Unlocking dark matter physics out of small-scale structures

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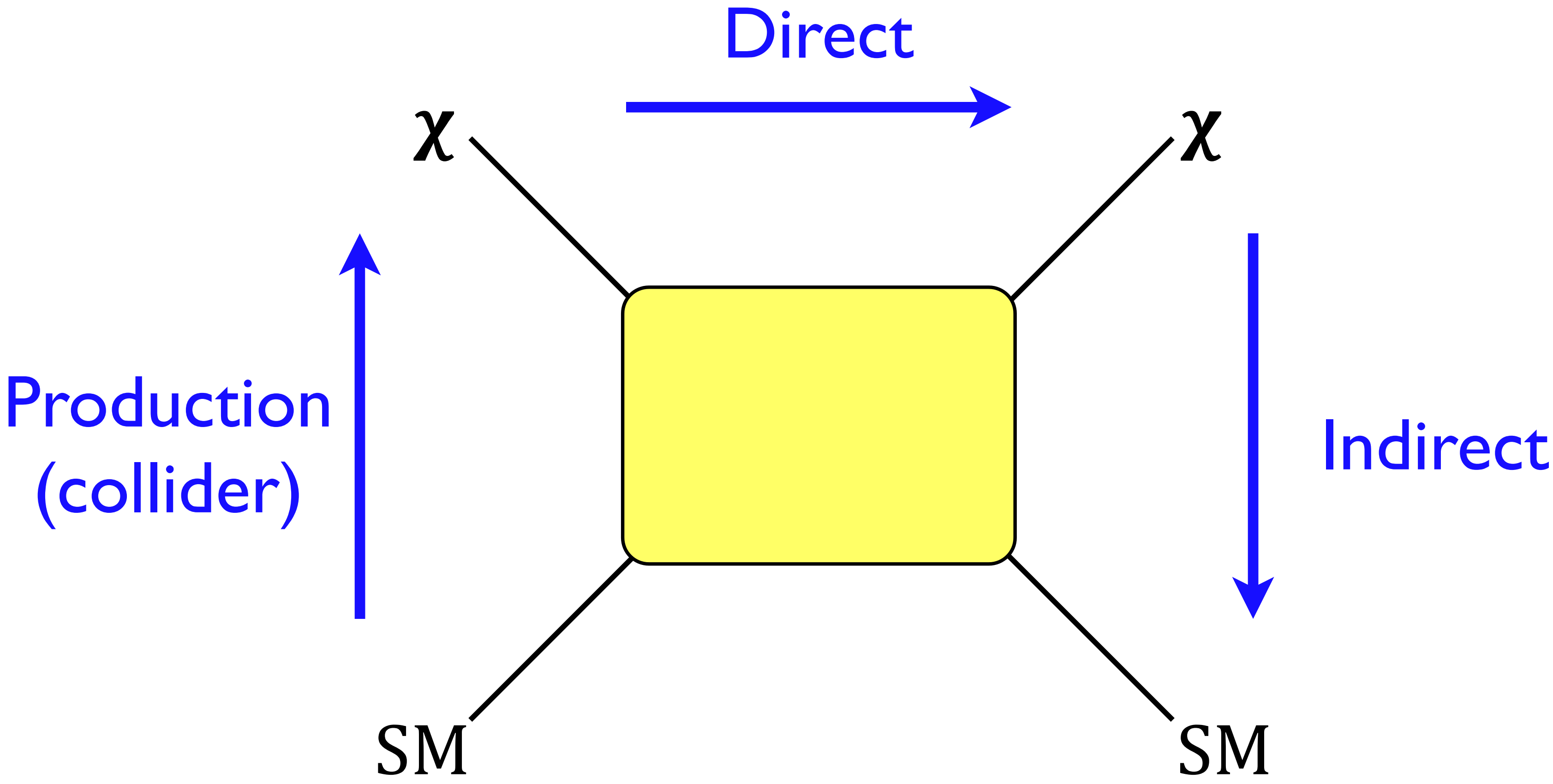
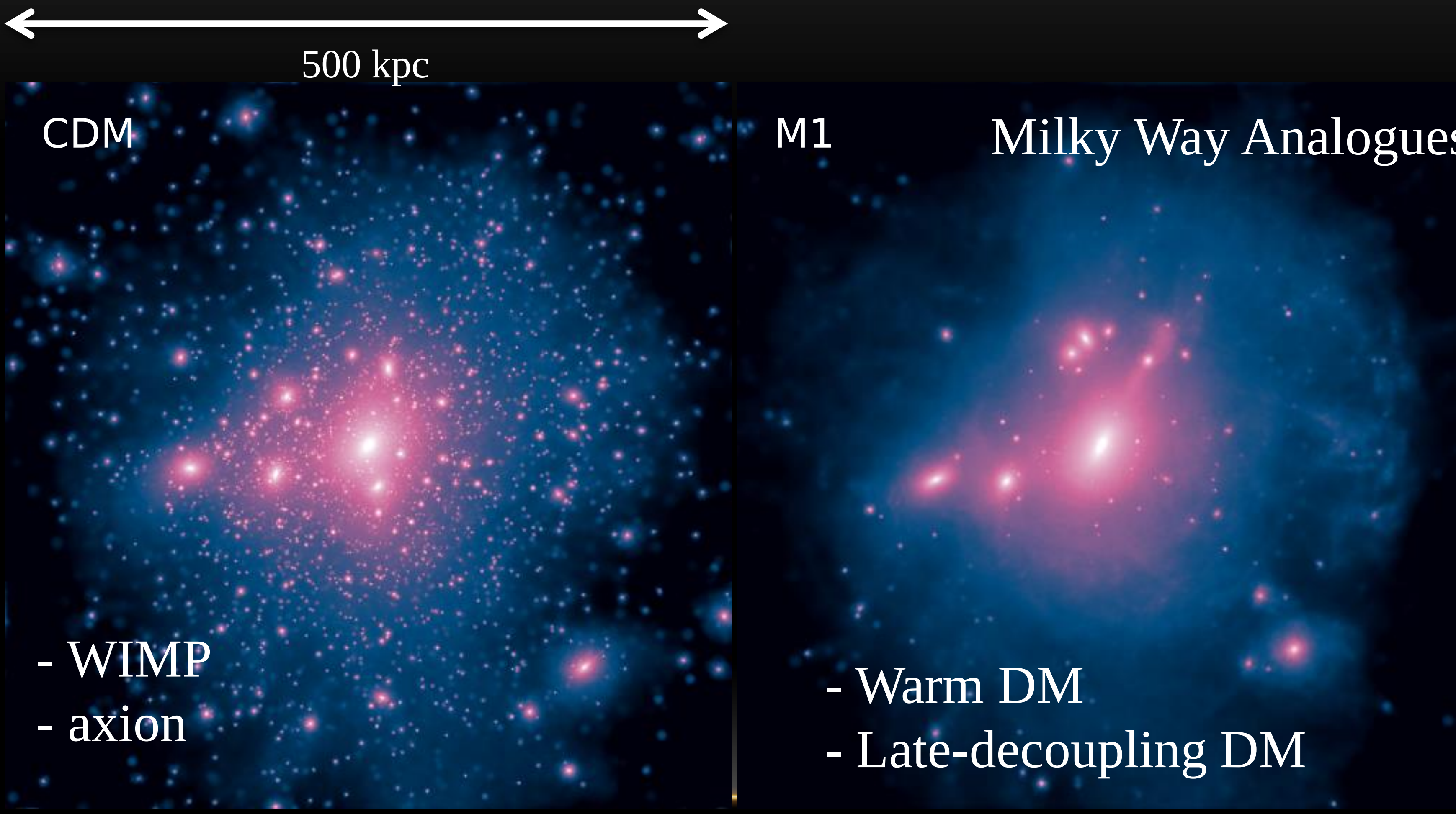
How to detect particle dark matter?



From Jennifer Gaskins

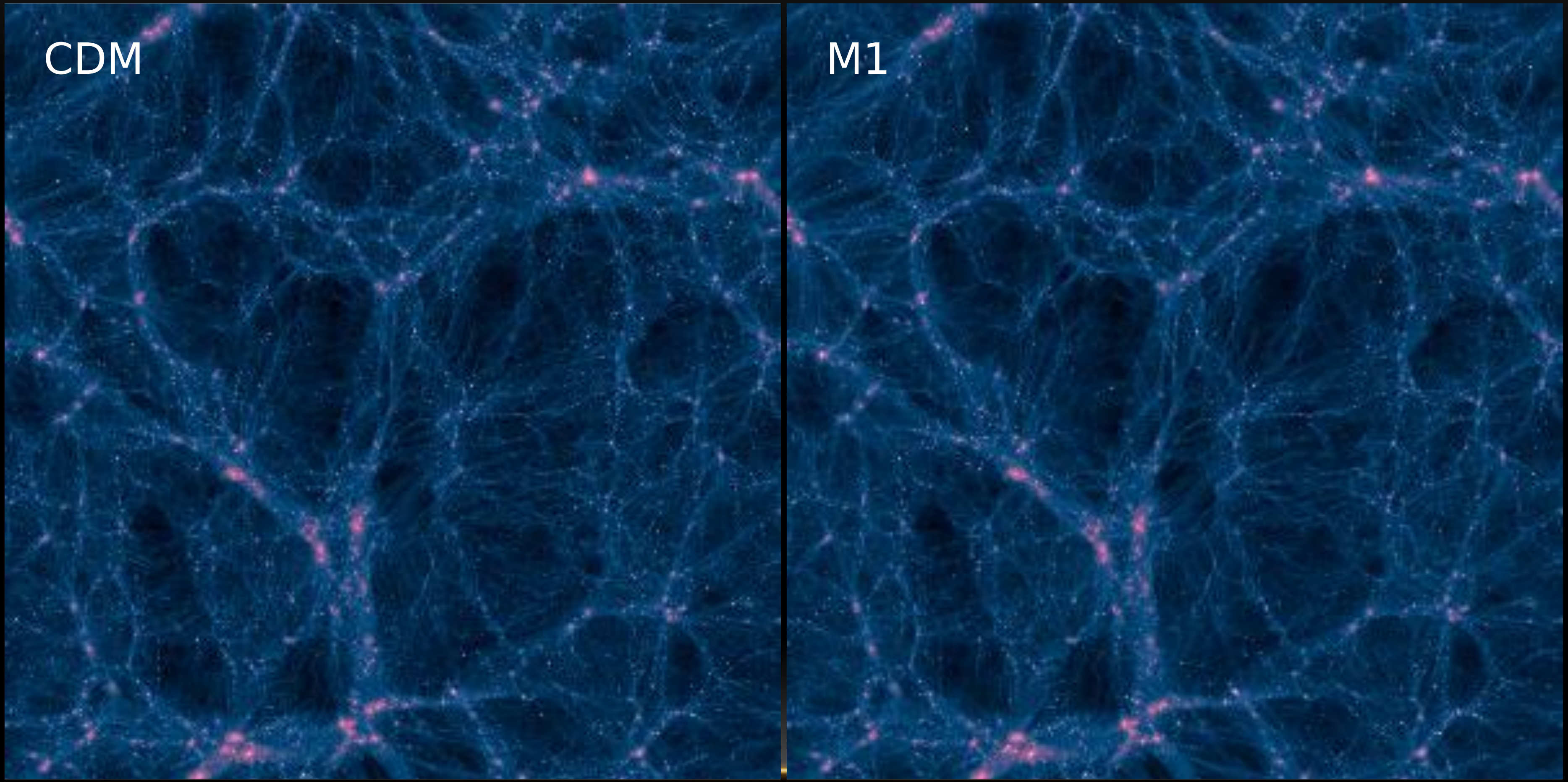
Key Question: Can we distinguish between these two dark matter (DM) scenarios?



Vogelsberger, Zavala, Cyr-Racine+, in prep.

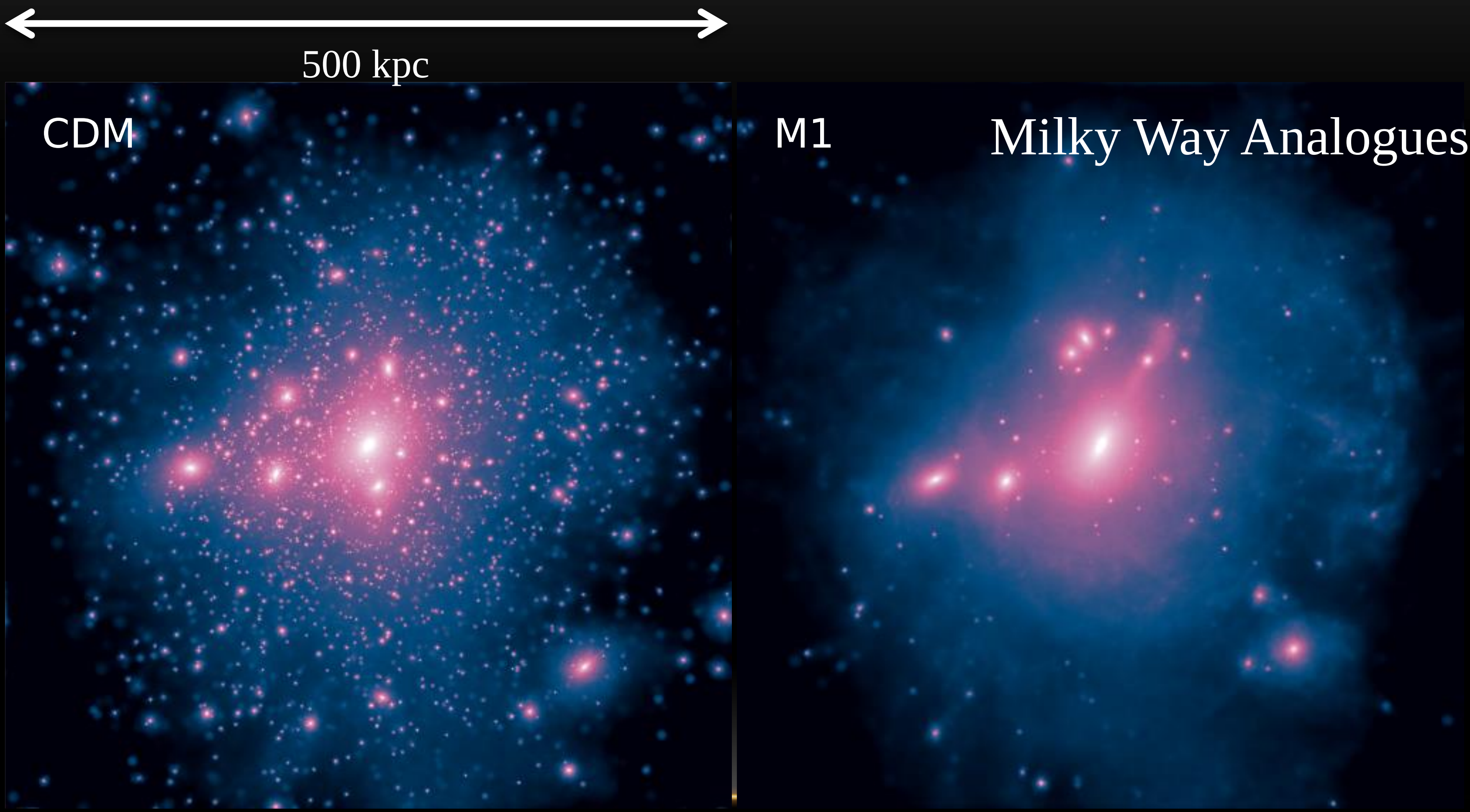
On large scales, dark matter physics essentially plays no role.

145 Mpc



Vogelsberger, Zavala, Cyr-Racine+, in prep.

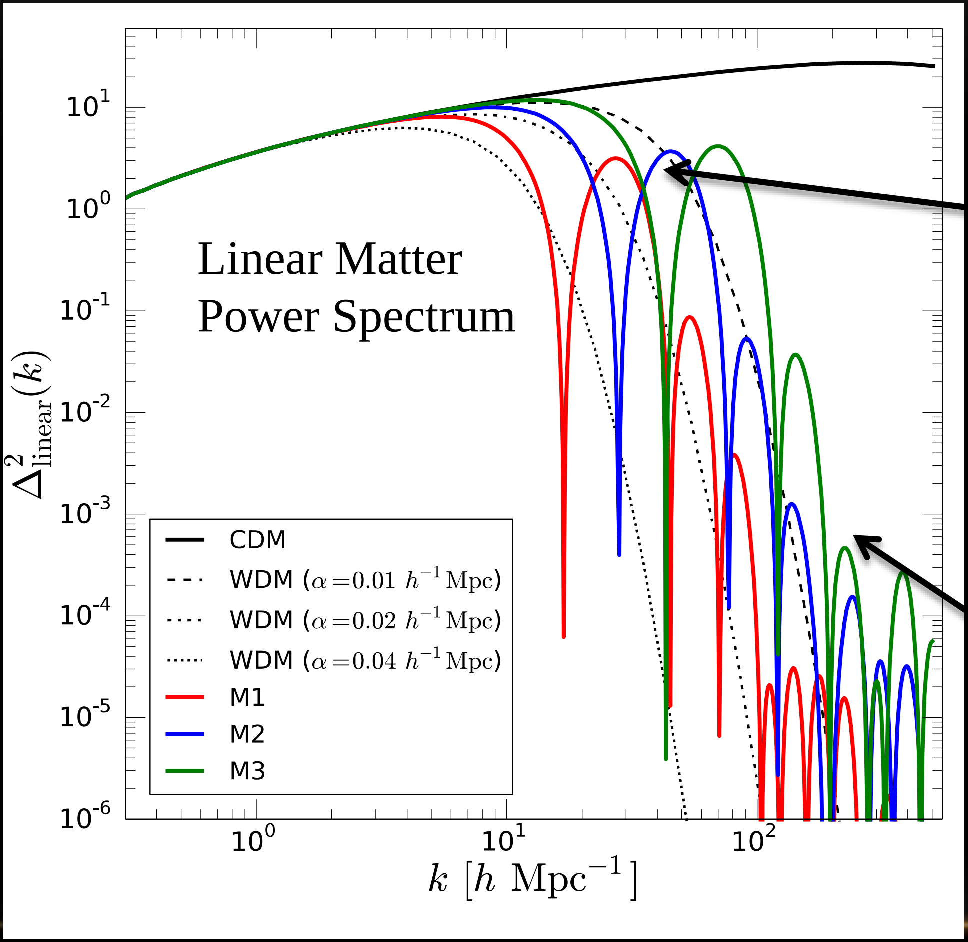
Clues about dark matter physics are locked deep inside the potential well of massive galaxies.



Vogelsberger, Zavala, Cyr-Racine+, in prep.

Why small scales?

- It's just causality, really.



Acoustic Oscillations caused by pressure support.

Damping tail caused by free streaming or diffusion

Vogelsberger, Zavala, Cyr-Racine+, in prep.

Why small scales?

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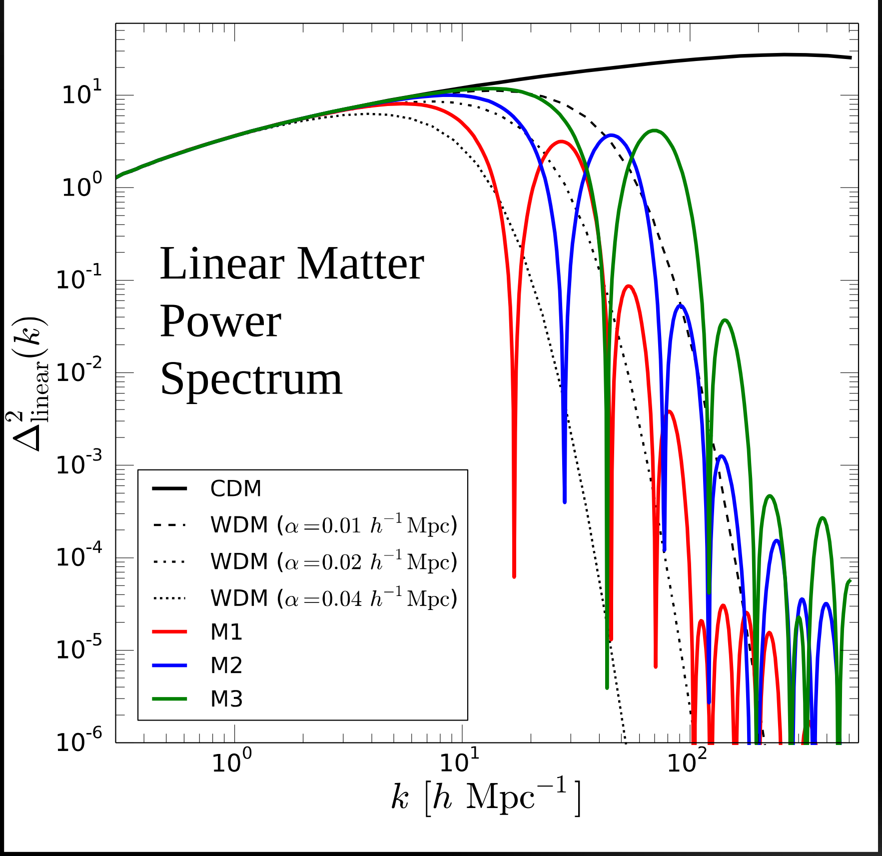
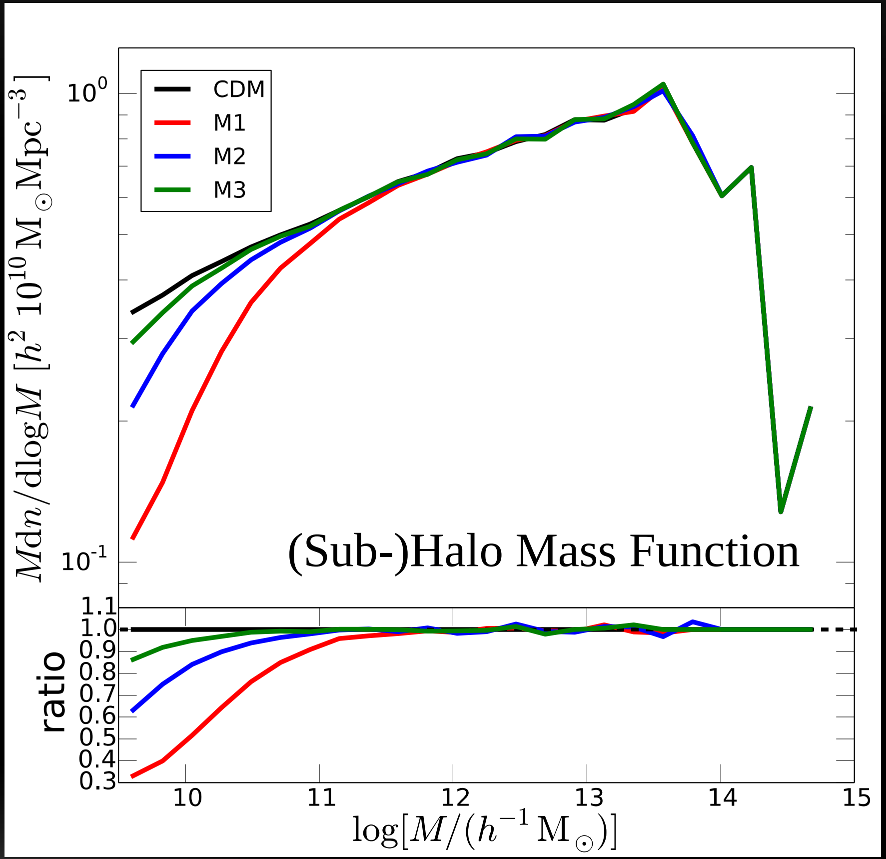
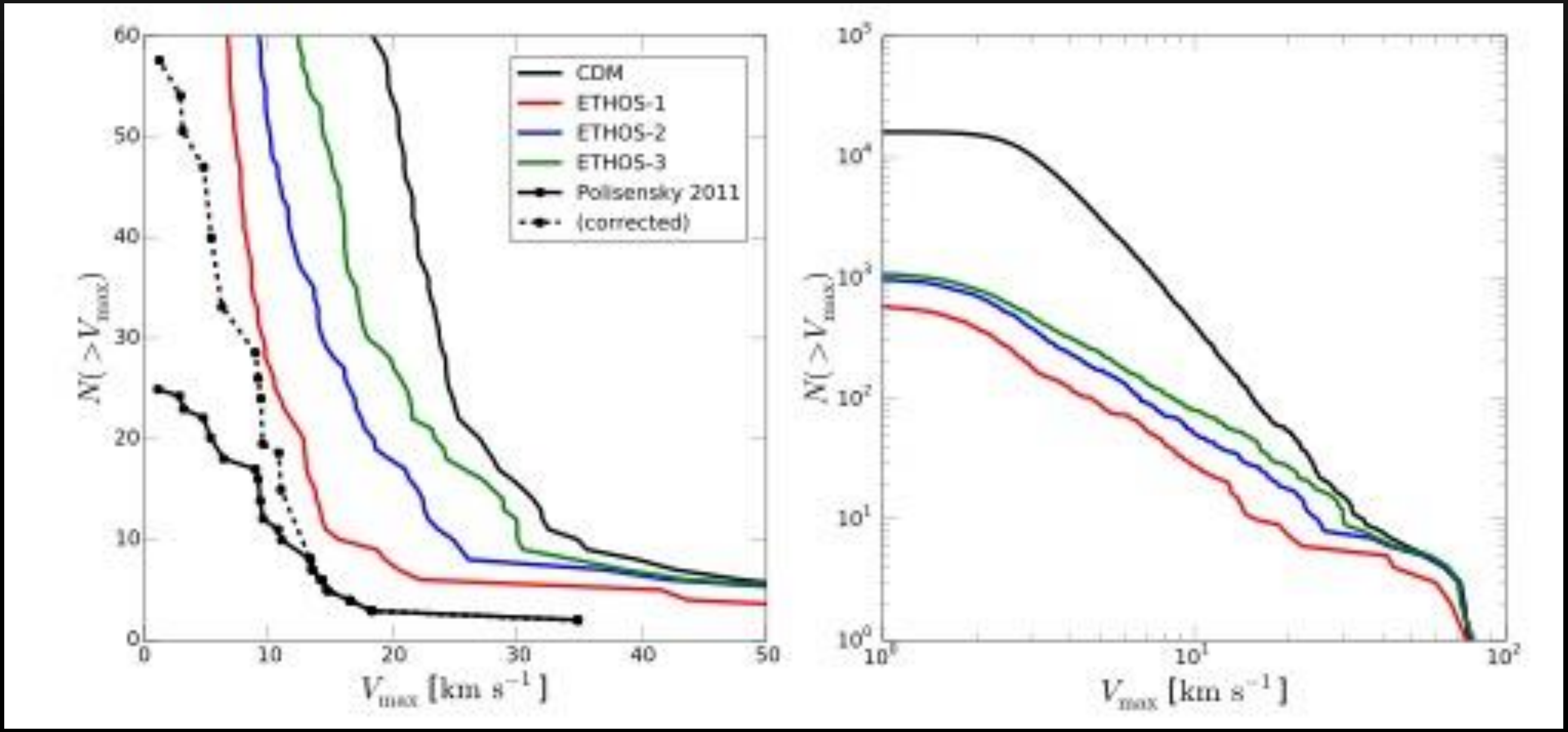




Vogelsberger, Zavala, Cyr-Racine+, in prep.

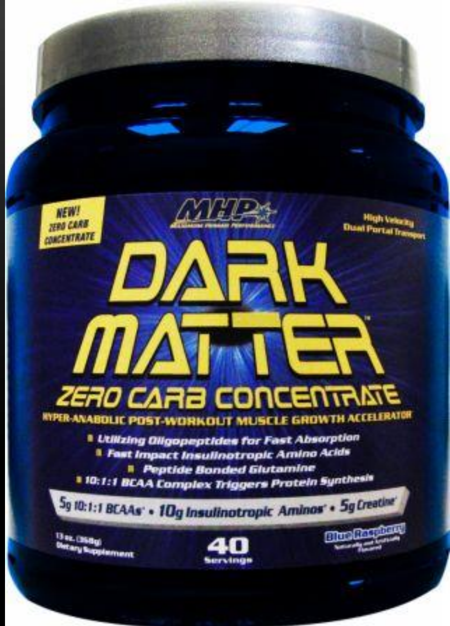
Modified Mass Function

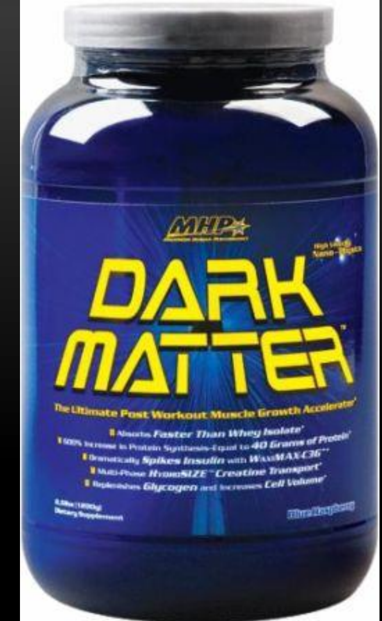


Vogelsberger, Zavala, Cyr-Racine+, in prep.

Revealing the physics of dark matter through the study of small-scale structures

- Advantage:
  - Purely gravitational probe: no need to assume a coupling between dark matter and the Standard Model (in contrast to direct/indirect detection and collider production).
- Drawback:
  - Astrophysics! Galaxy formation is messy, baryons play a major role.

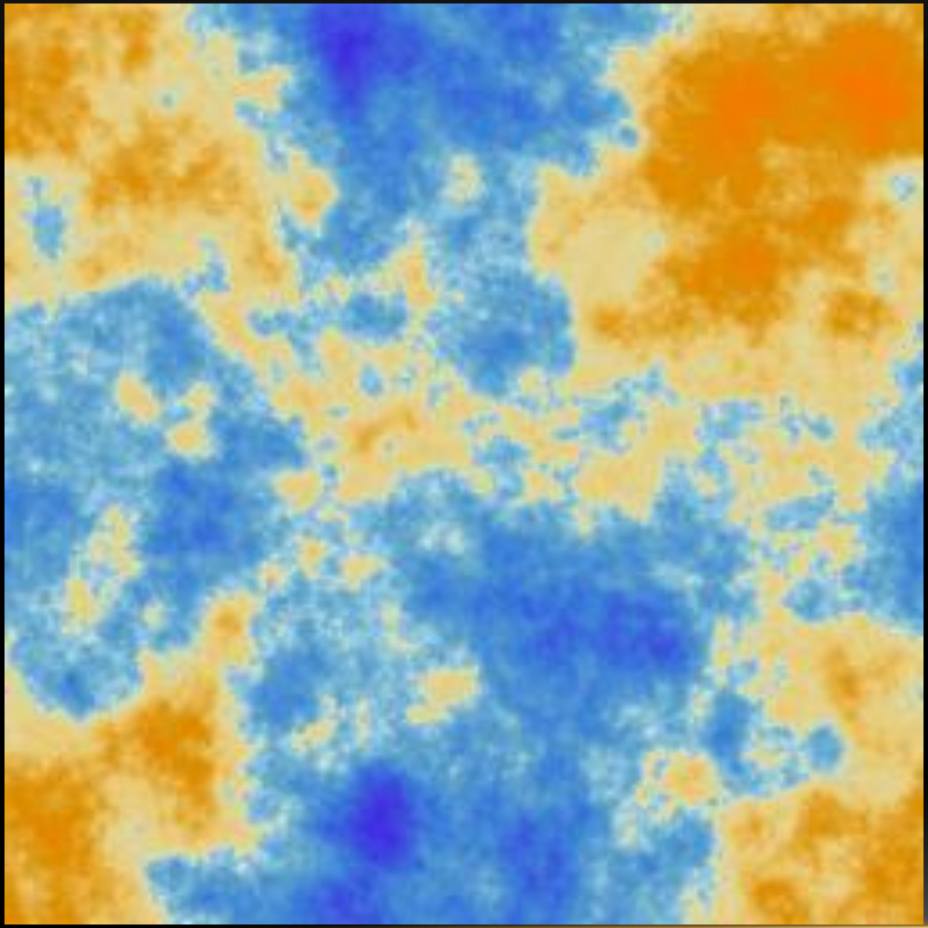




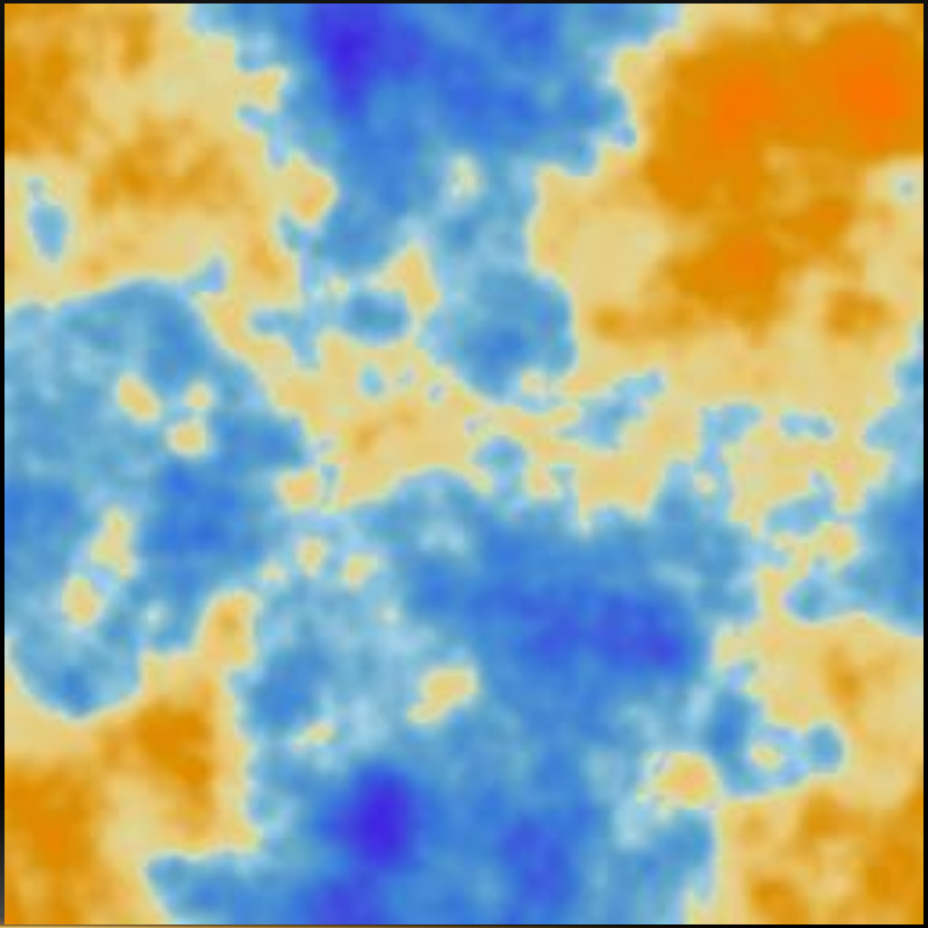
Which dark matter physics can we probe via its gravitational interactions?

Small-scale predictions for Warm Dark Matter

Cold DM

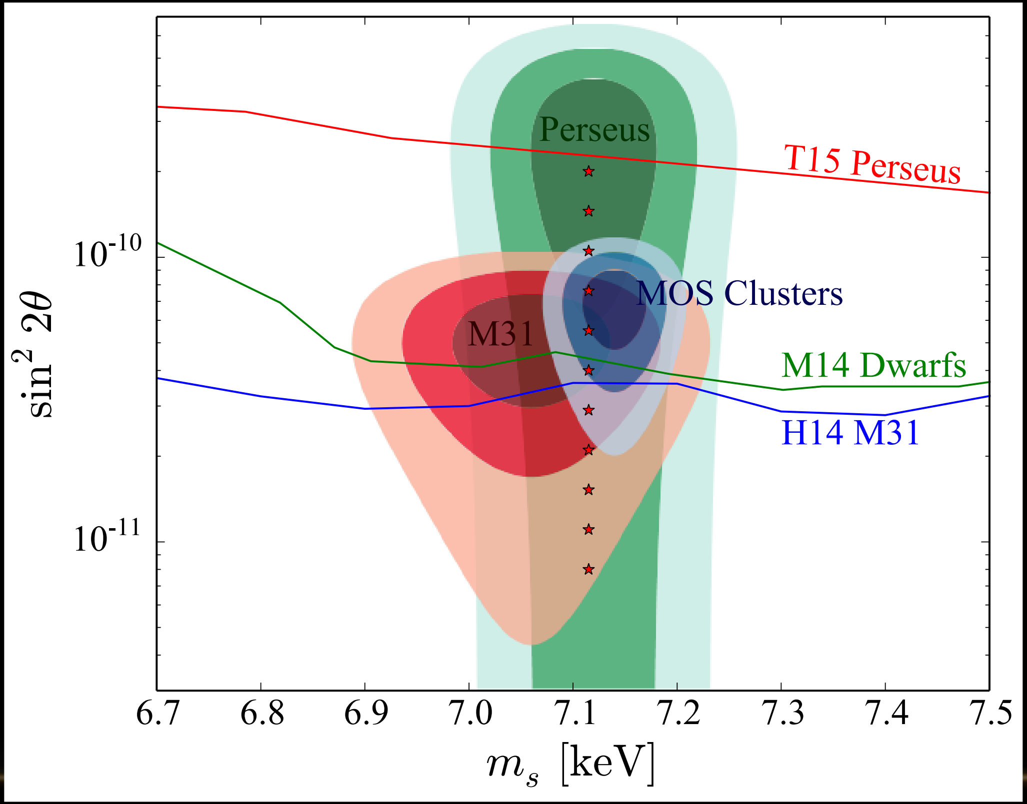


Warm DM, 3keV



Warm Dark Matter Candidate: Sterile Neutrino

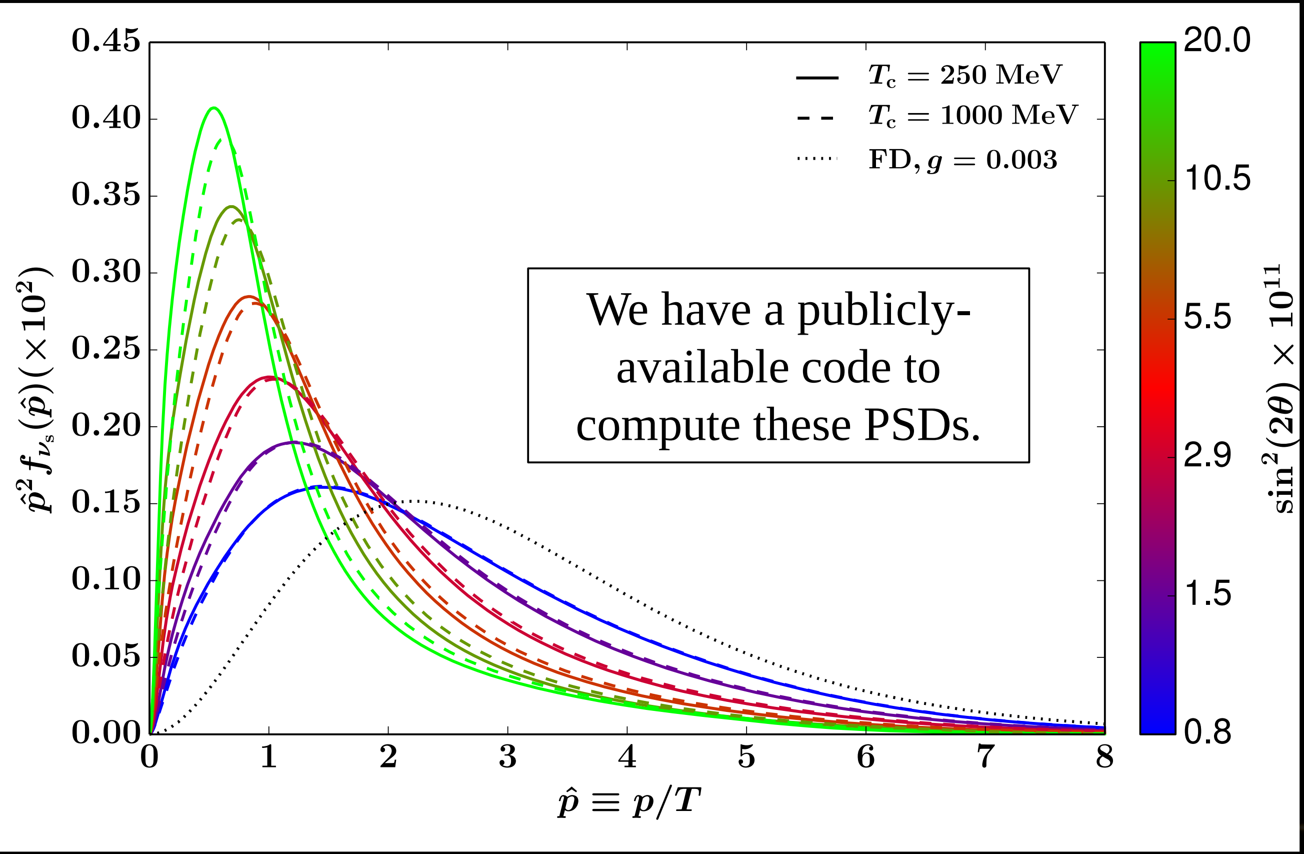
- Controversial (!) x-ray signal can be used to pinpoint the relevant parameter space for sterile neutrinos:



Venumadhav, Cyr-Racine, Abazajian, Hirata. arXiv:1507.06655

Warm DM Candidate: Resonantly-Produced Sterile Neutrinos

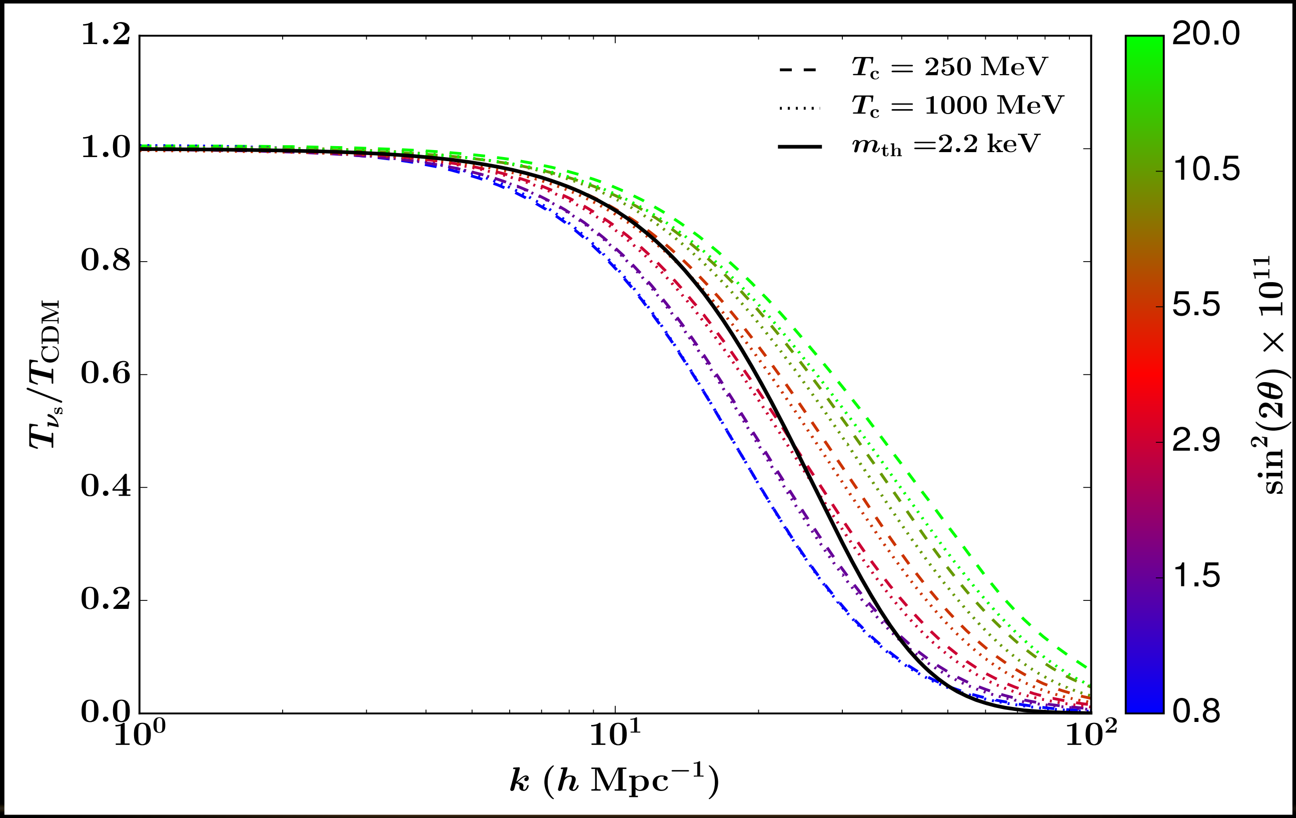
- Asymmetry-based resonant production leads to a much colder spectrum of sterile neutrinos than standard FD.



Venumadhav, Cyr-Racine, Abazajian, Hirata. arXiv:1507.06655

Warm DM Candidate: Resonantly-Produced Sterile Neutrinos

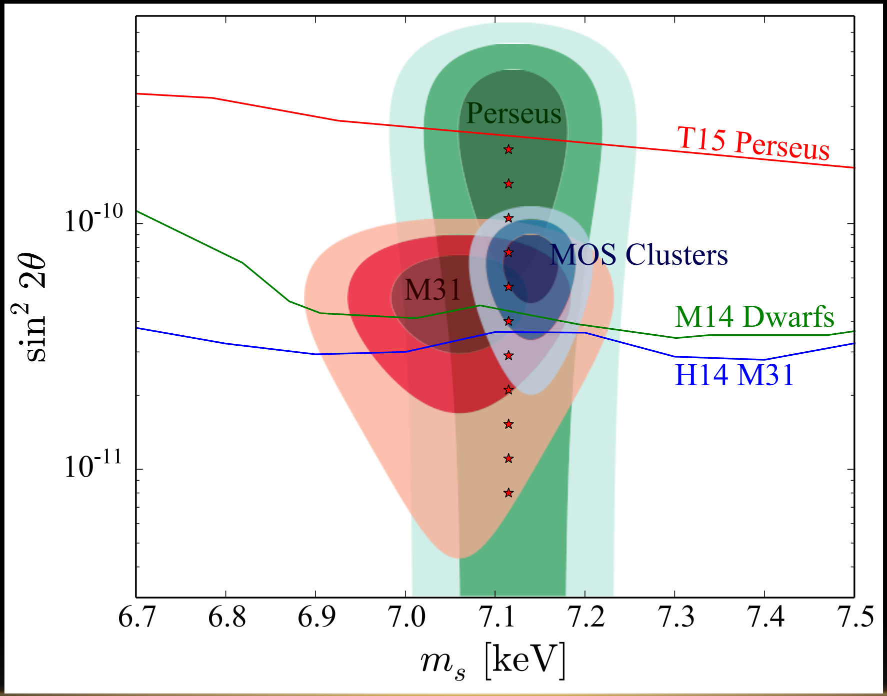
- Interestingly, the models that can explain the x-ray excess have a free-streaming cutoff in the "right" range to address issues on small scales inside the local group.



Venumadhav, Cyr-Racine, Abazajian, Hirata. arXiv:1507.06655

Warm DM Candidate: Resonantly-Produced Sterile Neutrinos

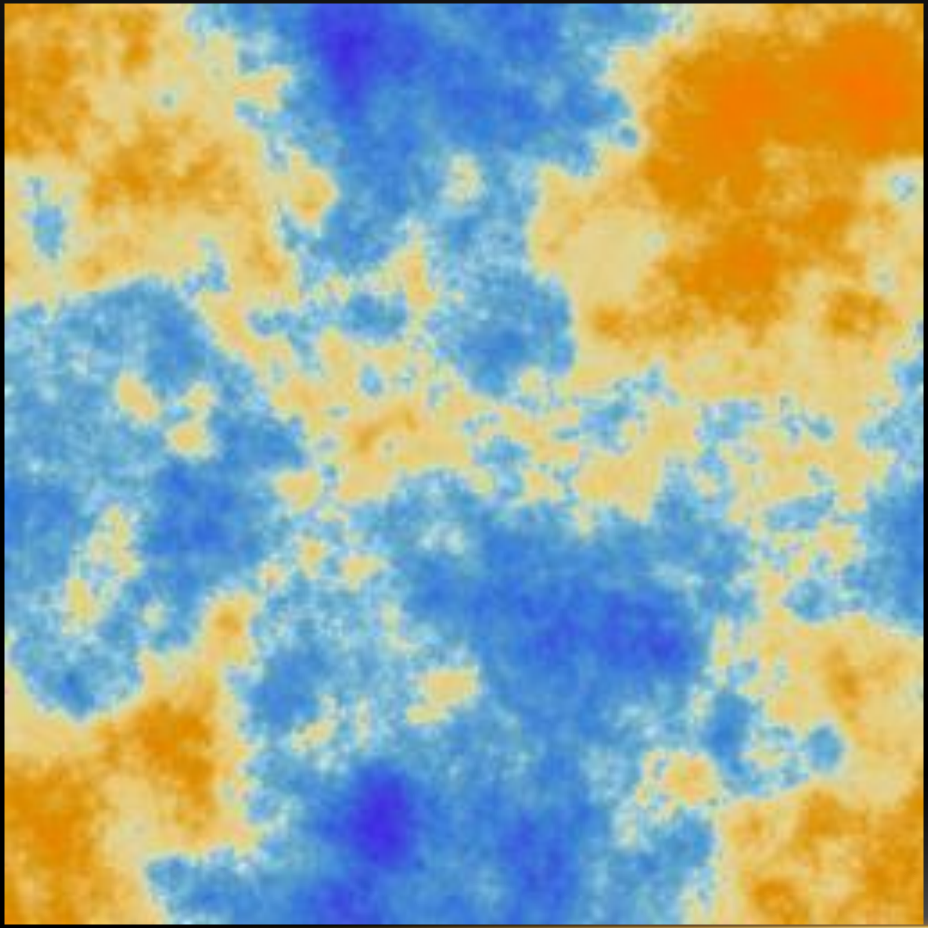
- Upcoming x-ray observations with Astro-H (JAXA) and improved structure formation constraints can rule out (or in!) this model.



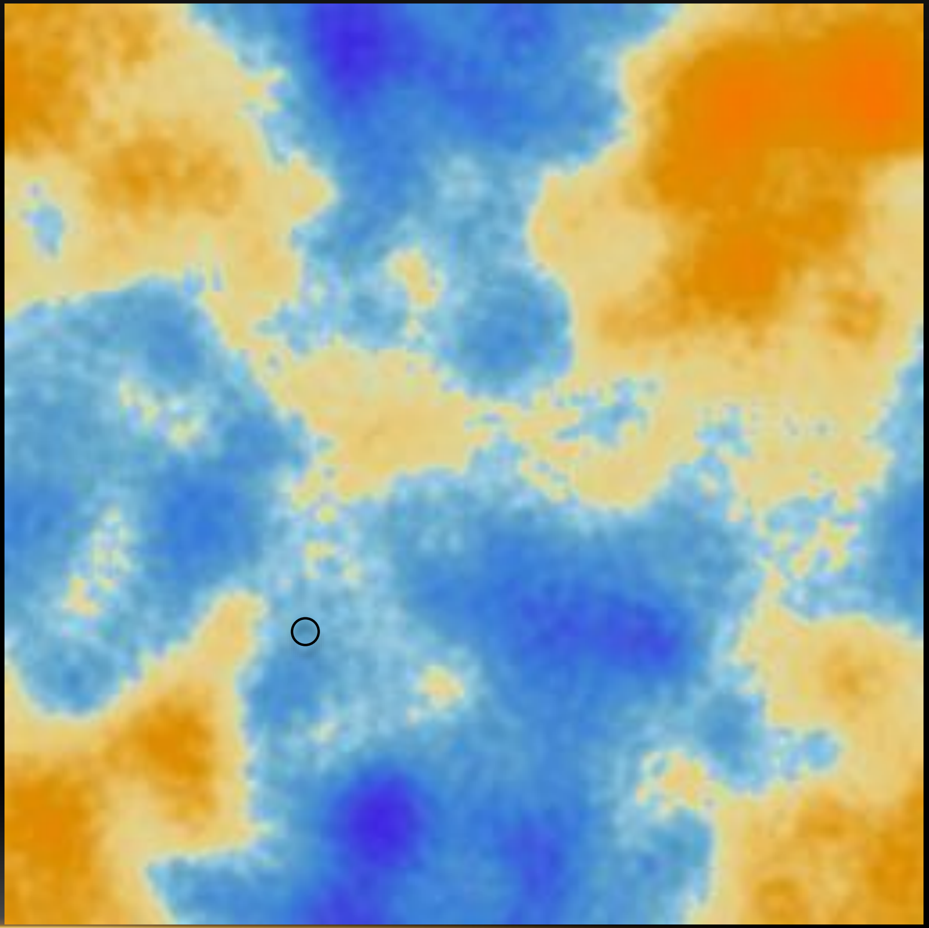
Venumadhav, Cyr-Racine, Abazajian, Hirata. arXiv:1507.06655

Small-scale predictions for late-decoupling dark matter

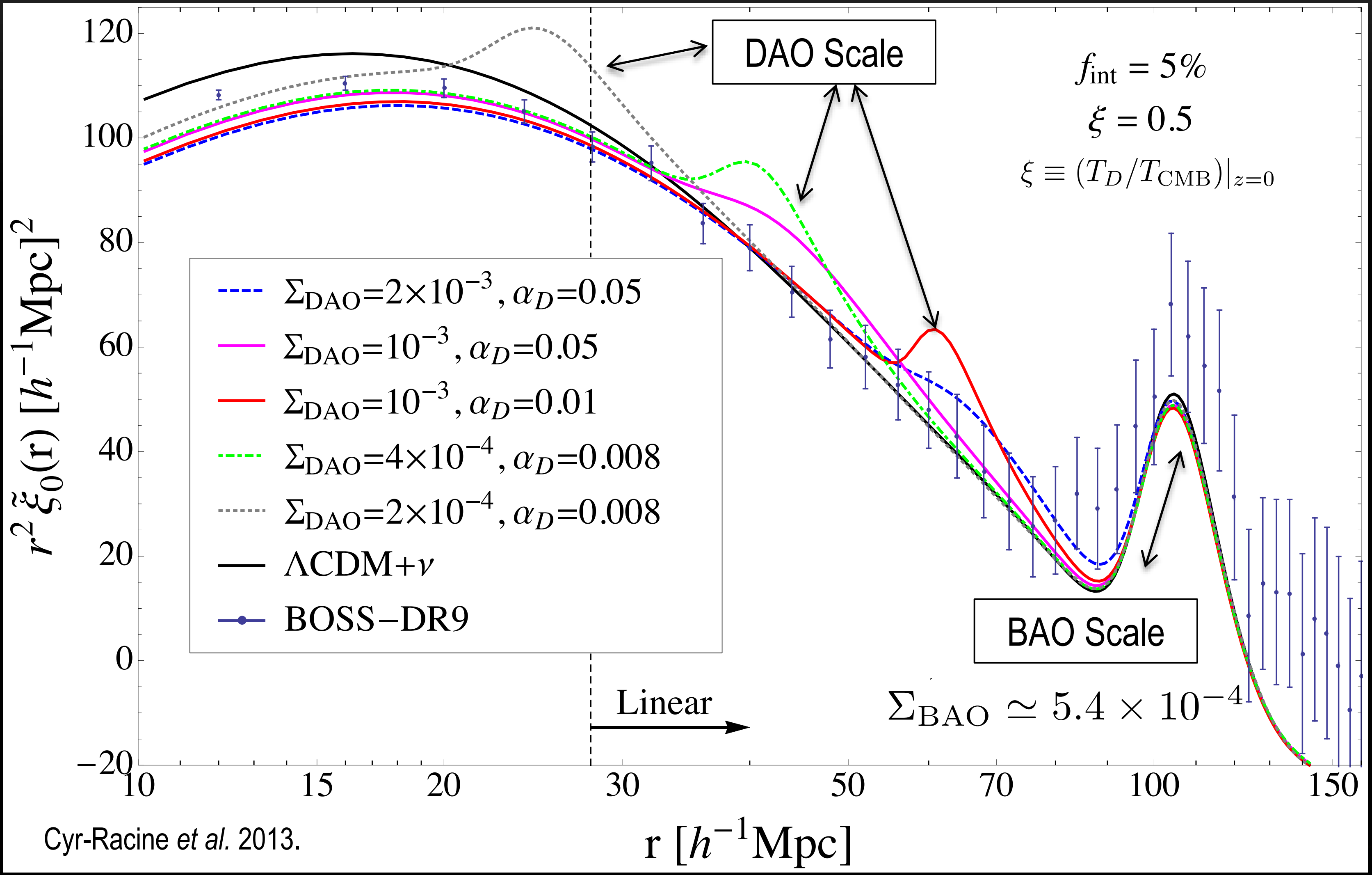
Cold DM



Late-decoupling DM

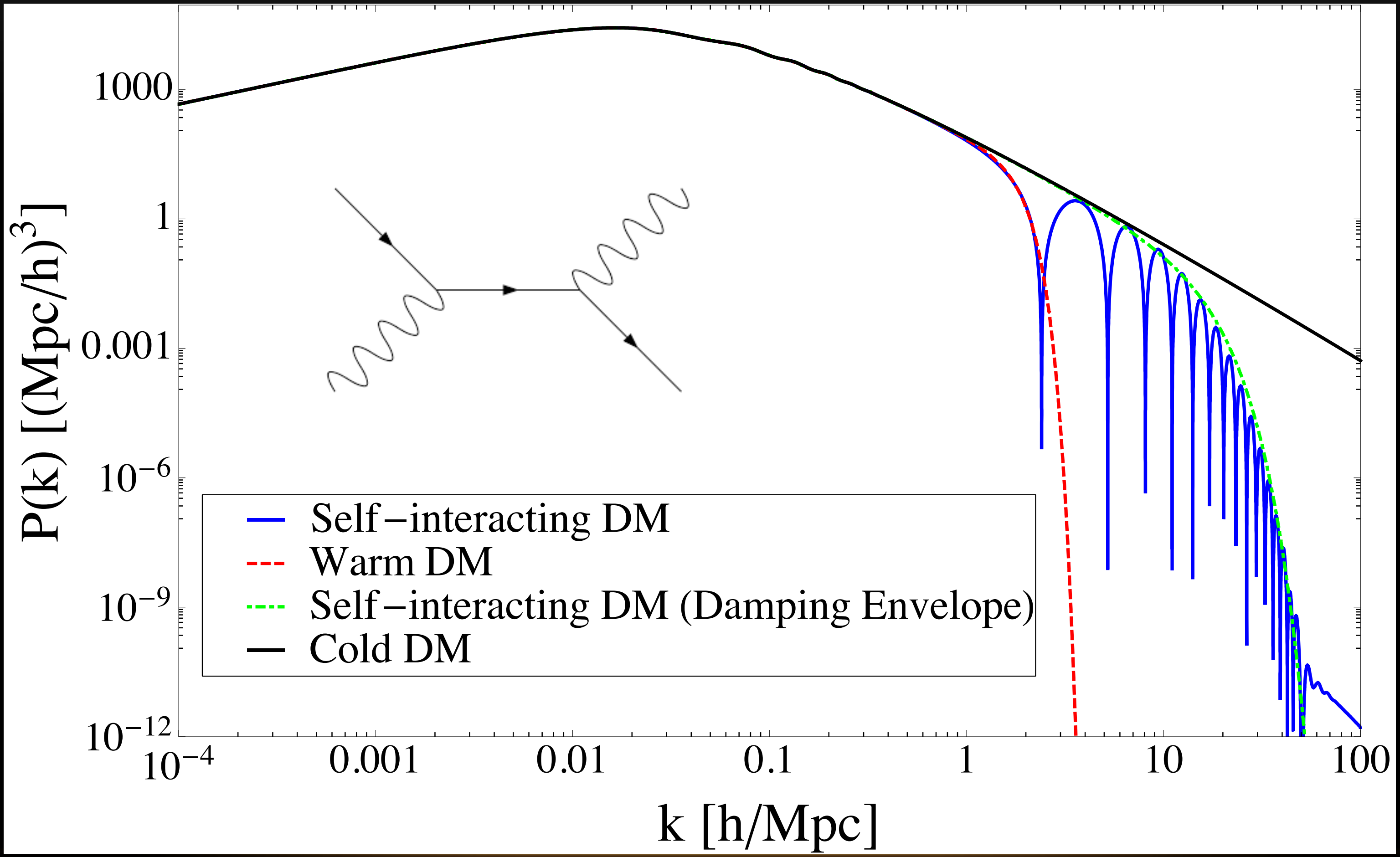


Dark Acoustic Oscillations (DAO)

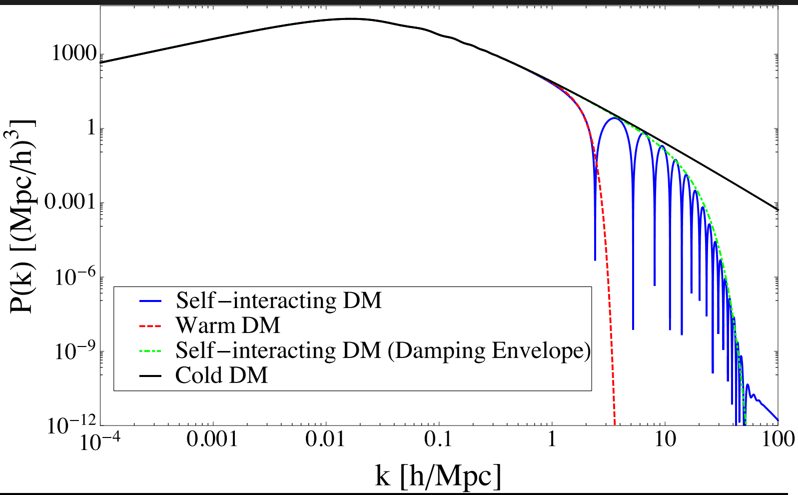


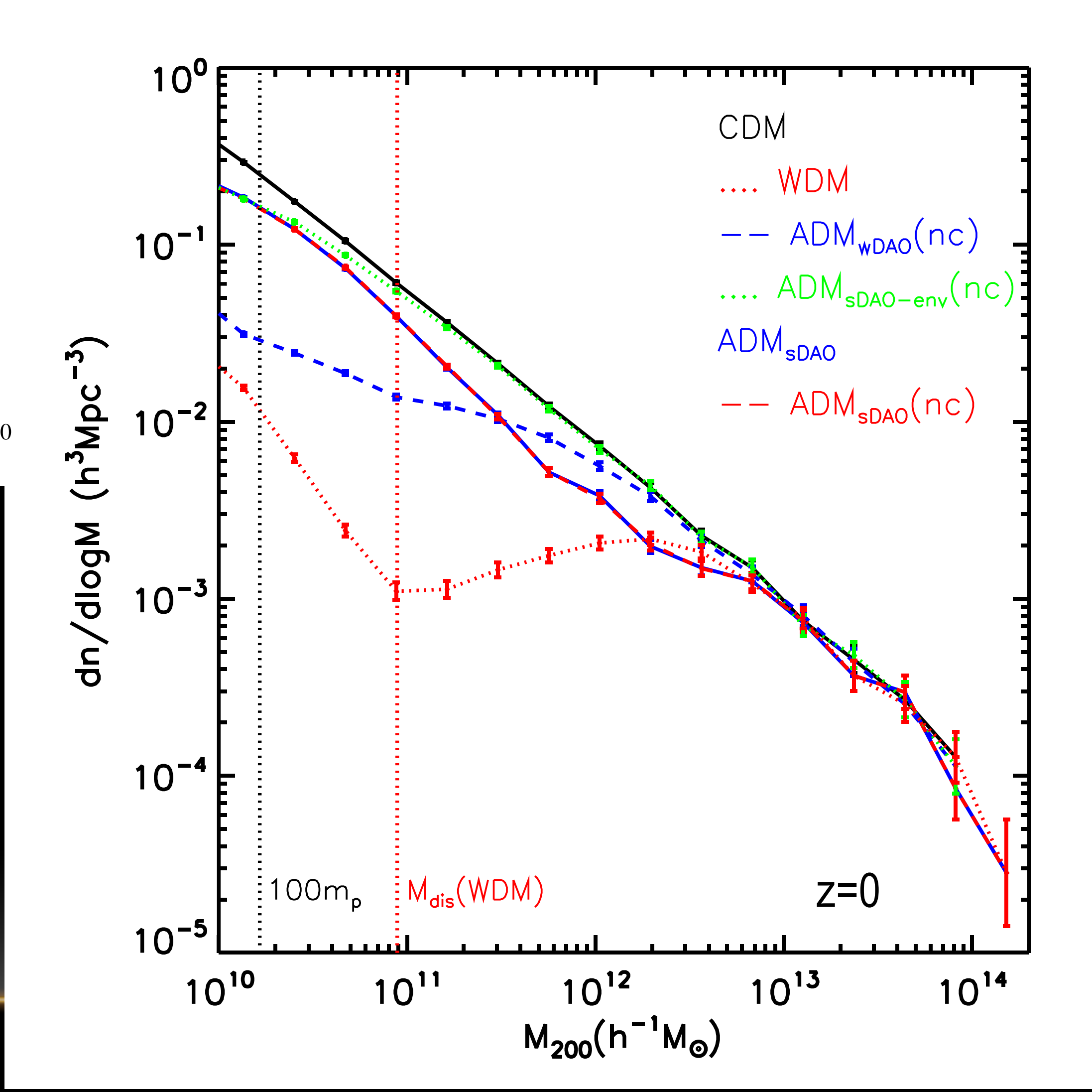
Large-Scale Structure: DAO Scale + Damping

Cyr-Racine & Sigurdson (2013), Cyr-Racine + (2014), Buckley, Zavala, Cyr-Racine + (2014)



Non-linear Evolution of DAO: Halo Mass Function



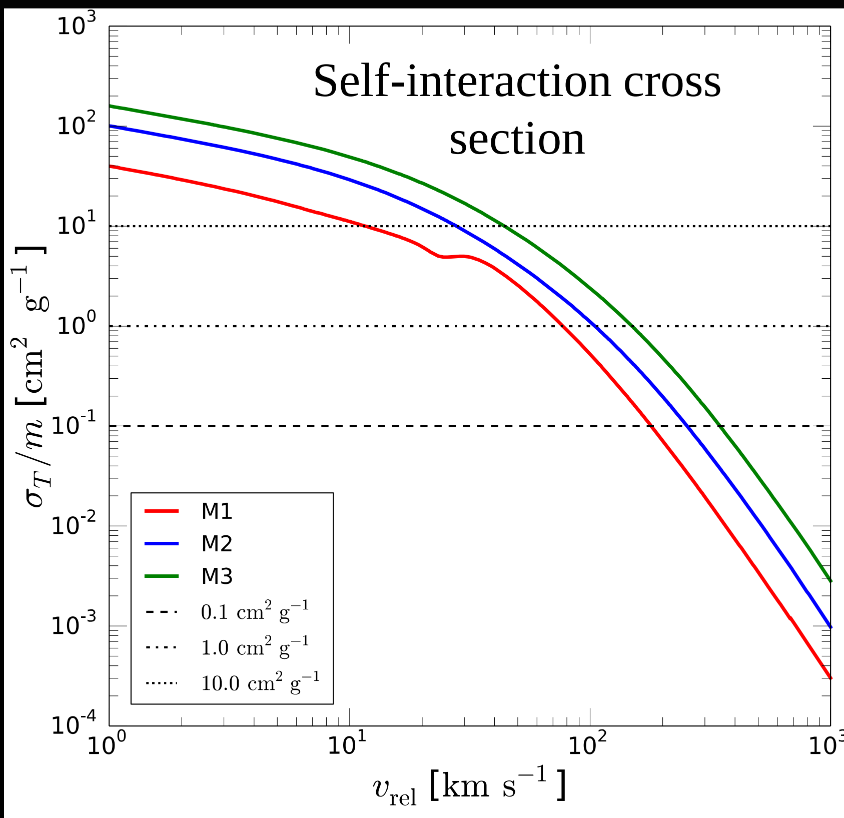


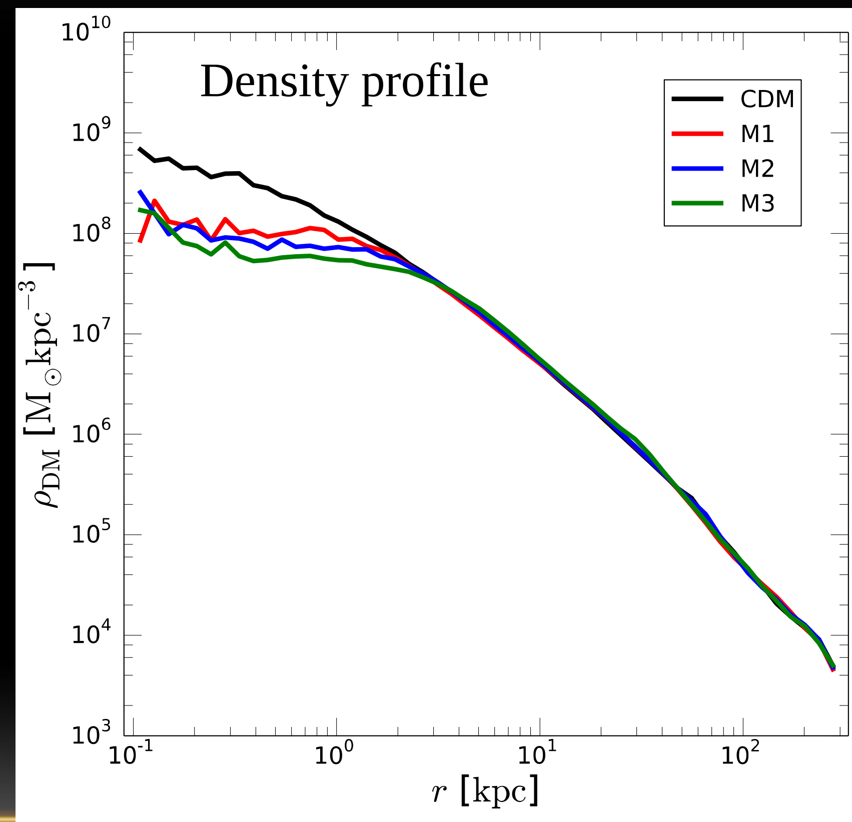
- Different behavior than CDM and WDM.
- Bridges the gap between CDM and WDM.

Buckley, Zavala, Cyr-Racine et al. 2014

Natural Extension: dark matter self interaction

- DM Self-interaction modifies the inner structure of halos, usually making them less dense in the center.



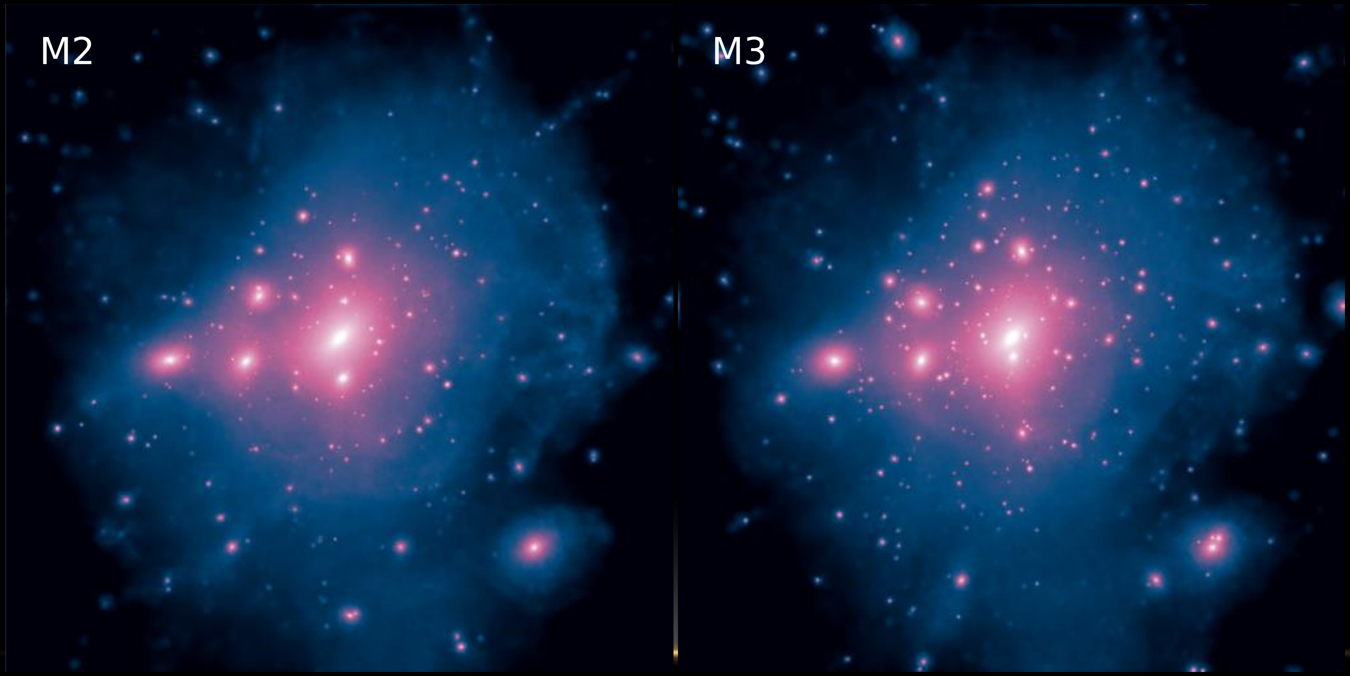


Vogelsberger, Zavala, Cyr-Racine+, in prep.

Which dark matter physics can we probe via its gravitational interactions?

- Free-streaming/collisional damping
- Self-interaction

These can be used to rule out broad classes of dark matter models



Revealing the physics of dark matter through the study of small-scale structures

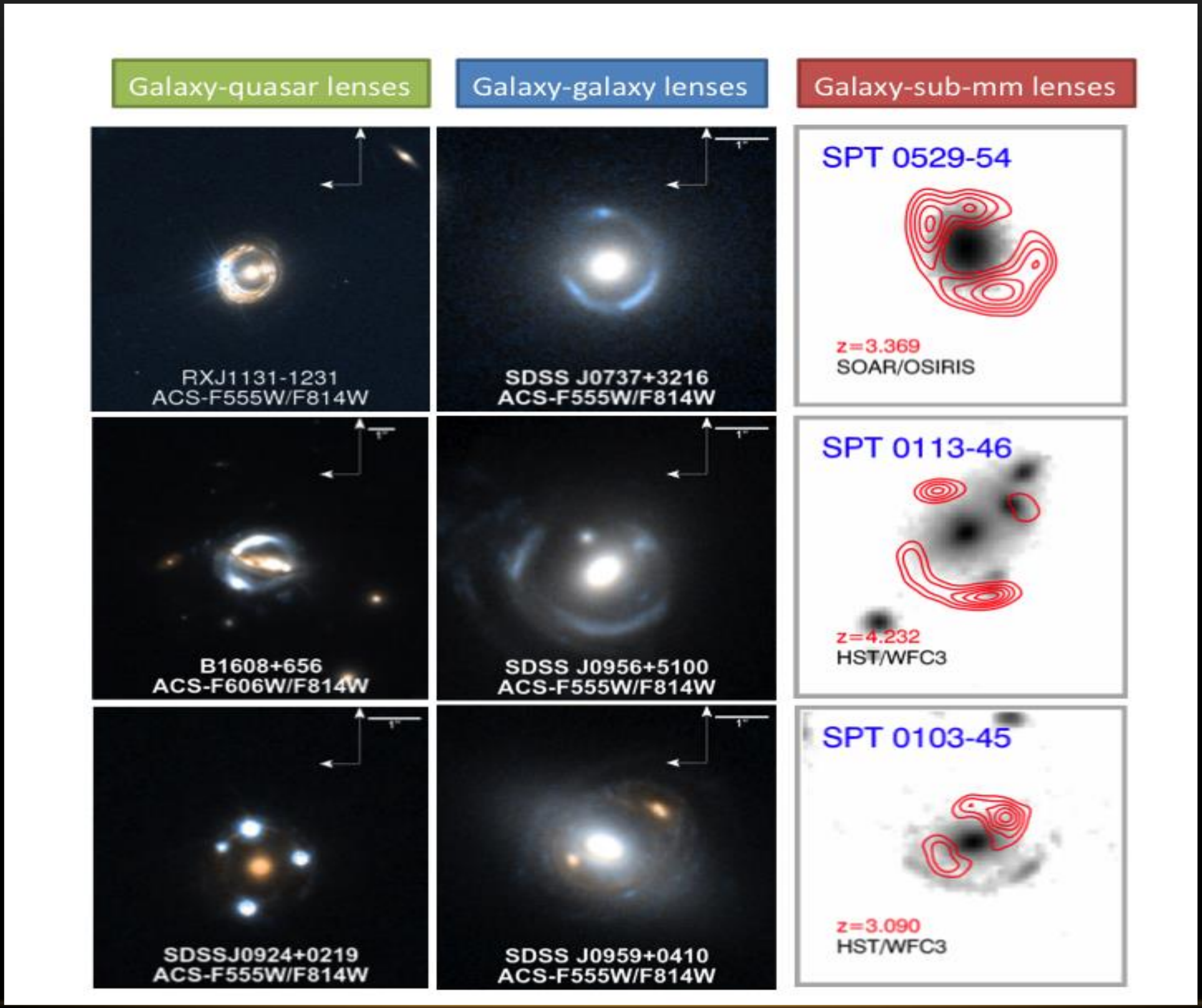
Self-Interacting DM

- Many possible approaches:
  - Disk Perturbations (Feldmann & Spolyar, 2015).
  - Stellar Stream Gaps (Carlberg 2012).
  - Astrometric Microlensing (Erickcek & Law, 2011)
  - Pulsar timing (Clark et al. 2015)
  - Dwarf kinematics
  - (…)
  - Using gravitational lensing to study the substructure content of distant galaxies.

Revealing the physics of dark matter through the study of small-scale structures

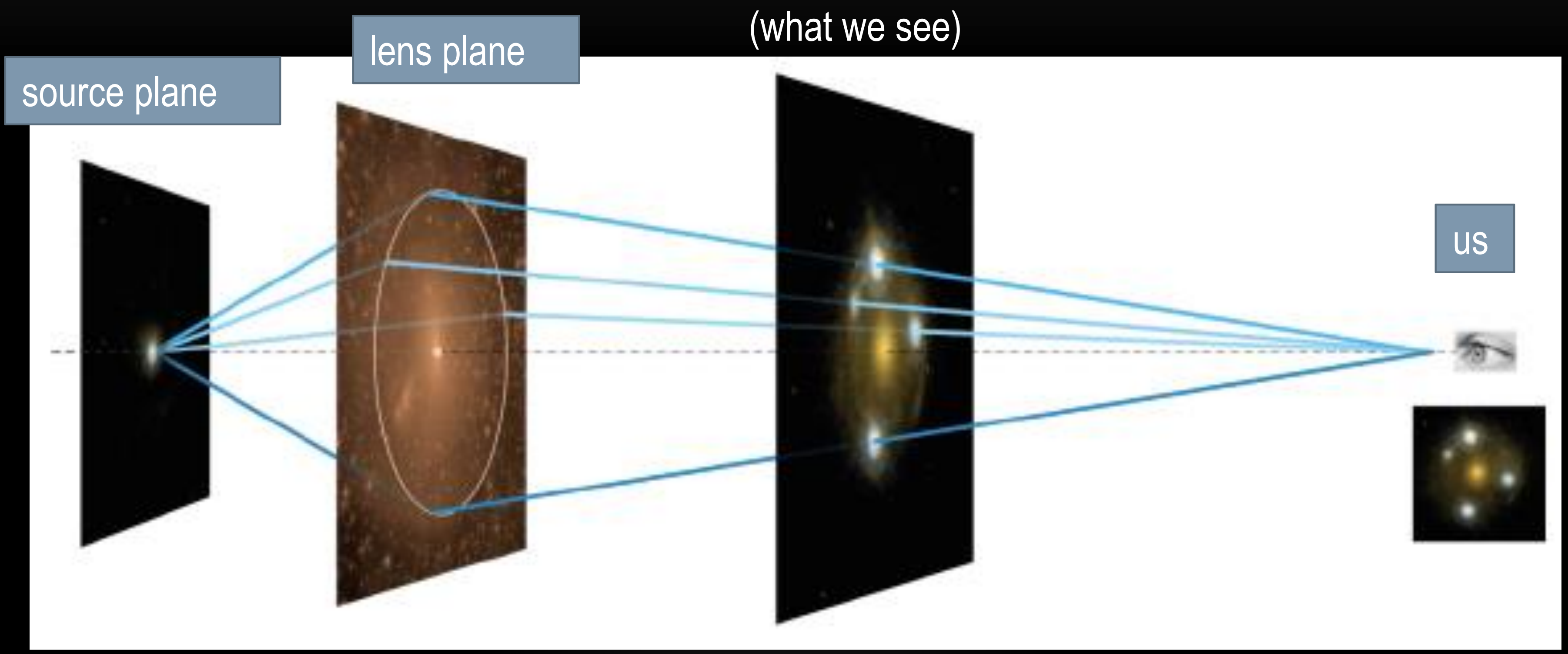
- Unlike dark energy science, “astrophysical” dark matter science is lacking a clear roadmap aimed a systematically determining its properties.
- We need to assess advantages/drawbacks/complementarity of different proposed techniques.
- We have to assess where THEIA fits in this broad picture.
- Will it be useful to define a “figure-of-merit” for dark matter?

Galaxy-scale Gravitational Lenses



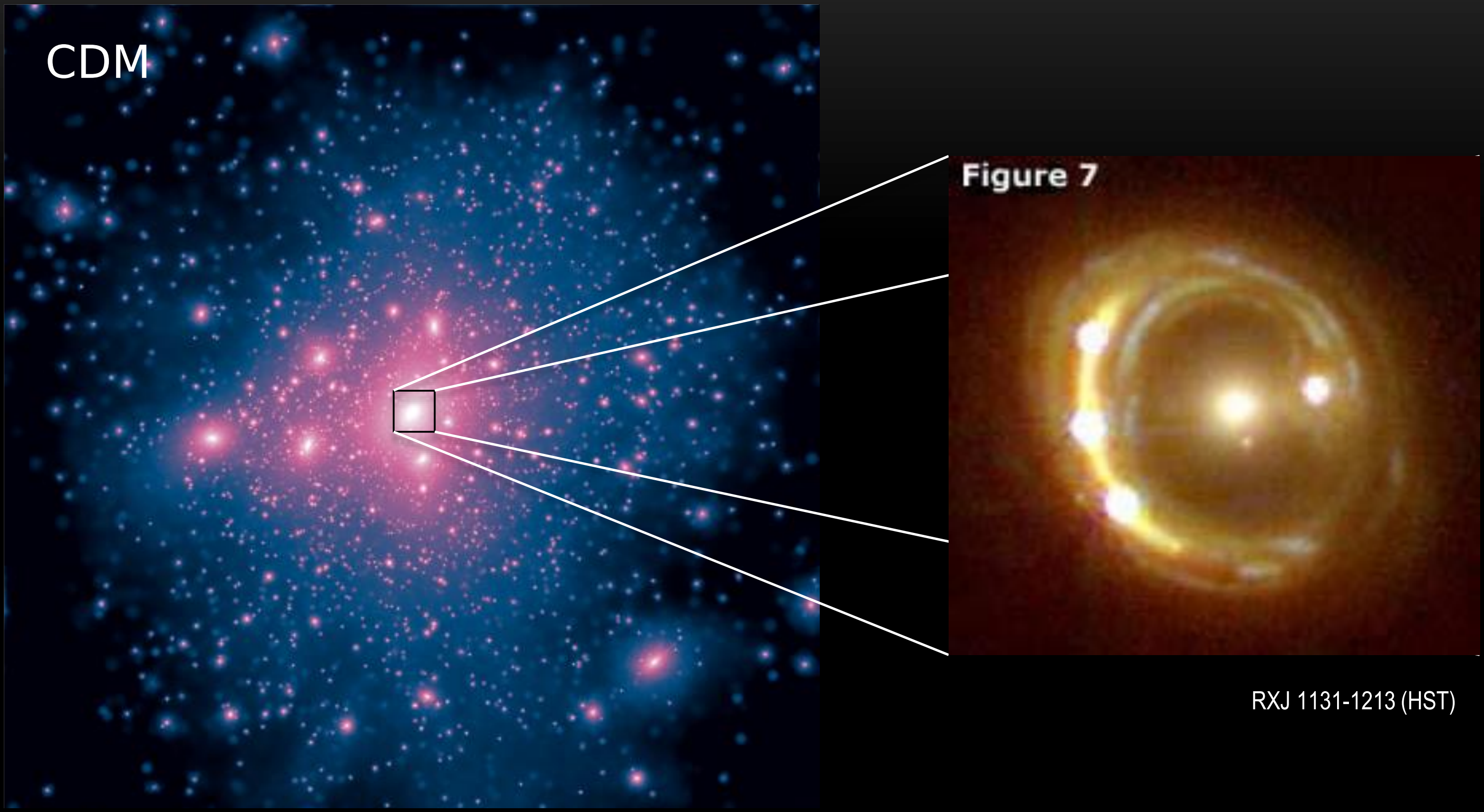
Credits: Leonidas Moustakas

Strong Gravitational Lensing



Credits: Leonidas Moustakas

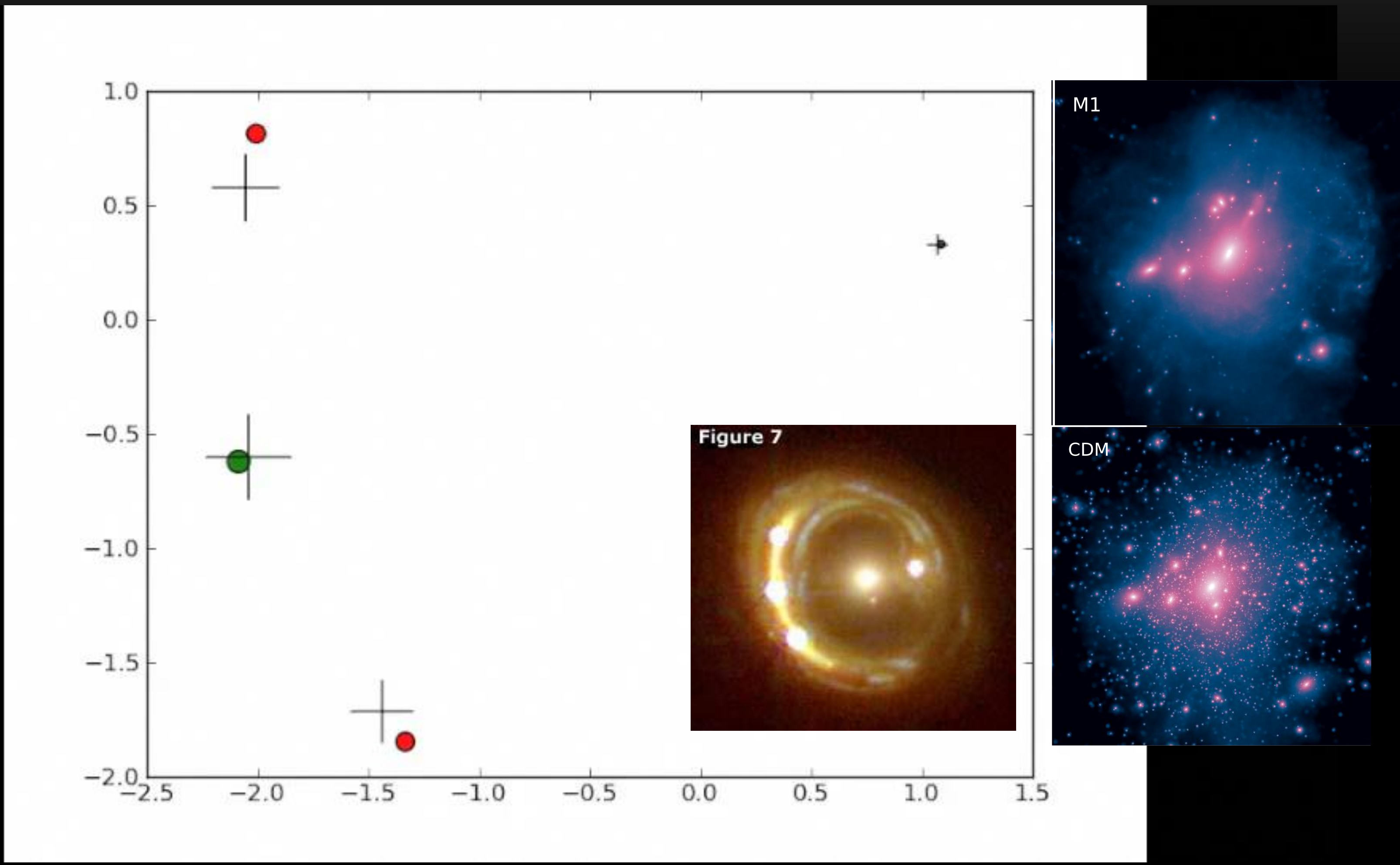
Galaxy Lenses: Typical Scale



RXJ 1131-1213 (HST)

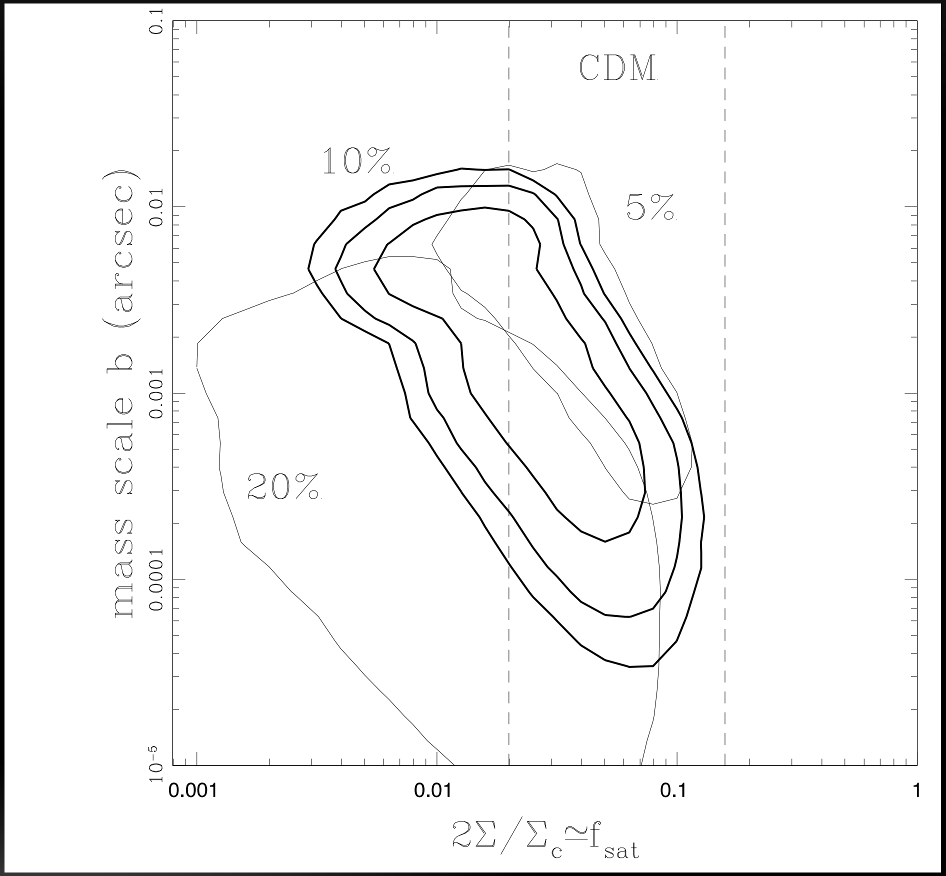
Galaxy-scale lenses probe the very inner part of their dark matter halo

Mass Substructures Cause Stochasticity in Lensing Observables



CDM Substructures: The Pioneers

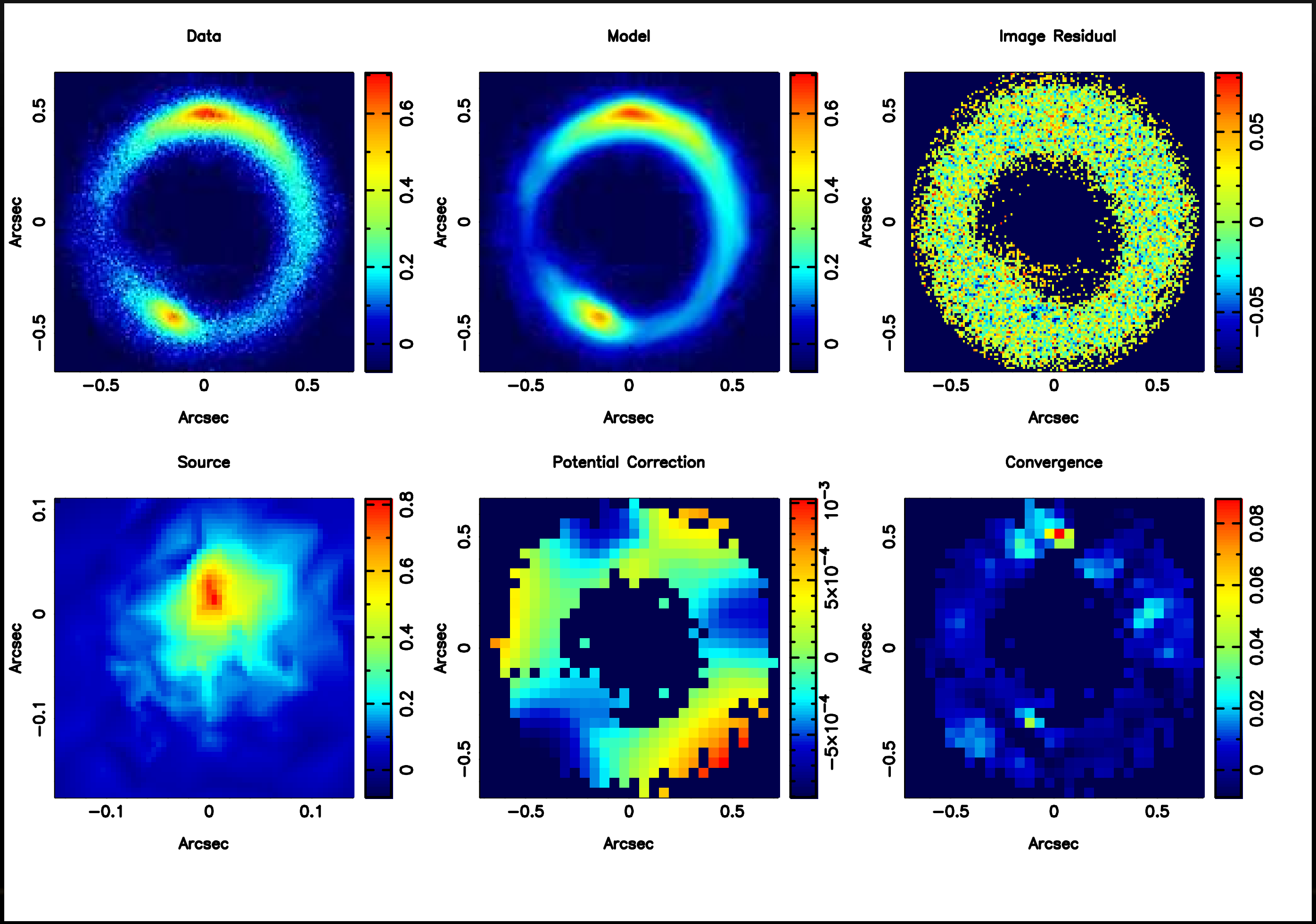
- Using the flux from 7 radio-loud quasars, Dalal and Kochanek were able to put bounds on the typical mass scales and the abundance of substructures.



Dalal & Kochanek (2002)

Direct Substructure Detection

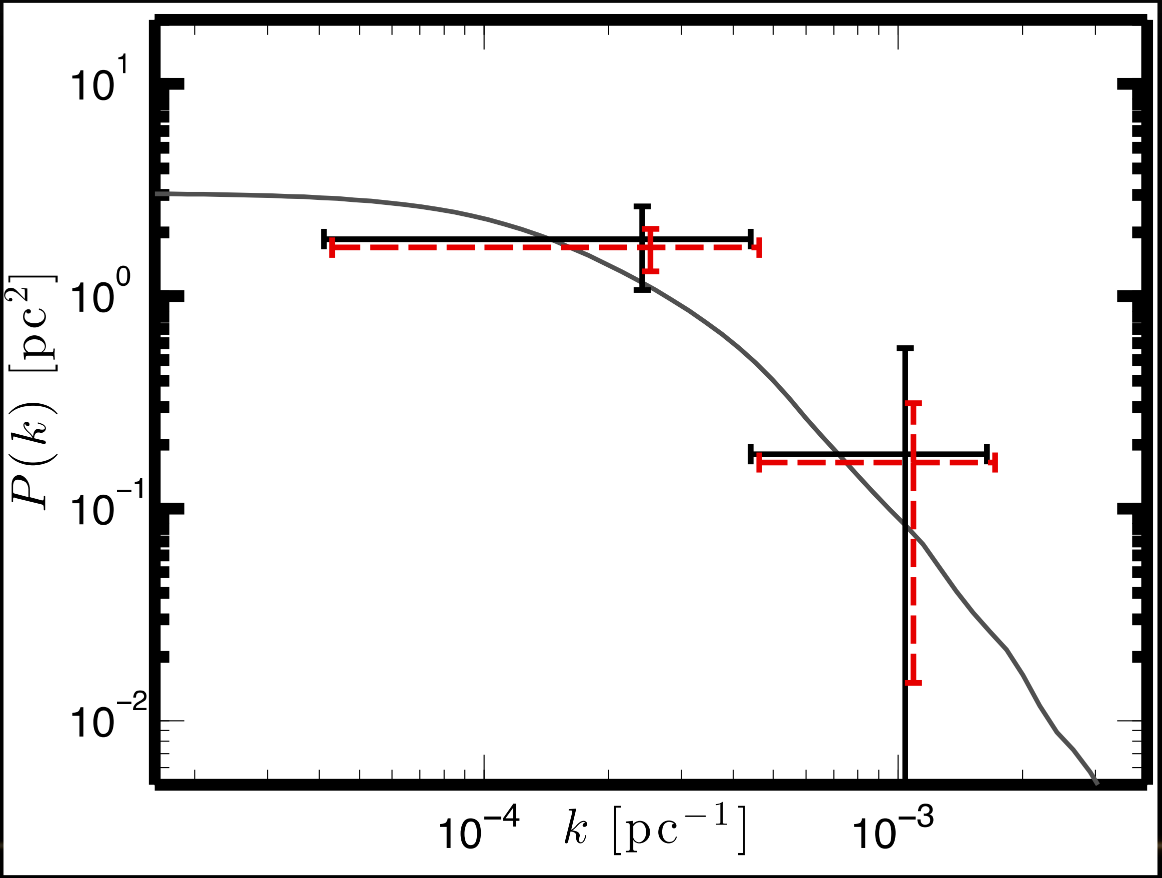
- "Gravitational Imaging" of Perturbed Einstein Rings



Vegetti et al. *Nature*, (2012)

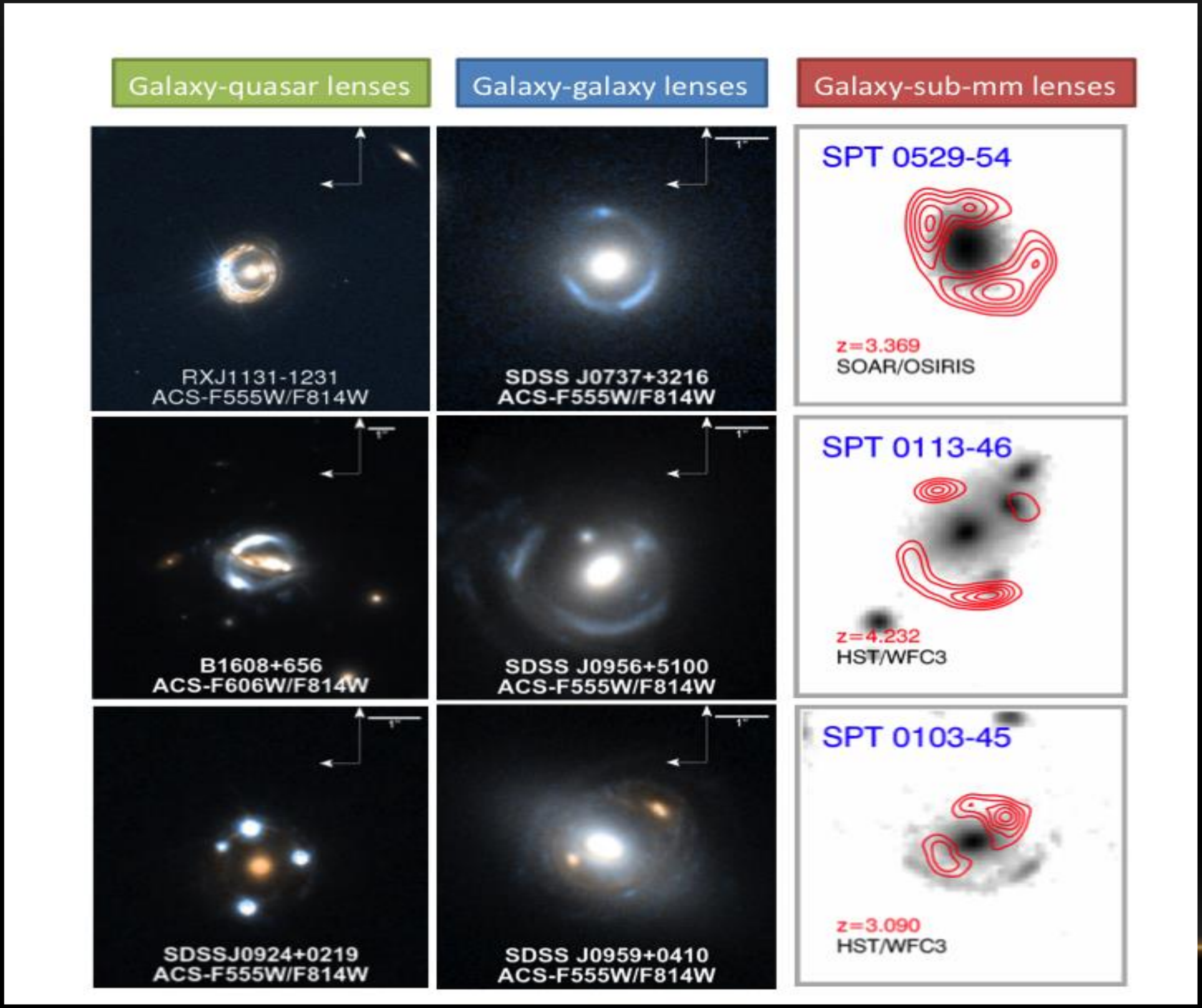
Measuring the Substructure Power Spectrum

- Use ALMA images of lensed sub-mm galaxies to directly measure the convergence power spectrum.



Hezaveh et al. 2014

All of these lenses contain some information about small-scale structures inside the lens galaxies



How do we extract it ??

We need a comprehensive framework that can handle any type of lens.

Back to basic: mathematical structure of gravitational lensing

- Lensing is a simple map from the source plane to the image plane:

PSF

$$O_\lambda(\mathbf{x},t) = \int d\mathbf{y}\,\left[S_\lambda\left(\mathbf{y} - \vec{\nabla}\phi_{\rm lens}(\mathbf{y}), t - \tau(\mathbf{y})\right) + L_\lambda(\mathbf{y},t)\right] W_R(\mathbf{x}-\mathbf{y},t).$$

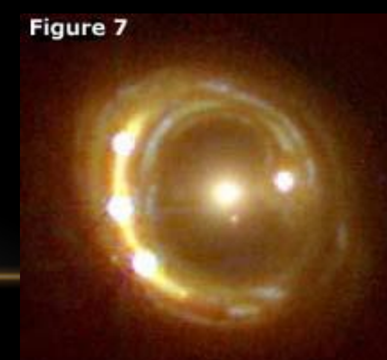
Image

Source

Lens

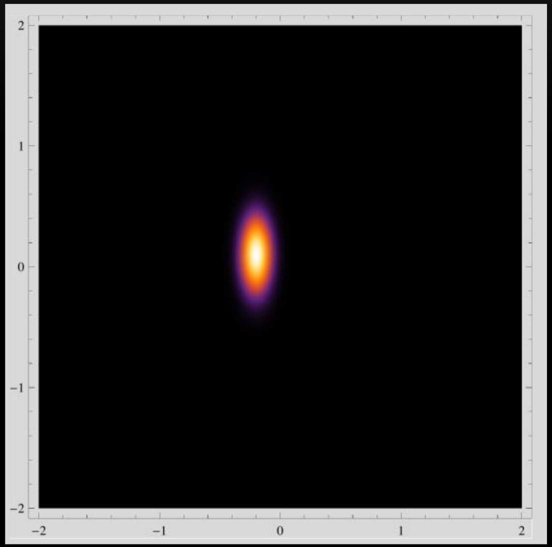
Light from lens galaxy

$$\tau(\mathbf{y},\mathbf{u}) = t_0\left[\frac{1}{2}|\mathbf{y}-\mathbf{u}|^2 - \phi_{\rm lens}(\mathbf{y})\right], \quad \text{with} \quad t_0 \equiv \frac{1+z_{\rm lens}}{c}\frac{D_l D_s}{D_{ls}},$$

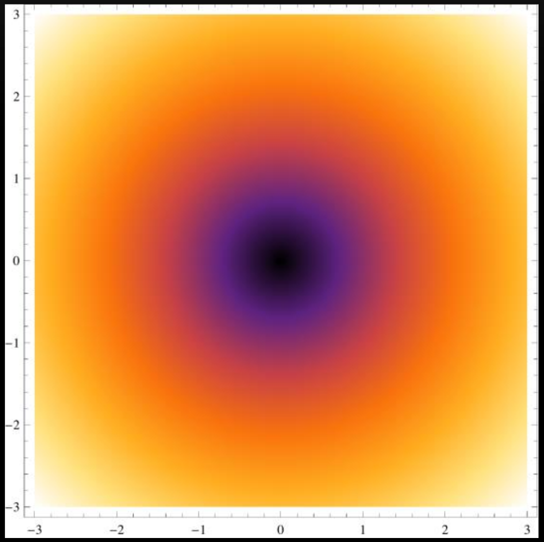


Simple Example

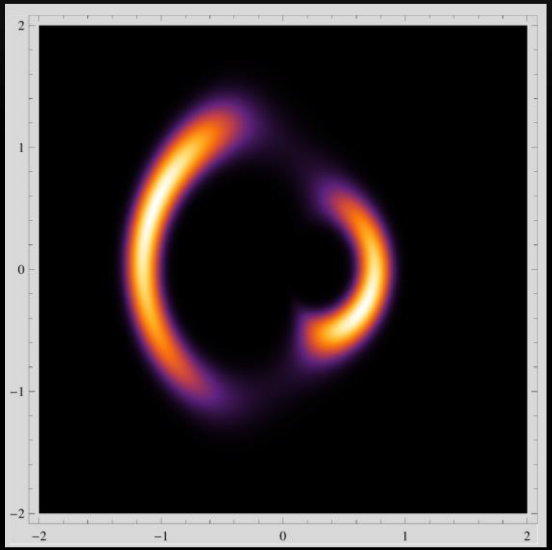
Source



Lens

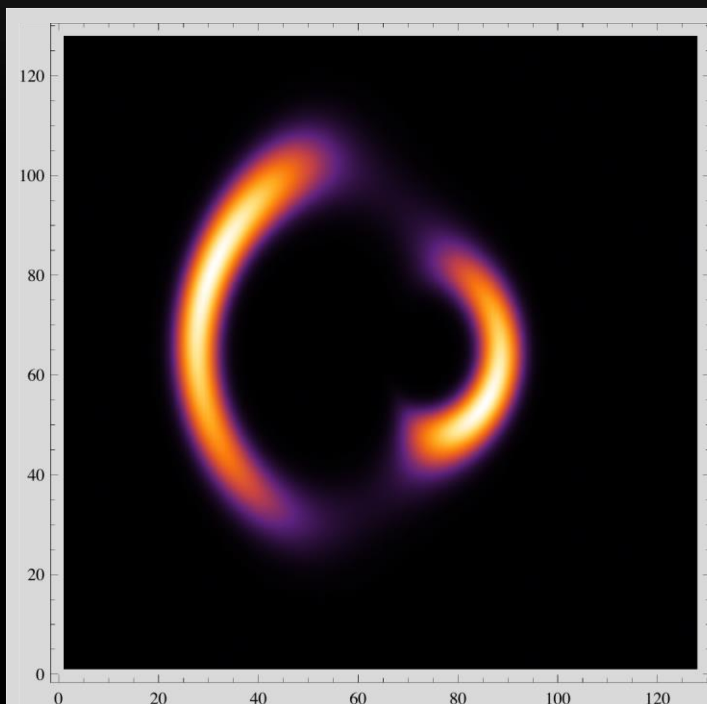


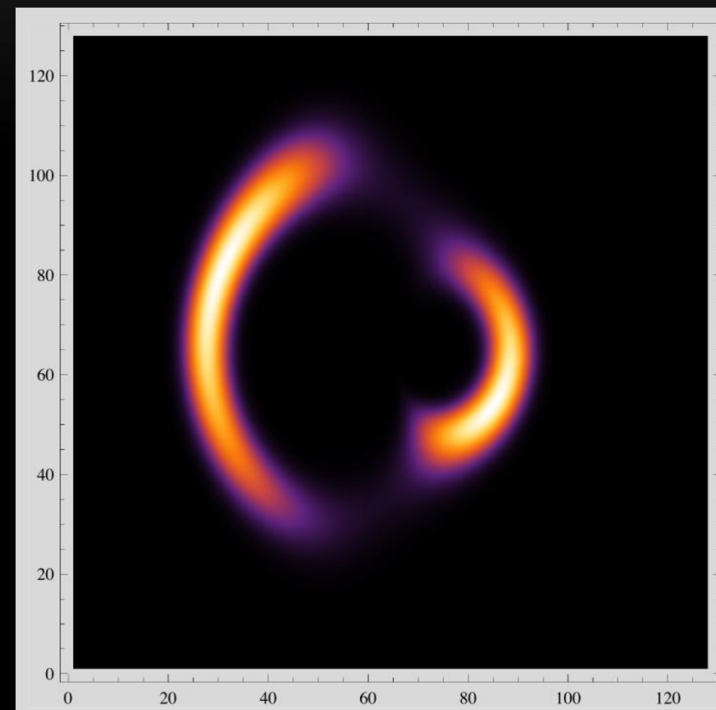
Image



- Here, we assume perfect PSF and no light from the lens galaxy.

Question: Which one of these images was created by a lens containing substructures?



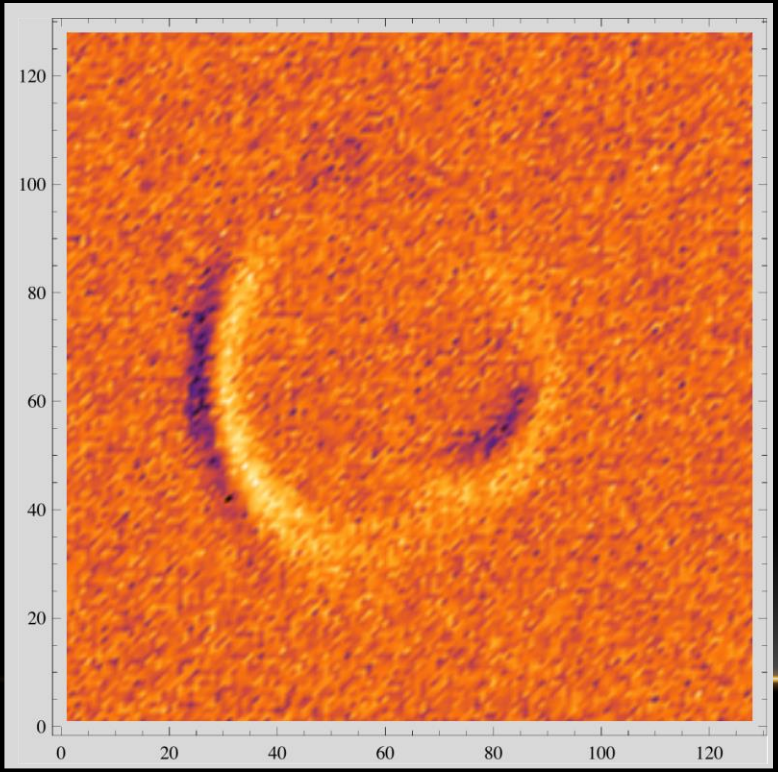


- To extract substructure information, we need to be able to distinguish between these two.

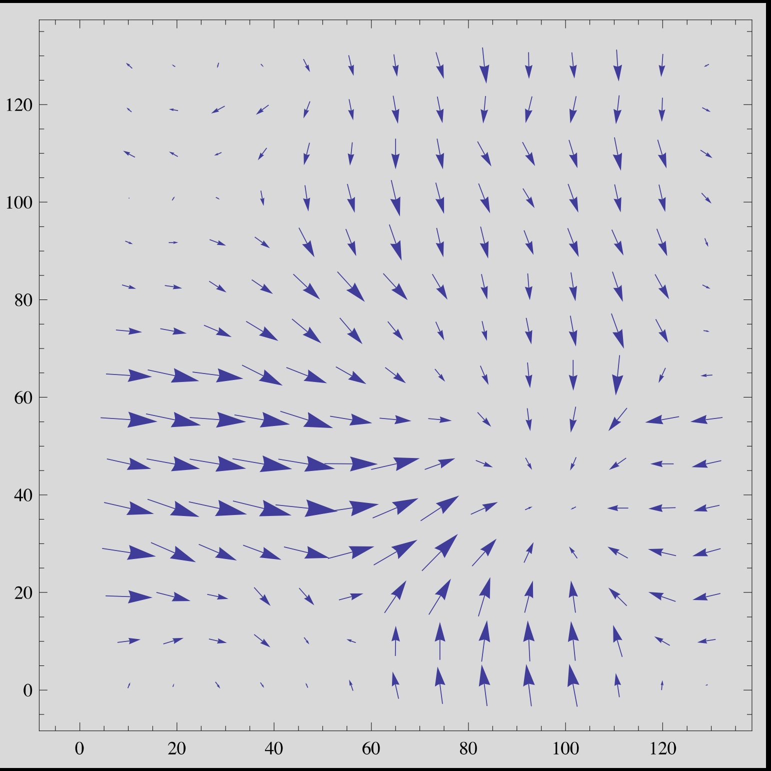
Consider the residuals between the two images

- All the information about substructures is contained in the residuals between the actual image and an image created from a purely smooth lens.

Residuals



Substructure Deflection Field



Understanding the structure of image residuals

- Divide the lens potential into a dominant smooth component and a small substructure correction:

$$\phi_{\rm lens}(\mathbf{y}) = \phi_0(\mathbf{y}) + \phi_{\rm sub}(\mathbf{y})$$

- Then the image residuals are simply given by:

PSF

$$\delta O_\lambda^{\rm sub}(\mathbf{x}) = -\int d\mathbf{y}\left[\mathbf{M}_0(\mathbf{y})\vec{\nabla}S_\lambda\left(\mathbf{y} - \vec{\nabla}\phi_0(\mathbf{y})\right)\cdot\vec{\alpha}_{\rm sub}(\mathbf{y})\right]W_R(\mathbf{x}-\mathbf{y})$$

Image residuals

Magnification tensor

Source

Substructure deflection field

Likelihood Analysis

- Since the residuals are linear in the substructure potential, the likelihood is Gaussian in the ϕ_k variables:

$$\mathcal{L}(t;\mathbf{q},\mathbf{q}_{\rm sub}) \propto \int \left[\prod_{\mathbf{k}>0} d\tilde{\phi}_{\mathbf{k}} d\tilde{\phi}^*_{\mathbf{k}}\right] P_{\rm sub}(\tilde{\phi}_{\mathbf{k}},\tilde{\phi}^*_{\mathbf{k}}|\mathbf{q}_{\rm sub}) \tag{25}$$
$$\times\, e^{-\frac{1}{2}\int d\mathbf{x}d\mathbf{x}'\,[\delta O^{\rm obs}_{\lambda}(\mathbf{x},t)-\sum_{\mathbf{k}}(\mathcal{W}_{\mathbf{k}}(\mathbf{x},t)\,\tilde{\phi}_{\mathbf{k}}+\mathcal{W}^*_{\mathbf{k}}(\mathbf{x},t)\,\tilde{\phi}^*_{\mathbf{k}})]\mathbf{C}^{-1}_{N_\lambda}(\mathbf{x},\mathbf{x}')[\delta O^{\rm obs}_{\lambda}(\mathbf{x}',t)-\sum_{\mathbf{k}'}(\mathcal{W}_{\mathbf{k}'}(\mathbf{x}',t)\,\tilde{\phi}_{\mathbf{k}'}+\mathcal{W}^*_{\mathbf{k}'}(\mathbf{x}',t)\,\tilde{\phi}^*_{\mathbf{k}'})]}$$

$$P_{\rm sub}(\tilde{\phi}_{\mathbf{k}},\tilde{\phi}^*_{\mathbf{k}}|\mathbf{q}_{\rm sub}) = \frac{1}{(2\pi)^{N_{\mathbf{k}}}|\mathcal{P}_{\mathbf{k}\mathbf{k}'}|}e^{-\frac{1}{2}\sum_{\mathbf{k},\mathbf{k}'>0}(\tilde{\phi}^*_{\mathbf{k}}\mathcal{P}^{-1}_{\mathbf{k}\mathbf{k}'}\tilde{\phi}_{\mathbf{k}'}+\tilde{\phi}_{\mathbf{k}}\mathcal{P}^{-1}_{\mathbf{k}\mathbf{k}'}\tilde{\phi}^*_{\mathbf{k}'})}$$

Dark matter parameters

- If we assume the ϕ_k to be a Gaussian random field, we can marginalize out the substructures to obtain a posterior distribution for dark matter parameters.

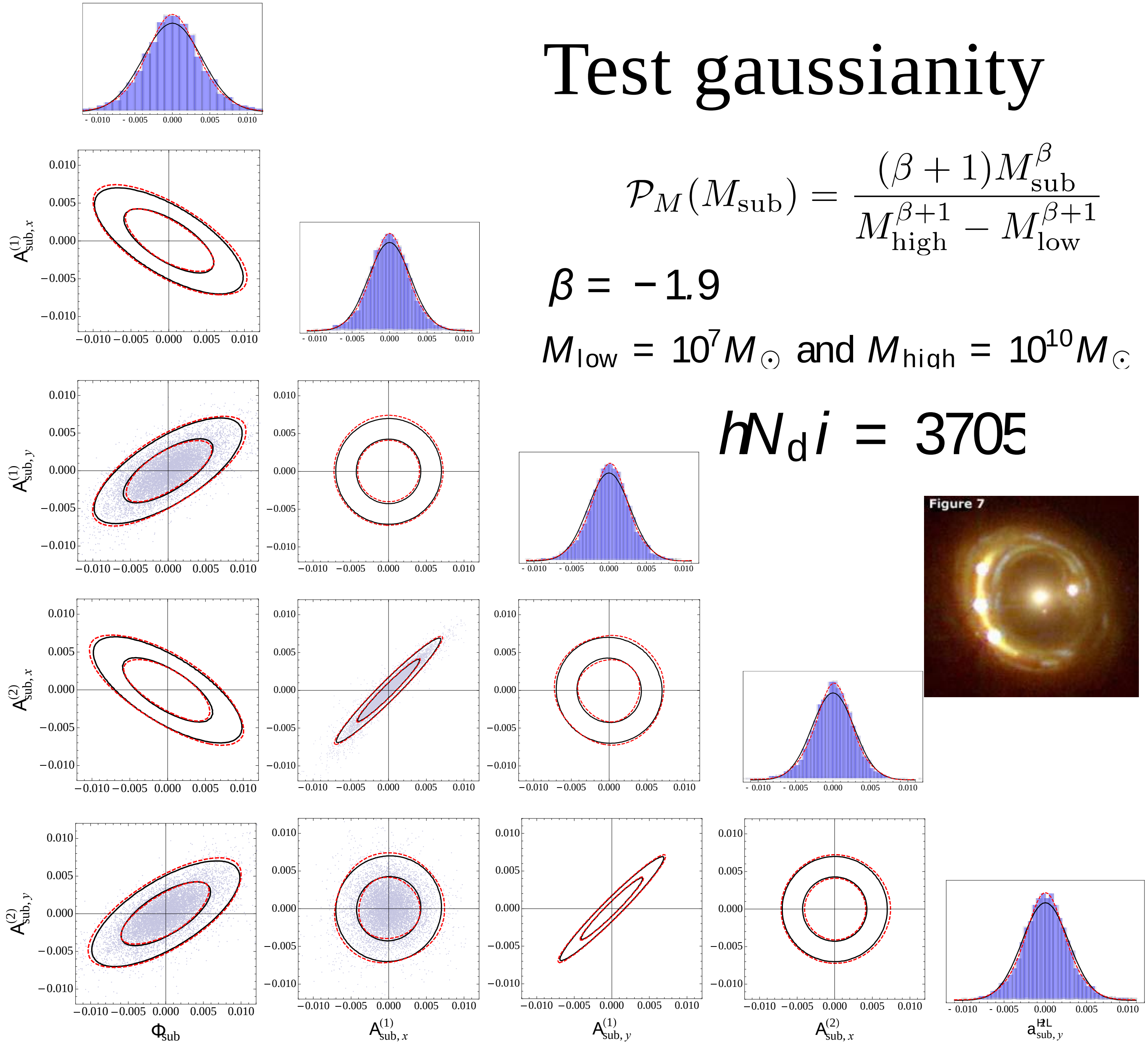
Test gaussianity

$$\mathcal{P}_M(M_{\rm sub}) = \frac{(\beta+1)M_{\rm sub}^{\beta}}{M_{\rm high}^{\beta+1} - M_{\rm low}^{\beta+1}}$$

$\beta = -1.9$

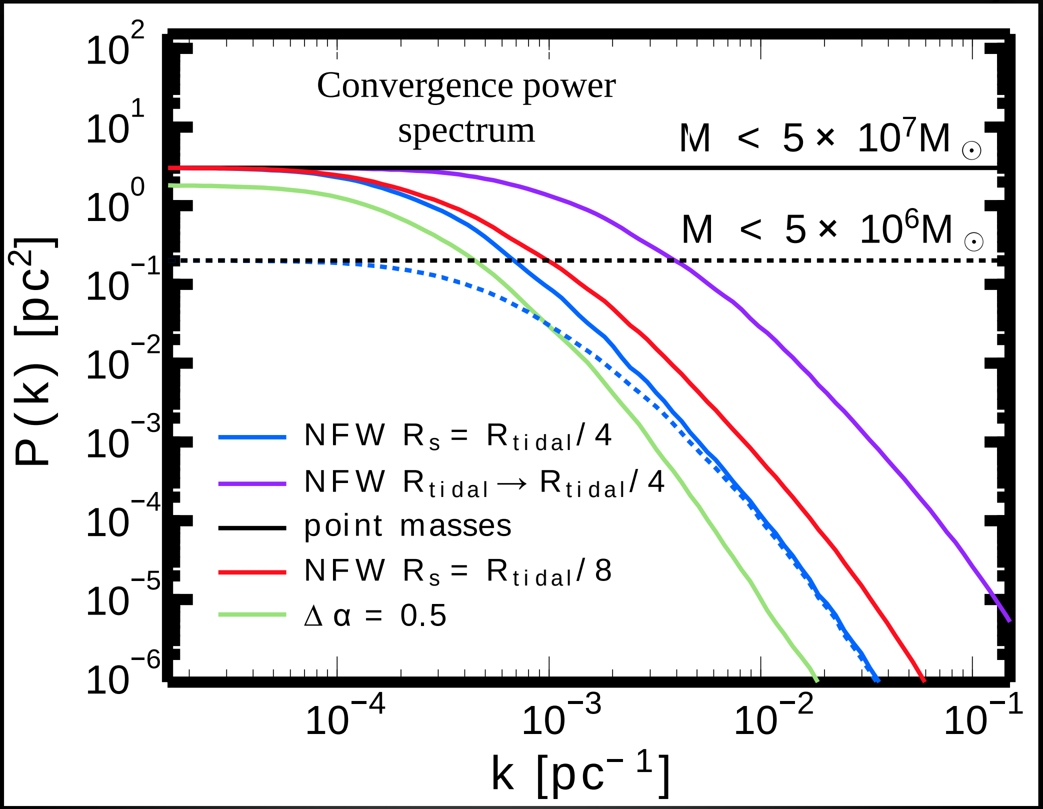
$M_{\rm low} = 10^7 M_\odot$ and $M_{\rm high} = 10^{10} M_\odot$

$\langle N_{\rm d} \rangle = 3705$



What are we trying to measure ?

- So far, there are few actual predictions for the substructure lensing potential power spectrum in the literature.

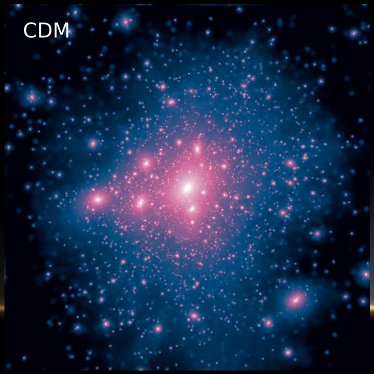


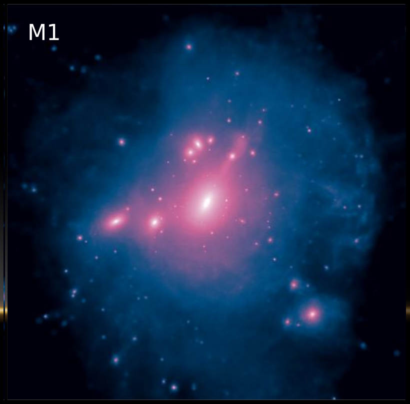
$$P_\phi(k) = \frac{4}{k^4} P_\kappa(k)$$

Hezaveh et al. 2014

Rethinking Galaxies

- Describing cosmologically distant lens galaxies in terms of their substructure power spectrum is largely unexplored.
- We must understand how the substructure population depends on the host galaxy's properties.
- The key assumption here is that the statistical properties of the substructures are similar across all lens galaxies.





Rethinking Galaxies

From Observations to Fundamental Physics

- It is timely to develop these techniques since upcoming surveys will discover thousands of new lenses.

WFIRST
Wide-Field Infrared Survey Telescope

LSST
Large Synoptic Survey Telescope

The OMEGA Explorer 2017
(PI: Moustakas)

Euclid
Consortium

Take-Home Message

- The interesting dark matter effects are on small sub-galactic scales.
- Combining strong gravitational lensing probes offers a unique way to probe dark matter on the smallest scales.
- We have developed a comprehensive framework that allows us to extract substructure information from a variety of lensed images.
- We are currently implementing it.
- Stay tuned for sensitivity forecast in the near future!