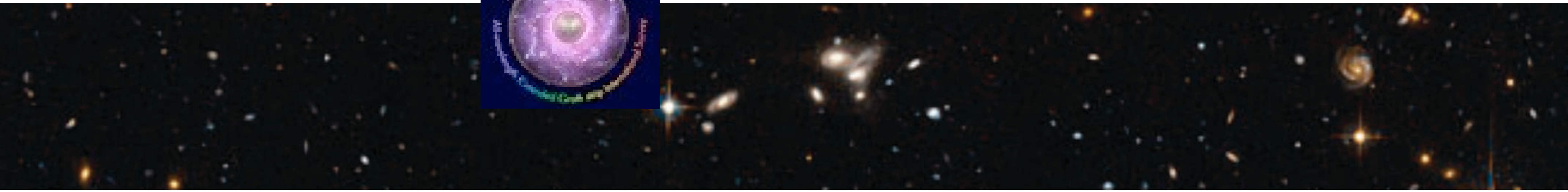

Galaxy Hydrodynamic Simulations and *Sunrise* Visualizations

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Galaxy Hydrodynamic Simulations

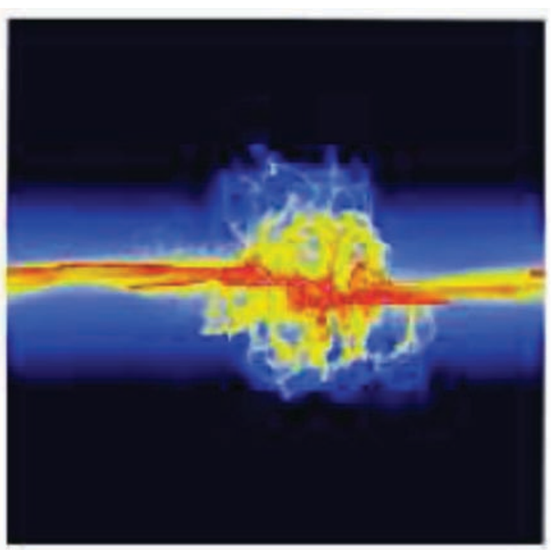
Galaxy formation is so complicated that observations and theory cannot give us a clear picture of how galaxies form without working hand-in-hand. Fortunately, new observations at $z > 1.5$ are clarifying the processes by which most of the stars in the universe formed, and at $z < 1.5$ how present-day galaxies assembled. And observations are finally closing in on the ΛCDM cosmological parameters, so that we have a definite cosmological framework within which to model galaxies.

We have run ~20 high-resolution cosmological hydrodynamic simulations of galaxy formation and evolution, and we are now gearing up to run hundreds more so that we can have a statistical sample of such simulations. We use our *Sunrise* code to model stellar evolution and radiative transfer through dusty galaxies, in order to produce realistic images in all accessible wavebands.

Galaxy Hydrodynamic Simulations

We are using the Hydro Adaptive Refinement Tree (hydroART) code, currently the most efficient of the three Adaptive Mesh Refinement (AMR) codes used for high-resolution galaxy simulations. The other AMR codes are ENZO and RAMSES. We will also be doing a high-resolution galaxy simulation comparison project using all three of these codes with the same initial conditions, and perhaps also the Gasoline, Gadget, and AREPO Smooth Particle Hydrodynamics (SPH) codes.

The resolution of our hydroART galaxy cosmological sims is 35-70 pc, with higher resolution studies of subregions as shown below.



Gas column density in a galactic chimney, which reaches T~10^8 K with outflow velocities >10^3 km/s. The volume is a 4 kpc cube, with 8-16 pc resolution. (From Ceverino & Klypin 2009.)

Galaxy Hydrodynamic Simulations

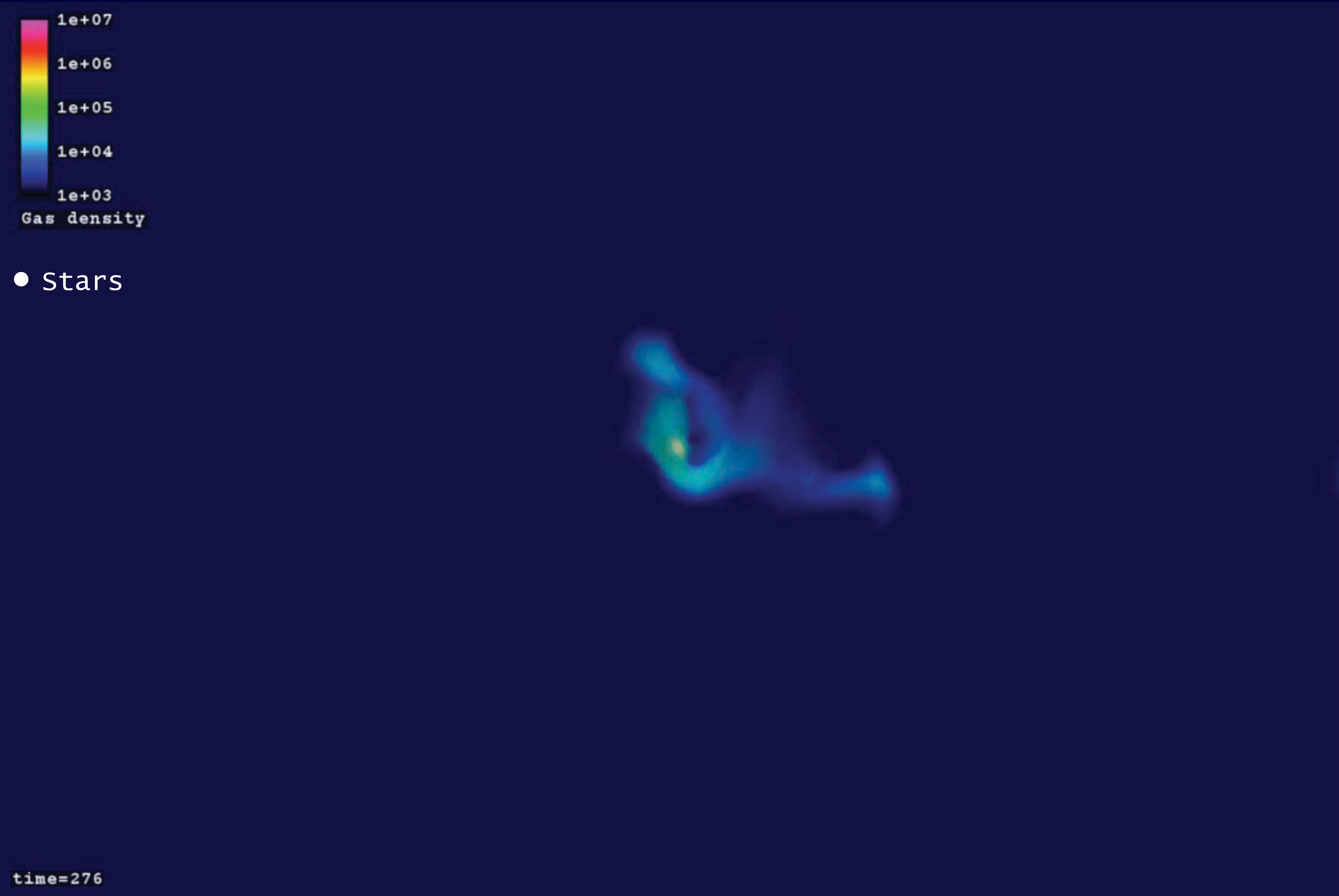
Physical phenomena included in ART simulations analyzed thus far:

Dark matter and baryons, metal and molecular hydrogen cooling to ~100K, UV background with self-shielding, star formation, energy input from stellar winds and supernovae, advection of metals.

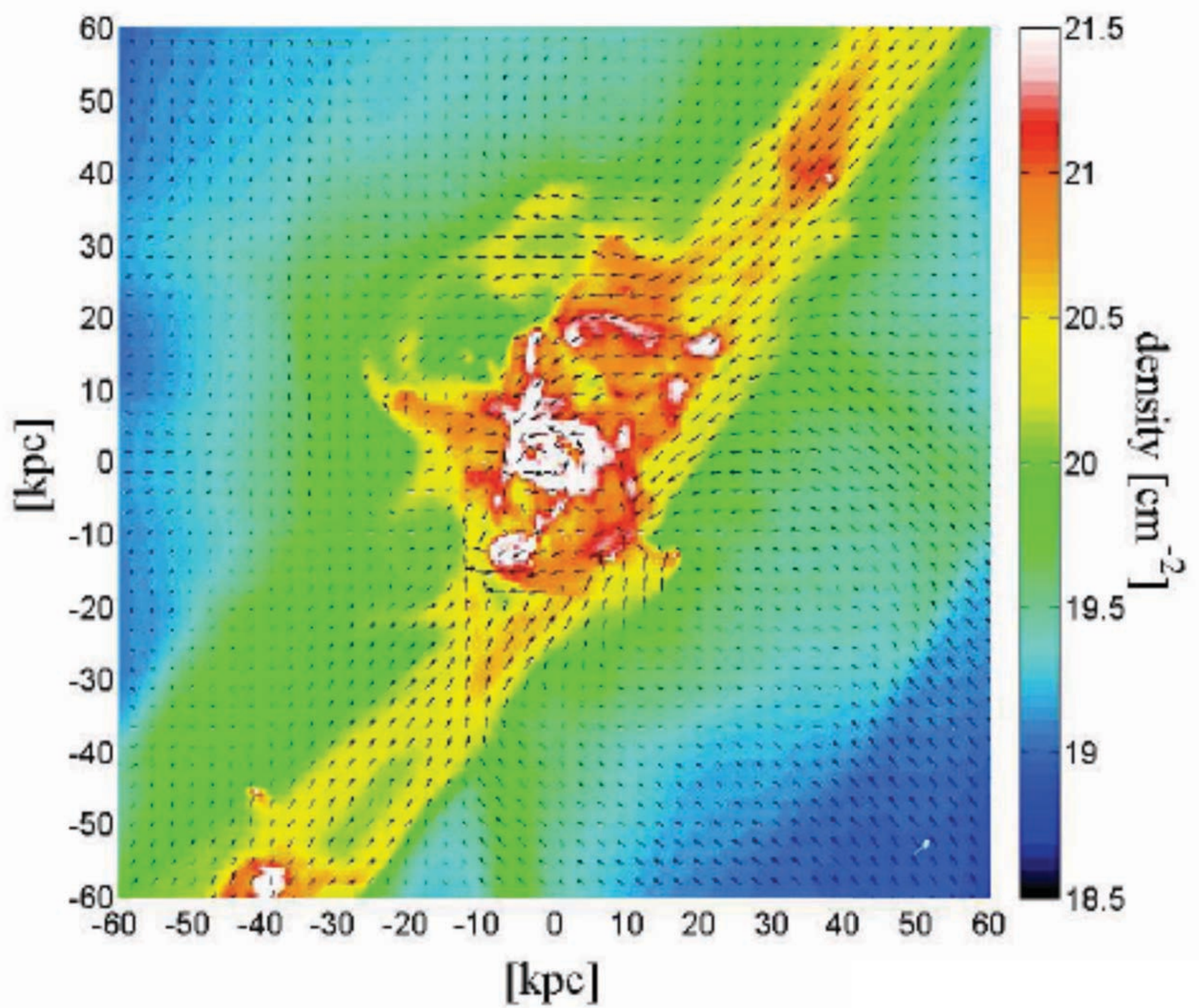
See Ceverino & Klypin 2009; Dekel, Sari, & Ceverino 2009; Ceverino, Dekel, & Bournaud 2010; Goerdt, Dekel, Sternberg, Ceverino, Teyssier, & Primack 2010; Fumagalli, Prochaska, Kasen, Dekel, Ceverino, & Primack 2011; Ceverino, Dekel, Mandelker, Bournaud, Burkert, Genzel, & Primack 2011; Kasen et al. 2011 and other papers in preparation.

Additional phenomena included in ART simulations currently running:

Radiative feedback from luminous stars and from AGN.


1e+07
1e+06
1e+05
1e+04
1e+03
Gas density
Stars
time=276

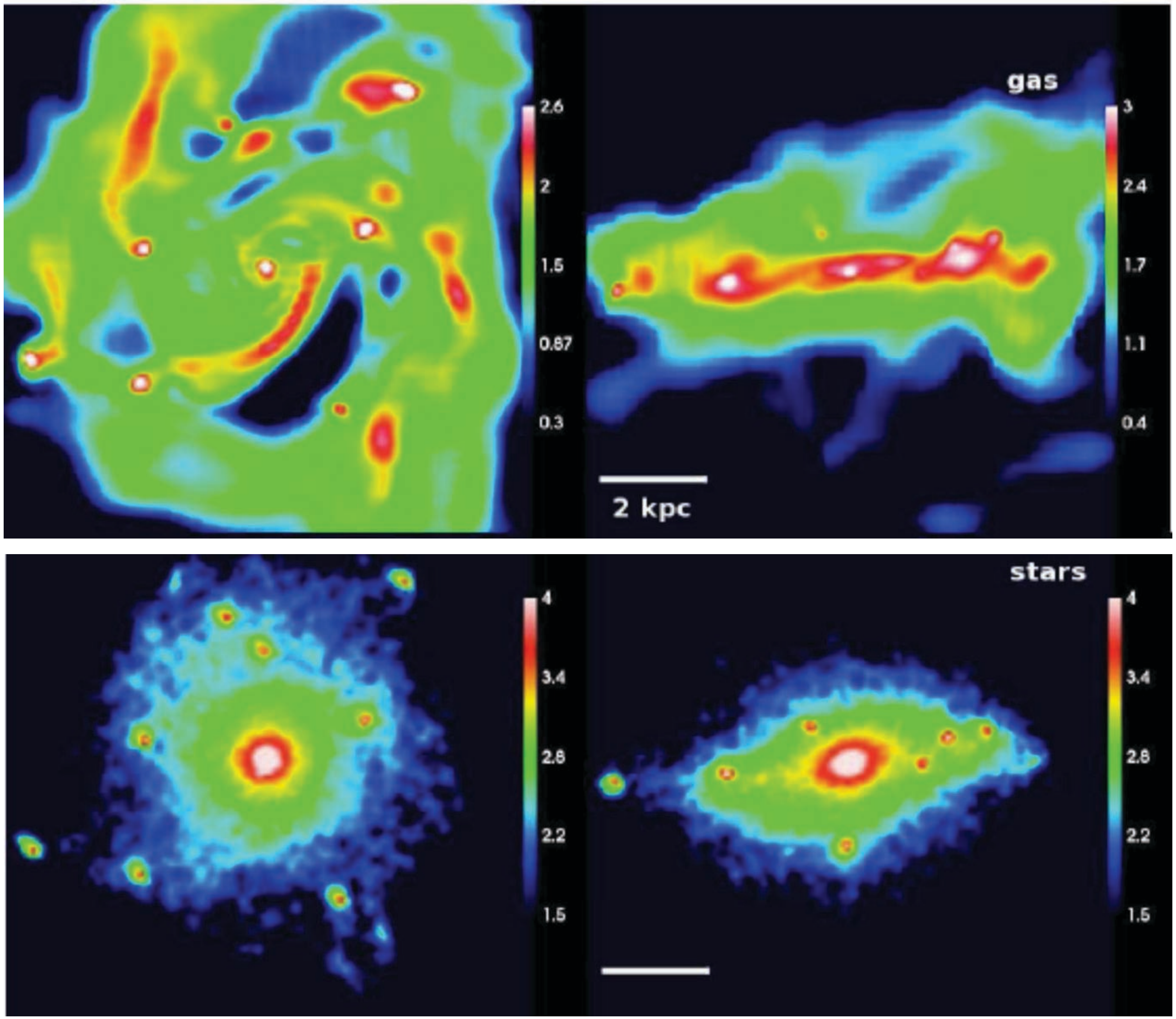
Galaxy Hydrodynamic Simulations



Gas surface density and projected velocity field within the halo of simulated galaxy A at $z = 2.3$. Long streams of cold gas and merging galaxies feed a central rotating disc through a messy interphase region. Arrows represent the velocity field (white arrow is 200 km/s). (From Ceverino et al. 2011, to be submitted this week.)

Galaxy Hydrodynamic Simulations

Face-on view Edge-on view

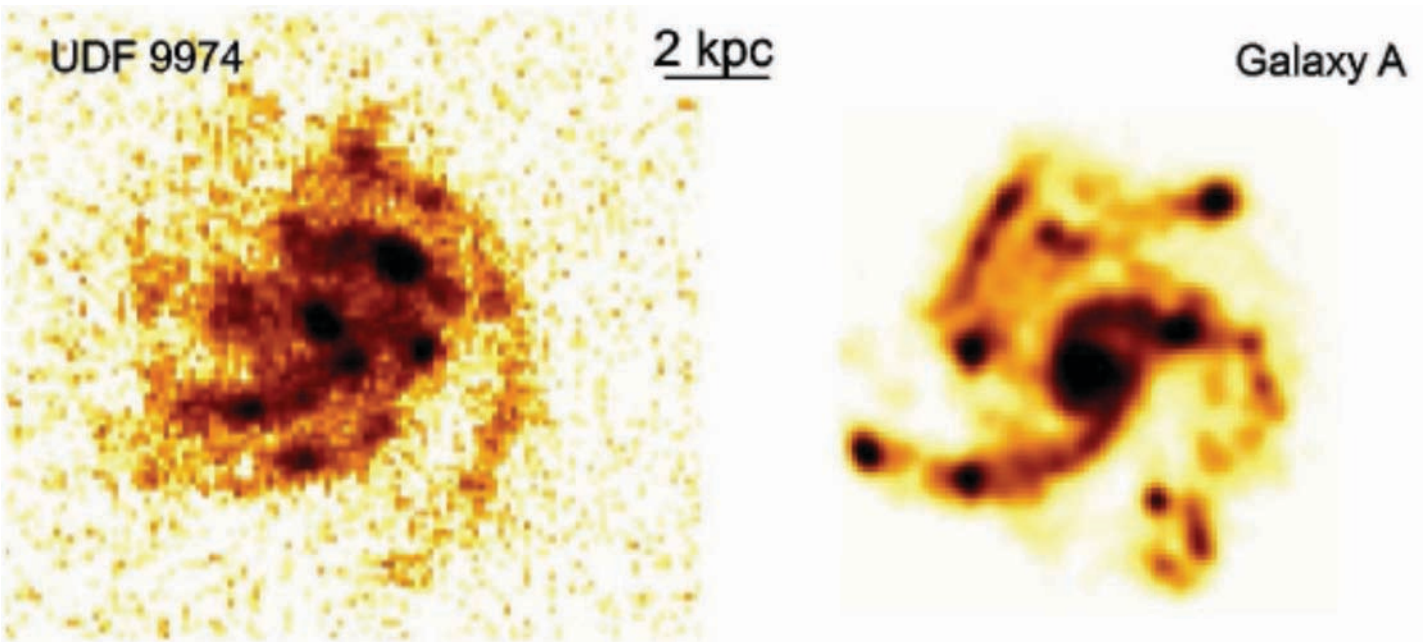


Galaxy A at $z = 2.3$, which has a disk of young stars (about half forming in the clumps) and a bulge of older stars formed largely by merging clumps.

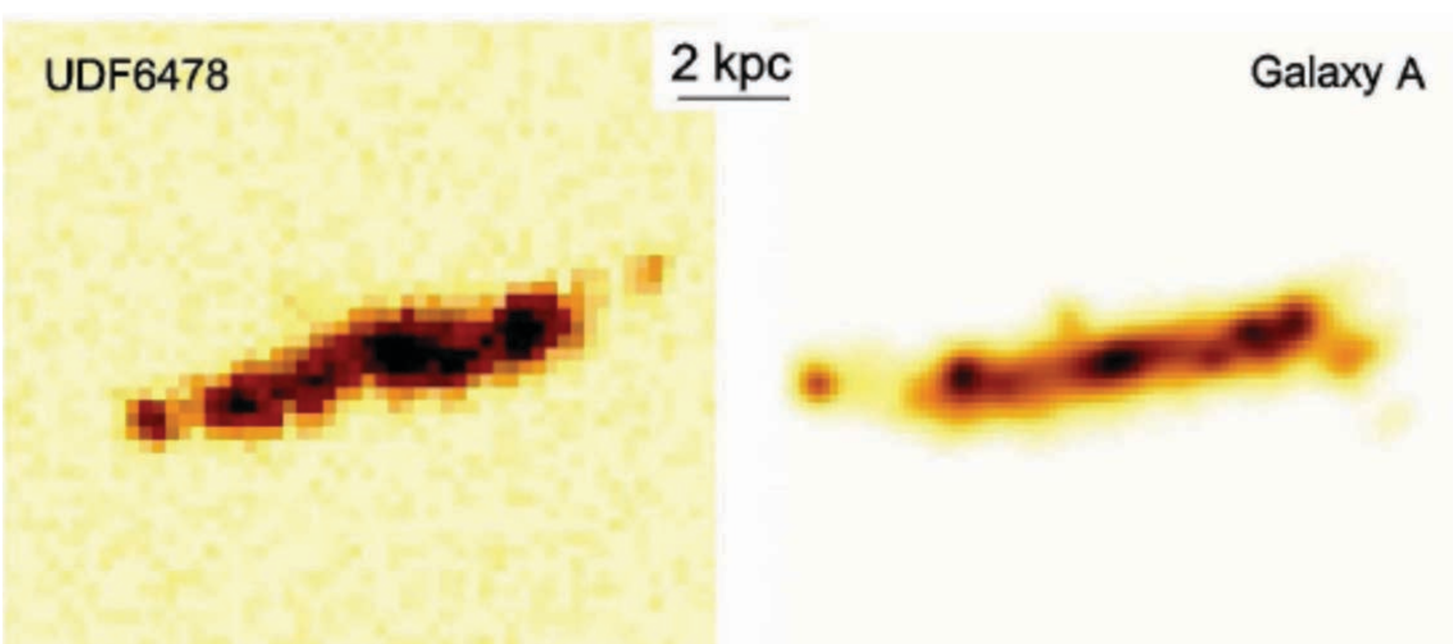
Ceverino, Dekel, & Bournaud 2010

Galaxy Hydrodynamic Simulations

Face-on views



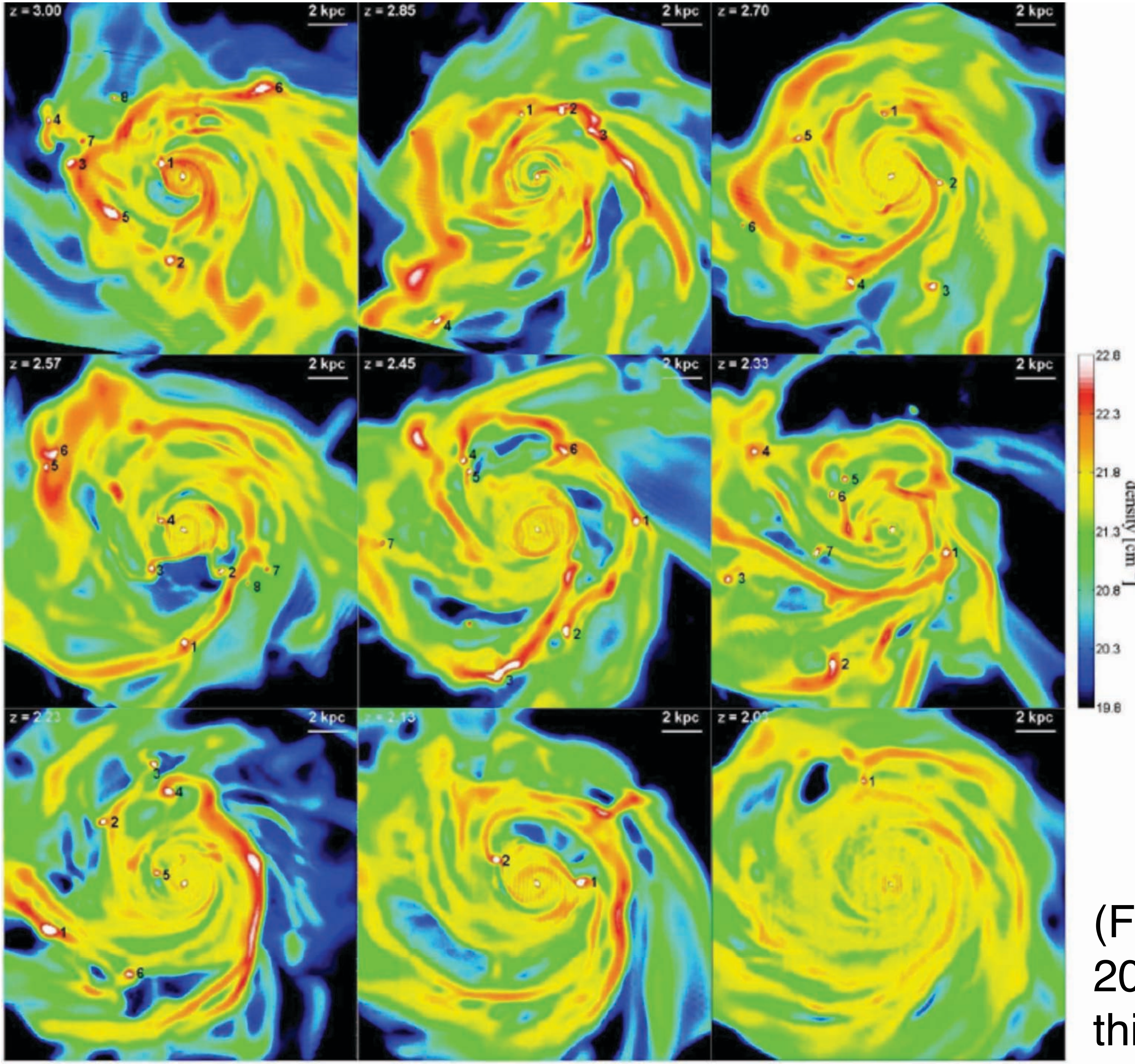
Edge-on views



Simulated galaxy A at z = 2.3 (M_{vir} = 4x10^{11} M_{sun}) viewed face-on and edge-on compared with similar appearing real galaxies

Ceverino, Dekel, & Bournaud 2010

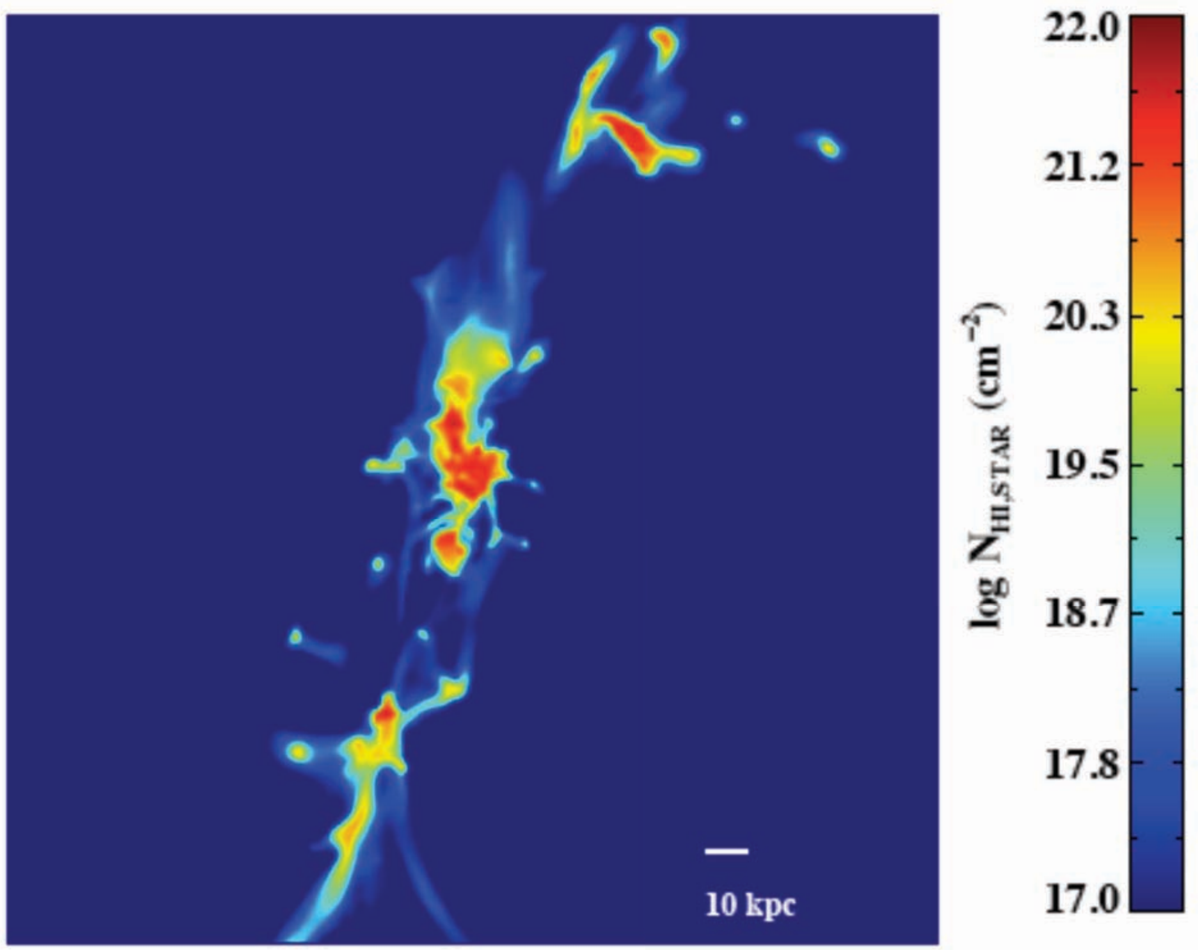
Galaxy Hydrodynamic Simulations

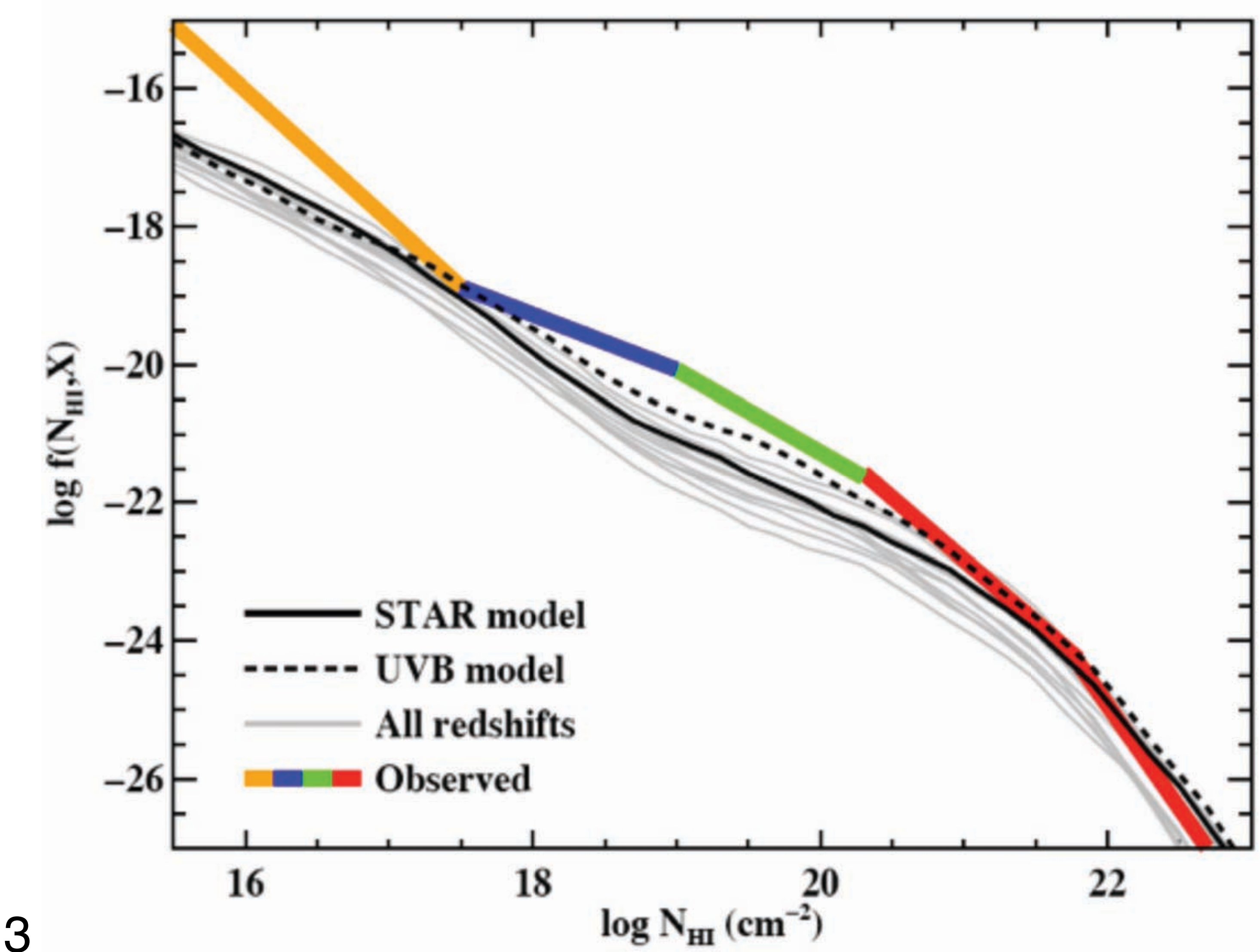


Gas surface density of galaxy E disk at z = 3 to 2. M_{vir} = 1.5x10^{12} M_{sun} at z = 2.3. Identified clumps are numbered; #1, 2, and 4 were small galaxies that merged.

(From Ceverino et al. 2011, to be submitted this week.)

Galaxy Hydrodynamic Simulations





Hydrogen column density in galaxy A at $z = 2.3$ using the STAR model, which includes ionizing radiation from local sources as well as the UV background. Most of the gas in the streams is ionized by electron collisions and the UVB, while photons from newly born stars affect the high column density inside the central and satellite galaxies and their surroundings.

Column density distribution function from observations at $z \sim 3.7$ (colors: Prochaska et al. 2010) and simulations for the STAR (solid line) and the UVB (dashed line) models at $z = 3.5$ within the virial radius.

Fumagalli, Prochaska, Kasen, Dekel, Ceverino, & Primack 2011

Sunrise Visualizations

- Dust in galaxies is important
  - Absorbs about 40% of the local bolometric luminosity
  - Makes brightness of spirals inclination-dependent
  - Completely hides the most spectacular bursts of star formation
  - Makes high-redshift star formation very uncertain
- Dust in galaxies is complicated
  - The mixed geometry of stars and dust makes dust effects geometry-dependent and nontrivial to deduce
  - Needs full radiative transfer model to calculate realistically
- Previous efforts have used 2 strategies
  - Assume a simple, schematic geometry like exponential disks, or
  - Simulate star-forming regions in some detail, assuming the galaxy is made up of such independent regions
  - Have not used information from hydrodynamic simulations
- The *Sunrise* code starts from hydro simulations

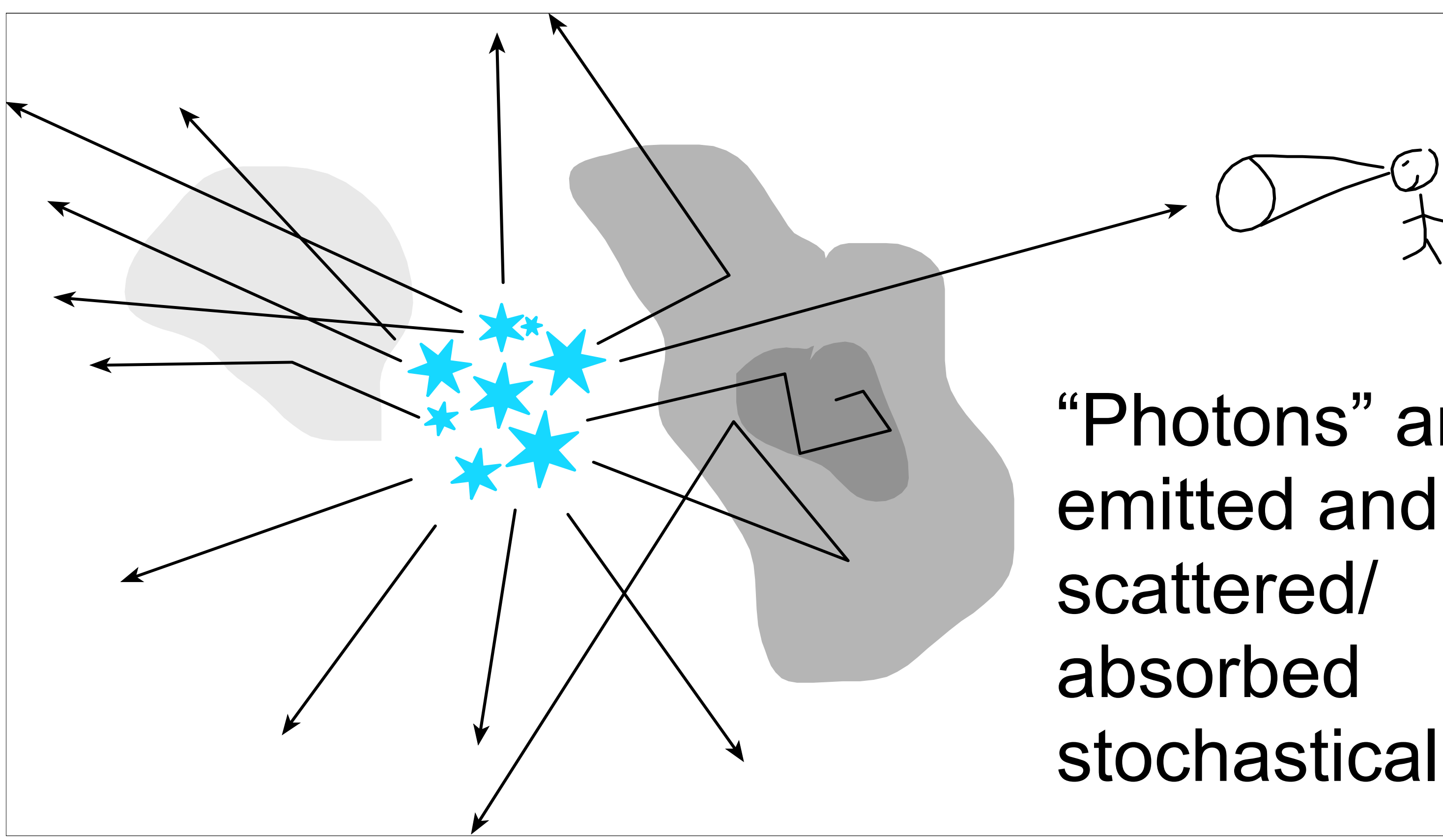
Sunrise Visualizations

In order to calculate the effects of stellar age, metallicity and dust, we use the open-source Monte-Carlo radiative-transfer code *Sunrise* (Jonsson 2006, Jonsson, Cox, Primack, & Somerville 2006). The stellar SEDs are calculated using *Starburst* (or Bruzual & Charlot, etc.). The spectral energy distribution of all stars in a given timestep is propagated through the dusty interstellar medium of the simulated galaxies. *Sunrise* uses a polychromatic algorithm, where every Monte-Carlo ray samples every wavelength. This algorithm makes it possible to calculate spectra efficiently with unprecedented spectral resolution. *Sunrise* uses subgrid models of star-forming regions from the photoionization/dust code MAPPINGS-III (Jonsson, Groves, & Cox 2009). Emission from diffuse dust is calculated self-consistently from the local radiation field, allowing calculation of spectral energy distributions out to the far-IR for comparison with Spitzer and Herschel data. This is the most computationally intensive part of the calculation, but it can be sped up by a factor of ~50 using an Nvidia Tesla graphic processor unit (Jonsson & Primack 2010).

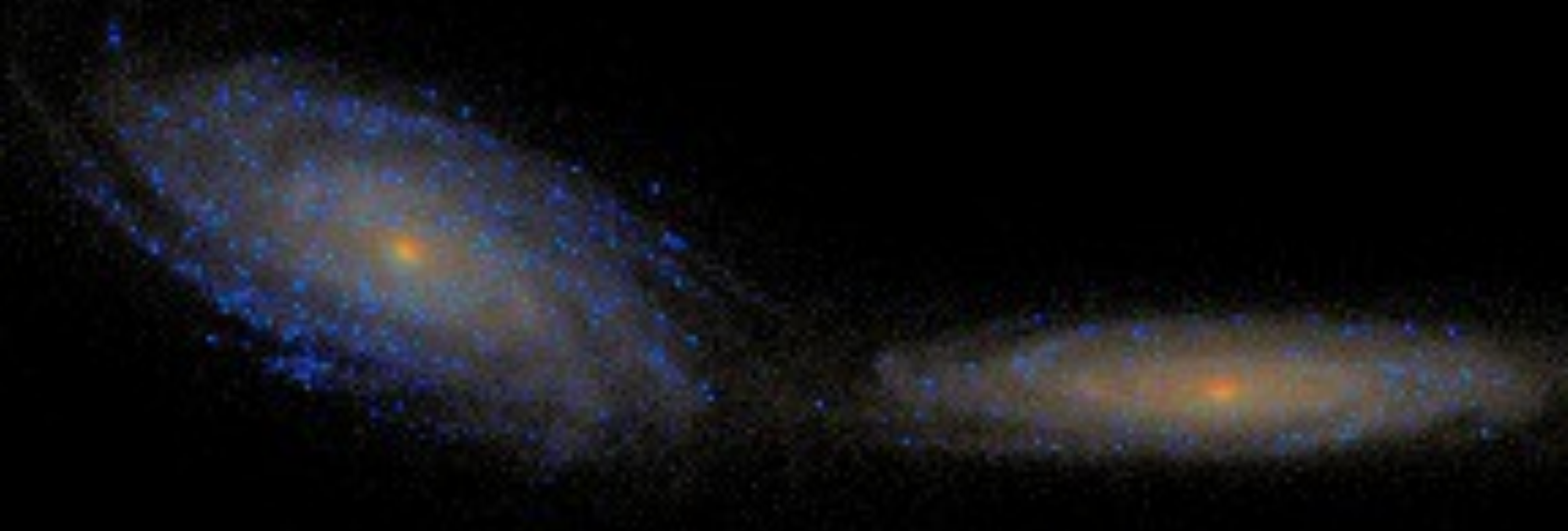
Sunrise Visualizations

For every simulation snapshot:

- SED calculation
- Adaptive grid construction
- Monte Carlo radiative transfer
- “Polychromatic” rays save CPU time

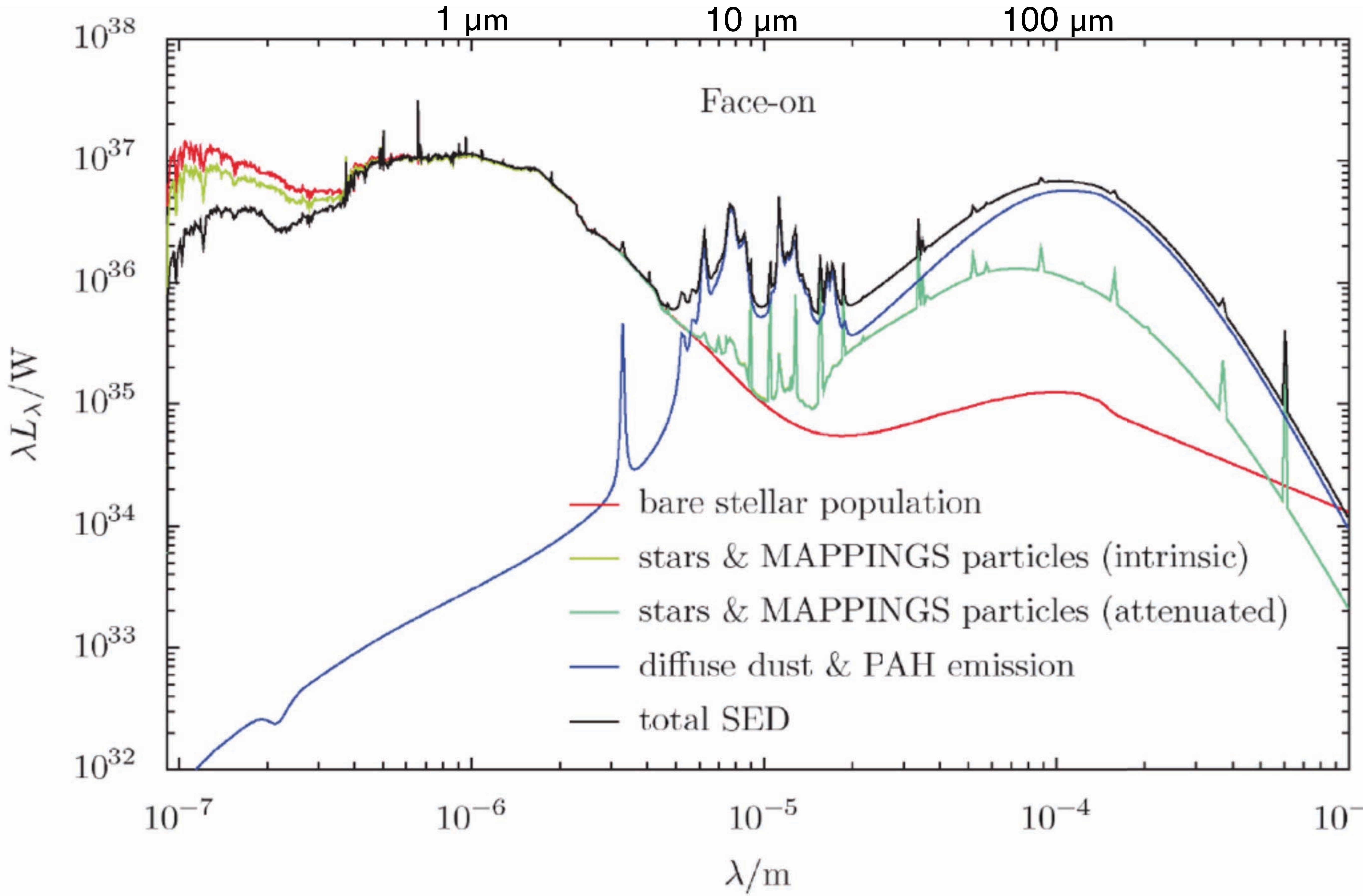


Galaxy Merger Simulation Visualized with *Sunrise*

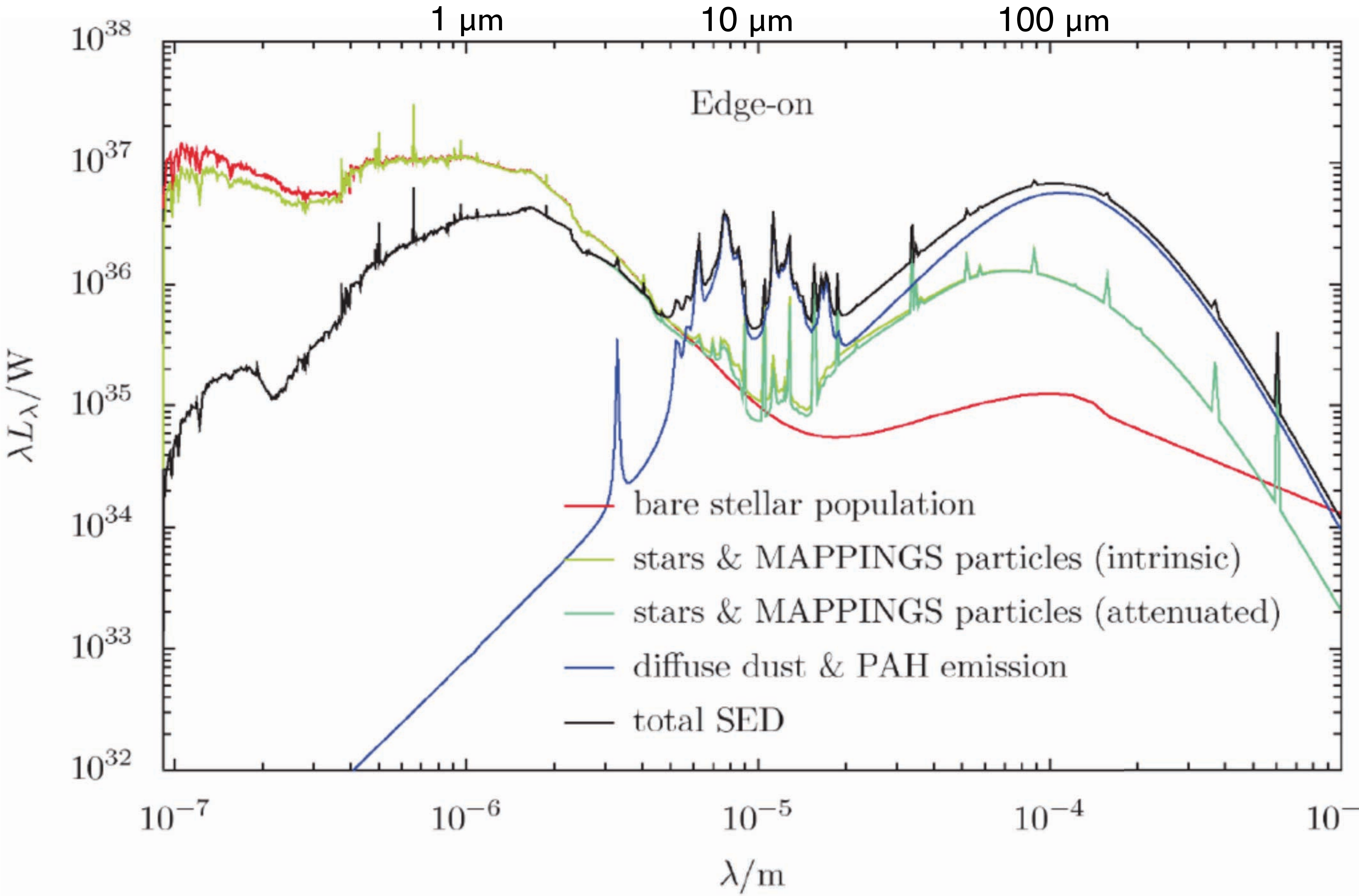


This image and the following video shows a merger between two Sbc galaxies, each simulated with 1.7 million particles using Gadget. The images are realistic color composites of u, r, and z-band images. Dust absorbs up to 90% of the light, and reradiates the energy in the far infrared. We calculate this “radiative transfer” using ~10^6 light rays per image. The simulation was run by Greg Novak and Joel Primack, and the visualization is by Patrik Jonsson.

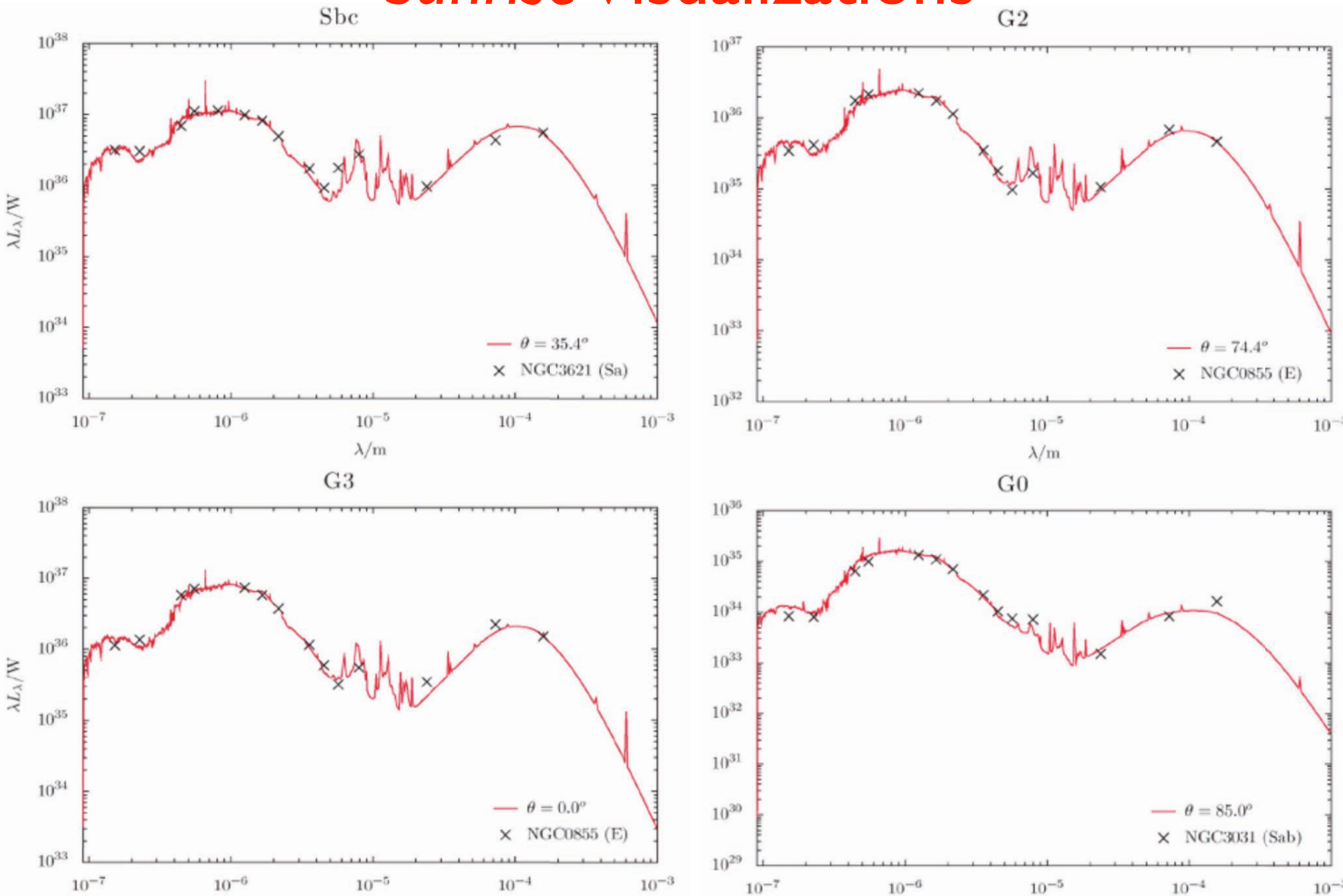
Sunrise Visualizations



Sunrise Visualizations

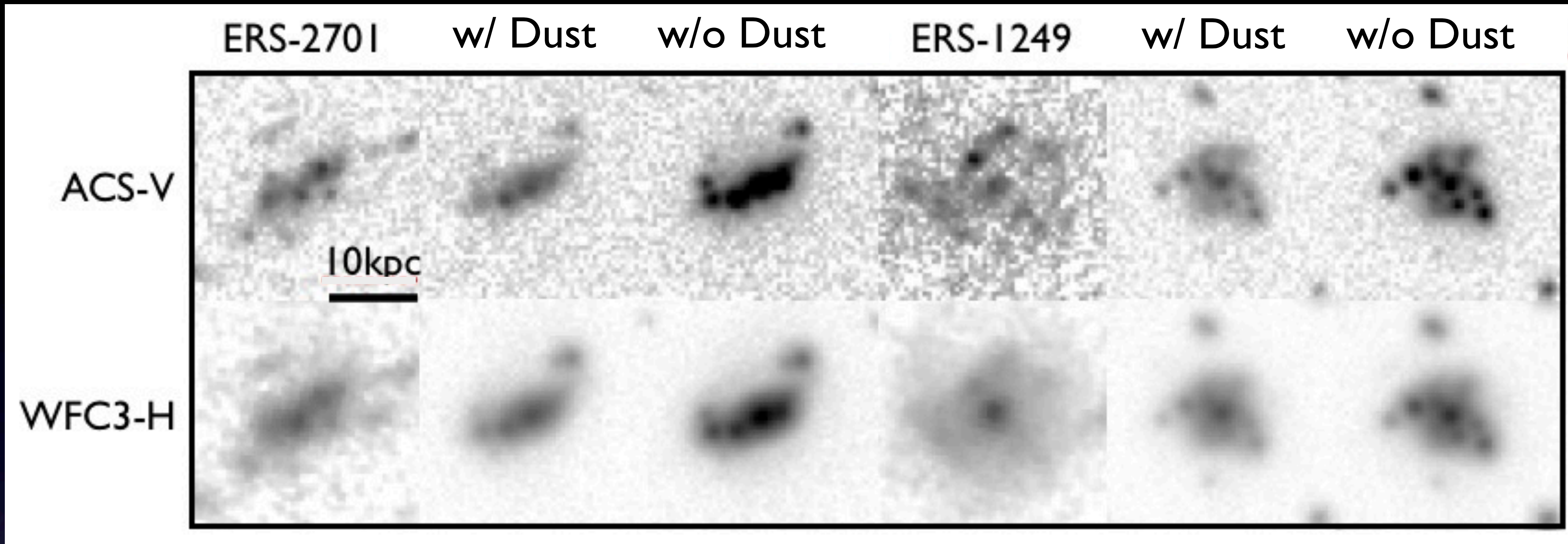


Sunrise Visualizations



The simulated galaxies (solid lines) with the best-fitting SINGS galaxy (symbols) overplotted. The inclination that best matched a SINGS galaxy was chosen. All SEDs are normalized to observations in the K band. (Jonsson, Groves, & Cox 2010.)

Simulation “edge-on” Simulation “face-on”



Simulation shown is MW3 at z=2.33 ‘imaged’ to match the CANDELS observations in ACS-Vband and WFC3-Hband

- 0.06” Pixel scale
- convolved with simulated psfs
- noise and background derived from ERS observations (same field as examples shown)

MW3 was imaged at ‘face-on’ and ‘edge-on’ viewing angles both with and without including dust models

Mark Mozena

Sunrise Visualizations

UCSC grad student Chris Moody (working with Primack, Matt Turk, and Patrik Jonsson) has created a pipeline to process ART simulation outputs efficiently to create multiwavelength *Sunrise* images. UCSC grad student Mark Mozena (working with Faber, Dekel, Koo, Lotz, and Primack) has perfected methods to convolve with appropriate PSFs and add noise to these *Sunrise* images, so that they can be compared directly with observations. We know that *Sunrise* with standard dust assumptions matches SEDs of nearby galaxies. We plan to run a number of dust models on hydro simulations of $z \sim 2$ to 3 galaxies to see what dust models will best agree with observed SEDs for similar galaxies. We plan to generate simulated images in ~5 wavebands of ~10 orientations of ~10 timesteps of the ~20 simulated galaxies that we have now (leading to about 10^4 images).

We plan to expand this by an order of magnitude over the next year or so (producing ~10^5 images). We are also looking into machine classification of real and simulated galaxy images.