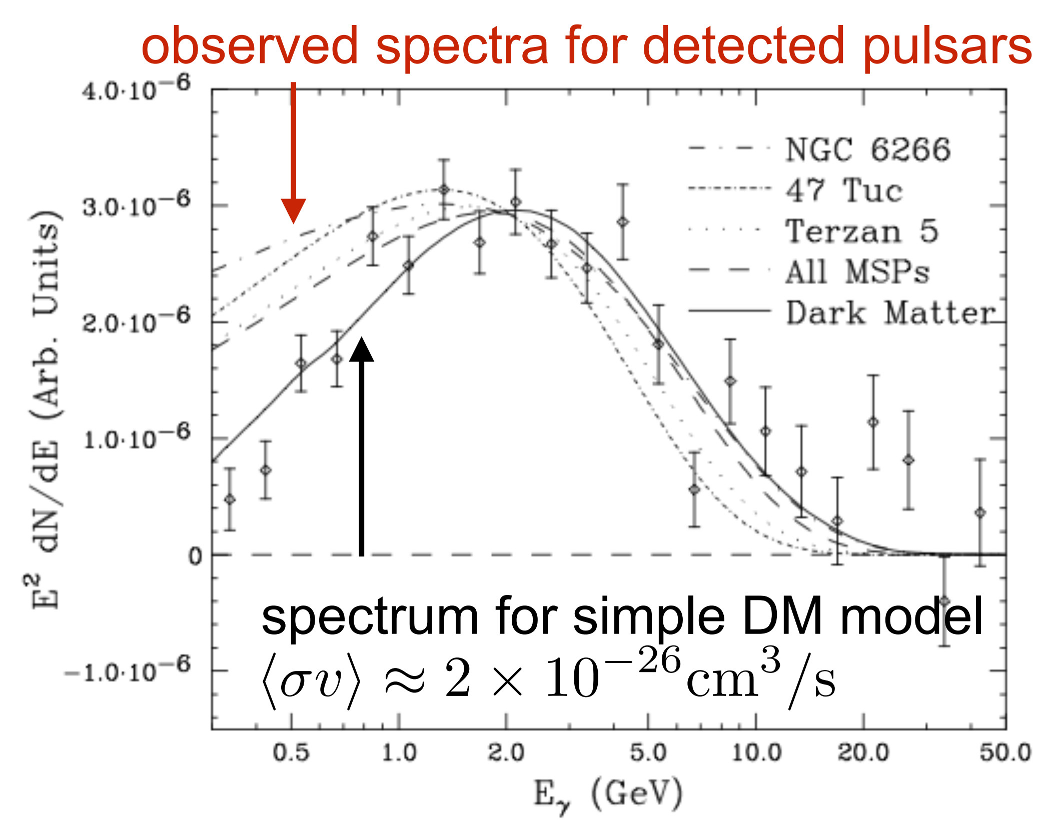
Dessert et al '20

- One strategy: seek energy resolution sufficient to probe velocity distribution of DM in Galactic halo, via Doppler shift causing line broadening [Speckhard et al '16, Powell et al '17].

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 detected sources / hot-spots 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

- What we know about dark matter: cosmological abundance (precisely), phase space distribution (steadily improving), upper limits on interactions, lower limit on lifetime, upper + lower bounds on mass (very widely separated!)

- Open questions: 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

- In indirect searches, 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

Plan for lectures

- Tuesday: computing DM abundance (thermal relic benchmark), forecasting DM annihilation/decay signals
- Wednesday: analyzing gamma-ray signals, backgrounds, template fitting, Galactic Center excess
- Thursday: cosmological signals of DM annihilation/decay, forecasting for CMB, Lyman-alpha, 21cm
- Friday: models of dark sectors, effects of long-range interactions