Challenges in Numerical Galaxy Formation and the AGORA Initiative

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Galaxy Formation Simulation

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

![Diagram showing a comparison between simulations with and without feedback and observed galaxies](image-url)
To verify that your success is physical, **compare across platforms**

- **Physics included**
- **No feedback**

**Enzo group**
- Sim-WithFeedback
- Sim-WithoutFeedback

**Gadget group**
- Sim-WithFeedback
- Sim-WithoutFeedback

**Observed Galaxies**

**AGORA Initiative**

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First Attempt: Aquilla Project (2012)

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

Scannapieco et al. 2012

![Image showing various galaxy simulations for different codes and parameters.](www.jihoonkim.org)
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

Einstein Fellows Symposium 2014
AGORA Initiative and Infrastructure

- **Common initial conditions**: cosmological ICs and disk ICs
  - 4 halo masses ($\sim 10^{10,11,12,13} \, M_\odot$ @ $z=0$) + 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

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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

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

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

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

Kim et al. 2014 in prep., high-z quasar host ($7\times10^{10} M_\odot$ @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.)

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

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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](image.png)

**GRACKLE documentation:** grackle.readthedocs.org

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 H₂ and HD, including H₂ 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).

GRACKLE Gas cooling, Kim et al. 2014

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AGORA Proof-of-Concept and Beyond

- Flagship paper with Dark Matter-only PoC tests (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

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

$\sim 10^{12} M_\odot$ 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)

<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>WG I  –  Common Physics and Introduction to Project</td>
<td>WG V  –  Isolated Galaxies and Subgrid Physics</td>
</tr>
<tr>
<td>WG II –  Common ICs: Isolated</td>
<td>WG VI –  Dwarf Galaxies in Cosmological Simulations</td>
</tr>
<tr>
<td>WG III –  Common ICs: Cosmological</td>
<td>WG VII –  Dark Matter</td>
</tr>
<tr>
<td>WG IV –  Common Analysis</td>
<td>WG VIII –  Satellite Galaxies</td>
</tr>
<tr>
<td></td>
<td>WG IX –  Characteristics of Cosmological Galaxies</td>
</tr>
<tr>
<td></td>
<td>WG X –  Galactic Outflows</td>
</tr>
<tr>
<td></td>
<td>WG XI –  High-redshift Galaxies</td>
</tr>
<tr>
<td></td>
<td>WG XII –  Interstellar Medium</td>
</tr>
<tr>
<td></td>
<td>WG XIII –  SMBH Accretion and Feedback</td>
</tr>
</tbody>
</table>

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.
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”

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

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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
Galaxy Formation Simulations: Challenge

- Star Cluster or GMC Formation & Feedback
  - $R_{\text{GMC}} \sim 10$ pc
  - SFR in M33

- Massive Black Hole (MBH) Accretion & Feedback
  - $R_{\text{Bondi}} \sim \text{pc}$
  - $R_{\text{Schw.}} \sim \text{AU}$
  - M87/VLA Radio

- (Inter-)Galactic Dynamics & Interaction
  - $R_{\text{halo}} \sim 100$ kpc
  - M51/HST

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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

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<table>
<thead>
<tr>
<th>Previous Work</th>
<th>Star Cluster or GMC Formation &amp; Feedback</th>
<th>Massive Black Hole (MBH) Accretion &amp; Feedback</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Insert stars simply by Schmidt law ($\rho_{\text{SFR}} \sim \rho_{\text{gas}}^{1.5}$)</td>
<td>Artificially boosted Bondi accretion</td>
</tr>
<tr>
<td></td>
<td>Turn off gas cooling or thermal energy</td>
<td>Thermal energy</td>
</tr>
</tbody>
</table>

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<tr>
<th>New Approach</th>
<th>UV photons radiative transfer (photoheating &amp; ionization) + Thermal energy</th>
<th>Bondi accretion without any boost</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Insert GMCs when a cell of $\sim 10^3 \ M_\odot$ turns Jeans unstable</td>
<td>X-ray photons + Bipolar wind</td>
</tr>
</tbody>
</table>

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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)

Stellar feedback only

Stellar + MBH feedback

~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

Two $2 \times 10^{11} \, M_\odot$ 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

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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 and photoheating rate](image)

**Escape fraction** $f_{\text{esc}}(i)$ from a GMC:

- $f_{\text{esc}}(i) = 0.27\%$ at $T = 0$ Myr
- $f_{\text{esc}}(i) = 2.1\%$ at $T = 6$ Myr

$8 \times$ increase from $2.3 \times 10^{11} M_\odot$ halo, 3.8 pc resolution, Kim et al. (2013a)

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Simulated Observations of H\(\alpha\) and H\(_2\)

- H\(\alpha\) 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 $\sim 7 \times 10^{10} M_\odot$ halo at $z \sim 7.5$ with 4.8 proper pc resolution
  → study how high-z quasar and its host galaxy acquire masses