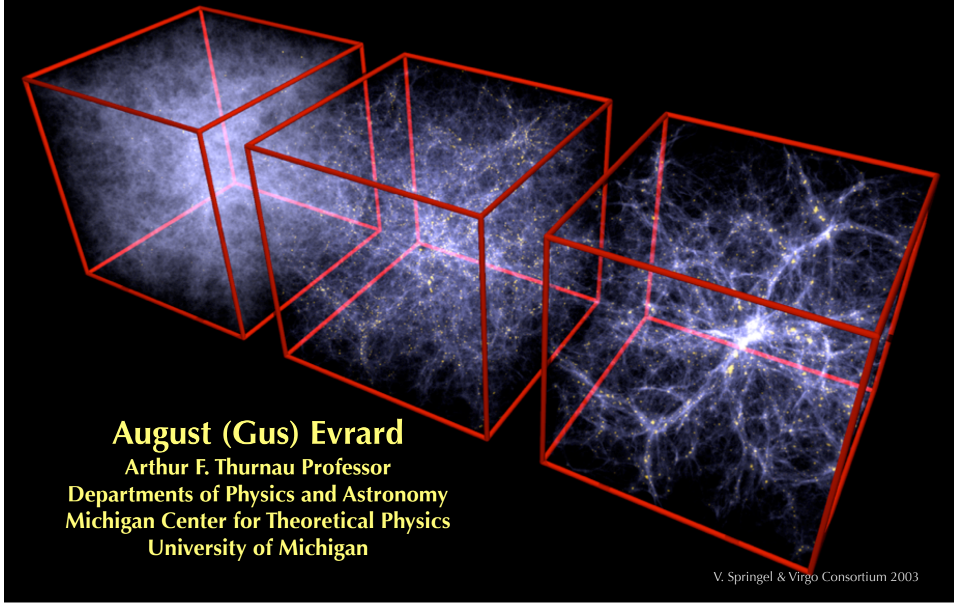
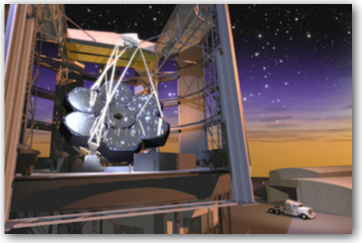
Cosmic Engineering: Past, Present and Future



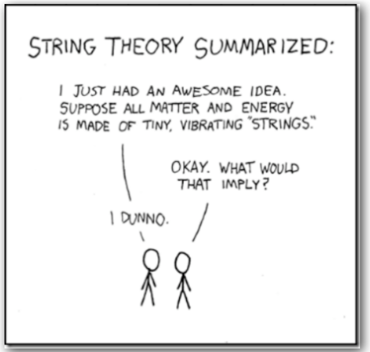
August (Gus) Evrard

Arthur F. Thurnau Professor
Departments of Physics and Astronomy
Michigan Center for Theoretical Physics
University of Michigan

V. Springel & Virgo Consortium 2003



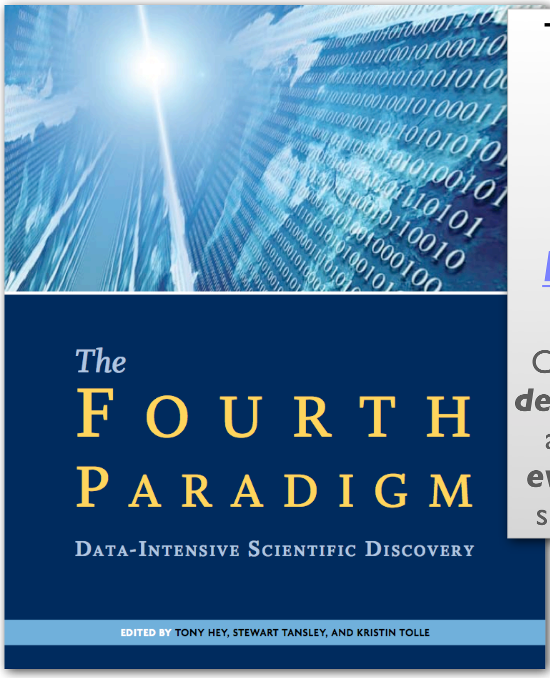
observation



theory

computation

The first three paradigms of scientific research



The
FOURTH
PARADIGM
DATA-INTENSIVE SCIENTIFIC DISCOVERY

EDITED BY TONY HEY, STEWART TANSLEY, AND KRISTIN TOLLE

The fourth paradigm?

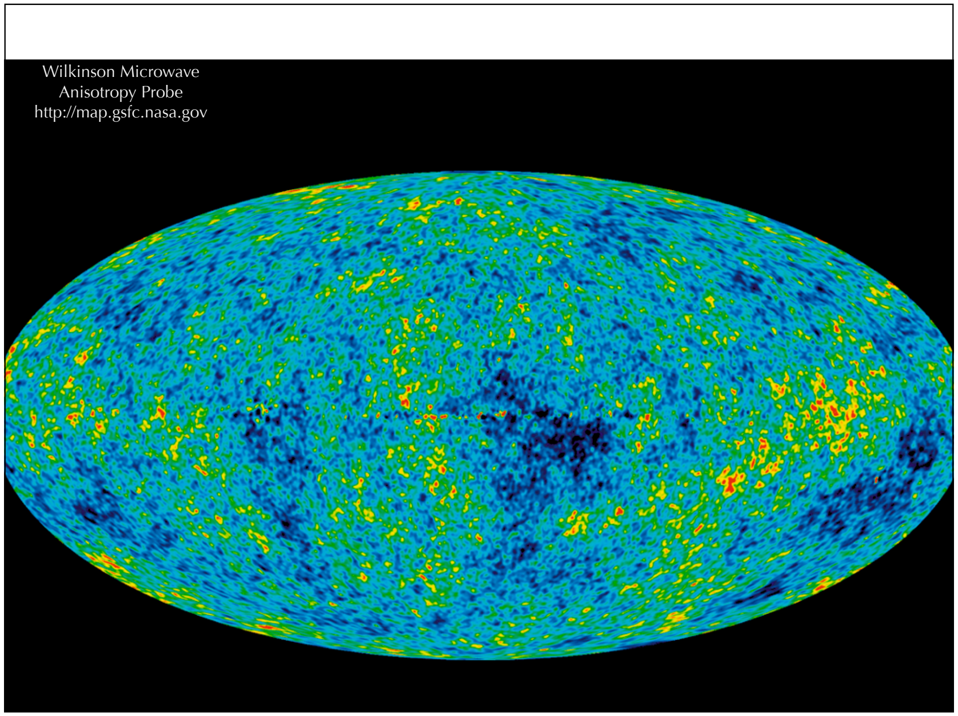
DATA-driven
scientific discovery

Phenomenology

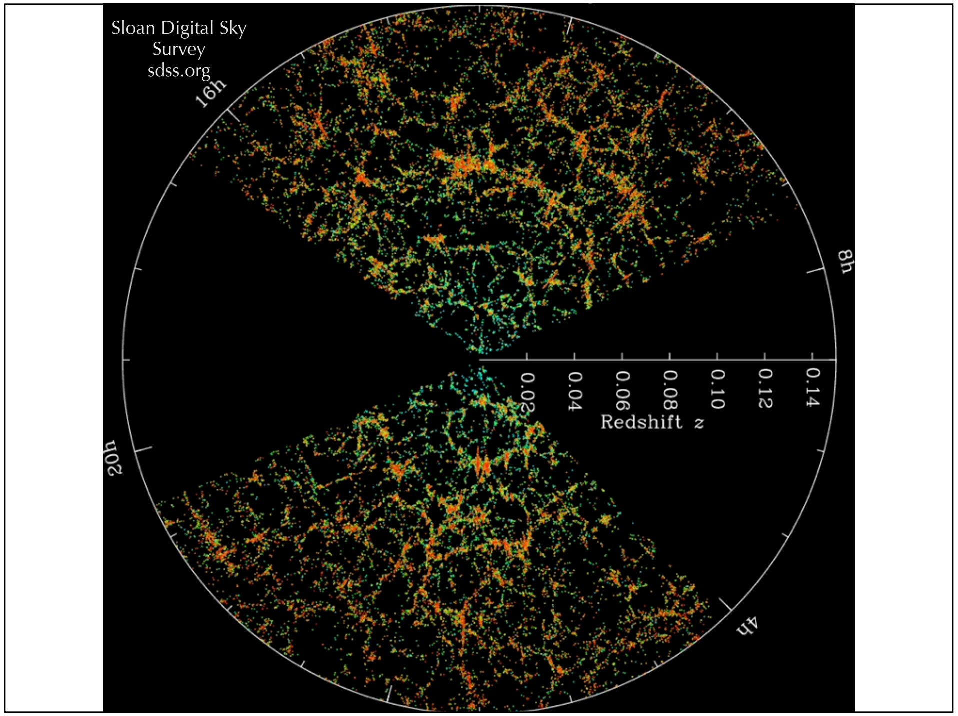
Cosmology + Astrophysics:
dense observational catalogs
and images supported by
even denser ensembles of
simulation (synthetic) data

mock catalog :(

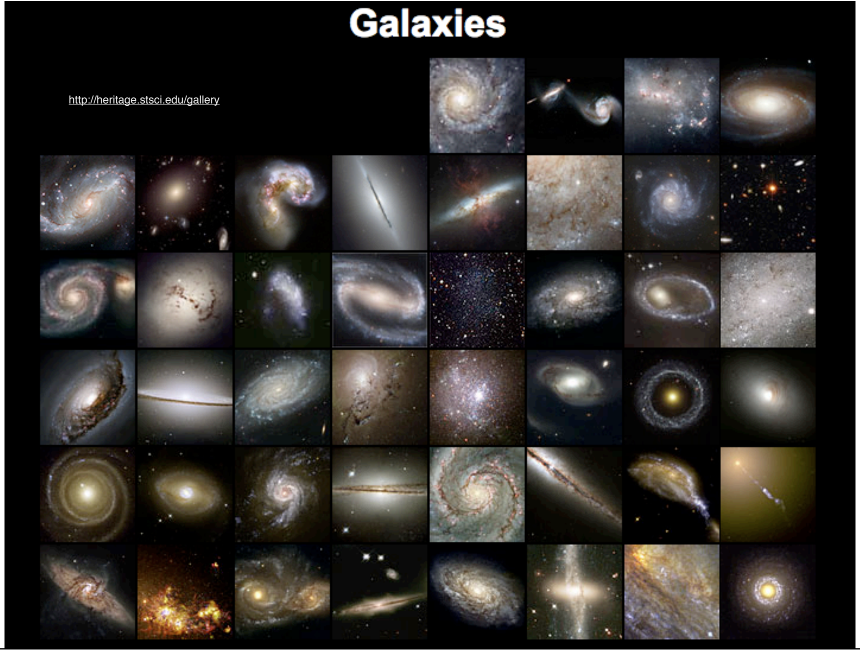
synthetic catalog :)

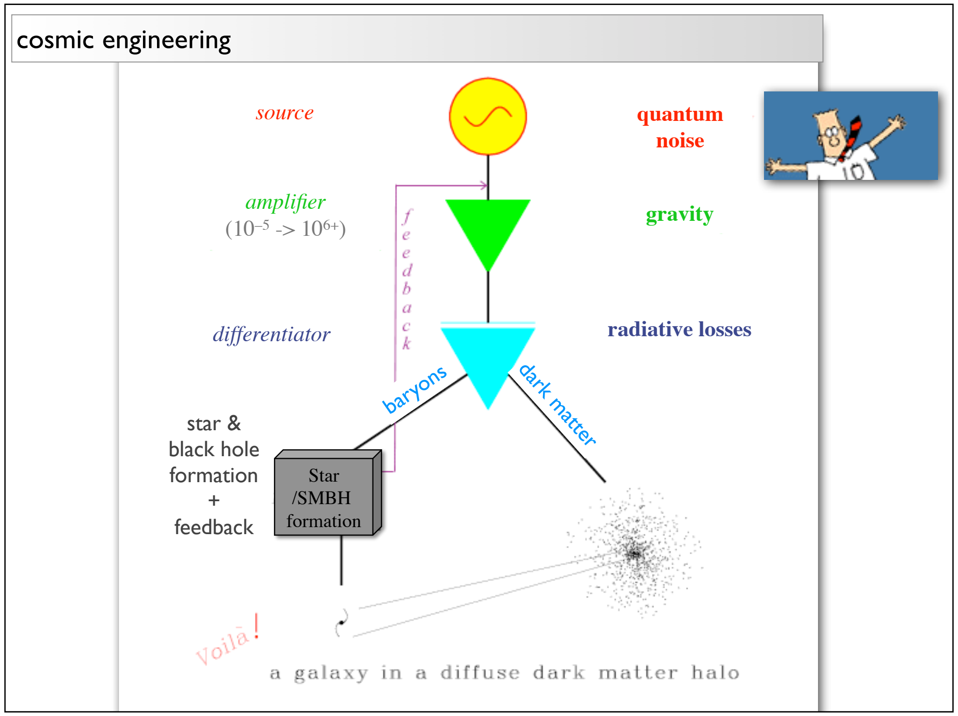


initial conditions for LSS imprinted on CMB



We see the evolved density field through a set of biased tracers (galaxies) goal: halos (and large sub-halos) should contain baryonic objects like this!





cosmic engineering

source

quantum noise

amplifier

(10^{-5} -> 10^{6+})

gravity

feedback

differentiator

radiative losses

baryons

dark matter

star & black hole formation + feedback

Star /SMBH formation

Voilà !

a galaxy in a diffuse dark matter halo

The theoretical framework is in place to understand this bias from first principles.

But:

-

clusters of galaxies are simple (relative to galaxies) astrophysical laboratories

* baryons in M>1e14 Msun halos are observed to reside mainly in a hot, intracluster medium (ICM)

– hot gas outweighs baryons in stars by factors >~5

0th order dynamics: ignore galaxy formation entirely (gravity + shock heating only)

1st order dynamics: include feedback effects of galaxy formation on ICM

via a simple `preheated' assumption => elevate gas entropy at high z

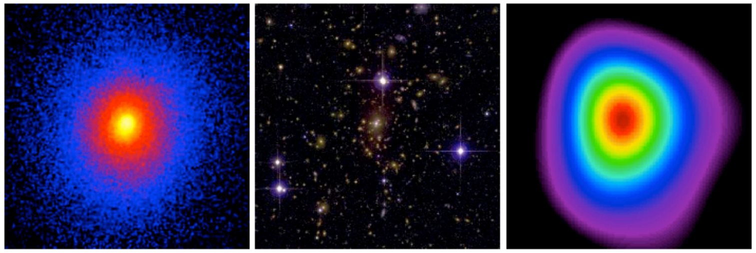


Figure 7: Images of Abell 1835 ($z = 0.25$) at X-ray, optical and mm wavelengths, exemplifying the regular multi-wavelength morphology of a massive, dynamically relaxed cluster. All three images are centered on the X-ray peak position and have the same spatial scale, 5.2 arcmin or ~ 1.2 Mpc on a side (extending out to $\sim r_{2500}$; Mantz et al. 2010a). Figure credits: *Left*: X-ray: Chandra X-ray Observatory/A. Mantz; *Center*, Optical: Canada France Hawaii Telescope/A. von der Linden et al.; *Right*, SZ: Sunyaev Zel'dovich Array/D.

what are clusters of galaxies?

* terminus of clustering hierarchy => largest, non-linear structures

easily visible **we can find all the biggest ones now**

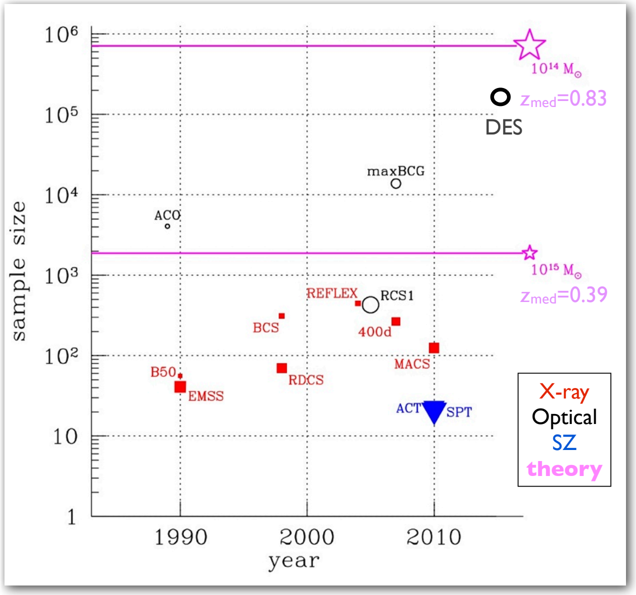
* multi-component - DM: hot gas: galaxies+stars :: ~100: 10: 1

many observational channels **radio/mm - IR/optical - X-ray**

* quasi-equilibrium (`frustrated') dynamical systems

~one-parameter family **tight mass-observable scalings**

cluster samples today are sparse relative to massive halos on the sky



Allen, Evrard & Mantz 2011

symbol size scales
with median redshift

Halo mass scale is
M_{200m}
(h = 0.7)

LSS Simulations
(past + present)

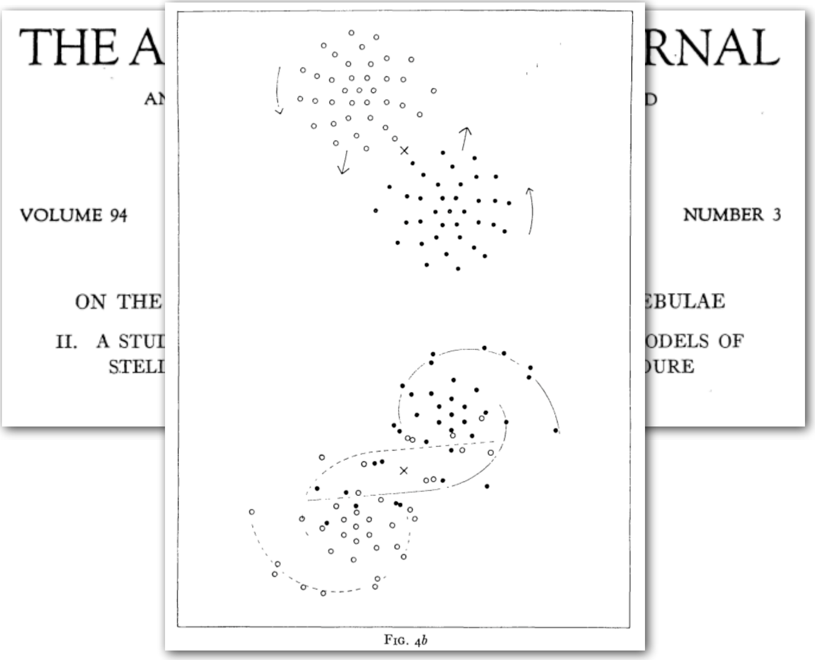


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FIG. 4*b*

key characteristics of LSS

* galaxies and clusters of galaxies are **weak-field** structures in the expanding FRW metric,

$$v^2/c^2 \ll 1$$

=> a **Newtonian** description of the gravitational potential is accurate to model the dynamics of sub-horizon LSS formation.

LSS simulations use Newtonian potential of perturbations in an expanding FRW metric.


http://heritage.stsci.edu/gallery

large-scale structure simulations: methodologies

* DM evolution using collisionless N-body simulations (single fluid)

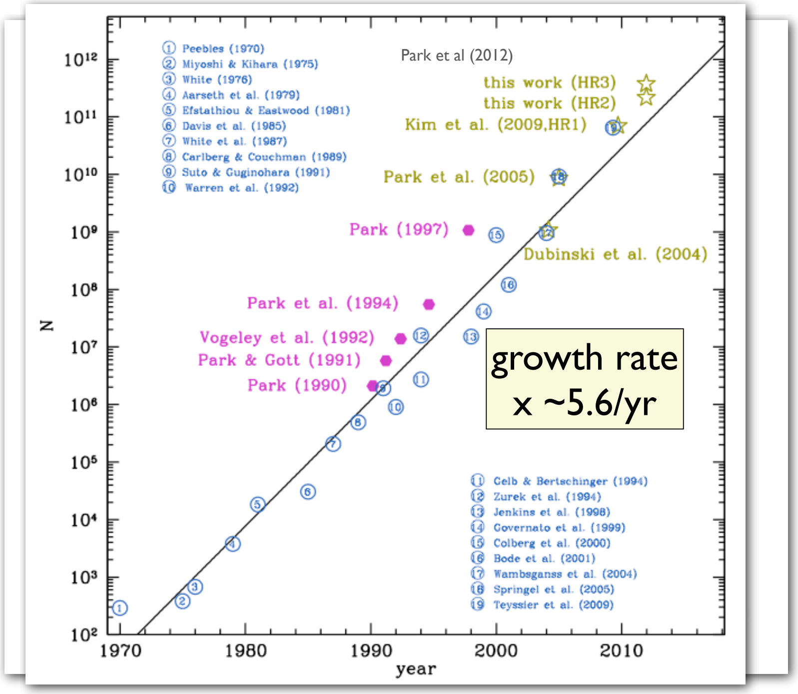
– assumes DM is weakly interacting massive particle (WIMP)
– initial density fluctuations are Gaussian random field with power spectrum, P(k), calculable from linear theory
– growing mode from linear perturbation theory sets initial conditions
– `particles' represent coarse-grained phase space kinematics
– `softening' of pair-wise force required to regularize dynamics
– individual timesteps improve performance
– Layzer-Irving equation benchmarks energy conservation (+ p,L cons.)

* direct N-body + gas dynamics simulation (≥ 2 fluids)

– on galactic and larger scales, baryons trace DM at high-z
– baryons are collisional, so intersecting streams generate shocks
– shocks generate thermal energy and entropy
– radiation field can produce cooling or heating in gas
– employ empirically motivated star formation and feedback prescriptions

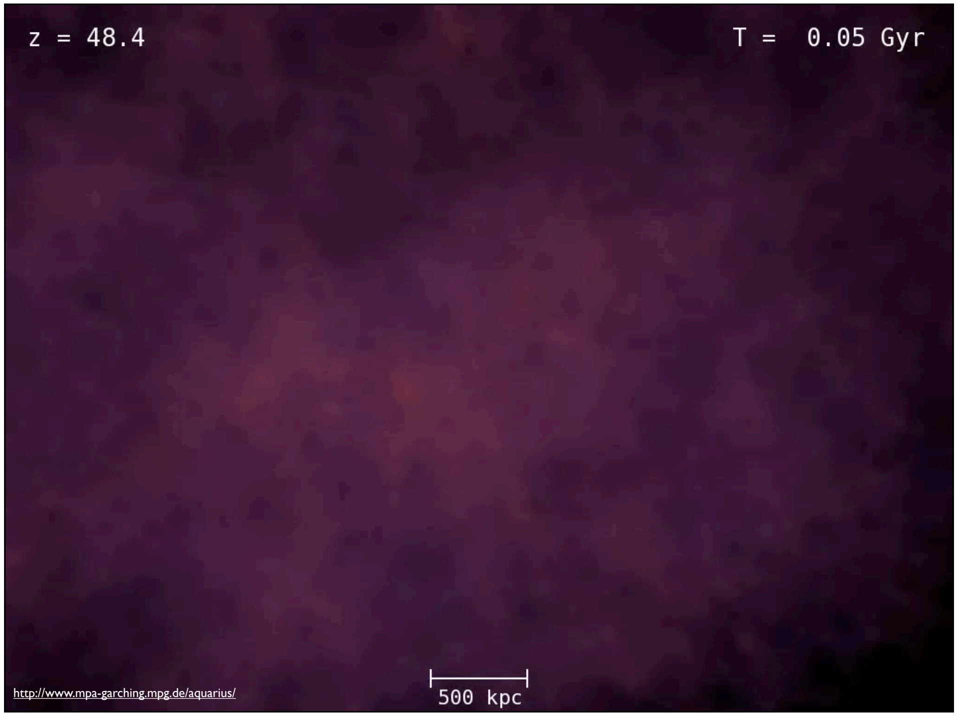
* indirect N-body + `semi-analytic' baryon evolution (PDE's => ODE's)

– determine halo and sub-halo formation history (from direct simulation or statistical summary thereof)
– write cooling, star formation and feedback in terms of analytic profiles within halo
– add seed BH's at high-z, write rules for BH merging and accretion
– add rules for effects of mergers, including morphological transitions
– predict observable features using stellar population synthesis modeling, including dust opacity



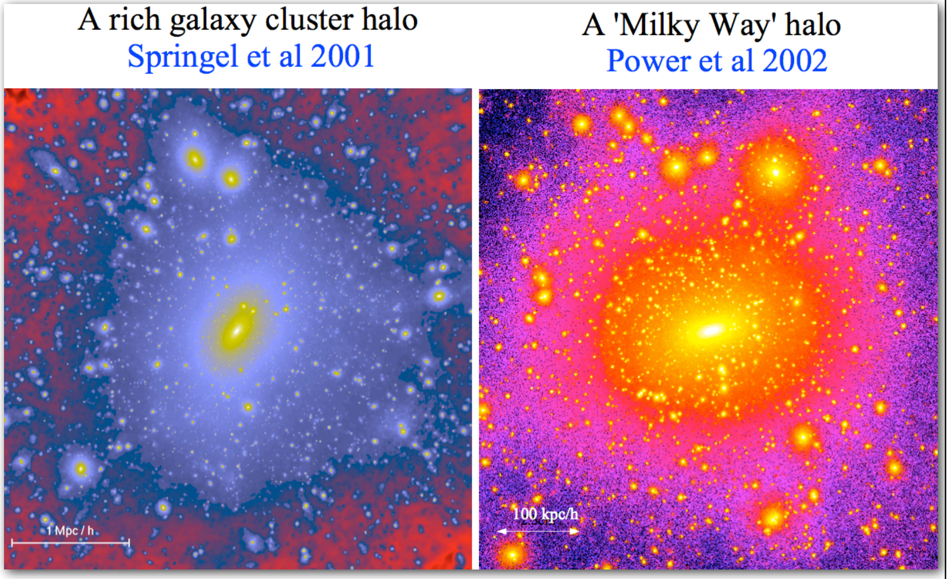
Park et al (2012)

growth rate
x ~5.6/yr



http://www.mpa-garching.mpg.de/aquarius/

similarity of internal halo structure, from galaxy to cluster scales

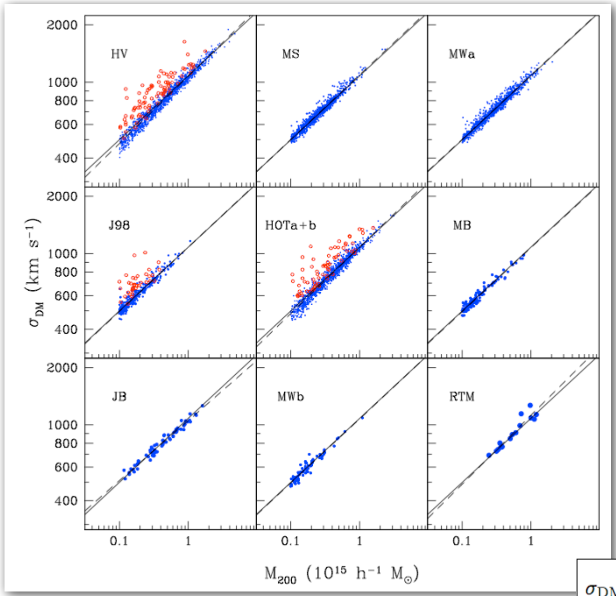


A rich galaxy cluster halo
Springel et al 2001

A 'Milky Way' halo
Power et al 2002

courtesy S.D.M.White, CATB2009

precision calibration of DM halo virial scaling relation



Evrard et al (2008)

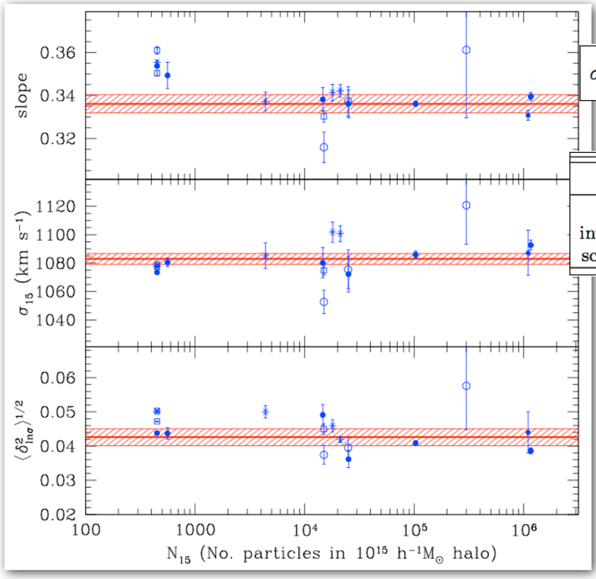
$$\sigma_{\rm DM}{}^2 = \frac{1}{3N_p}\sum_{i=1}^{N_p}\sum_{j=1}^{3}|v_{i,j}-\bar{v}_j|^2$$

- results from six different N-body codes

- mergers are dynamically soft (non-violent)

$$\sigma_{\rm DM}(M,z) = \sigma_{\rm DM,15}\left(\frac{h(z)M_{200}}{10^{15}\,{\rm M}_\odot}\right)^{\alpha}$$

precision calibration of DM halo virial scaling relation



Evrard et al (2008)

$$\sigma_{\mathrm{DM}}(M,z) \;=\; \sigma_{\mathrm{DM},15}\left(\frac{h(z)M_{200}}{10^{15}\ \mathrm{M}_\odot}\right)^{\alpha}$$

Parameter	Value
slope, α	0.3361 ± 0.0026
intercept, $\sigma_{\mathrm{DM},15}$	1082.9 ± 4.0 km s^{-1}
scatter, $\langle\delta^2_{\ln\sigma}\rangle^{1/2}$	0.0426 ± 0.0015

summary: lessons from N-body simulations about ***halo model*** of LSS

* general aspects of halos

- halos are dynamically evolving systems: close to virial equilibrium but frustrated by mergers and continual accretion
- ellipsoidal in shape (tending prolate) with 2:1 axis ratios common aligned with surrounding filaments

* internal structure of halos

- relaxation to common density + velocity radial profiles
- surviving substructures contain a small percentage of total mass
- hierarchical nesting of sub-structure families reflect accretion history

* low-order spatial distribution of halos

- functional forms for *mass function*, n(M,z), and *bias function*, b(M,z), precisely calibrated via similarity variable, $\sigma(M)$ (mainly wCDM)
- different, one-parameter mass assignment methods (FOF, SO) exist

  good: flexibility, reflects edge complexity **bad**: literature

N-body + gas dynamics
(past + present)

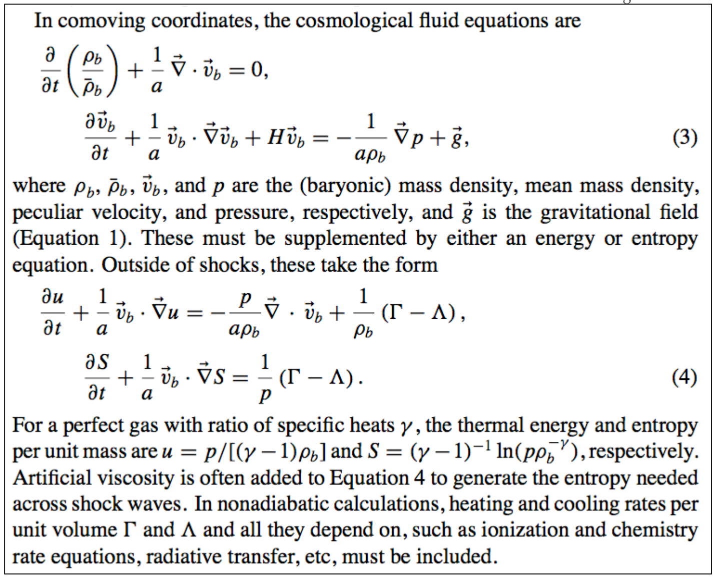
multi-fluid systems: N-body+gas dynamics

* baryon fluid coupled via gravity to DM

* solve Euler equation in comoving coordinates

* energy or entropy equation

* requires shock treatment



Bertschinger 1998

In comoving coordinates, the cosmological fluid equations are

$$\frac{\partial}{\partial t}\left(\frac{\rho_b}{\bar{\rho}_b}\right) + \frac{1}{a}\vec{\nabla}\cdot\vec{v}_b = 0,$$

$$\frac{\partial \vec{v}_b}{\partial t} + \frac{1}{a}\vec{v}_b\cdot\vec{\nabla}\vec{v}_b + H\vec{v}_b = -\frac{1}{a\rho_b}\vec{\nabla}p + \vec{g}, \qquad (3)$$

where ρ_b, $\bar{\rho}_b$, $\vec{v}_b$, and p are the (baryonic) mass density, mean mass density, peculiar velocity, and pressure, respectively, and $\vec{g}$ is the gravitational field (Equation 1). These must be supplemented by either an energy or entropy equation. Outside of shocks, these take the form

$$\frac{\partial u}{\partial t} + \frac{1}{a}\vec{v}_b\cdot\vec{\nabla}u = -\frac{p}{a\rho_b}\vec{\nabla}\cdot\vec{v}_b + \frac{1}{\rho_b}(\Gamma - \Lambda),$$

$$\frac{\partial S}{\partial t} + \frac{1}{a}\vec{v}_b\cdot\vec{\nabla}S = \frac{1}{p}(\Gamma - \Lambda). \qquad (4)$$

For a perfect gas with ratio of specific heats γ, the thermal energy and entropy per unit mass are $u = p/[(\gamma-1)\rho_b]$ and $S = (\gamma-1)^{-1}\ln(p\rho_b^{-\gamma})$, respectively. Artificial viscosity is often added to Equation 4 to generate the entropy needed across shock waves. In nonadiabatic calculations, heating and cooling rates per unit volume Γ and Λ and all they depend on, such as ionization and chemistry rate equations, radiative transfer, etc, must be included.

hydro solution methods: various flavors

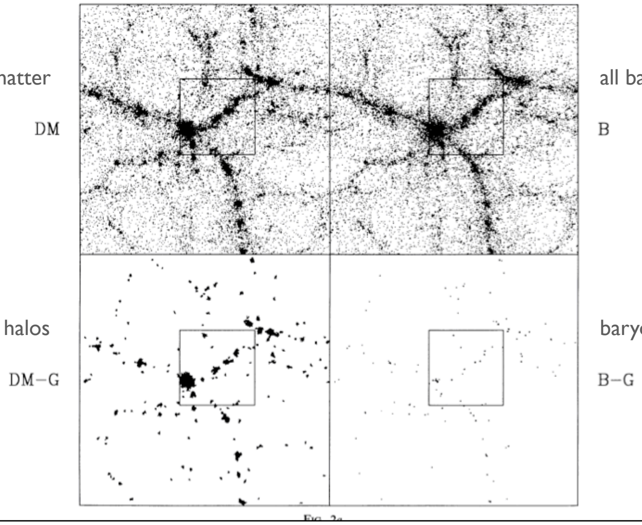
method	character	advantages	disadvantages	examples
Lagrangian (particle)	•solve energy eq'n along streamlines •local kernel density estimates	•simple, fast •good dynamic range w/ variable kernel scale	•approx. shock treatment •poor error control (no grid)	smoothed particle hydro (SPH) • gadget • gasoline
Eulerian fixed mesh	•uniform (cubic) spatial grid	•simple, fast •good (trunc.) error control •shocks	•limited spatial resolution	• c.f., Kang et al (1994)
Eulerian Adaptive Mesh Refi. (AMR)	•grid cells refined (sub-divided) in target regions	•improved spatial and mass resol'n •wider dynamic range	•complex to code •sensitive to sub-grid handling	• ART • Enzo • RAMSES • FLASH
Moving Mesh	•hybrid Lagr./Eul. •deformable, moveable grid cells (up to max.)	•best of breed?	•very complex to code	•Arepo

early results with P3MSPH

- 16 Mpc cube in Ω_m=1 universe (aka, SCDM)
- 2 x 64^3 particles on CRAY Y-MP (@SDSC)
- DM $m_p \approx$1e9 Msun, baryon $m_p \approx$1e8 Msun, soft$\approx$10kpc
- shock heating + radiative cooling only

Evrard, Summers and Davis (1994)

z = 3.0



all dark matter

all baryons

dark matter in halos

baryons in `globs'

early results with P3MSPH

- 16 Mpc cube in Ω_m=1 universe (aka, SCDM)
- 2 x 64^3 particles on CRAY Y-MP (@SDSC)
- DM $m_p \approx$1e9 Msun, baryon $m_p \approx$1e8 Msun, soft≈10kpc
- shock heating + radiative cooling only

Evrard, Summers and Davis (1994)

z = 3.0
(zoom in)

all dark matter

all baryons

dark matter in halos

baryons in \`globs'

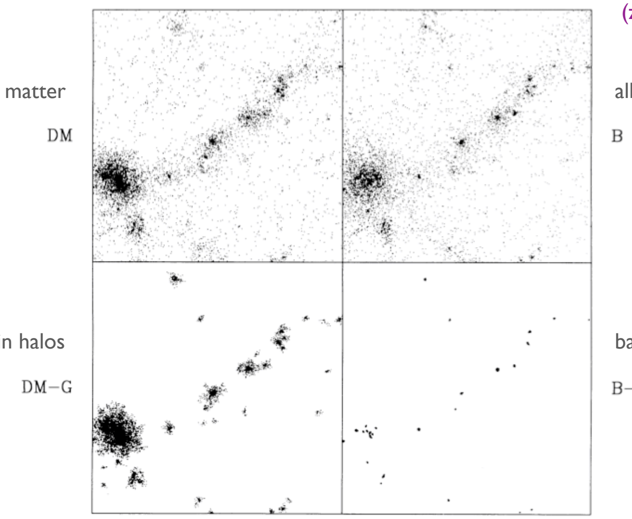


Fig. 2b

early results with P3MSPH

Evrard, Summers and Davis (1994)

the first theoretical Halo Occupation Distribution (HOD)

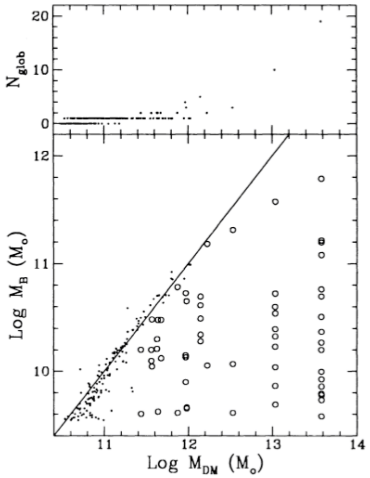


FIG. 11.—Halo occupation number N_{glob} and glob mass within each halo as a function of halo mass. Circles in the lower panel indicate halos containing multiple globs. The line in the lower panel is $M_B = \Omega_b M_{DM}$.

early results with P3MSPH

first cosmological simulation
to naturally form disk galaxies!

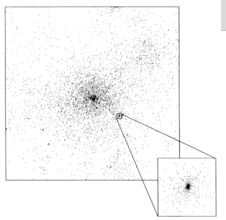


FIG. 17a

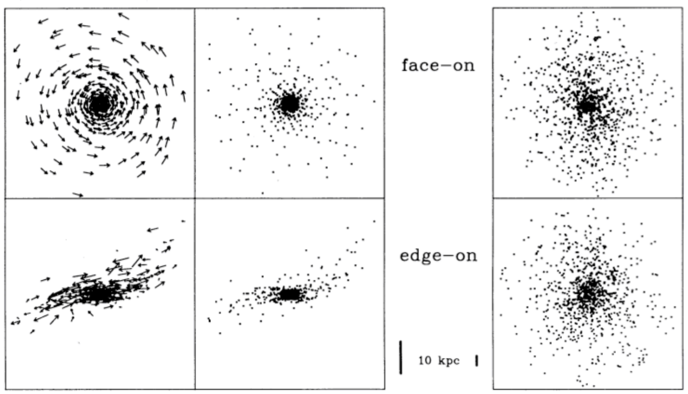


FIG. 17b

baryon physics available in current codes

Benson (2010)

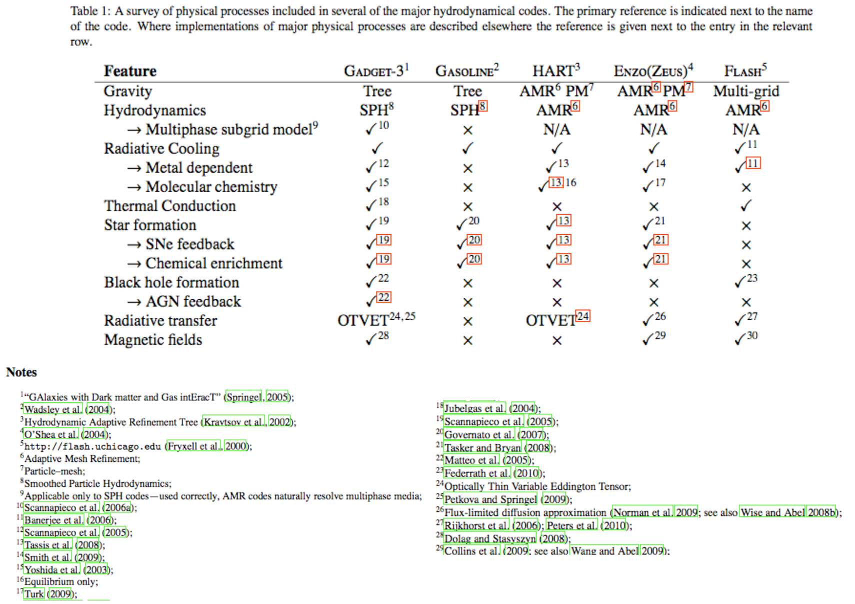


Table 1: A survey of physical processes included in several of the major hydrodynamical codes. The primary reference is indicated next to the name of the code. Where implementations of major physical processes are described elsewhere the reference is given next to the entry in the relevant row.

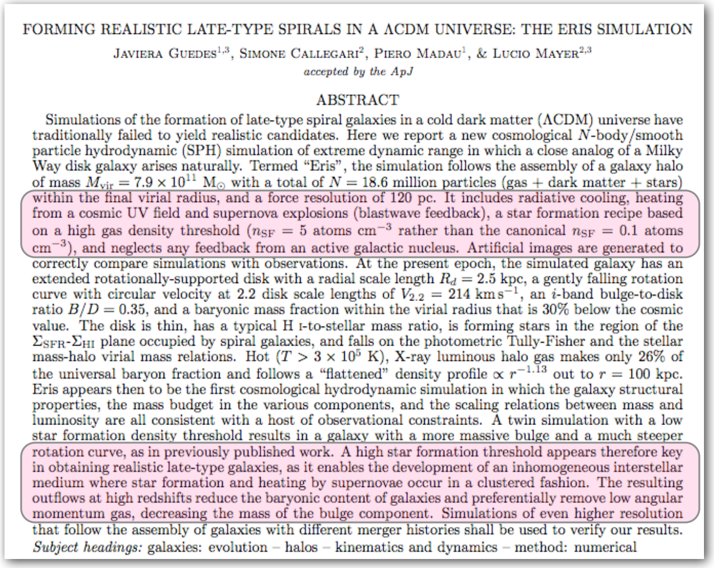
Feature	GADGET-3[1]	GASOLINE[2]	HART[3]	ENZO(ZEUS)[4]	FLASH[5]
Gravity	Tree	Tree	AMR[6] PM[7]	AMR[6] PM[7]	Multi-grid
Hydrodynamics	SPH[8]	SPH[8]	AMR[6]	AMR[6]	AMR[6]
→ Multiphase subgrid model[9]	✓[10]	×	N/A	N/A	N/A
Radiative Cooling	✓	✓	✓	✓	✓[11]
→ Metal dependent	✓[12]	×	✓[13]	✓[14]	✓[11]
→ Molecular chemistry	✓[15]	×	✓[13,16]	✓[17]	×
Thermal Conduction	✓[18]	×	×	×	✓
Star formation	✓[19]	✓[20]	✓[13]	✓[21]	×
→ SNe feedback	✓[19]	✓[20]	✓[13]	✓[21]	×
→ Chemical enrichment	✓[19]	✓[20]	✓[13]	✓[21]	×
Black hole formation	✓[22]	×	×	×	✓[23]
→ AGN feedback	✓[22]	×	×	×	×
Radiative transfer	OTVET[24,25]	×	OTVET[24]	✓[26]	✓[27]
Magnetic fields	✓[28]	×	×	✓[29]	✓[30]

Notes

[1] "GAlaxies with Dark matter and Gas intEracT" (Springel, 2005);
[2] Wadsley et al. (2004);
[3] Hydrodynamic Adaptive Refinement Tree (Kravtsov et al., 2002);
[4] O'Shea et al. (2004);
[5] `http://flash.uchicago.edu` (Fryxell et al., 2000);
[6] Adaptive Mesh Refinement;
[7] Particle–mesh;
[8] Smoothed Particle Hydrodynamics;
[9] Applicable only to SPH codes—used correctly, AMR codes naturally resolve multiphase media;
[10] Scannapieco et al. (2006a);
[11] Banerjee et al. (2006);
[12] Scannapieco et al. (2005);
[13] Tassis et al. (2008);
[14] Smith et al. (2009);
[15] Yoshida et al. (2003);
[16] Equilibrium only;
[17] Turk (2009);
[18] Jubelgas et al. (2004);
[19] Scannapieco et al. (2005);
[20] Governato et al. (2007);
[21] Tasker and Bryan (2008);
[22] Matteo et al. (2005);
[23] Federrath et al. (2010);
[24] Optically Thin Variable Eddington Tensor;
[25] Petkova and Springel (2009);
[26] Flux-limited diffusion approximation (Norman et al. 2009; see also Wise and Abel 2008b);
[27] Rijkhorst et al. (2006); Peters et al. (2010);
[28] Dolag and Stasyszyn (2008);
[29] Collins et al. (2009; see also Wang and Abel 2009);

best effort (circa 2011) at simulating formation of the Milky Way

Guedes et al (2011)



FORMING REALISTIC LATE-TYPE SPIRALS IN A ΛCDM UNIVERSE: THE ERIS SIMULATION

Javiera Guedes[1,3], Simone Callegari[2], Piero Madau[1], & Lucio Mayer[2,3]

accepted by the ApJ

ABSTRACT

Simulations of the formation of late-type spiral galaxies in a cold dark matter (ΛCDM) universe have traditionally failed to yield realistic candidates. Here we report a new cosmological N-body/smooth particle hydrodynamic (SPH) simulation of extreme dynamic range in which a close analog of a Milky Way disk galaxy arises naturally. Termed "Eris", the simulation follows the assembly of a galaxy halo of mass $M_{\rm vir} = 7.9 \times 10^{11}$ $M_\odot$ with a total of $N = 18.6$ million particles (gas + dark matter + stars) within the final virial radius, and a force resolution of 120 pc. It includes radiative cooling, heating from a cosmic UV field and supernova explosions (blastwave feedback), a star formation recipe based on a high gas density threshold ($n_{\rm SF} = 5$ atoms cm^{-3} rather than the canonical $n_{\rm SF} = 0.1$ atoms cm^{-3}), and neglects any feedback from an active galactic nucleus. Artificial images are generated to correctly compare simulations with observations. At the present epoch, the simulated galaxy has an extended rotationally-supported disk with a radial scale length $R_d = 2.5$ kpc, a gently falling rotation curve with circular velocity at 2.2 disk scale lengths of $V_{2.2} = 214$ km s^{-1}, an i-band bulge-to-disk ratio $B/D = 0.35$, and a baryonic mass fraction within the virial radius that is 30% below the cosmic value. The disk is thin, has a typical H I-to-stellar mass ratio, is forming stars in the region of the $\Sigma_{\rm SFR}$-$\Sigma_{\rm HI}$ plane occupied by spiral galaxies, and falls on the photometric Tully-Fisher and the stellar mass-halo virial mass relations. Hot ($T > 3 \times 10^5$ K), X-ray luminous halo gas makes only 26% of the universal baryon fraction and follows a "flattened" density profile $\propto r^{-1.13}$ out to $r = 100$ kpc. Eris appears then to be the first cosmological hydrodynamic simulation in which the galaxy structural properties, the mass budget in the various components, and the scaling relations between mass and luminosity are all consistent with a host of observational constraints. A twin simulation with a low star formation density threshold results in a galaxy with a more massive bulge and a much steeper rotation curve, as in previously published work. A high star formation threshold appears therefore key in obtaining realistic late-type galaxies, as it enables the development of an inhomogeneous interstellar medium where star formation and heating by supernovae occur in a clustered fashion. The resulting outflows at high redshifts reduce the baryonic content of galaxies and preferentially remove low angular momentum gas, decreasing the mass of the bulge component. Simulations of even higher resolution that follow the assembly of galaxies with different merger histories shall be used to verify our results.

Subject headings: galaxies: evolution – halos – kinematics and dynamics – method: numerical

Eris simulation synthetic images in optical-UV

Guedes et al (2011)

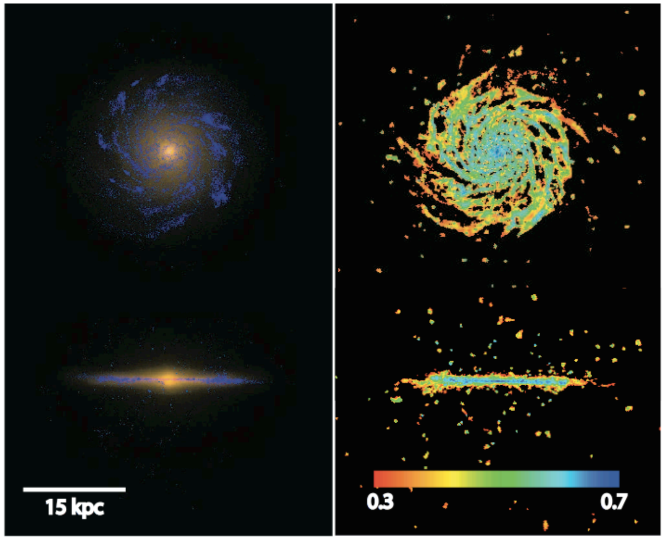


Fig. 2.— *Left panel:* The optical/UV stellar properties of Eris at $z = 0$. The images, created with the radiative transfer code Sunrise (Jonsson 2006), show an i, V, and FUV stellar composite of the simulated galaxy seen face-on and edge-on. A Kroupa IMF was assumed.

Eris simulation galaxy properties are realistic

Guedes et al (2011)

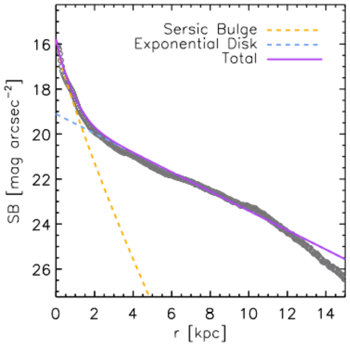


Fig. 3.— The 1D *i*-band radial surface brightness profile of Eris at $z = 0$. This is well fitted by a Sérsic bulge with index $n_s = 1.4$, an exponential disk with scale length $R_d = 2.5$ kpc, and a bulge-to-disk ratio $B/D = 0.35$. The dust reddened, face-on 2D light distribution created by Sunrise was analyzed with Galfit (Peng et al. 2002) following a procedure similar to that detailed in Weinzirl et al. (2009). The "downbending" in the brightness exponential profile at about 5 disk scale length and the surface brightness where the break occurs, 23.5 *i*-mag arcsec^{-2}, are characteristic of late-type spiral galaxies (Pohlen & Trujillo 2006).

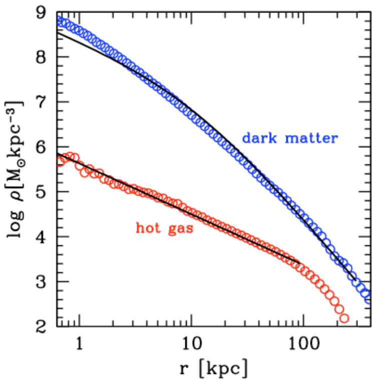
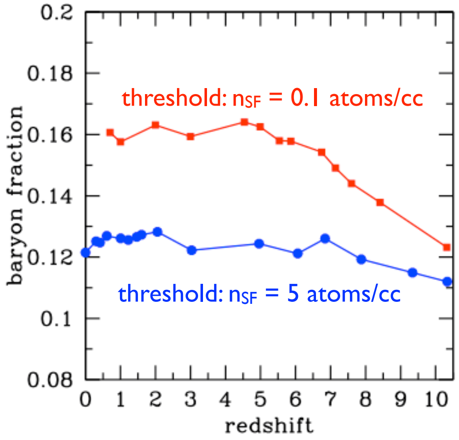


Fig. 5.— The average dark matter (*blue empty dots*) and hot ($T > 3 \times 10^5$ K) gas (*red empty dots*) density profiles of Eris at $z = 0$. The solid lines show the best-fit NFW profile for the dark matter (*upper curve*) and the best-fit power-law profile (with slope -1.13) for the hot gas (*lower curve*). The best-fit NFW profile is characterized by a large halo concentration parameter $c \equiv R_{\rm vir}/R_s = 22$ as the dark matter halo contracts in response to the condensation of baryons in its center.

Eris simulation: low baryon fraction with new star formation parameters

Guedes et al (2011)



Is the star formation threshold really uncertain by a factor of 50?

fundamental issue: **uniqueness** in the presence of process **complexity**

* modeling star formation in direct gas dynamic simulations requires

– shocks
– cooling in a plasma heated by multiple processes (non-LTE?)
– magnetic fields + cosmic ray heating?
– mass loading and metal pollution by SN blastwaves
– effects of jet heating from central BH (AGN activity)
– +...

All of this entails ***many tens of control parameters***, effects of which often compete against one another.

How do we know when we've reached THE solution of nature?
Does nature even follow a unique prescriptive solution? Or might elements be stochastic?
Do the stellar IMF and feedback processes depend only on local conditions?

* SAM models already have >100 input parameters :(

(e.g., galacticus.org)

multiple versions of SAMs with slightly different astrophysical processes

Benson (2010)

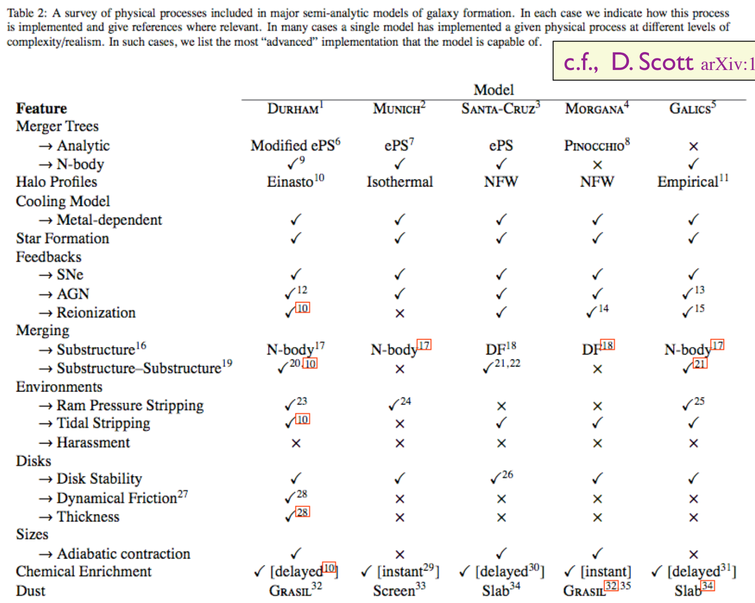


Table 2: A survey of physical processes included in major semi-analytic models of galaxy formation. In each case we indicate how this process is implemented and give references where relevant. In many cases a single model has implemented a given physical process at different levels of complexity/realism. In such cases, we list the most "advanced" implementation that the model is capable of.

c.f., D. Scott arXiv:1112.0285

Feature	Model DURHAM[1]	 MUNICH[2]	 SANTA-CRUZ[3]	 MORGANA[4]	 GALICS[5]
Merger Trees					
→ Analytic	Modified ePS[6]	ePS[7]	ePS	PINOCCHIO[8]	×
→ N-body	✓[9]	✓	✓	×	✓
Halo Profiles	Einasto[10]	Isothermal	NFW	NFW	Empirical[11]
Cooling Model					
→ Metal-dependent	✓	✓	✓	✓	✓
Star Formation	✓	✓	✓	✓	✓
Feedbacks					
→ SNe	✓	✓	✓	✓	✓
→ AGN	✓[12]	✓	✓	✓	✓[13]
→ Reionization	✓[10]	×	✓	✓[14]	✓[15]
Merging					
→ Substructure[16]	N-body[17]	N-body[17]	DF[18]	DF[18]	N-body[17]
→ Substructure–Substructure[19]	✓[20,10]	×	✓[21,22]	×	✓[21]
Environments					
→ Ram Pressure Stripping	✓[23]	✓[24]	×	×	✓[25]
→ Tidal Stripping	✓[10]	×	✓	✓	✓
→ Harassment	×	×	×	×	×
Disks					
→ Disk Stability	✓	✓	✓[26]	✓	✓
→ Dynamical Friction[27]	✓[28]	×	×	×	×
→ Thickness	✓[28]	×	×	×	×
Sizes					
→ Adiabatic contraction	✓	×	✓	✓	×
Chemical Enrichment	✓ [delayed[10]]	✓ [instant[29]]	✓ [delayed[30]]	✓ [instant]	✓ [delayed[31]]
Dust	GRASIL[32]	Screen[33]	Slab[34]	GRASIL[32,35]	Slab[34]

Will we ever declare galaxy formation a `solved problem'?

Is the solar wind a solved problem?

end run around complexity: ***statistical*** solutions for galaxy formation

Zehavi etal (2010)

* Halo Occupation Distribution (HOD) method:
assign galaxies to halos

- for given minimum luminosity, know n(L,z) empirically
- also know n(M,z) from sims
- also know two-point clustering of halos and galaxies
- write p(N_{gal} | M,z) to match n(L,z) and clustering

Conroy etal (2006)

* Sub-Halo Assignment Matching (SHAM) method:
assign galaxies to sub-halos

- for given minimum luminosity, know n(L,z) empirically
- also know n(M,z) and n(M_{sub}, z) from sims
- within given volume, rank order L and M_{sub}, and match ranks to assign L to M_{sub}
- scatter can be introduced during ranking process

role of LSS simulations
in dark energy studies
(the future)

basic steps to study dark energy (DE) with large-scale structure

1. produce a large survey of a class of cosmic objects to $z \geq 1$, using a class that enables statistical tracing of dark matter
    – extract statistics, $\mathbf{y}_i$, for DE test method *i* (*e.g.*, BAO, WL, CL)

2. compute model expectations for object survey statistics
    – calculate likelihood, $p(\mathbf{y}_i \mid \theta, \alpha)$, over cosmological params, θ, and within an assumed astrophysical model, α, for the specific object class use

3. perform the likelihood analysis, marginalizing over (or just fixing) α
    – extract cosmological constraints, $p(\theta)$

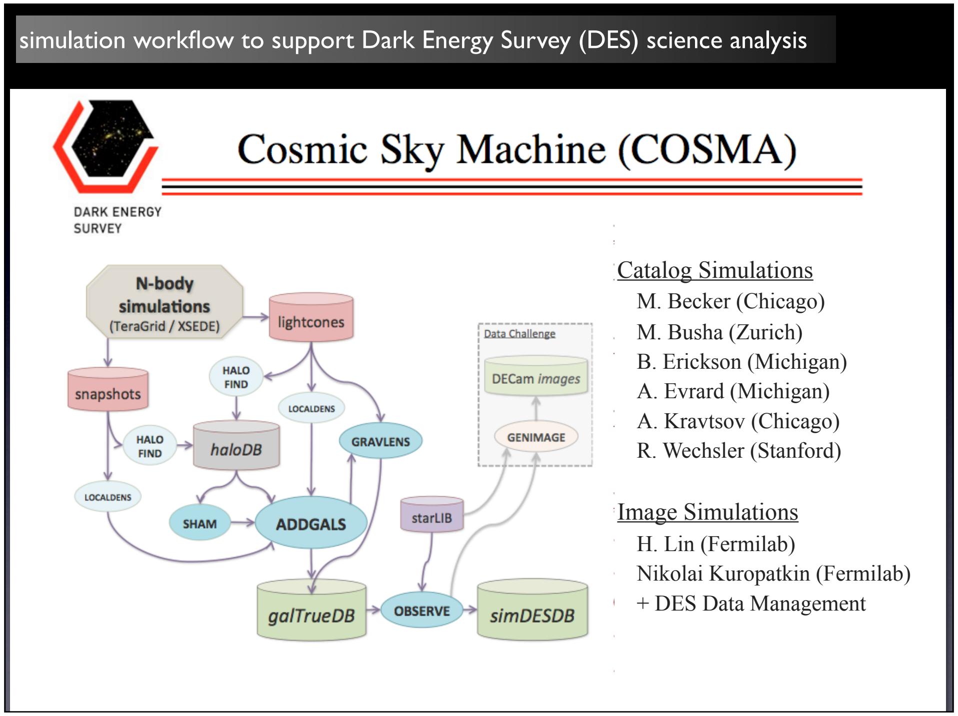
role of simulations in DE survey science

Survey-specific simulations enable **key capabilities:**

* to extract unbiased statistical signals, $\mathbf{y}_i$, from the raw object catalog

* to predict statistical expectations, $p(\mathbf{y}_i \mid \theta, \alpha)$ for a variety of models

* to calculate the expected signal covariance, $\mathrm{COV}(\mathbf{y}_i , \mathbf{y}_j)$



simulation workflow to support Dark Energy Survey (DES) science analysis

Cosmic Sky Machine (COSMA)

Catalog Simulations
M. Becker (Chicago)
M. Busha (Zurich)
B. Erickson (Michigan)
A. Evrard (Michigan)
A. Kravtsov (Chicago)
R. Wechsler (Stanford)

Image Simulations
H. Lin (Fermilab)
Nikolai Kuropatkin (Fermilab)
+ DES Data Management

DES Simulation Working Group: key personnel

Risa Wechsler, asst. professor (Stanford/SLAC)

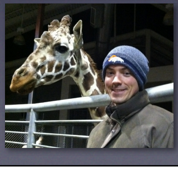
- ADDGALS methodology, empirical tuning
- DES catalog production lead

Michael Busha, postdoc (Zurich)

- N-body production + postprocessing
- ADDGALS development and application
- DES catalog production (masking, Data Challenge ingest)

Matt Becker, grad student (Chicago)

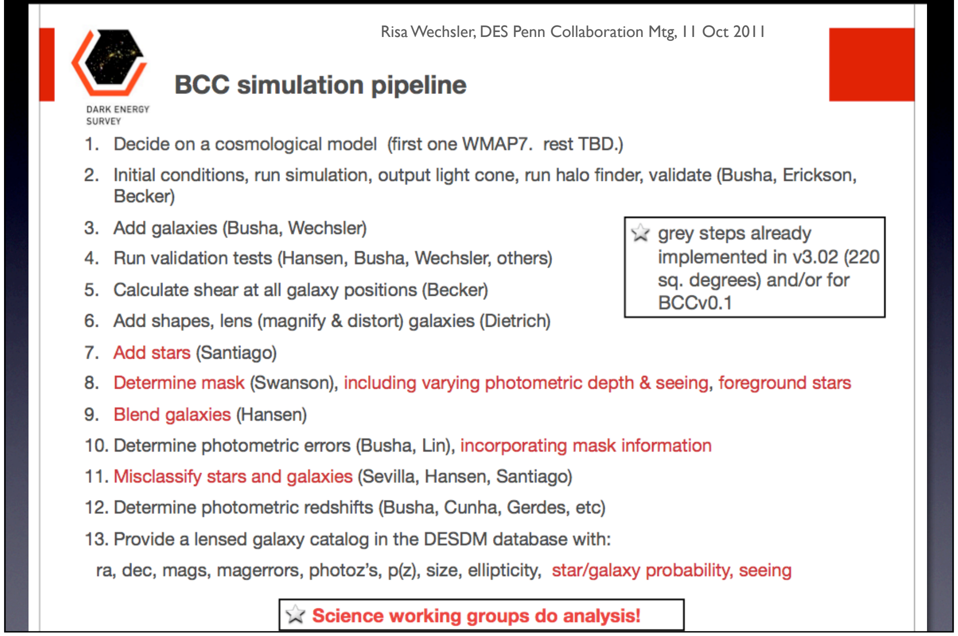
- N-body production + postprocessing
- gravitational lensing shear (new Spherical Harmonic Tree code)



Brandon Erickson, grad student (Michigan)

- N-body production + postprocessing
- workflow development for XSEDE/SLAC processing (BCC)

simulation workflow to support DES analysis



Risa Wechsler, DES Penn Collaboration Mtg, 11 Oct 2011

BCC simulation pipeline

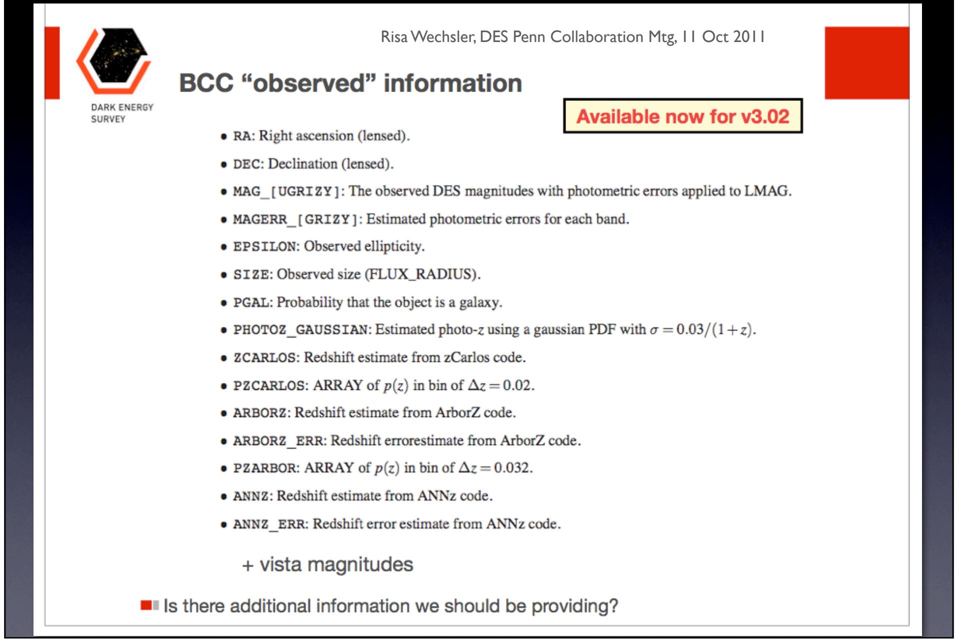
1. Decide on a cosmological model (first one WMAP7. rest TBD.)
2. Initial conditions, run simulation, output light cone, run halo finder, validate (Busha, Erickson, Becker)
3. Add galaxies (Busha, Wechsler)
4. Run validation tests (Hansen, Busha, Wechsler, others)
5. Calculate shear at all galaxy positions (Becker)
6. Add shapes, lens (magnify & distort) galaxies (Dietrich)
7. Add stars (Santiago)
8. Determine mask (Swanson), including varying photometric depth & seeing, foreground stars
9. Blend galaxies (Hansen)
10. Determine photometric errors (Busha, Lin), incorporating mask information
11. Misclassify stars and galaxies (Sevilla, Hansen, Santiago)
12. Determine photometric redshifts (Busha, Cunha, Gerdes, etc)
13. Provide a lensed galaxy catalog in the DESDM database with:

ra, dec, mags, magerrors, photoz's, p(z), size, ellipticity, star/galaxy probability, seeing

☆ grey steps already implemented in v3.02 (220 sq. degrees) and/or for BCCv0.1

☆ **Science working groups do analysis!**

simulation workflow to support DES analysis



DARK ENERGY SURVEY

Risa Wechsler, DES Penn Collaboration Mtg, 11 Oct 2011

BCC "observed" information

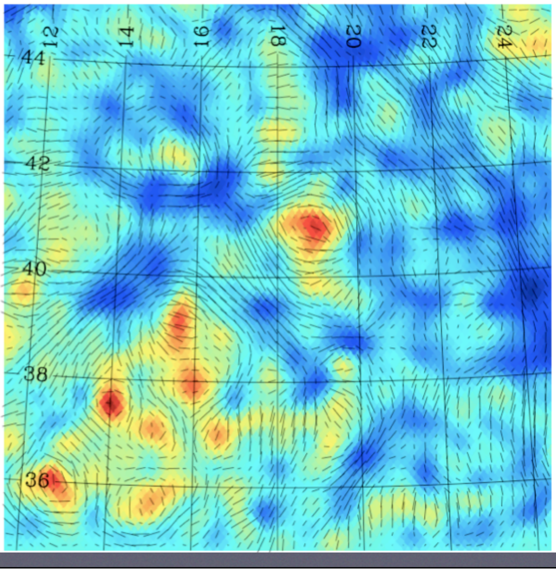
Available now for v3.02

- `RA`: Right ascension (lensed).
- `DEC`: Declination (lensed).
- `MAG_[UGRIZY]`: The observed DES magnitudes with photometric errors applied to LMAG.
- `MAGERR_[GRIZY]`: Estimated photometric errors for each band.
- `EPSILON`: Observed ellipticity.
- `SIZE`: Observed size (FLUX_RADIUS).
- `PGAL`: Probability that the object is a galaxy.
- `PHOTOZ_GAUSSIAN`: Estimated photo-z using a gaussian PDF with $\sigma = 0.03/(1+z)$.
- `ZCARLOS`: Redshift estimate from zCarlos code.
- `PZCARLOS`: ARRAY of $p(z)$ in bin of $\Delta z = 0.02$.
- `ARBORZ`: Redshift estimate from ArborZ code.
- `ARBORZ_ERR`: Redshift errorestimate from ArborZ code.
- `PZARBOR`: ARRAY of $p(z)$ in bin of $\Delta z = 0.032$.
- `ANNZ`: Redshift estimate from ANNz code.
- `ANNZ_ERR`: Redshift error estimate from ANNz code.

+ vista magnitudes

- Is there additional information we should be providing?

HEALPix-based map of DC6B 200 deg^2 convergence and shear fields



Colors indicates convergence ∝ surface mass density; redder ==> higher density

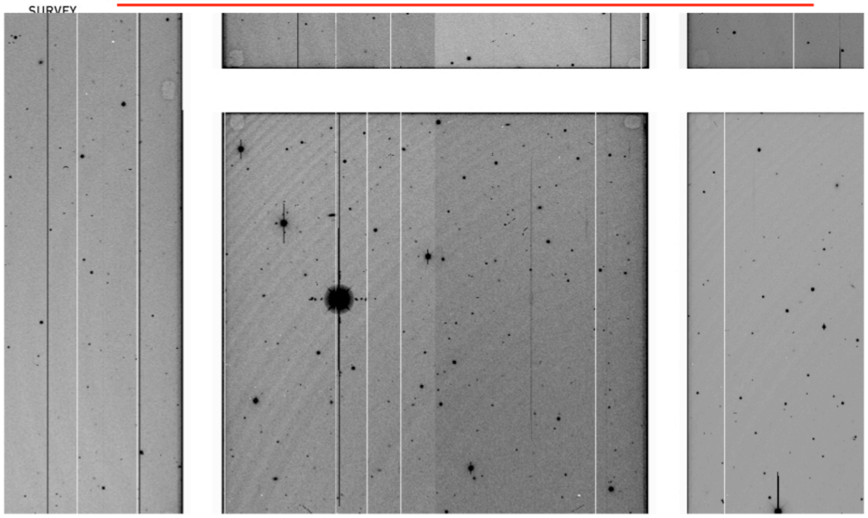
Black "whiskers" show shear field due to gravitational lensing

Figure from M. Becker

courtesy H. Lin (FNAL)

Close-up of raw simulated images

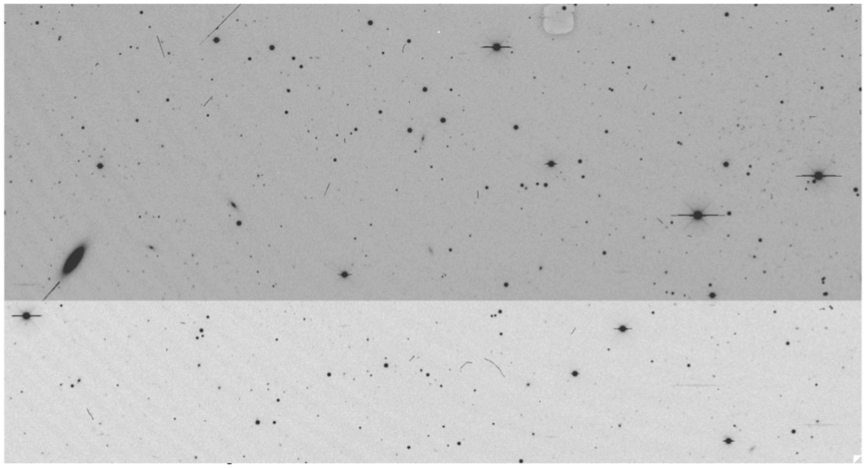
Note bright star artifacts, cosmic rays, cross talk, glowing edges, flatfield (“grind marks”, tape bumps), bad columns, 2 amplifiers/CCD



courtesy H. Lin (FNAL)

DARK ENERGY
SURVEY

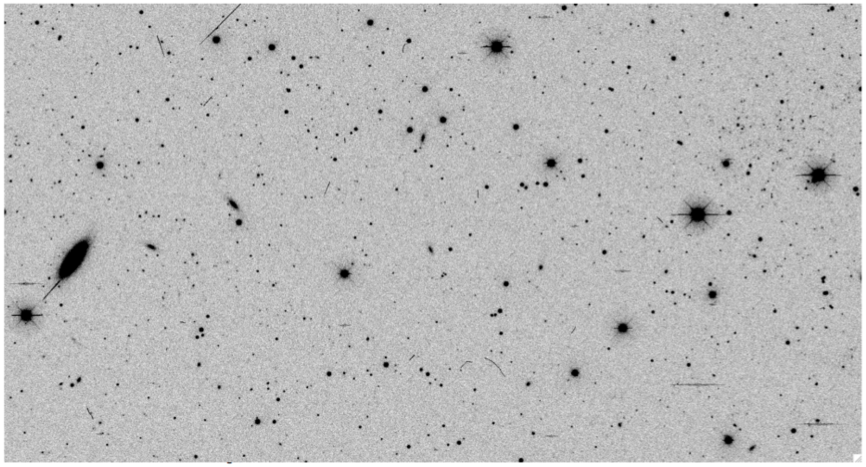
Example DC6B image using profile galaxies: Part of raw r-band image of one CCD



courtesy H. Lin (FNAL)

Same r-band image after bias subtraction and flatfielding (cosmic rays can be removed but left in here)

DARK ENERGY
SURVEY

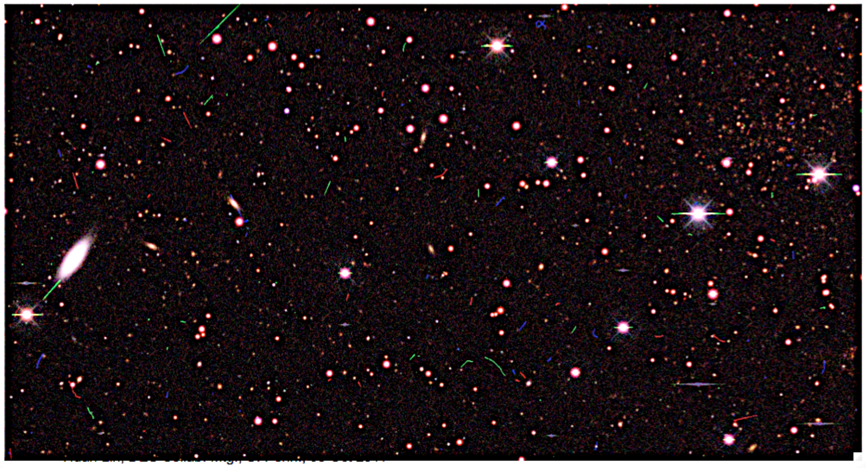


courtesy H. Lin (FNAL)

DARK ENERGY
SURVEY

Same area shown as color composite of separate images in g,r,i filters

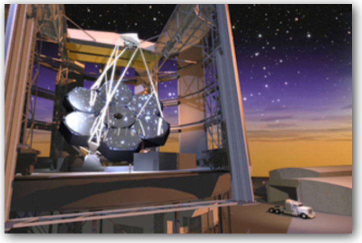
(note distinct color of rich galaxy cluster at upper right)



follow the $: DES SimWG activities remain an unfunded mandate

SDSS (NSF + private Sloan Foundation) = **astronomical survey**
- agencies pay to produce the catalog
- science emerges later (single investigator grants)

DES (DoE + NSF) ≈ **physics (dark energy) experiment**
- DoE pays for new camera (DECam)
- NSF pays for Data Management and CTIO facilities
- DES science teams are mandated to address nature of dark energy
- who pays for quality assurance of dark energy constraints?
- who pays for ensuring the validity of the science return?

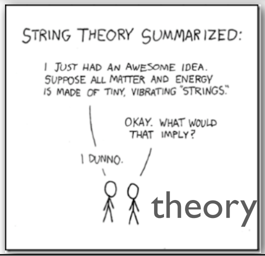


observation

computation

future:

- simulations as an integral element of large survey projects
- synthetic multiwavelength skies available to perform cross-survey science analysis
- improved theoretical constraints from *precision measurement and modeling*



theory

cosmology from
counts and clustering
of massive halos

basic ingredients for cosmology from cluster counts and clustering

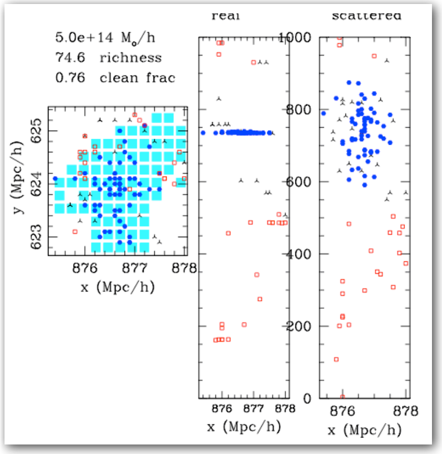
1. halo space density (aka, *mass function*), $dn(>M, z)/dV$
   - well calibrated (~5% in d*n*) by (dark matter only) simulations

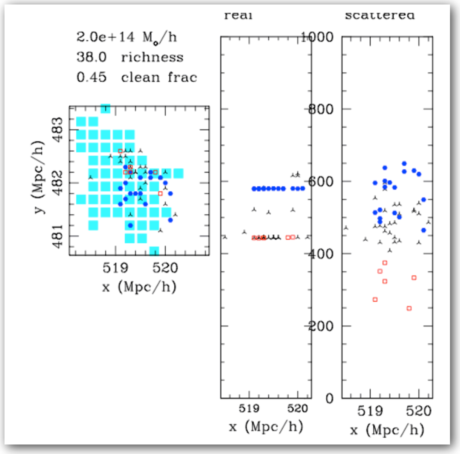
2. two-point spatial clustering of halos (aka, *bias function*), $b(M, z)$
   - similarly well calibrated

3. population model for signal, *S,* used to identify clusters, $p(S \mid M, z)$
   - power-law with log-normal deviations (typically self-calibrated)
   - projection effects (signal-dependent) $S_{\mathrm{observed}} \neq S_{\mathrm{intrinsic}}$

4. selection model for signal, *S*
   - completeness (missed clusters)
   - purity (false positives)

projection effects on clusters: blending of halos in z-space



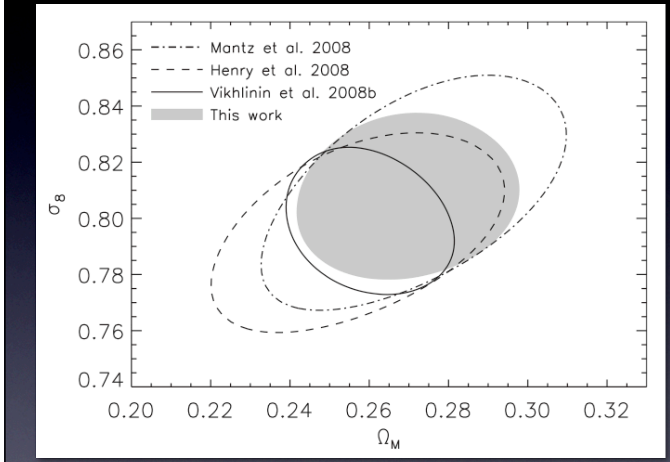


observable signal choices for surveys: pros and cons

Signal	Pros	Cons
X-ray	• spatially compact signal (relative to other methods) • hot thermal ICM is unique to clusters • 40+ year science history	• expensive (space-based) • flux confusion from AGN • surface brightness dimming • most sources will have moderate S/N
Optical	• inexpensive (*free* with any galaxy survey!) • old, `red sequence' galaxies reside in massive halos • 80+ year science history	• confusion from line-of-sight projection • moderate S/N (Poisson statistics for $N \geq 10$) • galaxy formation!
Sunyaev-Zel'dovich	• inexpensive (*free* with any CMB survey) • nearly redshift-independent signal	• point source confusion • l-o-s projected confusion with low angular resolution • moderate S/N for most

consistent cosmology from existing optical and X-ray samples

Rozo et al 2010



optical: maxBCG
(shaded)
~14,000 clusters

X-ray: 400d, BCS
(lines)
~100 clusters

systematics limited !

cosmological complementarity from cluster counts + clustering

Cunha, Huterer Frieman,
0904.1589

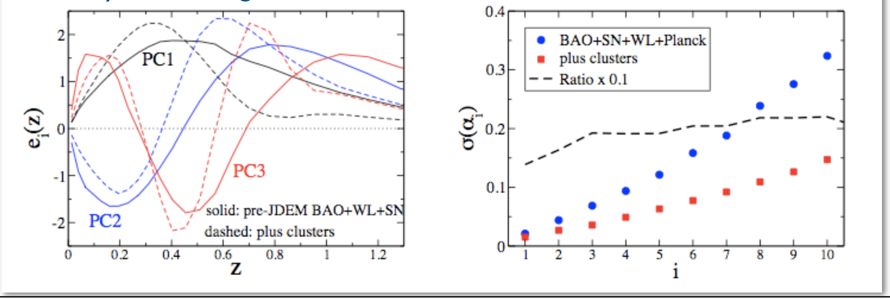
$$\bar{n}_{\alpha}(z) \equiv \int_{M_{\alpha}^{\rm obs}}^{M_{\alpha+1}^{\rm obs}} \frac{dM^{\rm obs}}{M^{\rm obs}} \int \frac{dM}{M} \frac{d\bar{n}}{d\ln M} p(M^{\rm obs}|M)$$

$$p(M^{\rm obs}|M) = \frac{1}{\sqrt{2\pi\sigma^2_{\ln M}}} \exp[-x^2(M^{\rm obs})], \qquad x(M^{\rm obs}) \equiv \frac{\ln M^{\rm obs} - \ln M - \ln M^{\rm bias}(M,z)}{\sqrt{2\sigma_{\ln M}(M,z)^2}}.$$

$$\begin{aligned} \ln M^{\rm bias}(M_{\rm obs},z) &= \ln M_0^{\rm bias} + a_1 \ln(1+z) \\ &\quad + a_2(\ln M_{\rm obs} - \ln M_{\rm pivot}) \qquad (3) \\ \sigma^2_{\ln M}(M_{\rm obs},z) &= \sigma_0^2 + \sum_{i=1}^{3} b_i z^i \\ &\quad + \sum_{i=1}^{3} c_i (\ln M_{\rm obs} - \ln M_{\rm pivot})^i \quad (4) \end{aligned}$$

nuisance:
4 mass bias params
7 mass variance params

PCA analysis of DE figure of merit



cluster cosmology:

solidifying theoretical framework

- halo space density (well-calibrated functional form)
- halo spatial clustering (“)
- multi-component signal model (power-law + log-norm scatter)
- growing body of empirical evidence to inform models
- improving fidelity of simulations

challenges to survey analysis

- survey-specific halo selection
- detailed form of mass-observable relations
- absolute calibration of cluster masses
- sensitivities to baryon physics (feedback)

optical surveys for BAO & WL get clusters “for free”!
large, multi-wavelength surveys are coming