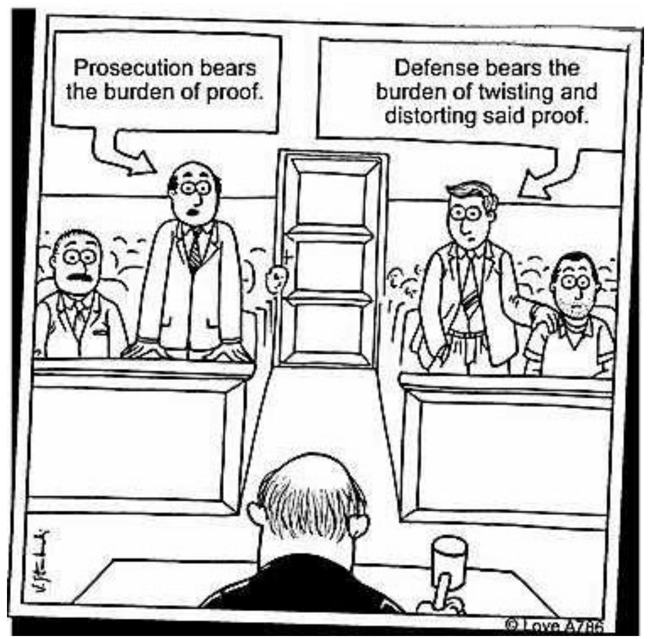
Alexander Knebe (*Universidad Autonoma de Madrid*)

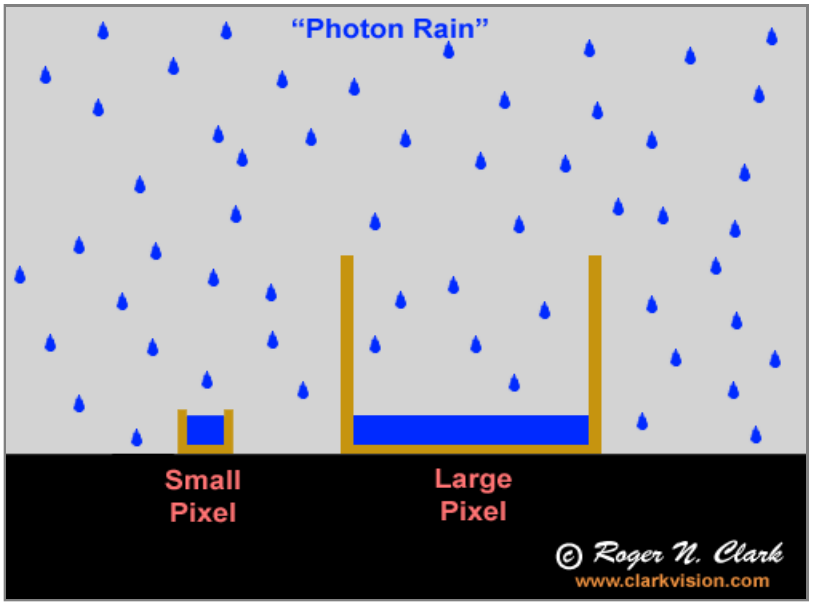


- CDM in crisis?

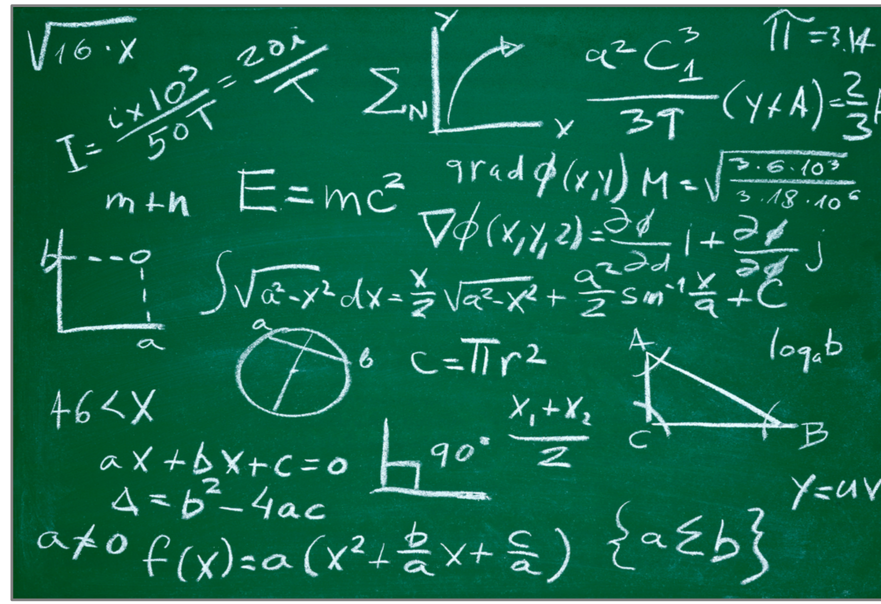
- solutions beyond the concordance model

- **CDM in crisis?**

- solutions beyond the concordance model observations



theory



observations

Keck telescopes (Mauna Kea)

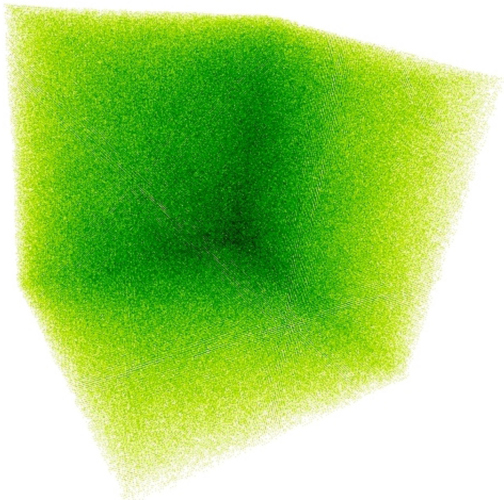
theory

Jaguar Cray XT (Oak Ridge National Lab), Top #1 June 2010

Computational Cosmology

Computational Cosmology

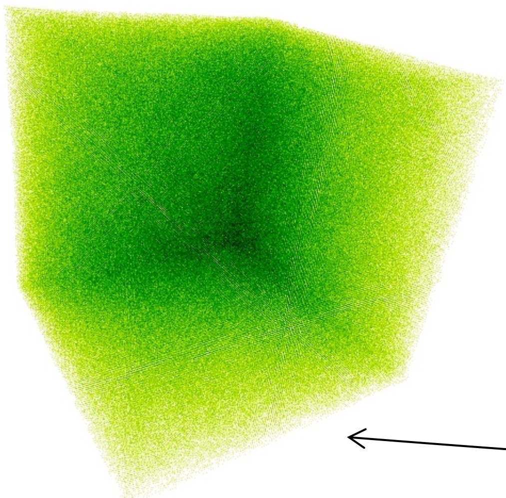
- simulation of cosmic structure formation – *initial conditions*

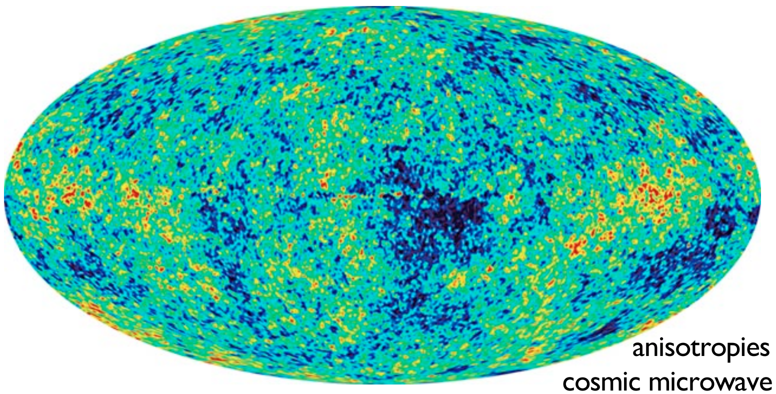


1. primordial matter density field

Computational Cosmology

- simulation of cosmic structure formation – *initial conditions*





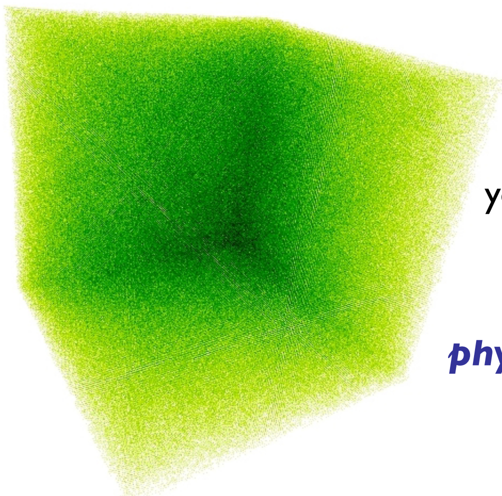
anisotropies in the
cosmic microwave background

physics of "the early Universe"

1. primordial matter density field

Computational Cosmology

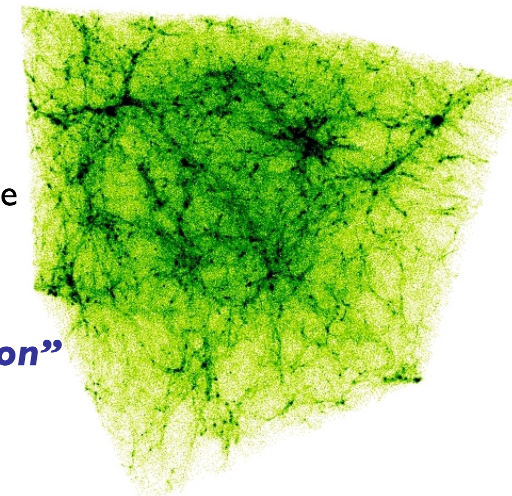
- simulation of cosmic structure formation – *temporal evolution*



1. primordial matter density field

your favourite simulation code →

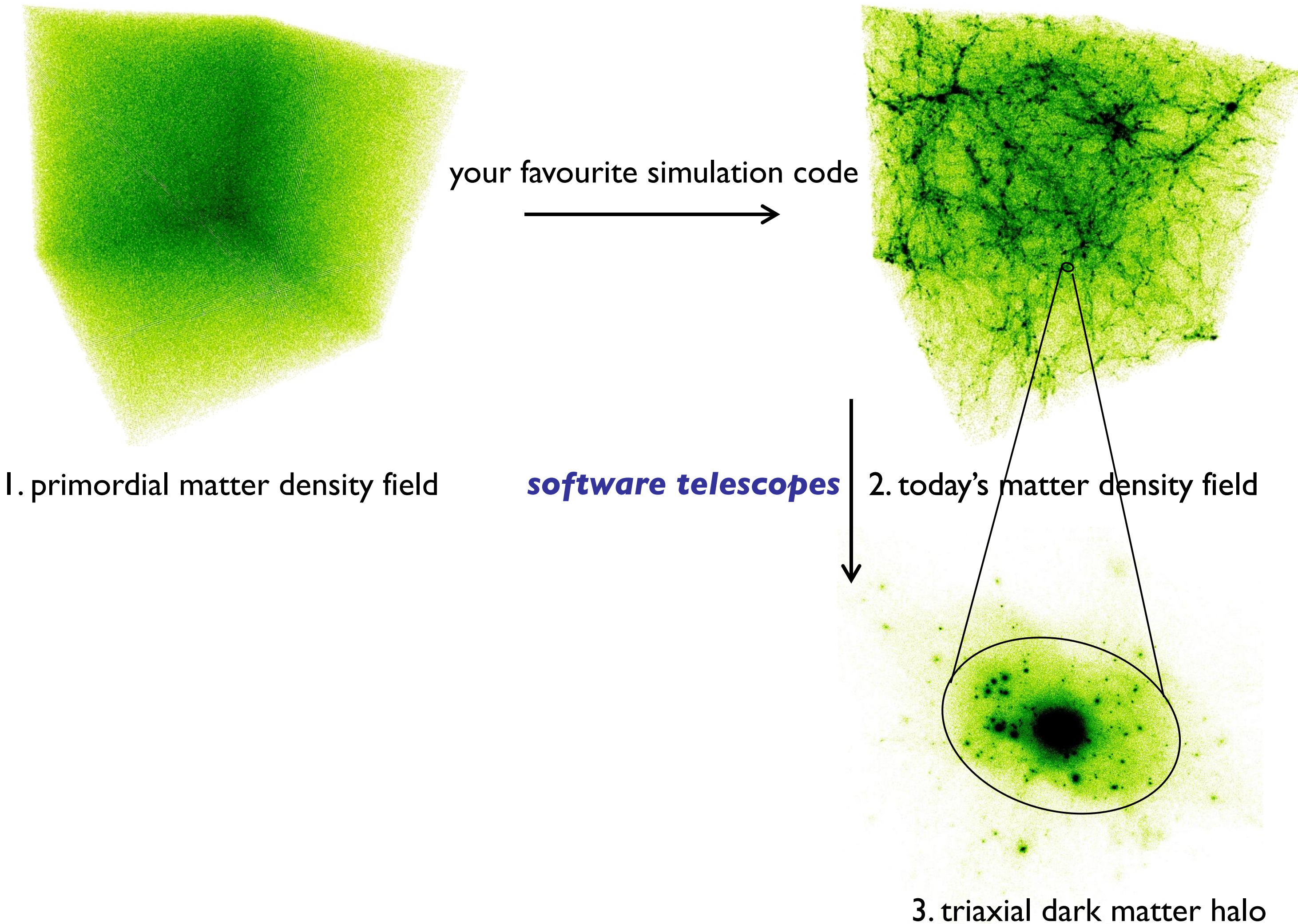
physics of "galaxy formation"



2. today's matter density field

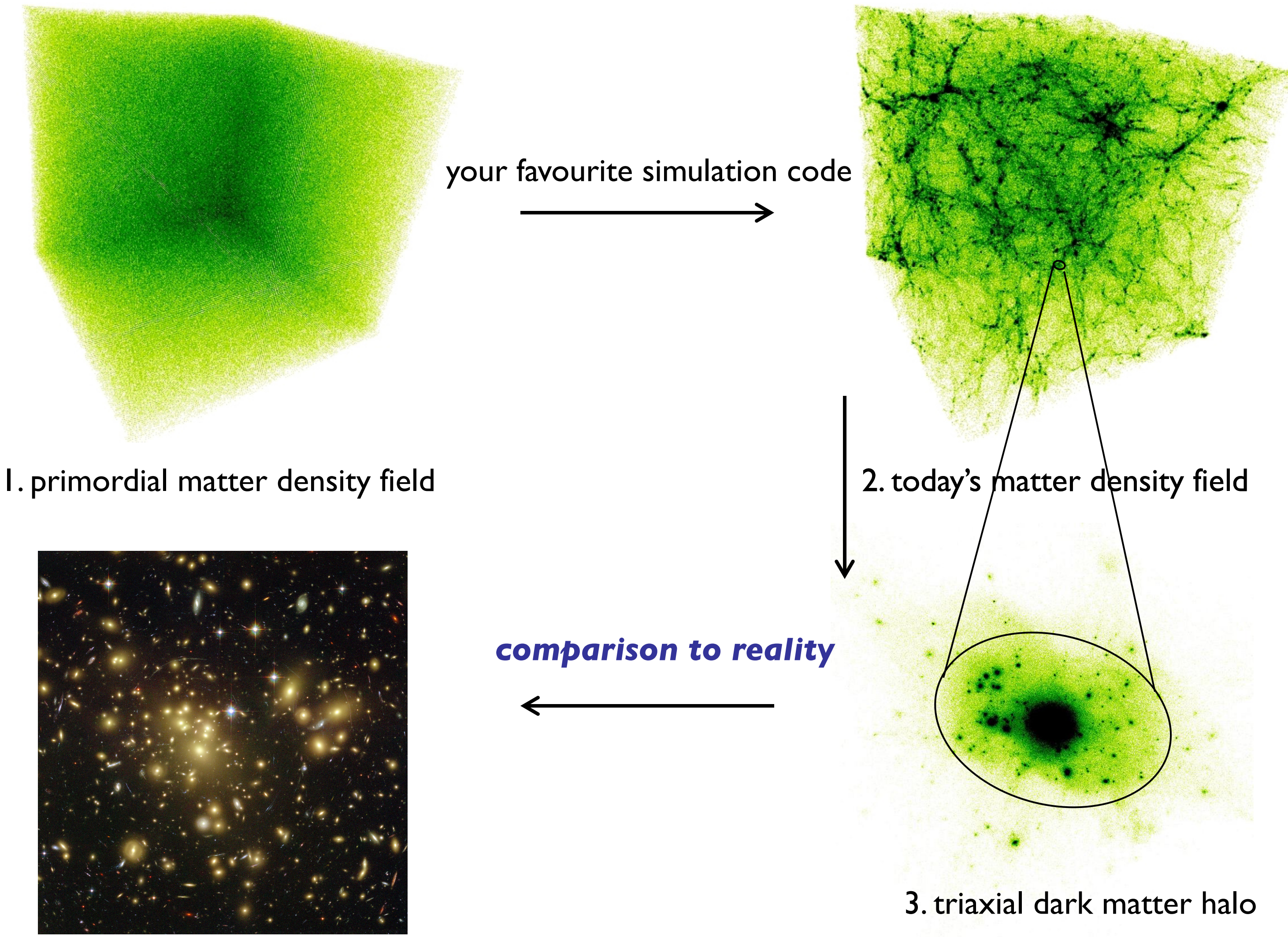
Computational Cosmology

- simulation of cosmic structure formation – *analysis of outputs*



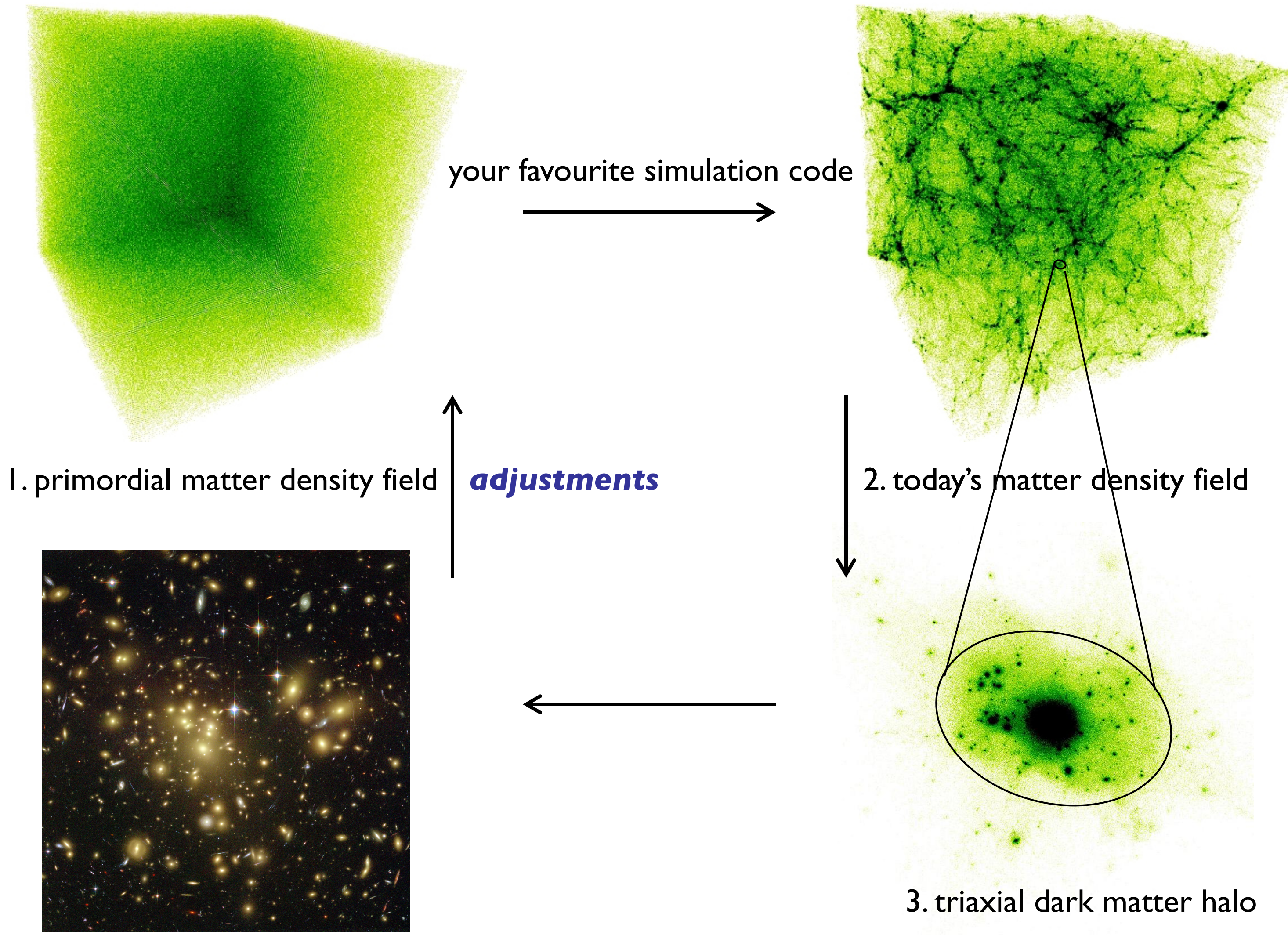
Computational Cosmology

- simulation of cosmic structure formation – *analysis of outputs*



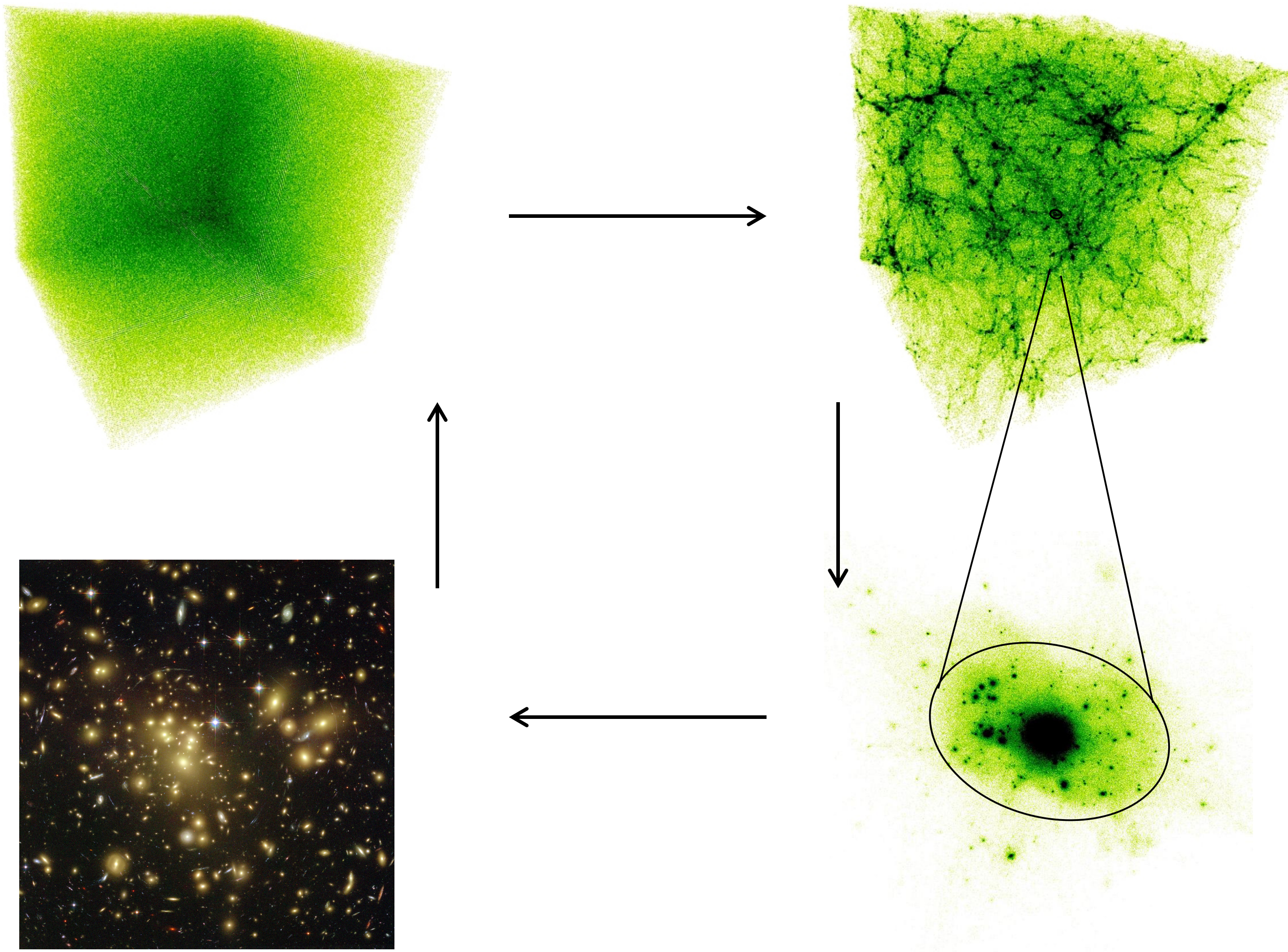
Computational Cosmology

- simulation of cosmic structure formation – *feedback!?*



Computational Cosmology

- simulation of cosmic structure formation



Computational Cosmology

observations

theory

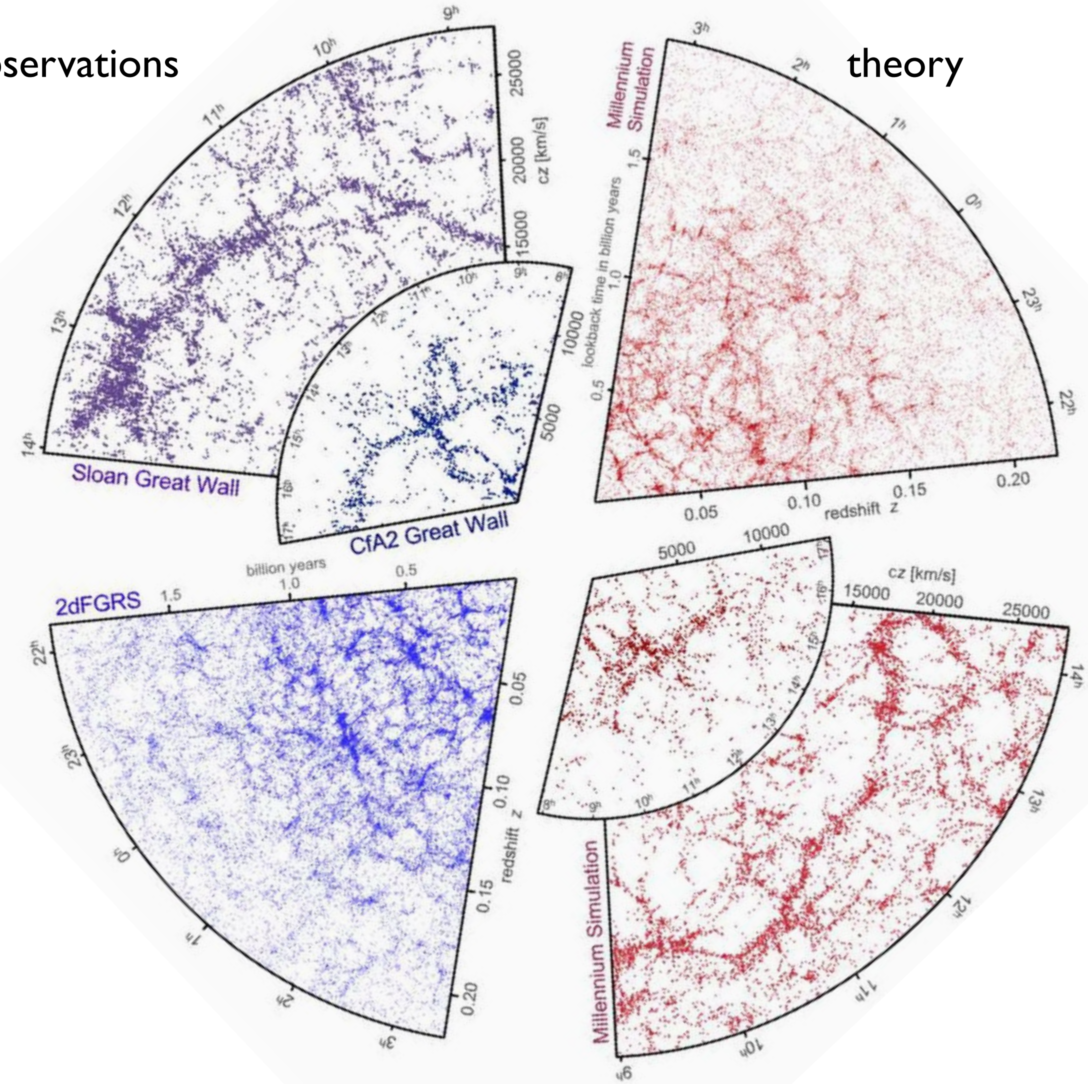
Keck telescopes (Mauna Kea)

Jaguar Cray XT (Oak Ridge National Lab), Top #1 June 2010

Computational Cosmology

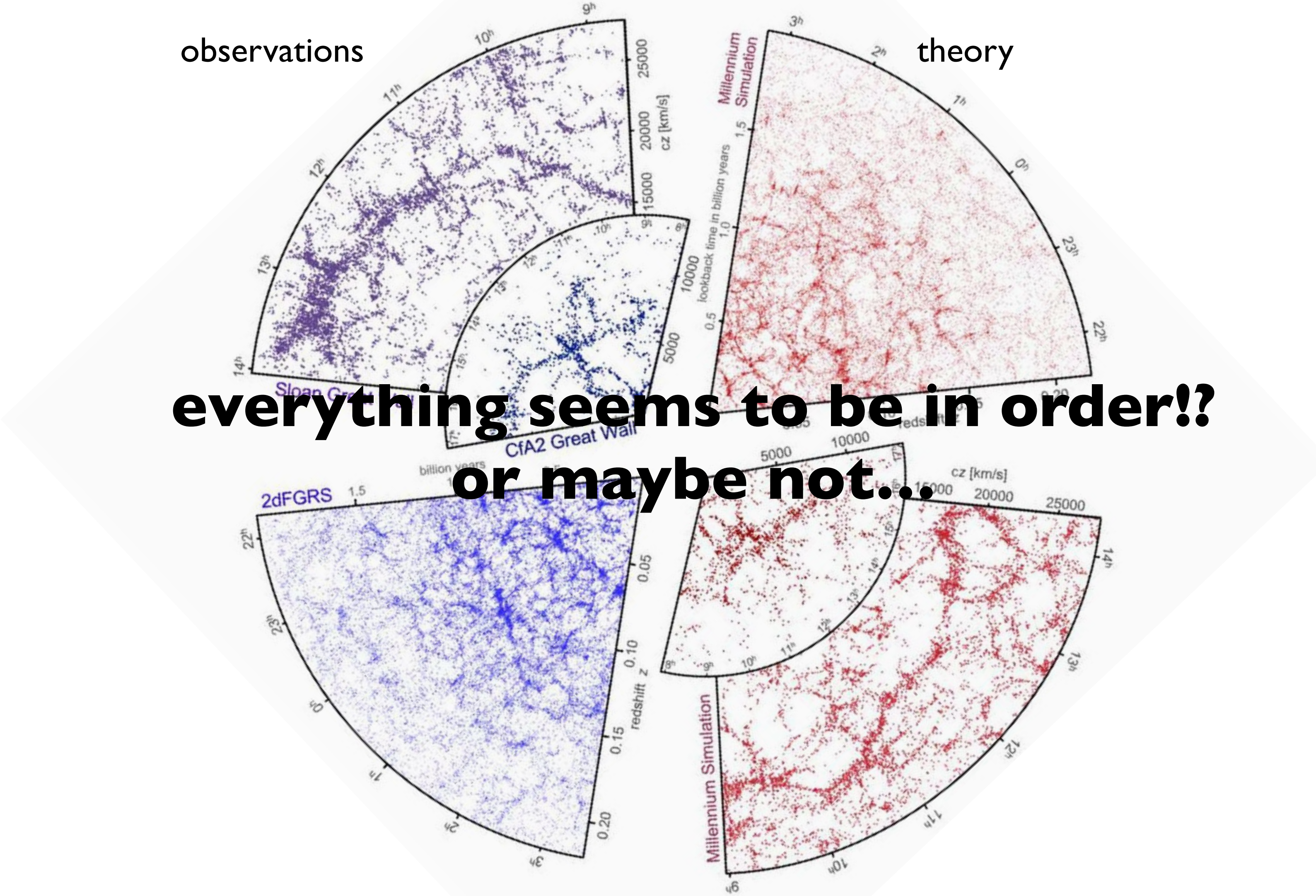
observations

theory



Computational Cosmology

observations theory



everything seems to be in order!?

or maybe not...

- the cusp-core problem
- satellite galaxies
- bulge-less disk galaxies
- the Council of Giants
- speeding bullets
- El Gordo
- Hubble tension

- the nature of dark matter?
- the nature of dark energy?

- the cusp-core problem
- satellite galaxies
- bulge-less disk galaxies

most recent review article on this:
Bullock & Boylan-Kolchin (2017)
https://www.annualreviews.org/doi/10.1146/annurev-astro-091916-055313

- El Gordo
- Hubble tension

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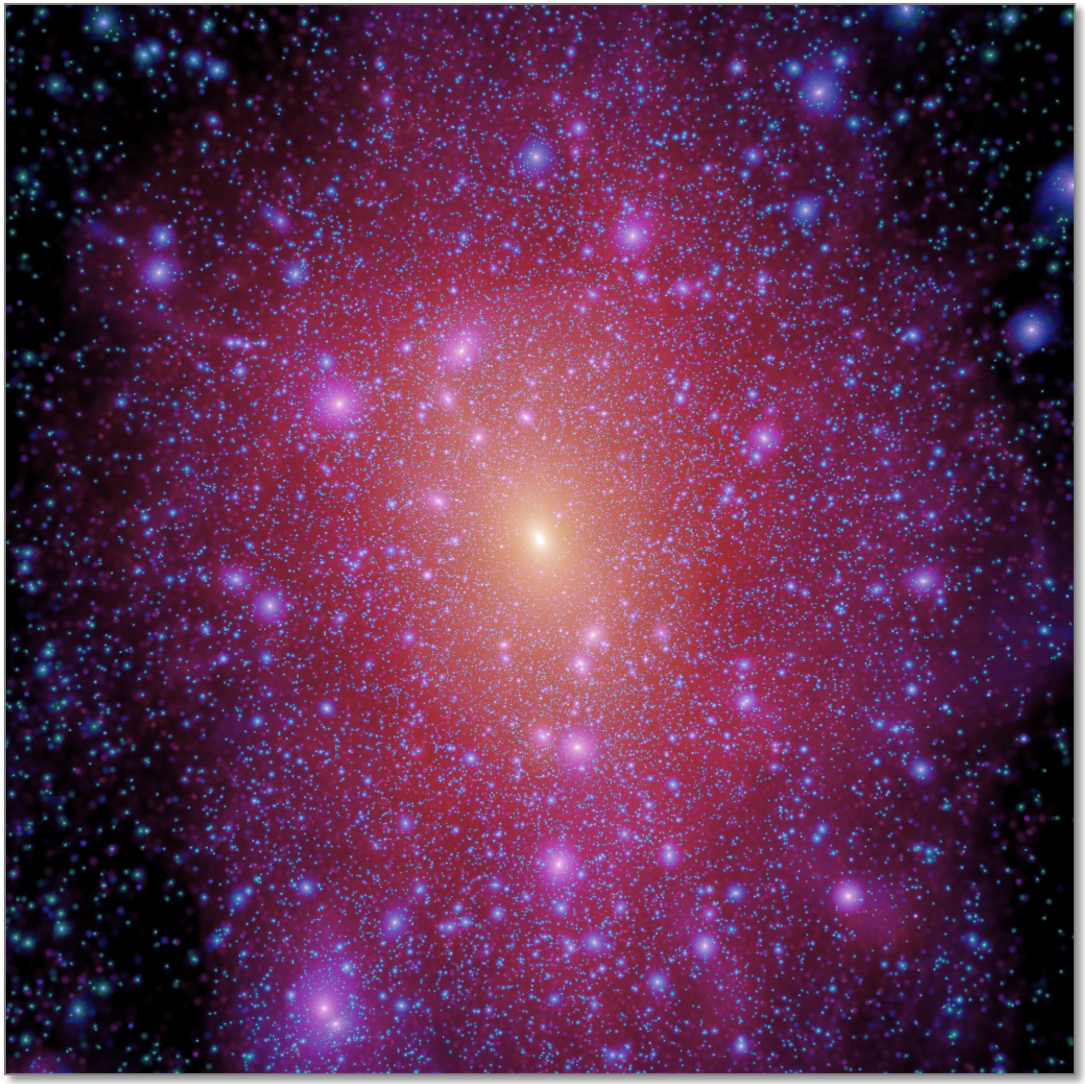
ΛCDM claims central density cusps: $\rho^{DM}_{central}(r) \propto r^{\alpha} \quad ; \alpha < 0$



(dark matter halo ‘Aquarius-A‘, Springel et al. 2008)

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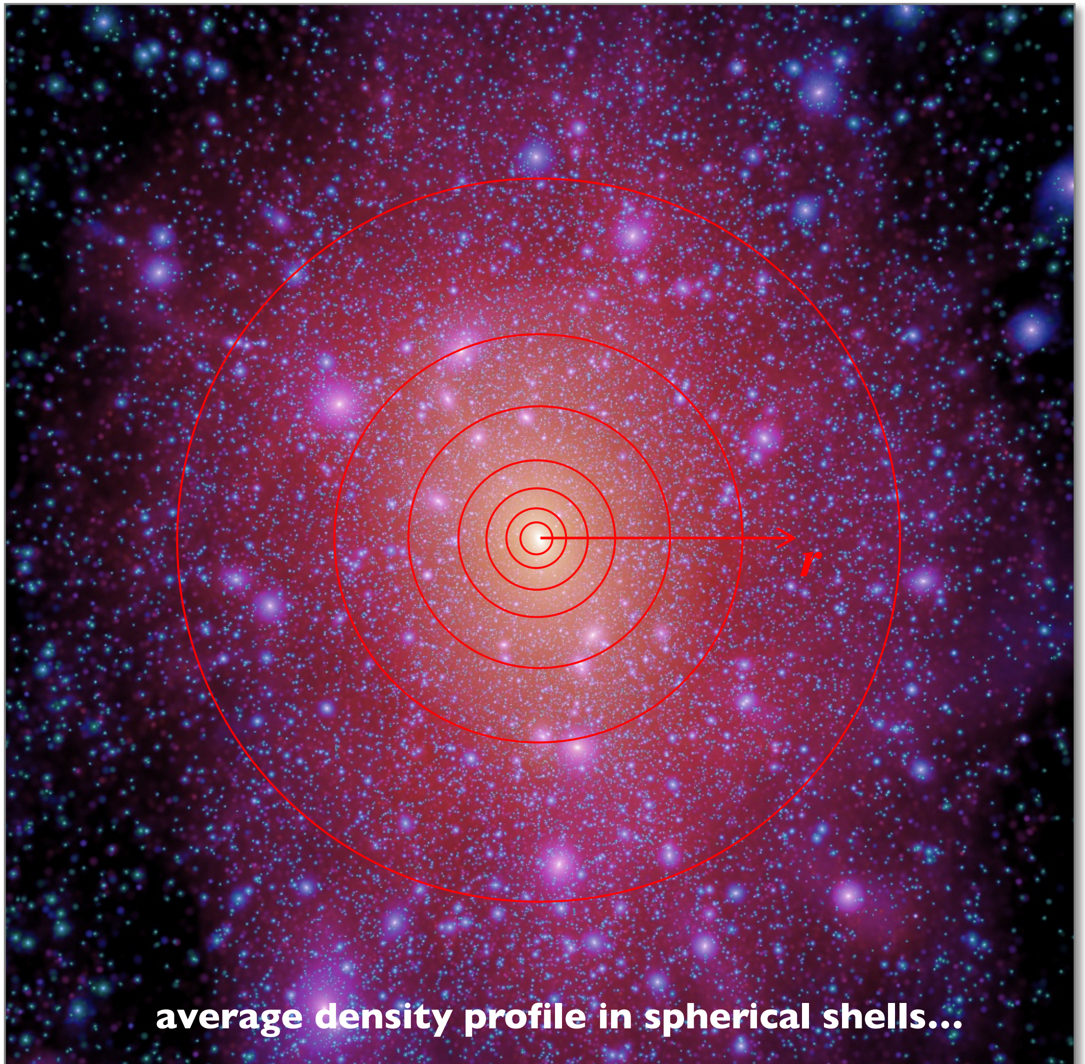

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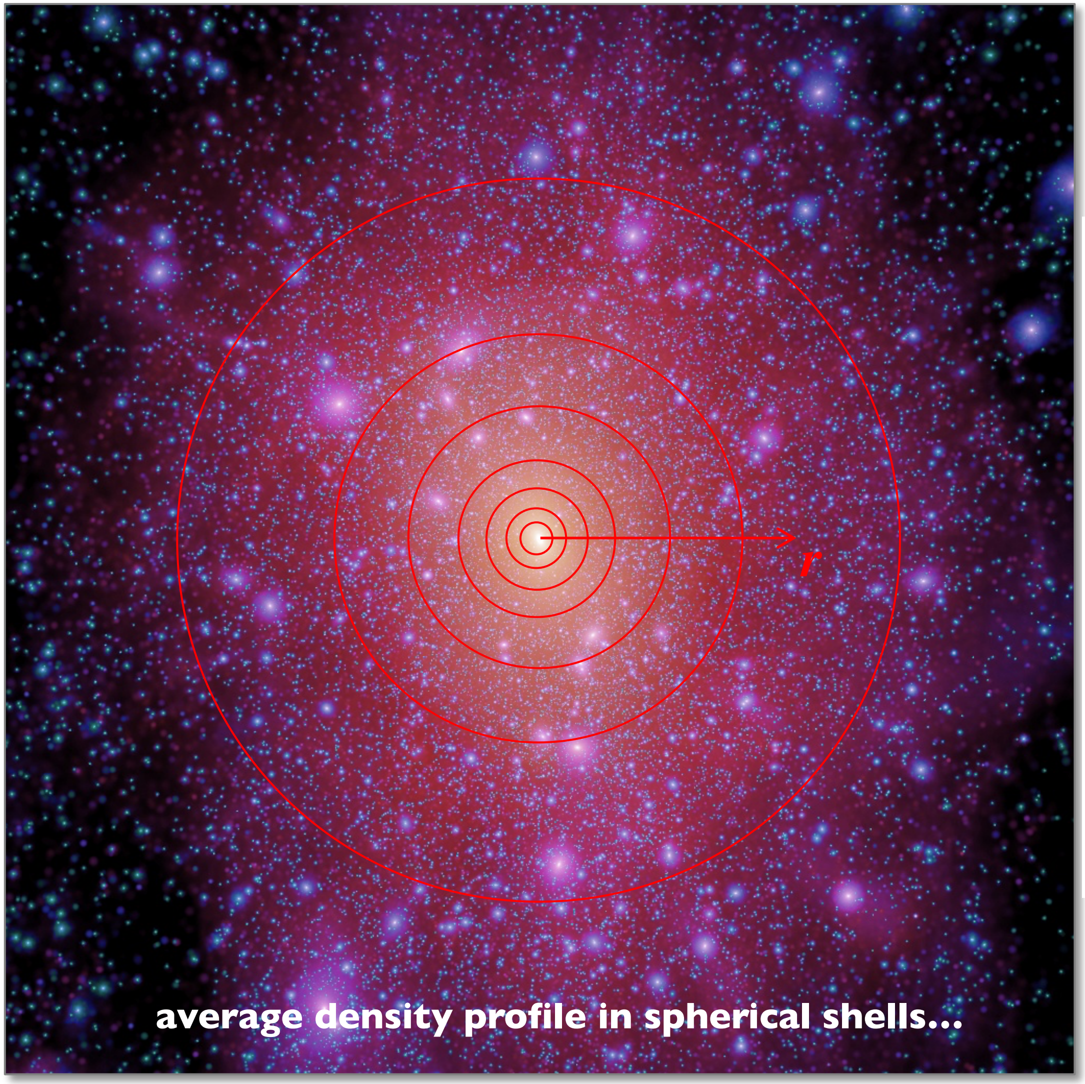
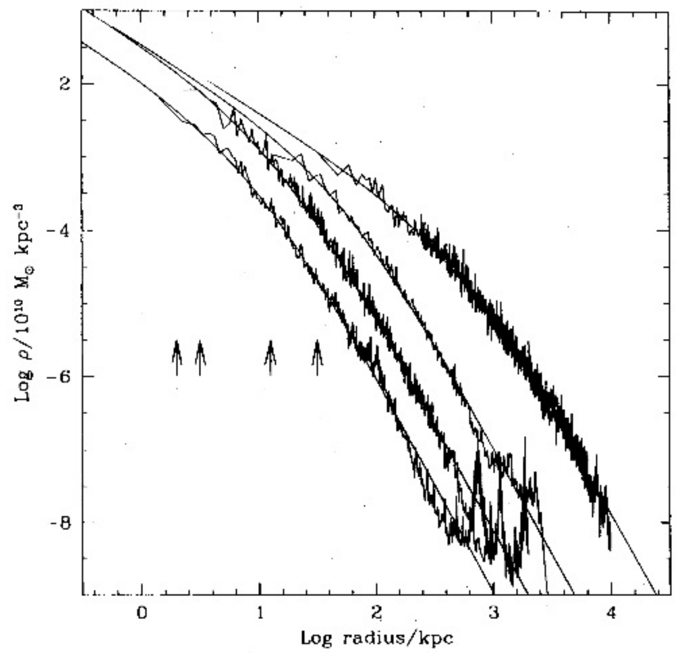


(dark matter halo 'Aquarius-A', Springel et al. 2008)

(Navarro, Frenk & White 1996)

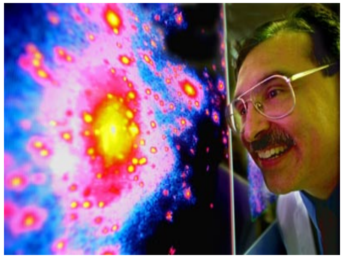


ΛCDM claims central density cusps: $\rho_{central}^{DM}(r) \propto r^{\alpha} \quad ; \alpha < 0$

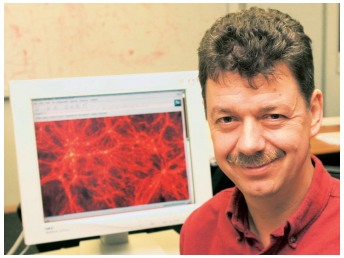
Navarro, Frenk & White (1996): a universal density profile!?

$$\frac{\rho(r)}{\rho_{crit}} = \frac{\delta_c}{(r/r_s)(1+r/r_s)^2}$$

N

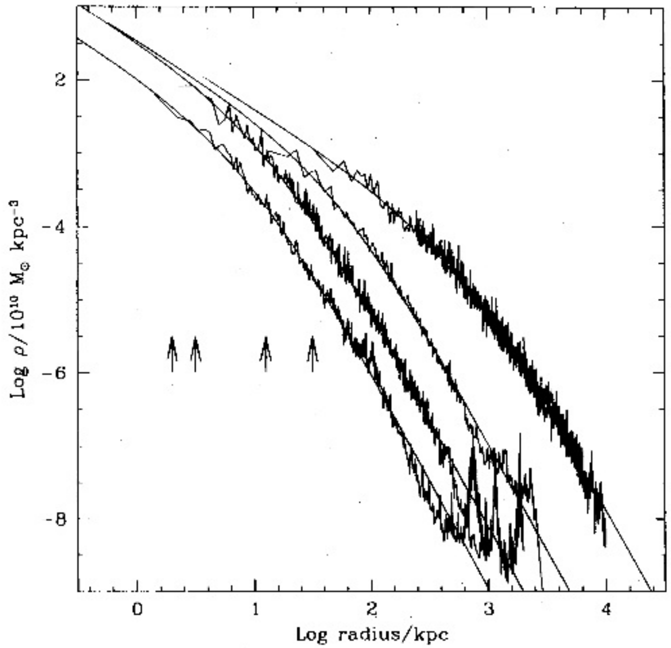


F



W

(Navarro, Frenk & White 1996)



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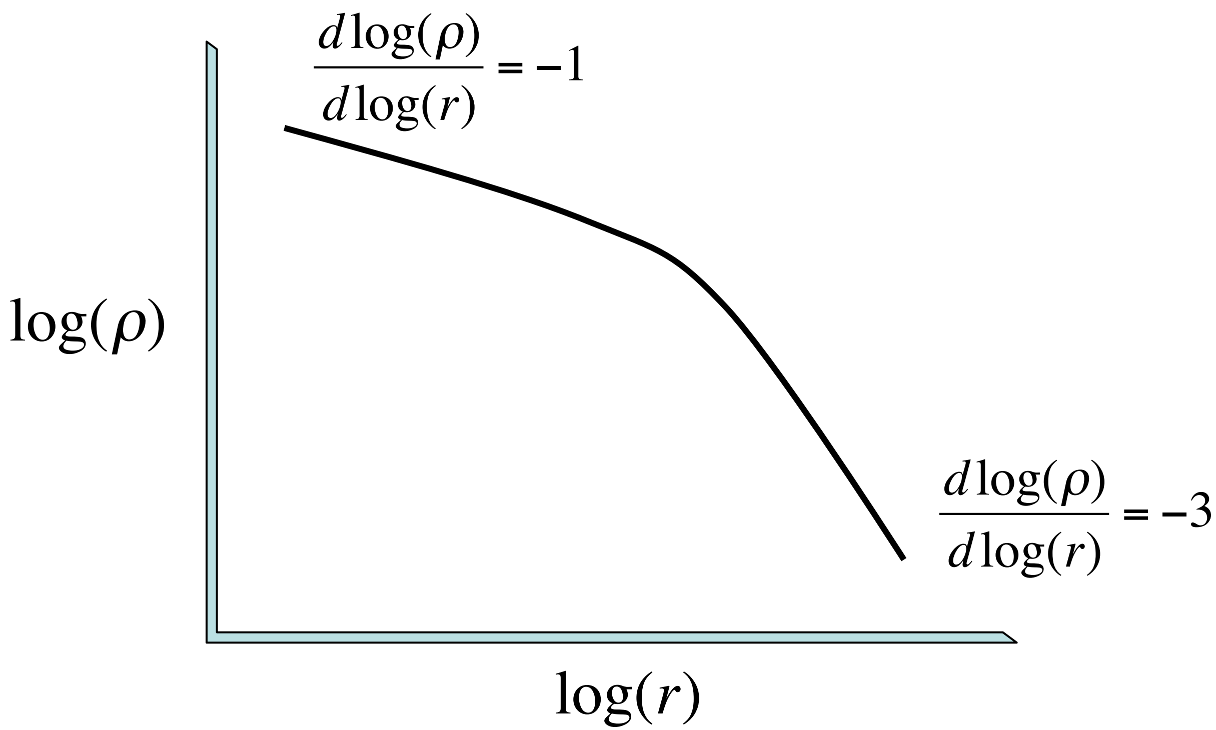


ΛCDM claims central density cusps: $\rho^{DM}_{central}(r) \propto r^{\alpha} \quad ; \alpha < 0$

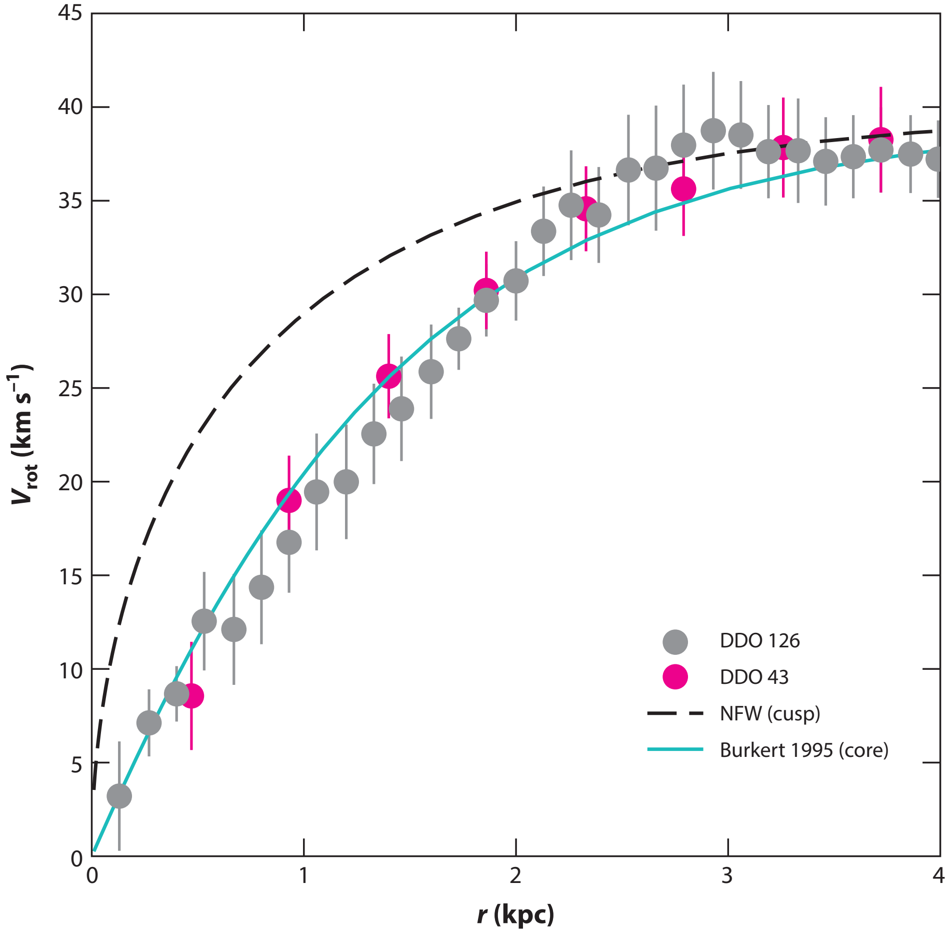
e.g.,

Navarro, Frenk & White (1996, 1997):	$\alpha = -1$
Moore (1999):	$\alpha = -1.5$
Ghigna (2000):	$\alpha = -1.5$
Fukushige & Makino (2001):	$\alpha = -1.5$
Dahle, Hannestad, Sommer-Larsen (2003):	$\alpha = -(0.9\text{-}1.6)$
Power et al. (2003):	$\alpha = -1.2$
Ricotti (2003):	$\alpha = -(1\text{-}1.4)$
Fukushige, Kawai & Makino (2004):	$\alpha < -1.5$
Tasitsiomi et al. (2004):	$\alpha = -1.2$
Hayashi et al. (2004):	$\alpha \approx -1.0$
Diemand, Moore & Stadel (2004):	$\alpha = -1.16$
Navarro et al. (2004):	$\alpha = \alpha(r)$
Caimmi, Marmo & Valentinuzzi (2005):	$\alpha = -1$
Reed et al. (2005):	$\alpha = -1.4$
Diemand et al. (2005):	$\alpha = -1.2$
…	

ΛCDM claims central density cusps: $\rho^{DM}_{central}(r) \propto r^{\alpha} \quad ; \alpha < 0$

...but cusps do not comply with the dynamics of galaxies

$$V_{rot}(r) = \sqrt{\frac{G\,M(<r)}{R}}$$



(Bullock & Boylan-Kolchin 2017)

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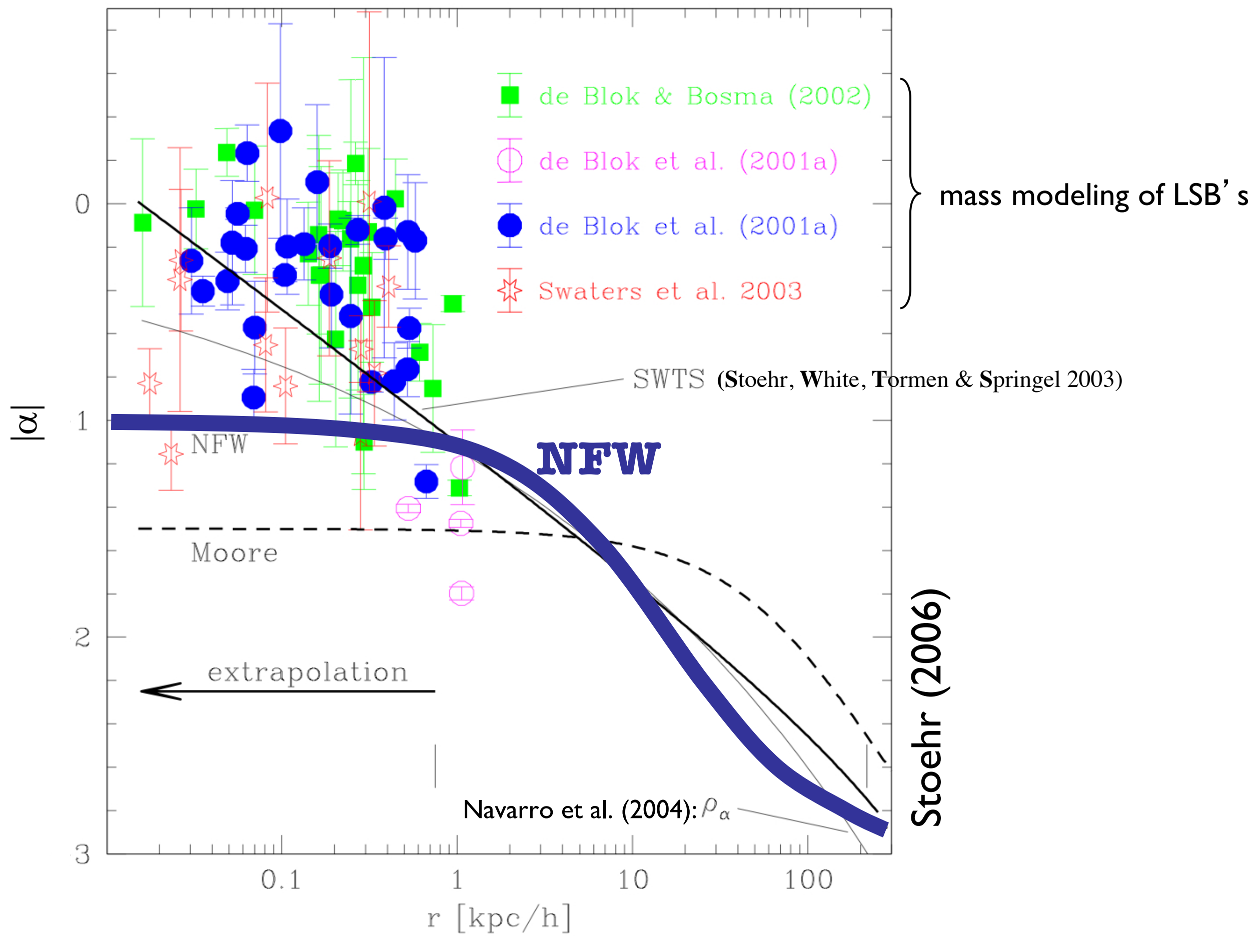

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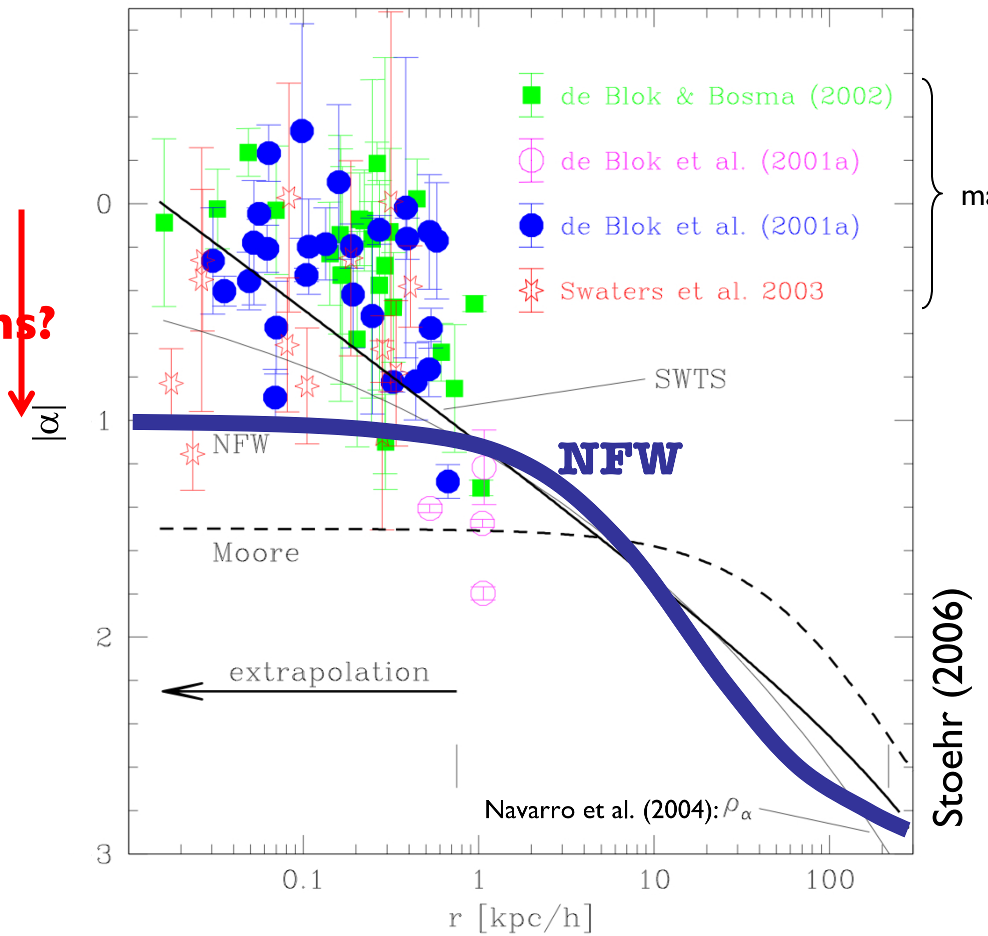
...but cusps do not comply with the dynamics of galaxies

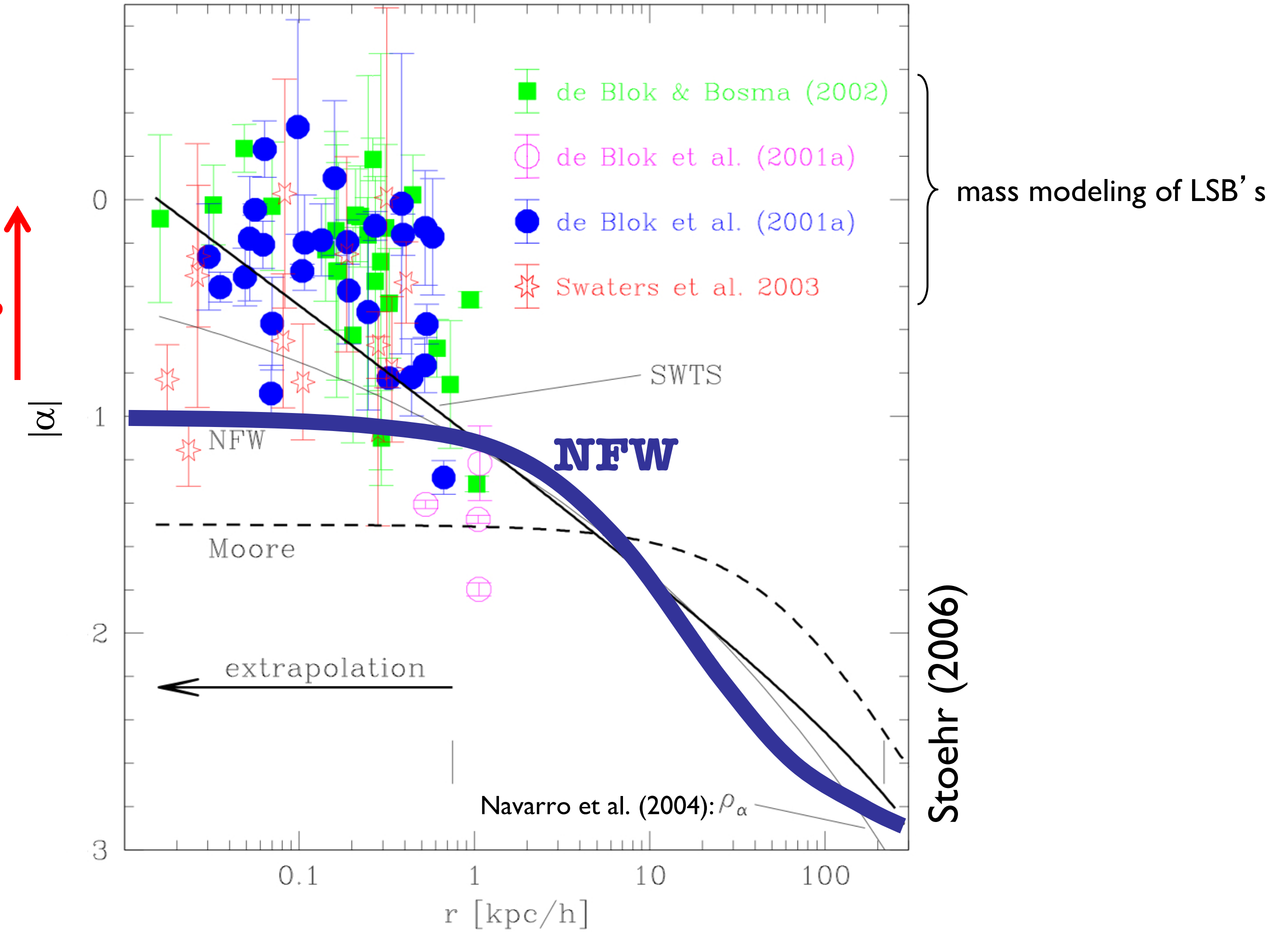
re-interpret the observations?



ΛCDM claims central density cusps: $\rho^{DM}_{central}(r) \propto r^{\alpha} \quad ; \alpha < 0$

...but cusps do not comply with the dynamics of galaxies

adjust CDM models?



Stoehr (2006)

▪ possible solutions

- "stationary": **(e.g. re-interpretation)**
  - triaxial halo
  - non-circular motions (bulge, bar, disk, …)
  - …
- dynamical: **(e.g. adjusting CDM)**
  - adiabatic contraction
  - bar-DM interactions
  - baryonic feedback
  - …
- tinkering with fundamental physics (gravity, WDM, cDE, VDE, …)

- <u>possible solutions</u>

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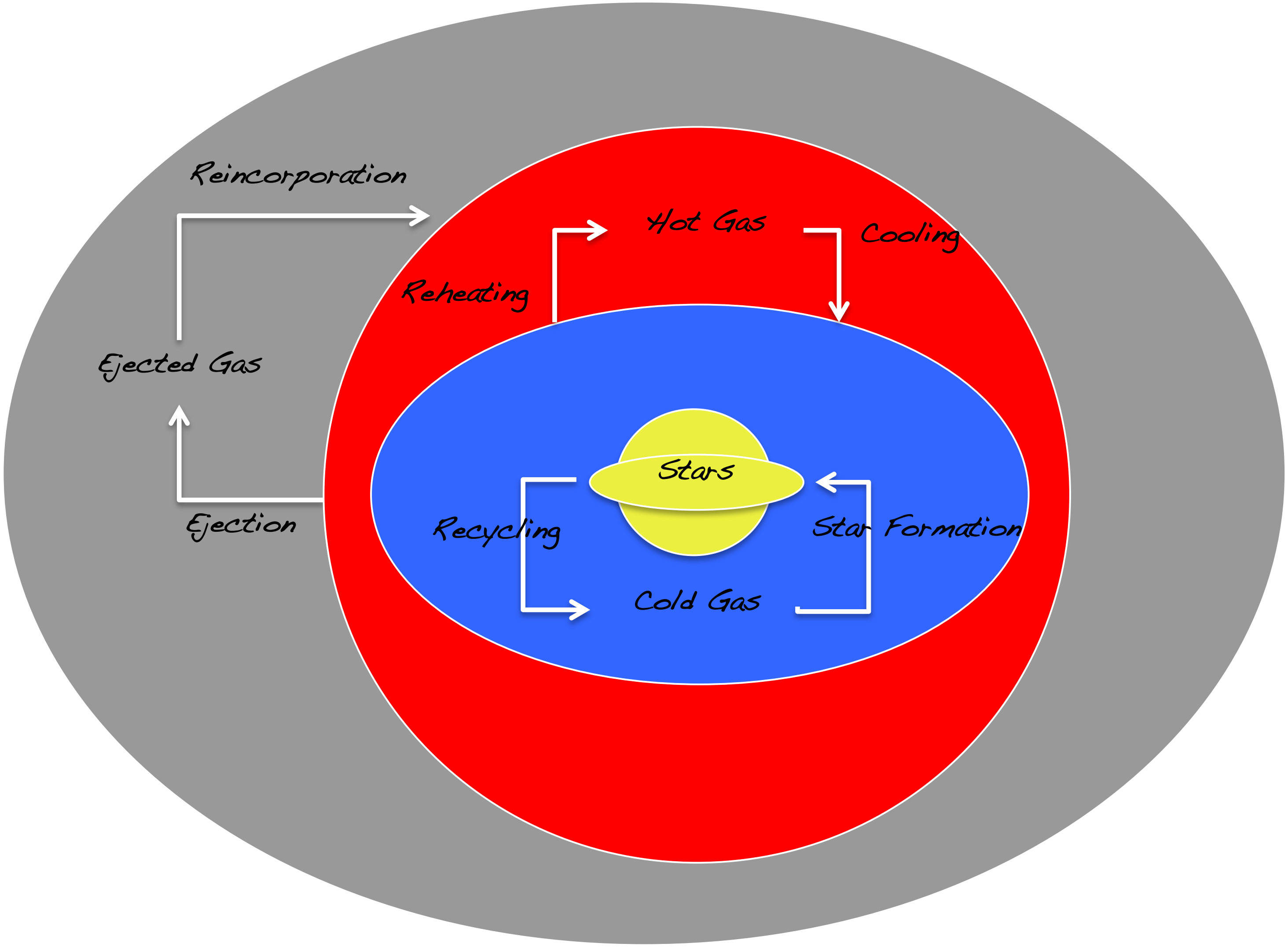
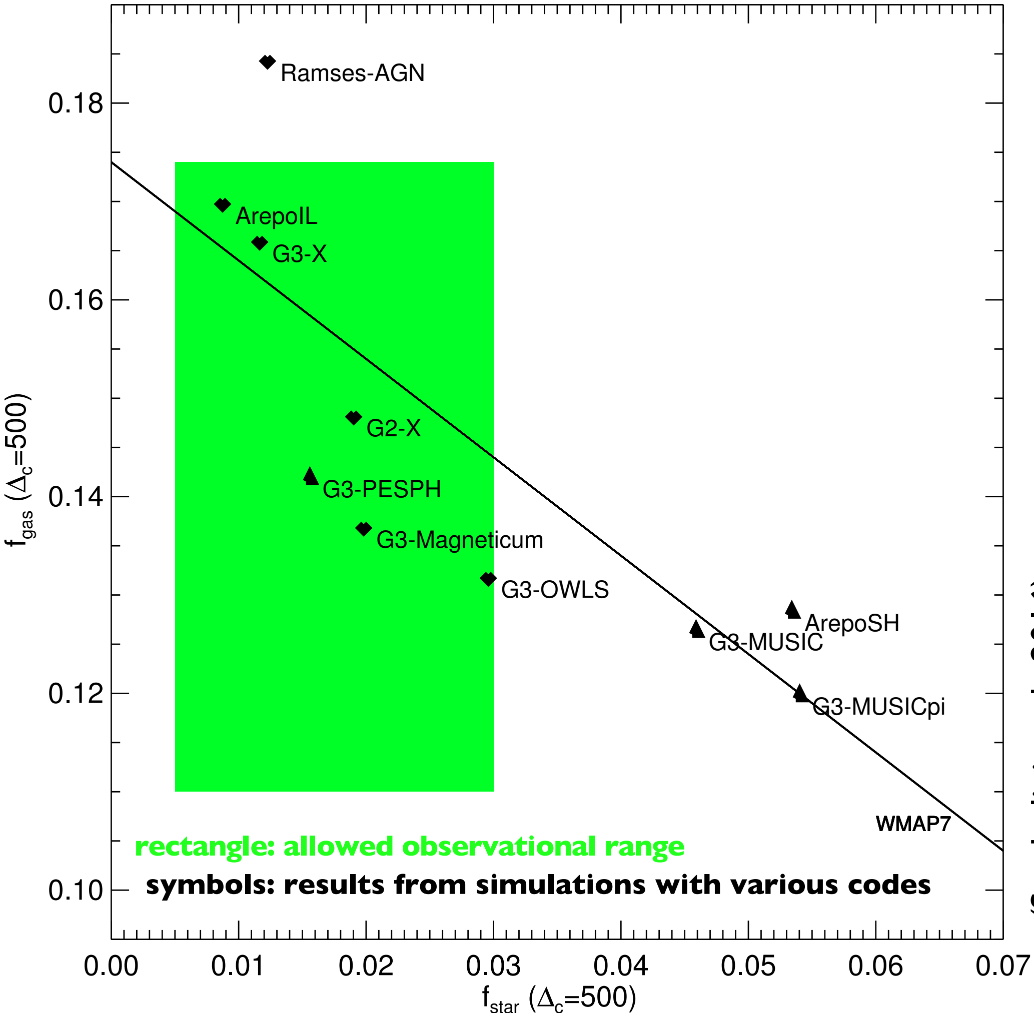
    } original $\rho(r) \neq$ present-day $\rho(r)$ due to ***baryonic processes***

  - tinkering with fundamental physics (gravity, WDM, cDE, VDE, …)

- possible solutions: ***baryonic processes***

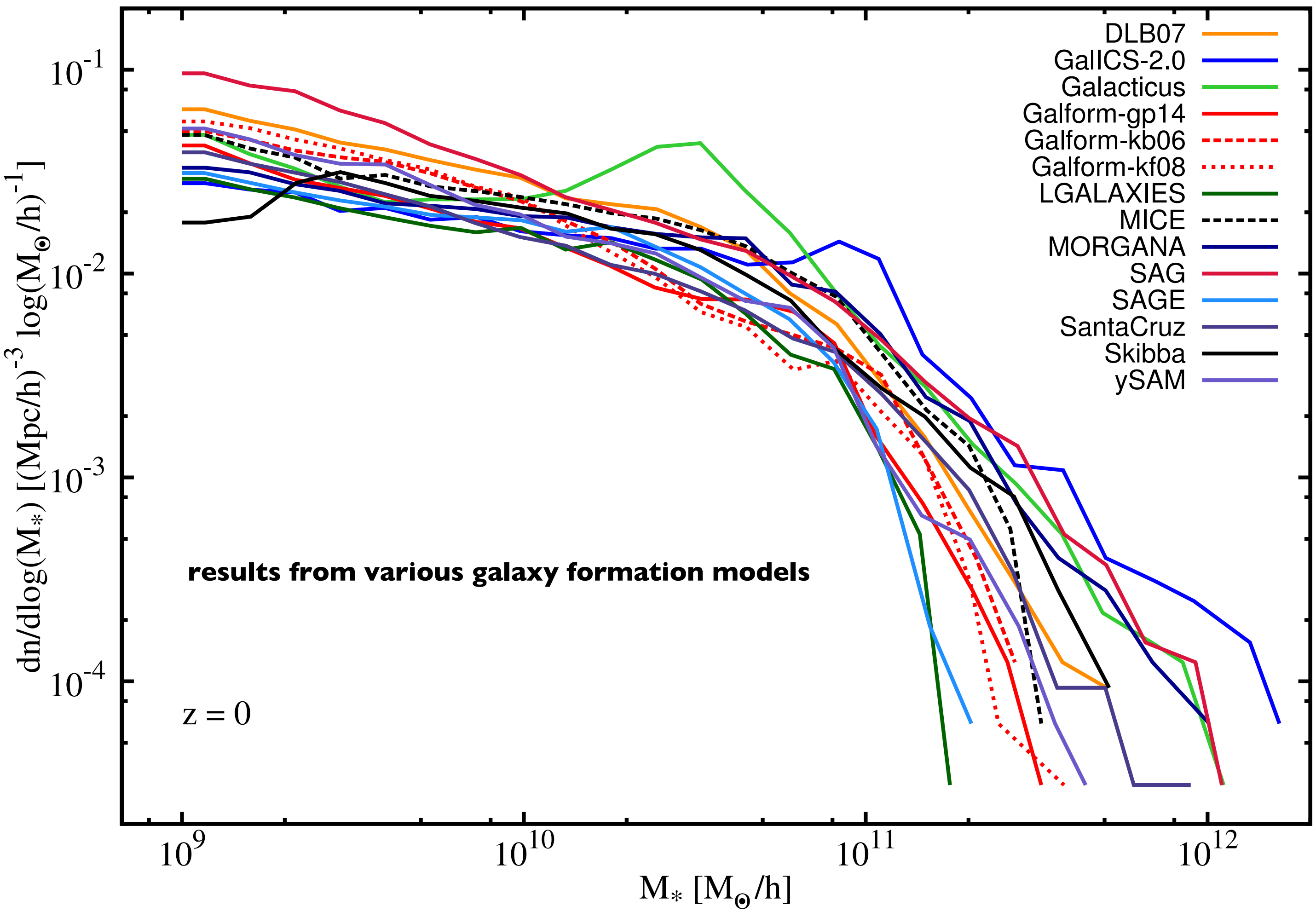


▪ possible solutions: ***baryonic processes are very complex***



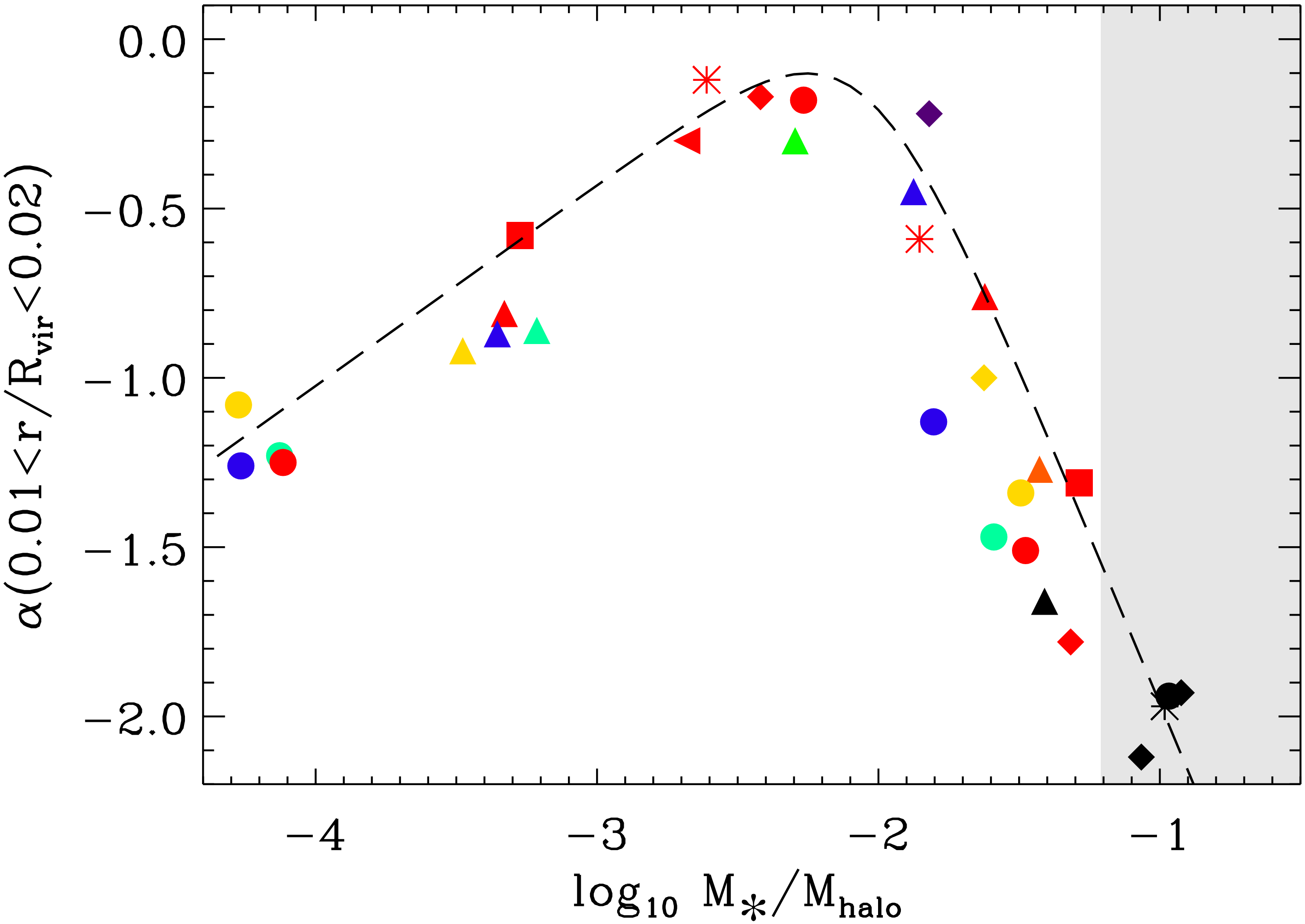
(Sembolini et al. 2016)

- possible solutions: ***baryonic processes are very complex***



(Knebe et al. 2015)

- possible solutions: ***baryonic processes are very complex***



(Di Cintio et al. 2014)

- the cusp-core problem
- ***satellite galaxies***
- bulge-less disk galaxies
- the Council of Giants
- speeding bullets
- El Gordo
- Hubble tension

- the nature of dark matter?
- the nature of dark energy?

- the cusp-core problem
- ***satellite galaxies:***
  - missing?
  - too big too fail?
  - planar distribution?
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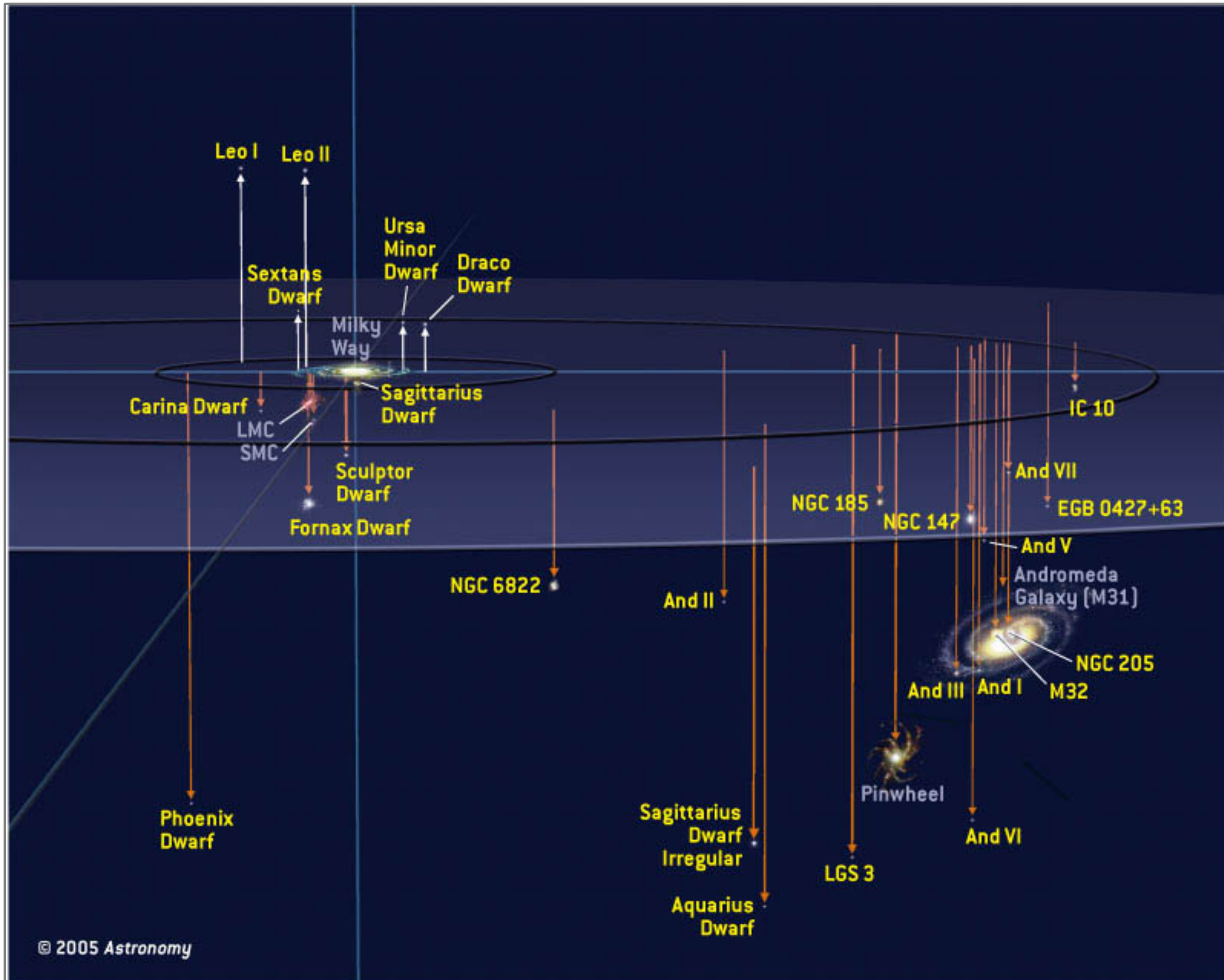
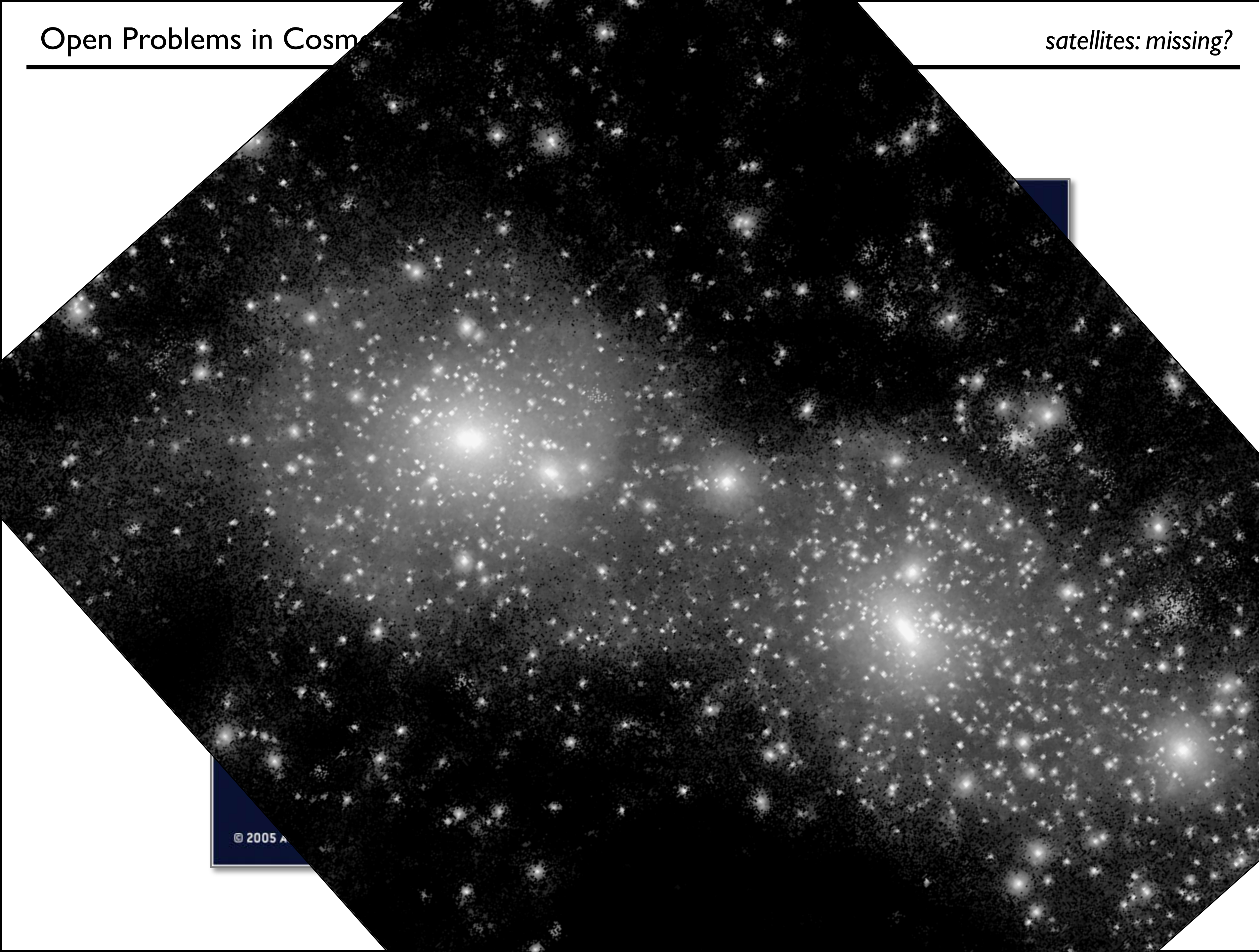
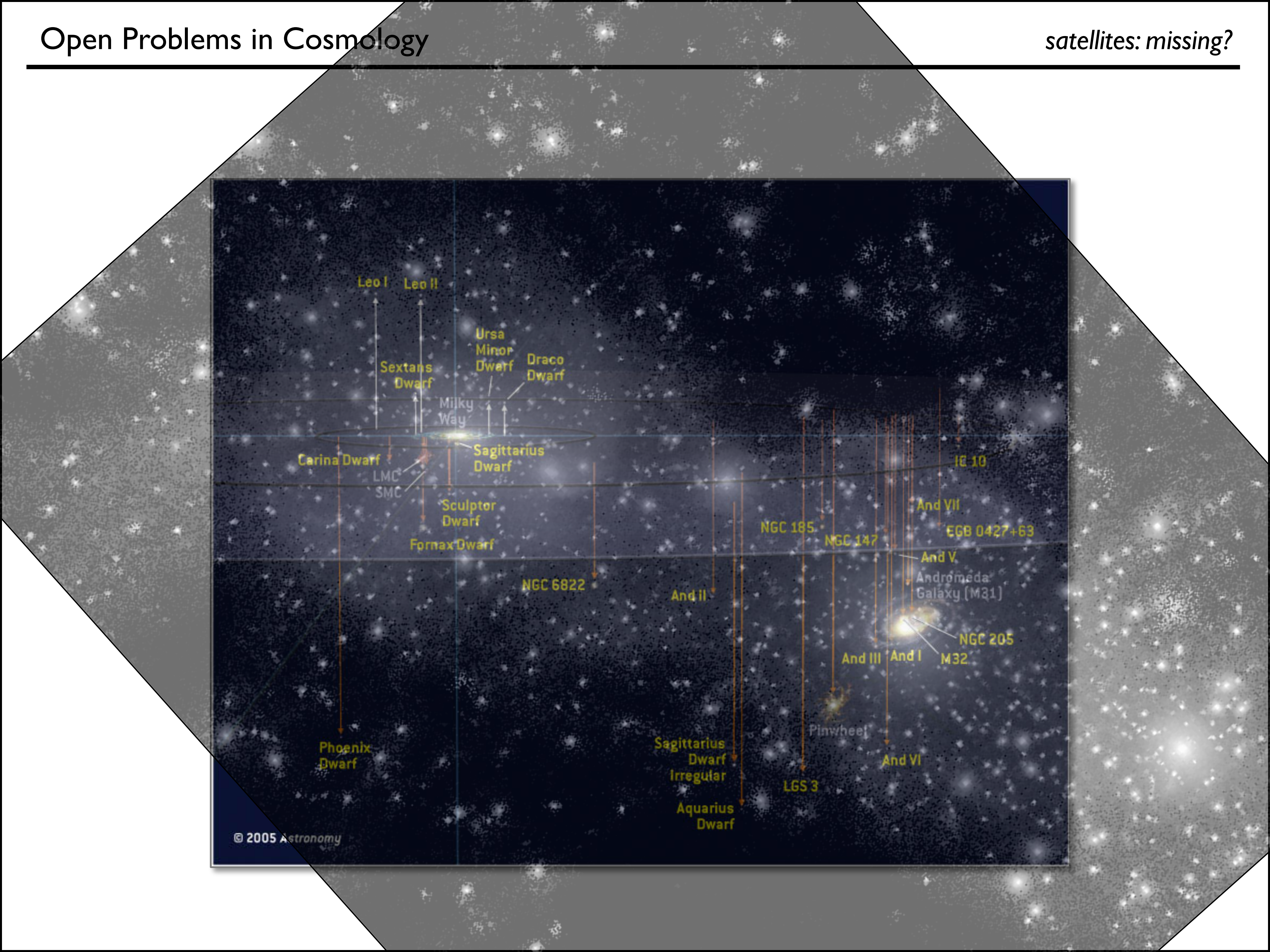

Leo I
Leo II
Ursa Minor Dwarf
Draco Dwarf
Sextans Dwarf
Milky Way
Carina Dwarf
Sagittarius Dwarf
LMC
SMC
Sculptor Dwarf
Fornax Dwarf
NGC 6822
And II
IC 10
And VII
EGB 0427+63
NGC 185
NGC 147
And V
Andromeda Galaxy (M31)
NGC 205
M32
And III
And I
Pinwheel
Phoenix Dwarf
Sagittarius Dwarf Irregular
LGS 3
And VI
Aquarius Dwarf
© 2005 Astronomy





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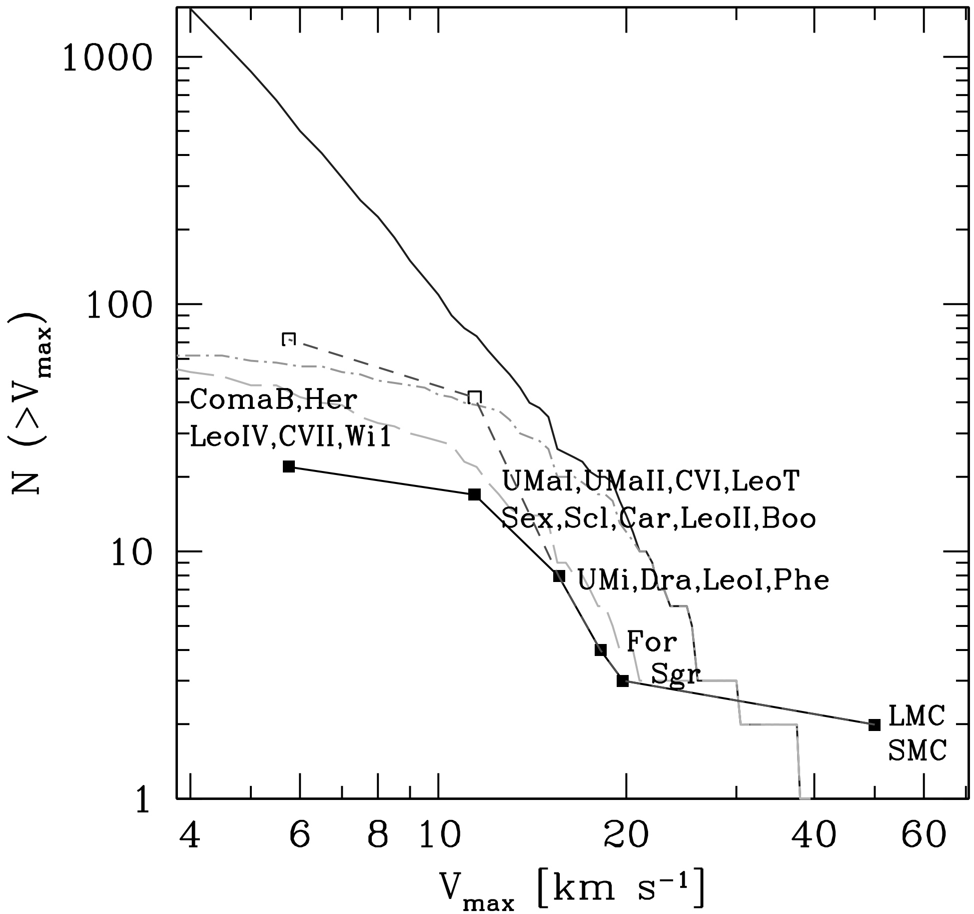
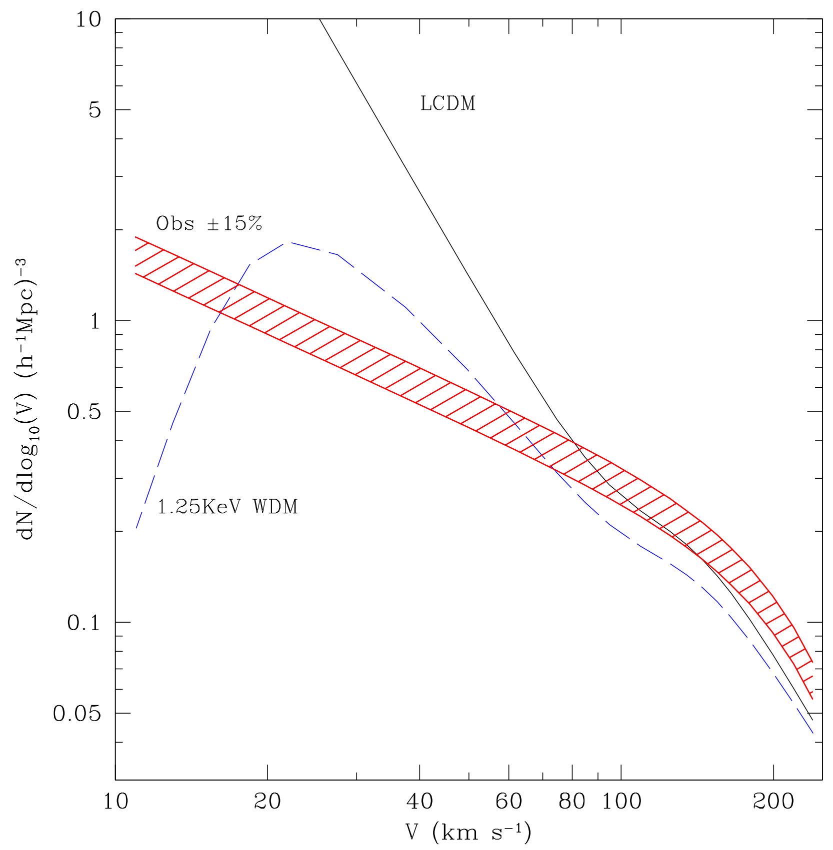
NGC 205
M32
And III
And I
Pinwheel
Phoenix Dwarf
Sagittarius Dwarf Irregular
LGS 3
And VI
Aquarius Dwarf
© 2005 Astronomy

- quantitative comparison…



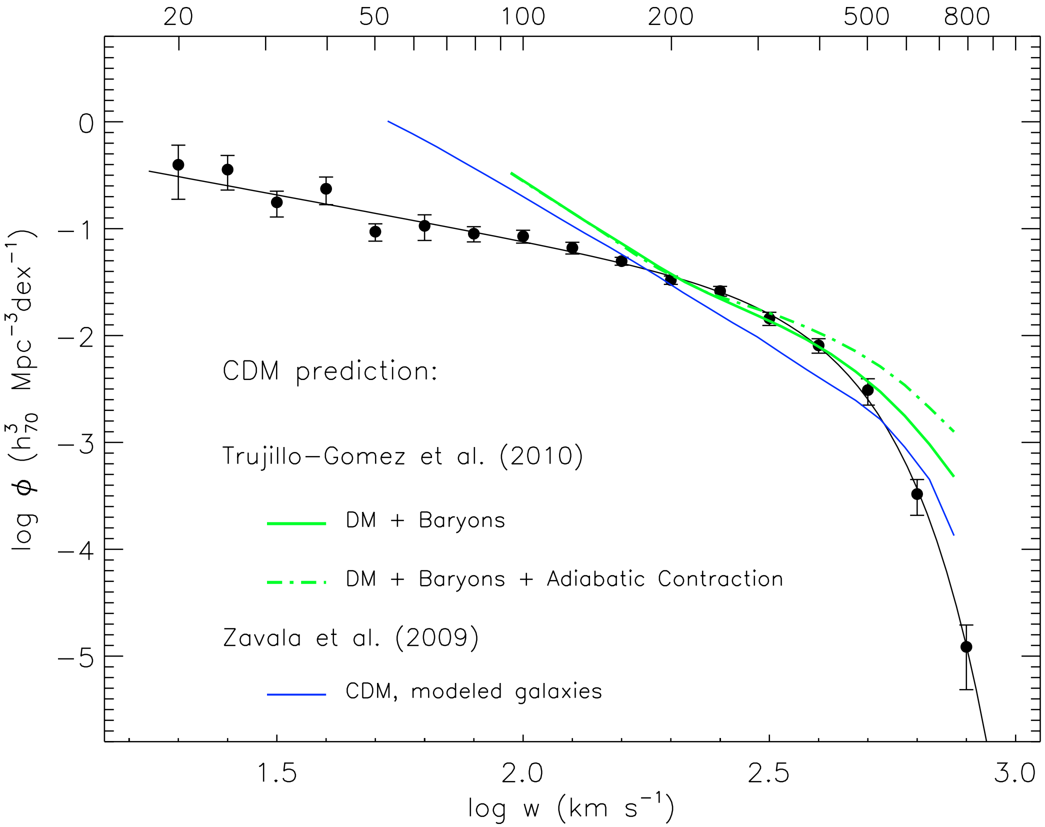
Madau et al. (2008)

- even problematic in the Local Volume…



Klypin et al. (2015)

- and even problematic in the field in general…



Papastergis et al. (2011)

- <u>possible solutions</u>

  - not (yet) discovered **(e.g. observational problem)**

  - missing physics: **(e.g. modeller problem)**
    - – baryonic feedback
    - – …

  - tinkering with fundamental physics (gravity, WDM, cDE, VDE, …)

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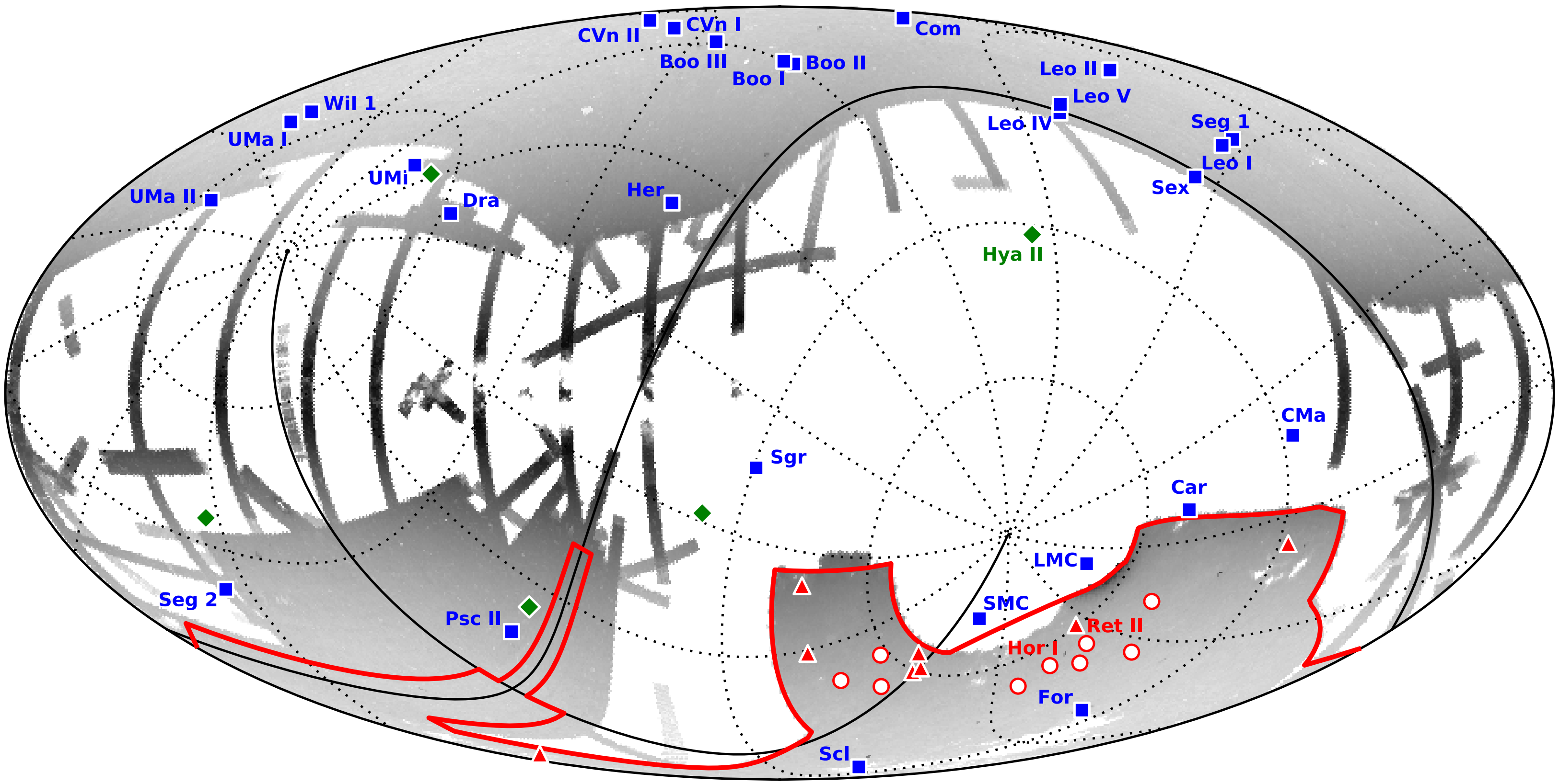

DES Collaboration (arXiv:1508.03622)
(red: new from DES, green: new from others, blue: previously known)

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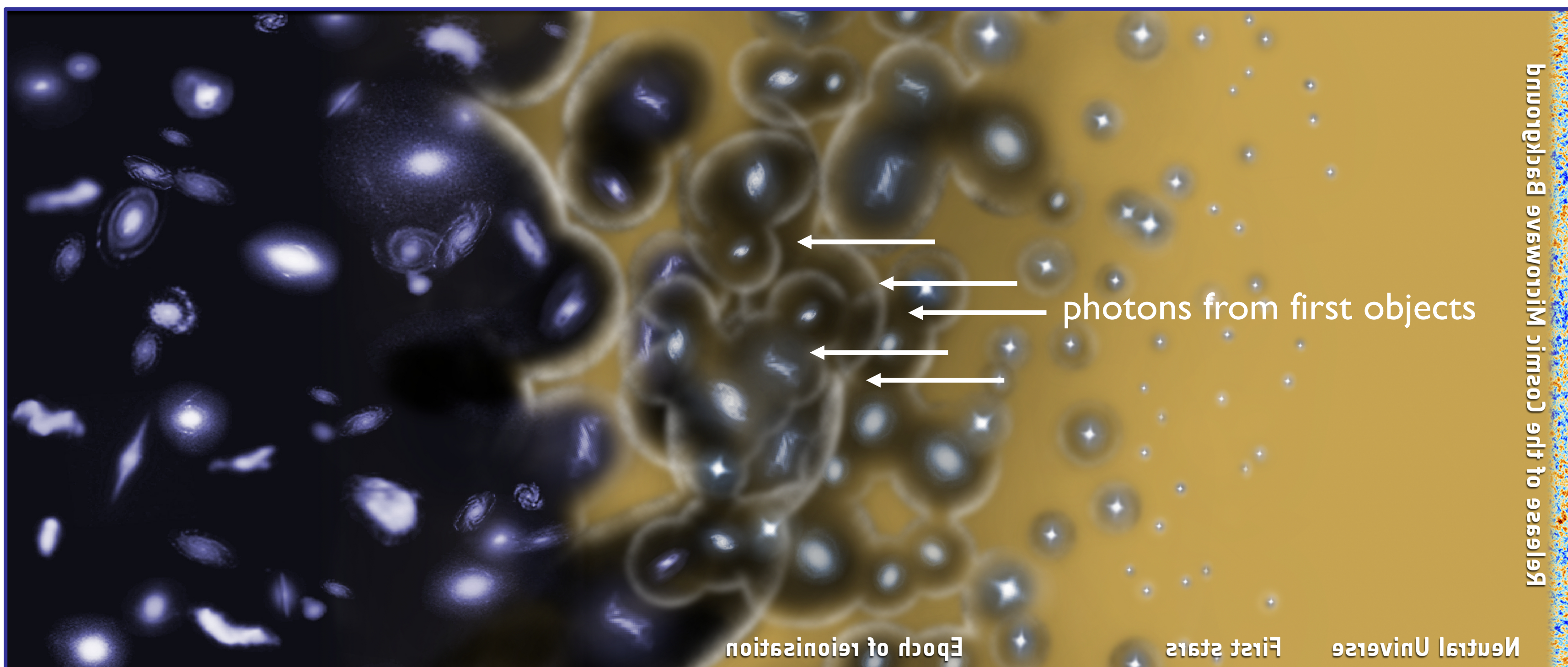

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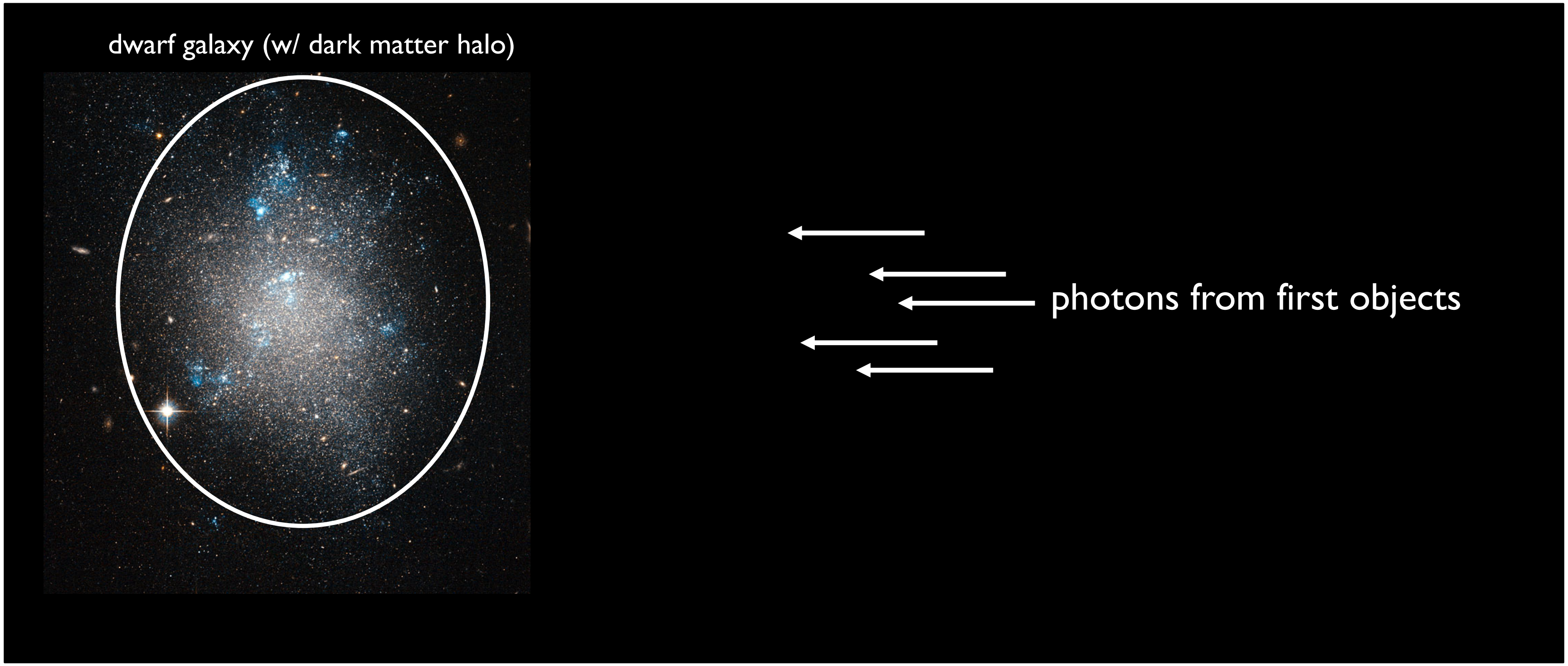

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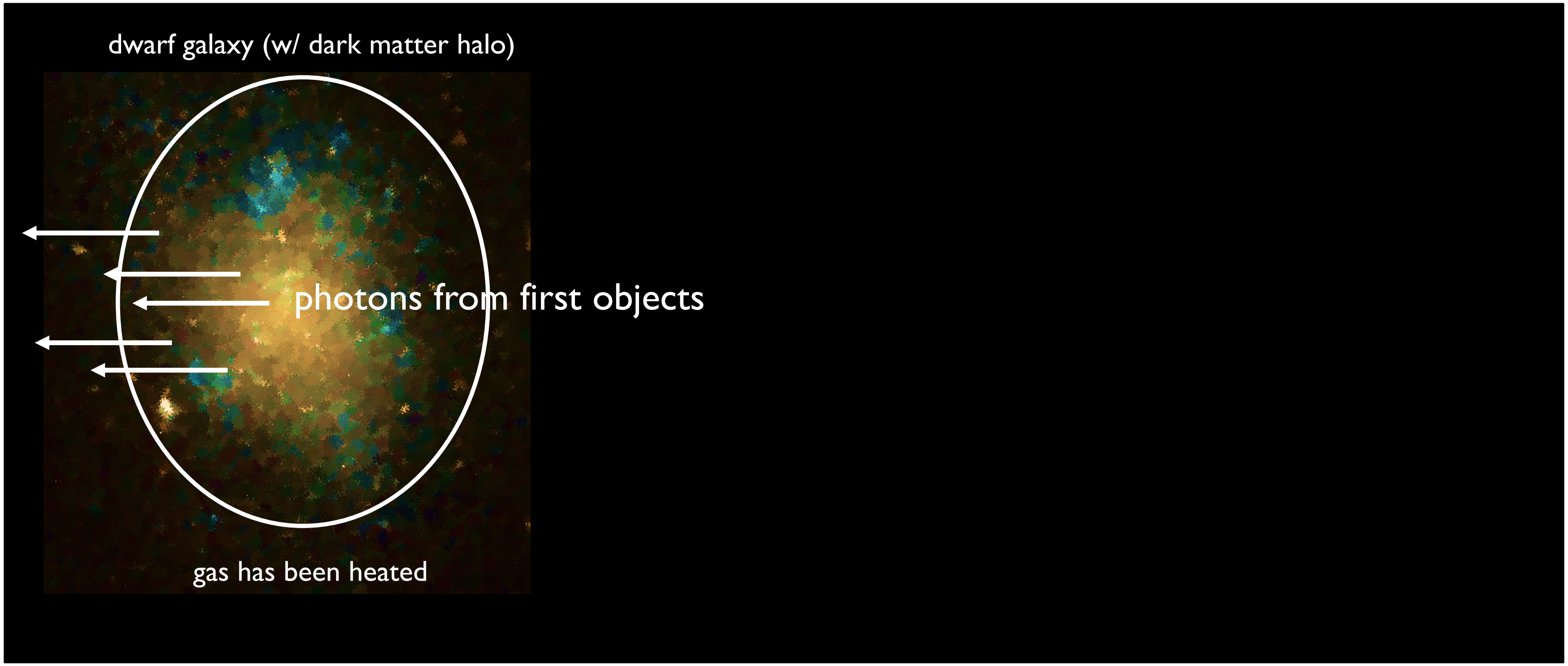

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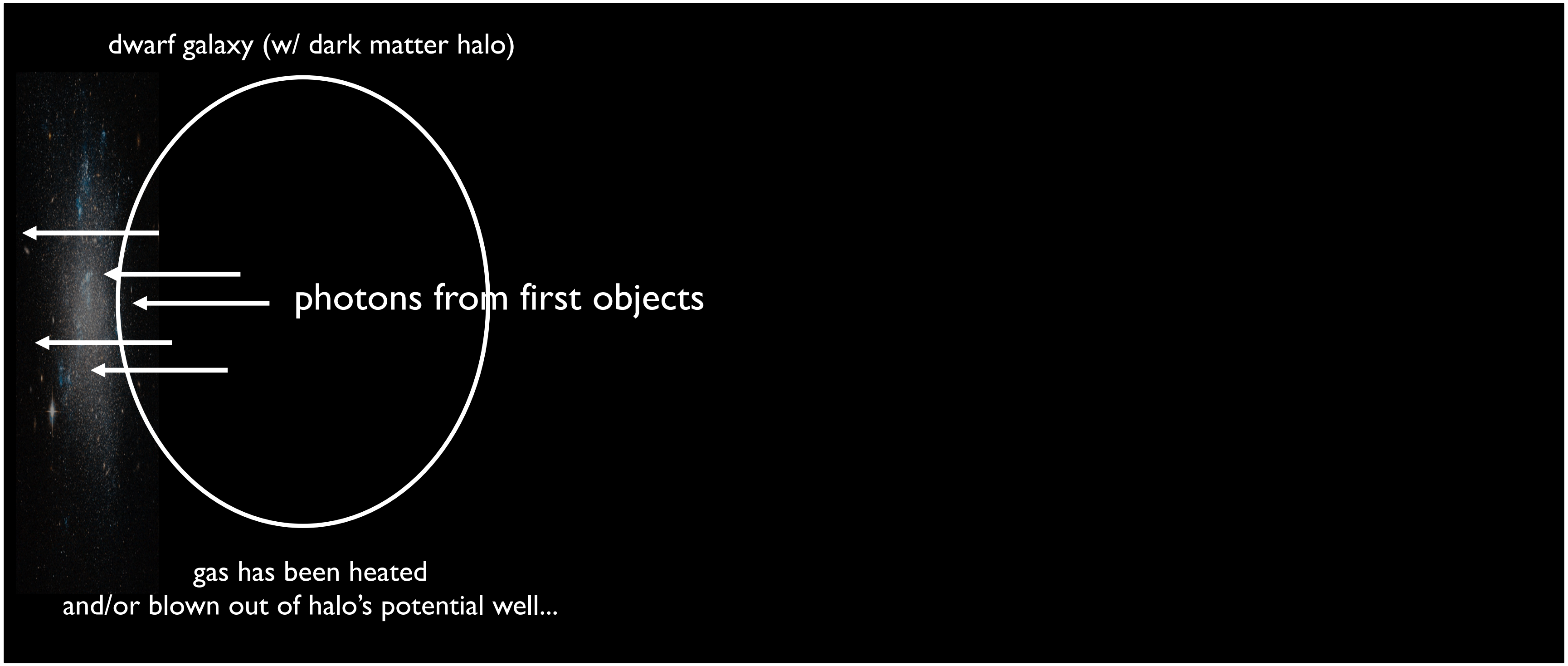

- possible solutions

  - Kim, Peter & Hargis (2018) "There is no MSP!"

There is No Missing Satellites Problem

Stacy Y. Kim[1,2,*] Annika H. G. Peter[1,2,3], and Jonathan R. Hargis[4]
[1] *Department of Astronomy, The Ohio State University, 140 W. 18th Ave., Columbus, OH 43210, USA*
[2] *Center for Cosmology and AstroParticle Physics, The Ohio State University, 191 W. Woodruff Ave., Columbus, OH 43210, USA*
[3] *Department of Physics, The Ohio State University, 191 W. Woodruff Ave., Columbus, OH 43210, USA and*
[4] *Space Telescope Science Institute, 3700 San Martin Drive, Baltimore, MD 21218, USA*
(Dated: June 14, 2018)

A critical challenge to the cold dark matter (CDM) paradigm is that there are fewer satellites observed around the Milky Way than found in simulations of dark matter substructure. We show that there is a match between the observed satellite counts corrected by the detection efficiency of the Sloan Digital Sky Survey (for luminosities $L \gtrsim 340$ L$_\odot$) and the number of luminous satellites predicted by CDM, assuming an empirical relation between stellar mass and halo mass. The "missing satellites problem", cast in terms of number counts, is thus solved. We also show that warm dark matter models with a thermal relic mass smaller than 4 keV are in tension with satellite counts, putting pressure on the sterile neutrino interpretation of recent X-ray observations. Importantly, the total number of Milky Way satellites depends sensitively on the spatial distribution of satellites, possibly leading to a "too many satellites" problem. Measurements of completely dark halos below 10^8 M$_\odot$, achievable with substructure lensing and stellar stream perturbations, are the next frontier for tests of CDM.

I. INTRODUCTION

One outstanding problem for the cold dark matter (CDM) paradigm is the missing satellites problem (MSP). When originally formulated, the MSP highlighted the discrepancy between the number of satellites predicted in CDM simulations, numbering in the 100s, and observed in the Milky Way (MW), numbering ∼10 [1–3]. Since then, increasingly sensitive surveys have pushed the observed satellite count to ∼50 (e.g., Ref. [4–6]). Simultaneously, however, improved resolution in numerical simulations has also increased the number of predicted satellites (e.g., [7]).

A crucial step towards resolving the MSP is to correct for those satellites that have not yet been detected. Only a fraction of the MW's virial volume has been surveyed [8]. The Sloan Digital Sky Survey (SDSS), by which ultra-faint dwarfs with luminosities as low as 340 L$_\odot$ (Segue I) were discovered, covered only about a third of the sky. For the faintest dwarfs, SDSS was complete to ∼10% of the MW's virial radius [9, 10]. The observed count is thus a lower bound on the luminous MW satellite population. Completeness corrections must be applied to derive the total number of luminous MW satellites.

Fully resolving the MSP requires that the completeness-corrected galaxy count match the predicted *luminous* satellite abundance. This depends on the physics of an additional key component: baryons. There is growing evidence that not all dark matter subhalos host an observable galaxy. Galaxy evolution models [11] and star-formation histories of ultra-faint dwarfs [12] indicate that feedback processes and reionization prevent star formation. In fact, subhalos below $\sim 10^9$ M$_\odot$ are inefficient in forming a luminous component [13, 14]. In CDM, most MW subhalos are dark.

In this work, we compare completeness corrections of the observed MW luminous galaxy population to theoretical predictions for the luminous galaxy population. We use an analytic approach to highlight specific physics, and provide a roadmap for future MW-based DM constraints. Our completeness correction is inspired by Refs. [8, 15–17], which used simulations or Bayesian techniques to estimate that the MW hosts hundreds of luminous satellites. We calculate the total number of luminous galaxies down to 340 L$_\odot$ based on the satellites observed by SDSS. For comparison, we predict the number of luminous satellites expected in CDM based on empirical scaling relations between halos and galaxies.

Successful dark matter models cannot produce just enough dark matter subhalos to match the corrected galaxy count—they must produce enough *luminous* galaxies. This places stringent constraints on warm dark matter (WDM) and sterile neutrino models, competitive with Lyman-α forest constraints [18].

Successful galaxy formation models must produce enough luminous galaxies to match the corrected galaxy count. This has implications for the mass threshold for the subhalos that host the faintest galaxies, the redshift of reionization, and the tidal stripping of subhalos.

II. COMPLETENESS CORRECTIONS

The total number of luminous satellites within the MW virial radius ($R_{\rm vir} = 300$ kpc) can be extrapolated from

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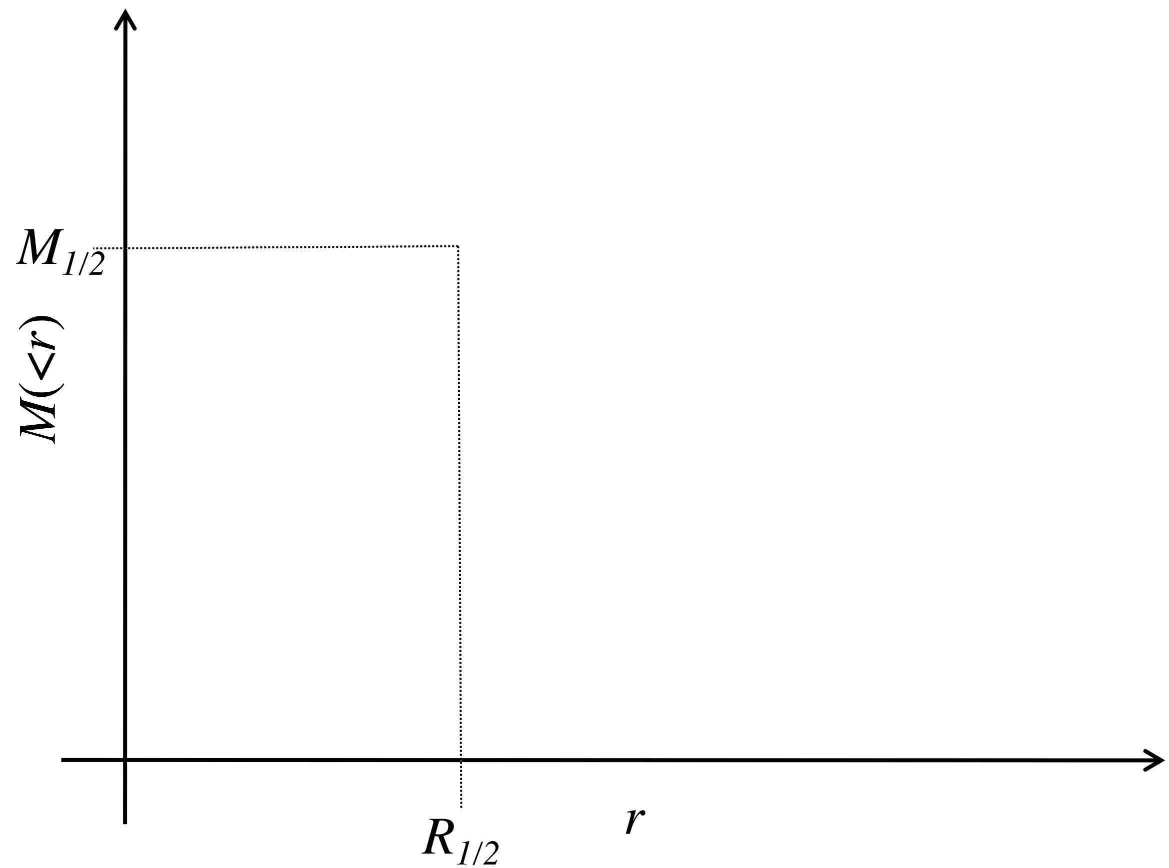
- the cusp-core problem
- ***satellite galaxies:***
  - missing?
  - **too big too fail?**
  - planar distribution?
- bulge-less disk galaxies
- the Council of Giants
- speeding bullets
- El Gordo
- Hubble tension

- the nature of dark matter?
- the nature of dark energy?

- use observed half-light radius $R_{1/2}$ and half-light mass $M_{1/2}$ to fix mass profile amplitude



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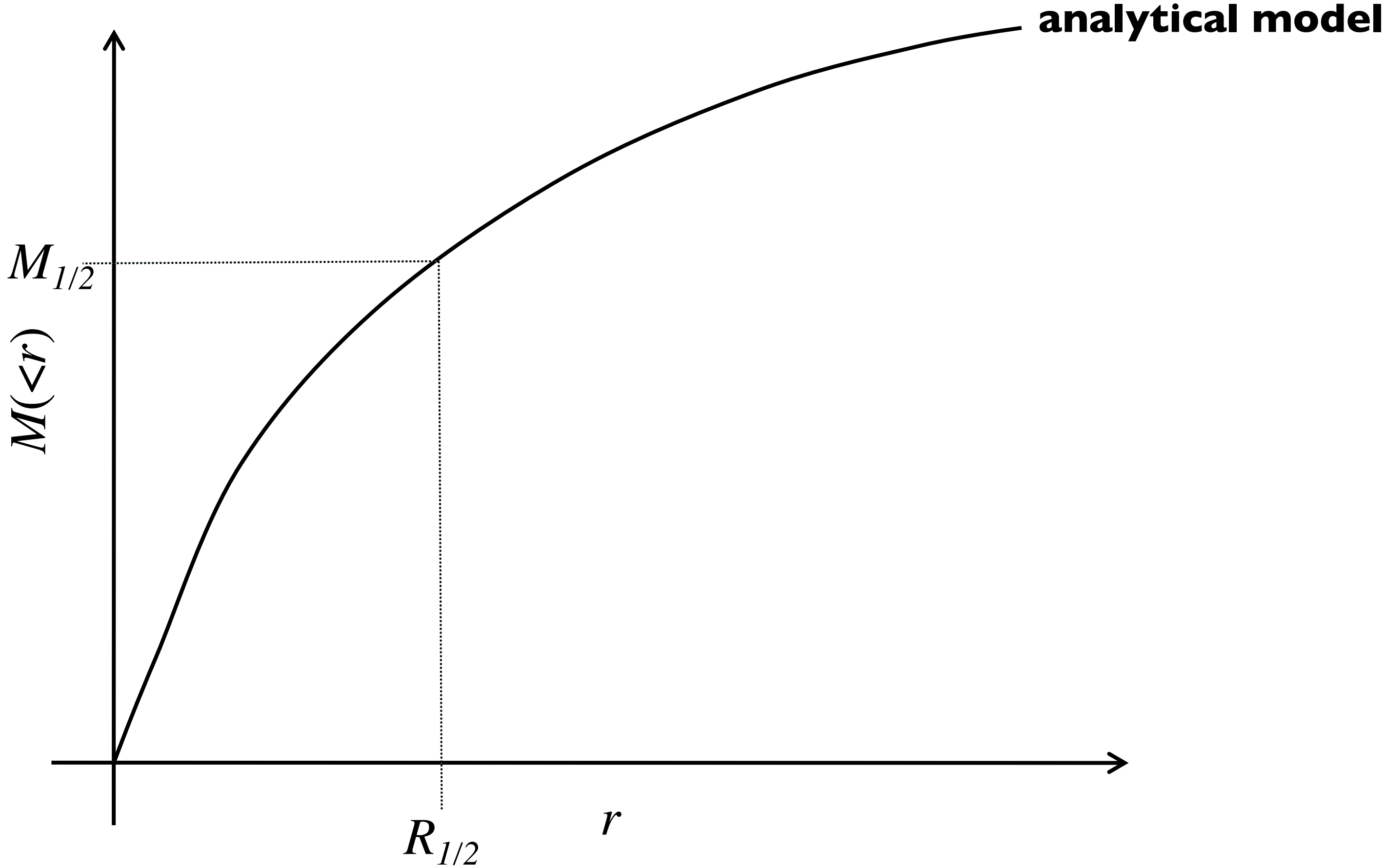

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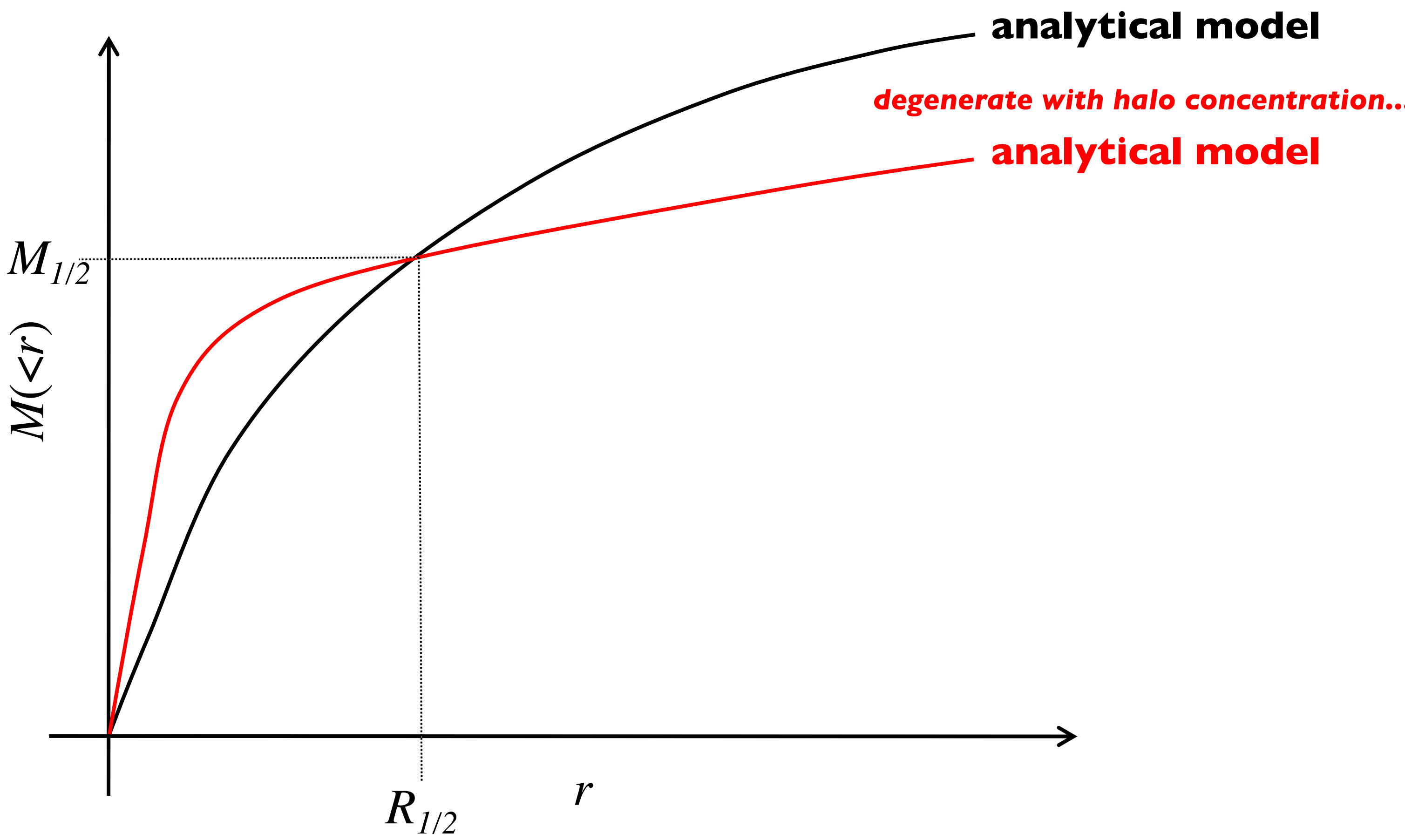

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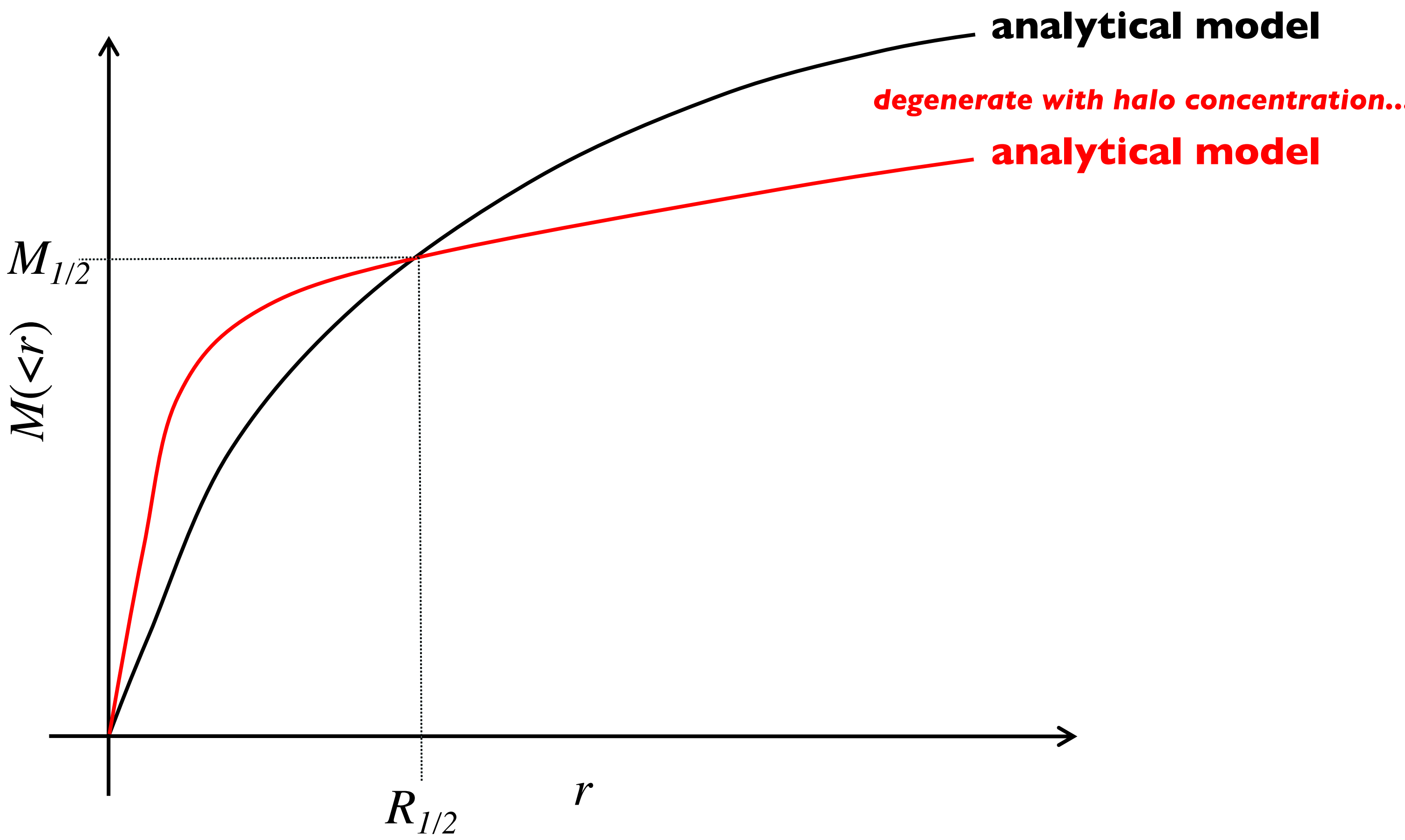
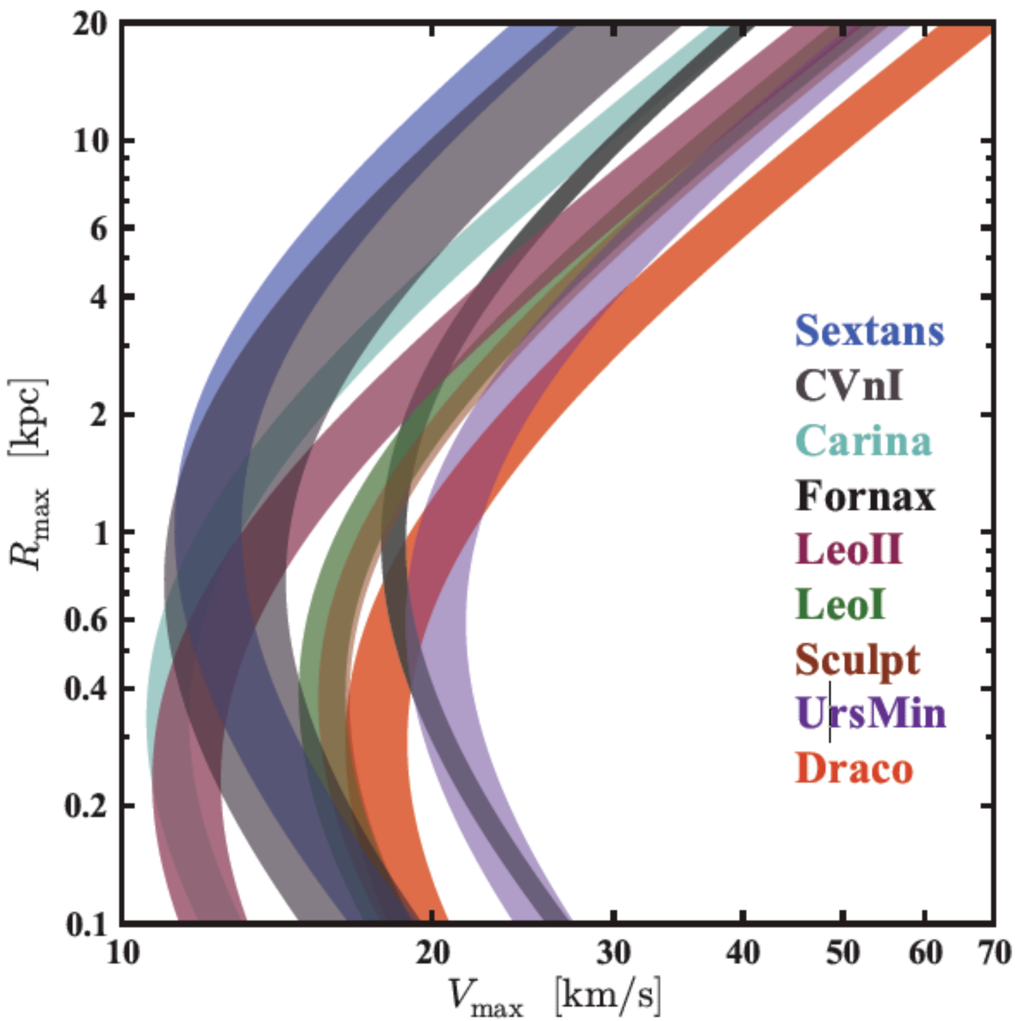
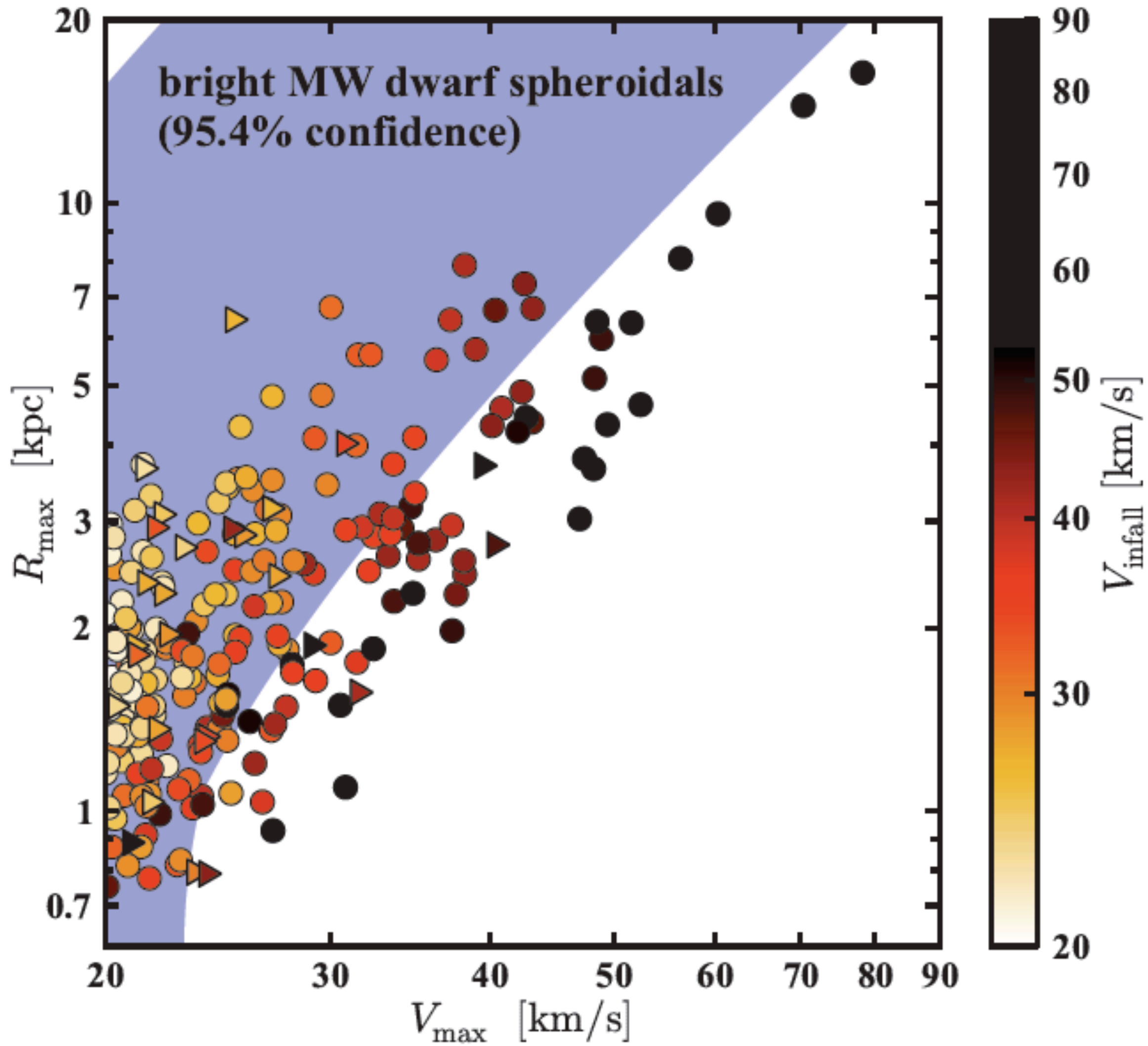


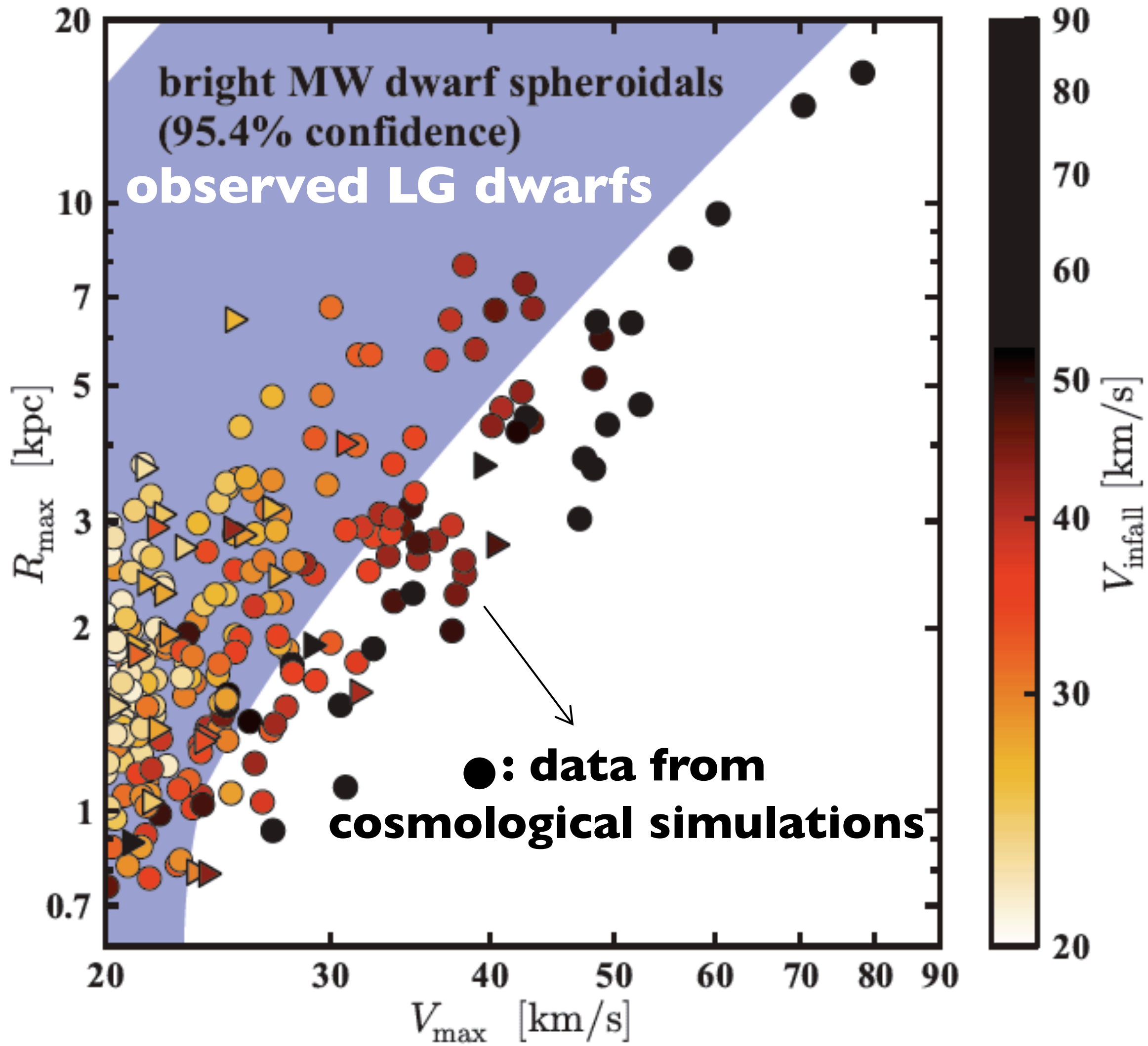
- for each possible $M(<r)$ get peak position $R_{\max}$ and value $V_{\max}$ of $V^2(r) = G\,M(<r)\,/\,r$



Boylan-Kolchin et al. (2011)



Boylan-Kolchin et al. (2011)



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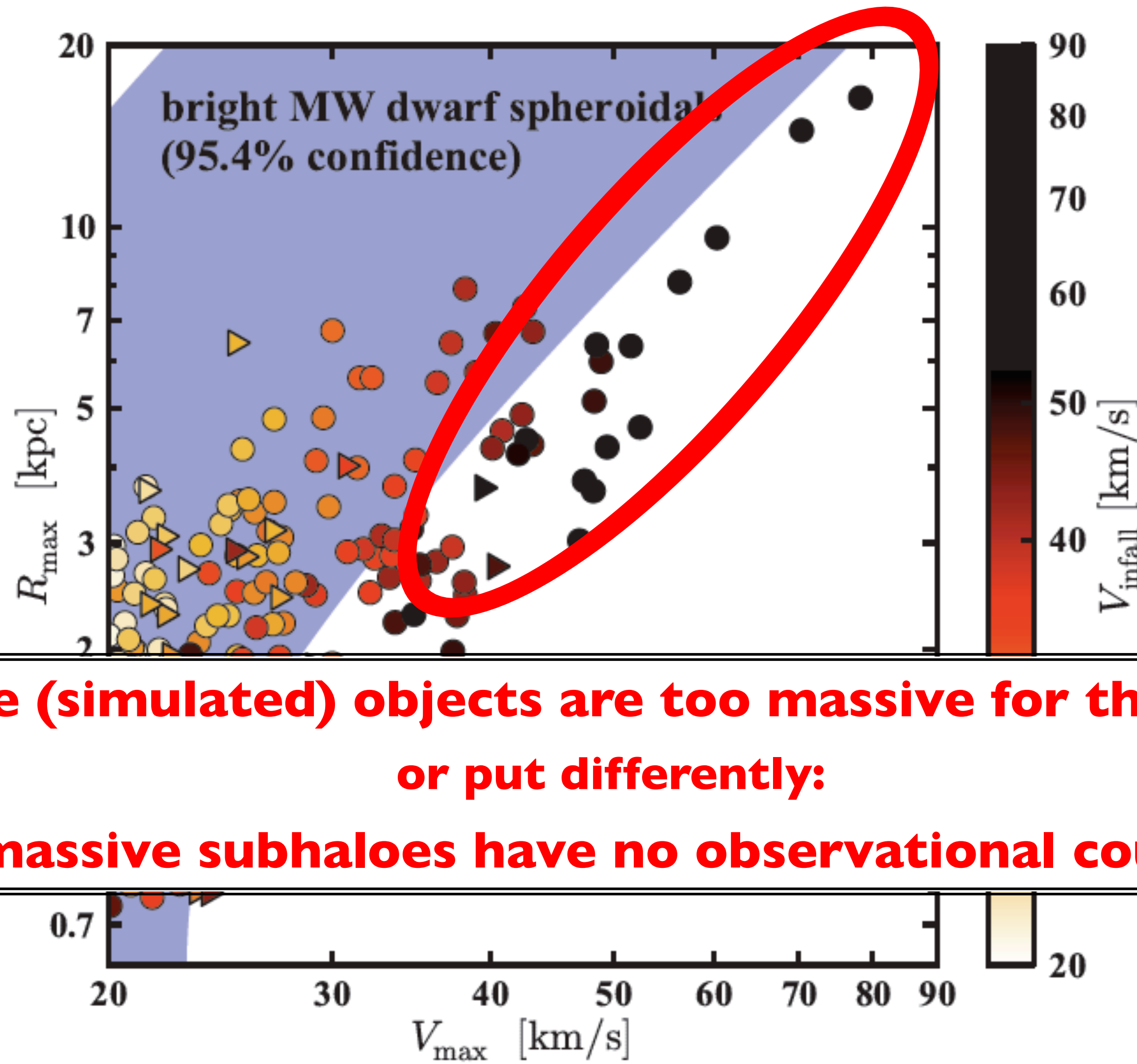


these (simulated) objects are too massive for their size!

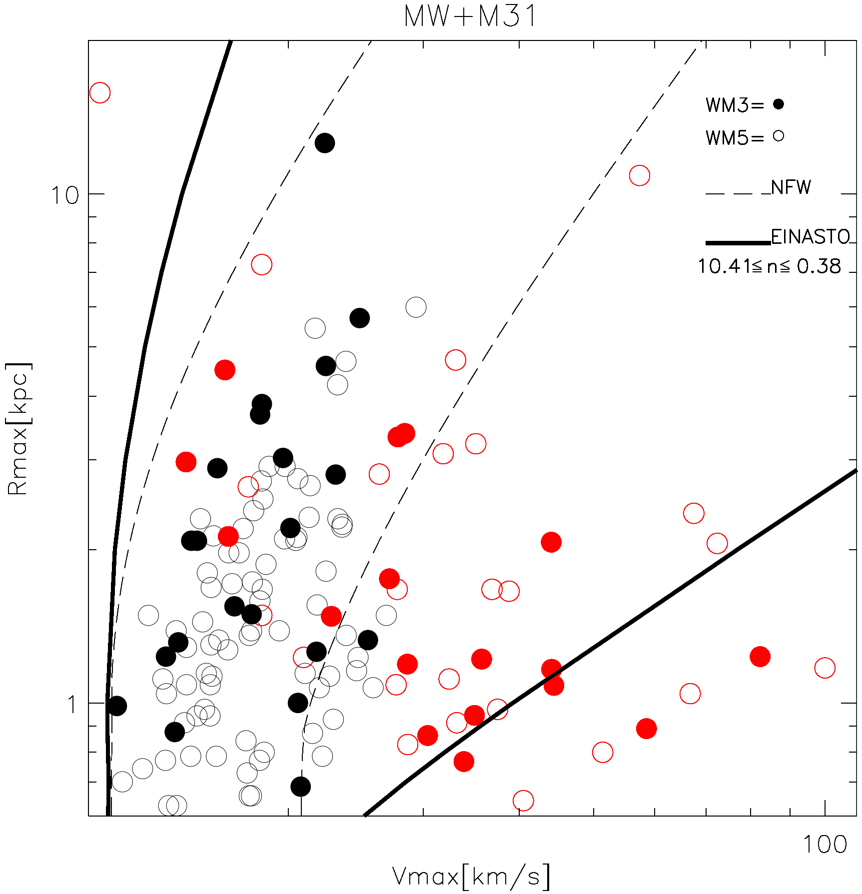
or put differently:

these massive subhaloes have no observational counterpart!

Boylan-Kolchin et al. (2011)

- possible solutions
    - baryonic physics
    - tinkering with DM particle (WDM, self-interacting, …)

- possible solutions
  - ***baryonic physics***
  - tinkering with DM particle (WDM, self-interacting, …)



(Di Cintio et al. 2013)

- the cusp-core problem
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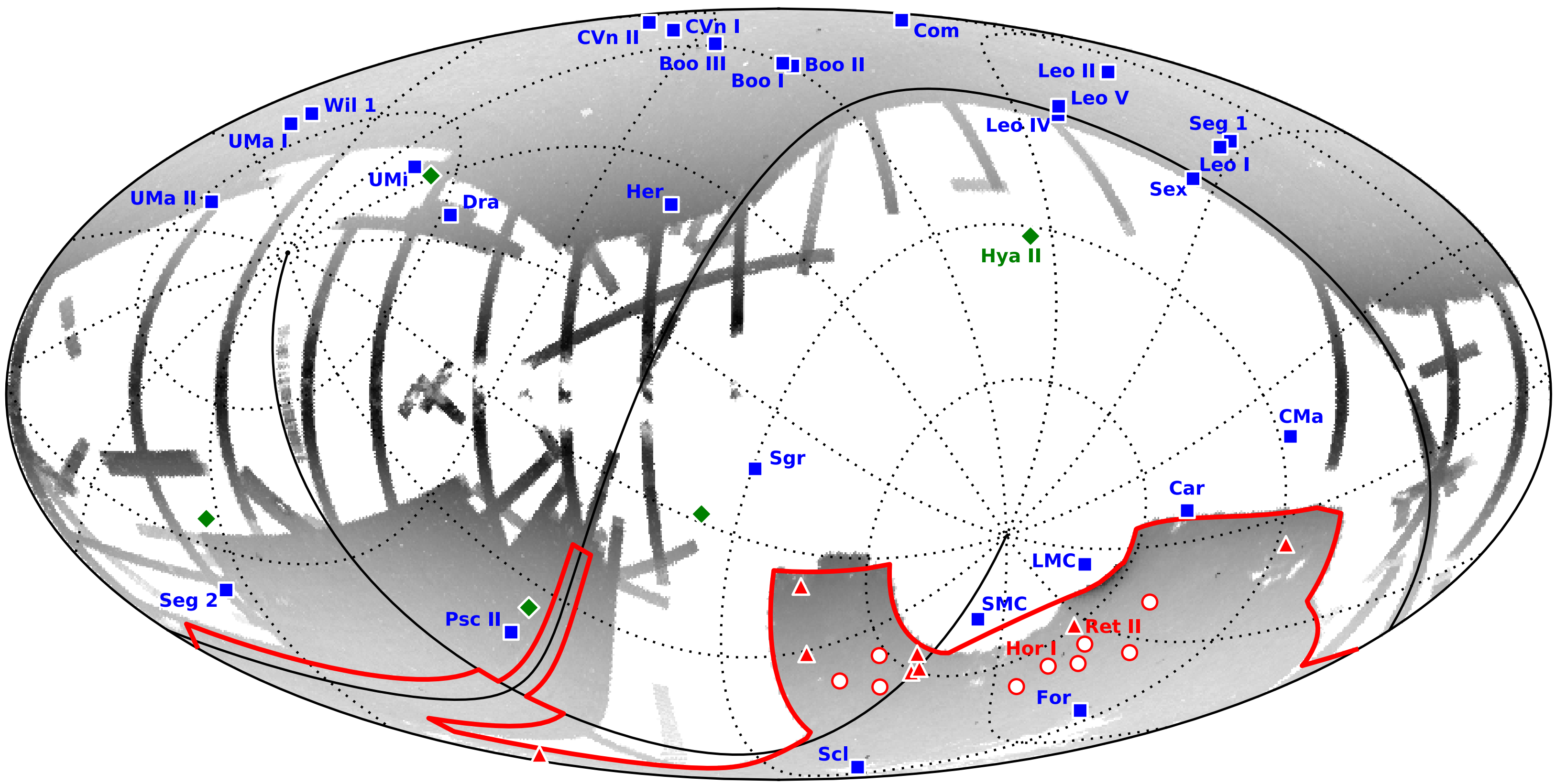
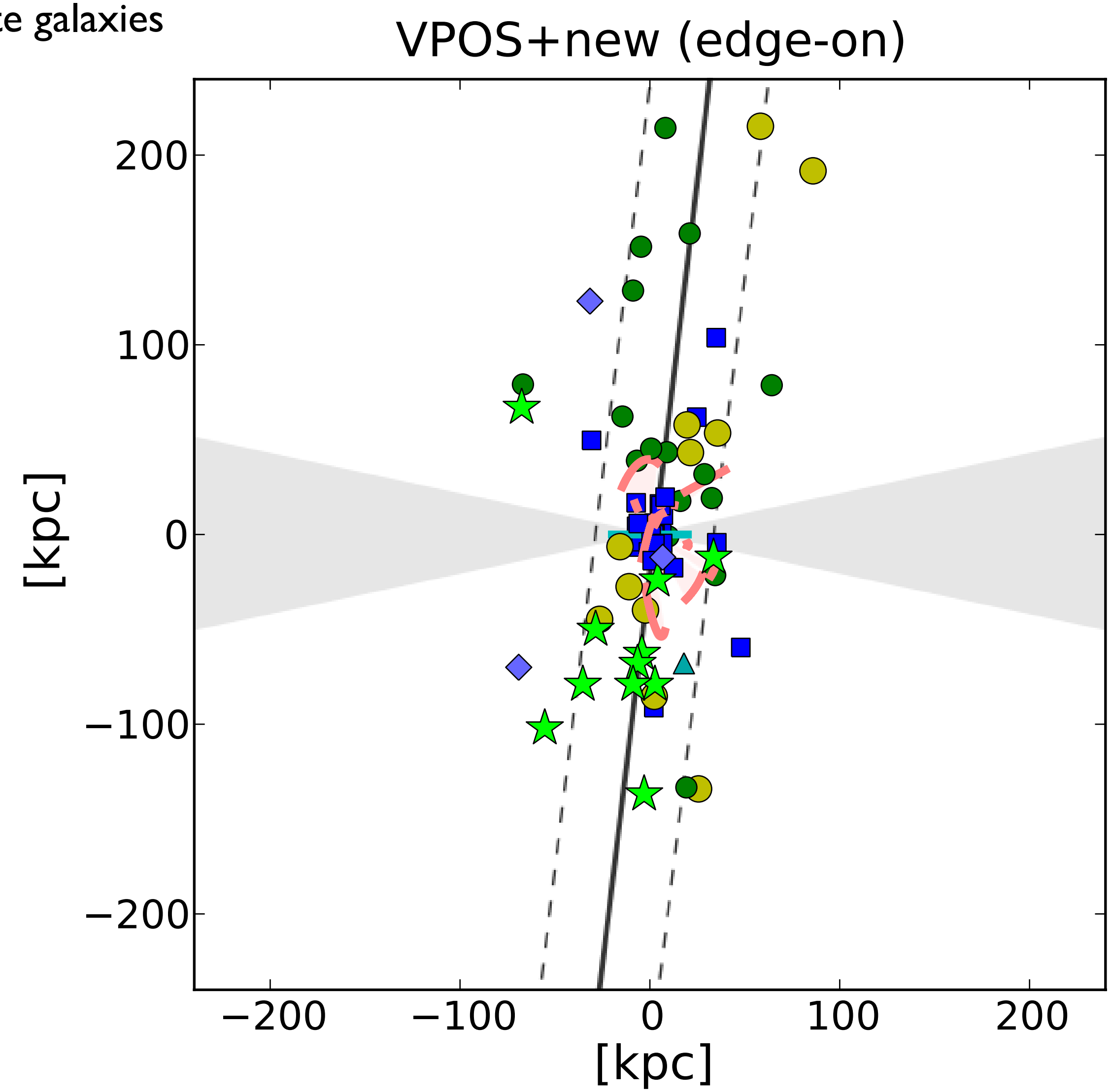
MW satellite galaxies

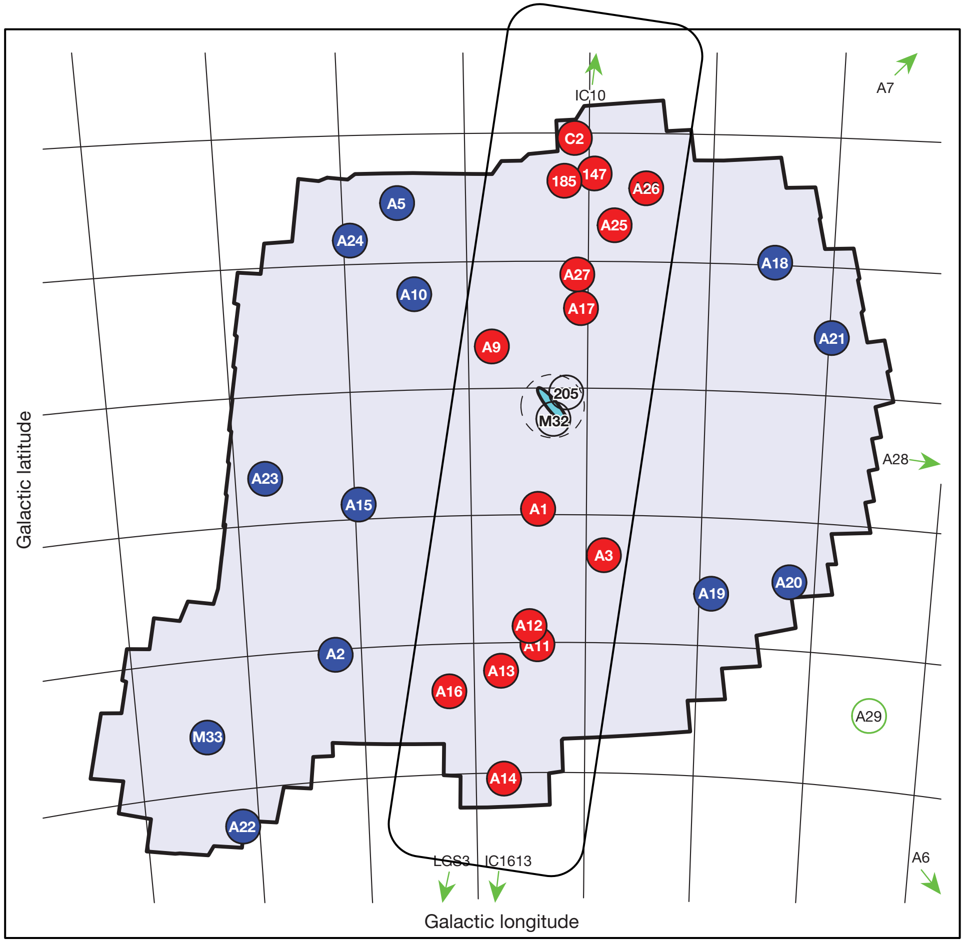


MW satellite galaxies



Pawlowski et al. (2015)

M31 satellite galaxies



Ibata et al. (2013, PAndAS survey)

- <u>possible solutions</u>

  - environmental effects, i.e. Local Group is a very special place:
    - binary system
    - situated in filament towards Virgo cluster

  - dynamical effects, e.g. radial alignment of orbits, …

  - how to (best) define planes?

▪ possible solutions

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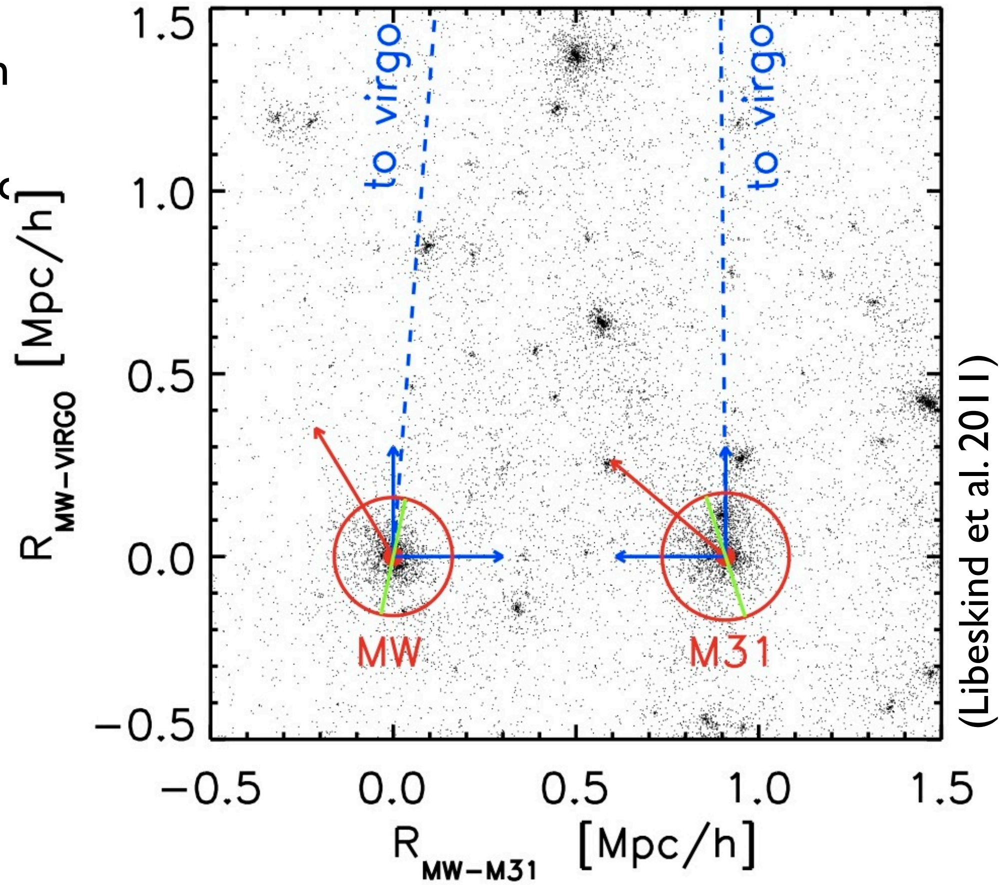
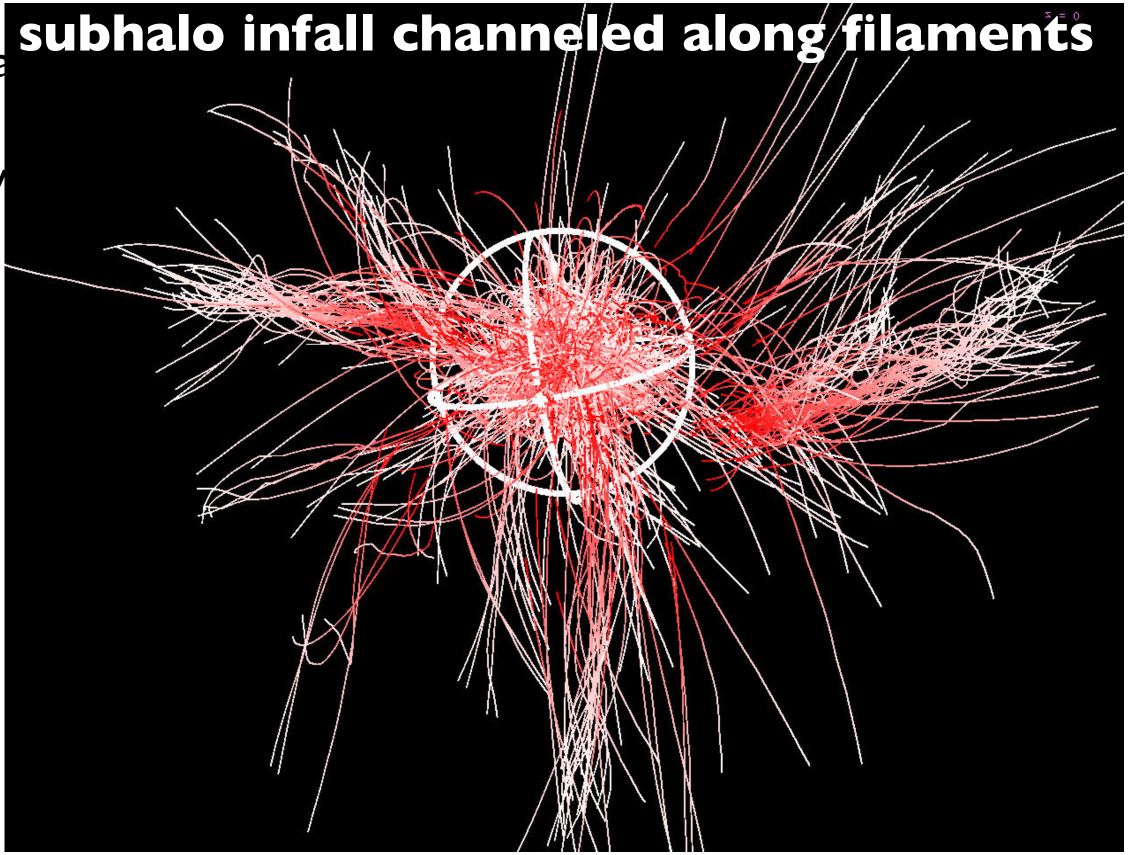
  - binary system
  - ***situated in filament towards Virgo cluster***
- dynam
- how tc



(Libeskind et al. 2011)

- possible solutions
  - environmental effects, i.e. Local Group is a very special place:
    - binary system
    - ***situated in filament towards Virgo cluster***
  - dyna
  - how



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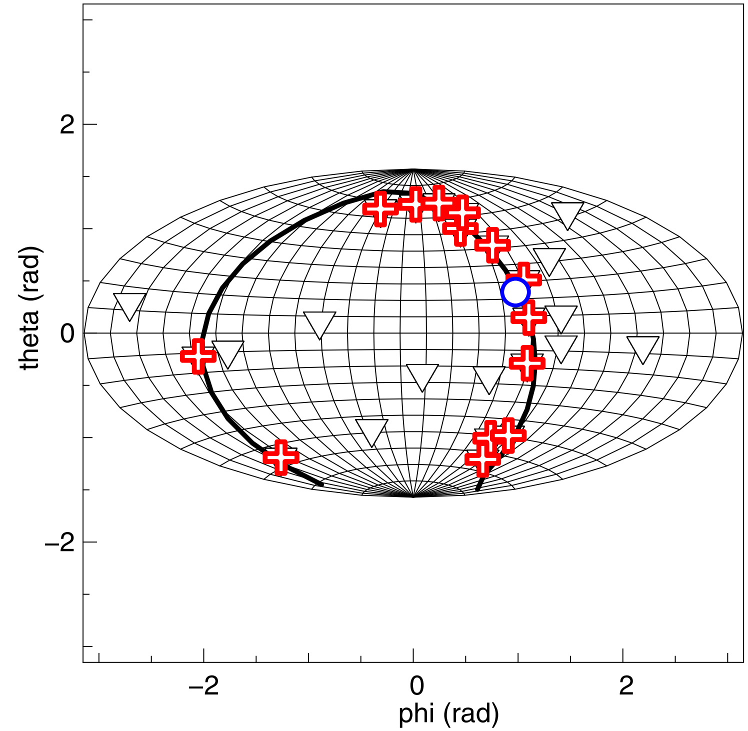

(Gillet et al. 2015)

- the cusp-core problem
- satellite galaxies:
  - missing?
  - too big too fail?
  - planar distribution?
- ***bulge-less disk galaxies***
- the Council of Giants
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- El Gordo
- Hubble tension

- the nature of dark matter?
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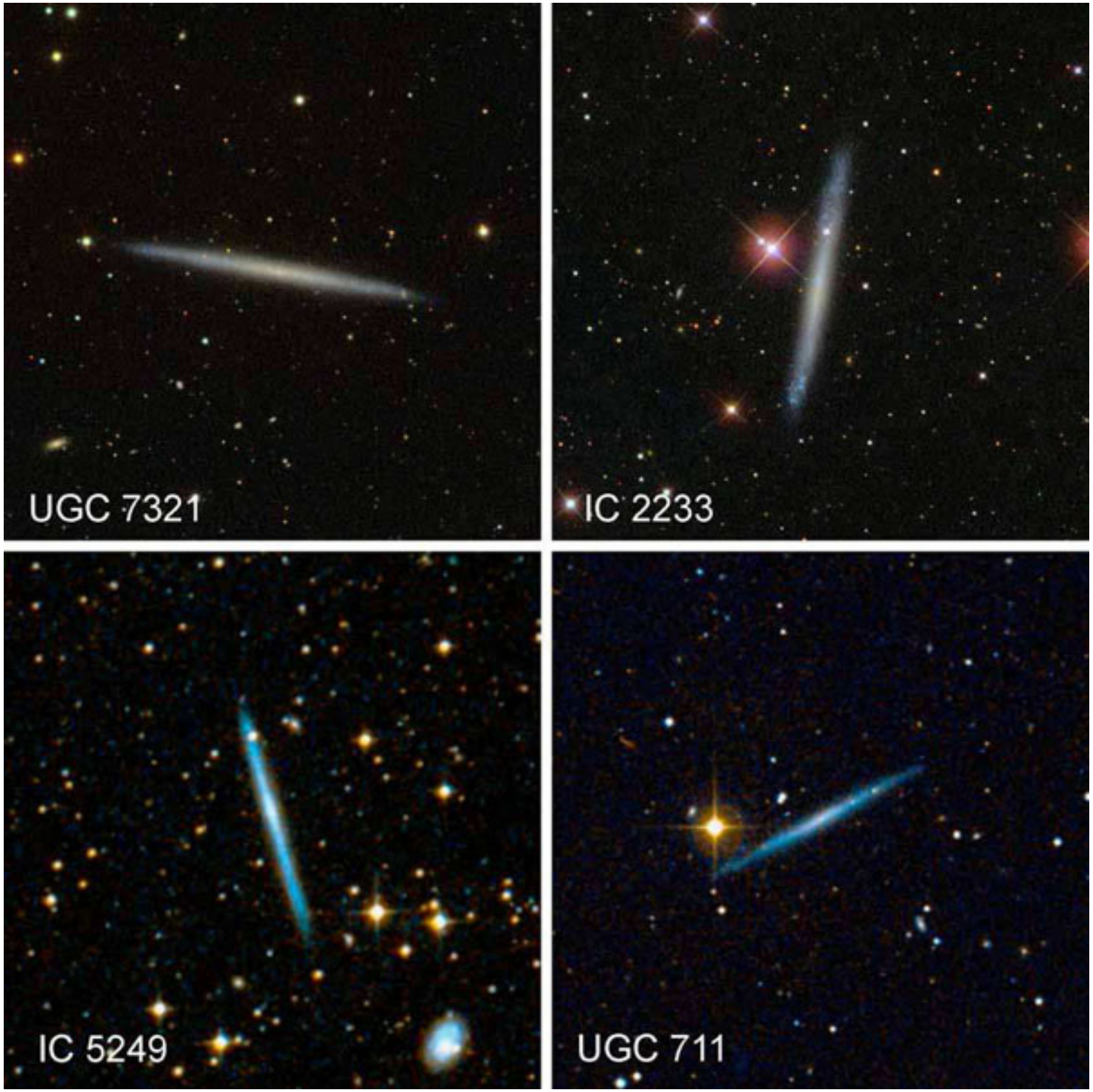
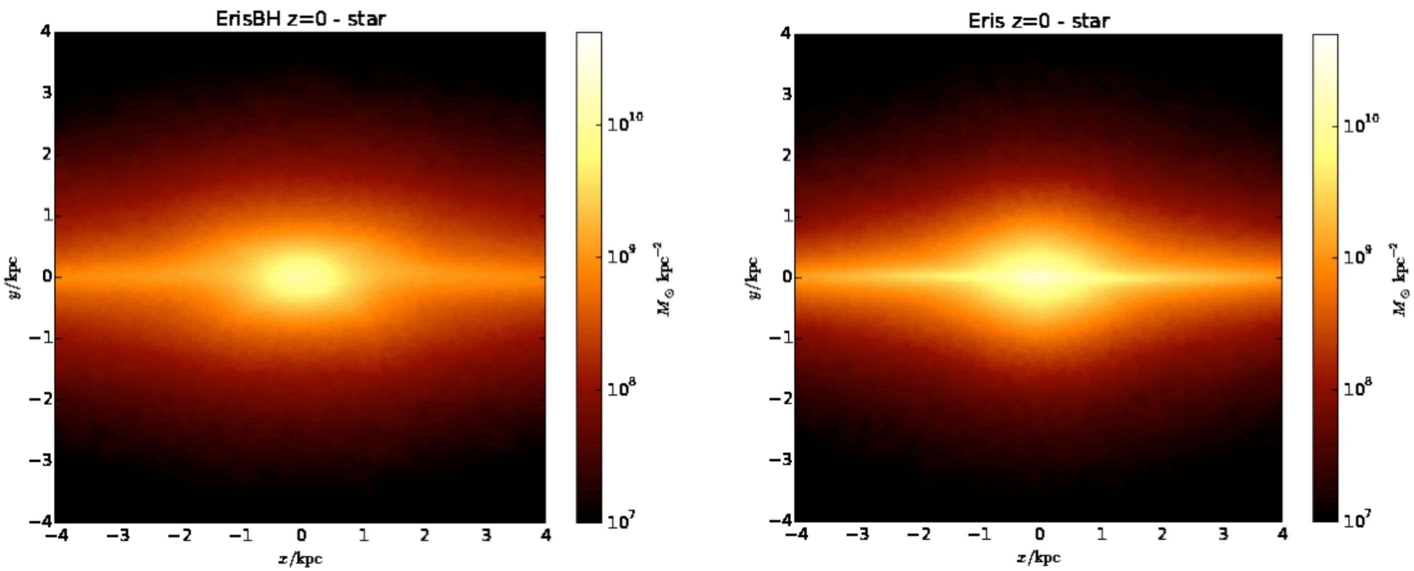
- observed

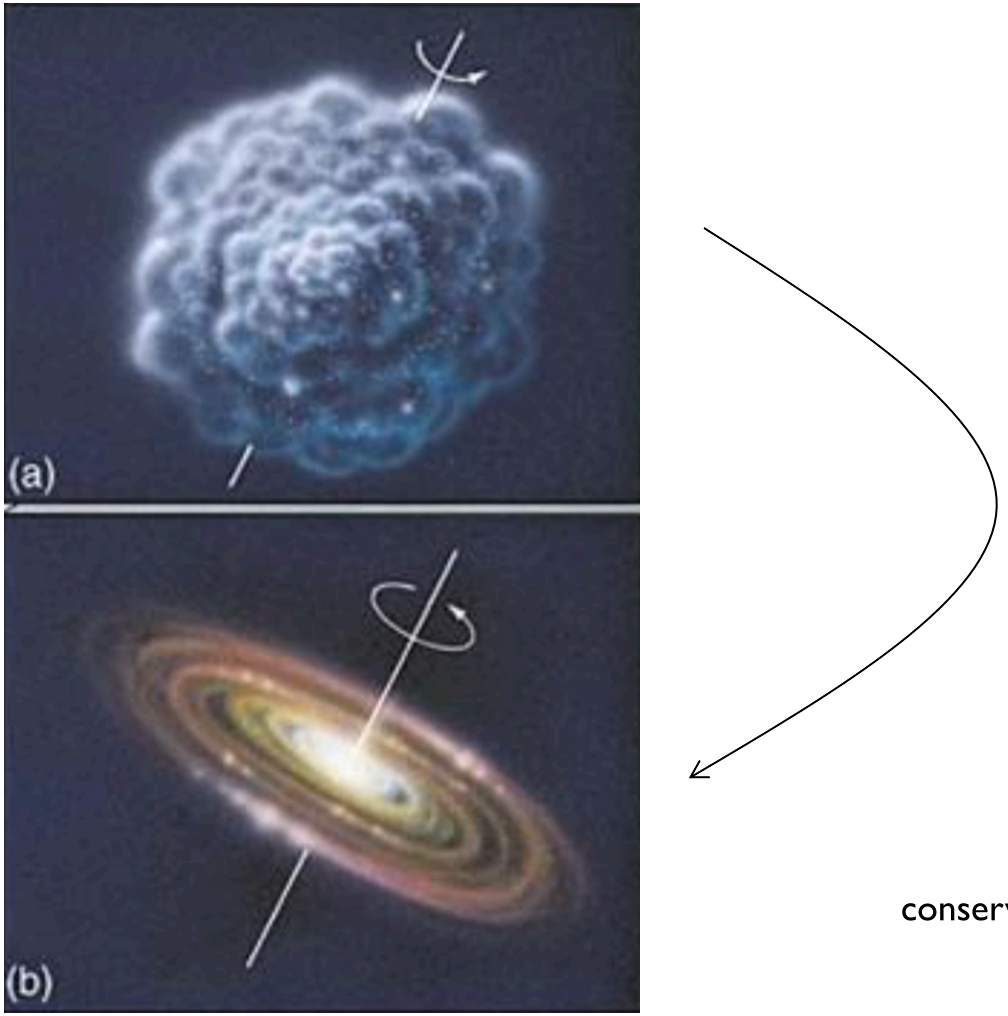


- simulated



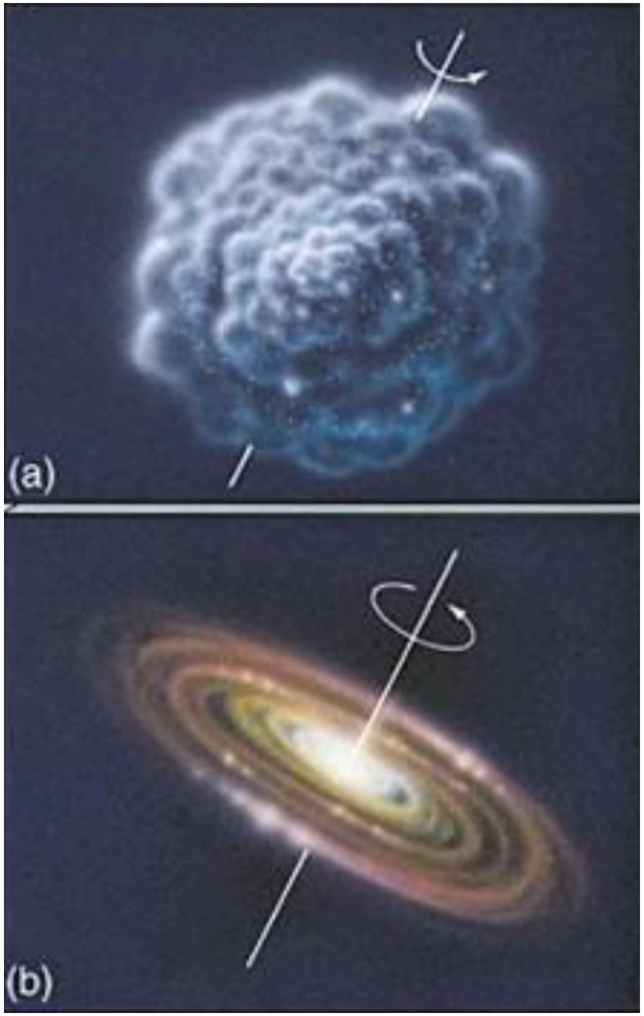
Bonoli et al. (2015)

- "angular momentum catastrophe"



conservation of angular momentum

- "angular momentum catastrophe"



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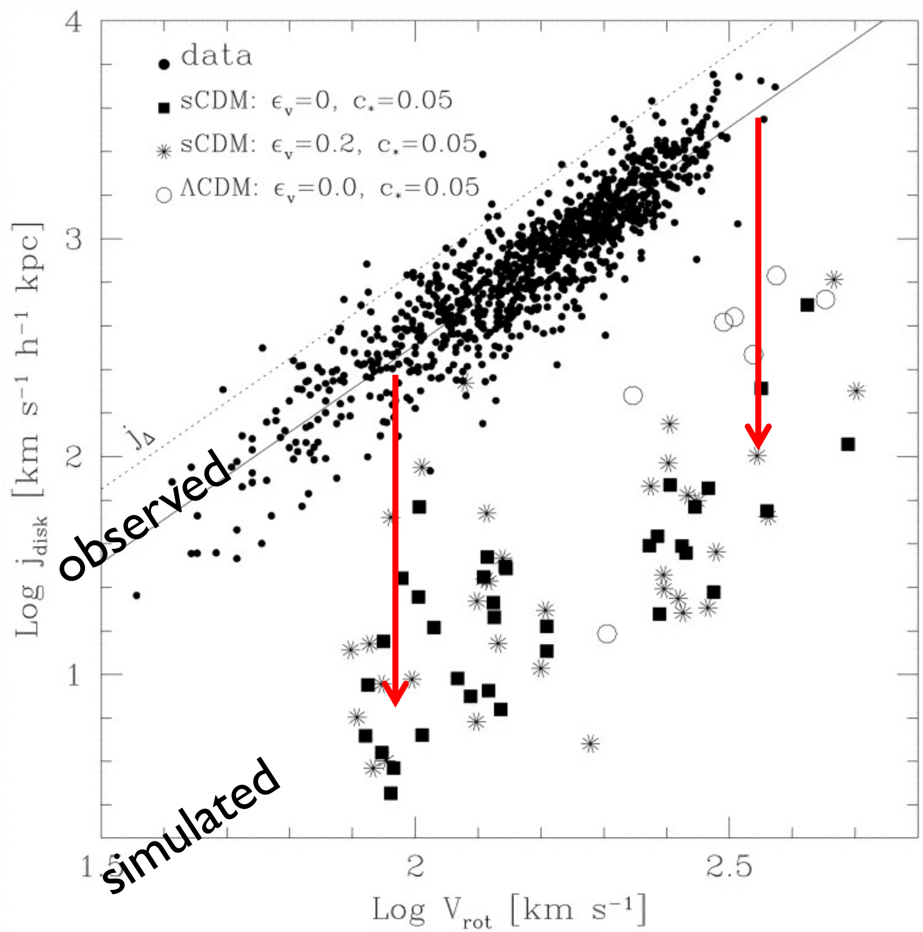
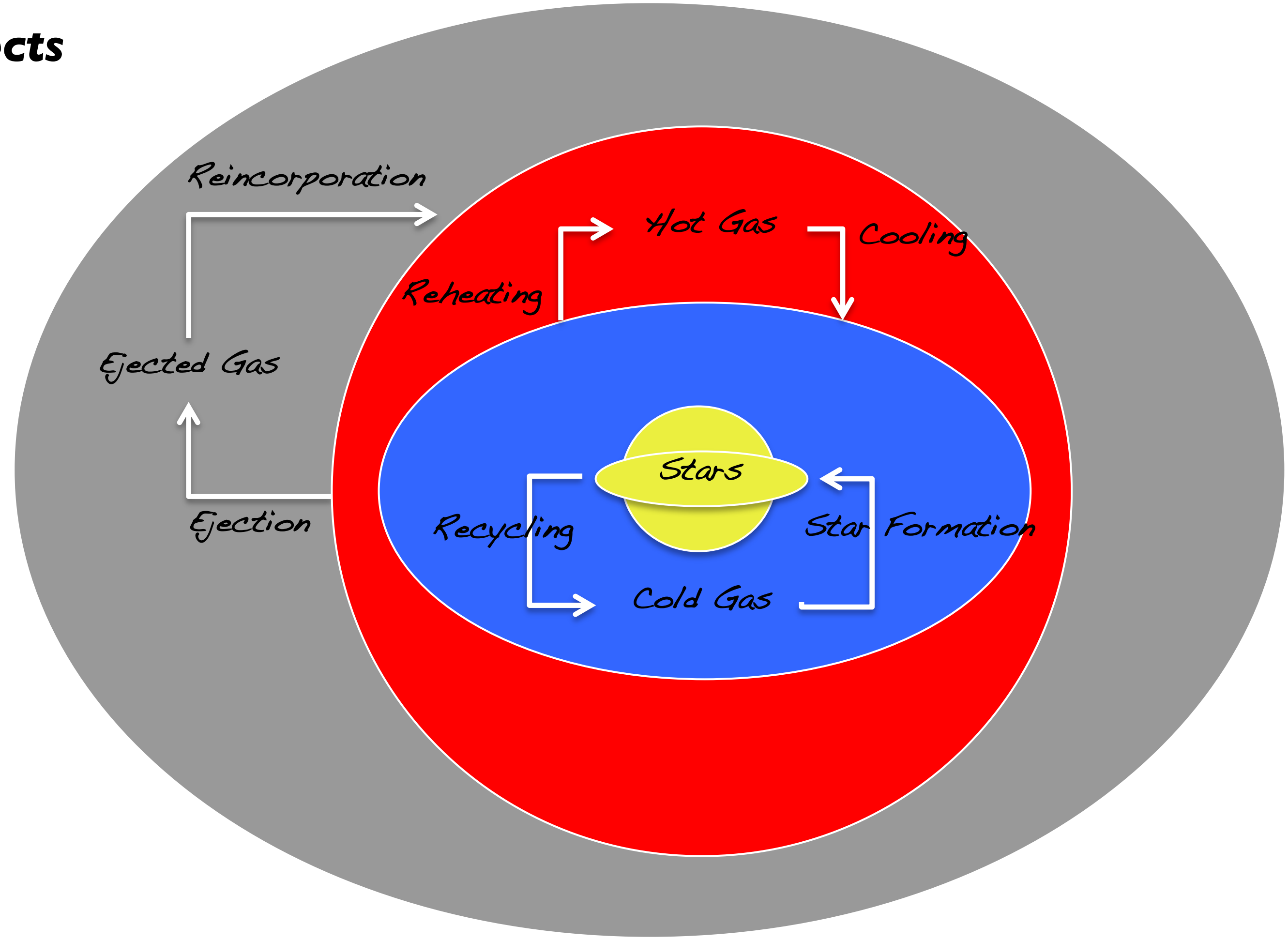


Steinmetz & Navarro (2000)

- <u>possible solutions</u>
  - proper numerical modelling
  - baryonic effects

▪ <u>possible solutions</u>

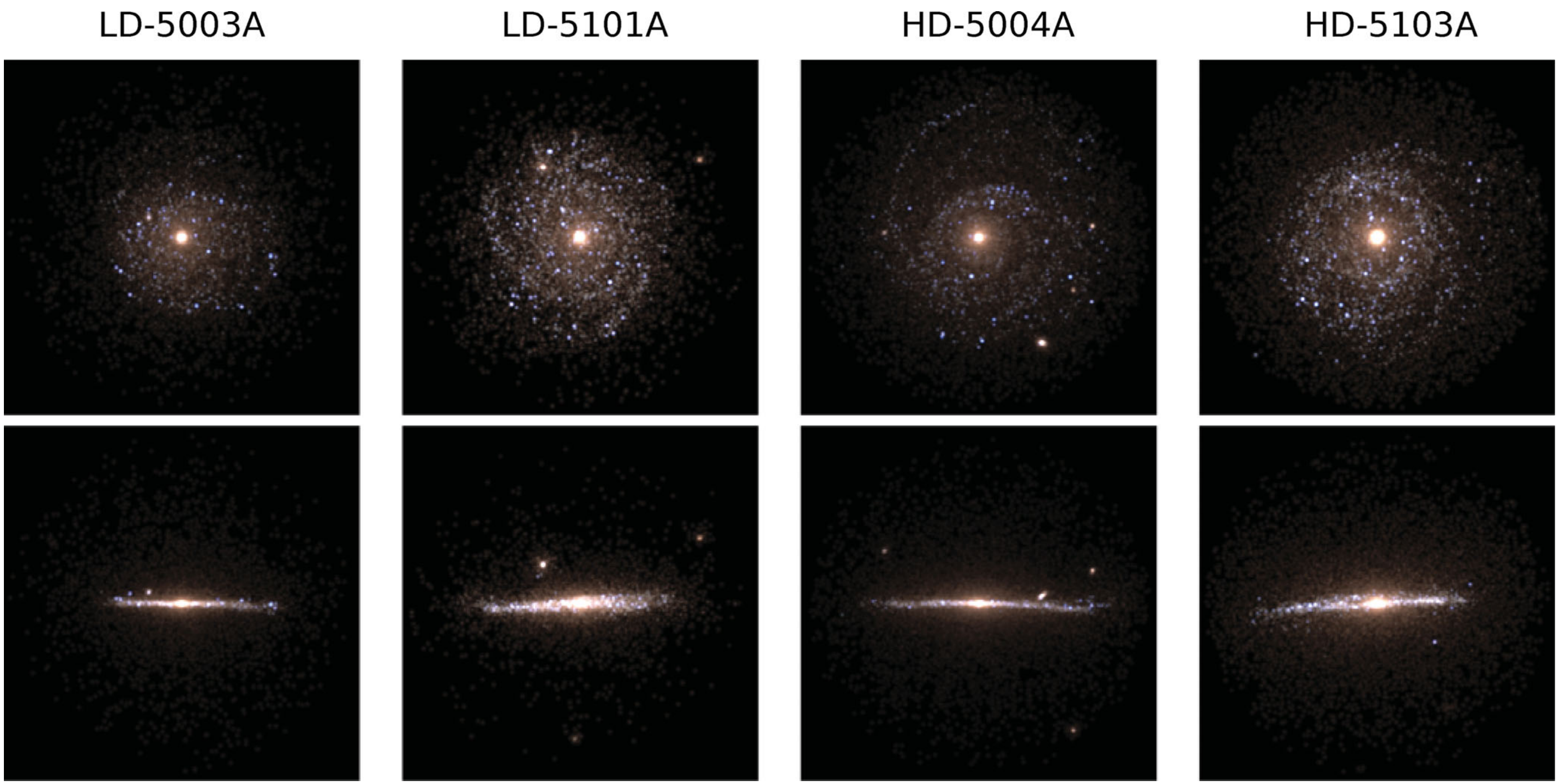
- proper numerical modelling
- ***baryonic effects***



▪ <u>possible solutions</u>

- ***proper numerical modelling***

- *baryonic effects*



(Domenech-Moral et al. 2012)

simulation code specifically designed to conserve angular momentum...

- the cusp-core problem
- satellite galaxies:
  - missing?
  - too big too fail?
  - planar distribution?
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- ***the Council of Giants***
- speeding bullets
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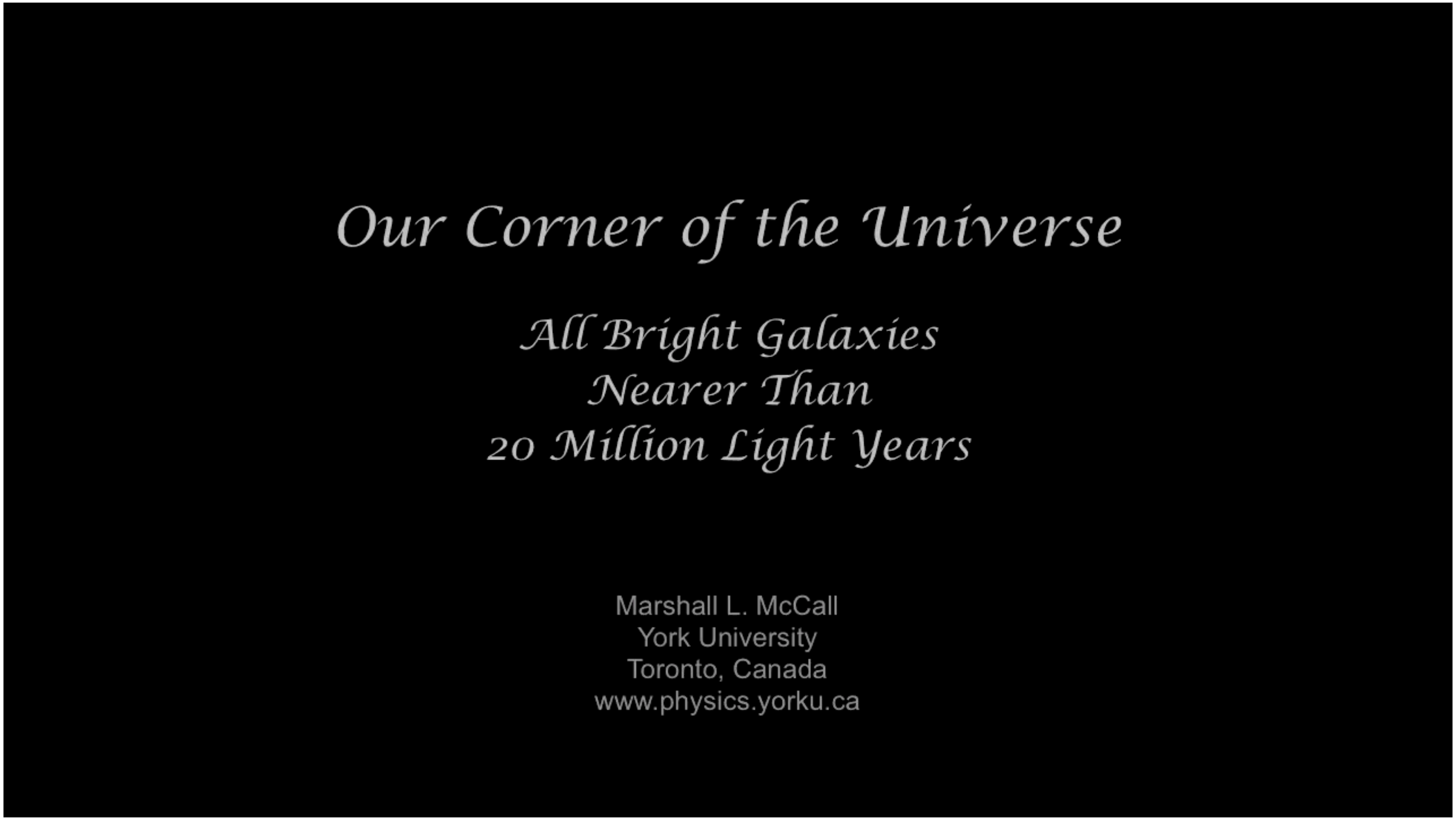
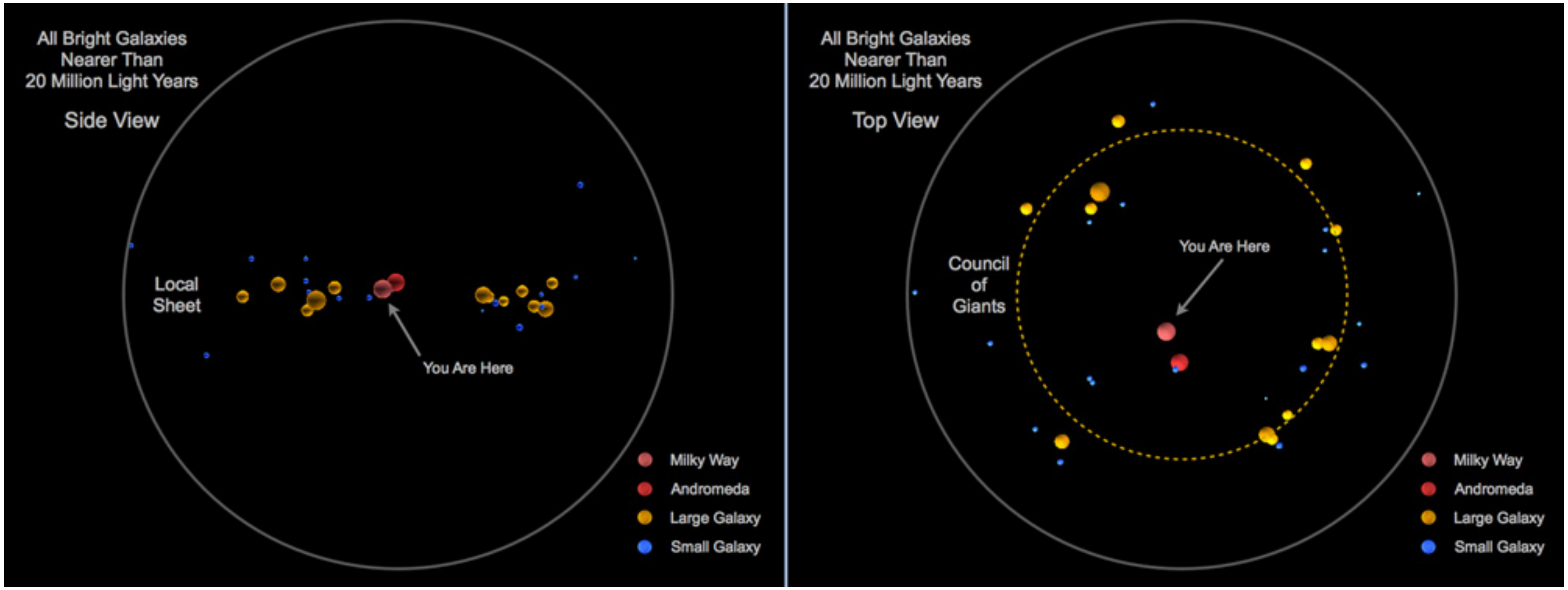


(c) Marshall McCall

https://www.youtube.com/watch?v=VzL7xGzfNlU



(c) Marshall McCall

- possible solutions
  - no explanation as of now!
  - currently investigating using Constrained Local Universe Simulations (CLUES)...

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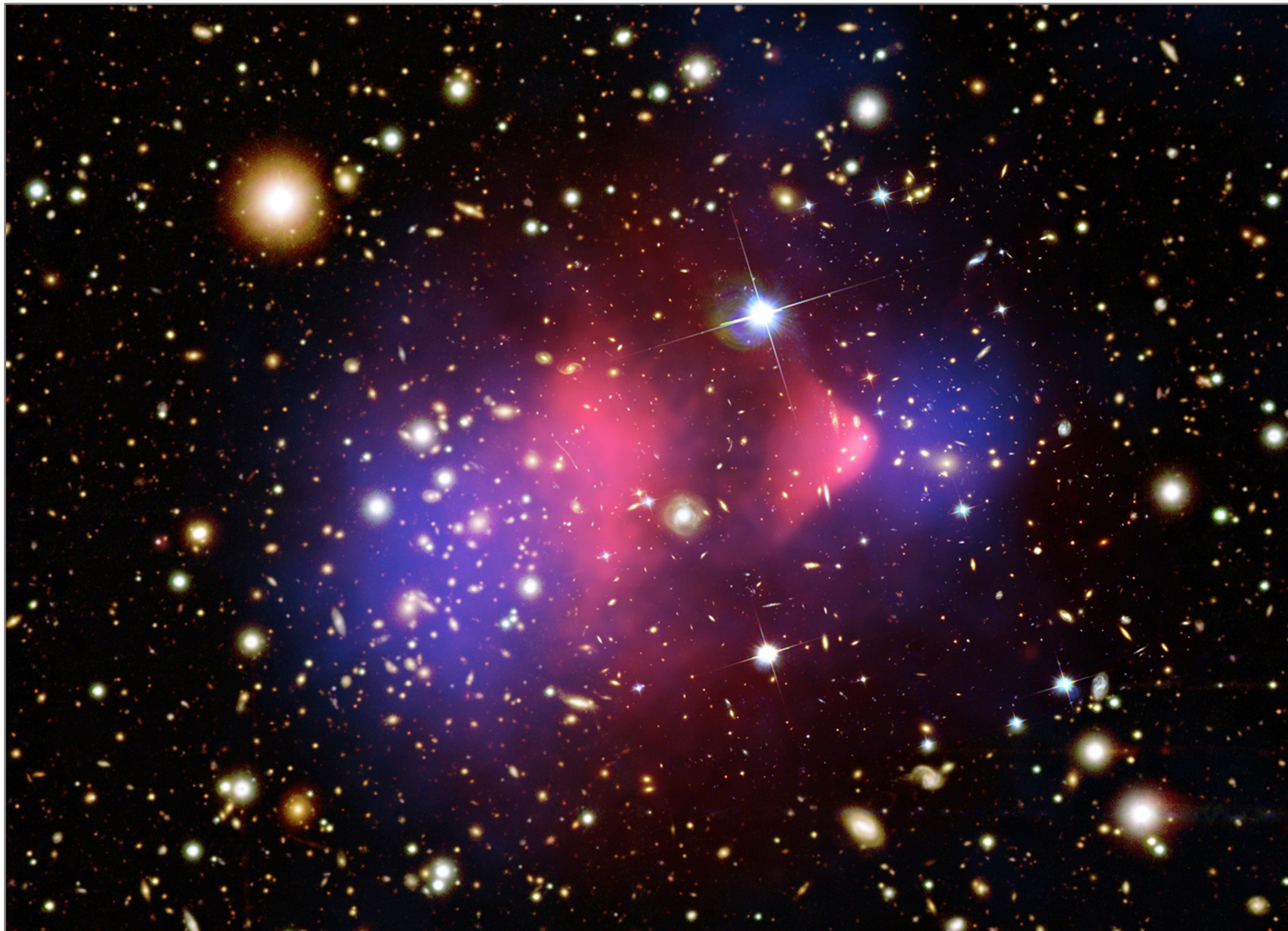
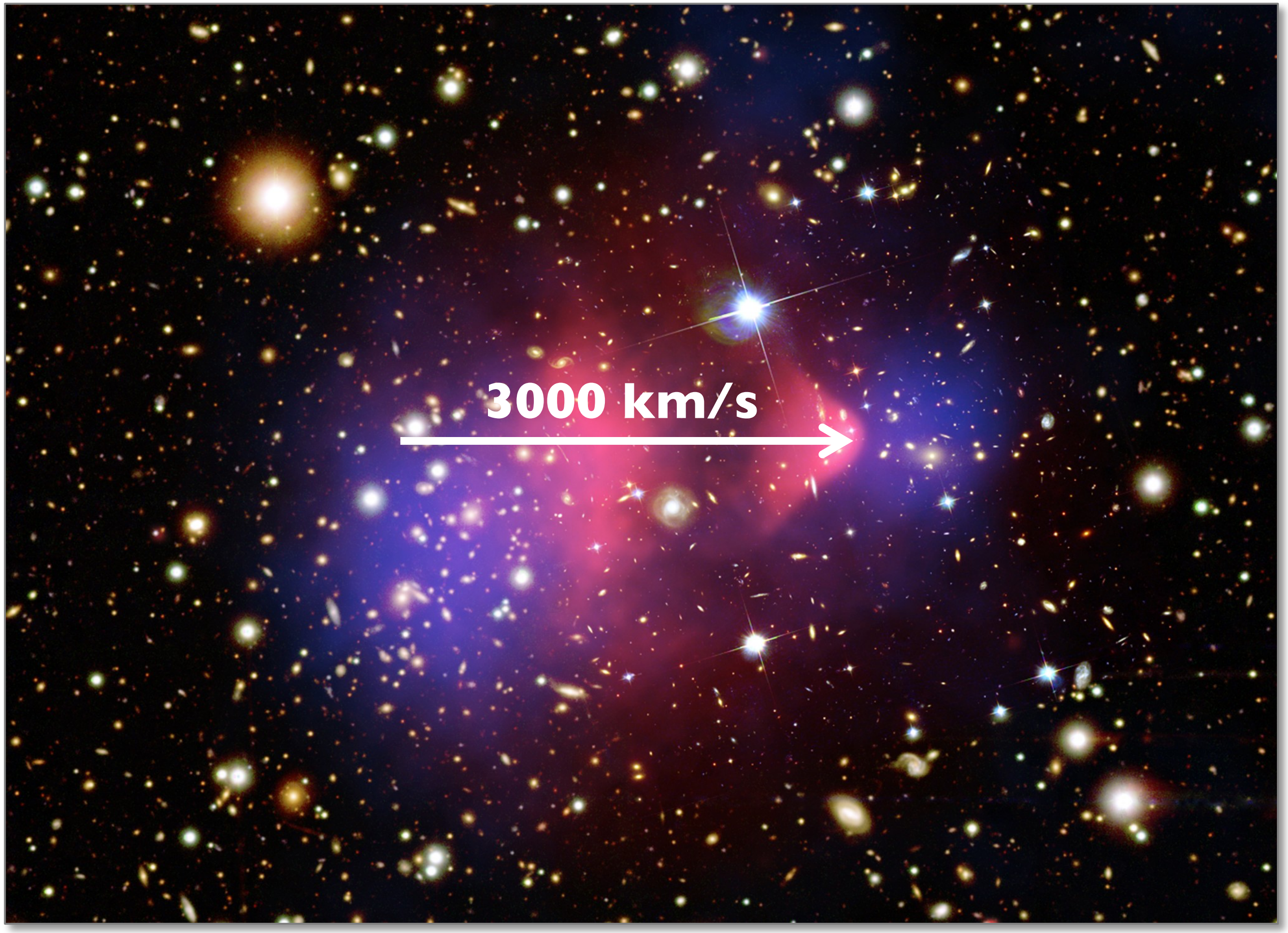
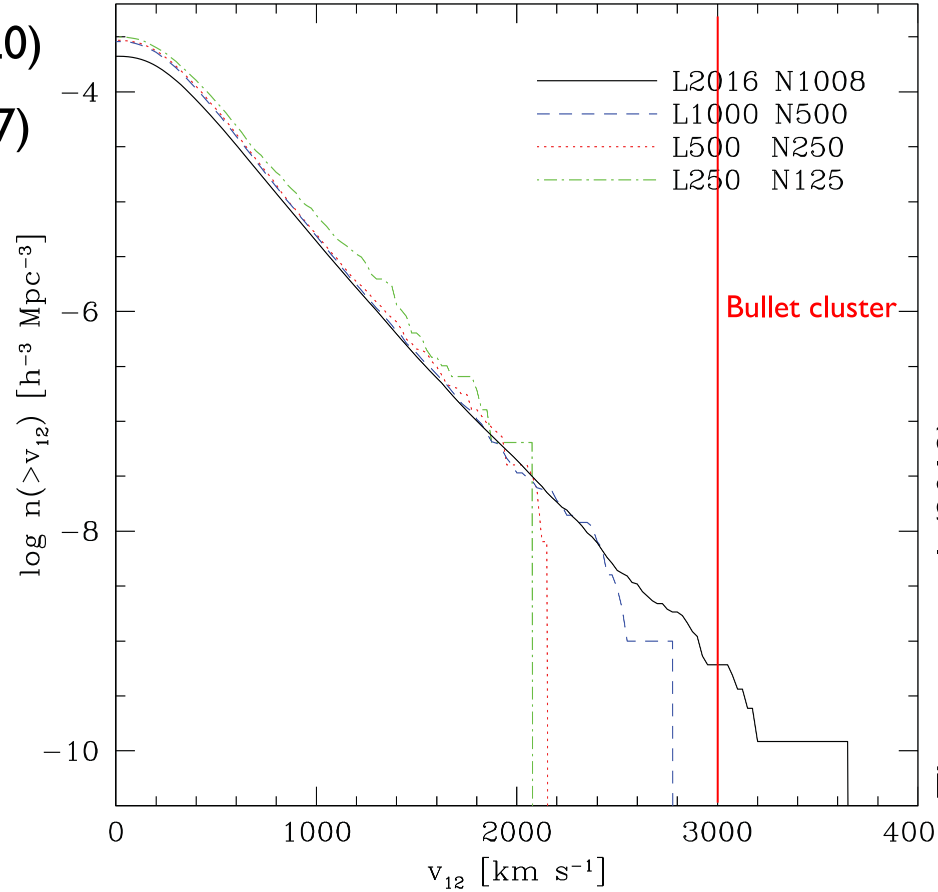


Bullet cluster (1E 0657-558)



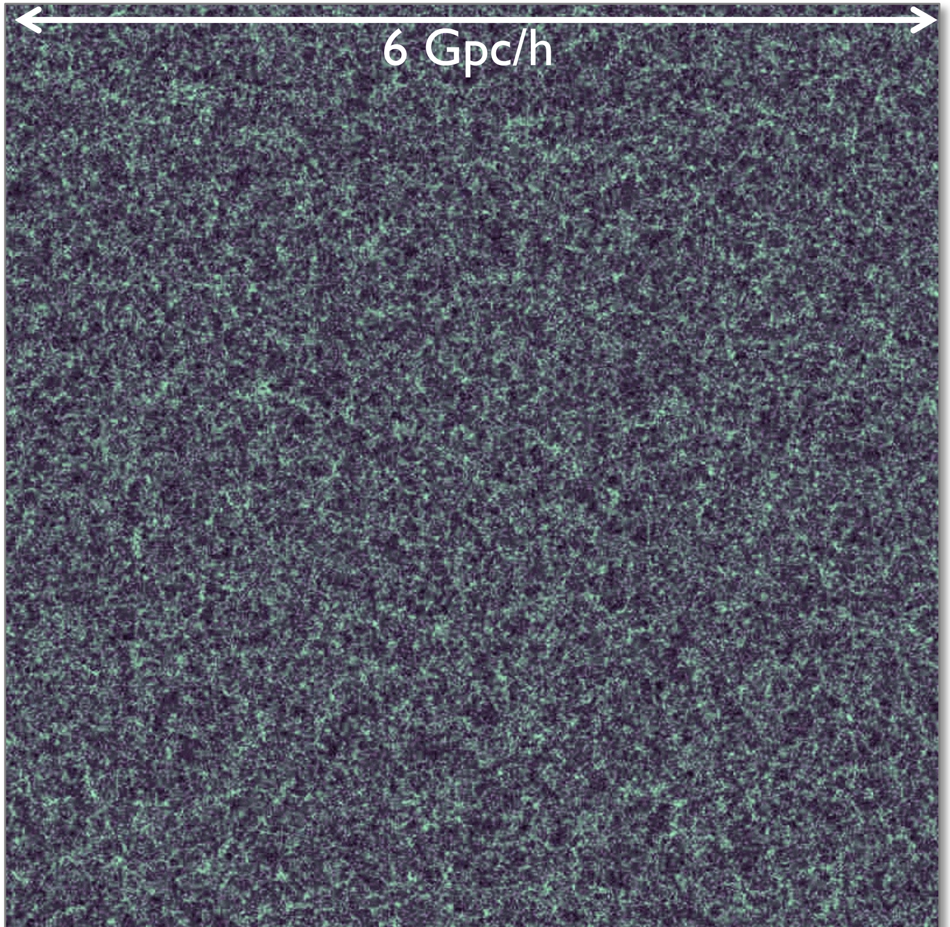
Bullet cluster (1E 0657-558)

- <u>very rare objects, yet we observe quite a few</u>
  - Bullet Cluster (1E0657-56)
  - “line-of-sight bullet”, (Abel 576)
  - “Cosmic Train Wreck” (Abel 520)
  - “Dark Matter Ring” (Cl0024+17)
  - MACS J0025.4−1222



Thomson et al. (2012)

- possible solutions
  - simulations volumes simply too small (i.e. cosmic variance)?



Jubilee simulation (http://jubilee.ft.uam.es)

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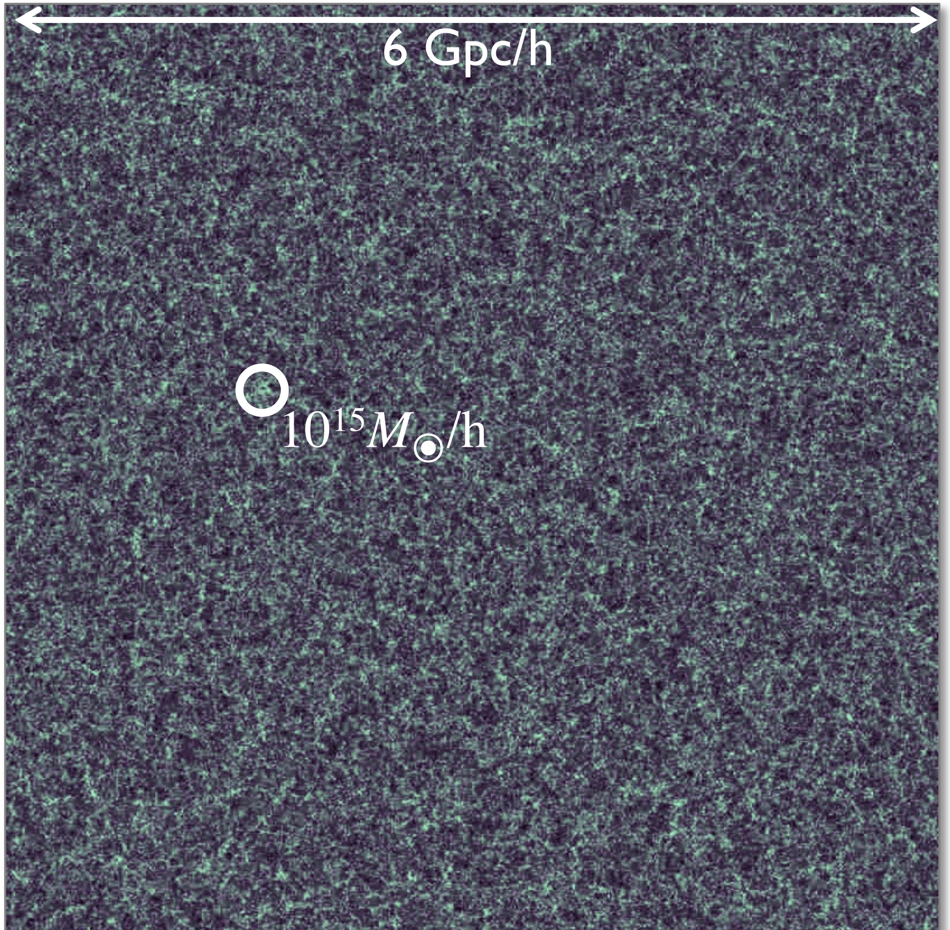

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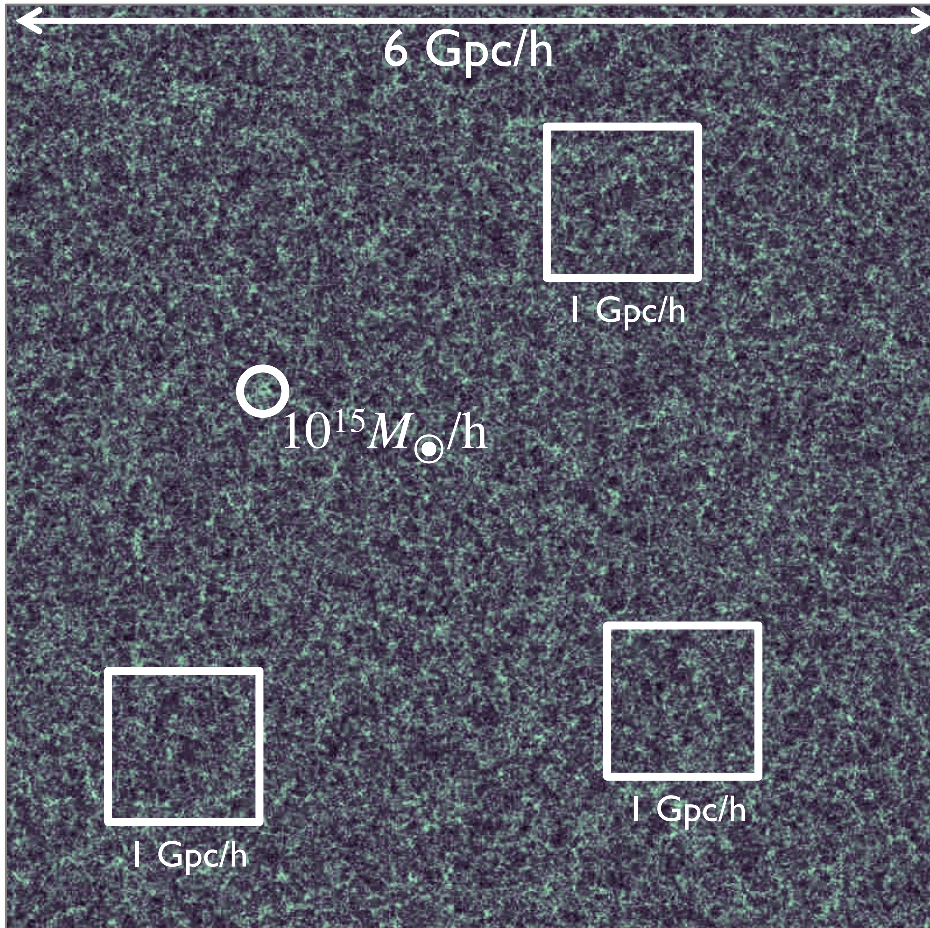
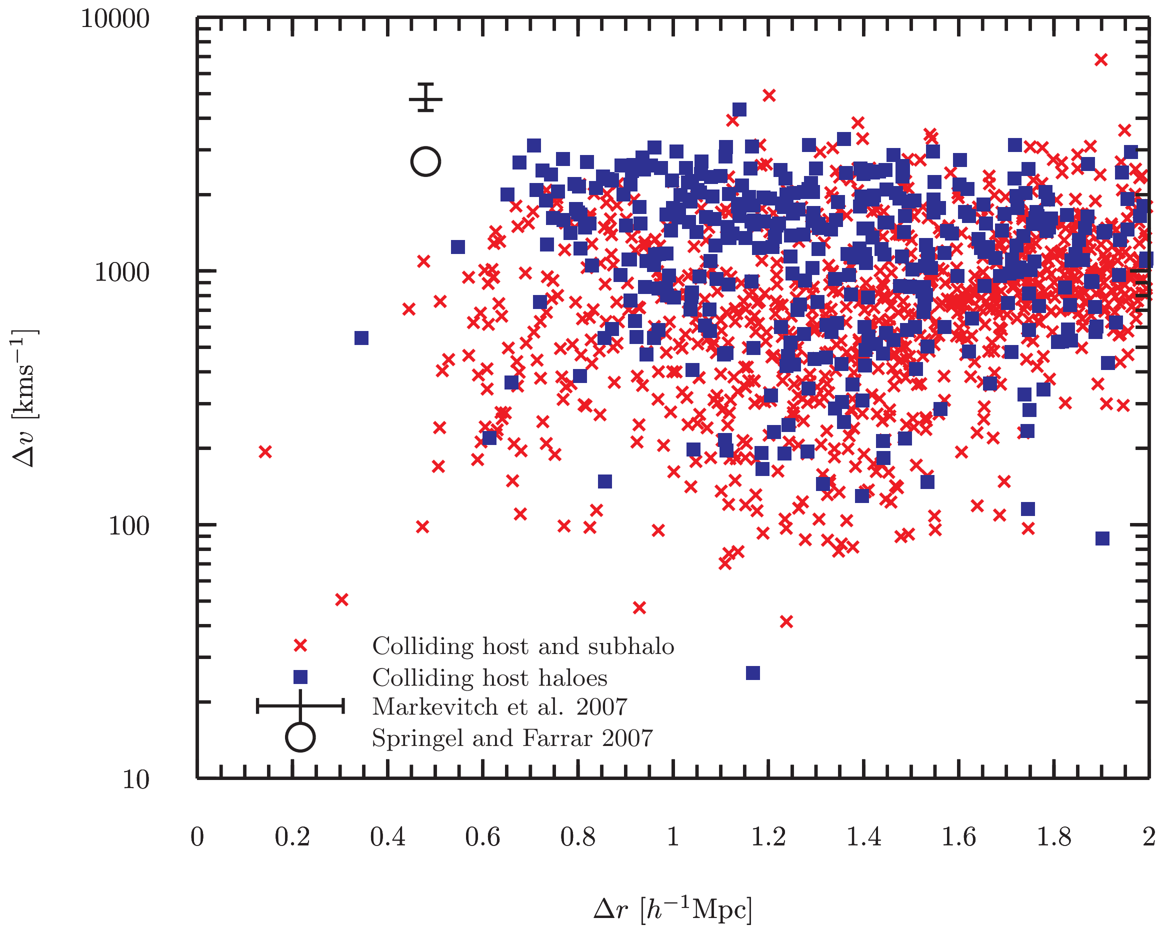


Jubilee simulation (http://jubilee.ft.uam.es)

- possible solutions
    - simulations volumes simply too small: Jubilee simulation!



Watson et al. (2014)

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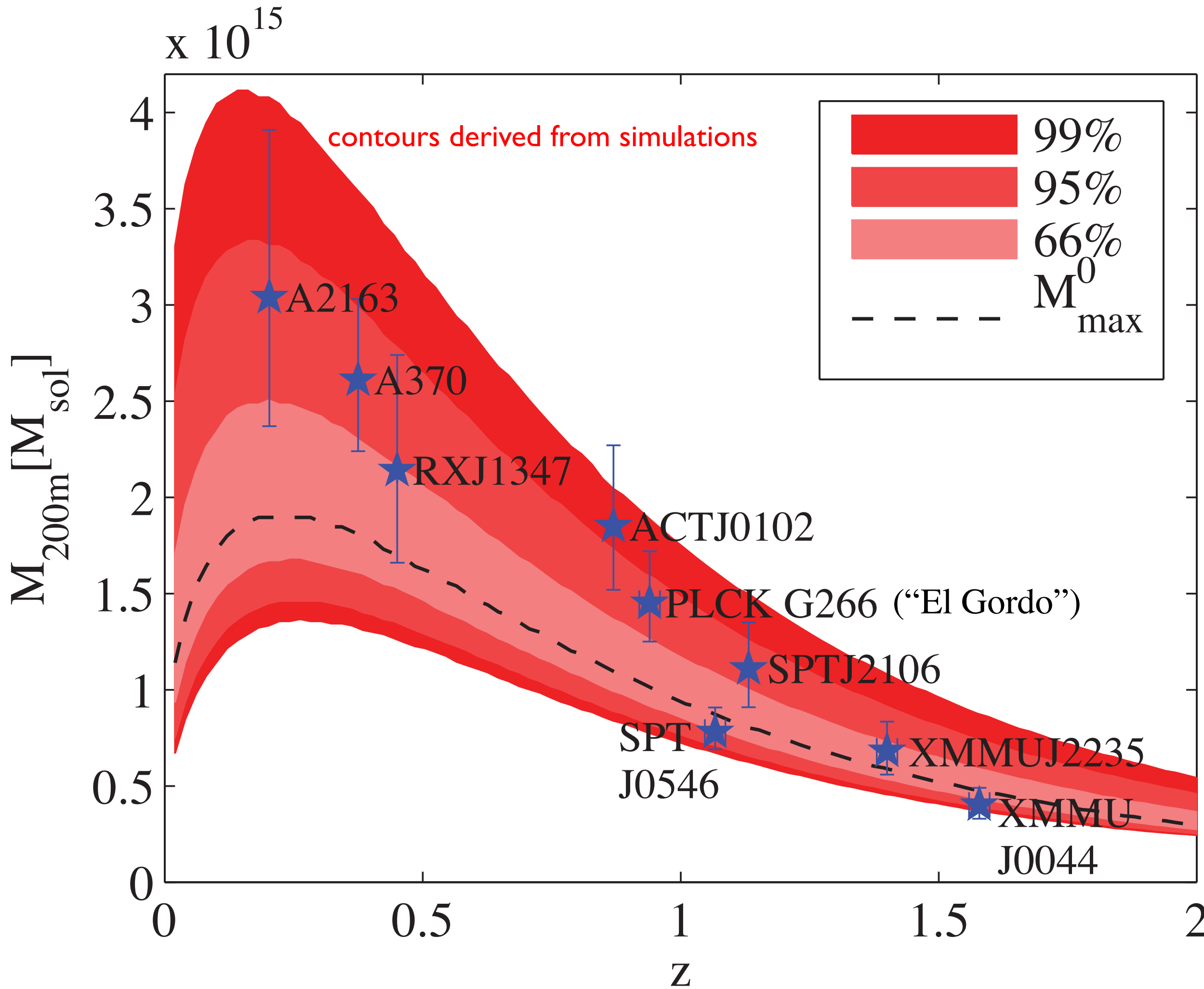
- the nature of dark energy?

$M \sim 1.5 \times 10^{15}\, M_\odot$ @ $z = 0.87$

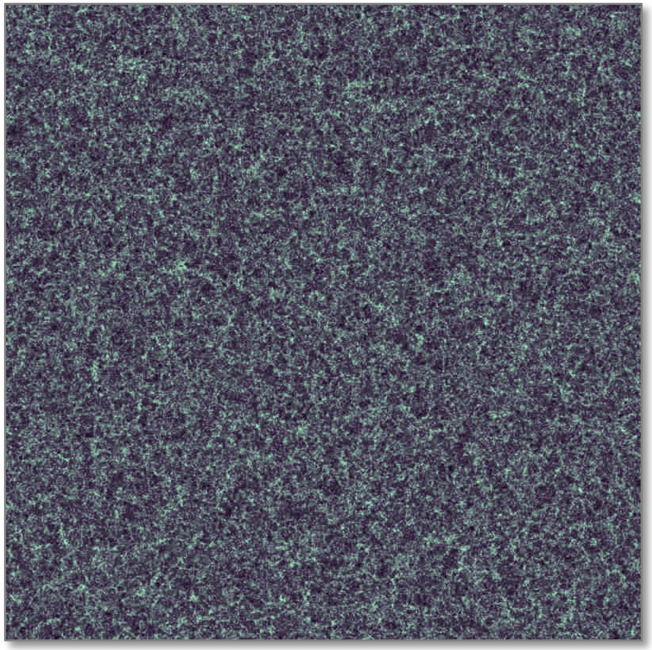
- galaxy clusters found at any given redshift too massive for ΛCDM?



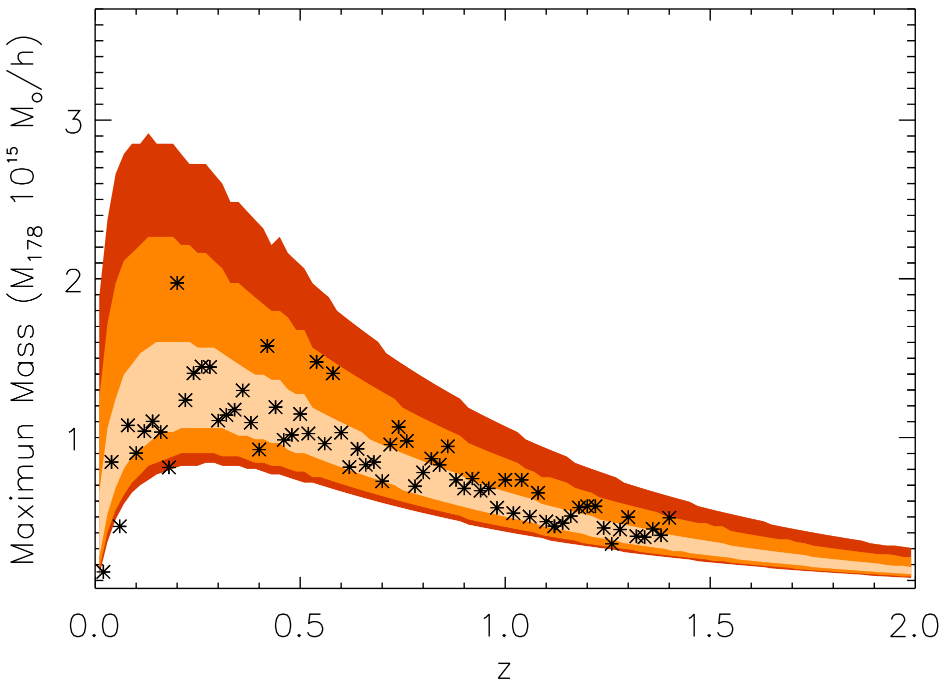
Harrison et al. (2011)

- or simulation volumes simply too small?

Jubilee simulation (http://jubilee.ft.uam.es)



Watson et al. (2015)



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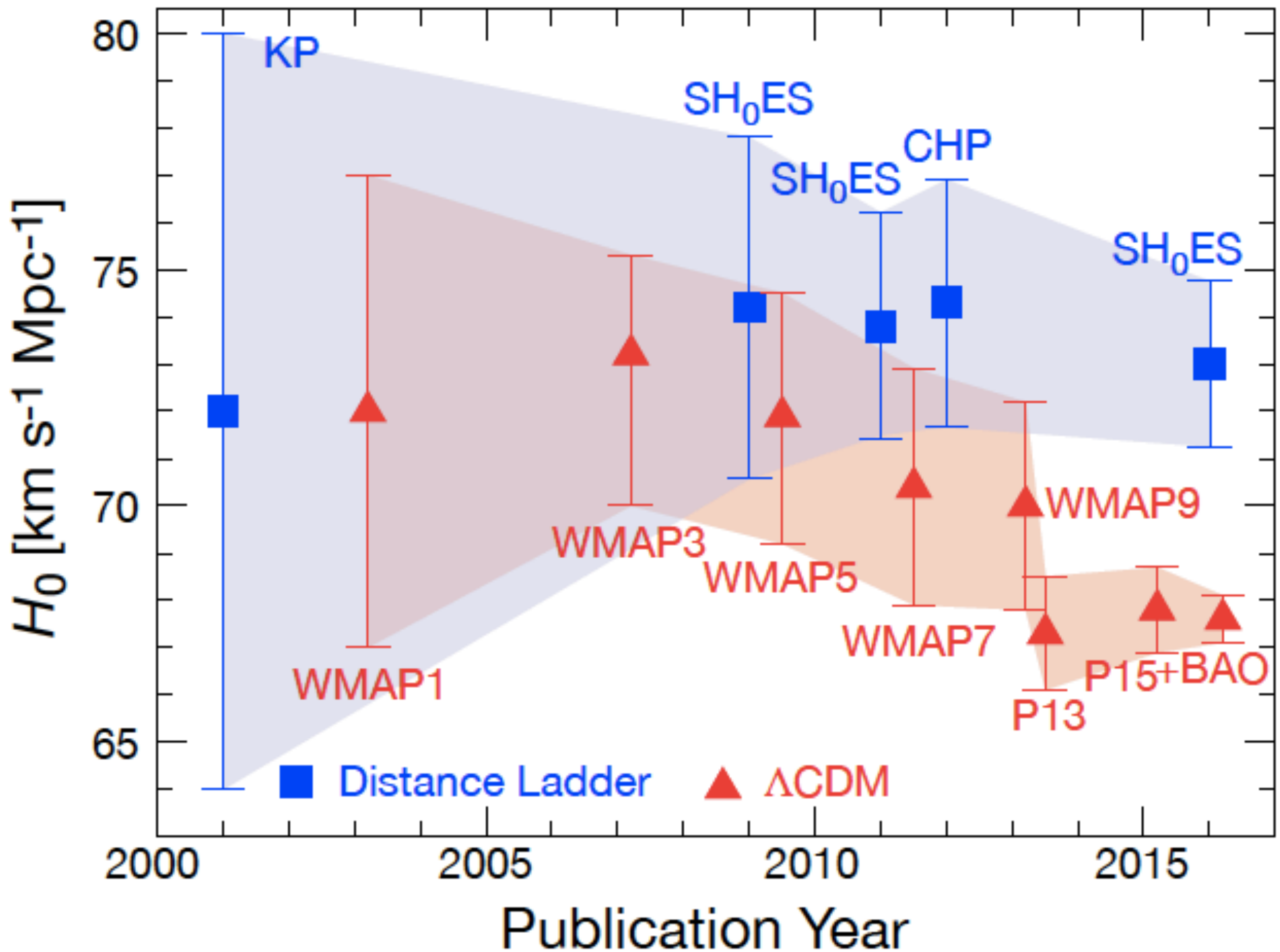
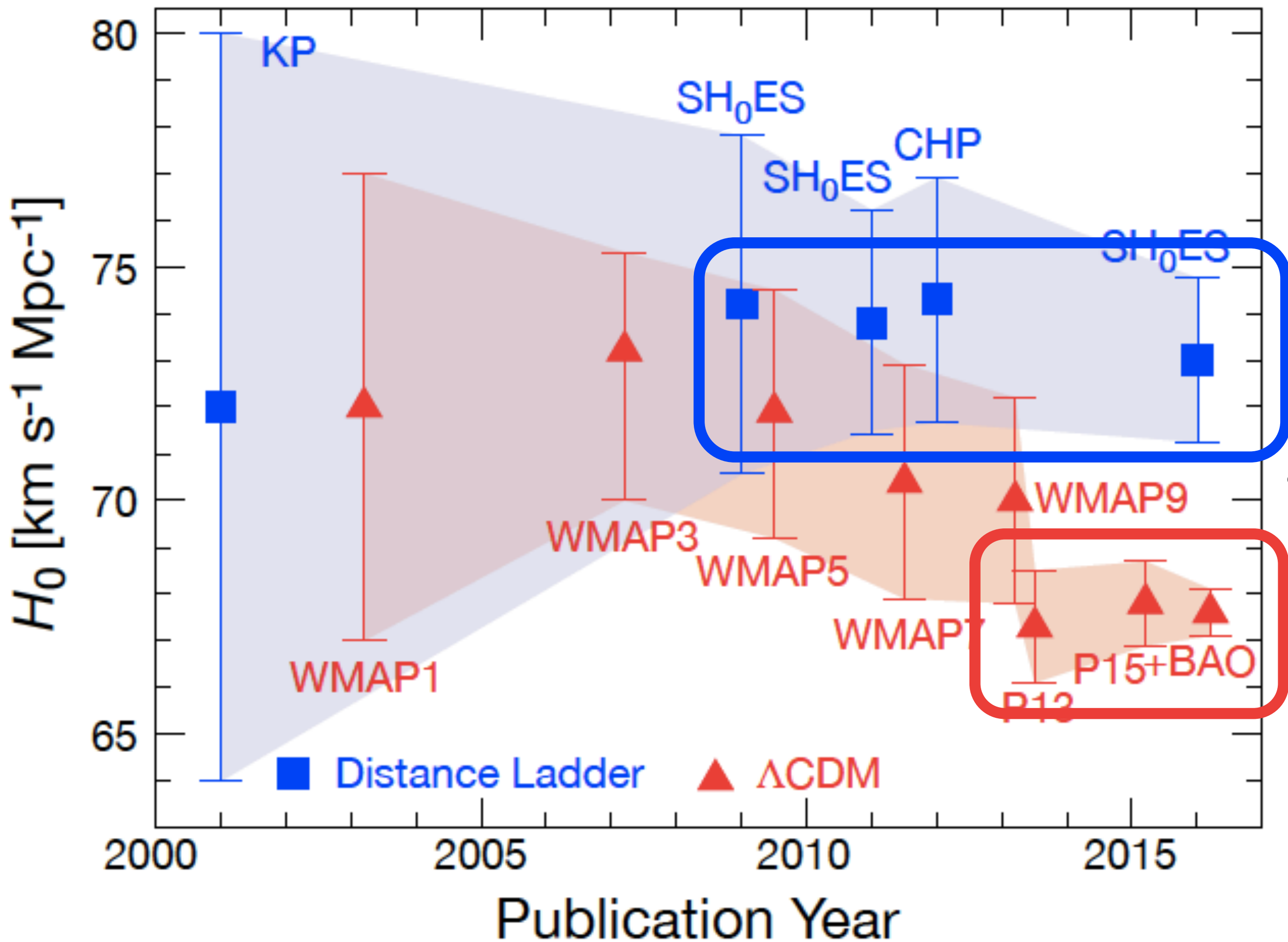
- independent measurements of H_0



Freedman (2017)

- independent measurements of H_0



outside each others error bars!

Freedman (2017)

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- the nature of dark energy?

we have not found the dark matter particle (yet)…

we have not found the dark matter particle (yet)…
…or did we!?

Did LIGO detect dark matter?

Simeon Bird,* Ilias Cholis, Julian B. Muñoz, Yacine Ali-Haïmoud, Marc Kamionkowski, Ely D. Kovetz, Alvise Raccanelli, and Adam G. Riess[1]

[1] *Department of Physics and Astronomy, Johns Hopkins University, 3400 N. Charles St., Baltimore, MD 21218, USA*

We consider the possibility that the black-hole (BH) binary detected by LIGO may be a signature of dark matter. Interestingly enough, there remains a window for masses $10\,M_\odot \lesssim M_{\rm bh} \lesssim 100\,M_\odot$ where primordial black holes (PBHs) may constitute the dark matter. If two BHs in a galactic halo pass sufficiently close, they can radiate enough energy in gravitational waves to become gravitationally bound. The bound BHs will then rapidly spiral inward due to emission of gravitational radiation and ultimately merge. Uncertainties in the rate for such events arise from our imprecise knowledge of the phase-space structure of galactic halos on the smallest scales. Still, reasonable estimates span a range that overlaps the $2-53$ Gpc^{-3} yr^{-1} rate estimated from GW150914, thus raising the possibility that LIGO has detected PBH dark matter. PBH mergers are likely to be distributed spatially more like dark matter than luminous matter and have no optical nor neutrino counterparts. They may be distinguished from mergers of BHs from more traditional astrophysical sources through the observed mass spectrum, their high ellipticities, or their stochastic gravitational wave background. Next generation experiments will be invaluable in performing these tests.

The nature of the dark matter (DM) is one of the most longstanding and puzzling questions in physics. Cosmological measurements have now determined with exquisite precision the abundance of DM [1, 2], and we know from a combination of observations and numerical simulations quite a bit about its distribution in Galactic halos. Still, the nature of the DM remains a mystery. Given the efficacy with which weakly-interacting massive particles—for many years the favored particle-theory explanation—have eluded detection, it may be warranted to consider other possibilities for DM. Primordial black holes (PBHs) are one such possibility [3, 4].

Here we consider whether the two $\sim 30\,M_\odot$ black holes detected by LIGO [5] could plausibly be PBHs. There is a window for PBHs to be DM if the BH mass is in the range $10\,M_\odot \lesssim M \lesssim 100\,M_\odot$ [6, 7]. Lower masses are excluded by microlensing surveys [8], and higher masses would disrupt wide binaries [7, 9, 10]. It has been argued that PBHs in this mass range are excluded by cosmic microwave background (CMB) constraints [11, 12]. However, these constraints require modeling of several complex physical processes, including the accretion of gas onto a moving BH, the conversion of the accreted mass to a luminosity, the self-consistent feedback of the BH radiation on the accretion process, and the deposition of the radiated energy as heat in the photon-baryon plasma. A significant (and difficult to quantify) uncertainty should therefore be associated with this upper limit, and it seems worthwhile to examine whether PBHs in this mass range could have other observational consequences.

In this *Letter*, we show that if DM consists of $\sim 30\,M_\odot$ BHs, then the rate for mergers of such PBHs falls within the merger rate inferred from GW150914. In any galactic halo, there is some small chance that two BHs will undergo a hard scatter and in so doing lose energy to a soft gravitational wave (GW) burst and thereby become gravitationally bound. This binary will then merge via emission of GWs in less than a Hubble time. Below we first estimate roughly the rate of such mergers and then present the results of more detailed calculations. We then discuss uncertainties in the calculation and some possible ways to distinguish PBHs from BH binaries from more traditional astrophysical sources.

Consider two PBHs that approach each other with some impact parameter on a hyperbolic orbit, with relative velocity $v_{\rm pbh}$. When the PBHs deflect each other, there is a time-varying quadrupole moment and thus GW emission. The PBH pair becomes gravitationally bound if the GW emission is greater than the initial kinetic energy. The cross section for this process is [13, 14],

$$\sigma = 2^{3/7}\pi\left(\frac{85\,\pi}{6\sqrt{2}}\right)^{2/7} R_s^2 \left(\frac{v_{\rm pbh}}{c}\right)^{-18/7} = 1.37\times10^{-14}\,M_{30}^2\,v_{\rm pbh-200}^{-18/7}\,{\rm pc}^2, \qquad (1)$$

where $R_s = 2GM_{\rm pbh}/c^2$ is the Schwarzschild radius, M_{30} the PBH mass in units of $30\,M_\odot$, and $v_{\rm pbh-200}$ the relative velocity in units of 200 km sec^{-1}.

We begin with a rough but simple and illustrative estimate of the rate per unit volume of such mergers. Suppose that all DM matter in the Universe resided in Milky-Way like halos of mass $M = M_{12}\,10^{12}\,M_\odot$ and uniform mass density $\rho = 0.002\,\rho_{0.002}\,M_\odot$ pc^{-3} with $\rho_{0.002}\sim 1$. The rate of mergers per halo, assuming a uniform-density halo of volume $V = M/\rho$, would then be

$$N \simeq (1/2)V(\rho/M_{\rm pbh})^2\sigma v \simeq 3.10\times10^{-12}\,M_{12}\,\rho_{0.002}\,v_{\rm pbh-200}^{-11/7}\,{\rm yr}^{-1}, \qquad (2)$$

where the relative velocity $v_{\rm pbh-200}$ is specified by a characteristic halo velocity. The mean cosmic DM mass density is $\rho_{\rm dm}\simeq 3.6\times10^{10}\,M_\odot$ Mpc^{-3}, and so the spatial

we have not found the dark matter particle (yet)…
…or did we!?

primordial black holes!?

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Simeon Bird,* Ilias Cholis, Julian B. Muñoz, Yacine Ali-Haïmoud, Marc Kamionkowski, Ely D. Kovetz, Alvise Raccanelli, and Ad[illegible]
[1] *Department of Physics and Astronomy, Johns Hopkins University, 3400 N. Charles St., Baltimore, MD 21218, USA*

We consider the possibility that the black-hole (BH) binary detected by LIGO may be a signature of dark matter. Interestingly enough, there remains a window for masses $10\,M_\odot \lesssim M_{\rm bh} \lesssim 100\,M_\odot$ where primordial black holes (PBHs) may constitute the dark matter. If two BHs in a galactic halo pass sufficiently close, they can radiate enough energy in gravitational waves to become gravitationally bound. The bound BHs will then rapidly spiral inward due to emission of gravitational radiation and ultimately merge. Uncertainties in the rate for such events arise from our imprecise knowledge of the phase-space structure of galactic halos on the smallest scales. Still, reasonable estimates span a range that overlaps the $2-53$ Gpc^{-3} yr^{-1} rate estimated from GW150914, thus raising the possibility that LIGO has detected PBH dark matter. PBH mergers are likely to be distributed spatially more like dark matter than luminous matter and have no optical nor neutrino counterparts. They may be distinguished from mergers of BHs from more traditional astrophysical sources through the observed mass spectrum, their high ellipticities, or their stochastic gravitational wave background. Next generation experiments will be invaluable in performing these tests.

The nature of the dark matter (DM) is one of the most longstanding and puzzling questions in physics. Cosmological measurements have now determined with exquisite precision the abundance of DM [1, 2], and we know from a combination of observations and numerical simulations quite a bit about its distribution in Galactic halos. Still, the nature of the DM remains a mystery. Given the efficacy with which weakly-interacting massive particles—for many years the favored particle-theory explanation—have eluded detection, it may be warranted to consider other possibilities for DM. Primordial black holes (PBHs) are one such possibility [3, 4].

Here we consider whether the two $\sim 30\,M_\odot$ black holes detected by LIGO [5] could plausibly be PBHs. There is a window for PBHs to be DM if the BH mass is in the range $10\,M_\odot \lesssim M \lesssim 100\,M_\odot$ [6, 7]. Lower masses are excluded by microlensing surveys [8], and higher masses would disrupt wide binaries [7, 9, 10]. It has been argued that PBHs in this mass range are excluded by cosmic microwave background (CMB) constraints [11, 12]. However, these constraints require modeling of several complex physical processes, including the accretion of gas onto a moving BH, the conversion of the accreted mass to a luminosity, the self-consistent feedback of the BH radiation on the accretion process, and the deposition of the radiated energy as heat in the photon-baryon plasma. A significant (and difficult to quantify) uncertainty should therefore be associated with this upper limit, and it seems worthwhile to examine whether PBHs in this mass range could have other observational consequences.

In this *Letter*, we show that if DM consists of $\sim 30\,M_\odot$ BHs, then the rate for mergers of such PBHs falls within the merger rate inferred from GW150914. In any galactic halo, there is some small chance that two BHs will undergo a hard scatter and in so doing lose energy to a soft gravitational wave (GW) burst and thereby become gravitationally bound. This binary will then merge via emission of GWs in less than a Hubble time. Below we first estimate roughly the rate of such mergers and then present the results of more detailed calculations. We then discuss uncertainties in the calculation and some possible ways to distinguish PBHs from BH binaries from more traditional astrophysical sources.

Consider two PBHs that approach each other with some impact parameter on a hyperbolic orbit, with relative velocity $v_{\rm pbh}$. When the PBHs deflect each other, there is a time-varying quadrupole moment and thus GW emission. The PBH pair becomes gravitationally bound if the GW emission is greater than the initial kinetic energy. The cross section for this process is [13, 14],

$$\sigma = 2^{3/7}\pi\left(\frac{85\,\pi}{6\sqrt{2}}\right)^{2/7} R_s^2\left(\frac{v_{\rm pbh}}{c}\right)^{-18/7} = 1.37\times10^{-14}\,M_{30}^2\,v_{\rm pbh-200}^{-18/7}\,{\rm pc}^2, \qquad (1)$$

where $R_s = 2GM_{\rm pbh}/c^2$ is the Schwarzschild radius, M_{30} the PBH mass in units of $30\,M_\odot$, and $v_{\rm pbh-200}$ the relative velocity in units of 200 km sec^{-1}.

We begin with a rough but simple and illustrative estimate of the rate per unit volume of such mergers. Suppose that all DM matter in the Universe resided in Milky-Way like halos of mass $M = M_{12}\,10^{12}\,M_\odot$ and uniform mass density $\rho = 0.002\,\rho_{0.002}\,M_\odot$ pc^{-3} with $\rho_{0.002}\sim 1$. The rate of mergers per halo, assuming a uniform-density halo of volume $V = M/\rho$, would then be

$$N \simeq (1/2)V(\rho/M_{\rm pbh})^2\sigma v \simeq 3.10\times10^{-12}\,M_{12}\,\rho_{0.002}\,v_{\rm pbh-200}^{-11/7}\,{\rm yr}^{-1}, \qquad (2)$$

where the relative velocity $v_{\rm pbh-200}$ is specified by a characteristic halo velocity. The mean cosmic DM mass density is $\rho_{\rm dm} \simeq 3.6\times10^{10}\,M_\odot$ Mpc^{-3}, and so the spatial

Density Perturbations and Black Hole Formation in Hybrid Inflation

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(May 15, 1996)

We investigate the recently proposed hybrid inflation models with two stages of inflation. We show that quantum fluctuations at the time corresponding to the phase transition between the two inflationary stages can trigger the formation of a large number of inflating topological defects. In order to study density perturbations in these models we develop a new method to calculate density perturbations in a system of two scalar fields. We show that density perturbations in hybrid inflation models of the new type can be very large on the scale corresponding to the phase transition. The resulting density inhomogeneities lead to a copious production of black holes. This could be an argument against hybrid inflation models with two stages of inflation. However, we find a class of models where this problem can be easily avoided. The number of black holes produced in these models can be made extremely small, but in general it could be sufficiently large to have important cosmological and astrophysical implications. In particular, for certain values of parameters these black holes may constitute the dark matter in the universe. It is also possible to have hybrid models with two stages of inflation where the black hole production is not suppressed, but where the typical masses of the black holes are very small. Such models lead to a completely different thermal history of the universe, where post-inflationary reheating occurs via black hole evaporation.

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I. INTRODUCTION

A period of "inflation" or accelerated expansion in the early universe is an attractive idea in modern cosmology. Acceleration of the scale factor could drive the universe towards homogeneity, isotropy and spatial flatness. However it is the ability of quantum fluctuations in the fields driving inflation to produce a nearly scale-invariant spectrum of quantum fluctuations that provides the most powerful test of the inflationary paradigm and may allow us to constrain the physics involved. Cosmological observations allow us to measure the amplitude and tilt of the primordial density and, possibly, gravitational wave spectra on scales that would have left the horizon during inflation.

The first inflationary models such as the old and the new inflationary universe scenario presumed that inflation began in the false vacuum state after the high temperature phase transitions in the early universe [1,2]. Later it was proposed that all possible initial conditions should be considered without necessarily assuming initial thermal equilibrium, and see whether some of these conditions may lead to inflation. This scenario was called chaotic inflation [3]. For many years the idea of chaotic initial conditions seemed too radical, since it implied a considerable deviation from the idea of the hot Big Bang. It was argued that for a successful realization of inflationary theory one should satisfy so-called "thermal constraints" [4]. However, gradually it was understood that the assumption of thermal initial conditions is neither natural nor helpful for inflationary theory [5]. As a result, most of the models investigated now belong to the class of chaotic inflation, which provides the most general framework for the development of inflationary cosmology.

The simplest models of chaotic inflation include theories with potentials $V(\phi)$ such as $m^2\phi^2/2$ or $\lambda\phi^4/4$. Inflation occurs in these theories at $\phi > M_{\rm P}$. However, one may also consider chaotic inflation near $\phi = 0$ in models with potentials which could be used for implementation of the new inflation scenario, such as $-m^2\phi^2/2+\lambda\phi^4/4$ [6]. For brevity, one may call inflation in such models "new inflation", to distinguish it from inflation at large ϕ, but strictly speaking these models also belong to the general class of chaotic inflation models: the original new inflationary universe scenario based on the theory of high temperature phase transitions have never been successfully implemented in realistic theories.

The simplest models of chaotic inflation such as the model $m^2\phi^2/2$ have many advantages, including natural initial conditions near the Planck density and the existence of the regime of eternal self-reproduction of the universe [5]. Normalizing the mass scale by the fluctuations in the microwave background observed by COBE [7] gives $m \simeq 2\times10^{13}$ GeV and the energy density at the end of inflation is $V(\phi)\simeq(10^{16}\,{\rm GeV})^4$. At this energy gravitational waves contribute about 10% of the microwave background fluctuations. The tilt of the density perturbation spectrum in this model is $n-1\simeq-0.03$.

However, inflation occurs in such models only for $\phi \gtrsim M_{\rm P}$. It is quite possible to have inflation at $\phi > M_{\rm P}$ in models with polynomial potentials, but in string theory and supergravity one often encounters potentials

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- satellite galaxies:
  - missing?
  - too big too fail?
  - planar distribution?
- bulge-less disk galaxies
- the Council of Giants
- speeding bullets
- El Gordo
- Hubble tension

- the nature of dark matter?
- ***the nature of dark energy?***

we have no theory for dark energy (yet)…

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most of the solutions to these problems involve complex and computationally challenging modelling of baryonic physics!

...but may also hint at something more fundamental!?

- CDM in crisis?
- **solutions beyond the concordance model**

▪ Alternative Cosmologies

- Warm Dark Matter
- MOdified Newtonian Dynamics
- Lemaitre-Tolman-Bondi void models
- Quintessence models
- Modified gravity f(R) models
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$$v(z) = 0.04371\,(1+z)\left(\frac{\Omega_X h^2}{0.15}\right)^{1/3}\left(\frac{g_X}{1.5}\right)^{-1/3}\left(\frac{m_X}{keV}\right)^{-4/3} \quad km/s$$

(Bode et al. 2001; Viel et al. 2013)

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43/4 = 10.75; g* = at decoupling of X

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ratio between photon and WDM degrees of freedom

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suppression of P(k)...

(Bode et al. 2001; Viel et al. 2013)

- warm dark matter suppresses small-scale structure

$$\frac{P^{WDM}(k)}{P^{CDM}(k)} = \left(\left[1+(\alpha k)^{2\nu}\right]^{-5/\nu}\right)^2$$

$$\alpha = 0.048\left(\frac{\Omega_X}{0.4}\right)^{0.15}\left(\frac{h}{0.65}\right)^{1.3}\left(\frac{g_X}{1.5}\right)^{-0.29}\left(\frac{m_X}{keV}\right)^{-1.15} h^{-1}Mpc$$

$$\nu = 1.2$$

(Bode et al. 2001)

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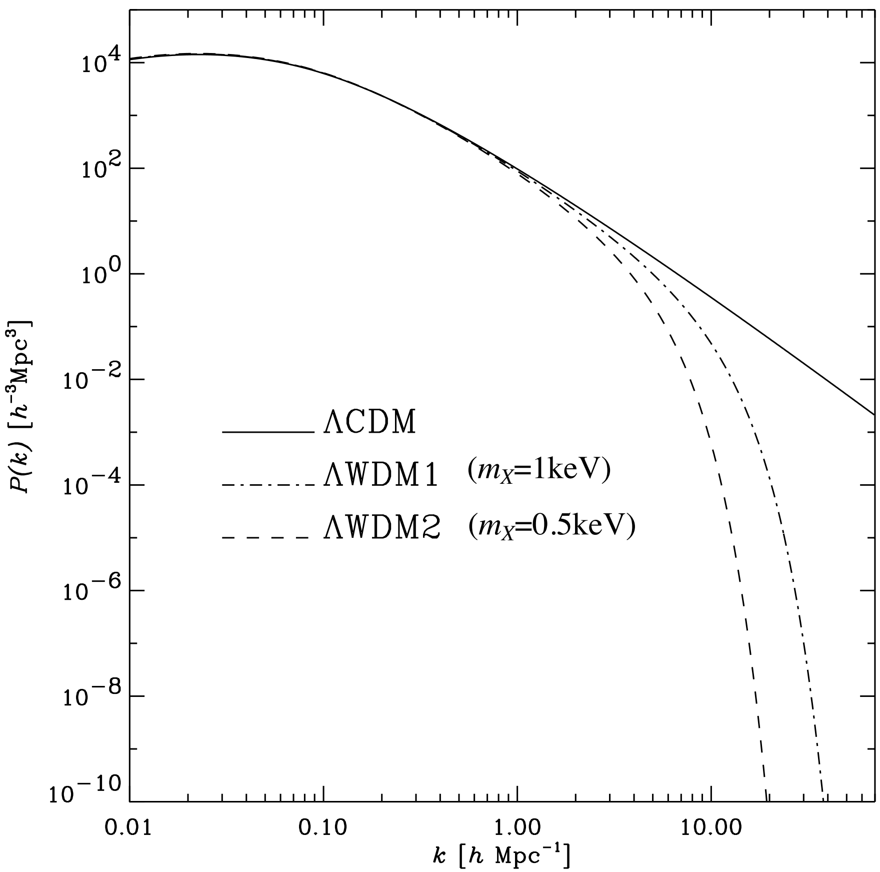

(Knebe et al. 2002)

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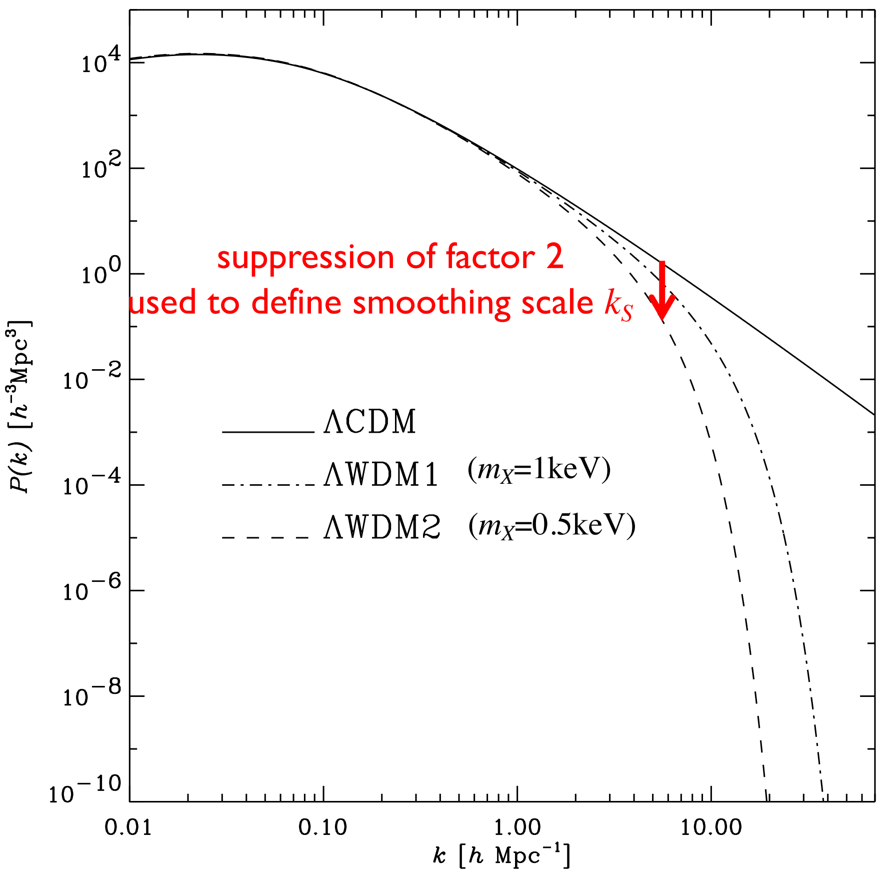

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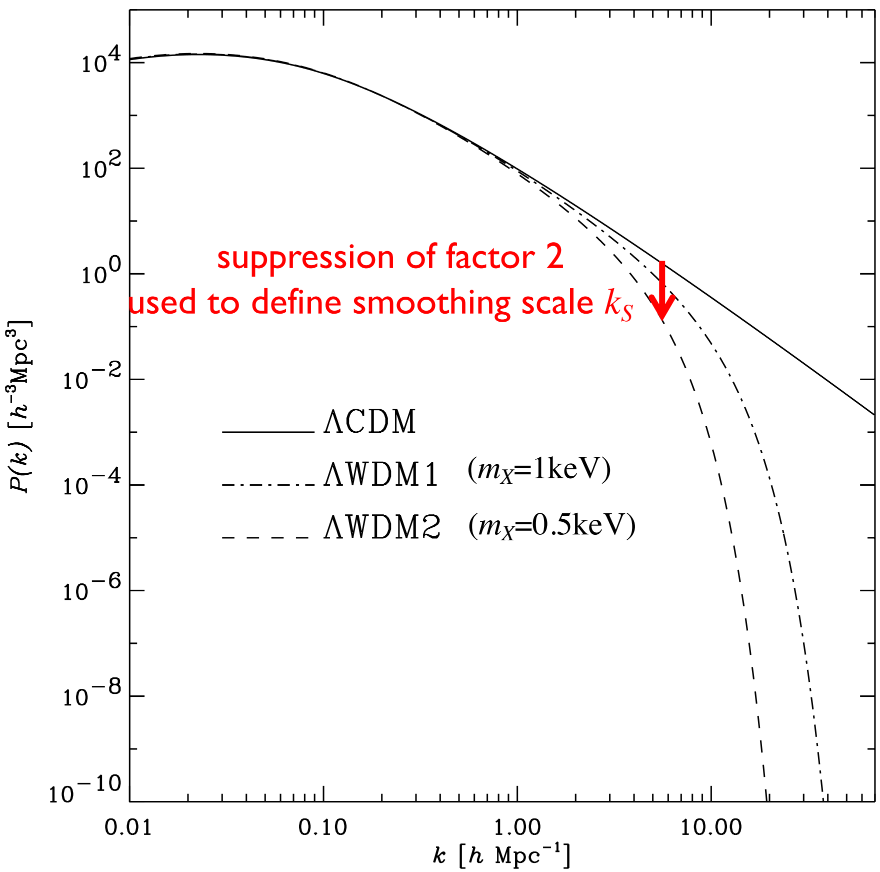
$$R_S = \frac{2\pi}{k_s} = 0.31 \left(\frac{\Omega_X}{0.3}\right)^{0.15} \left(\frac{h}{0.65}\right)^{1.3} \left(\frac{m_X}{keV}\right)^{-1.15} h^{-1} Mpc$$



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the formation of objects with mass $M<M_S$ will be suppressed

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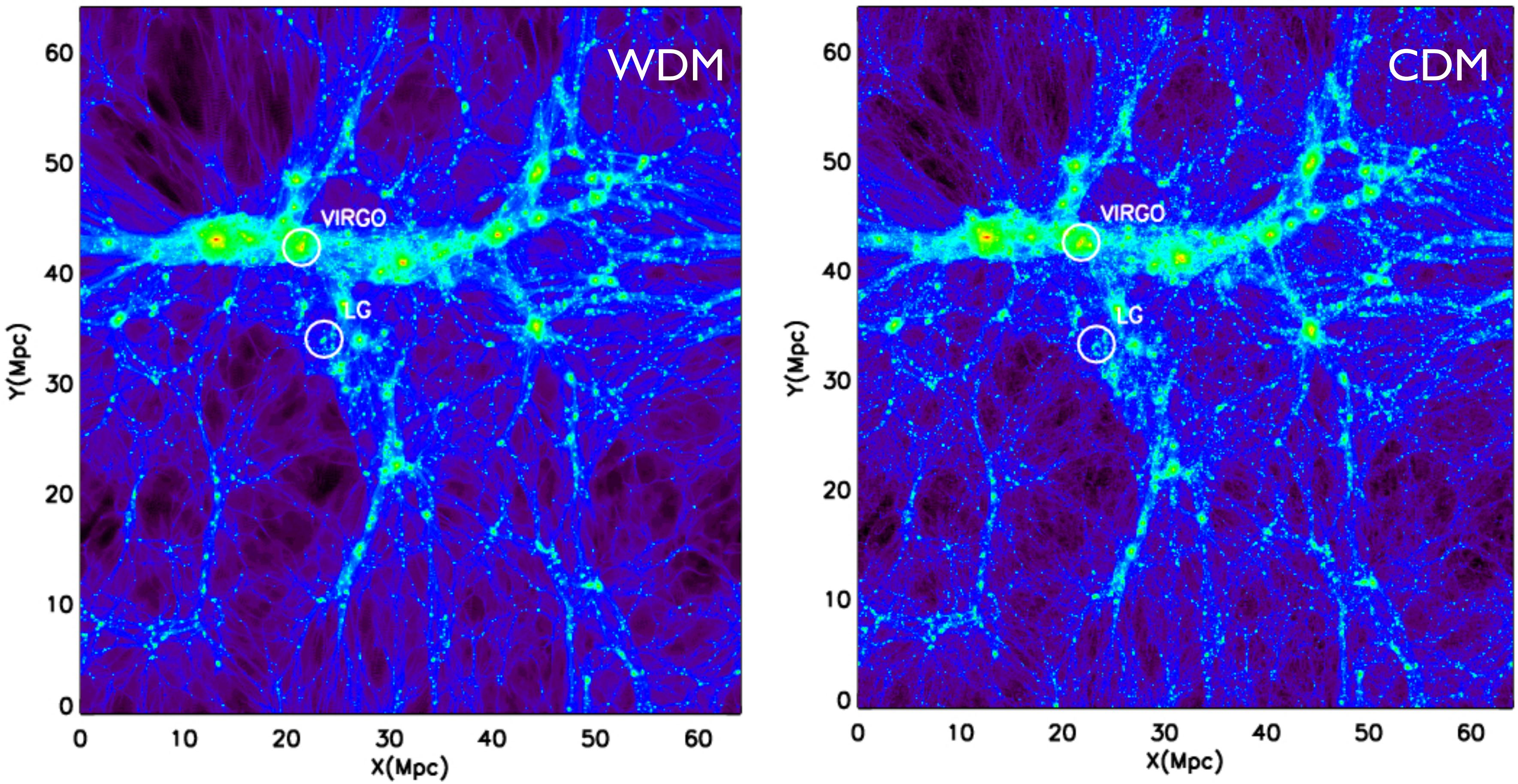

(CLUES collaboration, http://www.clues-project.org)

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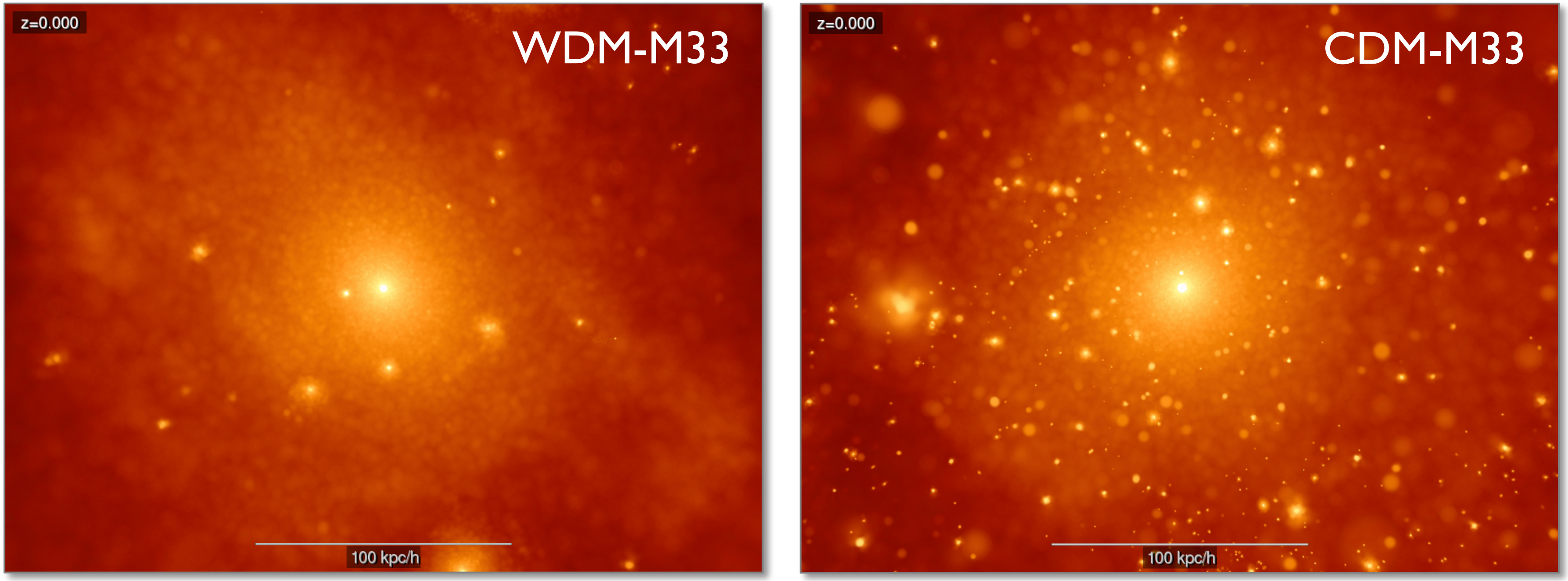

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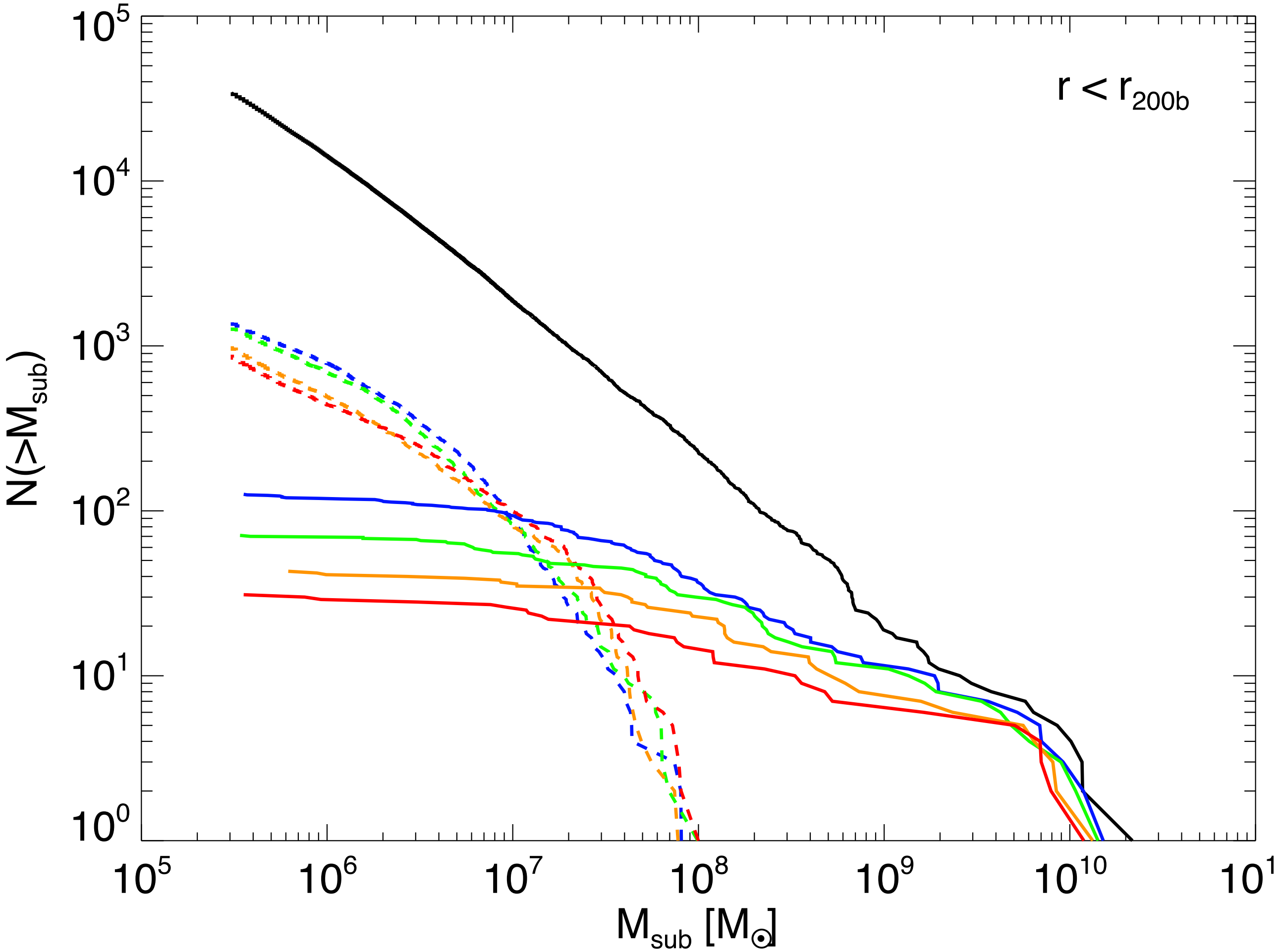

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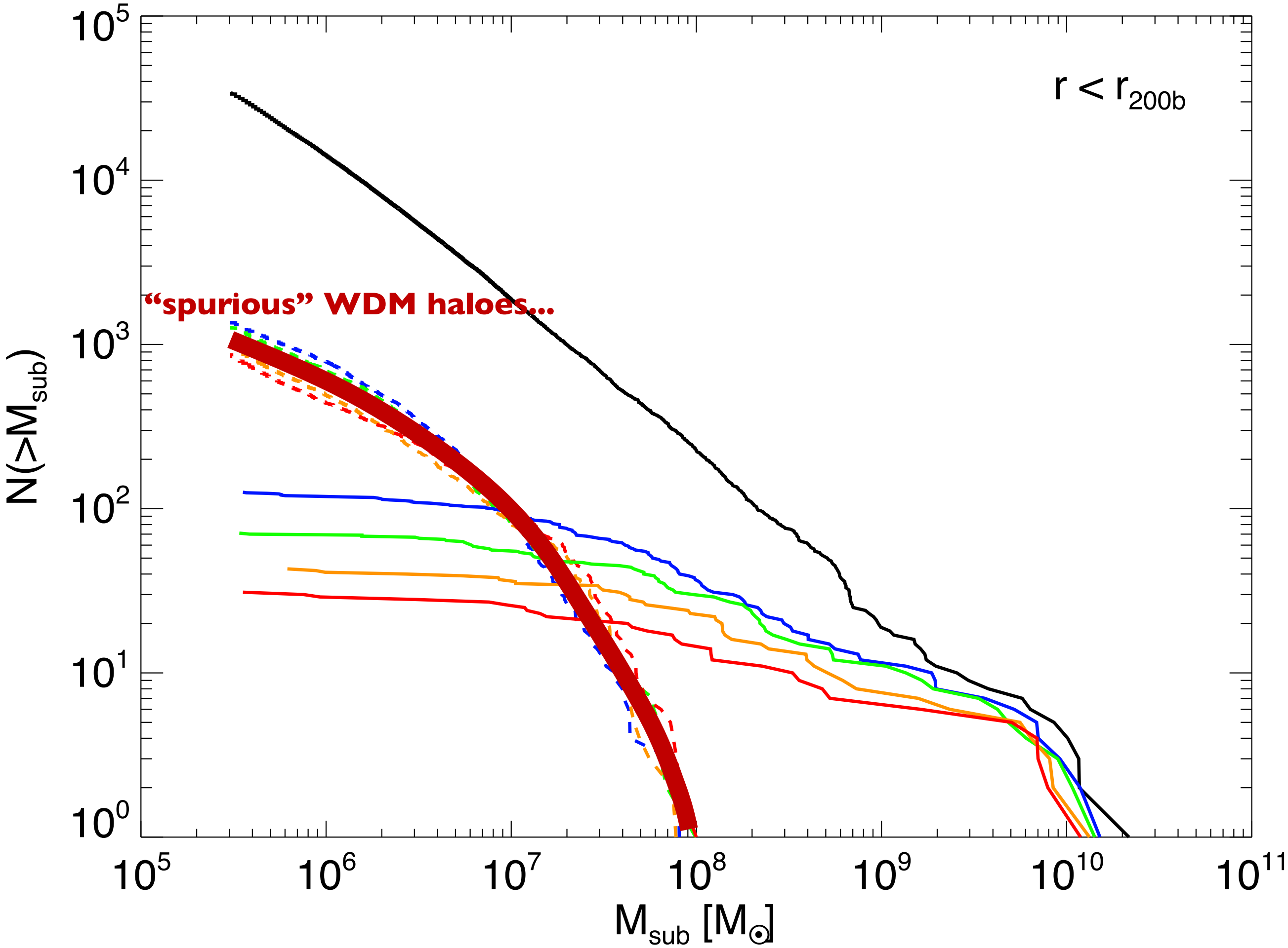
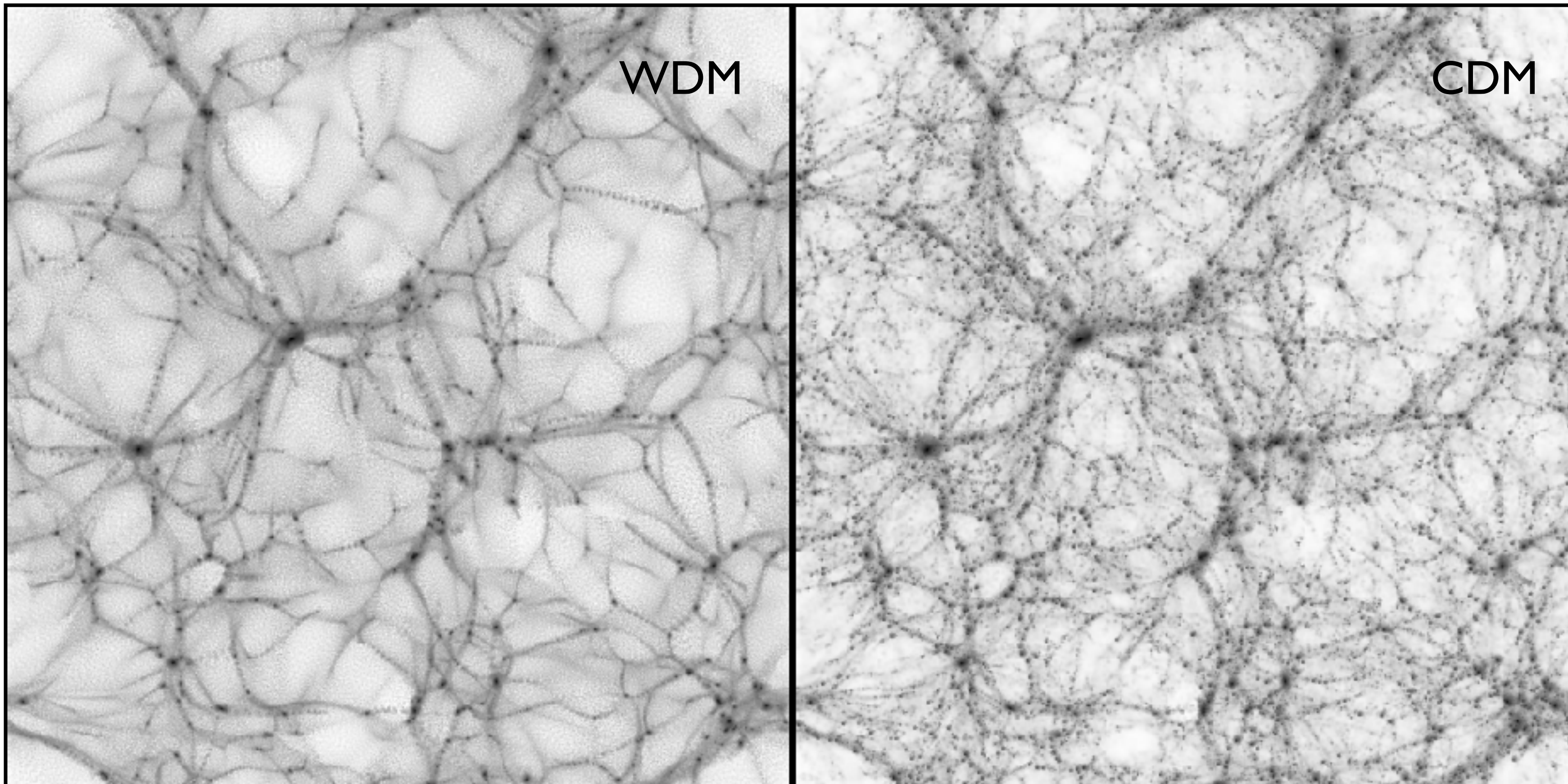


(Lovell et al. 2014)

- warm dark matter suppresses small-scale structure leaving LSS in place



(courtesy C. Power)

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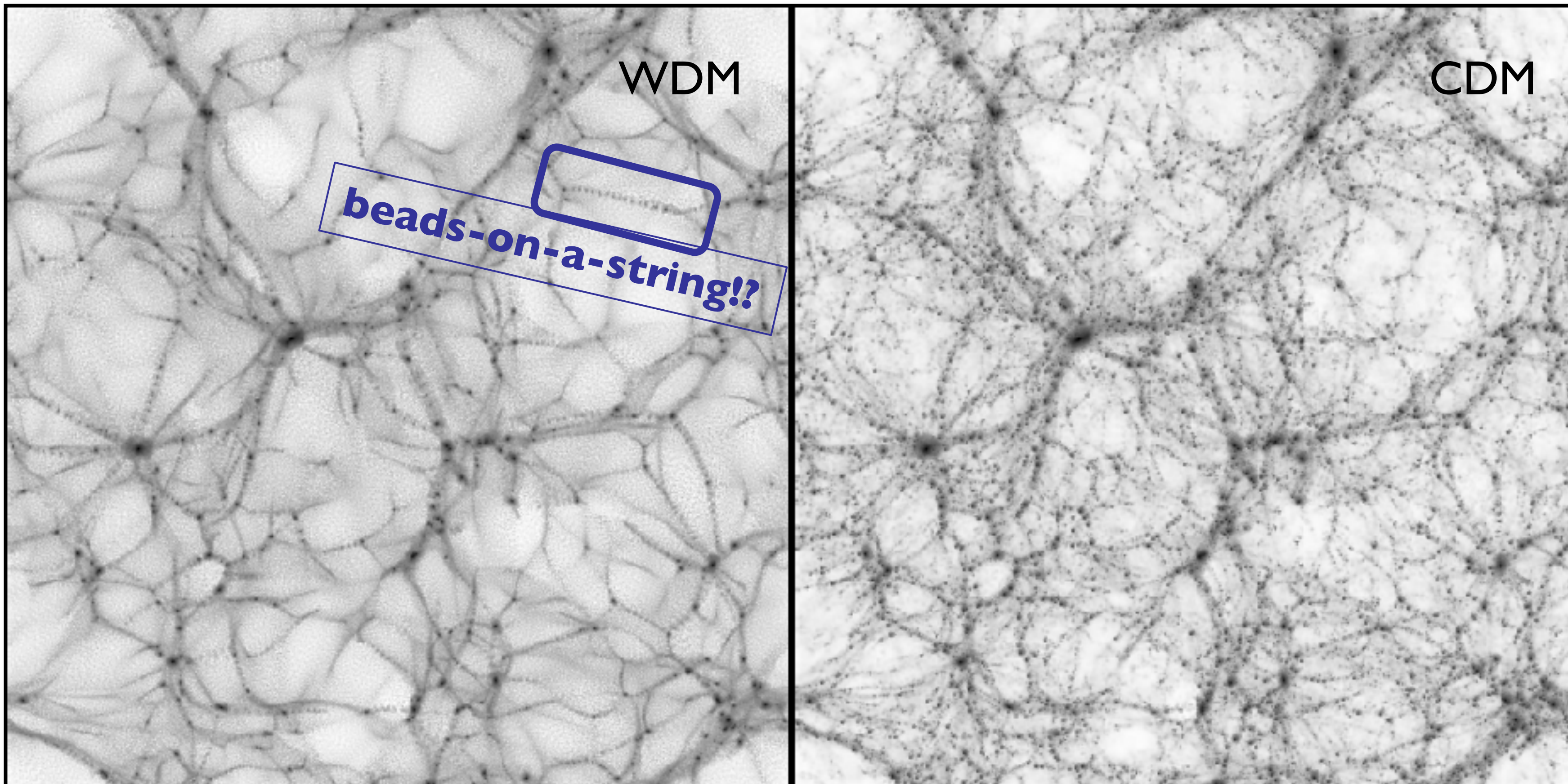

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Top-down fragmentation of a warm dark matter filament

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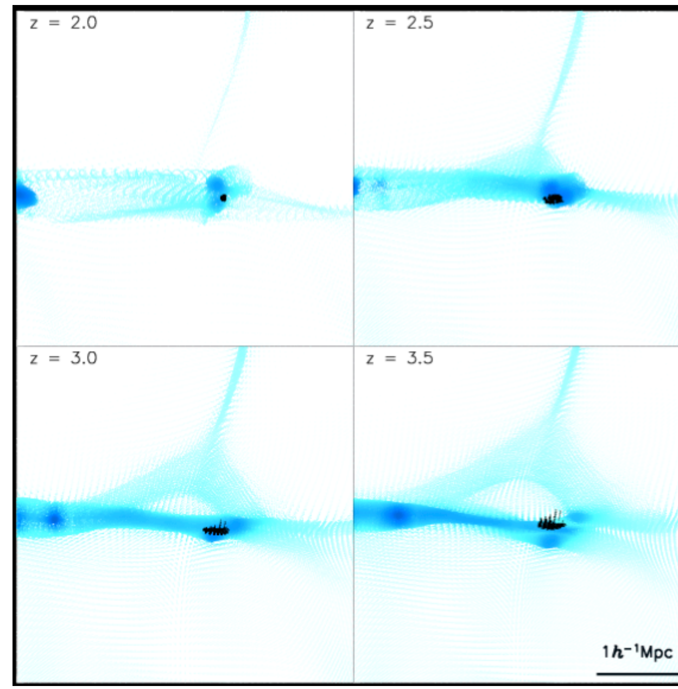
ABSTRACT
We present the first high-resolution N-body simulations of the fragmentation of dark matter filaments. Such fragmentation occurs in top-down scenarios of structure formation, when the dark matter is warm instead of cold. In a previous paper, we showed that warm dark matter (WDM) differs from the standard cold dark matter (CDM) mainly in the formation history and large-scale distribution of low-mass haloes, which form later and tend to be more clustered in WDM than in CDM universes, tracing the filamentary structures of the cosmic web more closely. Therefore, we focus our computational effort in this paper on *one* particular filament extracted from a WDM cosmological simulation and compare in detail its evolution to that of the same CDM filament. We find that the mass distribution of the haloes forming via fragmentation within the filament is broadly peaked around a Jeans mass of a few 10^9 $M_{\odot}$, corresponding to a gravitational instability of smooth regions with an overdensity contrast around 10 at these redshifts. Our results confirm that WDM filaments fragment and form gravitationally bound haloes in a top-down fashion, whereas CDM filaments are built bottom-up, thus demonstrating the impact of the nature of the dark matter on dwarf galaxy properties.

Key words: methods: numerical – cosmology: miscellaneous – cosmology: theory – dark matter – large-scale structure of Universe.



- warm dark matter suppresses small-scale structure leaving LSS in place

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Discreteness effects in simulations of hot/warm dark matter

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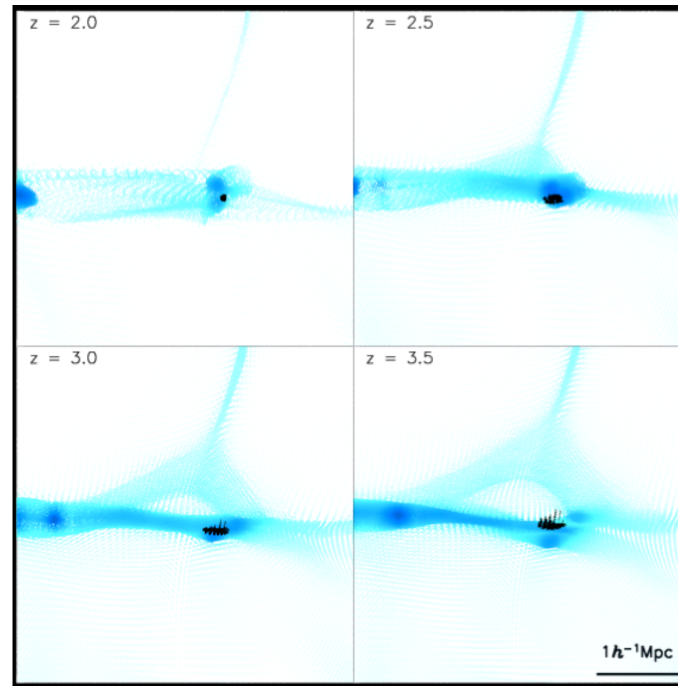
ABSTRACT
In hot/warm dark matter (HDM/WDM) universes the density fluctuations at early times contain very little power below a characteristic wavelength related inversely to the particle mass. We study how discreteness noise influences the growth of non-linear structures smaller than this coherence scale in *N*-body simulations of cosmic structure formation. It has been known for 20 yr that HDM simulations in which the initial uniform particle load is a cubic lattice exhibit artefacts related to this lattice. In particular, the filaments which form in such simulations break up into regularly spaced clumps which reflect the initial grid pattern. We demonstrate that a similar artefact is present even when the initial uniform particle load is not a lattice, but rather a glass with no preferred directions and no long-range coherence. Such regular fragmentation also occurs in simulations of the collapse of idealized, uniform filaments, although not in simulations of the collapse of infinite uniform sheets. In HDM or WDM simulations all self-bound non-linear structures with masses much smaller than the free streaming mass appear to originate through spurious fragmentation of filaments. These artificial fragments form below a characteristic mass which scales as $m_p^{1/3} k_{peak}^{-2}$, where m_p is the *N*-body particle mass and k_{peak} is the wavenumber at the maximum of $k^3 P(k)$[$P(k)$ is the power spectrum]. This has the unfortunate consequence that the effective mass resolution of such simulations improves only as the cube root of the number of particles employed.

Key words: neutrinos – methods: *N*-body simulations – methods: numerical – dark matter.



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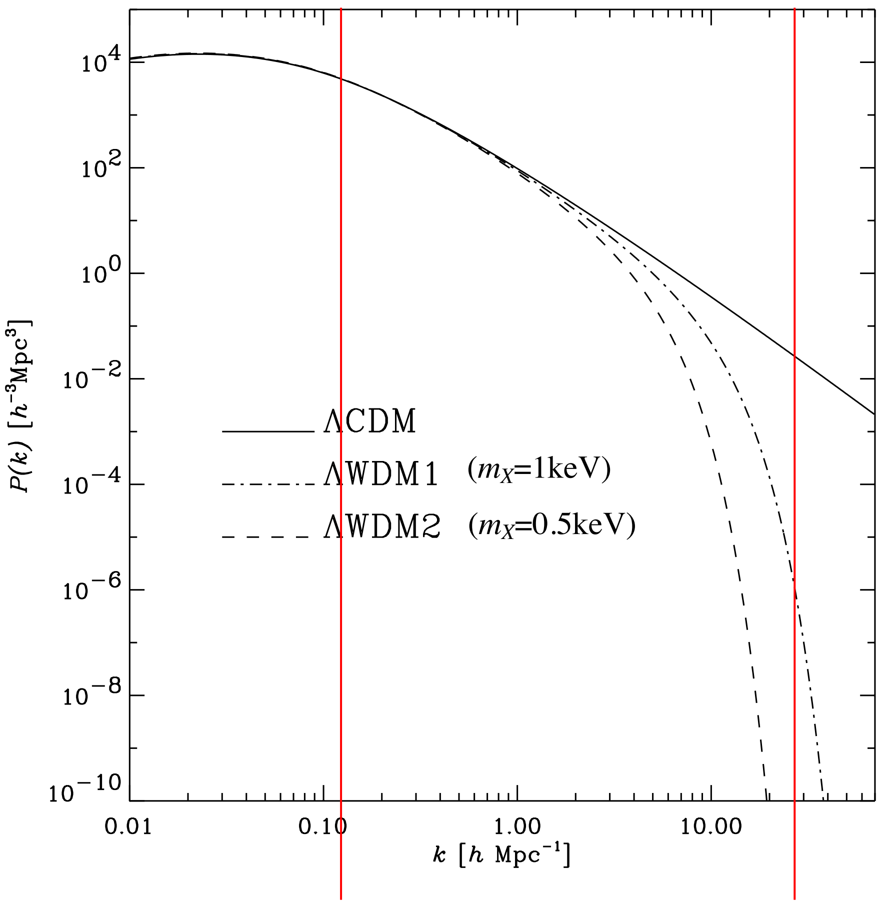

$$k_{\mathrm{min}} = \frac{2\pi}{B} \qquad k_{\mathrm{max}} = \frac{2\pi}{B}\frac{N^{1/3}}{2}$$

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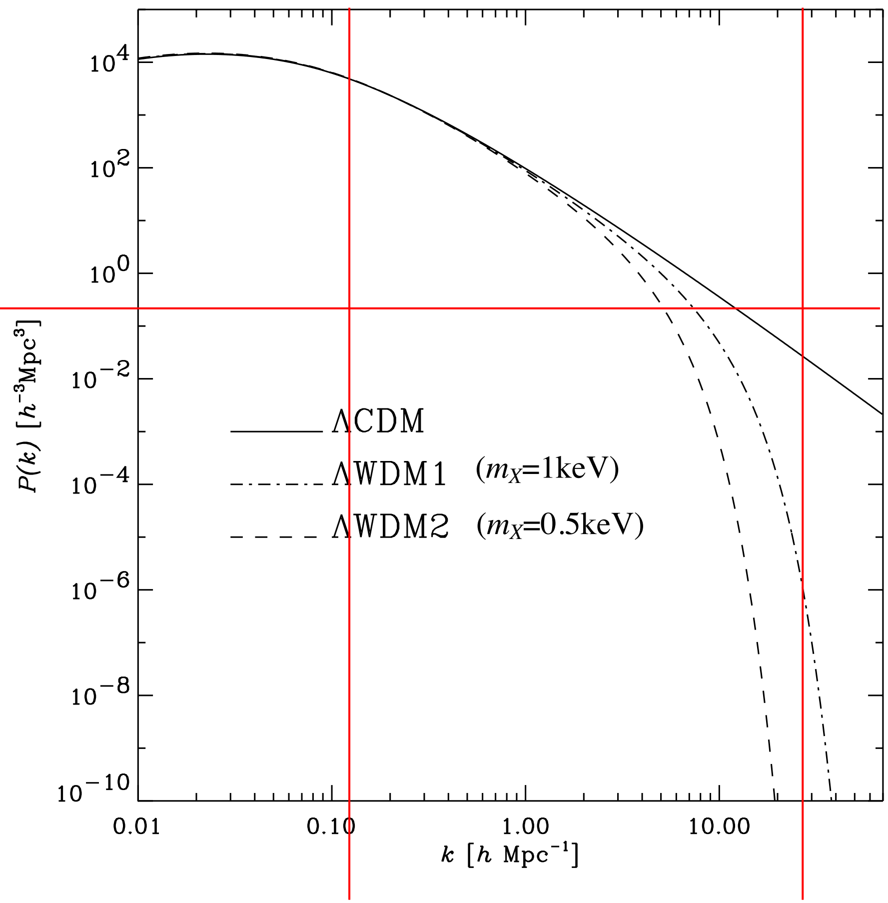
interparticle separation: $P_{WN} = \frac{B^3}{N}$



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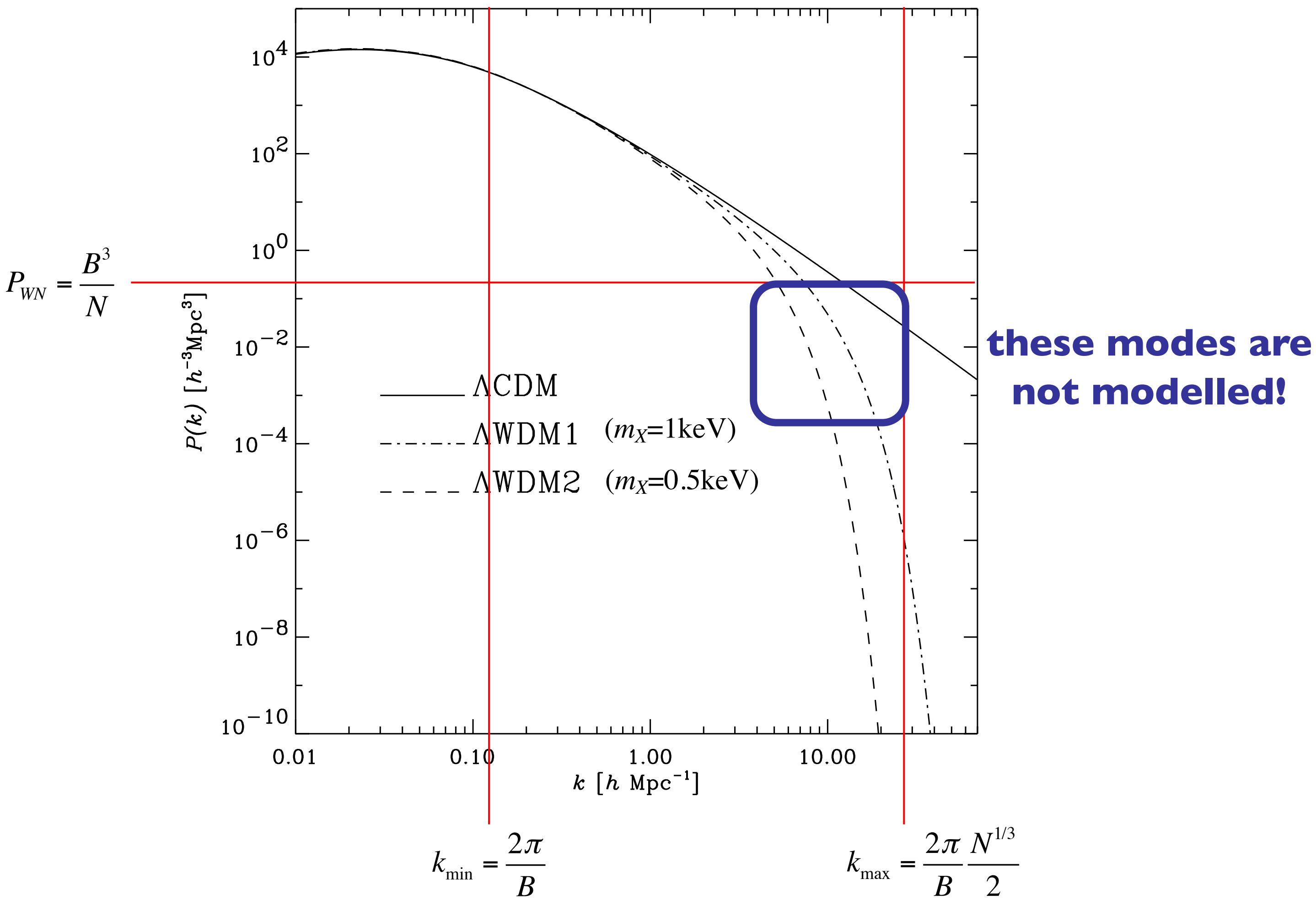
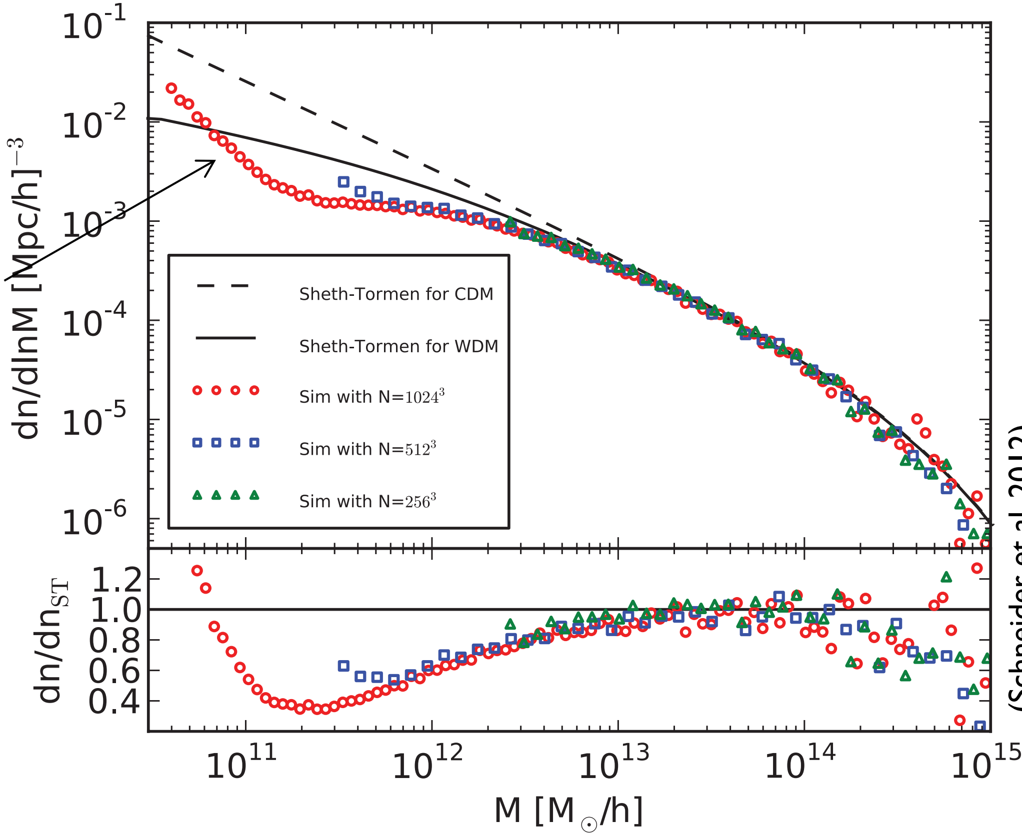


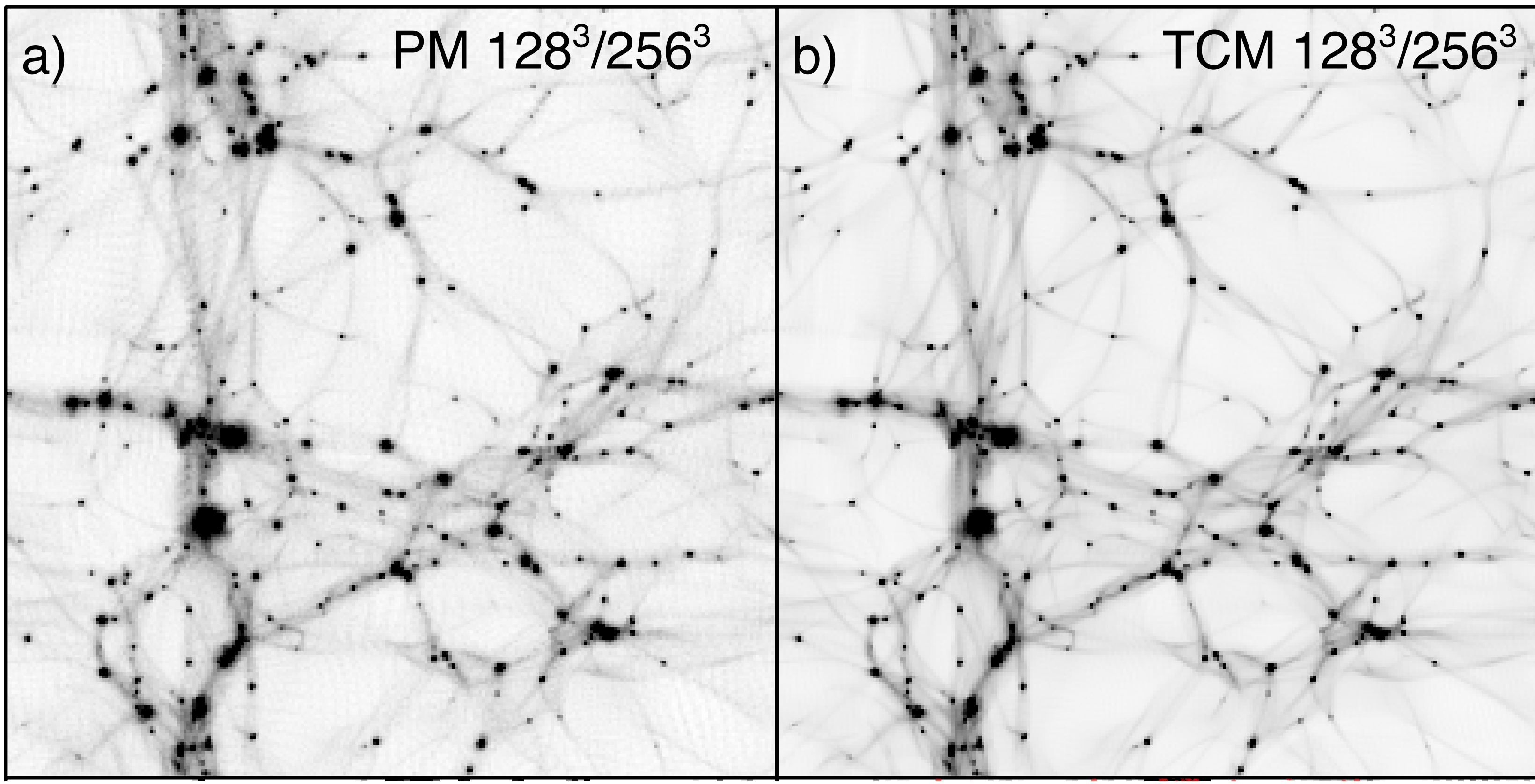
- warm dark matter simulations are not as easy as they appear…

while WDM was used to solve the missing satellite problem, those spurious strings-on-a-bead give rise to fake low-mass haloes!



(Schneider et al. 2012)

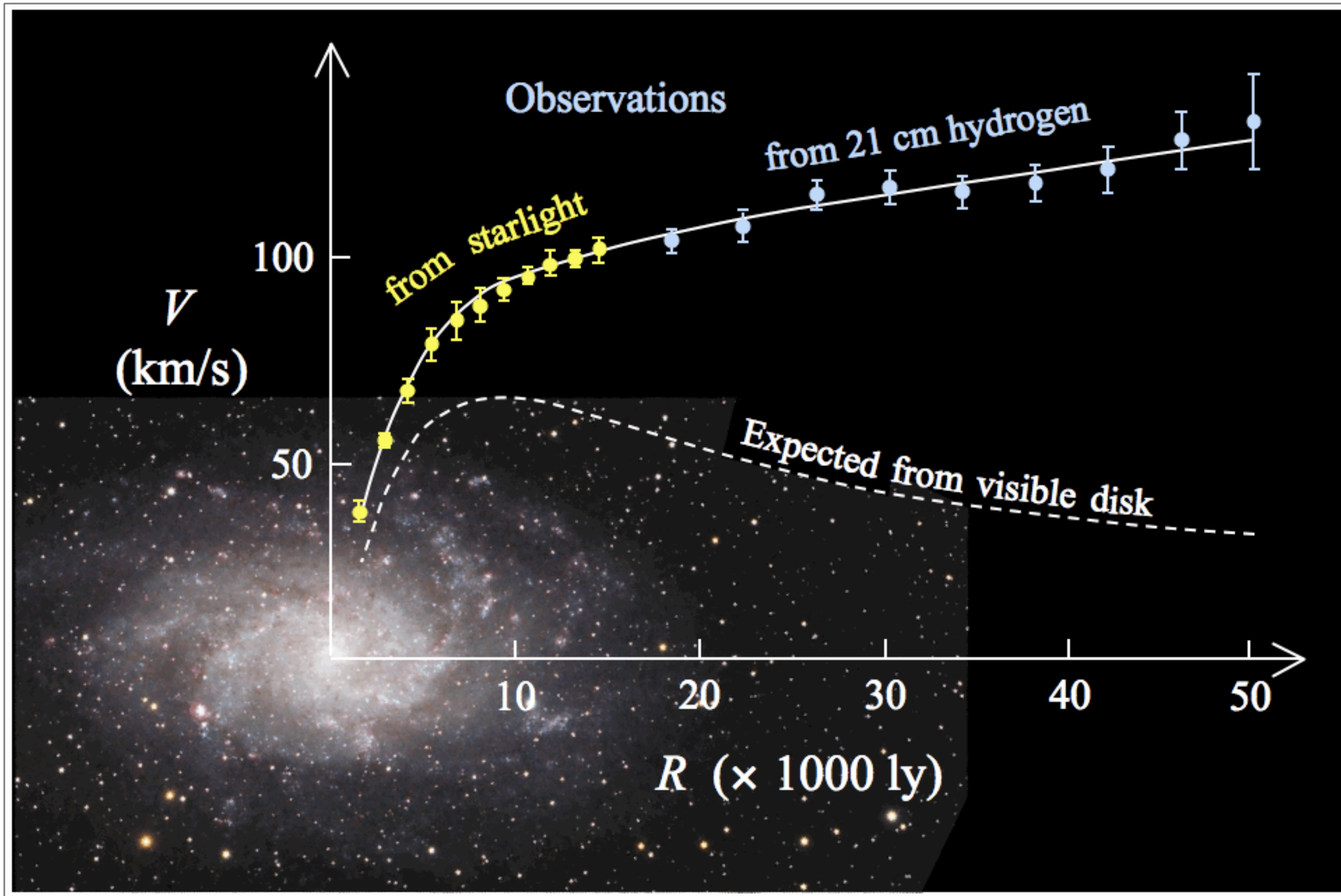
- warm dark matter simulations are not as easy as they appear…
  …and actually requires novel simulation techniques



(Hahn et al. 2013)

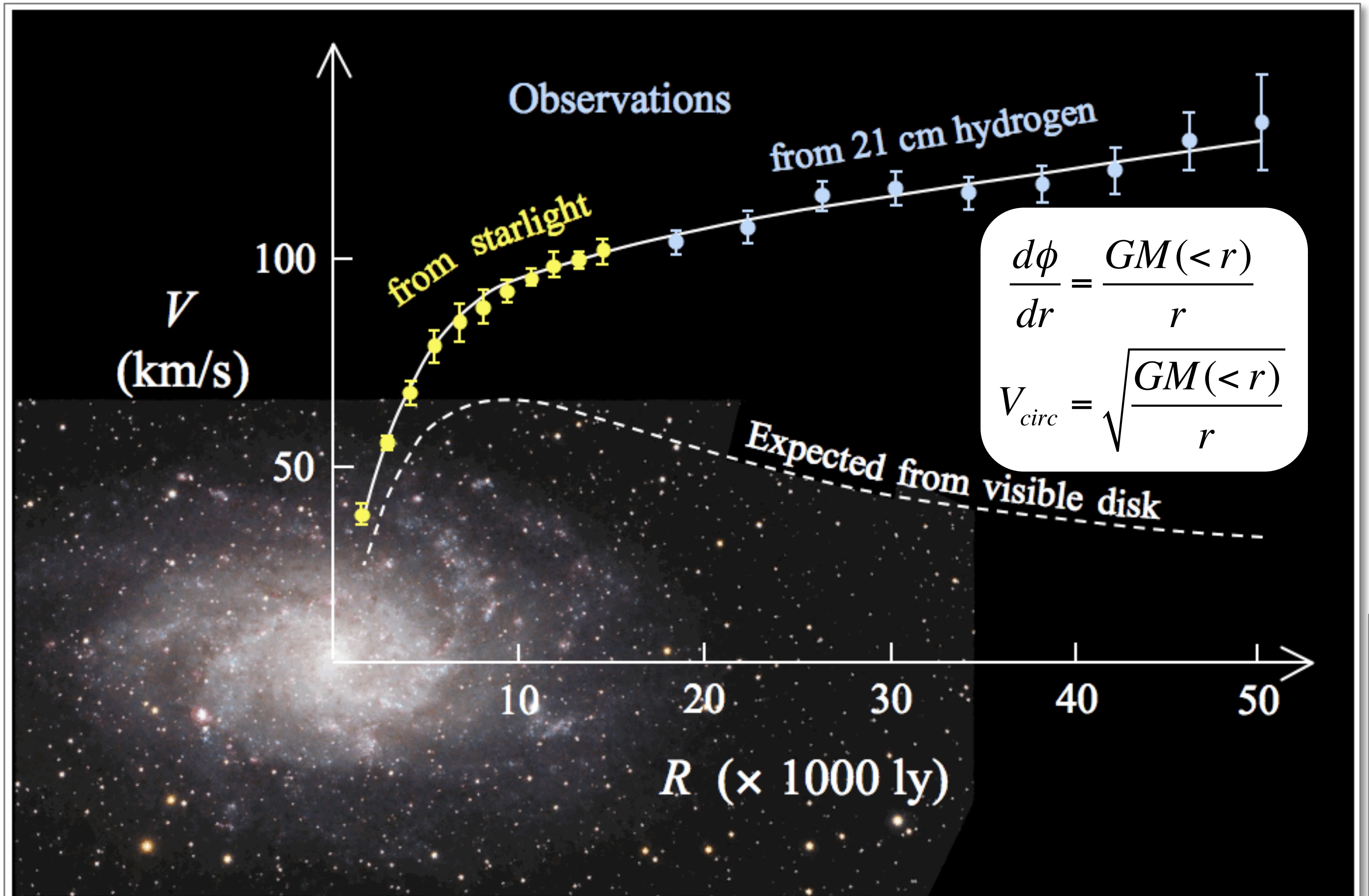
- Alternative Cosmologies
  - Warm Dark Matter
  - **MOdified Newtonian Dynamics**
  - Lemaitre-Tolman-Bondi void models
  - Quintessence models
  - Modified gravity f(R) models
  - …

“Dark Matter” needed to explain Vera Rubin’s galactic rotation curves* in 1975/80:



*actually, Fritz Zwicky already needed DM to explain stability of galaxy clusters in 1933

“Dark Matter” needed to explain Vera Rubin’s galactic rotation curves in 1975/80:



- Milgrom (1983, 1984):

  - Newtonian accelerations

$$F = m\, g_N(r) \qquad \text{with} \qquad g_N = \frac{GM(<r)}{r^2}$$

$$m\, g_N = m\, a$$

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  - modified accelerations

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$$\xrightarrow[a << a_0]{a = v_{circ}^2 / r} \boxed{v_{circ}^4 = GMa_0}$$

Tully-Fisher relation! (…and flat rotation curves)

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<u>very complicated to develop numerical solvers:</u>

- Brada & Milgrom (1999)
- Nipoti, Londrillo & Ciotti (2007)
- Tiret & Combes (2007)
- Llinares, Knebe & Zhao (2008) (cosmological setting!)
- Angus et al. (2012)
- Candlish, Smith & Fellhauer (2015)

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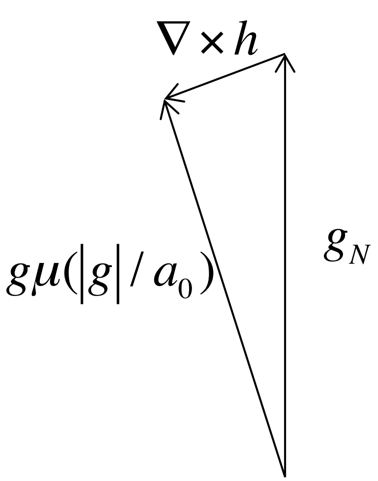

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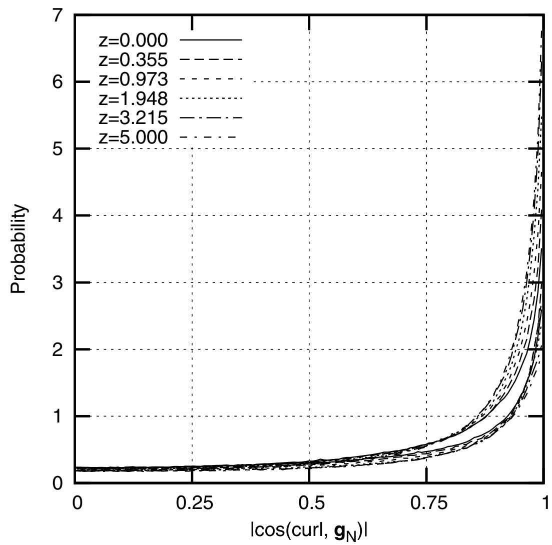
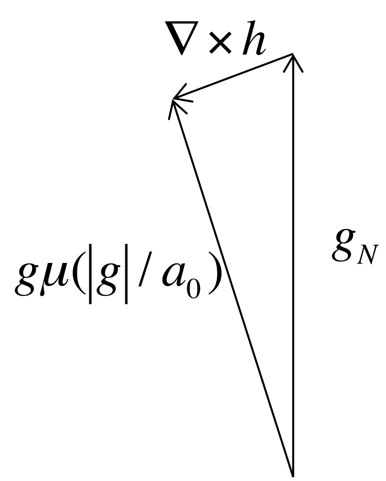


(Llinares et al. 2008)



- Cosmology with MOND

  - 2nd Friedmann equation: $$\ddot{R} = -\frac{4\pi G}{3}\left(\rho + \frac{3p}{c^2}\right)R$$

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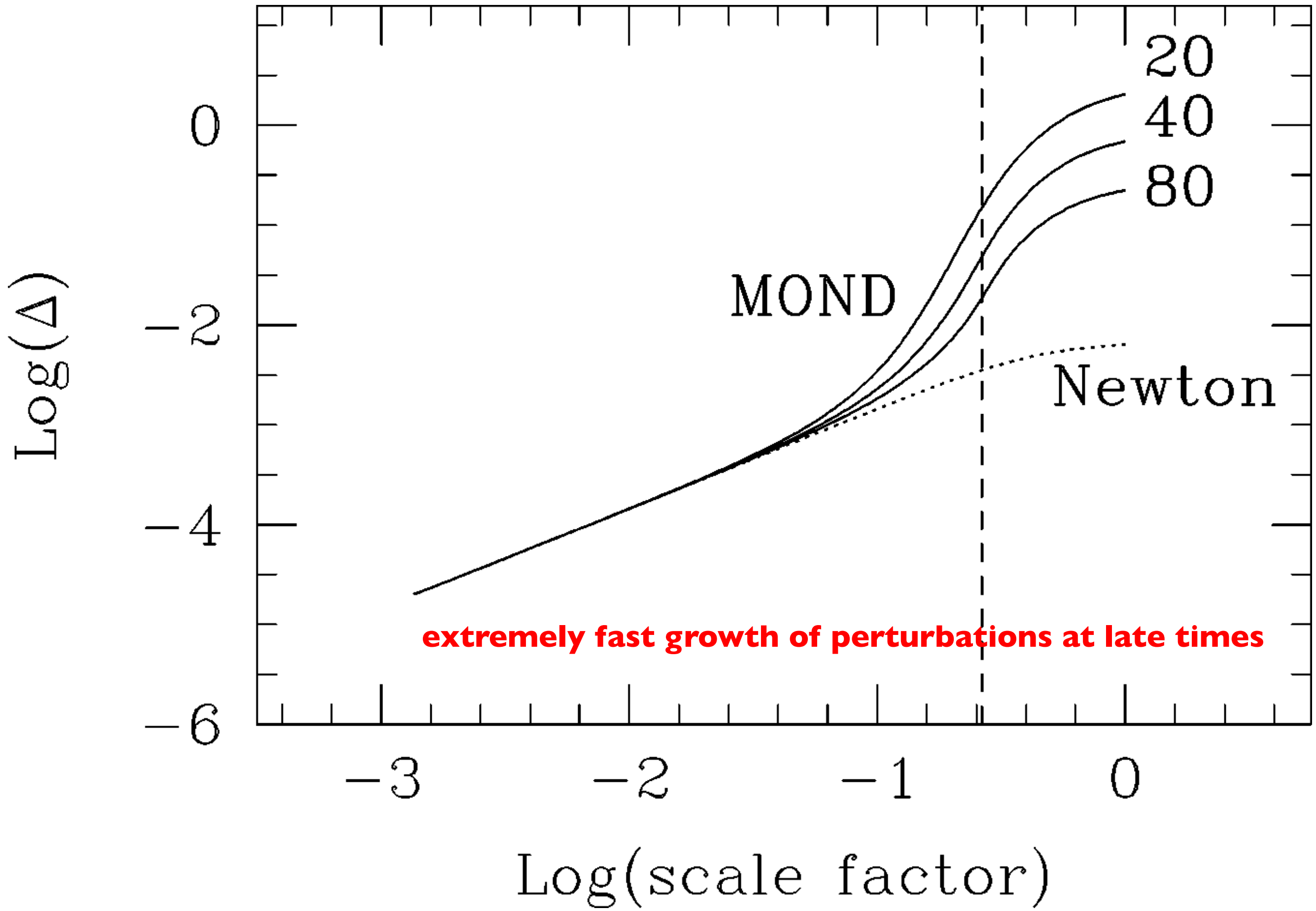
spherical top-hat collapse in MONDian Universe…

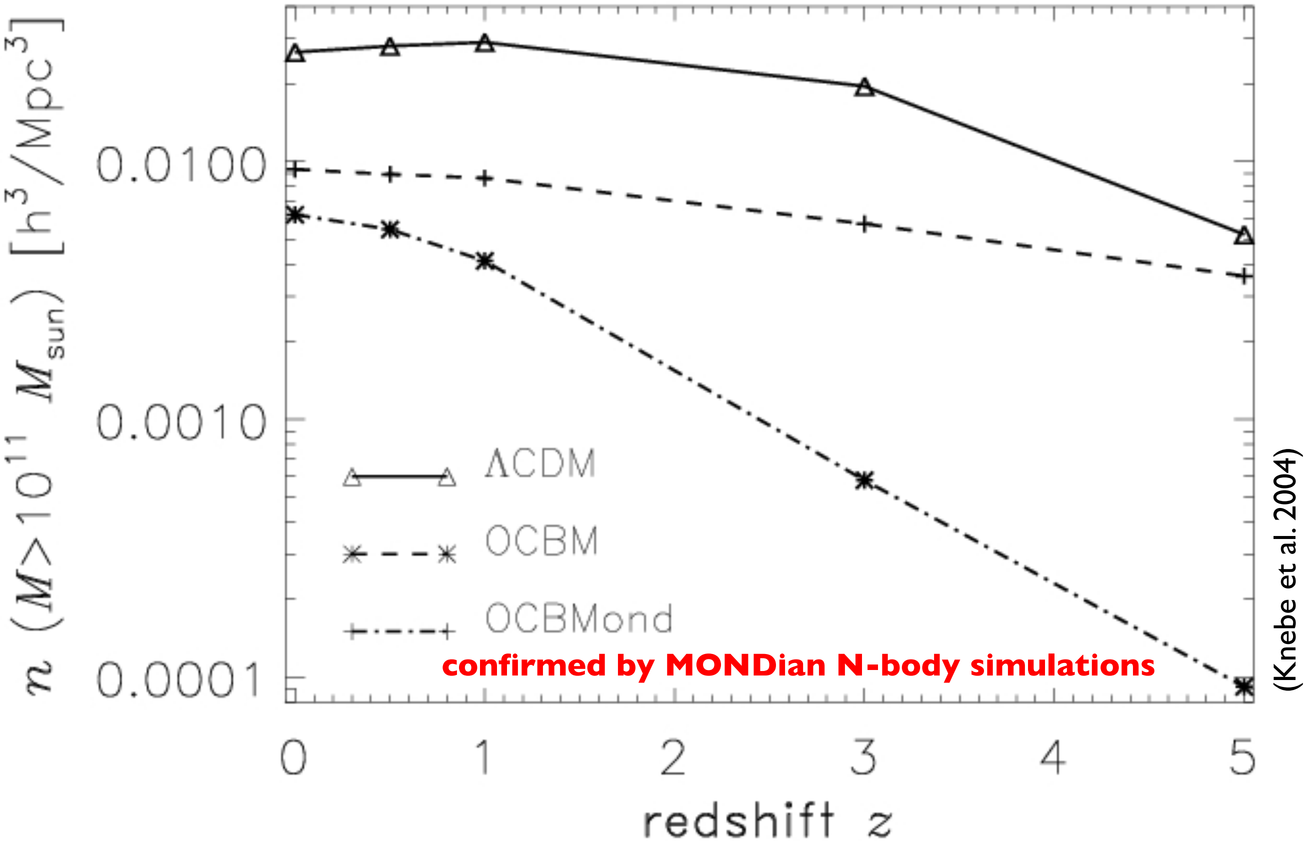
- Cosmology with MOND
  - growth of density perturbations:



(Sanders 1998)

- Cosmology with MOND

    - number density evolution of objects:



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