How to Form Realistic Disk Galaxies  
In Lambda CDM SPH Simulations

**F. Governato (UW), C. Brook, A. Brook**

B. Willman (CfA), J. Wadsley (McMaster), L. Mayer (U. of Zurich), Greg Stinson, Adrienne Stilp, Charlotte Christensen, T. Quinn and the UW N-Body Shop
SDSS low z galaxies.
Hydrodynamical simulations of galaxy formation in a cosmological context.

Brook et al. 05.
The Formation of a Milky Way like Galaxy.
Green = Gas
Blue and Red: Stars

Frame 40 Kpc
Force resolution 300pc
1 million DM +
1 million gas +
2 million star particles
Our Manifesto:

- Run Simulations at the Highest Possible Resolution
- Adopt a fully realistic cosmological context
- Explore a significant Range of Galaxy Masses
- Introduce a physically motivated description of the effects of Star Formation and SN Feedback.
- Complete Simulations to redshift $z = 0$
- Evaluate Resolution Effects
- Test Results vs Multiple Observational Constrains
Milky Way Substructure

Moore, Quinn, Governato, et al. 1999

CDM predicts hundreds of subhalos within the DM halo of an L*Galaxy.

Only 10 observed within the Milky Way’s halo.
Reproducing the slope and normalization of the Tully-Fisher Relation

Disks rotate too fast at a given luminosity

Or Simulated Galaxies too Red?

Portinari et al 2006
“Anti Hierarchical” Galaxy Formation?

L. MacArthur, S. Courteau, and E. Bell 2004

More Massive Galaxies Have older Stellar Populations

... in CDM Massive Halos Assemble Later Than Smaller Ones
- Parallel N-body Solver (Tree Method) and Smoothed Particle Hydrodynamics
- Physics: Gravity, Hydrodynamics, Atomic Chemistry, Radiative Heating+Cooling, UV field
- Subgrid Physics: Star Formation, Supernova Feedback, Metal Enrichment
- *Coupled with GRASIL/SUNRISE*: allows us to make detailed predictions of the observable properties of galaxies

Wadsley, Stadel & Quinn 2003, New Astronomy
Star Formation and Feedback details

- Star Particles formed from cold, dense gas
- A LOCAL Schmidt Law is assumed
- O and Fe yields from SN I & II
- Kroupa IMF
- Mass/metals loss from winds included.
- SN energy released as thermal energy within blastwave Radius, obtained from Sedov’s solution ~ 1kpc
- Cooling shut off ~ 20 Myrs (Sedov’s expansion phase)
- uniform, time varying UV field

Scheme gives a physically motivated description of the effects of SN feedback at unresolved scales.
**Test/Tune** Free Parameters for Star Formation and Feedback in Isolated Models of present day galaxies:

Gas Rich Dwarf
Milky Way - like disk galaxy

- Star Formation Efficiency
- Efficiency of SN energy injection into the ISM

*See Governato et al 2007 MNRAS for details*
DWF1 Galaxy. Disk is 10kpc across

LMC HI distribution Venn+Stavely Smith 2003
The simulation campaign II

Apply SF+SN algorithm to galaxy formation in a full cosmological context assuming post WMAP LCDM. to study the ab initio formation of disk galaxies over a range of masses. Keep best parameters fixed!

$1.2 \times 10^{11}$ (Irr Galaxy), $1 \times 10^{12}$ (Milky Way), $3 \times 10^{12}$ (S0) Solar masses

→ Good candidates to host disk dominated galaxies

Last Major Merger at $z \sim 2-2.5$

Lambda (spin parameter) within 0.01-0.05

Spatial resolution: 150-600 pc

Mass resolution >$1.000.000 + 1.000.000$ DM+gas particles within Virial Radius. Simulations carried to $z=0$. 
“Zoom in” technique:
high resolution halo surrounded by low resolution region

Computationally Efficient

Cosmic Infall and Torques correctly included

<------------------ 6 Mpc Sphere ------------------>
<------------------ 1000 Mpc Box ------------------>
Satellites’ Luminosity Function for a Milky Way sized Galaxy

UV + SN feedback reproduce the correct number of Satellites expected Within a Milky Way sized halo.
MW Satellites: UV field + SN feedback on

30-50 Km/sec

BARYONS TO DM RATIO

30-50 Km/sec

- UV off, $\epsilon_{SN} = 0$
- UV on, $\epsilon_{SN} = 0$
- UV on, $\epsilon_{SN} = 0.4$
Effect of SN feedback on SFH of a 10^{11} Solar Masses Galaxy

Star Formation peaks at $z < 1$ AFTER Last Major Merger.

Early mergers inefficient and gas rich.

SFH includes all progenitors at any given time.
Past & Present Star Formation Rates

SF delayed
In Smaller Halos.

Star Formation History
Strong Function of Halo Mass.
Good match with SDSS data.
(Brinkmann et al.)
SN Feedback Reproduces the Observed Vrot vs Age Trend.

Star Formation delayed/suppressed In small progenitors
I band TF & baryonic TF

Giovanelli & Haynes 05

MacGaugh et al 2005
Enlarging our galaxy sample: Brooks et al. 07.
Simulations reproduce the Metallicity – Stellar Mass relation

![Graph showing the mass-metallicity relation of simulated galaxies at z=0 (solid points) and z=2 (open diamonds). The solid curved line is the observational fit to >50,000 galaxies in SDSS from T04, shifted down by -0.26 dex as found by E08. Error bars show the observational mass-metallicity relation at z=2 from E08. Dotted lines connect some of the z=0 galaxies to their projections at z=2, showing how galaxies evolve in the M_\star-z plane with time.](image-url)
Are All Simulations Created Equal?

The effects of Resolution and details in the Star Formation and SN Feedback algorithms on The Spheroid/Disk components of Disk Galaxies.

Figure 3. The three panels show density maps of gas in a slice through the centre of the Milky Way gas disk after 5 Gyr, from left to right: HRLs, IRLs, LRLs. Box side length 20 kpc for every panel - clearly the disk is larger for higher resolution and the bulge to disk ratio lower.
Effects of Increasing Resolution on the Disk Rotation Curve

![Graph showing effects of increasing resolution on the disk rotation curve. The graph displays V_rot as a function of R/R_d with different curves representing varying resolutions. Central baryon concentration decreases as resolution increases.]

...central baryon concentration decreases
Monte-Carlo method

“Photons” are emitted and scattered/absorbed stochastically (courtesy Patrik Jonsson)
http://www.ucolick.org/~patrik/sunrise/
HST - ACS composite image
30 Kpc across. $z=0.15$

Image processing: Sunrise by P. Jonsson
Effect of Increasing Resolution on the size of disks

Blast Wave Feedback
n = 4e6

medium resolution
n = 7e5

low resolution
n = 7e4

SDSS i band

GALEX NUV
Effects of Feedback and Alternative SF

- medium resolution
- No supernova feedback
- Thermal feedback
  Star Formation Recipes: Kravtov

SDSS i-band

GALEX NUV
The effects of Resolution and SN Feedback on The Spheroid/Disk components of Disk Galaxies: Kinematic Decomposition.
Resolution, Feedback and the TF

![Graph showing the relationship between resolution, feedback, and the TF. The x-axis represents Log V_{rot} (Km/sec), and the y-axis represents M_\star. The graph illustrates that smaller Rd (radius) corresponds to higher Vrot (rotation velocity) and a redder disk.](image-url)
Summary:
Tested the CDM Galaxy Formation Model over a wide range of Observational Constraints.
We presented LCDM simulations of Galaxy Formation over a range of masses with: high resolution + realistic description of SF and SN feedback.

Both are necessary ingredients to reproduce the observed properties of galaxies.

- N > 100,000 DM needed to avoid ARTIFICIAL angular momentum loss

- Realistic Feedback necessary to make Star Formation inefficient
  - in low Vc halos and to create thin, extended disks.

Sophisticated artificial images in HST, Spitzer, SDSS filters are now possible.

Contacts: fabio@astro.washington.edu, cbrook@astro, abrooks@astro