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Dark Matter Theory

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U.S. DEPARTMENT OF ENERGY | Office of Science

What do we know about dark matter?

We know it:

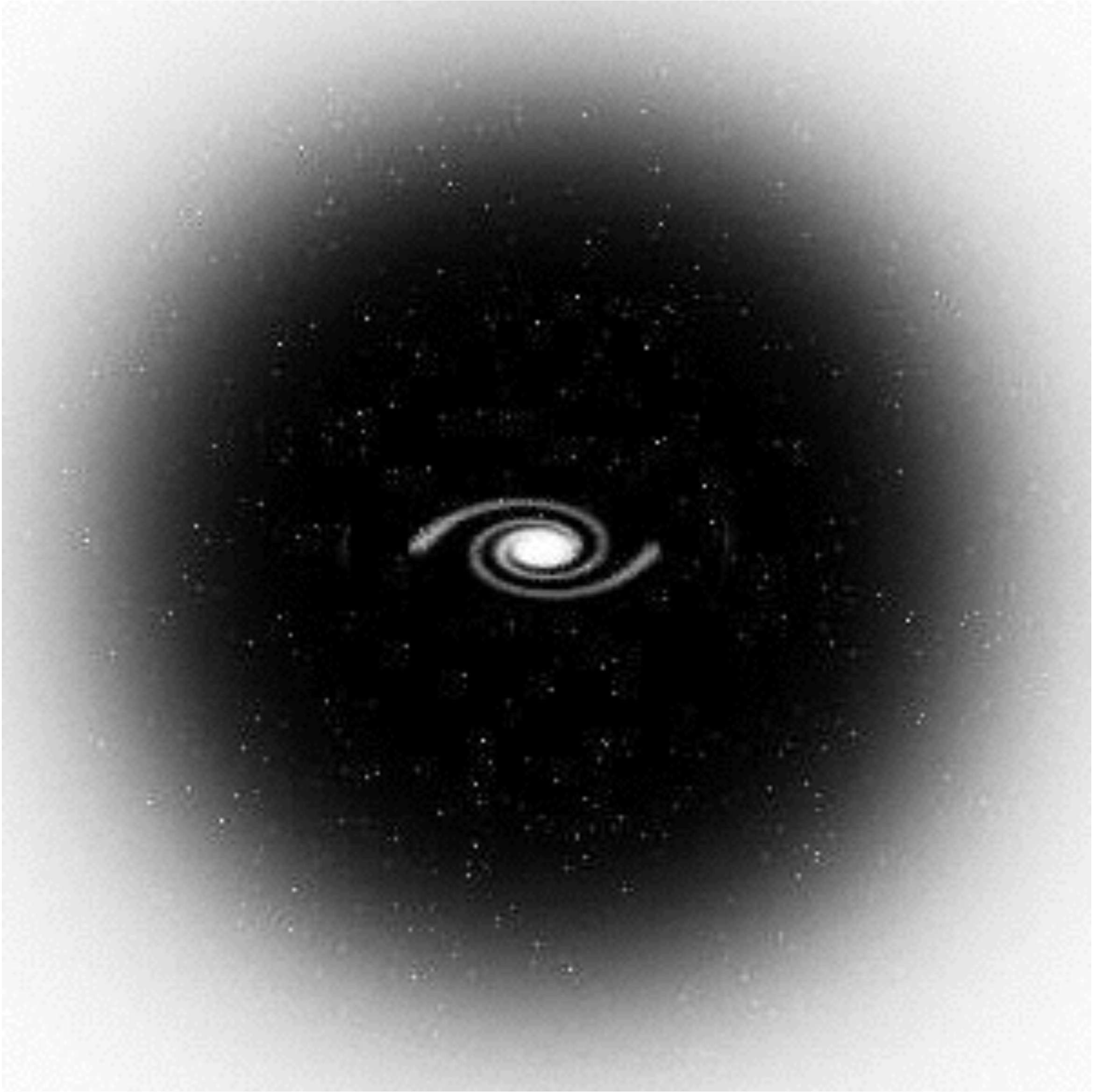
- Is roughly 80% of the matter in the universe.
- Has mass (and hence gravity).
- Doesn’t scatter/emit/absorb light (really “transparent matter”!)
- Interacts with other particles weakly or not at all (except by gravity).
- Is distributed through galaxies and the universe in a way that we can predict and map.

We don’t know:

- What it’s made from.
- 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.

Where is the dark matter?

- Invisible matter surrounds galaxies in large clouds or “haloes”
- Detectable by its gravitational pull on visible matter
- Dubbed “dark” as it does not radiate light (really “transparent”)

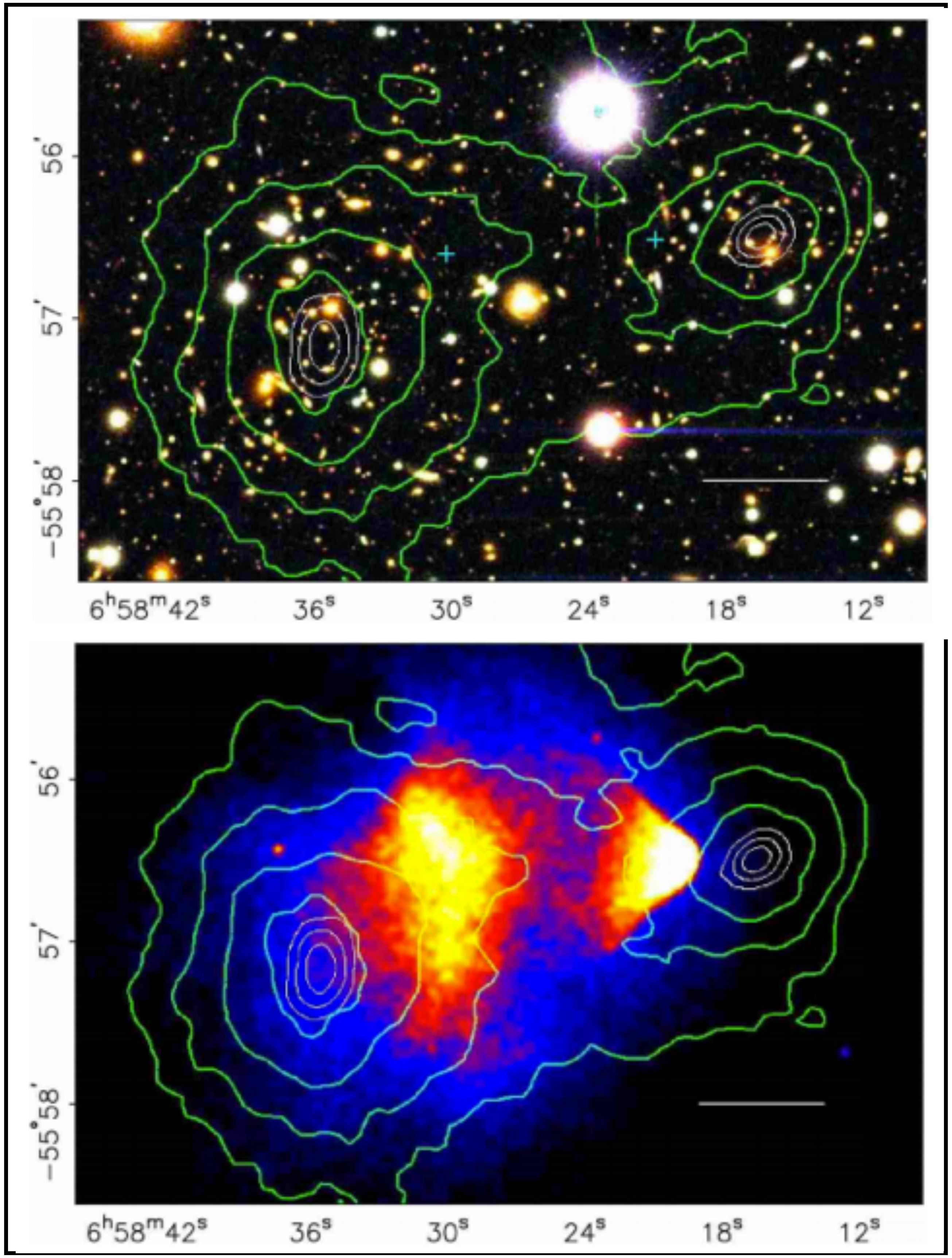


Initially discovered by the work of Vera Rubin & colleagues in the 1970s

Where is the dark matter?

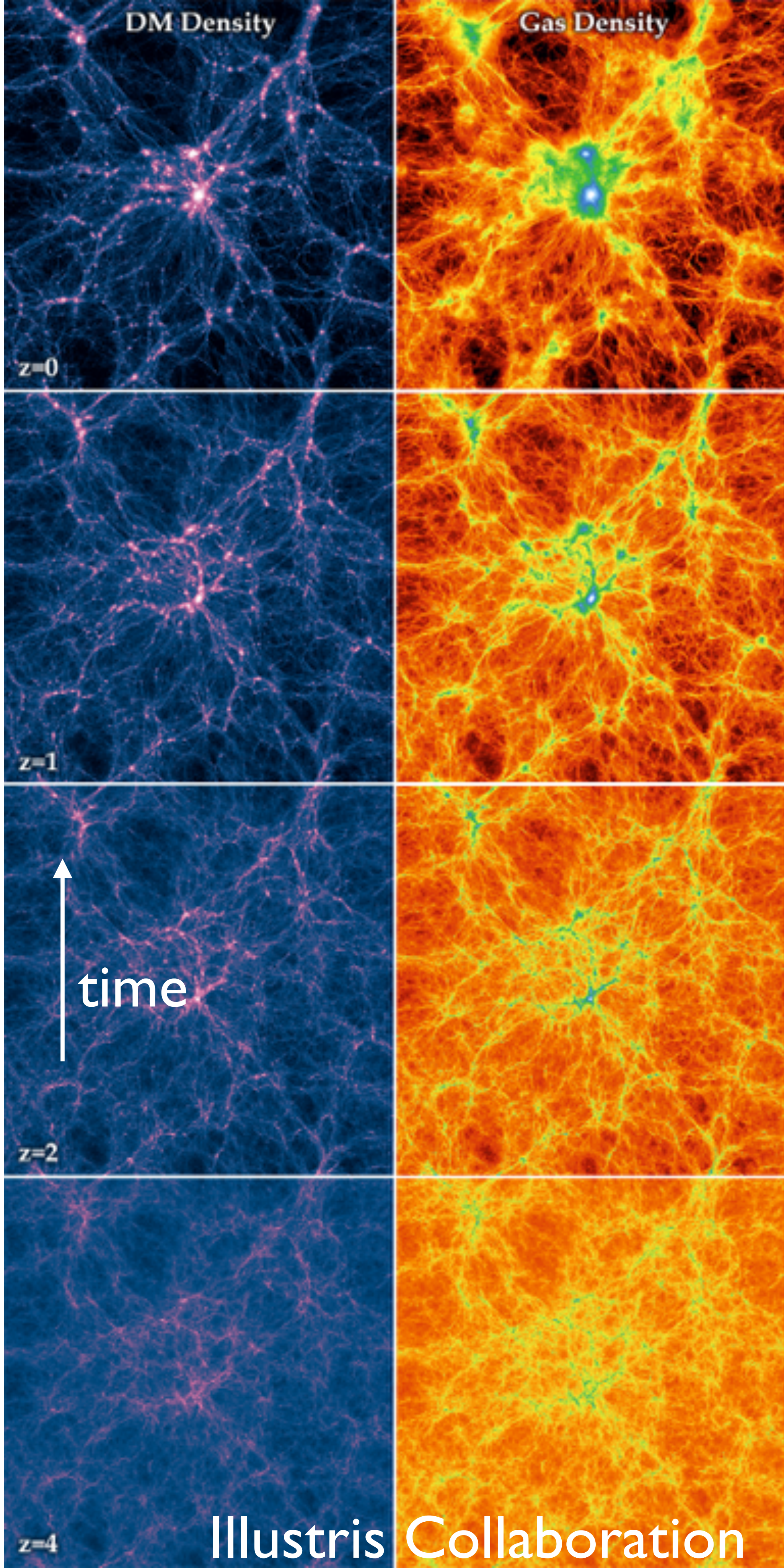
- Colliding galaxy clusters can filter dark matter from ordinary matter
- Works because dark matter seems to be approximately collisionless
- Dark-matter-rich regions bend light due to their gravity

Separation between hot gas and mass peaks was observed in the Bullet Cluster by Clowe et al in 2006



Where is the dark matter?

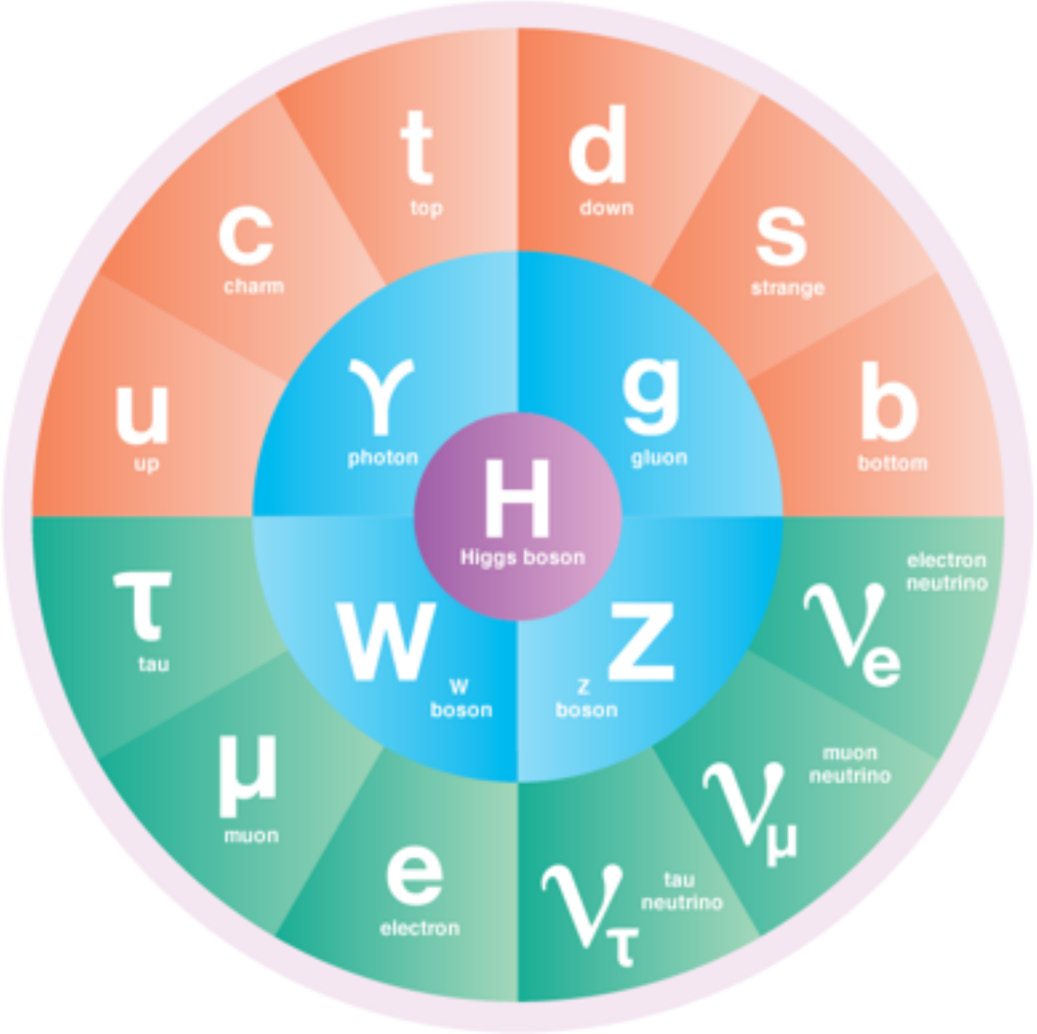
- Slow-moving, “cold” dark matter forms the scaffolding for the visible universe
- Dark matter structures formed first, galaxies later
- Detailed simulations of our universe match observations closely
- Huge advances in last few years, studying interplay between ordinary and dark matter



Illustris Collaboration

What is the dark matter?

The Standard Model of particle physics



Symmetry magazine

What is the dark matter?

- Dark - doesn’t interact with light, no electric charge

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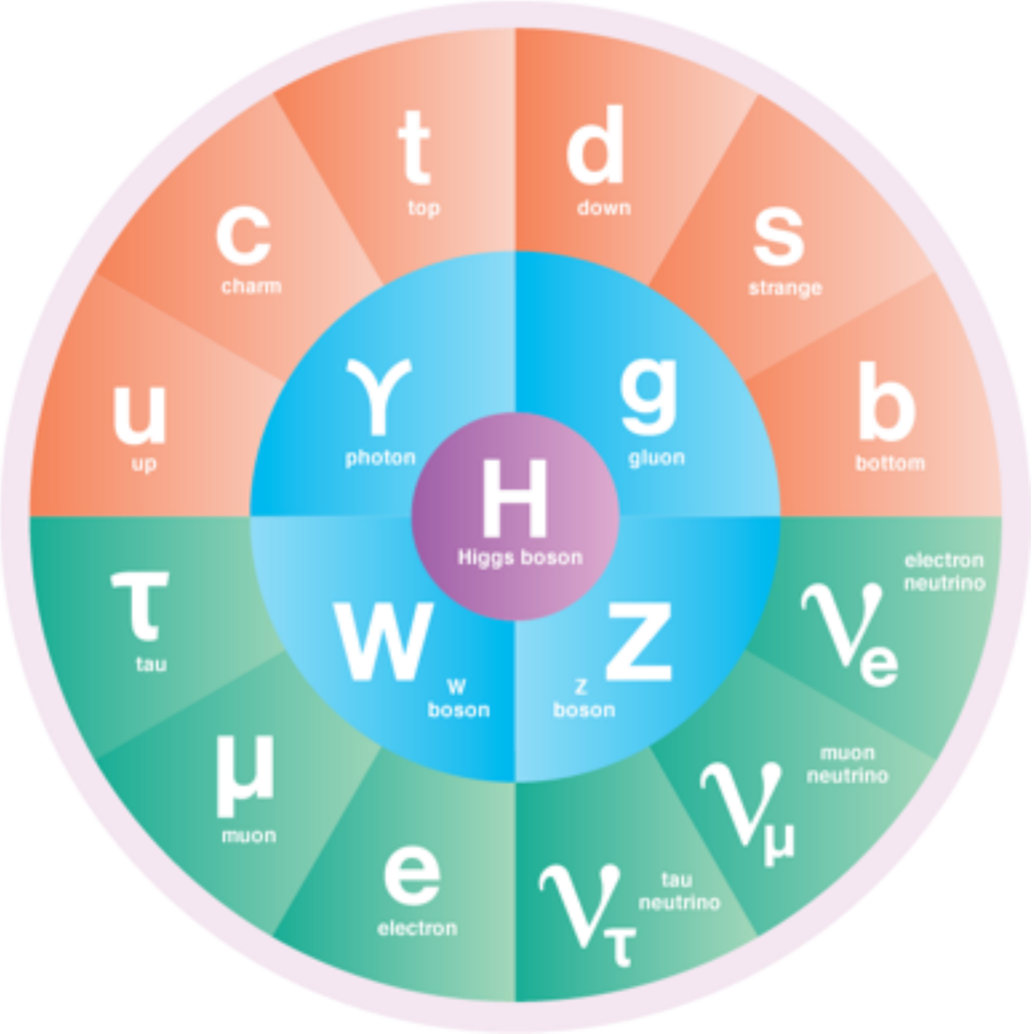

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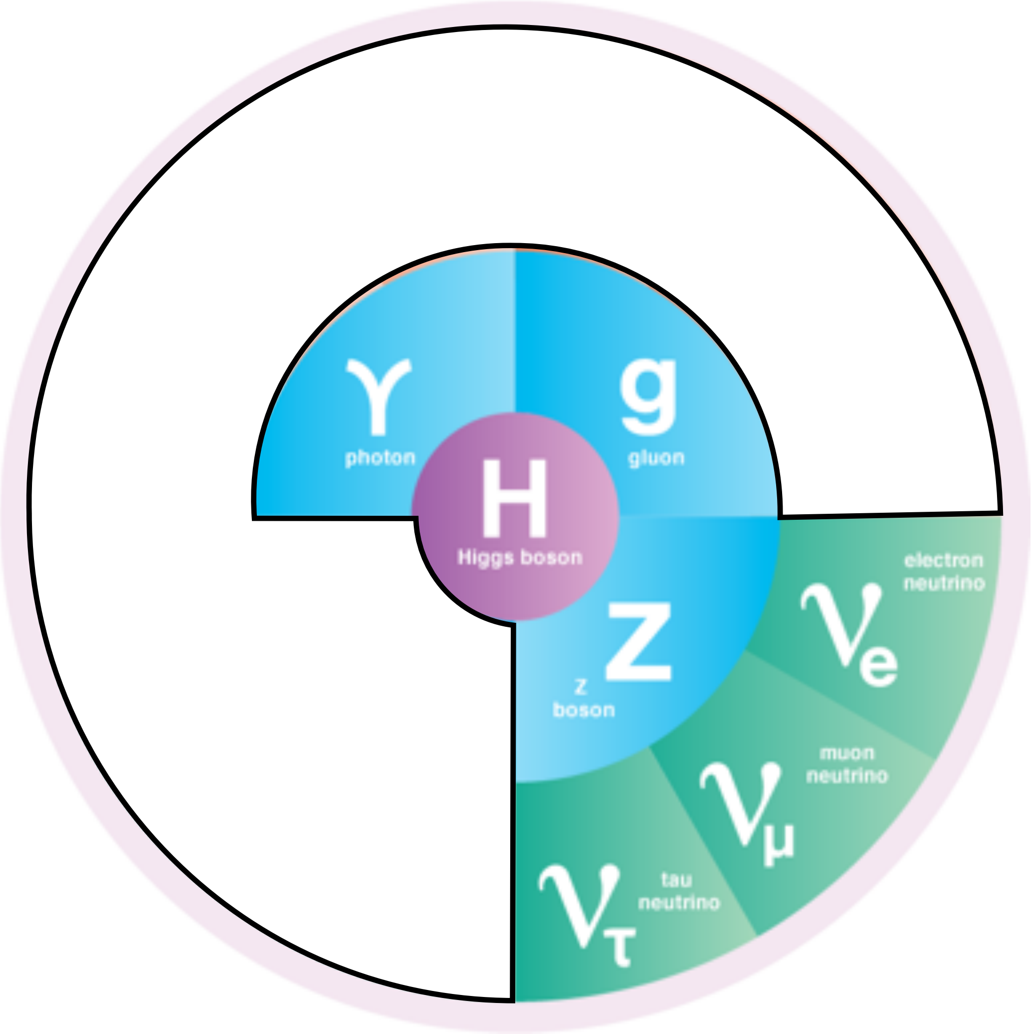

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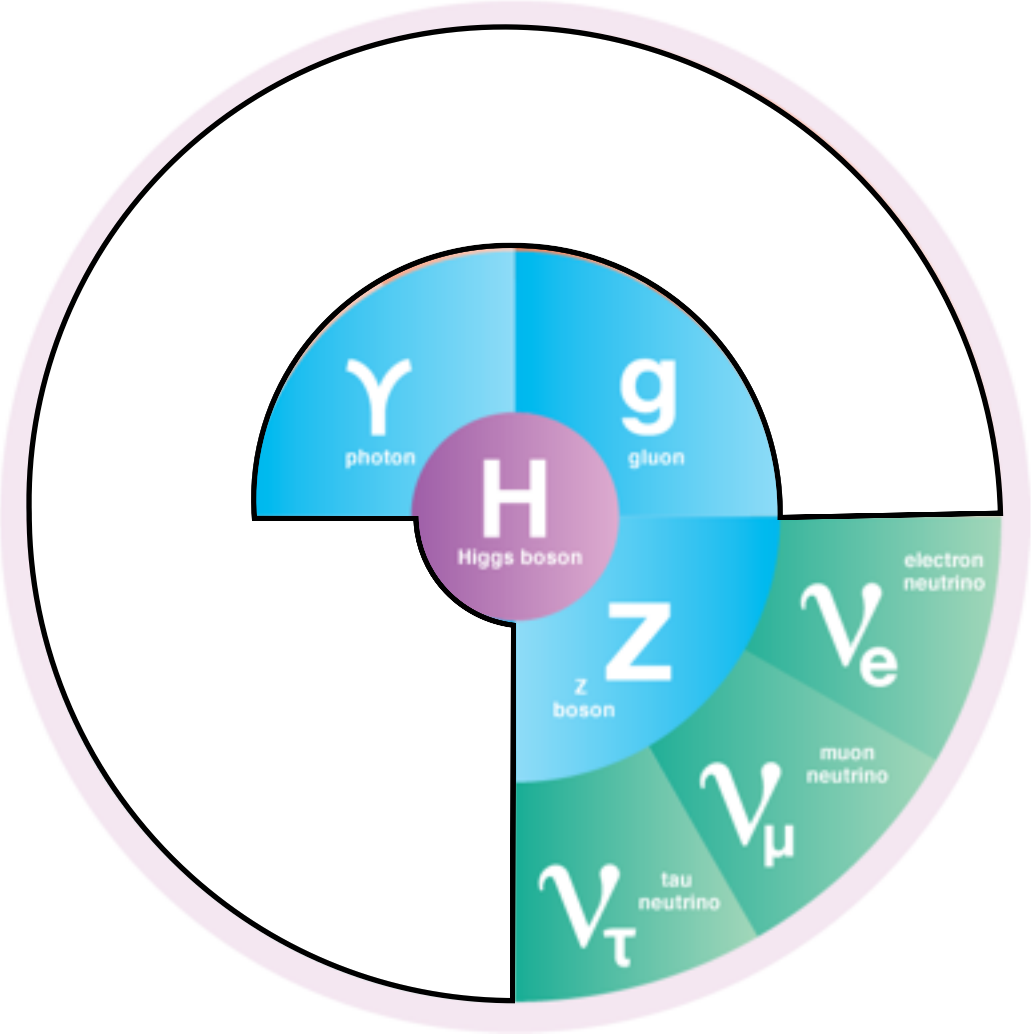

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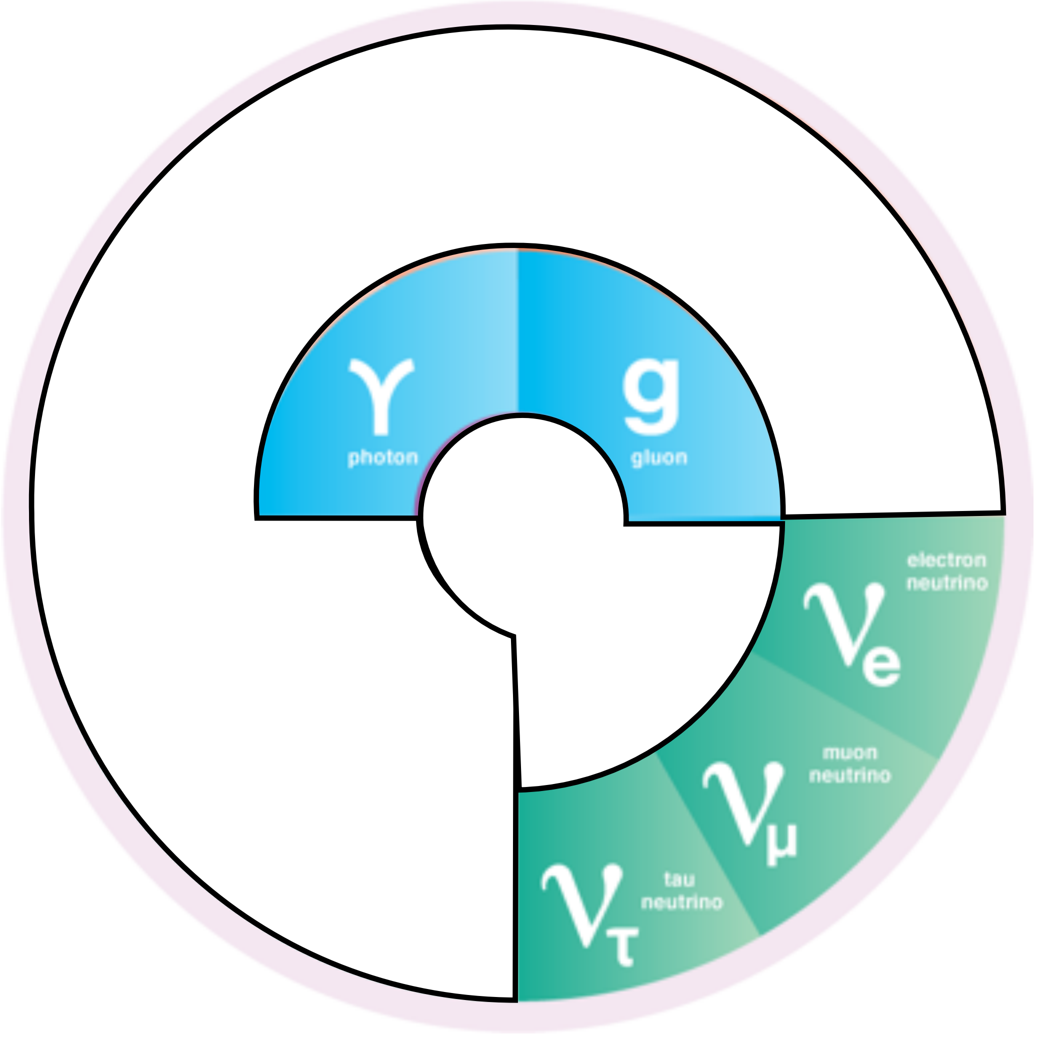

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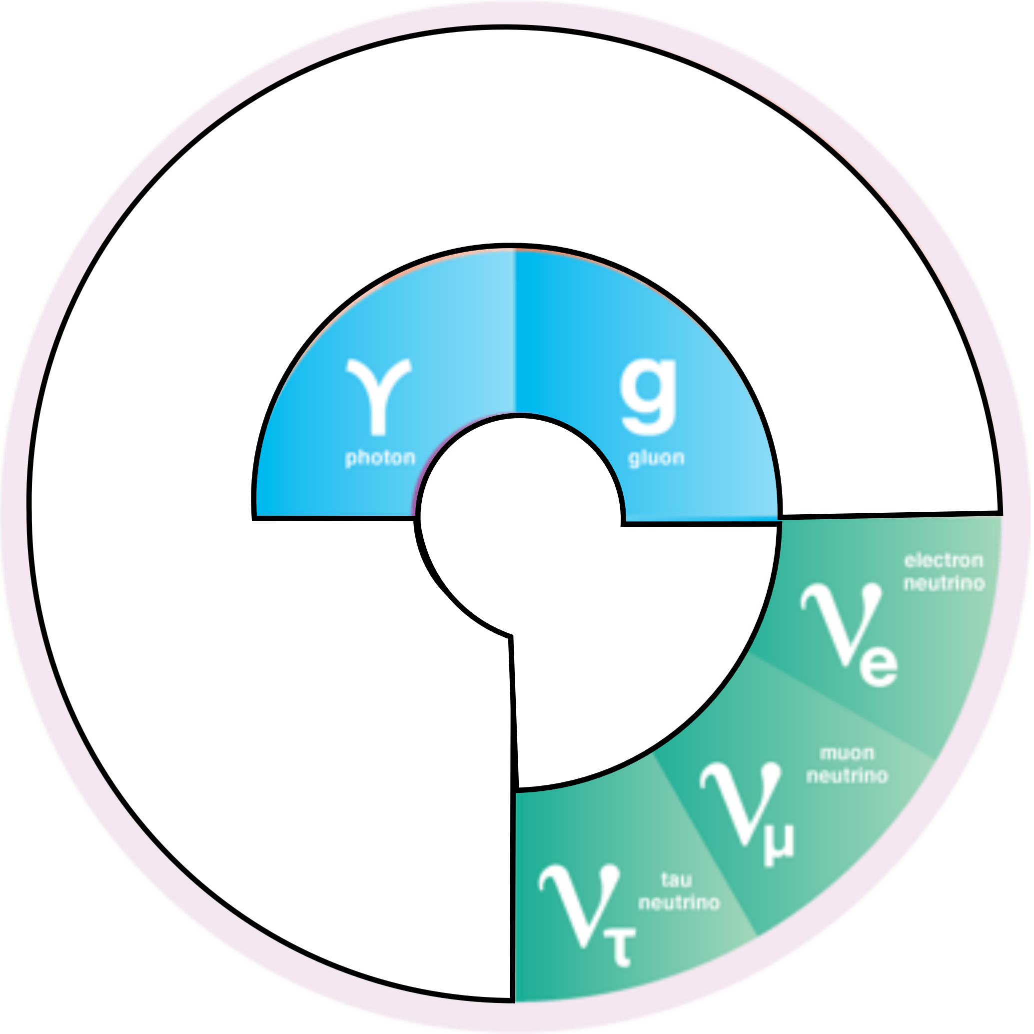

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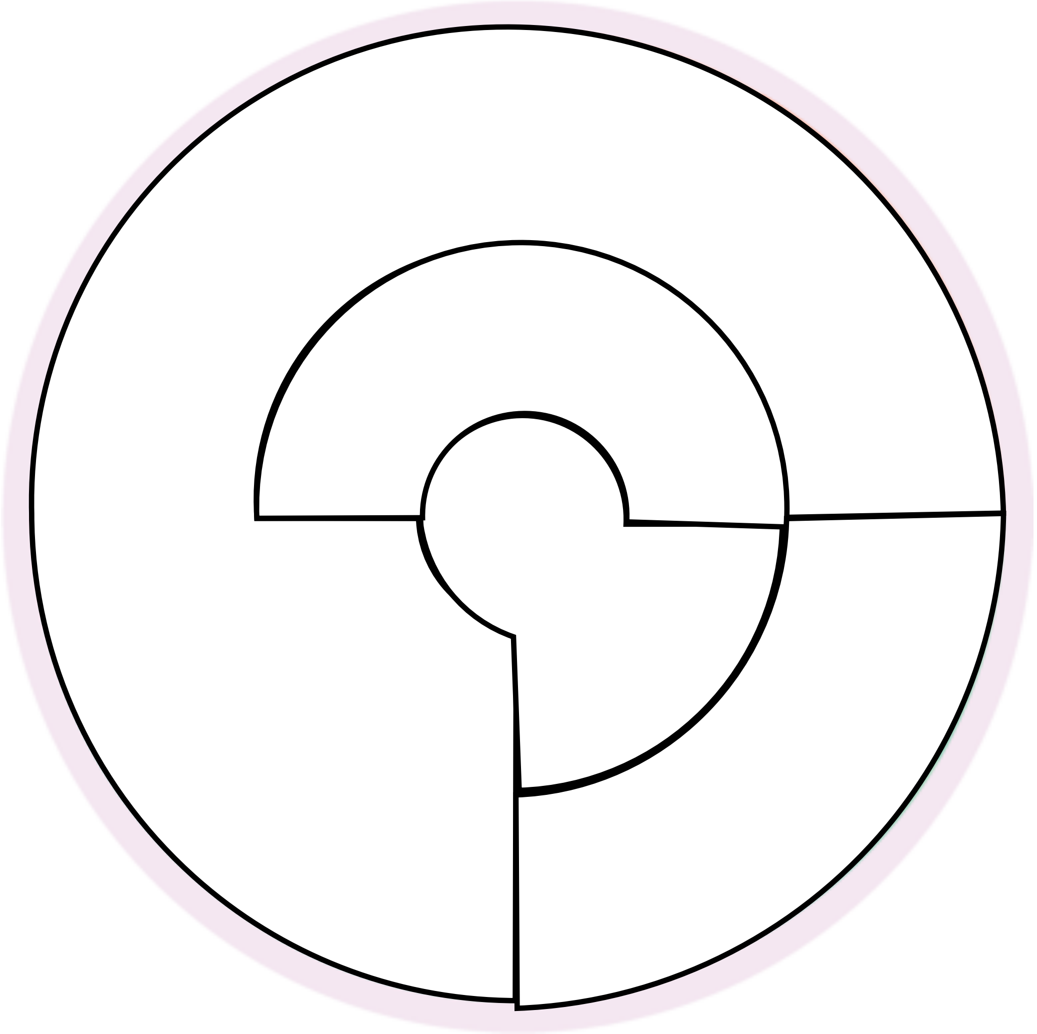

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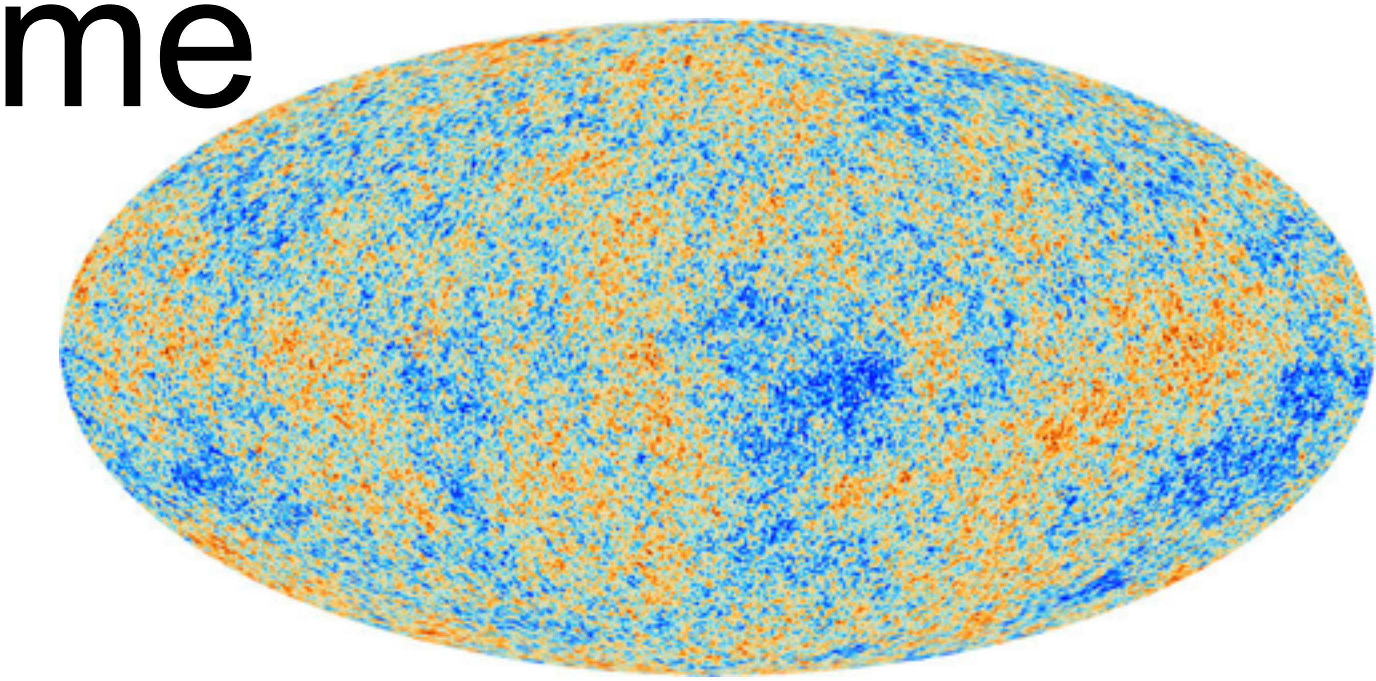
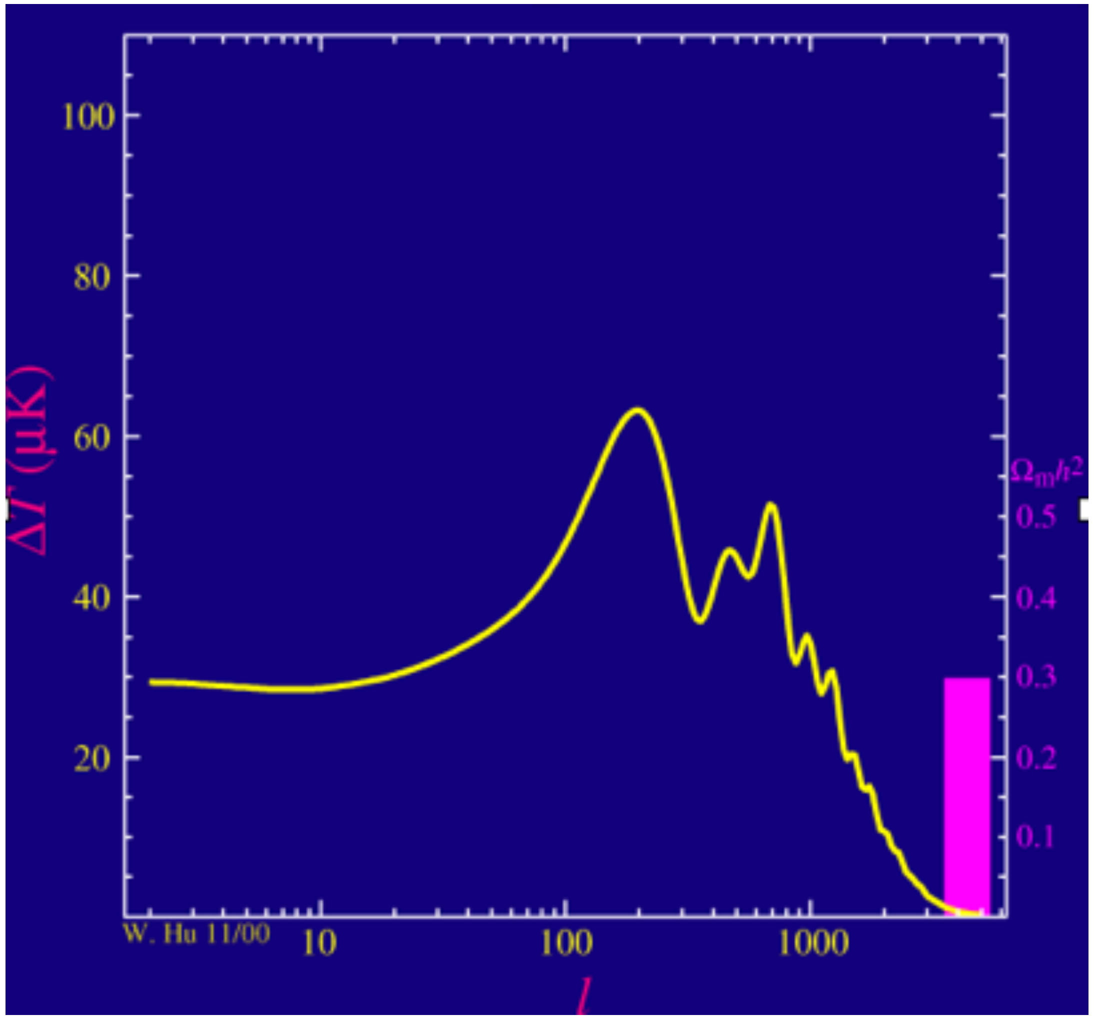
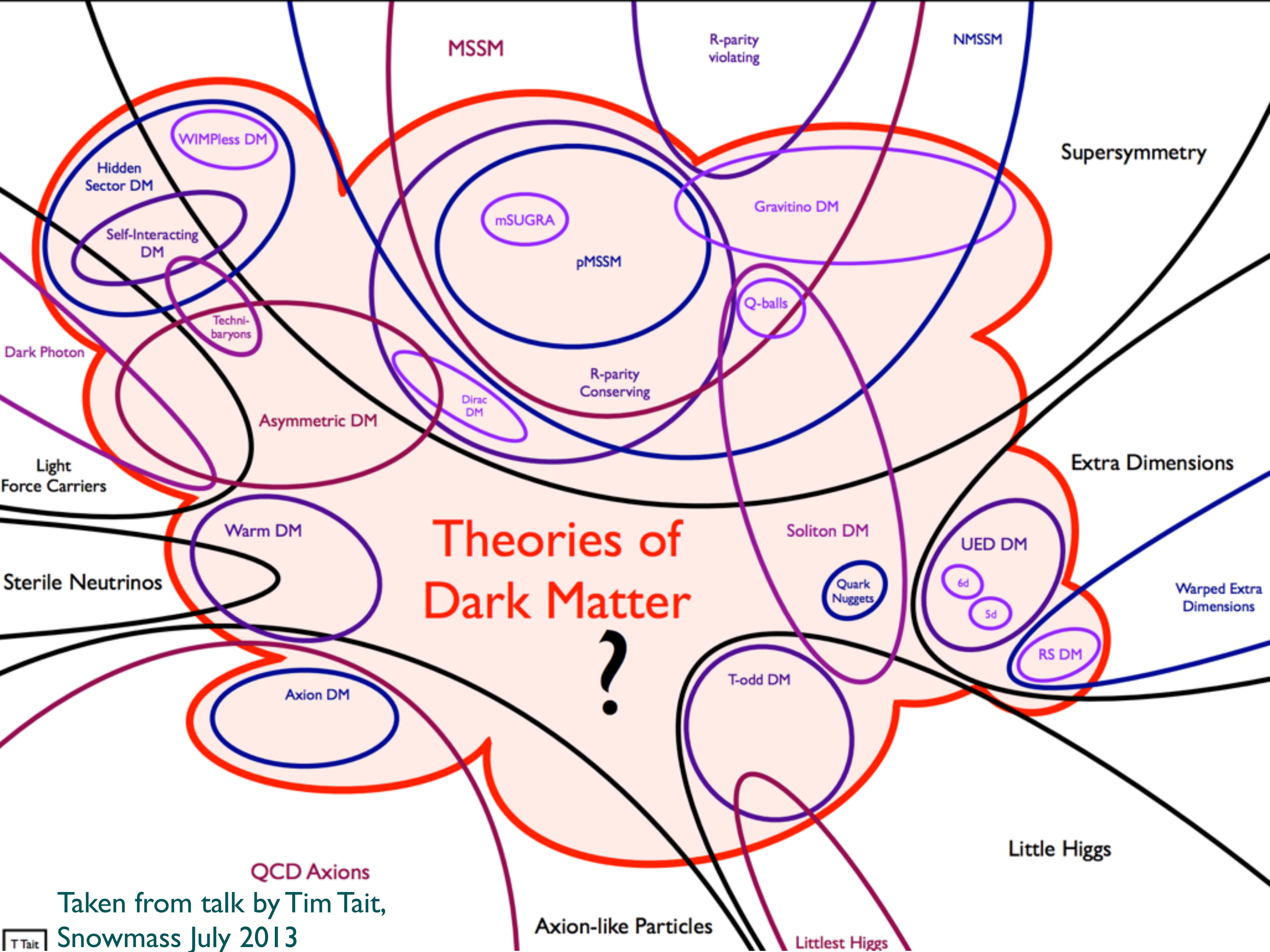
Where did it come from?



- The cosmic microwave background radiation - the “Big Bang afterglow” - holds information about the early universe
- Can be used to measure the amount of dark matter to percent-level precision
- We find there is roughly 5x as much dark matter (by mass) as ordinary matter
- Why?



Wayne Hu, http://background.uchicago.edu/~whu/



Theories of Dark Matter ?

MSSM

R-parity violating

NMSSM

Supersymmetry

WIMPless DM

Hidden Sector DM

Self-Interacting DM

Techni-baryons

mSUGRA

pMSSM

Gravitino DM

Q-balls

R-parity Conserving

Dirac DM

Dark Photon

Asymmetric DM

Light Force Carriers

Extra Dimensions

Warm DM

Soliton DM

UED DM

6d

5d

Quark Nuggets

RS DM

Warped Extra Dimensions

Sterile Neutrinos

Axion DM

T-odd DM

Little Higgs

QCD Axions

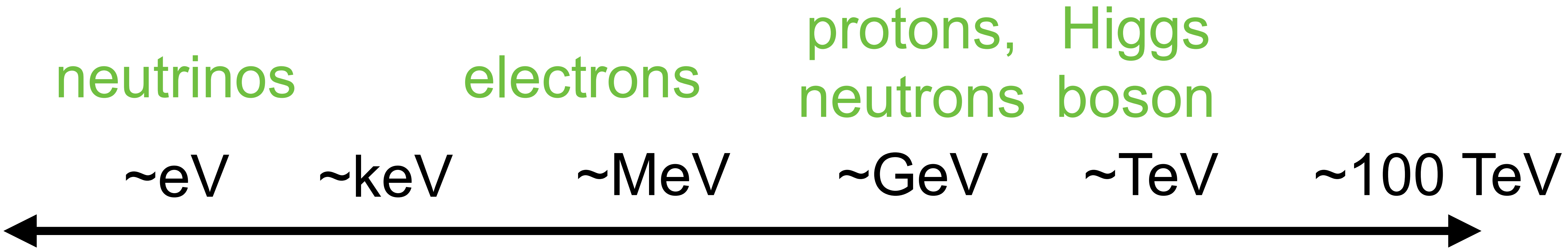
Axion-like Particles

Littlest Higgs

T Tait

Taken from talk by Tim Tait, Snowmass July 2013

What is its mass?



neutrinos

electrons

protons, neutrons

Higgs boson

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

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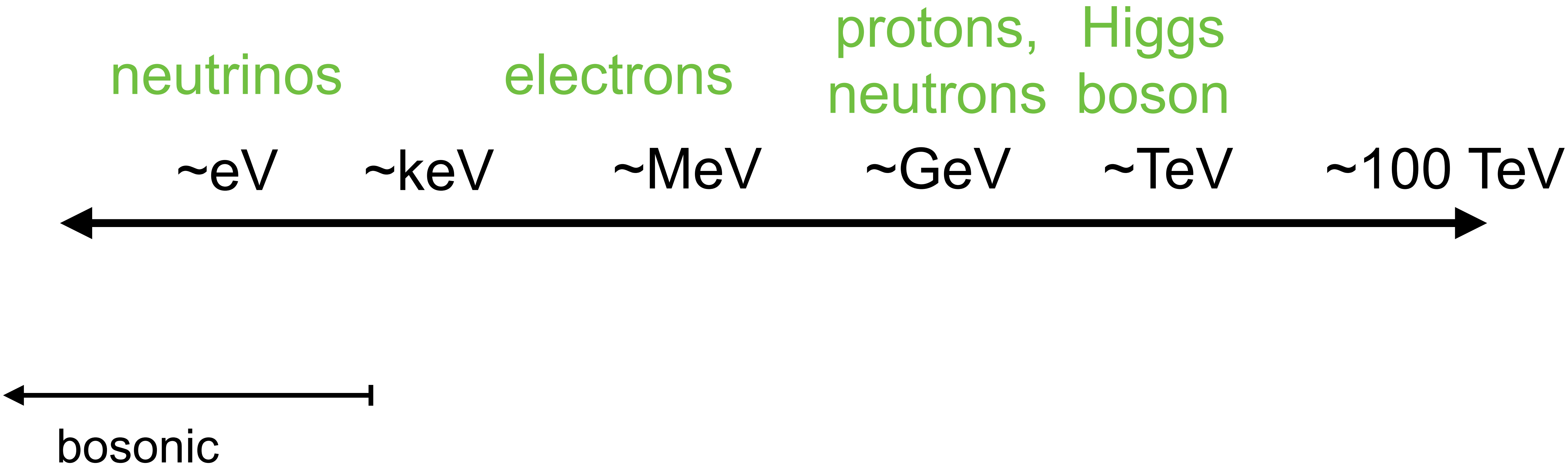

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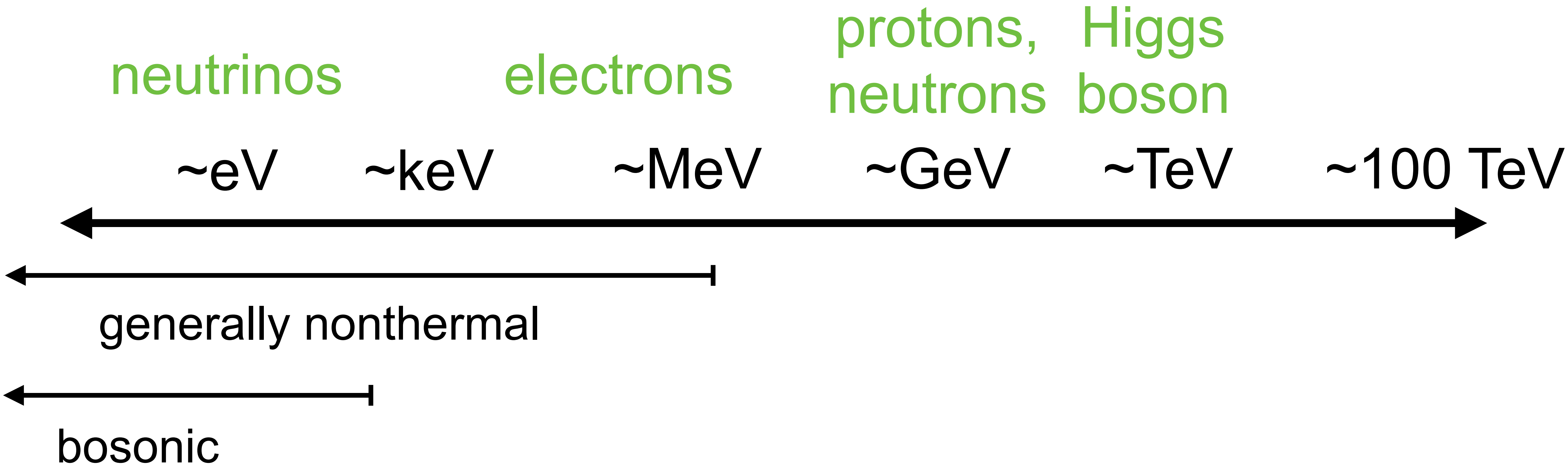

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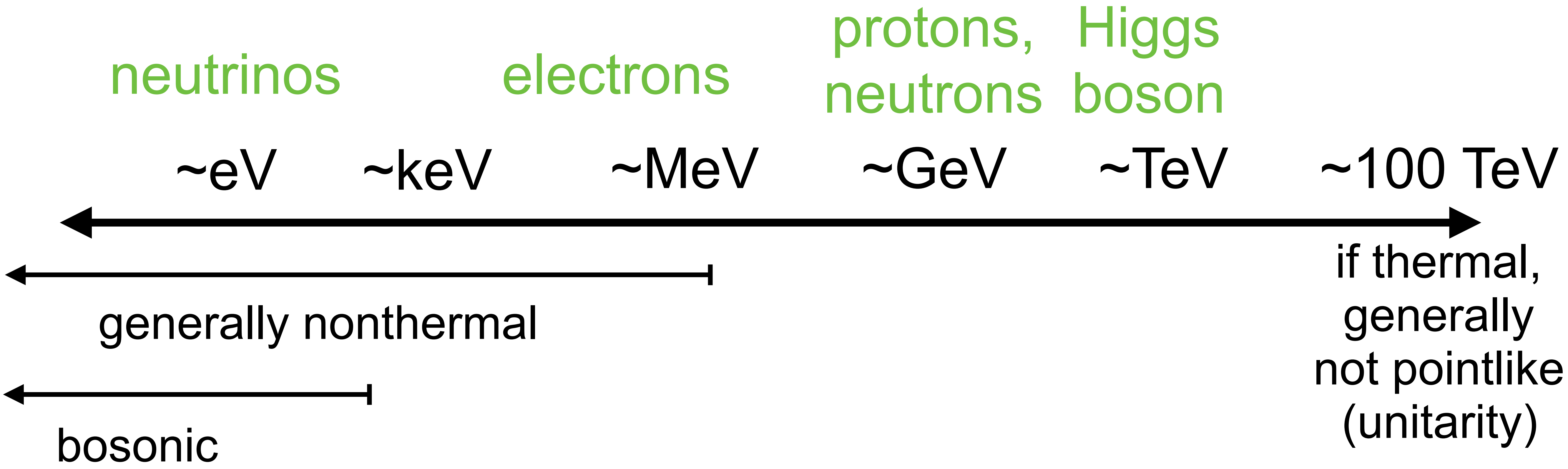

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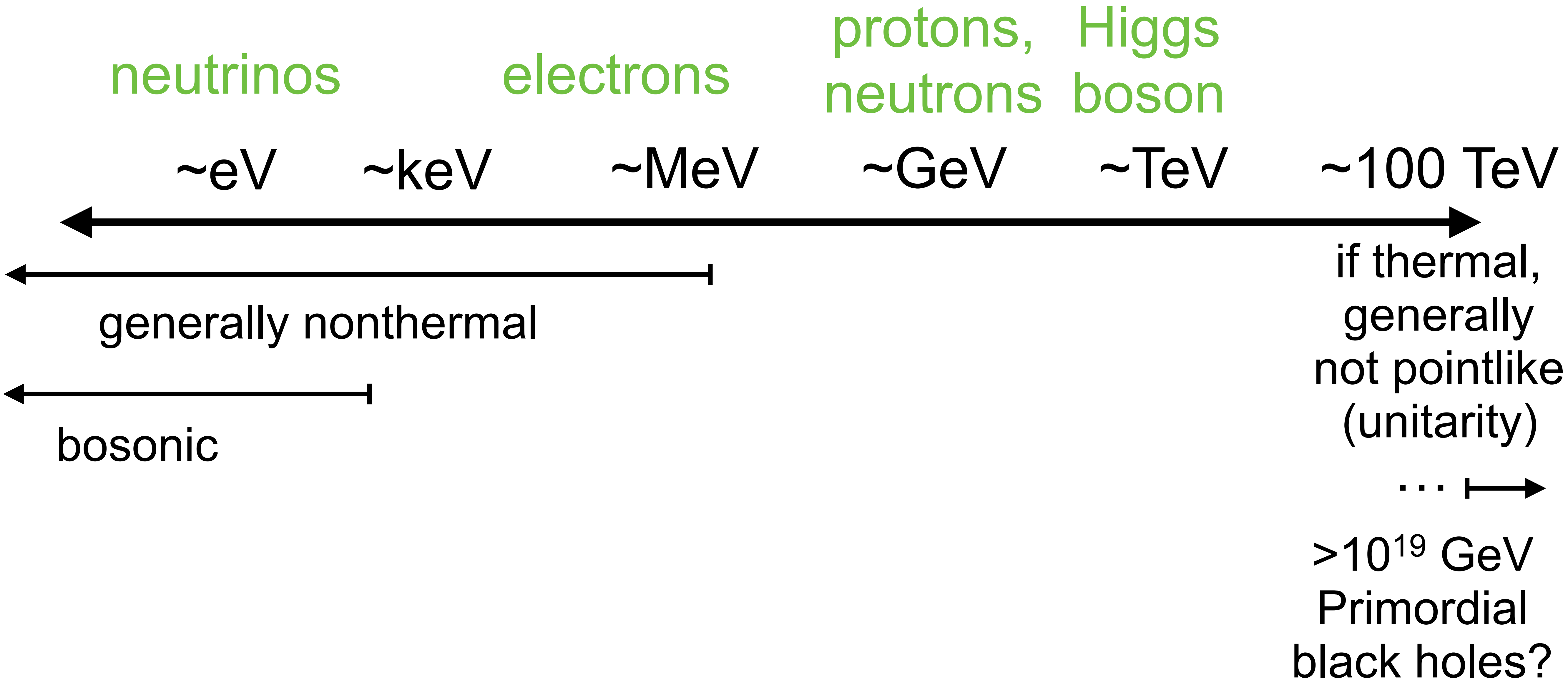

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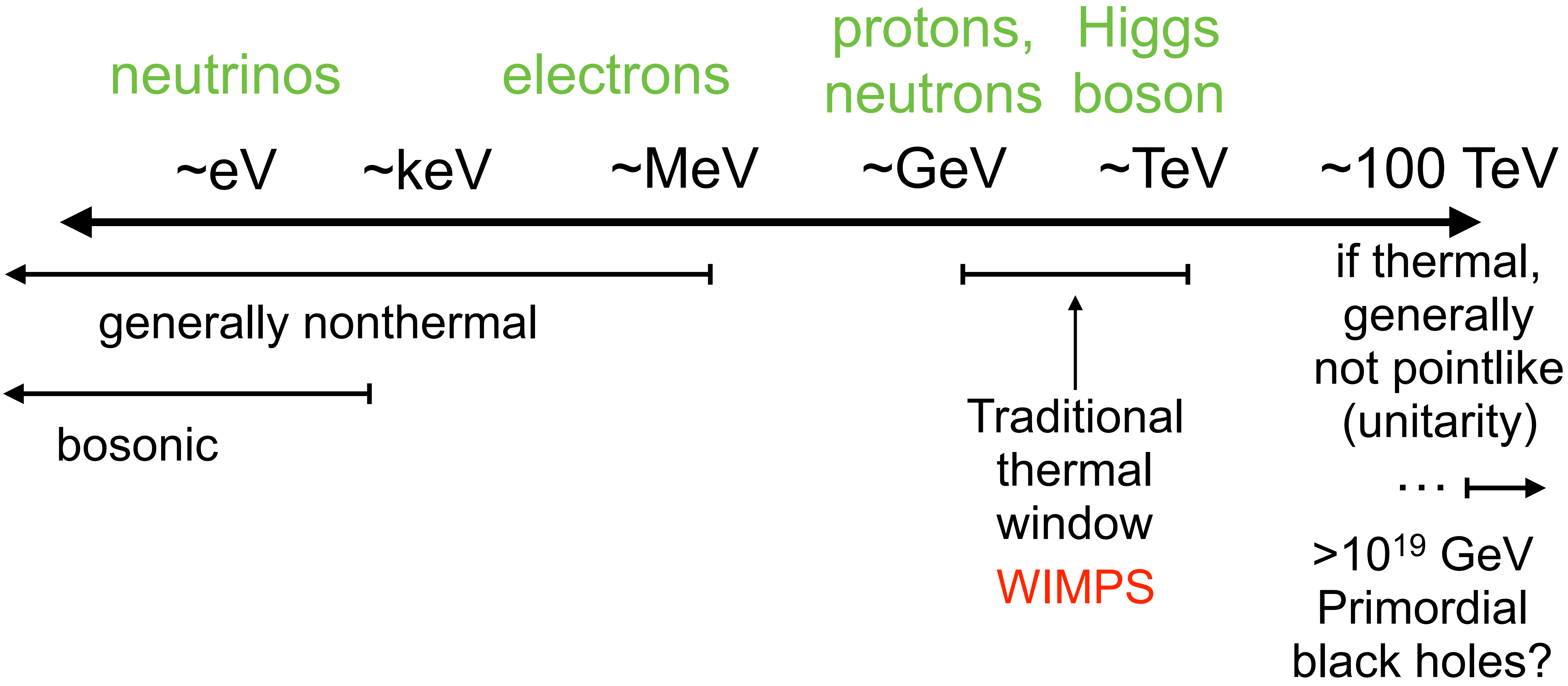

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Traditional thermal window

WIMPS

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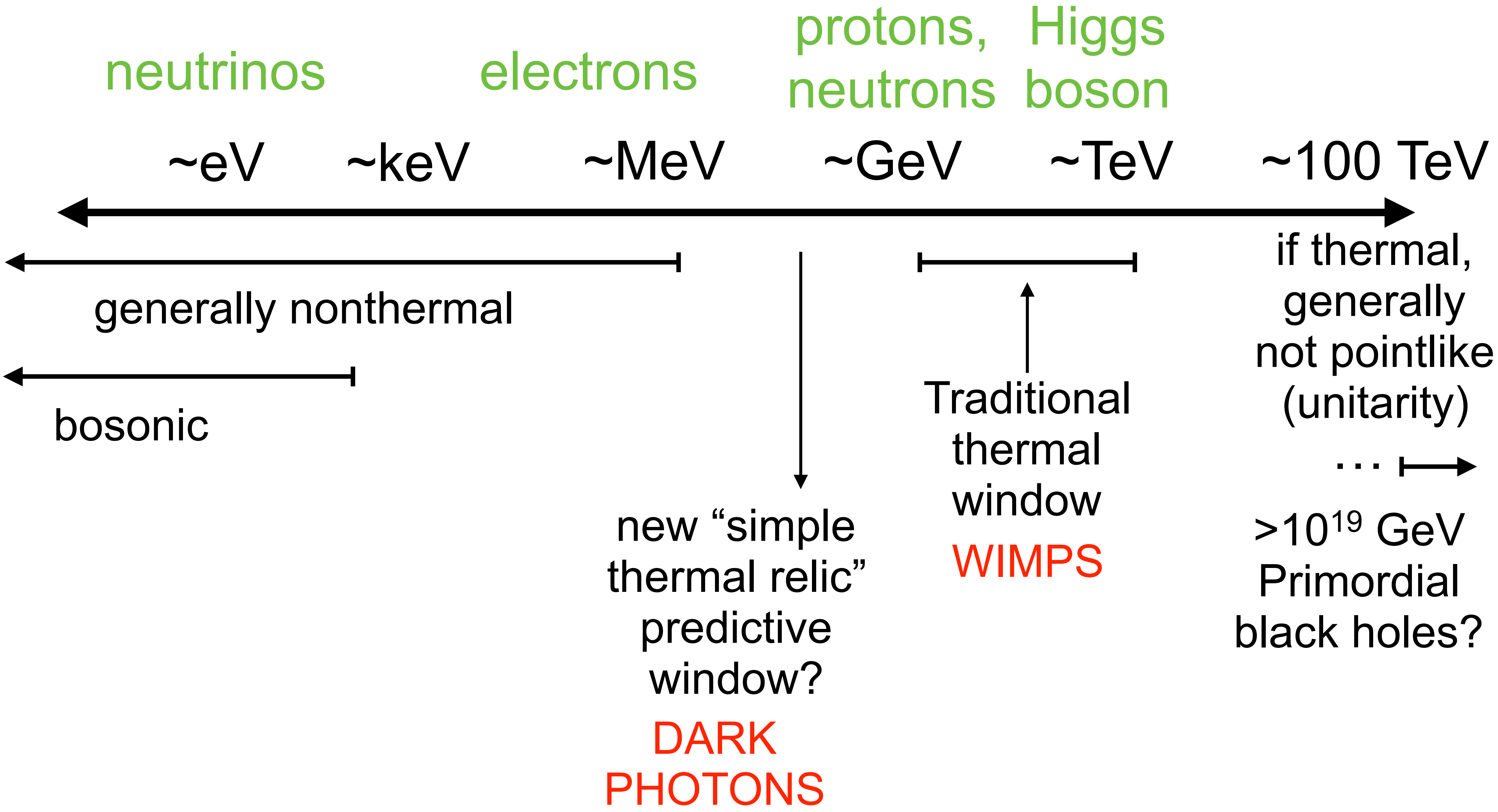

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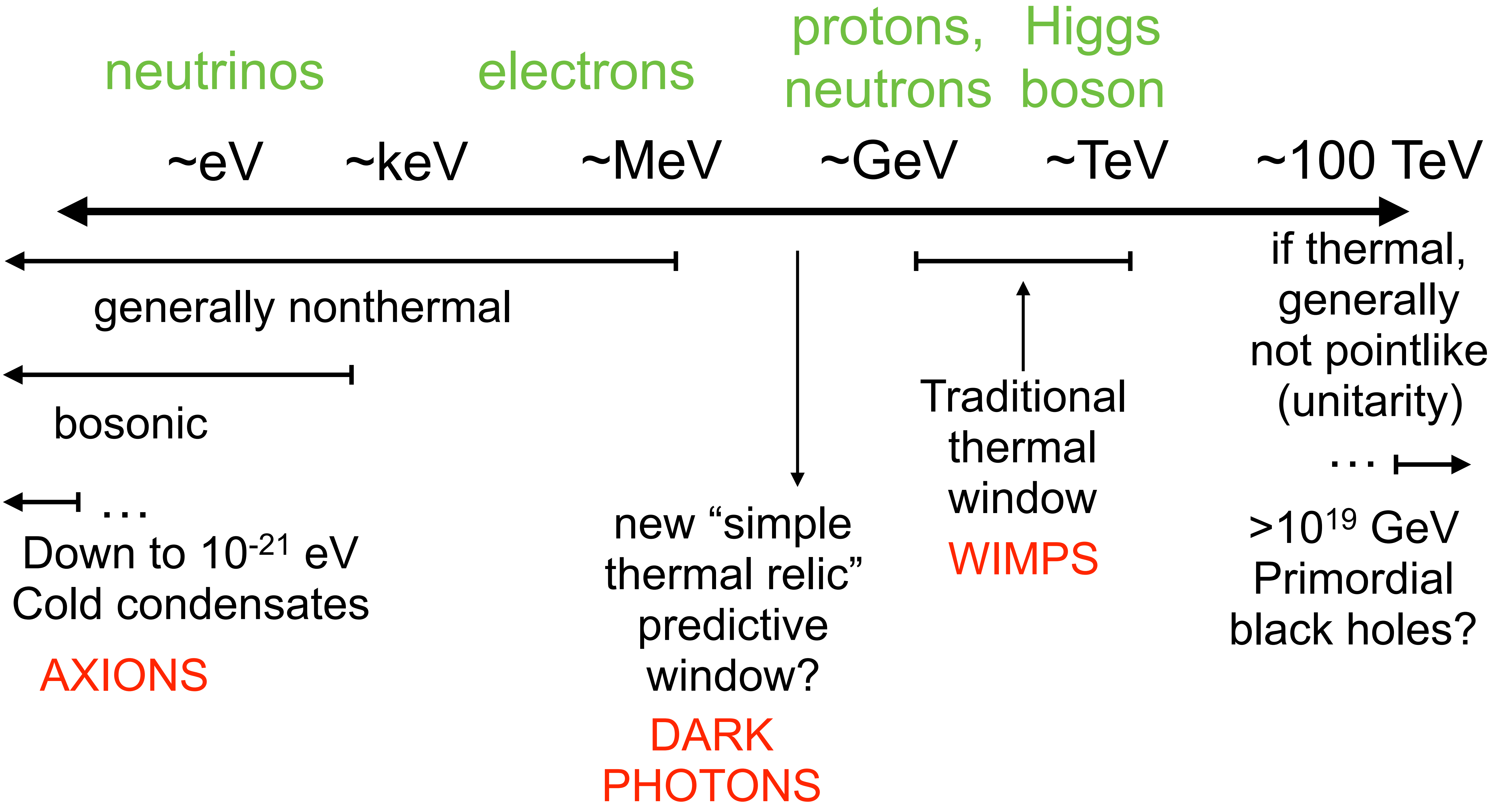

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Down to 10^{-21} eV
Cold condensates

AXIONS

new “simple thermal relic” predictive window?

DARK PHOTONS

Traditional thermal window

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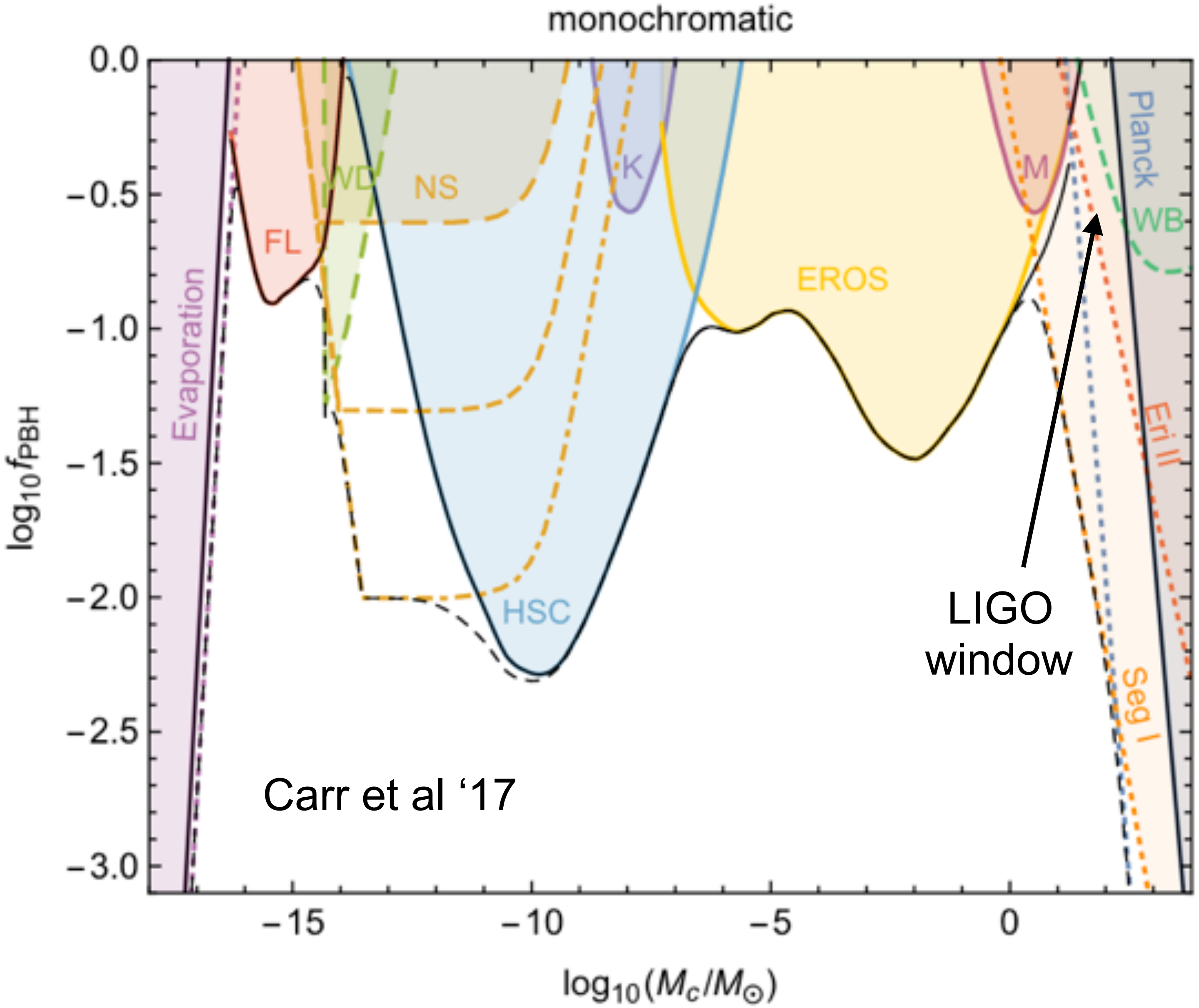
$>10^{19}$ GeV
Primordial black holes?

MACHOs

(MAssive Compact Halo Objects)

- Dark matter could be composed of <u>compact</u> objects, like stars or black holes.
- These objects are heavy but rare, so they don't collide often - "collisionless".
- Need to form very early in the universe, before stars/ galaxies, to explain observations.
- Primordial black holes could be left over from the Big Bang.

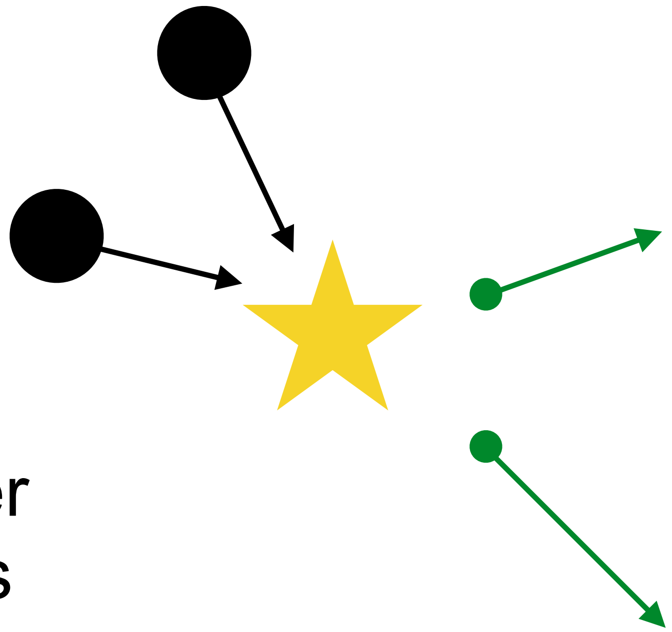


LIGO window

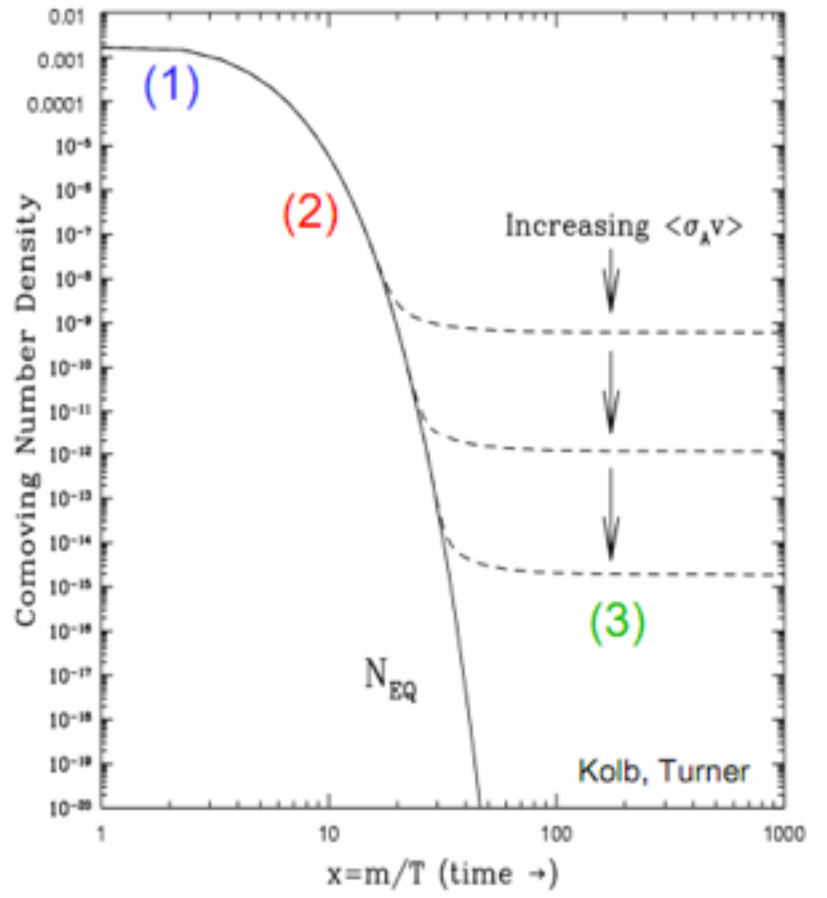
Carr et al '17

- Challenging to explain 100% of the dark matter this way.

Thermal dark matter



- Posits rapid interconversion between dark matter and ordinary matter in the early universe - keeps abundances similar.
- Dark matter abundance is depleted rapidly once temperature reaches a certain point (not enough energy to make more DM).
- Degree of depletion set by speed of dark-matter-destroying reaction - “dark matter annihilation”.
- There are variations on this scenario, but still true that interactions between DM and visible particles set eventual DM abundance.
- Thus can infer strength of dark matter interactions from measurements of abundance - predict present-day signals.



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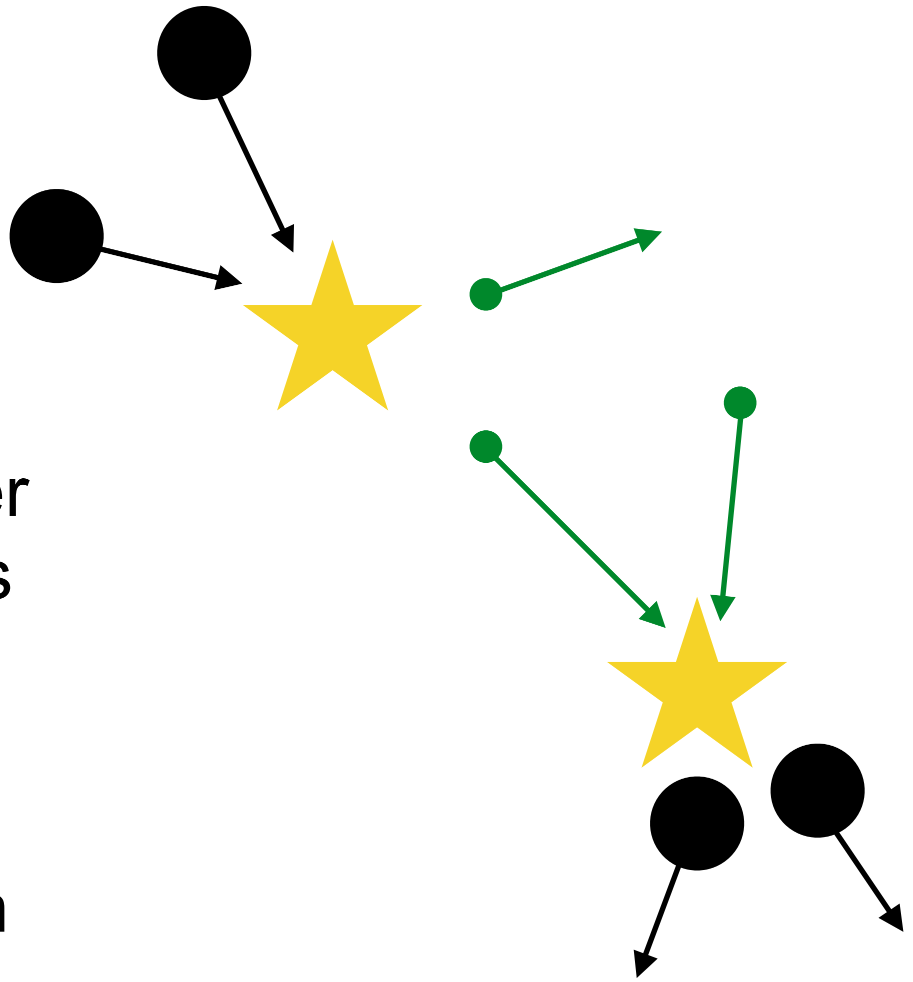

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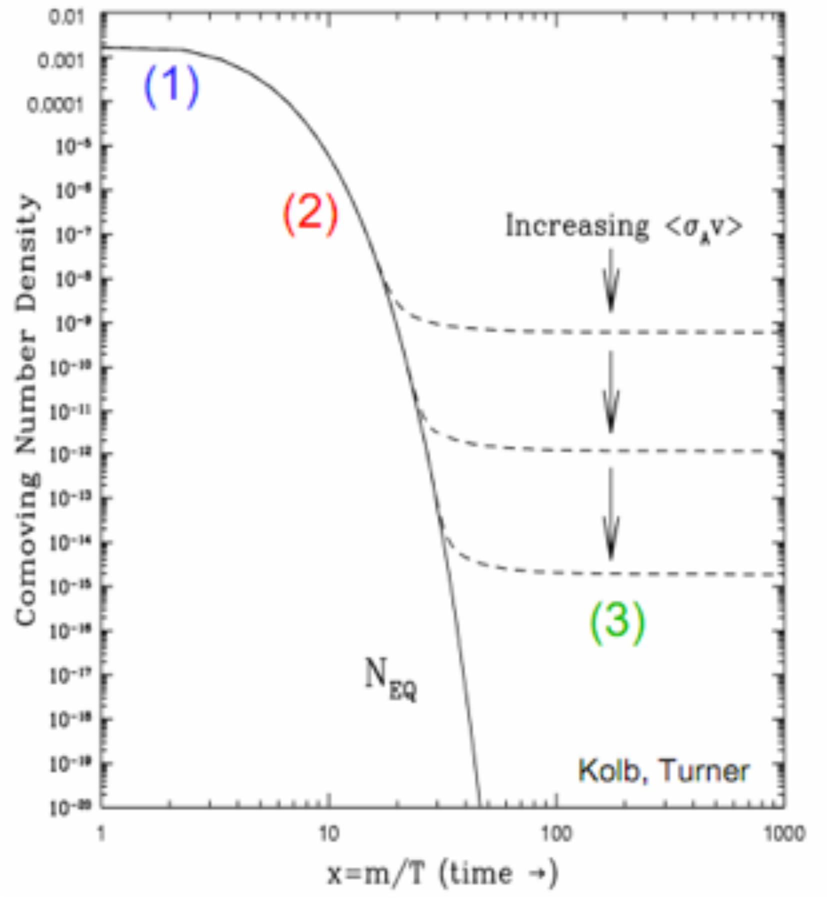
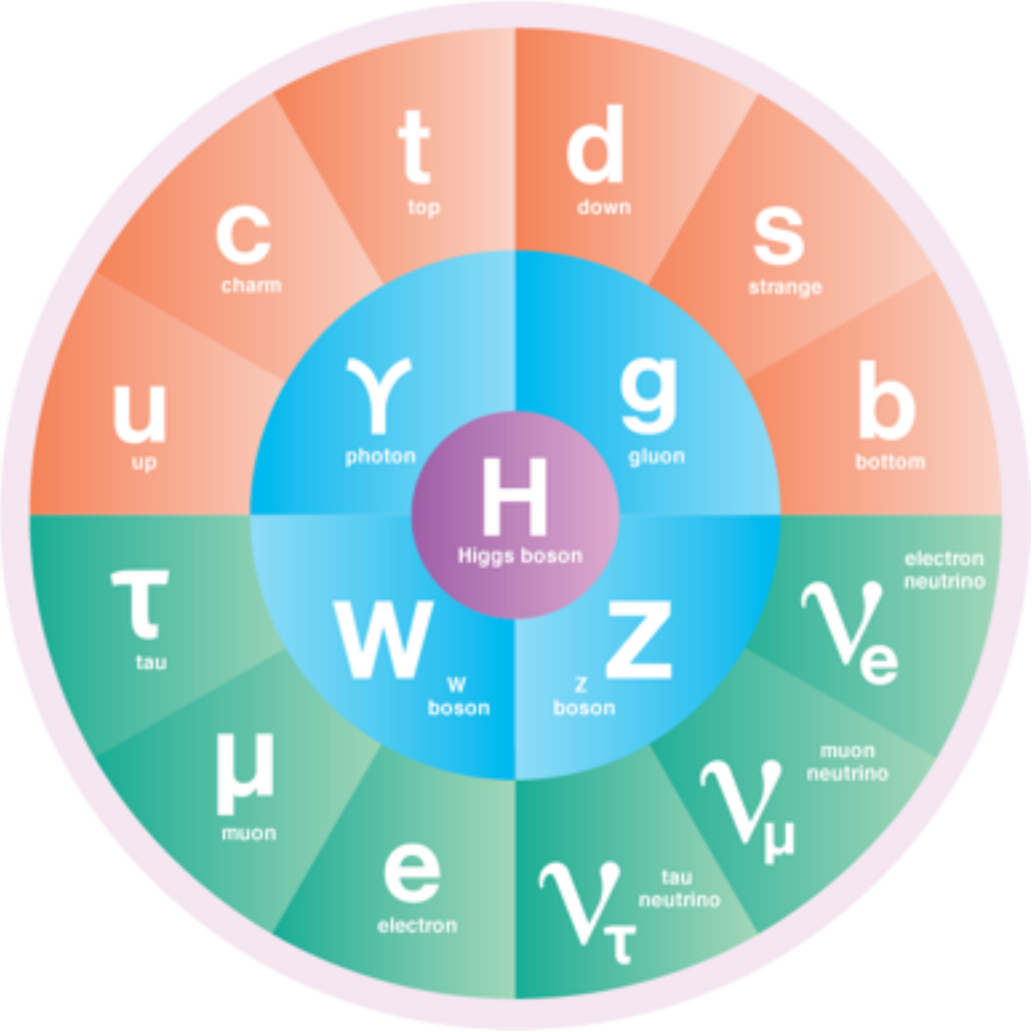


The WIMP window

(see talk by Jodi Cooley)

- Lighter particles generally expected to annihilate faster.
- Thermal scenario generally requires dark matter below ~100 TeV mass (~1000x mass of the Higgs boson).
- “Weak scale” - mass of W, Z, Higgs bosons of Standard Model.
- “Weak coupling” - similar interaction strength to these particles.
- Thermal scenario works well with weak-scale masses and weak couplings - WIMPs, Weakly Interacting Massive Particles.



WIMP scenarios can give rise to observable signals at colliders, underground experiments, telescopes

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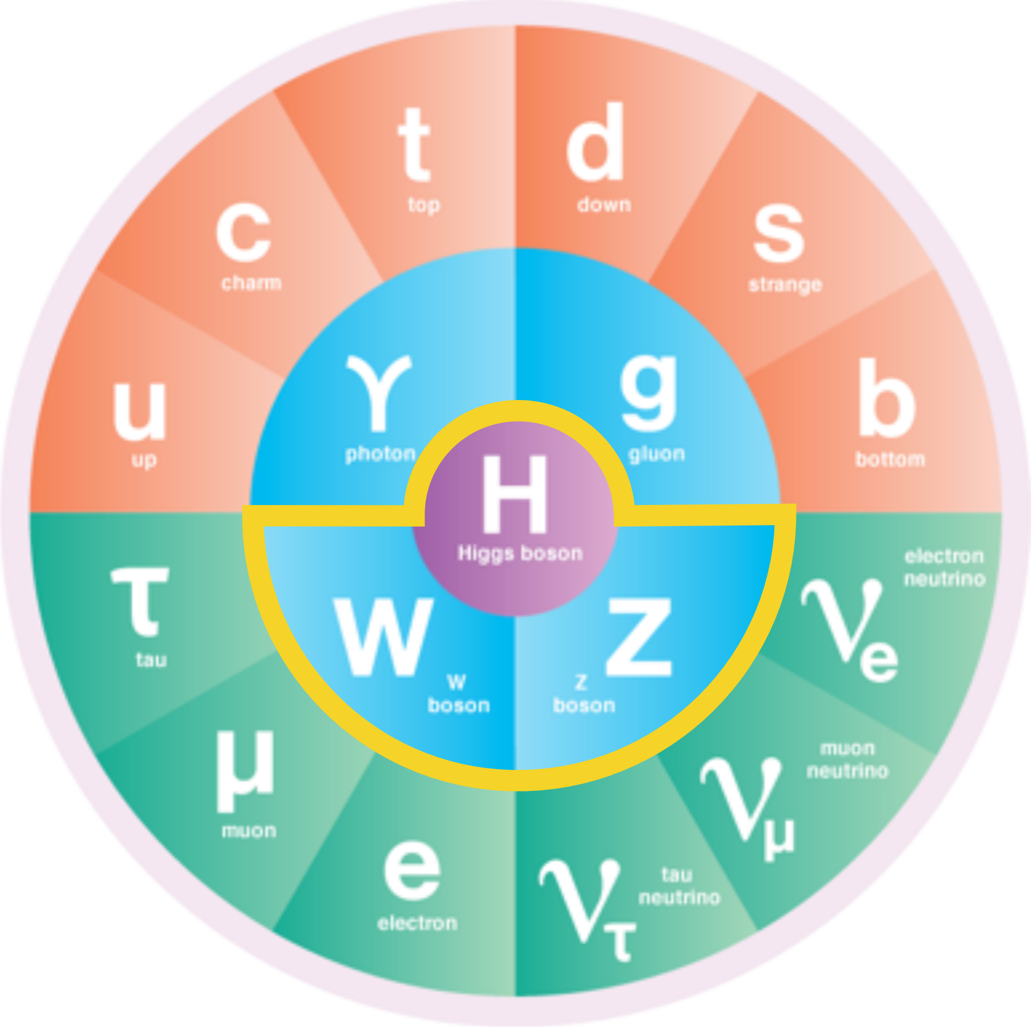

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The hierarchy problem

- Why is the Higgs boson so light?

- From theoretical perspective, expect large corrections to Higgs mass from interactions with “virtual” heavy particles - push its mass toward high-mass scale (like a cold object heating up in a warm room)

- How high? Planck mass, scale of gravity, is ~10^{19} GeV - 17 orders of magnitude above Higgs mass!

- Do all such corrections somehow cancel out?

- Or does our current picture of physics have to change not far above the measured Higgs mass scale?

- WIMP dark matter could be part of the same puzzle.

sketch taken from Quantum Diaries blogpost by Flip Tanedo; analogy due to Gian Giudice ‘08

How low can (thermal) DM go?

(see talk by Natalia Toro)

- Thermal scenario (+ variations) naturally works well with WIMPs, but doesn’t require them.
- Has the advantage of predicting DM interaction rates with visible particles.
- Works fairly straightforwardly down to MeV mass scales (~mass of electron) - new general thermal mass window, at lower masses than classic WIMPs. Many new ideas to probe this regime!

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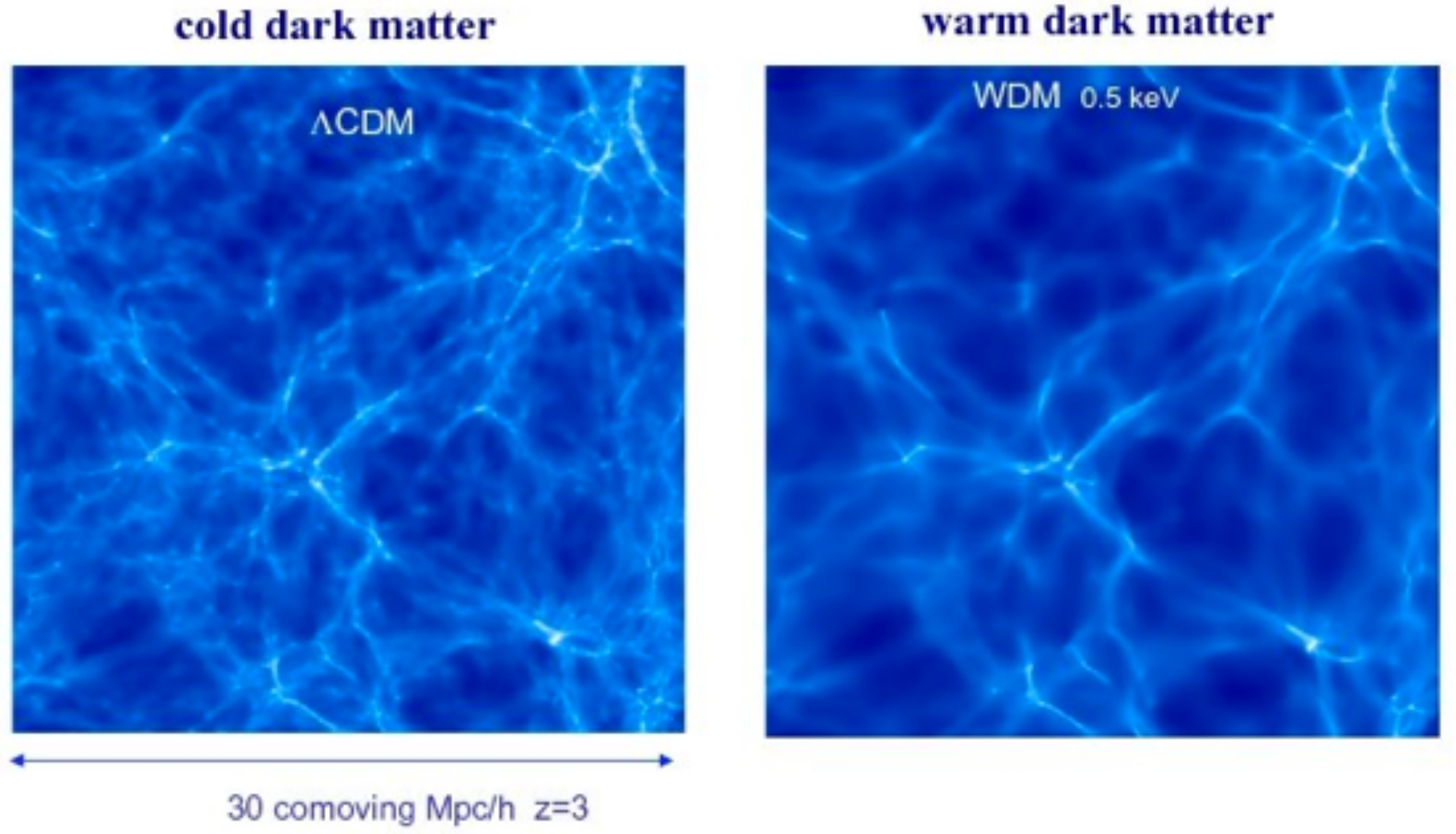
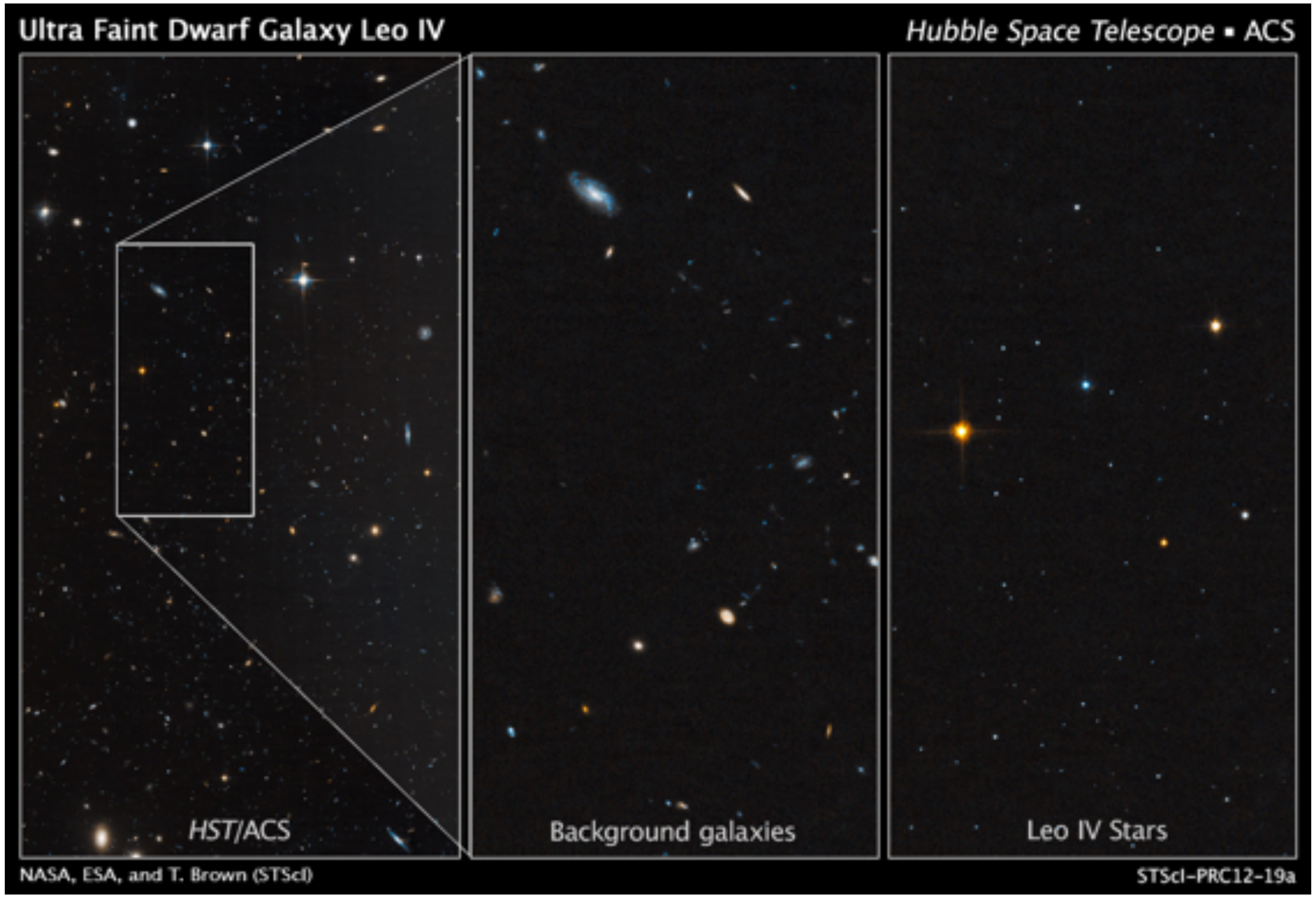
so what goes wrong for lighter DM?

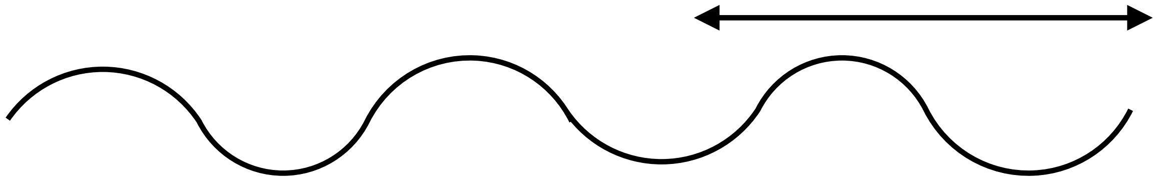
- When the temperature of the universe is ~1 MeV, atomic nuclei start to form.
- Abundance of different elements today probes dark matter interactions with visible particles at sub-MeV temperatures.
- If thermal dark matter is lighter than 2-5 keV, it moves too fast during structure formation - it would prevent formation of the smallest galaxies [e.g. Garzilli et al '15, Irsic et al '17].



How low can DM (ultimately) go?

- Light enough particles behave more like waves than particles - wavelength (proportional to 1/ mass) can be very large.
- Wavelength of dark matter must be smaller than the smallest observed DM structures.
- This requires the DM mass to be greater than 2-3 $\times 10^{-21}$ eV [e.g. Irsic et al ’17, Armengaud et al ’17] - this is 20 orders of magnitude lighter than even neutrinos!
- Such DM cannot be thermal - must have been undisturbed by visible matter since very early times.



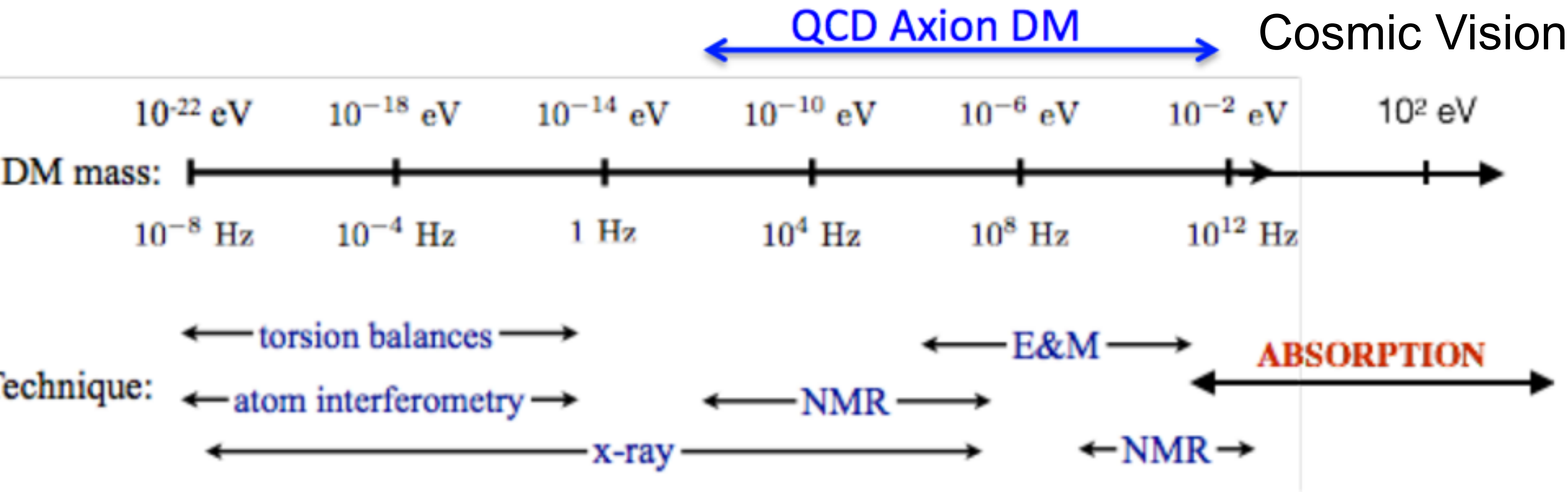


bound stars reveal clump of dark matter

no structures much smaller than the dark matter wavelength can form

Ultralight cold dark matter

(see talk by SungWoo Youn)



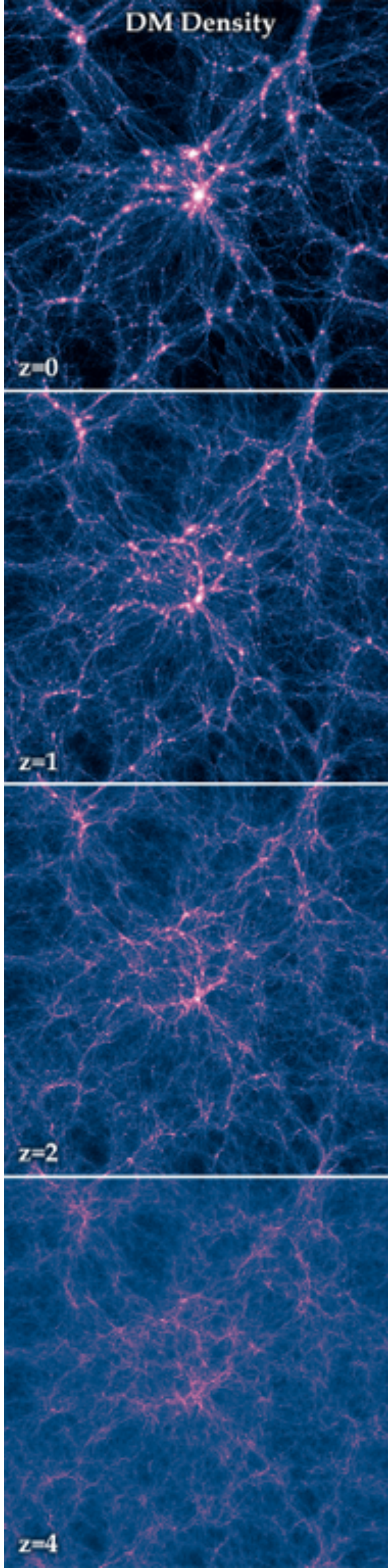
Cosmic Visions ‘17

- Two main parameter regions for sub-keV dark matter:
  - meV-keV: think of DM as a particle, can be absorbed onto target electrons in semiconductors or superconductors [e.g. Hochberg, Lin & Zurek ’16-’17, Bloch et al ’16]
  - 10^{-21} eV - meV: DM can be regarded as oscillating field, opens up a range of new detection methods targeting continuous wave signals (rather than individual particles). Axions - which could solve the strong CP puzzle of nuclear physics - lie in this range.

Taking stock

- Huge diversity of reasonable models for dark matter - crucial to have a broad search strategy that probes many possibilities.
- Lightest massive particle we know: neutrino - DM could be 21 orders of magnitude lighter.
- Heaviest fundamental particle we know: top quark - DM could be 17 orders of magnitude heavier.
- Next three talks: theoretical frameworks + creative experimental searches for interactions between dark matter and ordinary matter, for scenarios mapping out large parts of this range.
- What if DM doesn’t interact with ordinary matter?

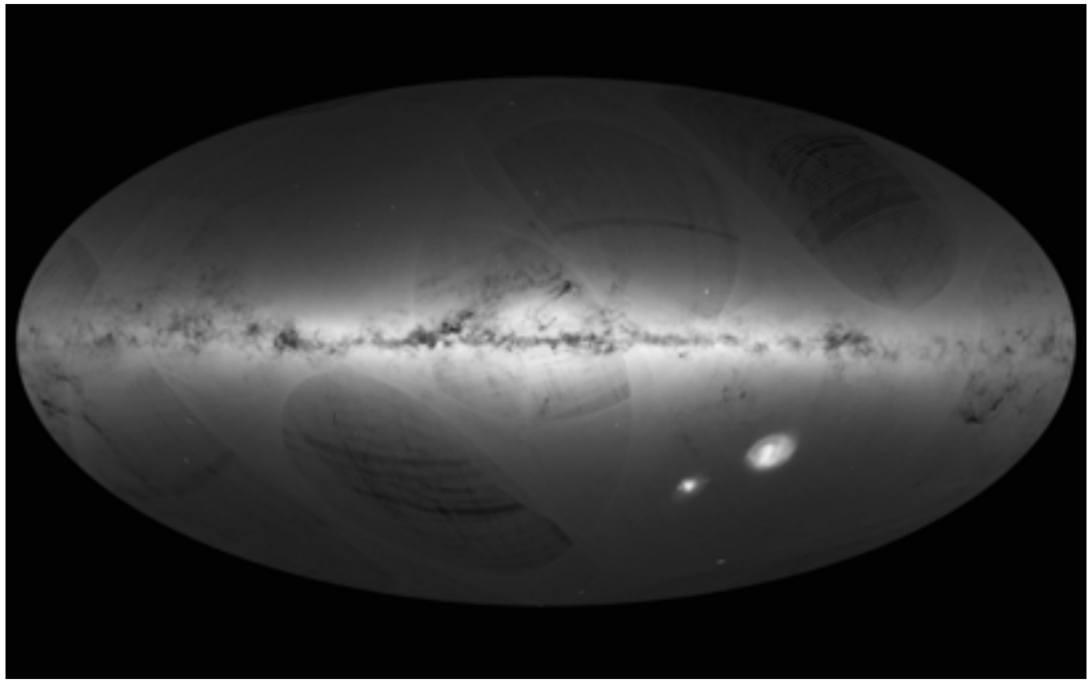
Learning from the dark matter distribution



- We know that DM interacts gravitationally - all we have learned about DM is from its gravitational effects.
- In principle, could be lots of information in the distribution of dark matter through the Galaxy and beyond - how much more can we learn?
- Note: even if DM does interact non-gravitationally, still <u>critical</u> to understand its distribution in the cosmos - matters for DM flux through experiments, annihilation signals from DM-rich regions, etc.
- We currently have theoretical estimates of DM distribution, but need to better understand full uncertainties, informed by data.

Opportunities and challenges

- New and upcoming stellar surveys (DES, Gaia - next data release 2018, LSST - 2022+) can provide detailed tracers of the gravitational potential.



Gaia's first stellar density map
ESA website

- Already being used to find dwarf galaxies, constrain local dark matter density, test for dark matter disks and dark matter clumps, probe the DM velocity distribution, etc.

- WFIRST (scheduled for mid-2020s) will greatly improve gravitational lensing measurements - potential for better probes of DM structure and substructure.

Opportunities and challenges II: theory and simulation

- What changes to the microscopic DM physics lead to changes in its macroscopic distribution and properties?
- Some work already done to codify possibilities - how should we approach this question in general?
- Can we accurately simulate the effects of changes to DM physics?
    - How to incorporate the effects of ordinary matter into DM structure-formation simulations?.
    - How do the effects of DM microphysics change in simulations with ordinary matter?
    - What happens in rare or non-equilibrium systems, e.g. colliding clusters?
- What do we need in the way of data in order to disentangle changes to DM microphysics from the effects of ordinary matter? Is there already solid evidence for DM properties beyond “cold and collisionless”?

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effective theory approach?

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    - What happens in rare or non-equilibrium systems, e.g. colliding clusters?
- What do we need in the way of data in order to disentangle changes to DM microphysics from the effects of ordinary matter? Is there already solid evidence for DM properties beyond “cold and collisionless”?

Opportunities and challenges II: theory and simulation

- What changes to the microscopic DM physics lead to changes in its macroscopic distribution and properties?
- Some work already done to codify possibilities - how should we approach this question in general?
- Can we accurately simulate the effects of changes to DM physics?
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enormous progress made in recent years - still significant uncertainties

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may be powerful probes of DM interactions, but hard to model

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Conclusions

- Dark matter comprises 80% of the matter in our universe, and we don’t know what it is.
- It could inhabit any of an enormous range of mass scales, from ~10^{-21} eV ultralight bosons up to primordial black holes.
- It could be connected to many other puzzles of physics beyond the Standard Model (e.g. hierarchy problem, strong CP problem, neutrino sector) - discovery could be a key to more than “just” the missing 80% of matter.
- Timely to consider theoretical frameworks for broad classes of DM scenarios, and a search strategy that goes <u>broad</u> as well as <u>deep</u> - we do not yet know the answer!
    - In many classes of models, DM-SM couplings are important in setting the relic density of DM - allows predictivity, defines general target regions.
    - To cover cases where DM-SM couplings are <u>not</u> predicted or may even be absent, need to ask what more we can learn from observing the distribution of DM in our cosmos. Theory, simulations, observations must keep pace with each other.
    - Interaction with other fields - atomic physics & astrophysics in particular - critical to understand uncertainties, devise new searches, and pave way for detection.