for movies, please see:
http://users.obs.carnegiescience.edu/tcox/movies/

2010 HIPACC Astro-Computing Summer School

Galaxy Simulations Using the N-Body/SPH code GADGET

T.J. Cox (Carnegie Observatories)

Outline

1. Who am I and what am I doing here? My perspective, my science, and where my focus will be this week
2. An overview of GADGET projects (+other practical - I hope - information)
3. A brief overview of GADGET
4. Adding "Astrophysics" to GADGET
5. Loose Ends ... data structures, analysis, and visualization (w/ P. Hopkins)
6. What's next? (higher resolution, new models, and Arepo: the next generation of code)

Hi, my name is ..

Who am I and what am I doing here?

- T.J. Cox (Ph.D., UC Santa Cruz, post-docs at CfA and Carnegie Observatories)
- ~10 years experience using Gadget (every version)
- I am a user of Gadget, and had no part in designing it, building it, or upgrading it.
- >65 publications
- Some of my scientific interests ... simulations of idealized galaxy models, not cosmological simulations! More about this in a minute....

In my opinion, unless you are part cyborg (some of you may be - if so, this will certainly help you in your future research endeavors), it is unrealistic, not very feasible, and not practical to build your own simulation code.

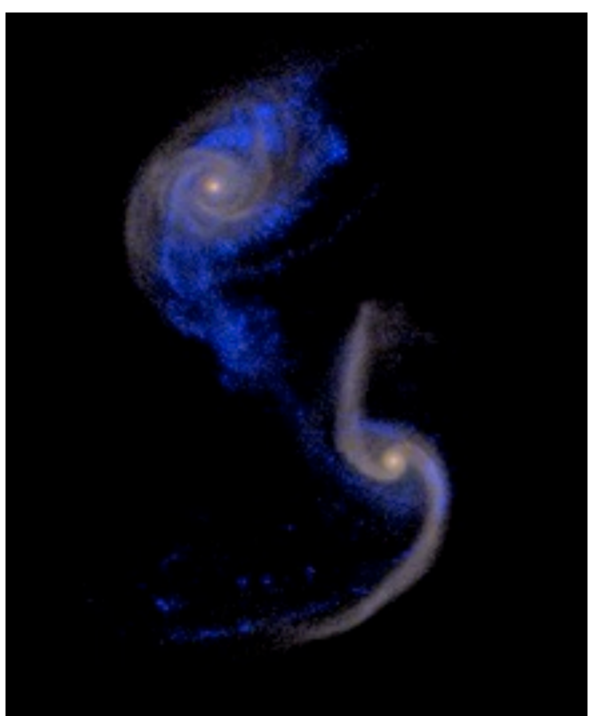
With the abundance of publically available, very powerful, parallelized codes, one can very quickly learn to do cutting-edge research which addresses many of the outstanding questions in galaxy formation.

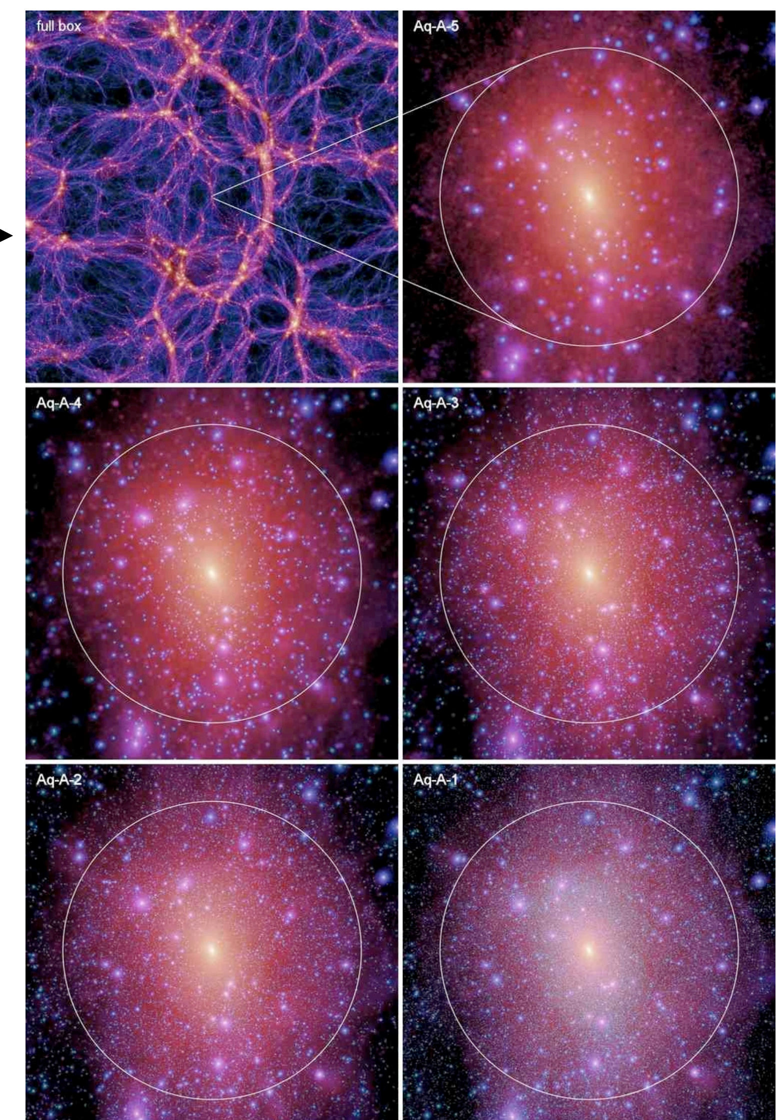
My goal for this week: to give you the knowledge necessary to use (compile, run, trouble-shoot, analyze) Gadget as a tool to perform publication-quality simulations and thus study relevant and interesting scientific questions. And, ideally, the ability to modify Gadget in novel ways.

My Science

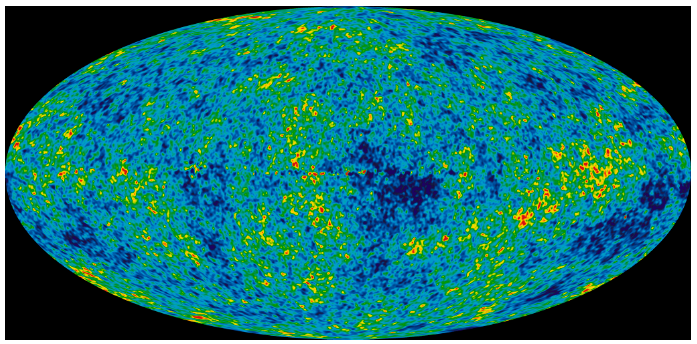
Idealized simulations of galaxy formation and evolution as opposed to cosmological simulations

this, not this

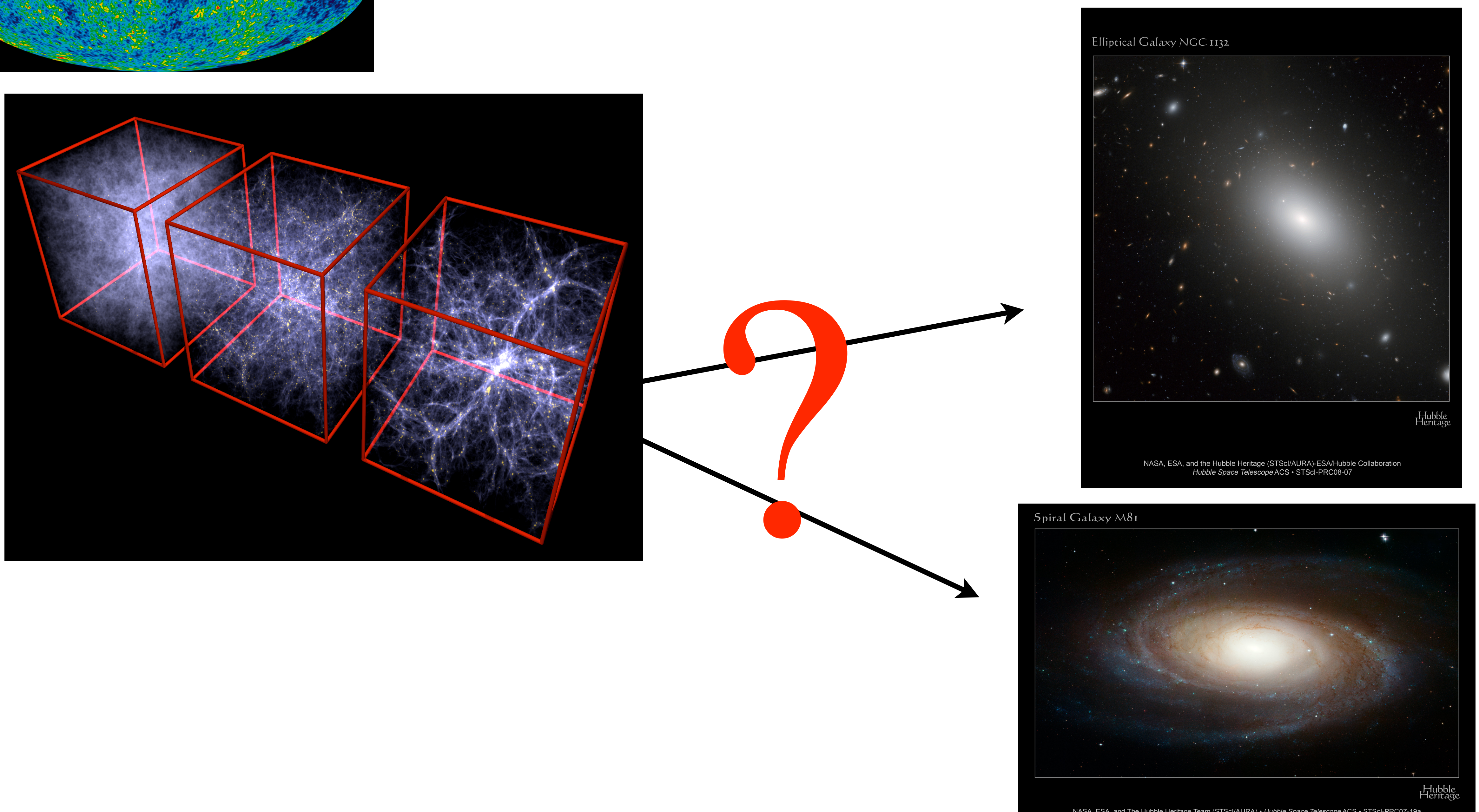




Galaxy Formation: The Challenge



A well constructed numerical problem with very well known initial conditions.



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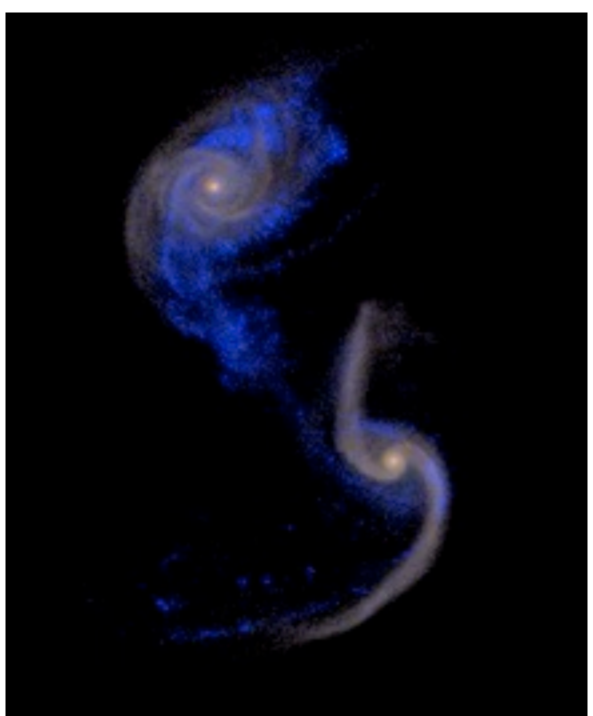
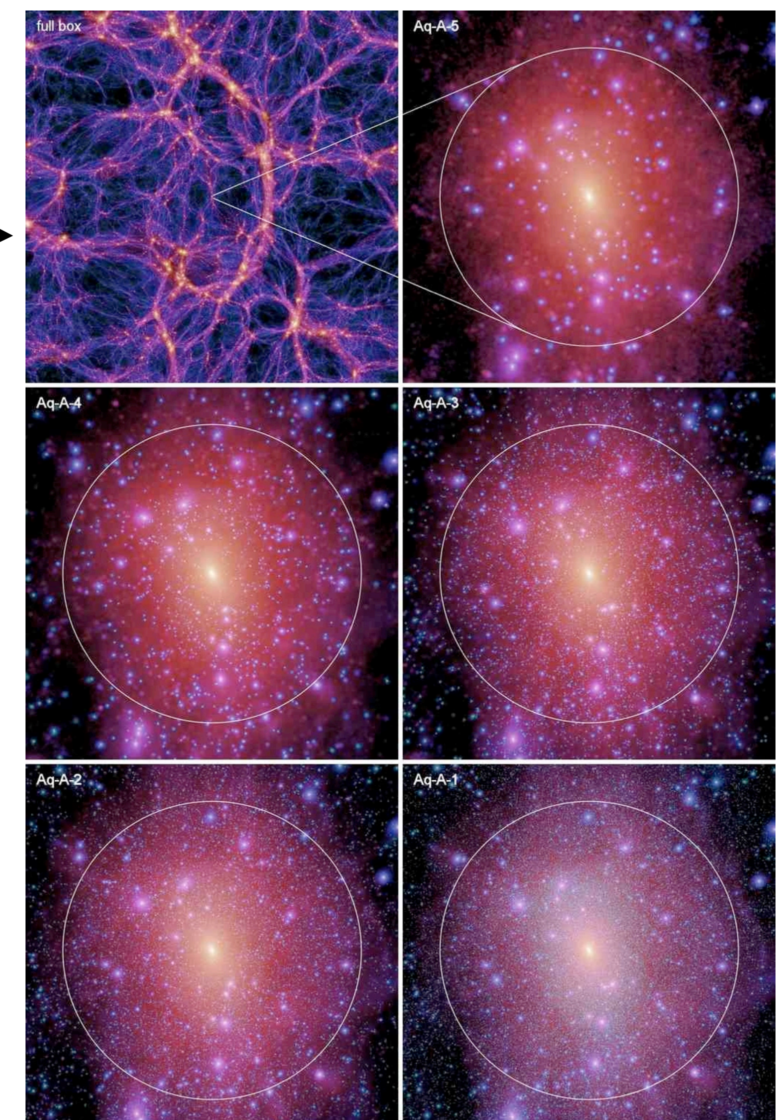
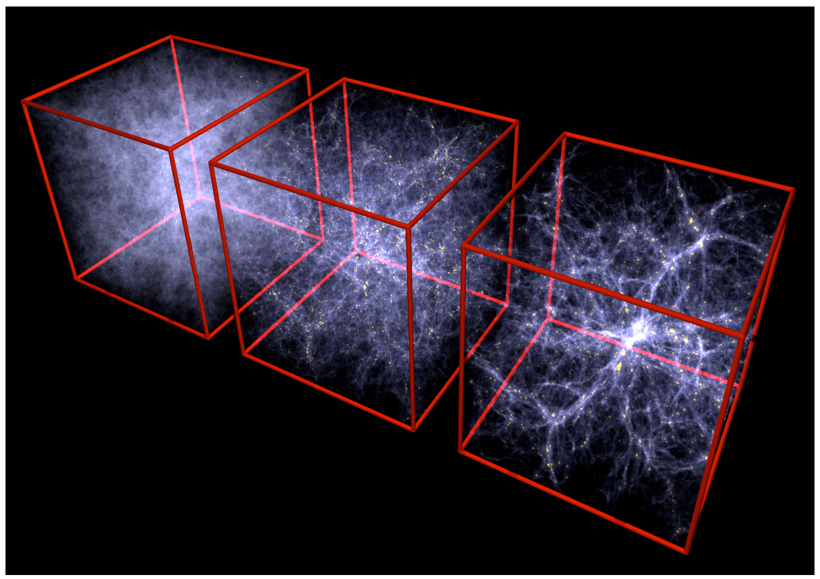


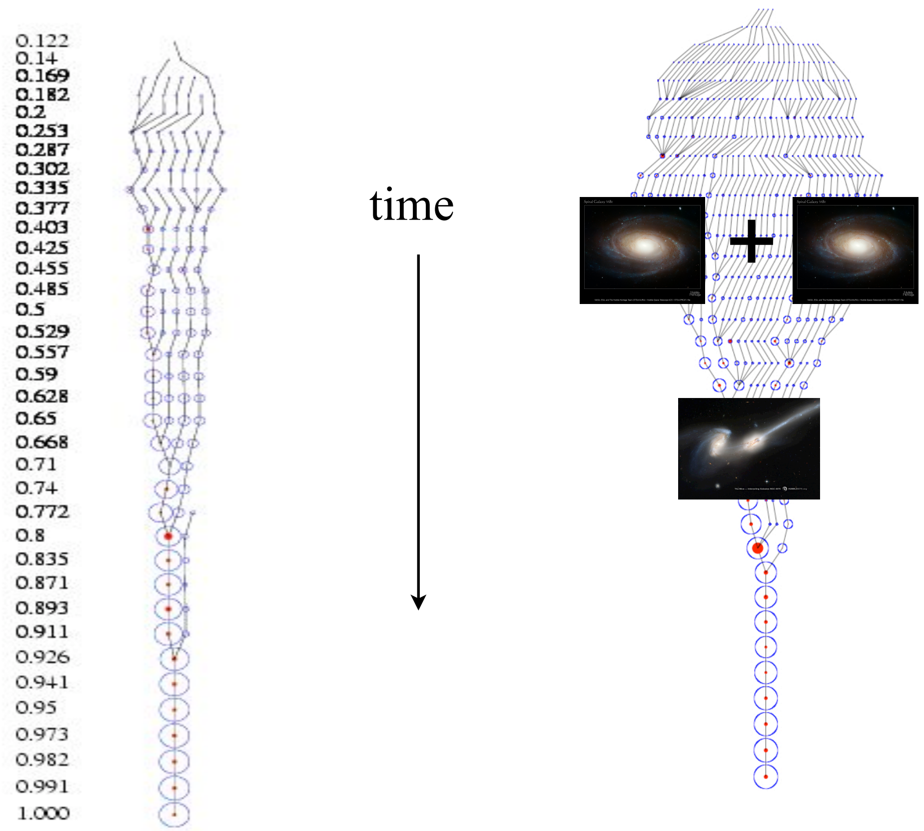


Hierarchical Formation of Galaxies

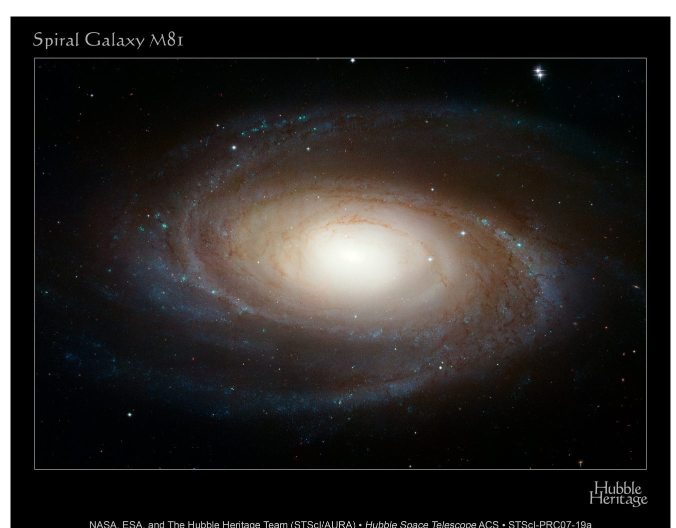


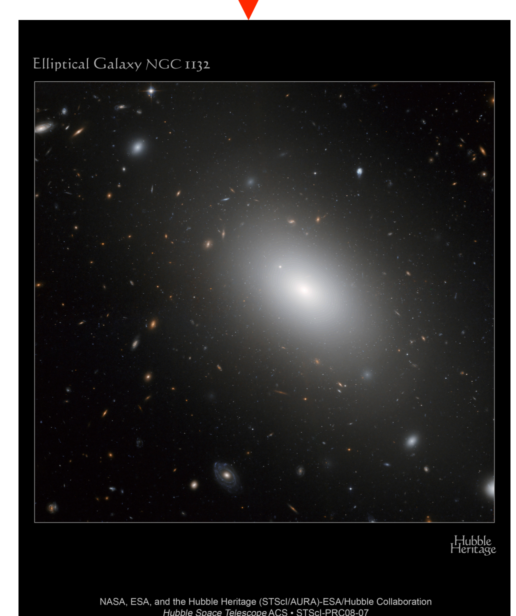
* The merger hypothesis (Toomre 1977) has gained traction as a result of the notion that structure grows hierachically, i.e. from the "bottom-up."

* The prevailing idea for the formation of galaxies is that the characteristics of individual galaxies are determined by their (hierarchical) merger history.



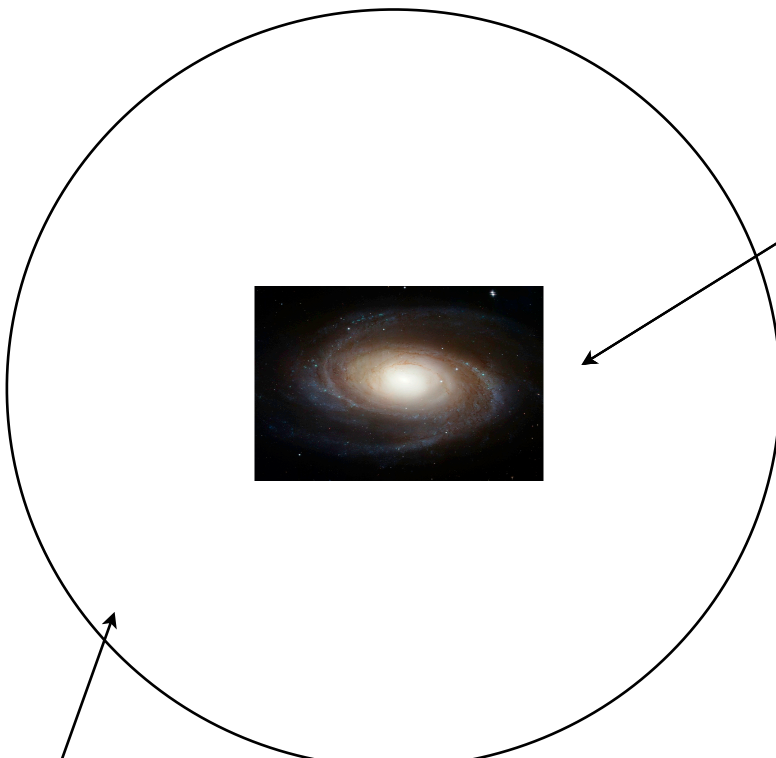
Wechsler et al. 2002 (but see also Lacey & Cole, Fakhouri & Ma, etc.)





Idealized Models

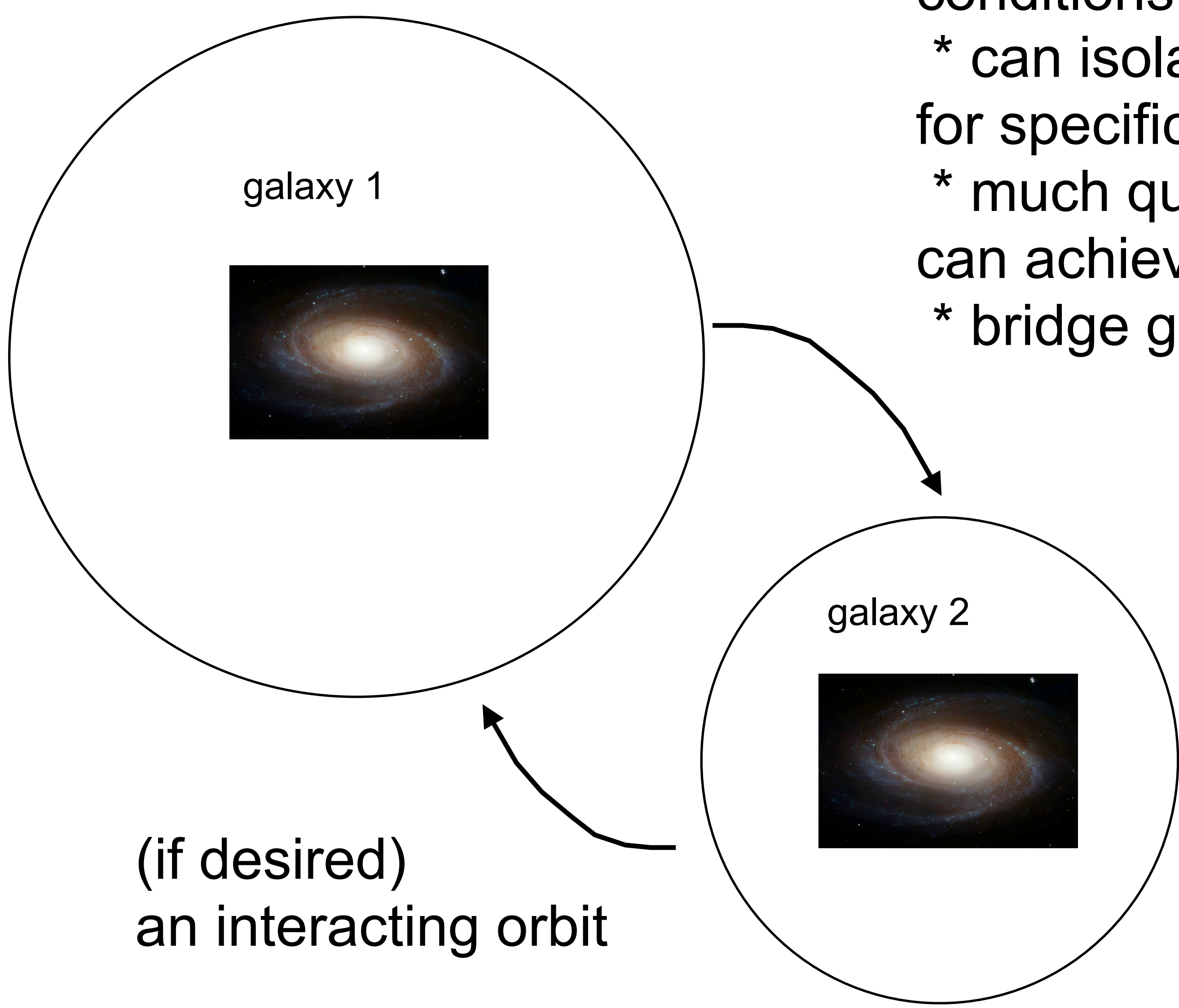
N-body representation of a galaxy



baryons:
 * stellar disk (collisionless, mass, exponential profile, thickness, stability)
 * stellar bulge (collisionless, mass, Hernquist 1990 profile)
 * gaseous disk (SPH, mass, various profiles, temperature)
 * gaseous halo (SPH, mass, profile, temperature)

dark matter halo (collisionless, mass, profile)

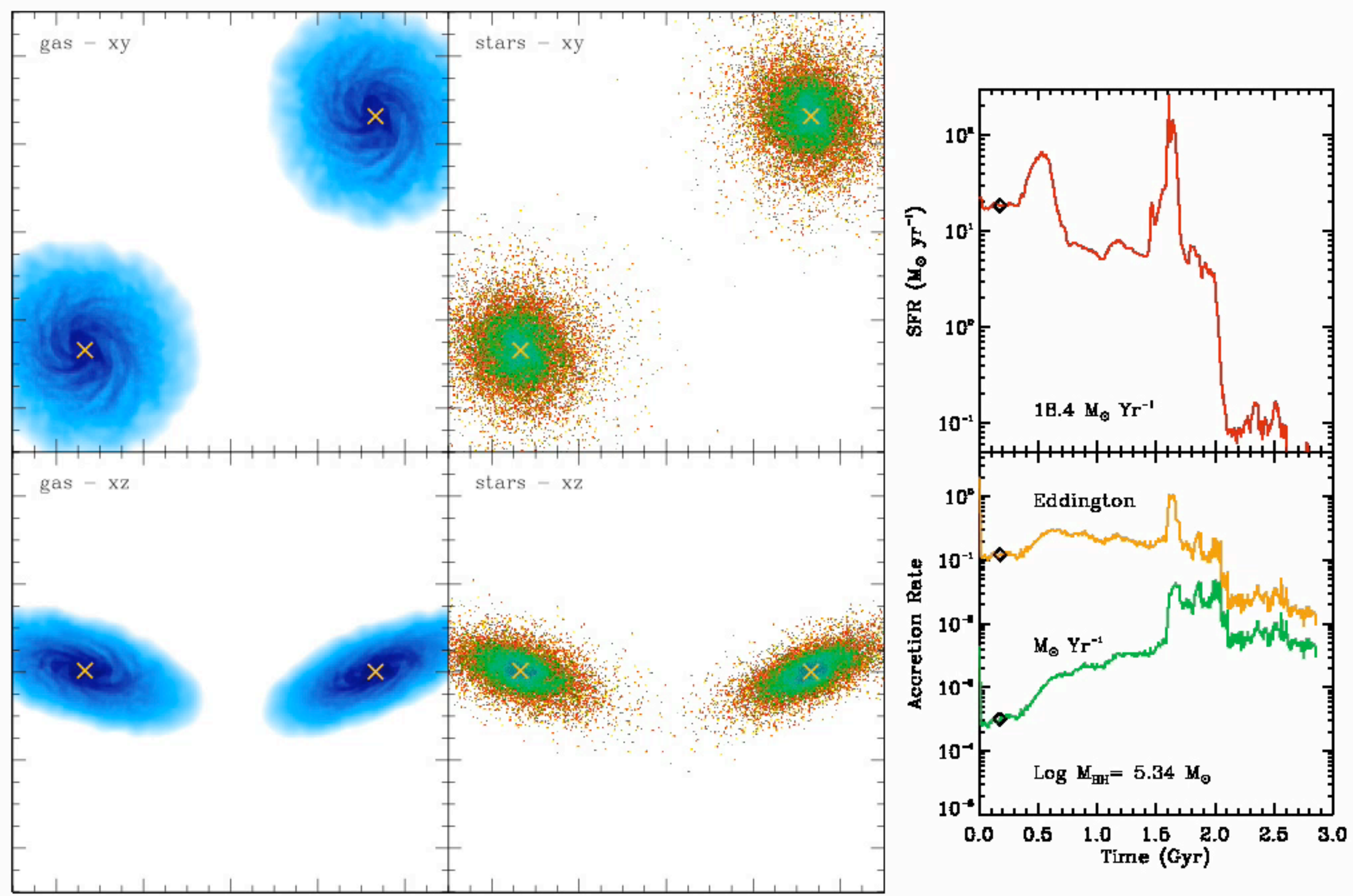
Idealized Models



Pros:
* can accurately control all aspects of the initial conditions
* can isolate the physical processes responsible for specific evolution
* much quicker than cosmological simulations and can achieve much higher resolution
* bridge galaxy, star-formation scales

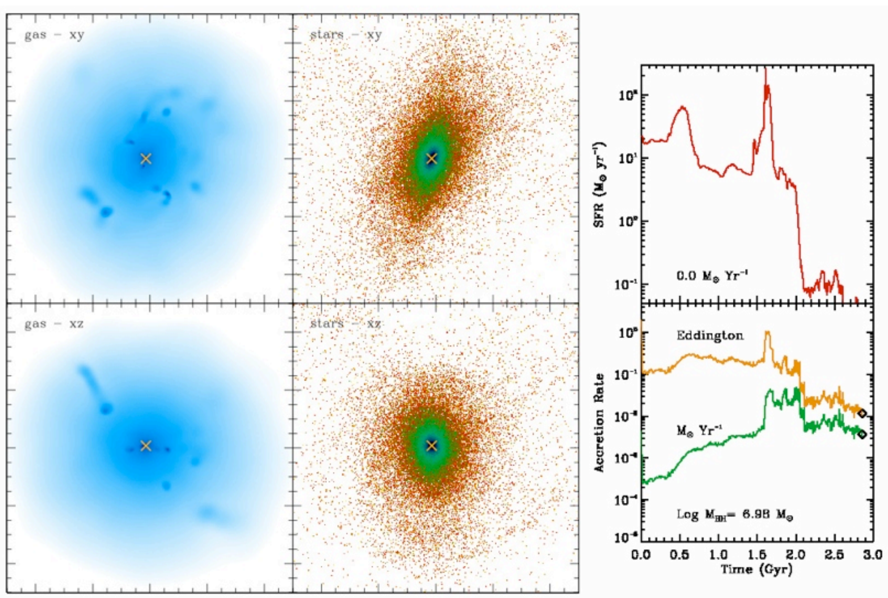
Cons:
* many possible structures for the initial galaxy models and their mutual interaction
* not cosmological

**** the cosmological and idealized approaches are very complimentary ****

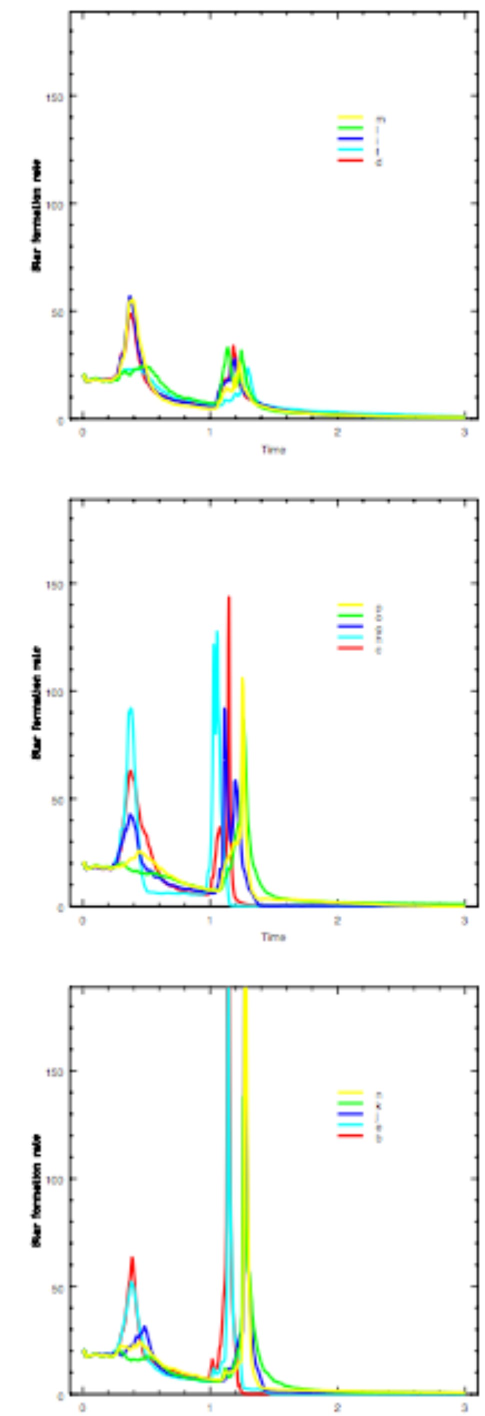


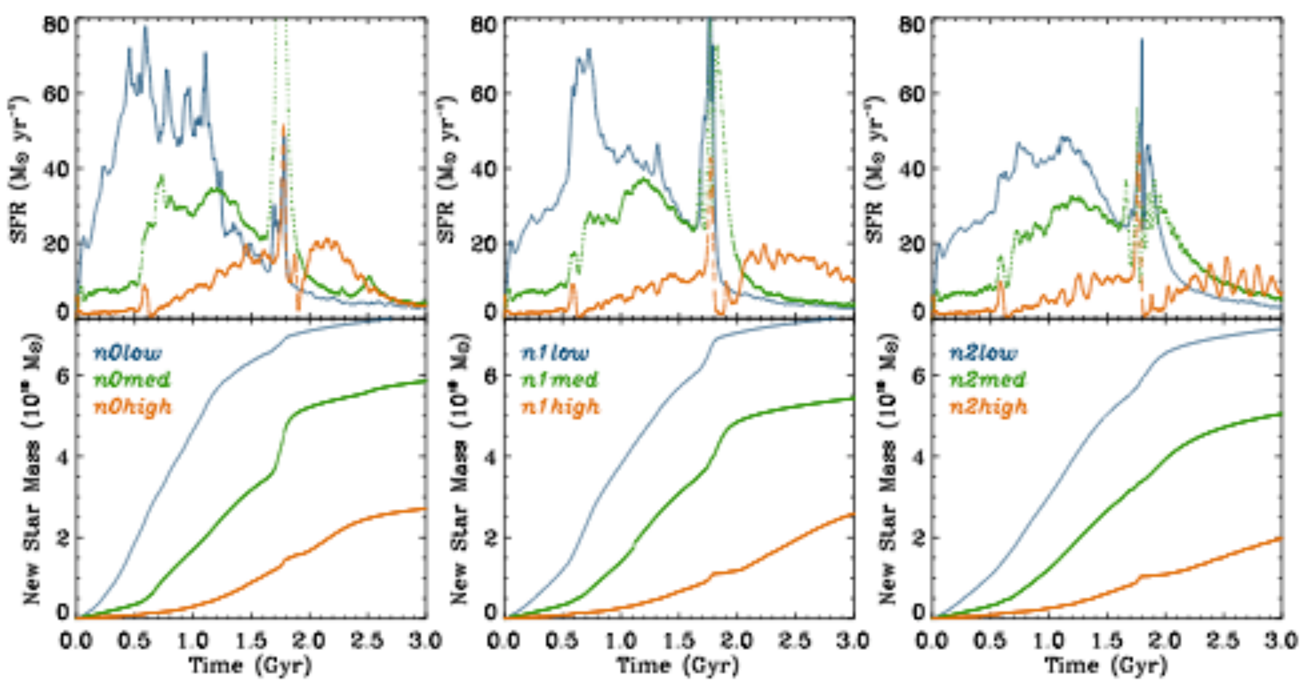
blue = projected gas density
color = projected stellar density

Merger-induced Activity



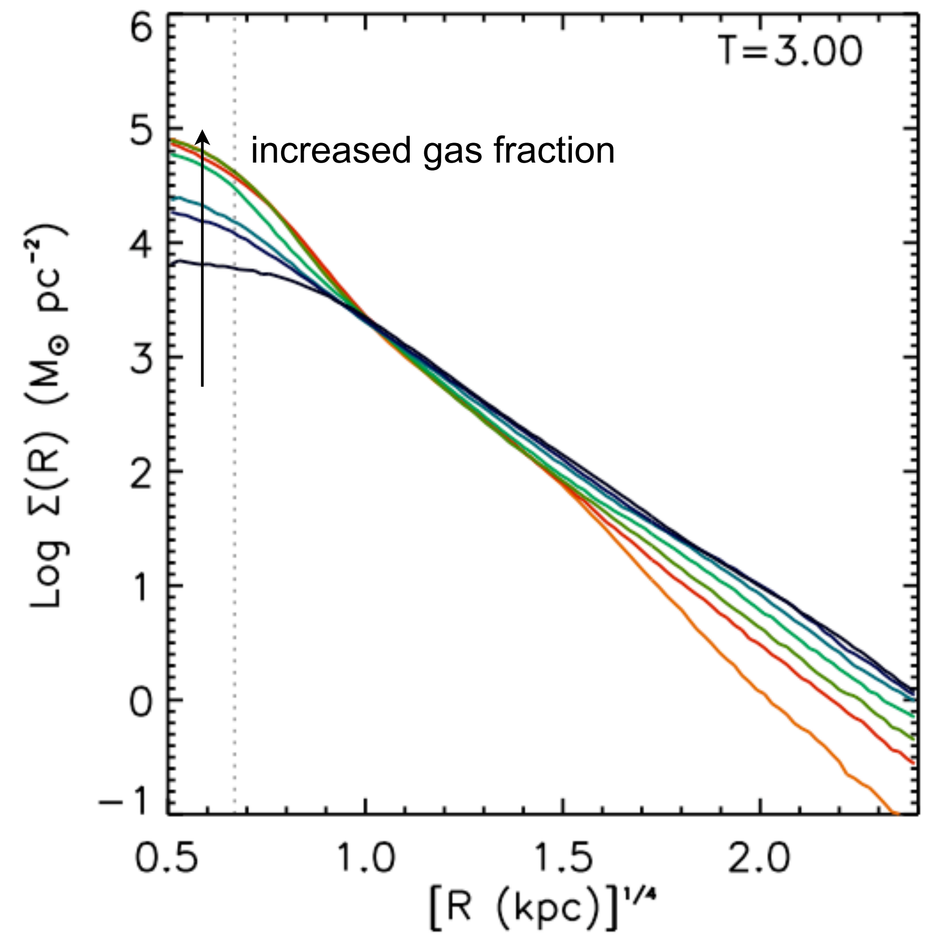
Idealized simulations of galaxy mergers are a good way to study how merger-induced star formation depends on interacting galaxy parameters or how the inter-stellar medium is treated.

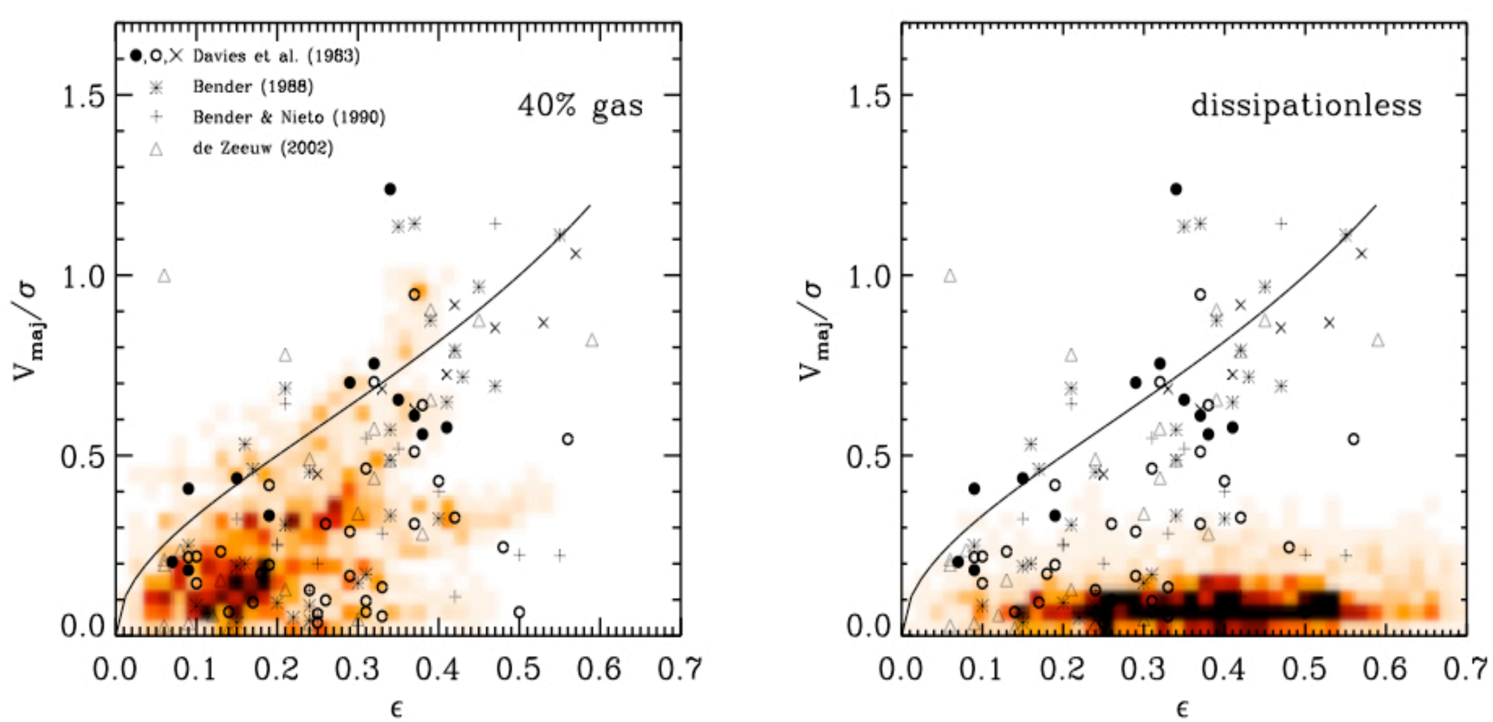




Merger Remnants

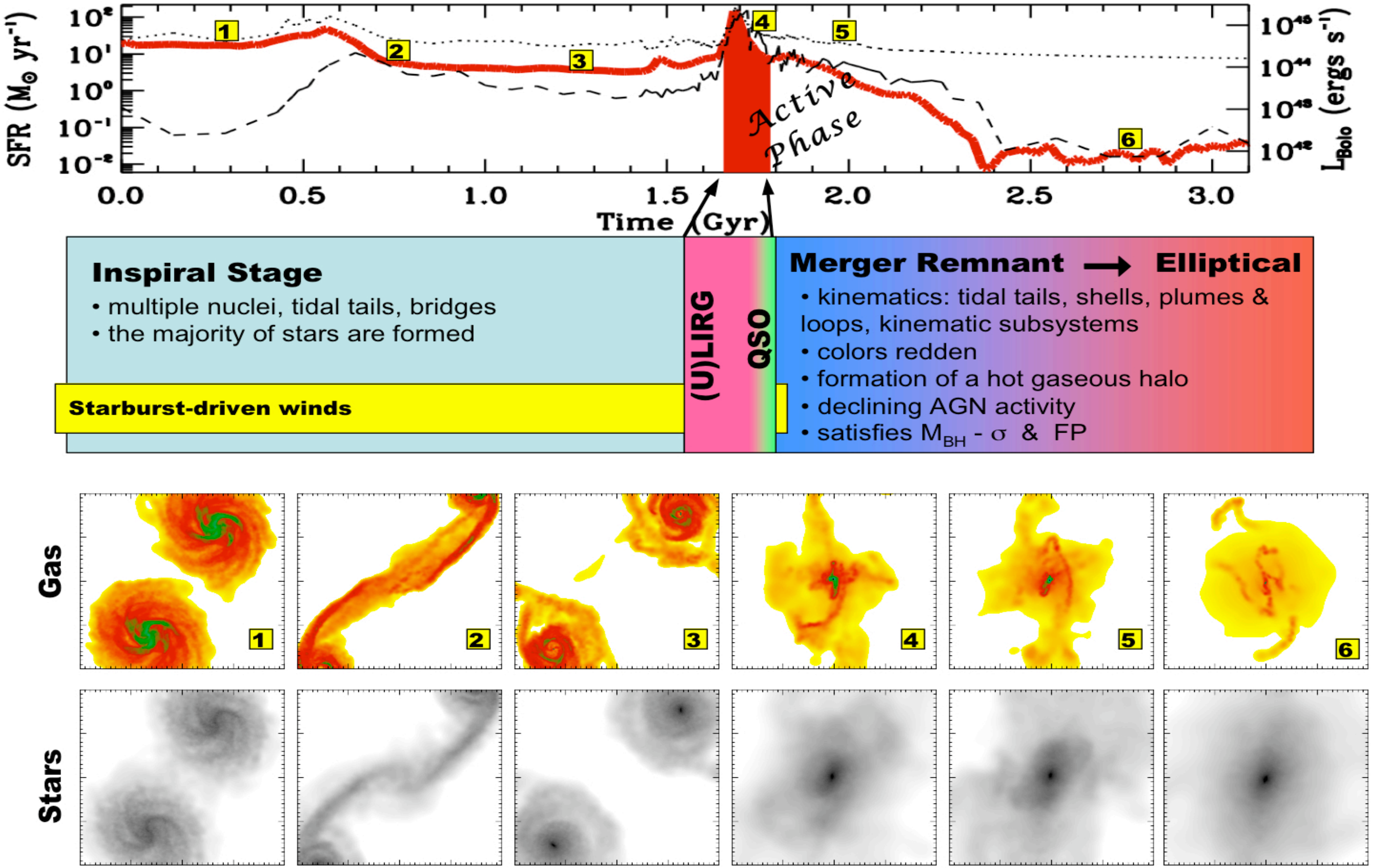
Galaxy mergers are a possible mechanism for the formation of elliptical galaxies - the "merger hypothesis" proposed by Toomre (1977).

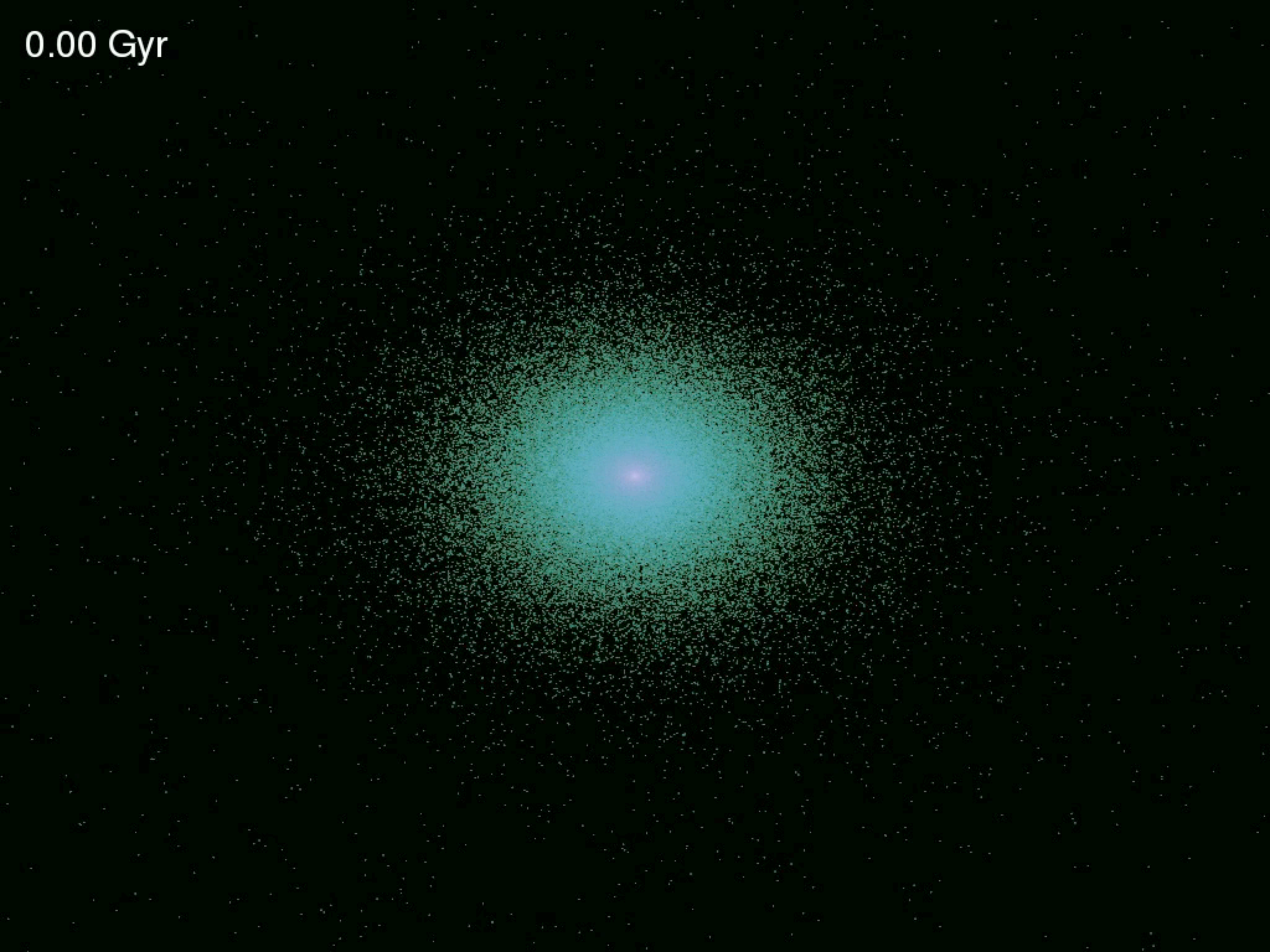




Cox et al. (2006) - see also Naab & Burkert (2003), and Naab, Jesseit, & Burkert (2006)

Proposed Chronology of a Galaxy Merger




0.00 Gyr

Possible Projects

(see triton;/home/hipacc-5)

1. Assemble an isolated disk galaxy (or many of them) and assess its stability

   1.1. Determine the fastest combination of compiler (plus any optimizations) and communication protocol

   1.2. Use an alternate galaxy generation code

2. Merge two disk galaxies and attempt to match an observed system

   2.1. Use Sunrise (next week's lectures) to make mock images of the above

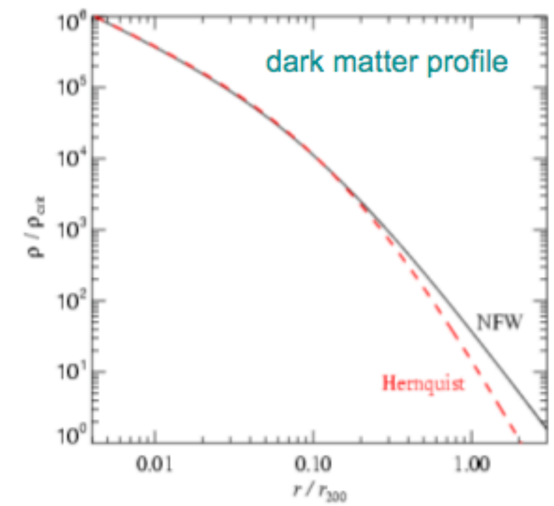
3. Modify GADGET (rSPH, Abel - next lecture; shock-SF, Barnes, etc.) and test what affect this has.

4. Compare results from two (or more - or <u>all</u>) codes.

5. .... or anything else you can think of ...

Step 0: Build an isolated disk galaxy

* *MakeDiskGalaxy* and *MakeHubbleType* both use the methods introduced by Hernquist (1993) and extended by Springel et al. (1999, 2000, 2005):



Dark matter:

$$\rho_{\rm dm}(r) = \frac{M_{\rm dm}}{2\pi}\frac{a}{r(r+a)^3}$$

Hernquist or NFW profile

Stars in the disk:

$$\Sigma_\star(r) = \frac{M_\star}{2\pi h^2}\exp(-r/h)$$

"Isothermal sheet" with exponential profile

$$\rho_\star(R,z) = \frac{M_\star}{4\pi z_0\, h^2}\,{\rm sech}^2\left(\frac{z}{2\,z_0}\right)\exp\left(-\frac{R}{h}\right)$$

Disk scale length h determined by spin parameter of halo.

Stars in the bulge:

$$\rho_{\rm b}(r) = \frac{M_{\rm b}}{2\pi}\frac{b}{r(r+b)^3}$$

Bulge scale length b can be set to a fraction of the disk scale-length h.

Gas in the disk:

$$\Sigma_{\rm gas}(r) = \frac{M_{\rm gas}}{2\pi h^2}\exp(-r/h)$$

Vertical structure given by hydrostatic equilibrium. Depends on the equation of state of the gas.

$$-\frac{1}{\rho_{\rm g}}\frac{\partial P}{\partial z} - \frac{\partial \Phi}{\partial z} = 0$$

Step 0: Build an isolated disk galaxy

* *MakeDiskGalaxy* and *MakeHubbleType* both use the methods introduced by Hernquist (1993) and extended by Springel et al. (1999, 2000, 2005):

We assume that the **velocity distribution function** of dark matter and stars can be approximated everywhere by a **triaxial Gaussian.**

Further, we assume axisymmetry, and that the distribution function depends only on E and L_z

Then cross-moments vanish: $$\langle v_R v_z \rangle = \langle v_z v_\phi \rangle = \langle v_R v_\phi \rangle = 0$$

$$\langle v_R \rangle = \langle v_z \rangle = 0$$

The radial and vertical moments are given by:

$$\left\langle v_z^2 \right\rangle = \left\langle v_R^2 \right\rangle = \frac{1}{\rho} \int_z^\infty \rho(z', R) \frac{\partial \Phi}{\partial z'} \, \mathrm{d}z'$$

The azimuthal dispersion fulfills a separate equation:

$$\left\langle v_\phi^2 \right\rangle = \left\langle v_R^2 \right\rangle + \frac{R}{\rho} \frac{\partial \left(\rho \left\langle v_R^2 \right\rangle\right)}{\partial R} + v_c^2$$

Circular velocity: $$v_c^2 \equiv R \frac{\partial \Phi}{\partial R}$$

A remaining freedom lies in the azimuthal streaming $\langle v_\phi \rangle$, which is not determined by the above assumptions. For the dark matter, it can be set to zero, or to a value corresponding to a prescribed spin.

$$\sigma_\phi^2 = \left\langle v_\phi^2 \right\rangle - \langle v_\phi \rangle^2$$

Note: For the stellar disk, we instead use the epicycle theory to relate radial and vertical dispersions.

Step 0: Build an isolated disk galaxy

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Note: Other methods exist, see, e.g., Barnes & Hibbard (2010), McMillian & Dehnen (2007), Kazantzidis & Magorrian (2004), or the GalactICS code of Dubinski & Kuijken (1995)

Step 0: Build an isolated disk galaxy

* MakeDiskGalaxy:

Output file! The ICs that will be read by Gadget.

```
OutputDir      ./                        % Output directory
OutputFile     Sb.dat             % Filename of generated initial conditions

CC             9.0        % halo concentration
V200         160.0        % circular velocity v_200 (in km/sec)
LAMBDA         0.05       % spin parameter
MD             0.03       % disk mass fraction
MB             0.02       % bulge mass fraction

MBH            0.00001    % black hole mass fraction. If zero, no black
                          % hole is generated, otherwise one at the centre
                          % is added.


JD             0.03       % disk spin fraction, typically chosen equal to MD

GasFraction    0.15       % relative content of gas in the disk, the rest is stars
DiskHeight     0.2        % thickness of stellar disk in units of radial scale length
BulgeSize      0.3        % bulge scale length in units of disk scale length

N_HALO         975000    % desired number of particles in dark halo
N_DISK         165000     % desired number of collisionless particles in disk
N_GAS          30000      % number of gas particles in disk
N_BULGE        130000     % number of bulge particles

HI_GasMassFraction     0.0      % mass of extended, flat HI disk in terms of the total gas mass
HI_GasDiskScaleLength  6        % scale length of extended gas disk in terms of scale length of the
disk
MaxGasDiskHeight       1.0      % to prevent too big flaring of isothermal outer gas disk


RadialDispersionFactor 1.0      % applies to stellar disk: Gives the radial
                                % dispersion in units of the z-dispersion


MaxSfrTimescale     4.5         % Gas consumption timescale (multi-phase model)
FactorSN            0.1         % beta, mass fraction of massive stars (multi-phase model)
FactorEVP           3000        % A_0, evaporation parameter (multi-phase model)
TempSupernova       3e+08       % T_SN, effective "supernova temperature",sets feedback energy (multi-
phase model)
TempClouds          1000        % temperature of cold clouds (multi-phase model)

FactorForSofterEQS  0.25        % Can be used to make the equation of state
                                % softer. For 1.0, the multiphase model is
                                % used, while for 0.0 isothermal at 10^4 K is
                                % assumed. Intermediate values interpolate
                                % linearly between the two pressures.

                                % Brants additions
REDSHIFT            0.0         % redshift to scale galaxy properties to
Omega_m0            0.3         % Omega_m
Omega_L0            0.7         % Omega_L
```

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```

Basic halo, disk, and bulge parameters a la Mo, Mao, & White (1998)

Step 0: Build an isolated disk galaxy

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```

Structural parameters of the disk and bulge.

Step 0: Build an isolated disk galaxy

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```

The number of particles.

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Omega_L0            0.7         % Omega_L
```

Temperature structure of the gas, assuming it follow the multiphase ISM structure outlined in Springel & Hernquist (2003).

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HI_GasDiskScaleLength  6        % scale length of extended gas disk in terms of scale length of the
disk
MaxGasDiskHeight       1.0      % to prevent too big flaring of isothermal outer gas disk


RadialDispersionFactor 1.0      % applies to stellar disk: Gives the radial
                                % dispersion in units of the z-dispersion


MaxSfrTimescale     4.5         % Gas consumption timescale (multi-phase model)
FactorSN            0.1         % beta, mass fraction of massive stars (multi-phase model)
FactorEVP           3000        % A_0, evaporation parameter (multi-phase model)
TempSupernova       3e+08       % T_SN, effective "supernova temperature",sets feedback energy (multi-
phase model)
TempClouds          1000        % temperature of cold clouds (multi-phase model)

FactorForSofterEQS  0.25        % Can be used to make the equation of state
                                % softer. For 1.0, the multiphase model is
                                % used, while for 0.0 isothermal at 10^4 K is
                                % assumed. Intermediate values interpolate
                                % linearly between the two pressures.

                                % Brants additions
REDSHIFT            0.0         % redshift to scale galaxy properties to
Omega_m0            0.3         % Omega_m
Omega_L0            0.7         % Omega_L
```

The halo structure can be scales to any redshift.

Step 0: Build an isolated disk galaxy

* MakeHubbleType:

```
OutputDir      ./               % Output directory
OutputFile     Sbc.dat          % Filename of generated initial conditions

CC              11.0       % halo concentration
Mvir            150.0      % virial mass (in 10^10 Msolar)
LAMBDA          0.050      % spin parameter

M_DISK          3.92       % total disk mass in units of 10^10 Msolar
M_GAS           2.4        % total disk mass in units of 10^10 Msolar
M_BULGE         1.00       % total disk mass in units of 10^10 Msolar

DARKMASS_IN_ROPT  9.95     % dark mass inside optical radius (3.2 * H)

H              5.5         % radial disk scale length
DiskHeight     0.125       % thickness of disk in units of radial scale length

N_HALO          200000      % desired number of particles in dark halo
N_DISK          60000       % desired number of collisionless particles in disk
N_GAS           60000       % number of gas particles in disk
N_BULGE         20000       % number of bulge particles

HUBBLE  0.70           % Hubble parameter (1 means units of h-1)

Z       0              % Redshift of Galaxy

GasDistribution  1             % 0 = exp. (normal, same Rd as disk)
                               %   1 = exp. (with Rd -> Rd*Alpha)
                               %   2 = Power Law (with PowerLawGamma < 2) and cut-off (PowerLawCutOff)
GasExpAlpha     3.0            % gas is exp. with Rd*Alpha scale length
PowerLawGamma   1              % power-law index, sigma ~ r^-gamma   (gamma=1 is mestel) - must be < 2
PowerLawCutOff  20             % in units of kpc, when gas disk is terminated

BulgeSize              0.45     % bulge scale length in units of disk scale length
BulgeDistribution      1        % 0 = Hernquist profile (BulgeSize sets a)
                                %  1 = Spherical exp. (BulgeSize sets 3D Rd)

HI_GasMassFraction     0.0     % in terms of the total gas mass
HI_GasDiskScaleLength  8       % in terms of scale length of the disk

Qstabilizefactor       1.0
```

It is unclear if using the basic model introduced by Mo, Mao, & White (1998) can capture the true range of properties observed in local disk galaxies so this program allows you to enter the structure explicitly.

Step 0: Build an isolated disk galaxy

* MakeDiskGalaxy and MakeHubbleType usage:

```
[hipacc-5@login-4-0 ~]$ cd Make???
[hipacc-5@login-4-0 Make???]$ make clean
[hipacc-5@login-4-0 Make???]$ make
cc -O3 ....
...
...
[hipacc-5@login-4-0 Make???]$ ./Make??? param.txt > param.output
[hipacc-5@login-4-0 Make???]$
```

-> This generates a xxx.dat file which is the initial conditions read-in by Gadget.

Step 1: Combining two isolated galaxies

* *CombineGalaxies* usage:

```
[hipacc-5@login-4-0 ~]$ cd CombineGalaxies
[hipacc-5@login-4-0 CombineGalaxies]$ dir
[hipacc-5@login-4-0 CombineGalaxies]$ make
cc         -O3 -Wall     -c -o main.o main.c
cc ........
....
[hipacc-5@login-4-0 CombineGalaxies]$ ./CombineGalaxies

wrong number of arguments
call with:

<fname_gal1> <theta1> <phi1>
<fname_gal2> <theta2> <phi2>
<rmin> <rstart>
<fname_galout>

(angles in degrees.)

[hipacc-5@login-4-0 CombineGalaxies]$
```

-> This generates a xxx.dat file which is the initial conditions read-in by Gadget.

NOTE:

In practice, Gadget doesn't care whether these initial conditions that it's reading in are equilibrium models of galaxies or not. ANY file with the appropriate format (head, xyz position, xyz velocity, if gas is present, a temperature - see the c-code *save.c* in any of the aforementioned programs) will suffice as an initial condition. This affords tremendous flexibility for you to study any process that you consider to be relevant or interesting.

APOLOGY:

Discussion of cosmological initial conditions, codes that generate these, and examples of these will be omitted from this discussion - but I’m certain there are numerous people sitting in this room that can aid in this regard.

Step 2: Getting to know your computational "environment"

A significant component of numerical work is being able to trouble-shoot the compilation of your code, the successful running of it within a multi-user environment, and handling the large quantity of complex data it generates.

* compiling from source: what libraries does Gadget require?

* communication protocols?

* optimization?

* space considerations, data analysis and visualization?

Project 1.1: Code Optimization

What's currently loaded (this is the triton default):

```
 [hipacc-5@login-4-0 ~]$ module list
Currently Loaded Modulefiles:
  1) pgi/10.5           2) openmpi_mx/1.4.1   3) hdf5/1.8.3         4) idl/706
[hipacc-5@login-4-0 ~]$
```

Other commands to know about:

```
module avail
module list
module load xxxx
module unload xxxx
```

Project 1.1: Code Optimization

Compilers and communication protocols are loaded via modules (this is the triton default):

```
[hipacc-5@login-4-0 ~]$ module avail

---------------------------------------- /opt/modulefiles/applications/.pgi ---------------------------------------
fftw/3.2.1(default)   hdf4/2r4(default)     hdf5/1.8.3(default)   netcdf/3.6.2    netcdf/4.0.1(default)

---------------------------------------- /opt/modulefiles/mpi/.pgi ------------------------------------------------
mpich_mx/1.2.7(default)   openmpi_mx/1.4.1(default)

---------------------------------------- /opt/modulefiles/compilers ----------------------------------------------
gnu/4.1.2(default)  intel/11.1(default) pgi/10.5(default)

---------------------------------------- /opt/modulefiles/applications -------------------------------------------
apbs/1.2.1(default)     bioroll/5.3(default)    fsa/1.15.2(default)     idl/706(default)        namd/2.6
nwchem/5.1.1(default)  bbftpc/320(default)     ddt/2.4.1(default)      gamess/1.2009(default)  lammps/28Nov09(default)
namd/2.7b1(default)

---------------------------------------- /opt/modules/Modules/versions -------------------------------------------
3.2.5
---------------------------------------- /opt/modules/Modules/3.2.5/modulefiles ----------------------------------
dot          module-cvs  module-info modules     null        use.own
[hipacc-5@login-4-0 ~]$
[hipacc-5@login-4-0 ~]$
```

Project 1.1: Code Optimization

```
---------------------------------------- /opt/modulefiles/compilers ----------------------------------------------
gnu/4.1.2(default)   intel/11.1(default) pgi/10.5(default)
```

triton has 3 different c compilers

```
[hipacc-5@login-4-0 ~]$ module unload pgi/10.5
Unloading compiler-dependent module openmpi_mx/1.4.1
Unloading compiler-dependent module hdf5/1.8.3
[hipacc-5@login-4-0 ~]$ module load gnu/4.1.2
```

the default

Project 1.1: Code Optimization

```
[hipacc-5@login-4-0 ~]$ module avail

--------------------------------------- /opt/modulefiles/applications/.pgi ---------------------------------------
fftw/3.2.1(default)   hdf4/2r4(default)     hdf5/1.8.3(default)   netcdf/3.6.2    netcdf/4.0.1(default)

--------------------------------------- /opt/modulefiles/mpi/.pgi ---------------------------------------
mpich_mx/1.2.7(default)   openmpi_mx/1.4.1(default)

--------------------------------------- /opt/modulefiles/compilers ---------------------------------------
gnu/4.1.2(default)  intel/11.1(default) pgi/10.5(default)

--------------------------------------- /opt/modulefiles/applications ---------------------------------------
apbs/1.2.1(default)     bioroll/5.3(default)    fsa/1.15.2(default)     idl/706(default)        namd/2.6
nwchem/5.1.1(default)  bbftpc/320(default)     ddt/2.4.1(default)      gamess/1.2009(default)  lammps/28Nov09(default)
namd/2.7b1(default)

--------------------------------------- /opt/modules/Modules/versions ---------------------------------------
3.2.5
--------------------------------------- /opt/modules/Modules/3.2.5/modulefiles ---------------------------------------
dot          module-cvs  module-info modules     null        use.own
[hipacc-5@login-4-0 ~]$
[hipacc-5@login-4-0 ~]$
```

the default portland compiler allows for two communication protocols

Project 1.1: Code Optimization

You can use specific compilers and communication protocols via the loading and unloading of the appropriate modules. This can make a significant difference in simulation run times.

Project 1.1: Code Optimization

PBS batchscript :

```
#!/bin/sh
#PBS -q batch
#PBS -N Sbc
#PBS -l nodes=2:ppn=2
#PBS -o Sbc.out
#PBS -e Sbc.err
#PBS -V
#PBS -M tcox@obs.carnegiescience.edu
#PBS -m abe

cd /home/hipacc-5/Sbc/

mpirun -v -machinefile $PBS_NODEFILE -np 4 ./Gadget2 Sbc.txt > output0.txt
```

Project 1.1: Code Optimization

PBS batchscript :

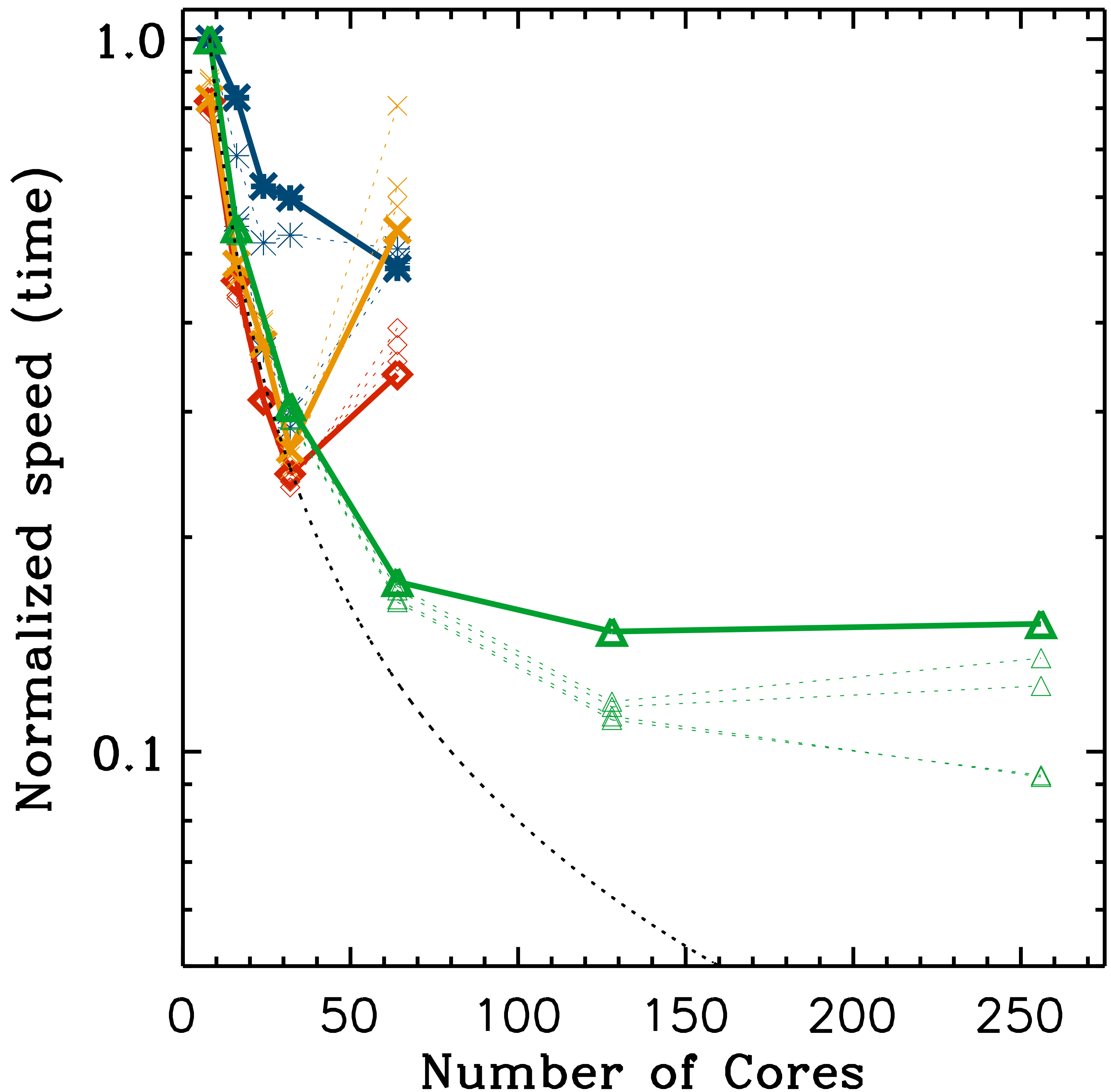
```
#!/bin/sh
#PBS -q batch
#PBS -N Sbc
#PBS -l nodes=2:ppn=2
#PBS -o Sbc.out
#PBS -e Sbc.err
#PBS -V
#PBS -M tcox@obs.carnegiescience.edu
#PBS -m abe

cd /home/hipacc-5/Sbc/

mpirun -v -machinefile $PBS_NODEFILE -np 4 ./Gadget2 Sbc.txt > output0.txt
```

How many cores (nodes & processors per node) should we be using?

Project 1.1: Code Optimization



* Speed scales with the number of processors up to a point.

* The point of deviation depends upon the problem (higher N, N_gas, smoother particle distributions all improve the scaling)

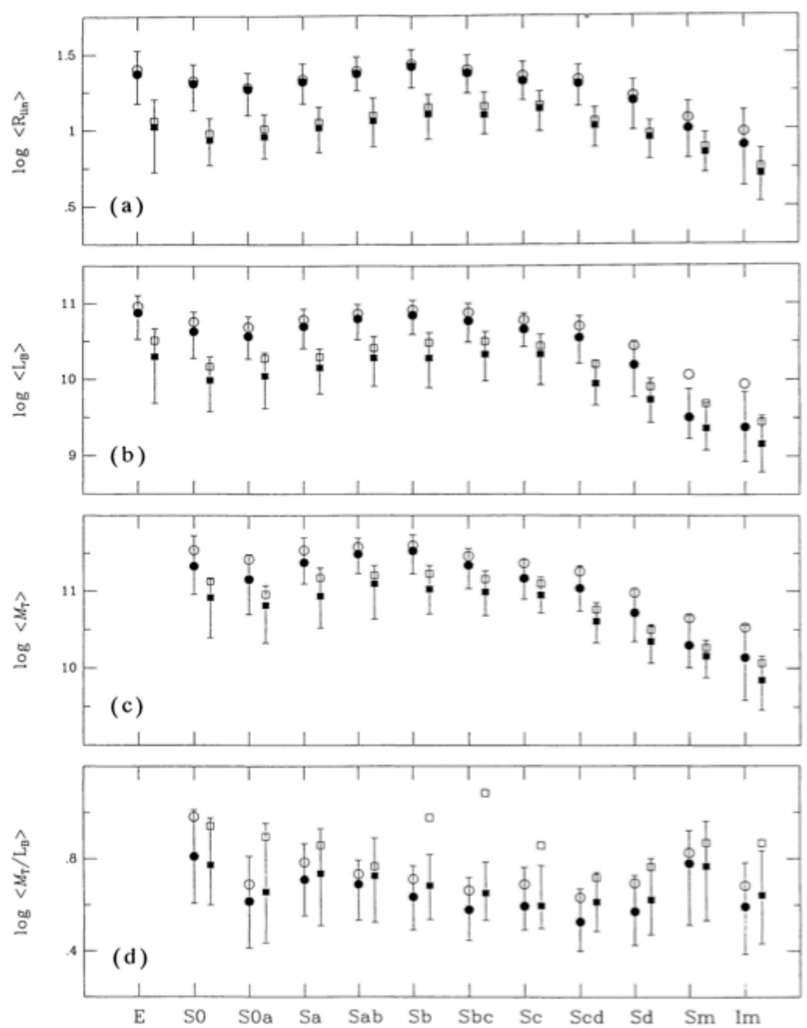
* Until you determine the scaling relation for the problem you're interested in, using a smaller number of cores will result in more efficient calculations.

Project 1: Build a disk, simulate its evolution, and assess its stability

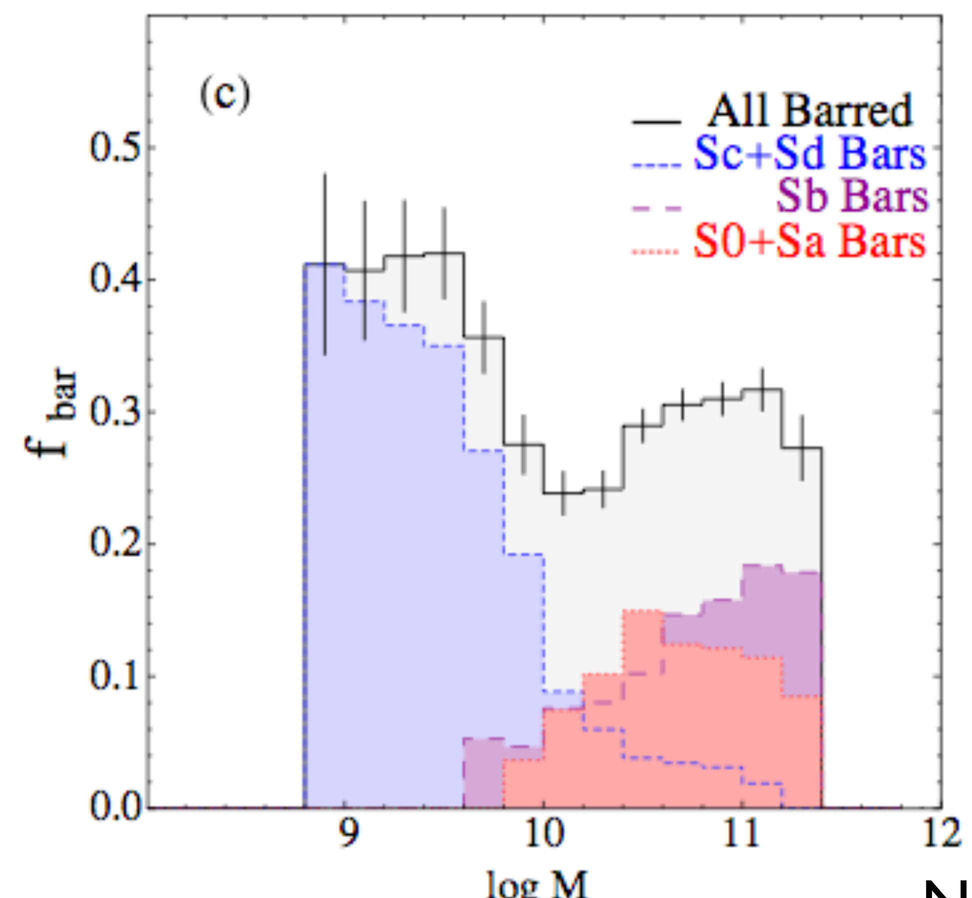
* This is the starting point for ALL of the projects suggested here.

* In practice, the underlying motivation of this project is to gain experience, building and using Gadget within a computational environment such as triton.

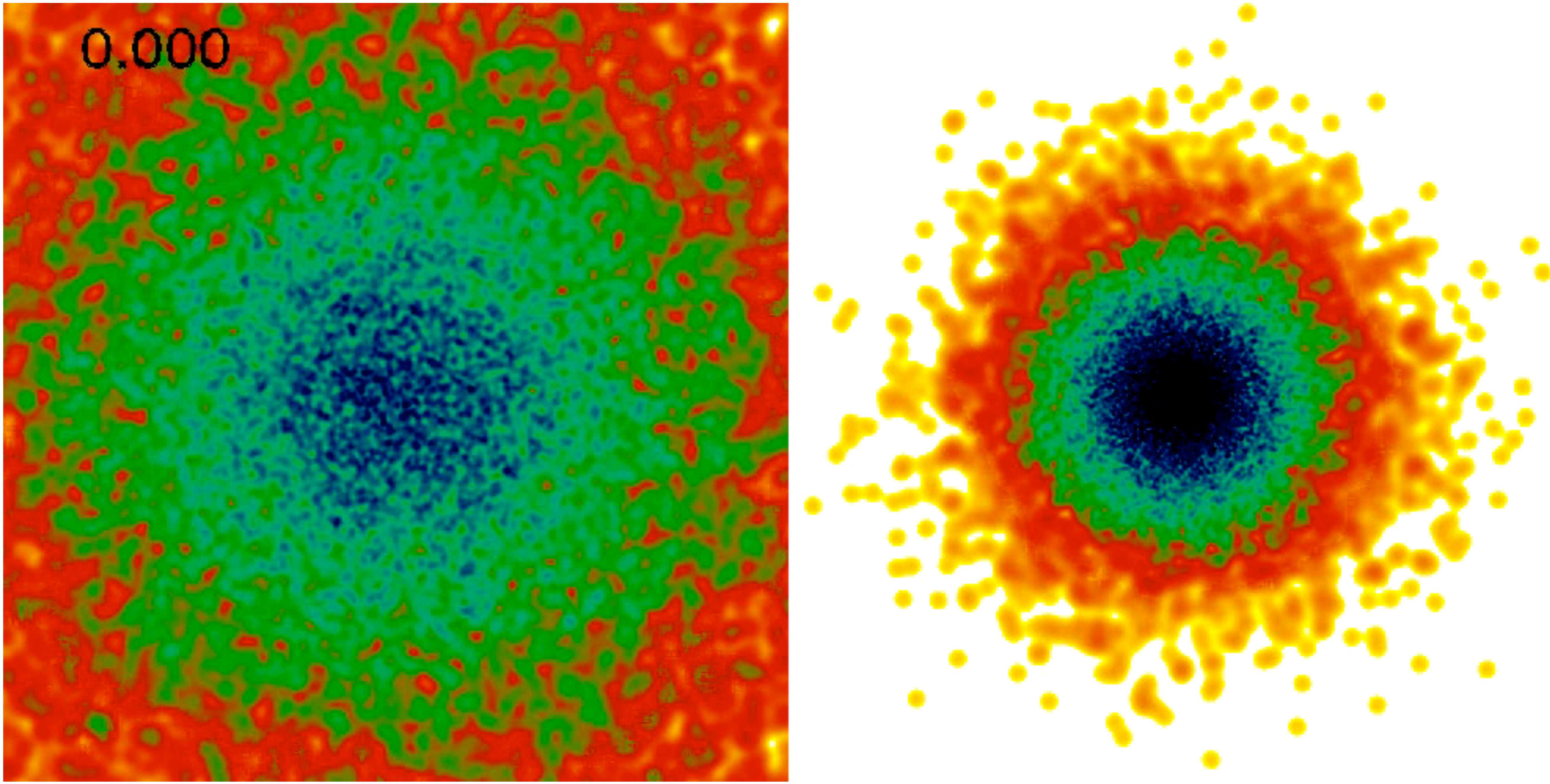
* However, the science involved within this project is still interesting: constructing galaxies of all Hubble types, testing commonly employed stability criteria, and understanding f_bar. Plus, these would be very useful initial condiitions for merger simulations.



Roberts & Haynes (1994)



Nair & Abraham (2010)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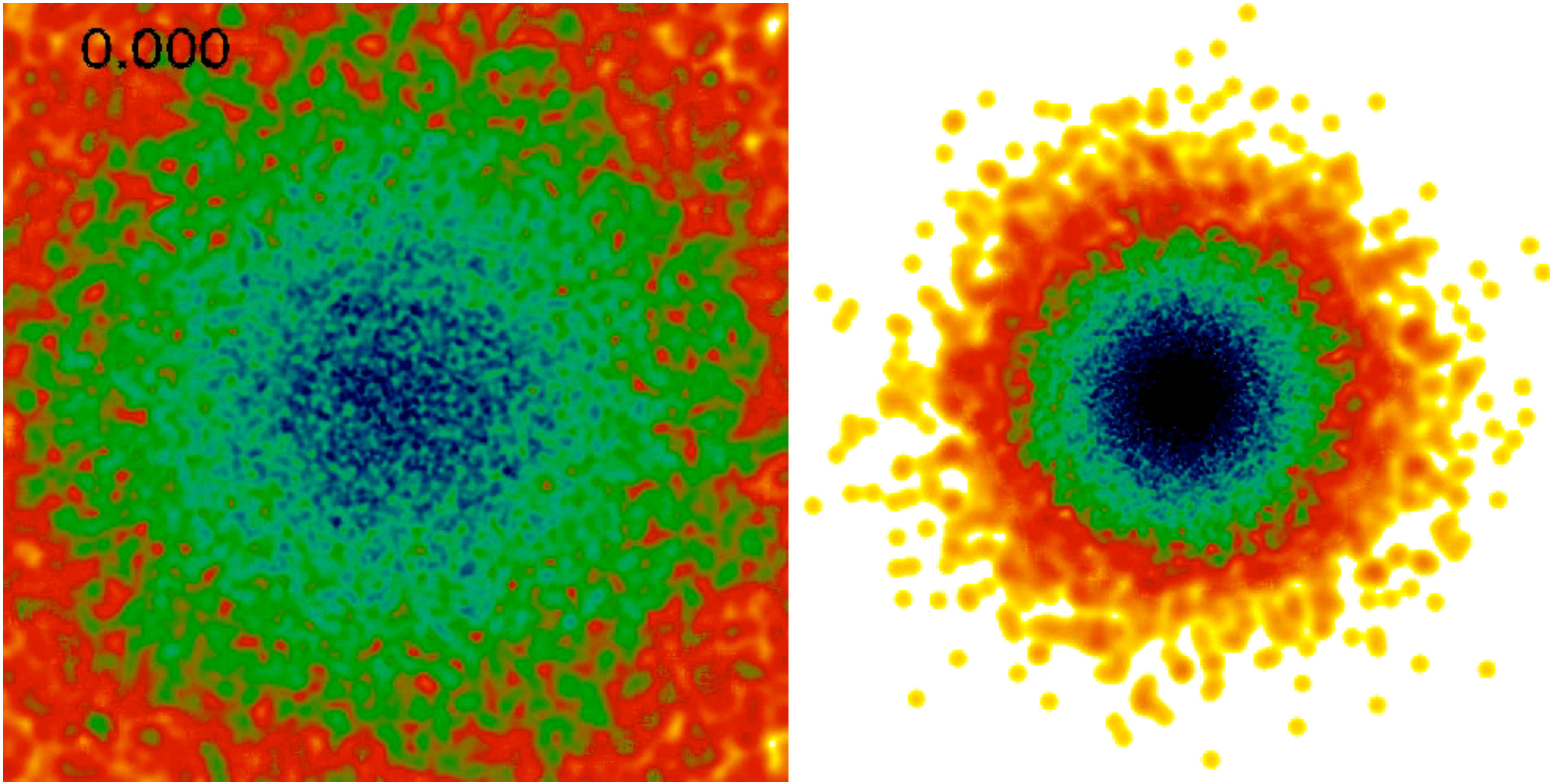
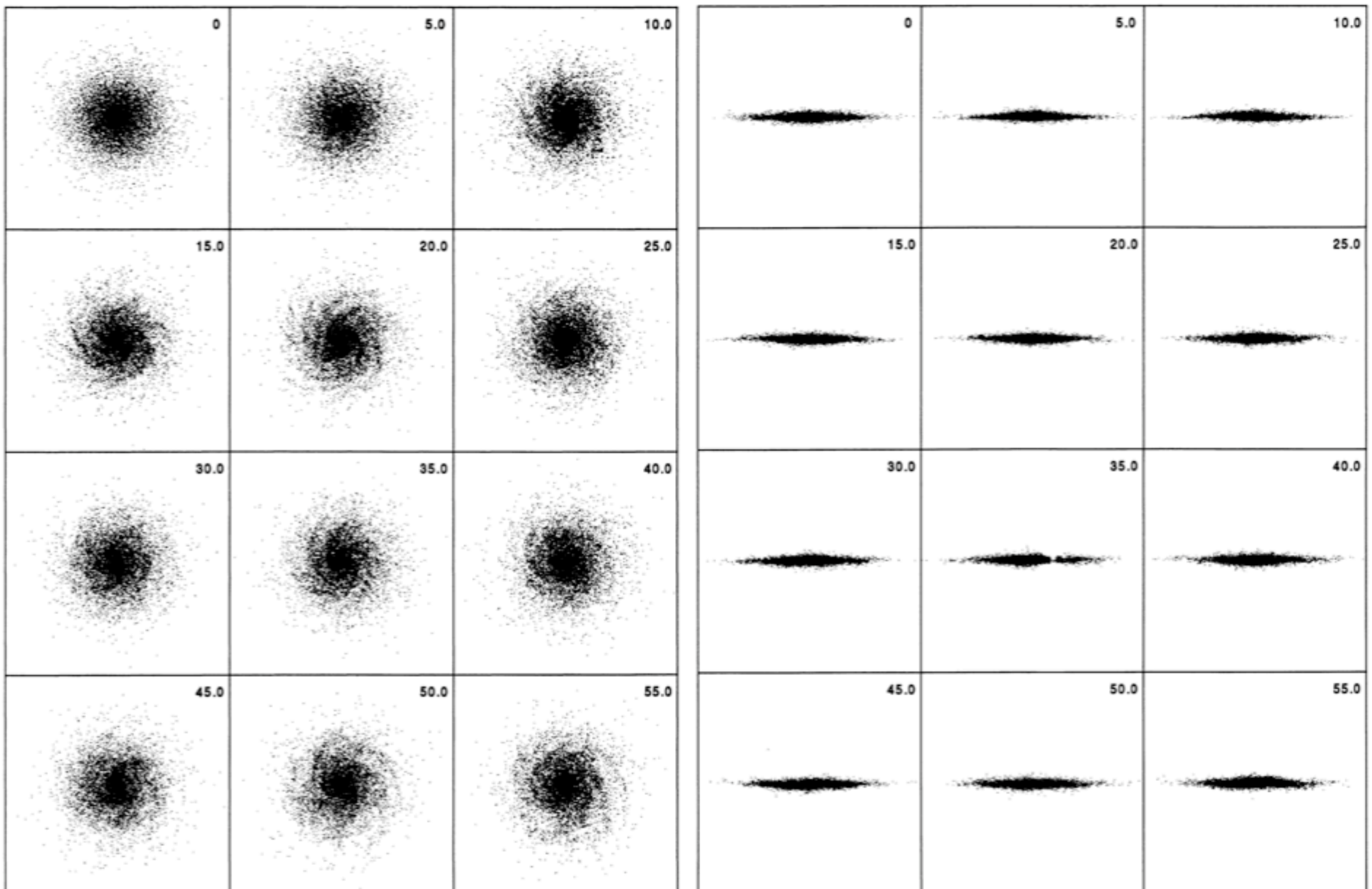

0.000

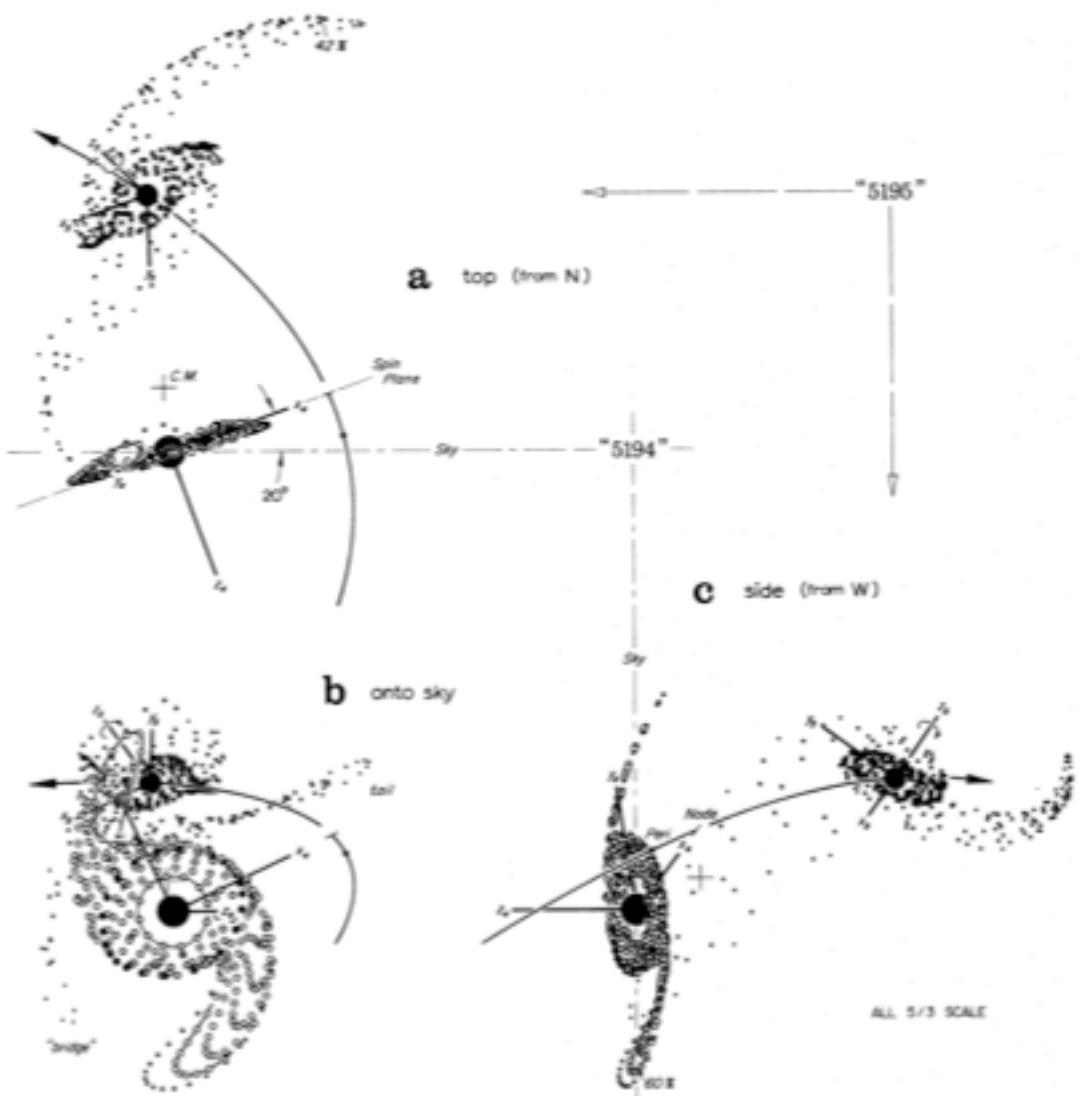
Project 1: Build a disk, simulate its evolution, and assess its stability

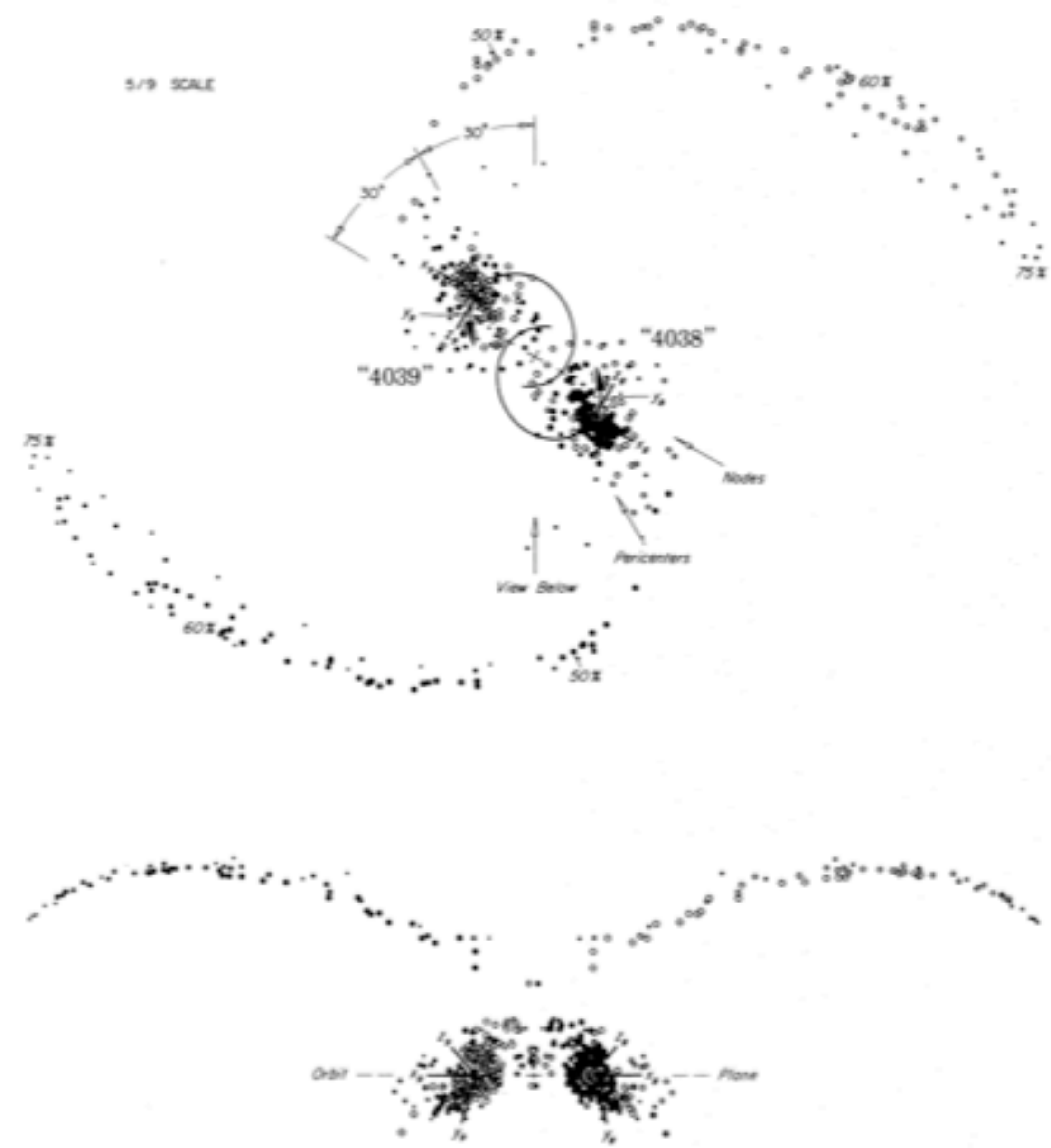
* A cautionary note: instabilities can be generated by both physical (dark matter content, bulge mass, disk kinematics, etc.) and numerical effects (noisy potential).



Hernquist (1993)

Project 2: Building merger models that match observed systems



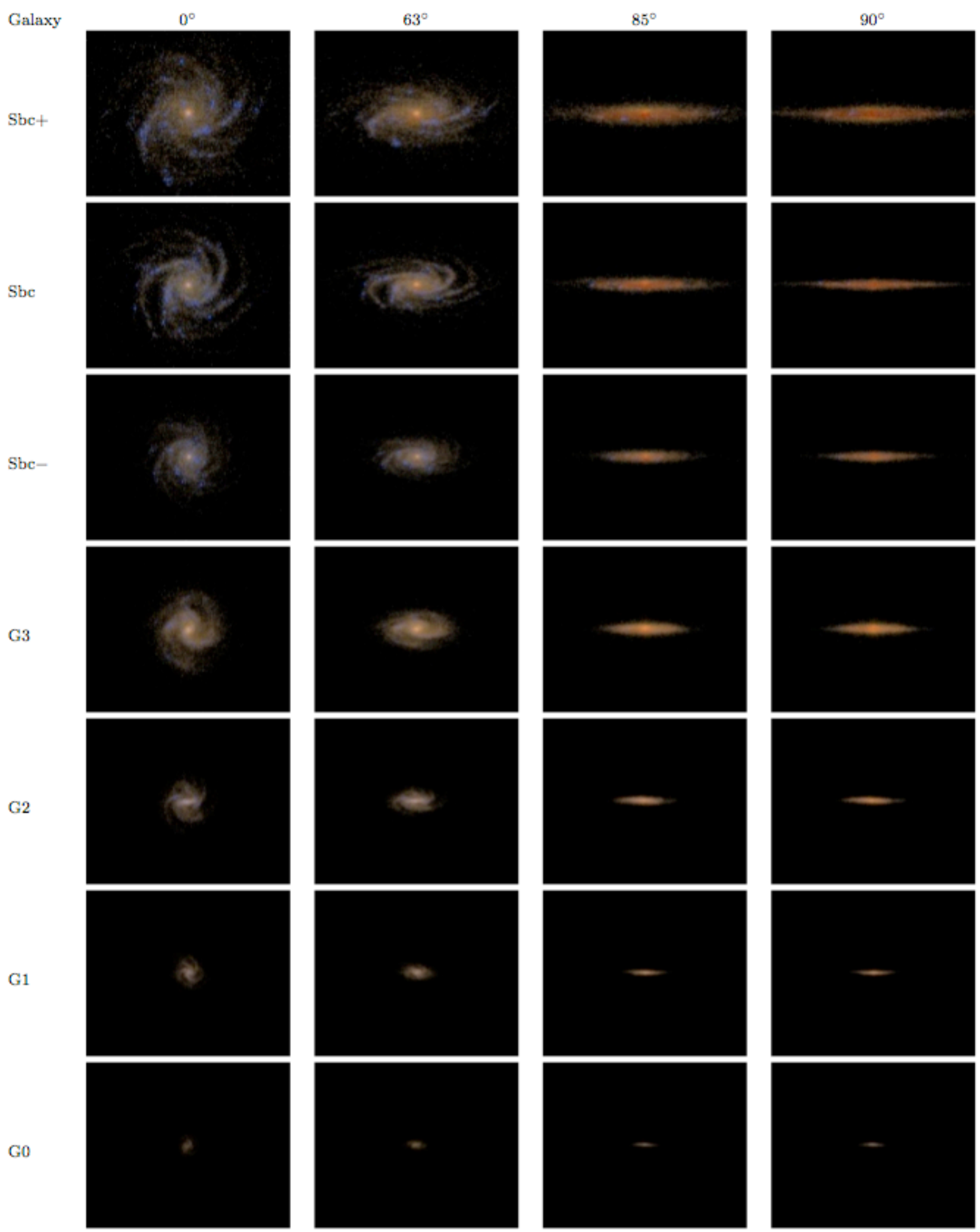


Toomre & Toomre (1972)

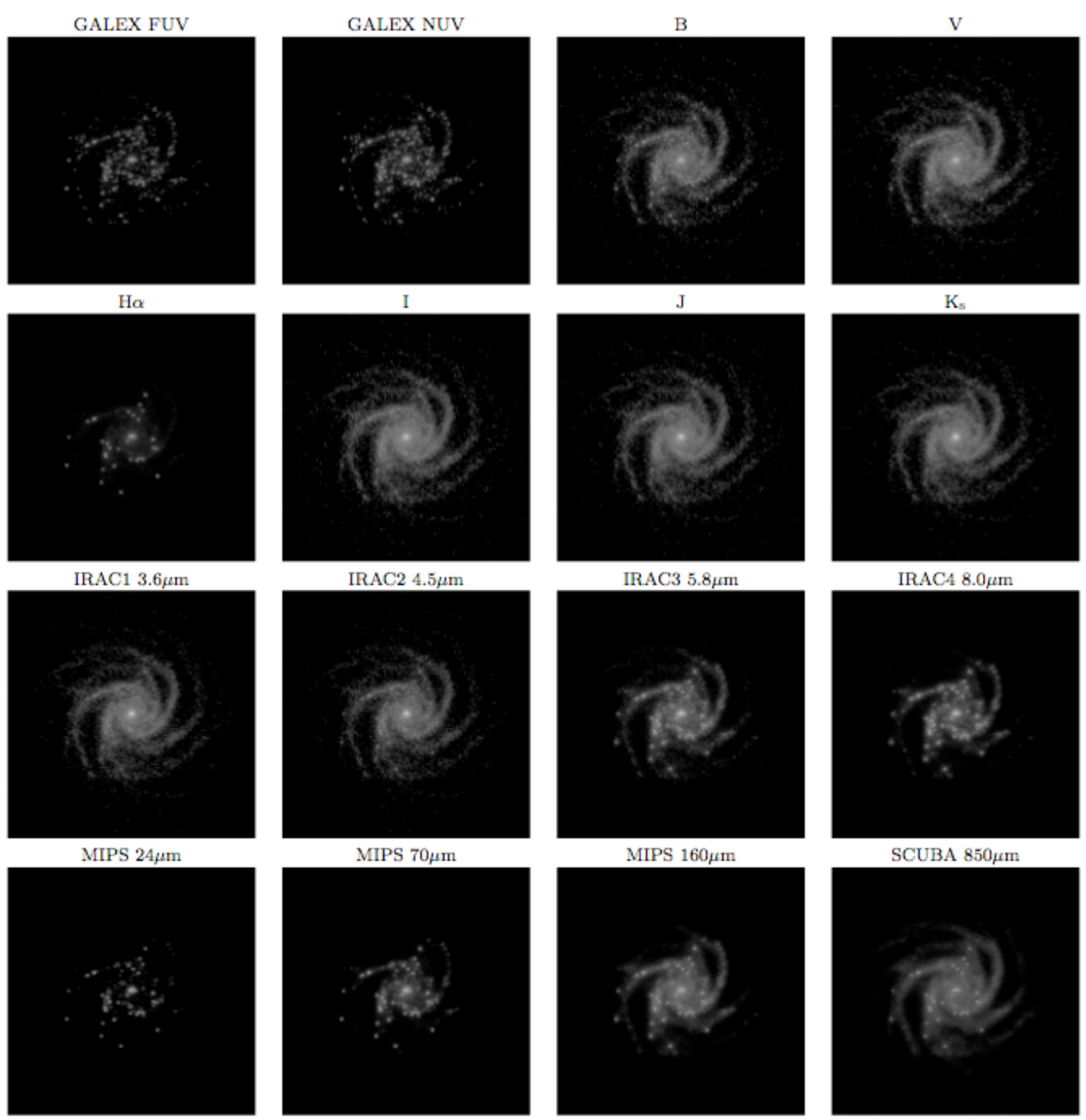
Project 2: Building merger models that match observed systems

- Confirmation (or revision to) our understanding of the merger hypothesis and the growth of galaxies.
- A great way to test the astrophysical models (both "resolved" and sub-grid) and radiative transfer post-processing.
- It's useful to do this for isolated systems AND mergers so that we can probe a wide range of ISM conditions.
- Fun!

Project 2: Building merger models that match observed systems

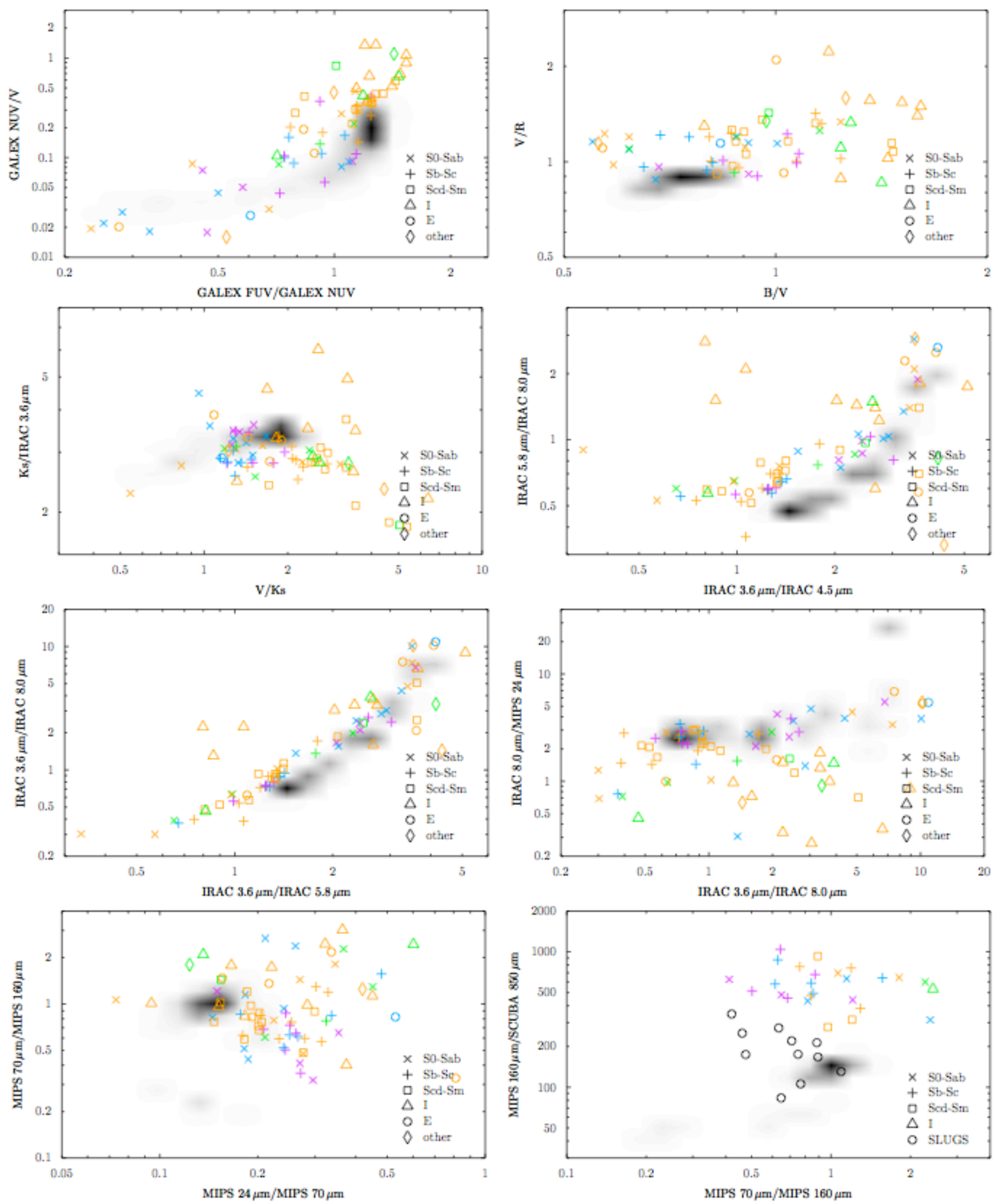


Using Sunrise we can now do model-observation comparisons in the observational realm (i.e., compare apples to apples).



Jonsson, Groves, & Cox (2010)

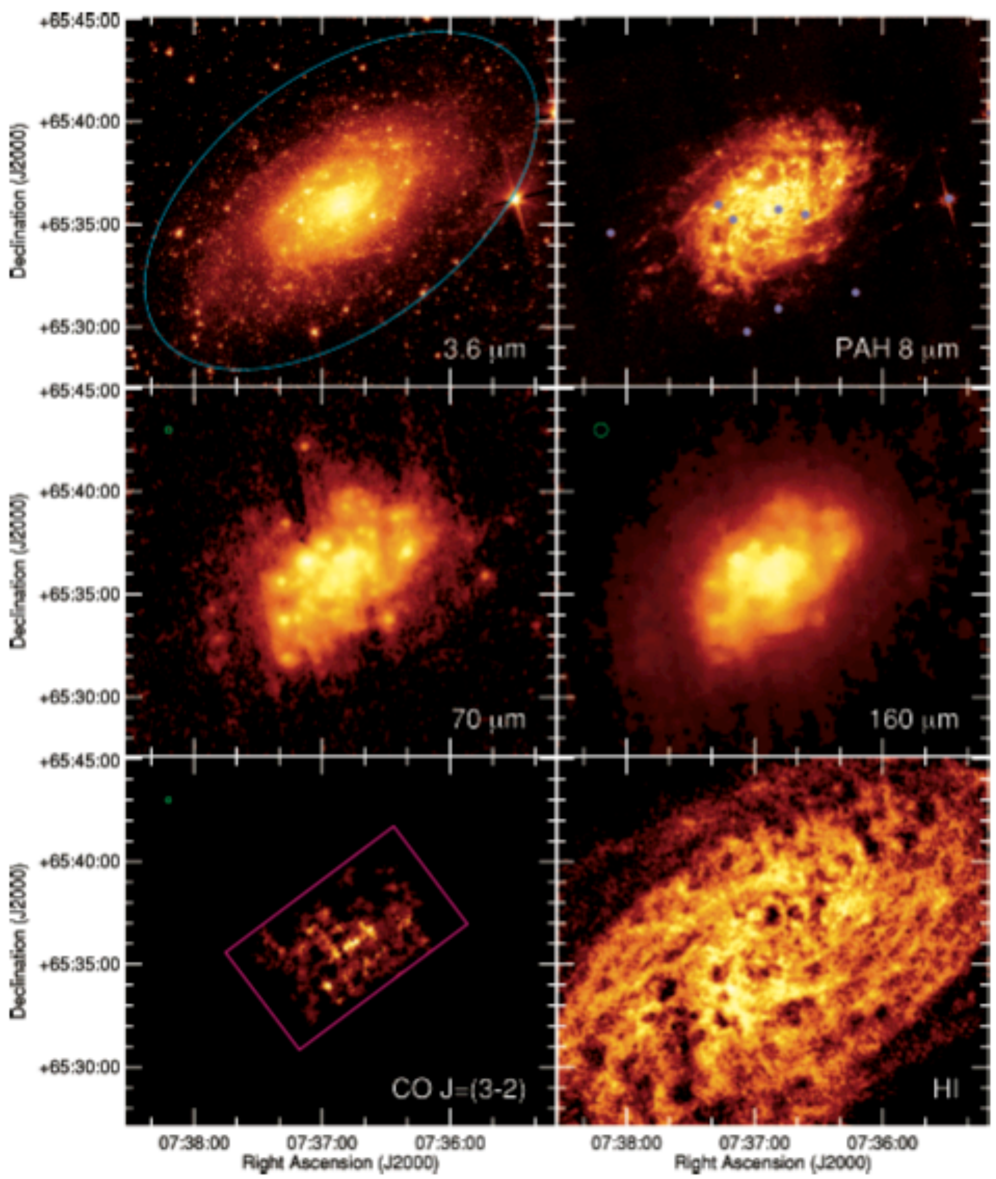
Project 2: Building merger models that match observed systems

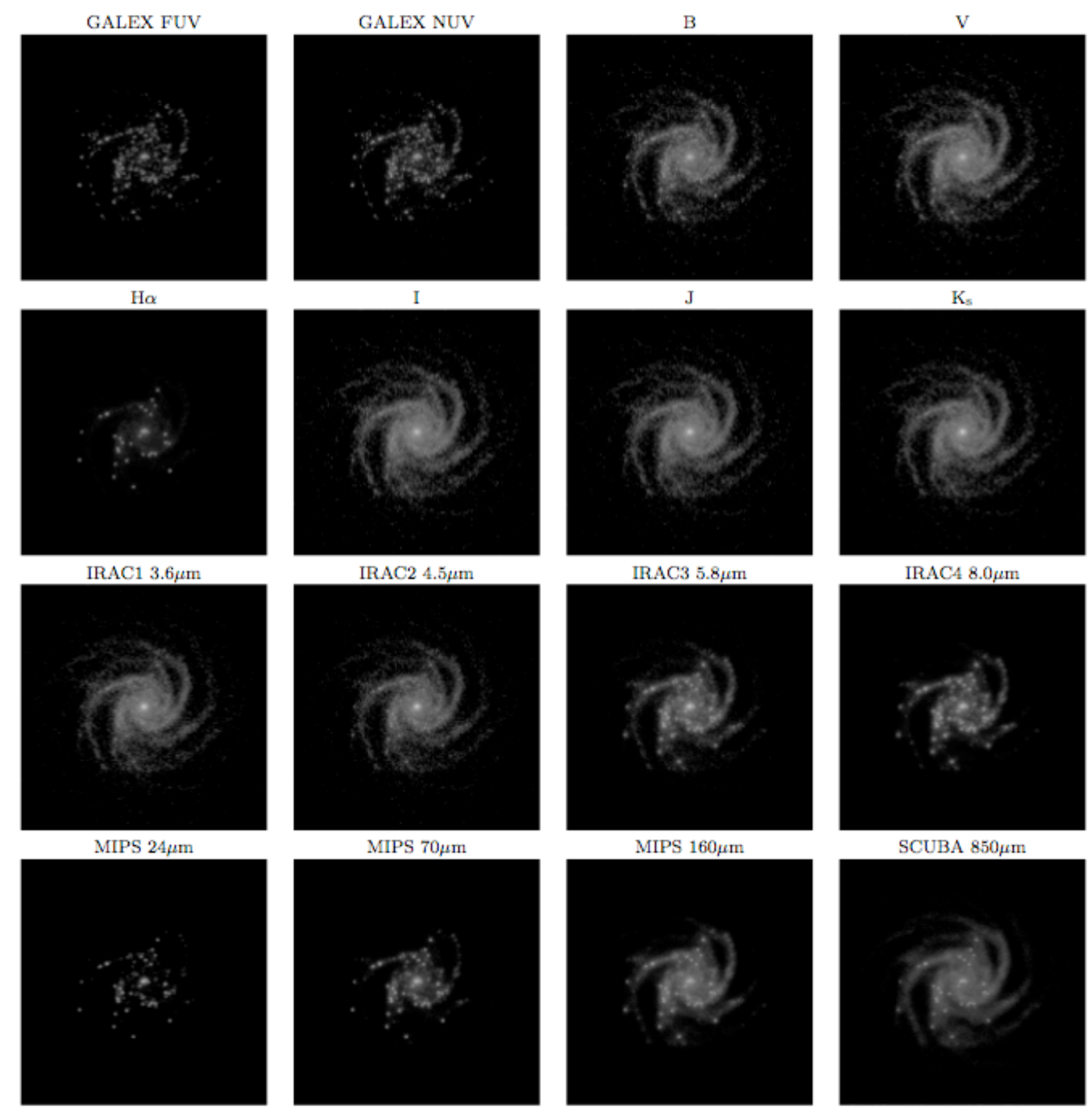


Comparison is encouraging, but are the differences due to modeling uncertainties, initial conditions, or both?

And, these are integrated quantities!

Project 2: Building merger models that match observed systems

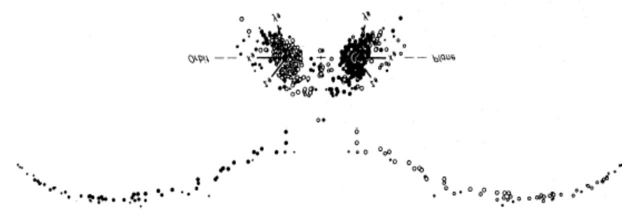


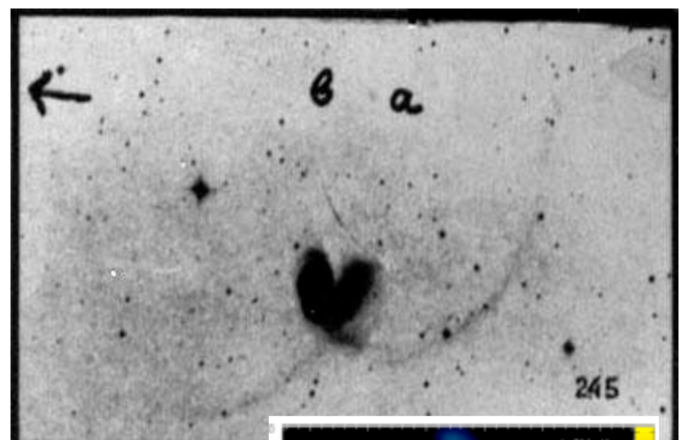


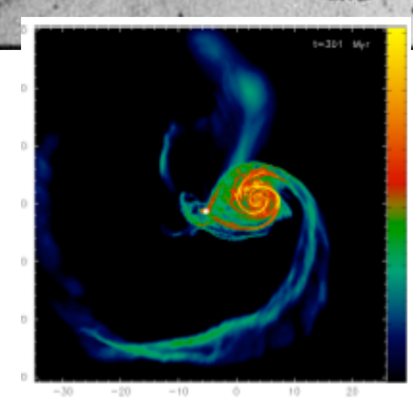
Project 2: Building merger models that match observed systems

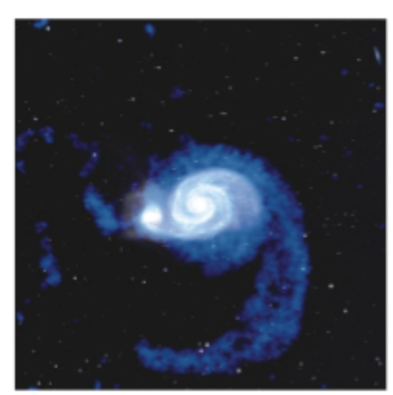
A partial list (see Barnes & Hibbard 2009 for a more complete list) .....

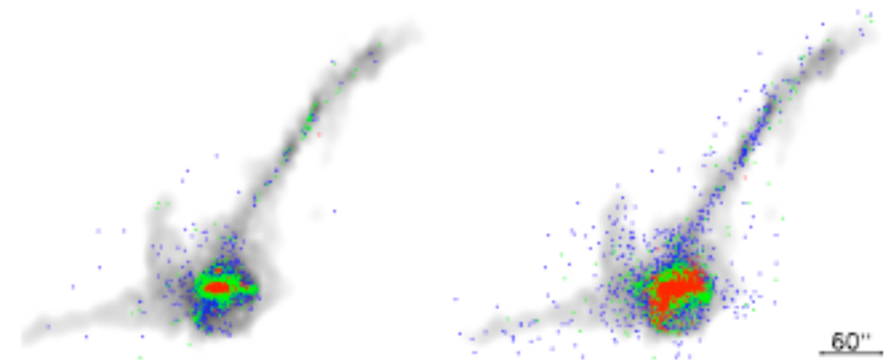
- 1970's: Toomre's (M51, Antennae, Arp 295, NGC 4676)
- 1995: NGC 7252
- 1997: Mihos & Bothun, NGC 2442
- 1998/2001: Hearn & Lamb, Arp 118/119
- 2000: Salo & Laurikainen, M51
- 2003: McDowell, Arp220
- 2004: Barnes, The Mice
- 2005: Smith/Struck, NGC 7714/15, NGC 2207
- 2006: Block, M31
- 2008: Bekki, M31/M33
- 2009: Renaud, The Antennae
- 2009: Dobbs, M51
- 2010: Chein/Barnes, NGC 7252 + a few more
- 2010: Green/Mulchaey/Cox, binary QSO

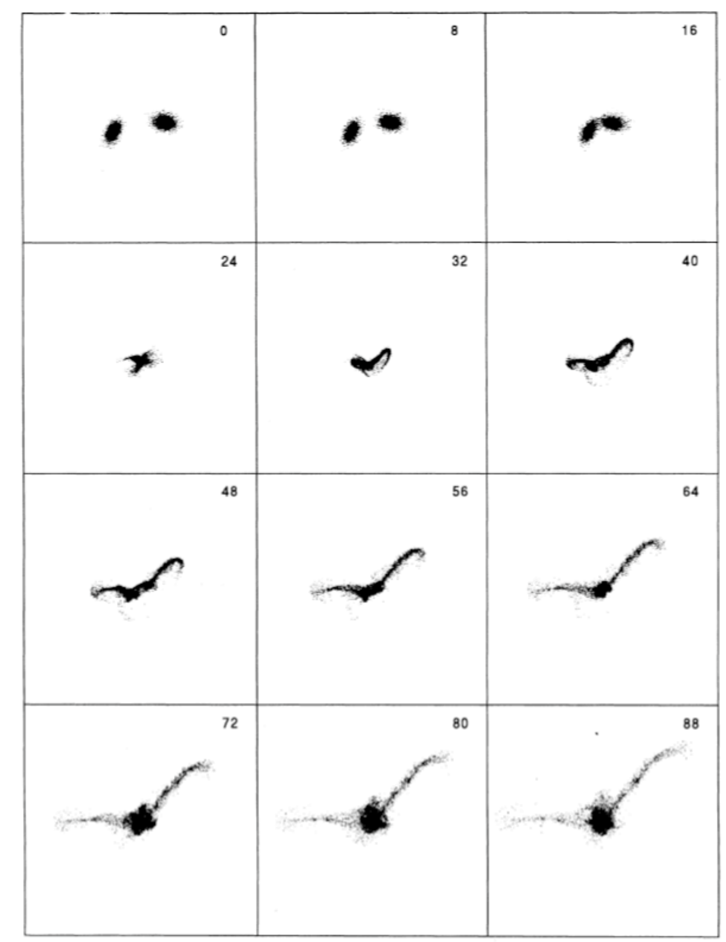












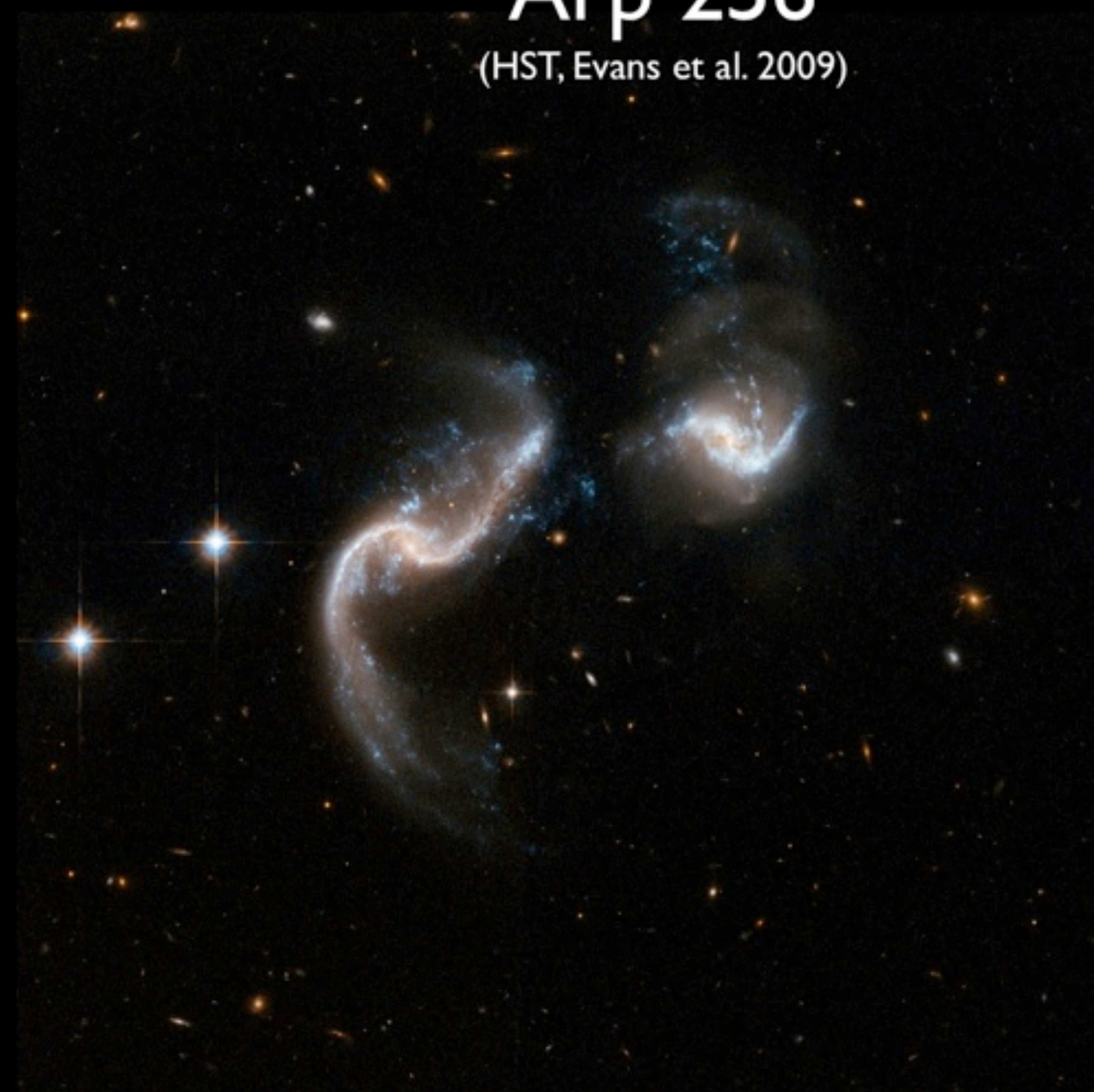
Project 2: Building merger models that match observed systems

- Since finding a matching model is quite difficult, I've compiled a handful of recent model-matching efforts that have been published.
- Read these papers, extract the disk galaxy models and interaction parameters and port these to the Makexxx and CombineGalaxies codes to generate Gadget initial conditions.
- Run with Gadget
- If we have time, we can run these outputs through Sunrise next week.

Numerical Simulation

Arp 256

(HST, Evans et al. 2009)



Project 3/4: Modifying Gadget and doing code comparisons

- If you've found enjoyment and success in doing some of the prior projects, then these additional projects are a great way to delve into the guts of Gadget.
- A code comparison (a la the Santa Barbara cluster comparison project, or some of the Enzo/Ramses/Gadget comparisons of O'Shea et al., or Agertz et al.) for an idealized simulation is long overdue .... and would be very useful for the community at large.