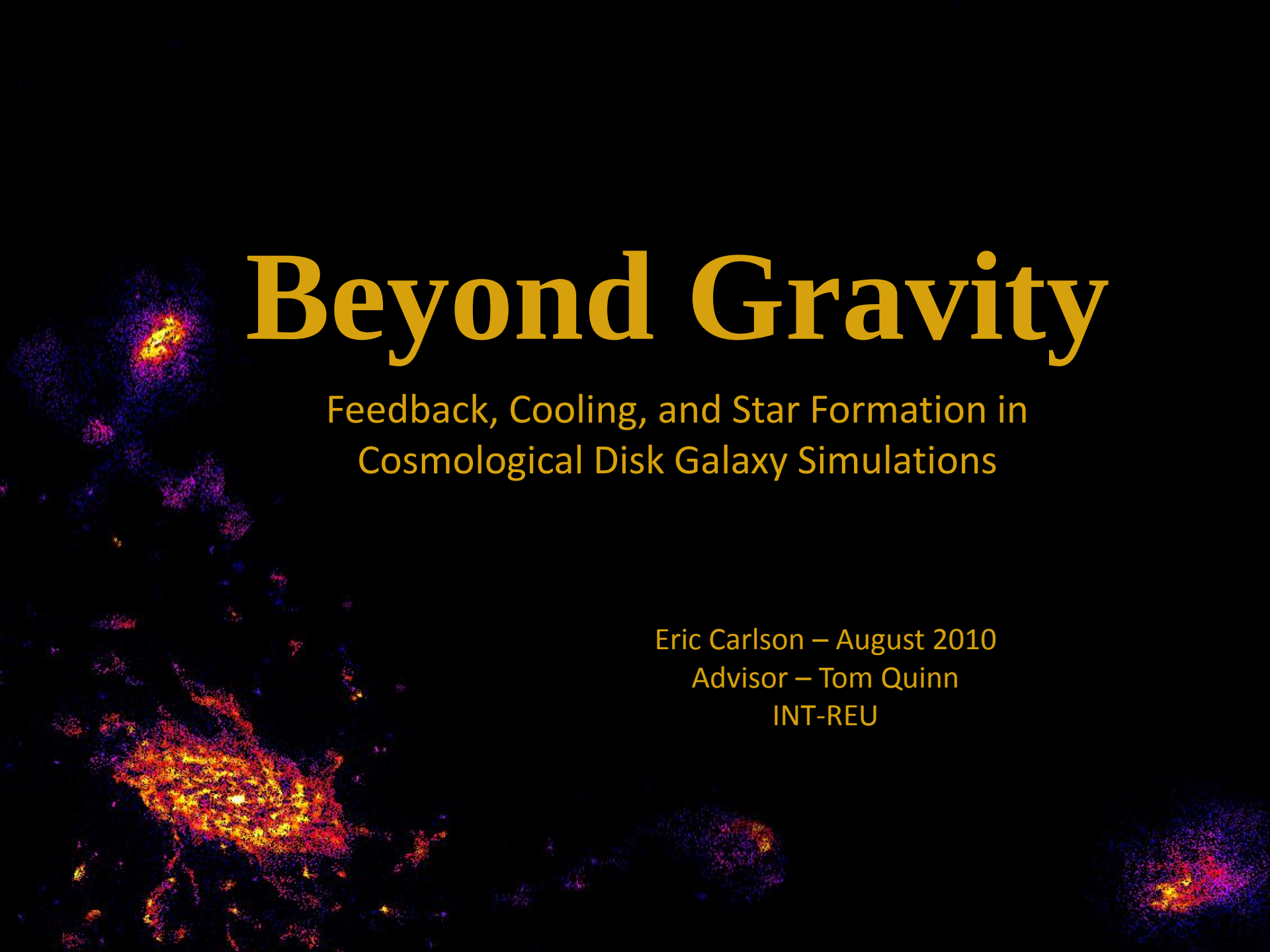


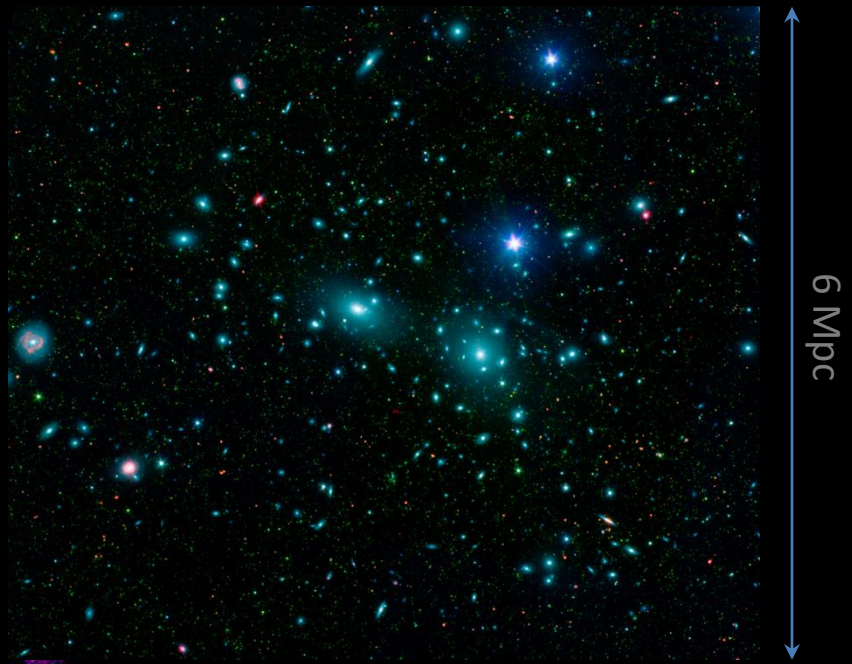
Beyond Gravity

Feedback, Cooling, and Star Formation in Cosmological Disk Galaxy Simulations

Eric Carlson – August 2010
Advisor – Tom Quinn
INT-REU

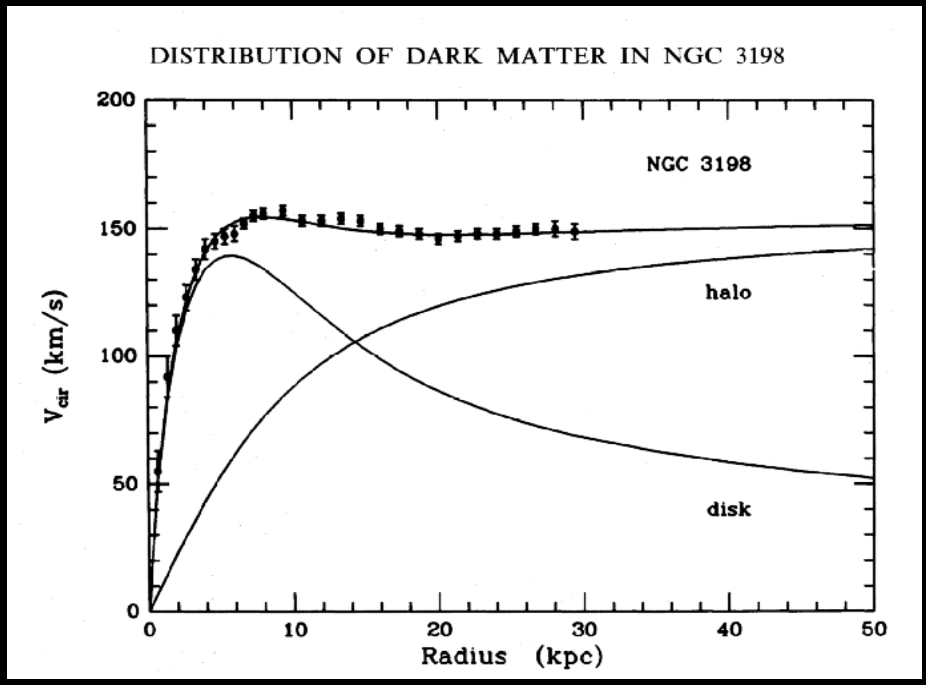
Energy Distribution of the Universe-Dynamical Indicators

Galaxy Clusters & Velocity Dispersion



http://apod.nasa.gov/apod/ap070531.html

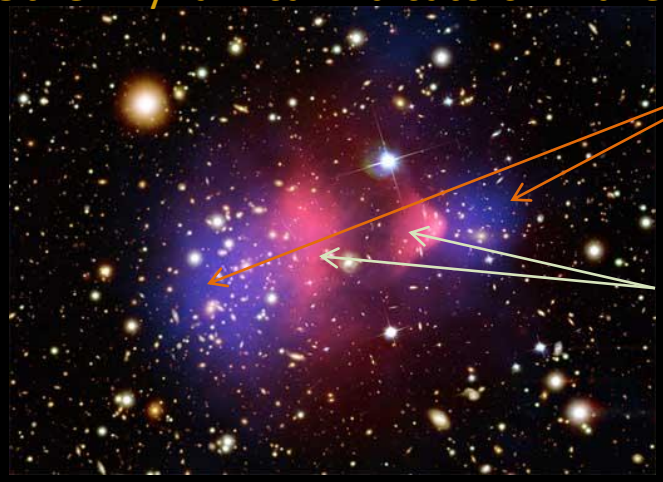
Galactic rotation curves do not fall off!



http://bustard.phys.nd.edu/Phys171/lectures/dm.html

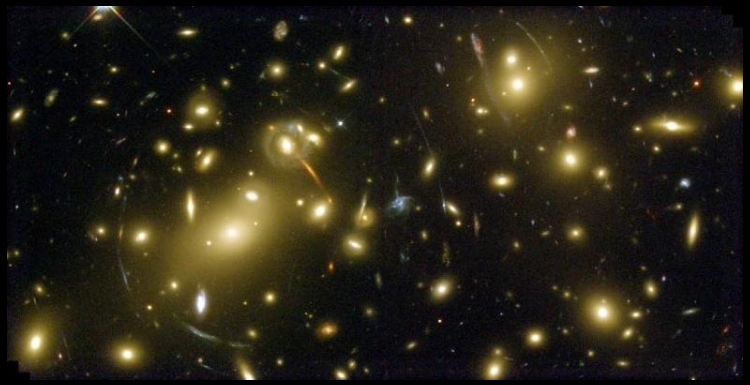
Energy Distribution of the Universe

Other Dynamical Indicators – Bullet Cluster



http://www.nasa.gov/mission_pages/chandra/multimedia/photos06-096.html

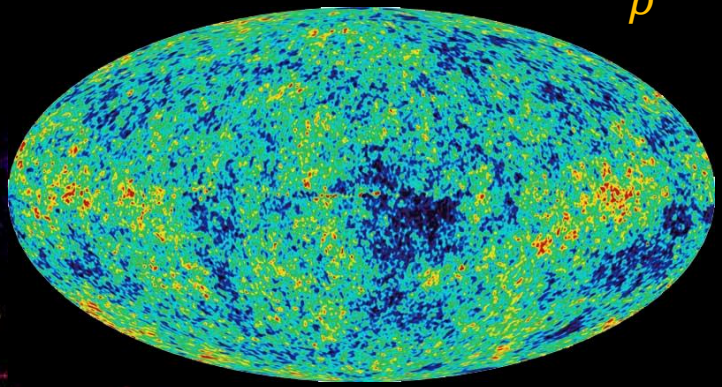
Gravitational Lensing



Gravitational Lensing in the Galaxy Cluster Abell 2218
NASA / A. Fruchter / STScI

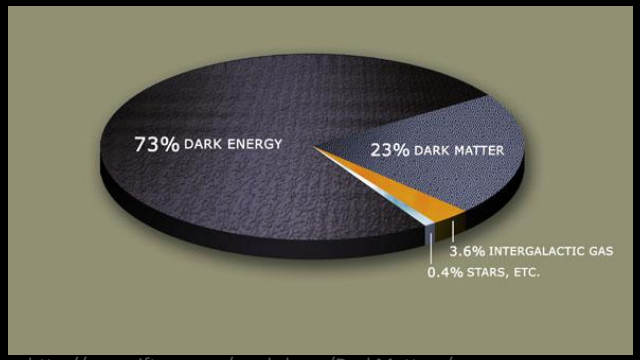
WMAP Density Fluctuations

$$\frac{\delta\rho}{\rho} \lesssim 10^{-4}$$



http://apod.nasa.gov/apod/ap050925.html

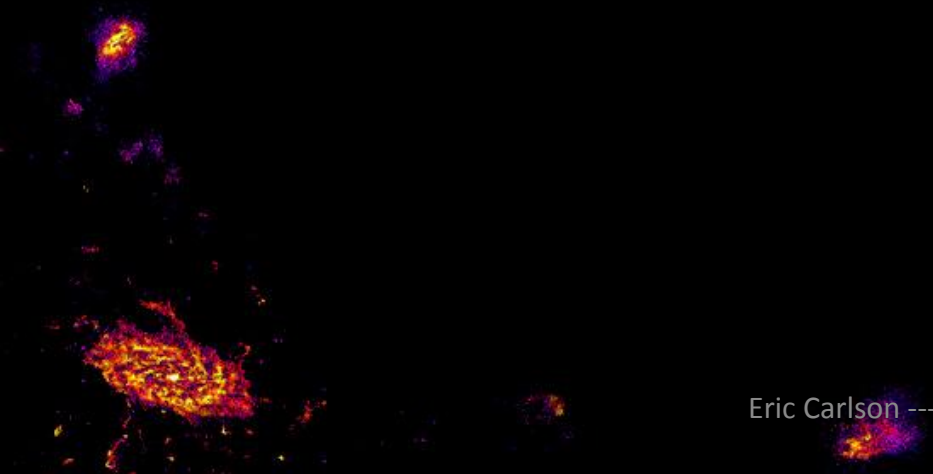
Bottom Line: Very different systems at vastly different scales, show that our currently observable universe is likely only 4.6% of the total energy density of the universe.



http://www.ift.uam.es/workshops/DarkMatters/

What do we stand to gain from simulations?

1. Mock catalogs
2. Observational methods
3. Test analytical models of structure formation
4. Testing of specific cosmological models
5. Reveal dominant effects in evolutionary stages
6. Etc…



Collisionless Dynamics – Simulations of Pure Gravitation

Gravitational equations of motion.

$$i.\ \nabla^2\varphi = 4\pi G\rho$$
$$ii.\ \frac{\partial f}{\partial t} + \boldsymbol{v}\cdot\boldsymbol{\nabla}_r f = \boldsymbol{\nabla}\varphi\frac{\partial f}{\partial v}$$

Results from major methods agree very well on collisionless dynamics.

Tree codes are the most common modern codes.

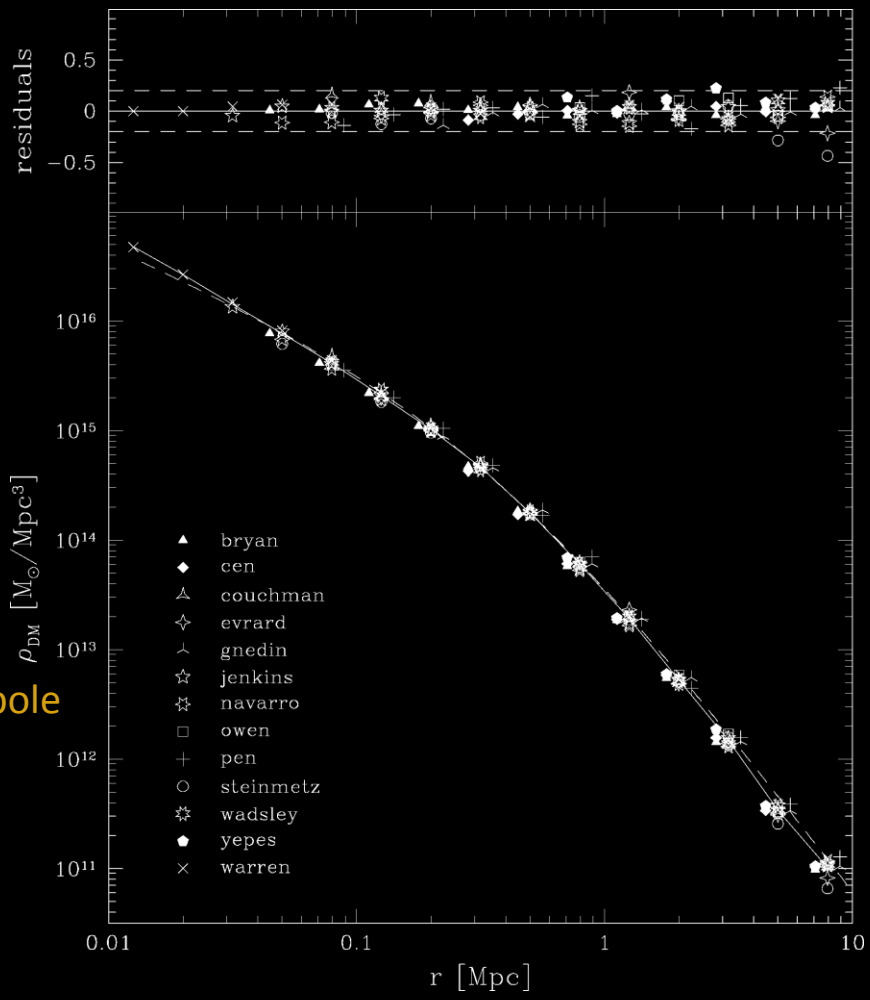
Direct Summation Tree Tree+Fast Multipole

$$\mathcal{O}(N^2) \rightarrow \mathcal{O}(Nln(N)) \rightarrow \mathcal{O}(N)$$

N up to $\sim 10^{10}$ particles!

The Santa Barbara Cluster Comparison Project

C. S. Frenk *et al* 1999 *ApJ* **525** 554



Gas Hydrodynamics – Dealing With Interacting Matter

Interacting particles require new algorithms.

i. Gravitational coupling
ii. Many radiative processes
iii. Mixing
iv. Need to model continuous distributions.

Smoothed Particle Hydrodynamics, SPH, smooths particle properties over a volume.

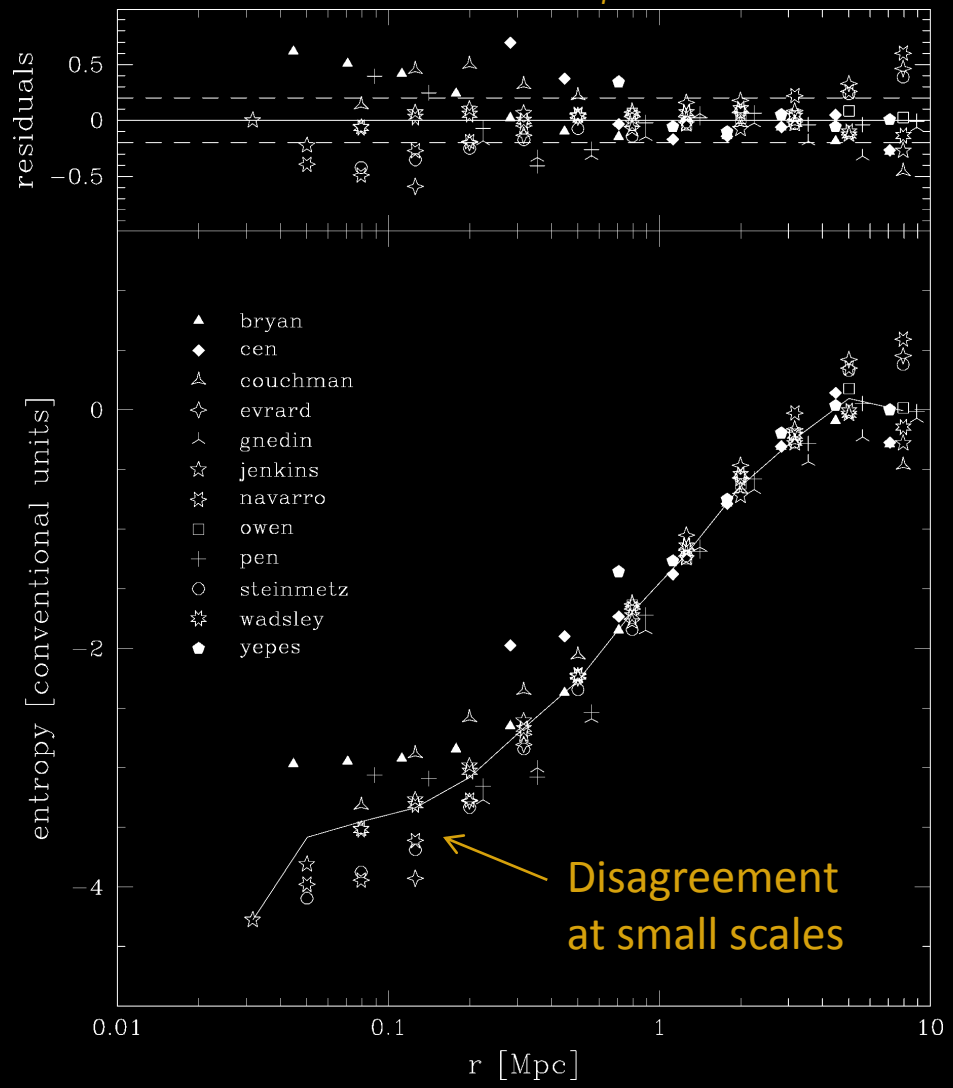
For any quantity q,

$$q_{\mathrm{i}} = \sum_{j=1}^{N} q_j W_{i,j}(|\boldsymbol{r}_i - \boldsymbol{r}_j|, hi, hj)$$

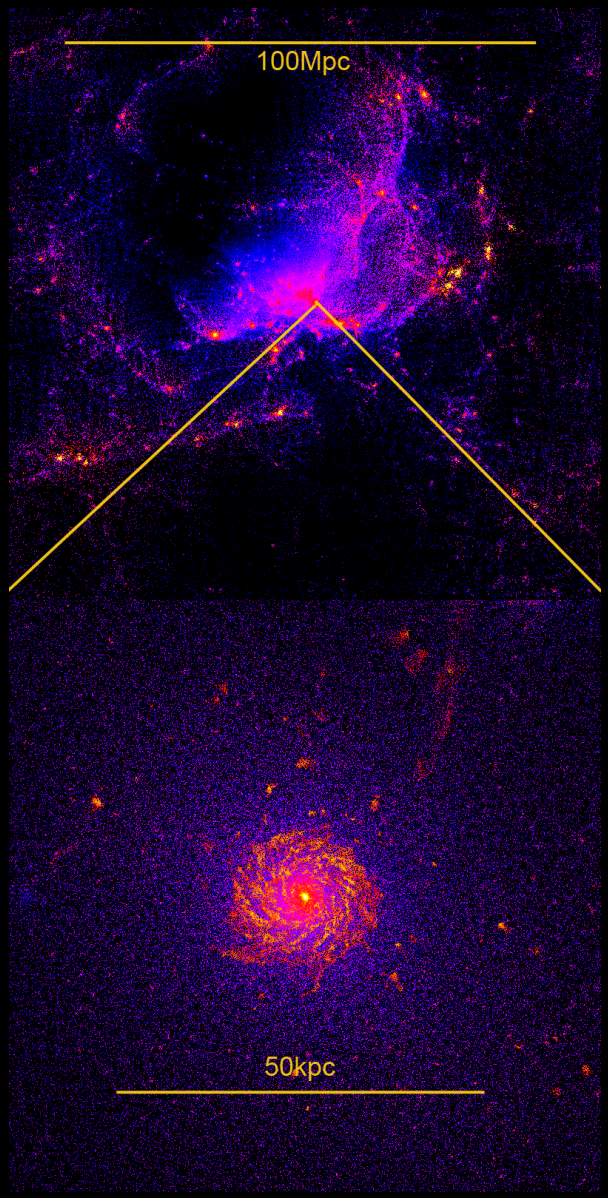
Where $W_{i,j}$ is a weighting function
h_i is the smoothing length

SPH inherently adapts resolution to dramatically improve dynamic range.

The Santa Barbara Cluster Comparison Project
C. S. Frenk *et al* 1999 *ApJ* **525** 554



Gas Hydrodynamics – Modeling Sub-resolution Physics



Trying to resolve structures in a volume 10^{10} times smaller than the simulation volume.

$\sim$0.1pc resolution required to explicitly model gas and star physics.

Cosmological simulations limited $\sim$1kpc

$\therefore$ Star particle represents 10,000 stars, gas particles are often large volumes.

How do we model processes that are below the resolution of our system?

Modeling Sub-resolution Physics – Star Formation

Star formation is far from being resolved. Statistics are our savior.

Identify Star Forming Regions

Selection Criteria for Star Forming Regions:

i. Minimum overdensity: $\delta\rho/\rho > 55$
ii. Maximum Temperature: T<20,000K
iii. Minimum local density: $\rho_{gas} > 0.1\ amu/cm^3$

Form Stars Probabilistically

$$\frac{d\rho_{star}}{dt} = c^{star}\frac{\rho_{gas}}{t_{form}}$$

$$P_{form} = \frac{m_{gas}}{m_{star}}(1 - \exp(-\frac{c^{star}\Delta t}{t_{form}}))$$

Evolve Stars

Metal Enrichment

Energy Feedback

All free parameters are constrained by observations!

Reproduces Kennicutt-Schmidt Law

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Modeling Sub-resolution Physics – Feedback Mechanisms

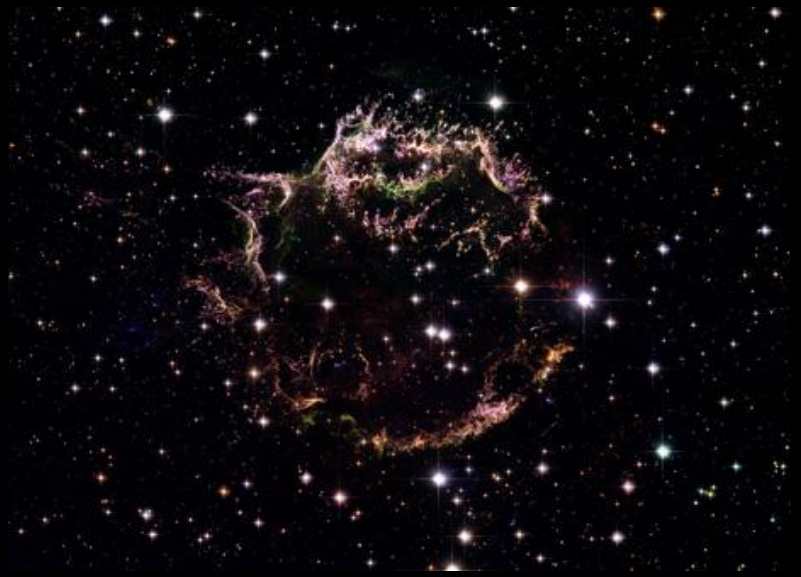
Type II supernova
Yields $\approx 10^{51}$erg!

Cooling Disabled
Energy Deposited

Adiabatic Expansion
Drives Outflows

Stellar Winds
Type Ia SNe

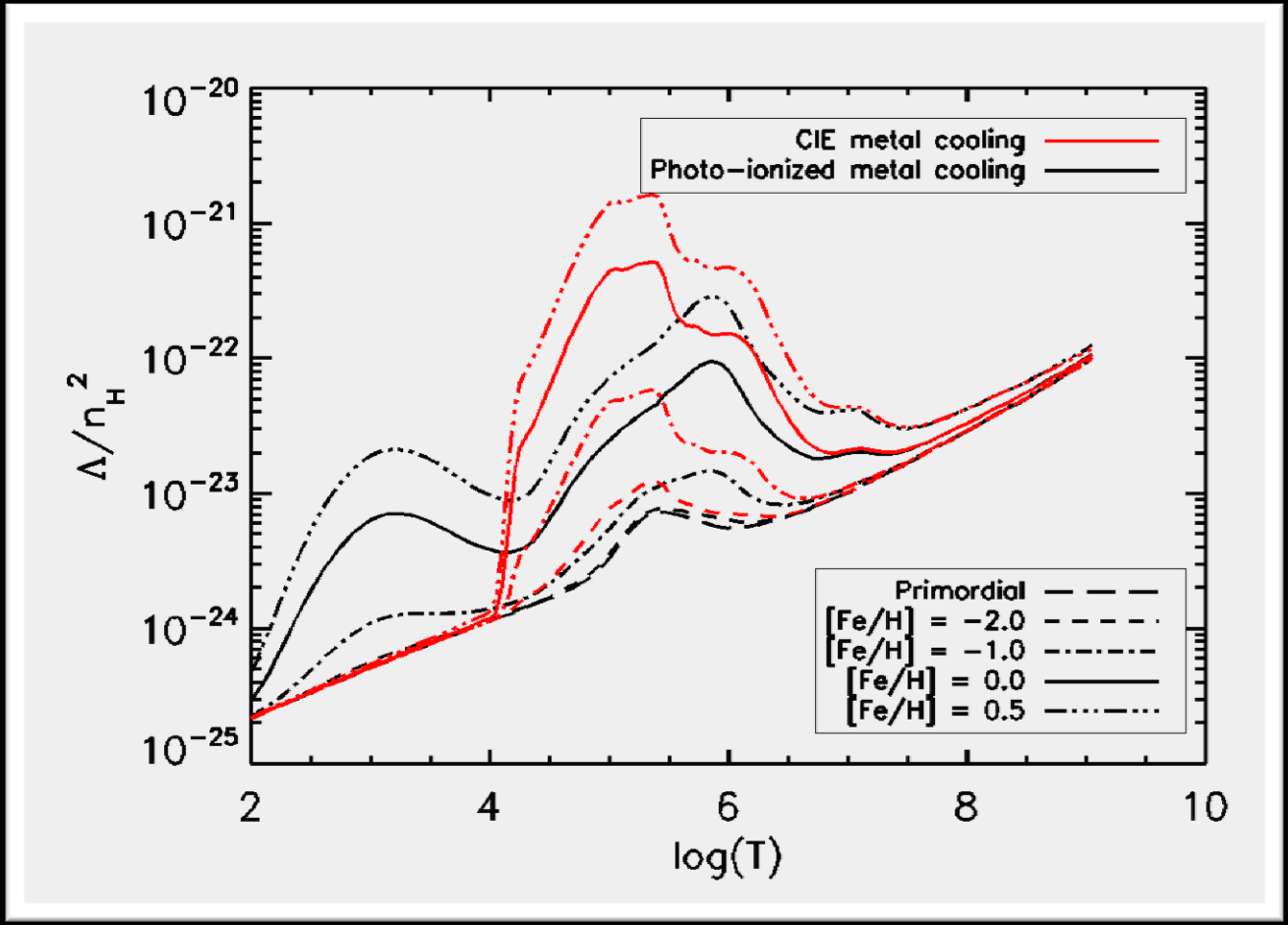
Metal Enrichment



The two free parameters in this implementation are constrained by observations.

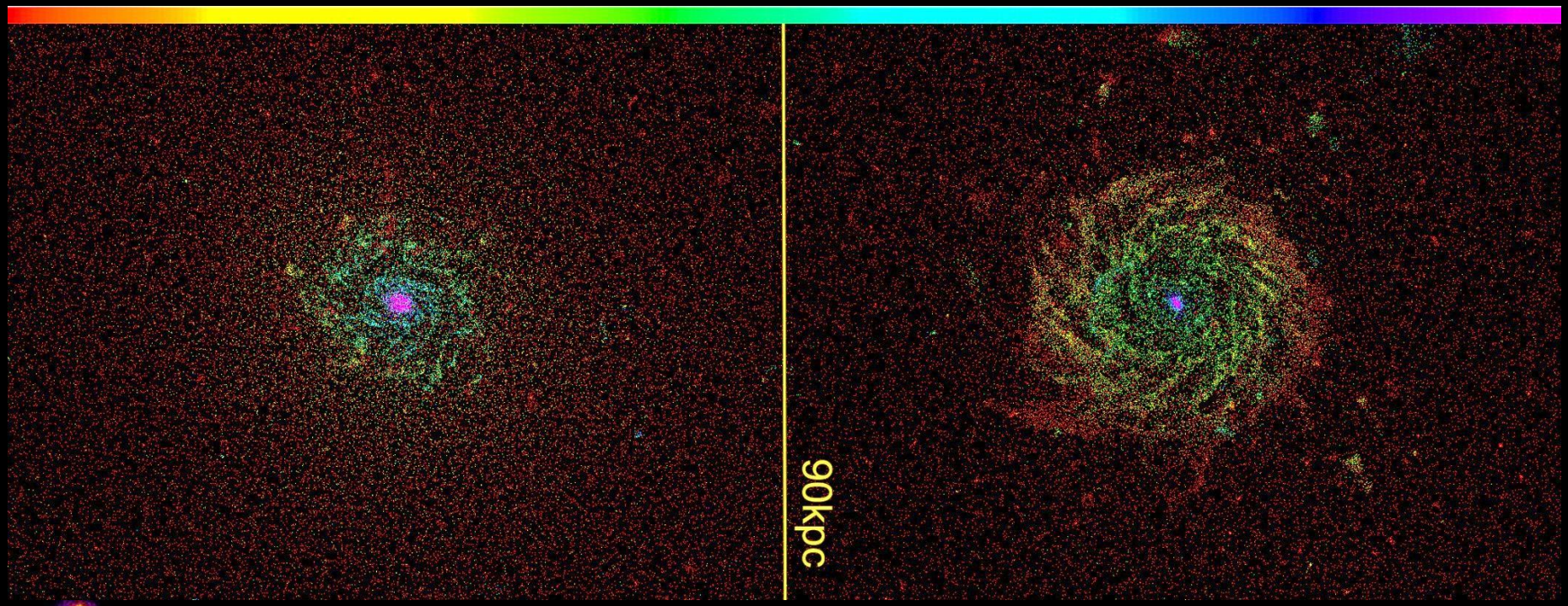
Modeling Sub-resolution Physics –Cooling Mechanisms

- Primordial Cooling
- Metal Cooling (with UV)
- Adiabatic Cooling
- Compton Cooling



Shen, Wadsley, Stinson 2010; arXiv:0910.5956v2

Modeling Sub-resolution Physics –Diffusion Mechanisms



No Metal Cooling/Diffusion

With Metal Cooling and Diffusion

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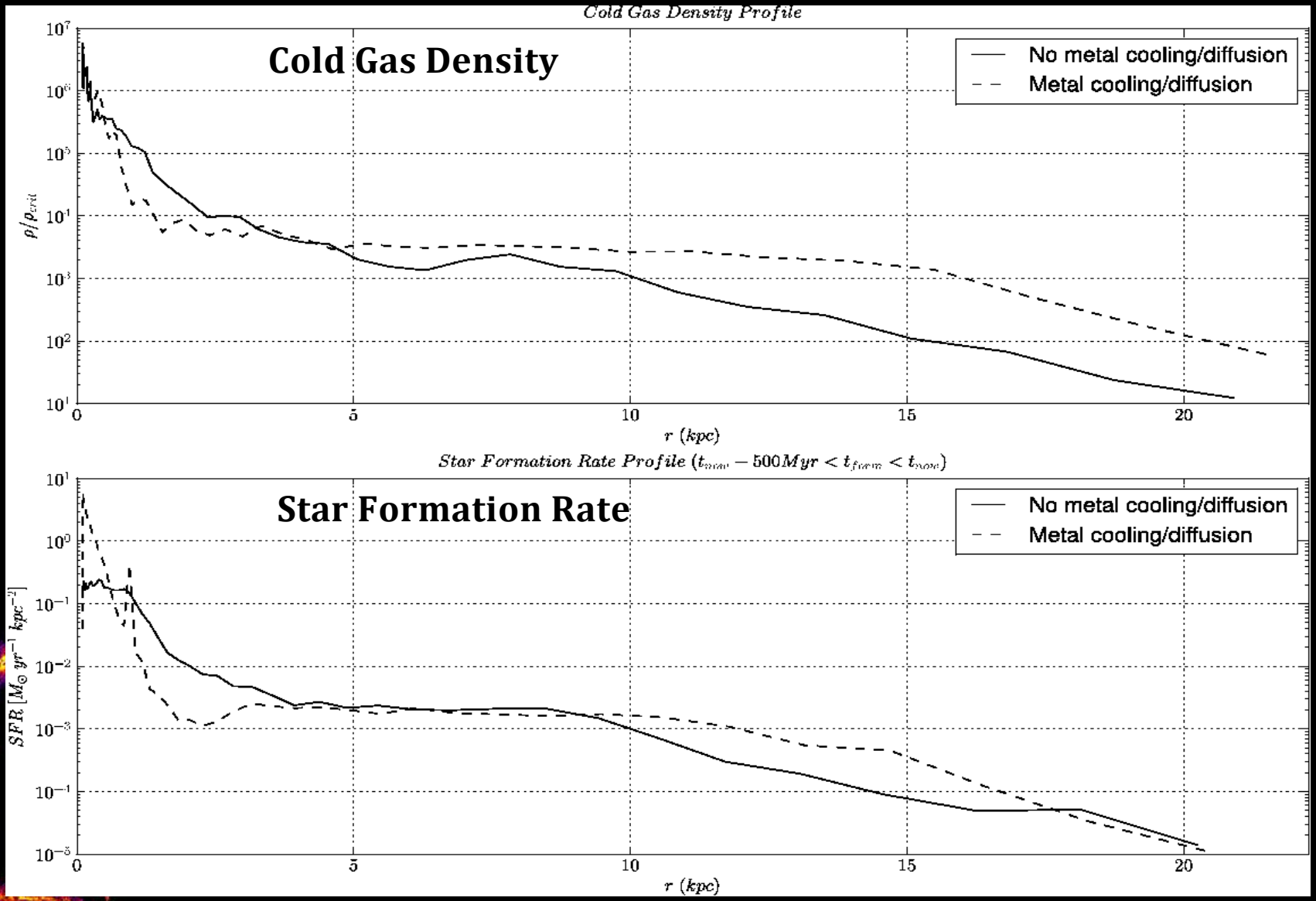
http://thebigfoto.com/messier-objects-gallery-m56-m66#p

Modeling Sub-resolution Physics –Diffusion Mechanisms



Dominant Problems in Galactic Properties

- Overabundance of central baryons
- IGM metal deficiency at low redshift
- High SFR at low redshift

Summary

- Baryon's are a small fraction of energy density.
- Simulations have been, and will continue to be a powerful tool.
- Dominant Models agree on gravity
- Gas dynamics are very important to galaxy simulations.
- Gas dynamics are working toward convergence among methods
- Feedback mechanisms play a central role in formation of galaxies
- Still problems

Future

- More particles
- More physics
- Greater understanding of galaxy formation

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WHERE DISCOVERIES BEGIN