Novel Cosmic Probes of Dark Matter

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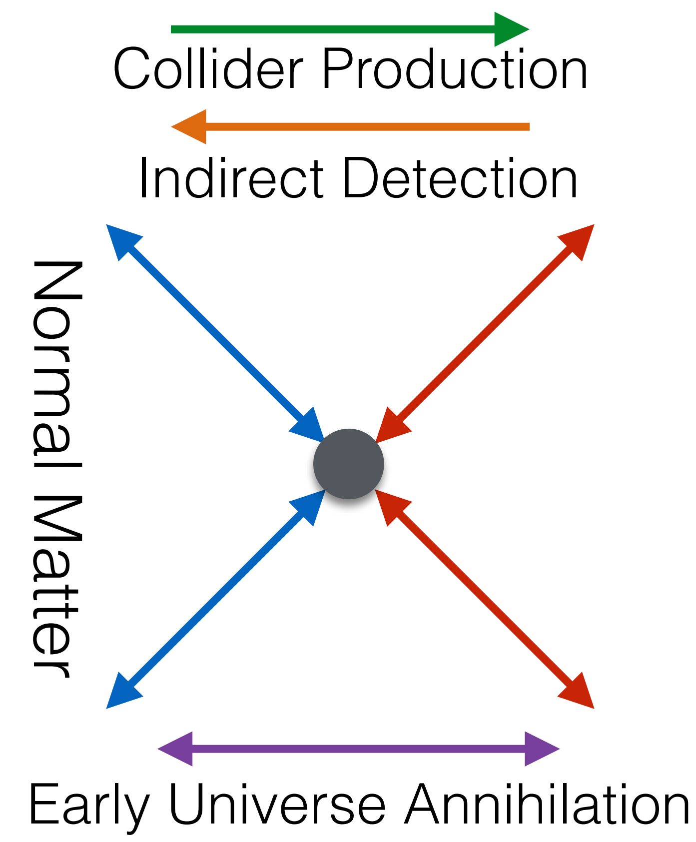
The Problem of Dark Matter

- We have well-motivated ideas about what the *particle physics* of dark matter could be:
  - Axions! (solve the CP-problem)
  - WIMPs! (solve the Naturalness and Hierarchy problems)
  - sterile neutrinos



- We just haven't found convincing evidence for any of them.

- The question we theorists want to answer:
  - ***What is the particle physics of dark matter?***

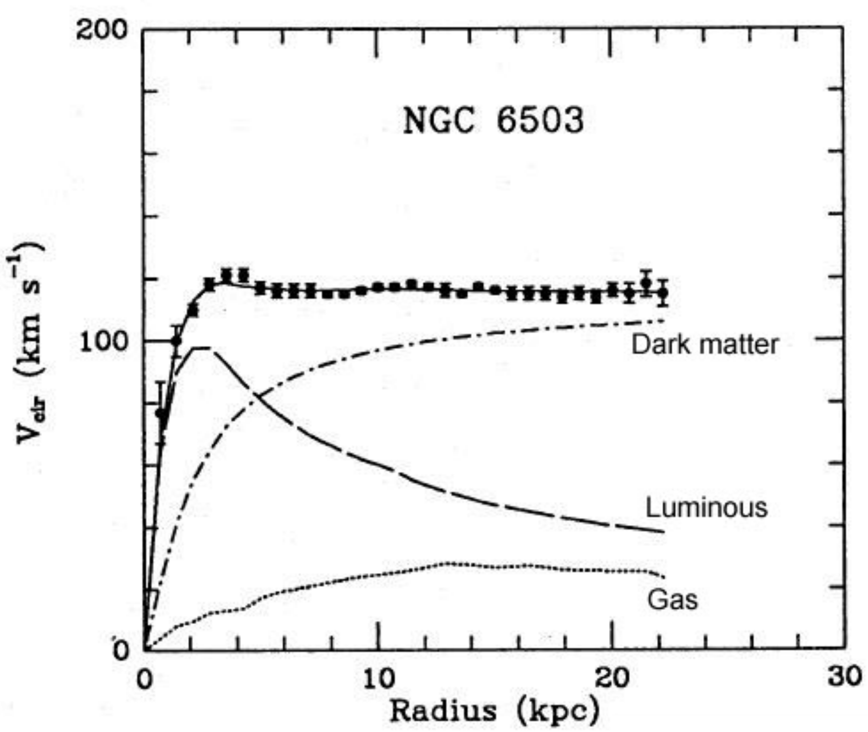
Back to the Basics

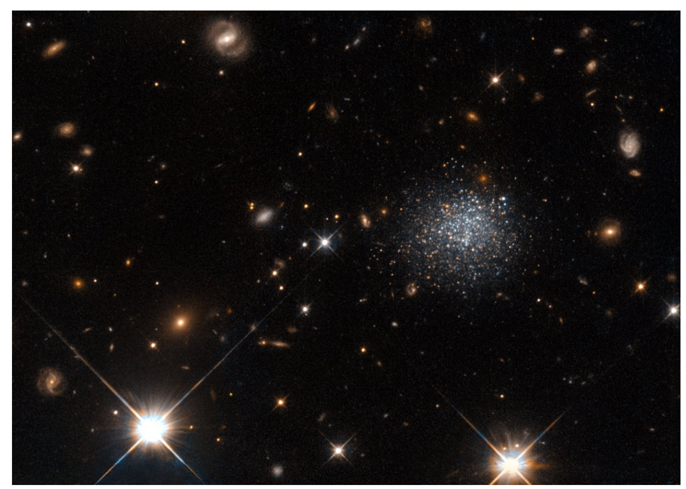
- What do we *know* about dark matter?
  - It exists! (in galaxies today)
  - It existed in the early Universe
  - It doesn't interact with unsuppressed weak/EM/strong charges
  - It was non-relativistic by $z \sim 3000$
  - If fermionic, its mass is $\gtrsim 100~\mathrm{eV}$. If bosonic, $\gtrsim 10^{-22}~\mathrm{eV}$
  - It doesn't interact with itself very much.

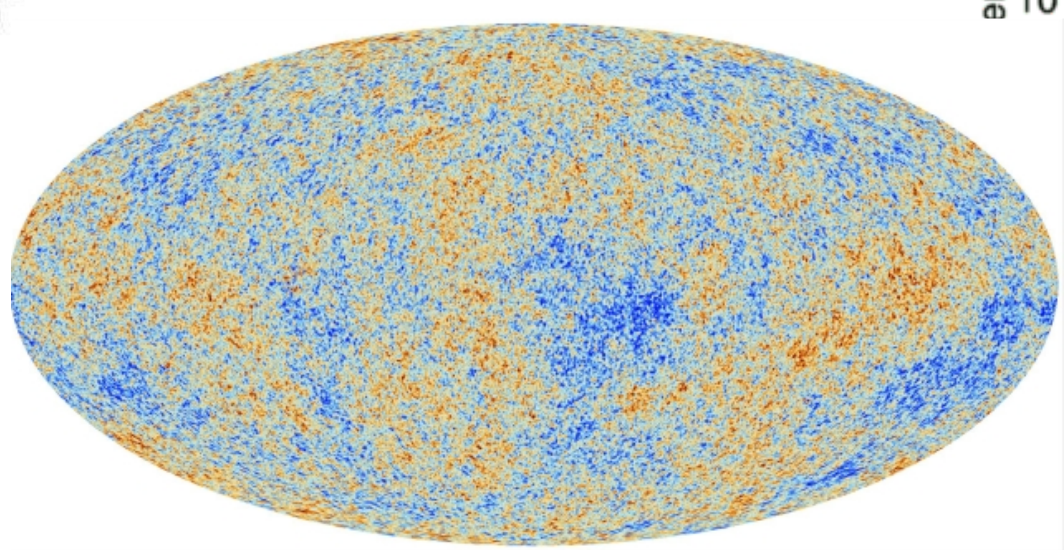
- That is it. That's everything we *know* for a fact about dark matter.
  - **But how do I know any of this?**

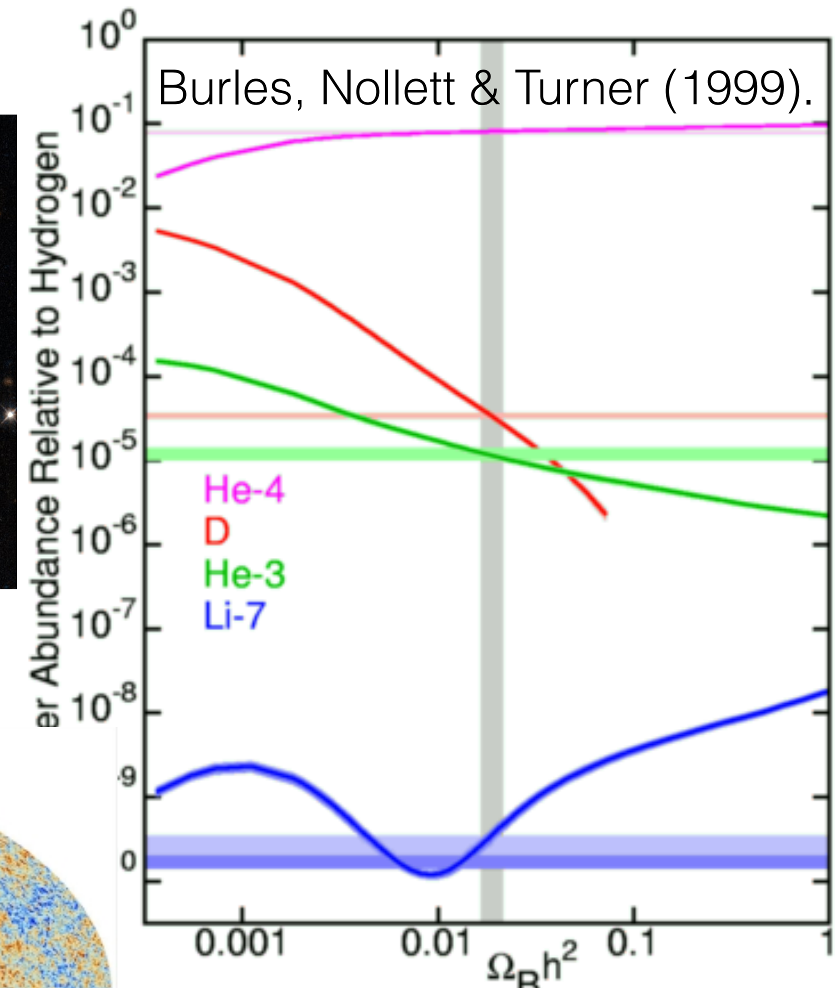
Gravity!

- Every property of dark matter we know of (other than non-observation in the lab) comes from its gravitational interactions.



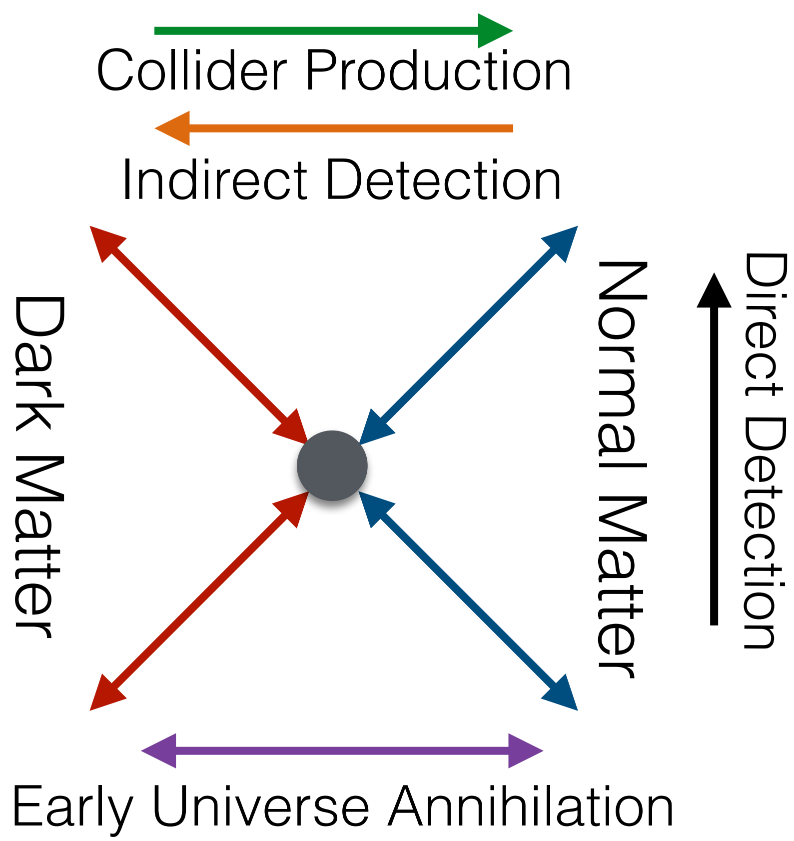






So What? A Thought Experiment

- We’re interested in the *particle physics* of dark matter, not the astrophysics.
    - How do we extract these things from the distribution and evolution of dark matter?
- Imagine you’re a scientist in the dark sector: you can see dark matter, but not baryons.
    - Using the Dark CMB, you discover something with $\Omega_b \sim 0.05$
    - What can you learn about its *particle physics?*
- Dark scientists would by stymied if they use the classic experimental triad



Credit to Annika Peter (OSU) for idea.
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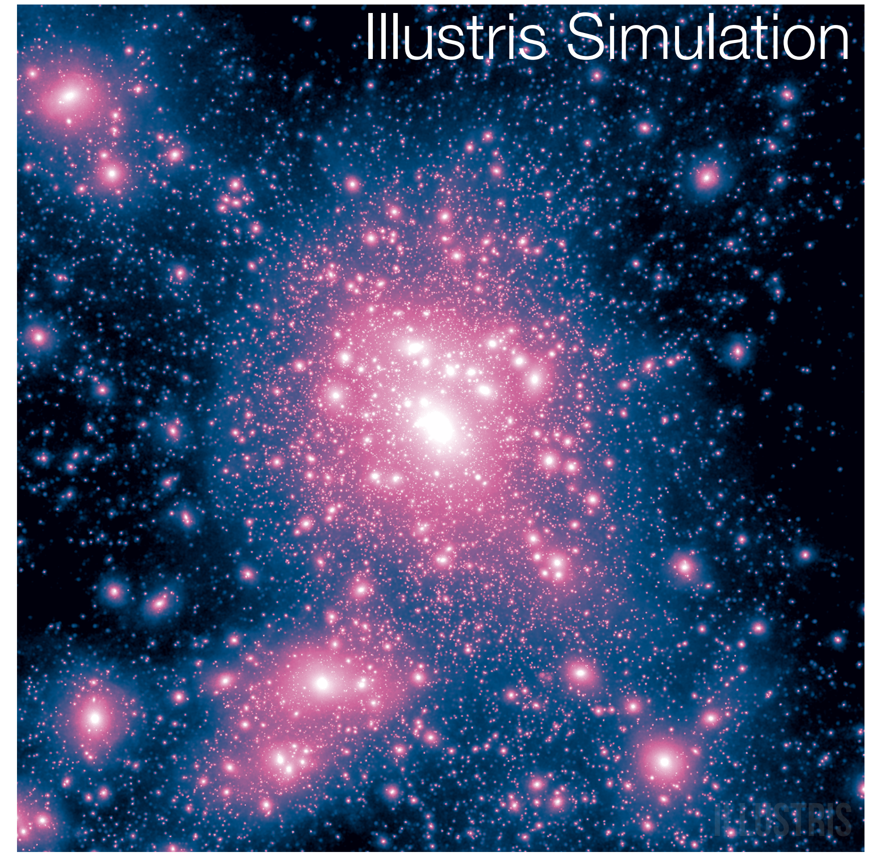
A Thought Experiment

- But what if you turn to the astrophysics?
  - The z of matter-radiation equality gives you baryonic light degrees of freedom.
  - Two-point correlation of dark halos gives you Baryon Acoustic Oscillation — baryons are strongly self-interacting
  - A difference between dark matter halos and baryonic galaxies — baryons must be capable of cooling.
  - Reasonable to conclude that the light d.o.f. are responsible



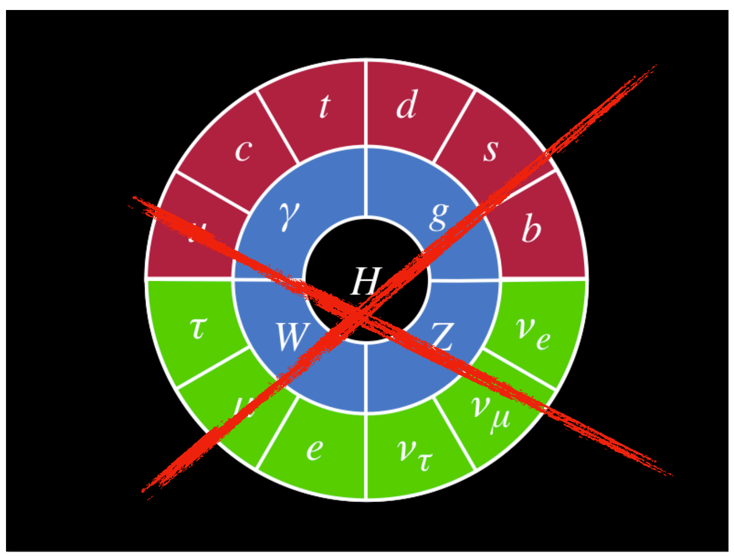
A Thought Experiment

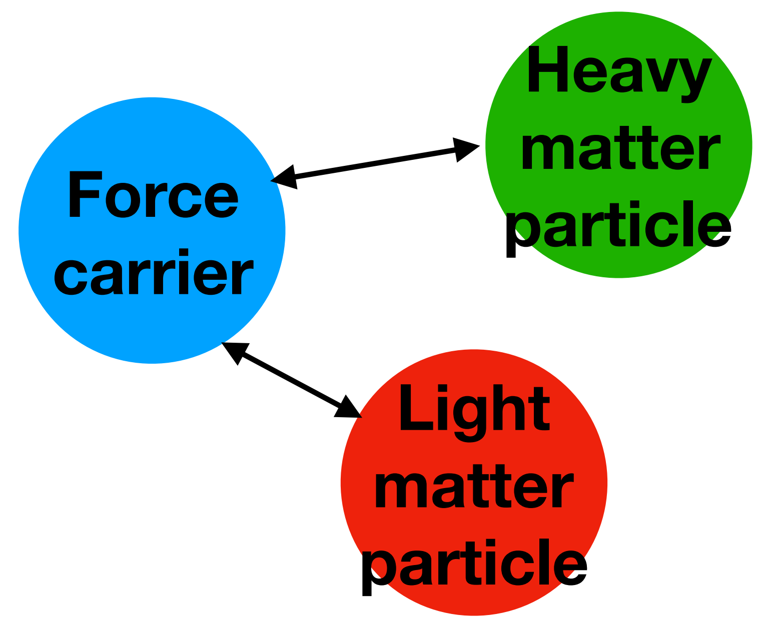
- Scattering rate implied by disk cooling would be too high for a thermal relic: the baryons consist of particles but not antiparticles!
- Other particle physics solutions certainly possible, but if the dark scientists consider a $U(1)$ gauge interaction, they'll find they need
  - a virialized kinetic energy set by a heavy particle
  - a scattering rate set by a light particle.
  - a fine-structure constant large enough to allow thermal bremsstrahlung, but not too large so that the biggest galaxies can't reionize.

$$10^{-7/3}\left(\frac{m_H/m_L}{m_p/m_e}\right)^{1/2}\left(\frac{m_L}{m_e}\right) \lesssim \alpha \lesssim 10^{-2}\left(\frac{m_H/m_L}{m_p/m_e}\right)^{1/2}$$

A Thought Experiment

- Can't guarantee that dark scientists would hit on the right answer.
  - But they can learn that baryons must be multicomponent, strongly interacting, with a complicated cooling history involving relativistic particles.



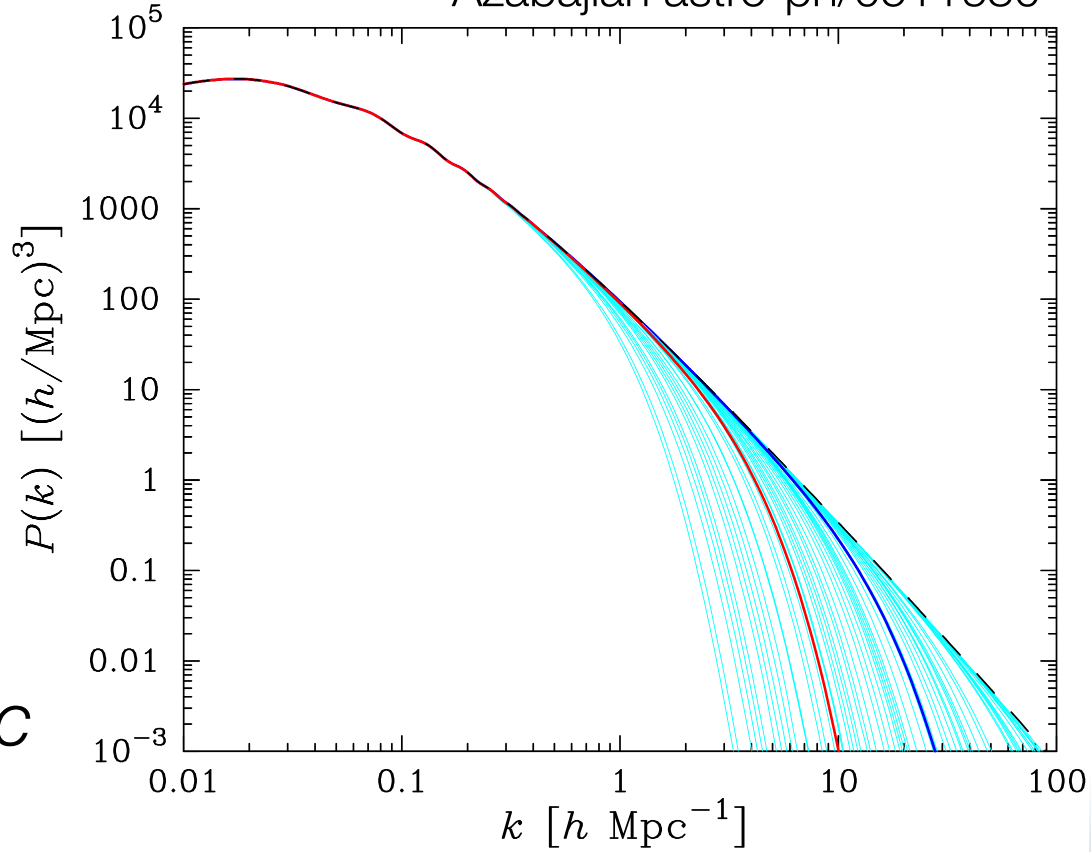


- So, let's ask: if we're studying the dark matter particle physics…
  - …what can astrophysics do for us?

Particle Physics from Astrophysics

- Not a novel idea — we constrain dark matter models with astrophysics all the time.
- Sterile neutrinos:
  - Warm dark matter free-streams out of small structures in the early Universe.
- Self-Interacting Dark Matter:
  - Bullet Cluster, tri-axiality of halos, *etc* limit σ/m_χ

Azabajian astro-ph/0511630



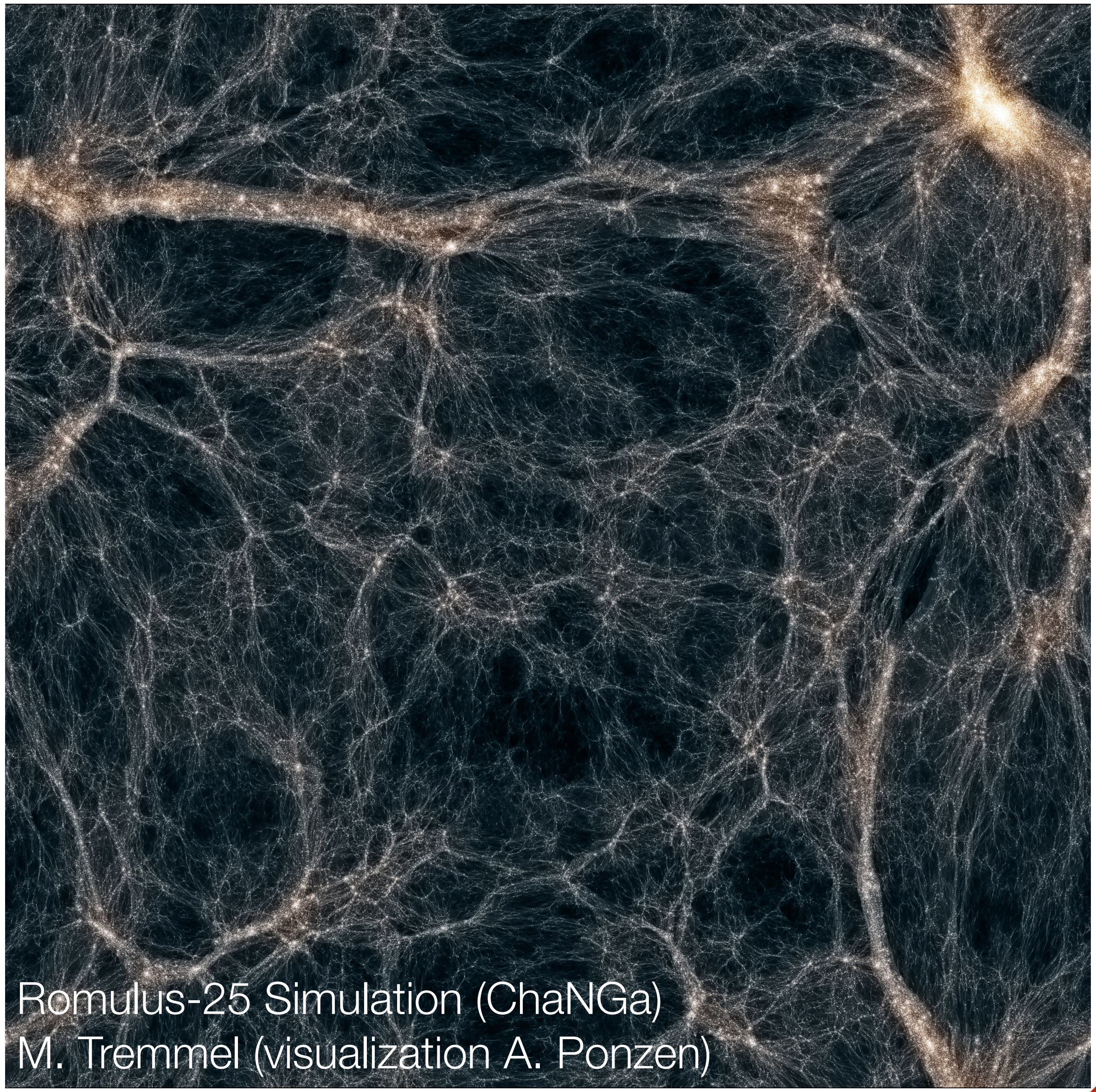
Particle Physics from Astrophysics

- So what's new?
- On the astrophysics side:
  - New big-data surveys and observatories:
    SDSS, DES, GAIA, LSST,… JWST….
  - New dwarf galaxies, gravitational lensing, stellar kinematics, galaxy surveys, galaxy evolution from high-*z* to today,…
- On the theoretical physics side:
  - A recognition that WIMPs are not the end-all-be all
  - A need for new data to narrow down the possibilities

The Goal

- Use astrophysical probes of the structure of dark matter to constrain the *particle physics* of the dark sector.

- Compare to "pure" cold dark matter — gravity-only interactions
  - Predicts a primordial power spectrum of dark matter structure that extends down to arbitrarily small scales.
  - This is perhaps the key prediction of cold dark matter.



Views of Dark Matter

- Particle physicists and astrophysicists speak different languages:

- Dark matter as a particle physicist problem:
  - What is its mass?
  - Its interactions?
  - How does it fit into some larger model?

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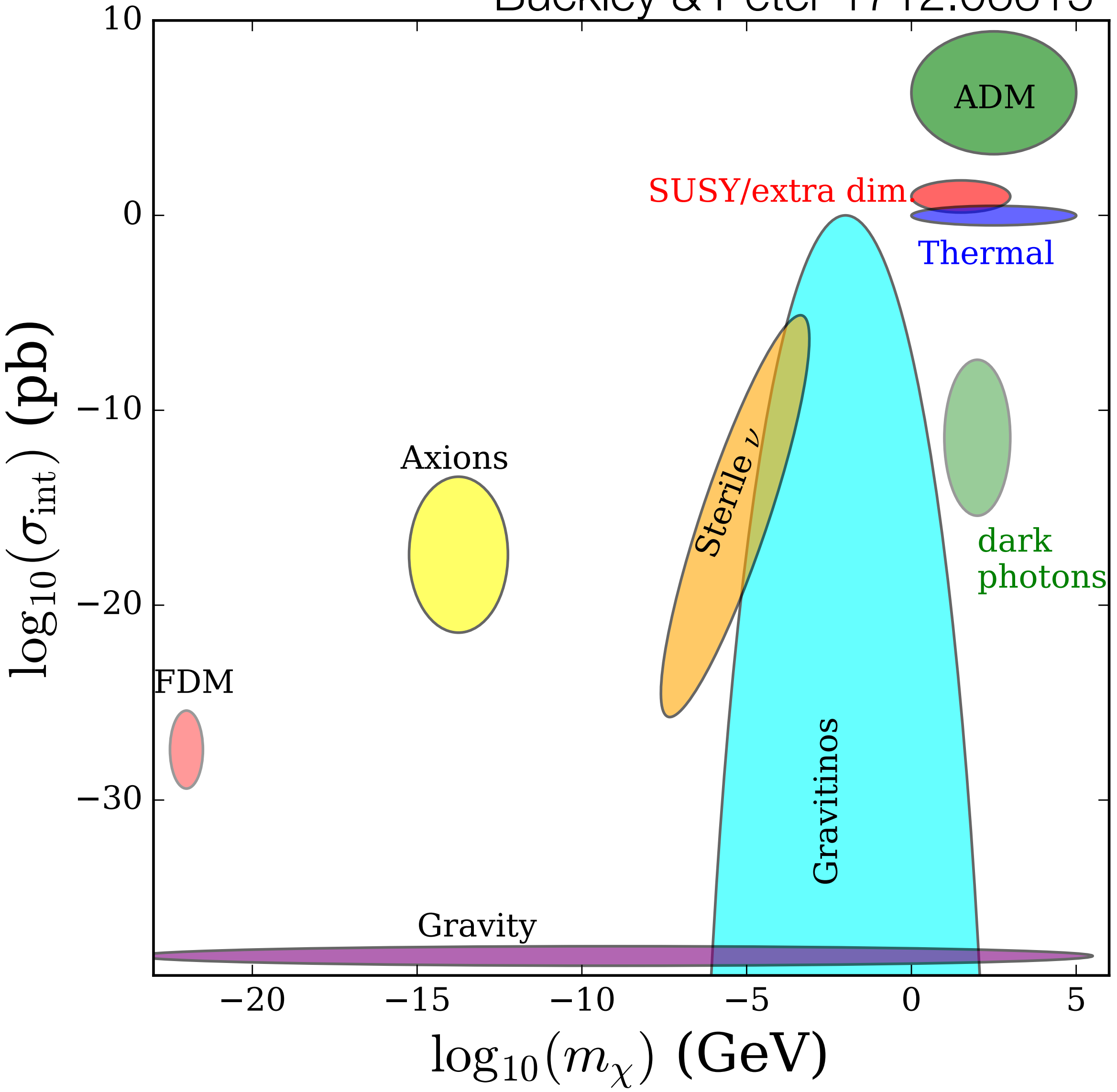
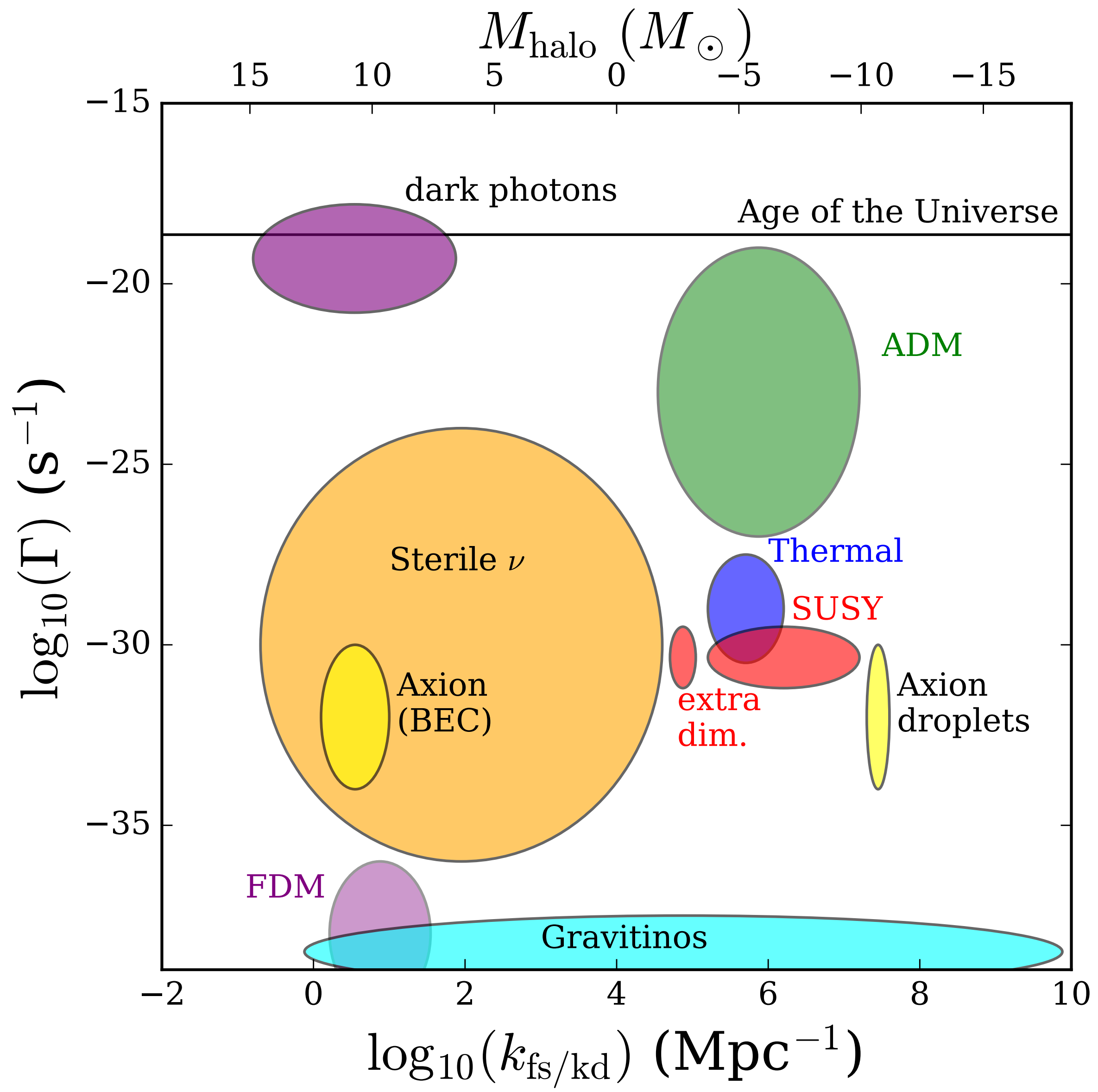


Views of Dark Matter

- Particle physicists and astrophysicists speak different languages:

- Dark matter as an astrophysicist problem:
  - How is it distributed in the Universe?
  - Is our cosmology correct?
  - Are we modeling galaxies correctly?
- Not always clear how a particle model of dark matter fits into this



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A Common Language

- A parameter space that captures important phenomenology for both particle physics and astrophysics.
- Particle Physics parameter: strength of interaction with the Standard Model

$$\Lambda^{-1} \equiv \lambda^2/4\pi M$$

- Astrophysics parameter: the mass of a dark matter halo at which a deviation from pure CDM occurs $M_{\rm halo}$

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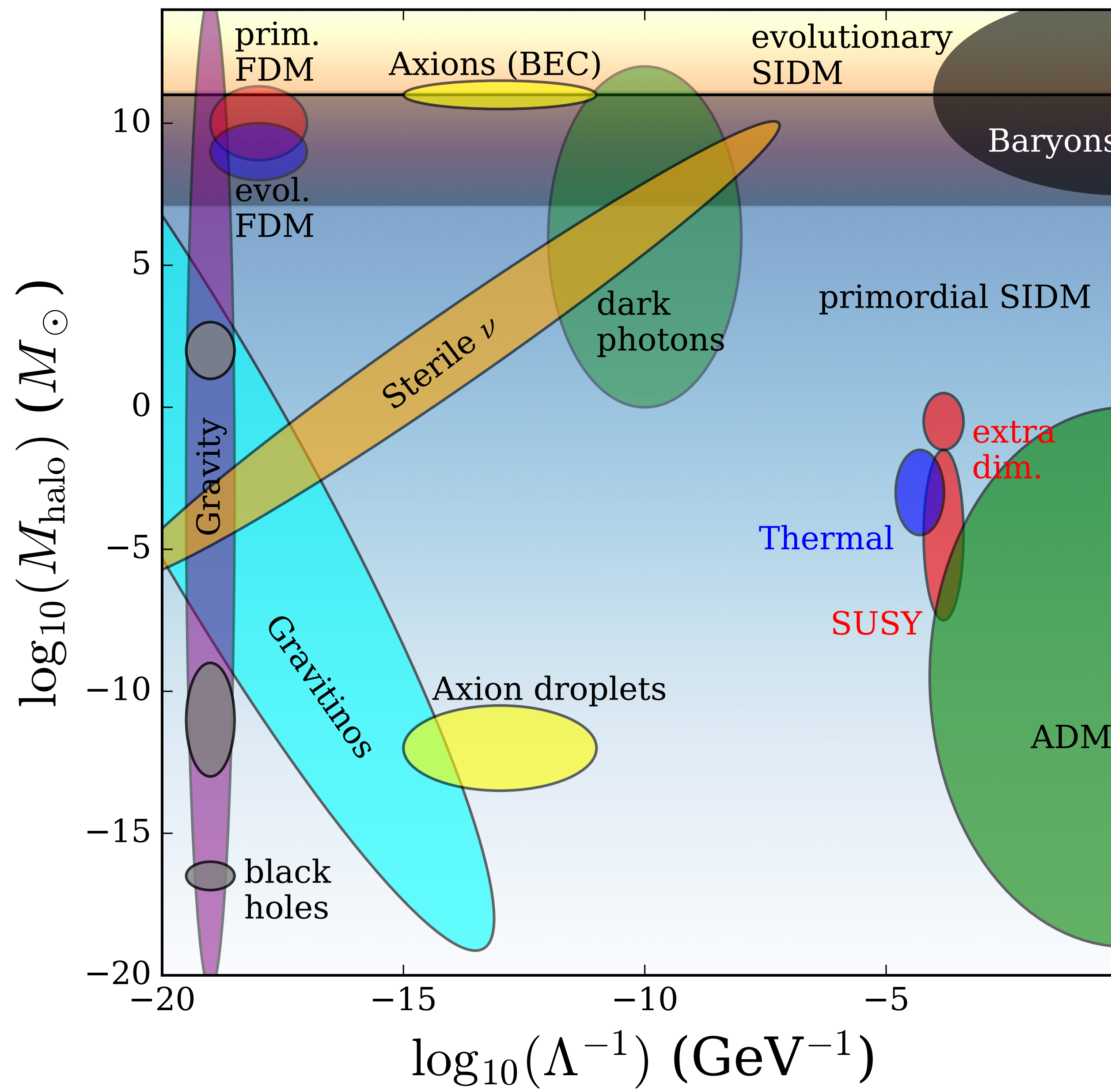


Example: Axions

- All phenomenology controlled by a single parameter, f_a

$$\Lambda^{-1} \sim \frac{e^2}{4\pi f_a} \sim 10^{-(11-15)}\ \mathrm{GeV}^{-1}$$

  - Or could be axion-like, suppressing interactions even further (ALPs or fuzzy dark matter)

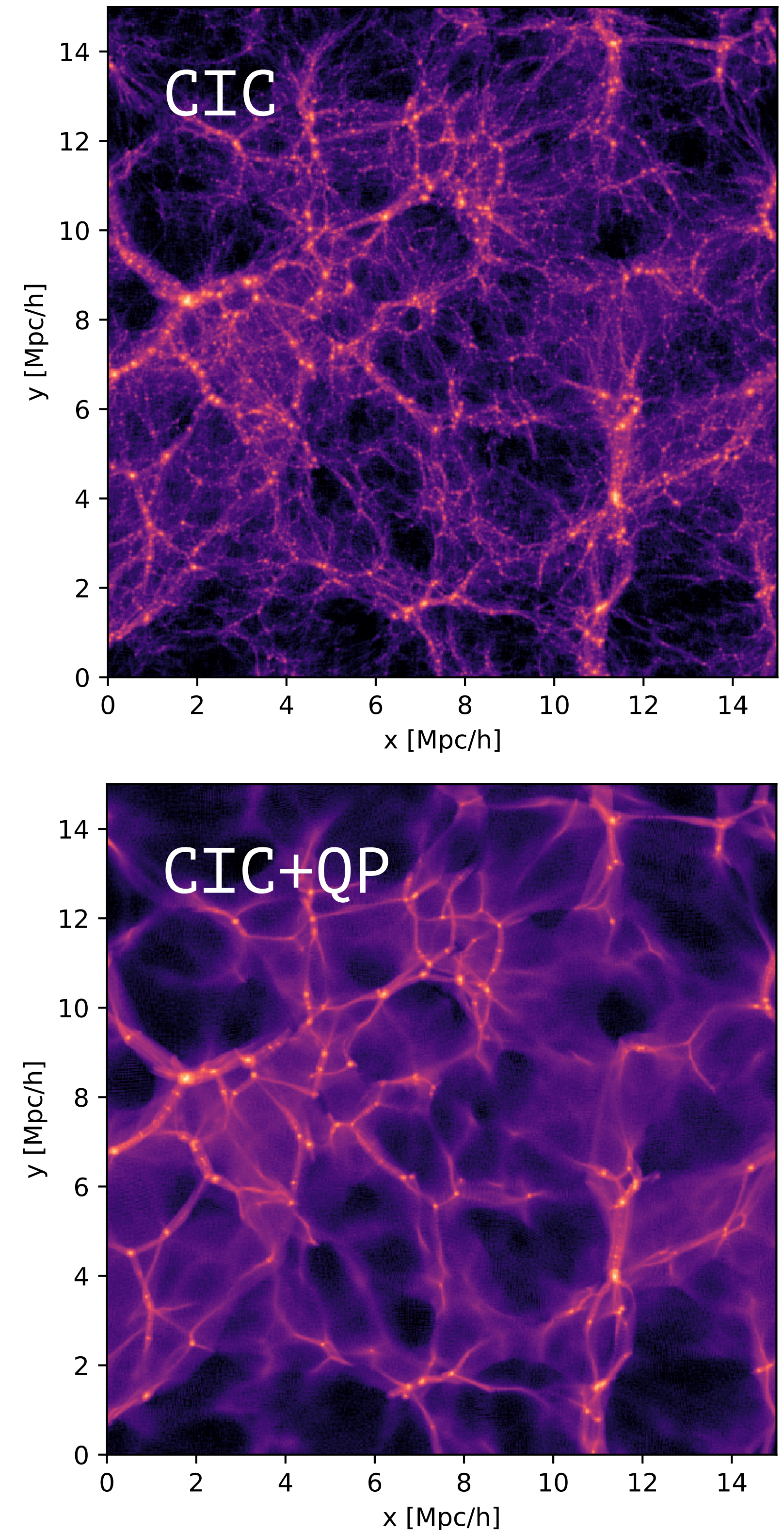
$$m_\chi \sim 10^{-(21-22)}\ \mathrm{eV}$$

$$\Lambda^{-1} \sim 10^{-(17-19)}\ \mathrm{GeV}^{-1}$$

- Halos modified by large wavelengths, possible BECs (caustics? or axion "nuggets"?)

$$M_{\mathrm{halo}} = 10^{-11}\, M_\odot - 10^{11}\, M_\odot$$

Nori and Baldi 1801.08144



The Crisis at Small Scales

- There are already indications of deviations from pure CDM:

$$M_{\rm halo} \sim 10^{8-11}\, M_\odot$$

  - Missing Satellites
  - "Too Big to Fail"
  - cusp/core

- Has driven model-building that alter halos at these scales

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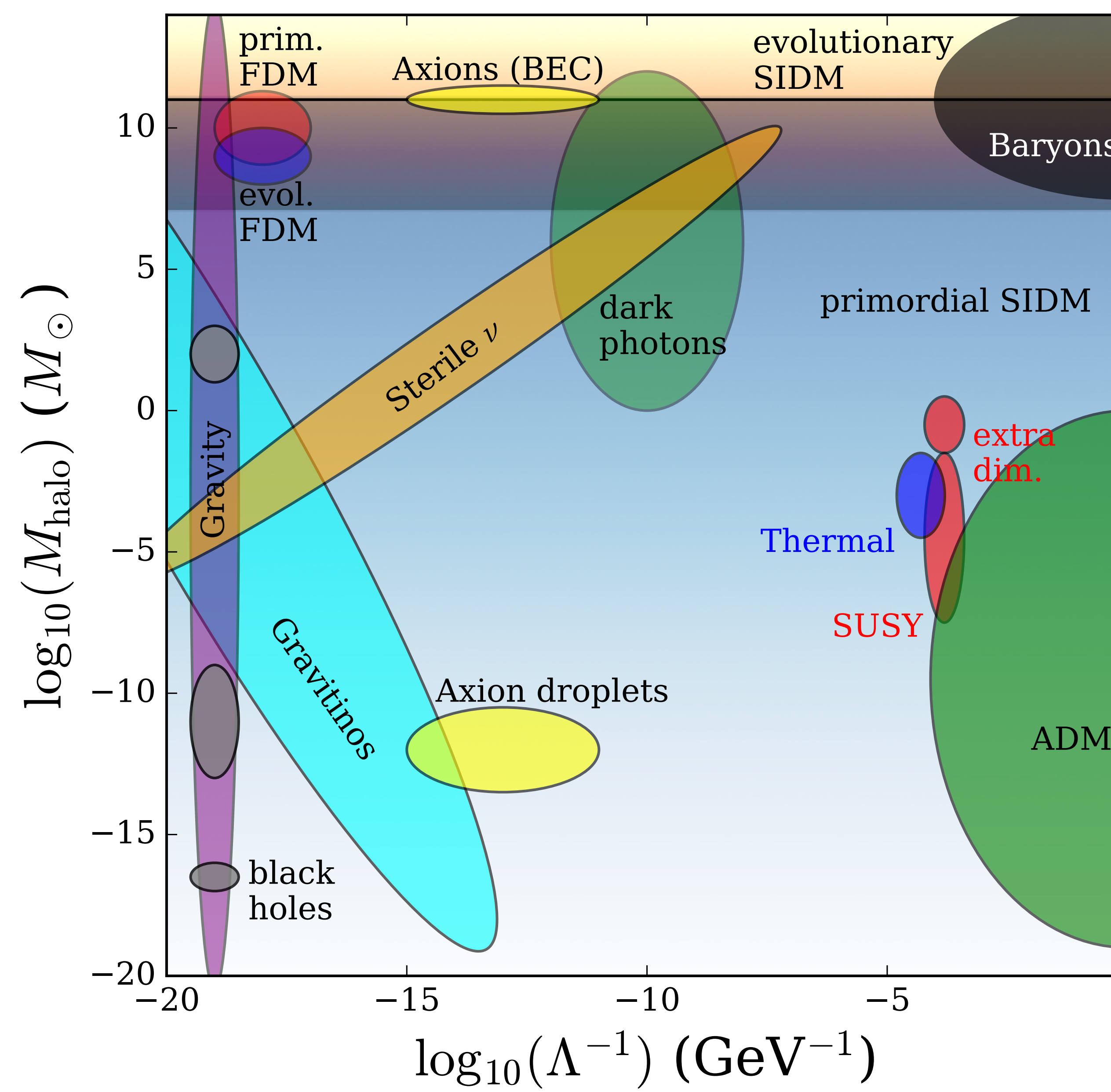
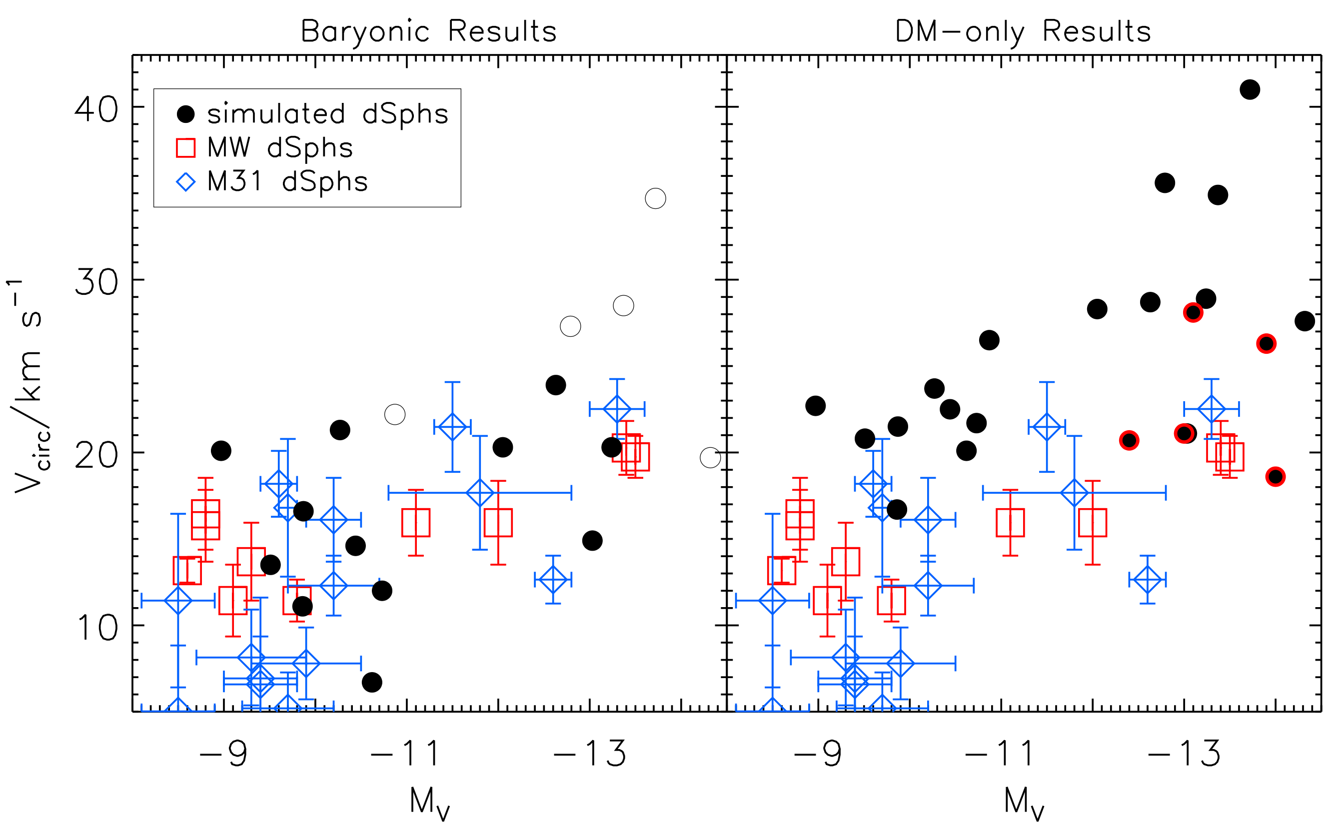


Lessons from a Crisis

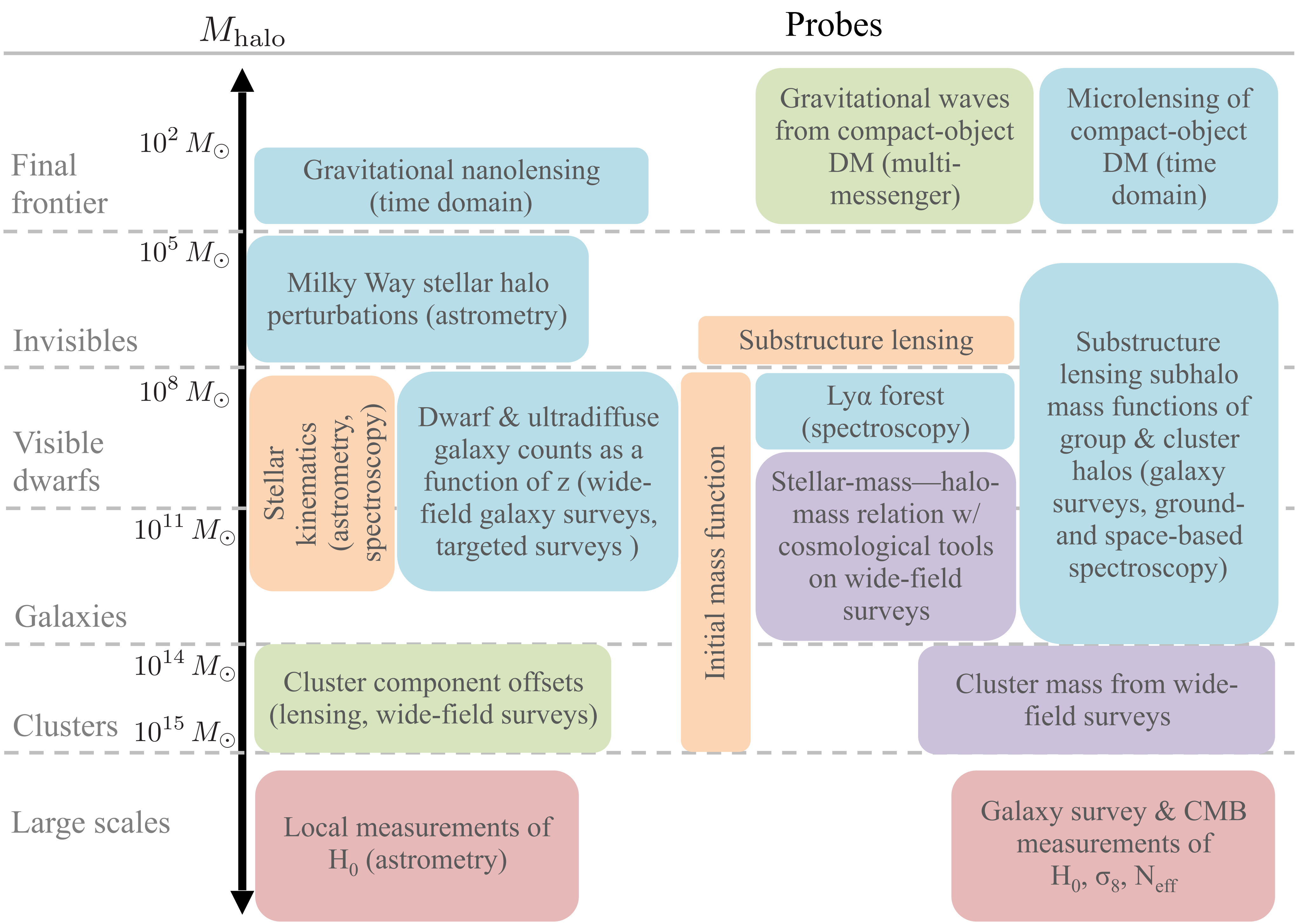
- CDM predictions were derived from dark-matter only simulations
- But baryons can have an important effect on the structure of halos at exactly the scales where the deviations appear.
    - May solve the “Crisis.”

- Take-away: we need to know the predictions of CDM+ baryons if we are to use astrophysics to discover particle physics.



Brooks & Zolotov 1207.2468

Astrophysical Opportunities



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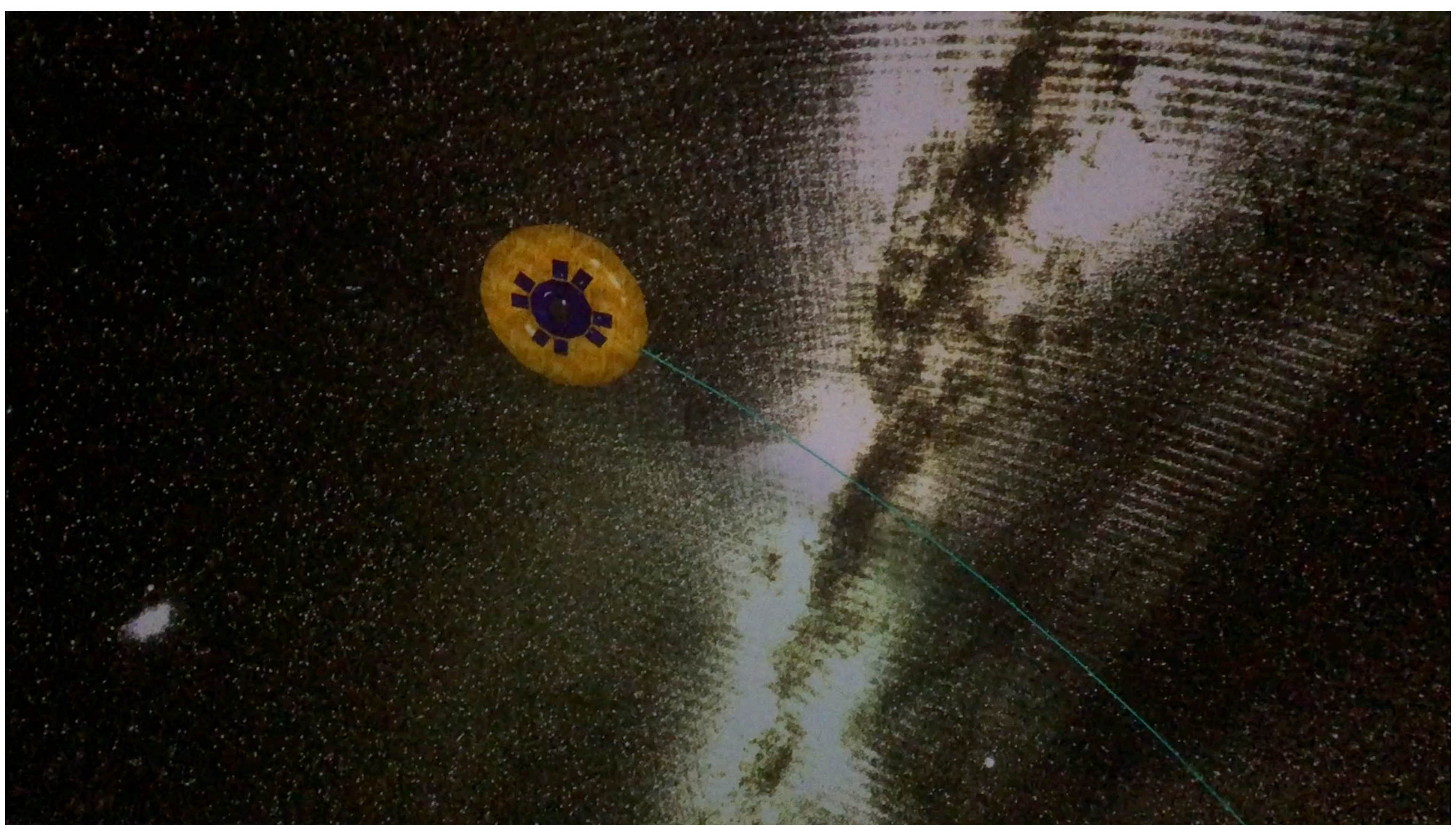
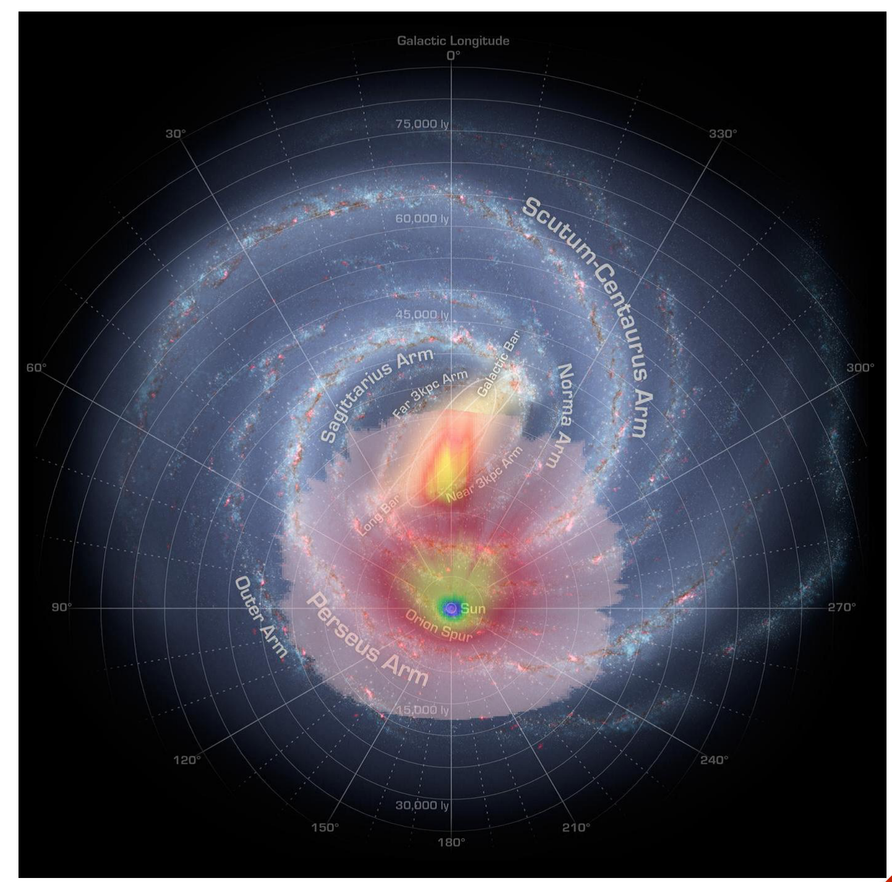
Opportunities from *Gaia*

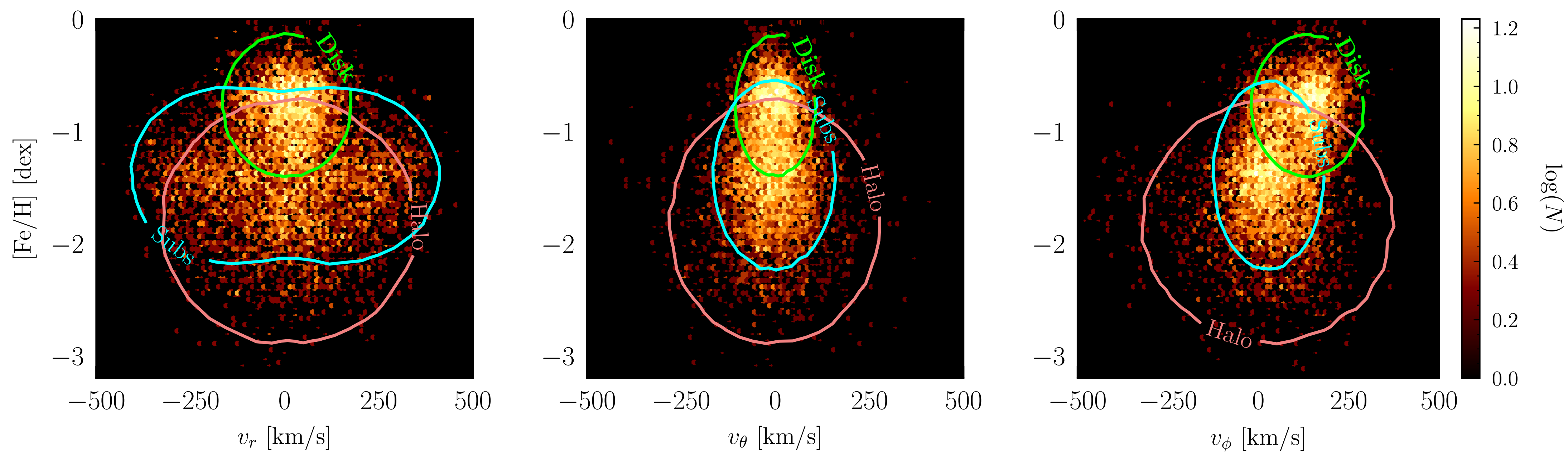
- My current obsession
  - 1.4 billion stars, mas/yr accuracy
  - A huge data set with lots to say about Galactic structure





Local Dark Matter Structure

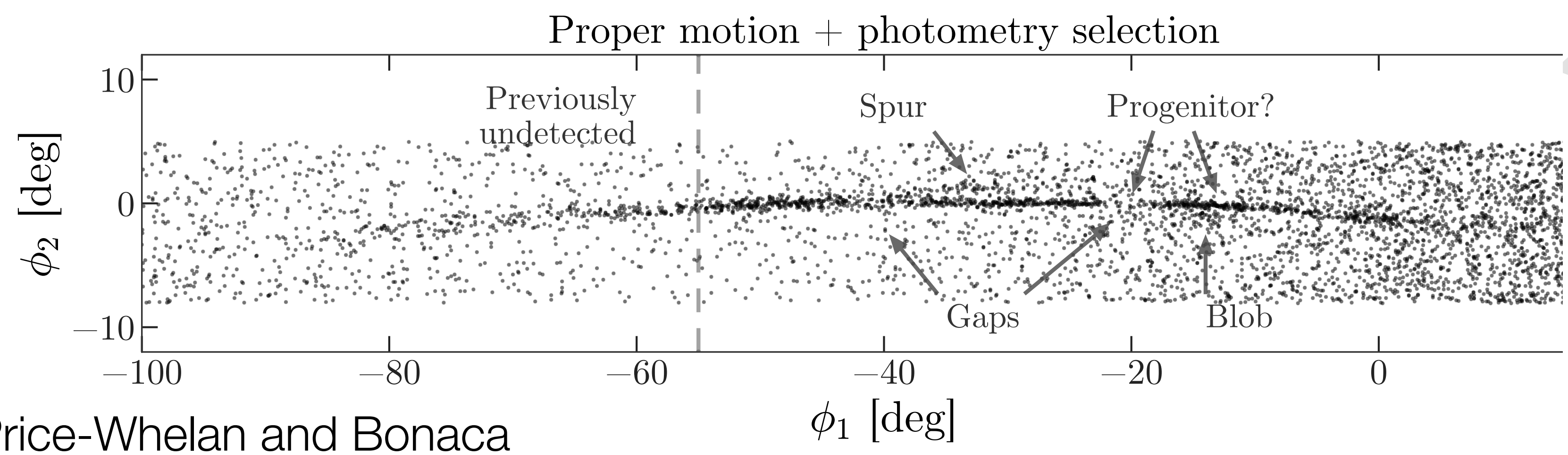
- The Milky Way was built hierarchically from smaller subhalos over cosmological time.
- Relics of these mergers are still apparent in the stellar velocity distributions.
- This impacts direct detection experiments, but what if we can use this data to get at the Galaxy's merger history? What can we learn about distribution of $M_{\rm halo}$



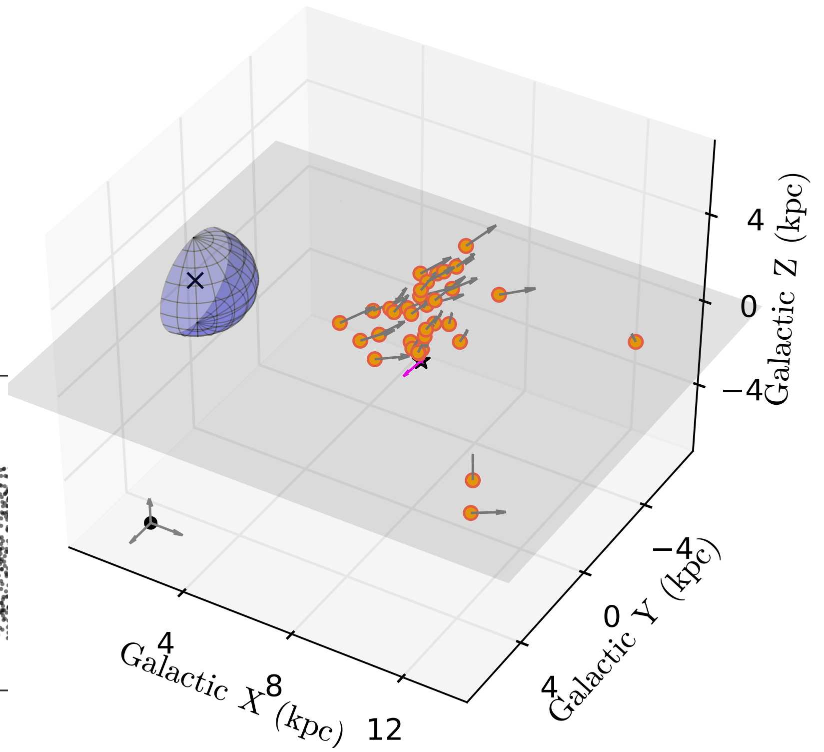
Necib *et al* 1807.02519

Dark Matter Streams

- Dark matter substructure forms streams as it is tidally disrupted
- Again, implications for direct detection.
- Gaps in the streams can indicate dark matter substructure



Price-Whelan and Bonaca 1805.00425

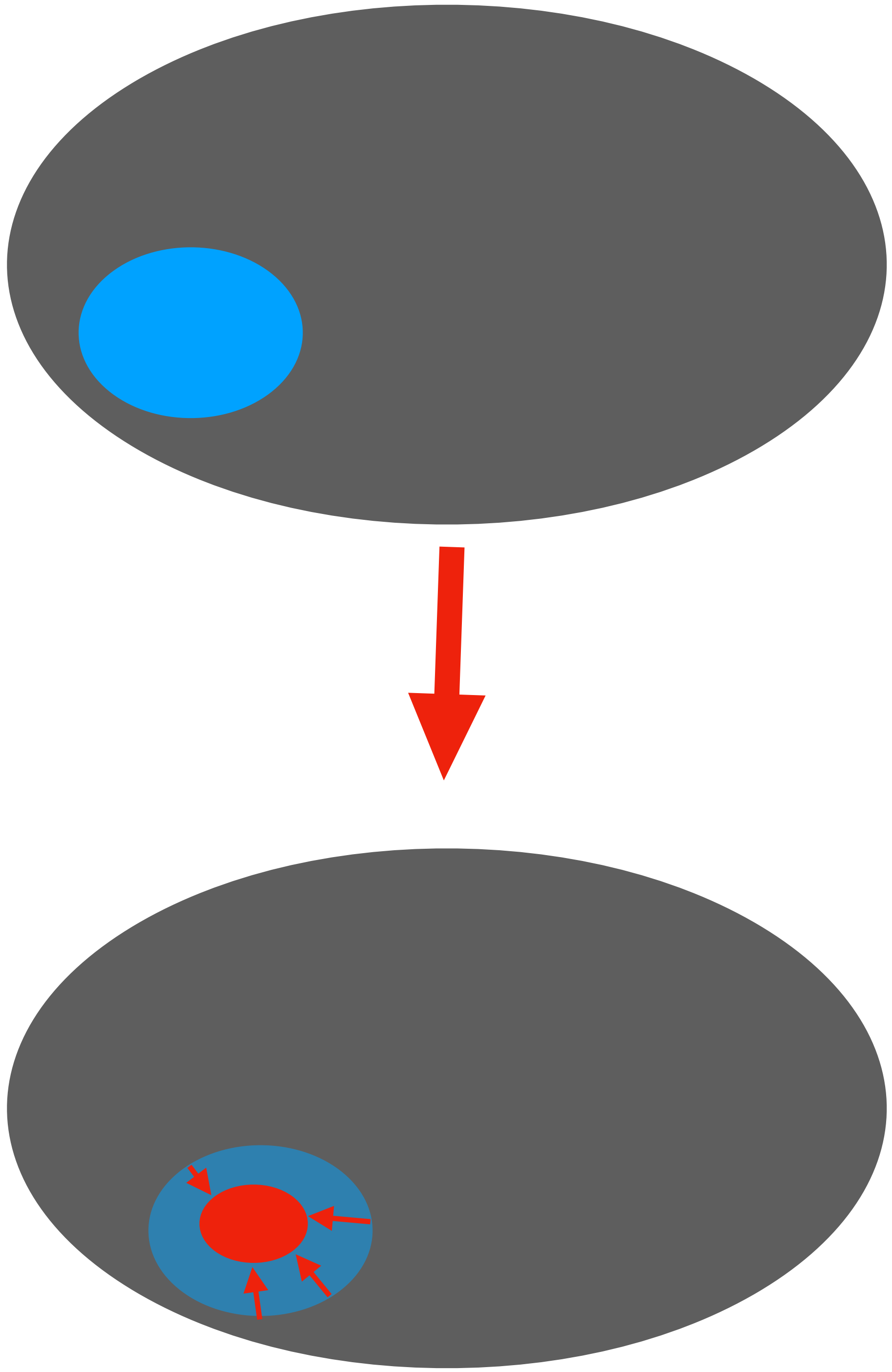


O'Hare *et al* 1807.09004

- But can we learn about the number and structure of these objects as they are tidally stripped? Or afterwards?

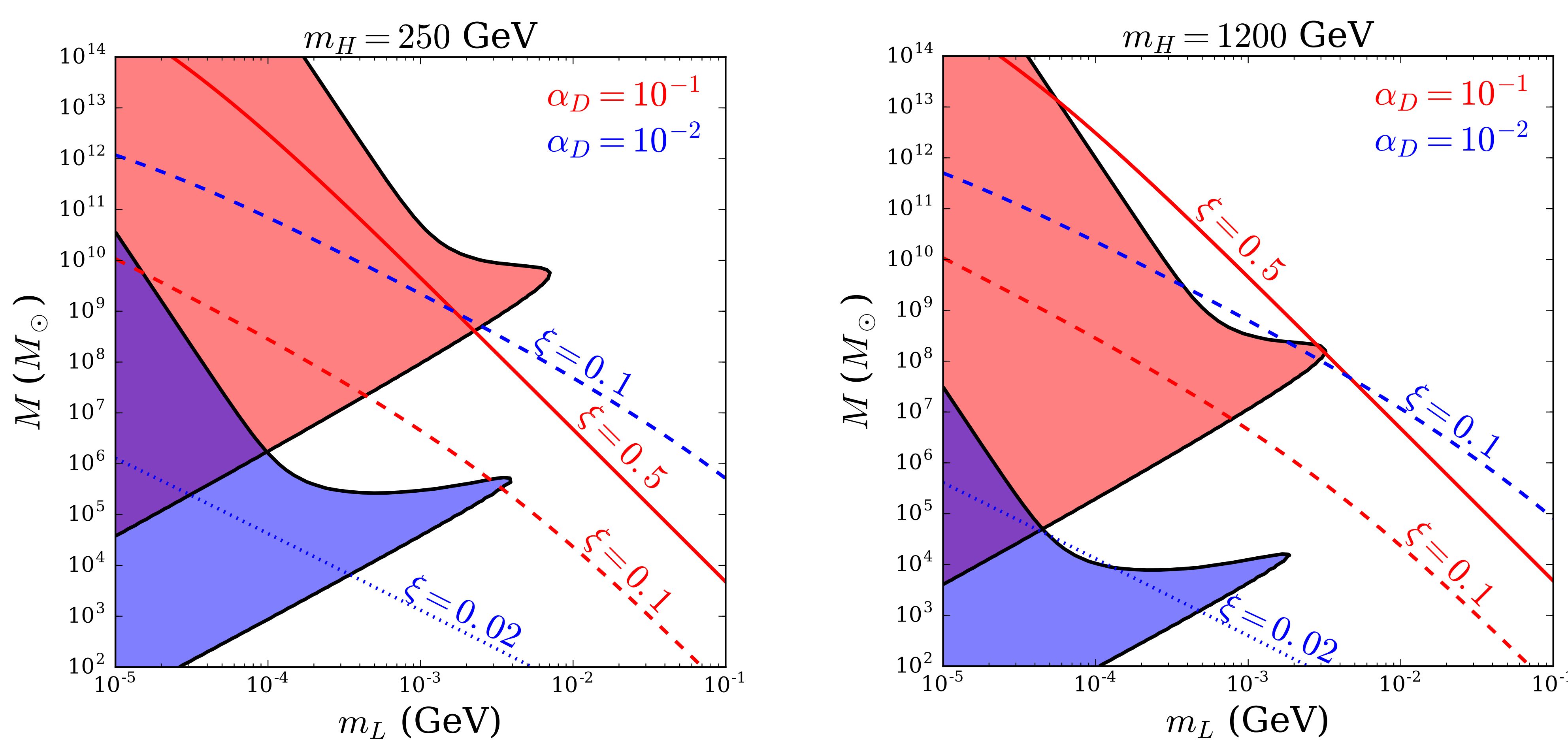
Collapsing Dark Matter

- CDM subhalos are expected to be tidally disrupted this close to the Milky Way disk.
  - So we haven't looked for them
  - Can we develop a dark matter model which makes denser subhalos that would survive close to a galaxy?
  - Without modifying the bigger halos.
- That is: get small halos to cool and collapse, while keeping the big halos untouched.



Like Baryons, but Dark

- Baryons in Milky Way-mass galaxies ($M_{\text{halo}} \sim 10^{12}\, M_{\odot}$) cool and collapse
- Baryons in galaxy clusters don't — the virial temperature is too large
- In a simple model, we found a range of parameters that would allow small dark matter halos to collapse, leaving large ones intact.



Buckley & Difranzo
1707.03829

Astrophysical Opportunities

- Dark matter is new physics.
  - We theorists just need a hint as to what kind of new physics
  - Astrophysicists need to know what to look for.

- Gravity has been the key to dark matter
  - It has a lot more to tell us

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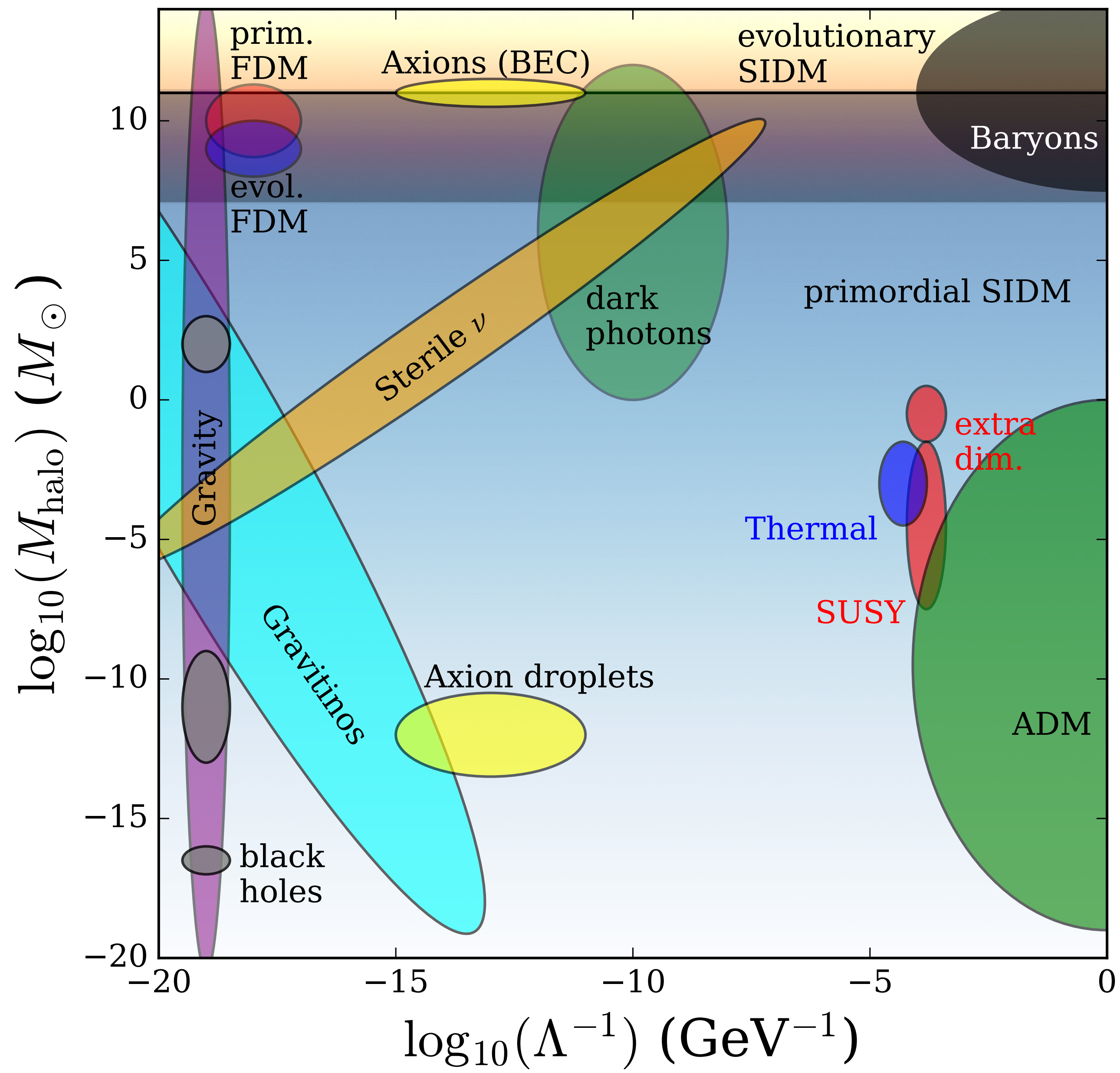

24