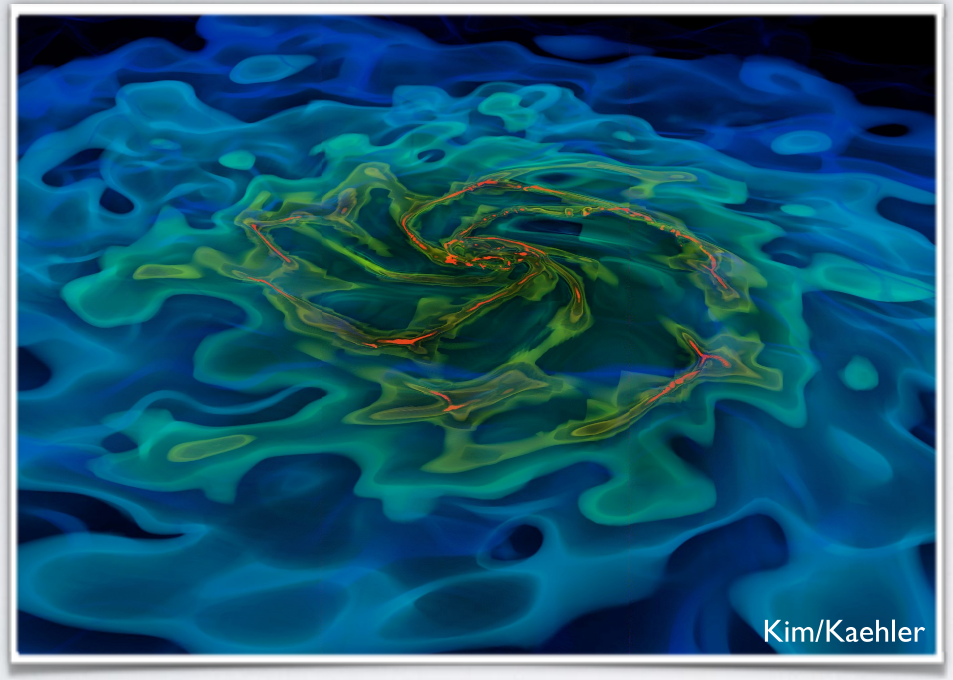
Challenges in Numerical Galaxy Formation and the AGORA Initiative



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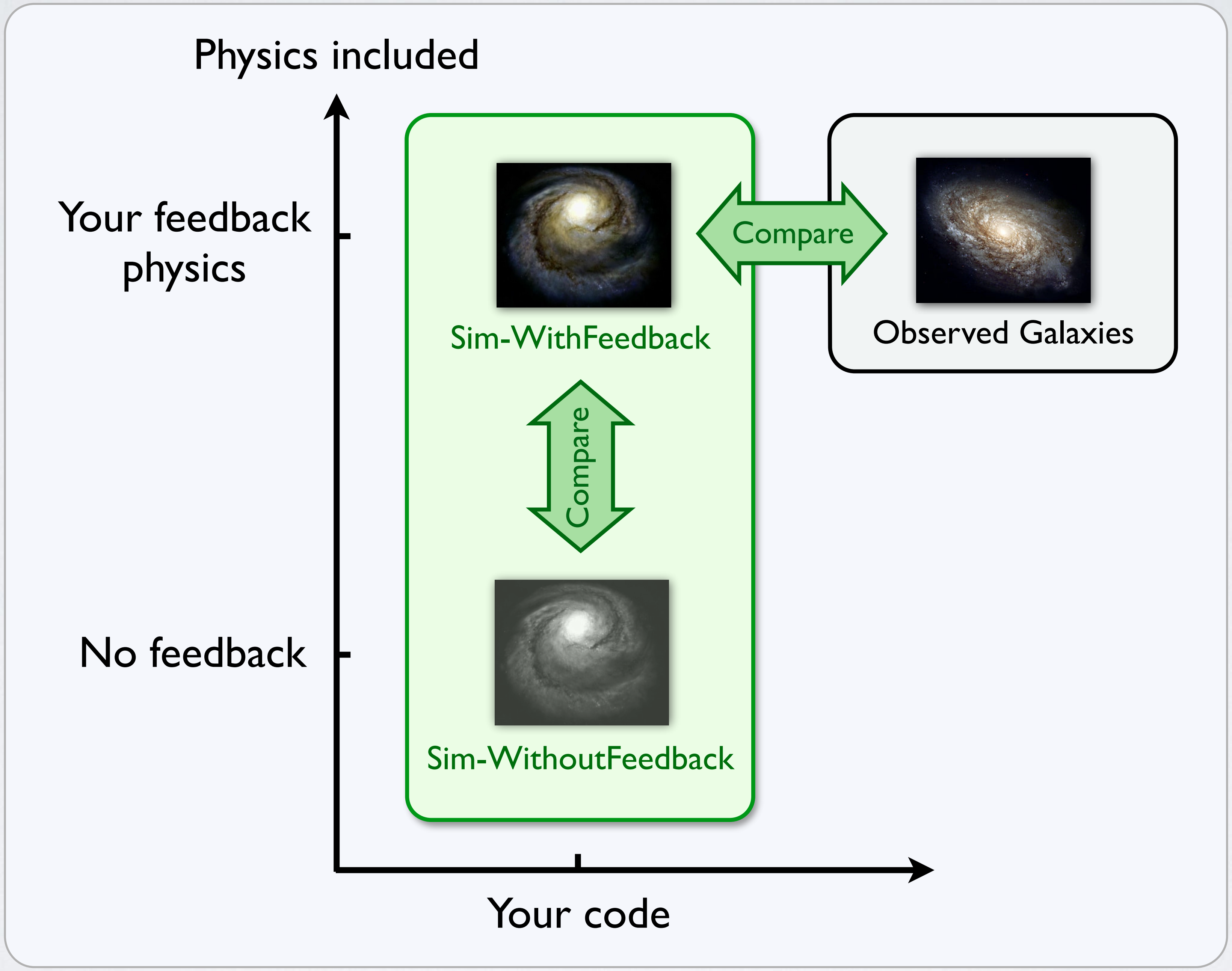
Thanks to: O. Agertz (Surrey), M. Butler (Zurich), N. Gnedin (Fermilab), O. Hahn (ETH), A. Hobbs (ETH), C. Hummels (Arizona), A. Klypin (NMSU), S. Leitner (Maryland), P. Madau (UCSC), L. Mayer (Zurich), J. Onorbe (MPIA), M. Rocha (UCSC), S. Shen (Cambridge), B. Smith (Edinburgh), K. Todoroki (UNLV), R. Teyssier (Zurich), M. Turk (NCSA), J. Wadsley (McMaster)

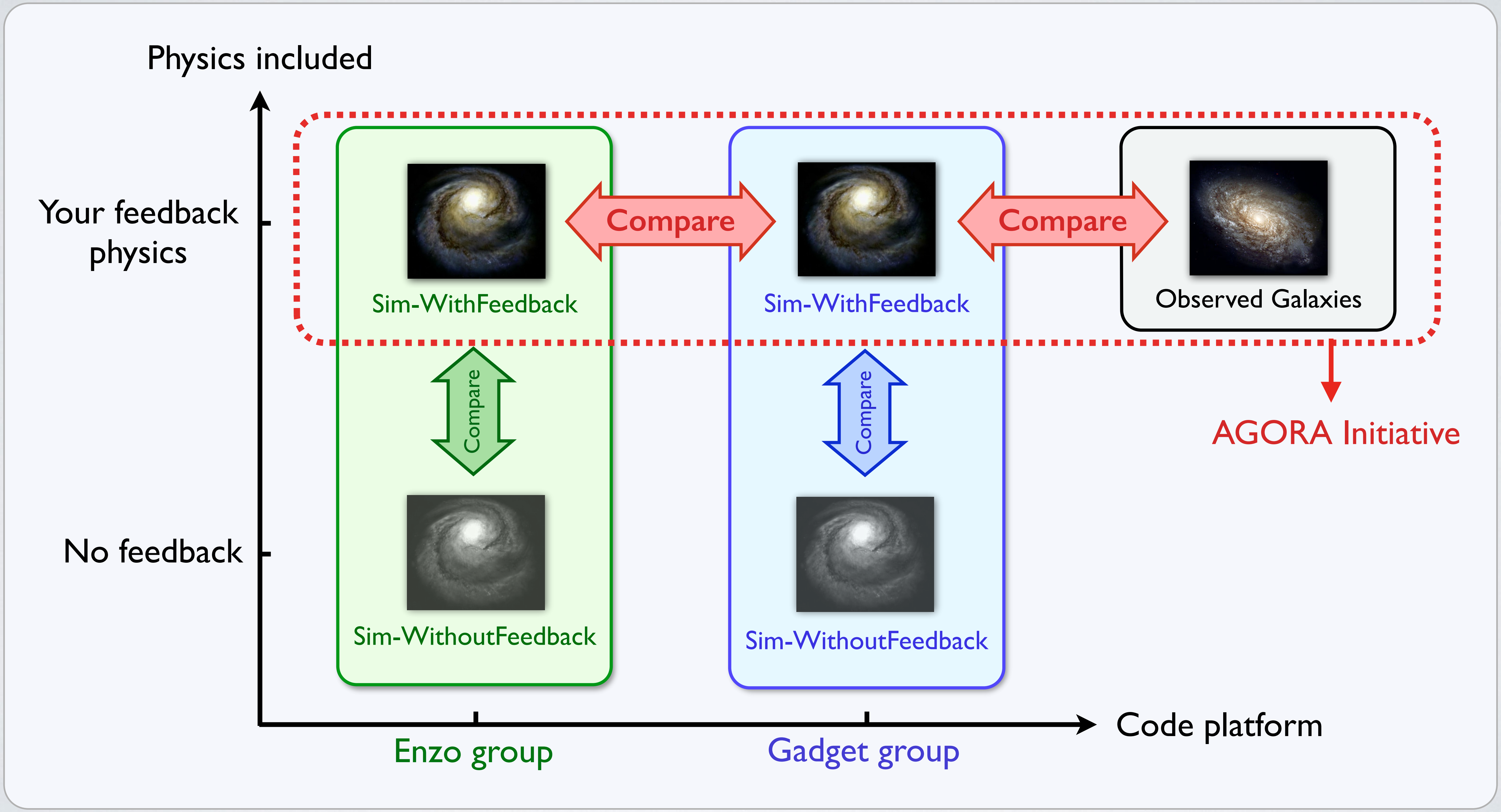
Galaxy Formation Simulation

- Galaxies are the building blocks of our Universe
  → Numerical study inevitable due to galaxy's nonlinear evolution



Compare Simulations To Raise Realism

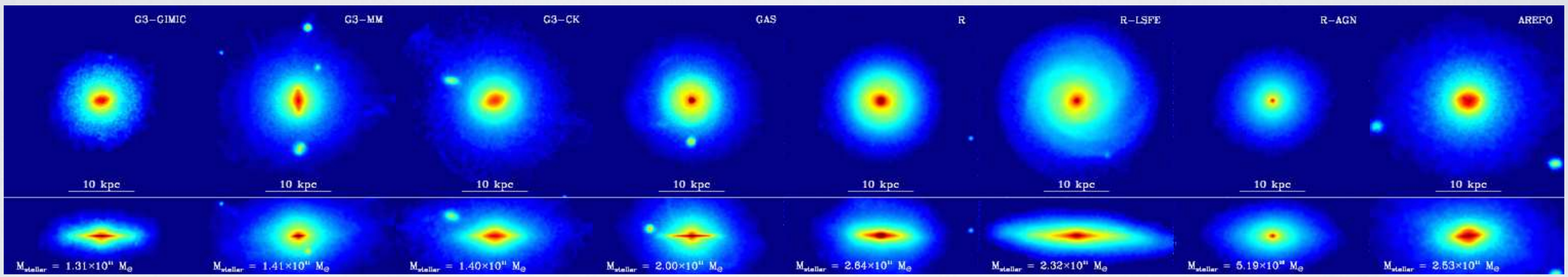
- To verify that your success is physical, compare across platforms



First Attempt: Aquilla Project (2012)

- Comparison of zoom-in cosmological galaxies of MW-type across multiple codes at ~0.5 physical kpc resolution

Scannapieco et al. 2012



Code		Particle mass		Force softening	
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]	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)

Code			UVB		Cooling	Stellar Fbck
Code	Reference	Type	UV background (z_{UV})	(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)

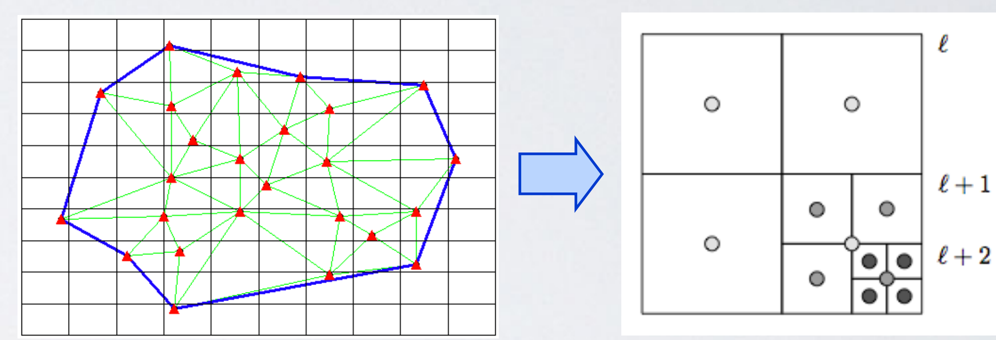
Problems in Past Comparisons

- Astrophysical input not carefully constrained (e.g. UVB, cooling, SF)

  - Insufficient resolution makes any stellar feedback model inefficient (e.g. Guedes et al. 2011)

- Common initial conditions hard to generate

  - Especially between particle- and grid-based codes



- Cross-platform analysis tricky

  - Challenging to ensure that analyses are identical across codes

- Not necessarily designed with an astrophysical question in mind

  - Project ended when a single paper was out even though the framework gathered could have been used to explore many problems in galaxy evolution

AGORA

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

AGORA Project: Goal and Team

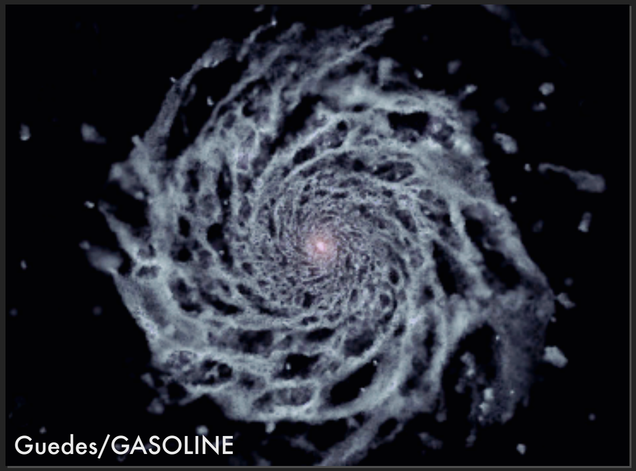
- GOAL: A collaborative, multi-code platform to raise the realism and predictive power of high-res galaxy simulations

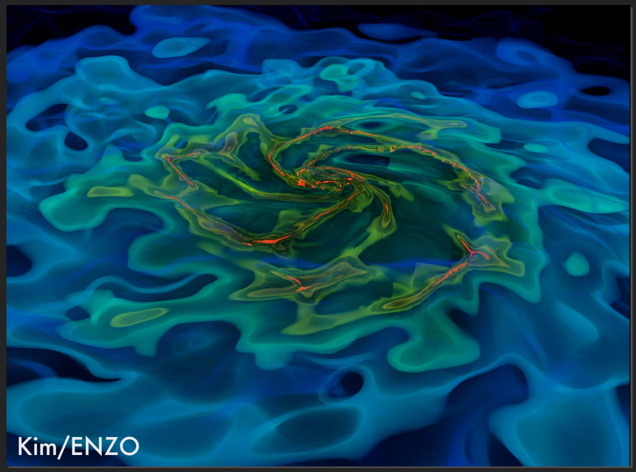
- TEAM - 115 participants from 60 institutions, Oct. 2014
  - 10+ groups each with variations of 6+ codes
  - 7-member Science Steering Committee
  - Project Coordinator: J. Kim

- DATA SHARING: Initial conditions, astrophysics modules, analysis software, and simulation outputs all to be public

- FIRST LIGHT: Flagship paper by J. Kim et al. (2014)

High-res Galaxy Simulation





Variation of the official AGORA intro slide (Credit: Kim & Governato) / Project funded in part by:

AGORA Initiative and Infrastructure

- Common initial conditions: cosmological ICs and disk ICs

  - 4 halo masses (~$10^{10, 11, 12, 13}$ $M_\odot$ @ z=0) + 2 merger histories ("violent" and "quiescent")

- Common analysis platform makes comparison easy

  - Available for all participating codes

- Common physics modules

  - Cooling, UV background, SN yields, etc.

- Specifically designed with astrophysical questions in mind

  - Project is not a simple code comparison

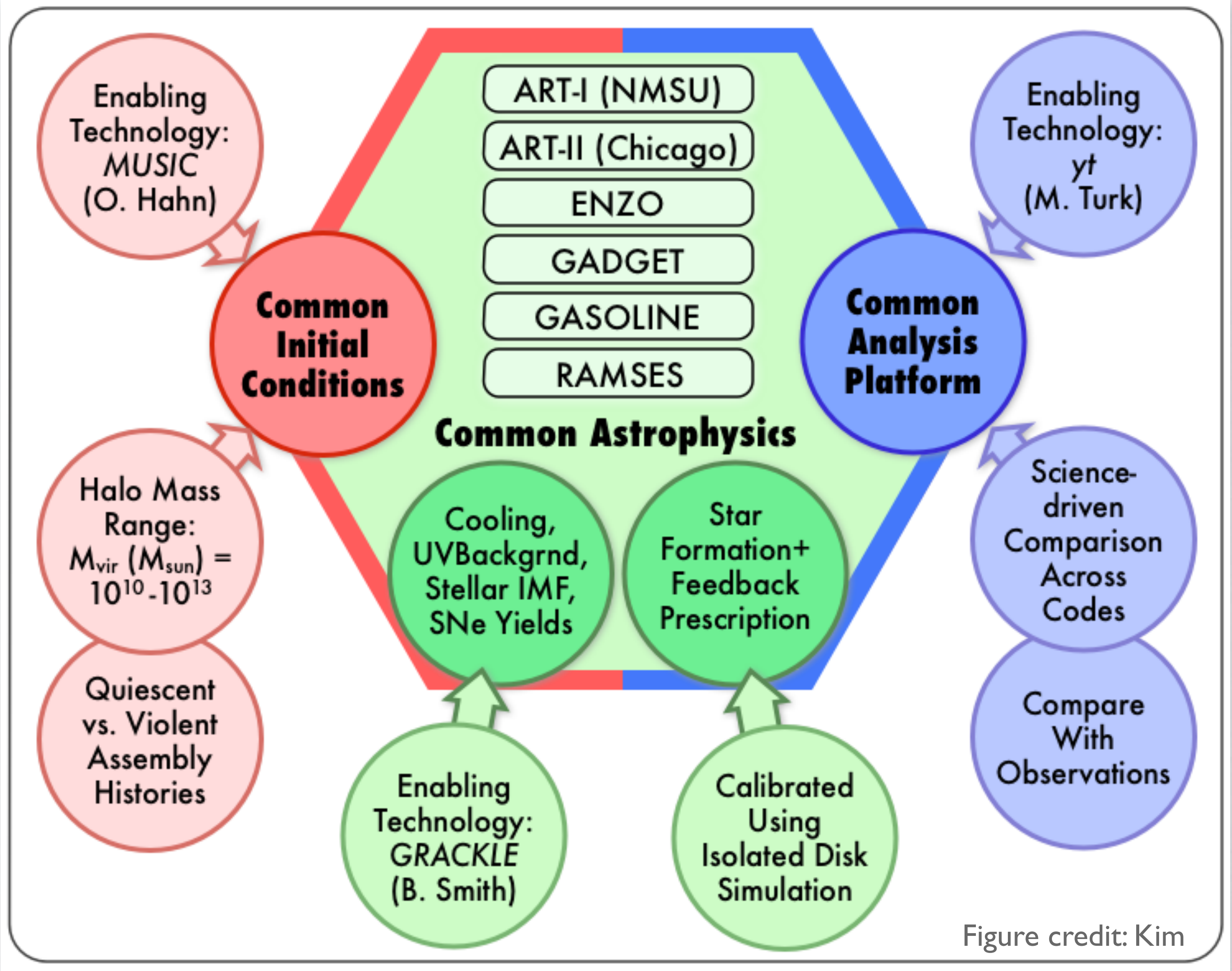


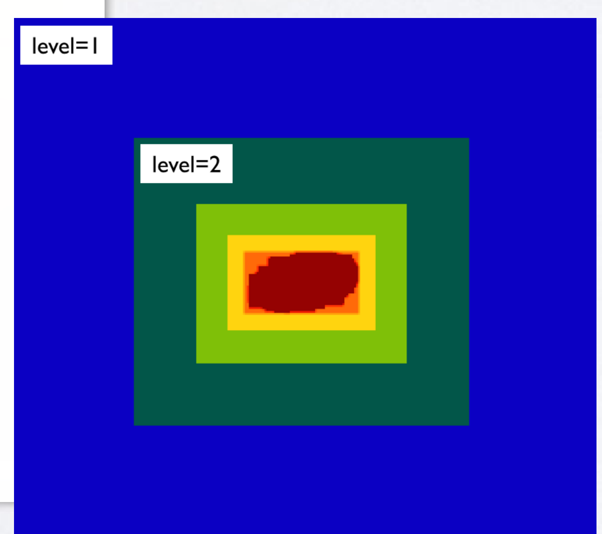
Figure credit: Kim

AGORA ICs: Ready for Your Experiments

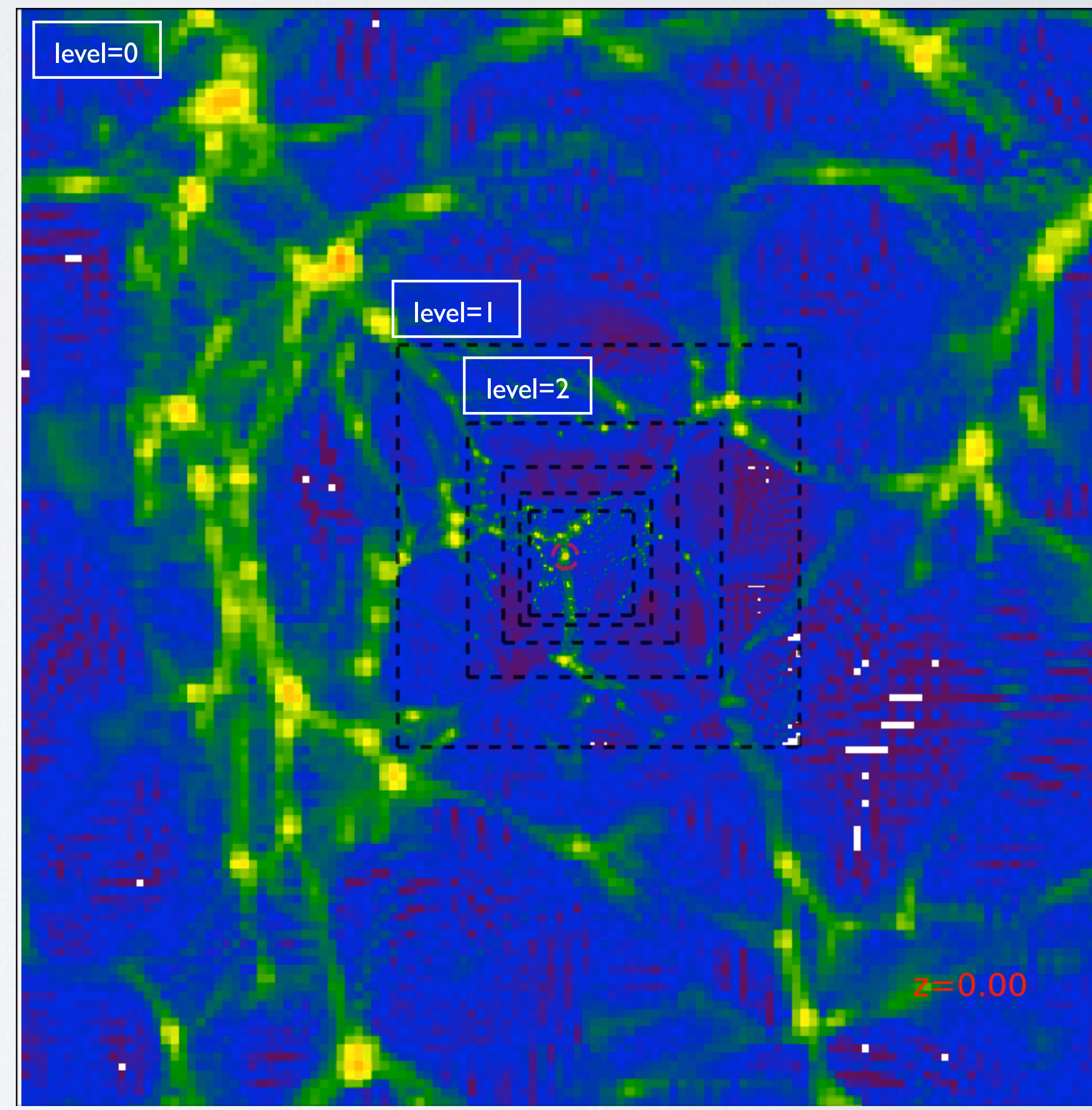
- Highly portable ICs made possible by MUSIC (Hahn et al.)
  - Cosmological ICs by Kim, Onorbe, Hahn, et al. + Disk ICs by Agertz, Teyssier, et al.
  - Open for use (AGORA or not); no data conversion necessary between codes

```
[setup]
boxlength                    = 60
zstart                       = 100
levelmin                     = 7
levelmin_TF                  = 9
levelmax                     = 12
padding                      = 16
overlap                      = 4
align_top                    = no
baryons                      = no
use_2LPT                     = no
use_LLA                      = no
region                       = ellipsoid
region_ellipsoid_matrix[0]   = 2710.833984, -498.042755, -260.366791
region_ellipsoid_matrix[1]   = -498.042755, 1496.330933, 864.111267
region_ellipsoid_matrix[2]   = -260.366791, 864.111267, 5030.364746
region_ellipsoid_center      = 0.638273, 0.576312, 0.447929

[cosmology]
Omega_m                      = 0.272
Omega_L                      = 0.728
Omega_b                      = 0.0455
H0                           = 70.2
sigma_8                      = 0.807
nspec                        = 0.961
transfer                     = eisenstein

[random]
cubesize                     = 256
seed[8]                      = 95064
seed[9]                      = 31415
seed[10]                     = 27183

[output]
format               = enzo
filename             = ic.enzo
##enzo_refine_region_fraction = 0.8

[poisson]
fft_fine             = yes
accuracy             = 1e-6
grad_order           = 6
laplace_order        = 6
```

MUSIC parameter file for a $10^{10}\ M_\odot$ halo

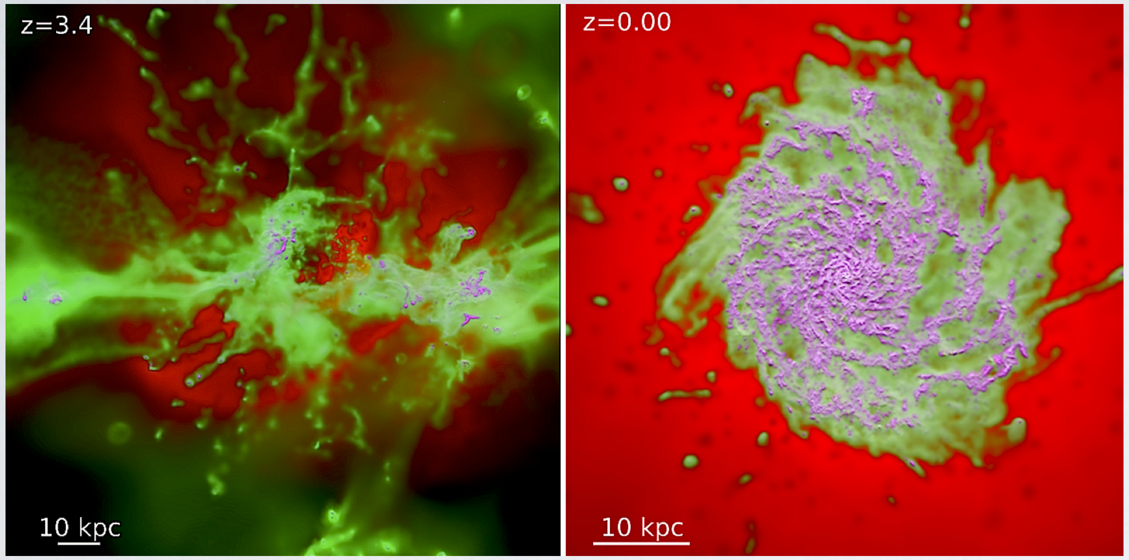


Maximum level along LOS @ z=50

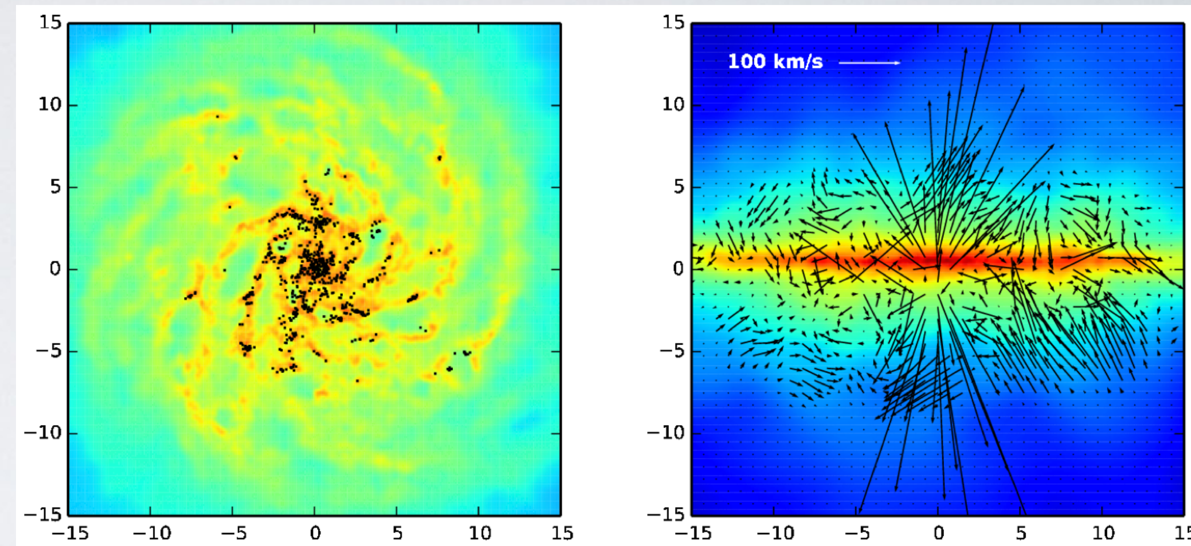


Pathfinder run for a $10^{12}\ M_\odot$ target halo

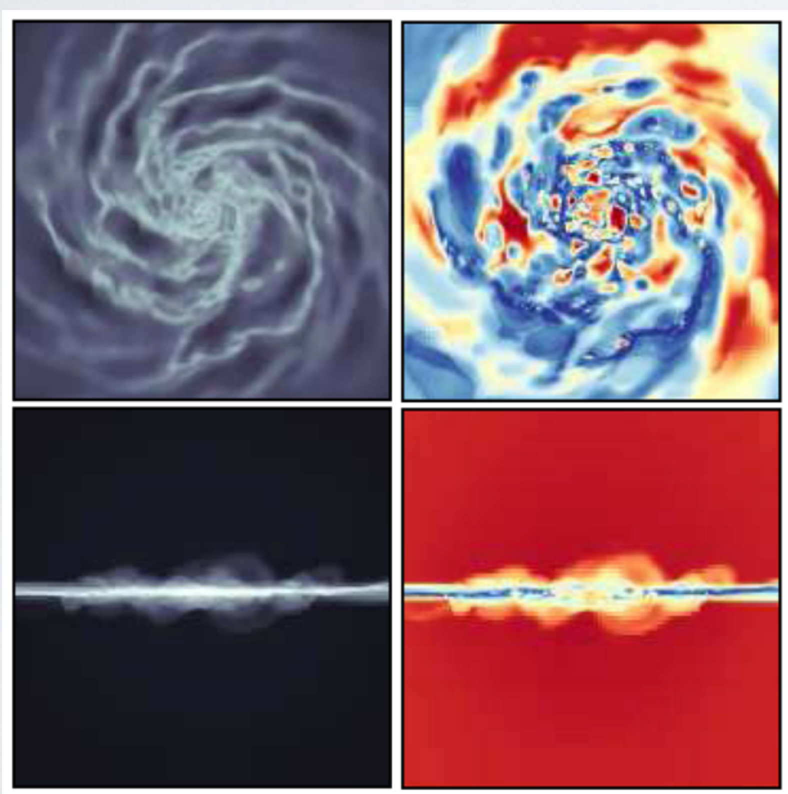
Researches Using AGORA ICs



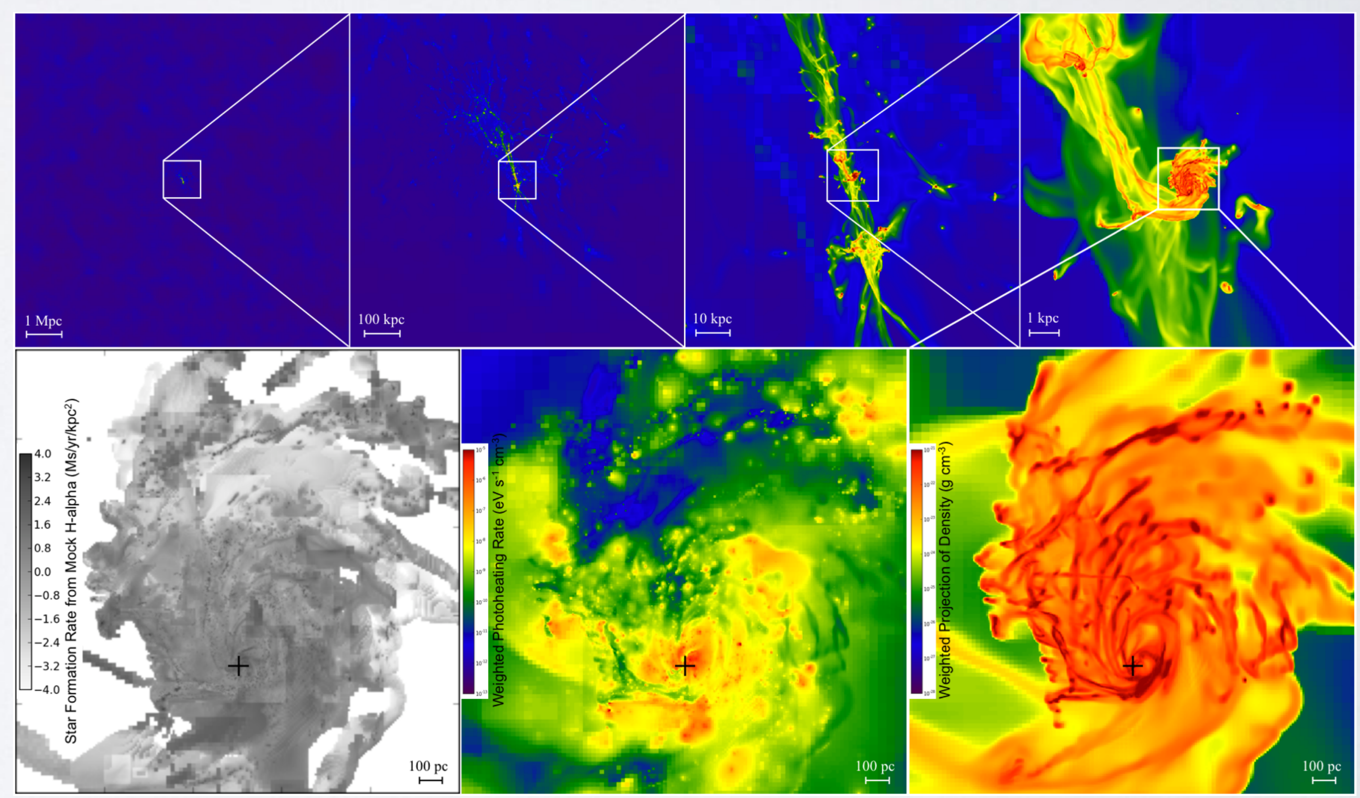
Hopkins et al. 2013, van de Voort et al. 2014,
MW-size halo (~10^{12} $M_\odot$ @z=0) with 50 pc/h softening



Keller et al. 2014,
MW-size halo (1.3×10^{12} $M_\odot$ @z=0) with 20 pc softening



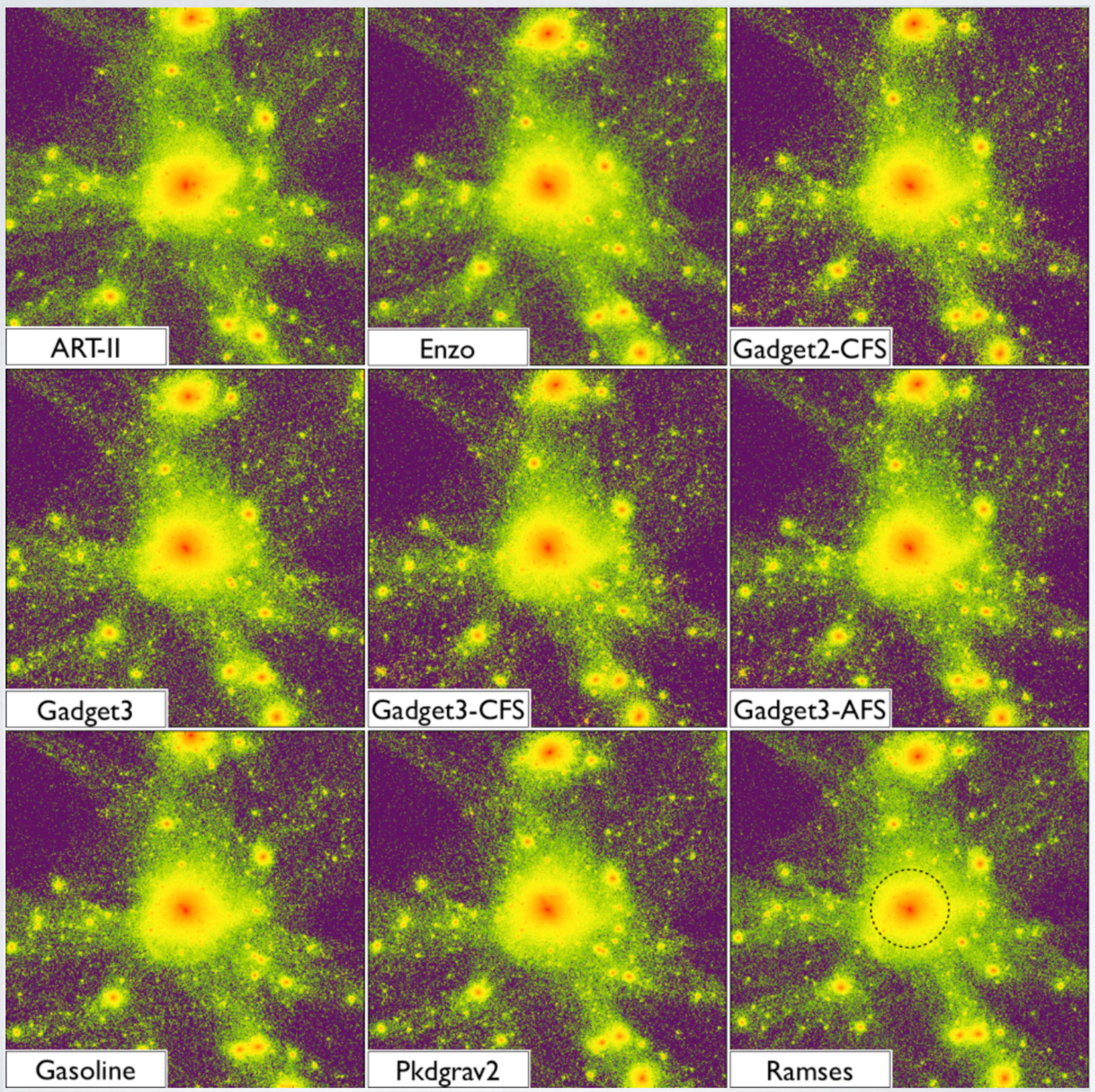
Agertz et al. 2013,
MW-size halo with 70 pc resolution



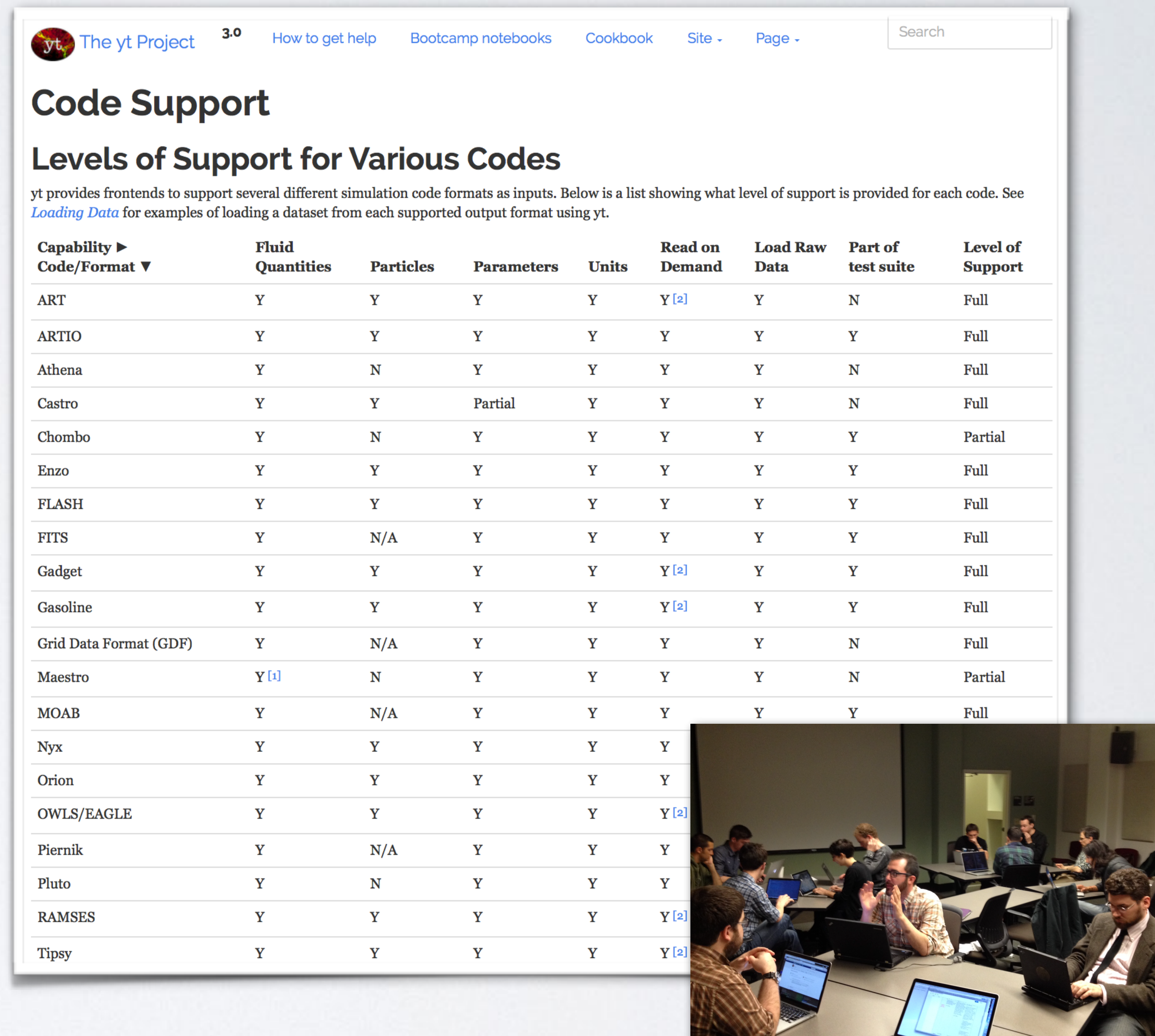
Kim et al. 2014 in prep., high-z quasar host
(7×10^{10} $M_\odot$ @z~7.5 → ~10^{13} $M_\odot$ @z=0) with 4.8 pc resolution

yt Analysis Toolkit: Choice for AGORA

- Supports many codes, including all in AGORA (Turk et al.)
  - yt-3.0 developed thanks in part to AGORA members (e.g. yt-AGORA joint workshop)



~10^{11} $M_\odot$ halo at z=0, projected DM density, Kim et al. 2014



The yt Project 3.0 | How to get help | Bootcamp notebooks | Cookbook | Site | Page | Search

Code Support

Levels of Support for Various Codes

yt provides frontends to support several different simulation code formats as inputs. Below is a list showing what level of support is provided for each code. See *Loading Data* for examples of loading a dataset from each supported output format using yt.

Capability ▶ Code/Format ▼	Fluid Quantities	Particles	Parameters	Units	Read on Demand	Load Raw Data	Part of test suite	Level of Support
ART	Y	Y	Y	Y	Y [2]	Y	N	Full
ARTIO	Y	Y	Y	Y	Y	Y	Y	Full
Athena	Y	N	Y	Y	Y	Y	N	Full
Castro	Y	Y	Partial	Y	Y	Y	N	Full
Chombo	Y	N	Y	Y	Y	Y	Y	Partial
Enzo	Y	Y	Y	Y	Y	Y	Y	Full
FLASH	Y	Y	Y	Y	Y	Y	Y	Full
FITS	Y	N/A	Y	Y	Y	Y	Y	Full
Gadget	Y	Y	Y	Y	Y [2]	Y	Y	Full
Gasoline	Y	Y	Y	Y	Y [2]	Y	Y	Full
Grid Data Format (GDF)	Y	N/A	Y	Y	Y	Y	N	Full
Maestro	Y [1]	N	Y	Y	Y	Y	N	Partial
MOAB	Y	N/A	Y	Y	Y	Y	Y	Full
Nyx	Y	Y	Y	Y	Y			
Orion	Y	Y	Y	Y	Y			
OWLS/EAGLE	Y	Y	Y	Y	Y [2]			
Piernik	Y	N/A	Y	Y	Y			
Pluto	Y	N	Y	Y	Y			
RAMSES	Y	Y	Y	Y	Y [2]			
Tipsy	Y	Y	Y	Y	Y [2]			

yt-AGORA joint workshop@UCSC (Mar. 2014)

GRACKLE Physics Package

- Cooling + chemistry library developed for AGORA (Smith et al.)

  - Implementation in (non-)equilibrium mode completed or underway in all participating codes

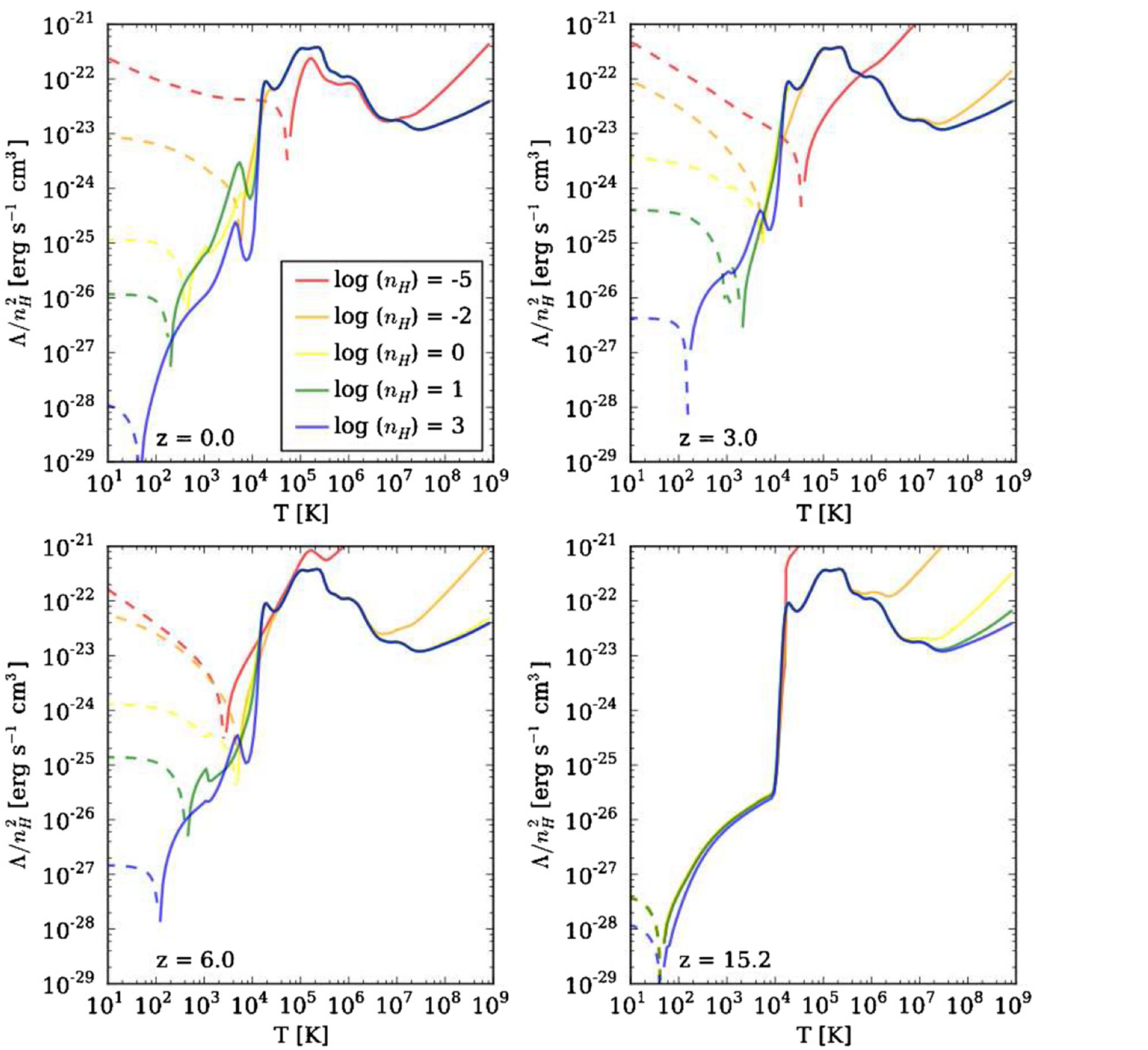
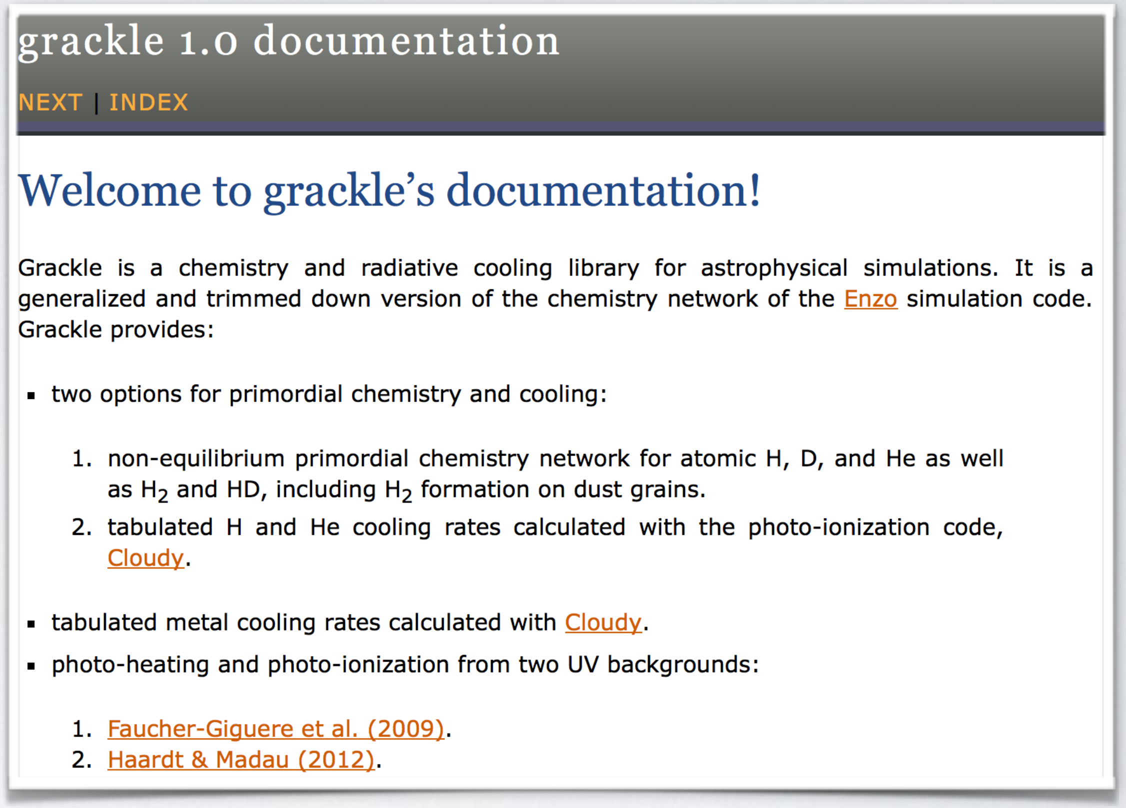


Figure 1. Gas cooling in the AGORA simulations. Equilibrium cooling rates normalized by n_H^2 calculated with the GRACKLE cooling library for H number densities of 10^{-5} (red), 10^{-2} (orange), 1 (yellow), 10 (green), and 10^3 (blue) cm^{-3} at redshifts $z = 0$, 3, 6, and 15.2 (just before the UV 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).

GRACKLE Gas cooling, Kim et al. 2014



grackle 1.0 documentation

NEXT | INDEX

Welcome to grackle's documentation!

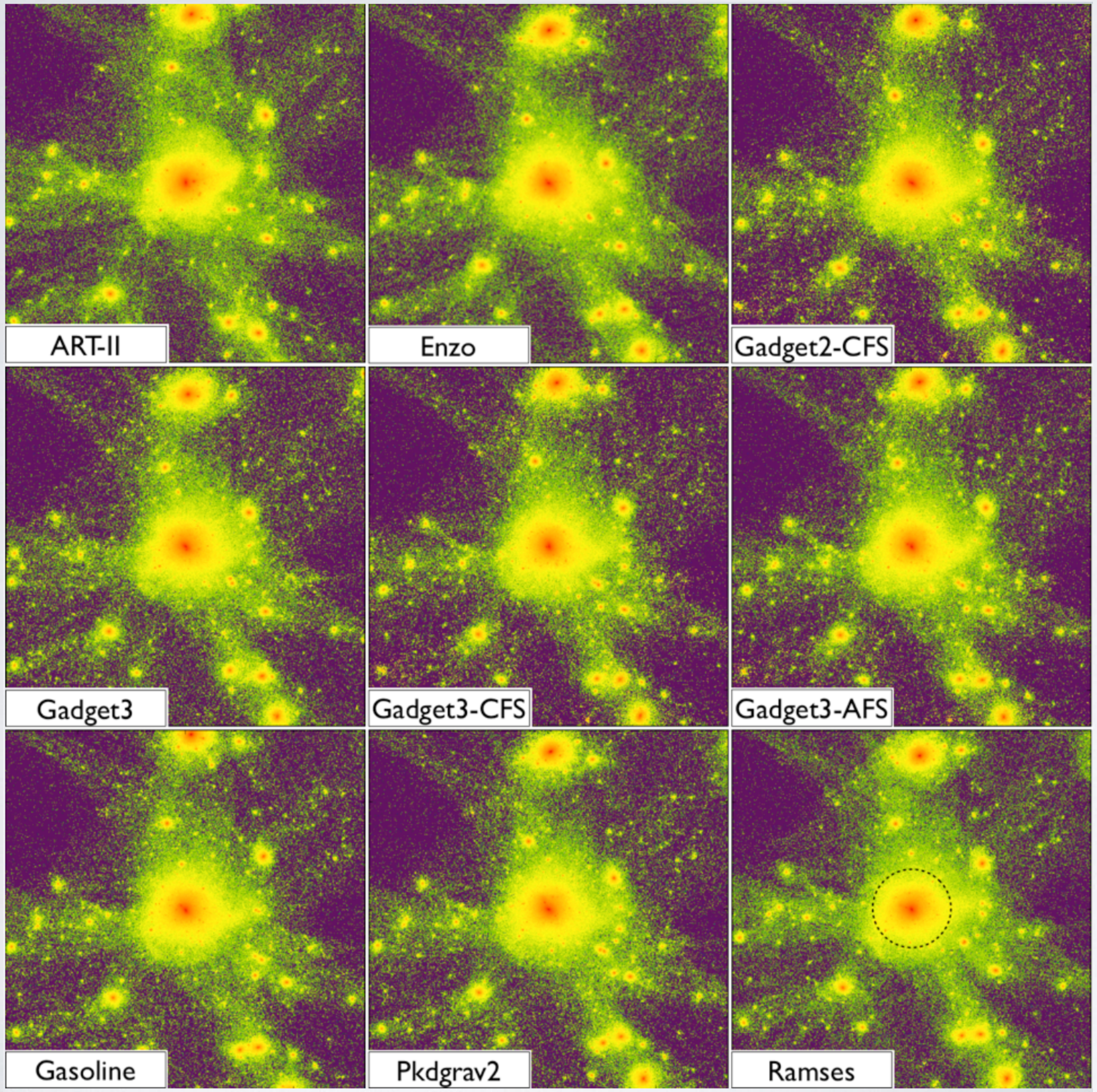
Grackle is a chemistry and radiative cooling library for astrophysical simulations. It is a generalized and trimmed down version of the chemistry network of the Enzo simulation code. Grackle provides:

- two options for primordial chemistry and cooling:
  1. non-equilibrium primordial chemistry network for atomic H, D, and He as well as H_2 and HD, including H_2 formation on dust grains.
  2. tabulated H and He cooling rates calculated with the photo-ionization code, Cloudy.
- tabulated metal cooling rates calculated with Cloudy.
- photo-heating and photo-ionization from two UV backgrounds:
  1. Faucher-Giguere et al. (2009).
  2. Haardt & Madau (2012).

GRACKLE documentation: grackle.readthedocs.org

AGORA Proof-of-Concept and Beyond

- Flagship paper with Dark Matter-only PoC tests (Kim et al. 2014)

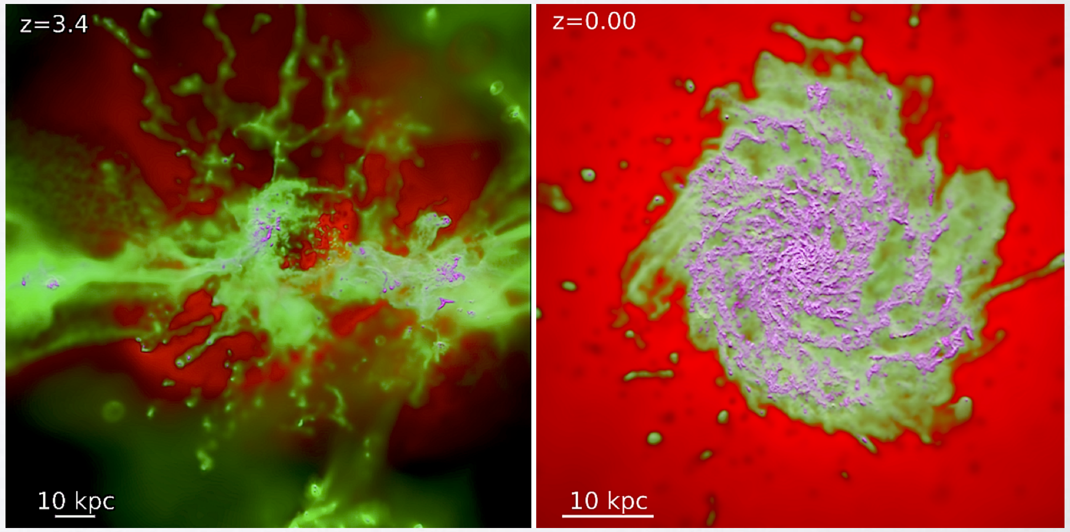


~10^{11} $M_\odot$ halo at z=0, projected DM density, Kim et al. 2014

- Established & tested comparison pipeline

- Runtime parameters identified that make codes compatible with one another

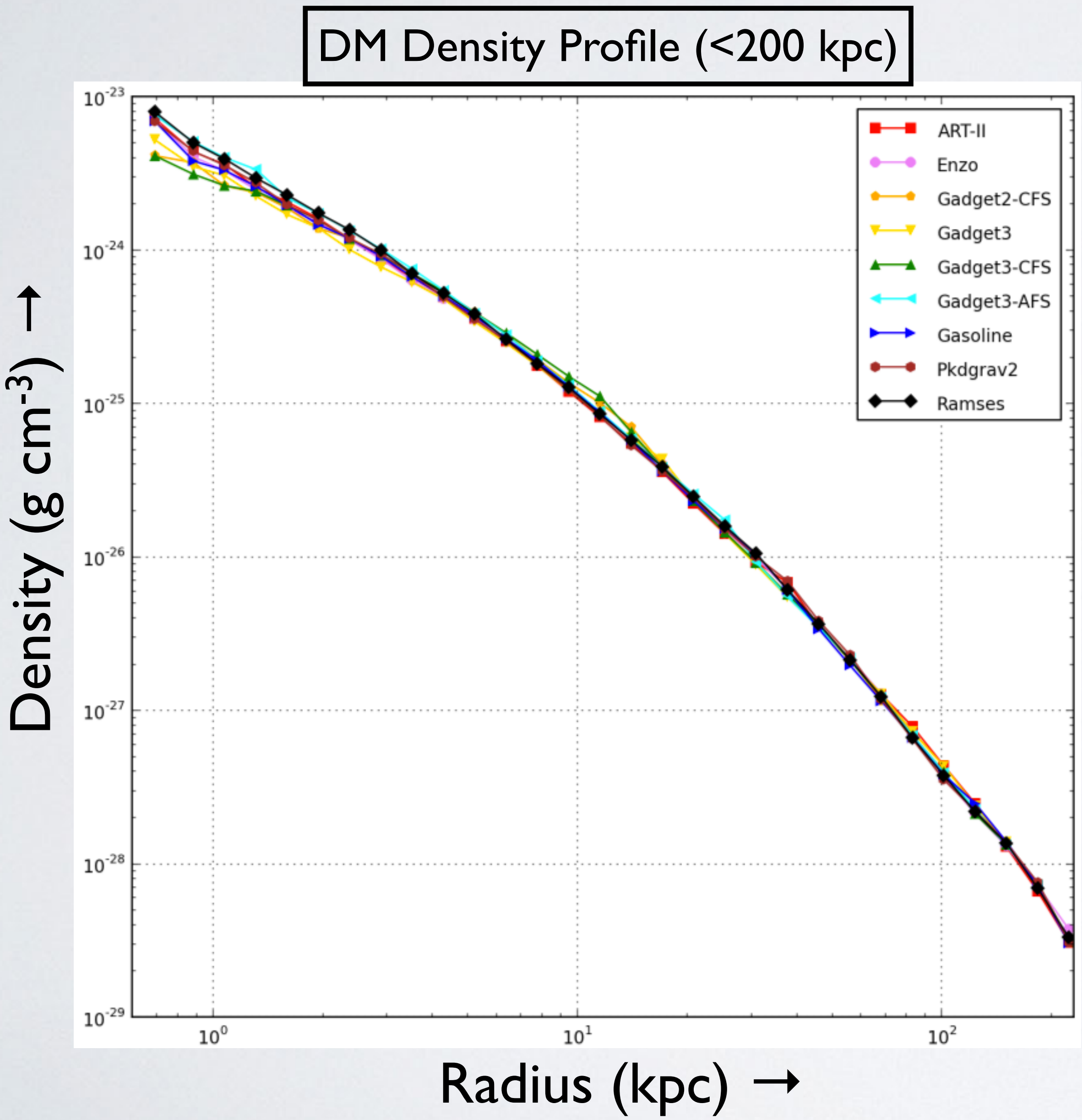
- Publicly available ICs are being used to build a library of AGORA simulations making future comparisons very trivial

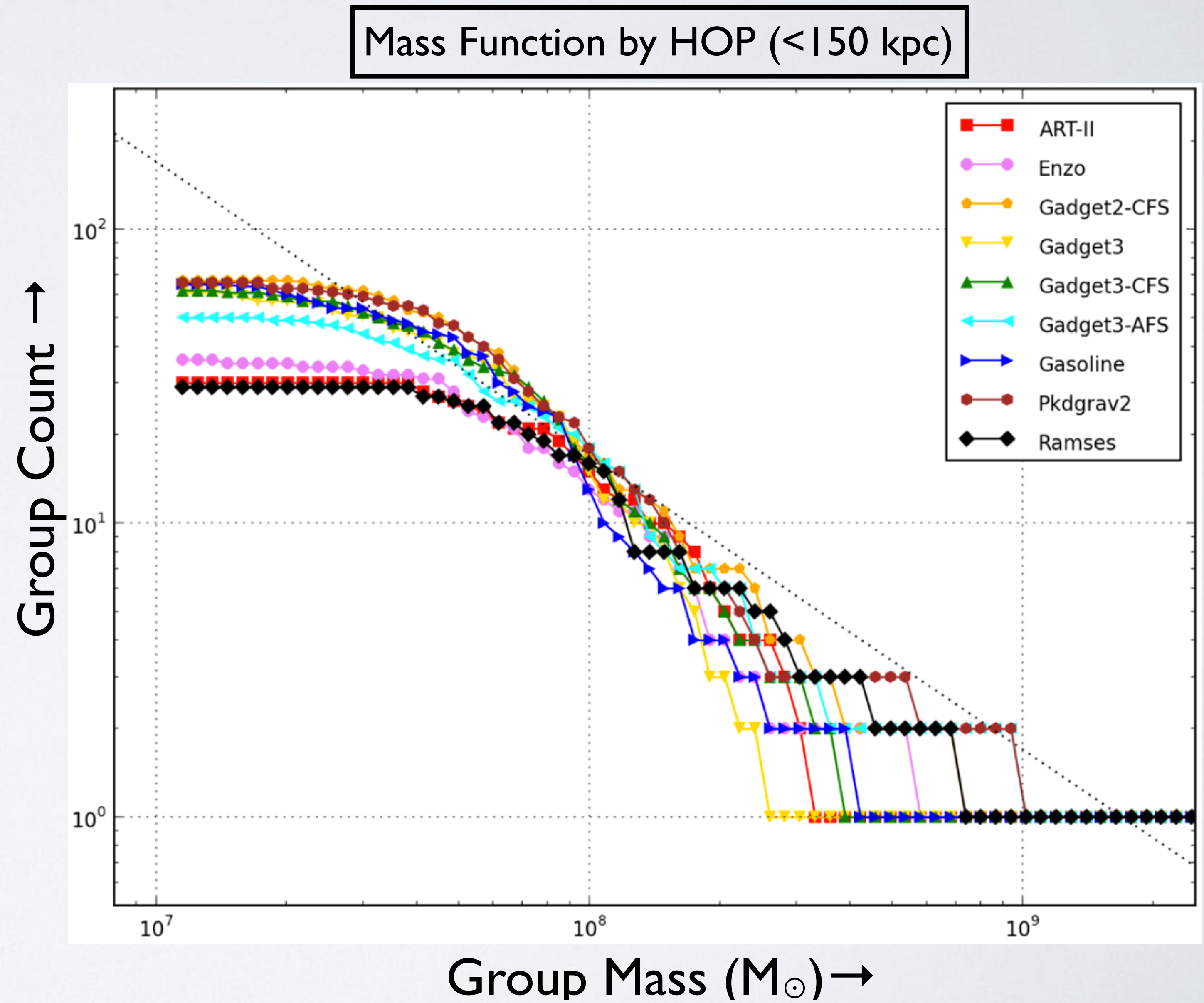


~10^{12} $M_\odot$ halo at z=0, Hopkins et al. 2013, van de Voort et al. 2014

Foundation for Future Comparisons

- Overall density profile and mass function in good agreement
  - Provides solid foundation for future hydrodynamic comparisons





AGORA Science In Years To Come

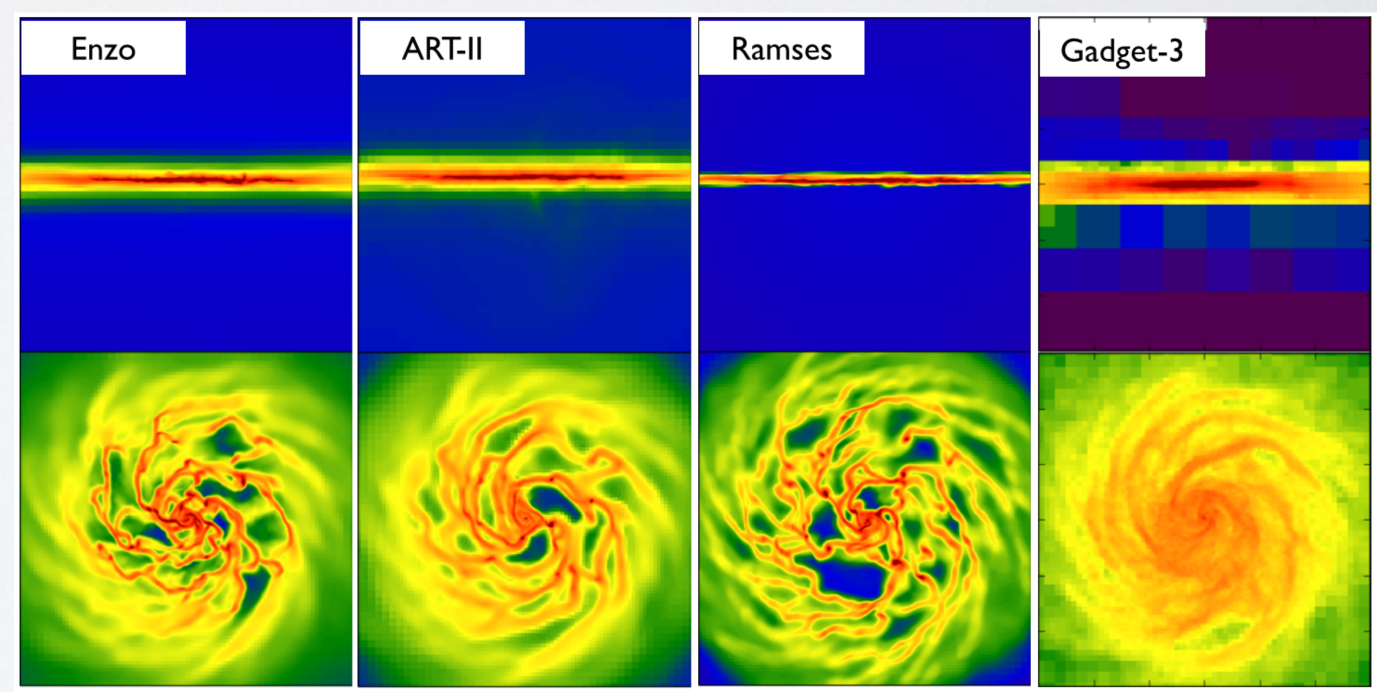
- AGORA provides a unique opportunity to validate our answers to long-standing problems in galaxy formation theory

  - 4 Task-oriented Working Groups + 9 Science-oriented Working Groups launched

  - 3 papers in preparation to characterize code differences and improve pipeline (as of Oct. 2014)

Task-oriented Working Groups (I–IV)	
WG I	– Common Physics and Introduction to Project
WG II	– Common ICs: Isolated
WG III	– Common ICs: Cosmological
WG IV	– Common Analysis
Science-oriented Working Groups (V–XIII)	
WG V	– Isolated Galaxies and Subgrid Physics
WG VI	– Dwarf Galaxies in Cosmological Simulations
WG VII	– Dark Matter
WG VIII	– Satellite Galaxies
WG IX	– Characteristics of Cosmological Galaxies
WG X	– Galactic Outflows
WG XI	– High-redshift Galaxies
WG XII	– Interstellar Medium
WG XIII	– SMBH Accretion and Feedback

From AGORAsimulations.org (created & maintained by Kim)

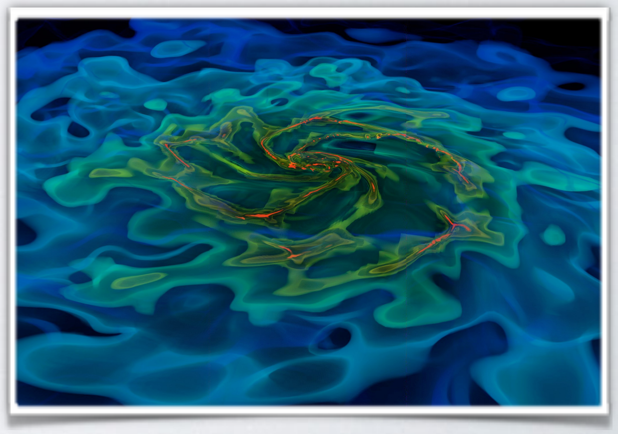


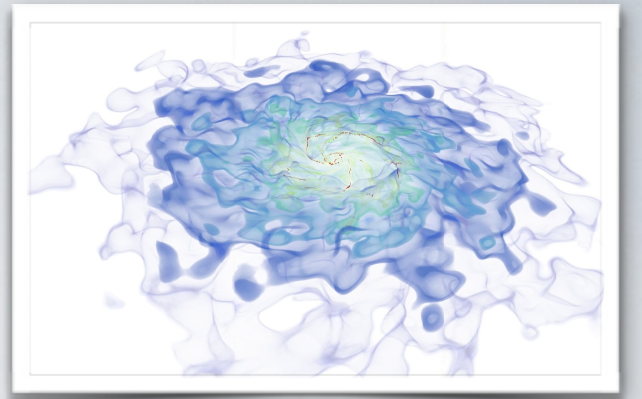
MW-size disk, projected gas density, Agertz et al. 2014 (in prep.)

Challenges in Numerical Galaxy Formation and the AGORA Initiative

- The need and opportunity for a comprehensive comparison of galaxy formation simulations has never been greater.

- The AGORA High-resolution Galaxy Simulations Comparison Initiative offers a unique opportunity to validate our answers to long-standing problems in galaxy formation.

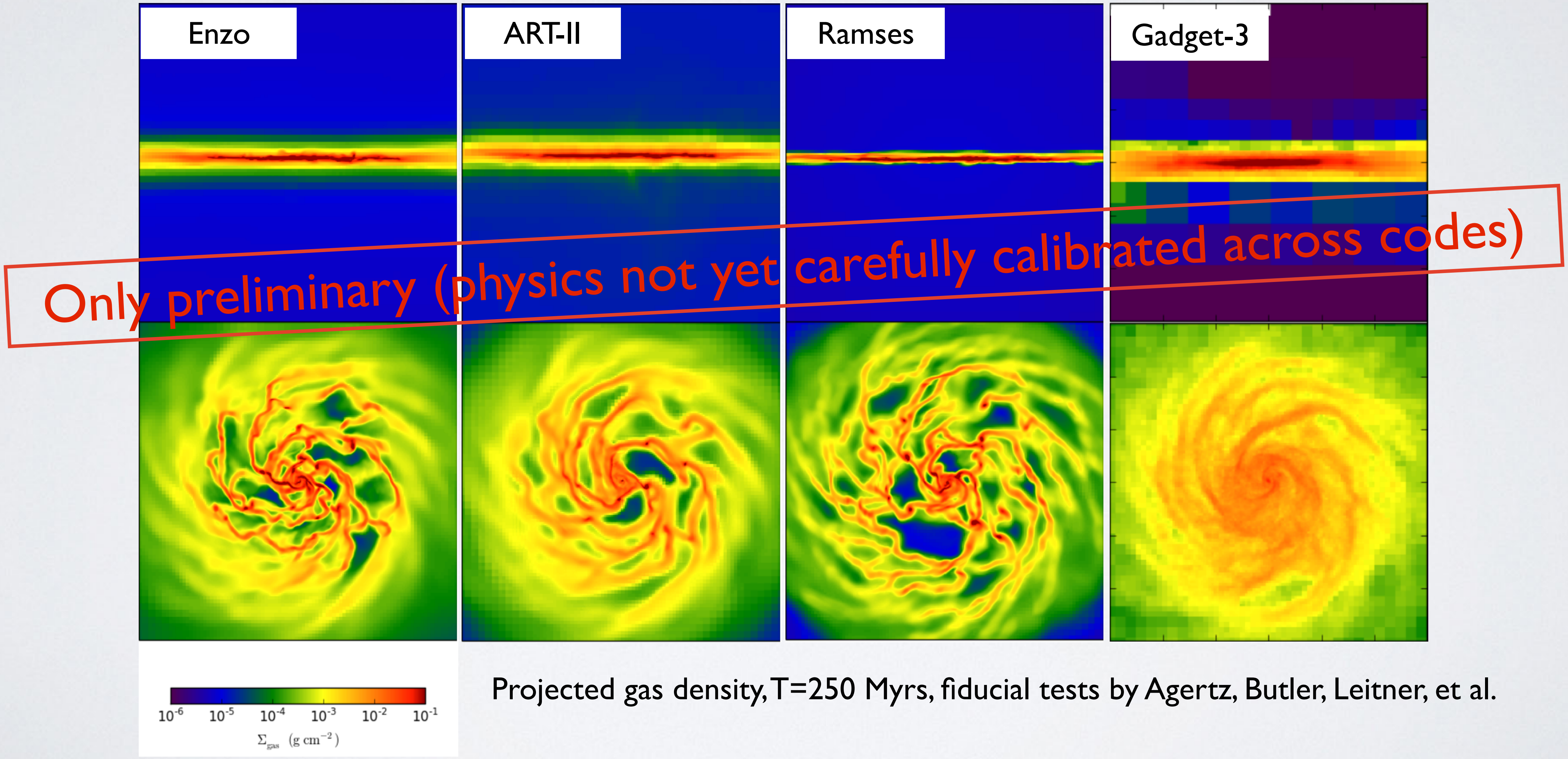




Supplemental Slides

Disk ICs: Built and Running

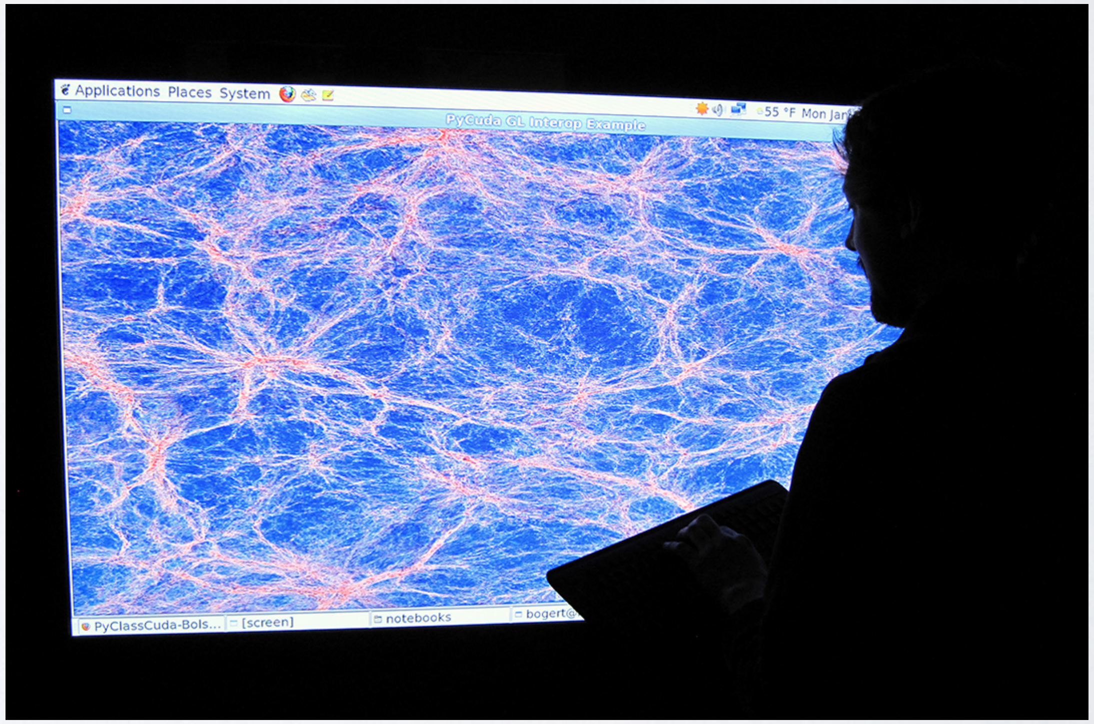
- ICs of a MW-size isolated disk galaxy (built w/ Springel's MakeDisk) now on Project Workspace
  - 4-component galaxy, 3 resolution choices (low/med/high), to be employed in Paper "4"



Projected gas density, T=250 Myrs, fiducial tests by Agertz, Butler, Leitner, et al.

AGORA Analysis Pipeline on NERSC

- AGORA data analysis pipeline using yt has been built on NERSC thanks to Rocha, Bogert, Steffens, Turk, et al.
  - GPU volume rendering possible with yt thanks to Bogert, Turk, et al.
  - Remotely rendered images can be streamed via iPython notebook or flash video streaming (e.g. images rendered on Kepler cards on NERSC, then streamed to your laptop in real time)
  - yt output can also be fed into SUNRISE thanks to Moody, Turk, et al.
  - As AGORA members on NERSC, you don't need to install anything! (Rocha's talk on Sun)



From Bogert et al.'s GTC poster; see WG IV Workspace page for more information

yt-3.0 Just Released: Aug. 4, 2014

- Supports many codes, including all participating in AGORA

… This release of yt features an entirely rewritten infrastructure for data ingestion, indexing, and representation. While past versions of yt were focused on analysis and visualization of data structured as regular grids, this release features full support for particle (discrete point) data such as N-body and SPH data, irregular hexahedral mesh data, and data organized via octrees. This infrastructure will be extended in future versions for high-fidelity representation of unstructured mesh datasets.

Highlighted changes in yt 3.0:
- Units now permeate the code base, enabling self-consistent unit transformations of all arrays and quantities returned by yt.
- Particle data is now supported using a lightweight octree. SPH data can be smoothed onto an adaptively-defined mesh using standard SPH smoothing
- Support for octree AMR codes
- Preliminary Support for non-Cartesian data, such as cylindrical, spherical, and geographical
- Revamped analysis framework for halos and halo catalogs, including direct ingestion and analysis of halo catalogs of several different formats
- Support for multi-fluid datasets and datasets containing multiple particle types
- Flexible support for dynamically defining new particle types using filters on existing particle types or by combining different particle types.
- Vastly improved support for loading generic grid, AMR, hexahedral mesh, and particle without hand-coding a frontend for a particular data format.
- New frontends for ART, ARTIO, Boxlib, Chombo, FITS, GDF, Subfind, Rockstar, Pluto, RAMSES, SDF, Gadget, OWLS, PyNE, Tipsy, as well as rewritten frontends for Enzo, FLASH, Athena, and generic data.
- First release to support installation of yt on Windows
- Extended capabilities for construction of simulated observations, and new facilities for analyzing and visualizing FITS images and cube data
- Many performance improvements

AGORA Mass Storage on NERSC

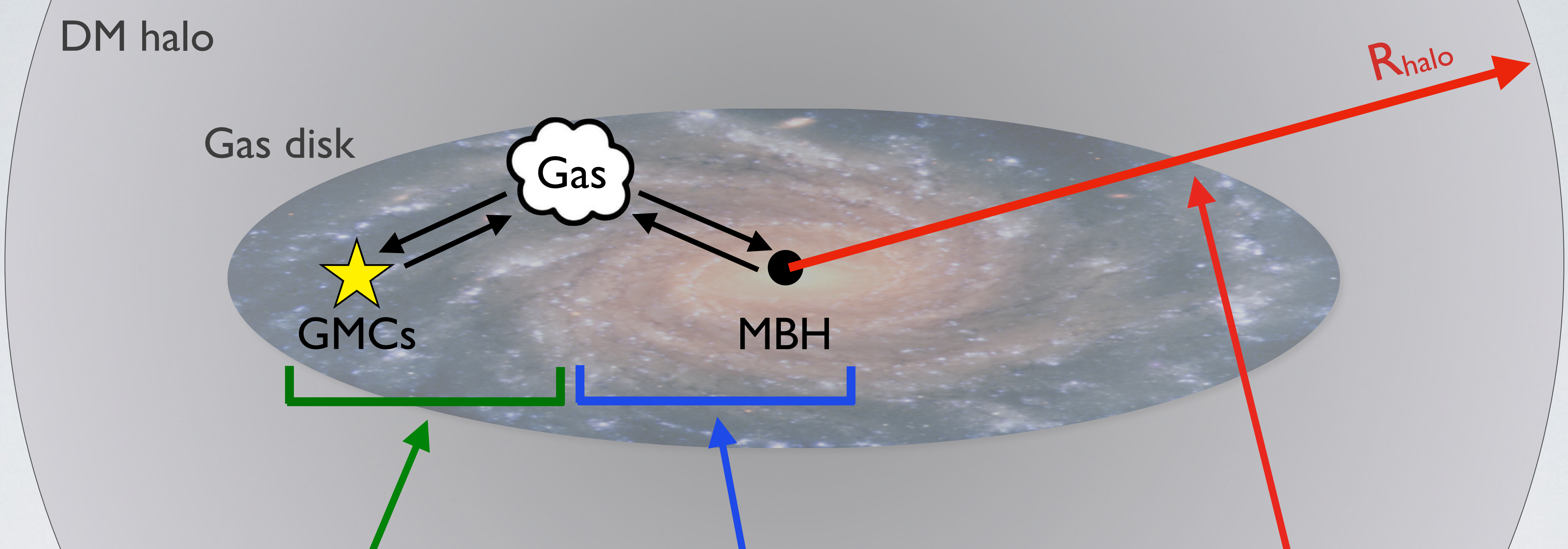
- Data Pilot Program allocation by NERSC (PI: Primack, Madau)

  - To be used as one of the mass storages for AGORA
  - 5M cpu-hours (XT4-equivalent MPP hours for data analysis, mainly with yt and SUNRISE) + 0.6M storage resource units (SRUs) enough to transfer ~100 TB in and out of their HPSS
  - Storage and managing policies have been established since Mar. 2014

Cray XE6 Hopper @NERSC

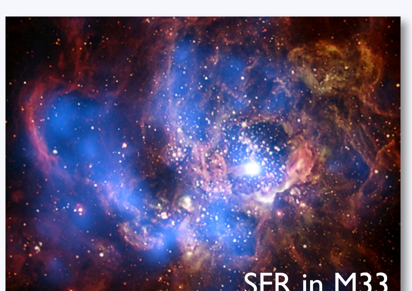
Cray XC30 Edison @NERSC

Galaxy Formation Simulations: Challenge



Star Cluster or GMC Formation & Feedback

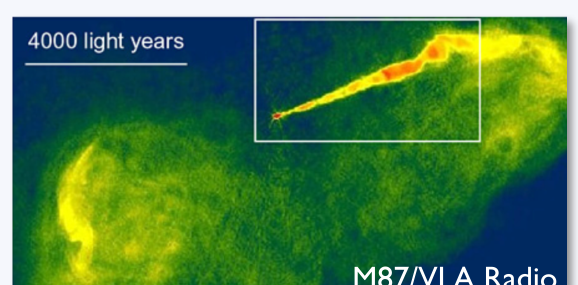
$R_{GMC} \sim 10$ pc



Massive Black Hole (MBH) Accretion & Feedback

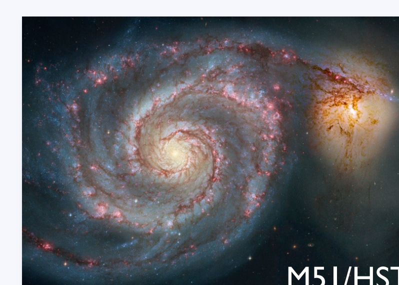
$R_{Bondi} \sim$ pc

$R_{Schw.} \sim$ AU



(Inter-)Galactic Dynamics & Interaction

$R_{halo} \sim 100$ kpc

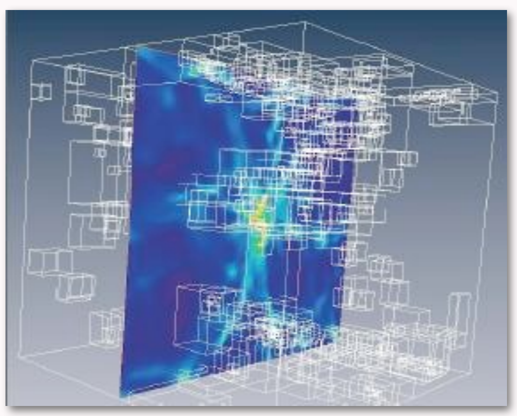


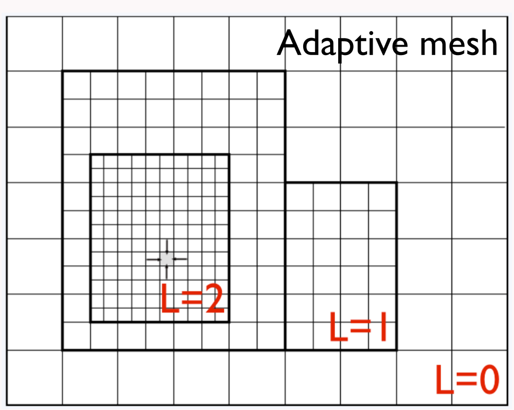
Galaxy Simulation In High-Resolution Era

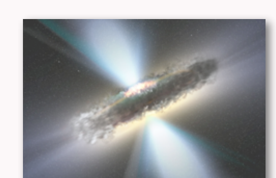
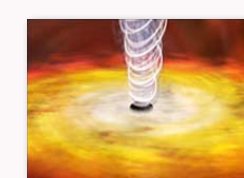
- Build unabridged, self-consistent galaxies from first principles
  → AMR helps to achieve less fine-tuning but more physics

Adaptive Mesh Refinement
ENZO (Bryan et al. 2014)

Includes all the relevant physics for galaxy formation

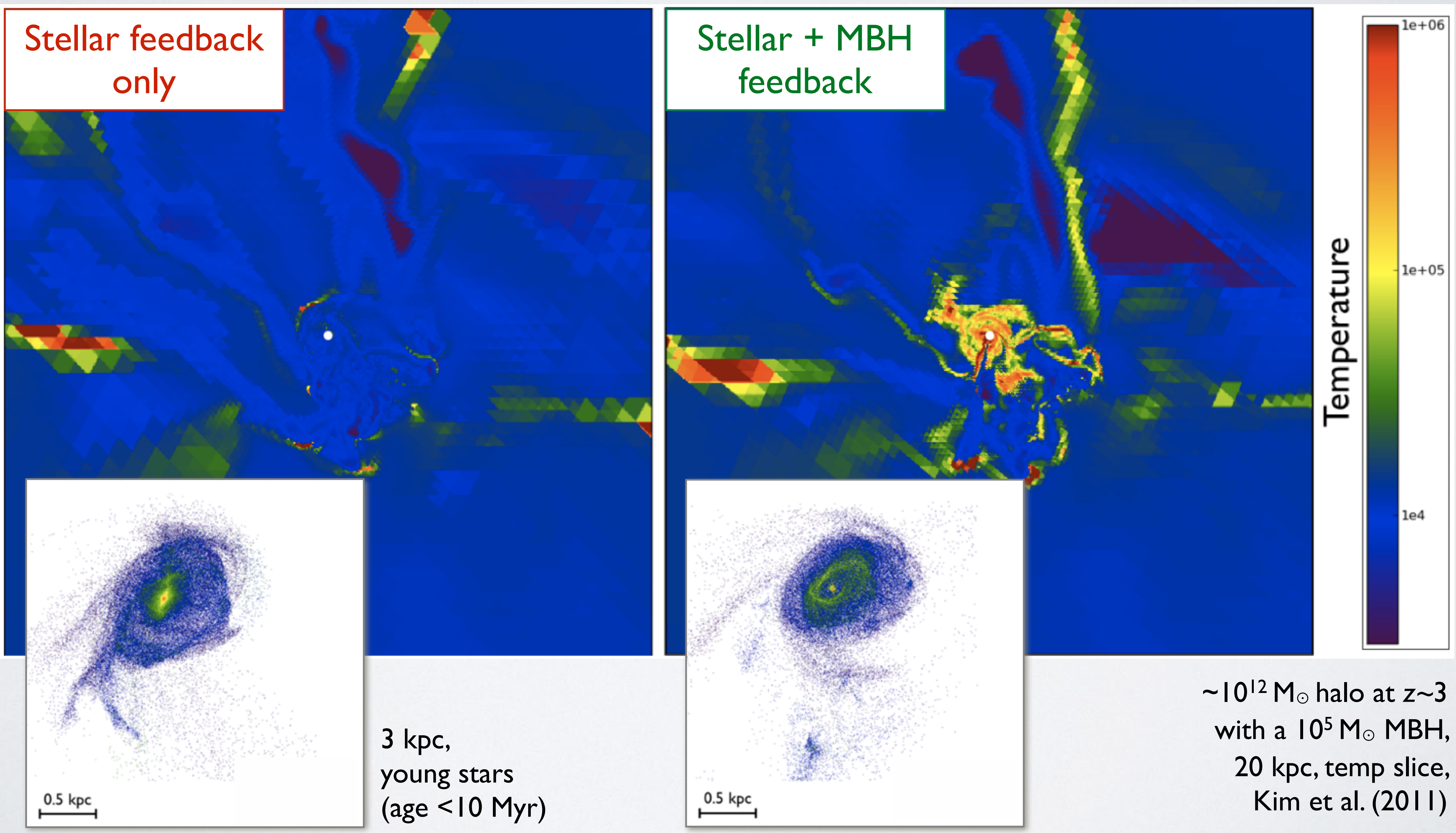




	Star Cluster or GMC Formation & Feedback	Massive Black Hole (MBH) Accretion & Feedback
Previous Work	Insert stars simply by Schmidt law ($\rho_{SFR} \sim \rho_{gas}^{1.5}$)	Artificially boosted Bondi accretion
	Turn off gas cooling or thermal energy	Thermal energy 
New Approach	Insert GMCs when a cell of $\sim 10^3\ M_\odot$ turns Jeans unstable	Bondi accretion without any boost
	UV photons radiative transfer (photoheating & ionization) + Thermal energy	X-ray photons + Bipolar wind  

MBH Radiation Feedback In Galaxy Cores

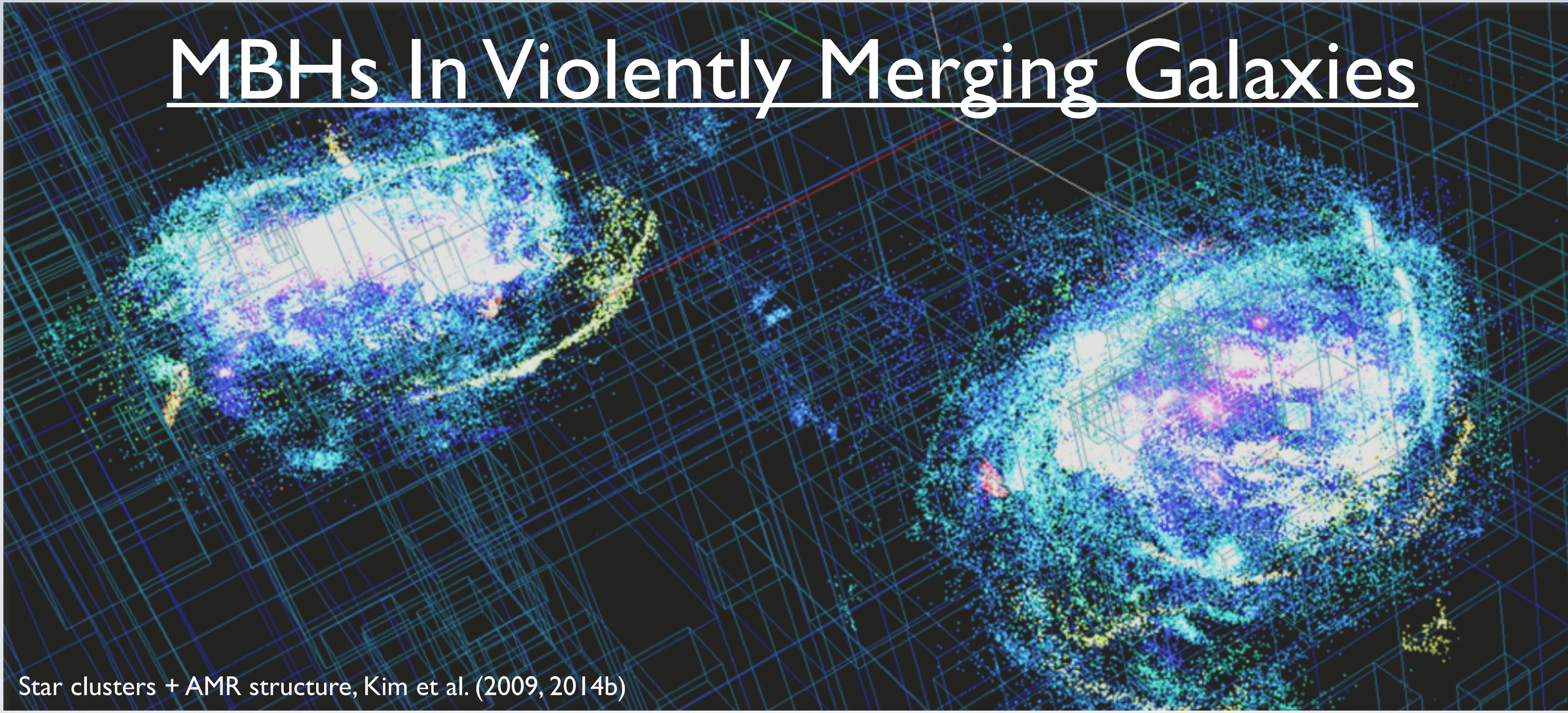
- Photons from MBHs heat up gas by photo- and Compton heating → self-regulate its growth, suppress star formation (Kim et al. 2011)



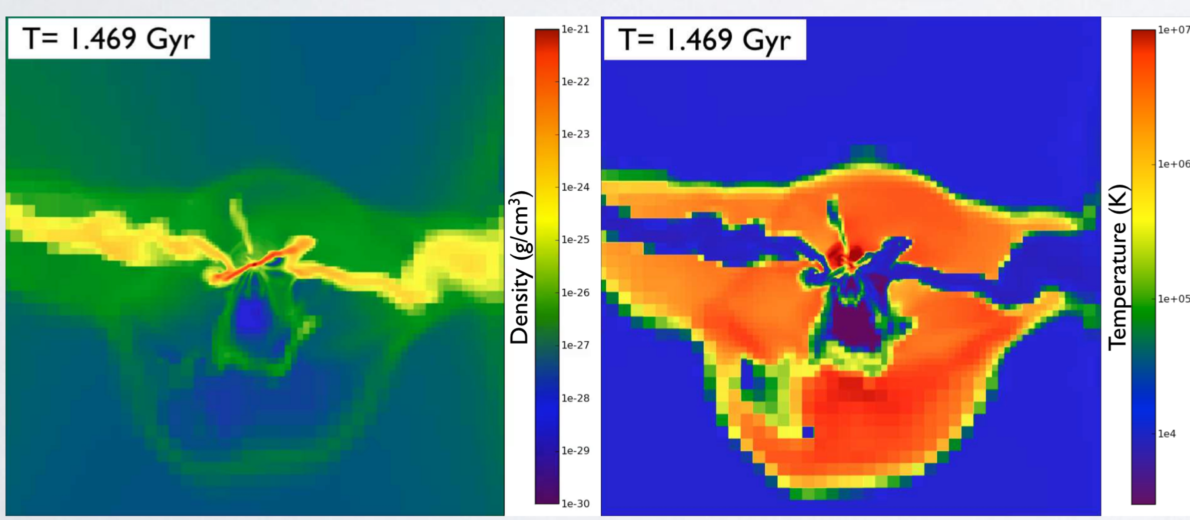
3 kpc, young stars (age <10 Myr)

~10^{12} $M_\odot$ halo at z~3 with a 10^5 $M_\odot$ MBH, 20 kpc, temp slice, Kim et al. (2011)

MBHs In Violently Merging Galaxies



Star clusters + AMR structure, Kim et al. (2009, 2014b)

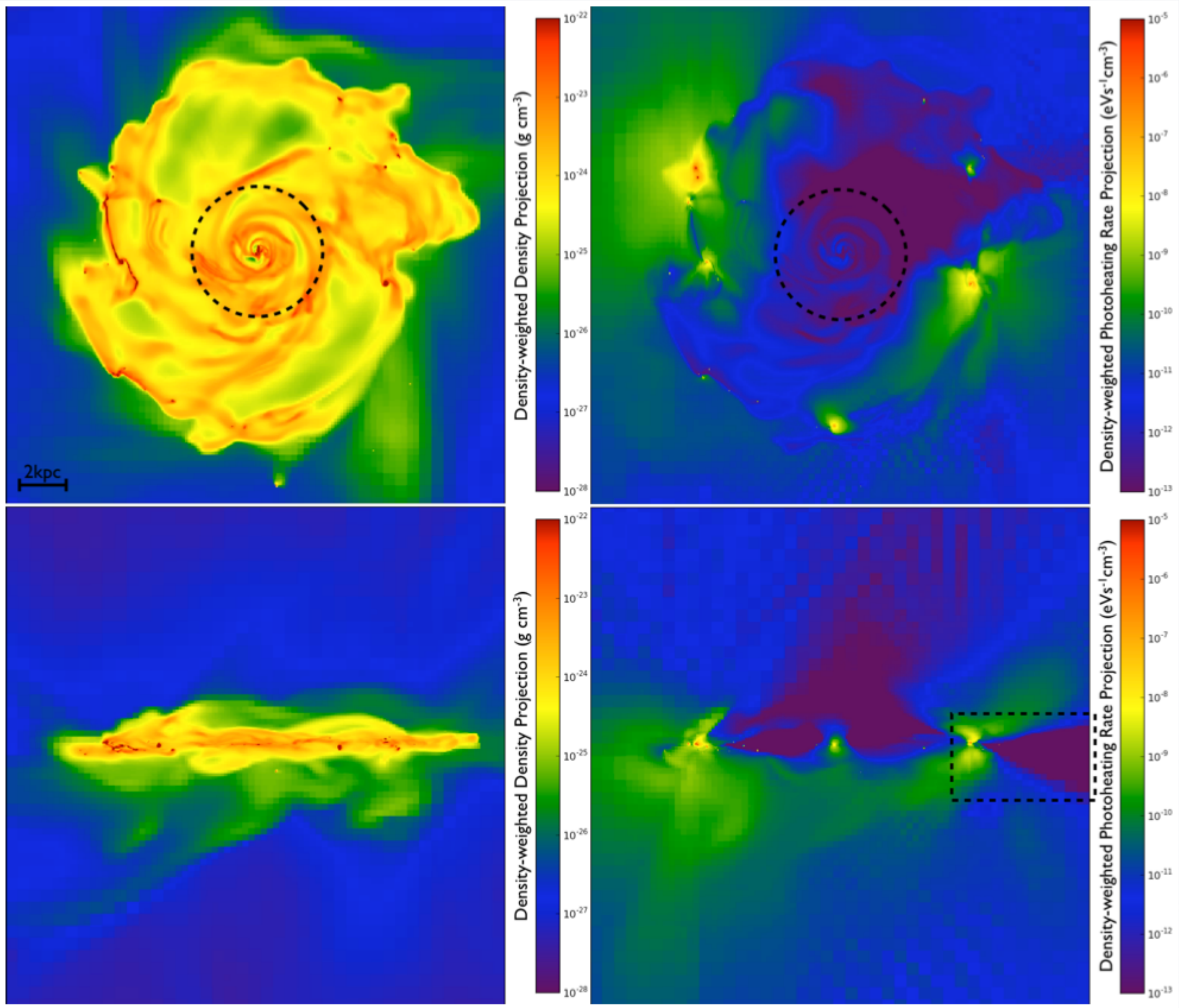


Two 2×10^{11} $M_\odot$ halos w/ 10^6 $M_\odot$ MBHs, 10 kpc, Kim et al. (2014b)

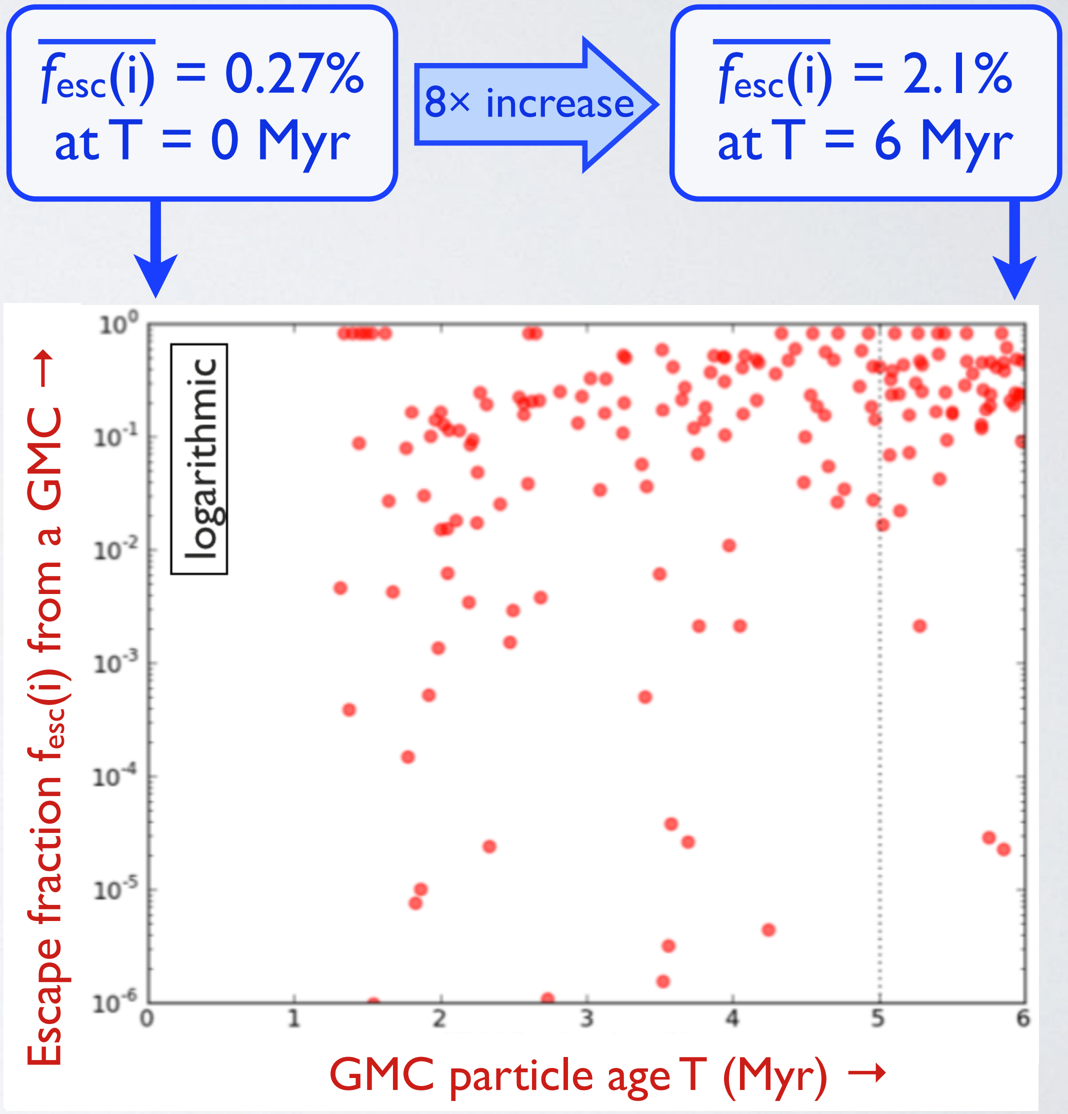
- Merger-induced MBH feedback launches winds (Kim et al. 2014b)
- High-res AMR captures shock-induced SF and disk-halo interplay

Radiating GMCs On A Galactic Disk

- Photons escape easily from old star-forming clumps
  → old clumps dominate galactic escape fraction (Kim et al. 2013a)



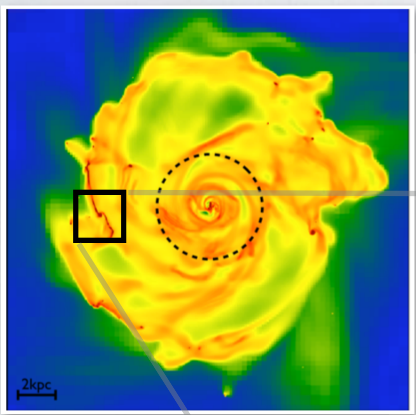
Projected density Projected photoheating rate (eV s^{-1} cm^{-3})



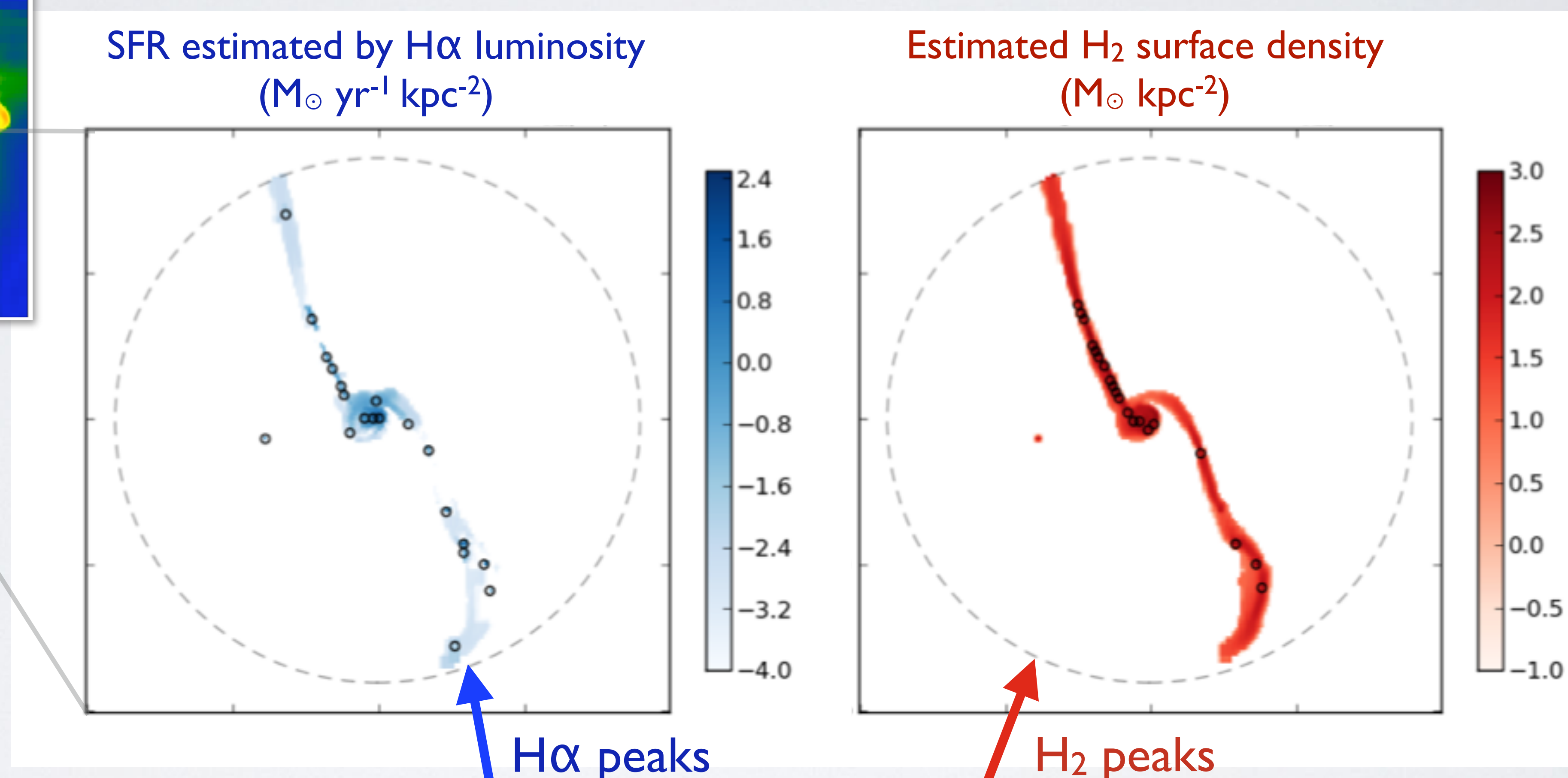
2.3×10^{11} $M_\odot$ halo, 3.8 pc resolution, Kim et al. (2013a)

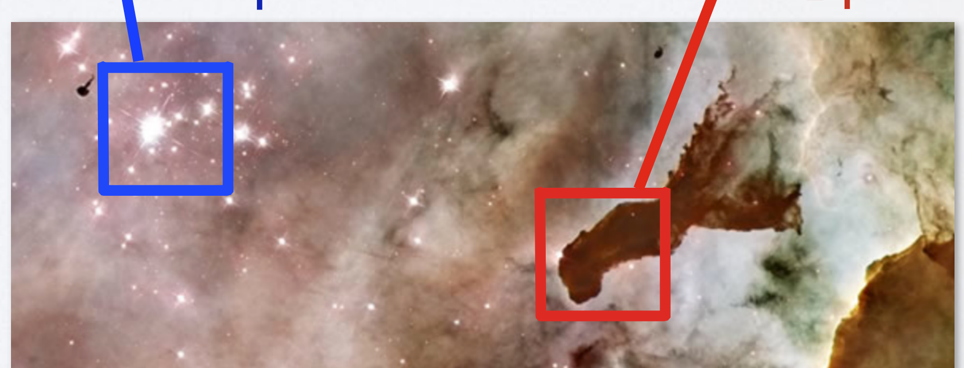
Simulated Observations of Hα and H_2

- Hα and H_2 peaks **don't coincide with apertures of < GMC size**
  → K-S relation breaks down with small aperture (Kim et al. 2013b)



Mock observations with 15 pc aperture, 3 kpc wide, Kim et al. (2013b)





Carina Nebula/HST

Quasar-Hosts With Radiating GMCs/MBHs

- Targets ~7×10^{10} M$_\odot$ halo at z~7.5 with 4.8 proper pc resolution
  → study how high-z quasar and its host galaxy acquire masses