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/Caltech (Coordinator)

~90 astrophysicists using 9 codes have joined AGORA
Next meeting: Aug 16-19, 2013

www.AGORAsimulations.org

Key Earlier Galaxy Simulation Comparison

The Aquila comparison Project: The Effects of Feedback and Numerical Methods on Simulations of Galaxy Formation

C. Scannapieco,[1] M. Wadepuhl,[2] O.H. Parry,[3,4] J.F. Navarro,[5] A. Jenkins,[3] V. Springel,[6,7] R. Teyssier,[8,9] E. Carlson,[10] H.M.P. Couchman,[11] R.A. Crain,[12,13] C. Dalla Vecchia,[14] C.S. Frenk,[3] C. Kobayashi,[15,16] P. Monaco,[17,18] G. Murante,[17,19] T. Okamoto,[20] T. Quinn,[10] J. Schaye,[13] G. S. Stinson,[21] T. Theuns,[3,22] J. Wadsley,[11] S.D.M. White,[2] R. Woods[11]
2012 MNRAS 423, 1726

ABSTRACT

We compare the results of various cosmological gas-dynamical codes used to simulate the formation of a galaxy in the ΛCDM structure formation paradigm. **The various runs** (thirteen in total) differ in their numerical hydrodynamical treatment (SPH, moving-mesh and AMR) but **share the same initial conditions and adopt in each case their latest published model of gas cooling, star formation and feedback**. Despite the common halo assembly history, **we find large code-to-code variations in the stellar mass, size, morphology and gas content of the galaxy at z = 0, due mainly to the different implementations of star formation and feedback**. Compared with observation, **most codes tend to produce an overly massive galaxy, smaller and less gas-rich than typical spirals, with a massive bulge and a declining rotation curve**. A stellar disk is discernible in most simulations, although its prominence varies widely from code to code. There is a well-defined trend between the effects of feedback and the severity of the disagreement with observed spirals. In general, **models that are more effective at limiting the baryonic mass of the galaxy come closer to matching observed galaxy scaling laws, but often to the detriment of the disk component.** Although numerical convergence is not particularly good for any of the codes, our conclusions hold at two different numerical resolutions. Some differences can also be traced to the different numerical techniques; for example, more gas seems able to cool and become available for star formation in grid-based codes than in SPH. However, this effect is small compared to the variations induced by different feedback prescriptions. **We conclude that state-of-the-art simulations cannot yet uniquely predict the properties of the baryonic component of a galaxy, even when the assembly history of its host halo is fully specified. Developing feedback algorithms that can effectively regulate the mass of a galaxy without hindering the formation of high-angular momentum stellar disks remains a challenge.**

Aquila Comparison Project

Code	Reference	Type	UV background (z_{UV})	UV background (spectrum)	Cooling	Feedback
G3 (GADGET3)	[1]	SPH	6	[10]	primordial [13]	SN (thermal)
G3-BH	[1]	SPH	6	[10]	primordial [13]	SN (thermal), BH
G3-CR	[1]	SPH	6	[10]	primordial [13]	SN (thermal), BH, CR
G3-CS	[2]	SPH	6	[10]	metal-dependent [14]	SN (thermal)
G3-TO	[3]	SPH	9	[11]	element-by-element [15]	SN (thermal+kinetic)
G3-GIMIC	[4]	SPH	9	[11]	element-by-element [15]	SN (kinetic)
G3-MM	[5]	SPH	6	[10]	primordial [13]	SN (thermal)
G3-CK	[6]	SPH	6	[10]	metal-dependent [14]	SN (thermal)
GAS (GASOLINE)	[7]	SPH	10	[12]	metal-dependent [16]	SN (thermal)
R (RAMSES)	[8]	AMR	12	[10]	metal-dependent [14]	SN (thermal)
R-LSFE	[8]	AMR	12	[10]	metal-dependent [14]	SN (thermal)
R-AGN	[8]	AMR	12	[10]	metal-dependent [14]	SN (thermal), BH
AREPO	[9]	Moving Mesh	6	[10]	primordial [13]	SN (thermal)

All simulations share the same initial conditions a zoomed-in resimulation of the Aquarius Project halo “Aq-C”.

Code	f_b (Ω_b/Ω_m)	m_{DM} [$10^6 M_\odot$]	m_{gas} [$10^6 M_\odot$]	Softening $\epsilon_g^{z=0}$ [kpc]	Softening z_{fix}
G3 G3-BH G3-CR G3-CS G3-CK Arepo	0.16	2.2 (17)	0.4 (3.3)	0.7 (1.4)	0 (0)
G3-TO G3-GIMIC	0.18	2.1 (17)	0.5 (3.7)	0.5 (1)	3 (3)
G3-MM	0.16	2.2 (17)	0.4 (3.3)	0.7 (1.4)	2 (2)
GAS	0.18	2.1 (17)	0.5 (3.7)	0.46 (0.9)	8 (8)
R R-LSFE R-AGN	0.16	1.4 (11)	0.2 (1.8)	0.26 (0.5)	9 (9)

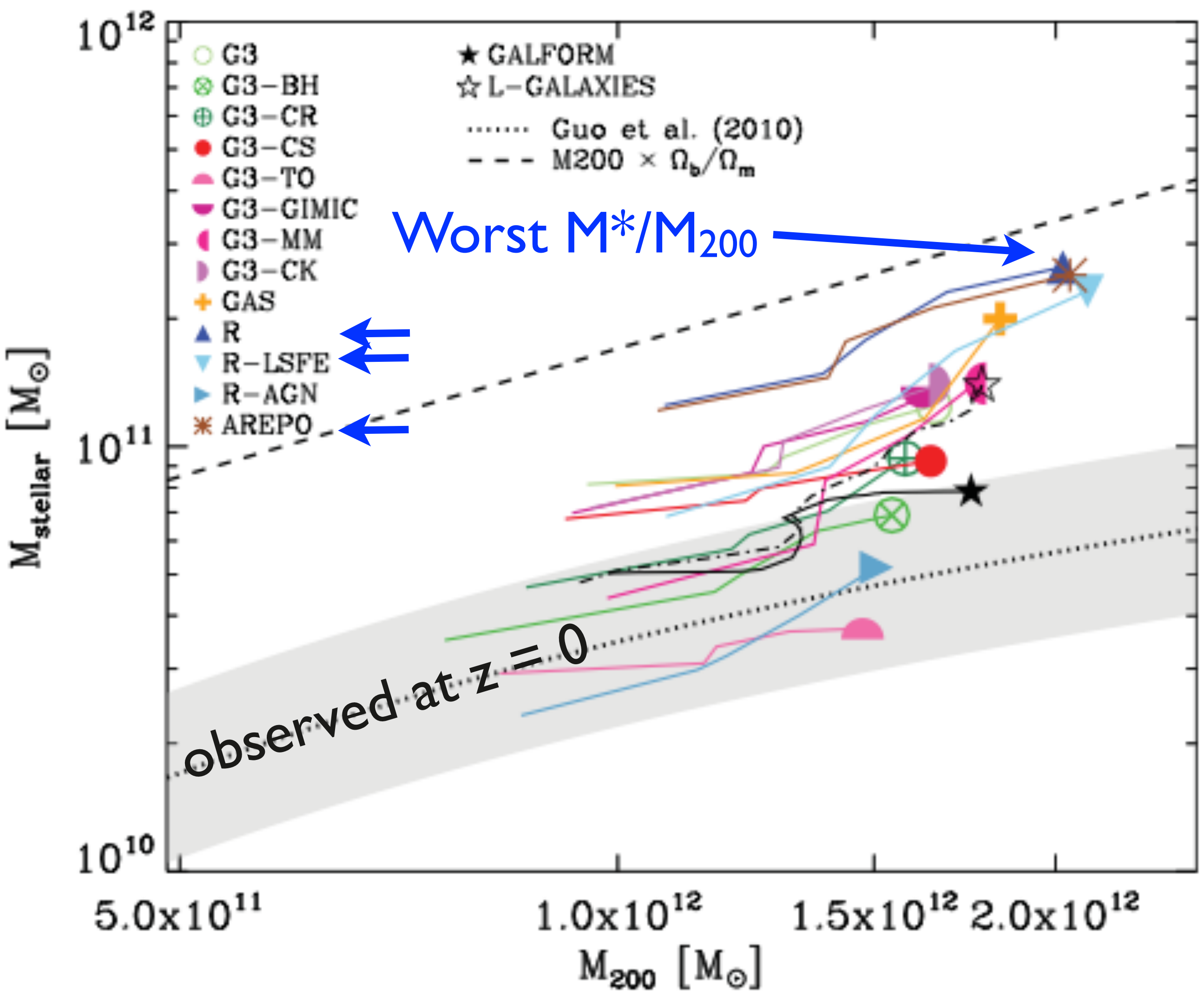
Most stars form in galactic disks, so realistic simulations should resolve disks. The scale height of the MWy disk is about 100 pc. It’s better yet to resolve GMCs, 10s of pc.

Softening is 500 pc or worse (fixed in comoving coordinates at $z = z_{fix}$).

Softening is 260 pc (fixed in comoving coordinates at $z_{fix} = 9$)

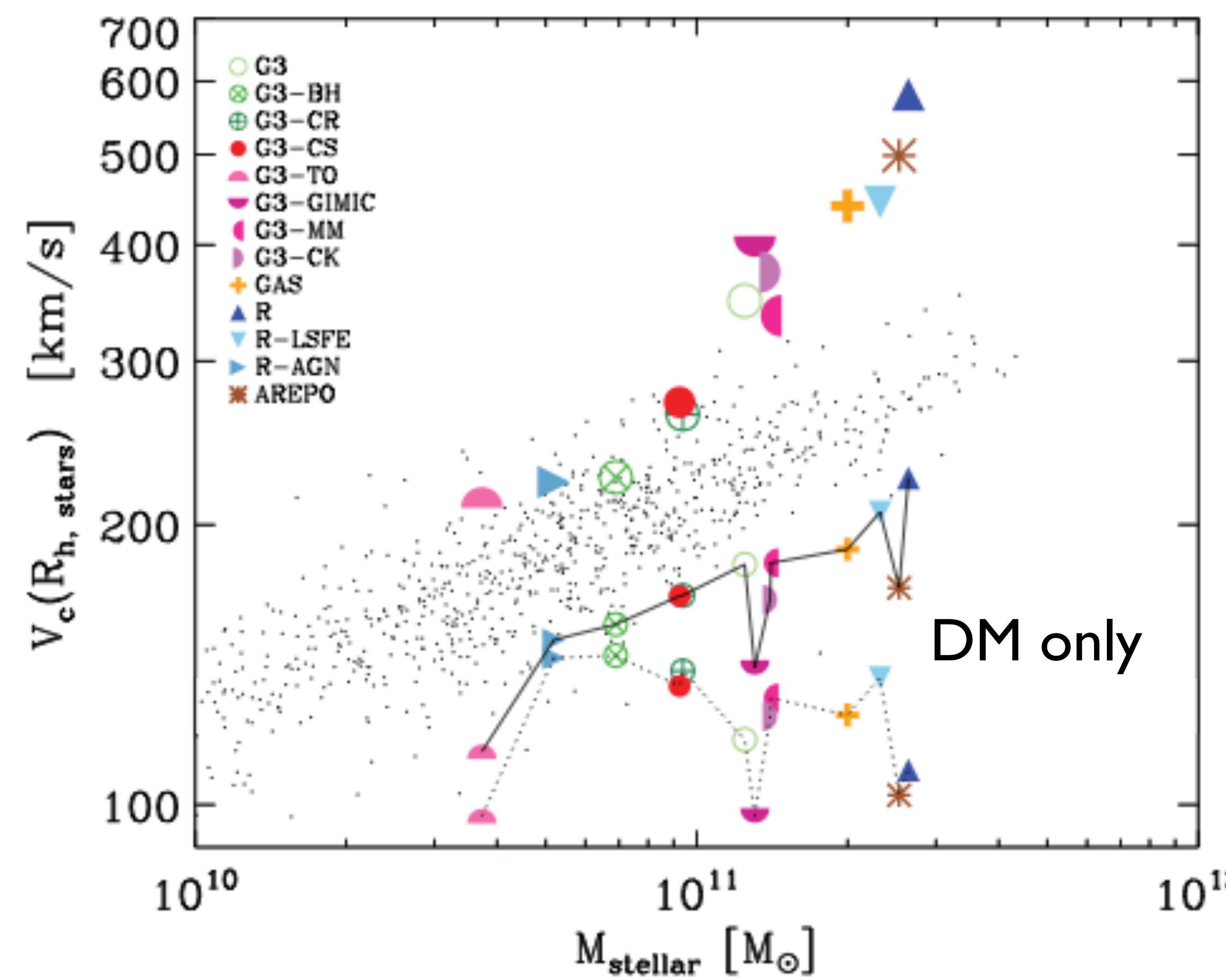
Aquila Comparison Project

$M_{stellar}$ vs M_{vir}



Curves track evolution z = 2 to 0.

Tully-Fisher Relation

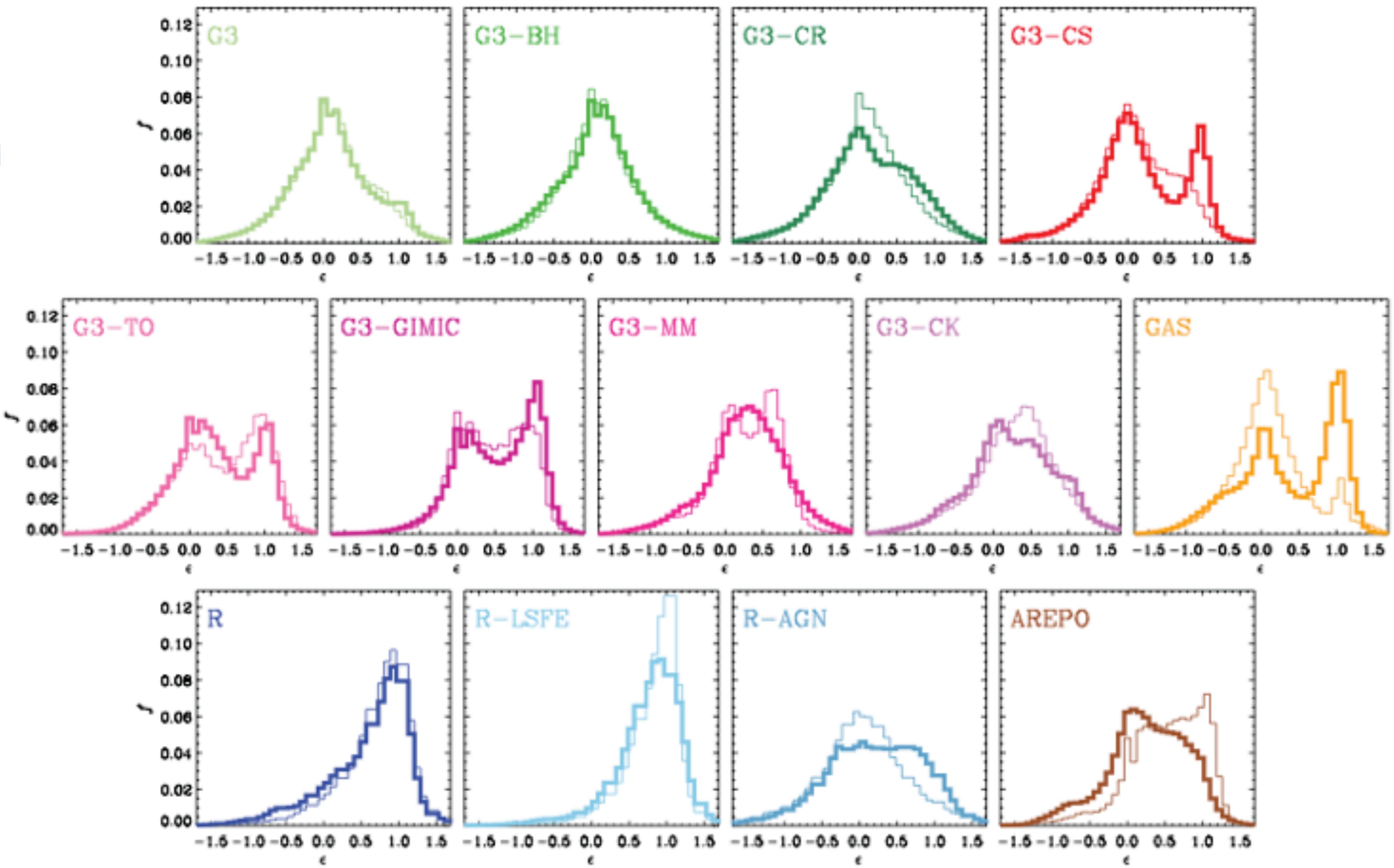


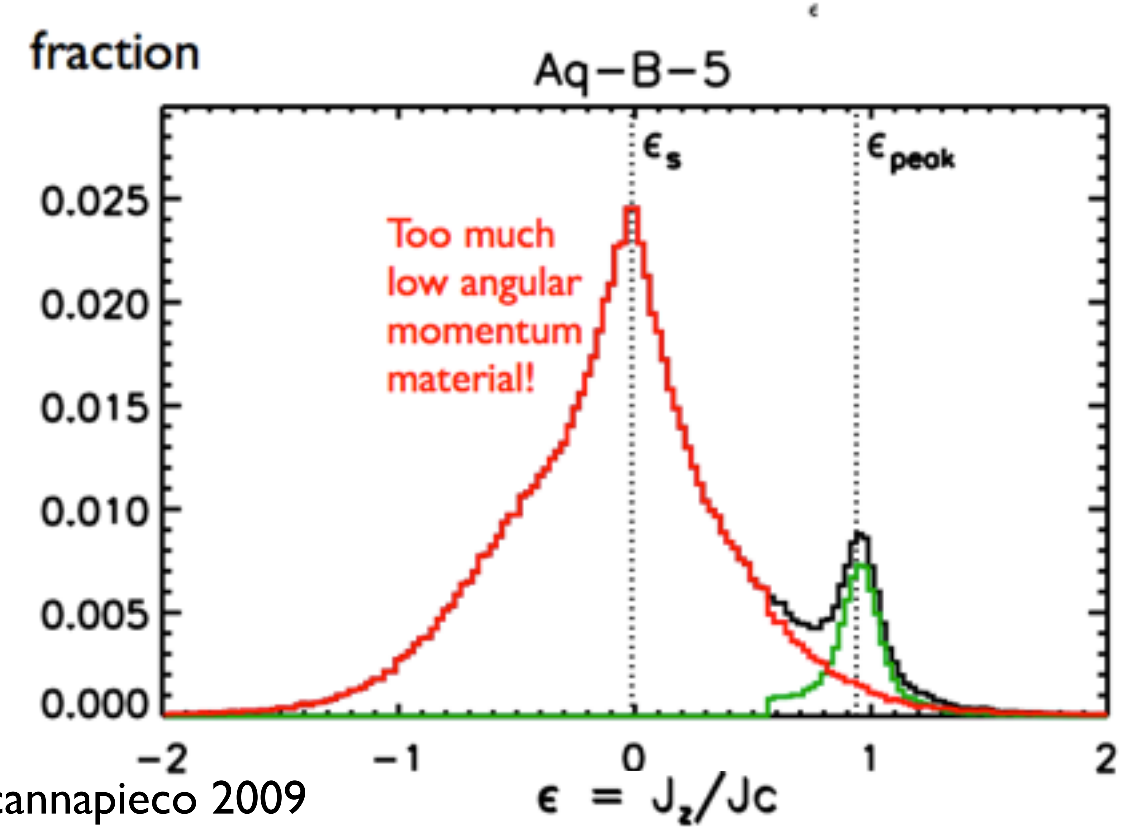
Circular velocity at stellar half-mass radius.

Aquila Comparison Project

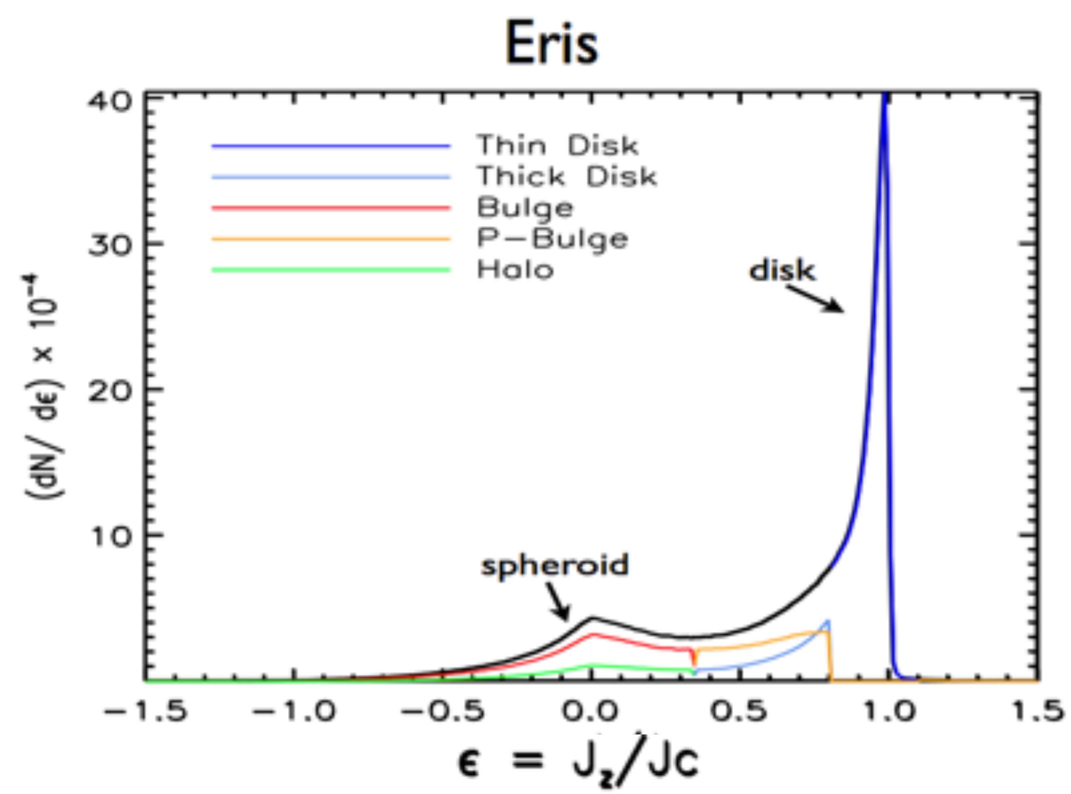
Stellar Circularities

$$\frac{j_z}{R\, V_{circ}(R)}$$





C. Scannapieco 2009



The AGORA High-resolution Galaxy Simulations Comparison

https://sites.google.com/site/santacruzcomparisonproject/

http://www.agorasimulations.org

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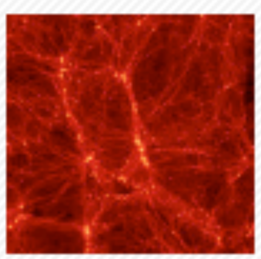

Santa Cruz Galaxy Workshop 2013

Recent site activity

2. Project Details
edited by Ji-hoon Kim

3. AGORA Workshop 2013
edited by Ji-hoon Kim

AGORA Flagship Paper
edited by Ji-hoon Kim

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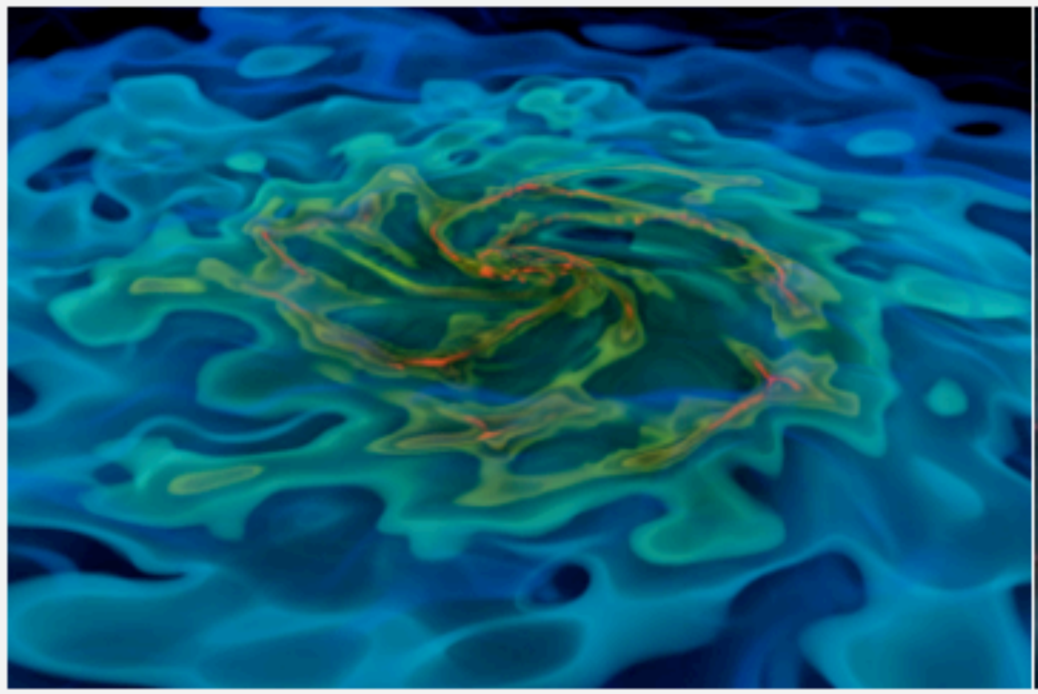

Welcome to Project AGORA! We investigate galaxy formation with high-resolution numerical simulations and compare the results across code platforms and with observations. We welcome any individual or group interested in participating in the Project. For the consensus reached in the 1st Workshop and the working groups formed, please visit here.

Project Announcements & News

AGORA Flagship Paper Great thanks to many of you who have contributed to the writing of the Flagship paper, and have sent us your invaluable feedback. With the Steering Committee's approval, the ...
Posted Aug 13, 2013, 5:32 PM by Ji-hoon Kim

2nd AGORA Workshop – Welcome & Logistics Thank you very much for signing up for the 2nd Workshop for the AGORA High-resolution Galaxy Simulations Comparison Project, Aug.16-18, 2013. ---- SCIENTIFIC PROGRAM : A tentative program of ...

AGORA High-Resolution Simulation Comparison

AGORA Goals

(1) Inaugurate framework to compare high-resolution galaxy simulations (with resolution better than ~100 parsecs) across different high-resolution numerical platforms

(2) Establish cosmological and isolated disk initial conditions and shared astrophysics so each participating group can run a suite of simulations

(3) Maintain the collaboration online (telecon+webpage) between the in-person meetings

(4) Compare simulations with each other, with theory, and with observations

(5) Produce a set of simulation comparisons and scientific papers starting ~ 2014

AGORA Is Timely

We are launching this project at the time when several key technologies have just become available including

the **MUlti-Scale Initial Conditions generator (MUSIC)**,
the new **UV-background model CUBA,**
the new **Grackle hydro cooling code**,
several of the **simulation codes**, and
the **yt code for analyzing the outputs** from all the simulations in a parallel way.

This project will be state-of-the-art, and it will surely advance the entire field of galaxy simulations.

Project AGORA: High-resolution Galaxy Simulation Comparison

https://sites.google.com/site/santacruzcomparisonproject/

http://www.agorasimulations.org

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Sister Workshop

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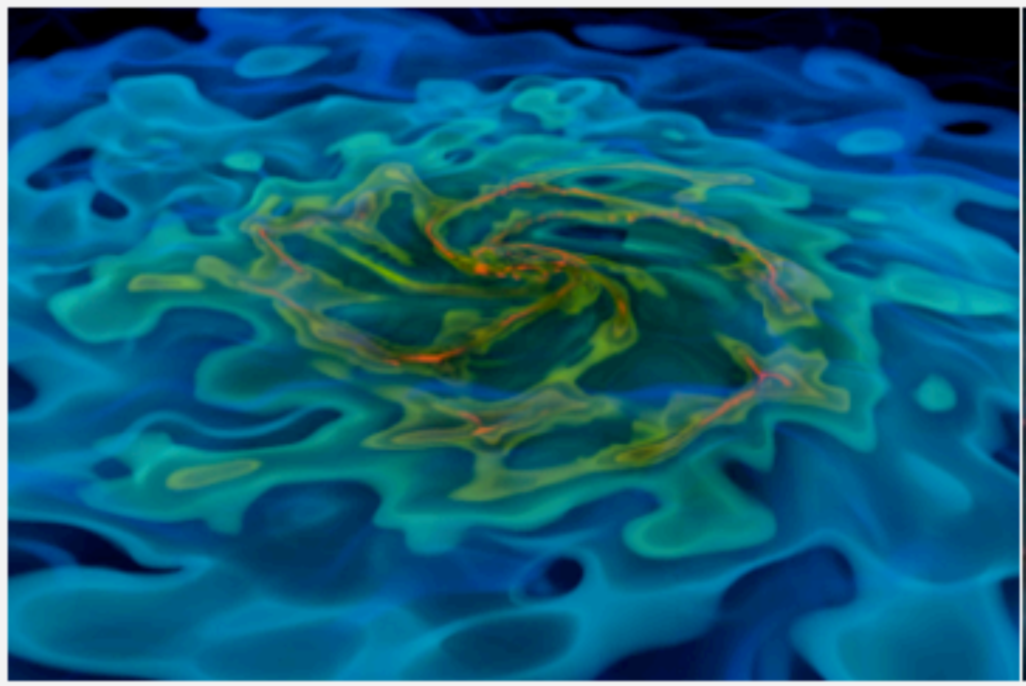

Welcome to Project AGORA: Assembling Galaxies Of Resolved Anatomy! We investigate galaxy formation with high-resolution numerical simulations and compare the results across different platforms and with observations. Learn what we plan to do by visiting Project Details. We welcome any group or persons who are interested in participating in the Project.

Project Announcements & News

Announcing 2nd AGORA Workshop (Aug. 16-19, 2013) We are pleased to announce that the 2nd Workshop of the AGORA Project will be held 16-19 August 2013 at the University of California, Santa Cruz. This workshop is ...

Posted May 21, 2013, 9:16 PM by Ji-hoon Kim

WGs I & IV Discussion Summary posted on the New Workspace Page for Rockstar+yt Thank you all very much for participating in the discussion on "Rockstar and YT in the AGORA Project". We had a very fruitful discussion on how to test the newest

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

	Dwarf spheroidals	Dwarf-sized galaxies	MW-sized Galaxies	Ellipticals or Galaxy Groups
Halo virial mass at $z = 0$	$\sim 10^{10}\,M_\odot$	$\sim 10^{11}\,M_\odot$	$\sim 10^{12}\,M_\odot$	$\sim 10^{13}\,M_\odot$
Maximum circular velocity	$\sim 30\,\mathrm{km\,s^{-1}}$	$\sim 90\,\mathrm{km\,s^{-1}}$	$\sim 160\,\mathrm{km\,s^{-1}}$	$\sim 250\,\mathrm{km\,s^{-1}}$
Selected merger histories	quiescent/violent at $z > 0$	quiescent/violent at $z > 0$	quiescent/violent at $z > 0$	quiescent/violent at $z > 2$

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

	Dark matter halo	Stellar disk	Gas disk	Stellar bulge
Density profile	Navarro et al. (1997)	Exponential	Exponential	Hernquist (1990)
Physical properties	$v_{c,200} = 150\,\mathrm{km\,s^{-1}}$, $M_{200} = 1.074 \times 10^{12}\,M_\odot$, $r_{200} = 205.4$ kpc, $c = 10$, $\lambda = 0.04$	$M_d = 4.297 \times 10^{10}\,M_\odot$, $r_d = 3.432$ kpc, $z_d = 0.1\,r_d$	$f_{gas} = 20\%$	bulge-to-disk mass ratio $B/D = 0.1$
Number of particles	10^5 (low res.), 10^6 (medium), 10^7 (high)	10^5, 10^6, 10^7	10^5, 10^6, 10^7	1.25×10^4, 1.25×10^5, 1.25×10^6

* MUltiScale Initial Conditions Hahn & Abel (2011)

http://bitbucket.org/ohahn/music/

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AGORA High-Resolution Simulation Comparison

Initial Conditions for Simulations

MUSIC galaxy masses at z~0: $\sim 10^{10}, 10^{11}, 10^{12}, 10^{13}\ M_{\odot}$

with both quiet and busy merging trees

isolation criteria agreed for Lagrangian regions

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

Astrophysics that all groups will include

UV background (Haardt-Madau 2012)

cooling function (based on ENZO and Eris cooling)

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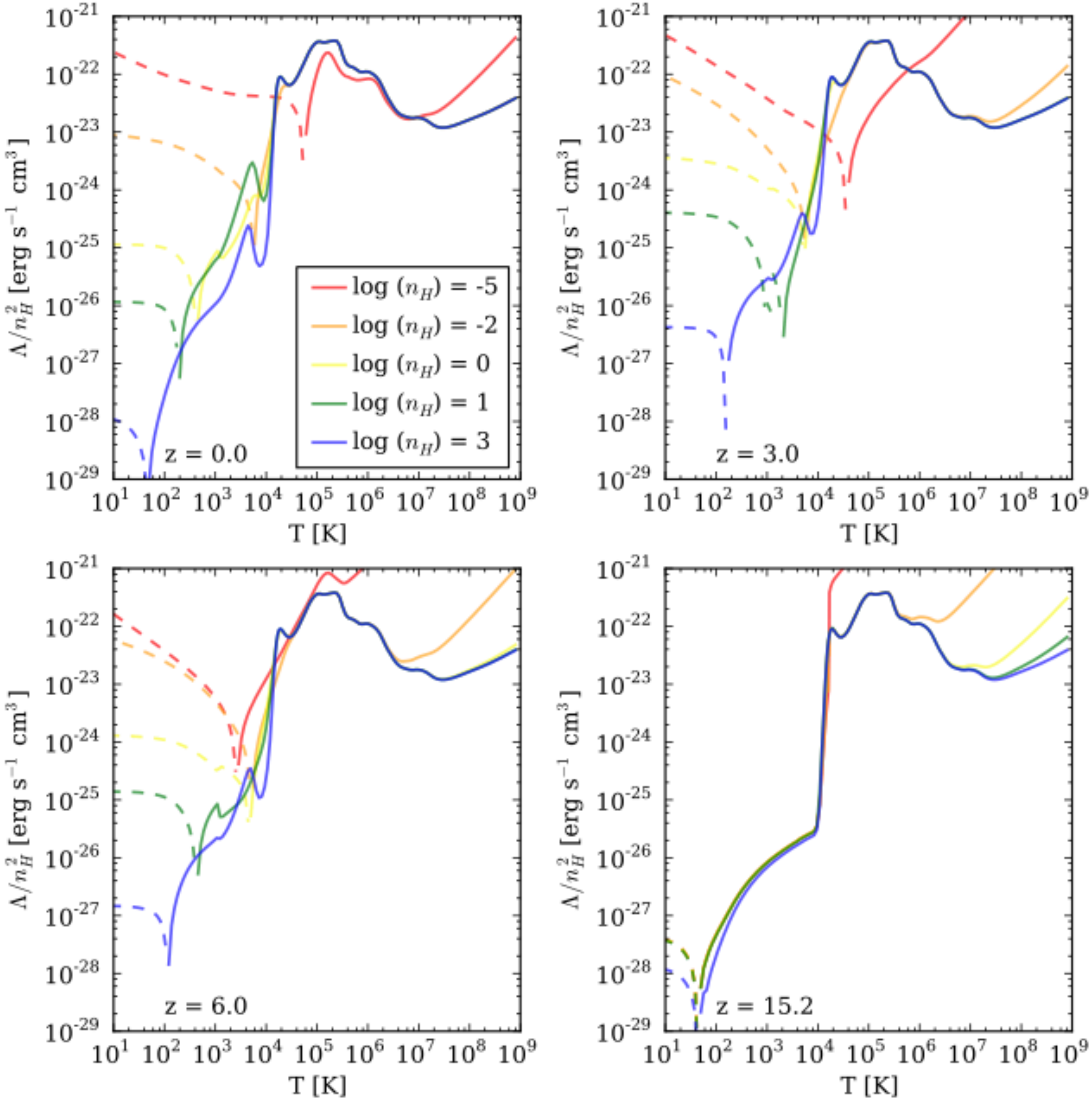
Gas cooling in the AGORA simulations

Equilibrium cooling rates normalized by n^2H calculated with the GRACKLE* cooling library for H number densities of 10^{-5} (red), 10^{-2} (orange), 1 (yellow), 10 (green), and 10^3 (blue) cm^{-3} at redshifts z = 0, 3, 6, and 15.2 (just before the UV background turns on) and solar metallicity gas. Solid lines denote net cooling and dashed lines denote net heating. The curves plotted are made with the non-equilibrium chemistry network of H, He, H_2, and HD with tabulated metal cooling assuming the presence of a UV metagalactic background from Haardt & Madau (2012).



* http://grackle.readthedocs.org

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, M ~ 10^{10}, 10^{11}, 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*, available for all codes used here (work in progress)

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

• **Data management:** Each participating codes will generate large quantities of unprocessed, intermediate data, in the form of “checkpoints” describing the state of the simulation at a given time. These outputs can be used both to restart the simulation and to conduct analysis. We plan to store 200 timesteps equally spaced in expansion parameter in addition to redshift snapshots at $z = 6, 3, 2, 1, 0.5, 0.2, 0.0$ at the very least. For many timesteps of simulations to be analyzed, central data repositories and post-processing compute time will be available at the San Diego Supercomputer Center at the University of California at San Diego, the new Hyades system at the University of California at Santa Cruz, and/or the Data-Scope system at the John Hopkins University. Additionally, we plan to reduce the barrier to entry for the simulation data by making a subset of derived data products available through a web interface.*

• **Public access:** One of the key objectives of the AGORA project is to help interpret the massive and rapidly increasing observational data on galaxy evolution being collected with increasing angular resolution at many different wavelengths by instruments on the ground and in space. We intend to make simulation results rapidly available to the entire community, placing computational outputs on data servers in formats that will enable easy comparisons with results from other simulations and with observations.

• **Multi-platform analysis:** the common analysis scripts can be applied to analyze outputs from grid codes and SPH codes. yt* will be used to access and analyze data from all of the simulation codes, enabling direct technology transfer between participants, ensuring reproducible scripts and results, and allowing for physically-motivated questions to be asked independent of the simulation platform.

*The first iteration of yt Data-Hub website is http://hub.yt-project.org/

www.AGORAsimulations.org

AGORA Task-Oriented Working Groups

	Working Group	Objectives and Tasks
T1	Common Astrophysics	UV background, metal-dependent cooling, IMF, metal yields
T2	ICs: Isolated	common initial conditions for isolated low-z disk galaxies
T3	ICs: Cosmological	common initial conditions for cosmological zoom-in simulations
T4	Common Analysis	support `yt` and other analysis tools, define quantitative and physically meaningful comparisons across simulations

AGORA Science Working Groups

	Working Group	Science Questions (includes, but not limited to)
S1	Isolated Galaxies and Subgrid Physics	tune the subgrid physics across platforms to produce similar results for similar astrophysical assumptions
S2	Dwarf Galaxies	simulate $\sim 10^{10} M_\odot$ halos, compare results across all platforms
S3	Dark Matter	radial profile, shape, substructure, core-cusp problem
S4	Satellite Galaxies	effects of environment, UV background, tidal disruption
S5	Galactic Characteristics	surface brightness, stellar properties, metallicity, images, SEDs
S6	Outflows	outflows, circumgalactic medium, metal absorption systems
S7	High-redshift Galaxies	cold flows, clumpiness, kinematics, Lyman-limit systems
S8	Interstellar Medium	galactic interstellar medium, thermodynamics
S9	Massive Black Holes	black hole growth and feedback in galactic context
S10	Lyα Absorption and Emission	prediction of Lyα maps for simulated galaxies and their environments including effects of radiative transfer

AGORA Task Oriented Working Groups

To successfully commence the project and ensure the consistent comparison across different codes, four task-oriented working groups are formed. Participants listed below are in an alphabetical order and will be regularly updated according to the most recent results of the sign-up.

(1) Working Group I - Common Physics and Introduction to Project

- Task: Provide a common physics package for cosmological simulations, write a flagship paper introducing the comparison project and its rationale
- Leader: **Piero Madau**
- Participants: Tom Abel, Greg Bryan, Daniel Ceverino, Nick Gnedin, Oliver Hahn, Cameron Hummels, Ji-hoon Kim, Andrey Kravtsov, Mike Kuhlen, Piero Madau, Lucio Mayer, Daisuke Nagai, Ken Nagamine, Jose Onorbe, Brian O'Shea, Joel Primack, Tom Quinn, Brant Robertson, Sijing Shen, Britton Smith, Romain Teyssier, Matthew Turk, James Wadsley, [to be added]
- Description: We will provide a package of common physics for cosmological simulations. Participants to the Project will agree to a minimal set of common input parameters, from the initial stellar mass function to the metal yield, and to the ionizing ultraviolet background. Gas cooling tables as a function of density, temperature, metallicity, and UV background (or redshift) will be provided over the next six weeks or so to all Project participants for code implementation. We also aim to reach the first milestone of this project by publishing a flagship paper on a proposed comparison, common physics, and common analysis, in early 2013. [authored by Piero Madau]

...

(4) Working Group IV - Common Analysis

- Task: Develop a pipeline for common data analysis, write a research article introducing such analysis
- Leader: **Matthew Turk**
- Participants: Nathan Goldbaum, Cameron Hummels, Chris Moody, Daisuke Nagai, Jose Onorbe, Joel Primack, Britton Smith, Robert Thompson, Matthew Turk, [to be added]
- Description: This working group will focus on defining repeatable, quantitative and physically-meaningful comparisons of simulation results. Additionally, tools will be identified and developed to support making these comparisons. [authored by Matthew Turk]

AGORA Science Working Groups

In order to achieve the astrophysics-based comparison of high-resolution galaxy formation simulations, nine science-oriented working groups are formed. Each working group consists of individual volunteers from interested codes. Each group aims to perform original research based on its code comparison, and to produce a standalone journal article. The group leader is responsible for making every effort to initiate and maintain the collaboration within the working group, online and offline. Participants listed below are in an alphabetical order and will be regularly updated according to the most recent results of the sign-up.

(1) Working Group V – Isolated Galaxies and Subgrid Physics

- Science Question: Common vs. favorite physics in isolated galaxy formation simulations
- Leader: **Oscar Agertz** and **Romain Teyssier** (co-leadership)
- Participants: Oscar Agertz, Samantha Benincasa, Daniel Ceverino, Ben Keller, Nick Gnedin, Nathan Goldbaum, Javiera Guedes, Alexander Hobbs, Phil Hopkins, Amit Kashi, Ji-hoon Kim, Andrey Kravtsov, Sam Leitner, Nir Mandelker, Lucio Mayer, Ken Nagamine, Brian O'Shea, Joel Primack, Tom Quinn, Justin Read, Rok Roskar, Wolfram Schmidt, Sijing Shen, Robert Thompson, Dylan Tweed, James Wadsley, [to be added]

(2) Working Group VI – Dwarf Galaxies in Cosmological Simulations

- Science Question: Simulate and compare a 10^{10} M_{sun} galactic halo across *all* participating codes
- Leader: **Jose Onorbe**
- Participants: Kenza Arraki, Greg Bryan, Javiera Guedes, Jason Jaacks, Dusan Keres, Ji-hoon Kim, Mike Kuhlen, Ken Nagamine, Jose Onorbe, Brian O'Shea, Joel Primack, Justin Read, Emilio Romano-Diaz, Sijing Shen, Christine Simpson, Matteo Tomassetti, Sebastian Trujillo-Gomez, Dylan Tweed, John Wise, Adi Zolotov, [to be added]

(3) Working Group VII – Dark Matter

- Science Question: Dark matter profile, distribution, substructure, core-cusp problem, triaxiality, etc.
- Leader: **Mike Kuhlen**
- Participants: Javiera Guedes, Mike Boylan-Kolchin, Mike Kuhlen, Piero Madau, Annalisa Pillepich, Joel Prima Justin Read, Miguel Rocha, [to be added]

(4) Working Group VIII – Satellite Galaxies

– Science Question: Environmental effects, UV background, tidal disruption, too-big-to-fail, etc.
– Leader: **Adi Zolotov**
– Participants: Javiera Guedes, Mike Boylan-Kolchin, Mike Kuhlen, Piero Madau, Lucio Mayer, Annalisa Pillepich, Joel Primack, Justin Read, Miguel Rocha, Christine Simpson, Adi Zolotov, [to be added]

(5) Working Group IX – Characteristics of Cosmological Galaxies

– Science Question: Surface brightness, disks, bulges, stellar properties, metallicity, images and SEDs generated by SUNRISE/yt, etc.
– Leader: **Javiera Guedes** and **Cameron Hummels** (co-leadership)
– Participants: Oscar Agertz, Daniel Ceverino, Maria Emilia De Rossi, Javiera Guedes, Cameron Hummels, Jason Jaacks, Dusan Keres, Andrey Kravtsov, Sam Leitner, Lucio Mayer, Daisuke Nagai, Ken Nagamine, Brian O'Shea, Joel Primack, Justin Read, Brant Robertson, Emilio Romano-Diaz, Rok Roskar, Sijing Shen, Britton Smith, Robert Thompson, Matteo Tomassetti, [to be added]

(6) Working Group X – Outflows

– Science Question: Galactic outflows, circum-galactic medium, metal absorption systems, the effect of AGN feedback, etc.
– Leader: **Sijing Shen**
– Participants: Greg Bryan, Daniel Ceverino, Colin DeGraf, Michele Fumagalli, Javiera Guedes, Alexander Hobbs, Phil Hopkins, Cameron Hummels, Amit Kashi, Dusan Keres, Sam Leitner, Piero Madau, Ken Nagamine, Justin Read, Wolfram Schmidt, Sijing Shen, Britton Smith, James Wadsley, [to be added]

(7) Working Group XI – High-redshift Galaxies

– Science Question: Cold flows, clumpiness, kinematics, Lyman-limit systems, etc.
– Leader: **Daniel Ceverino**
– Participants: Oscar Agertz, Daniel Ceverino, Maria Emilia De Rossi, Jan Engels, Michele Fumagalli, Nick Gnedin, Javiera Guedes, Jason Jaacks, Dusan Keres, Andrey Kravtsov, Mike Kuhlen, Sam Leitner, Piero Madau, Ken Nagamine, Brian O'Shea, Joel Primack, Brant Robertson, Emilio Romano-Diaz, Sijing Shen, Robert Thompson, Matteo Tomassetti, John Wise, [to be added]

(8) Working Group XII - Interstellar Medium

- Science Question: Interstellar medium, thermodynamics, etc.
- Leader: **Sam Leitner**
- Participants: Oscar Agertz, Daniel Ceverino, Charlotte Christensen, Nick Gnedin, Nathan Goldbaum, Cameron Hummels, Amit Kashi, Dusan Keres, Andrey Kravtsov, Sam Leitner, Piero Madau, Lucio Mayer, Ken Nagamine, Brian O'Shea, Brant Robertson, Emilio Romano-Diaz, Sijing Shen, Robert Thompson, Matteo Tomassetti, James Wadsley, [to be added]

(9) Working Group XIII - Black Hole Accretion and Feedback

- Science Question: Effect of black hole feeding and feedback on the evolution of galaxies (isolated and cosmological) across participating codes, etc.
- Leader: **Alexander Hobbs**
- Participants: Colin DeGraf, Alexander Hobbs, Phil Hopkins, Amit Kashi, Ben Keller, Lucio Mayer, Daisuke Nagai, Brian O'Shea, Justin Read, Romain Teyssier, [to be added]

(10) Tentative Working Group XIV - Lyman alpha absorption and emission

- Science Question: Lyman alpha absorption and emission predicted for simulated galaxies and their environments across participating codes including effects of radiative transfer, including associated metal lines, etc.
- Leader: Michele Fumagalli and Sebastiano Cantalupo (?)
- Participants: [to be added]

(11) Additional Working Groups - to be organized as needed

Online Collaboration

The leader of each working group is in charge of organizing the online collaboration via Google Sites, Skype, EVO-SeeVogh, etc. **One possible option is the newly-designed "Workspace" page on Google Sites.** In the new Workspace, each working group has its own page, and every registered collaboration member is granted a full access to read and write. This page may be used as a simplest option to share the data.

AGORA "Flagship Paper" submitted to ApJS

THE *AGORA* HIGH-RESOLUTION GALAXY SIMULATIONS COMPARISON PROJECT

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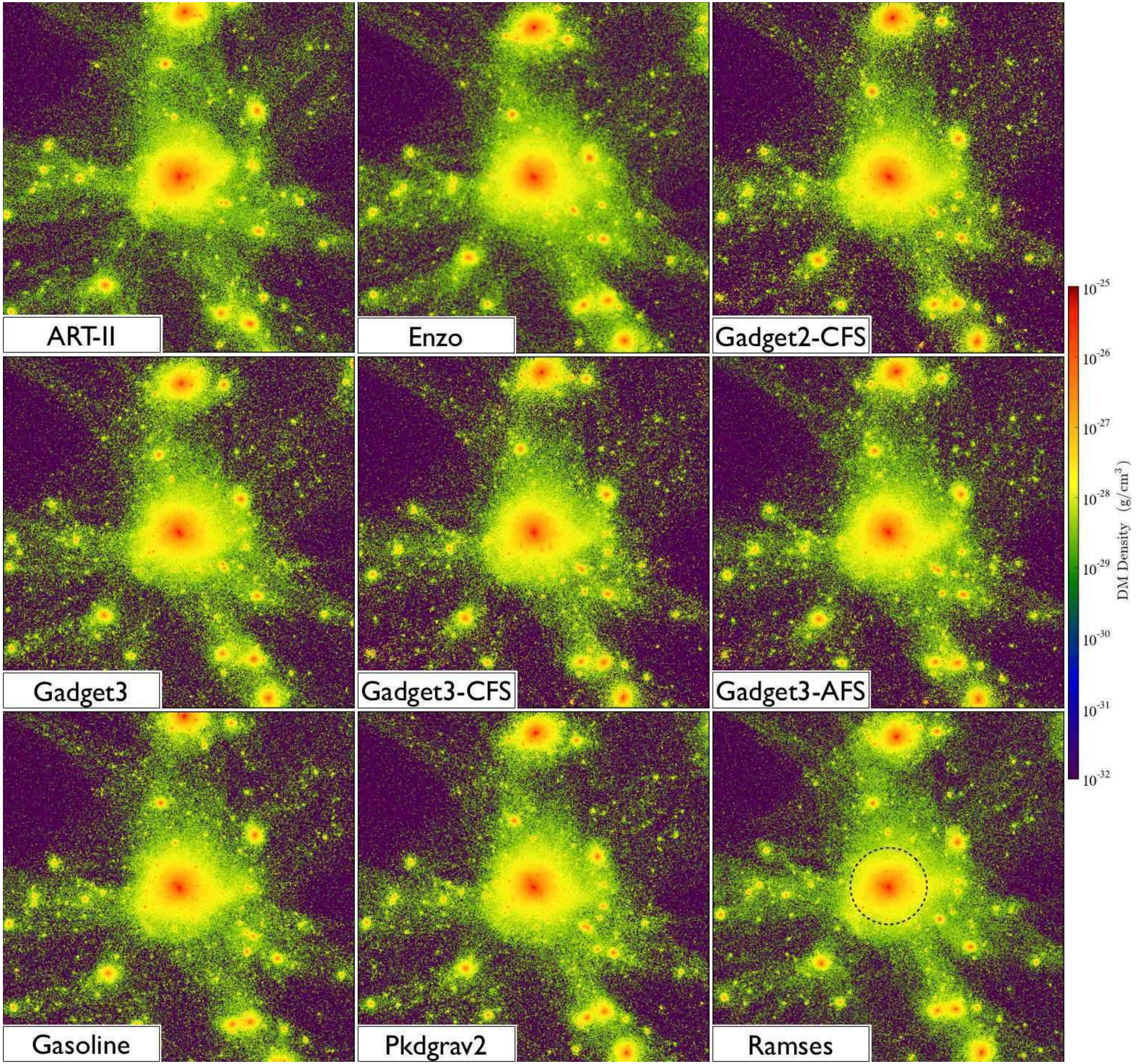
ABSTRACT

We introduce the *AGORA* project, a comprehensive numerical study of well-resolved galaxies within the ΛCDM cosmology. Cosmological hydrodynamic simulations with force resolutions of ~ 100 proper pc or better will be run with a variety of code platforms to follow the hierarchical growth, star formation history, morphological transformation, and the cycle of baryons in and out of 8 galaxies with halo masses $M_{\rm vir} \simeq 10^{10}$, 10^{11}, 10^{12}, and 10^{13} $M_\odot$ at $z = 0$ and two different ("violent" and "quiescent") assembly histories. The numerical techniques and implementations used in this project include the smoothed particle hydrodynamics codes GADGET and GASOLINE, and the adaptive mesh refinement codes ART, ENZO, and RAMSES. The codes will share common initial conditions and common astrophysics packages including UV background, metal-dependent radiative cooling, metal and energy yields of supernovae, and stellar initial mass function. These are described in detail in the present paper. Subgrid star formation and feedback prescriptions will be tuned to provide a realistic interstellar and circumgalactic medium using a non-cosmological disk galaxy simulation. Cosmological runs will be systematically compared with each other using a common analysis toolkit, and validated against observations to verify that the solutions are robust – i.e., that the astrophysical assumptions are responsible for any success, rather than artifacts of particular implementations. The goals of the *AGORA* project are, broadly speaking, to raise the realism and predictive power of galaxy simulations and the understanding of the feedback processes that regulate galaxy "metabolism." The initial conditions for the *AGORA* galaxies as well as simulation outputs at various epochs will be made publicly available to the community. The proof-of-concept dark matter-only test of the formation of a galactic halo with a $z = 0$ mass of $M_{\rm vir} \simeq 1.7 \times 10^{11}$ $M_\odot$ by 9 different versions of the participating codes is also presented to validate the infrastructure of the project.

Panels showing z = 0 result of proof-of-concept dark matter-only tests on a quiescent ~1.7 × 10^{11} M⊙ halo. Density-weighted projections produced with the common analysis toolkit yt of the finest resolution dark matter particles in a 1 h^{-1} Mpc box.

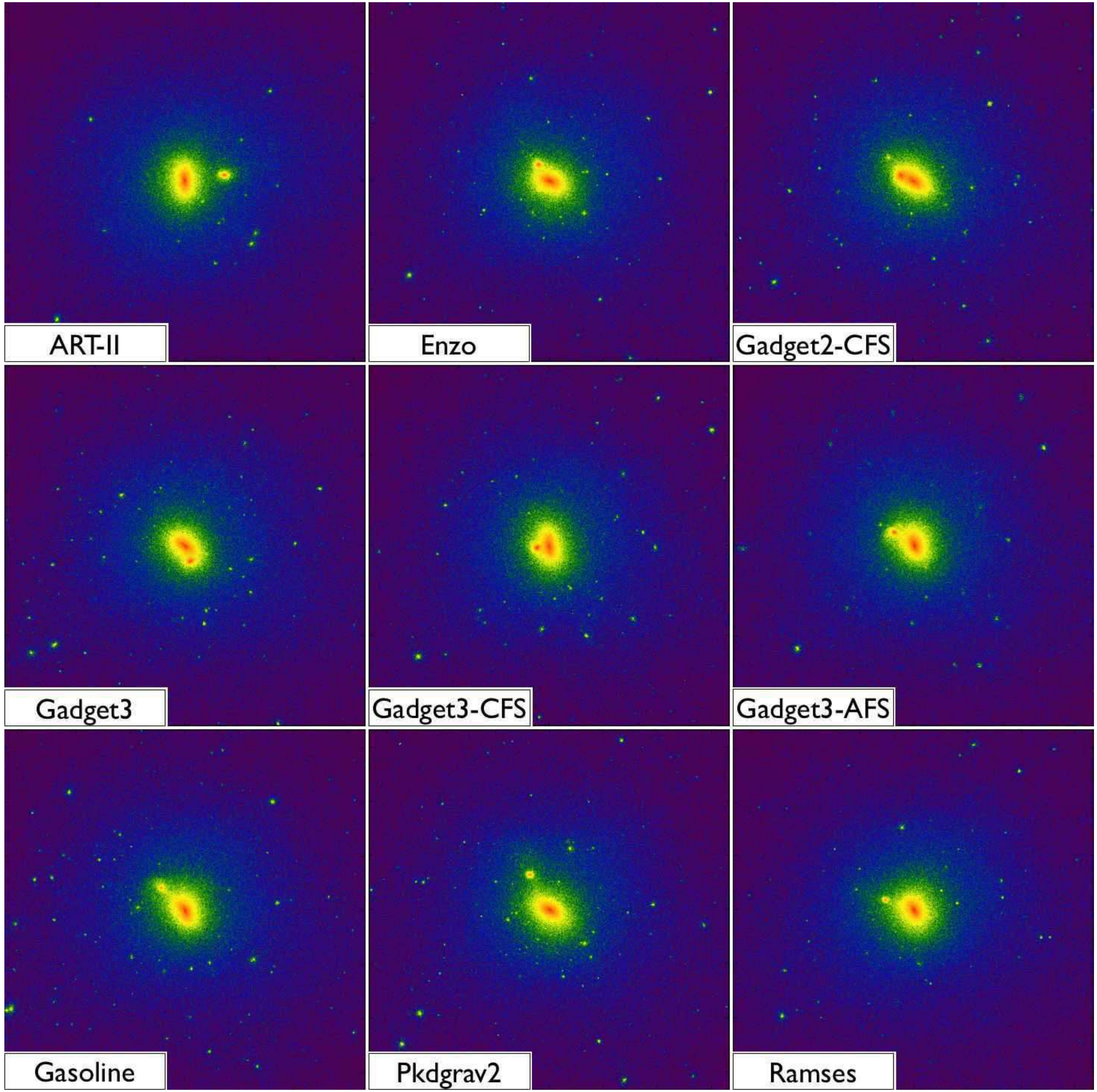
Simulation credits: Samuel Leitner (ART-II), Ji-hoon Kim (ENZO), Oliver Hahn (GADGET-2-CFS), Keita Todoroki (GADGET-3), Alexander Hobbs (GADGET-3-AFS), Sijing Shen (GASOLINE), Michael Kuhlen (PKDGRAV-2), Oliver Hahn and Romain Teyssier (RAMSES).



Density-weighted projection of squared dark matter density at z = 0 from the proof-of-concept dark matter-only tests on a quiescent ~1.7 × 10^{11} $M_\odot$ halo.

Density-weighted projections produced with the common analysis toolkit yt of the finest resolution dark matter particles in a 200 h^{-1} kpc box.

Simulation credits: Samuel Leitner (ART-II), Ji-hoon Kim (ENZO), Oliver Hahn (GADGET-2-CFS), Keita Todoroki (GADGET-3), Alexander Hobbs (GADGET-3-AFS), Sijing Shen (GASOLINE), Michael Kuhlen (PKDGRAV-2), Oliver Hahn and Romain Teyssier (RAMSES).



Examples of galaxy issues to be addressed by AGORA

- How to solve the too-high SF at high z in intermediate-mass galaxies?
- Producing as many bulgeless disk galaxies as observed?
- Effects of baryons on dwarf galaxies: core/cusp? TBTF problem?
- What quenches star formation in galaxies above a characteristic central density? Roles of FB and cutoff of cold flows above $M_{halo} \sim 10^{12}\ M_\odot$?
- Feedback from SF and AGN - effects of different recipes, comparisons with observations such as SF efficiency, high-velocity outflows, **clumps**
- Observations show that about half of all star-forming galaxies at z = 1-3 are **clumpy**. Do simulations see this? Role in forming spheroids?

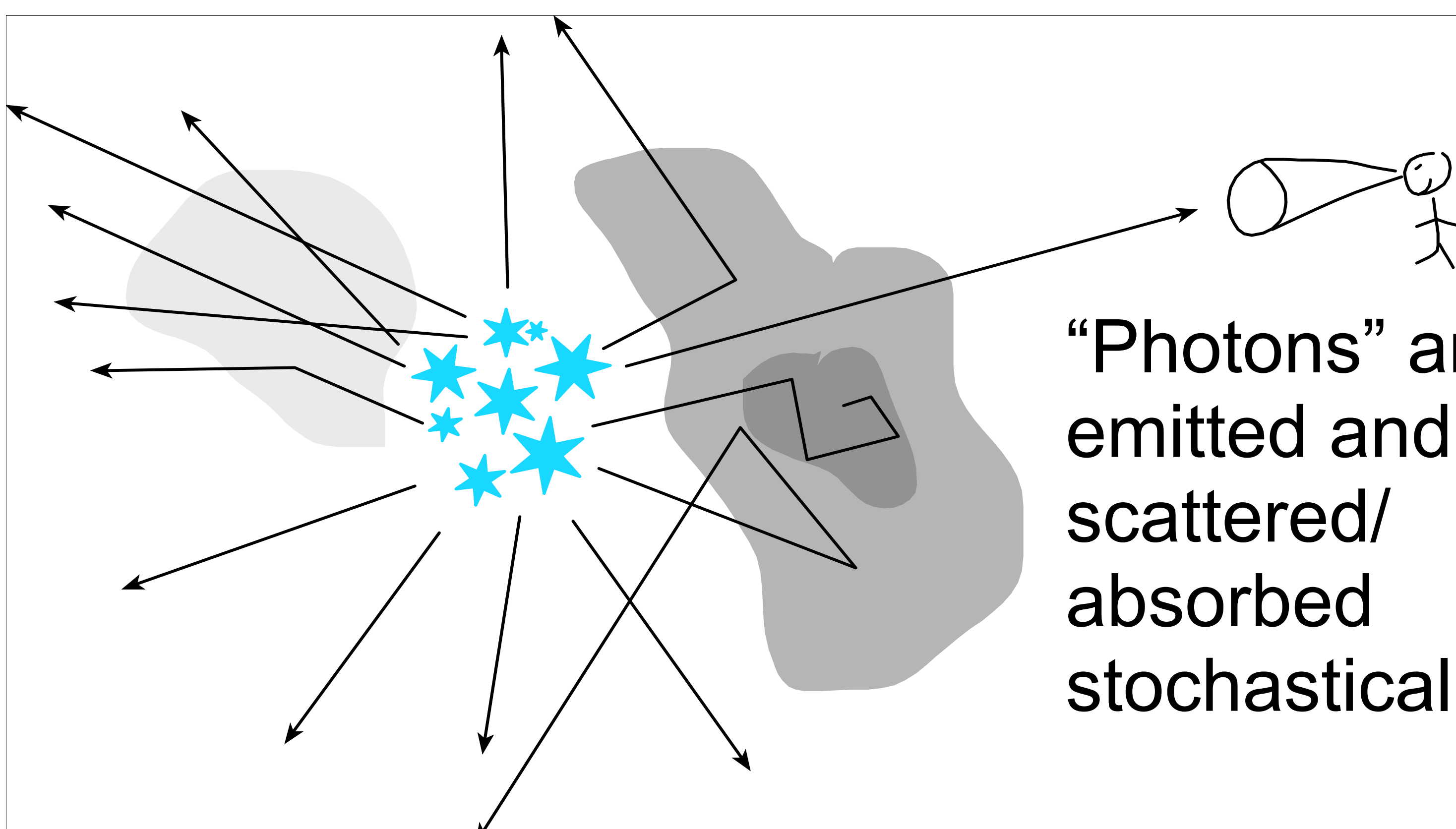
Most stars form in galactic disks, but 2/3 to 3/4 of stars today are in spheroids. ΛCDM simulations such as Bolshoi show that there are not nearly enough major mergers to produce the observed intermediate-mass spheroids. Semi-analytic models (SAMs) find that including violent disk instability (VDI) creating **clumps** that migrate to the galactic centers produces the observed abundance and properties of spheroids and compact “nugget” galaxies at z > 2 (Lauren Porter, Rachel Somerville, JP, et al. 2013). The next several slides show how we create realistic images from Daniel Ceverino’s simulations using our *Sunrise* code and how we are comparing simulations and SAMs...

Sunrise Radiative Transfer Code

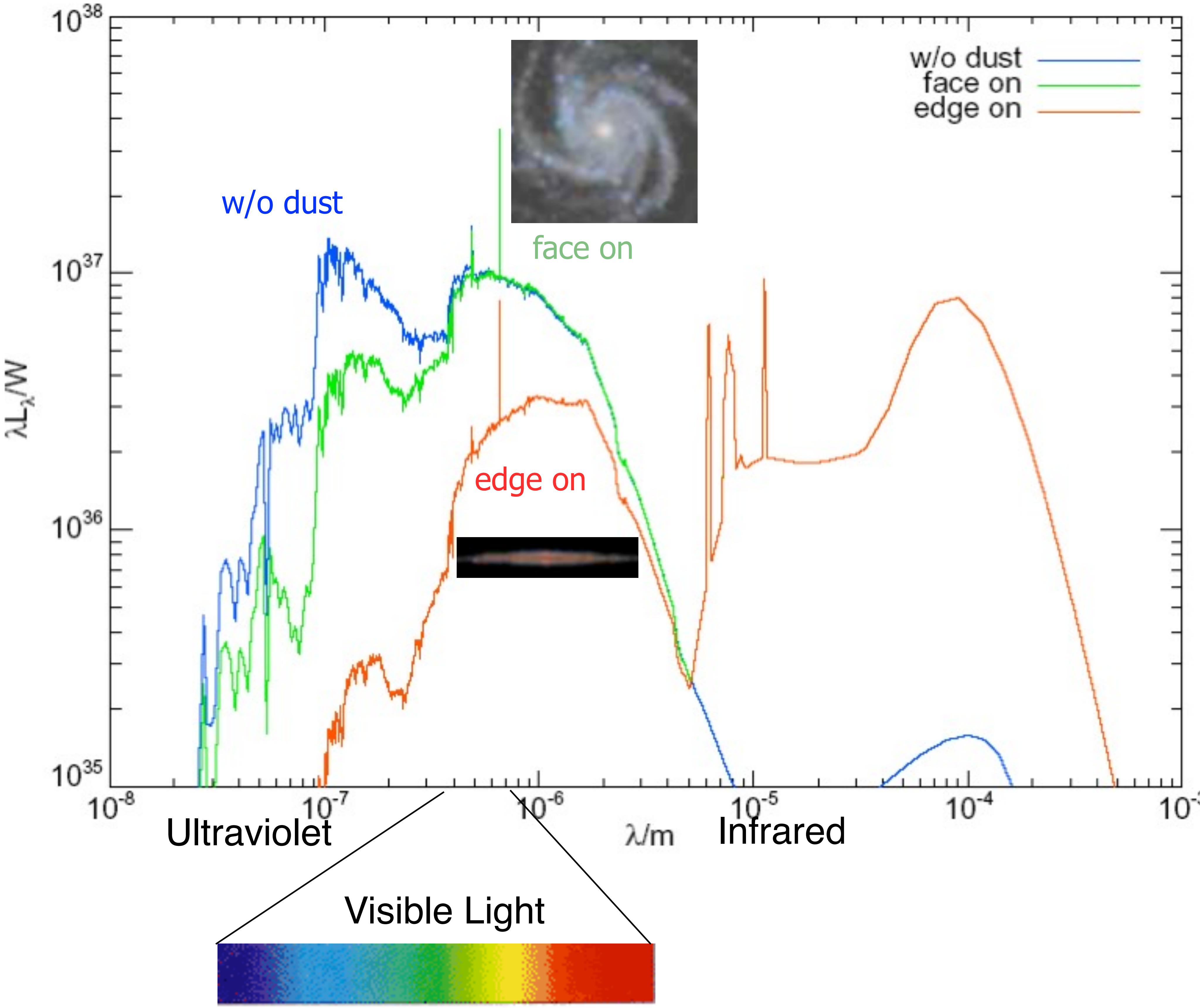
Patrik Jonsson
& Joel Primack

For every simulation snapshot:

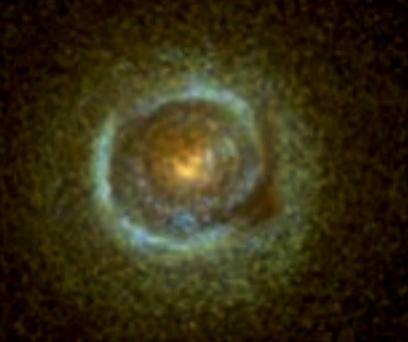
- Evolving stellar spectra calculation
- Adaptive grid construction
- Monte Carlo radiative transfer
- "Polychromatic" rays save 100x CPU time
- Graphic Processor Units give 10x speedup



Spectral Energy Distribution

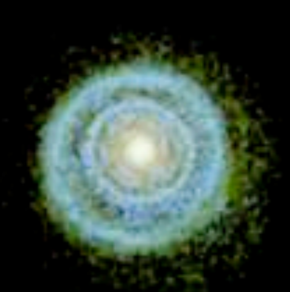


What’s the effect of including dust?



with
dust

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

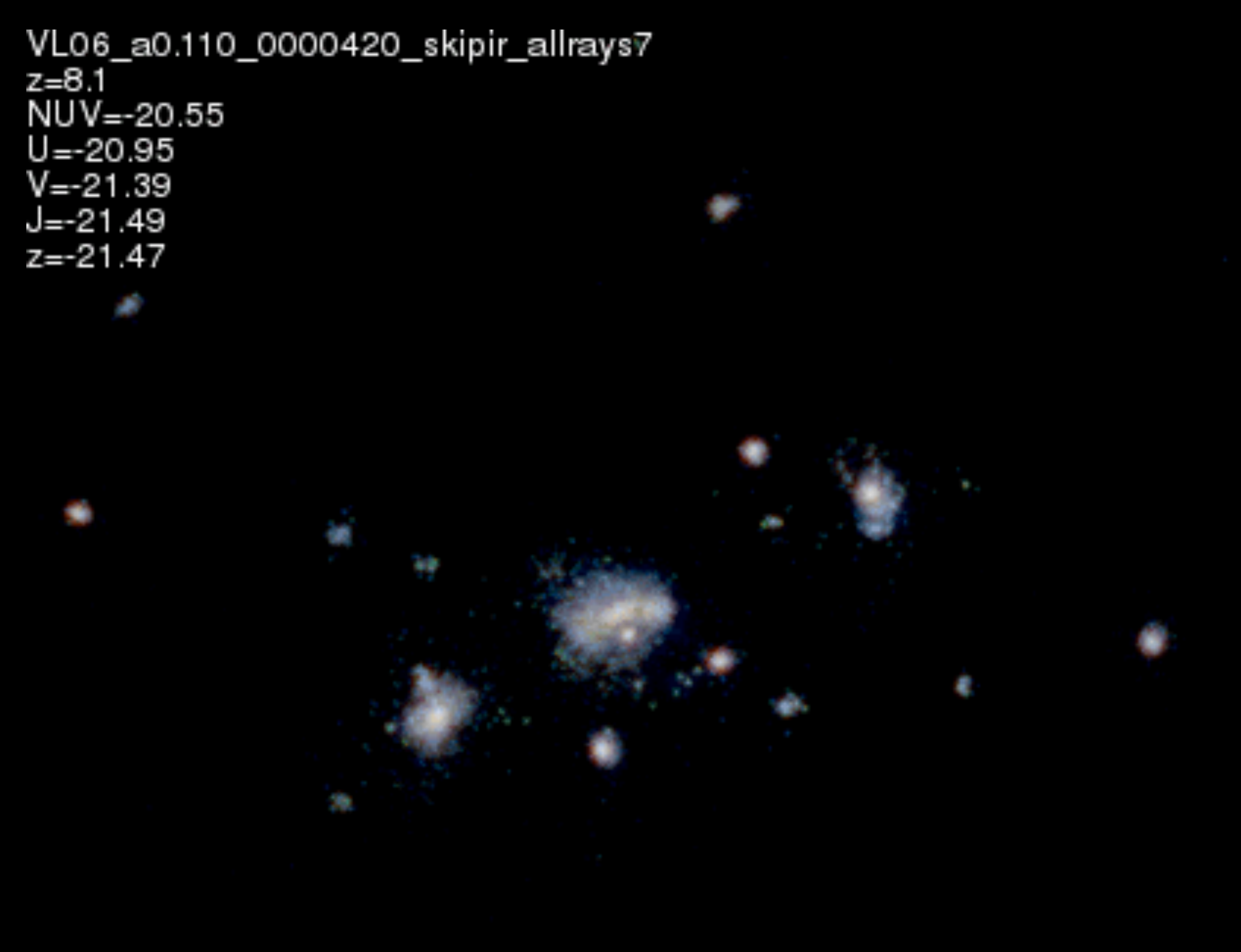


stars
only

cemoody.imgur.com

Ceverino+ VL6 Cosmological Zoom-in Simulation

Face-On



Edge-On

$z = 8.1$

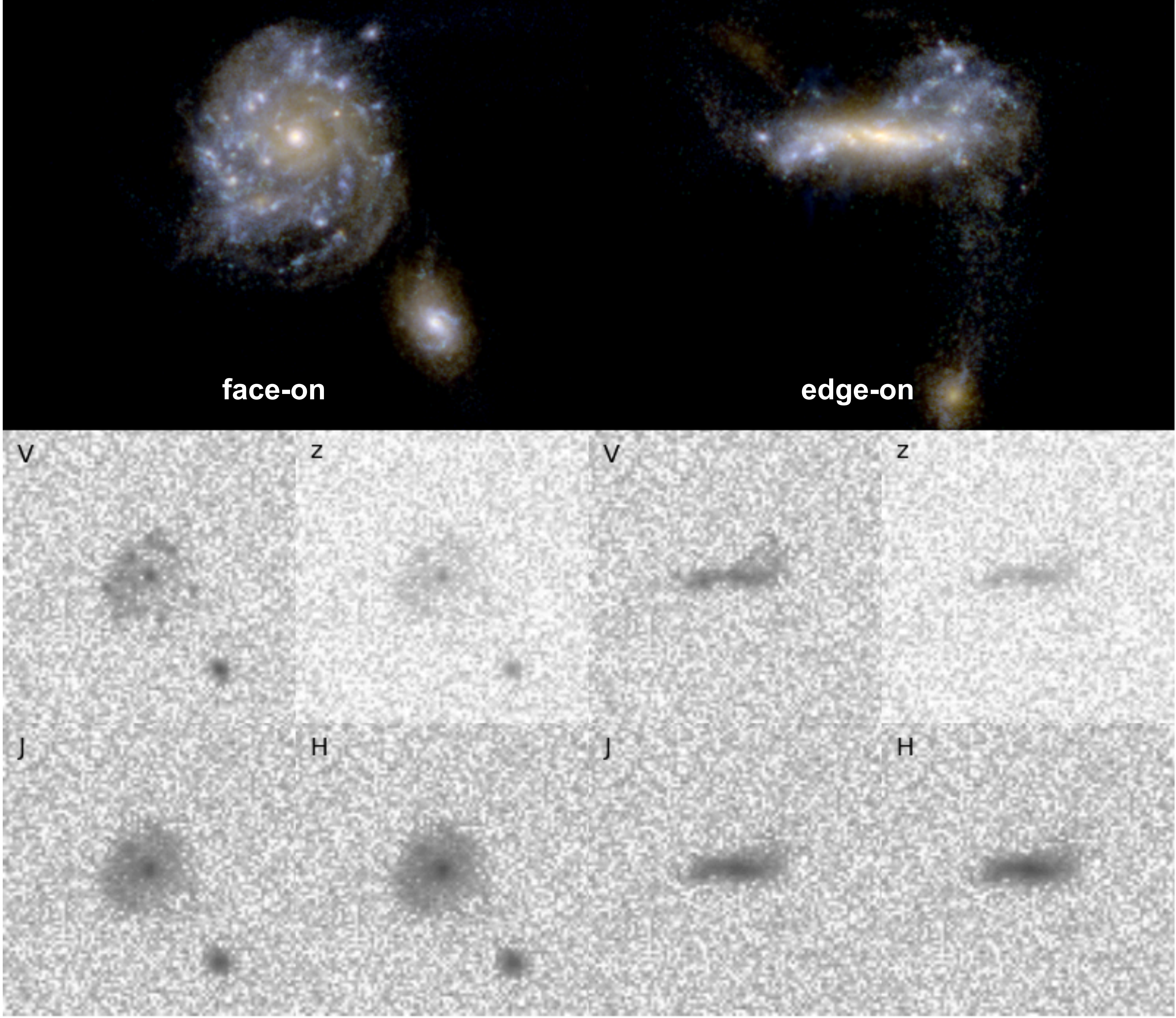
Chris Moody

Simulated Galaxy 10 billion years ago

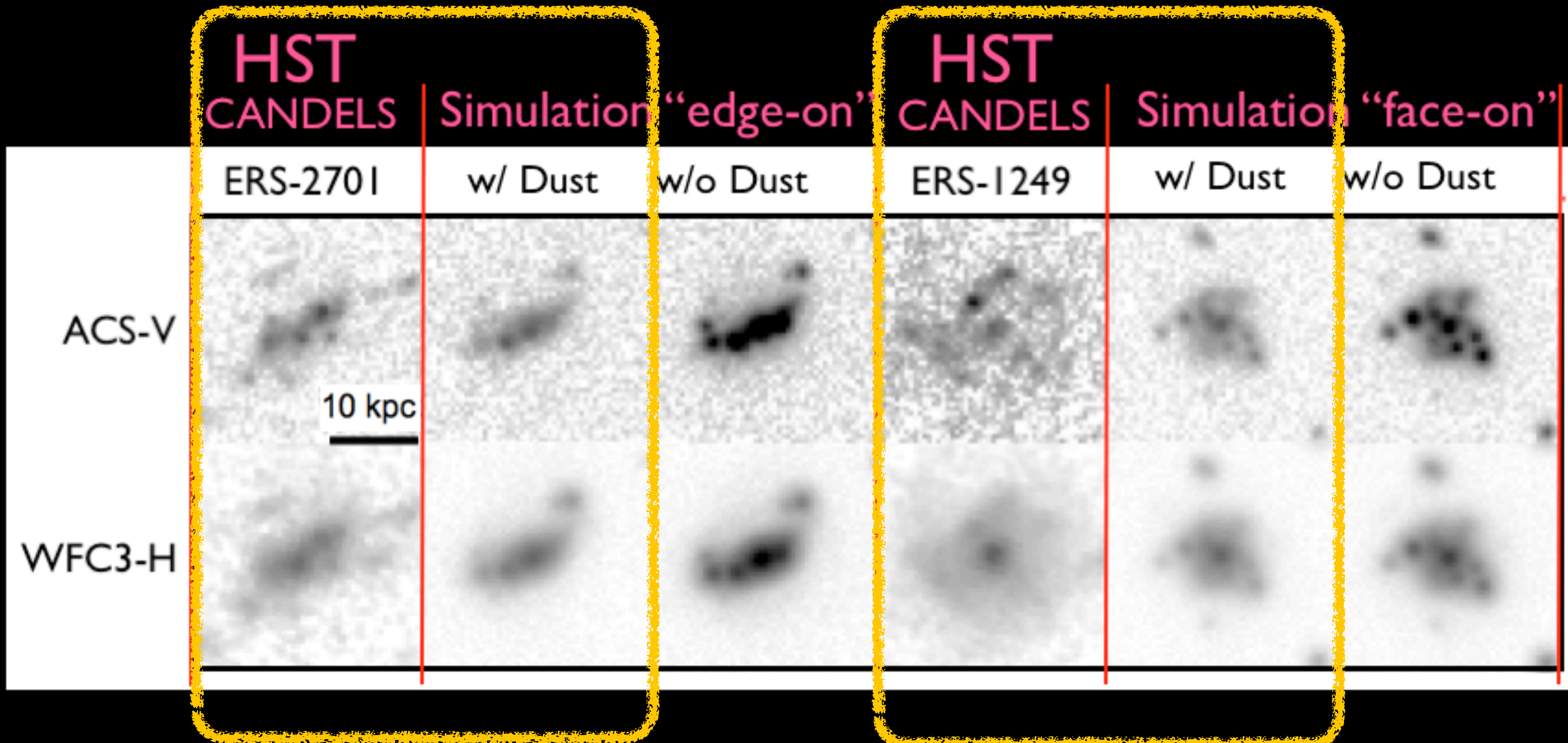
as it would appear nearby to our eyes

as it would appear to Hubble's ACS visual camera

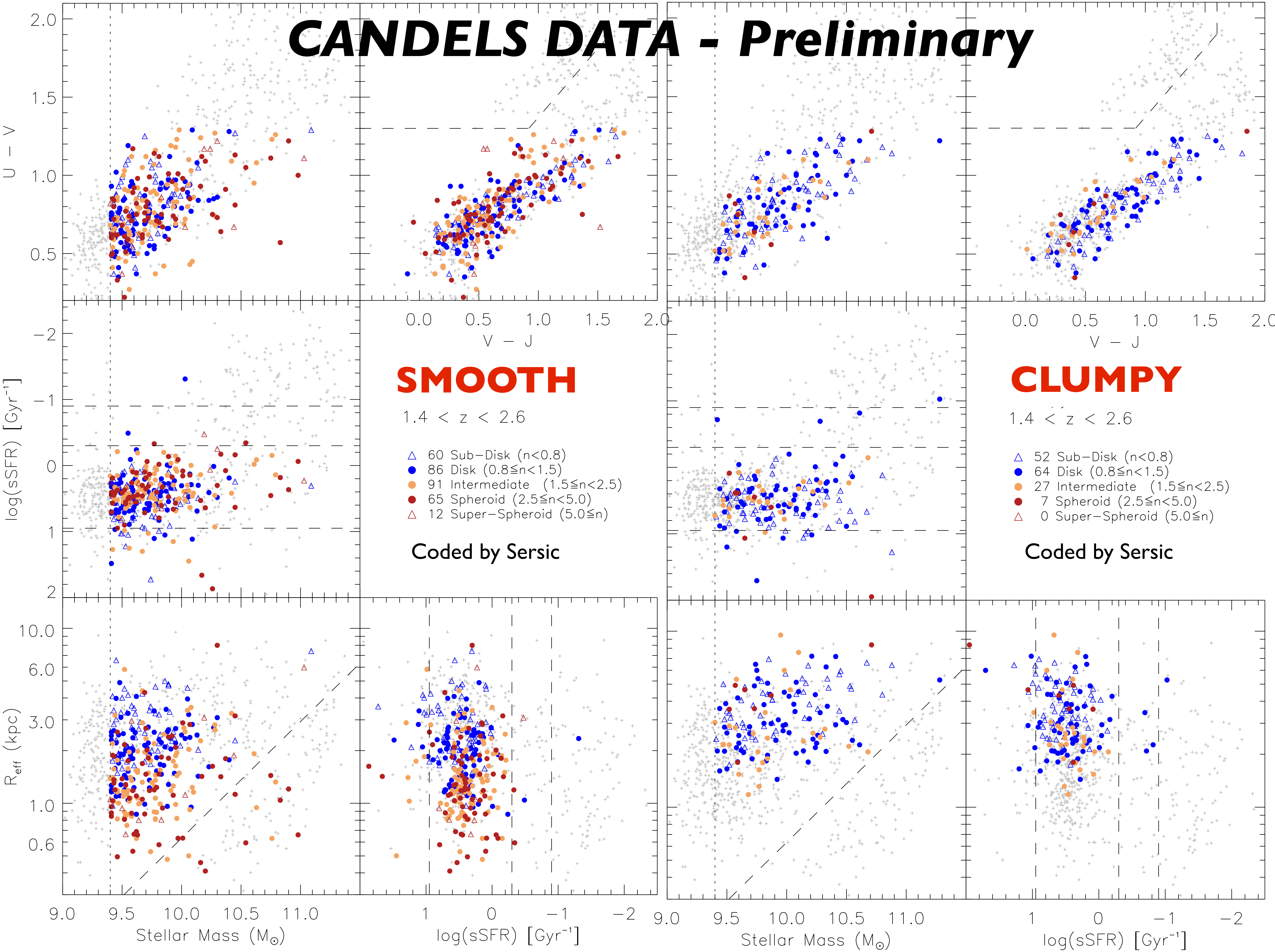
as it would appear to Hubble's WFC3 infrared camera

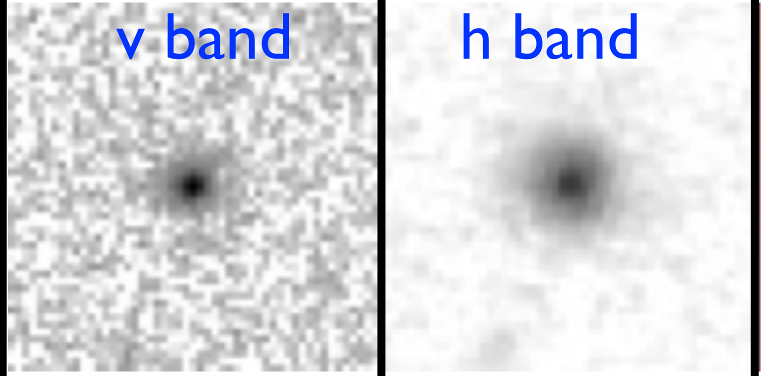


Our Simulations w/ Dust look a lot like galaxies from 10 billion years ago that we see with Hubble Space Telescope

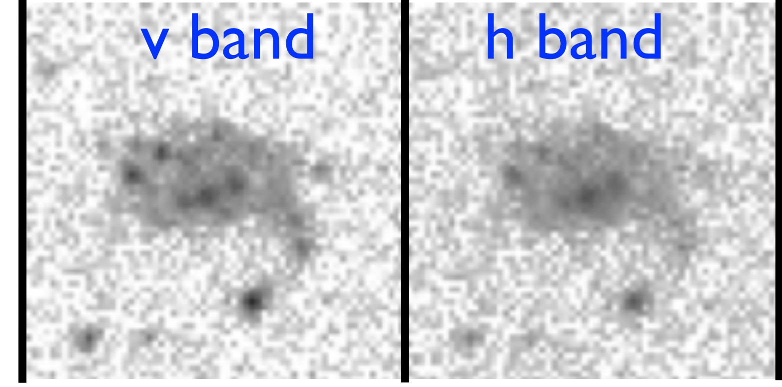


We are now systematically comparing simulated and observed galaxy images


CANDELS DATA - Preliminary
SMOOTH
1.4 < z < 2.6
60 Sub−Disk (n<0.8)
86 Disk (0.8≤n<1.5)
91 Intermediate (1.5≤n<2.5)
65 Spheroid (2.5≤n<5.0)
12 Super−Spheroid (5.0≤n)
Coded by Sersic
CLUMPY
1.4 < z < 2.6
52 Sub−Disk (n<0.8)
64 Disk (0.8≤n<1.5)
27 Intermediate (1.5≤n<2.5)
7 Spheroid (2.5≤n<5.0)
0 Super−Spheroid (5.0≤n)
Coded by Sersic
U − V
V − J
log(sSFR) [Gyr⁻¹]
R_eff (kpc)
Stellar Mass (M☉)

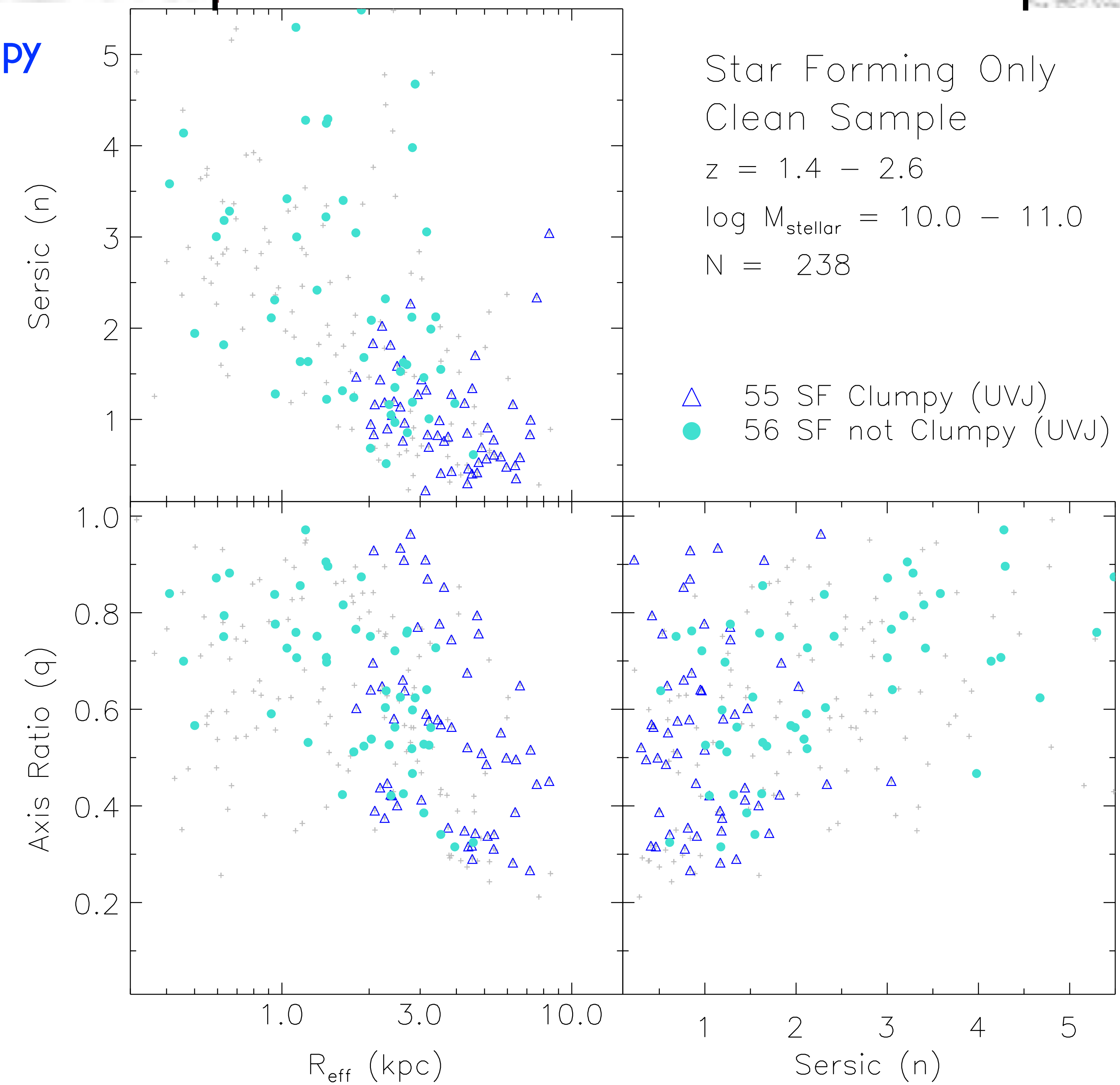


CANDELS DATA *Preliminary*

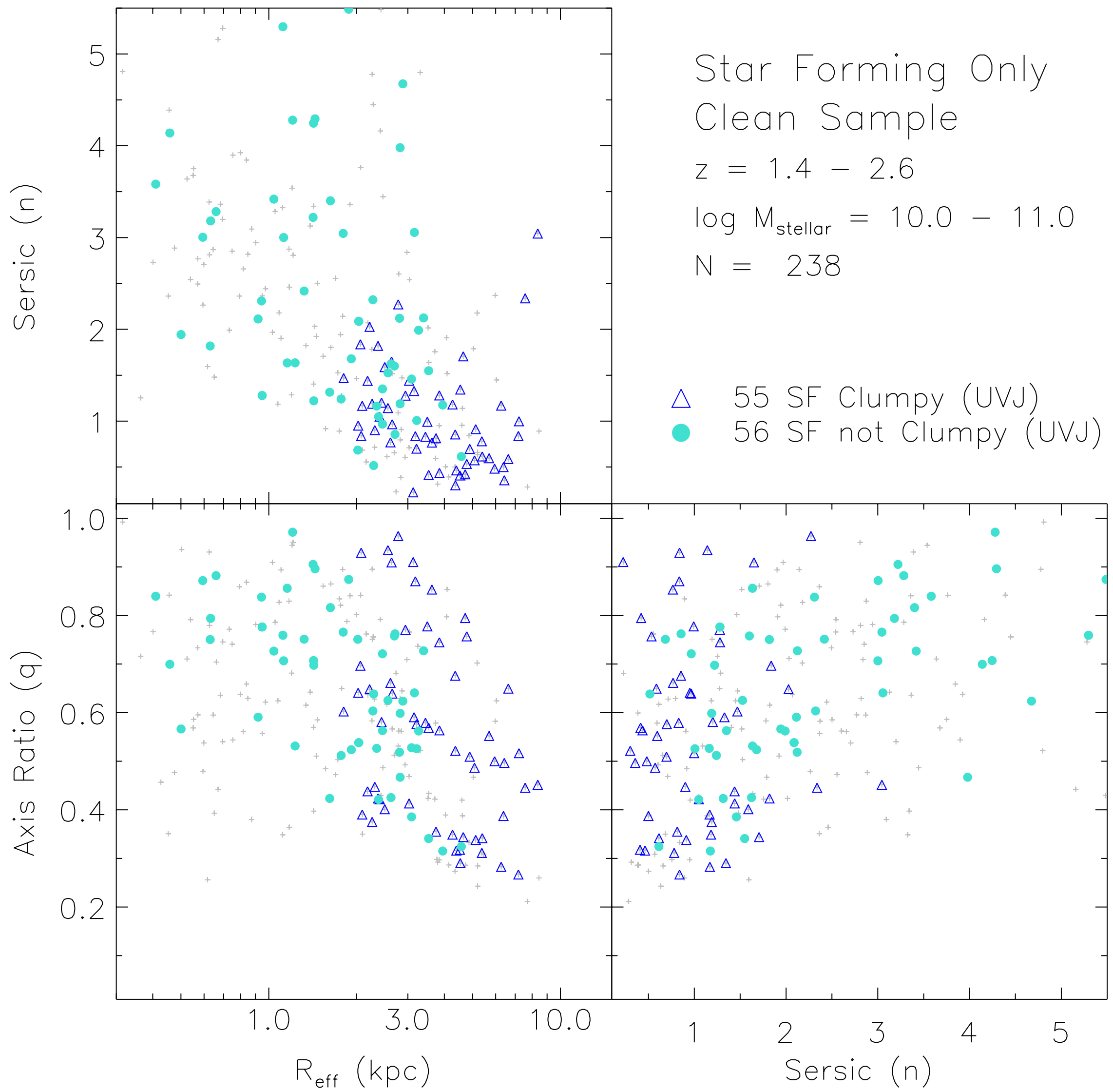


Not Clumpy

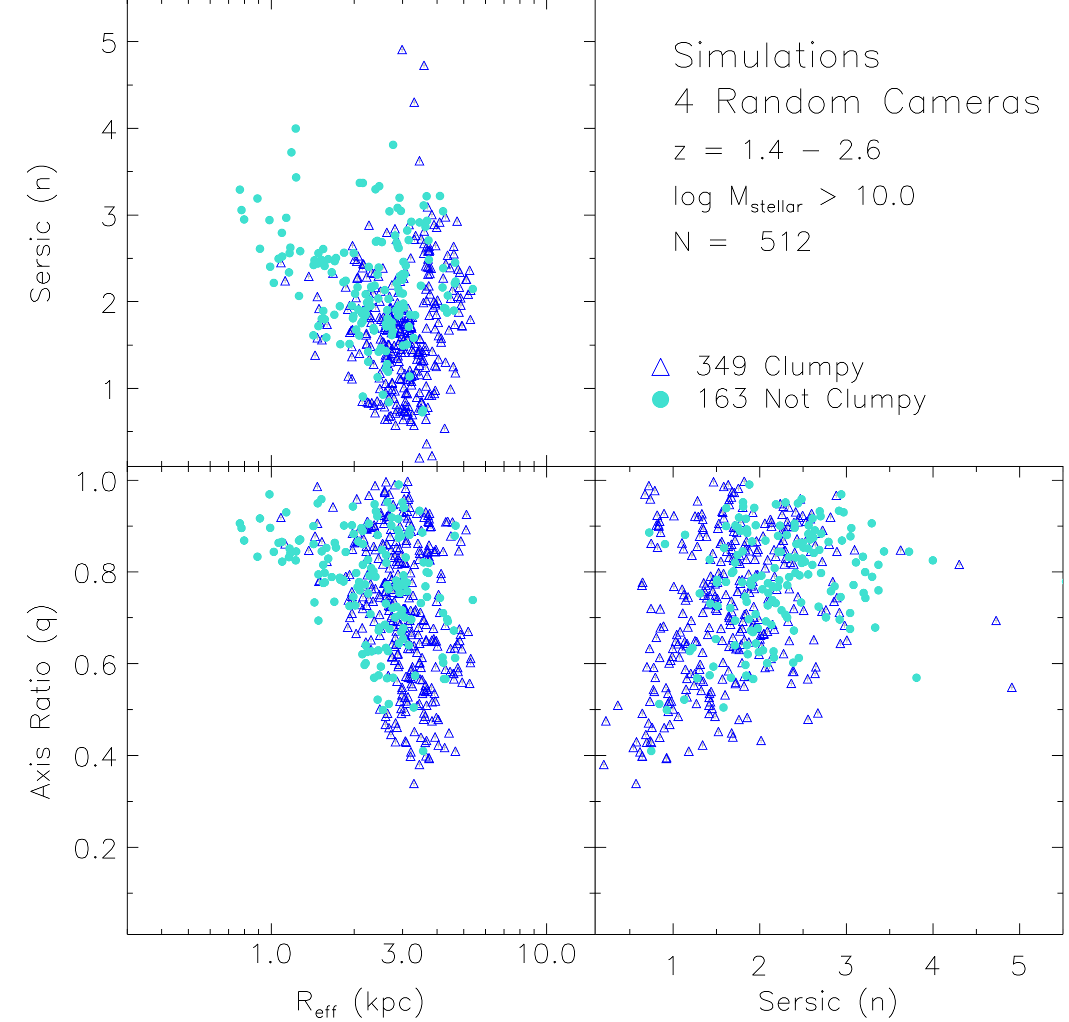
Clumpy

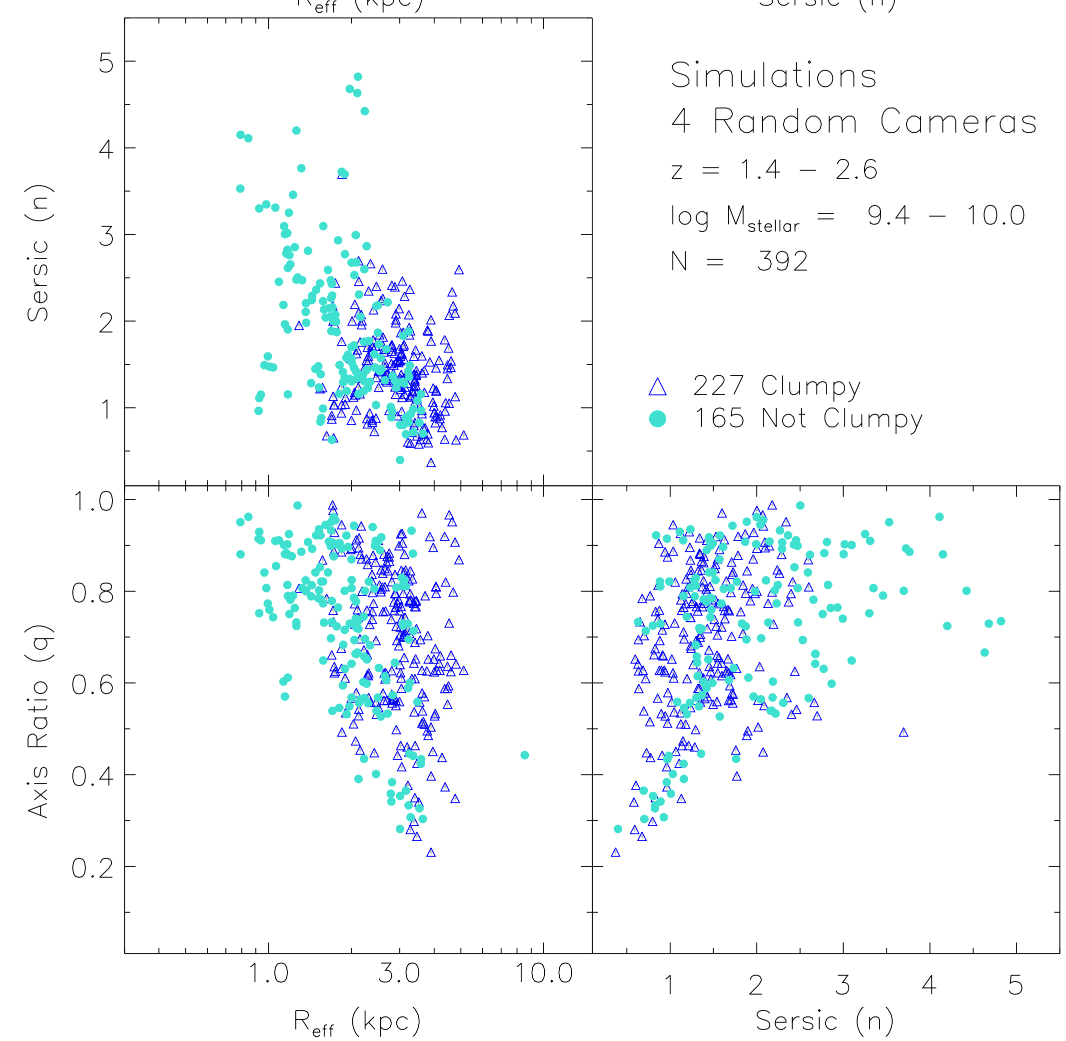


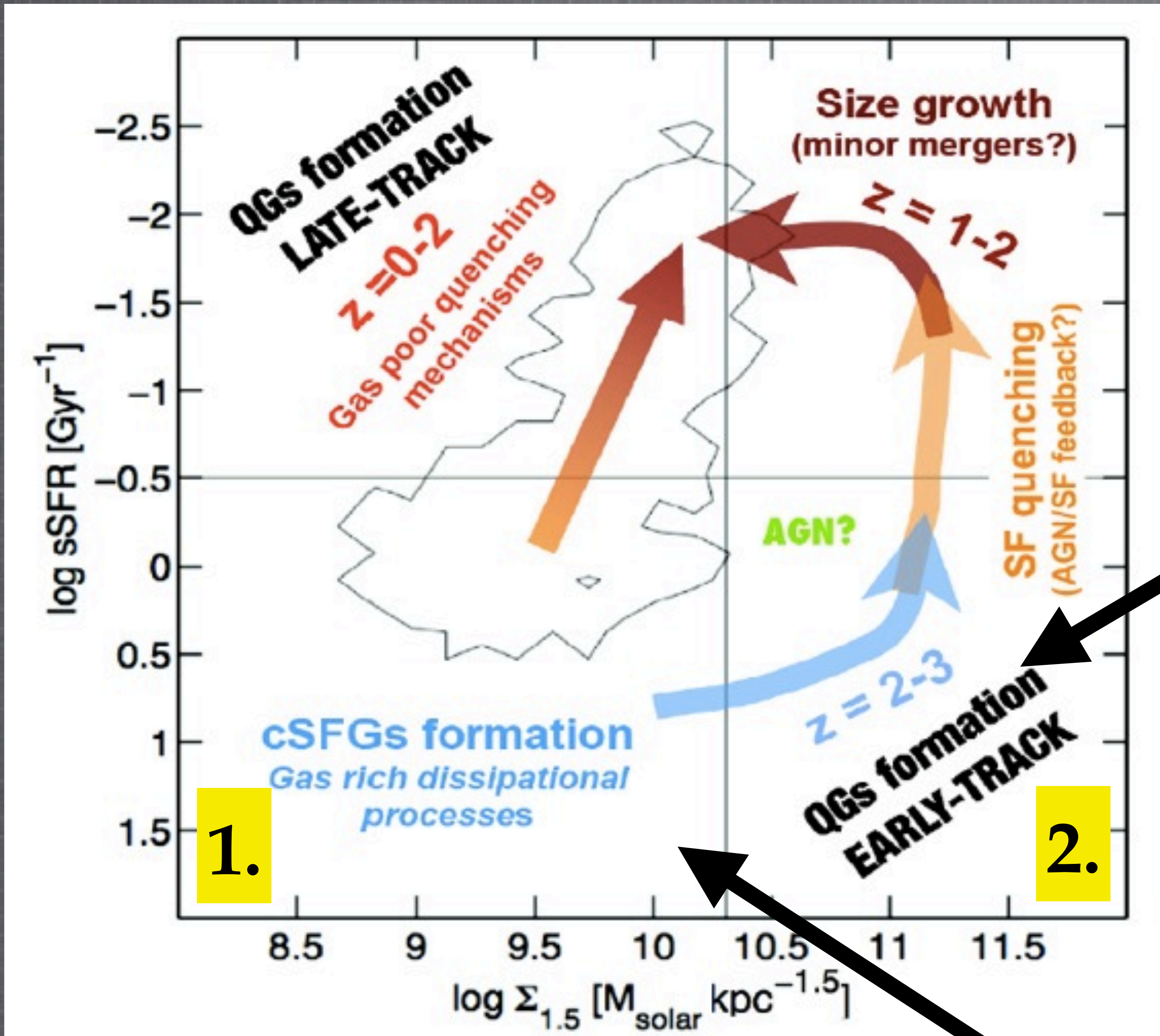
CANDELS DATA Preliminary



Compared with Daniel Ceverino's simulations without RP by Mark Mozena, Chris Moody, Priya Kollipara, & JP ➔







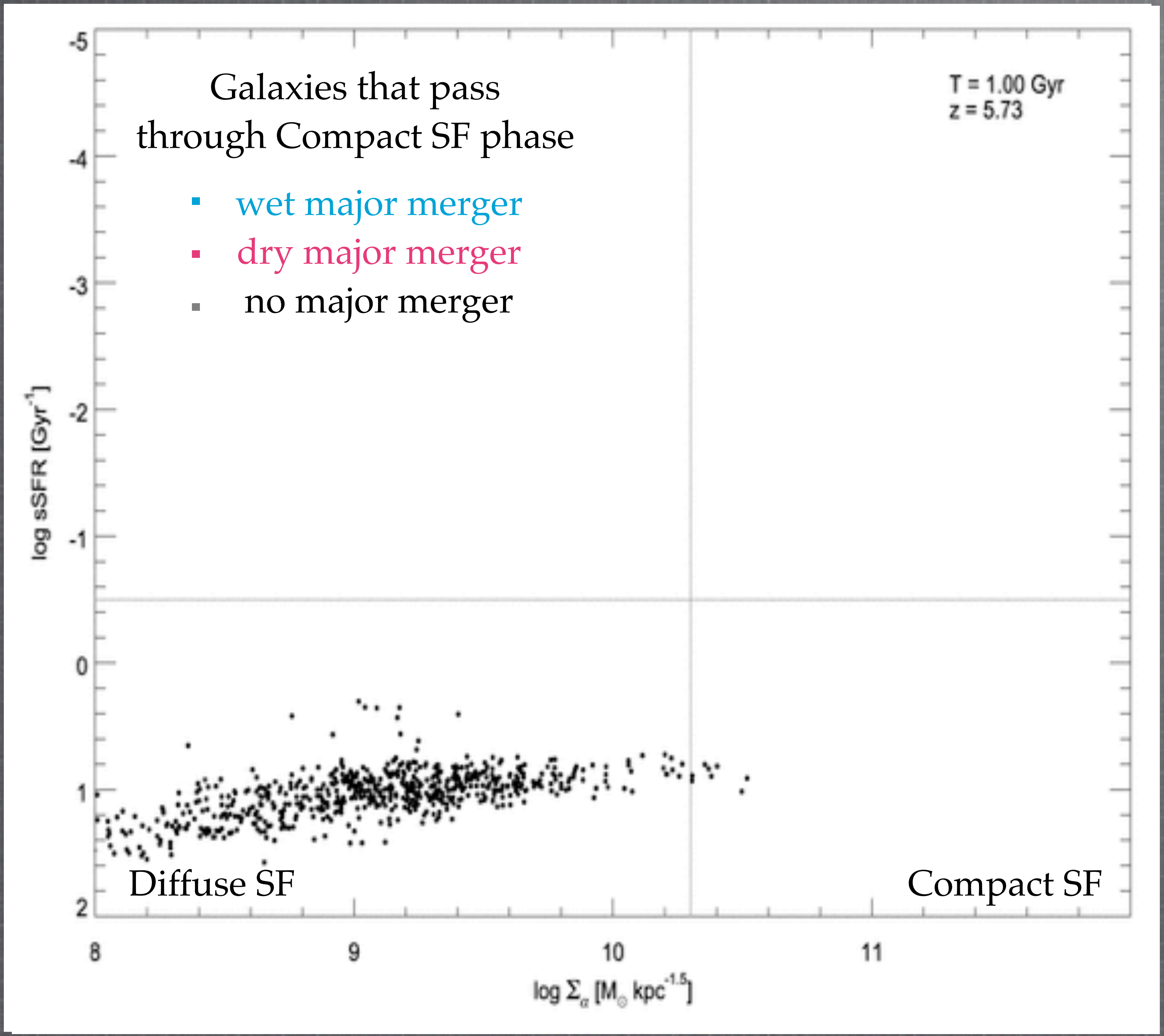
Compact SFGs properties 2.

- 80% dusty (IR-) star-formation.
- high-sersic, undisturbed app.
- 40% AGN det. fraction.
- 300 Myr -1 Gyr quenching times.
- AGN/SF feedback (outflows?)

Compact SFGs formation 1.

- SAMs - DI (60%) % wet mergers
- SAMs - Preferentially in already compact gal.
- ART-hydro - VDI time-scale 300 - 500 Myrs.

Guillermo Barro



Semi-Analytic Model:

Lauren Porter, Rachel Somerville, JP, et al.

Reproduces the CANDELS observations

Will AGORA simulations agree with the CANDELS observations?