Gravitational Probes of Dark Matter

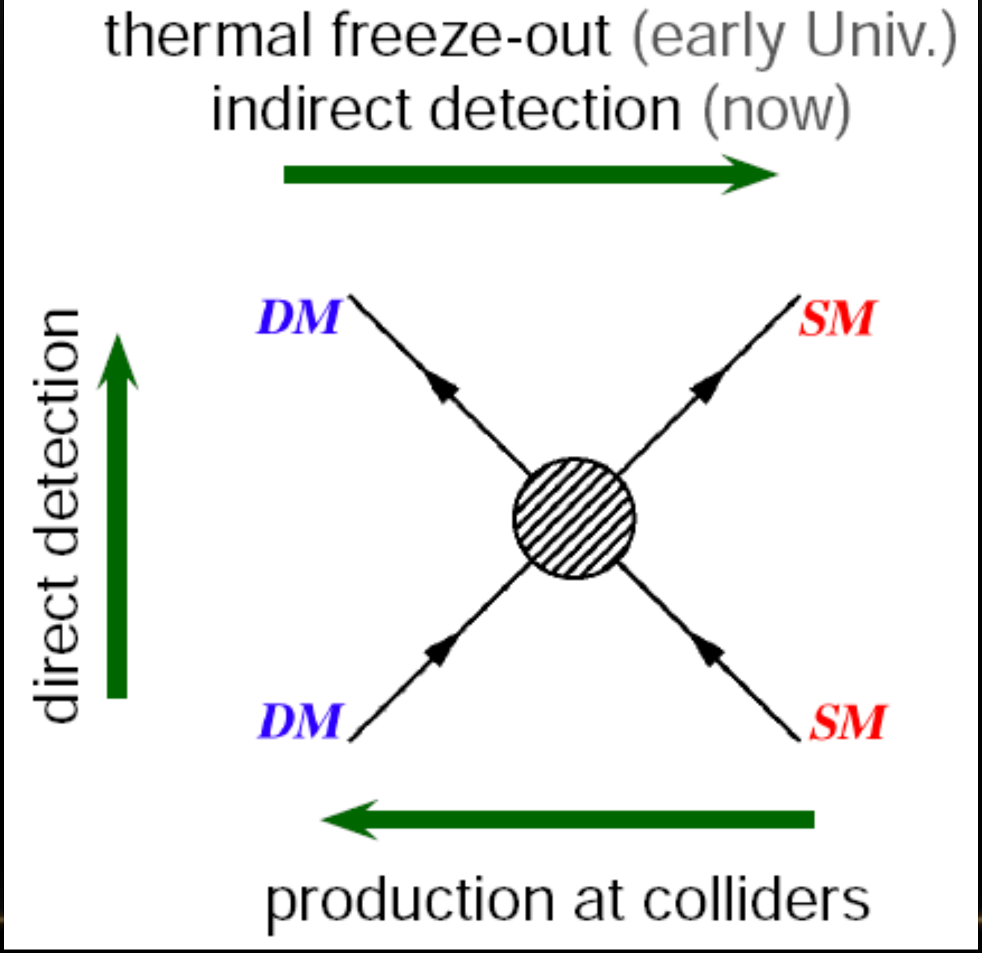
Annecy-le-Vieux, France
June 28, 2018

Francis-Yan Cyr-Racine

Department of Physics, Harvard University

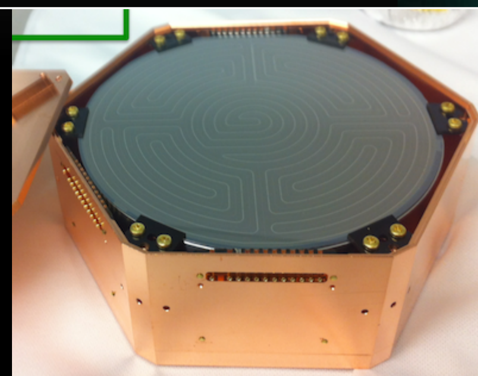
The current dark matter research effort is often summarized like this:

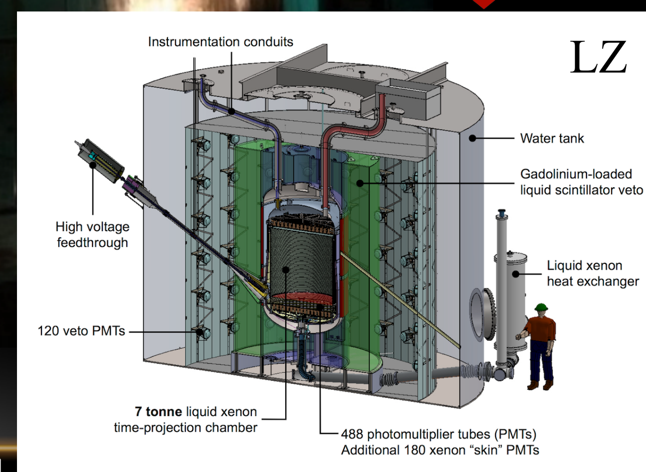
The Standard "triad"



With many experiments pushing forward different sides of the "triad"

SuperCDMS

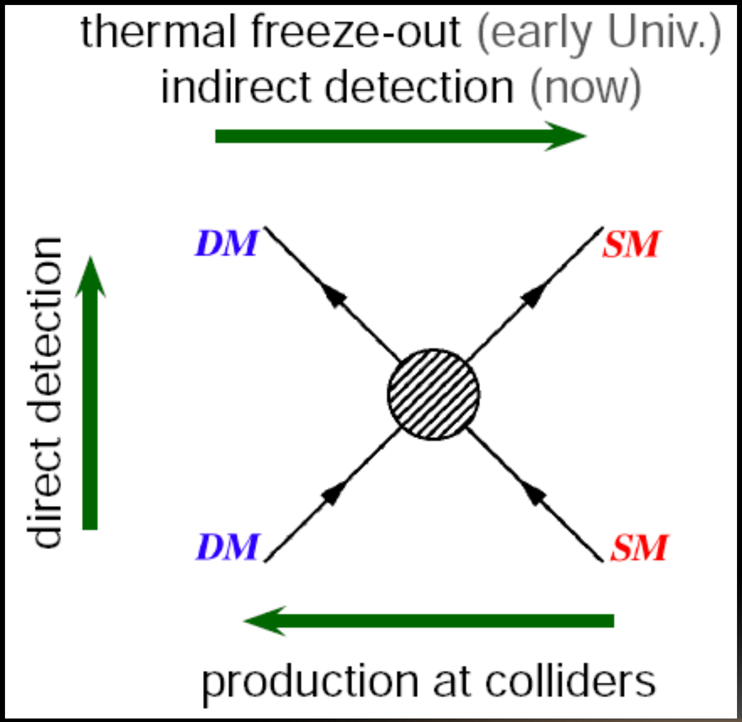




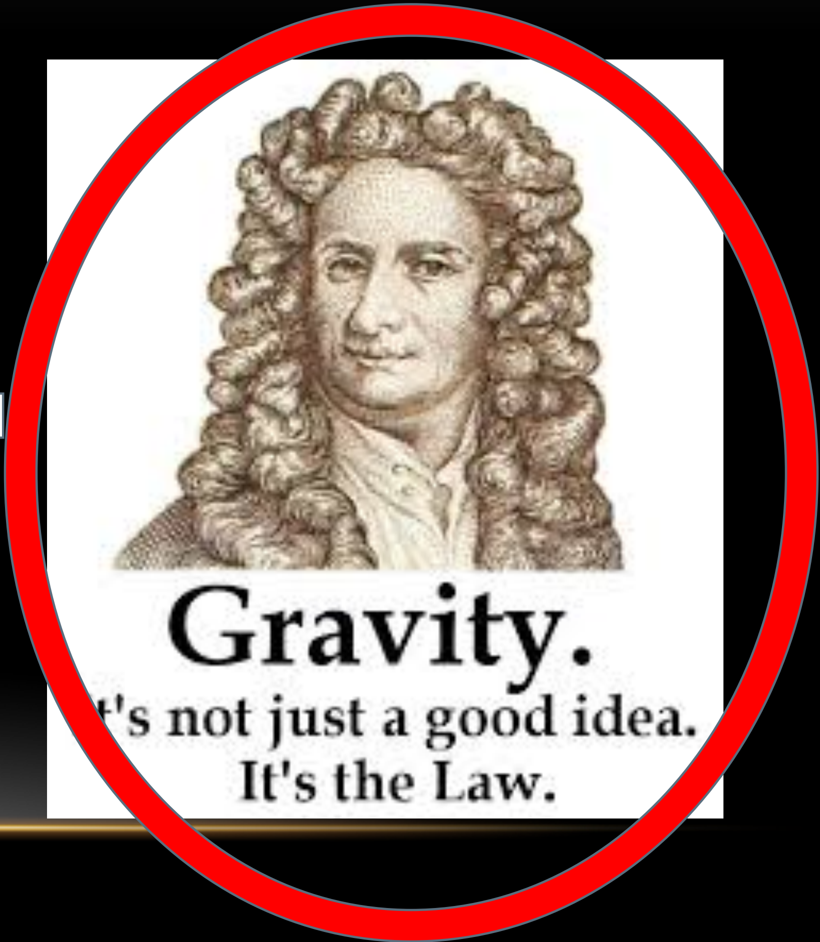
…and many more!

Of course, the actual dark matter research program is more something like this:

- Or, how to probe dark sector physics through its gravitational impact on luminous matter.



+



Gravitational probes of dark matter: From local to cosmological

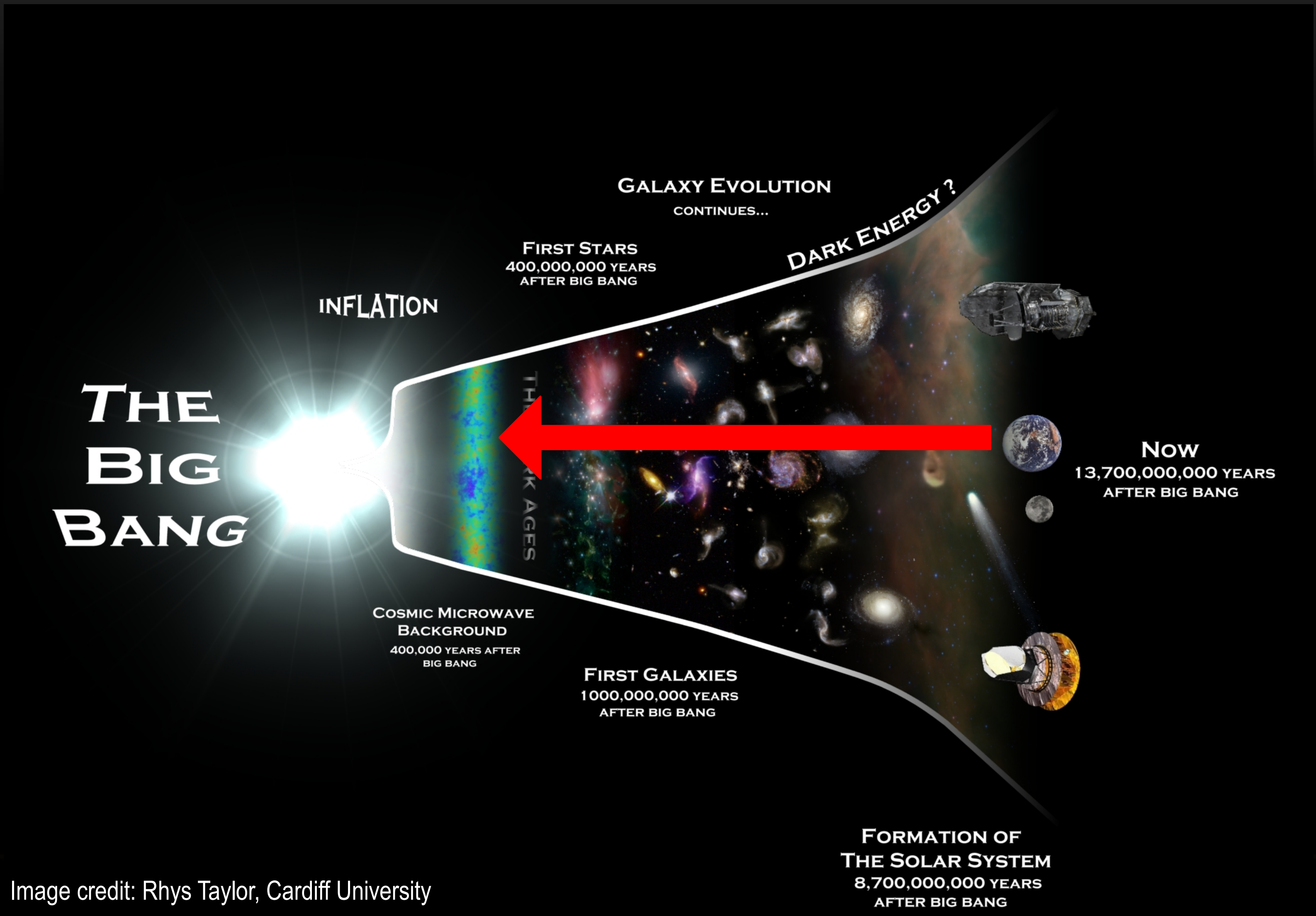
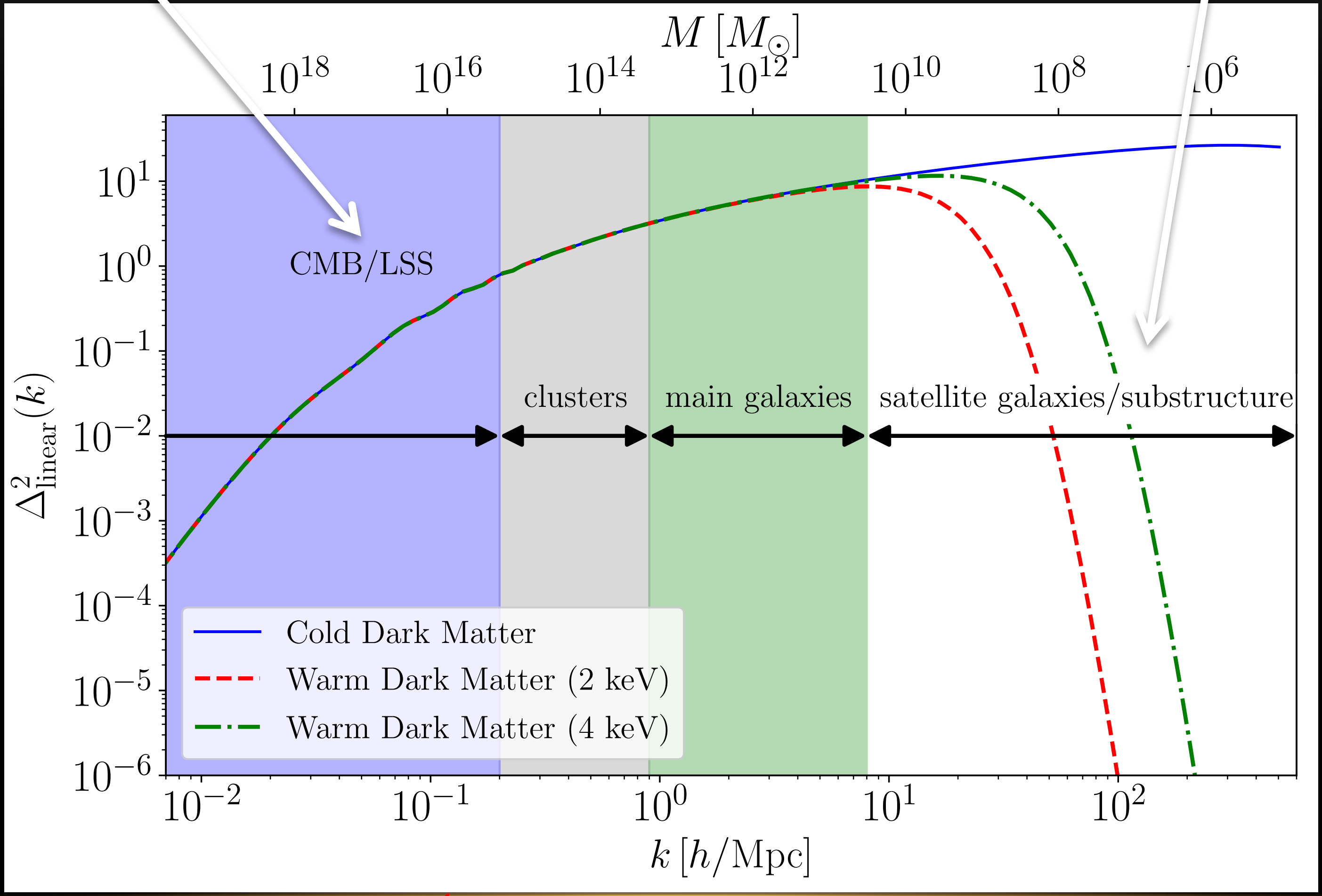


Image credit: Rhys Taylor, Cardiff University

From small to large scales

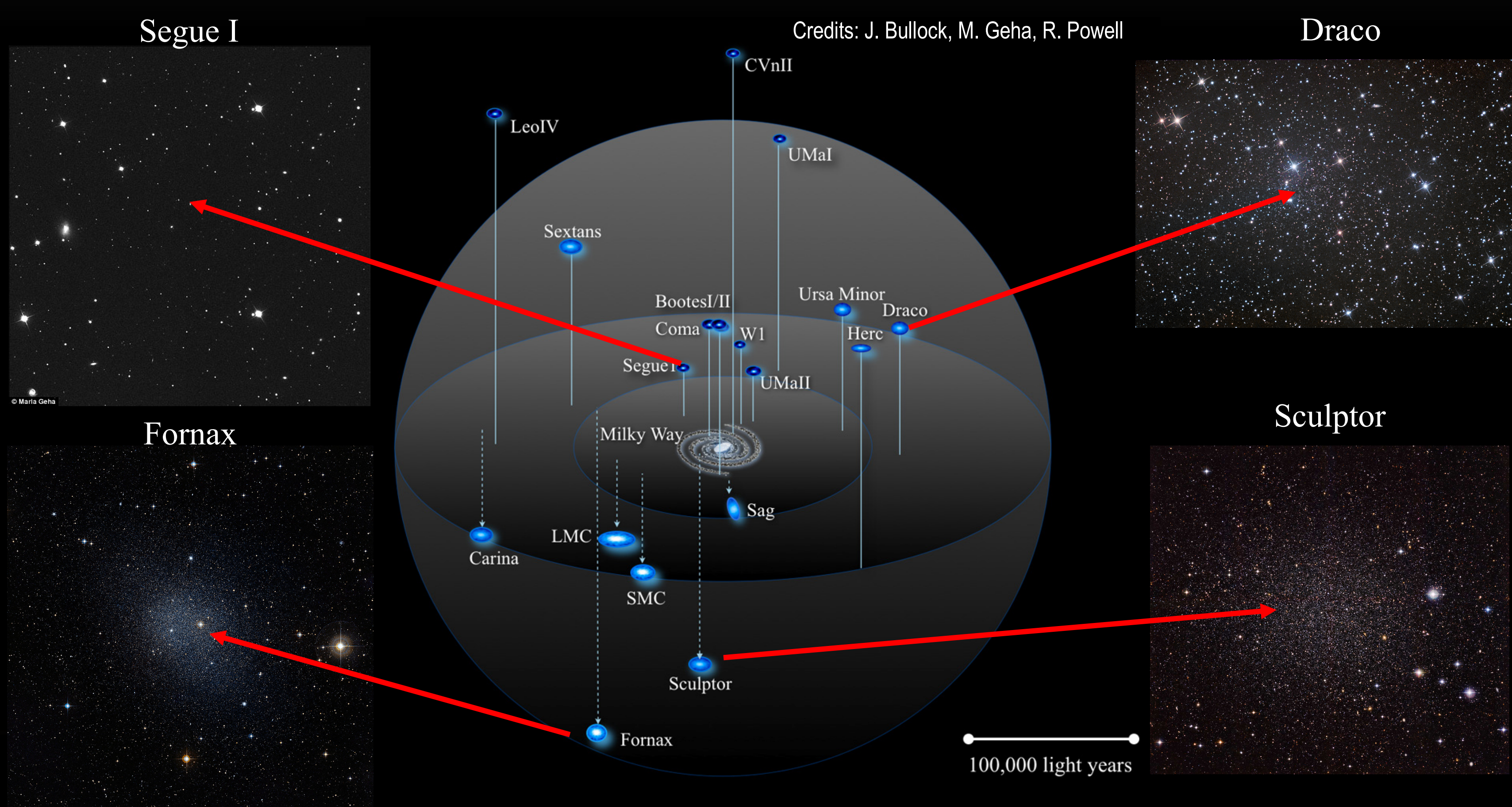
Linear and well-understood

Nonlinear and difficult measurement

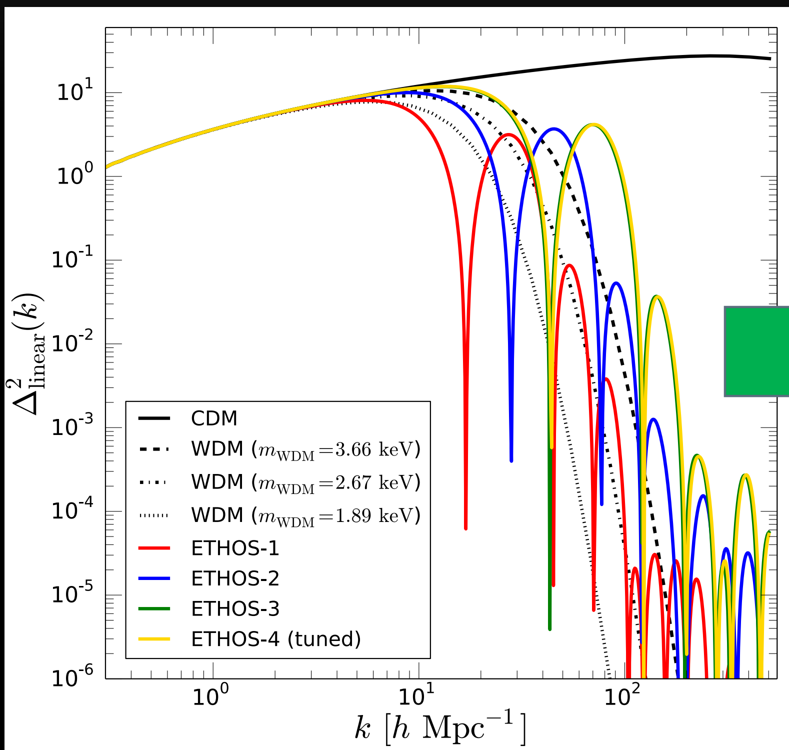


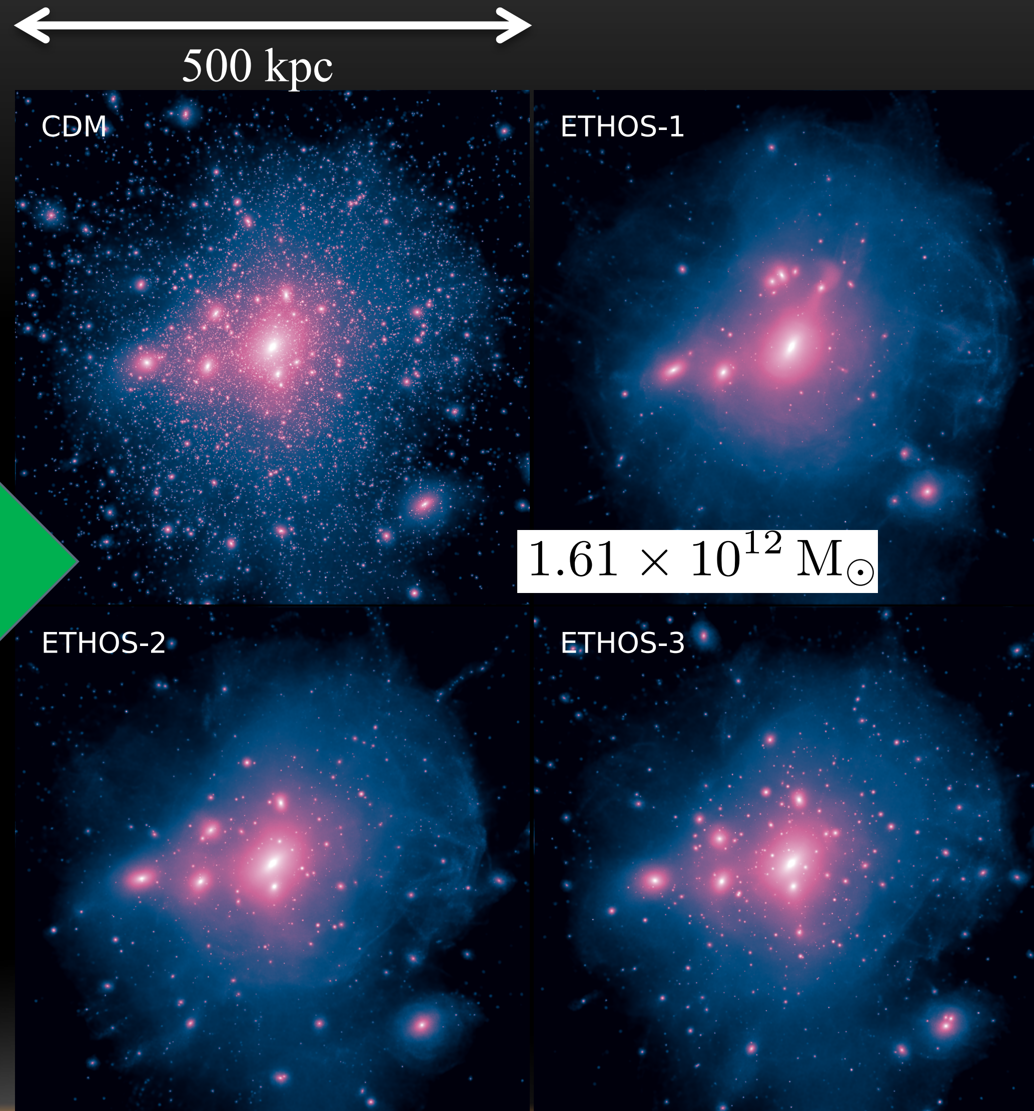
Milky Way satellites

- Probing the local small-scale structure



Constraints from Milky Way satellites

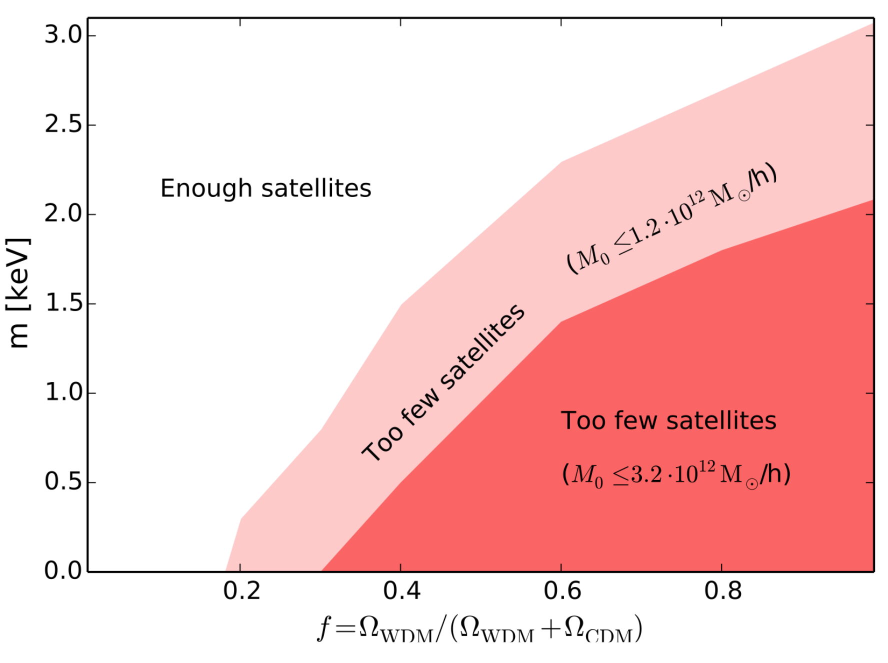




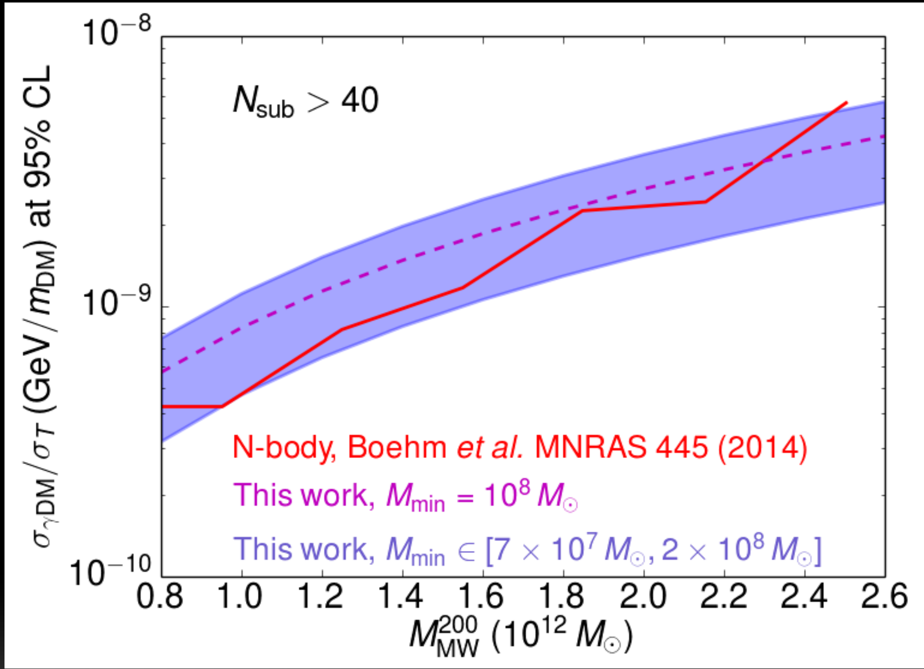
Vogelsberger, Zavala, Cyr-Racine +, arXiv:1512.05349

Constraints from Milky Way satellites

- Observed number of MW satellites constrains the small-scale matter power spectrum.
- Also, kinematical studies might also yield important clues.



(Schneider 2015)

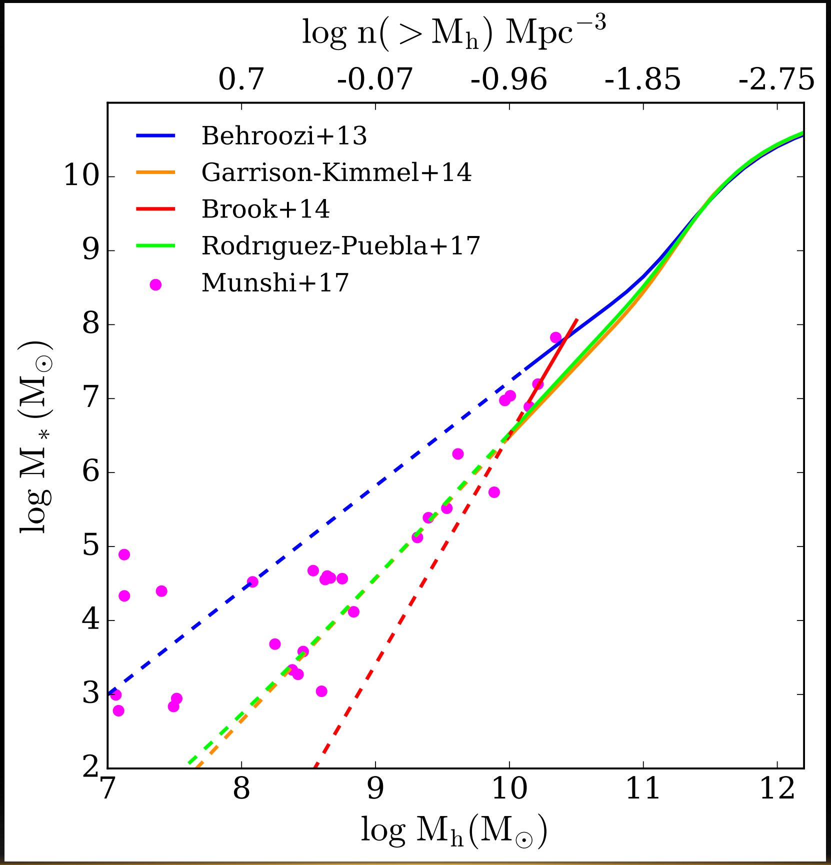


(Escudero et al. 2018)

See Laura Lopez-Honorez's talk

Constraints from Milky Way satellites

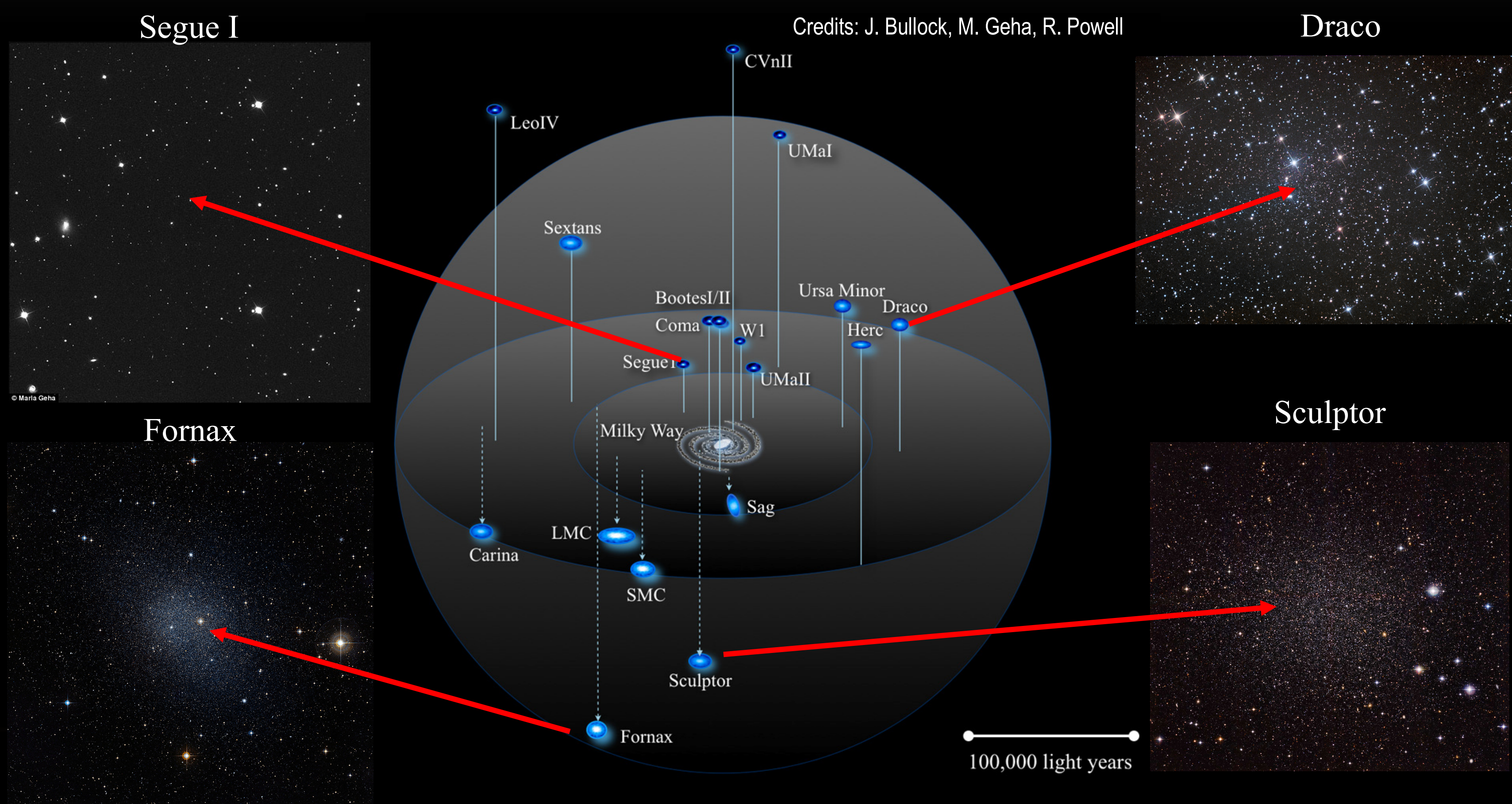
- Difficulty in obtaining halo mass from observations for low stellar-mass objects



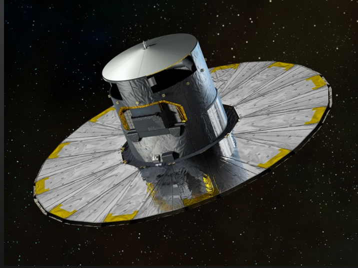
(Danieli, Van Dokkum & Conroy 2018)

Mapping the Milky Way satellites

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

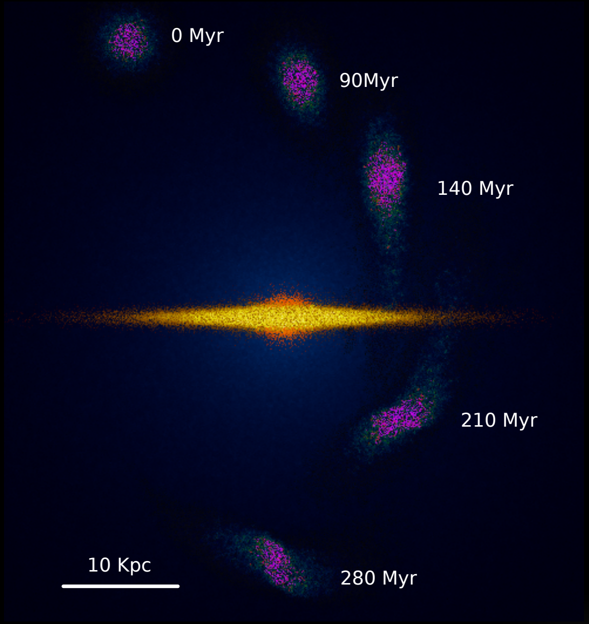


Solution: Astrometric probes



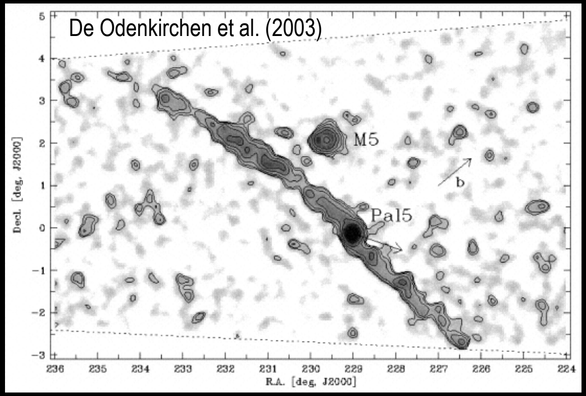
- Look for correlated velocity and density structure in the stellar disk, stellar streams, and halo stars.

Stellar disk perturbations



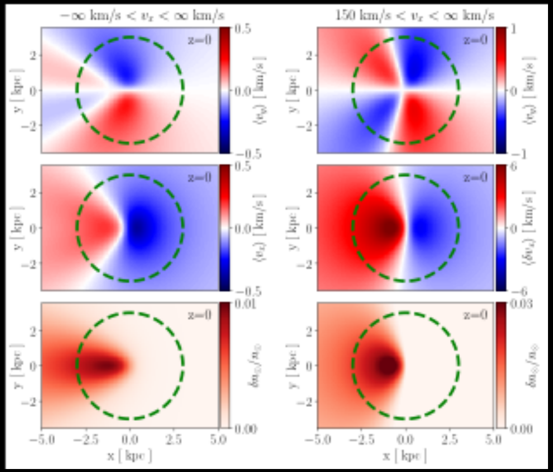
Feldmann & Spolyar (2014)
Widrow et al. (2012)

Stellar stream perturbations



Yoon, Johnston & Hogg (2011)
Carlberg (2009, 2012, 2013)
Erkal & Belokurov (2015a, b)
Sanders, Bovy & Erkal (2016)
Bovy (2016)
Bovy, Erkal & Sanders (2017)
Banik, Bertone, Bovy & Bozorgnia (2018)

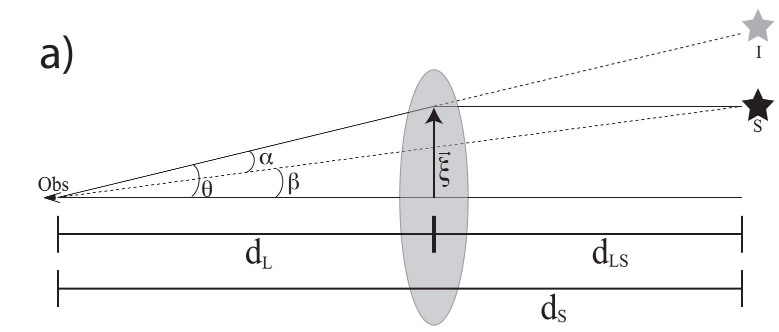
Stellar wakes



Buschmann, Kopp, Safdi, & Wu, 2018

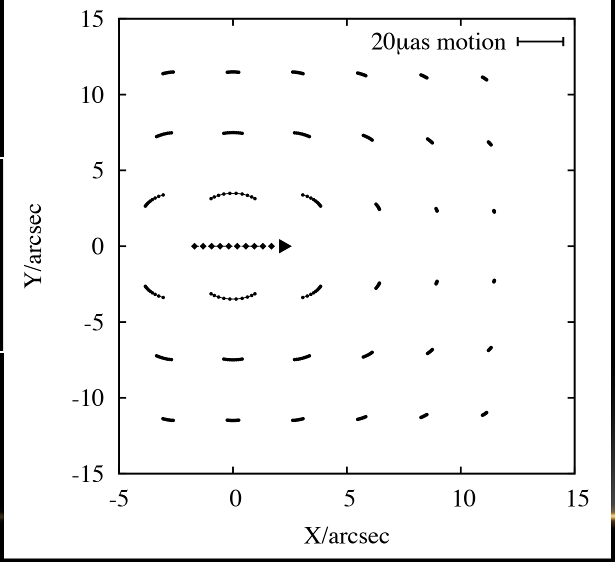
Another solution: Astrometric microlensing

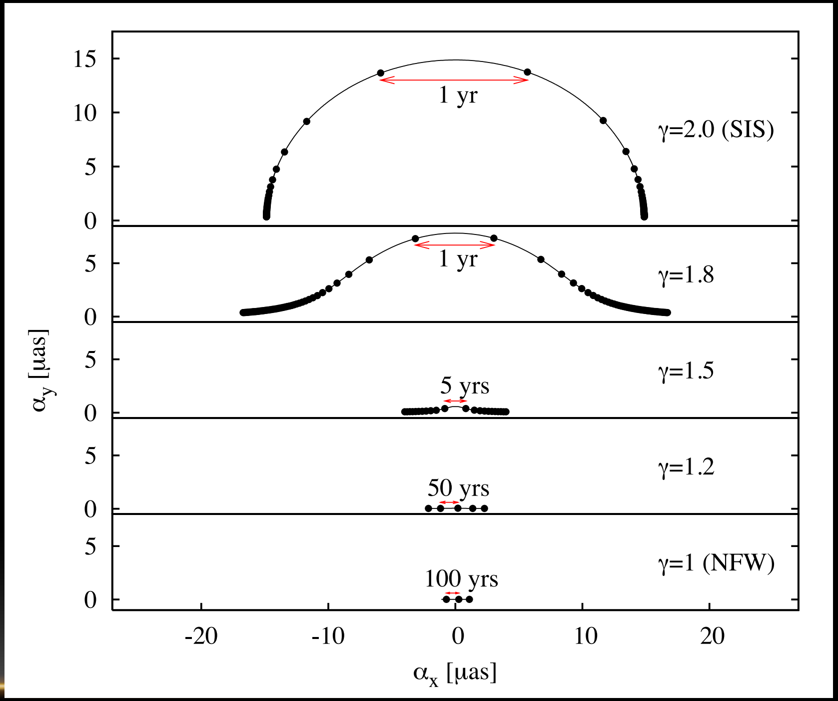
- Detecting dark subhalos through a coherent microlensing signal



Challenging Measurements!

4 yrs of observation, SIS subhalos

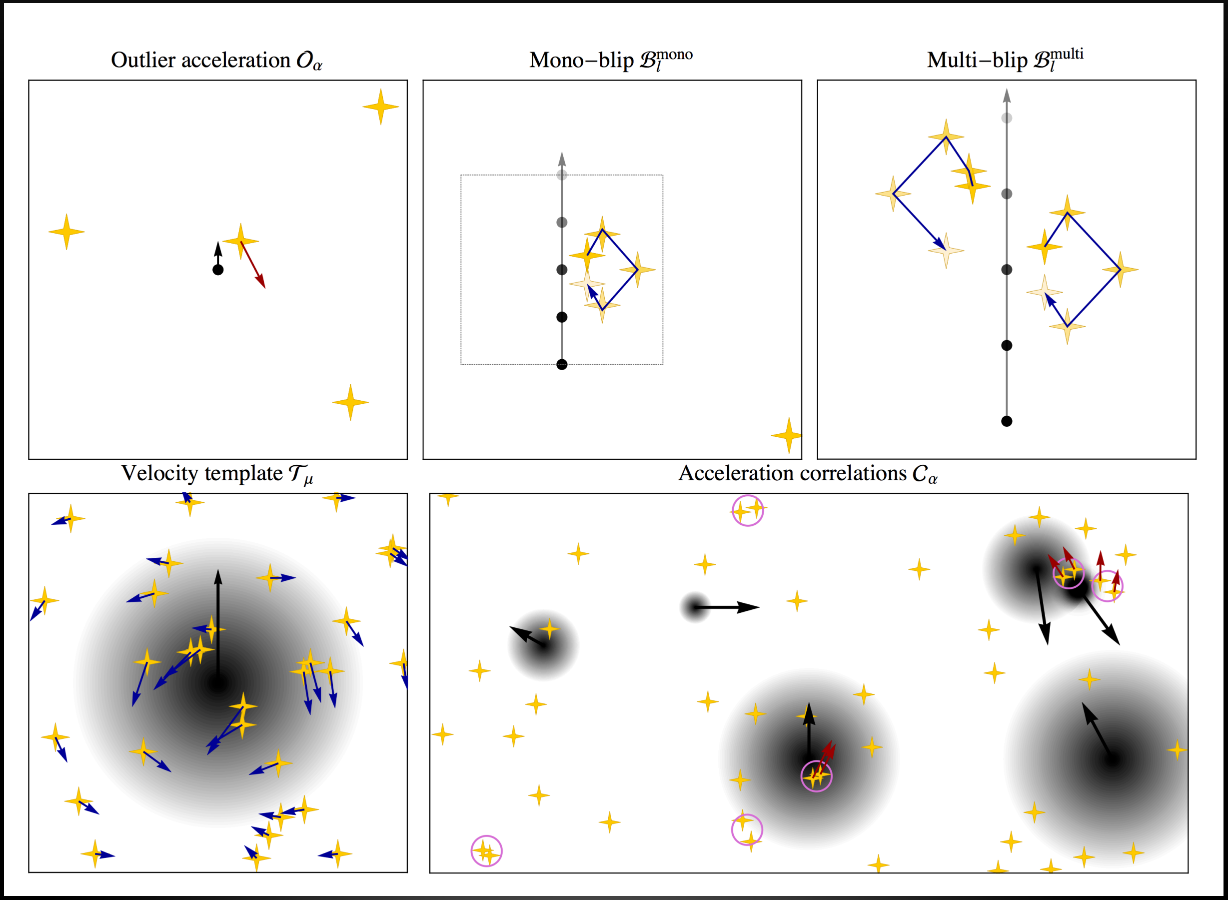




Erickcek & Law (2011)

Astrometric microlensing

- Detecting dark subhalos through a coherent microlensing signal



Van Tilburg, Taki & Weiner (2018)

Gravitational probes of dark matter: From local to cosmological

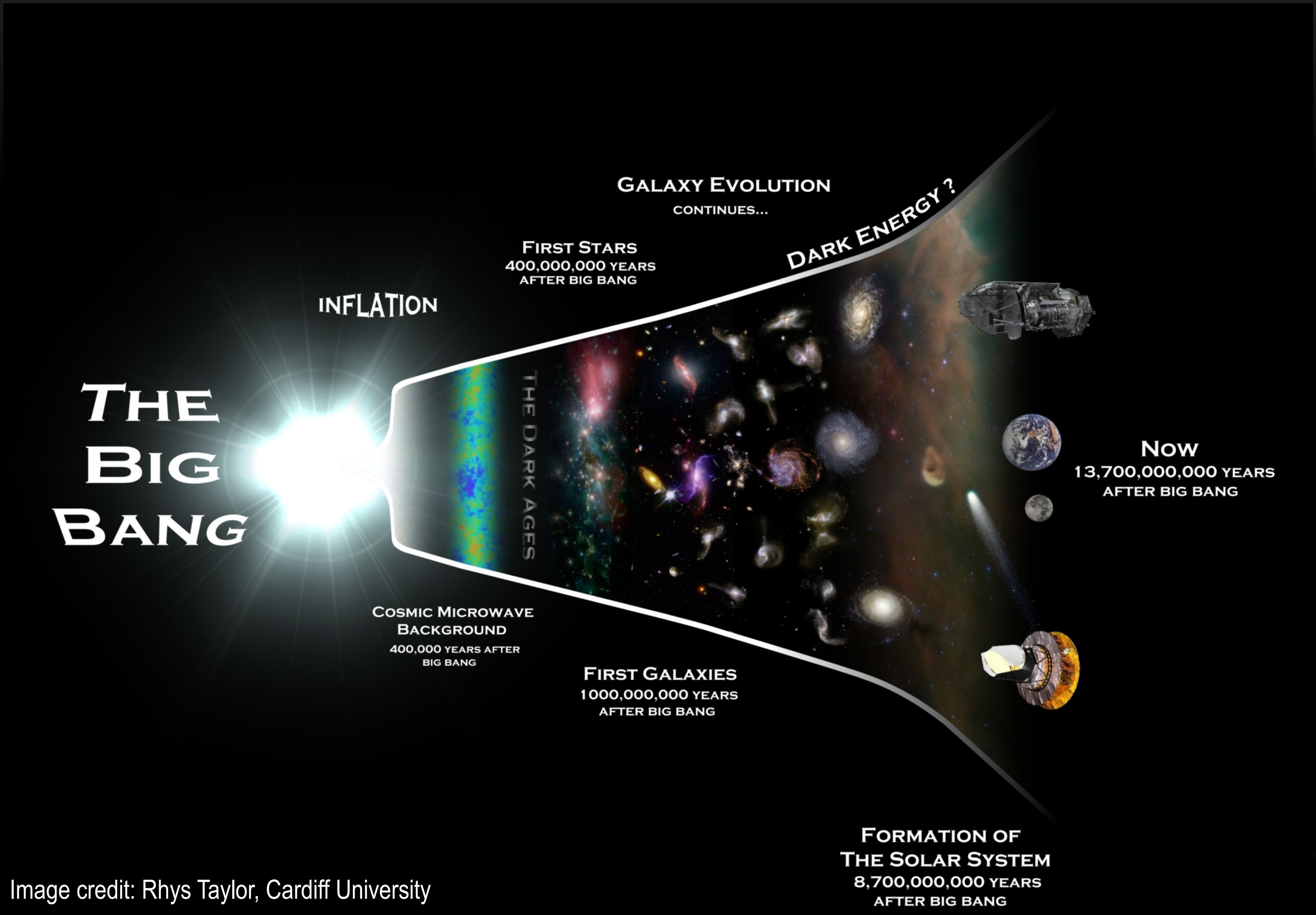
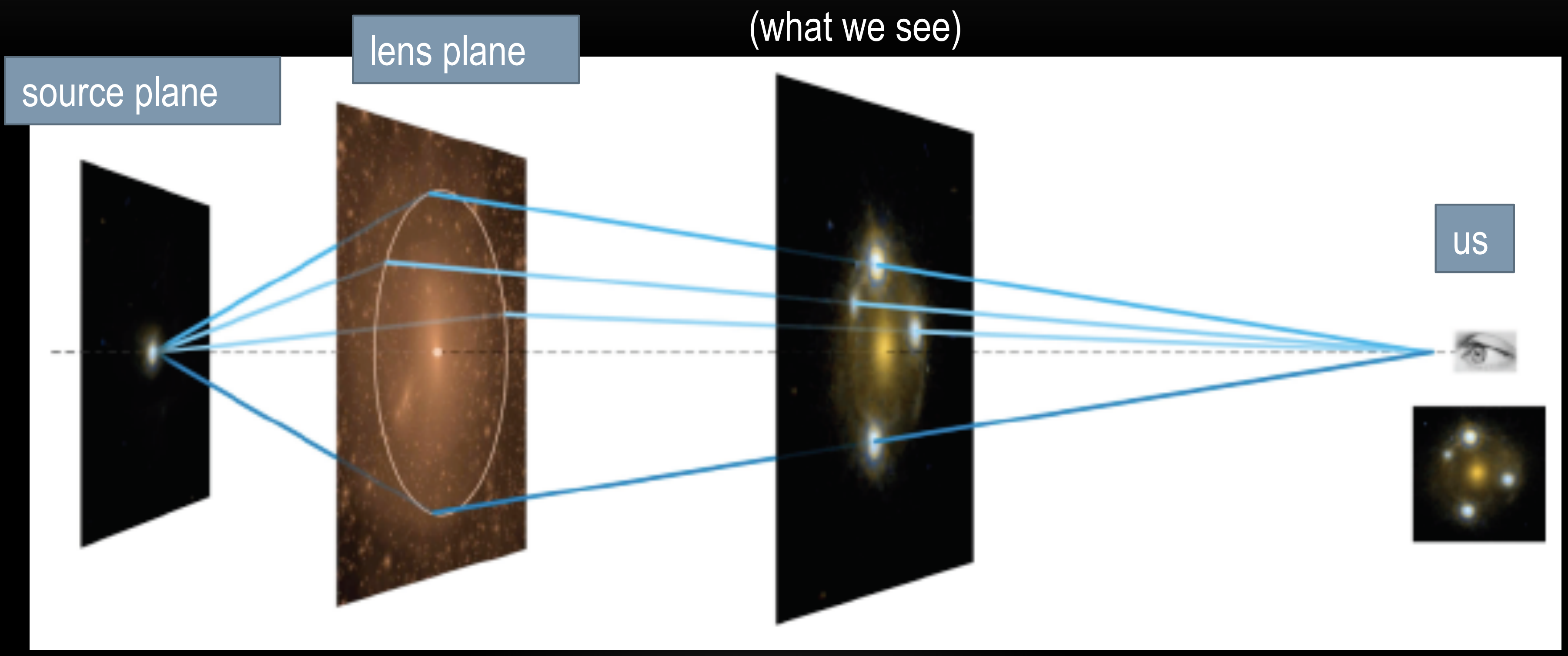


Image credit: Rhys Taylor, Cardiff University

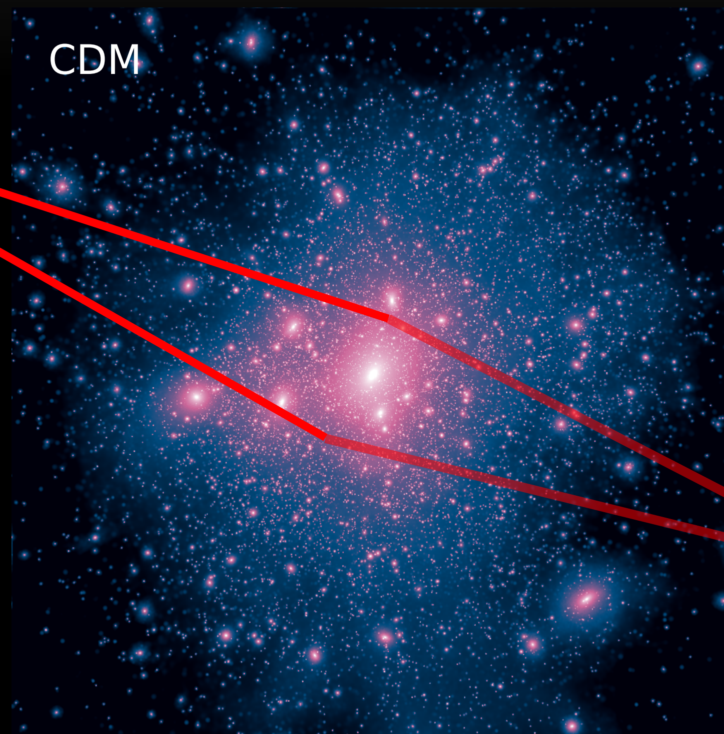
Strong Gravitational Lensing

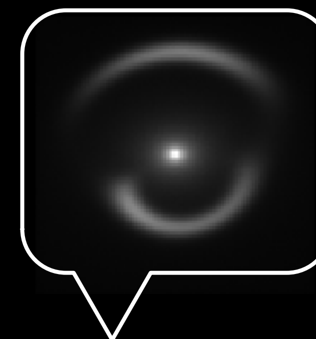


Credits: Leonidas Moustakas

Probing substructure through gravitational lensing

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



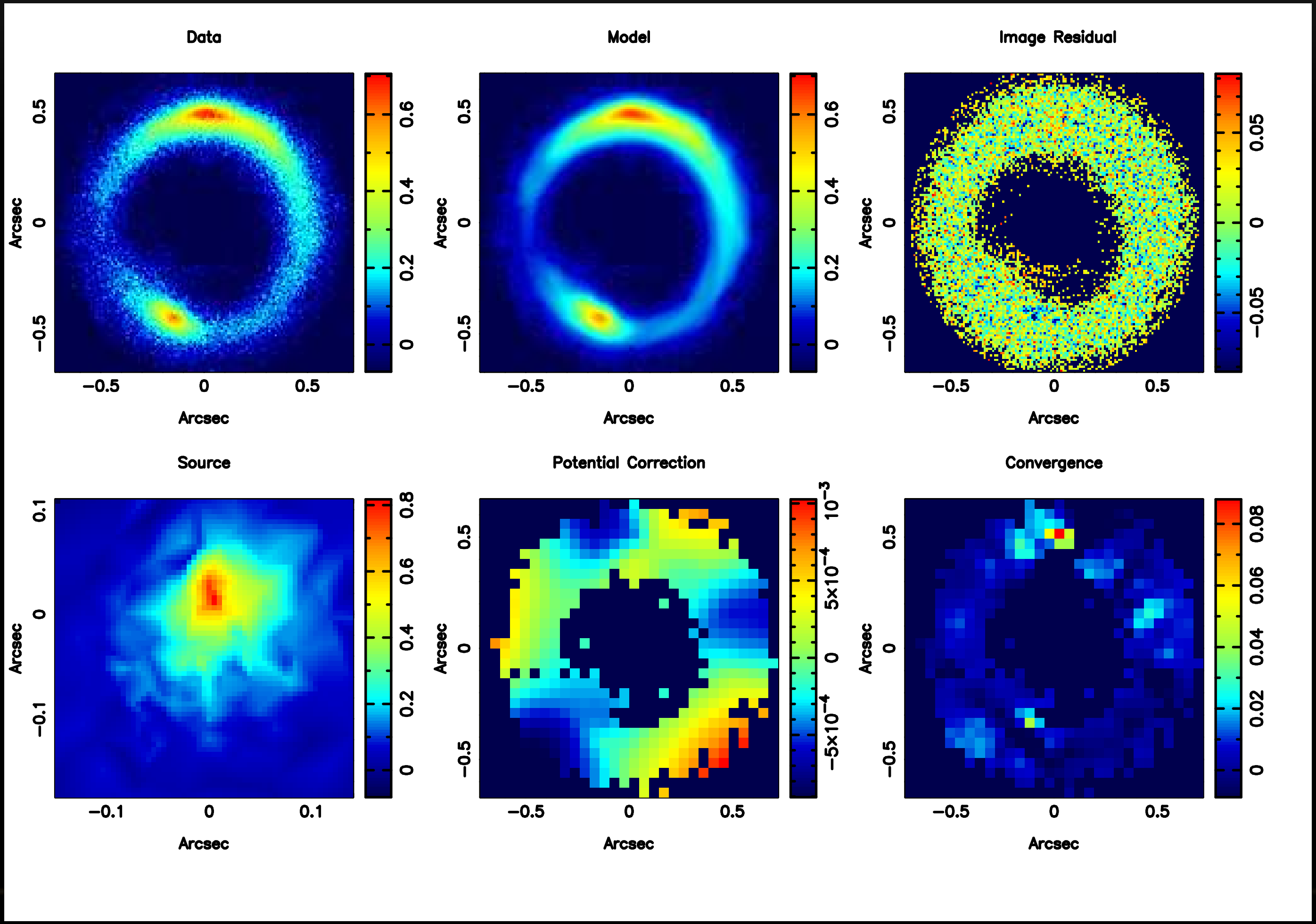


Not to scale!

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

Direct Substructure Detection

- “Gravitational Imaging” of Perturbed Einstein Rings



Vegetti et al. *Nature*, (2012)

Direct Substructure Detection

- "Gravitational Imaging" of Perturbed Einstein Rings

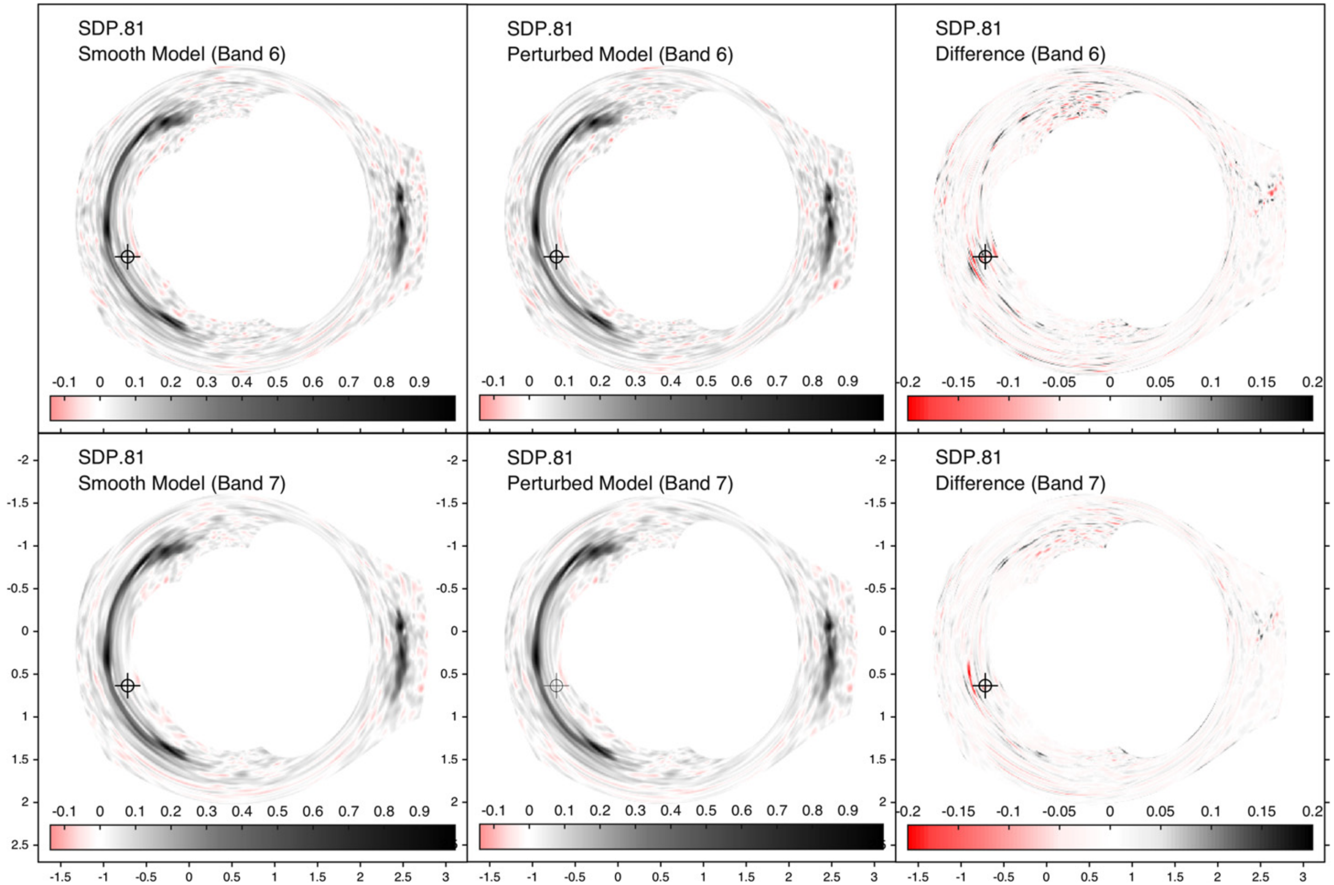
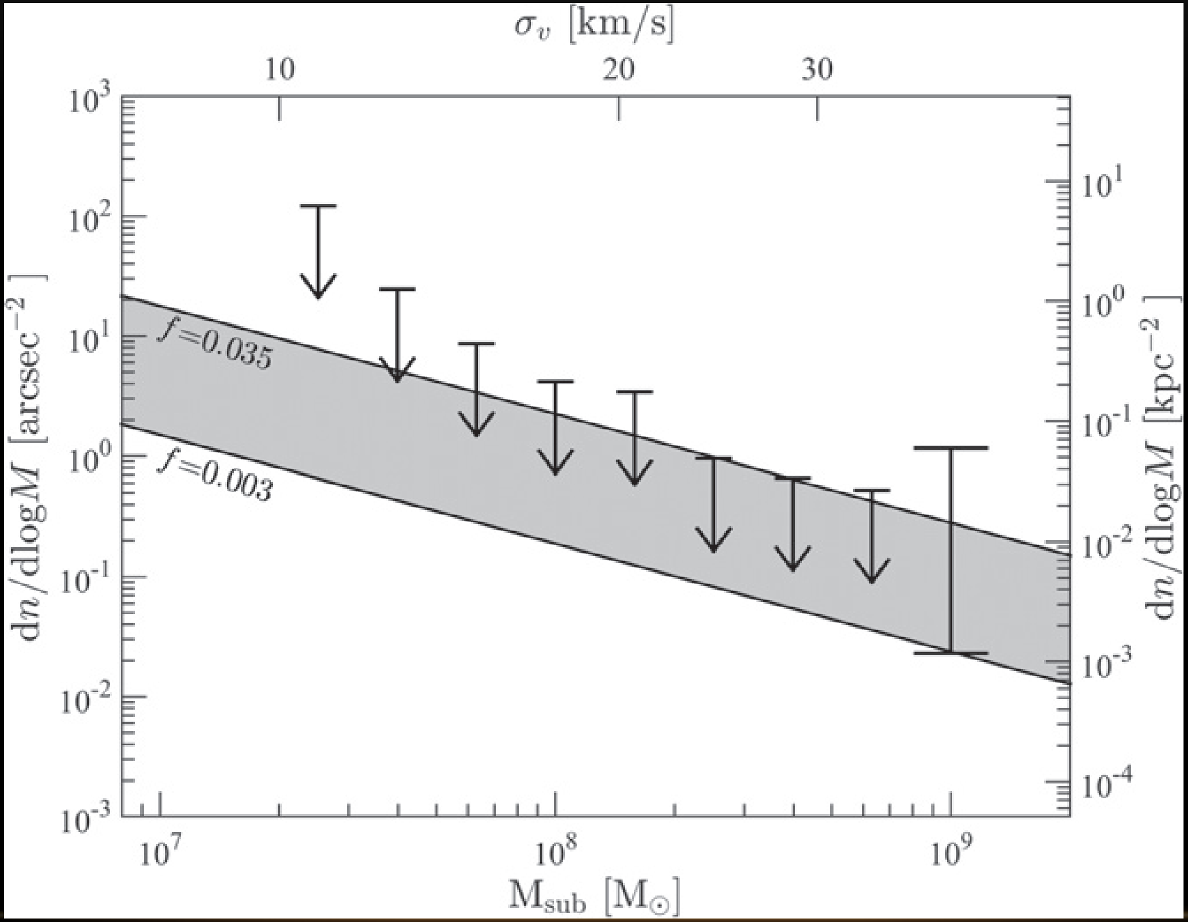


Figure 6. Top left: the sky emission model in band 6 for the best-fit smooth lens parameters for the SDP.81 data. Top middle: the same for the perturbed model. Top right: the difference between the two models. The bottom panels show the same for band 7. The bright feature in the difference plots is mainly caused by the astrometric anomaly of the arc. In each row, the images have been scaled to the peak flux of the smooth model.

Hezaveh et al., (2016)

Direct Substructure Detection

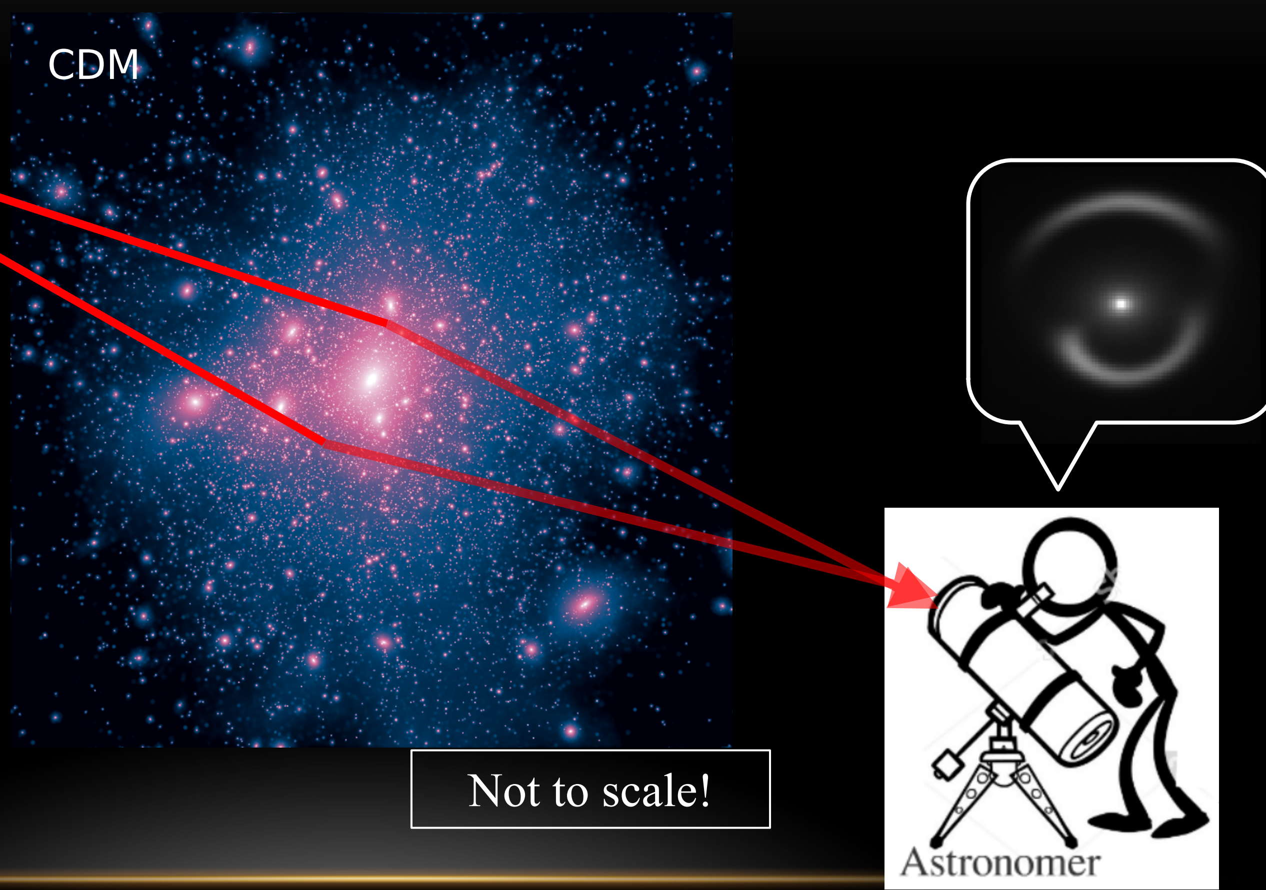
- Constraints on the subhalo mass function



Hezaveh et al., (2016) (see also Vegetti et al. (2014), Li et al. (2016))

Other approach: characterizing the collective effect of the small-scale structure

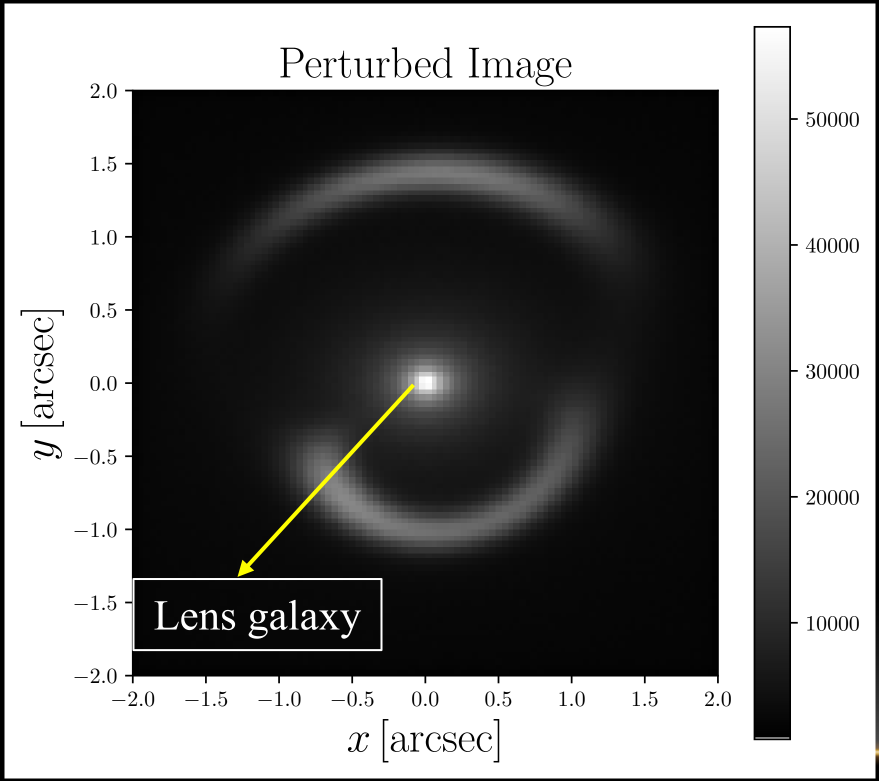
- Measure the power spectrum of small-scale structure

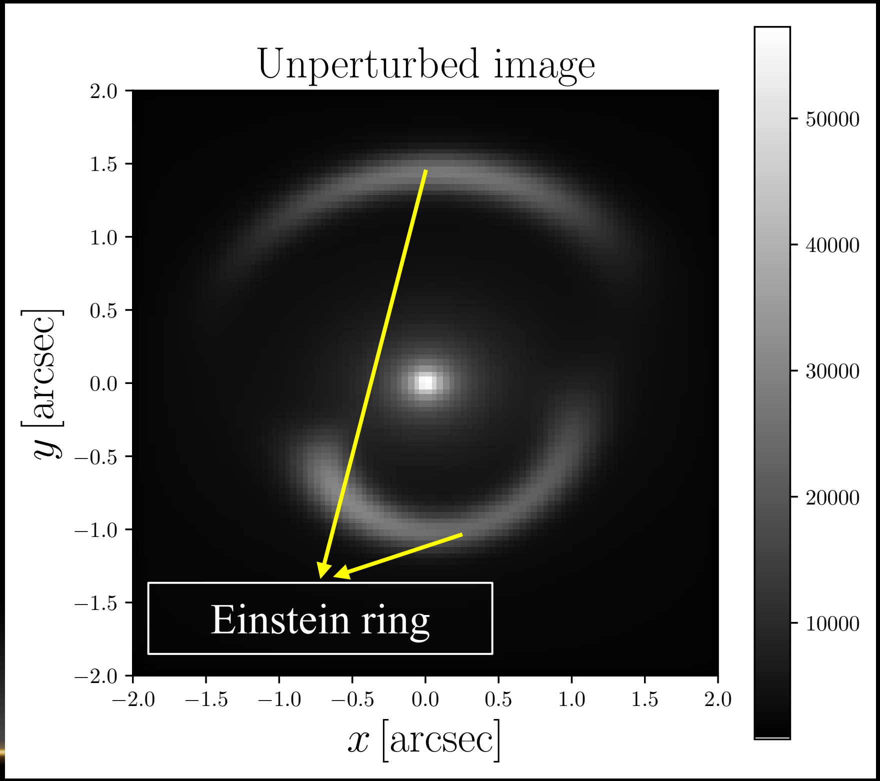


Hezaveh et al. (2016), Diaz Rivero et al. (2017), Chatterjee et al. (2018), Bayer et al. (2018)

Effect of substructures on lensed images

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





Cyr-Racine, Keeton & Moustakas, arXiv:1806.07897

Effect of substructures on lensed images

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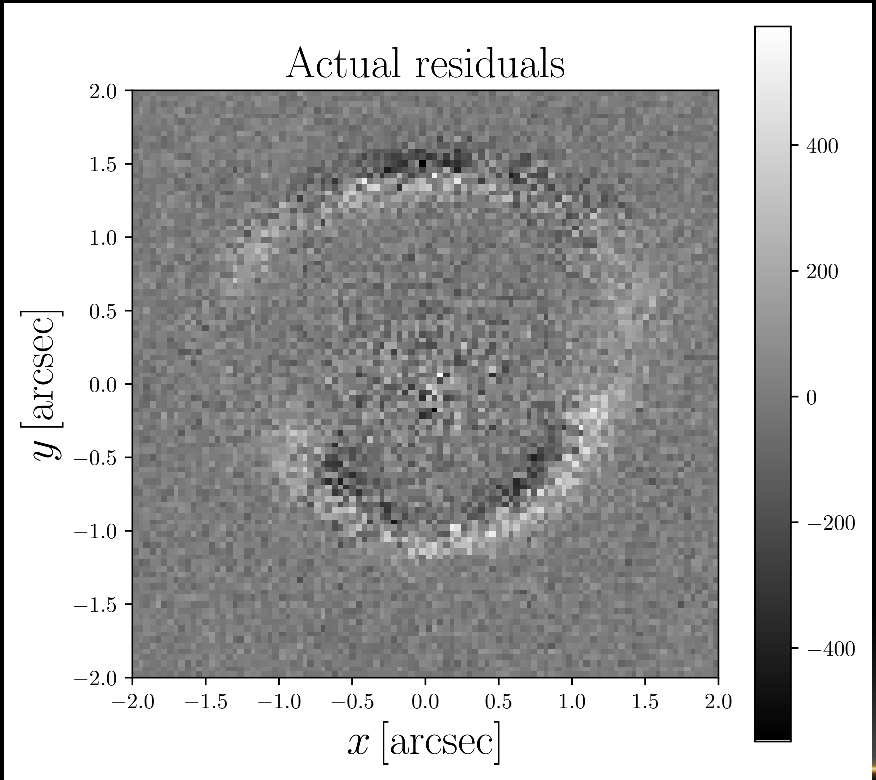
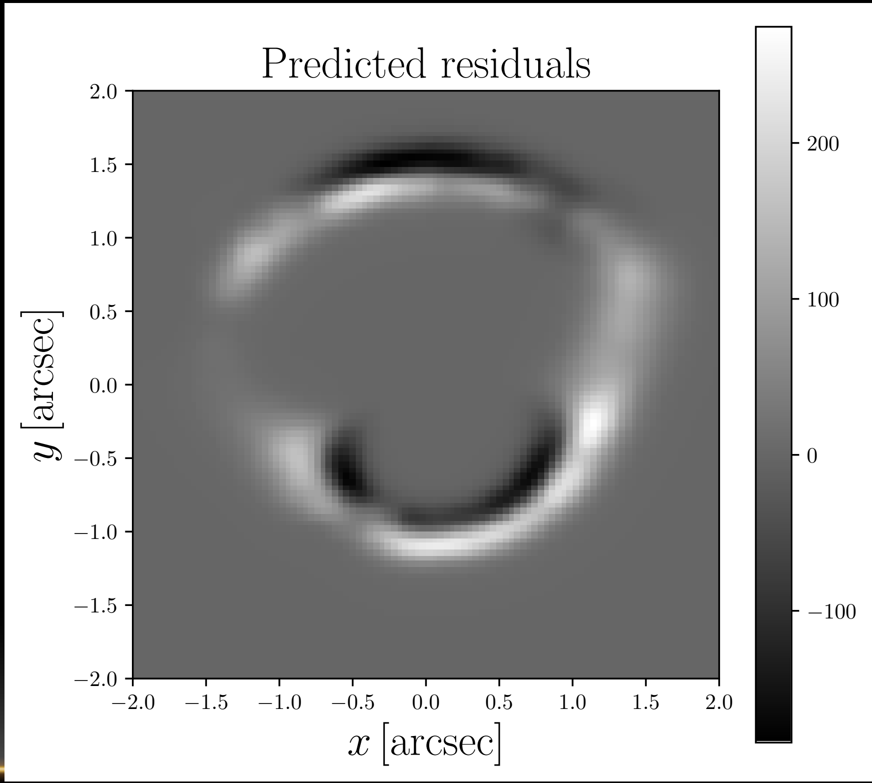
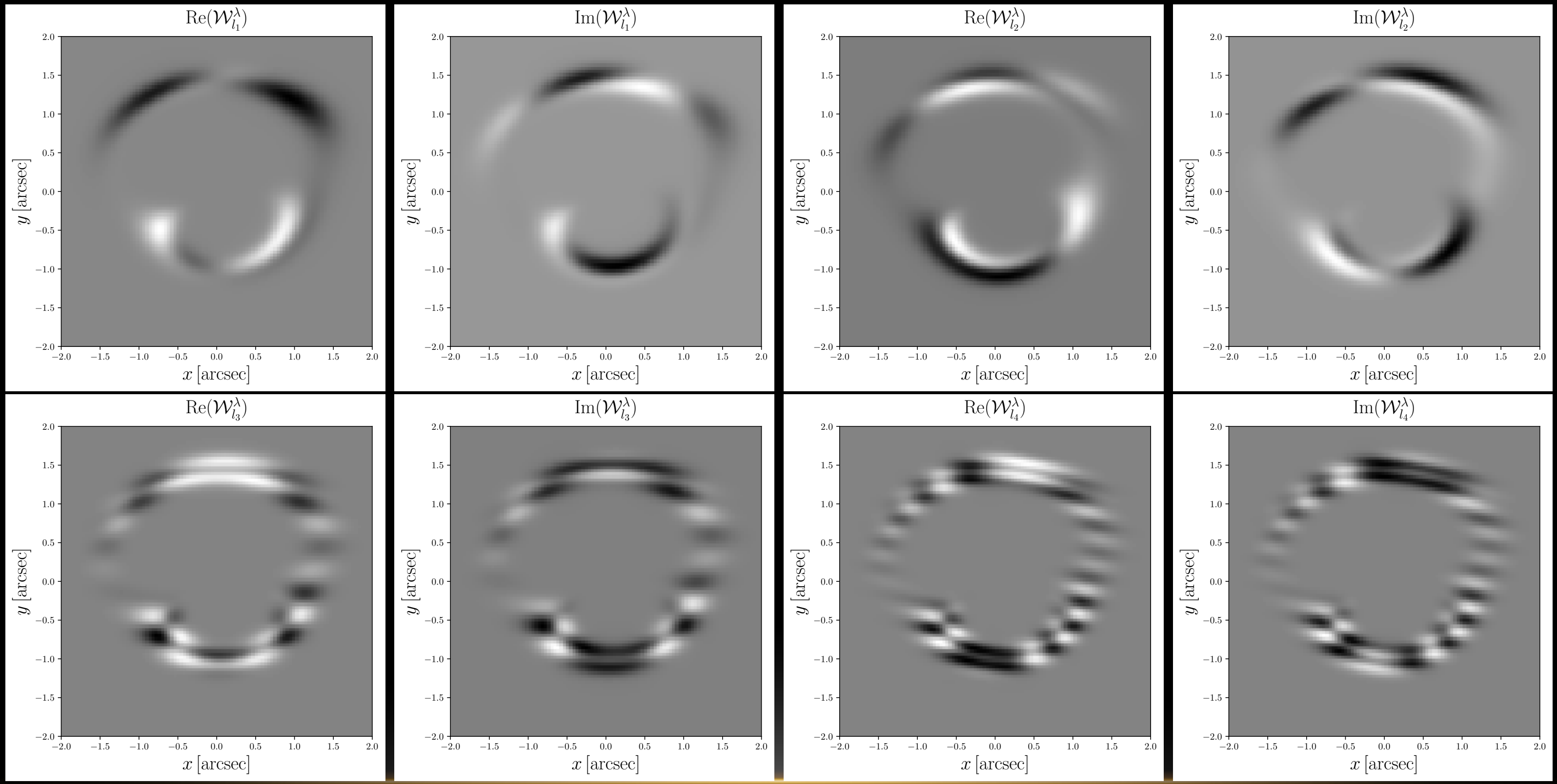




Cyr-Racine, Keeton & Moustakas, arXiv:1806.07897

From image residuals to substructure power spectrum

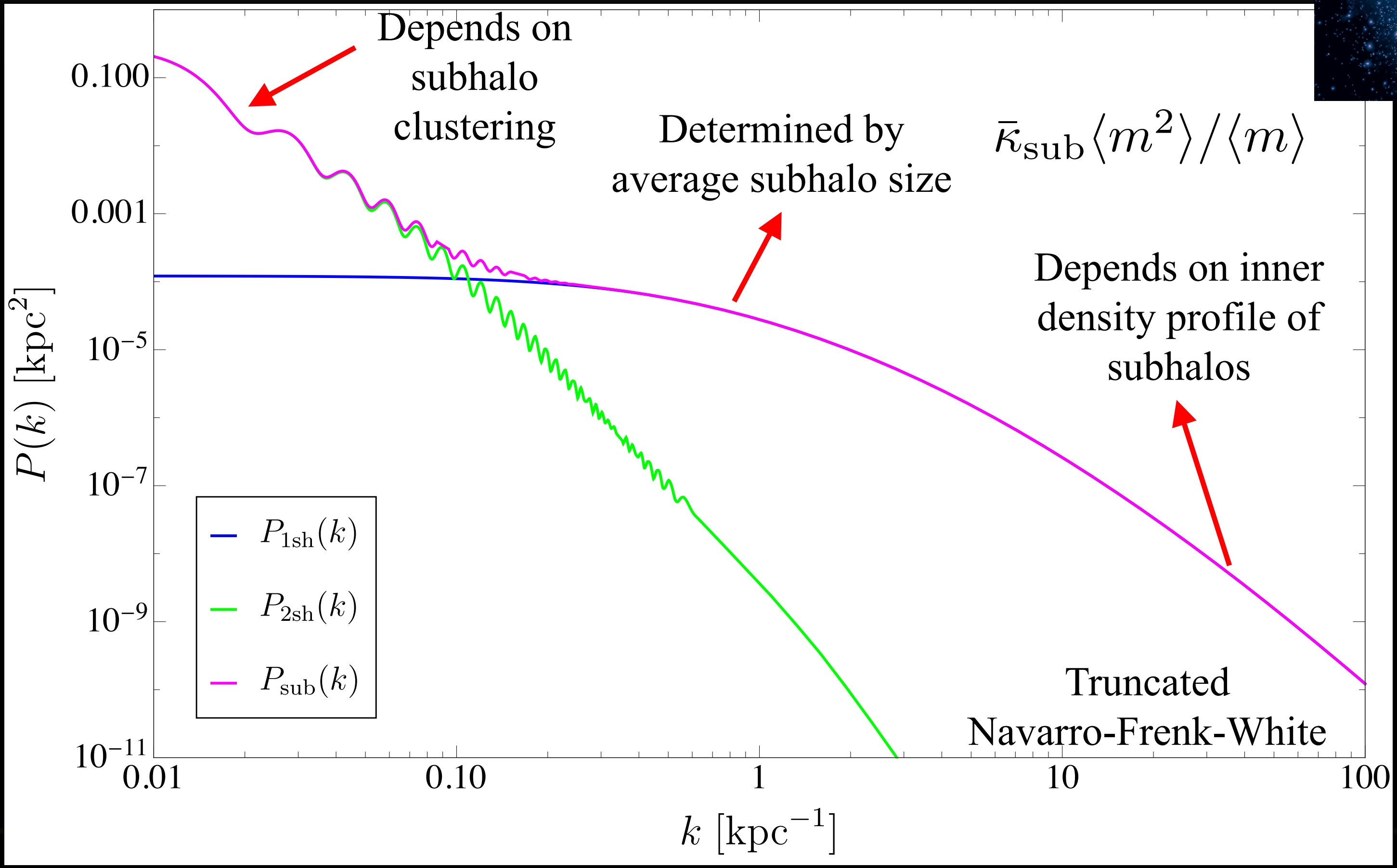
- We can decompose the image residuals in a Fourier-like basis to determine which modes are present in the data.



Cyr-Racine, Keeton & Moustakas, arXiv:1806.07897

What do we expect: Substructure power spectrum

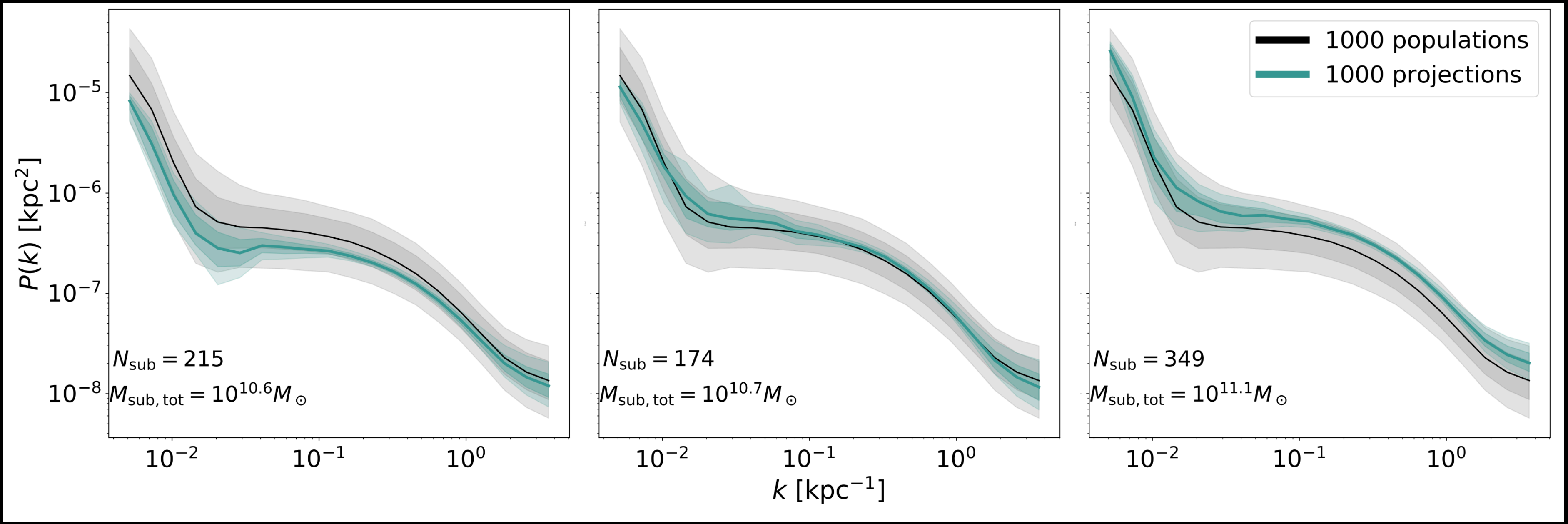
- The power spectrum has 2 main contributions:



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

What do we expect: Substructure power spectrum

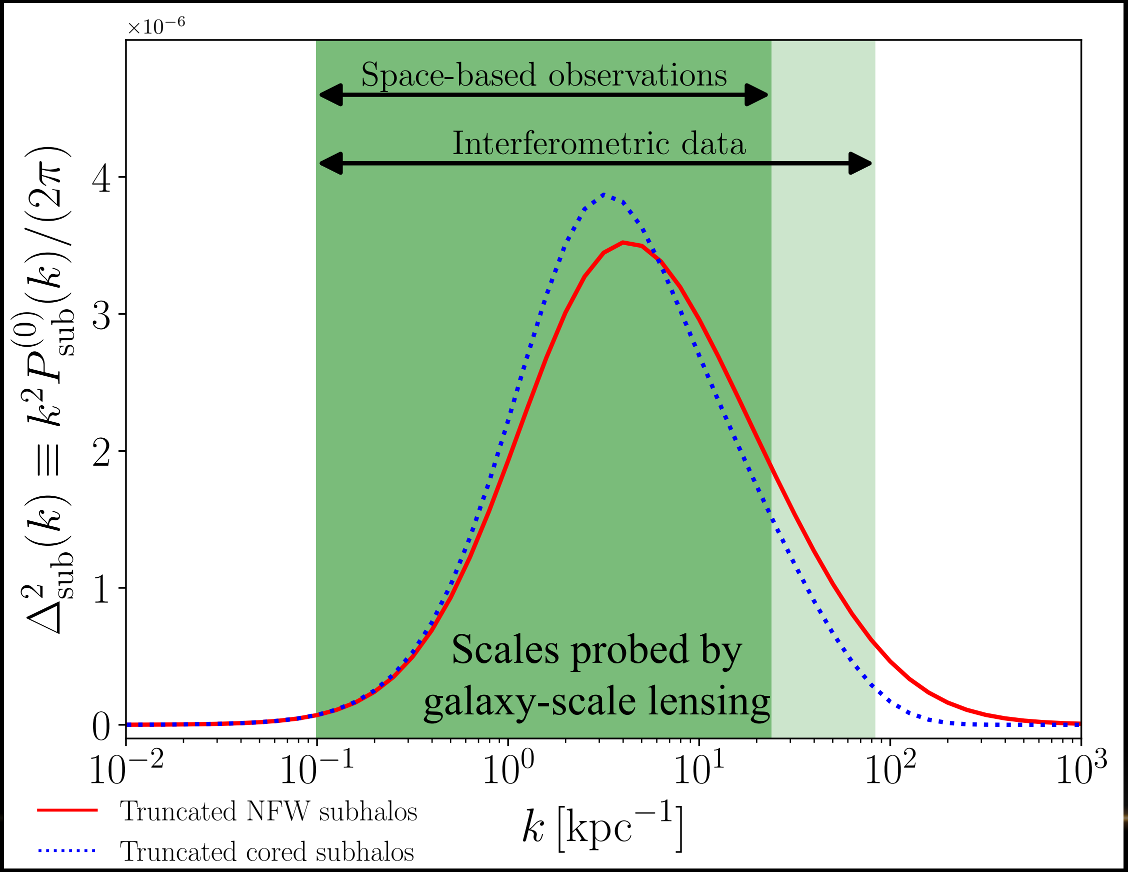
- These predictions closely match what we get from semi-analytic galaxy formation models (Galacticus)

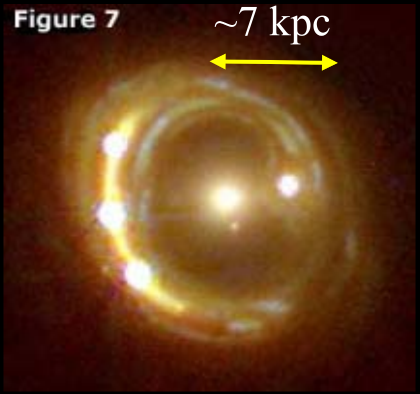


Brennan, Benson, Cyr-Racine +, in prep.

In a realistic scenario, are we sensitive to the substructure power spectrum?

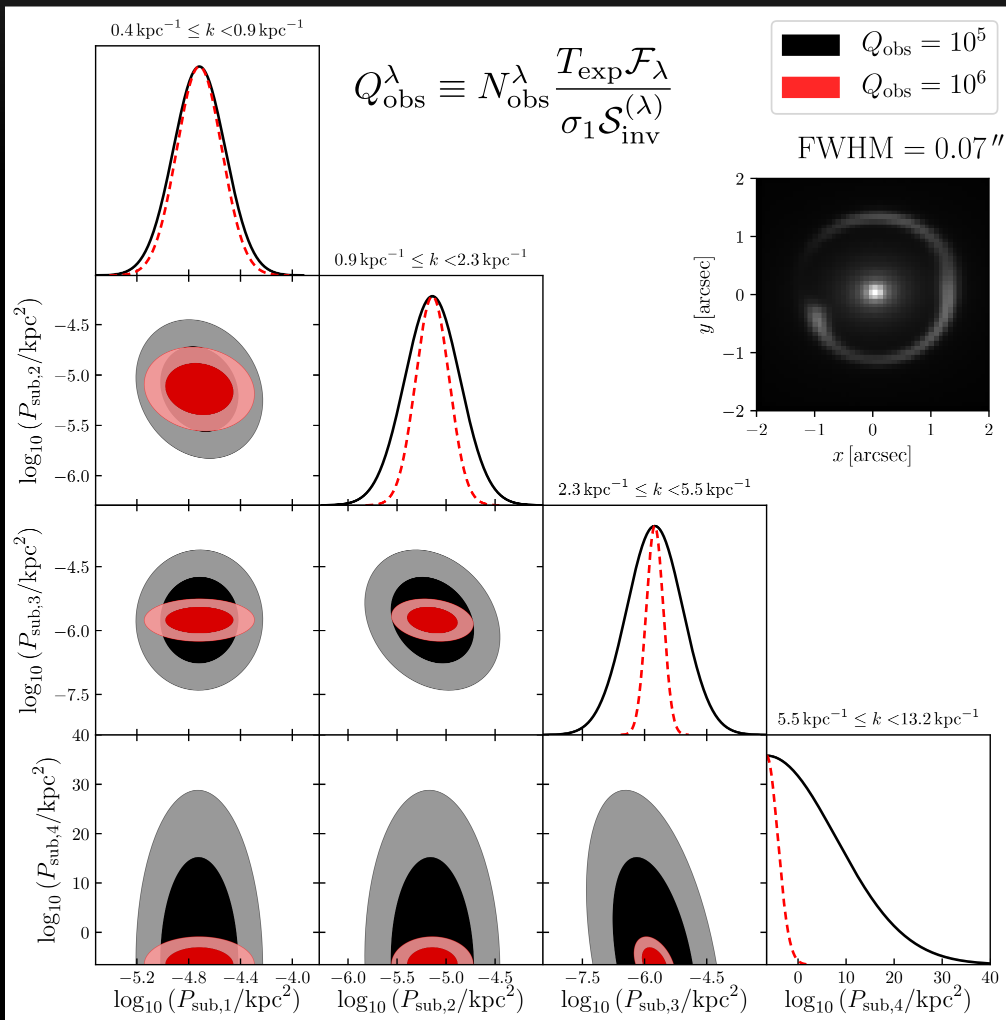
- For galaxy scale lenses, Yes!





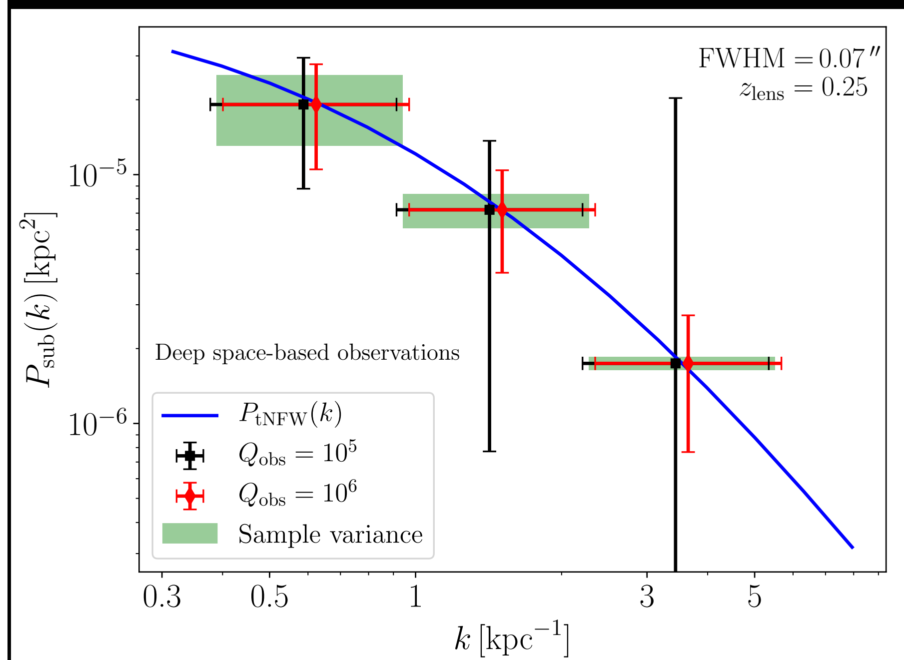
Cyr-Racine, Keeton & Moustakas, arXiv:1806.07897

Use *Hubble Space Telescope* mock images to assess sensitivity



Fisher Forecasts

WFC3 UVIS F555W

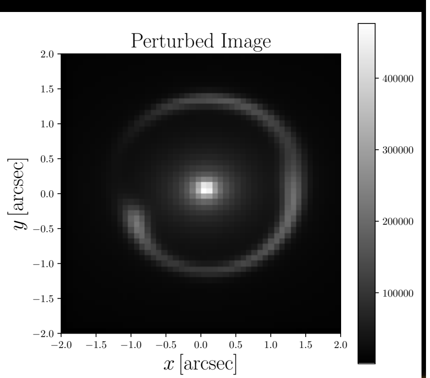


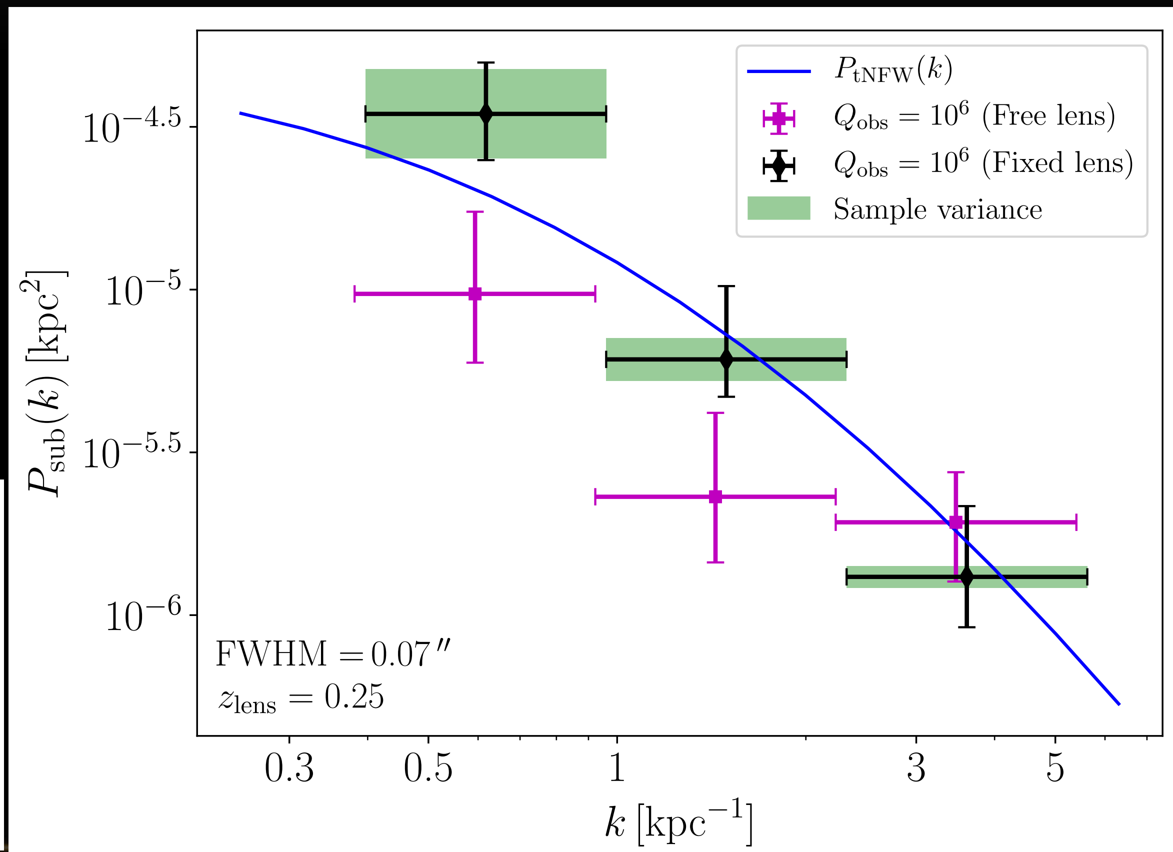
Cyr-Racine, Keeton & Moustakas, arXiv:1806.07897

Use *Hubble Space Telescope* mock images to assess sensitivity

- Degeneracies in lens model can bias the power spectrum low

$$Q^{\lambda}_{\rm obs} \equiv N^{\lambda}_{\rm obs} \frac{T_{\rm exp}\mathcal{F}_{\lambda}}{\sigma_1 \mathcal{S}^{(\lambda)}_{\rm inv}},$$





WFC3 UVIS
F555W

Cyr-Racine, Keeton & Moustakas, arXiv:1806.07897

Gravitational probes of dark matter: From local to cosmological

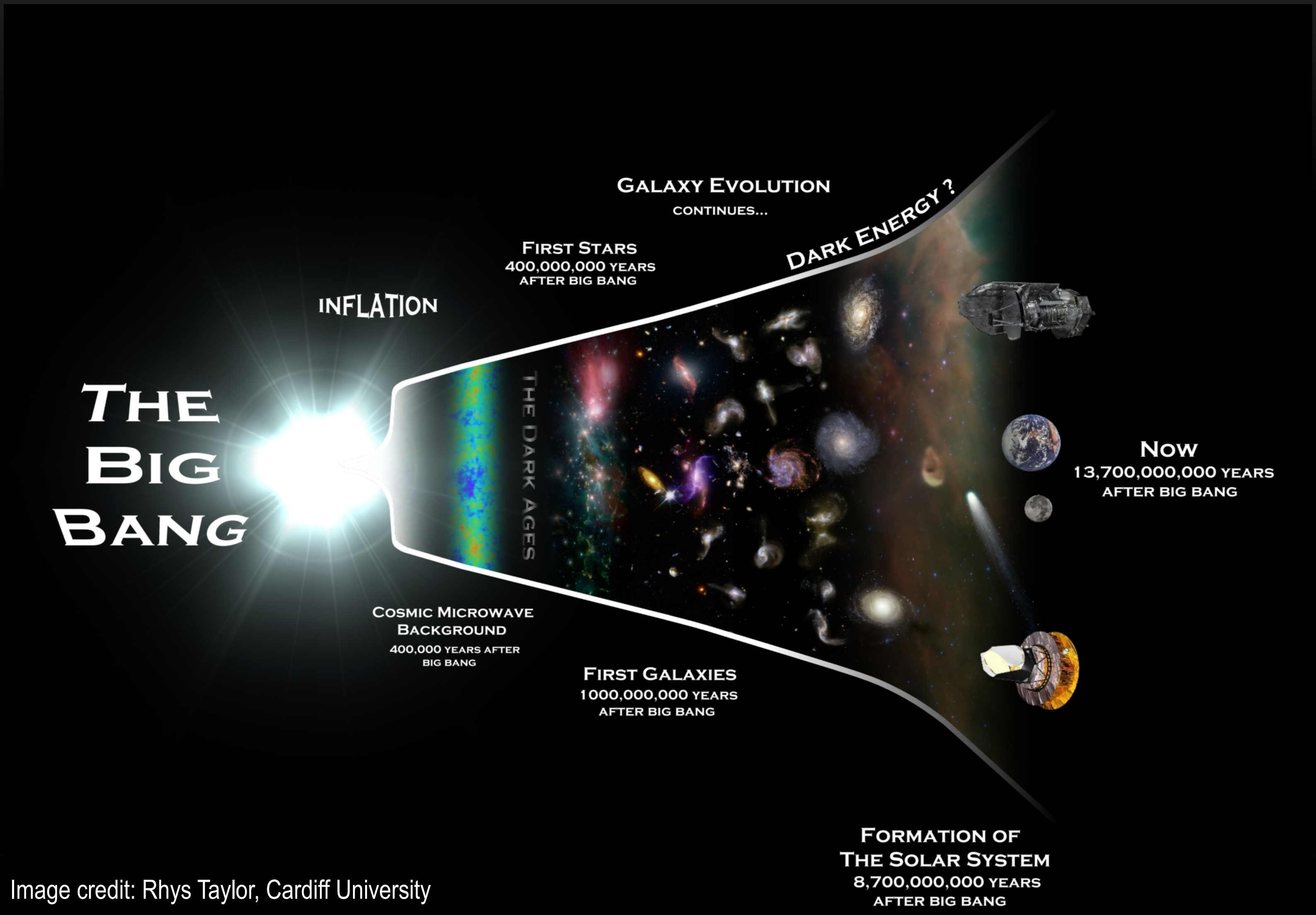
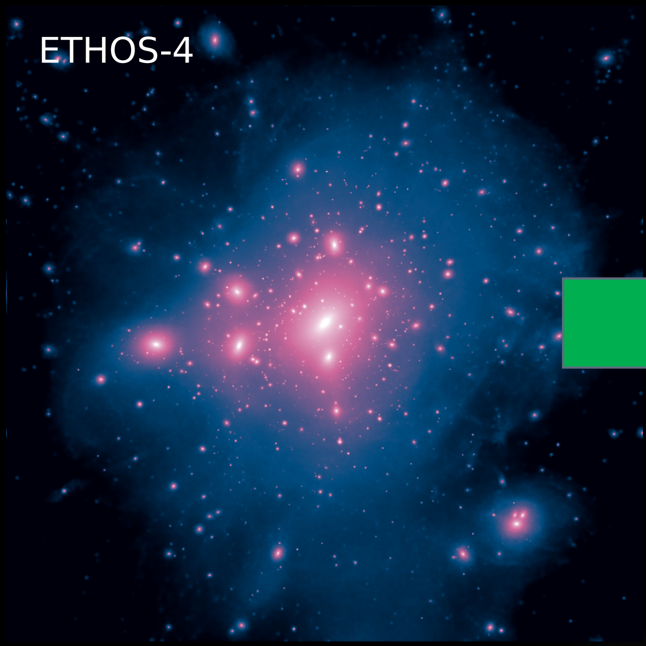


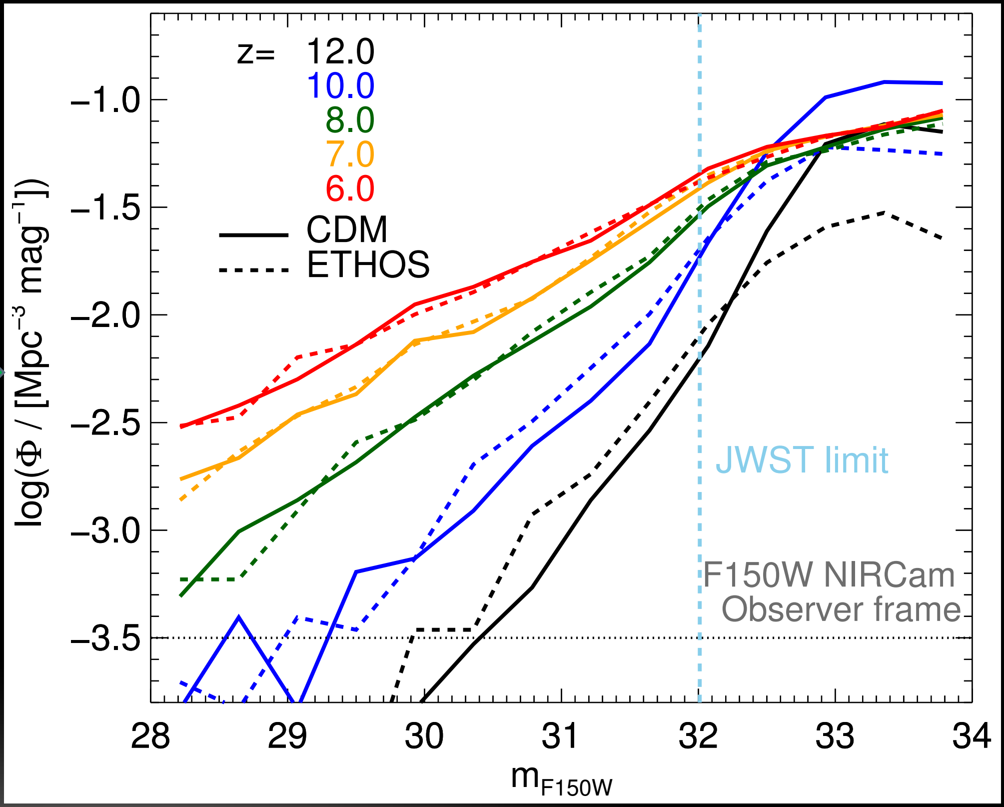
Image credit: Rhys Taylor, Cardiff University

Dark matter physics affects the formation of the first stars/galaxies

- Impact on high-z UV luminosity function, reionization, and cosmic dawn.

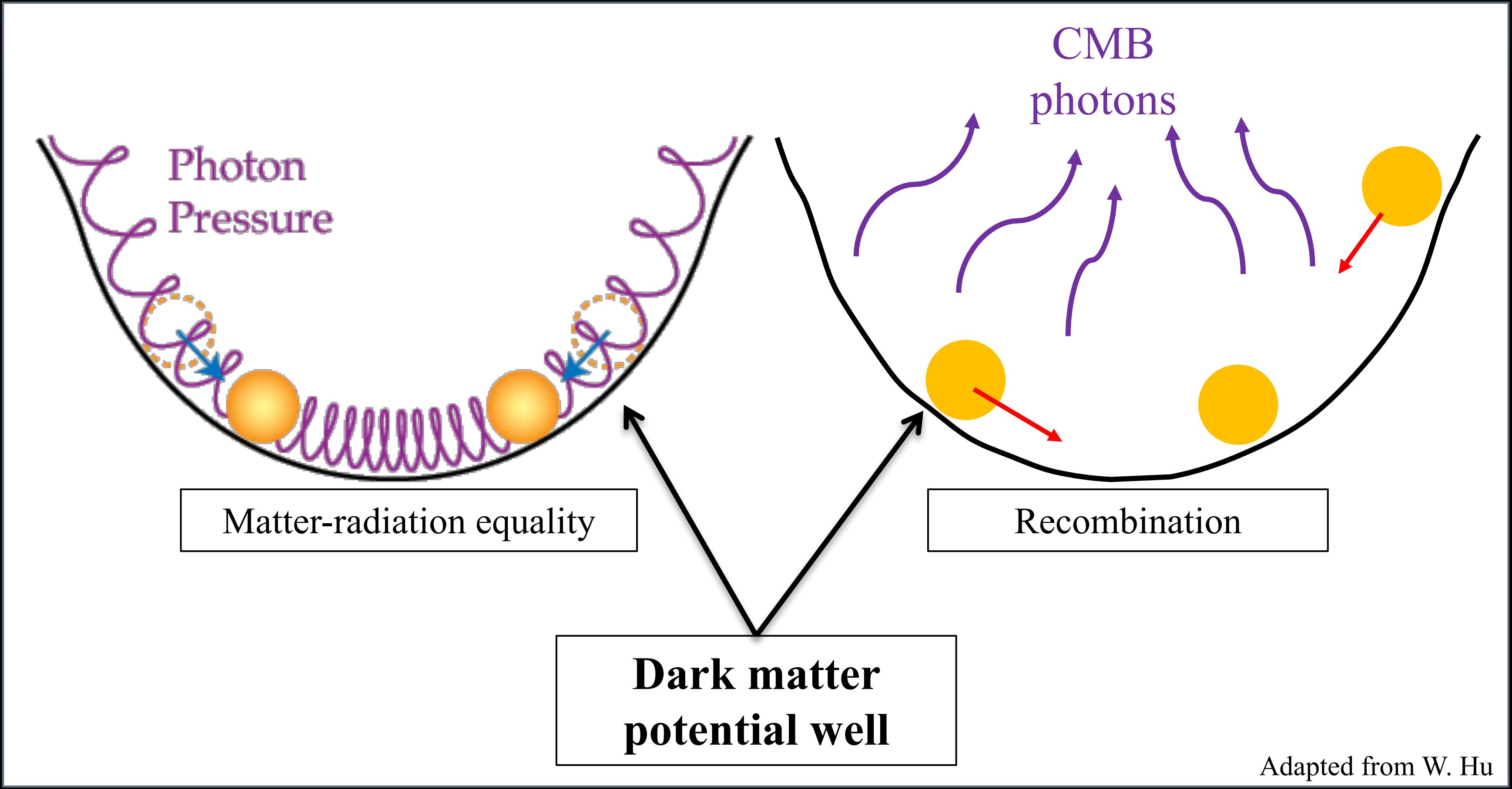


See Laura Lopez-Honorez's talk

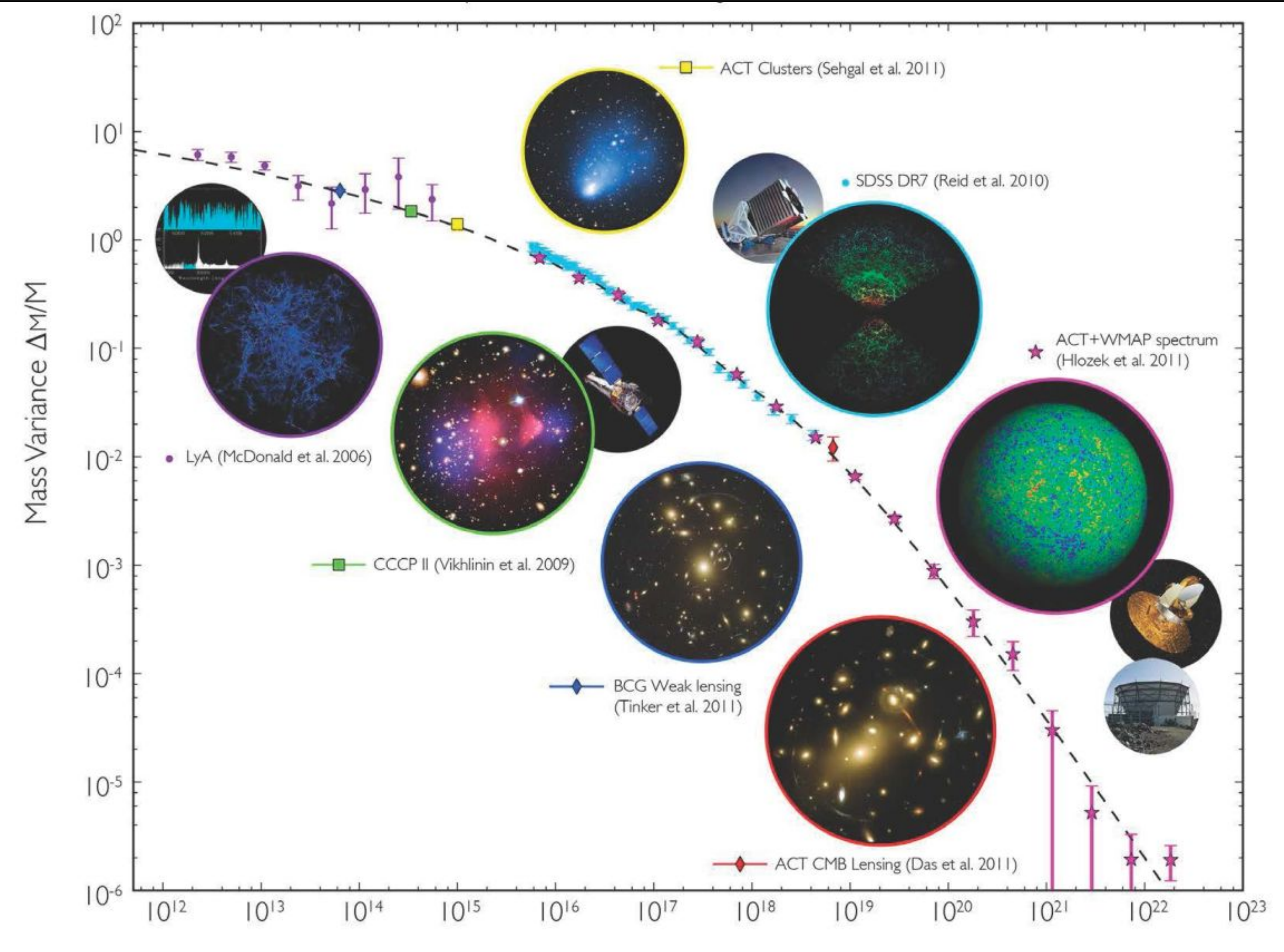


Lovell, Zavala, Vogelsberger Shen, Cyr-Racine +, arXiv:1711.10497

CMB: Dark matter provides gravitational potential wells for baryons to fall into

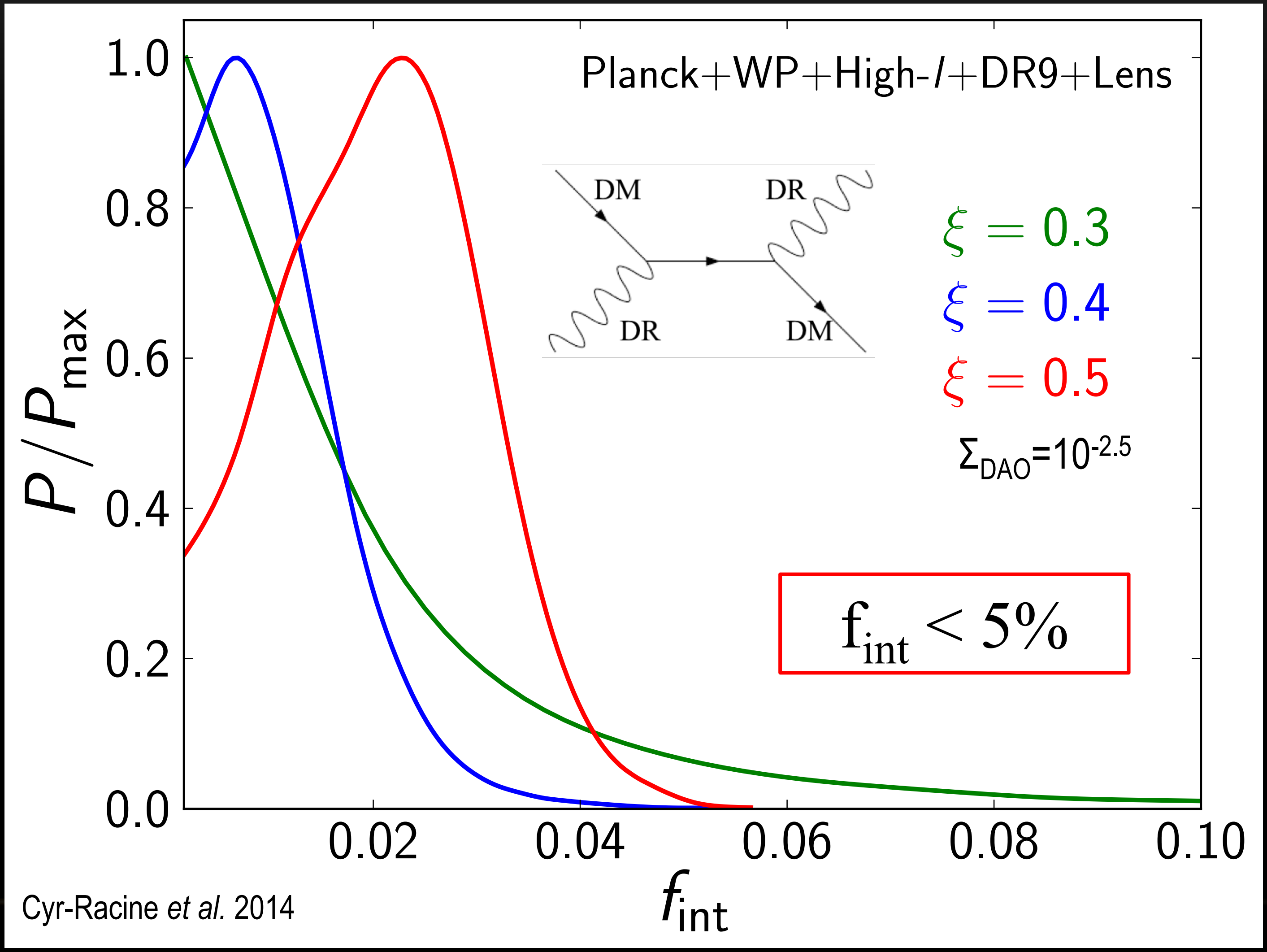


On scales probed by the CMB, the cold dark matter picture is remarkably consistent



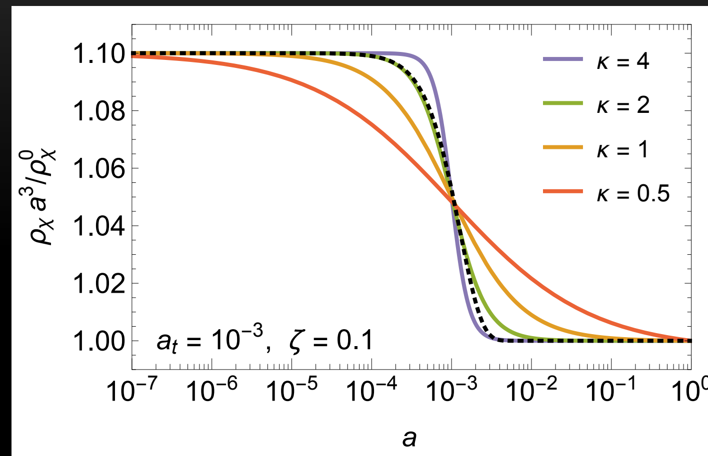
Calabrese et al. (2011)

Interacting DM: Allowed Fraction



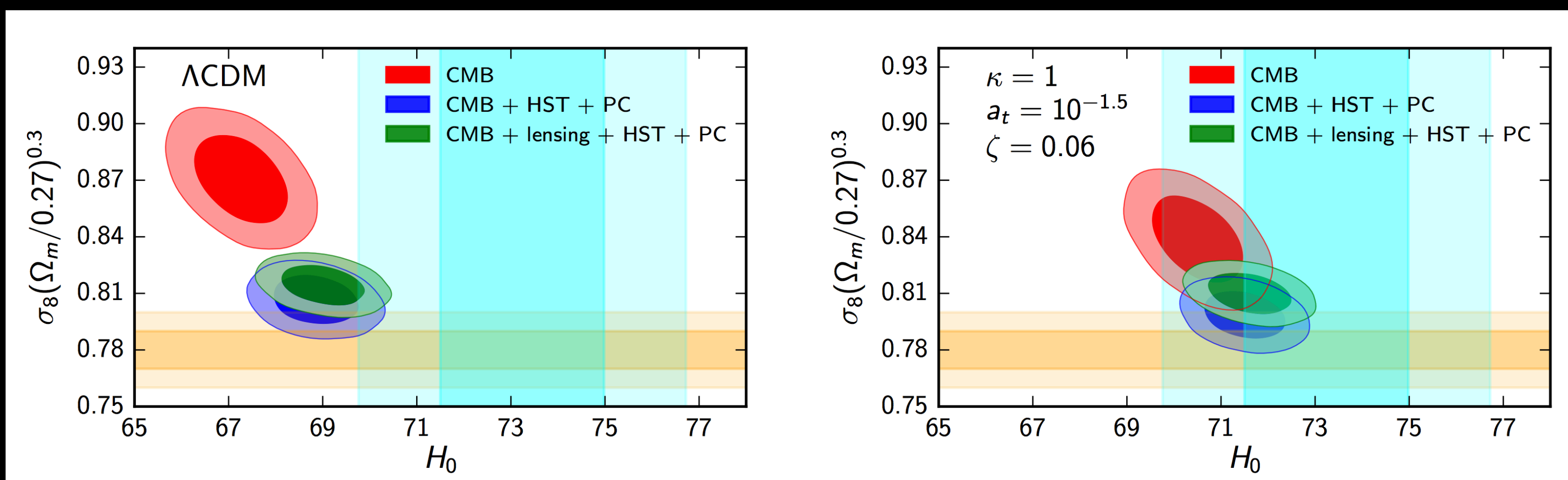
Still lots of interesting scenarios to play with!

Allows some of the DM to decay to dark radiation



See Felix's talk from Monday

See Jan Hamann's talk tomorrow



Bringmann, Kahlhoefer, Schmidt-Hoberg, Walia (2018)

Executive summary

- Gravitational probes of dark matter physics are very diverse in their methods, just like the standard “triad” .
- There are a lot of good ideas out there. We now need to do the dirty work of getting actual measurements and constraints.
- We need better studies of the possible complementarity between different gravitational probes (just like dark energy science).
- In the long term, I think strong gravitational lensing offers the best prospects due to the large number of targets that will be discovered in the next decade, especially with LSST and Euclid.

The next decade of dark matter science: LSST

Probing the Nature of Dark Matter with LSST

October 29-31, Lawrence Livermore National Lab

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

Goal | Graphic | Agenda | Registration | Participants | Local Info | Transportation | Previous Workshops | CoC

Workshop Goal

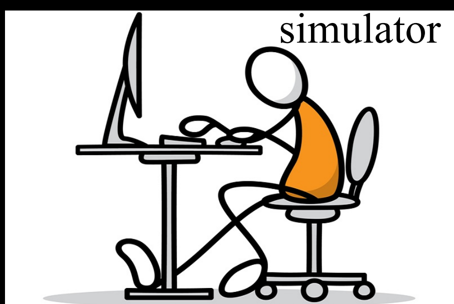
This is the second in a series of workshops attempting to answer the question: how can we utilize LSST to help us understand the microphysics of dark matter, to identify the fundamental constituents of dark matter (e.g., new fundamental particles, compact objects, etc.), and to characterize the properties of these constituents (e.g, mass, temperature, self-interaction rate, etc.)? LSST offers a unique avenue to attack the dark matter problem through "astrophysical probes". Hence, the primary goal of this workshop is build on the work of the U. Pittsburg 2018 workshop towards an LSST dark matter white paper. In this white paper, we hope to provide a comprehensive summary of the various techniques that can be used to test the fundamental nature of dark matter with LSST.

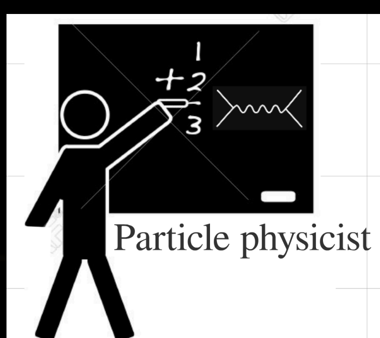
Activity from the last workshop are summerized in a series of github issues and tweets: #lsstdarkmatter.

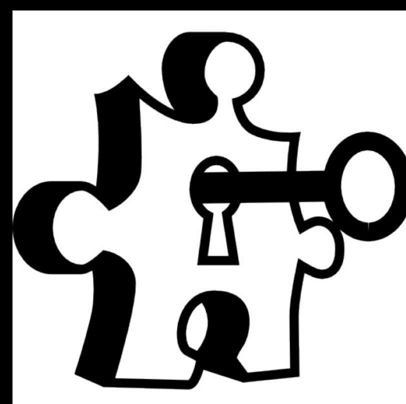
https://lsstdarkmatter.github.io/

The next decade of dark matter science

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

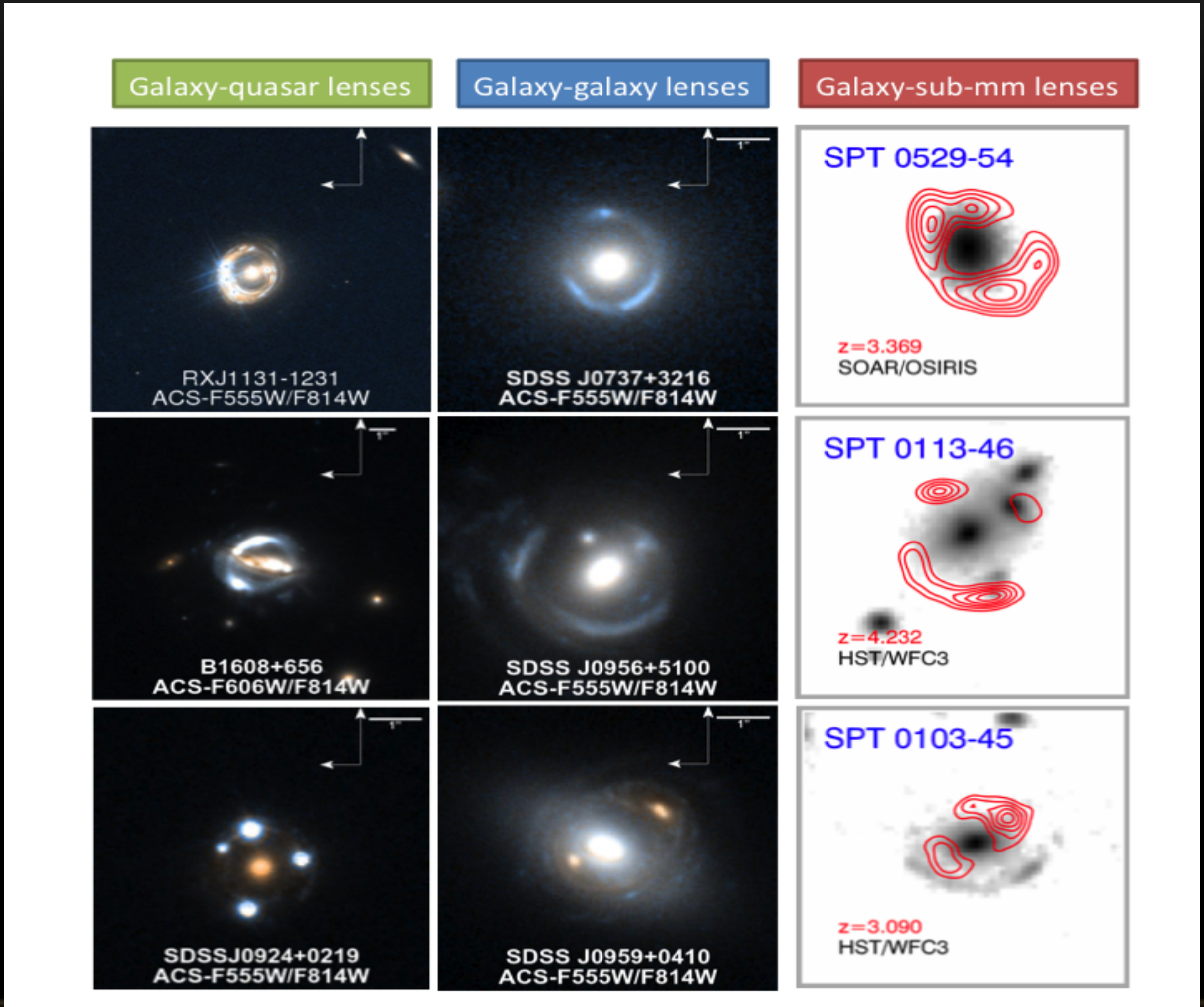






Thank you!

Backup: Galaxy-scale Gravitational Lenses



Credits: Leonidas Moustakas