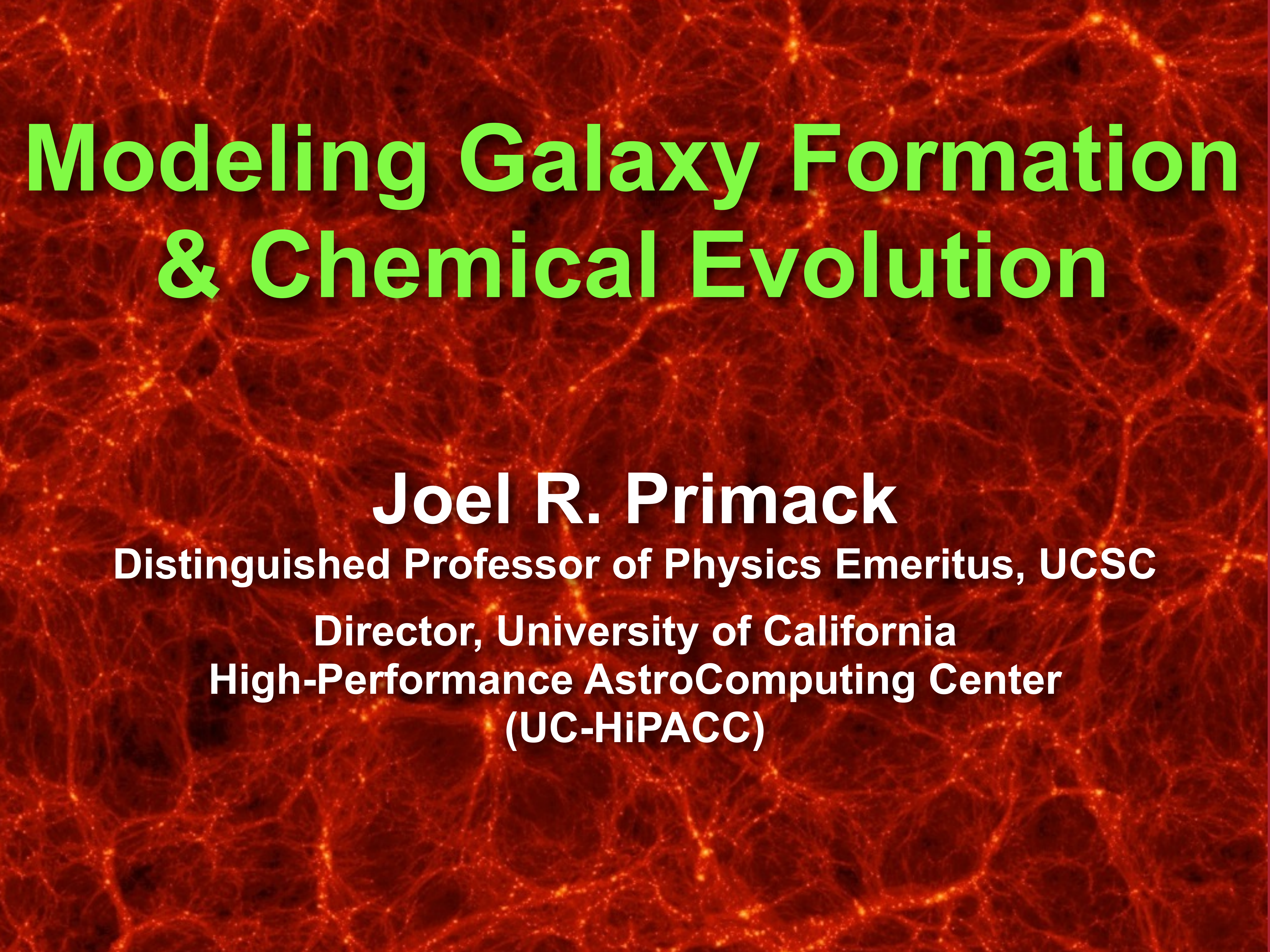


Modeling Galaxy Formation & Chemical Evolution

Joel R. Primack

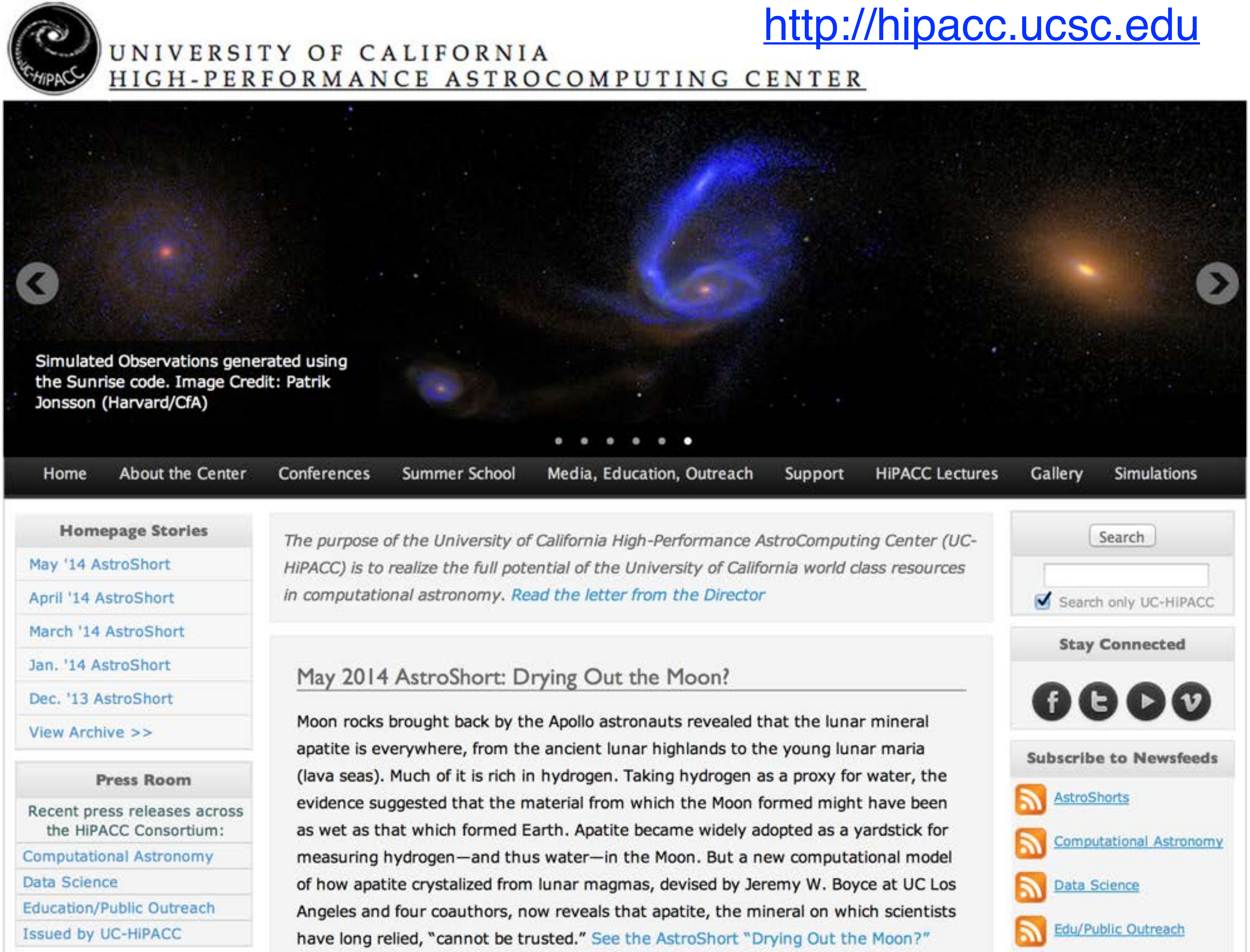
Distinguished Professor of Physics Emeritus, UCSC

Director, University of California
High-Performance AstroComputing Center
(UC-HiPACC)

Outline

- The UC High-Performance AstroComputing Center
- Summary of Standard ΛCDM Cosmology
- Large Scale Simulations - Bolshoi
  - Halo Abundance/Age Matching vs. Observations
  - Galactic Chemical Evolution: Data and Theory
  - Semi-Analytic Models vs. Galaxy Observations
- High Resolution Galaxy Simulations
  - Making Mock Observations with Sunrise
  - Comparing Mocks with CANDELS Galaxies
- The AGORA Galaxy Simulation Comparison Project
- Supercomputing the Universe: Challenges

http://hipacc.ucsc.edu



UNIVERSITY OF CALIFORNIA
HIGH-PERFORMANCE ASTROCOMPUTING CENTER

Simulated Observations generated using the Sunrise code. Image Credit: Patrik Jonsson (Harvard/CfA)

Homepage Stories

- May '14 AstroShort
- April '14 AstroShort
- March '14 AstroShort
- Jan. '14 AstroShort
- Dec. '13 AstroShort
- View Archive >>

Press Room

Recent press releases across the HiPACC Consortium:

- Computational Astronomy
- Data Science
- Education/Public Outreach
- Issued by UC-HiPACC

The purpose of the University of California High-Performance AstroComputing Center (UC-HiPACC) is to realize the full potential of the University of California world class resources in computational astronomy. *Read the letter from the Director*

May 2014 AstroShort: Drying Out the Moon?

Moon rocks brought back by the Apollo astronauts revealed that the lunar mineral apatite is everywhere, from the ancient lunar highlands to the young lunar maria (lava seas). Much of it is rich in hydrogen. Taking hydrogen as a proxy for water, the evidence suggested that the material from which the Moon formed might have been as wet as that which formed Earth. Apatite became widely adopted as a yardstick for measuring hydrogen—and thus water—in the Moon. But a new computational model of how apatite crystalized from lunar magmas, devised by Jeremy W. Boyce at UC Los Angeles and four coauthors, now reveals that apatite, the mineral on which scientists have long relied, "cannot be trusted." See the AstroShort "Drying Out the Moon?"

☑ Search only UC-HiPACC

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The University of California
High–Performance AstroComputing Center

A consortium of nine UC campuses and three DOE laboratories

UC-HiPACC Support: $350,000/yr from the University of California, 2010-2014

UC-HiPACC Executive Committee

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Webmaster and Videographer: Steve Zaslaw <sjzaslaw@gmail.com>

Funding Opportunities

Calls for proposals scheduled twice annually for Fall/Winter & Spring/Summer funding Cycles.

UC-HIPACC will support focused working groups of UC scientists from multiple campuses to pursue joint projects in computational astrophysics and related areas by providing funds for travel and lodging. At the heart of UC-HIPACC are working groups.

1. Small travel grants enable scientists, graduate students, and post-doctoral students to travel easily and spontaneously between Center nodes. UC-HIPACC will fund travel grant proposals submitted by faculty members, senior scientists, postdocs or graduate students up to $1000 on a first-come-first-served basis with a simple application describing the plan and purpose of the travel.

2. Grants ranging between $1000 - $5,000 to support larger working groups or participation in scientific meetings.

3. Mini Conference grants of up to $5,000 to support collaborations of multiple UC campuses and DOE labs.

4. Grants to faculty to support astrocomputing summer research projects by undergraduates.

5. Matching grants of up to $10,000 for astrocomputing equipment.

6. Innovative initiative proposals for other purposes that are consistent with the goals of UC-HIPACC. Such purposes could include meetings or workshops, software development, or education and outreach.

Annual Conferences in Northern and Southern California

UC-HiPACC sponsors international conferences each year especially (but not exclusively) for scientists working on computational astrophysics and related topics at the UC campuses and labs. Unlike the more specialized meetings of working groups, these larger meetings are broad,with the purpose of bringing theoretical astrophysicists together with observational astronomers and other relevant experts including computer scientists. 2014 meetings: *Near Field-Deep Field Connection* (UC Irvine, with Center for Galaxy Evolution, February); *Computational Astrophysics 2014-2020: Approaching Exascale* (LBNL, March); *Galaxy Workshop* & *Assembling Galaxies of Resolved Anatomy* (UCSC, August).

Annual International AstroComputing Summer Schools (ISSAC)

UC-HiPACC supports an annual school aimed at graduate students and postdocs who are currently working in, or actively interested in doing research in, AstroComputing. Topics and locations of the annual school rotate. Codes are put on a supercomputer where the students have accounts. Lecture slides and videos, codes, inputs and outputs are on the UC-HIPACC website http://hipacc.ucsc.edu.

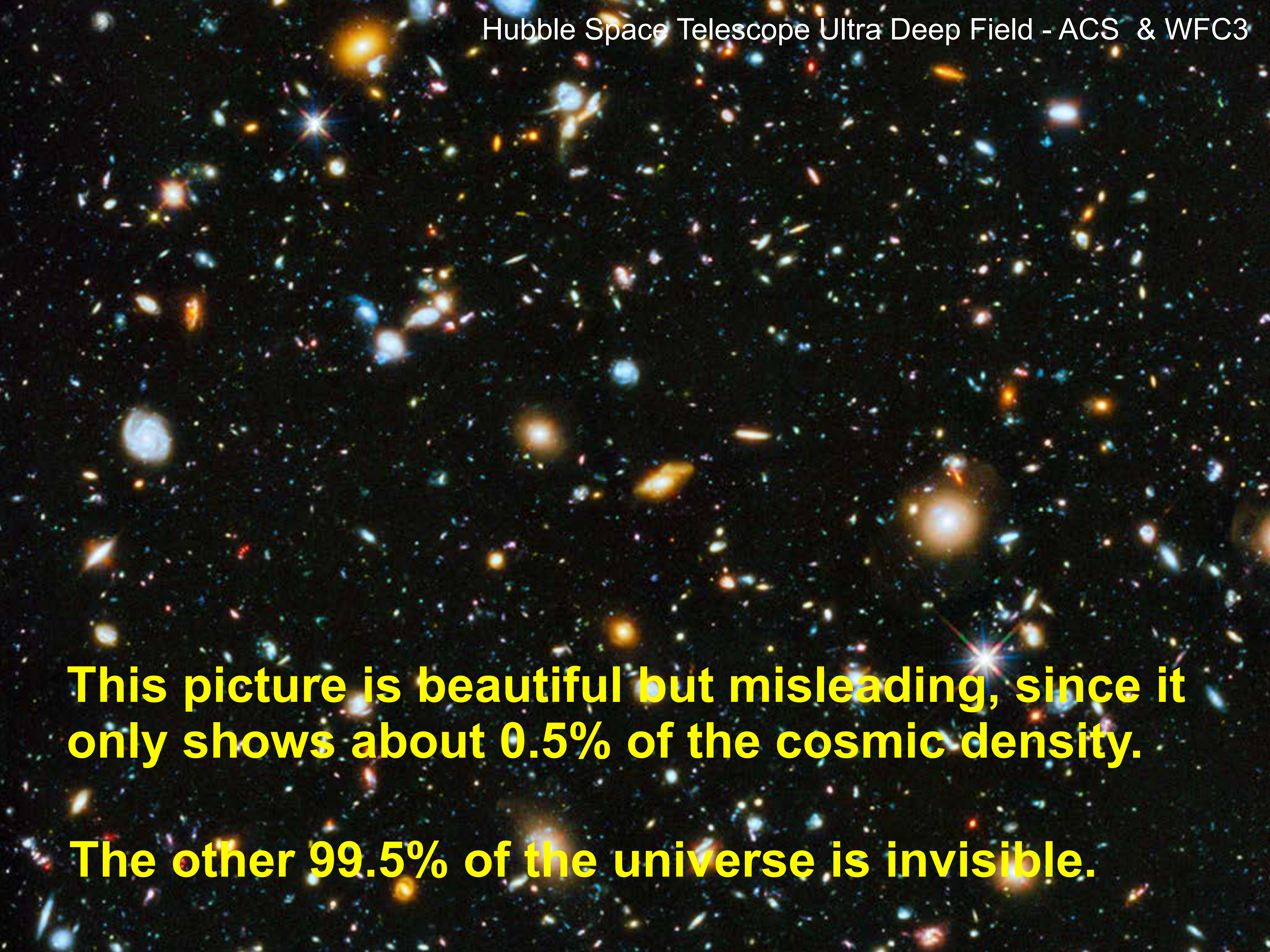
The 2010 school was at UCSC, on the topic of Hydrodynamic Galaxy Simulations. Lectures were presented by experts on the leading codes (AMR codes ART, Enzo, and RAMSES, and SPH codes Arepo, GADGET, and Gasoline) and the Sunrise code for making realistic visualizations including stellar SED evolution and dust reprocessing. There were 60 students, including 20 from outside the USA. Funding from NSF helped to support non-UC participant expenses.

The 2011 school was July 11-23 at UC Berkeley/LBNL/NERSC, on the topic of Computational Explosive Astrophysics: novae, SNe, GRB, and binary mergers. The scientific organizers were Daniel Kasen (LBNL/UCB) and Peter Nugent (LBNL). There was additional funding from DOE.

The 2012 school was at UC San Diego/SDSC, on AstroInformatics and Astrophysical Data Mining. The scientific director was Alex Szalay (Johns Hopkins) and the host was Michael Norman, director, SDSC.

The 2013 school was at UCSC, on Star and Planet Formation; the director was Mark Krumholz (UCSC).

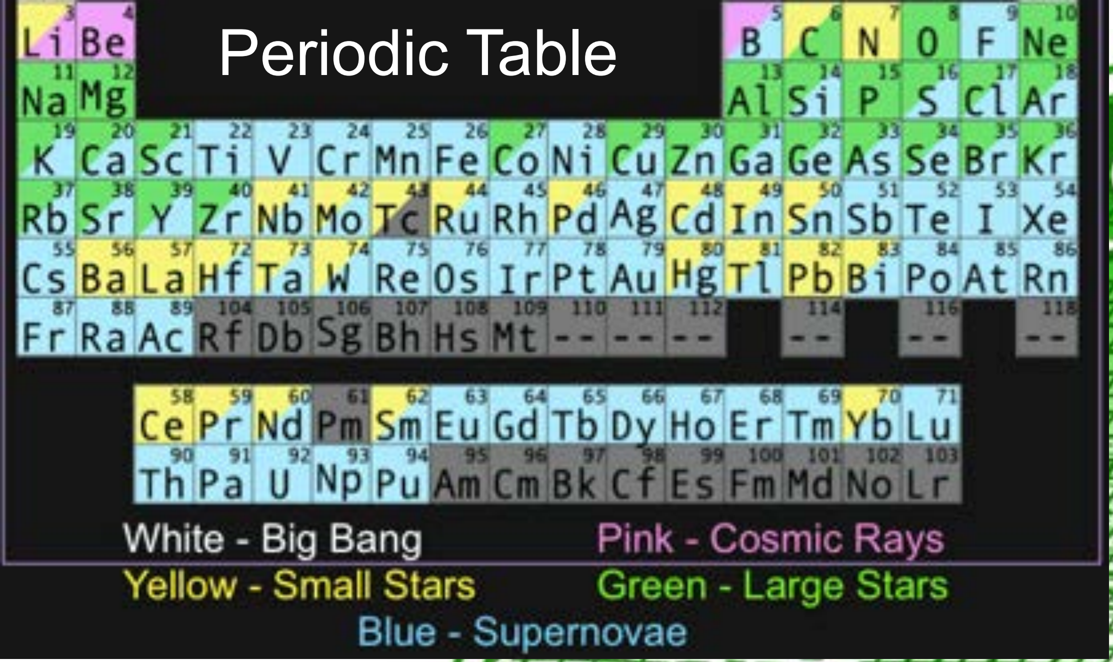
The 2014 school is at UC San Diego/SDSC, on Neutrino and Nuclear Astrophysics; the director is George Fuller (UCSD). There is additional funding from DOE.



Hubble Space Telescope Ultra Deep Field - ACS & WFC3

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.



Periodic Table

3 Li	4 Be											5 B	6 C	7 N	8 O	9 F	10 Ne
11 Na	12 Mg											13 Al	14 Si	15 P	16 S	17 Cl	18 Ar
19 K	20 Ca	21 Sc	22 Ti	23 V	24 Cr	25 Mn	26 Fe	27 Co	28 Ni	29 Cu	30 Zn	31 Ga	32 Ge	33 As	34 Se	35 Br	36 Kr
37 Rb	38 Sr	39 Y	40 Zr	41 Nb	42 Mo	43 Tc	44 Ru	45 Rh	46 Pd	47 Ag	48 Cd	49 In	50 Sn	51 Sb	52 Te	53 I	54 Xe
55 Cs	56 Ba	57 La	72 Hf	73 Ta	74 W	75 Re	76 Os	77 Ir	78 Pt	79 Au	80 Hg	81 Tl	82 Pb	83 Bi	84 Po	85 At	86 Rn
87 Fr	88 Ra	89 Ac	104 Rf	105 Db	106 Sg	107 Bh	108 Hs	109 Mt	110 --	111 --	112 --		114 --		116 --		118 --
		58 Ce	59 Pr	60 Nd	61 Pm	62 Sm	63 Eu	64 Gd	65 Tb	66 Dy	67 Ho	68 Er	69 Tm	70 Yb	71 Lu		
		90 Th	91 Pa	92 U	93 Np	94 Pu	95 Am	96 Cm	97 Bk	98 Cf	99 Es	100 Fm	101 Md	102 No	103 Lr		

White - Big Bang

Pink - Cosmic Rays

Yellow - Small Stars

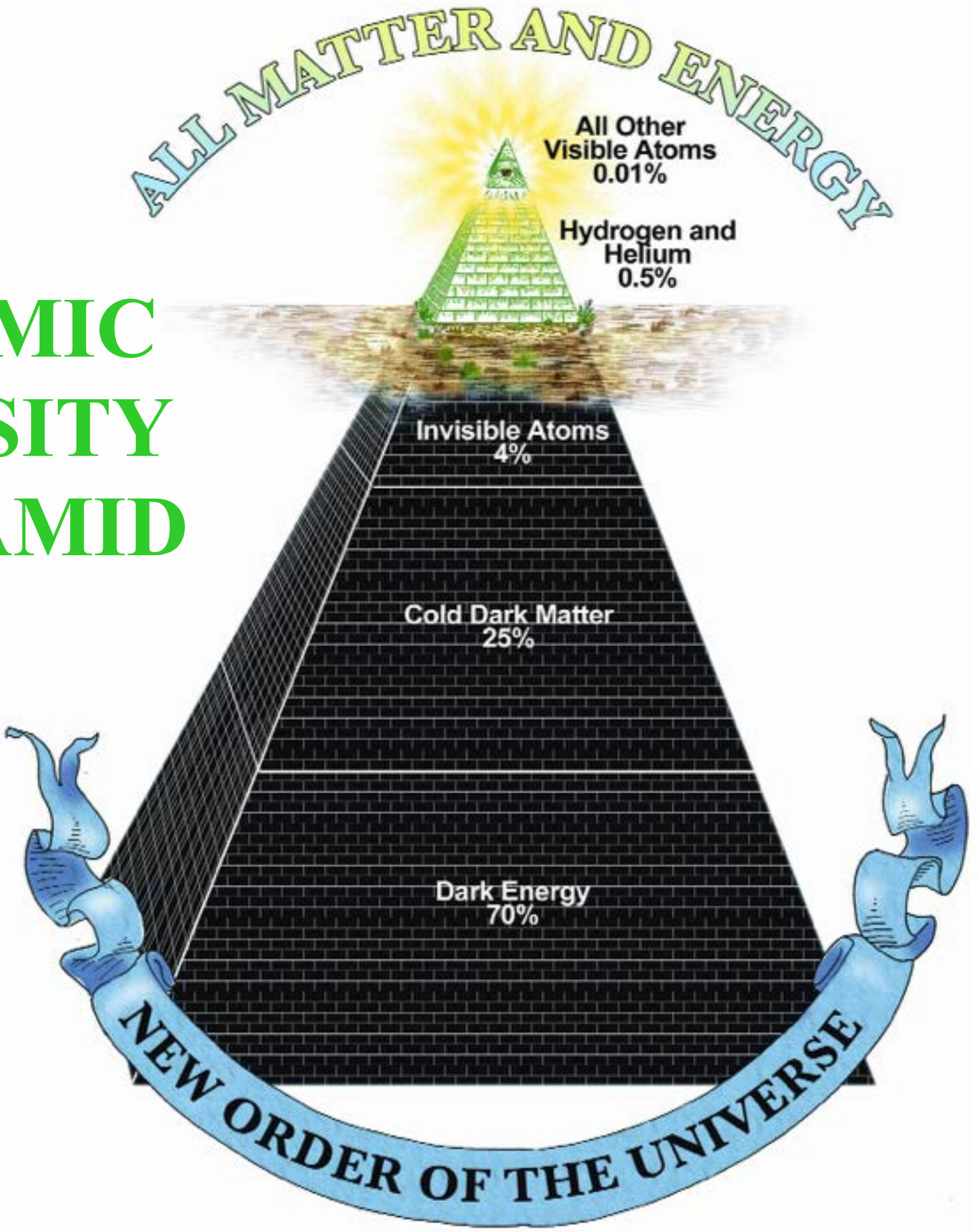
Green - Large Stars

Blue - Supernovae

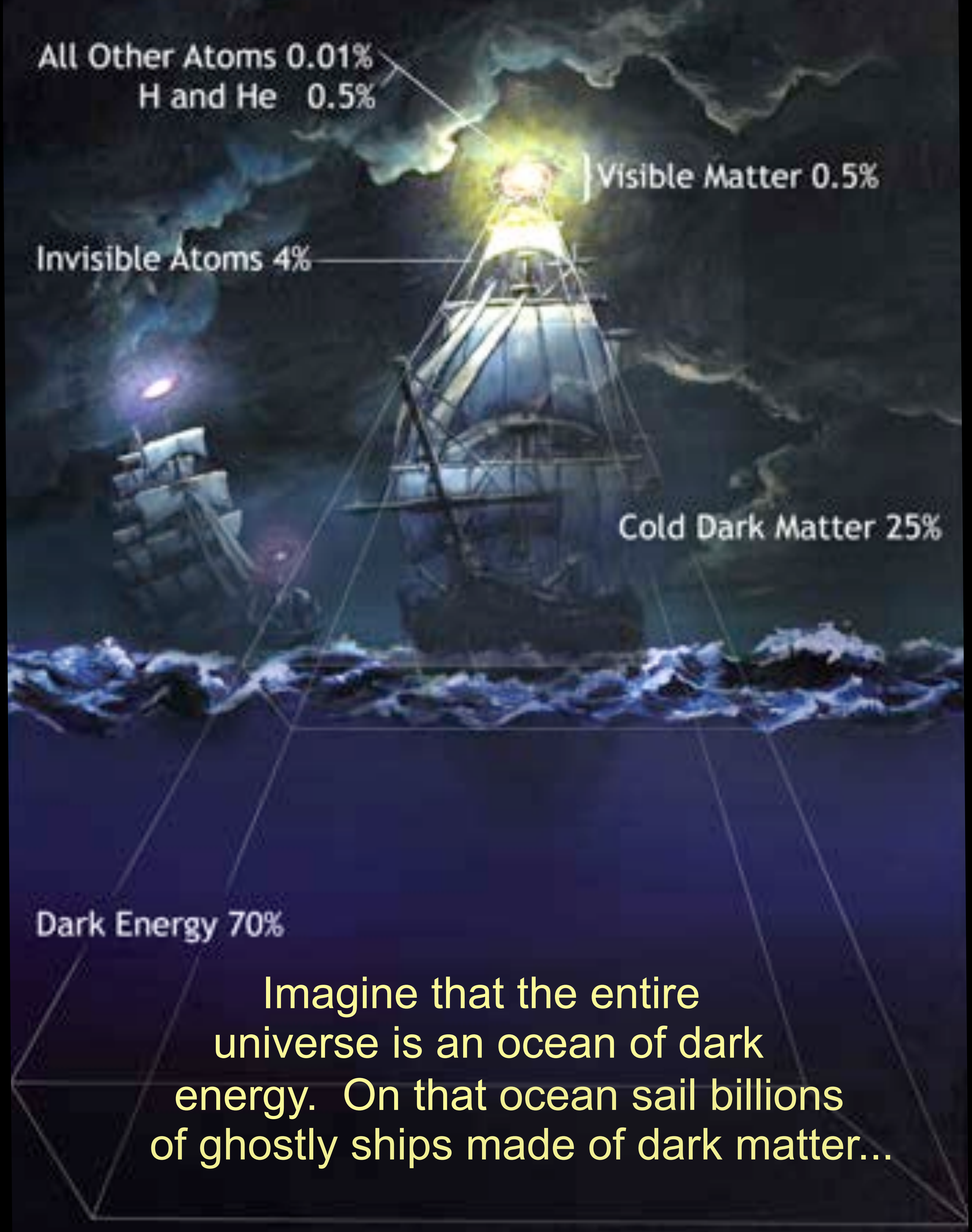
stardust

stars

COSMIC DENSITY PYRAMID



Matter and Energy Content of the Universe

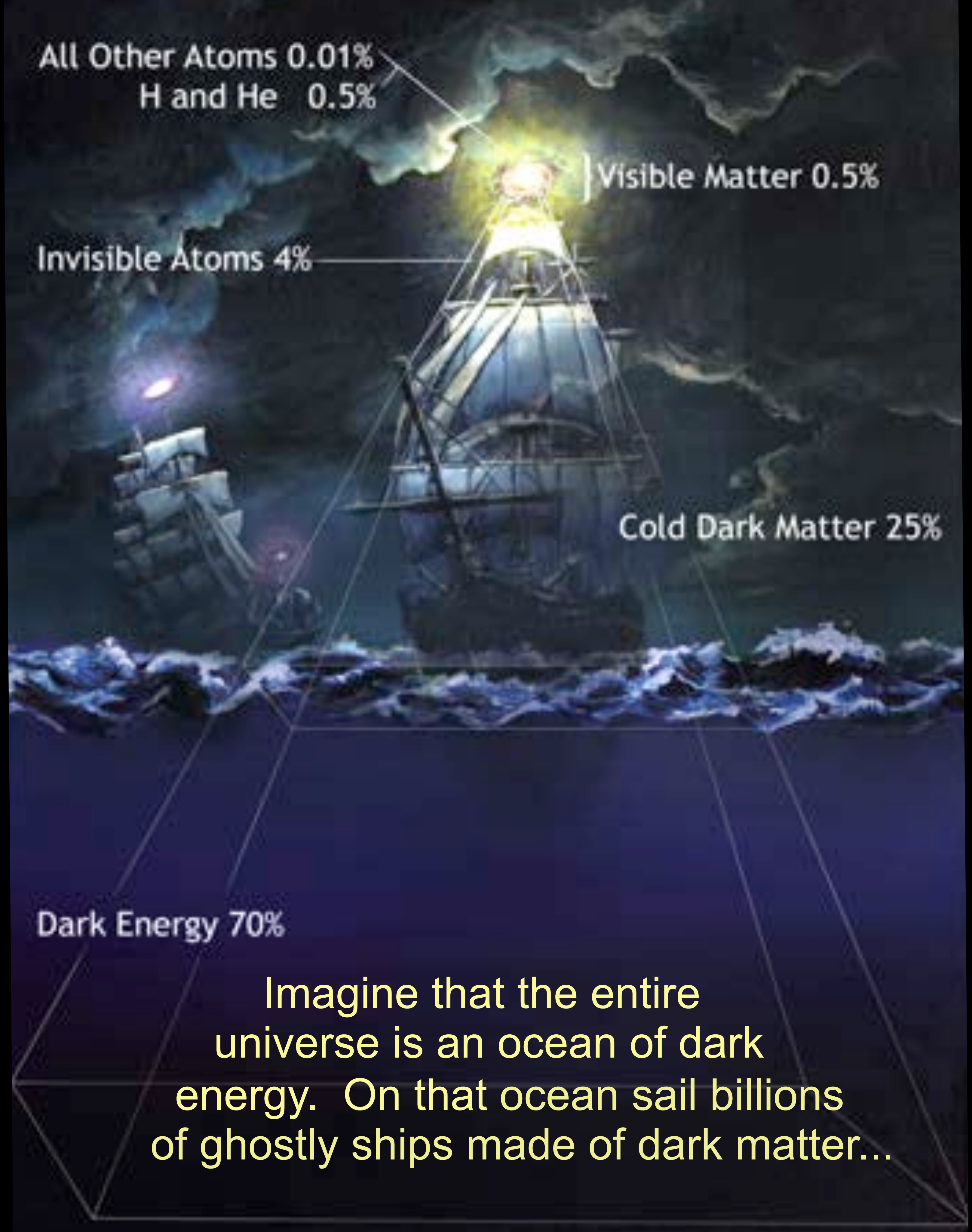


Imagine that the entire universe is an ocean of dark energy. On that ocean sail billions of ghostly ships made of dark matter...

Dark Matter Ships

on a

Dark Energy Ocean



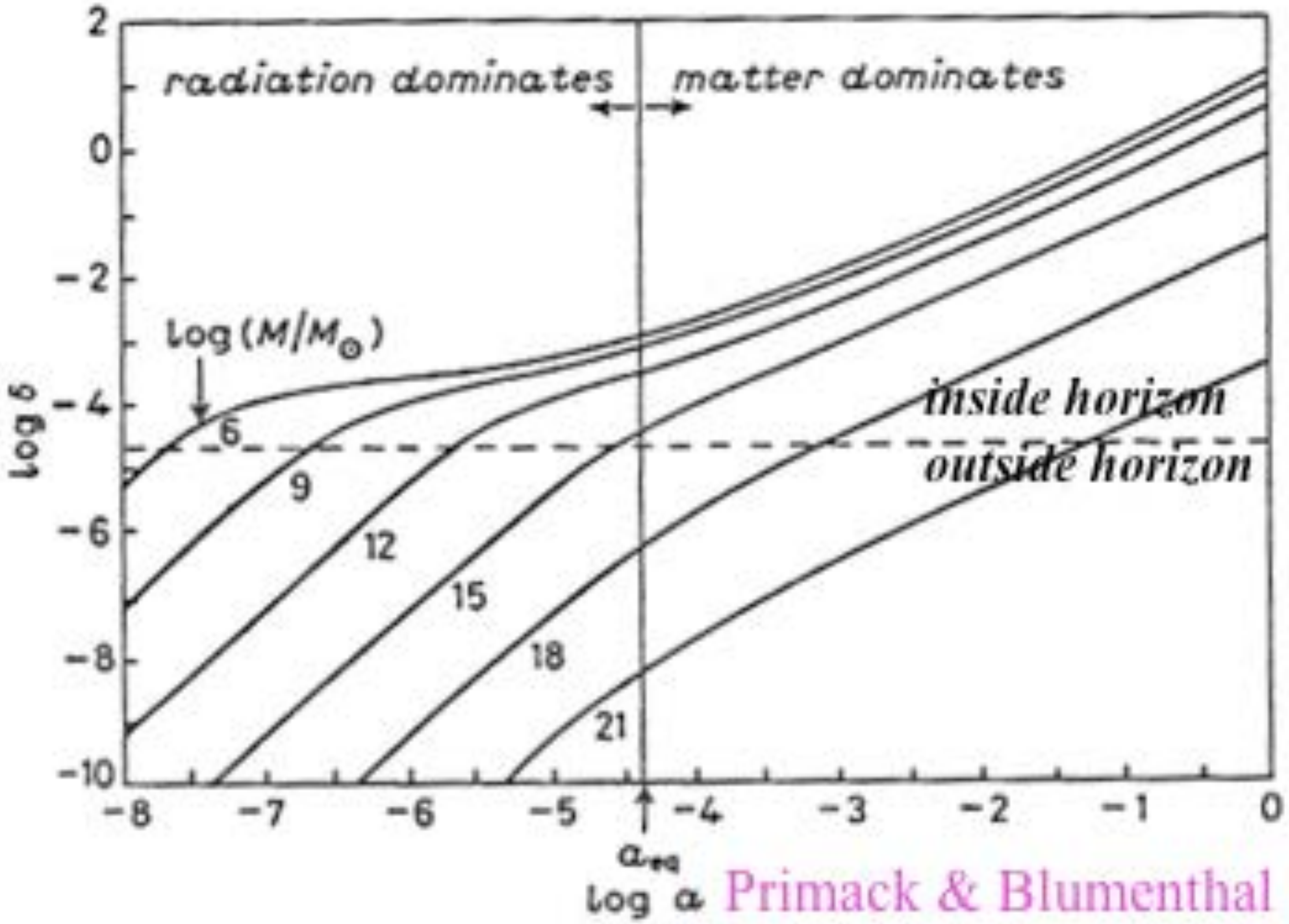
Imagine that the entire universe is an ocean of dark energy. On that ocean sail billions of ghostly ships made of dark matter...

Matter and Energy Content of the Universe

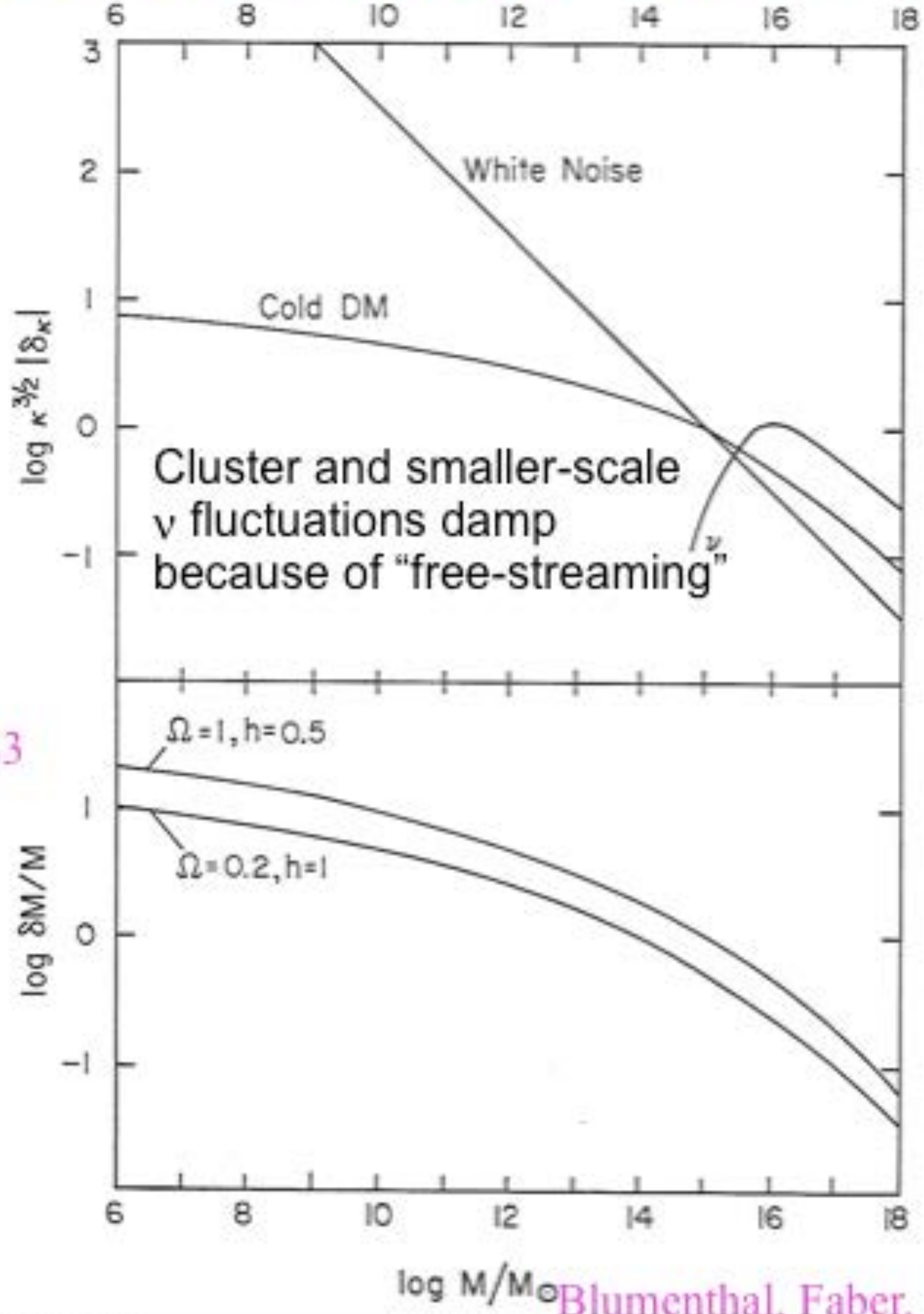
ΛCDM

Double Dark Theory

CDM Structure Formation: Linear Theory



Primack & Blumenthal 1983

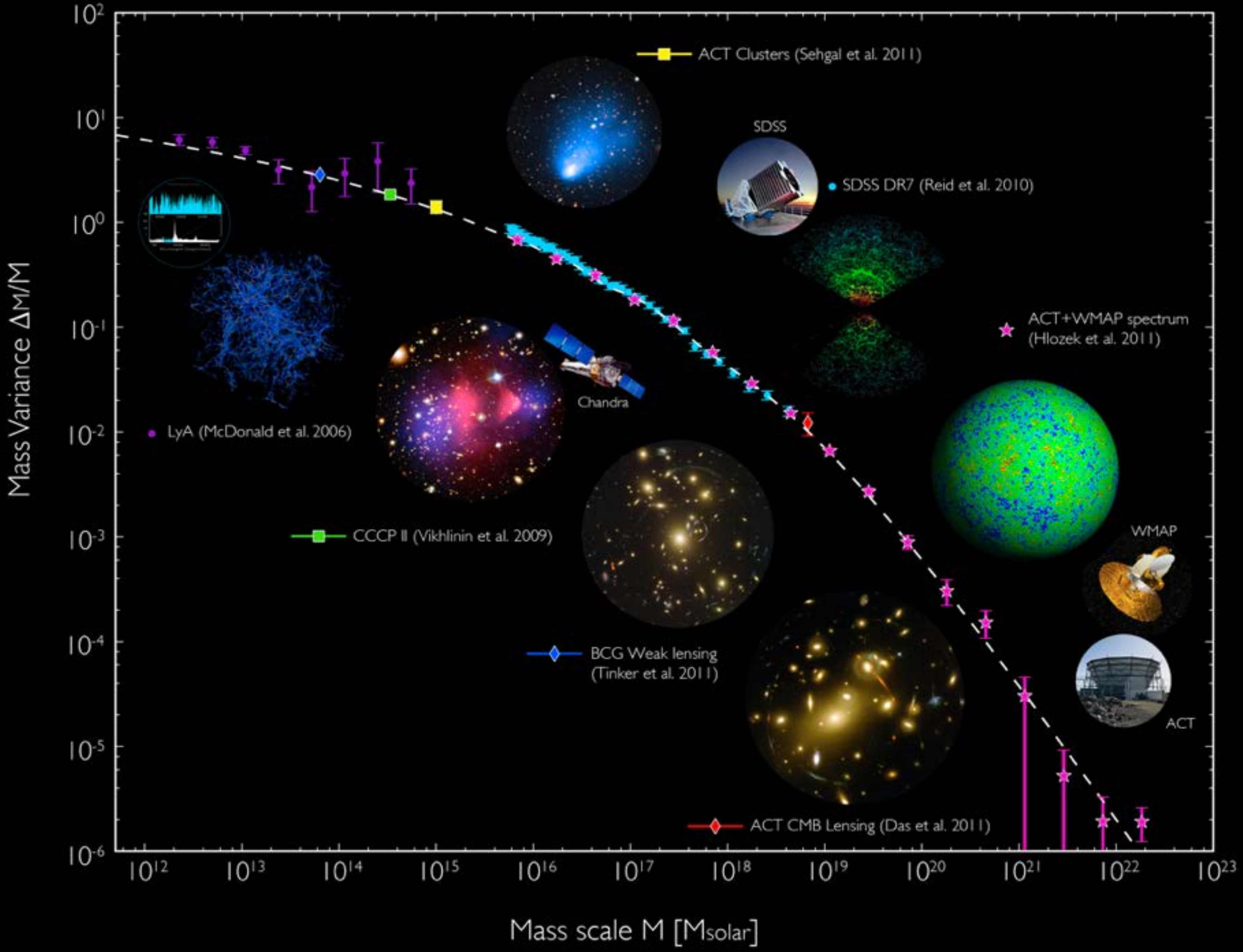


Cluster and smaller-scale ν fluctuations damp because of "free-streaming"

Blumenthal, Faber, Primack, & Rees 1984

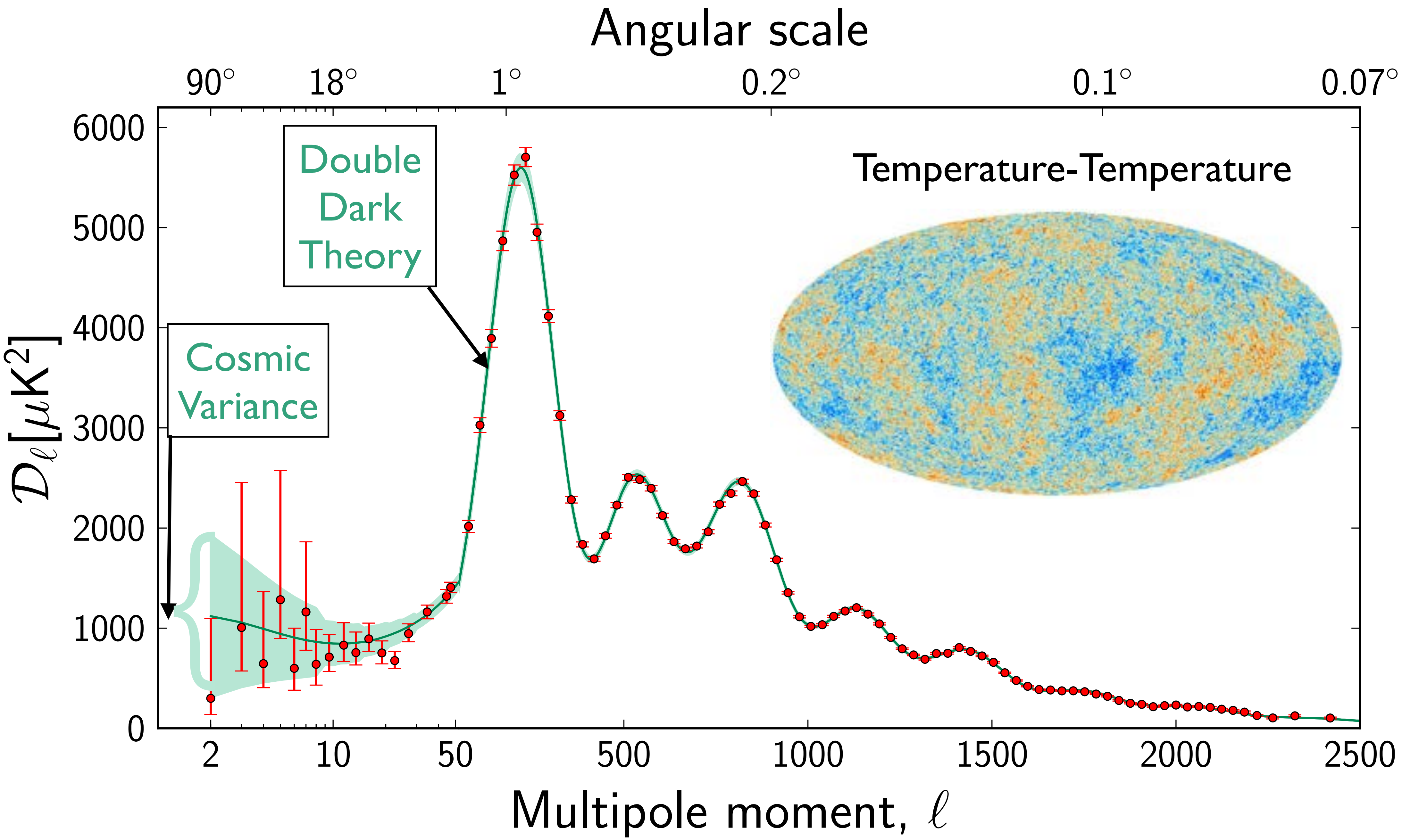
Matter fluctuations that enter the horizon during the radiation dominated era, with masses less than about $10^{15} M_\odot$, grow only $\propto \log a$, because they are not in the gravitationally dominant component. But matter fluctuations that enter the horizon in the matter-dominated era grow $\propto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

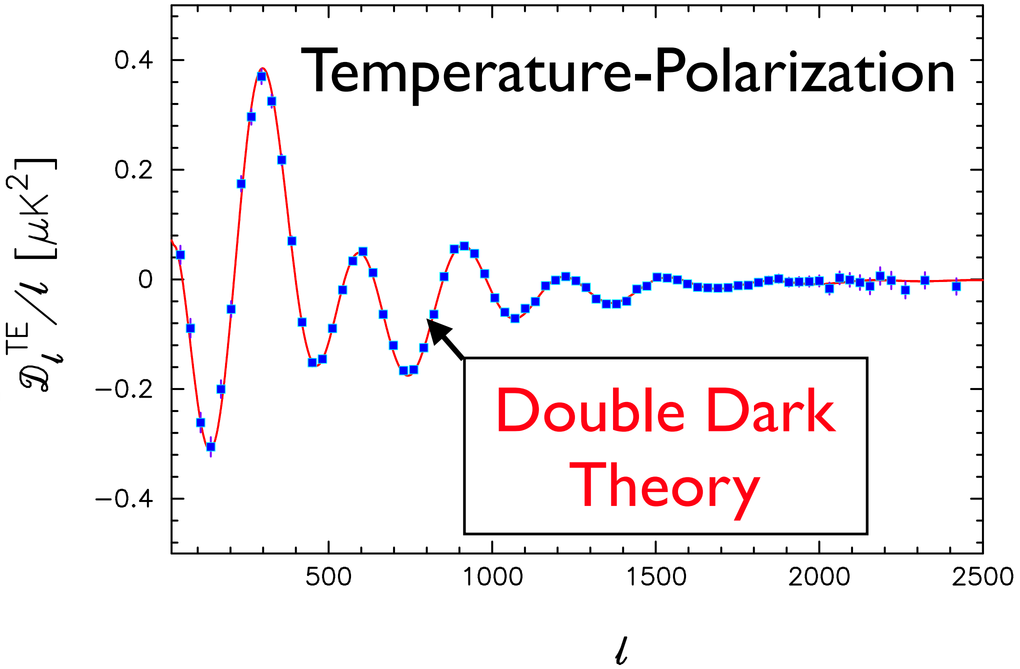
Matter Distribution Agrees with Double Dark Theory!

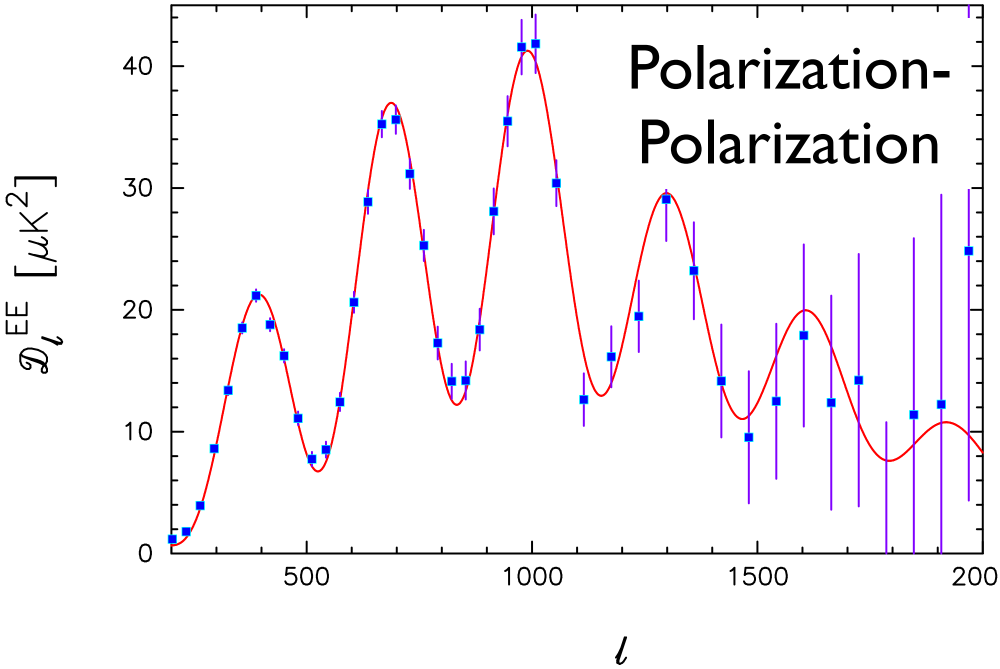


European Space Agency PLANCK Satellite Data

Released March 21, 2013







Cosmological Simulations

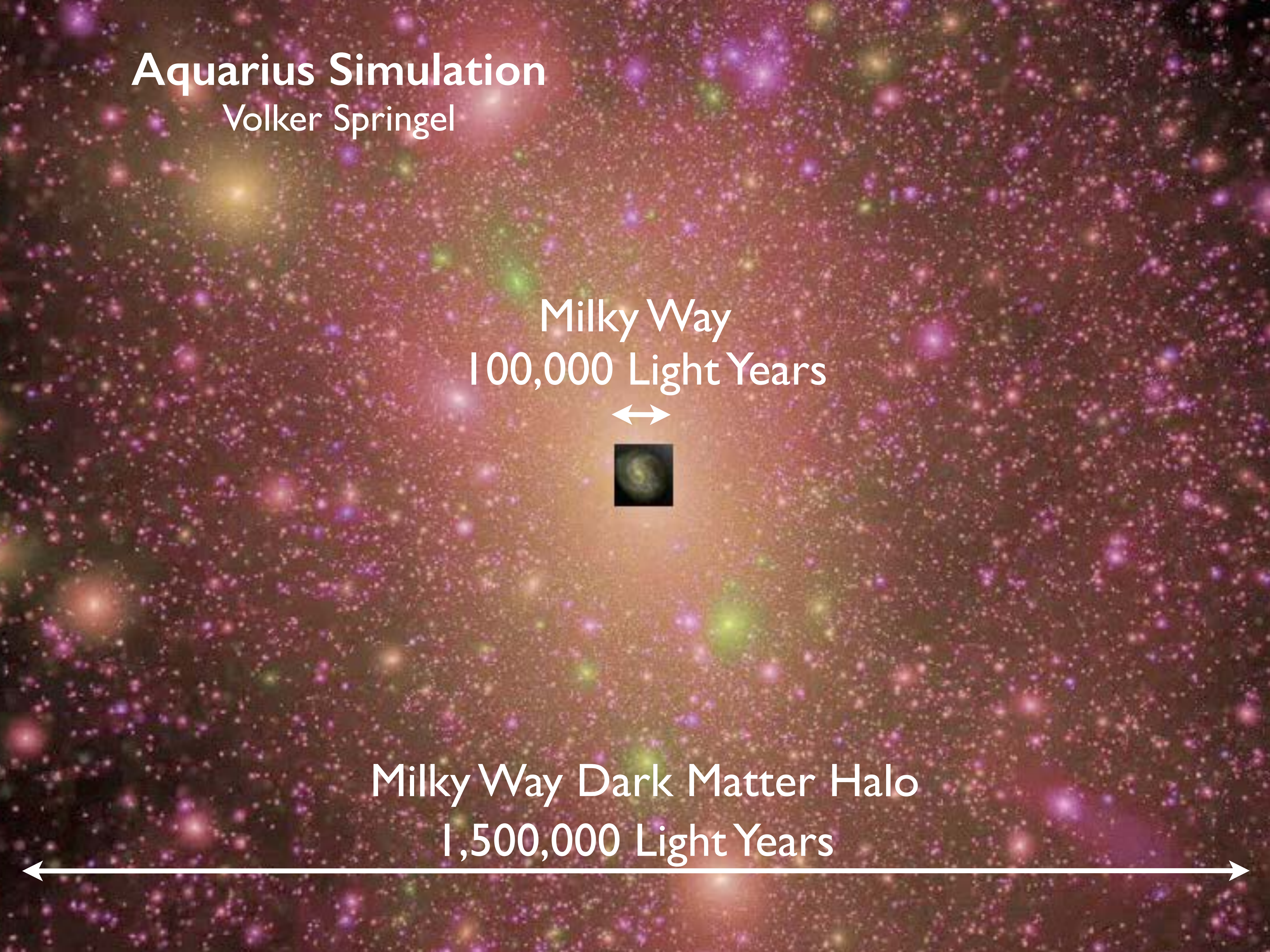
Astronomical observations represent snapshots of moments in time. It is the role of astrophysical theory to produce movies -- both metaphorical and actual -- that link these snapshots together into a coherent physical theory.

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

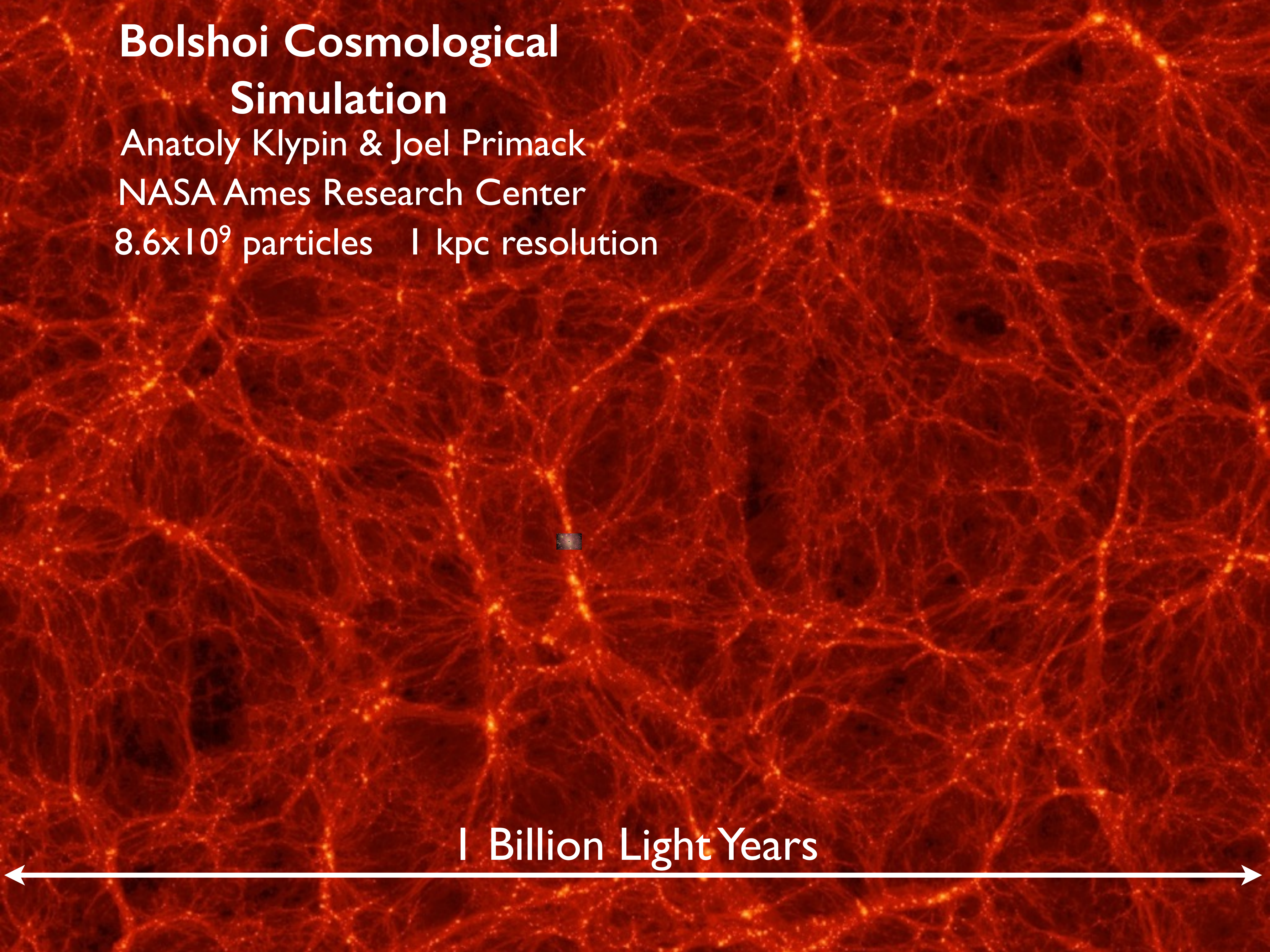
Aquarius Simulation

Volker Springel



Milky Way
100,000 Light Years

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



Bolshoi Cosmological Simulation

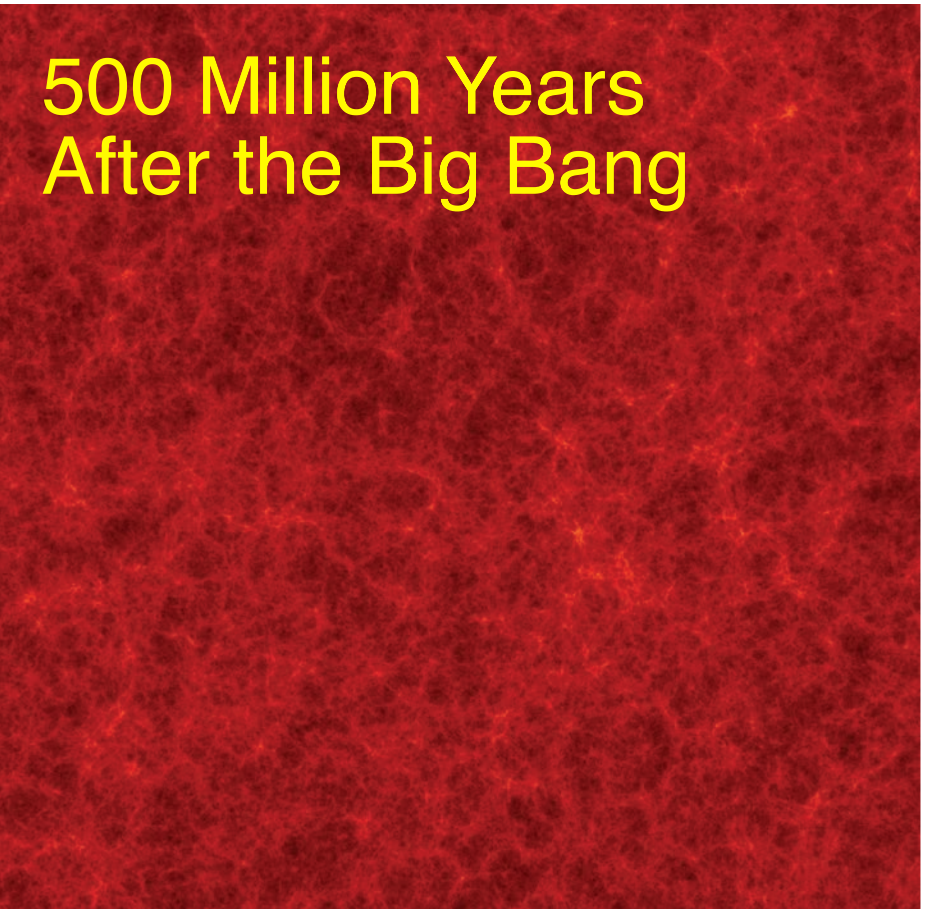
Anatoly Klypin & Joel Primack

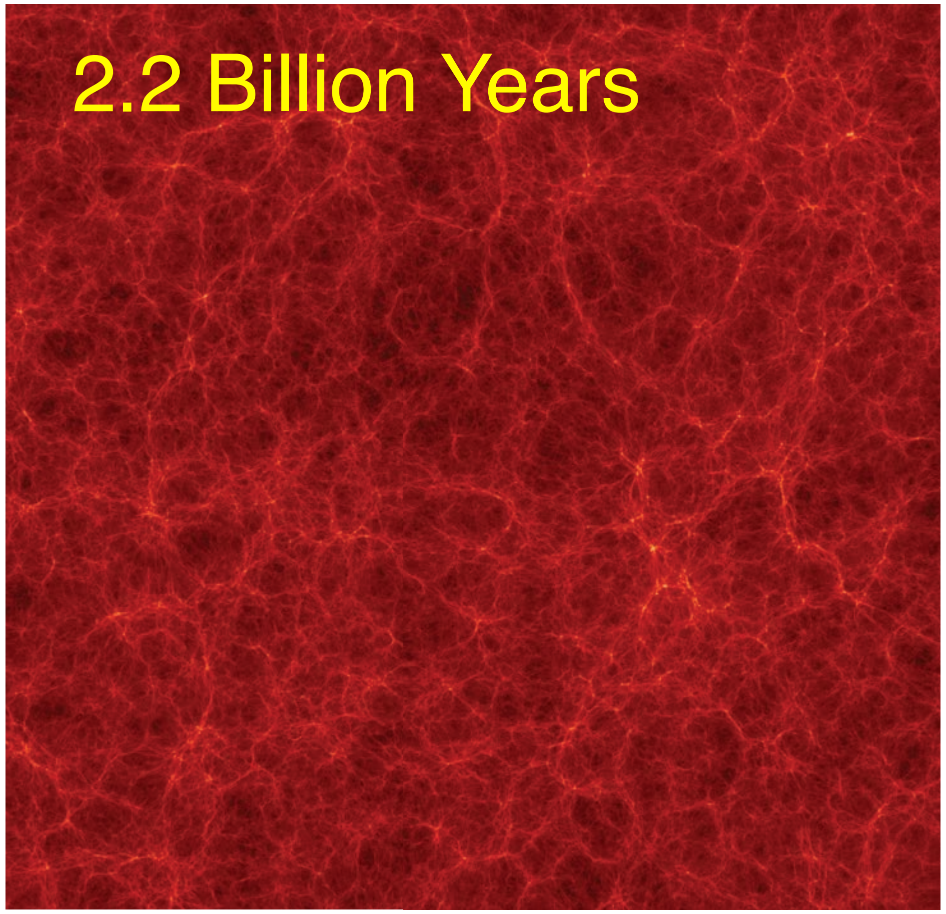
NASA Ames Research Center

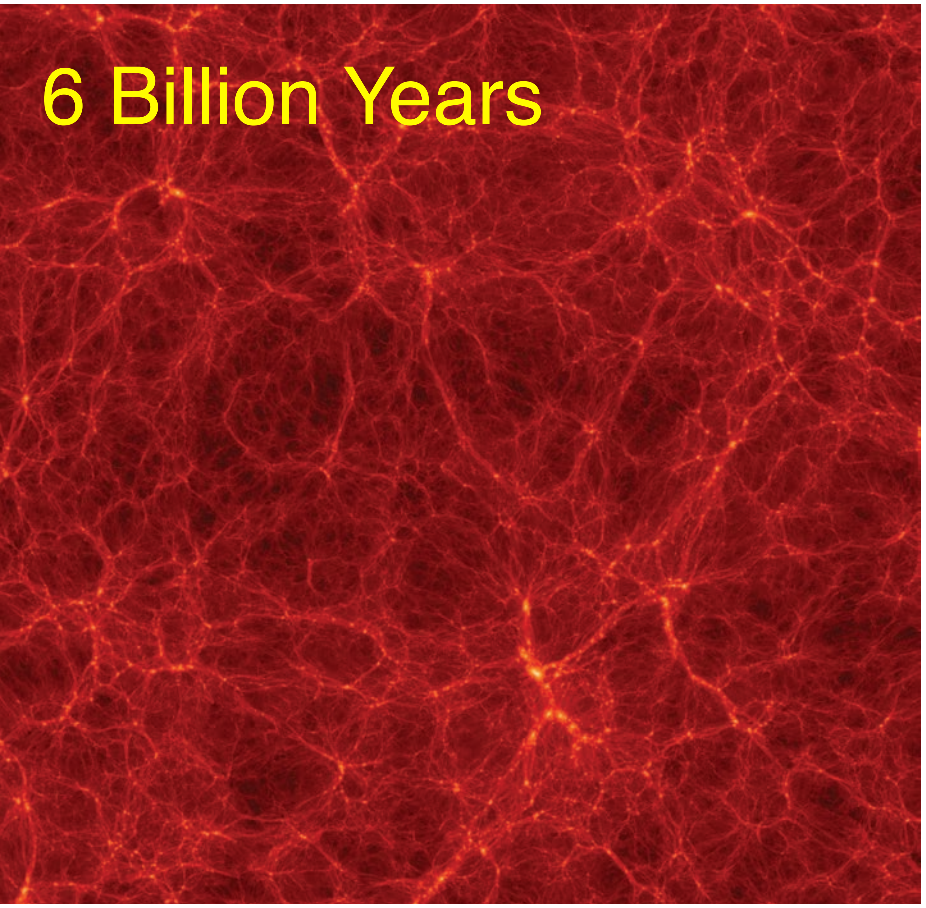
8.6×10^9 particles 1 kpc resolution

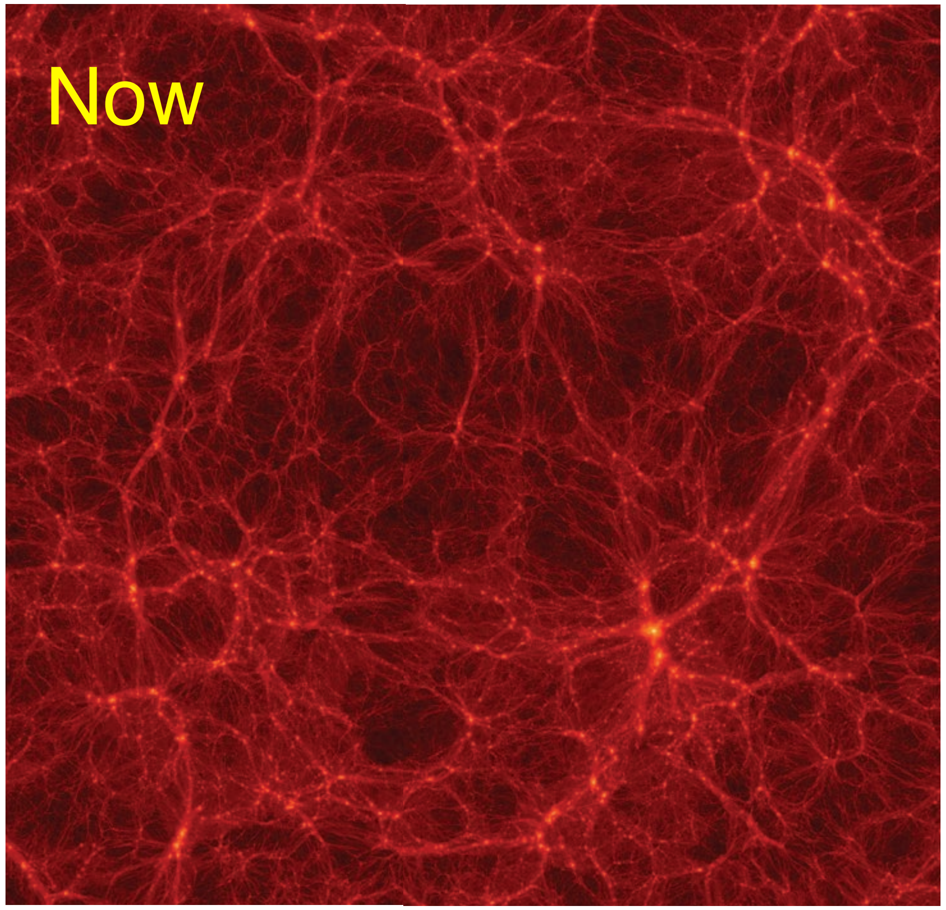
IEEE Spectrum - October 2012

THE UNIVERSE IN A SUPERCOMPUTER









COSMIC WEB: The Bolshoi simulation models the evolution of dark matter, which is responsible for the large-scale structure of the universe. Here, snapshots from the simulation show the dark matter distribution at 500 million and 2.2 billion years [top] and 6 billion and 13.7 billion years [bottom] after the big bang. These images are 50-million-light-year-thick slices of a cube of simulated universe that today would measure roughly 1 billion light-years on a side and encompass about 100 galaxy clusters.

SOURCES: SIMULATION, ANATOLY KLYPIN AND JOEL R. PRIMACK; VISUALIZATION, STEFAN GOTTLÖBER/LEIBNIZ INSTITUTE FOR ASTROPHYSICS POTSDAM

To understand the cosmos, we must evolve it all over again

By Joel R. Primack

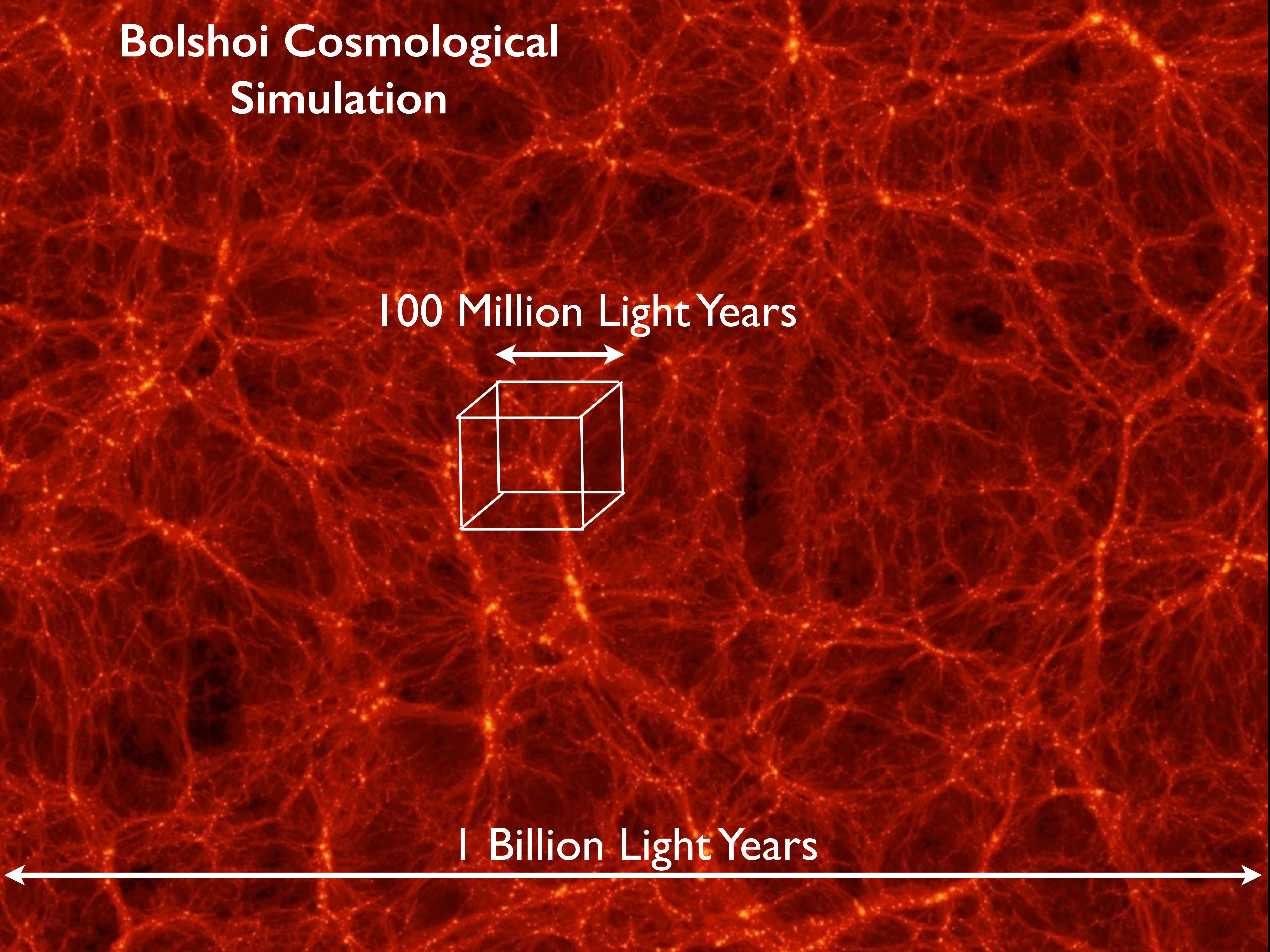
WHEN IT COMES TO RECONSTRUCTING THE PAST, you might think that astrophysicists have it easy. After all, the sky is awash with evidence. For most of the universe's history, space has been largely transparent, so much so that light emitted by distant galaxies can travel for billions of years before finally reaching Earth. It might seem that all researchers have to do to find out what the universe looked like, say, 10 billion years ago is to build a telescope sensitive enough to pick up that ancient light.

Actually, it's more complicated than that. Most of the ordinary matter in the universe—the stuff that makes up all the atoms, stars, and galaxies astronomers can see—is invisible, either sprinkled throughout intergalactic space in tenuous forms that emit and absorb little light or else swaddled inside galaxies in murky clouds of dust and gas. When astronomers look out into the night sky with their most powerful telescopes, they can see no more than about 10 percent of the ordinary matter that's out there.

To make matters worse, cosmologists have discovered that if you add up all the mass and energy in the universe, only a small fraction is composed of ordinary matter. A good 95 percent of the cosmos is made up of two very different kinds of invisible and as-yet-unidentified stuff that is "dark," meaning that it emits and absorbs no light at all. One of these mysterious components, called dark matter, seems immune to all fundamental forces except gravity and perhaps the weak interaction, which is responsible for

6 Billion Years

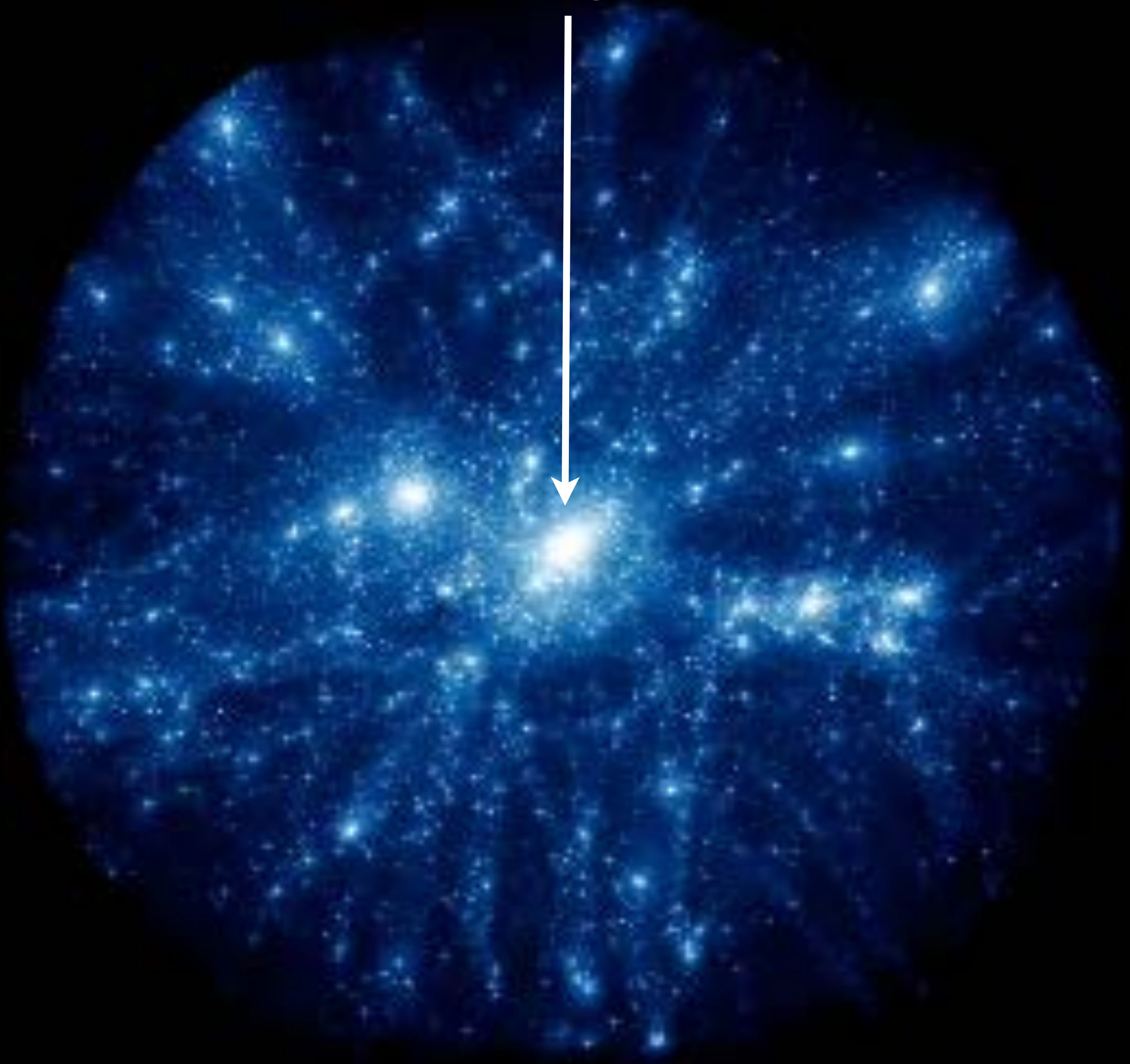
Bolshoi Cosmological Simulation



Bolshoi Cosmological Simulation

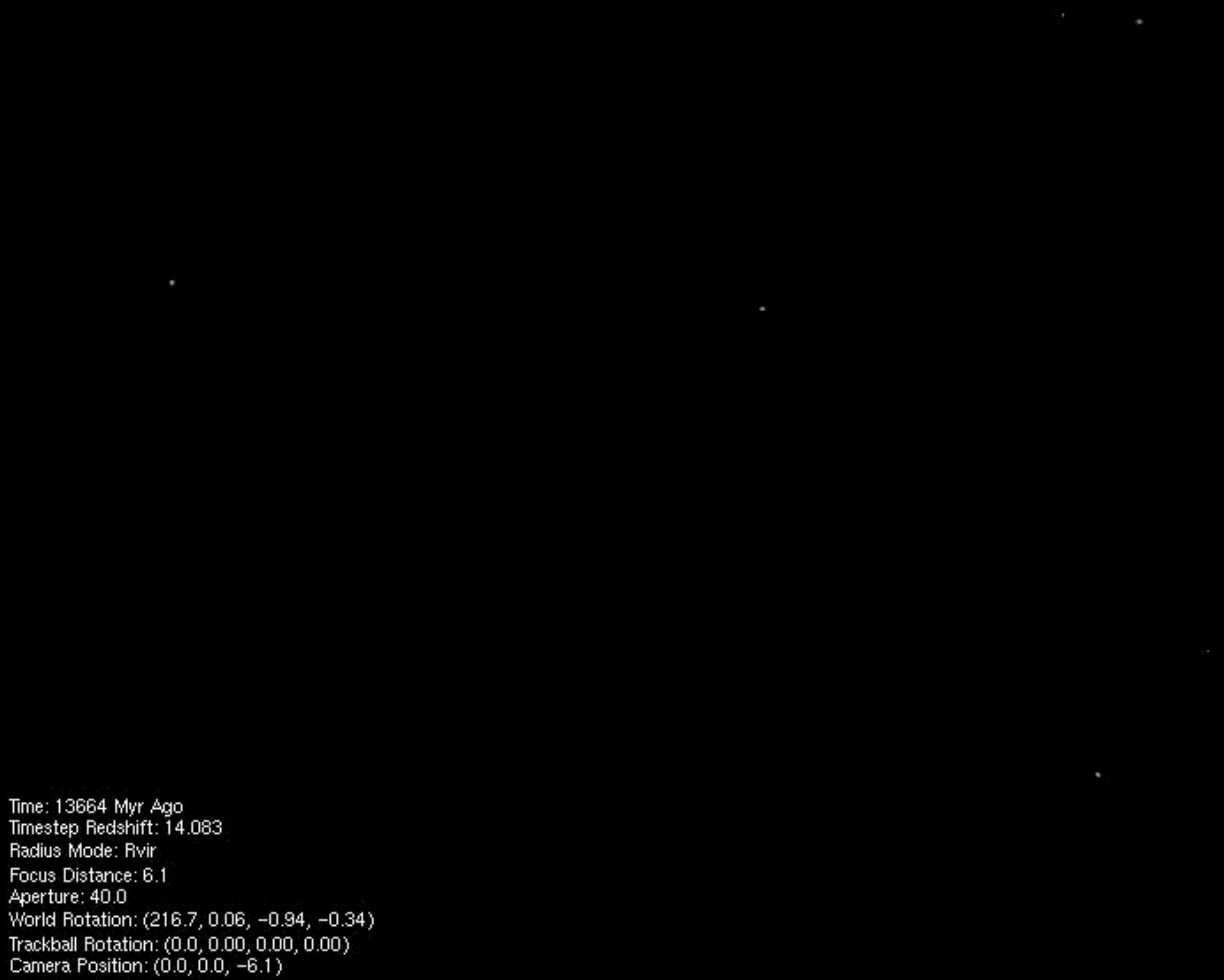
100 Million Light Years

How the Halo of the Big Cluster Formed



How the Halo of the Big Cluster Formed

Merger Tree (History) of All the Halos that Have Merged by Today



```
Time: 13664 Myr Ago
Timestep Redshift: 14.083
Radius Mode: Rvir
Focus Distance: 6.1
Aperture: 40.0
World Rotation: (216.7, 0.06, -0.94, -0.34)
Trackball Rotation: (0.0, 0.00, 0.00, 0.00)
Camera Position: (0.0, 0.0, -6.1)
```

Peter Behroozi

SKY & TELESCOPE

Dive Deep In the Lagoon p. 61

JULY 2012

Universe in a Box

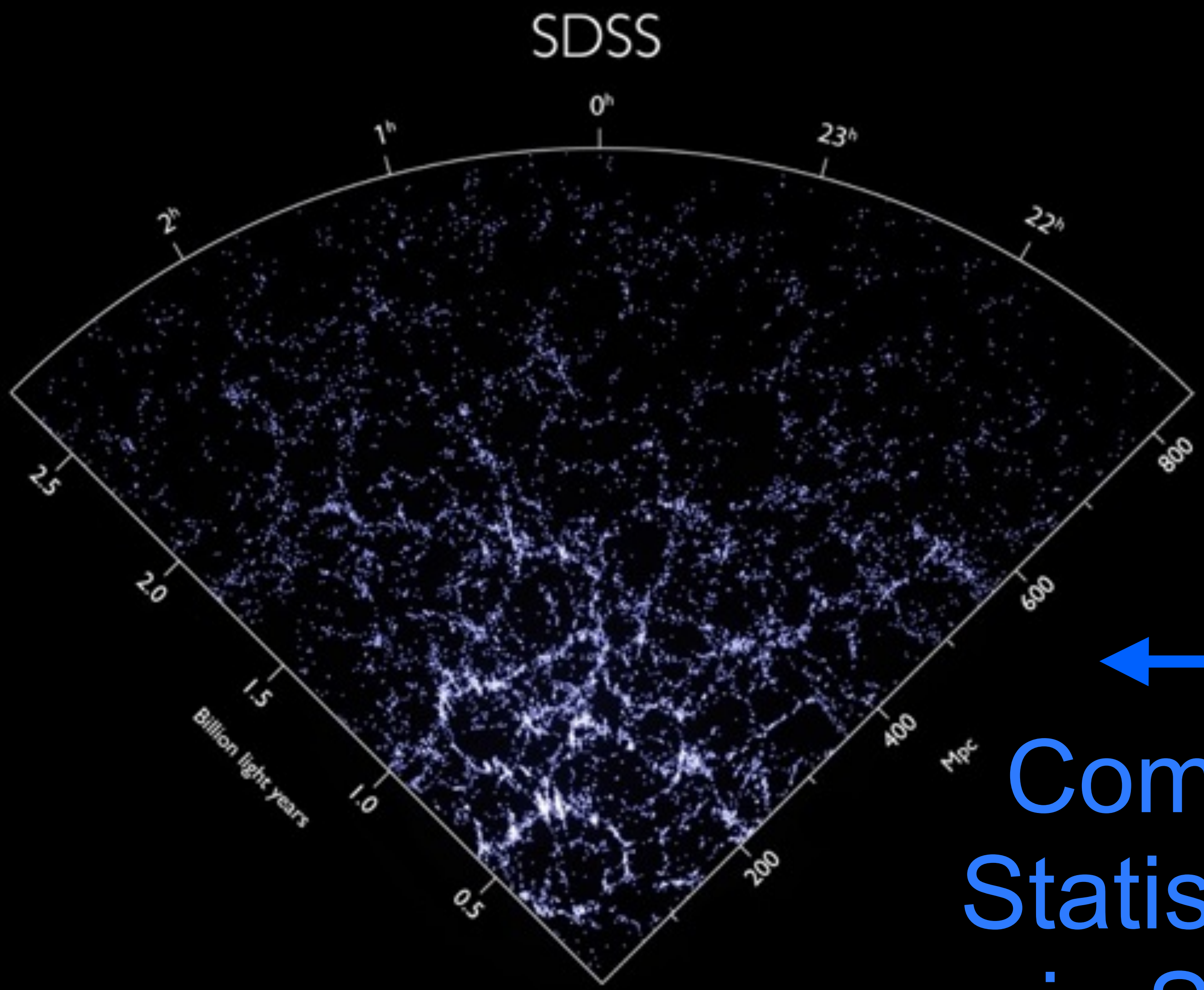
From the Big Bang to Now p. 26

Observational Data

Sloan Digital Sky Survey

Bolshoi Simulation

Anatoly Klypin, Joel Primack, Peter Behroozi
Risa Wechsler, Ralf Kahler, Nina McCurdy



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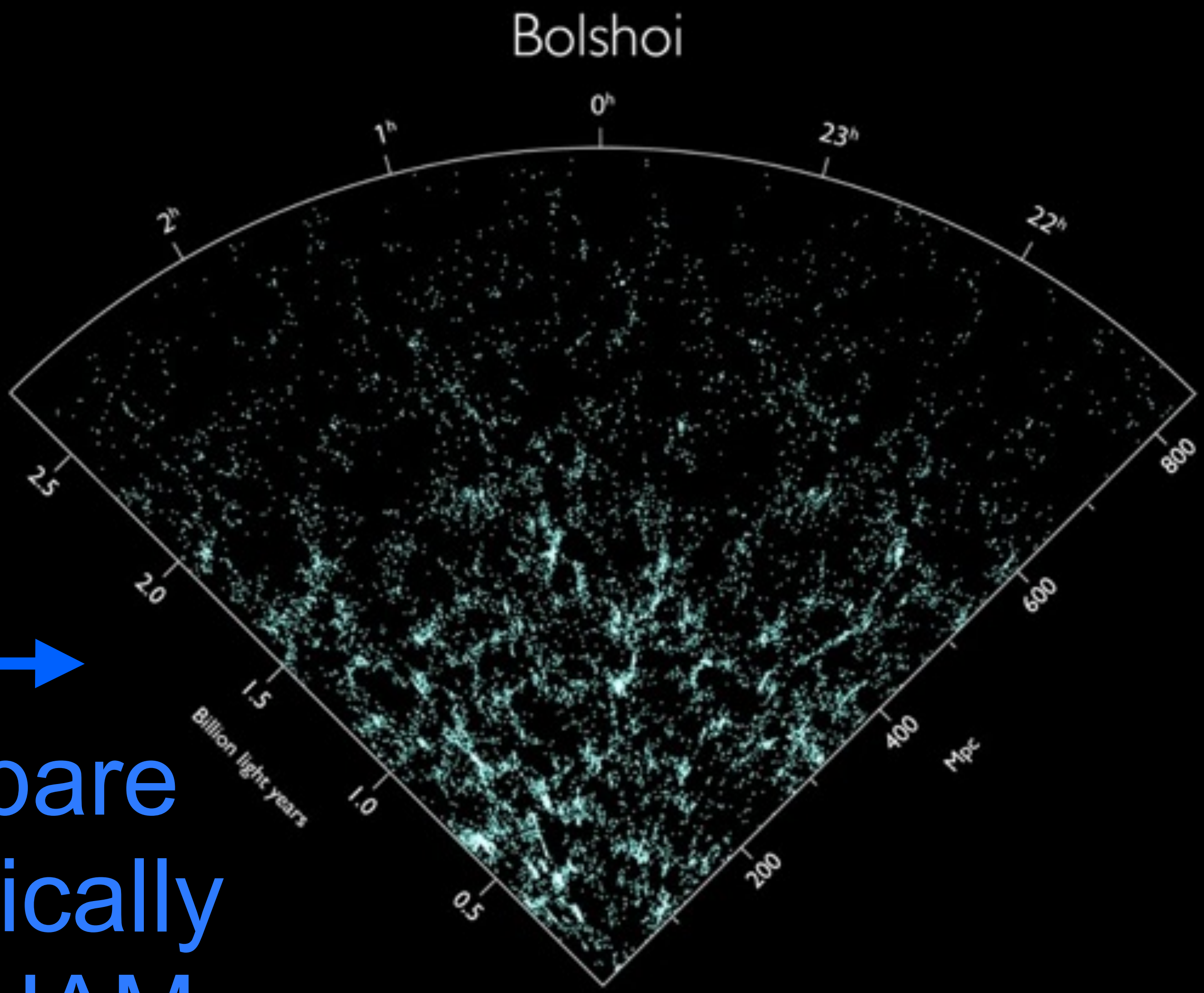
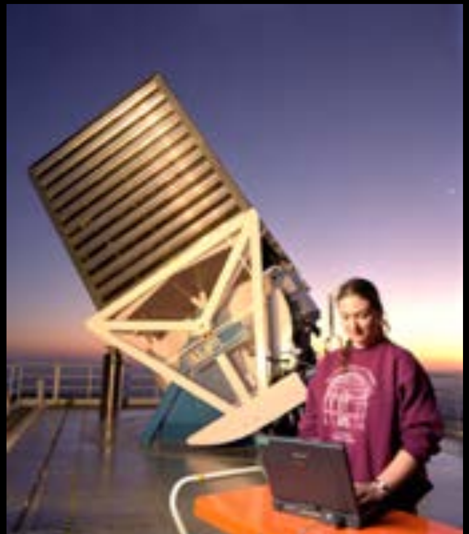
Compare
Statistically
via SHAM





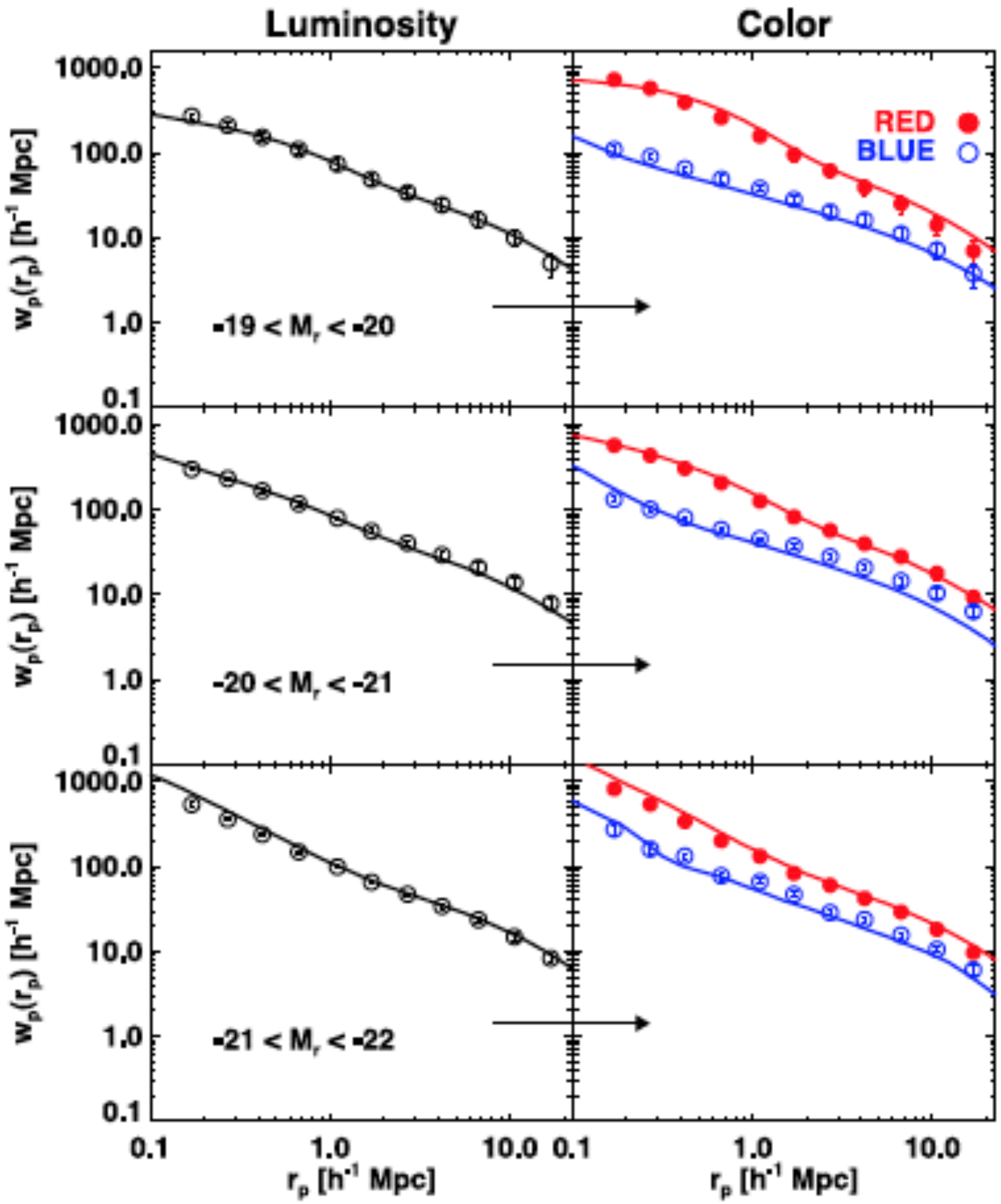
The dark side of galaxy colour

Andrew P. Hearin & Douglas F. Watson MNRAS 435, 1313 (2013)

Hearin and Watson 2013 showed that by extending the traditional abundance matching formalism to consider an additional halo property beyond V_{max}, the observed spatial distribution of galaxies as a function of luminosity and color could be accurately reproduced. Specifically, the authors considered the redshift, dubbed z_{starve}, that correlates with the epoch at which the star formation in the galaxy is likely stifled, ultimately leading to the quenching of the galaxy.

By using Bolshoi merger trees to map the full mass assembly history (MAH) of halos, a halo's z_{starve} value is determined by whichever of the following three events happens first in its MAH: (1) the epoch a halo accretes onto a larger halo, thus becoming a subhalo, (2) the epoch a halo reaches a characteristic mass, and (3) the epoch a halo transitioned from the fast- to slow-accretion regime. Under the simple assumption that z_{starve} correlates with g – r color at fixed luminosity, the age matching technique was able to accurately predict color-dependent clustering in the Sloan Digital Sky Survey (SDSS) and a variety of galaxy group statistics. **The success of the model supports the idea that the assembly history of ΛCDM halos and their central galaxies are correlated.**

Galaxy Angular Correlations



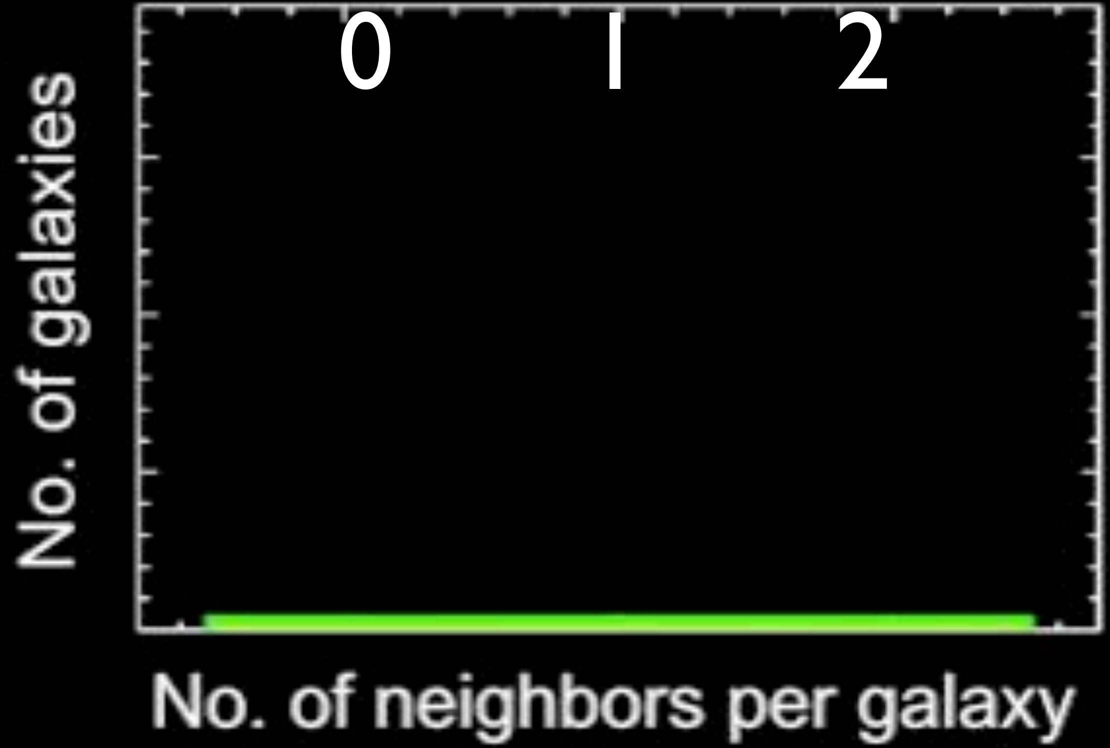
The Milky Way has two large satellite galaxies, the small and large Magellanic Clouds

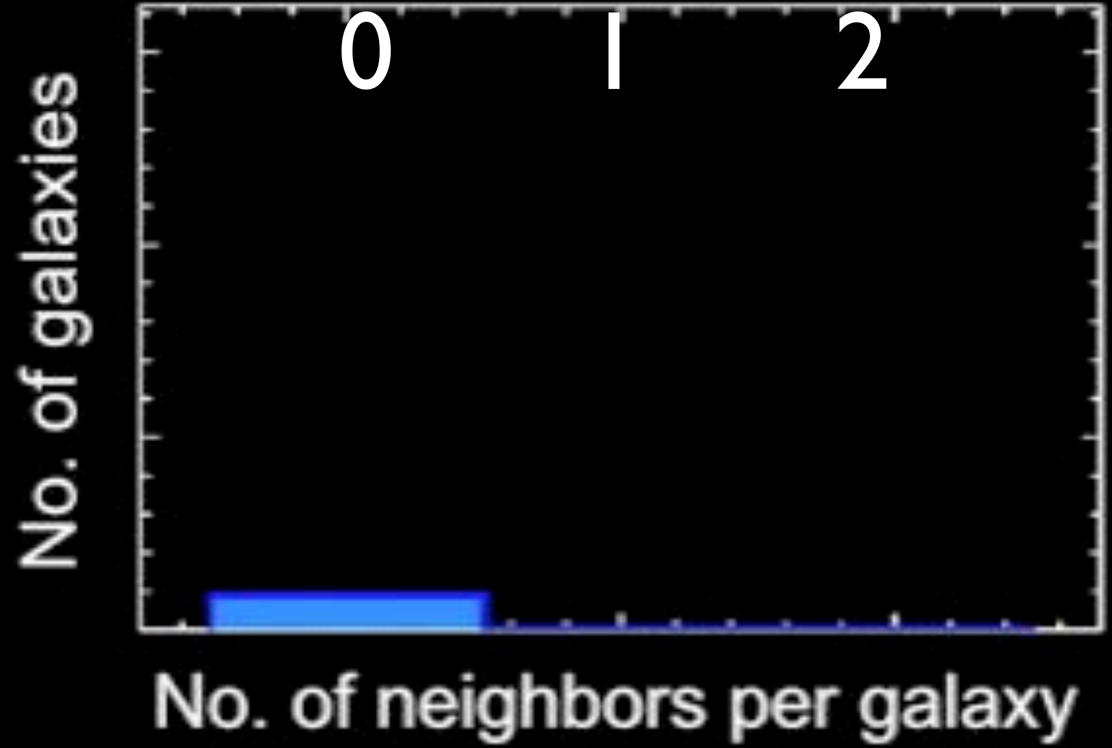
How common is this?

The Bolshoi simulation + sub-halo abundance matching predicts the likelihood of 0, 1, 2, 3, ... large satellites

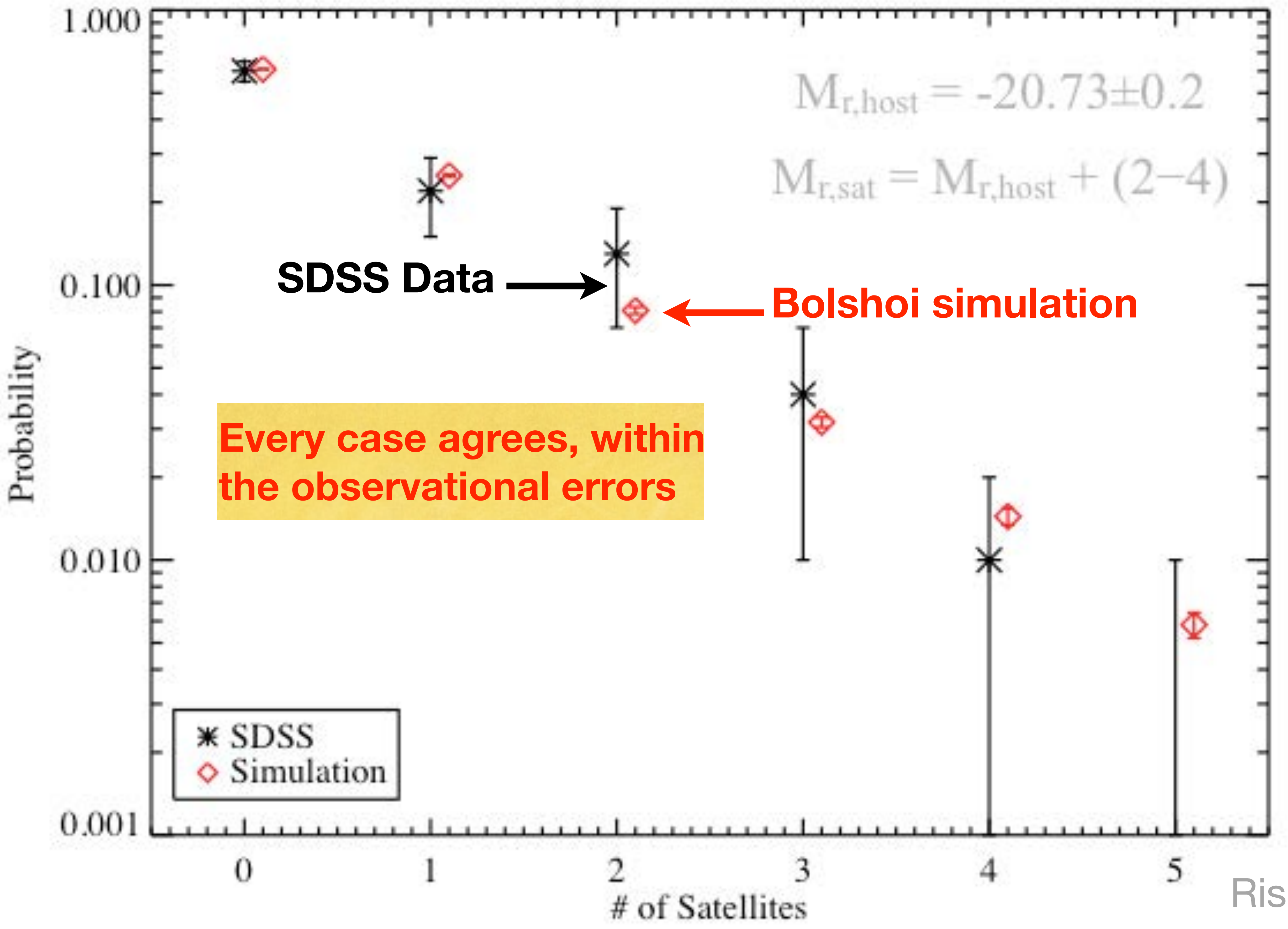

SDSS sky
E
W
S


Bolshoi simulation


0
1
2
No. of galaxies
No. of neighbors per galaxy


0
1
2
No. of galaxies
No. of neighbors per galaxy

Statistics of MW bright satellites:
Sloan Digital Sky Survey data vs. Bolshoi simulation



SDSS Data

Bolshoi simulation

Every case agrees, within the observational errors

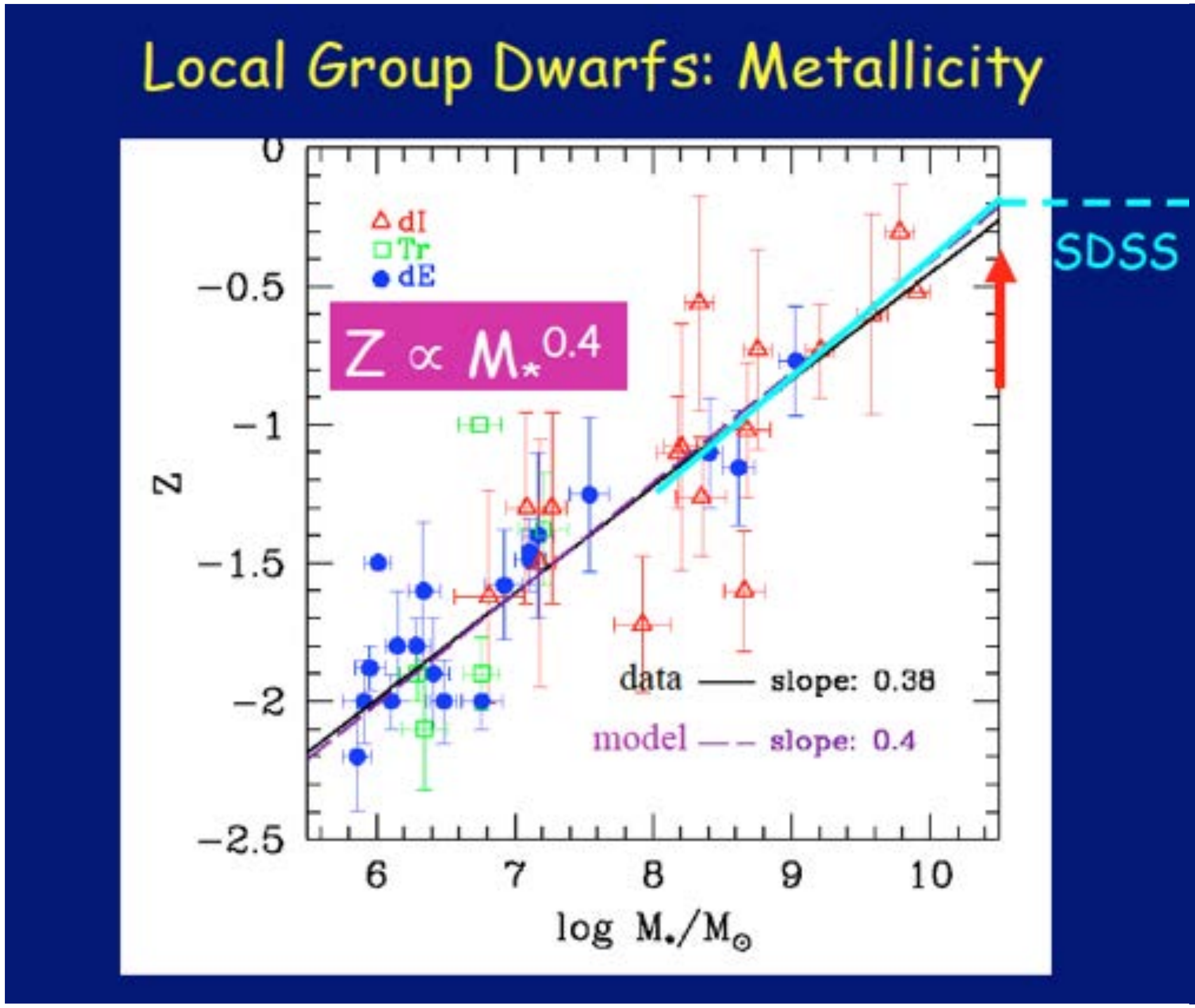
Risa Wechsler

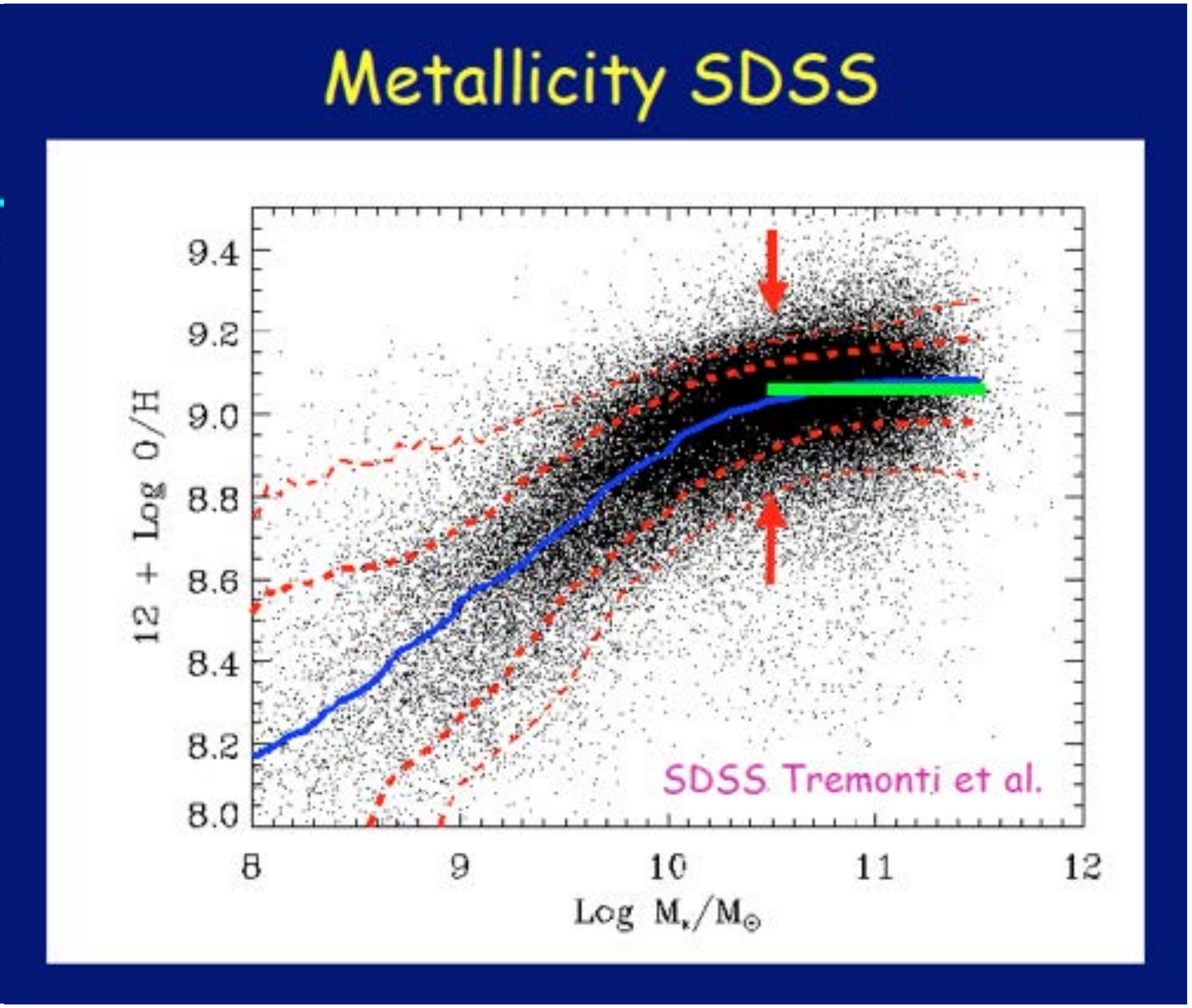
Busha et al. 2011 ApJ
Liu et al. 2011 ApJ

Galaxy Metallicity Observations

$Z \propto M_{*}$, $M_{*} < 3\mathrm{x}10^{10}\ M_{\odot}$

$Z \approx \mathrm{const}$, $M_{*} < 3\mathrm{x}10^{10}\ M_{\odot}$

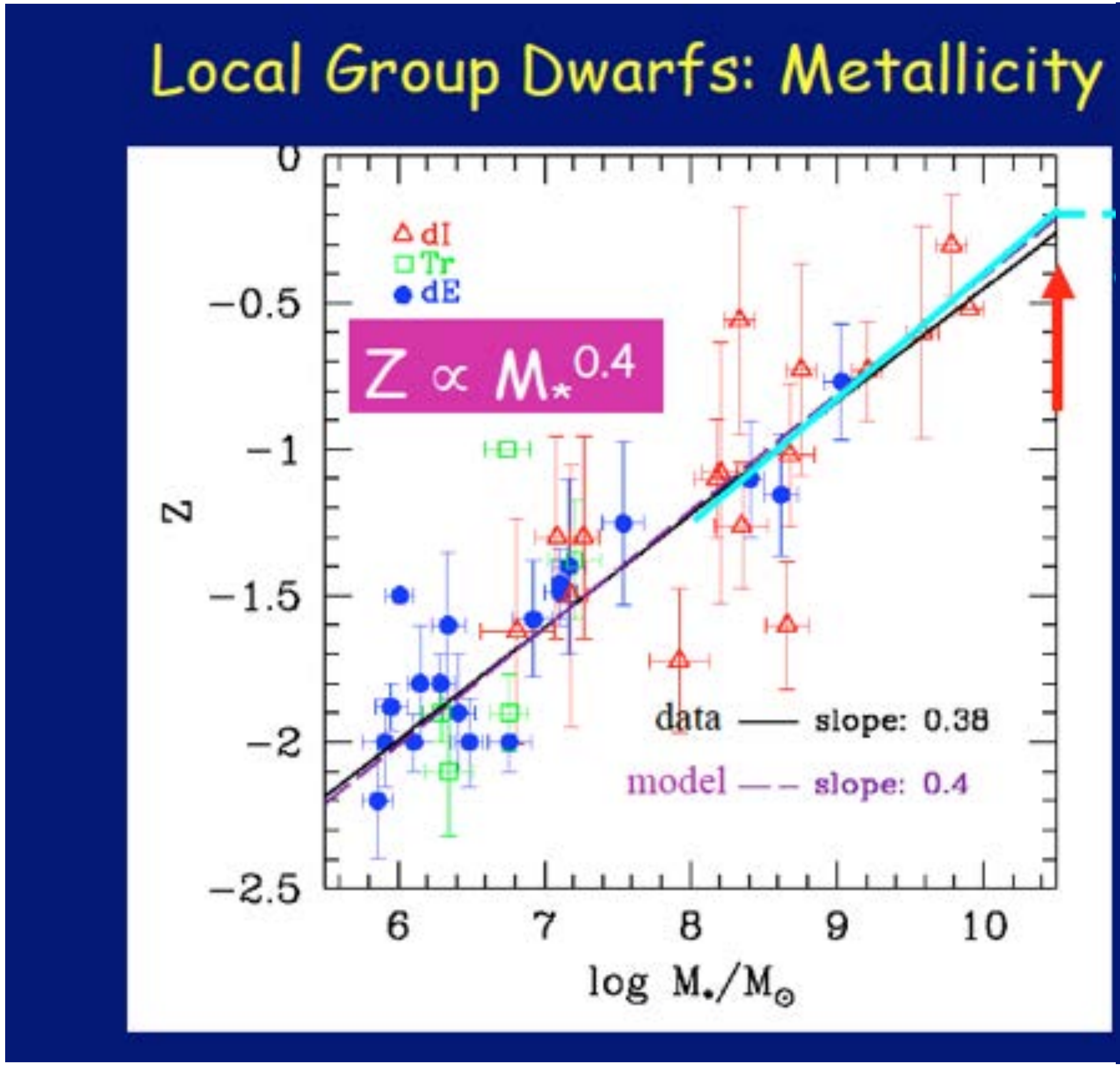

Local Group Dwarfs: Metallicity


Metallicity SDSS

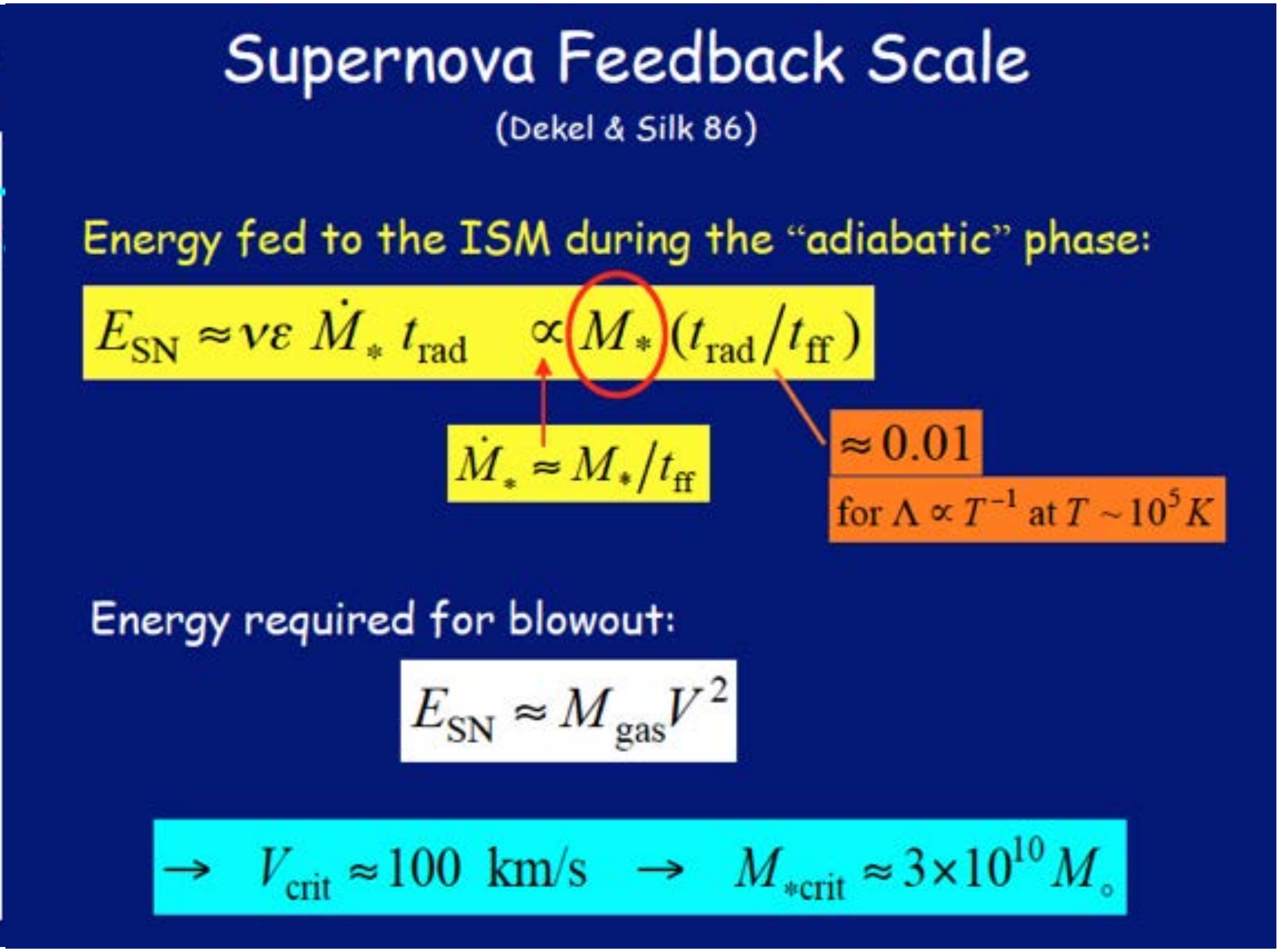
Galaxy Metallicity Observations

$Z \propto M_*$, $M_* < 3\times10^{10}\ M_\odot$

Supernova Feedback Explanation



Local Group Dwarfs: Metallicity



Supernova Feedback Scale

(Dekel & Silk 86)

Energy fed to the ISM during the "adiabatic" phase:

$$E_{SN} \approx \nu\varepsilon \dot{M}_* t_{rad} \propto M_* (t_{rad}/t_{ff})$$

$$\dot{M}_* \approx M_*/t_{ff}$$

≈ 0.01

for $\Lambda \propto T^{-1}$ at $T \sim 10^5 K$

Energy required for blowout:

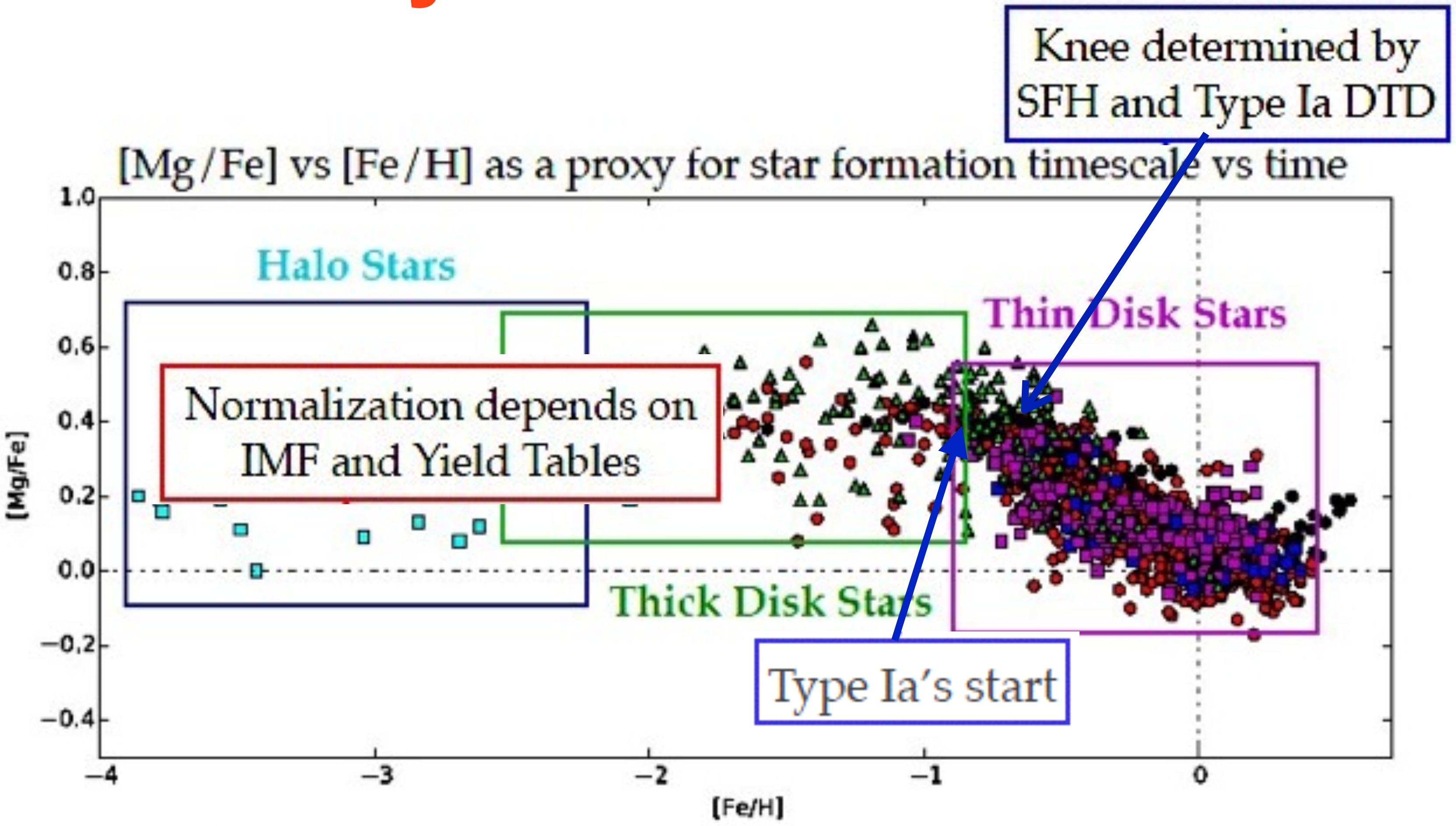
$$E_{SN} \approx M_{gas} V^2$$

$$\rightarrow \quad V_{crit} \approx 100\ \text{km/s} \quad \rightarrow \quad M_{*crit} \approx 3\times10^{10} M_\circ$$

Galaxy Metallicity Observations

Milky Way Chemical Evolution

Star Formation Timescale



[Mg/Fe] vs [Fe/H] as a proxy for star formation timescale vs time

Knee determined by SFH and Type Ia DTD

Normalization depends on IMF and Yield Tables

Type Ia's start

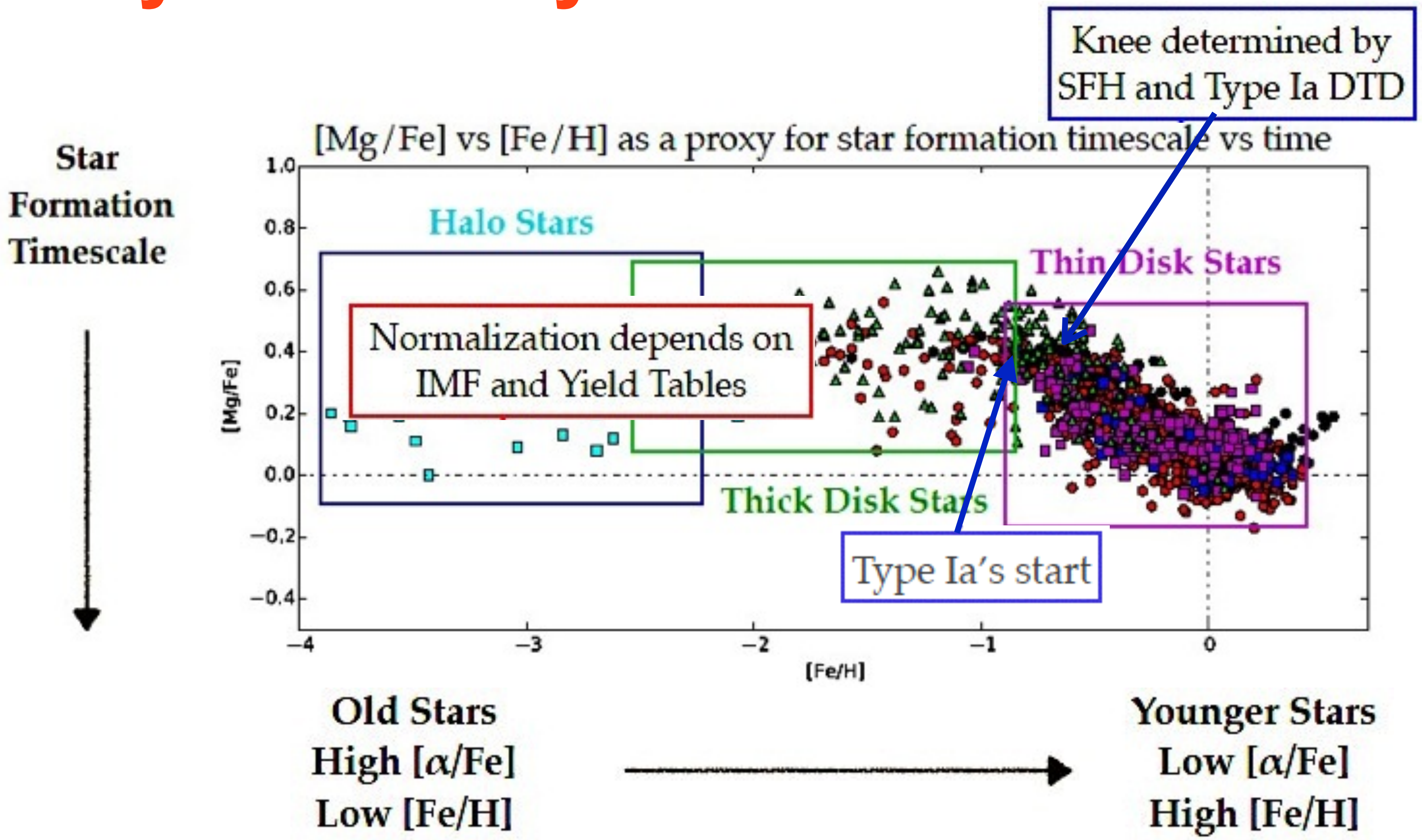
Old Stars
High [α/Fe]
Low [Fe/H]

Younger Stars
Low [α/Fe]
High [Fe/H]

with thanks to Camille Liebler, UCSC

Galaxy Metallicity Observations

Milky Way Chemical Evolution



[Mg/Fe] vs [Fe/H] as a proxy for star formation timescale vs time

Knee determined by SFH and Type Ia DTD

Normalization depends on IMF and Yield Tables

Type Ia's start

Star Formation Timescale

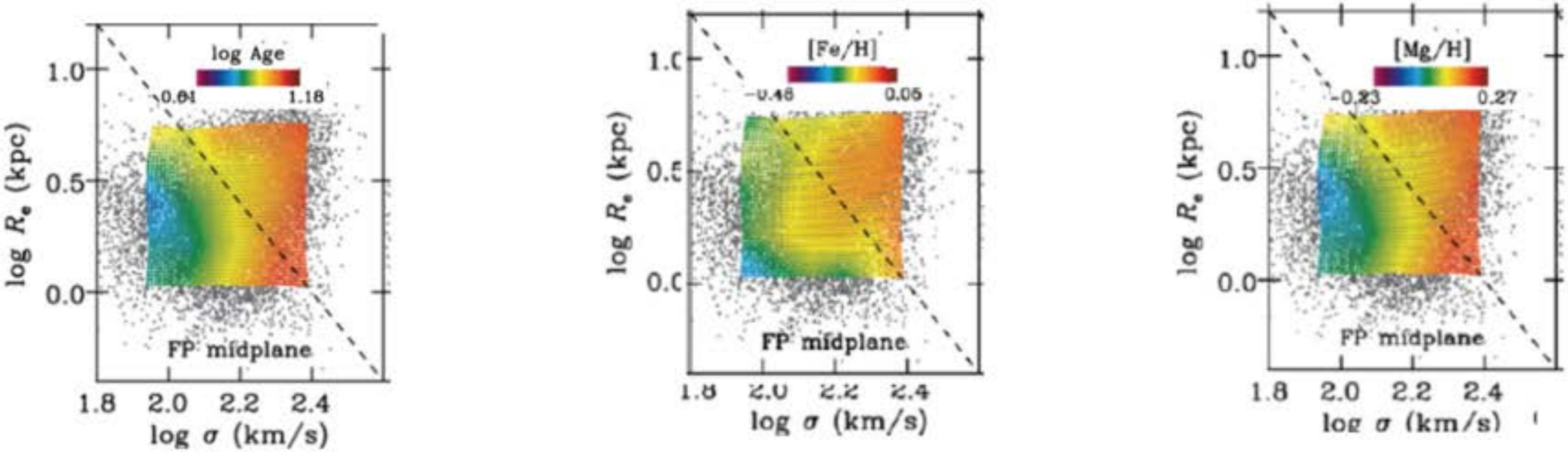
Old Stars
High [α/Fe]
Low [Fe/H]

Younger Stars
Low [α/Fe]
High [Fe/H]

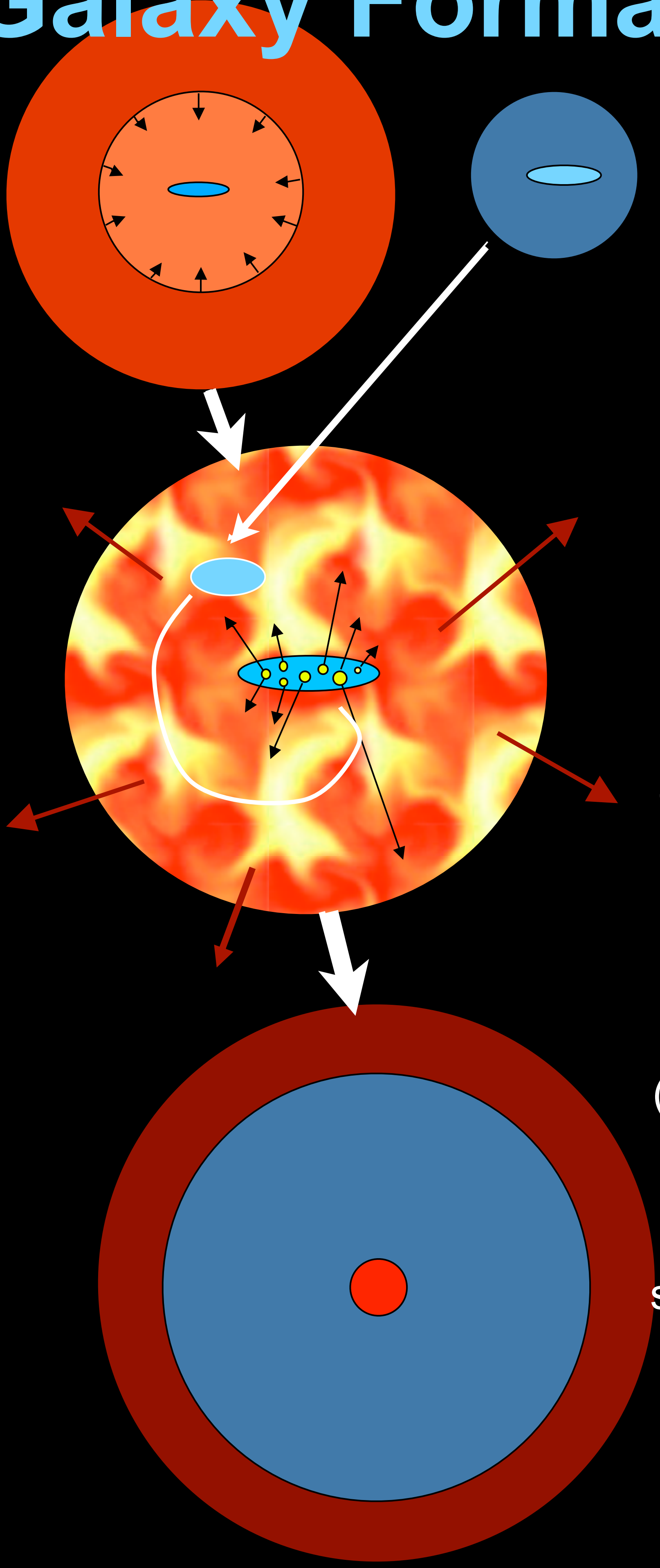
Age and Metallicity depend mainly on velocity dispersion σ, not R

SDSS Observations

Jenny Graves et al. 2009

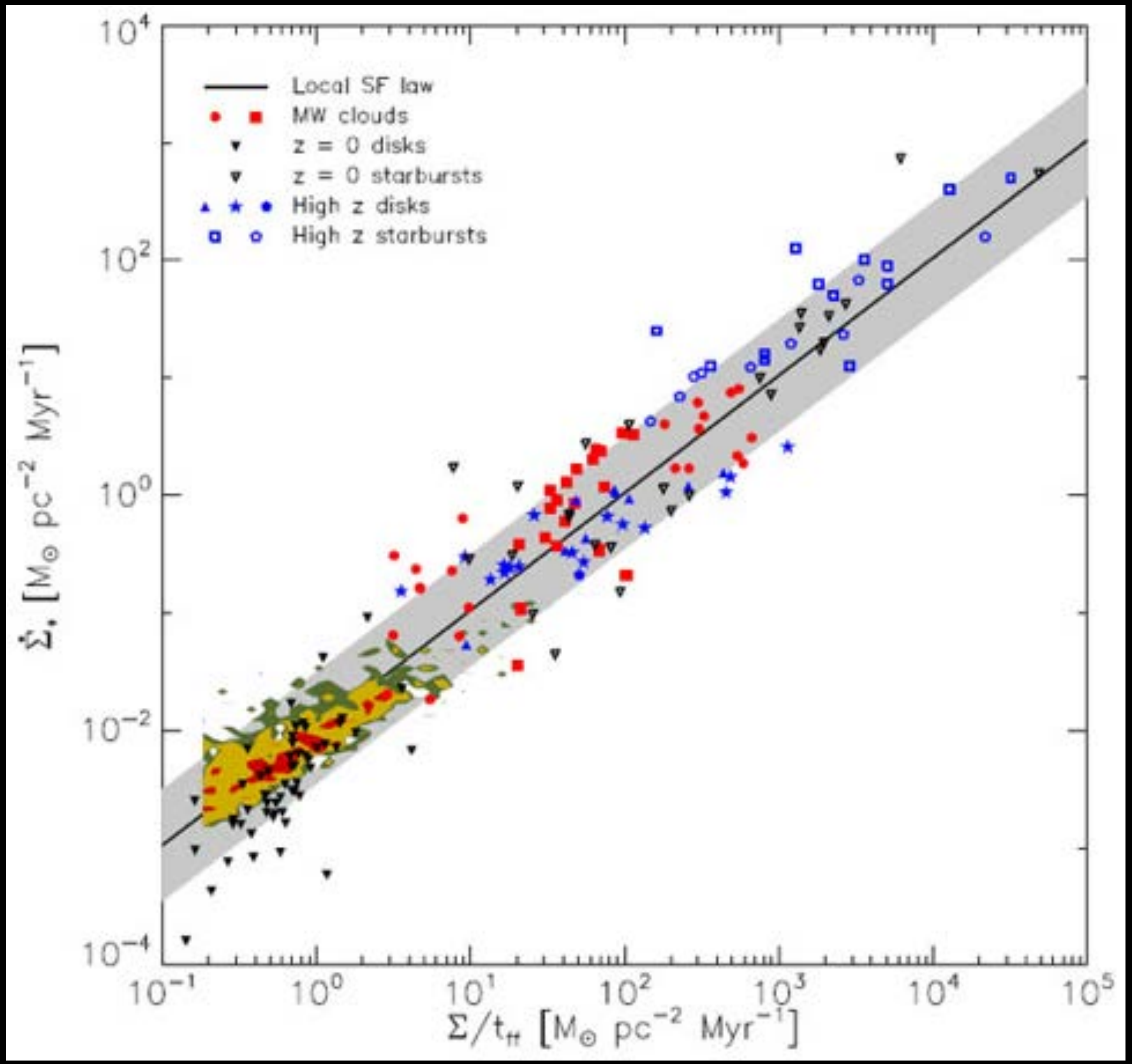


Galaxy Formation via SemiAnalytic Models

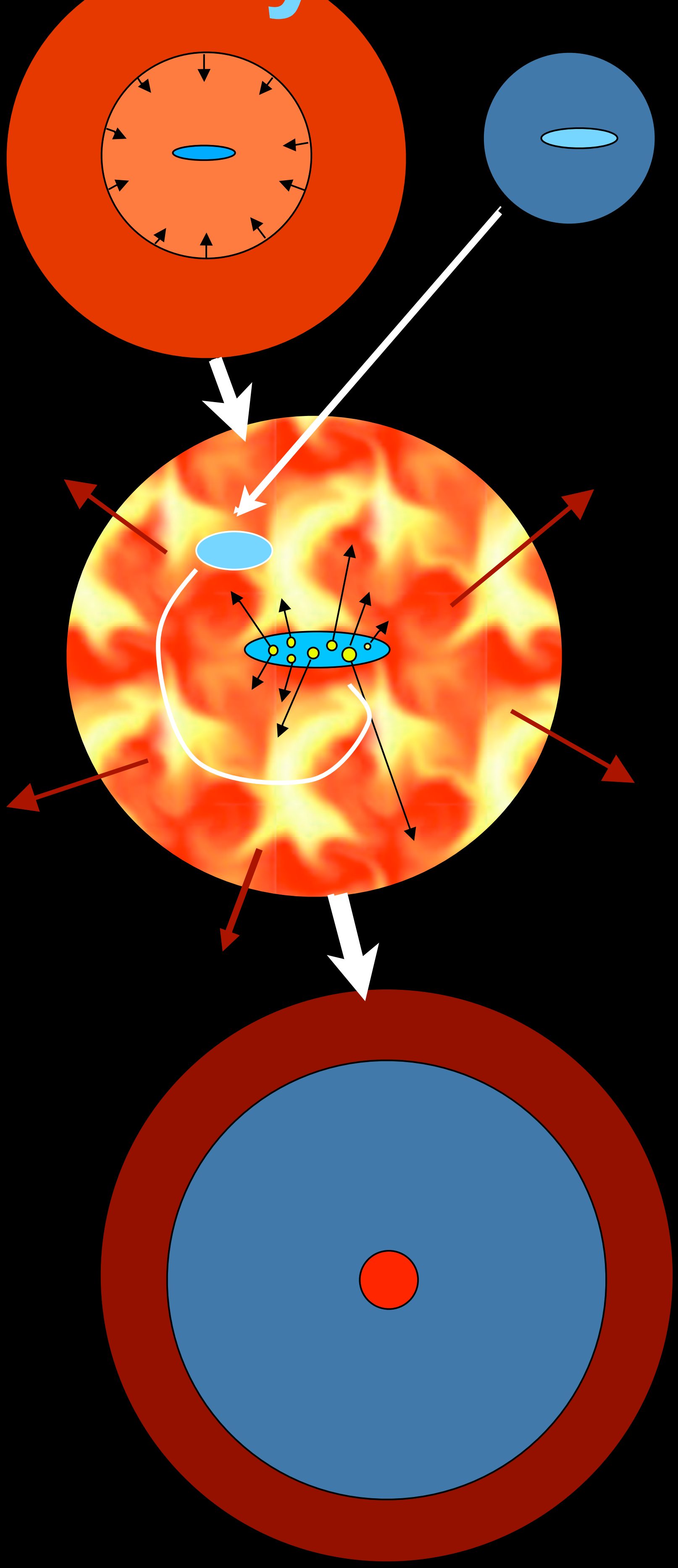


- gas is collisionally heated when perturbations ‘turn around’ and collapse to form gravitationally bound structures
- gas in halos cools via atomic line transitions (depends on density, temperature, and metallicity)
- cooled gas collapses to form a rotationally supported disk
- cold gas forms stars, with efficiency a function of gas density (e.g. Schmidt-Kennicutt Law, metallicity effects?)

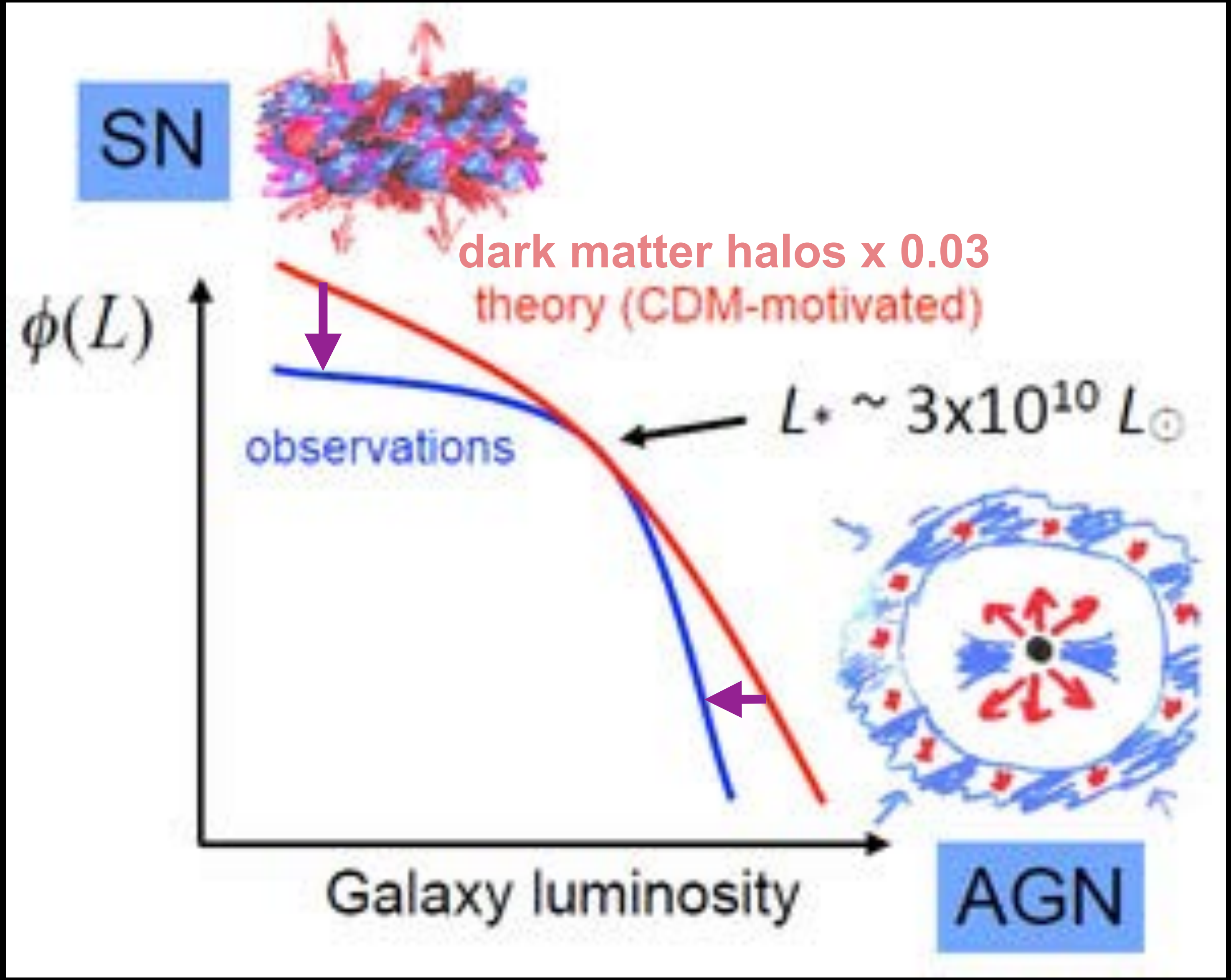
Schmidt-Kennicutt laws on nearby (including Local Group galaxies as shaded regions) and distant galaxies, as well as Milky Way Giant Molecular Clouds (Krumholz et al. 2012): Rate of change of stellar surface density is proportional to gas surface density divided by free-fall time $t_{ff}=(G\rho)^{-1/2}$



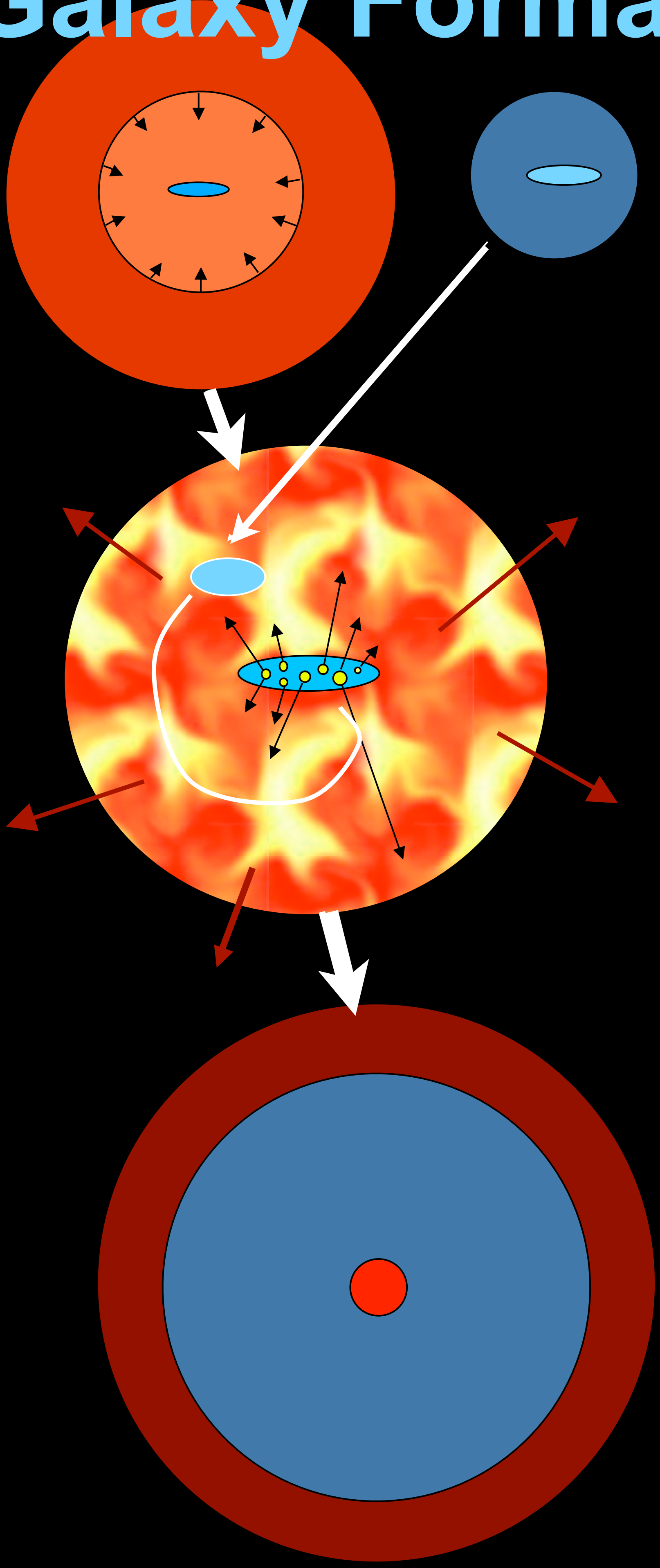
Galaxy Formation via SemiAnalytic Models



- cooled gas collapses to form a rotationally supported disk
- cold gas forms stars, with efficiency a function of gas density (e.g. Schmidt-Kennicutt Law, metallicity effects)
- massive stars and SNe reheat (and in small halos expel) cold gas and some metals
- galaxy mergers trigger bursts of star formation; ‘major’ mergers transform disks into spheroids and fuel AGN
- AGN feedback cuts off star formation

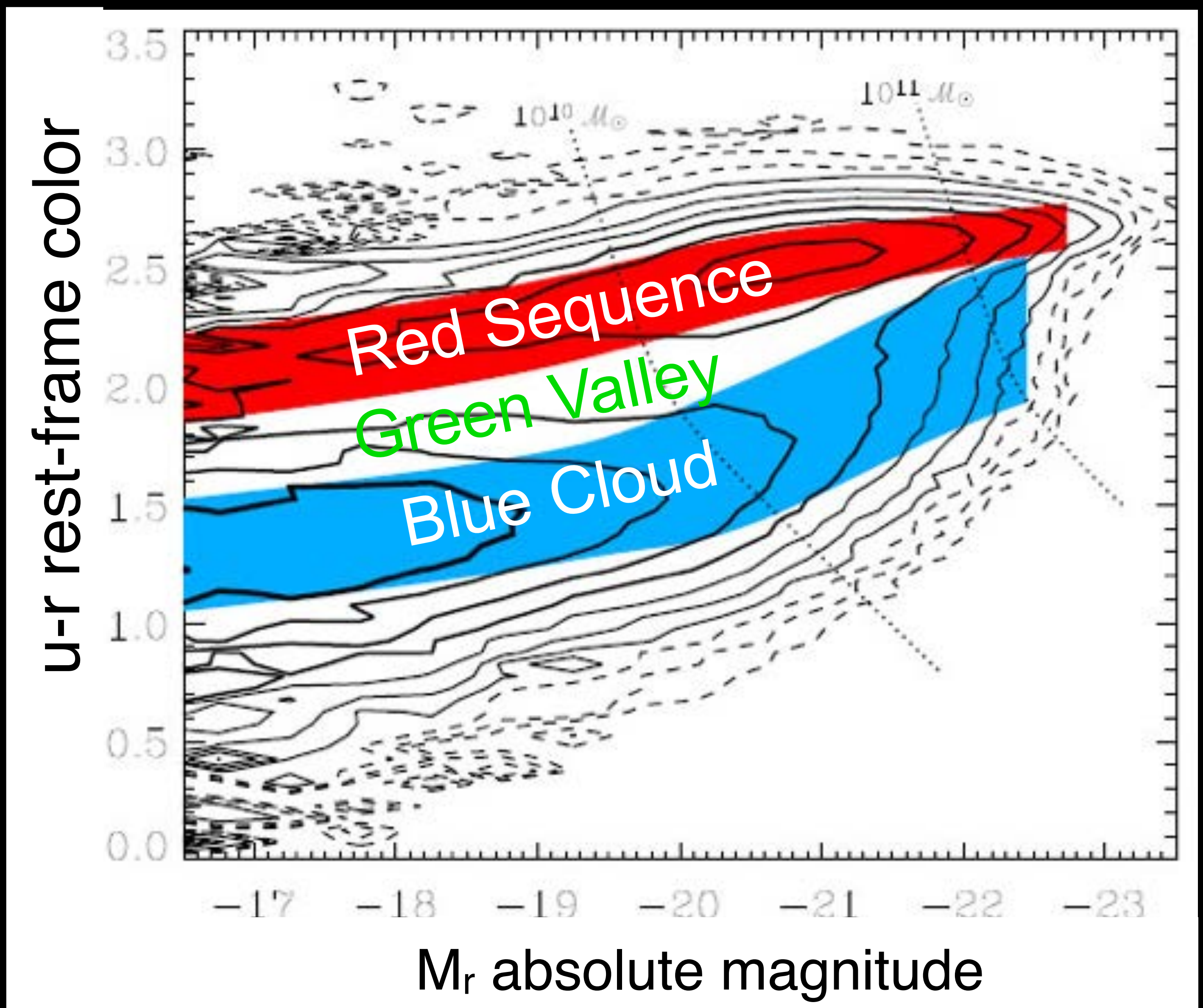


Galaxy Formation via SemiAnalytic Models

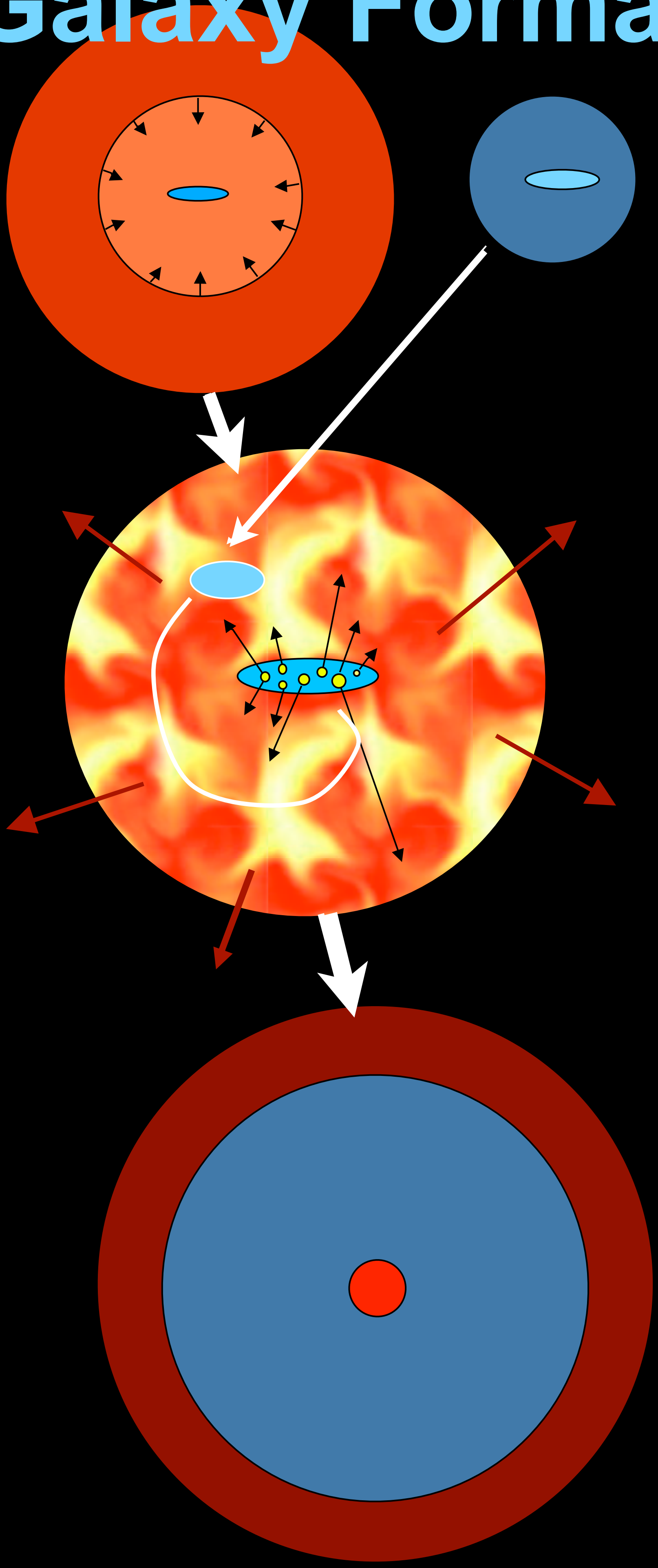


- cold gas forms stars, with efficiency a function of gas density (e.g. Schmidt-Kennicutt Law, metallicity effects)
- massive stars and SNe reheat (and in small halos expel) cold gas and some metals
- AGN feedback cuts off star formation

- Illustration of galaxy bimodality. The contours are the density of SDSS galaxies in color-luminosity space, after correction for selection effects (Baldry et al. 2004).



Galaxy Formation via SemiAnalytic Models



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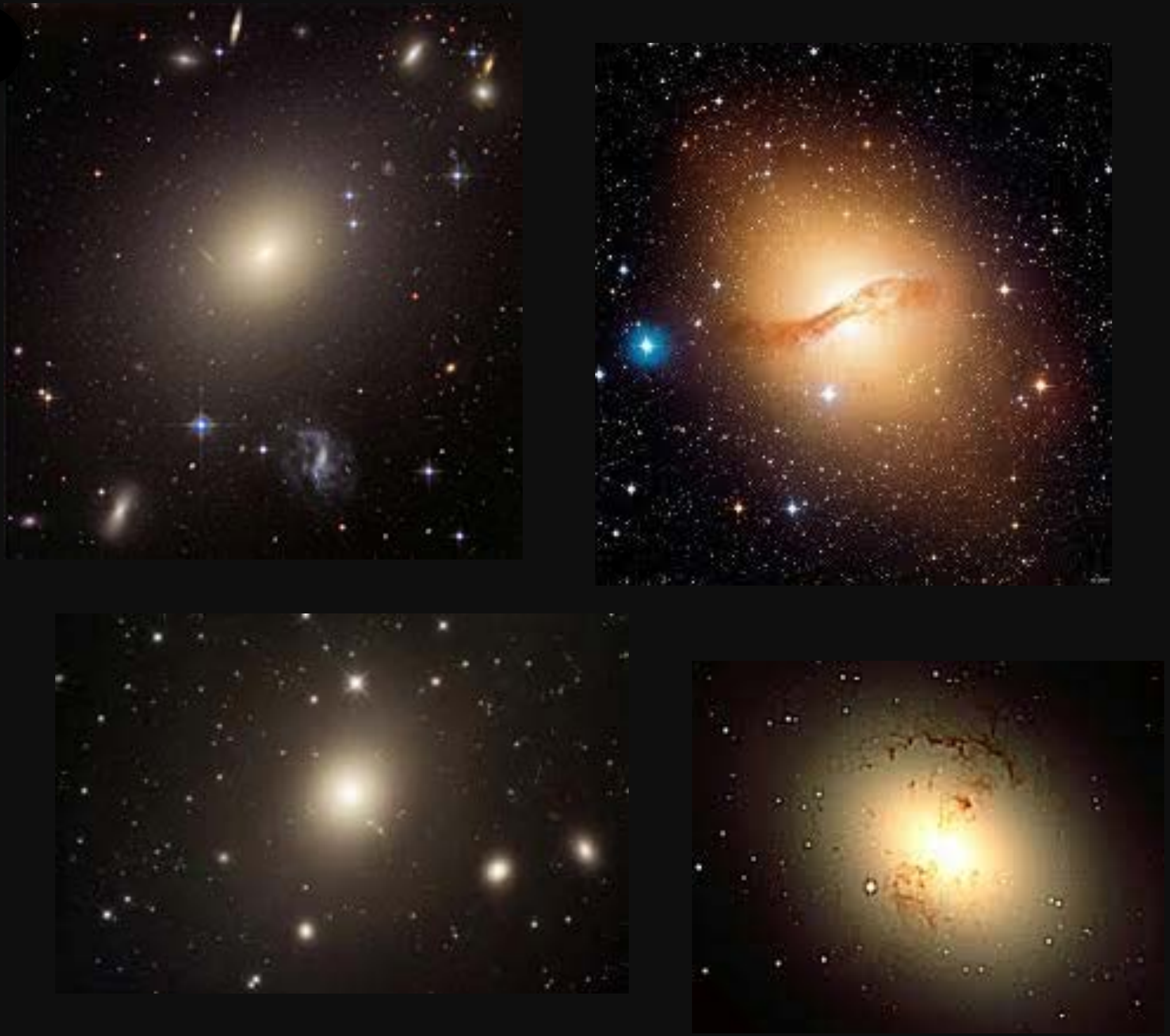
- massive stars and SNe reheat (and in small halos expel) cold gas and some metals
- galaxy mergers trigger bursts of star formation; ‘major’ mergers transform disks into spheroids and fuel AGN
- AGN feedback cuts off star formation
- **including effects of dissipation in gas-rich galaxy mergers leads to observed elliptical size-mass relation**
- **including spheroid formation by disk instability is essential to reproduce the observed elliptical luminosity function**

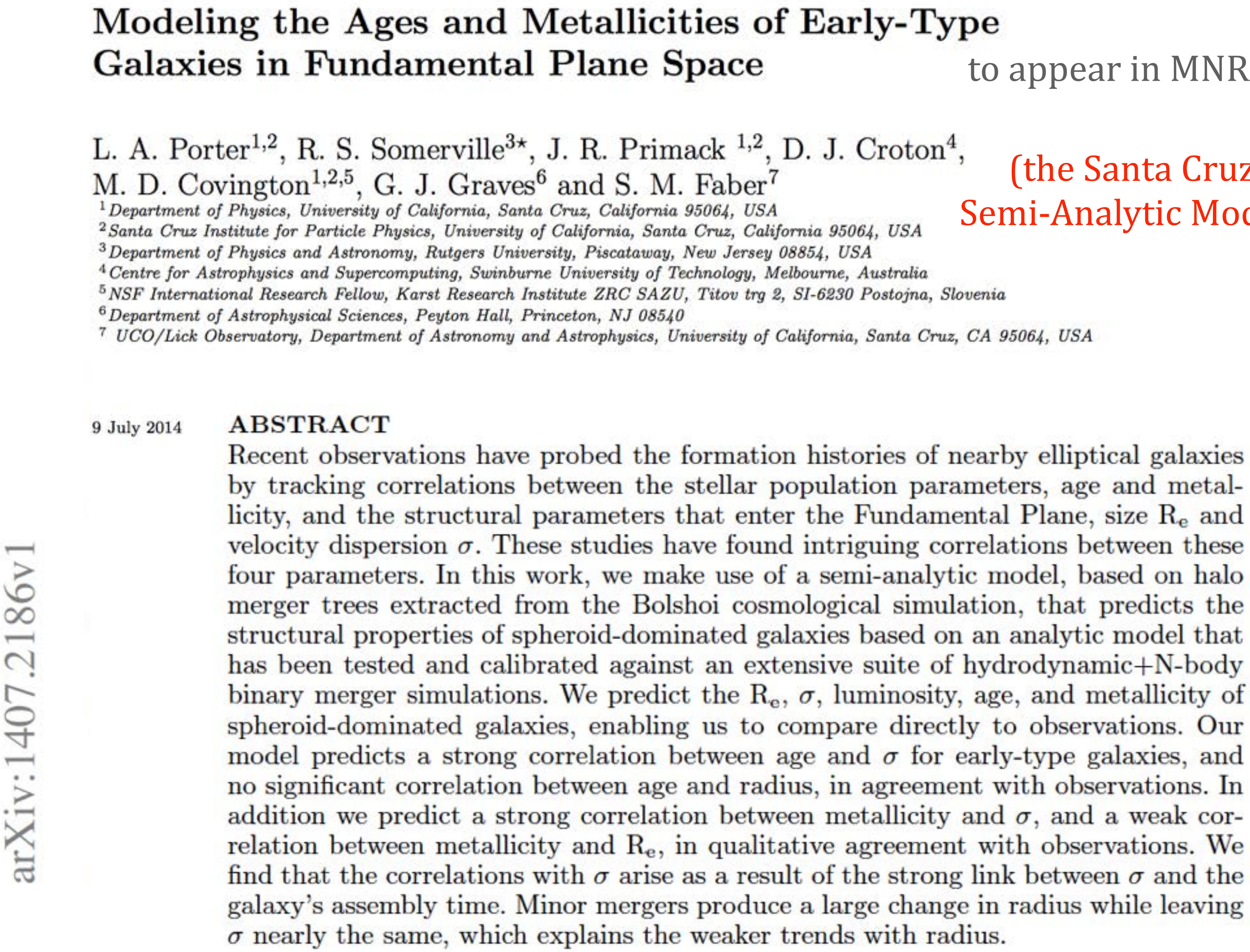
White & Frenk 91; Kauffmann+93; Cole+94; Somerville & Primack 99; Cole+00; Somerville, Primack, & Faber 01; Croton et al. 2006; Somerville +08; Fanidakis+09; Covington et al. 10, 11; Somerville, Gilmore, Primack, & Dominguez 11; Porter et al.

- Elliptical galaxies follow a size-mass relation. Our semi-analytic model correctly predicts this and the other scaling relations of elliptical galaxies.

- Disk galaxies follow a relation between their rotation velocity and their luminosity. The model also correctly predicts this.



- Our semi-analytic model also correctly predicts the numbers of Disk galaxies and Elliptical galaxies of all masses.



Modeling the Ages and Metallicities of Early-Type Galaxies in Fundamental Plane Space

to appear in MNRAS

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M. D. Covington[1,2,5], G. J. Graves[6] and S. M. Faber[7]
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[6] *Department of Astrophysical Sciences, Peyton Hall, Princeton, NJ 08540*
[7] *UCO/Lick Observatory, Department of Astronomy and Astrophysics, University of California, Santa Cruz, CA 95064, USA*

(the Santa Cruz Semi-Analytic Model)

9 July 2014

ABSTRACT

Recent observations have probed the formation histories of nearby elliptical galaxies by tracking correlations between the stellar population parameters, age and metallicity, and the structural parameters that enter the Fundamental Plane, size R_e and velocity dispersion σ. These studies have found intriguing correlations between these four parameters. In this work, we make use of a semi-analytic model, based on halo merger trees extracted from the Bolshoi cosmological simulation, that predicts the structural properties of spheroid-dominated galaxies based on an analytic model that has been tested and calibrated against an extensive suite of hydrodynamic+N-body binary merger simulations. We predict the R_e, σ, luminosity, age, and metallicity of spheroid-dominated galaxies, enabling us to compare directly to observations. Our model predicts a strong correlation between age and σ for early-type galaxies, and no significant correlation between age and radius, in agreement with observations. In addition we predict a strong correlation between metallicity and σ, and a weak correlation between metallicity and R_e, in qualitative agreement with observations. We find that the correlations with σ arise as a result of the strong link between σ and the galaxy's assembly time. Minor mergers produce a large change in radius while leaving σ nearly the same, which explains the weaker trends with radius.

SAM Predictions vs. SDSS Observations

Age and Metallicity depend mainly on velocity dispersion σ, not R

SAM

Predictions

Lauren Porter et al. 2013b

SDSS

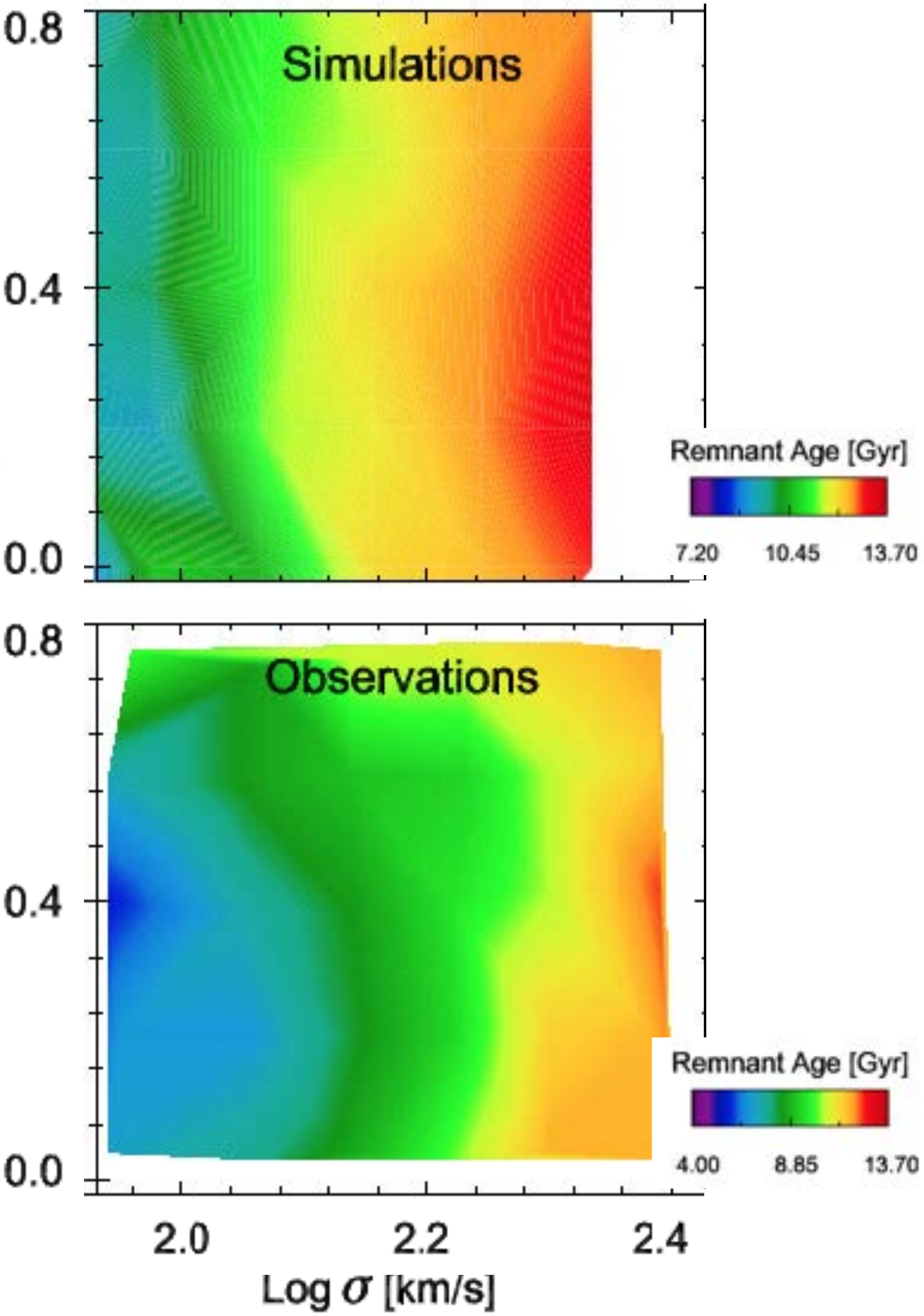
Observations

Jenny Graves et al. 2009

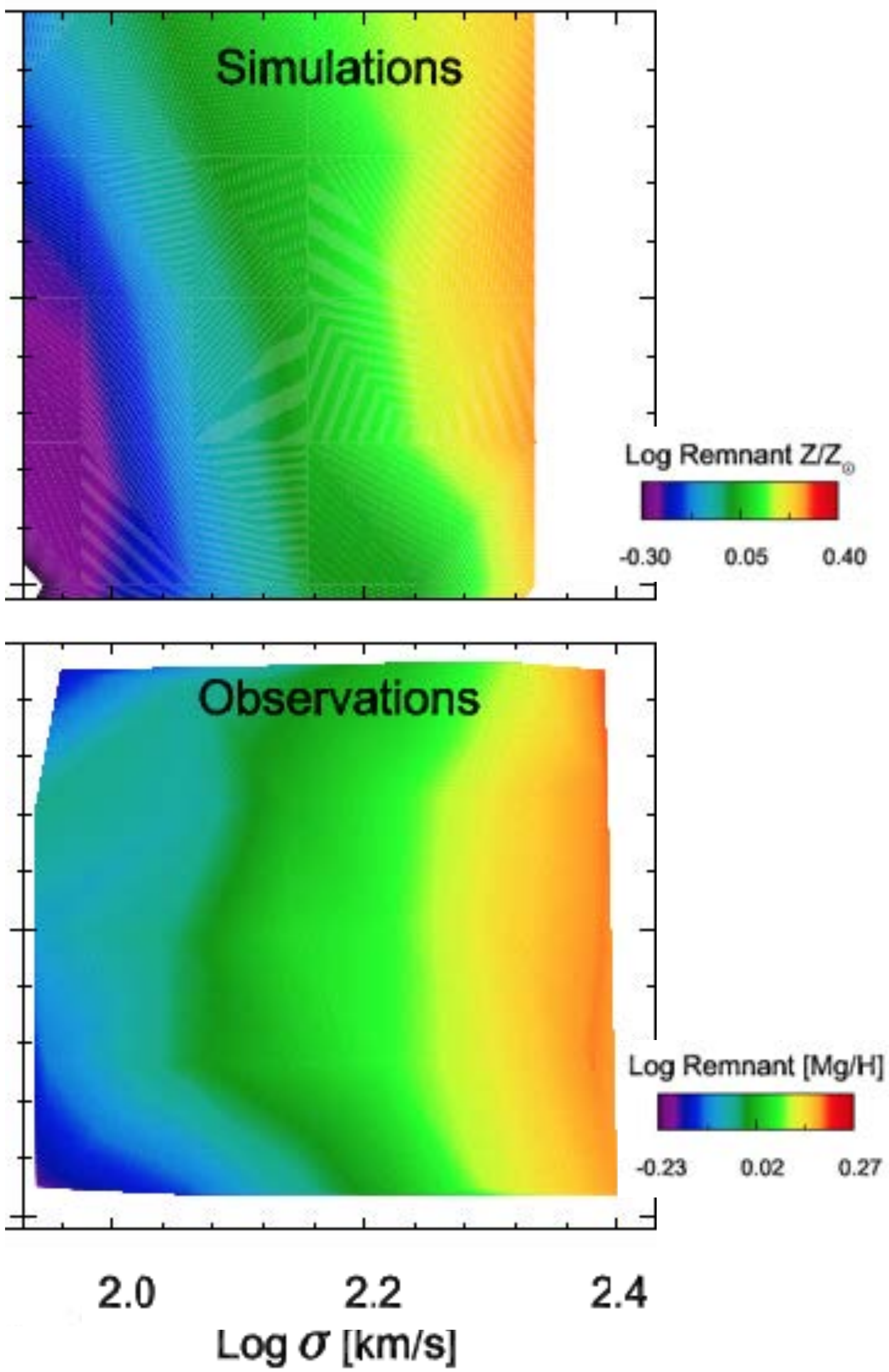
COSMIC WEB: The Bolshoi simulation models the evolution of dark matter, which is responsible for the large-scale structure of the universe. Here, snapshots from the simulation show the dark matter distribution at 500 million and 2.2 billion years [top] and 6 billion and 13.7 billion years [bottom] after the big bang. These images are 50-million-light-year-thick slices of a cube of simulated universe that today would measure roughly 1 billion light-years on a side and encompass about 100 galaxy clusters.

SOURCES: SIMULATION, ANATOLY KLYPIN AND JOEL R. PRIMACK; VISUALIZATION, STEFAN GOTTLÖBER/LEIBNIZ INSTITUTE FOR ASTROPHYSICS POTSDAM

Galaxy Age



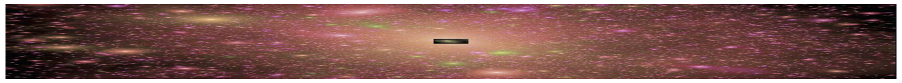
Galaxy Metallicity



Lauren Porter, Rachel Somerville, Joel Primack, et al. 2014b

Another top Semi-Analytic Model

Modelling element abundances in semi-analytic models of galaxy formation



(the Munich L-Galaxies Semi-Analytic Model)

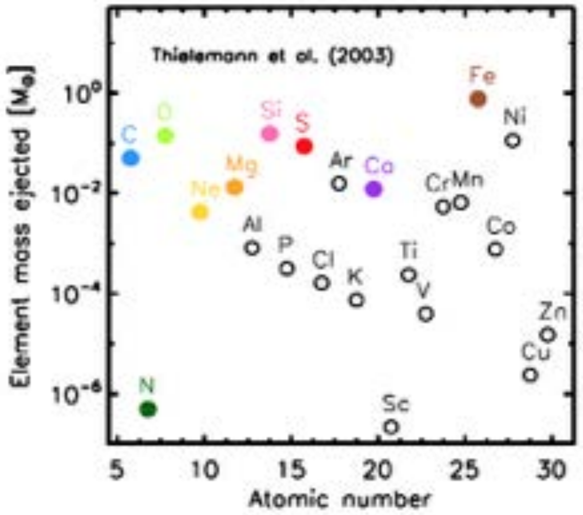
Robert M. Yates,[1]★ Bruno Henriques,[1] Peter A. Thomas,[2] Guinevere Kauffmann,[1]
Jonas Johansson[1] and Simon D. M. White[1]

[1]*Max Planck Institut für Astrophysik, Karl-Schwarzschild-Str. 1, D-85741, Garching, Germany*
[2]*Astronomy Centre, University of Sussex, Falmer, Brighton BN1 9QH, UK*

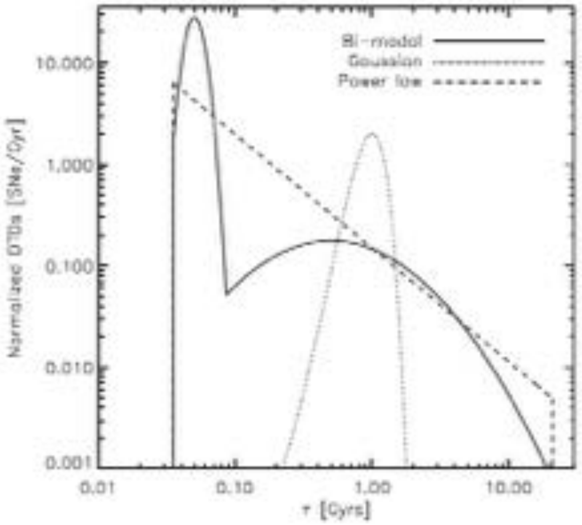
ABSTRACT

We update the treatment of chemical evolution in the Munich semi-analytic model, L-GALAXIES. Our new implementation includes delayed enrichment from stellar winds, Type II supernovae (SNe-II) and Type Ia supernovae (SNe-Ia), as well as metallicity-dependent yields and a reformulation of the associated supernova feedback. Two different sets of SN-II yields and three different SN-Ia delay-time distributions (DTDs) are considered, and 11 heavy elements (including O, Mg and Fe) are self-consistently tracked. We compare the results of this new implementation with data on (a) local, star-forming galaxies, (b) Milky Way disc G dwarfs and (c) local, elliptical galaxies. We find that the $z = 0$ gas-phase mass–metallicity relation is very well reproduced for all forms of DTD considered, as is the [Fe/H] distribution in the Milky Way disc. The [O/Fe] distribution in the Milky Way disc is best reproduced when using a DTD with $\lesssim$50 per cent of SNe-Ia exploding within ~400 Myr. Positive slopes in the mass–[α/Fe] relations of local ellipticals are also obtained when using a DTD with such a minor 'prompt' component. Alternatively, metal-rich winds that drive light α elements directly out into the circumgalactic medium also produce positive slopes for all forms of DTD and SN-II yields considered. Overall, we find that the best model for matching the wide range of observational data considered here should include a power-law SN-Ia DTD, SN-II yields that take account of prior mass-loss through stellar winds and some direct ejection of light α elements out of galaxies.

8 of the 11 Elements Tracked



Three SN Ia DTDs Used



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

Galaxy Hydro Simulations: 2 Approaches

1. Low resolution (~ kpc)

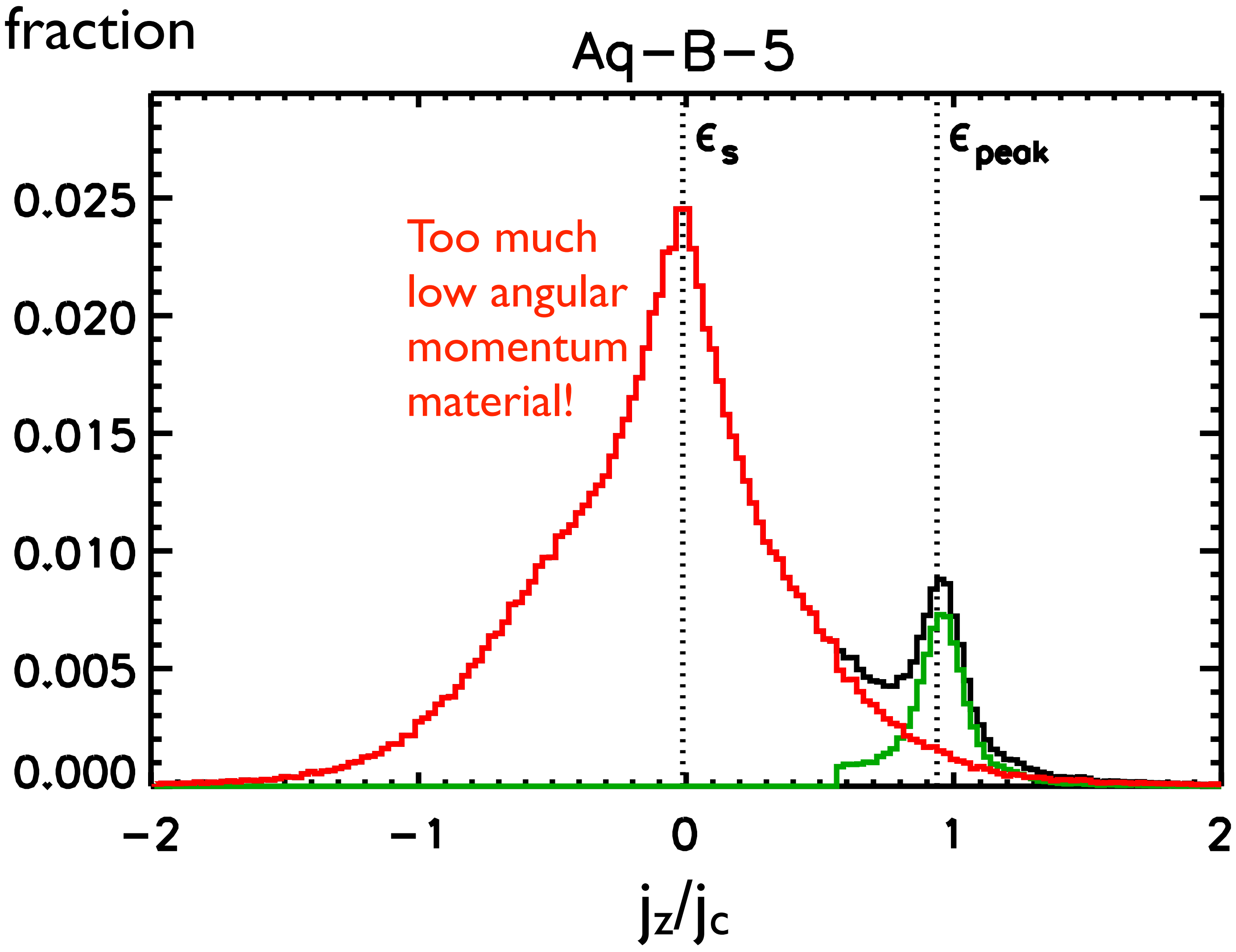
Advantages: it's possible to simulate many galaxies and study galaxy populations and their interactions with CGM & IGM
Disadvantages: we learn little about how galaxies themselves evolve, and cannot compare with high-z galaxy images and spectra.
Examples: Overwhelmingly Large Simulations (OWLs), AREPO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

2. High resolution (~10s of pc)

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, origins of galactic spheroids, quenching)
Disadvantages: it's hard to run statistical galaxy samples, so the best approach uses uses simulation insights in SAMs
Examples: ART simulation suite, AGORA simulation comparison project

The Angular Momentum Catastrophe

In practice it is not trivial to form galaxies with massive, extended disks and small spheroids. The angular momentum content of the disk determines its final structure.



Too much low angular momentum material!

$\neq$

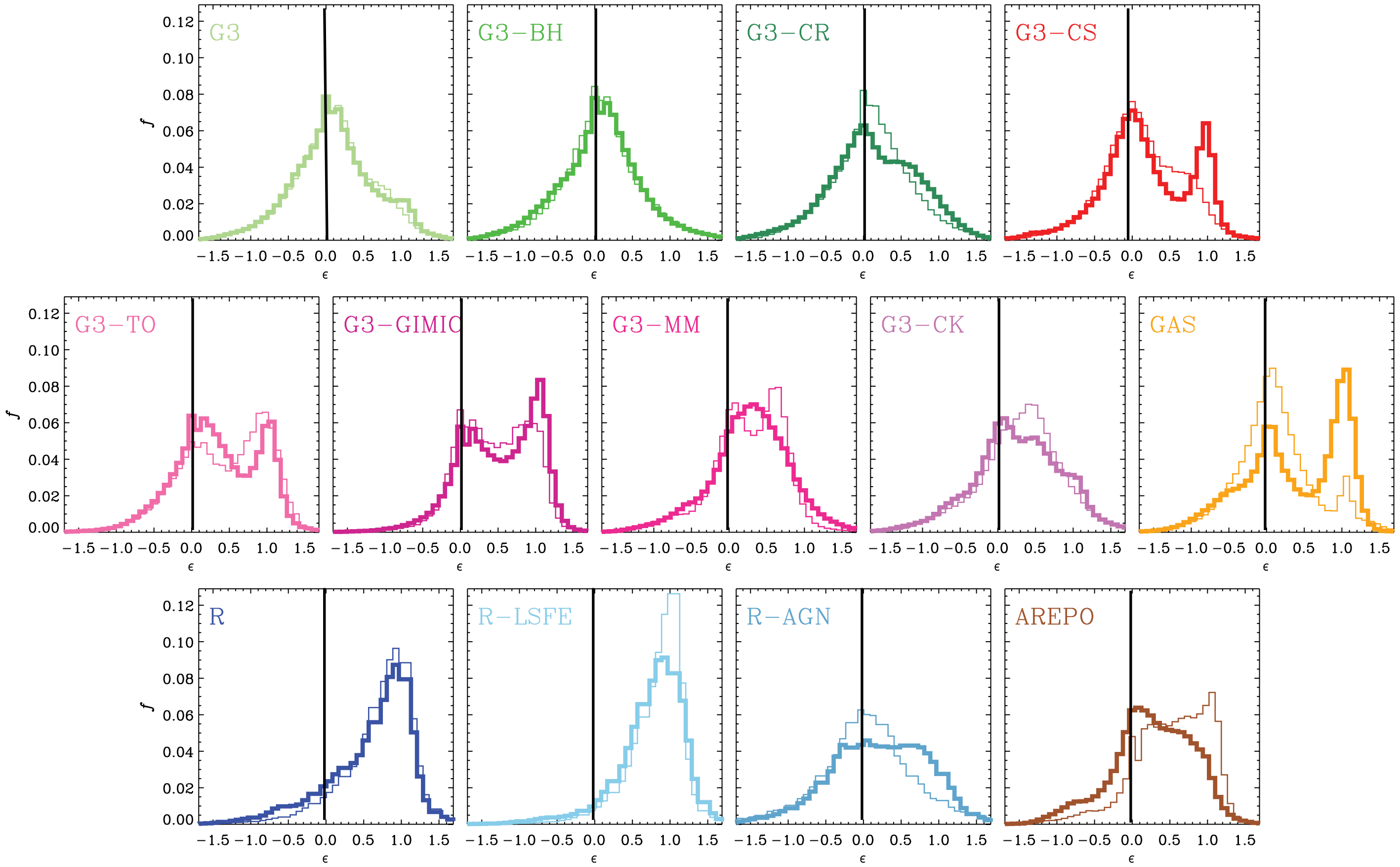
Scannapieco et al. 2009

angular momentum / ang mom needed for rotational support

The Angular Momentum Catastrophe

In practice it is not trivial to form galaxies with massive, extended disks and small spheroids. The angular momentum content of the disk determines its final structure. None of the 2012 Aquila low-resolution galaxy simulations had realistic disks.

fraction of stars with given angular momentum



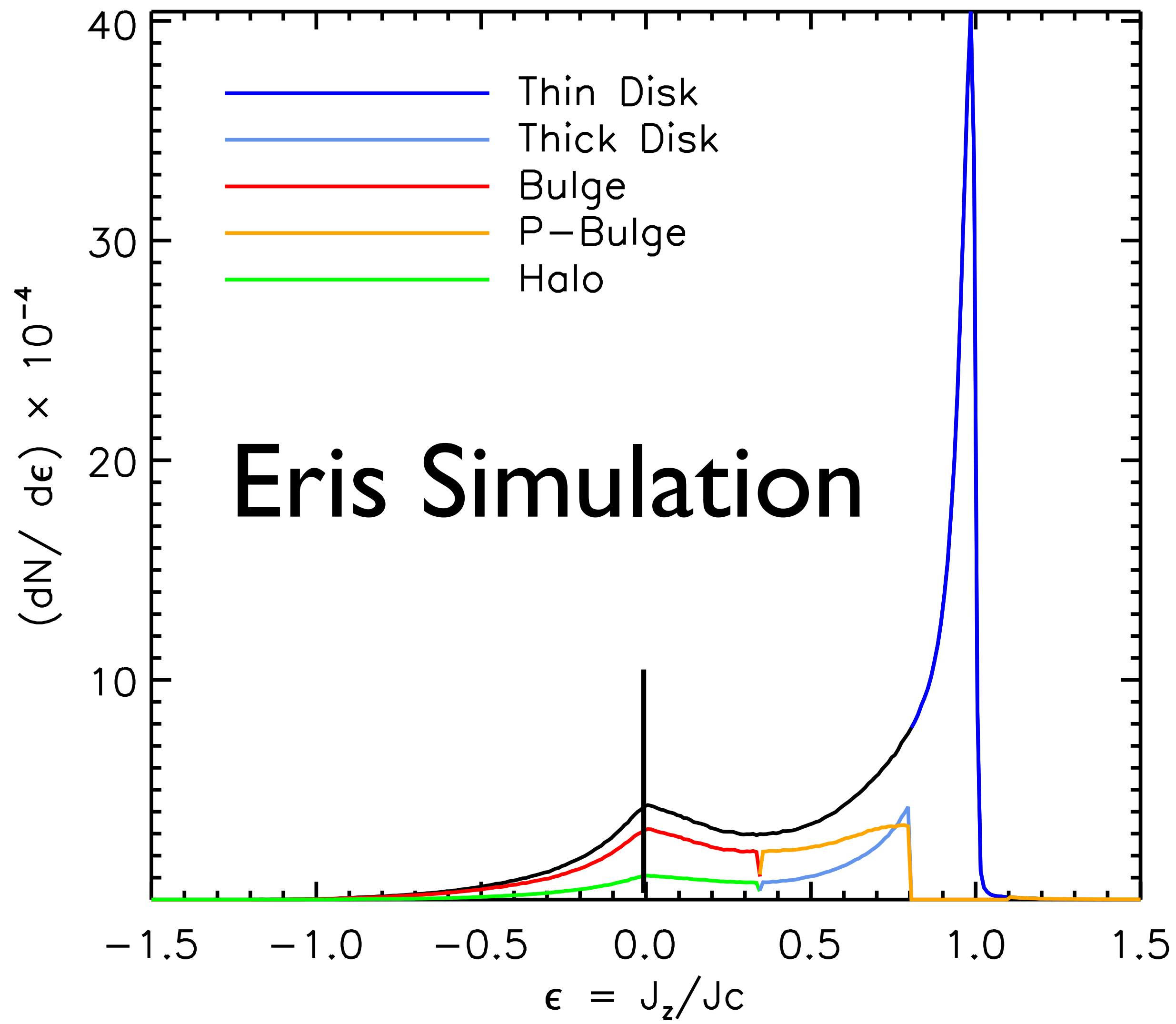
j_z/j_c

$\neq$

Scannapieco et al., Aquila Galaxy Simulation Comparison, 2012

The Angular Momentum ~~Catastrophe~~

Eris, the first high-resolution simulation of formation of a ~10^{12} $M_\odot$ galaxy, produced a realistic spiral galaxy. Adequate resolution and physically realistic feedback appear to be sufficient.



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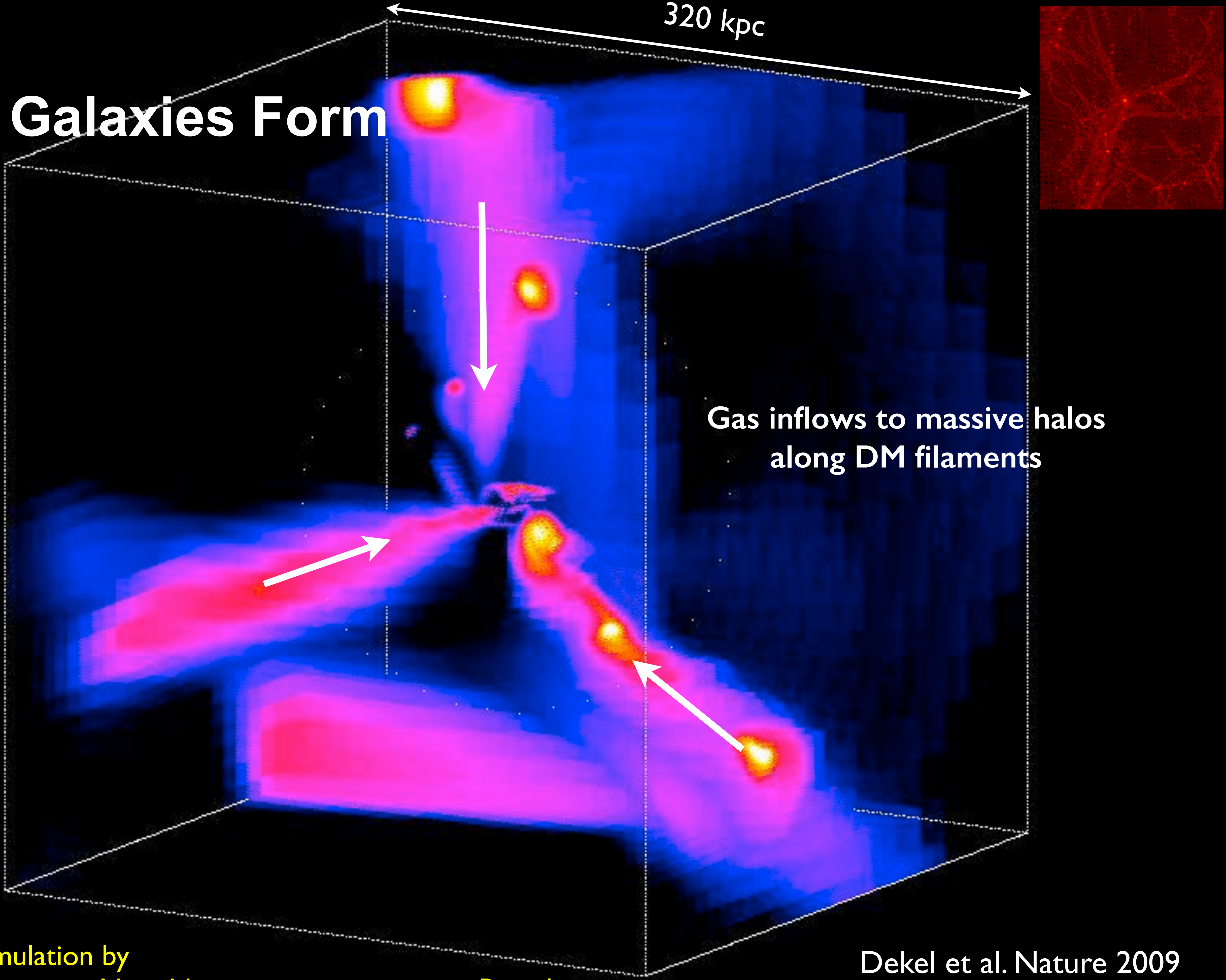
Guedes, Callegari, Madau, Mayer 2011 ApJ

How Galaxies Form

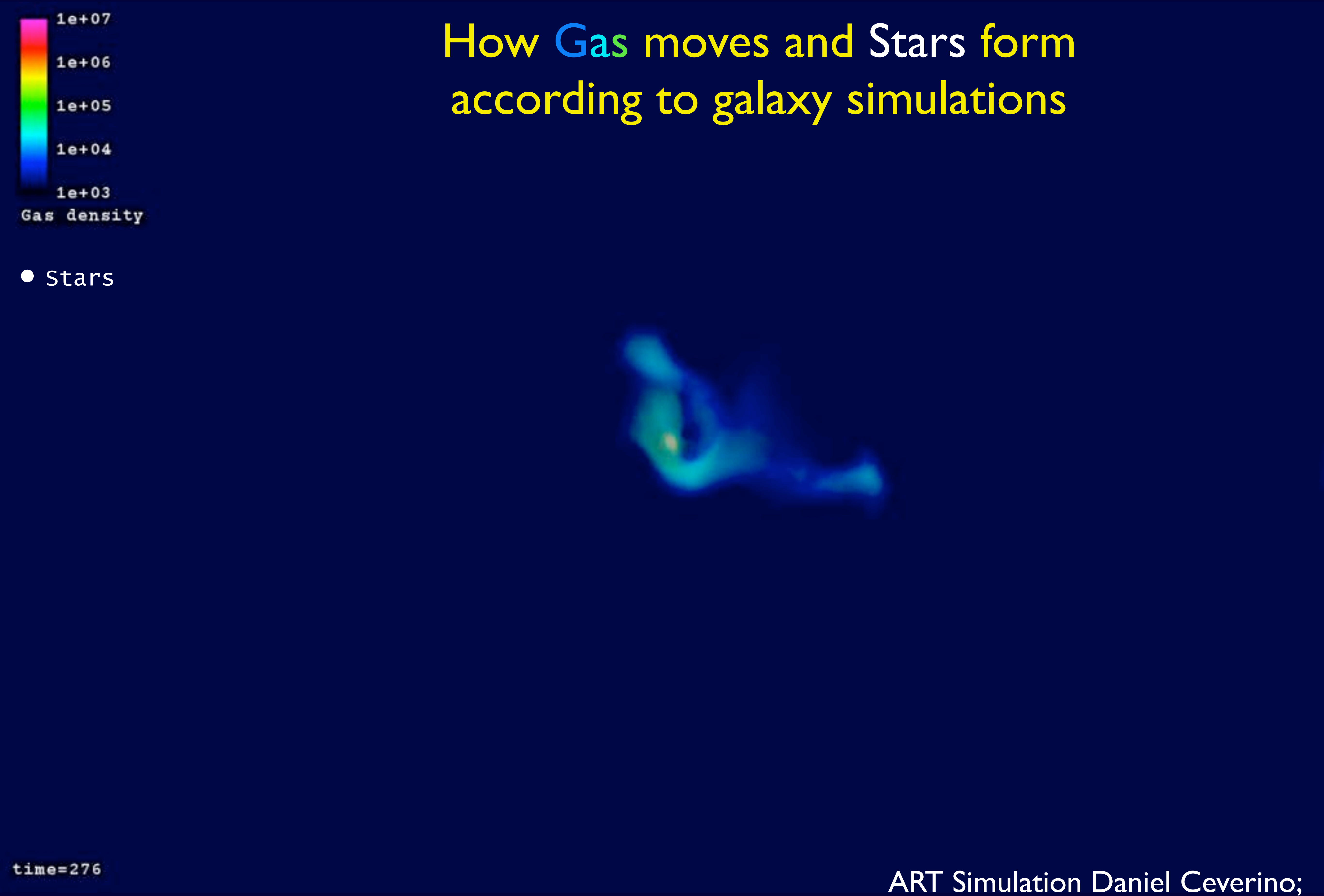


Gas inflows to massive halos along DM filaments

RAMSES simulation by
Romain Teyssier on Mare Nostrum supercomputer, Barcelona

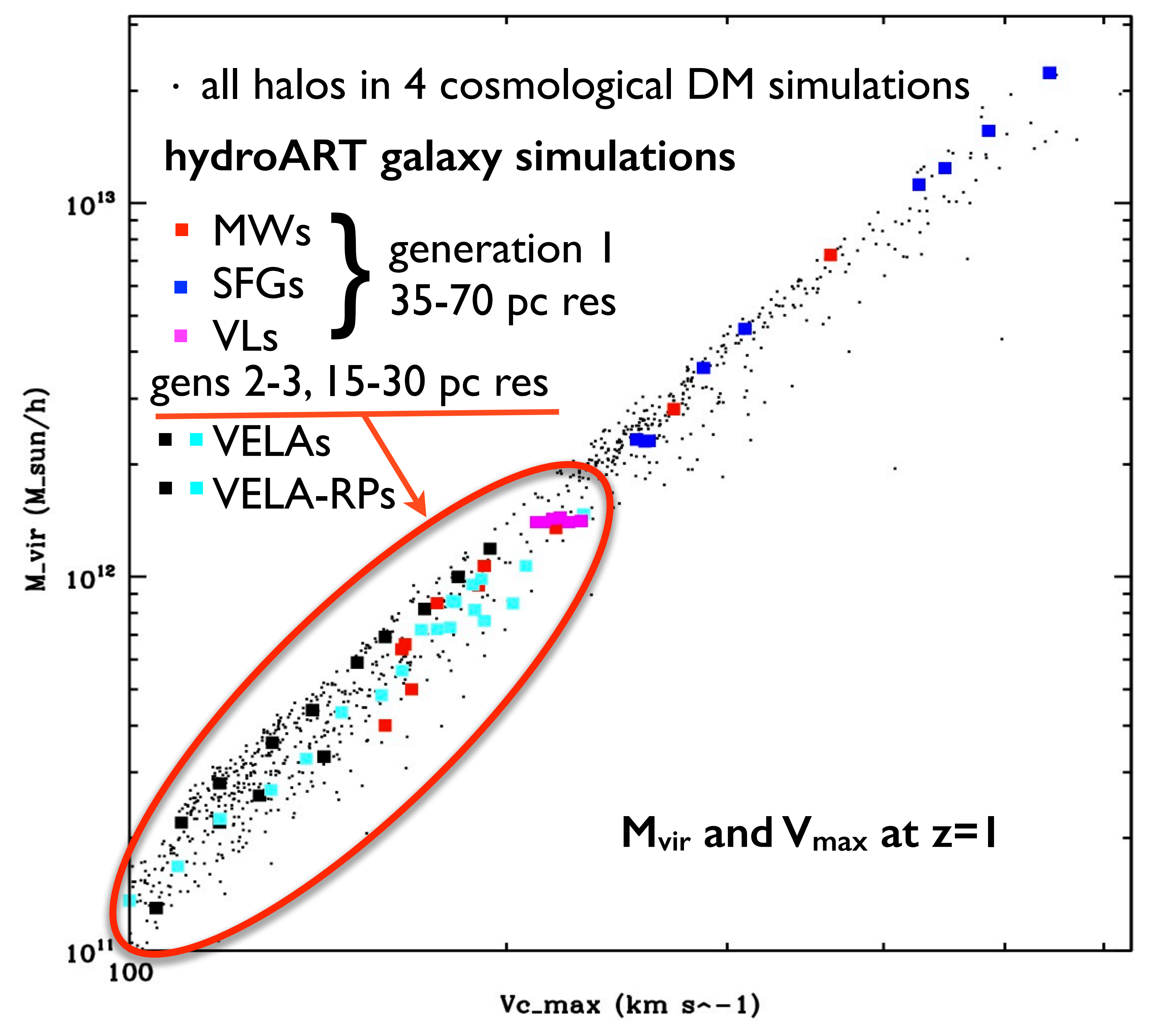
Dekel et al. Nature 2009

How Gas moves and Stars form according to galaxy simulations



ART Simulation Daniel Ceverino;
Visualization: David Ellsworth

3 Generations of hydroART simulations



Generations 2 & 3

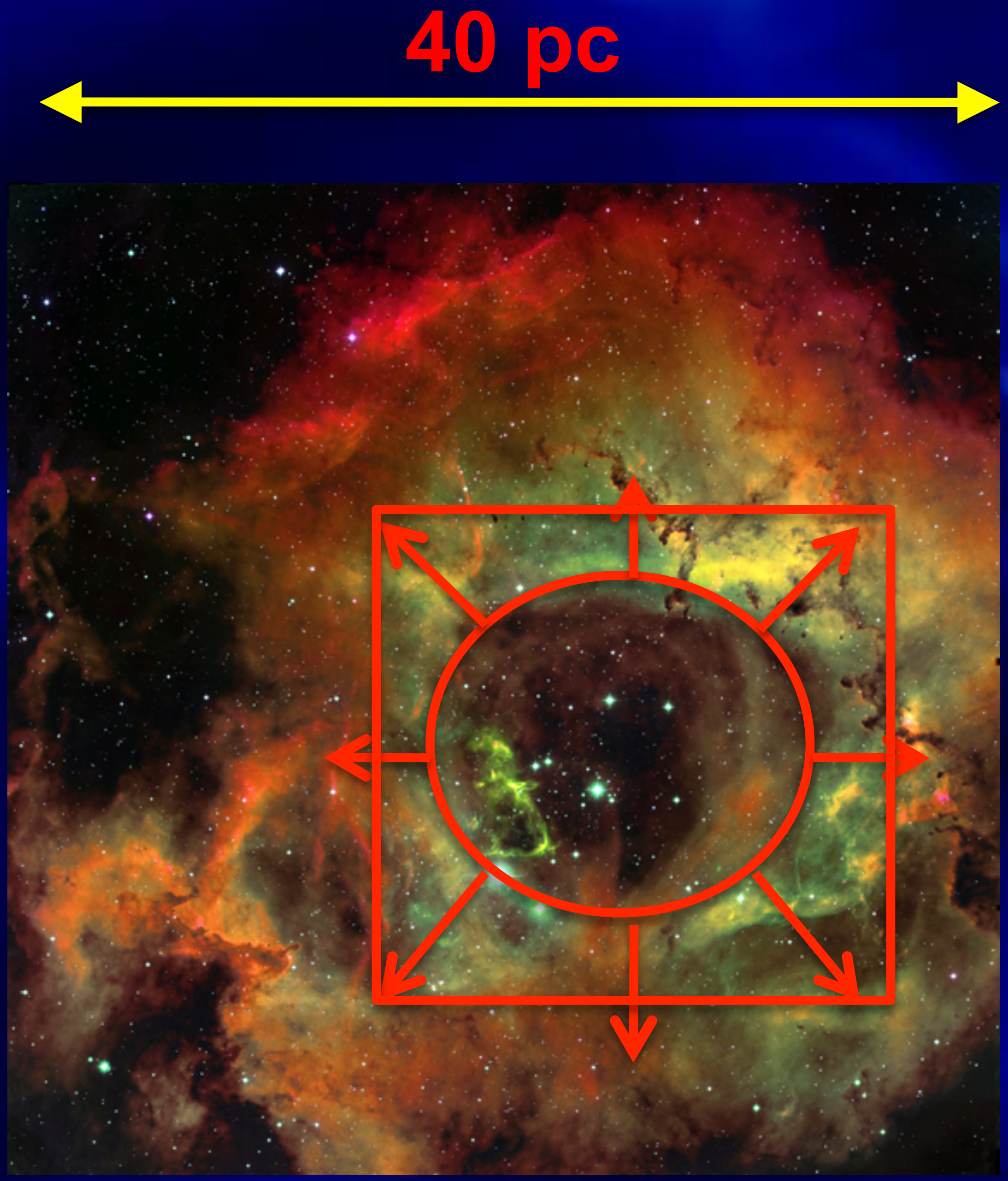
- ~35 zoom-in simulations
- 15-30 pc reso
- M_{DM}=8 10^4 Ms
- M_*=10^3 Ms
- z=1-3

10^{11} Ms/h < M_H < 10^{12} Ms/h
Vc_max =100-200 km/s @ z=1

Daniel Ceverino

Radiative feedback

Rosette Nebula

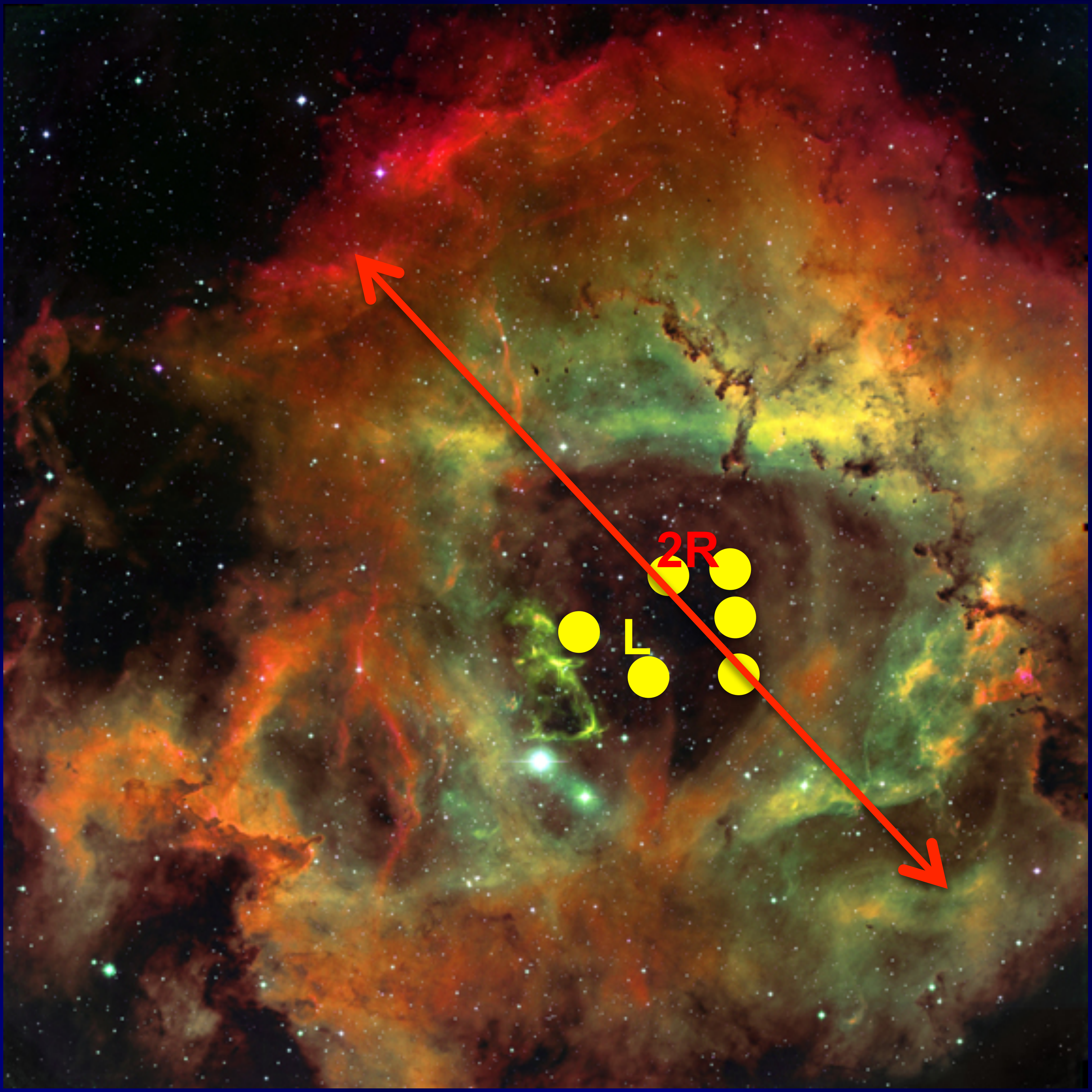


No Supernova explosion yet

- Stellar winds
- Thermal pressure
- Radiation pressure
  - from ionizing photons

Typical resolution of our zoom-in, cosmological simulation: ~ 20 pc

Daniel Ceverino



- At high column densities
- Add pressure

$P_{rad} = L / (R^2 c)$

$L = M_* \Gamma$

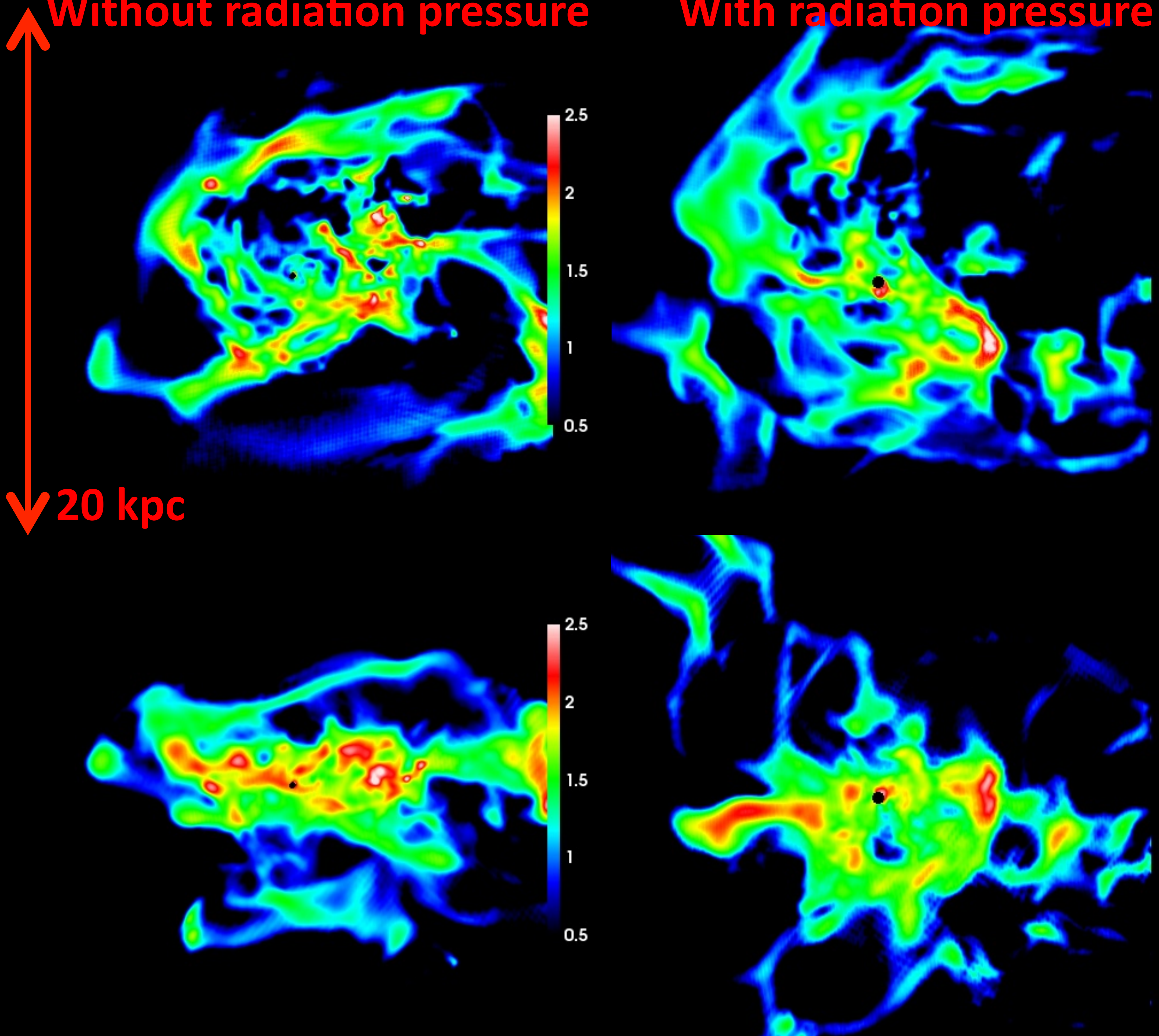
Γ = cte for 5 Myr

For column densities $>10^{21}$ cm^{-2}

No free parameters

Daniel Ceverino

Gas distributions



Without radiation pressure

With radiation pressure

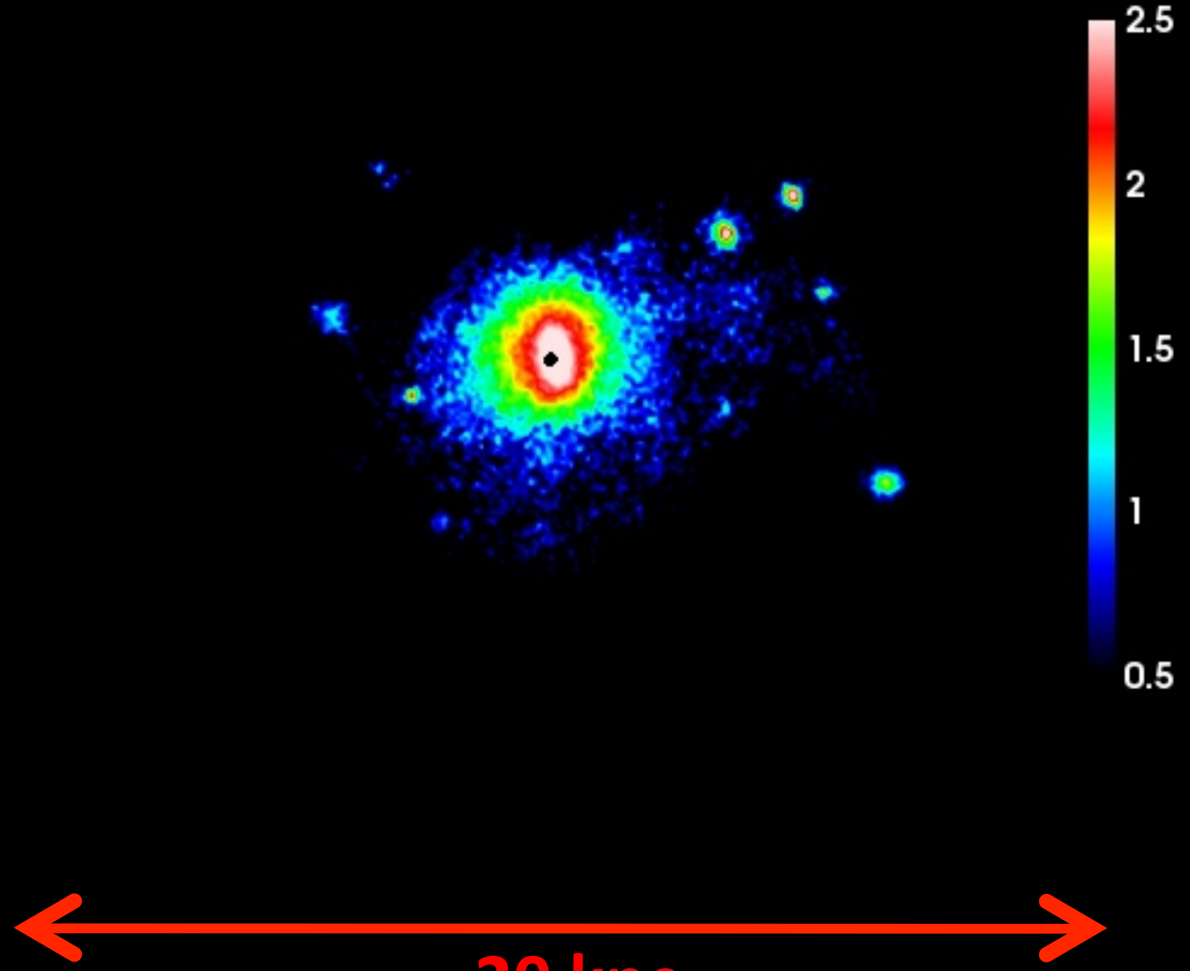
Gas face-on

Gas edge-on

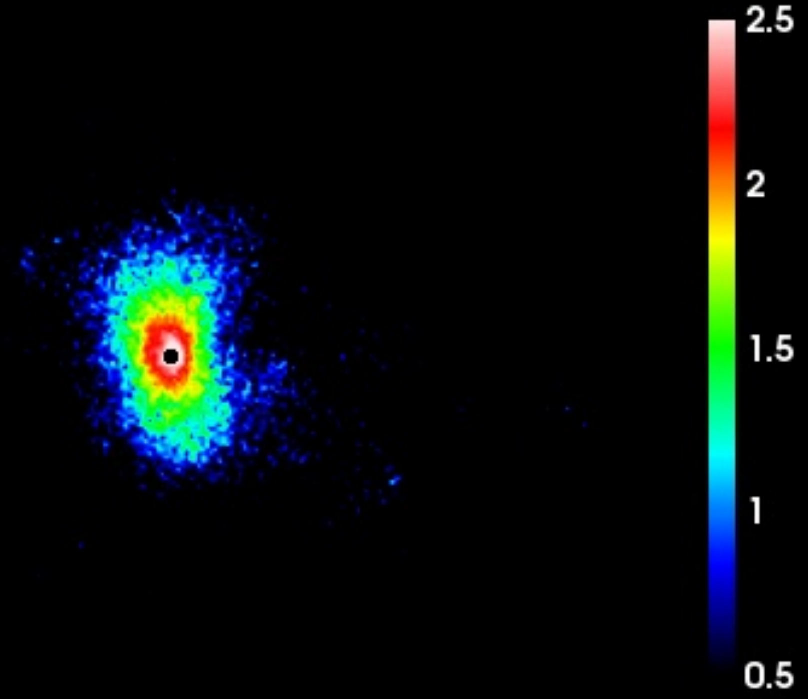
Daniel Ceverino

Stars face-on

Without radiation pressure

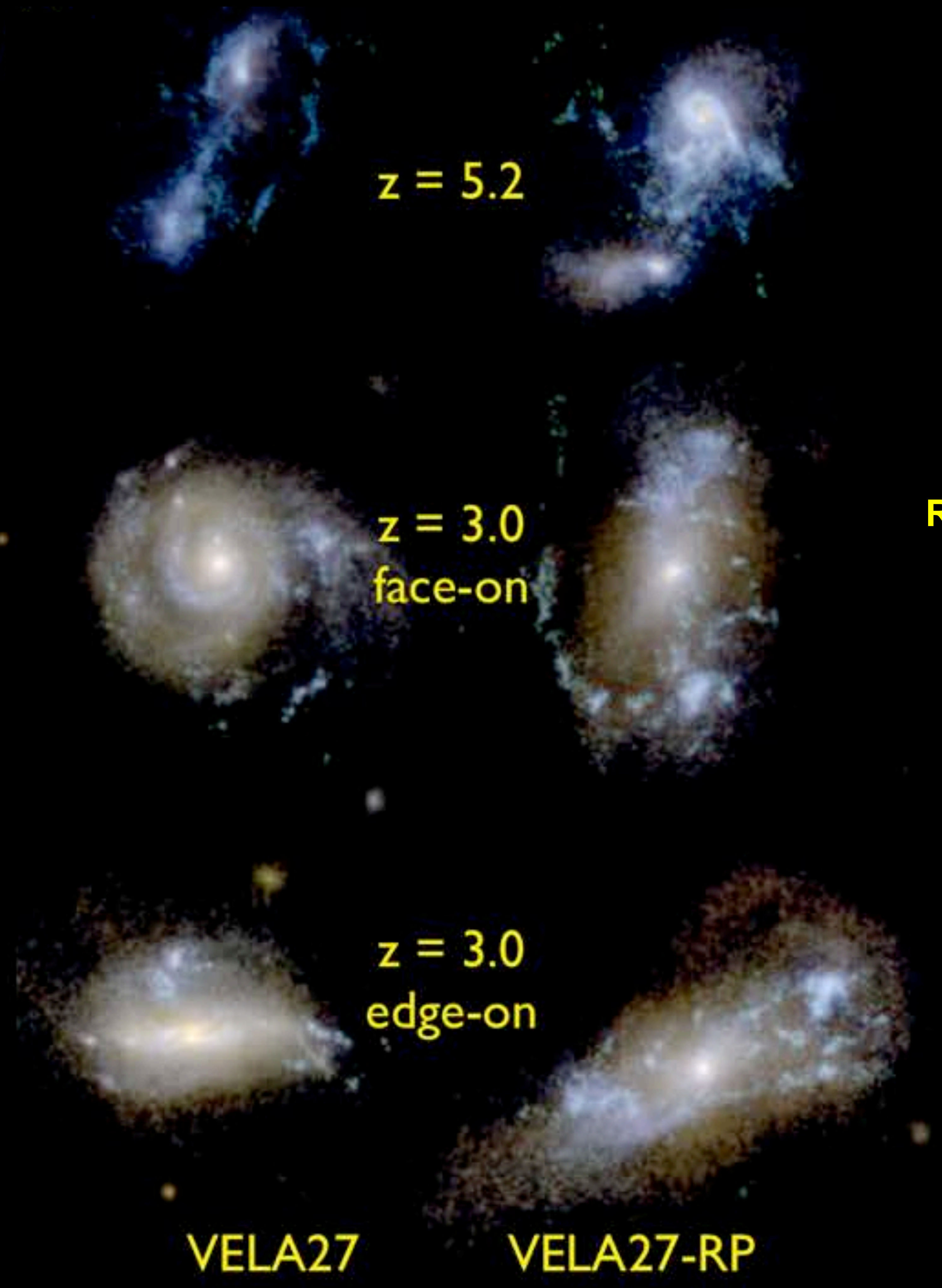


With radiation pressure



Daniel Ceverino

Left: Simulation without Radiation Pressure feedback



Right: Same Simulation with Radiation Pressure feedback

Radiative Feedback Makes Galaxies More Elongated

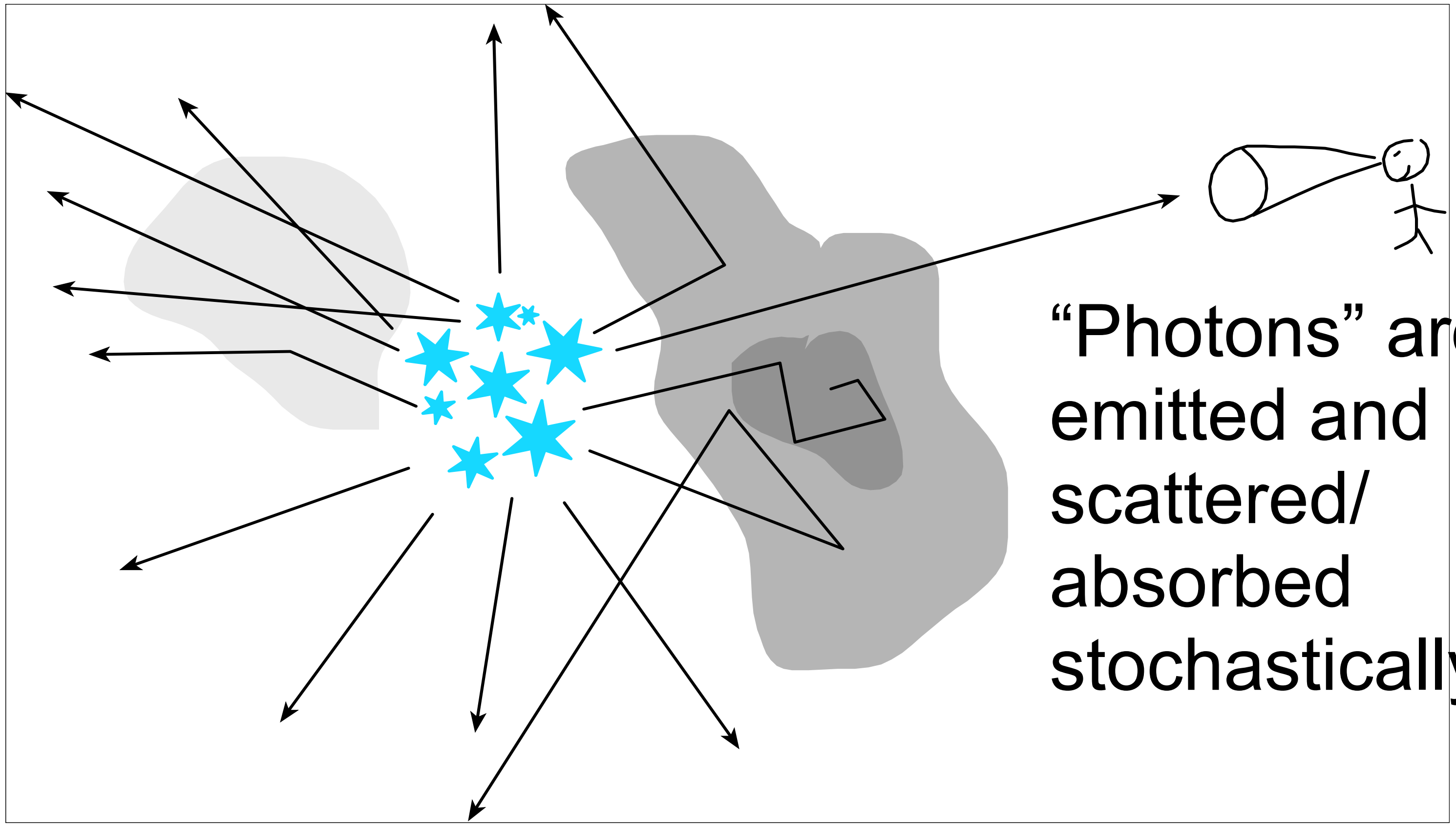
New CANDELS paper: galaxy elongation observed

Sunrise Radiative Transfer Code

Patrik Jonsson
& Joel Primack

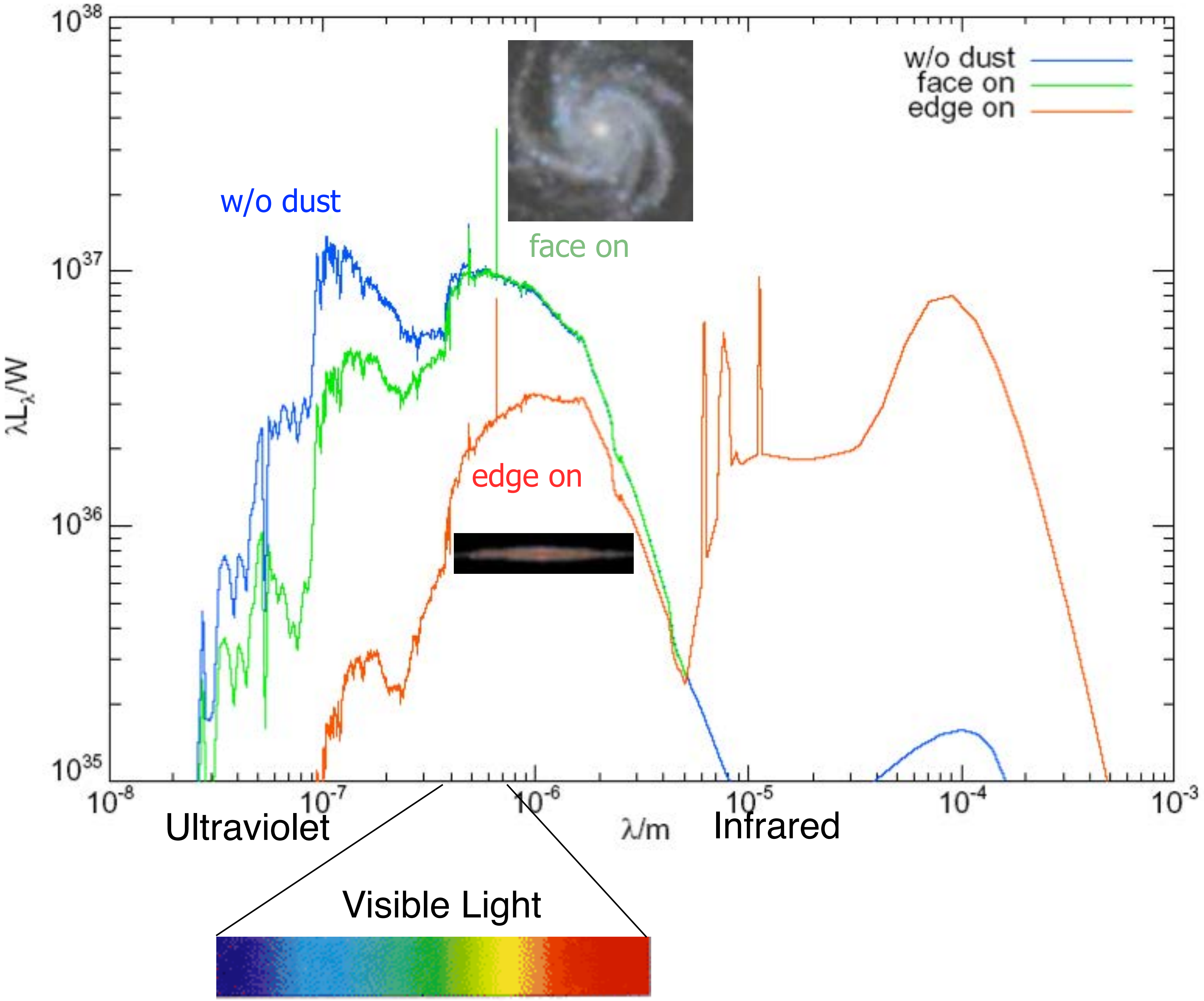
For every simulation snapshot:

- Evolving stellar spectra calculation
- Adaptive grid construction
- Monte Carlo radiative transfer
- “Polychromatic” rays save 100x CPU time
- Graphic Processor Units give 10x speedup



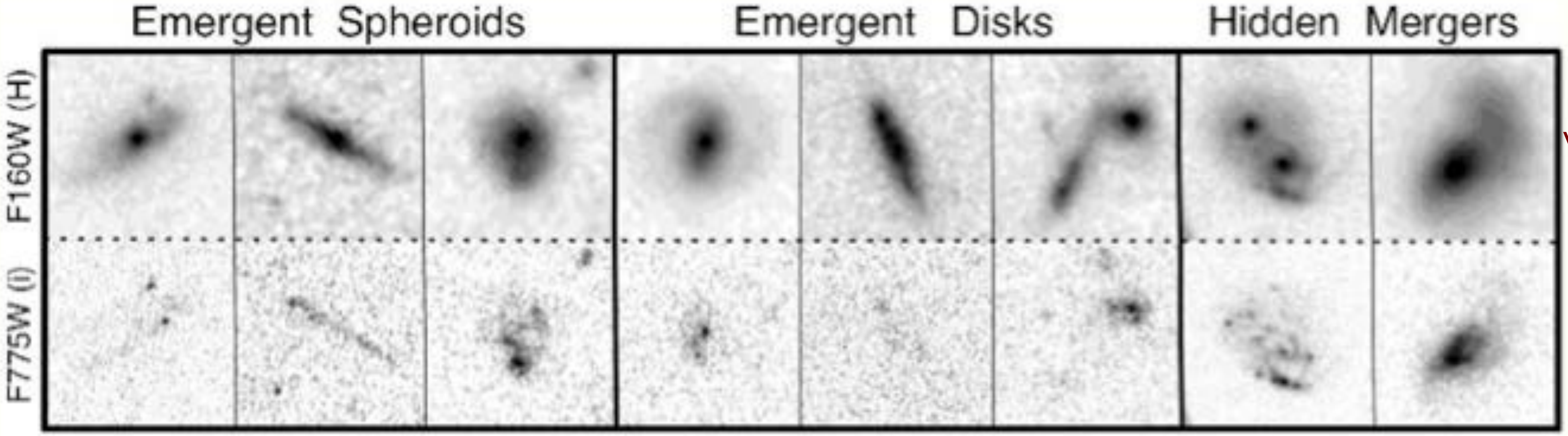
“Photons” are emitted and scattered/ absorbed stochastically

Spectral Energy Distribution



The CANDELS Survey with new near-IR camera WFC3

GALAXIES ~10 BILLION YEARS AGO



WFC3

ACS

CANDELS makes use of the near-infrared WFC3 camera (top row) and the visible-light ACS camera (bottom row). Using these two cameras, CANDELS will reveal new details of the distant Universe and test the reality of cosmic dark energy.

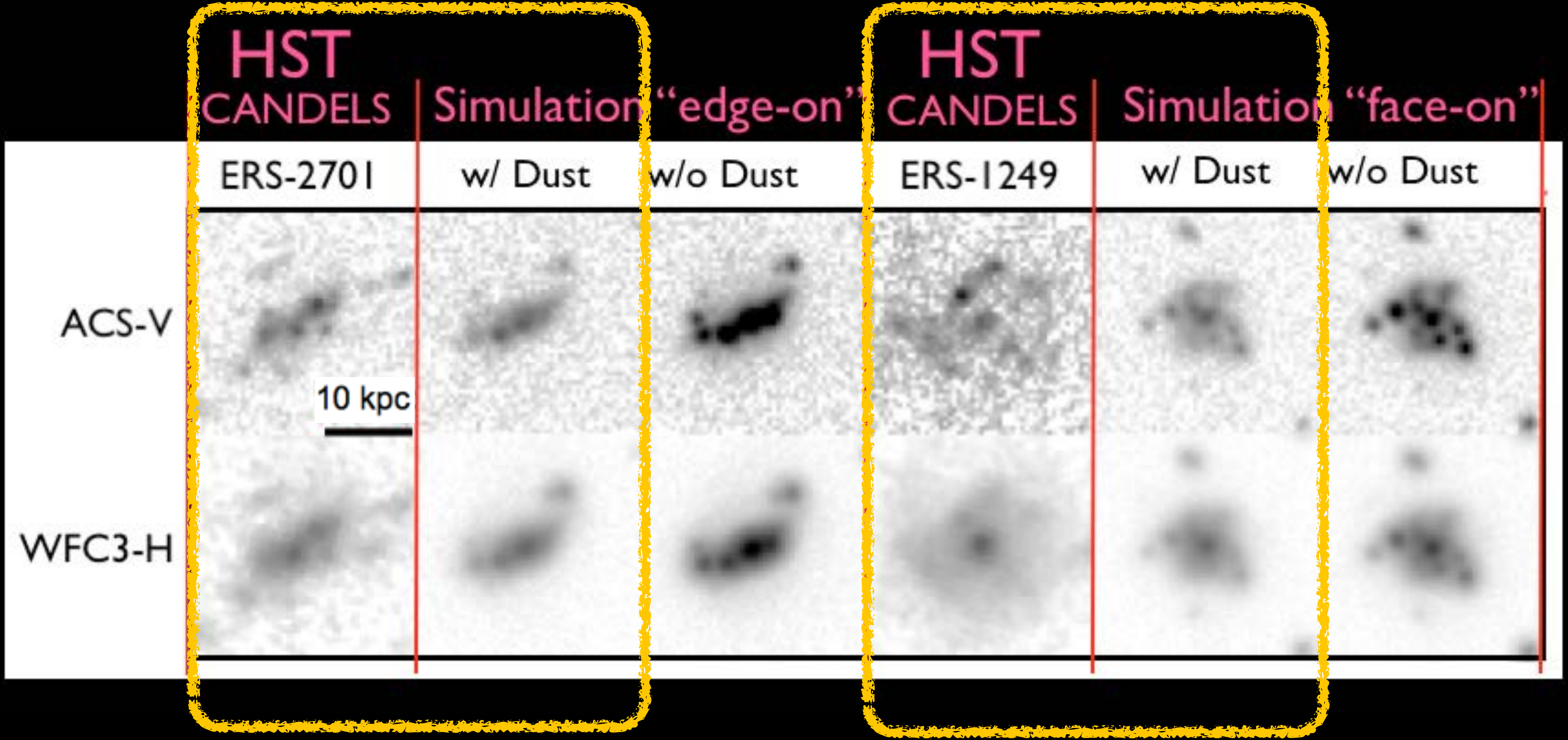
Hubble
Space
Telescope

http://candels.ucolick.org

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

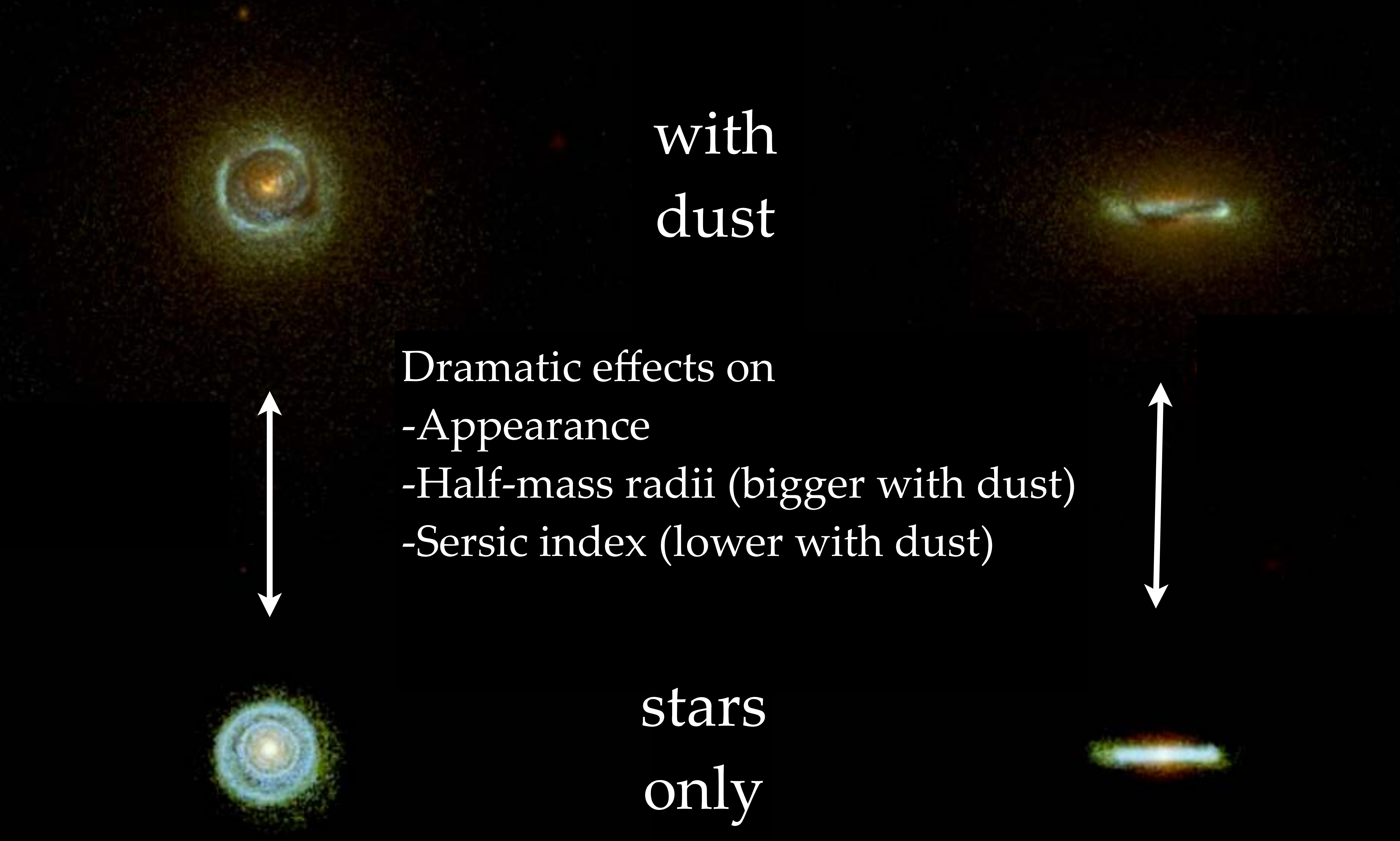
- CANDELS is the largest project in the history of Hubble, with 902 assigned orbits of observing time. This is the equivalent of four months of Hubble time if executed consecutively, but in practice CANDELS will take three years to complete (2010-2013).
- The core of CANDELS is the revolutionary near-infrared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

Our Simulations w/ Dust look a lot like galaxies from 10 billion years ago that we see with Hubble Space Telescope



We are now systematically comparing simulated and observed galaxy images

What’s the effect of including dust?



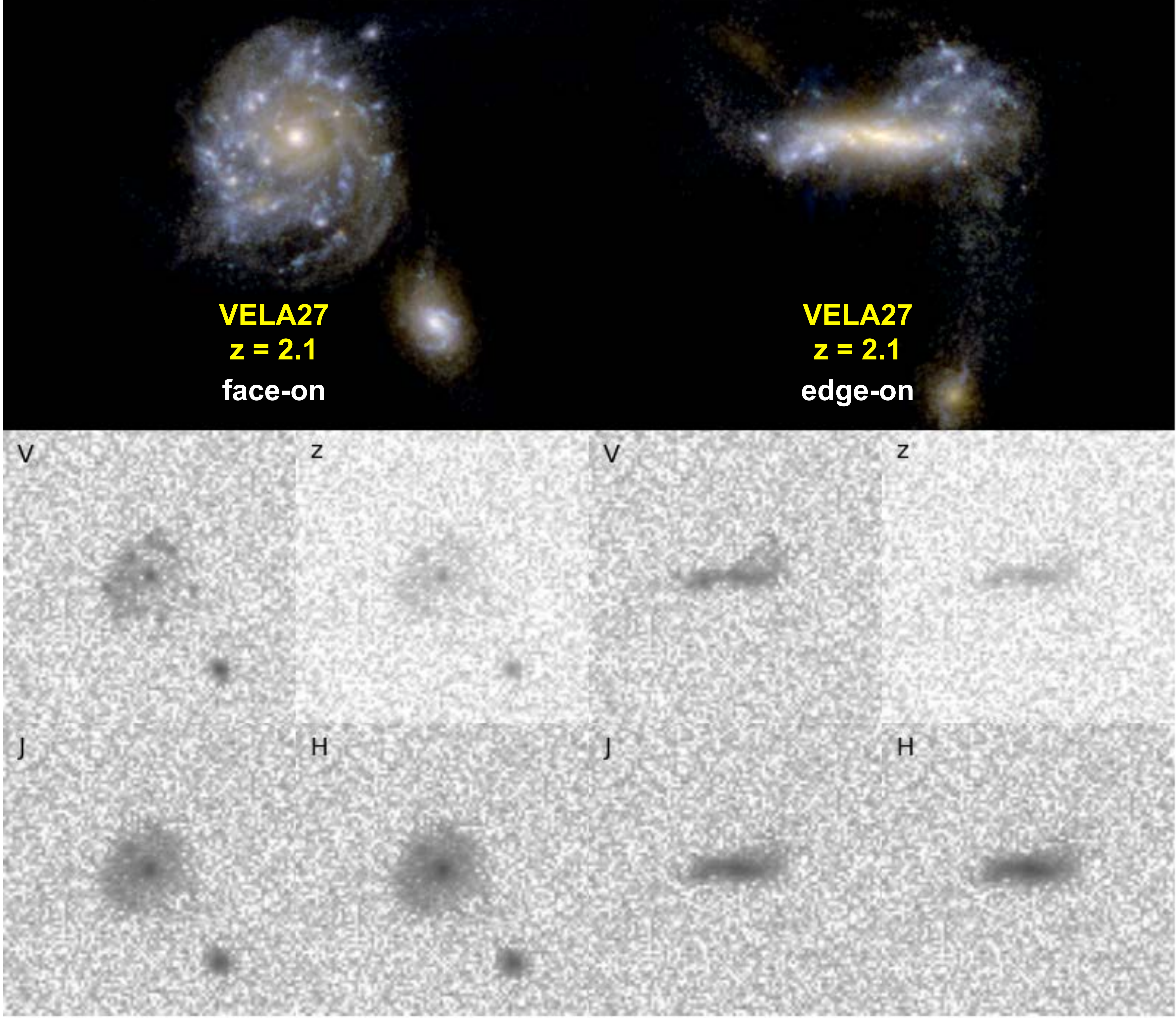
with
dust

Dramatic effects on
- Appearance
- Half-mass radii (bigger with dust)
- Sersic index (lower with dust)

stars
only

cemoody.imgur.com

Simulated Galaxy 10 billion years ago



as it would appear nearby to our eyes

as it would appear to Hubble’s ACS visual camera

as it would appear to Hubble’s WFC3 infrared camera

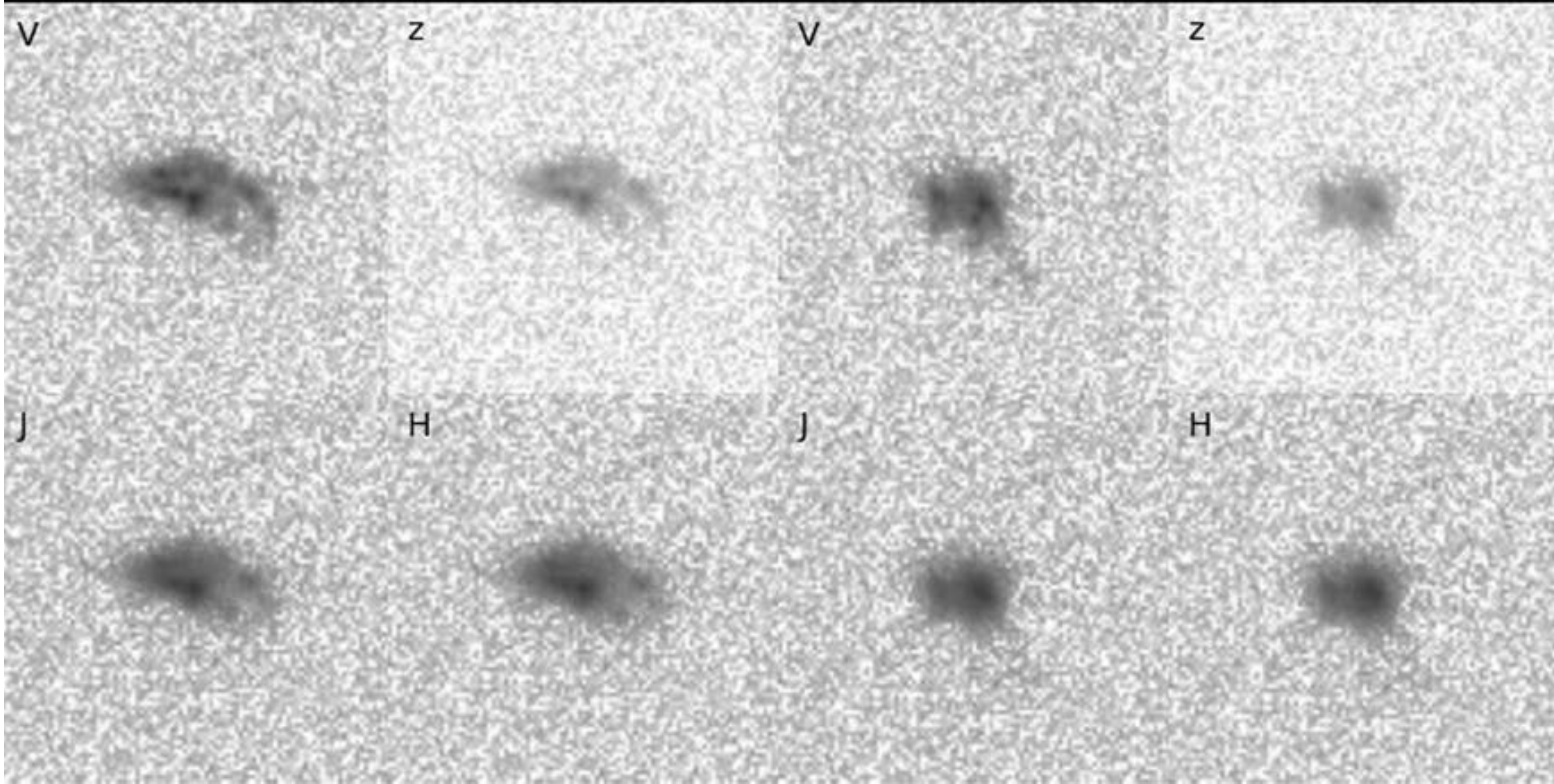
Simulated with Radiative Pressure feedback

Same initial conditions with radiative feedback

as it would appear nearby to our eyes

as it would appear to Hubble's ACS visual camera

as it would appear to Hubble's WFC3 infrared camera



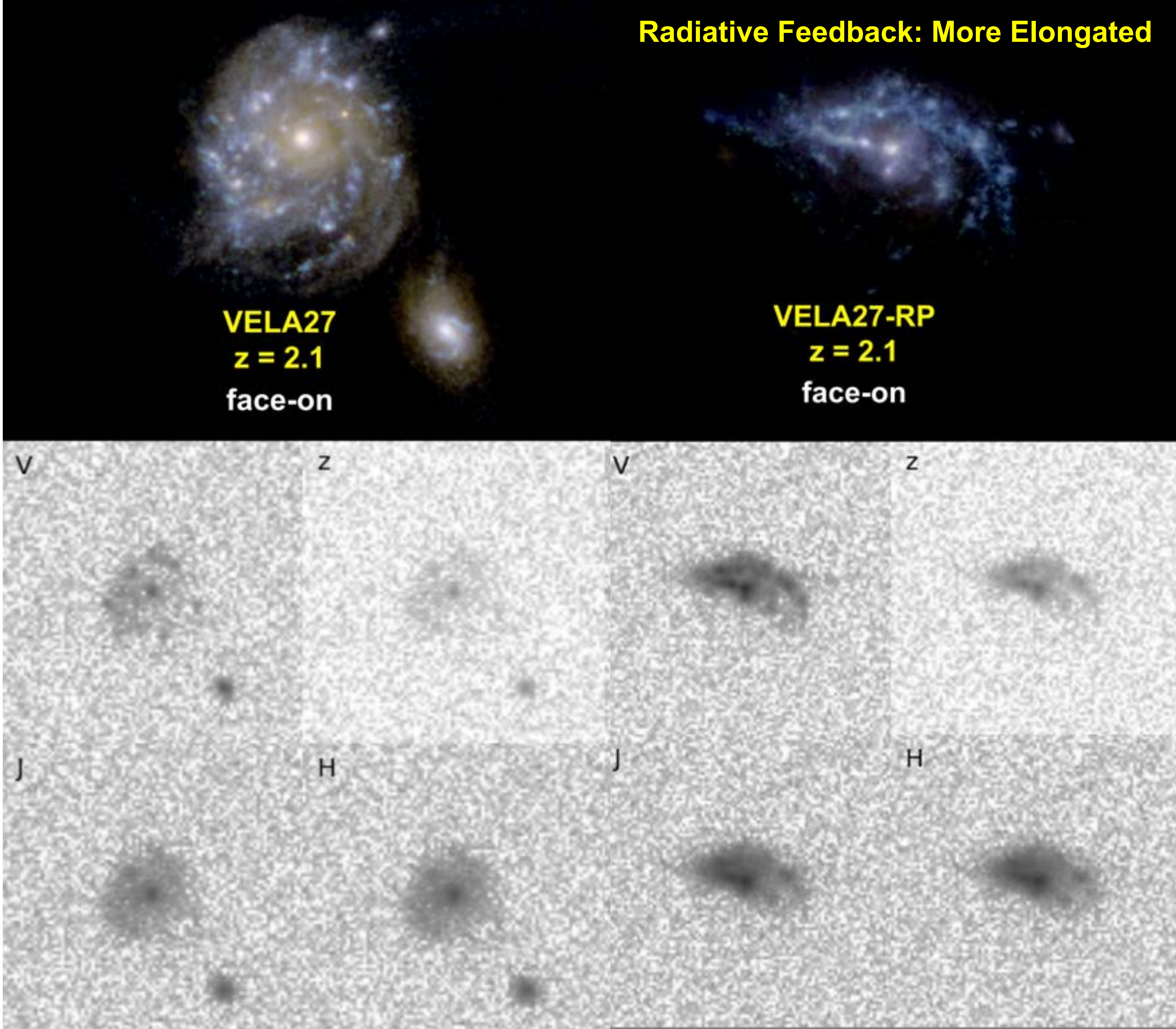
Radiative Feedback: More Elongated

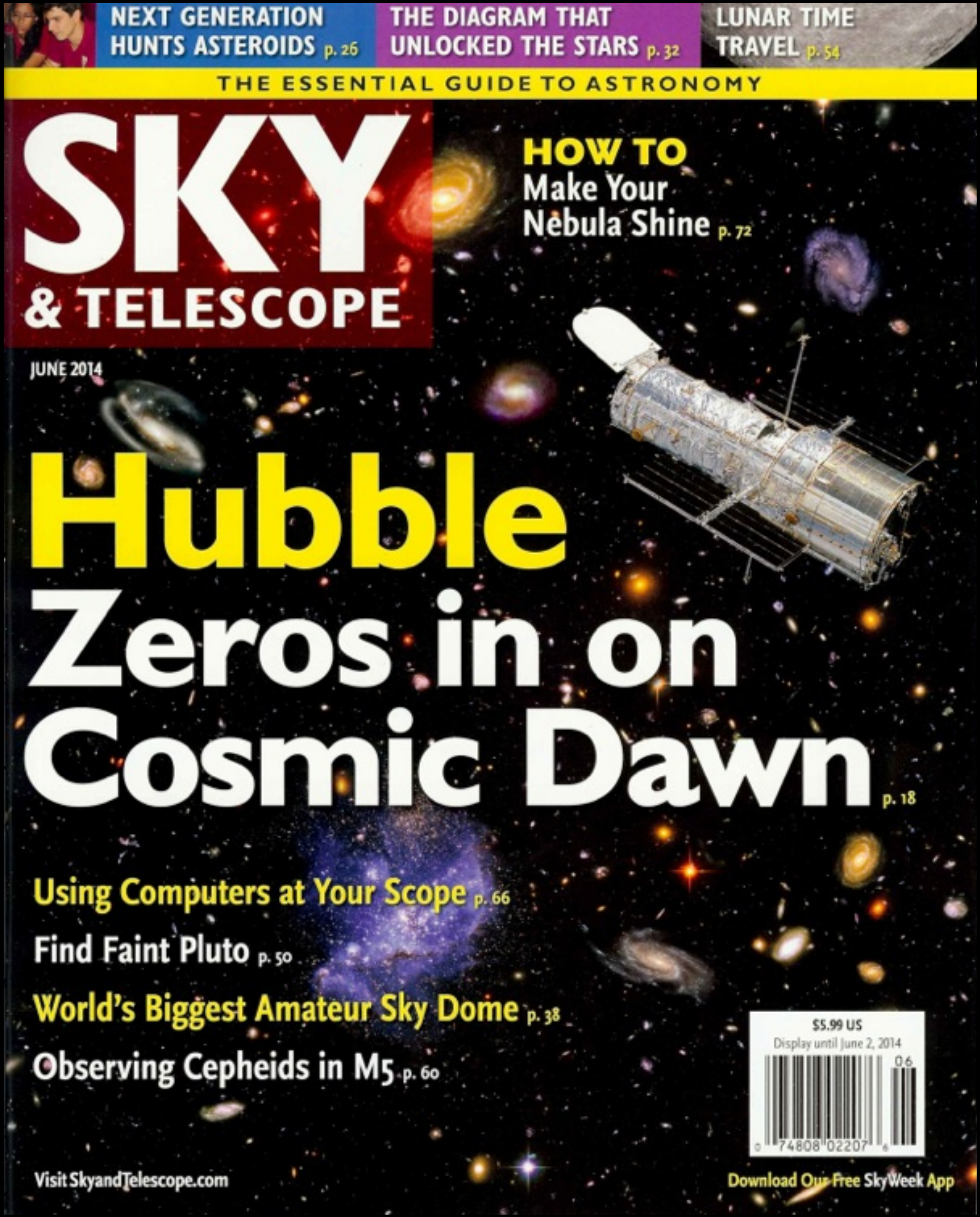
Simulated Galaxy 10 billion years ago

as it would appear nearby to our eyes

as it would appear to Hubble's ACS visual camera

as it would appear to Hubble's WFC3 infrared camera





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THE ESSENTIAL GUIDE TO ASTRONOMY

SKY & TELESCOPE

JUNE 2014

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Hubble Zeros in on Cosmic Dawn p. 18

Using Computers at Your Scope p. 66

Find Faint Pluto p. 50

World's Biggest Amateur Sky Dome p. 38

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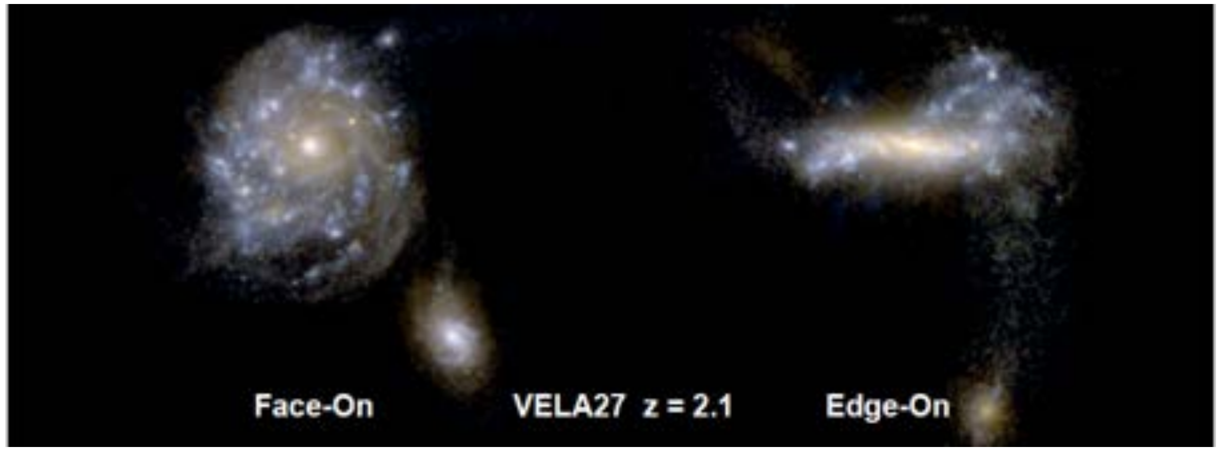
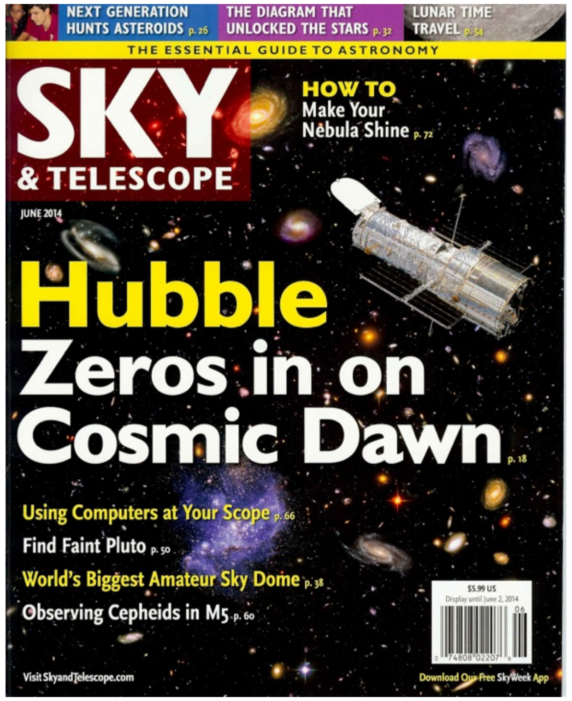
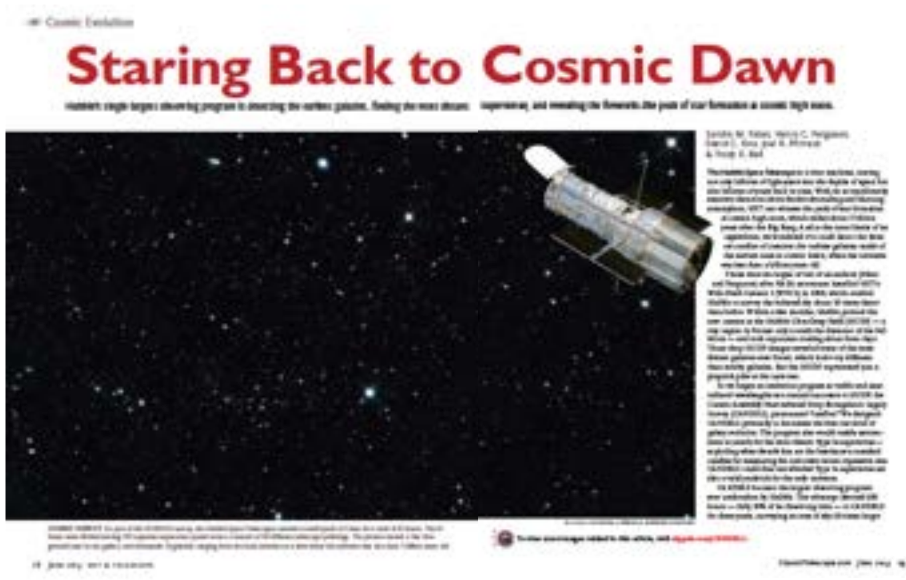
High-resolution Sunrise Images



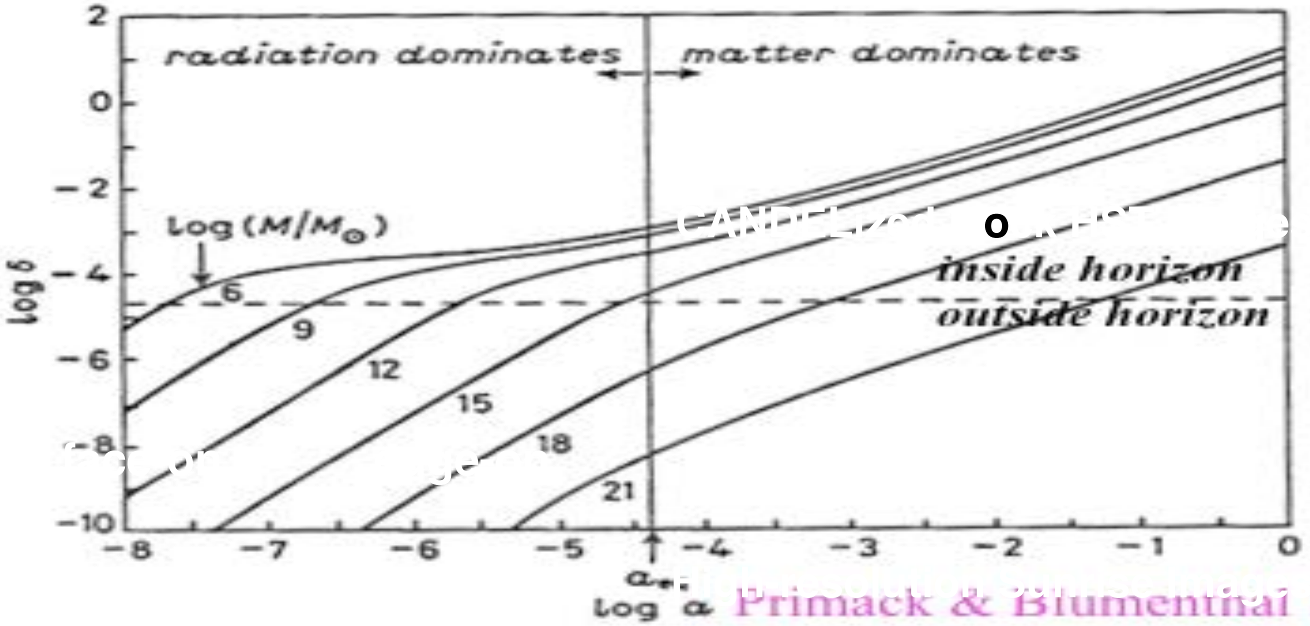
From June 2014 *Sky & Telescope* article



http://hipacc.ucsc.edu/NewsArchive/June2014-S&T-CANDELS-CoverStory.pdf

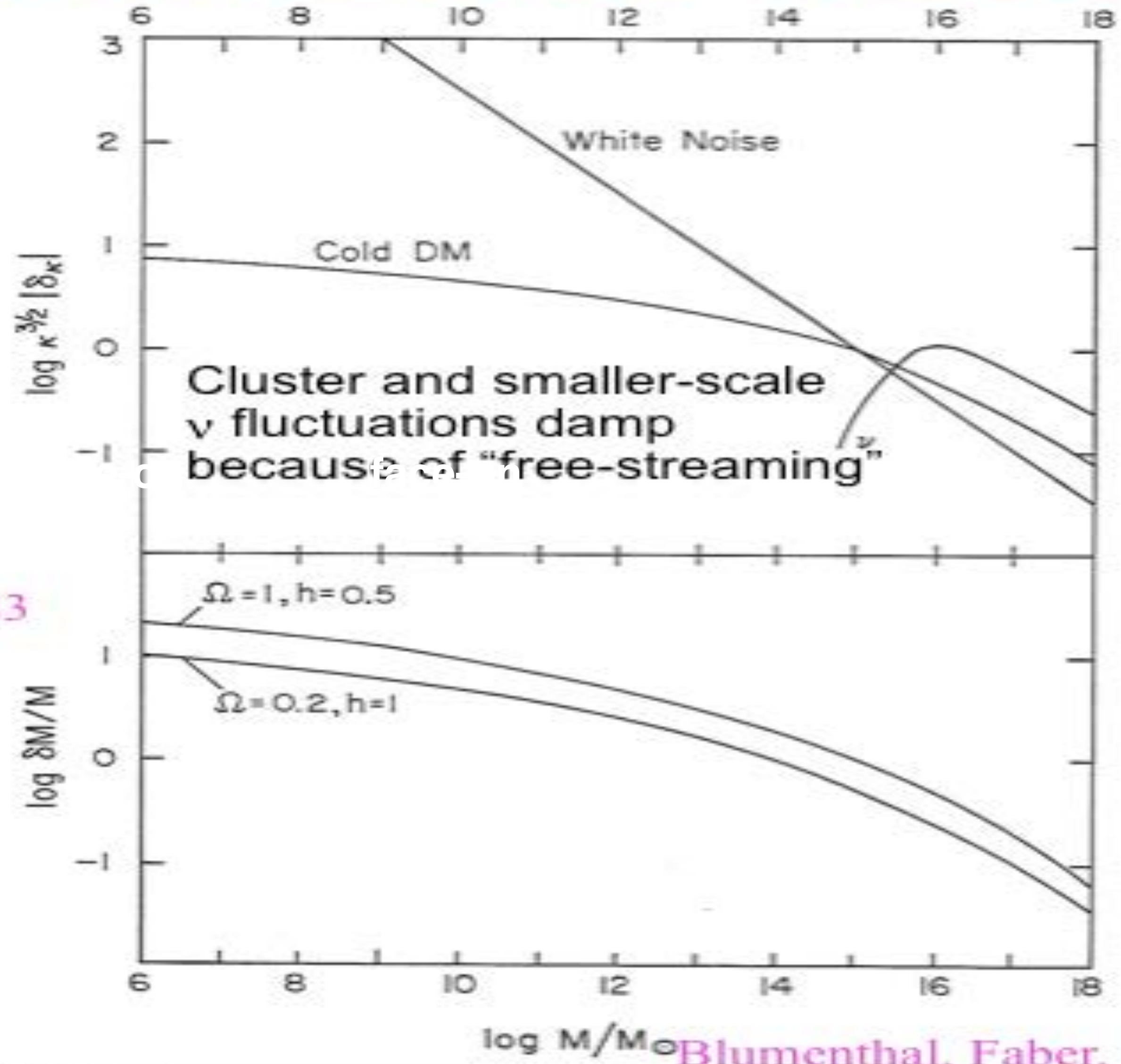

Staring Back to Cosmic Dawn

CDM Structure Formation: Linear Theory



Primack & Blumenthal 1983

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



Cluster and smaller-scale ν fluctuations damp because of "free-streaming"

Blumenthal, Faber, Primack, & Rees 1984

Most $M_* < 10^{9.5}\ M_\odot$ Star Forming Galaxies at $z > 1$ Are Prolate

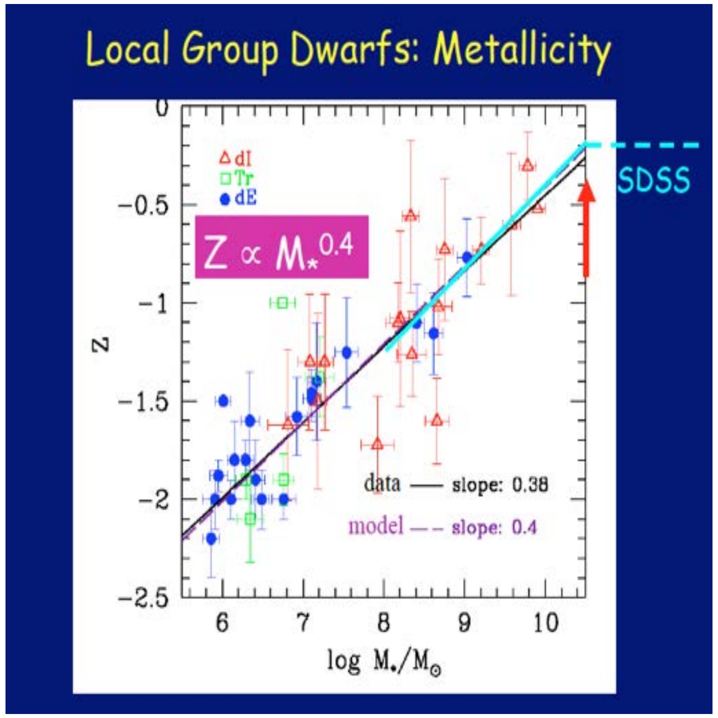
GEOMETRY OF STAR-FORMING GALAXIES FROM SDSS, 3D-HST AND CANDELS

A. van der Wel[1], Yu-Yen Chang[1], E. F. Bell[2], B. P. Holden[3], H. C. Ferguson[4], M. Giavalisco[5], H.-W. Rix[1], R. Skelton[6], K. Whitaker[7], I. Momcheva[8], G. Brammer[4], S. A. Kassin[4], A. Dekel[9], D. Ceverino[10], D. C. Koo[3], M. Mozena[3], P. G. van Dokkum[8], M. Franx[11], S. M. Faber[3], and J. Primack[12]

ApJ in press

ABSTRACT

We determine the intrinsic, 3-dimensional shape distribution of star-forming galaxies at $0 < z < 2.5$, as inferred from their observed projected axis ratios. In the present-day universe star-forming galaxies of all masses $10^9 - 10^{11}\ M_\odot$ are predominantly thin, nearly oblate disks, in line with previous studies. We now extend this to higher redshifts, and find that among massive galaxies ($M_* > 10^{10}\ M_\odot$) disks are the most common geometric shape at all $z \lesssim 2$. Lower-mass galaxies at $z > 1$ possess a broad range of geometric shapes: the fraction of elongated (prolate) galaxies increases toward higher redshifts and lower masses. Galaxies with stellar mass $10^9\ M_\odot$ ($10^{10}\ M_\odot$) are a mix of roughly equal numbers of elongated and disk galaxies at $z \sim 1$ ($z \sim 2$). This suggests that galaxies in this mass range do not yet have disks that are sustained over many orbital periods, implying that galaxies with present-day stellar mass comparable to that of the Milky Way typically first formed such sustained stellar disks at redshift $z \sim 1.5 - 2$. Combined with constraints on the evolution of the star formation rate density and the distribution of star formation over galaxies with different masses, our findings imply that the majority of all stars across cosmic epochs formed in disks.



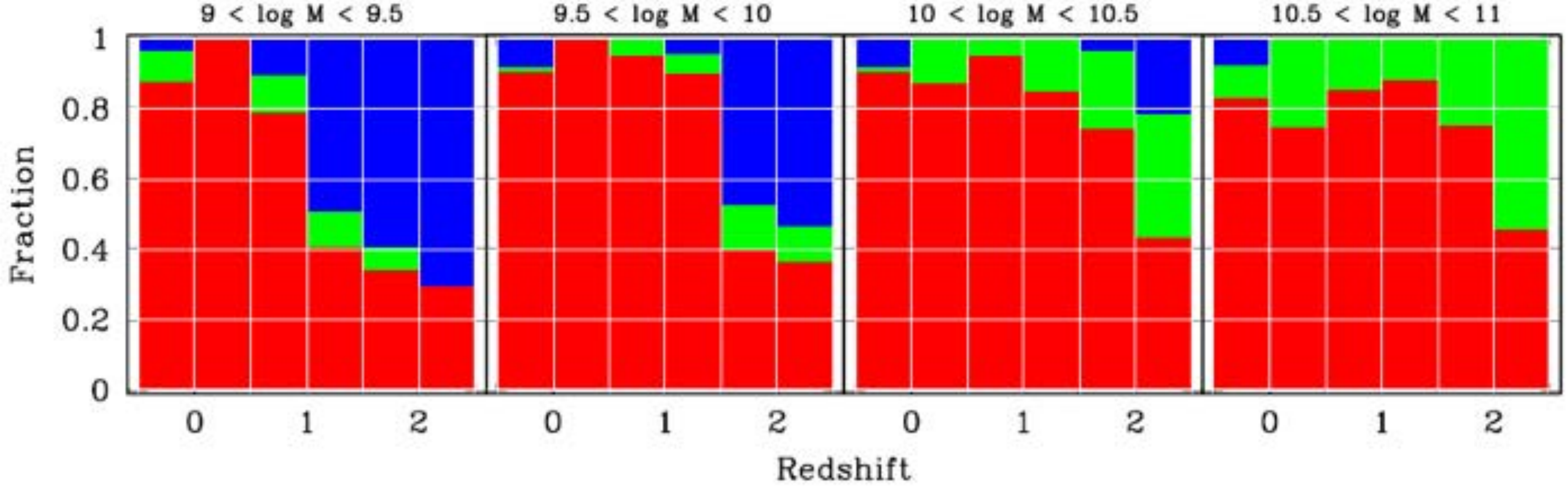


Figure 4. Color bars indicate the fraction of the different types of shape defined in Figure 2 as a function of redshift and stellar mass. The negative redshift bins represent the SDSS results for $z < 0.1$; the other bins are from 3D-HST/CANDELS.

A Star Forming Galaxy with $M_* < 10^{9.5}\ M_\odot$ at $z > 1$

Triangulum Galaxy (M33)
3rd brightest galaxy
in the Local Group

$10^{8\text{-}9}$ $M_\odot$ Clumps in Simulated Galaxies

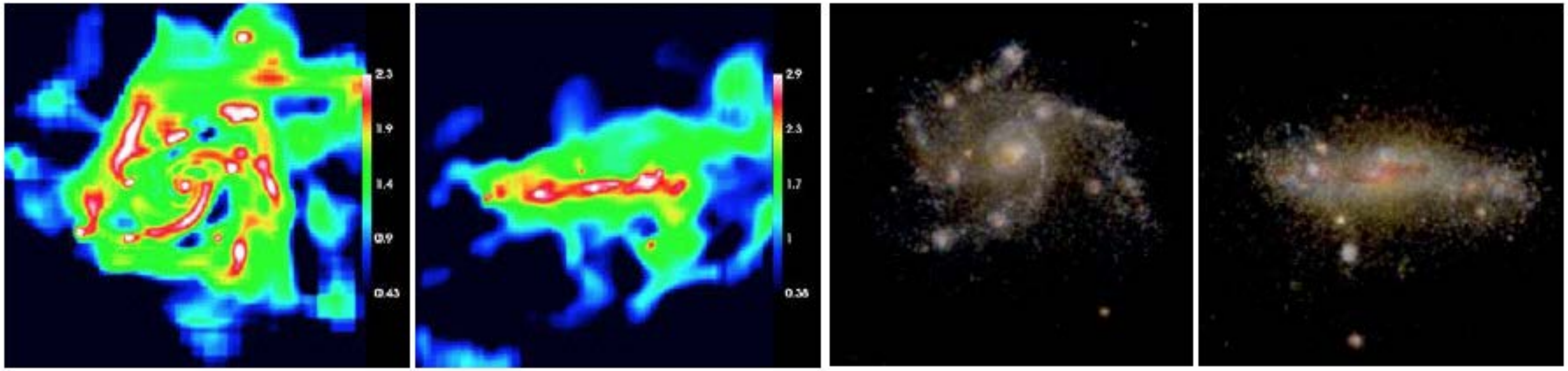
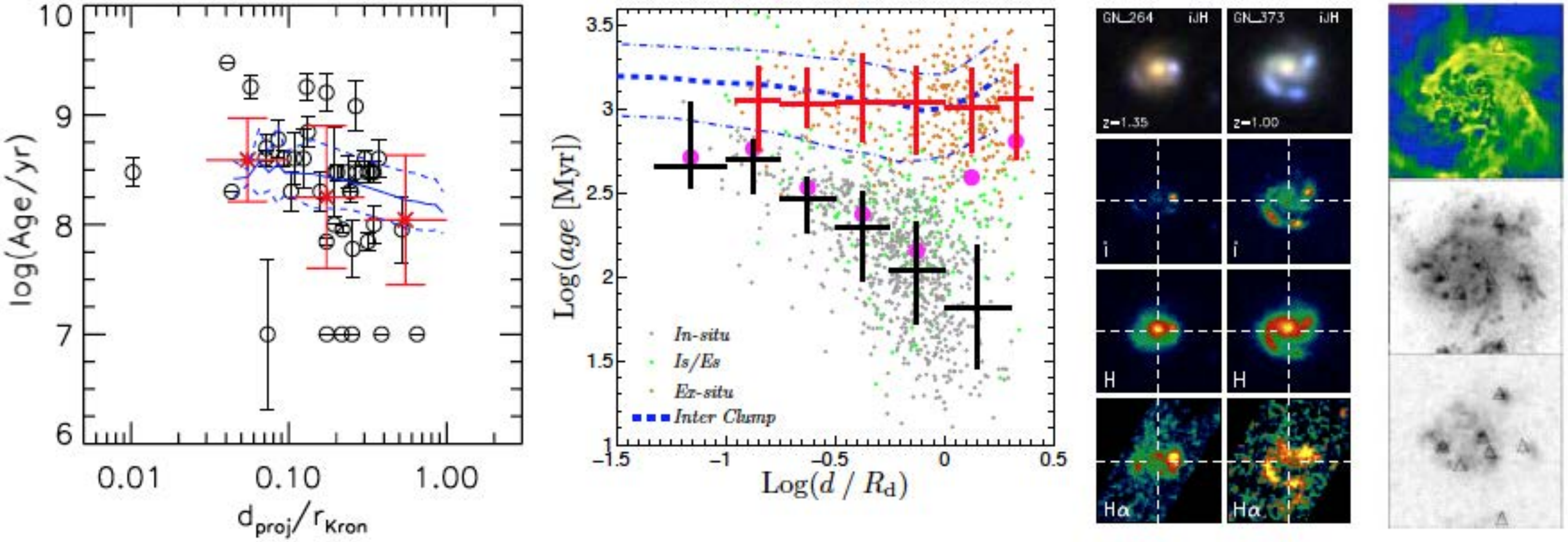


Figure 1: Violently unstable disks in $\sim 10^{11} M_\odot$ halos with $\sim 10^9 M_\odot$ clumps at $z = 2.3$: (a) face-on, (b) edge-on (Ceverino et al. 2009, resolution 70 pc, images 10 kpc across). RGB color images of the same simulated galaxy through dust using *Sunrise*: (c) face-on, (d) edge-on, illustrating how the clumps can be reddened and obscured when viewed edge-on.

Recall: Semi-Analytic Models find that a majority of galactic spheroids form by violently unstable disks forming clumps and bars that drive stars and gas to the galactic center, rather than by galaxy mergers.

10^{8-9} $M_\odot$ Clumps in Real and Simulated Galaxies



CANDELS observations

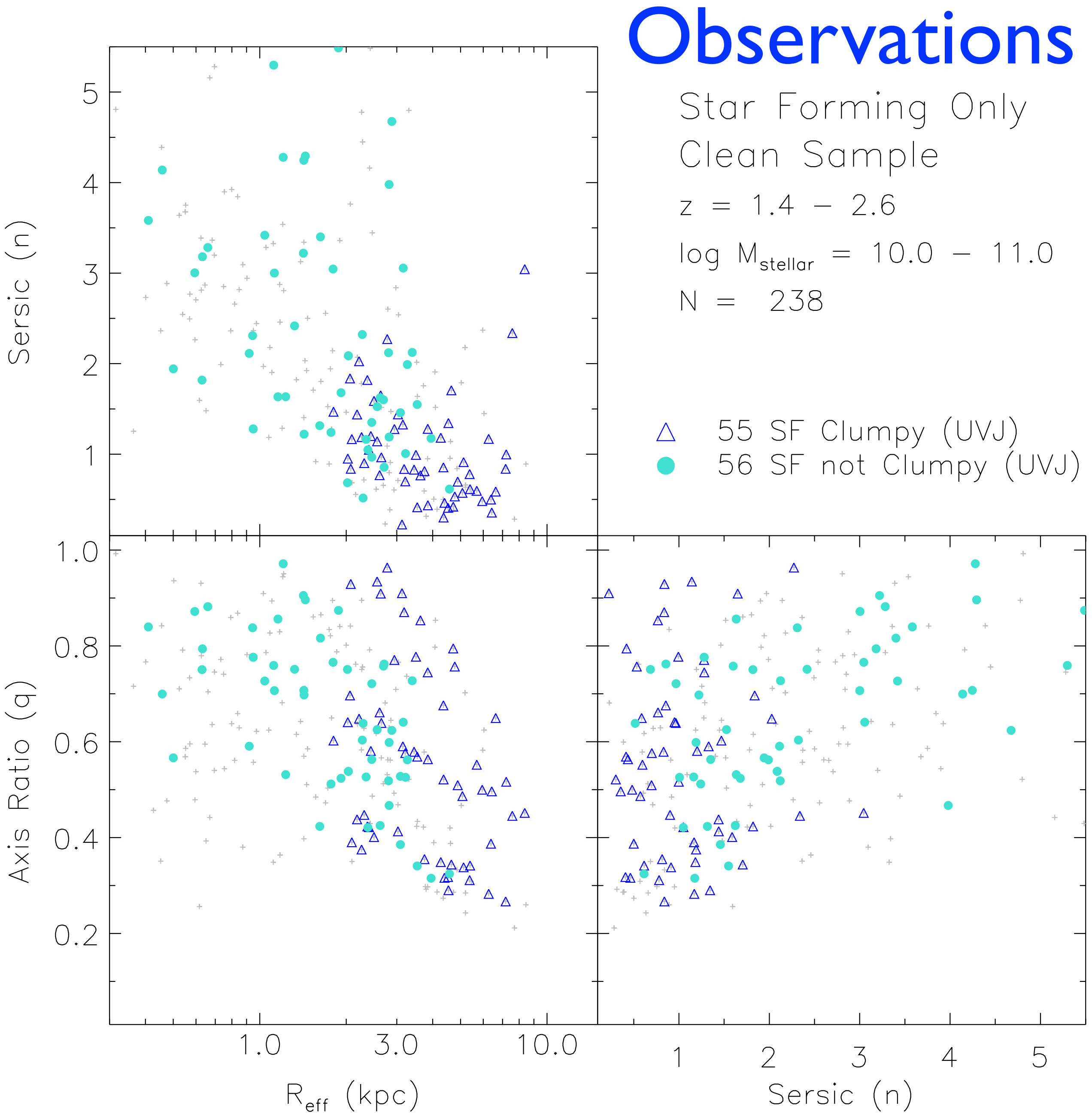
ART simulations

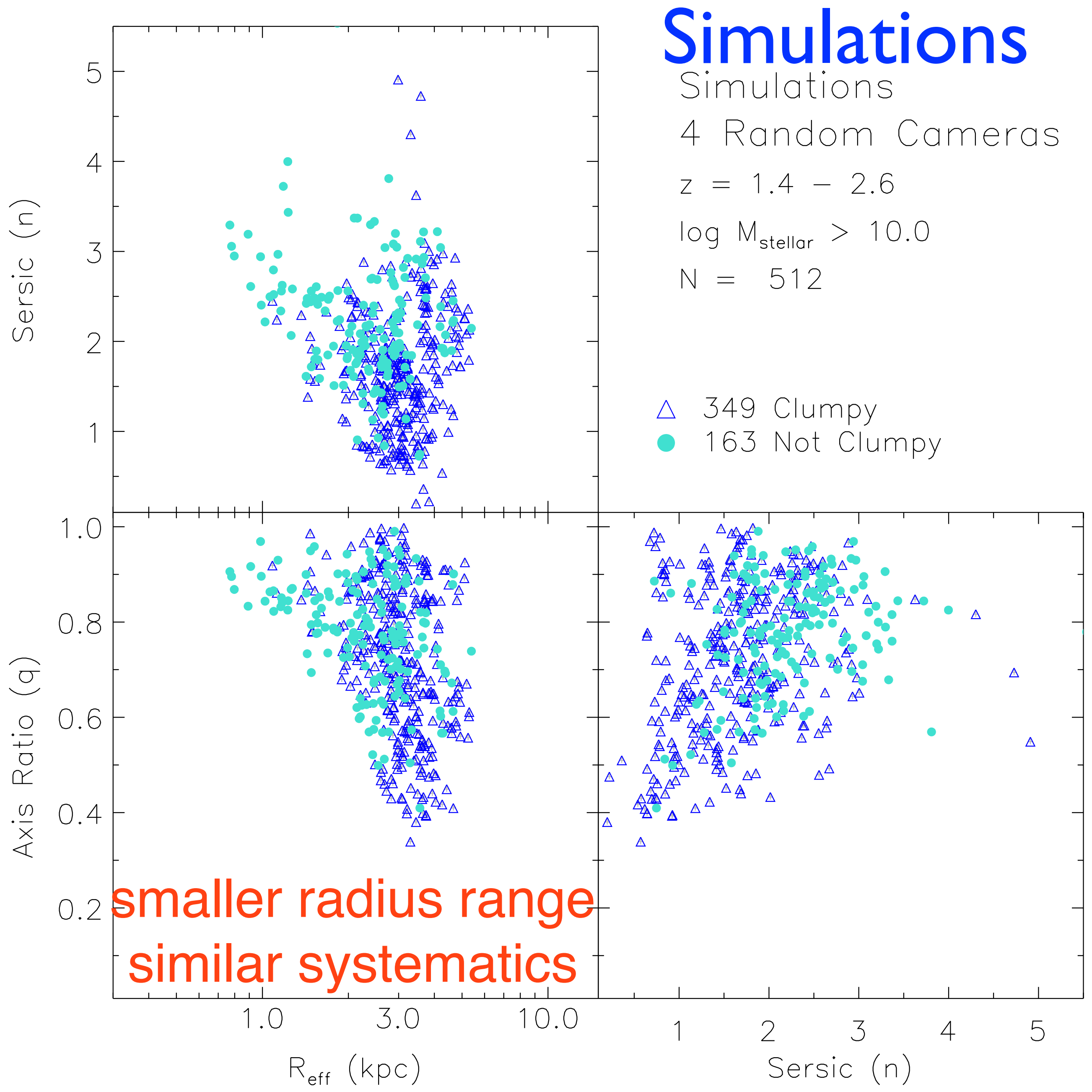
3D-HST data

ART sims

Figure 3: Clump stellar age vs. radius in (a) CANDELS observations (Guo et al. 2012, with black points showing individual clumps and red points showing mean and 1σ range) and (b) analysis of our generation 1 simulations, with black and red crosses showing in situ and ex situ clumps, respectively, and magenta points showing median values for all clumps, both in situ and ex situ (Mandelker et al. 2013). In both figures, the blue curves show the disk inter-clump stellar age and 1σ scatter. (c) 3D-HST observations of two clumpy galaxies (Wuyts et al. 2013); comparing Hα from the grism observations with i and H band images allows estimation of the dust extinction. (d) (*bottom*) Clumps (triangles) found by Yicheng Guo's automated method on CANDELized V-band image, and the same clumps plotted on (*middle*) the V-band image before CANDELization and (*top*) on the projected gas map (Moody et al. 2014).

CANDELS Galaxies Compared with Generations 1 & 2 hydroART simulations using R_{eff}, Axis Ratio q, Sersic n, with clumpy vs. not clumpy from by-eye classification


Observations


Simulations

smaller radius range
similar systematics

Mark Mozena (PhD dissertation Dec 2013)

University of California
High-Performance
AstroComputing Center
(UC-HiPACC)
Joel Primack, Director

University of California
Santa Cruz
Next Telescope Science
Institute (NEXSI)
Piero Madau, Director

Assembling Galaxies of Resolved Anatomy
AGORA High-Resolution Galaxy Simulation Comparison Project Steering Committee

Piero Madau & Joel R. Primack, UCSC, Co-Chairs
Tom Abel, Stanford
Nick Gnedin, Chicago/Fermilab
Lucio Mayer, University of Zurich
Romain Teyssier, Saclay & Zurich
James Wadsley, McMaster

Ji-hoon Kim, UCSC (Coordinator)

108 astrophysicists have joined AGORA from 50 institutions in 8 countries using 11 simulation codes

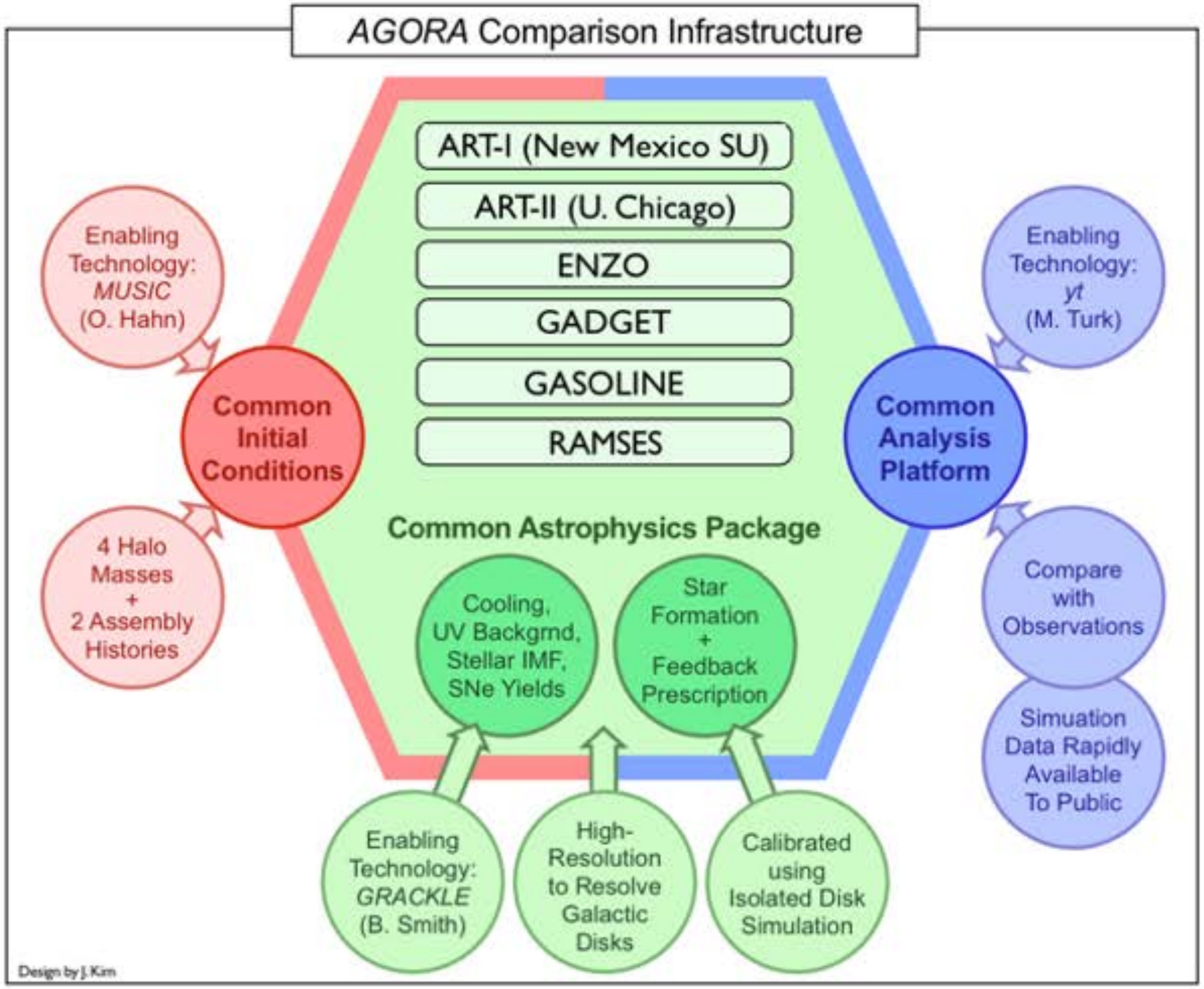
www.AGORAsimulations.org

AGORA High-resolution Galaxy Simulations Comparison Initiative

"A Multi-Platform Approach to Longstanding Challenges in Galaxy Formation Theory"

- High-resolution galaxy simulations comparison initiative specifically designed with astrophysical questions in mind
  1) Common initial conditions chosen to meet isolation + assembly history criteria, easily transferable across codes through *MUSIC* parameters
  2) Common astrophysics + high-resolution (<100 pc) to be adopted by all participating codes in their zoom-in cosmological runs
  3) Common analysis platform available in the *yt* framework, enabling "direct technology transfer" within and across code platforms

- Aim to verify that the astrophysical assumptions are responsible for any success, rather than artifacts of particular implementations
  → raise the realism and predictive power of galaxy simulations collectively by subjecting numerical experiments to independent tests



AGORA Comparison Infrastructure

ART-I (New Mexico SU)
ART-II (U. Chicago)
ENZO
GADGET
GASOLINE
RAMSES

Common Astrophysics Package

Cooling, UV Backgrnd, Stellar IMF, SNe Yields

Star Formation + Feedback Prescription

Common Initial Conditions

Enabling Technology: *MUSIC* (O. Hahn)

4 Halo Masses + 2 Assembly Histories

Common Analysis Platform

Enabling Technology: *yt* (M. Turk)

Compare with Observations

Simuation Data Rapidly Available To Public

Enabling Technology: *GRACKLE* (B. Smith)

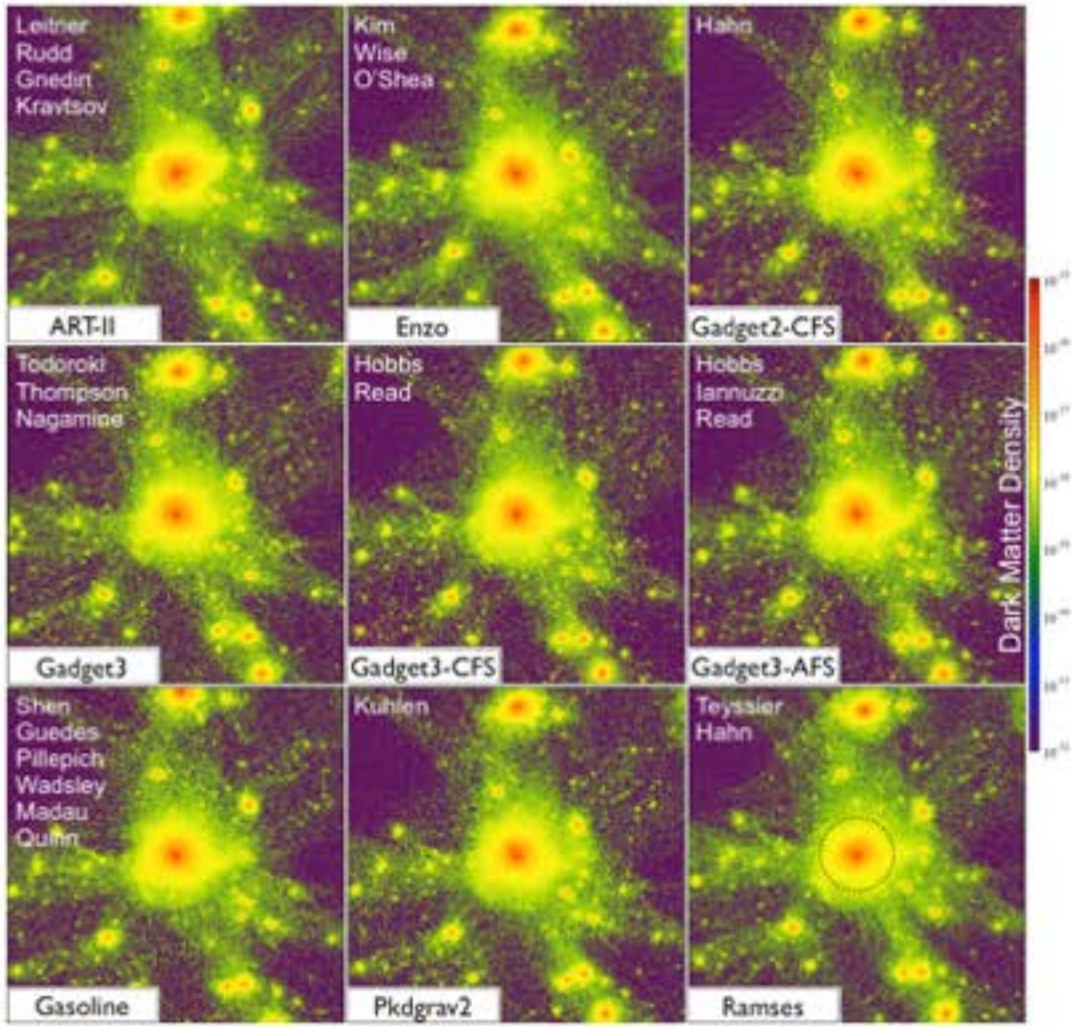
High-Resolution to Resolve Galactic Disks

Calibrated using Isolated Disk Simulation

Design by J. Kim

- **First Light: Flagship paper by Ji-hoon Kim et al. for the AGORA collaboration (ApJS 2014)**

- **www.AGORAsimulations.org, 108 participants from 50 institutions worldwide**



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)
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

Thanks!