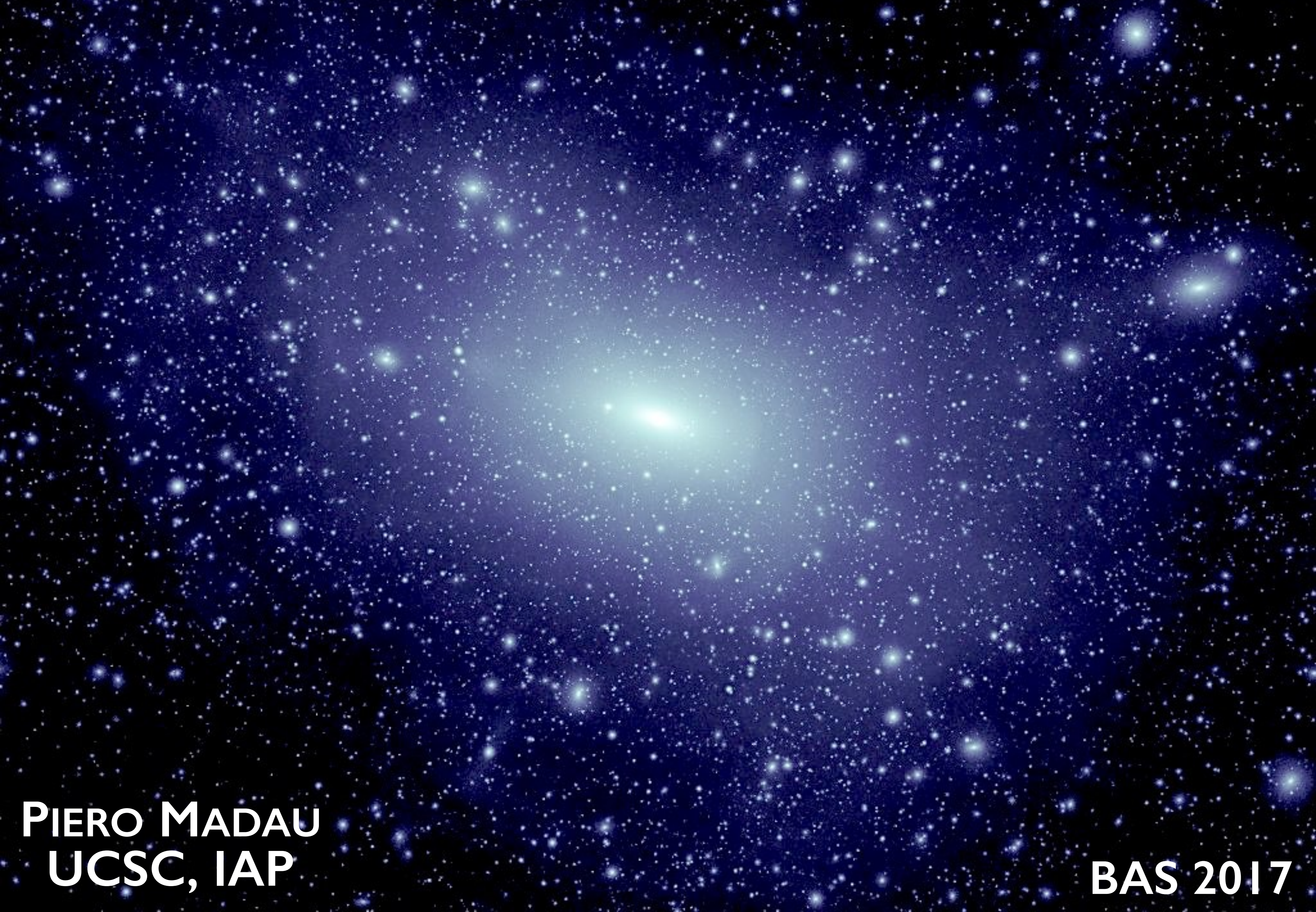
Dark and Light Side of Galaxy Formation



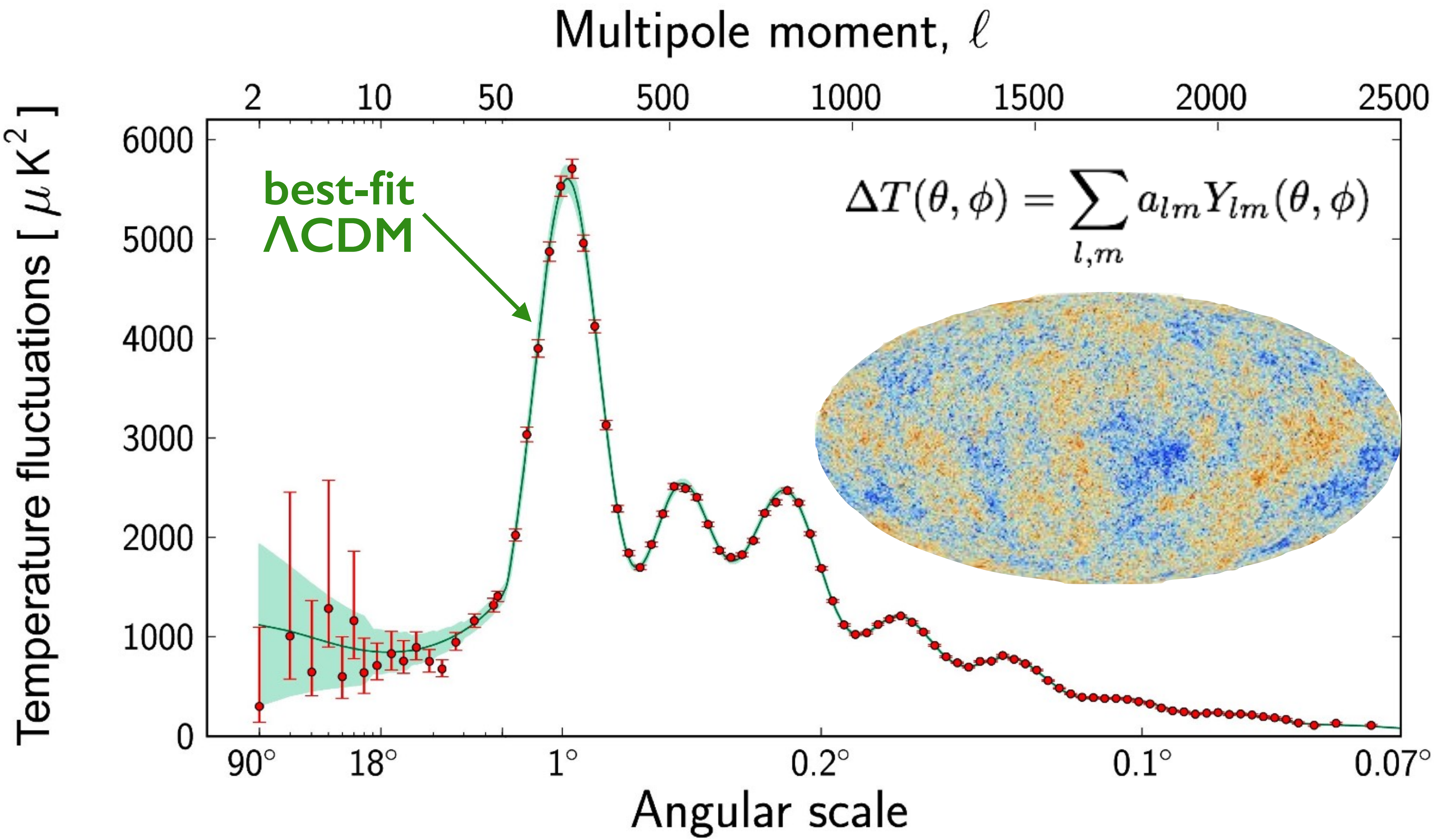
Piero Madau
UCSC, IAP

BAS 2017

FROM QUANTUM FOAM TO GALAXIES

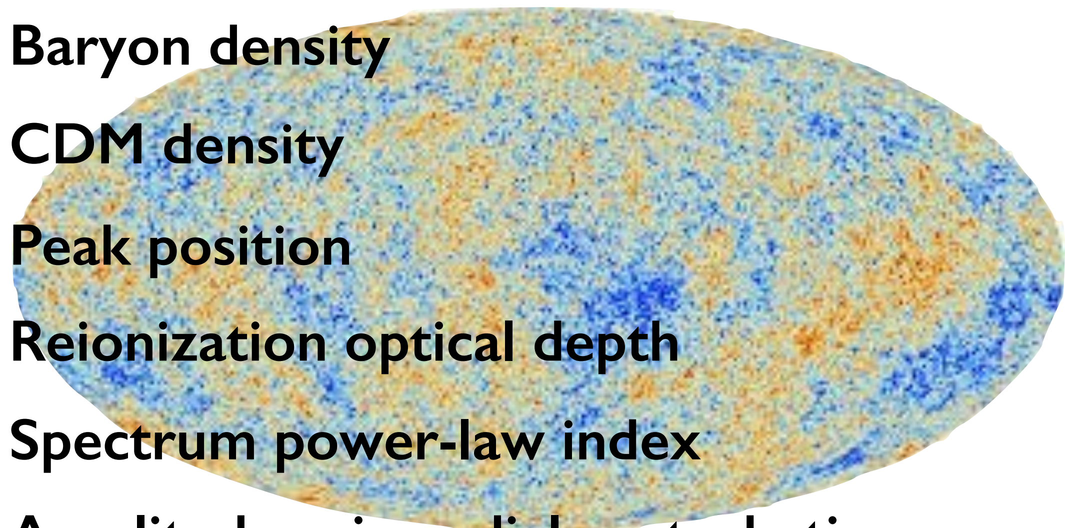
Galaxy Formation is the *dot-com* of Astrophysics. It's about nothing less than the origin and 14 Gyr-evolution of the building blocks of our Universe as a result of quantum fluctuations in the aftermath of the Big Bang. *It is a bold enterprise and not for the faint of heart.*

A NEARLY PERFECT UNIVERSE



Angular power spectrum of CMB: its precise shape depends upon cosmological parameters as well as the underlying density fluctuation spectrum, and encodes a wealth of crucial information.

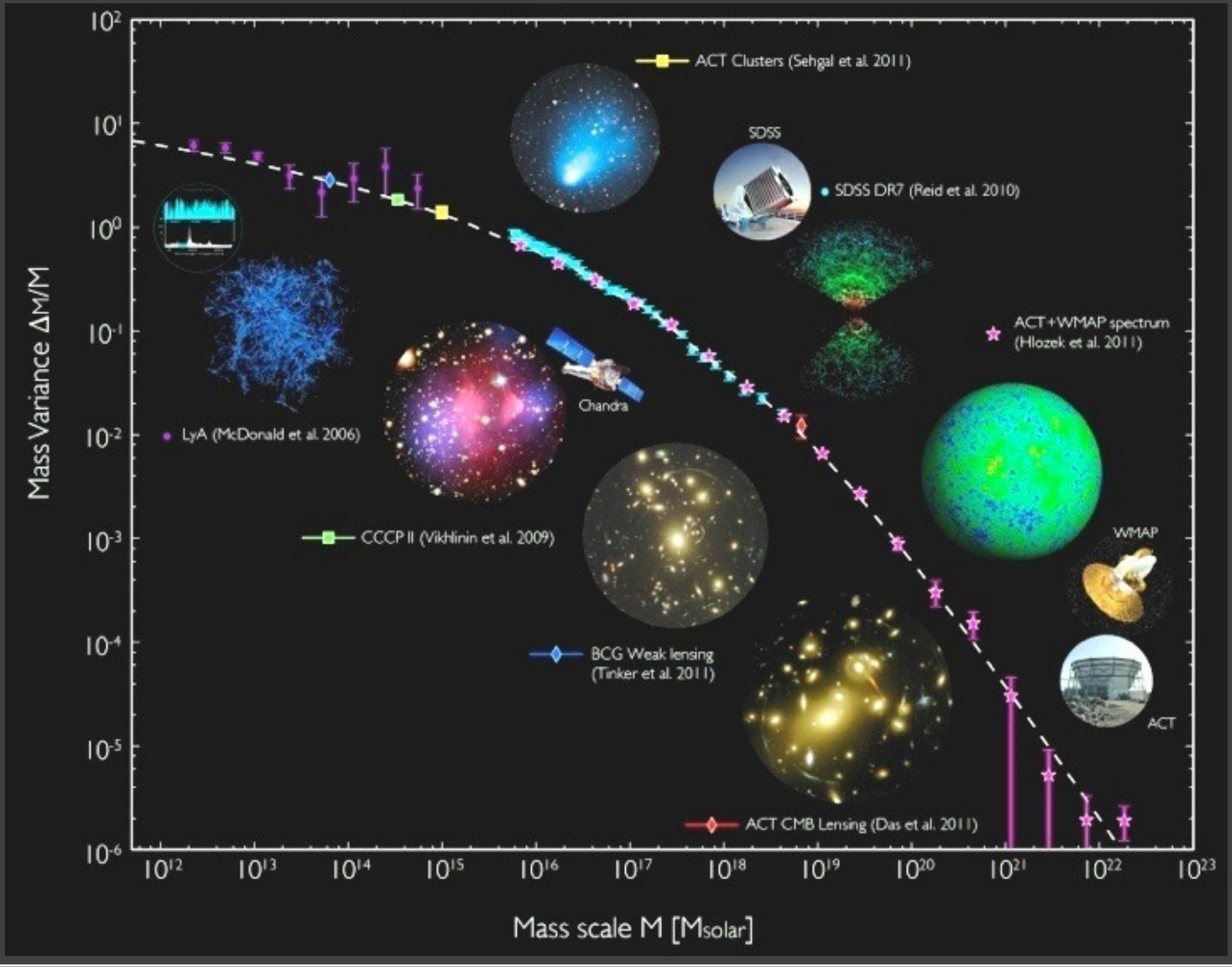
JUST SIX NUMBERS (FLAT ΛCDM)



$\Omega_b h^2$	$= 0.02230 \pm 0.00014$	Baryon density
$\Omega_X h^2$	$= 0.1188 \pm 0.0010$	CDM density
$100\theta_{MC}$	$= 1.04093 \pm 0.00030$	Peak position
τ	$= 0.066 \pm 0.012$	Reionization optical depth
n_s	$= 0.9667 \pm 0.0040$	Spectrum power-law index
σ_8	$= 0.8159 \pm 0.0086$	Amplitude primordial perturbations

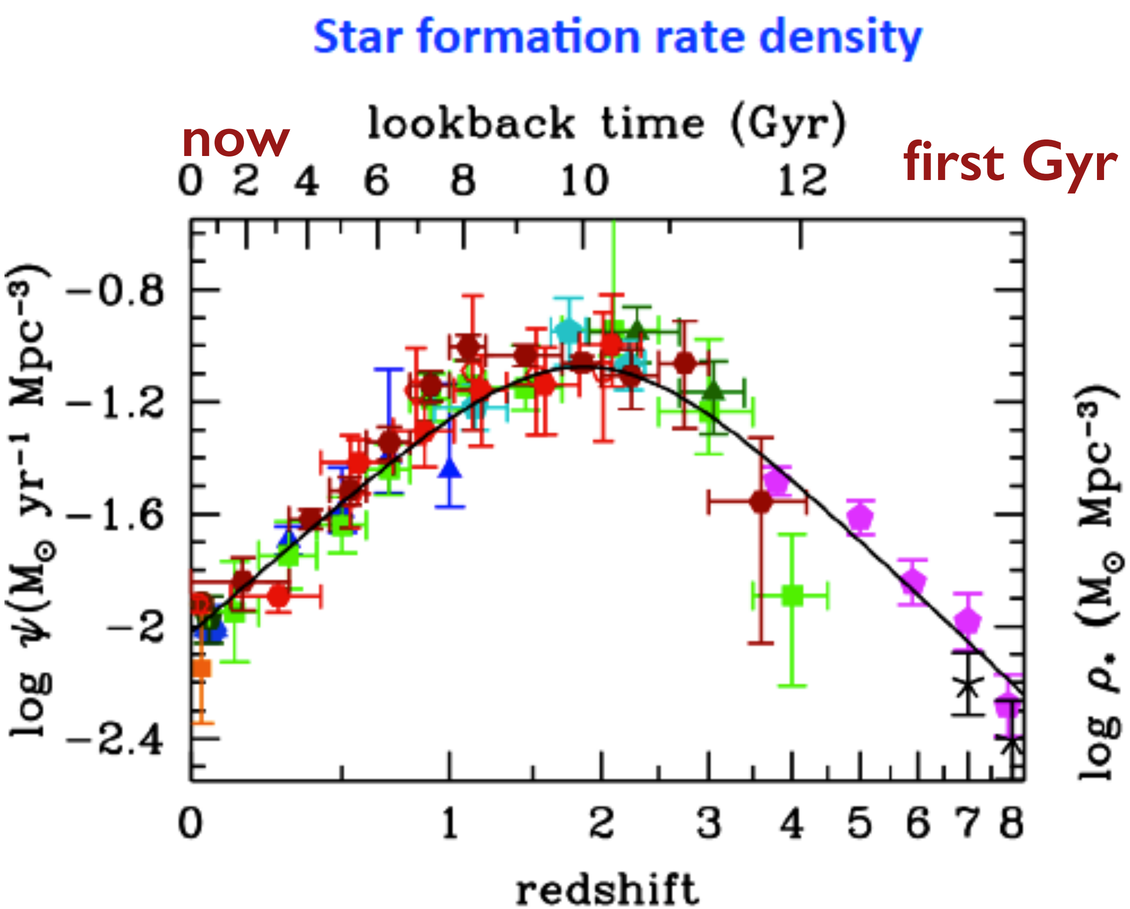
A *160σ* measurement of the cosmic baryon density and a *120σ* detection of non-baryonic DM ☛ DM *is 5 times more abundant than ordinary matter!*

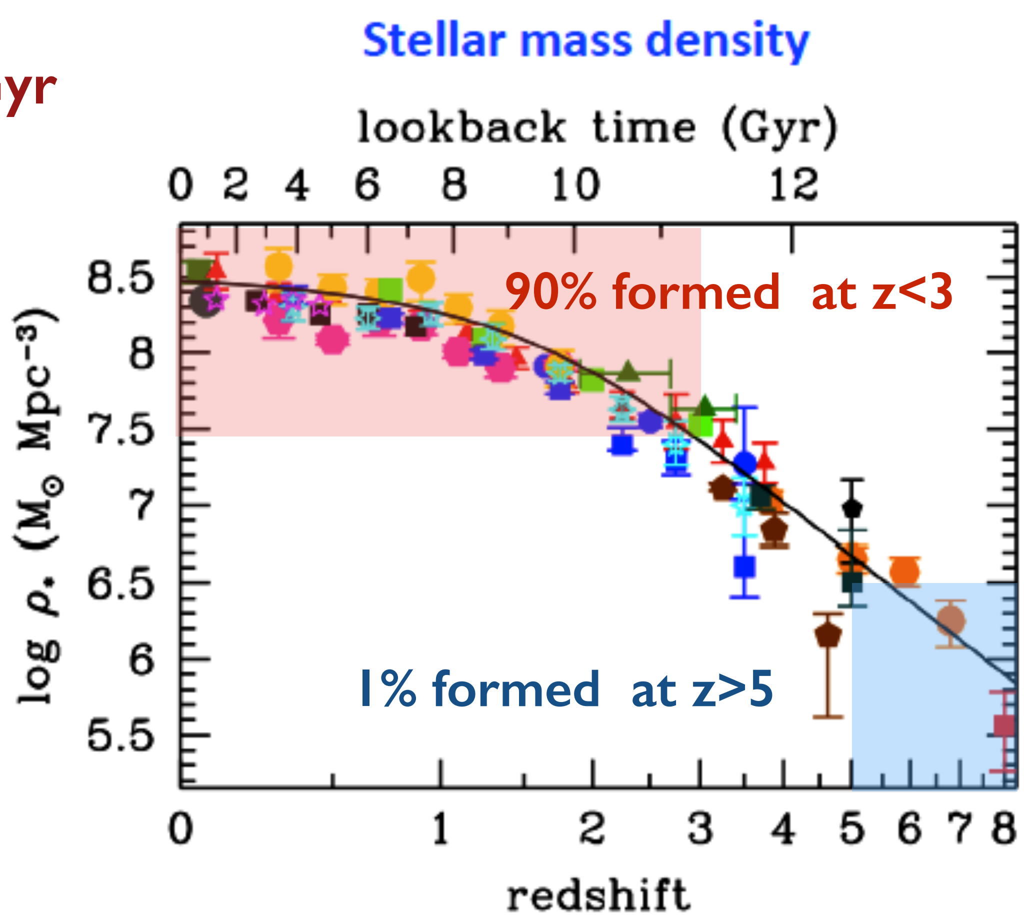
DENSITY FLUCTUATIONS DATA AGREE WELL WITH ΛCDM



The r.m.s. mass variance $\Delta M/M$ predicted by *ΛCDM* compared with observations, from *CMB* on large scales, *weak gravitational lensing, clusters abundance*, SDSS *galaxy clustering*, down to the scales of the *Lyα forest.*

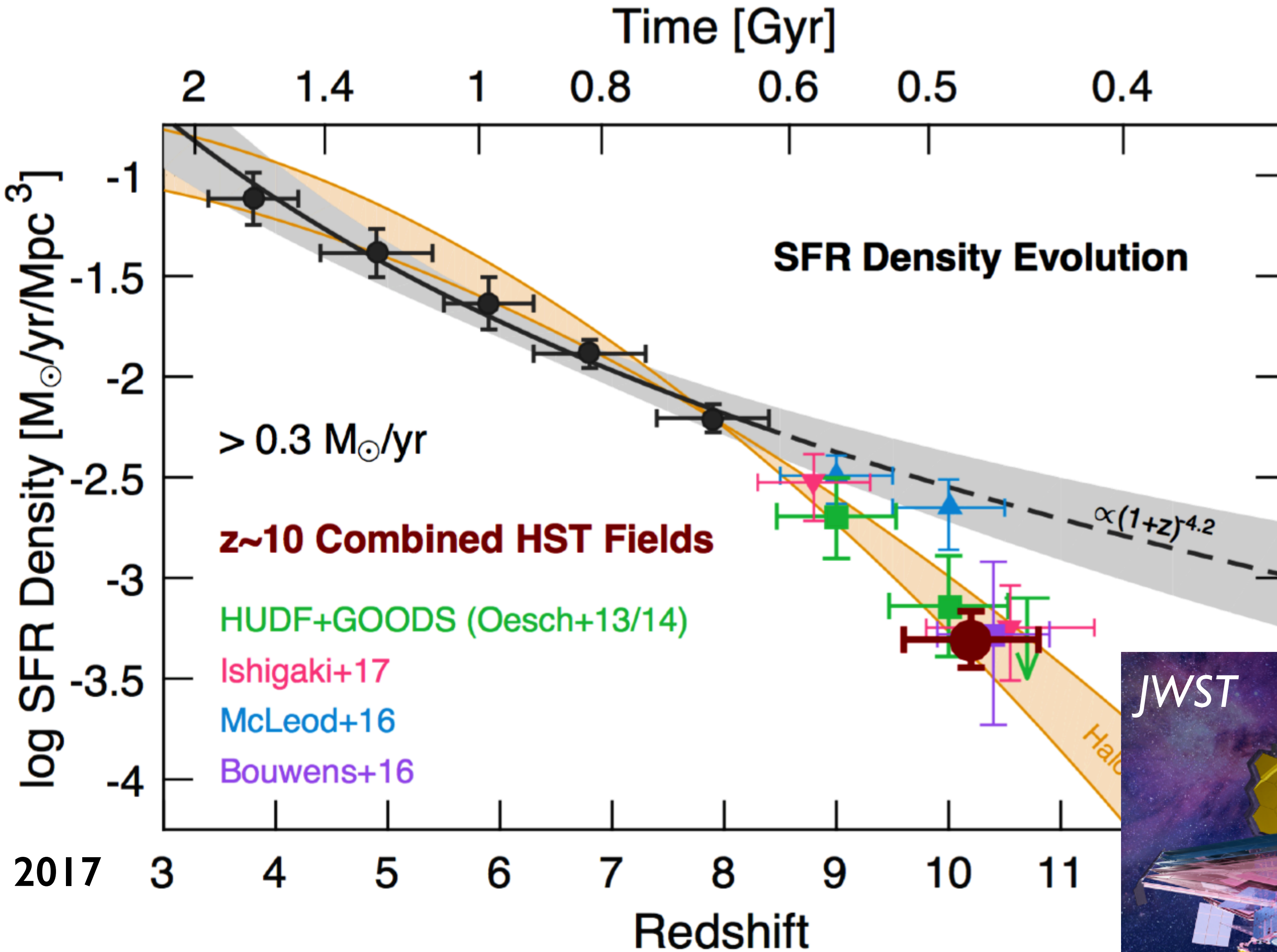
The past decade has also seen much progress in measuring the properties of galaxies across the em spectrum and over cosmic history. Astronomers have mapped the *cosmic history of star formation* from the dark ages to the present epoch. A *consistent* picture has emerged, whereby the SFRD peaked ~3.5 Gyr after the Big Bang and dropped exponentially at *z<1* with an e-folding timescale ~4 Gyr.

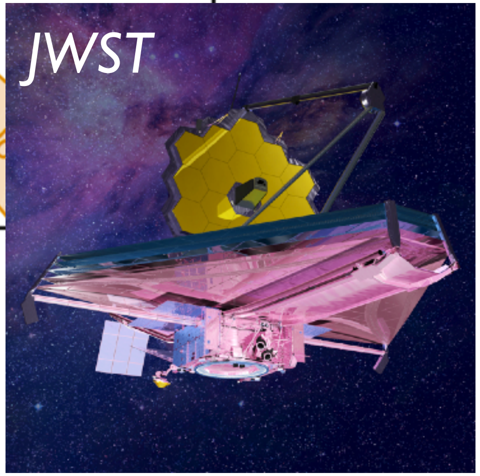




Madau & Dickinson 2014

FIRST LIGHT: SFRD AT *z~10*





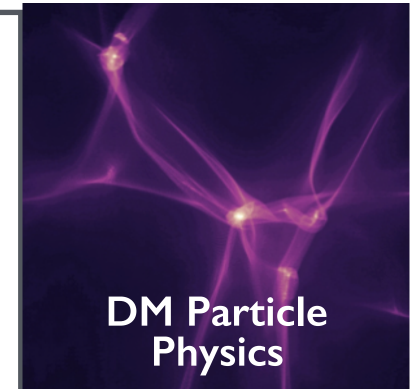
Oesch 2017

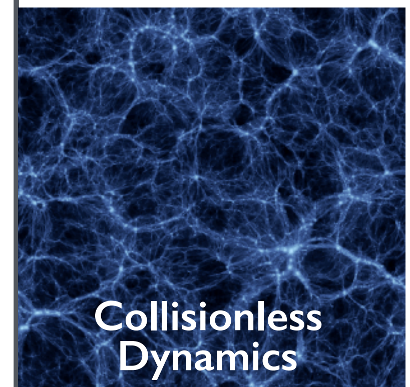
And yet fully *predictive* theory of *Galaxy Formation* remains one of the great, unsolved problems of Astrophysics. *Modern Cosmological Galaxy Formation* is largely about understanding:

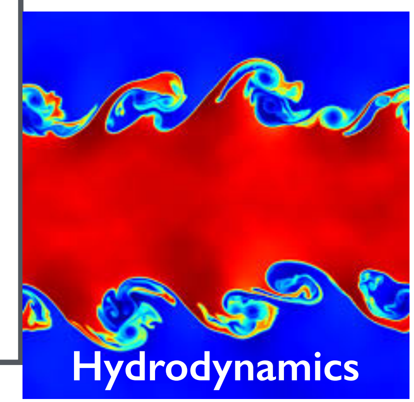
- the *mapping* between dark matter halos and their baryonic luminous components;

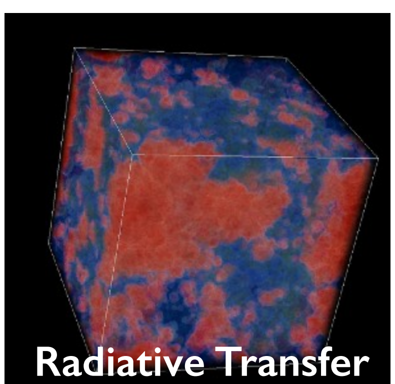
- galaxy *metabolism* and the basic processes of gas *ingestion* (infall and cooling), *digestion* (star formation/ feedback), and *excretion* (large-scale outflows);

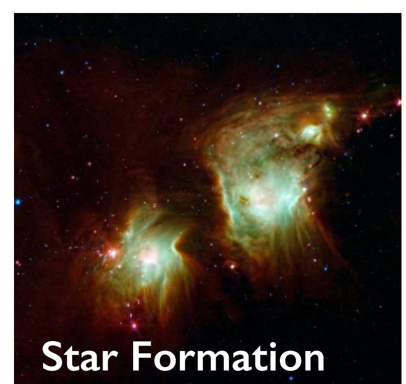
- the epoch of *first light* in the Universe, cosmic metal enrichment and reionization.

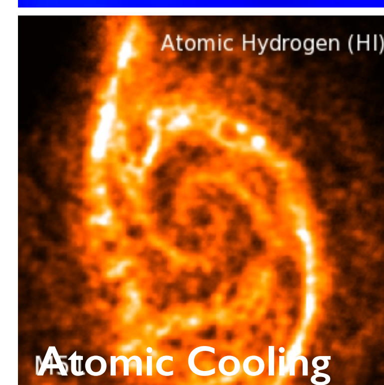








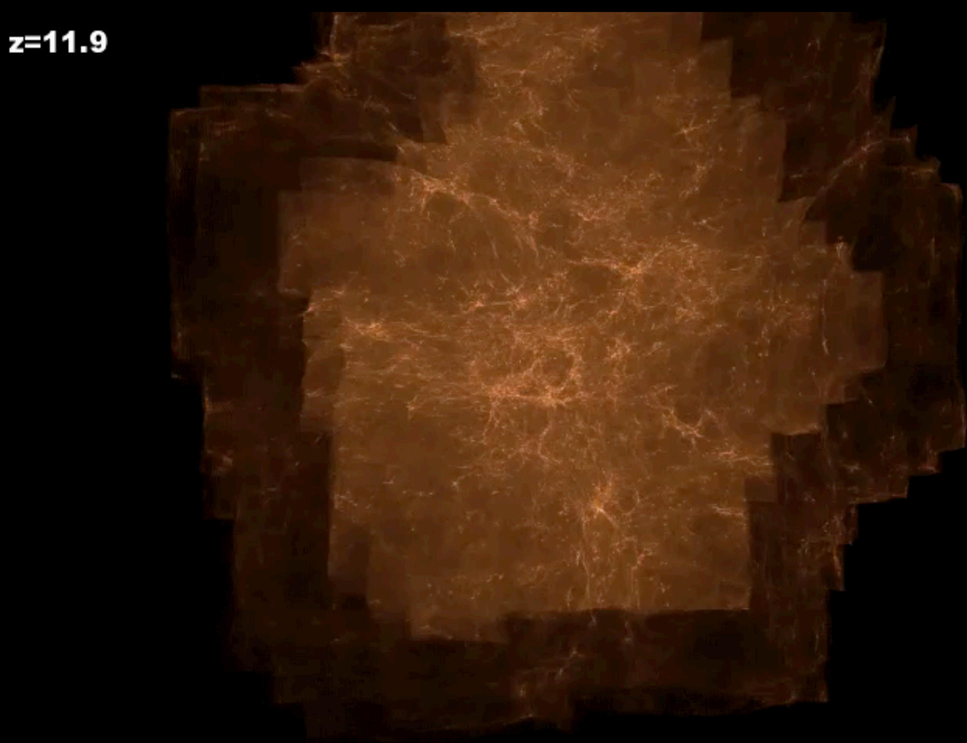




Almost by definition, what we saw has whetted our appetite for *__more data and theory__*; some problems have been *solved*, some have been *re-named*, perhaps *more have been discovered than have been put to rest.* And while there is general agreement on the basic ingredients of galaxy formation:

hierarchical build-up of DM halos, generation of angular momentum via tidal torques

accretion of baryons from the IGM via inflows and mergers, the transport of angular momentum, gas cooling and condensation, star formation, and a *__lot of feedback…__*



…there is little consensus on anything else:

- *Dark Matter*: Cold, Warm, Self-Interacting, Fuzzy, Not Even There?
- *Mass Density Profiles*: Cored or Cuspy?
- *Gaseous Assembly*: Cold vs Hot Accretion, Smooth/Clumpy/Filamentary, How Much Wind Recycling?
- *Numerical Technique*: Hydro Solver, Softening, Convergence.
- *Star Formation*: Need for H_2, Metallicity-Dependent, Impact of Turbulence/Magnetic Fields?
- *Stellar Feedback*: Algorithm, Momentum or Thermal Energy, Radiation Pressure, Ejective or Preventive, Cosmic Rays?
- *AGN Activity/Feeback*: Radiative or Mechanical, Local or Global, Intermittent or Persistent, Self-Regulated or Stuff Simply Happens, Role in Quenching?
- *Galactic Winds*: Mass-loading, Z-loading, How Far, Episodic or Steady, Gas Coming-in vs Going-out, Where Does Ejected Gas Go?

STUMBLING FROM CRISIS TO CRISIS

Small-Scale Challenges to ΛCDM

1. The prevalence of bulgeless galaxies (aka *angular momentum problem*)

2. The under-abundance of dwarf satellite galaxies in the Milky Way (aka *missing satellite problem*)

3. The unexpected dark matter distribution within dwarf galaxies (aka *cusp/core problem*)

4. The low central circular velocities of Milky Way's dwarf satellites (aka *too-big-to-fail*)

5. The origin of red, passively evolving galaxies (aka *quenching problem*)

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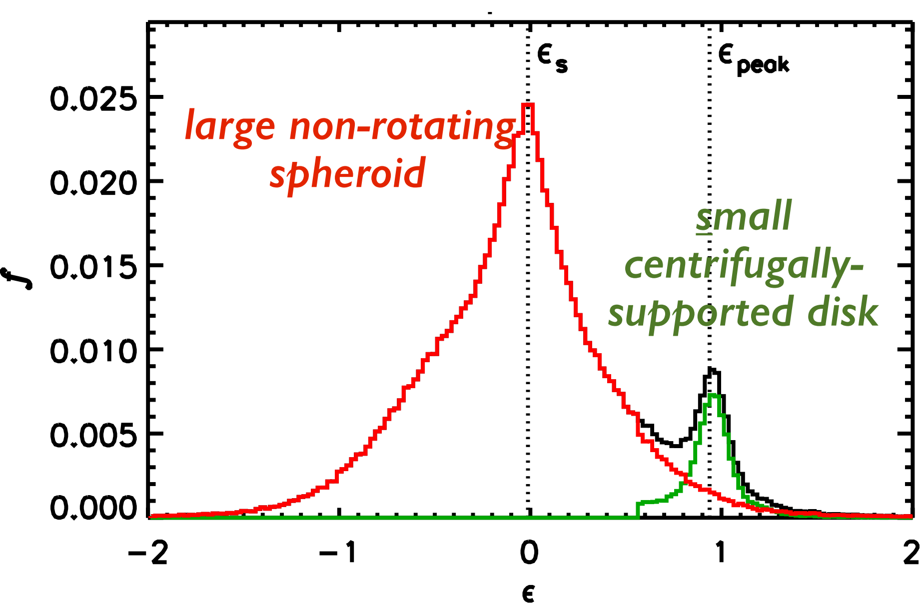
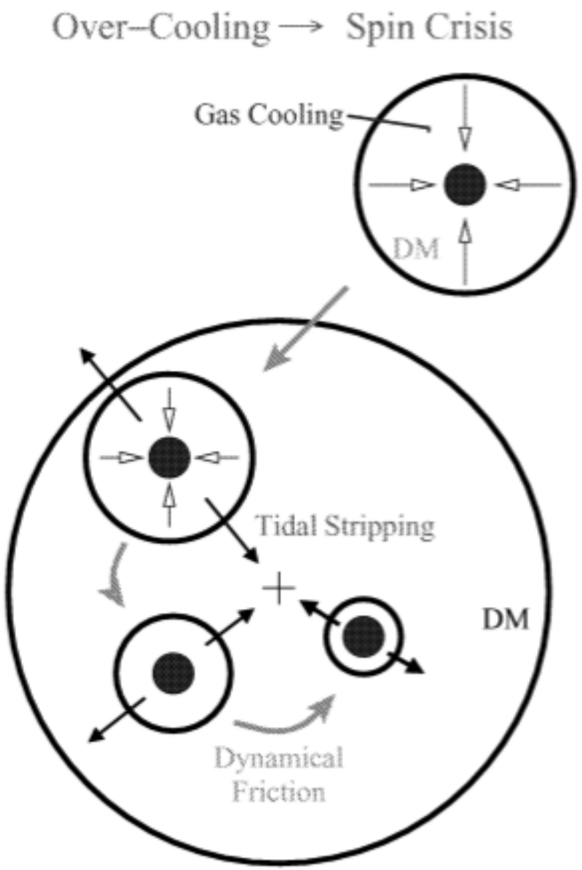
Angular Momentum Problem

The formation of *realistic late-type spirals* has been a long-standing problem of galaxy formation in ΛCDM. Until ~2010, numerical simulations produced 1) centrifugally supported disks that were too small; 2) oversized stellar bulges; 3) steep rotation curves; 4) excess stellar mass at $z=0$.

Scannapieco et al. 2009

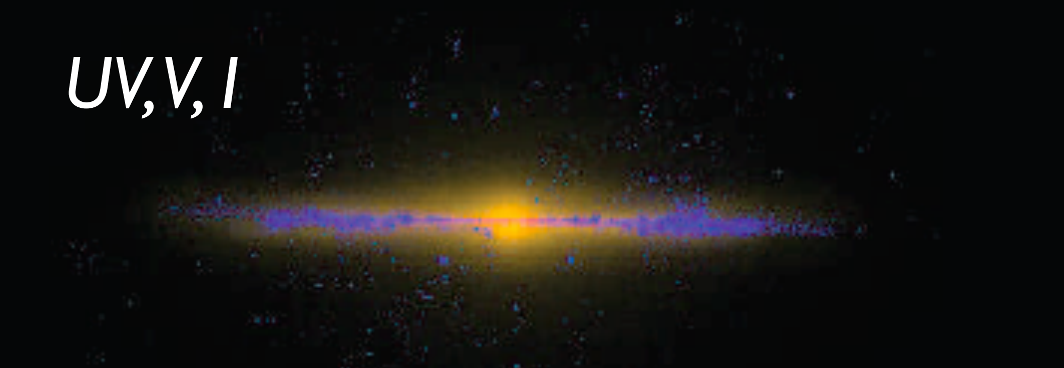




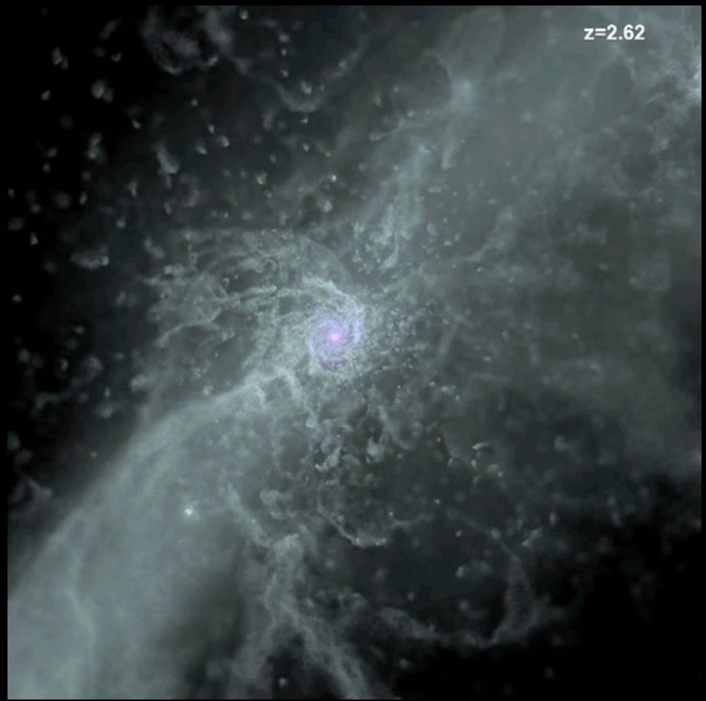
1)+2) ☛ excess of low angular momentum material (cf. 60% of spiral galaxies have B/D<0.3).

3) ☛ rotation curve should be flat or slowly rising in MW-sized galaxies.

SN-Driven Galactic Outflows



ERIS (Guedes ert al. 2011)

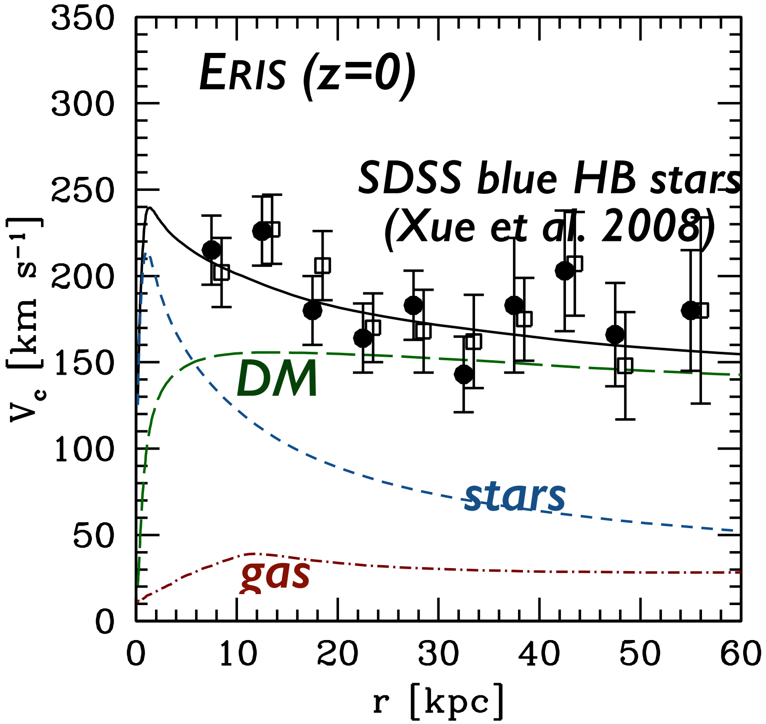


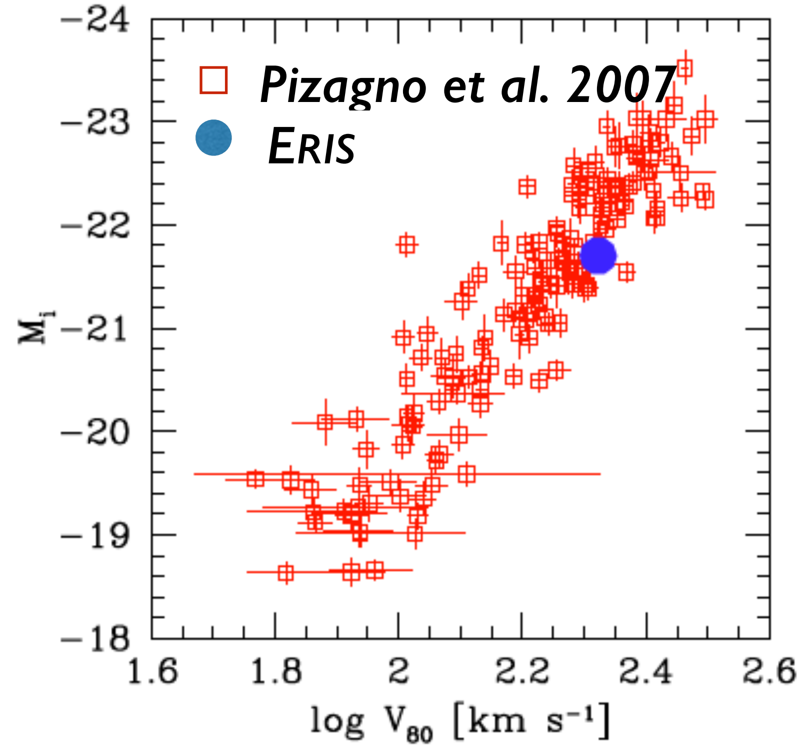
higher resolution ➪ ability to resolve GMC-scales (≲10^4 M⊙, n ≳10 cm^{-2}) ➪ clustered SF ➪ more efficient feedback

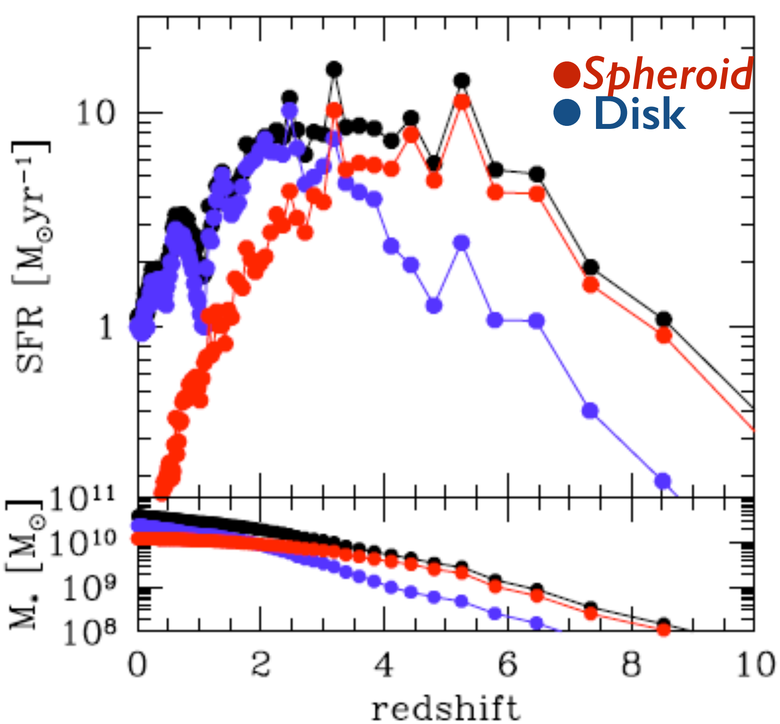
UVB heating & photoionization

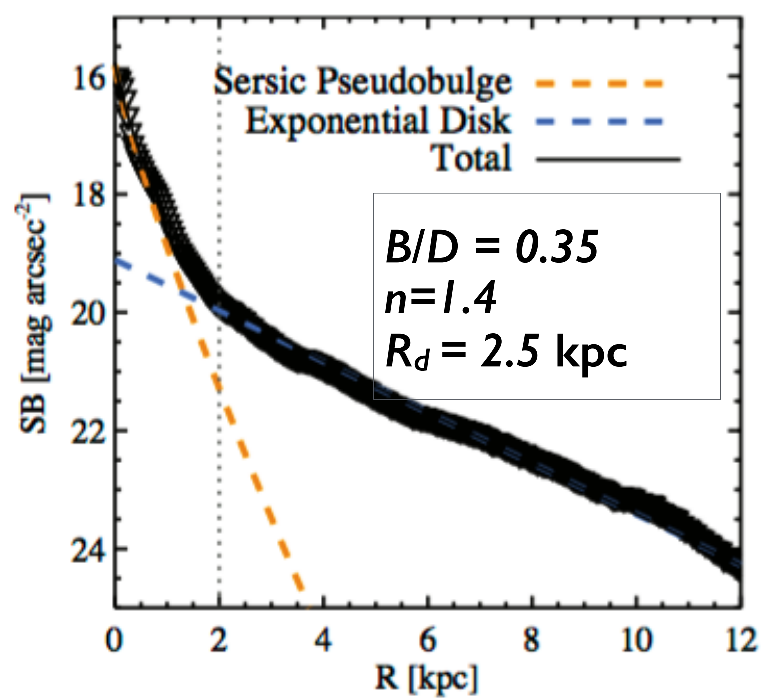
SN ejective feedback ➪ produce large-scale gas motions ➪ reduce SF in satellites and remove baryons from the center of the main host!

Eris' Mass and Light Distribution



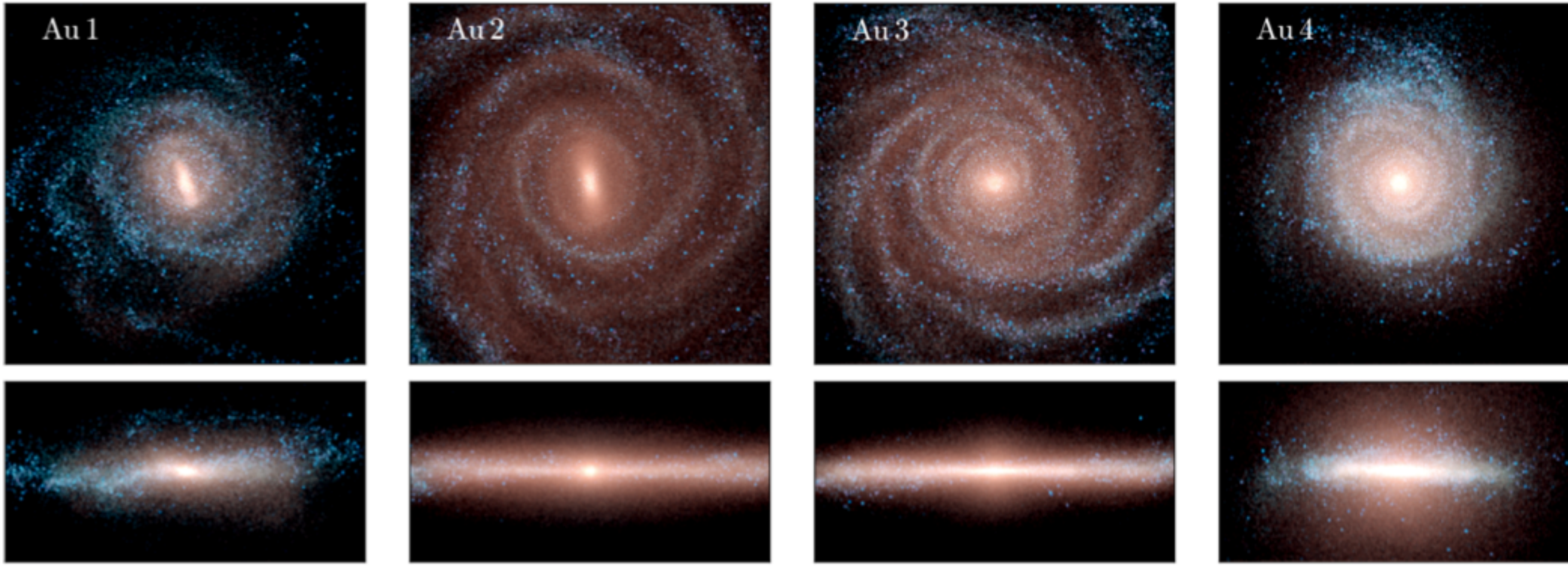




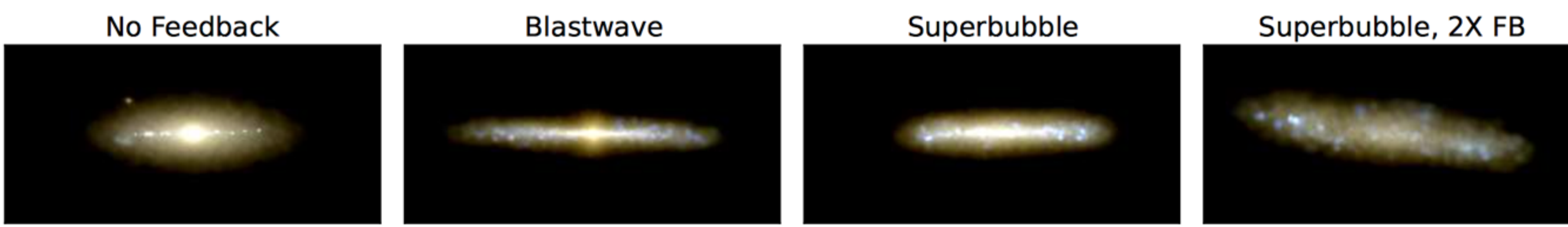


A Profusion of Disks…

Auriga Project: Grand et al. (2017)



…With Ad-Hoc FB/Wind Recipes!



SN+AGN Feedback

Illustris Simulation

MISSING SATELLITE PROBLEM

- *N*-body simulations have routinely been used to study the growth of nonlinear structures in an expanding universe:

- assume all Ω_M is in *cold particles that interact only gravitationally*, and sample it with $N \sim 10^9$ particles.

- bad approximation in the center of a massive galaxy where baryons dominate, OK for *faint dwarfs* ($M/L \lesssim 1000$).

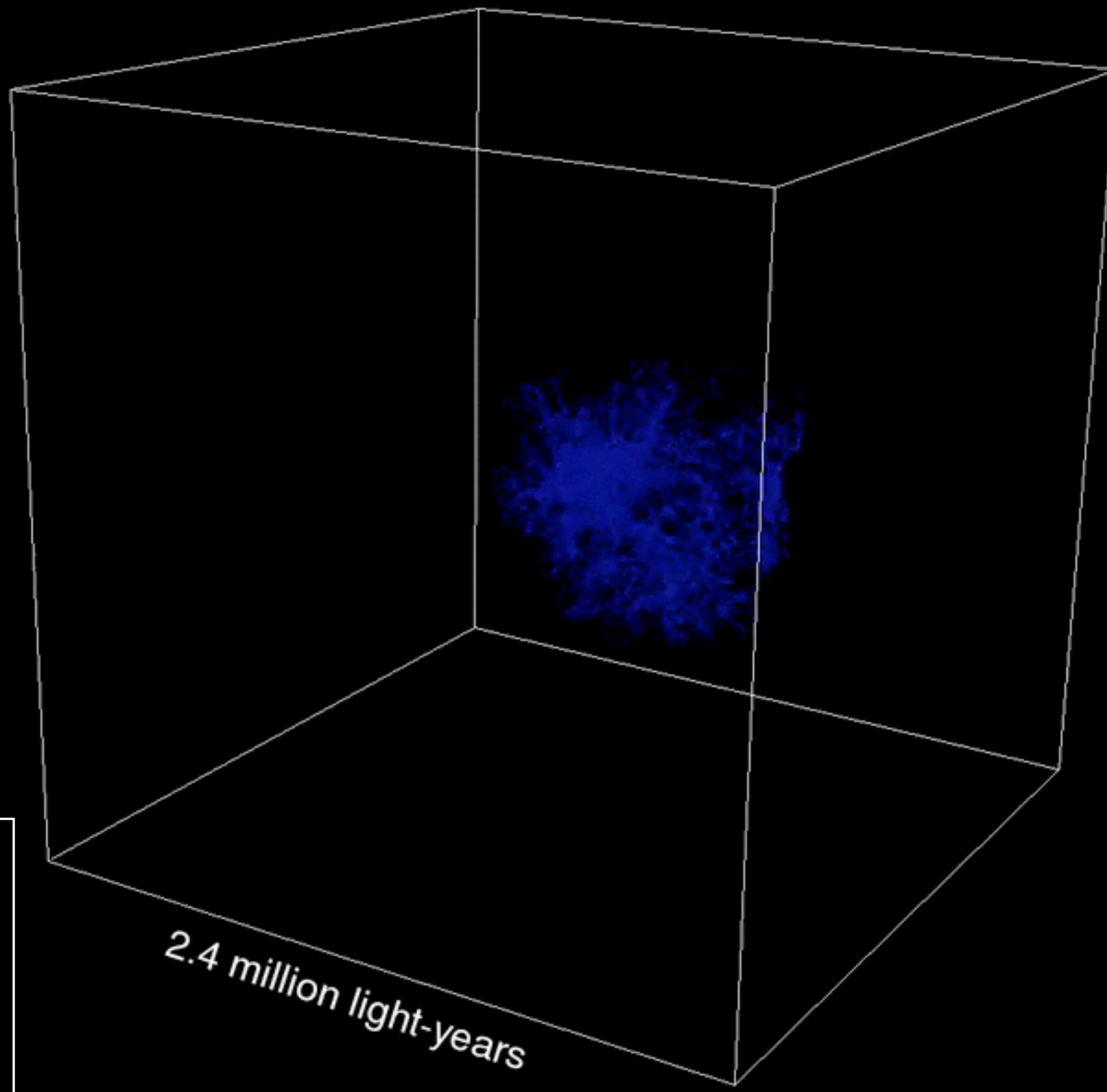
- simple physics (just gravity) & good CPU scaling ⇨ high spatial and temporal resolution.

- no free parameters (ICs known from CMB and LSS)

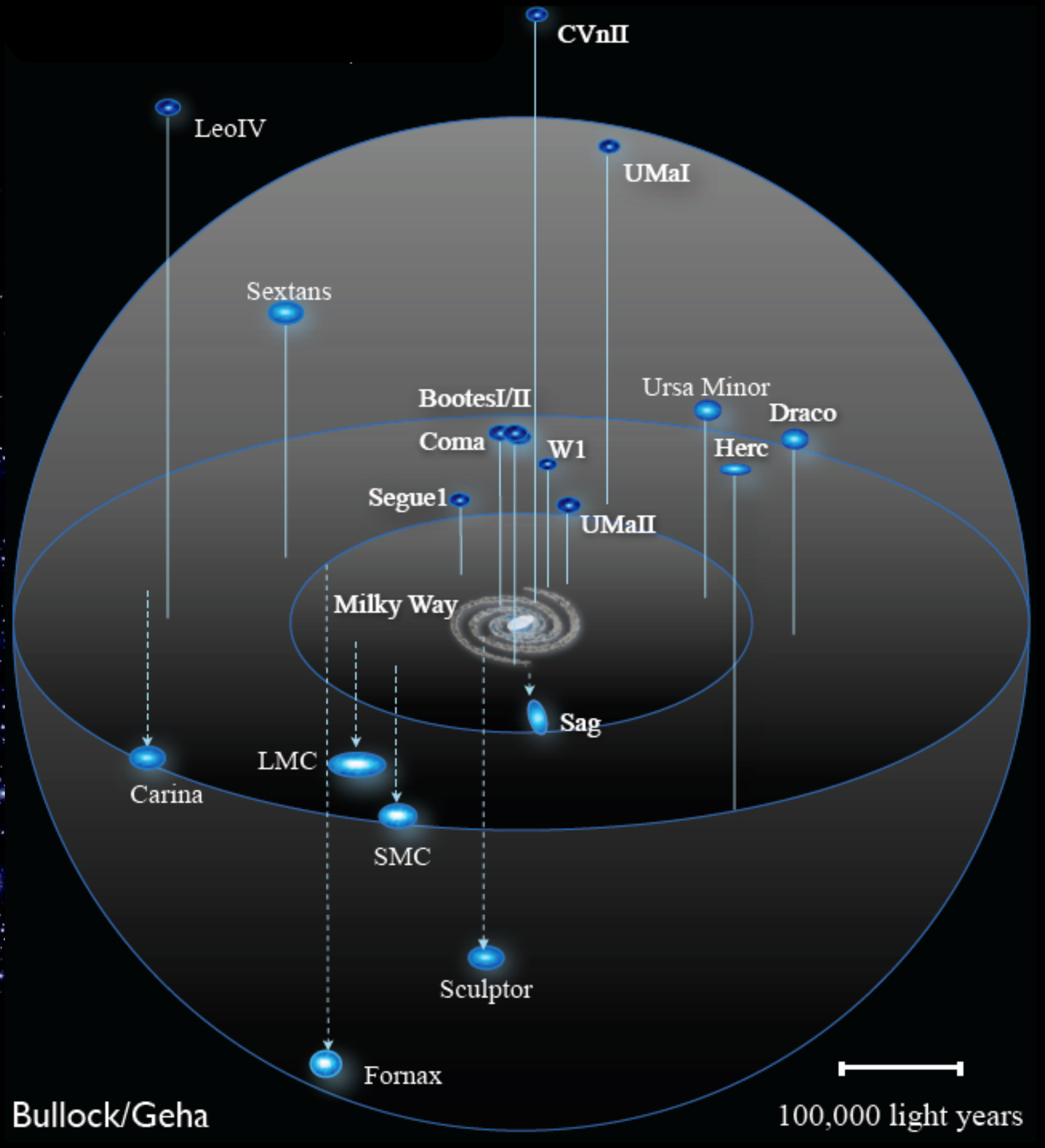
Substructure: A Unique Prediction of ΛCDM

Time since Big Bang: 0.19 billion years

Code: PKDGRAV2
Halo: VIA LACTEA II



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

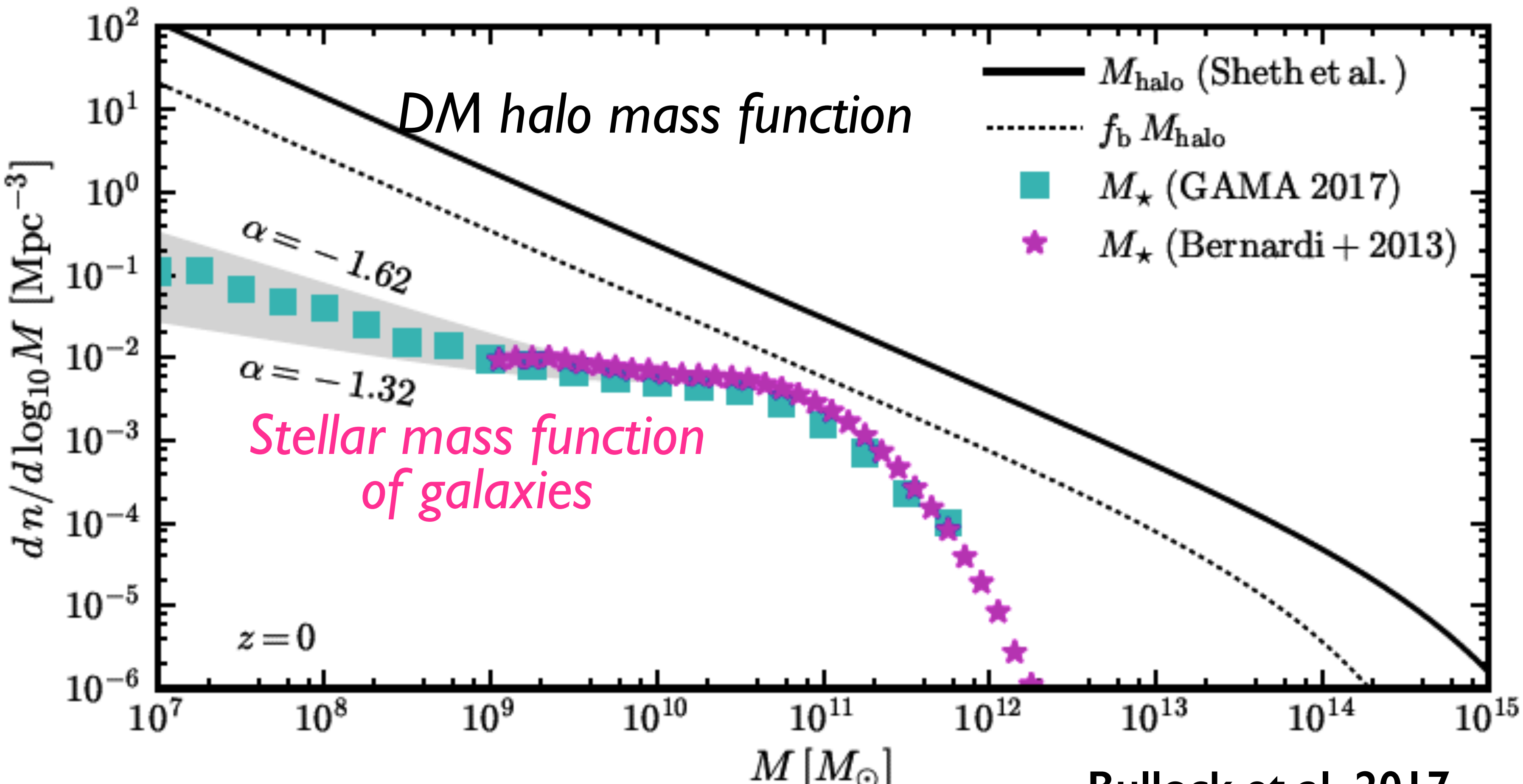


Theory: $N_{sub} \approx 1{,}000$
w V_c (*infall*) $\gtrsim 10$ km/s

Observations: $N_{sat} \approx 40$

Solutions to the MSP:

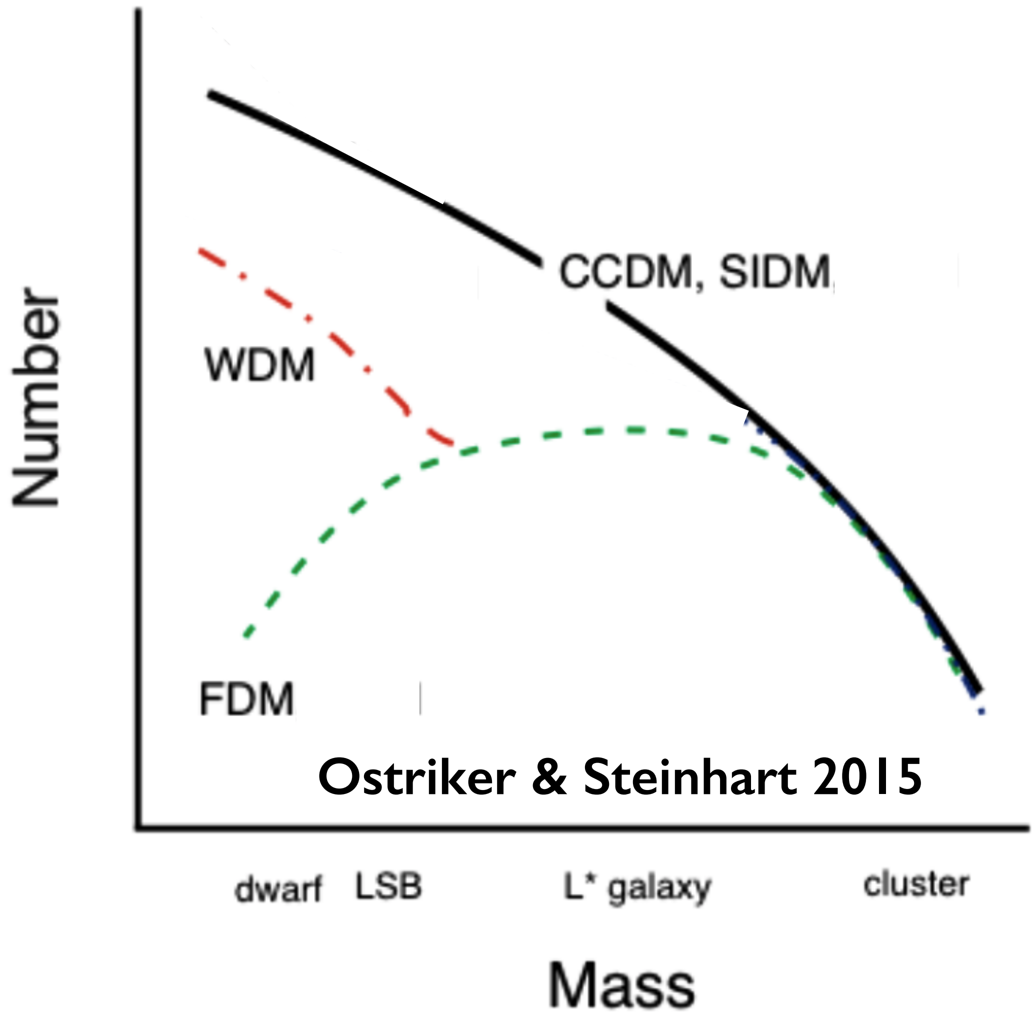
1) Blame Baryonic Physics



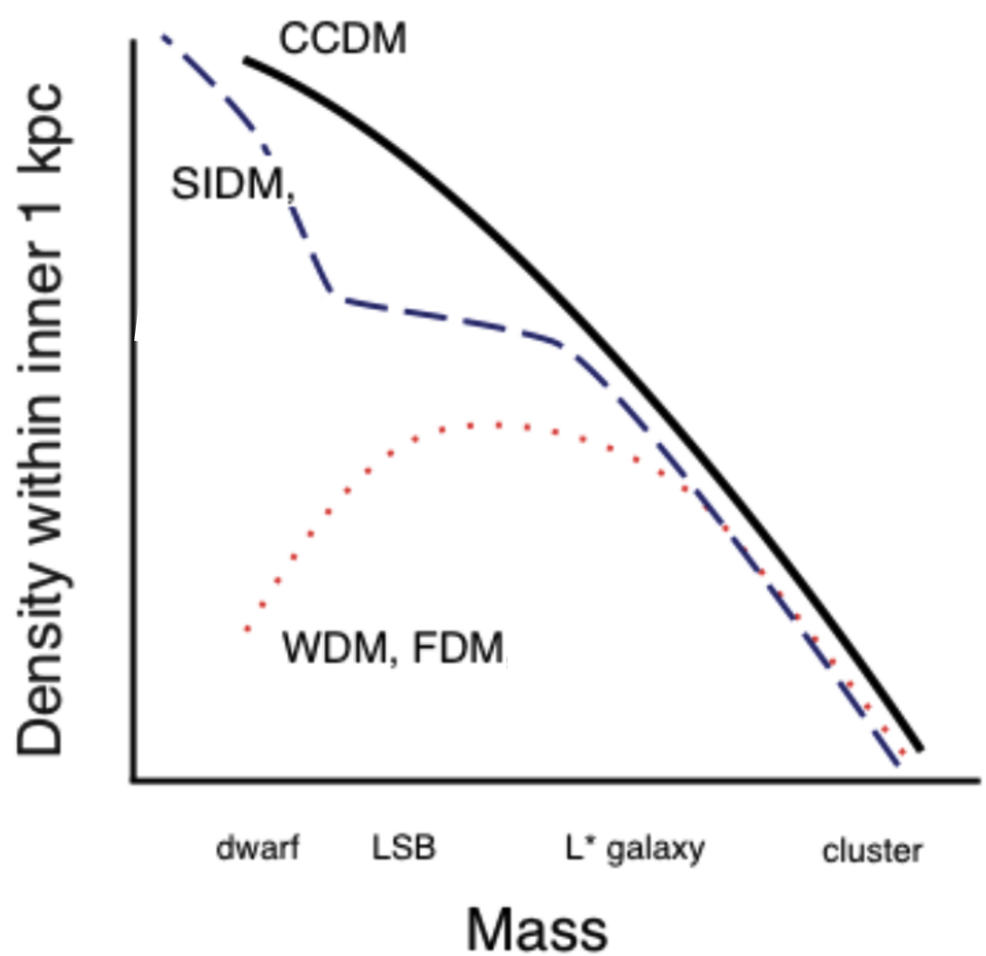
Bullock et al. 2017

Solutions to the MSP:

1) Blame Baryonic Physics
2) Blame C(C)DM

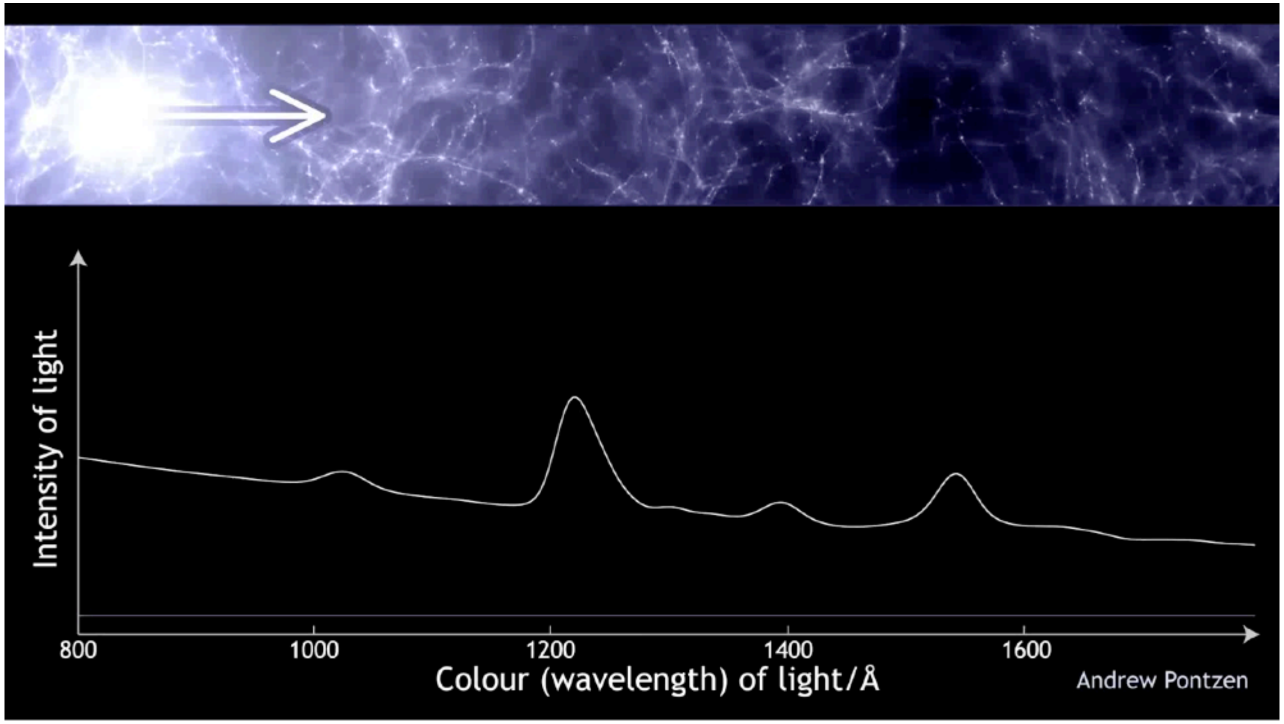


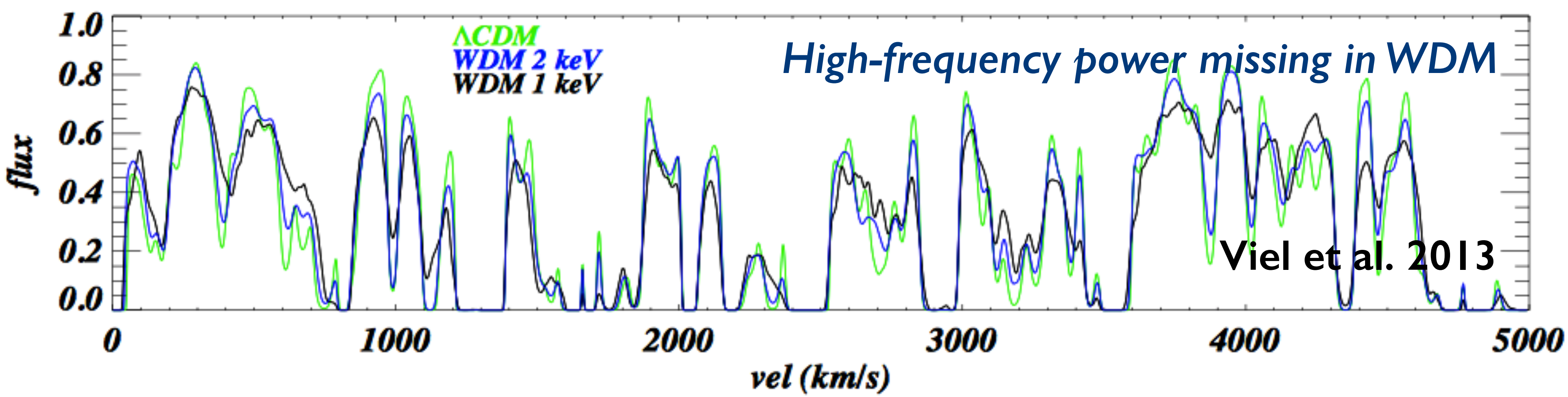
Internal structure: how the density density of the inner one kiloparsec depends on the mass of the system for different dark matter models.



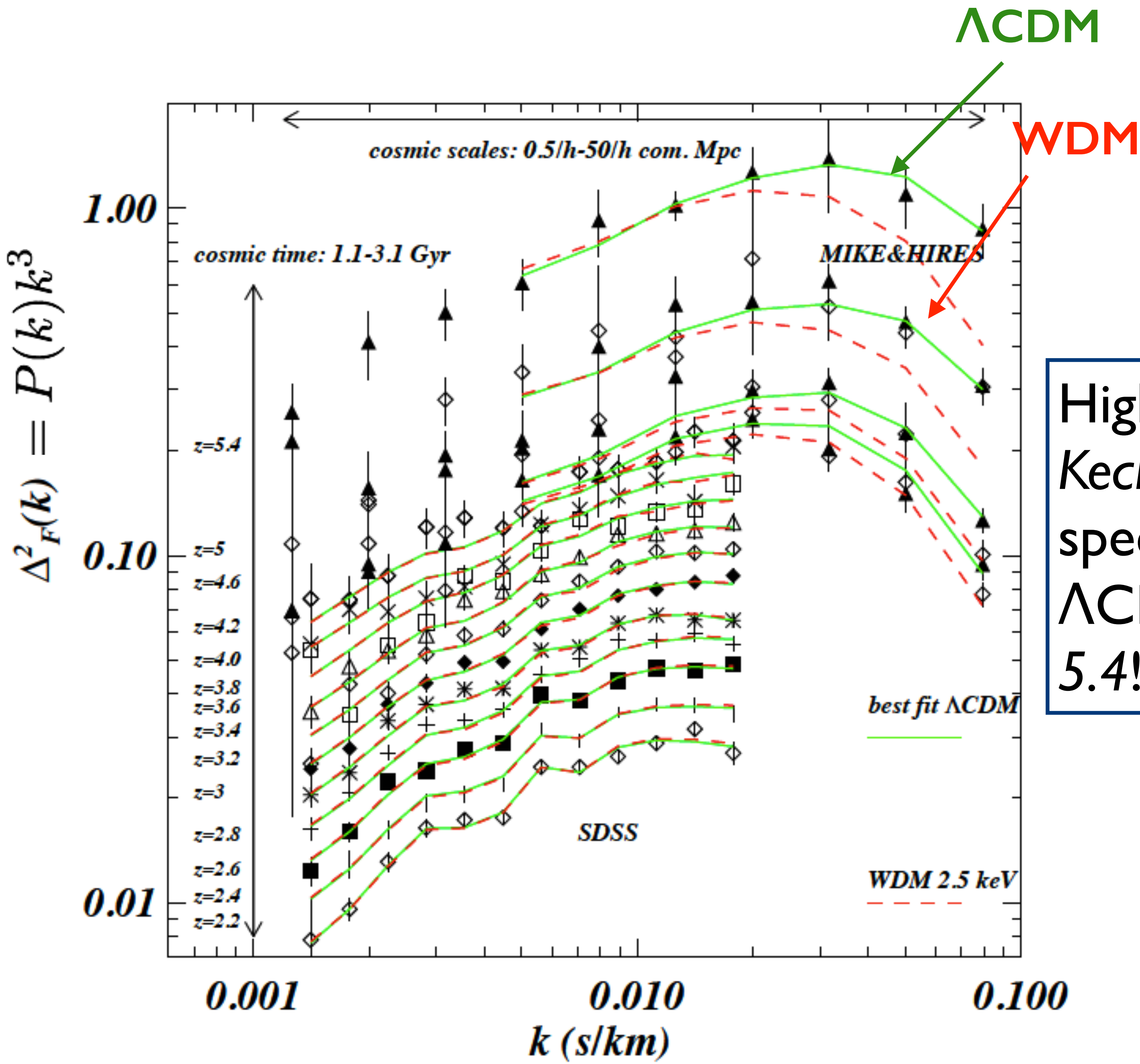
Demography: how the number of objects of a given type depends on their mass (as observed today) for different DM models.

The Forest Likes it Cold





The Lyman-α forest probes the matter power spectrum in velocity space. Structures in the absorption are due to fluctuations in the density and gravitationally induced velocity.



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

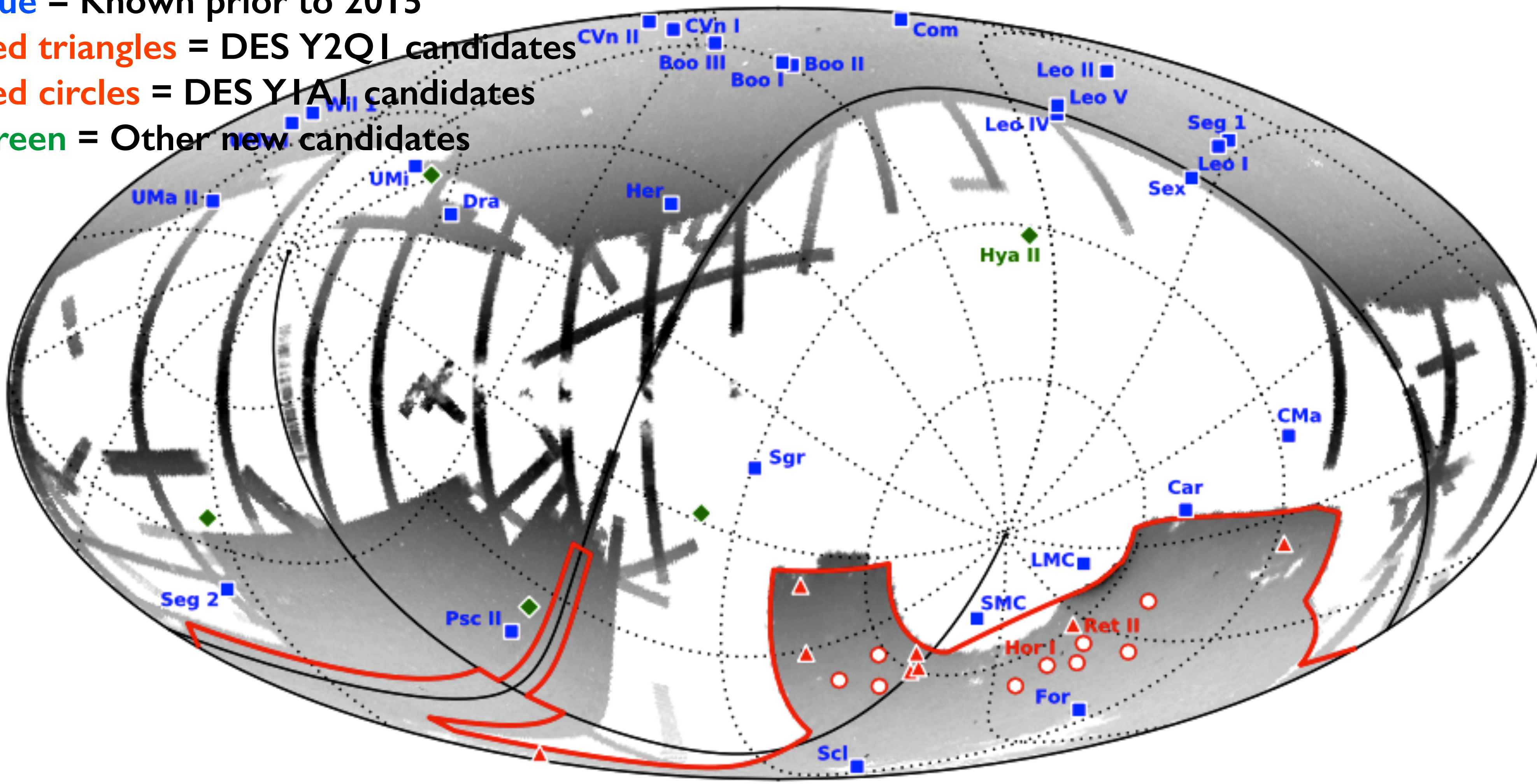
Solutions to the MSP:

1) Blame Baryonic Physics

2) Blame CDM

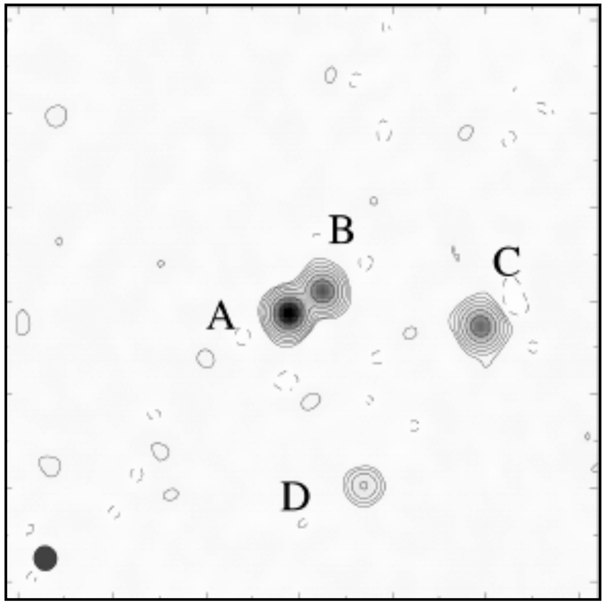
3) Blame Observations!

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

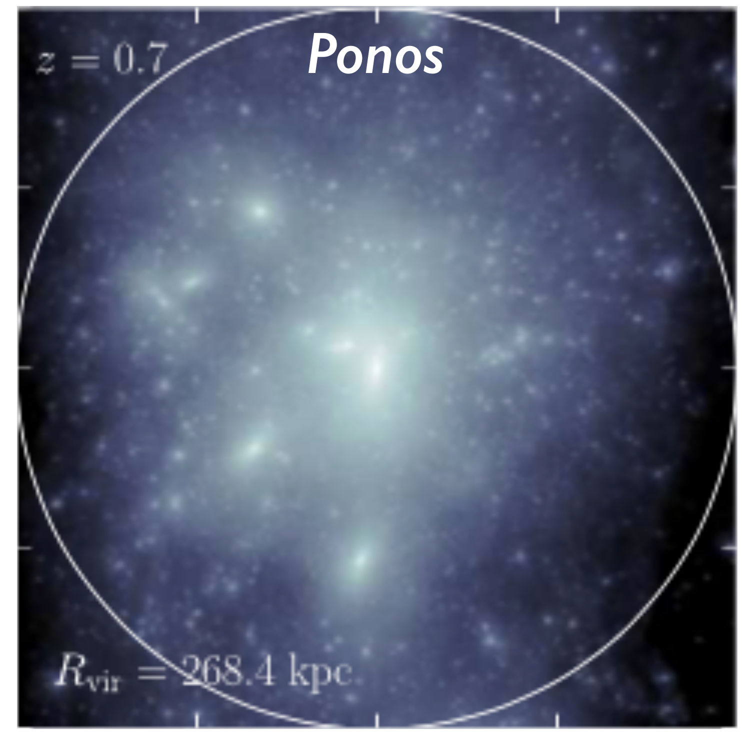


1)+3) ➪Q: Are Galaxy DM Halos Really Lumpy?

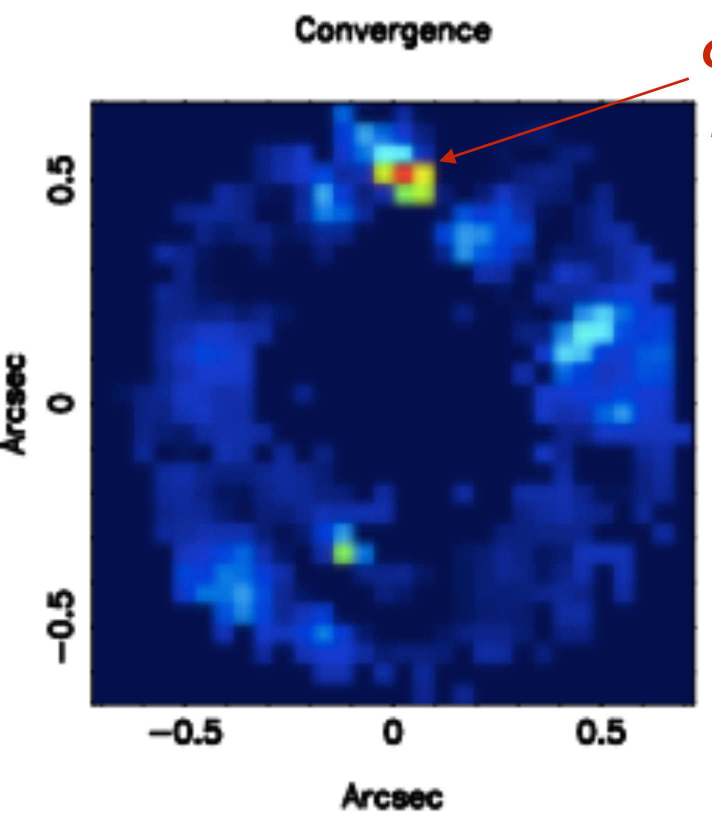
PROBES OF CDM SUBSTRUCTURE



First indication of *galaxy DM halo substructure*: flux ratio anomalies in lensed quasars (Metcalf & PM 2001; Dalal & Kochanek 2002).



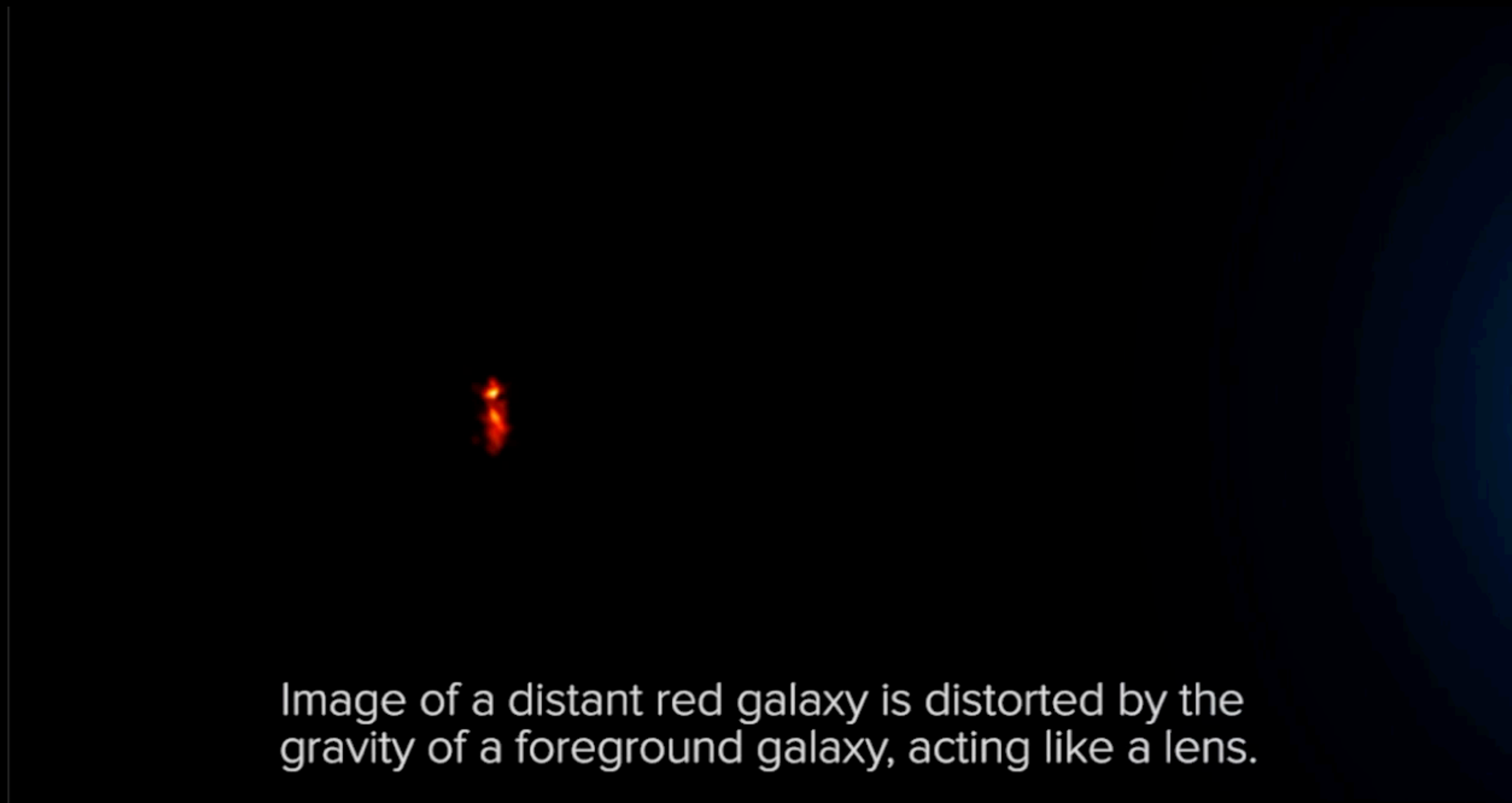
Fiacconi et al. 2016



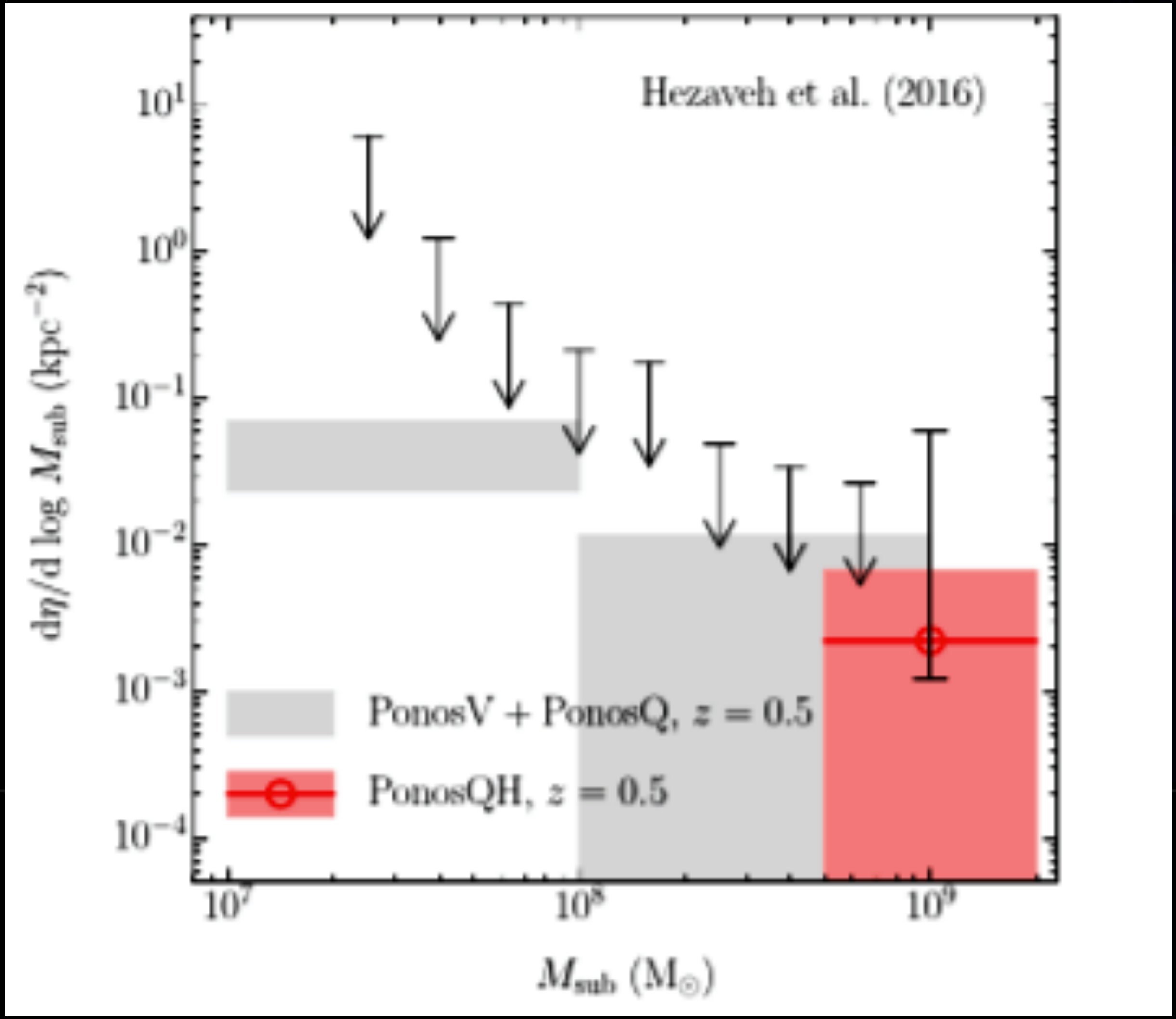
dark clump
$10^{8.3}$ $M_\odot$

Another lensing indication of mass substructure: surface brightness anomalies in bright Einstein rings (Vegetti et al. 2012).

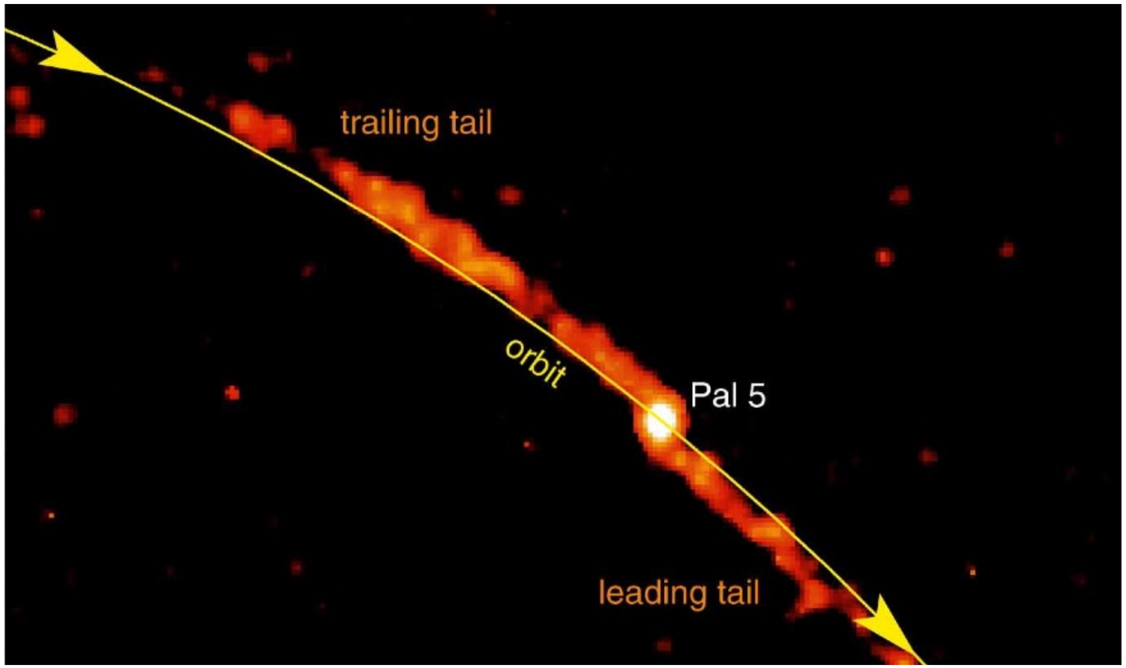
Detection of Lensing Substructure Using ALMA

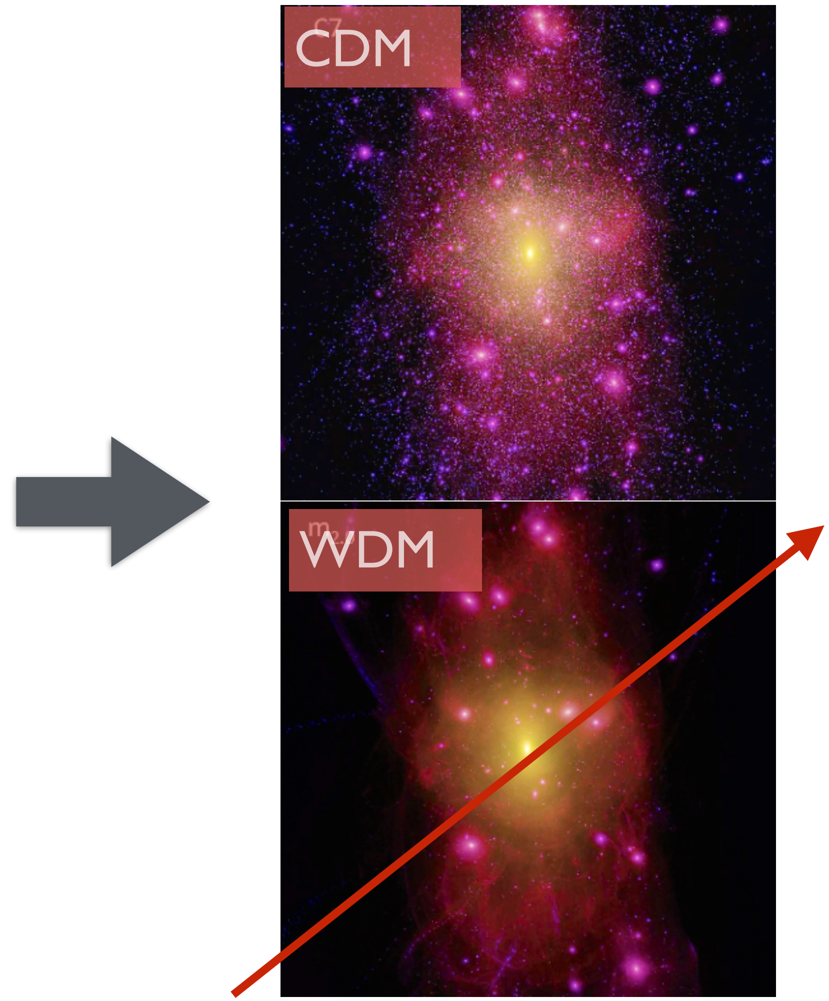


Detection of Lensing Substructure Using ALMA



A completely independent way of determining DM halo substructure: *cold stellar streams* (Yoon et al. 2001; Calberg 2012; Ngan et al. 2016). Streams suffer tens of impacts with *10^5-10^7* M⊙ subhalos that cause density fluctuations — *gaps* — along its length.

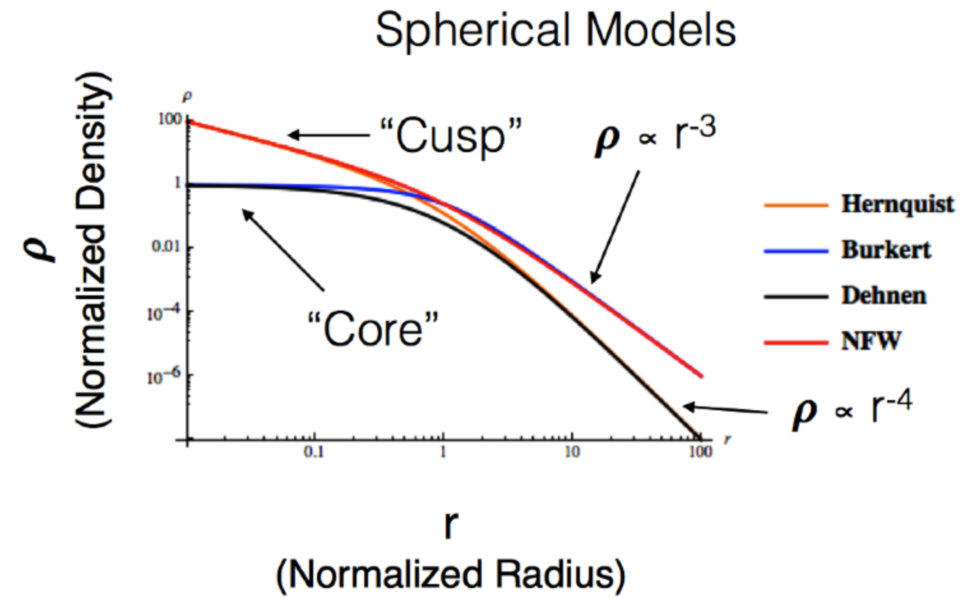


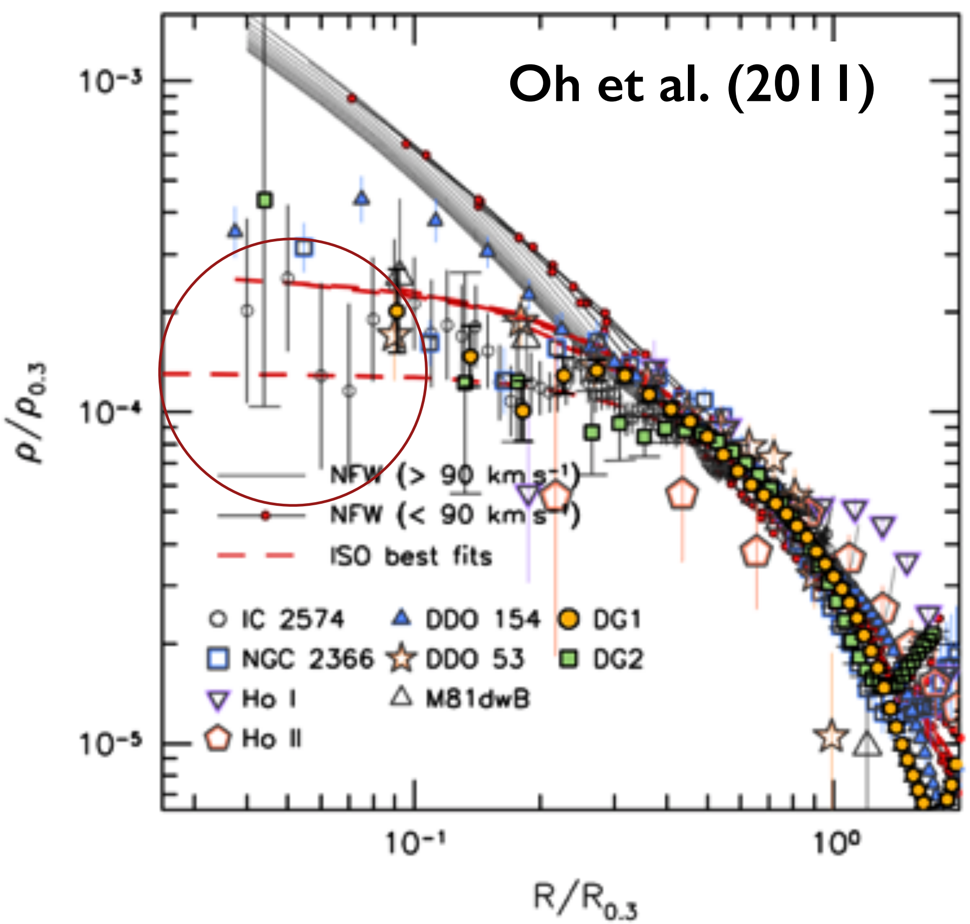


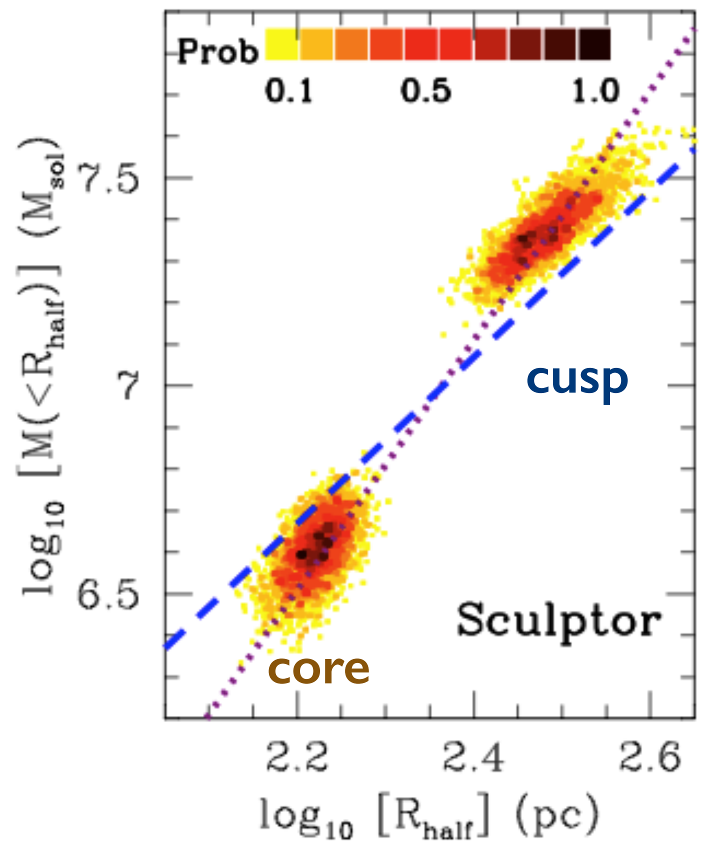
Bovy et al. 2017 (Pal 5): first determination of *10^{+11}_{-6}* dark matter subhalos with masses between *$10^{6.5}$* and *10^9* M⊙ within 20 kpc from the GC.

THE CORE-CUSP PROBLEM

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

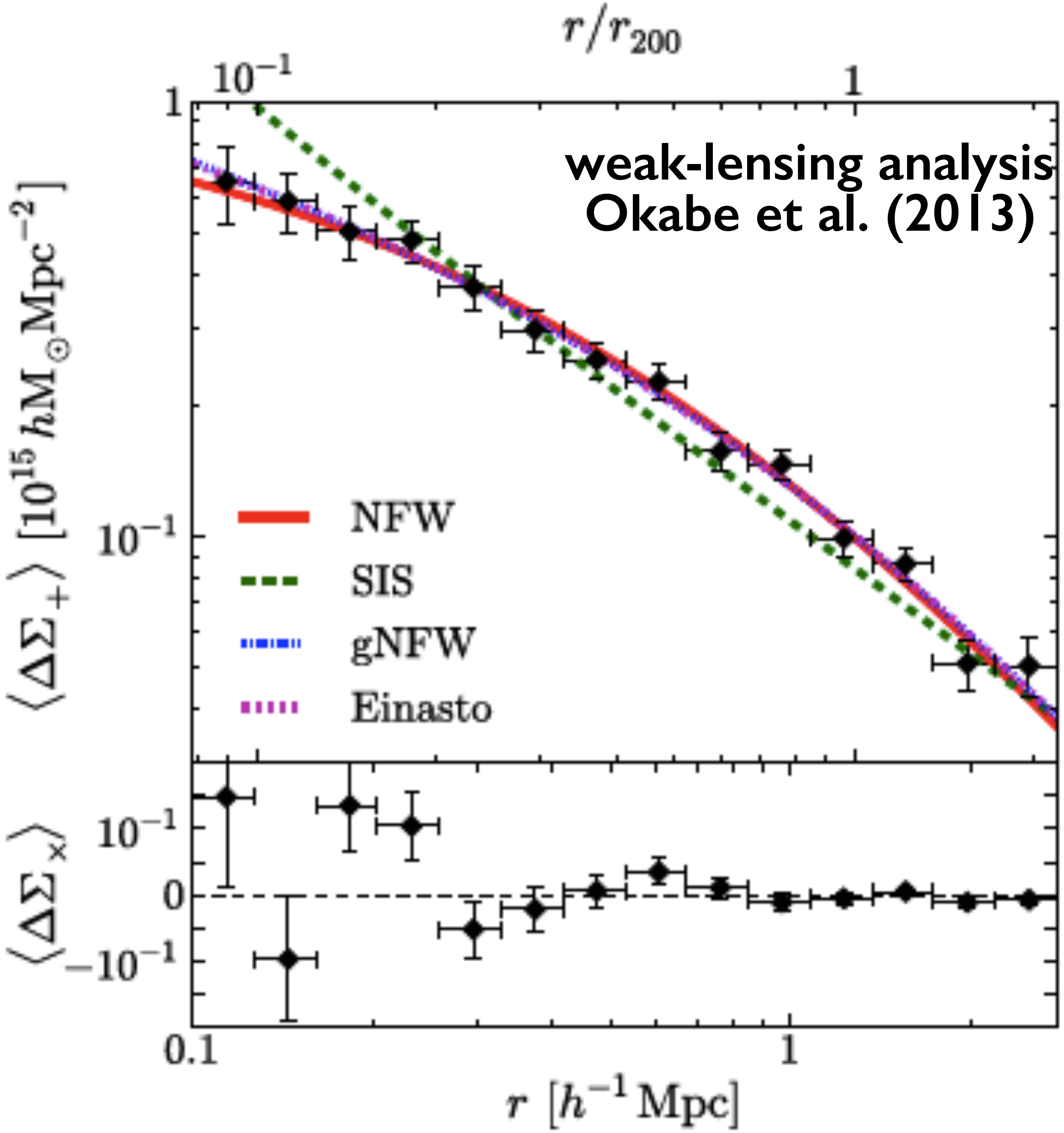






Walker et al. (2011)

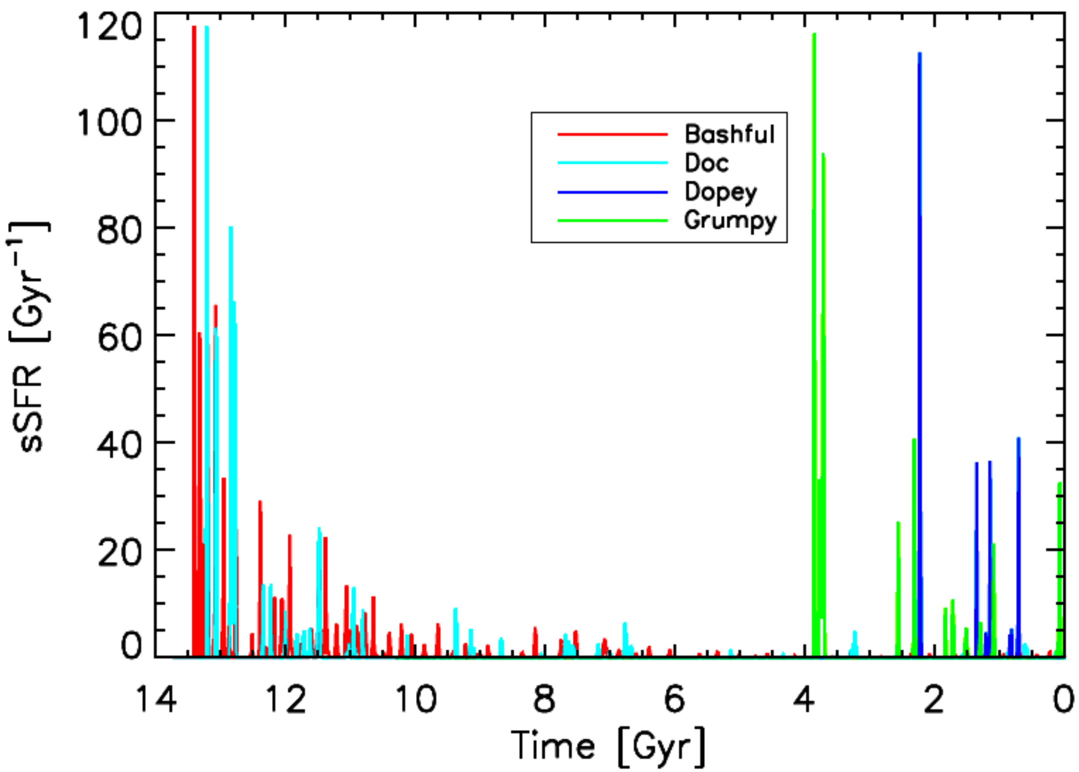
By contrast, rich galaxy clusters appear to have cuspy profiles…

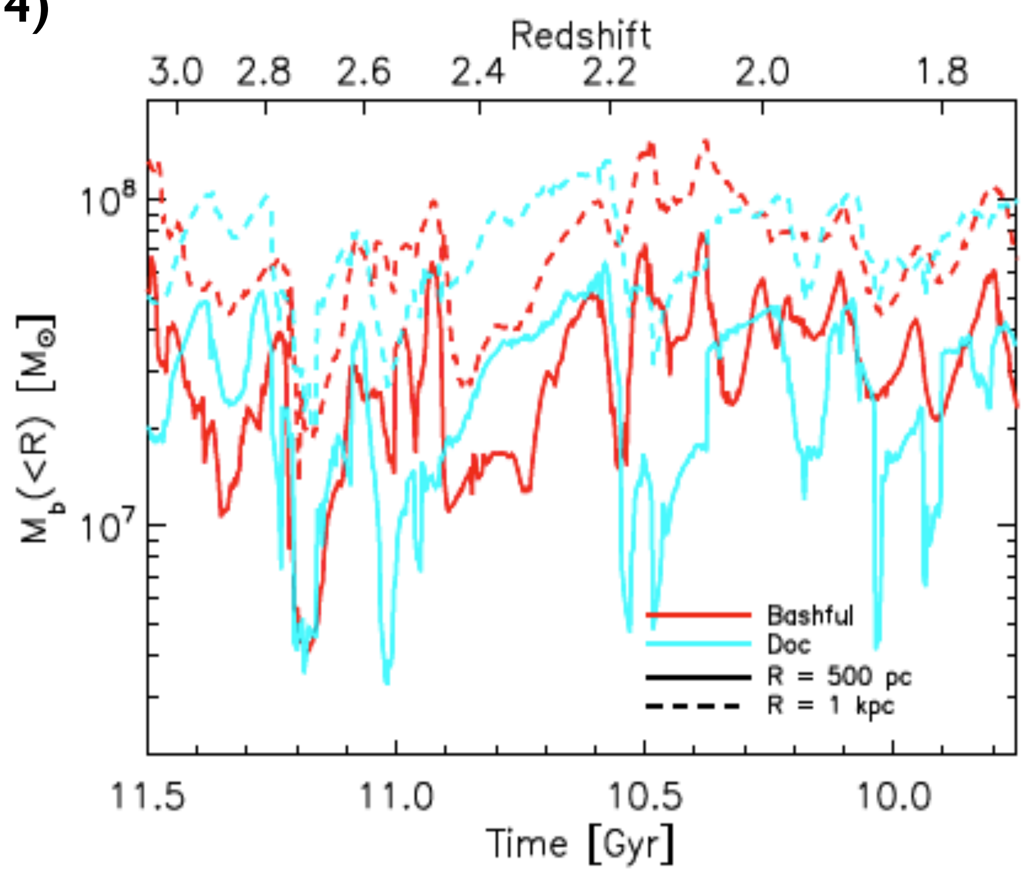


SN FEEDBACK ON DG SCALES

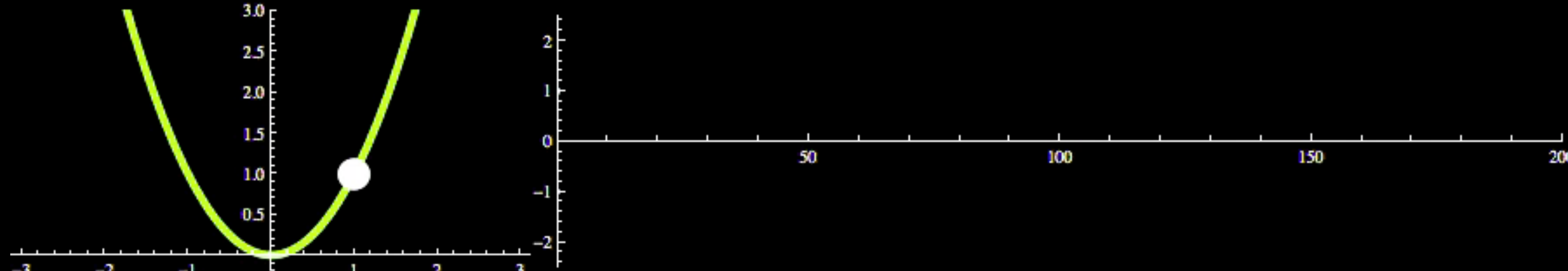
A new generation of hydrodynamic simulations, with *sufficient resolution to model clustered star formation and the impact of SN-driven winds*, have shown that *gravitational potential fluctuations* tied to efficient SN feedback can flatten the central cusps of halos in the most massive dwarfs.

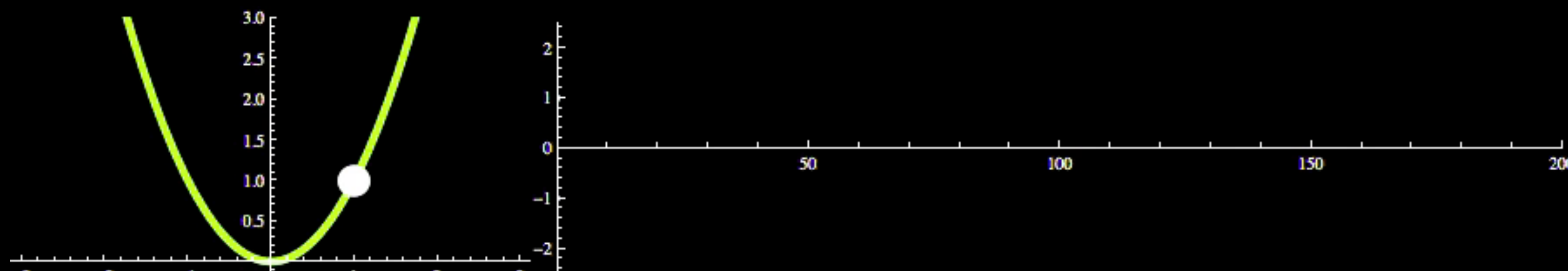
Governato et al. 2010, Madau et al. (2014)





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

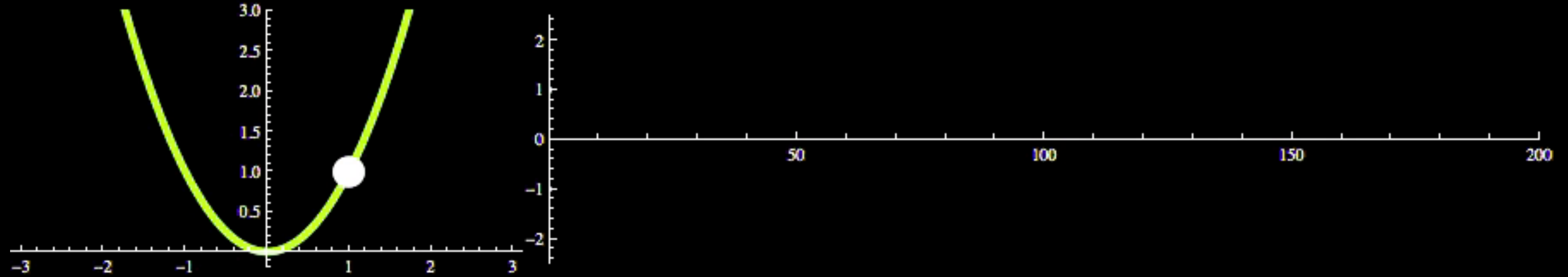


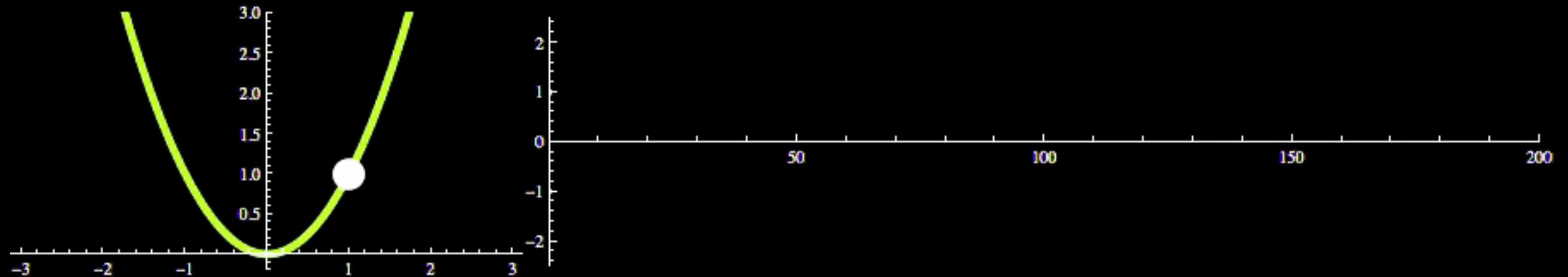


Pontzen & Governato 2012

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

Adiabatic Blow-Out & Recondensation





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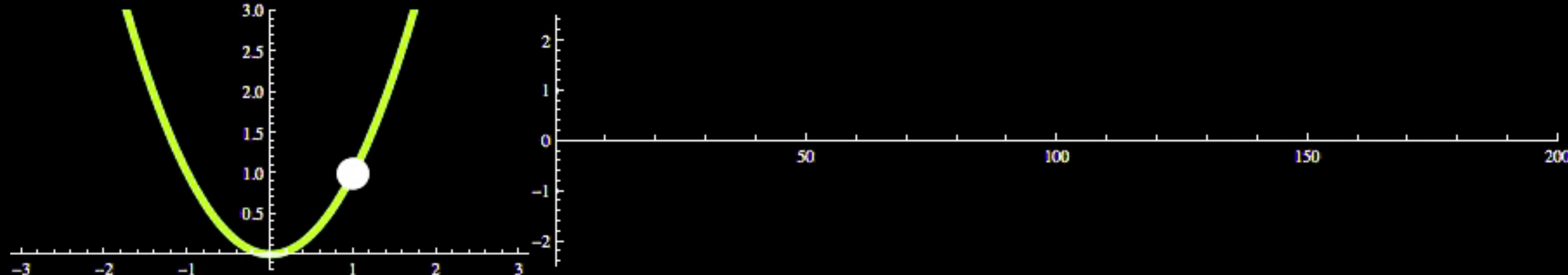
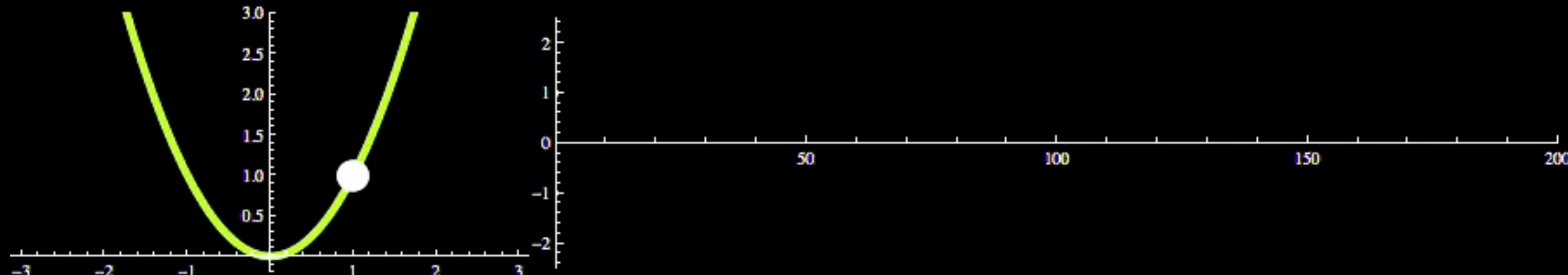
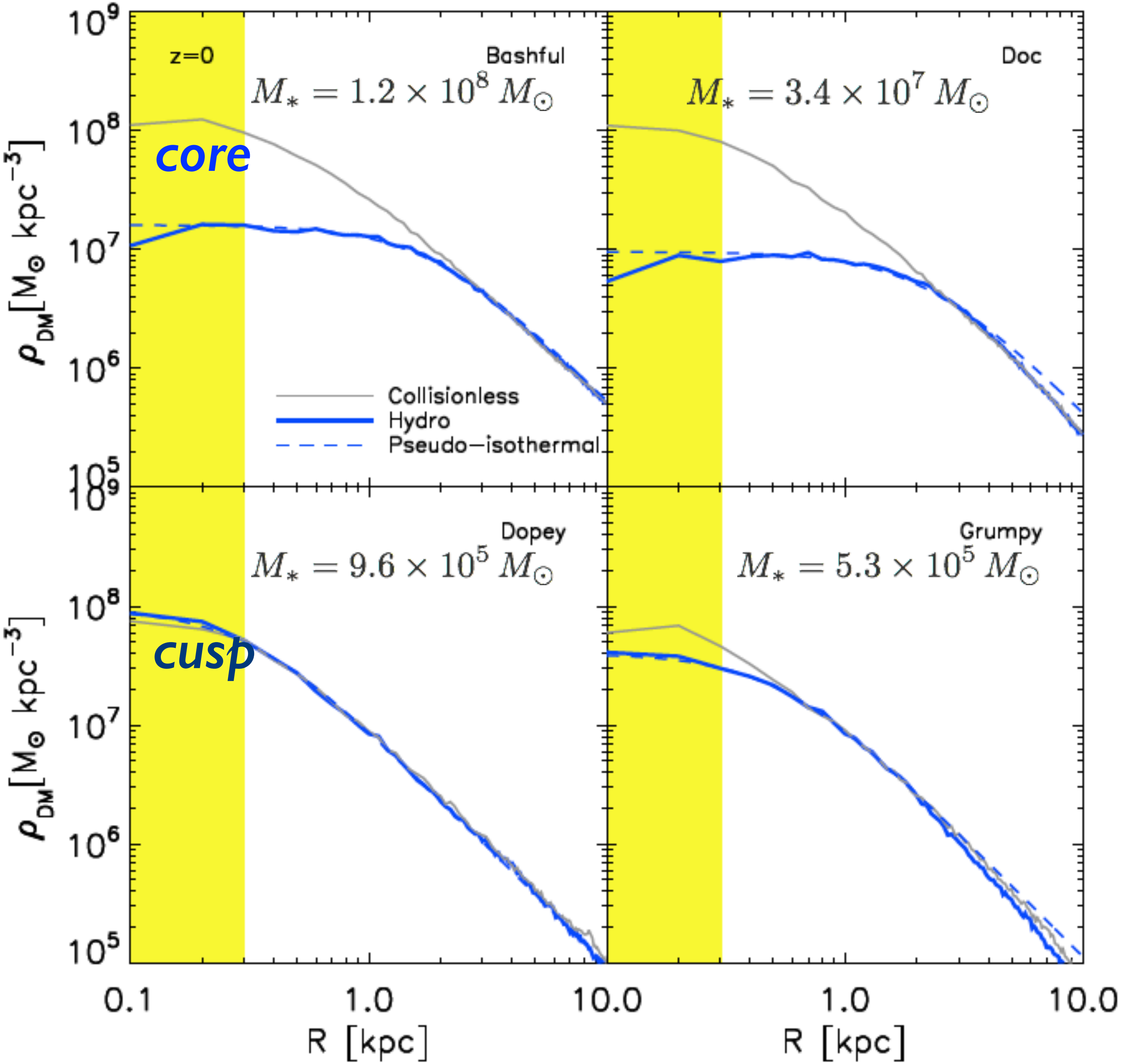


Sudden Blow-out, then Adiabatic Recondensation



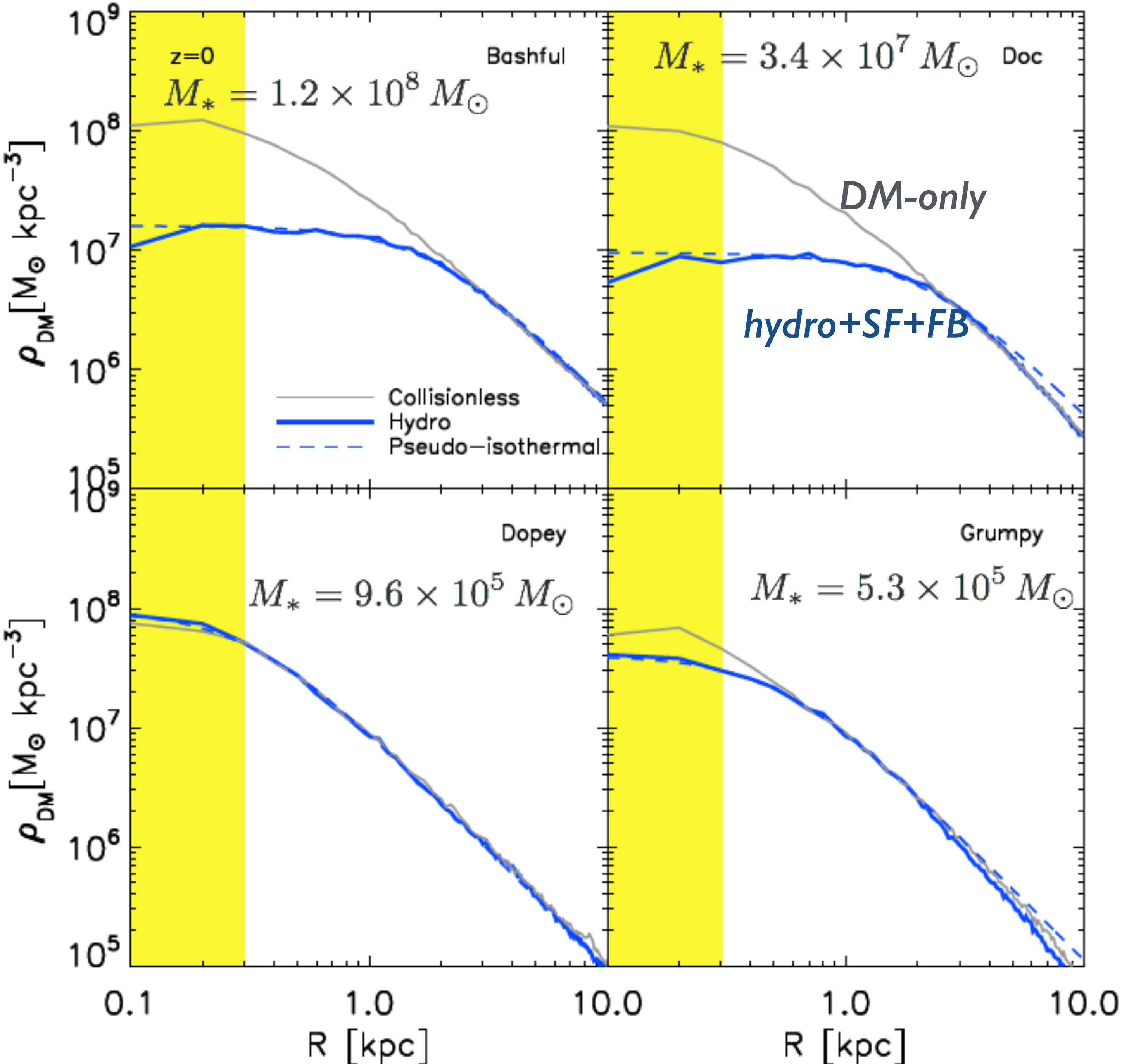
Pontzen & Governato 2012

CDM Heats up



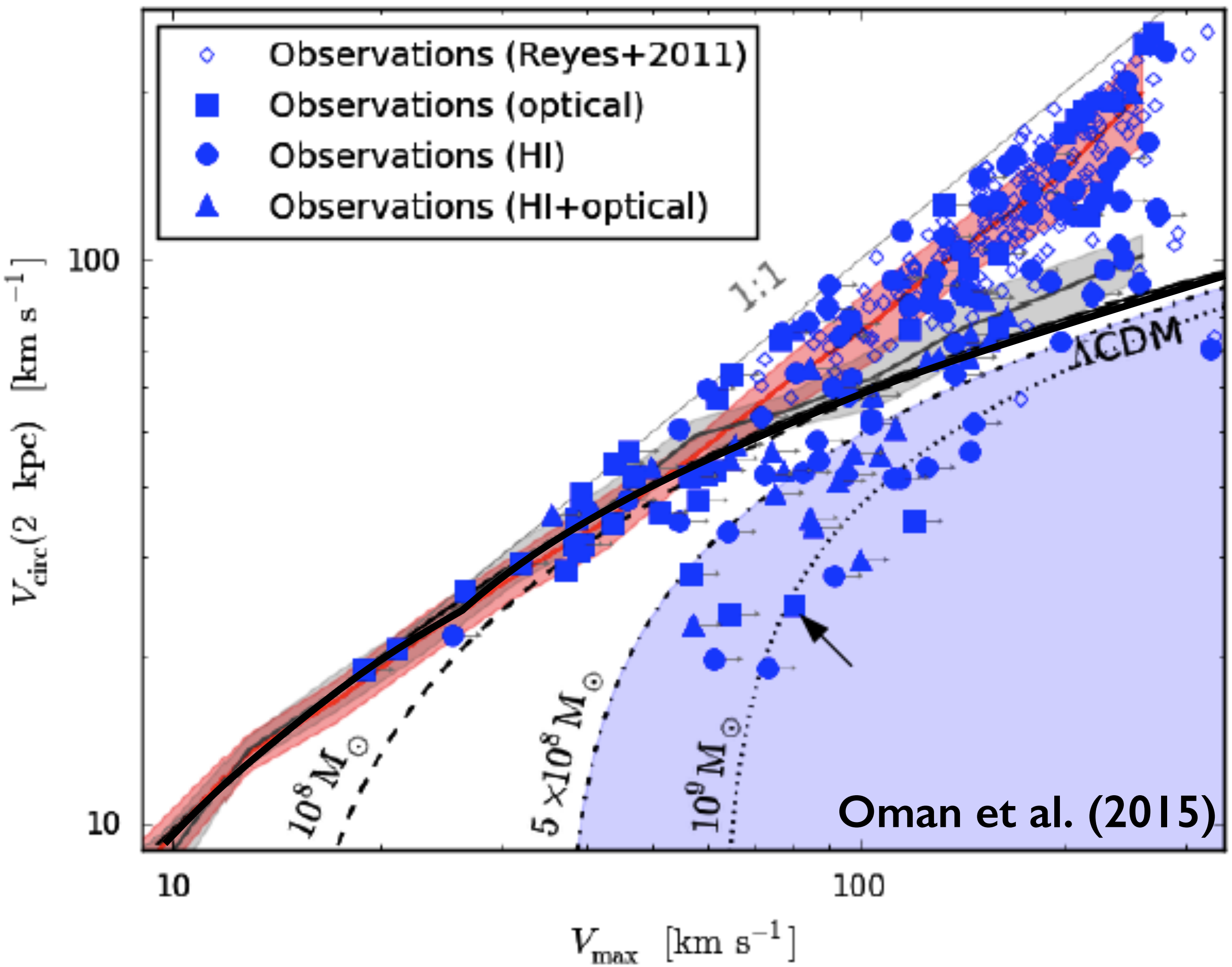
Madau et al 2014

CDM HEATS UP



Madau et al. (2014)

No Need for Modification of Standard ΛCDM Paradigm?



The diversity of observed rotation curves is *unexpected* in alternative dark matter scenarios. Can it be explained by baryonic effects?

WE KNOW MUCH, UNDERSTAND SOME, NEED HELP

- 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.

A Real Challenge for ΛCDM?

The unambiguous detection of
a dark matter core in a low stellar mass MW satellite!


THE END