Cold Dark Matter's Not Enough

Piero Madau
UC Santa Cruz

Madrid 2015

JUST SIX NUMBERS (FLAT ΛCDM)

ΛCDM (PLANCK 2015, TT,TE,EE+lowP+lensing+ext)

$\Omega_b h^2$ = 0.02230 ± 0.00014

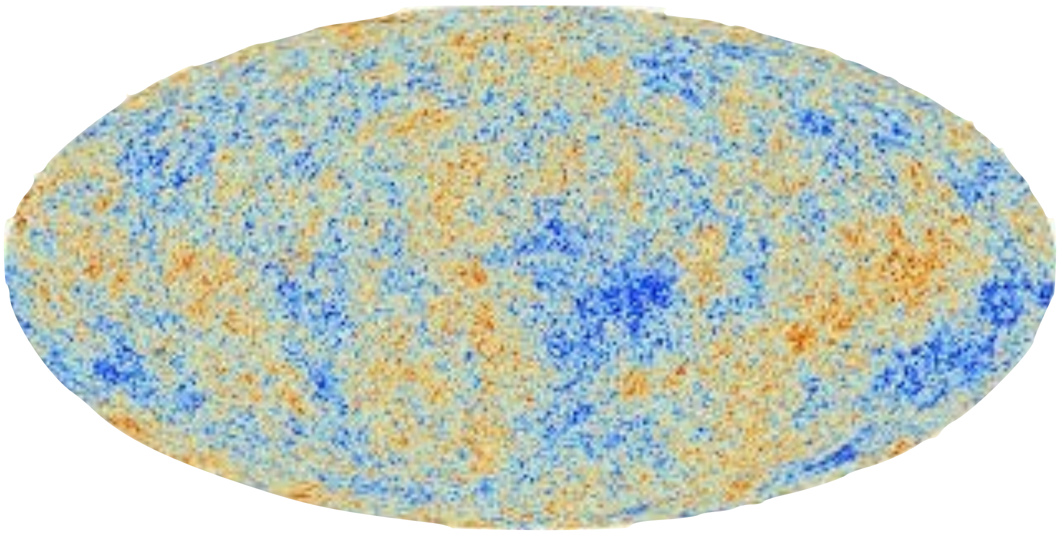
$\Omega_X h^2$ = 0.1188 ± 0.0010

$100\theta_{MC}$ = 1.04093 ± 0.00030

τ = 0.066 ± 0.012

n_s = 0.9667 ± 0.0040

σ_8 = 0.8159 ± 0.0086



A *160σ* measurement of the cosmic baryon density and a *120σ* detection of non-baryonic DM!

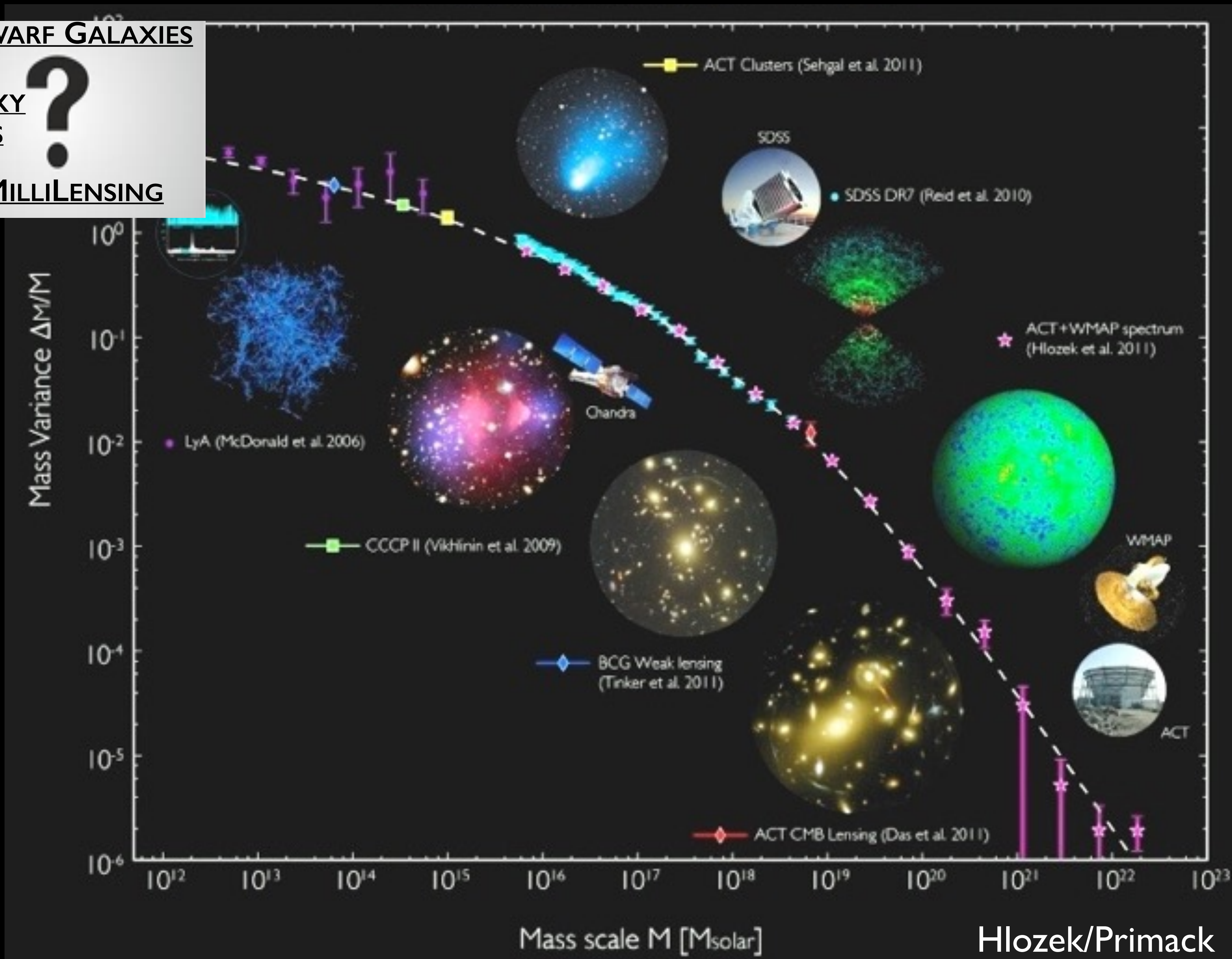
Density Fluctuations Data Agree with ΛCDM

Dwarf Galaxies

galaxy cores

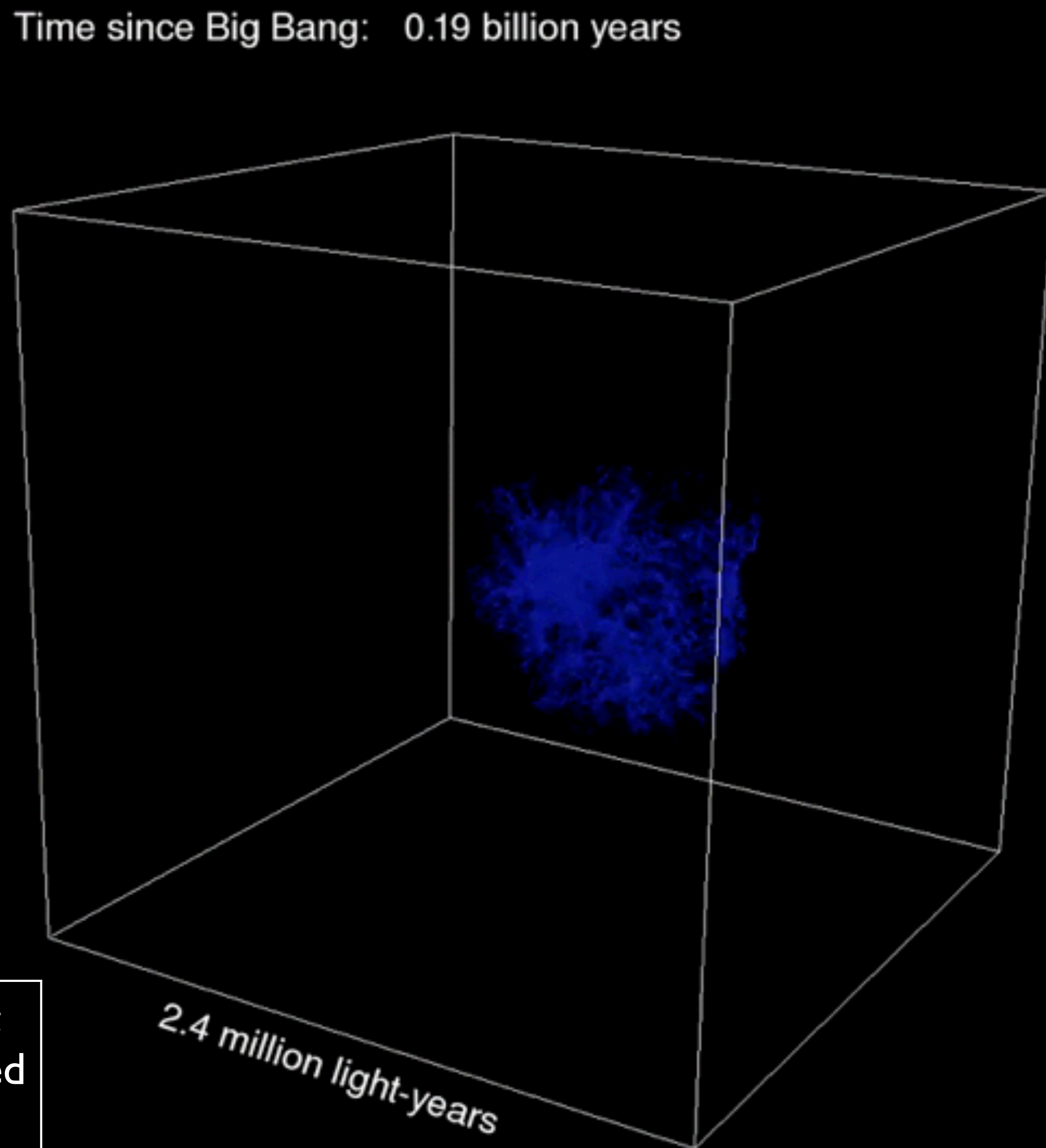
?

MilliLensing



Substructure: A Unique Prediction of ΛCDM

Subhalo differential mass function has slope −1.9
➪ equal mass per decade of mass



In a MW-sized halo at $z=0$:
5-10% of host mass locked in self-bound subhalos

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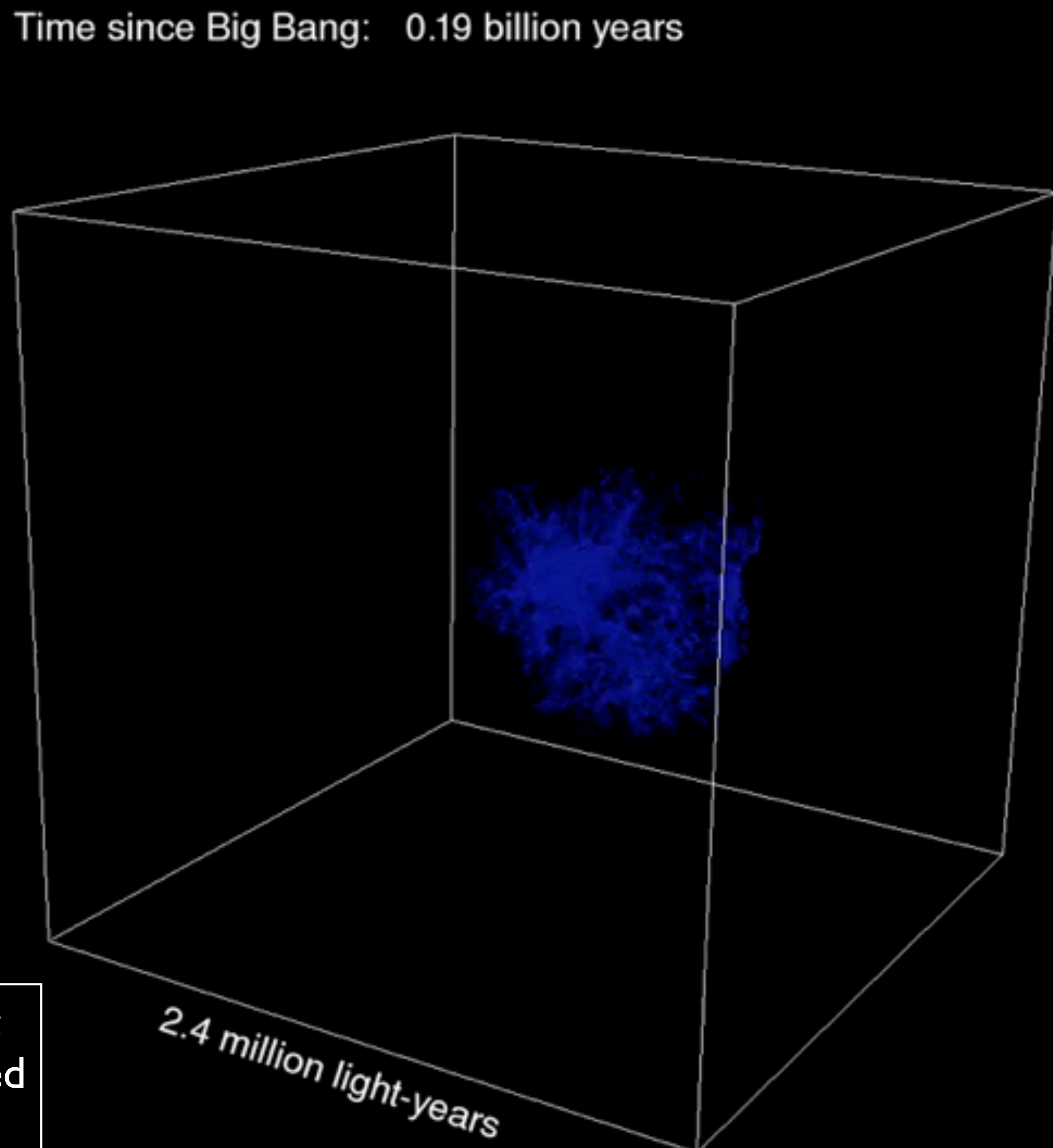

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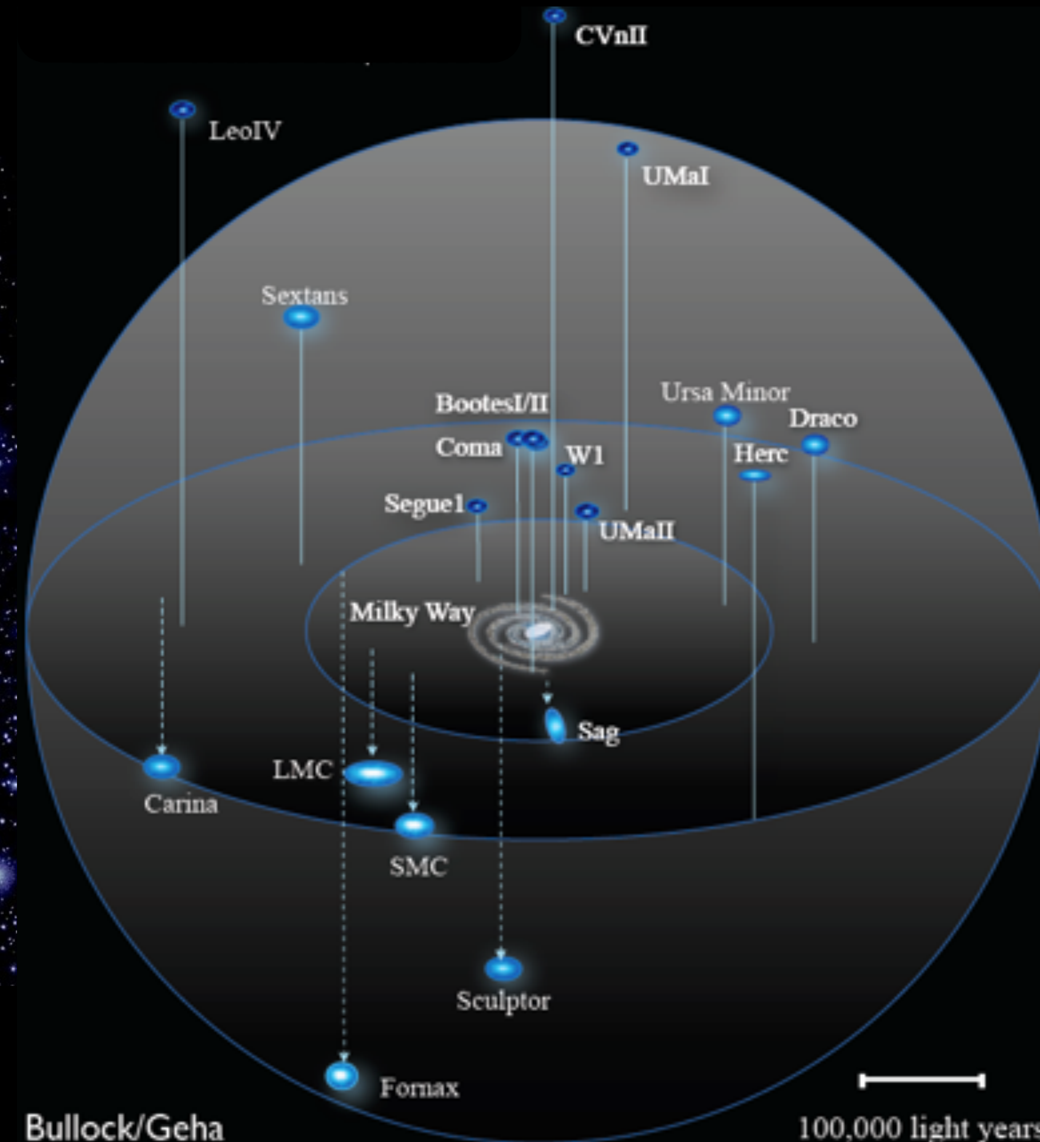
<u>DWARF GALAXY PROBLEM</u>



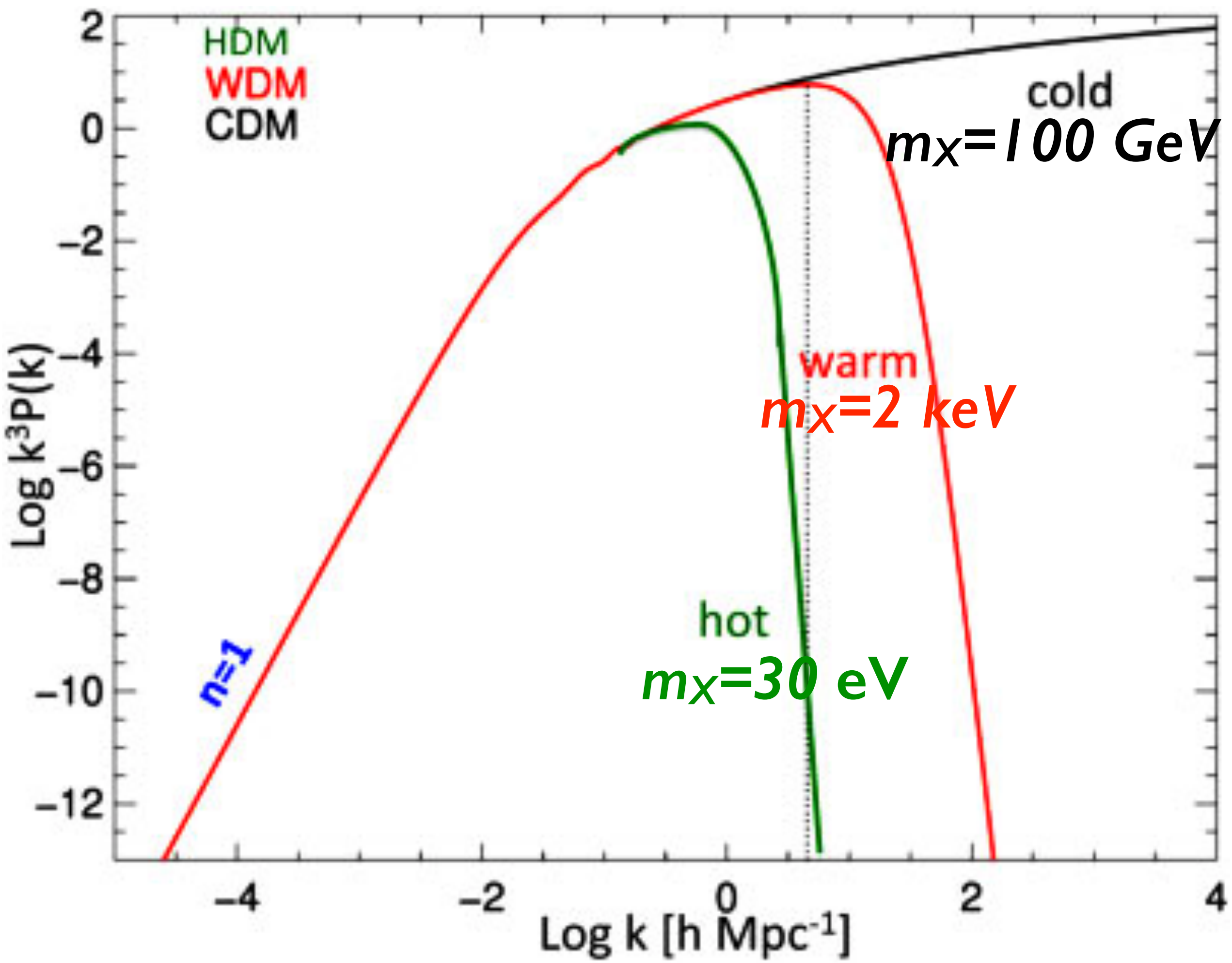
THEORY: $N_{sub} \approx 1{,}000$
w V_c(infall)$\gtrsim 10$ km/s

OBSERVATIONS: $N_{sat} \approx 25$

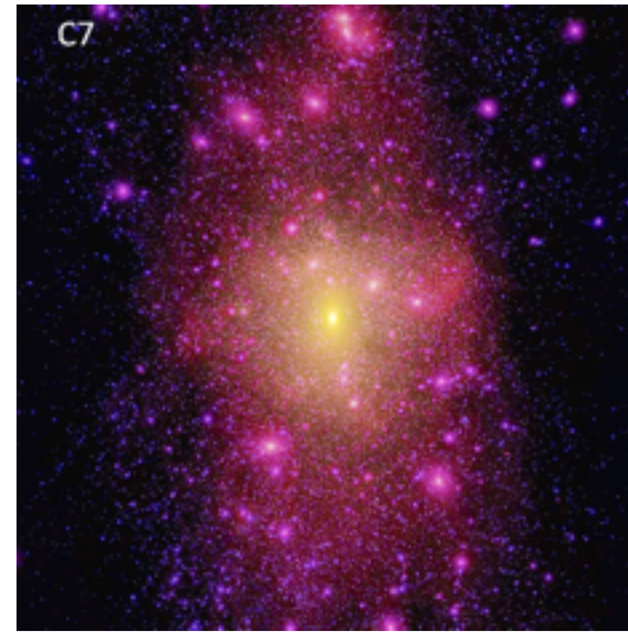
SOLUTIONS TO THE DGP:

1) BLAME "GASTROPHYSICS"

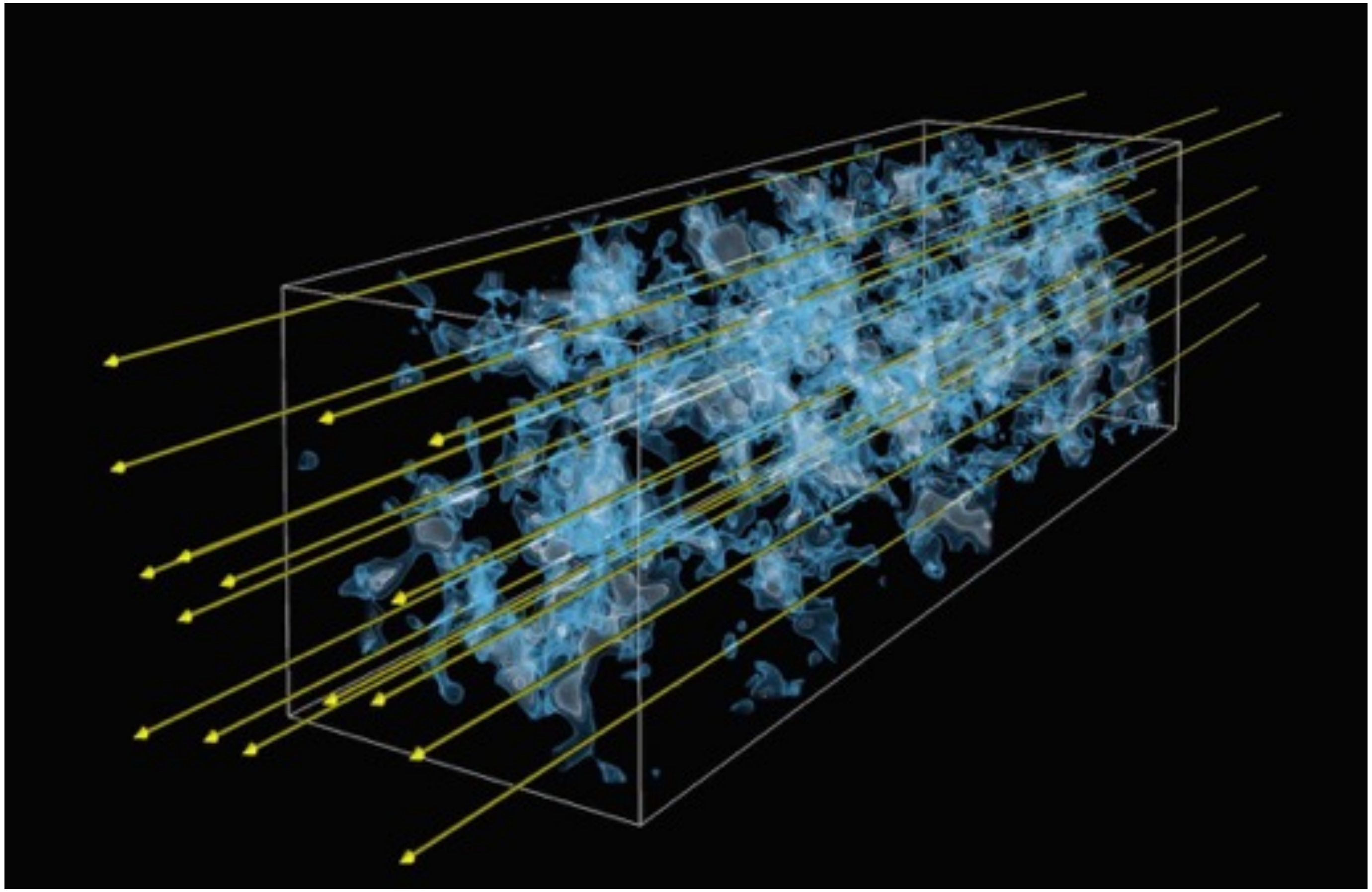
2) BLAME CDM

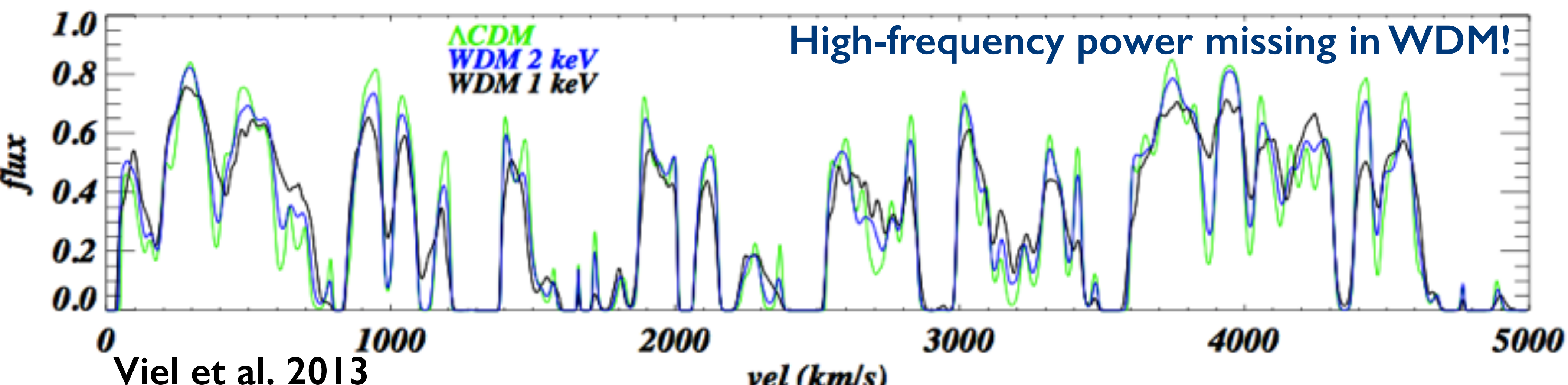


Late-time linear power spectra for density perturbations in universes dominated by hot, warm and cold dark matter.



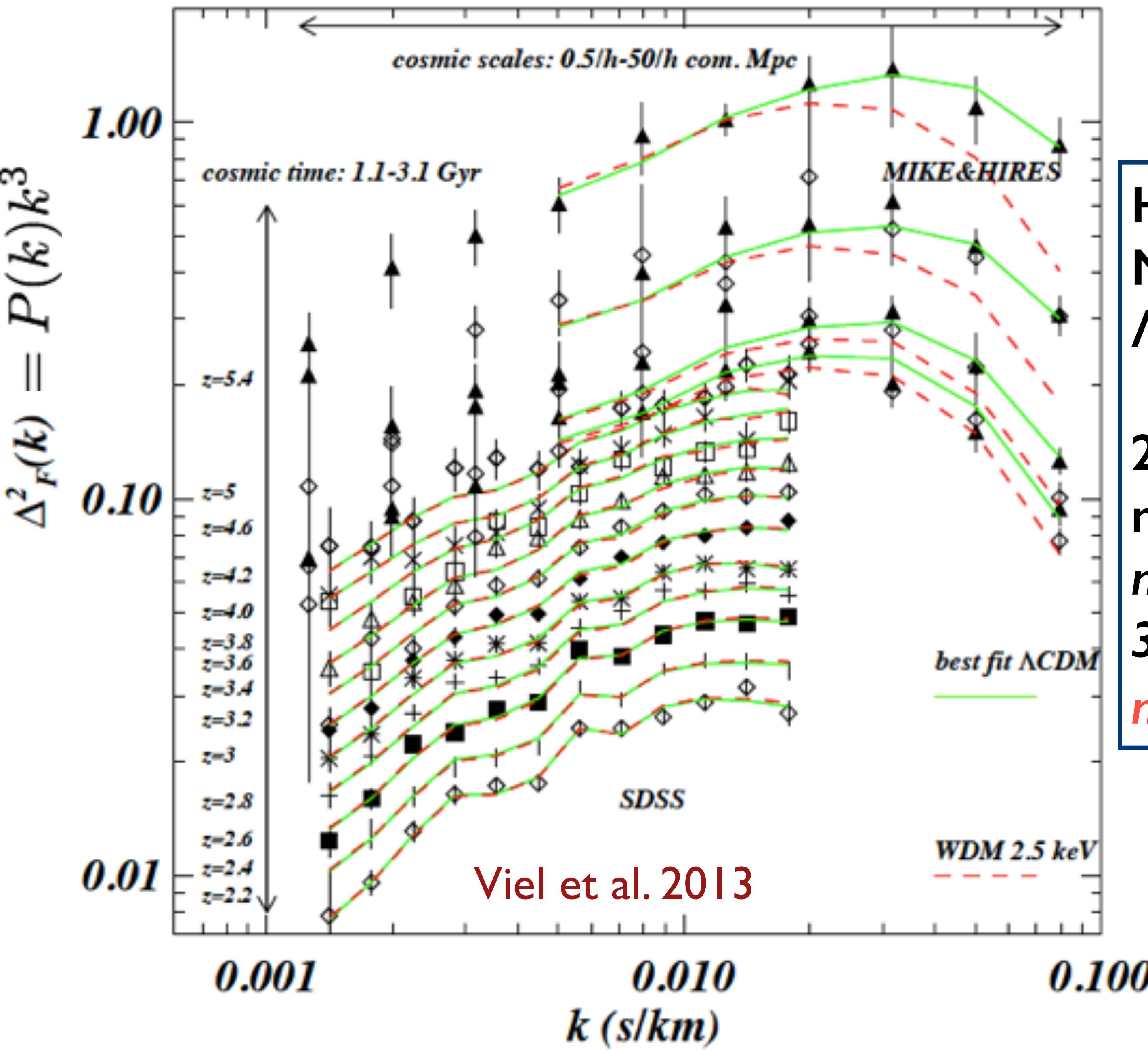
LYMAN-ALPHA FOREST SPECTRA: CDM VS. WDM





Viel et al. 2013

Someone Likes it Cold/Tepid



High-resolution Keck and Magellan spectra match ΛCDM up to z = 5.4!

2σ lower limit on the mass of a thermal relic: m_{WDM} > 3.3 keV ⇨ M_{FS} < 3×10^8 M$_\odot$

~~m_{WDM}=2 keV at 4σ C.L.~~

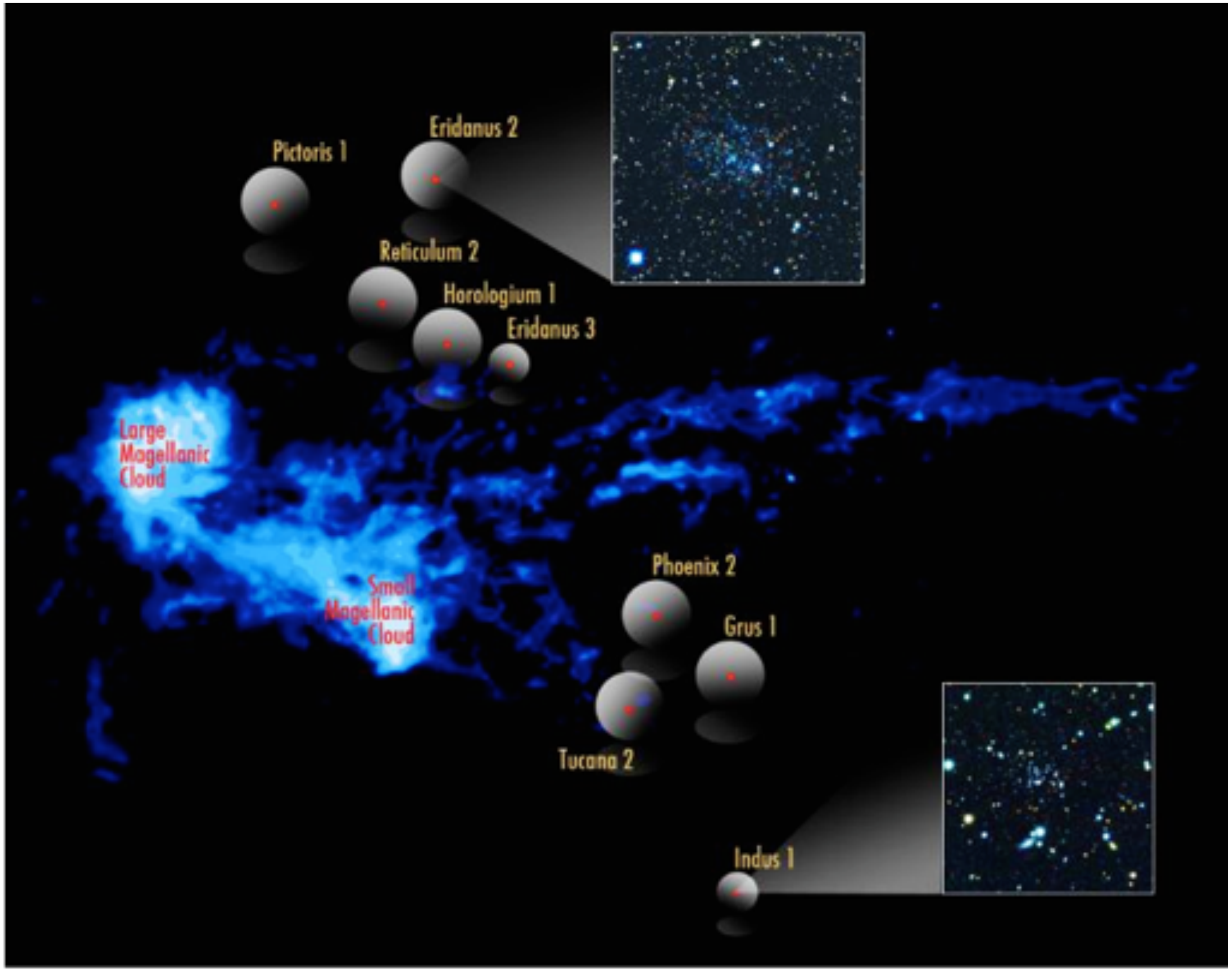
Lower limit is too large for WDM to have much effect on the DGP!

Solutions to the DGP:

1) Blame Gastrophysics

2) Blame CDM

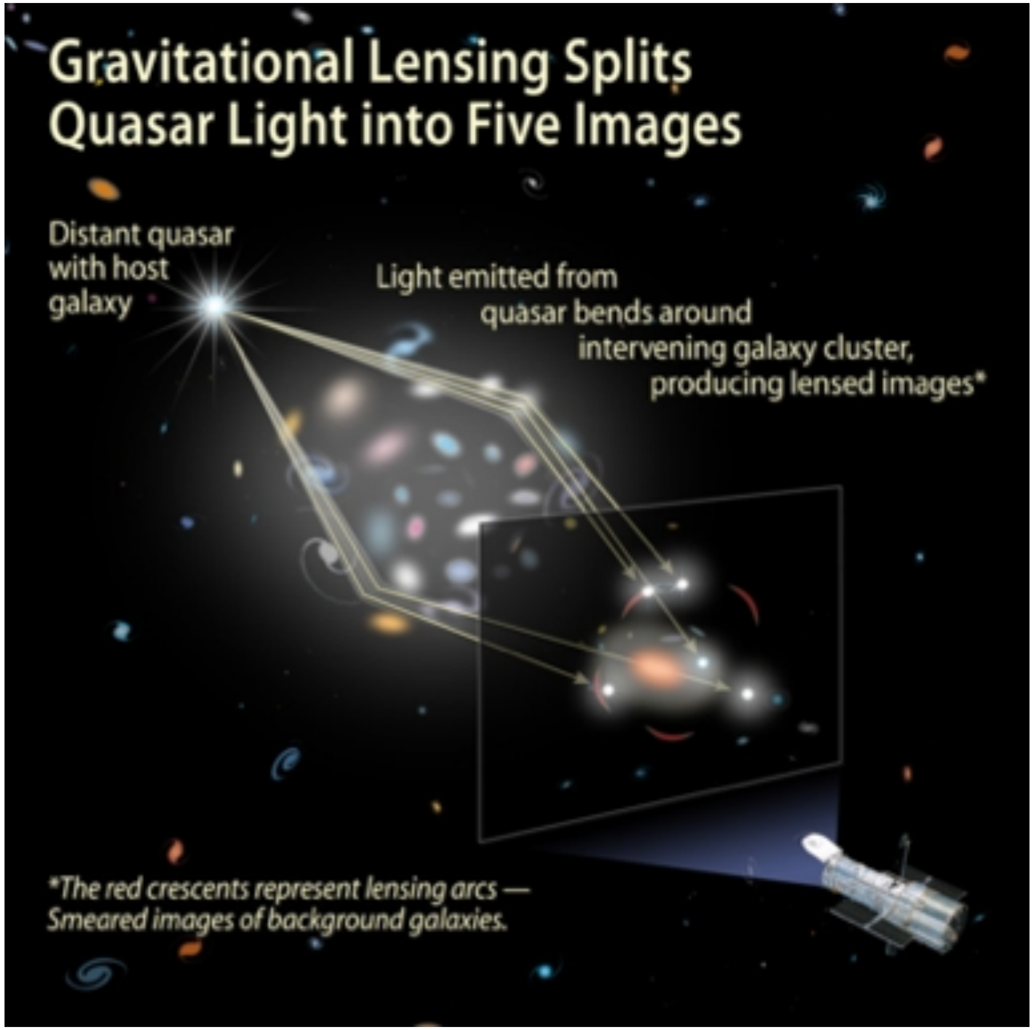
3) Blame Observations!



1)+3) ➪Q: Are DM Halos Really so Lumpy?

SUBSTRUCTURE LENSING

Potential perturbations by **DM substructure** produce *anomalies* (compared to a simple smooth mass profile) in the relative magnifications of the lensed images. **Effect is sensitive to subhalo surface mass density in the inner 5-10 kpc of lens.**



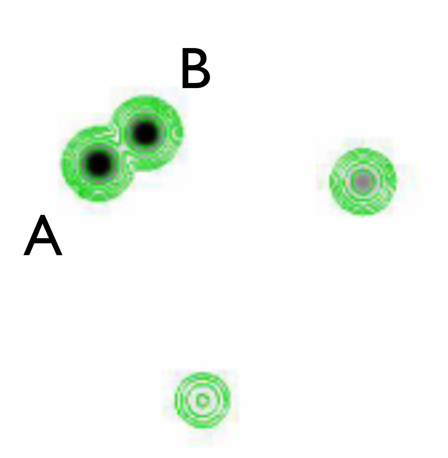
Metcalf & Madau 2001; Chiba 2001; Mao & Schneider 1998

$$\mathbf{M} = \left(\frac{\partial \boldsymbol{u}}{\partial \boldsymbol{x}}\right)^{-1} = \begin{bmatrix} 1-\phi_{xx} & -\phi_{xy} \\ -\phi_{xy} & 1-\phi_{yy} \end{bmatrix}^{-1}$$

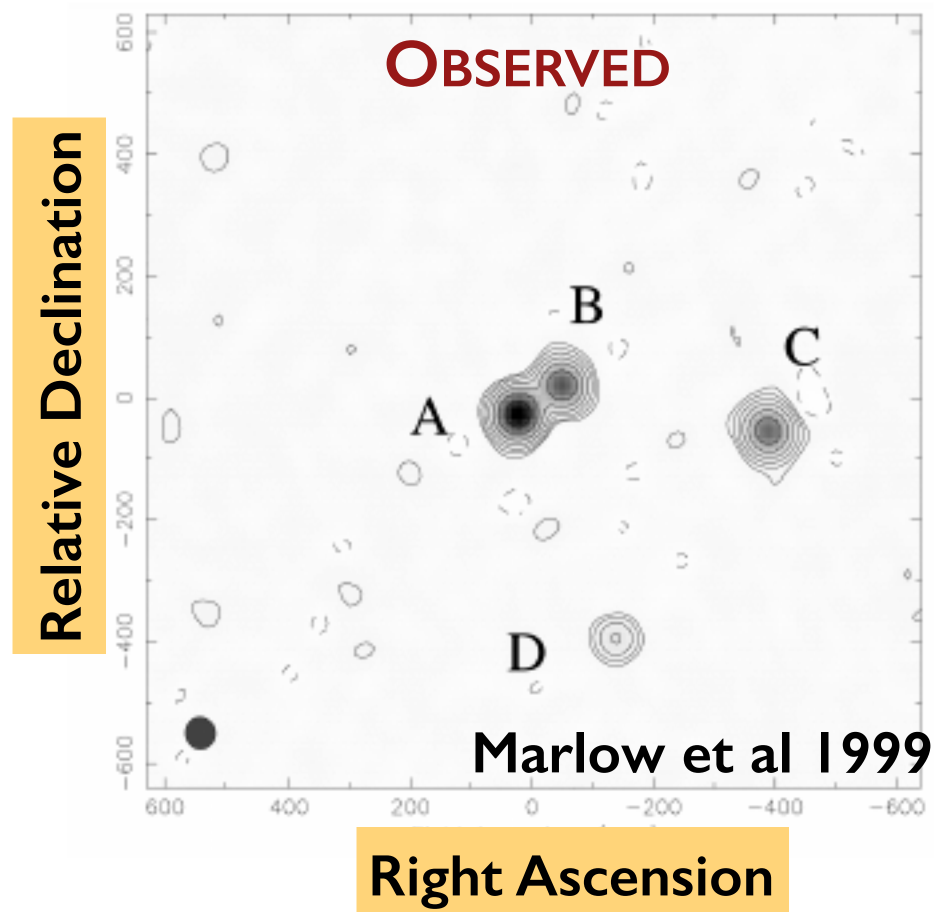
EXPECTED

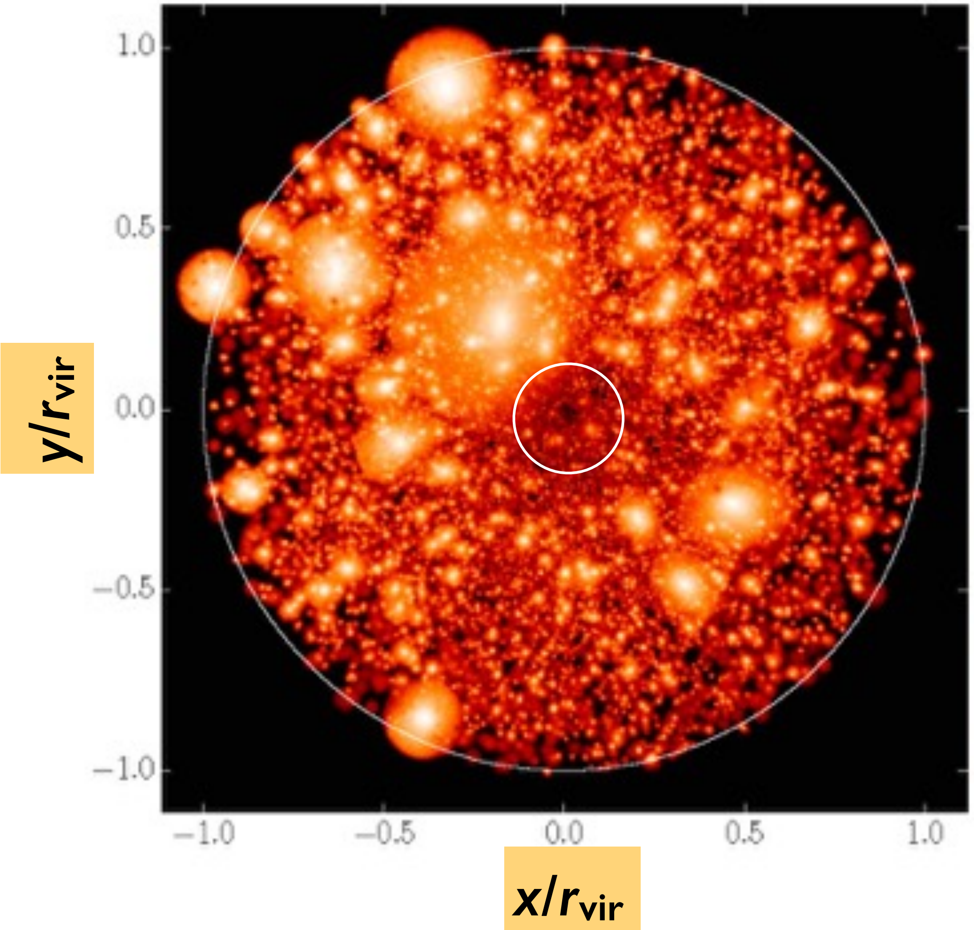
CLASS B1555+375

A−B≈0



Keeton et al 2005





Dalal & Kochanek (2002)

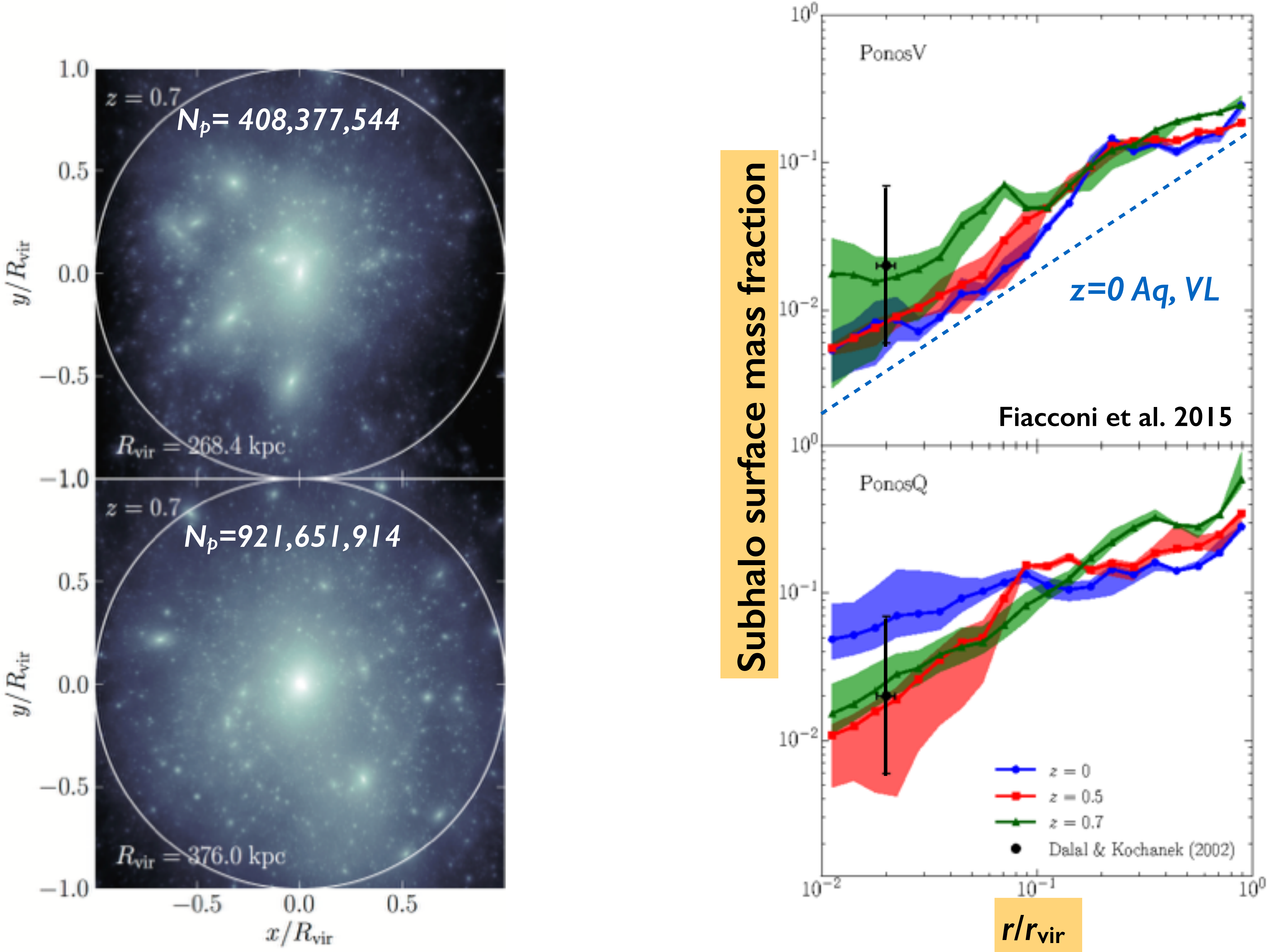
☛ flux ratios in 7 quad lenses

☛ f_{sub}= $2.0^{+5.0}_{-1.4}$ percent

☛ little constraints on clump mass scale

Is there enough substructure in CDM *N*-body simulations to cause the observed flux anomalies? MAYBE

Sensitivity to: ellipticity of lens, intergalactic small-scale structure, baryons, small # of lensed QSOs, etc etc



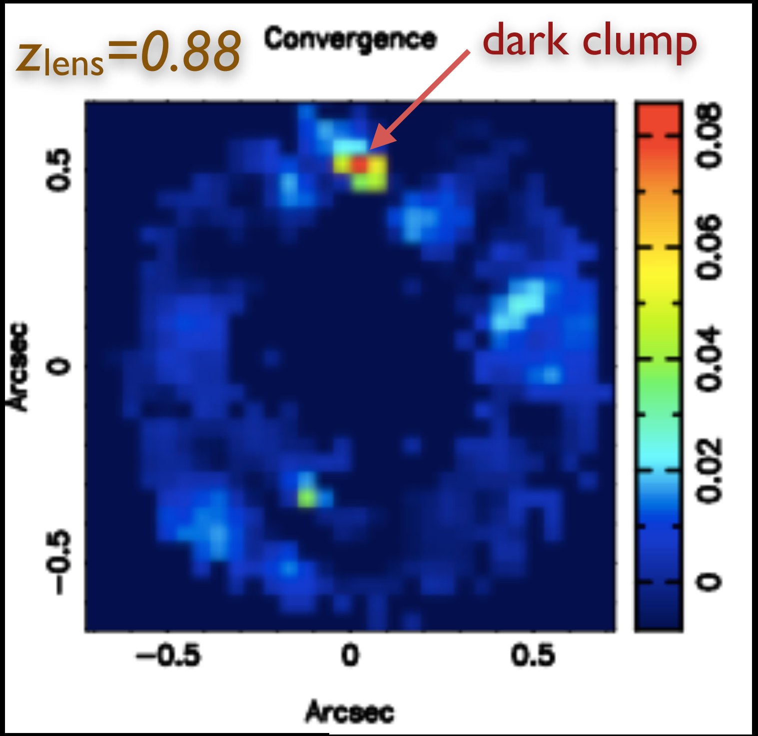
z = 0.7
Np= 408,377,544
Rvir = 268.4 kpc
z = 0.7
Np=921,651,914
Rvir = 376.0 kpc
y/Rvir
x/Rvir
PonosV
PonosQ
Subhalo surface mass fraction
z=0 Aq, VL
Fiacconi et al. 2015
z = 0
z = 0.5
z = 0.7
Dalal & Kochanek (2002)
r/rvir

Expected Numbers of Lensed QSOs in Wide-Field Optical Surveys

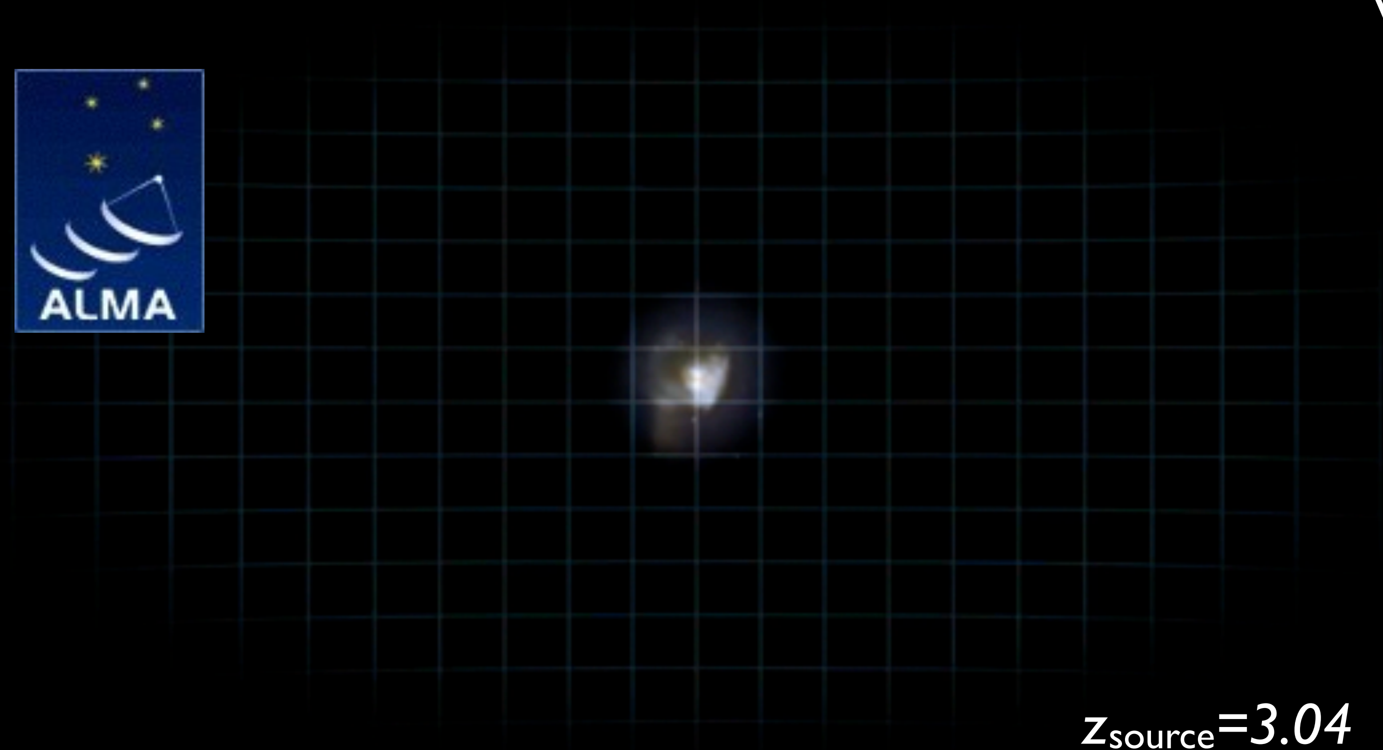
Oguri & Marshall 2010

Survey	QSO (detected) $N_{\text{non-lens}}$	N_{lens}
SDSS-II	1.18×10^5	26.3 (15 per cent)
SNLS	9.23×10^3	3.2 (12 per cent)
PS1/3π	7.52×10^6	1963 (16 per cent)
PS1/MDS	9.55×10^4	30.3 (13 per cent)
DES/wide	3.68×10^6	1146 (14 per cent)
DES/deep	1.26×10^4	4.4 (12 per cent)
HSC/wide	1.76×10^6	614 (13 per cent)
HSC/deep	7.96×10^4	29.7 (12 per cent)
JDEM/SNAP	5.00×10^4	21.8 (12 per cent)
LSST	2.35×10^7	8191 (13 per cent)

Another <u>technique</u>: surface brightness anomalies in bright Einstein rings (*direct gravitational imaging of mass substructure*).



Vegetti et al. 2014



z_{source}=*3.04*

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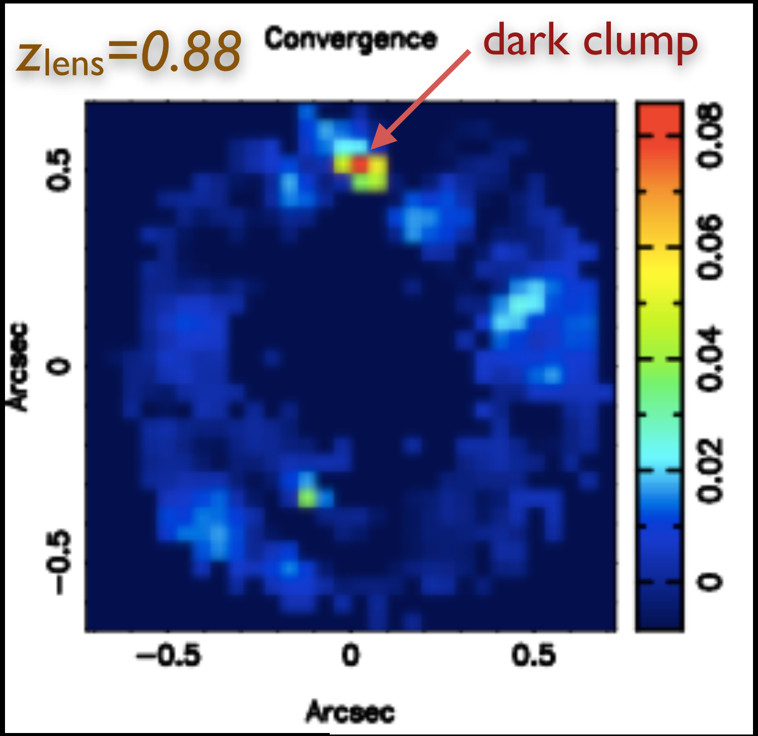

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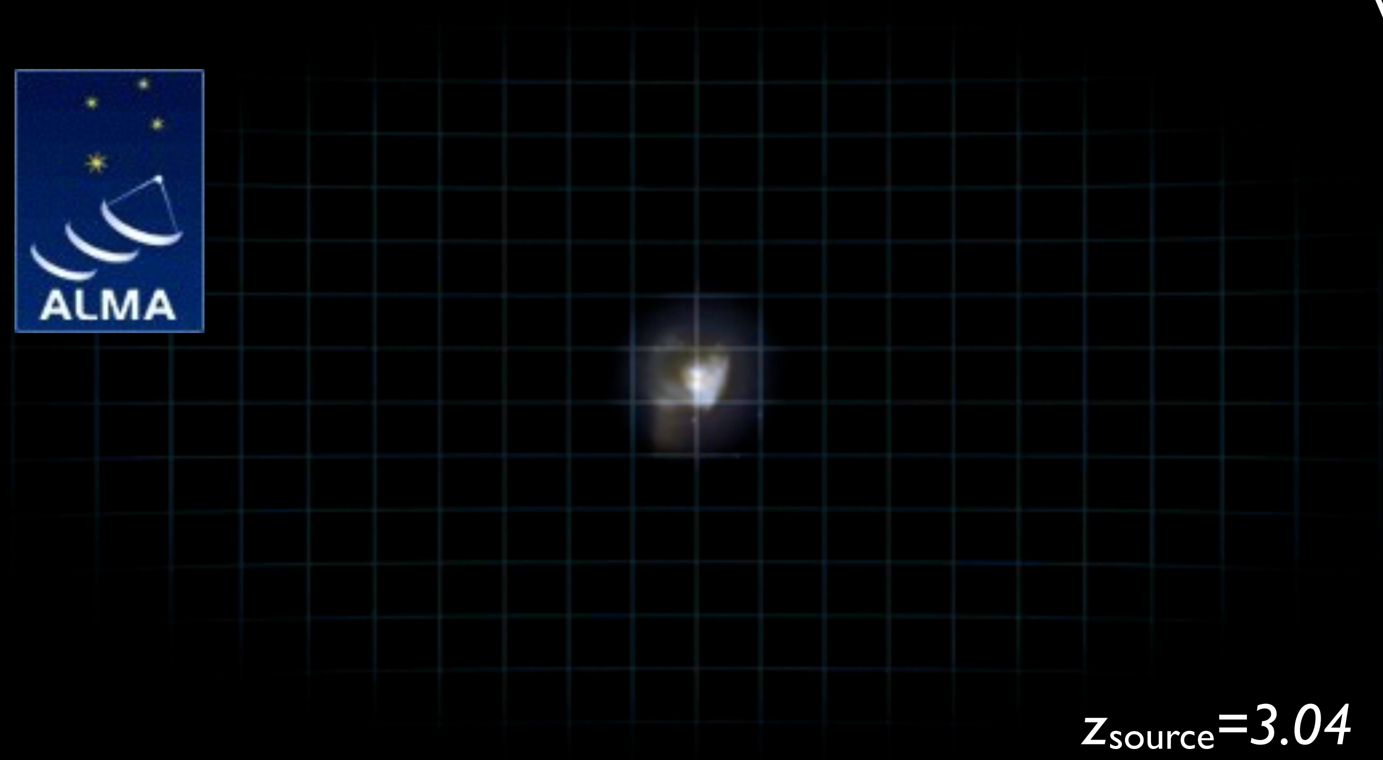


z_{source}=*3.04*

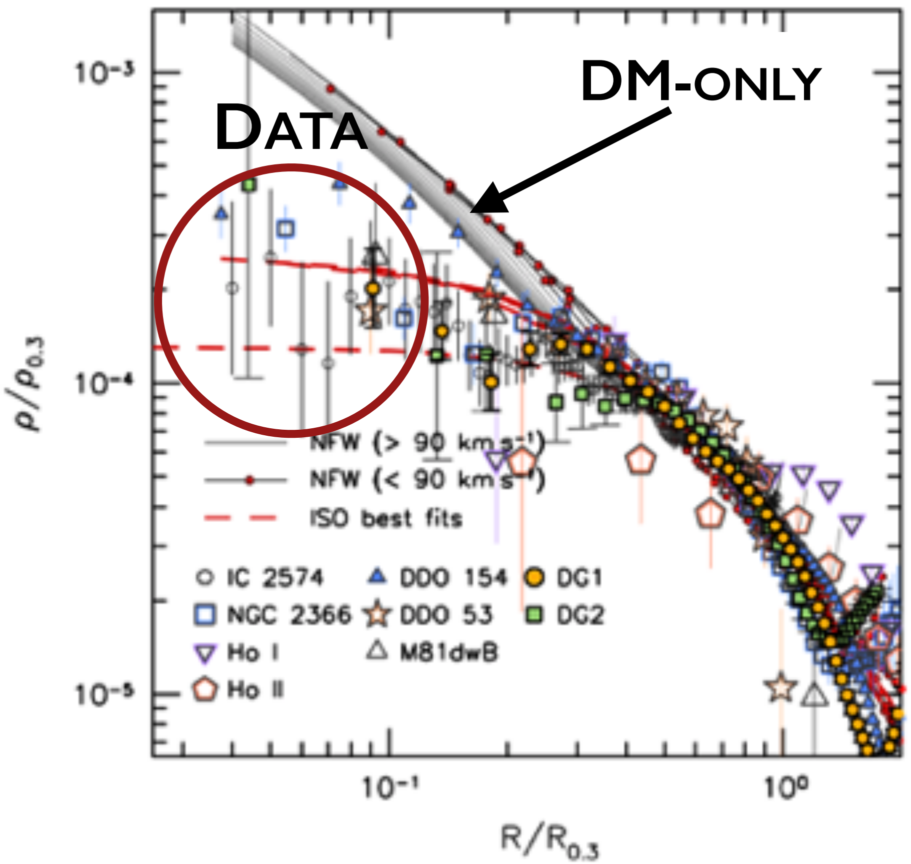
Core/Cusp Problem

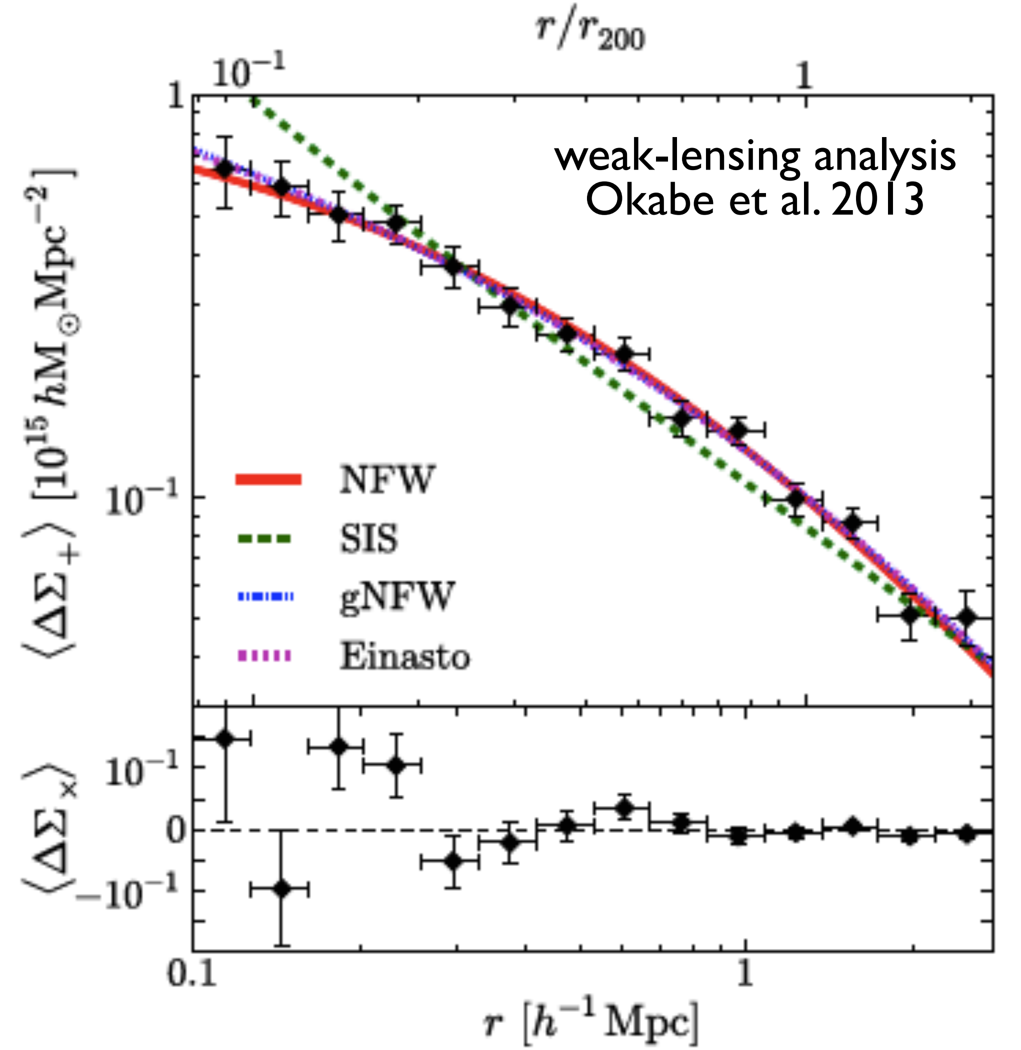
DM-only *N*-body simulations predict cuspy inner density profiles

Mean density profile of rich clusters has the predicted ΛCDM shape!

Observations in dwarf galaxies appear to prefer cores instead!

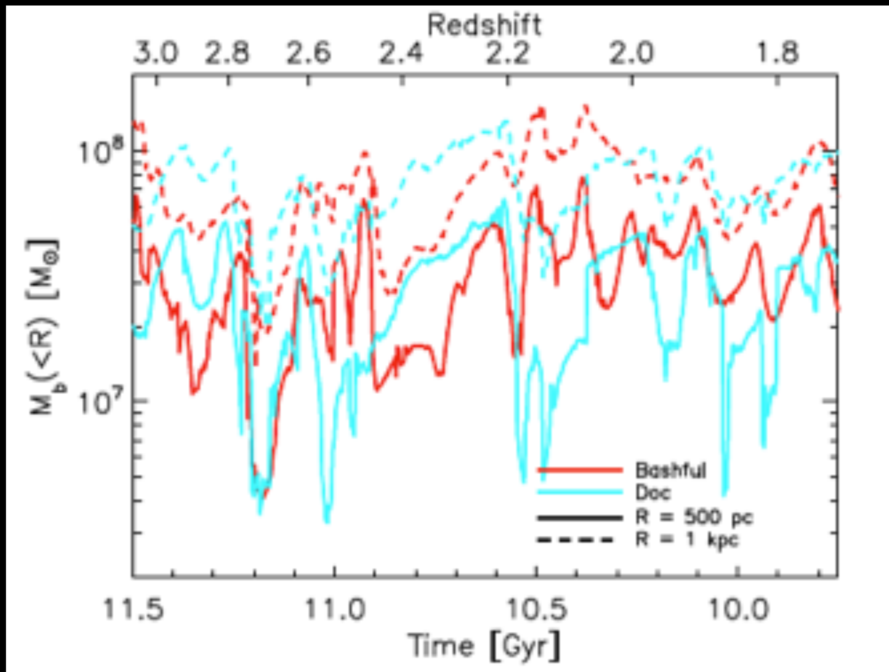
THINGS

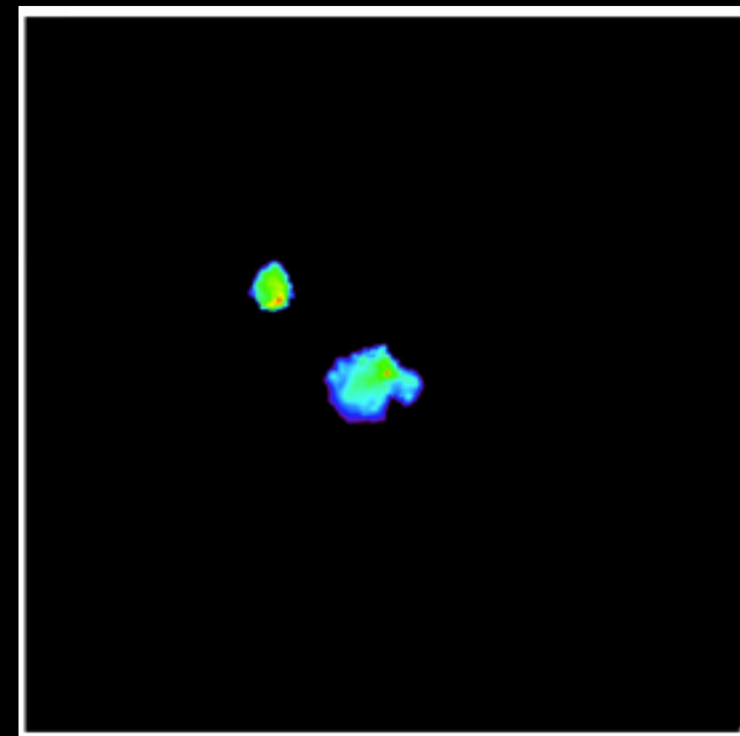


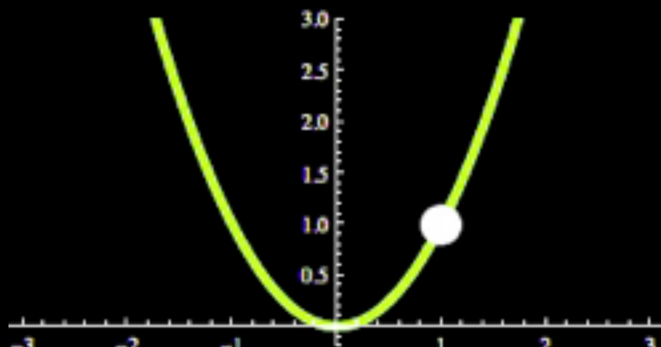


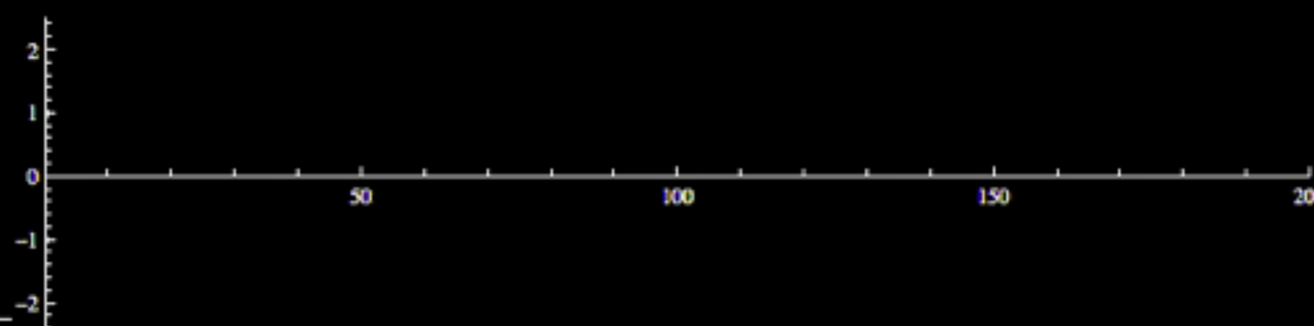
CDM Heats Up

Bursty Star Formation in DGs
➪ Potential Fluctuations









Pontzen & Governato 2012

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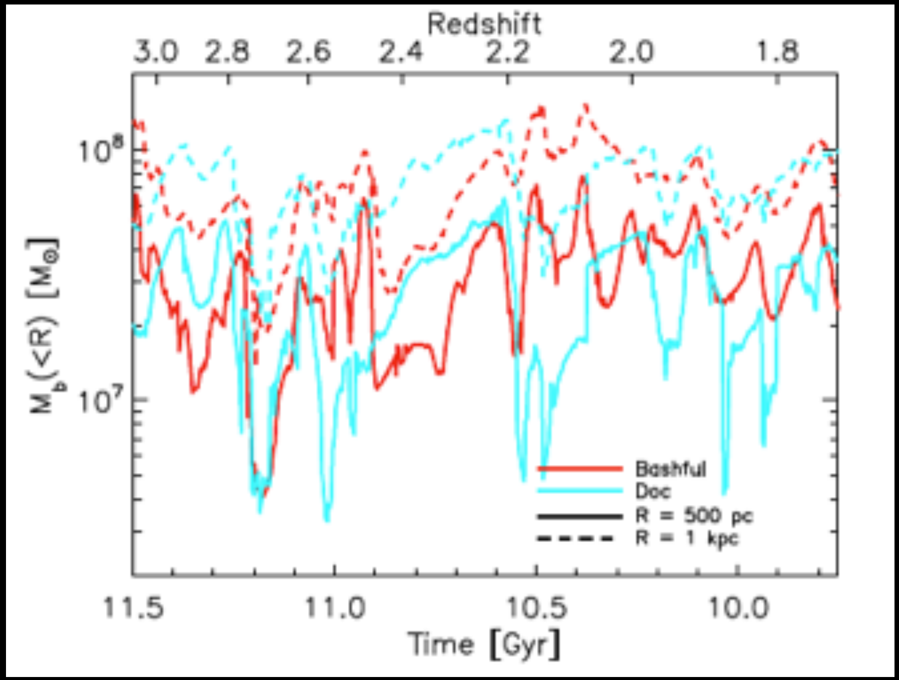

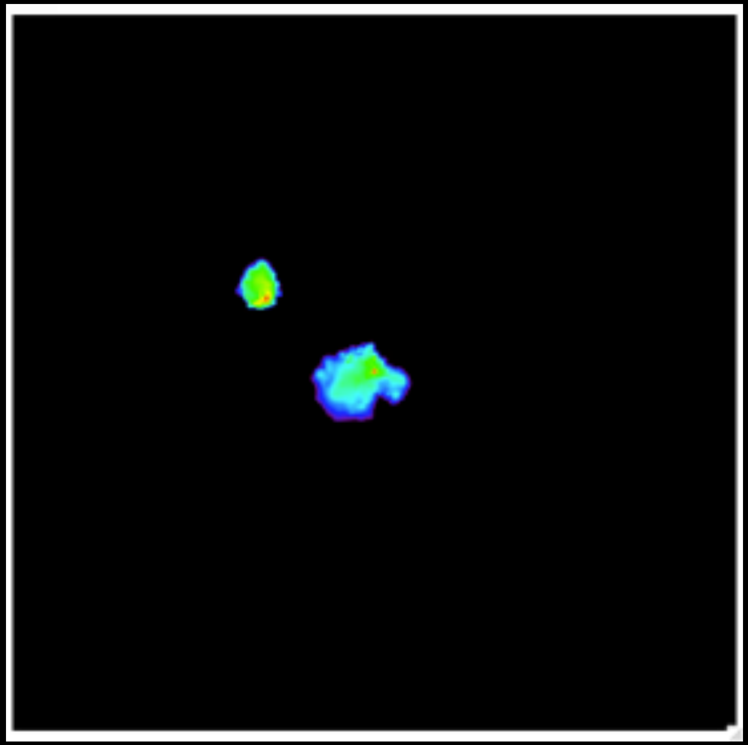

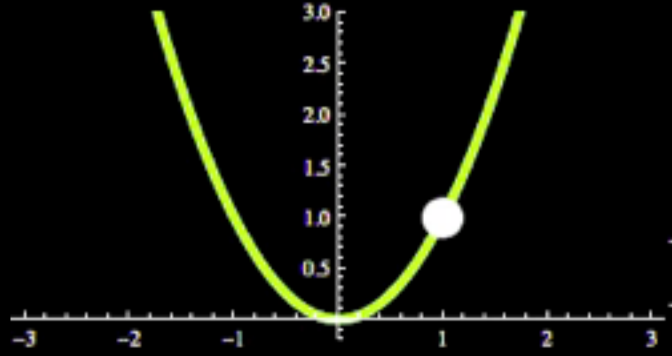

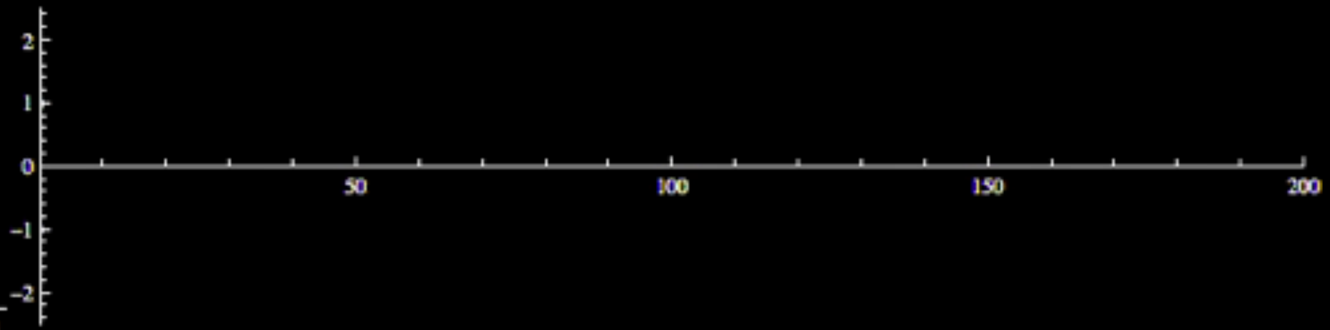

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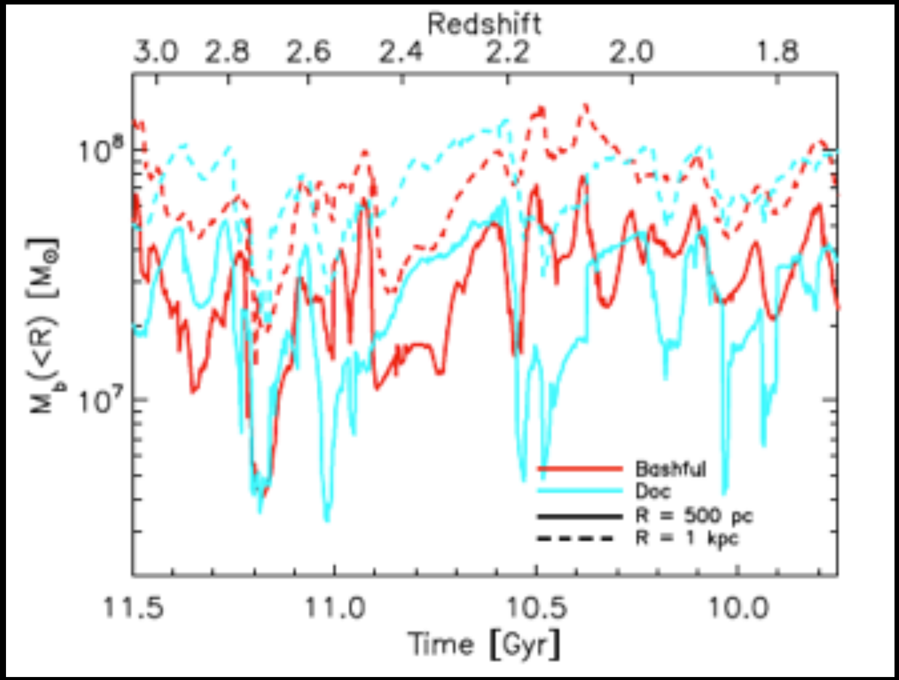

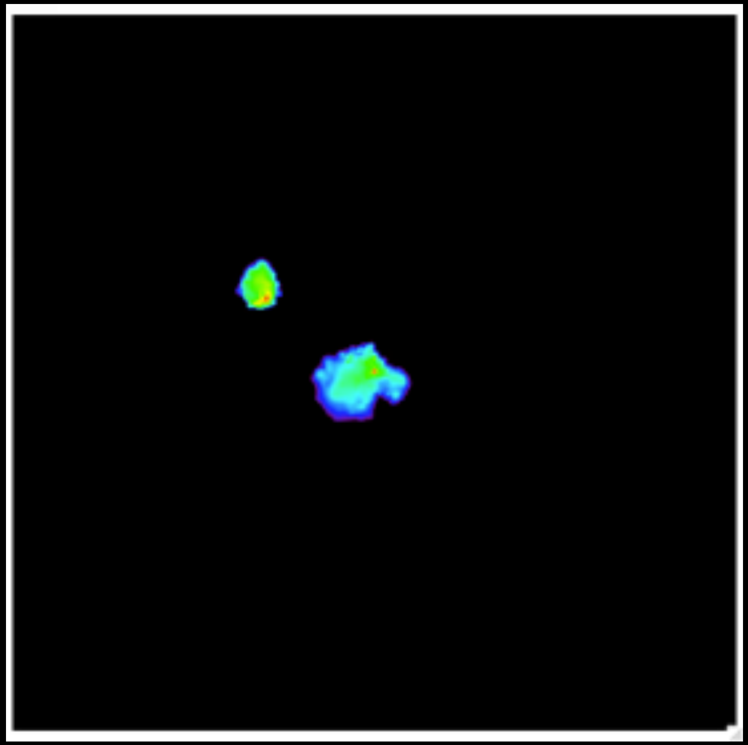

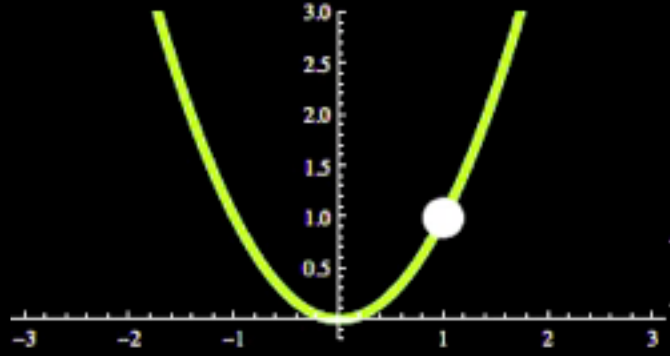

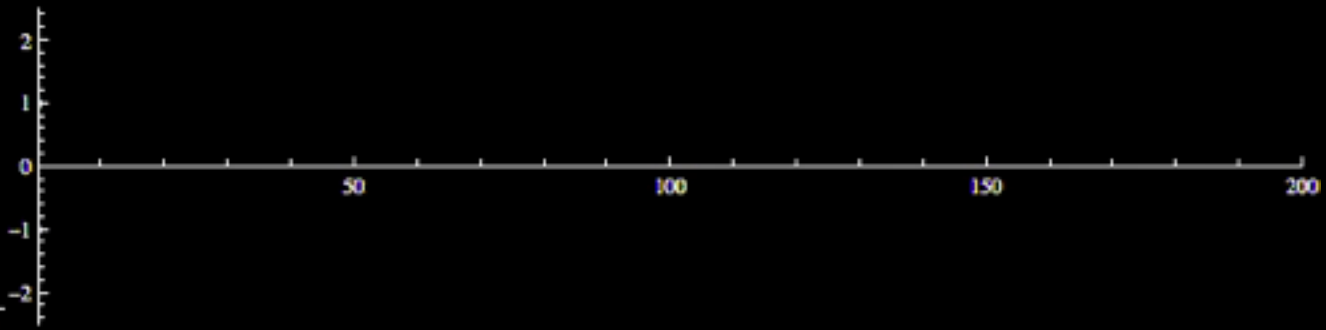

Sudden Blow-out, then Adiabatic Recondensation

Pontzen & Governato 2012

ASTROPHYSICISTS KNOW MUCH, UNDERSTAND SOME

- Evidence that the Universe conforms to the expectations of the ΛCDM model is *compelling but hardly definitive*. Current observational tests span a very wide range of scales, and state-of-the-art simulations are exploring the predictions of the "standard model" with increasingly higher precision.

- In galaxy centres DM densities appear lower than expected. Tensions between CDM predictions and observations may be telling us something about the *fundamental properties of DM* or more likely something about the *complexities of galaxy formation.*

- Emerging evidence may suggest that a *poor understanding of the baryonic processes* involved in galaxy formation may be at the origin of these *small scale controversies* ➪ *on small scales clearly CDM is not enough…..*

- Still no show-stoppers for ΛCDM. More exotic possibilities like WDM/SIDM may still be viable, but require careful tuning and do not provide any silver bullet. Over the next decade, *gravitational lensing* may provide important evidence for CDM substructure.