Computational Astrophysics in South Africa

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with Multi-wavelength Data
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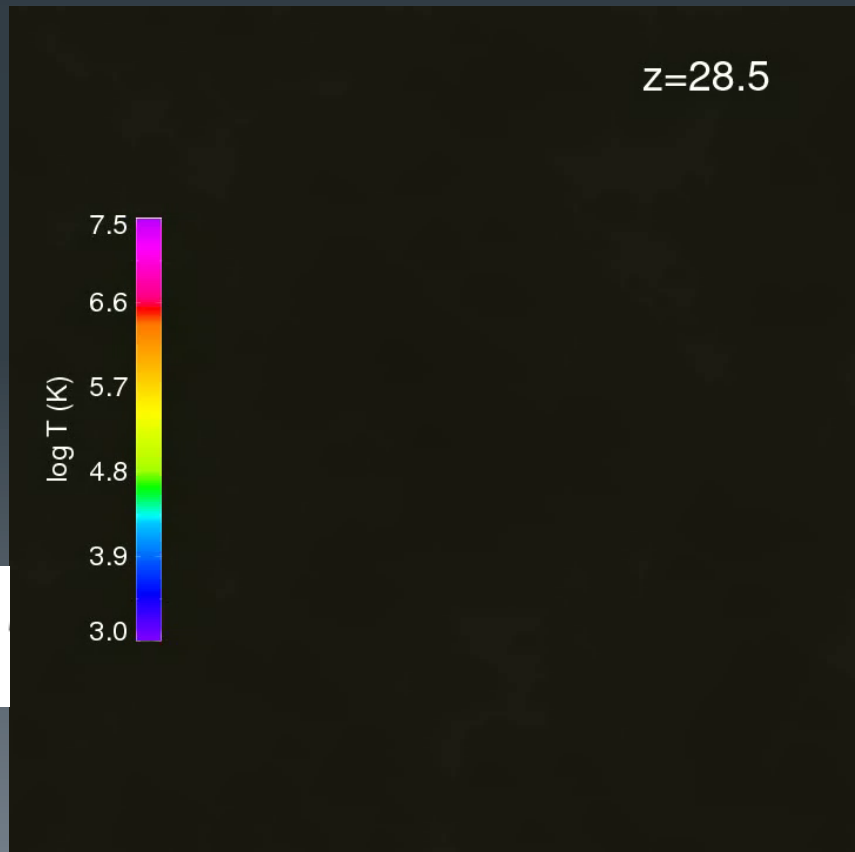
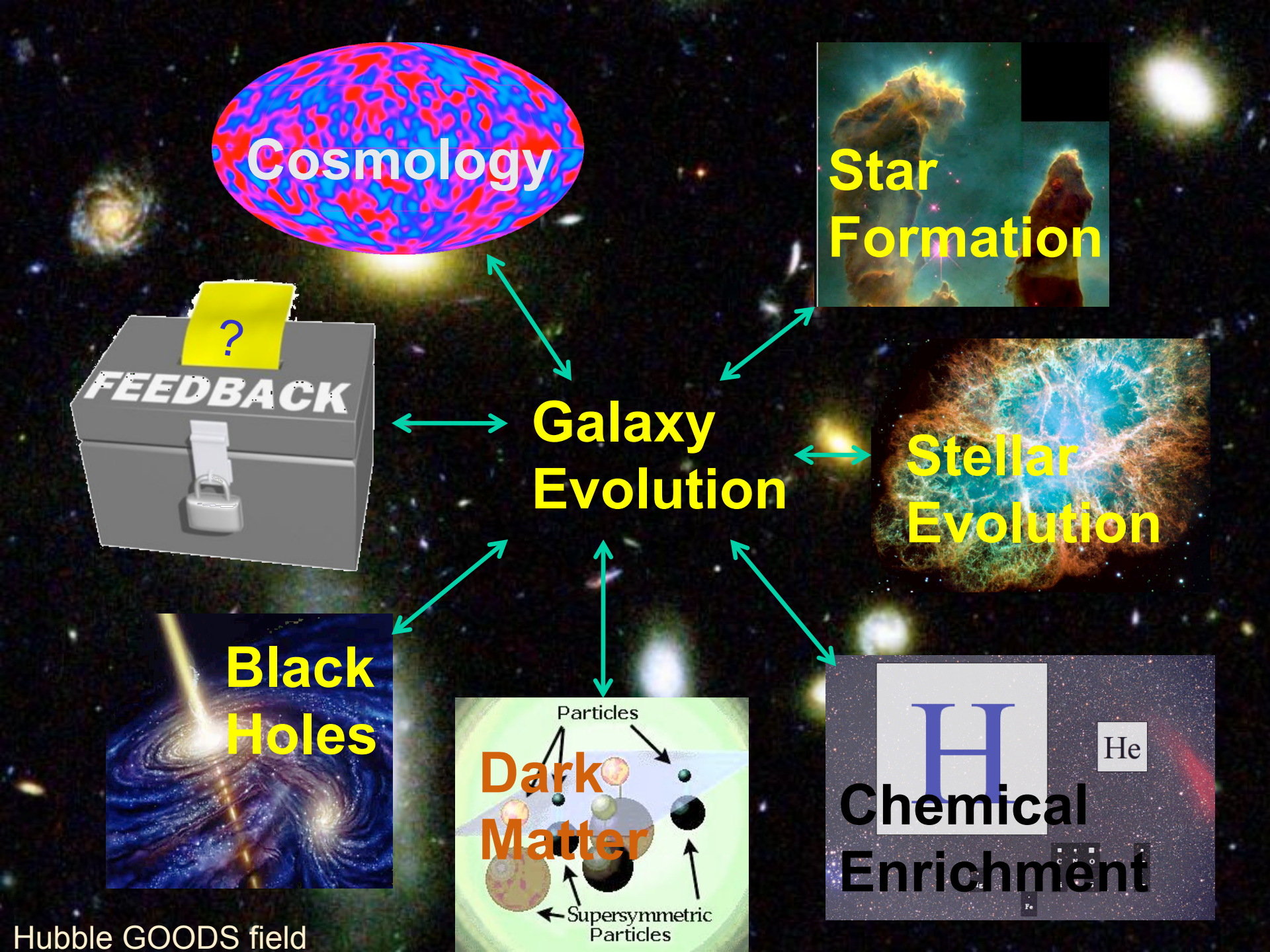


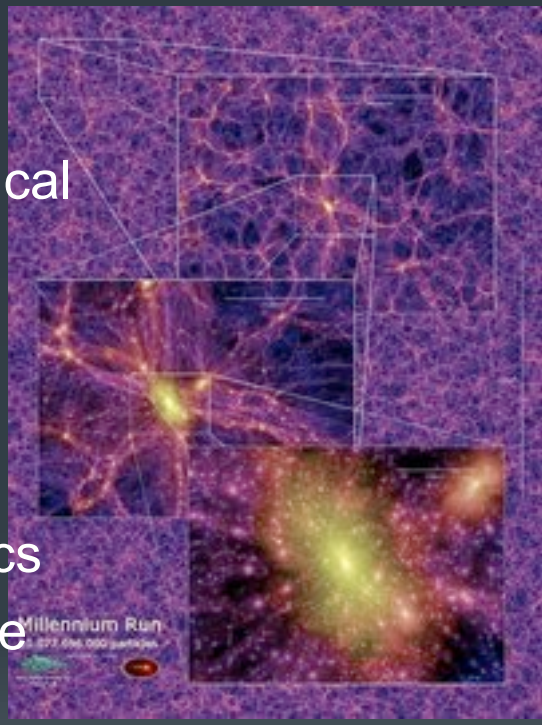
The diverse evolution of galaxies: Can we reproduce this on a computer?

Hubble Space Telescope: The GOODS Survey


Cosmology
Star Formation
?
FEEDBACK
Galaxy Evolution
Stellar Evolution
Black Holes
Particles
Dark Matter
Supersymmetric Particles
H
He
Chemical Enrichment
Hubble GOODS field

Simulations of Galaxy Formation and Cosmology

- Multi-physics:
  - Direct: Gravity, pressure, shocks, cooling & heating
  - "Sub-grid": Star formation, black hole growth, chemical enrichment, *feedback* (BH, SNe, CR, …)
  - Optional: Radiative transfer, magnetic fields, conduction, cosmic rays
- Multi-scale:
  - "Cosmological" – Representative volume for statistics
  - "Zoom" – Individual object(s) within in cosmo volume
  - "Isolated" – Single object for controlled experiments
- Typical production runs take several months on hundreds of cores. Need ~dozens+ of runs.
- Sophisticated in-house analysis suites to extract predictions in a range of wavelengths.

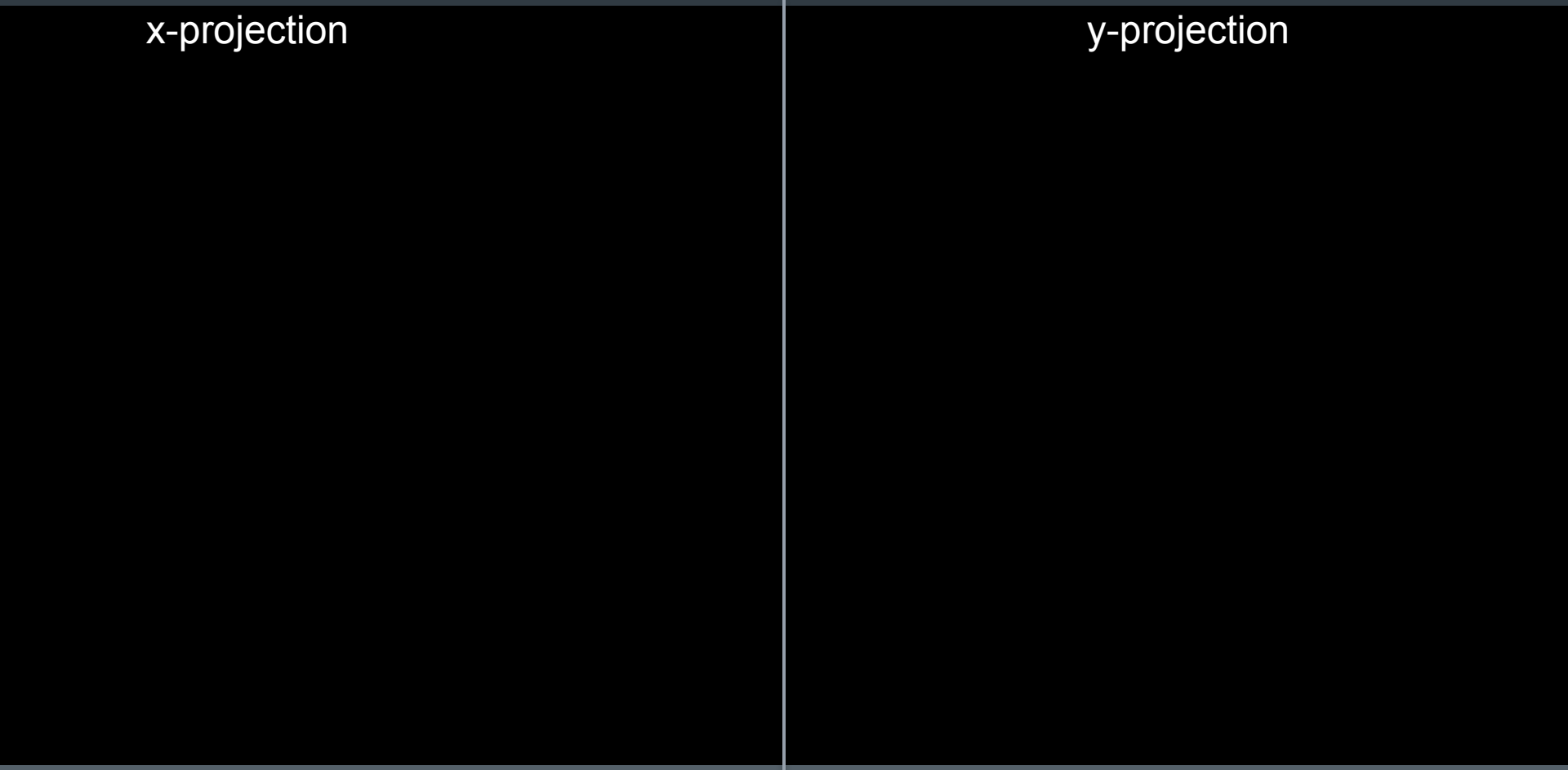


Why Numerical Simulations?

- *A robust and valued tool to study emergent phenomena*
  - Can model (formally) complex astrophysical systems
  - Rapid improvement input physics, algorithms, & hardware
- *Helps maximize science from observational facilities.*
  - Synthesize data into a coherent physical scenarios.
  - Provide testable predictions to discriminate hypotheses.
  - Guide key science questions for observations.
- *When I first came to SA in 2010:*
  - Very few groups doing numerical astrophysics.
  - No internationally competitive computing facilities.
- *Today:*
  - Many computational groups -- cosmology, galaxy formation, stars.
  - Strong investment in Big Data and machine learning.
  - Many universities have substantial local computing, plus CHPC.


GPU cluster @CHPC

Galaxy Growth in the Cosmic Web



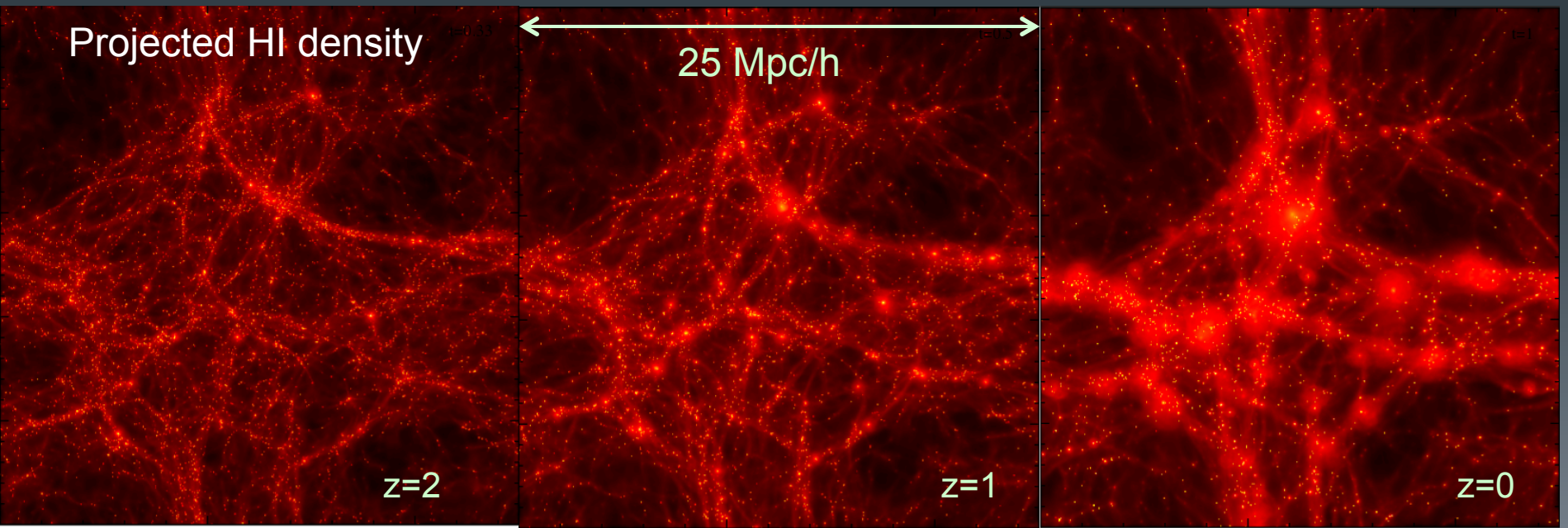
Stellar growth within LSS: color-coded by *urk*.

movie by B. Oppenheimer

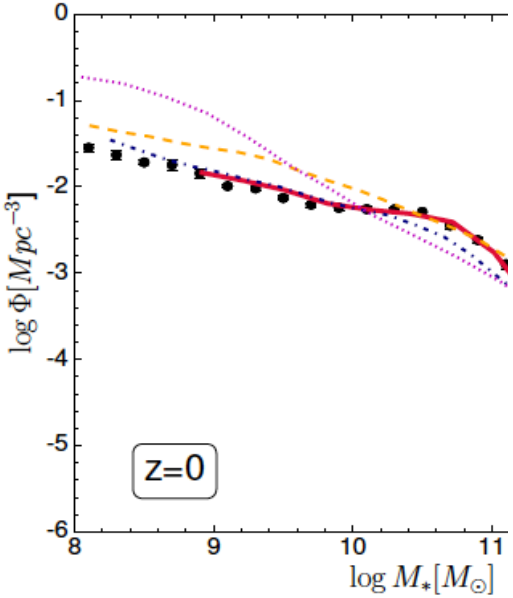
MUFASA: South Africa's Galaxy Formation Simulations

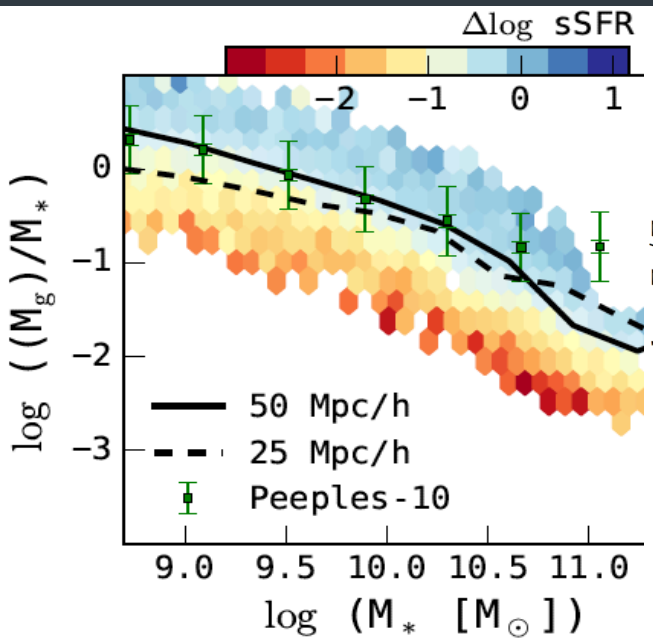
RD et al 2016,2017a,b
Rafieferantsoa+17

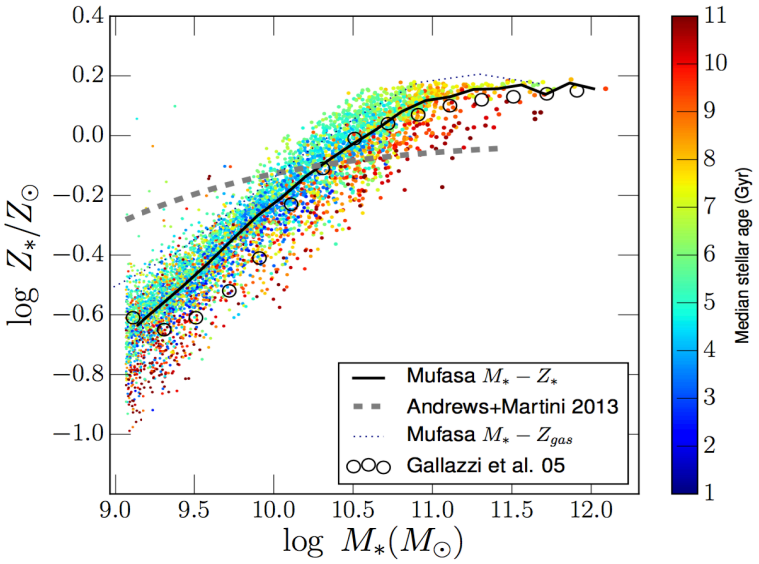
- Modern "meshless" hydro solver Gizmo handles instabilities better
- Star formation based on tracking molecular gas
- Chemical enrichment tracking 9 metals from SNII, SNIa, AGB stars
- Stellar feedback based on recipes taken from high-resolution individual galaxy simulations from the FIRE project
- Black hole growth and AGN feedback that quenches galaxies

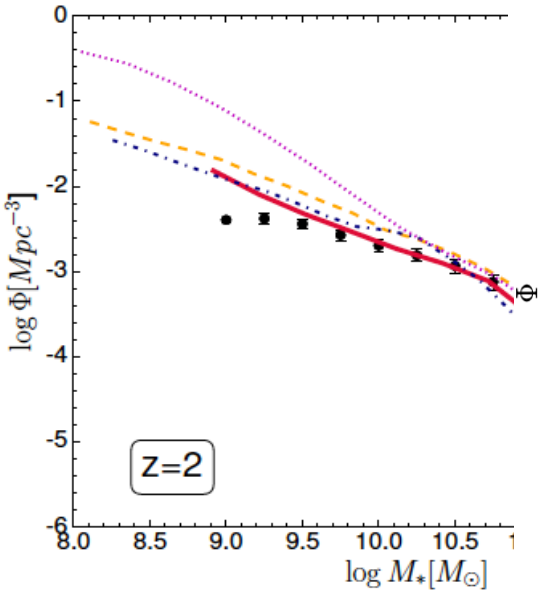


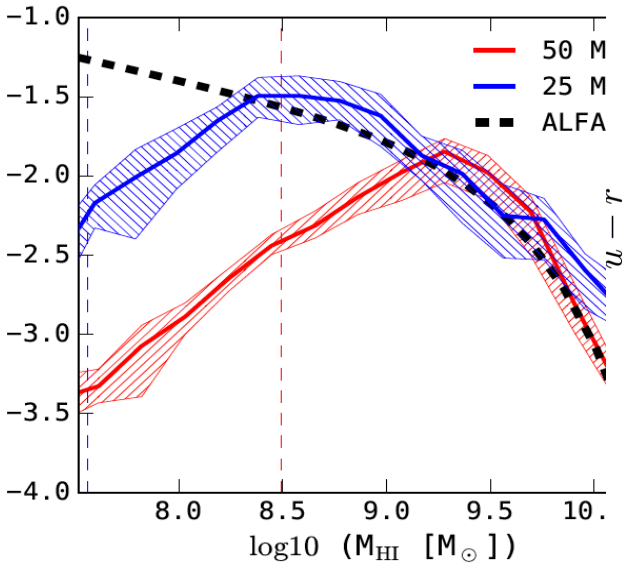
MUFASA matches many observations
(but far from all!)

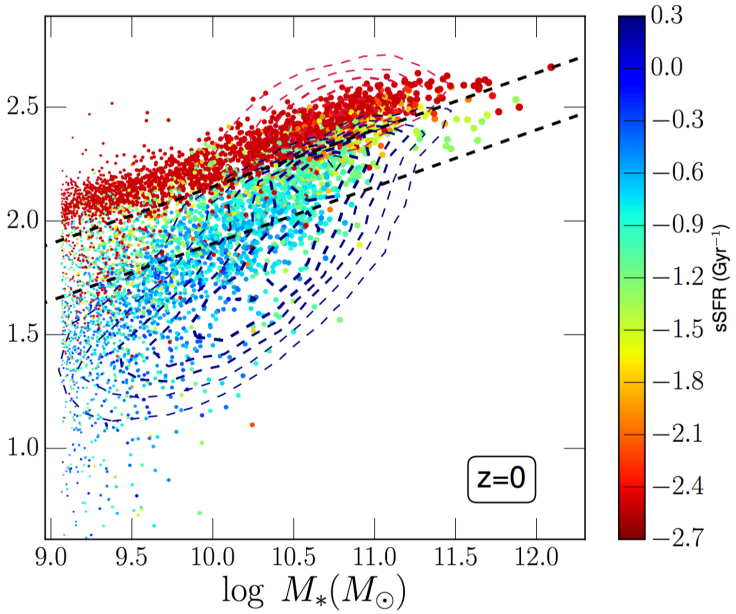






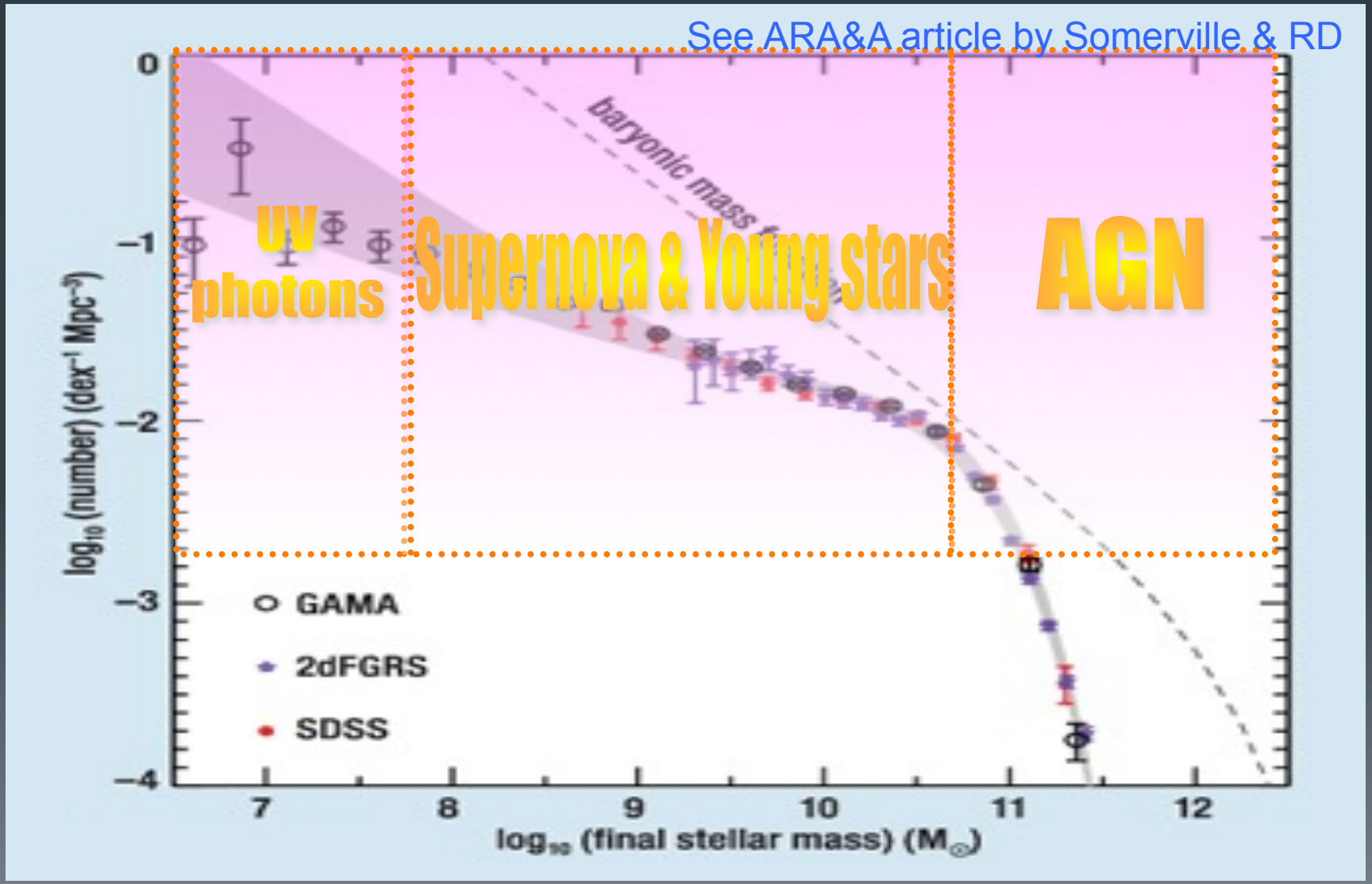






Inefficient Galaxy Formation: The Physics of Feedback

See ARA&A article by Somerville & RD

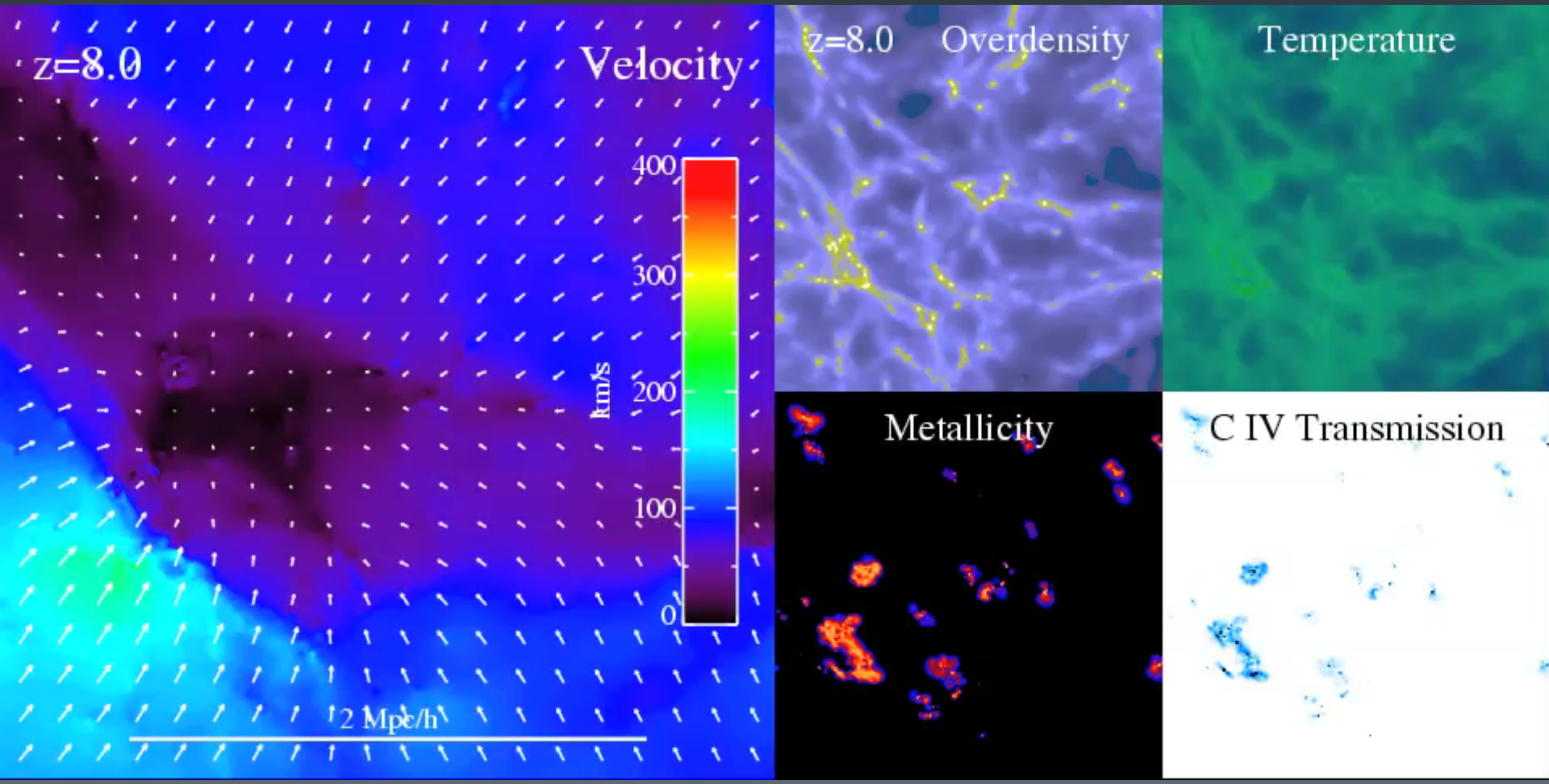


Open Questions

- Supernova feedback:
  - How does energy couple to drive gas out of galaxies?
  - What is the role of momentum vs energy input?
  - Is this enough? (no…)
- Other stellar feedback:
  - Radiation pressure from OB stars?
  - Stellar winds and pulsating stars?
  - Cosmic rays? Magnetic fields? Unknown unknown?
- AGN feedback:
  - How does accretion translate into energy output?
  - Disk winds (radiation-driven) vs. jets (energy/magnetic-driven)?
  - Interplay between star formation and AGN feedback?

New tools, new physics, new hardware!

The Baryon Cycle: Gas Inflows and Outflows



SKA is crucial for characterizing the HI reservoir that traces the baryon cycle

Zooming in to small scales

- "Zoom" simulations: Follow an individual halo within a full cosmological volume at much higher resolution
- Can implement more detailed stellar & ISM models to connect cosmology to small scale feedback physics.

FIRE: "Feedback in Realistic Environments" simulations (Hopkins+14)

Synergy with Multi-wavelength data

- Advanced toolkits to make multi-λ predictions:
  - X-ray: *pyxsim & soxs (J. ZuHone, yt team)*
  - UV/optical/near-IR emission: *loser (R. Davé)*
  - UV/optical absorption: *pygad (B. Roettgers)*
  - Far-IR: *powderday (D. Narayanan)*
  - Millimetre (CO, CII, etc): *SIGAMÉ (K. Olsen)*
  - Radio (HI & continuum data cubes): ??? *(IDIA?)*
- Surveys: CANDELS, COS-Halos, LADUMA, …

M31: X-rays | UV | Optical | Mid-IR | Far-IR | Radio

Summary

- *Simulations are of growing importance in astronomy; essential to maximize science output from telescopes.*
- *South Africa gaining steam in computation & related areas.*
- *Multi-wavelength data/theory synergy is crucial; SA to play a major role with MeerKAT/SKA & SALT.*
- *MUFASA provides an internationally competitive simulation platform for studying galaxy formation.*
- *Understanding galaxy self-regulation via the baryon cycle is the main open question. What role will SA play?*
- *User-friendly analysis codes means that you don't have to be a code ninja to use simulation data – ask if interested!*