Dark Matter Theory and Cosmology

Tracy Slatyer

EPS-HEP 2021
28 July 2021

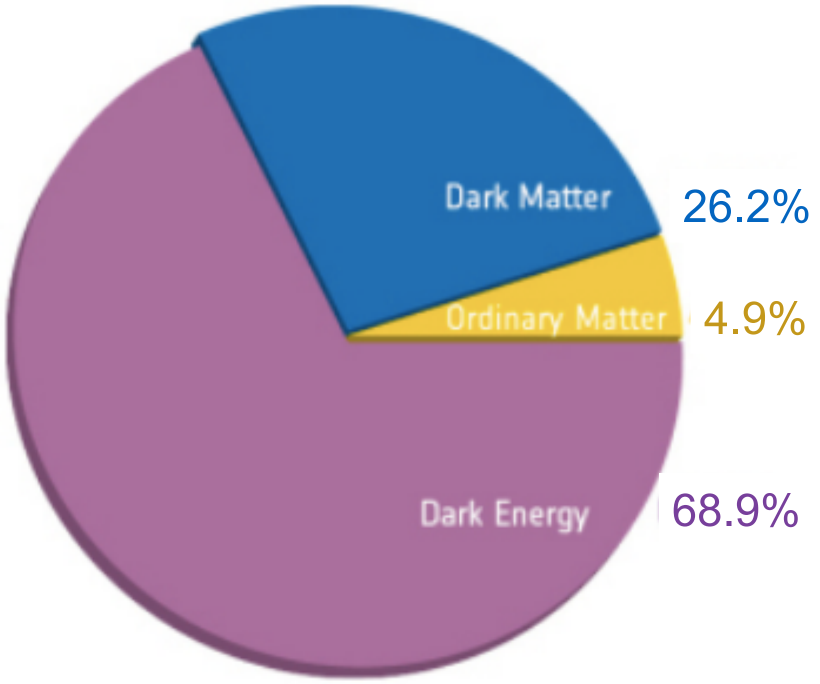
U.S. DEPARTMENT OF ENERGY | Office of Science

Outline

- Introduction to ΛCDM cosmology and the puzzle of dark matter
- A sketch of the space of theoretical explanations
  - by top-down explanations
  - by mass scale
- Some examples of current active areas of investigation

ΛCDM cosmology

- Six-parameter model has been spectacularly successful, making detailed predictions across a wide range of scales
- Requires two new components: dark energy (Λ) and cold dark matter (CDM)
- Big-picture theoretical puzzles include:
  - origin and nature of dark energy and dark matter
  - origin of ordinary matter / baryogenesis
  - physics of the very early universe / inflation



- Also some hints of divergences from ΛCDM
  - Most striking is the Hubble tension, discrepancy between early- and late-time measurements of H_0
  - Many ideas, but no especially compelling resolutions yet - recent reviews / comparisons by Di Valentino et al 2103.01183, Schoneberg et al 2107.10291

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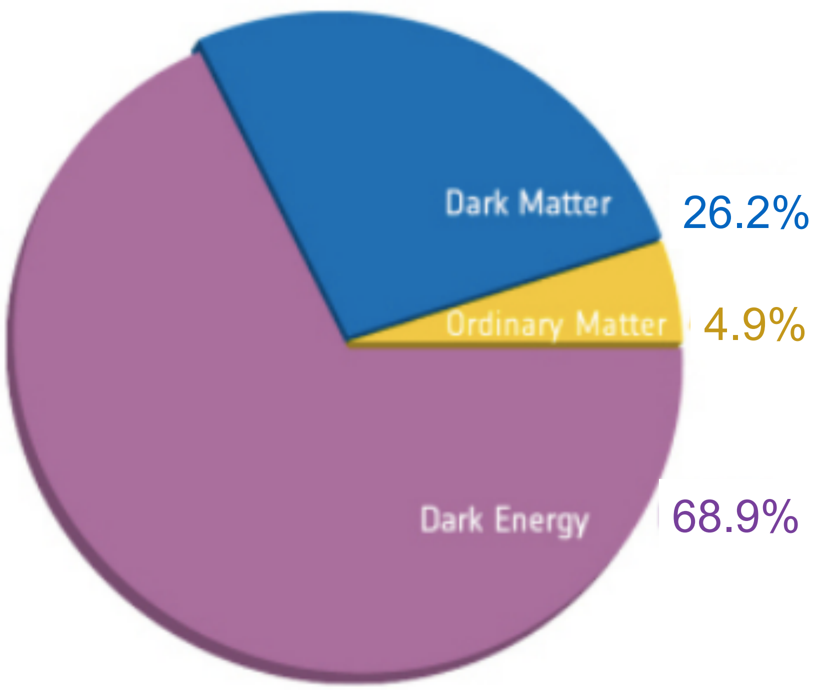

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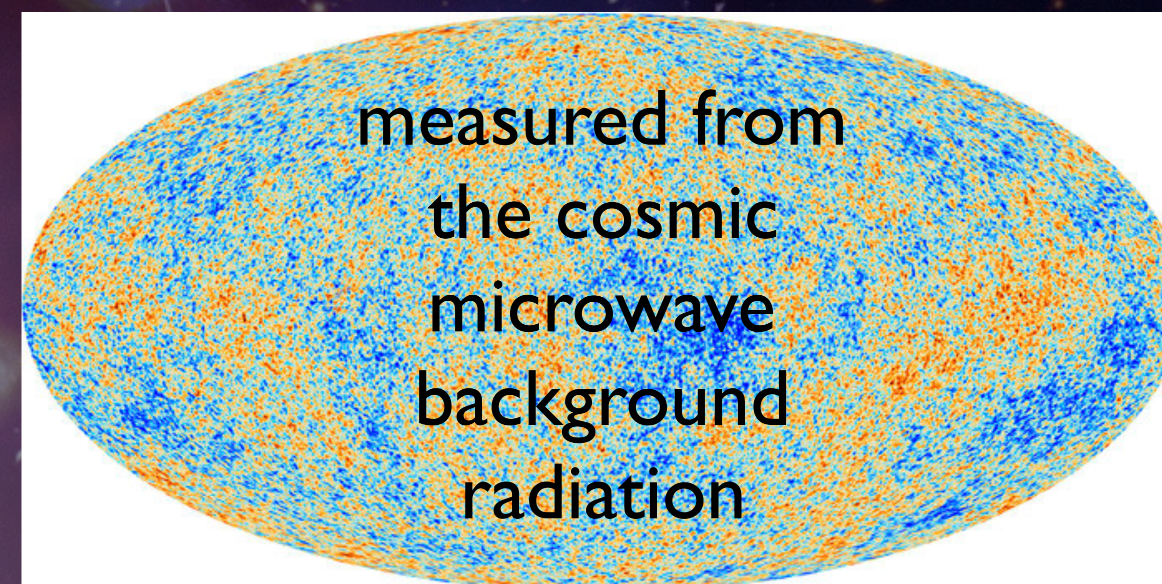

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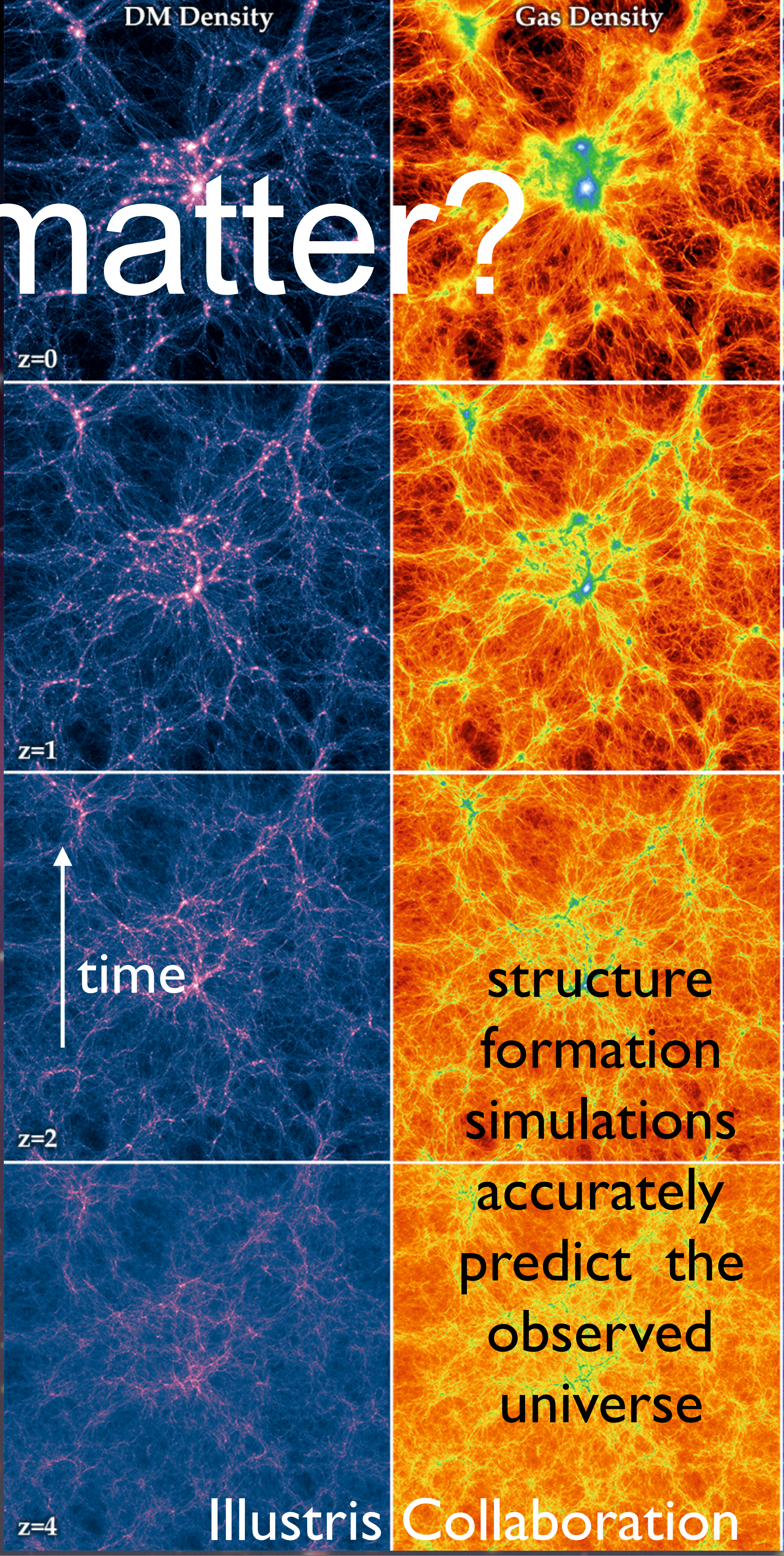

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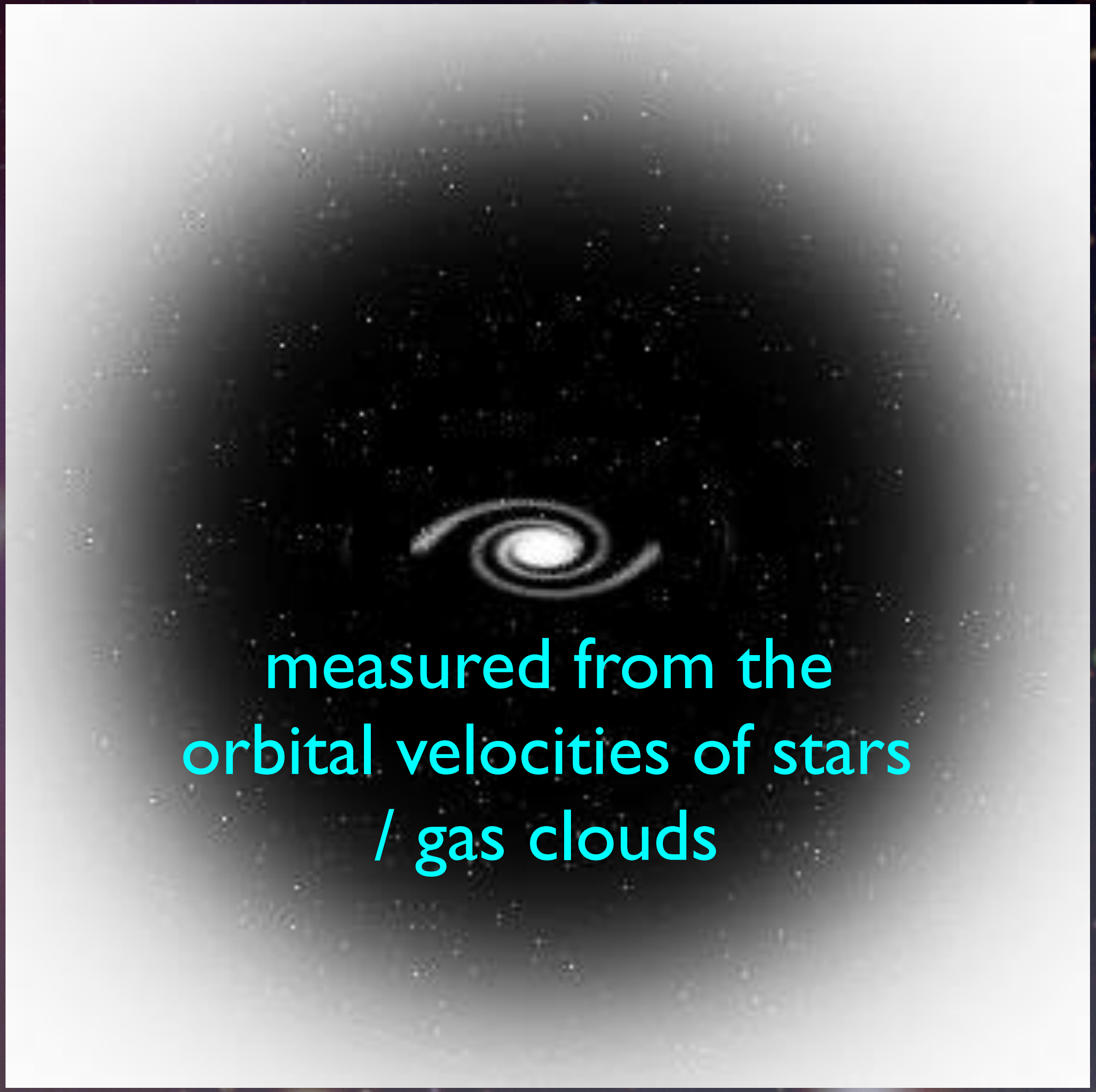

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- Interacts with other particles weakly or not at all (except by gravity).

null results of
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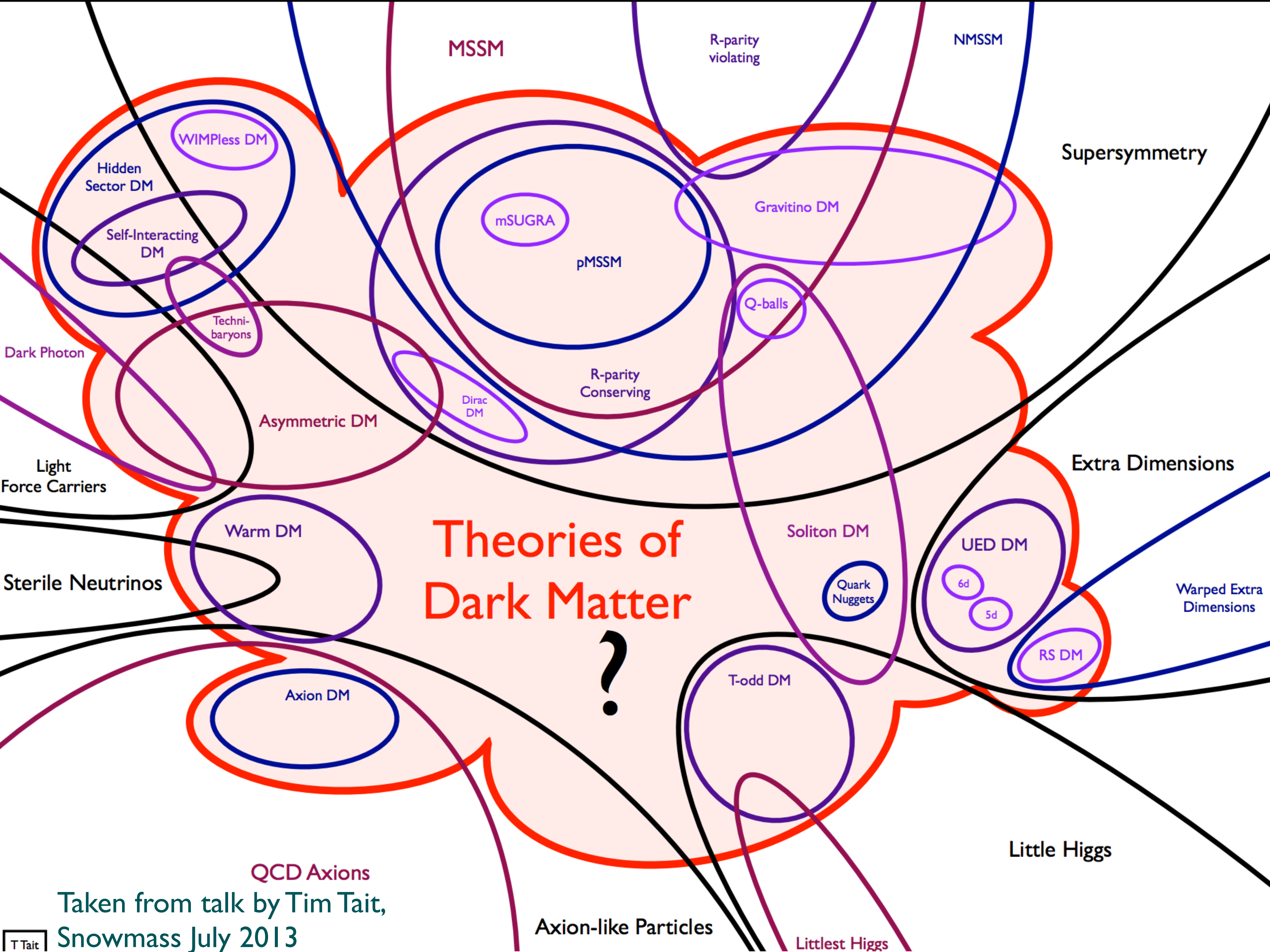
Open questions

- 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…



Taken from talk by Tim Tait, Snowmass July 2013

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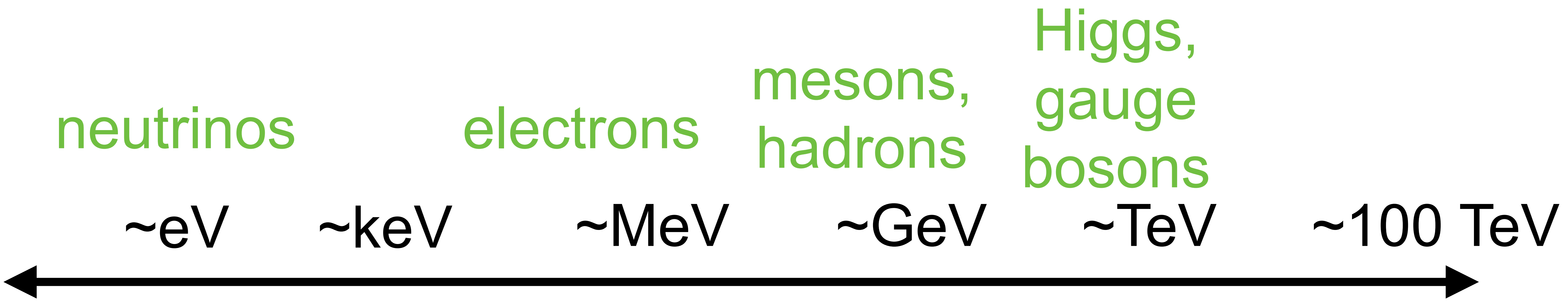

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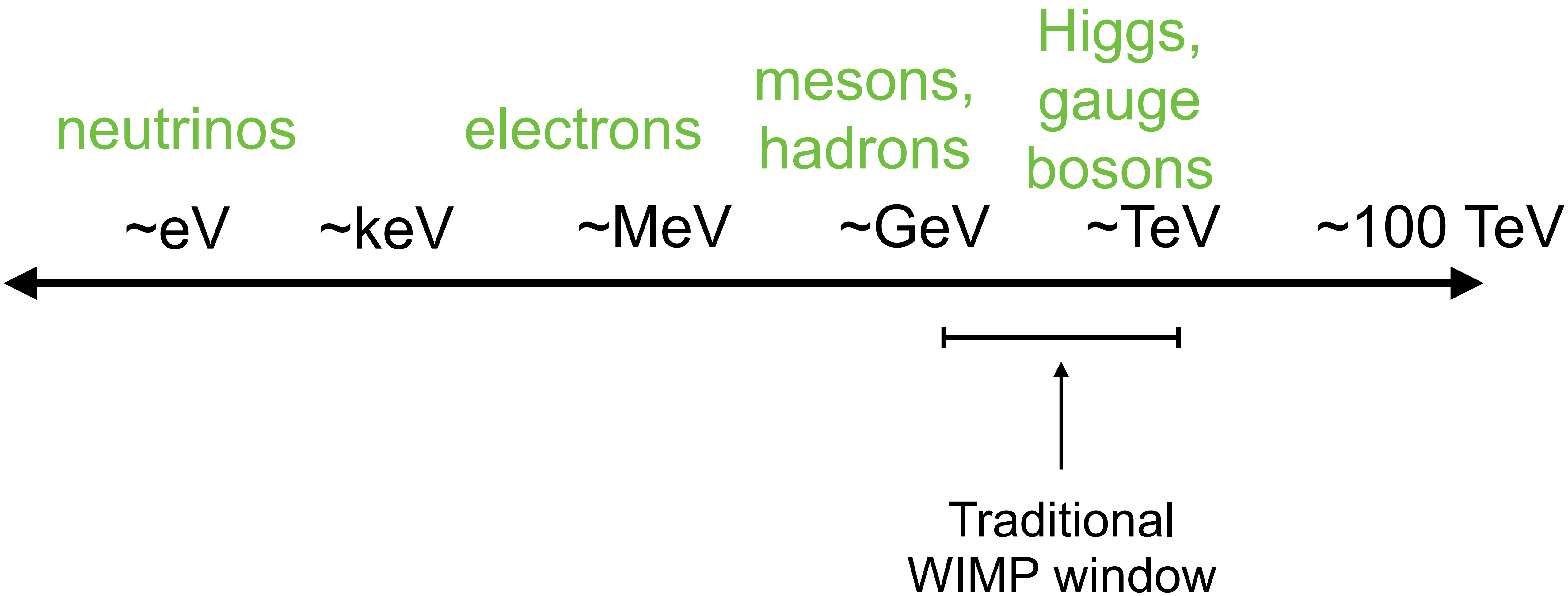

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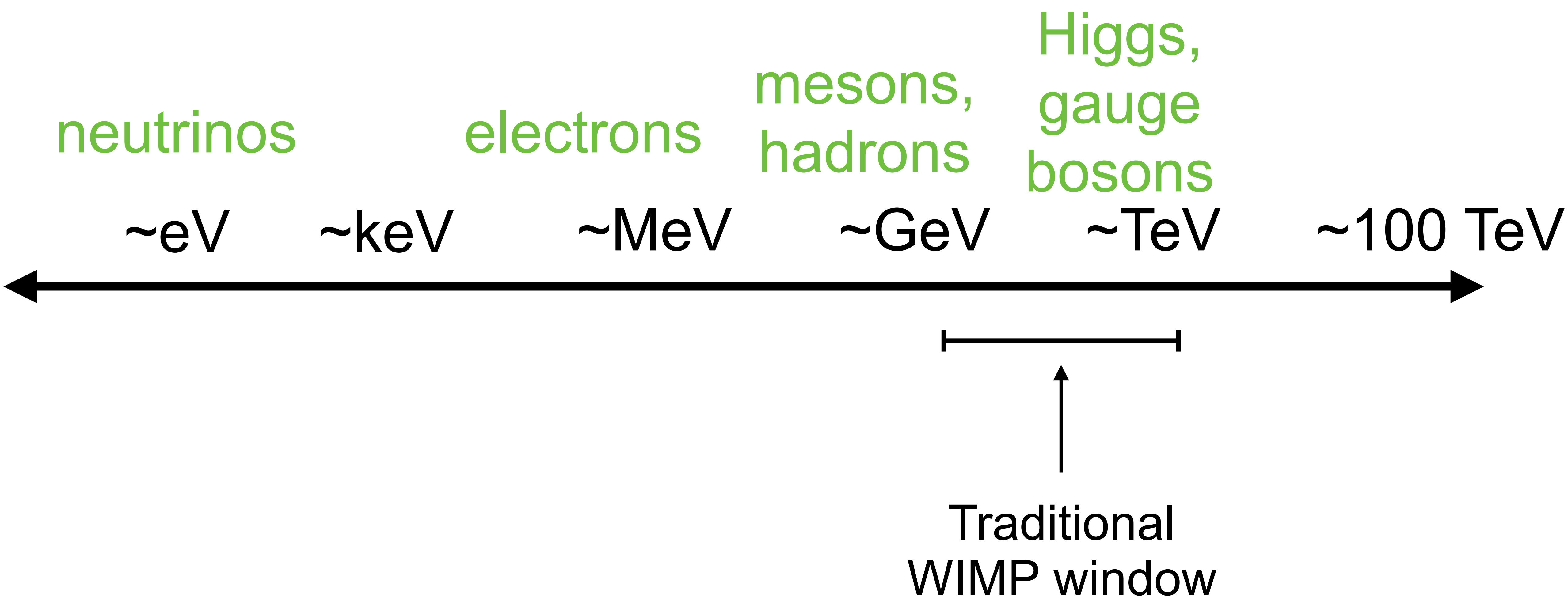

Thermal relics - abundance fixed by annihilation in the early universe

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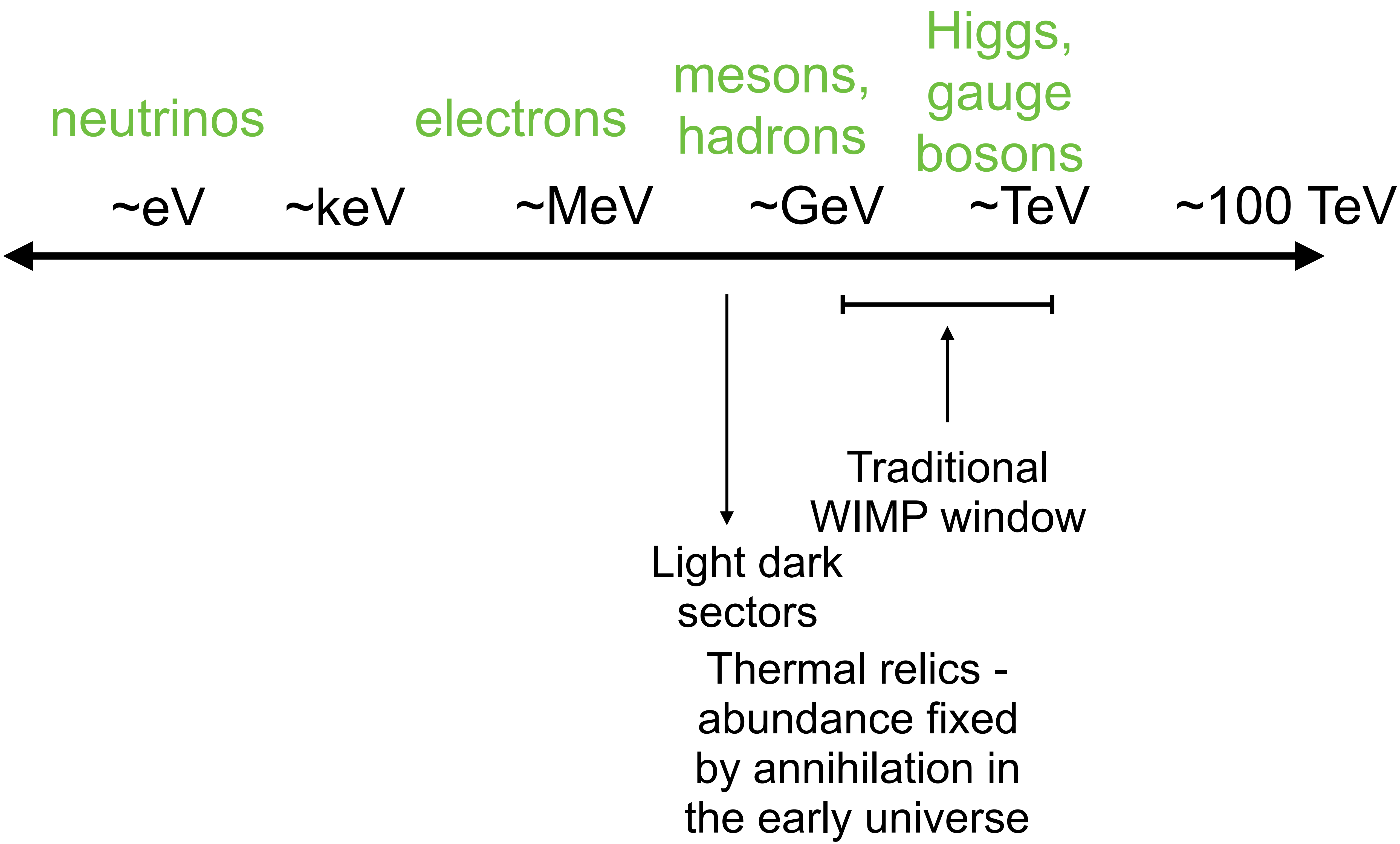

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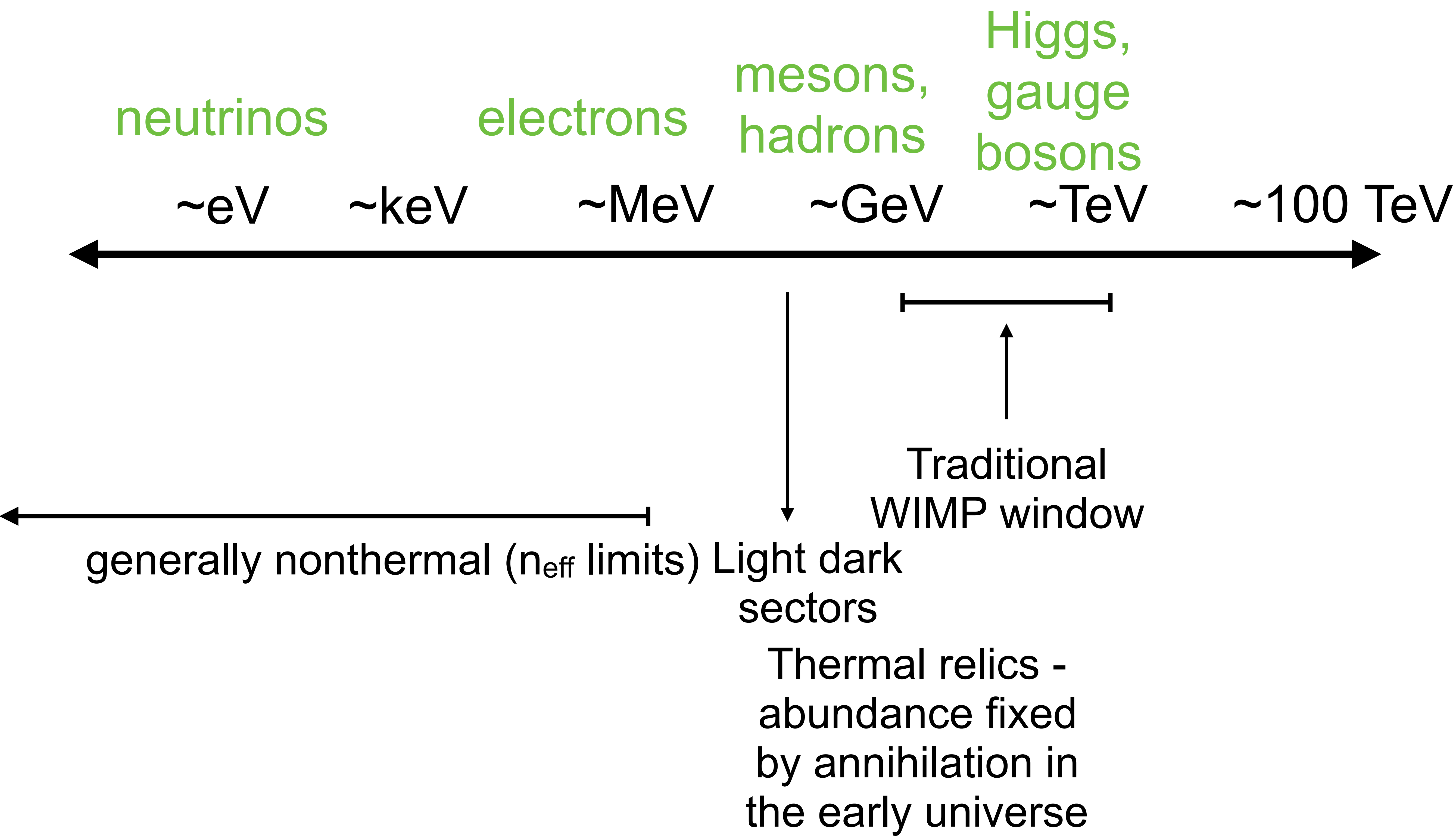

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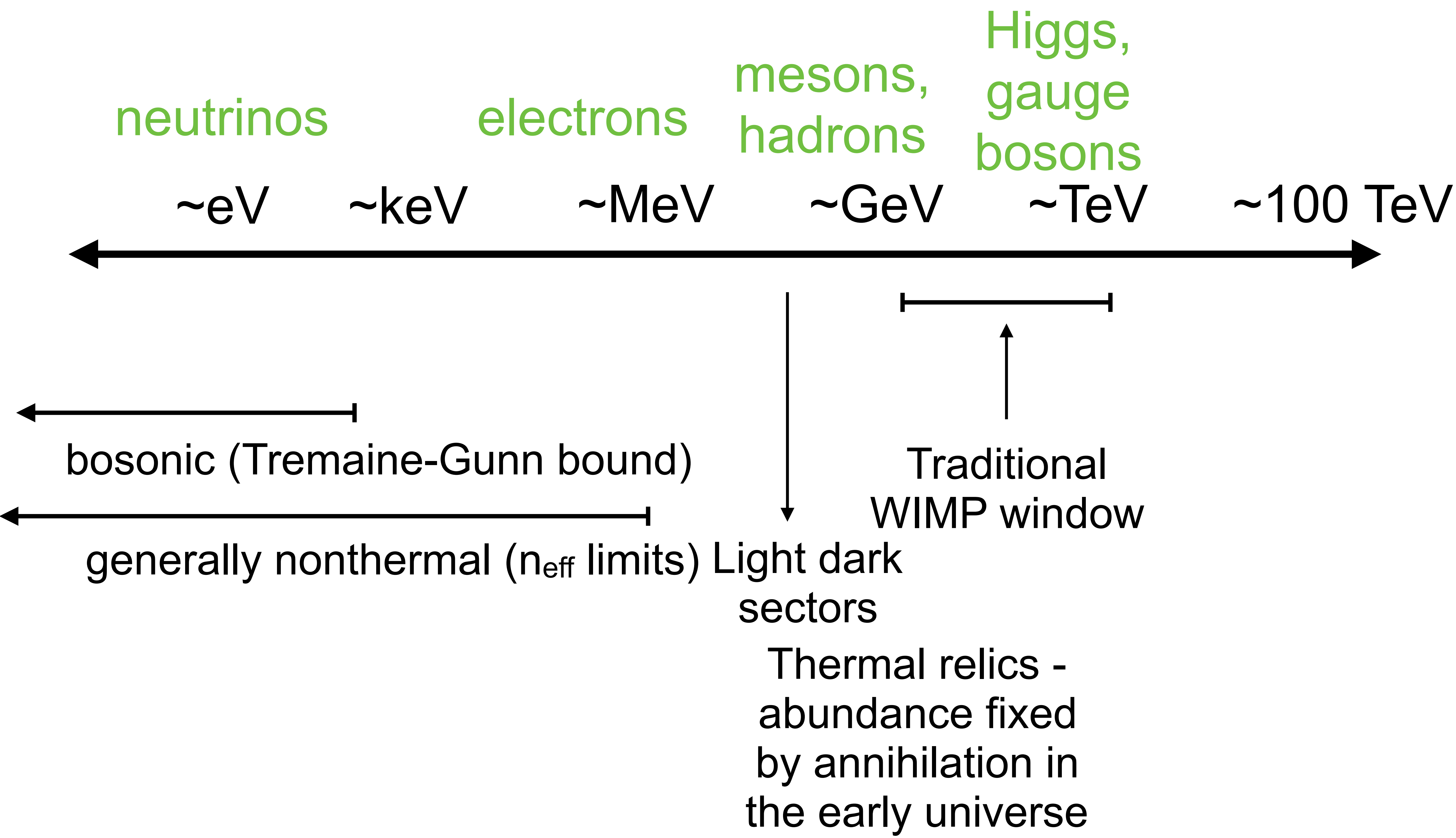

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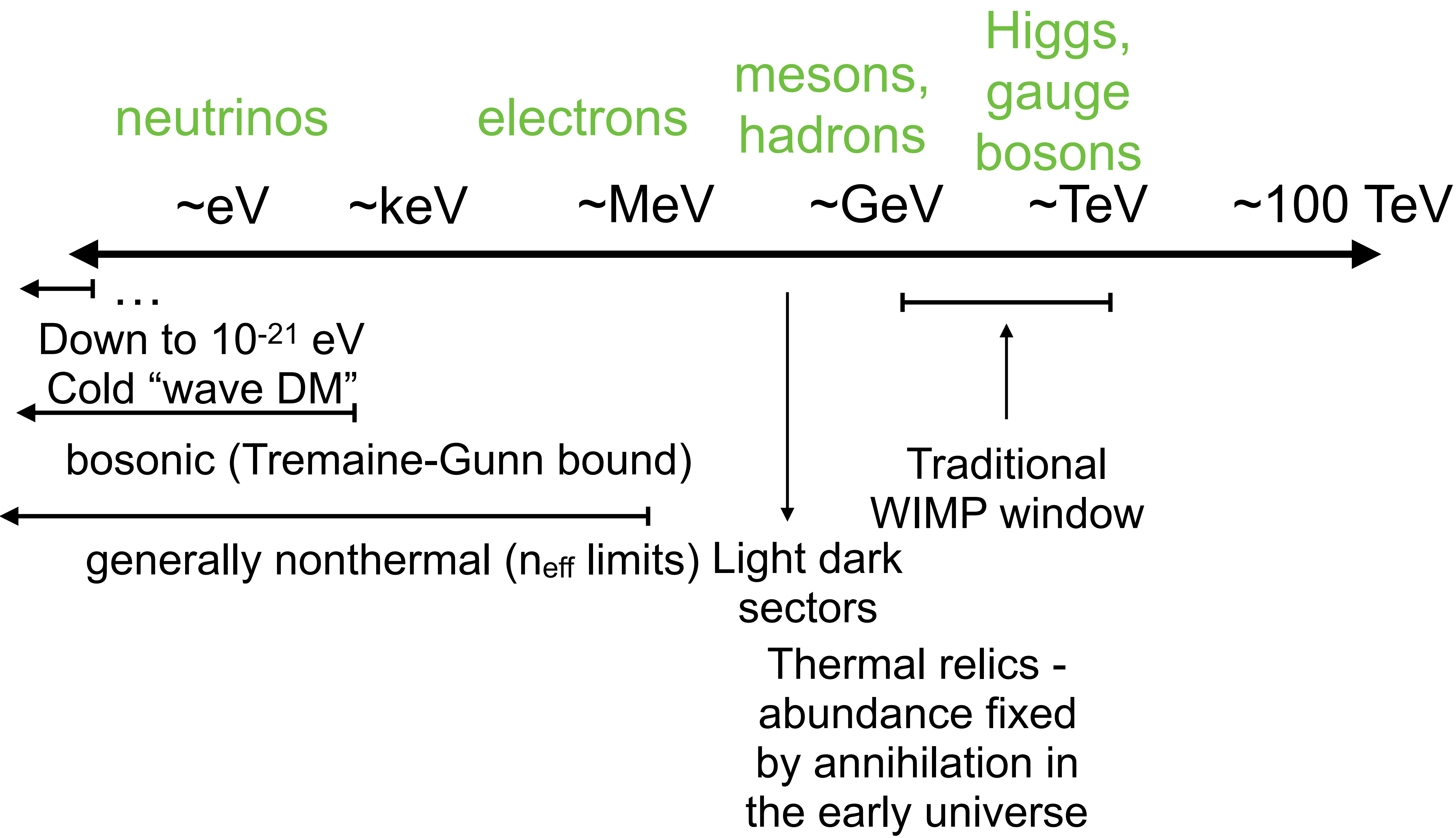

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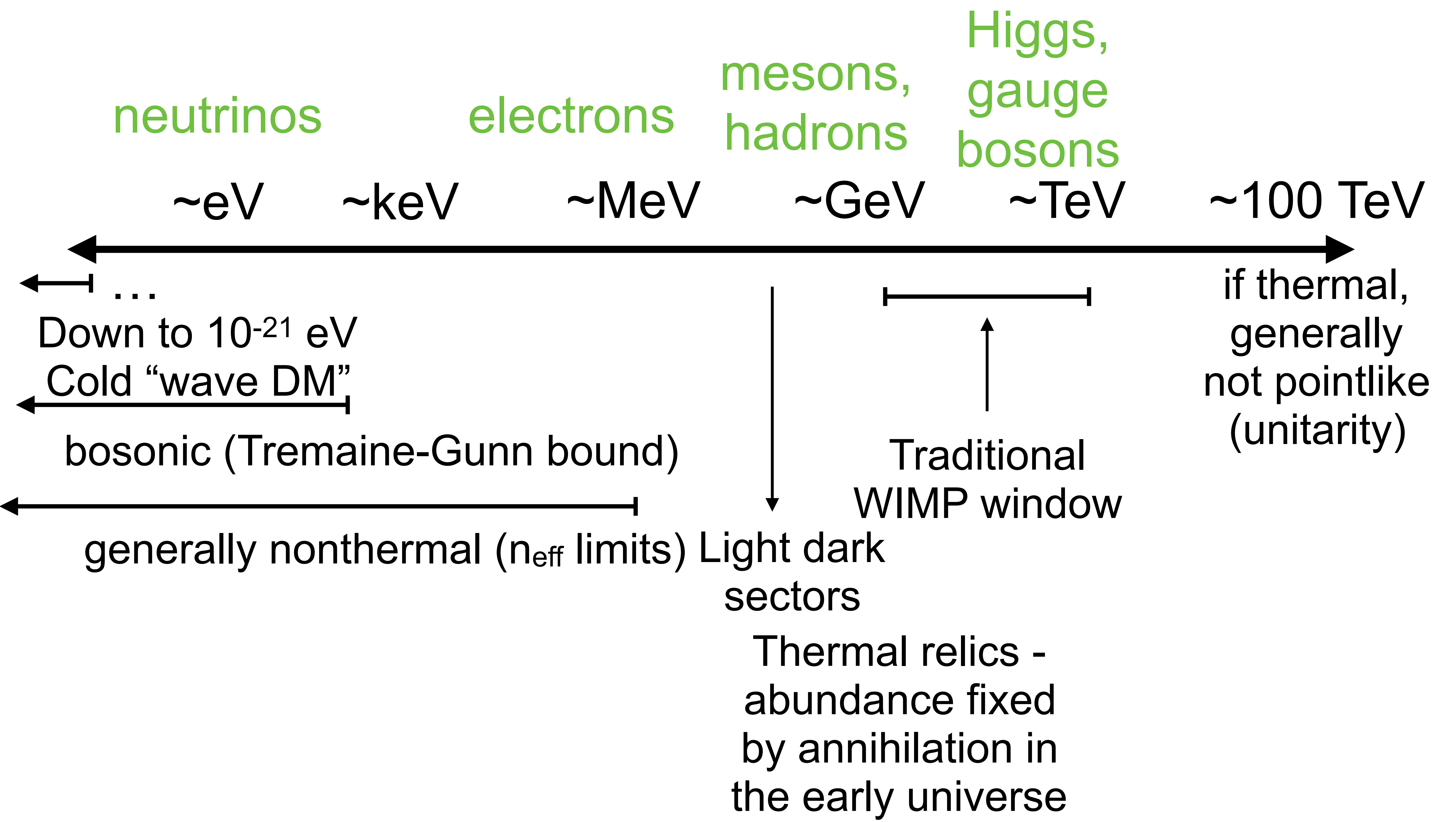

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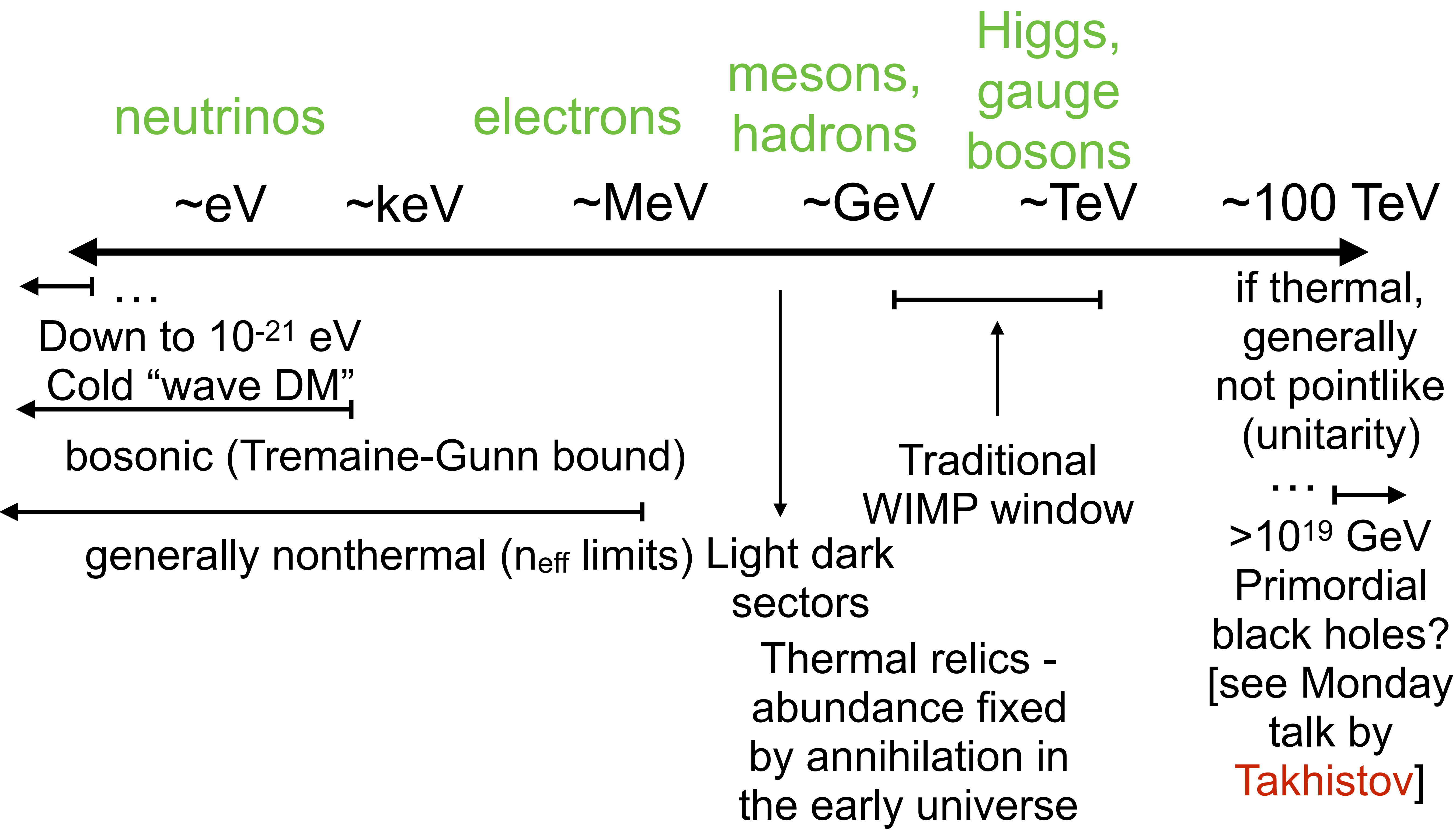


Some active areas of inquiry for DM theorists

(not a complete list!)

- What more can we learn from purely gravitational probes of the distribution of DM in the cosmos?
- How can we accurately predict tiny non-gravitational signals of interactions between DM and visible matter?
- How does the DM get its abundance? How does this question intersect with other puzzles of early-universe cosmology?
- Are any of the current anomalies/excesses actually telling us about DM?

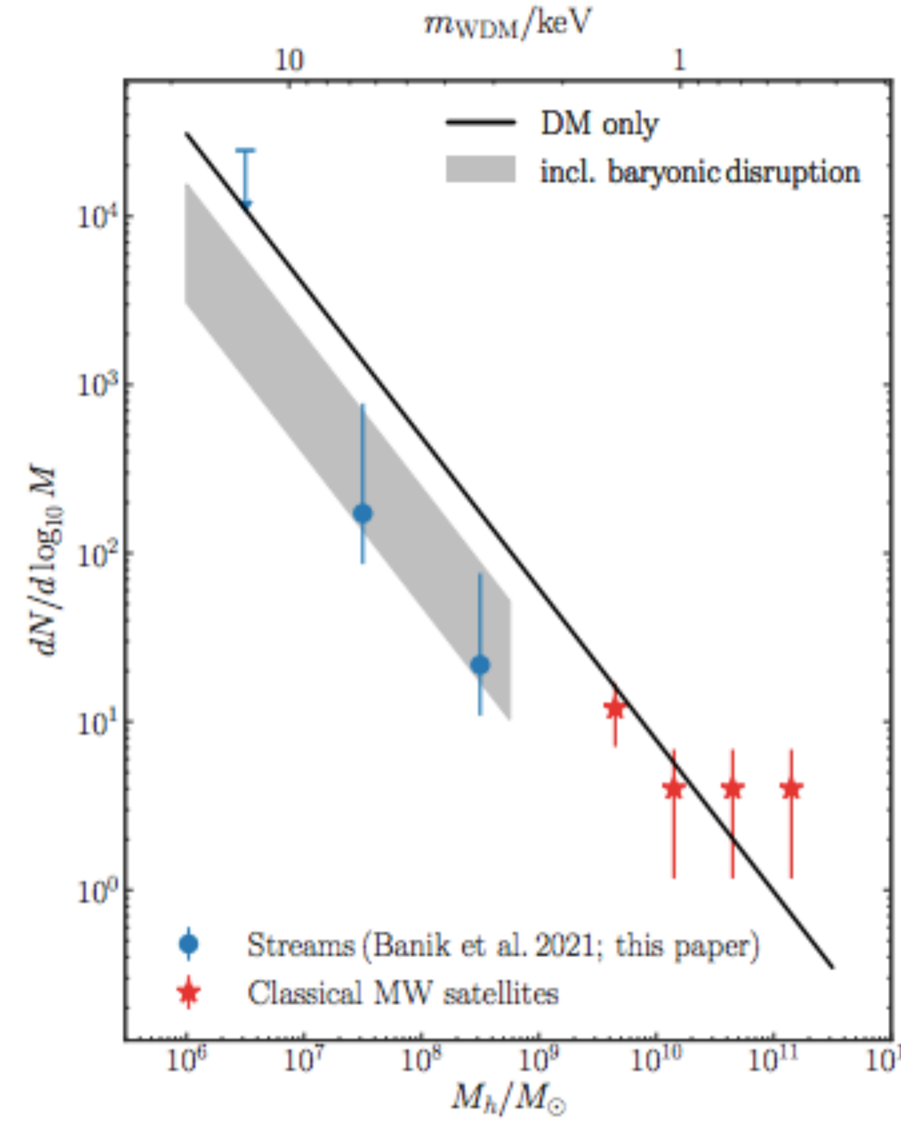
Gravitational probes

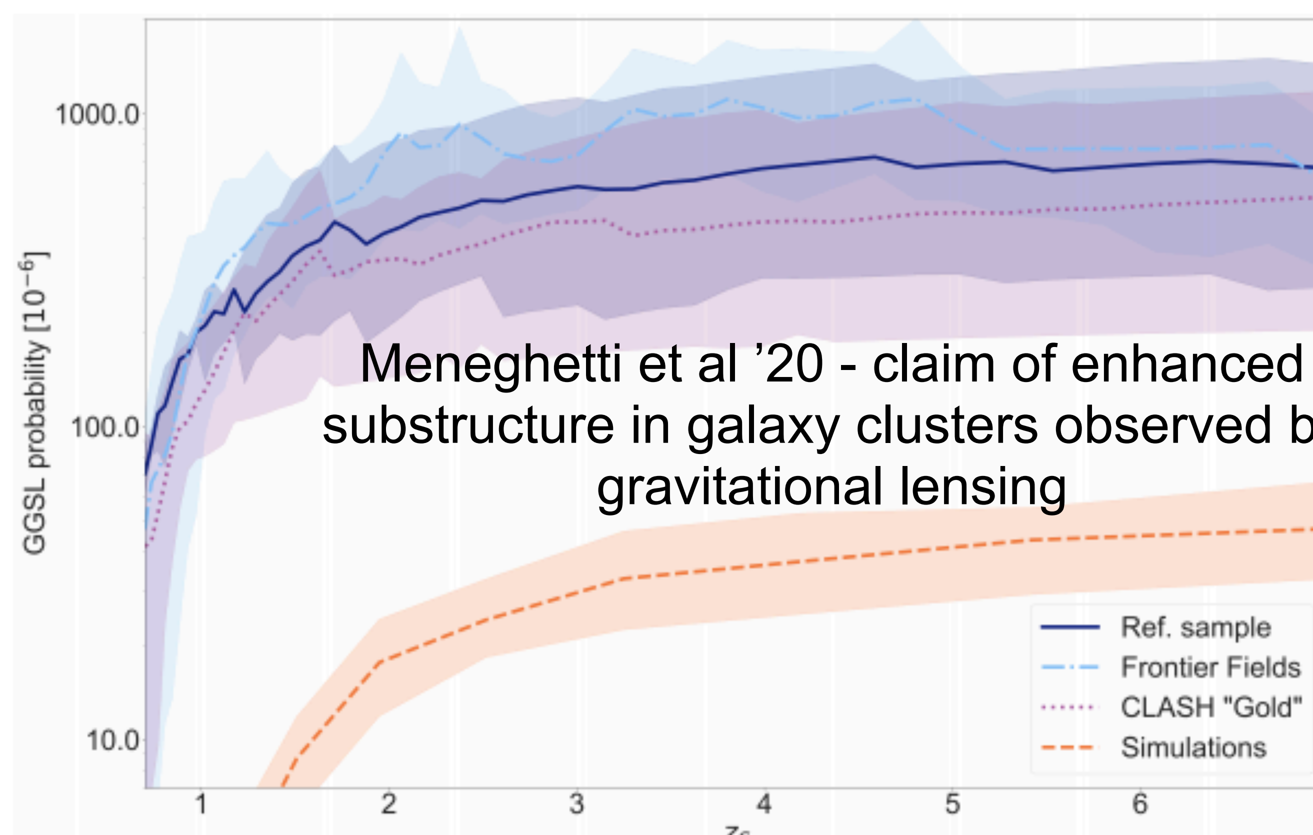
- Gravitational lensing + observations of stellar streams allow mapping smallest DM structures [e.g. Banik et al '19, Bonaca et al '19]

- New data + analyses map the shape and history of the DM halo, predict local DM velocity/density distribution [e.g. Buch et al '19, Posti et al '19, Necib et al '19, '20].

- Analyses provide lower bound on DM mass of 2-3 x 10^{-21} eV [Schutz '20], lower bound on thermally coupled DM mass of O(5) keV, limits on new DM physics such as self-interaction [e.g. Bondarenko et al '21, Andrade et al '20], and new tests of CDM paradigm.

Banik et al '19 - probing dark subhalos using stellar streams

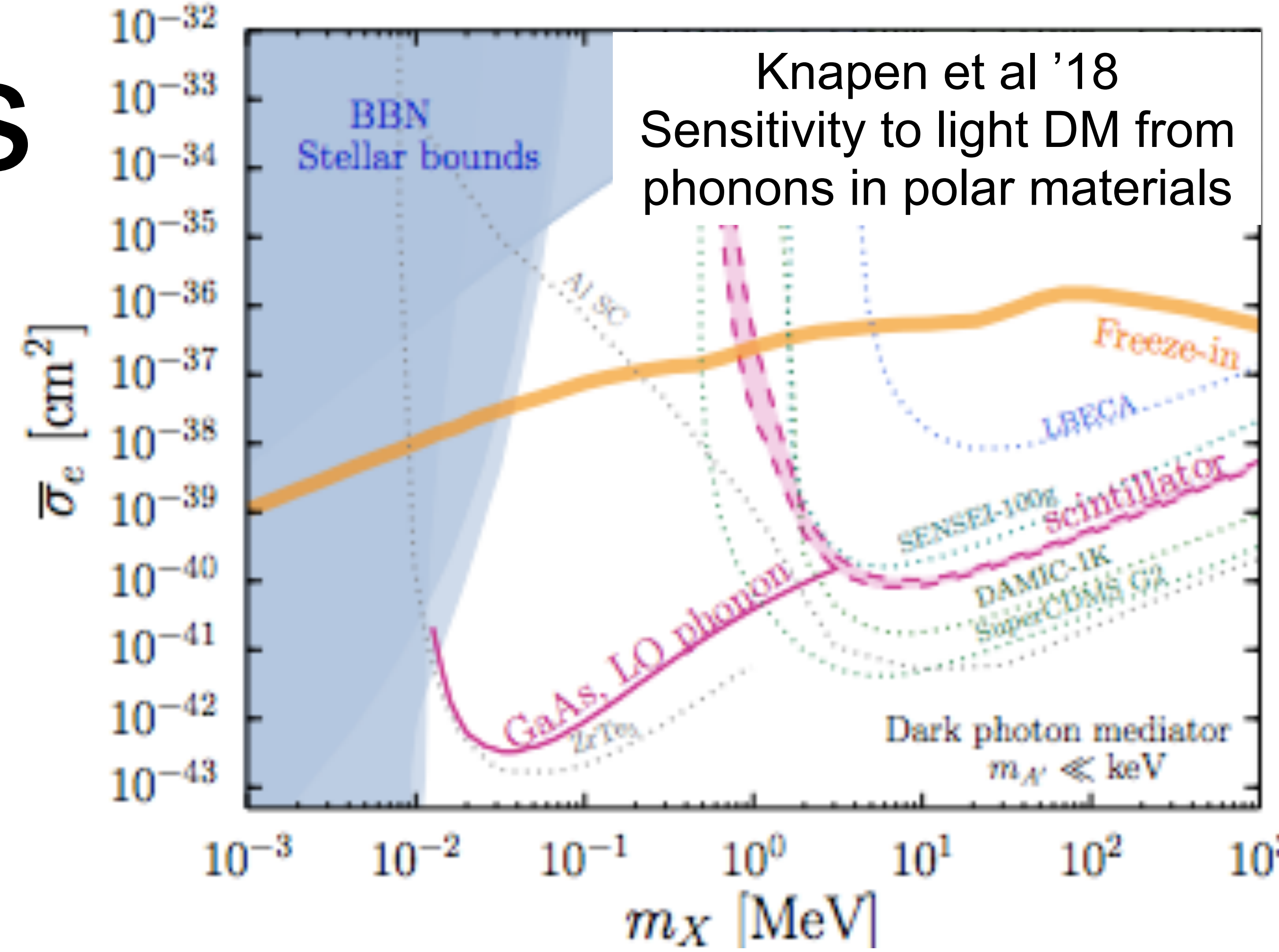


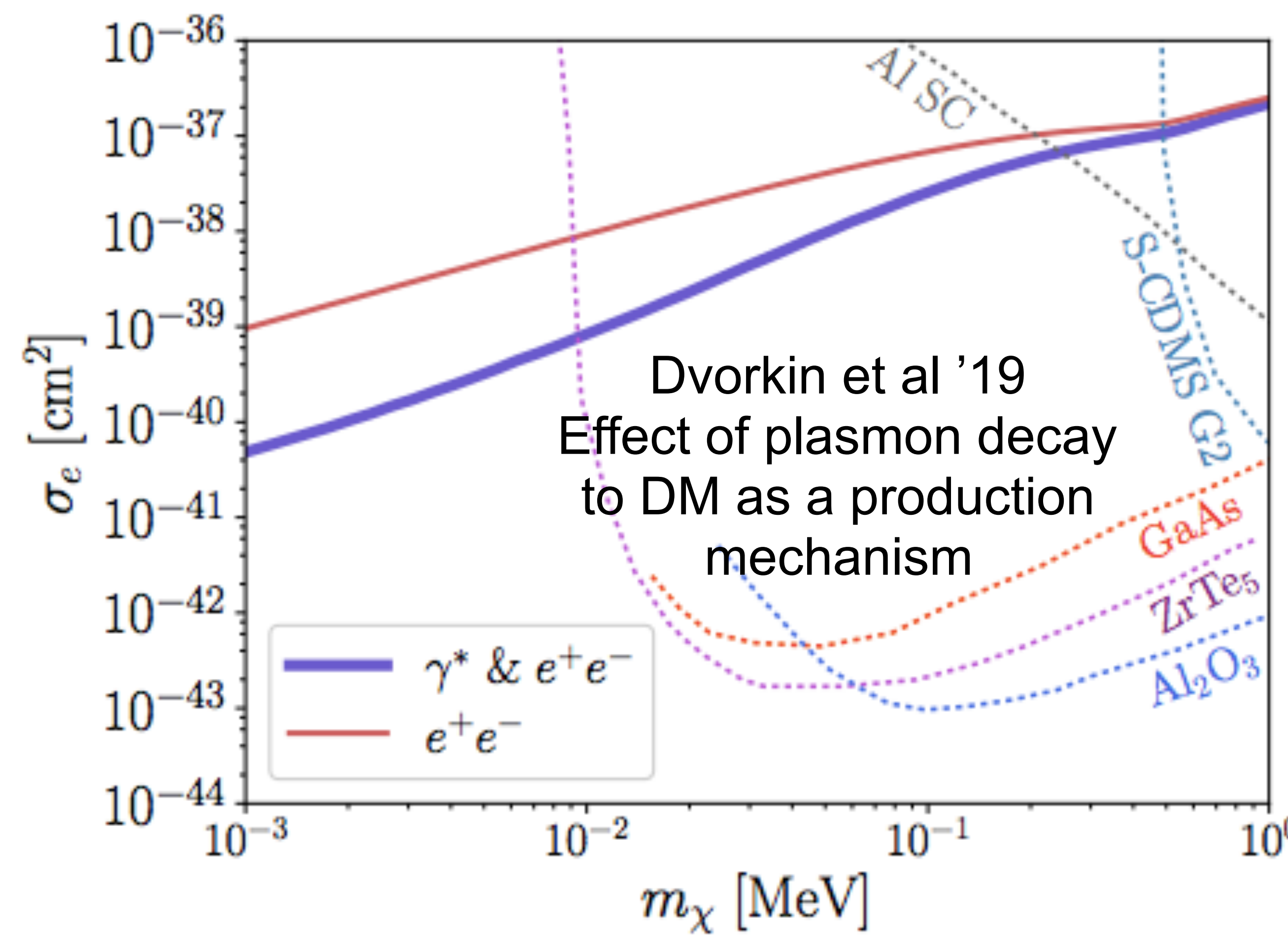


Meneghetti et al '20 - claim of enhanced substructure in galaxy clusters observed by gravitational lensing

Collective effects for light DM

- Large theoretical + experimental effort ongoing to devise new direct-detection searches for light dark matter
- Needs accurate modeling of signals - intersection with materials science / condensed matter theory
- Collective behavior allows for excitations with sub-eV energies - studying tiny energy depositions requires understanding of collective excitations (phonons, magnons, etc)
- In the early universe, photons acquire plasma masses - these “plasmons” can decay producing light DM [Dvorkin et al '19], allow for resonant oscillations with dark particles [e.g. Liu et al ’19], etc



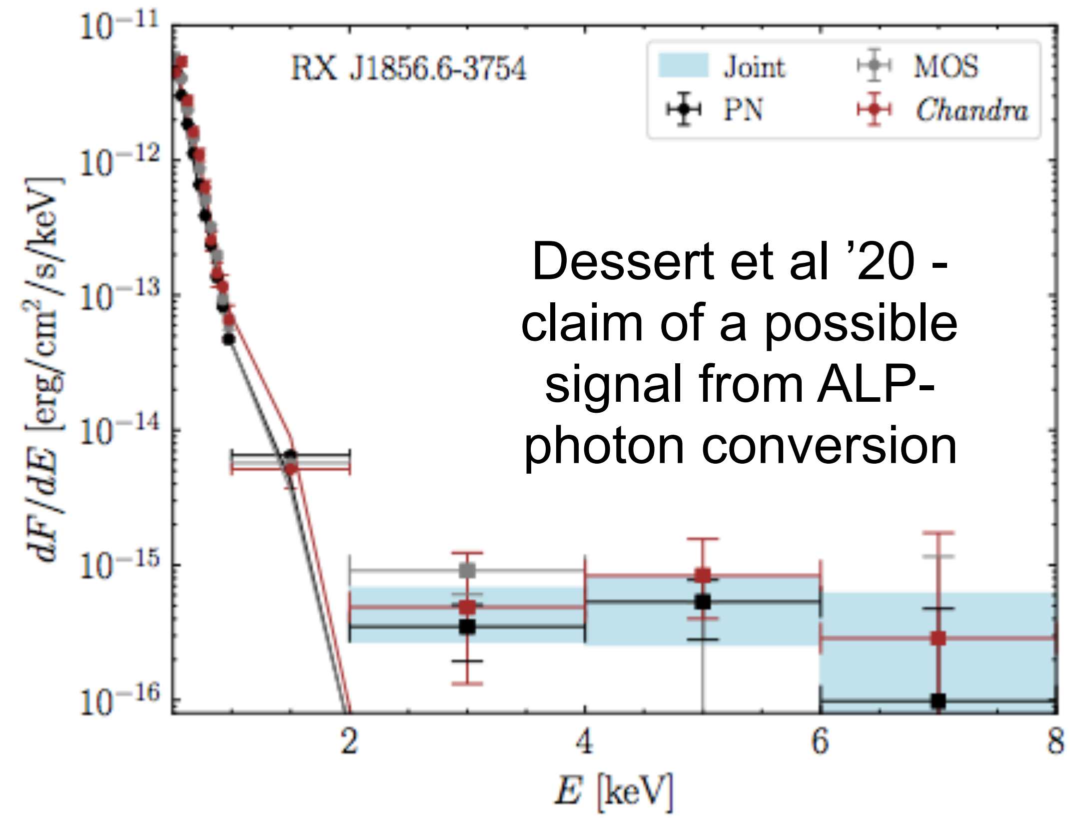


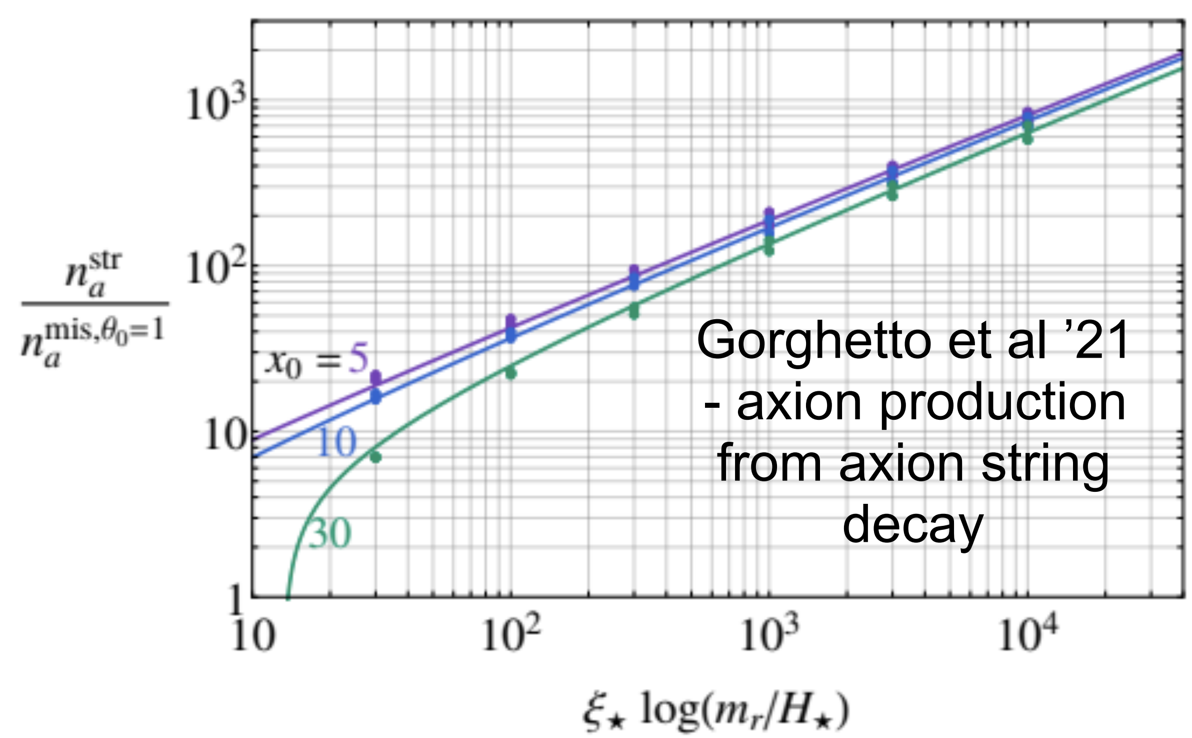
Astrophysics/cosmology of axion-like particles

- Many new ideas to search for axion-like particles converting to/from photons [see tomorrow's parallel session on axions]

- One example: photon-axion conversion in stars with strong magnetic fields - either conversion from ambient DM or conversion from photons to ALPs (whether DM or not)

- Simultaneously, new predictions for the abundance of axions - traditionally assumed to be set by misalignment of the field from the potential minimum in the early universe
  - new ways to achieve a small misalignment angle + other variations on misalignment [e.g. Co et al '18; see also talk by Eroncel yesterday]
  - simulating contributions from decay of the axion string network - still controversial [Buschmann et al '20, Gorghetto et al '21]





The path to the observed relic abundance

- Best-measured property of DM is its cosmological abundance
- Wide range of scenarios - correlated with mass scale + connections to other BSM physics
- Enormous range of work in recent years, including both:
  - suggesting entirely new production mechanisms (as in the plasmon decay example, see also Monday talk by Massina)
  - performing in-depth studies to allow for detailed predictions (as in the axion example)

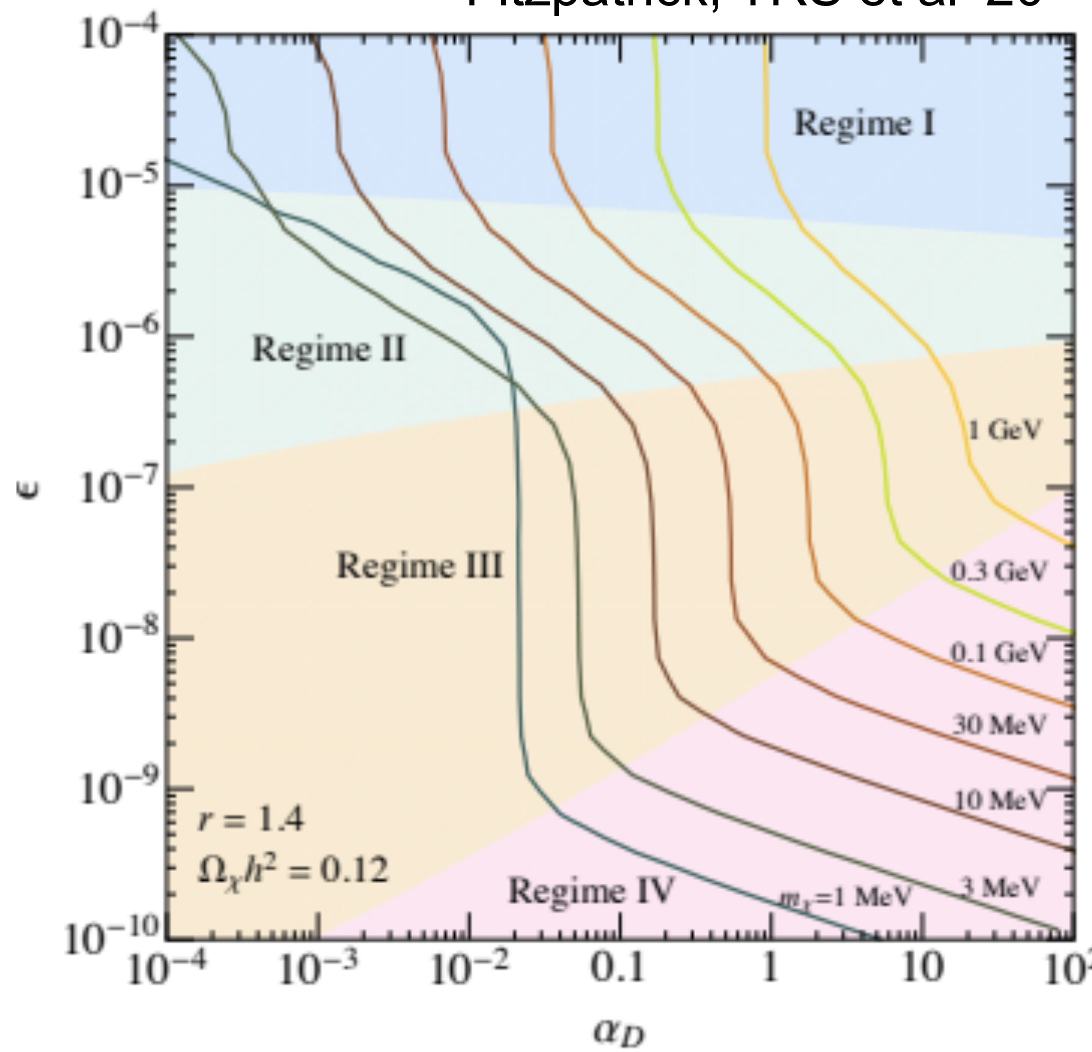
Relic abundance for light dark sectors…

- For MeV+ DM, searches often focus on the thermal freezeout regime - DM has relatively strong interactions with SM, is produced and then depleted by 2-body annihilations in the early universe

- Many variations on this scenario - detailed studies have shown the abundance can be controlled by 3-body or kinematically suppressed annihilation processes [Hochberg et al ’14, Ruderman et al ‘15], by elastic scatterings [Kuflik et al ’16], by decay of the mediator [Fitzpatrick, TRS et al ’20], etc

- New studies/tools for handling freezeout when standard assumptions are violated [see talks by Hryczuk, Heisig from earlier today]

Fitzpatrick, TRS et al ‘20



- These variations lead to different target regions in parameter space for direct-detection and accelerator experiments probing these light dark sectors

… and heavy strongly-interacting dark sectors

- At high masses (> 100 TeV), classic thermal freezeout fails - unitarity requires a cross section too small to match the observed relic abundance

- Even saturating the limit requires strong/long-range interactions - bound state formation becomes relevant, intersecting with quarkonium theory [e.g. Oncala et al ’19, ’20, ’21, Binder et al ’20, ’21, Bottaro et al ’21; see also talk by Binder yesterday].

- Exceeding this bound typically requires non-thermal production or modified cosmology

- One modification to cosmology is natural in a confining dark sector - phase transition! A first-order dark-sector phase transition can automatically raise the mass scale for heavy thermal DM to 1-1000 PeV [Asadi, TRS et al ’21]

New analyses for anomalies

- The Galactic Center excess (GCE) in GeV-scale gamma rays
  - previous claims of a pulsar origin may have been too strong due to systematic errors [Leane & TRS ‘19, 20; Buschmann et al '20]
  - new analyses using machine learning [List et al ’20, '21], Gaussian processes [Mishra-Sharma et al '20], photon statistics [Calore et al '21] aiming to disentangle DM and pulsar explanations [see talk by Calore earlier today]
- Anti-helium events (preliminarily) seen by AMS-02
  - puzzling from a BSM perspective - signal expected to be ~zero
  - recent claim that event generators underestimate effect of $\bar{\Lambda}_b$ baryons forming in DM annihilation, decaying to antihelium [Winkler et al ’21]
- Many other anomalies still outstanding / debated (AMS-02 antiprotons and positrons, 3.5 keV X-ray line, EDGES 21cm absorption trough, XENON1T electronic recoil events, muon g-2…)

Summary

- There is an enormous range of models and available parameter space to explain the observed properties of DM
- Gravitational probes provide some of the most model-independent bounds on the properties of DM; new analyses have mapped the lightest known DM halos, set novel bounds on ultralight, warm, and self-interacting DM, and helped unravel contributions to the DM velocity and density distribution
- Many recent directions in DM theory intersect fruitfully with other areas of theoretical physics - e.g. condensed matter theory and materials science for signals of light DM in direct detection, quarkonium physics for understanding heavy strongly-interacting dark sectors, etc
- Improved analyses of the DM abundance are helping set new target regions for experiments, from axions to light dark sectors to heavy electroweak DM.
- Studies are ongoing to try to understand anomalies/excesses in a range of searches.