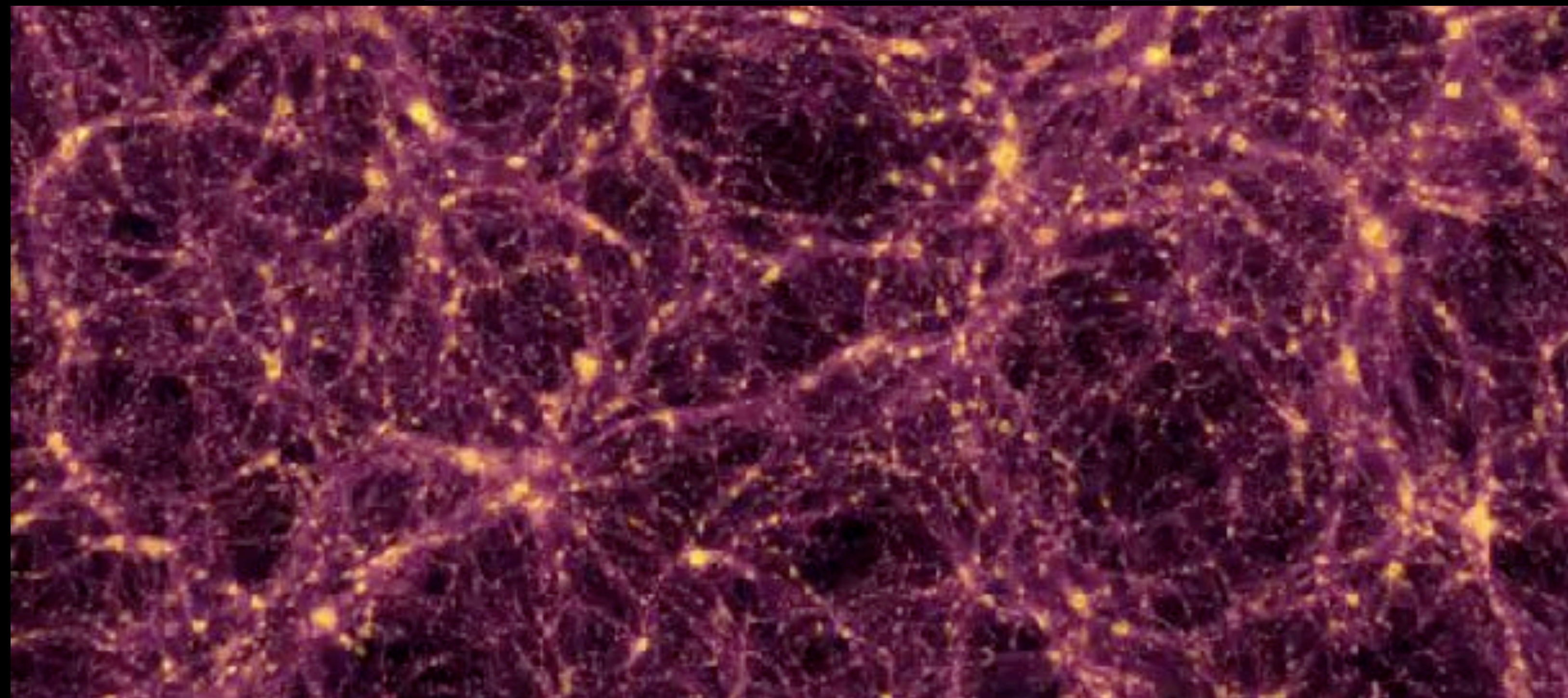
LSU
Department of Physics & Astronomy

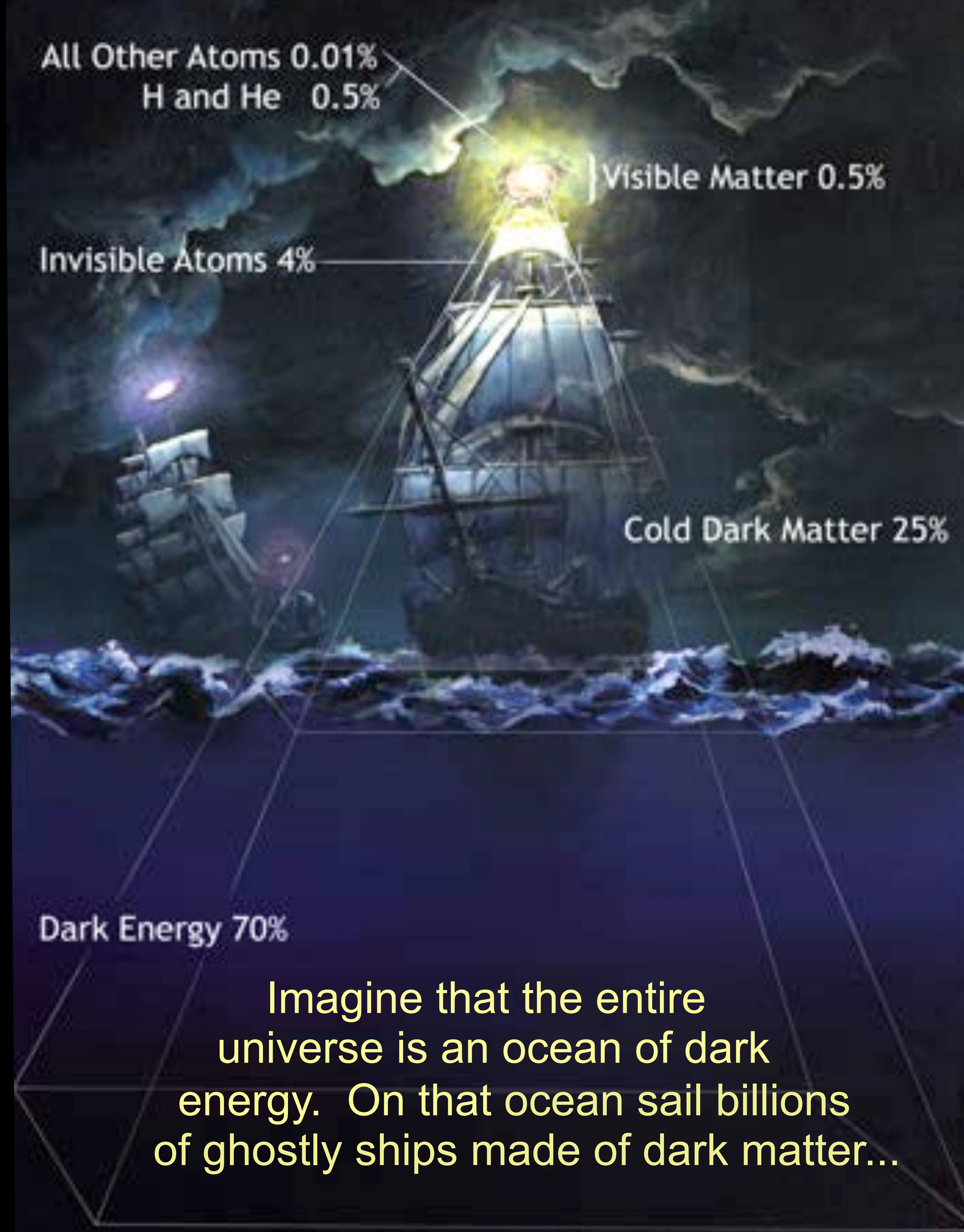


ΛCDM cosmology: successes, challenges, and opportunities for progress

Joel Primack, UC Santa Cruz

- **Successes:** CMB, Expansion History, Large Scale Structure, Galaxy Formation and Evolution
- **Challenges:** Cusp-Core, Too Big To Fail, Satellite Galaxies
- **Opportunities for Progress Now:** Halo Substructure by Gravitational Lensing and Stellar Motions, Early Galaxies, Compare and Improve Galaxy Simulations

Matter and Energy Content of the Universe



Imagine that the entire universe is an ocean of dark energy. On that ocean sail billions of ghostly ships made of dark matter...

Dark Matter Ships

on a

Dark Energy Ocean

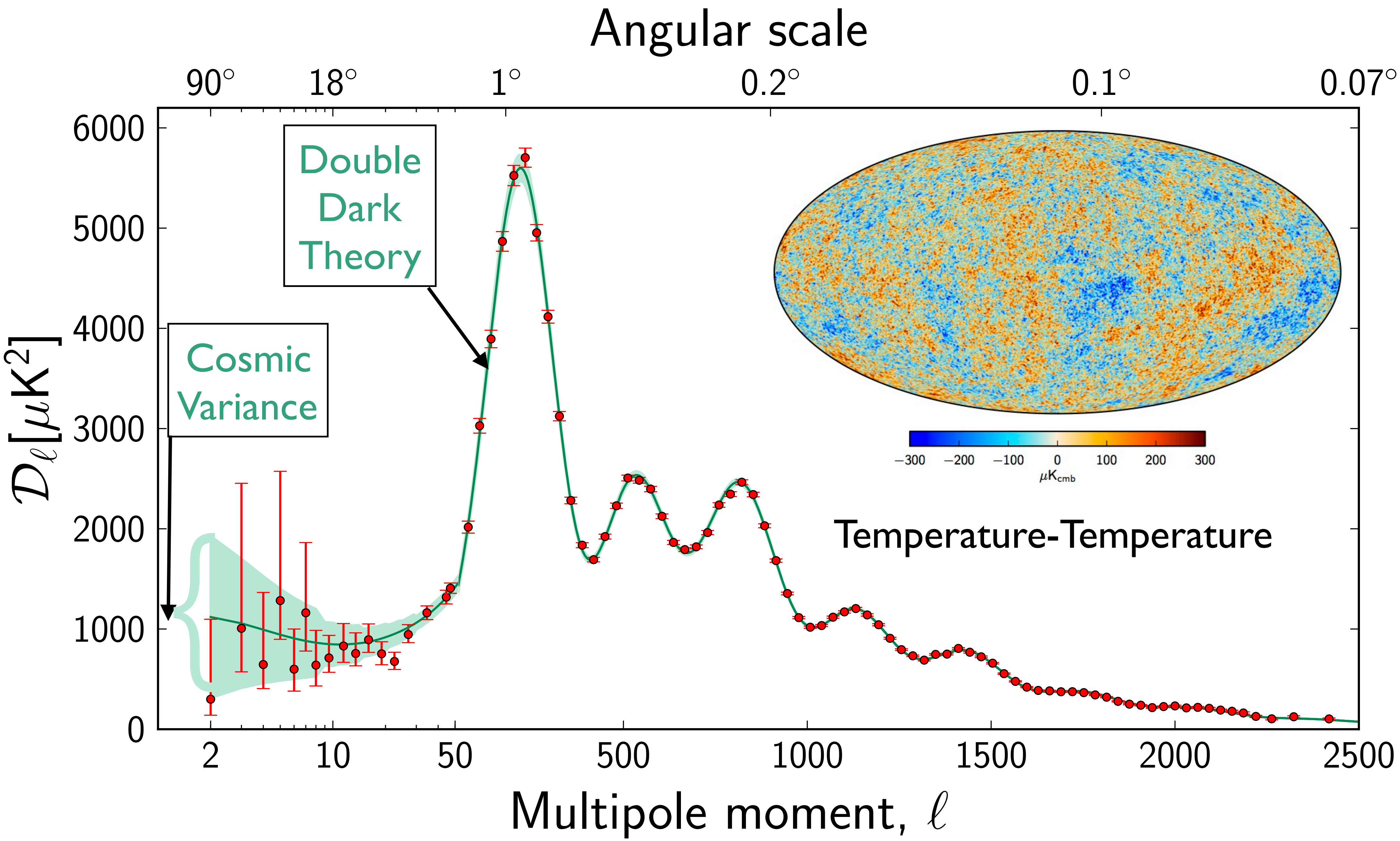
Matter and Energy Content of the Universe

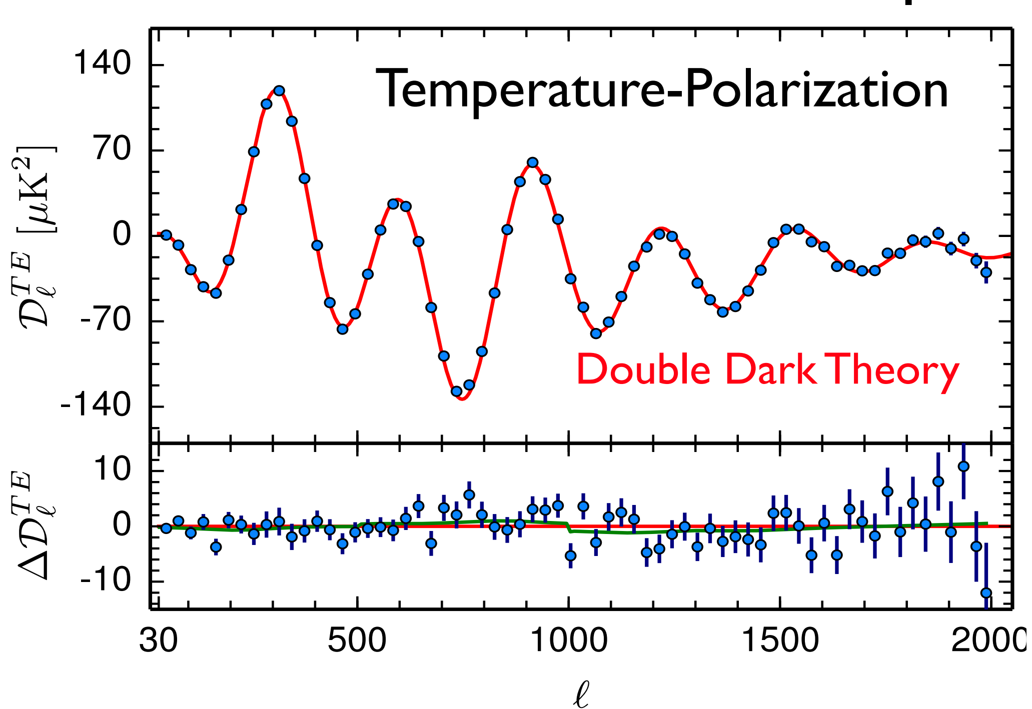
ΛCDM

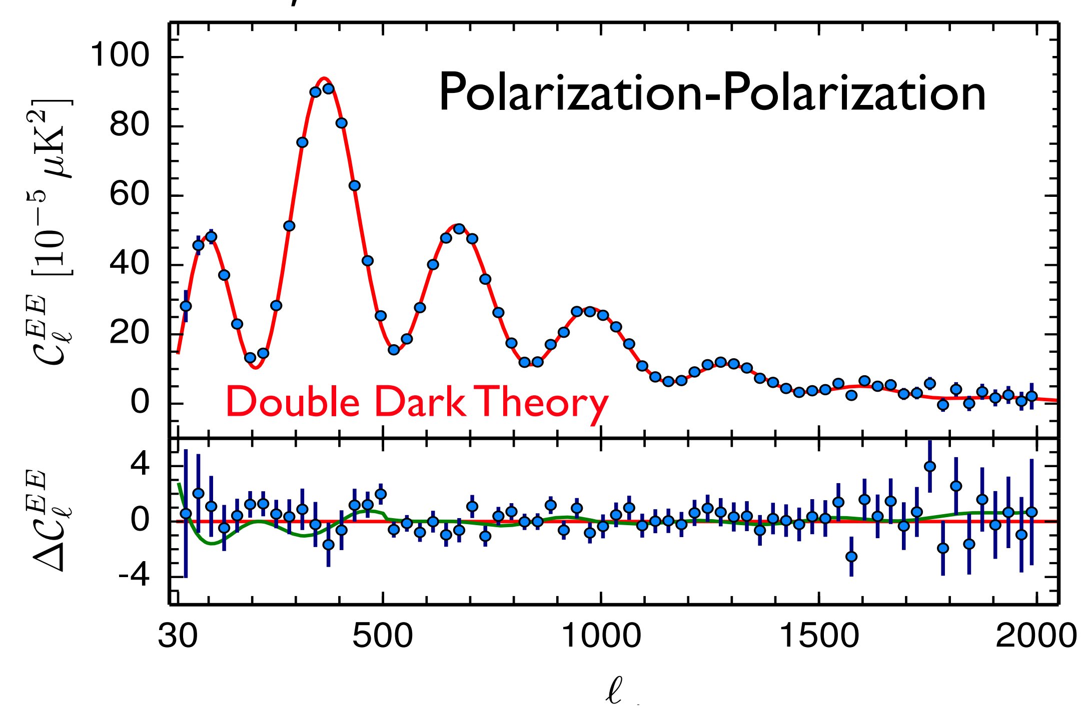
Double Dark Theory

European Space Agency PLANCK Satellite Data

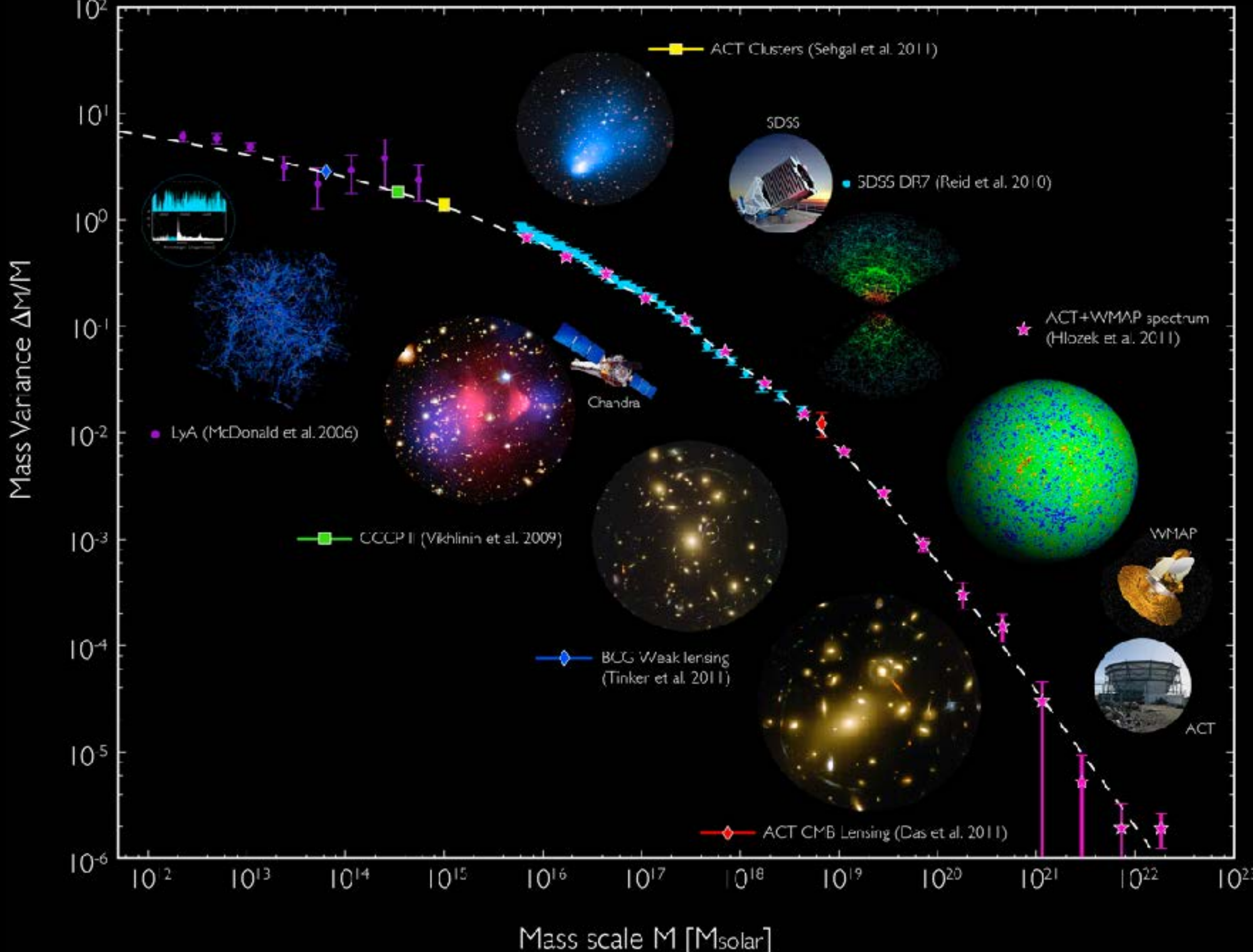
Released February 9, 2015







Matter Distribution Agrees with Double Dark Theory!



Planck 2015 XIII Cosmology Conclusions

The six-parameter base ΛCDM model continues to provide a very good match to the more extensive 2015 *Planck* data, including polarization. This is the most important conclusion of this paper.

The *Planck TT*, *TE*, and *EE* spectra are accurately described with a purely adiabatic spectrum of fluctuations with a spectral tilt $n_s = 0.968 \pm 0.006$, consistent with the predictions of single-field inflationary models. Combining the *Planck* and BICEP2/Keck/Planck likelihoods, we find a tight constraint on tensor modes $r_{0.002} < 0.08$ (95%CL), strongly disfavouring inflationary models with $V(\phi) \sim \phi^2$ (Planck XX, Inflation, 2016).

The *Planck* best-fit base ΛCDM cosmology is in good agreement with results from BAO surveys, with the recent JLA sample of Type Ia SNe, and with the recent analysis of redshift-space distortions of the BOSS CMASS-DR11.

The Hubble constant in this cosmology is $H_0 = (67.8 \pm 0.9)$ km s^{-1}Mpc^{-1}. Dark energy is constrained to $w = -1.006 \pm 0.045$ and is therefore compatible with a cosmological constant, as assumed in the base ΛCDM cosmology.

Combining *Planck* TT+lowP+lensing with BAO we find $N_{eff} = 3.15 \pm 0.23$ for the effective number of relativistic degrees of freedom, consistent with the value $N_{eff} = 3.046$ of the standard model. The sum of neutrino masses is constrained to $\sum m_\nu < 0.23$ eV. The standard theory of big bang nucleosynthesis is in excellent agreement with *Planck* data and observations of primordial light element abundances.

The analysis of 2015 *Planck* data reported in Planck Collaboration XVII (2015) sets unprecedentedly tight limits on primordial non-Gaussianity. If there is new physics beyond base ΛCDM, then the corresponding observational signatures in the CMB are weak and difficult to detect. This is the legacy of the *Planck* mission for cosmology.

Neutrino masses and cosmology with Lyman-alpha forest power spectrum

Nathalie Palanque-Delabrouille et al., JCAP 11 (2015) 011

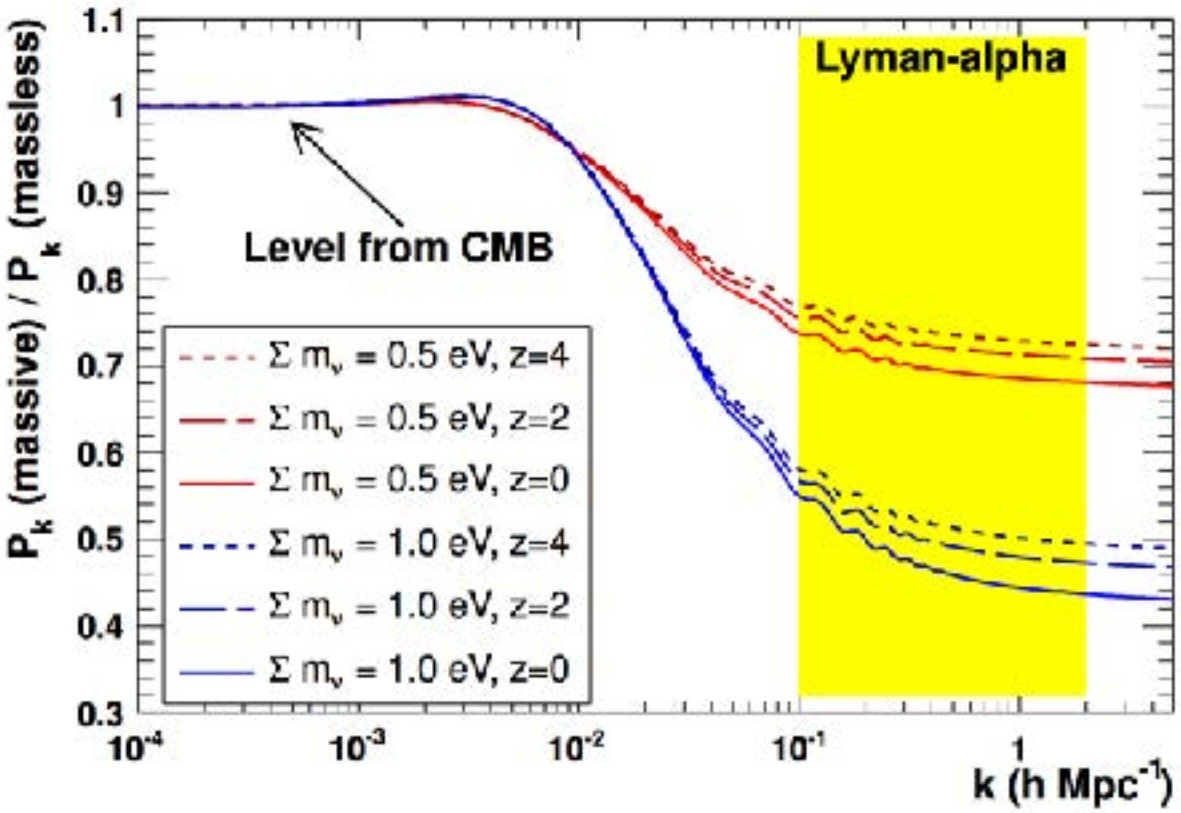
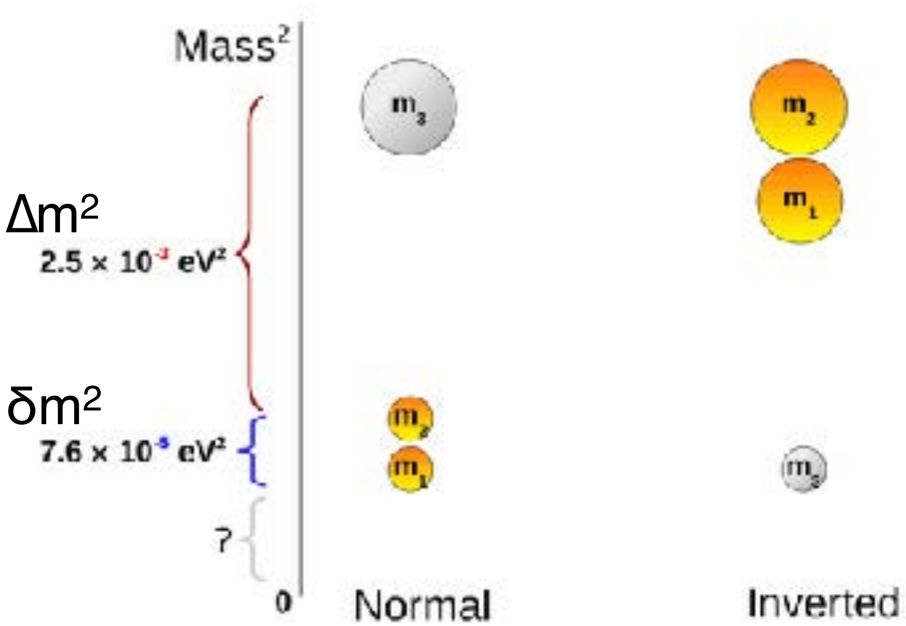
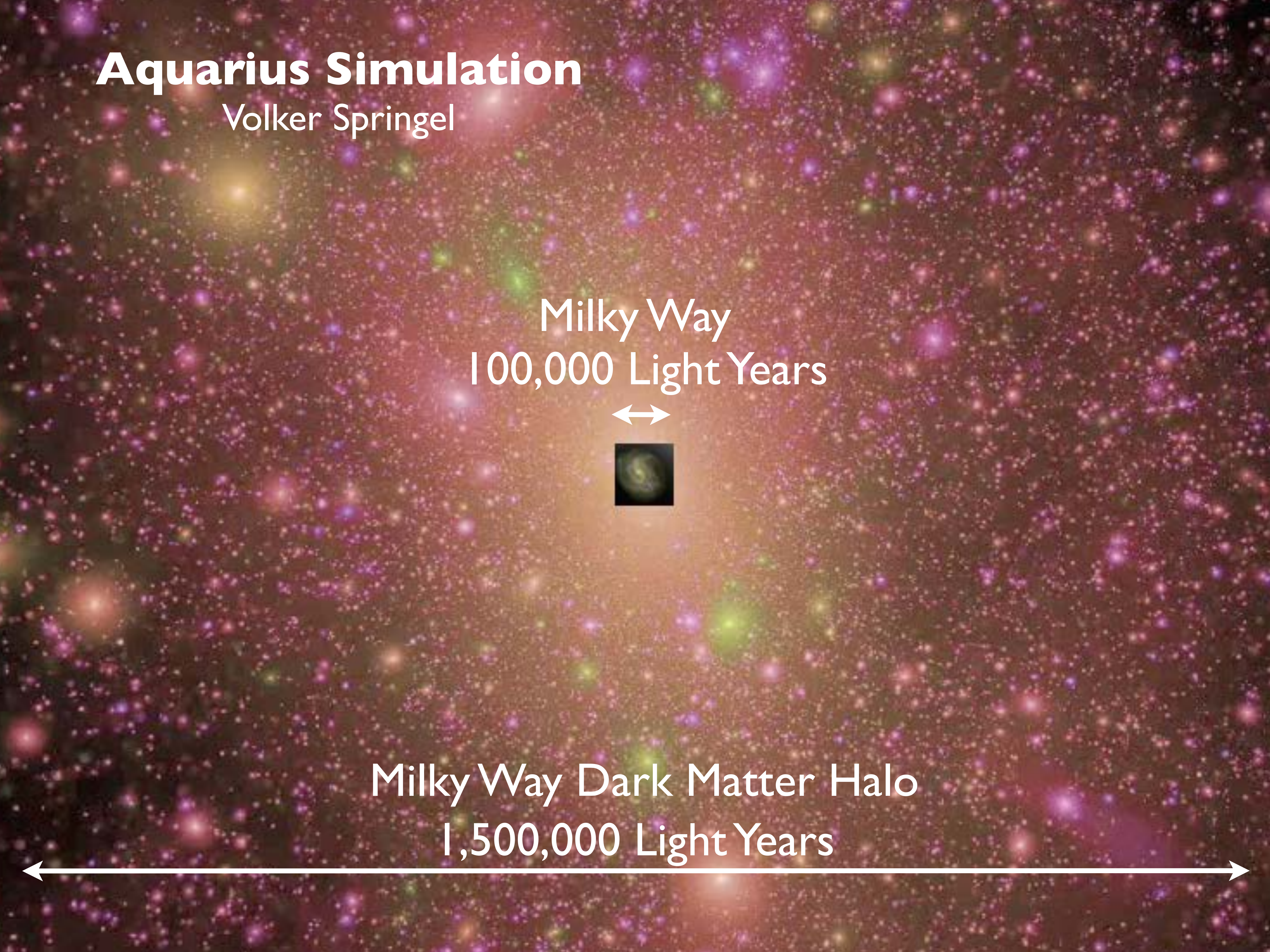


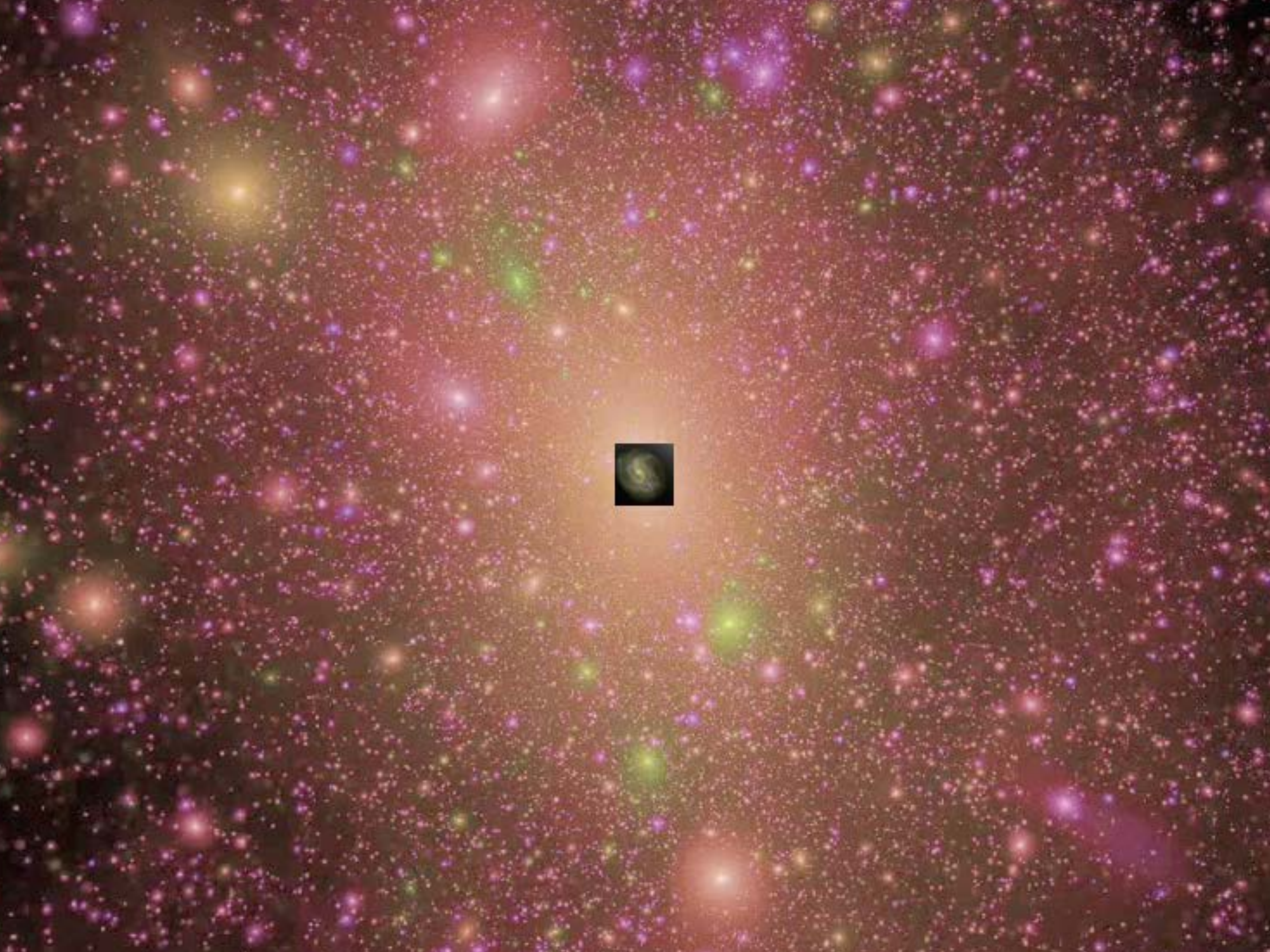
Figure 1. Linear theory prediction for the matter power spectra with massive neutrinos, normalized to the corresponding massless neutrino case. The yellow zone delimits the range of k covered by the 1D Lyα flux power spectrum from the BOSS survey.

Combining BOSS Lyα with Planck CMB constrains the sum of neutrino masses to $\sum m_\nu < 0.12$ eV (95% C.L.) including all identified systematic uncertainties. This is close to ruling out the Inverted Hierarchy.



According to the 2014 compilation of Capozzi et al. (Phys Rev D89, 093018) from atmospheric, solar, reactor and accelerator neutrino experiments, the squared neutrino mass differences satisfy $\delta m^2 = 7.54 \pm 0.24 \times 10^{-5}$ eV^2 and $\Delta m^2 = 2.43 \pm 0.06 \times 10^{-3}$ eV^2. The masses can follow a normal hierarchy (NH) with two light states and a heavier one, in which case the minimum total mass is $\sum m_\nu = 0.06$ eV. In case of inverted hierarchy (IH), the two heavy states are split by δm^2 and the lighter one is separated from the other two by Δm^2, i.e. the mass difference is $\sqrt{\Delta m^2} = 0.049$ eV. The minimum total mass is then 0.098 eV.


Aquarius Simulation
Volker Springel
Milky Way
100,000 Light Years
Milky Way Dark Matter Halo
1,500,000 Light Years

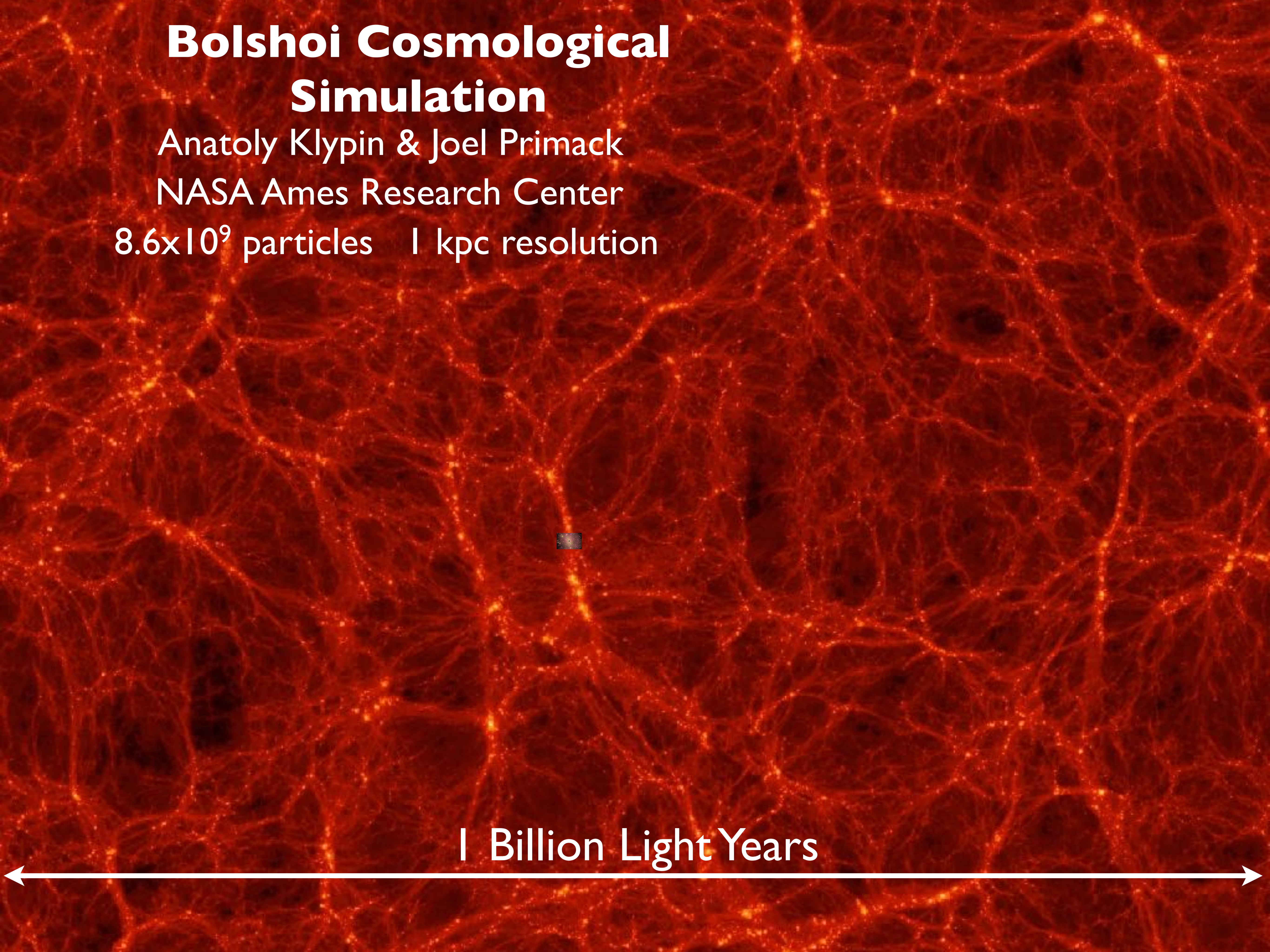


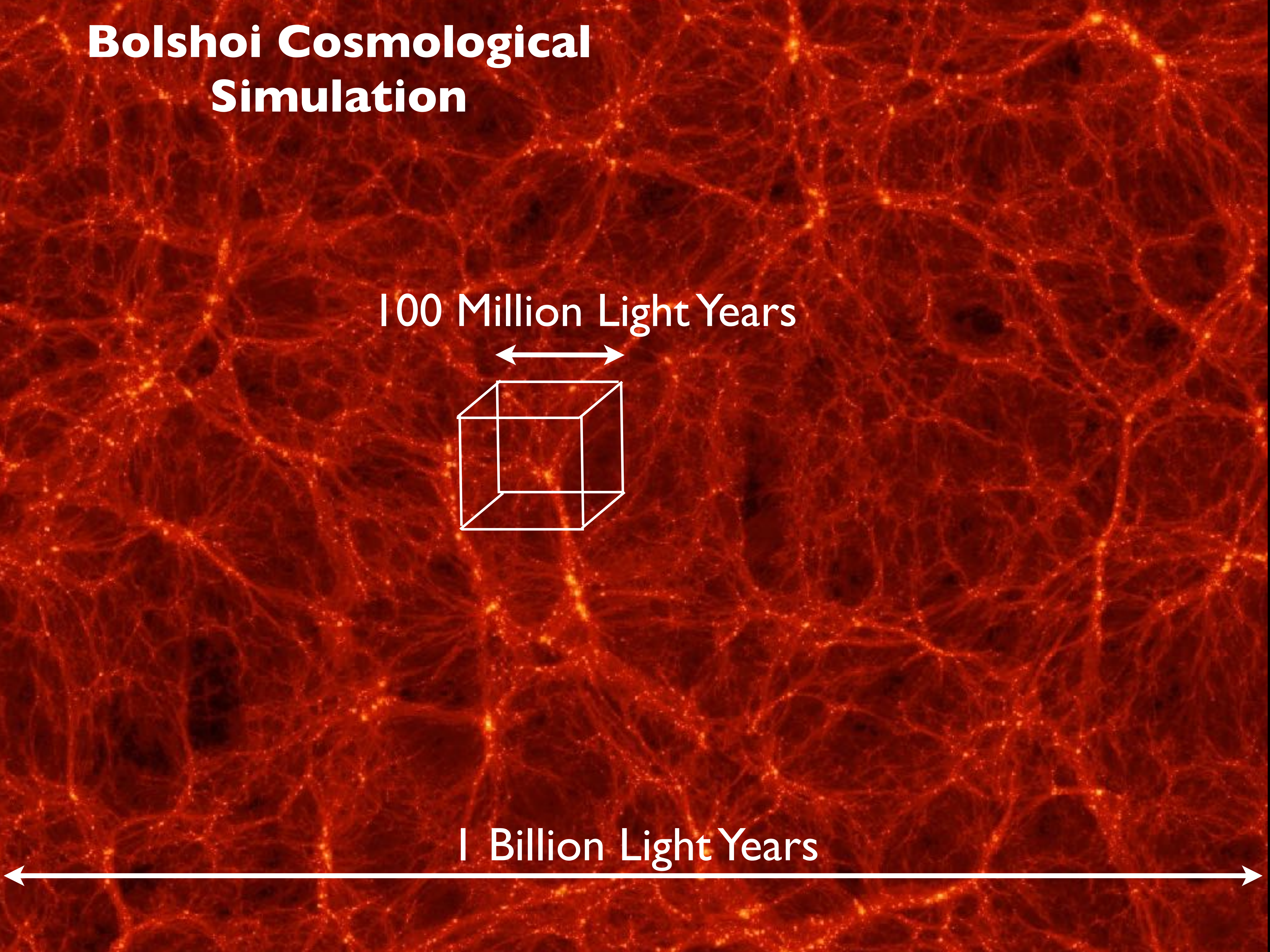
Bolshoi Cosmological Simulation

Anatoly Klypin & Joel Primack

NASA Ames Research Center

8.6×10^9 particles   1 kpc resolution




Bolshoi Cosmological Simulation
100 Million Light Years
1 Billion Light Years

How the Halo of the Big Cluster Formed

100 Million Light Years

Bolshoi-Planck Cosmological Simulation

Merger Tree of a Large Halo

Structure Formation Methodology

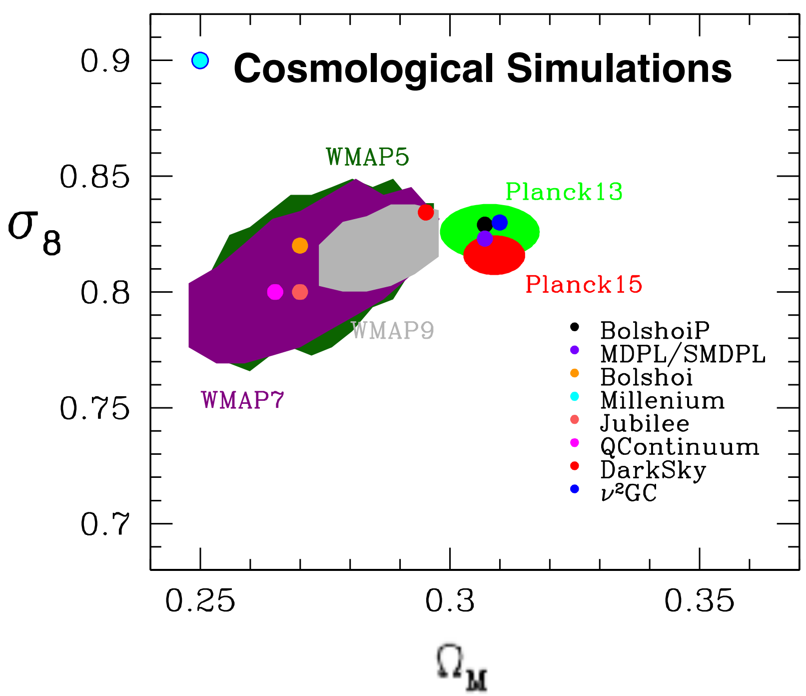
- Starting from the Big Bang, we simulate the evolution of a representative part of the universe according to the Double Dark theory to see if the end result matches what astronomers actually observe.

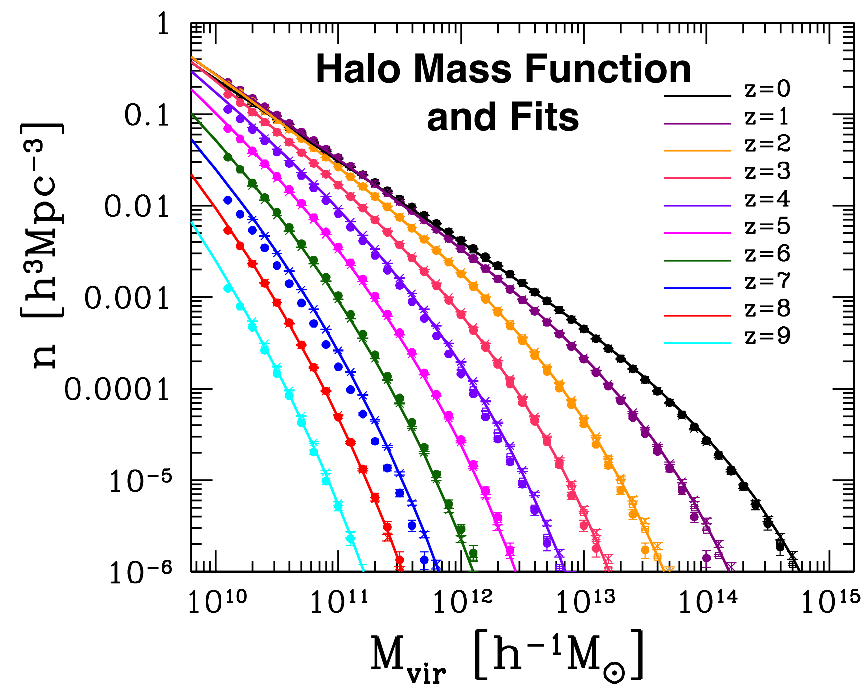
Structure Formation Methodology

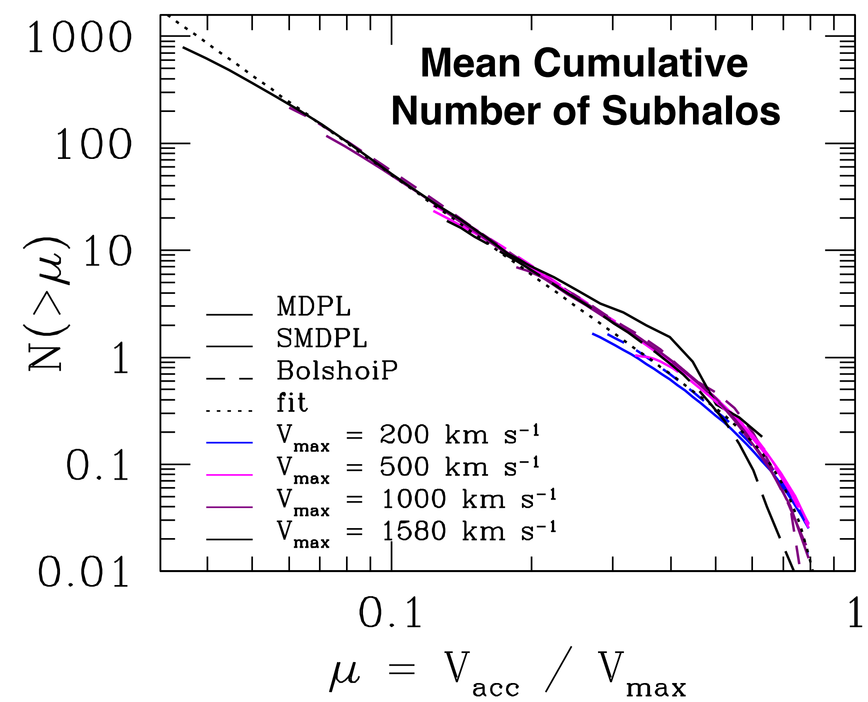
- Starting from the Big Bang, we simulate the evolution of a representative part of the universe according to the Double Dark theory to see if the end result matches what astronomers actually observe.
- On the large scale the simulations produce a universe just like the one we live in. We're always looking for new phenomena to predict — every one of which tests the whole theory!

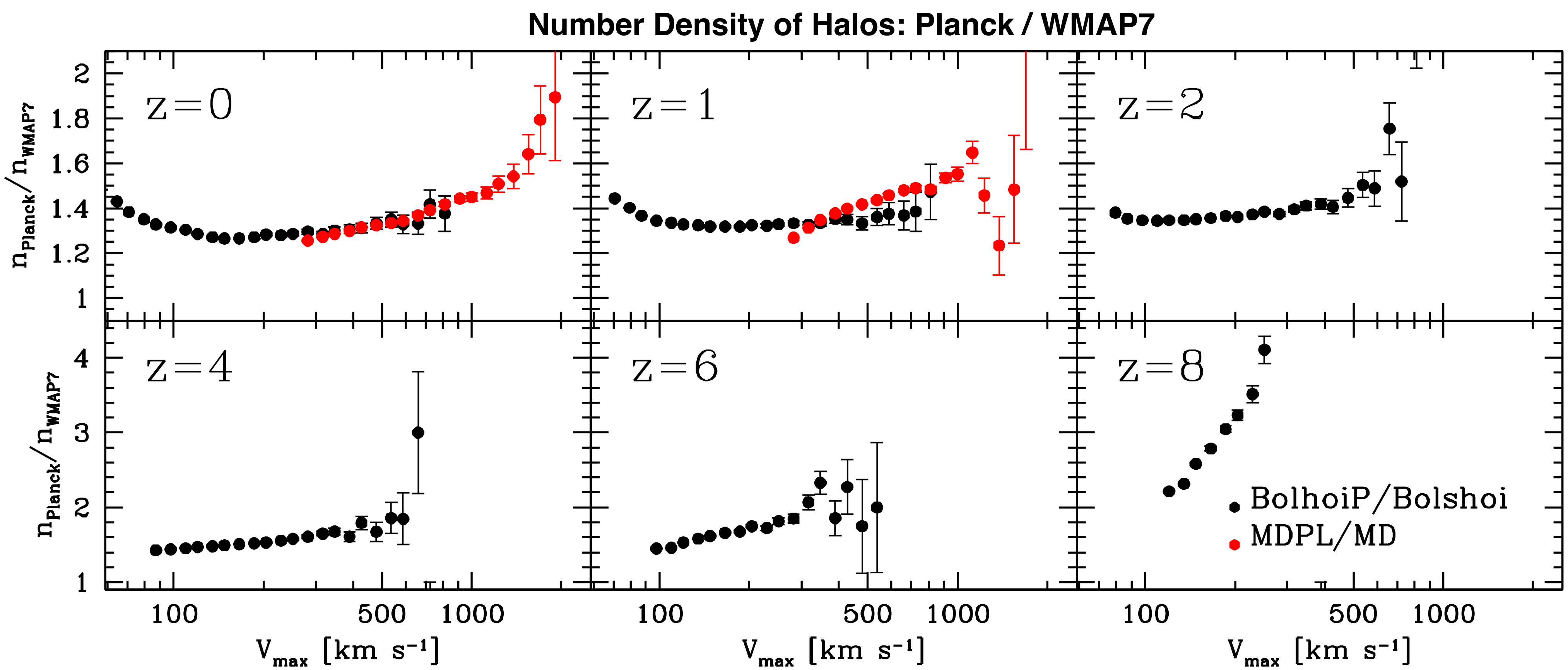
Halo and Subhalo Demographics with Planck Cosmological Parameters: Bolshoi-Planck and MultiDark-Planck Simulations

Aldo Rodrìguez-Puebla, Peter Behroozi, Joel Primack, Anatoly Klypin, Christoph Lee, Doug Hellinger







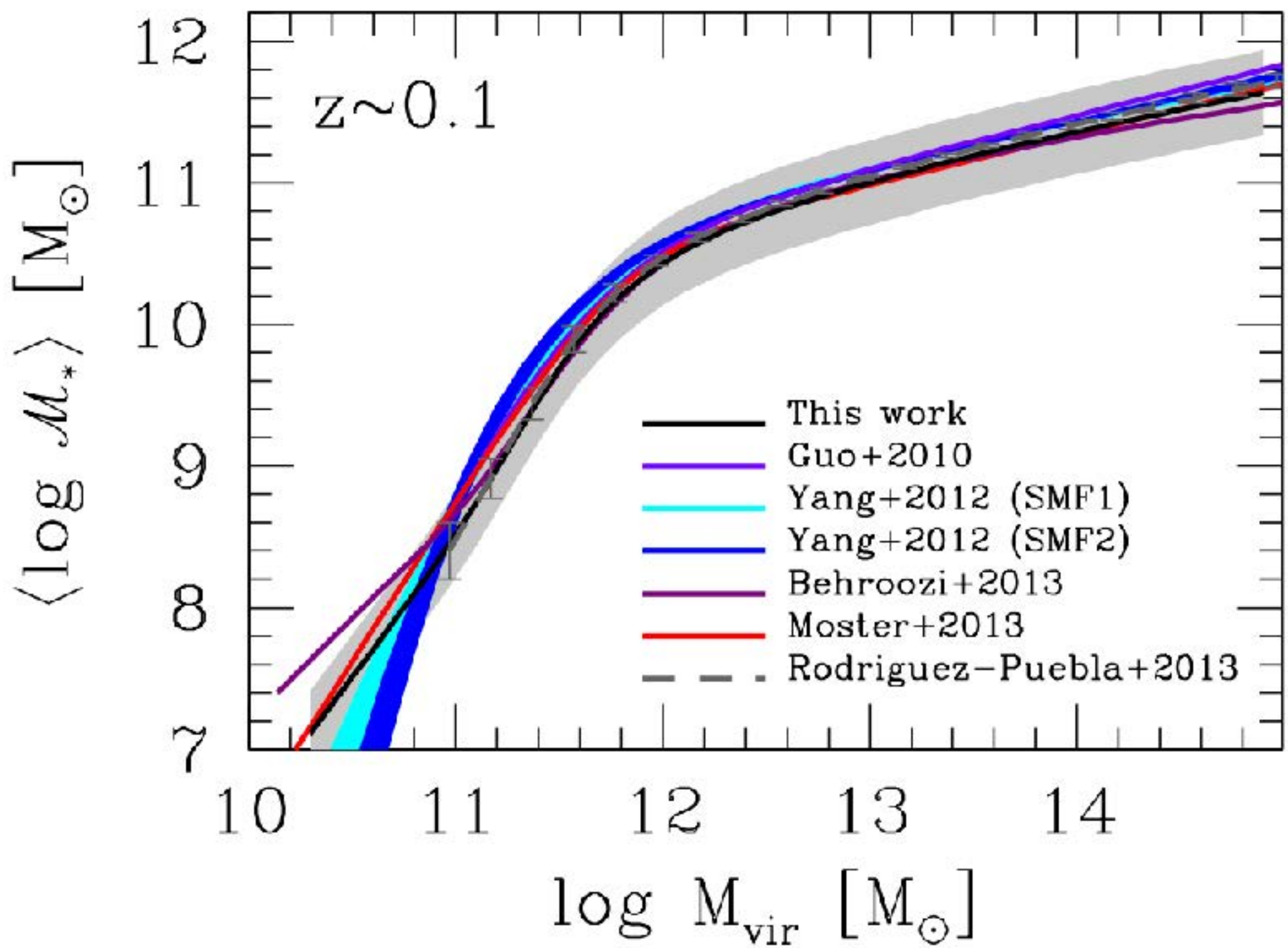


There are many more halos with the Planck cosmology, especially at high masses and redshifts.

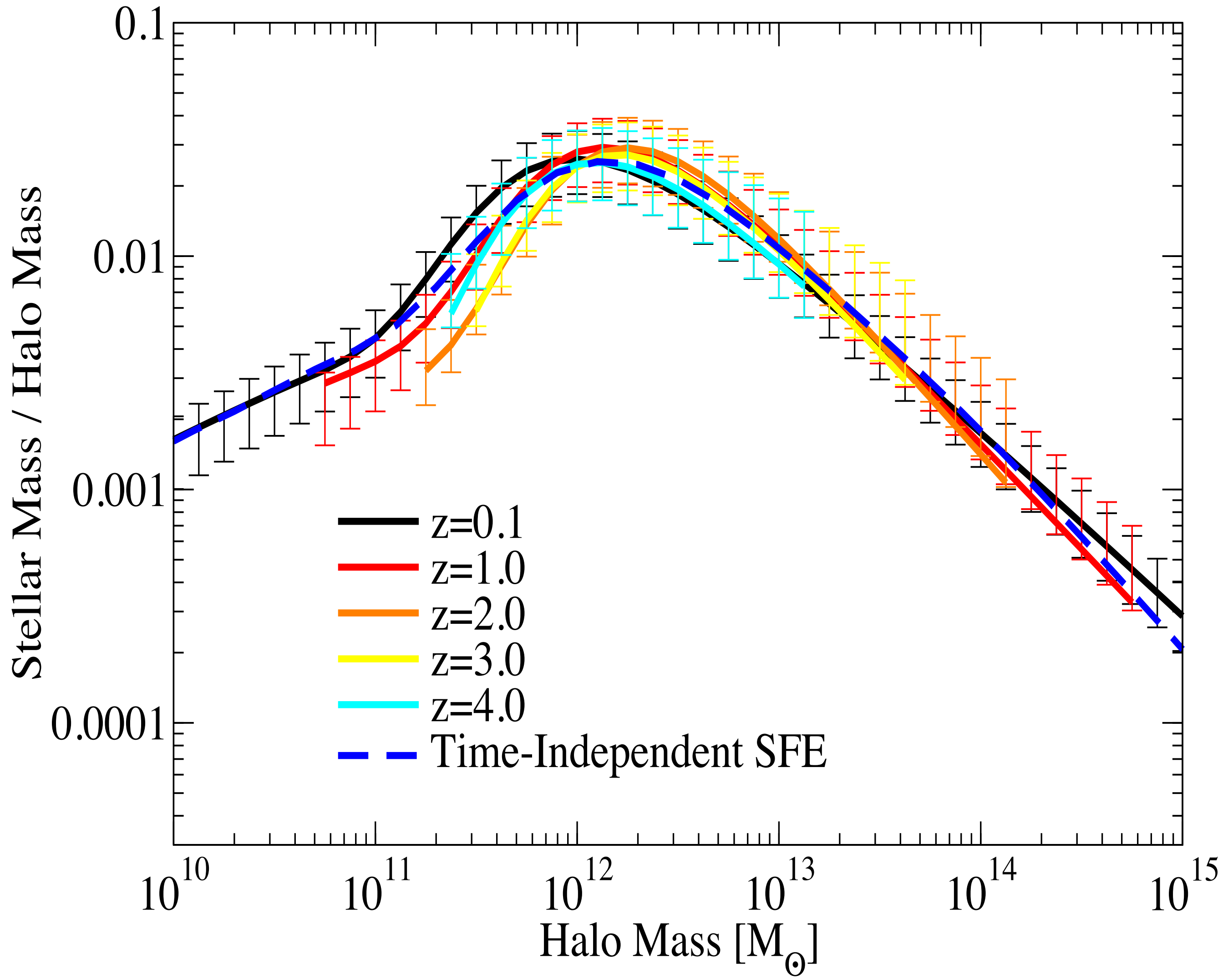
We have now released the halo catalogs and merger trees from all our new cosmological simulations. The paper includes Appendices with instructions for reading these files.

Constraining the Galaxy-Halo Connection Over The Last 13.3 Gyrs: Star Formation Histories, Galaxy Mergers and Structural Properties

Aldo Rodriguez-Puebla, Joel Primack, Vladimir Avila-Reese, Sandra Faber 2017

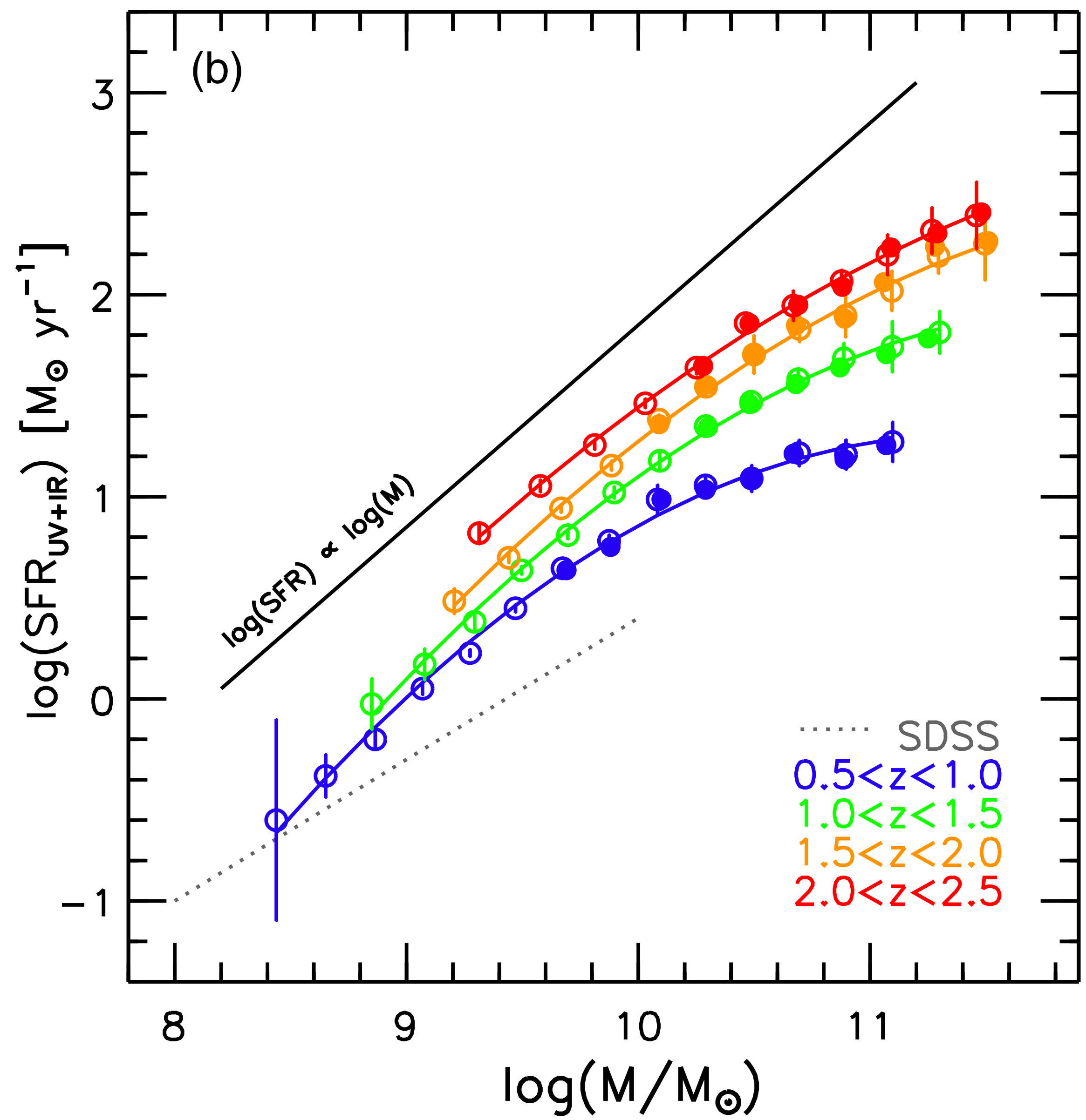


Relationship Between Galaxy Stellar Mass and Halo Mass



The stellar mass to halo mass ratio at multiple redshifts as derived from observations compared to a model which has a time-independent star formation efficiency (SFE). Error bars show 1σ uncertainties. A time-independent SFE predicts a roughly **time-independent stellar mass to halo mass relationship**. (Behroozi, Wechsler, Conroy, ApJL 2013 updated to the Planck cosmological parameters in Rodriguez-Puebla, Primack, Avila-Reese, Faber 2017)

Star-forming Galaxies Lie on a "Main Sequence"

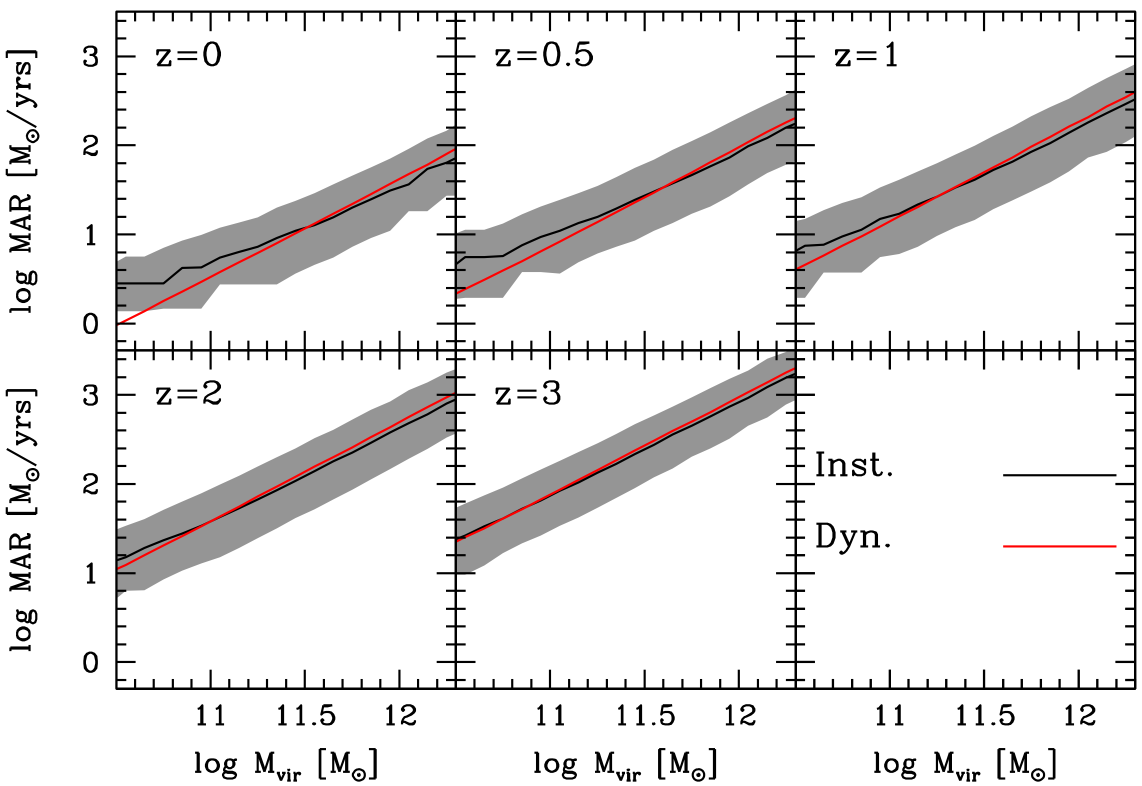


Just as the properties of hydrogen-burning stars are controlled by their mass, the galaxy star formation rate (SFR) is approximately proportional to the stellar mass, with the proportionality constant increasing with redshift up to about z = 2.5. (Whitaker et al. ApJ 2014)

Is Main Sequence SFR Controlled by Halo Mass Accretion?

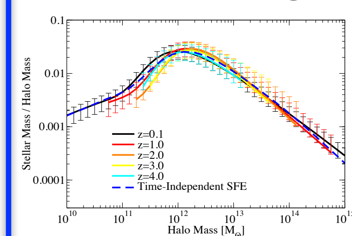
by Aldo Rodríguez-Puebla, Joel Primack, Peter Behroozi, Sandra Faber MNRAS 2016

Halo mass accretion rates z=0 to 3

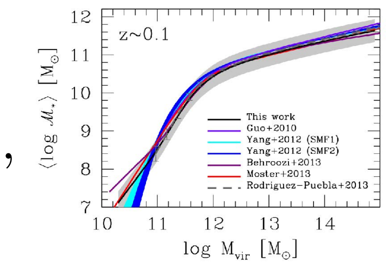


$$\frac{dM_*}{dt} = \frac{\partial M_*(M_{\rm vir}(t), z)}{\partial M_{\rm vir}} \frac{dM_{\rm vir}}{dt} + \frac{\partial M_*(M_{\rm vir}(t), z)}{\partial z} \frac{dz}{dt}$$

but if the M_*–M_{vir} relation is independent of redshift then the stellar mass of a central galaxy formed in a halo of mass $M_{vir}(t)$ is $M_* = M_*(M_{vir}(t))$. From this relation star formation rates are given simply by

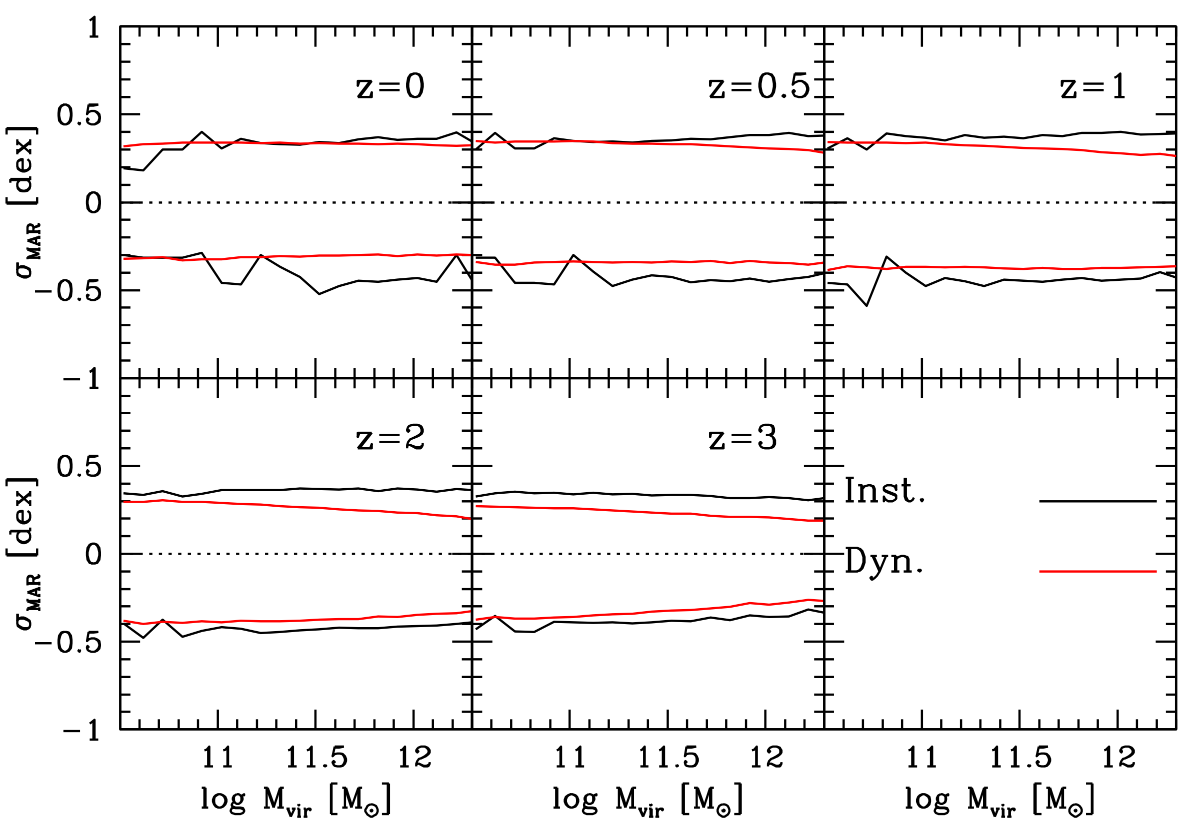


$$\frac{dM_*}{dt} = f_* \frac{d\log M_*}{d\log M_{\rm vir}} \frac{dM_{\rm vir}}{dt},$$

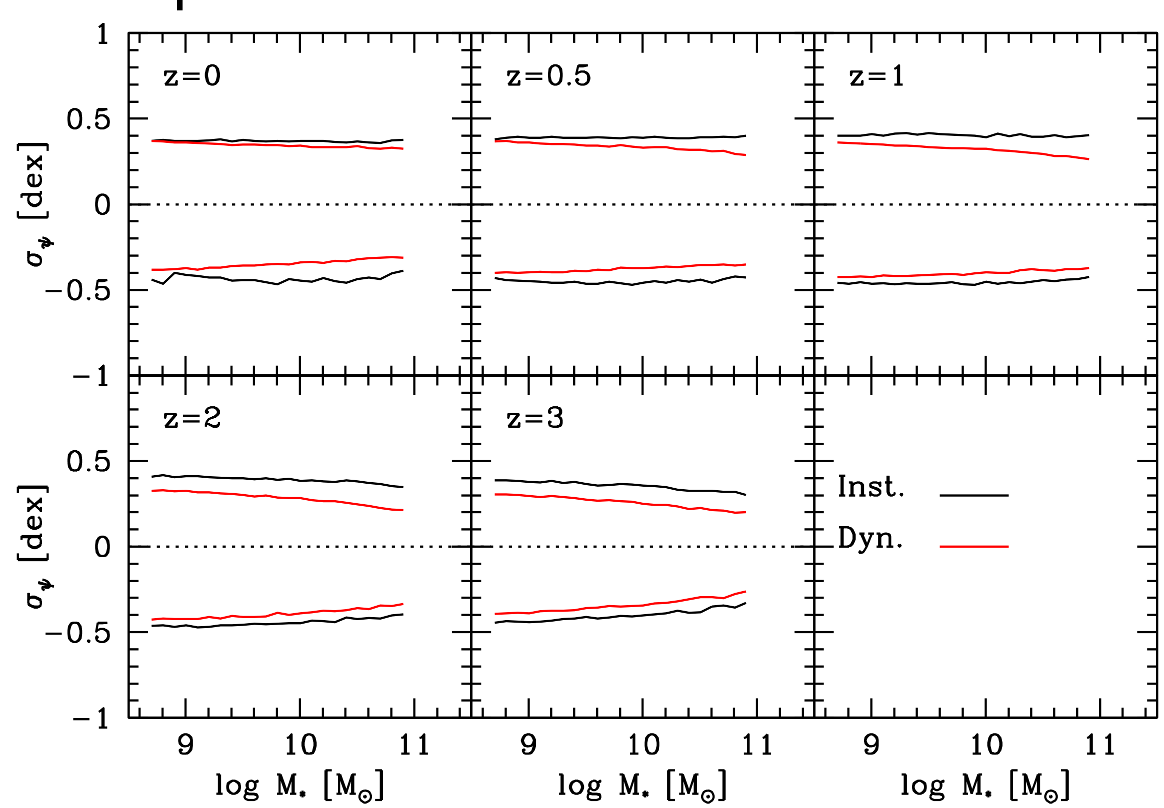


where $f_* = M_*/M_{vir}$. We call this **Stellar-Halo Accretion Rate Coevolution** (**SHARC**) if true halo-by-halo.

Scatter of halo mass accretion rates



Implied scatter of star formation rates

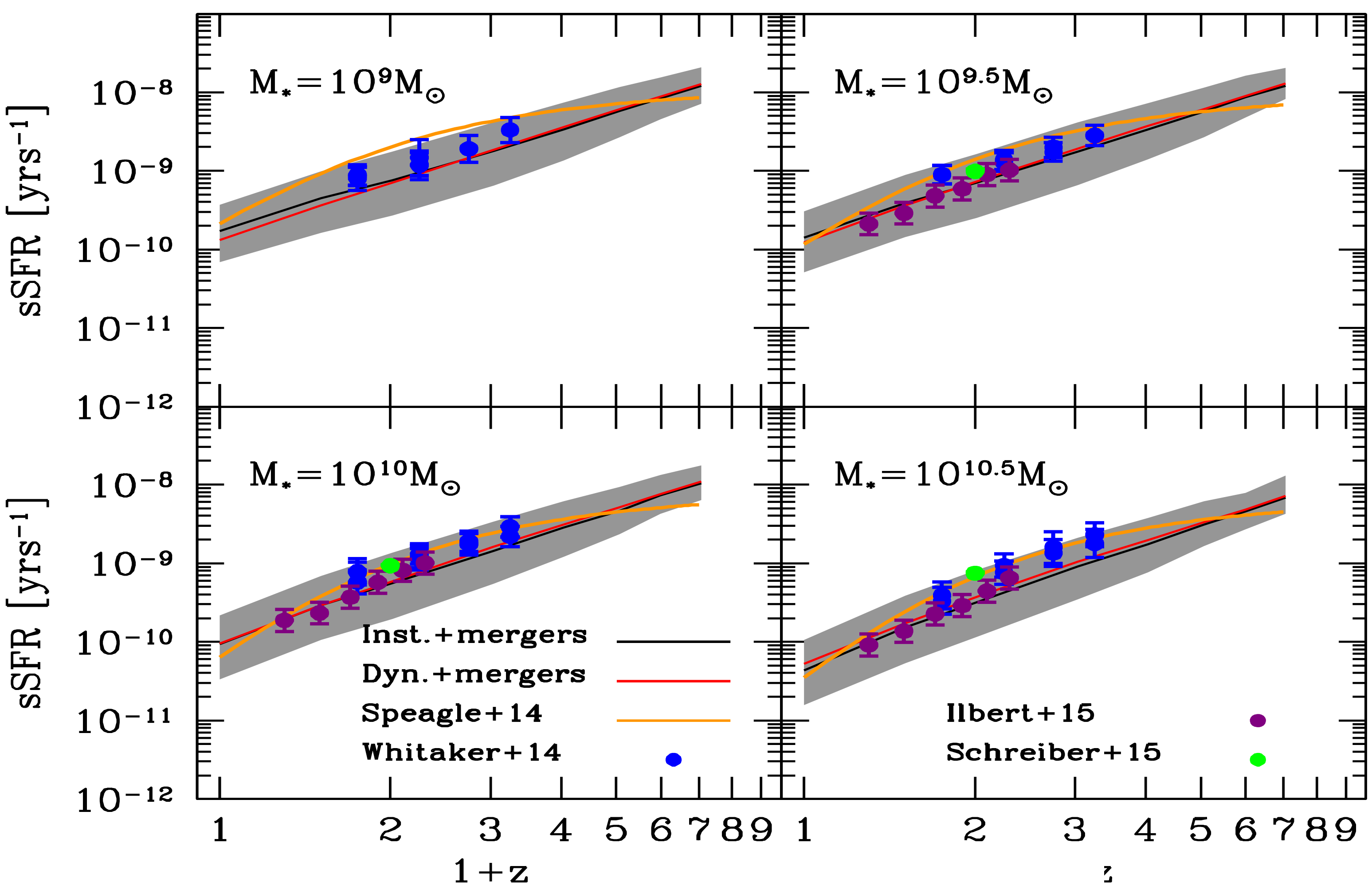


Consistent w observed σ ~ 0.3 dex

Is Main Sequence SFR Controlled by Halo Mass Accretion?

by Aldo Rodríguez-Puebla, Joel Primack, Peter Behroozi, Sandra Faber MNRAS 2016

SHARC correctly predicts star formation rates to z ~ 4



SHARC predicts "Age Matching" (blue galaxies in accreting halos) and "Galaxy Conformity" at low z

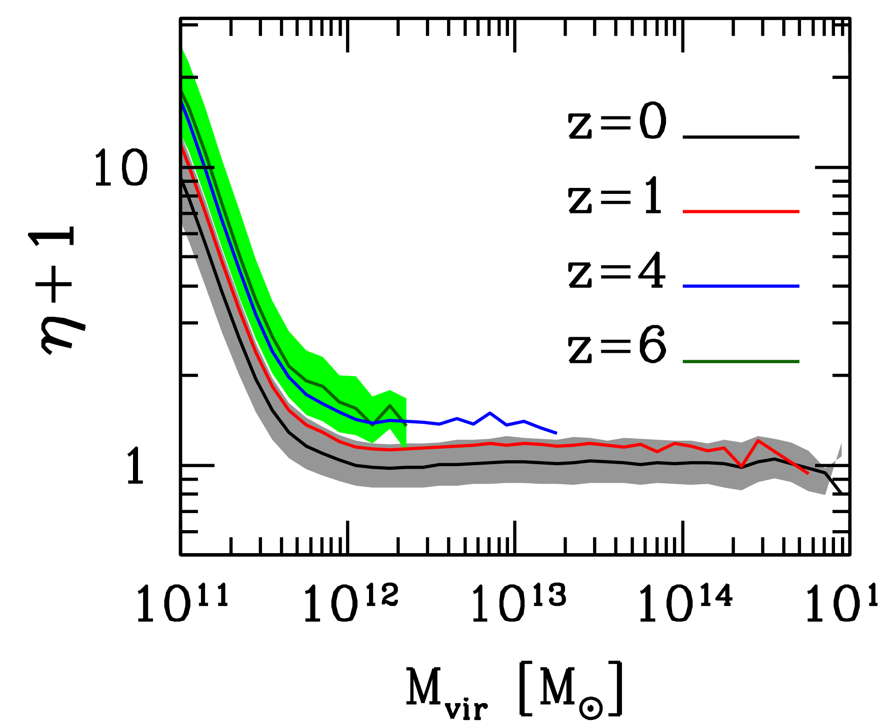
Open Questions:

Extend SHARC to higher-mass galaxies

Check predicted correlations vs. observations at high z

Can SHARC be used to measure growth rate of halos from the star formation rate, as a dark energy vs. gravity test?

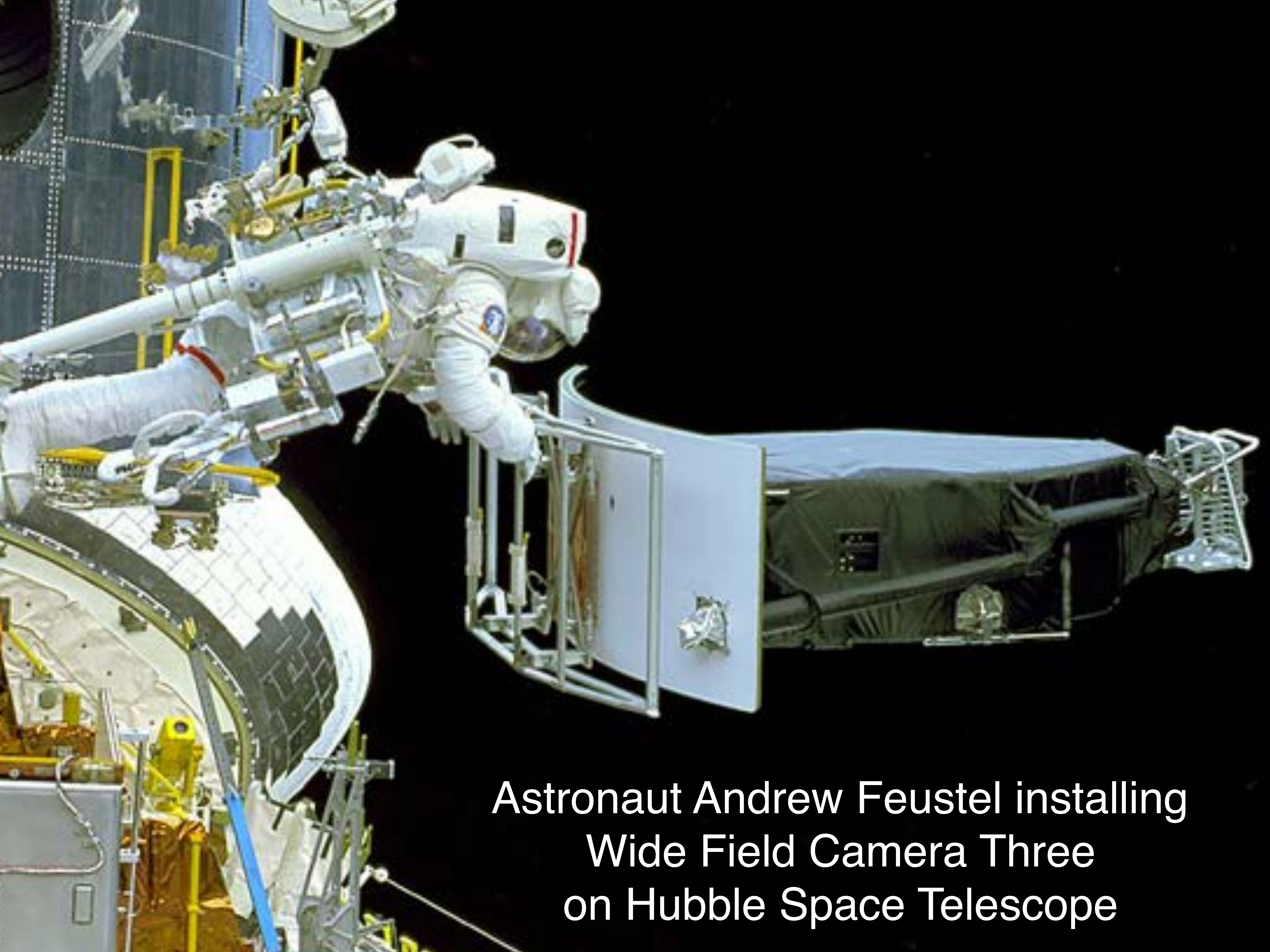
We put SHARC in "bathtub" equilibrium models of galaxy formation & predicted mass loading and metallicity evolution



Net mass loading factor η from an equilibrium bathtub model (E+SHARC)

Structure Formation Methodology

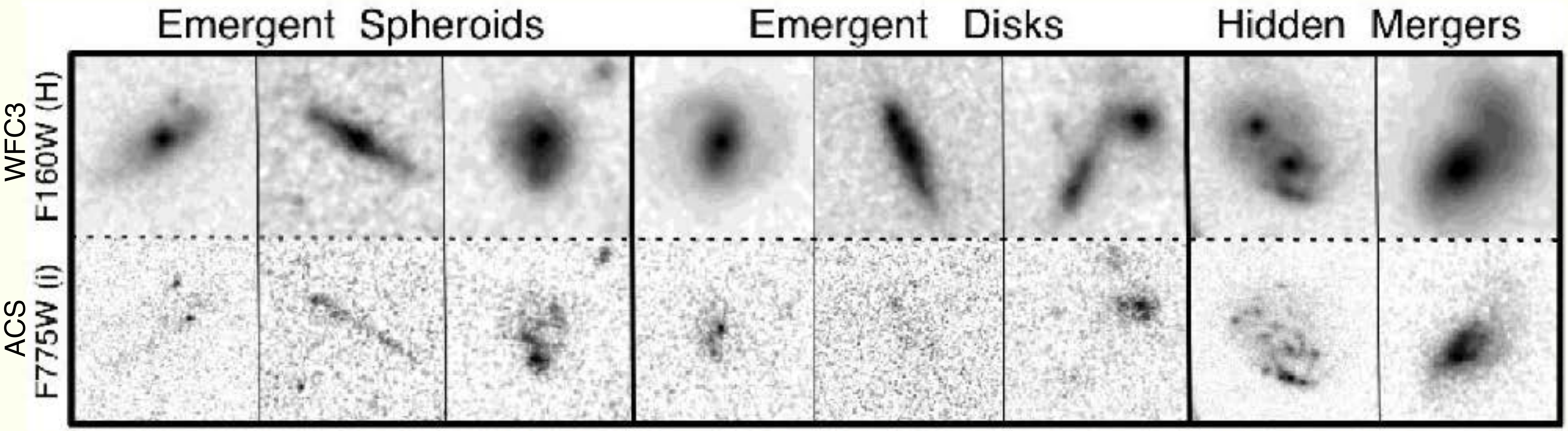
- Starting from the Big Bang, we simulate the evolution of a representative part of the universe according to the Double Dark theory to see if the end result matches what astronomers actually observe.
- On the large scale the simulations produce a universe just like the one we live in. We're always looking for new phenomena to predict — every one of which tests the theory!
- But the way individual galaxies form is only partly understood because it depends on the interactions of the ordinary atomic matter, as well as the dark matter and dark energy, to form stars and black holes. We need help from observations.



Astronaut Andrew Feustel installing
Wide Field Camera Three
on Hubble Space Telescope

The CANDELS Survey

candels.ucolick.org



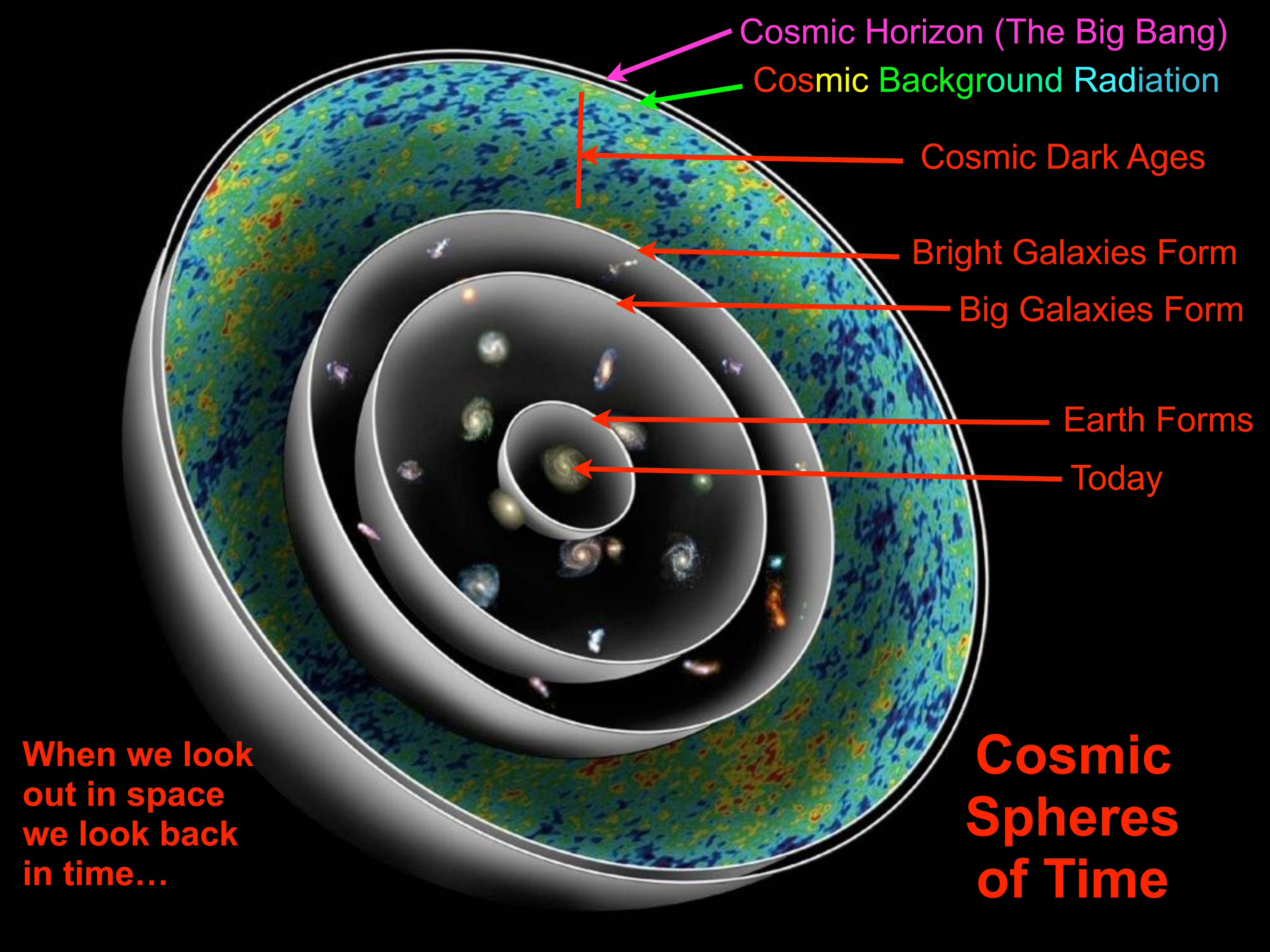
CANDELS: A Cosmic Odyssey

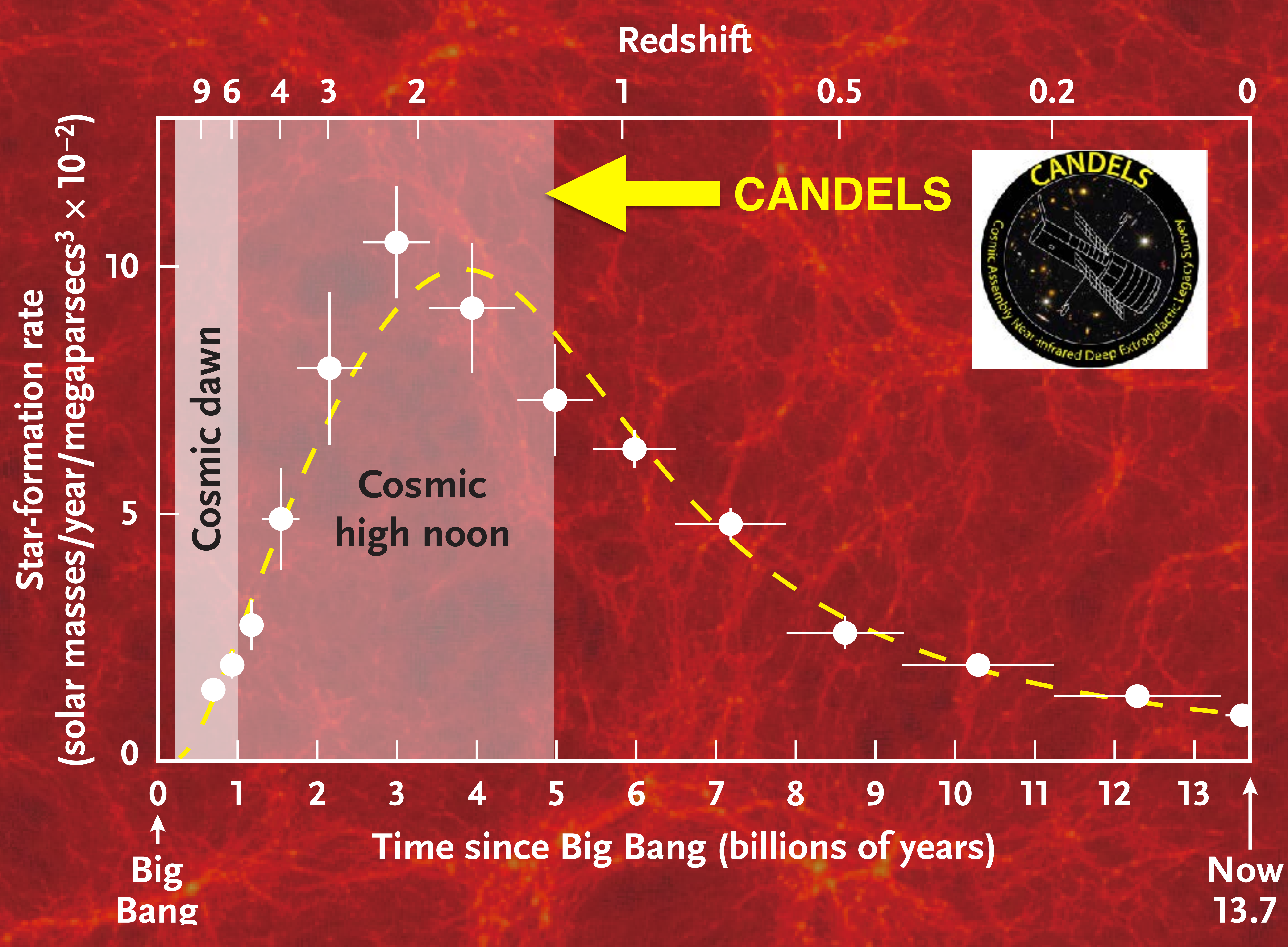
(blue 0.4 μm)(1+z) = 1.6 μm @ z = 3

(red 0.7 μm)(1+z) = 1.6 μm @ z = 2.3

CANDELS is a powerful imaging survey of the distant Universe being carried out with two cameras on board the Hubble Space Telescope.

- CANDELS is the largest project in the history of Hubble, with 902 assigned orbits of observing time. This is the equivalent of four months of Hubble time if executed consecutively, but in practice CANDELS will take three years to complete (2010-2013).
- The core of CANDELS is the revolutionary near-infrared WFC3 camera, installed on Hubble in May 2009. WFC3 is sensitive to longer, redder wavelengths, which permits it to follow the stretching of lightwaves caused by the expanding Universe. This enables CANDELS to detect and measure objects much farther out in space and nearer to the Big Bang than before. CANDELS also uses the visible-light ACS camera, and together the two cameras give unprecedented panchromatic coverage of galaxies from optical wavelengths to the near-IR.
- CANDELS will exploit this new lookback power to construct a "cosmic movie" of galaxy evolution that follows the life histories of galaxies from infancy to the present time. This work will cap Hubble's revolutionary series of discoveries on cosmic evolution and bequeath a legacy of precious data to future generations of astronomers.


Cosmic Horizon (The Big Bang)
Cosmic Background Radiation
Cosmic Dark Ages
Bright Galaxies Form
Big Galaxies Form
Earth Forms
Today
When we look out in space we look back in time…
Cosmic Spheres of Time



Redshift
9 6 4 3 2 1 0.5 0.2 0
CANDELS
CANDELS
Cosmic Assembly Near-infrared Deep Extragalactic Legacy Survey
Star-formation rate
(solar masses/year/megaparsecs^3 × 10^{-2})
10
5
0
Cosmic dawn
Cosmic
high noon
0 1 2 3 4 5 6 7 8 9 10 11 12 13
Time since Big Bang (billions of years)
Big
Bang
Now
13.7

Galaxy Hydro Simulations: 2 Approaches

1. Low resolution (~ kpc)

Advantages: it's possible to simulate many galaxies and study galaxy populations and their interactions with CGM & IGM.
Disadvantages: since feedback &winds are "tuned," we learn little about how galaxies themselves evolve, and cannot compare in detail with high-z galaxy images and spectra.
Examples: Overwhelmingly Large Simulations (OWLs, EAGLE), AREPO simulations in 100 Mpc box (Illustris).

2. High resolution (~10s of pc) ← THIS TALK

Advantages: it's possible to compare in detail with high-z galaxy images and spectra, to discover how galaxies evolve, morphological drivers (e.g., galaxy shapes, clumps and other instabilities, origins of galactic spheroids, quenching). Radiative pressure & AGN feedbacks essential?
Disadvantages: statistical galaxy samples take too much computer time; can we model galaxy population evolution using simulation insights in semi-analytic models (SAMs)?
Examples: ART/VELA and FIRE simulation suites, AGORA simulation comparison project.

CANDELS

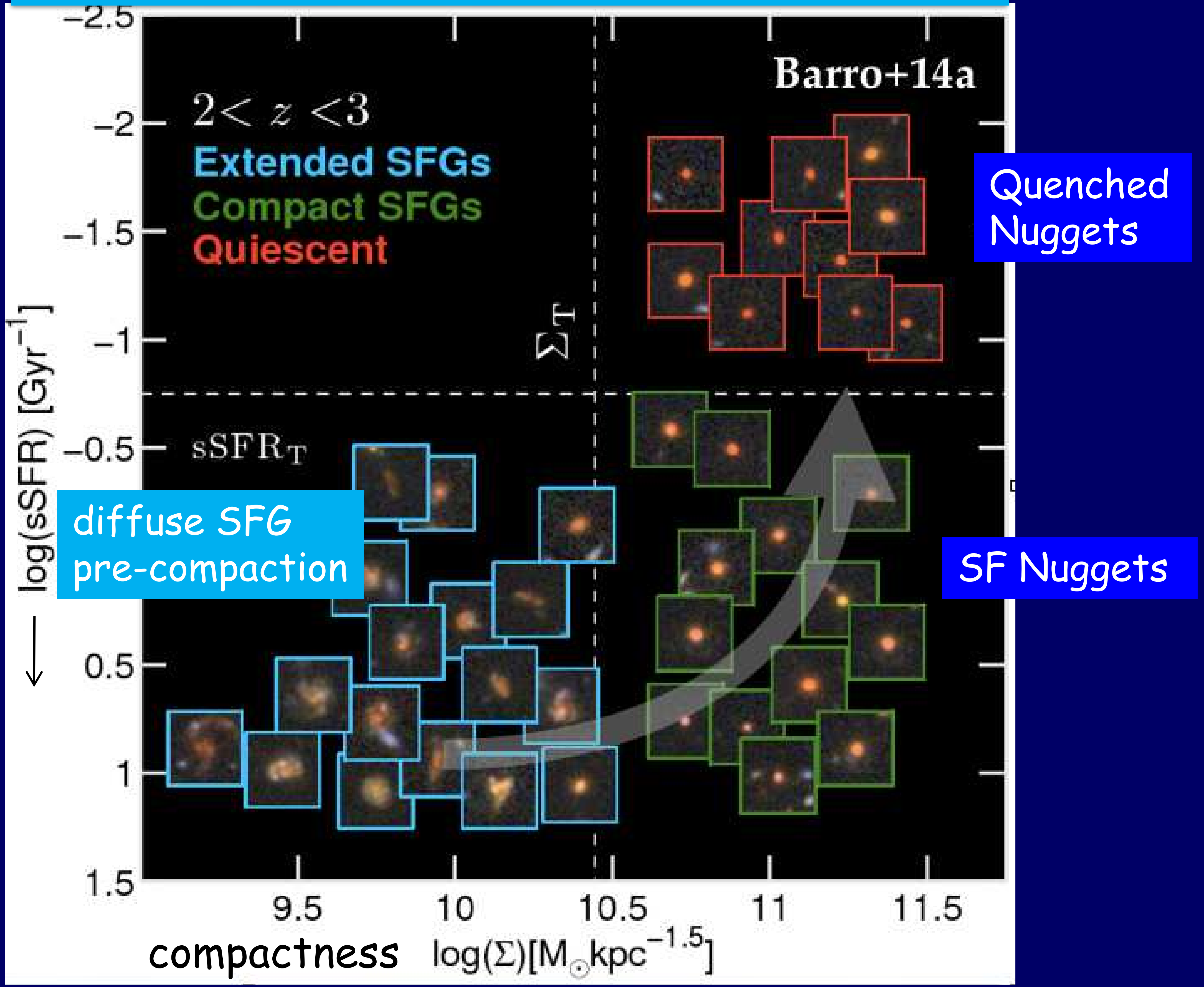
Cosmic Assembly Near-infrared Deep Extragalactic Legacy Survey

- 3 Aspects of Star-Forming Galaxies Seen in CANDELS
  - Compaction
  - Elongation
  - Clumps

} Challenge for Observers & Simulators!

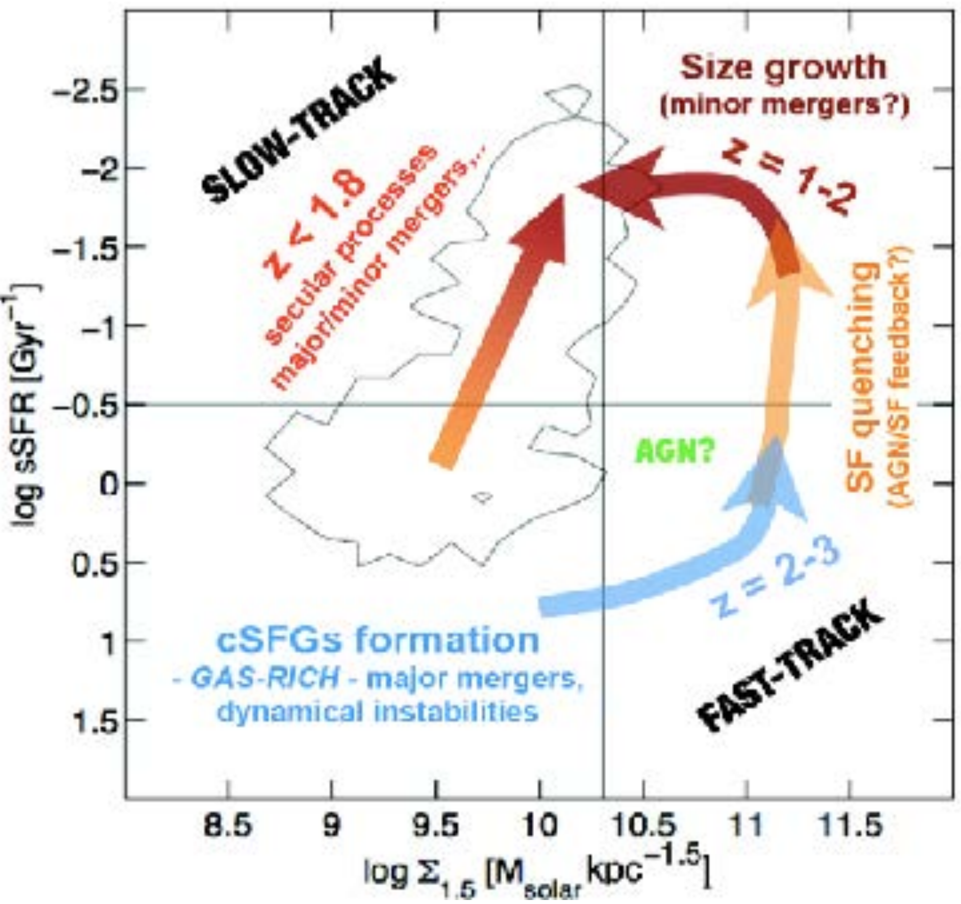
Our hydroART cosmological zoom-in simulations produce all of these phenomena!

The Fast Track of Galaxy Evolution



Ceverino+ RP simulations analyzed by Zolotov, Dekel, Tweed, Mandelker, Ceverino, & Primack MNRAS 2015

Barro+ (CANDELS) 2013

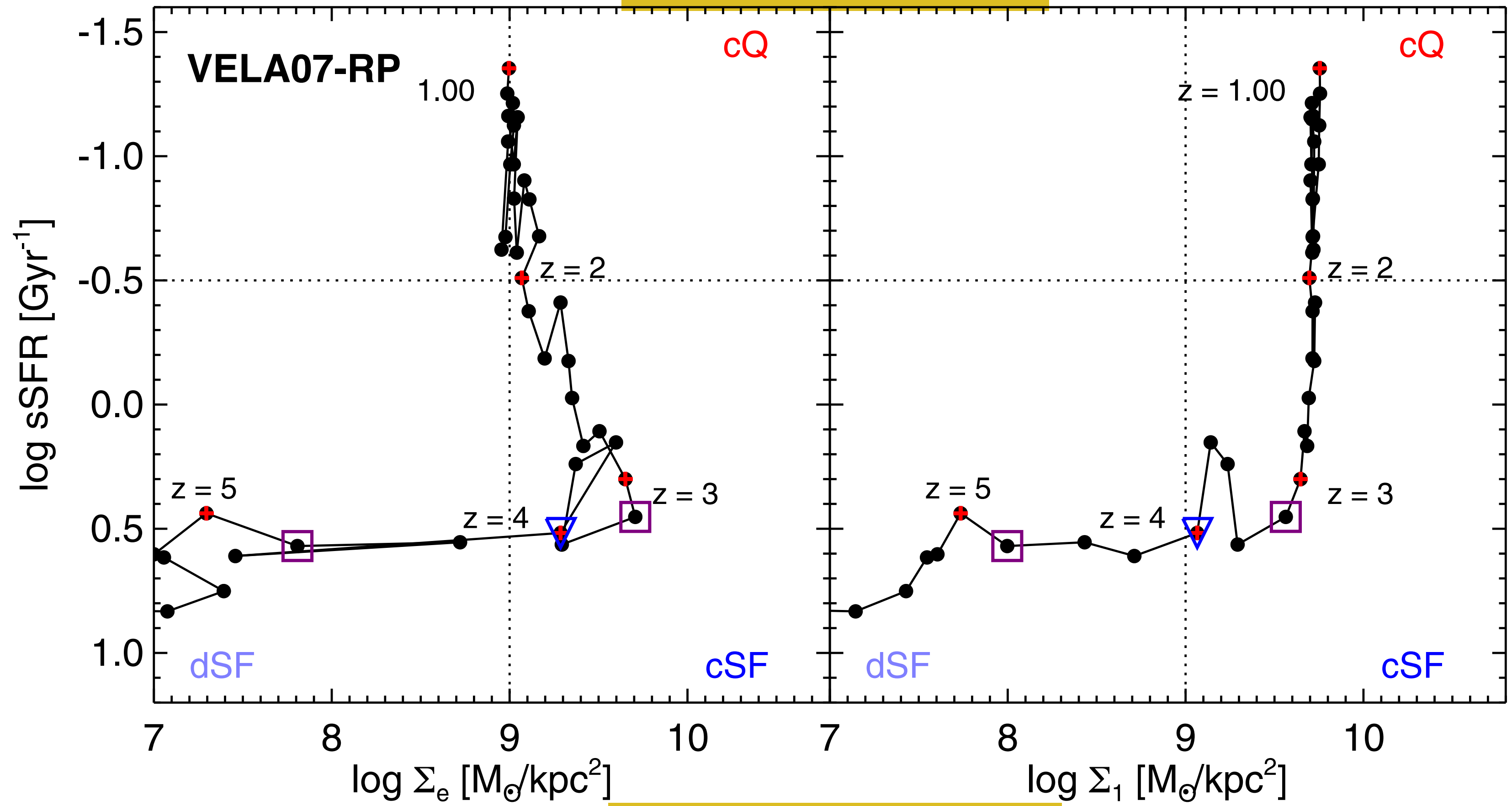


COMPACTION —>

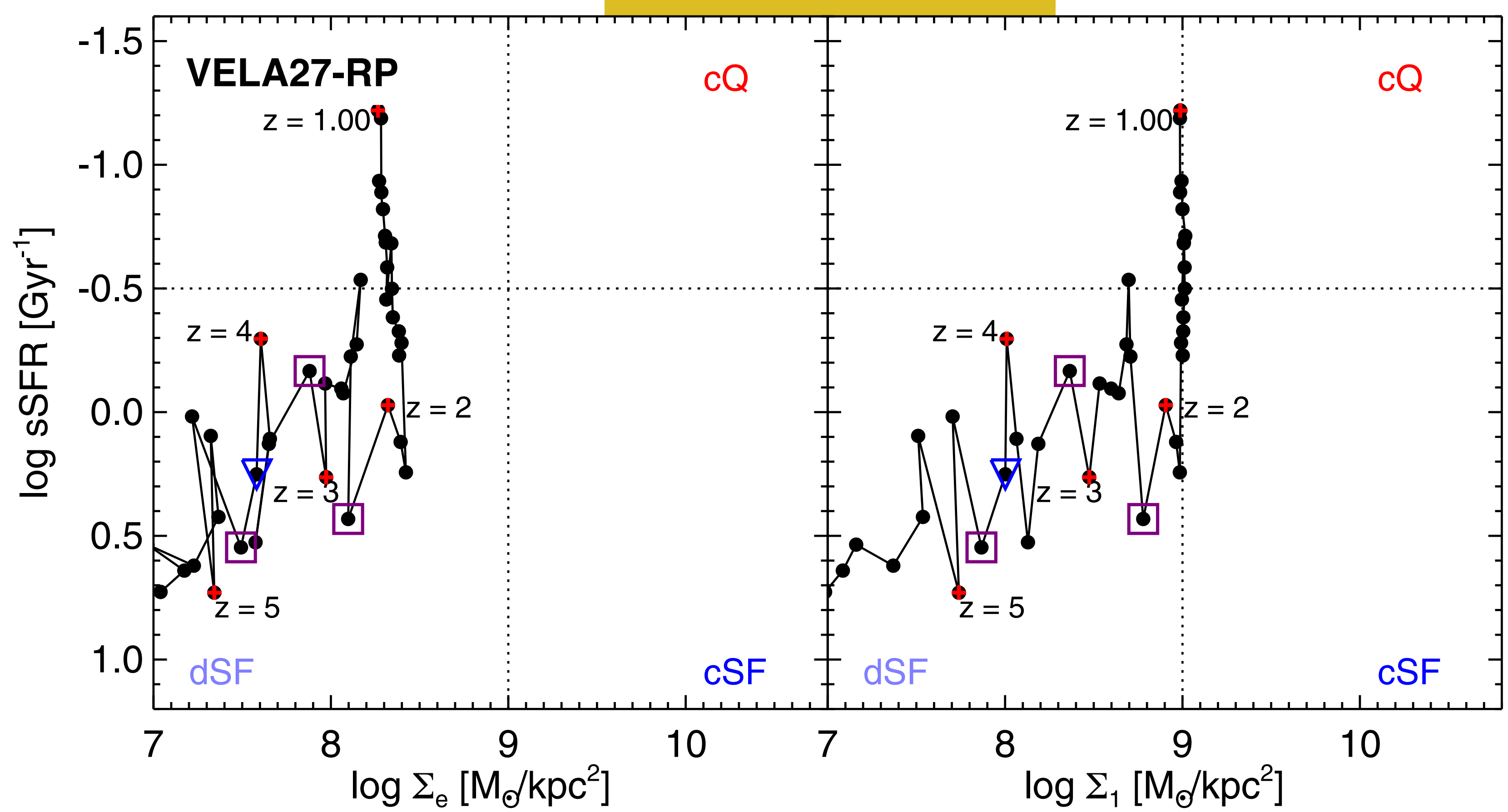
major merger

minor merger

FAST-TRACK

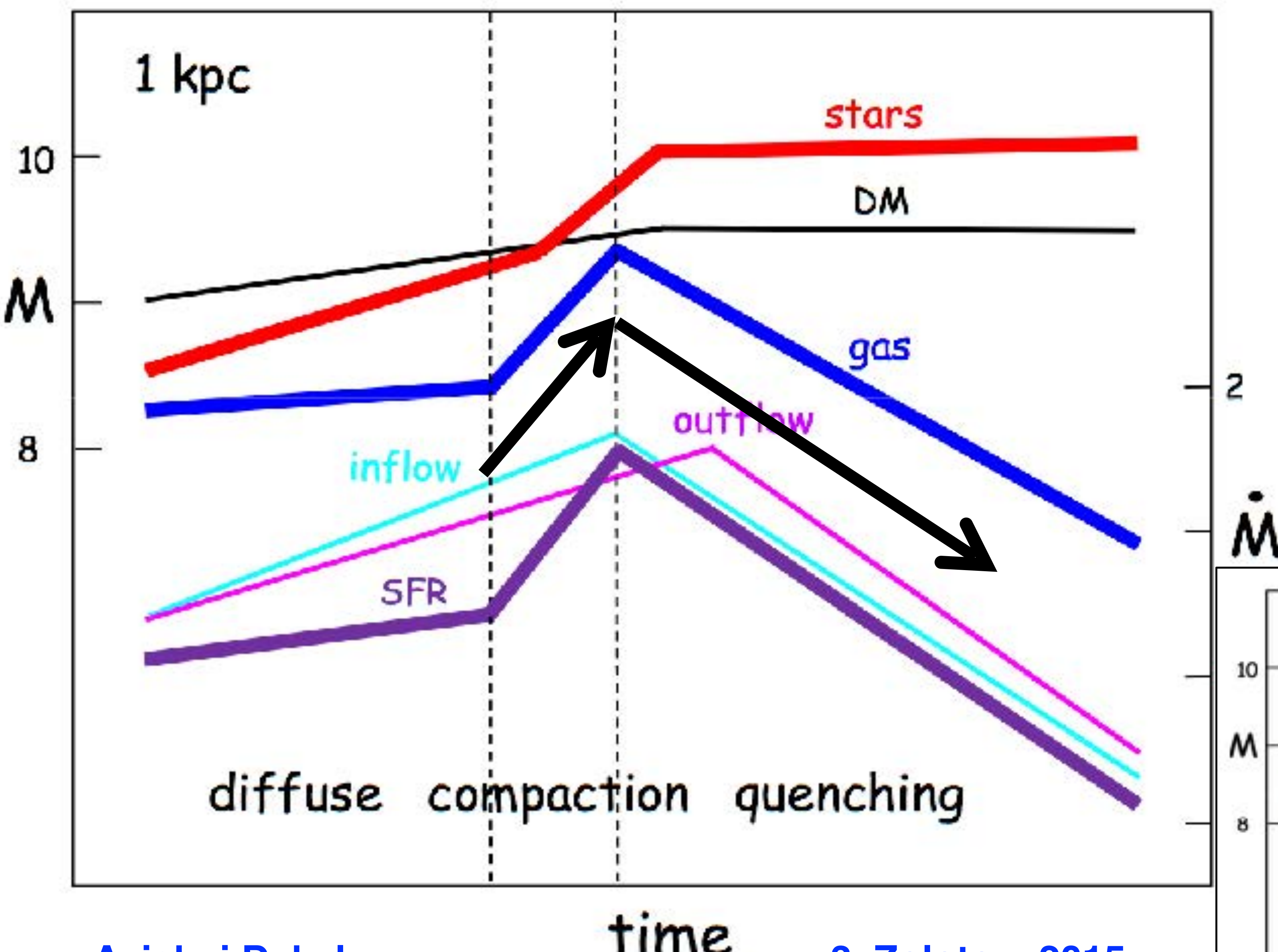


SLOW-TRACK

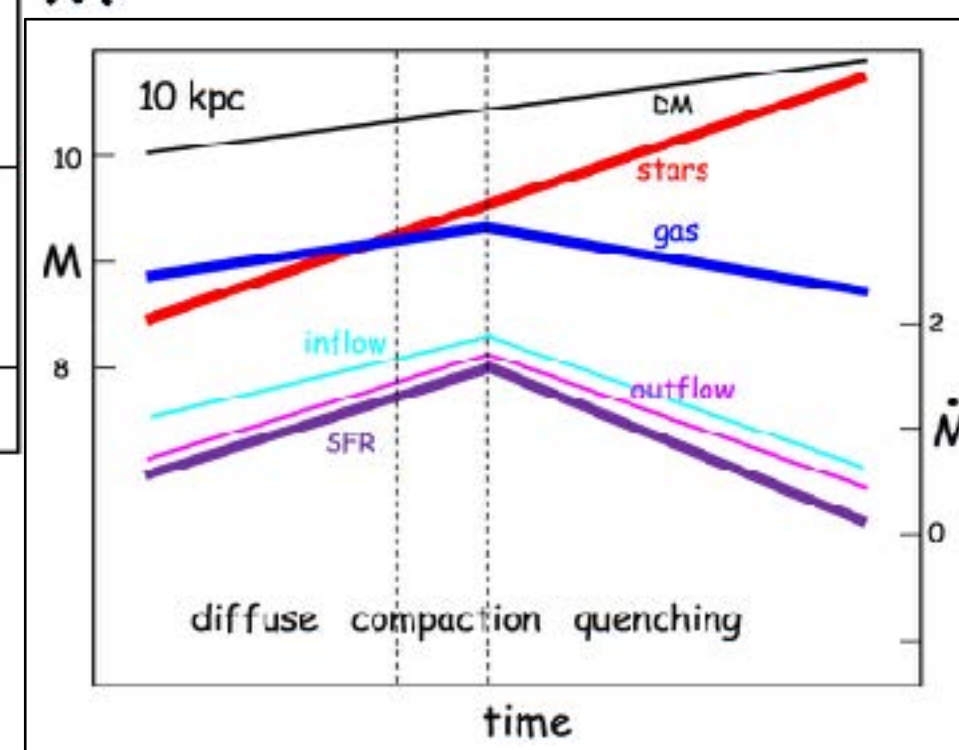


Zolotov+2015

Compaction and Quenching in the Inner 1 kpc



Inner 10 kpc



Avishai Dekel

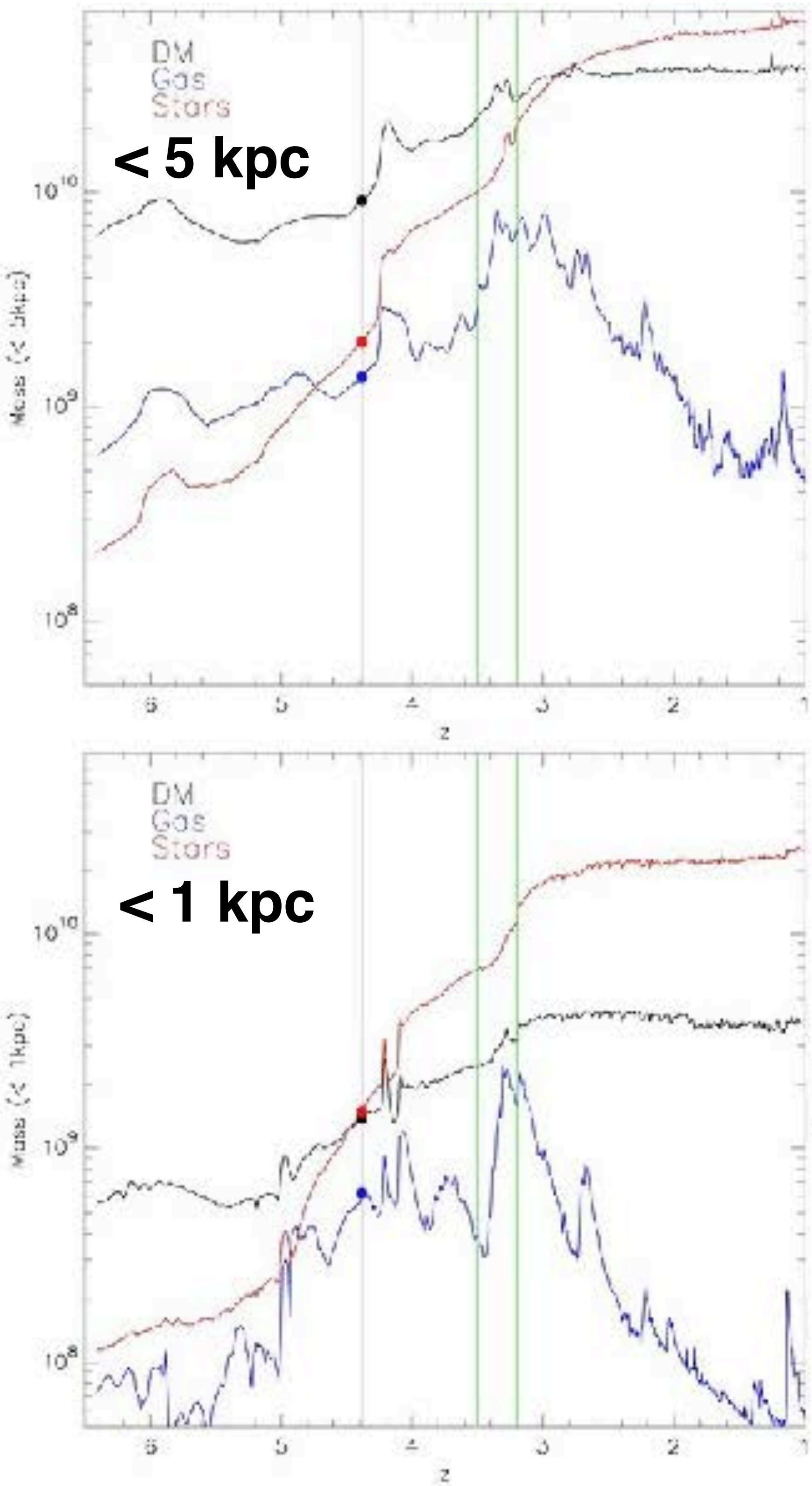
gen3 Zolotov+2015

VELA07-RP Animations z = 4.4 to 2.3

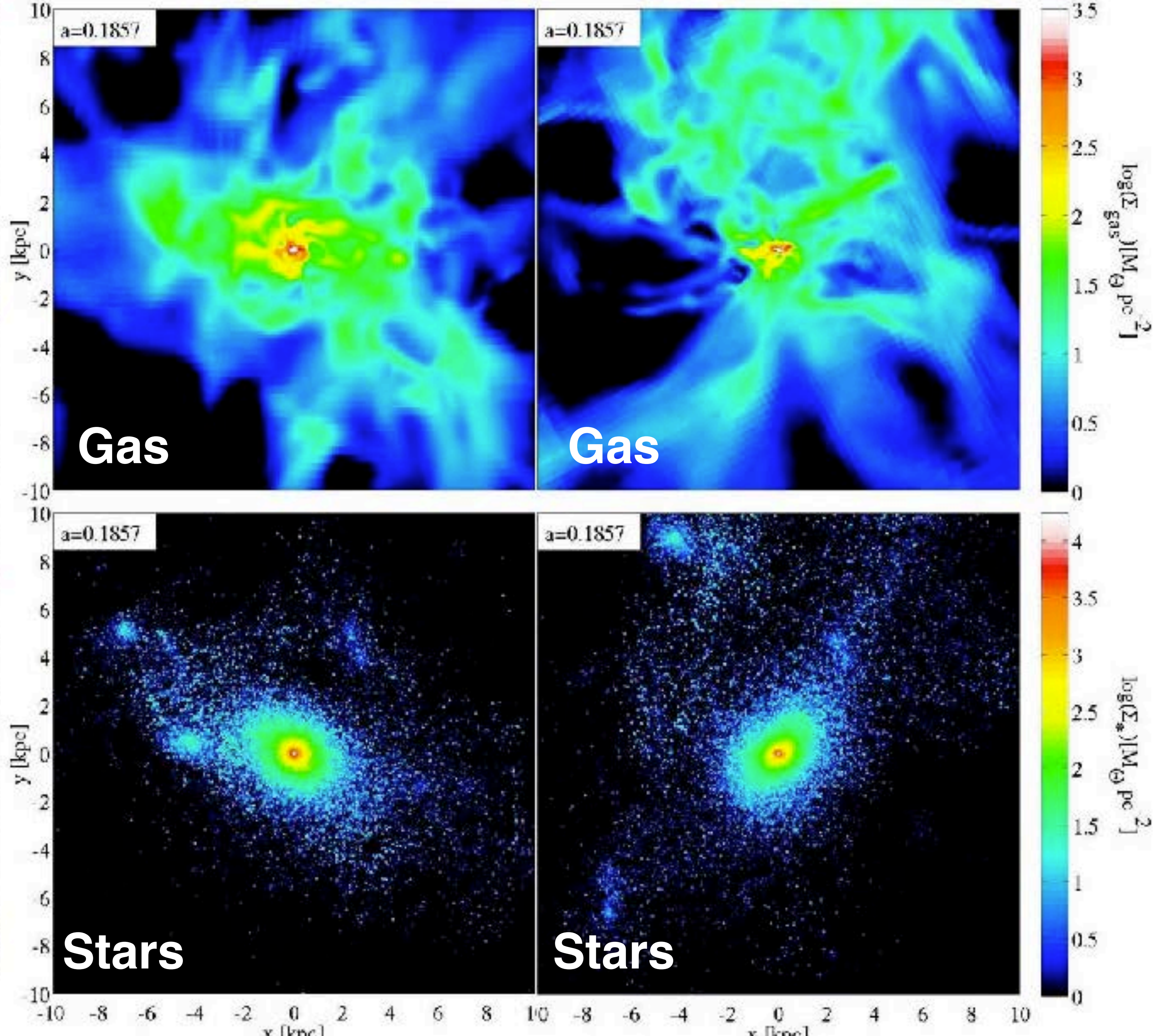
Daniel Ceverino, Nir Mandelker

DM
Gas
Stars

Compaction

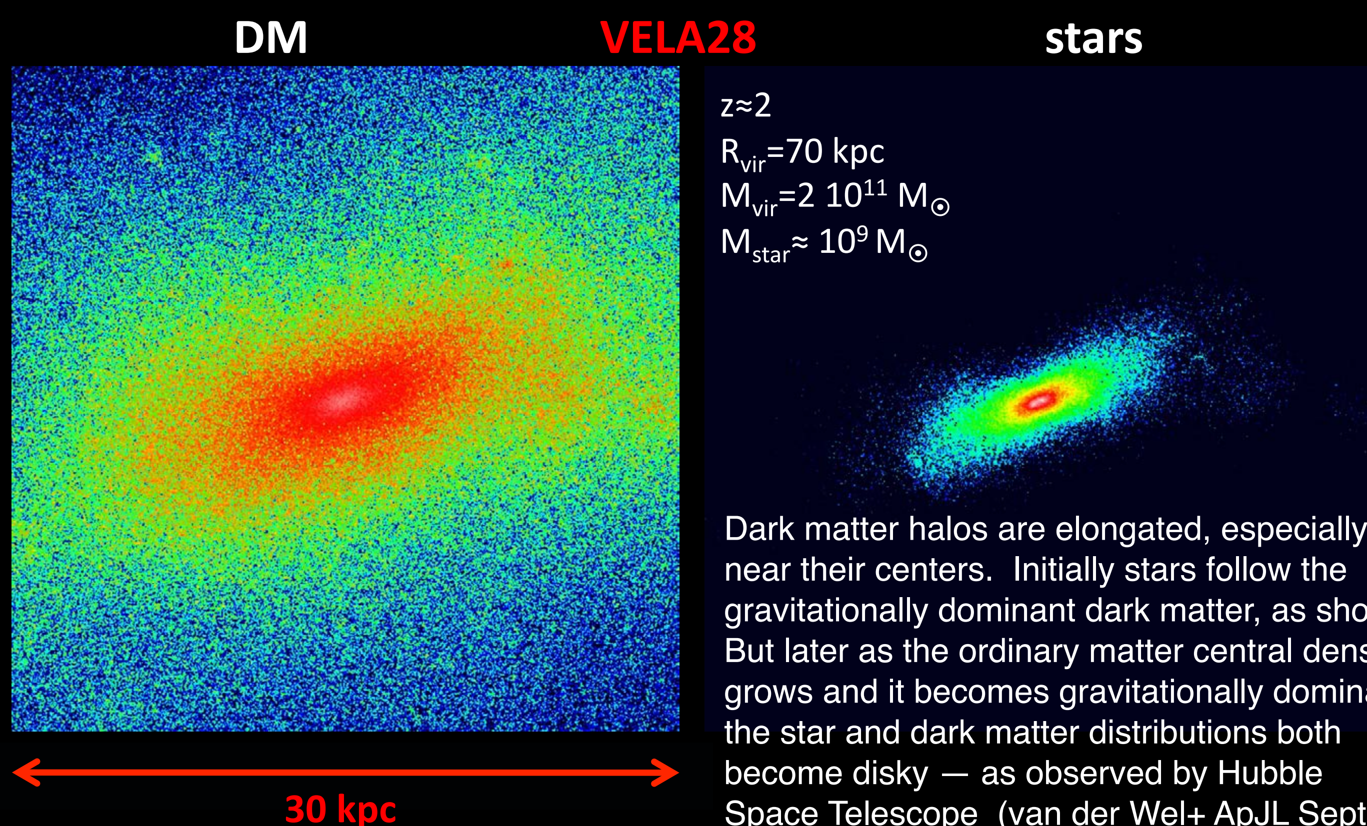


Face-on
Edge-on



Our cosmological zoom-in simulations often produce elongated galaxies like observed ones. The elongated distribution of stars follows the elongated inner dark matter halo.

Prolate DM halo → elongated galaxy



Dark matter halos are elongated, especially near their centers. Initially stars follow the gravitationally dominant dark matter, as shown. But later as the ordinary matter central density grows and it becomes gravitationally dominant, the star and dark matter distributions both become disky — as observed by Hubble Space Telescope (van der Wel+ ApJL Sept 2014).

Monthly Notices of the ROYAL ASTRONOMICAL SOCIETY

MNRAS **453,** 408–413 (2015)

Formation of elongated galaxies with low masses at high redshift

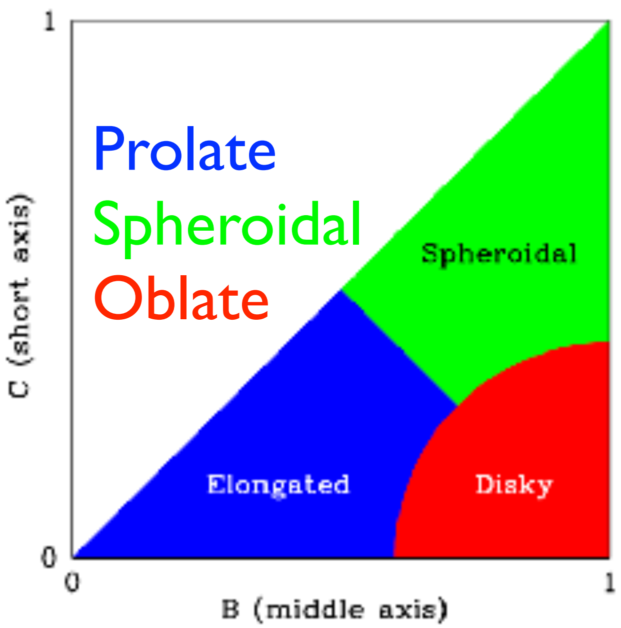
Daniel Ceverino, Joel Primack and Avishai Dekel

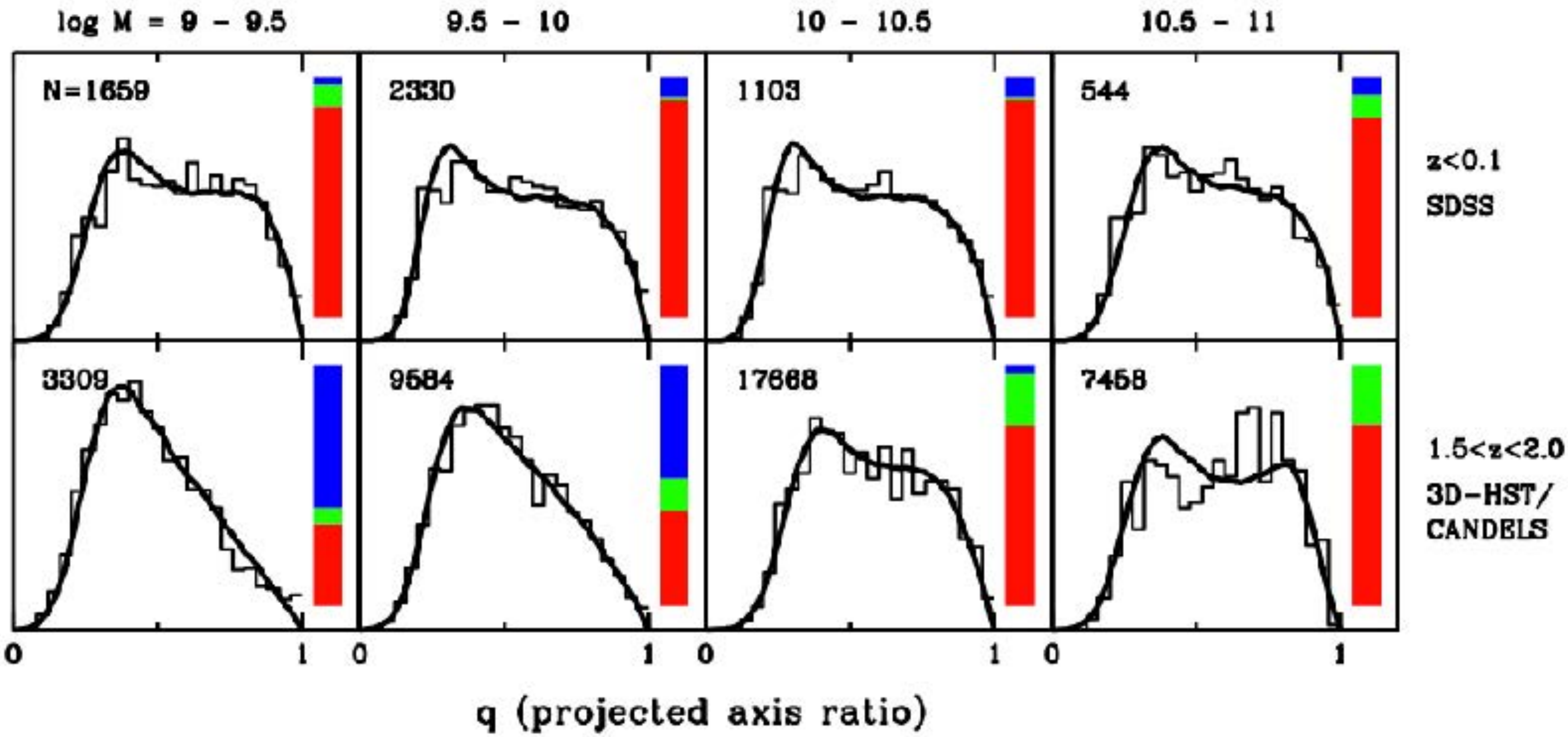
ABSTRACT

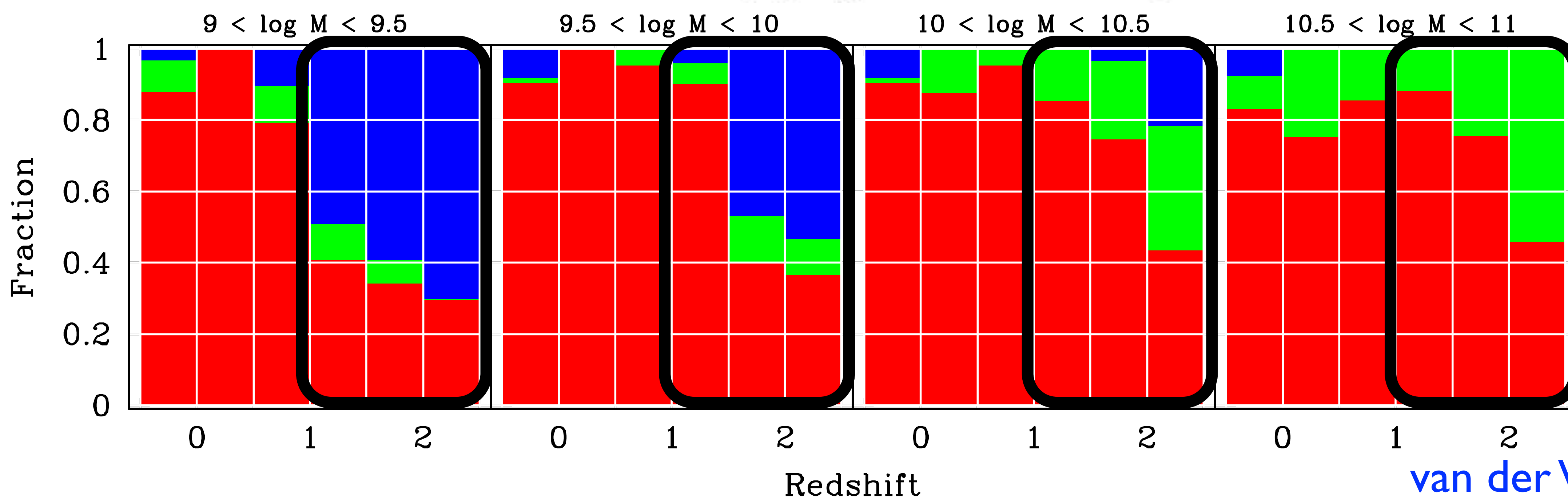
We report the identification of elongated (triaxial or prolate) galaxies in cosmological simulations at $z \sim 2$. These are preferentially low-mass galaxies ($M_* \leq 10^{9.5}\ M_\odot$), residing in dark matter (DM) haloes with strongly elongated inner parts, a common feature of high-redshift DM haloes in the cold dark matter cosmology. A large population of elongated galaxies produces a very asymmetric distribution of projected axis ratios, as observed in high-z galaxy surveys. This indicates that the majority of the galaxies at high redshifts are not discs or spheroids but rather galaxies with elongated morphologies

Nearby large galaxies are mostly disks and spheroids — but they start out looking more like pickles.

Prolate galaxies dominate at high redshift/low masses



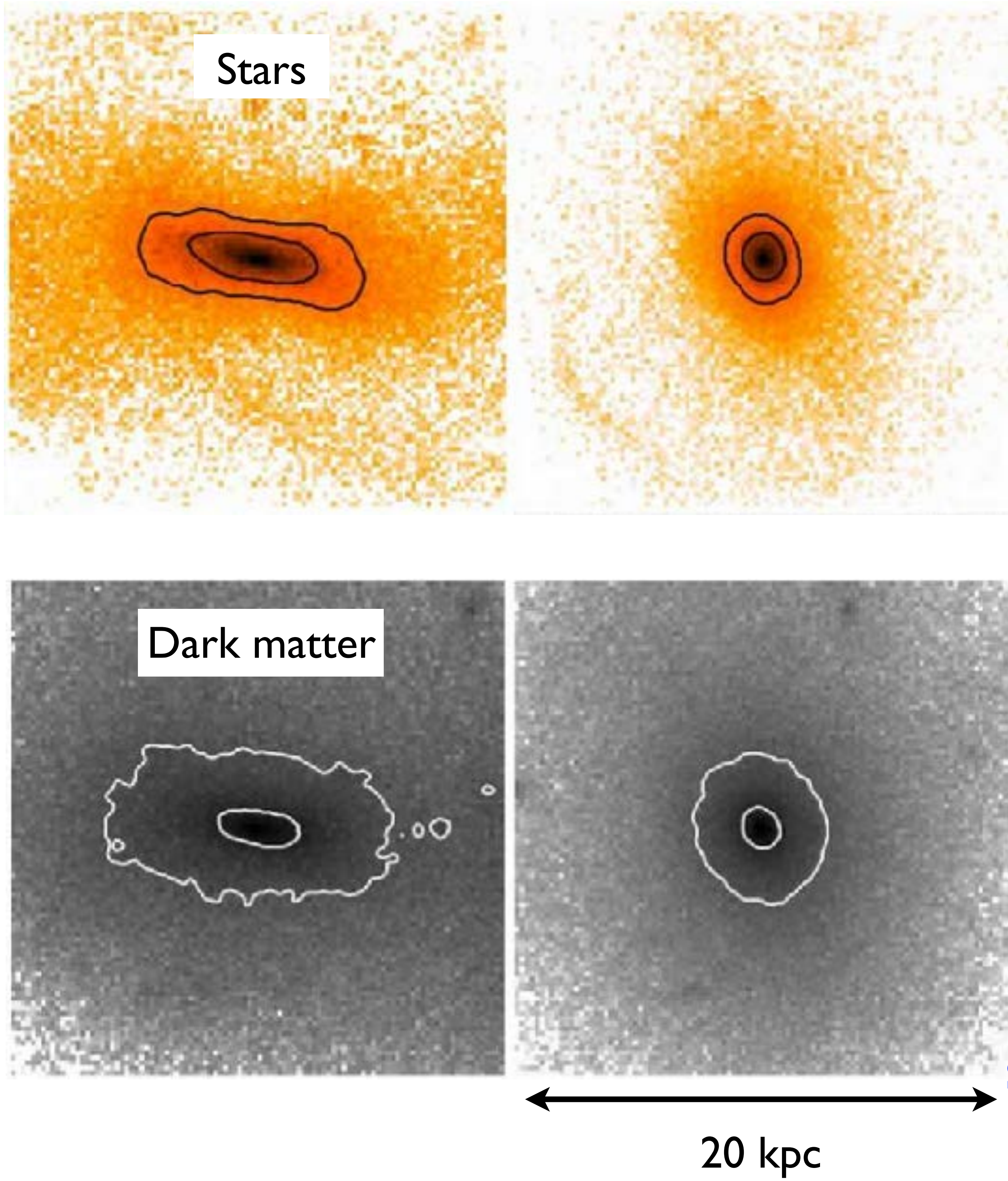


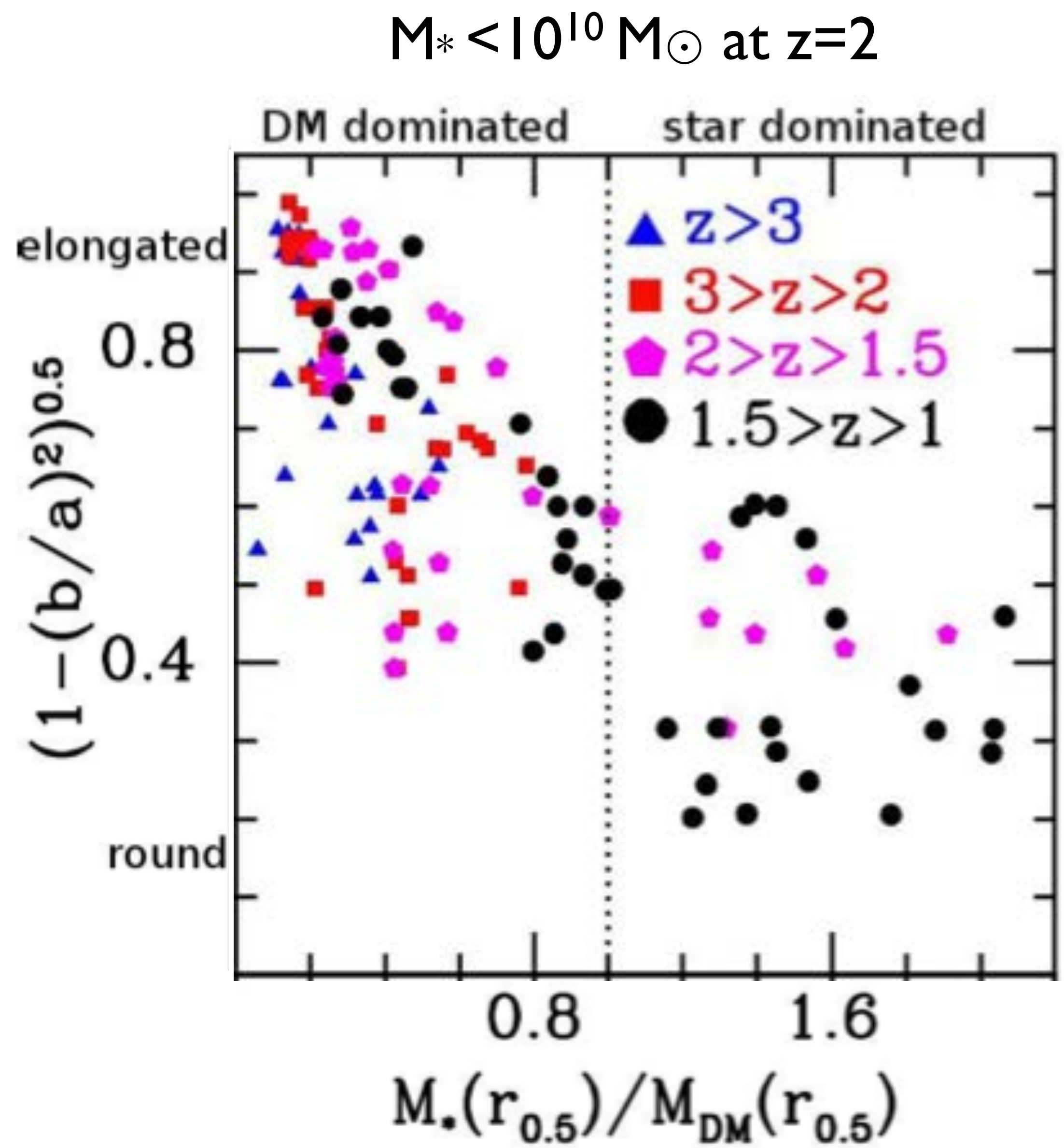


van der Wel+2014

See also WHEN DID ROUND DISK GALAXIES FORM? T. M. Takeuchi et. al ApJ 2015

Formation of elongated galaxies with low masses at high redshift





See also Tomassetti et al. 2016 MNRA

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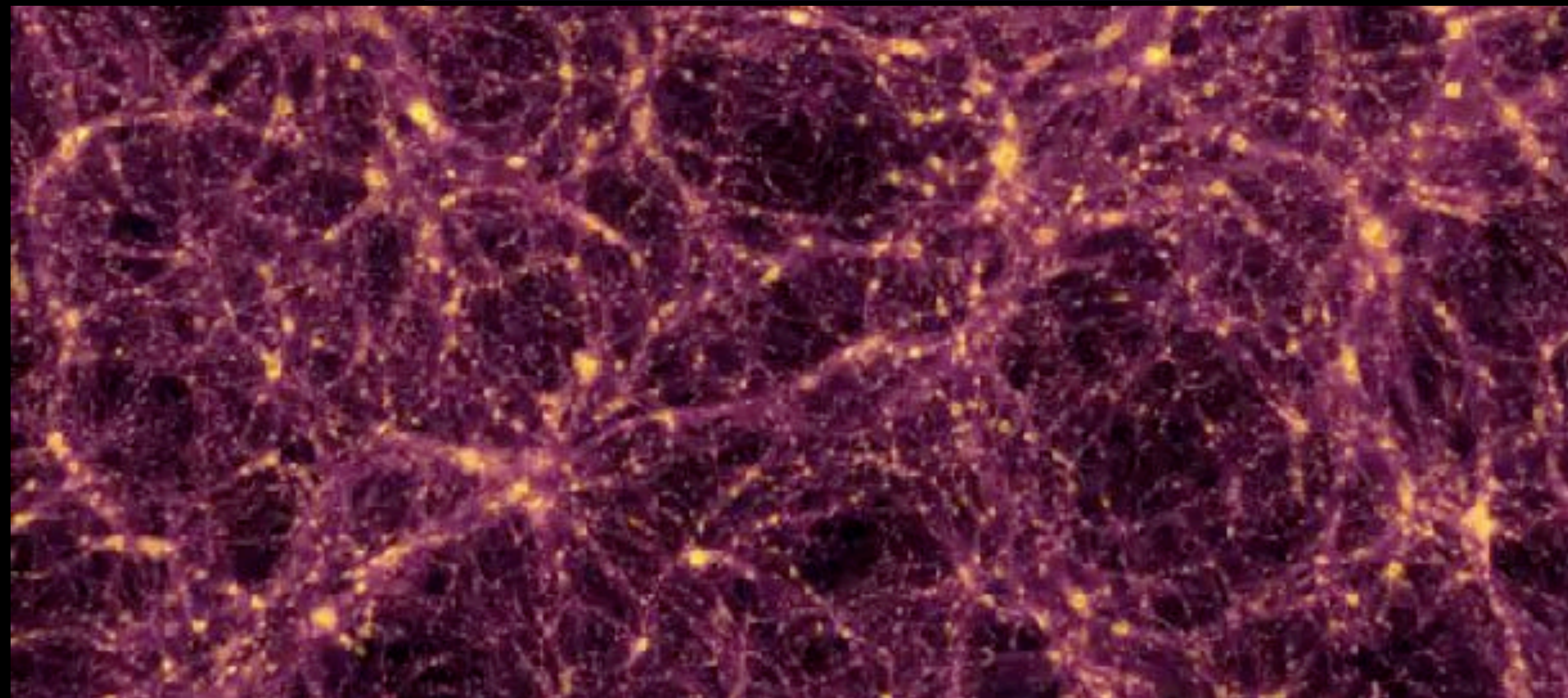


ΛCDM cosmology: successes, challenges, and opportunities for progress

Joel Primack, UC Santa Cruz

- **Successes:** CMB, Expansion History, Large Scale Structure, Galaxy Formation and Evolution
- **Challenges:** Cusp-Core, Too Big To Fail, Satellite Galaxies
- **Opportunities for Progress Now:** Halo Substructure by Gravitational Lensing and Stellar Motions, Early Galaxies, Compare and Improve Galaxy Simulations

ΛCDM Challenges: Cusp-Core, Too Big to Fail, Satellite Galaxies

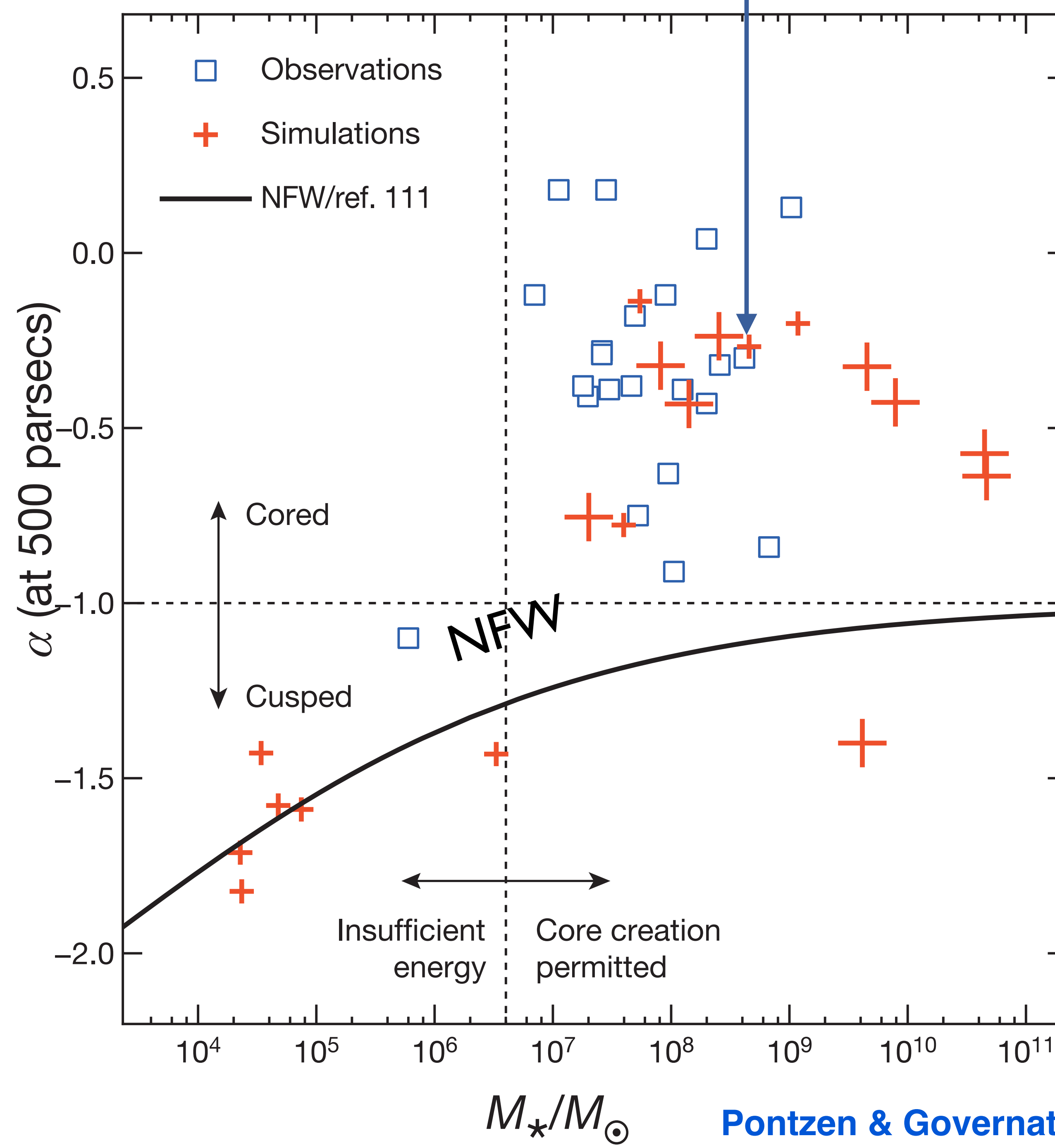
Flores & Primack94 and Moore94 first pointed out that dark matter simulations have density $\rho(r) \sim r^{\alpha}$ at small r with $\alpha \approx -1$ ("cusp") while observed small spiral galaxies and clusters appeared to have $\alpha \approx 0$ ("core").

Governato+10,13 and the *Nature* review by Pontzen & Governato14 show that in high-resolution galaxy simulations, baryonic physics softens the central DM cusp to a core as long as enough stars form, $M^* \geq 10^7\ M_\odot$. This happens because of repeated episodes when the baryons cool and slowly fall into the galaxy center, and are then expelled rapidly (in less than a dynamical time) by energy released by stars and supernovae.

Observers (e.g., Walker & Peñarrubia11, Amorisco & Evans12) had agreed that the larger dwarf spheroidal Milky Way satellite galaxies such as Fornax ($L \approx 1.7\text{x}10^7\ L_\odot$) have cores, but recent papers (e.g., Breddels & Helmi13,14, Jardel & Gebhardt13, Richardson & Fairbairn14) have questioned this. (Reviewed in Kormendy & Freeman16.)

Thus the cusp-core question is now more observational than theoretical!

Adams, Simon+14 find $\rho(r) \sim r^{\alpha}$, $\alpha \approx 0.5$ for dwarf spirals, in agreement with recent high-resolution simulations with baryons.

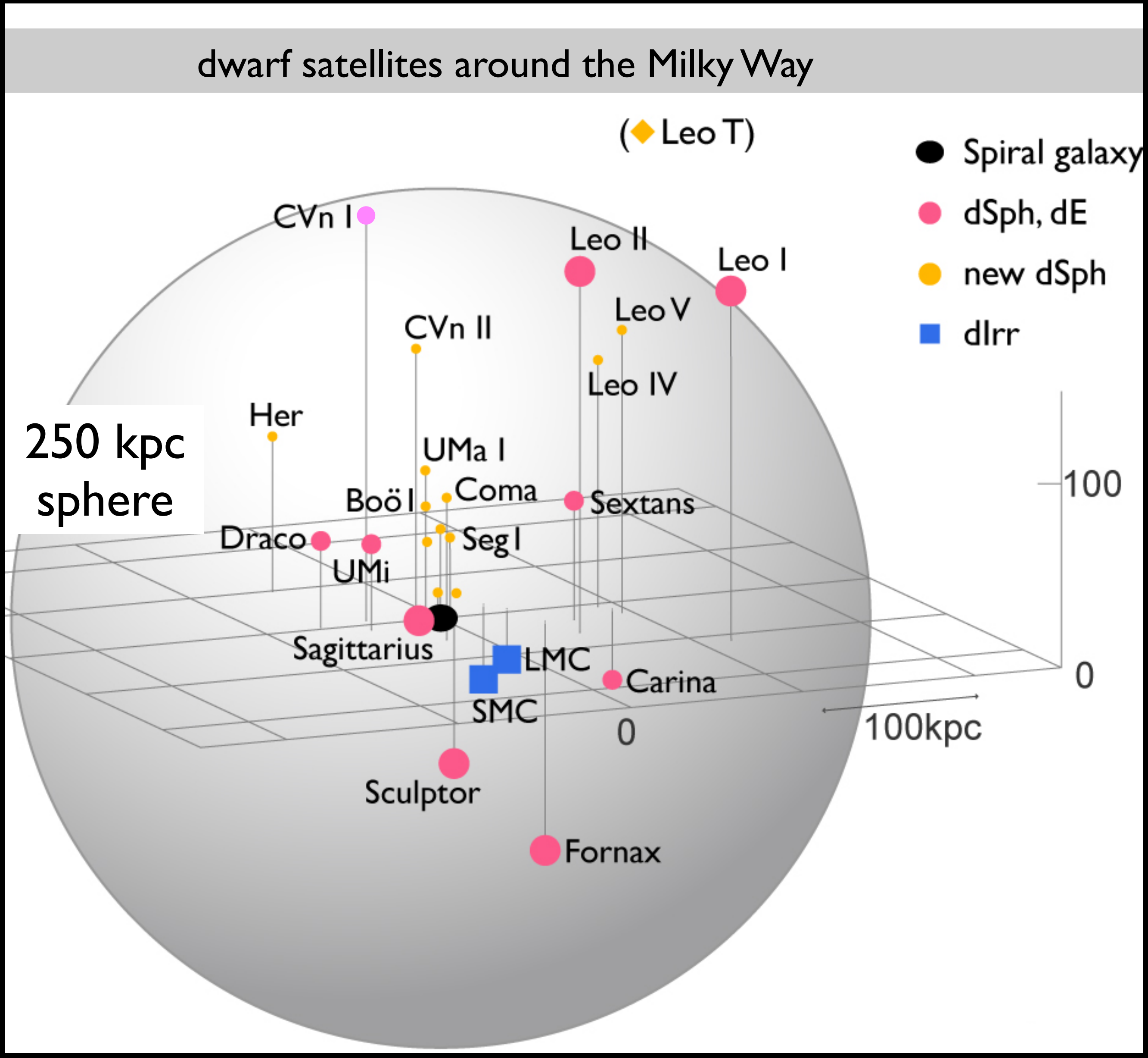


Pontzen & Governato14

"Too Big To Fail" MWy Satellite Problem

ΛCDM subhalos vs. Milky Way satellites

"Missing satellites": Klypin et al. 1999, Moore et al. 1999



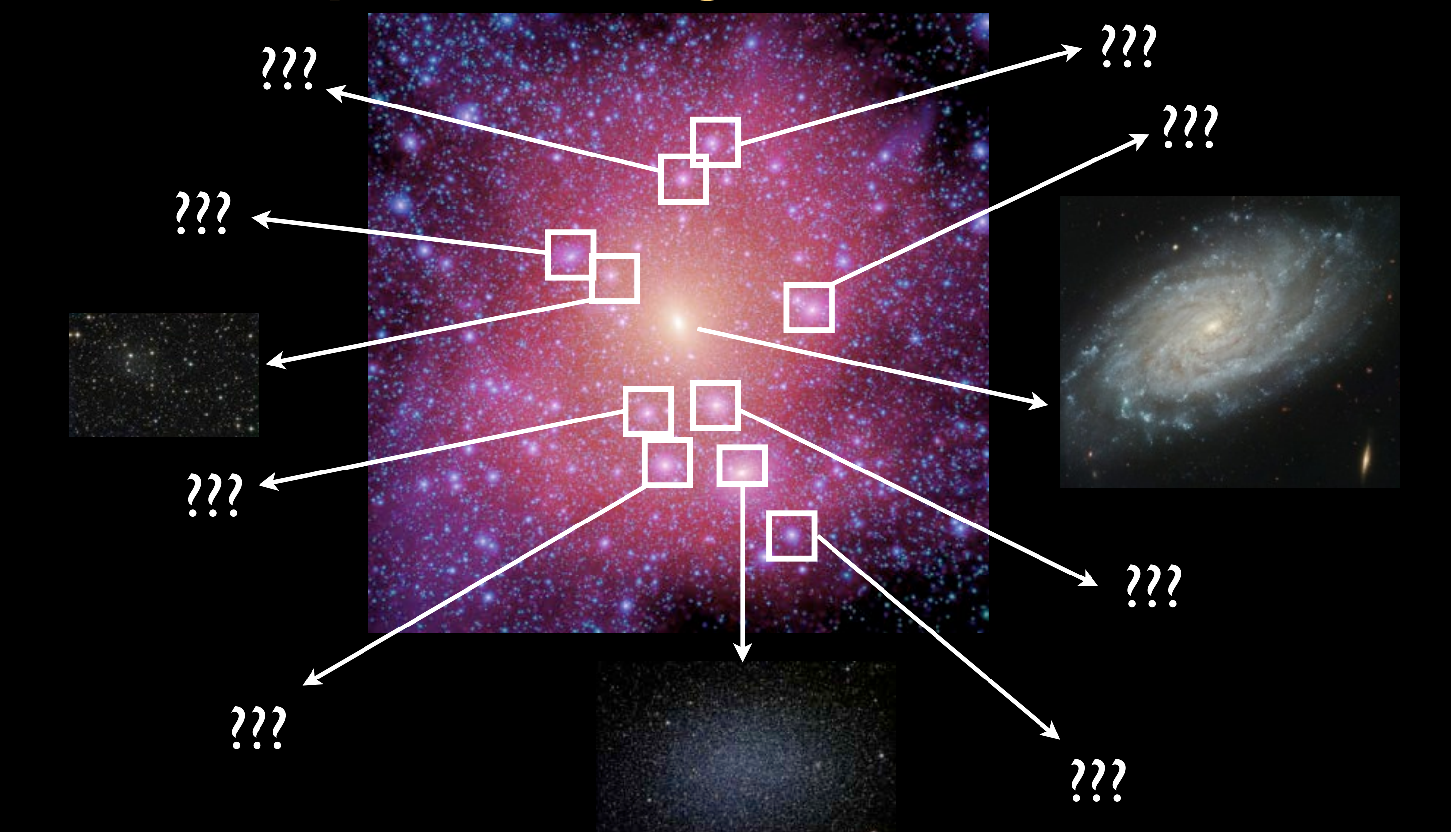
$>10^5$ identified subhalos

12 bright satellites $(L_V > 10^5 L_\odot)$

V. Springel / Virgo Consortium

S. Okamoto

Of the ~10 biggest subhalos, ~8 cannot host *any* known bright MW satellite

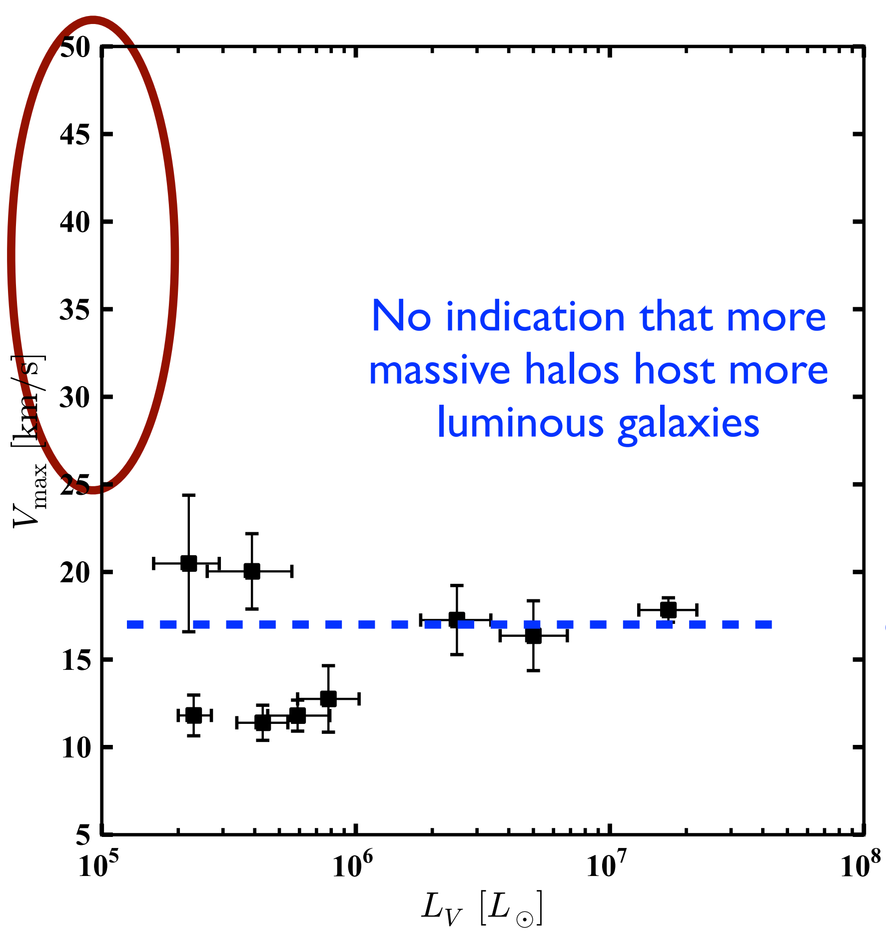


Observed Milky Way Satellites

"massive failures": highest resolution LCDM simulations predict ~10 subhalos in this range in the MW, but we don't see ***any*** such galaxies [except Sagittarius (?)]

All of the bright MW dSphs are consistent with $V_{\max} \lesssim 25\,\mathrm{km/s}$

(see also Strigari, Frenk, & White 2010)



LMC

SMC

c.f. Strigari et al. 2008

Possible Solutions to "Too Big to Fail"

The Milky Way is anomalous?

The Milky Way has a low mass dark matter halo?

Galaxy formation is stochastic at low masses?

Dark matter is not just CDM -- maybe WDM (e.g., Lovell+12,13,14)?

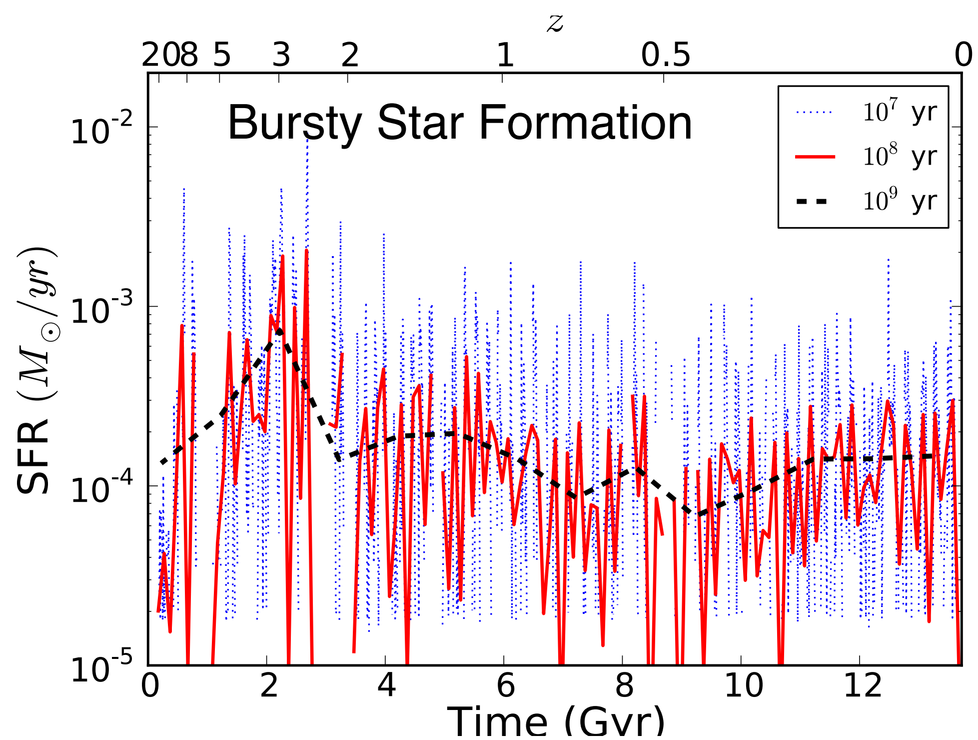
Or even self-interacting DM (Rocha+13, Peter+13, Zavala+14, Vogelsberger+14)?

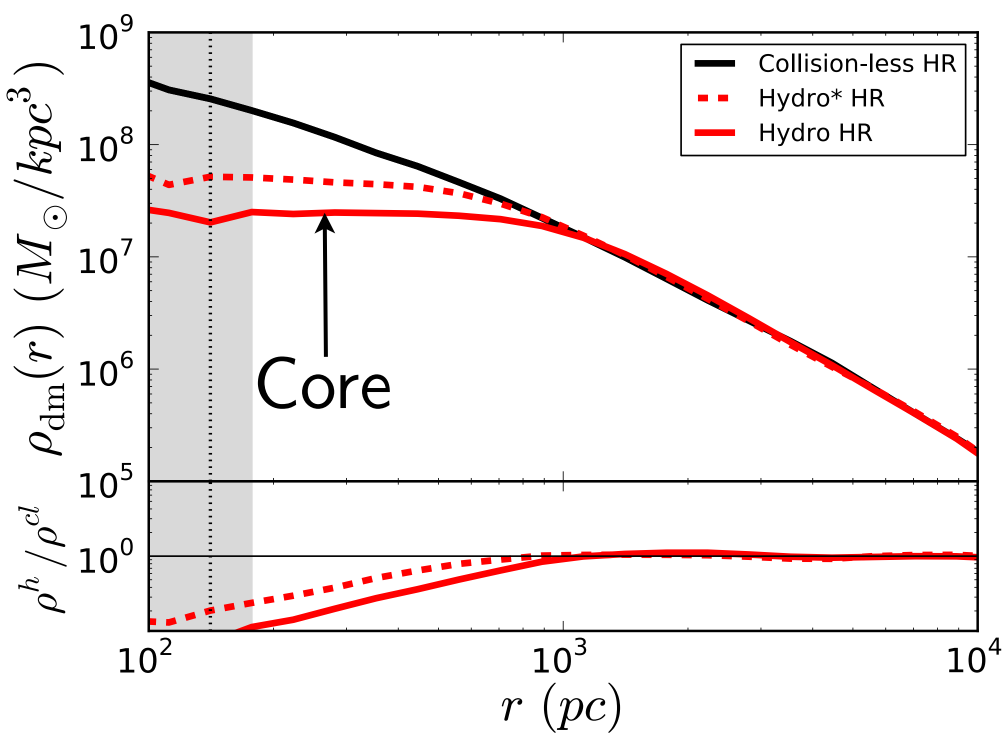
But maybe just including baryons properly will do the trick.

Boylan-Kolchin, Bullock, Kaplinghat 2011, 2012

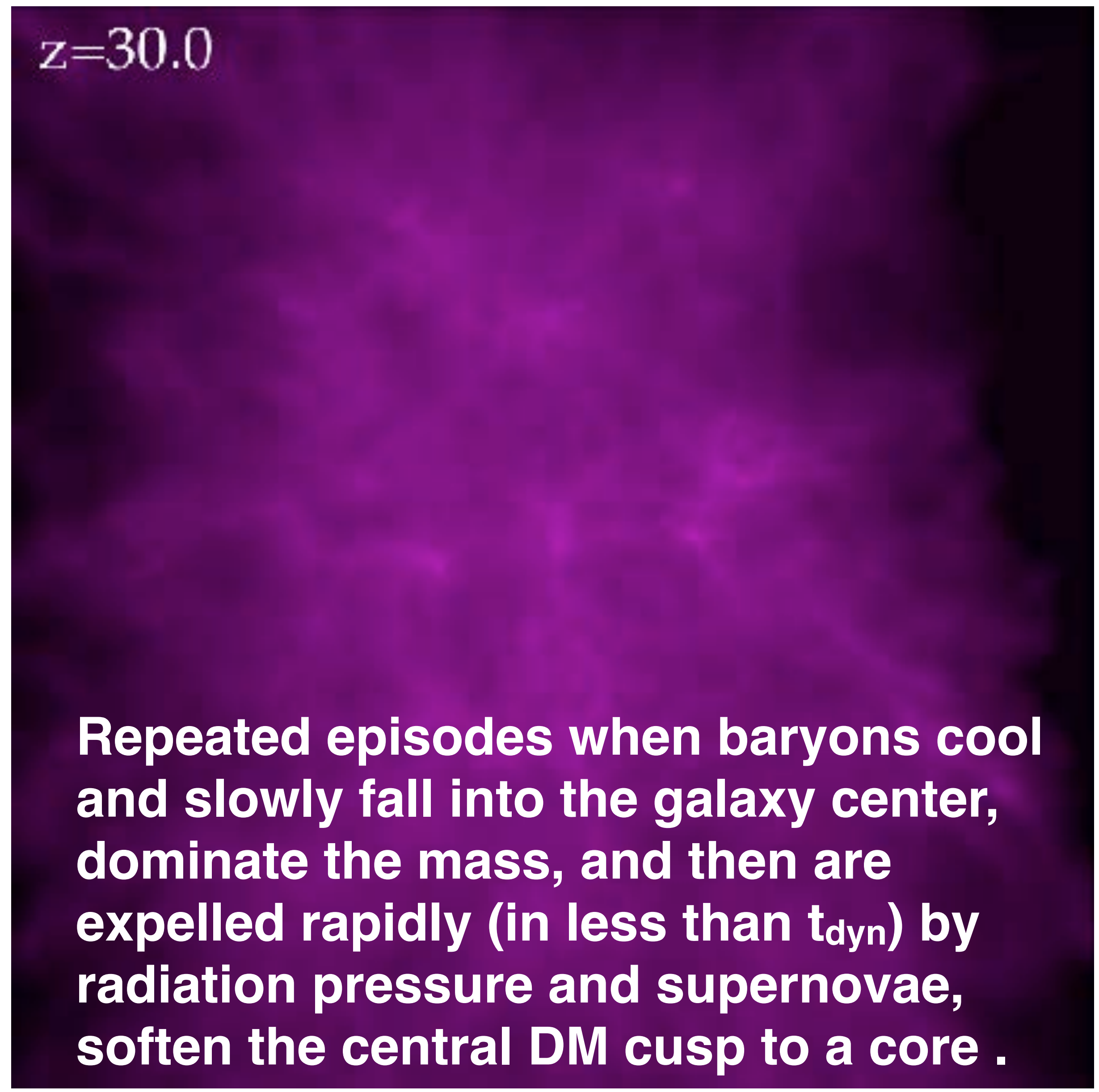
Challenges: Cusp-Core, Too Big to Fail, Satellite Galaxies

In addition to the Governato group's papers on this (including Zolotov+12, Brooks+13) there are several other recent papers (e.g., Teyssier+13, Arraki+14, Trujillo-Gome+14, DelPololo&Pace15, Simpson+15) arguing that baryonic effects convert the DM cusp to a core. **The highest-resolution simulation yet of a dwarf spiral was presented in Onorbe, Boylan-Kolchin, Bullock, et al. 2015. The continuous central star formation converted the central cusp to a core, reducing the rotation velocity, and thus resolving the TBTF challenge.**





$M_{vir} = 1E10 M_\odot$ at $z = 0$ $\quad M_* = 4 \times 10^6 M_\odot$



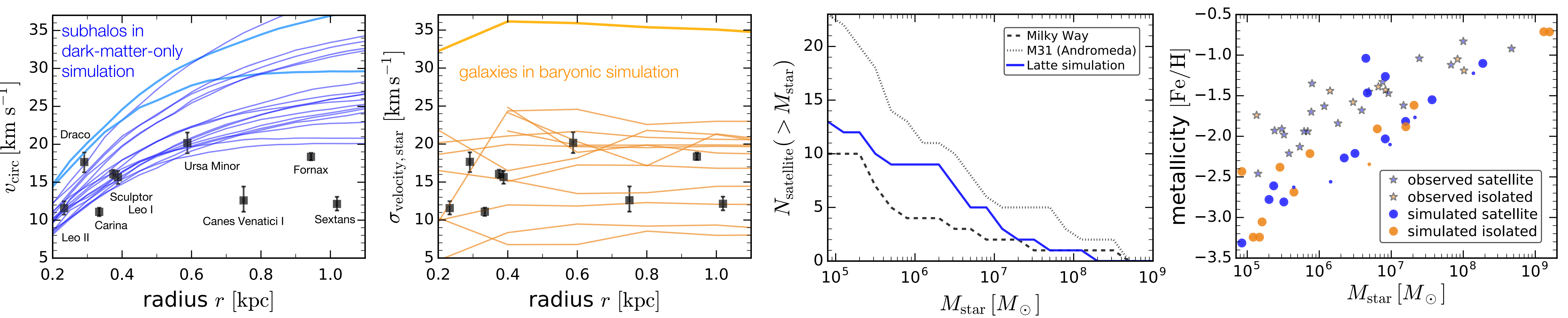
Onorbe, Hopkins+14 FIRE (Feedback in Realistic Environments) simulations

RECONCILING DWARF GALAXIES WITH ΛCDM COSMOLOGY: SIMULATING A REALISTIC POPULATION OF SATELLITES AROUND A MILKY WAY–MASS GALAXY

Andrew R. Wetzel Philip F. Hopkins , Ji-hoon Kim , Claude-André Faucher-Giguère , Dušan Kereš, and Eliot Quataert

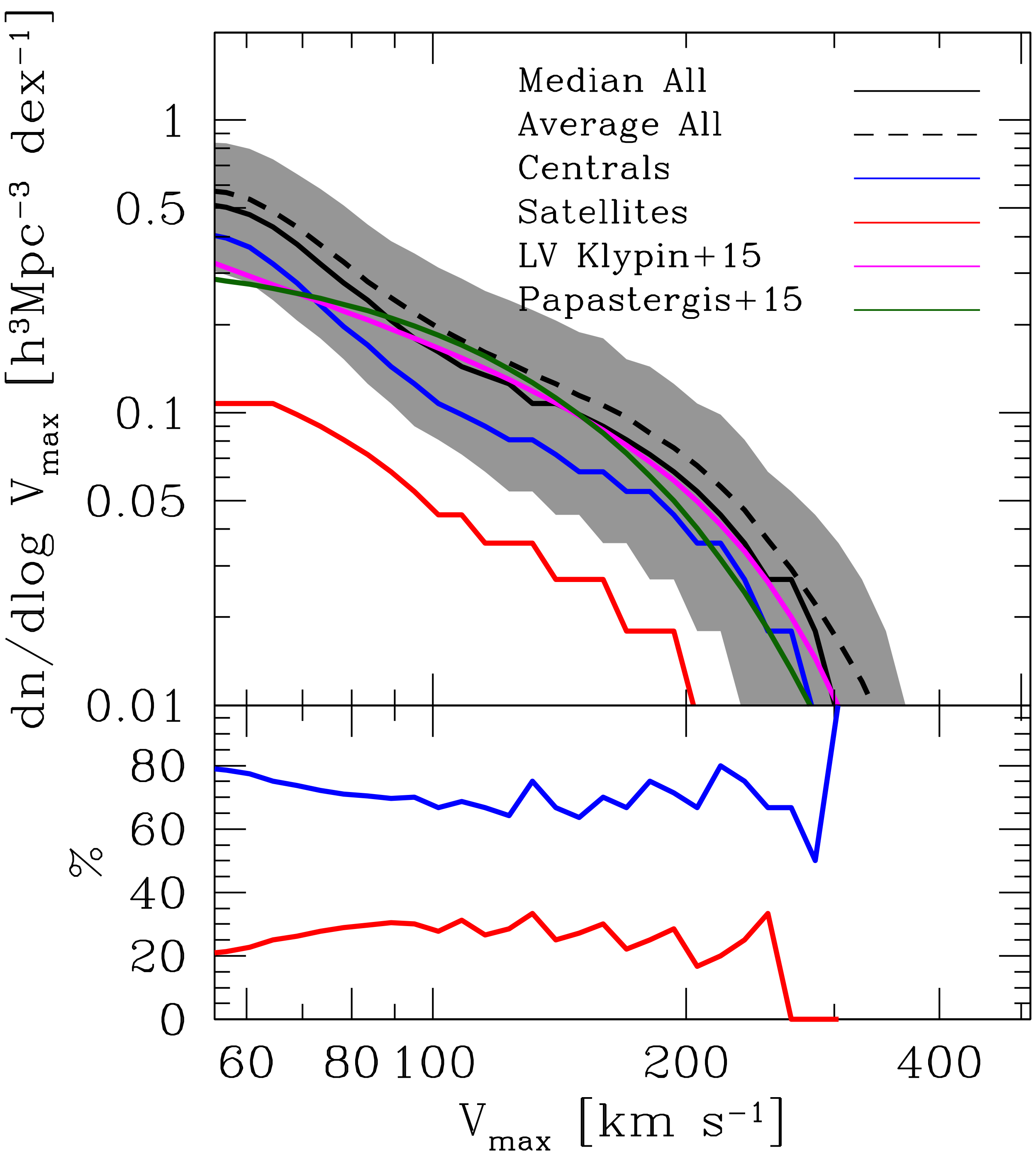
ApJLetters, 827:L23 (2016)

Low-mass “dwarf” galaxies represent the most significant challenges to the cold dark matter (CDM) model of cosmological structure formation. Because these faint galaxies are (best) observed within the Local Group (LG) of the Milky Way (MW) and Andromeda (M31), understanding their formation in such an environment is critical. We present first results from the Latte Project: the Milky Way on Feedback in Realistic Environments (FIRE). This simulation models the formation of an MW-mass galaxy to $z = 0$ within ΛCDM cosmology, including dark matter, gas, and stars at unprecedented resolution: baryon particle mass of 7070 $M_{\odot}$ with gas kernel/softening that adapts down to 1 pc (with a median of 25–60 pc at $z = 0$). Latte was simulated using the GIZMO code with a mesh-free method for accurate hydrodynamics and the FIRE-2 model for star formation and explicit feedback within a multi-phase interstellar medium. For the first time, Latte self-consistently resolves the spatial scales corresponding to half-light radii of dwarf galaxies that form around an MW-mass host down to $M_{\rm star} \gtrsim 10^5\, M_{\odot}$. Latte’s population of dwarf galaxies agrees with the LG across a broad range of properties: (1) distributions of stellar masses and stellar velocity dispersions (dynamical masses), including their joint relation; (2) the mass– metallicity relation; and (3) diverse range of star formation histories, including their mass dependence. Thus, **Latte produces a realistic population of dwarf galaxies at $M_{\rm star} \gtrsim 10^5\, M_{\odot}$ that does not suffer from the “missing satellites” or “too big to fail” problems of small-scale structure formation. We conclude that baryonic physics can reconcile observed dwarf galaxies with standard ΛCDM cosmology.**



Is there a "Too Big To Fail" problem in the field?

Not down to Bolshoi-Planck simulation V_{max} > 50 km/s



Comparison of the Local Volume 3D velocity function dN/d log V from the SMDPL simulation with the observed Local Volume optical velocity function of galaxies within ~ 10 Mpc (Figure 12 of Klypin, Karachentsev et al. 2015) and the HI radio velocity function from the ALFALFA survey (Papastergis et al. 2015). The grey band is the 1σ spread around mock Milky Way centers of 10 Mpc Local Volume. (Rodriguez-Puebla et al. 2016)

No discrepancy, with baryonic effects & observability

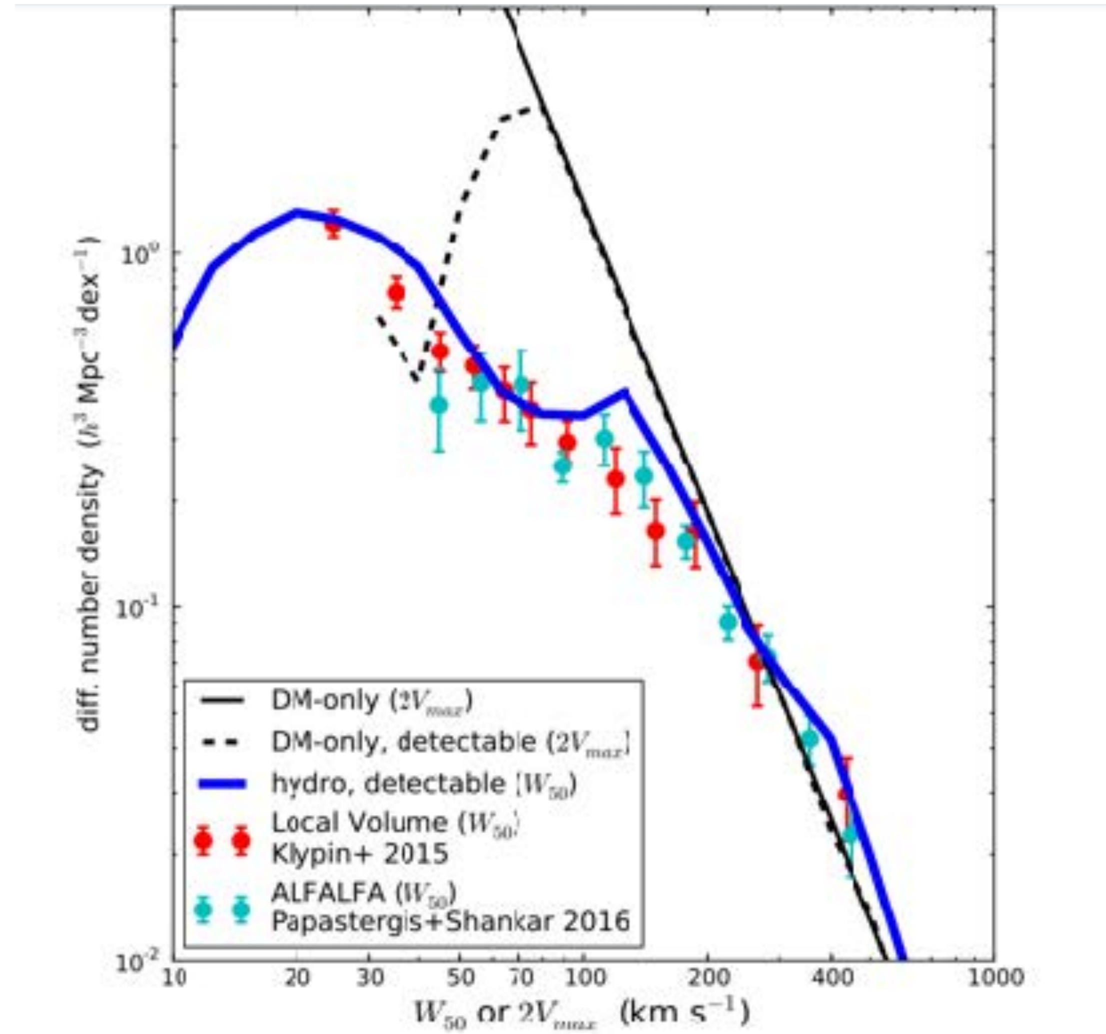


FIG. 4.— The expected VF including baryonic effects compared to observations. The red and cyan datapoints with errorbars are observational measurements of the VF, based respectively on Local Volume galaxies and on galaxies detected by the ALFALFA survey (Klypin et al. 2015; Papastergis & Shankar 2016). The observational VFs are plotted in terms of w_{50}, which is the line-of-sight width of the HI line profile. The thin black solid line is the theoretical VF of halos in a DM-only simulation with *Planck* cosmological parameters (Rodríguez-Puebla et al. 2016). The thin black dashed line is the DM-only VF for halos that are expected to host detectable galaxies with $M_* > 10^6 \, M_\odot$, according to our simulations (Fig. 1). These two DM-only VFs are plotted in terms of $2v_{max,dmo}$, which is twice the maximum circular velocity of the halo in the DM-only case. The thick blue solid line is the expected VF of detectable *galaxies* according to our simulations. It is derived based on the $2v_{max,dmo} - w_{50}$ relation observed for our simulated galaxies (Fig. 3), and it is corrected for line-of-sight projection assuming random galactic orientations.

(Brooks, Papastergis+ arXiv:1701.07835)

Challenges: Cusp-Core, Too Big to Fail, Satellite Galaxies

Some papers (e.g., Garrison-Kimmel,Rocha,Boylan-Kolchin,Bullock+13) claimed that feedback can't solve the TBTF problem. But Onorbe,Boylan-Kolchin,Bullock+15 (including some of the same authors) showed that a better treatment of feedback *can* do so, as have Maxwell,Wadsley,Couchman15 and Nipoti&Binney15.

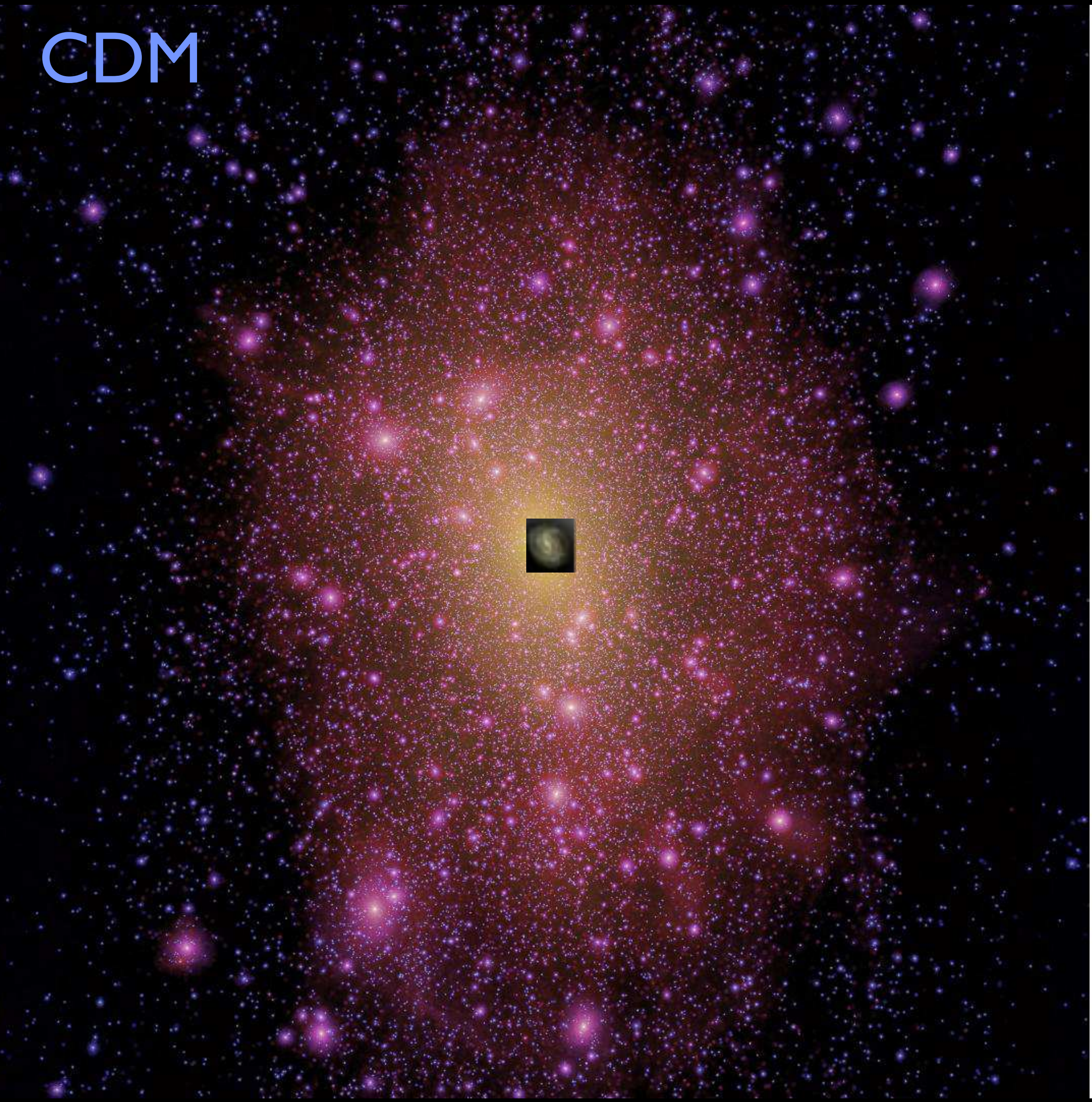
Despite the growing consensus among galaxy simulators that including baryons appears to convert the DM cusp to a core and can resolve the Too Big To Fail and Satellites challenges, papers continue to explore alternative solutions such as WDM and SIDM.

Recent Warm Dark Matter (WDM) papers

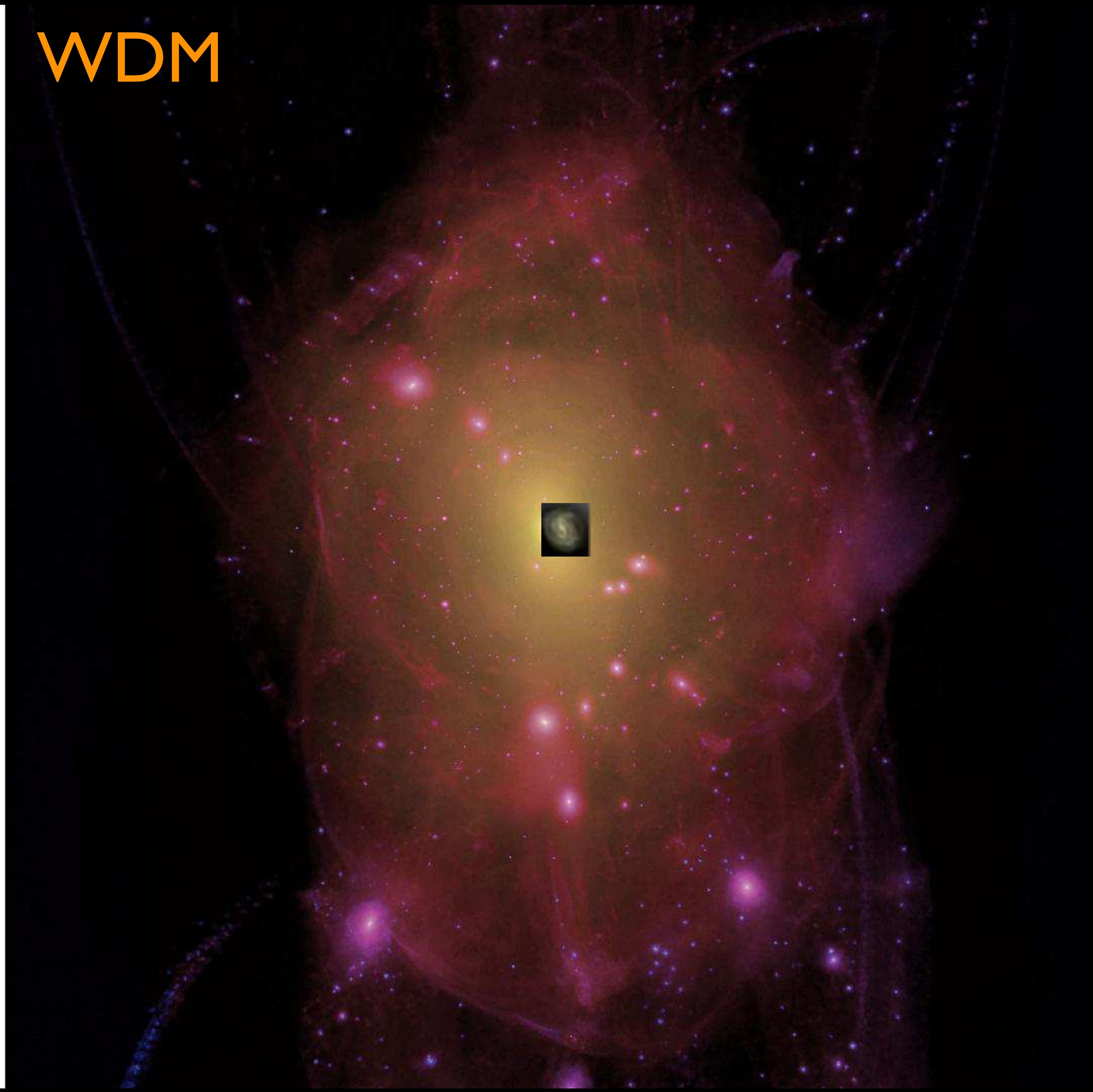
- **WDM doesn't resolve small scale problems: Schneider,Anderhalden,Maccio,Diemand14**
- **WDM constraints from lensing: Li,Frenk+1512.06507**
- **WDM constraints from reionization - strong: Schultz,Onorbe+14**
  - **- weak: Lapi&Danese15 - but this conflicts with Behroozi&Silk15**

Non-thermal (Shi&Fuller99) WDM for 3.5 keV line

- **MWy mass > 1.2×10^{12} $M_\odot$: Lovell,Bose+1511.04078**
- **Barely produces enough satellites w/o baryons: Horiuchi+16**
- **Excluded at 2σ by Lyα Forest: Schneider1601.07553**

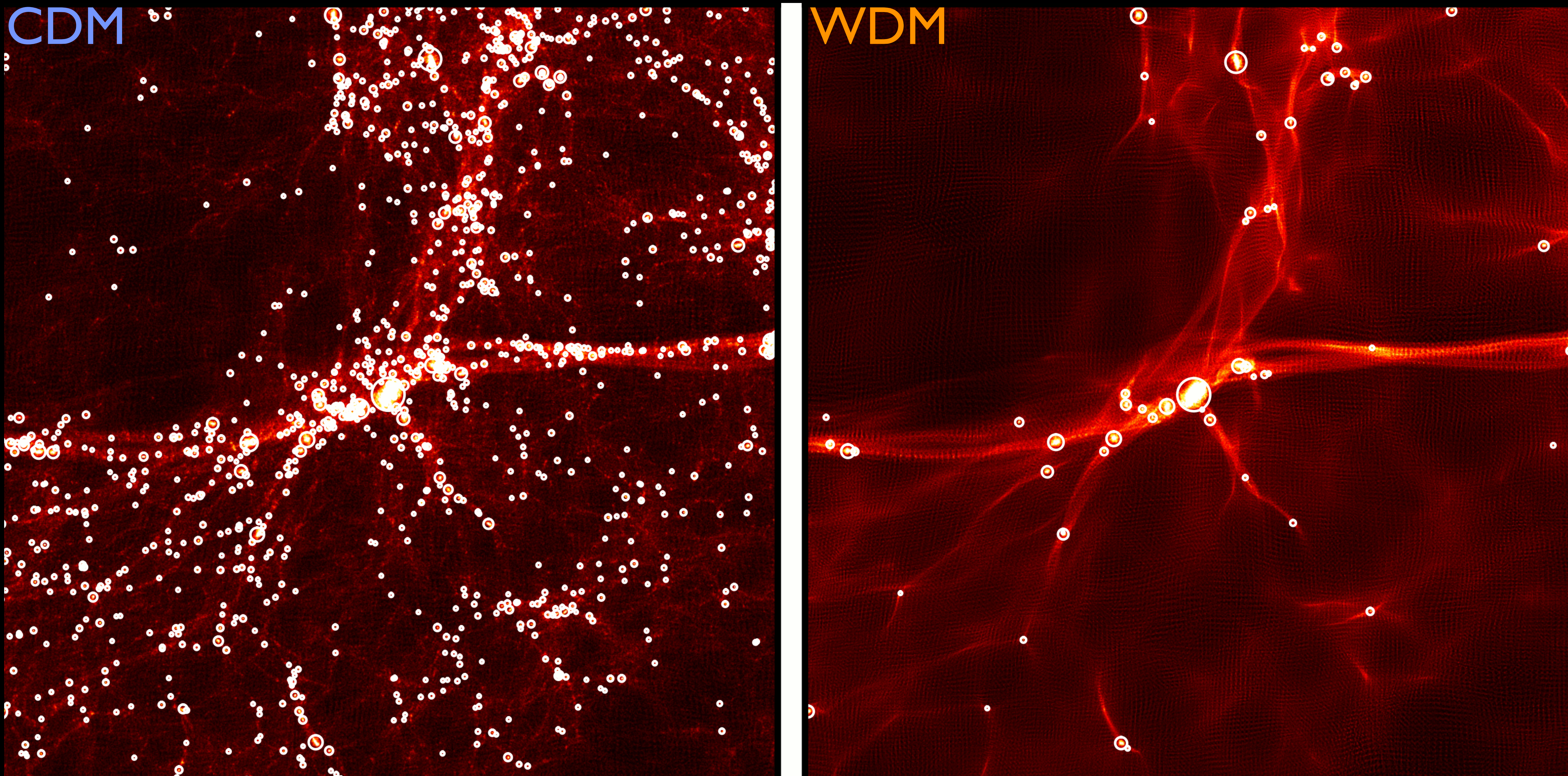


Aquarius simulation. Springel et al. 2008



Lovell, Eke, Frenk, et al. 2012

WDM simulation at right has no "too big to fail" subhalos, but it doesn't lead to the right systematics to fit dwarf galaxy properties as Kuzio de Naray+10 showed. It also won't have the subhalos needed to explain grav lensing flux anomalies and gaps in stellar streams.



WDM simulation at right has no "too big to fail" subhalos, but it is inconsistent at >10σ with Ultra Deep Field galaxy counts. It also won't have the subhalos needed to reionize the universe unless $m_{\nu}^{thermal} \gtrsim 2.6$ keV (or $m_{\nu}^{sterile} \gtrsim 15$ keV) assuming an optimistic ionizing radiation escape fraction (Schultz, Onorbe, Abazajian, Bullock14). Faint z=2 galaxies exclude $m_{\nu}^{thermal} \lesssim 1.8$ keV and $m_{\nu}^{ShiFuller} \lesssim 4$ keV (Menci+16). And the Ly-α forest(Viel+13) excludes $m_{\nu}^{thermal} \lesssim 2$ keV at 4σ, $\lesssim 3.3$ keV at 2σ.

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Self-Interacting Dark Matter (SIDM)

- Cluster shapes: $\sigma/m < 1$ cm^2/g : Peter+12
- Merging clusters: $\sigma/m < 1.5$ cm^2/g : Kalhoefer+15
- Velocity-dependent SIDM simulations: Vogelsberger+12, Zavela+13
- $\sigma/m = 2$ cm^2/g SIDM w baryons just like CDM, need V-dependence: Fry,Governato+15
- SIDM with V^{-4} dependence can arise from Rutherford-like scattering: Feng+09, Tulin+13
- $\sigma/m = 50$ cm^2/g for dwarf galaxies OK with V-dependence, makes them rounder: Elbert+15

But forming galaxies are not round, they are elongated (prolate, sausage-shaped)

Self-Interacting Dark Matter (SIDM)

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But forming galaxies are not round, they are elongated (prolate, sausage-shaped)

Cluster shapes (elongated, not spherical) and the similar behavior of DM and galaxies in merging clusters put strong limits on any dark matter self-interaction cross section $\sigma/m < 1.5\ cm^2/g$. Much larger cross sections such as $\sigma/m = 50\ cm^2/g$ are needed to have any effect at the centers of dwarf galaxies, which could arise if the self-interaction were strongly inversely dependent on the internal velocity of the system — i.e., small for clusters with large velocities ~ 1000 km/s but large for dwarf galaxies with small velocities ~ 10 km/s. However, just as DM self-interaction can make clusters round, it could also make dwarf galaxies round — but both clusters and low-mass forming galaxies are elongated. Calculations are still needed to clarify the limits from this on self-interaction in dwarf galaxies.

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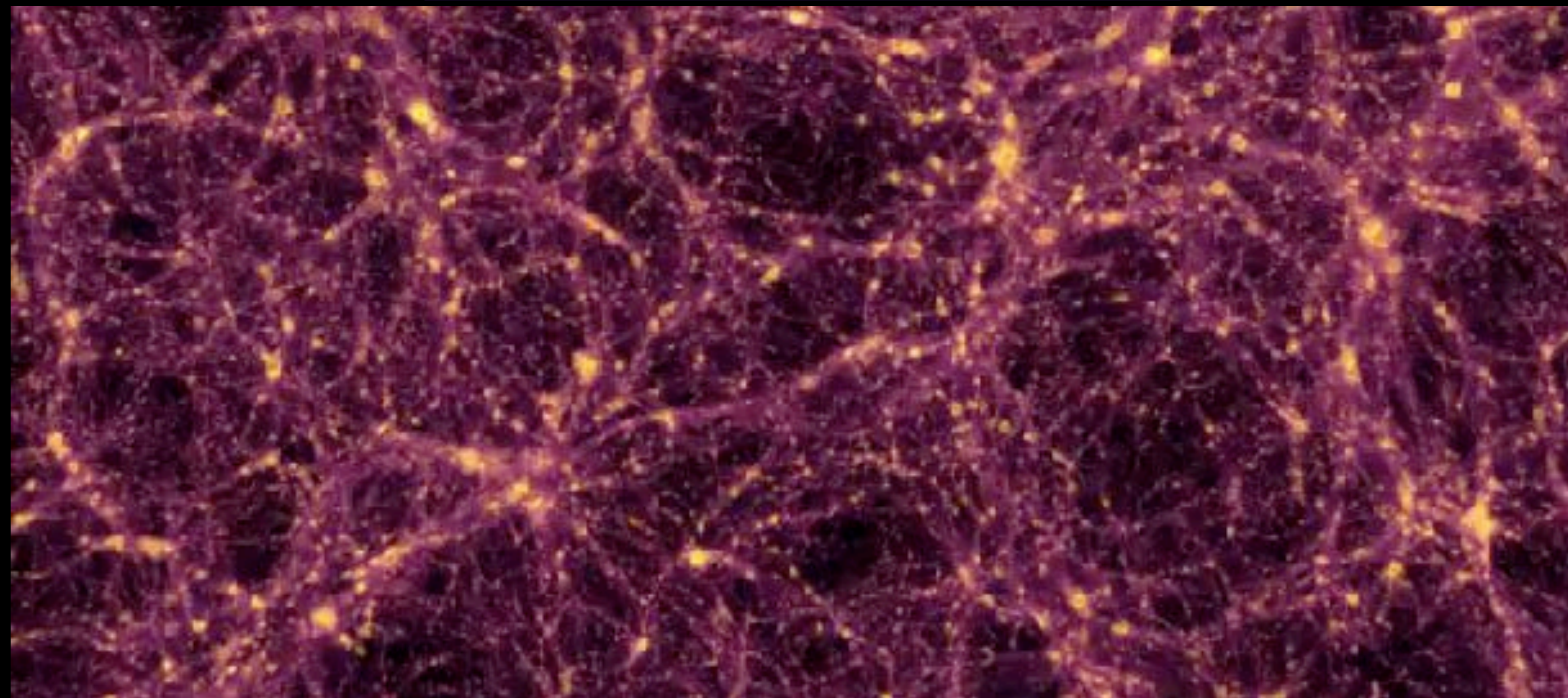

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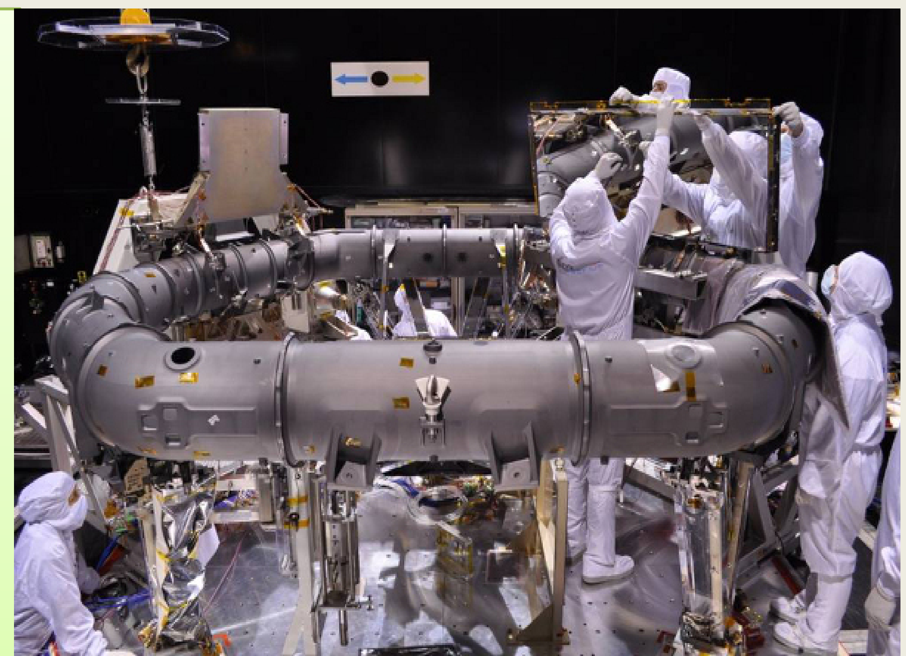
Gaia: ESA's premier astrophysics mission of the decade

Gaia is transformational – the first 3-D galaxy **precision distances and motions for 1 billion stars**

Gerry Gilmore, IoA Cambridge, UK Gaia PI

Launch:	12/2013
Work started:	1990
Project approved:	2000
Operations start	7/2014
5-7.5 years data	
Project end:	2023+
Total cost:	960M€



The heart of Gaia is a large camera array, 1 giga-pixel, sending us a video of the sky for 5-8 years.

The imaging data is being processed in Cambridge.
4 billion transits processed so far

2 telescopes, 1.45 x 0.5 m primary, monolithic SiC optical bench, 0.06arcsec pixels

Data flow: 50Gb/day for 5-8 years; total processed data and archives → 1PByte
Computational challenge : 1.5 x 10^{21} FLOP – and highly sophisticated algorithms

Gaps in Cold Stellar Streams Probe DM Halo Substructures

Direct Detection of Cold Dark Matter Substructure
Yoon, Johnston, Hogg ApJ (2011)
Density fluctuations in cold stellar streams will reflect DM substructure. Fluctuations in the Pal5 stream suggest the existence of missing satellites in numbers predicted by ΛCDM.

Dark Matter Sub-Halo Counts via Star Stream Crossings
R. G. Carlberg ApJ (2012), Carlberg,Grillmair, Hetherington ApJ (2012), Carlberg & Grillmair ApJ (2013)
Comparison of the CDM based prediction of the gap rate-width relation with published data for four streams shows generally good agreement within the fairly large measurement errors. The result is a statistical argument that the vast predicted population of sub-halos is indeed present in the halos of galaxies like M31 and the Milky Way.

Feeling the pull, a study of natural Galactic accelerometers - I. Stellar Stream of Palomar 5
R. Ibata, G. Lewis, N. Martin ApJ (2016)
Our deep CFHT data do ***not*** support the presence of significant gaps along the stream. The origin of the difference between our results and those of Carlberg et al. (2012) is likely that it is due to variations in homogeneity of the SDSS as one approaches the limiting magnitude of that survey.

Properties of dark subhaloes from gaps in tidal streams
D. Erdal, V. Belokurov MNRAS (2015) SDSS, DES, *Gaia*, and LSST can measure the *complete* set set of properties (including the phase-space coordinates during the flyby) of dark perturbers with $M > 10^7\,M_\odot$ (MNRAS 2016) ΛCDM predicts only 0.7 gaps in the Pal 5 tidal tails

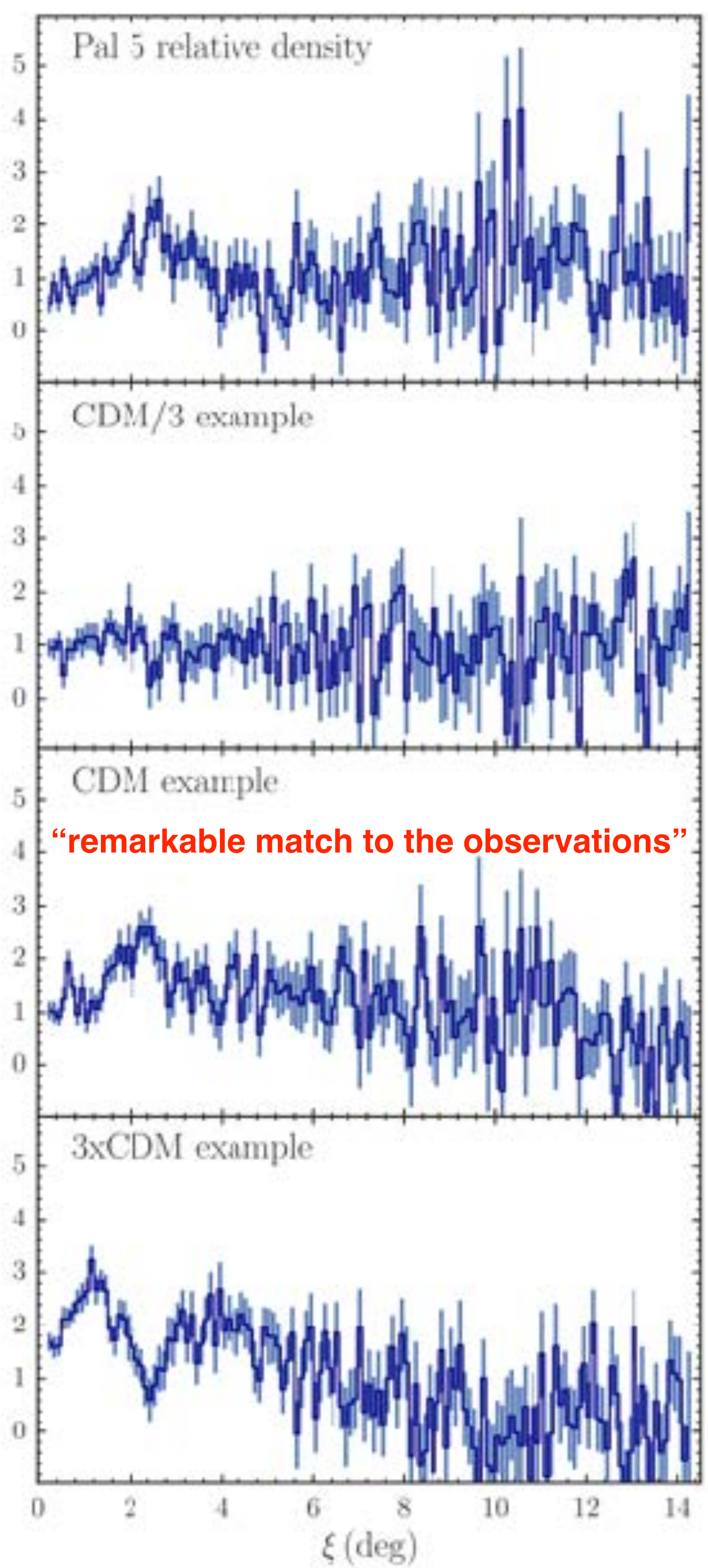
Detecting dark matter substructures around the Milky Way with Gaia
R. Feldmann, D. Spolyar MNRAS (2015)
Gaia should detect the kinematic signatures of a few starless substructures

Reviewed in *Tidal Streams in the Local Group and Beyond* (Springer, 2016)

Gaps in Cold Stellar Streams Probe DM Halo Substructures

Linear perturbation theory for tidal streams and the small-scale CDM power spectrum

Jo Bovy, Denis Erkal and Jason L. Sanders MNRAS 466, 628 (2017)



Tidal streams, when perturbed by a population of subhalo impacts, are unlikely to display clearly identifiable gaps in their density profiles, even when the number of impacts is relatively small and especially for those gaps that are due to low-mass subhaloes ($M \sim 10^7\ M_\odot$). But the subhalo impacts induce a rich structure of fluctuations on different scales, which can be observed through the power spectrum of the density and track. The structure in the density and that in the track are strongly correlated – indeed, it is the structure in the track that gives rise to the density fluctuations at later times. Because cold dark matter subhalos follow a somewhat tight concentration–mass relation, different-mass subhalos give rise to structure on different scales, with smaller scales dominated by very low mass subhalos ($M < 10^7\ M_\odot$).

Data for the Pal 5 stream (Ibata, Lewis, Martin 2016) allow a first rigorous determination of 10^{+11}_{-6} dark matter subhalos with masses between $10^{6.5}$ and $10^9\ M_\odot$ within 20 kpc from the Galactic centre [corresponding to $1.4^{+1.6}_{-0.9}$ times the number predicted by CDM-only simulations, or to $f_{sub}(r < 20\ \text{kpc}) \approx 0.2\%$] assuming that the Pal 5 stream is 5 Gyr old. Improved data will allow measurements of the subhalo mass function down to $10^5\ M_\odot$, thus definitively testing whether dark matter is clumpy on the smallest scales relevant for galaxy formation.

More evidence for substructure in DM halos: lensing flux anomalies

Direct Detection of Cold Dark Matter Substructure

Neal Dalal & Christopher S. Kochanek ApJ 572, 25 (2002)

We devise a method to measure the abundance of satellite halos in gravitational lens galaxies and apply our method to a sample of seven lens systems. After using Monte Carlo simulations to verify the method, we find that substructure comprises f_{sat}=0.02 (median, 0.006<f_{sat}<0.07 at 90% confidence) of the mass of typical lens galaxies, in excellent agreement with predictions of cold dark matter (CDM) simulations.

Effects of Line-of-Sight Structures on Lensing Flux-ratio Anomalies in a ΛCDM Universe

D. D. Xu, Shude Mao, Andrew Cooper, Liang Gao, Carlos S. Frenk, Raul Angulo, John Helly MNRAS (2012)

We conclude that line-of-sight structures can be as important as intrinsic substructures in causing flux-ratio anomalies. ...This alleviates the discrepancy between models and current data, but a larger observational sample is required for a stronger test of the theory.

Constraints on Small-Scale Structures of Dark Matter from Flux Anomalies in Quasar Gravitational Lenses

R. Benton Metcalf, Adam Amara MNRAS 419, 3414 (2012)

We investigate the statistics of flux anomalies in gravitationally lensed QSOs as a function of dark matter halo properties such as substructure content and halo ellipticity. ...The constraints that we are able to measure here with current data are roughly consistent with ΛCDM N-body simulations.

Constraints on WDM from weak lensing in anomalous quadruple lenses

K. T. Inoue, R. Takahashi, T. Takahashi, T. Ishiyama MNRAS (2015)

Observed four quadruple lenses that show anomalies in the flux ratios, we obtain constraints on the mass of thermal WDM, $m_{WDM} \geq 1.3$ keV (95 per cent CL).

More evidence for substructure in DM halos: lensing flux anomalies

How well can CDM substructures account for the observed radio flux-ratio anomalies

D. D. Xu, Dominique Sluse, Liang Gao, Jie Wang, C. Frenk, Shude Mao, P. Schneider, V. Springel MNRAS (2015)

We find that CDM substructures are unlikely to be the whole reason for radio flux anomalies.

How well can CDM substructures account for the observed radio flux-ratio anomalies

J.-W. Hsueh, C. Fassnacht, S. Vigetti, J. McKean, C. Singola, M. Auger, L. Koopmans, D. Lagattuta MNRAS (2016)

Keck~II adaptive optics imaging and HST data reveal the lensing galaxy to have a clear edge-on disc that crosses directly over the pair of images that exhibit the flux-ratio anomaly. Another: arXiv:1701.06575

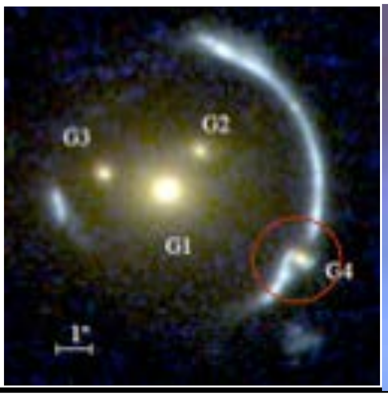
CDM Substructures in Early-Type Galaxy Halos

Davide Fiacconi, Piero Madau, Doug Potter, Joachim Stadel ApJ (2016)

Very high-resolution DM simulations of ~10^{13} $M_\odot$ halos show more substructure than previous simulations. Baryonic contraction increases the number of massive subhalos in the inner regions of the main host. The host density profiles and projected subhalo mass fractions appear to be broadly consistent with observations of gravitational lenses.

Gravitational detection of a low-mass dark satellite galaxy at cosmological distance, Simona Vigetti+ 2012 Nature

This group uses galaxy-galaxy lensing to look for the effects of substructure. Our results are consistent with the predictions from cold dark matter simulations at the 95 per cent confidence level, and therefore agree with the view that galaxies formed hierarchically in a Universe composed of cold dark matter.



Inference of the cold dark matter substructure mass function at $z = 0.2$ using strong gravitational lenses

S. Vegetti, L. V. E. Koopmans, M. W. Auger, T. Treu and A. S. Bolton MNRAS (2015)

No detection of substructure in 11 lens galaxies from the SDSS ACS survey. With earlier detections, the inferred fraction is consistent with the expectations from CDM simulations and with inference from flux ratio anomalies at 68% C.L.

New ways of observing dark matter halo substructure

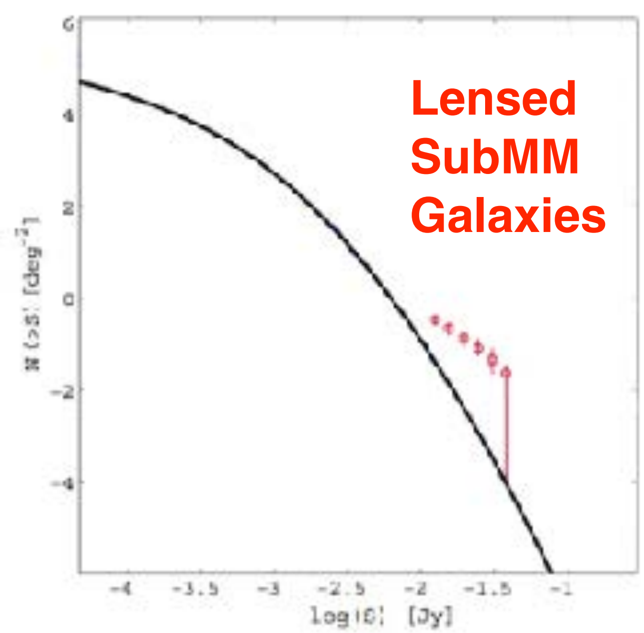
Optical lensing of quasar narrow line regions

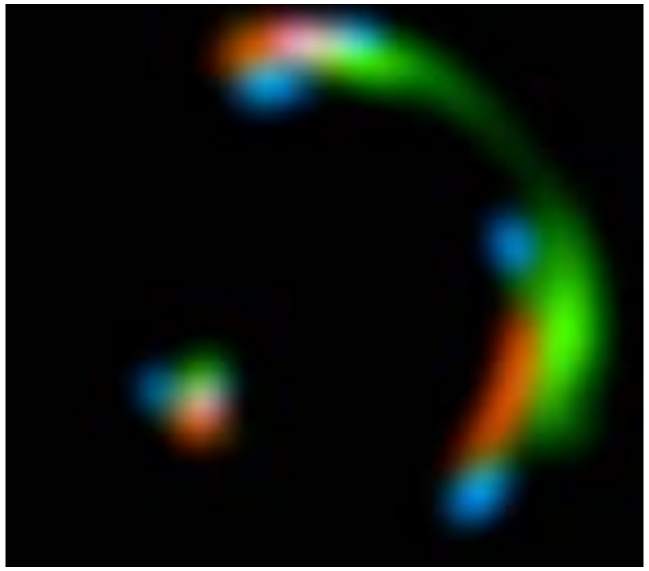
Detection of a substructure with adaptive optics integral field spectroscopy of the gravitational lens B1422+231
A. M. Nierenberg, T. Treu, S. A. Wright, C. D. Fassnacht, M. W. Auger MNRAS (2014)

In this paper we demonstrate for the first time that subhalos can be detected using strongly lensed narrow-line quasar emission, as originally proposed by Moustakas & Metcalf (2003). Many quasars have detectable narrow line emission, so this technique can really measure substructure.

ALMA spectral detection of lensing of dusty galaxies

Dark Matter Substructure Detection Using Spatially Resolved Spectroscopy of Lensed Dusty Galaxies
Yashar Hezaveh, Neal Dalal, G. Holder, M. Kuhlen, D. Marrone, N. Murray, J. Vieira ApJ (2013)





We find that in typical DSFG lenses, there is a ~55% probability of detecting a substructure with $M > 10^8\,M_\odot$ with $>5\sigma$ significance in *each lens*, if the abundance of substructure is consistent with previous lensing results.

Detection of Lensing Substructure in SDP.81
Yashar Hezaveh, Neal Dalal+ ApJ (2016)

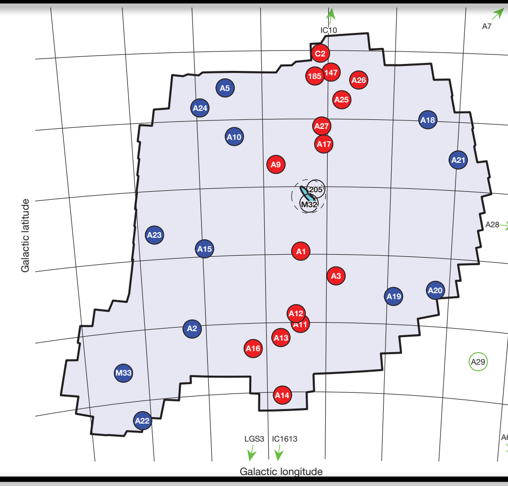
We find evidence for the presence of a $M = 10^{8.96\pm0.12} M_\odot$ subhalo with 6.9σ significance.

Rotating Planes of Galaxies About the Milky Way and Andromeda

A vast, thin plane of corotating dwarf galaxies orbiting the Andromeda galaxy

Ibata et al. Nature 2013

Intriguingly, the plane we identify is approximately aligned with the pole of the Milky Way's disk.

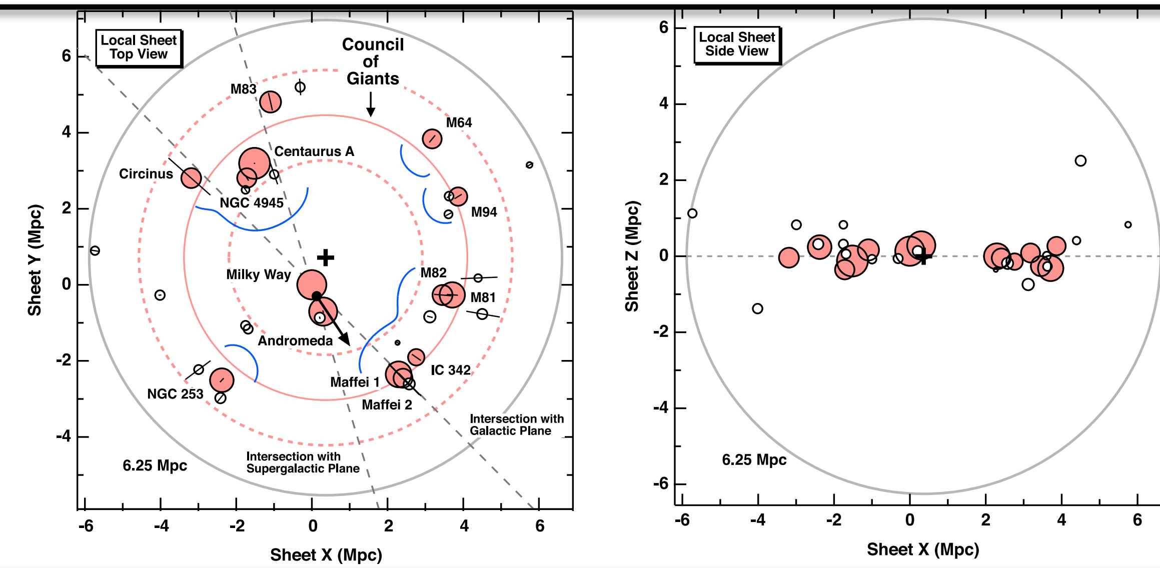


All the northern red satellites are coming towards us and all the southern ones are moving away

A Council of Giants

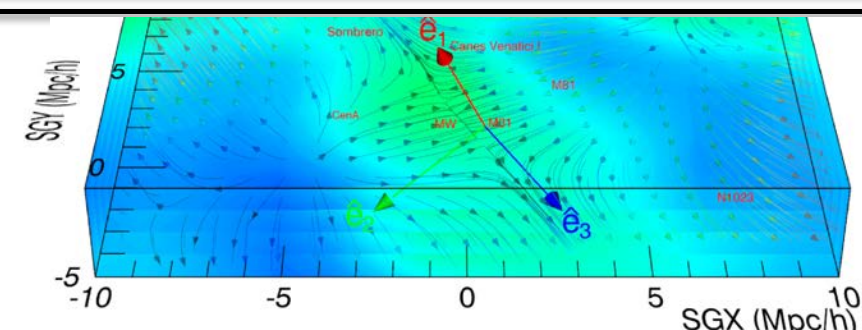
Marshall McCall MNRAS 2014

A 'Council of Giants' with a radius of 3.75 Mpc and thickness of 0.2 Mpc defines the Local Sheet, which is perpendicular to the Milky Way disk. [The plane of satellite galaxies about the Milky Way lie in the Local Sheet.]



Planes of satellite galaxies and the cosmic web

Libeskind, Hoffman, Tully et al. MNRAS 2015



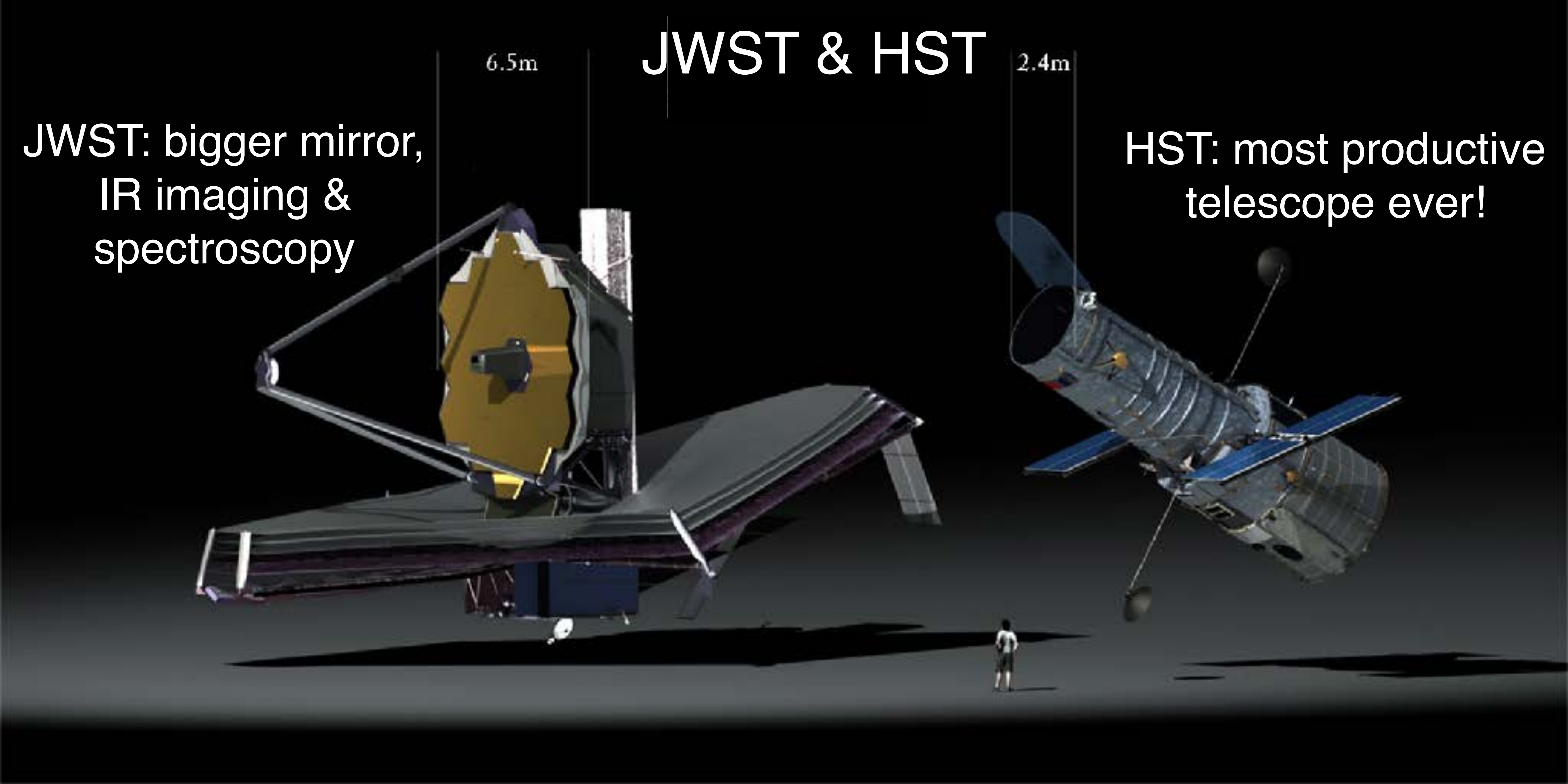
The Local Group and Centaurus A reside in a filament stretched by the Virgo cluster and compressed by the expansion of the Local Void. The alignment of satellite systems in the local Universe with the ambient shear field is thus in general agreement with predictions of ΛCDM.

Planes of satellite galaxies: when exceptions are the rule

Catun, Bose, Frenk, Qi Guo, Han, Hellwing, Sawala, Wang MNRAS 2015

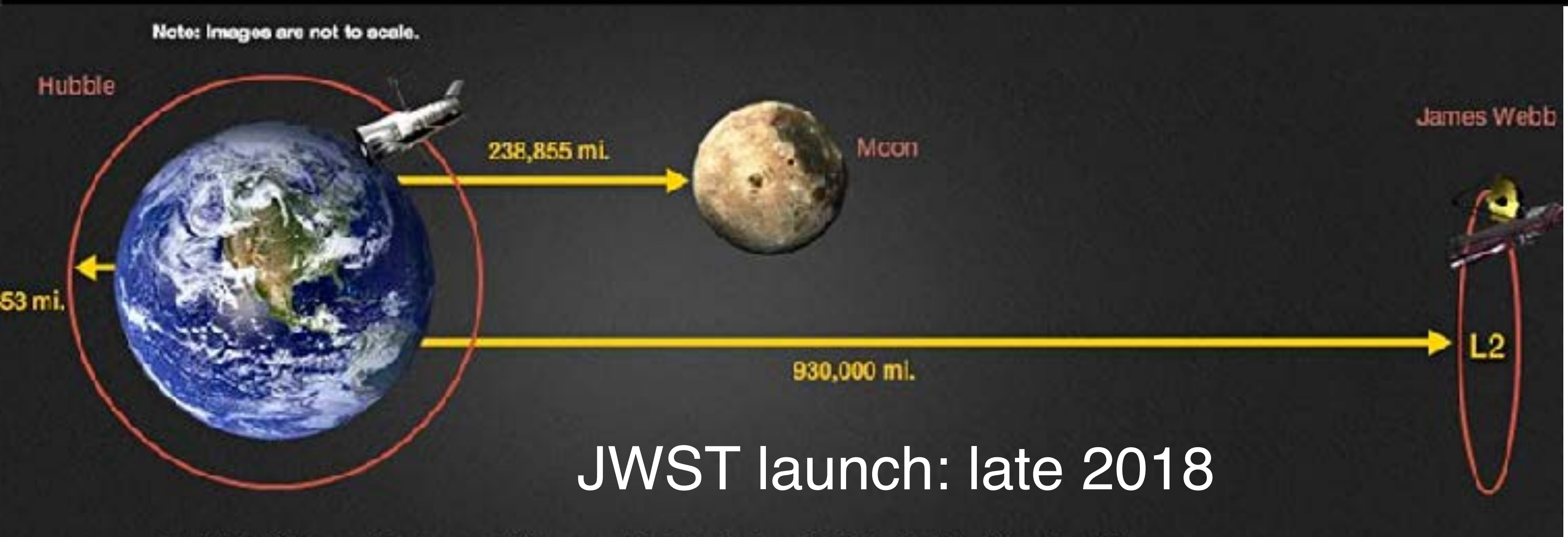
~10% of simulated Local Groups have satellite planes even more prominent than observed.

JWST & HST



JWST: bigger mirror, IR imaging & spectroscopy

HST: most productive telescope ever!



JWST launch: late 2018

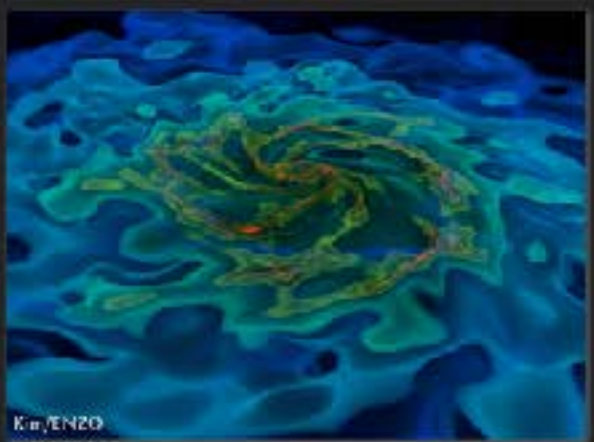
MIRI: Mid Infrared Instrument, 5-28 μm
NIRCam: Near Infrared Camera, 0.6 - 5 μm
NIRISS: Near-InfraRed Imager/SSpectrograph
NIRSpec: Near Infrared Spectrograph, 0.6-5 μm

James Webb Space Telescope Deployment

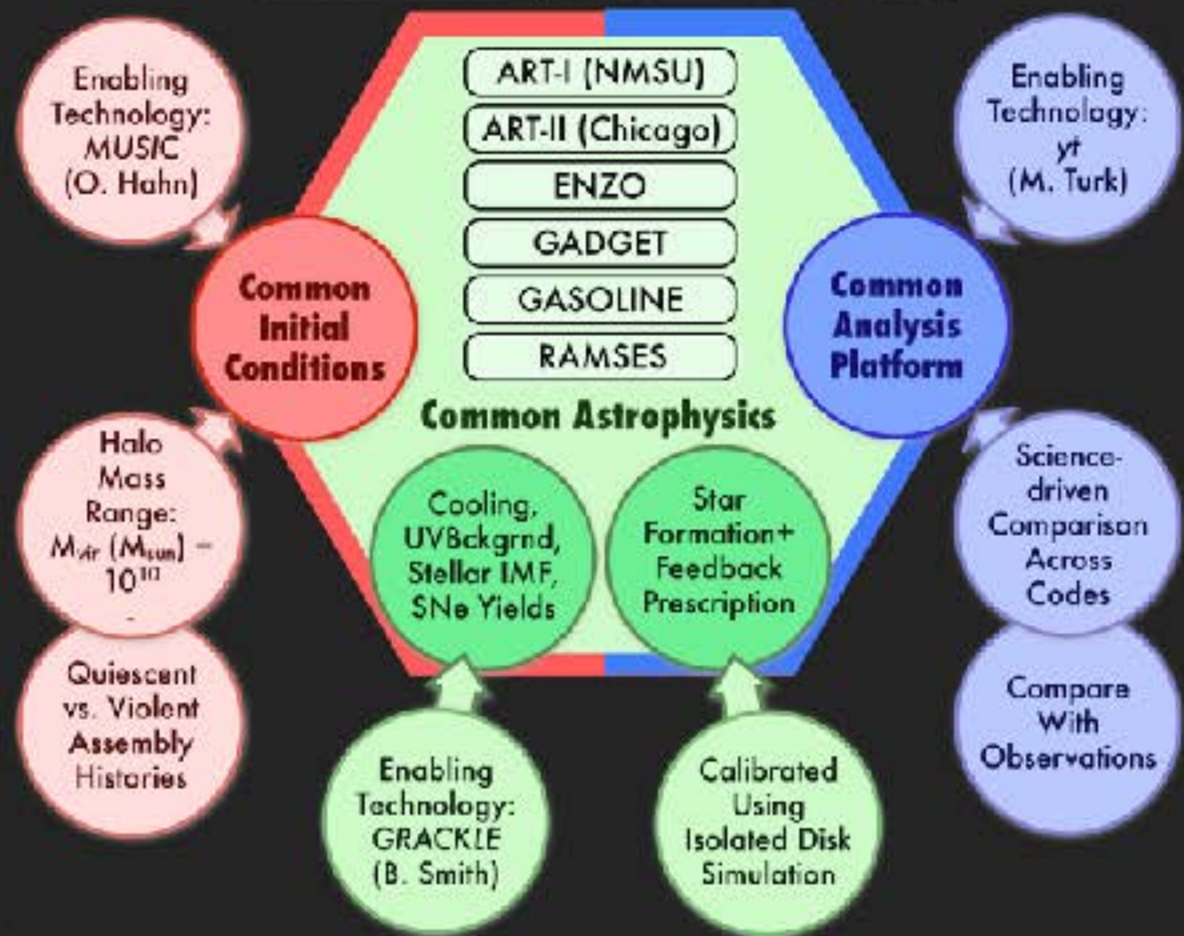
AGORA Assembling Galaxies of Resolved Anatomy

A High-resolution Galaxy Simulations Comparison Initiative: www.AGORAsimulations.org

High-res Galaxy Simulations



AGORA Comparison Infrastructure



AGORA Goal & Team

- GOAL: A collaborative, multi-platform study to raise the realism and predictive power of galaxy formation simulations
- TEAM: 140+ participants from 60+ institutions worldwide, as of August 2016
- DATA SHARING: Simulations outputs and analysis softwares will be shared with the community

- Contact: santacruzgalaxy@gmail.com
- AGORA First Light: Flagship paper by Ji-hoon Kim et al. (ApJS 2014)
- Project funded in part by:

AGORA High-Resolution Simulation Comparison

Initial Conditions for Simulations

MUSIC galaxy masses at z~0: ~10^{10}, 10^{11}, 10^{12}, 10^{13} $M_{\odot}$
with both quiet and busy merging trees
isolation criteria agreed for Lagrangian regions

Isolated Spiral Galaxy at z~1: ~10^{12} $M_{\odot}$

Astrophysics that all groups will include

UV background (Haardt-Madau 2012); Grackle cooling function (based on ENZO and Eris cooling)

Tools to compare simulations based on *yt*, for all codes used in AGORA, with instantaneous visualization

Images and SEDs for all timesteps from *yt* ➠ *Sunrise*

www.AGORAsimulations.org

AGORA Isolated Disk Comparison

ApJ 2016

Milky Way-mass Disk Galaxy Formation with 80 pc Resolution

Summary of results:

- If carefully constrained, galaxy simulation codes agree well with one another despite having evolved largely independently for many years without cross-breedings
- Simulations are more sensitive to input physics than to intrinsic code differences.
- AGORA continues to promote collaborative and reproducible science in the community.

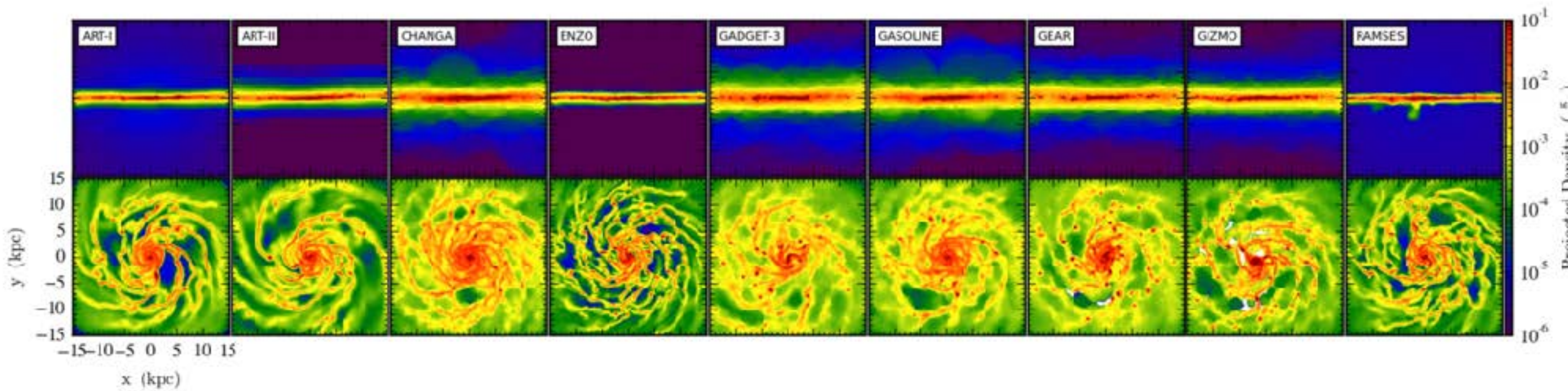


Figure 2. The 500 Myr composite snapshots of gas surface density from *Sim-1* with radiative gas cooling but without star formation or feedback. Each frame is centered on the location of maximum gas density within 1 kpc from the center of gas mass. Simulations performed by: Daniel Ceverino (ART-I), Robert Feldmann (ART-II), Spencer Wallace (CHANGA), Mike Butler (ENZO), Jun-Hwan Choi (GADGET-3), Ben Keller (GASOLINE), Yves Revaz (GEAR), Alessandro Lupi (GIZMO), and Romain Teyssier (RAMSES).

Website: AGORAsimulations.org

Data and computation will increase exponentially

This will be challenging!

Big Data

Sloan Digital Sky Survey (SDSS) 2008

2.5 Terapixels of images
40 TB raw data ➠ 120 TB processed
35 TB catalogs

Mikulski Archive for Space Telescopes (MAST) 2013

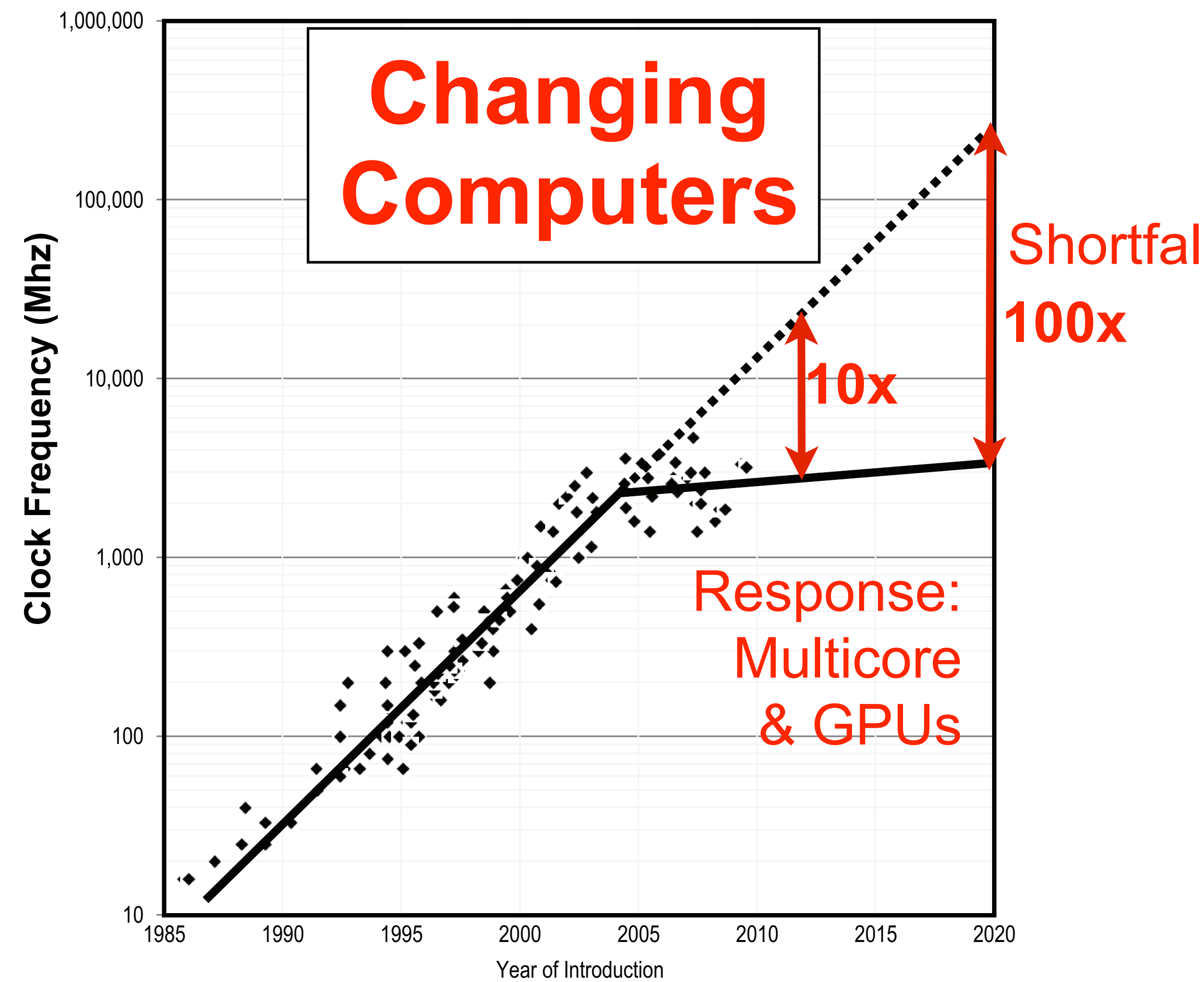
185 TB of images
25 TB/year ingest rate
>100 TB/year retrieval rate

Large Synoptic Survey Telescope (LSST) ~2022

15 TB per night for 10 years
100 PB image archive
20 PB final database catalog

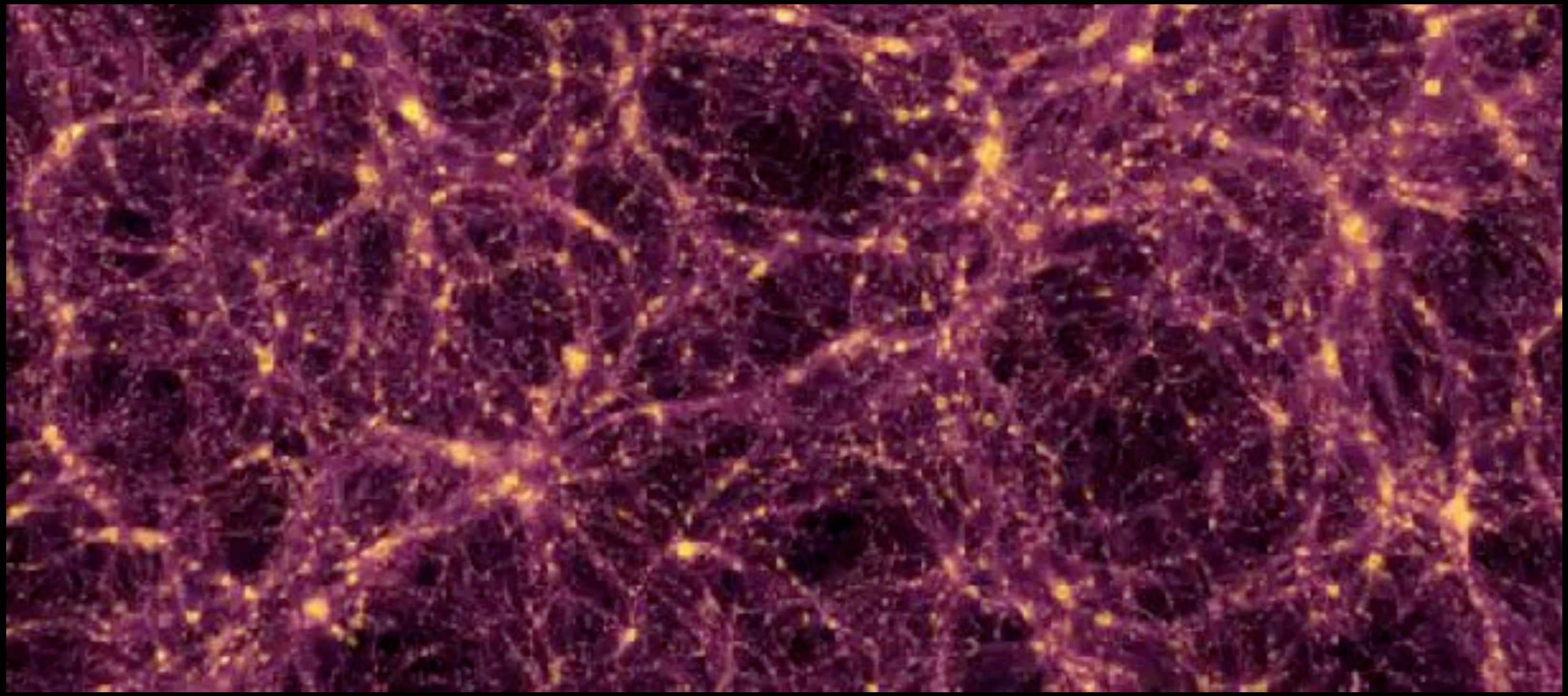
Square Kilometer Array (SKA) ~2024

1 EB per day (~ internet traffic today)
100 PFlop/s processing power
~1 EB processed data/year



Increasingly inhomogeneous computers are harder to program! We need computational scientists and engineers and new compilers that generate code for nodes with cores+accelerators with automatic load balancing and fault tolerance.

LSU
Department of Physics & Astronomy



ΛCDM cosmology: successes, challenges, and opportunities for progress

Joel Primack, UC Santa Cruz

- **Successes:** CMB, Expansion History, Large Scale Structure, Galaxy Formation and Evolution
- **Challenges:** Cusp-Core, Too Big To Fail, Satellite Galaxies
- **Opportunities for Progress Now:** Halo Substructure by Gravitational Lensing and Stellar Motions, Early Galaxies, Compare and Improve Galaxy Simulations