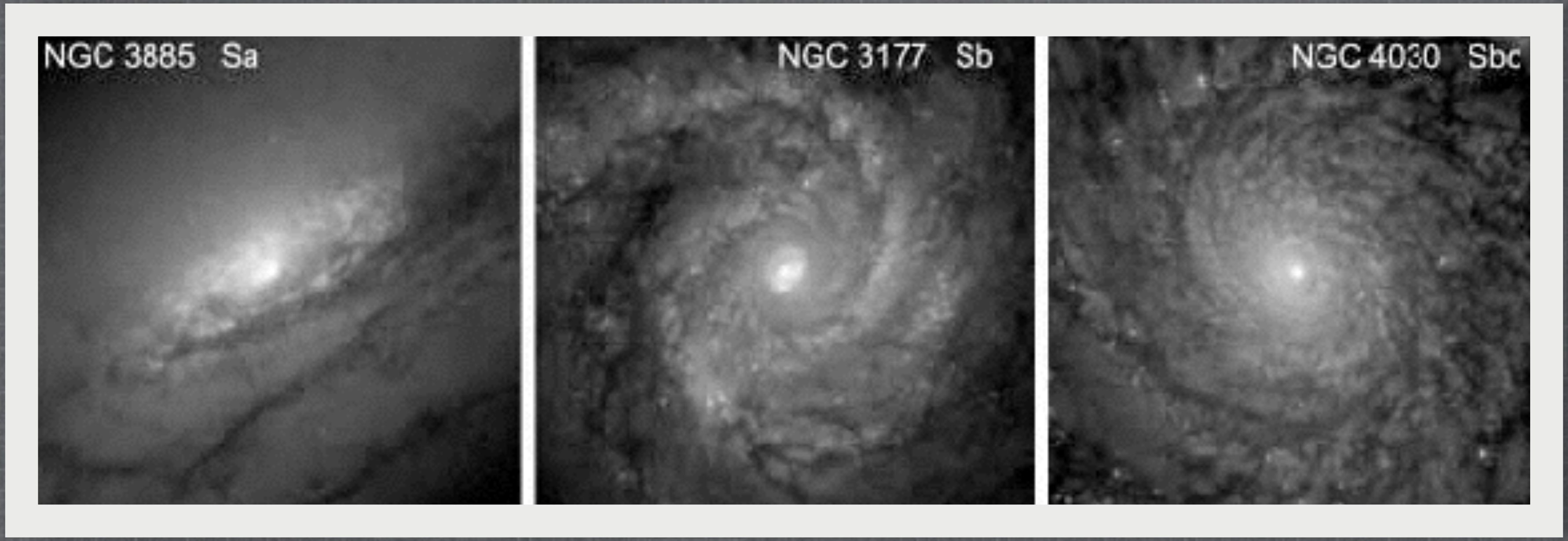
The Effect of Baryons on Dark Matter Potentials

Montpellier, August 30 2013



Javiera Guedes

Einstein Fellow / Lyman Spitzer Fellow, Princeton University
ETH Zurich

with Lucio Mayer (U. Zurich), Piero Madau (UCSC), Sijing Shen (UCSC), Michael Kuhlen (Berkeley), Annalisa Pillepich (UCSC), Jonathan Bird (Vanderbilt), Marcella Carollo (ETH Zurich) + Gasoline Community

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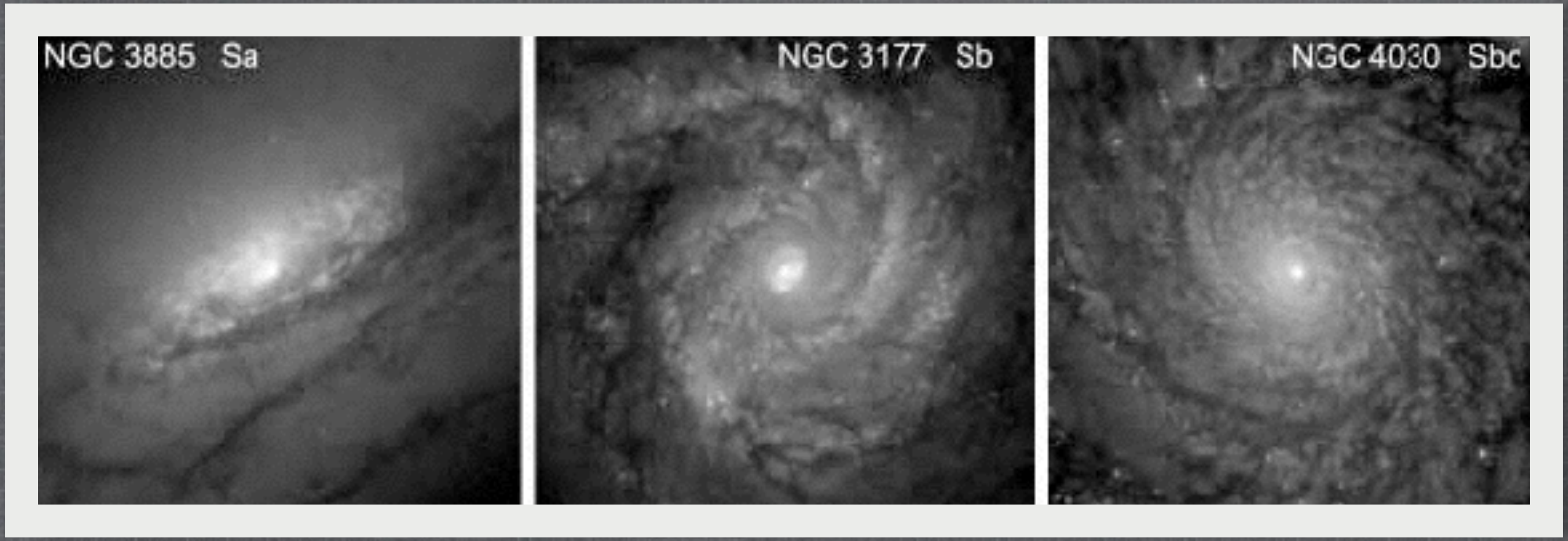

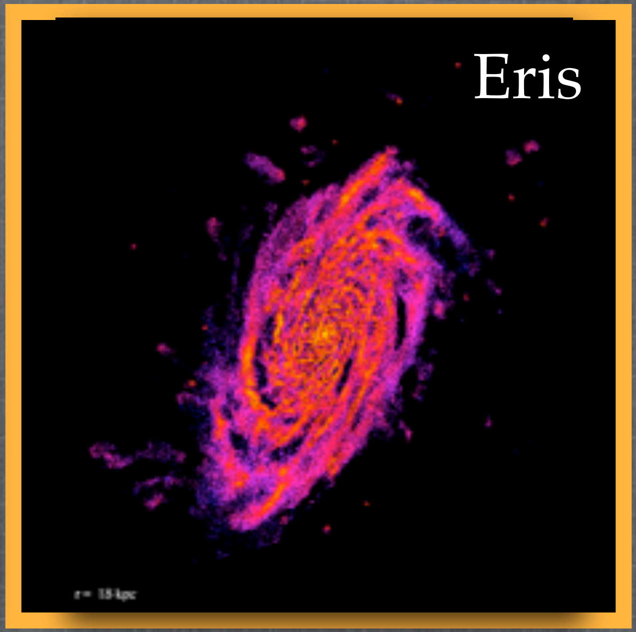

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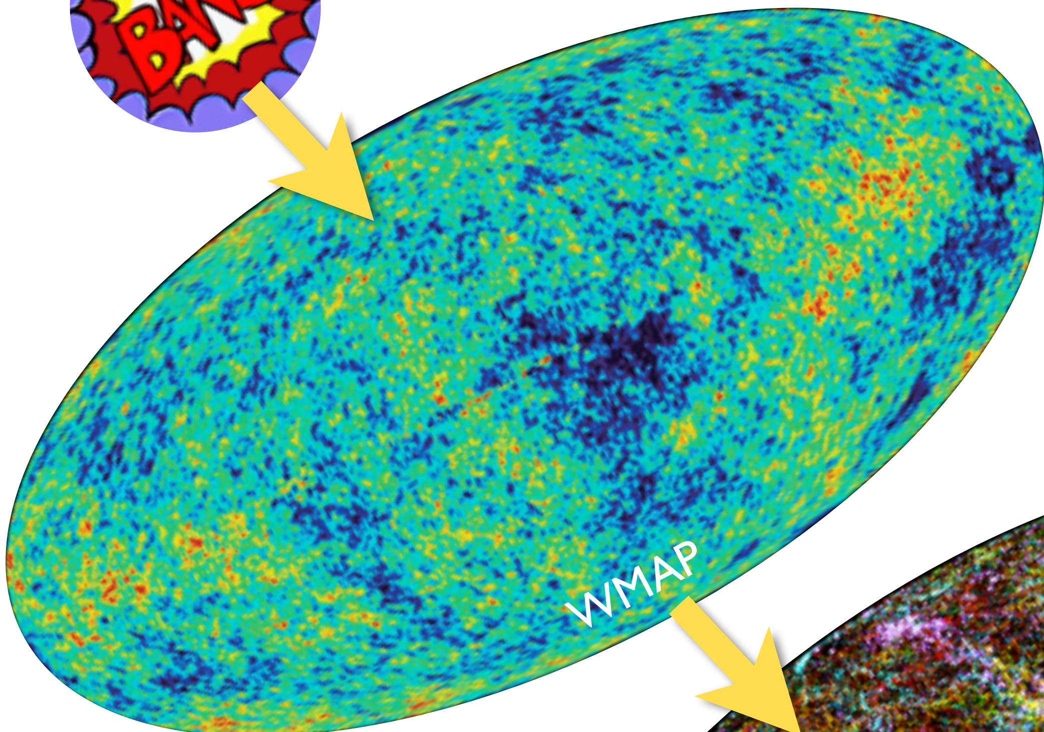
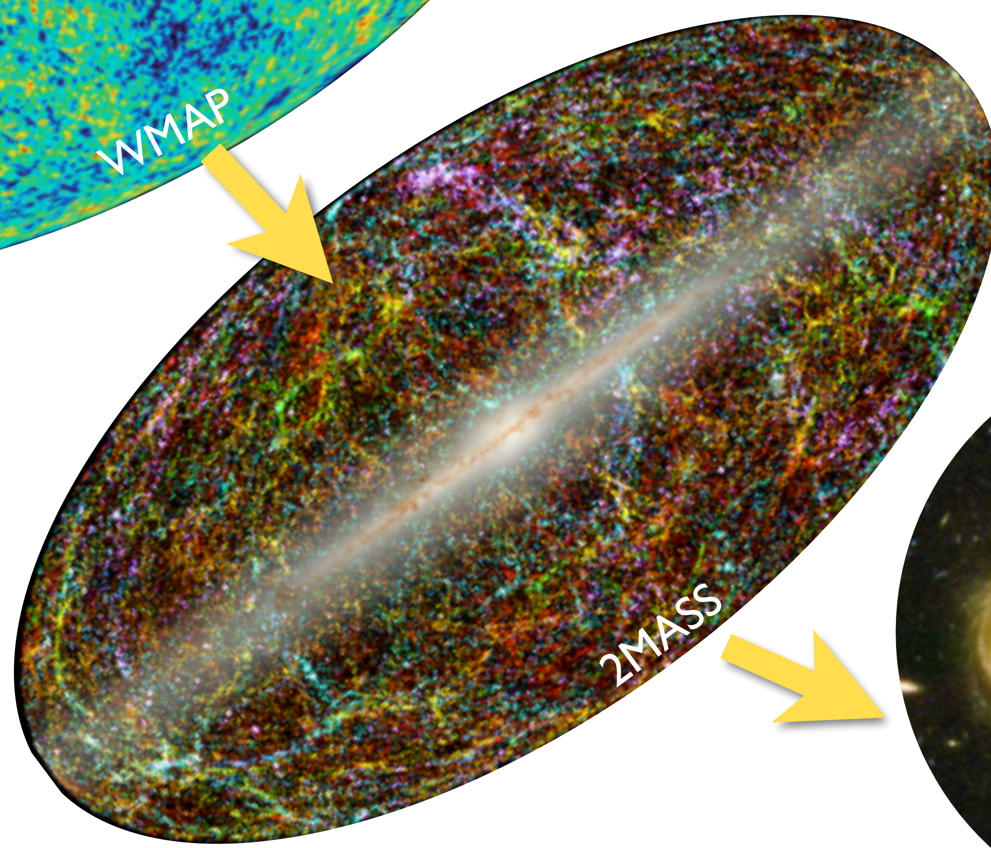
Early Universe Physics predicts the spectrum of
density fluctuations.

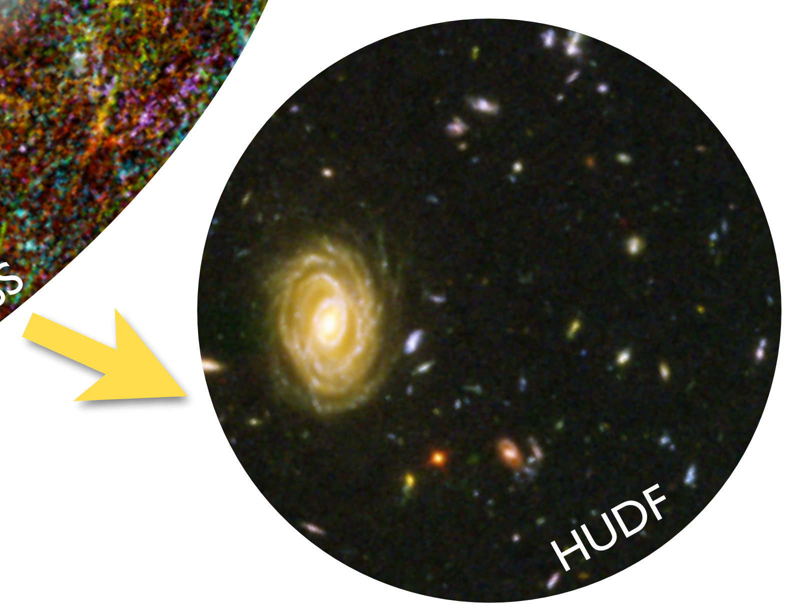


Self-gravitating **multi-species plasma**
during pre-CMB ages.

Two-component **baryon+CDM fluid**
after recombination



Baryons condense to
stars and galaxies



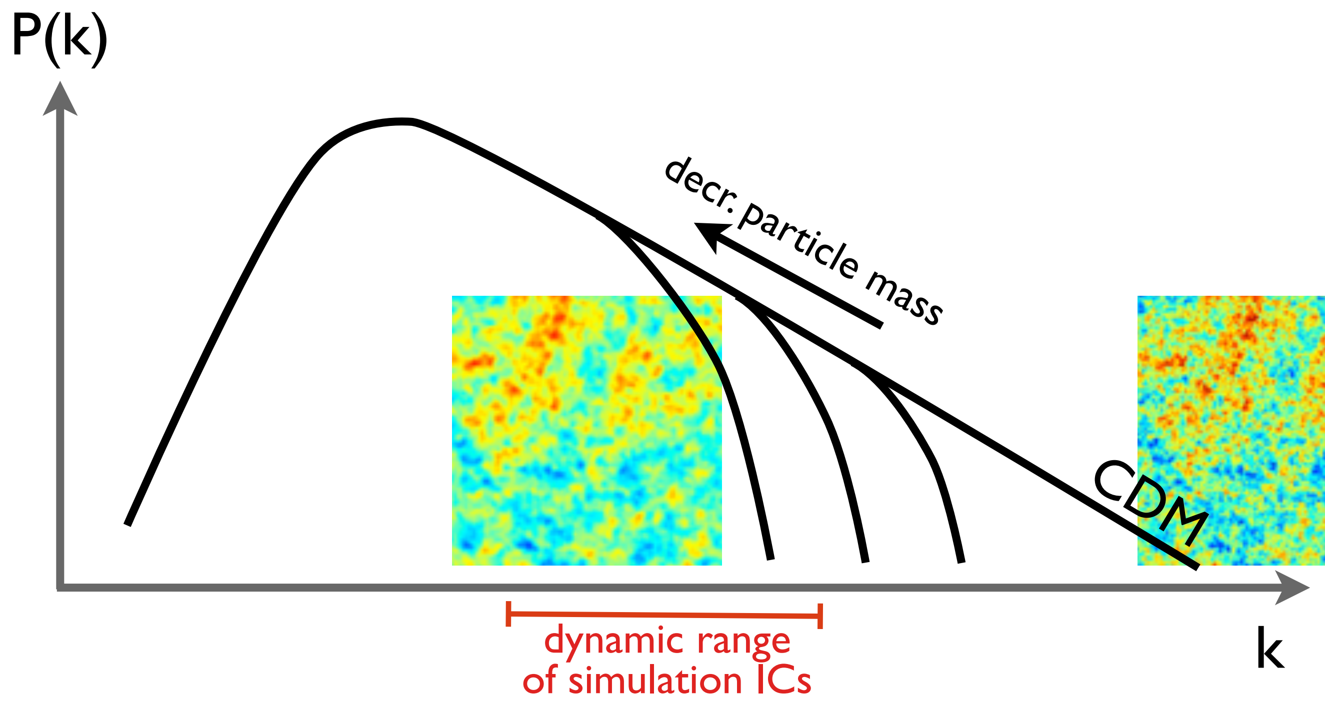
Simulator's Challenge:
model *everything*

Credit: Oliver Hahn

Dark Matter - properties on cosmological scales

- microscopic, i.e. continuum limit applicable
- very cold (WIMPs, Axions), or quite cold (WDM)
- negligible cross section, purely gravitationally interacting
- dominant dynamical component of structure formation

⇒ linear perturbation theory predicts perturbation spectra:

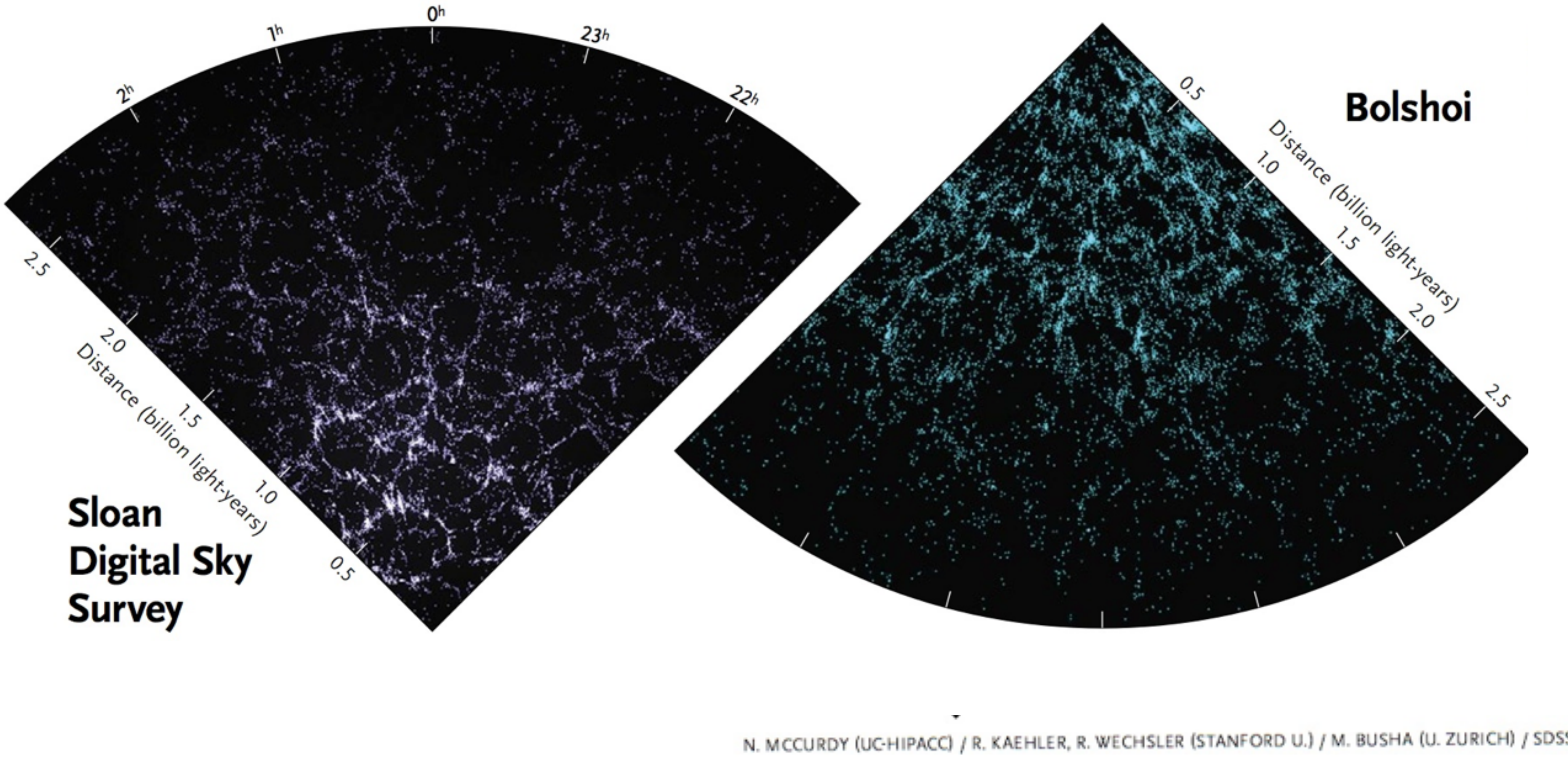


For cosmological problems, initial conditions are irrotational!
All structure formation starts from purely potential flow

Credit: Oliver Hahn

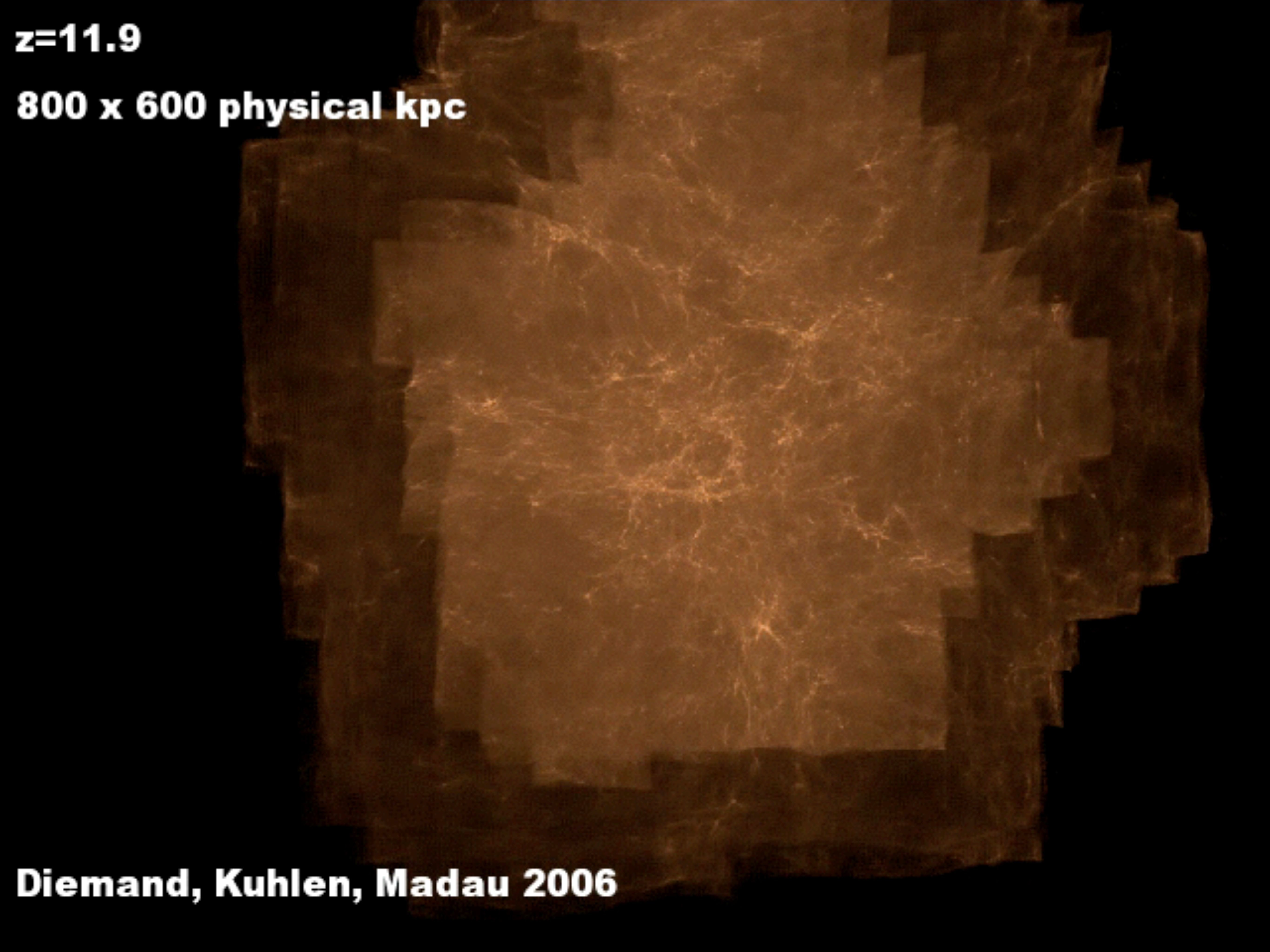
Huge Successes in modeling structure formation

for example:

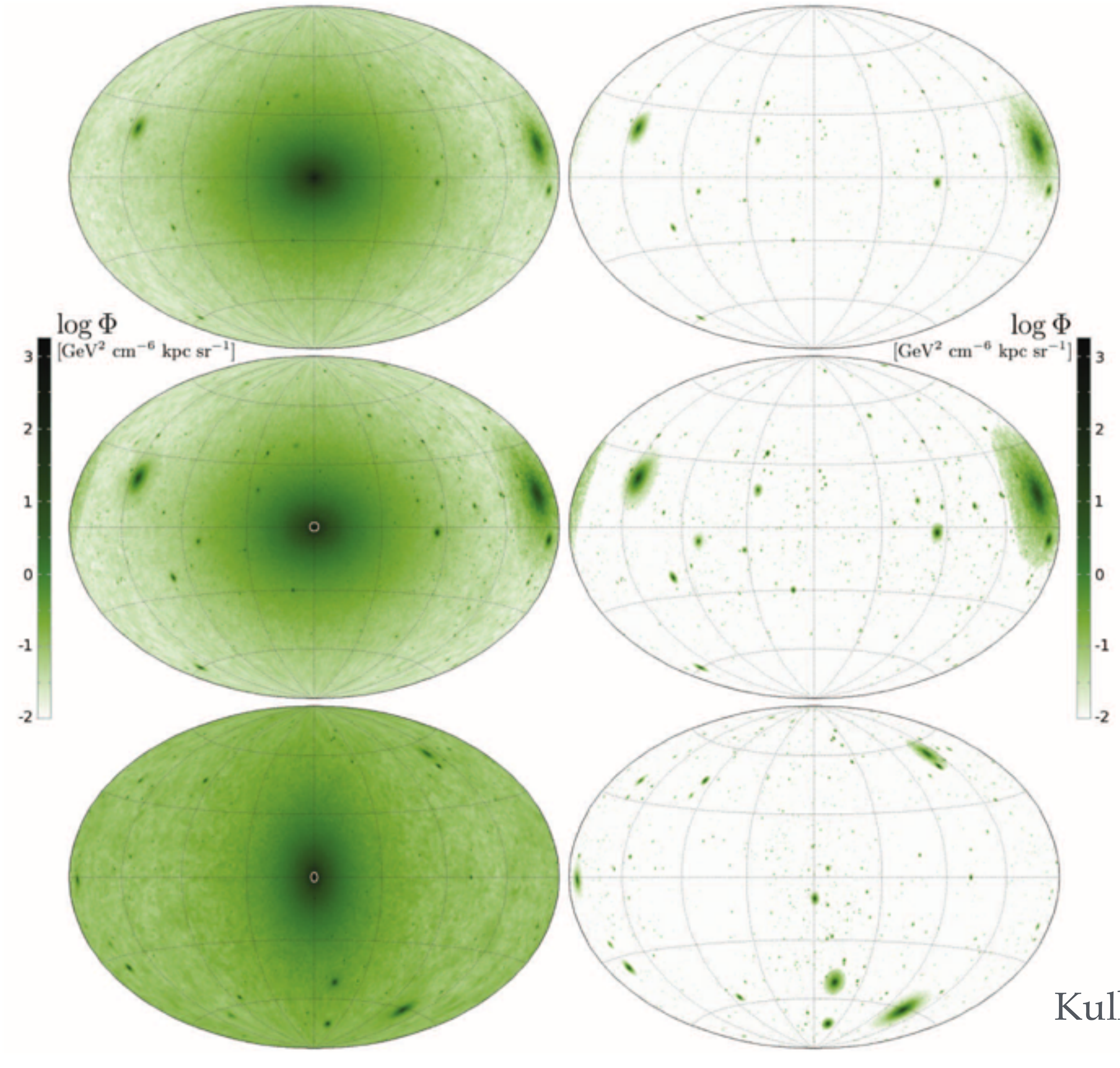


but arguably less successful with non-vanilla (non-WIMP) DM...

Credit: Oliver Hahn


z=11.9
800 x 600 physical kpc
Diemand, Kuhlen, Madau 2006

Annihilation Signal



Kulhen et al. 2008

A summary of outstanding issues

In CDM simulations, we study the effect of baryons on:

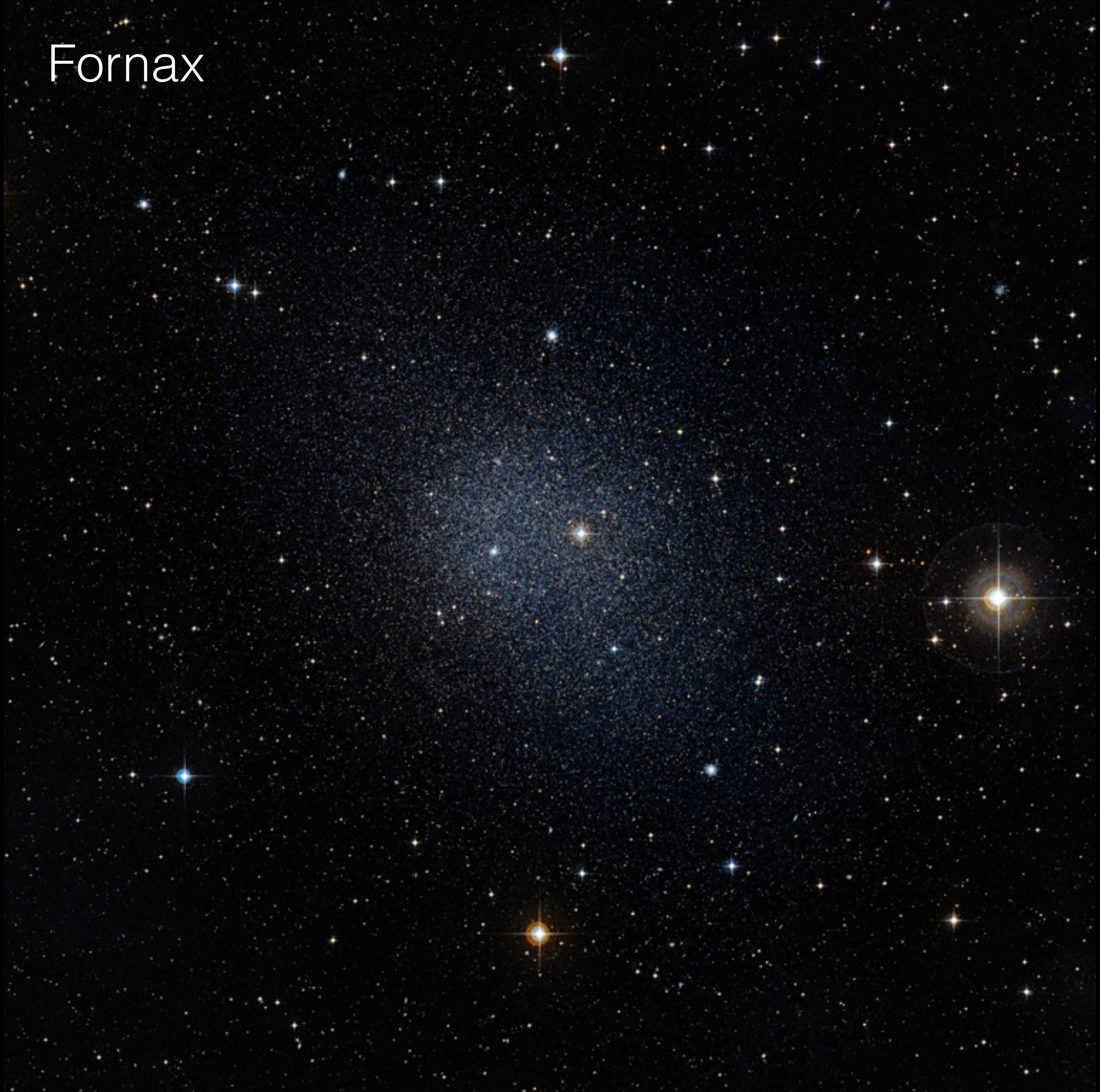
1. Small scales, i.e. dwarf galaxies:
   - Core Formation
   - Missing Satellite Problem
   - Too Big to Fail "Problem"

2. Central regions of spiral galaxies
   - Dark disk formation
   - Center of density displacements

What about Warm Dark Matter?

Key: improved force-calculation techniques, high-resolution, realistic recipes for star formation and supernova feedback

Dwarf Galaxies


Fornax

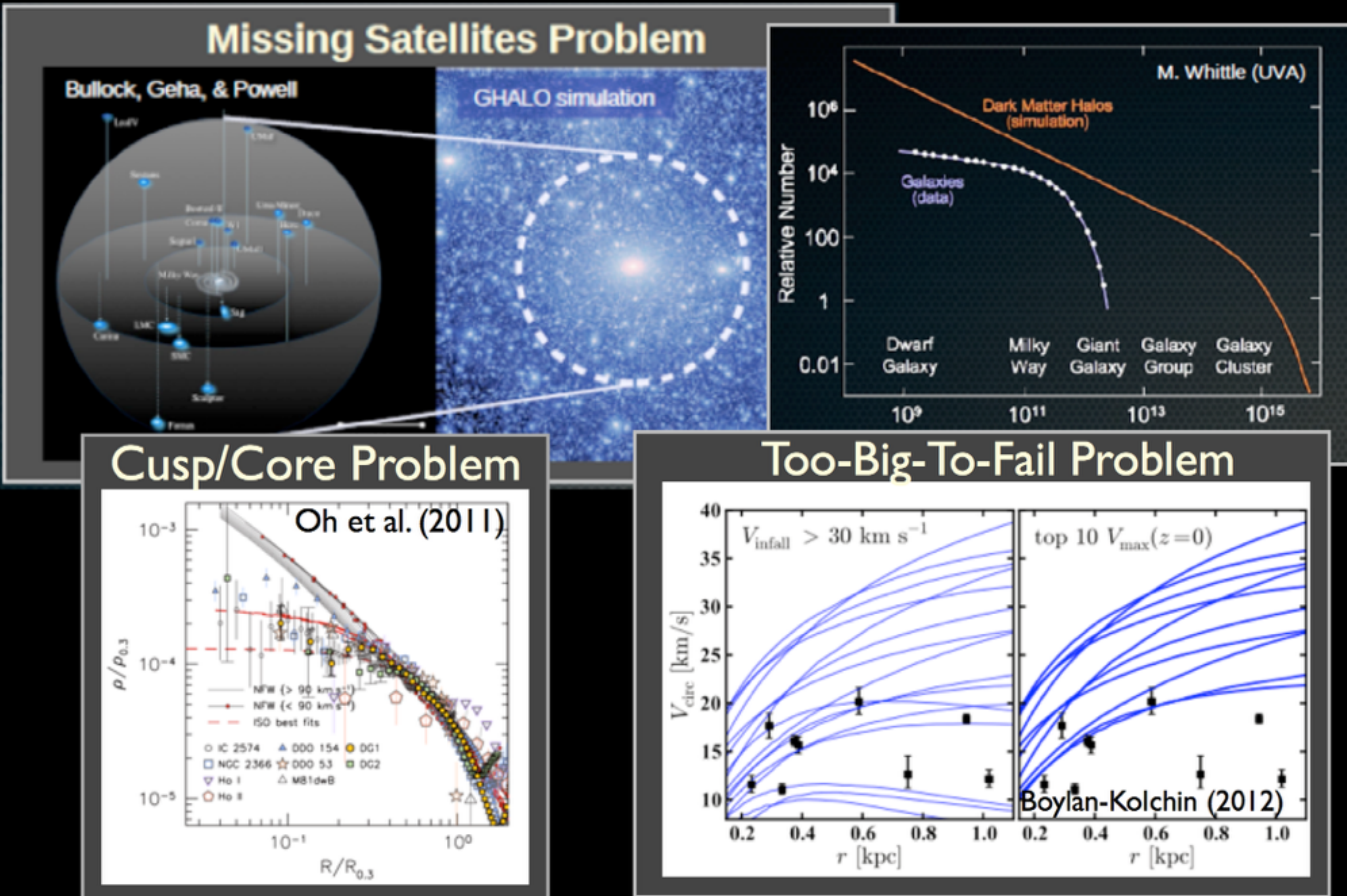
Draco

What's so Wrong with Dwarf Galaxies Anyway?

Credit: Madau

ABUNDANCE VS. STRUCTURAL MISMATCH

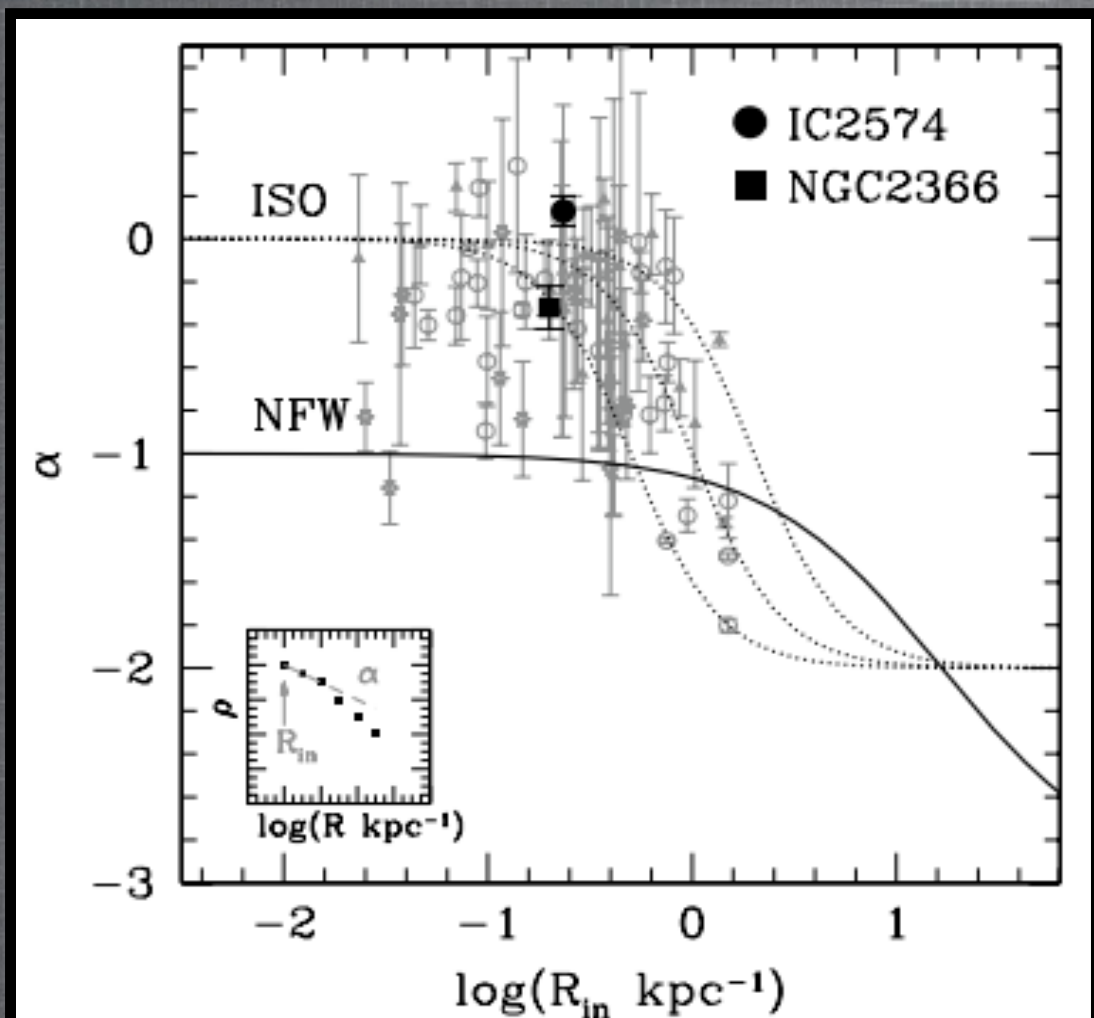
Credit: Madau

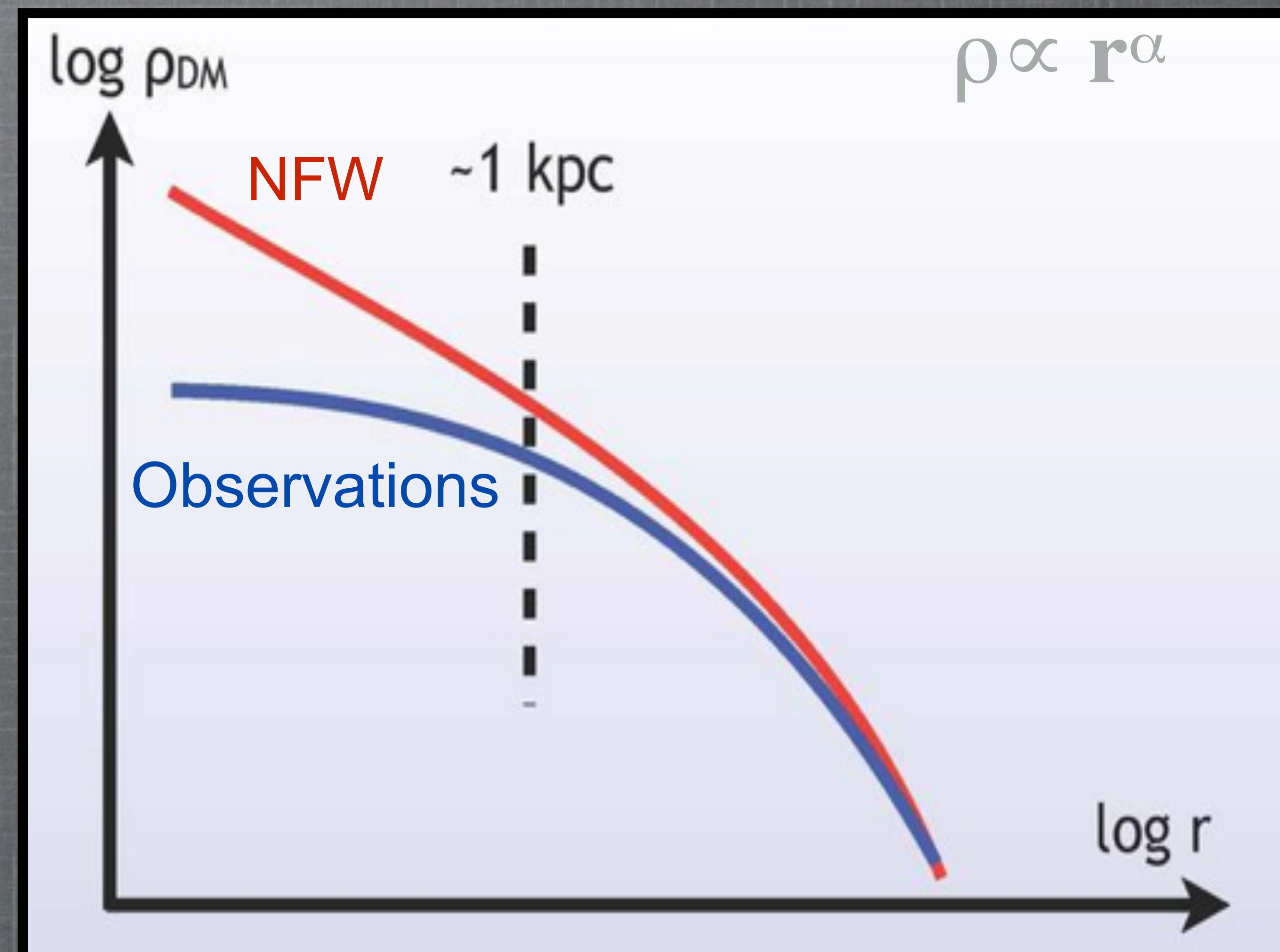


Many problems, and one possible solution:

Baryons

The Core/Cusp Problem





Also: Dekel & Silk (1986), Navarro et al. (1996), Read & Gilmore (2005), Mashchenko et al. (2008), Teyssier et al. (2013)… +

LETTERS

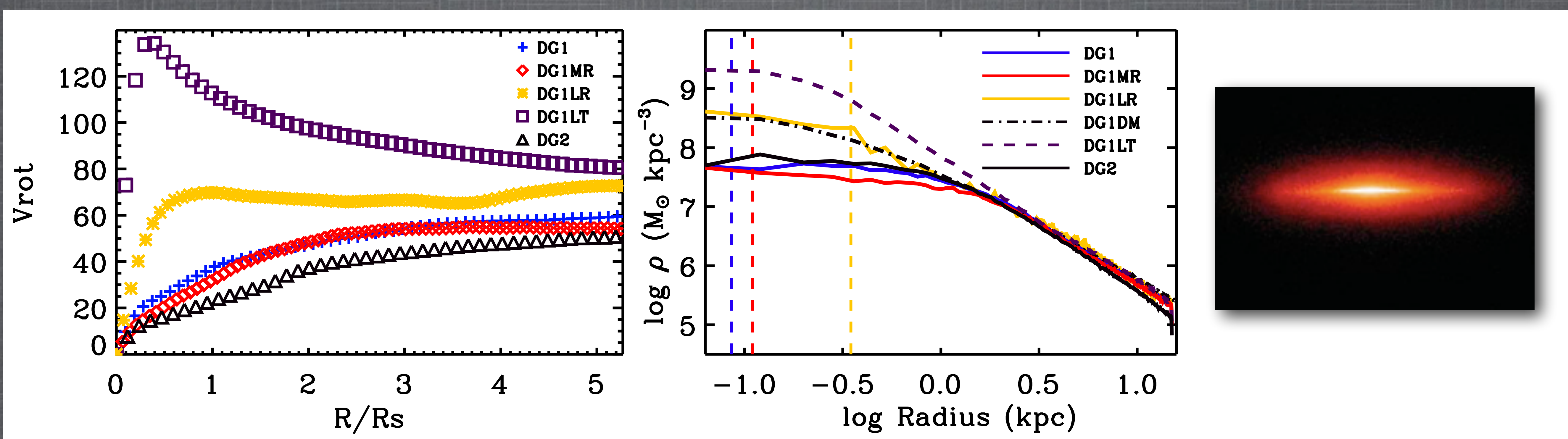
Bulgeless dwarf galaxies and dark matter cores from supernova-driven outflows

F. Governato[1], C. Brook[2], L. Mayer[3], A. Brooks[4], G. Rhee[5], J. Wadsley[6], P. Jonsson[7], B. Willman[9], G. Stinson[6], T. Quinn[1] & P. Madau[8]

For almost two decades the properties of 'dwarf' galaxies have challenged the cold dark matter (CDM) model of galaxy formation[1]. Most observed dwarf galaxies consist of a rotating stellar disk[2] embedded in a massive dark-matter halo with a near-constant-density core[3]. Models based on the dominance of CDM, however, invariably form galaxies with dense spheroidal stellar

resulting feedback have been applied to the formation of high-redshift protogalaxies, leading to significant baryon loss and less concentrated systems[8,20]. Similarly, dynamical arguments[21,22] suggest that bulk gas motions (possibly supernova-induced) and orbital energy loss of gas clouds due to dynamical friction can transfer energy to the centre of the dark-matter component. Sudden gas removal through outflows

Governato et al. 2010



Gasoline: Star Formation Recipe

Galaxy	M_{vir}	V_{peak}	M_*	f_b	f_{cold}
Eris ($z = 0$)	7.9	238	3.9	0.121	0.12
Eris ($z = 1$)	5.4	237	2.9	0.126	0.40
ErisLT ($z = 1$)	5.5	308	3.4	0.158	0.18

The K-S relation of each particle:

$$\frac{d\rho_*}{dt} = \frac{\epsilon_{\rm SF}\rho_{\rm gas}}{t_{\rm dyn}} \propto \rho_{\rm gas}^{1.5} \quad \rho > \rho_{\rm thres}$$

In reality, stars form in cold high-density H_2 clouds that sit at the peaks of the HI distribution.

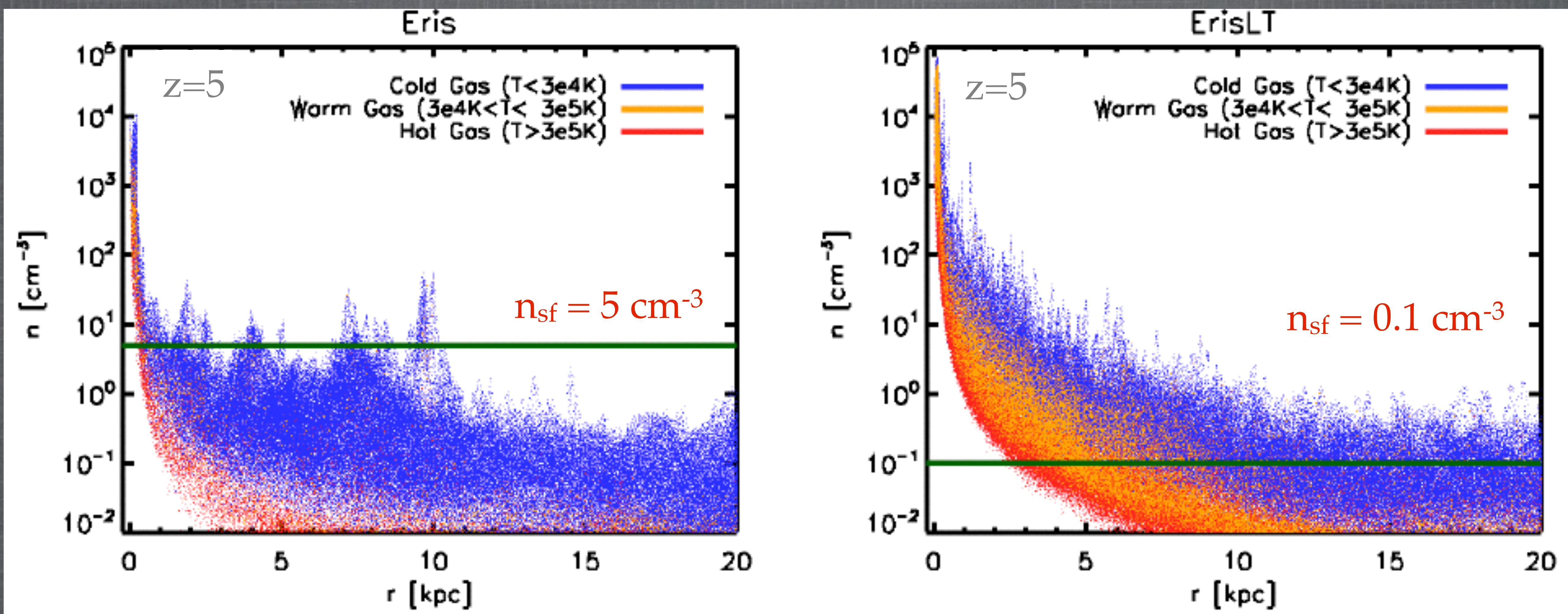
SN feedback (blast-wave):

$$E_{\rm SN} = \epsilon_{SN} \times 10^{51}\,{\rm erg\,s^{-1}}$$
$$\tau_{\rm off} \sim 0.5\ \epsilon_{\rm SN}^{0.31}\ {\rm Myr}$$

$$\frac{\rm N_{new*}}{\rm m_{gas}} \propto \sqrt{n_{\rm SF}}$$

$$\Sigma_{\rm SFR} \propto \Sigma_{\rm H2}^{1.0\pm0.2}$$

Bigiel et al. 2008



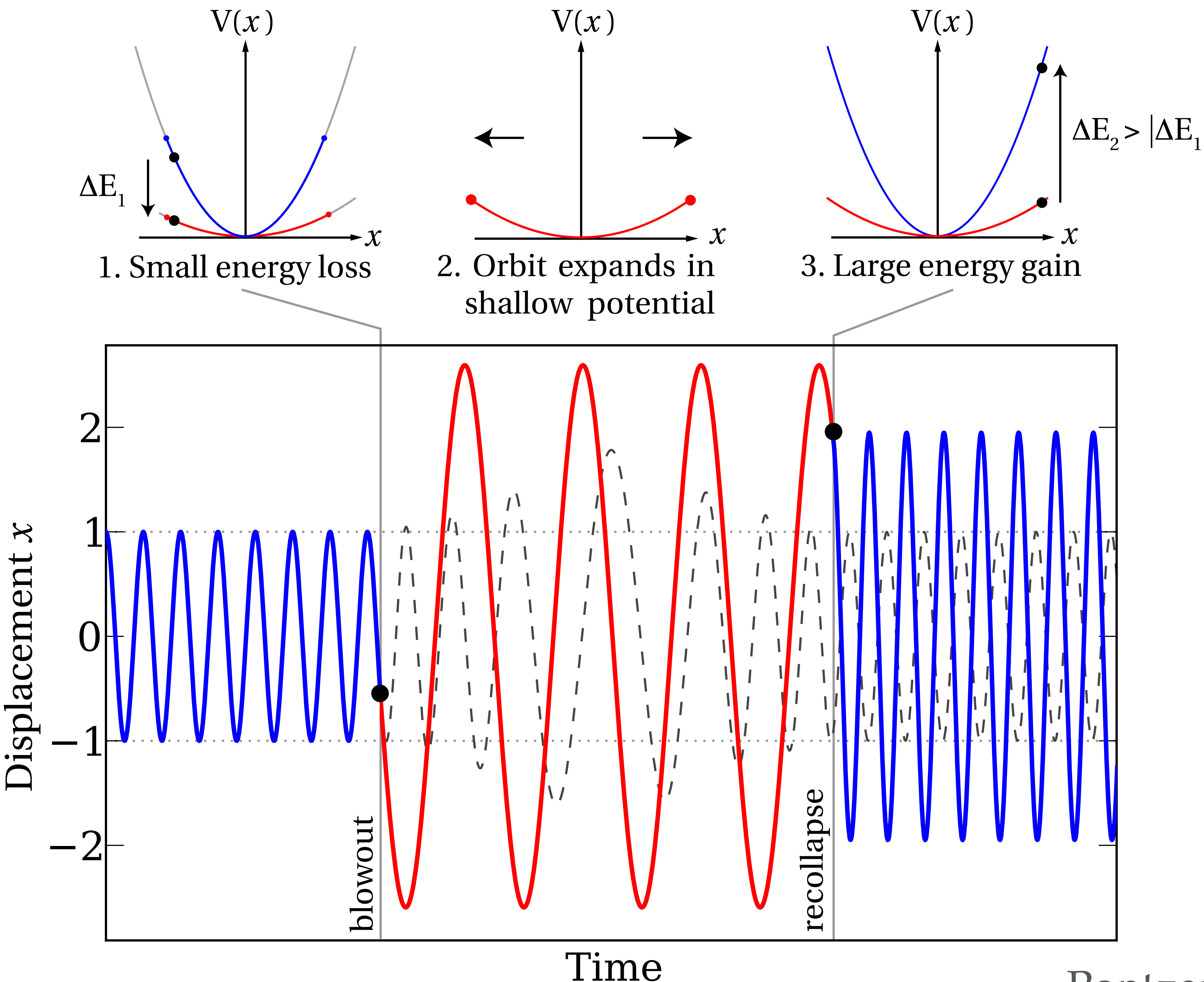
THE FORMATION OF A BULGELESS GALAXY WITH A SHALLOW DARK MATTER CORE

Fabio Governato (University of Washington)
Chris Brook (University of Central Lancashire)
Lucio Mayer (ETH and University of Zurich)
and the N-Body Shop

KEY: Blue: gas density map. The brighter regions represent gas that is actively forming stars. The clock shows the time from the Big Bang. The frame is 50,000 light years across.

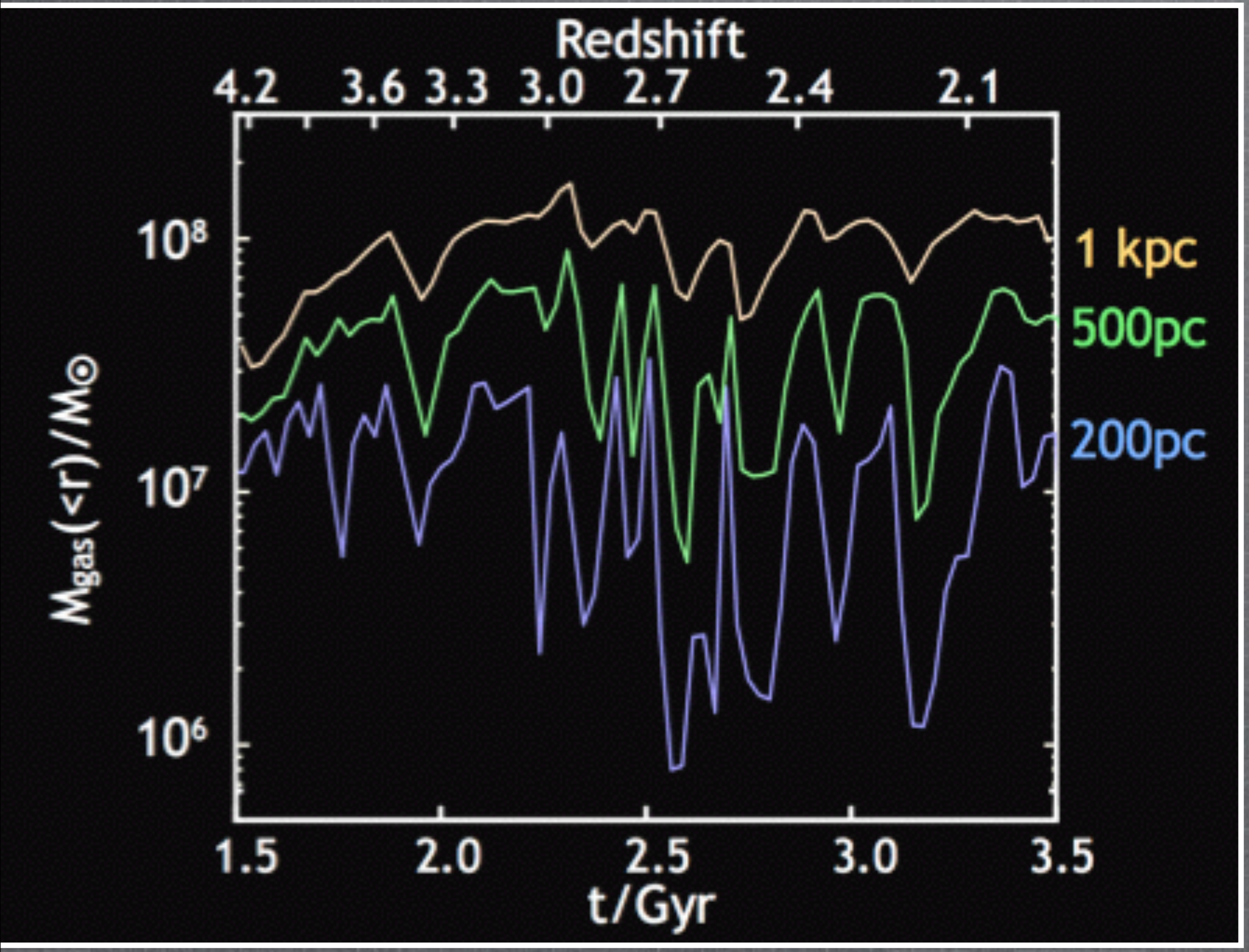
Simulations were run on Columbia (NASA Advanced Supercomputing Center) and at ARSC

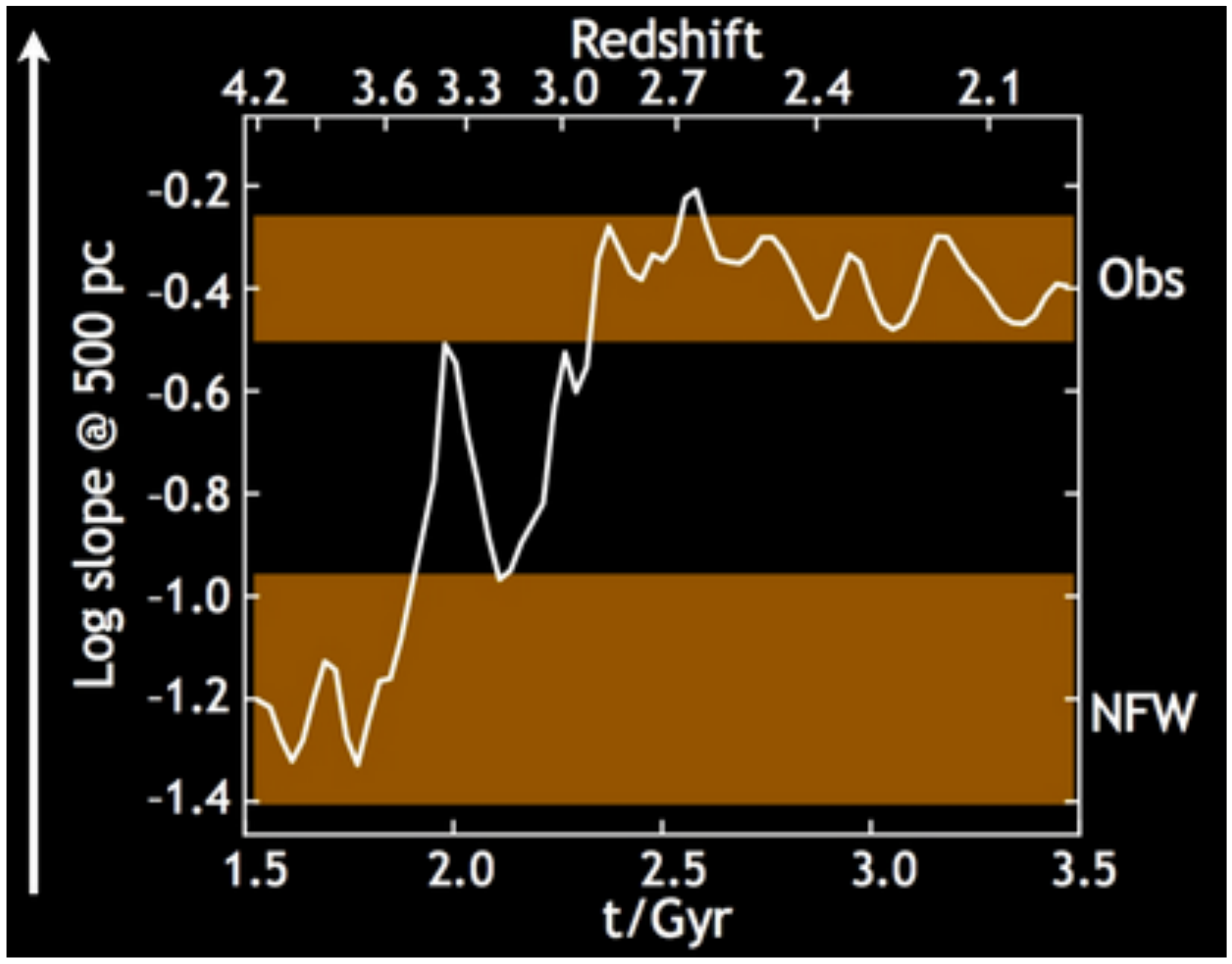
Solving the Core/Cusp Problem



Pontzen et al. 2012

Solving the Core/Cusp Problem





Change in central gas mass

Change in DM density

Pontzen & Governato (2012)

A Group of Seven Dwarfs

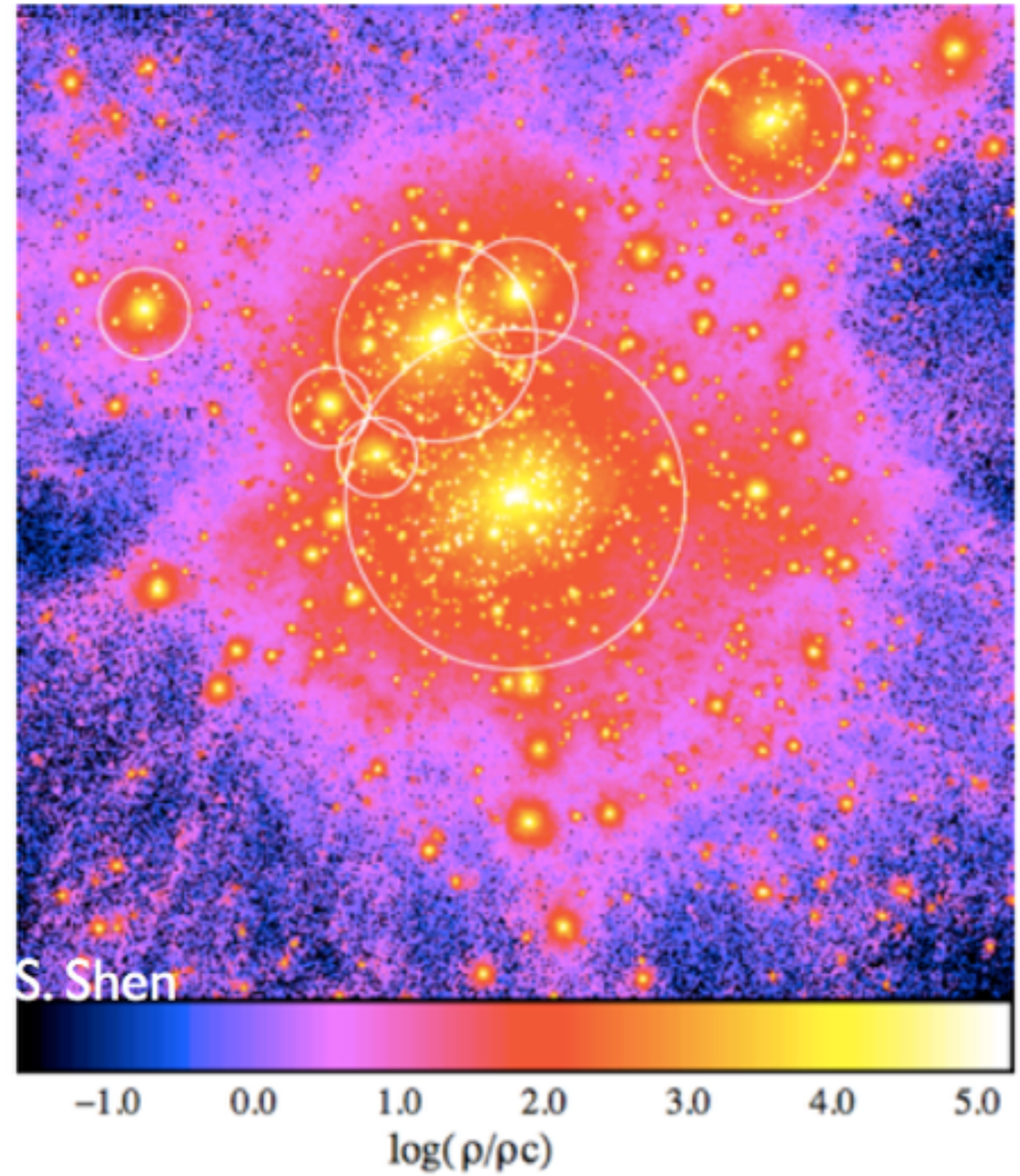
- LCDM cosmological SPH simulation run to *z=0* with GASOLINE
- mass resolution $m_{\rm DM} = 1.6 \times 10^4\,{\rm M}_\odot$ $m_* = 1000\,{\rm M}_\odot$

- softening=85 (p)pc
- metal-dependent gas cooling
- UVB heating & photoionization
- high SF gas density threshold of 100 cm^{-3} ⇨ SF is clustered

$$d\rho_*/dt = 0.1\rho_{\rm gas}/t_{\rm dyn}$$

- SN feedback: blastwave scheme where heated gas has its cooling shut off ⇨ <u>galactic ouflows</u>

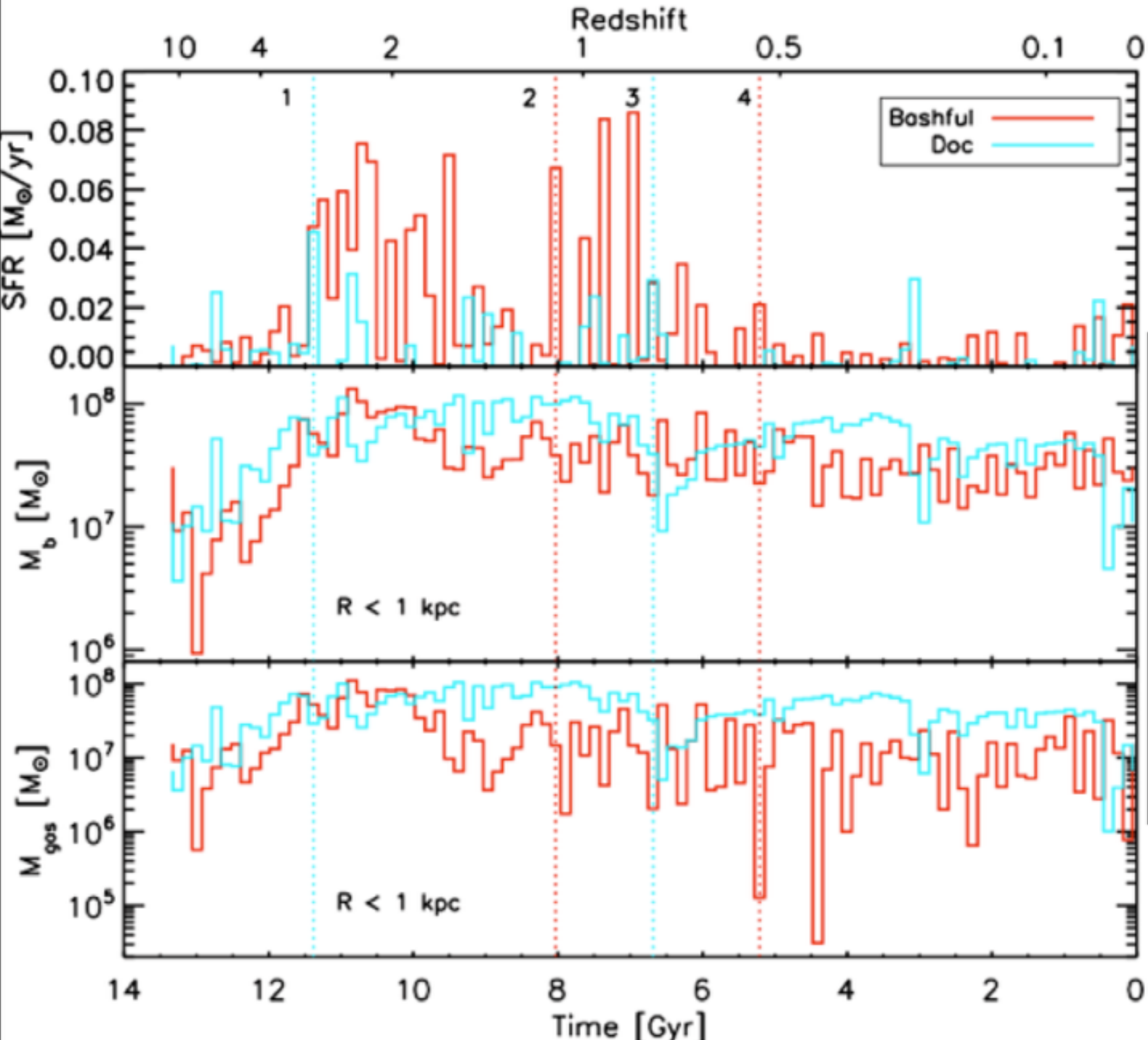
cf. explicit wind particles/mass+metal loading/ 2-phase subgrid ISM/AGN feedback/hydro decoupling (e.g. Vogelsberger et al. 2013)



$t_{\rm blast} = 10^{6.85}\ E_{51}^{0.32}\ n^{-0.16} P_{04}^{-0.2}$ yr
$R_{\rm blast} = 10^{1.74}\ E_{51}^{0.32}\ n^{0.34} P_{04}^{-0.7}$ pc
($t_{\rm cool} \sim T^{1/2}$ above 1 keV)

Credit: Madau

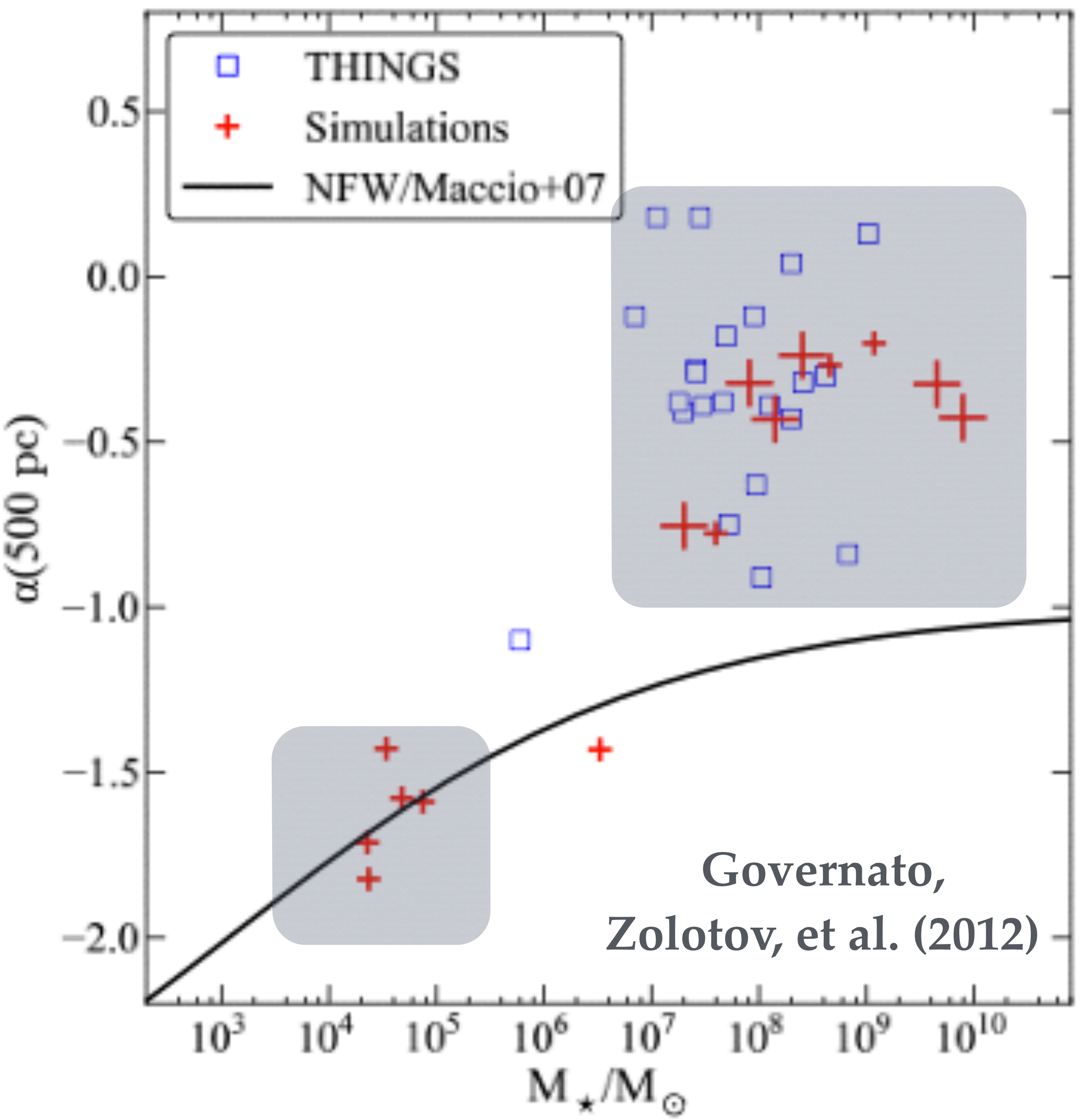
BURSTY STAR FORMATION HISTORIES



The bursty star formation histories of Bashful and Doc (Δt=130 Myr.) Bottom and middle panels: fluctuating gas and baryonic (gas+stars) central (within 1 kpc) masses of the two simulated DGs.

Credit: Madau

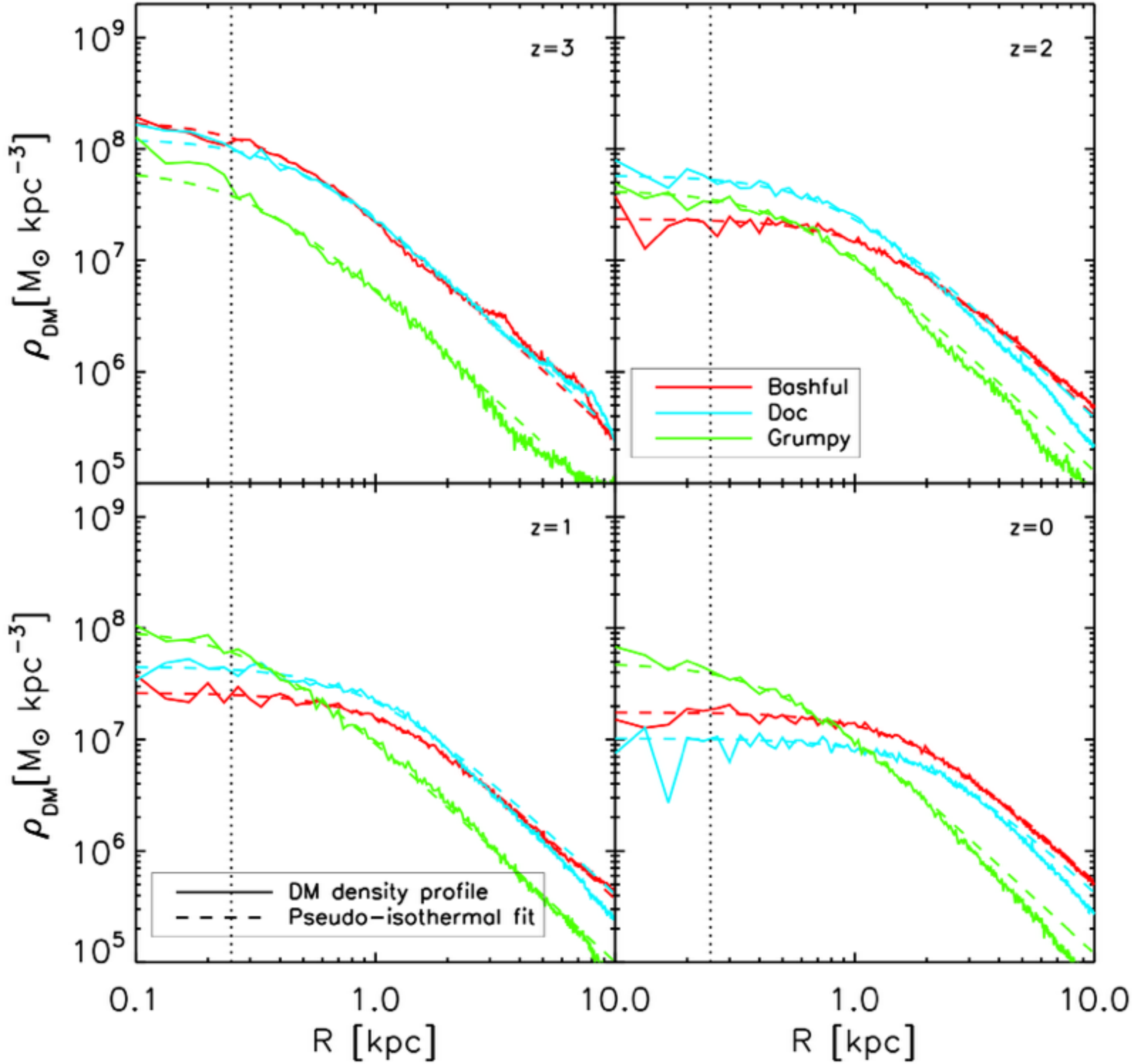
CORE FORMATION IS STELLAR MASS DEPENDENT



CORED

The slope of the dark matter density profile α vs stellar mass measured at 500 pc and *z=0* for the 4 luminous DGs. The small crosses represent observational data points from the THINGS survey.

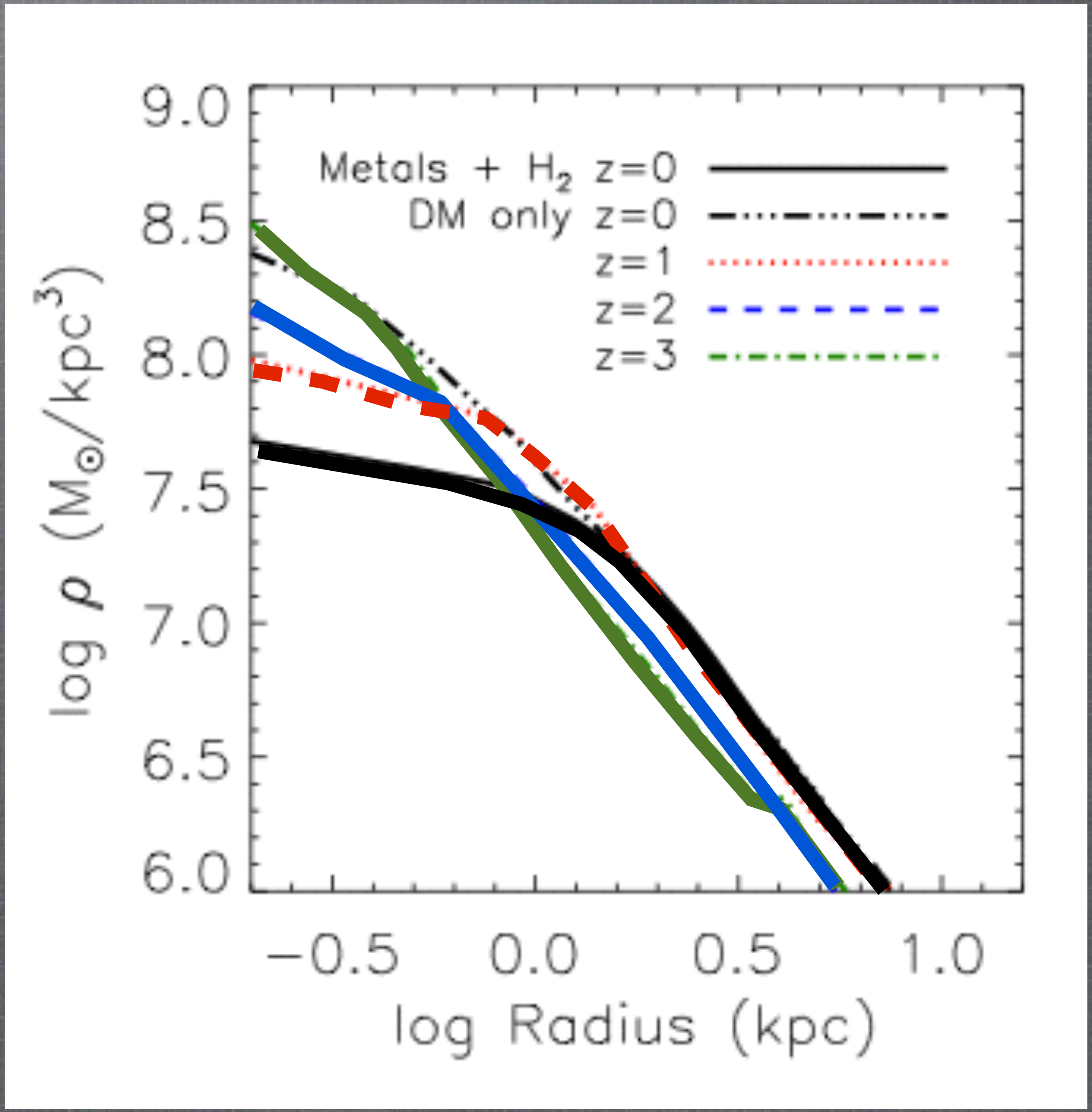
Credit: Madau



z=3
z=2
z=1
z=0
Bashful
Doc
Grumpy
DM density profile
Pseudo-isothermal fit
$\rho_{DM}[M_\odot\ kpc^{-3}]$
R [kpc]
0.1
1.0
10.0
10^5
10^6
10^7
10^8
10^9

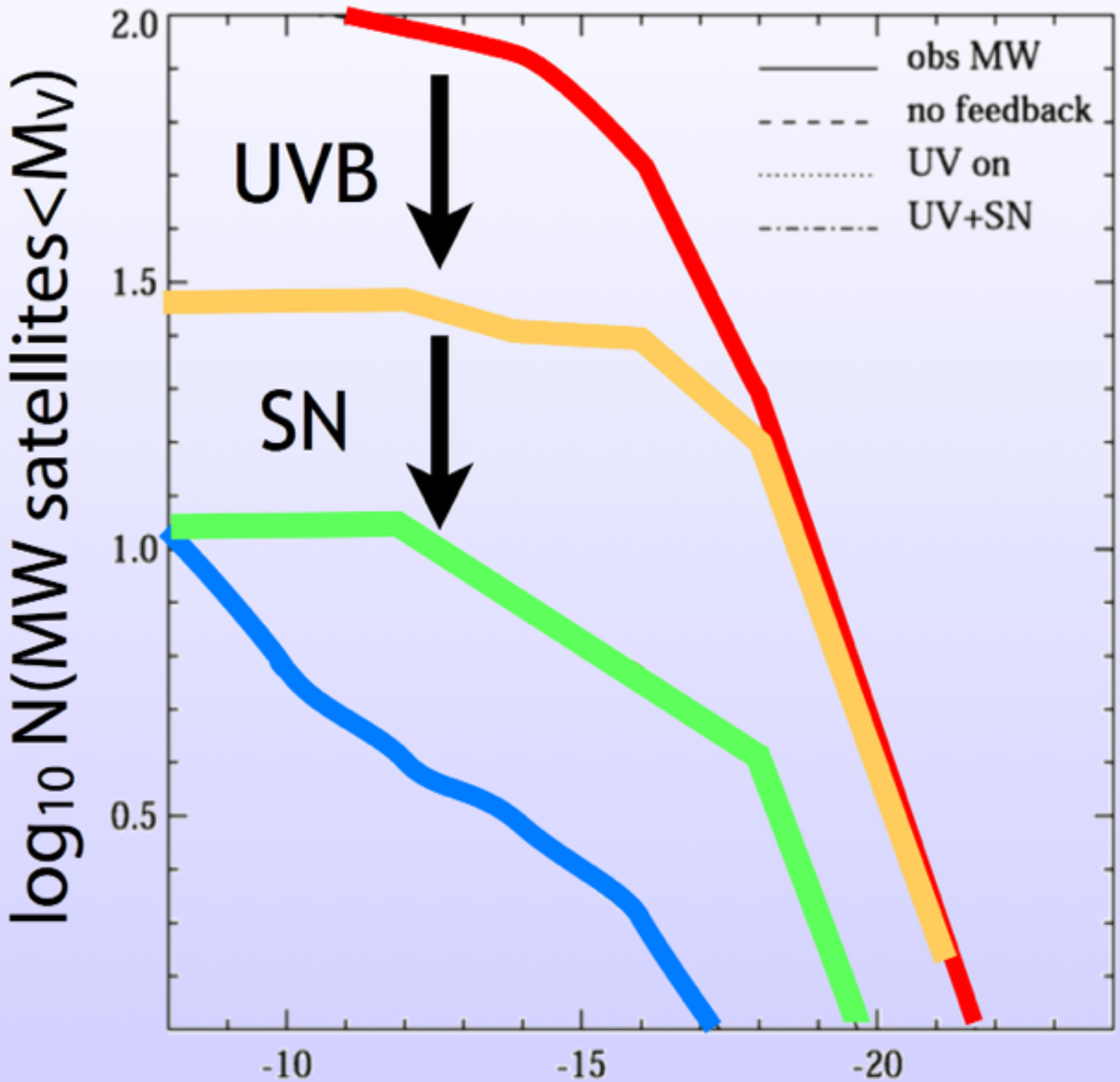
Solving the Core/Cusp Problem

⇛Repeated bursts of star formation gradually flatten the central DM profile



Governato, Zolotov, et al. (2012)

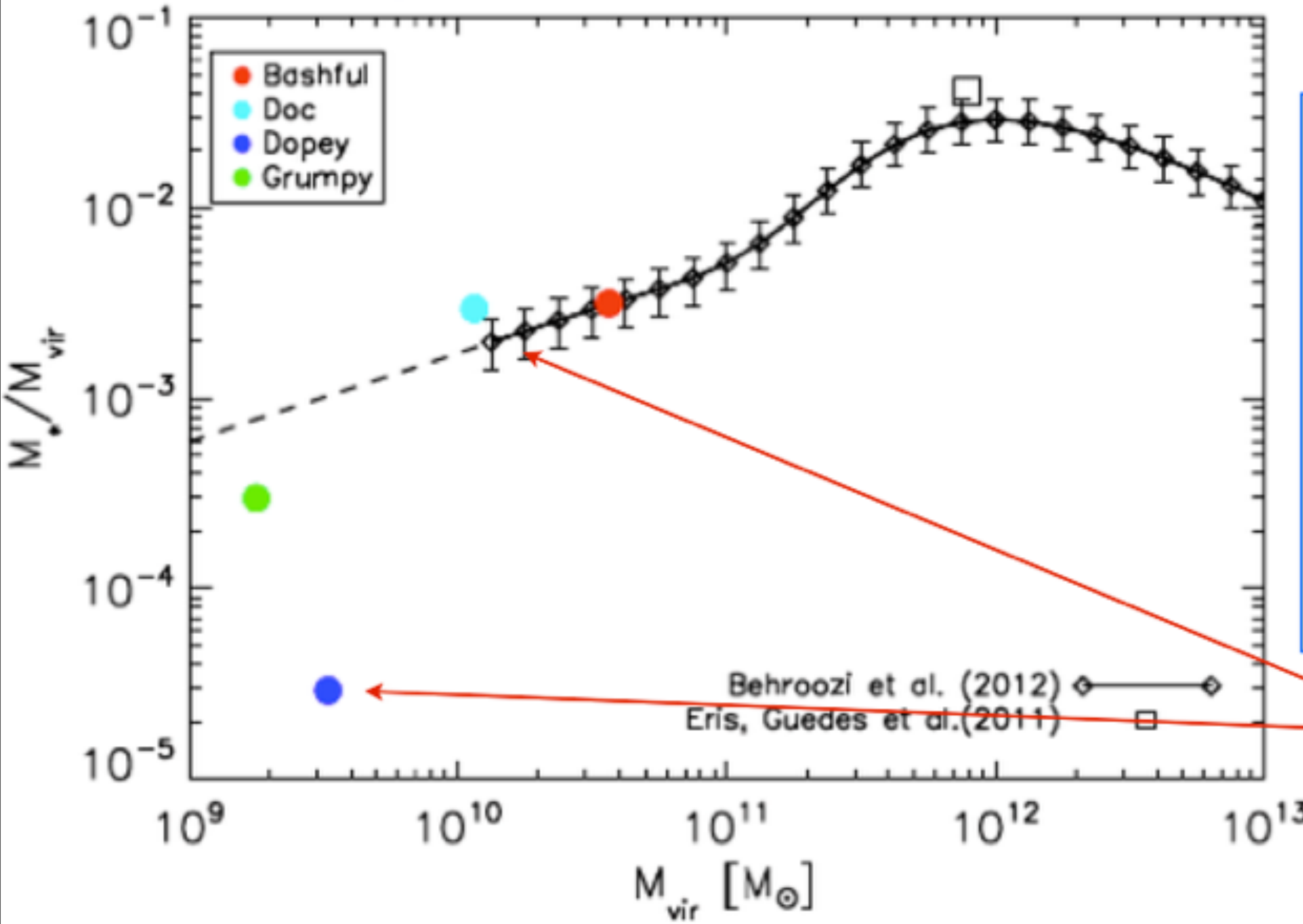
Satellite Luminosity Function



Governato+ 07

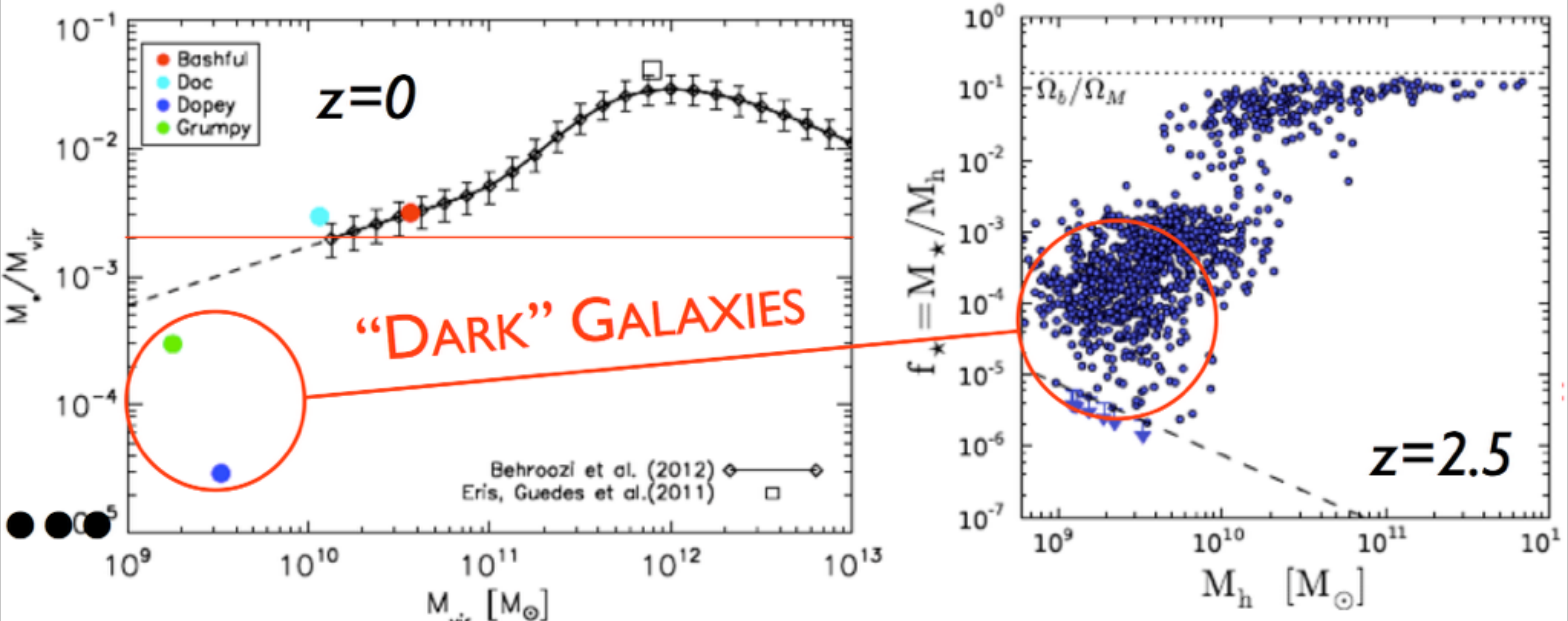
Name	$M_{\rm vir}$ $[\mathrm{M}_\odot]$	$R_{\rm vir}$ [kpc]	$V_{\rm max}$ $[\mathrm{km\,s^{-1}}]$	M_* $[\mathrm{M}_\odot]$	$M_{\rm gas}$ $[\mathrm{M}_\odot]$	$M_{\rm HI}$ $[\mathrm{M}_\odot]$	M_V
Bashful	3.59×10^{10}	85.23	50.7	1.15×10^{8}		2.34×10^{7}	-15.5
Doc	1.16×10^{10}	50.52	38.2	3.40×10^{7}		1.98×10^{7}	-14.0
Dopey	3.30×10^{9}	38.45	22.9	9.60×10^{4}		1.96×10^{6}	-8.61
Grumpy	1.78×10^{9}	29.36	22.2	5.30×10^{5}		5.40×10^{5}	-11.0
Happy	6.60×10^{8}	22.49	15.6	—		—	—
Sleepy	4.45×10^{8}	19.71	14.8	—		—	—
Sneezy	4.38×10^{8}	19.62	13.2	—		—	—

UVB



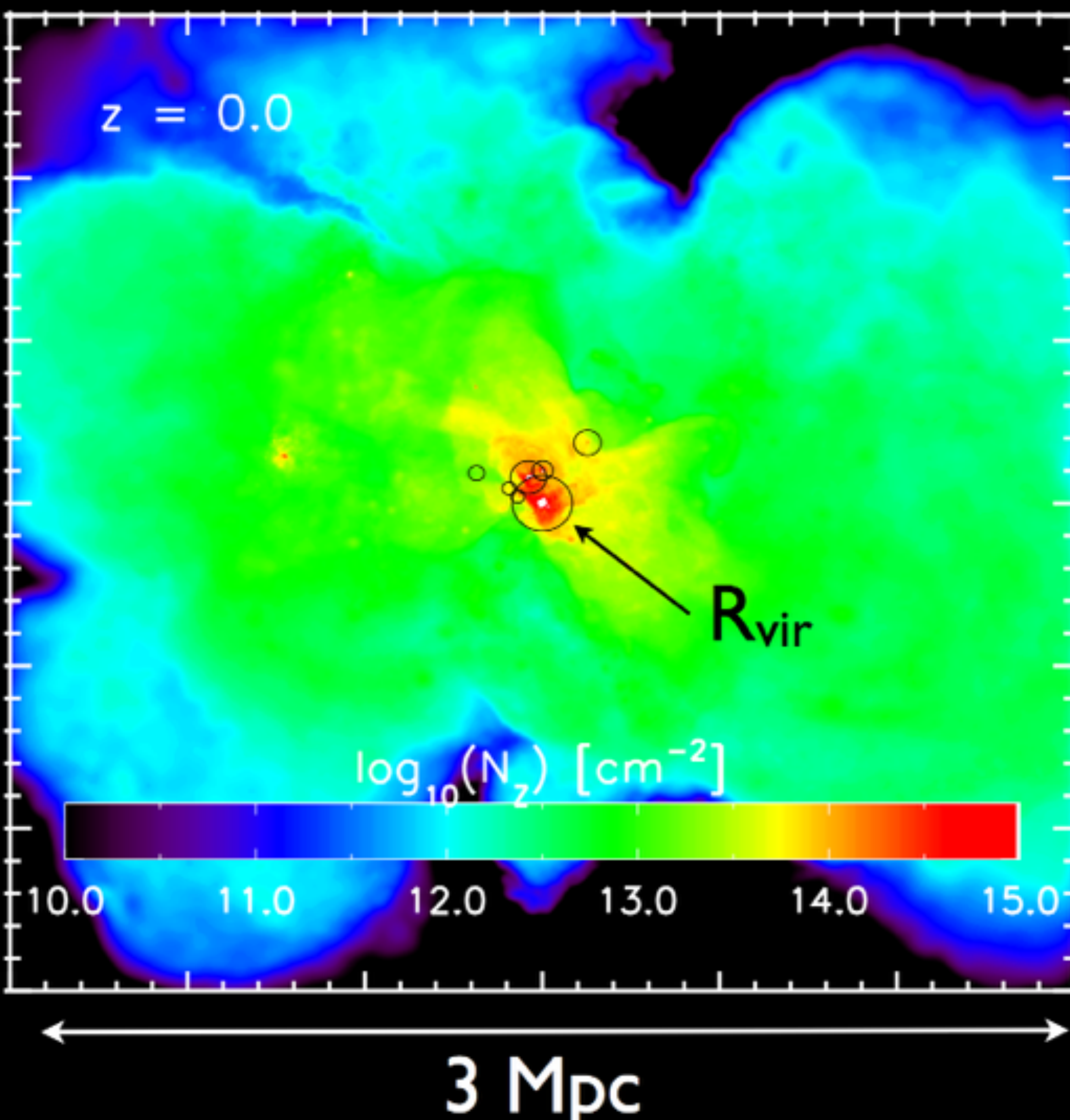
The stellar mass fraction of dwarf galaxies at *z=0*. Filled colored circles: the simulated Bashful, Doc, Dopey, and Grumpy dwarfs. Empty square: Eris. Solid line with error bars: the present-day stellar mass-halo mass relation of Behroozi et al. (2013) for a Kroupa IMF.

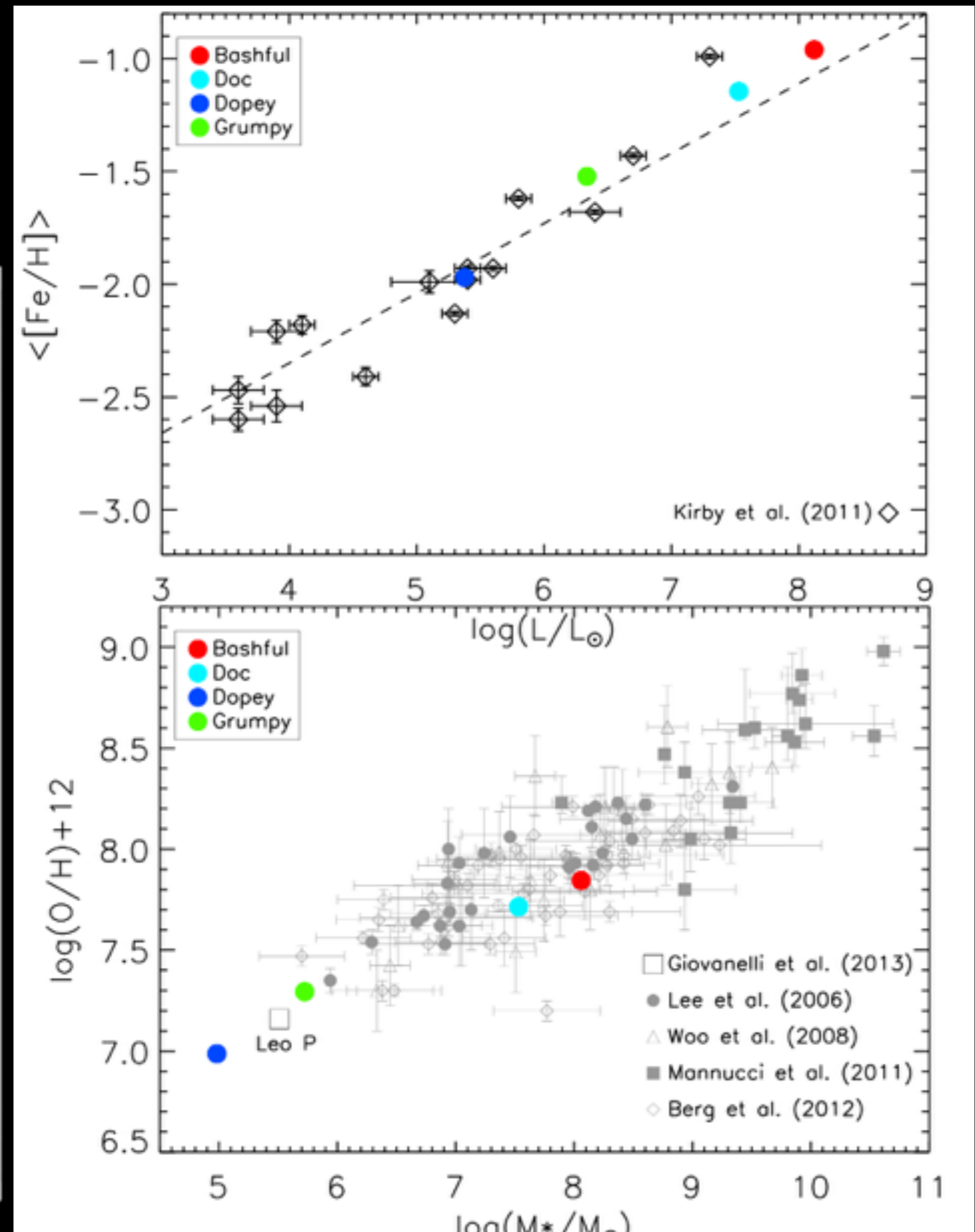
SF EFFICIENCIES STRONGLY MODULATED BY THE DEPTH OF THE POTENTIAL WELL!



z=0
Bashful
Doc
Dopey
Grumpy
Behroozi et al. (2012)
Eris, Guedes et al.(2011)
$M_\bullet/M_{vir}$
M_{vir} [$M_\odot$]
"DARK" GALAXIES
Ω_b/Ω_M
$f_\star = M_\star/M_h$
M_h [$M_\odot$]
z=2.5

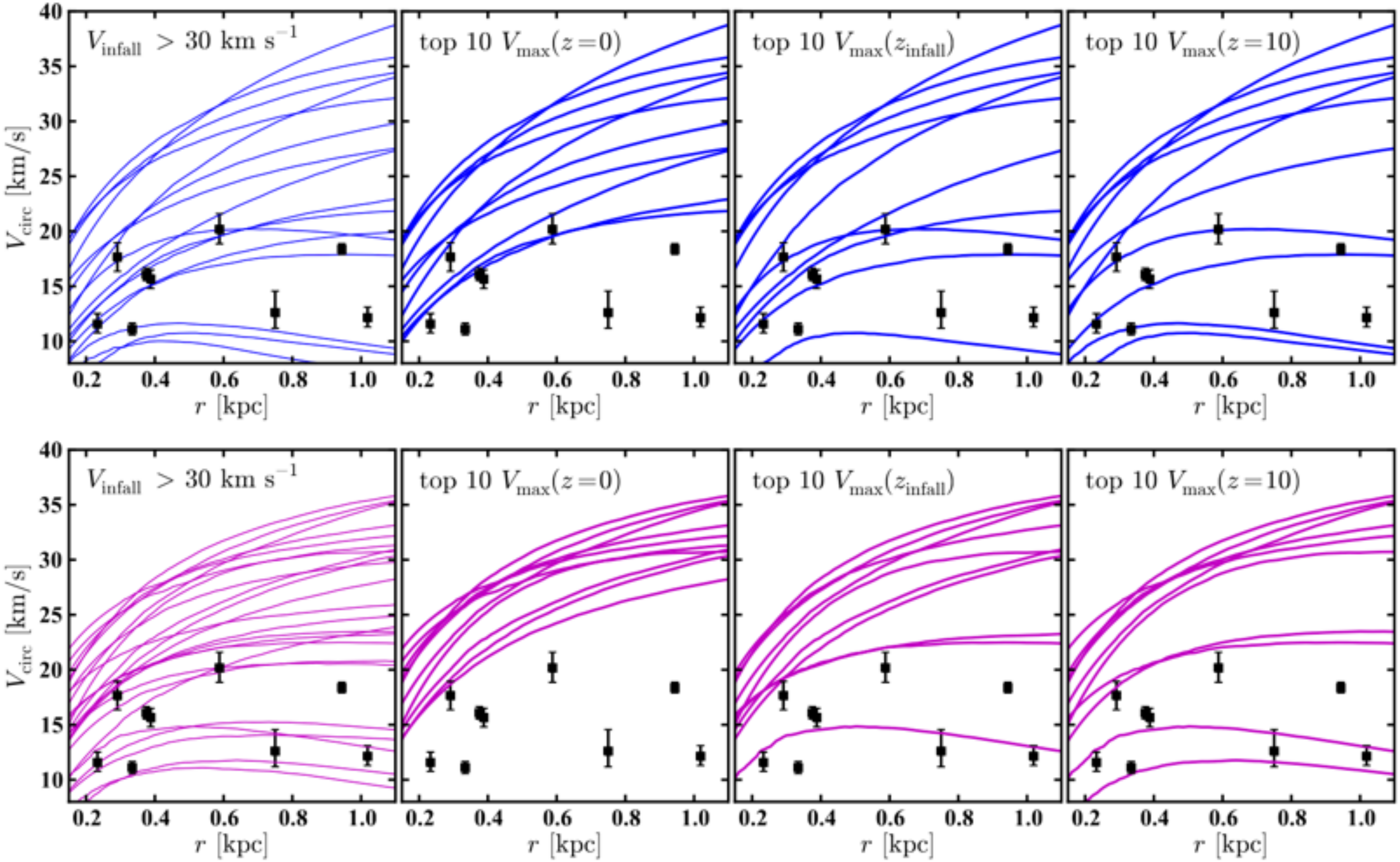
Metal Polluters, Metal Poor





Credit: Madau

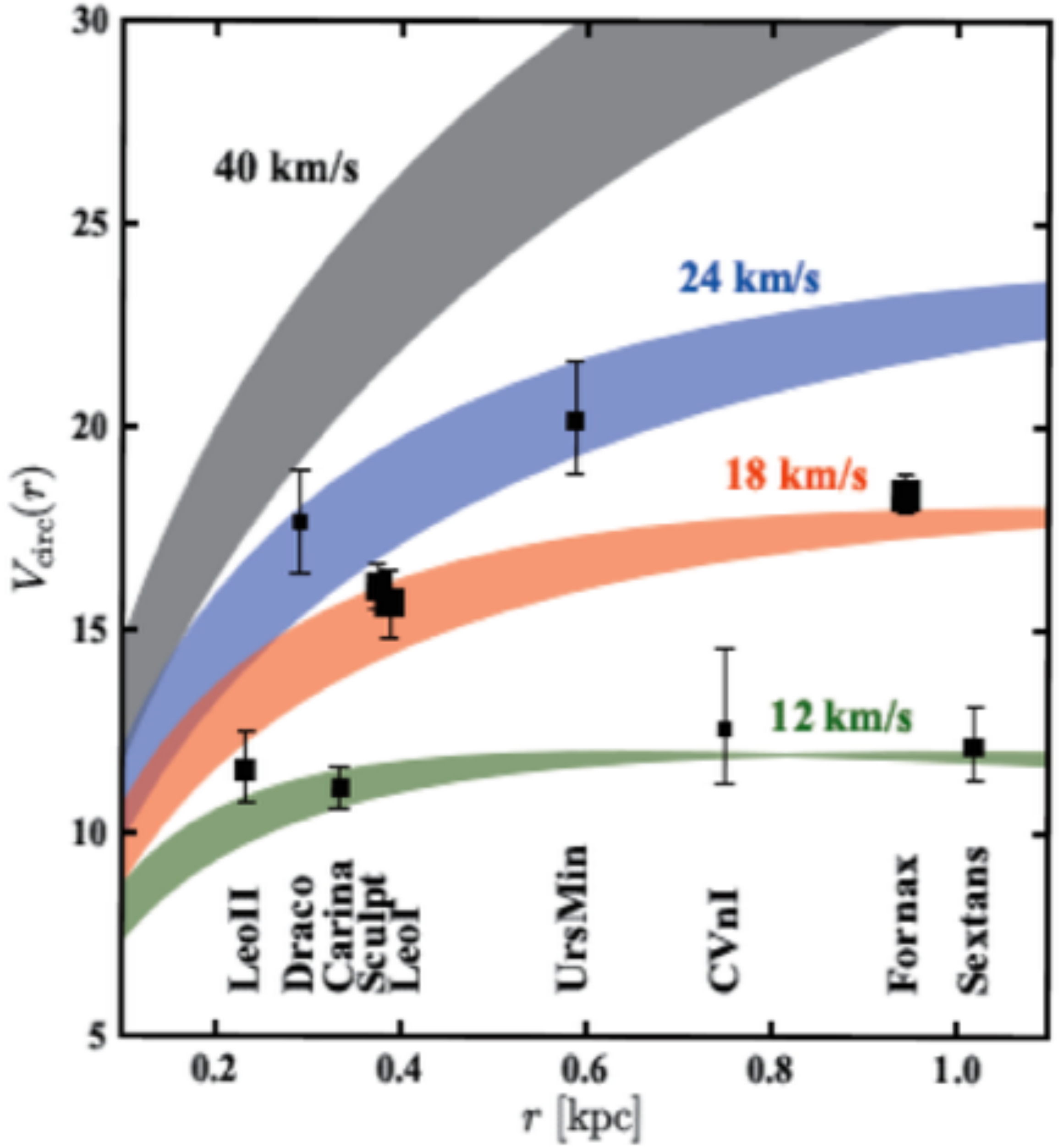
TOO BIG TO FAIL

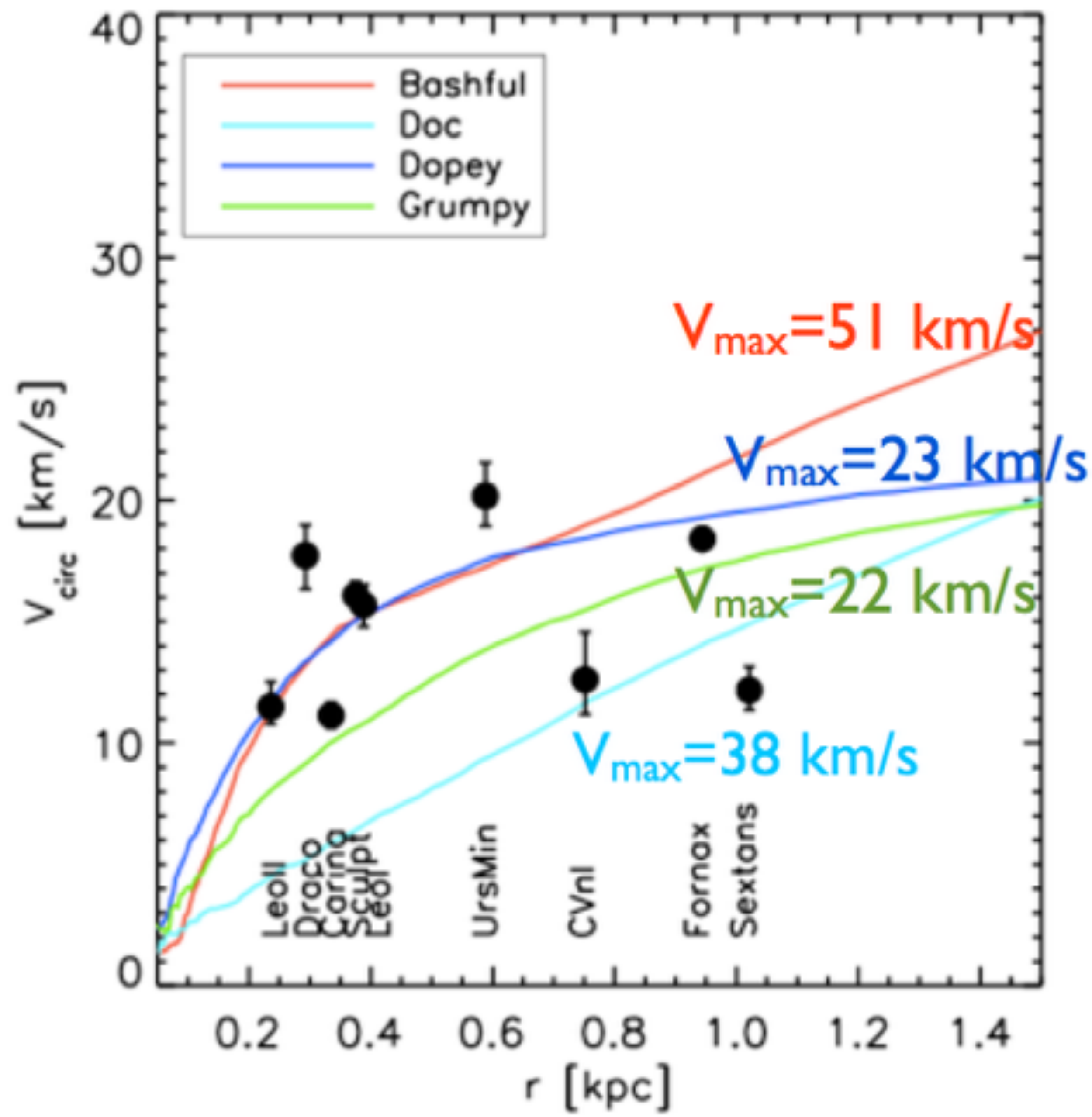


Boylan-Kolchin et al. 2012

Too Big To Fail

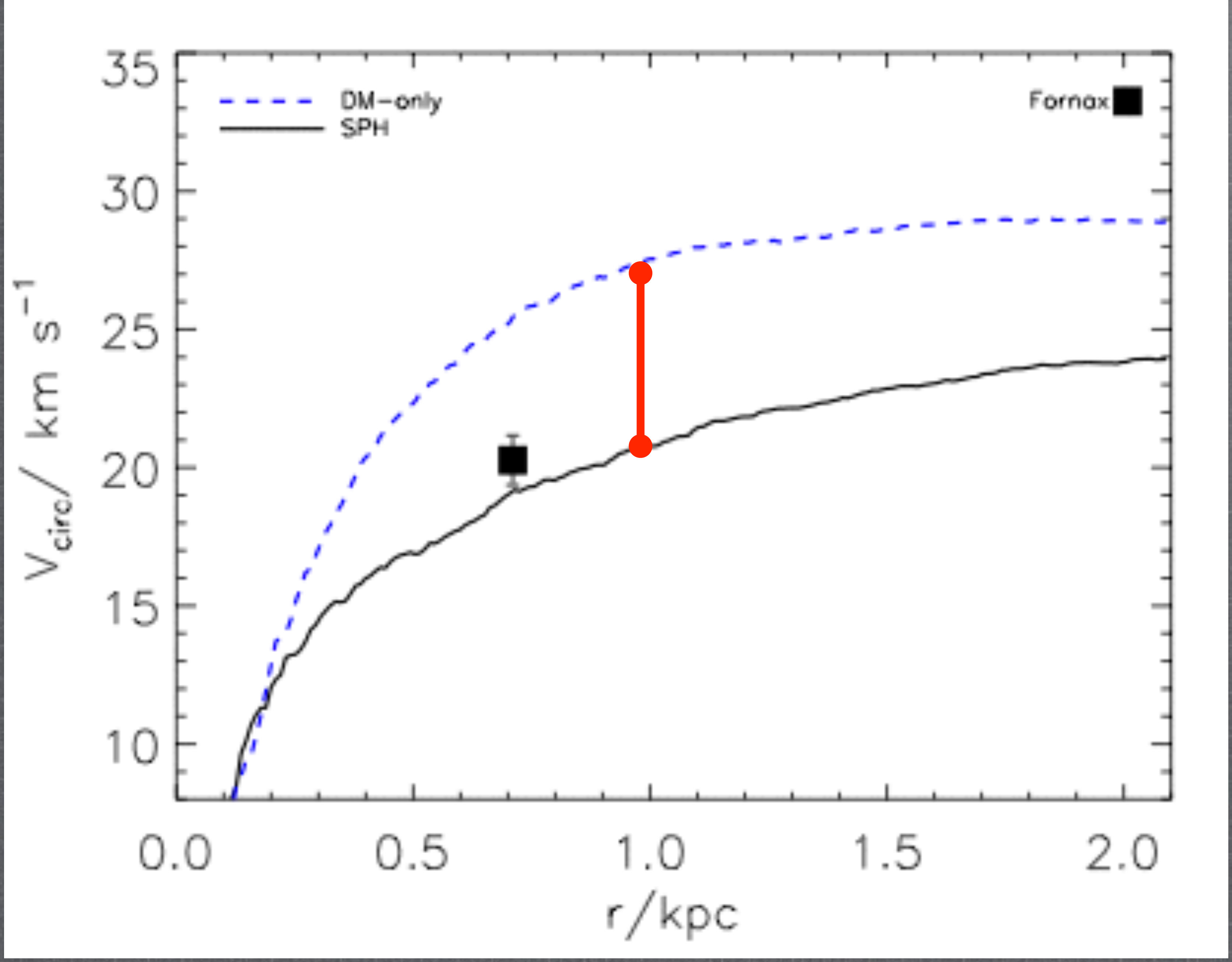
Simulated dwarfs with $22 < V_{max} < 51$ km/s all have $V_{circ} < 20$ km/s within 1 kpc!





Credit: Madau

TO BIG TO FAIL



Luminous satellites are 2 - 4 x less massive in central few kpc than DM-only satellites:

✓ Baryon loss

✓ Enhanced tidal stripping

✓ DM core-creation

$$\Delta(v_c, 1\,\mathrm{kpc}) = 0.2\, v_{\mathrm{max,DM-only}} - 0.26\ \mathrm{km\ s^{-1}}$$

Late-Type Galaxies


M61
Spiral galaxies are... complex

M61

Spiral galaxies are... complex

Observational Constraints:

B/D ratio, rotation curve, surface brightness breaks, Tully-Fischer relation, mass-metallicity relation, dispersion measure, K-S relation, metallicity gradients, metal pollution, the satellite properties, distribution, and number density, HI distribution

What can we learn?

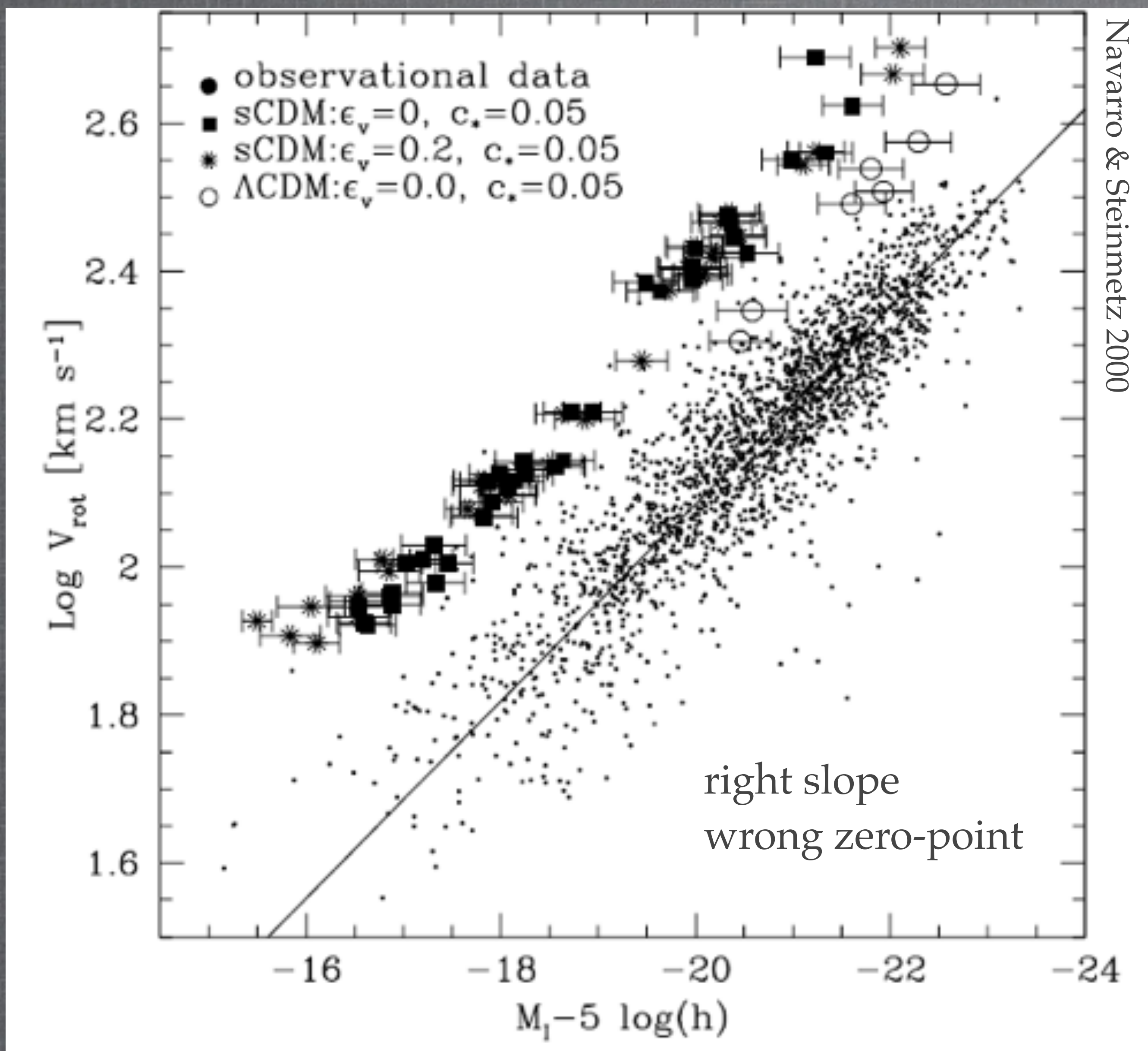
The formation mechanism of the main structures of the galaxy, the evolution of bars, bulges, and spiral arms, the behavior of the dark matter component, the origin of metals in the CGM, the cosmic evolution of the baryon fraction, the gas accretion history

What is the price?

High resolution simulations are computationally expensive, and produce large data volumes

THE ANGULAR MOMENTUM CATASTROPHE IN ΛCDM

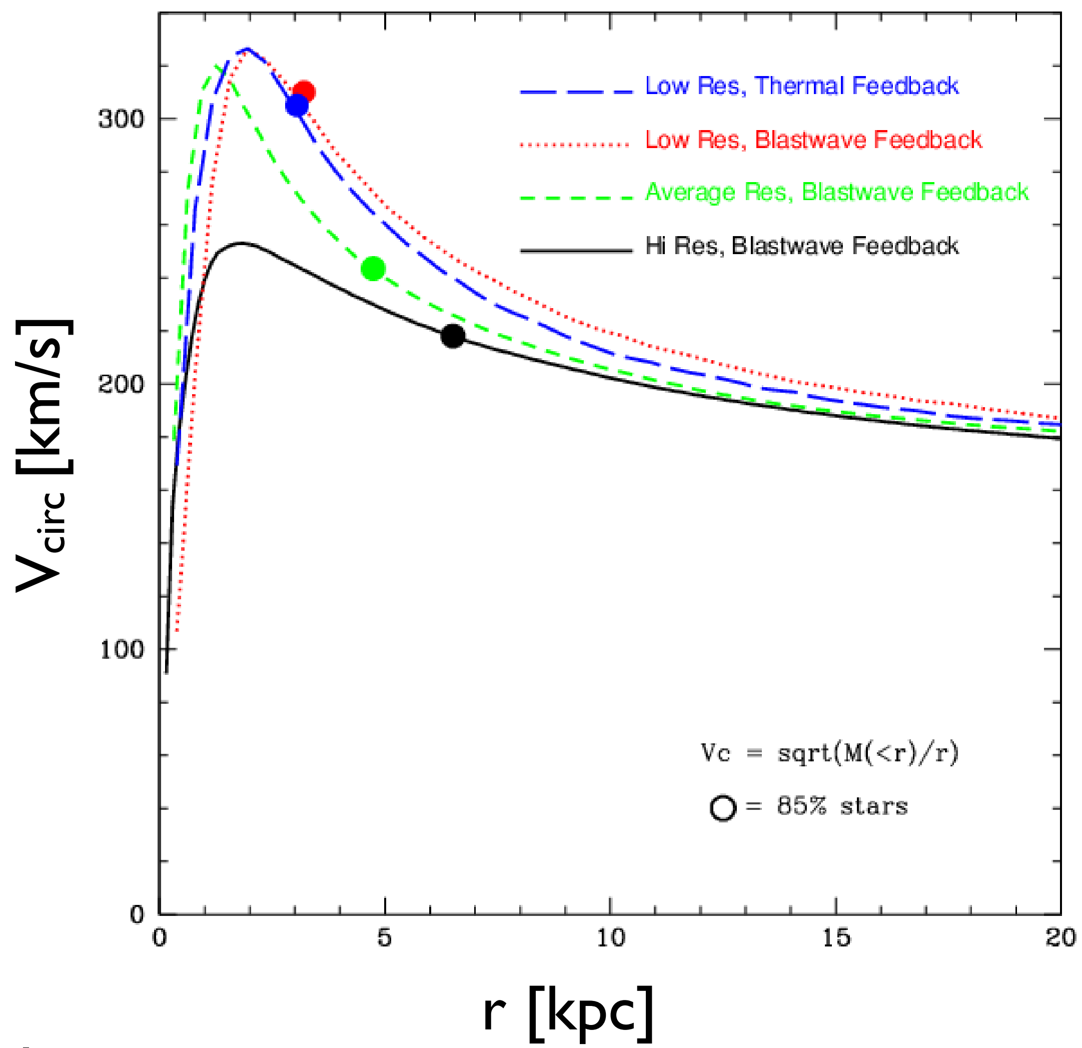
Low mass halos cooling too effectively at high z, sink, and loose their angular momentum. Disks formed in simulations too small.

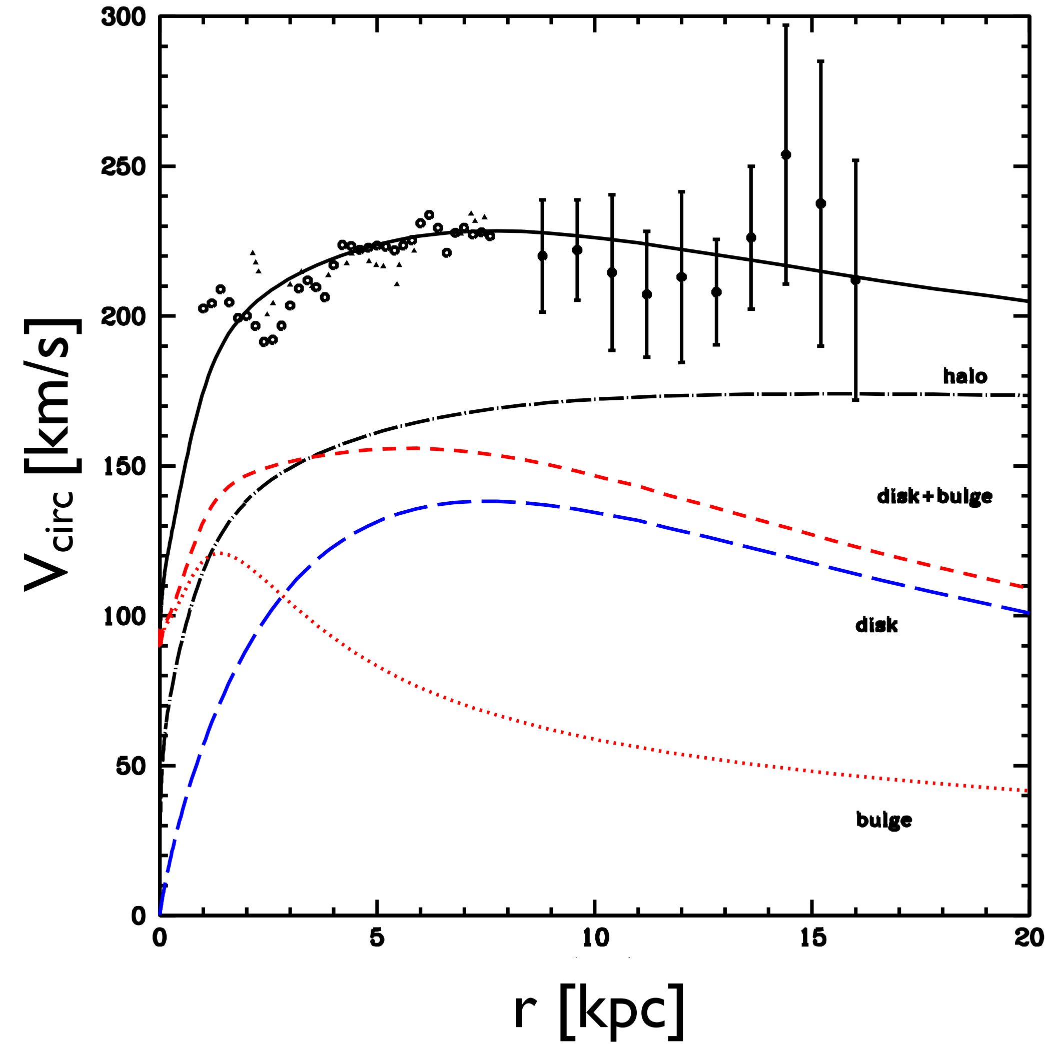


"Agreement between model and observations appears to demand substantial revision to the CDM scenario or to the manner in which baryons are thought to assemble and evolve into galaxies in hierarchical universes."

The Mass Concentration Issue

Simulations tend to produce too many stars at the center, which translates into steeply rising rotation curves.





Solution:

* Mimic star formation as occurs in real galaxies, i.e. localized, on high-density peaks only.
* Feedback from SN becomes more efficient in removing gas from high-density regions.

These outflows remove preferentially low angular momentum material, suppressing the formation of large bulges.

THE ANGULAR MOMENTUM CATASTROPHE IN ΛCDM

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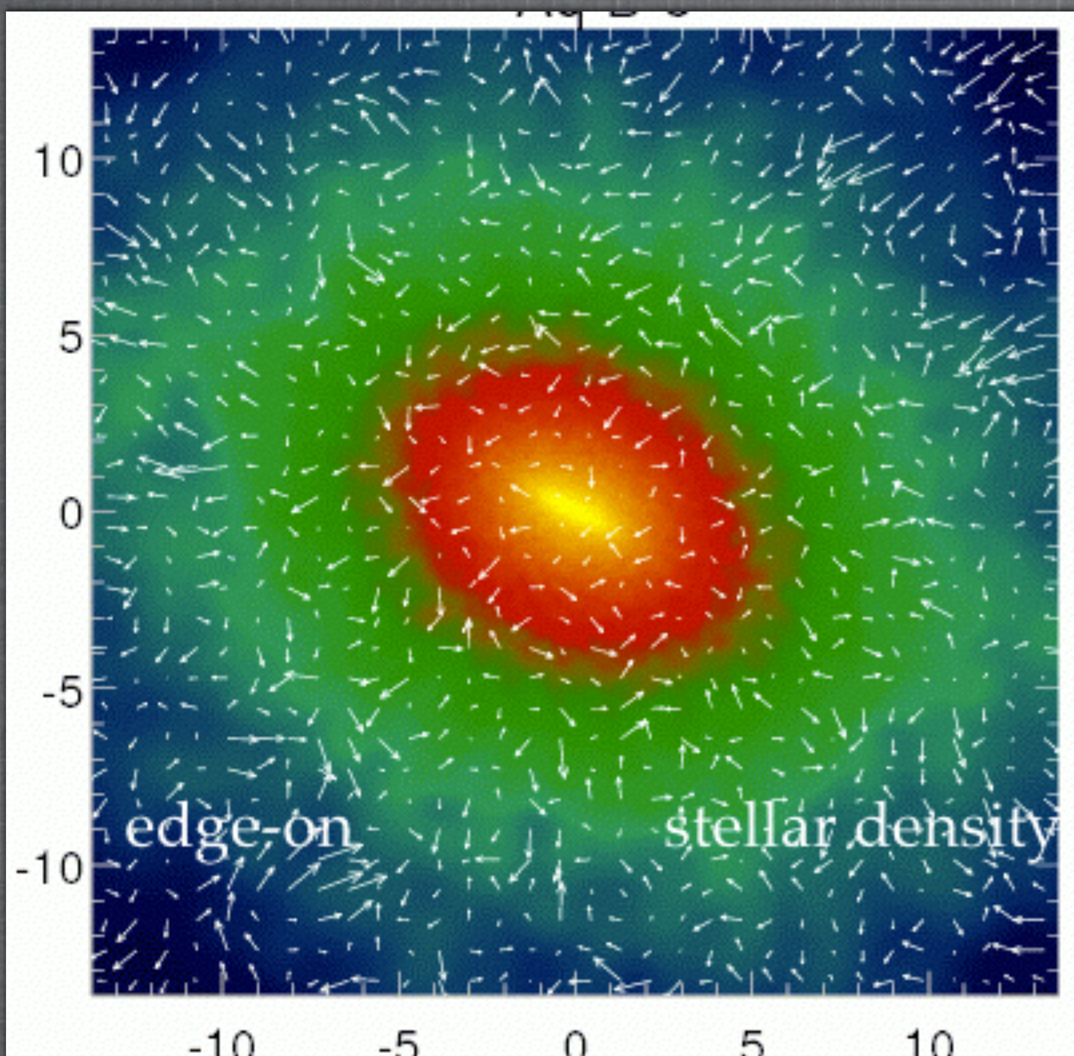
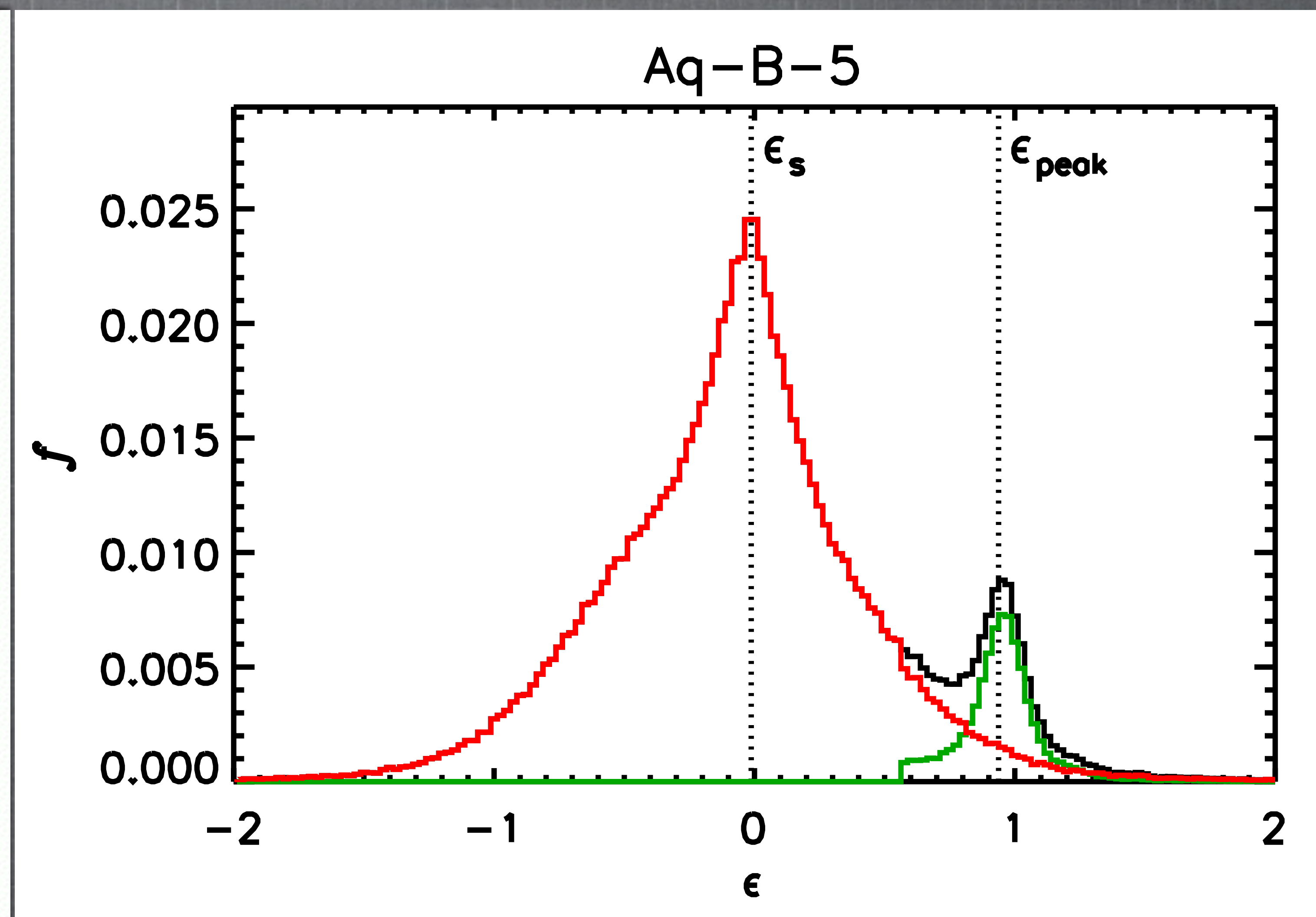




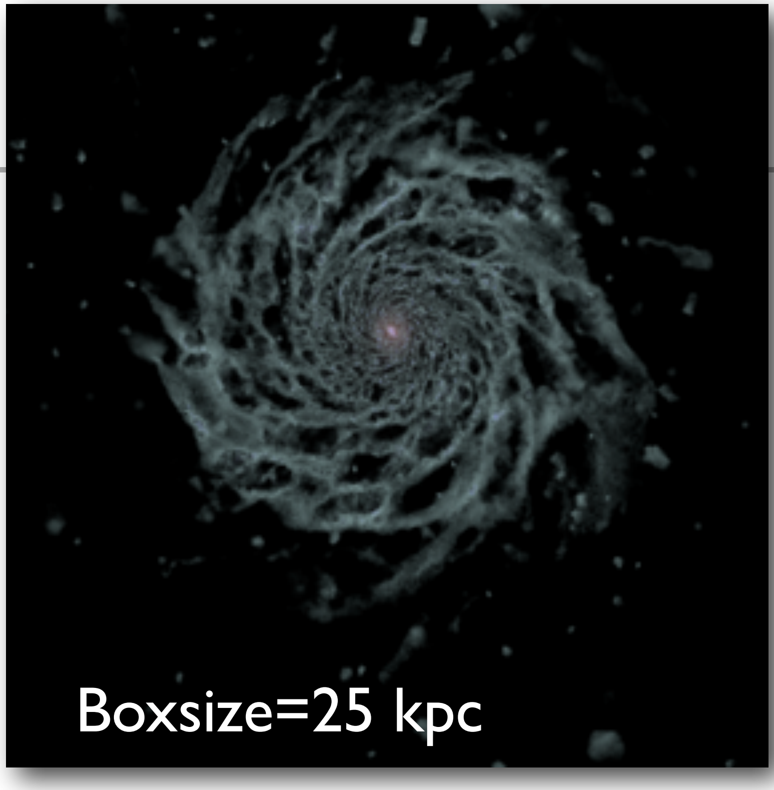
x [kpc]

Key:

Form the right amount of stars at the right places and at the right times.

This worked for the dwarf, but does it work for more massive galaxies like the Milky Way?

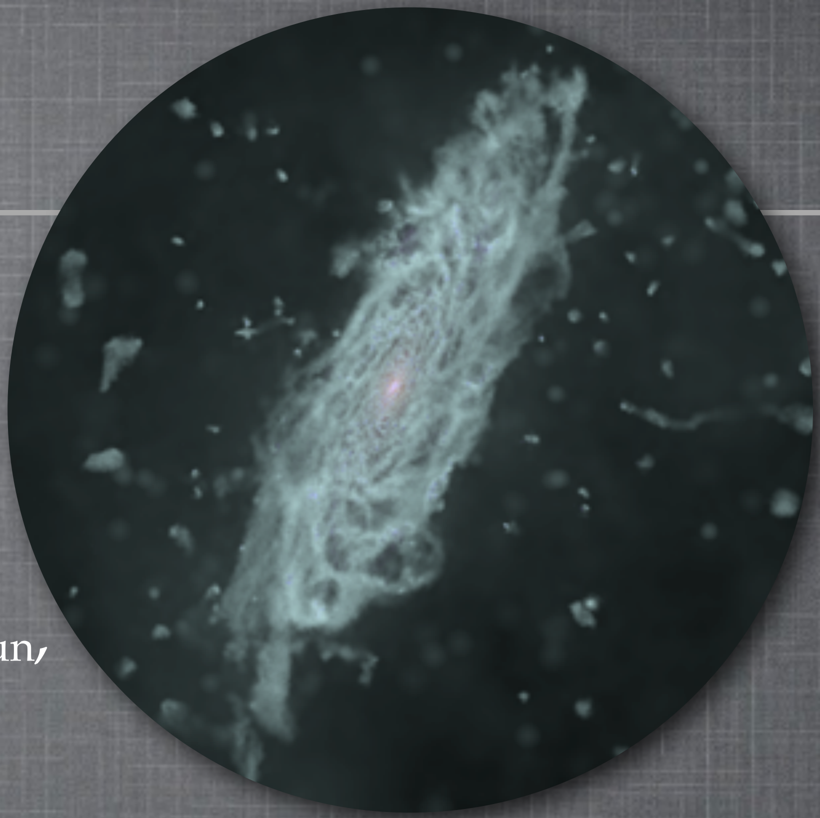
Eris: The Basics



	M_{vir} [$10^{12} M_{sun}$]	V_{sun} [km/s]	M^* [$10^{10} M_{sun}$]	f_b	B/D	R_d [kpc]	M_i	SFR [M_{sun} yr^{-1}]
Eris	0.79	206	3.9	0.12	0.35	2.5	-21.7	1.1
MW	1±0.2	221±18	4.9-5.5	?	0.33	2.3±0.6	?	0.68-1.45

	N	ε [kpc]	m_{dark} [10^4 M_{sun}]	m_{gas} [10^4 M_{sun}]	n_{SF} [cm^{-3}]
Eris	18.6 M 3M+7M+8.6M (gas+dark+star)	0.12	9.8	2	5
Brooks et al. 2010 (h258)	2.8 M	0.35	1200	21	0.1
Scannapieco et al. 2009, 2010	1 M	0.7-1.4	2600	56	0.05

ERIS: The Basics



✳ Campaign of extreme resolution cosmological *zoom-in* simulation of Milky Way-sized galaxies. **GASOLINE** (*N*-body+SPH) for *Eris* suite.

✳ *Eris:* follows the formation of a light MW (M_{vir}=7.9x10^{11} M_{sun}, no >1:10 merger @ z<3) with N_{DM}+Ngas+N_*=7M + 3M + 8.6M = 18.6M (r<Rvir @ z=0), ε_G=120 pc.

✳ Physics: lowT metal gas cooling, UVB heating, SN Type Ia and Type II thermal feedback. High SF gas density threshold: *nSF*=5 atoms cm^{-3} (50x higher than "standard" sims). High res allows to resolve Jeans length with >5 SPH kernels. No AGN. No stellar radiation feedback, galactic outflows are generated without explicit wind prescriptions.

✳ Resources: *Eris* was run on NASA Pleiades supercomputer for 1.5M cpuh, it took 9 months Including overhead.

✳ Twin simulations with low star formation threshold, low star formation efficiency, low resolution, and metal diffusion will be referred to as ErisLT, ErisLE, ErisLR, and ErisMD, respectively.

The *Eris* N-body simulation of a massive late-type spiral galaxy in a WMAP3 cosmology (Guedes, Callegari, Madau, & Mayer 2011. The simulation was performed with the GASOLINE code on NASA's *Pleiades* supercomputer and used 1.5 million cpu hours.

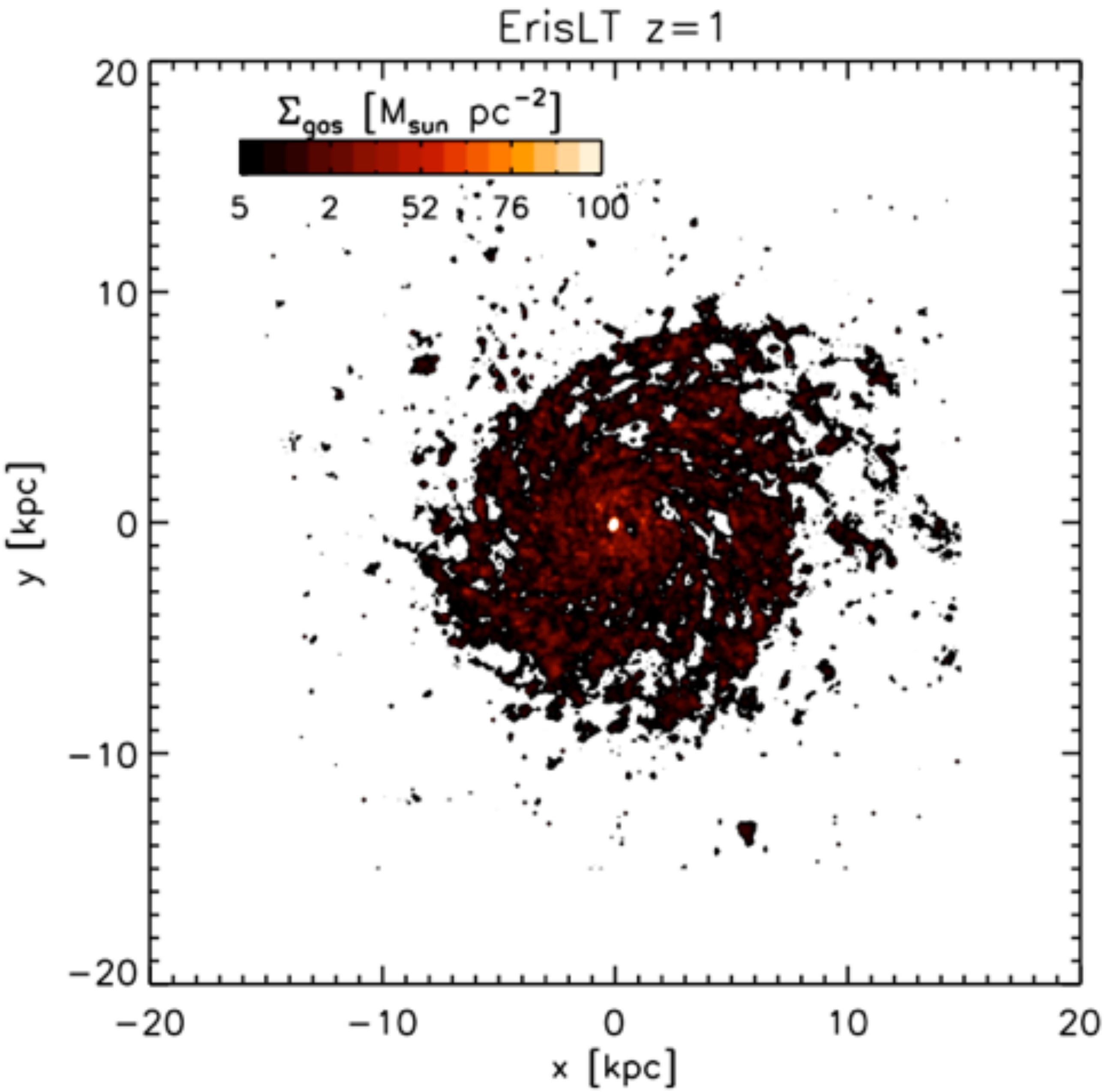
M_{vir}=7.9 x 10^{11} M_{sun}
N_{DM}+N_{gas}+N_{star}=7M+3M+8.6M within the final R_{vir}
force resolution=120 pc

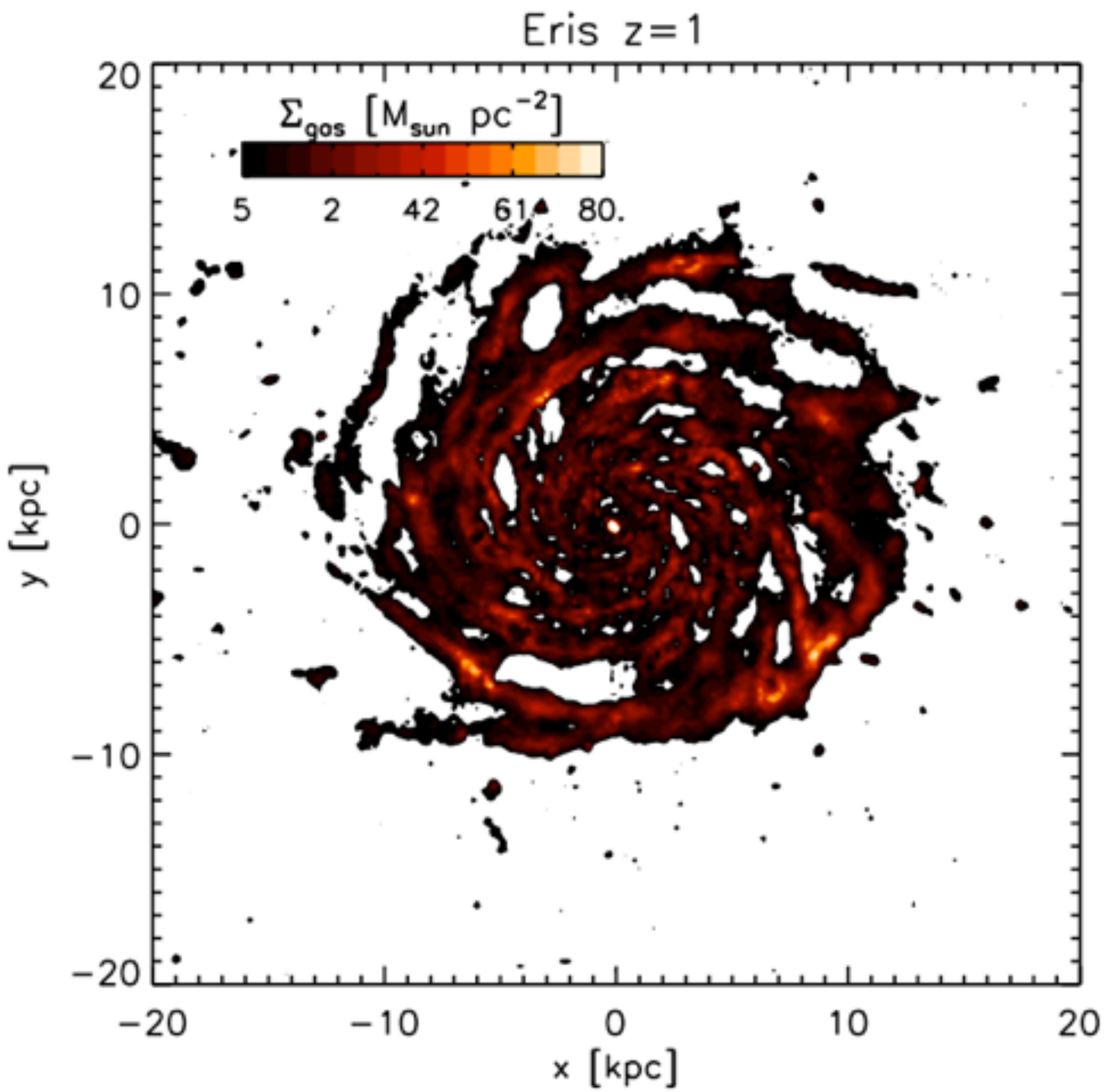
RESEARCH FUNDED BY NASA, NSF, AND SNF

Low vs. high star formation threshold

With higher threshold, Eris' disk at z=2 is

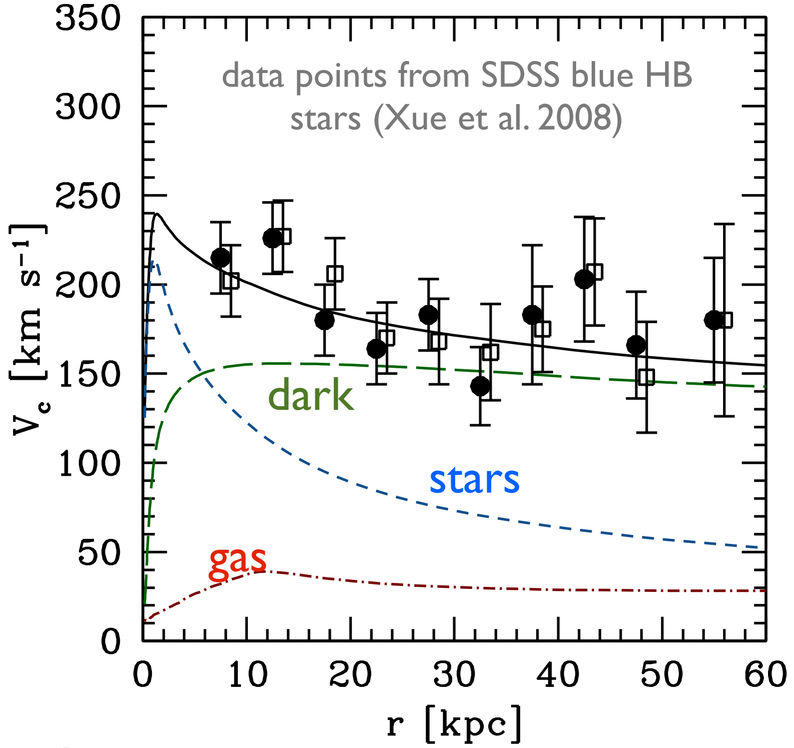
50% larger
30% less massive
30% higher gas fraction
5x lower density at r < 1 kpc



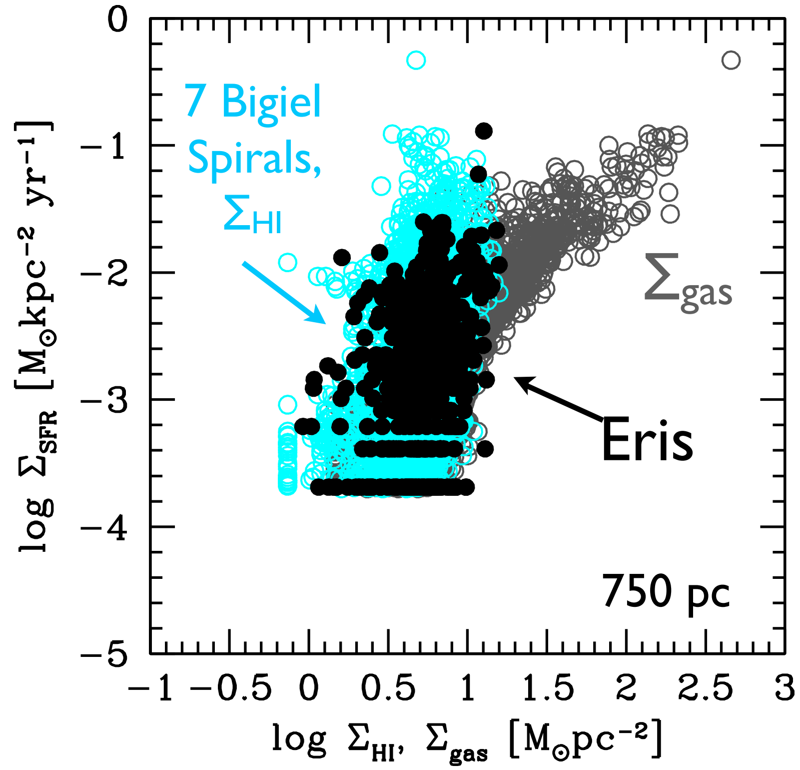


Eris Satisfies a Host of Observational Constraints

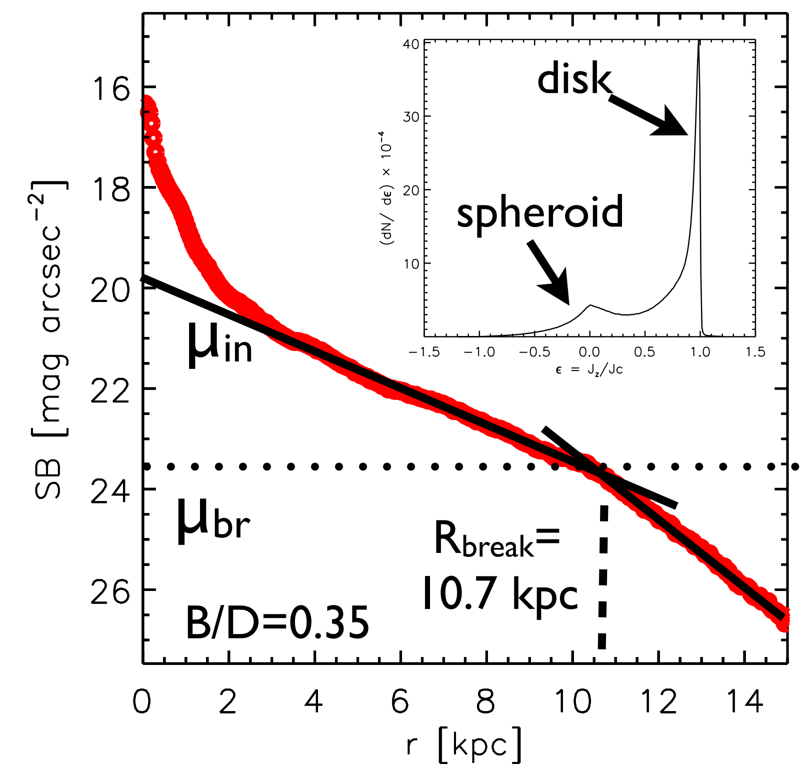
Rotation Curve



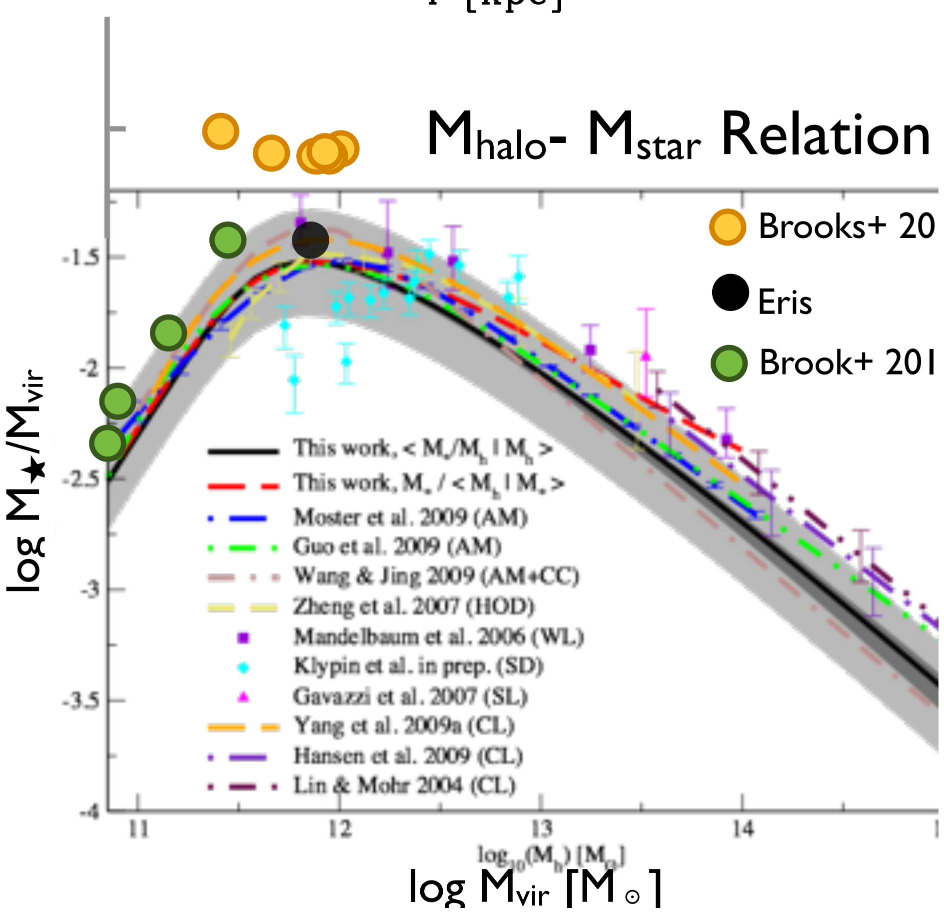
K-S Relation



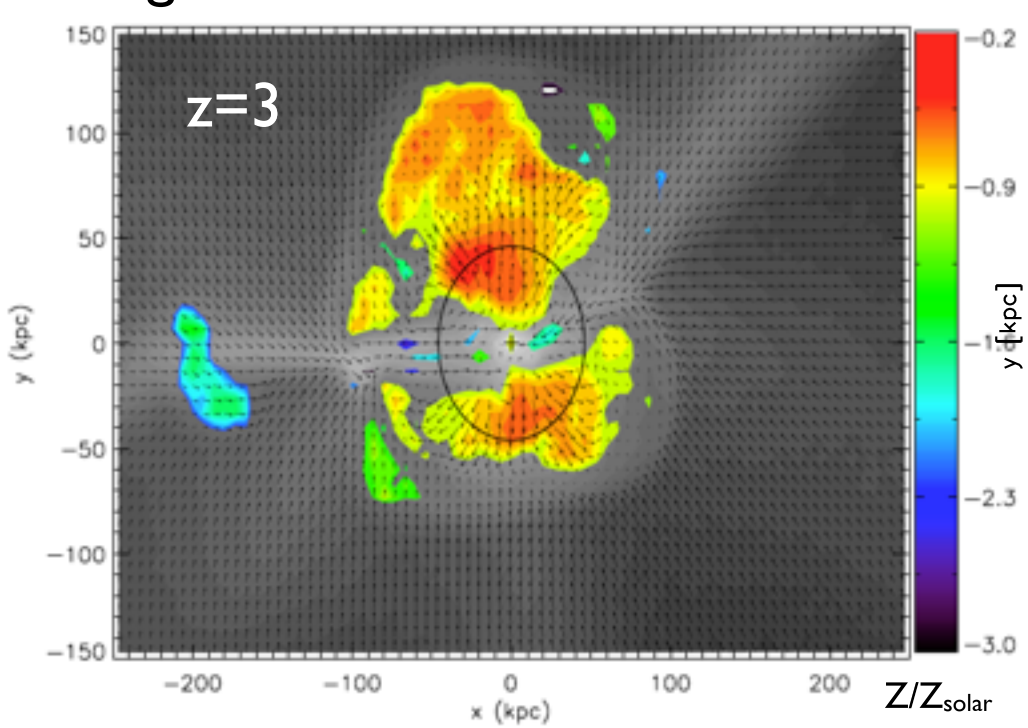
SB Profile, B/D, and SB Break



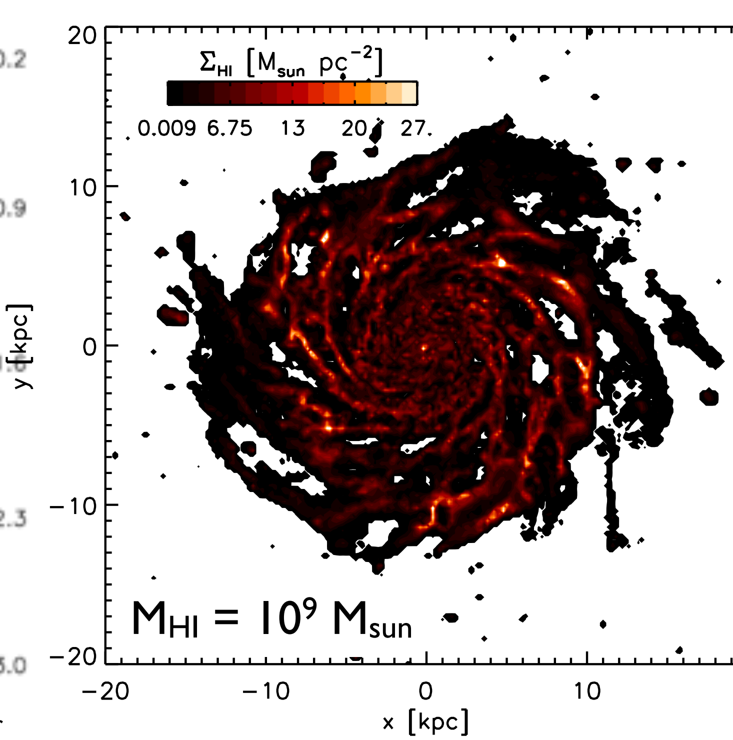
Mhalo- Mstar Relation



Large scale SNe-driven outflows



HI distribution



AN OFF-CENTER DENSITY PEAK IN THE MILKY WAY'S DM HALO?

DRAFT VERSION JUNE 15, 2012
Preprint typeset using LaTeX style emulateapj v. 03/07/07

STRONG EVIDENCE FOR GAMMA-RAY LINE EMISSION FROM THE INNER GALAXY

MENG SU[1,3], DOUGLAS P. FINKBEINER[1,2]

Draft version June 15, 2012

ABSTRACT

Using 3.7 years of *Fermi*-LAT data, we examine the diffuse $80-200$ GeV emission in the inner Galaxy and find a resolved gamma-ray feature at $\sim 110-140$ GeV. We model the spatial distribution of this emission with a $\sim 3^\circ$ FWHM Gaussian, finding a best fit position 1.5° West of the Galactic Center. Even better fits are obtained for off-center Einasto and power-law profiles, which are preferred over the null (no line) hypothesis by 6.5σ ($5.0\sigma/5.4\sigma$ after trials factor correction for one/two line case) assuming an NFW density profile centered at $(\ell, b) = (-1.5^\circ, 0^\circ)$ with a power index $\alpha = 1.2$. The energy spectrum of this structure is consistent with a single spectral line (at energy 127.0 ± 2.0 GeV with $\chi^2 = 4.48$ for 4 d.o.f.). A pair of lines at 110.8 ± 4.4 GeV and 128.8 ± 2.7 GeV provides a marginally better fit (with $\chi^2 = 1.25$ for 2 d.o.f.). The total luminosity of the structure is $(3.2 \pm 0.6) \times 10^{35}$ erg/s, or $(1.7 \pm 0.4) \times 10^{36}$ photons/sec. The energies in the two-line case are compatible with a 127.3 ± 2.7 GeV WIMP annihilating through $\gamma\gamma$ and γZ (with $\chi^2 = 1.67$ for 3 d.o.f.). We describe a possible change to the *Fermi* scan strategy that would accumulate S/N on spectral lines in the Galactic center 4 times as fast as the current survey strategy.

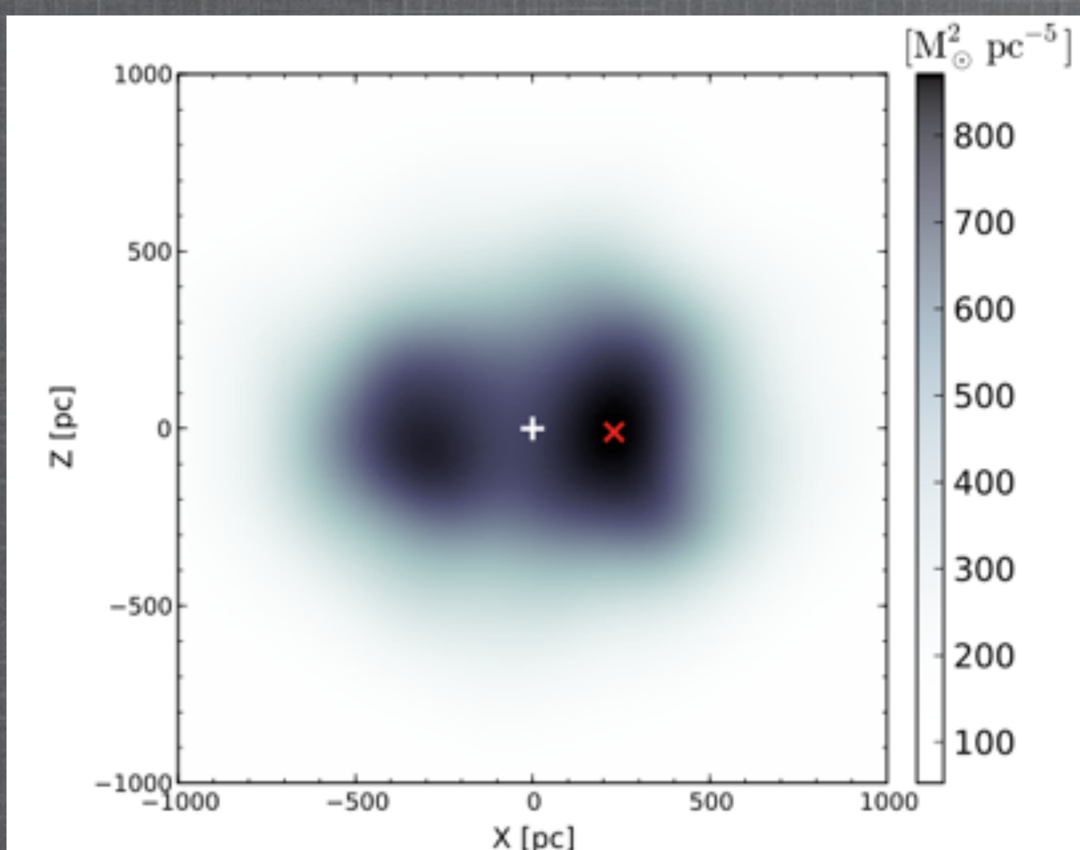
Subject headings: gamma rays — diffuse emission — milky way — dark matter

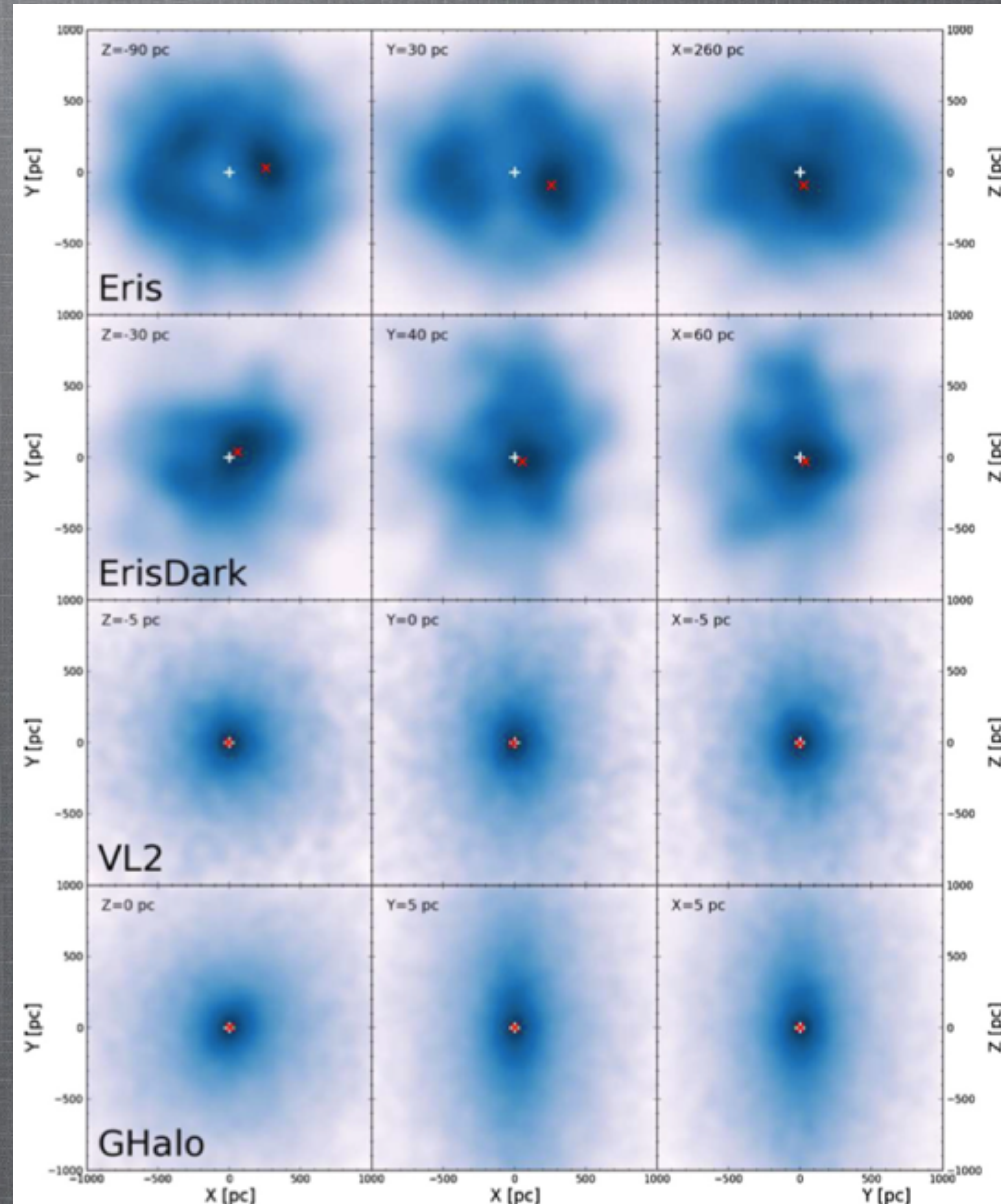
Displaced annihilation signal

Kuhlen, Guedes + 2013

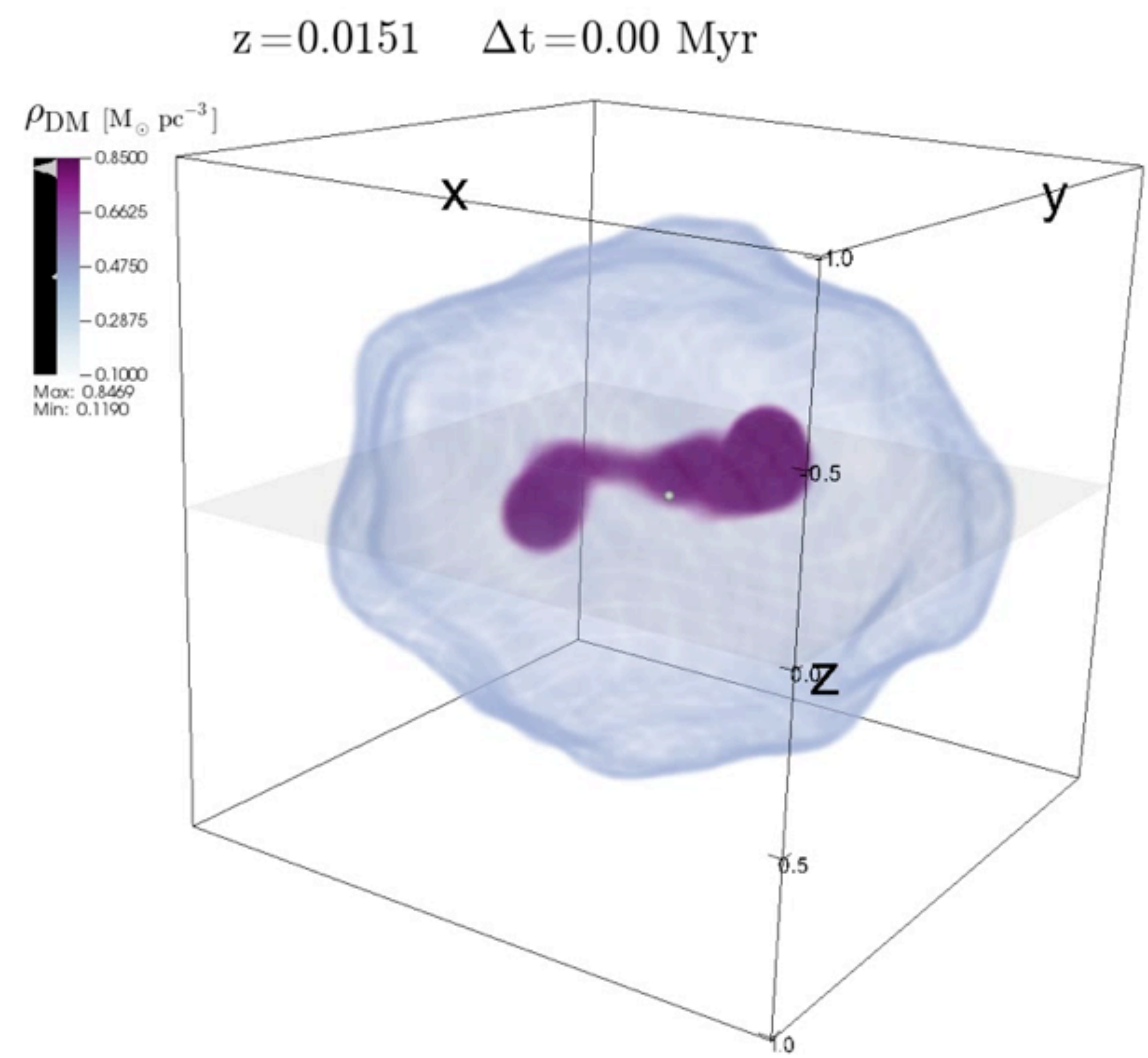
Offset is seen in baryonic simulation only, not on dark matter only version, and it's possibly a side effect of the stellar bar.

DM annihilation luminosity "surface density" ($\int \varrho^2 \, dl$) in the central 2 kpc × 2 kpc region of Eris.





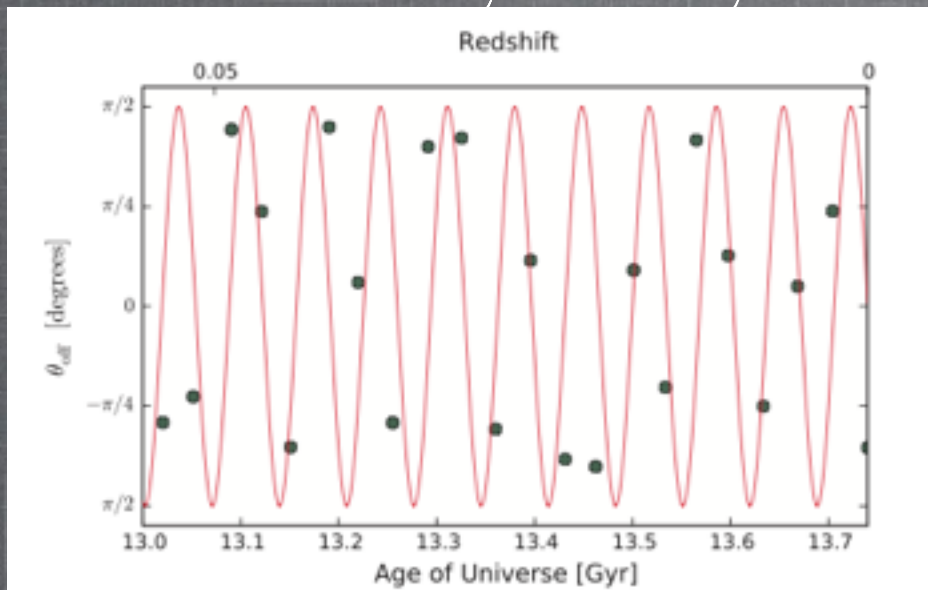
The effect of the stellar bar on the dark matter distribution



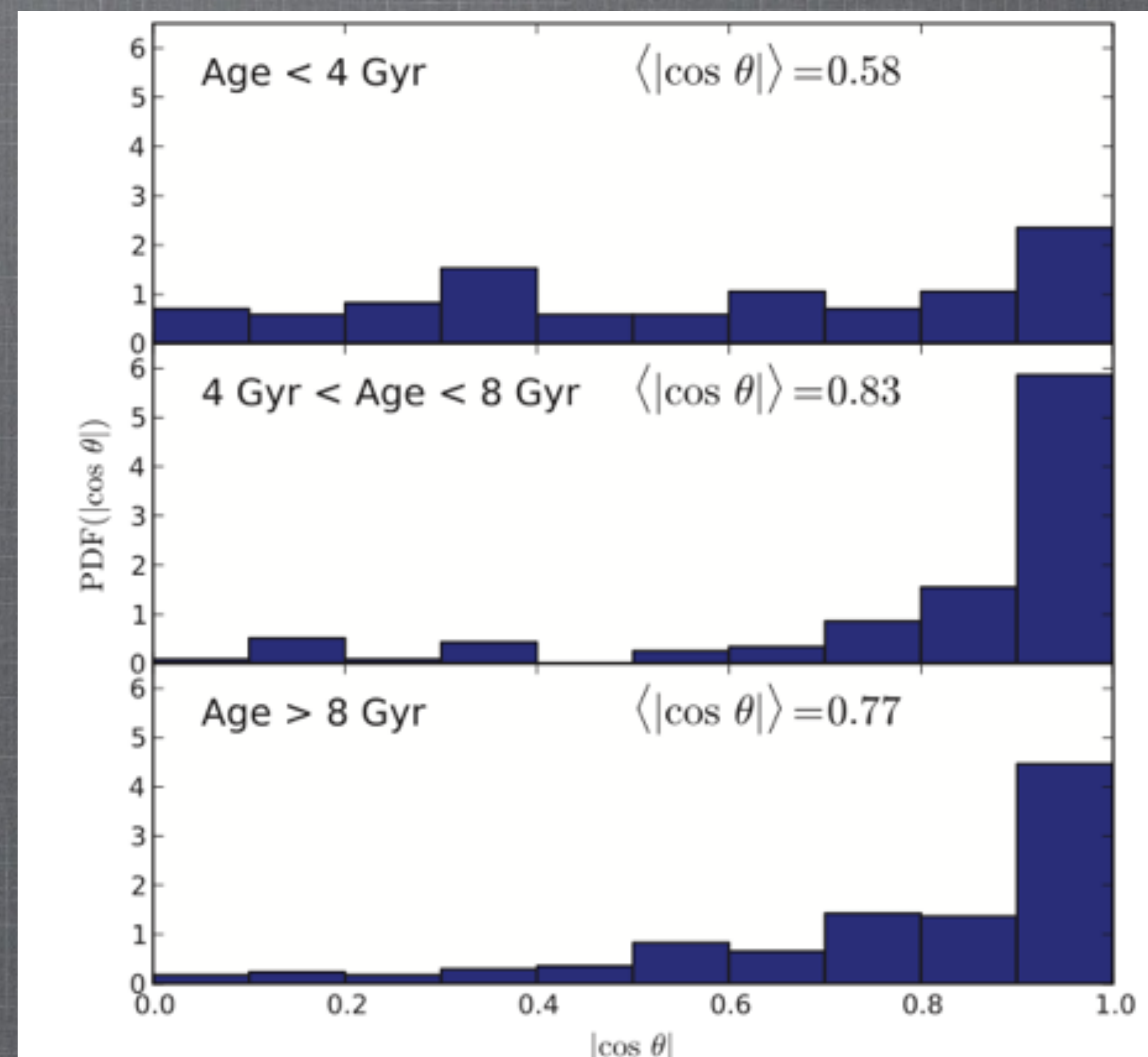
Kuhlen, Guedes + 2013

Effect of the stellar bar on the dark matter distribution

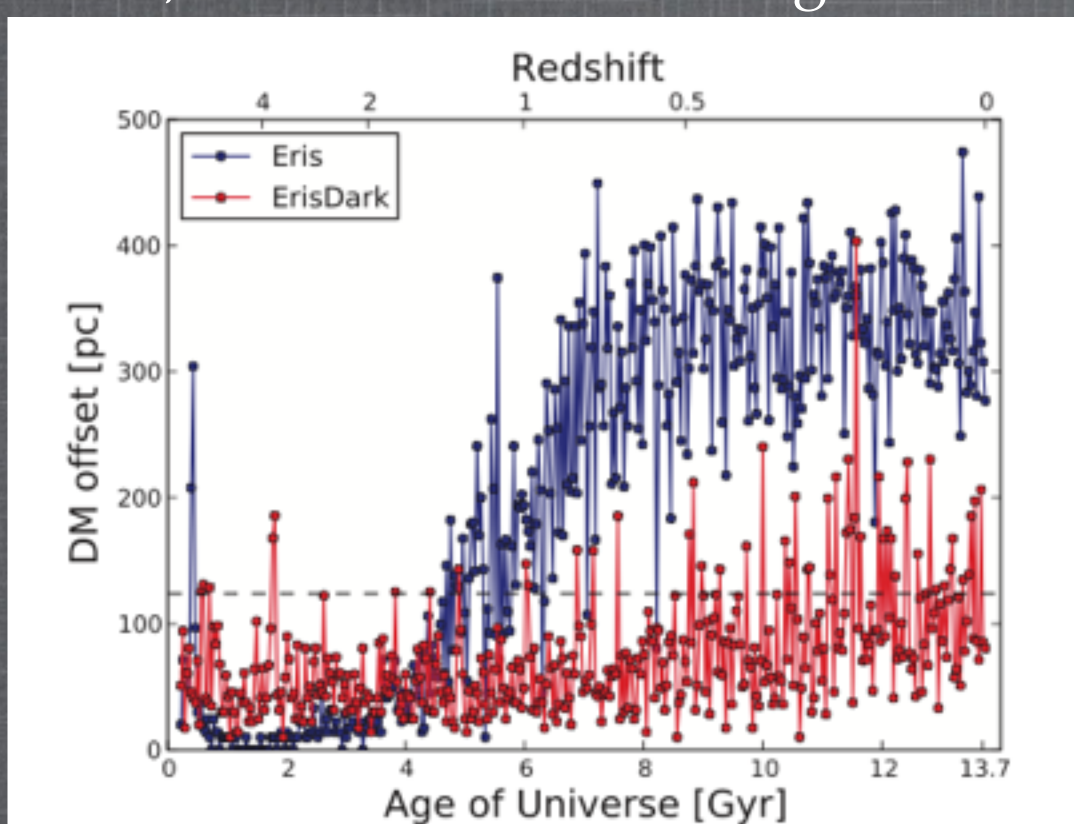
Periodicity ~ 70 Myr



Once the DM offset becomes pronounced the distributions prefer large values of $|\cos\theta|$, indicating alignment between the offset peak and the stellar bar.



The offset becomes more pronounced at z~1, when the bar is stronger



The distribution of DM in Eris and consequences for direct detection

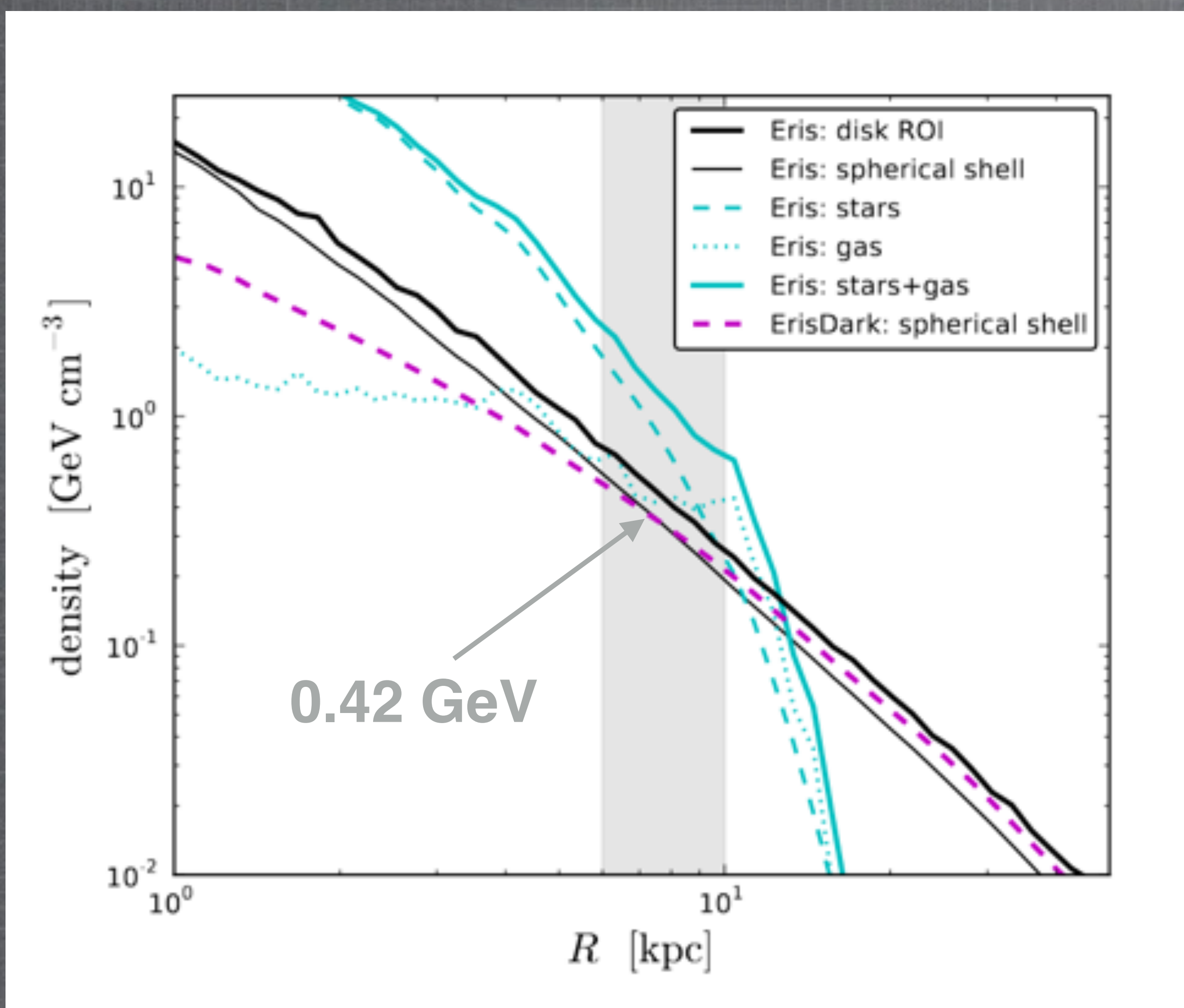
- All direct detection analyses must make an assumption about the local phase-space distribution of the DM particles incident on Earth.
- The most commonly used model is the so-called Standard Halo Model (SHM), in which the local DM density is taken to be 0.3 GeV (consistent with current observational constraints, Garbari et al. 2011; Bovy & Tremaine 2012)
- The halo rest-frame speed distribution f(v) is assumed to be a Maxwellian with a peak (most probable) speed of 220 km/s.

Direct detection: DM nucleus scattering rate

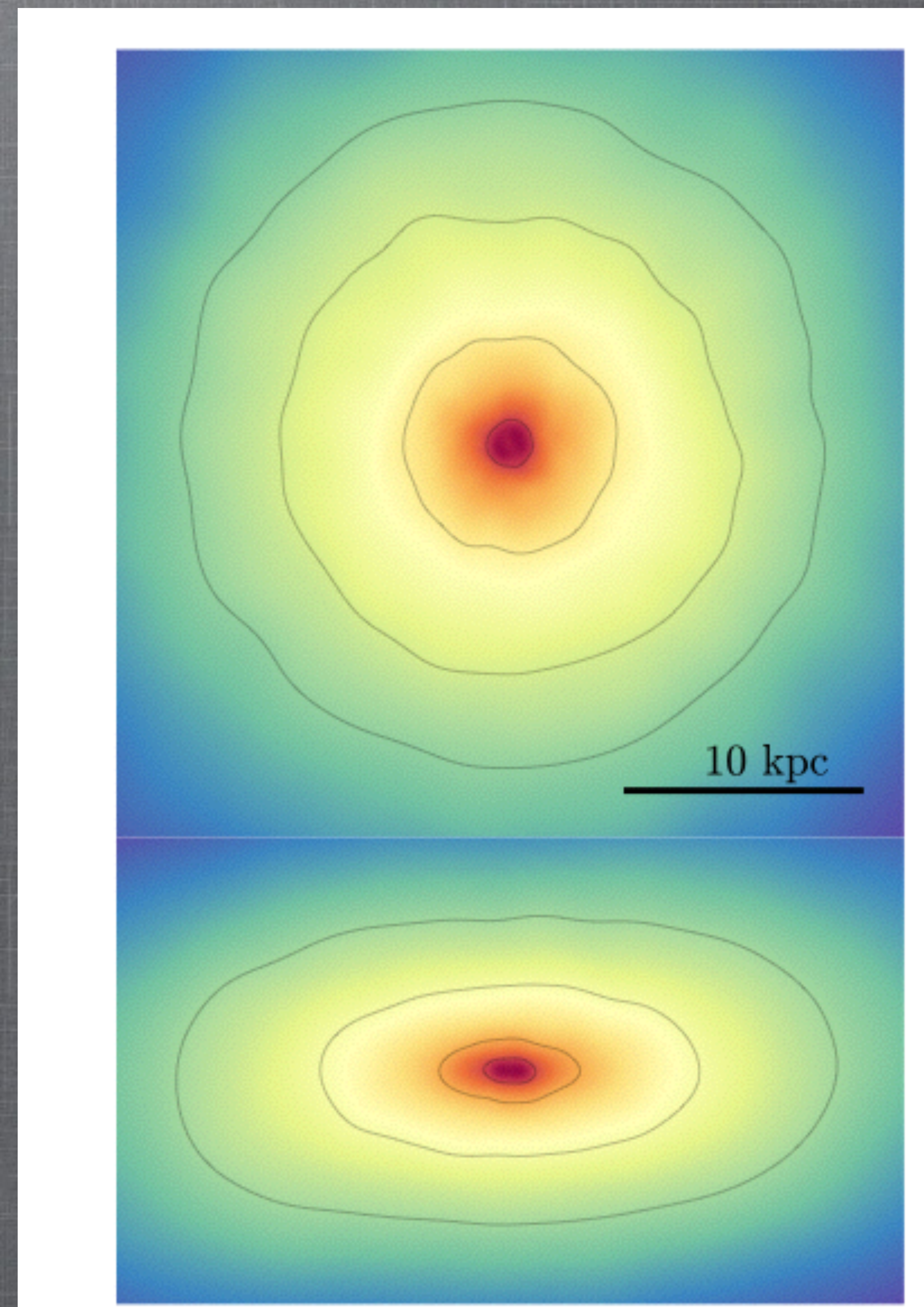
diferential DM-nucleus scattering rate per unit detector mass

$$\frac{dR}{dE_r} = \frac{\rho_0}{m_N\, m_\chi}\, \sigma(E_r) \int_{v_{\min}}^{\infty} \frac{f(v)}{v}\, dv,$$

Eris has an enhanced density profile due to contraction and dark disk formation



30% enhancement in disk plane w.r.t. DM only simulation

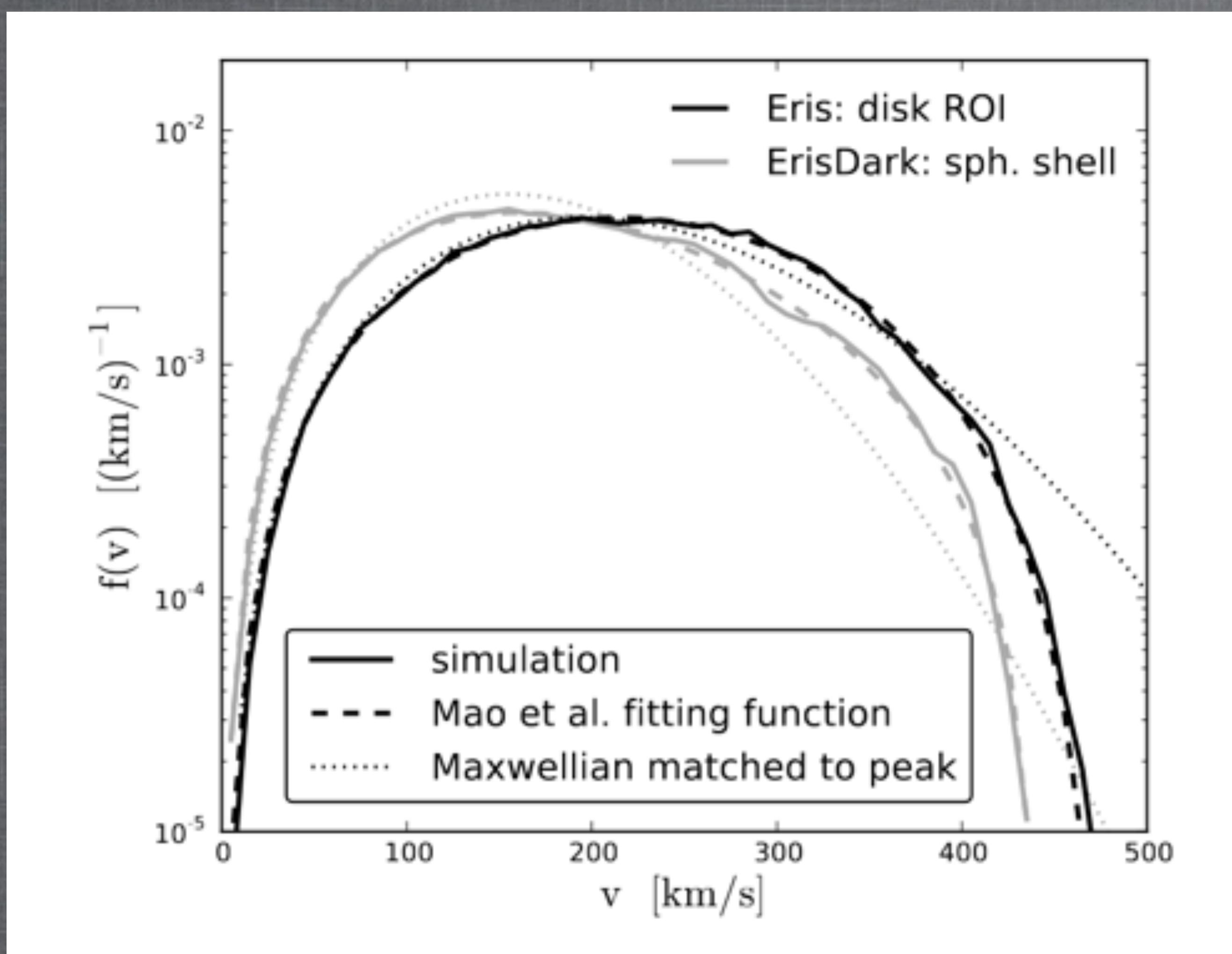


Direct detection: DM nucleus scattering rate

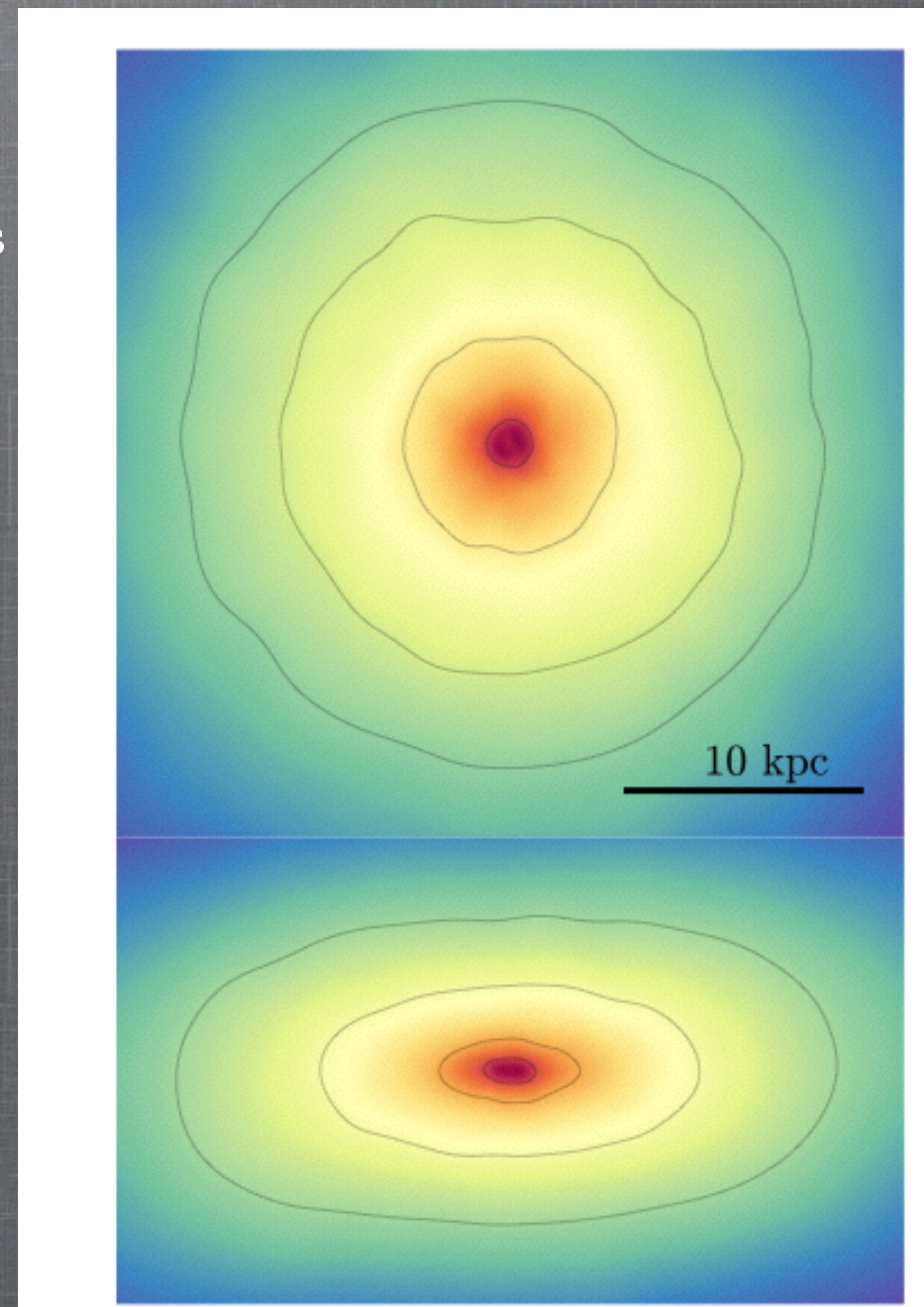
diferential DM-nucleus scattering rate per unit detector mass

$$\frac{dR}{dE_r} = \frac{\rho_0}{m_N\, m_\chi}\,\sigma(E_r) \int_{v_{\min}}^{\infty} \frac{f(v)}{v}\, dv,$$

The velocity distribution of the Eris is broadened and shifted toward higher velocities



30% enhancement in disk plane w.r.t. DM only simulation



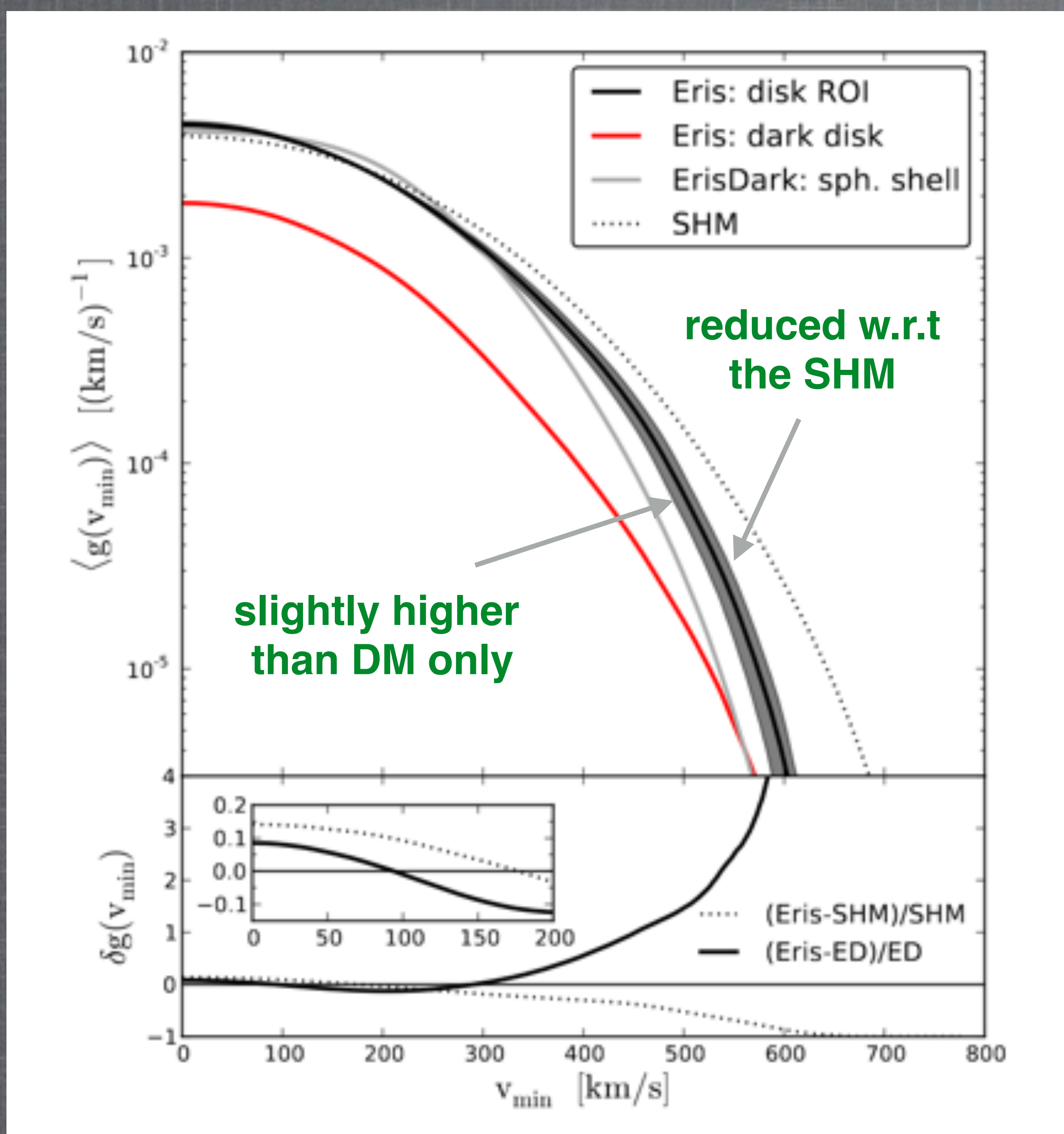
Kuhlen et al. 2013

Direct detection: DM nucleus scattering rate

diferential DM-nucleus scattering rate per unit detector mass

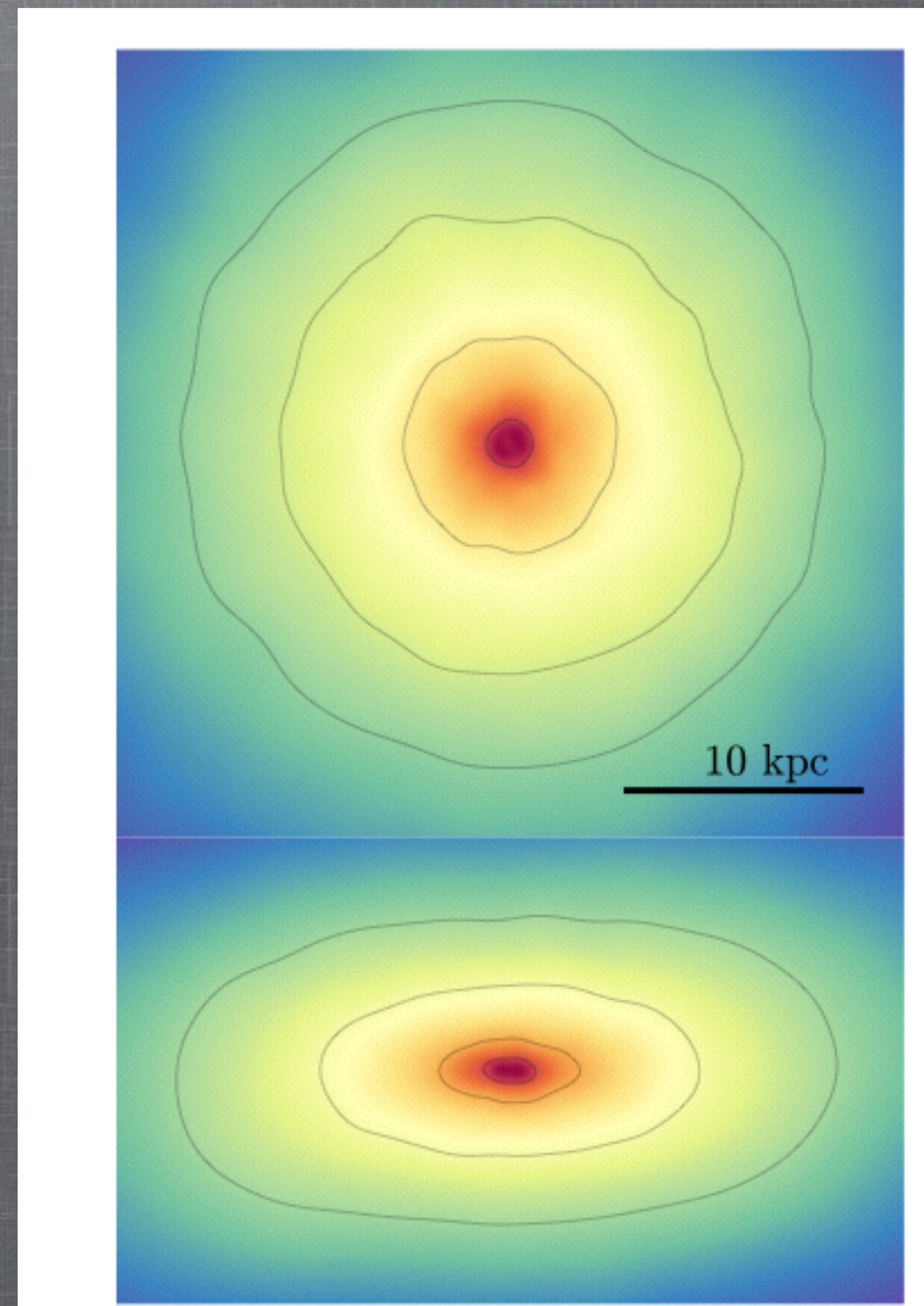
$$\frac{dR}{dE_r} = \frac{\rho_0}{m_N\, m_\chi}\,\sigma(E_r)\int_{v_{\rm min}}^{\infty}\frac{f(v)}{v}\,dv,$$

The velocity distribution of the Eris is slightly shifted with respect to DM only simulations



Kuhlen et al. 2013

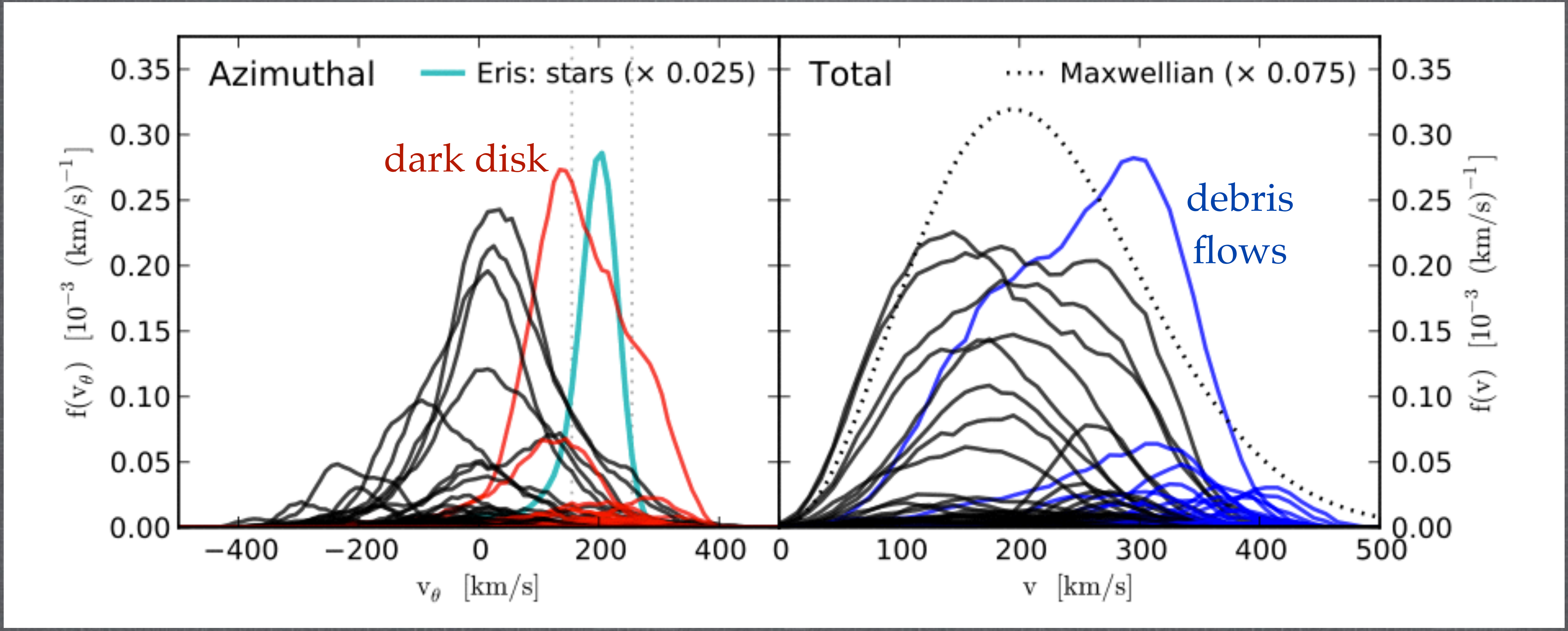
30% enhancement in disk plane w.r.t. DM only simulation



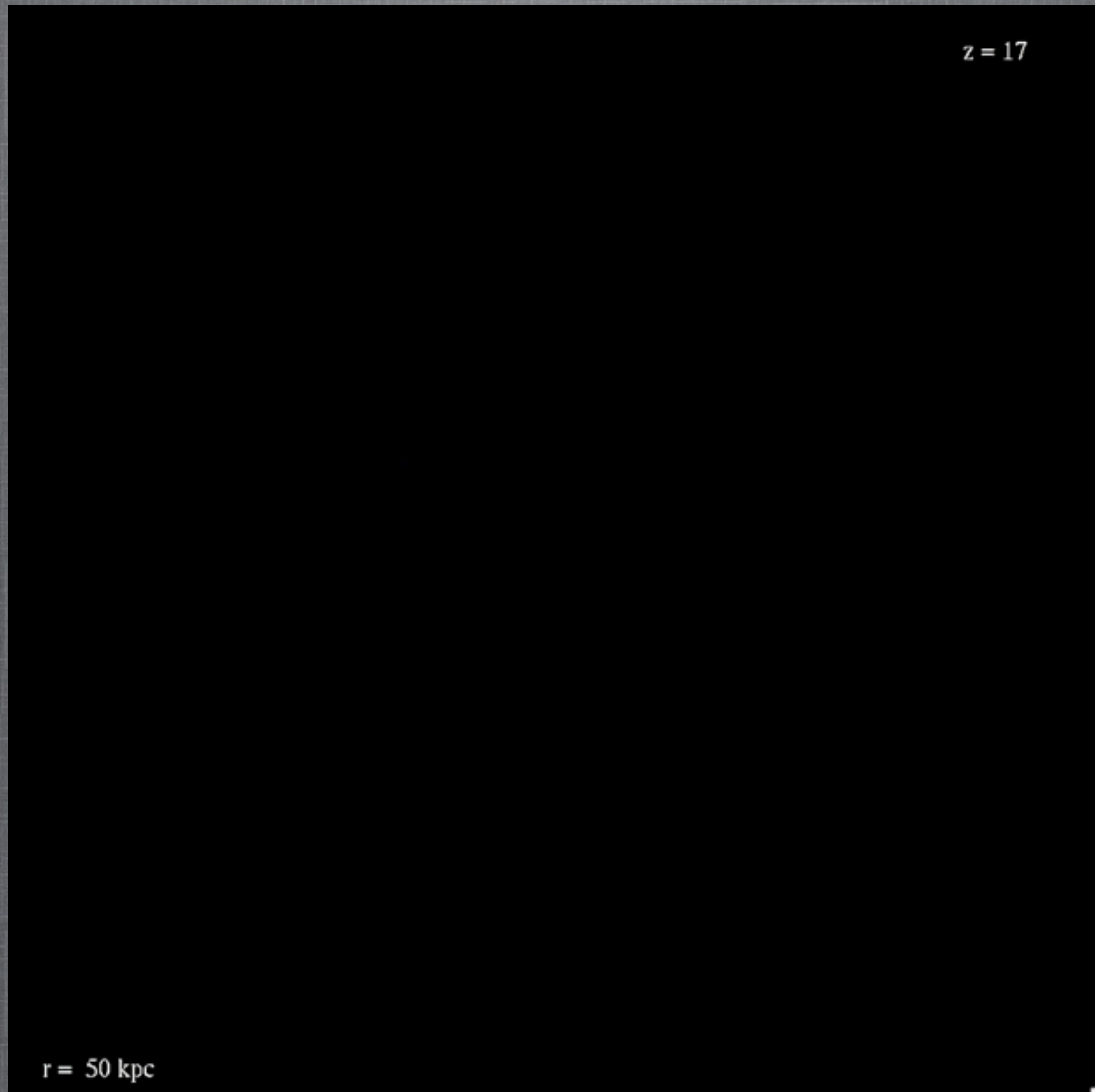
Direct detection: DM nucleus scattering rate

$$\frac{dR}{dE_r} = \frac{\rho_0}{m_N\, m_\chi}\, \sigma(E_r) \int_{v_{\min}}^{\infty} \frac{f(v)}{v}\, dv,$$

Contribution of more massive satellites to the velocity distribution. The stellar disk drags late-infall satellite's orbit to the disk plane and their remains co-rotate with it.



Formation of the Dark Disk

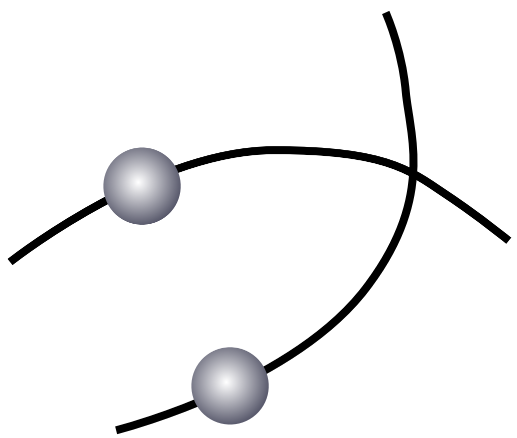


What about warm dark matter?

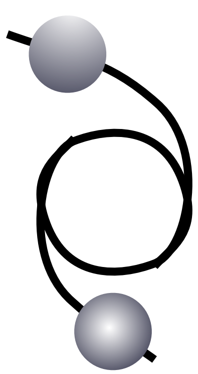
Problems of the N-body method: WDM

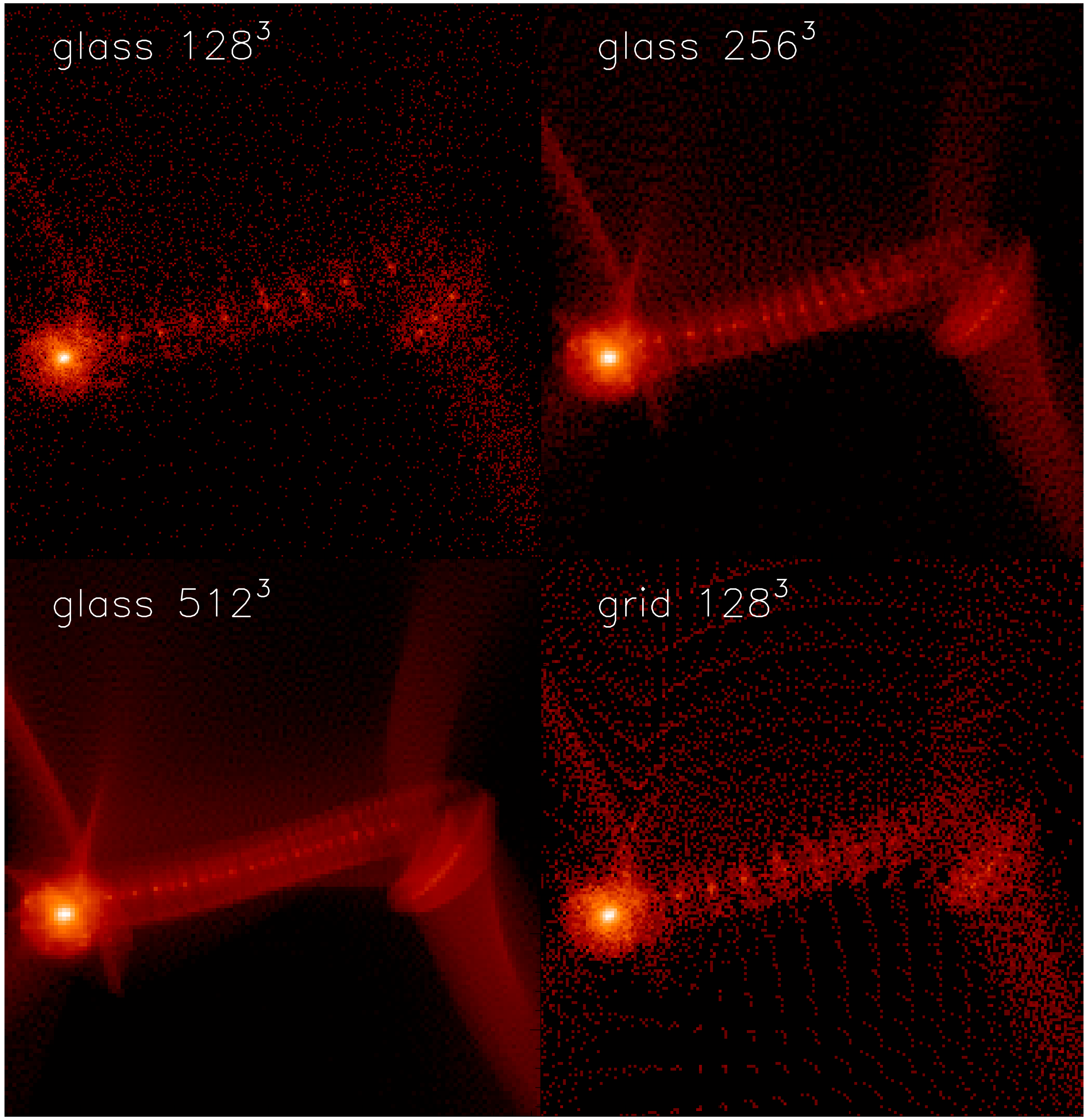
Main Problem: two-body effects, directly related to force softening

Scattering



Clumping/
Fragmentation





Wang&White 2007

Most obvious for non-CDM simulations!

(e.g. Centrella&Melott 1983, Melott&Shandarin 1989, Wang&White 2007)

Credit: Oliver Hahn

How do N-body methods work?

Vlasov-Poisson system

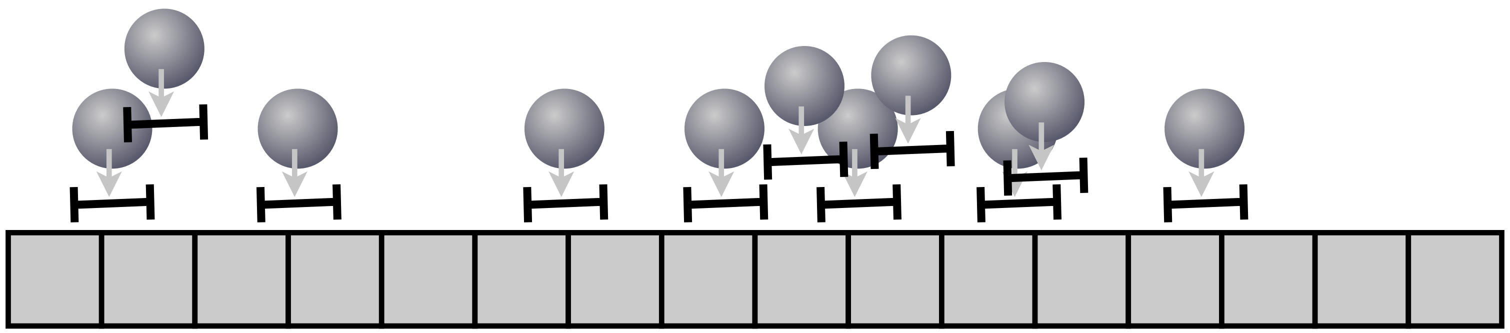
$$\frac{\partial f}{\partial t} = \underbrace{\boxed{-\frac{\mathbf{p}}{m}\cdot\boldsymbol{\nabla}_x f}}_{\text{Advection}} - \underbrace{\boxed{\boldsymbol{\nabla}_x \phi \cdot \boldsymbol{\nabla}_p f}}_{\text{Gravity}} \qquad \Delta\phi = 4\pi G \int \mathrm{d}^3 p\, f$$

Distribution function

$$f(\mathbf{x},\mathbf{p},t) = \sum_{i=1}^{N} \delta_D(\mathbf{x}-\mathbf{x}_i(t))\,\delta_D(\mathbf{p}-\mathbf{p}_i(t))$$

⇒ eq. of motion for N massive particles, not a continuum

PM methods: compute density on a grid



Solve Poisson's equation (typically in Fourier space)

$$\nabla^2\phi \propto \delta \quad \Leftrightarrow \quad \tilde{\phi} \propto -\tilde{\delta}/k^2$$

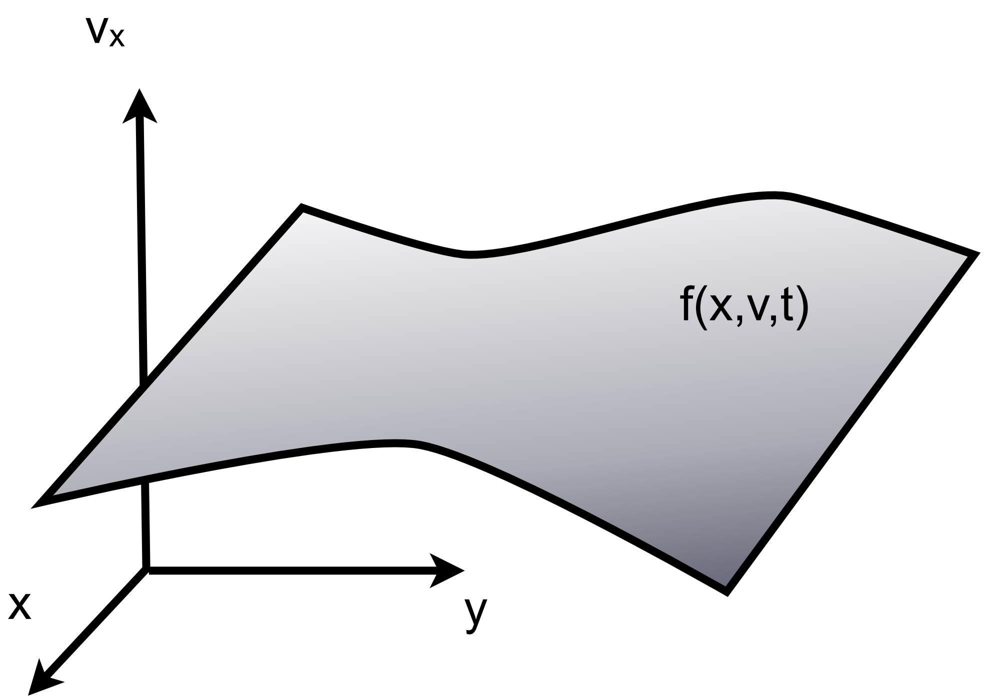
Compute accelerations and move particles (typically symplectic integrator)

$$a = -\nabla\phi \quad \Rightarrow \quad v(t+\Delta t) = v(t) + a(t)\,\Delta t \quad \Rightarrow x(t+\Delta t) = x(t) + v(t)\,\Delta t$$

Credit: Oliver Hahn

The cold dark matter sheet

WIMP (say 100 GeV) very cold, i.e. very thin along velocity direction.
Almost perfectly uniformly distributed in space in the early Universe



CDM covers a 3D submanifold of 6D phase space

extends over all of space

initially ‘delta’-function in velocity

Continuum limit for all practical purposes

never tears, never self-intersects

We call this 3D surface the dark matter sheet.

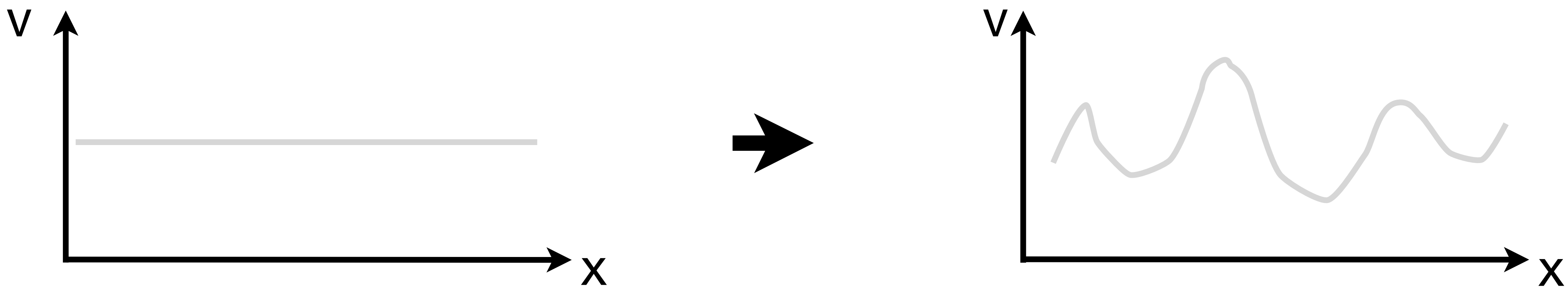
$$\mathbb{Q} \subset \mathbb{R}^3 \to \mathbb{R}^6 \, : \, \mathbf{q} \mapsto (\mathbf{x}_\mathbf{q}, \mathbf{p}_\mathbf{q})$$

$$f(\mathbf{x}, \mathbf{p}, t) = \int \delta_D(\mathbf{x} - \mathbf{x}_\mathbf{q}(t))\, \delta_D(\mathbf{p} - \mathbf{p}_\mathbf{q}(t))\, \mathrm{d}^3 q$$

Credit: Oliver Hahn

DM initial conditions

Cold sheet is perturbed by density + velocity perturbations

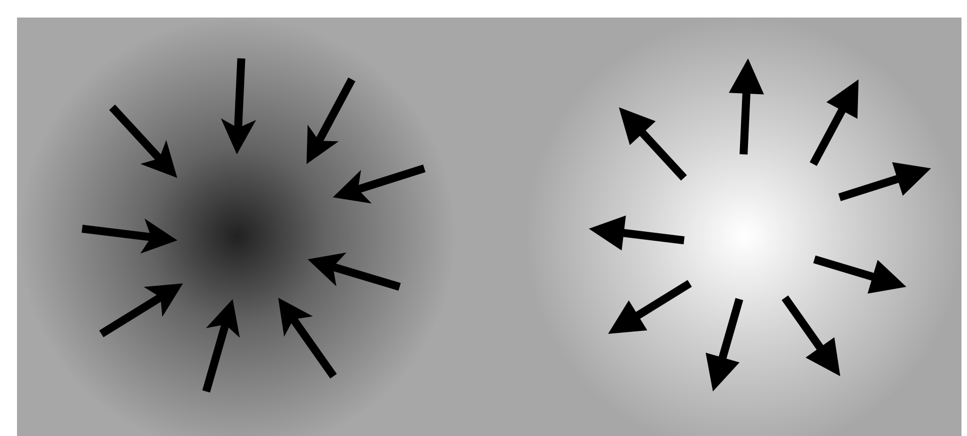


Lagrangian perturbation theory
relates density perturbations to displacements and velocities

$$\mathbf{x_q} = \mathbf{q} + \mathbf{L_q}(t), \quad \dot{\mathbf{x}}_\mathbf{q} = \frac{\partial}{\partial t}\mathbf{L_q}(t)$$

at 1st order, displacement field is proportional to **gravitational force** (Zel'dovich 1970)

$$\mathbf{L}(\mathbf{q}) \propto \boldsymbol{\nabla}_\mathbf{q}\Phi(\mathbf{q}, t)$$



need to solve **Poisson's equation**

$$\Delta_\mathbf{q}\Phi \propto \delta$$

Credit: Oliver Hahn

Discretizing the DM fluid (in the cold limit)

True cold distribution function: the dark matter sheet

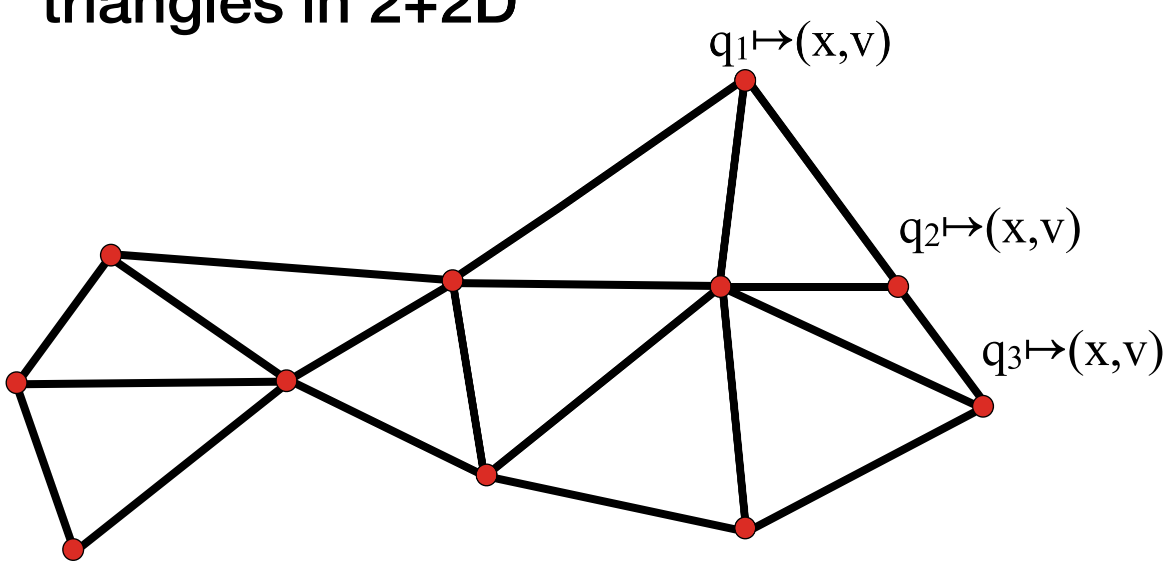
$$\mathbb{Q} \subset \mathbb{R}^3 \to \mathbb{R}^6 \,:\, \mathbf{q} \mapsto (\mathbf{x_q}, \mathbf{p_q}) \qquad f(\mathbf{x}, \mathbf{p}, t) = \int \delta_D(\mathbf{x} - \mathbf{x_q}(t))\, \delta_D(\mathbf{p} - \mathbf{p_q}(t))\, \mathrm{d}^3 q$$

The N-body limit:

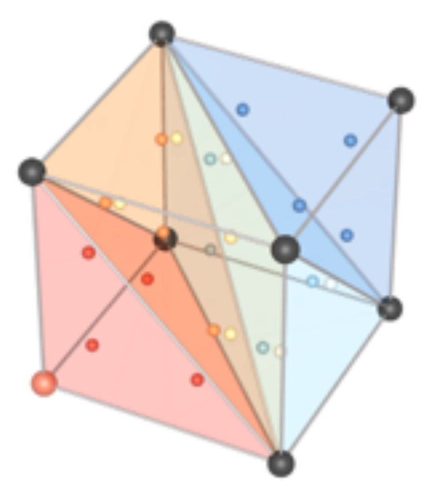
$$f(\mathbf{x}, \mathbf{p}, t) = \sum_{i=1}^{N} \delta_D(\mathbf{x} - \mathbf{x}_i(t))\, \delta_D(\mathbf{p} - \mathbf{p}_i(t))$$

Can try a **piecewise linear approximation!** (e.g. Abel, Hahn, Kaehler 2012 and Hahn, Abel, Kaehler 2013)
⇒ use a finite number of points on sheet and generate a tessellation

triangles in 2+2D



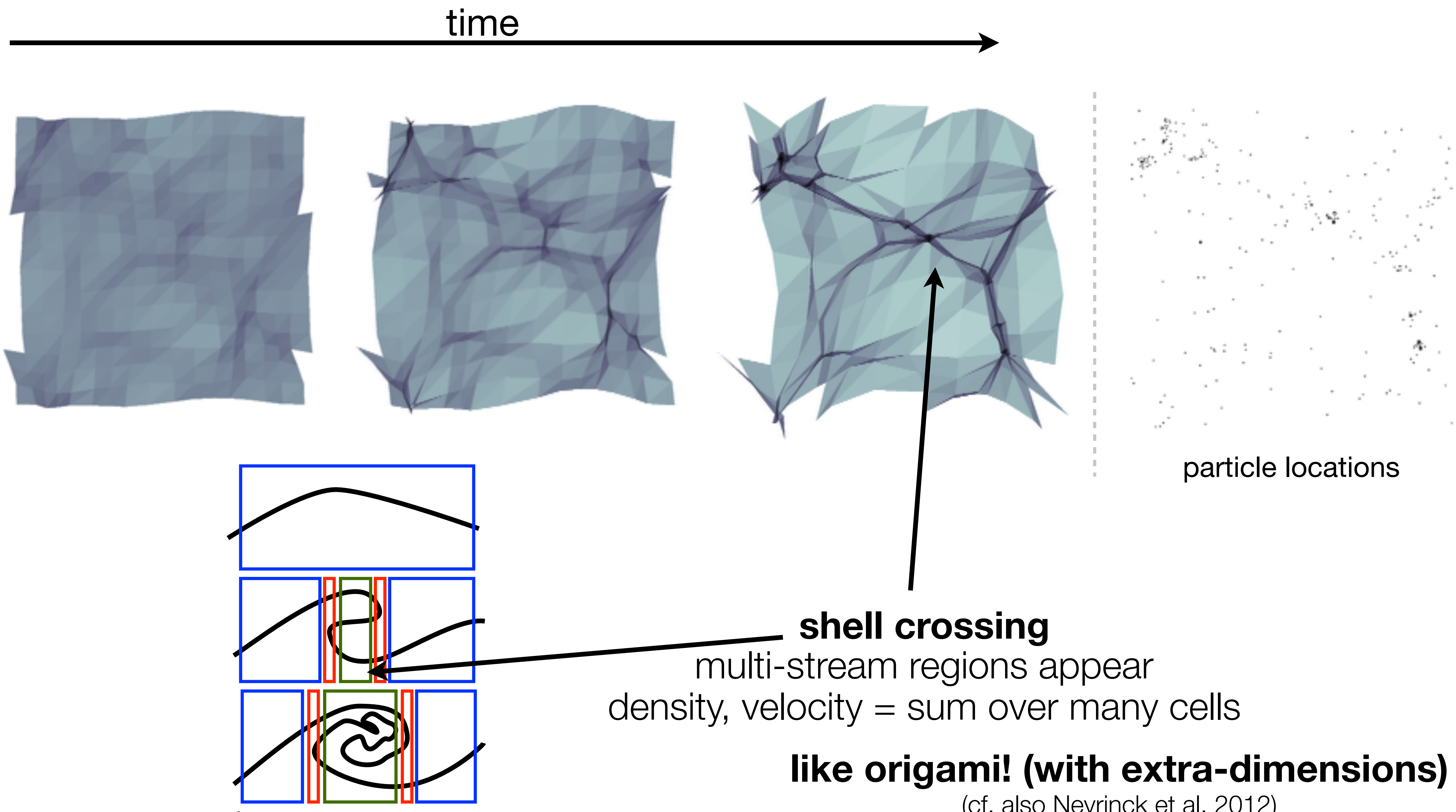
tetrahedra in 3+3D,
can approximate the mass with second kind of particles e.g.



Credit: Oliver Hahn

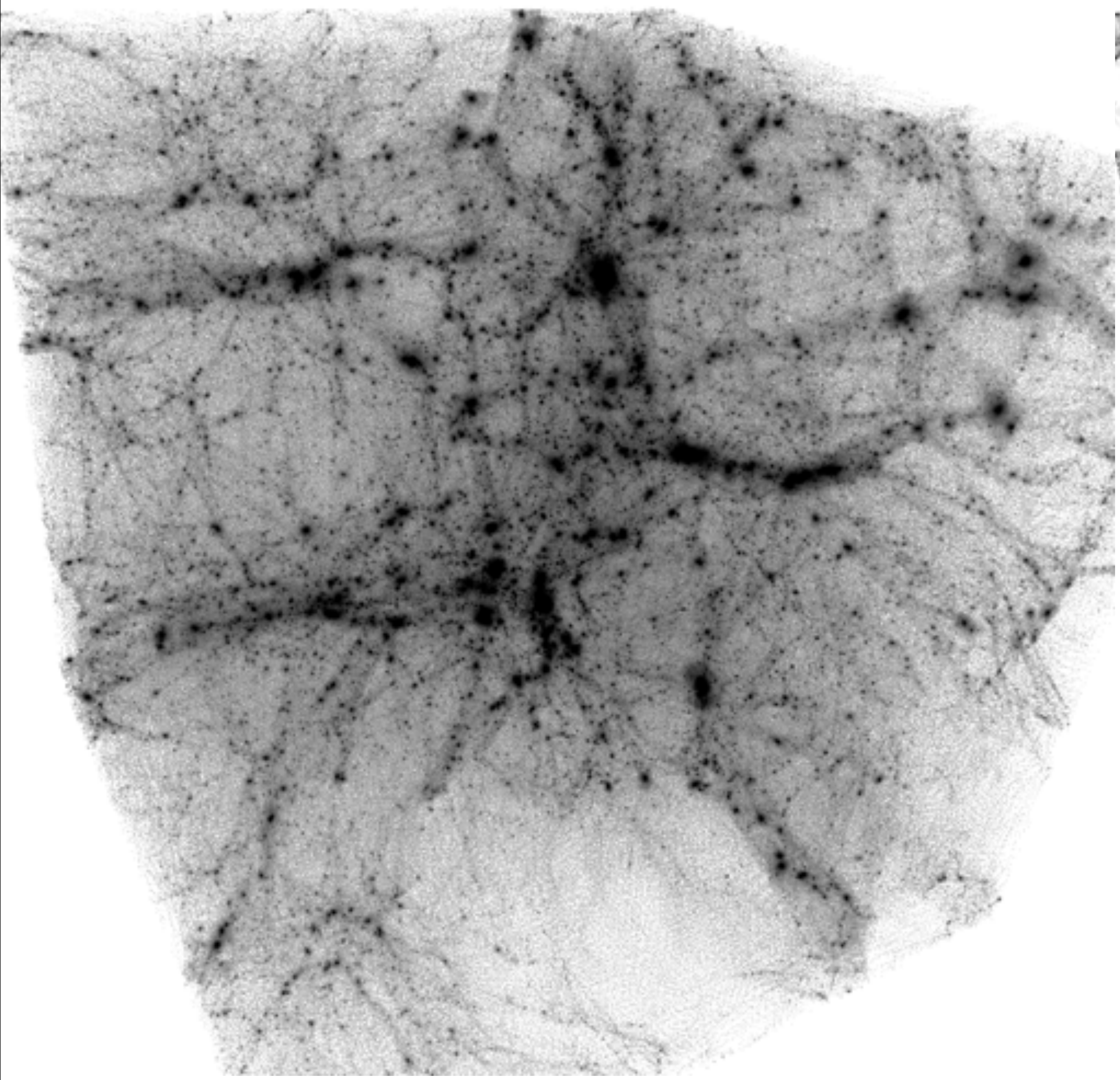
Evolution in two dimensions

- The real space density, velocity field, etc., at any given point can then be determined from **all** cells that contain that point.

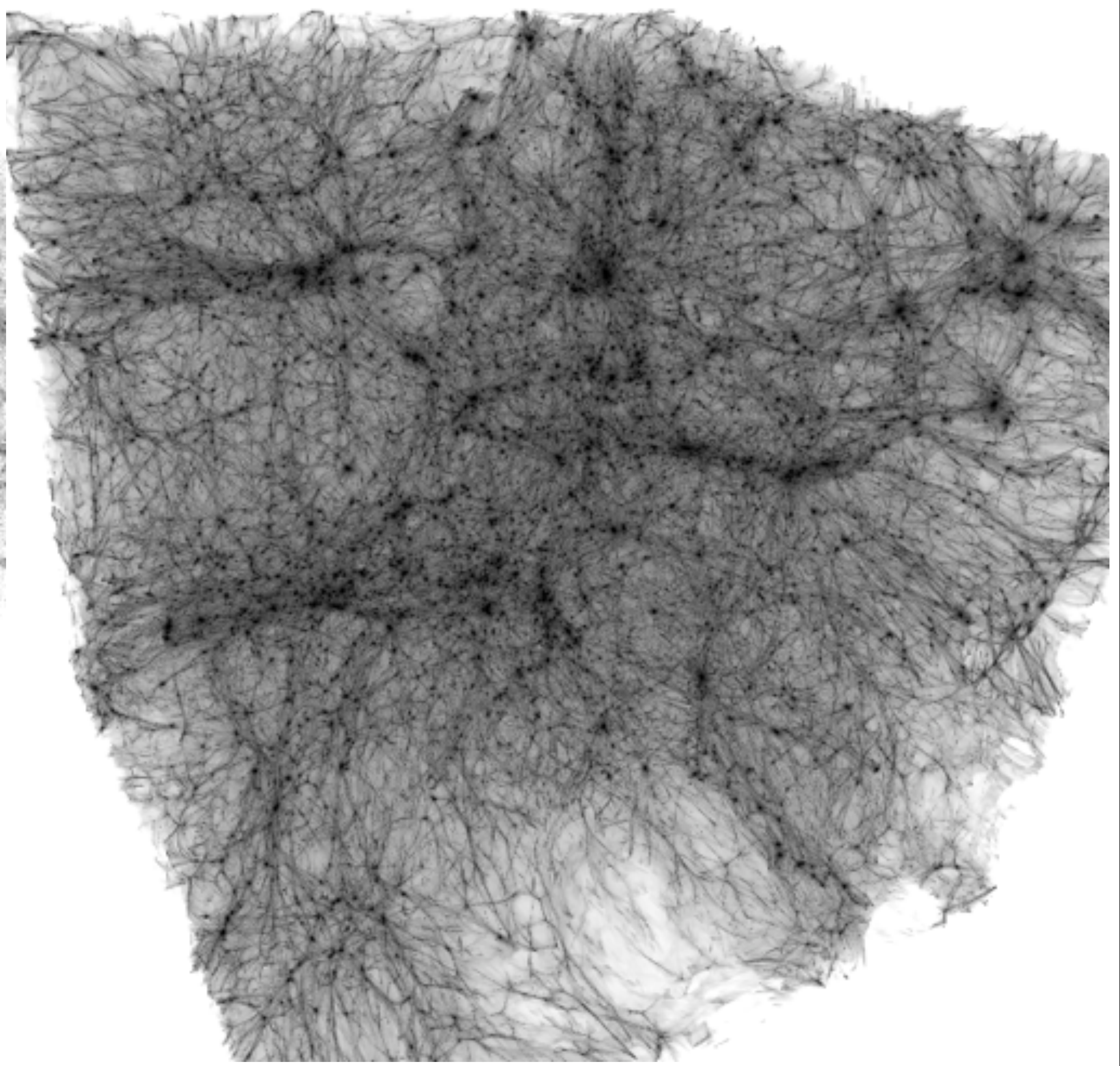


Credit: Oliver Hahn

Much more intricate web structure...



rendering points for particles.



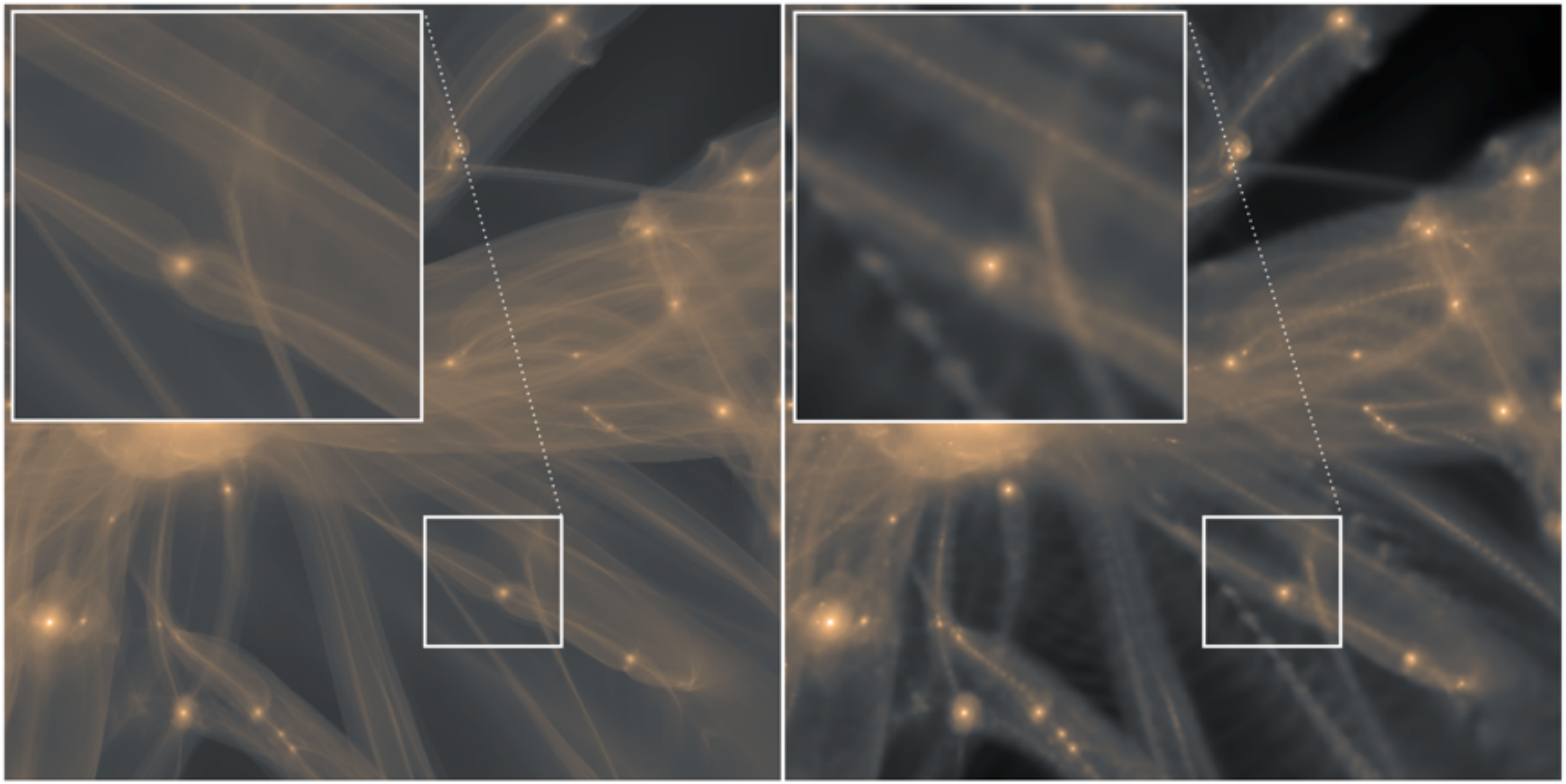
rendering tetrahedral phase space cells.

Same simulation data! Small-scale structure not lost in shot noise

Credit: Oliver Hahn

Much improvement over adaptive softening

Renderings of same WDM simulation data



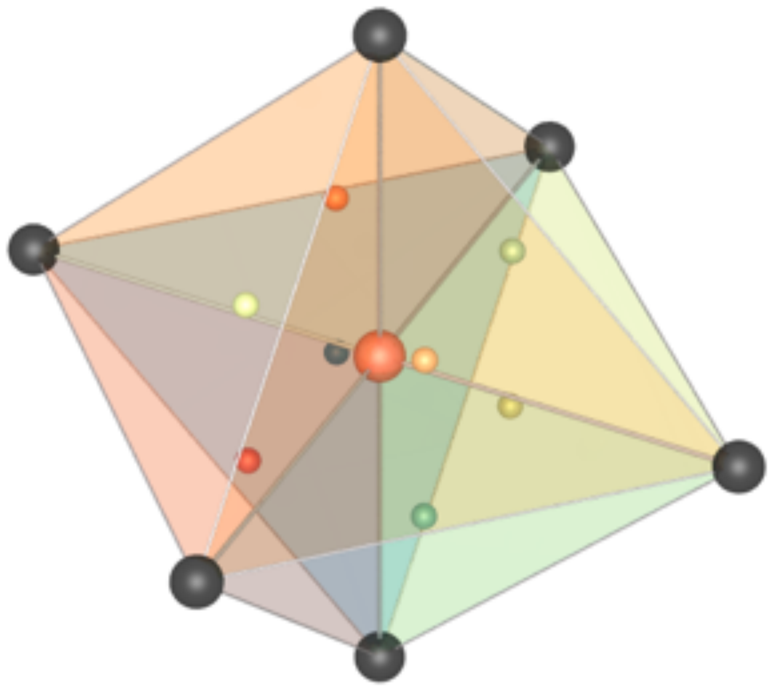
Kaehler et al. 2012 full tet rendering | Adaptive kernel filtered

Mass is spread out ⇒ fragmentation reduced

Credit: Oliver Hahn

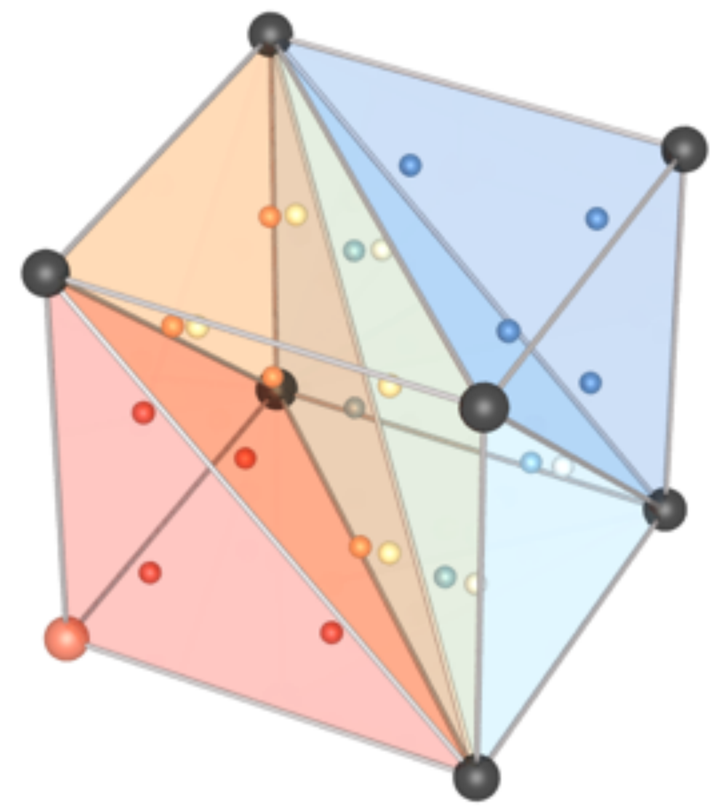
Compute the force due to tetrahedra

- Expensive! -> use pseudo-particle approximation to tets



Monopole approximation

does not capture linear deformations w.r.t CoM



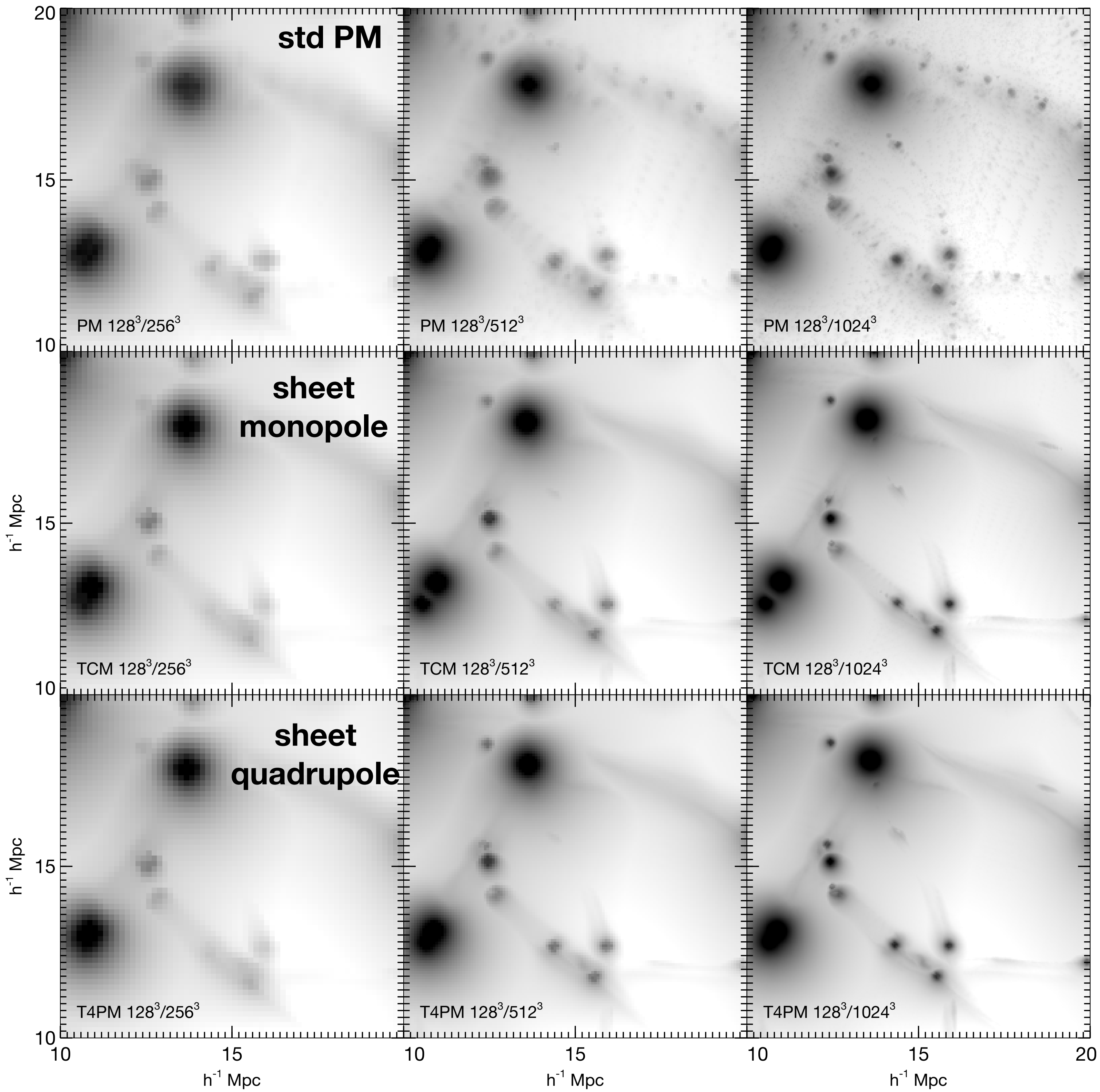
Quadrupole approximation

- use pseudo-particles for mass deposit
- **now 2-kinds of particles -> mass tracer vs. flow tracer particles**

Credit: Oliver Hahn

300eV toy WDM problem

fixed mass resolution, varying force resolution:



force res. →

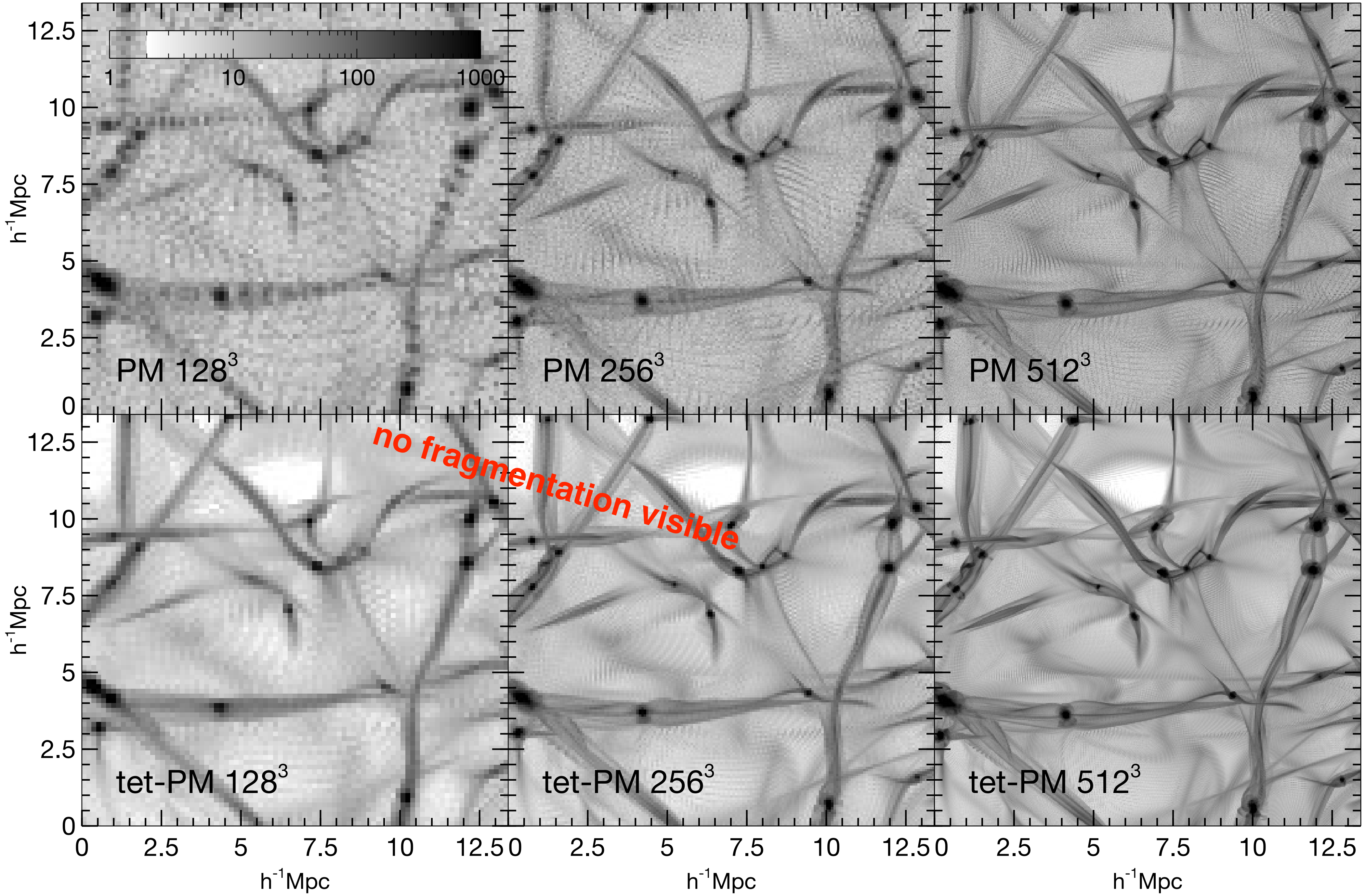
features become sharper
fragmentation appears

sheet tesselation
based method cures
artificial fragmentation

Credit: Oliver Hahn

300 eV toy problem cosmological run

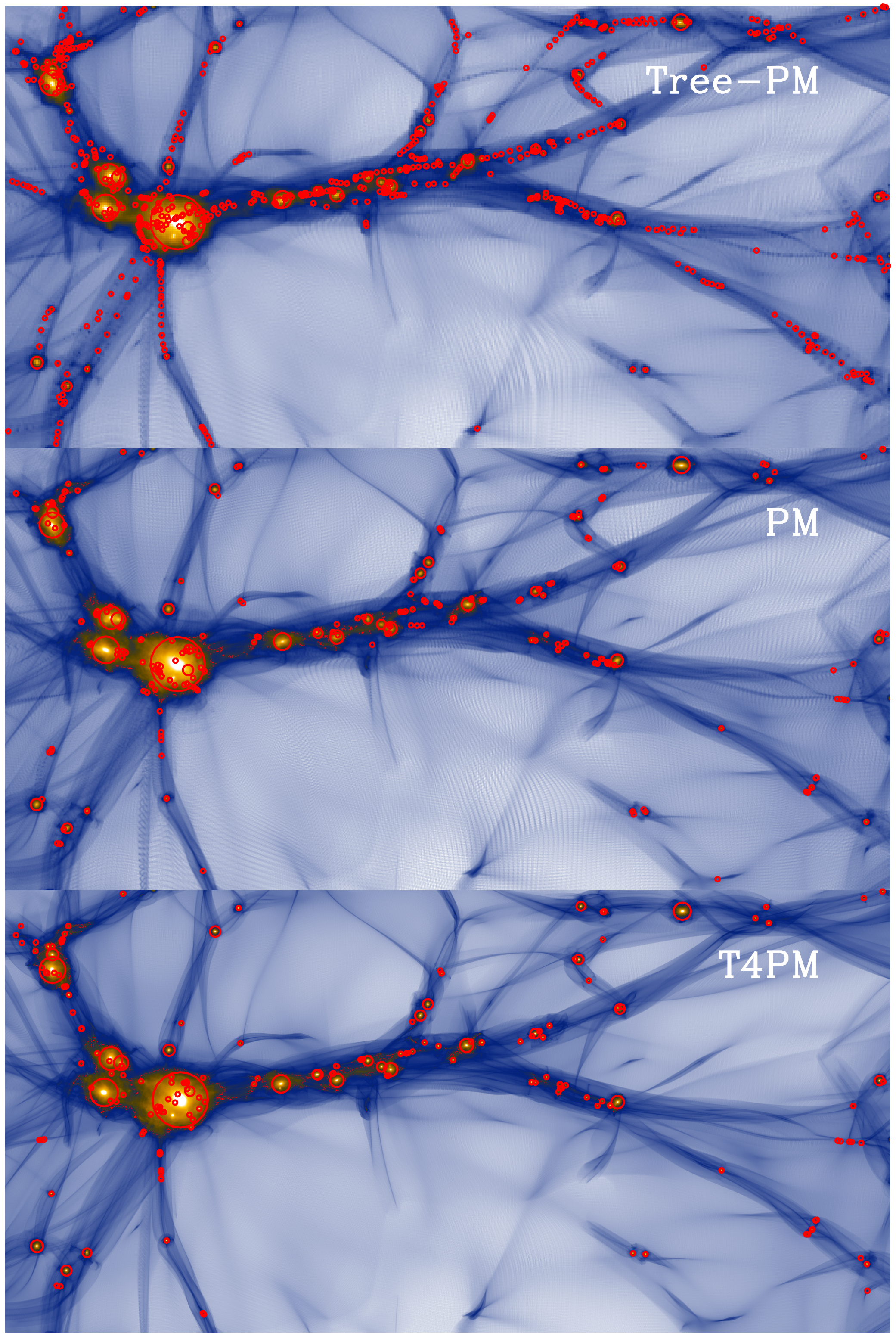
fixed force, varying mass resolution:

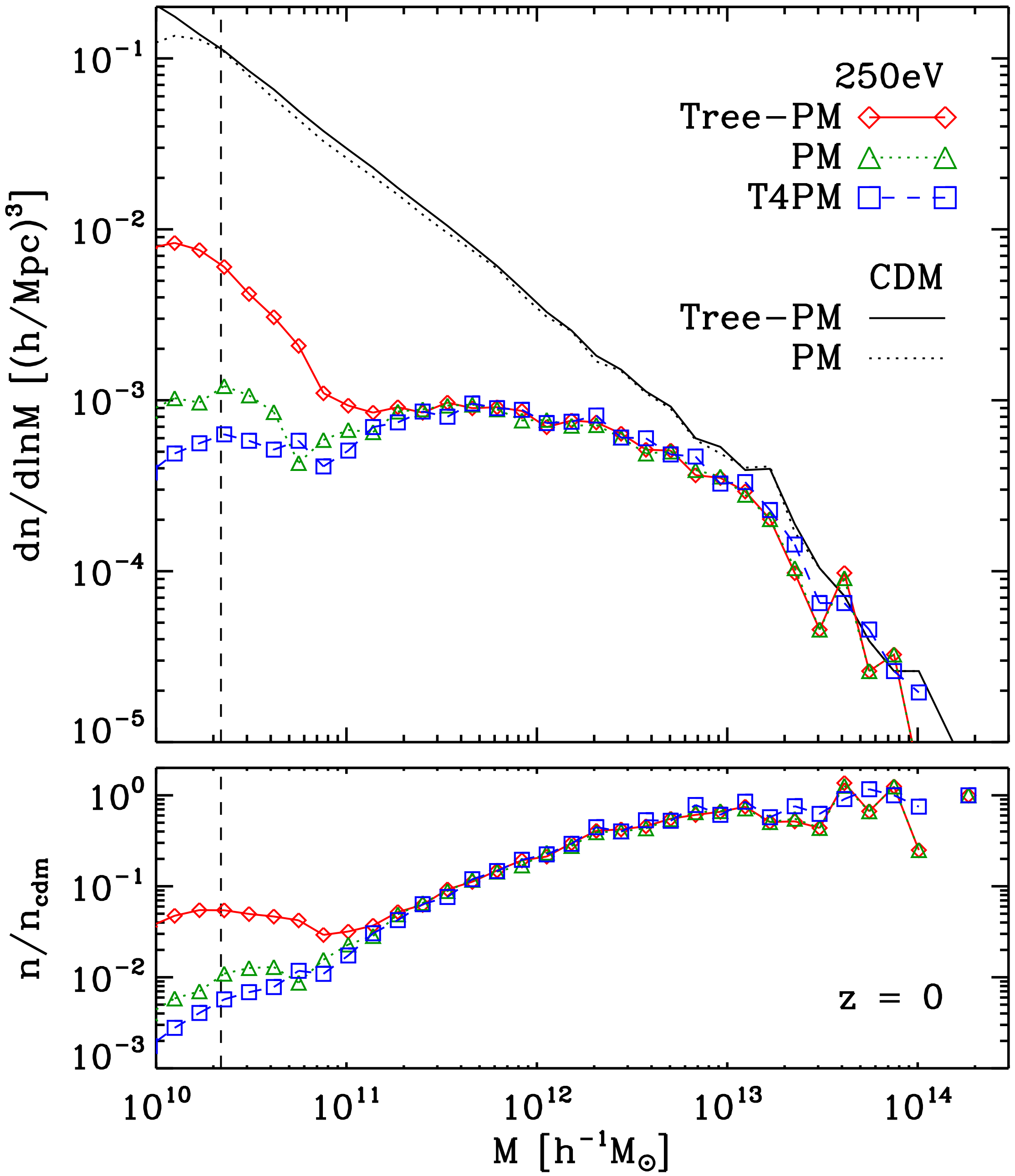


mass functions problematic,
no halo finder works really well

Credit: Oliver Hahn

First determination of WDM halo mass function!

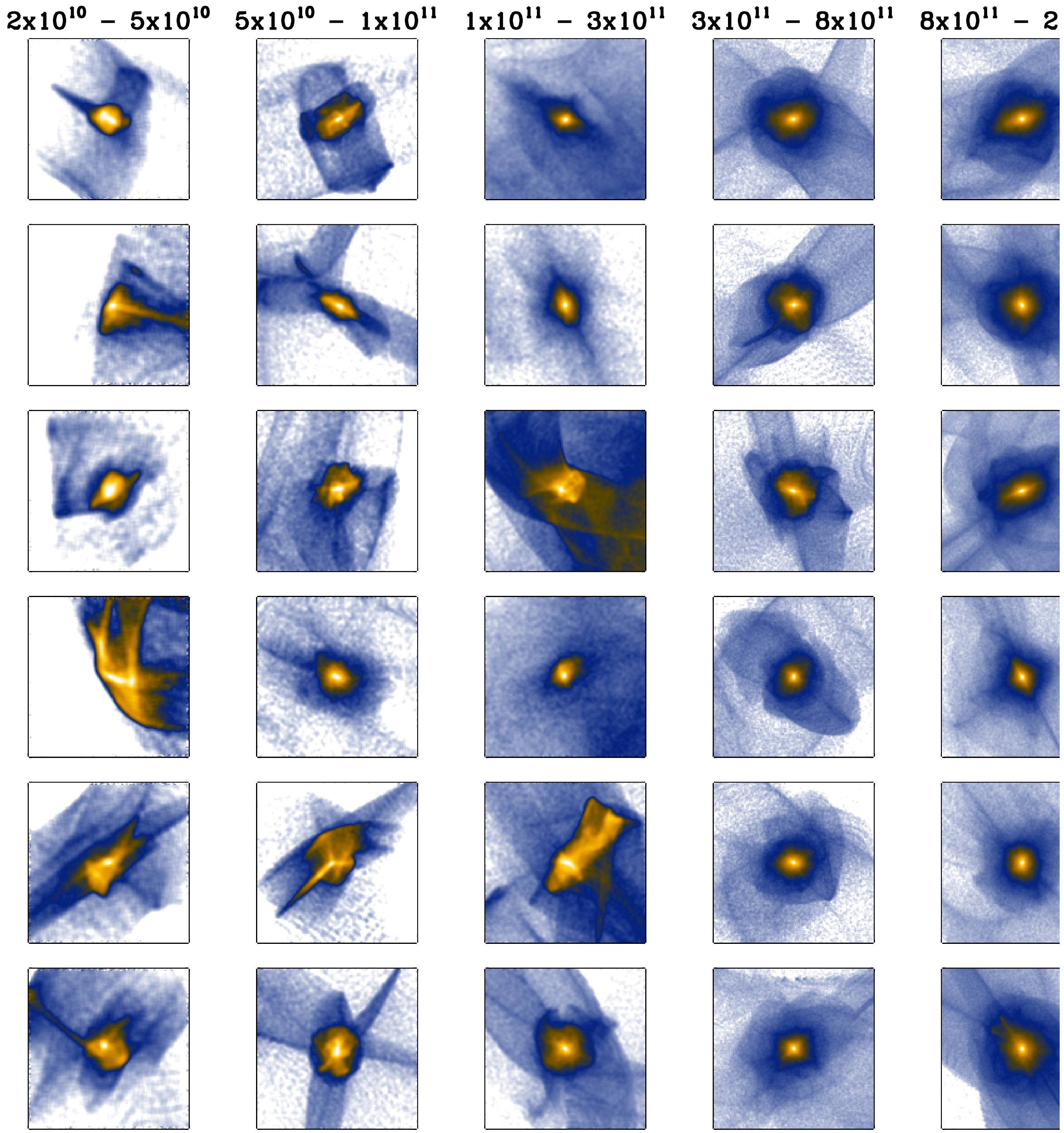


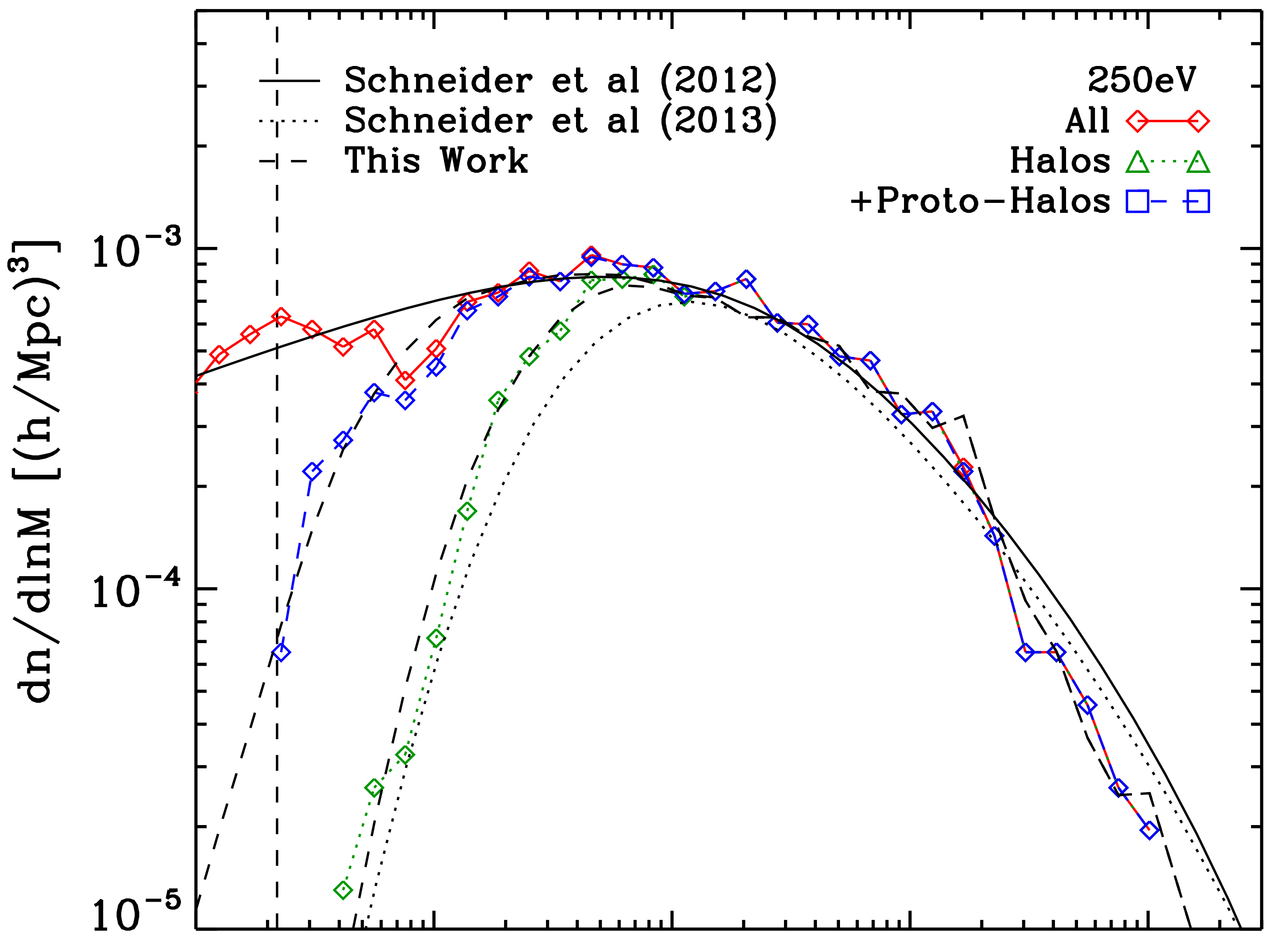


Angulo, Hahn & Abel 2013

Credit: Oliver Hahn

Structures at different masses...





Are at different stages of formation...

Credit: Oliver Hahn

Formation of a halo at the truncation scale

Conclusions

- Latest simulations of dwarf galaxies have attempted to solve outstanding issues with CDM, namely cusp / core profiles, the missing satellite problem, and the too-big-to-fail problem

- Latest simulations of Milky-Way size galaxies are beginning to address issues of mass-concentration, highly-peaked oration curves, Mstar / Mhalo, etc. They suggest the existence of a dark disk, and displacements of the central dark matter cusp.

- Novel N-body approaches are beginning to remove clumping issues with warm dark matter.