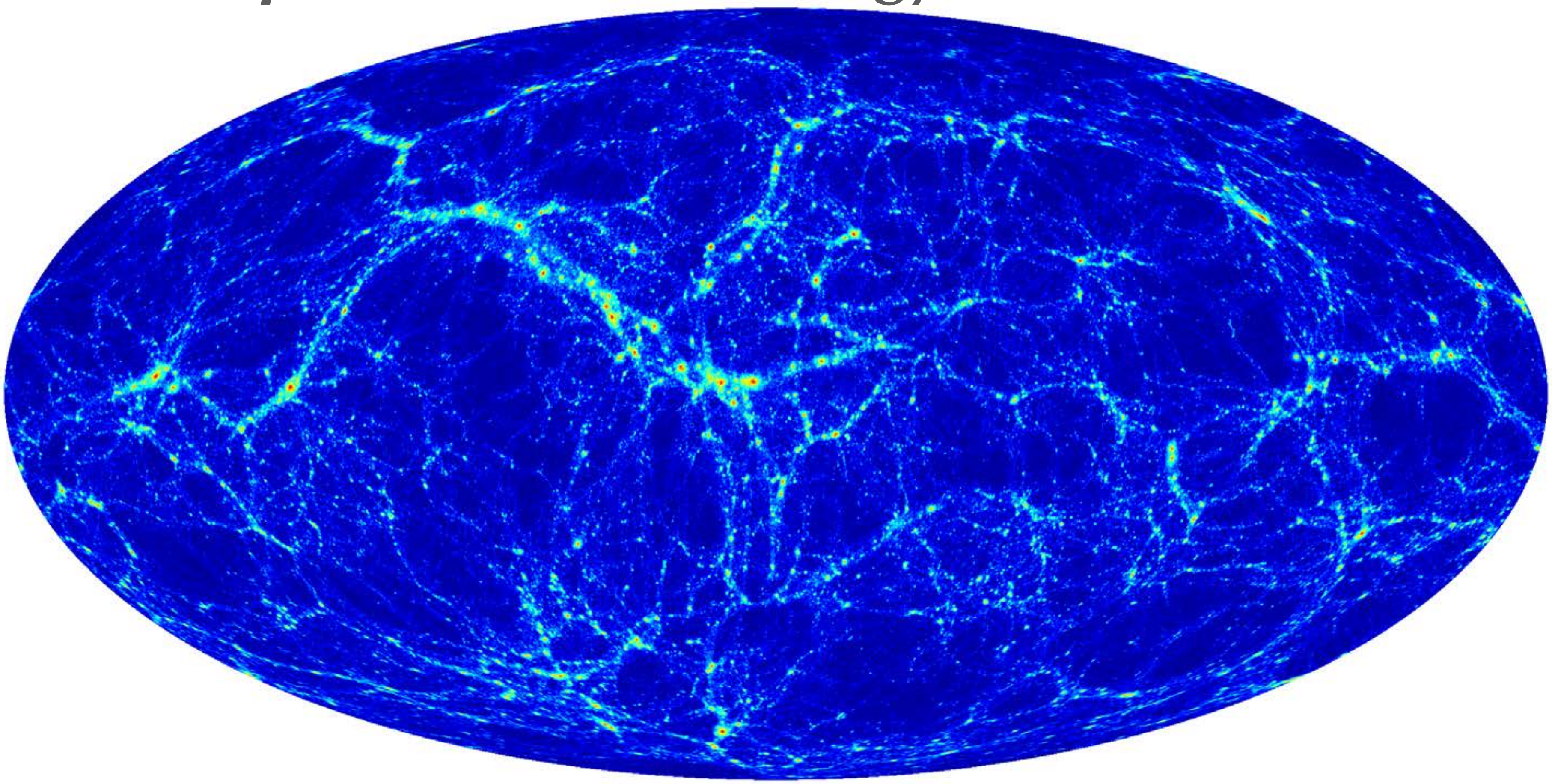
Toward High-Fidelity Synthetic Skies: Computational Cosmology in Adolescence



August (Gus) Evrard
Arthur F. Thurnau Professor
Departments of Physics and Astronomy
Michigan Center for Theoretical Physics
University of Michigan

Paris `banlieue', 1746

Paris banlieue, 2012

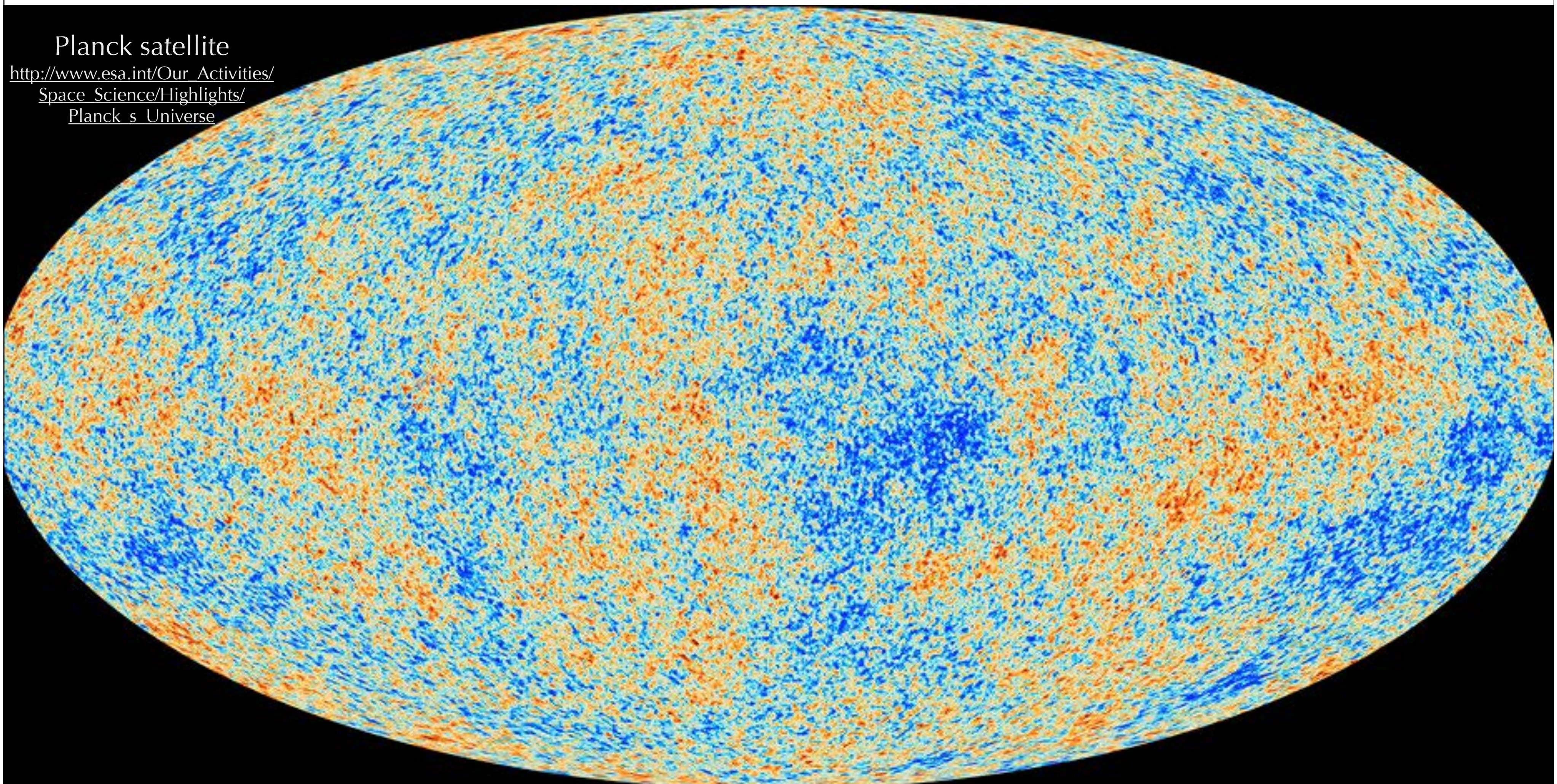
Parc de la Haute-Ile

http://parcsinfo.seine-saint-denis.fr/spip.php?rubrique11

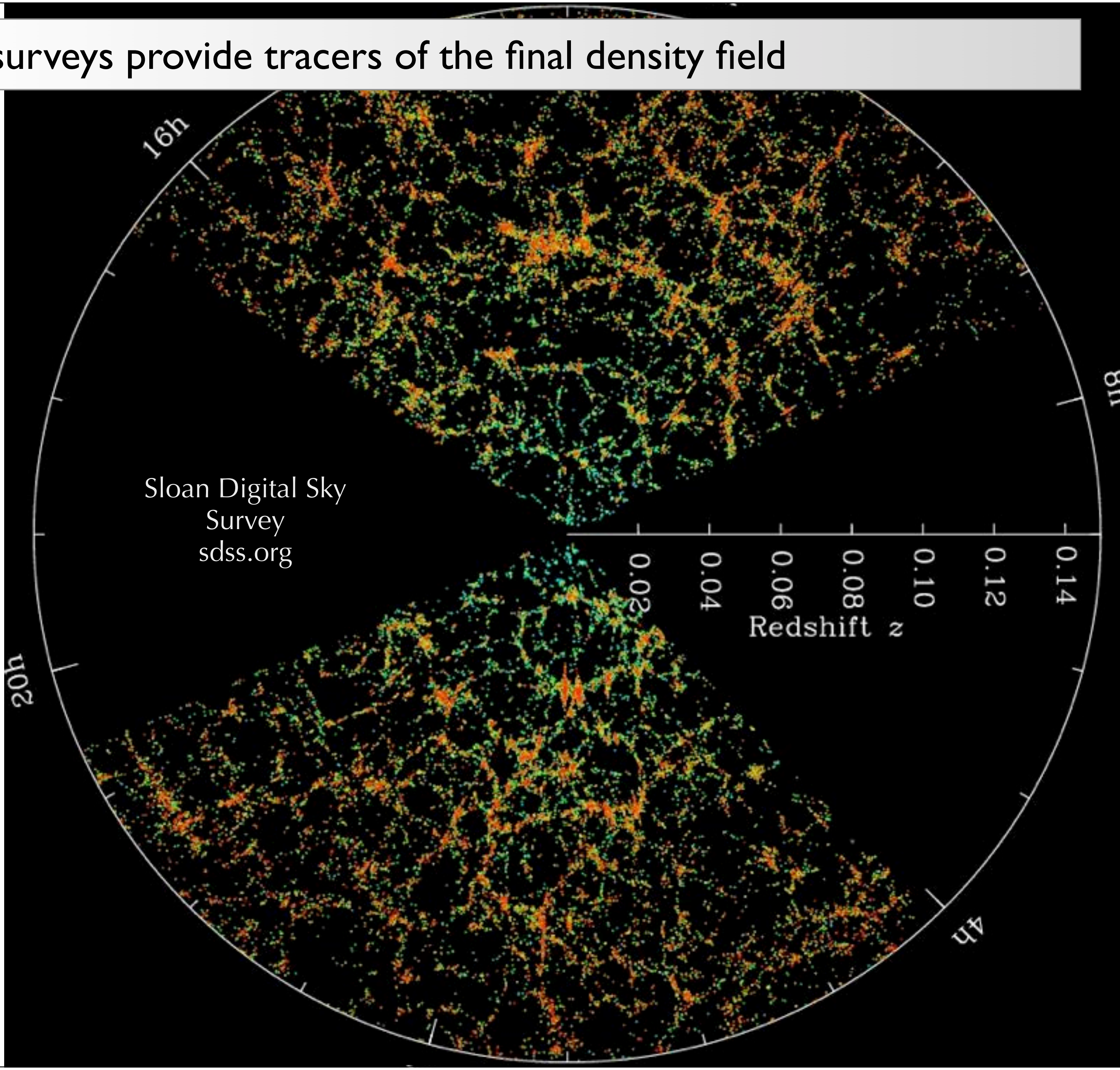
outline

* cosmic structure as a (complex) initial-value problem
  – clusters of galaxies as a motivational example
* the N-body era
  – broad and deep expertise in non-linear behavior
* beyond N-body: hydro and other methods to trace baryons
  – galaxy formation: many recipes, improving insights
* synthetic skies for Dark Energy Survey + XMM-XXL
  – empirical, statistical approaches circumvent complex physics
* post-adolescent thoughts
  – community / identify / workflow infrastructure

the cosmic microwave background provides initial conditions



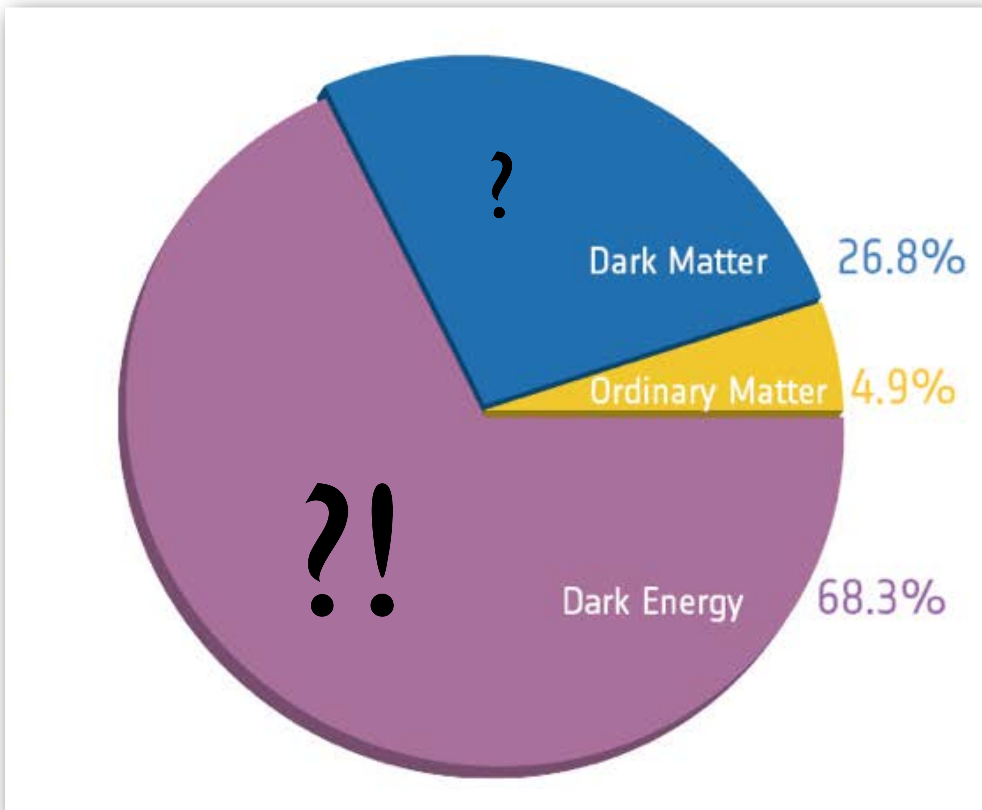
galaxy surveys provide tracers of the final density field



constraints on the energy density of today's universe

Combined statistical constraints from:

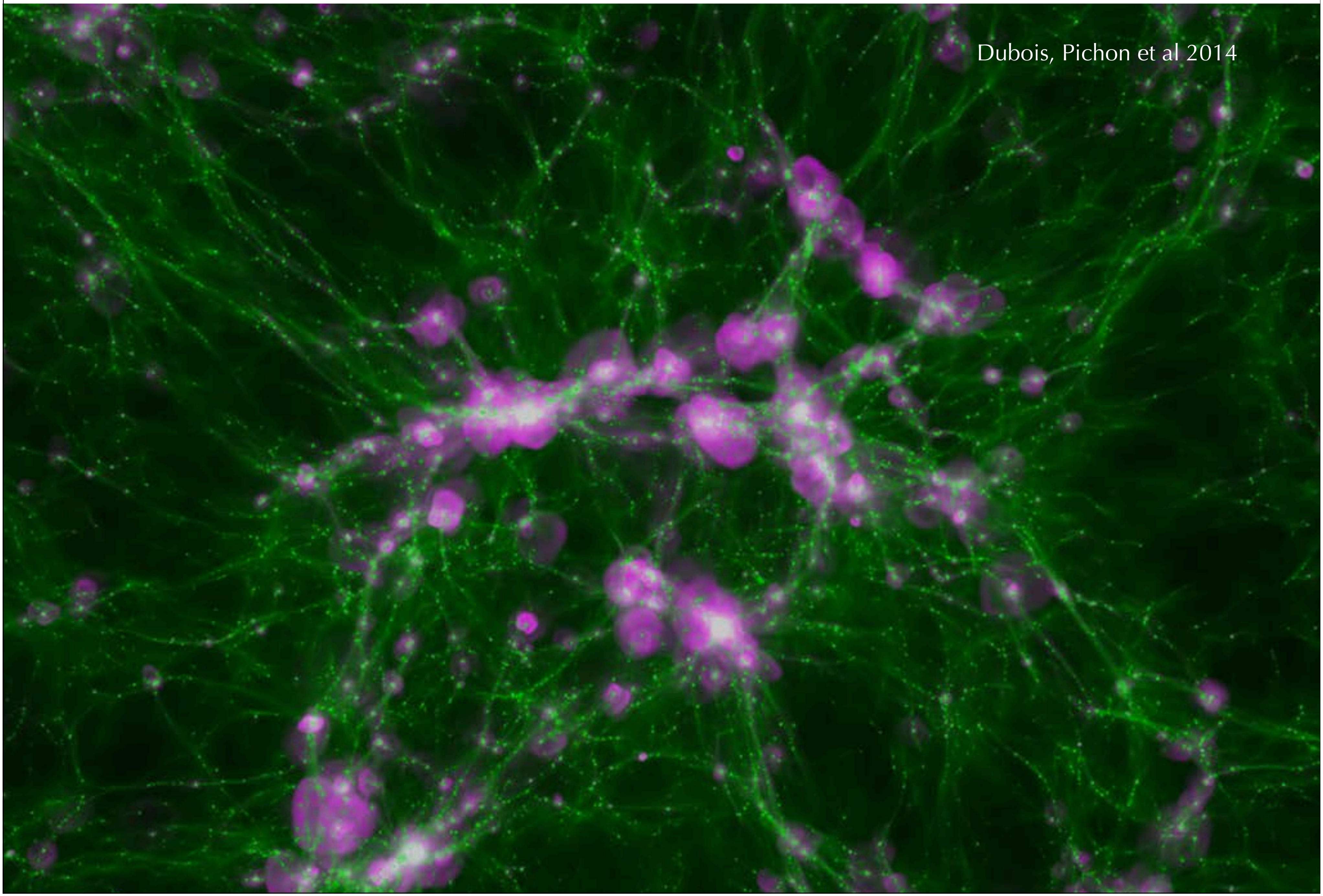
- Cosmic Microwave Background (CMB)
- Large-Scale Structure (LSS) traced by galaxies
- local cosmic expansion rate (Hubble constant)



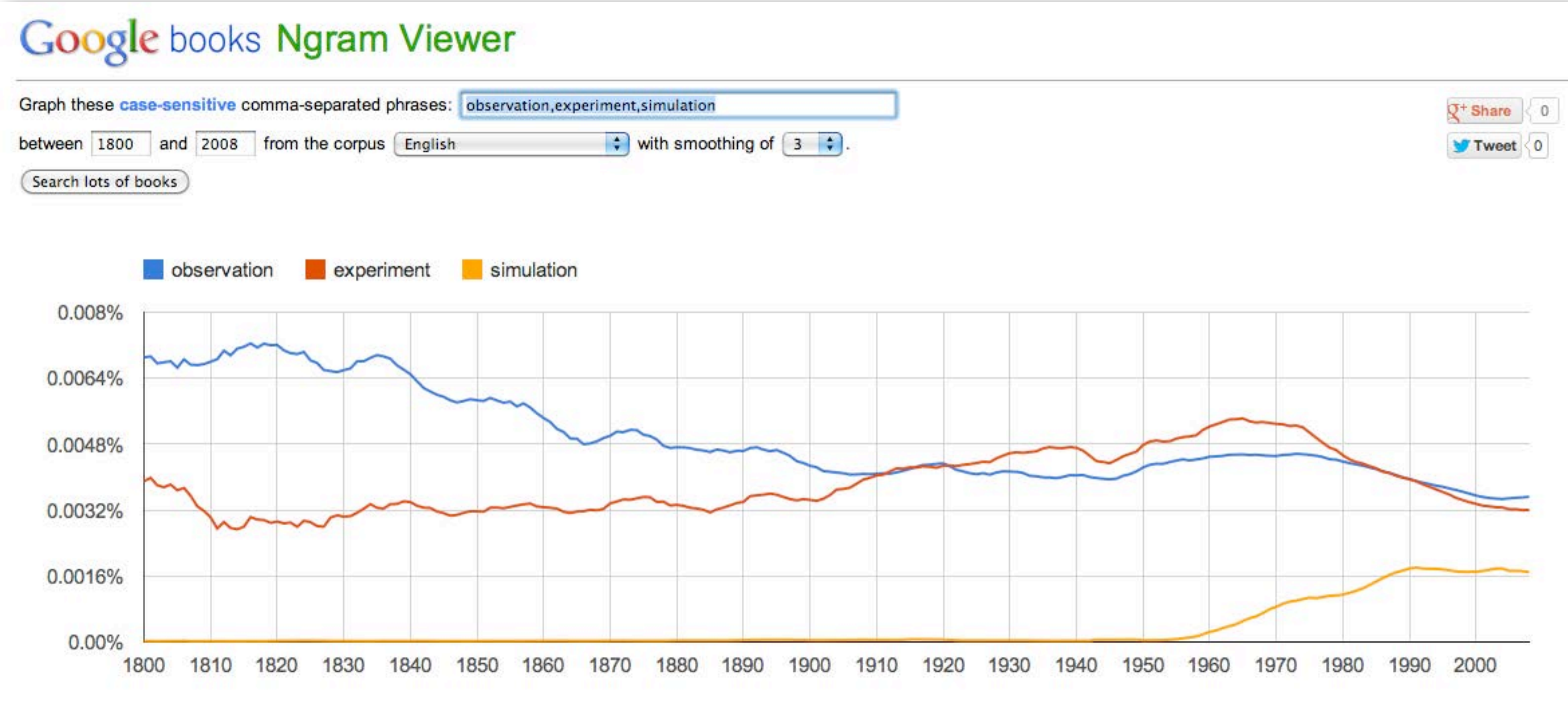
essence of cosmic structure formation (real-space perspective)

Gravity amplifies
tiny random noise into a
cosmic web
of *hierarchically-evolving*
large-scale structure,
which features
locally bound, ellipsoidal
halos
as an essential component.

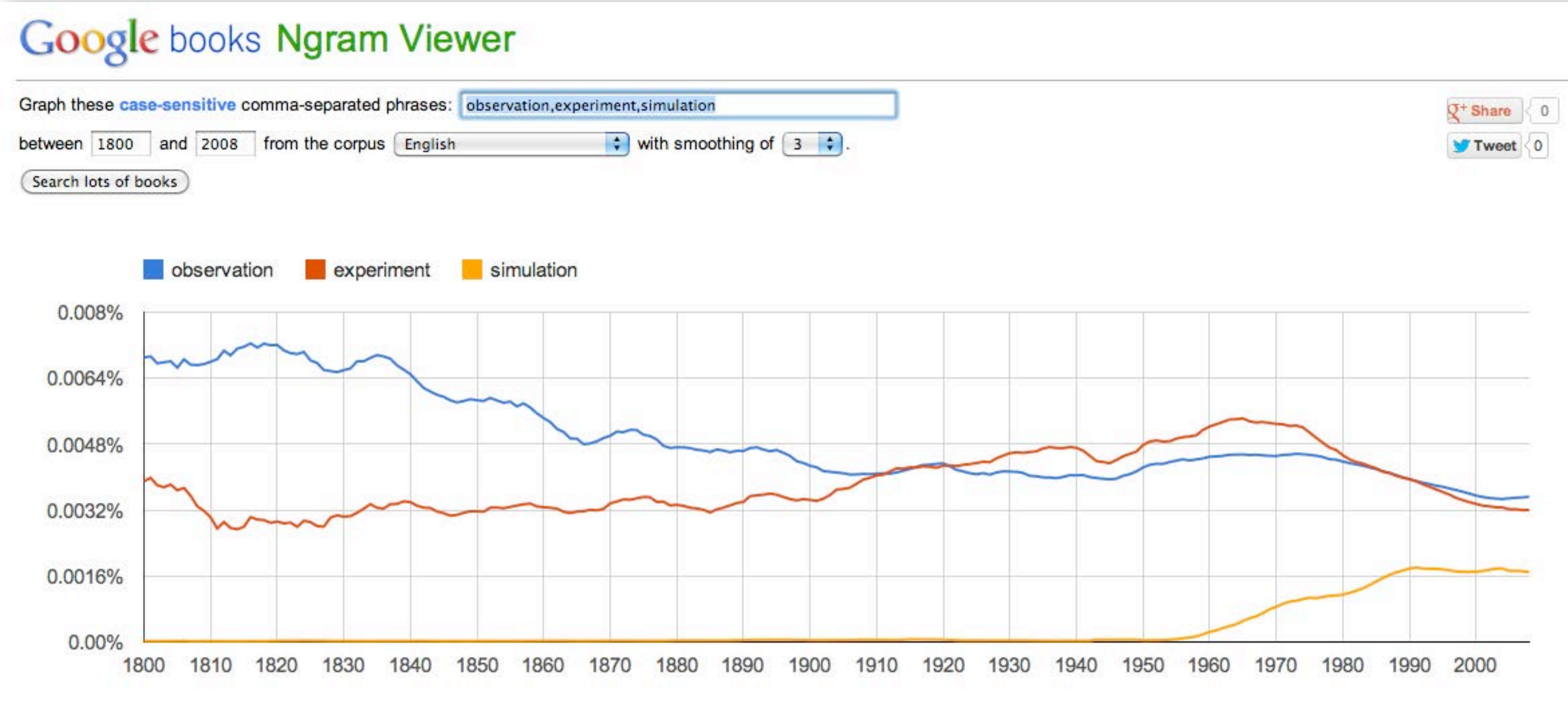
example of baryonic web at z~1.5 http://spine-public.projet-horizon.fr



frequency of "simulation" in the Google Books corpus



frequency of "simulation" in the Google Books corpus



Relative to observation and experiment, simulation is in an adolescent phase.

clusters of galaxies =
manifestations of massive,
dark matter-dominated halos

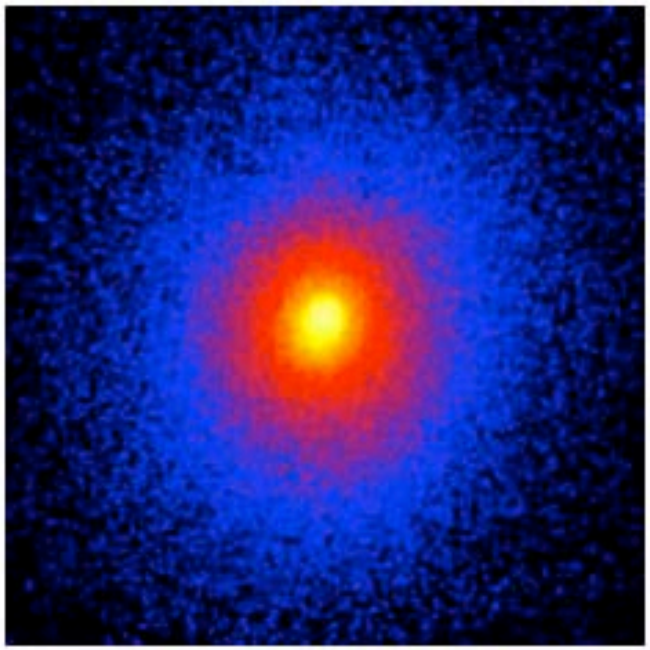
clusters of galaxies are simple (relative to galaxies) astrophysical laboratories

* baryons in M>~1e14 Msun **halos** reside mainly in a

hot, intracluster medium (ICM)

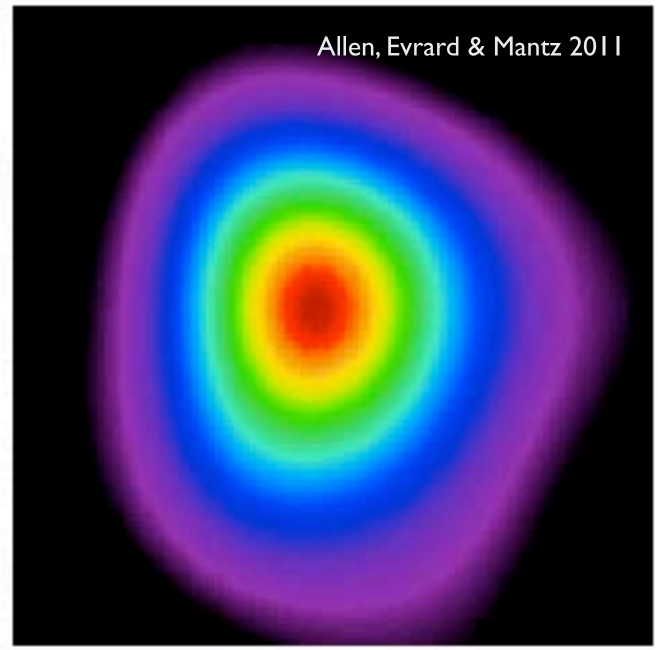
– hot gas outweighs baryons in stars by factors >~5

Abell 1835 (z=0.25) 5.2 arcmin ~ 1.2 Mpc images



X-ray

optical



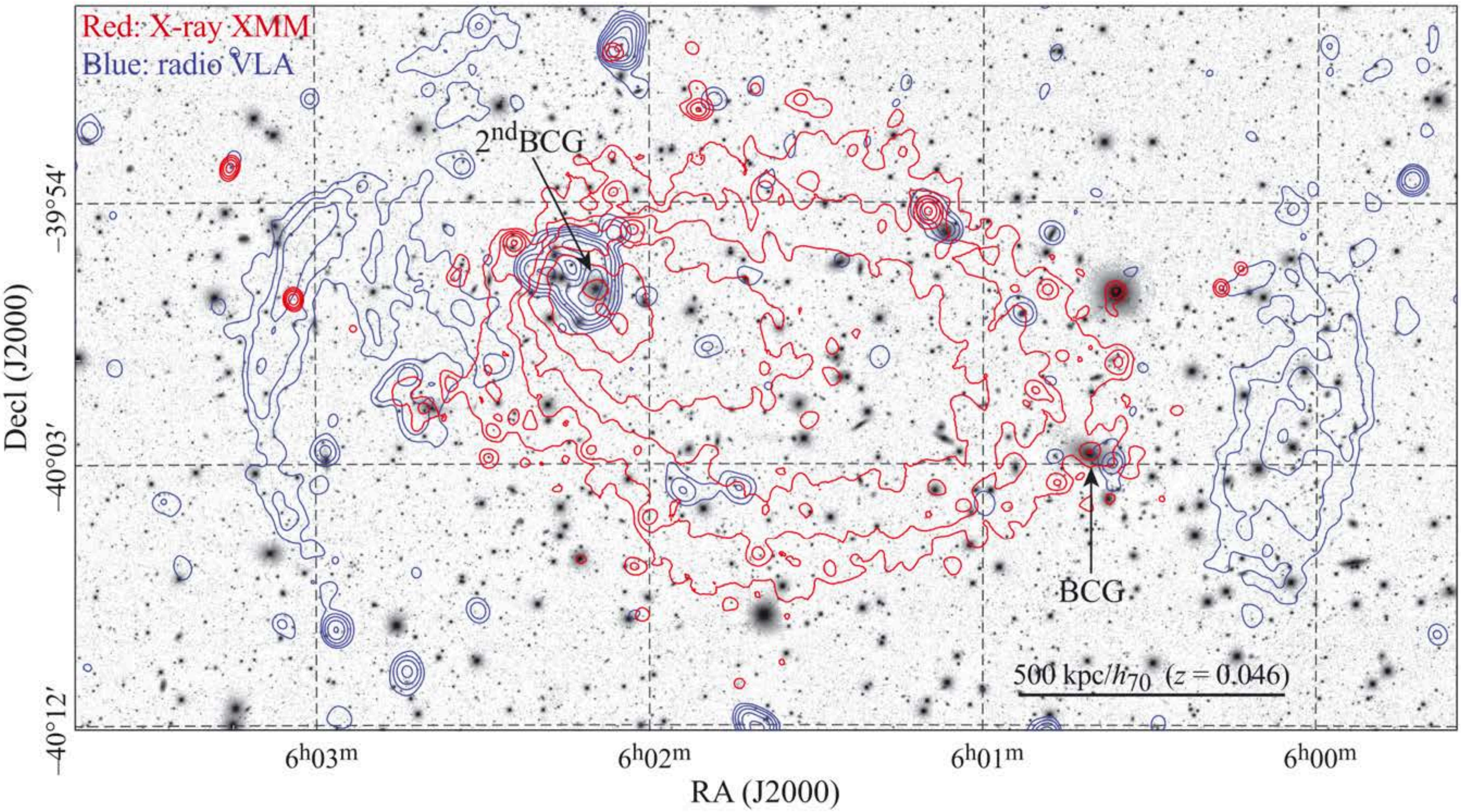
mm (Sunyaev-Zel'dovich)

levels of physical modeling

level	approach	pros	cons
0	collisionless N-body	inexpensive, mature methods, DM phenom.	limited physical scope
1	coupled N-body + simple gas dynamics	+ hot gas phenom., good hydro methods	no galaxy phenom., limited applicability
2	+ star/BH formation + SN/AGN feedback	+ galaxy phenom., wide applicability	expensive, large modeling uncertainties

some clusters are more dynamic, like Abell 3376

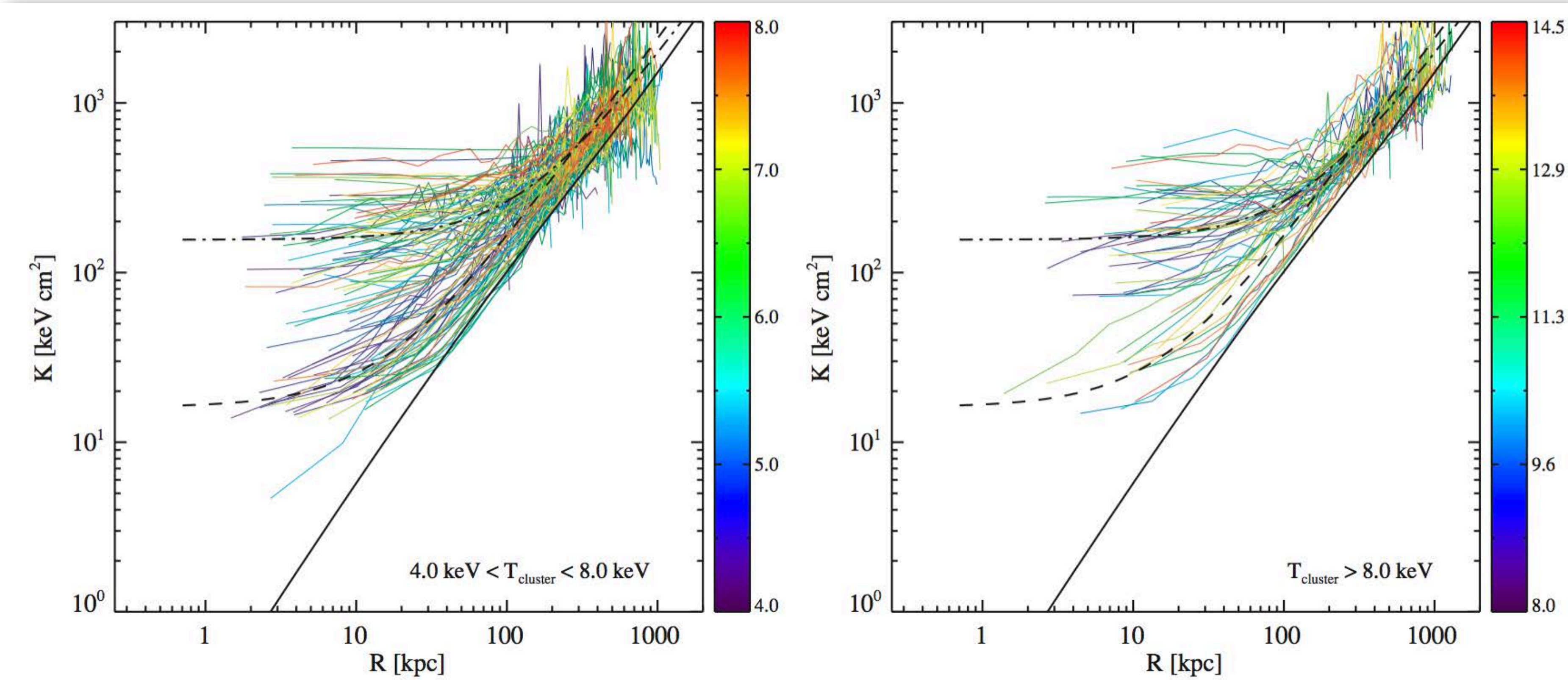
Durret et al 2013



wide range of core entropies signals complex core astrophysics

Cavagnolo et al. 2009

archival Chandra data of ACCEPT cluster sample



low entropy core clusters have BCG's that

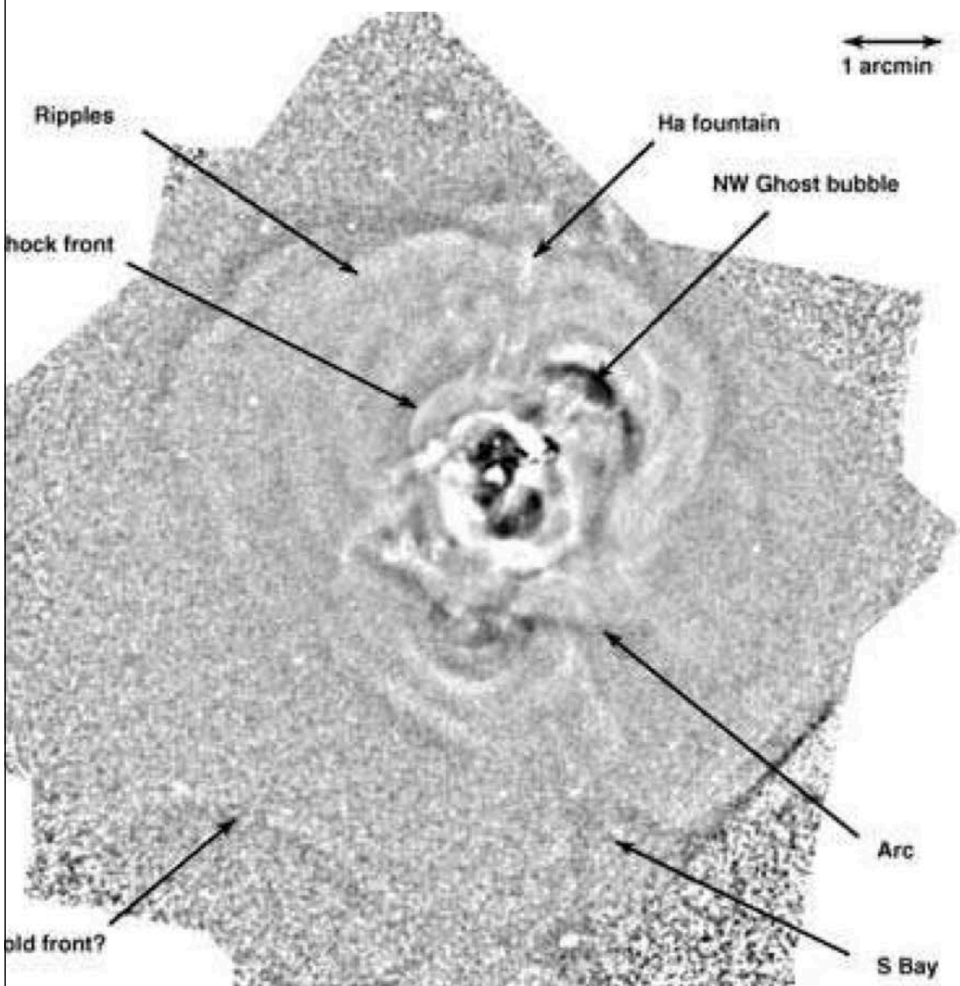
- are centered closely with X-ray peak,
- show more evidence of recent star formation

Hoffer et al. 2012

the central galaxies of clusters are sometimes quite active

Fabian et al. 2005

~Msec Chandra observation of Perseus cluster core



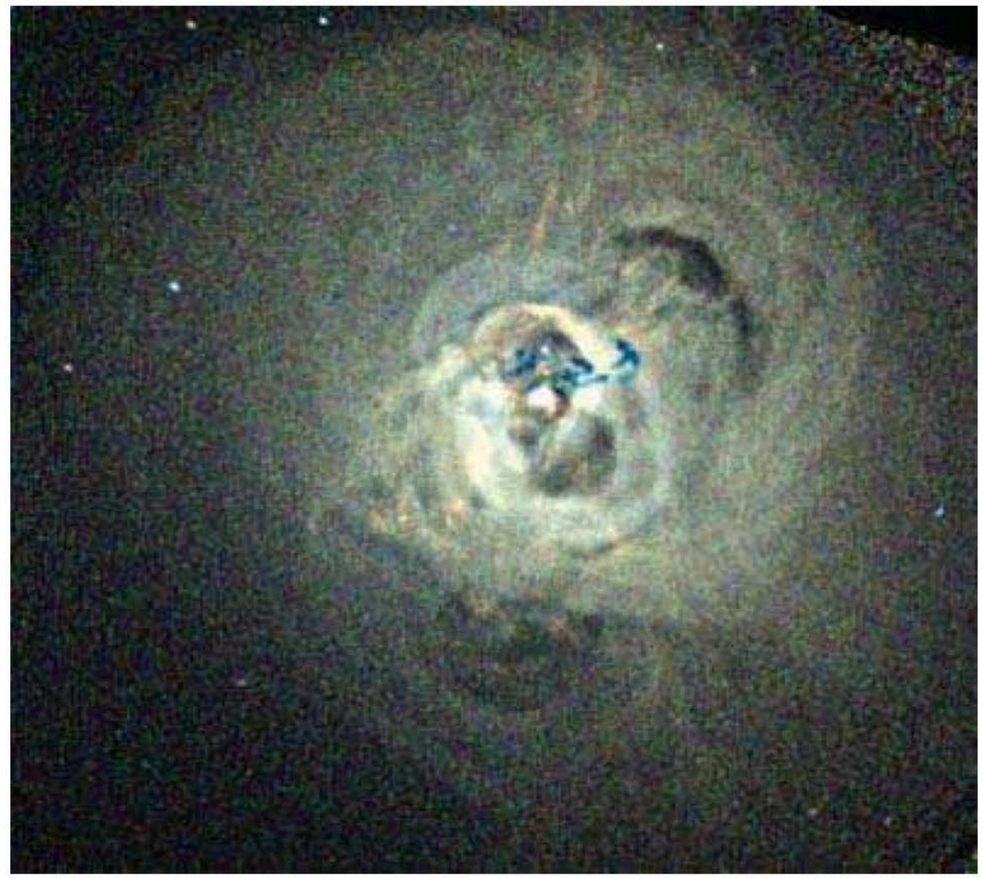


Figure 3. Colour image made from the 0.3–1.2 (red), 1.2–2 (green) and 2–7 keV (blue) bands. A 10-arcsec smoothed image has been scaled to 80 per cent of its intensity and then subtracted in order to bring out fainter features lost in the high-intensity range of raw images. The blue structure to the N of the nucleus is caused by absorption in the infalling high-velocity system,

the N-body era

humble beginnings in pre-internet times

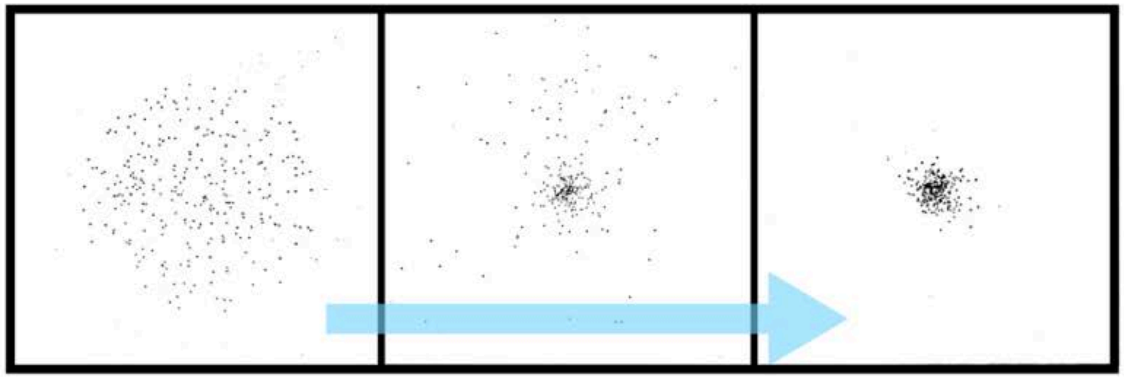
- **Suite of 300 (and less) particle simulations**
- **Run on a CDC 3600, ~1Mflops, 32KB+ at LANL**
- **Is nine orders of magnitude improvement in both performance and memory good enough for precision cosmology?**

THE ASTRONOMICAL JOURNAL VOLUME 75, NUMBER 1

Structure of the Coma Cluster of Galaxies*

P. J. E. Peebles†
Palmer Physical Laboratory, Princeton University, Princeton, New Jersey
(Received 7 October 1969)

In some cosmologies, a cluster of galaxies is imagined to be a gravitationally bound system which, in analogy with the formation of the Galaxy, originated as a collapsing protocluster. It is shown that a numerical model based on this picture is consistent with the observed features of the Coma Cluster of galaxies. The cluster mass derived from this model agrees with previous values; however, an analysis of the observational uncertainty within the framework of the model shows that the derived mass could be consistent with the estimated total mass provided by the galaxies in the cluster.



"The Universe is far too complicated a structure to be studied deductively, starting from initial conditions and solving the equations of motion."

Robert Dicke (Jayne Lectures, 1969)

(courtesy S. Habib, 2013 APS mtg.)

cosmological simulations: algorithmic evolution

1960's+70's - direct (NxN) force summation

studies of galaxy encounters and stellar clusters

1980's - particle-mesh (FFT's) and Tree algorithms for large-scale gravity

studies of `cosmic web' topology from initial random noise field

1990's - parallelization on Beowulf clusters, special purpose chips (GRAPE)

detailed studies of clustering statistics, cosmological dependence

- first multi-fluid codes to model coupled dark matter and baryons

initial studies of galaxy formation

>2000's - massive parallelization on large-scale supercomputers

precise calibration of large-scale structure statistics

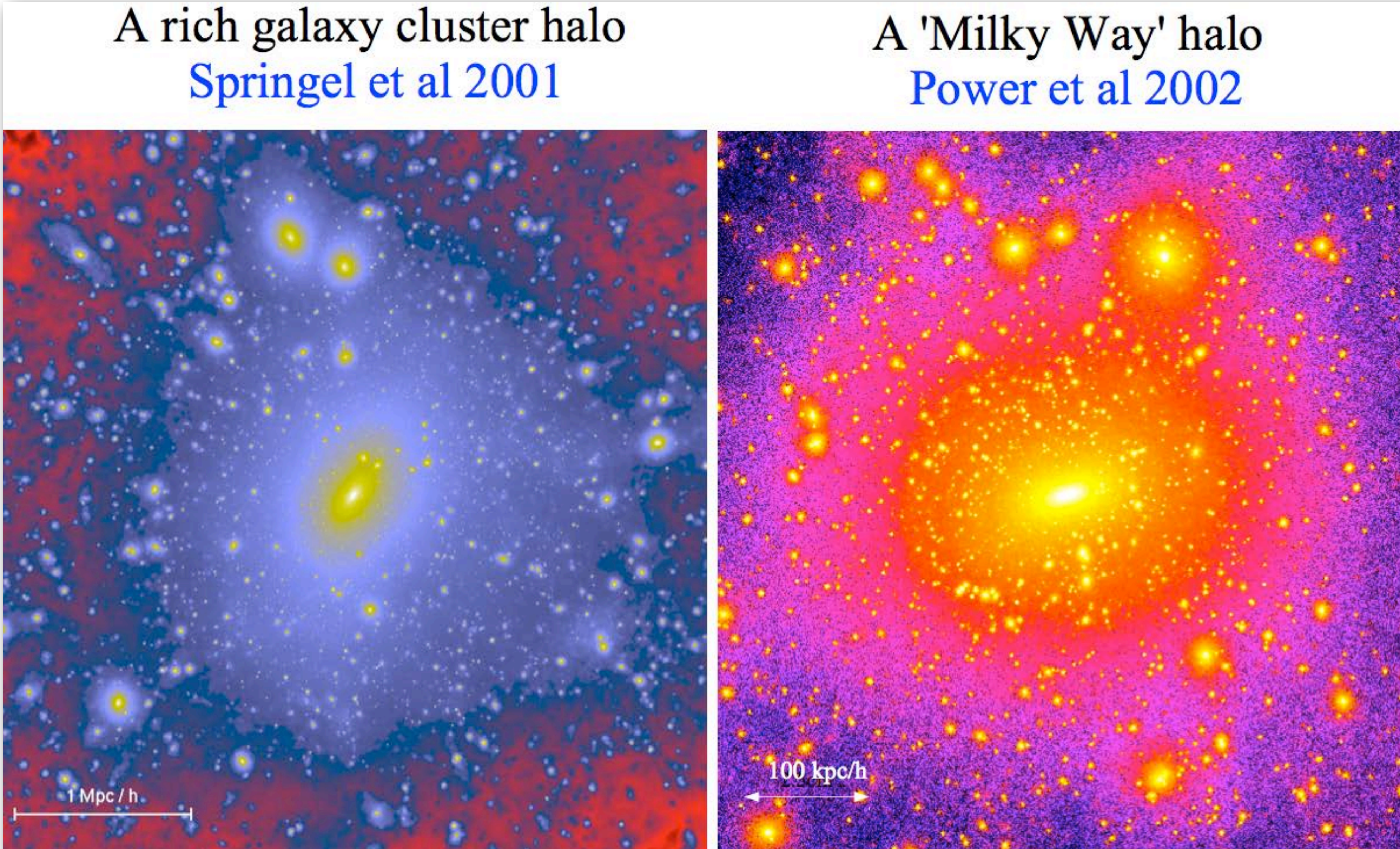
- multi-fluid codes with hydro + approx. radiation transfer, MHD

SMBH formation, feedback effects, high-rez galaxy formation, ...

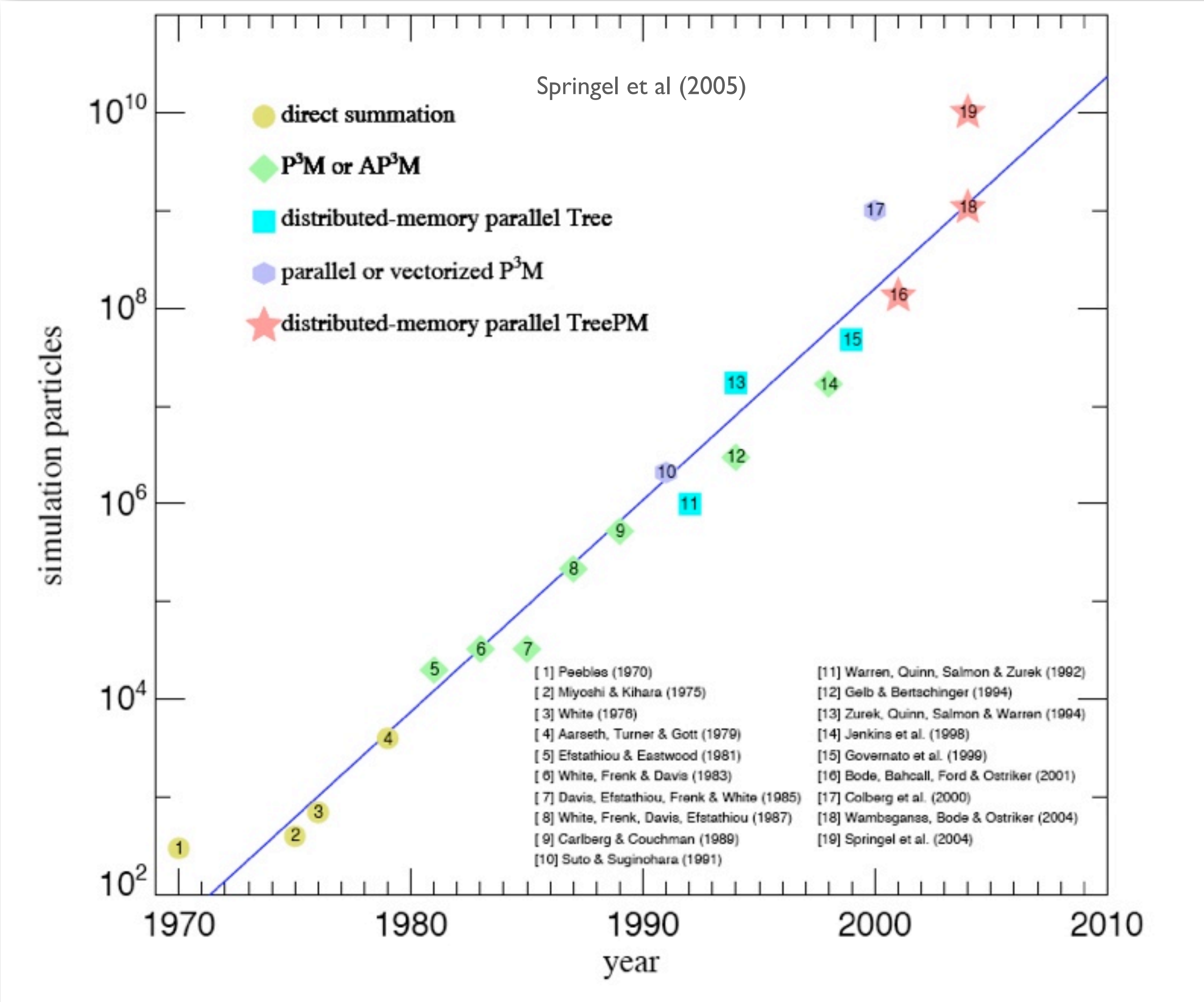
http://www.mpa-garching.mpg.de/aquarius/

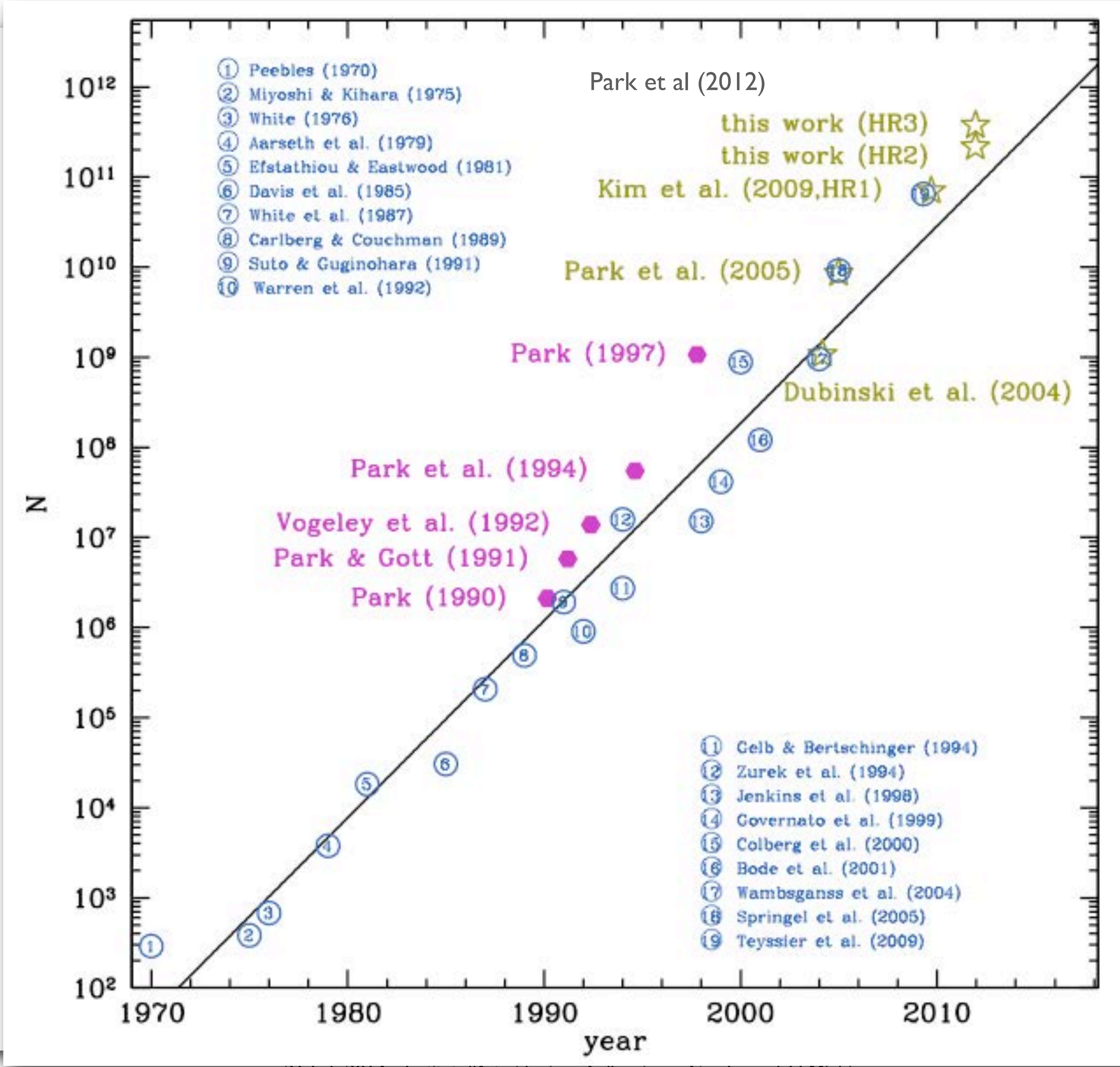
similarity of internal halo structure, from dwarf galaxy to cluster scales

$M_{cluster} \sim 1000\, M_{galaxy}$

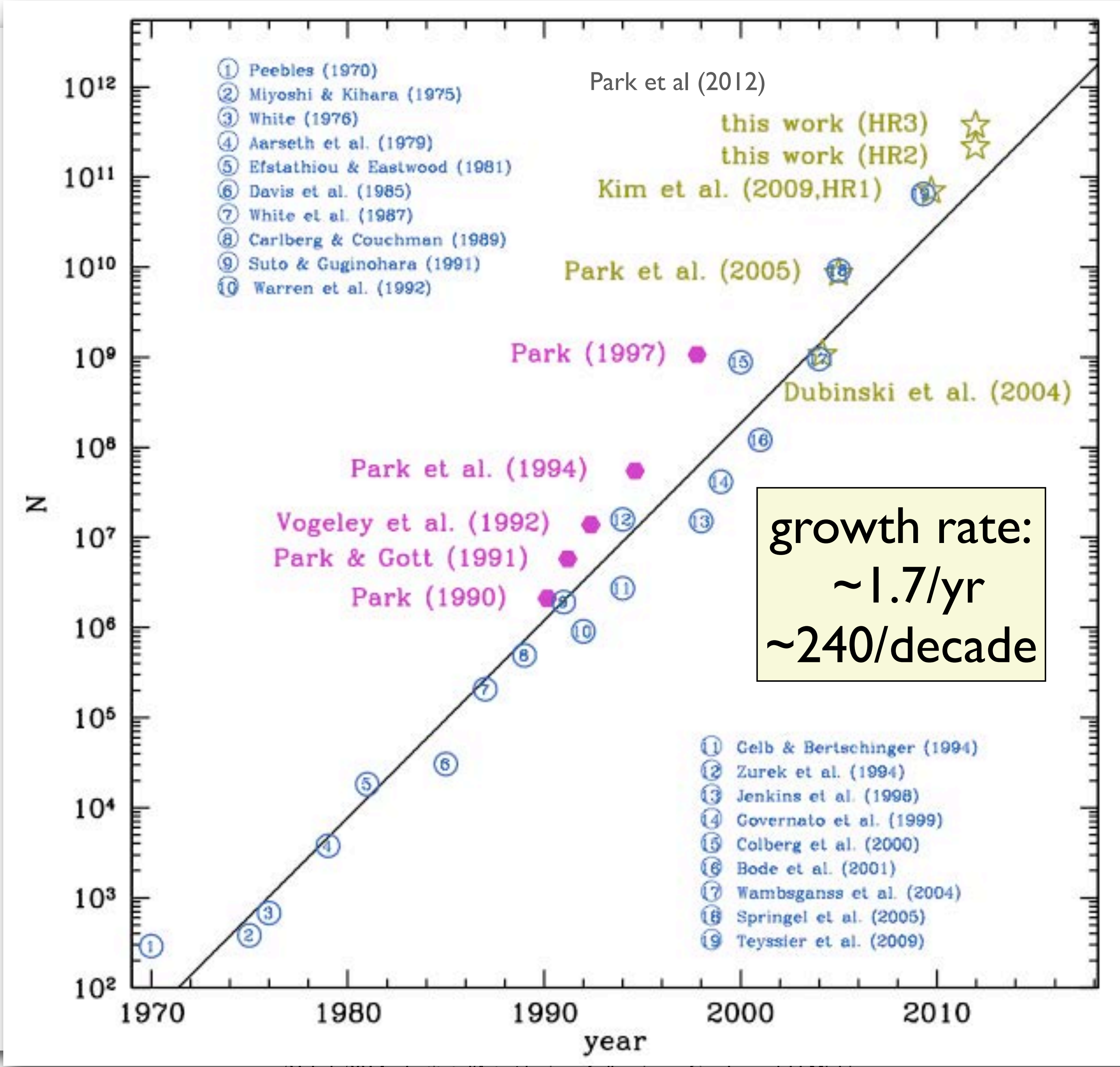


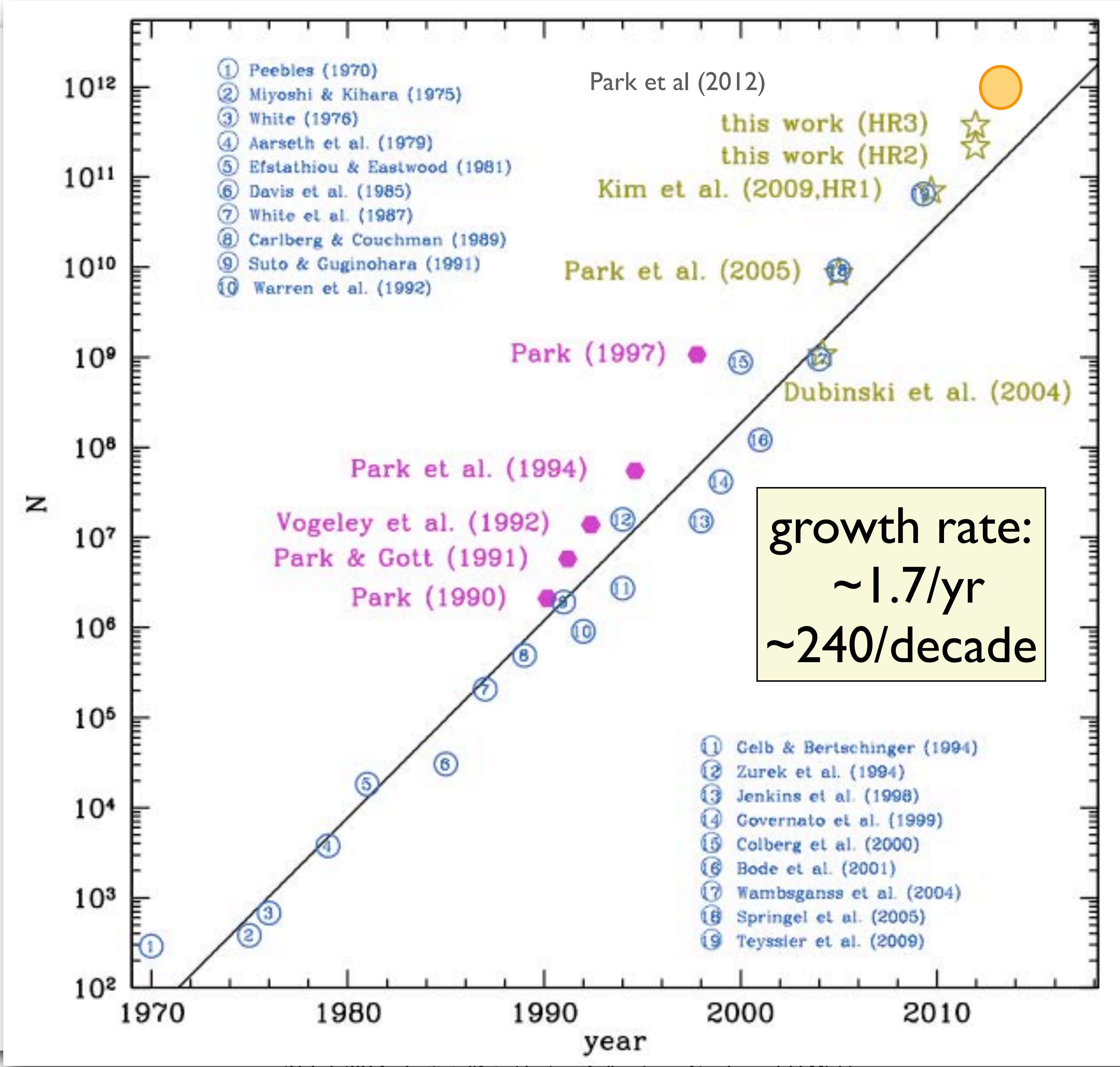
courtesy S.D.M. White, CATB2009


Springel et al (2005)
direct summation
P³M or AP³M
distributed-memory parallel Tree
parallel or vectorized P³M
distributed-memory parallel TreePM
simulation particles
year
[1] Peebles (1970)
[2] Miyoshi & Kihara (1975)
[3] White (1976)
[4] Aarseth, Turner & Gott (1979)
[5] Efstathiou & Eastwood (1981)
[6] White, Frenk & Davis (1983)
[7] Davis, Efstathiou, Frenk & White (1985)
[8] White, Frenk, Davis, Efstathiou (1987)
[9] Carlberg & Couchman (1989)
[10] Suto & Suginohara (1991)
[11] Warren, Quinn, Salmon & Zurek (1992)
[12] Gelb & Bertschinger (1994)
[13] Zurek, Quinn, Salmon & Warren (1994)
[14] Jenkins et al. (1998)
[15] Governato et al. (1999)
[16] Bode, Bahcall, Ford & Ostriker (2001)
[17] Colberg et al. (2000)
[18] Wambsganss, Bode & Ostriker (2004)
[19] Springel et al. (2004)



Park et al (2012)
1 Peebles (1970)
2 Miyoshi & Kihara (1975)
3 White (1976)
4 Aarseth et al. (1979)
5 Efstathiou & Eastwood (1981)
6 Davis et al. (1985)
7 White et al. (1987)
8 Carlberg & Couchman (1989)
9 Suto & Suginohara (1991)
10 Warren et al. (1992)
this work (HR3)
this work (HR2)
Kim et al. (2009,HR1)
Park et al. (2005)
Park (1997)
Dubinski et al. (2004)
Park et al. (1994)
Vogeley et al. (1992)
Park & Gott (1991)
Park (1990)
11 Gelb & Bertschinger (1994)
12 Zurek et al. (1994)
13 Jenkins et al. (1998)
14 Governato et al. (1999)
15 Colberg et al. (2000)
16 Bode et al. (2001)
17 Wambsganss et al. (2004)
18 Springel et al. (2005)
19 Teyssier et al. (2009)
N
year


Park et al (2012)
Peebles (1970)
Miyoshi & Kihara (1975)
White (1976)
Aarseth et al. (1979)
Efstathiou & Eastwood (1981)
Davis et al. (1985)
White et al. (1987)
Carlberg & Couchman (1989)
Suto & Guginohara (1991)
Warren et al. (1992)
this work (HR3)
this work (HR2)
Kim et al. (2009,HR1)
Park et al. (2005)
Park (1997)
Dubinski et al. (2004)
Park et al. (1994)
Vogeley et al. (1992)
Park & Gott (1991)
Park (1990)
growth rate:
~1.7/yr
~240/decade
Gelb & Bertschinger (1994)
Zurek et al. (1994)
Jenkins et al. (1998)
Governato et al. (1999)
Colberg et al. (2000)
Bode et al. (2001)
Wambsganss et al. (2004)
Springel et al. (2005)
Teyssier et al. (2009)
N
year



Park et al (2012)
① Peebles (1970)
② Miyoshi & Kihara (1975)
③ White (1976)
④ Aarseth et al. (1979)
⑤ Efstathiou & Eastwood (1981)
⑥ Davis et al. (1985)
⑦ White et al. (1987)
⑧ Carlberg & Couchman (1989)
⑨ Suto & Guginohara (1991)
⑩ Warren et al. (1992)
this work (HR3)
this work (HR2)
Kim et al. (2009,HR1)
Park et al. (2005)
Park (1997)
Dubinski et al. (2004)
Park et al. (1994)
Vogeley et al. (1992)
Park & Gott (1991)
Park (1990)
growth rate:
~1.7/yr
~240/decade
⑪ Gelb & Bertschinger (1994)
⑫ Zurek et al. (1994)
⑬ Jenkins et al. (1998)
⑭ Governato et al. (1999)
⑮ Colberg et al. (2000)
⑯ Bode et al. (2001)
⑰ Wambsganss et al. (2004)
⑱ Springel et al. (2005)
⑲ Teyssier et al. (2009)
N
year
10^2
10^3
10^4
10^5
10^6
10^7
10^8
10^9
10^{10}
10^{11}
10^{12}
1970
1980
1990
2000
2010

2012 Gordon-Bell Prize Winner!

4.45 Pflops Astrophysical N-Body Simulation on K computer - The Gravitational Trillion-Body Problem

Tomoaki Ishiyama
Center for Computational Science
University of Tsukuba
ishiyama@ccs.tsukuba.ac.jp

Keigo Nitadori
Center for Computational Science
University of Tsukuba
keigo@ccs.tsukuba.ac.jp

Junichiro Makino
Graduate School of Science and Engineering
Tokyo Institute of Technology
makino@geo.titech.ac.jp

***Abstract*—As an entry for the 2012 Gordon-Bell performance prize, we report performance results of astrophysical N-body simulations of one trillion particles performed on the full system of K computer. This is the first gravitational trillion-body simulation in the world. We describe the scientific motivation, the numerical algorithm, the parallelization strategy, and the performance analysis. Unlike many previous Gordon-Bell prize winners that used the tree algorithm for astrophysical N-body simulations, we used the hybrid TreePM method, for similar level of accuracy in which the short-range force is calculated by the tree algorithm, and the long-range force is solved by the particle-mesh algorithm. We developed a highly-tuned gravity kernel for short-range forces, and a novel communication algorithm for long-range forces. The average performance on 24576 and 82944 nodes of K computer are 1.53 and 4.45 Pflops, which correspond to 49% and 42% of the peak speed.**

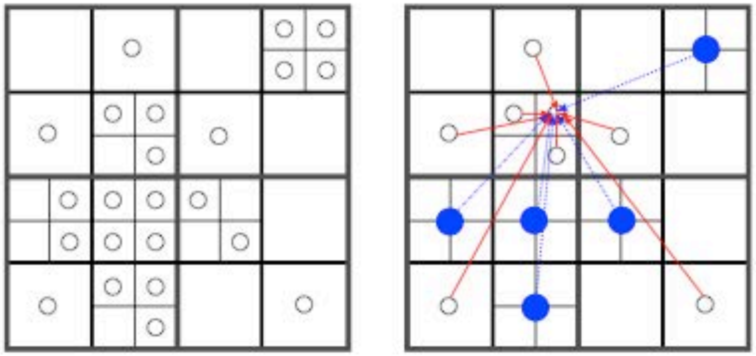


Fig. 1. The hierarchical tree algorithm. White circles represent particles. Blue circles are the multipole expansions of tree nodes. Red solid arrows and blue dotted arrows show the particle-particle and the particle-multipole interactions, respectively.

600 parsec cubic volume (~2000 light years)
particle mass ~ 2x10^{-6} Earth masses!

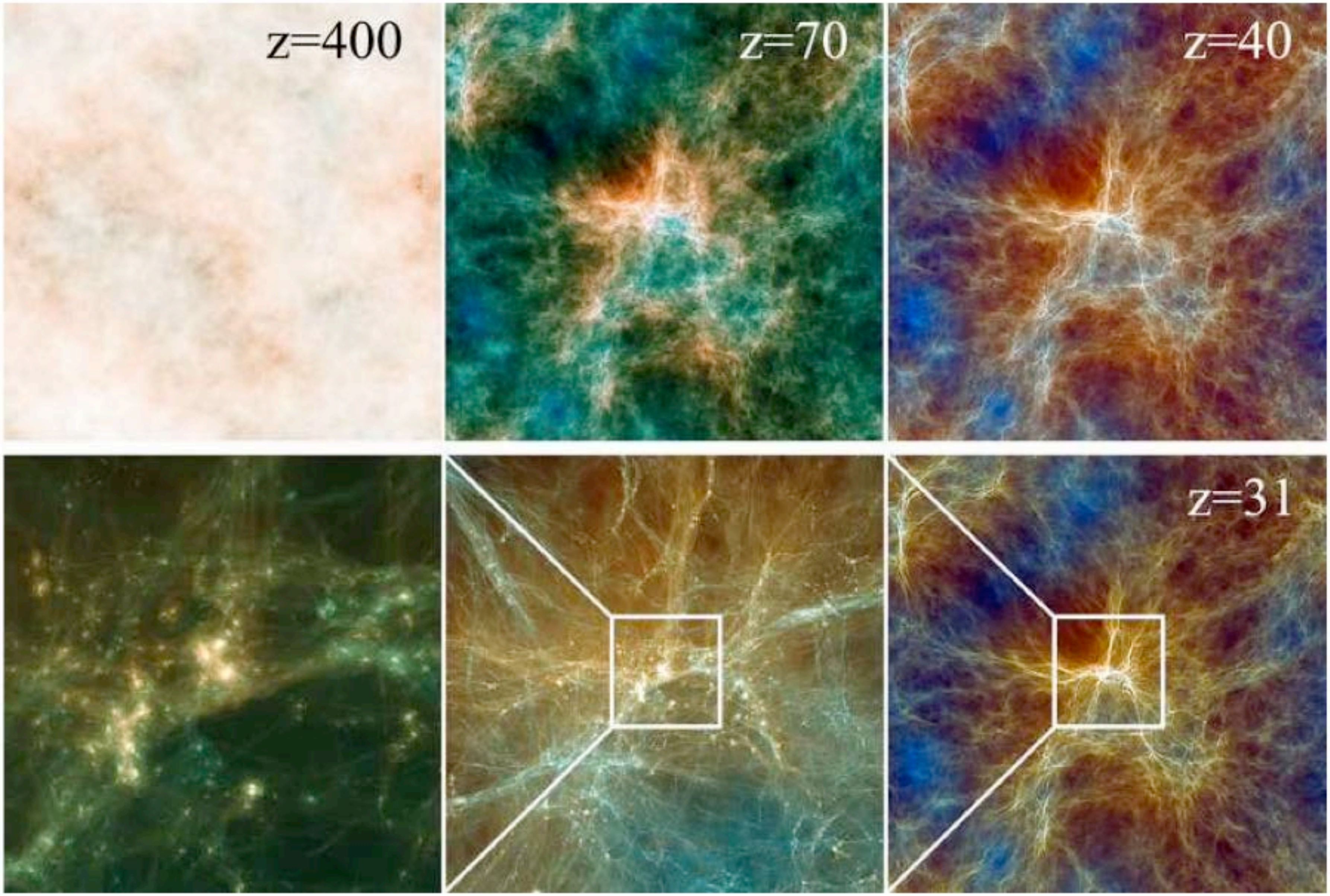
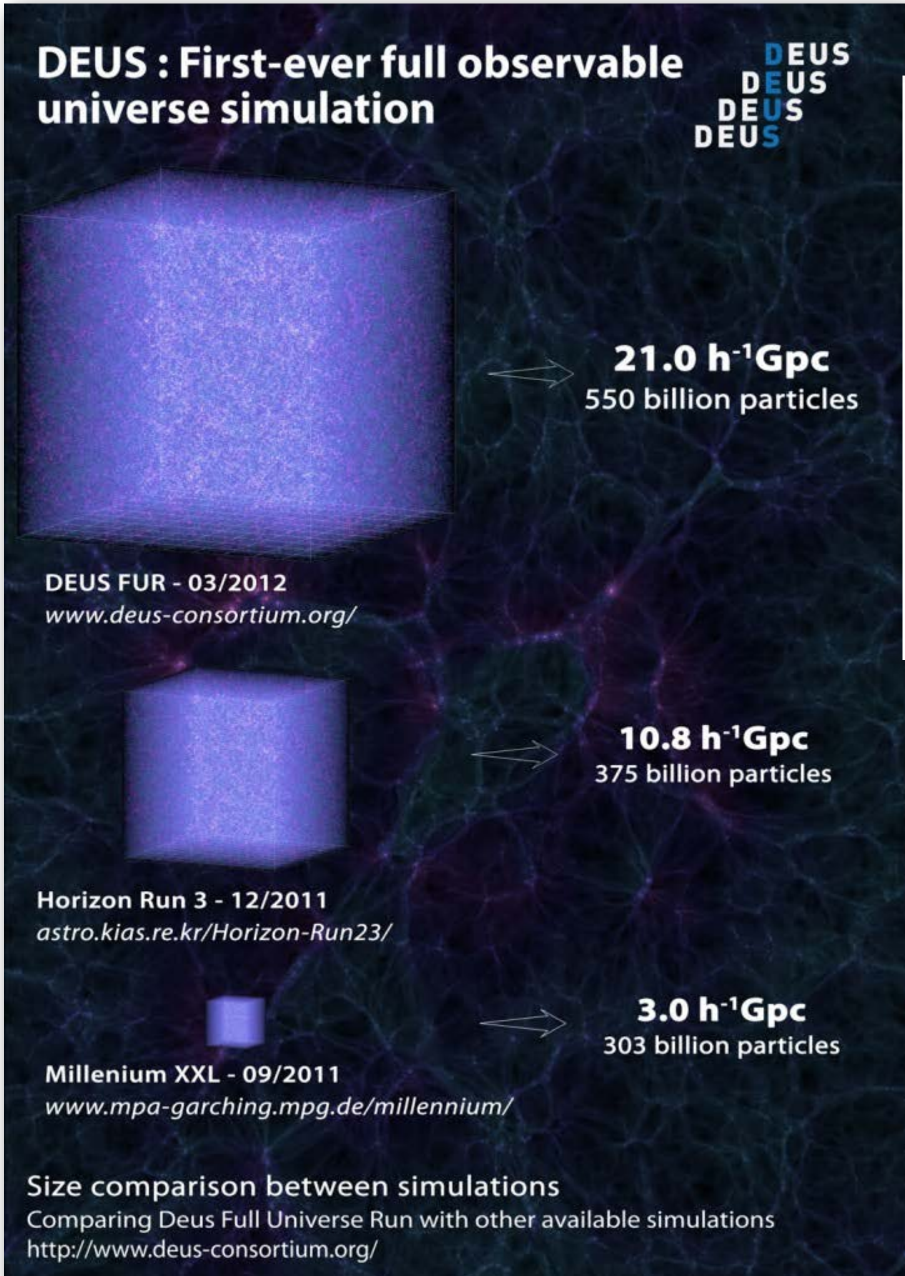


Fig. 6. The distribution of dark matter of the 16.8G particles simulation at redshift 400 (initial), 70, 40, and 31. The width of each image corresponds to 600 comoving parsecs. Bottom-left and bottom-middle images are enlargements of the image of $z = 31$. The sizes correspond to 37.5 (bottom-left) and 150 (bottom-middle) comoving parsecs.

DEUS simulation effort by Obs. de Paris Meudon group (~0.5 teraparticle)



http://www.deus-consortium.org/

DEUS FUR Characteristics

DEUS FUR is currently the largest and most performing dark matter simulation of the entire cosmos ever realized probing scales from 40 kpc/h to 21 Gpc/h for three dar energy models; the concordance ΛCDM model a quintessence model and a fantom model.

DEUS FUR is an acronym for **« Dark Energy Universe Simulation – Full Universe Run »**.

The simulation has followed the self-gravitational evolution of **8192^3** (**549 755 813 888**) particles in cubic volume of (**21 Gpc)^3** .

This simulation has required **5** million cpu hour on **76032** cores of the Curie Supercomputer at TGCC

It has used **304 128** Go of memory.

150 Po data have been generated during the run. Using an optimized chain of post-processing programs we have been able to reduce these data to about **1.5 Po**.

Energy cost estimate:

5M core-hours x ~50 W/core
= 250,000 kW-hours
x $0.1/kW-hour

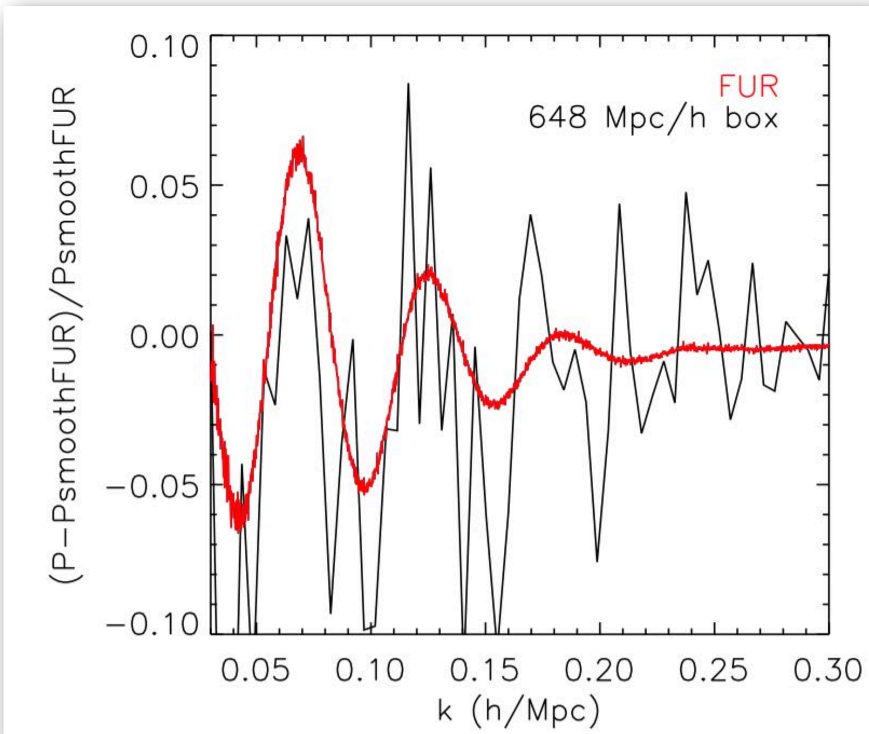
=> $25,000 x (PUE) ~ $50,000

DEUS-FUR detailed study of BAO spectral features

http://www.deus-consortium.org/

Cosmic variance limited Baryon Acoustic Oscillations from the DEUS-FUR ΛCDM simulation

Y. Rasera⋆, P.-S. Corasaniti, J.-M. Alimi, V. Bouillot, V. Reverdy, and I. Balmes
CNRS, Laboratoire Univers et Théories (LUTh), UMR 8102 CNRS, Observatoire de Paris, Université Paris Diderot ; 5 Place Jules Janssen, 92190 Meudon, France

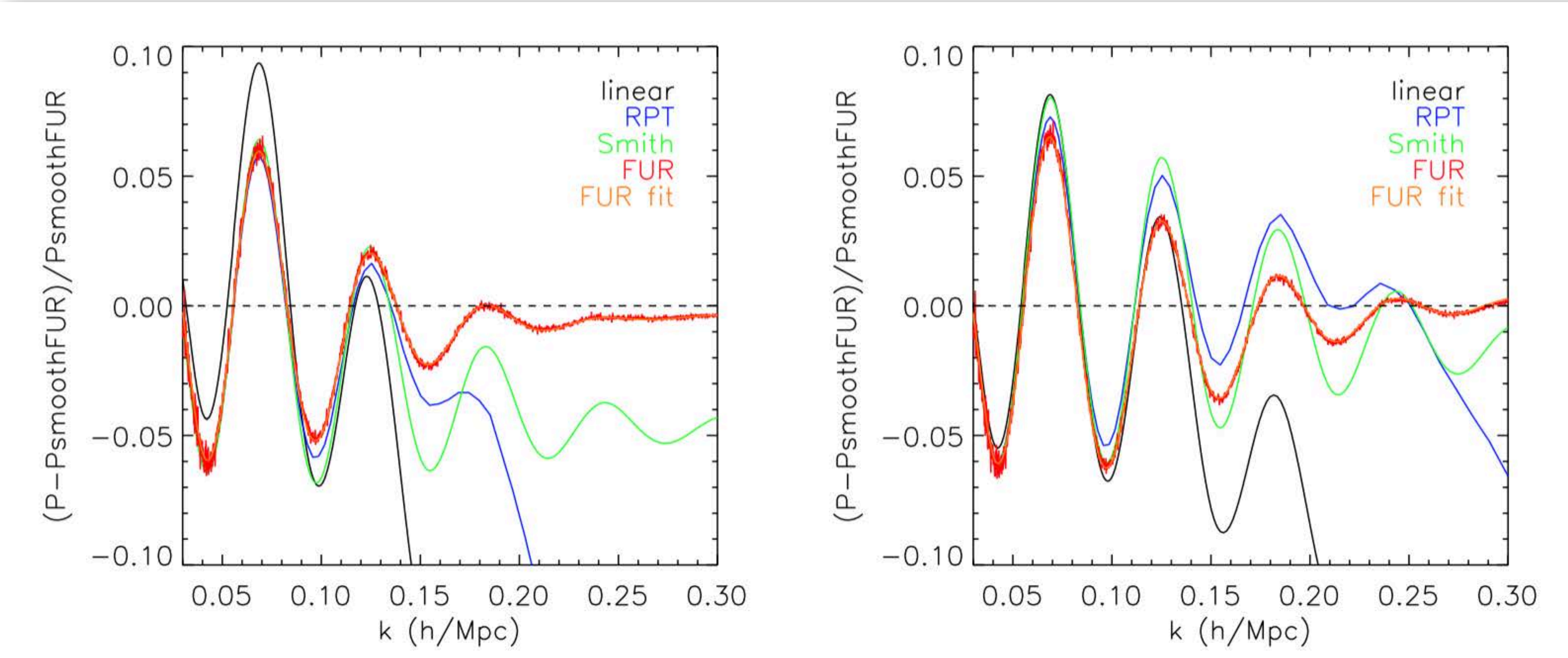


DEUS-FUR detailed study of BAO spectral features

http://www.deus-consortium.org/

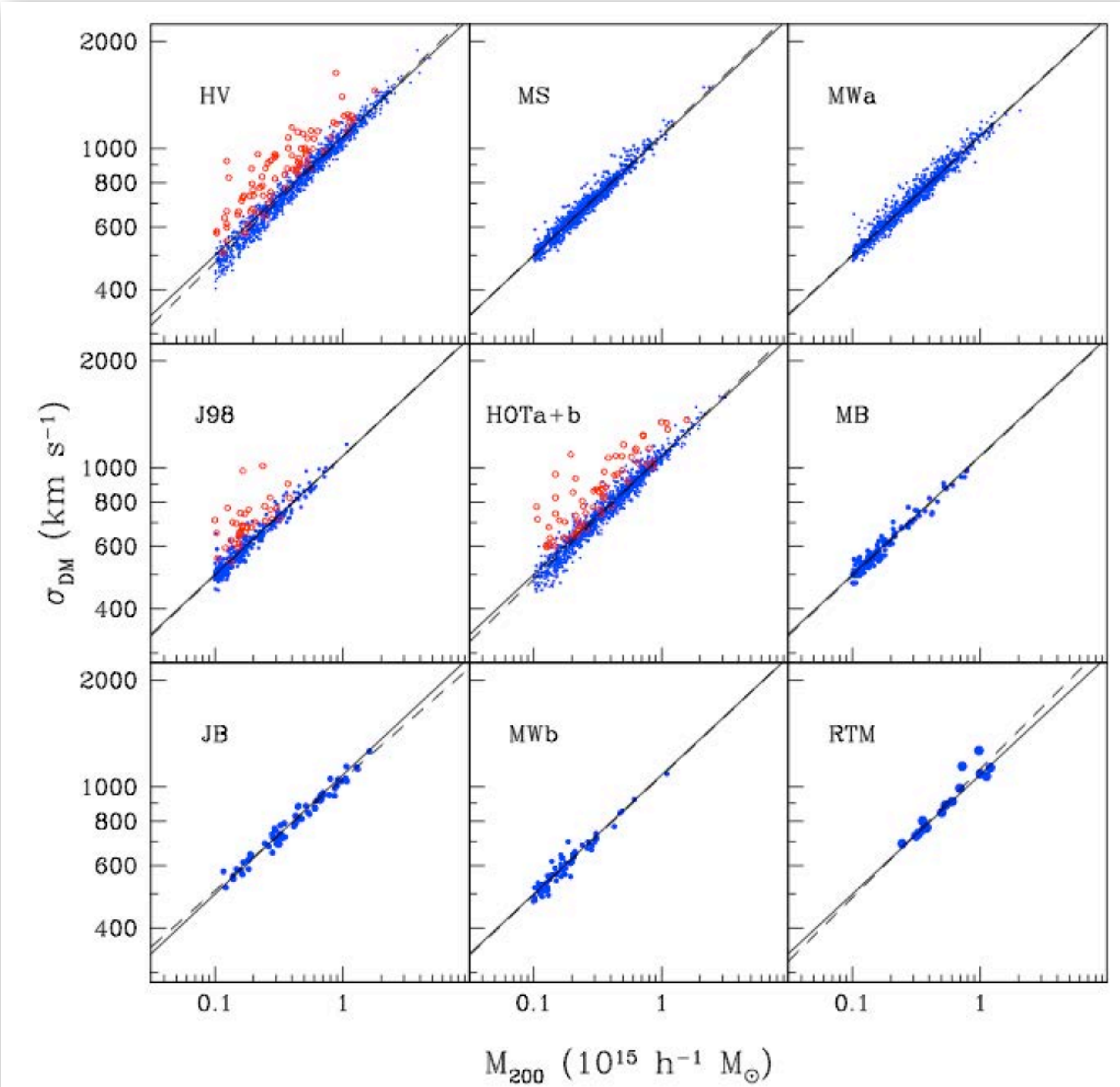
Cosmic variance limited Baryon Acoustic Oscillations from the DEUS-FUR ΛCDM simulation

Y. Rasera⋆, P.-S. Corasaniti, J.-M. Alimi, V. Bouillot, V. Reverdy, and I. Balmes
CNRS, Laboratoire Univers et Théories (LUTh), UMR 8102 CNRS, Observatoire de Paris, Université Paris Diderot ; 5 Place Jules Janssen, 92190 Meudon, France



multi-code, precise calibration of DM halo virial scaling relation

Evrard et al (2008)

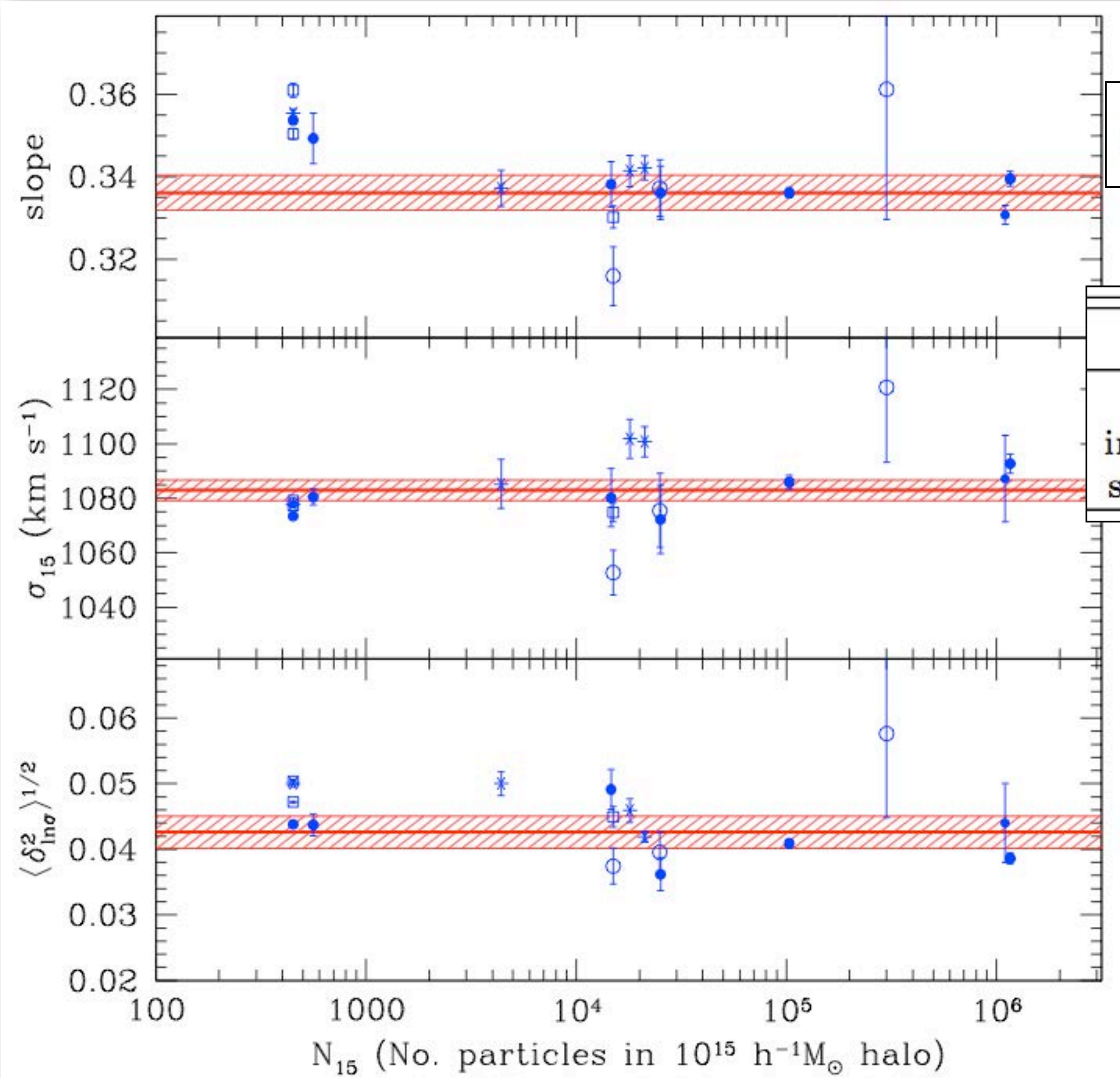


$$\sigma_{DM}{}^2 = \frac{1}{3N_p} \sum_{i=1}^{N_p} \sum_{j=1}^{3} |v_{i,j} - \bar{v_j}|^2$$

* results from six different N-body codes

* evidence that mergers are dynamically soft (non-violent)

multi-code, precise calibration of DM halo virial scaling relation



Evrard et al (2008)

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

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

N-body simulations inform an increasingly precise **halo model** of LSS

* general aspects
  – 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
  – relaxation to similar density + velocity radial profiles
  – surviving sub-halo structures contain a small percentage of total mass
  – hierarchical nesting of sub-structure families reflect accretion history

* low-order spatial distribution
  – functional forms for *mass function*, n(M,z), and *bias function*, b(M,z), precisely calibrated via similarity variable, σ(M) (mainly wCDM)
  – different, one-parameter mass assignment methods (FOF, SO) exist
    good: flexibility, reflects edge complexity **bad**: literature confusing

multi-fluid models:
N-body + baryons
(+ chemistry + radiation + ...)

multi-fluid systems: N-body + baryonic 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

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

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

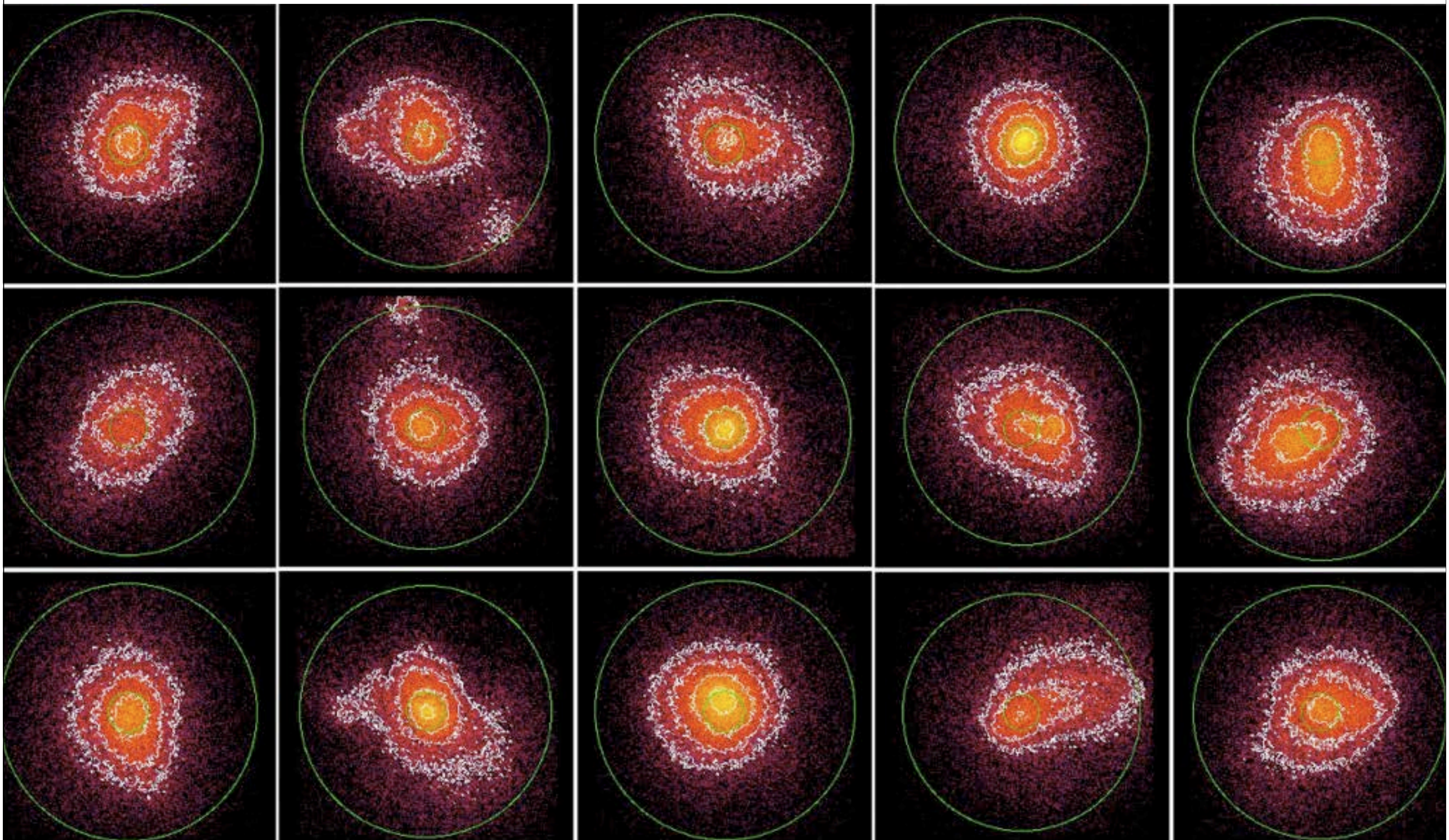
For a perfect gas with ratio of specific heats γ, the thermal energy and entropy per unit mass are $u = p/[(\gamma-1)\rho_b]$ and $S = (\gamma-1)^{-1}\ln(p\rho_b^{-\gamma})$, respectively. Artificial viscosity is often added to Equation 4 to generate the entropy needed across shock waves. In nonadiabatic 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 fluid 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	•memory intensive •complex post-processing	• ART • Enzo • RAMSES • FLASH
Moving Mesh	•hybrid Lagr./Eul. •deformable, moveable grid cells (up to max.)	•best of breed?	•complex to code	•Arepo

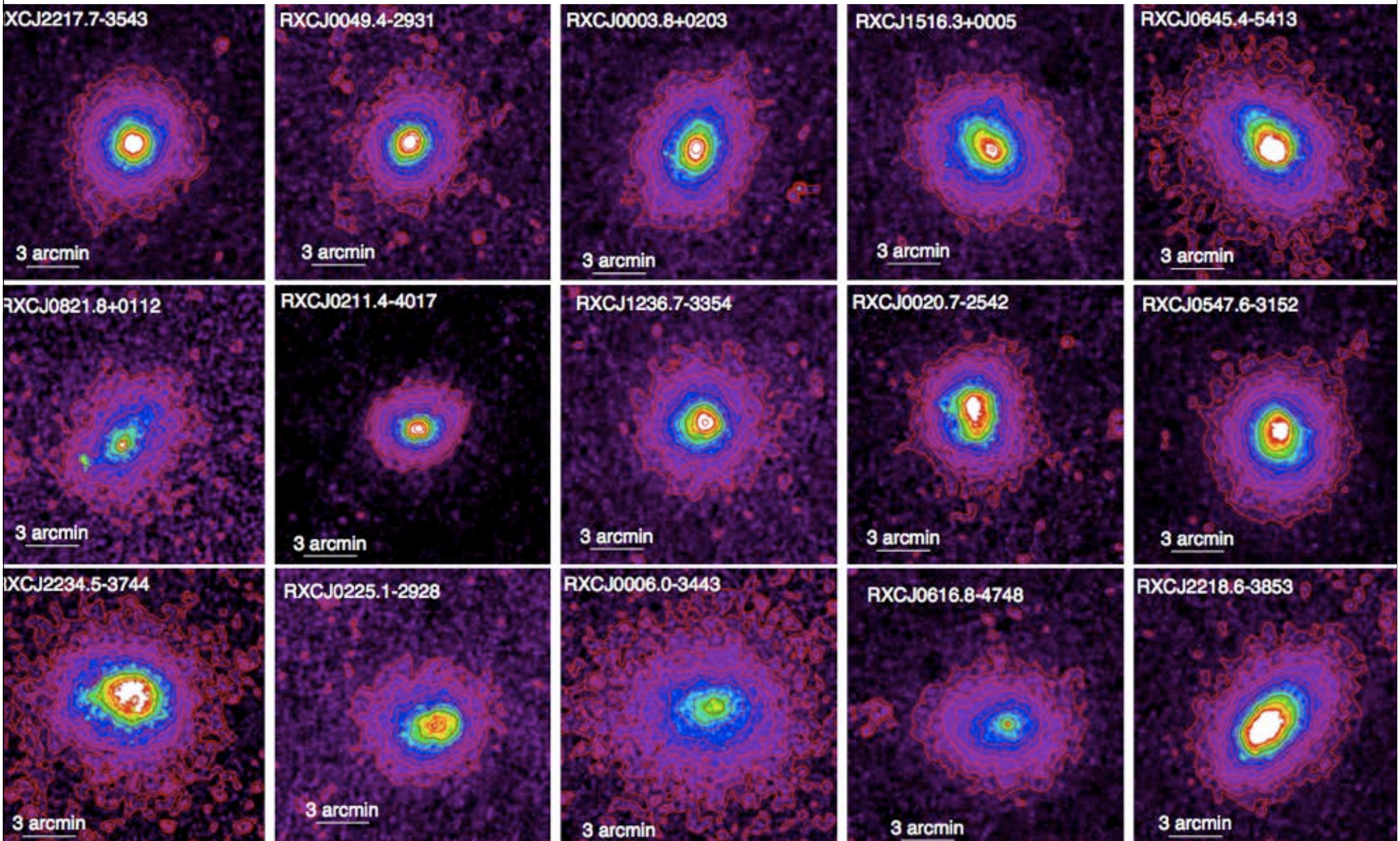
synthetic XMM images of Millennium Gas simulations (Gadget SPH)

courtesy E. Rasia



XMM images of REXCESS cluster sample

Pratt et al. (2009)



`designer' simulation: SPH 2-body model of X-ray emission from A3376

Machado & Lima Neto 2013

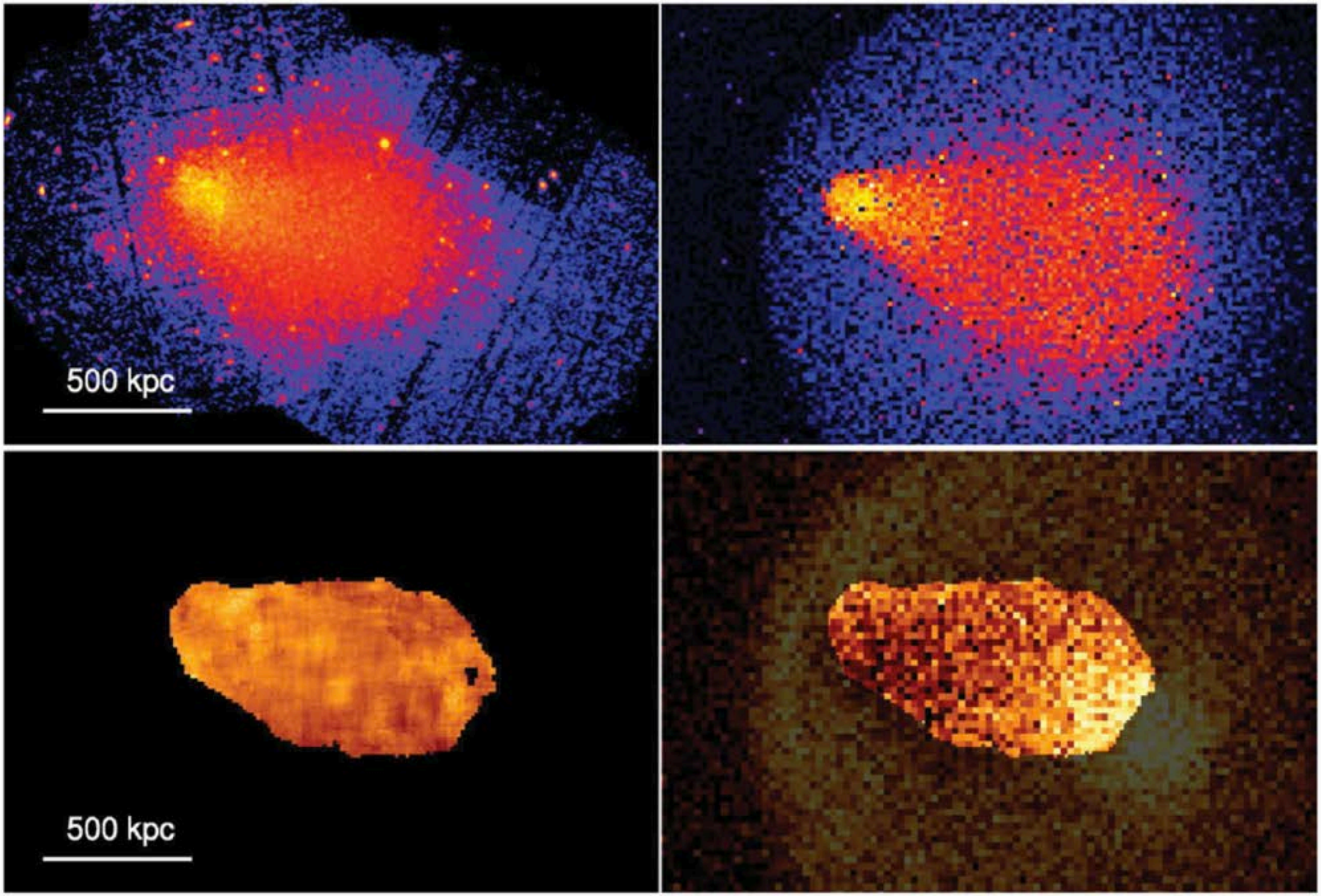
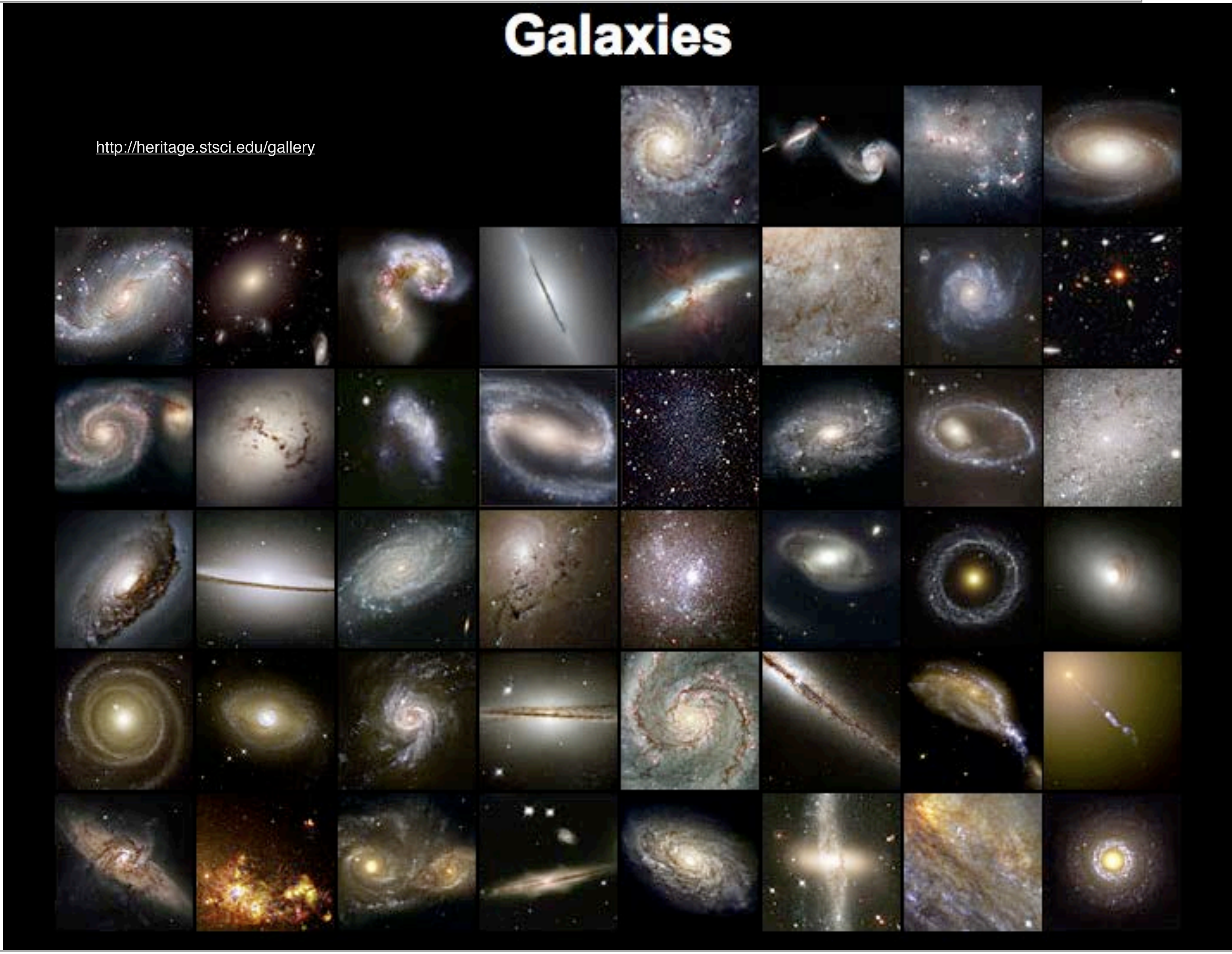
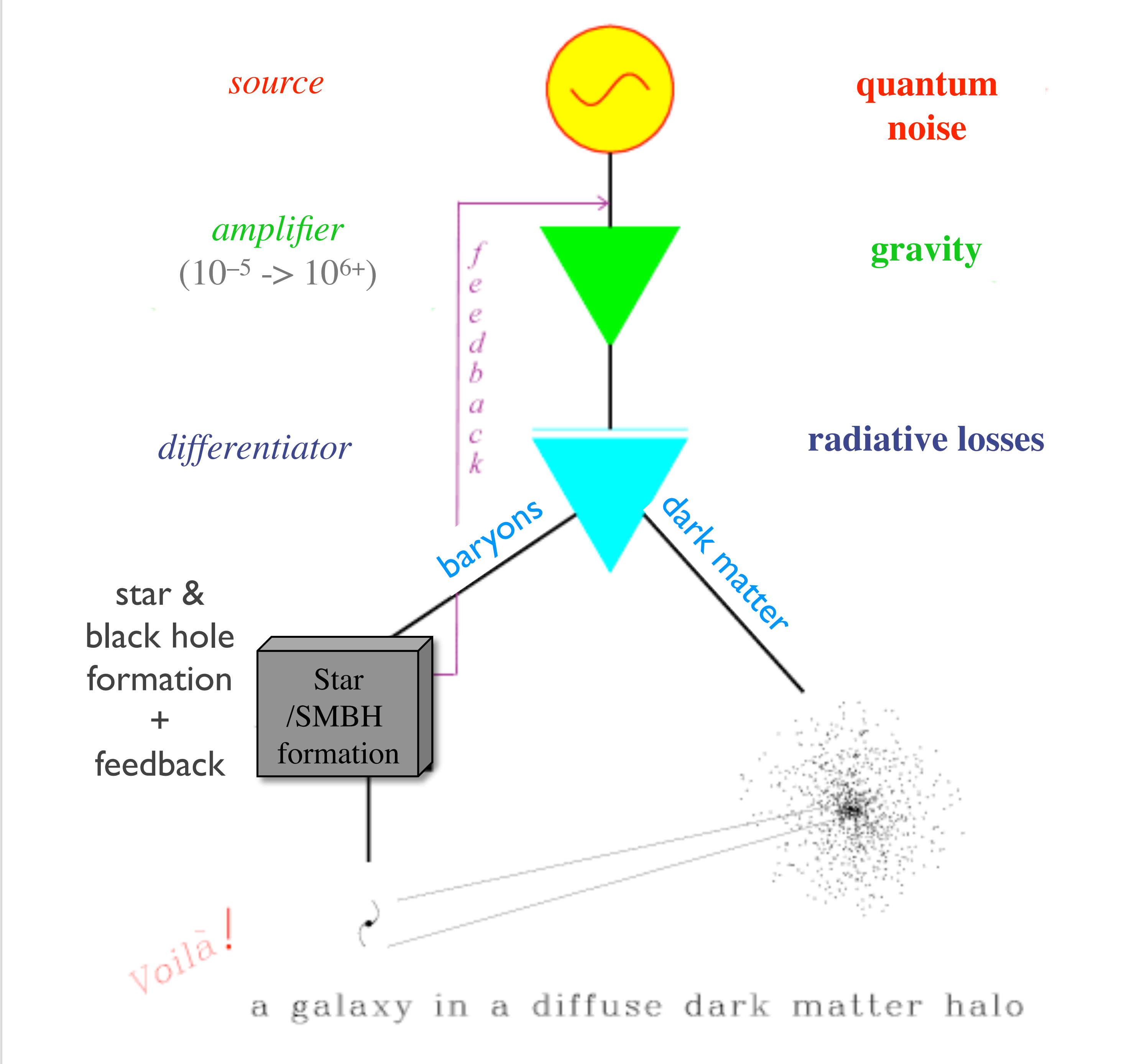


Figure 3. Comparison between observations of A3376 (left) and model 233

challenge: halos (and sub-halos) should contain baryonic objects like this!



cosmic engineering: a flowchart for galaxy formation



early results on galaxy formation 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

first cosmological simulation to naturally form disk galaxies

Evrard, Summers & Davis 1994

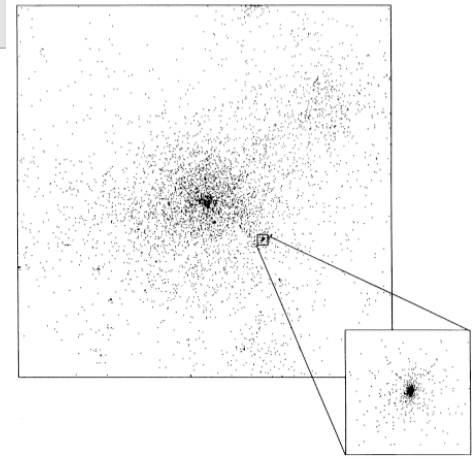


Fig. 17a

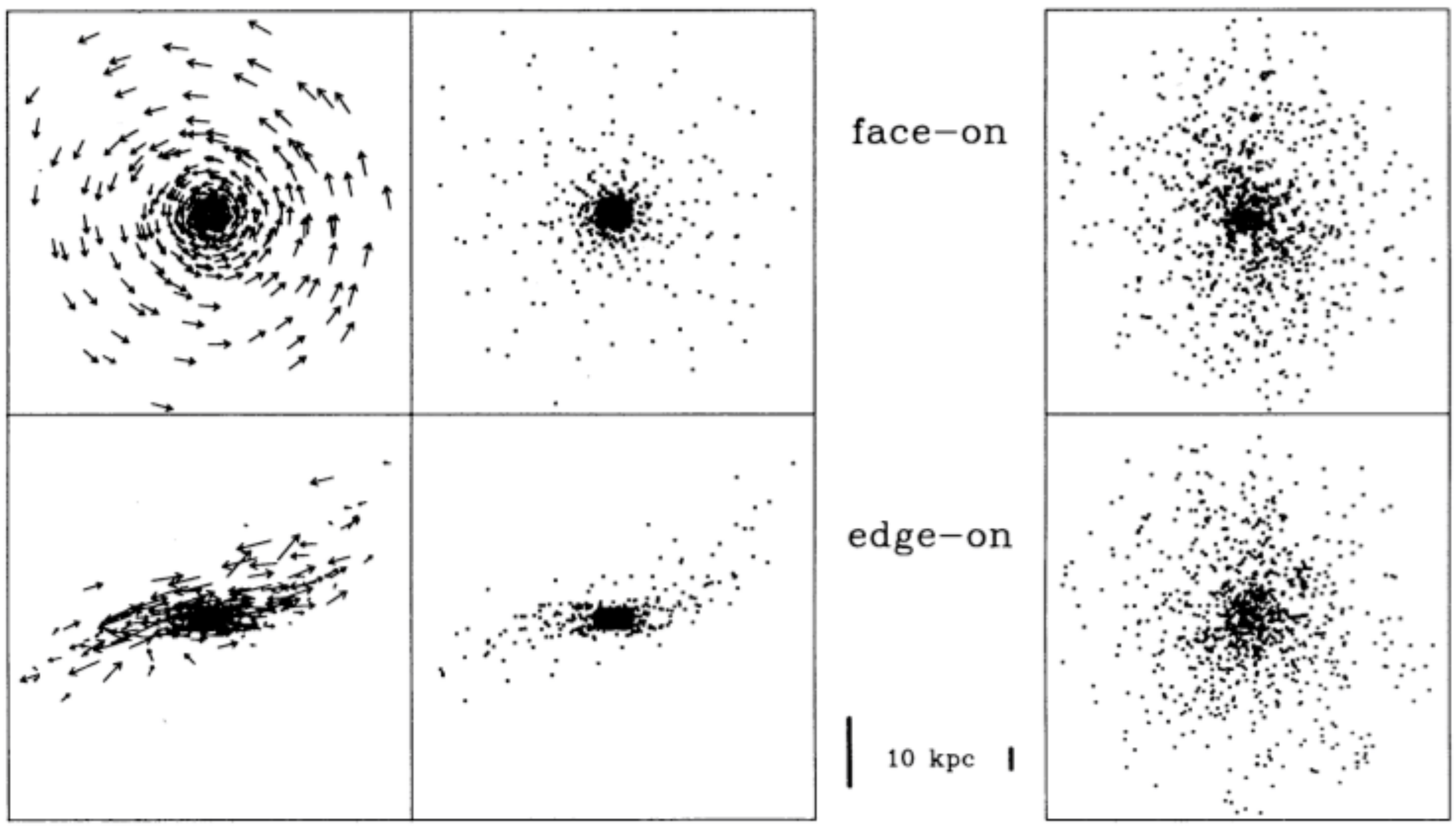


Fig. 17b

early results on galaxy formation with P3MSPH

Evrard, Summers & Davis 1994

first estimate of the galaxy Halo Occupation Distribution (HOD)

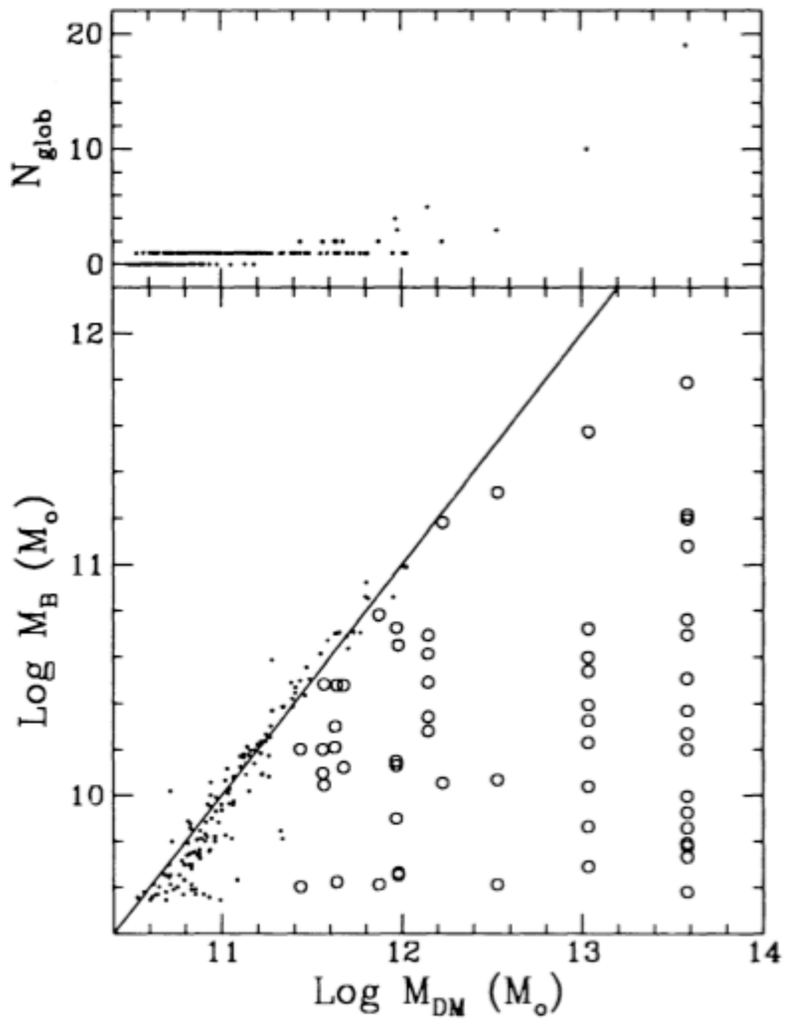


FIG. 11.—Halo occupation number N_{glob} and glob mass within each halo as a function of halo mass. Circles in the lower panel indicate halos containing multiple globs. The line in the lower panel is $M_B = \Omega_b M_{DM}$.

`GLOBs'
= Galaxy-Like OBjects

Evrard & Charlot
1994

first spectrophotometric modeling of simulated galaxies (2 citations...)

OPTICAL SIGNATURES OF HIGH-REDSHIFT GALAXY CLUSTERS

AUGUST E. EVRARD
Physics Department, University of Michigan, Ann Arbor, MI 48109

AND

STÉPHANE CHARLOT[1]
Astronomy Department, University of California, Berkeley, CA 94720
Received 1993 July 8; accepted 1994 January 7

ABSTRACT

We combine an *N*-body and gasdynamic simulation of structure formation with an updated population synthesis code to explore the expected optical characteristics of a high-redshift cluster of galaxies. We examine a poor (2 keV) cluster formed in a biased, cold dark matter cosmology and employ simple, but plausible, threshold criteria to convert gas into stars.

At $z = 2$, the forming cluster appears as a linear chain of very blue ($g - r \simeq 0$) galaxies, with 15 objects brighter than $r = 25$ within a 1 square arcmin field of view. After 2 Gyr of evolution, the cluster viewed at $z = 1$ displays both freshly infalling blue galaxies and red galaxies robbed of recent accretion by interaction with the hot intracluster medium. The range in $G - R$ colors is ~ 3 mag at $z = 1$, with the reddest objects lying at sites of highest galaxy density. We suggest that red, high-redshift galaxies lie in the cores of forming clusters and that their existence indicates the presence of a hot intracluster medium at redshifts $z \simeq 2$.

The simulated cluster viewed at $z = 2$ has several characteristics similar to the collection of faint, blue objects identified by Dressler et al. in a deep *Hubble Space Telescope* observation. The similarities provide some support for the interpretation of this collection as a high-redshift cluster of galaxies.

baryon physics in current codes is now much more sophisticated

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.

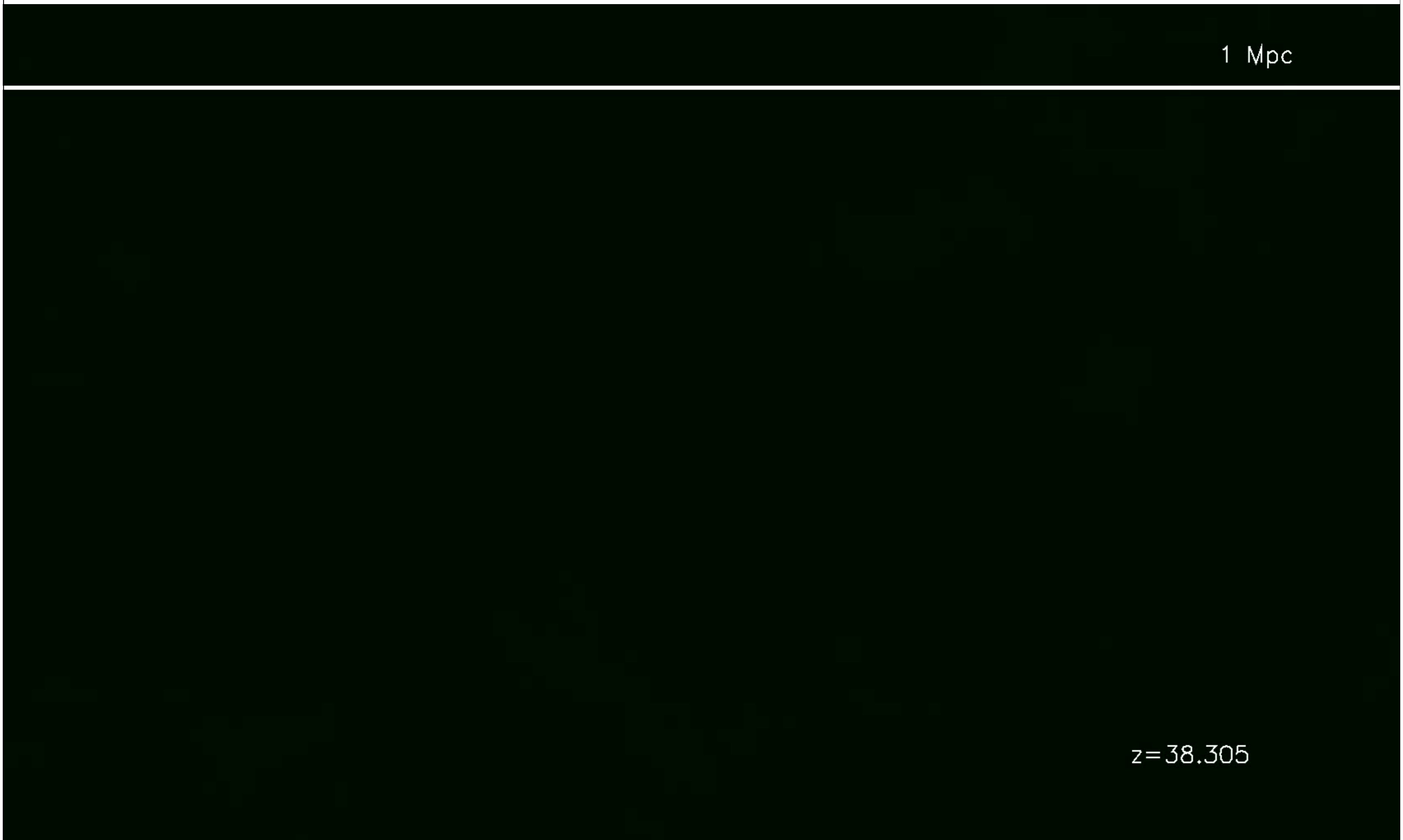
Feature	GADGET-3[1]	GASOLINE[2]	HART[3]	ENZO(ZEUS)[4]	FLASH[5]
Gravity	Tree	Tree	AMR[6] PM[7]	AMR[6] PM[7]	Multi-grid
Hydrodynamics	SPH[8]	SPH[8]	AMR[6]	AMR[6]	AMR[6]
→ Multiphase subgrid model[9]	✓[10]	×	N/A	N/A	N/A
Radiative Cooling	✓	✓	✓	✓	✓[11]
→ Metal dependent	✓[12]	×	✓[13]	✓[14]	✓[11]
→ Molecular 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);

RAMSES simulations w/ AGN feedback

DuBois, Pinchon et al 2014

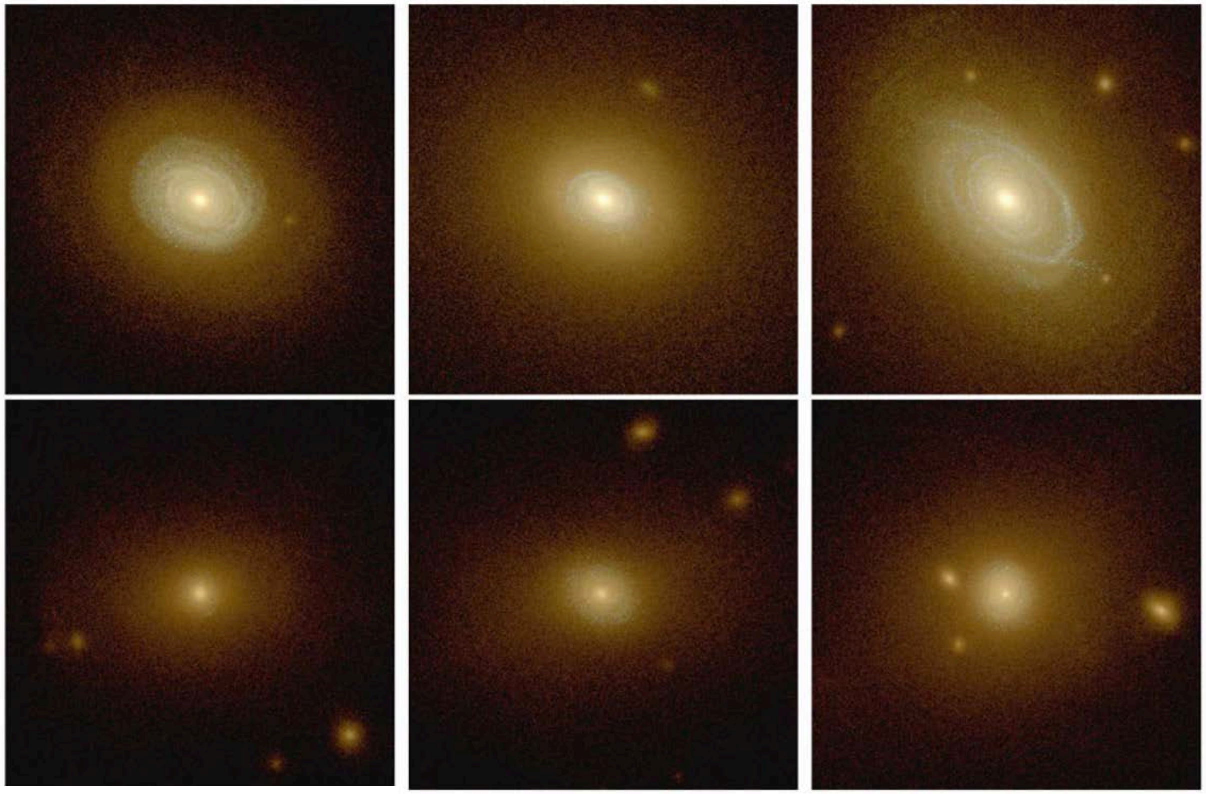


RAMSES simulations w/ AGN feedback

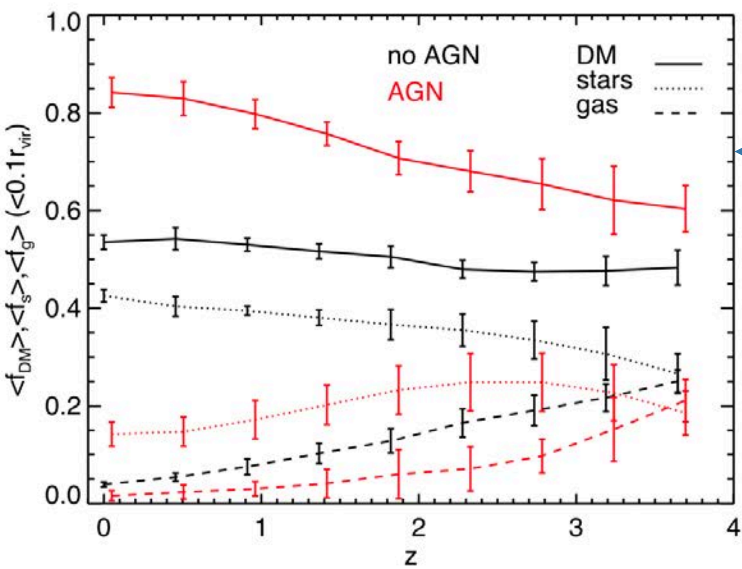
Dubois et al 2013

no AGN

AGN

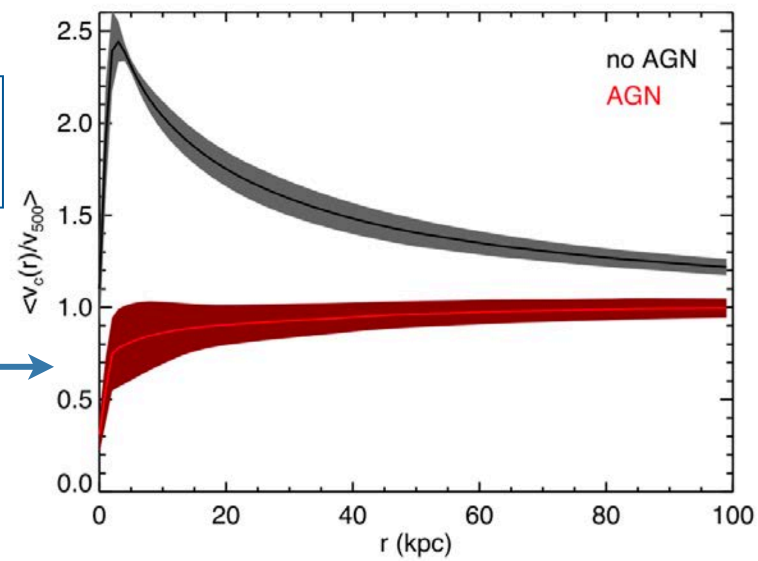


central galaxies in group-scale halos $\sim 10^{13}\ M_{sun}$



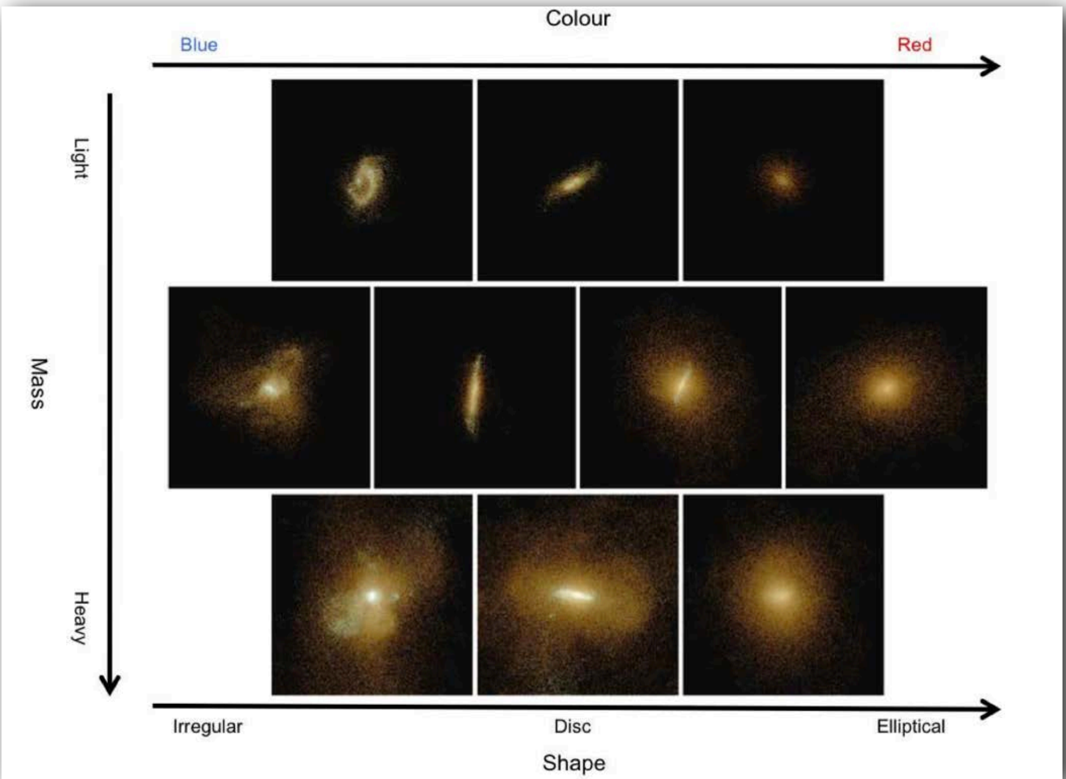
reduces fraction of baryons in stars

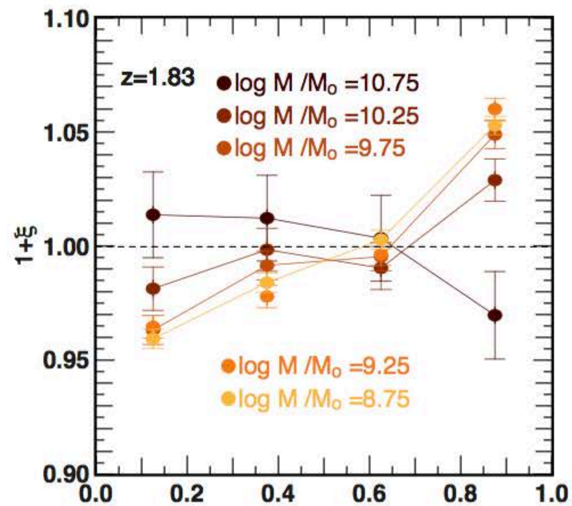
reduces core density; better rotation curves



RAMSES simulations w/ AGN feedback

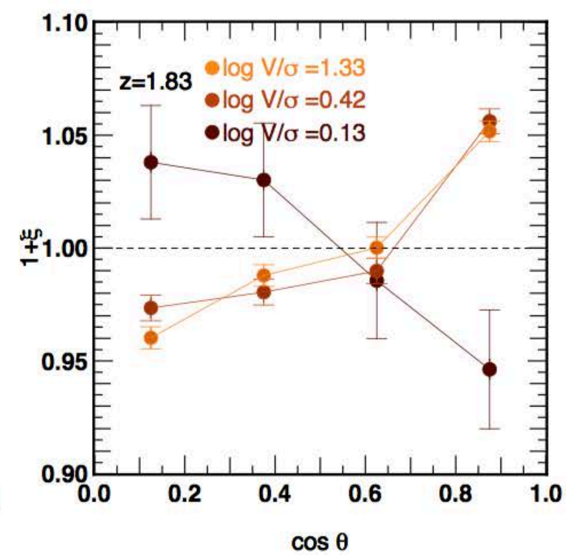
Dubois, Pinchon et al 2014





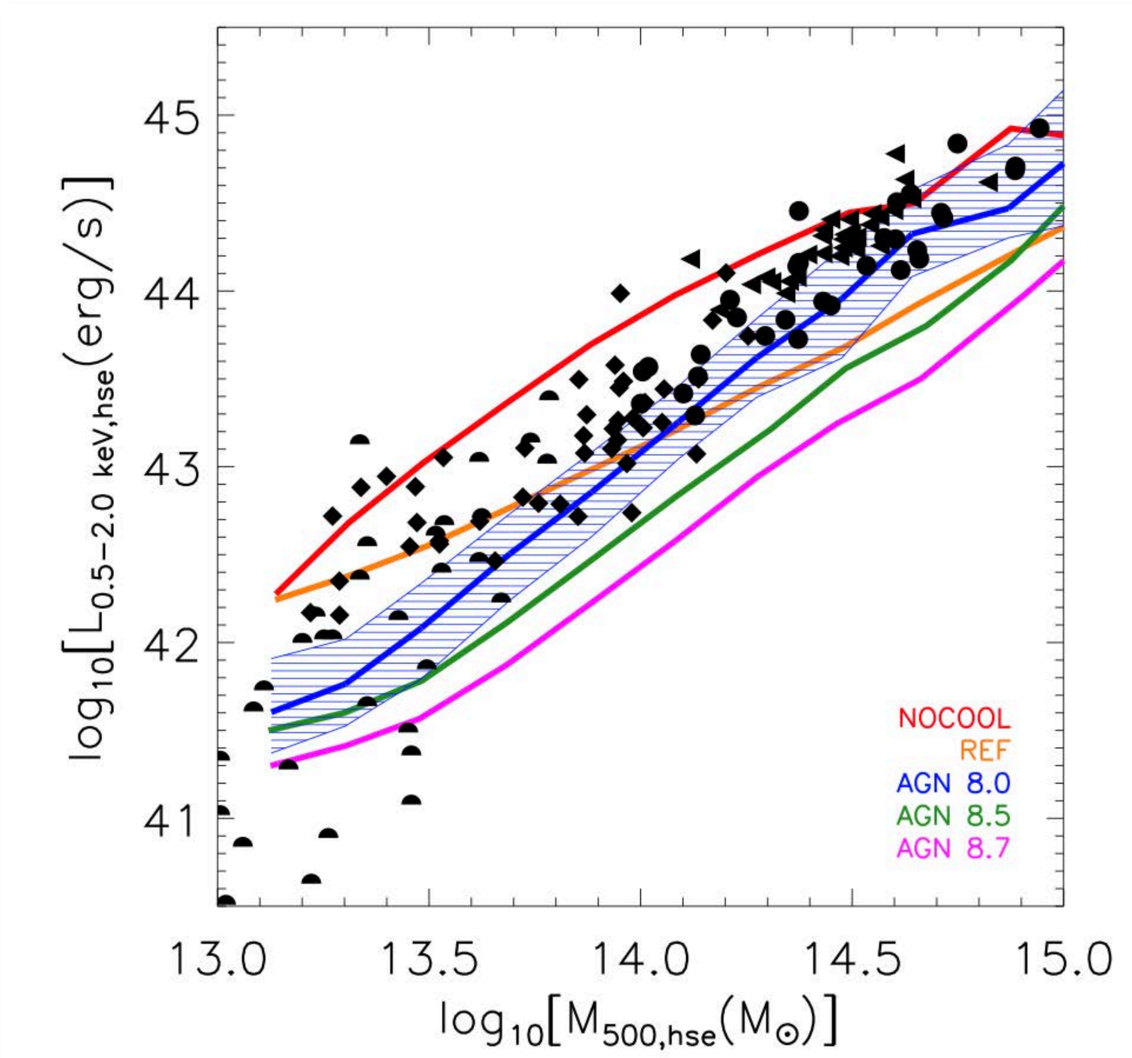
lower stellar mass, rotationally-supported galaxies (i.e., spirals) have slight tendency to align with local filaments.

higher mass, non-rotators tend to perpendicularly align (due to merging)



GADGET-3 simulations w/ AGN feedback

Le Brun, McCarthy et al 2014

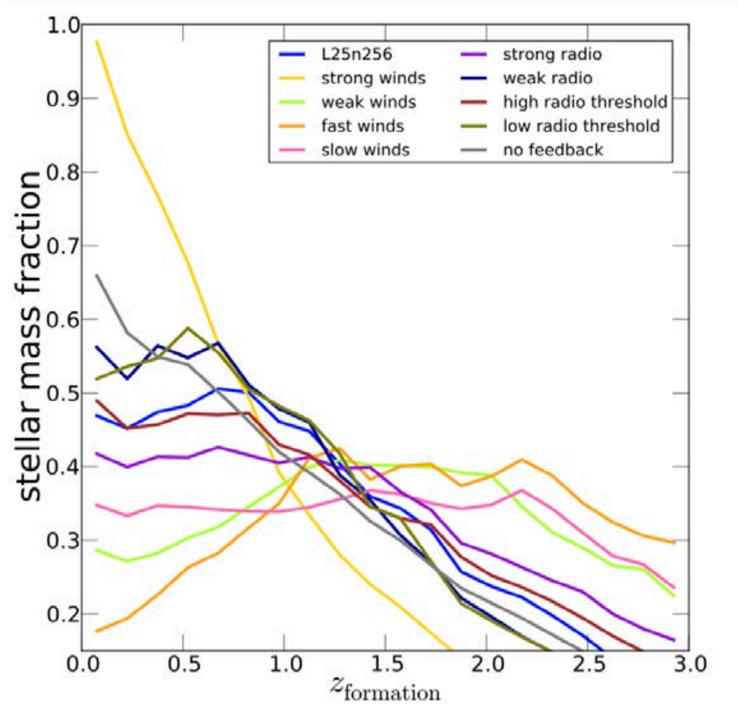


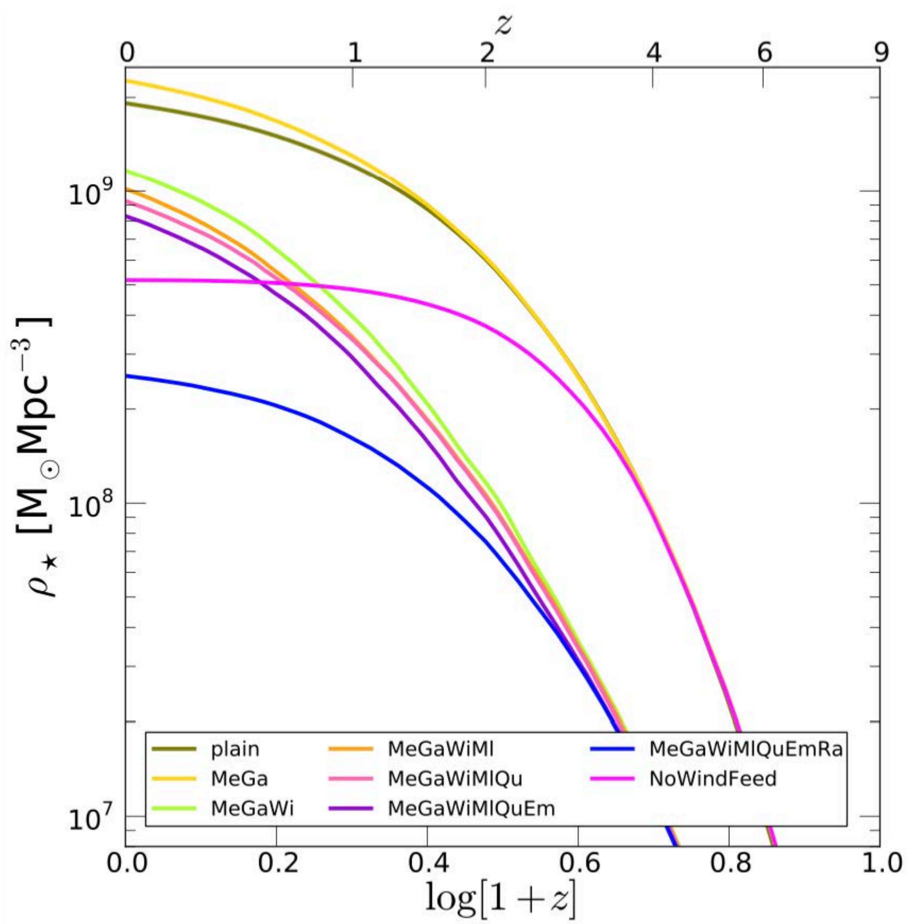
`cosmo-OWLS' SPH simulations with AGN feedback produce better hot gas scaling relations in high-mass halos.

AREPO models with layered physics, up to 3 modes of AGN feedback

Vogelsburger et al 2013

name	physics
plain	same as in Vogelsberger et al. (2012) (except for IMF, softer eEOS, self-shielding)
MeGa	+ met. line cool., gas recycl. = "no feedback"
MeGaWi	+ stellar winds
MeGaWiMl	+ separate metal mass loading of winds
MeGaWiMlQu	+ quasar-mode AGN feedback
MeGaWiMlQuEm	+ electro-magnetic AGN feedback
MeGaWiMlQuEmRa	+ radio-mode AGN = L25n256
NoWindFeed	L25n256 without stellar feedback





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
– species chemistry and dust
– mass loading and metal pollution by SN blastwaves
– effects of jet heating from central BH (AGN activity)
– +...

All of this entails ***many 'sub-grid' control parameters***, effects of which can often be degenerate.

Do purely *DETERMINISTIC* sub-grid solutions make sense?

Are resolved solutions of local astrophysical conditions sufficient?

Would `missing' small-scale physics add stochasticity?

* semi-analytic models already have >100 input parameters :(

(e.g., galacticus.org)

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
– species chemistry and dust
– mass loading and metal pollution by SN blastwaves
– effects of jet heating from central BH (AGN activity)
– +...

All of this entails ***many 'sub-grid' control parameters***, effects of which can often be degenerate.

How do we know we've reached *THE* solution of nature?

Do purely *DETERMINISTIC* sub-grid solutions make sense?

Are resolved solutions of local astrophysical conditions sufficient?

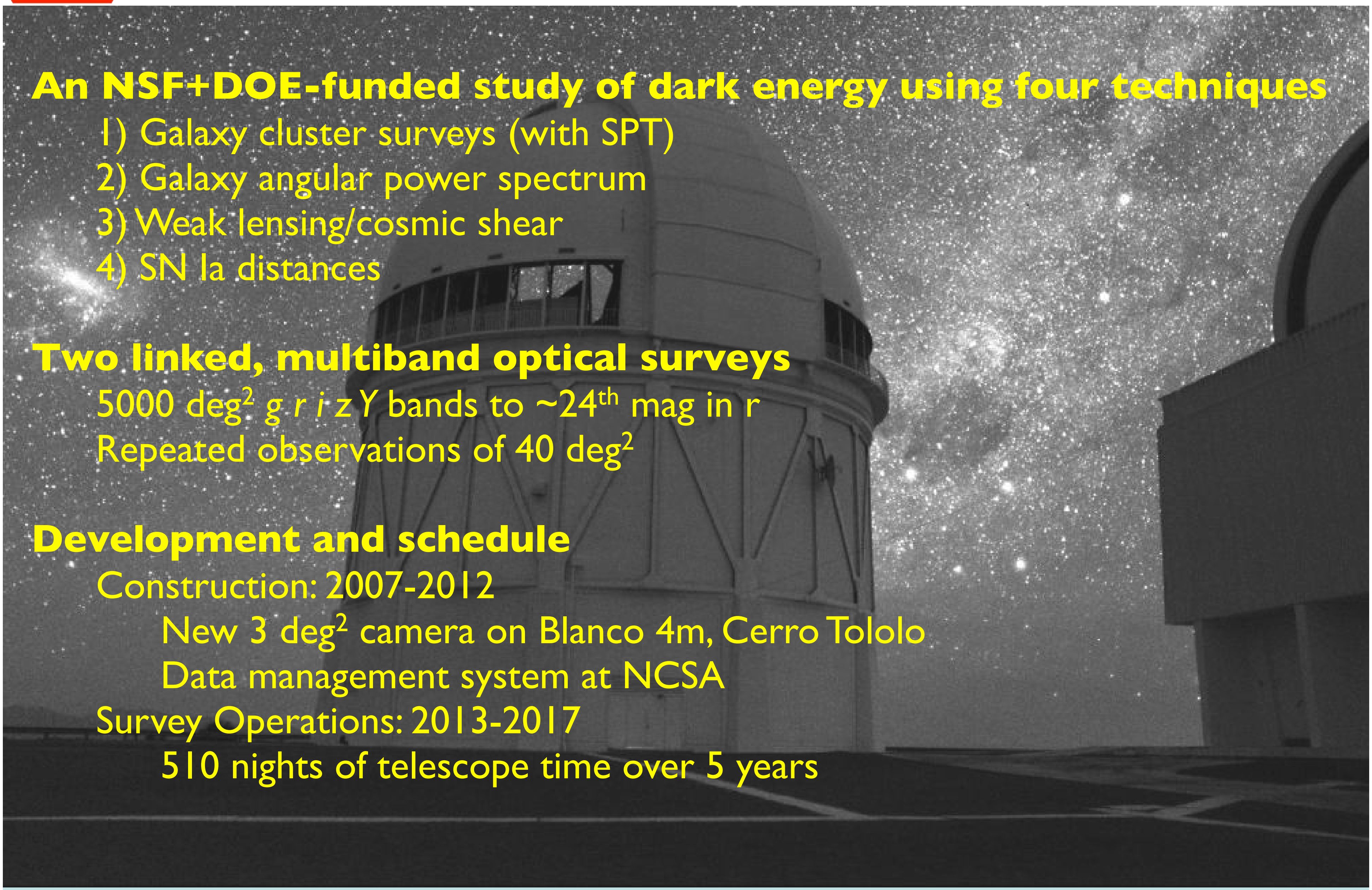
Would `missing' small-scale physics add stochasticity?

* semi-analytic models already have >100 input parameters :(

(e.g., galacticus.org)

synthetic skies
in support of
dark energy studies

Dark Energy Survey



An NSF+DOE-funded study of dark energy using four techniques

1) Galaxy cluster surveys (with SPT)
2) Galaxy angular power spectrum
3) Weak lensing/cosmic shear
4) SN Ia distances

Two linked, multiband optical surveys

5000 deg^2 *g r i z Y* bands to ~24^{th} mag in r
Repeated observations of 40 deg^2

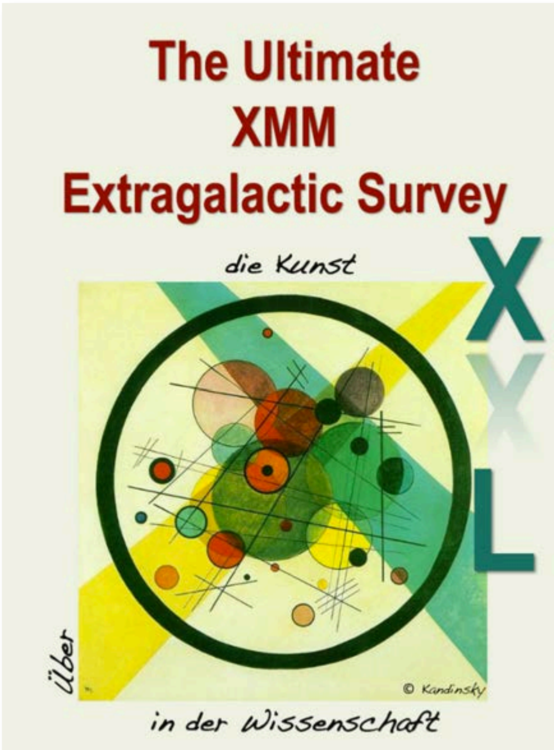
Development and schedule

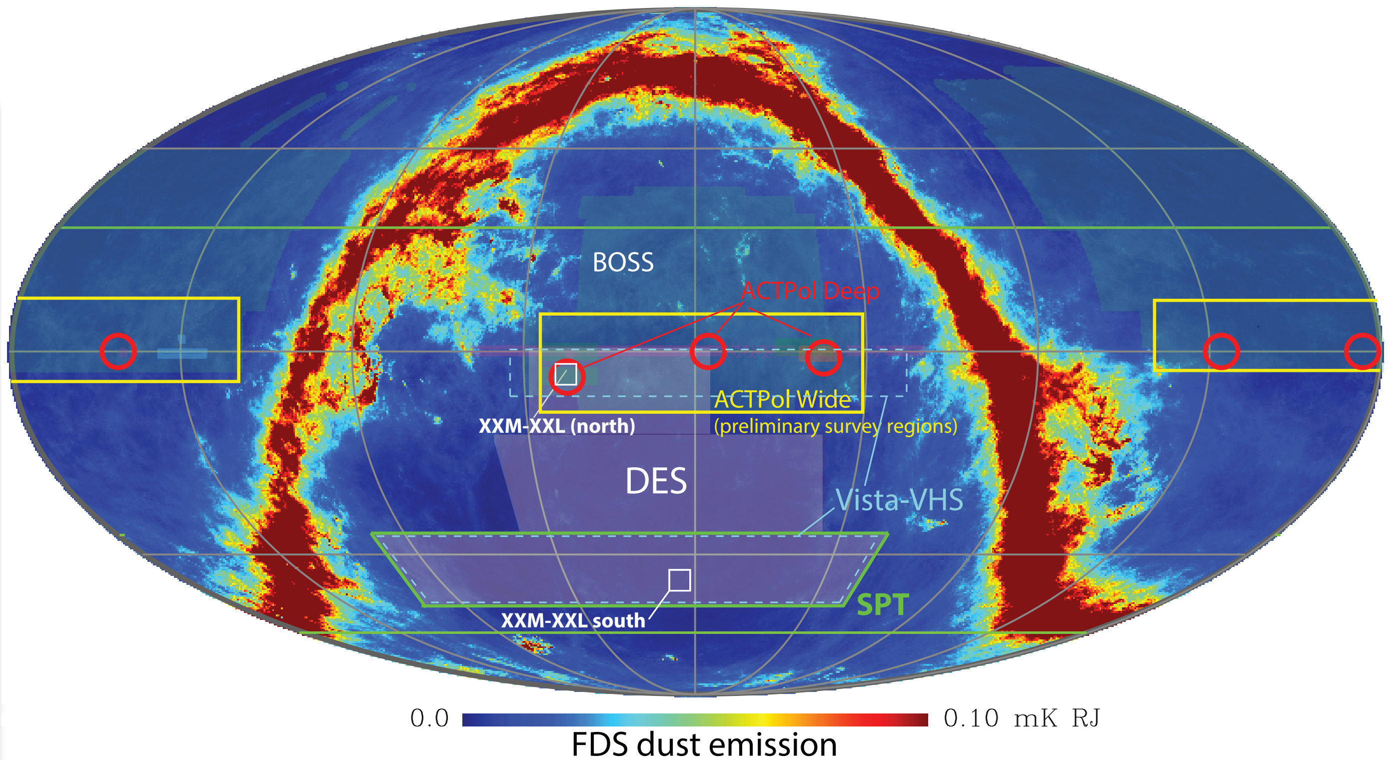
Construction: 2007-2012
- New 3 deg^2 camera on Blanco 4m, Cerro Tololo
- Data management system at NCSA

Survey Operations: 2013-2017
- 510 nights of telescope time over 5 years

XMM-XXL survey will use X-ray detected cluster counts to test DE

PI: M. Pierre (Saclay)



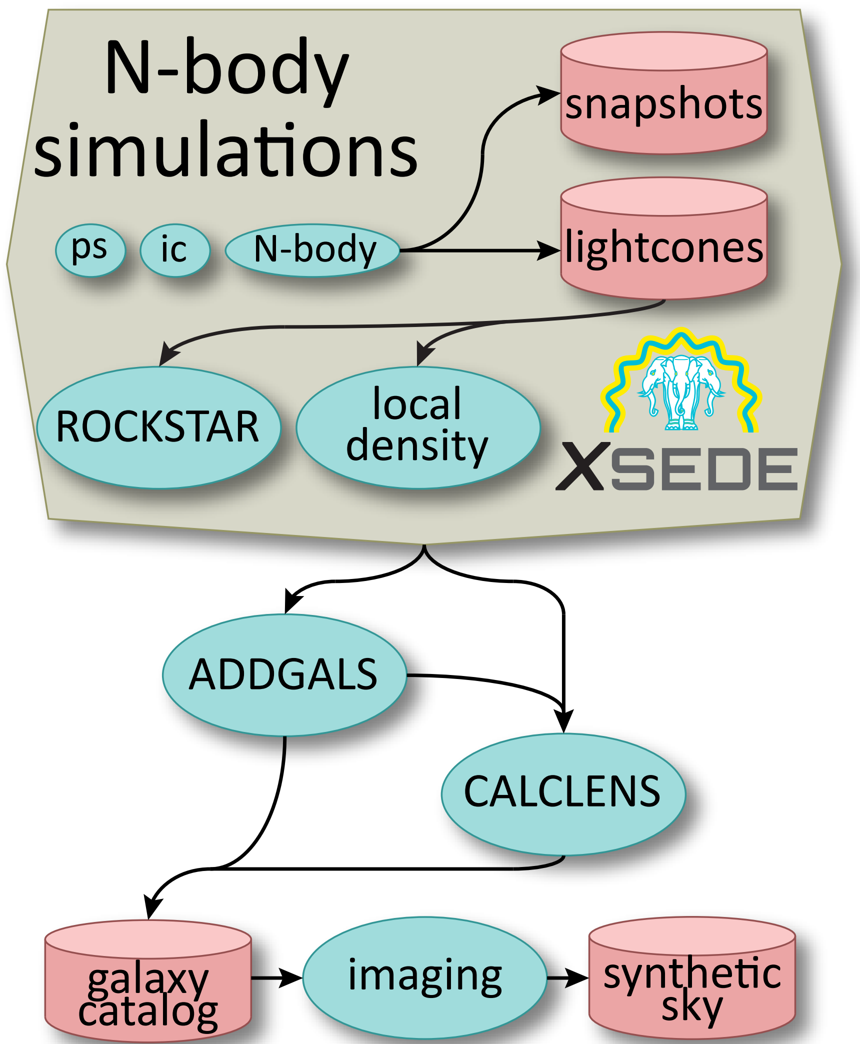


6 Msec XMM allocation, 10 ksec exposures
tiling 2 x 25 sq deg regions (S field overlaps DES)
+ multi-wavelength campaigns
expect ~500 groups and clusters to z~2

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

* test signal extraction from survey data (create *truth catalogs*)
* predict (range of) observable features for a cosmology
* calculate expected signal covariance

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



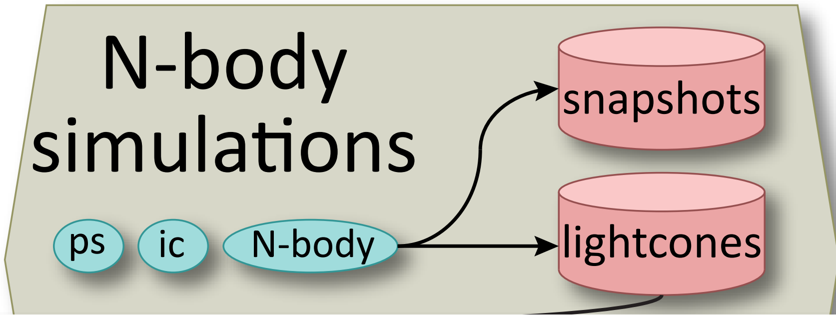
Catalog Simulations

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

Image Simulations

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

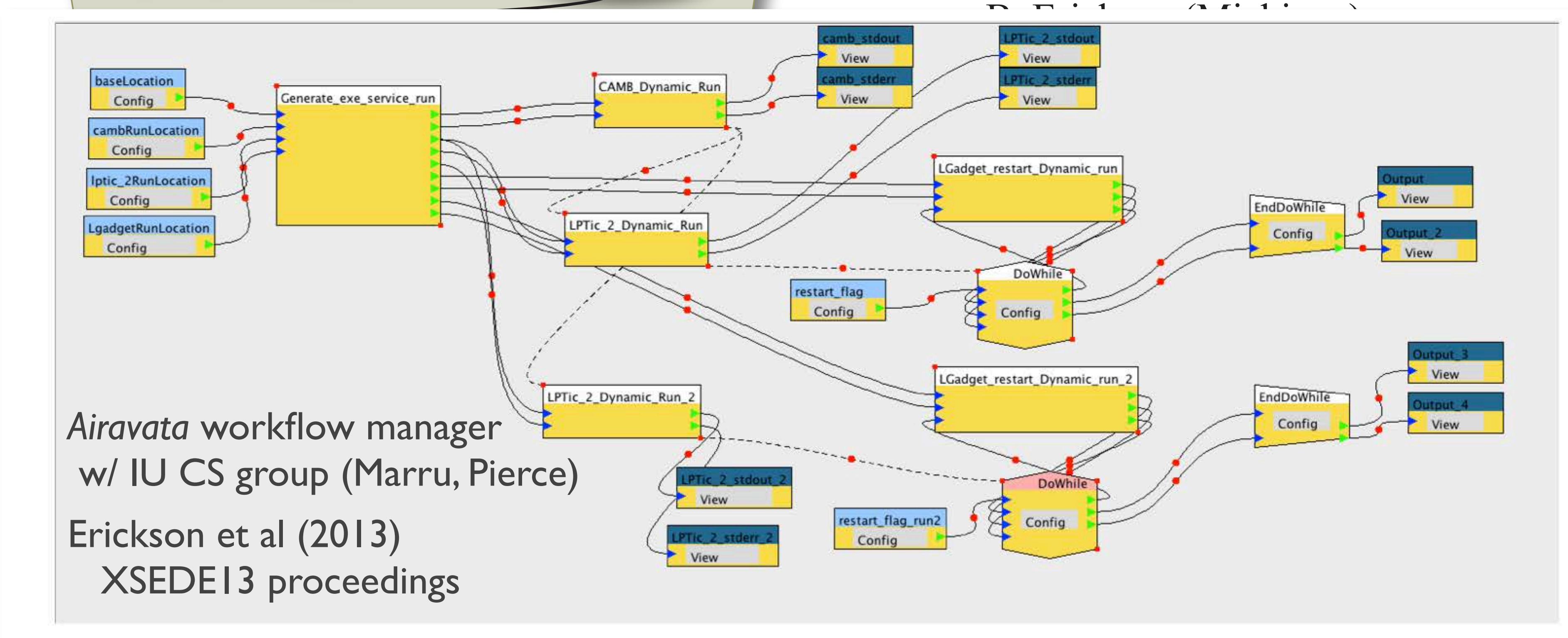
simulation workflow to support Dark Energy Survey (DES) science analysis



Catalog Simulations

M. Becker (Stanford)

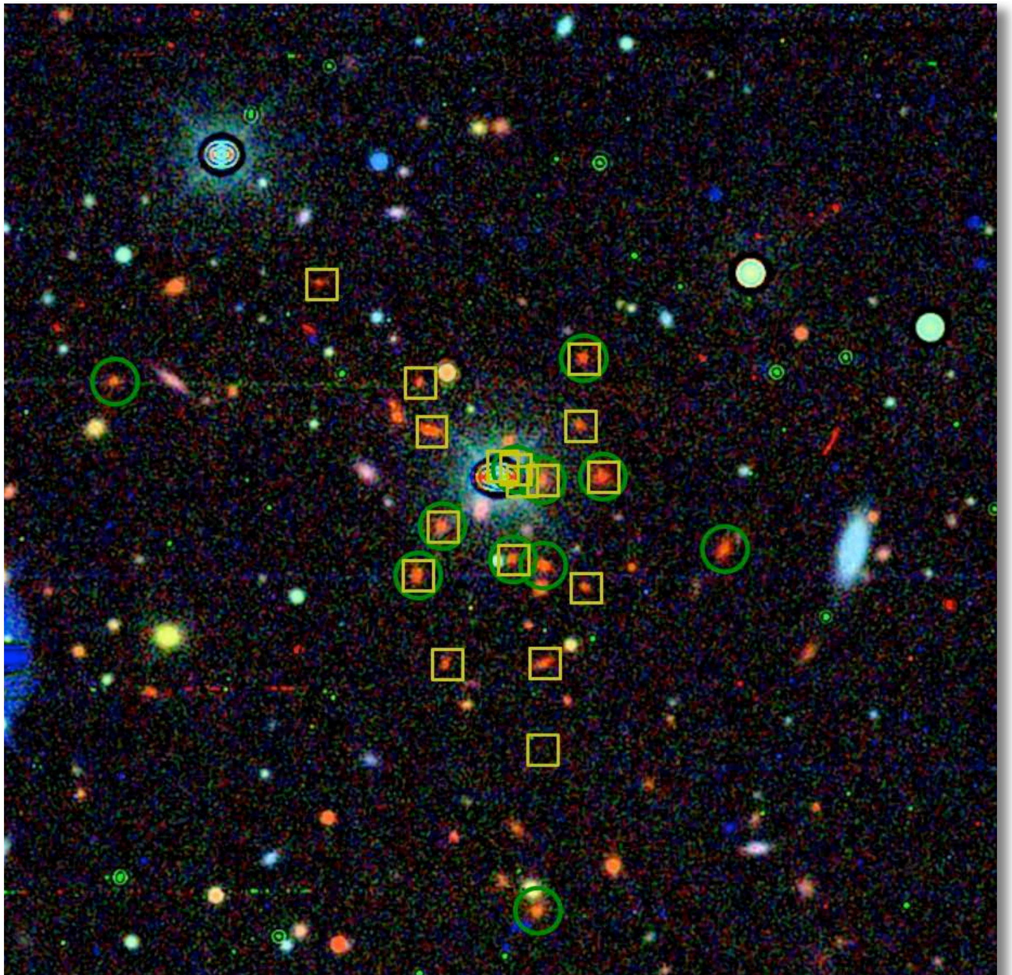
M. Busha (Stanford)

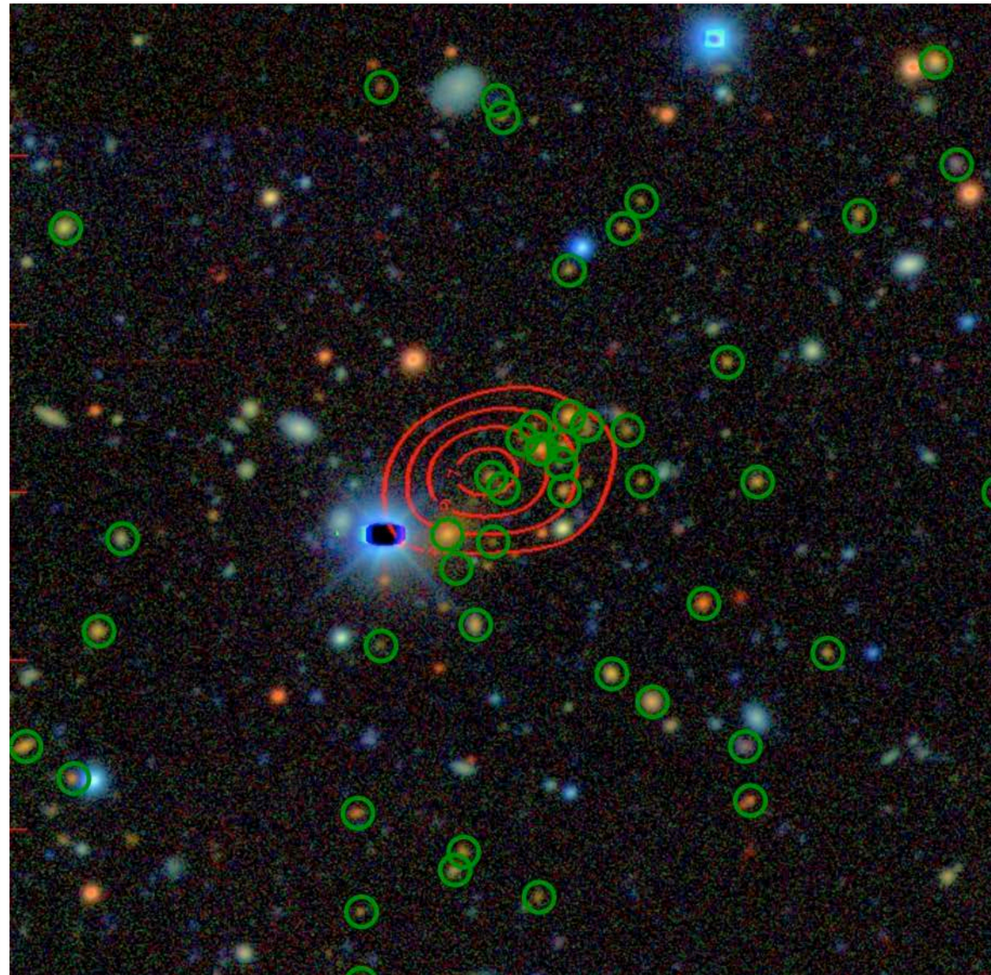


Airavata workflow manager
w/ IU CS group (Marru, Pierce)

Erickson et al (2013)
XSEDE13 proceedings

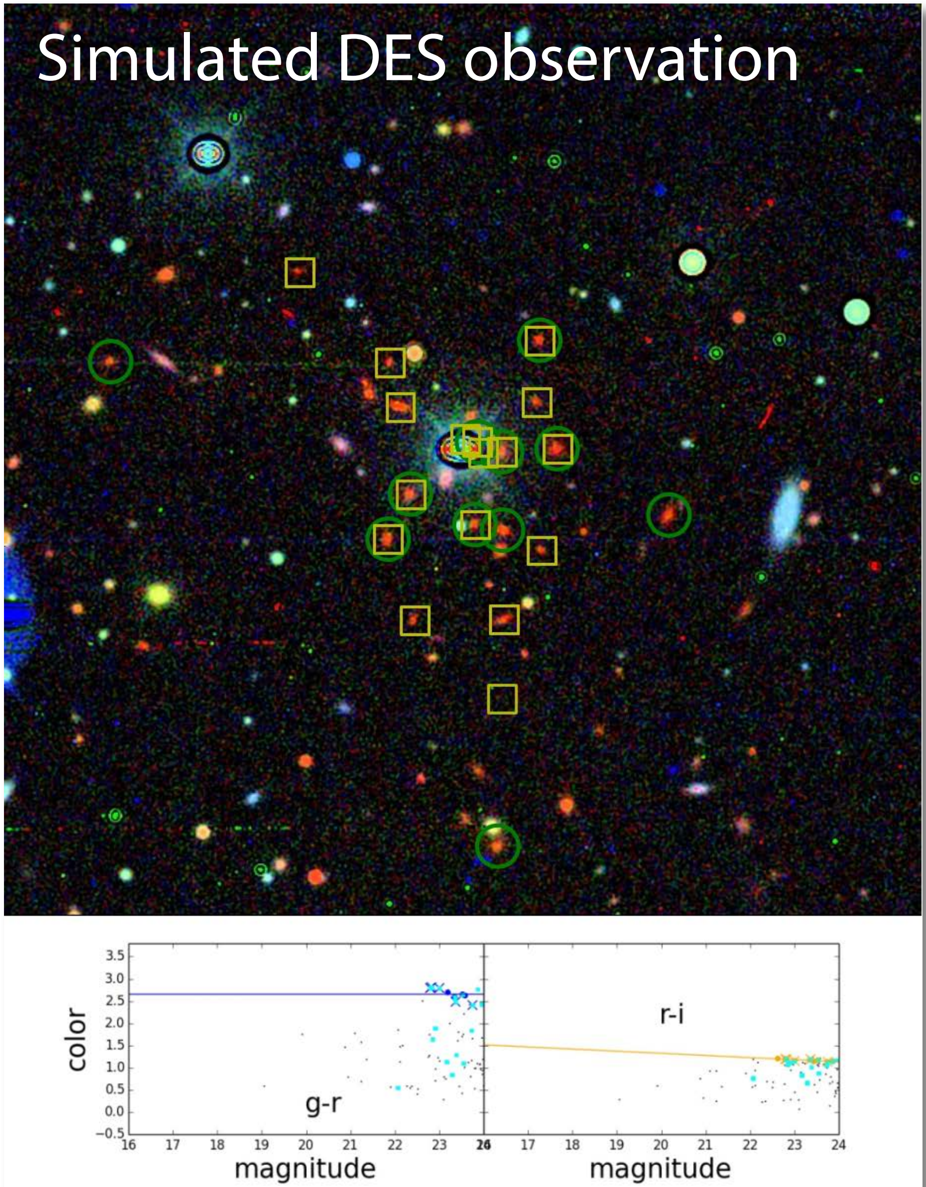
one real and one synthetic galaxy cluster image from DECam: *which is which?*

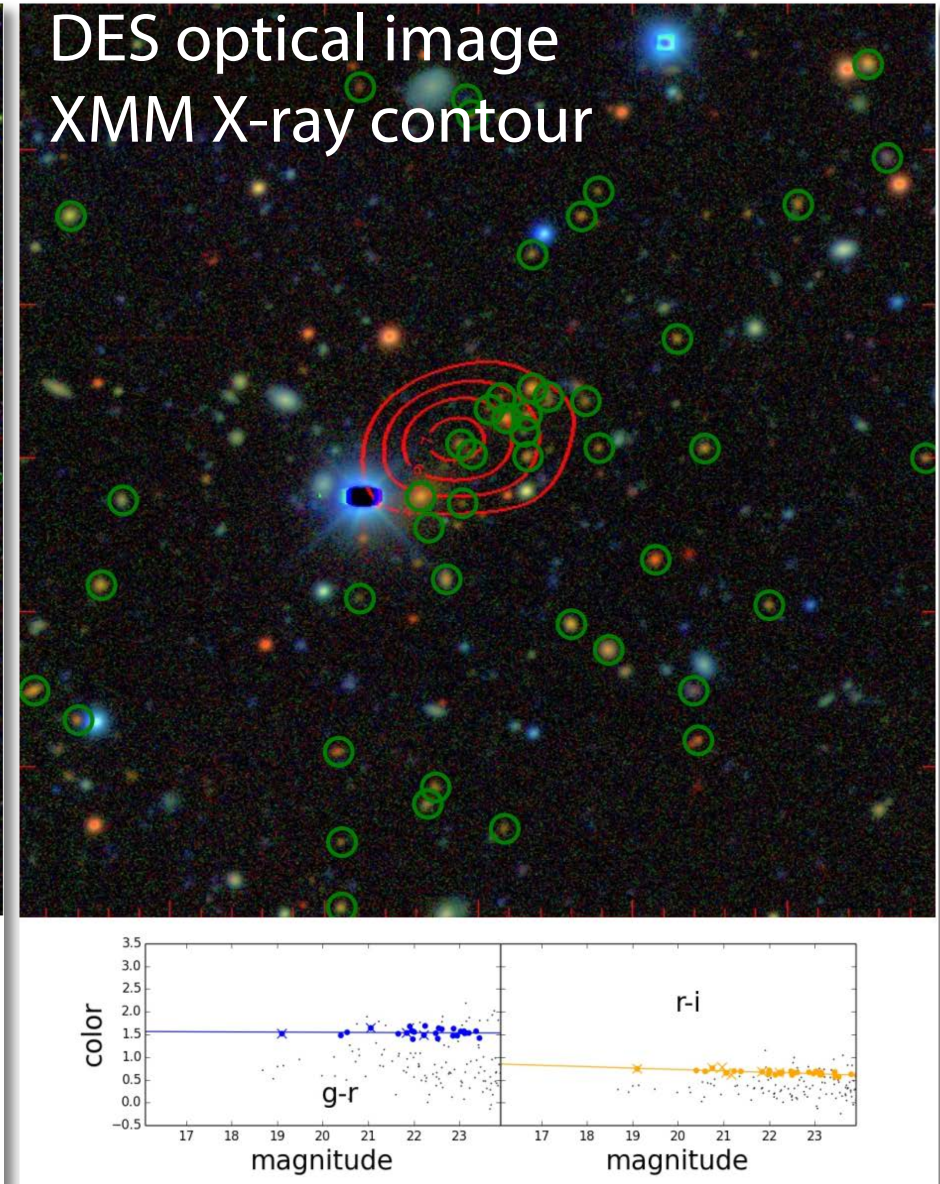




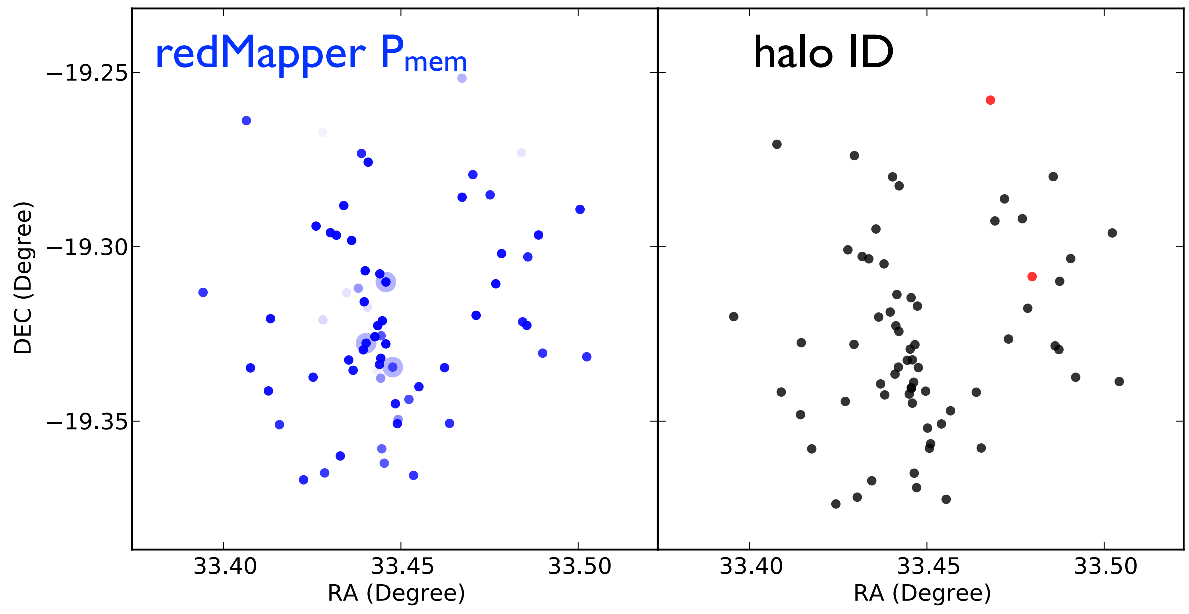
Courtesy Chris Miller (Michigan)

synthetic and real galaxy cluster images from DECam





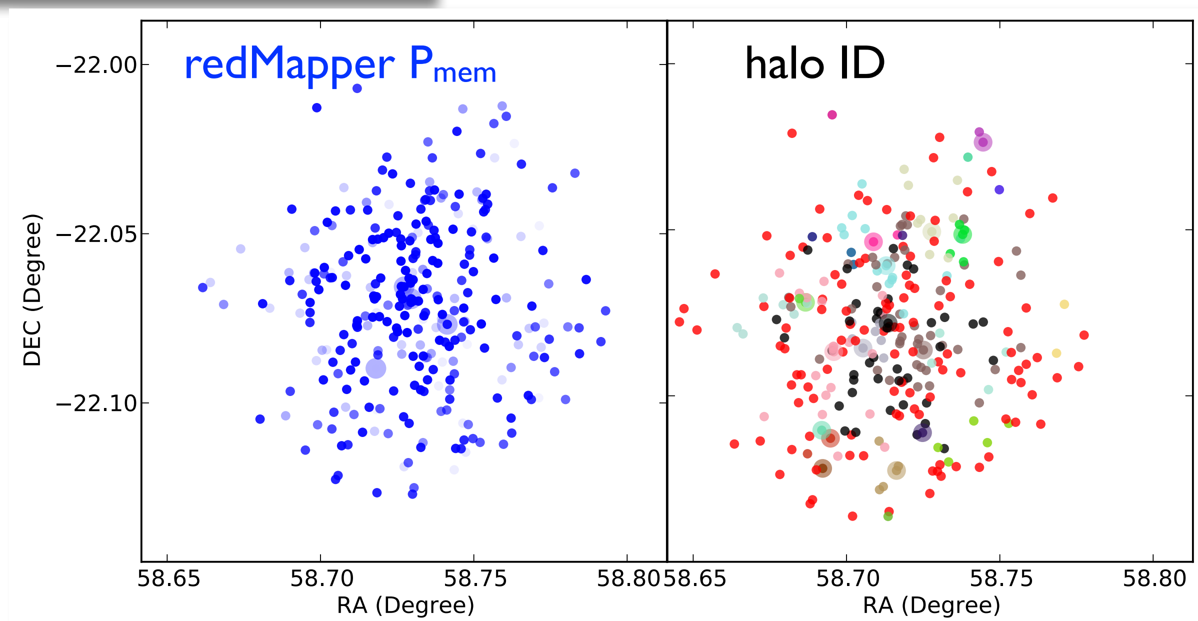
connecting clusters to halos through galaxy membership



Farahi et al, in prep.

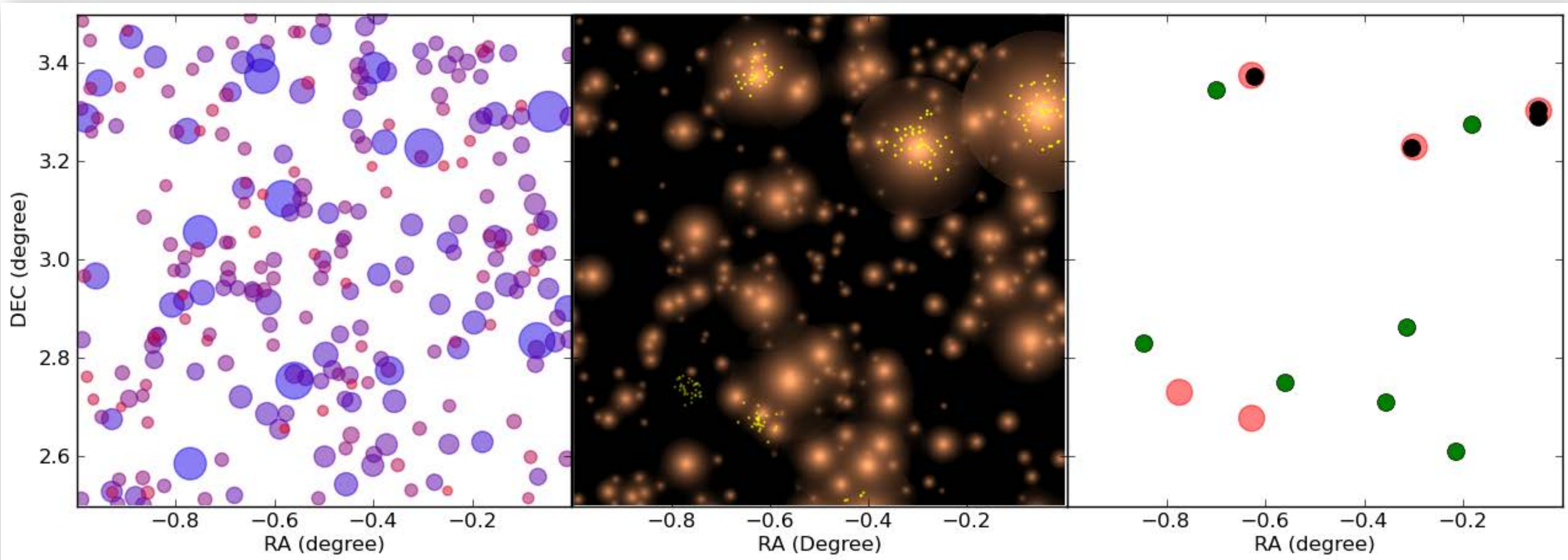
"clean" cluster-halo match

"dirty" cluster-halo match



testing methods to find clusters using X-ray of optical signatures

Farahi et al, in prep.



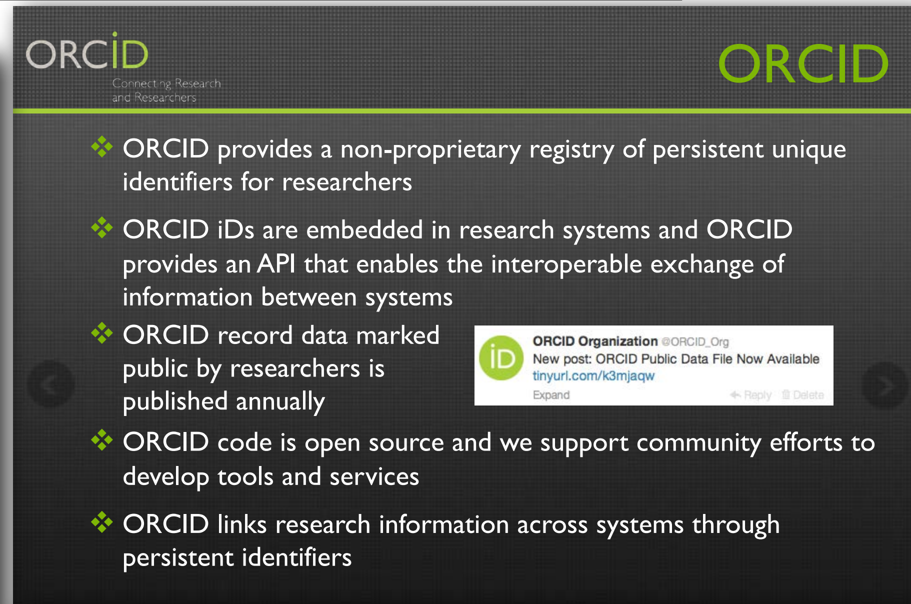
halos
(angular size;
color = redshift)

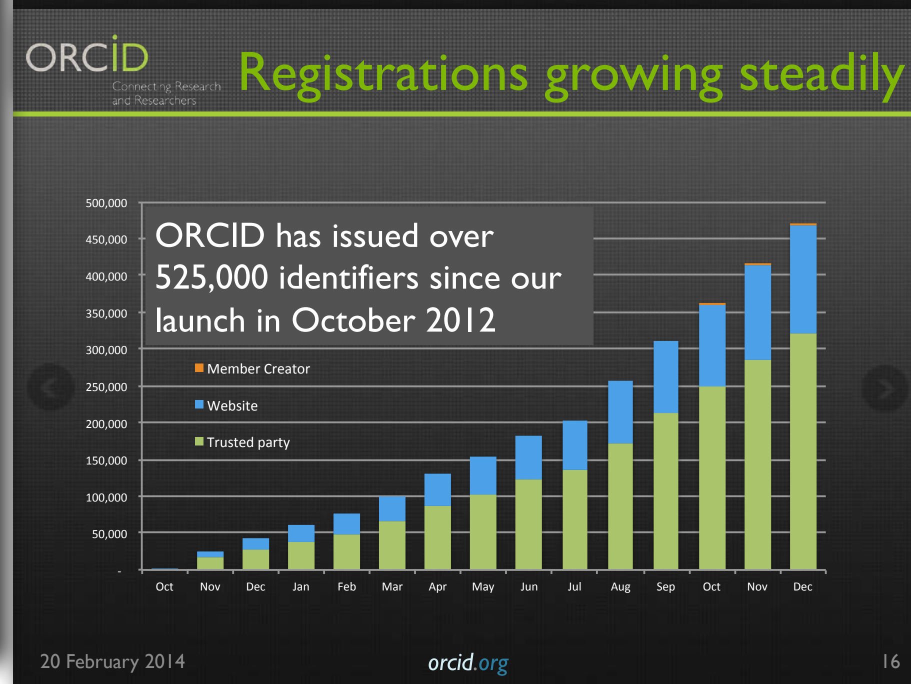
X-ray emission (greyscale)
+ optical galaxies in r
redMaPPer clusters (points)

X-ray cluster detections
(**black**/**green** = hi/lo S/N)
+ optically-detected
redMaPPer clusters (**red**)

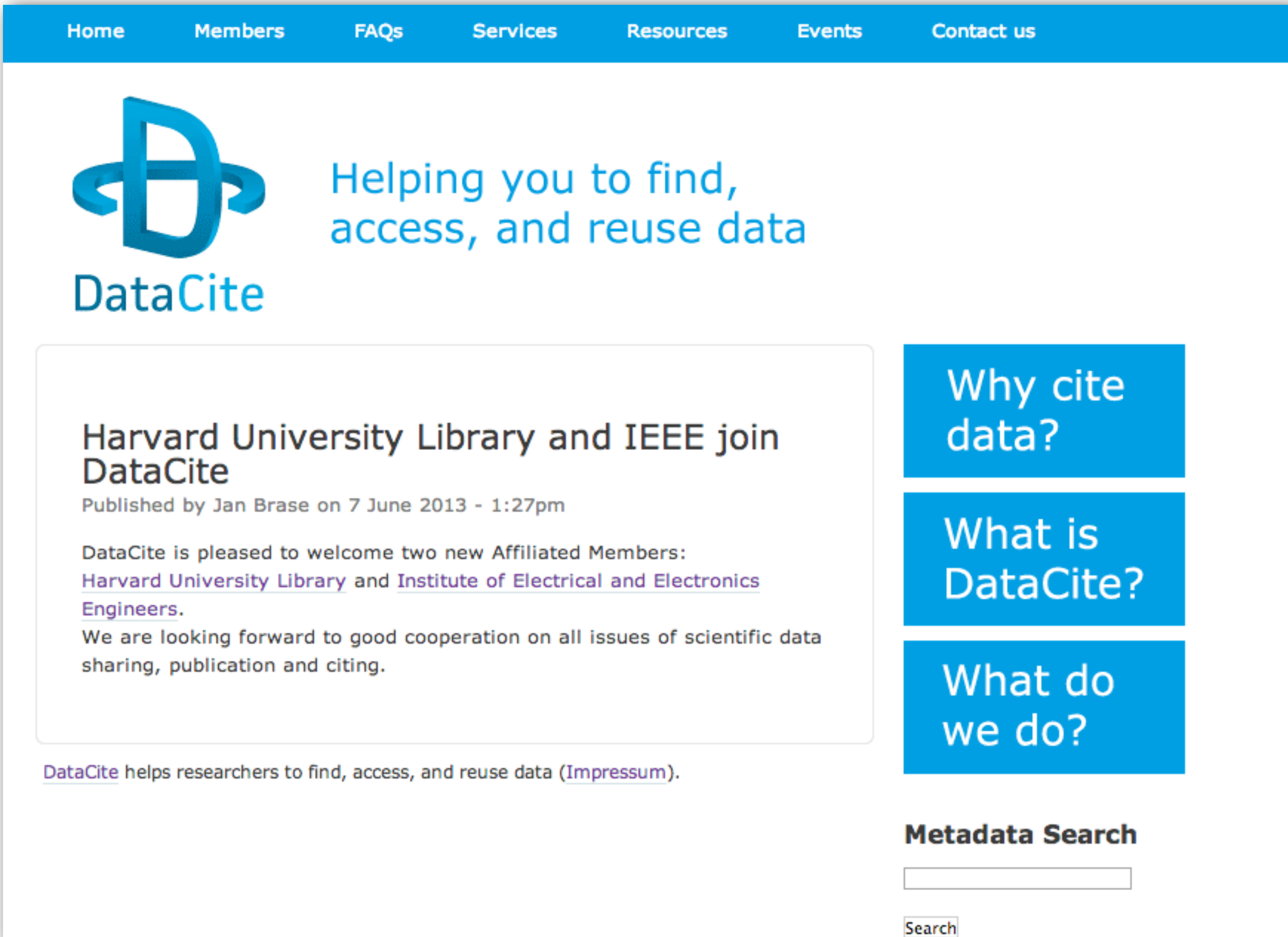
thoughts on
post-adolescent
computational cosmology

personal identity: a foundation for scholarly reputation





data identity: a foundation for re-use and reproducibility



data/code repositories: emerging public/private solutions

a notional stack of production/access layers

ORCID / DataCite / alt-metrics

- provisioning (condo-of-condo's?, ...)
- portal (hub-zero, ...)
- workflow (galaxy, pegasus, Airavata, ...)
- analysis, post-proc. (yt, RT, ADDGALS, XMAS, ...)
- cosmo codes (Enzo, RAMSES, gadget, ART, ...)
- physics modules (TBD)

Goal: Improve community coordination to maximize science return of exascale simulations.

a notional stack of production/access layers

ORCID / DataCite / alt-metrics

- provisioning (condo-of-condo's?, ...)
- portal (hub-zero, ...)
- workflow (galaxy, pegasus, Airavata, ...)
- analysis, post-proc. (yt, RT, ADDGALS, XMAS, ...)
- cosmo codes (Enzo, RAMSES, gadget, ART, ...)
- physics modules (TBD)

Goal: Improve community coordination to maximize science return of exascale simulations.

How to build across institutions?
How to incentivize community alignment?

positive developments in community structure

nIFTy Cosmology: NUMERICAL SIMULATIONS FOR LARGE SURVEYS

SOC:
Alexander Knebe (UAM)
Frazer Pearce (Nottingham)
Juan Garcia-Bellido (UAM/IFT-CSIC)
Chris Power (Western Australia)
Richard Bower (Durham)

The AGORA High-resolution Galaxy Simulations Comparison

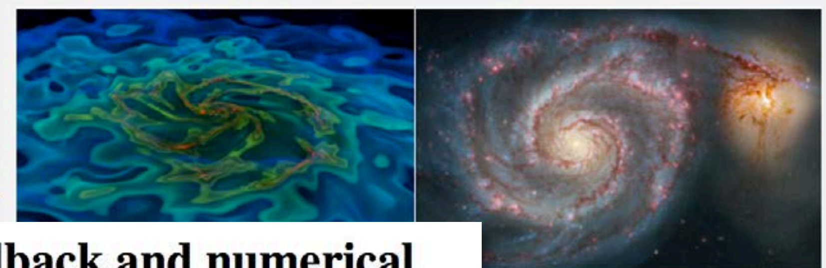
Search this site

Home | 1. Outline | 2. Project Details | 3. AGORA Workshop 2013 | 4. Project Workspace | 5. Blog | 6. Join Us

Navigation
- Home
- 1. Outline
- 2. Project Details
- 3. AGORA Workshop 2013
- 4. Project Workspace
- 5. Blog
- 6. Join Us

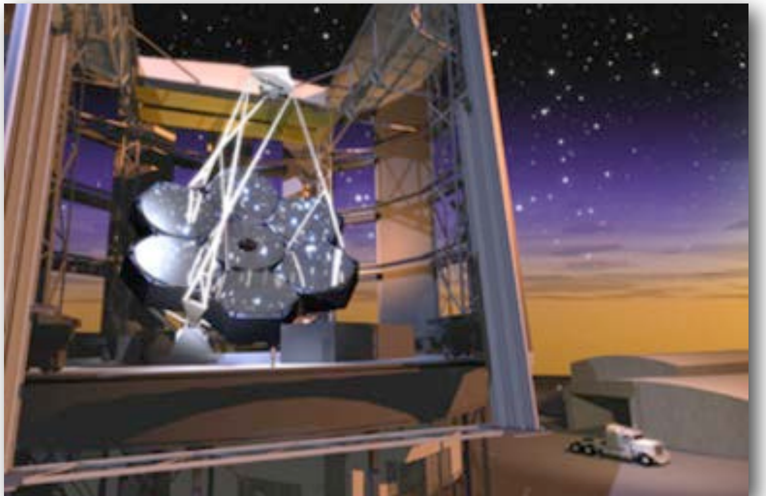
Sponsored by

Home



The Aquila comparison project: the effects of feedback and numerical methods on simulations of galaxy formation

C. Scannapieco,[1★] M. Wadepuhl,[2] O. H. Parry,[3,4] J. F. Navarro,[5] A. Jenkins,[3] V. Springel,[6,7] R. Teyssier,[8,9] E. Carlson,[10] H. M. P. Couchman,[11] R. A. Crain,[12,13] C. Dalla Vecchia,[14] C. S. Frenk,[3] C. Kobayashi,[15,16] P. Monaco,[17,18] G. Murante,[17,19] T. Okamoto,[20] T. Quinn,[10] J. Schaye,[13] G. S. Stinson,[21] T. Theuns,[3,22] J. Wadsley,[11] S. D. M. White[2] and R. Woods[11]

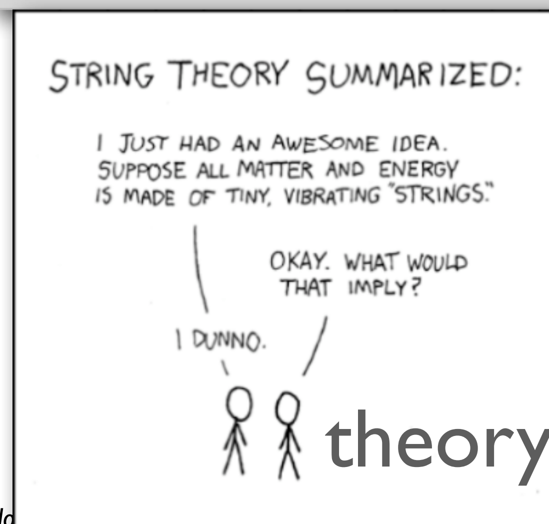


observation

computation

a mature future:

- simulations as an integral element of large survey projects
- synthetic multi-wavelength skies available to perform cross-survey science analysis
- gain physical understanding by *precision* ***measurement*** *and* *precision* ***modeling***



theory

The End