Astrophysical probes of dark matter: Challenge and solutions

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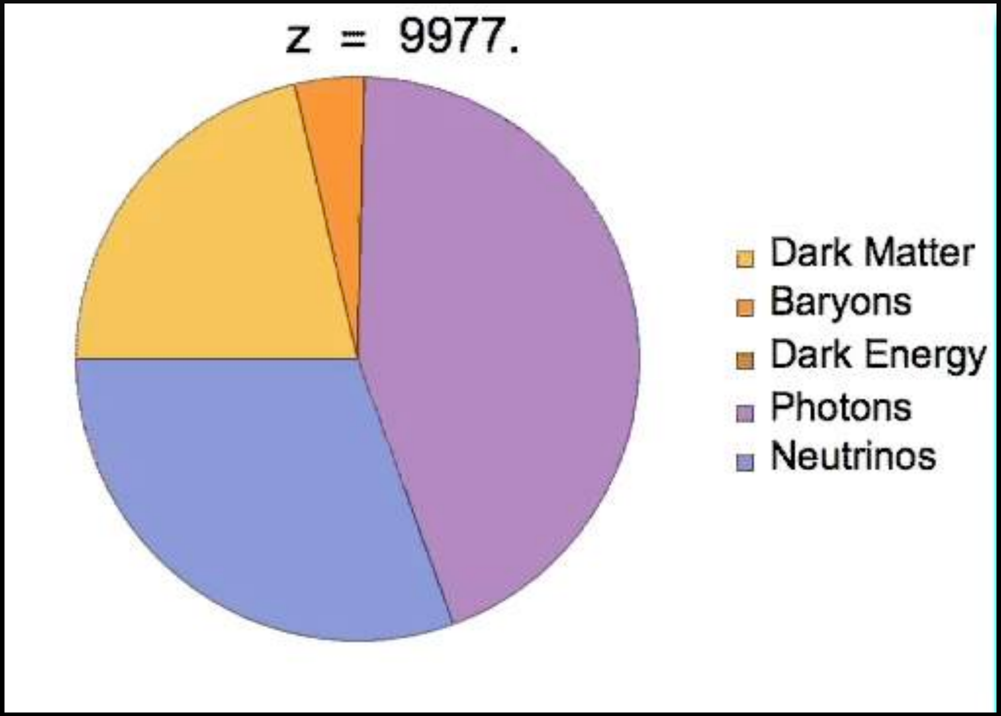
Dark Matter

- Dark matter forms 85% of the matter content of the Universe.
- For a significant part of the cosmological evolution, it is the most important constituent of our Universe.



Dark matter shapes the evolution of our Universe

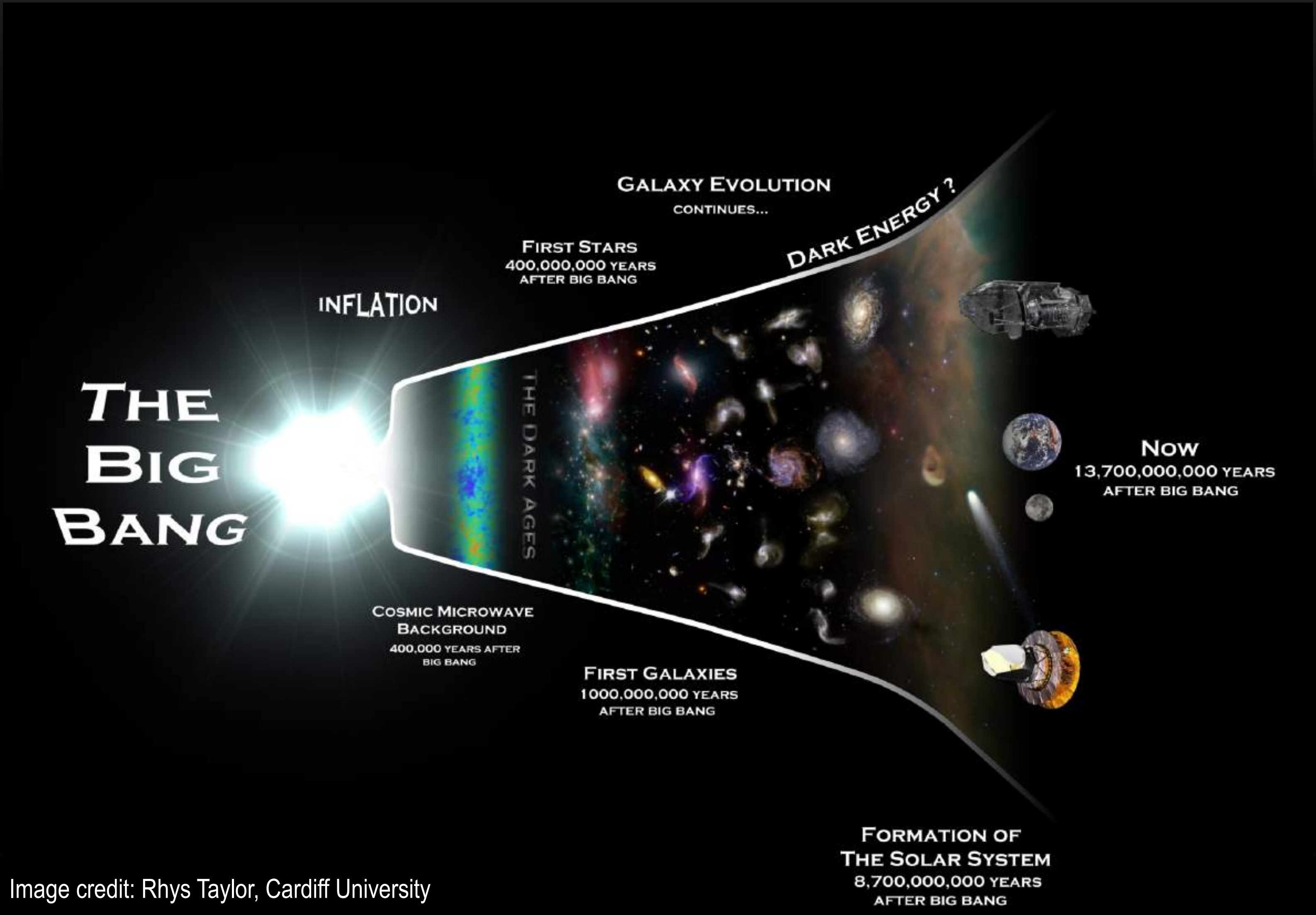
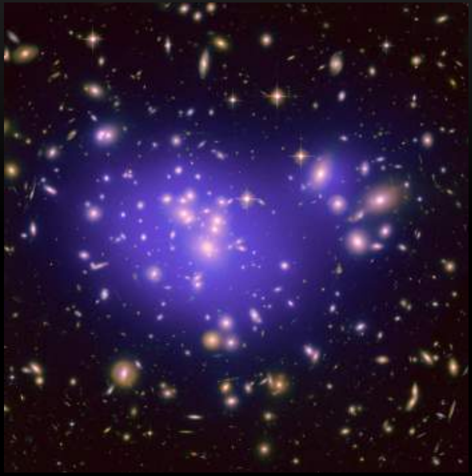


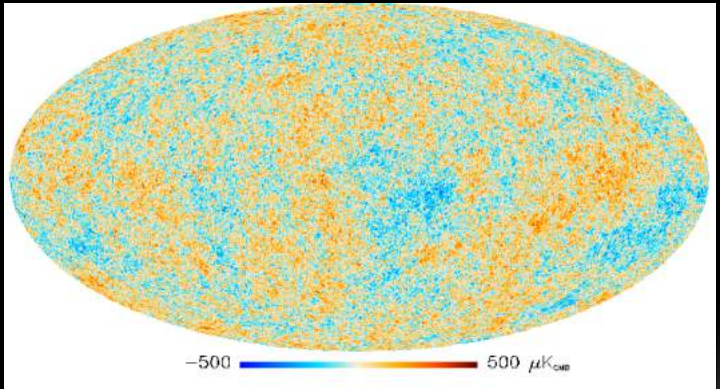
Image credit: Rhys Taylor, Cardiff University

Dark matter betrays its existence via its gravitational pull



- ✓ Motion of galaxies in clusters and gravitational lensing

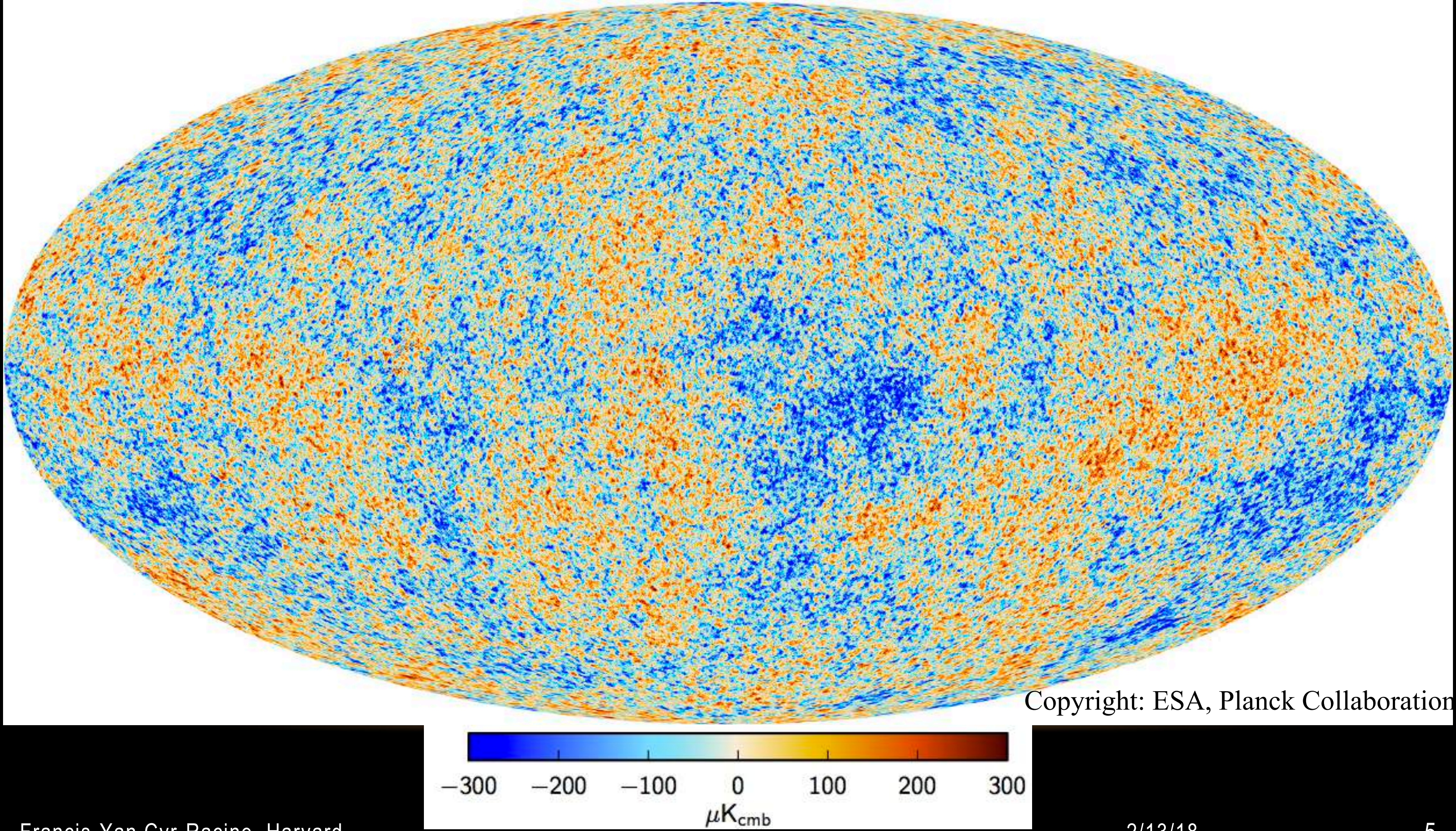
- ✓ Galaxy rotation curves



- ✓ Cosmic Microwave Background

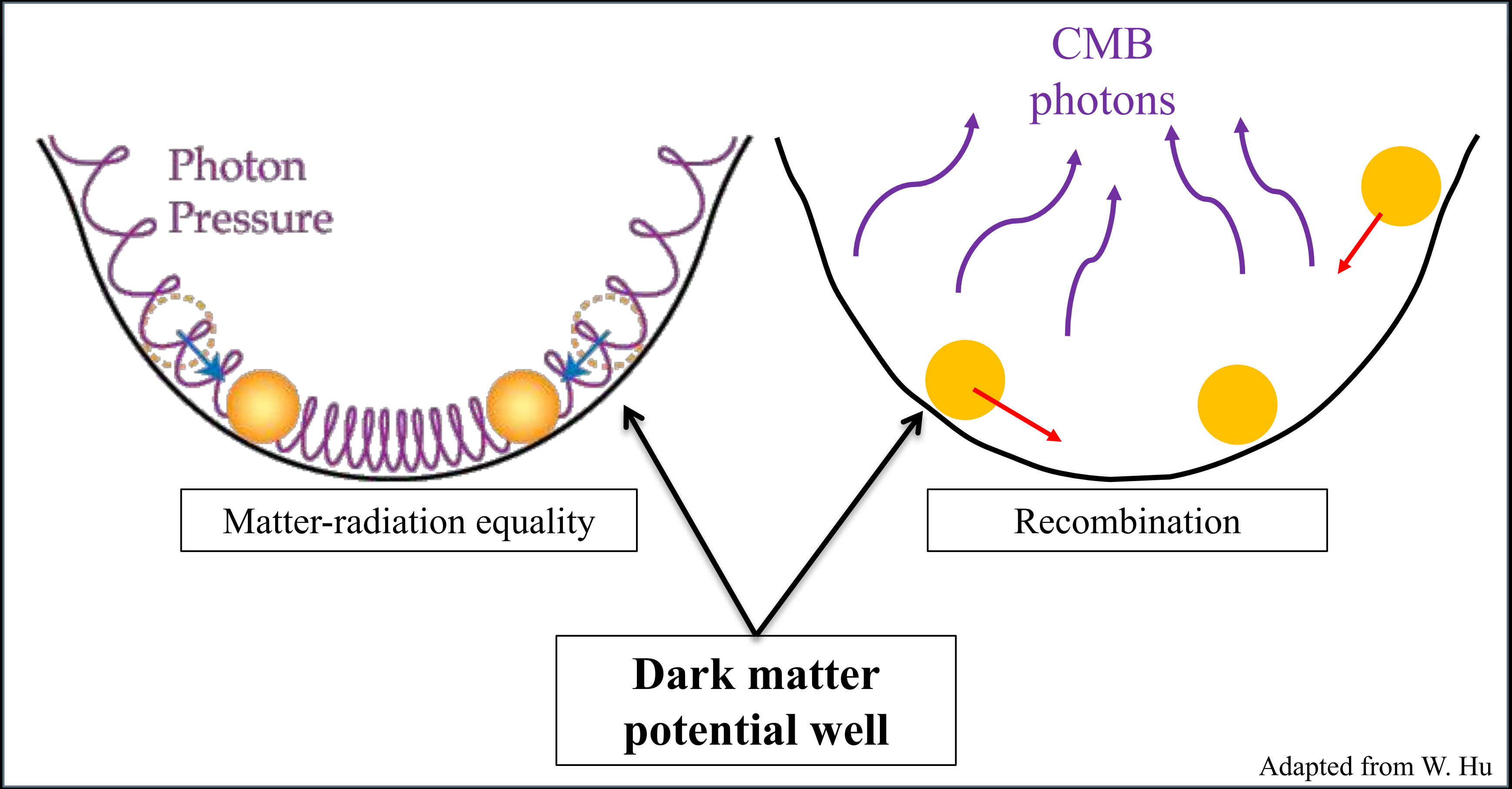
Strongest evidence for dark matter: CMB

CMB temperature fluctuation map as seen by the Planck satellite
“Picture” of the Universe when it is ~380,000 years old.



Copyright: ESA, Planck Collaboration

Dark matter provides gravitational potential wells for baryons to fall into



Matter-radiation equality

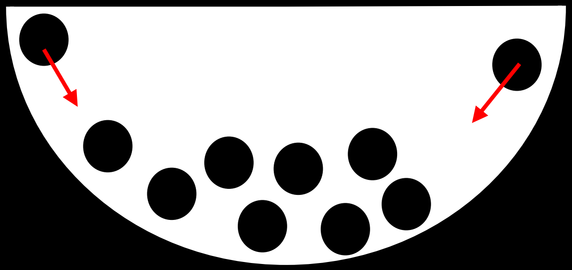
Recombination

Dark matter potential well

Adapted from W. Hu

The CMB not only tells us about the existence of dark matter, it tells us some of its properties

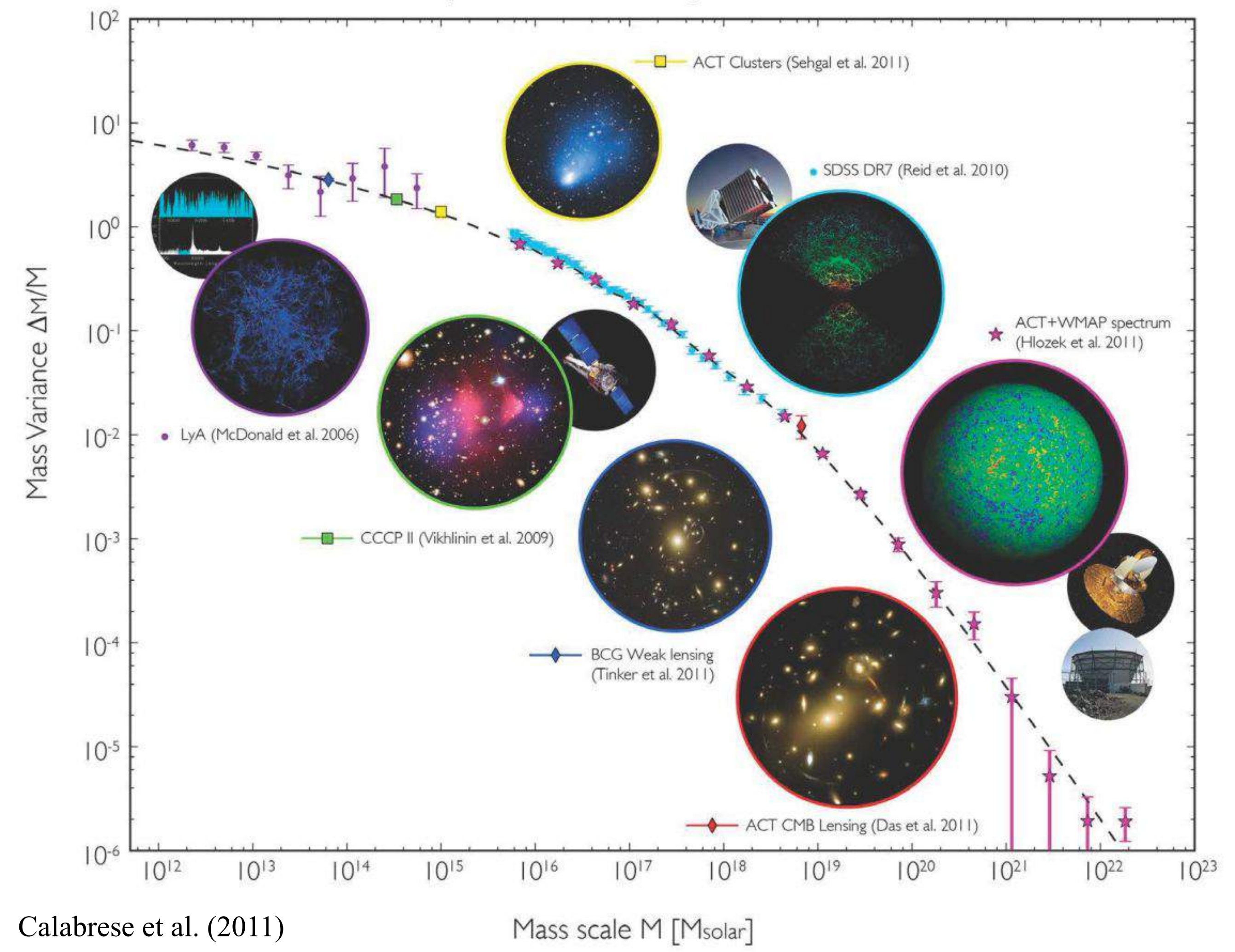
- The Cold Dark Matter (CDM) paradigm:
  1. Cold: A massive, non-relativistic particle.



(So that DM can form bound structure!)

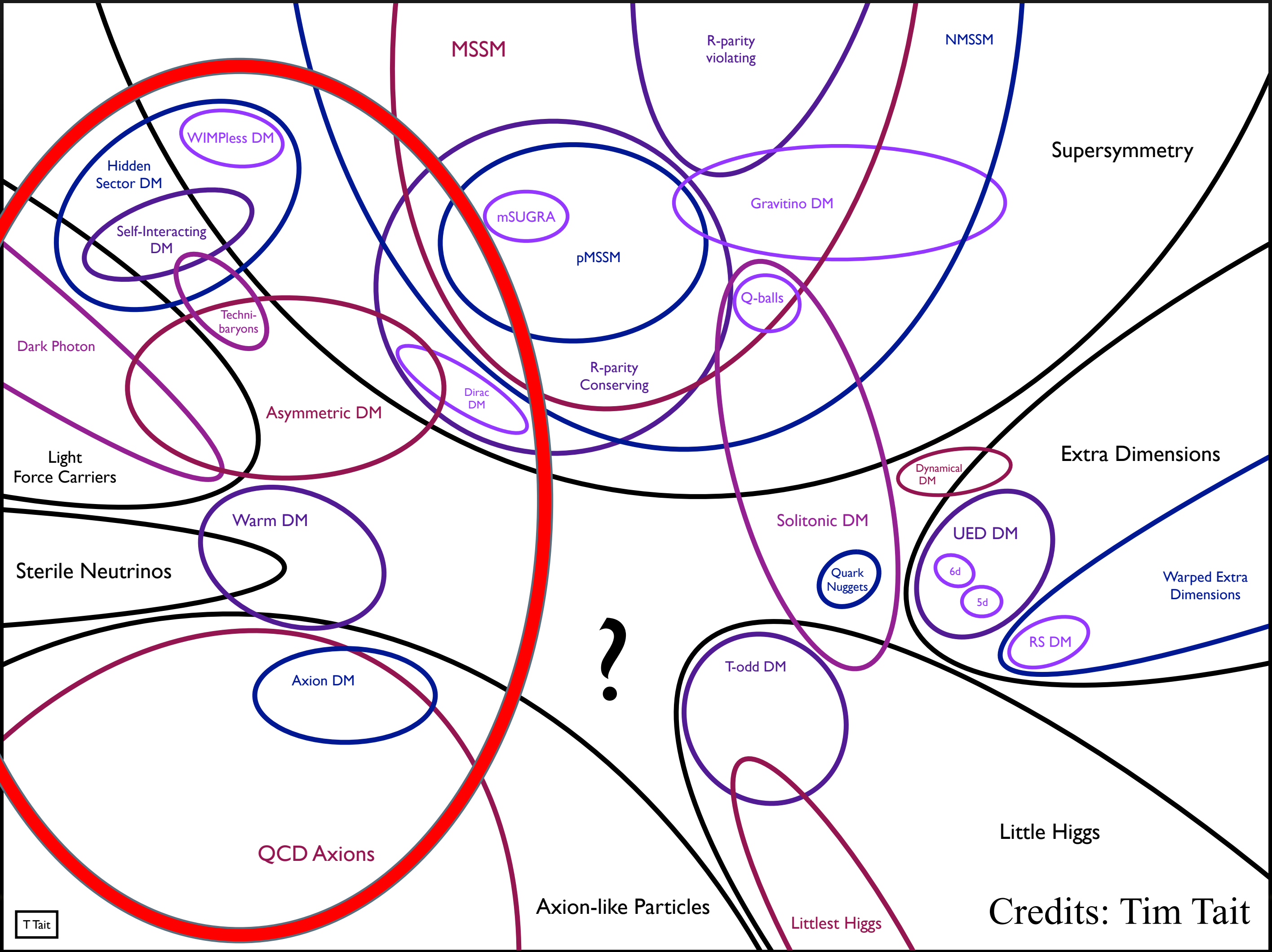
  2. Dark: Dark matter does not strongly interact with Standard Model particles, if at all.
  3. Collisionless: Dark matter particles do not interact with one another.

On large scales, the cold dark matter picture is remarkably consistent



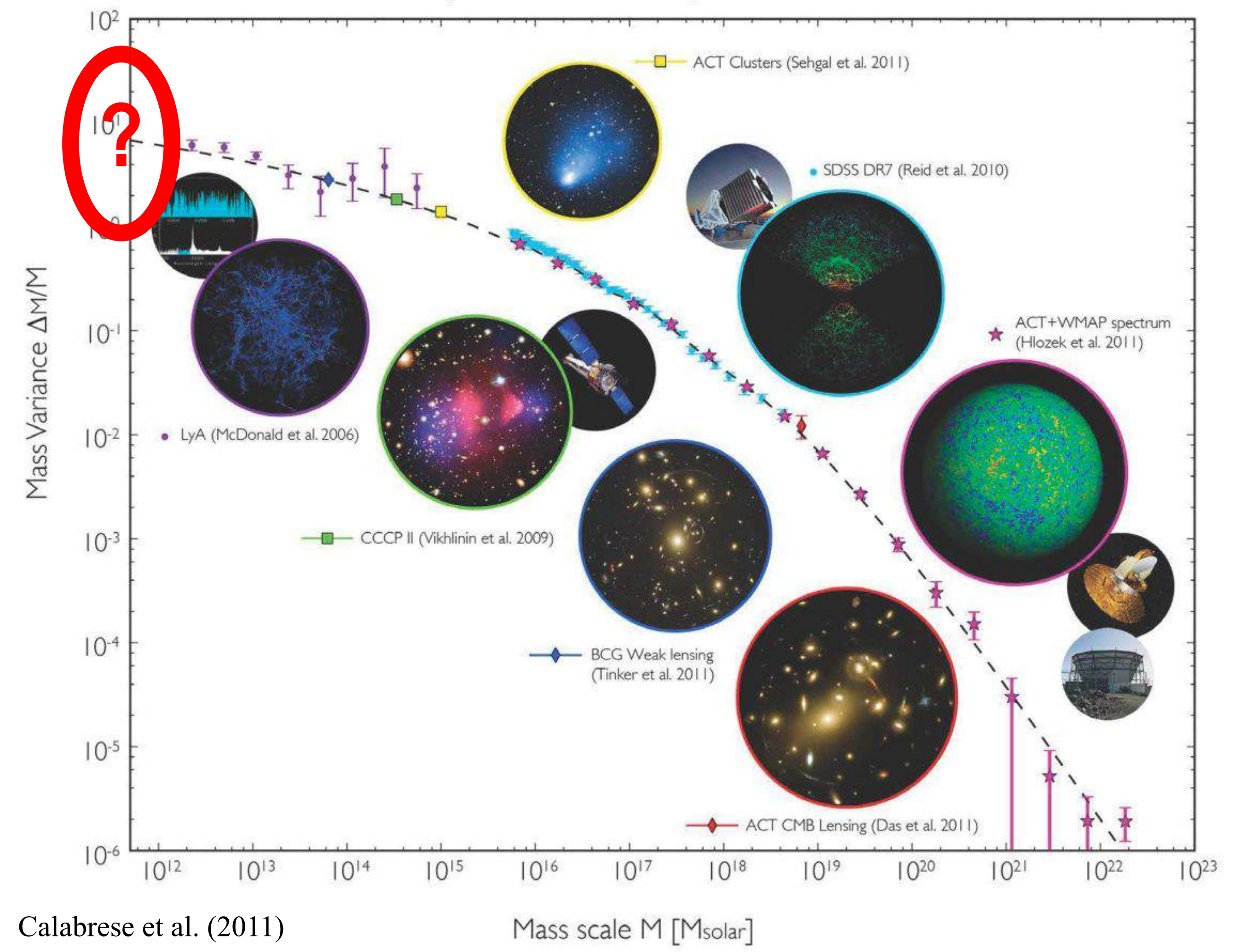
Calabrese et al. (2011)

This is great, but so many particle candidate can fit the CMB data…which one is right??



Credits: Tim Tait

Probing small mass/length scales is key to determine the particle properties of DM

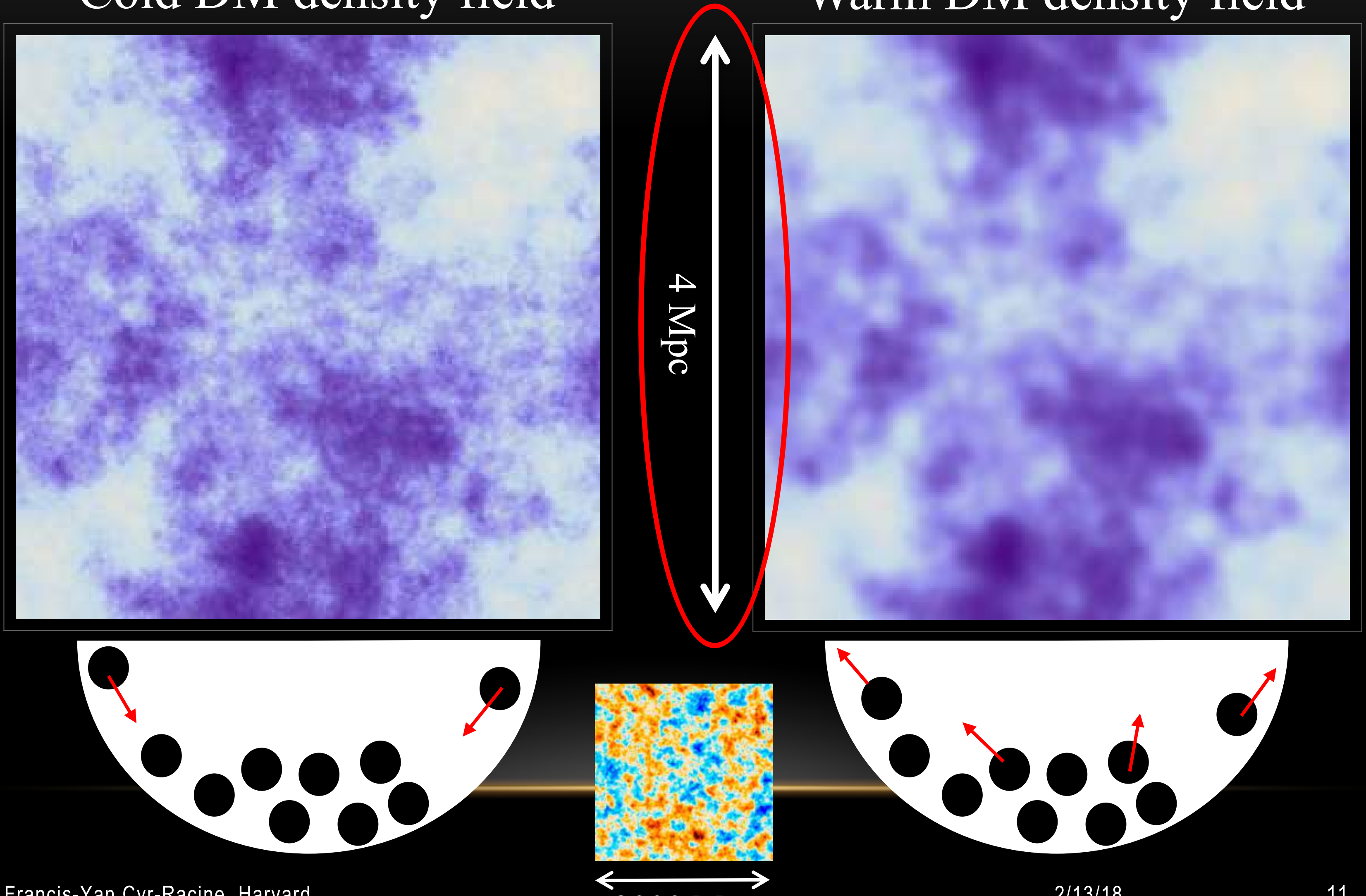


Calabrese et al. (2011)

Example: Distinguishing cold DM from a 2 keV warm DM

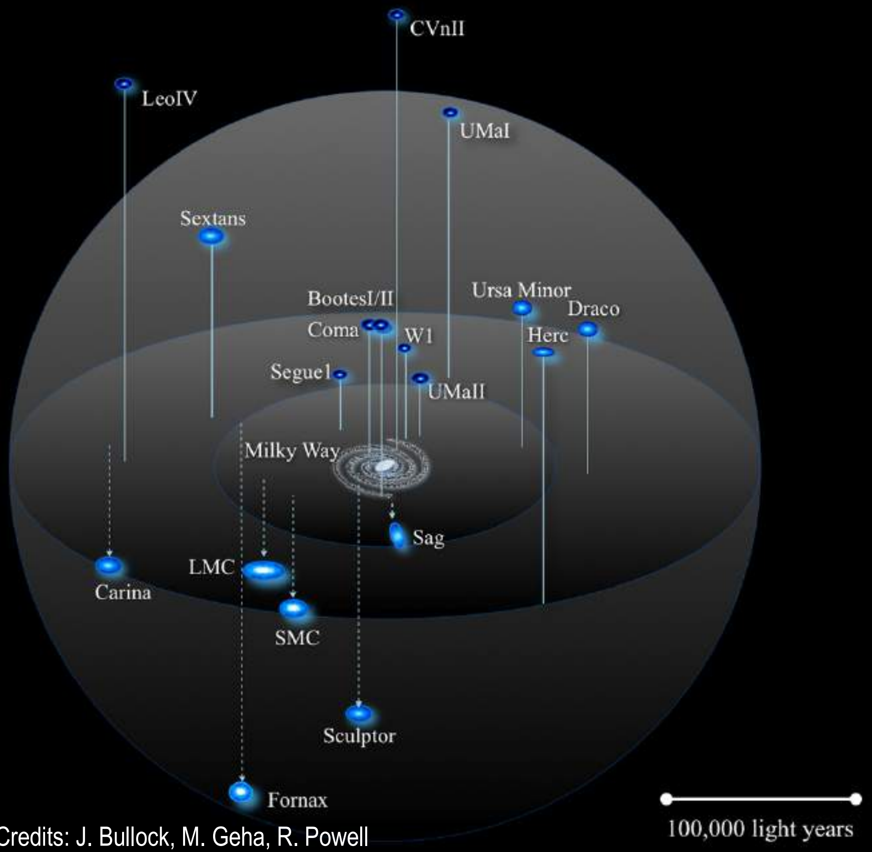
Cold DM density field

Warm DM density field

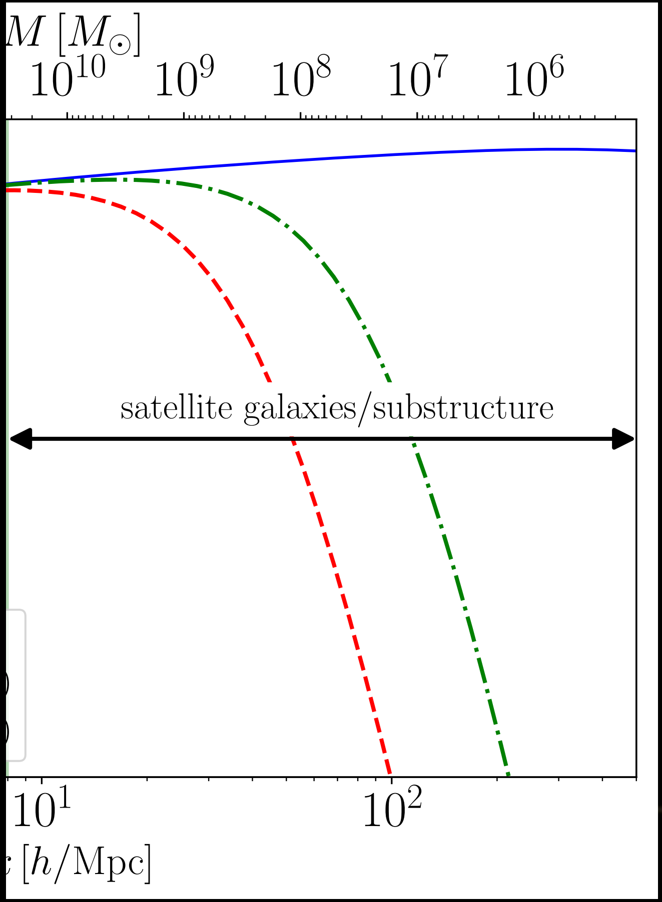


A quantitative comparison between dark matter models

- The matter power spectrum tells us the typical amplitude of matter fluctuations at different scales.

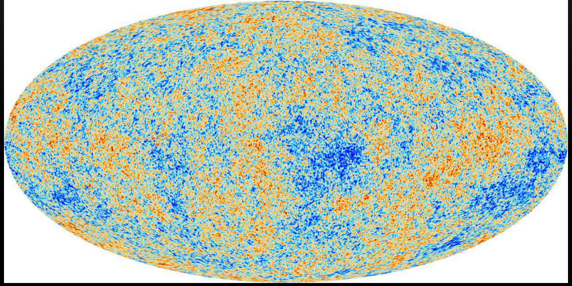


Credits: J. Bullock, M. Geha, R. Powell

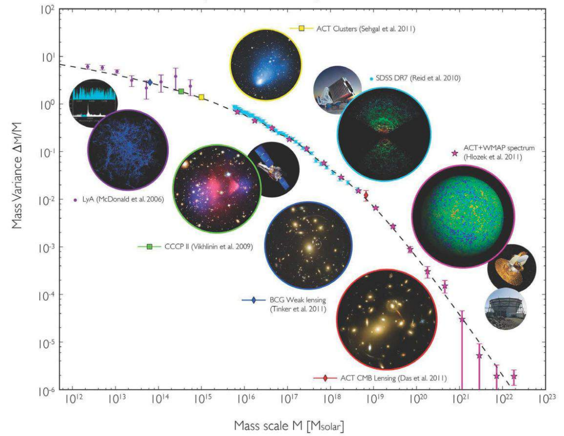


Introduction: Executive summary

- The CMB provides extremely compelling evidence for the existence of dark matter, based on simple and well-understood physics.



- The cold dark matter paradigm is remarkably consistent with observations of the CMB and large-scale structure.



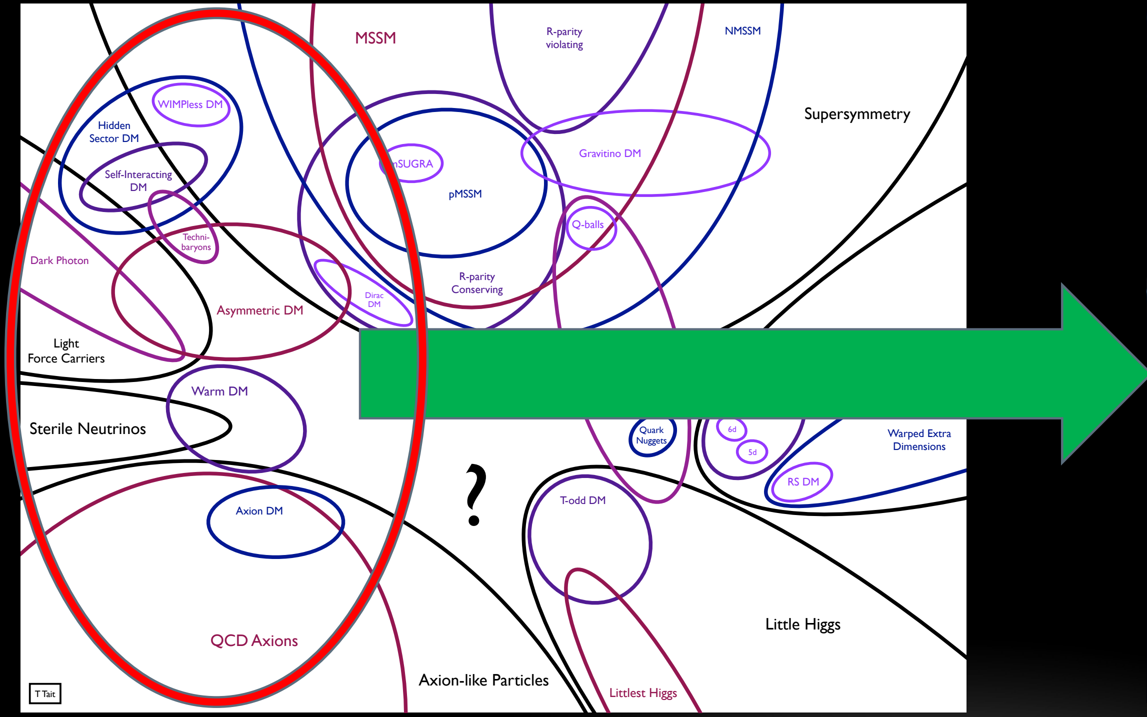
- The particle nature of dark matter only becomes apparent on small sub-galactic scales.

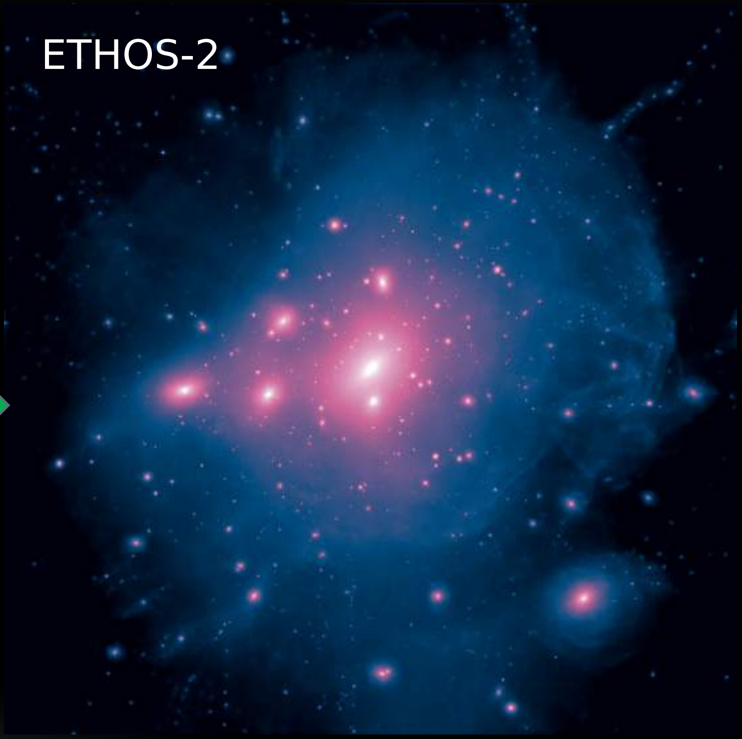
Probing small-scale structure: Outline

1) Part I: Understanding how the different possible dark matter physics affect structure formation on sub-galactic scales.
   - The ETHOS collaboration: bringing together simulators, theorists, astronomers, and cosmologists to explore uncharted territory in dark matter science.
2) Part II: Using observations of small-scale structure to constrain dark matter physics.
   - Probing substructure through galaxy-scale strong gravitational lensing.

Part I: From dark matter physics to observable predictions

- We need to understand how dark matter microphysics affects small-scale structure.





Vogelsberger, Zavala, Cyr-Racine +, arXiv:1512.05349

The ETHOS collaboration

- The ETHOS collaboration brings together simulators, theorists, astronomers, and cosmologists to understand the impact of dark matter microphysics on a broad range of astronomical observations.

Simulation

Jesús Zavala
Iceland

Simulation

M. Vogelsberger
MIT

Particle astrophysics

F.-Y. Cyr-Racine
Harvard

Particle theory

T. Bringmann
Oslo

Astronomy

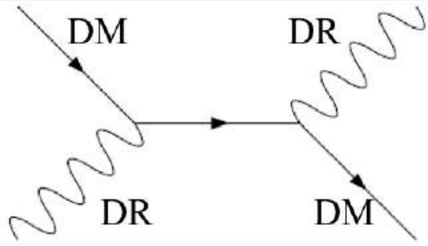
C. Pfrommer
Potsdam

+ New Members!

Cosmology

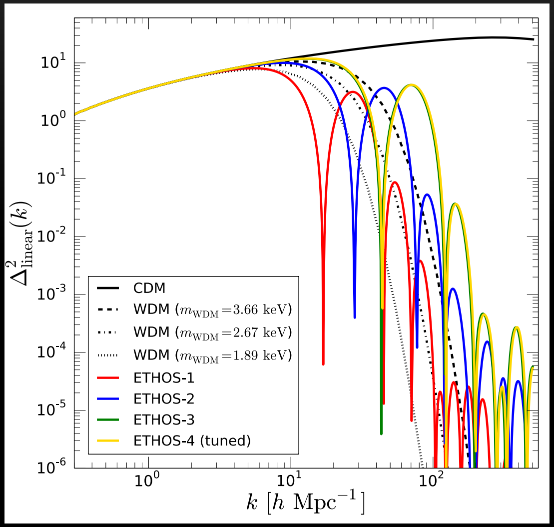
Kris Sigurdson
UBC

The ETHOS research program



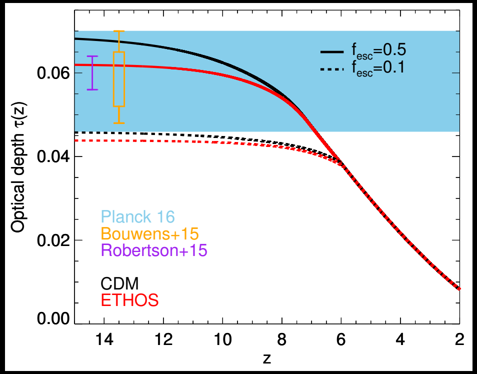
Impact on matter power spectrum

Cyr-Racine et al., PRD (2016)



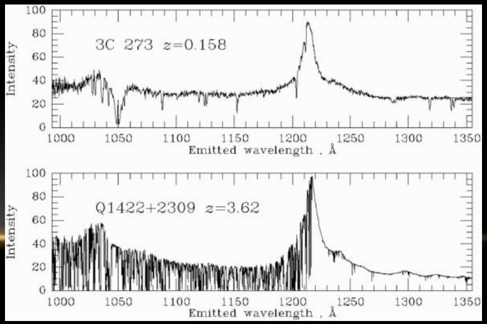
Impact on reionization

Lovell, Zavala, Vogelsberger, Shen, Cyr-Racine et al. (2017)



Impact on Milky Way galaxy

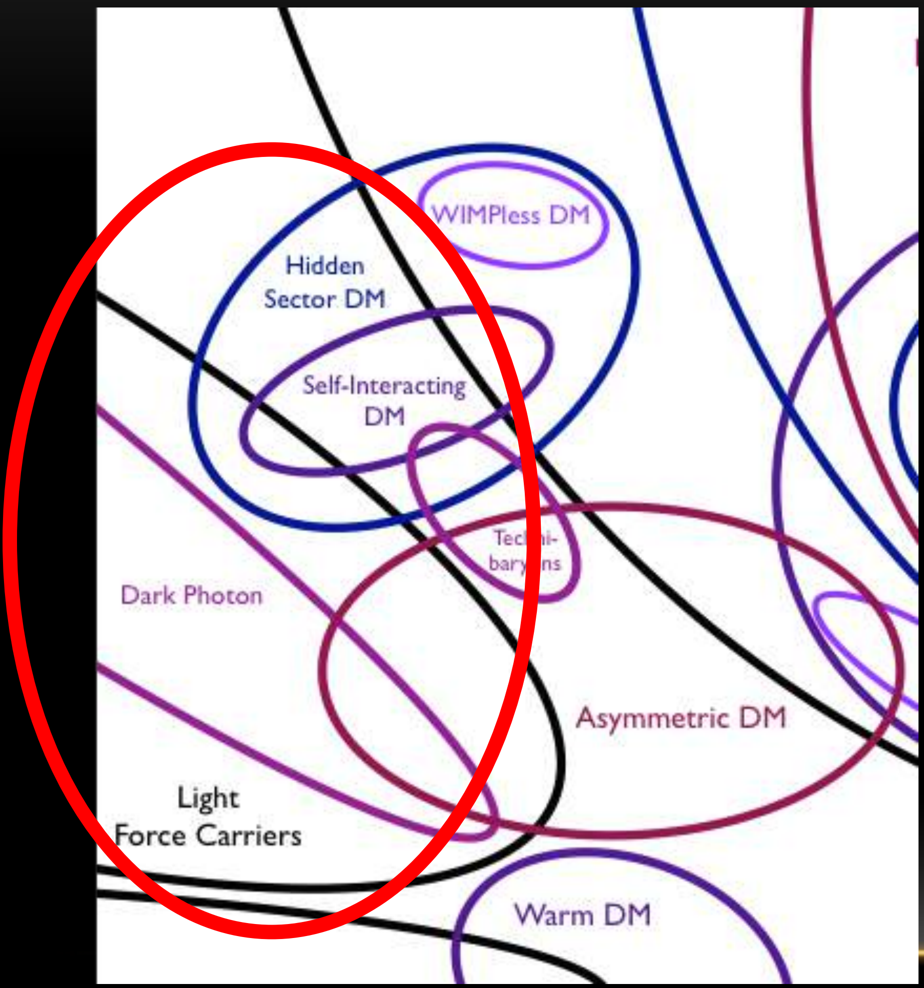
Vogelsberger, Zavala, Cyr-Racine et al., MNRAS (2016)

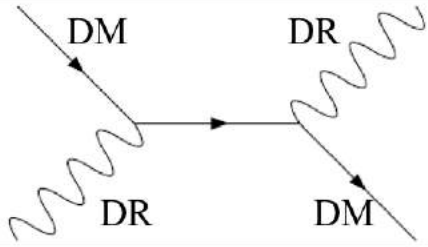


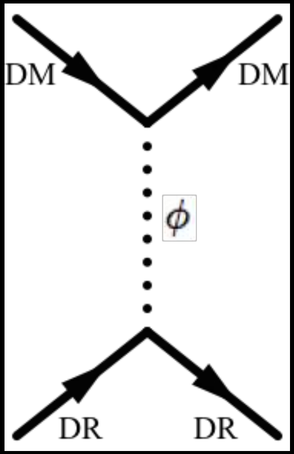
Impact on Lyman-α forest

Bose, Zavala, Vogelsberger, Cyr-Racine et al. in prep. (2018)

Exploring the impact of new interactions in the dark sector

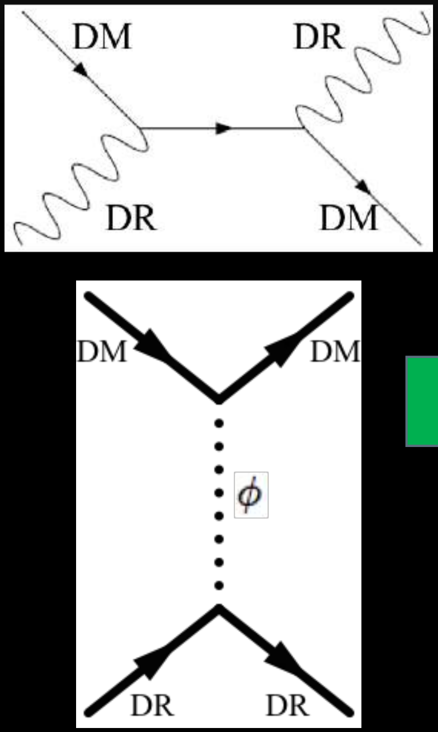




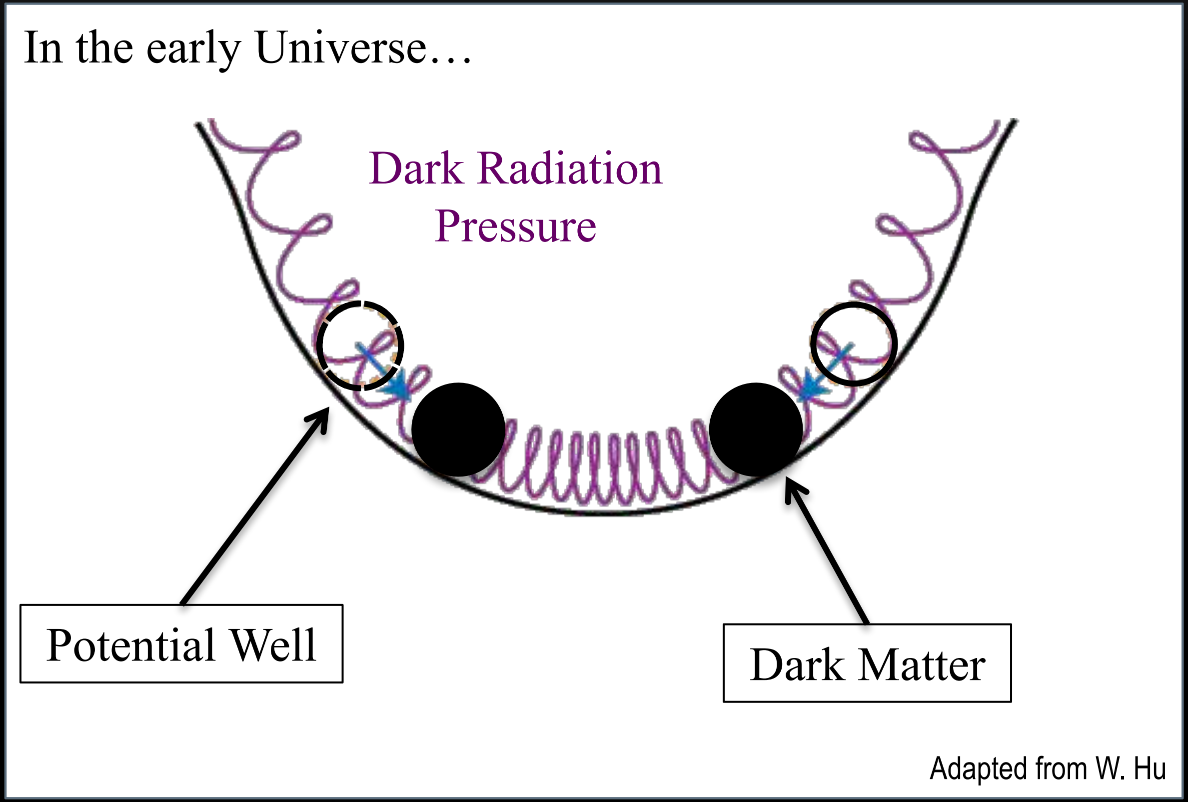


And many more!

The effect of new dark matter-dark radiation (DR) interactions



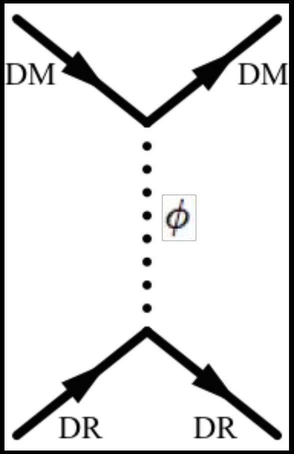
Cyr-Racine et al. (2016)
Cyr-Racine et al. (2014)
Cyr-Racine & Sigurdson (2013)


In the early Universe…

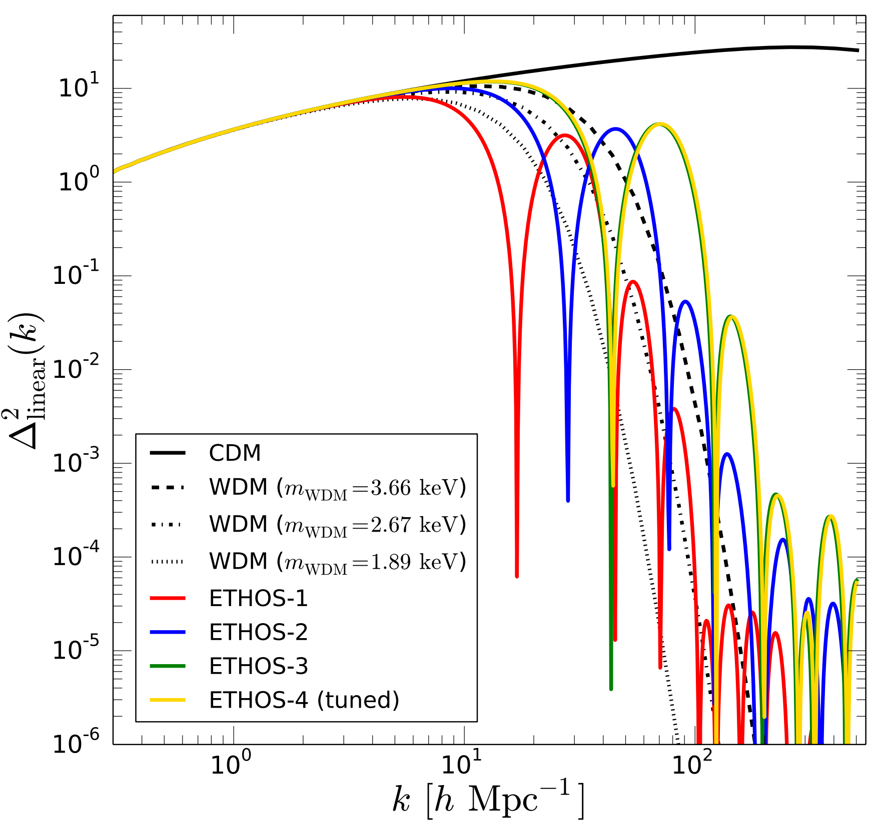
Adapted from W. Hu

Dark acoustic oscillation (DAO)

The effect of new dark matter-dark radiation (DR) interactions



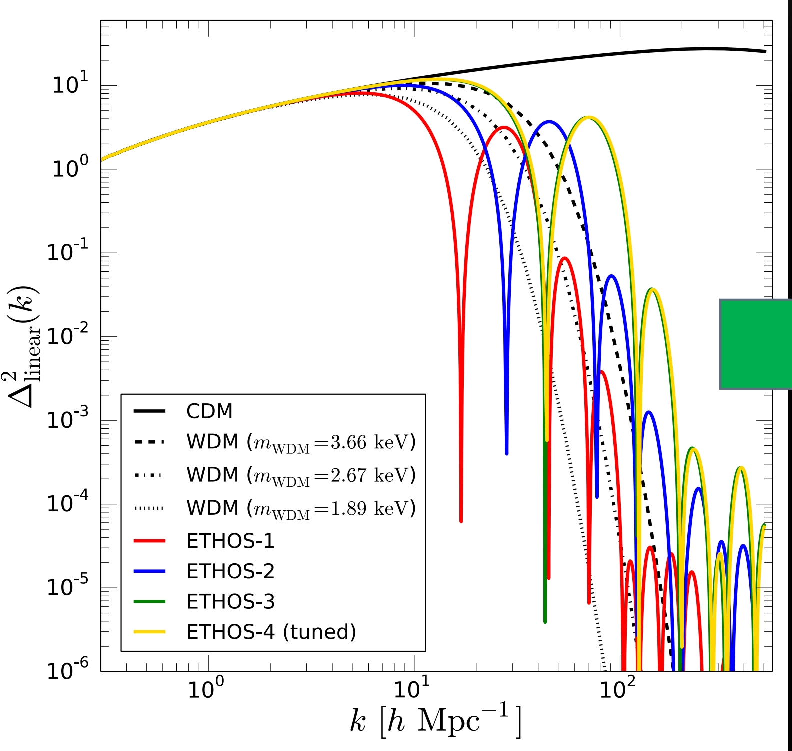
Boltzmann equations

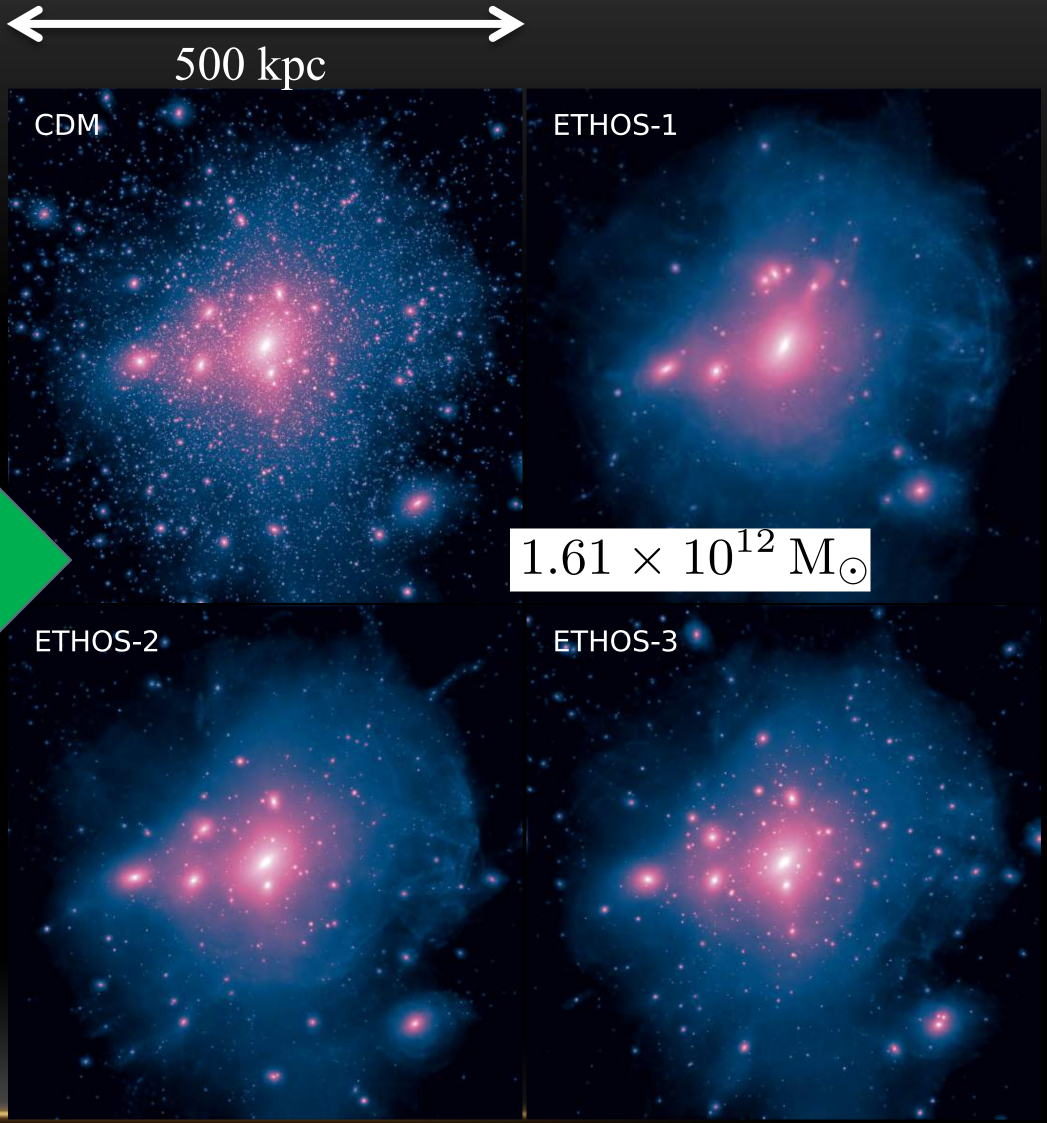


Cyr-Racine et al. (2016)
Vogelsberger, Zavala, Cyr-Racine et al. (2016)

Dark acoustic oscillation (DAO)

ETHOS: Understanding the Milky Way





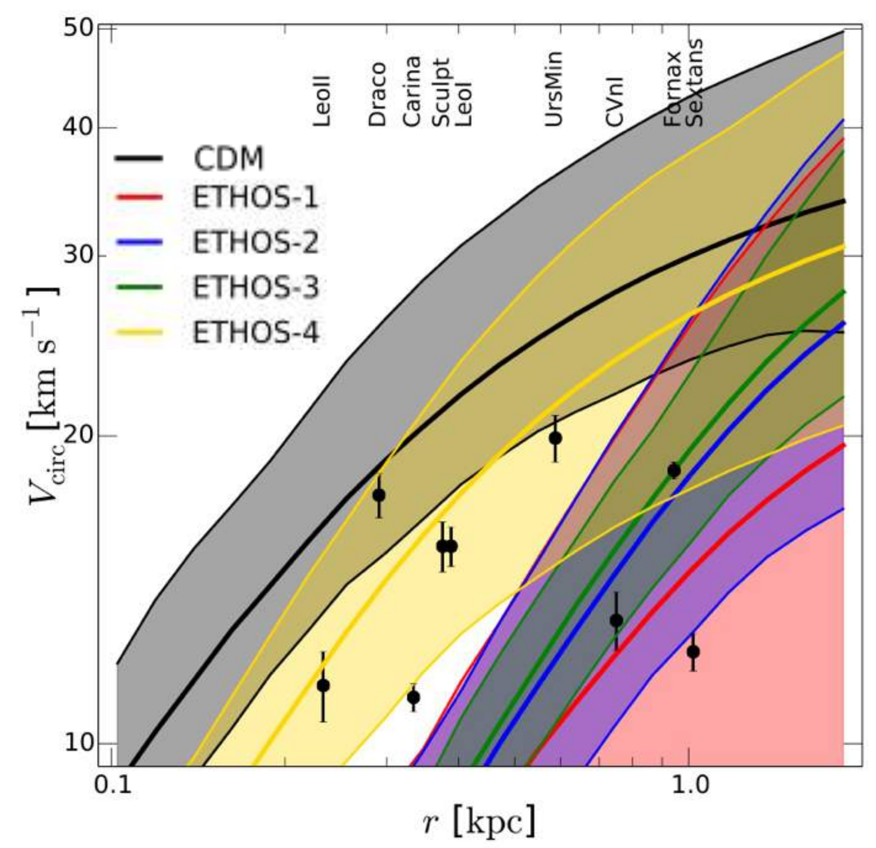
Vogelsberger, Zavala, Cyr-Racine +, arXiv:1512.05349

ETHOS: Understanding the Milky Way

Vogelsberger, Zavala, Cyr-Racine +, arXiv:1512.05349

ETHOS: Impact on satellite galaxies

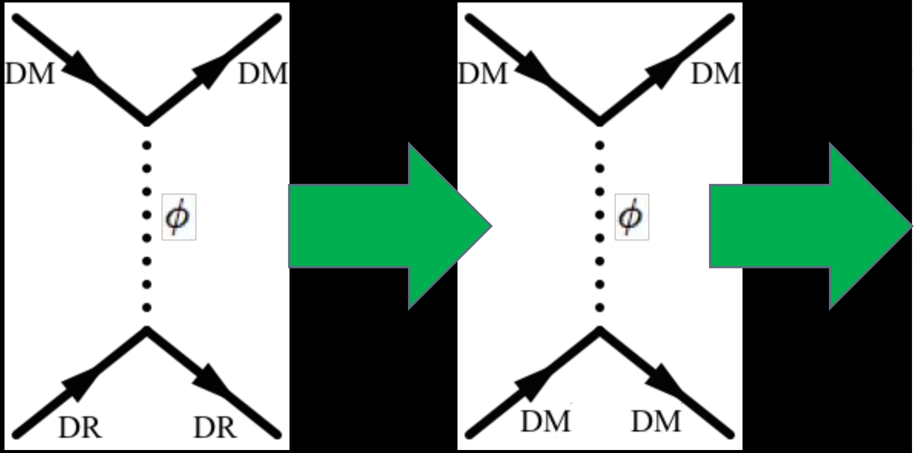
- To be successful, a dark matter model must reproduce the rotation profile of Milky Way satellites

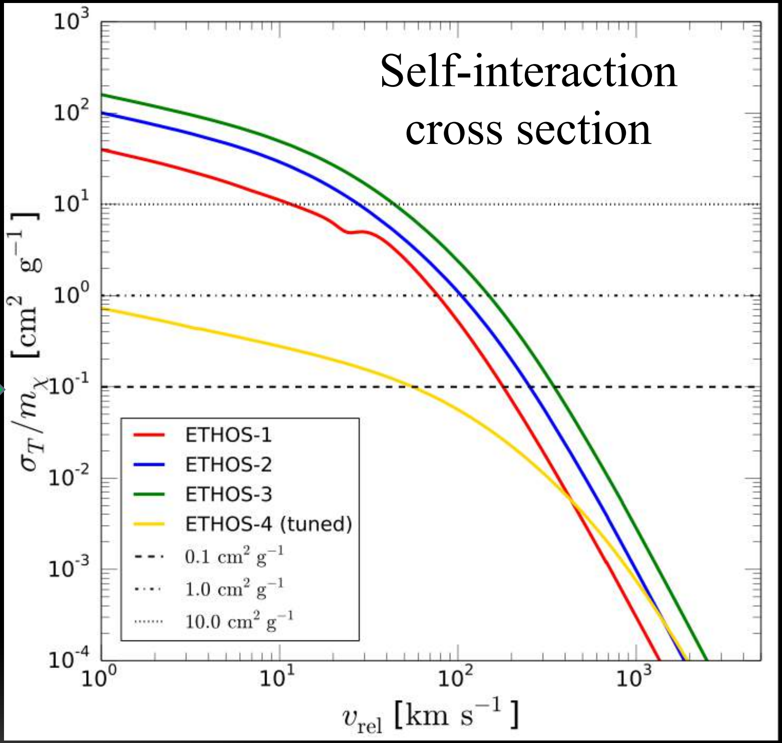


Vogelsberger, Zavala, Cyr-Racine +, arXiv:1512.05349

ETHOS: Impact on satellite galaxies

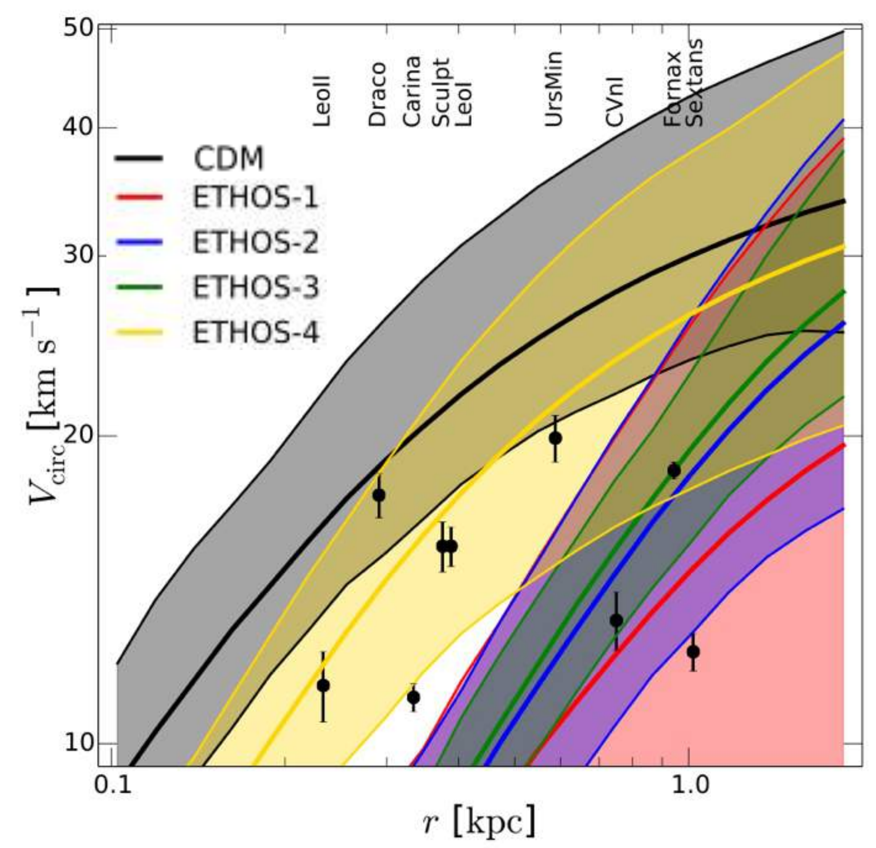
- Self-interaction between dark matter particles are self-consistently taken into account in our simulations





ETHOS: Impact on satellite galaxies

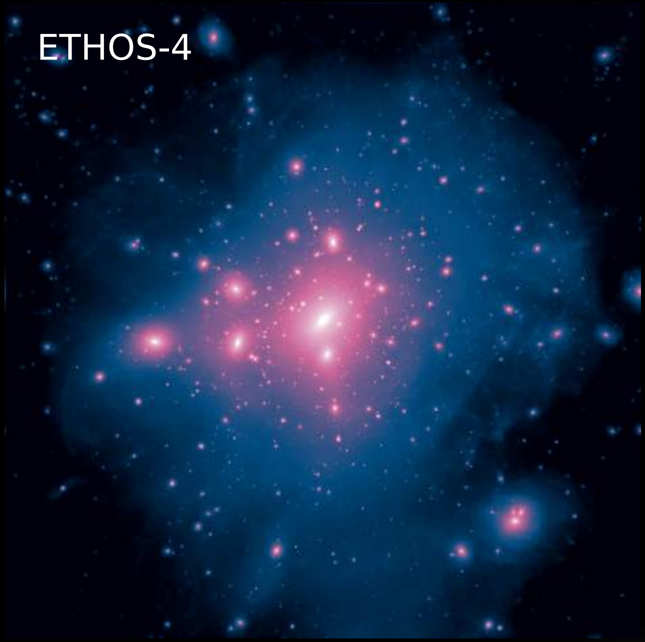
- Dark matter self-interaction can also have important consequences on small-scale structure.

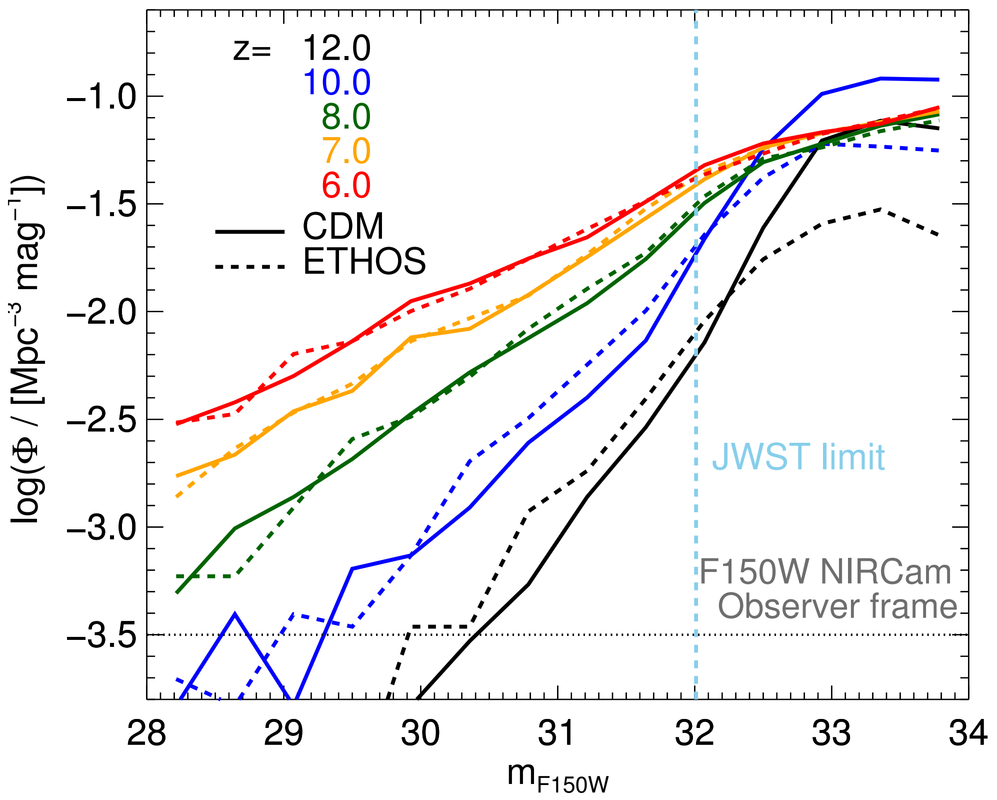


Vogelsberger, Zavala, Cyr-Racine +, arXiv:1512.05349

ETHOS: Impact on UV luminosity function

- Dark matter physics also affects the first galaxies form.

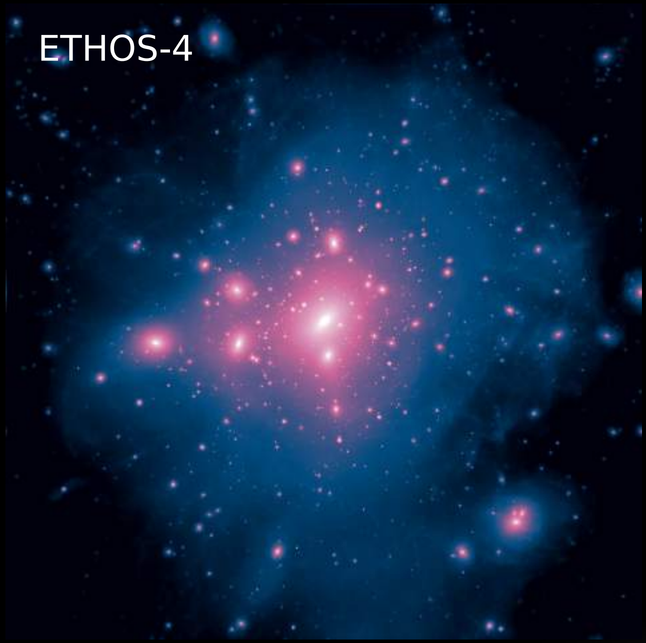


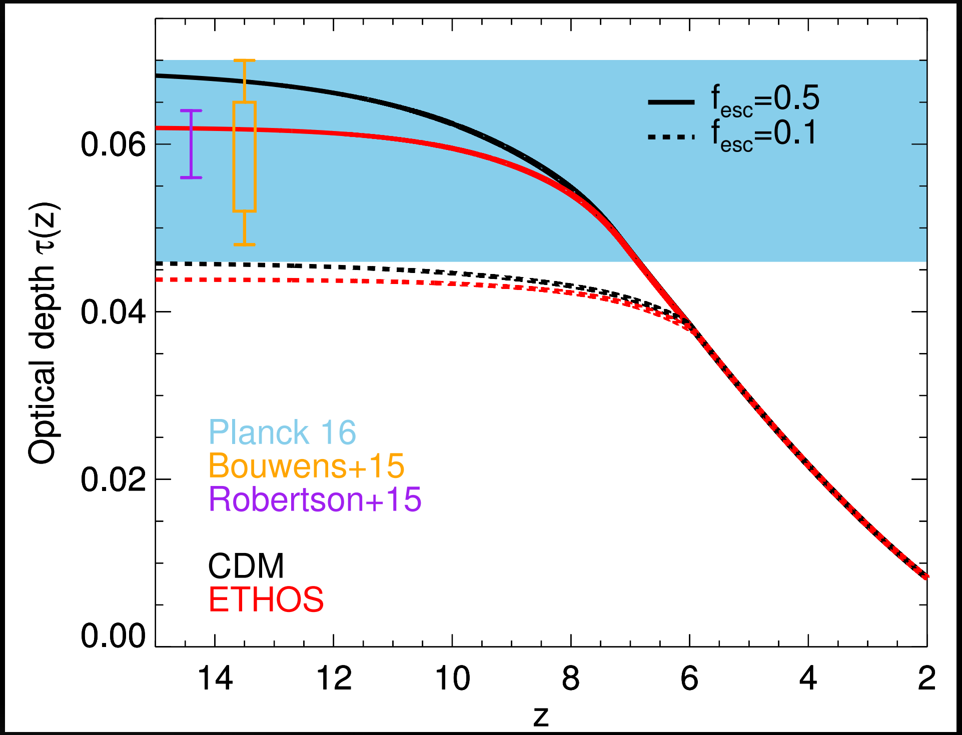


Lovell, Zavala, Vogelsberger Shen, Cyr-Racine +, arXiv:1711.10497

ETHOS: Impact on CMB optical depth

- Dark matter physics also affects the optical depth.





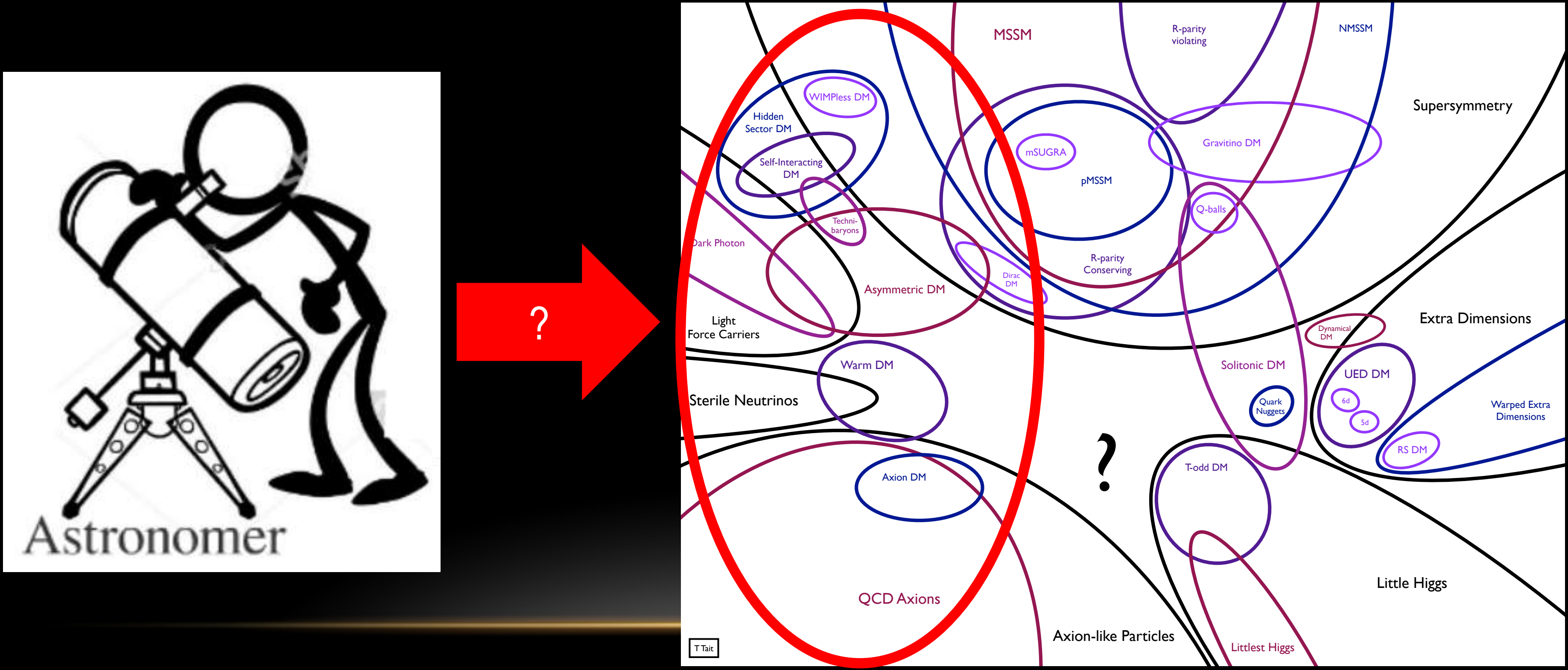
Lovell, Zavala, Vogelsberger Shen, Cyr-Racine +, arXiv:1711.10497

Executive summary: ETHOS

- The ETHOS collaboration aims at revolutionizing our understanding of how dark matter microphysics shapes the Universe on sub-galactic scales.
- We have performed the first fully self-consistent analysis of the impact of new dark matter interactions on the Milky Way galaxy and its satellites => A few surprises!
- In our latest work, we are charting new territory in terms of understanding how the first stars and galaxies form in the presence of new dark matter interactions.
- Many exciting directions remain to be explored, including several theory-focused projects.

Part II: From observations to dark matter physics

- What are the most promising observations that can tell us about dark matter physics?

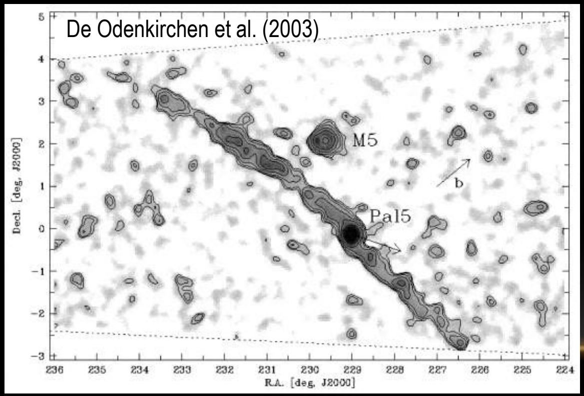


Many possible ways to probe small-scale structure

Gravitational Lensing

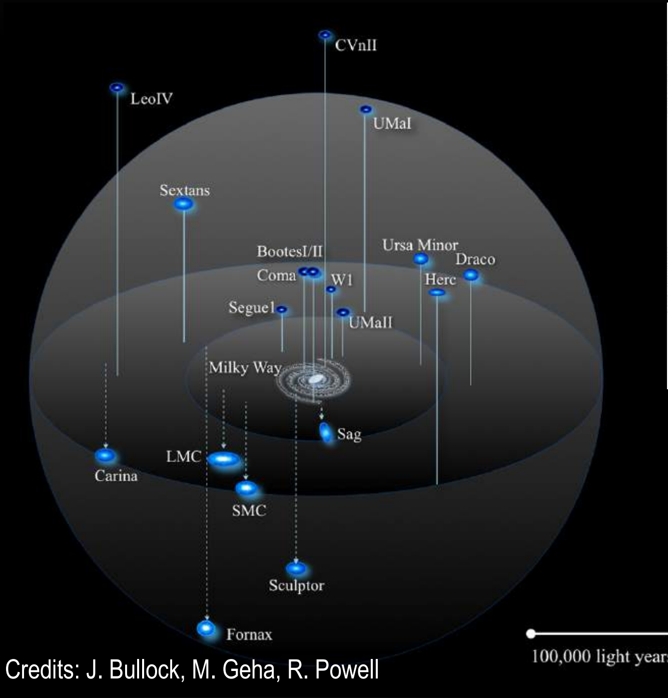
RXJ 1131-1231 (HST/NASA)

Stellar Streams



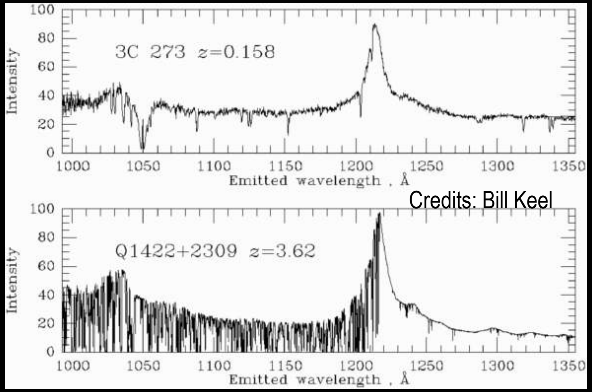
De Odenkirchen et al. (2003)

Dwarf galaxies



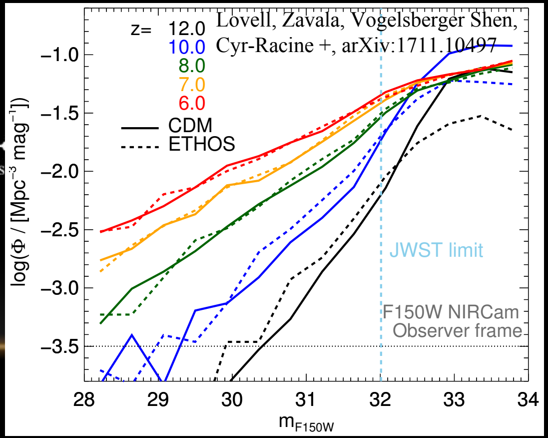
Credits: J. Bullock, M. Geha, R. Powell

Lyman-alpha forest



Credits: Bill Keel

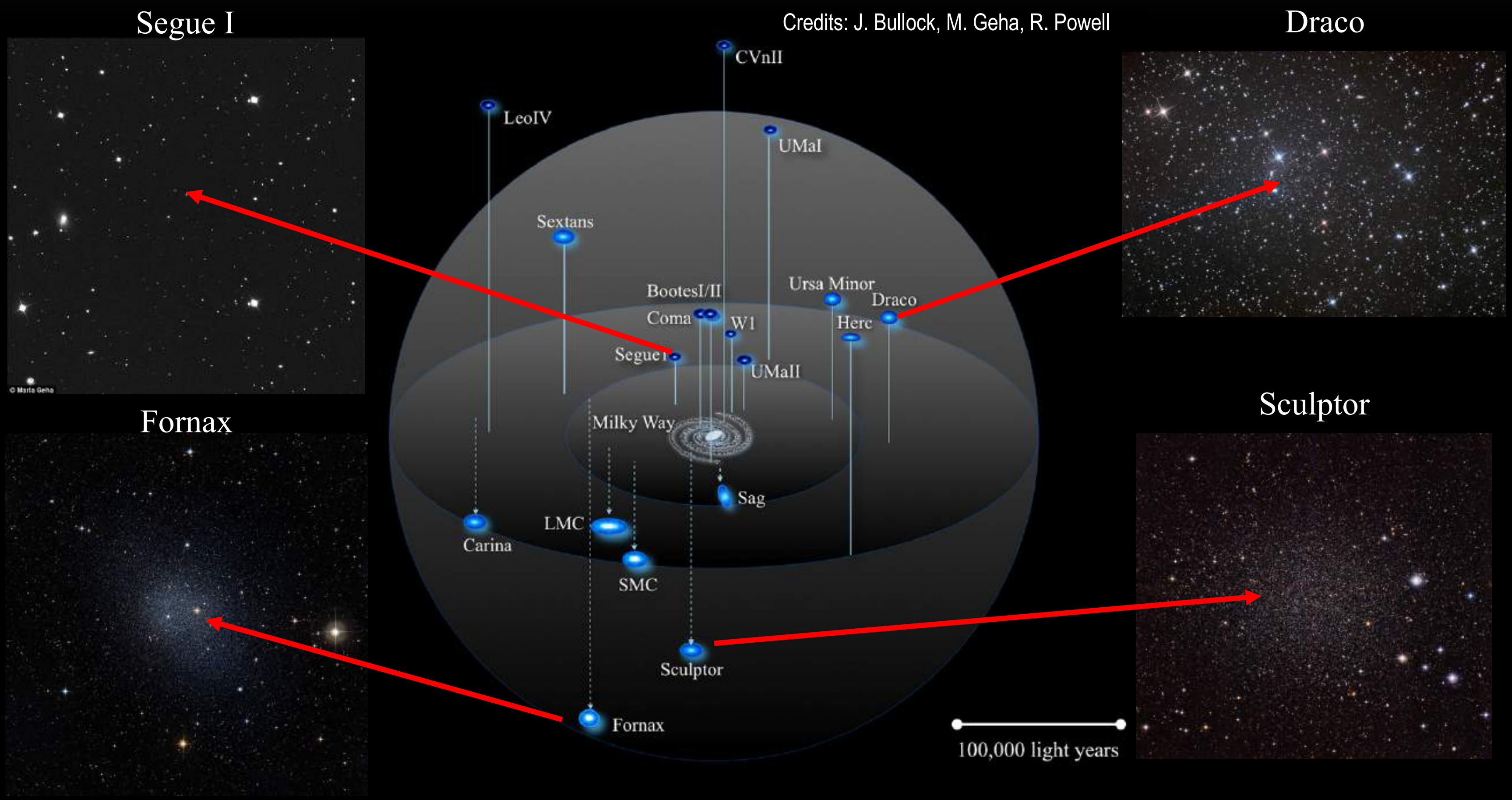
UV Luminosity Function



Lovell, Zavala, Vogelsberger Shen, Cyr-Racine +, arXiv:1711.10497

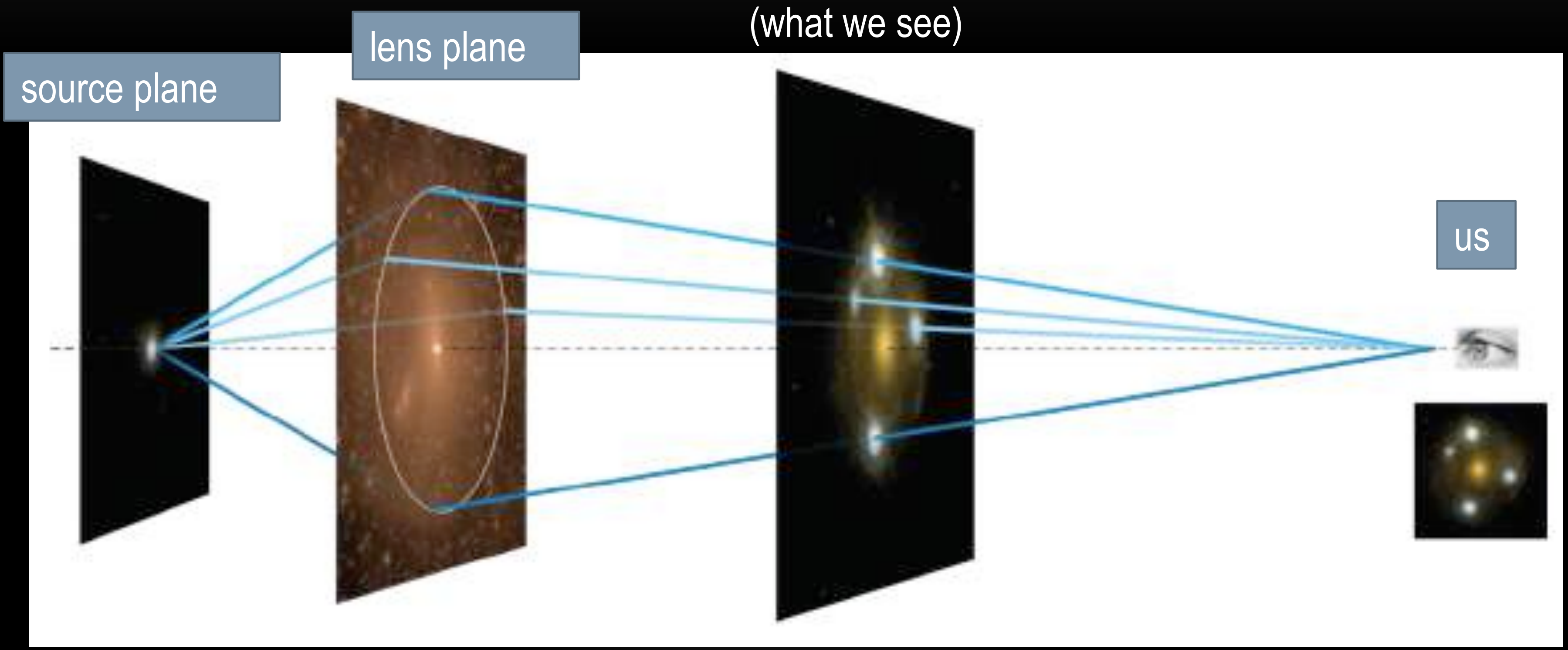
Mapping the Milky Way satellites

- We are approaching the limit of visible small-scale structure!



Credits: J. Bullock, M. Geha, R. Powell

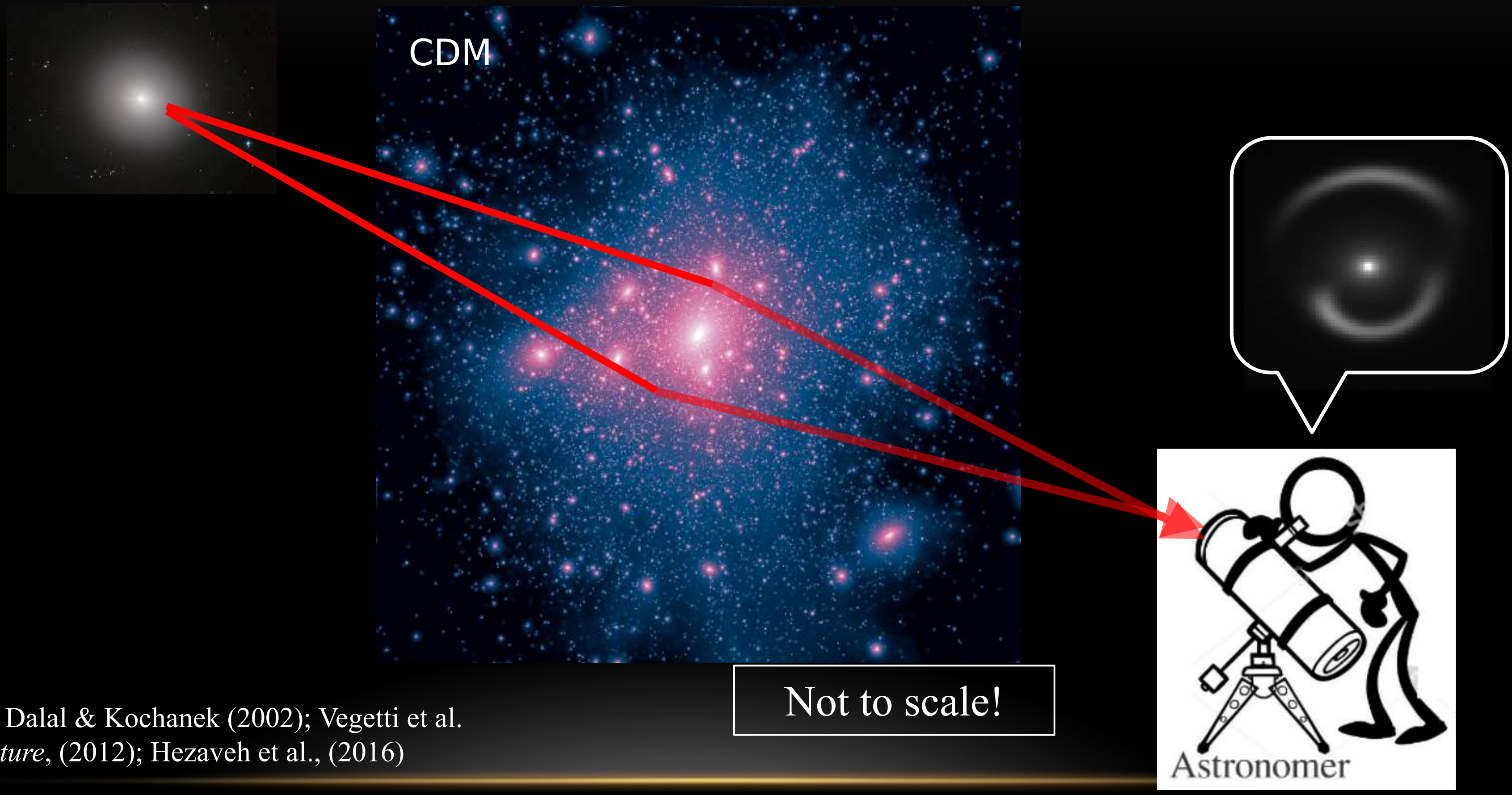
Solution: Strong Gravitational Lensing



Credits: Leonidas Moustakas

Solution: Probing substructure through gravitational lensing

- Use universality of gravity to probe smallest dark matter structures.



Not to scale!

See e.g. Dalal & Kochanek (2002); Vegetti et al. *Nature*, (2012); Hezaveh et al., (2016)

Substructure lensing analogy: Looking through a textured window

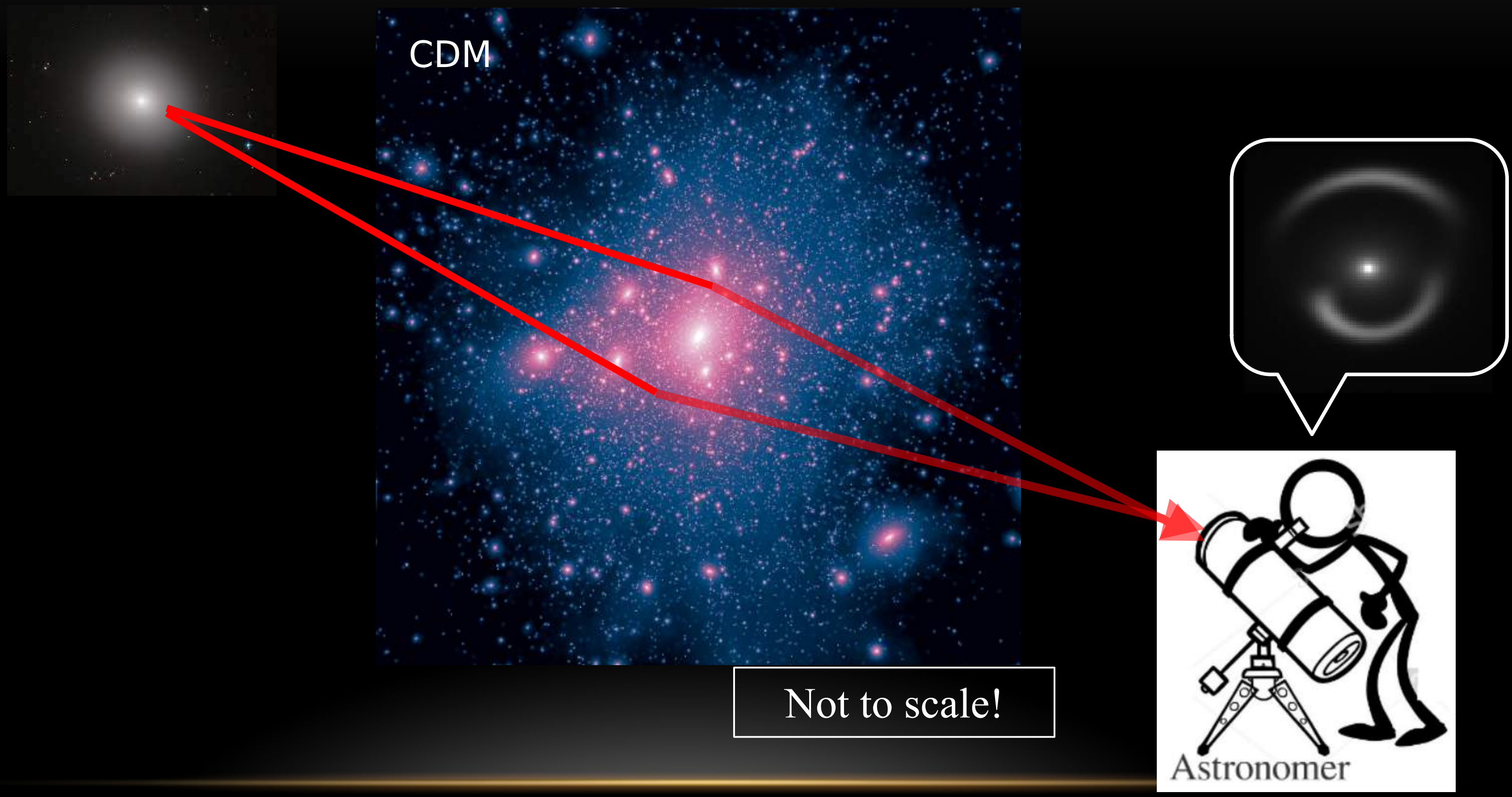
- The textured window introduces perturbation on a given scale.

1) Unperturbed image

2) Image seen through textured glass

How do we characterize the collective effect of the small-scale structure?

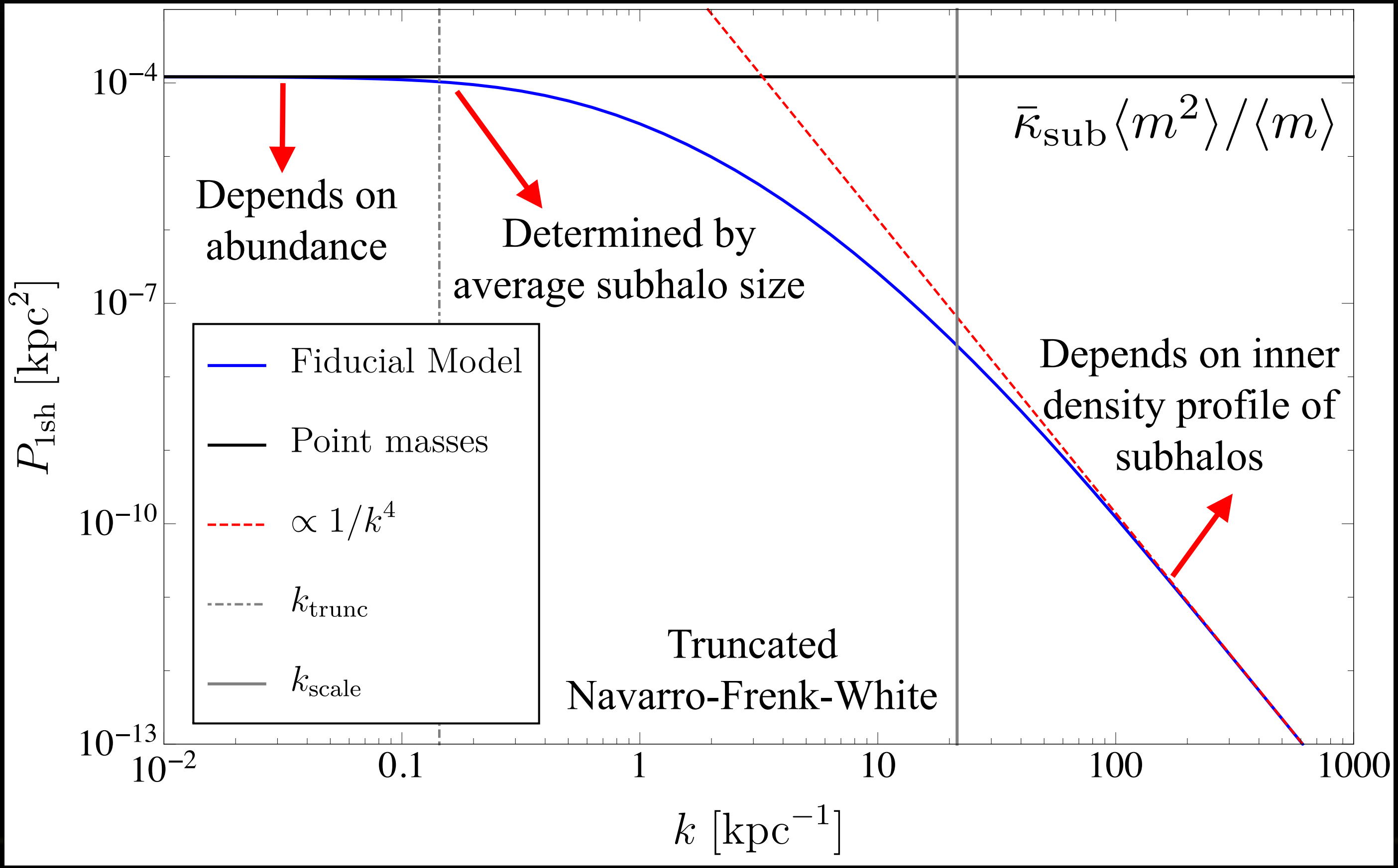
- By their power spectrum of course!



Not to scale!

Substructure power spectrum

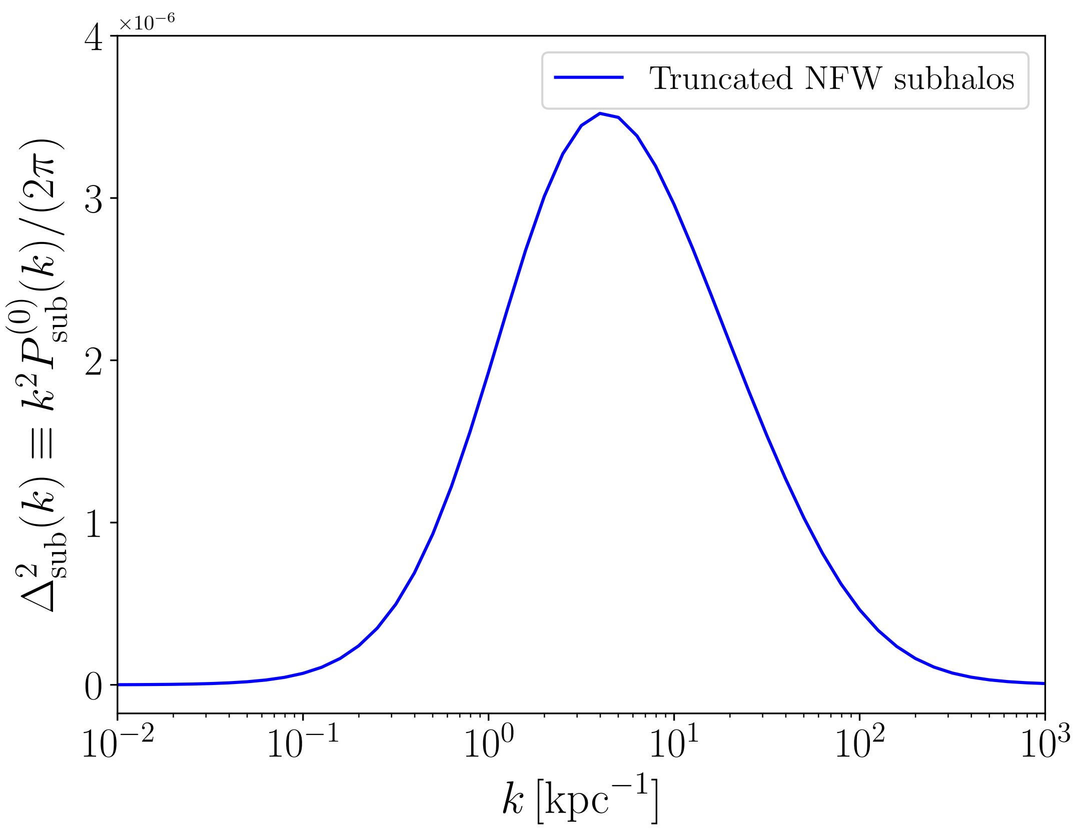
- The power spectrum has three main features:

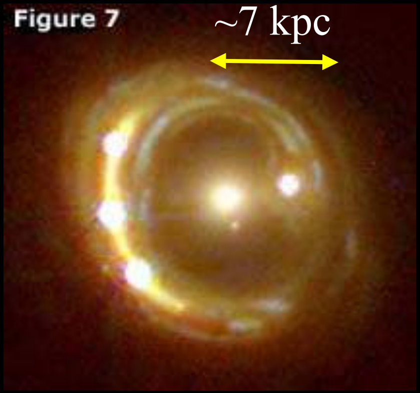


Díaz Rivero, Cyr-Racine, & Dvorkin, arXiv:1707.04590

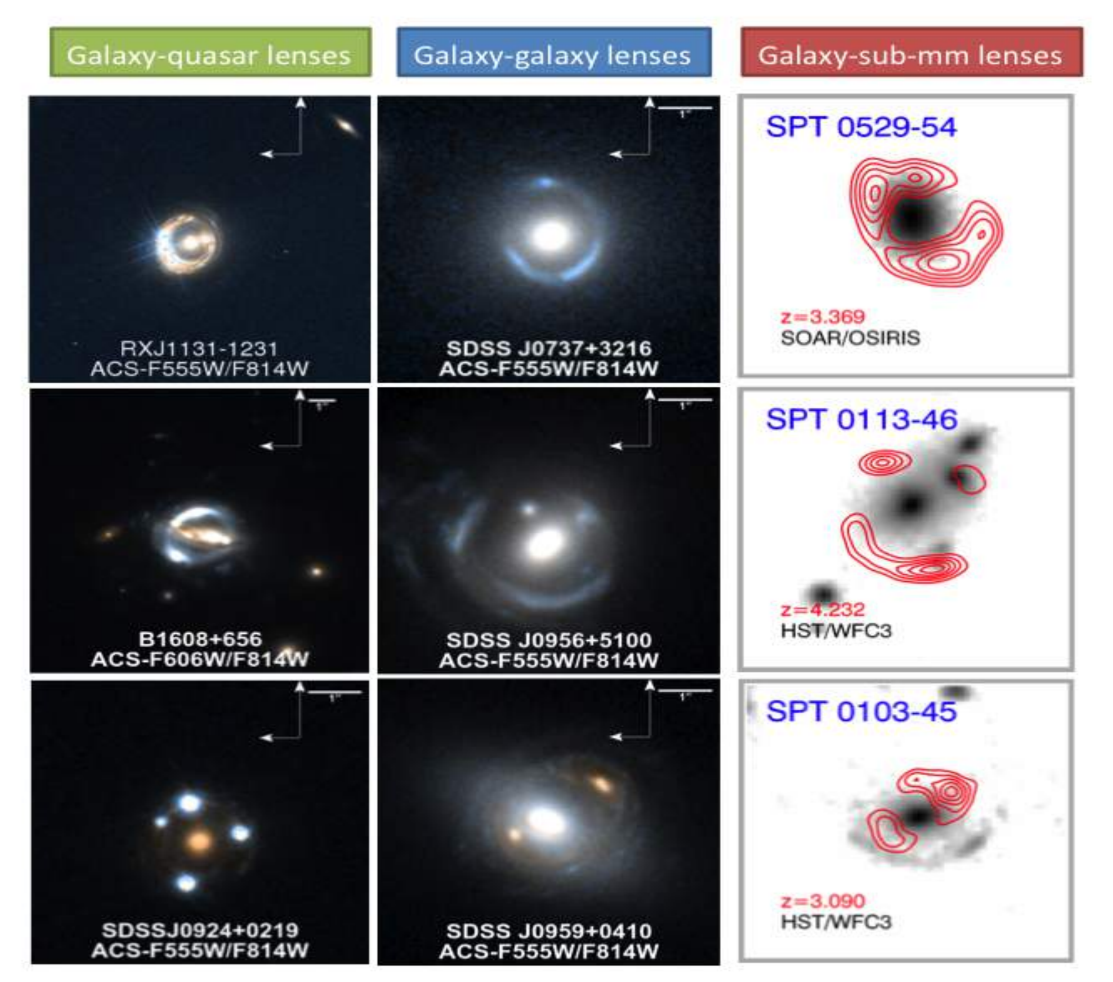
Where is the largest sensitivity?

- Coincidentally, substructures have the largest effects on scales probed by galaxy-scale gravitational lenses.





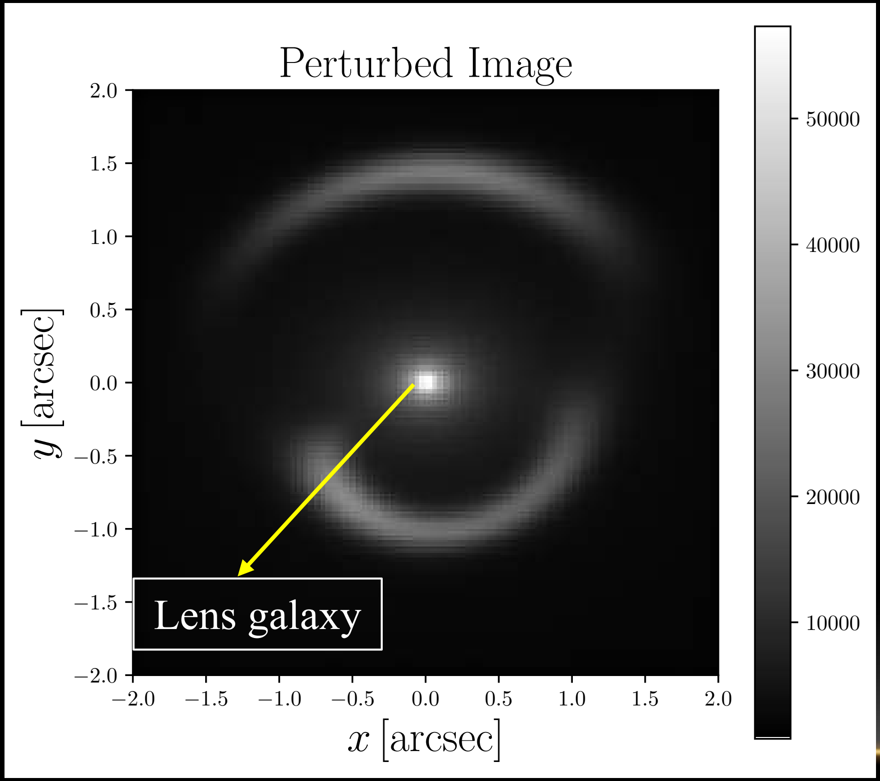
Galaxy-scale Gravitational Lenses



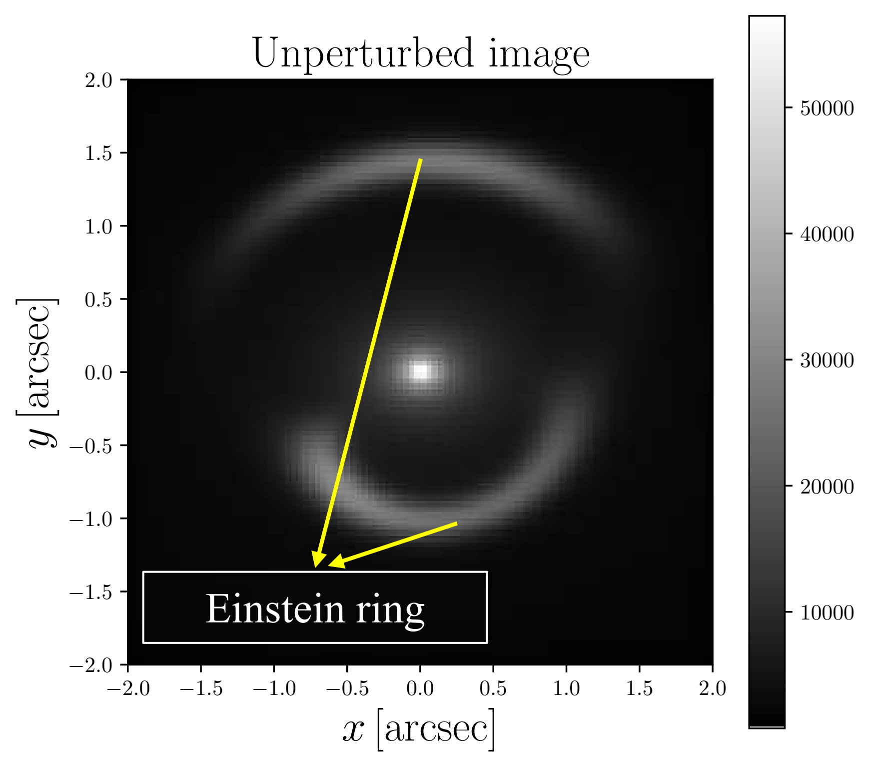
Credits: Leonidas Moustakas

Effect of substructures on lensed images

- The substructure deflection field, leads to subtle surface brightness variations along the Einstein ring


Perturbed Image

Lens galaxy

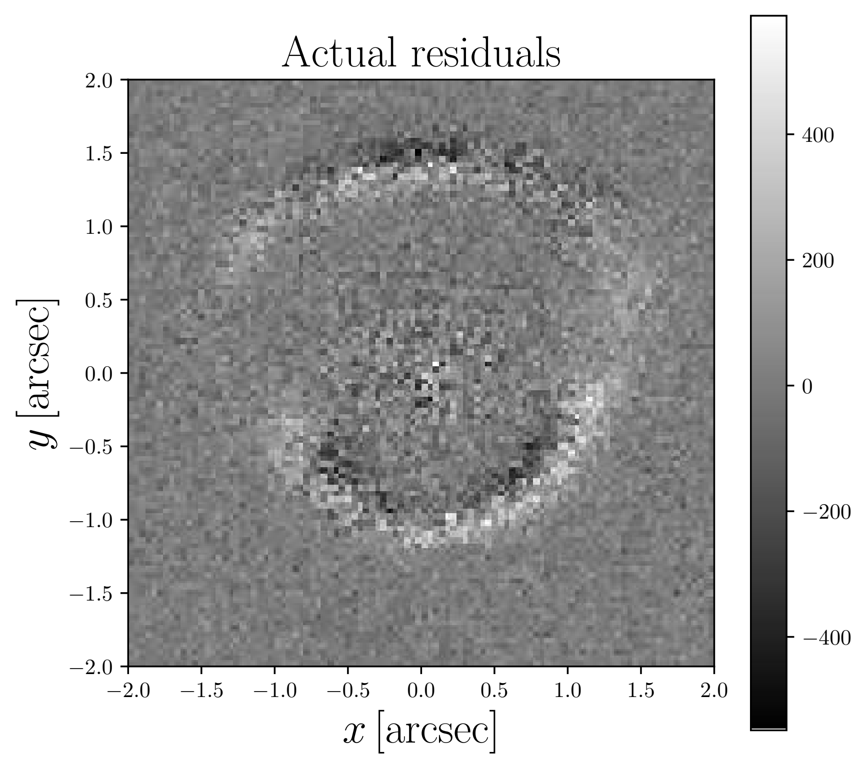

Unperturbed image

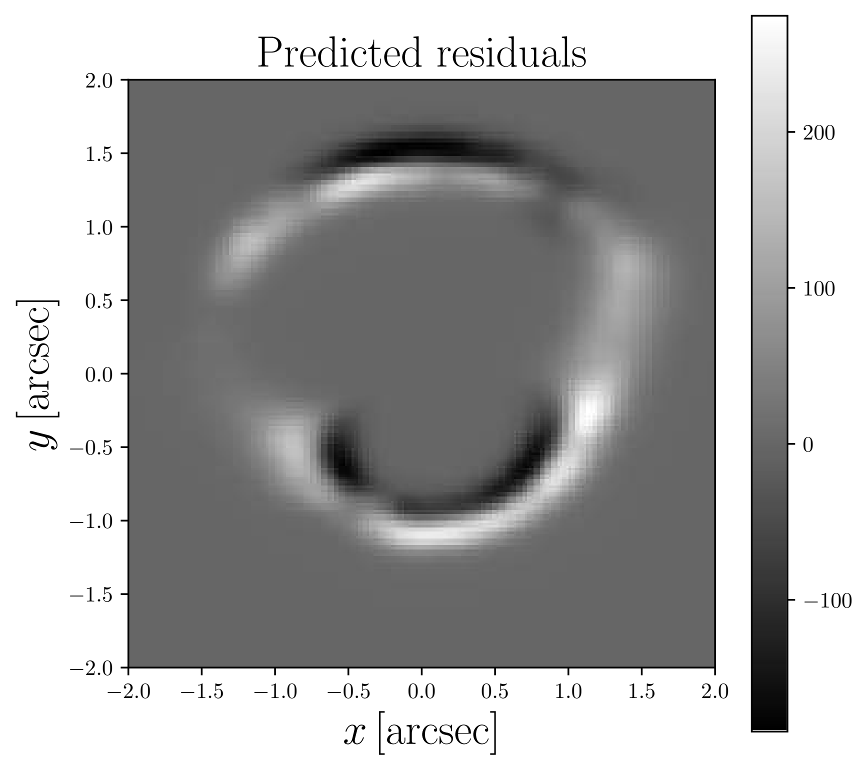
Einstein ring

Cyr-Racine, Keeton & Moustakas, in prep.

Effect of substructures on lensed images

- The substructure deflection field, leads to subtle surface brightness variations along the Einstein ring

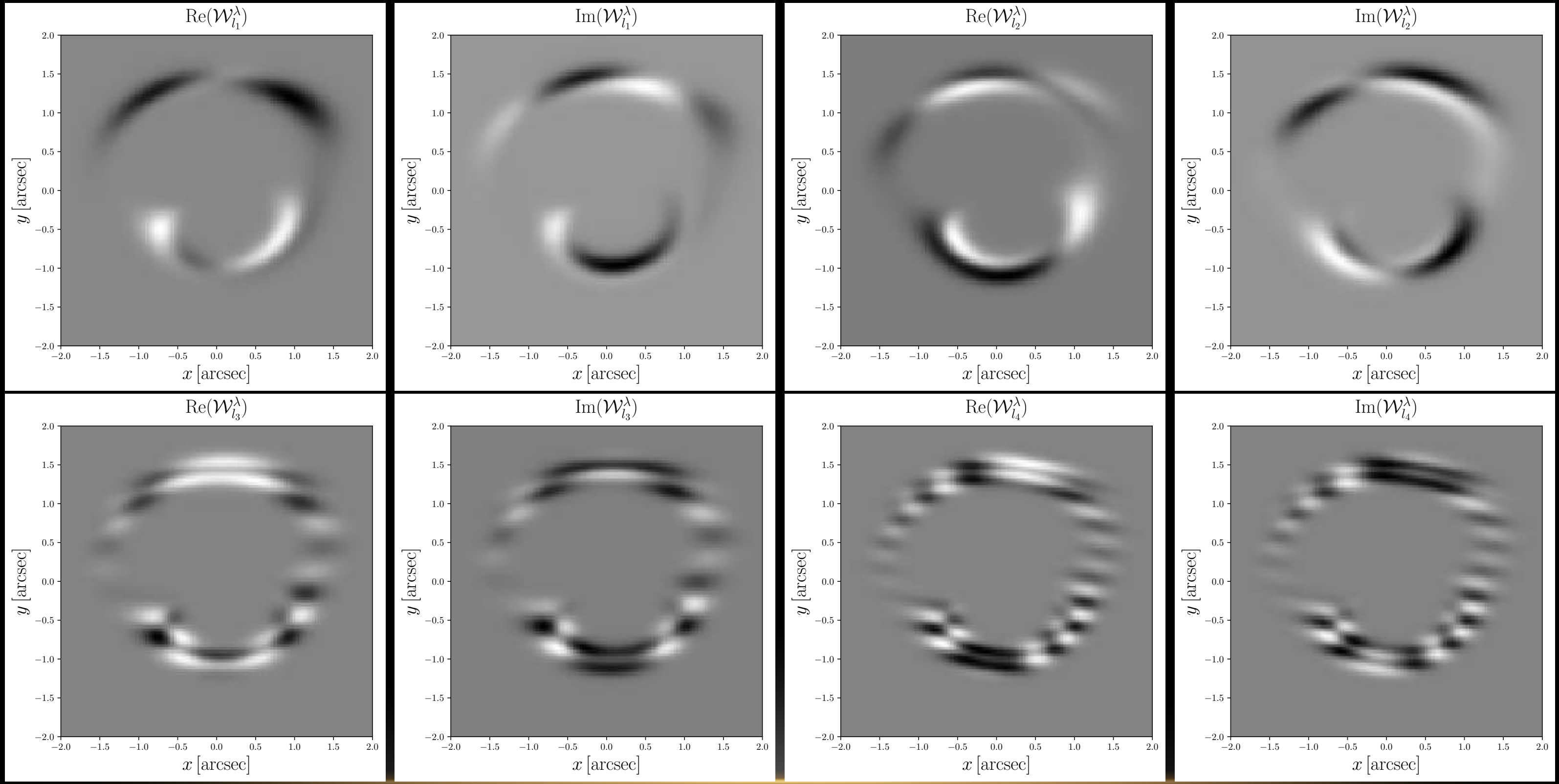




Cyr-Racine, Keeton & Moustakas, in prep.

From image residuals to substructure power spectrum

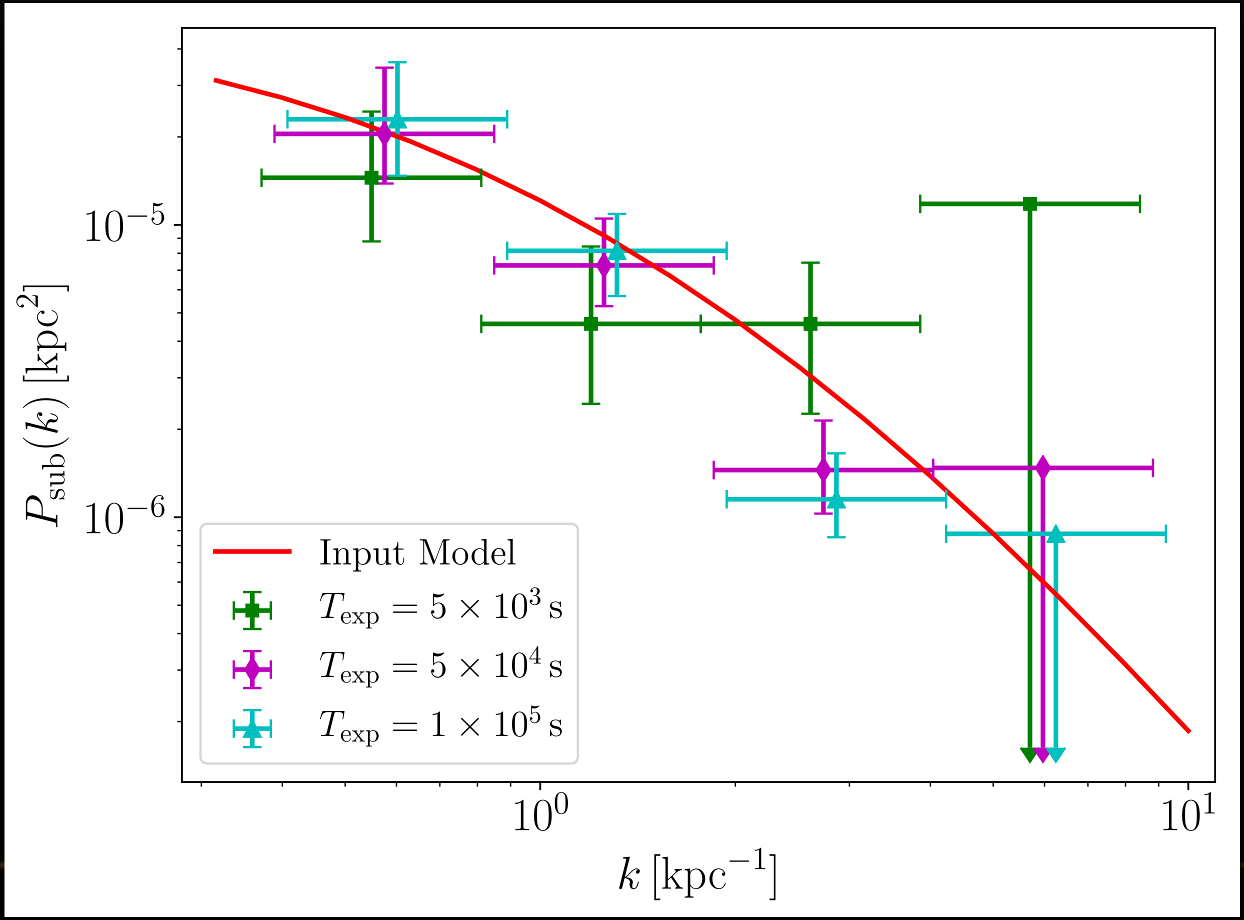
- We can decompose the image residuals in a Fourier-like basis to determine which modes are present in the data.



Cyr-Racine, Keeton & Moustakas, in prep.

Use *Hubble Space Telescope* mock images to assess sensitivity

- We show a significant detection of the power spectrum:

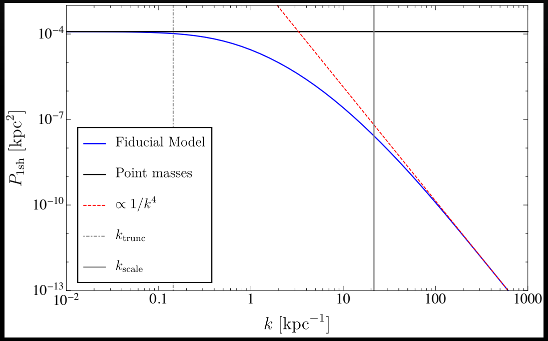


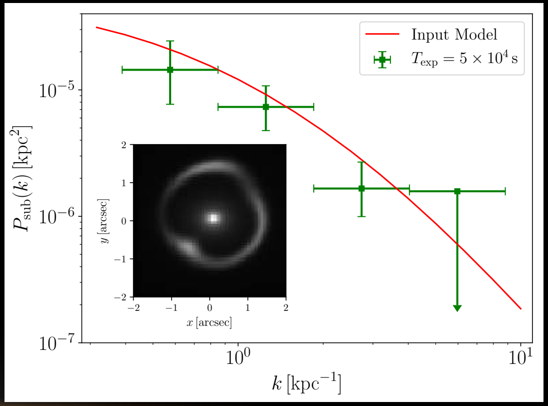
WFC3 UVIS
F555W

Cyr-Racine, Keeton & Moustakas, in prep.

Executive summary: Substructure lensing

- Strong gravitational lensing allows us to probe dark matter structure that are impossible to detect via other techniques.
- Given the possible large number of small-scale structures in a typical lens galaxy, a statistical approach that can detect the collective effect of substructure is warranted.
- For realistic mock data, we show very significant detections of the substructure power spectrum. Application to real data is pending.

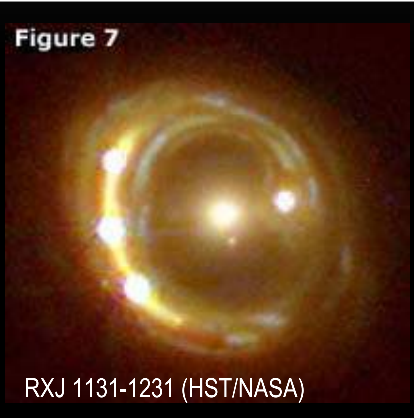




The next decade of dark matter science

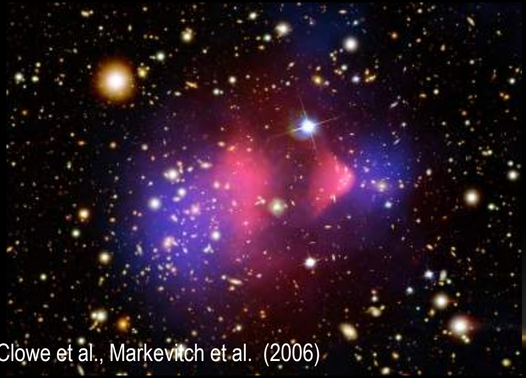
- Developing a comprehensive strategy for dark matter science

Gravitational Lensing



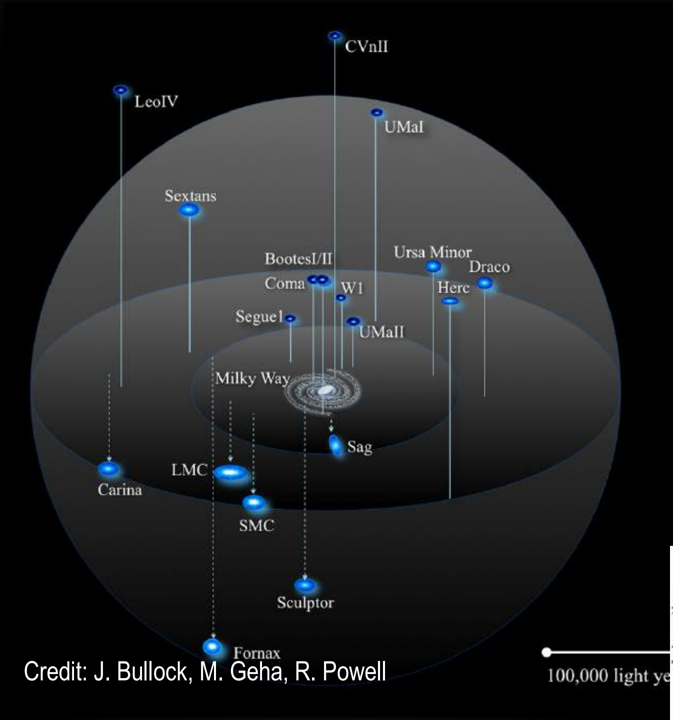
RXJ 1131-1231 (HST/NASA)

Merging Clusters



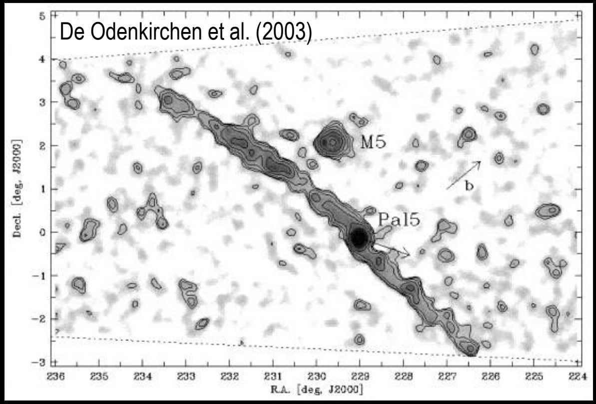
Clowe et al., Markevitch et al. (2006)

Dwarf galaxies



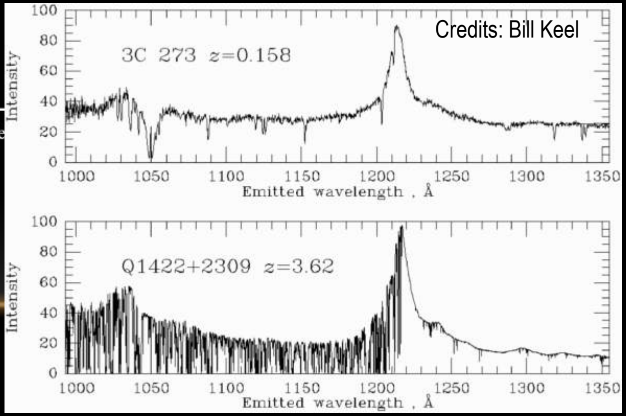
Credit: J. Bullock, M. Geha, R. Powell

Stellar Streams



De Odenkirchen et al. (2003)

Lyman-alpha forest



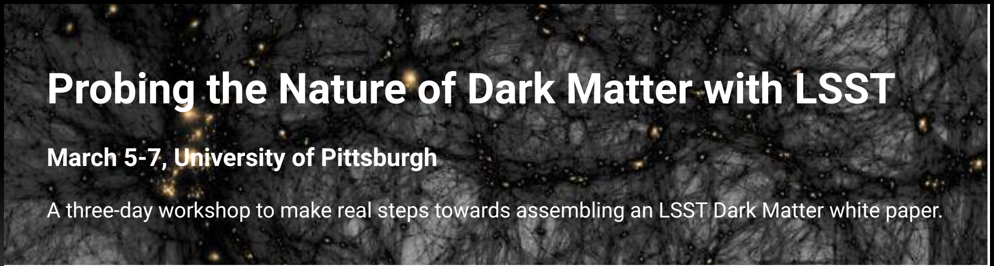
Credits: Bill Keel

The next decade of dark matter science: LSST

- The Large Synoptic Survey Telescope (LSST) will produce an enormous amount of data relevant to dark matter science, including finding new Milky Way satellites and new gravitational lenses.

As of January 16, 2018

- 8.4m telescope with very large field of view: can image the entire sky every 3 nights!
- Survey begins in 2022.



Probing the Nature of Dark Matter with LSST

March 5-7, University of Pittsburgh

A three-day workshop to make real steps towards assembling an LSST Dark Matter white paper.

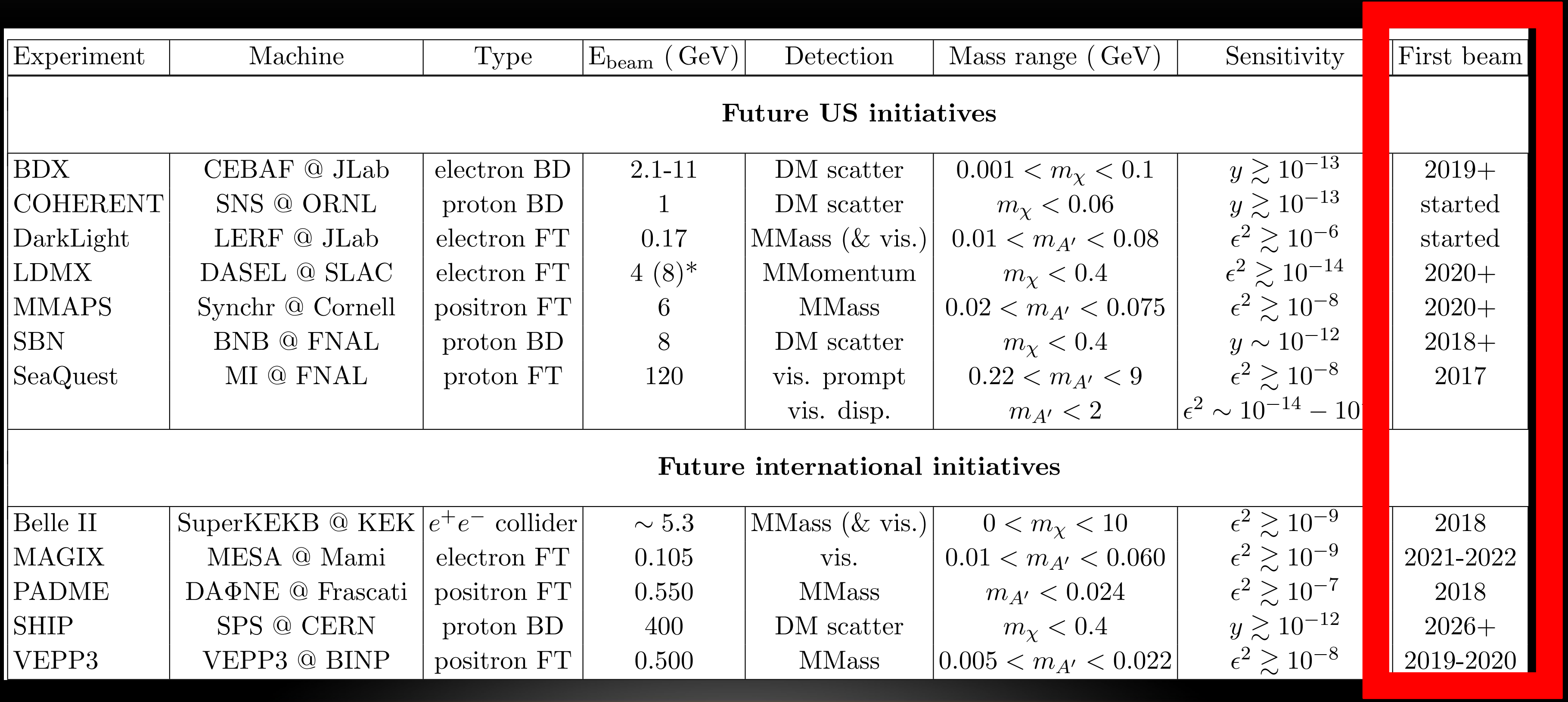
The next decade of dark matter science: Gravitational lensing

- With LSST and WFIRST, the number of known galaxy-scale gravitational lenses will grow dramatically (from ~100 to ~10000).
- This will open the "statistical era" of strong lensing.
- Several exciting challenges to tackle, including how to jointly analyze a large number of lenses.

Lots of opportunity for undergraduate and graduate students to be at the forefront of research

The next decade of dark matter science

- The astrophysical program is highly complementary to laboratory-based experiments



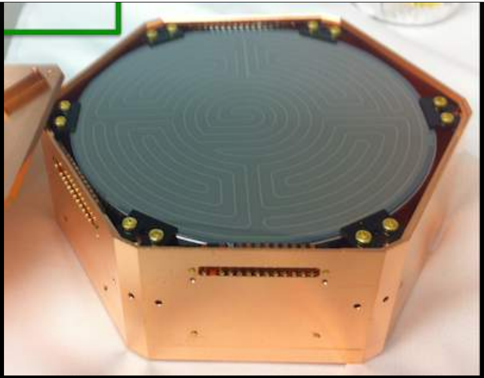
Experiment	Machine	Type	E_{beam} (GeV)	Detection	Mass range (GeV)	Sensitivity	First beam
Future US initiatives							
BDX	CEBAF @ JLab	electron BD	2.1-11	DM scatter	$0.001 < m_\chi < 0.1$	$y \gtrsim 10^{-13}$	2019+
COHERENT	SNS @ ORNL	proton BD	1	DM scatter	$m_\chi < 0.06$	$y \gtrsim 10^{-13}$	started
DarkLight	LERF @ JLab	electron FT	0.17	MMass (& vis.)	$0.01 < m_{A'} < 0.08$	$\epsilon^2 \gtrsim 10^{-6}$	started
LDMX	DASEL @ SLAC	electron FT	4 (8)*	MMomentum	$m_\chi < 0.4$	$\epsilon^2 \gtrsim 10^{-14}$	2020+
MMAPS	Synchr @ Cornell	positron FT	6	MMass	$0.02 < m_{A'} < 0.075$	$\epsilon^2 \gtrsim 10^{-8}$	2020+
SBN	BNB @ FNAL	proton BD	8	DM scatter	$m_\chi < 0.4$	$y \sim 10^{-12}$	2018+
SeaQuest	MI @ FNAL	proton FT	120	vis. prompt	$0.22 < m_{A'} < 9$	$\epsilon^2 \gtrsim 10^{-8}$	2017
				vis. disp.	$m_{A'} < 2$	$\epsilon^2 \sim 10^{-14} - 10$	
Future international initiatives							
Belle II	SuperKEKB @ KEK	e^+e^- collider	~ 5.3	MMass (& vis.)	$0 < m_\chi < 10$	$\epsilon^2 \gtrsim 10^{-9}$	2018
MAGIX	MESA @ Mami	electron FT	0.105	vis.	$0.01 < m_{A'} < 0.060$	$\epsilon^2 \gtrsim 10^{-9}$	2021-2022
PADME	DAΦNE @ Frascati	positron FT	0.550	MMass	$m_{A'} < 0.024$	$\epsilon^2 \gtrsim 10^{-7}$	2018
SHIP	SPS @ CERN	proton BD	400	DM scatter	$m_\chi < 0.4$	$y \gtrsim 10^{-12}$	2026+
VEPP3	VEPP3 @ BINP	positron FT	0.500	MMass	$0.005 < m_{A'} < 0.022$	$\epsilon^2 \gtrsim 10^{-8}$	2019-2020

Battaglierri et al., arXiv:1707.04591

The next decade of dark matter science

- Lots of remaining ground for discovery!

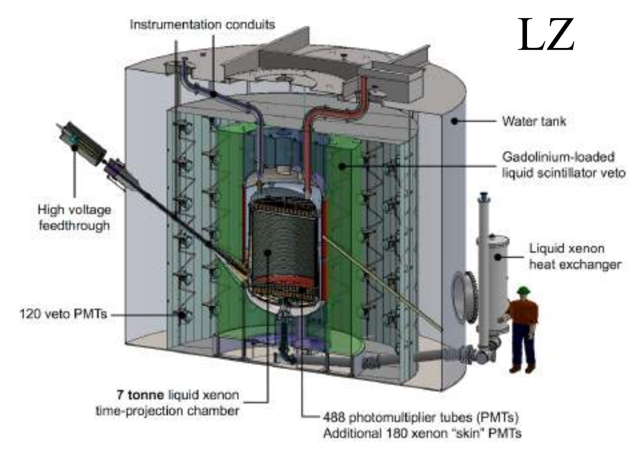
SuperCDMS



ABRACADABRA

Xe
XENON
Dark Matter Project

LZ



…and many more!

Conclusions

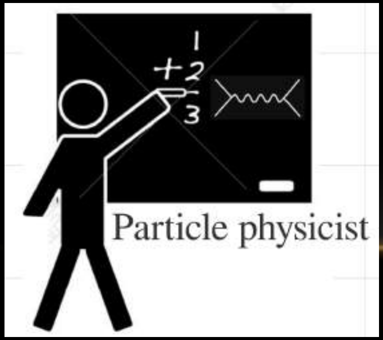
- There is overwhelming evidence for the existence of dark matter in our Universe, and clues about its particle nature are most apparent on sub-galactic scales.

- Understanding structure formation on these small scales is challenging, but our research group is leading the way into this largely uncharted territory.

- The observational prospects of small-scale structure are excellent in the next decade. Together with lab-based experiments, it is likely that our state of knowledge will dramatically improve by the late 2020s.

The next decade of dark matter science

- Unlocking the mystery of dark matter is a truly multi-disciplinary endeavor.



Thank you!