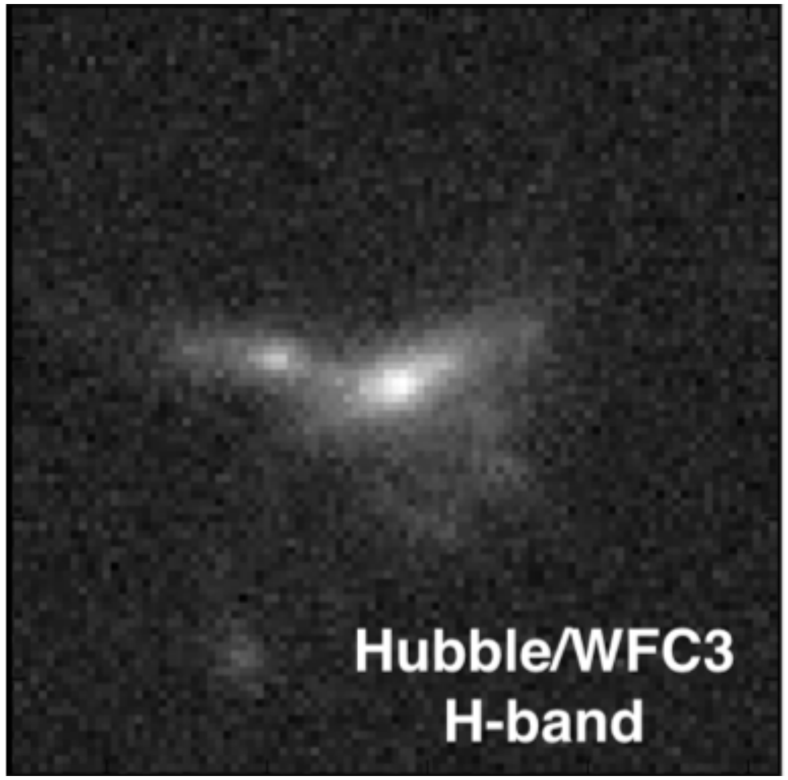
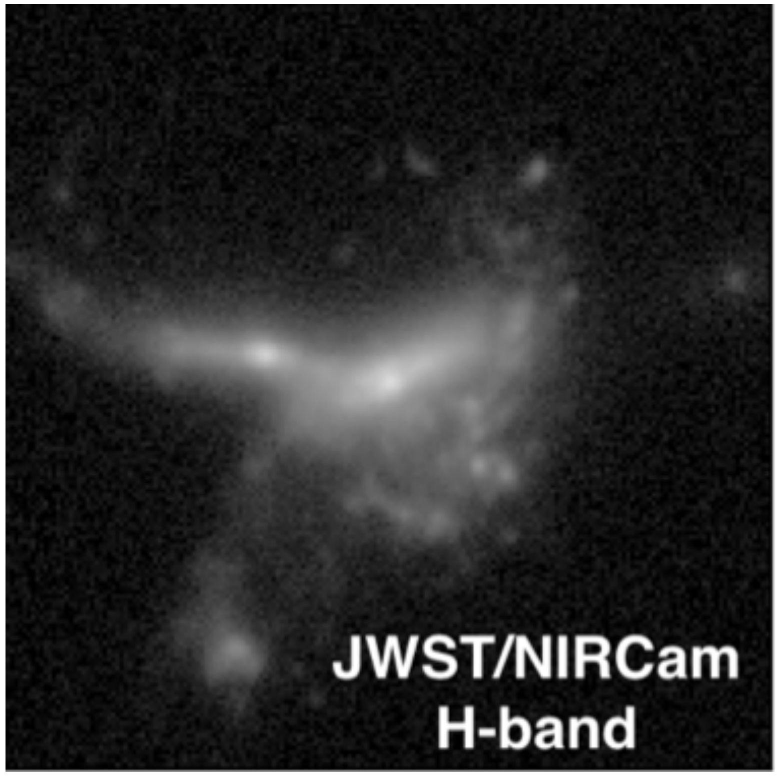
Research Projects on Galaxy Formation & Evolution

Joel Primack

James Webb Space Telescope will see the same simulated galaxies much more clearly than Hubble Space Telescope can!





Student Projects

Analyze simulated galaxies in 3D to measure shapes and features
Make and/or analyze realistic images and spectra of simulated galaxies
Compare simulated galaxies with HST and JWST images and spectra

Available Simulations and Mock Images

VELA-3 & VELA-6 high resolution simulations (Google: VELA MAST)
NewHorizon & Charlotte’sWeb volume simulations
AGORA galaxy simulation code comparison project
FIRE-2 high-resolution simulations

Key Collaborators

UCSC Faculty: Sandra Faber and David Koo, Doug Hellinger
UCSC Physics Grad Students: James Kakos, Clayton Strawn, Conghao Zhou
Other Faculty: Avishai Dekel & Nir Mandelker, Hebrew University & UCSC
Marc Huertas-Company, Spain and Paris Observatory & UCSC
Aldo Rodriguez-Puebla, UNAM Mexico City

Recent Relevant Online Seminars by Joel Primack

Golden Webinar in Astrophysics https://www.youtube.com/watch?v=0_uSahQ3gWo

CCA, NY https://www.simonsfoundation.org/event/cca-colloquium-joel-primack/

Available Simulations and Mock Images

VELA-3 HST, JWST Images https://archive.stsci.edu/prepds/vela/

VELA-3 & 6 HST, JWST Images (still private)

NewHorizon & Charlotte'sWeb volume simulations

AGORA galaxy simulation code comparison project

FIRE-2 http://www.tapir.caltech.edu/~phopkins/Site/animations/gallery-of-simulated-galaxi/
https://wetzel.ucdavis.edu/public-data-release-of-the-fire-2-simulations/

Software to Analyze Galaxy Images

GALFIT https://users.obs.carnegiescience.edu/peng/work/galfit/galfit.html

Some Relevant References

Popular article https://www.americanscientist.org/article/why-do-galaxies-start-out-as-cosmic-pickles

My group's VELA galaxy simulations compared with HST observations

Formation of elongated galaxies with low masses at high redshift

Compaction and quenching of high-z galaxies in cosmological simulations: blue and red nuggets

Evolution of galaxy shapes from prolate to oblate through compaction events

Giant clumps in simulated high- z Galaxies: properties, evolution and dependence on feedback

The evolution of galaxy shapes in CANDELS: from prolate to discy

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

Stellar masses of giant clumps in CANDELS and simulated galaxies using machine learning

The nature of giant clumps in high-z discs: a deep-learning comparison of simulations and observations

High resolution VELA simulations mock images https://archive.stsci.edu/prepds/vela/

NewHorizon & Charlotte'sWeb volume simulations

The HORIZON-AGN simulation: morphological diversity of galaxies promoted by AGN feedback

Introducing the NEWHORIZON simulation: Galaxy properties with resolved internal dynamics across cosmic time

AGORA galaxy simulation code comparison project

The AGORA High-resolution Galaxy Simulations Comparison Project

The AGORA High-resolution Galaxy Simulations Comparison Project. II. Isolated Disk Test

The AGORA High-resolution Galaxy Simulations Comparison Project. III. Cosmological Zoom-in Simulation of a Milky Way-mass Halo

FIRE-2 high-resolution simulations

Public data release of the FIRE-2 cosmological zoom-in simulations of galaxy formation

GizmoAnalysis: Read and analyze Gizmo simulations

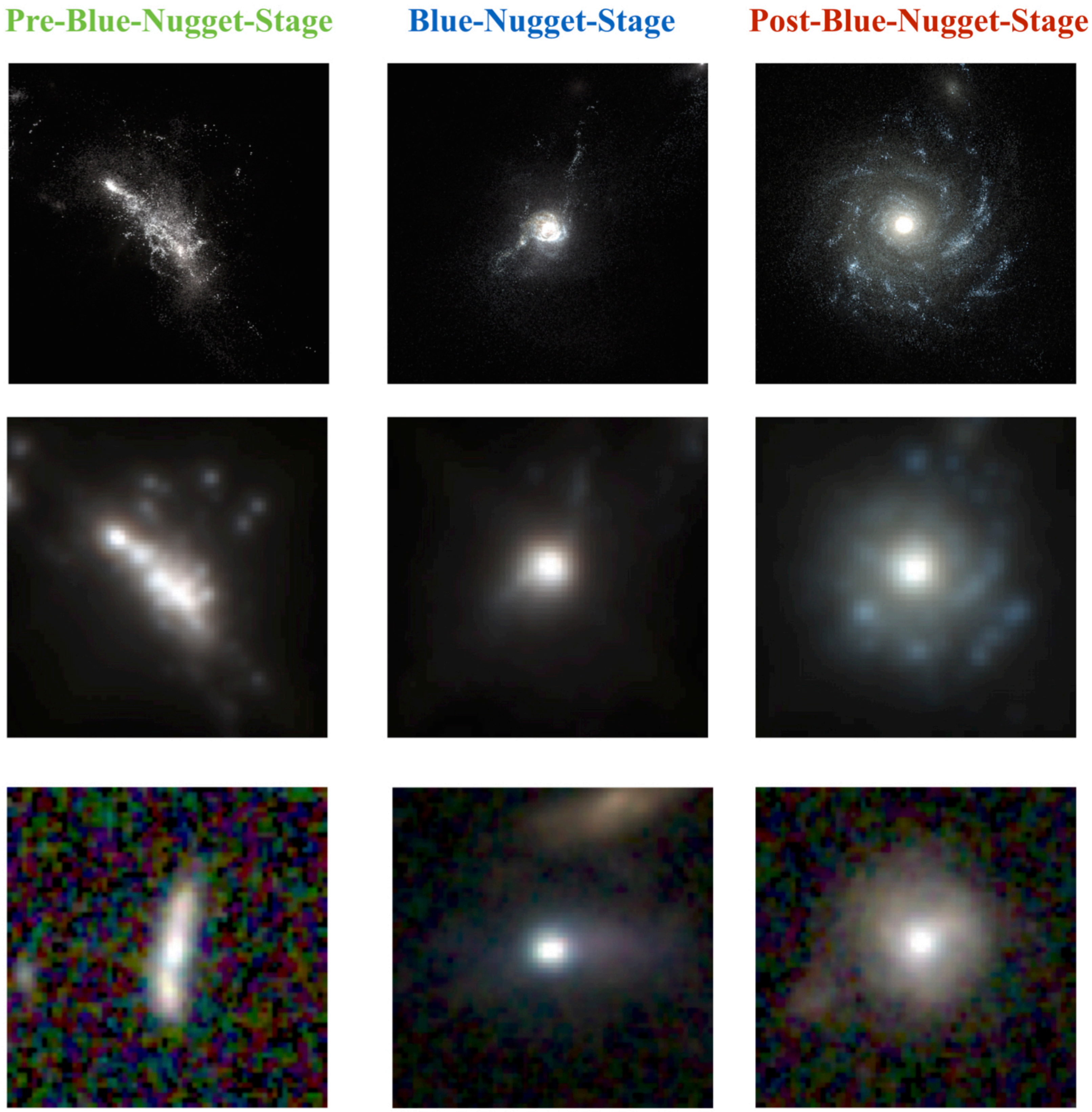
3D Analysis of Simulations https://yt-project.org/

GALAXY FORMATION

“Face Recognition for Galaxies”

Huertas-Company, Primack, et al. ApJ 2018

Pre-BN **BN** **Post-BN**



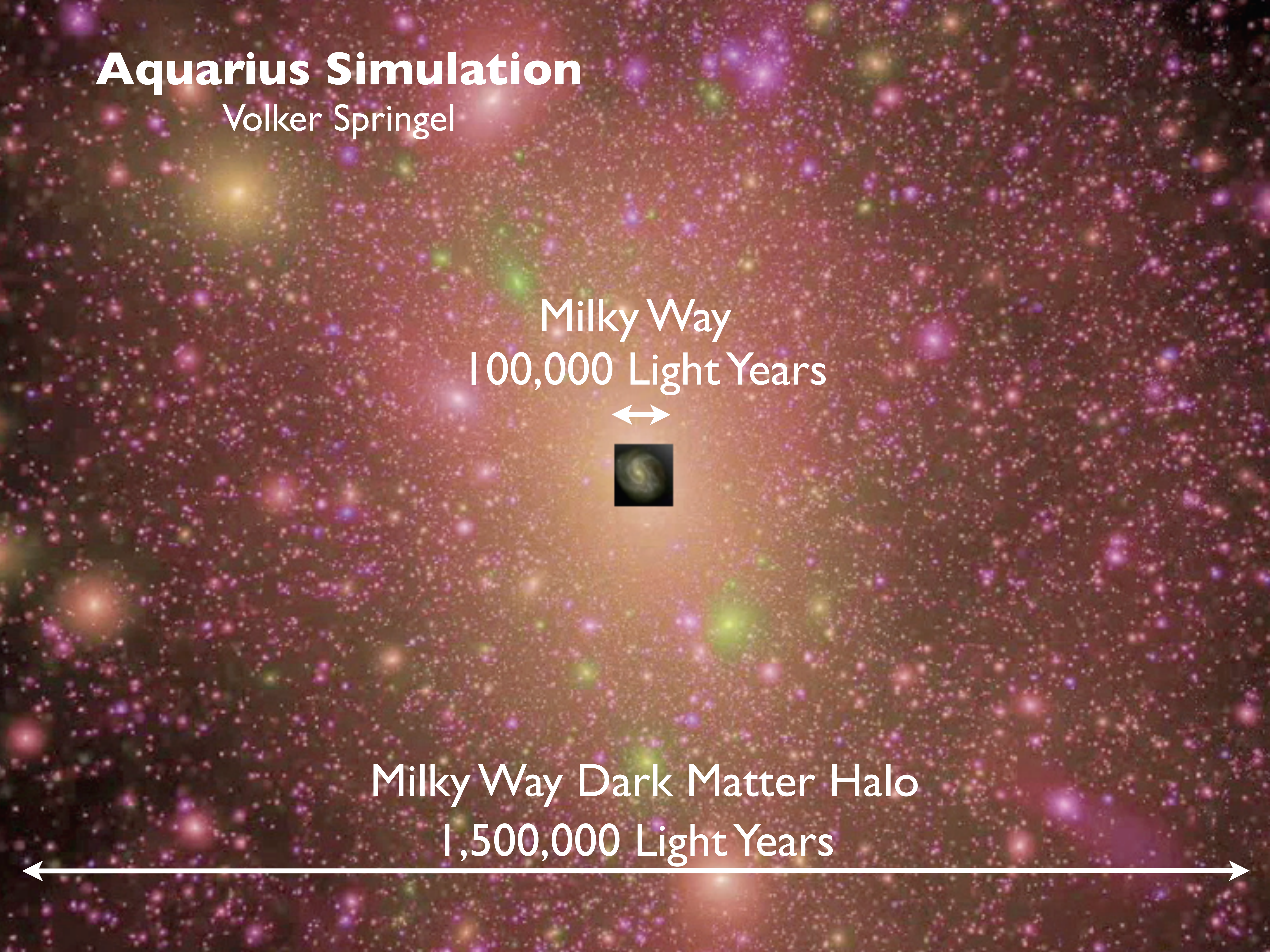
VELA High-Res Sunrise Images

VELA HST-Res Sunrise Images

CANDELS HST Images

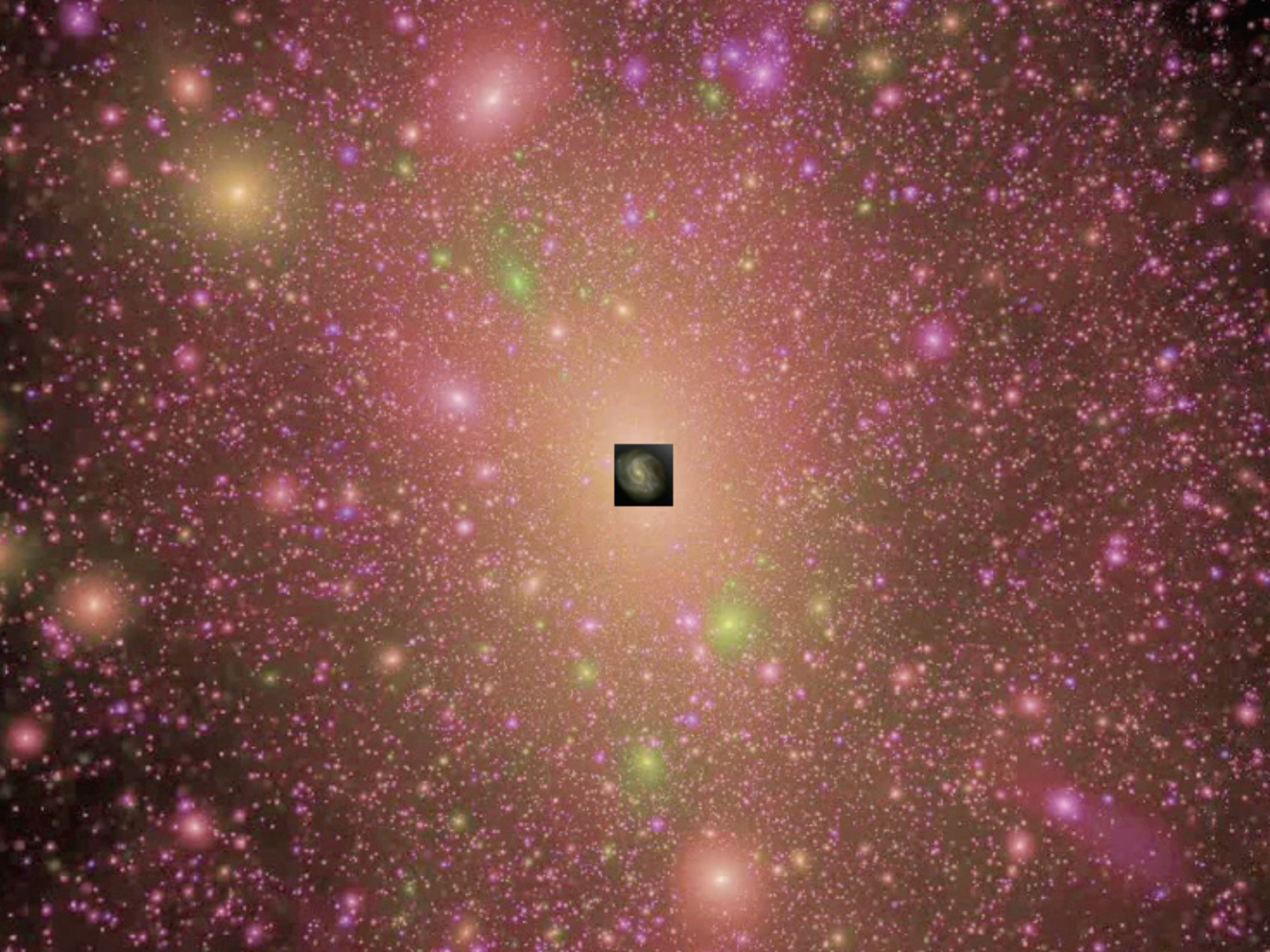
Aquarius Simulation

Volker Springel



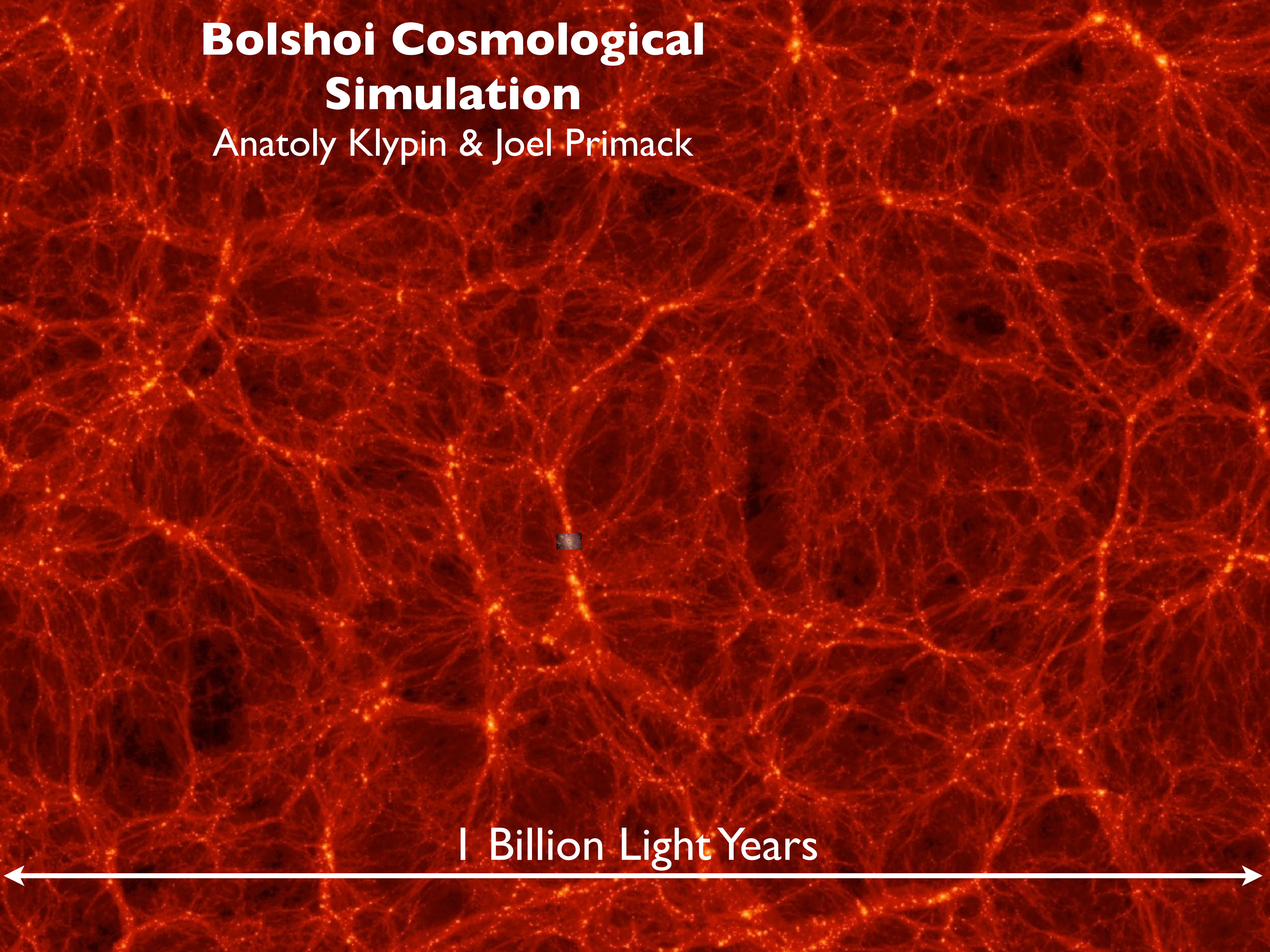
Milky Way
100,000 Light Years

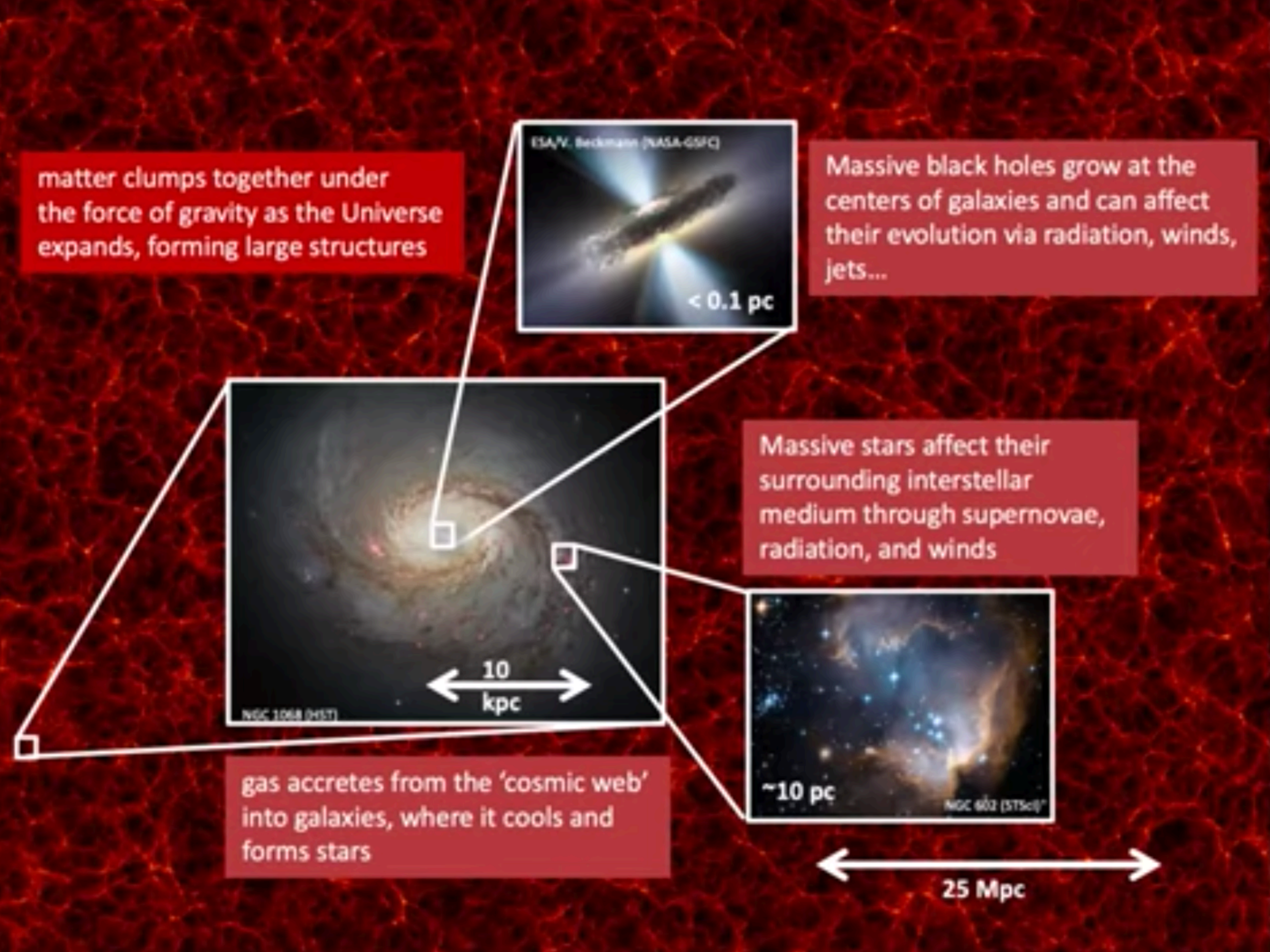
Milky Way Dark Matter Halo
1,500,000 Light Years



Bolshoi Cosmological Simulation

Anatoly Klypin & Joel Primack



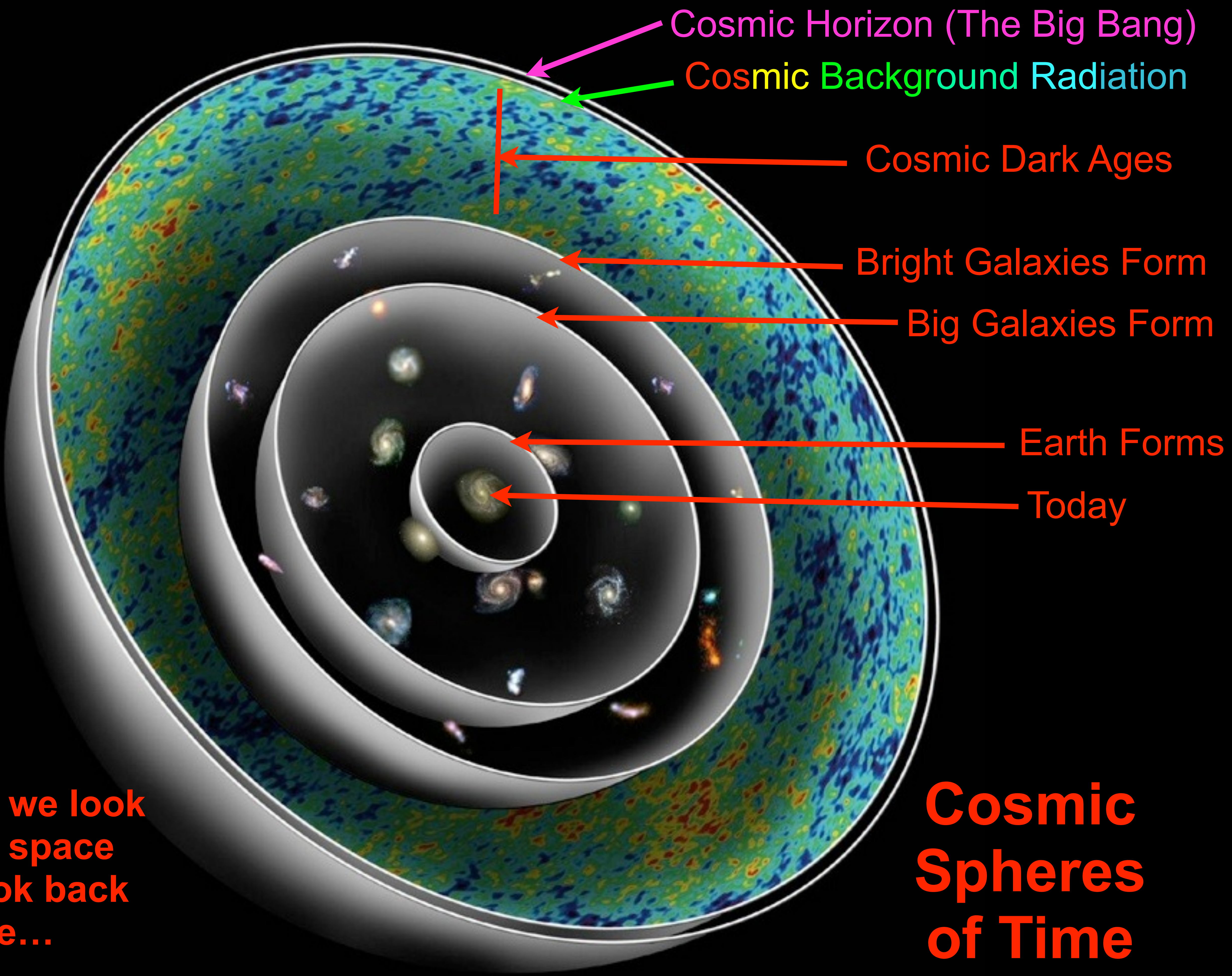


matter clumps together under the force of gravity as the Universe expands, forming large structures

Massive black holes grow at the centers of galaxies and can affect their evolution via radiation, winds, jets...

Massive stars affect their surrounding interstellar medium through supernovae, radiation, and winds

gas accretes from the 'cosmic web' into galaxies, where it cools and forms stars



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

Cosmic Spheres of Time

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.

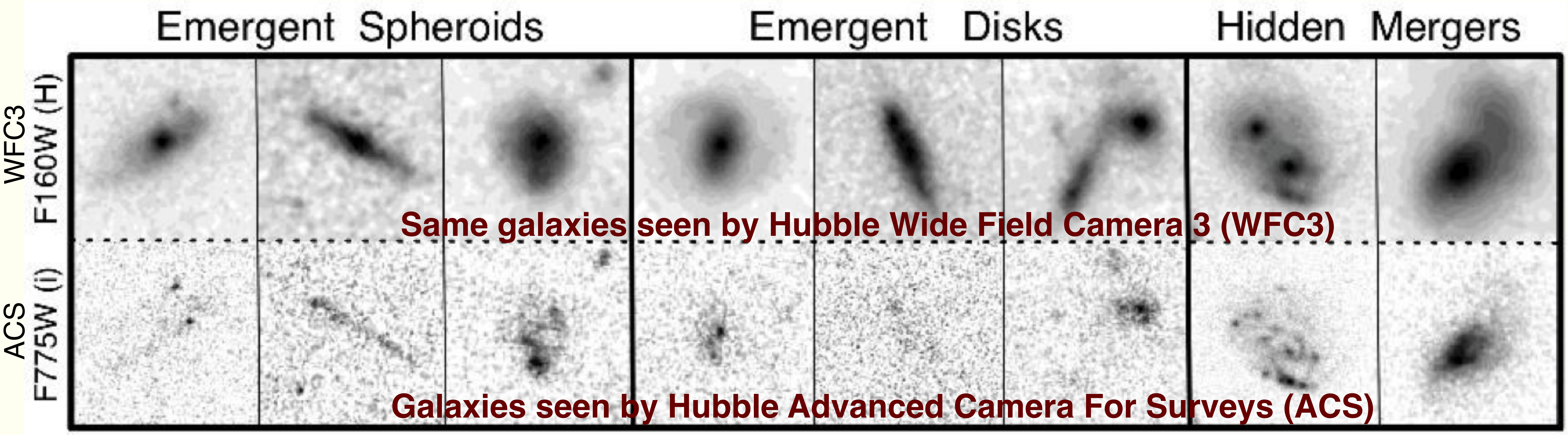
We are just now figuring out how galaxies form and evolve with the help of big ground-based telescopes, and Hubble and other space telescopes that let us see radiation clearly without interference from earth’s atmosphere.

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 $z \sim 2$
(~10 billion years ago)

The CANDELS Survey shows shapes of $z \lesssim 2.5$ galaxies

candels.ucolick.org



Same galaxies seen by Hubble Wide Field Camera 3 (WFC3)

Galaxies seen by Hubble Advanced Camera For Surveys (ACS)

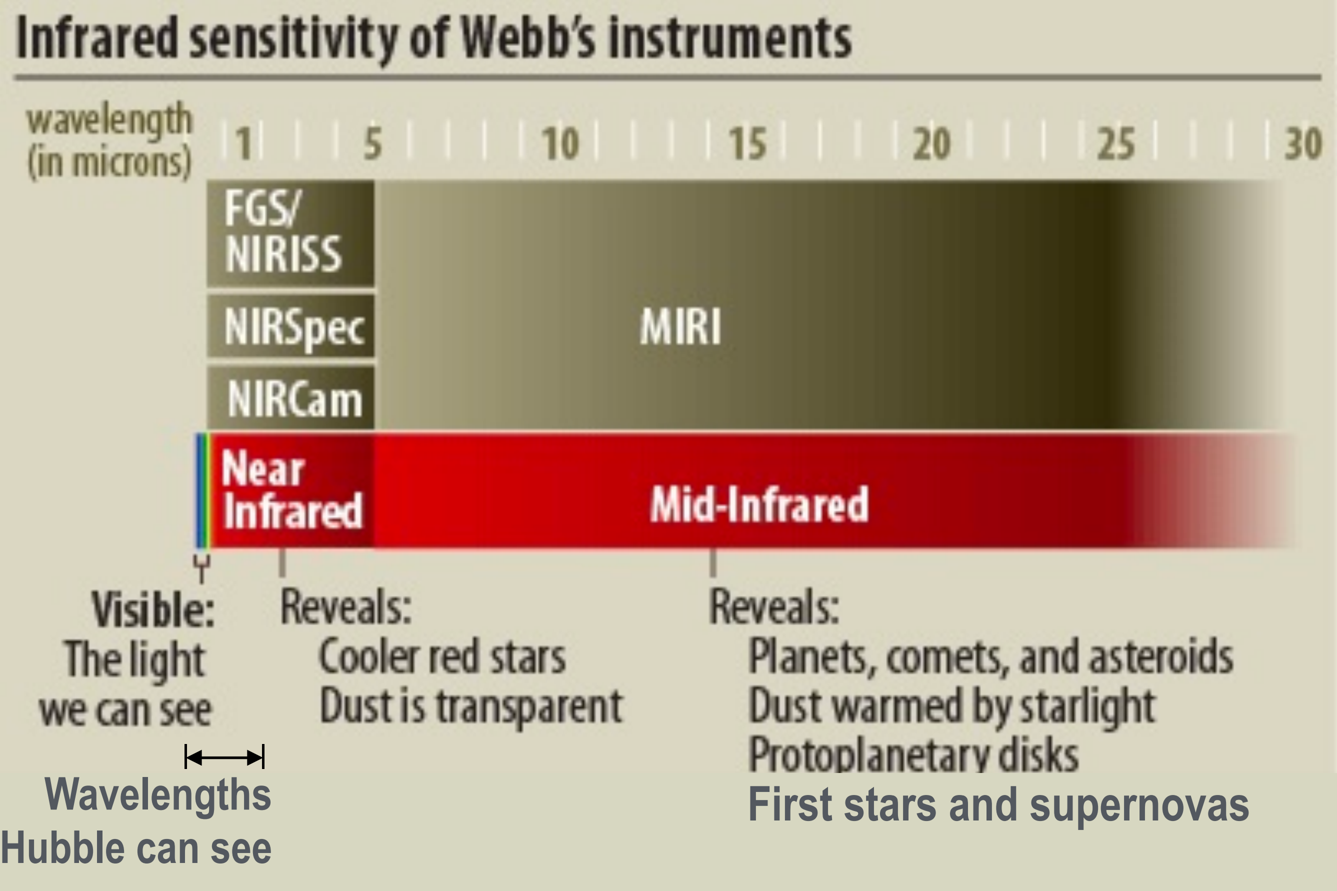
CANDELS: A Cosmic Odyssey

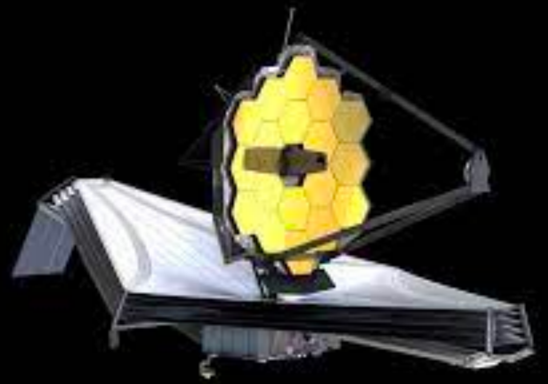
(blue 0.4 μm)(1+z) = 1.6 μm @ z = 3

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

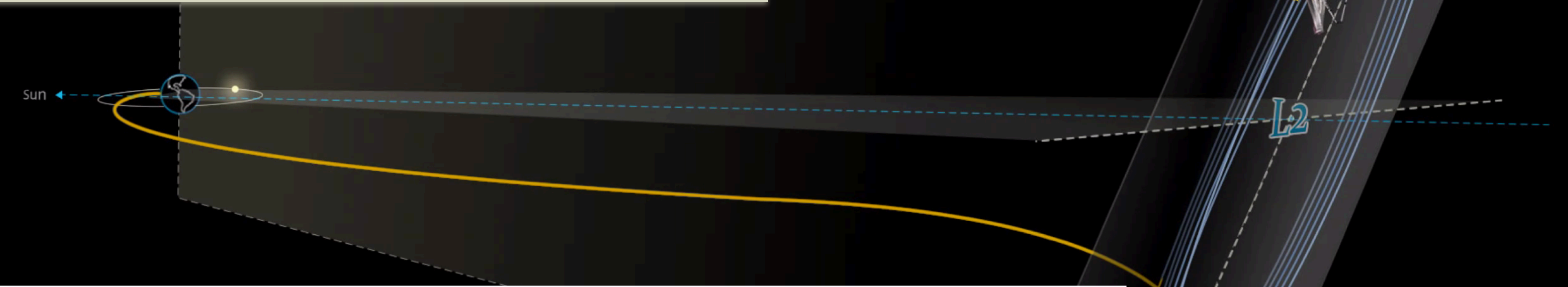
CANDELS is a powerful imaging survey of the distant Universe being carried out with two cameras on board the Hubble Space Telescope.

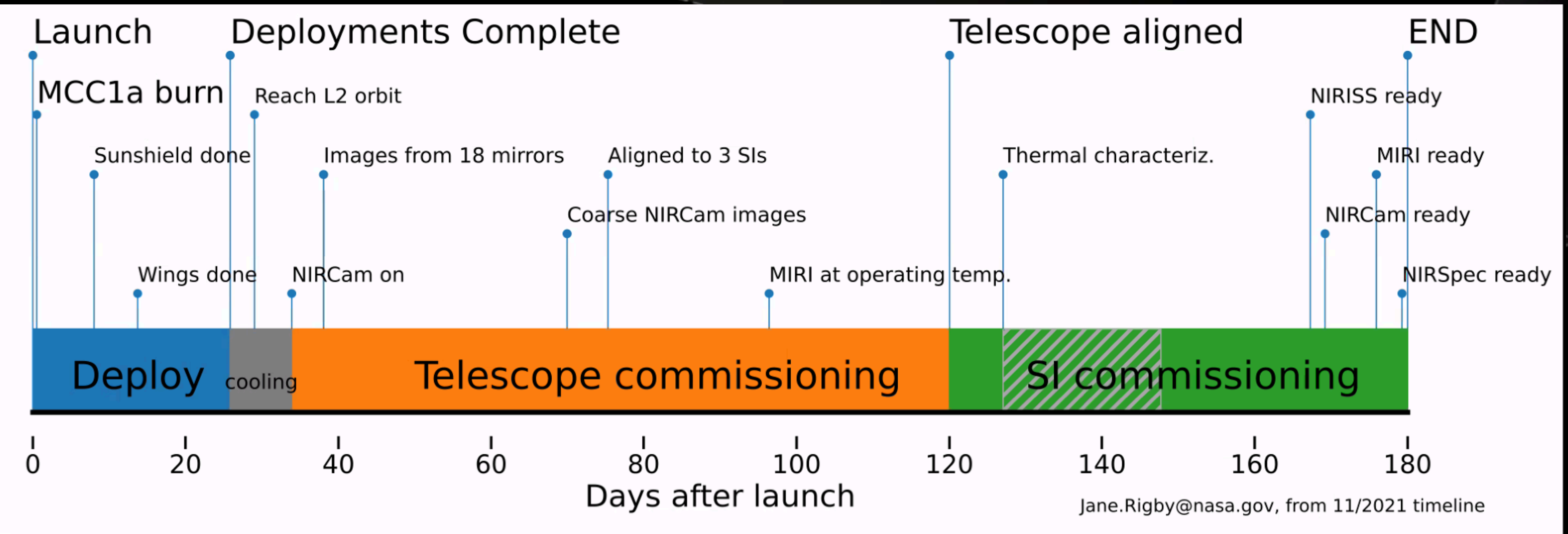
- CANDELS is the largest project in the history of Hubble, with 902 assigned orbits of observing time. This is the equivalent of four months of Hubble time if executed consecutively, but in practice CANDELS will take three years to complete (2010-2013).
- The core of CANDELS is the revolutionary near-infrared 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.





James Webb Space Telescope

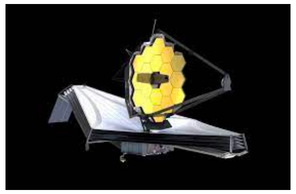




Jane.Rigby@nasa.gov, from 11/2021 timeline

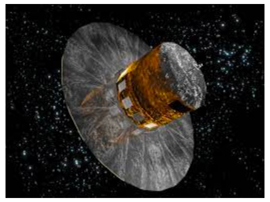
James Webb Space Telescope Joins the League of Super-Telescopes

Like geology and evolutionary biology, astronomy is an historical science. The goal of the historical sciences is to reconstruct the past and thereby understand the present. But astronomy has a great advantage over these other sciences. Landforms on Earth erode and only a tiny fraction of organisms fossilize, but almost all the energy that was ever radiated by galaxies is still streaming through the universe in some form. The trick is to be able to detect all this energy and be clever enough to understand it. Fortunately, new observatories on the ground and in space are making this possible.



Webb's most important superpower is its ability to collect and analyze light of much longer wavelengths than visible light, including heat radiation from planets and the light from very distant galaxies.

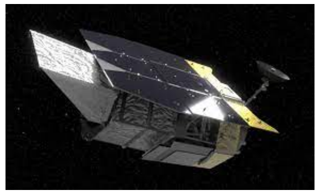
LIGO opened a new window on the universe when it started detecting gravity waves from merging black holes in 2015 and merging neutron stars in 2017. LIGO is now working with the **VIRGO** gravity-wave detector in Italy, and they will soon be joined by similar detectors in Japan and India.



Gaia, launched in 2013, is mapping more than a billion stars in our Milky Way galaxy so precisely that it can measure their velocities across the sky by seeing how their locations change over a few years.

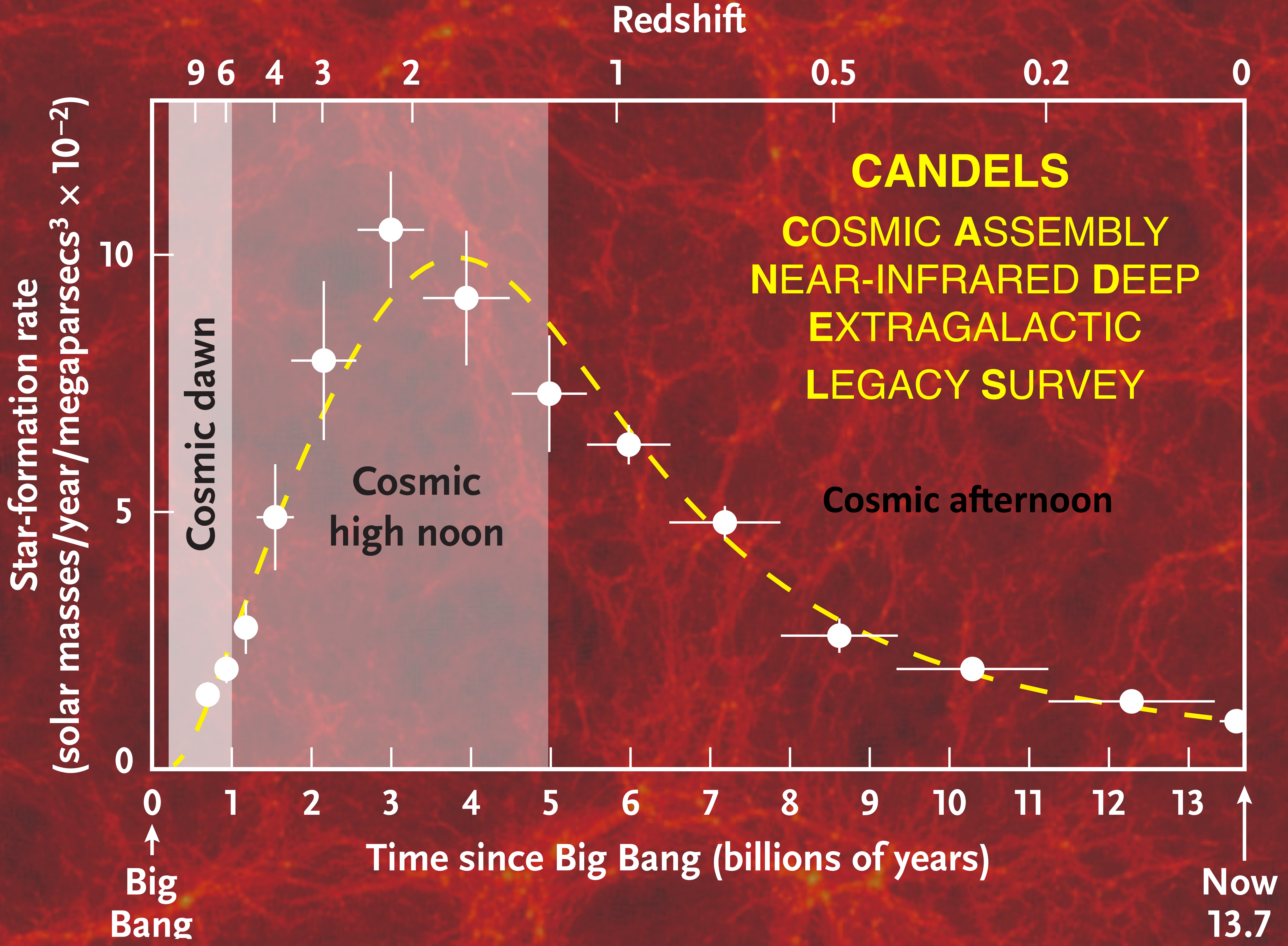
eROSITA, launched in 2019, is an X-ray telescope that for the first time is cataloging the 100,000 brightest clusters of galaxies and the brightest quasars over the entire sky.

Vera Rubin Observatory in northern Chile is the first wide-field giant telescope and its Legacy Survey of Space and Time (**LSST**) will soon begin making a high-resolution movie of the entire southern sky.



Nancy Roman Space Telescope is like Hubble on steroids. Every image of the sky from Roman Space Telescope will cover about 100 times the area of each Hubble image with almost the same resolution

Square Kilometer Array (SKA) of thousands of radio telescopes, now being built in southern Africa, Australia, and New Zealand, will discover how the universe evolved during the cosmic dark ages, before the first stars formed. SKA will also search for signals from intelligent life in the universe.



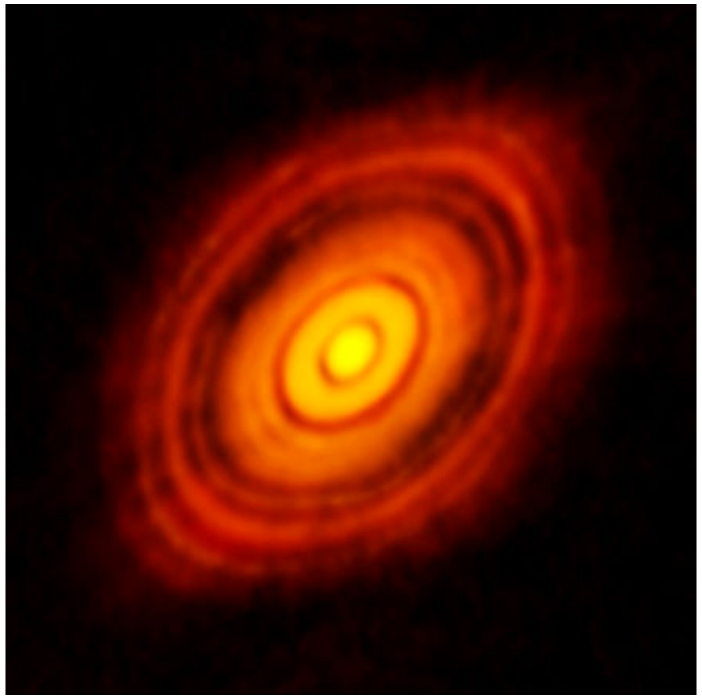
CANDELS

COSMIC **A**SSEMBLY **N**EAR-INFRARED **D**EEP **E**XTRAGALACTIC **L**EGACY **S**URVEY

Do Galaxies Start as Disks?

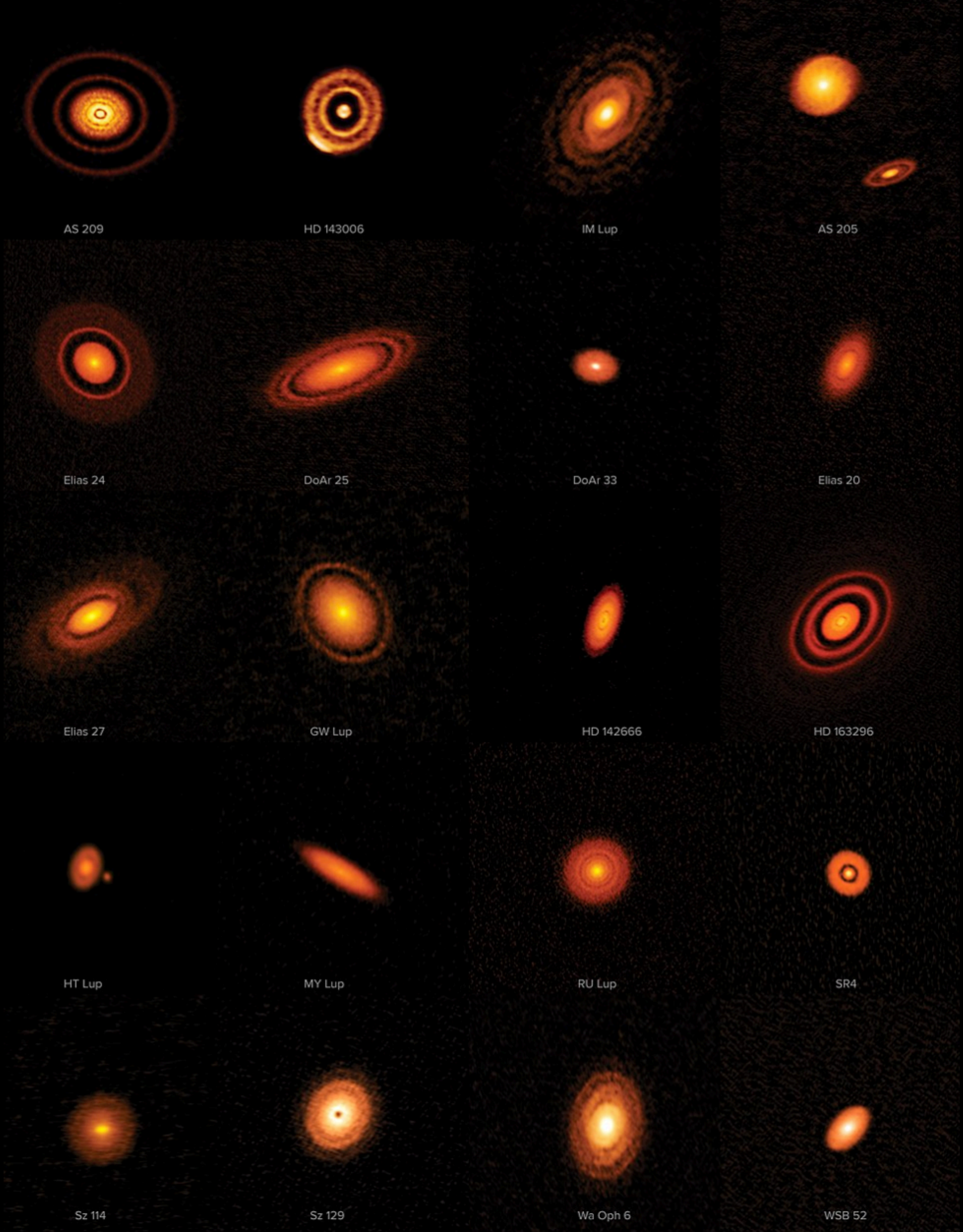
Newton's laws explained why planetary orbits are elliptical, but not why the planetary orbits in the solar system are nearly circular, in the same plane, and in the same direction as the sun rotates.

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)



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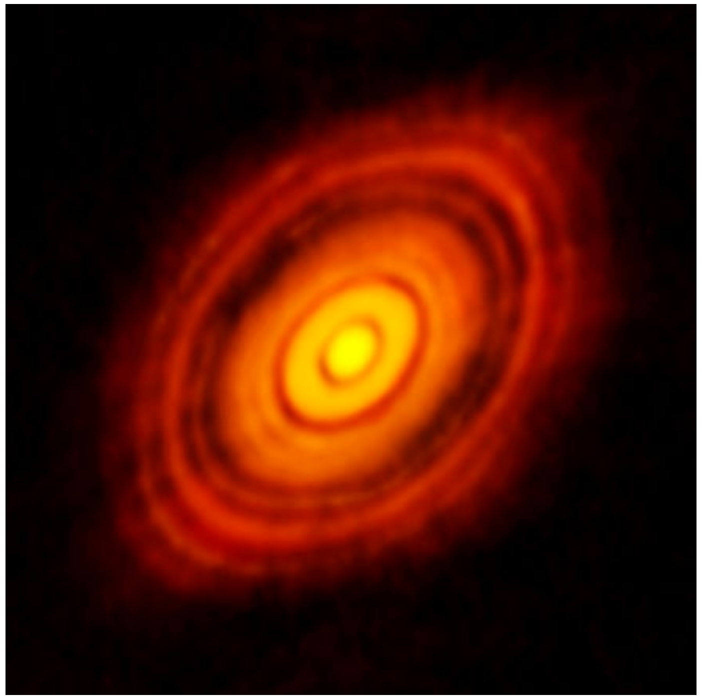
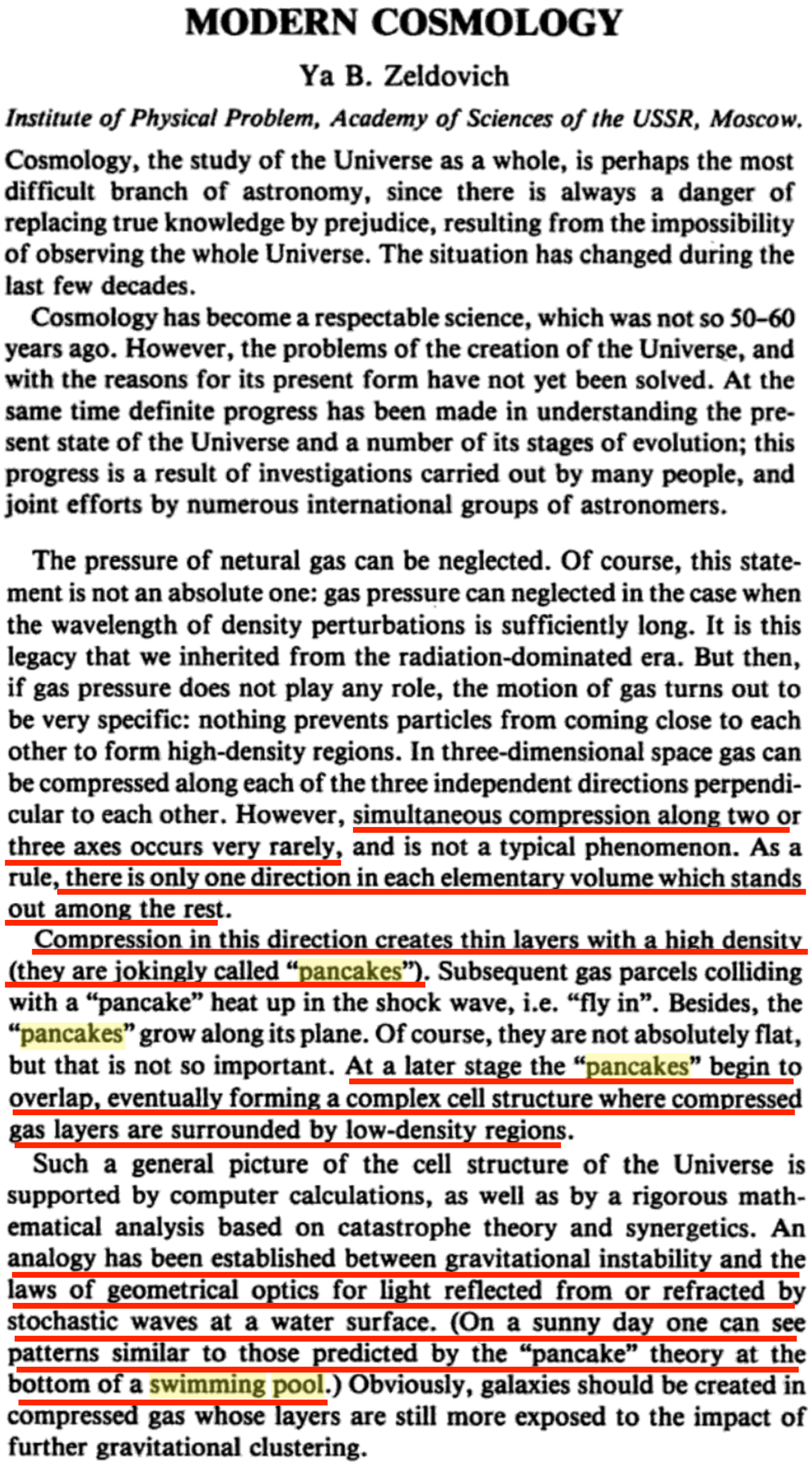


ALMA image of HL Tauri

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.



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)

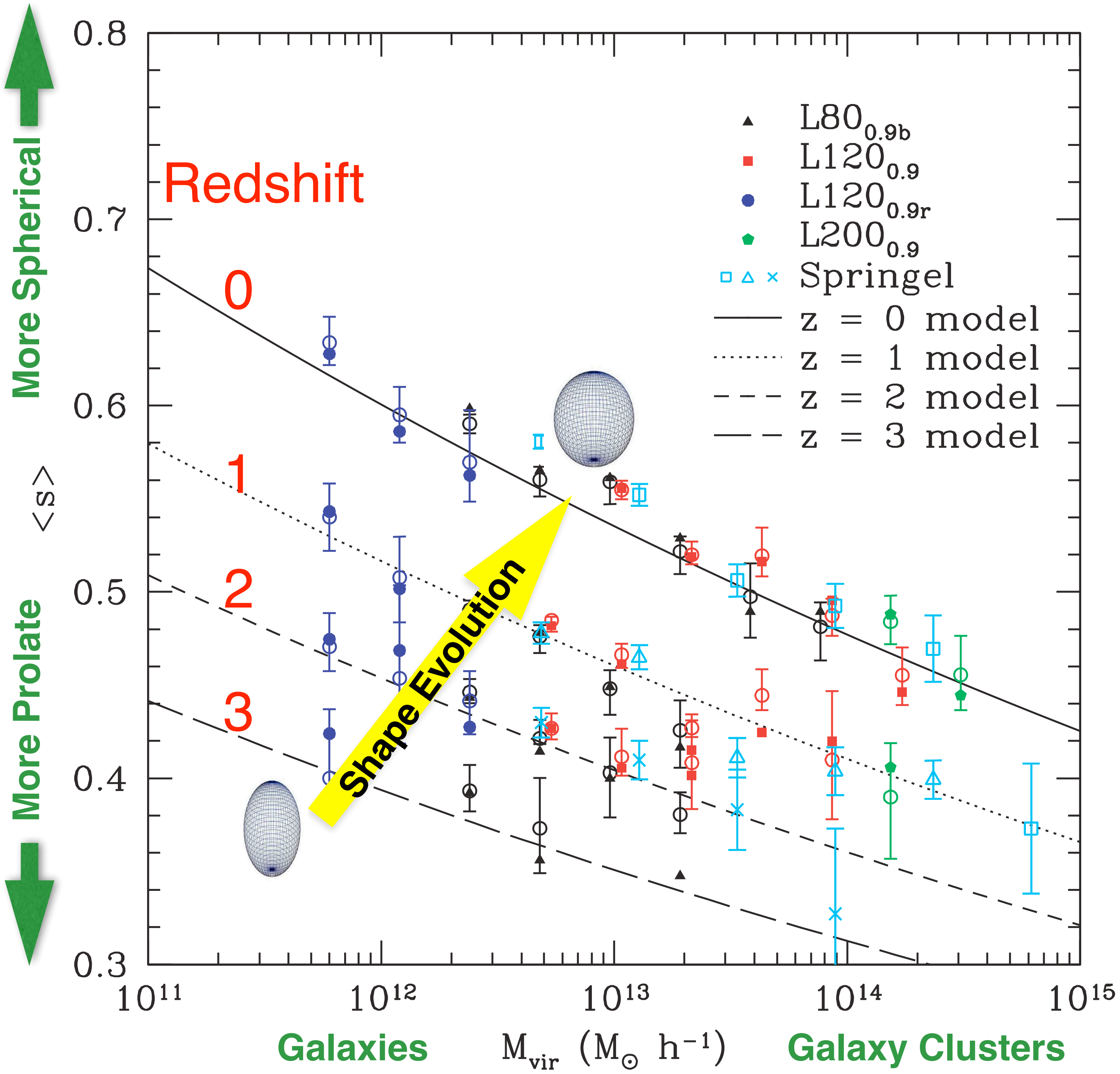
The shape of dark matter haloes: dependence on mass, redshift, radius and formation

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

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

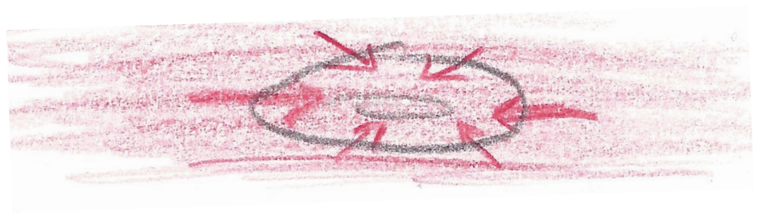
Halos are approximately triaxial ellipsoids

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



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

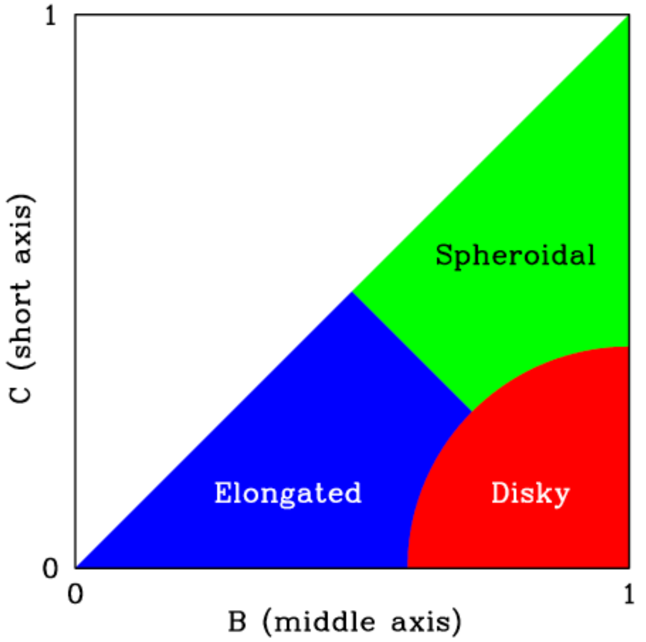
The Evolution of Galaxy Shapes in CANDELS: from Prolate to Oblate

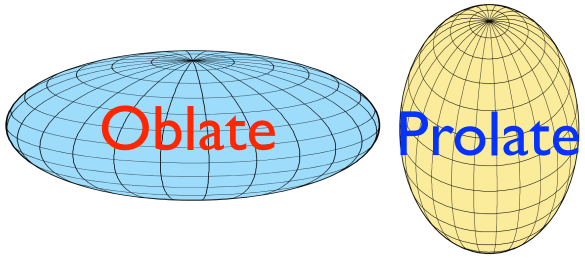
Haowen Zhang, Joel R. Primack, S. M. Faber, David C. Koo, Avishai Dekel, Zhu Chen, Daniel Ceverino, Yu-Yen Chang, Jerome J. Fang, Yicheng Guo, Lin Lin, and Arjen van der Wel

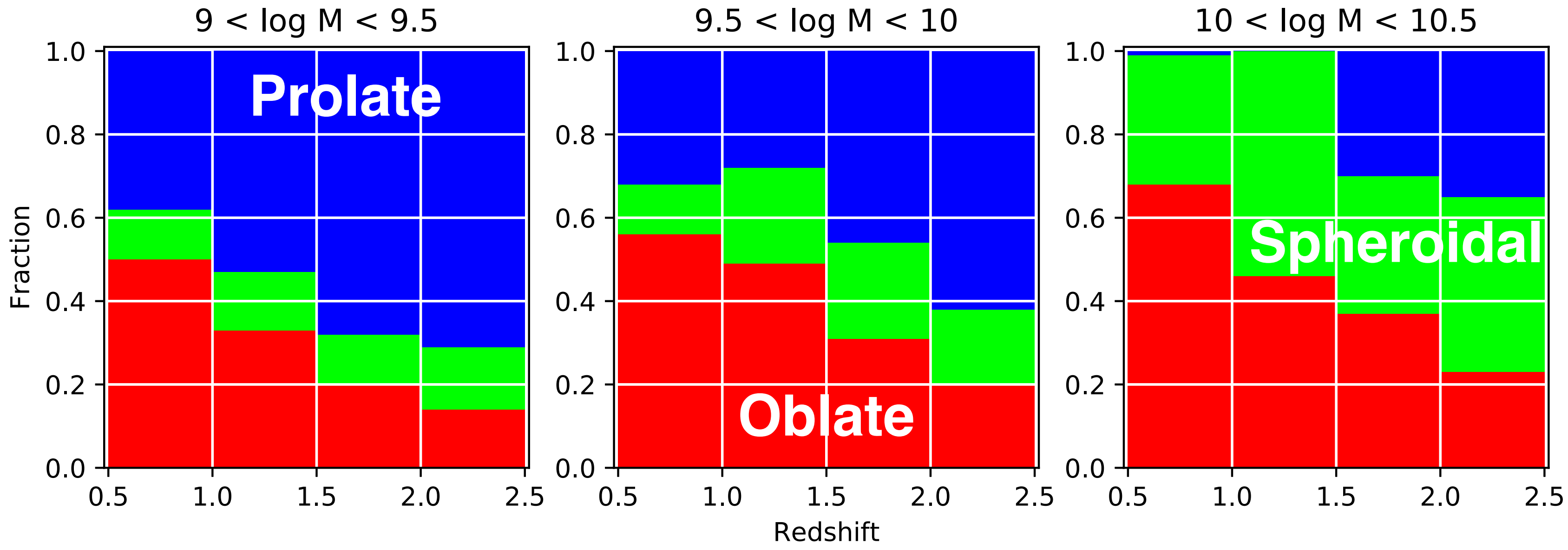
MNRAS 484, 5170 (2019)

ABSTRACT

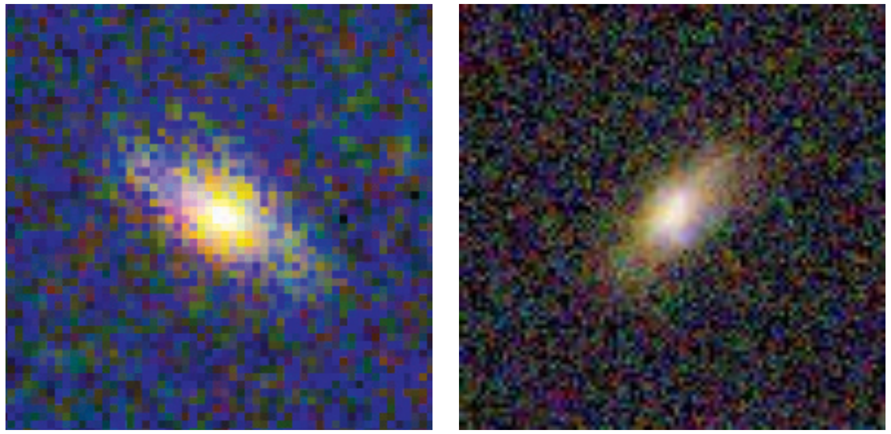
We model the projected b/a – $\log a$ distributions of CANDELS main sequence star-forming galaxies, where a (b) is the semi-major (semi-minor) axis of the galaxy images. We find that smaller-a galaxies are rounder at all stellar masses M_* and redshifts, so we include a when analyzing b/a distributions. 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.







Observed **Simulated**



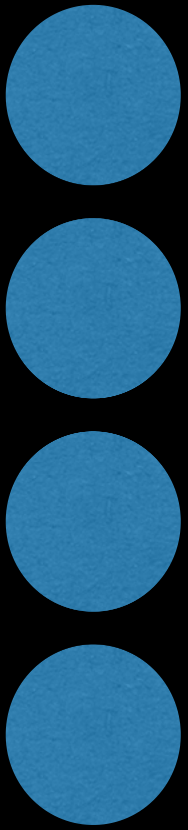
(a) CANDELS galaxy (b) VELA galaxy

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

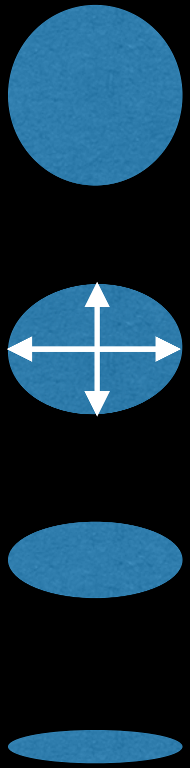
How Can We Determine 3D Galaxy Shapes from 2D Telescope Images? Statistics!

We see galaxies in all possible orientations

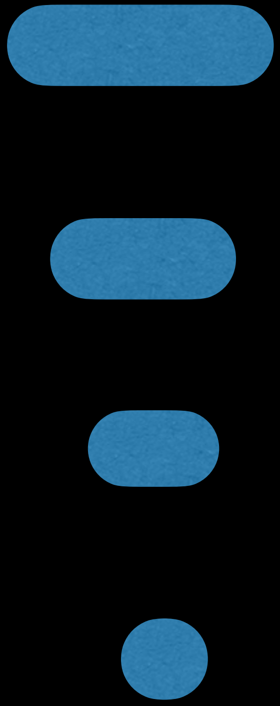
Let’s orient them with their long axes horizontal and see the short/long axis ratio distribution



Spheroidal galaxies always have large axis ratio



Disk galaxies have even distribution of axis ratios

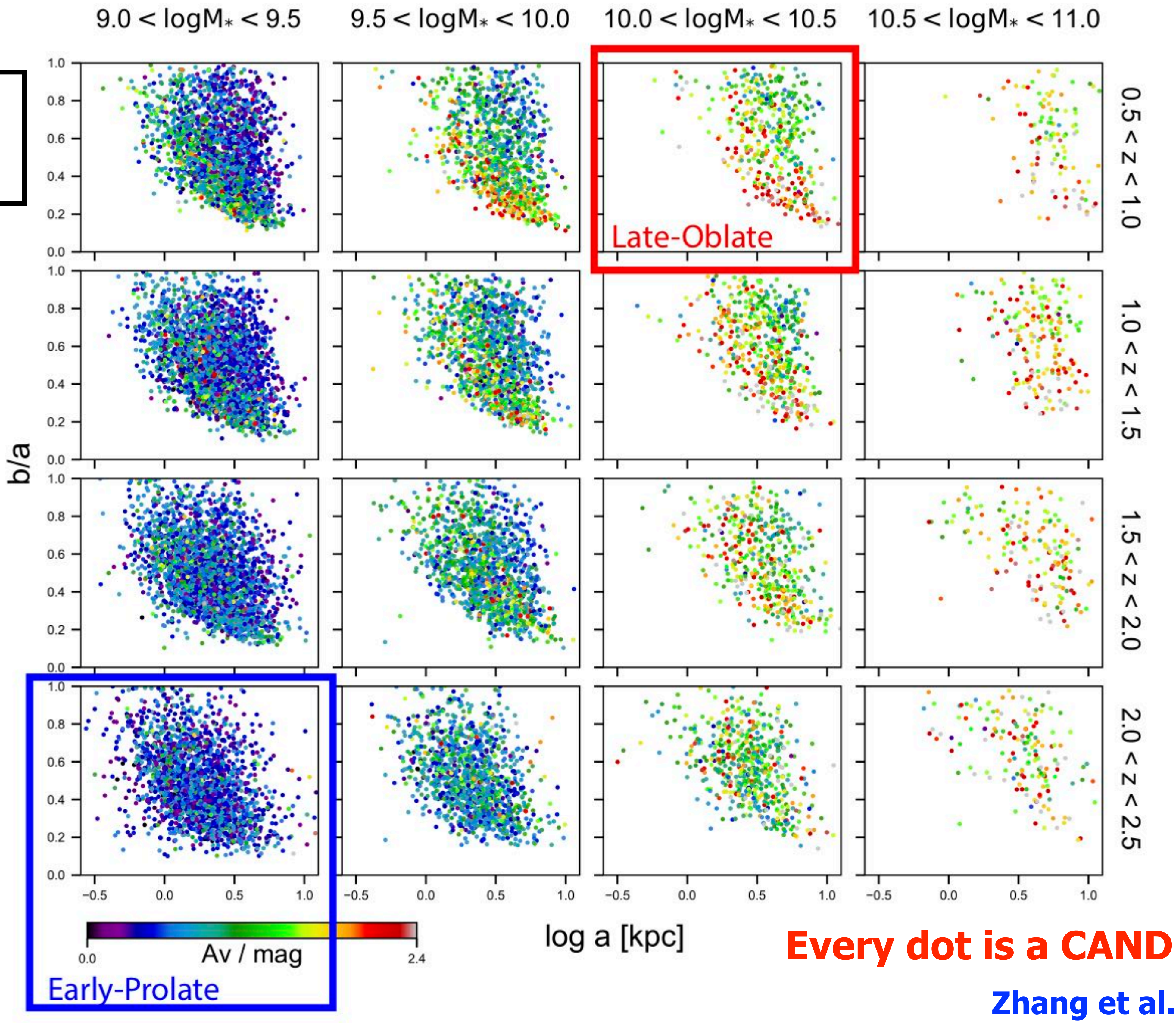


Prolate galaxies have small axis ratios except end-on

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

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

Every · dot is a galaxy



mass increasing

redshift increasing

galaxy evolution

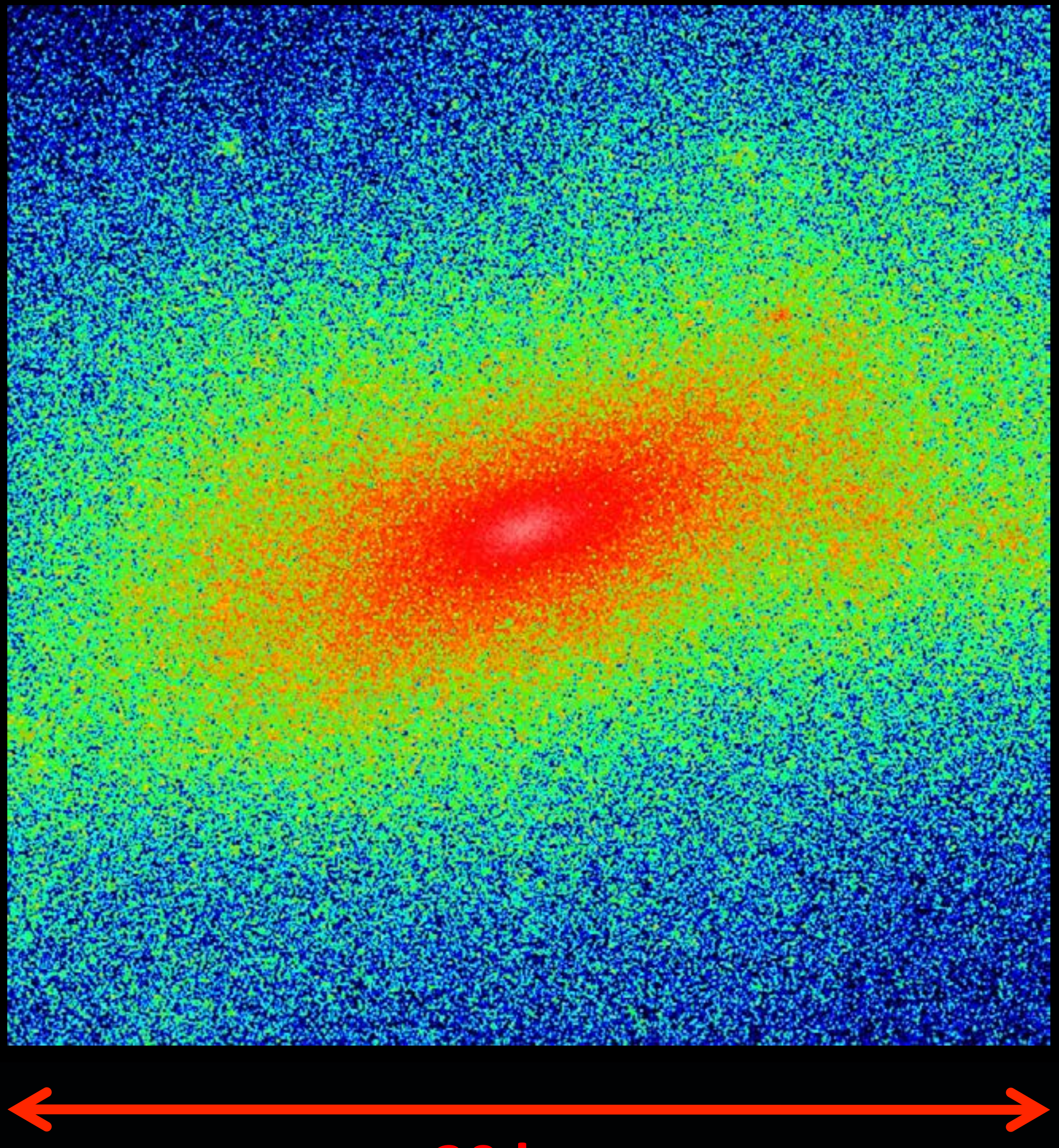
Every dot is a CANDELS galaxy!

Zhang et al. 2019

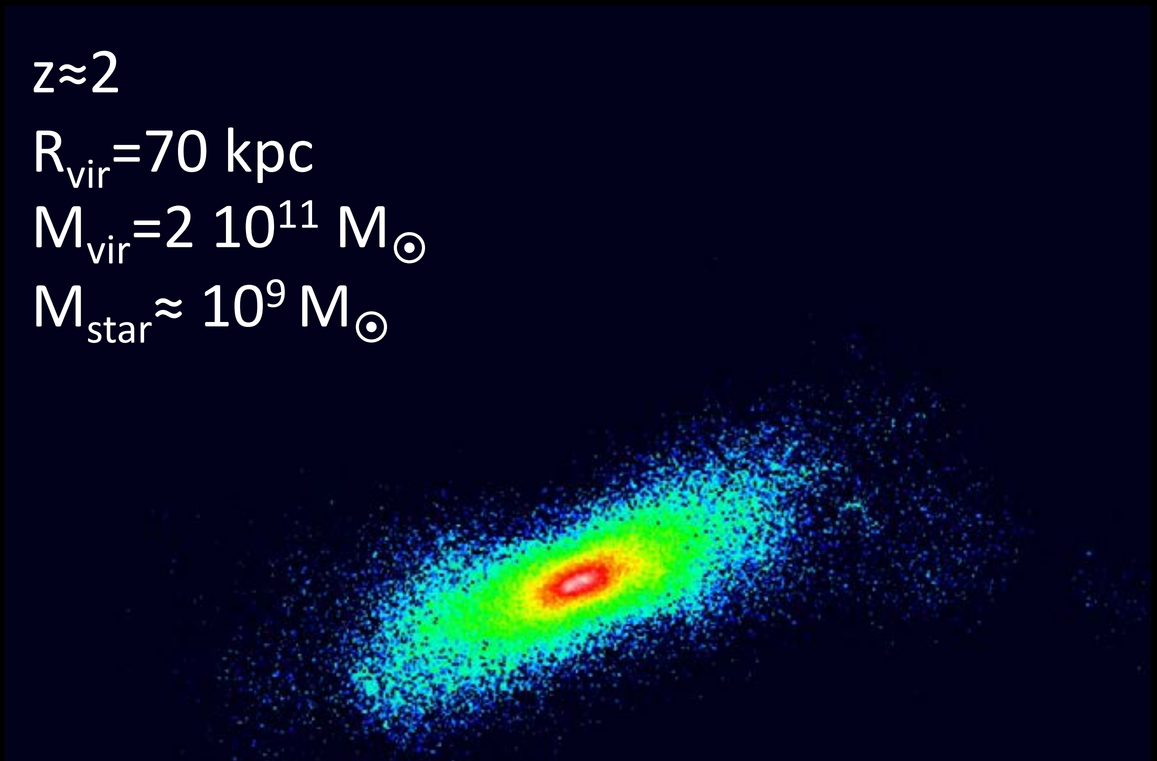
Our cosmological zoom-in simulations often produce elongated galaxies like the observed ones. The elongated distribution of stars follows the elongated inner dark matter halo.

Prolate DM halo → elongated galaxy

DM **VELA28RP** **stars**



30 kpc



z≈2

R_{vir}=70 kpc

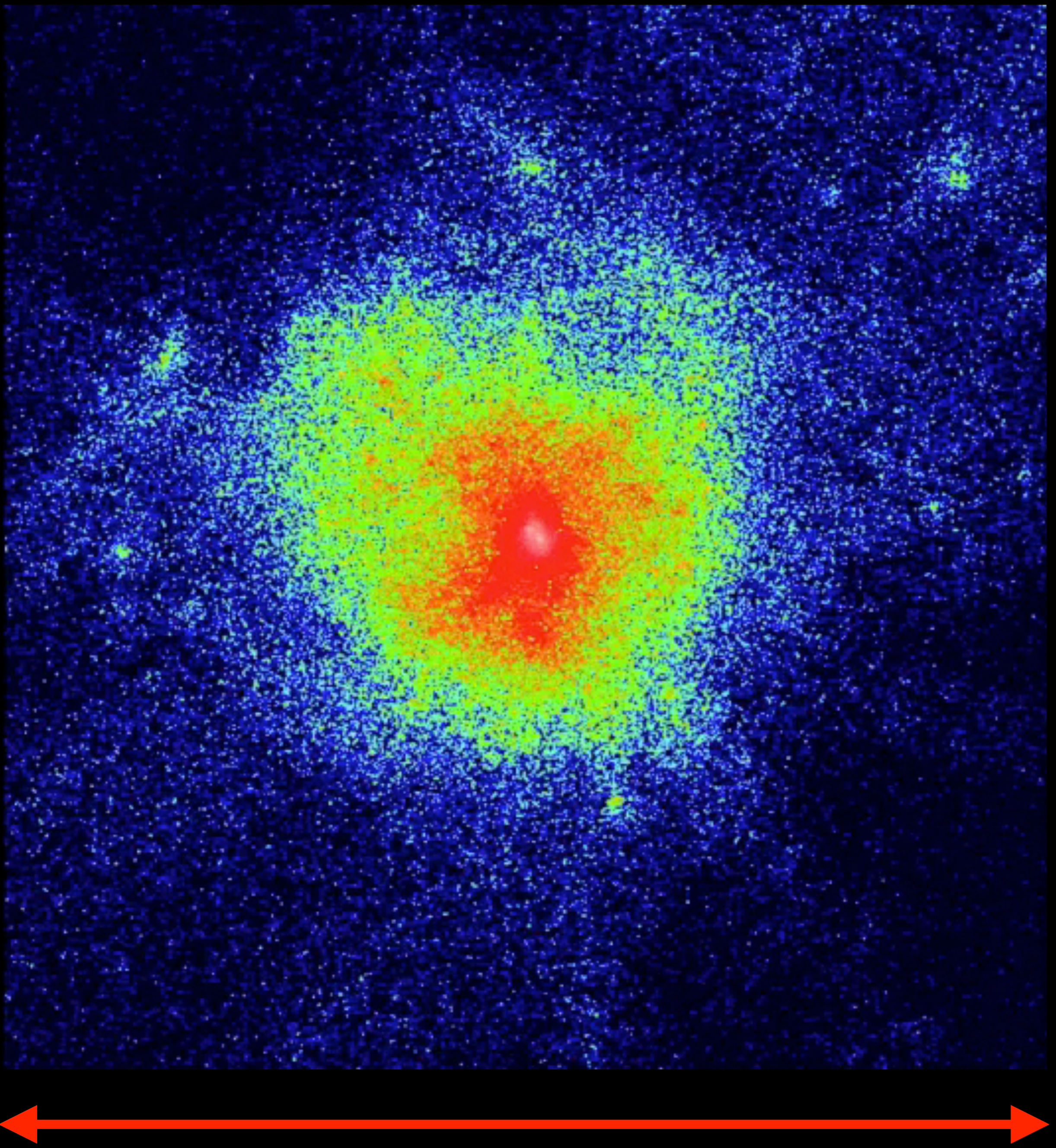
M_{vir}=2 10^{11} $M_\odot$

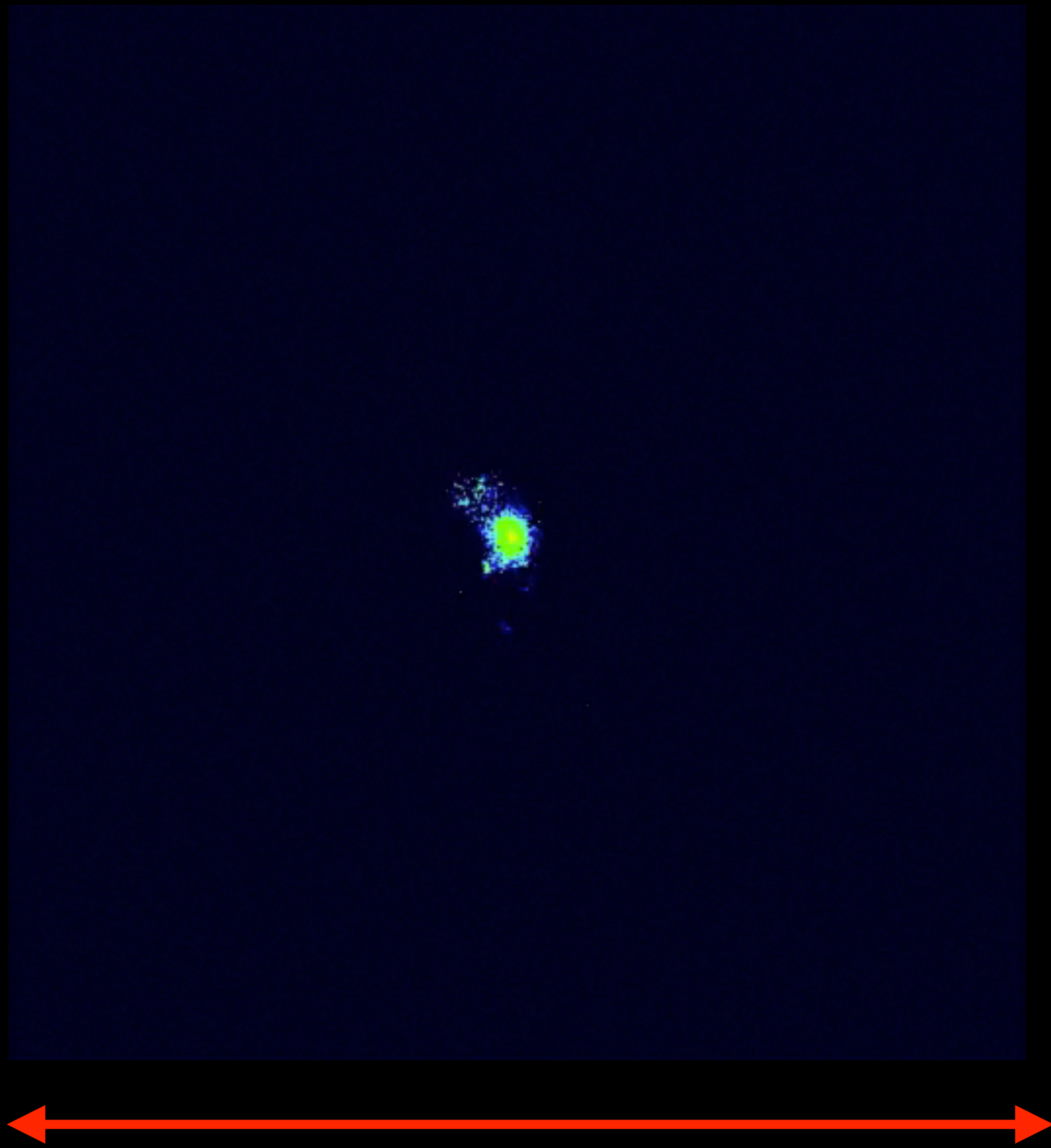
M_{star}≈ 10^9 $M_\odot$

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.

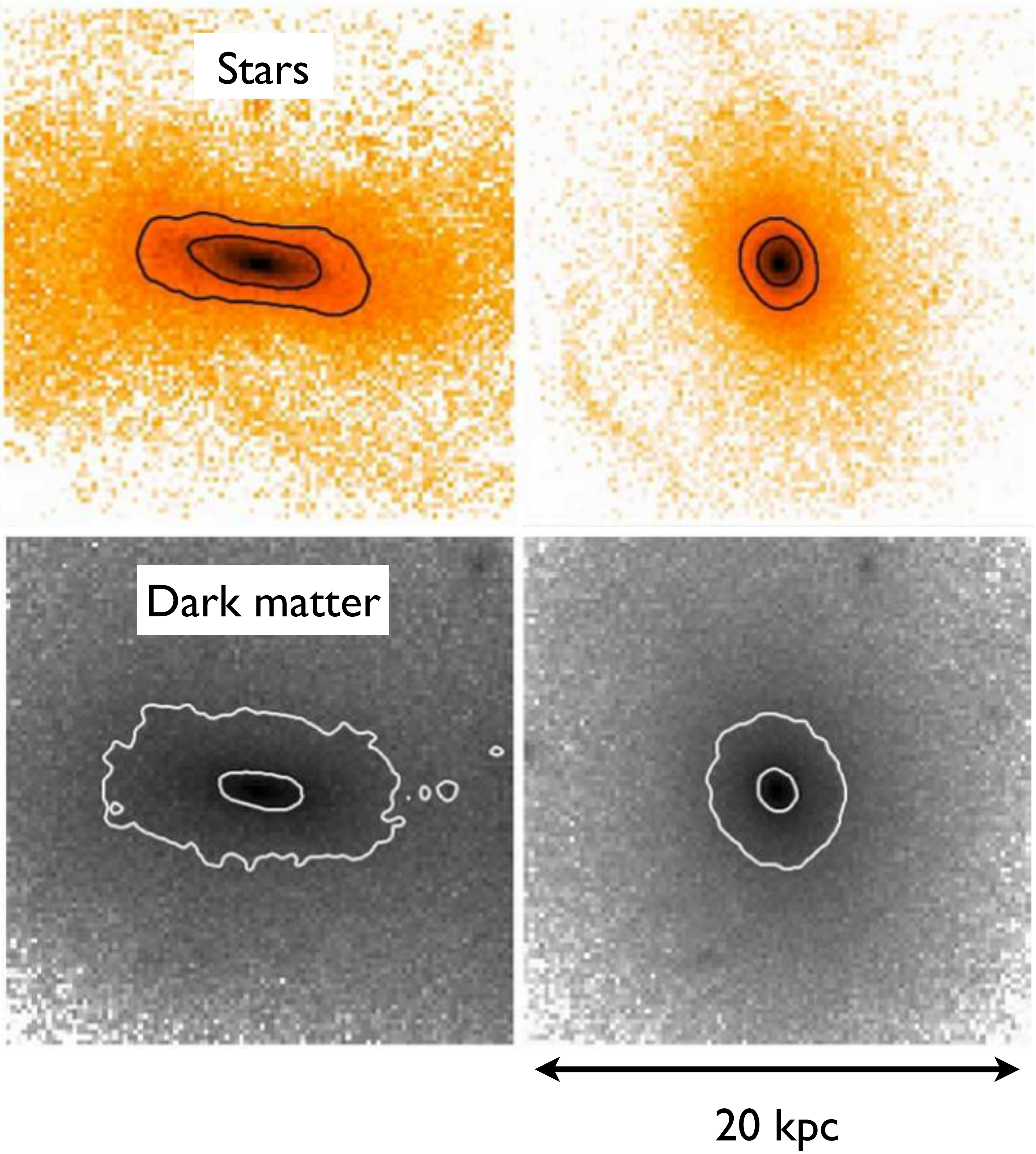
VELA28-gen3


DM

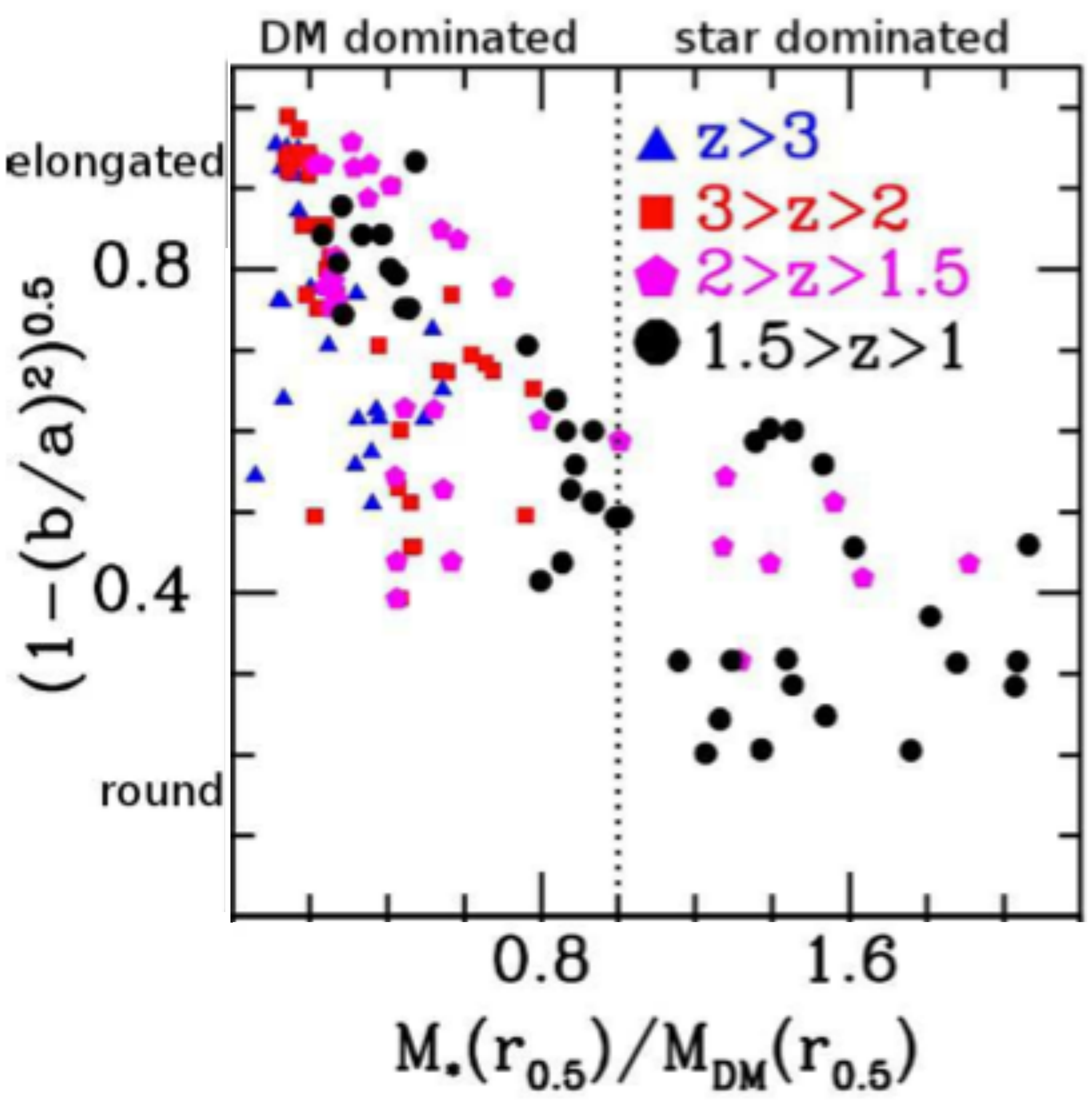

stars

Formation of elongated galaxies with low masses at high redshift

Daniel Ceverino, Joel Primack and Avishai Dekel **MNRAS 2015**



$M_* < 10^{10}\, M_\odot$ at z=2



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?