THE UNIVERSITY OF SYDNEY

Centre for Dark Matter Particle Physics

Dark Matter

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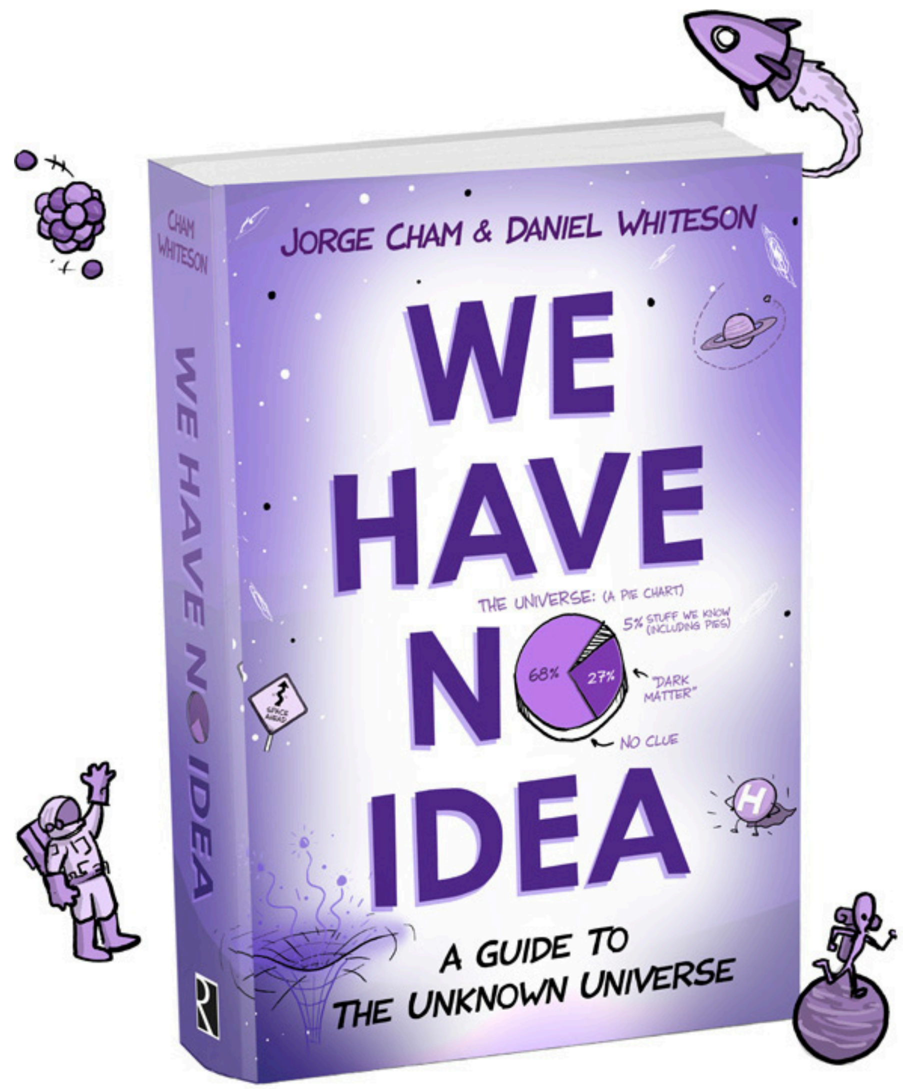
What you often hear: "scientists have no idea what dark matter is"



Take home point of this talk: we don't have "no idea" what dark matter is.

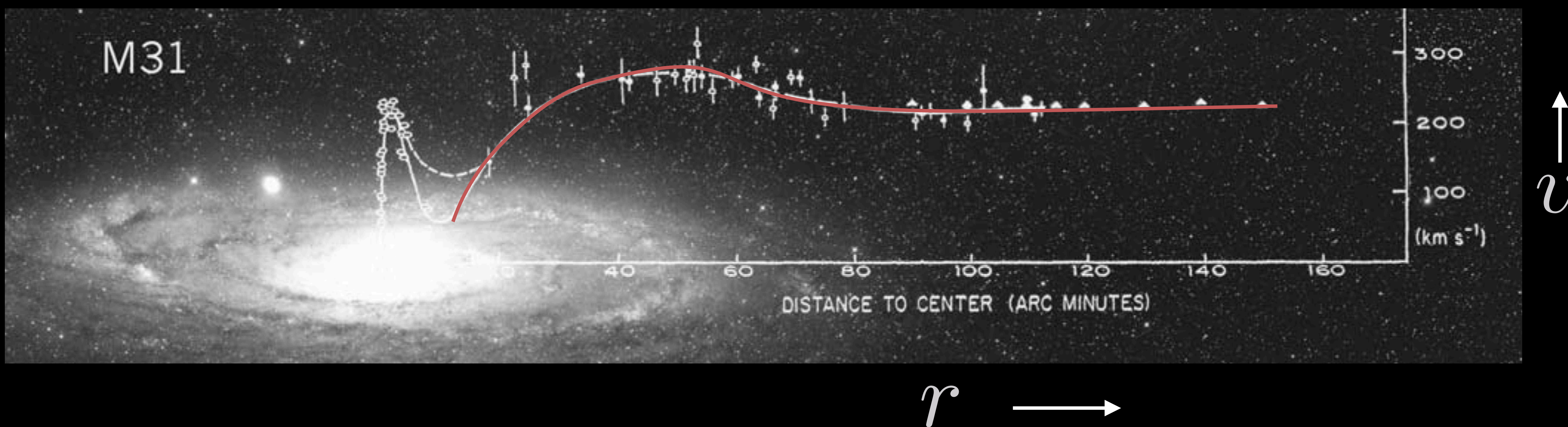
We do, we have lots of ideas…

Evidence for dark matter

Candidates for dark matter

The future

Rotation of stars around a galaxy
e.g. Andromeda (Rubin & Ford 1970s)

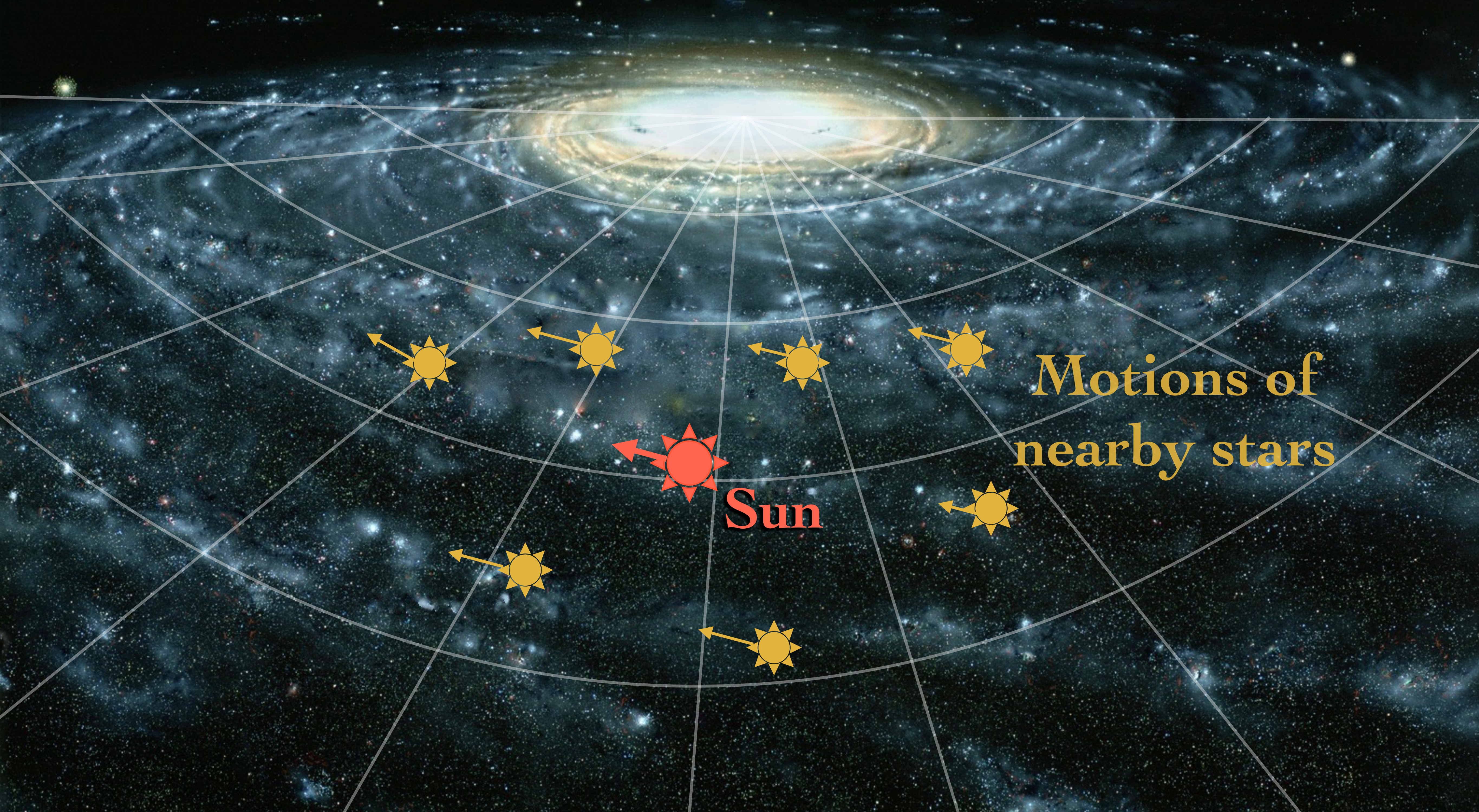


$$\frac{mv^2}{r} = \frac{GM(r)m}{r^2} \longrightarrow v(r) = \sqrt{\frac{GM(r)}{r}}$$

Observation: $v(r)$~const → flattening of rotation curves at large radii

Implication: $M(r)$~increasing → galactic disks embedded in halos of invisible matter.

Dynamics of the Milky Way

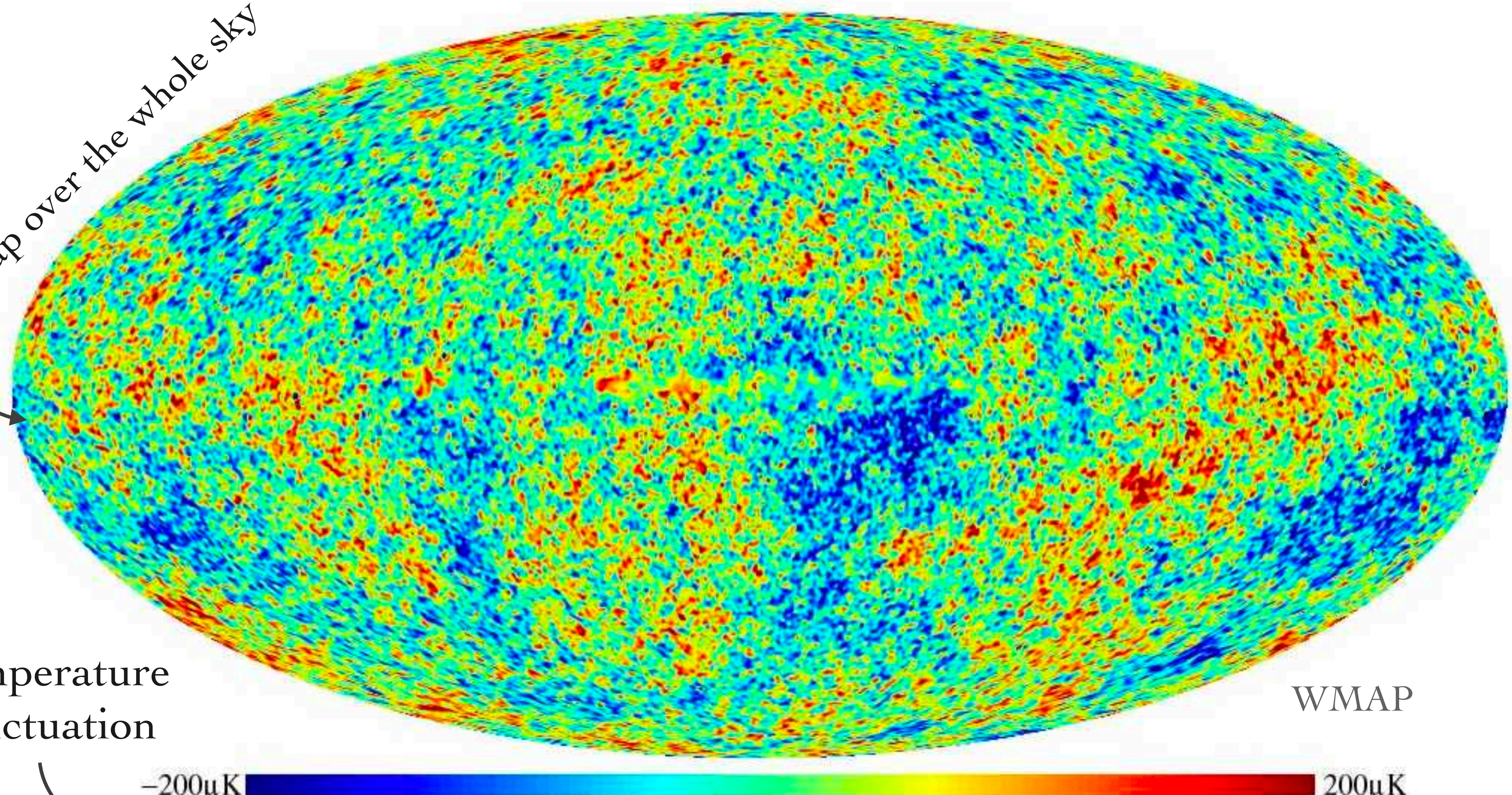


Kinematics of nearby stars → local gravitational potential → how much dark matter → local dark matter density around ~0.008 M_{sun}/pc^3

The cosmic microwave background (CMB)

The first light we can see after the Big Bang, the Universe is around 380,000 years old

Map over the whole sky

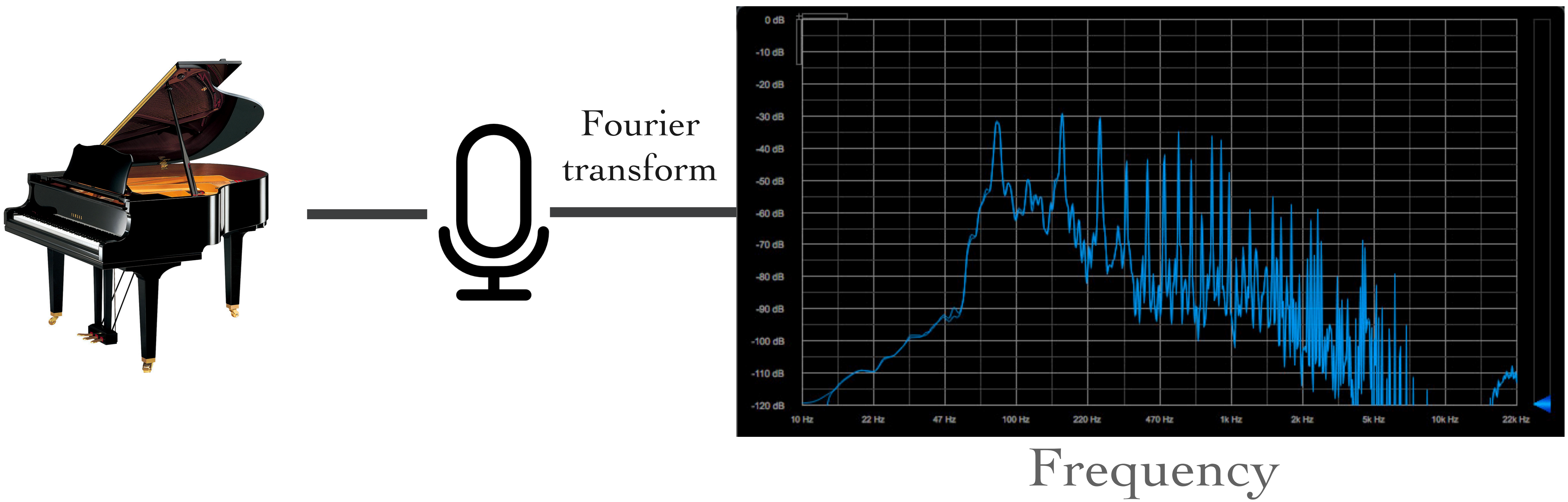


Temperature fluctuation

CMB is a near perfect black body spectrum with a temperature ~ 2.7 K + <u>tiny fluctuations</u> (1 part in 10^5)

Putting an oscillating signal through a frequency analysis… e.g. sound waves

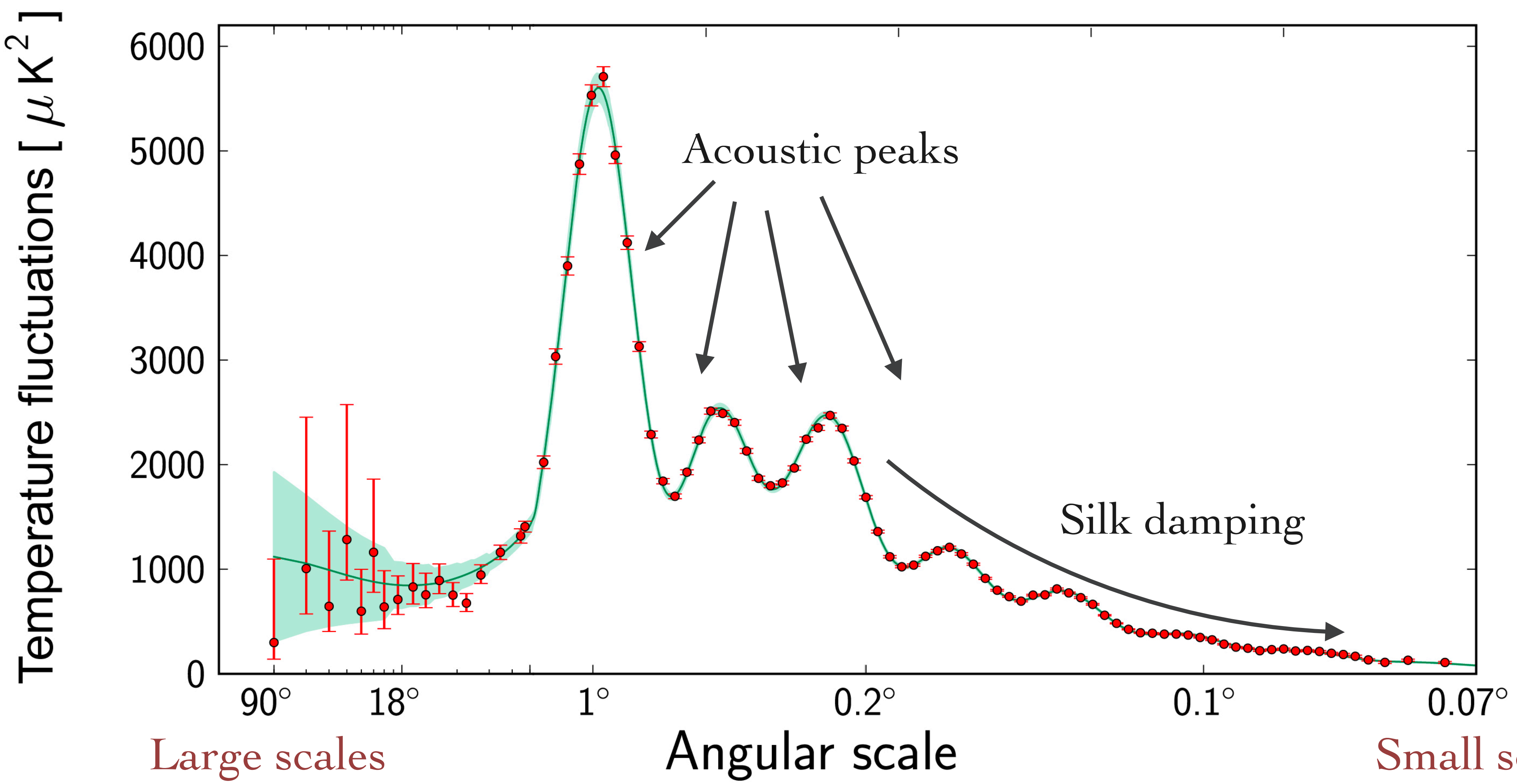
Fourier transform of a musical note gives the distribution of component frequencies



Positions of peaks → gives the pitch, i.e. the harmonic series
Ratios of peaks → tells you what instrument it is, i.e. timbre

The baby universe through a frequency analyser…

Looking at the oscillations in the hot plasma a few hundred-thousand years after the Big Bang → the "CMB power spectrum"

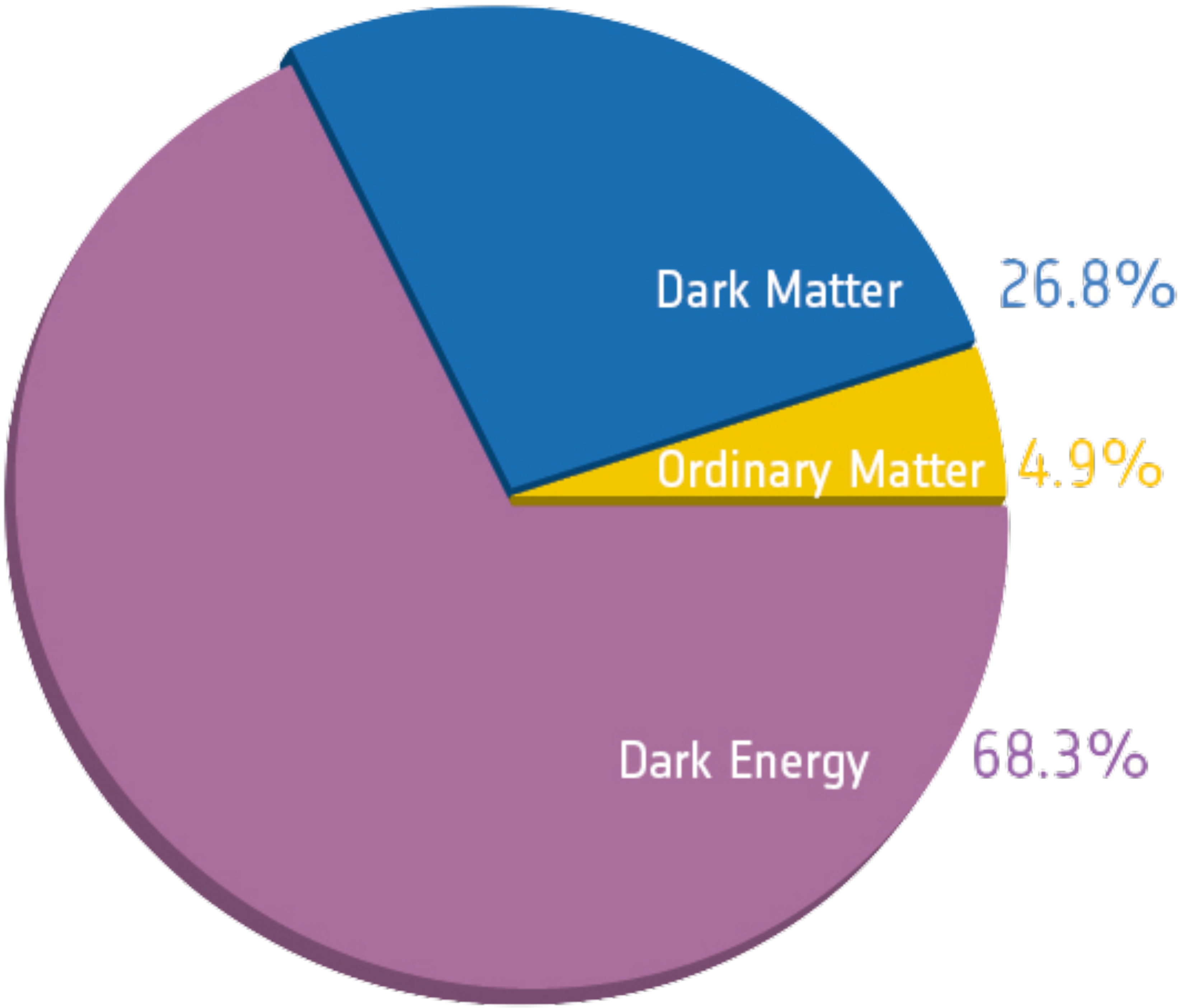


Planck 2013

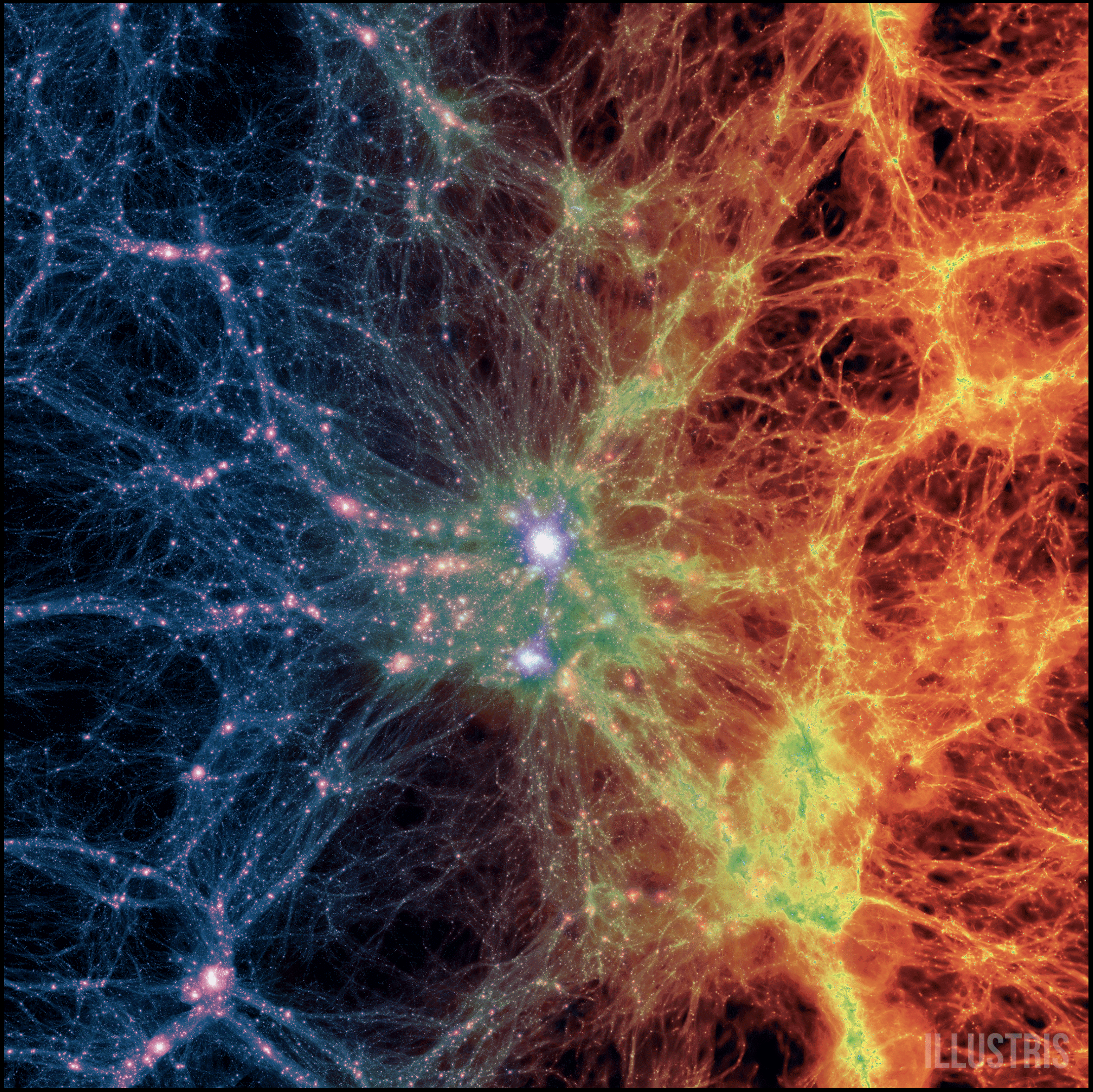
Positions of peaks → Tells us the size, geometry and total energy of the Universe

Ratios of peaks → Tells us what the Universe contains

The CMB tells us (with remarkable precision) that the Universe is made of…



Dark matter



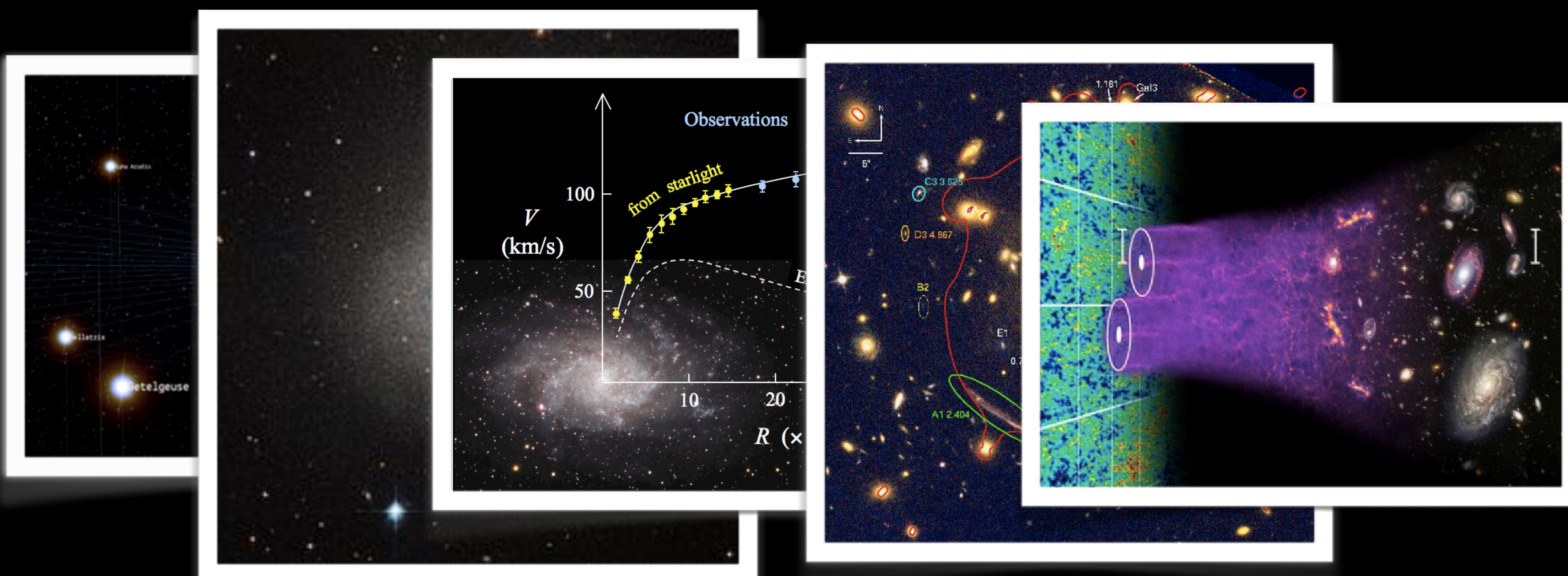
Baryons

Hot gas, dust, stars etc.

Illustris simulation

We have evidence for dark matter's existence on length scales spanning ~10 orders of magnitude, and across cosmic time

~100 pc	~kpc	~100 kpc	~Mpc	>Gpc
Affects nearby stars	Dominates dwarf galaxies	Supports galaxy rotation	Fills galaxy clusters	CMB+ Large scale structure



Requirements for a theory of dark matter

1. It needs to be something **with mass**, produced before the primordial synthesis of nuclei (<10 seconds after Big Bang) with an abundance making up ~1/4 of the Universe's energy budget.

2. Preferably it should **interact with stuff** in some way way (other than gravitationally) but not too strongly, or we would have seen it

3. It needs to behave in a way that reproduces the galaxies we see*

*In the past this meant "cold dark matter" (which means slow-moving, collisionless particles), but this paradigm is being questioned…

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Mass scale of dark matter

Note about units:

Particle physicist's mass: eV

(i.e. the rest mass energy, technically eV/c^2 but we tend to set $c=1$)

e.g. electron = 511 keV, proton = 938 MeV, neutrino < 0.3 eV.

Astronomer's mass: $M_{sun} = 2 \times 10^{30}$ kg

e.g. Sun = 1 M_{sun}, supermassive BH = 10^6

Possible masses of dark matter candidates

Is the range of possible masses bounded?

- **Absolute lightest mass** ~ 10^{-22} eV: at this point the de Broglie wavelength of the DM particles is larger than the smallest dwarf galaxies which we have seen contain dark matter

- **Heaviest mass for an elementary particle** = 10^{19} GeV, above this DM must be a composite object or a black hole

- **Heaviest possible mass:** DM needs to "fit" inside the smallest dwarf galaxies with masses $10^{5\text{-}6}\,M_{sun}$, so it could be made up of objects with masses up to, say, $10^{4\text{-}5}\,M_{sun}$.

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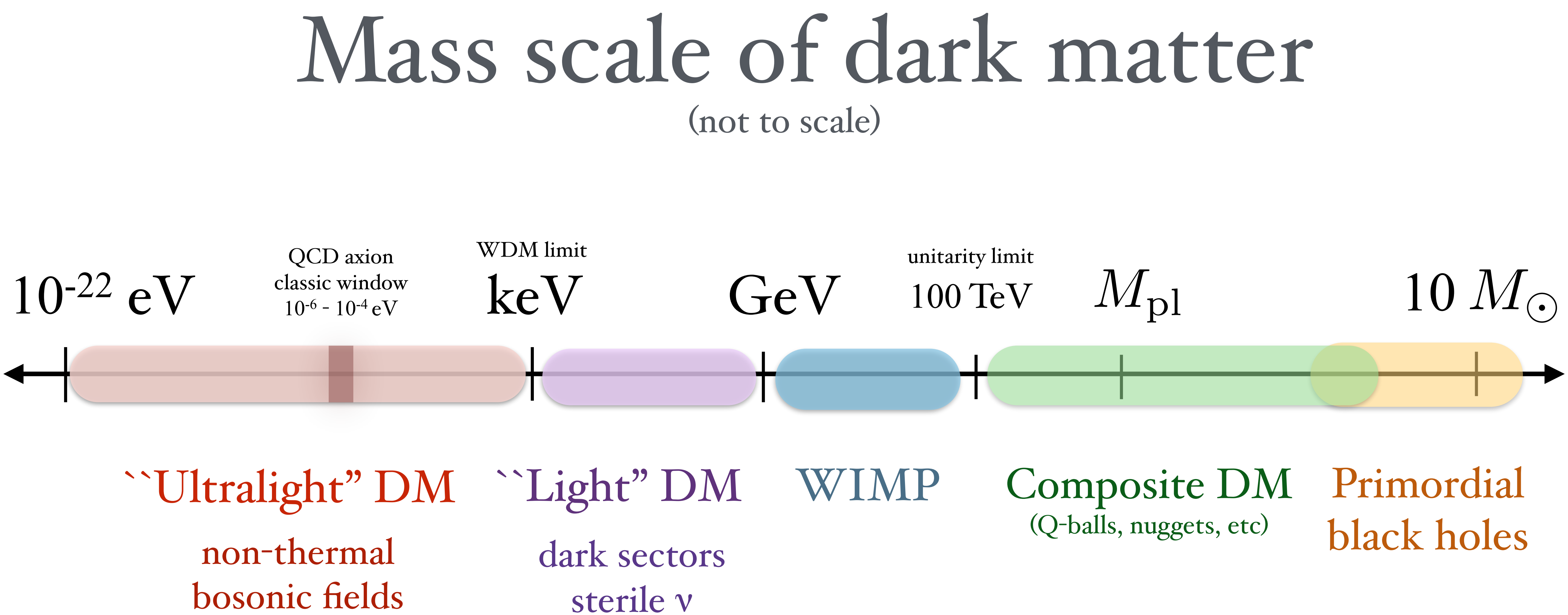
Depending on the mass, the DM must have certain properties to match observations. This gives a way to categorise a range of candidates:



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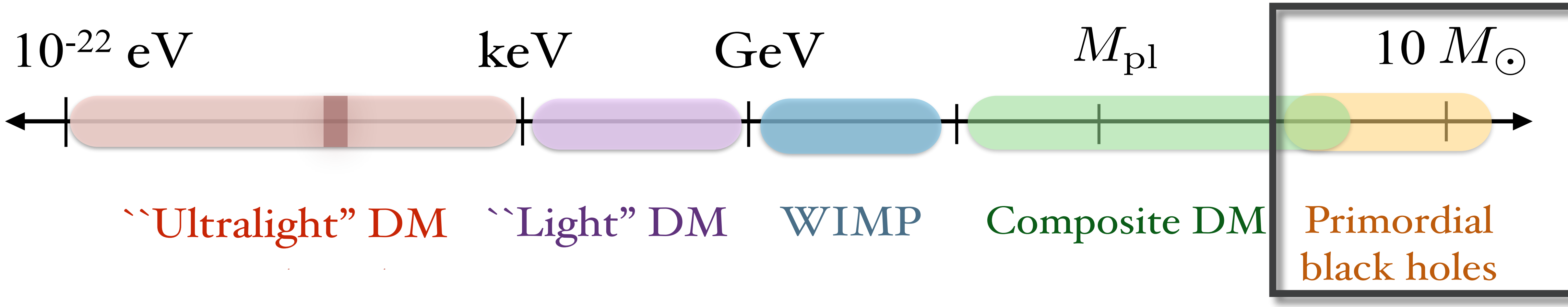
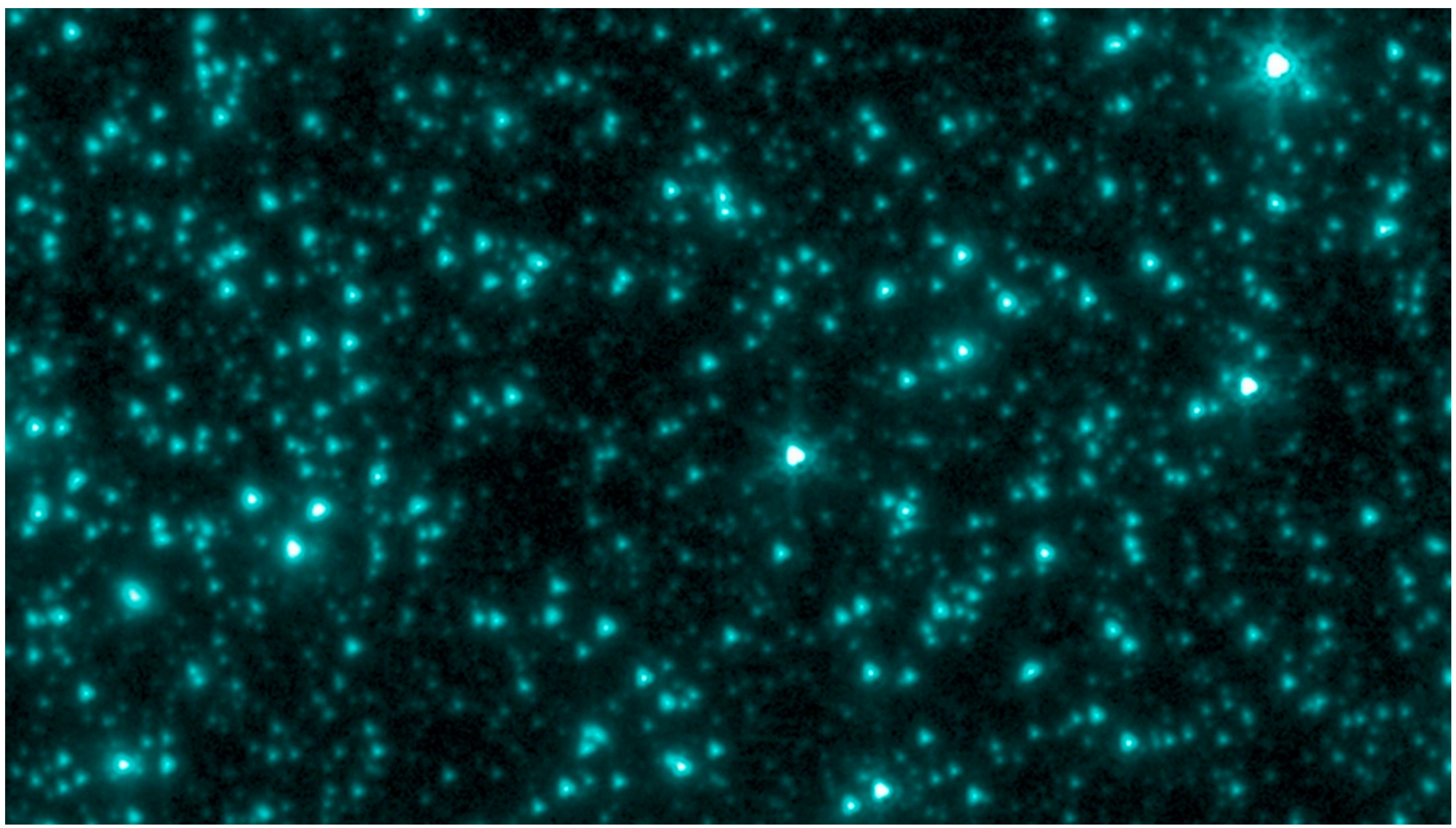
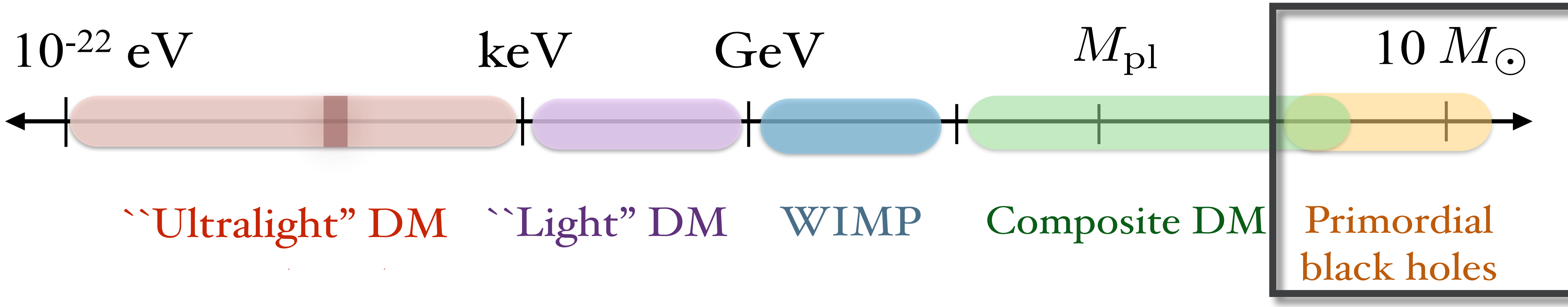
http://arxiv.org/abs/1904.07915



Primordial black holes form in the inhomogeneous conditions of the very early Universe

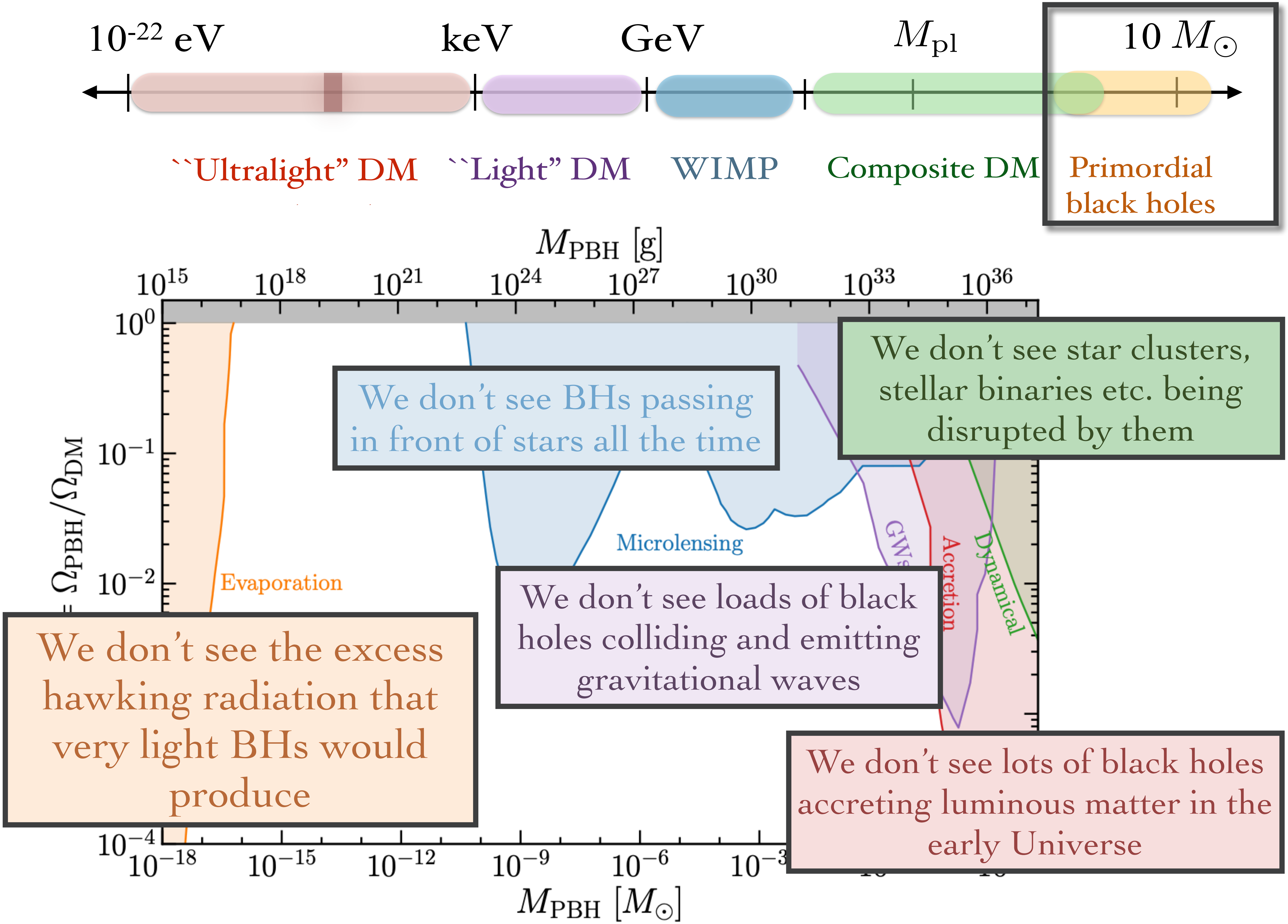


A few random patches of the Universe would have high enough densities to collapse and form black holes



Reasons to like PBH dark matter:

- "In principle" no new physics needed to explain dark matter (though in practice new physics is often needed to explain how the early universe created *so many* of them)
- At the very least they would have similar properties as objects we already know to exist (so we can predict how they should behave)
- Can be tested in with a large number of astrophysical probes



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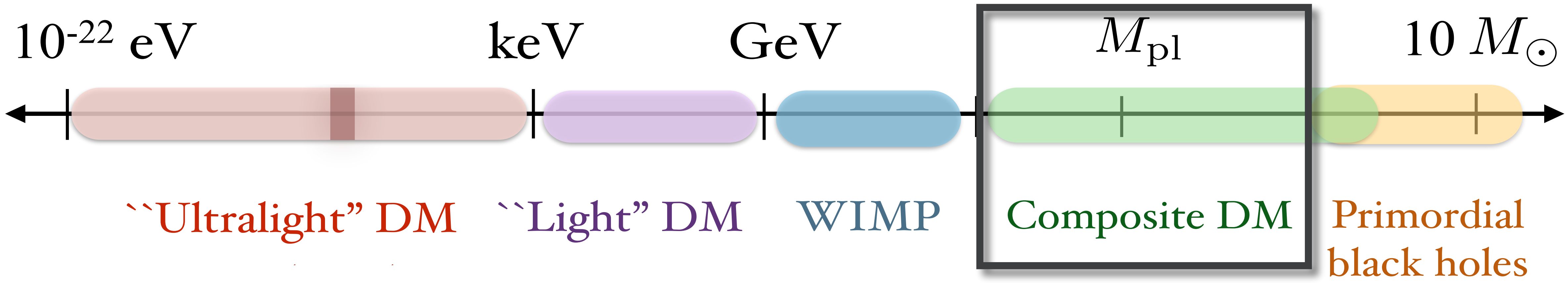
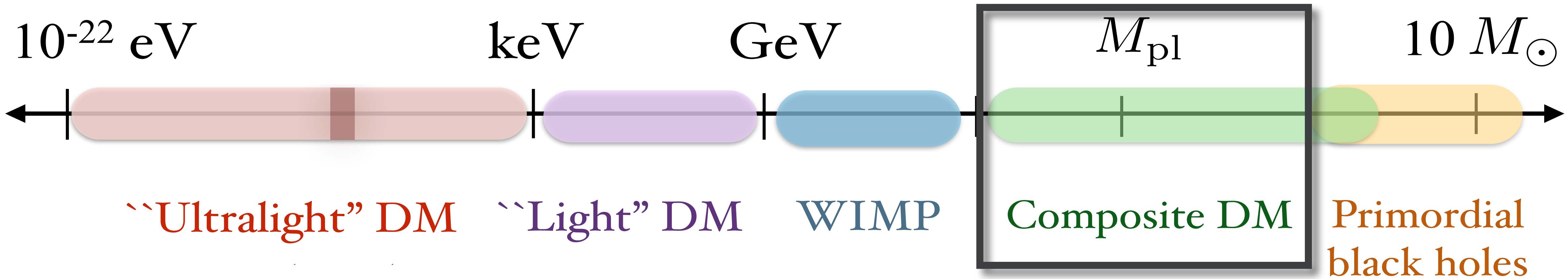
Green & Kavanagh http://arxiv.com/abs/2007.10722



Composite dark matter

Dark matter that is neither a single particle, nor a black hole e.g.

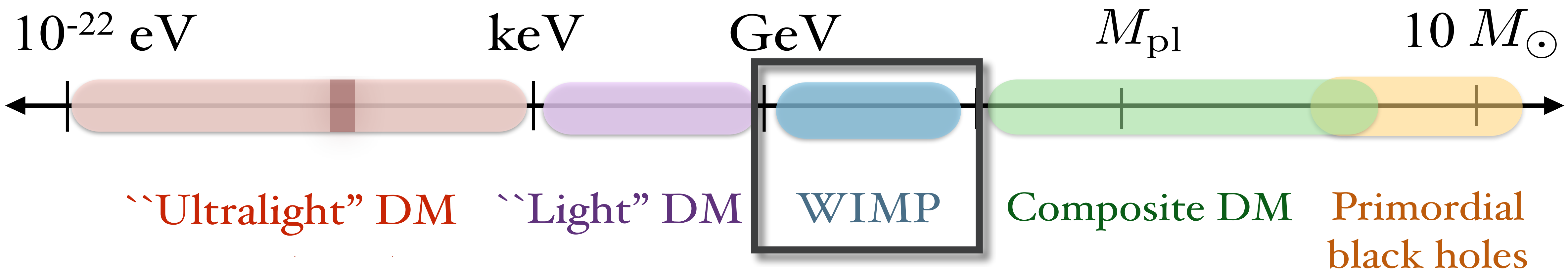
- **MACHOs** - Generic name for massive, dark and compact bodies floating around in space. One of the original dark matter candidates. Are constrained in a similar way to PBHs.
- **Quark nuggets** - large macroscopic clusters of quarks which are bound together in some way. Observations tell us they must be both very massive ***and*** very weakly interacting to be dark matter - hard to figure out how this could work.
- **Dark stars** - the idea that a single species of dark matter particle forms large star-like objects ("star" is a slight misnomer, there is no nuclear fusion or hydrostatic equilibrium going on, just think of big balls of dark matter)



Composite dark matter

Composite dark matter is currently slightly unfashionable. It is easy to come up with a theory for a single particle - much harder to come up with a mechanism to generate large macroscopic objects in the early universe.

However all we need is one good idea, there is **no** reason observationally why dark matter can't be composite and/or macroscopic, you just need to explain **how** it got there



WIMP (Weakly interacting massive particle)

- Exact definition has shifted over the years, but these days it's basically just a massive particle, with very feeble interactions with any standard model particle
- Long considered the "favourite" dark matter candidate
- Their popularity stemmed from the fact that WIMPs appear in a very notable extension of the Standard Model of particle physics called **supersymmetry**

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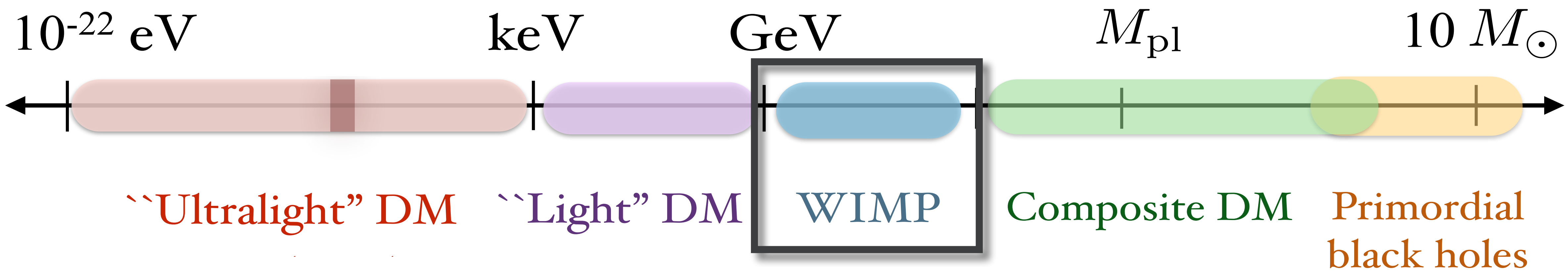
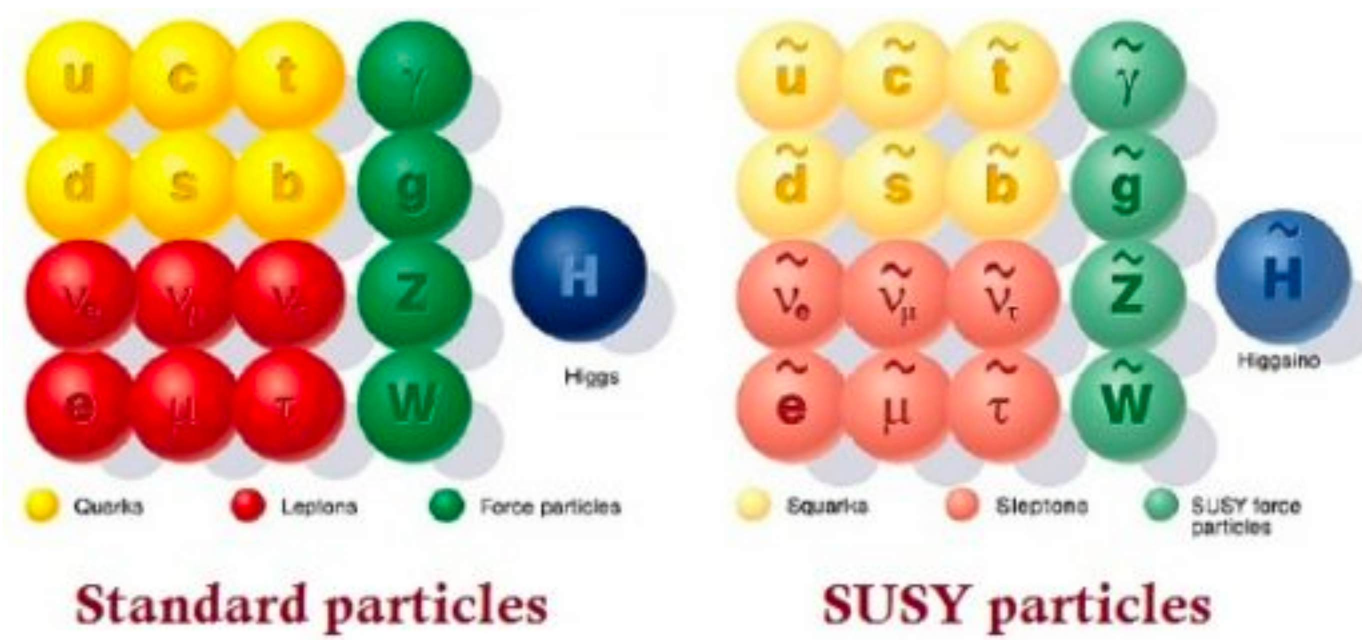
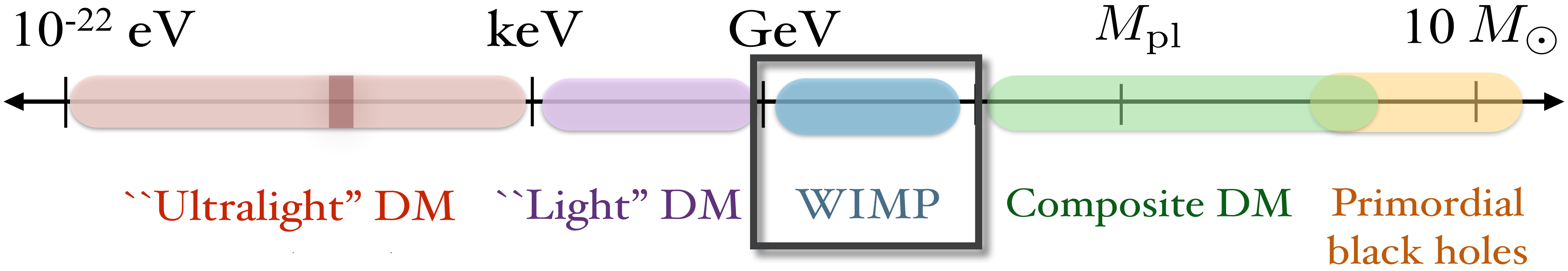


Supersymmetry

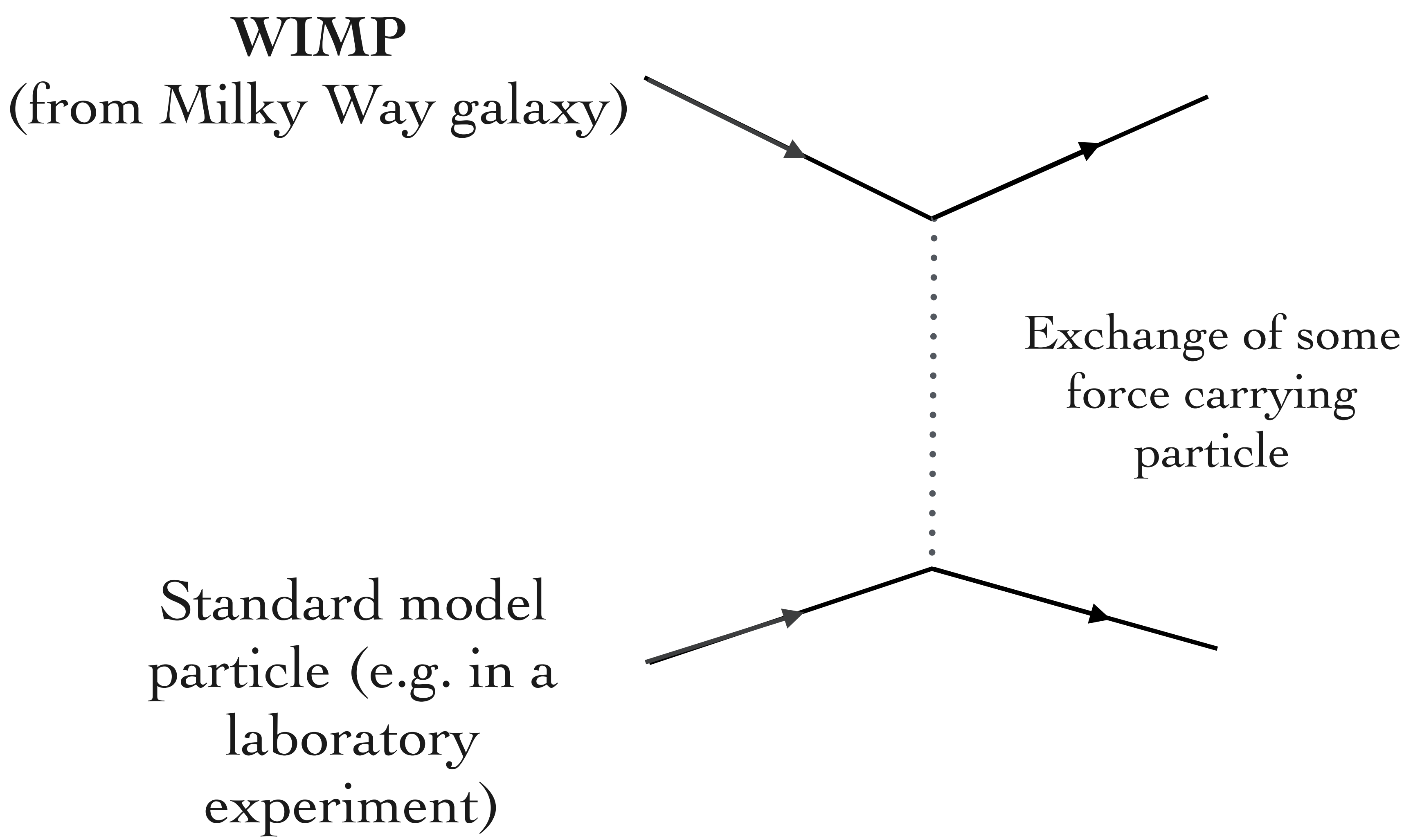
- Posits a fundamental symmetry of nature between bosons and fermions.
- Motivation has nothing to do with dark matter, but instead to solve several problems in particle physics + it is the most "natural" way to expand the symmetries of the Standard Model from a mathematical perspective
- For many people supersymmetry remains very convincing, despite no evidence for any of the new particles in LHC experiments

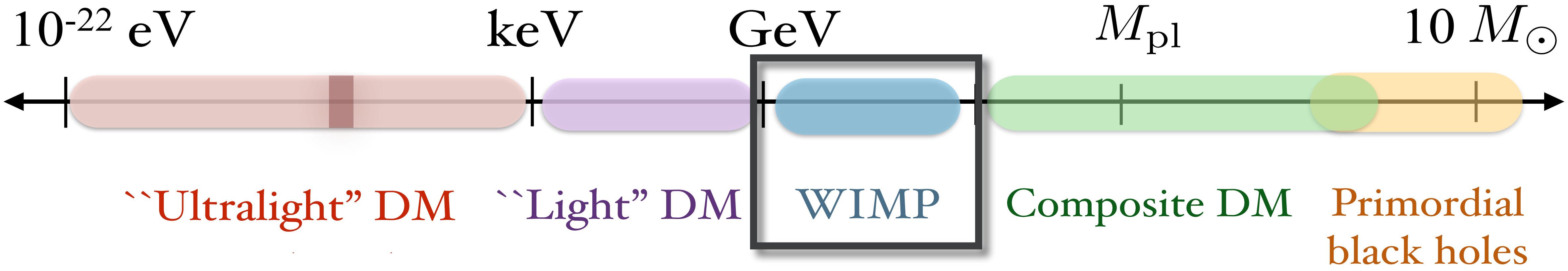


<u>But:</u> The lightest supersymmetric particle is **stable** and therefore an excellent dark matter candidate in the form of a WIMP

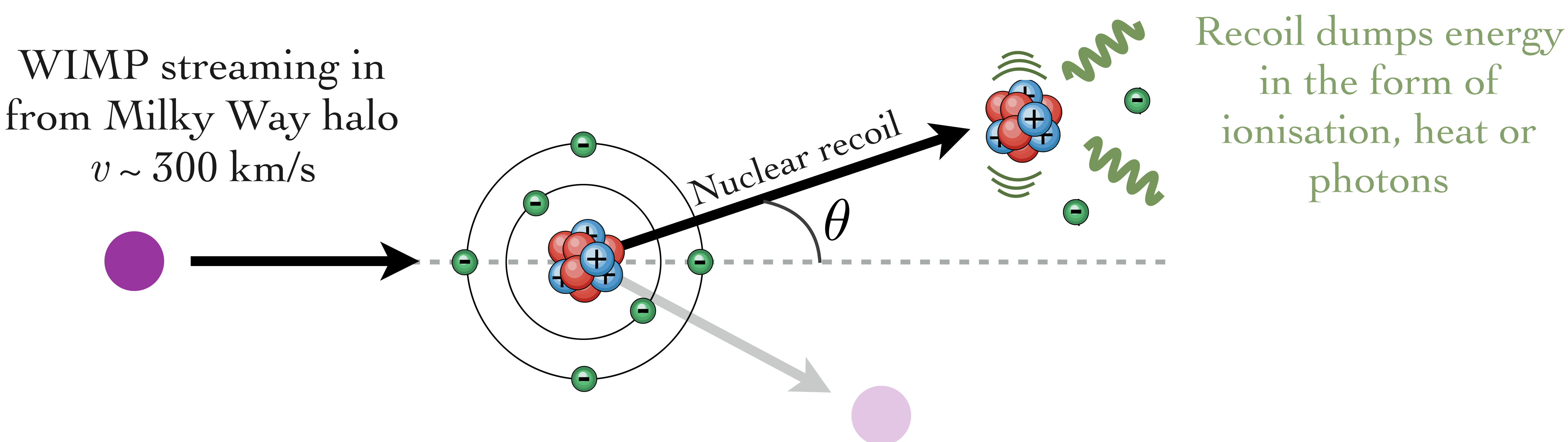


Detecting WIMPs





Typical WIMP interaction: nuclear scattering



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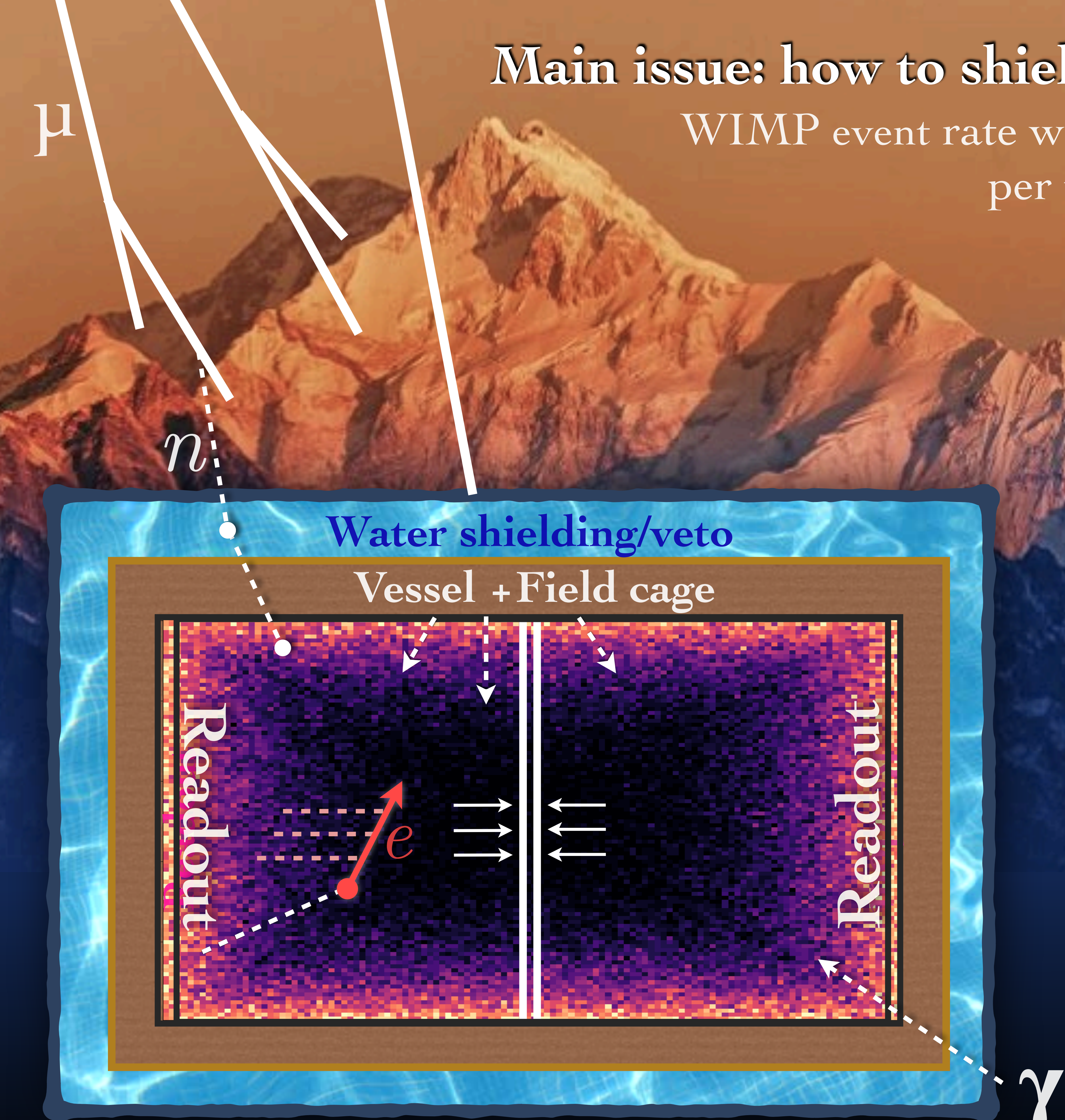
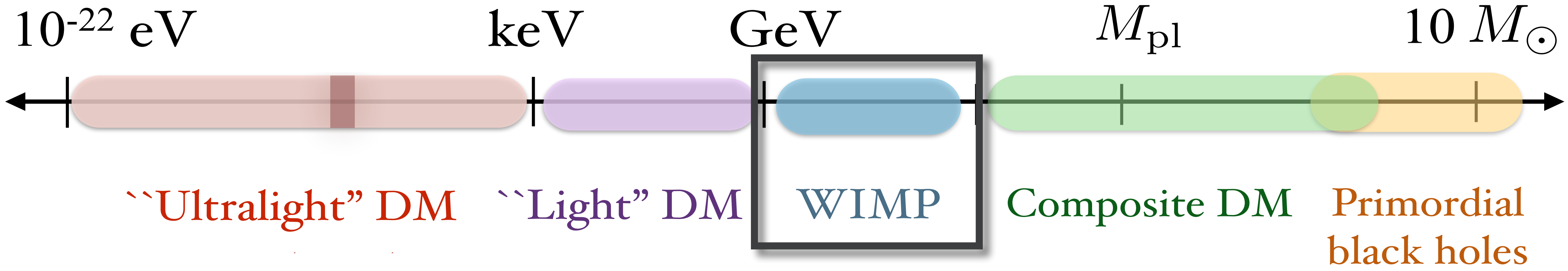
Main issue: how to shield the background?

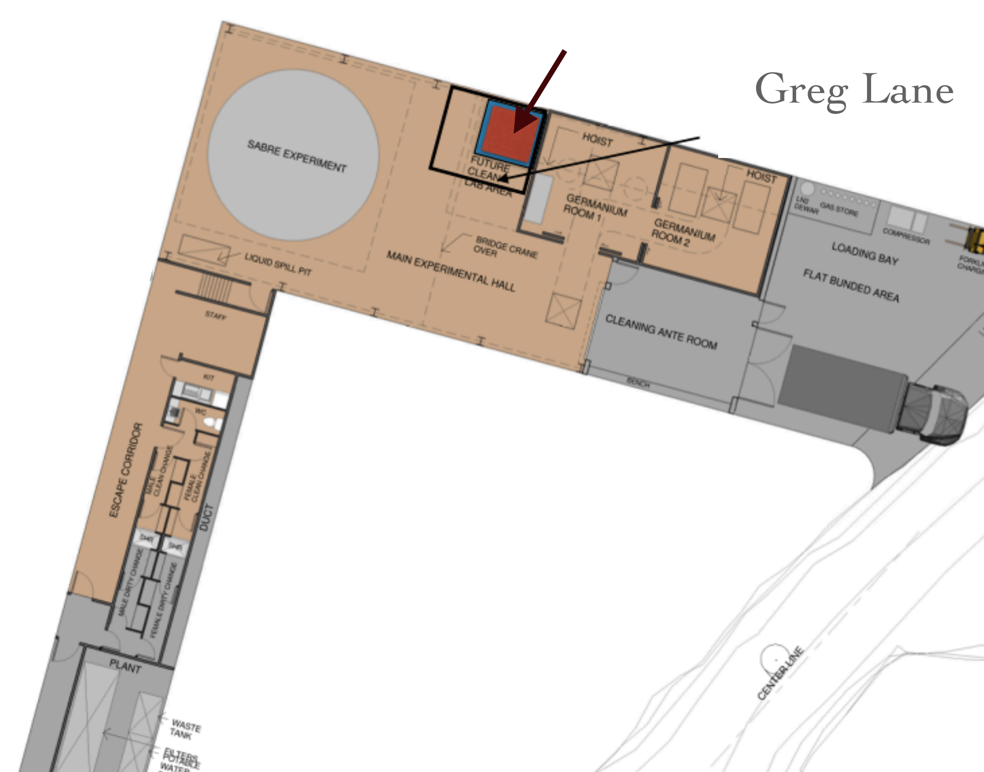
WIMP event rate will be < 1 event per year per ton of detector material



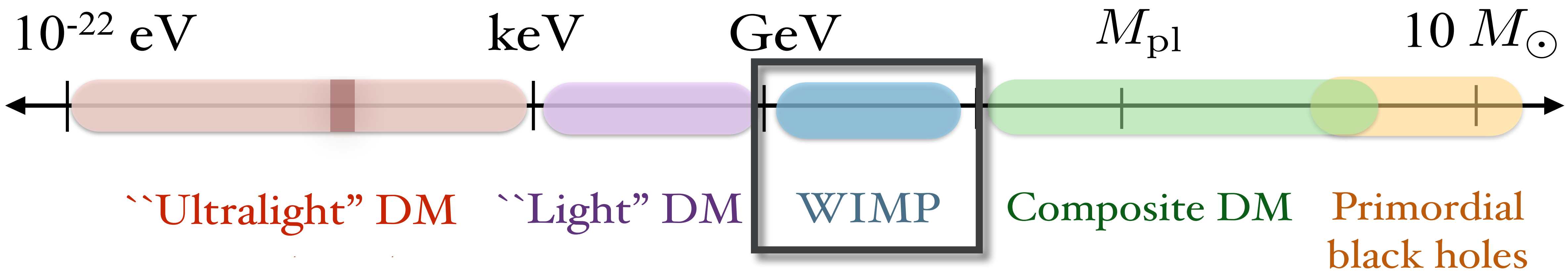


Stawell underground lab (SUPL)

- Construction began in old Victoria gold mine a few months ago
- SUPL will be the first underground physics lab in the Southern Hemisphere
- First experiment it will host is **SABRE** which will address a long-standing disputed detection of dark matter by an Italian experiment, DAMA

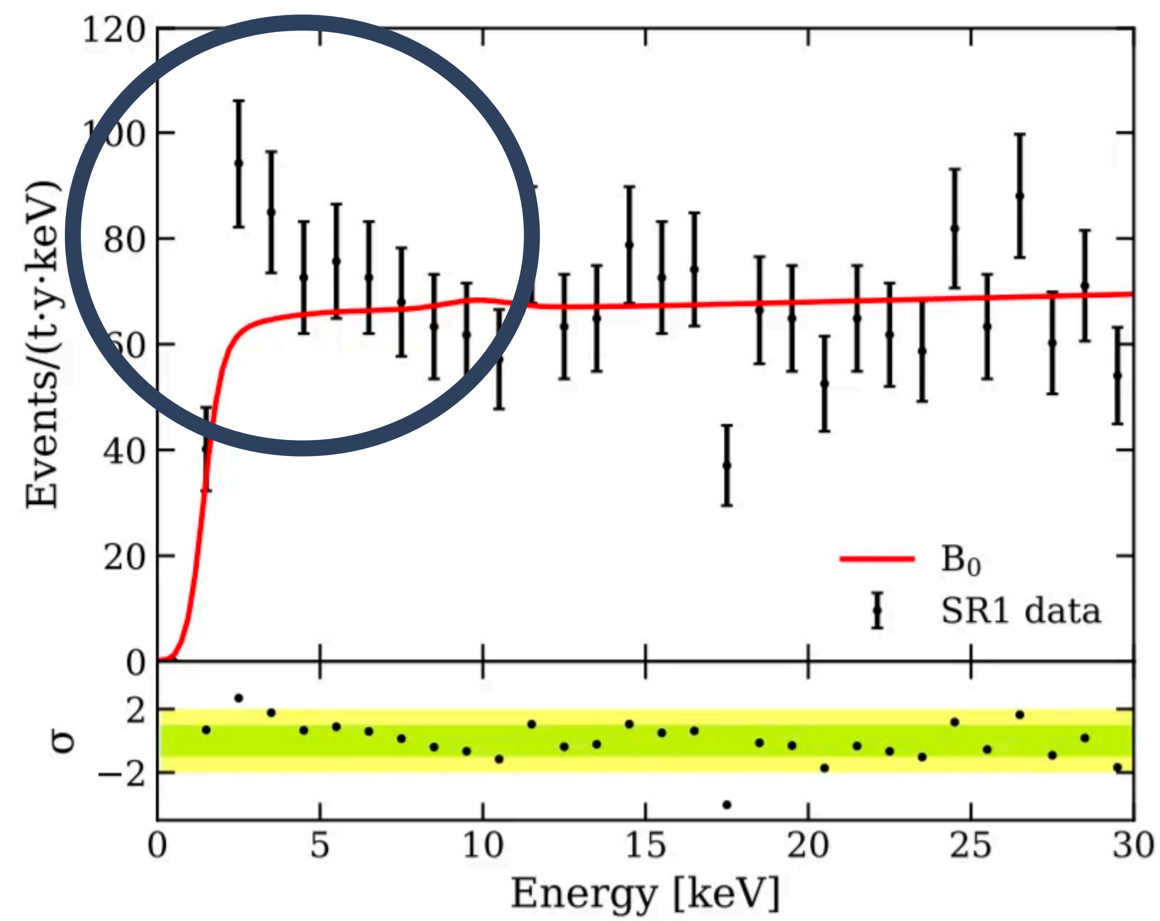


Greg Lane

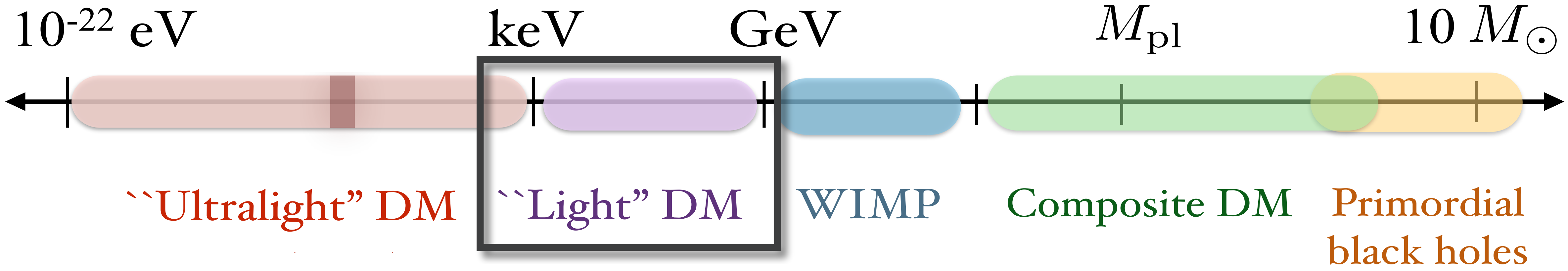


Despite decades of work, no positive WIMP signals yet, except… a few weeks ago we saw this:

The experiment **XENON1T** reported an excess number of electron recoils above their expected background

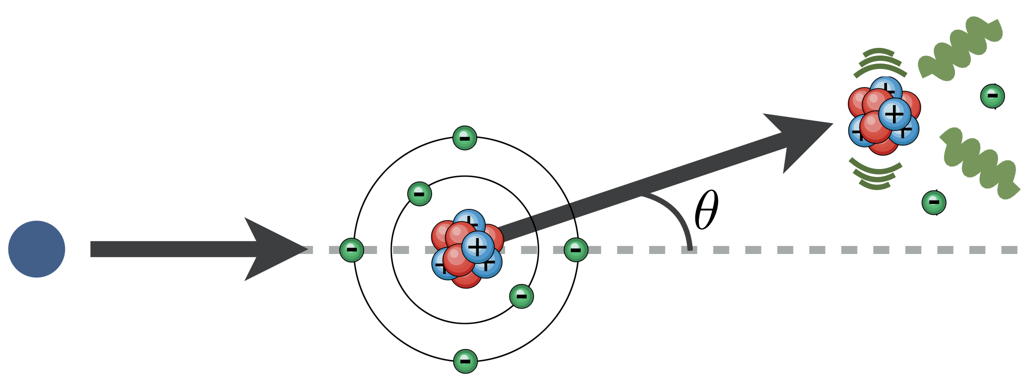


…Already 90+ papers have been written in a couple of weeks trying to explain this excess, more data will be needed to see if it’s real or just a statistical fluctuation



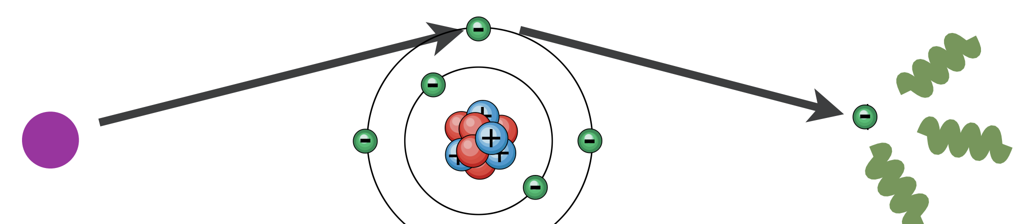
WIMPs have masses around the mass of a proton or small nucleus.
→ "**Light DM**" extends the concept of a WIMP to include lighter particles of similar masses to quarks

Typical WIMP interactions
~ keV scale



Hard nuclear scattering

Typical light DM interactions
~ eV scale



Atomic interactions

- ionising single electrons
- transitions between energy levels
- "nudging" the nucleus (Migdal effect)

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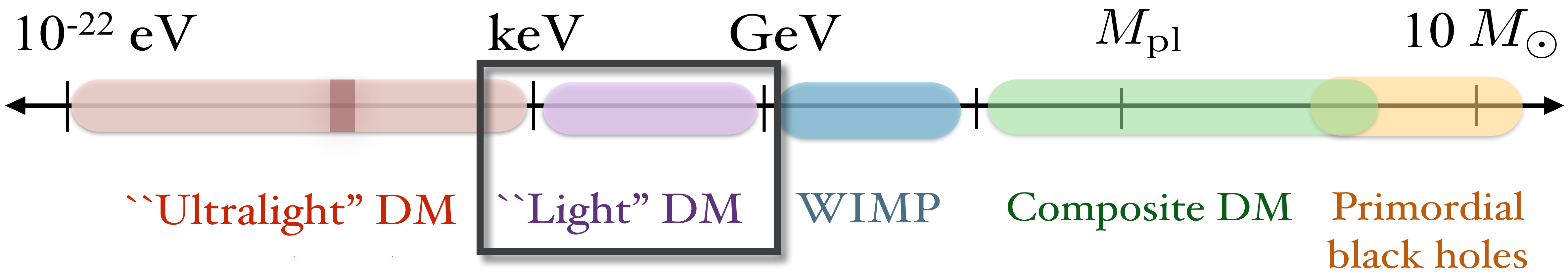
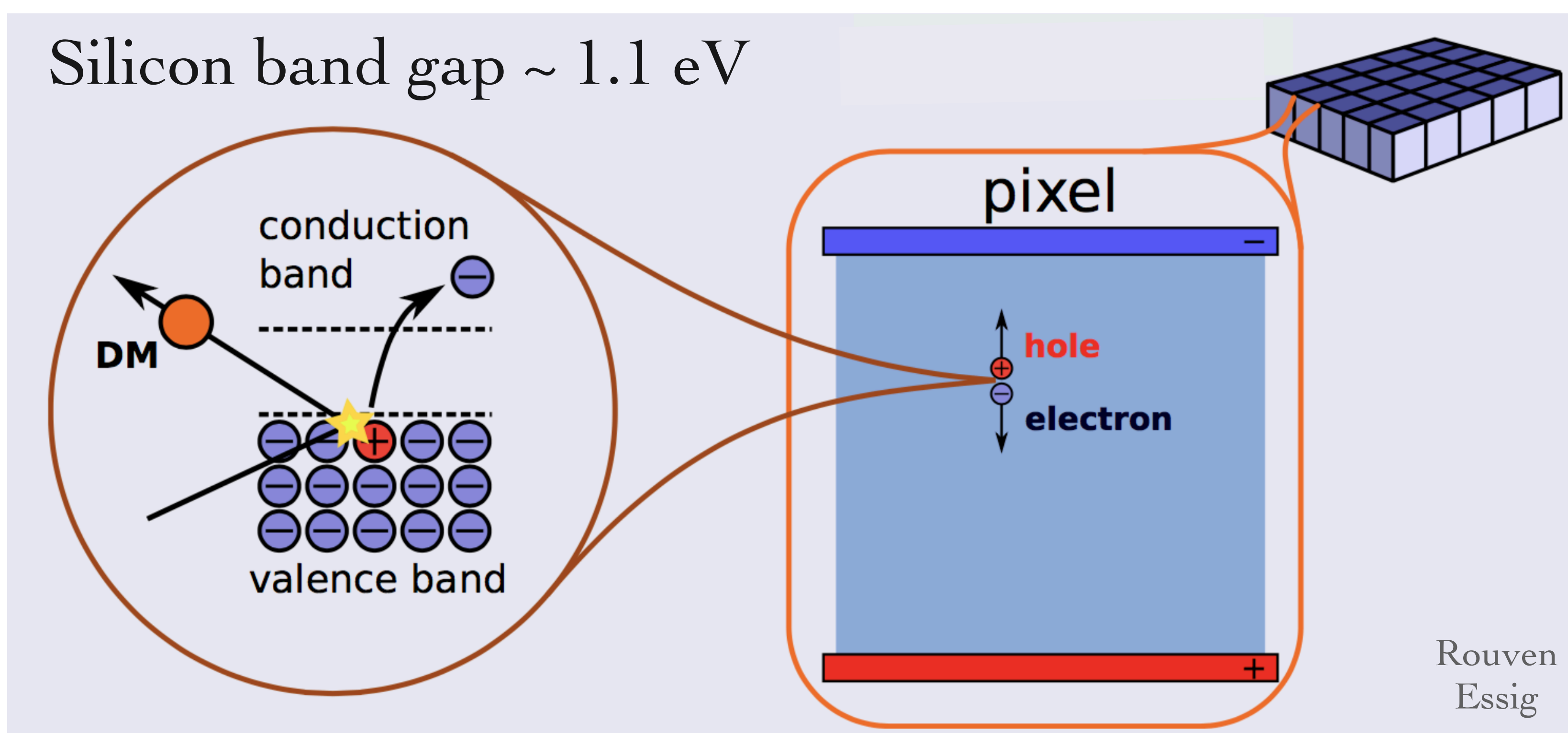
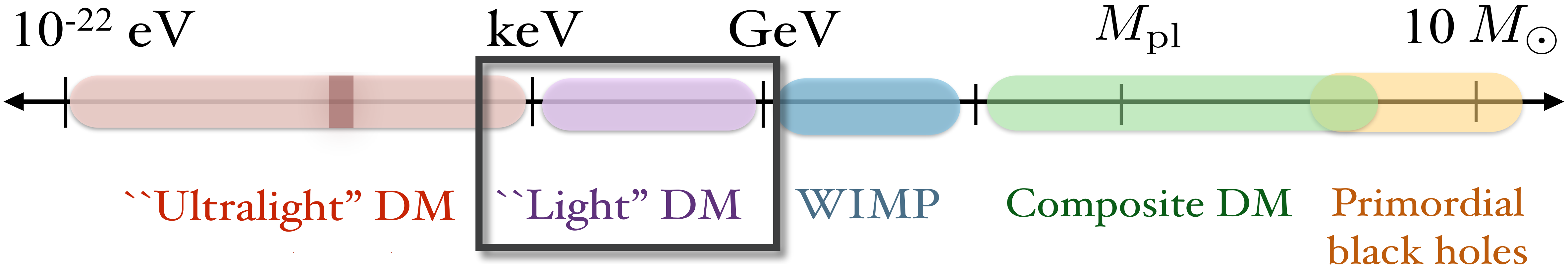


Light DM: recent surge in interest partly from experiments and partly from theory

- **Experiments** → new technologies (e.g. semiconductors) can be used to detect very low energy interactions (energies ~ band gap)

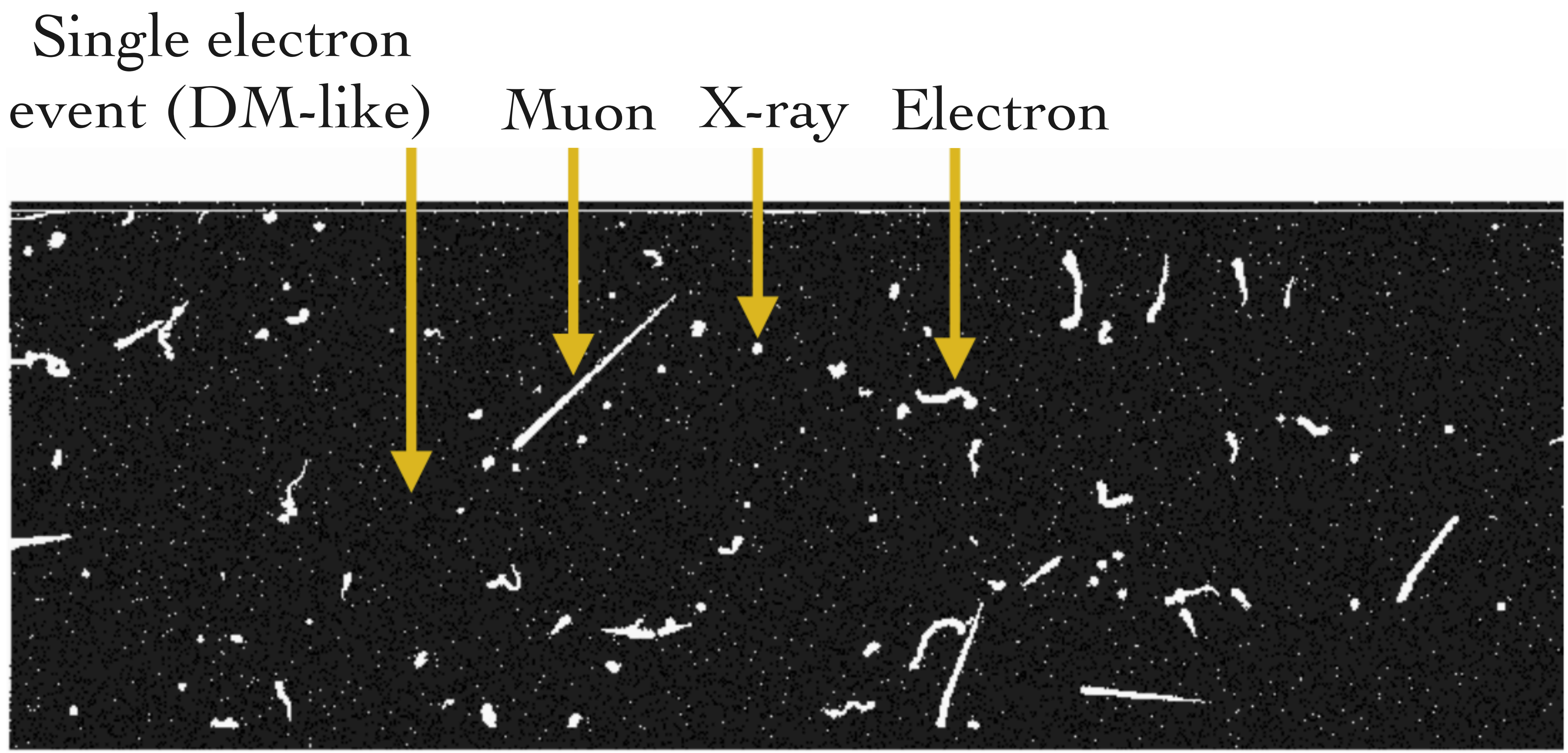


- **Theory** → people have come up with novel models and mechanisms that can explain how the universe produced light DM (dark photons, millicharged dark matter, asymmetric dark matter, and more…)

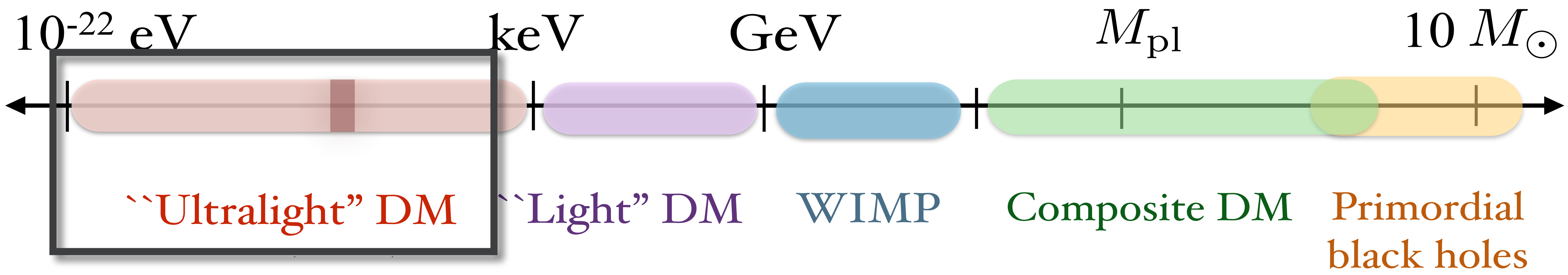


SENSEI (Si CCDs)

Searching for light dark matter interacting with electrons

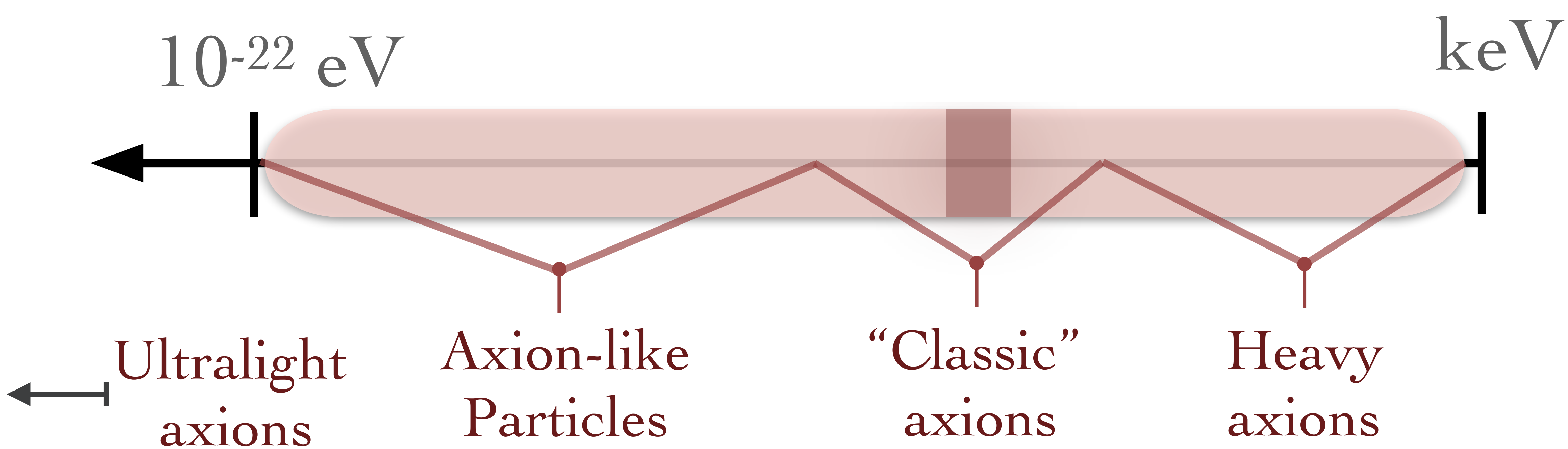


Rouven Essig



Ultralight DM goes for candidates lighter than a ~keV

The main types of particle that live here are called **axions**, the main property that they share is that they are all **bosons**



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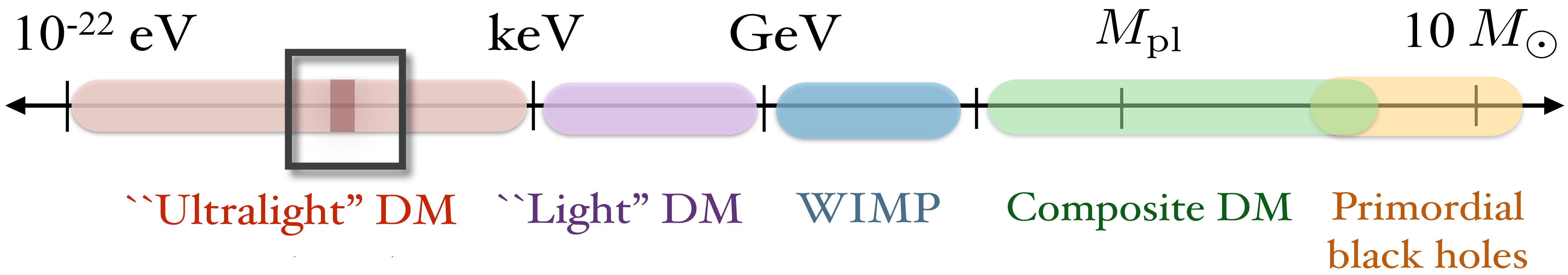
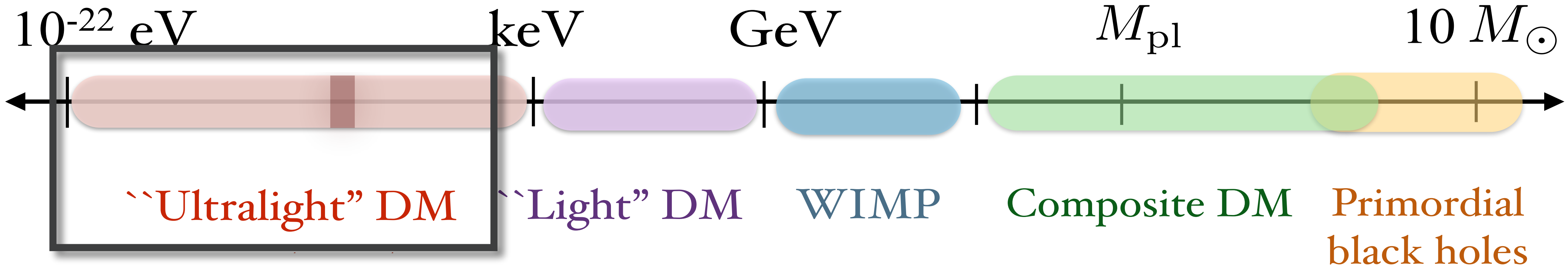


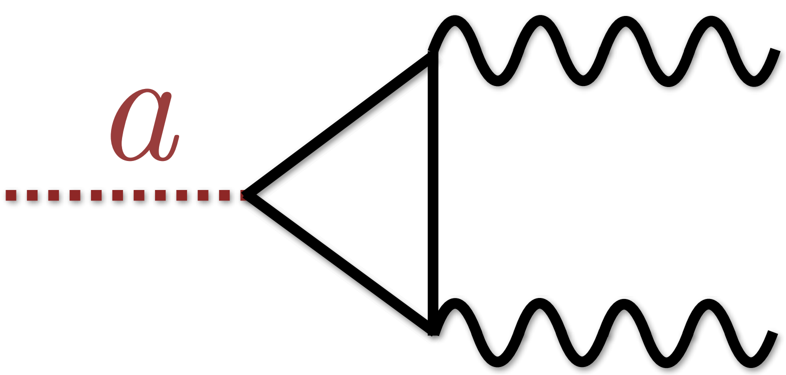
The axion

- The axion is extremely light, between meV and neV masses and much more weakly coupled than anything so far.
- It's also probably the most well-motivated candidate for dark matter right now because: **it was proposed independently of DM**

In the 1970s, Helen Quinn and Roberto Peccei came up with the axion to "clean up" a separate problem in particle physics (the strong CP problem)

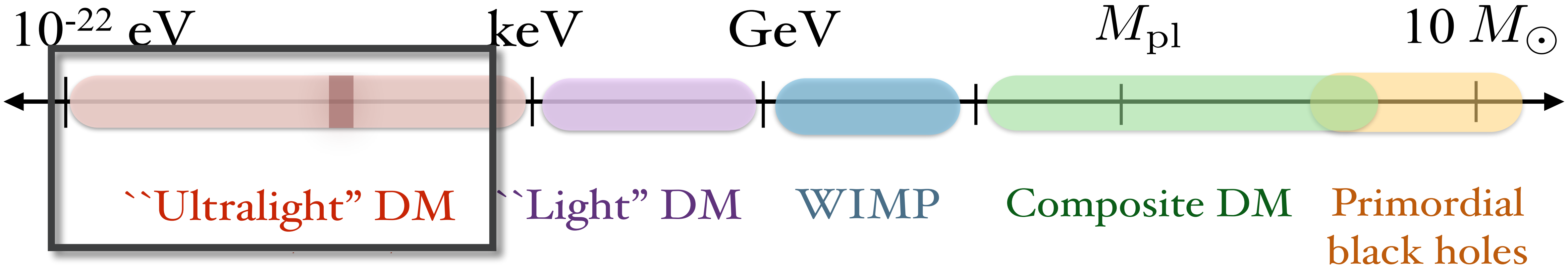


The **axion** couples to the photons → and therefore violates Maxwell’s equations

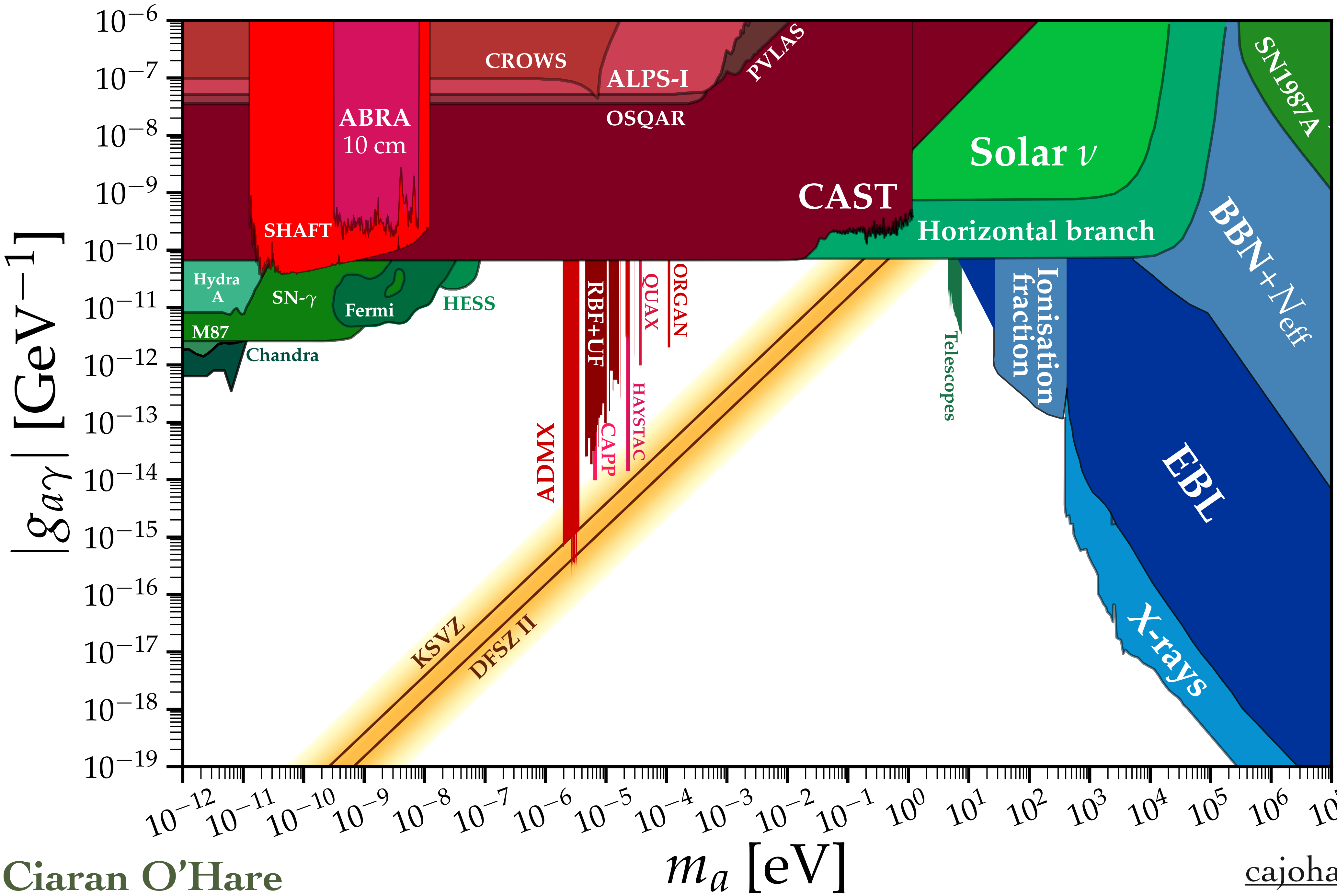


$$\nabla \cdot \mathbf{E} = \rho_q$$
$$\nabla \times \mathbf{B} - \dot{\mathbf{E}} = \mathbf{J}$$
$$\nabla \cdot \mathbf{B} = 0$$
$$\nabla \times \mathbf{E} + \dot{\mathbf{B}} = 0$$

Okay to do this, as long as $g_{a\gamma}$ is small



We use light to do a lot of stuff in physics, so **axions** can be constrained in a number of ways



Experiments

Astrophysics

Cosmology

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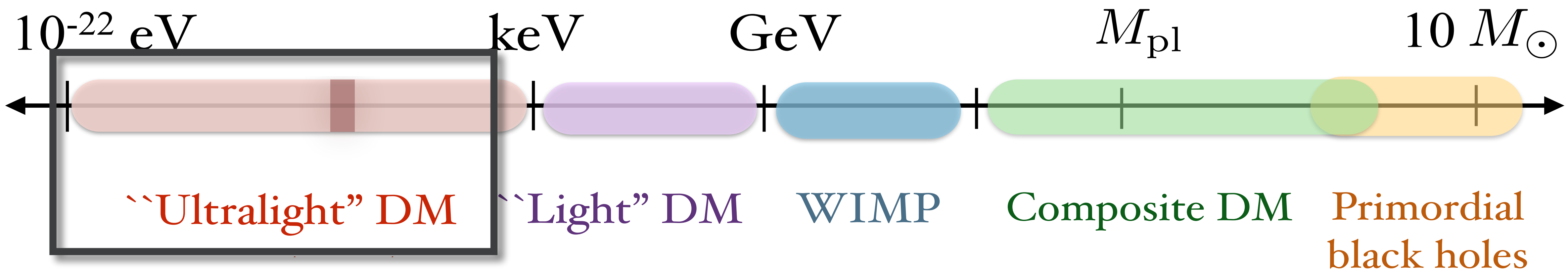
cajohare.github.io/AxionLimits/



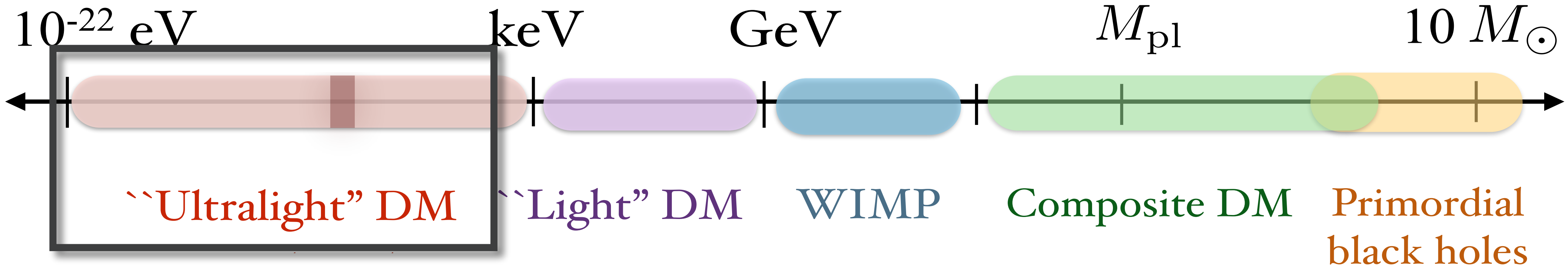
Super-ultra light dark matter: masses > 10^{-22} eV

- If you have very light particles moving with typical galactic velocities v ~ 300 km/s they will behave slightly differently…

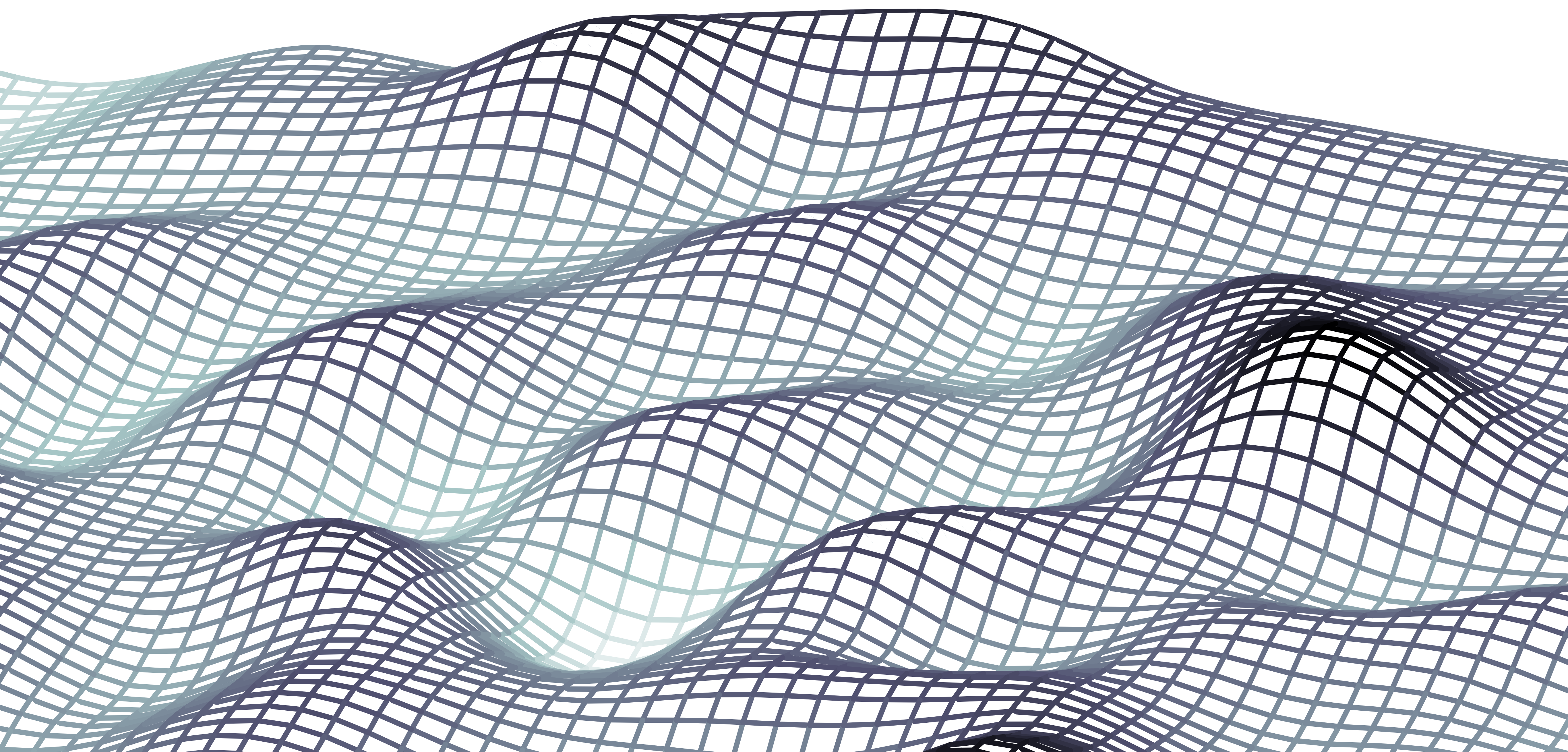
→ At this point the **de Broglie wavelength** (i.e. the length scale over which wave-like effects take place) is as large as some small galaxies ~ kpc:

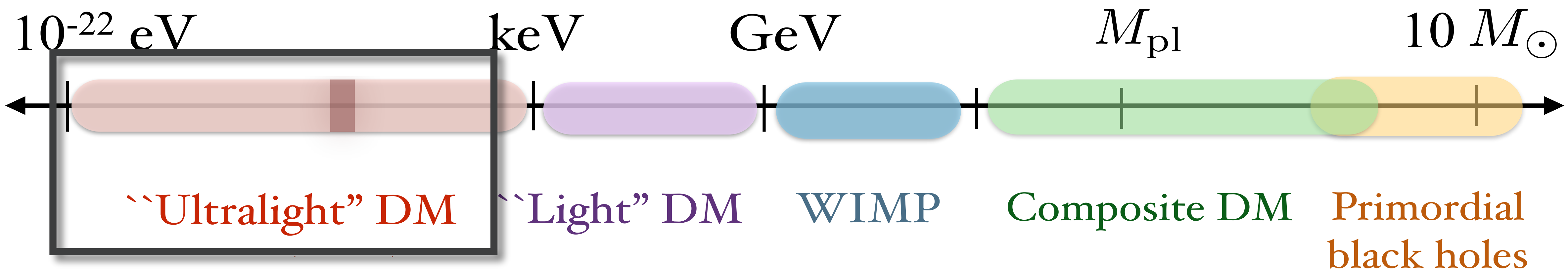
$$\lambda_{\rm dB} = \frac{2\pi}{m_{\rm DM} v} \approx \underline{0.4\,{\rm kpc}} \left(\frac{10^{-22}{\rm eV}}{m_{\rm DM}}\right)$$

- Leads to very interesting effects on galactic scales → in the context of astrophysics this is called **"Fuzzy dark matter"**



Fuzzy dark matter: think of it as like an oscillating field

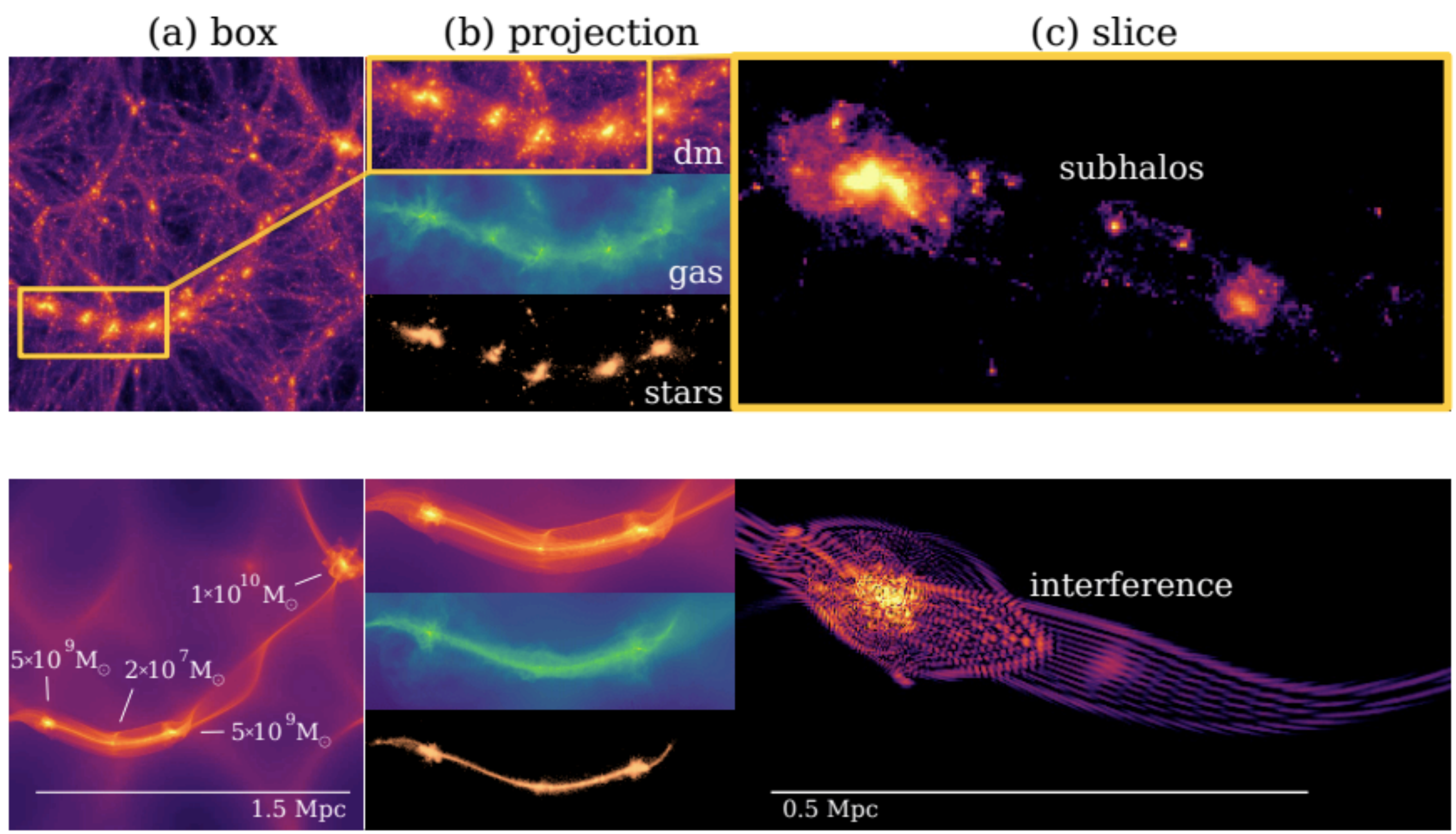




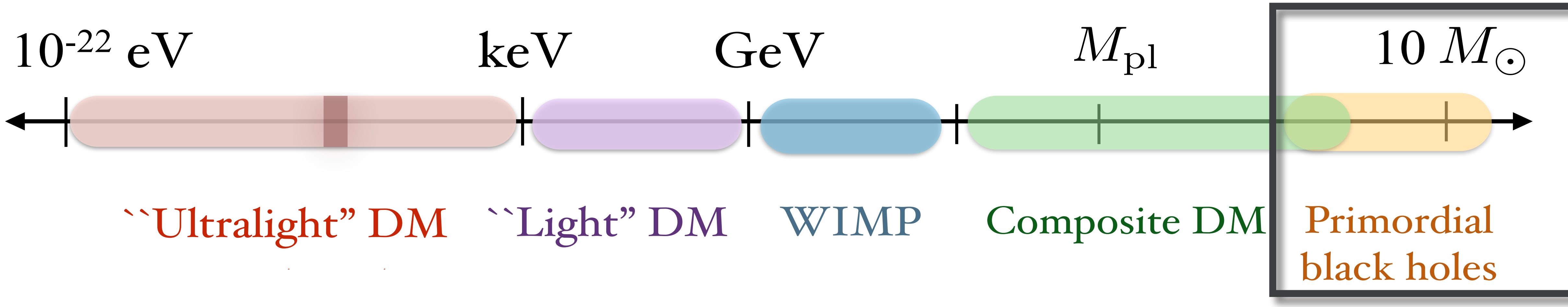
Fuzzy dark matter leads to structure that exhibits wave-like effects

standard, "cold" dark matter →

Fuzzy dark matter →



Mocz et al. 2019

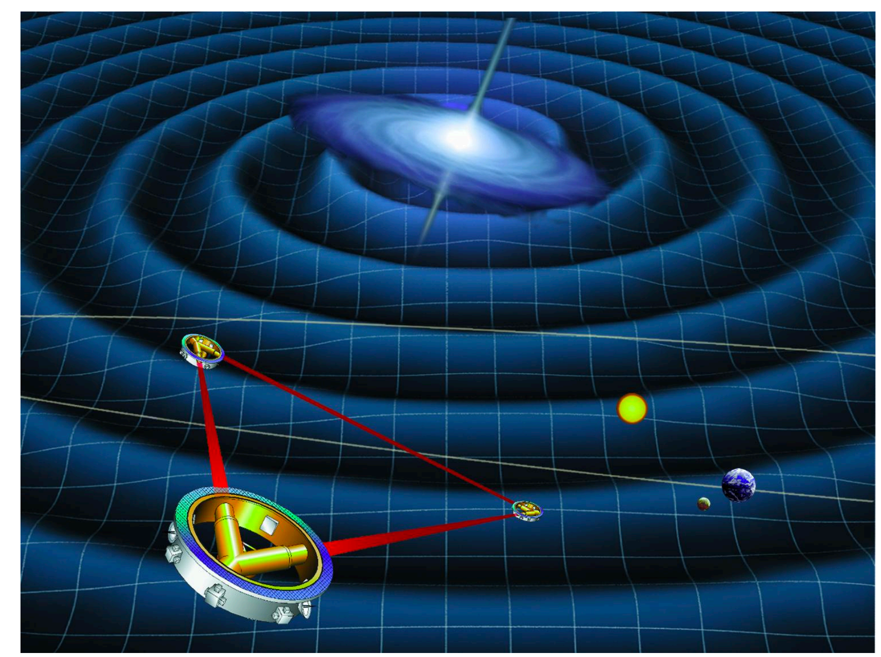


So what can be expected in the next, say, 10 years…

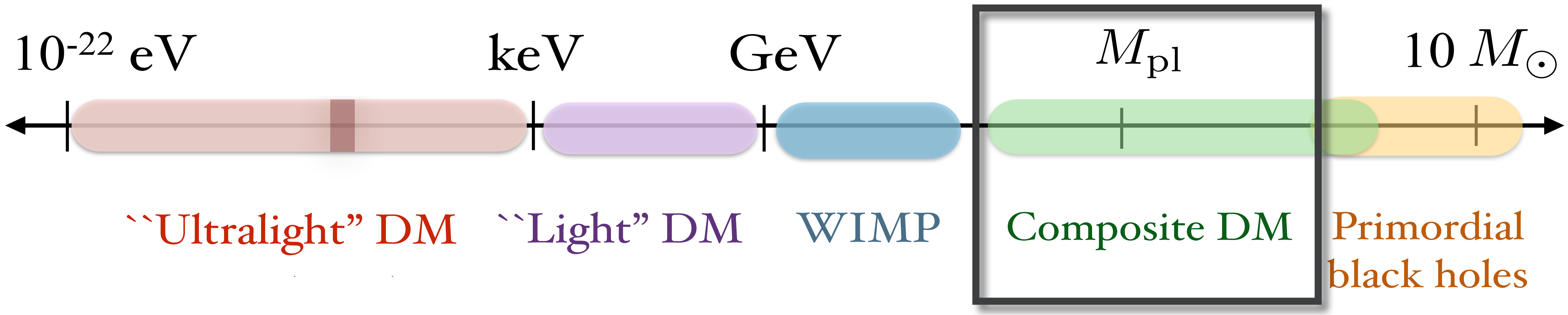
Primordial black holes:

- Currently enjoying invigorated interest thanks to a new probe → Gravitational waves
- GW observatories (LIGO/VIRGO) will continue to improve over the next ten years + there is possibility for a space-based gravitational wave observatory: **LISA**
- New wide and deep astronomical surveys could detect PBHs as they pass in front of stars

… many potential avenues



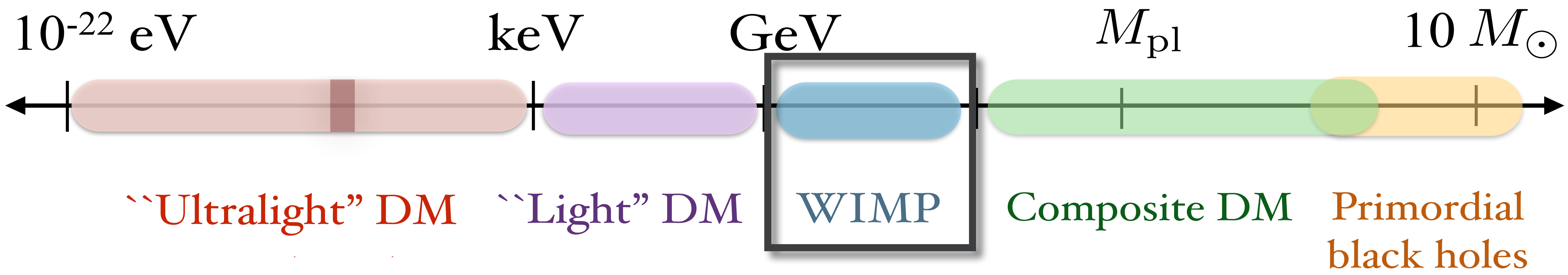
LISA



Composite DM

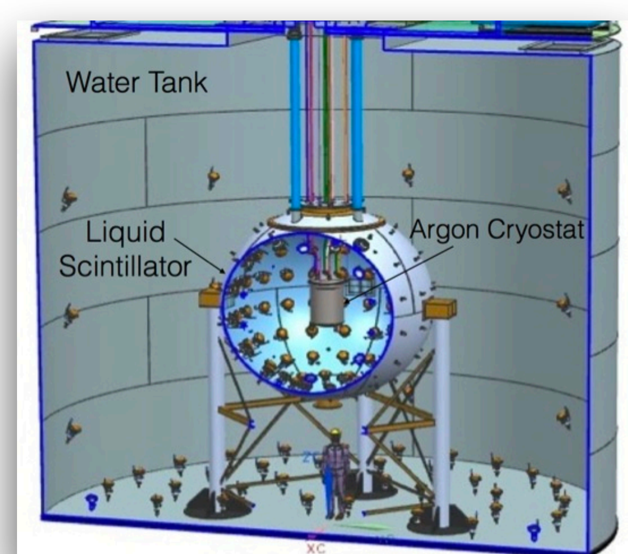
- Not clear what the future holds for composite DM ideas
- On the observational side, there are many many ways to look for them.
- But there are outstanding theoretical problems in making them <u>work</u> as DM

→ Probably we need a new fresh idea from theory if DM is some composite object

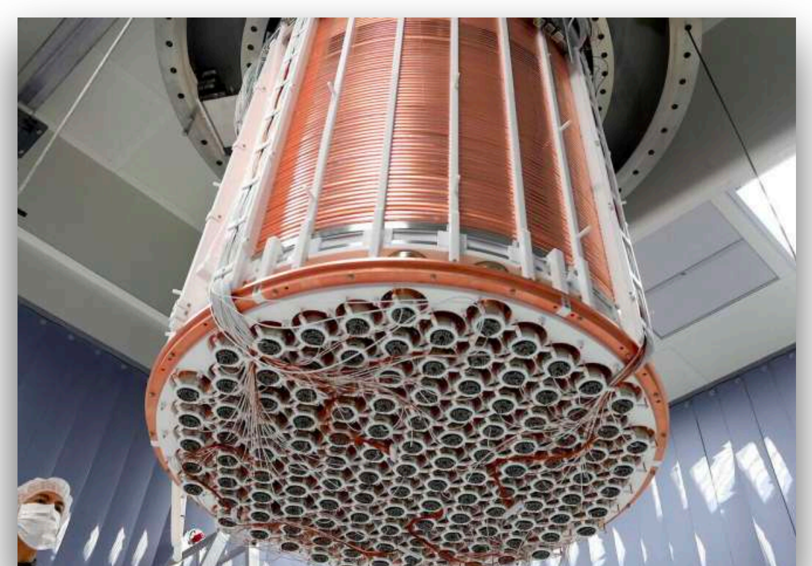


WIMPs

- WIMP detectors are by far the most sensitive of all DM experiments and a new generation (G3) is currently being built which will be some of the most sensitive physics experiments ever…
- No luck so far, but my guess is that in 10 years if we don't see any WIMPs, they will significantly wane in popularity.



DarkSide



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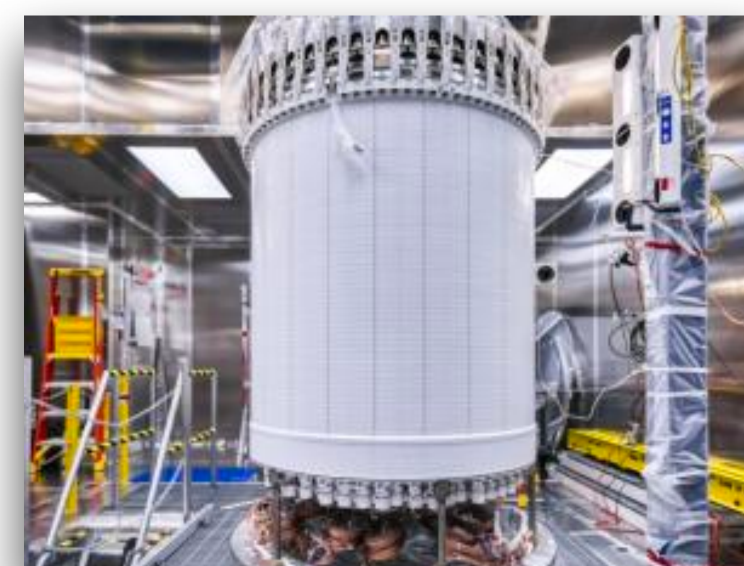

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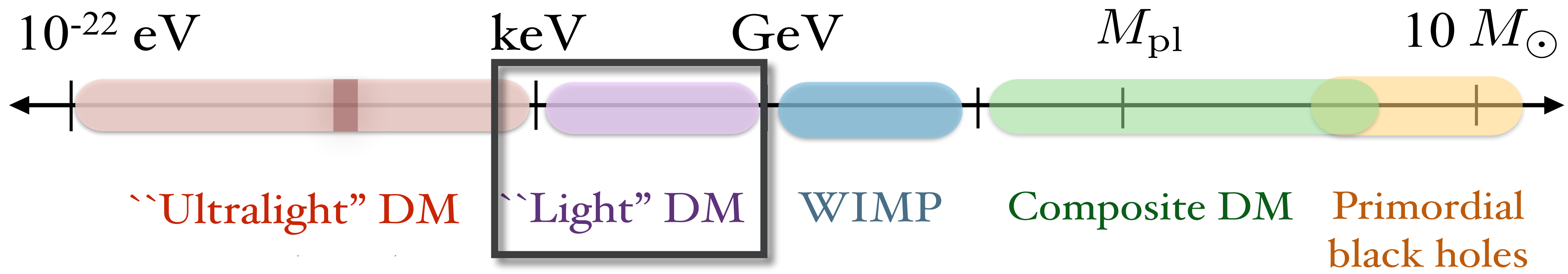
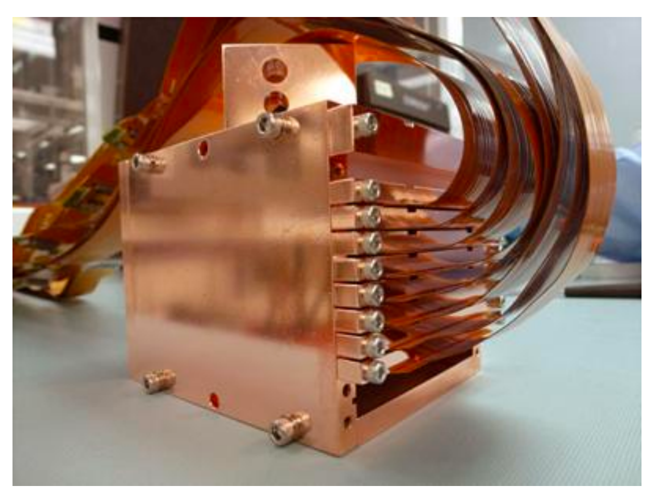


Light DM

- Last ~5 years has rapid growth in popularity thanks to advances on both theoretical and experimental sides
- Many more questions to be answered and technologies to be repurposed
- For example, light DM searches currently rely the most on interdisciplinary physics, especially from condensed matter physics and nanoscience
- **a really exciting field that is certain to keep growing**

SENSEI



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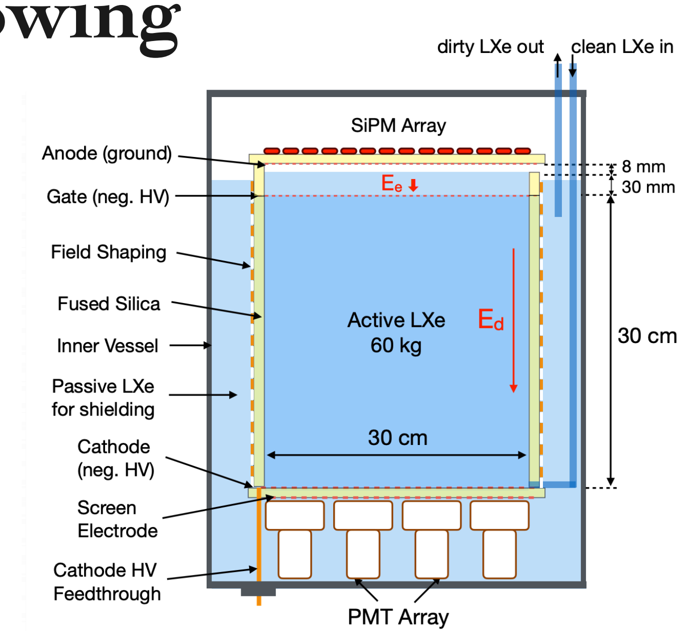
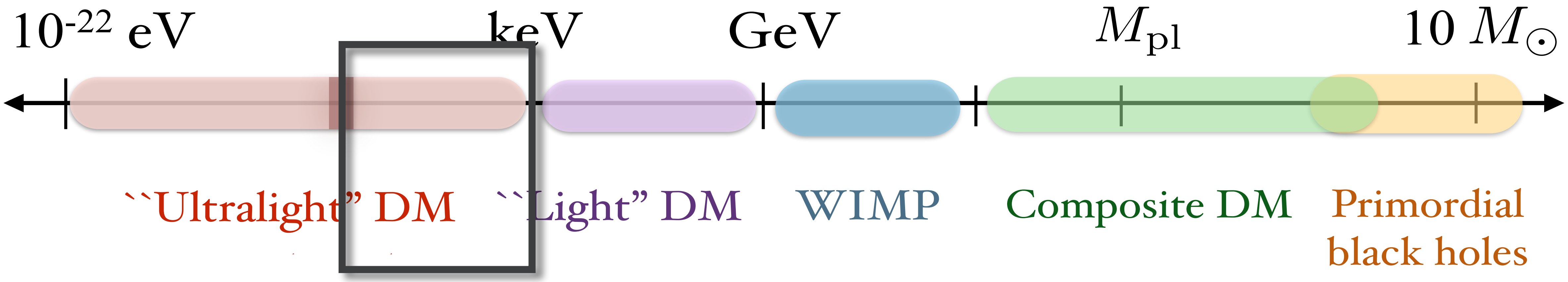
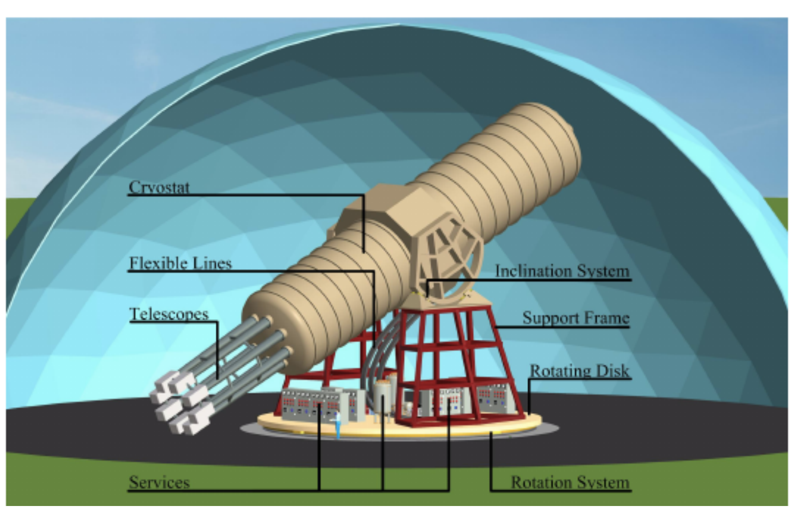


LBECA

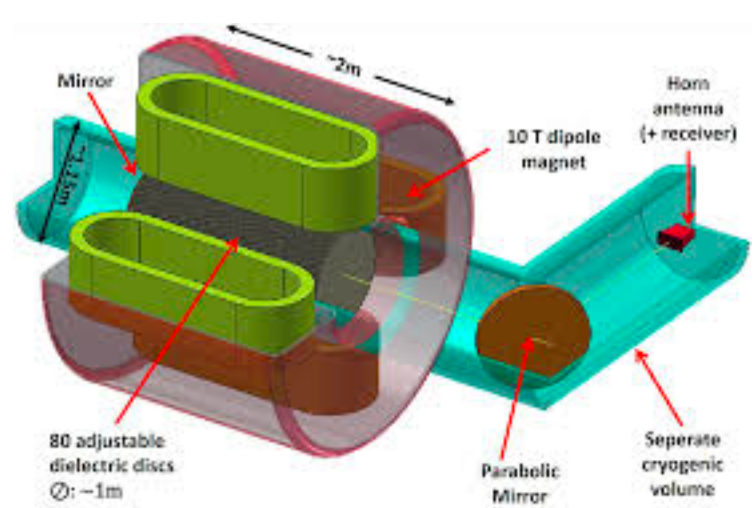


The axion

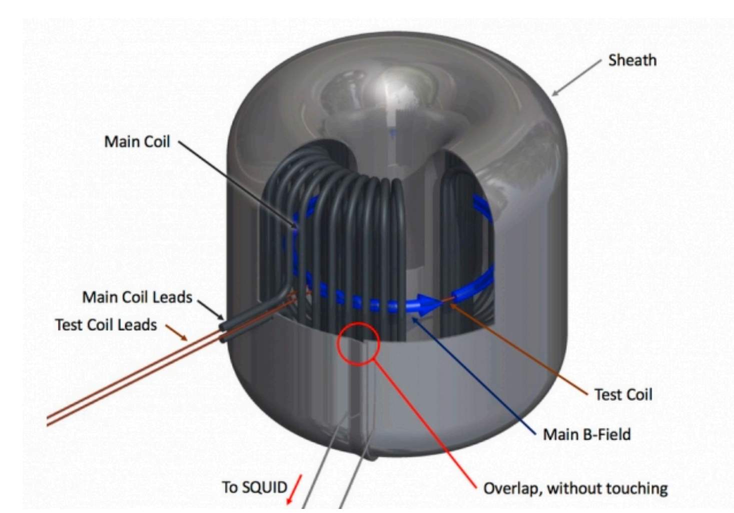
- The axion has extremely solid backing as a DM candidate from theory - it is the most “attractive” idea from an Occam’s razor standpoint
- We’re also probably 10, maybe even 20 years, away from ruling it out completely since it is one of the hardest particles to detect and many experiments are still in their very early stages.
- **Don’t believe anyone who says we’re out of ideas for DM**



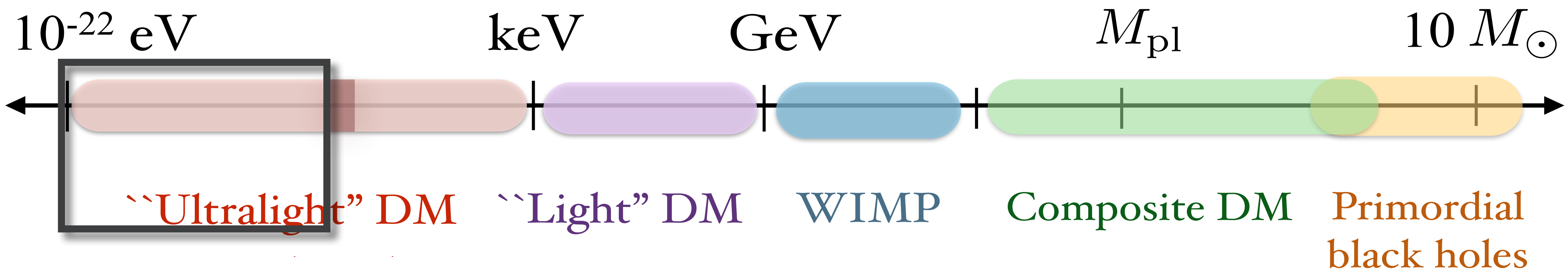
IAXO



MADMAX



ABRACADABRA



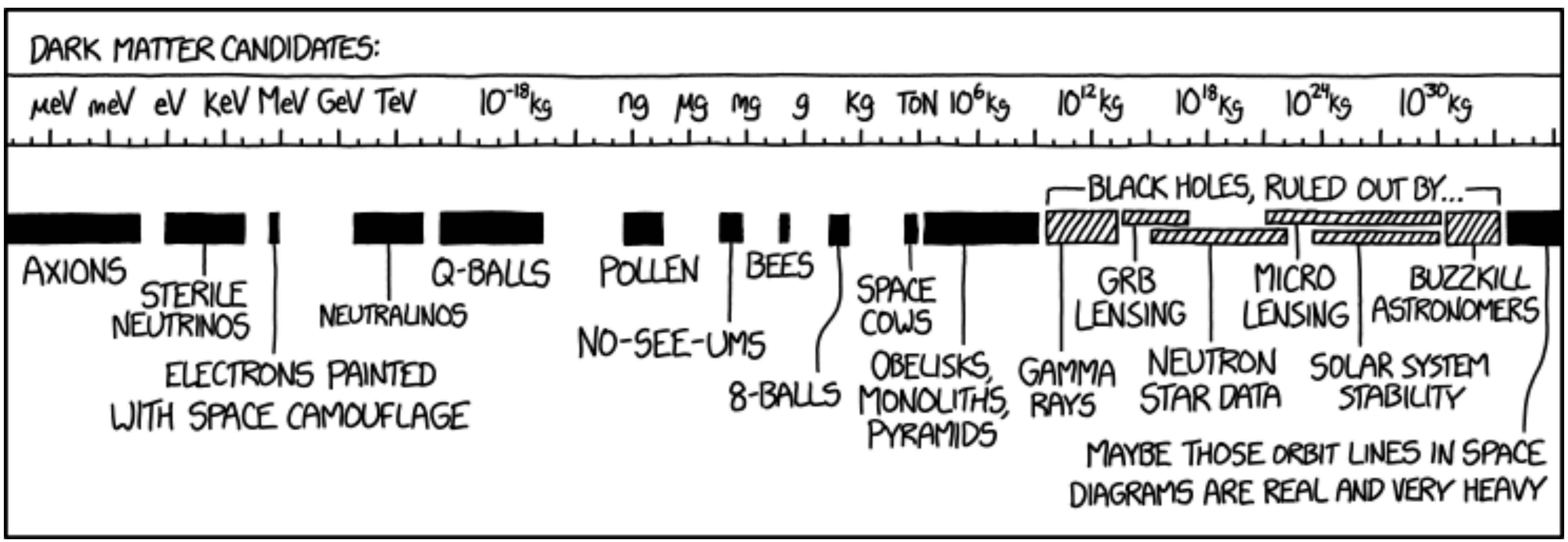
So what can be expected in the next, say, 10 years…

Fuzzy dark matter & astrophysics

- Many more massive astronomical surveys are planned and they will help us refine our understanding of the astrophysical properties of dark matter… we may find something unexpected, who knows?
- However, one of the most exciting developments in the next 10 years will be from <u>computer simulations</u> of galaxies/the Universe
- Increasing computational power + novel techniques like machine learning will help us expand the scope of simulations beyond just reproducing galaxies - **but to actually test ideas for new physics**

Take home point of this talk: we don't have "no idea" what dark matter is.

We do, we have lots of ideas…



xkcd.com/2035