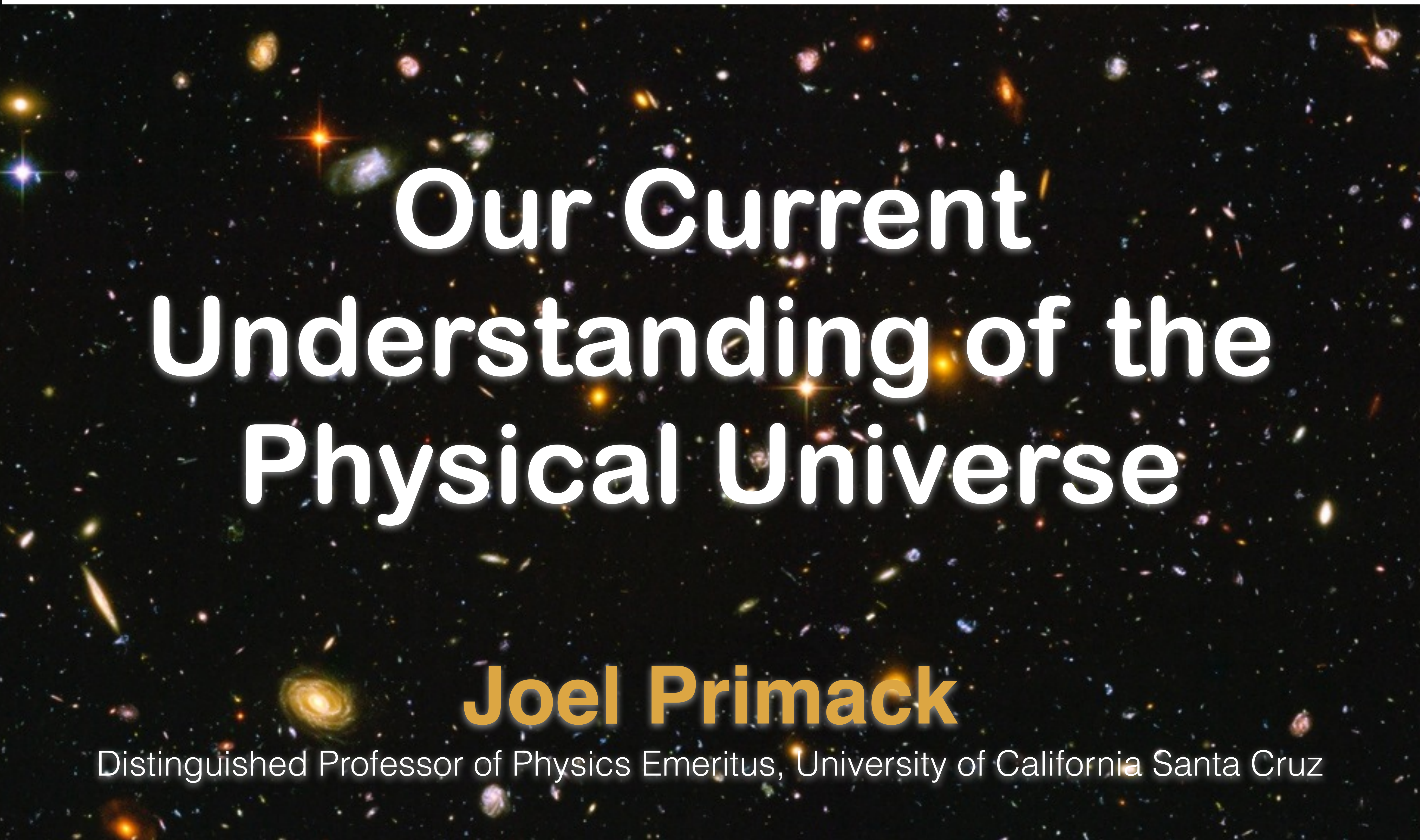
Deciphering Dark Matter: From Galaxies to the Universe
Summer School on Galaxies and Cosmology 2020 | 14 – 25 September 2020



Our Current Understanding of the Physical Universe

Joel Primack
Distinguished Professor of Physics Emeritus, University of California Santa Cruz

Our Current Understanding of the Physical Universe

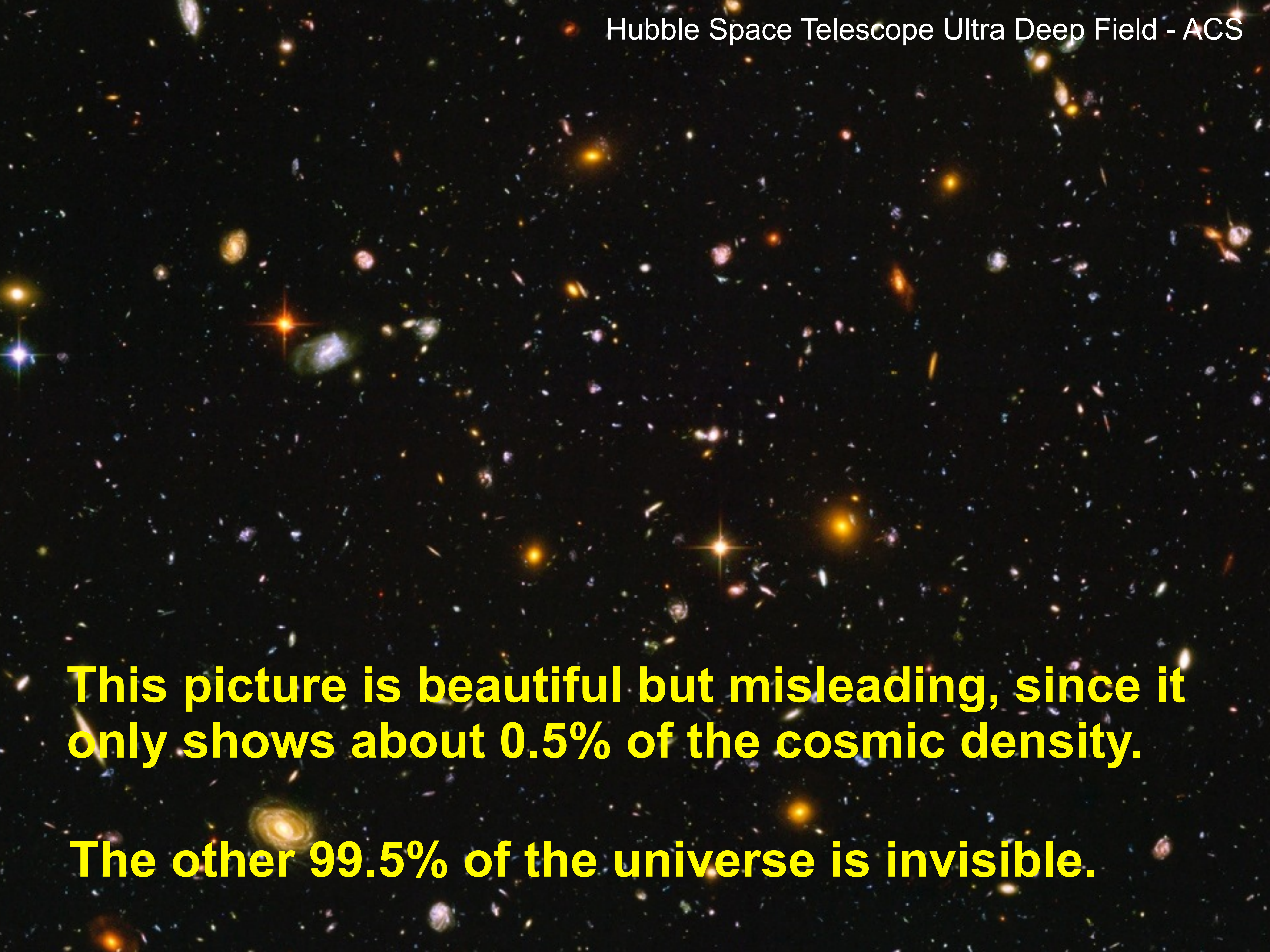
COSMOS

GALAXIES

PLANETS

Our Current Understanding of the Physical Universe

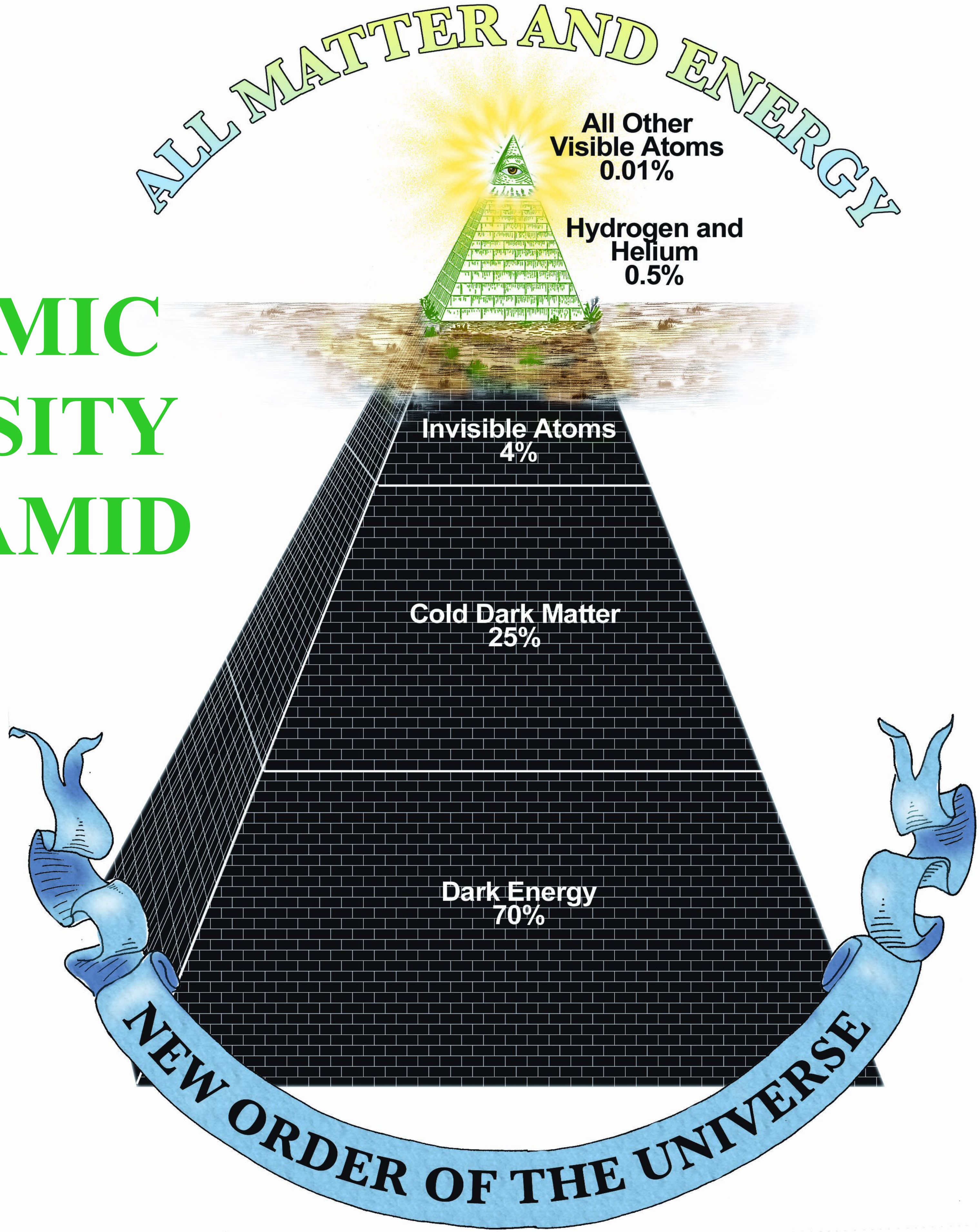
COSMOS

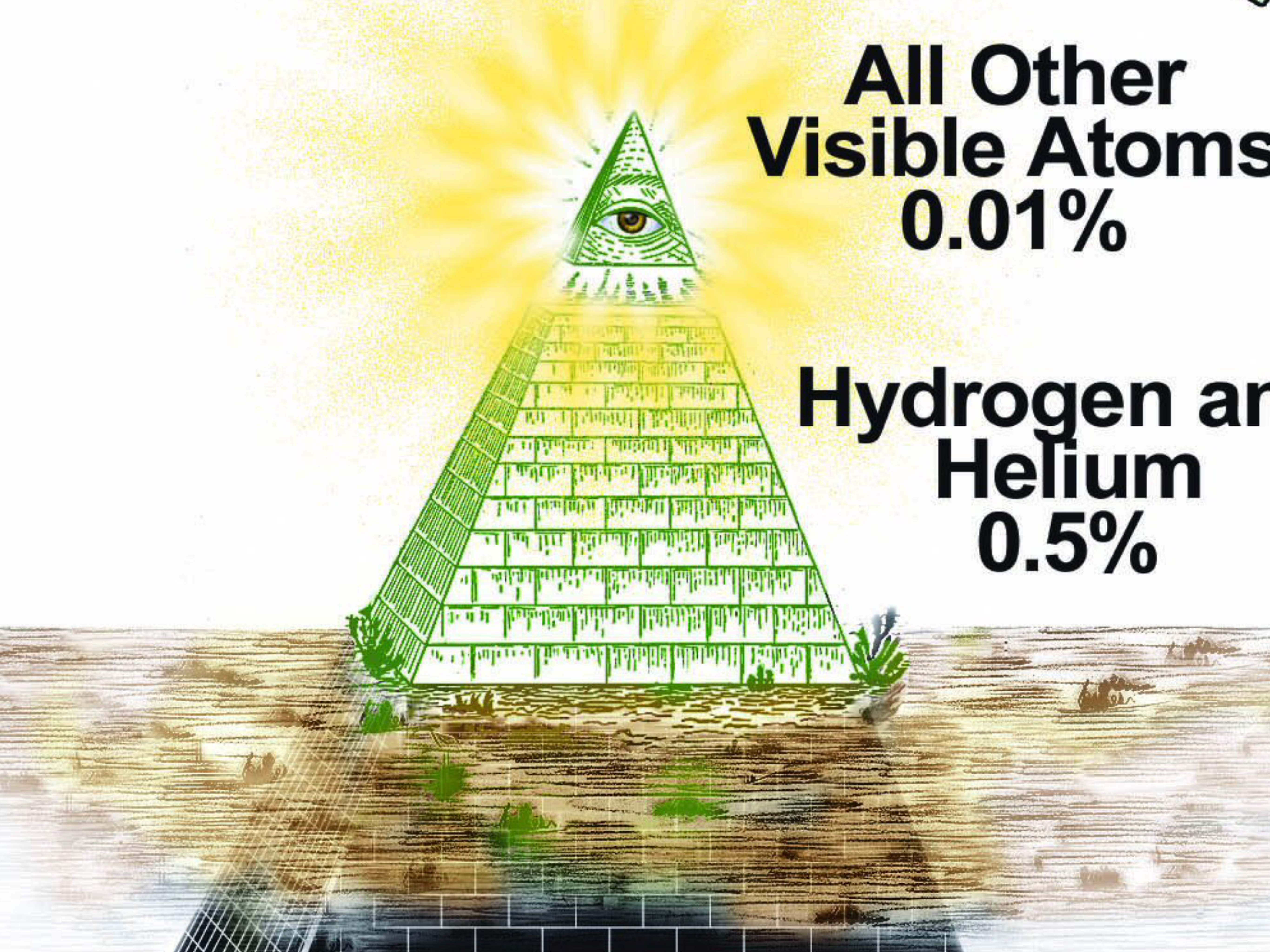


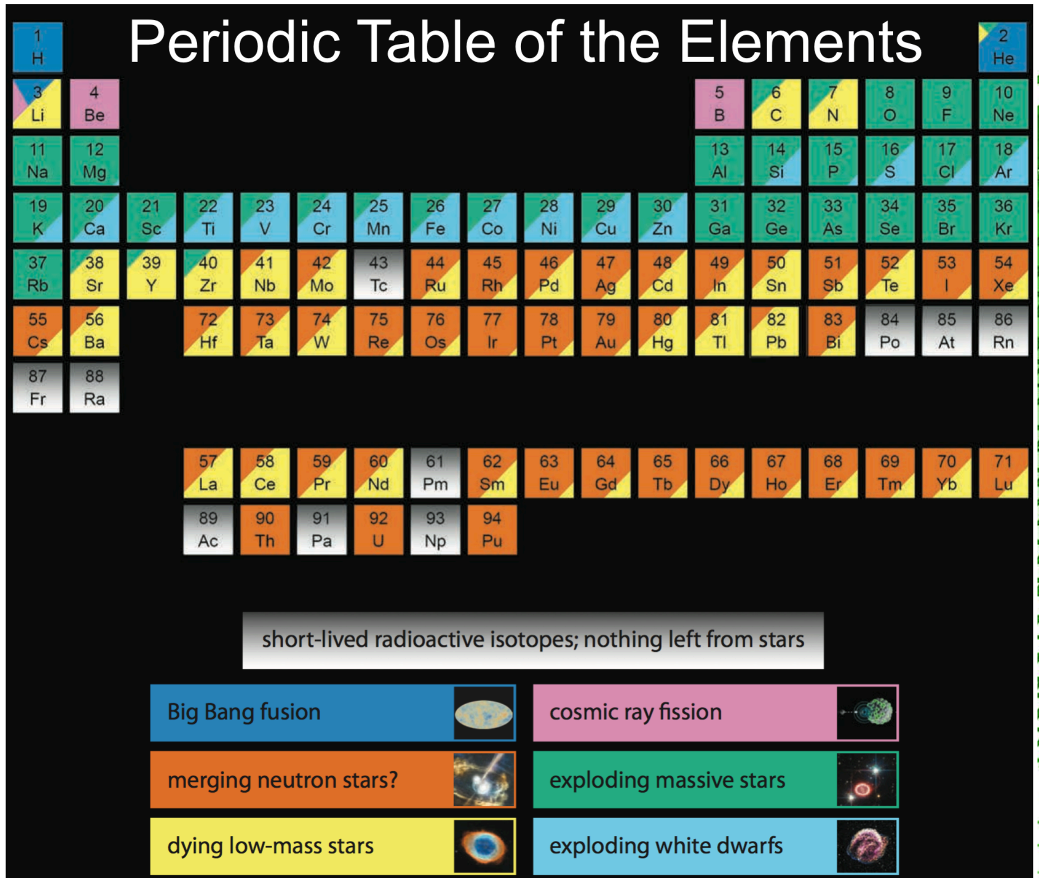
This picture is beautiful but misleading, since it only shows about 0.5% of the cosmic density.

The other 99.5% of the universe is invisible.

COSMIC DENSITY PYRAMID




All Other
Visible Atoms
0.01%
Hydrogen a
Helium
0.5%

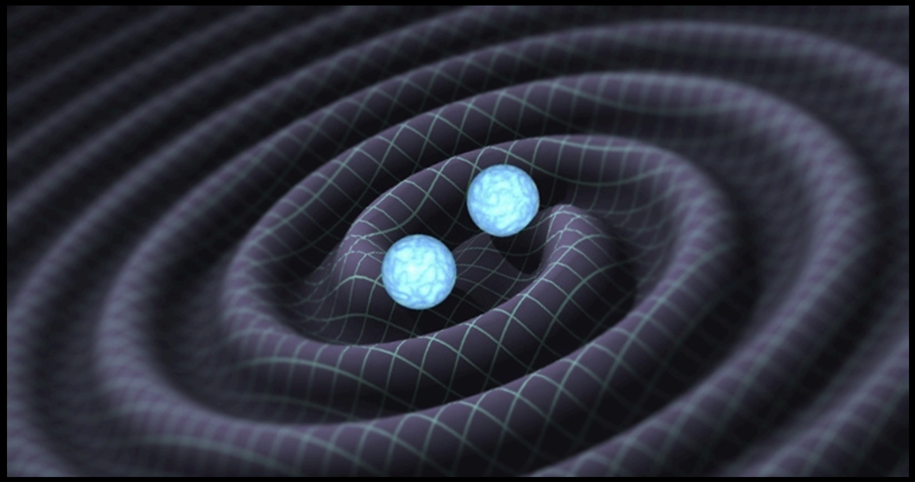


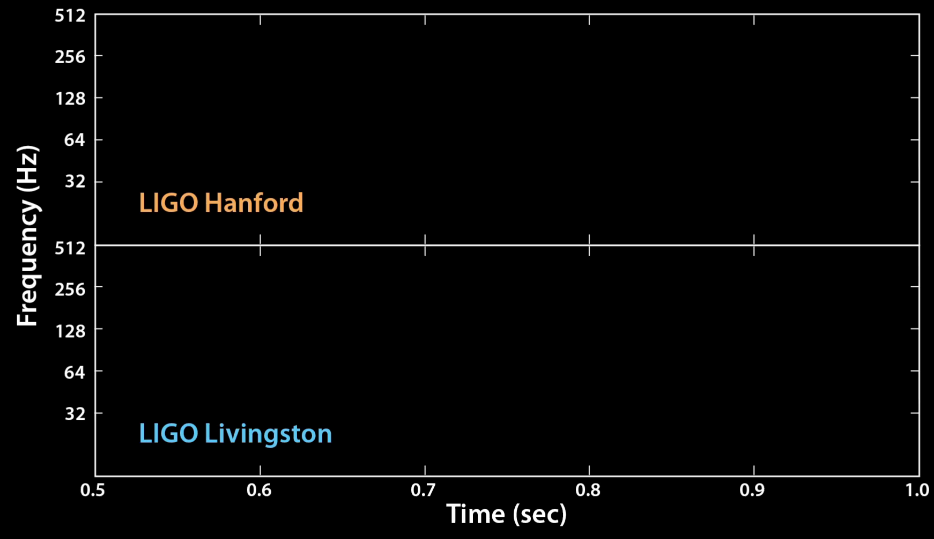
stardust

stars

Many stars in the very early universe may have been much more massive than our sun, in binary star systems with other massive stars. When these stars ended their lives as supernovas, they became massive black holes. The Laser Interferometer Gravitational-wave Observatory (LIGO) has now detected > 50 mergers of massive black holes. This confirmed predictions of Einstein's general relativity that had never been tested before.

In August 2017 LIGO and VIRGO announced the discovery of gravity waves from merging neutron stars. Data from telescopes shows that such events perhaps generate most of the heavy elements like europium, gold, thorium, and uranium.



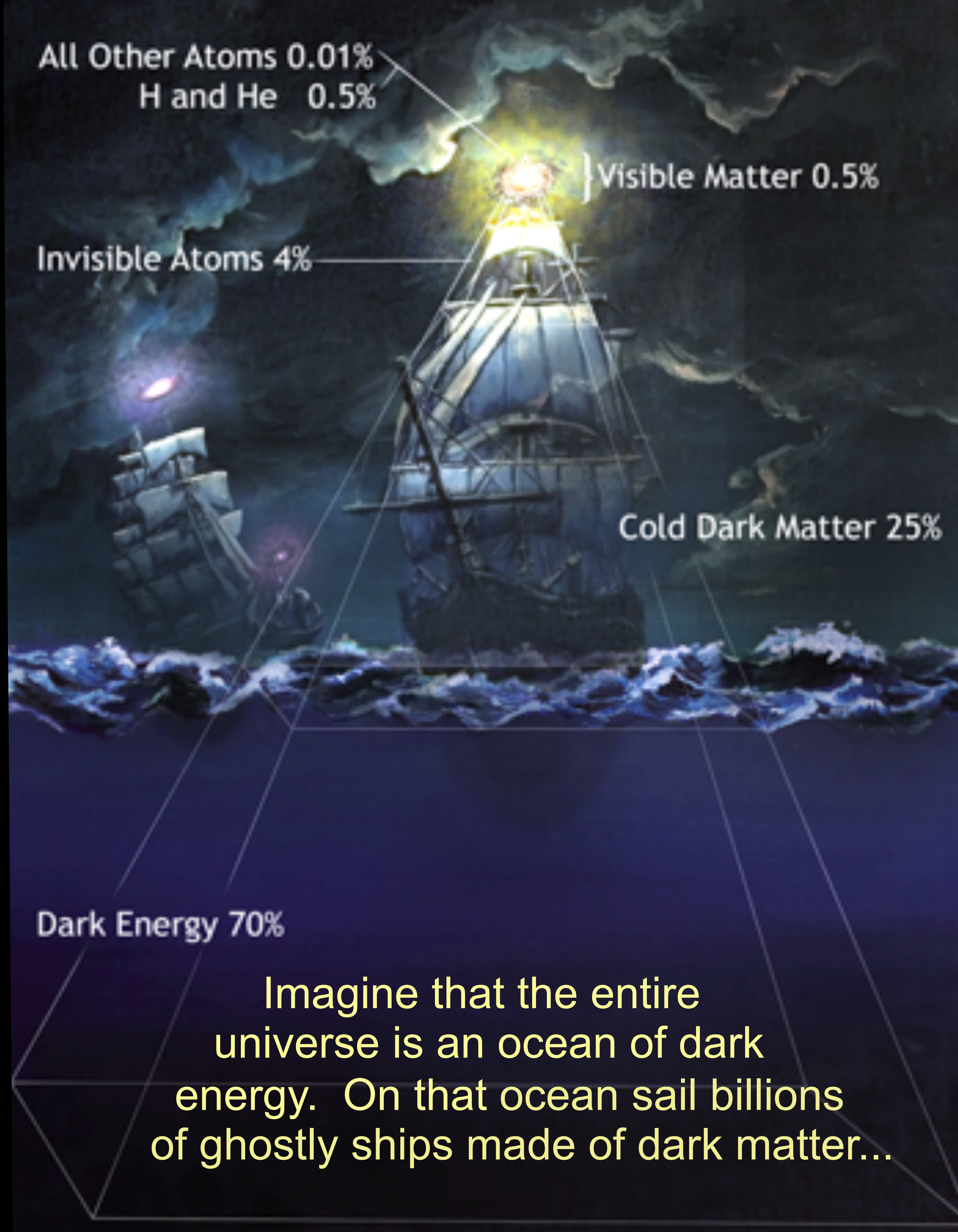


Periodic Table of the Elements

Dark Matter Ships

on a

Dark Energy Ocean

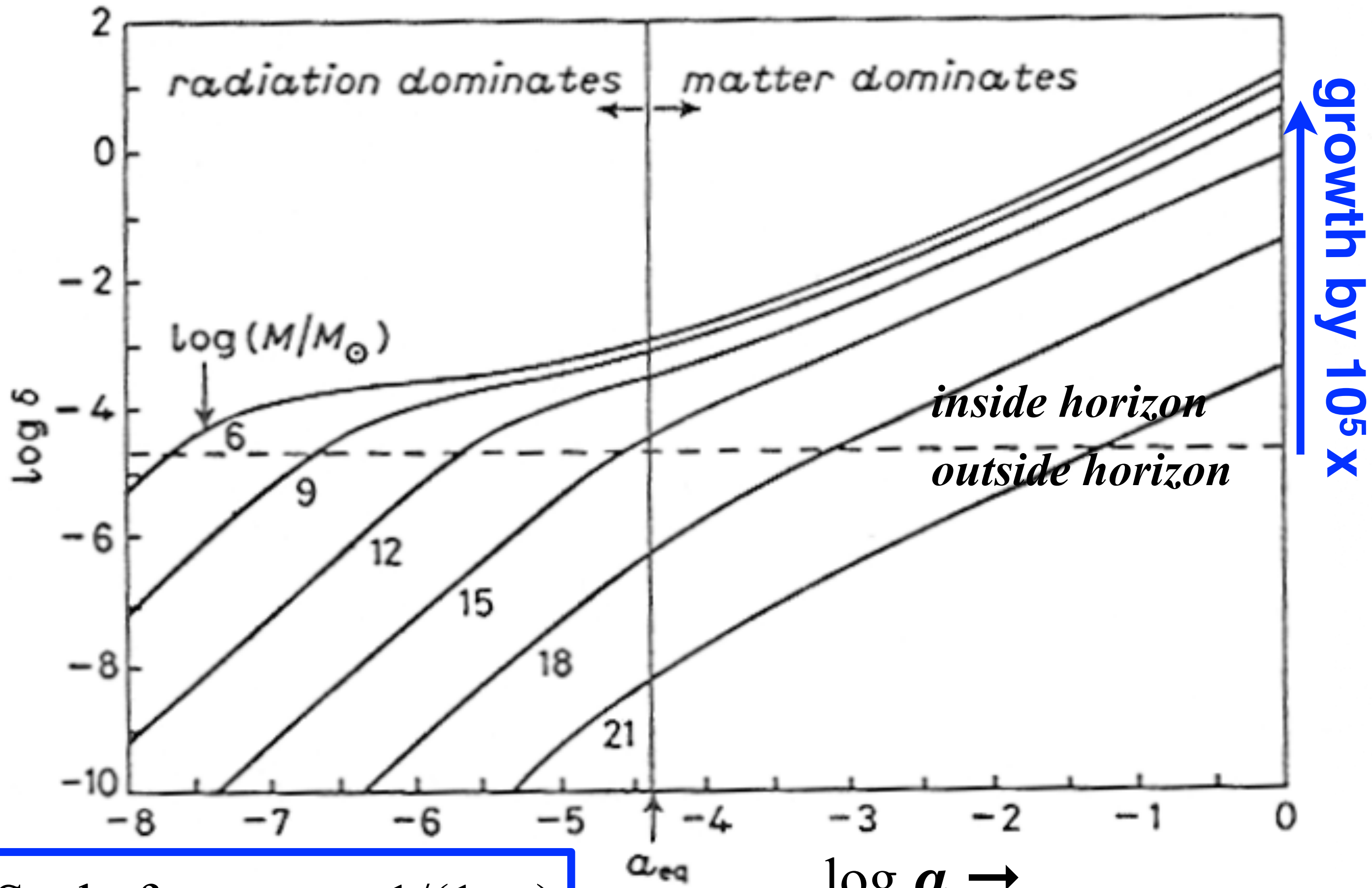


Matter and Energy Content of the Universe

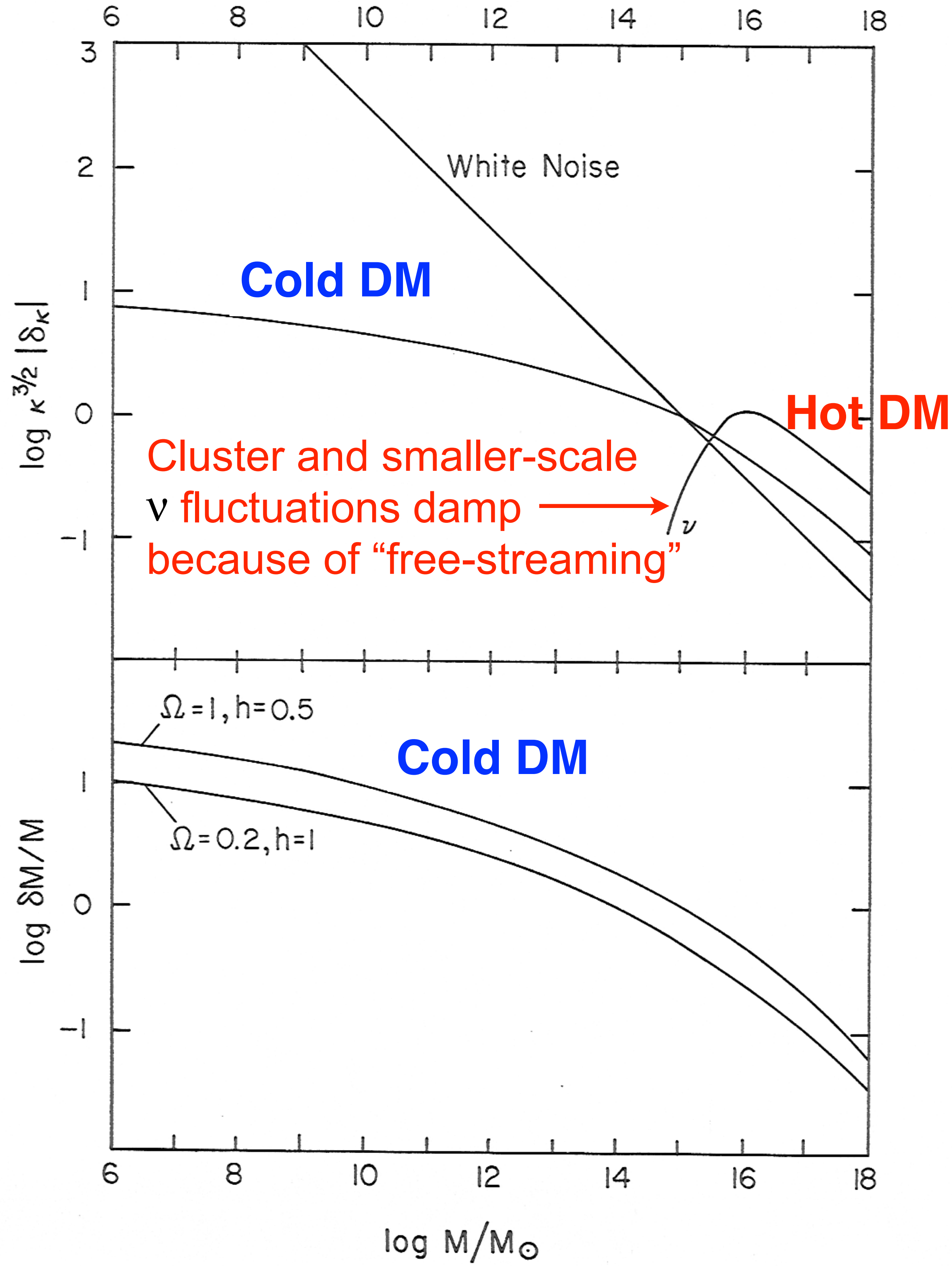
ΛCDM

Double Dark Theory

CDM Structure Formation: Linear Theory



Scale factor a = 1/(1+z)

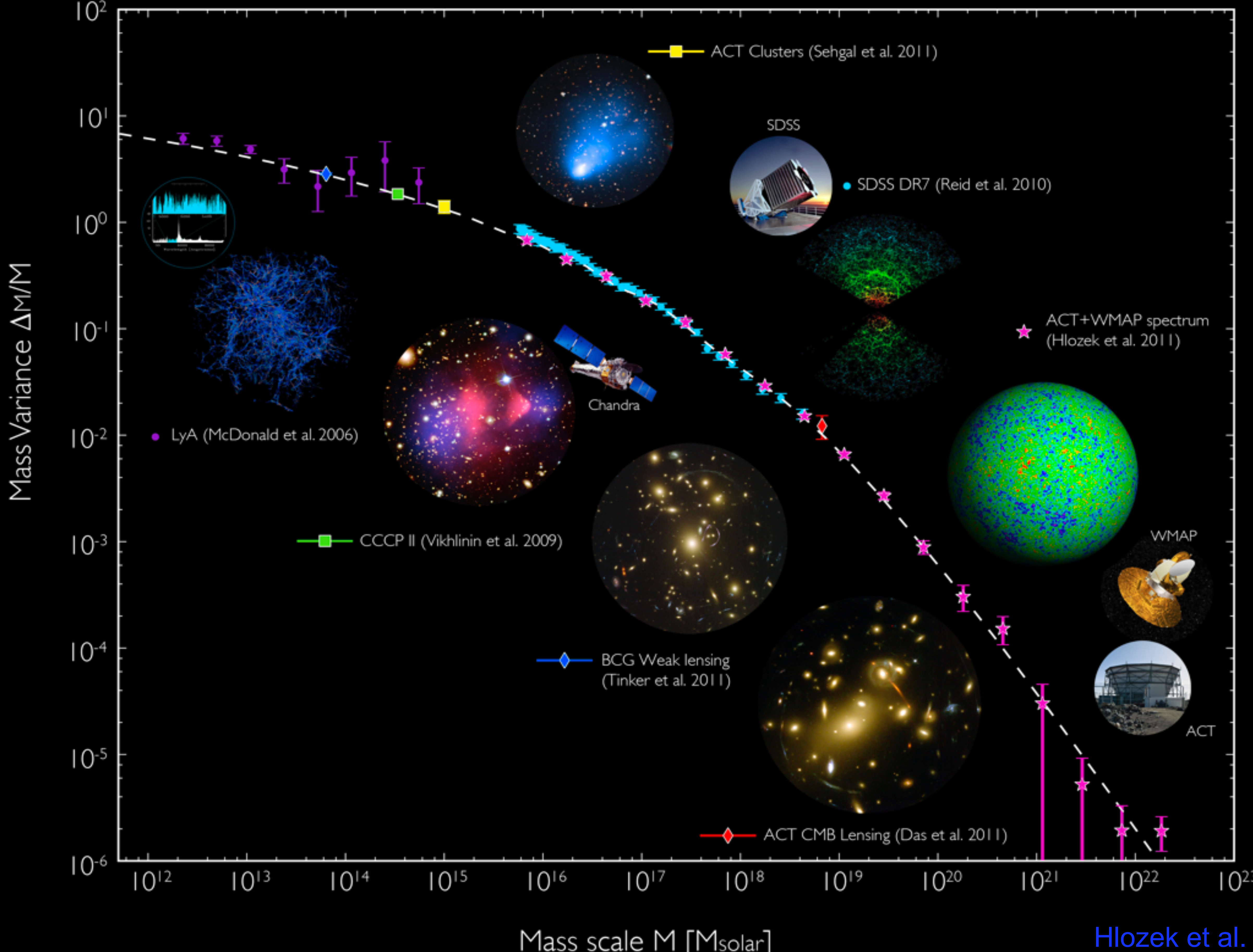


CDM fluctuations that enter the horizon during the radiation dominated era, with masses less than about 10^{15} M$_\odot$, grow only ∝ log a, because they are not in the gravitationally dominant component. But matter fluctuations that enter the horizon in the matter-dominated era grow ∝ a. This explains the characteristic shape of the CDM fluctuation spectrum, with $\delta(k) \propto k^{-n/2-2} \log k$

Primack & Blumenthal 1983,
Primack Varenna Lectures 1984

Blumenthal, Faber, Primack, & Rees 1984

Matter Distribution Agrees with Double Dark Theory!

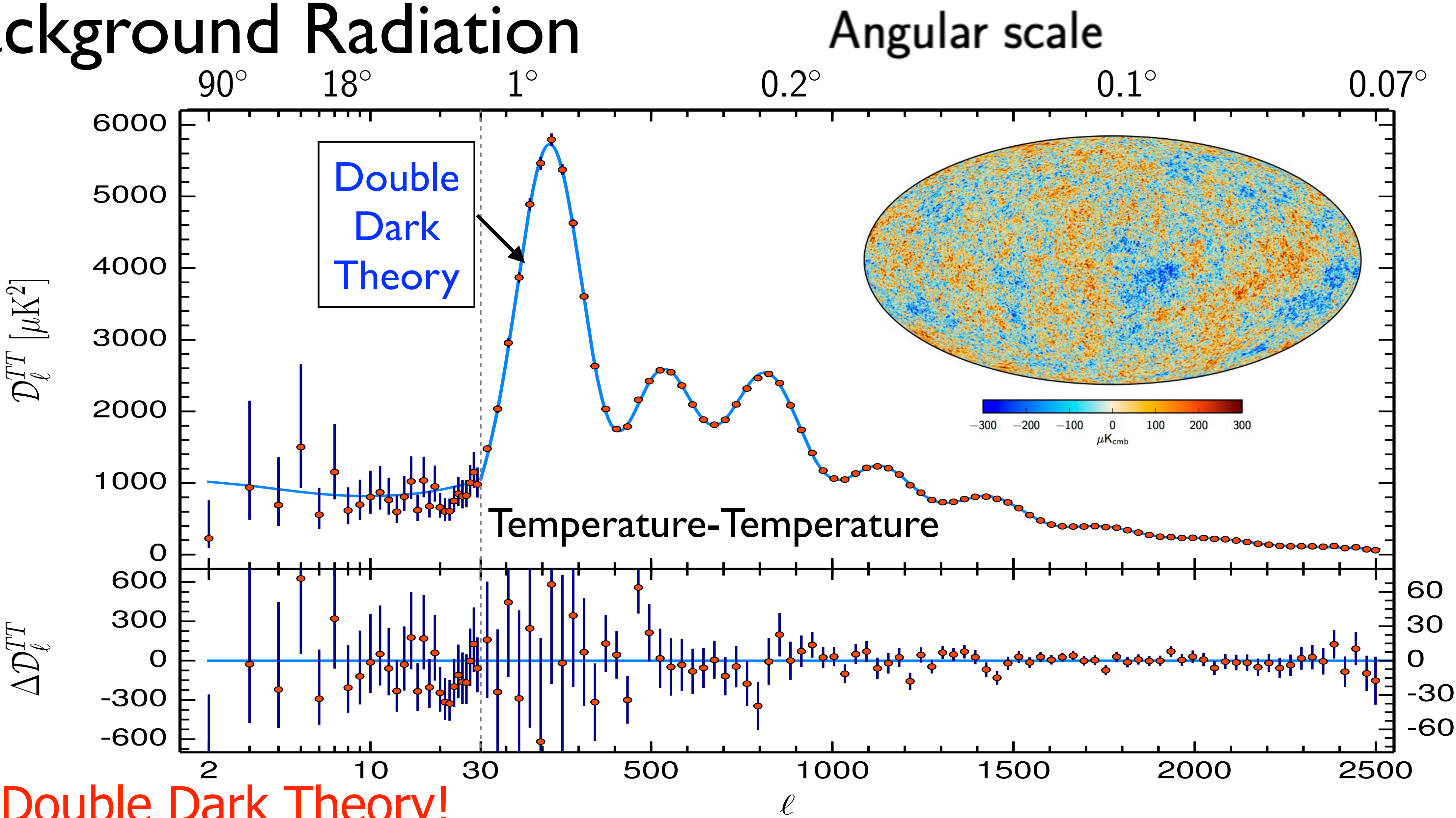


Hlozek et al. 2012

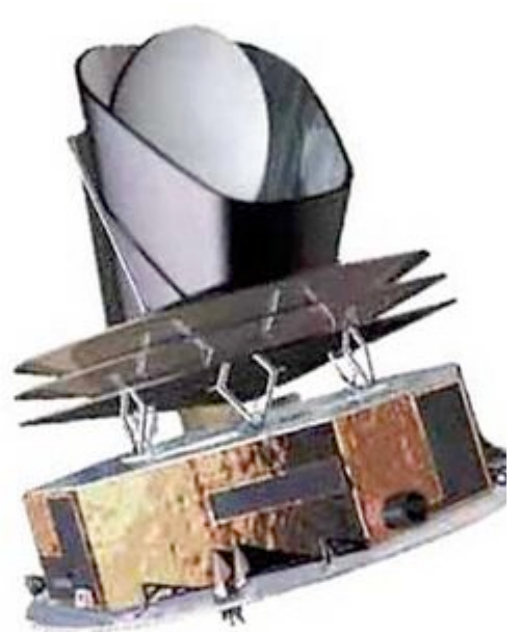
Cosmic Background Radiation

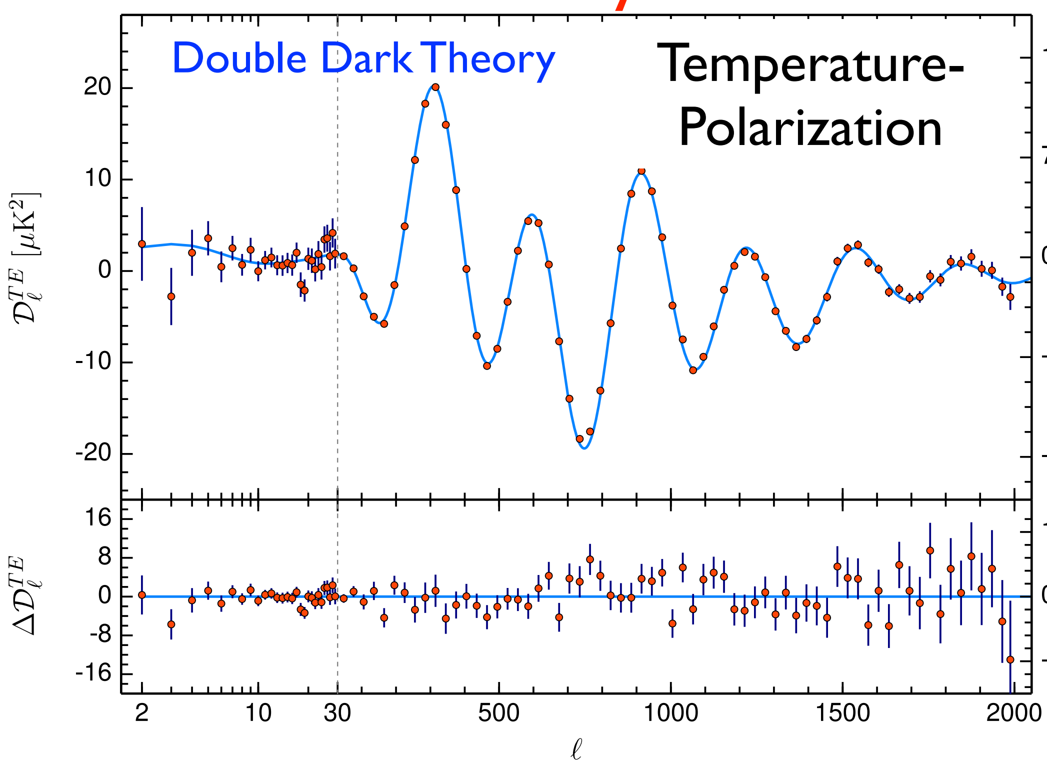
European Space Agency PLANCK Satellite Data

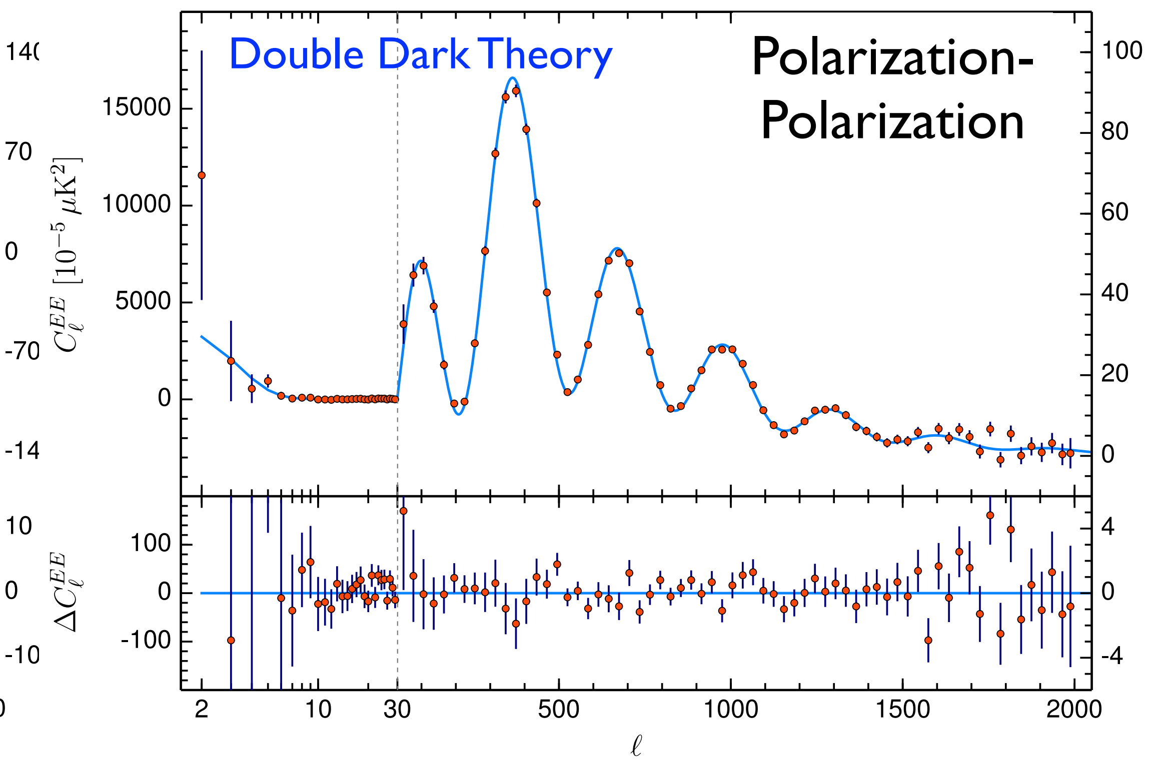
Released September 24, 2019



Agrees with Double Dark Theory!

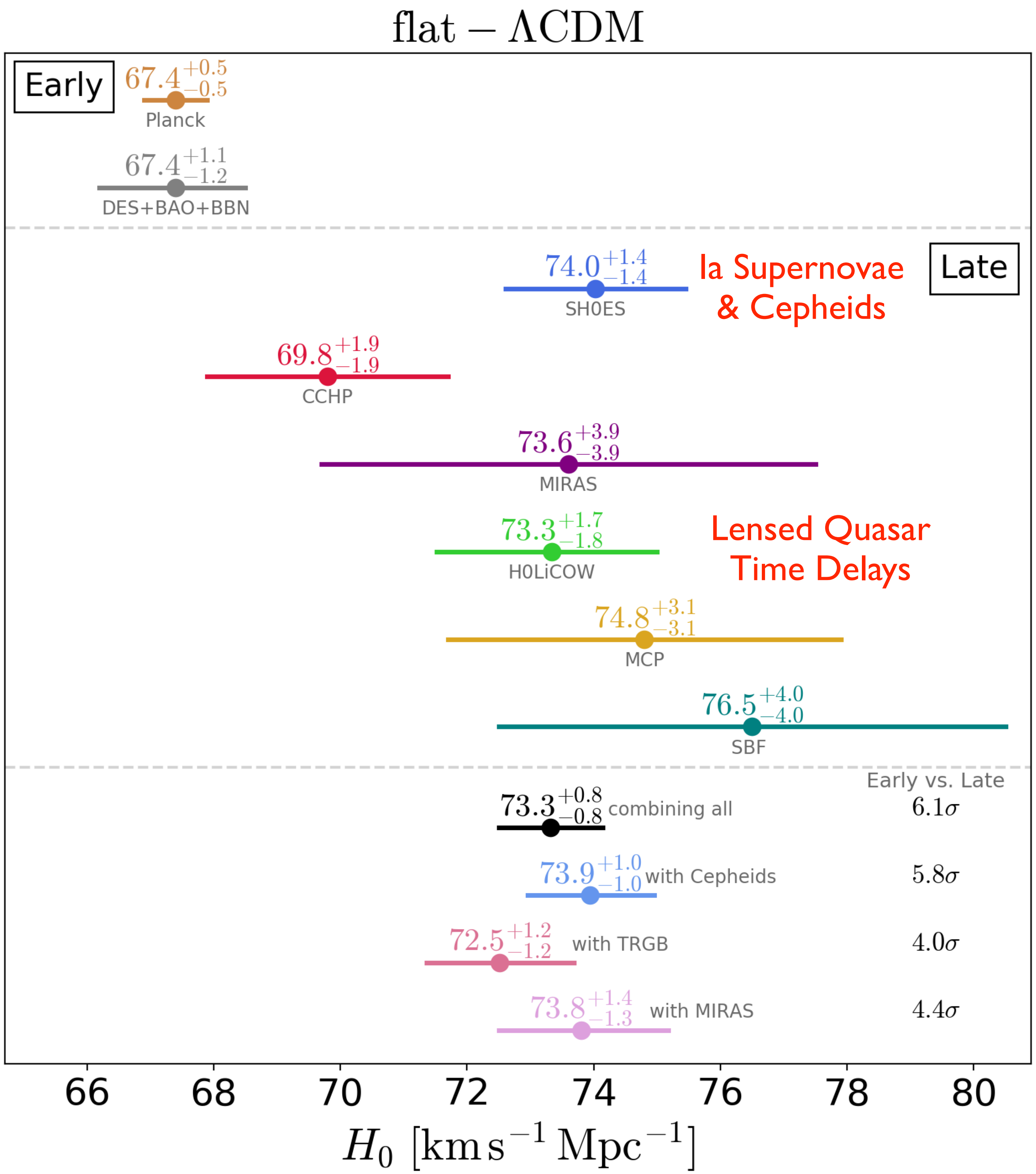






A possibly serious difficulty for ΛCDM is the **Hubble parameter tension**:

Cosmic Background Radiation plus ΛCDM gives H_0 = 67.4±0.4



Several kinds of nearby observations give H_0 = 73.3±0.8

Verde Treu Riess 2019

"Early Dark Energy," a brief period of ~5% extra dark energy at z ~ 4000, could resolve this

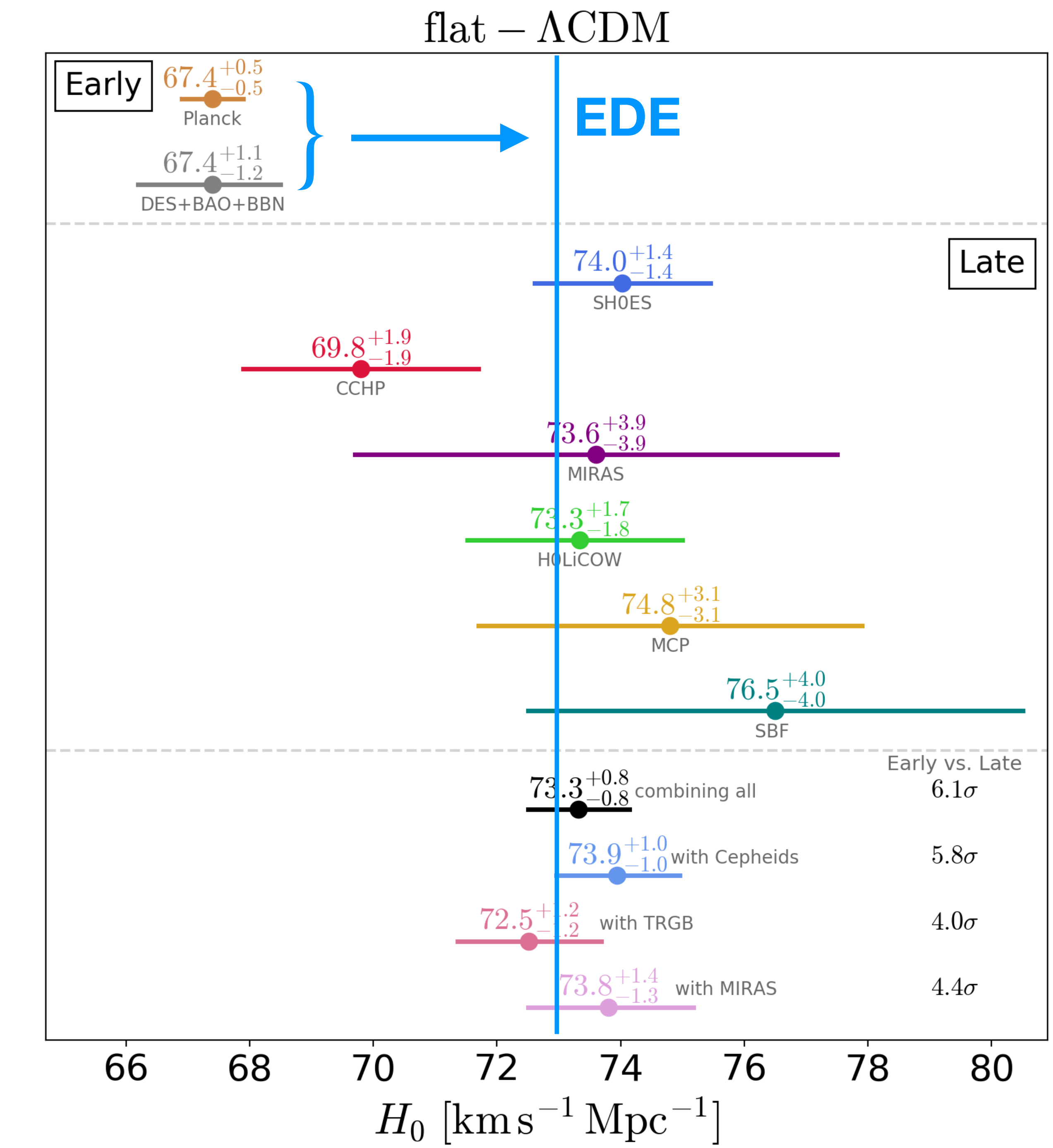
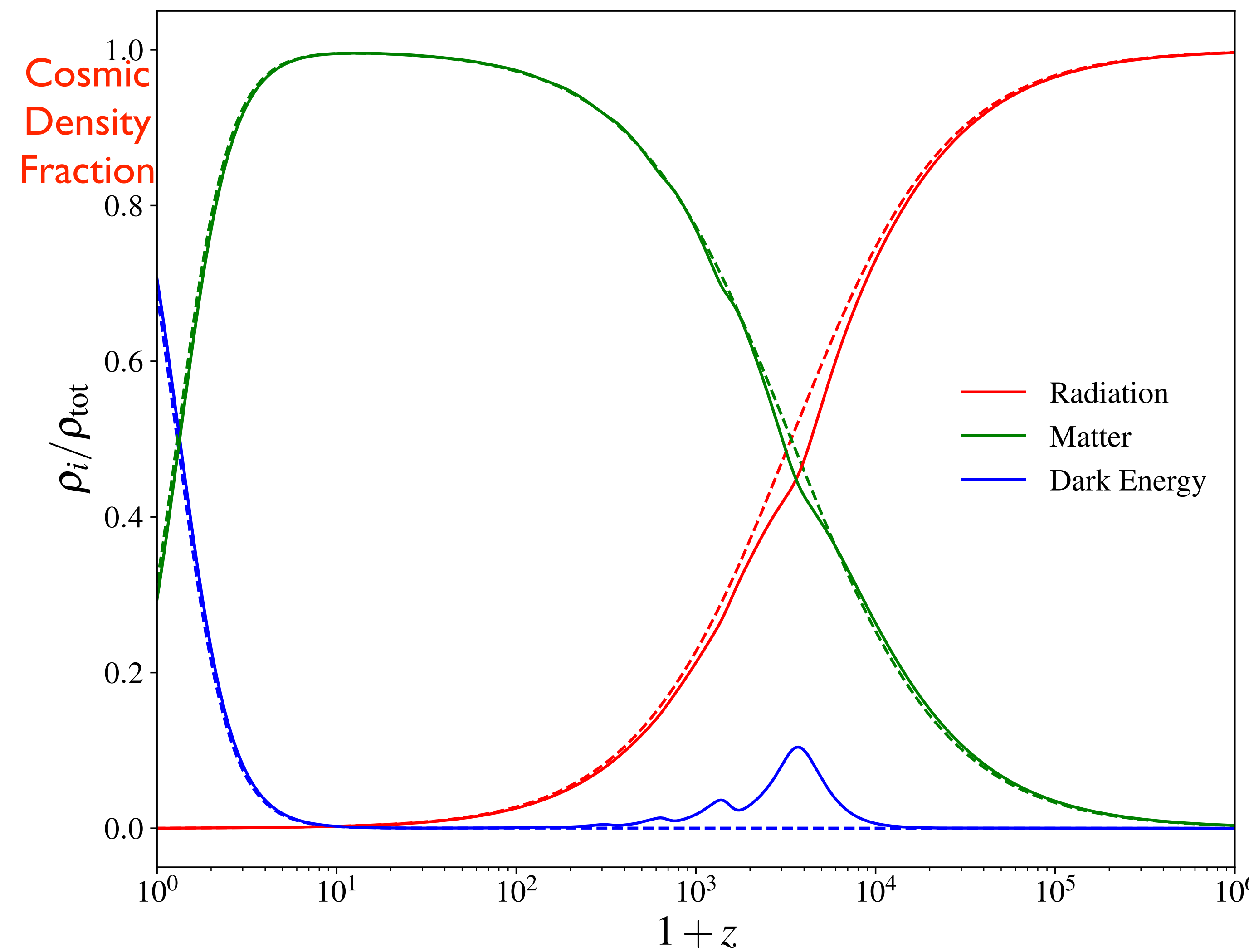


Figure 1. Compilation of Hubble Constant predictions and measurements taken from the r cent literature and presented or discussed at the meeting. Two independent predictions based on early-Universe data (Planck Collaboration et al. 2018; Abbott et al. 2018) are shown at the top left (more utilizing other CMB experiments have been presented with similar findings), while the middle panel shows late Universe measurements. The bottom panel shows combinations of the late-Universe measurements and lists the tension with the early-Universe predictions. We stress that the three variants of the local distance ladder method (SHOES=Cepheids; CCHP=TRGB; MIRAS) share some Ia calibrators and cannot be considered as statistically independent. Likewise the SBF method is calibrated based on Cepheids or TRGB and thus it cannot be considered as fully independent of the local distance ladder method. Thus the "combining all" value should be taken for illustration only, since its derivation neglects covariance between the data. The three combinations based on Cepheids, TRGB, Miras are based on statistically independent datasets and therefore the significance of their discrepancy with the early universe prediction is correct - even though of course separating the probes gives up some precision. A fair summary is that the difference is more than 4 σ, less than 6 σ, while robust to exclusion of any one method, team or source. Figure courtesy of Vivien Bonvin.

Verde, Treu, Riess 2019

A brief episode of Early Dark Energy about ~ 35,000 years after the Big Bang modifies the ΛCDM extrapolation of H_0 and avoids the Hubble tension.



Solid curves represent our ΛCDM+EDE model, and dashed curves are standard ΛCDM with the Planck parameters. Our N-body simulations show that structure forms earlier than in standard ΛCDM, but the *z* ~ 0 mass functions are very similar.

Klypin, Poulin, Prada, Primack, et al. 2020

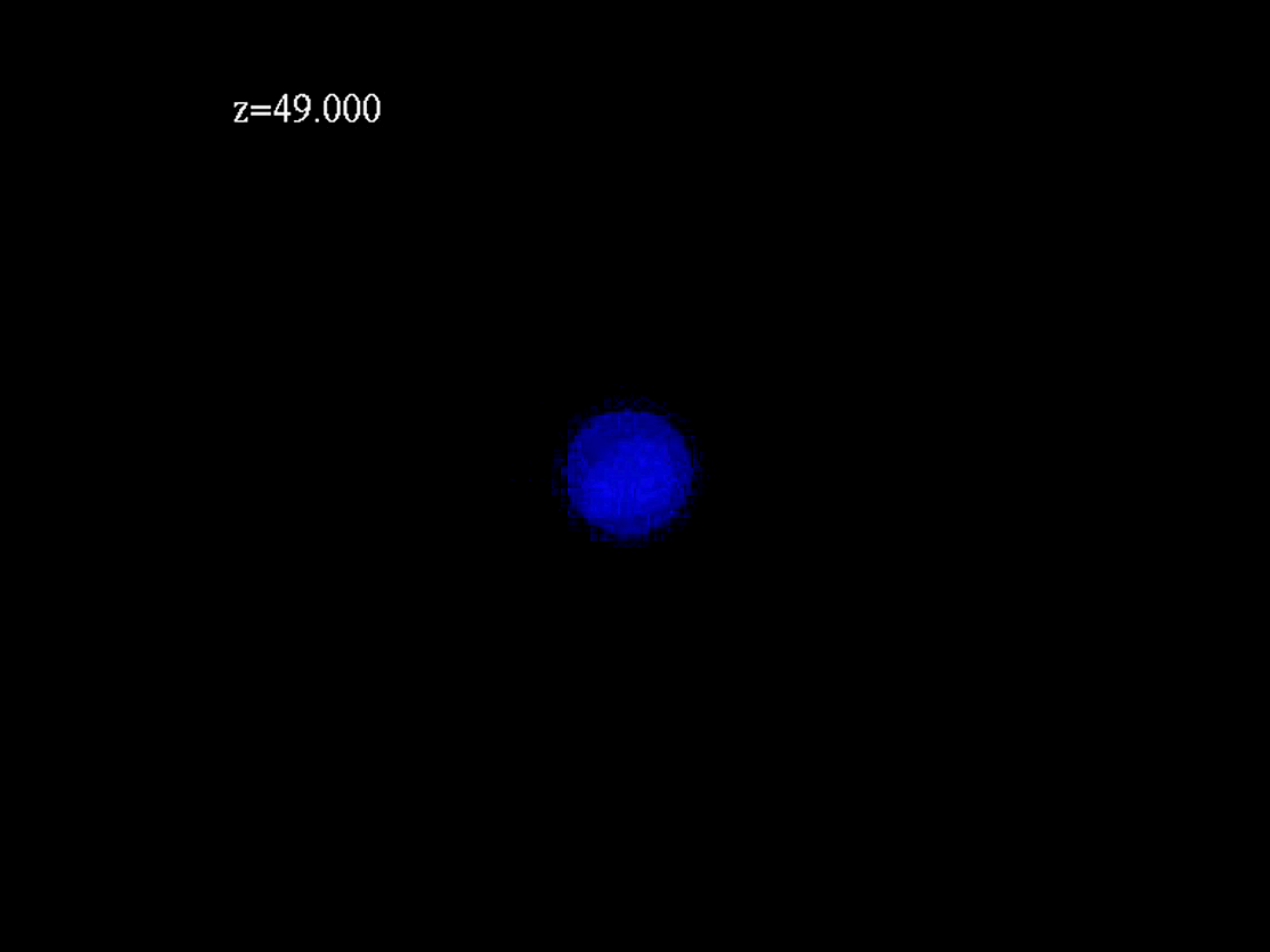
Cosmological Simulations

Astronomical observations represent snapshots of moments in time. It is the role of astrophysical theory to produce movies -- both metaphorical and actual -- that link these snapshots together into a coherent physical theory.

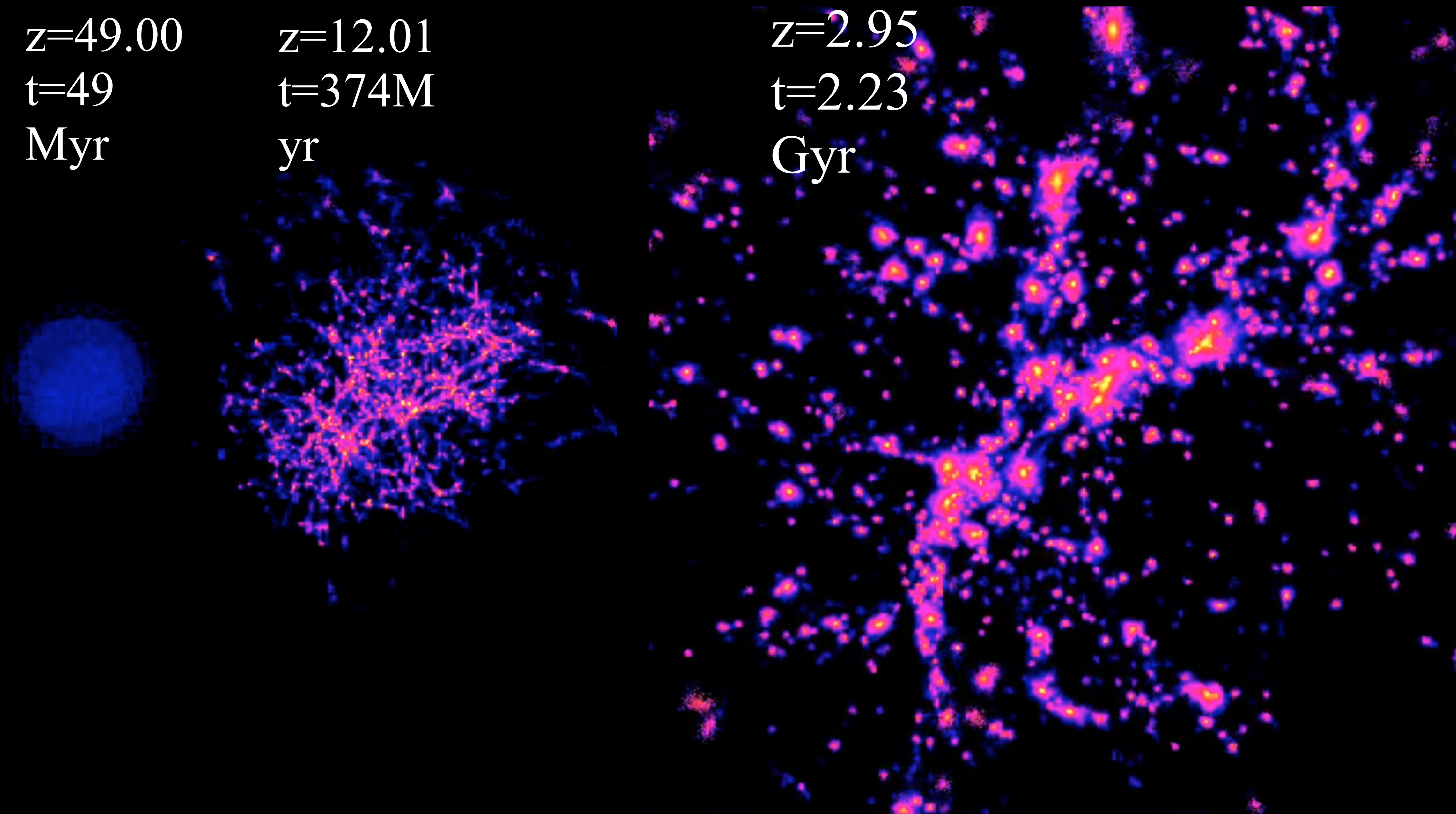
Cosmological dark matter simulations show large scale structure and dark matter halo properties, basis for semi-analytic models

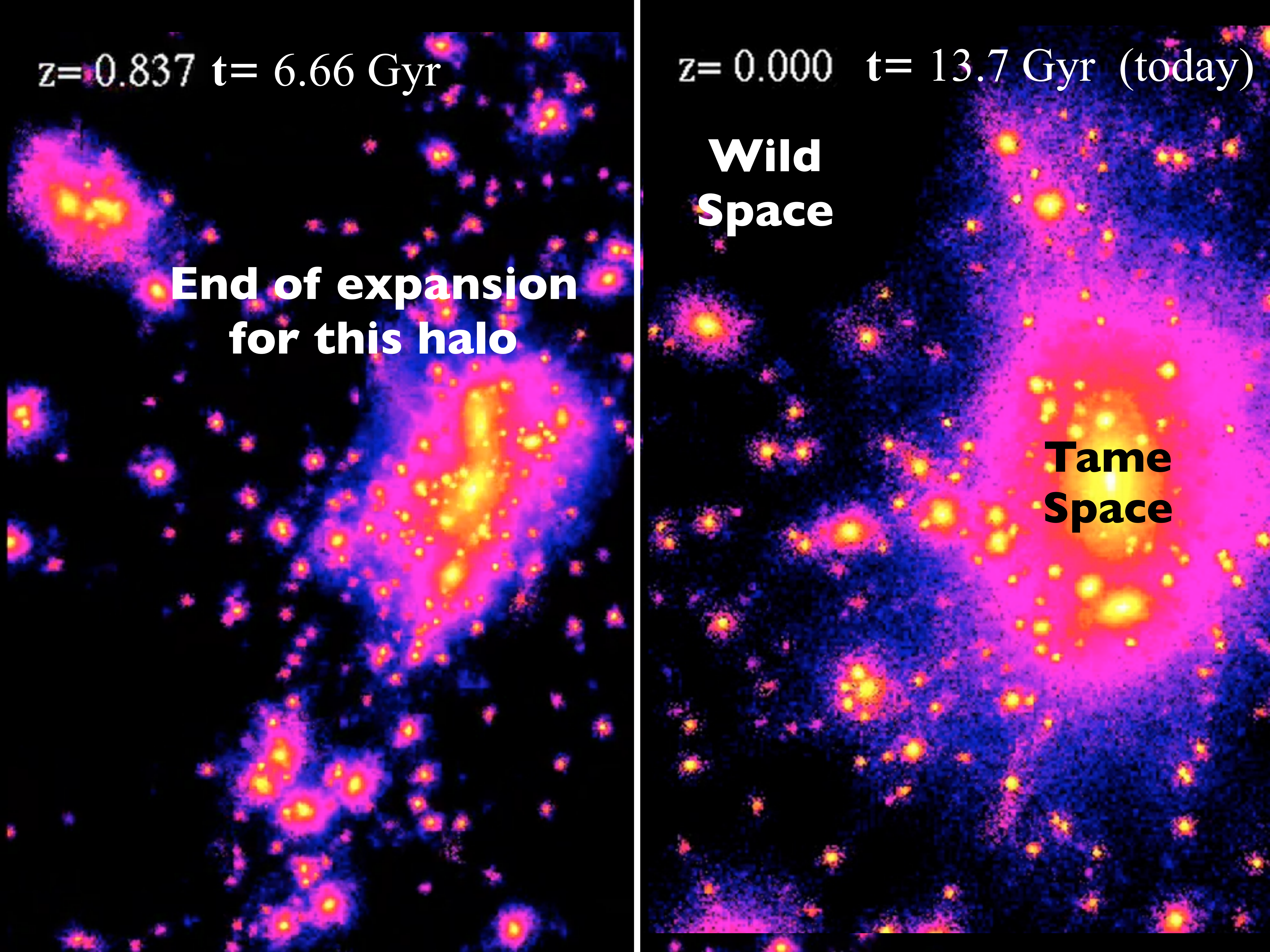
Hydrodynamic galaxy formation simulations: evolution of galaxies, formation of galactic spheroids via mergers, galaxy images and spectra including stellar evolution and dust

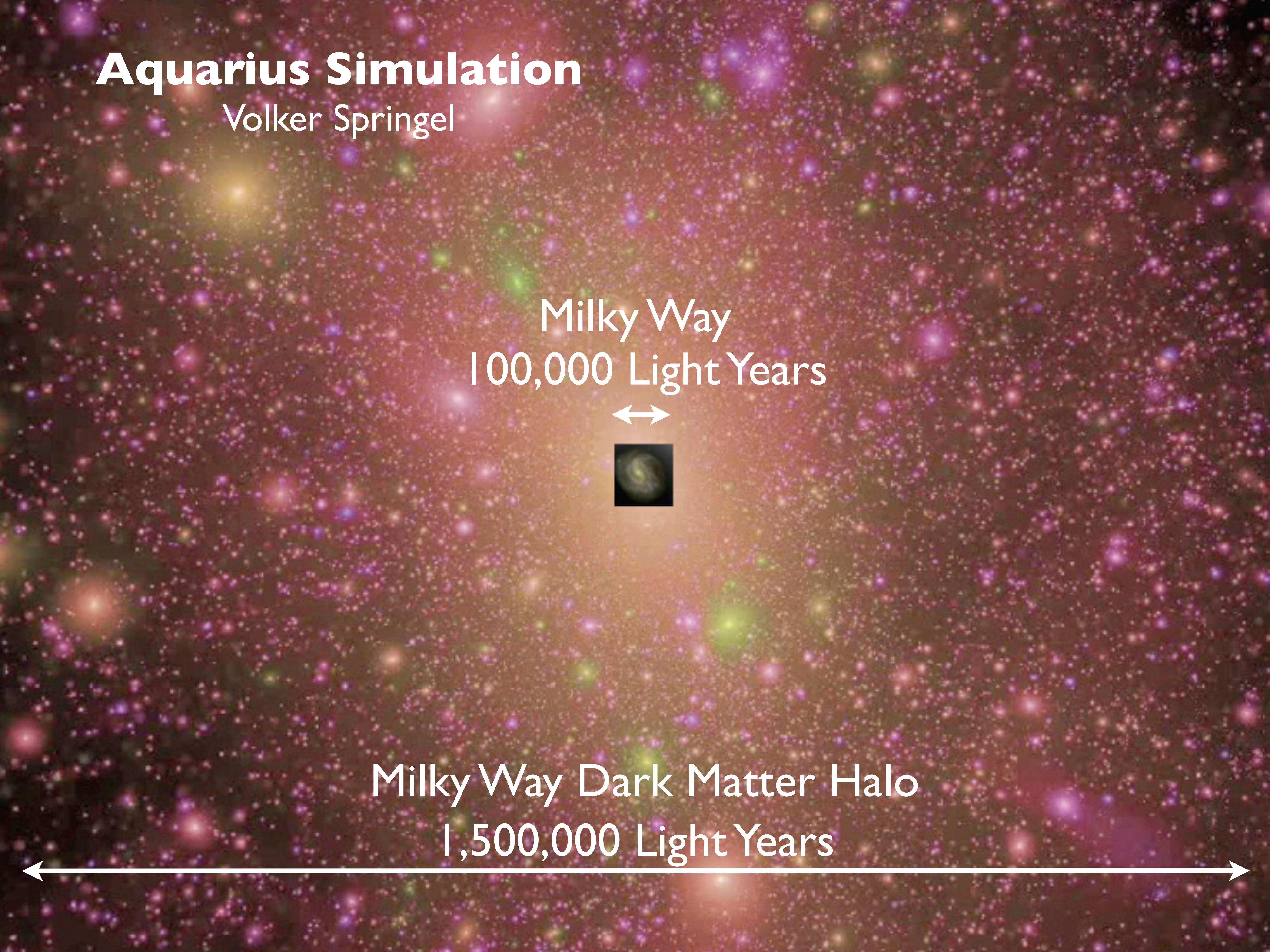
"QUARKS. NEUTRINOS. MESONS. ALL THOSE DAMN PARTICLES YOU CAN'T SEE. THAT'S WHAT DROVE ME TO DRINK. BUT NOW I CAN SEE THEM!"


z=49.000

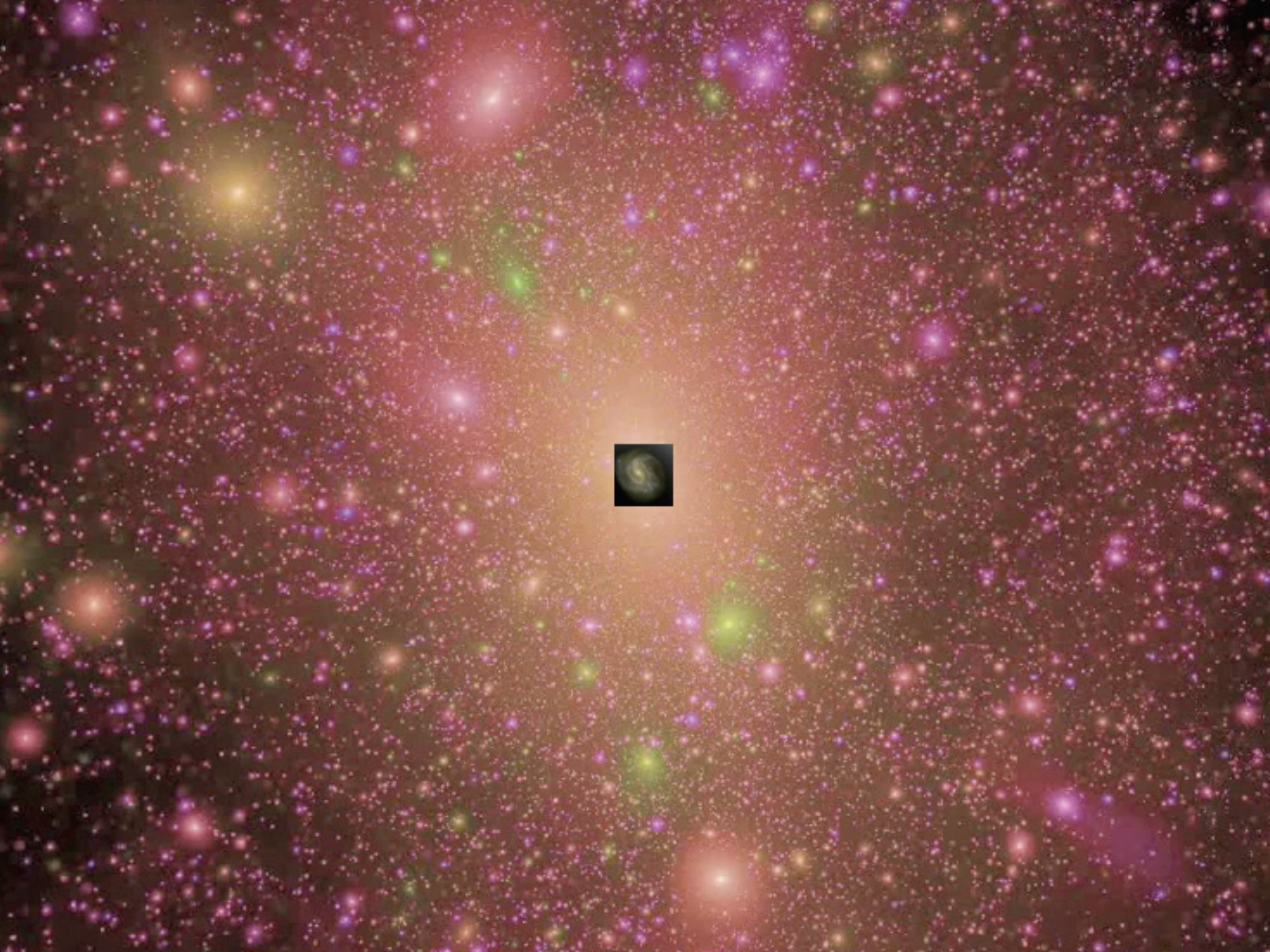
Expansion....

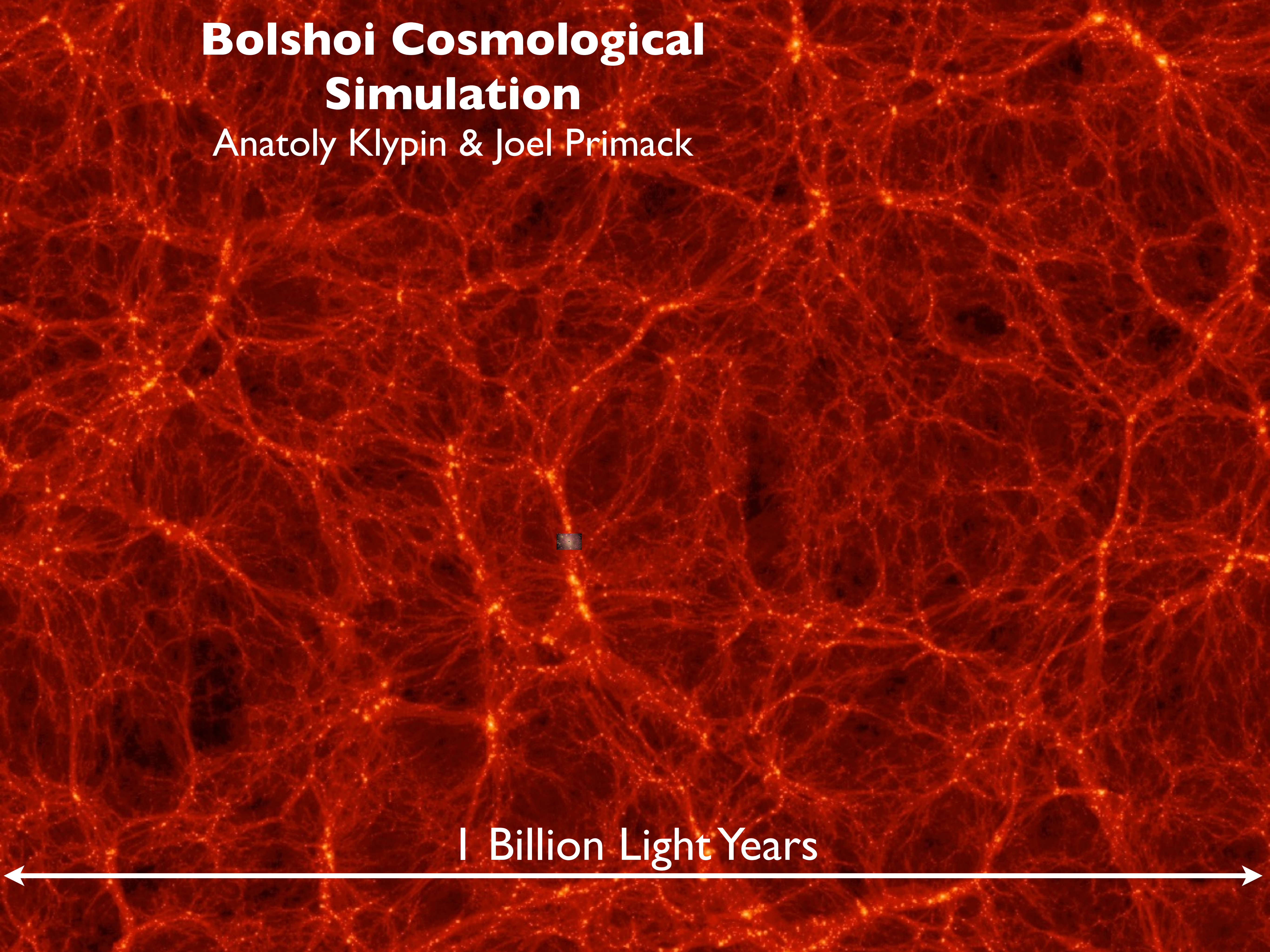


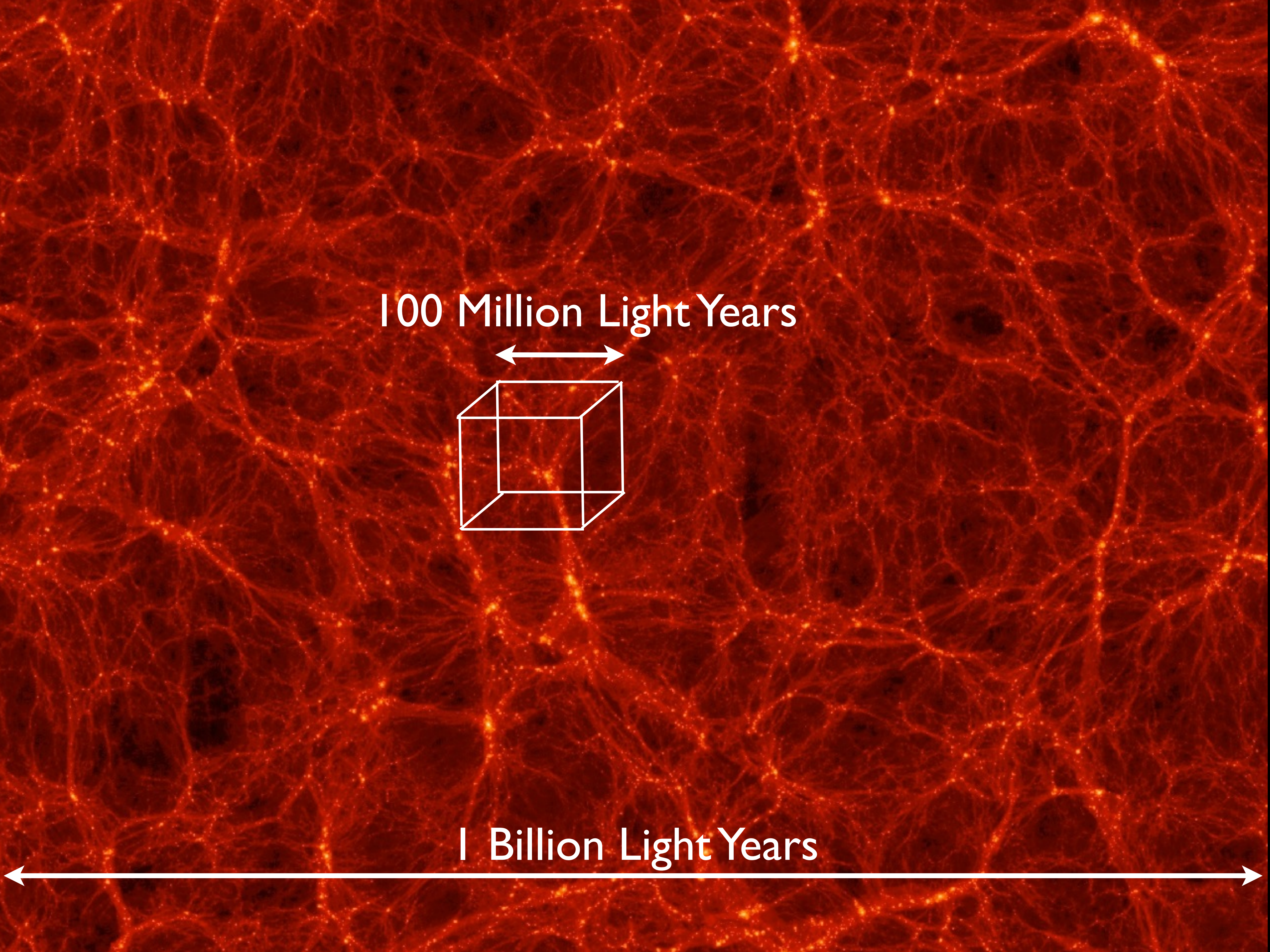

z= 0.837 t= 6.66 Gyr
End of expansion for this halo
z= 0.000 t= 13.7 Gyr (today)
Wild Space
Tame Space



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
1 Billion Light Years


100 Million Light Years
1 Billion Light Years

How the Halo of the Big Cluster Formed

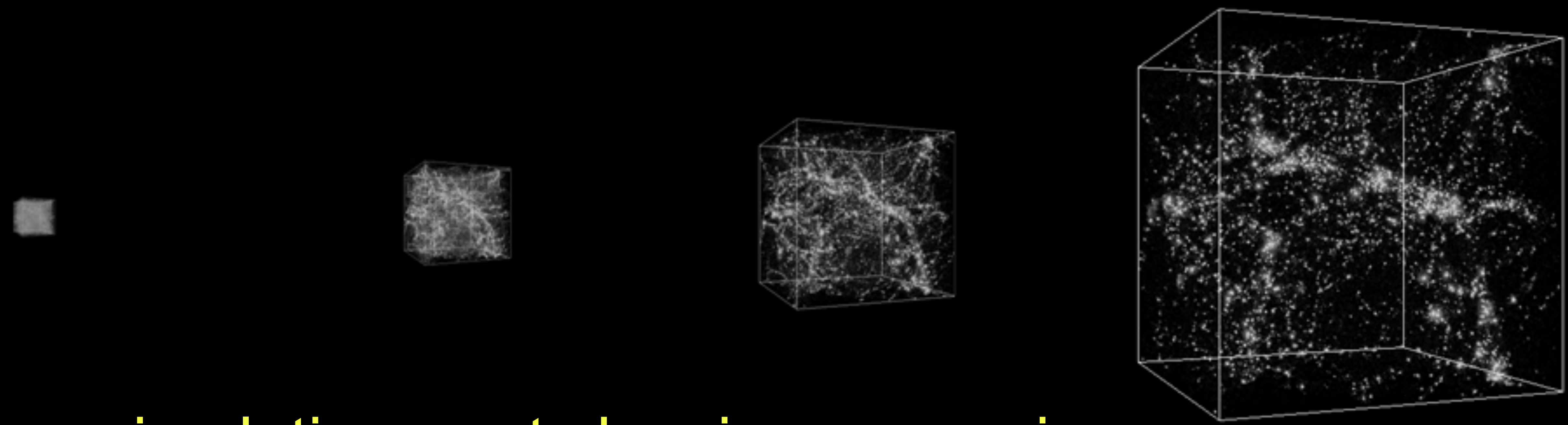
100 Million Light Years

Bolshoi-Planck Cosmological Simulation

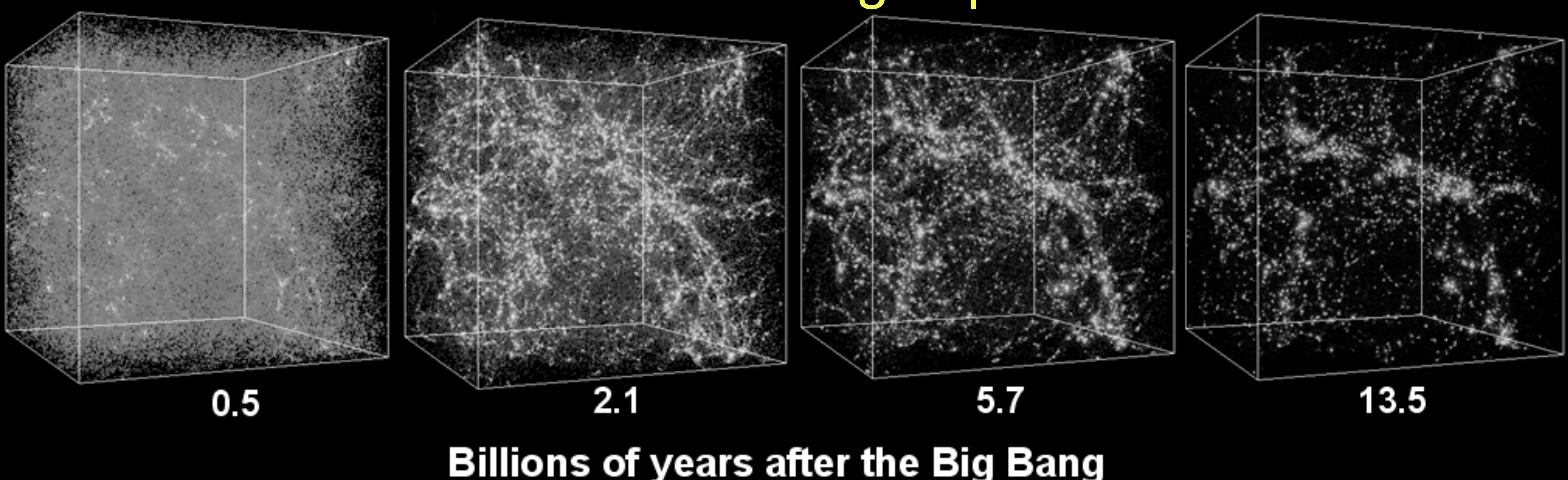
Merger Tree of a Large Halo

Peter Behroozi & Christoph Lee

dark matter simulation - expanding with the universe



same simulation - not showing expansion



Andrey Kravtsov

CONSTRAINED LOCAL UNIVERSE SIMULATION
Stefan Gottloeber, Anatoly Klypin, Joel Primack
Visualization: Chris Henze (NASA Ames)

MODERN COSMOLOGY

Ya B. Zeldovich

Institute of Physical Problem, Academy of Sciences of the USSR, Moscow.

Cosmology, the study of the Universe as a whole, is perhaps the most difficult branch of astronomy, since there is always a danger of replacing true knowledge by prejudice, resulting from the impossibility of observing the whole Universe. The situation has changed during the last few decades.

Cosmology has become a respectable science, which was not so 50–60 years ago. However, the problems of the creation of the Universe, and with the reasons for its present form have not yet been solved. At the same time definite progress has been made in understanding the present state of the Universe and a number of its stages of evolution; this progress is a result of investigations carried out by many people, and joint efforts by numerous international groups of astronomers.

The pressure of netural gas can be neglected. Of course, this statement is not an absolute one: gas pressure can neglected in the case when the wavelength of density perturbations is sufficiently long. It is this legacy that we inherited from the radiation-dominated era. But then, if gas pressure does not play any role, the motion of gas turns out to be very specific: nothing prevents particles from coming close to each other to form high-density regions. In three-dimensional space gas can be compressed along each of the three independent directions perpendicular to each other. However, simultaneous compression along two or three axes occurs very rarely, and is not a typical phenomenon. As a rule, there is only one direction in each elementary volume which stands out among the rest.

Compression in this direction creates thin layers with a high density (they are jokingly called "pancakes"). Subsequent gas parcels colliding with a "pancake" heat up in the shock wave, i.e. "fly in". Besides, the "pancakes" grow along its plane. Of course, they are not absolutely flat, but that is not so important. At a later stage the "pancakes" begin to overlap, eventually forming a complex cell structure where compressed gas layers are surrounded by low-density regions.

Such a general picture of the cell structure of the Universe is supported by computer calculations, as well as by a rigorous mathematical analysis based on catastrophe theory and synergetics. An analogy has been established between gravitational instability and the laws of geometrical optics for light reflected from or refracted by stochastic waves at a water surface. (On a sunny day one can see patterns similar to those predicted by the "pancake" theory at the bottom of a swimming pool.) Obviously, galaxies should be created in compressed gas whose layers are still more exposed to the impact of further gravitational clustering.

Zel'dovich - *My Universe: Selected Reviews* 1992

MNRAS 367, 1781–1796 (2006)

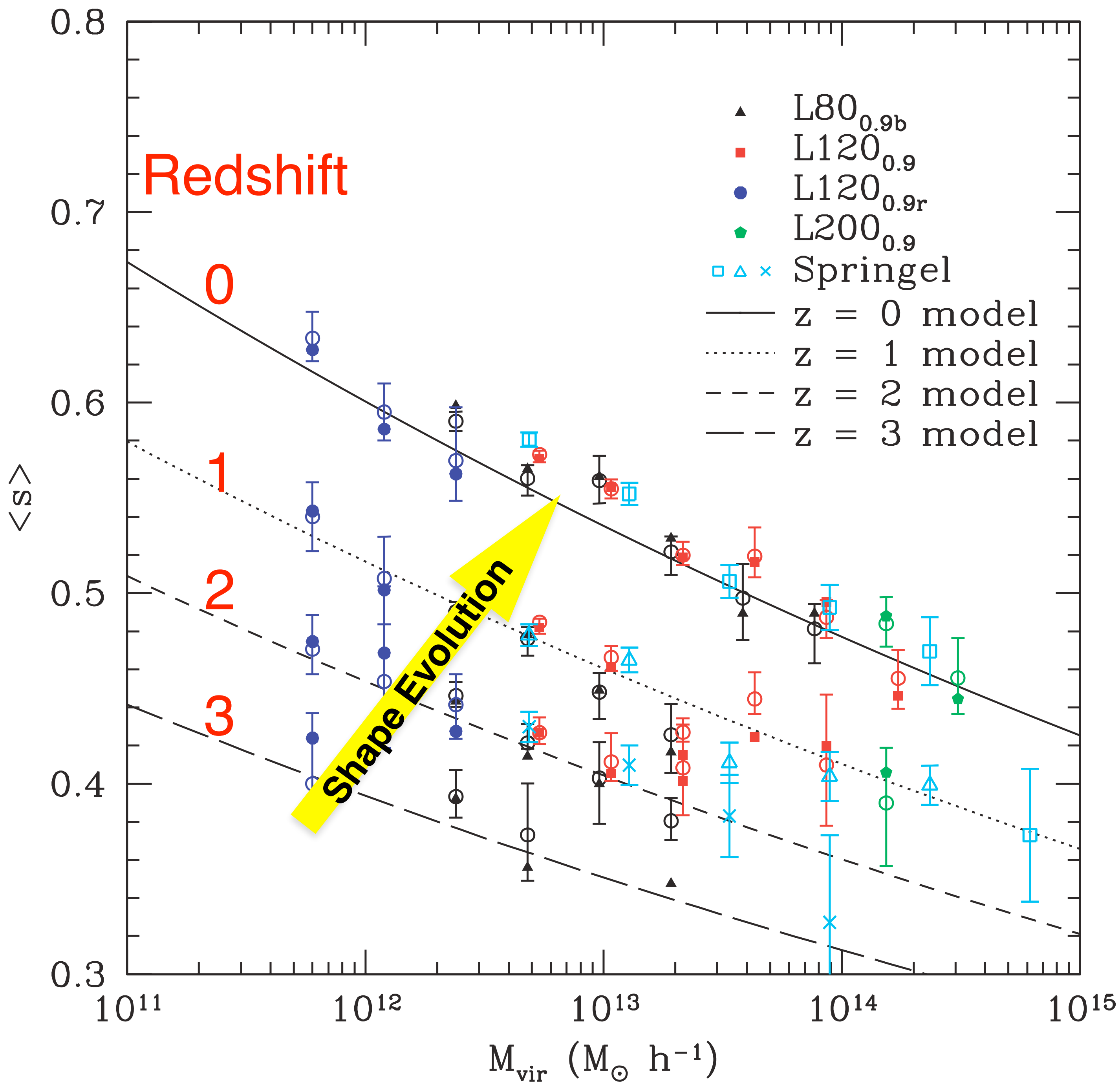
The shape of dark matter haloes: dependence on mass, redshift, radius and formation

Brandon Allgood, Ricardo Flores, Joel R. Primack, Andrey V. Kravtsov, Risa Wechsler, Andreas Faltenbacher and James S. Bullock

Halos are approximately triaxial ellipsoids

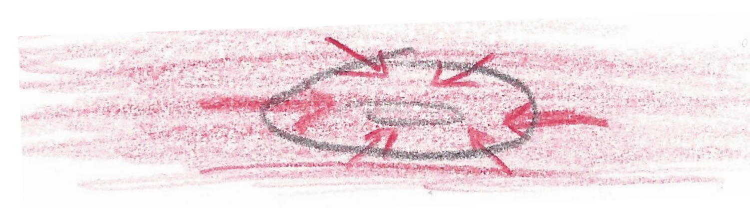
$$\frac{x^2}{a^2} + \frac{y^2}{b^2} + \frac{z^2}{c^2} = 1 \qquad a \geq b \geq c$$

$s = c/a$ = short axis / long axis



Halos start prolate, especially at low radius, and later become more spherical.

Low-redshift halo, accreting more spherically



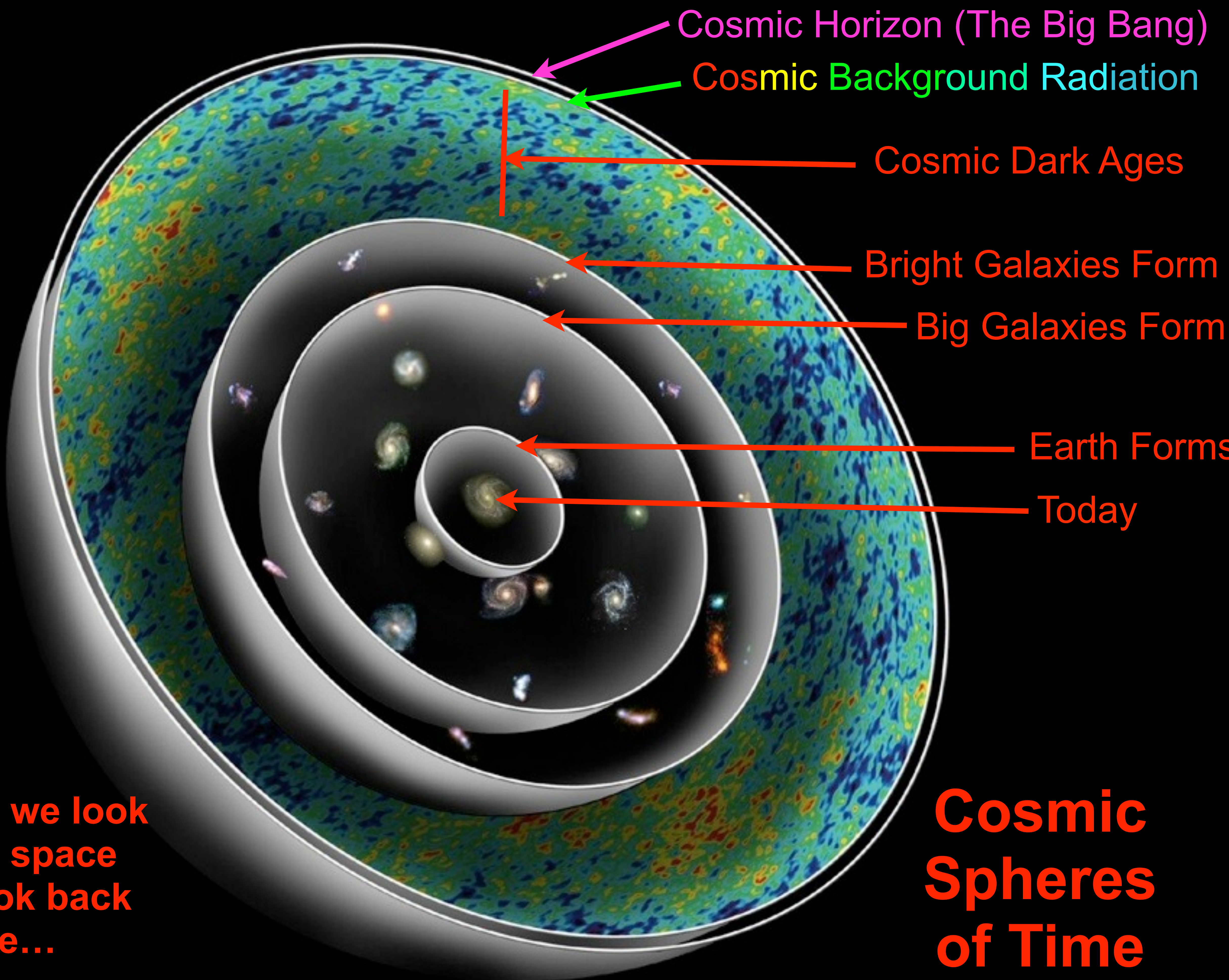
High-redshift halo, accreting mainly along filament

supported by anisotropic velocity dispersion, larger along principal axis

Our Current Understanding of the Physical Universe

COSMOS

GALAXIES

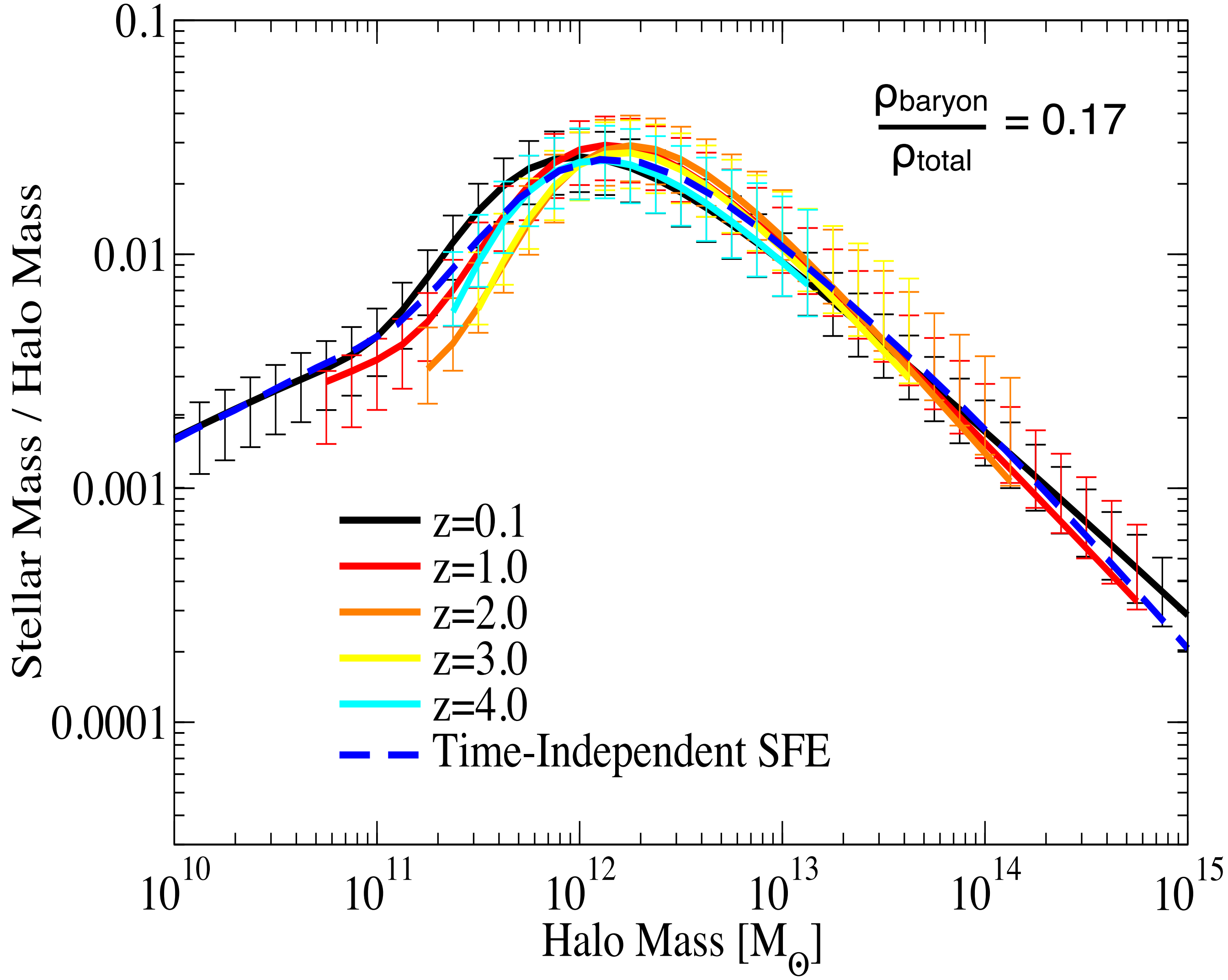


When we look out in space we look back in time…

Cosmic Spheres of Time

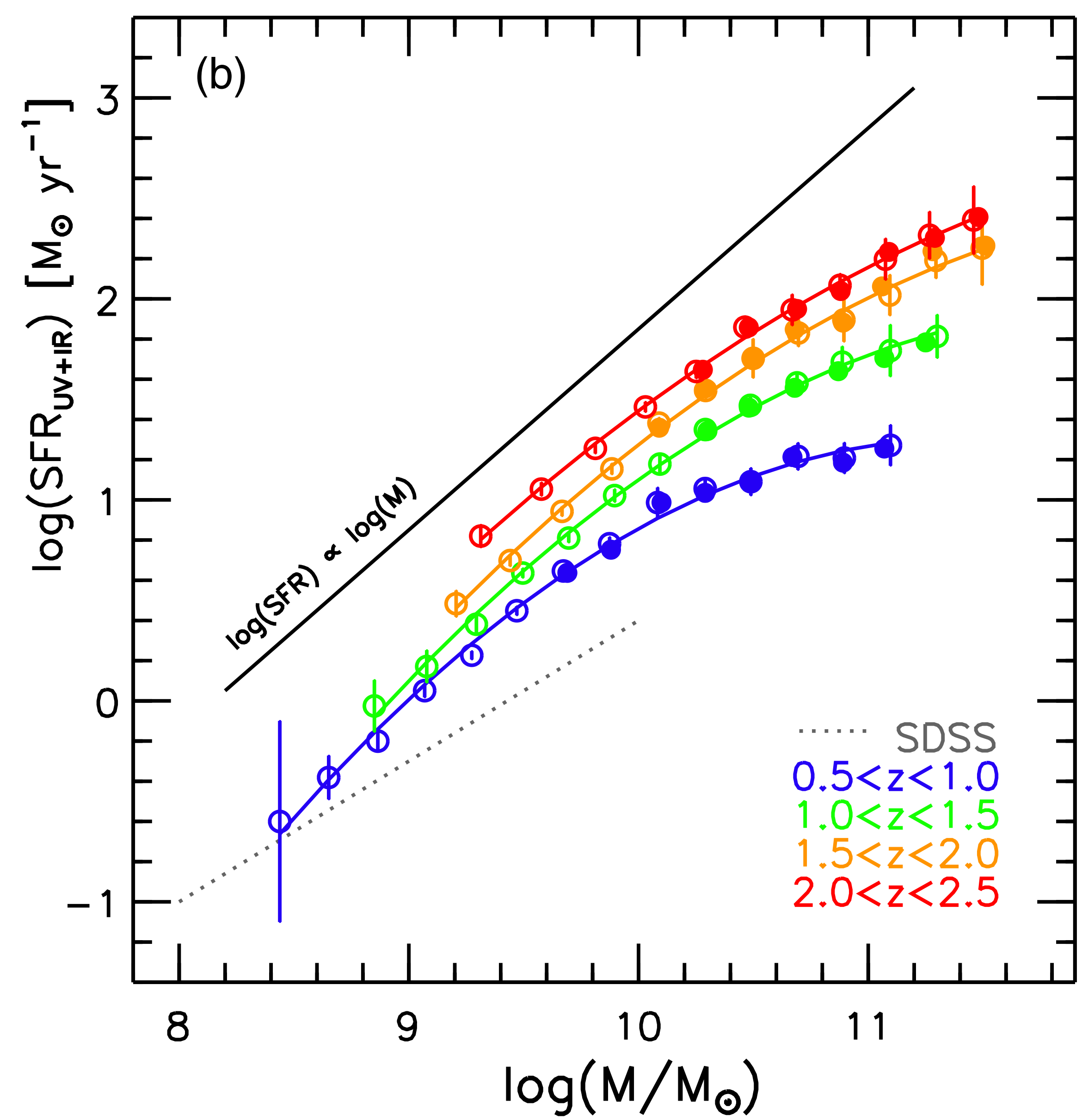
Two Key Discoveries About Galaxies

Relationship Between Galaxy Stellar Mass and Halo Mass



The stellar mass to halo mass ratio at multiple redshifts as derived from observations compared to the Bolshoi cosmological simulation. Error bars show 1σ uncertainties. A time-independent Star Formation Efficiency predicts a roughly **time-independent stellar mass to halo mass relationship**. (Behroozi, Wechsler, Conroy, ApJL 2013)

Star-forming Galaxies Lie on a "Main Sequence"

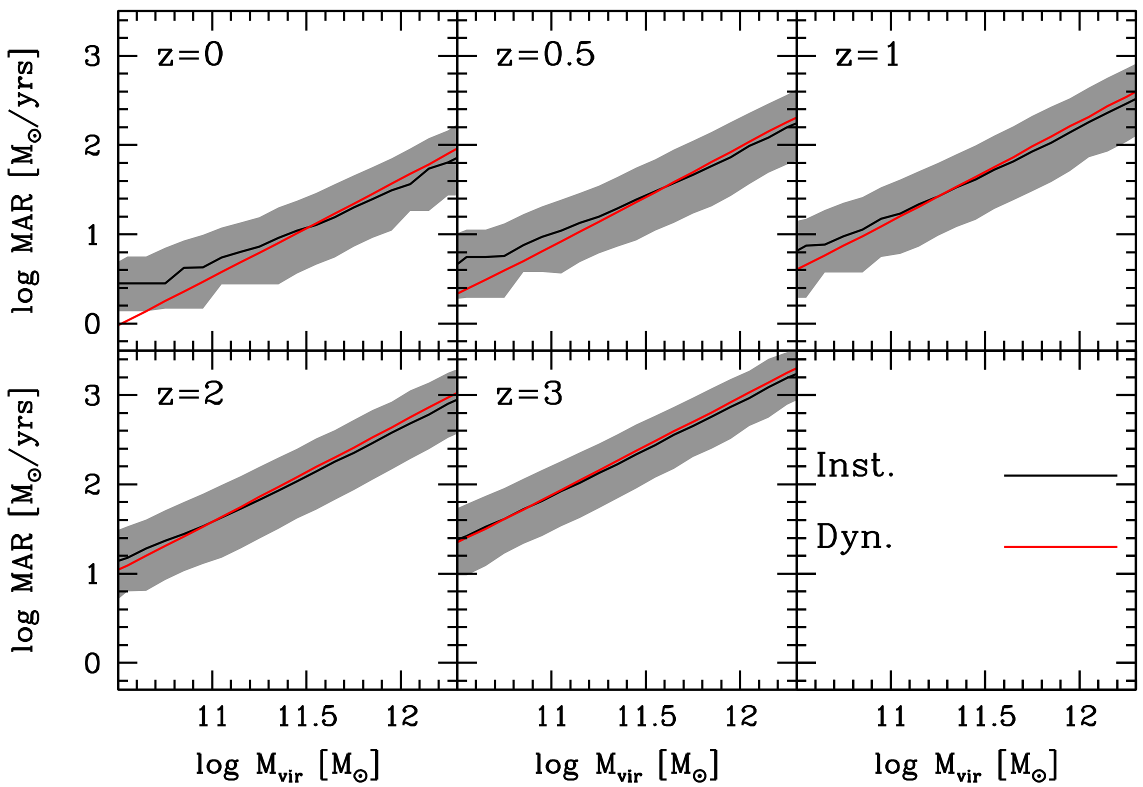


Just as the properties of hydrogen-burning stars are controlled by their mass, **the galaxy star formation rate (SFR) is approximately proportional to the stellar mass**, with the proportionality constant increasing with redshift up to about $z = 2.5$. (Whitaker et al. ApJ 2014)

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



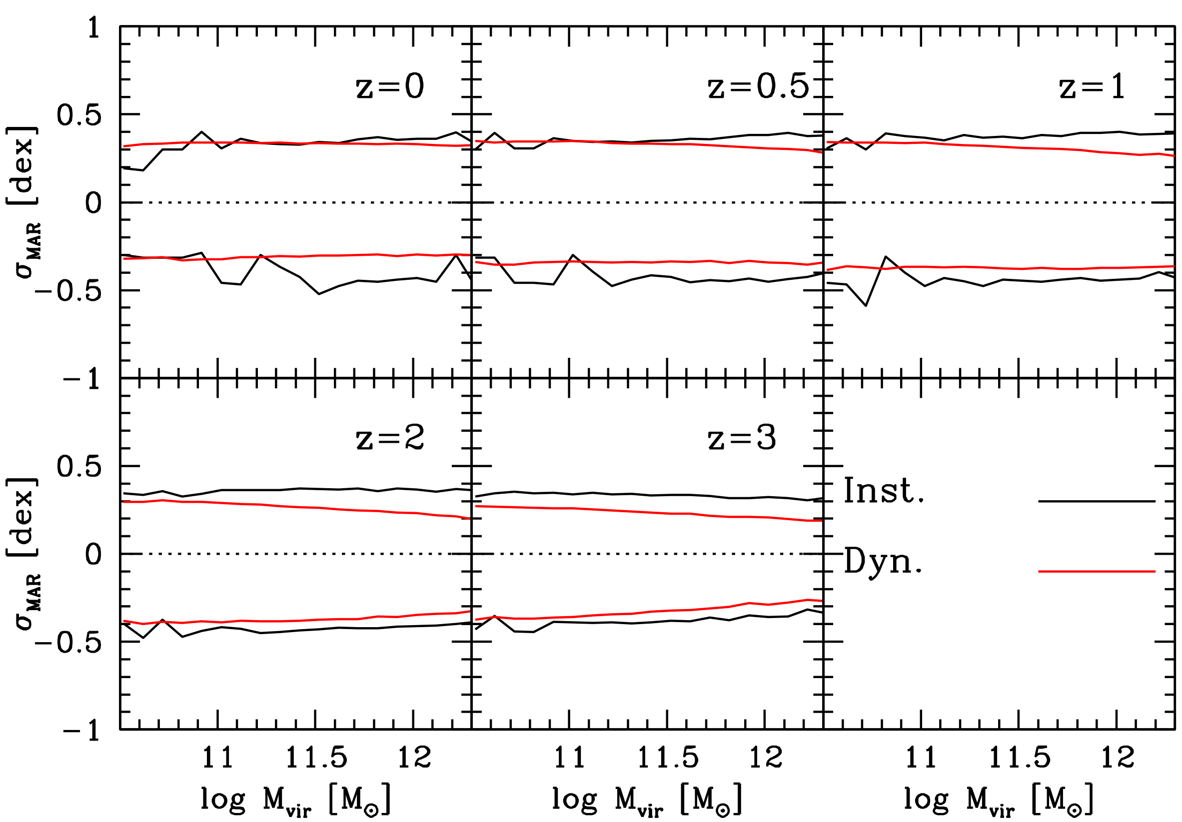
$$\frac{dM_*}{dt} = \frac{\partial M_*(M_{\rm vir}(t), z)}{\partial M_{\rm vir}} \frac{dM_{\rm vir}}{dt} + \frac{\partial M_*(M_{\rm vir}(t), z)}{\partial z} \frac{dz}{dt}$$

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

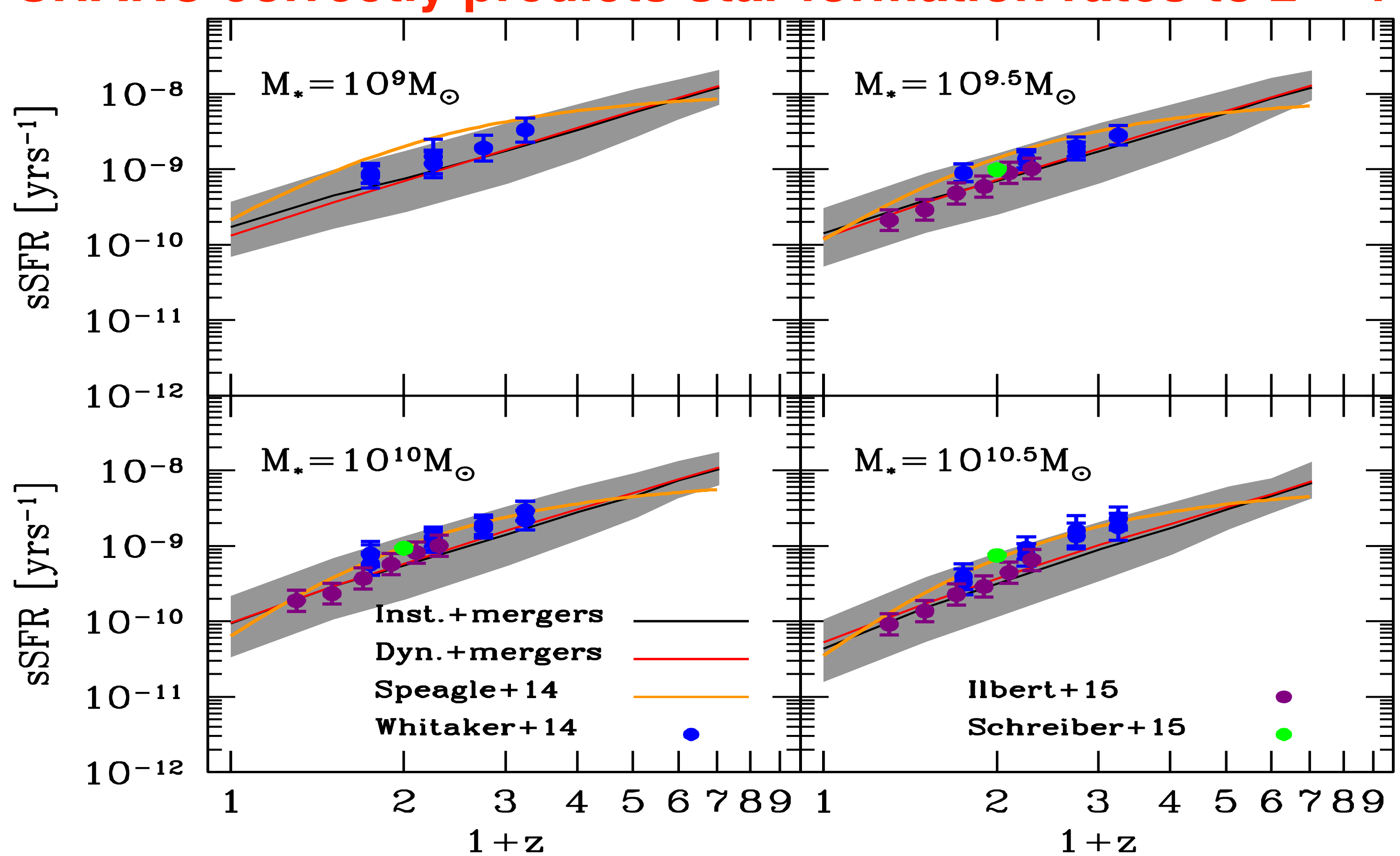
$$\frac{dM_*}{dt} = f_* \frac{d\log M_*}{d\log M_{\rm vir}} \frac{dM_{\rm vir}}{dt},$$

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



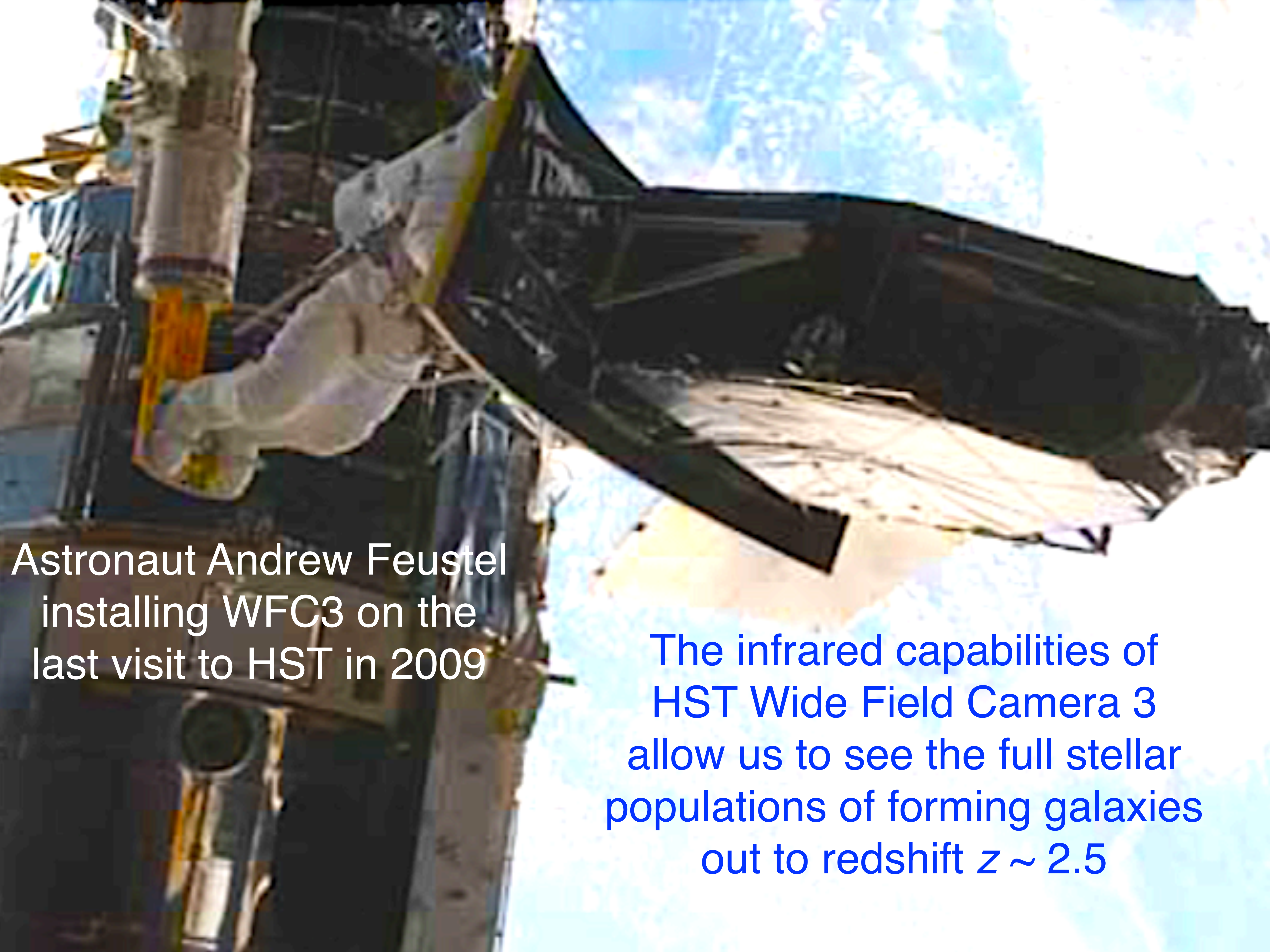
SHARC correctly predicts star formation rates to z ~ 4



Almost all the stars today are in large galaxies like our Milky Way. Nearby large galaxies are disk galaxies like our galaxy or big balls of stars called elliptical galaxies. But most galaxies in the early universe didn't look anything like our Milky Way. Many of them are pickle-shaped and clumpy.

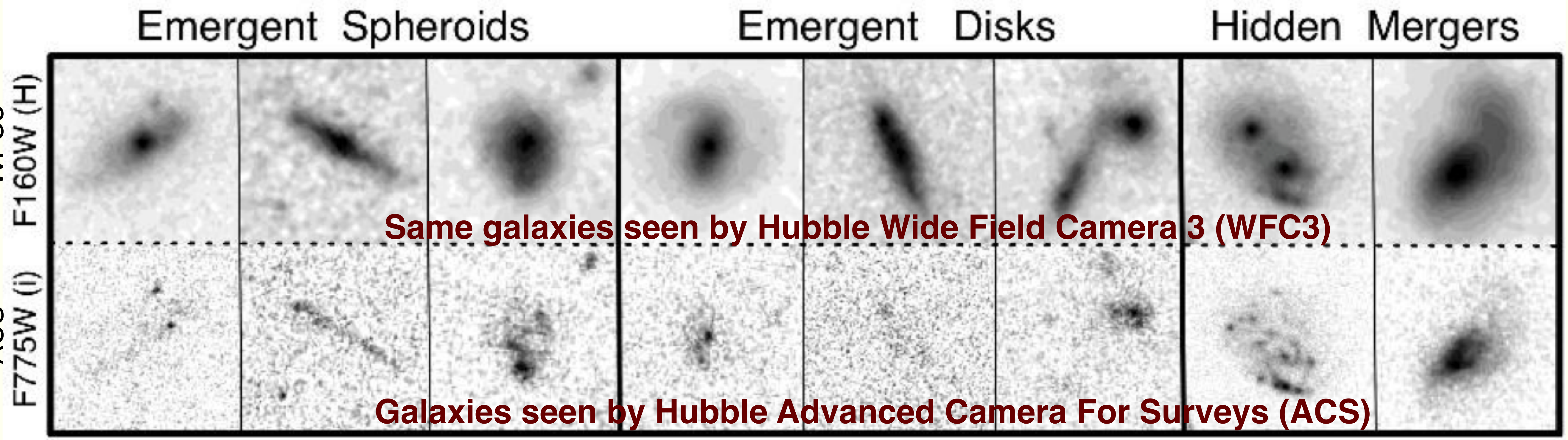


We are just now figuring out how galaxies form and evolve with the help of big ground-based telescopes, and Hubble and other space telescopes that let us see radiation that doesn't penetrate the atmosphere.


Astronaut Andrew Feustel
installing WFC3 on the
last visit to HST in 2009
The infrared capabilities of
HST Wide Field Camera 3
allow us to see the full stellar
populations of forming galaxies
out to redshift $z \sim 2.5$

The CANDELS Survey shows shapes of z ≲ 2.5 galaxies

candels.ucolick.org



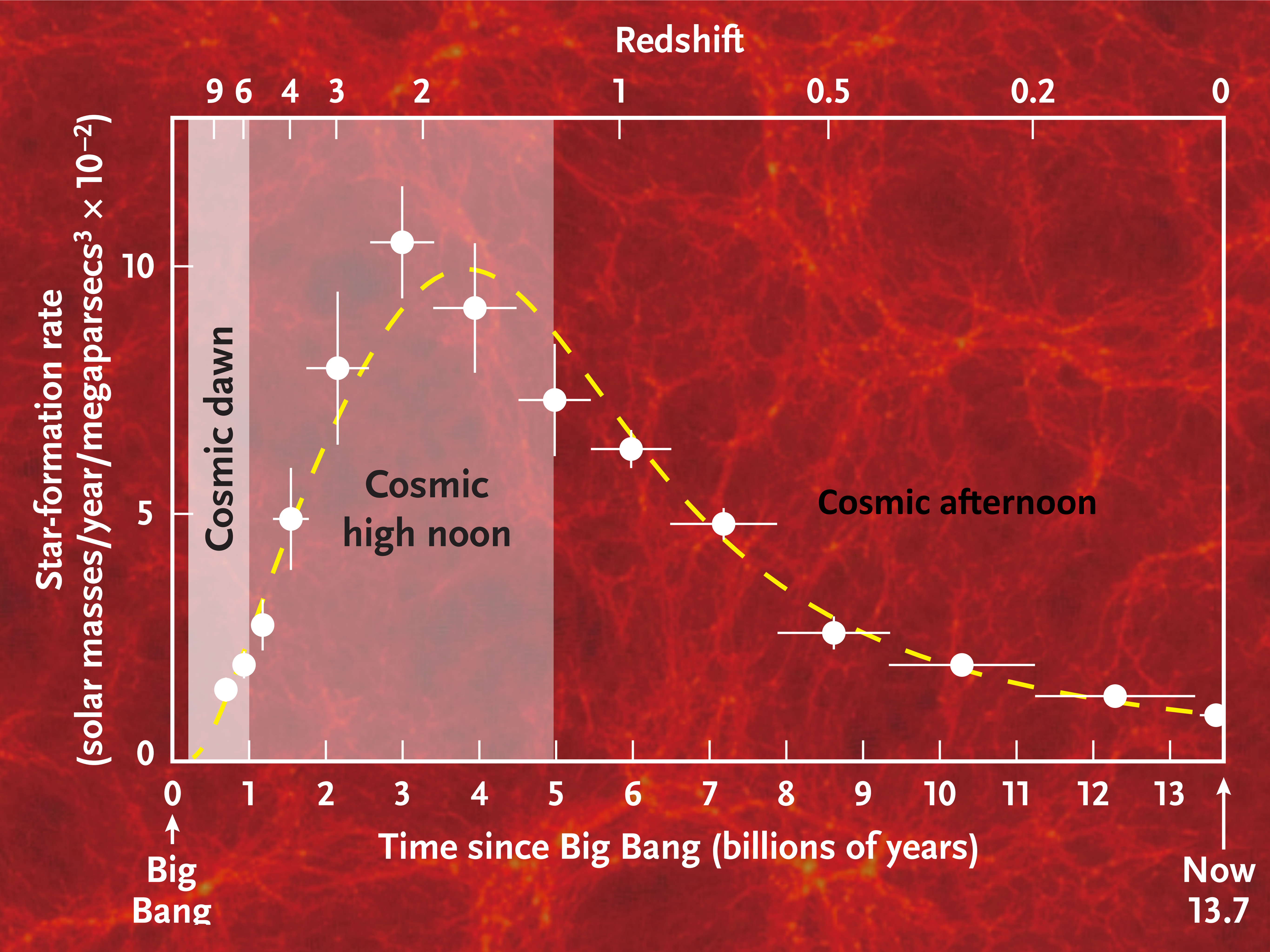
CANDELS: A Cosmic Odyssey

(blue 0.4 μm)(1+z) = 1.6 μm @ z = 3

(orange 0.6 μm)(1+z) = 1.6 μm @ z = 1.7

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.

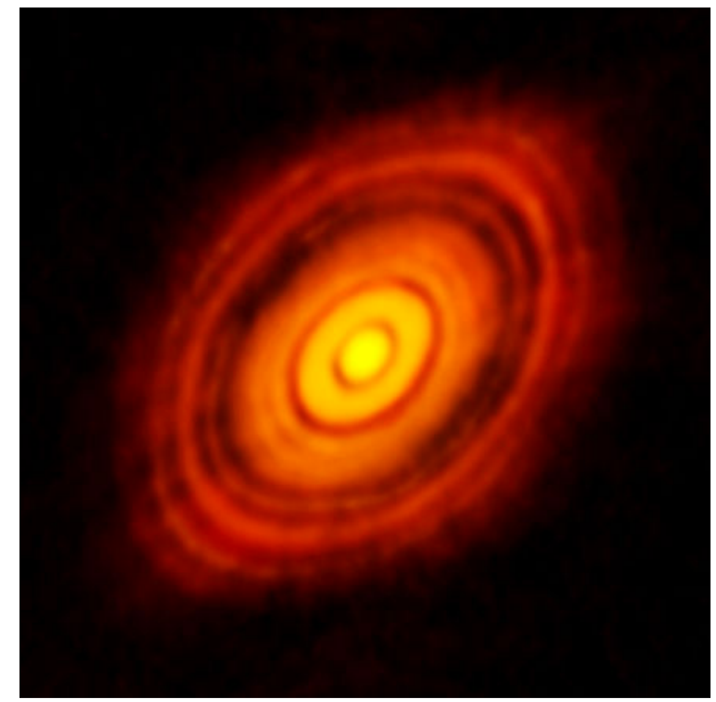


Redshift
9
6
4
3
2
1
0.5
0.2
0
Star-formation rate
(solar masses/year/megaparsecs³ × 10⁻²)
10
5
0
Cosmic dawn
Cosmic
high noon
Cosmic afternoon
0
1
2
3
4
5
6
7
8
9
10
11
12
13
Time since Big Bang (billions of years)
Big
Bang
Now
13.7

Do Galaxies Start as Disks?

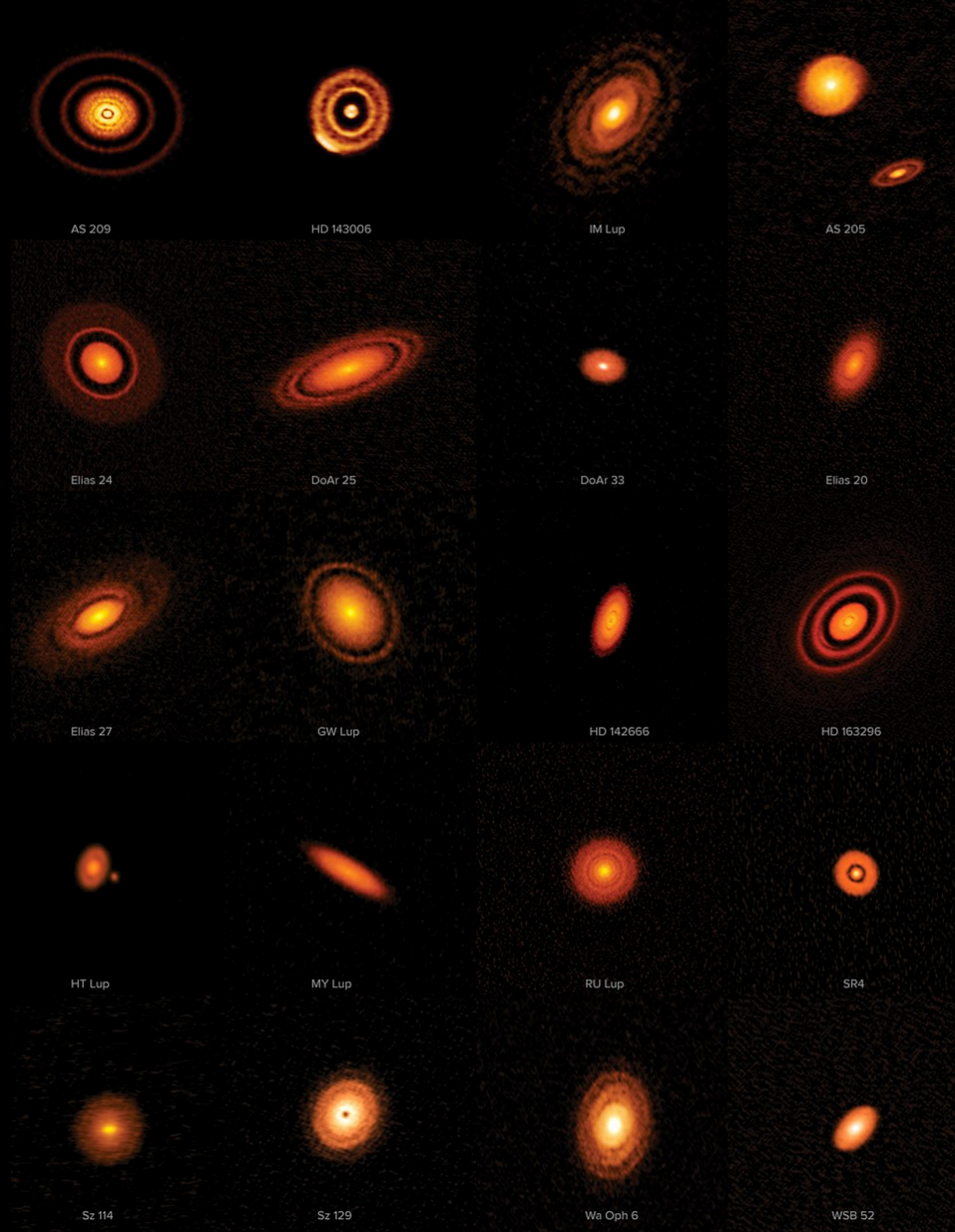
Newton's laws explained why planetary orbits are elliptical, but not why the planetary orbits in the solar system are nearly circular, in the same plane, and in the same direction as the sun rotates.

Laplace explained this as a consequence of angular momentum conservation as the sun and planets formed in a cooling and contracting protoplanetary gas cloud that formed a disk— like this one:



ALMA image of HL Tauri

20 Protoplanetary Disks from ALMA's High Angular Resolution Project DSHARP (2019)



Do Galaxies Start as Disks?

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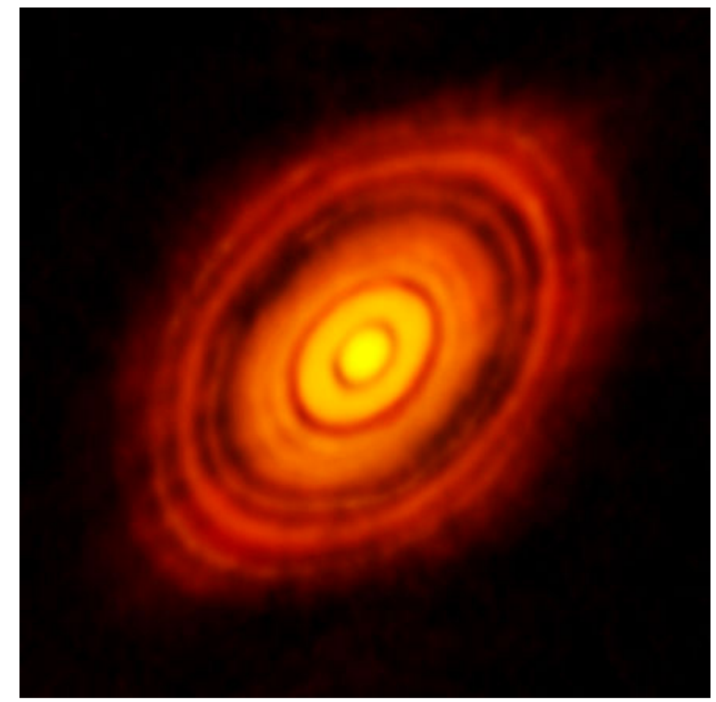


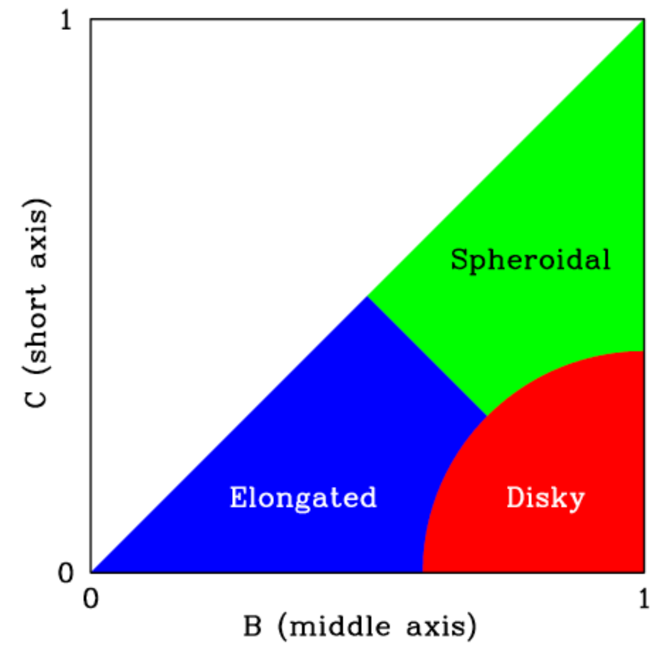
ALMA image of HL Tauri

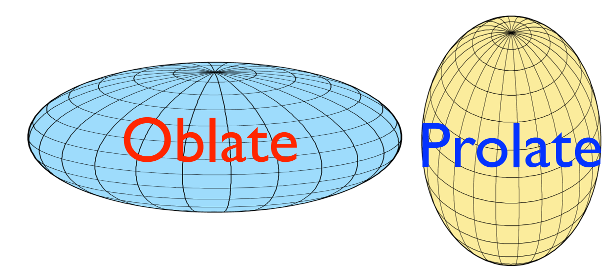
For similar reasons, many astronomers once thought that galaxies would start as disks. But Hubble Space Telescope images of forming galaxies instead show that most forming galaxies are prolate – that is, pickle-shaped. As we will see, this is a consequence of most galaxies forming in prolate dark matter halos oriented along massive dark matter filaments.

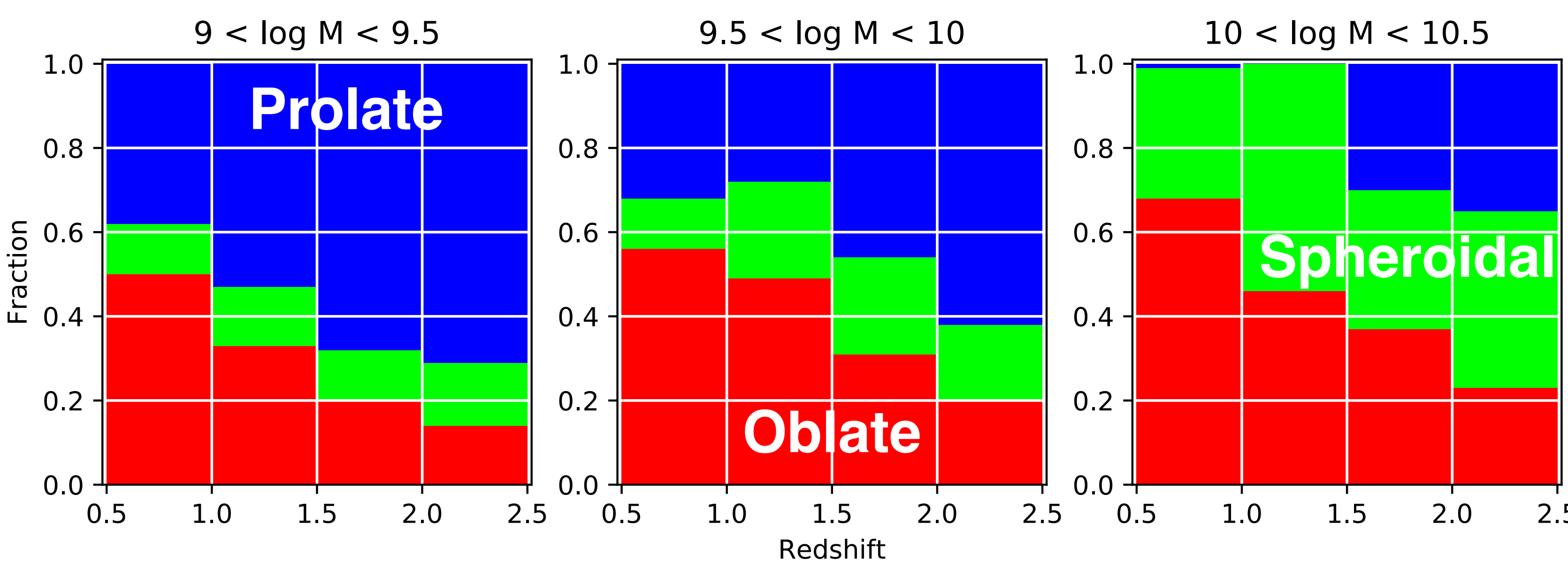
The Evolution of Galaxy Shapes in CANDELS: from Prolate to Oblate

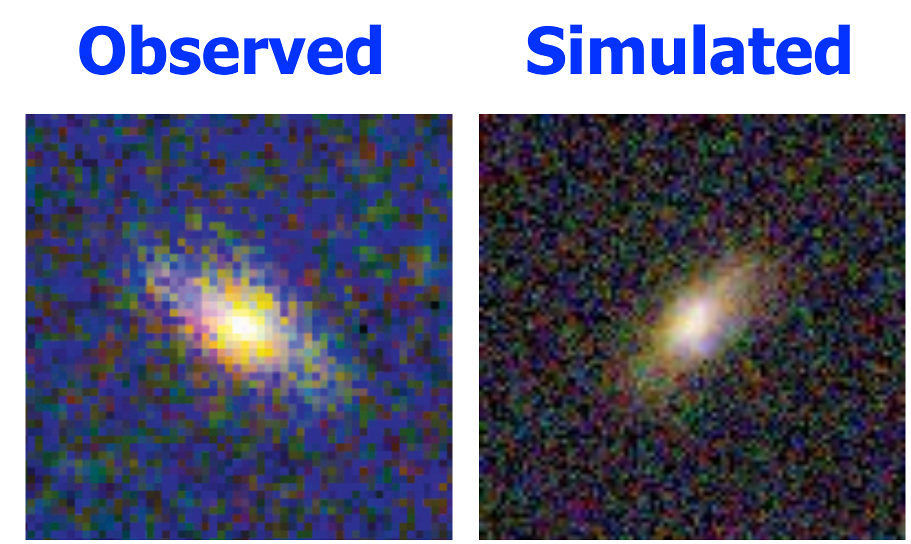
Haowen Zhang, Joel R. Primack, S. M. Faber, David C. Koo, Avishai Dekel, Zhu Chen, Daniel Ceverino, Yu-Yen Chang, Jerome J. Fang, Yicheng Guo, Lin Lin, and Arjen van der Wel MNRAS 484, 5170 (2019)

ABSTRACT
We model the projected b/a – $\log a$ distributions of CANDELS main sequence star-forming galaxies, where a (b) is the semi-major (semi-minor) axis of the galaxy images. We find that smaller-a galaxies are rounder at all stellar masses M_* and redshifts, so we include a when analyzing b/a distributions. Approximating intrinsic shapes of the galaxies as triaxial ellipsoids and assuming a multivariate normal distribution of galaxy size and two shape parameters, we construct their intrinsic shape and size distributions to obtain the fractions of prolate, oblate, and spheroidal galaxies in each redshift and mass bin. We find that galaxies tend to be prolate at low M_* and high redshifts, and oblate at high M_* and low redshifts, qualitatively consistent with van der Wel et al. (2014), implying that galaxies tend to evolve from prolate to oblate. These results are consistent with the predictions from simulations (Ceverino et al. 2015, Tomassetti et al. 2016) that the transition from prolate to oblate is caused by a compaction event at a characteristic mass range, making the galaxy center baryon dominated. We give probabilities of a galaxy's being prolate, oblate, or spheroidal as a function of its M_*, redshift, and projected b/a and a, which can facilitate target selections of galaxies with specific shapes at high redshifts. We also give predicted optical depths of galaxies, which are qualitatively consistent with the expected correlation that A_V should be higher for edge-on disk galaxies in each $\log a$ slice at low redshift and high mass bins.





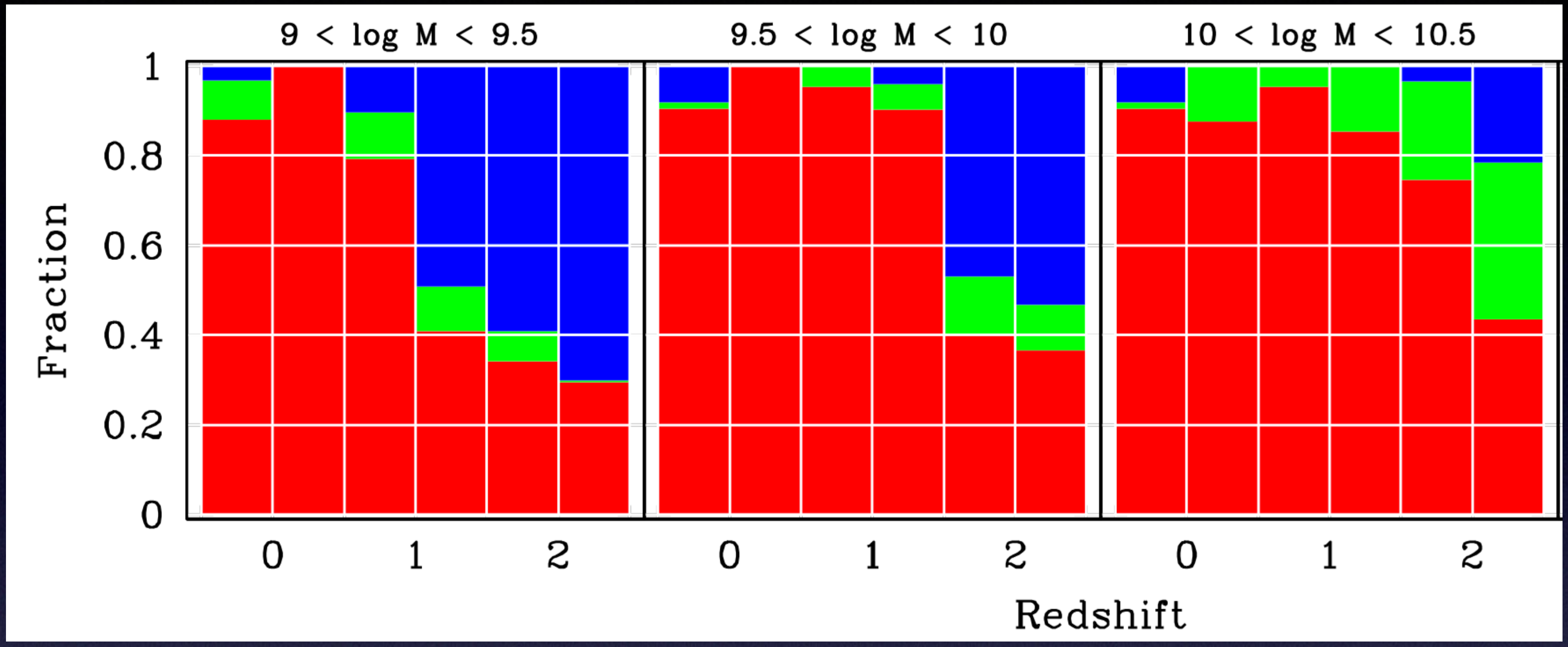




(a) CANDELS galaxy (b) VELA galaxy

CANDELS: galaxies start out elongated

Arjen van der Wel+14

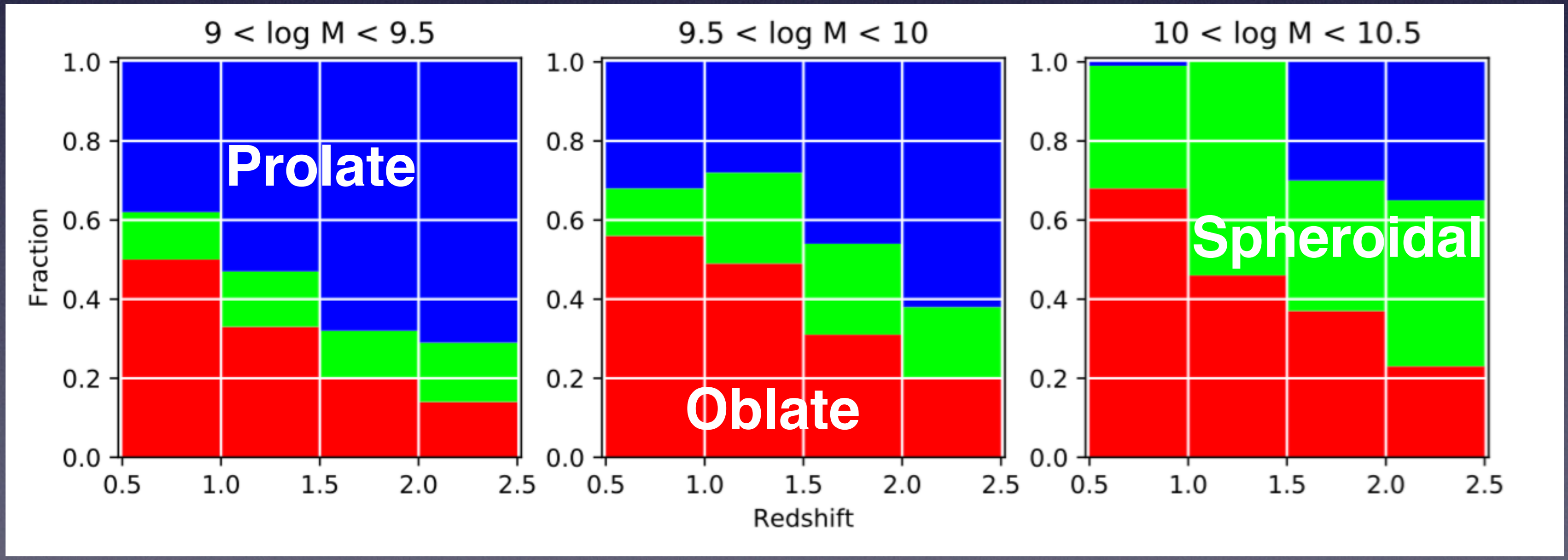


Blue = elongated

Green = Spheroidal

Red = disky

Haowen Zhang+19



Sophisticated new analysis => more Prolate & Spheroid, fewer Oblate

Four stellar mass—redshift bins with >50% prolate fractions:

$1.0 < z < 1.5, 9.0 < \log M_* < 9.5$

$2.0 < z < 2.5, 9.0 < \log M_* < 9.5$

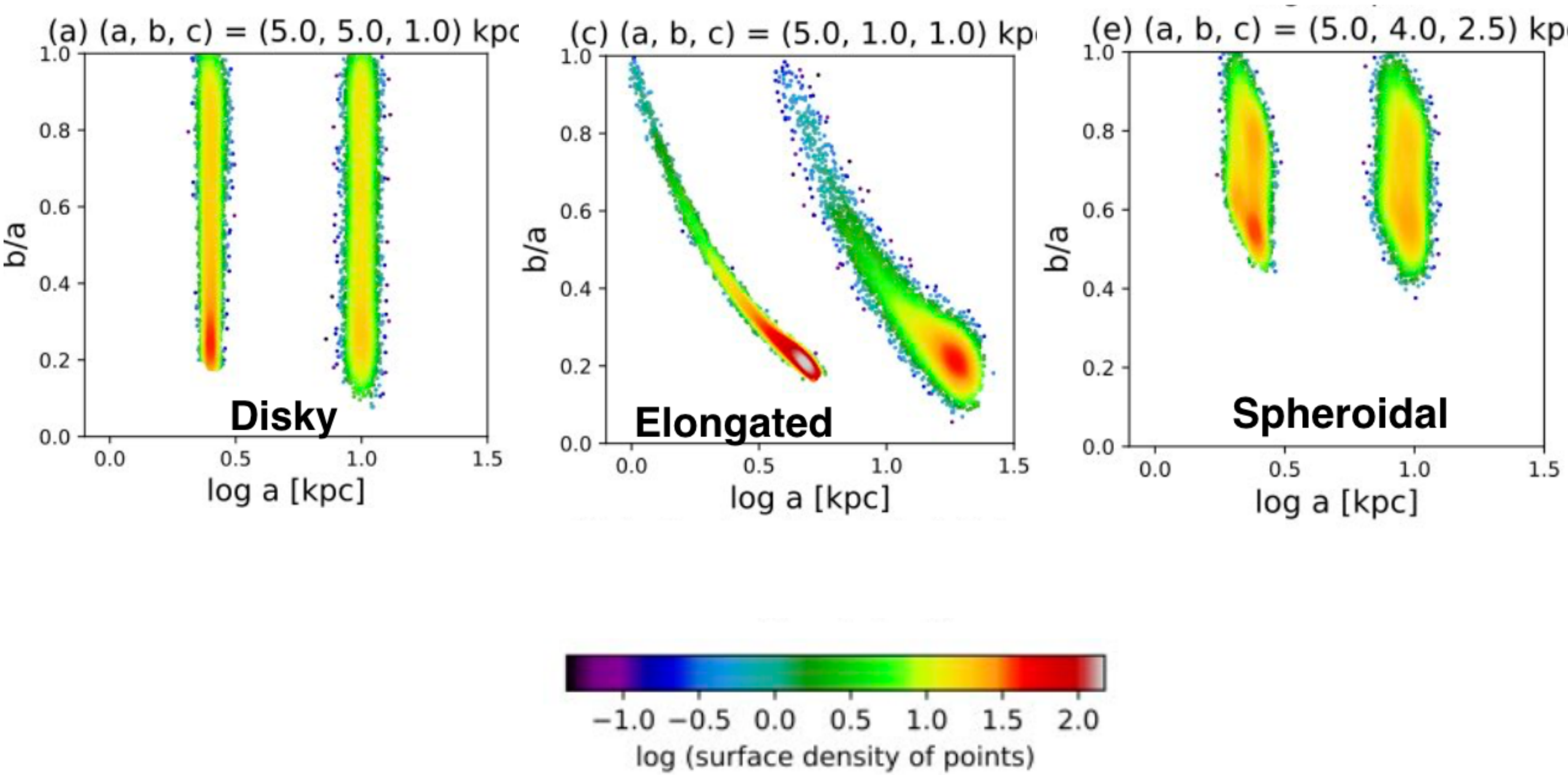
$1.5 < z < 2.0, 9.0 < \log M_* < 9.5$

$2.0 < z < 2.5, 9.5 < \log M_* < 10.0$

The Evolution of Galaxy Shapes in CANDELS: from Prolate to Oblate

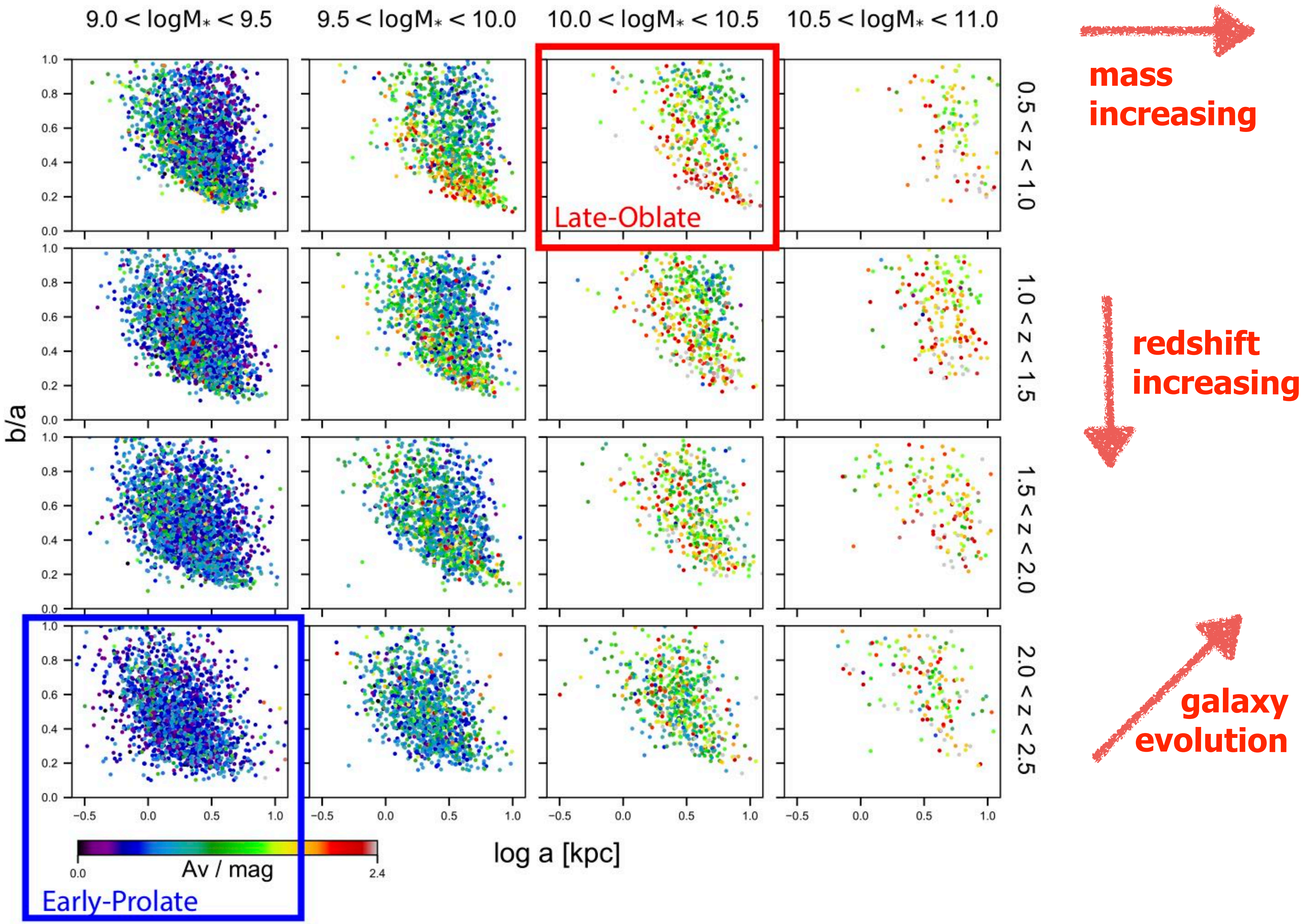
Haowen Zhang, Joel R. Primack, S. M. Faber, David C. Koo, Avishai Dekel, Zhu Chen, Daniel Ceverino, Yu-Yen Chang, Jerome J.
Yicheng Guo, Lin Lin, and Arjen van der Wel MNRAS 484, 5170 (2019)

b/a - log a distribution modeling to determine the shape distribution statistics



The Evolution of Galaxy Shapes in CANDELS: from Prolate to Oblate

Projected b/a - log a distributions of CANDELS galaxies in redshift-mass bins



Cosmological Simulations

Astronomical observations represent snapshots of moments in time. It is the role of astrophysical theory to produce movies -- both metaphorical and actual -- that link these snapshots together into a coherent physical theory.

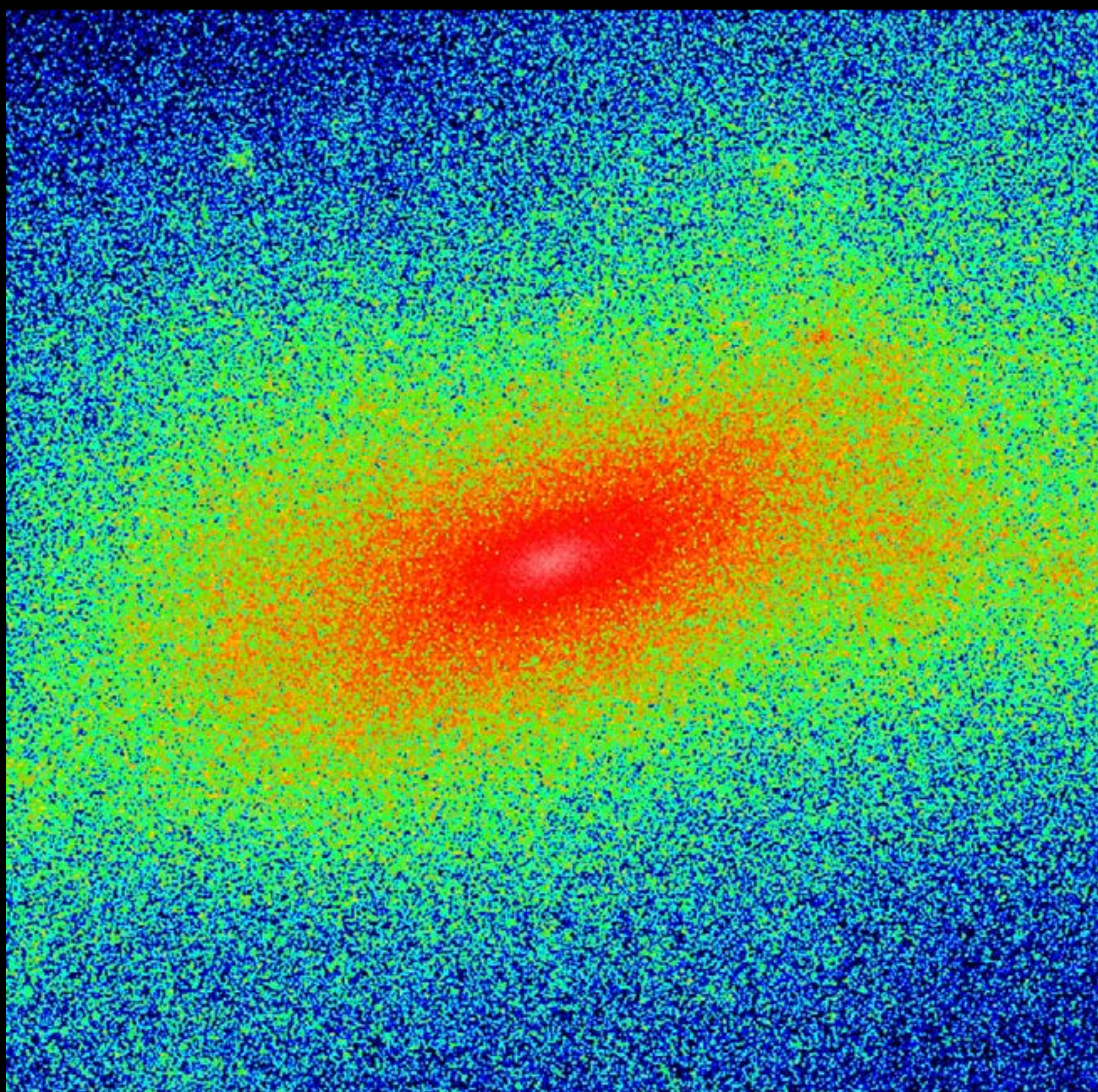
Cosmological dark matter simulations show large scale structure and dark matter halo properties, basis for semi-analytic models

Hydrodynamic galaxy formation simulations: evolution of galaxies, formation of galactic spheroids via mergers, galaxy images and spectra including stellar evolution and dust

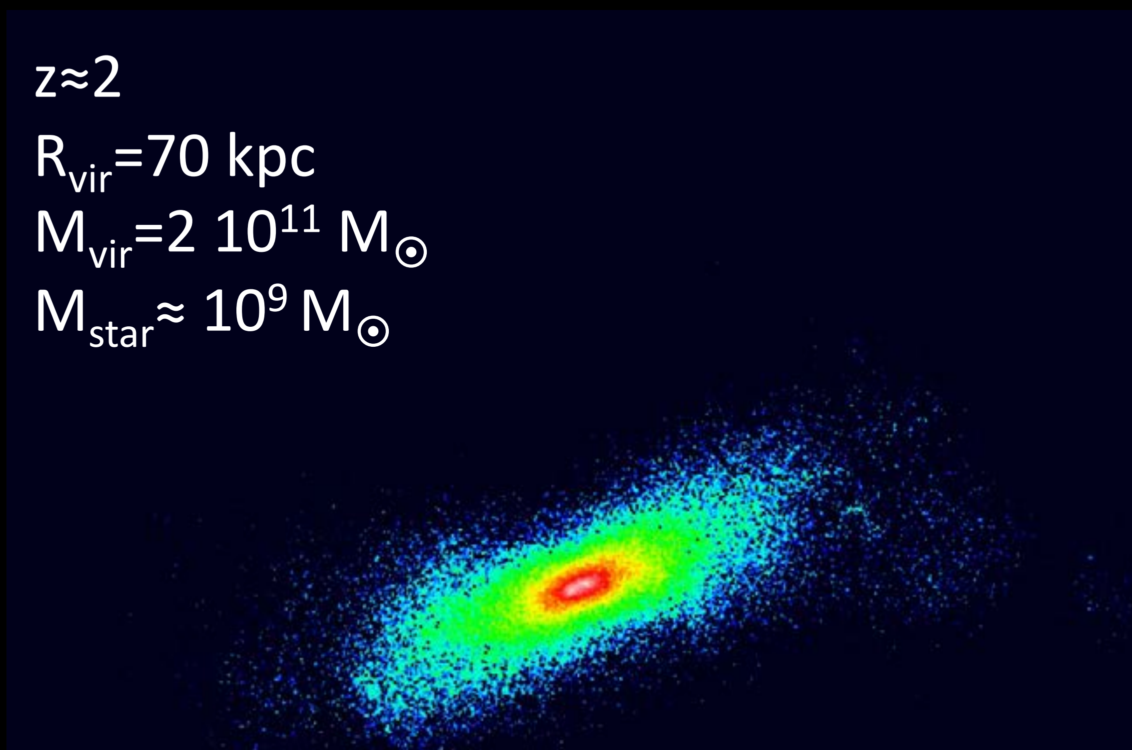
Our cosmological zoom-in simulations often produce elongated galaxies like the observed ones. The elongated distribution of stars follows the elongated inner dark matter halo.

Prolate DM halo → elongated galaxy

DM **VELA28RP** **stars**



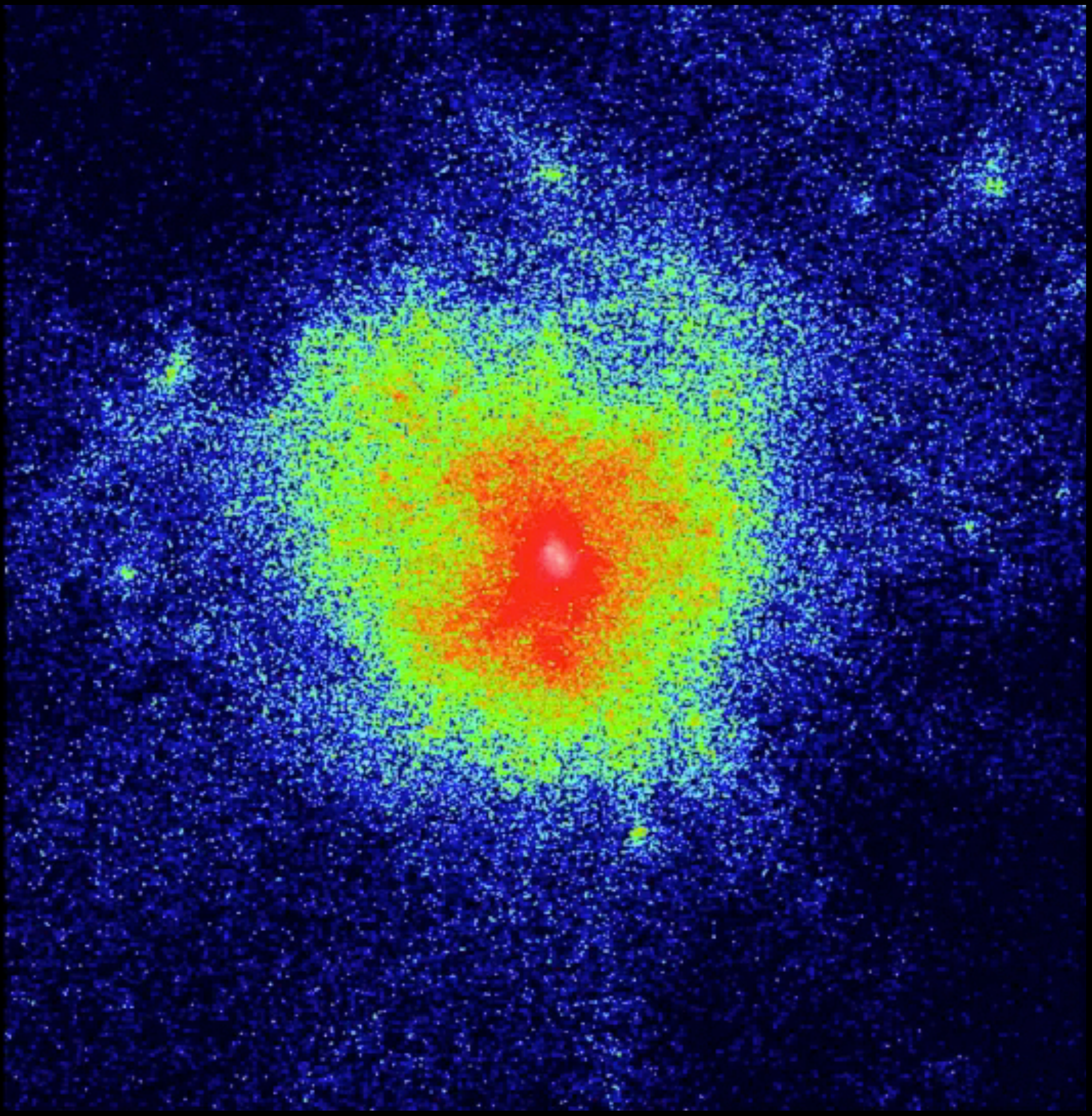
↔ **30 kpc**

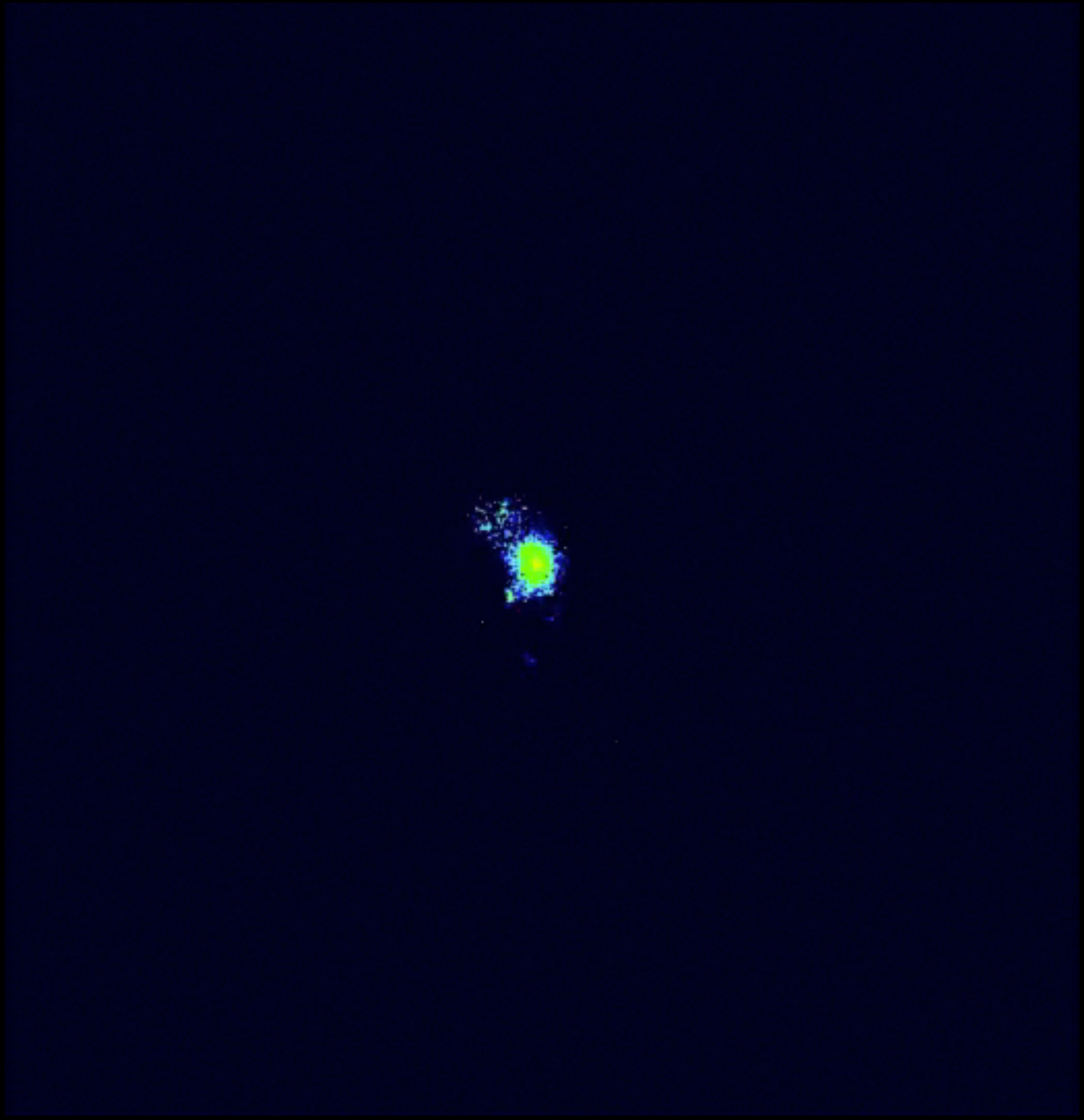


Dark matter halos are elongated, especially near their centers. Initially stars follow the gravitationally dominant dark matter, as shown. But later as the ordinary matter central density grows and it becomes gravitationally dominant, the star and dark matter distributions both become disky — as observed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

Our cosmological zoom-in simulations often produce elongated galaxies like observed ones. The elongated distribution of stars follows the elongated inner dark matter halo. Here we show the evolution of the dark matter and stellar mass distributions in our zoom-in galaxy simulation VELA28, viewed from the same fixed vantage point.

DM **VELA28-gen3** **stars**

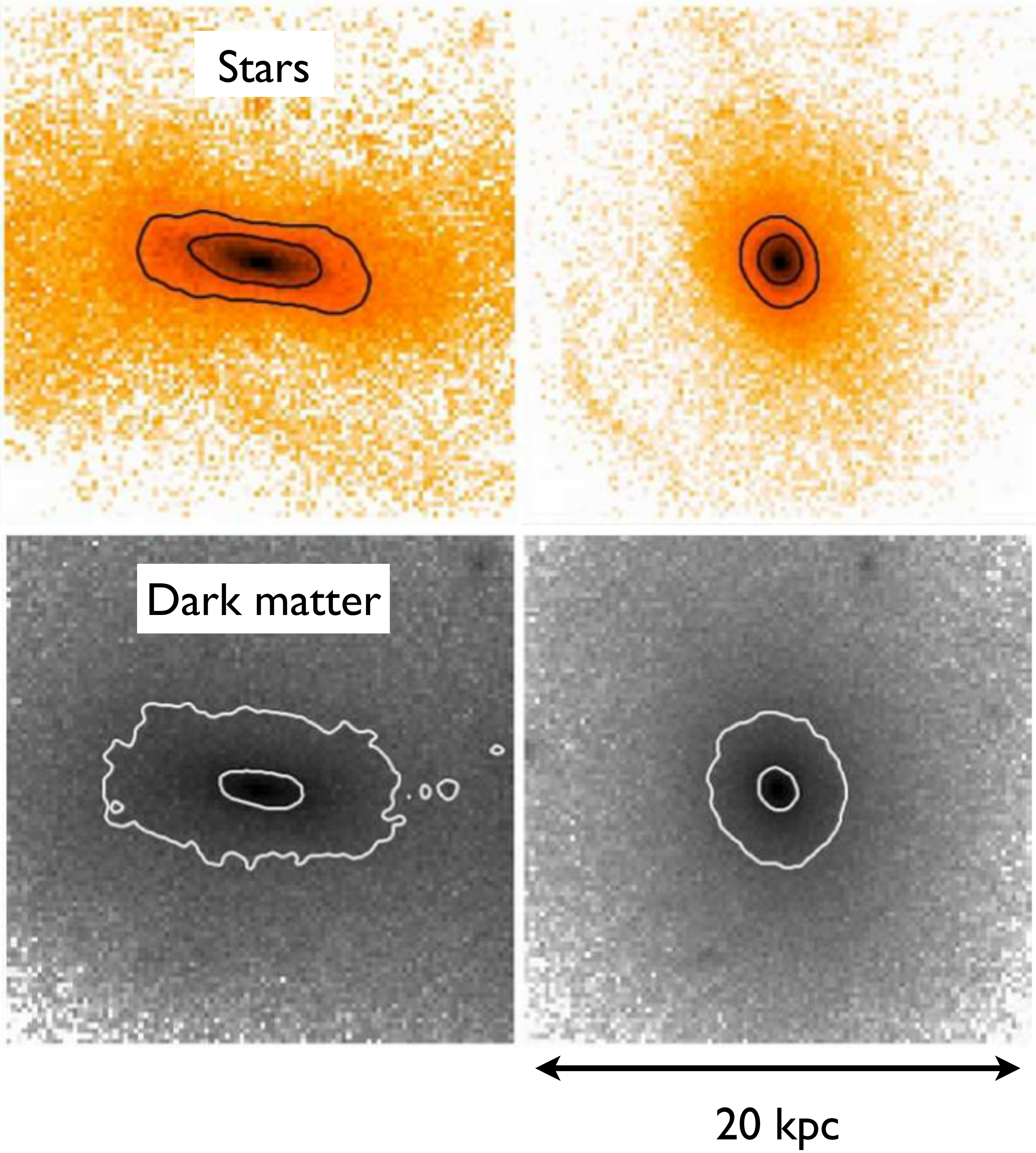


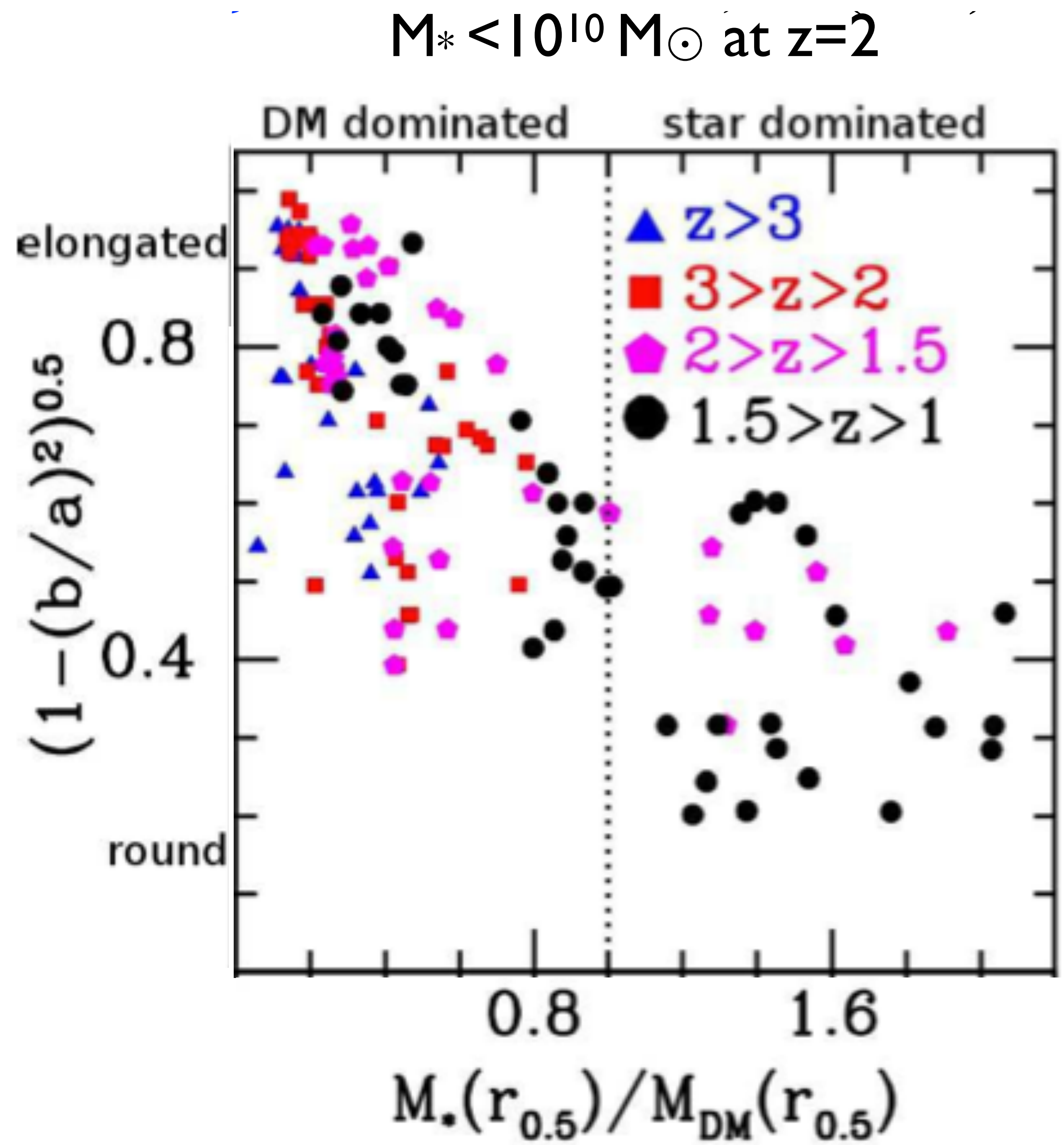


30 kpc **30 kpc**

Formation of elongated galaxies with low masses at high redshift

Daniel Ceverino, Joel Primack and Avishai Dekel   MNRAS 2015



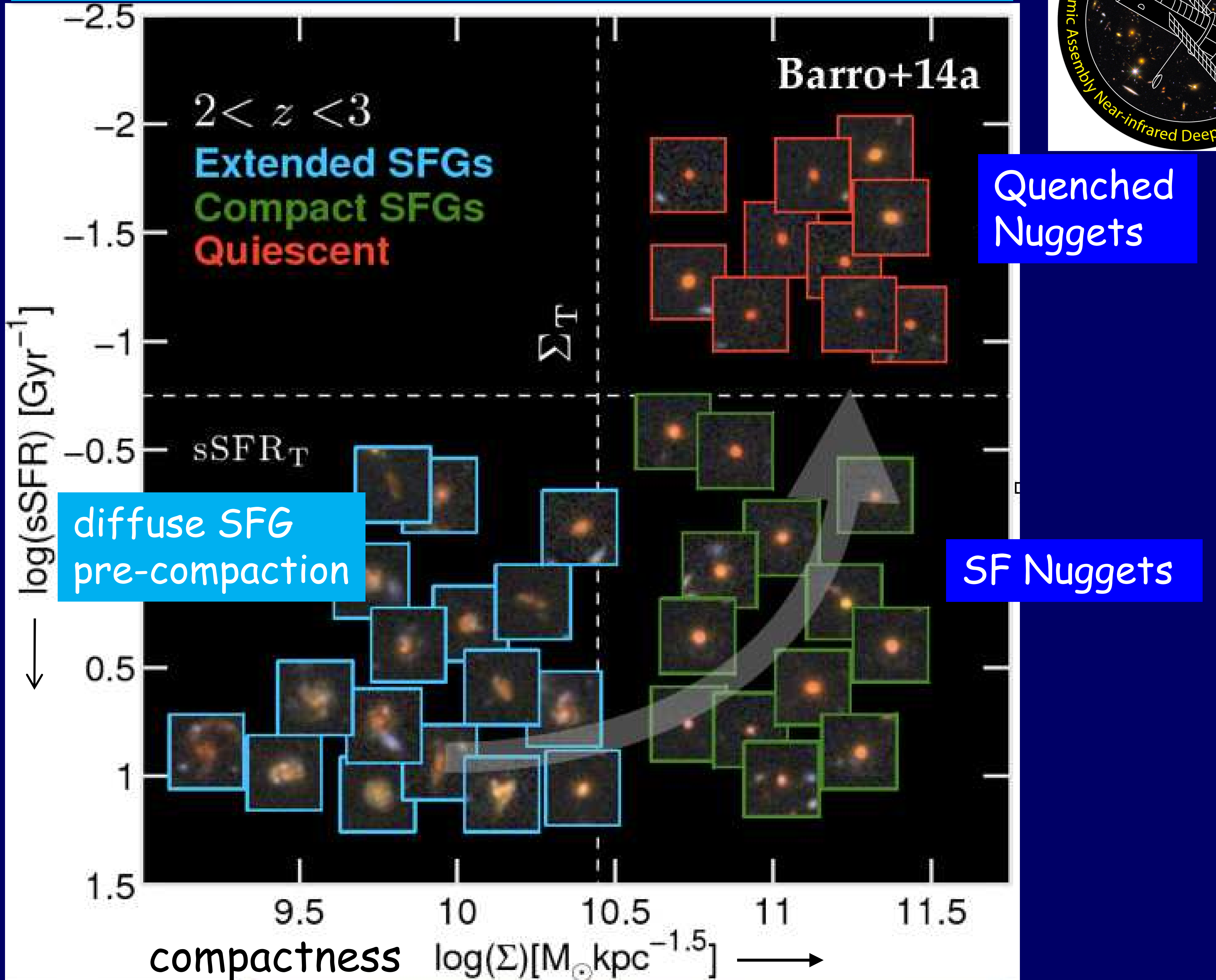


Tomassetti et al. 2016 MNRAS

Simulated elongated galaxies are aligned with cosmic web filaments, become round after compaction (gas inflow fueling central starburst)

Pandya, Primack, et al. 2019 Alignments of prolate galaxies trace cosmic web?

The Fast Track of Galaxy Evolution



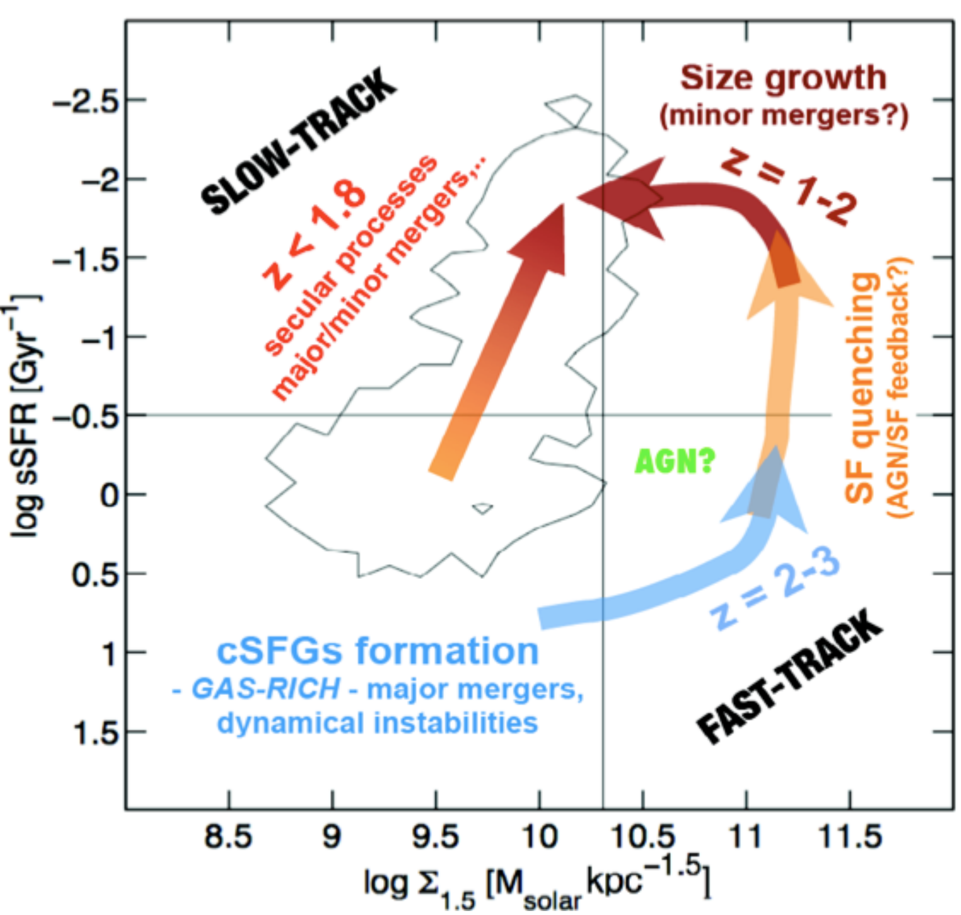
The Astrophysical Journal, 846:112 (13pp), 2017 September 10 https://doi.org/10.3847/1538-4357/aa8566

"blue nuggets", many of which have X-ray detected AGN

CANDELS: Elevated Black Hole Growth in the Progenitors of Compact Quiescent Galaxies at $z \sim 2$

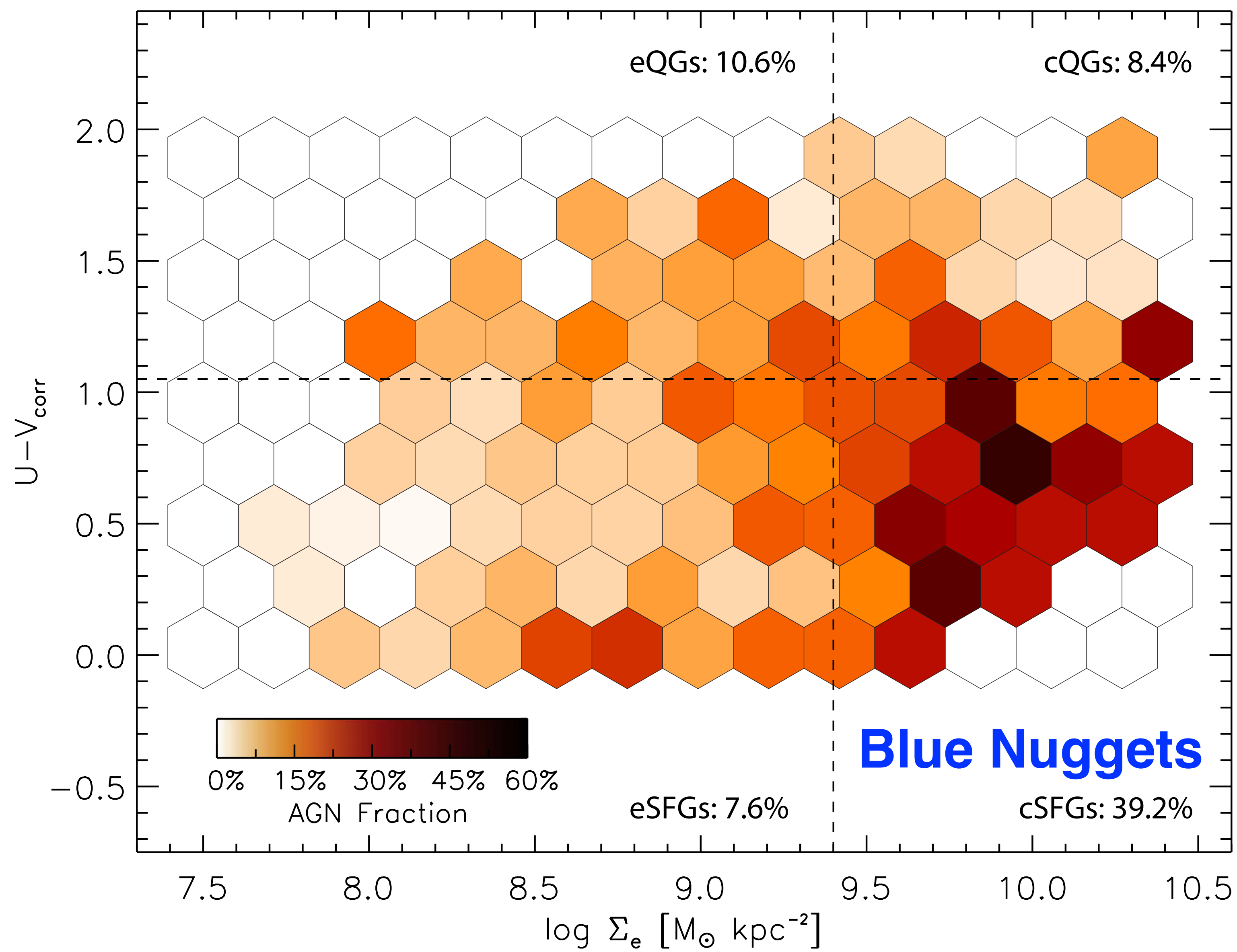
Dale D. Kocevski[1], Guillermo Barro[2], S. M. Faber[3], Avishai Dekel[4], Rachel S. Somerville[5,6], Joshua A. Young[1], Christina C. Williams[7], Daniel H. McIntosh[8], Antonis Georgakakis[9], Guenther Hasinger[10], Kirpal Nandra[9], Francesca Civano[11], David M. Alexander[12], Omar Almaini[13], Christopher J. Conselice[13], Jennifer L. Donley[14], Harry C. Ferguson[15], Mauro Giavalisco[16], Norman A. Grogin[15], Nimish Hathi[15], Matthew Hawkins[1], Anton M. Koekemoer[15], David C. Koo[3], Elizabeth J. McGrath[1], Bahram Mobasher[17], Pablo G. Pérez González[18], Janine Pforr[19], Joel R. Primack[20], Paola Santini[21], Mauro Stefanon[22,23], Jonathan R. Trump[24], Arjen van der Wel[25], Stijn Wuyts[26], and Haojing Yan[23]

Barro+ (CANDELS) 2013



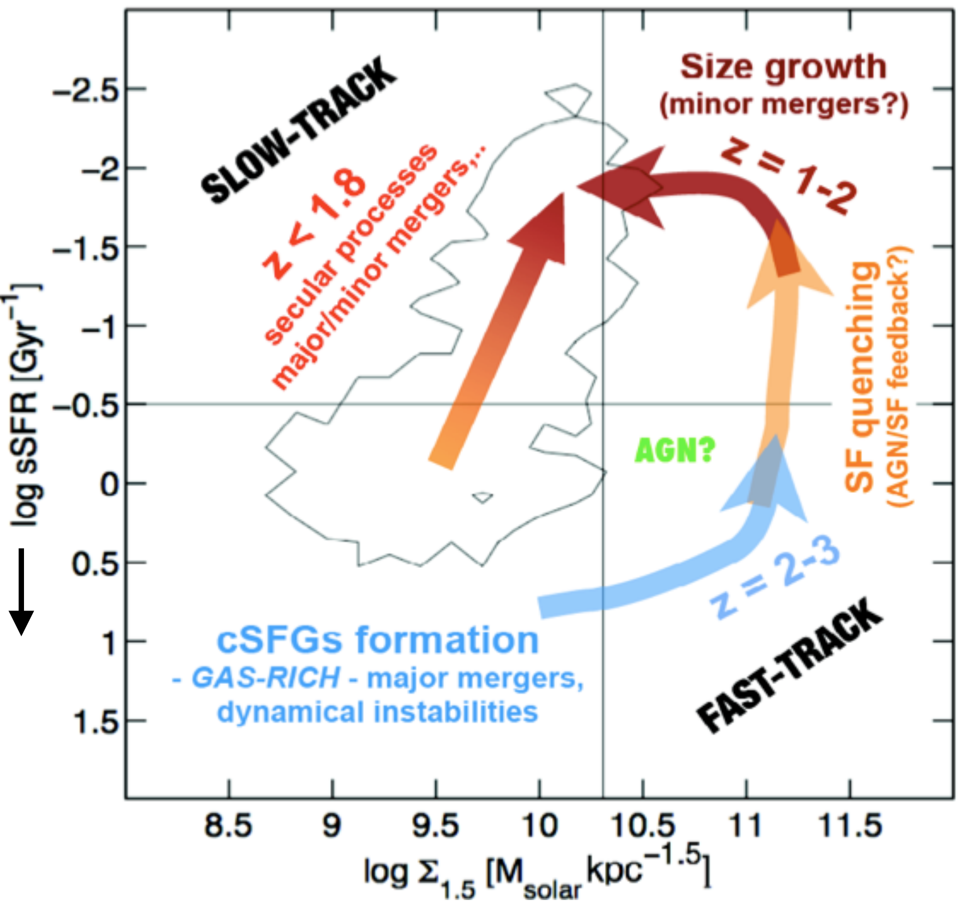
COMPACTION –>

QUENCHING –>

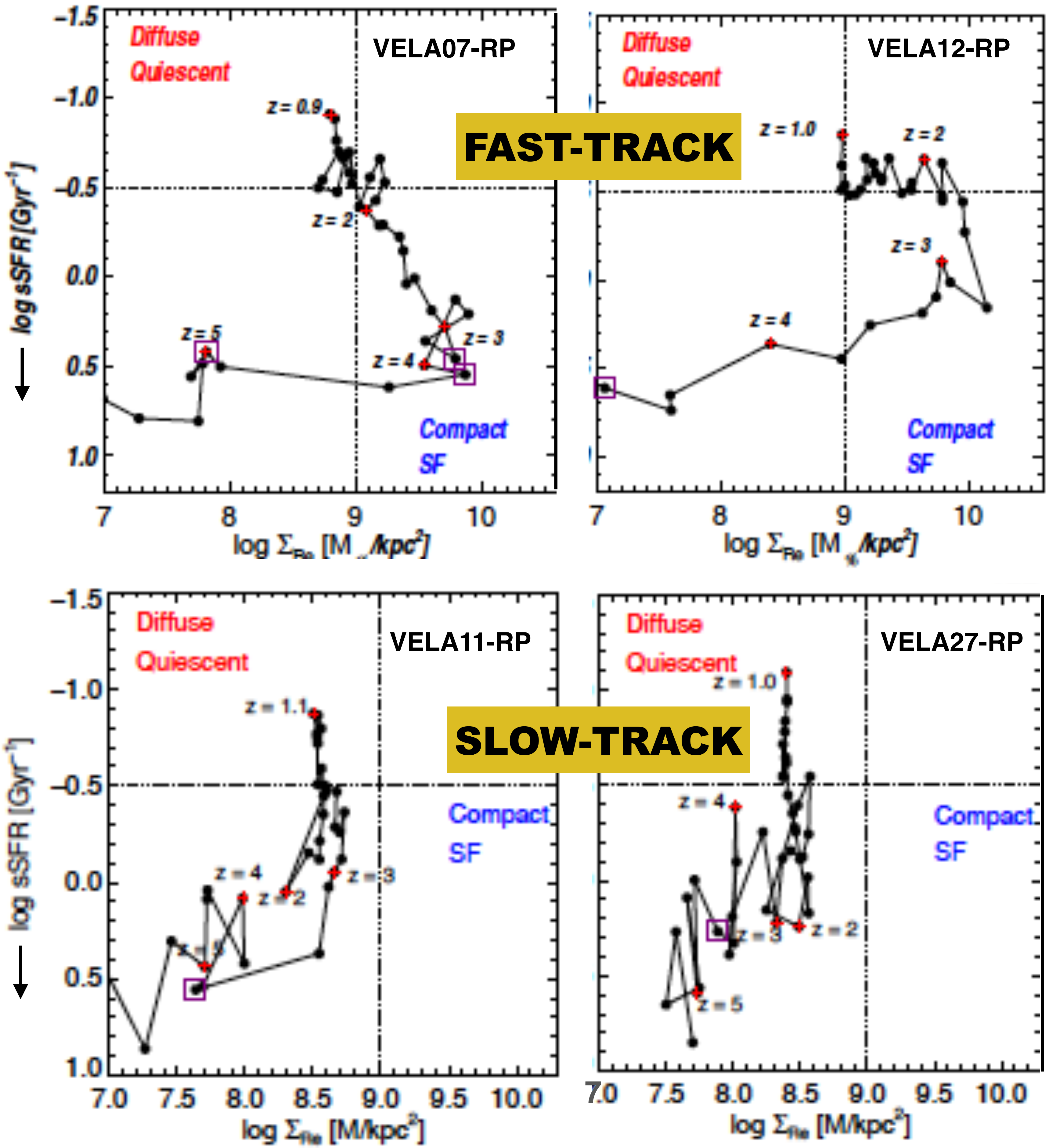


Ceverino+ RP simulations analyzed by Zolotov, Dekel, Tweed, Mandelker, Ceverino, & Primack MNRAS 2015

Barro+ (CANDELS) 2013



COMPACTION ⟶

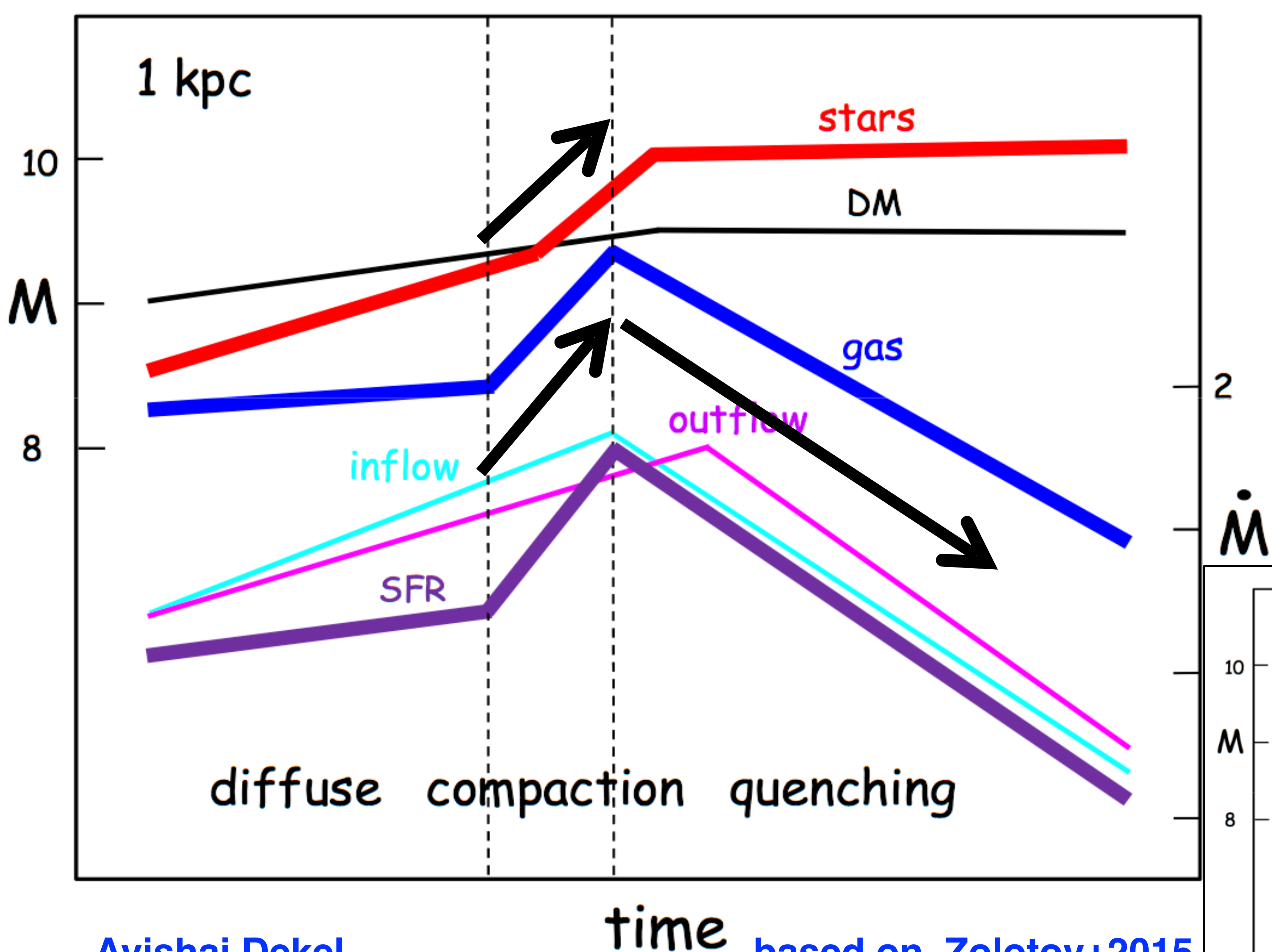


minor merger

major merger

Zolotov+2015

Compaction and Quenching in the Inner 1 kpc

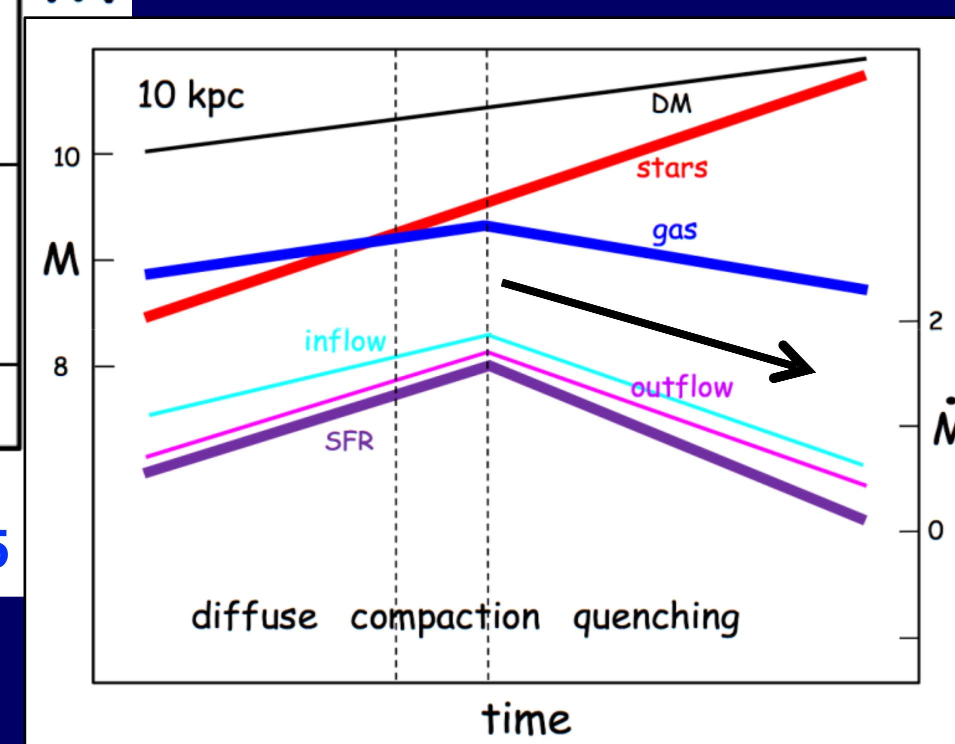


Avishai Dekel

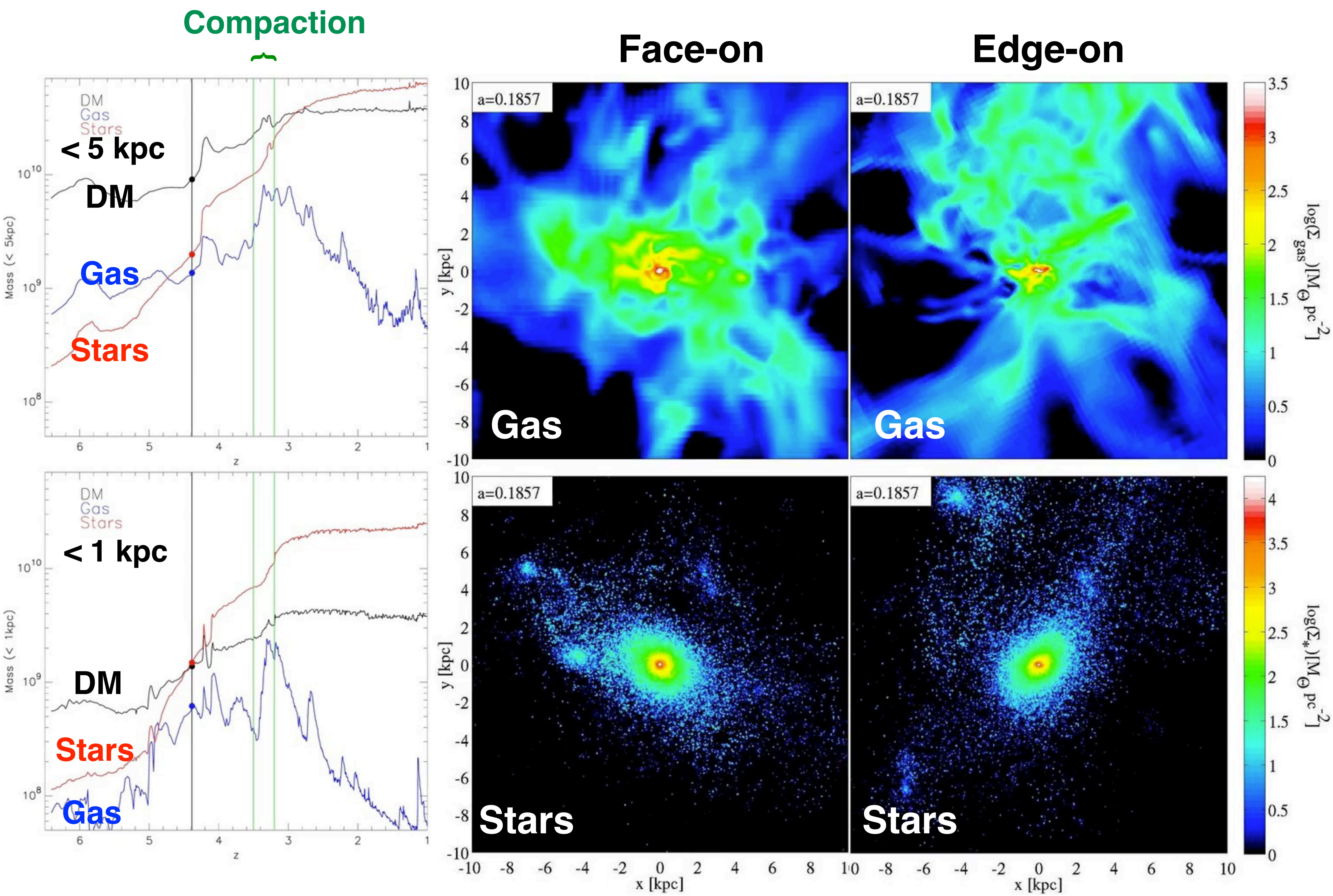
based on Zolotov+2015

inner 1 kpc

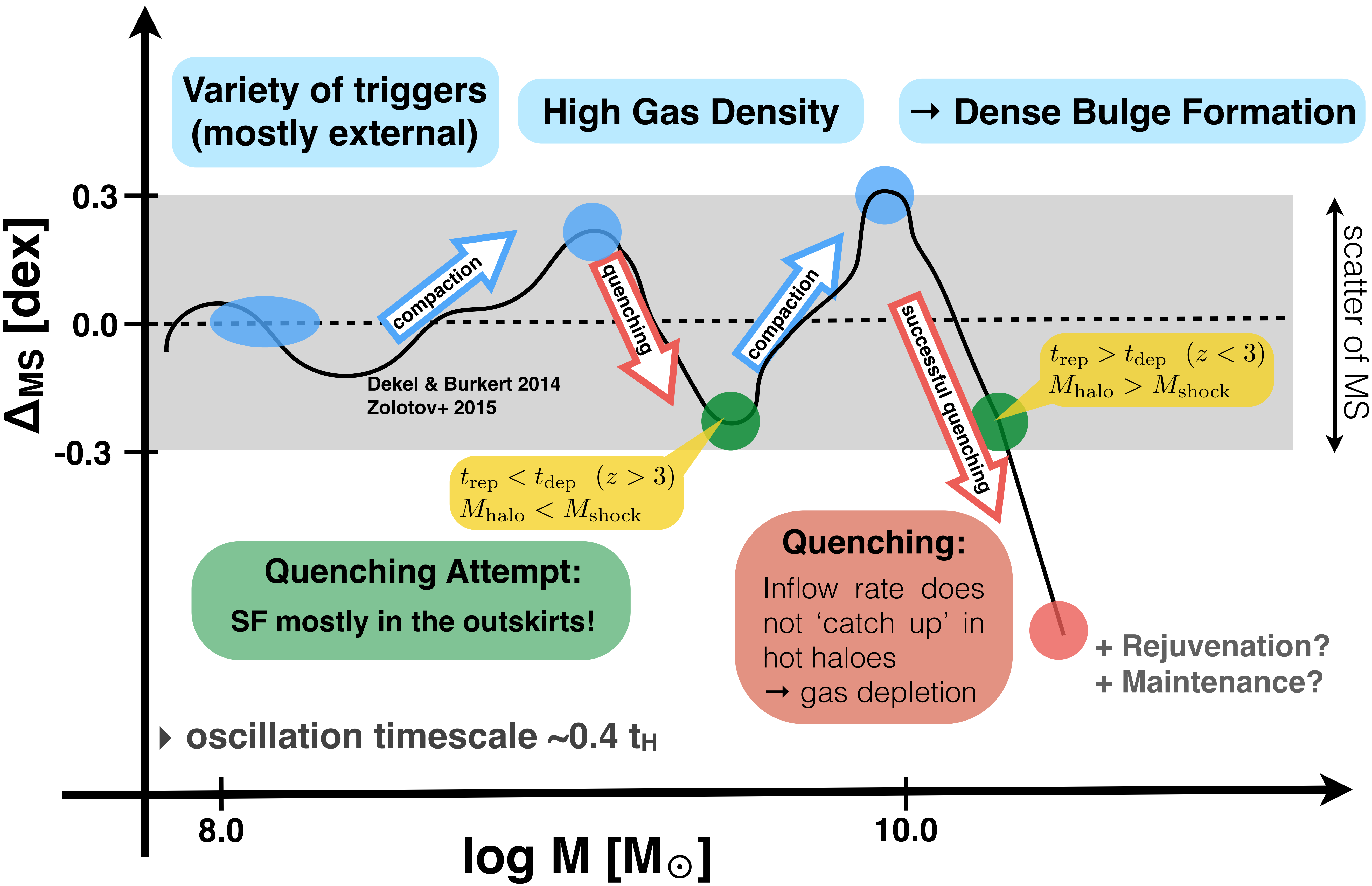
Inner 10 kpc



Gen 3 VELA07-RP Animations z = 4.4 to 2.3



Evolution of Galaxies about the Star-Forming Main Sequence



“Face Recognition for Galaxies”

Deep Learning Identifies High-z Galaxies in a Central Blue Nugget Phase in a Characteristic Mass Range

Marc Huertas-Company, Joel Primack, Avishai Dekel, David Koo, Sharon Lapiner, Daniel Ceverino, Raymond Simons, Greg Snyder, et al. **ApJ 2018**

Cosmological zoom-in simulations model how individual galaxies evolve through the interaction of atomic matter, dark matter, and dark energy

Our VELA galaxy simulations agree with HST CANDELS observations that most galaxies start prolate, becoming spheroids or disks after compaction events

A deep learning code was trained with VELA galaxy images plus metadata describing whether they are pre-compaction, compaction, or post-compaction

The trained deep learning code was able to identify the compaction and post-compaction phases in CANDELized images

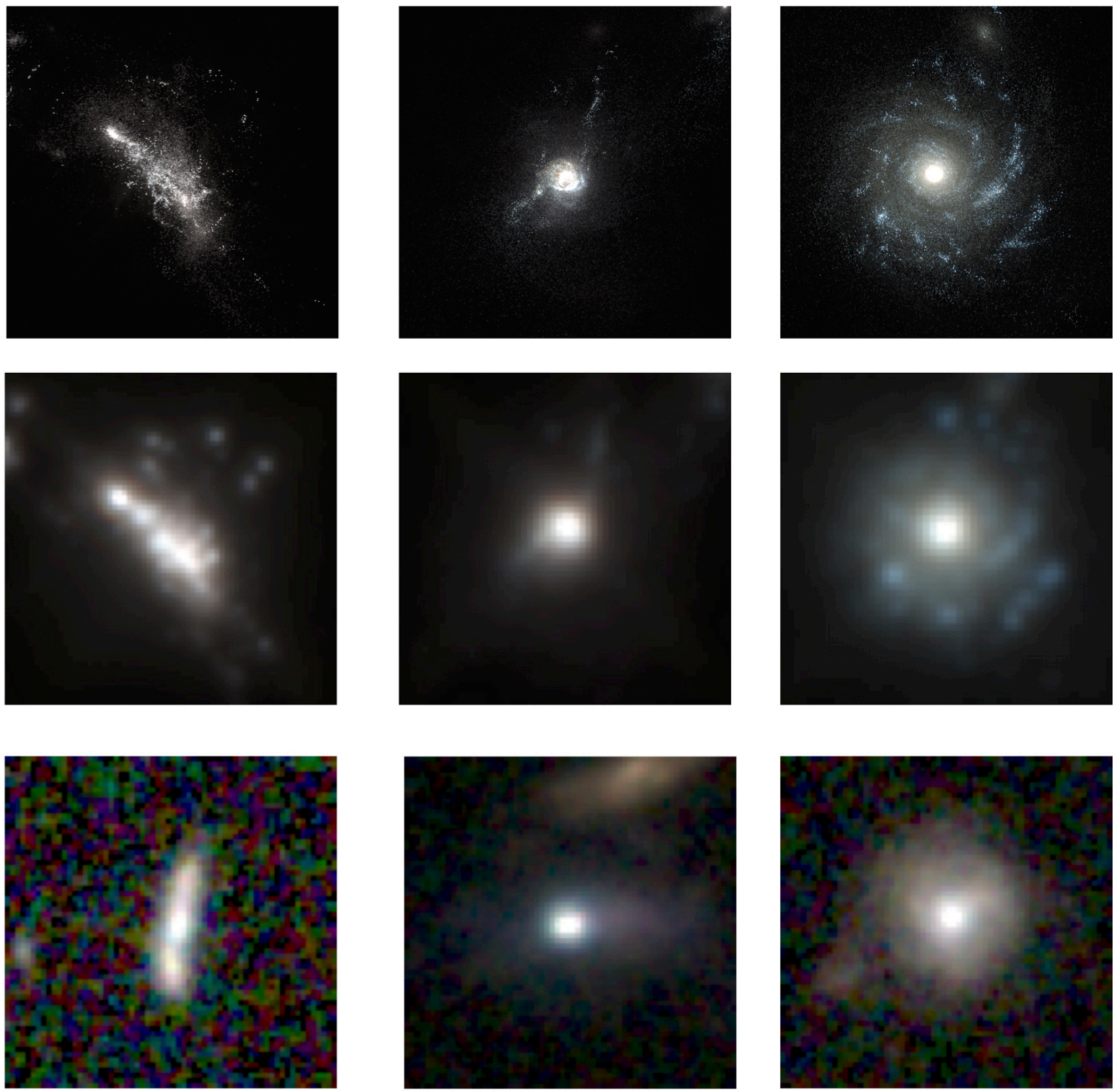
The trained deep learning code was also able to identify these phases in real HST CANDELS observations, finding that compaction occurred for stellar mass $10^{9.5\ -10.3}$ M_{sun}, as in the simulations

James Webb Space Telescope will allow us to do even better

“Face Recognition for Galaxies”

Huertas-Company, Primack, et al. ApJ 2018

Pre-BN	BN	Post-BN	
Pre-Blue-Nugget-Stage	Blue-Nugget-Stage	Post-Blue-Nugget-Stage	

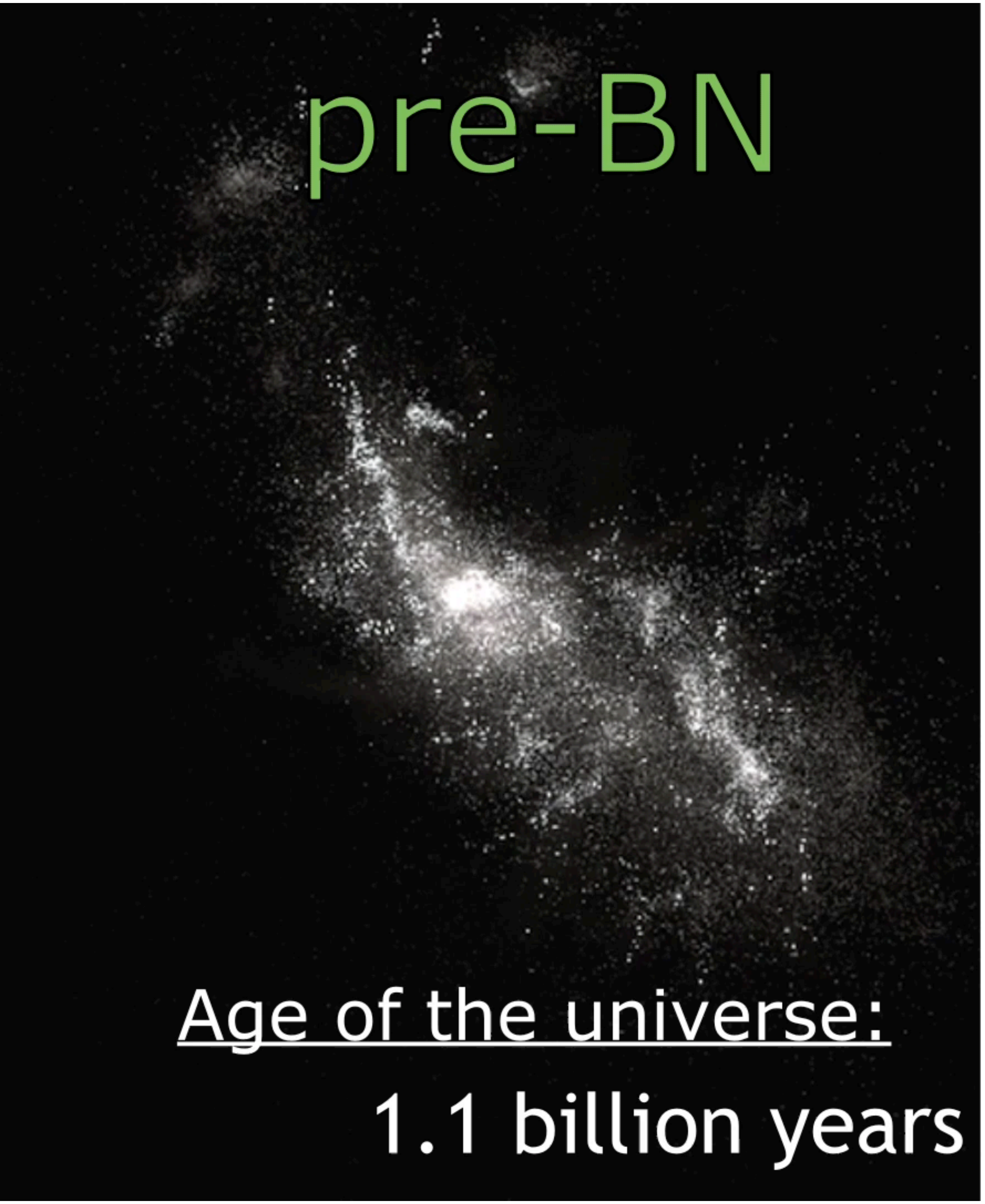


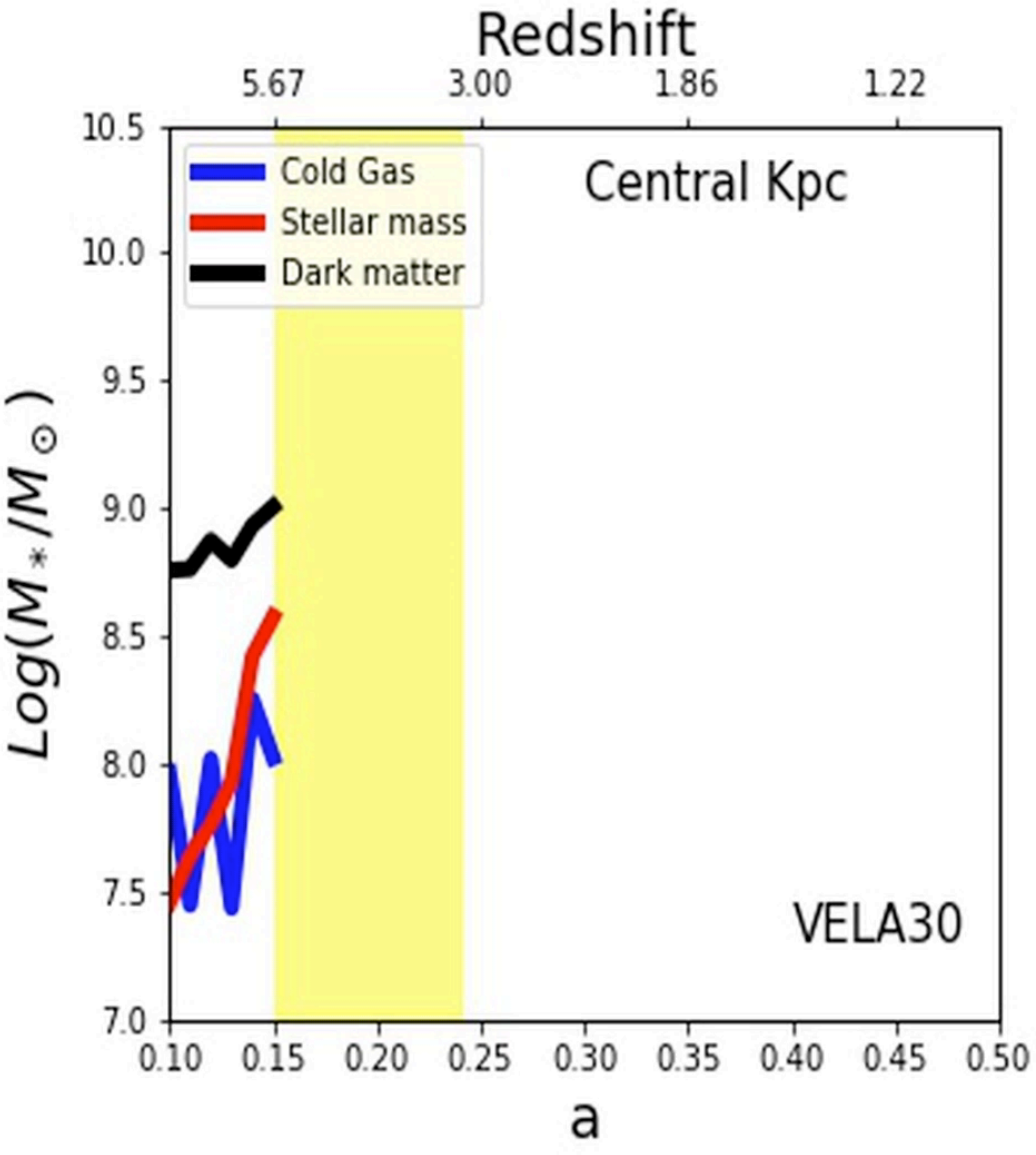
VELA High-Res Sunrise Images

VELA HST-Res Sunrise Images

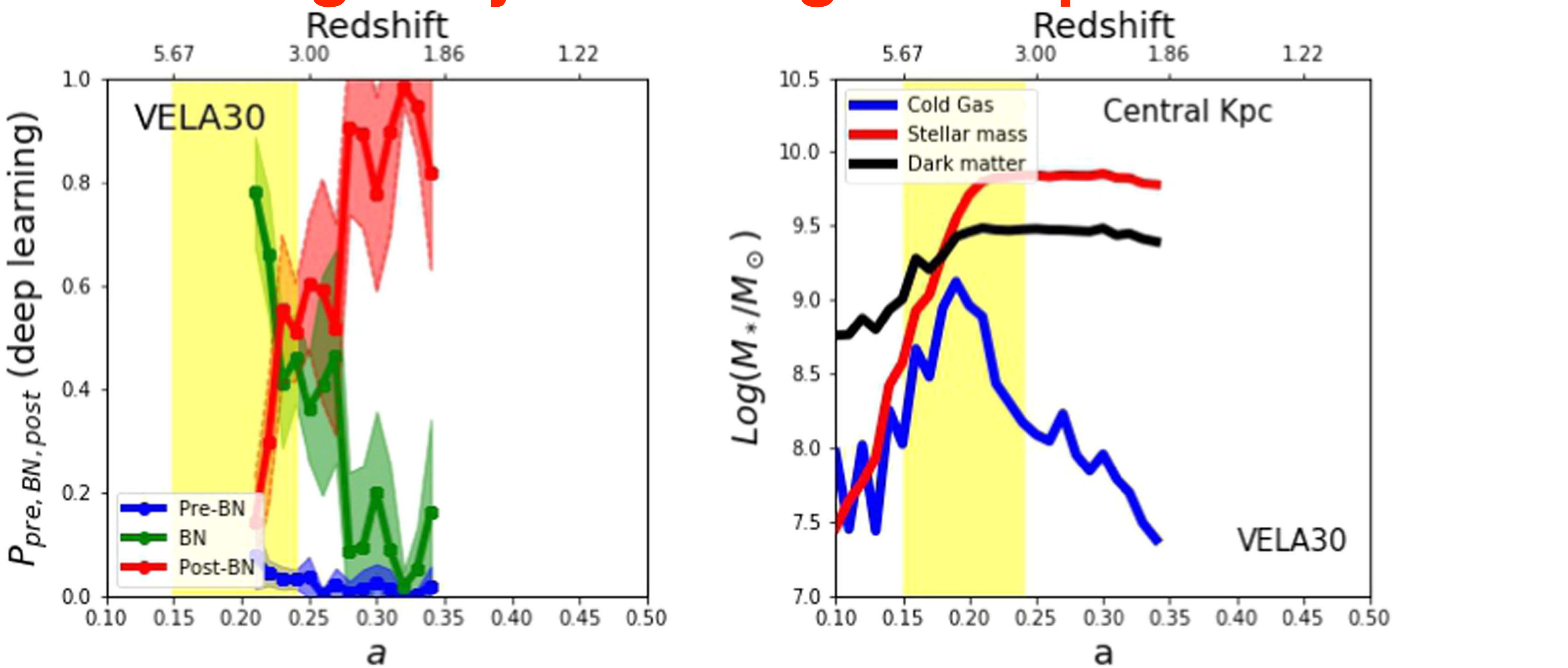
CANDELS HST Images

"Face Recognition for Galaxies"

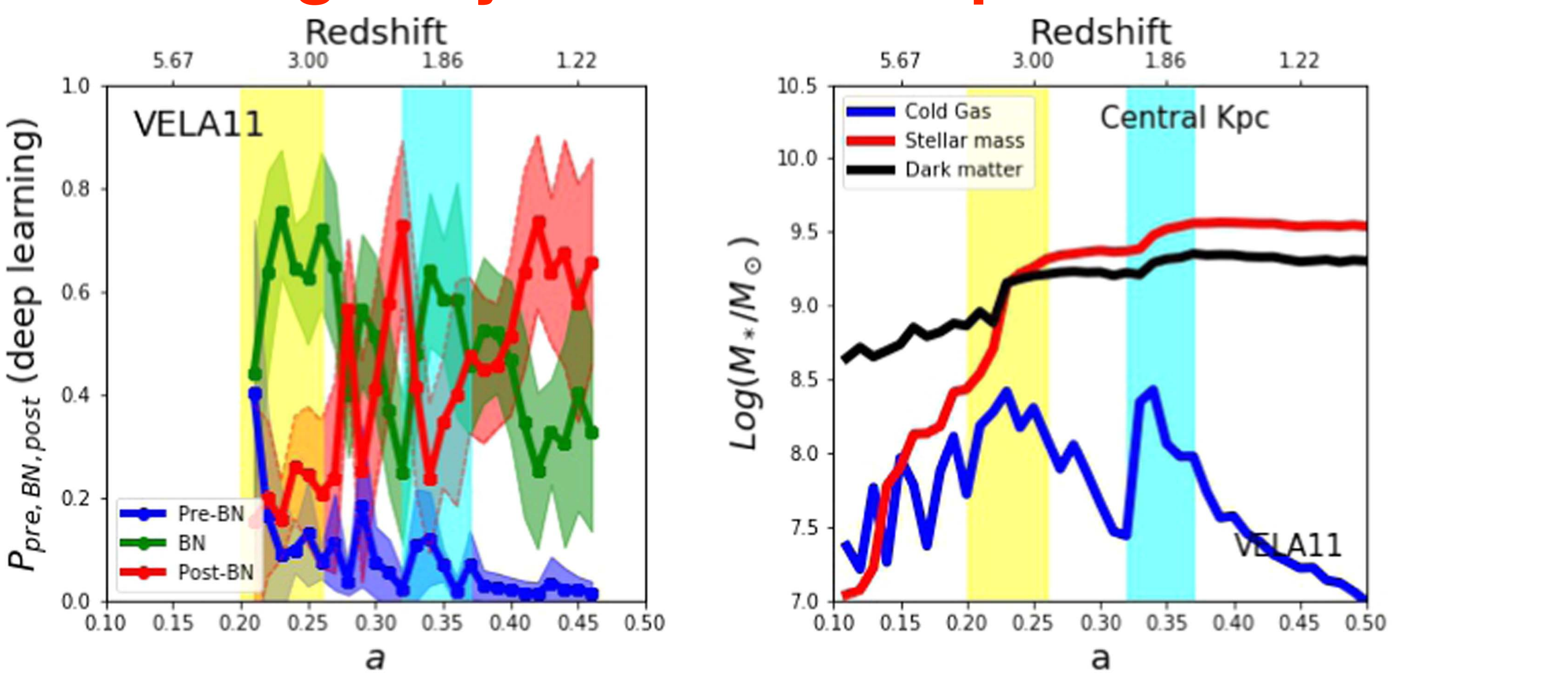




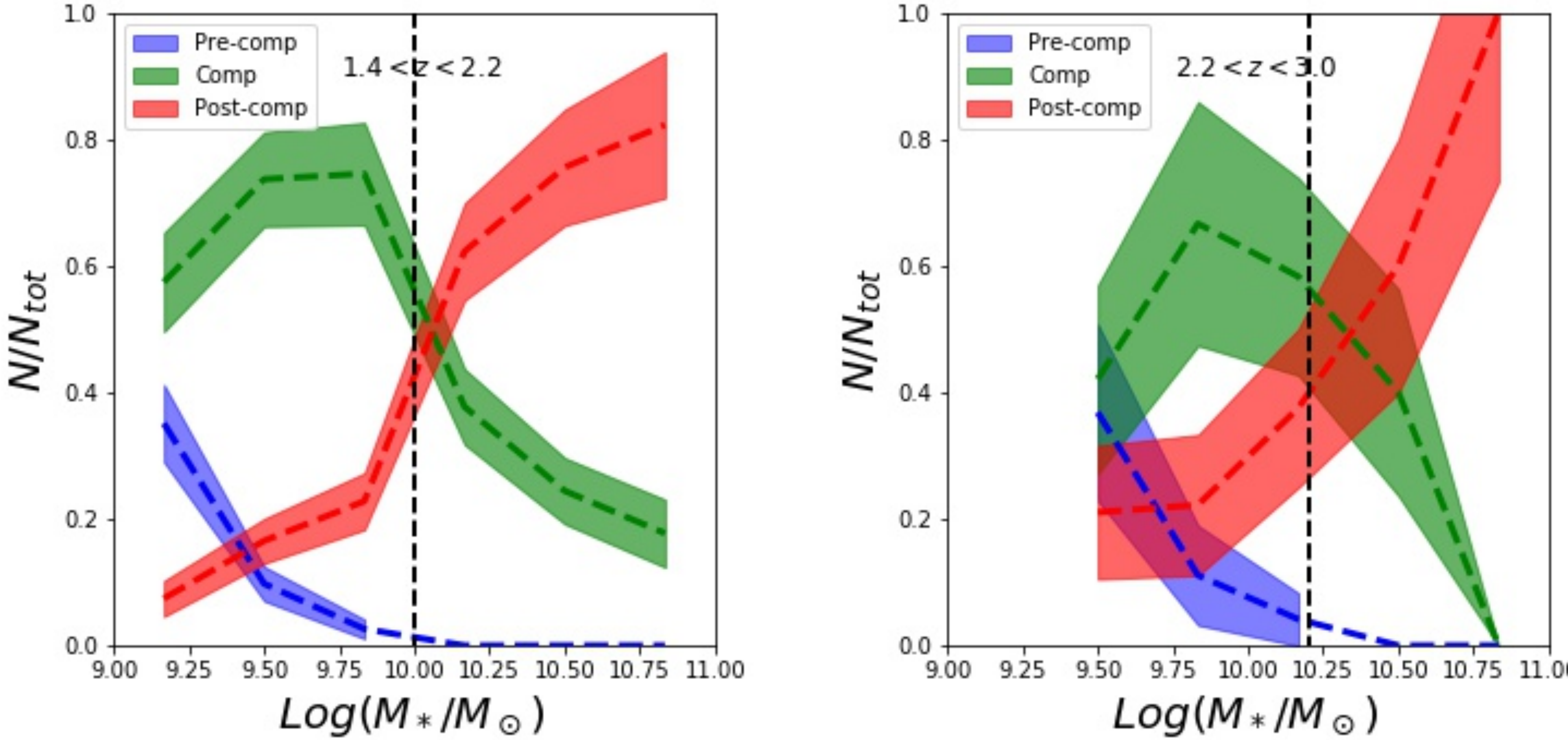
Simulated galaxy with single compaction event



Simulated galaxy with two compaction events

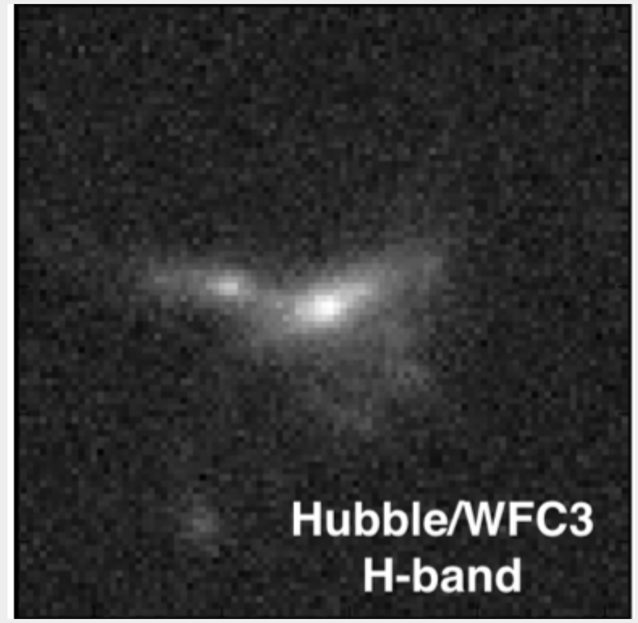


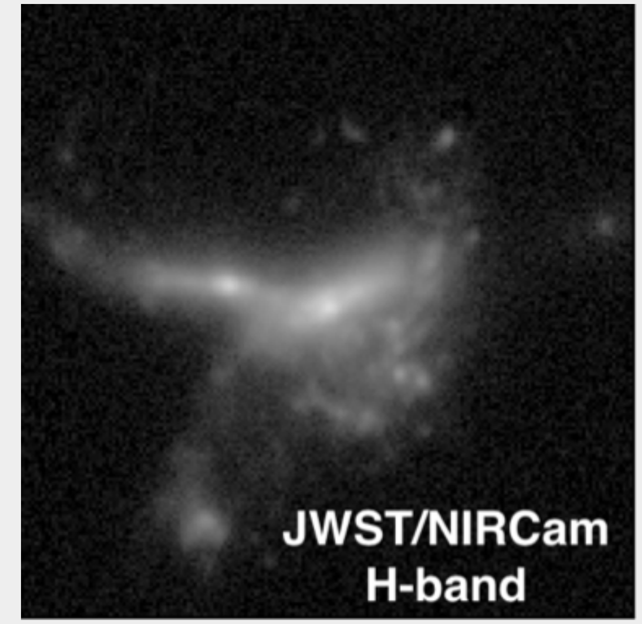
Applying the Trained Deep Learning Code to CANDELS Galaxies



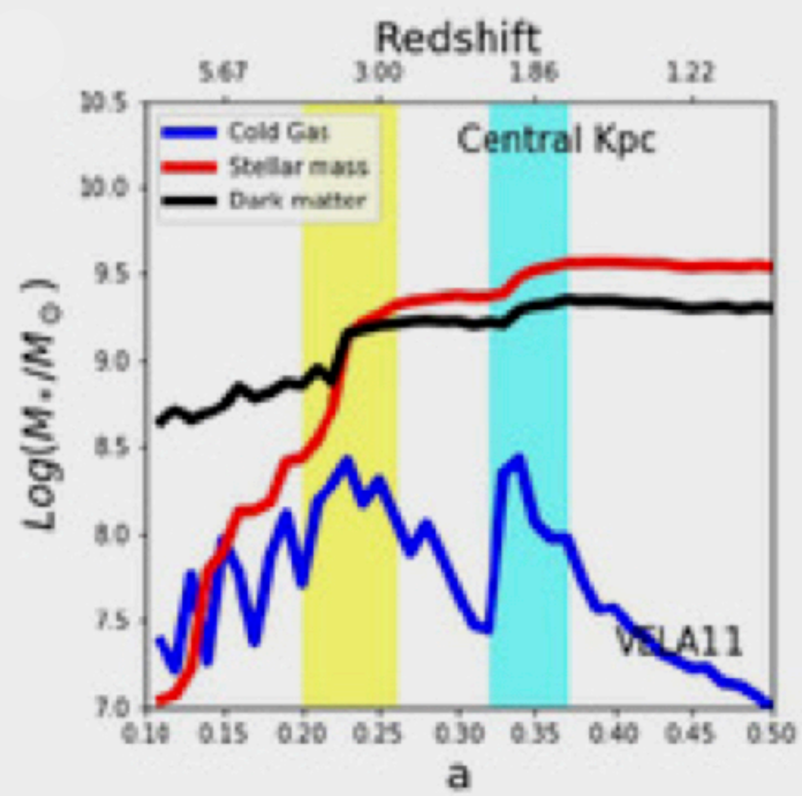
Stellar mass distributions of HST CANDELS galaxies in pre-compaction, compaction, and post-compaction phases in different redshift bins. The DL code correctly shows the temporal evolution. Galaxies in the compaction phase typically peak at stellar masses $10^{9.5\text{–}10}$ M_{sun} at all redshifts, as in the VELA simulations.

Convolutional Neural Net (Deep Learning) Galaxy Evolution Phase Determination: HST vs. JWST

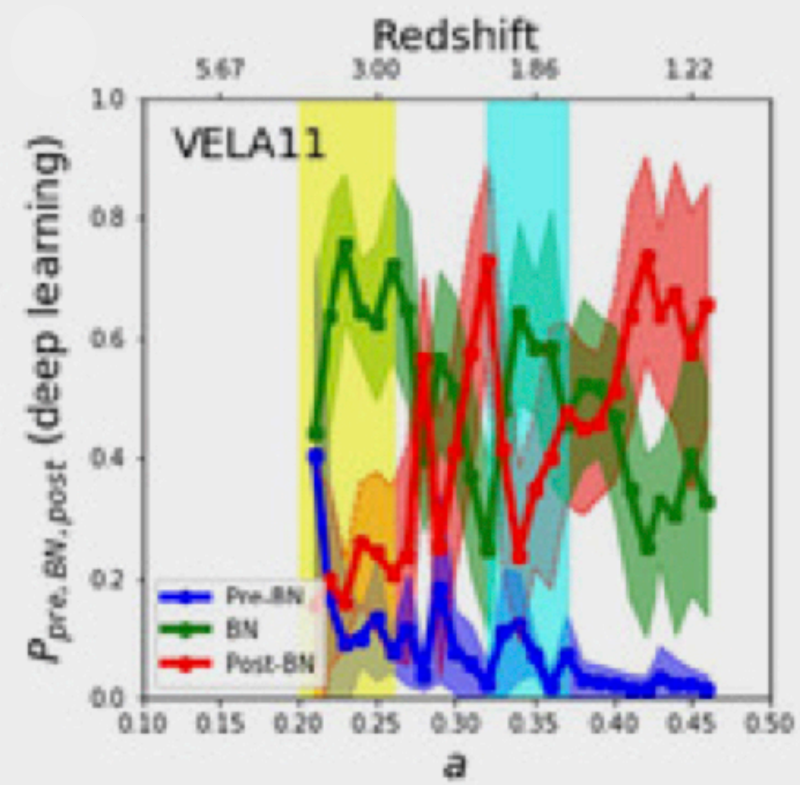




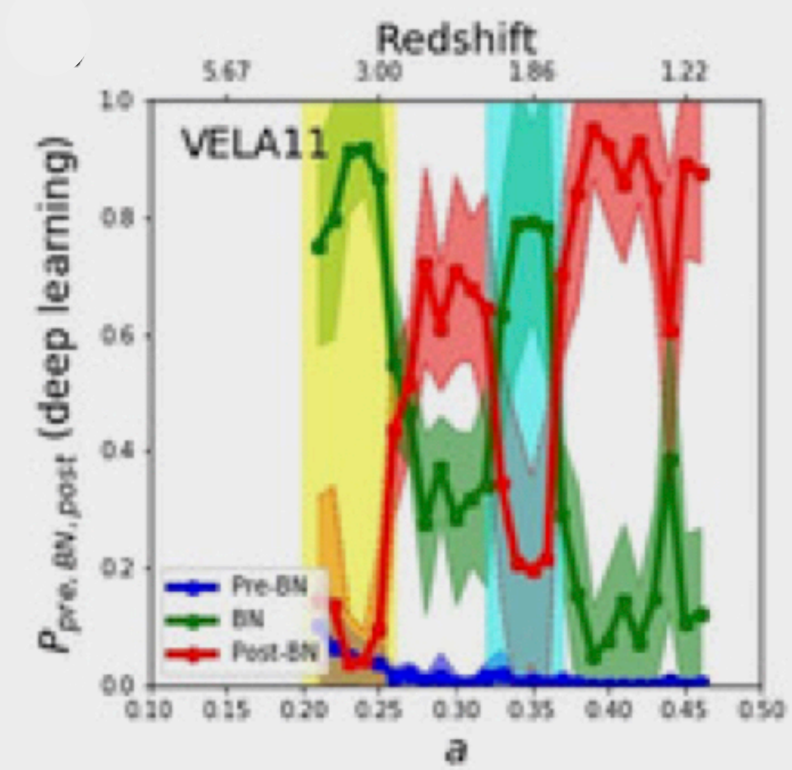
Simulation Metadata



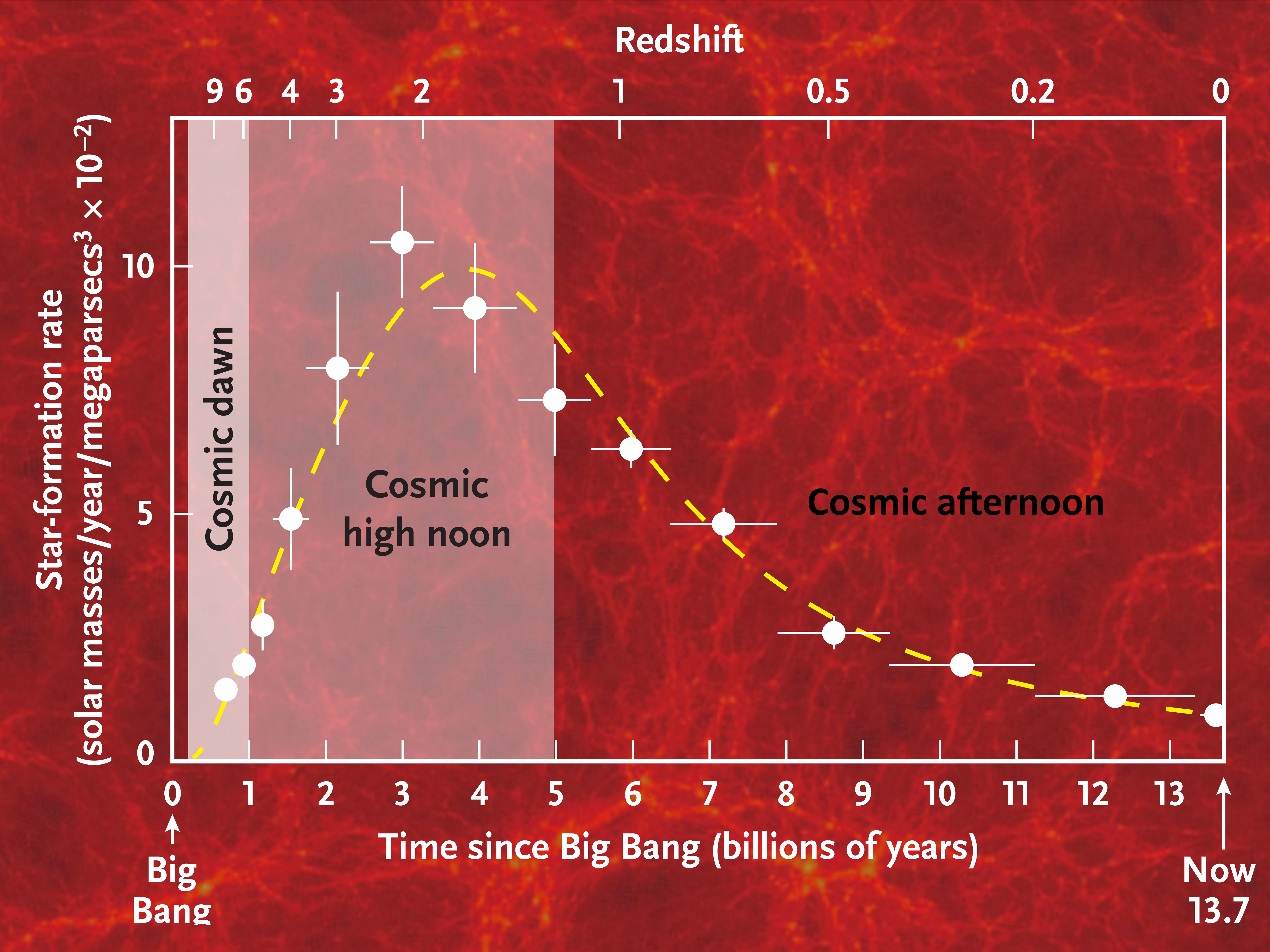
CNN Trained with HST-like Images (3 NIR filters)



CNN Trained with JWST-like Images (3 NIR filters)



Deep learning does much better with JWST image

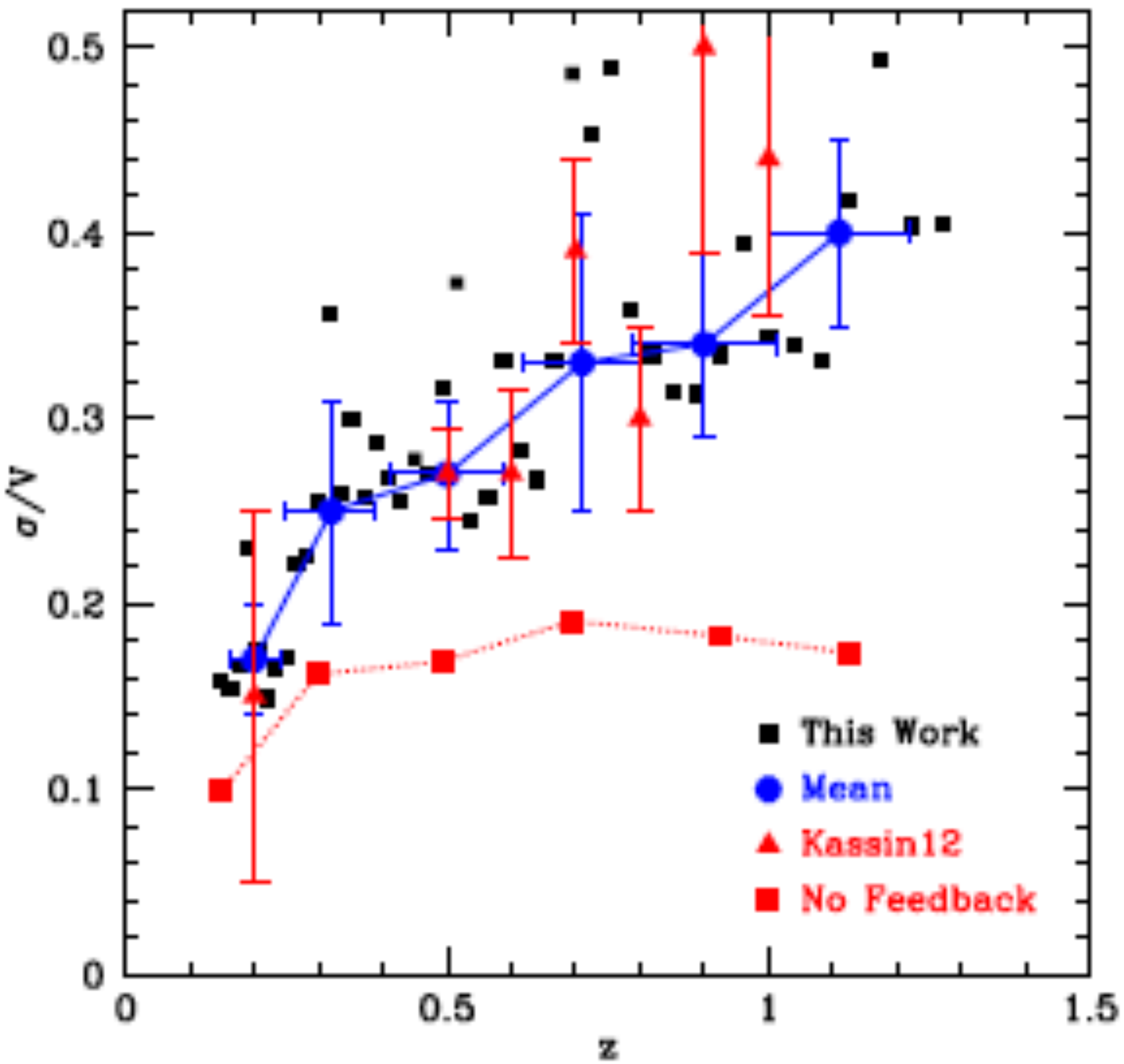


Redshift
9
6
4
3
2
1
0.5
0.2
0
Star-formation rate
(solar masses/year/megaparsecs³ × 10⁻²)
10
5
0
Cosmic dawn
Cosmic
high noon
Cosmic afternoon
0
1
2
3
4
5
6
7
8
9
10
11
12
13
Time since Big Bang (billions of years)
Big
Bang
Now
13.7

Low redshift (z < 1) galaxies are different

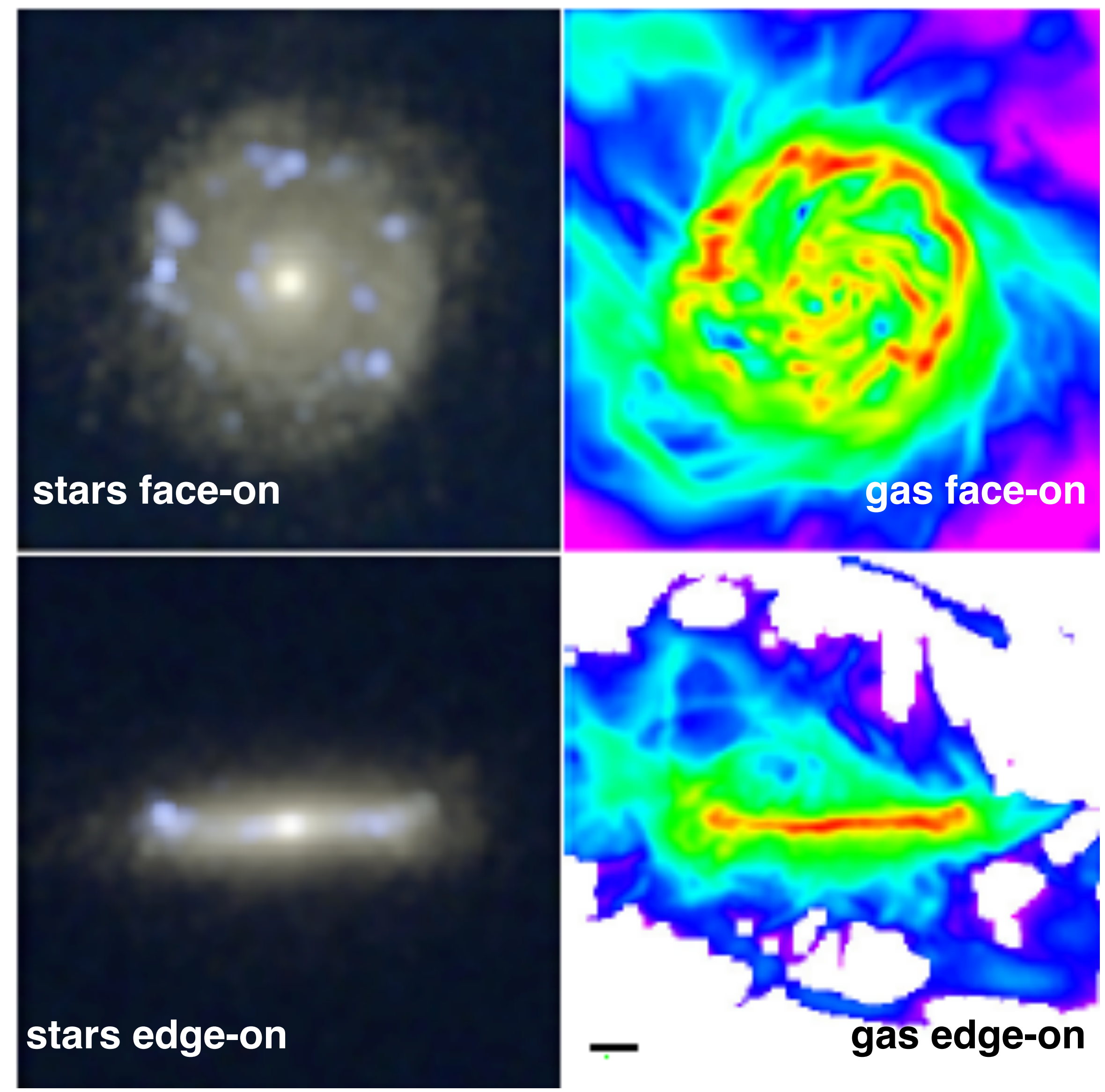
Formation and Settling of a Disc Galaxy During the Last 8 Billion Years in a Cosmological Simulation

Daniel Ceverino, Joel Primack, Avishai Dekel, Susan A. Kassin MNRAS 2017



Disk Settling: Hα σ/V declines as observed in similar-mass galaxies (M_{halo} = 1.7x10^{11}$M_\odot$)

This is one of the AGORA initial conditions.



The simulation at $z = 0.1$ produces a thin disk, much like observed galaxies of this mass

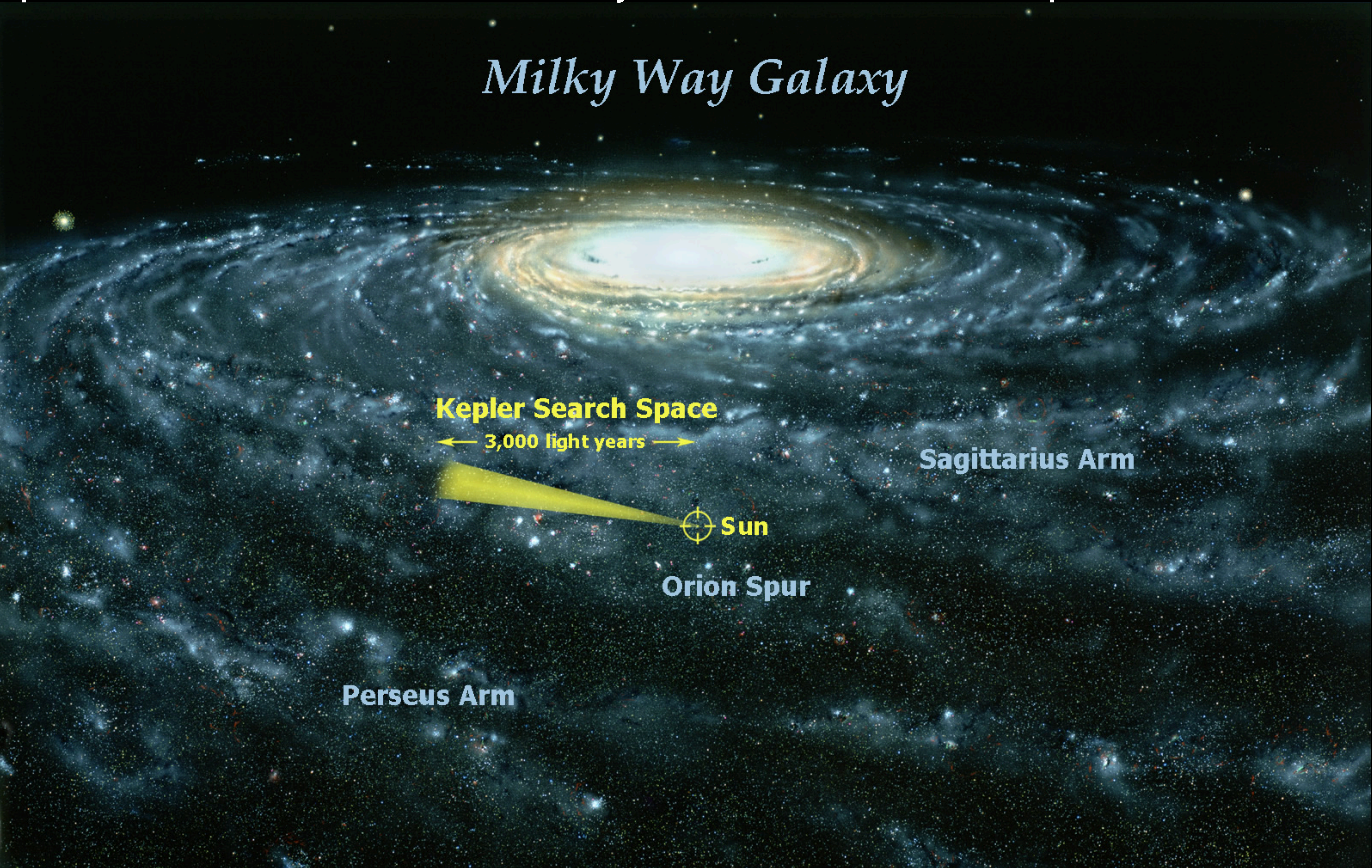
Our Current Understanding of the Physical Universe

COSMOS

GALAXIES

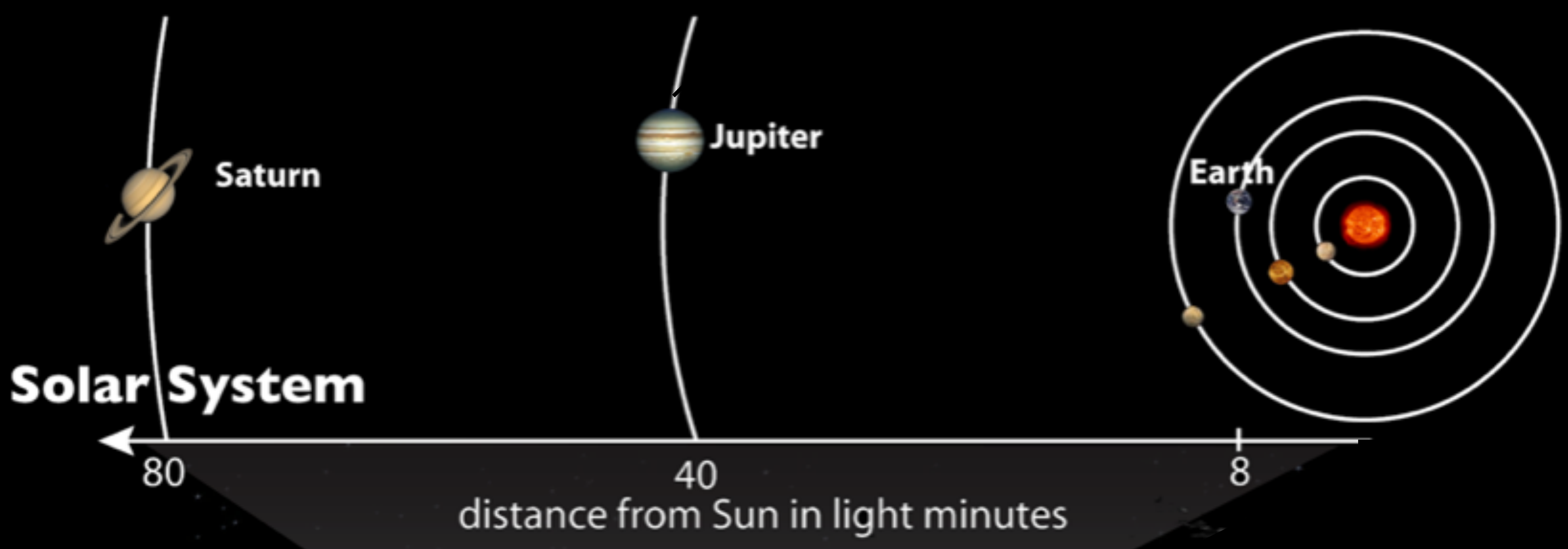
PLANETS

We have now discovered about 4000 planetary systems, mainly using star radial velocities from ground-based telescopes and planet-star transits observed by NASA's satellites Kepler and TESS.



We have now discovered about 4000 planetary systems, mainly from ground-based star radial velocity measurements and planet-star transits observed by NASA's Kepler and TESS satellites.

We used to think that our system is typical, with rocky planets near our star and gas giants farther away.



There may be **galactic habitable zones** — not too close to galaxy centers where there are frequent supernovae, nor too far where metals may be too rare to form rocky planets.

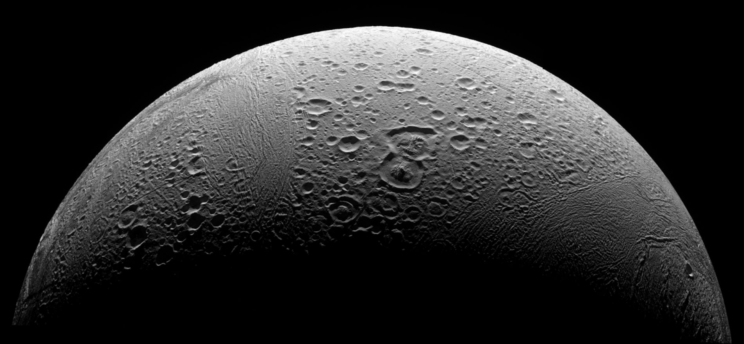
Of the ~ 4000 planetary systems astronomers have discovered, there are none like ours, with all the planets widely spaced in nearly circular orbits. Most planetary systems are much smaller.

The most common type of planet seems to be 2 to 6 times Earth's mass, a "**super-Earth**". No such planet exists in our Solar System.

Some planets are in the **habitable zone around their stars** in which water would be in liquid form, but most of these planets are probably not hospitable to advanced forms of life. For one thing, they might not have an optimal abundance of the long-lived radioactive elements thorium and uranium to power a magnetic dynamo and plate tectonics. Too much Th and U would result in a lava world with frequent flood vulcanism, which caused the greatest mass extinction events on Earth. **Our living Earth may be a rare "Goldilocks" planet.**

There is evidence that there was a "Late Great Bombardment" of the inner planets about 750 million years after the solar system formed. It seems likely that there was a gigantic rearrangement of the outer solar system that caused many comets to hit the inner planets about 3.8 billion years ago. Primitive microbial life got started on Earth soon after the Late Great Bombardment ended — so primitive life may be very common in the universe, at least on planets with liquid water. There are also moons in the outer solar system with liquid water under their icy surfaces, including Jupiter's moon Europa and Saturn's moon Enceladus.

Enceladus



Geysers on Enceladus
from NASA's Cassini spacecraft

But it took another 2 billion years for complex eukaryotic cells to develop on Earth, and complex multicellular creatures only evolved about a ½ billion years ago. Intelligent life and science only arose once on Earth — so it may be very rare.

New space observatories may make it possible for us to detect the effects of life on distant planets, for example by atmospheric composition. We will also keep searching for messages, and the huge Square Kilometer Array of radio telescopes being built in Australia and South Africa will help.

Some Concluding Thoughts

Without Dark Matter We Wouldn't Exist

With only the ordinary matter, the universe would be a low-density featureless soup

Dark matter started to form structures very early

Galaxies formed within bound "halos" of dark matter

Stars formed within galaxies, and stars made elements beyond hydrogen and helium: carbon, oxygen, …

Rocky planets formed from these heavier elements

Life began and evolved on one such planet

Dark matter is our ancestor and our friend!

Science Is Much Stranger Than Fiction

Before the discovery that most of the density of the universe is invisible, no one imagined this

What else remains to be discovered?