Connecting the Dark and Light Side of Galaxy Formation

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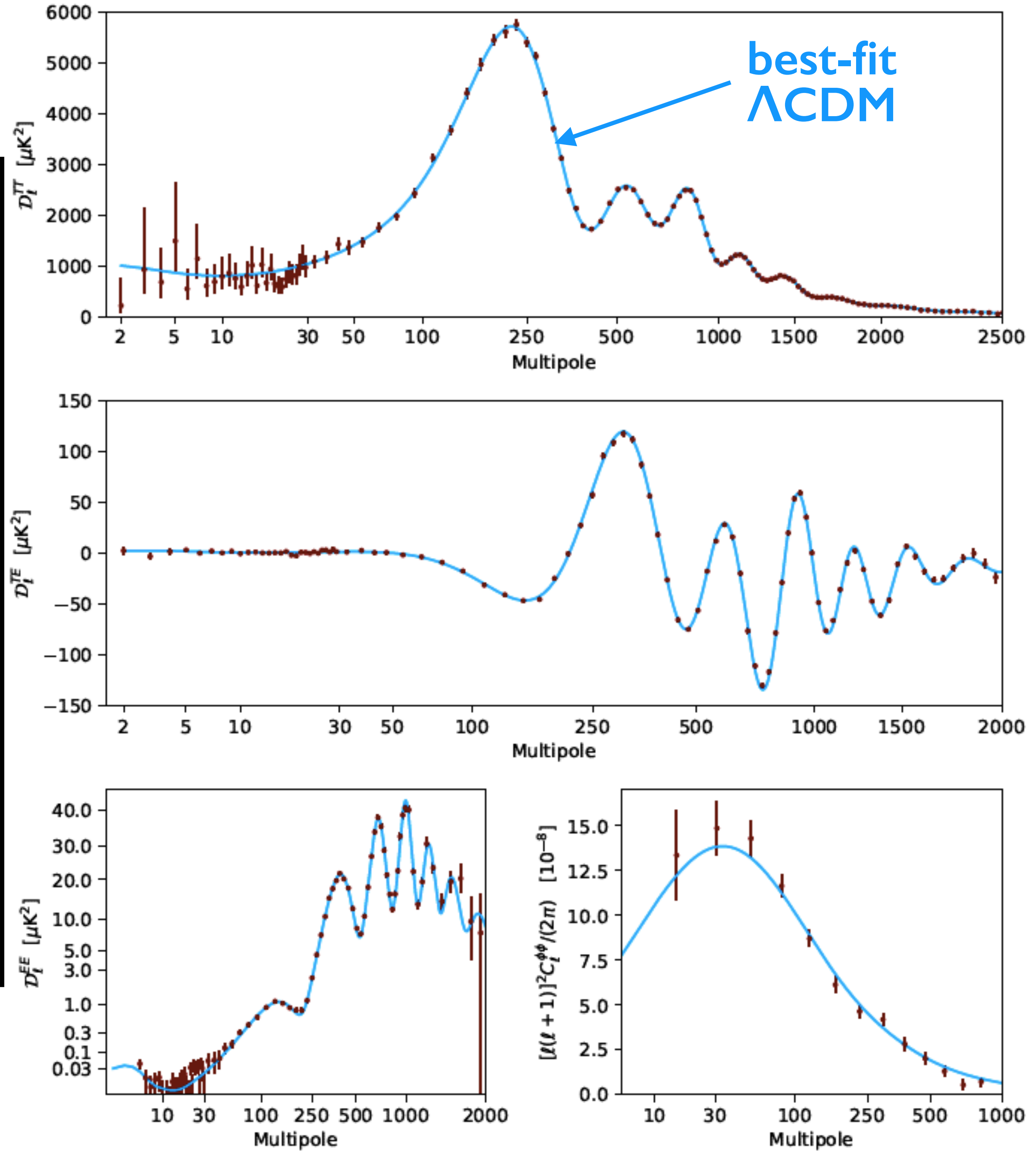
FROM QUANTUM FOAM TO GALAXIES

Galaxies are the building blocks of our Universe and *Galaxy Formation* is about nothing less than the 14 Gyr evolution of such fundamental units as a result of small density fluctuations present in the aftermath of the Big Bang. *Galaxy Formation* is also about understanding the mapping between *dark matter halos* and their *baryonic luminous* components.

Galaxies are molded by *highly non-linear processes* at work from the *small* scales of star formation and accretion onto massive black holes *(where baryons dominate)* up to the *large* scales of the *cosmic web (the realm of non-baryonic dark matter)*. It is this special property that makes them so fascinating and so challenging to study, both observationally and theoretically.

A Nearly Perfect Universe

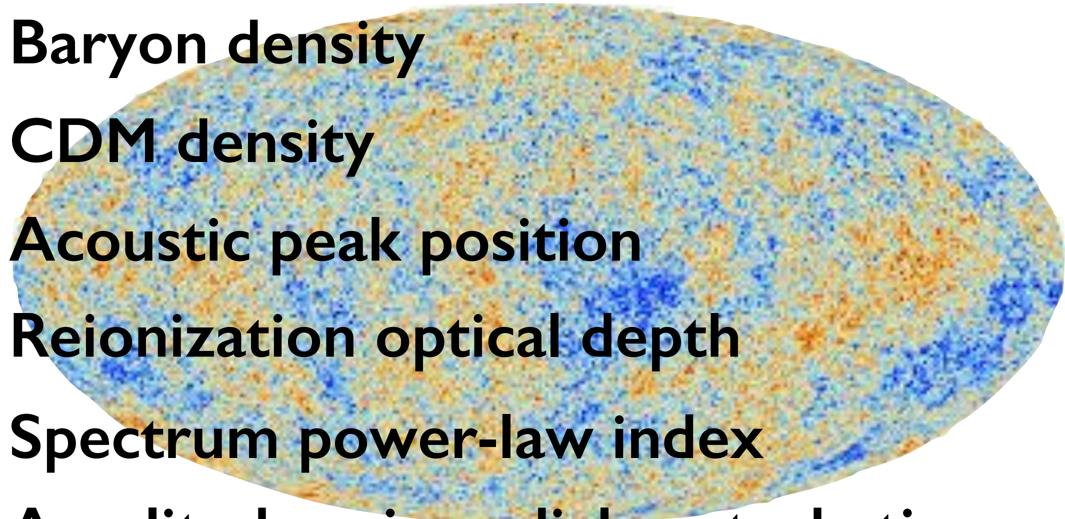
Planck CMB angular power spectra for *temperature* (top), the *temperature-polarization* cross-spectrum (middle), the *E*-mode of *polarization* (bottom left) and the *lensing potential* (bottom right). Within ΛCDM these spectra contain most of the cosmological information available from *Planck*, and the blue lines show the best-fitting ΛCDM model.



Just Six Numbers (Flat ΛCDM)

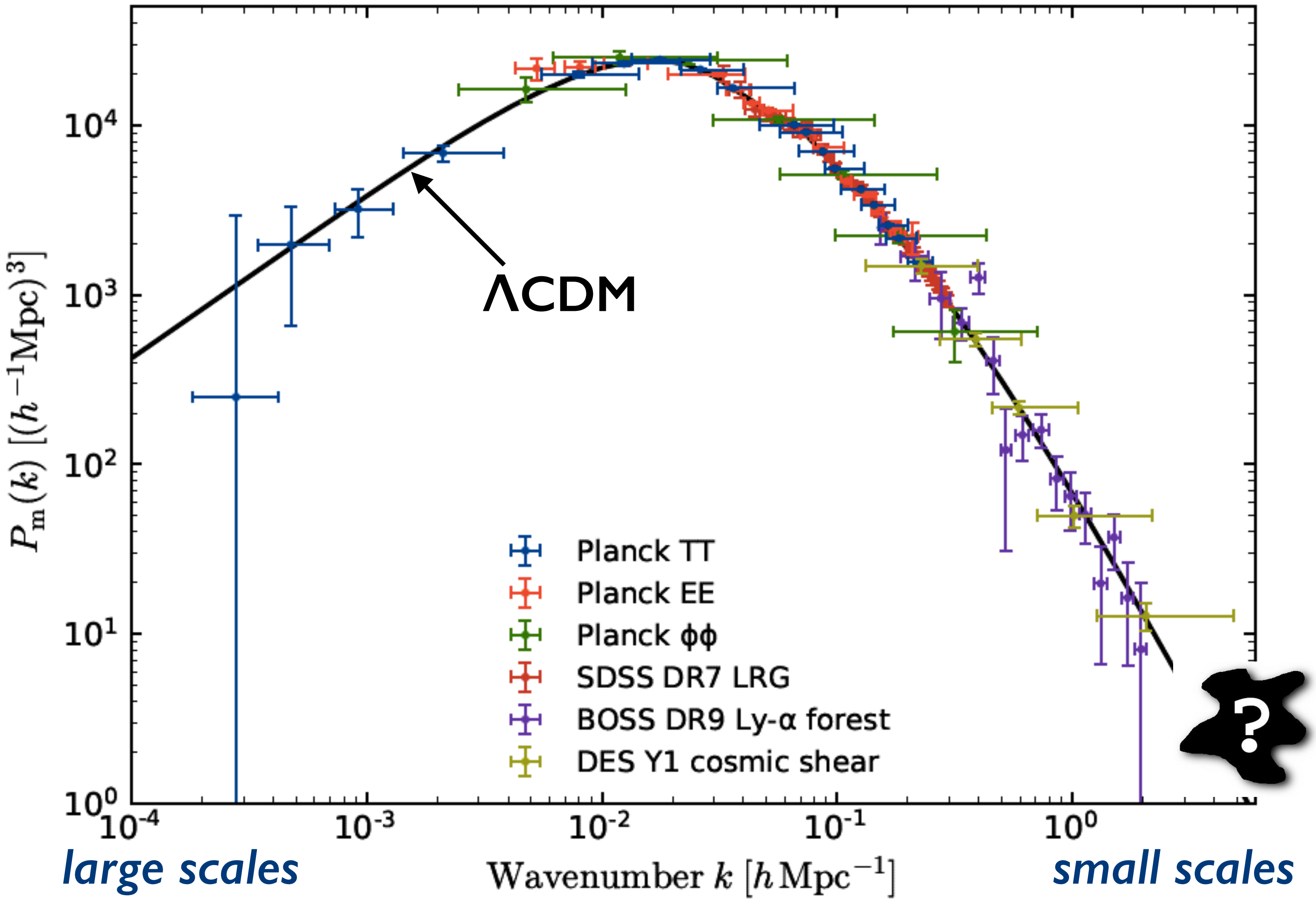
Planck final full-mission

$\Omega_b h^2$	$= 0.0223 \pm 0.0001$	Baryon density
$\Omega_c h^2$	$= 0.120 \pm 0.001$	CDM density
$100\theta_*$	$= 1.0401 \pm 0.0003$	Acoustic peak position
τ	$= 0.054 \pm 0.007$	Reionization optical depth
n_s	$= 0.965 \pm 0.004$	Spectrum power-law index
$\ln(10^{10} A_s)$	$= 3.043 \pm 0.014$	Amplitude primordial perturbations



A 220σ measurement of the cosmic baryon density and a *120σ* detection of non-baryonic DM ☛ DM *is 5.4 times more abundant than ordinary matter!*

Density Fluctuation Data Agree with ΛCDM



The (linear theory) matter power spectrum (at $z = 0$) inferred from different *cosmological probes*. The agreement of the model with a disparate compilation of data, spanning 14 Gyr in time and > 3 decades in scale, is an impressive testament to the *explanatory power* of CDM.

The Universe in a Box: *N*-Body Simulations

- *N*-body simulations have routinely been used to study the growth of nonlinear structure in an expanding Universe, and the size of feasible calculations has increased rapidly.

- Assume all Ω_M is in cold particles that interacts only gravitationally, and sample it with $N \sim 10^9 - 10^{10}$ particles.

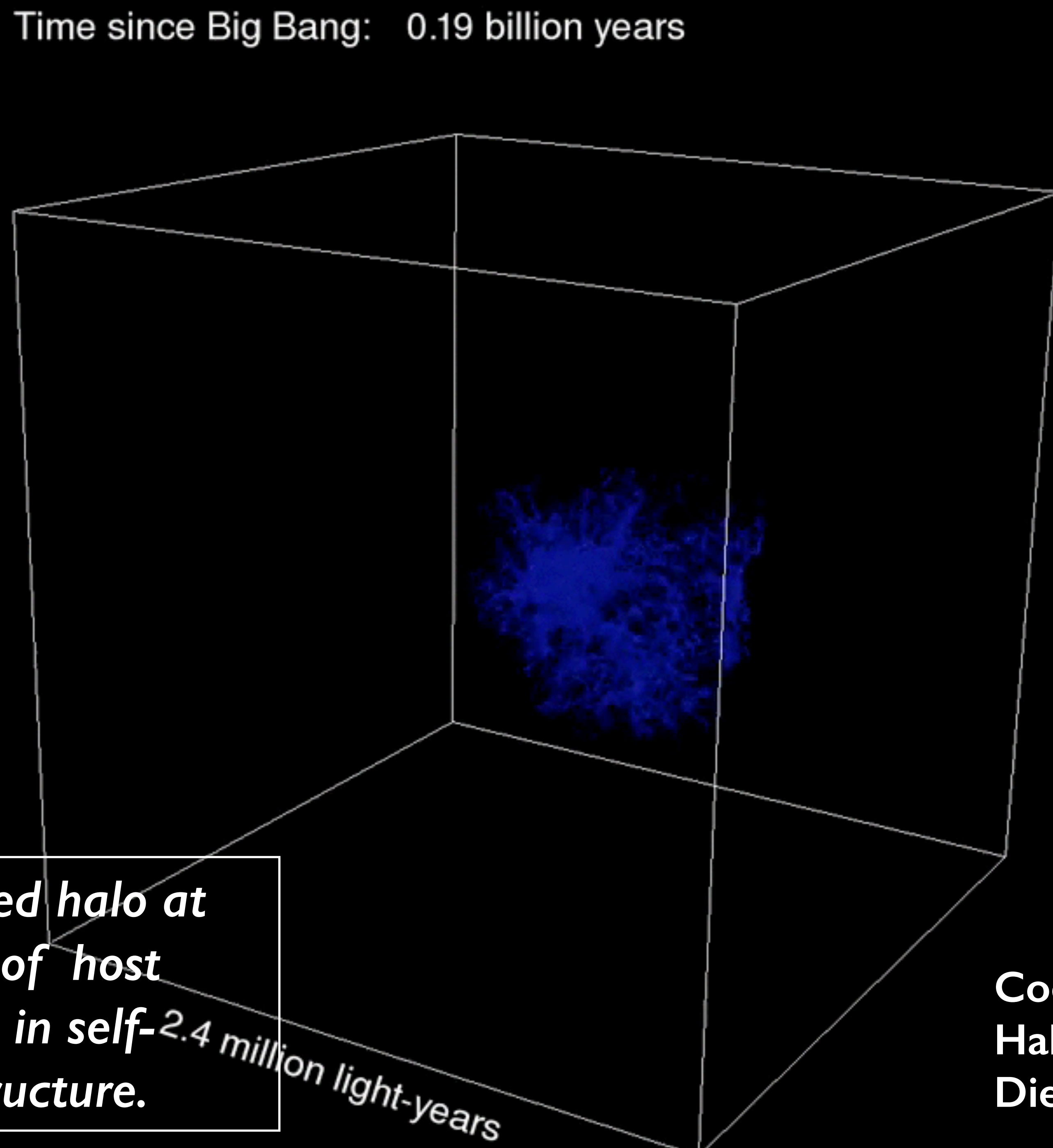
- Bad approximation in the center of a massive galaxy where baryons dominate, but okay in galaxy halos and faint dwarfs ($M/L \lesssim 1000$).

- Simple physics (just gravity) & good CPU scaling ⇨ high spatial and temporal resolution.

- There is no minimum scale for the gravitational aggregation of collisionless CDM ⇨ no free parameters.

⇨ Accurate solution to an idealized problem!

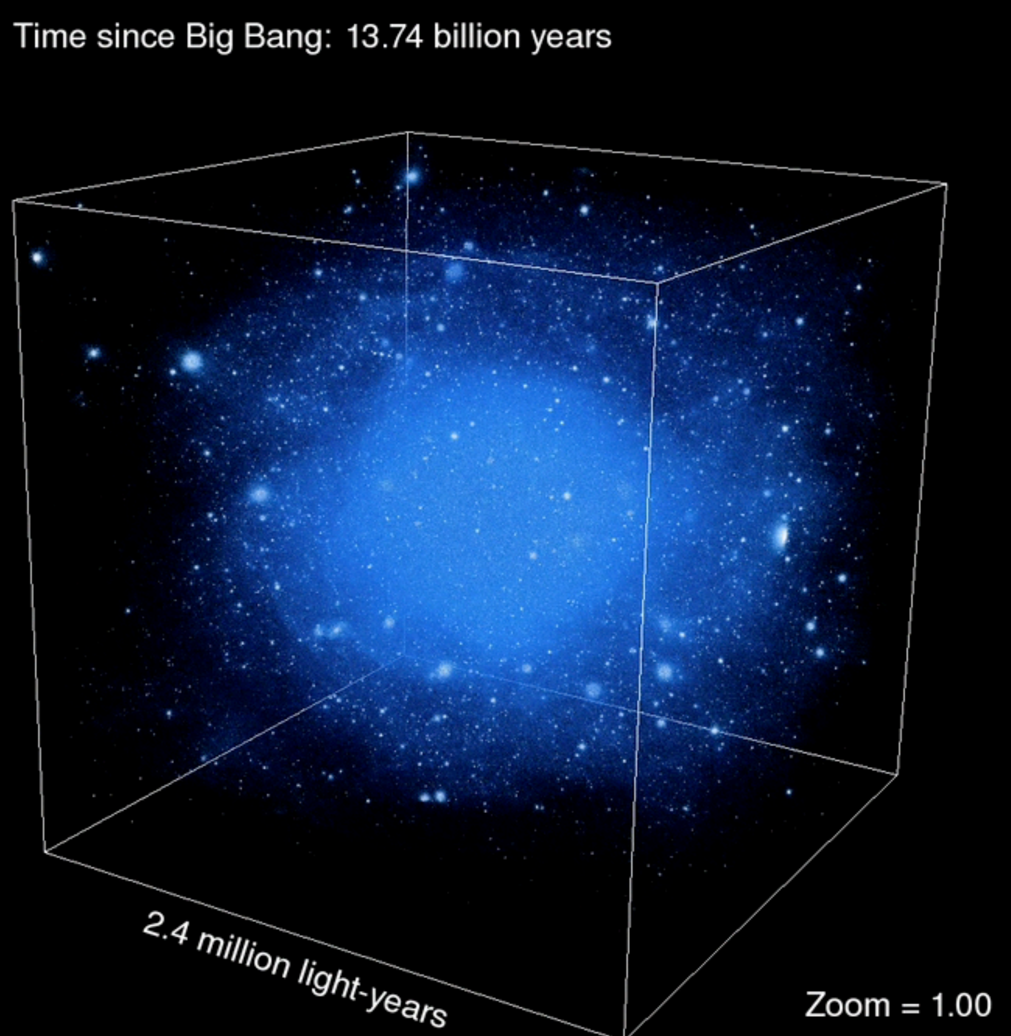
Substructure: A Unique Prediction of ΛCDM

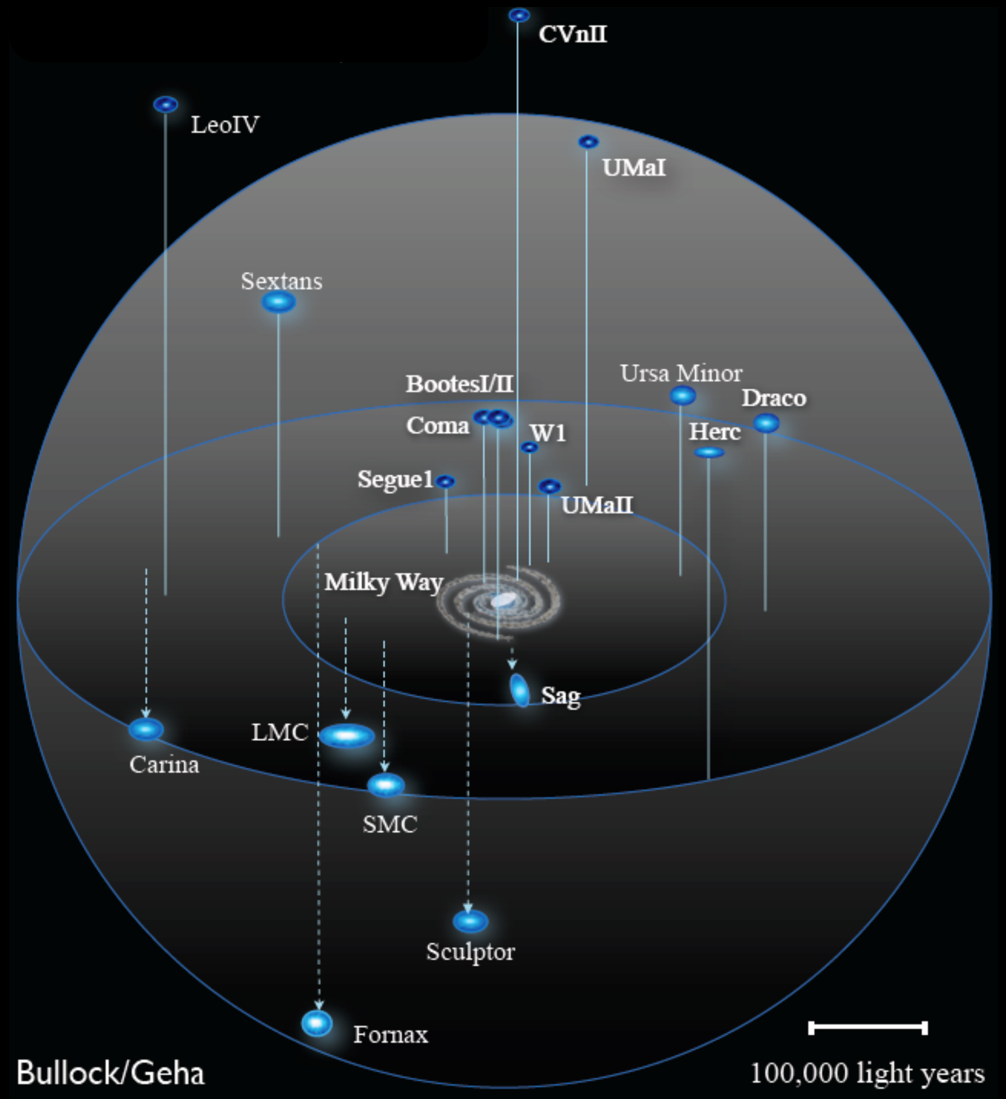


In a MW-sized halo at z=0: 5-10% of host mass locked in self-bound substructure.

Code: PKDGRAV2
Halo: VIA LACTEA II
Diemand et al. 2008

Missing Satellites Problem

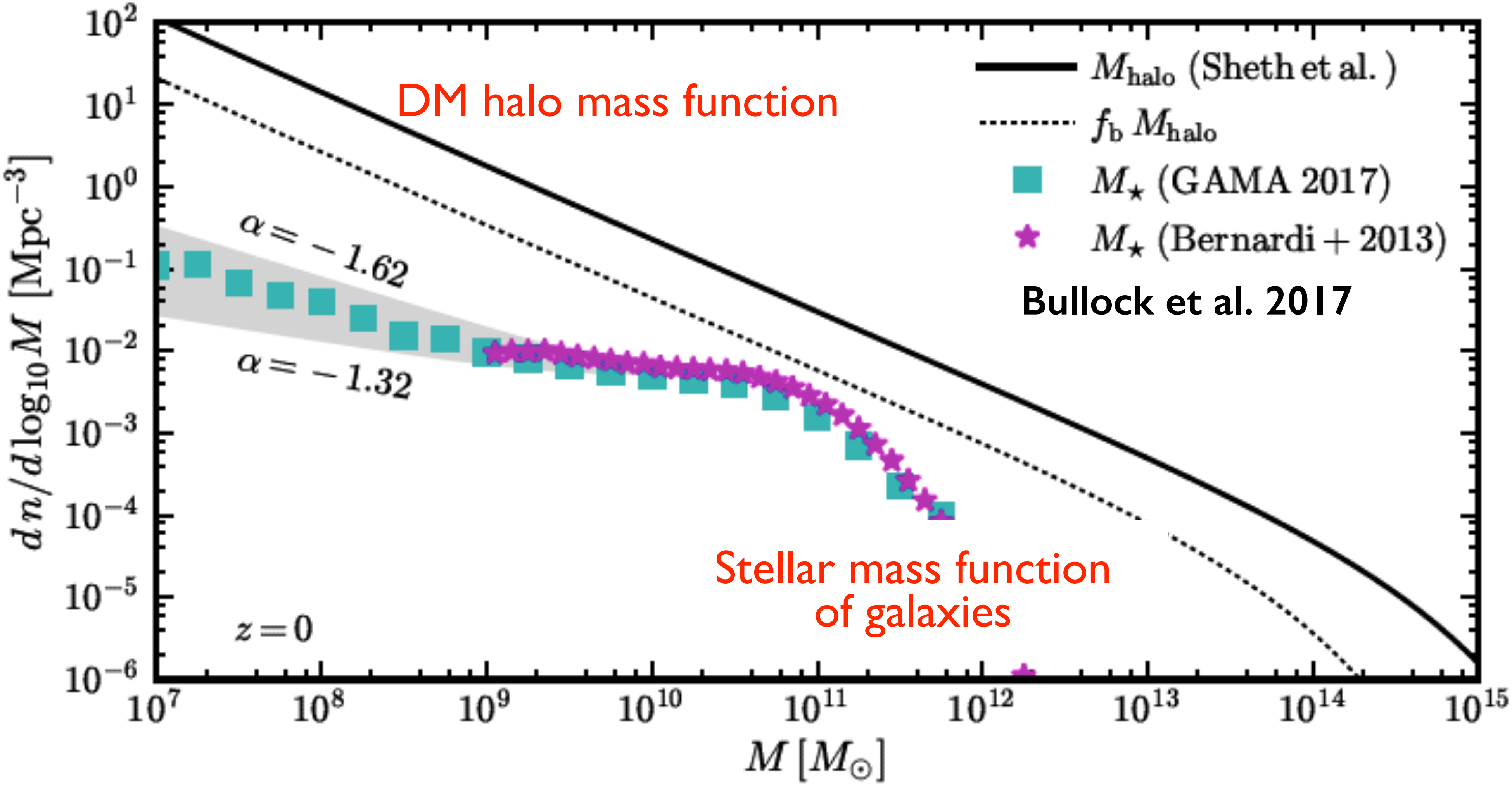




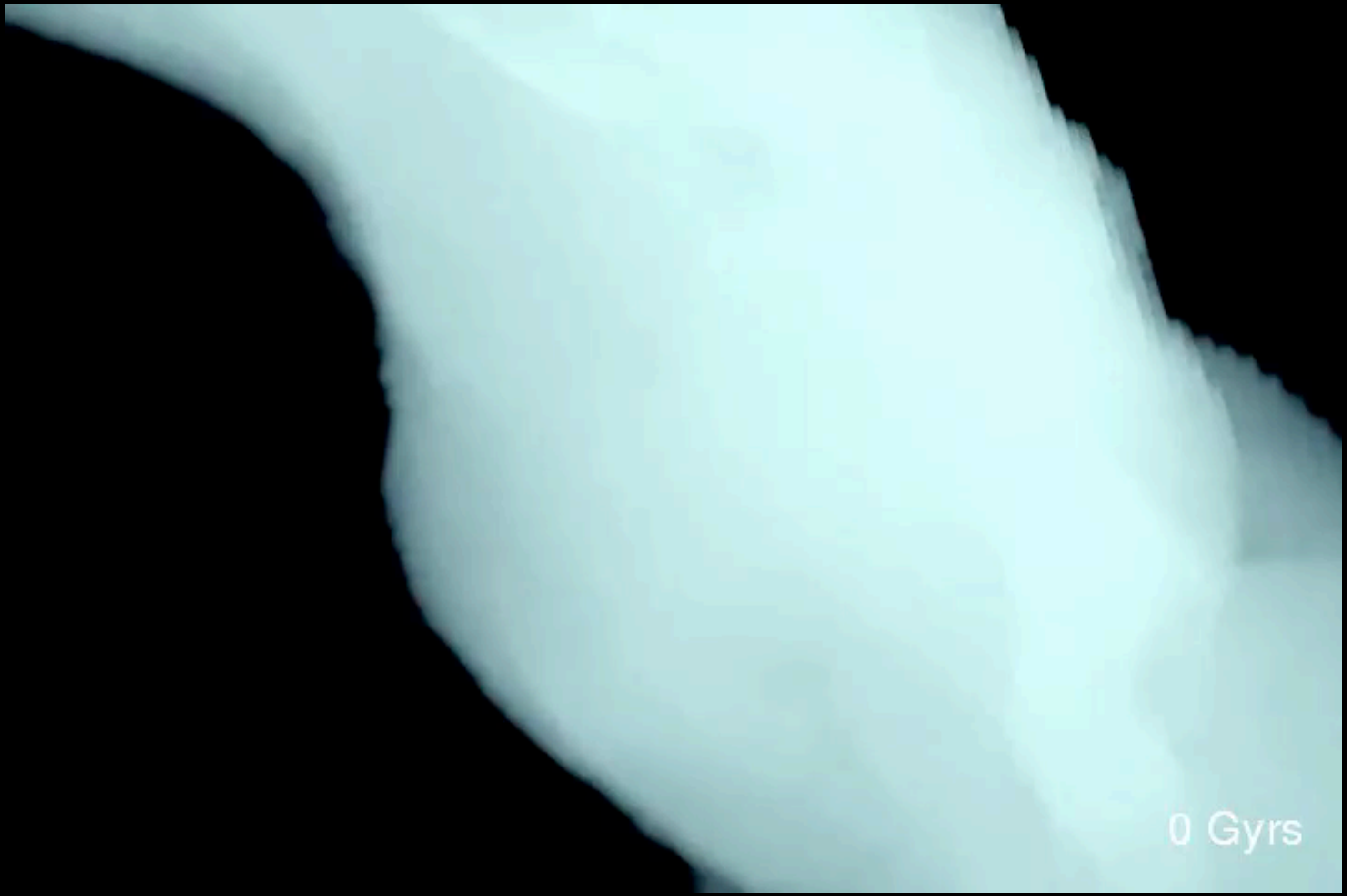
Far fewer faint satellites observed around the Milky Way than DM clumps found in *N*-body sims: is this a puzzle of galaxy formation/SF physics or a contradiction of CDM?

Possible solutions to the MSP: *1) blame baryonic physics*

A Basic Mismatch in Shape

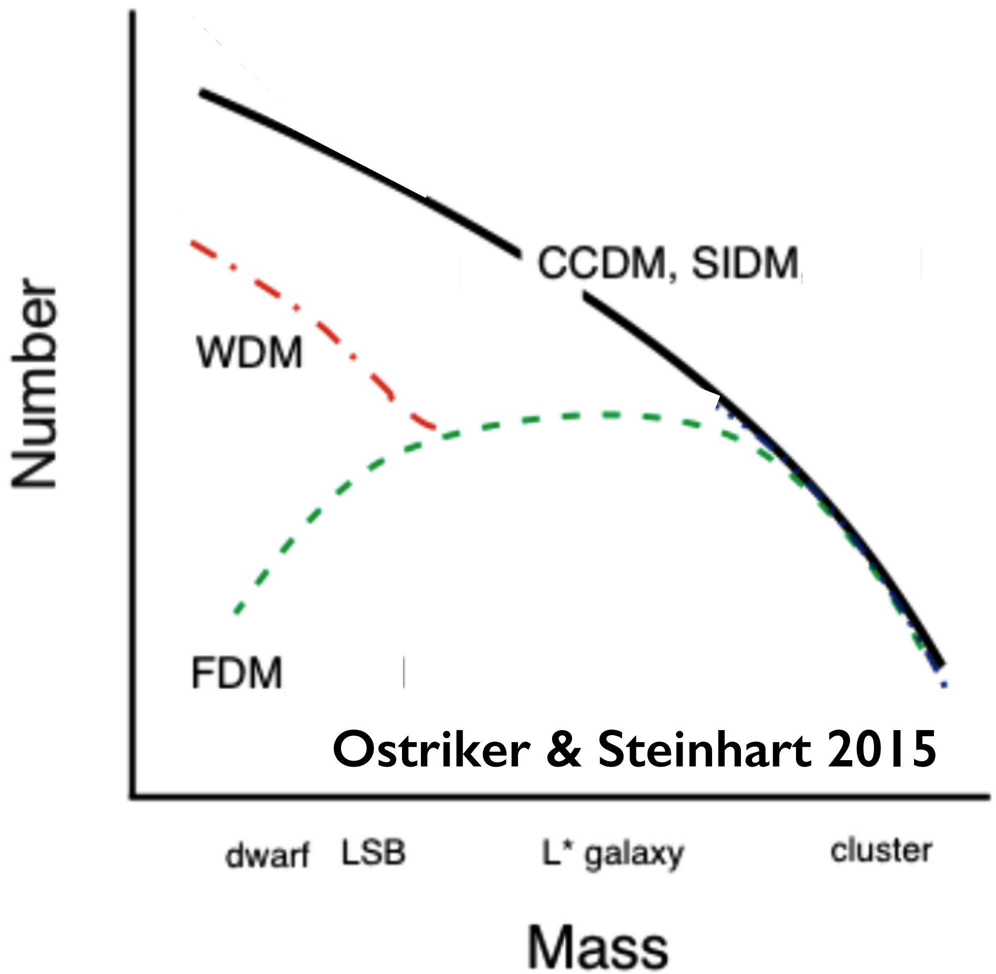


A new generation of cosmological hydrodynamic simulations, with sufficient resolution/physics to model gas cooling, star formation, and the impact of SN-driven winds, have shown that efficient stellar feedback can quench star formation in shallow potential wells.



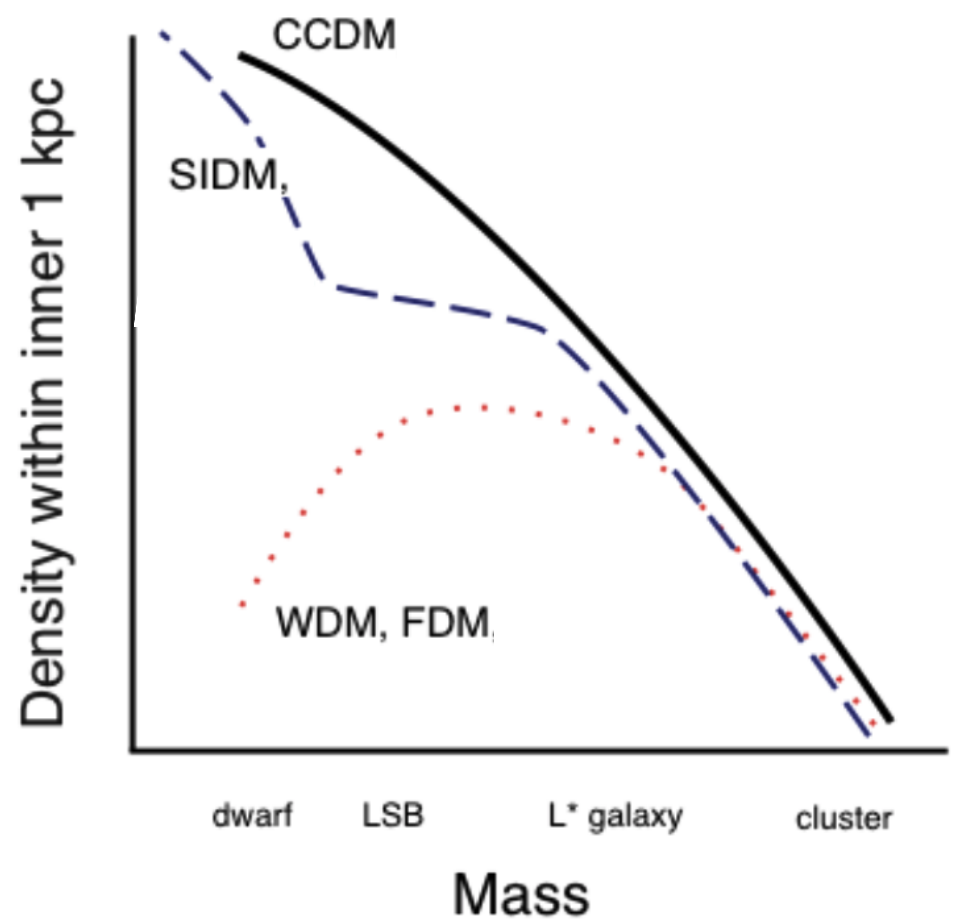
Governato et al. (2010)

Possible solutions to the MSP: *2) blame C(C)DM*



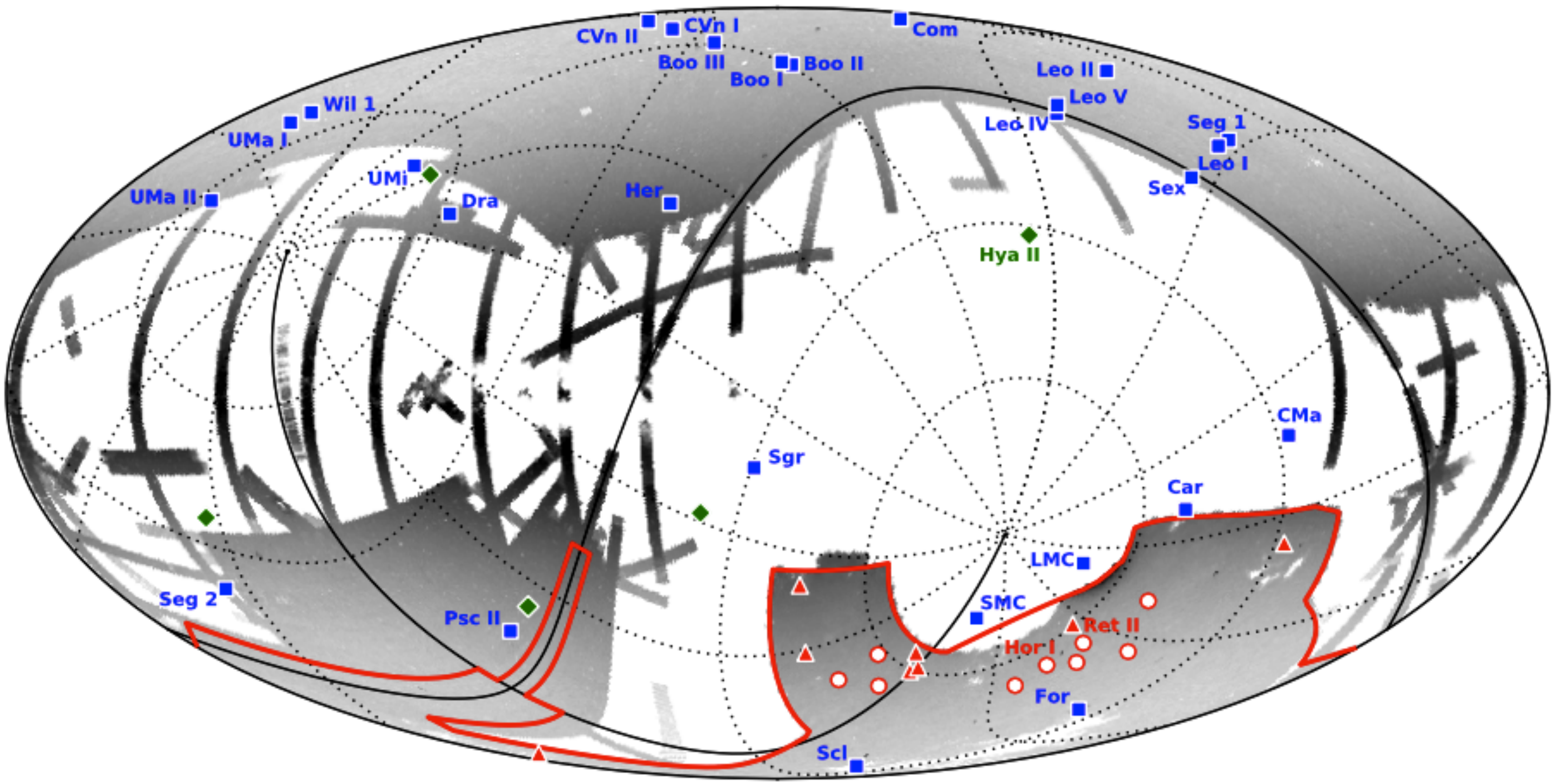
Internal structure: how the density density of the inner one kpc depends on the mass of the system for different dark matter models.

Demography: how the number of objects of a given type depends on their mass (as observed today) for different DM models.



Possible solutions to the MSP: *3) blame observations!*

Blue = Known prior to 2015
Red triangles = DES Y2Q1 candidates
Red circles = DES Y1A1 candidates
Green = Other new candidates



If 1)+3) are correct ⇨ galaxy CDM halos must be very lumpy!

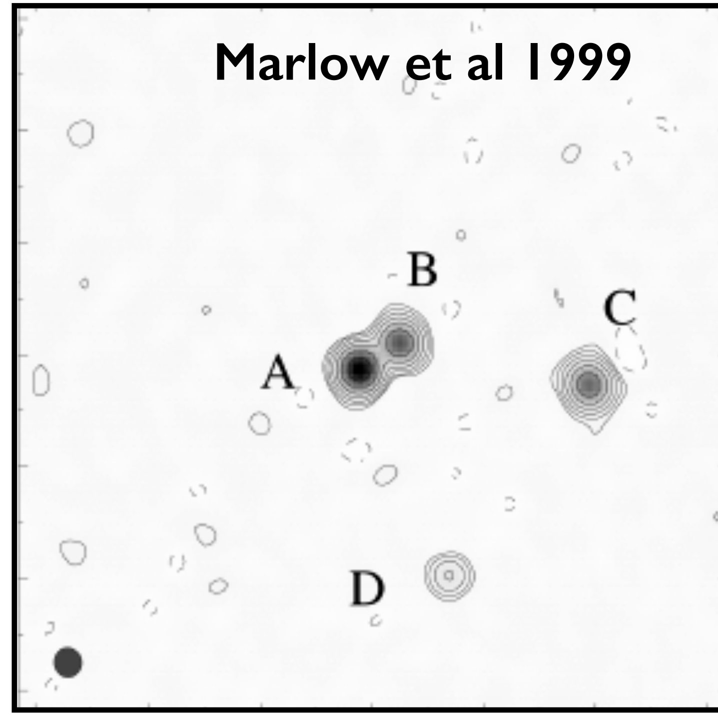
Gravitational Lensing

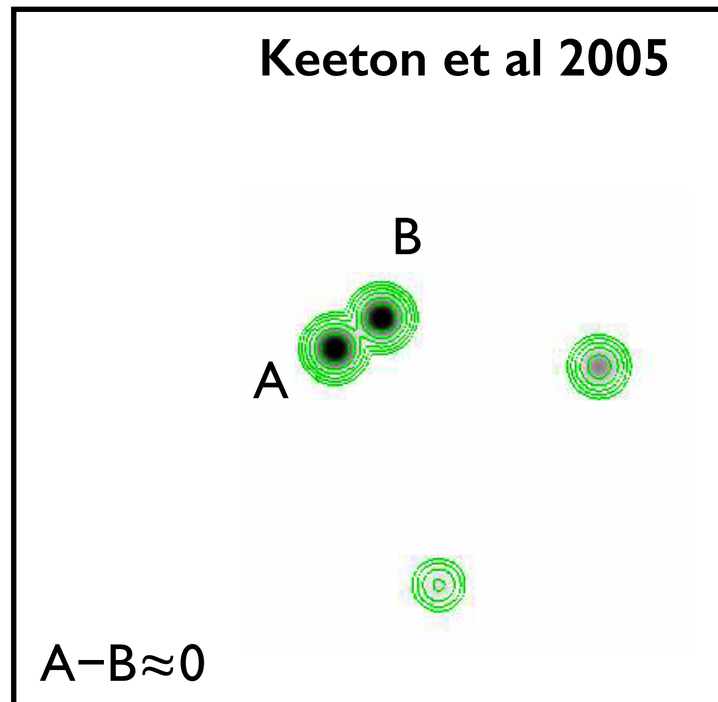
The effect of a gravitational field is to delay the part of the light wavefront that passes through it.

In the case in which multiple images form, the position of images depend on the *first derivative* of the potential, while the magnification or fluxes of the images depend on the *second derivative* of the potential.

Observations of gravitationally lensed QSOs show *flux anomalies* (compared to expectations from a *simple smooth mass profile* for the intervening lens) in the relative magnifications of the multiple images.

CLASS B1555+375

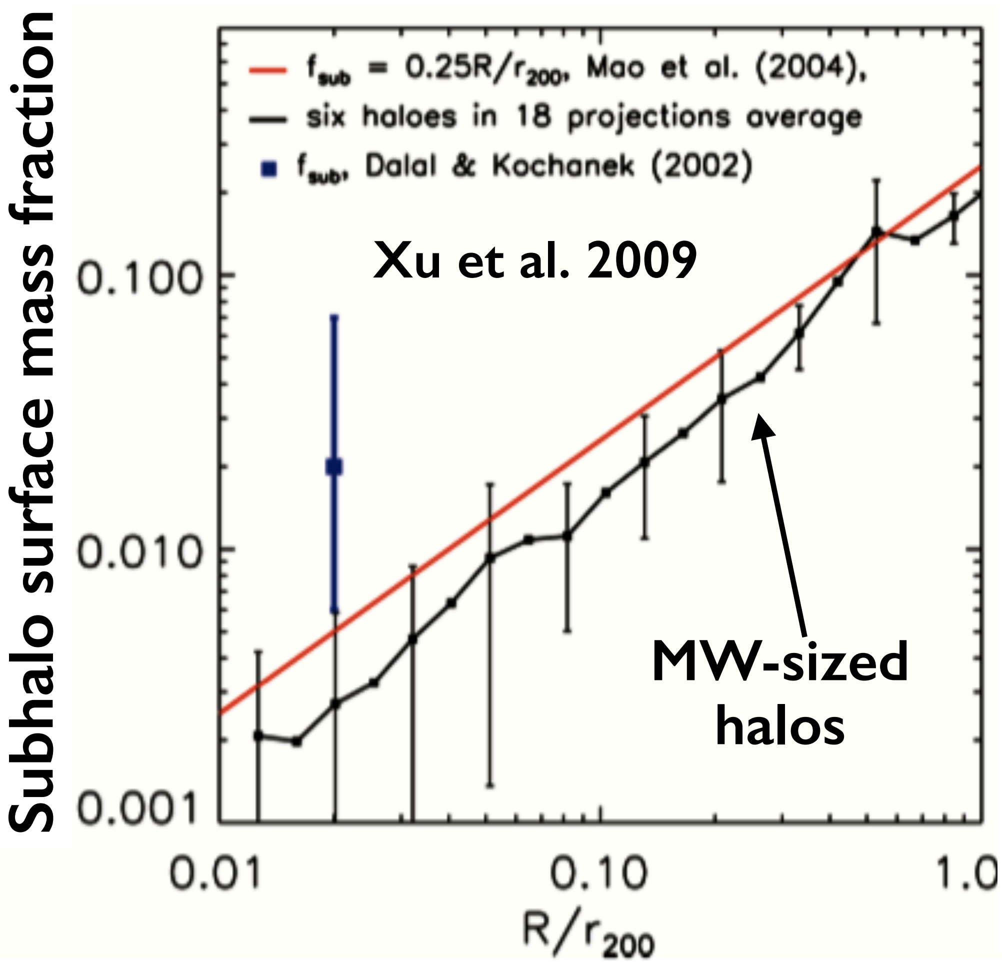


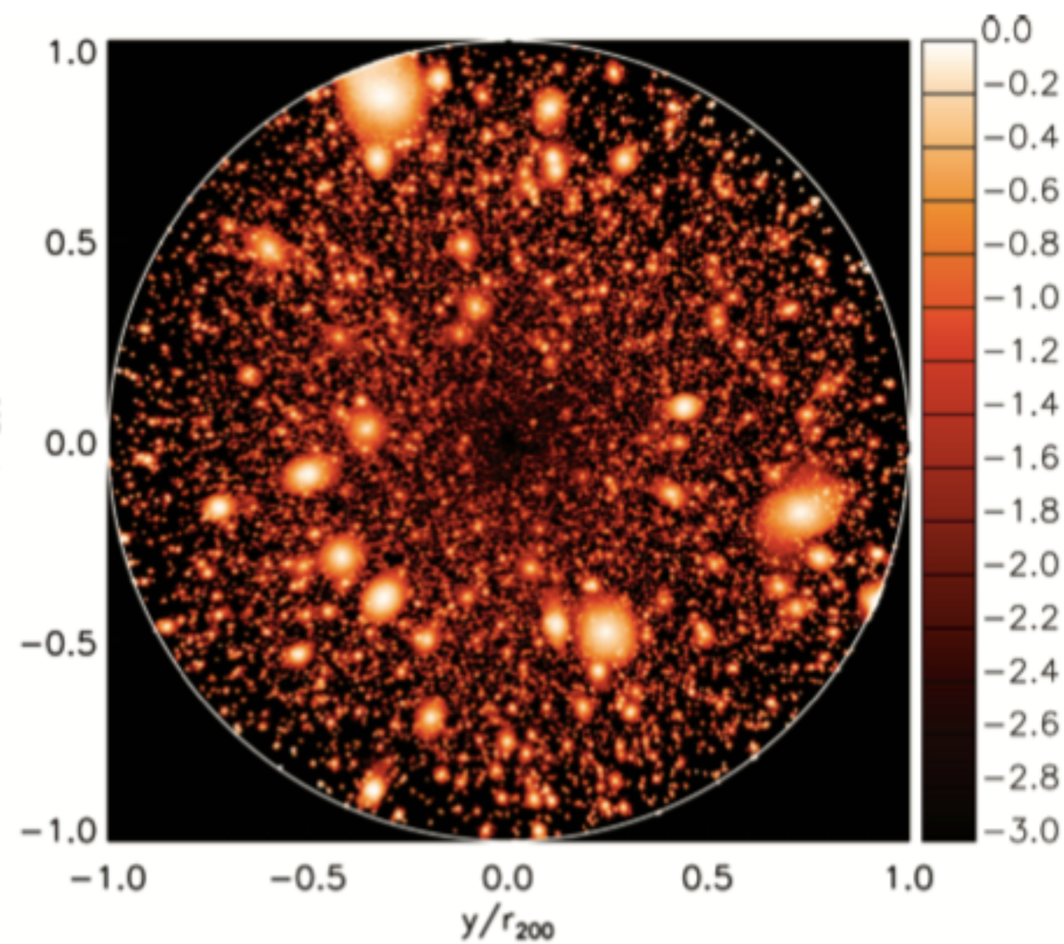


Metcalfe & Madau (2001): Potential perturbations by *DM substructure* can be responsible for the observed flux anomalies! (cf. **Mao & Schneider 1998**)

Dalal & Kochanek (2002): Seven four-image radio lenses ☛ f_{sub} *(annuli around Einstein radius)* ~ *0.02* *(0.006 < f_{sub} < 0.07, 90% CL)*.

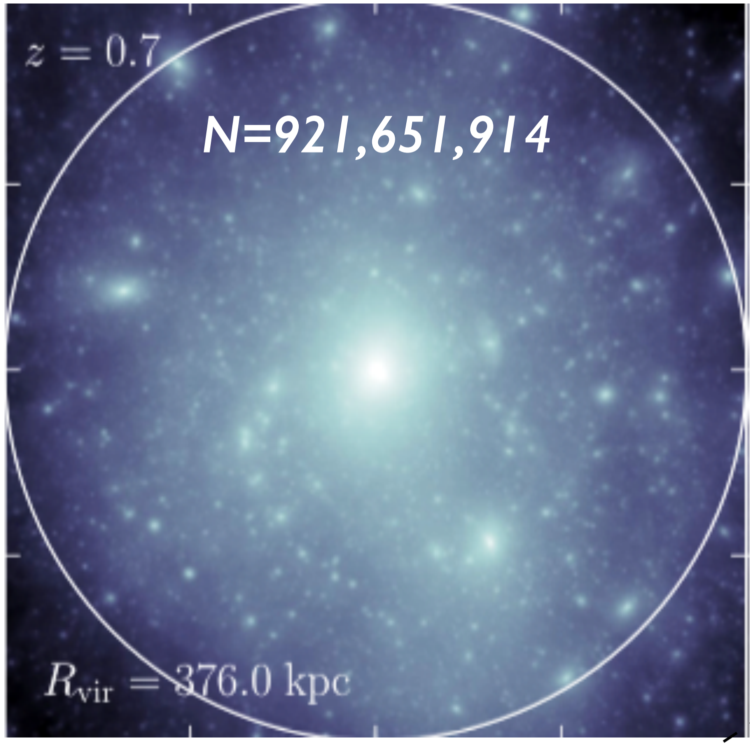
Not enough substructure in MW-sized halos at *z=0*…

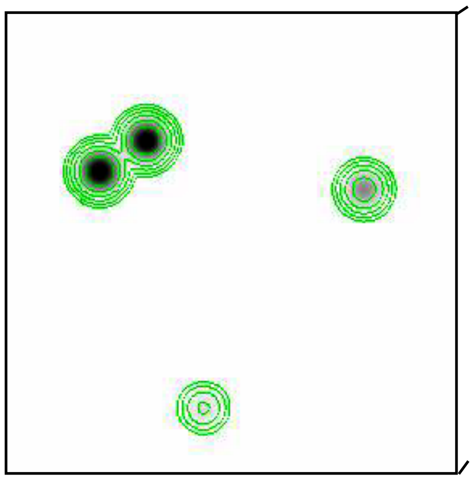


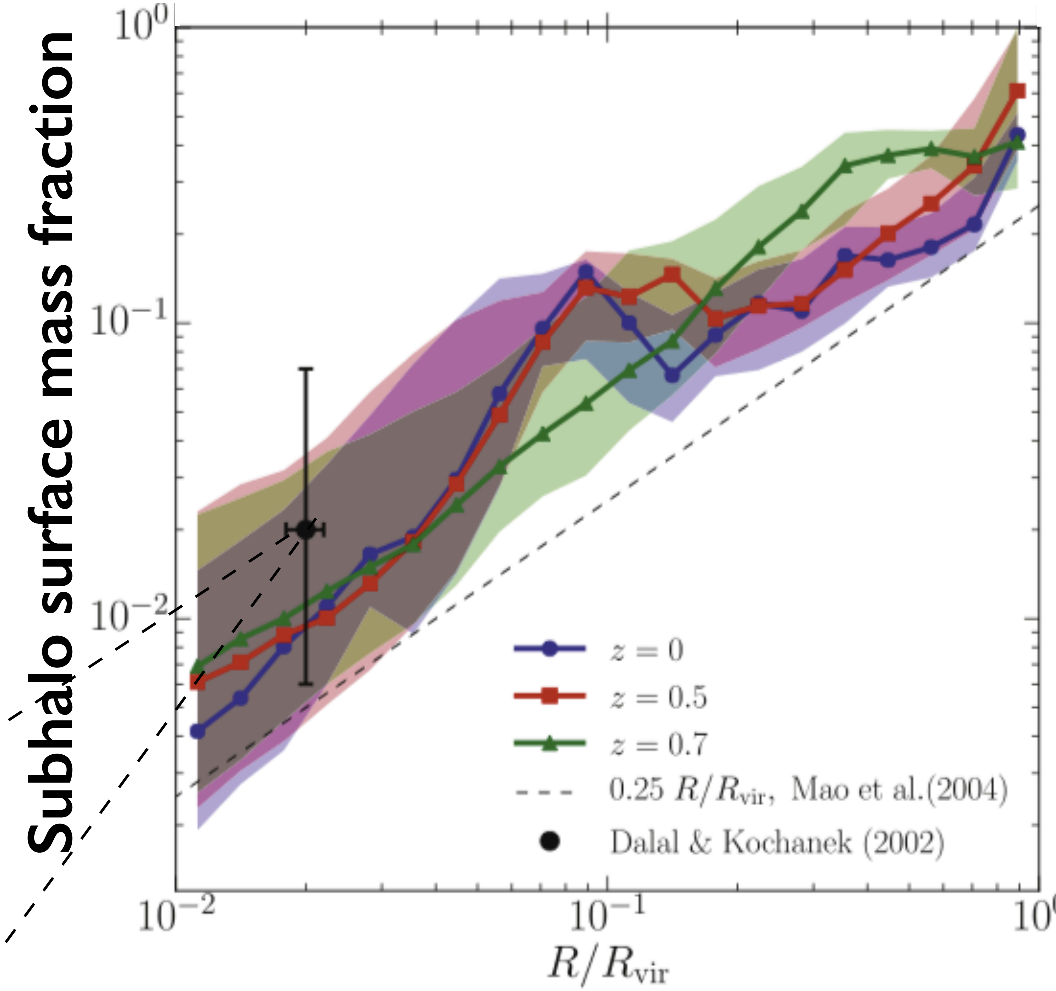


…but the right amount in E-size halos at $z=0.5$!

Fiacconi et al. 2016



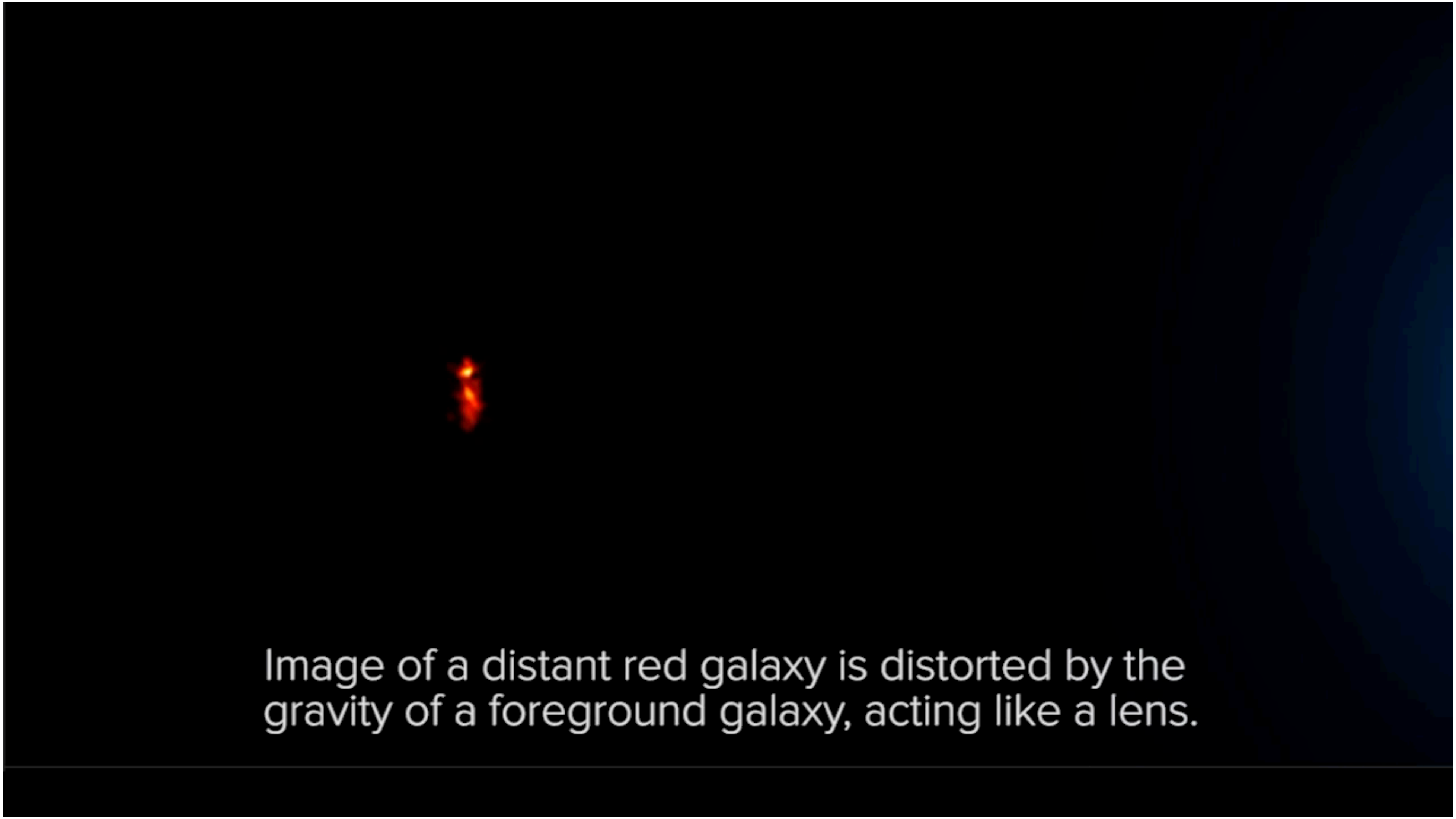




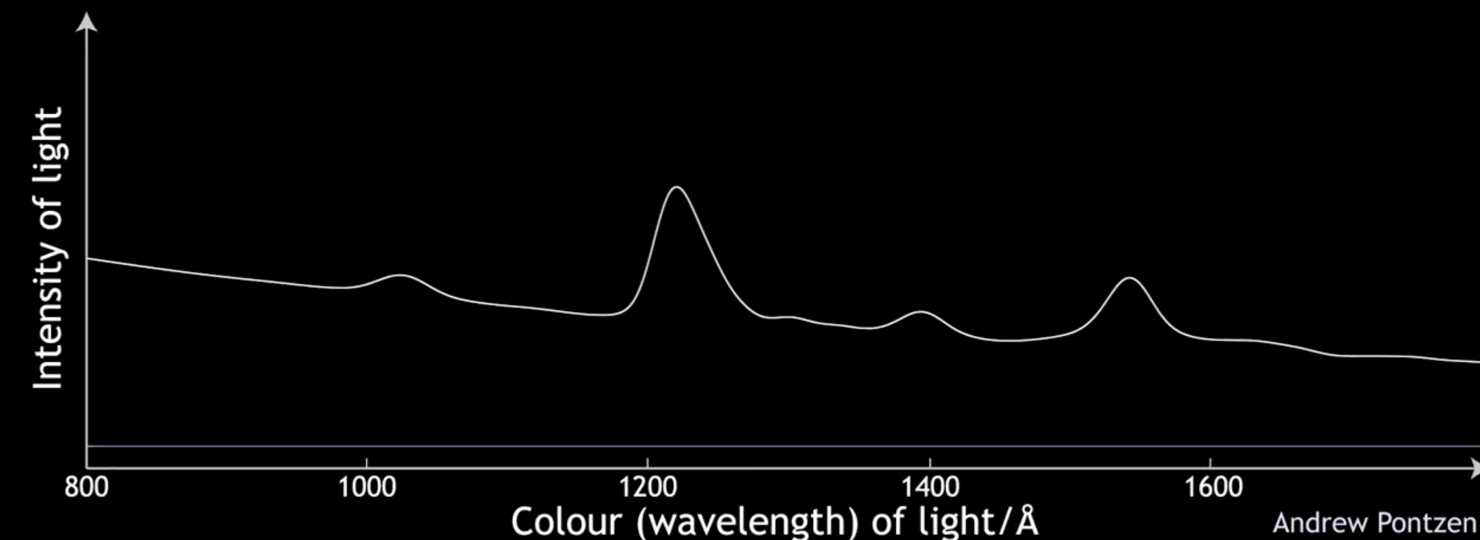
Predicted substructure surface mass fraction in azimuthal annuli vs projected radius R. The solid lines depict the median over 300 random projections, the colored bands mark the 68% scatter.

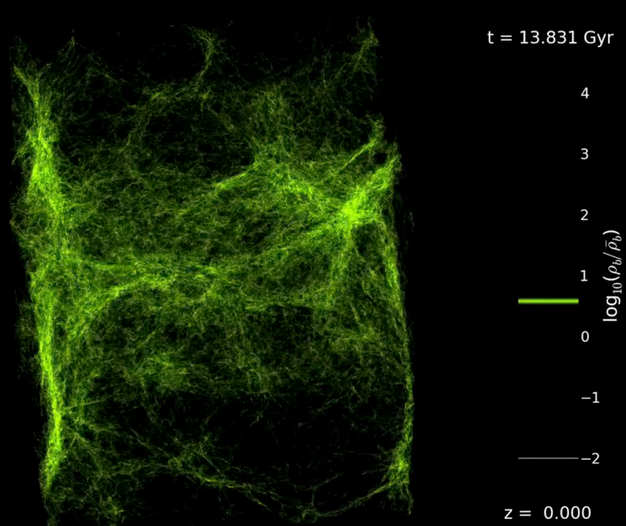
There are complications: baryonic effects, line-of-sight halos, ability to distinguish between CDM and WDM, small number of lenses, etc….

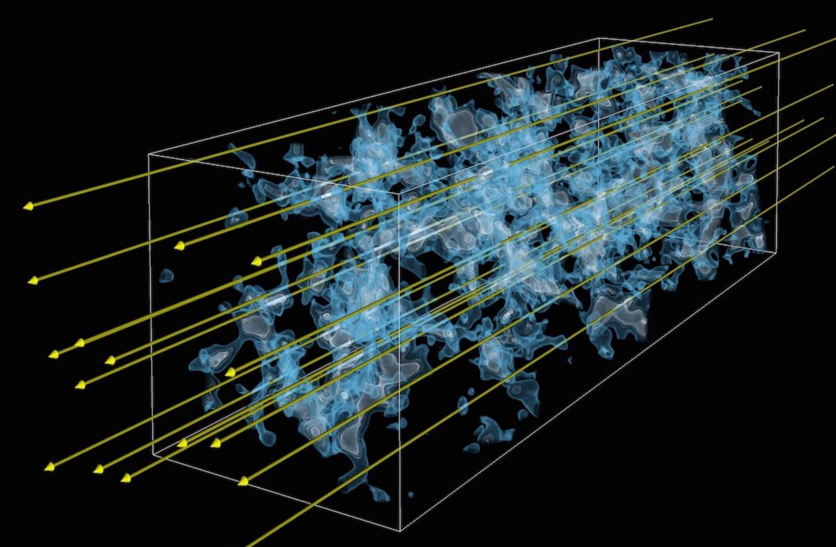
ALMA Detection of Lensing Substructure

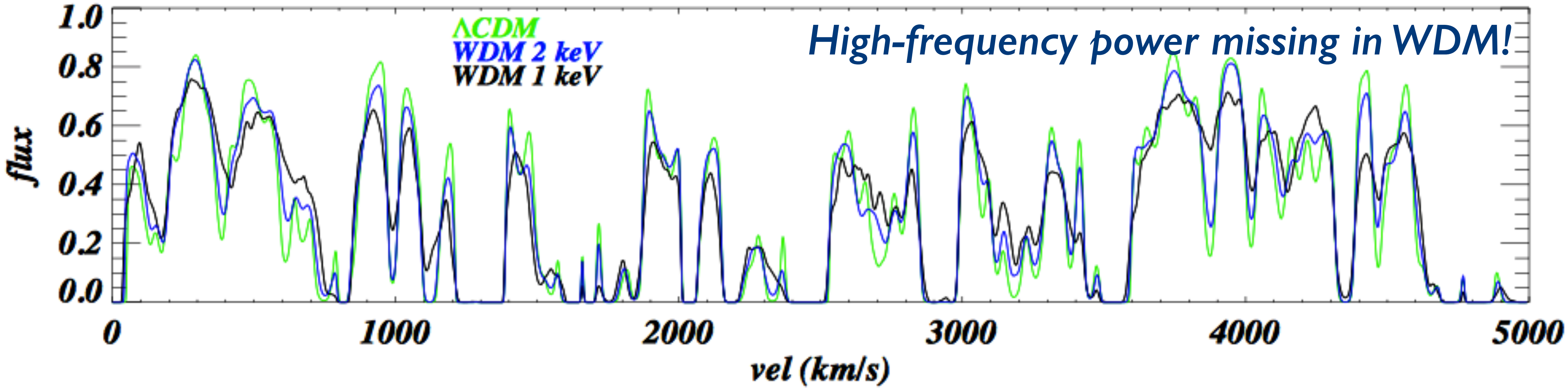


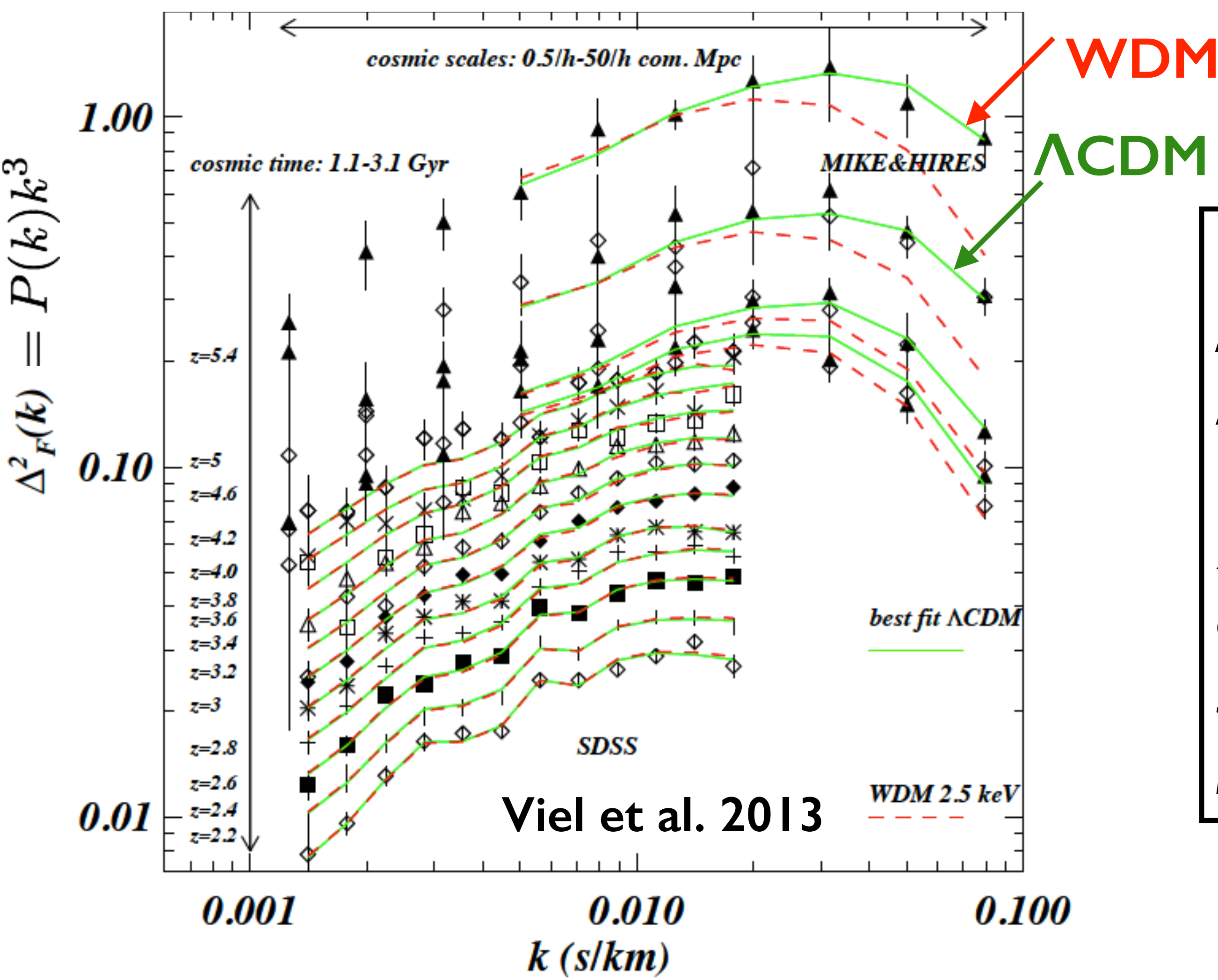
THE FOREST LIKES IT COLD....







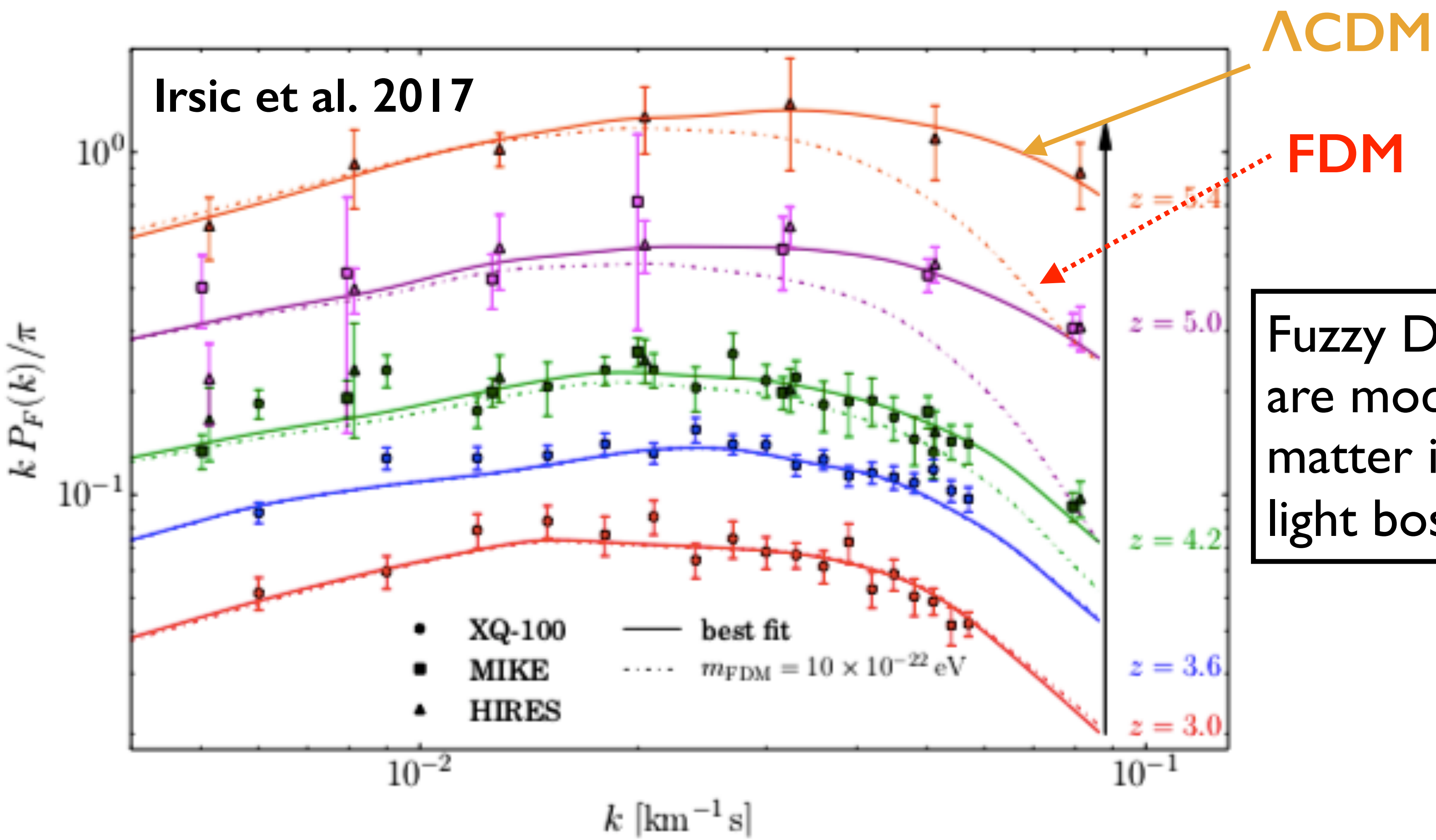




High-resolution *Keck* and *Magellan* spectra match ΛCDM up to z = *5.4*!

2σ lower limit on the mass of a *thermal relic*: m_{WDM} > *3.3* keV ⇨ $M_{FS} < 3\times10^8\,M_\odot$

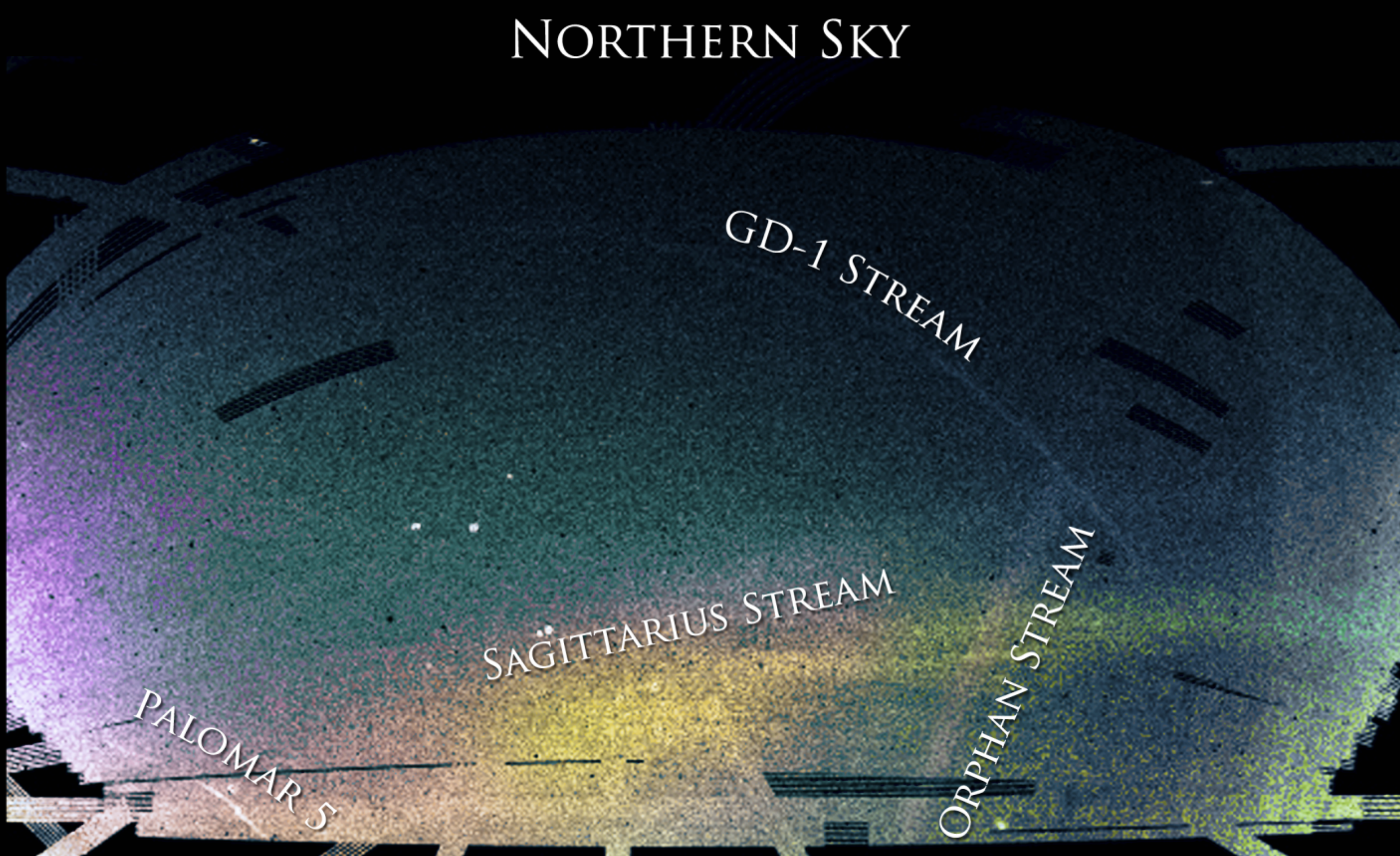
m_{WDM}=2 keV at 4σ C.L.



Fuzzy Dark Matter (FDM) are models where the dark matter is made of ultra-light bosons (λ_{dB}~1 kpc).

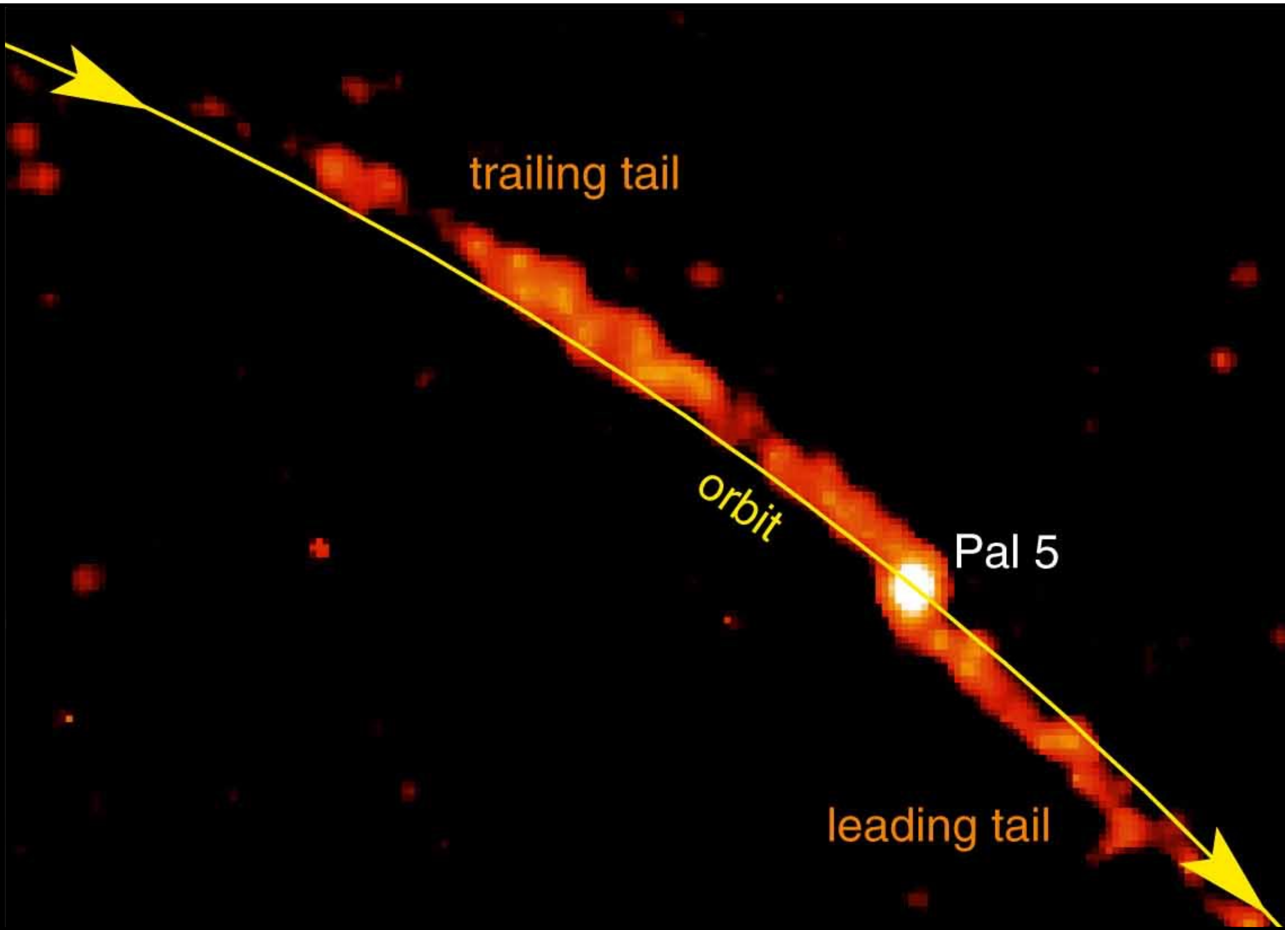
There are complications: Gas physics imprints two distinct scales on the distribution of the flux: 1) *thermal Doppler broadening*, which depends on the temperature at a given redshift; and 2) Jeans thermal pressure smoothing which affects the gas distribution relative to the 3D dark matter distribution and depends on the *thermal history* evolution at earlier times.

…and So Perhaps Do Stellar Streams…



A completely independent way of detecting DM halo substructure: *cold stellar streams*. Stellar streams are the consequence of the disruption by tidal forces of satellites that orbit around them, whether dwarf galaxies or globular clusters. These streams are particularly interesting probes of the global shape and granularity of the gravitational potential.

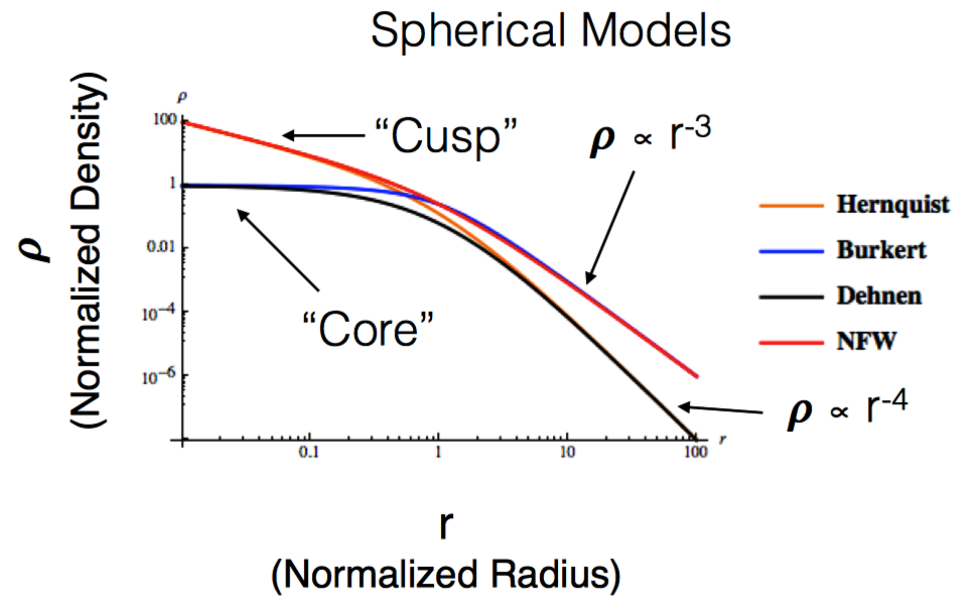
Streams orbiting a CDM halo are predicted to suffer tens of impacts with 10^5-10^7 $M_\odot$ subhalos that cause density fluctuations, gaps, along its length.

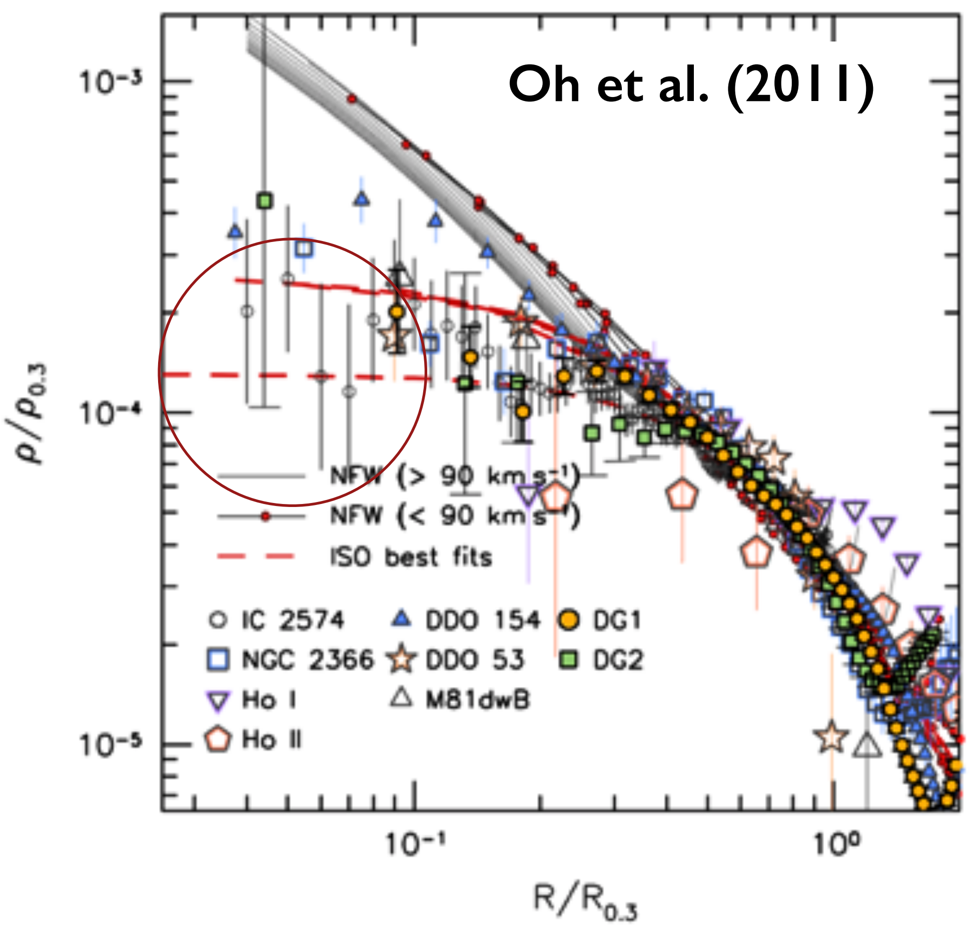


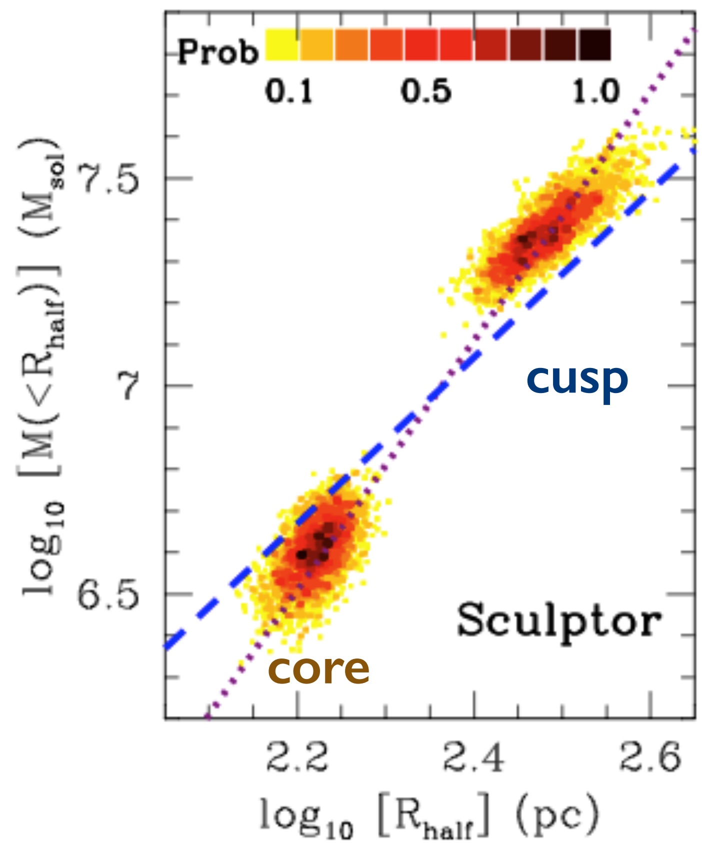
Bovy et al. 2017 (Pal 5): first determination of ~*10* dark matter subhalos with masses between $10^{6.5}$ and 10^9 $M_\odot$ within 20 kpc from the GC. But there are complications….

The Core-Cusp Problem

N-body simulations predict cuspy inner density profiles, but observations in dwarf galaxies appear to prefer cores.

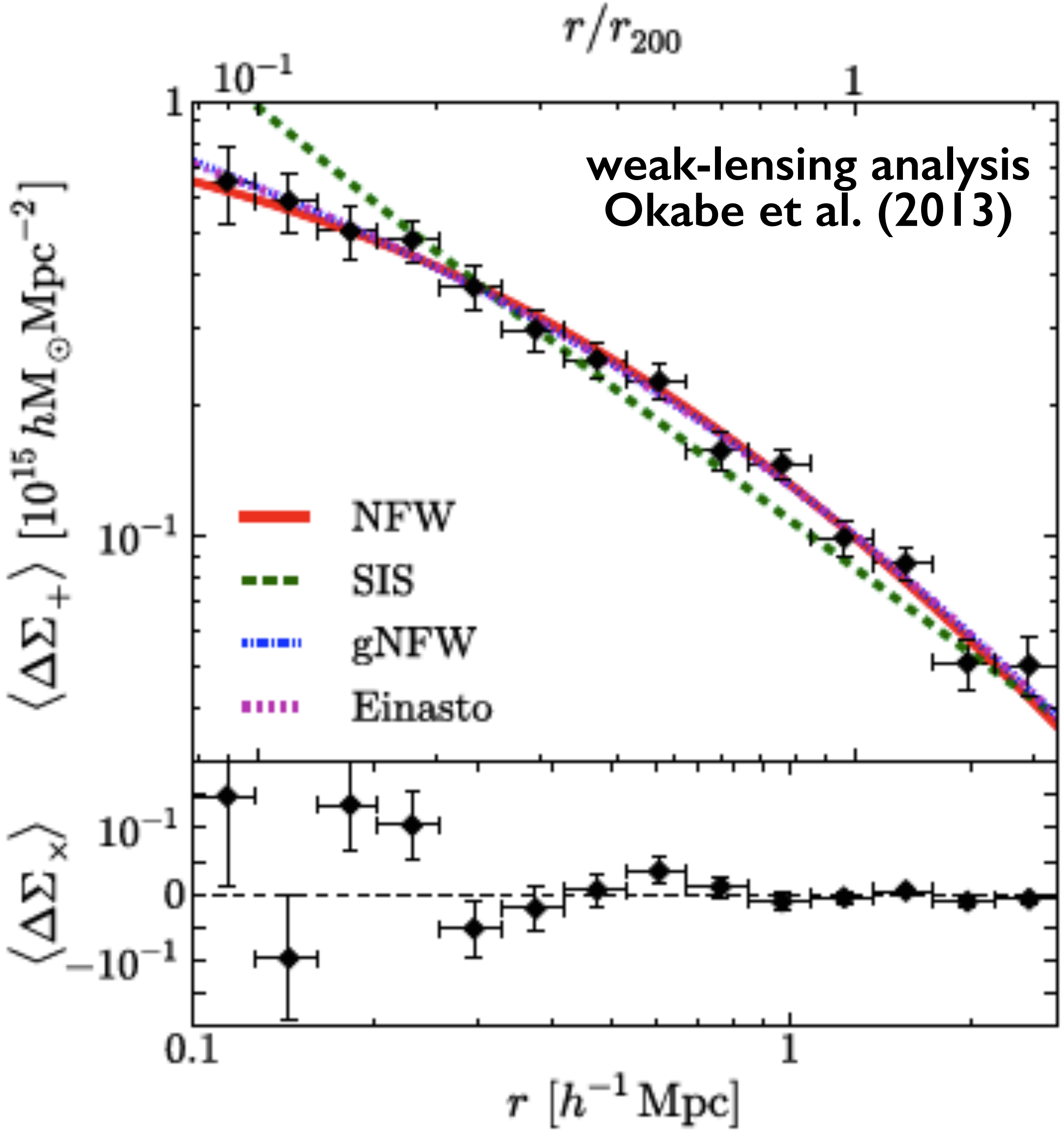






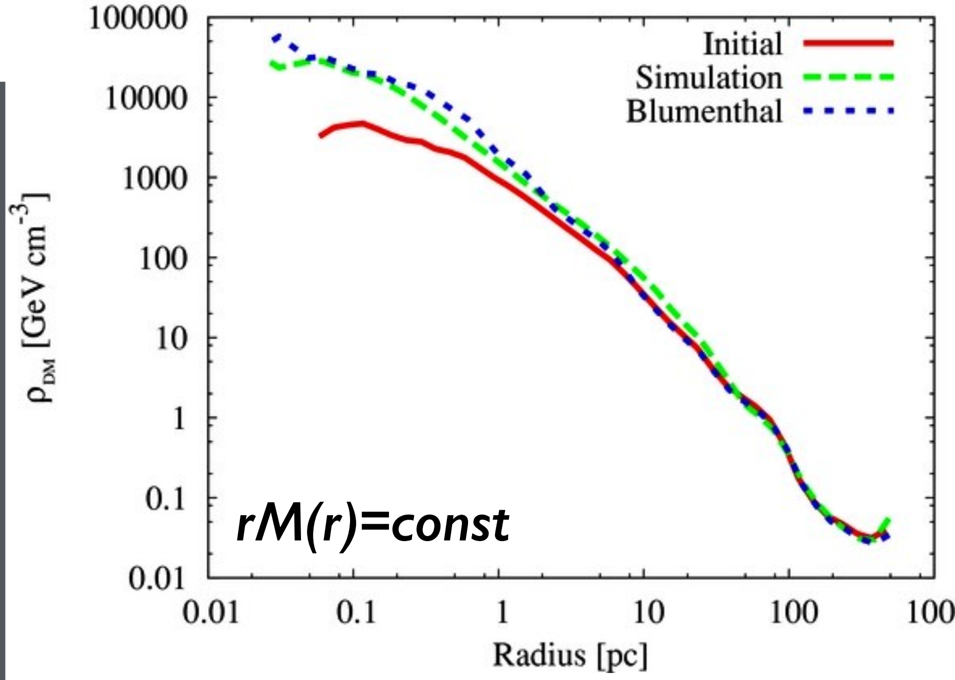
Walker et al. (2011)

In contrast, rich galaxy clusters appear to have cuspy profiles…

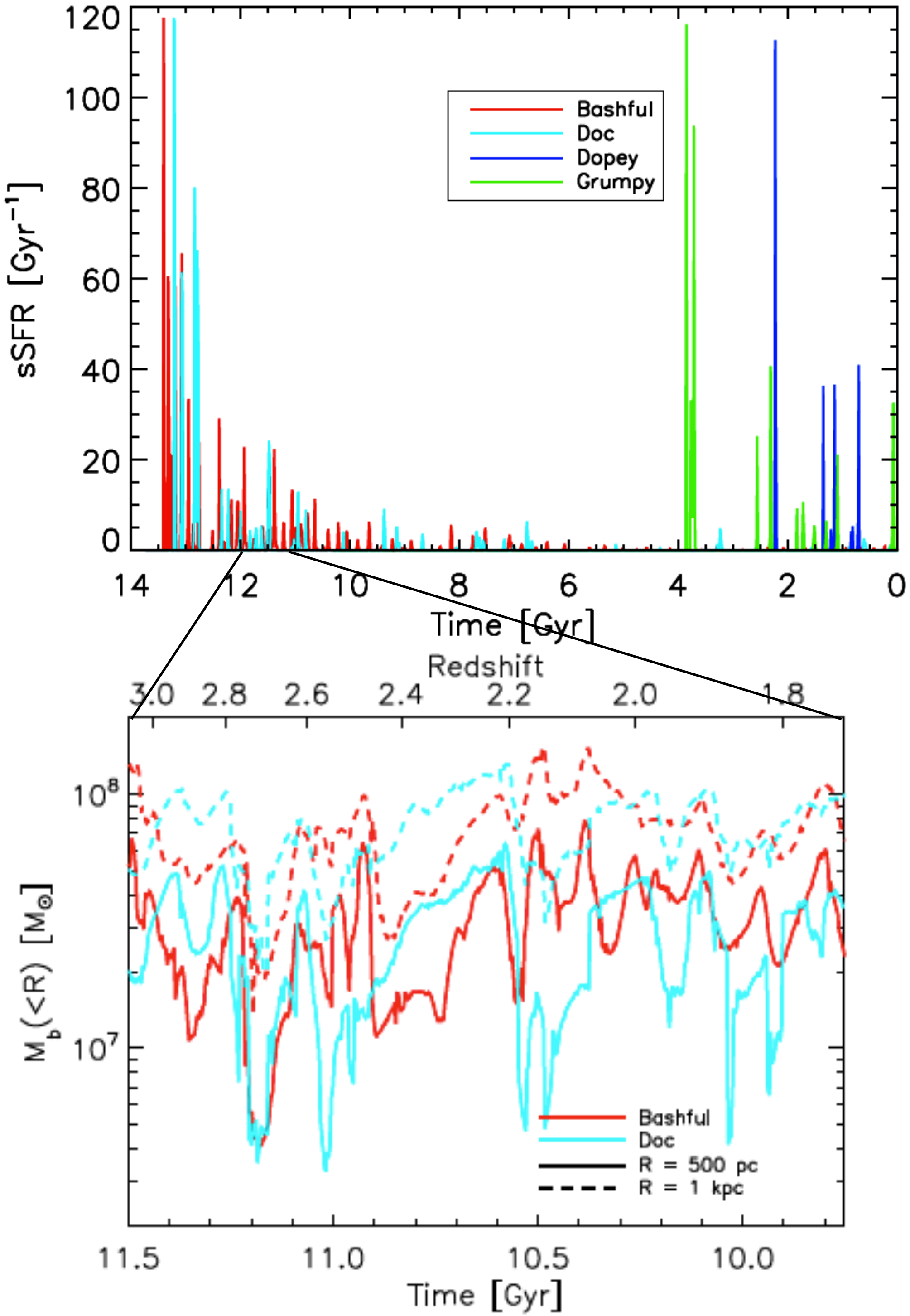


• Until recently any direct effect of the baryonic component on the DM was limited to a *minor adiabatic correction,* i.e. baryonic processes modulate the SFR *without changing the underlying DM scaffolding*.

• This picture has recently been subverted. Spectroscopic observations have revealed the *ubiquity of galaxy-scale outflows,* even in dwarfs with SFR $\ll 1 M_\odot/yr$. It has been realized that these processes can have a *non-adiabatic* impact on the host DM halo.



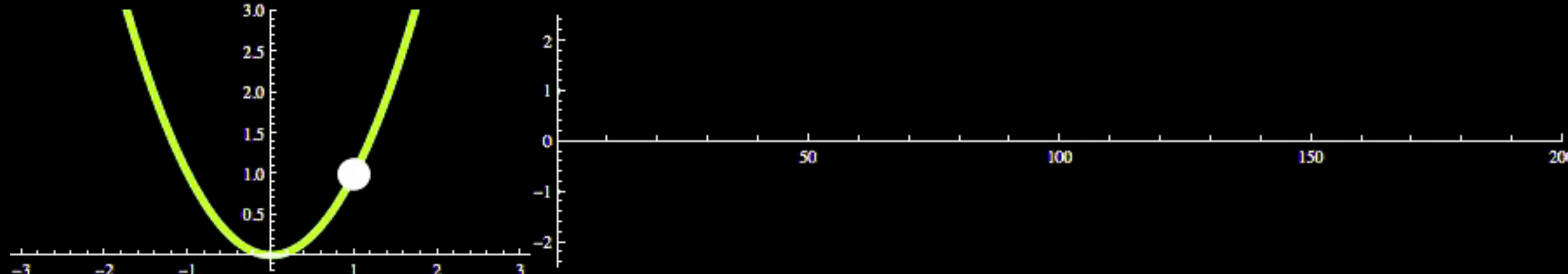
Potential Fluctuations from SN Feedback



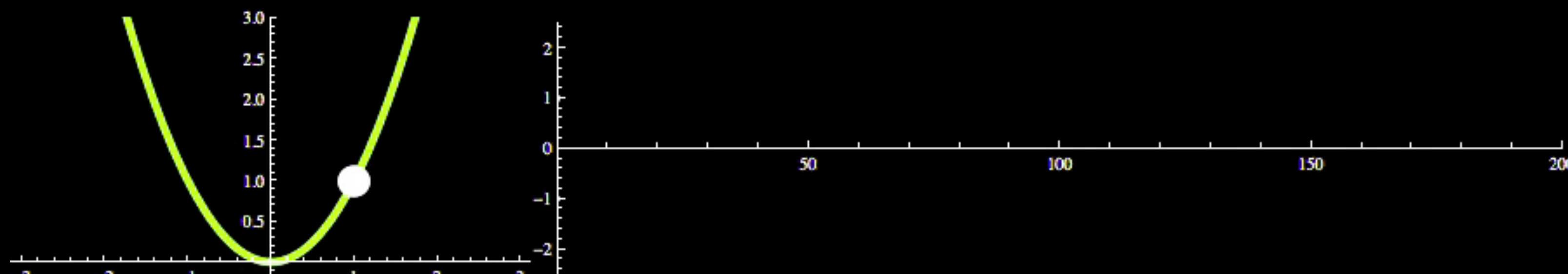
The bursty SF histories of sim DGs. Bottom left panel: fluctuating baryonic central masses.

Mechanism for injecting energy into the dark matter orbits illustrated by exact solution for a time-varying harmonic oscillator potential.

ADIABATIC BLOW-OUT & RECONDENSATION

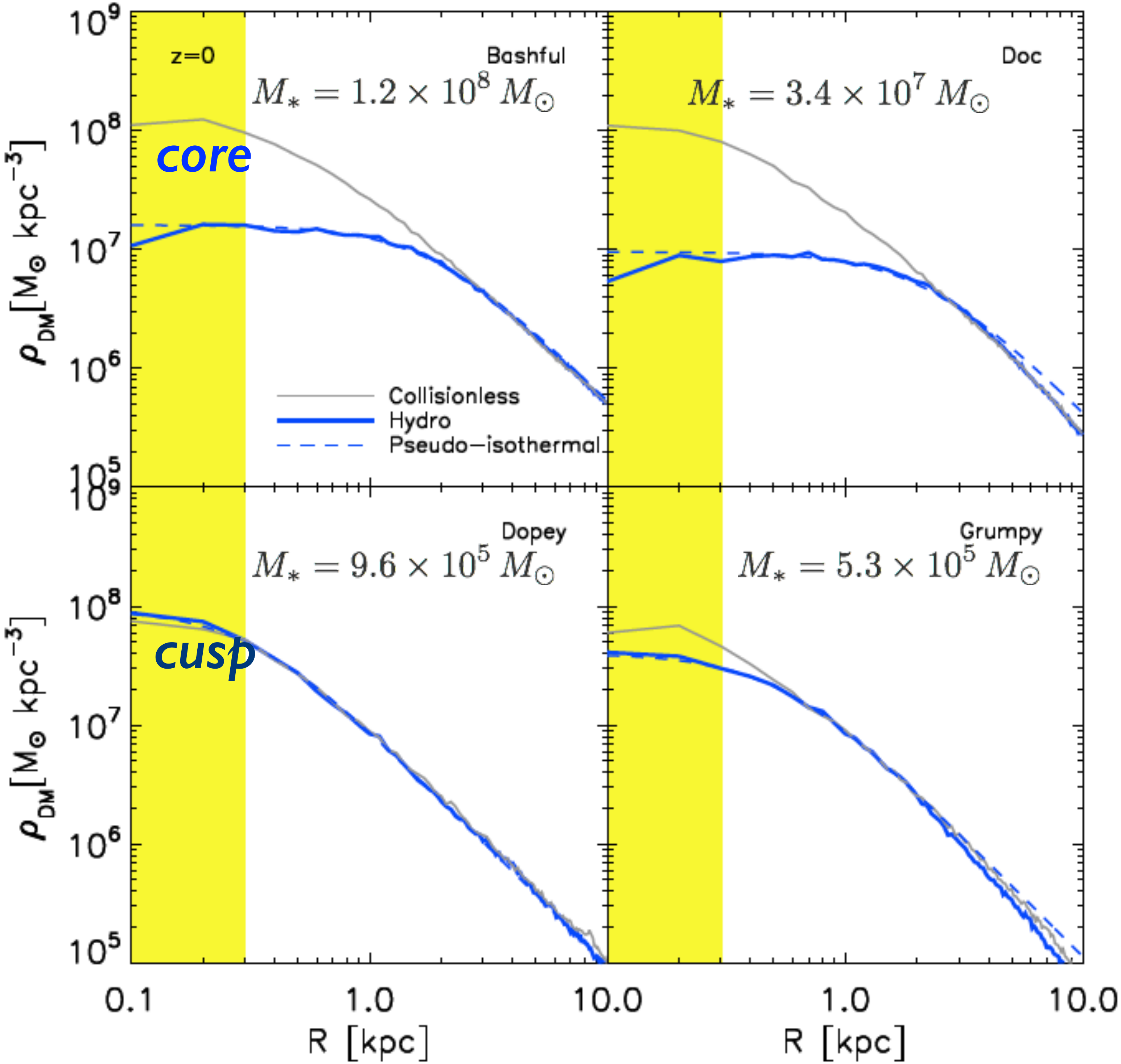


SUDDEN BLOW-OUT, THEN ADIABATIC RECONDENSATION



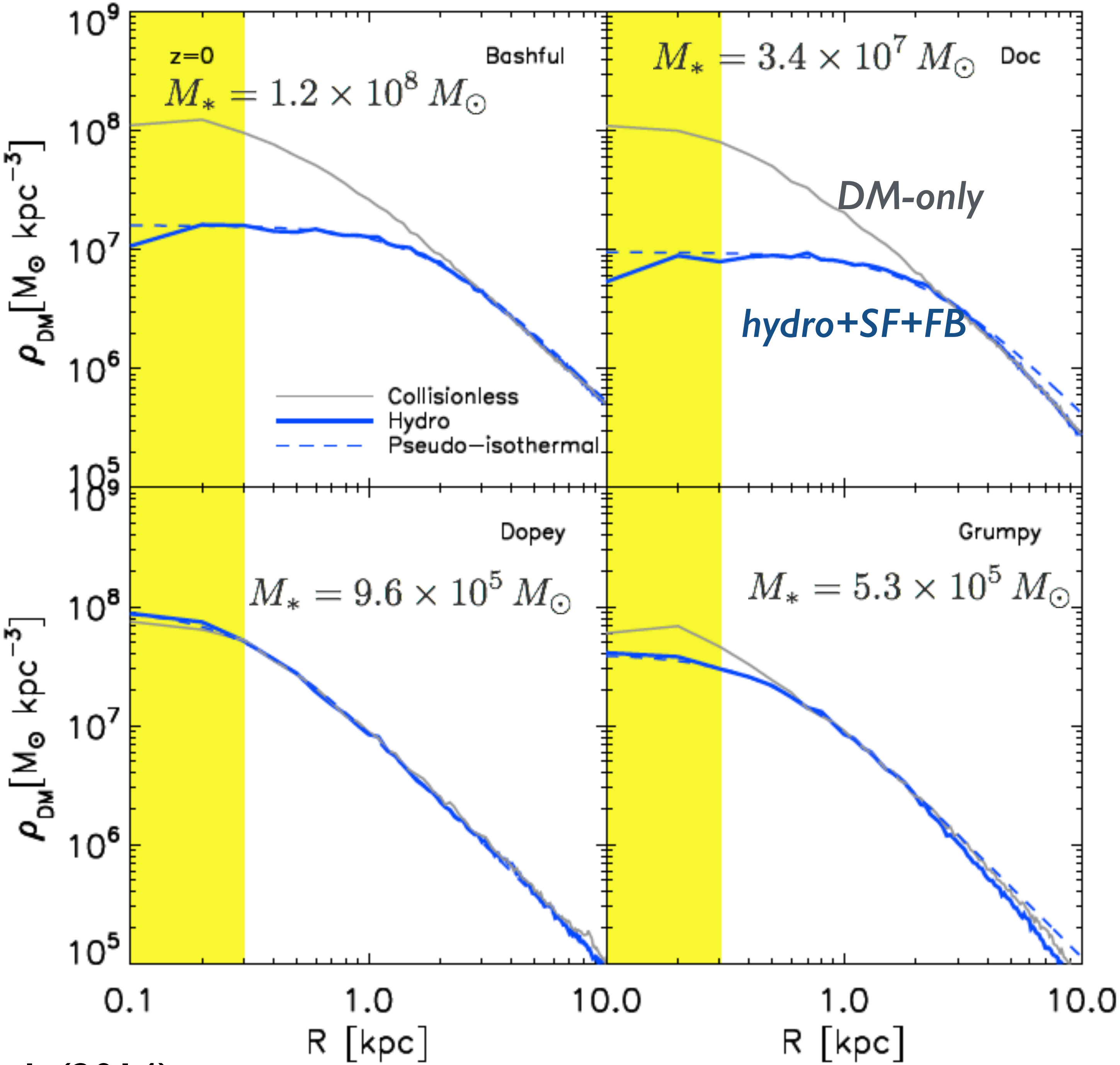
Pontzen & Governato 2012

CDM Heats up



Madau et al 2014

CDM HEATS UP



Madau et al. (2014)

We 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, and small subhalos must be dark. 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 *C(C)DM is not enough.*

- Still no show-stoppers for ΛCDM. More exotic possibilities like WDM/SIDM/FDM may still be viable, but require *careful tuning* and do not provide any silver bullet. There are great hopes that underground detection experiments, γ-ray observations, or collider experiments will identify the DM particle *within the next decade….*

- In the meantime, astronomers will continue their decades-long practice of studying the *dark sector* by observing and modeling *the visible.* Over the next decade, *strong gravitational lensing+GC stellar streams* may provide important evidence for/against CDM substructure.


THE END