

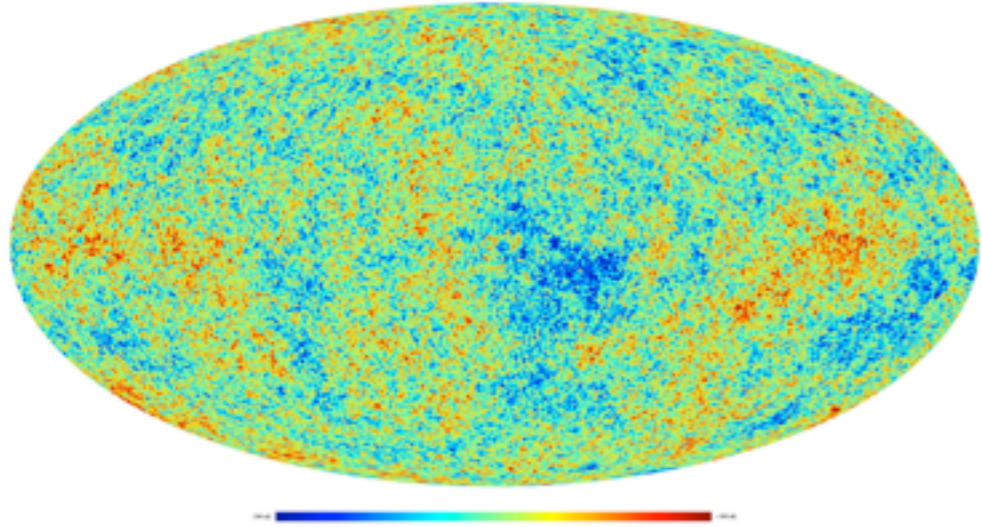
Astrophysical probes of dark matter

Prof. Justin Read, University of Surrey

Alexander Hobbs, Oscar Agertz, Silvia Garbari, George Lake, Romain Teyssier

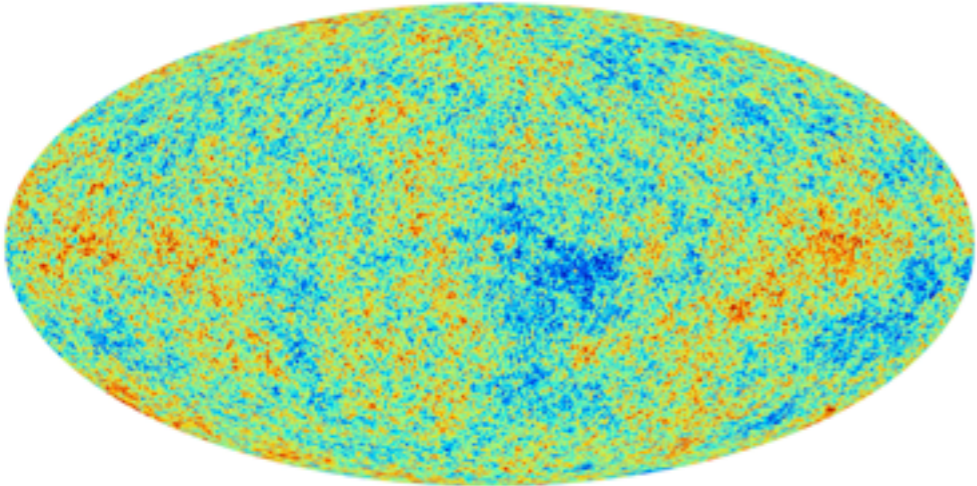
Background | Probing dark matter through gravity

CMB

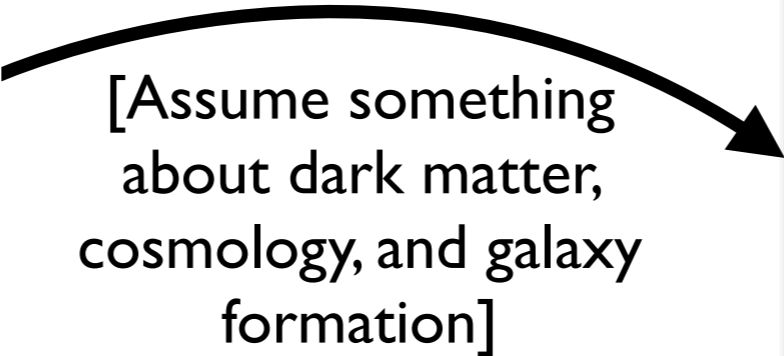


Background | Probing dark matter through gravity

CMB



N-body

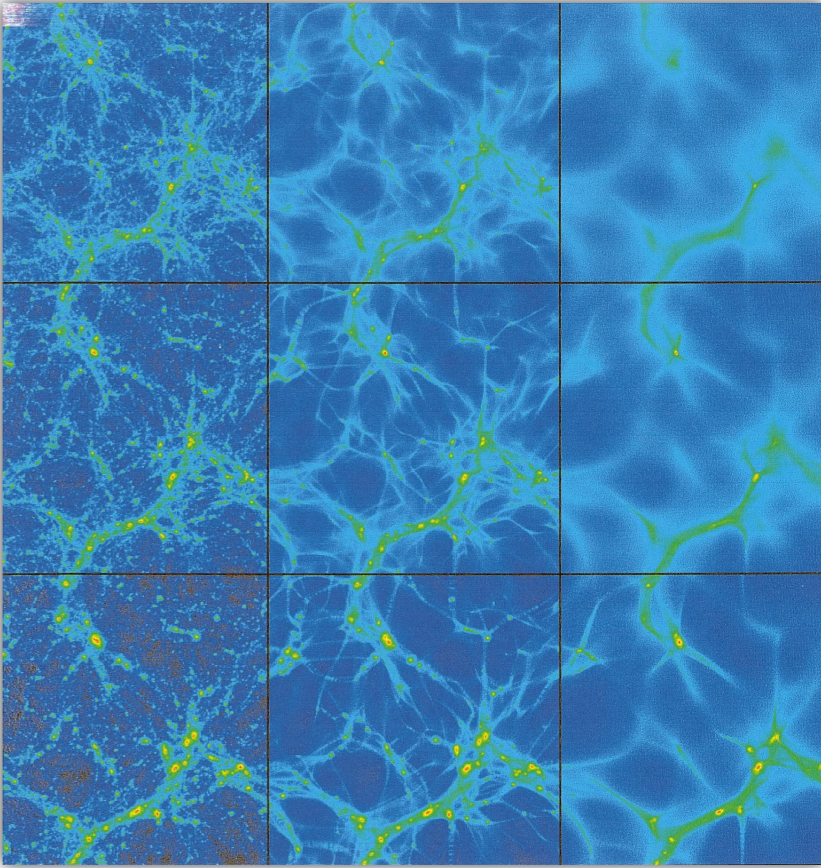


[Assume something about dark matter, cosmology, and galaxy formation]

COLD

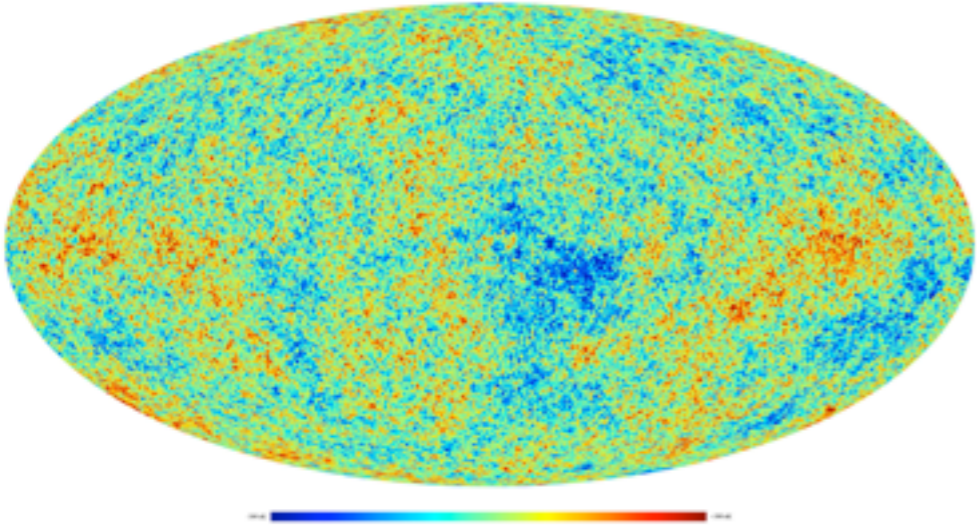
WARM

HOT



Background | Probing dark matter through gravity

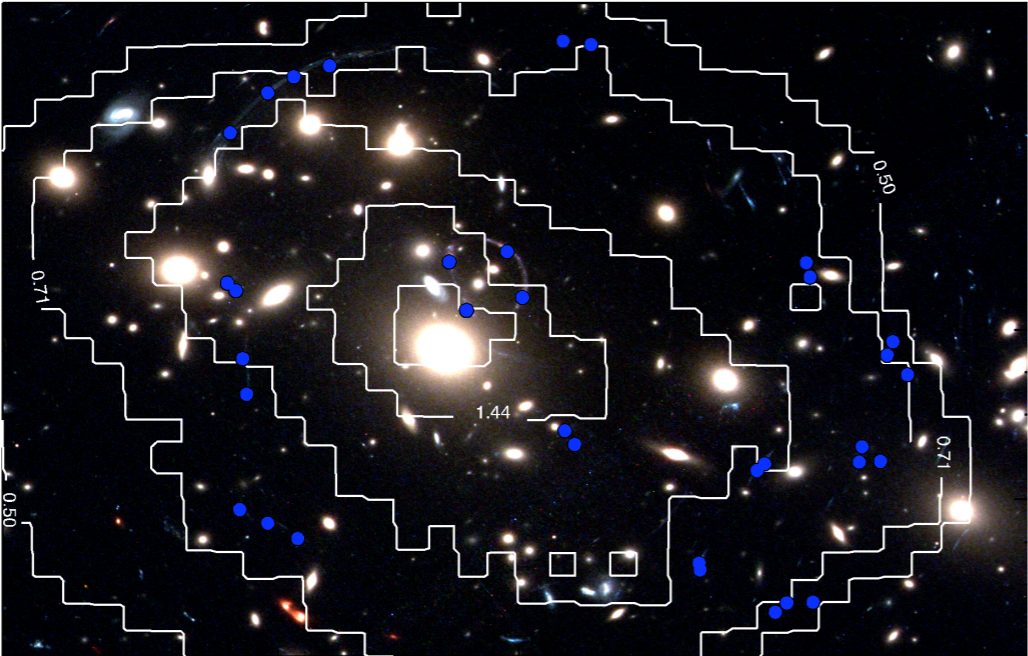
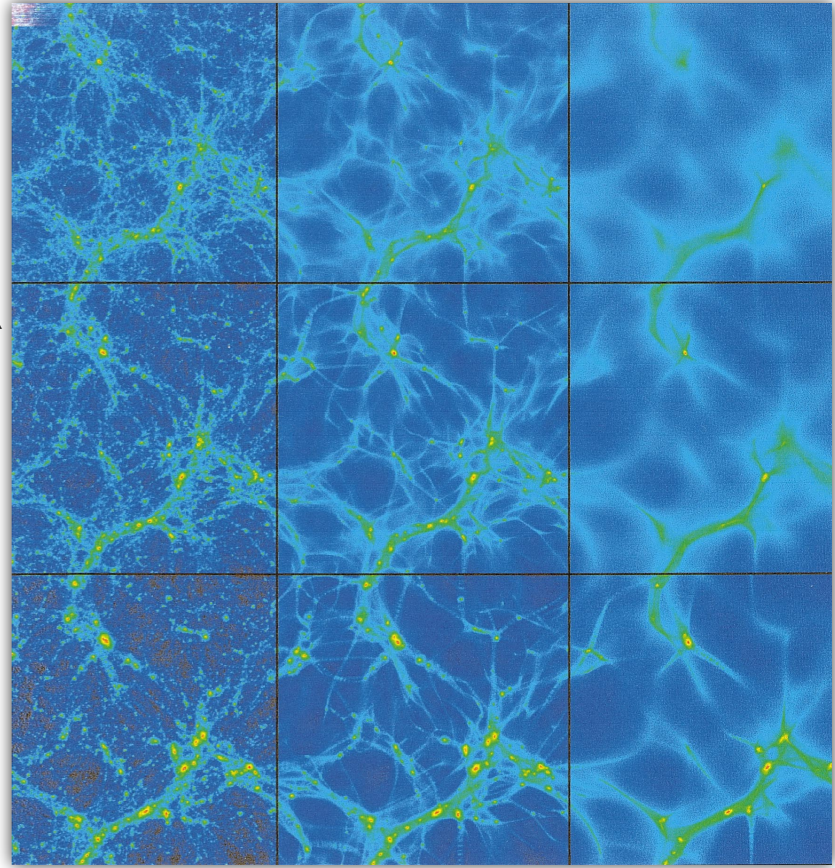
CMB



N-body

[Assume something about dark matter, cosmology, and galaxy formation]

COLD WARM HOT



Observation

[e.g. rotation curves; lensing; galaxy counts etc.]

Gravity

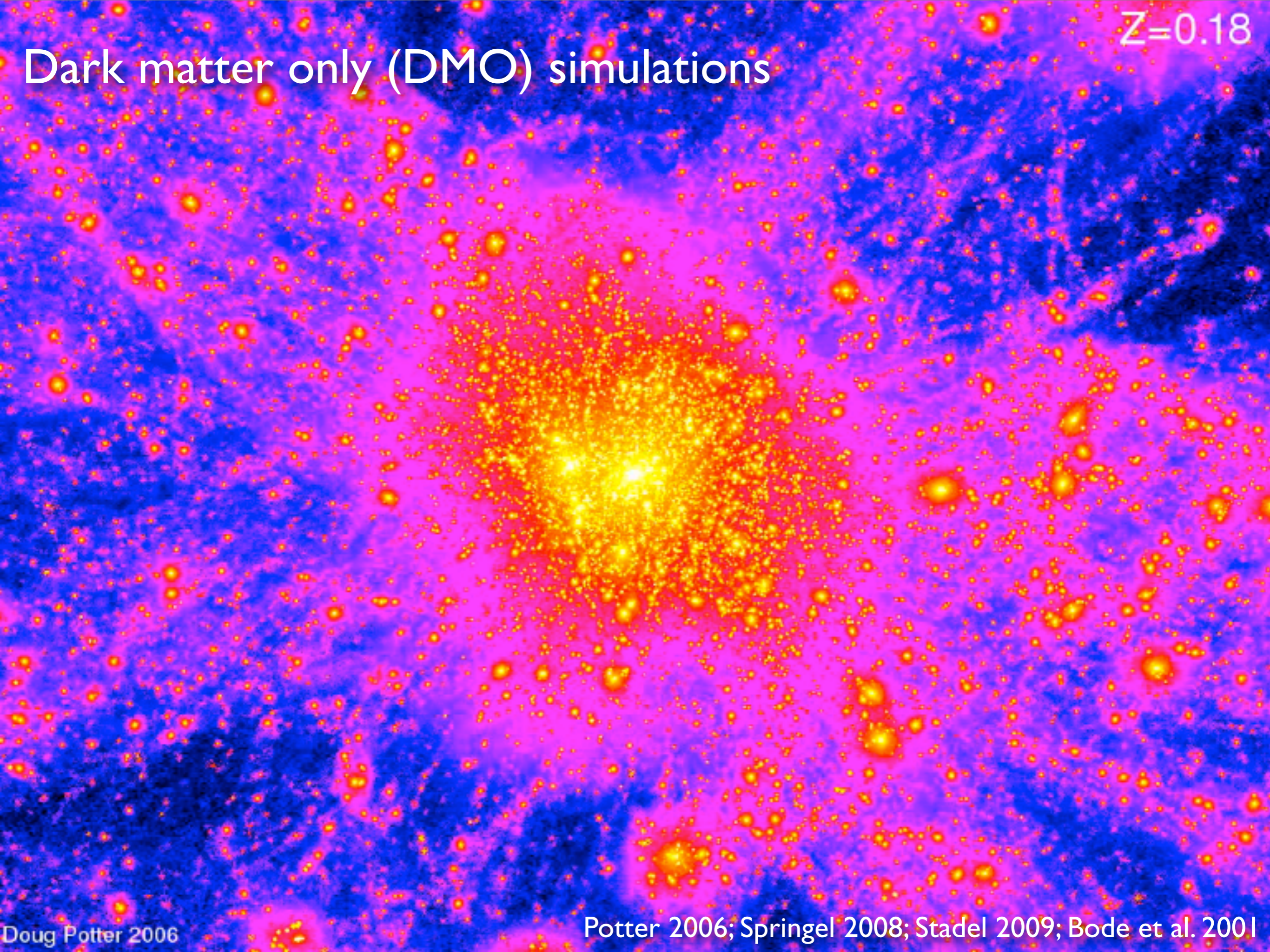
['Dark Matter Only' (DMO) simulations]

Dark matter only (DMO) simulations

Dark matter only (DMO) simulations

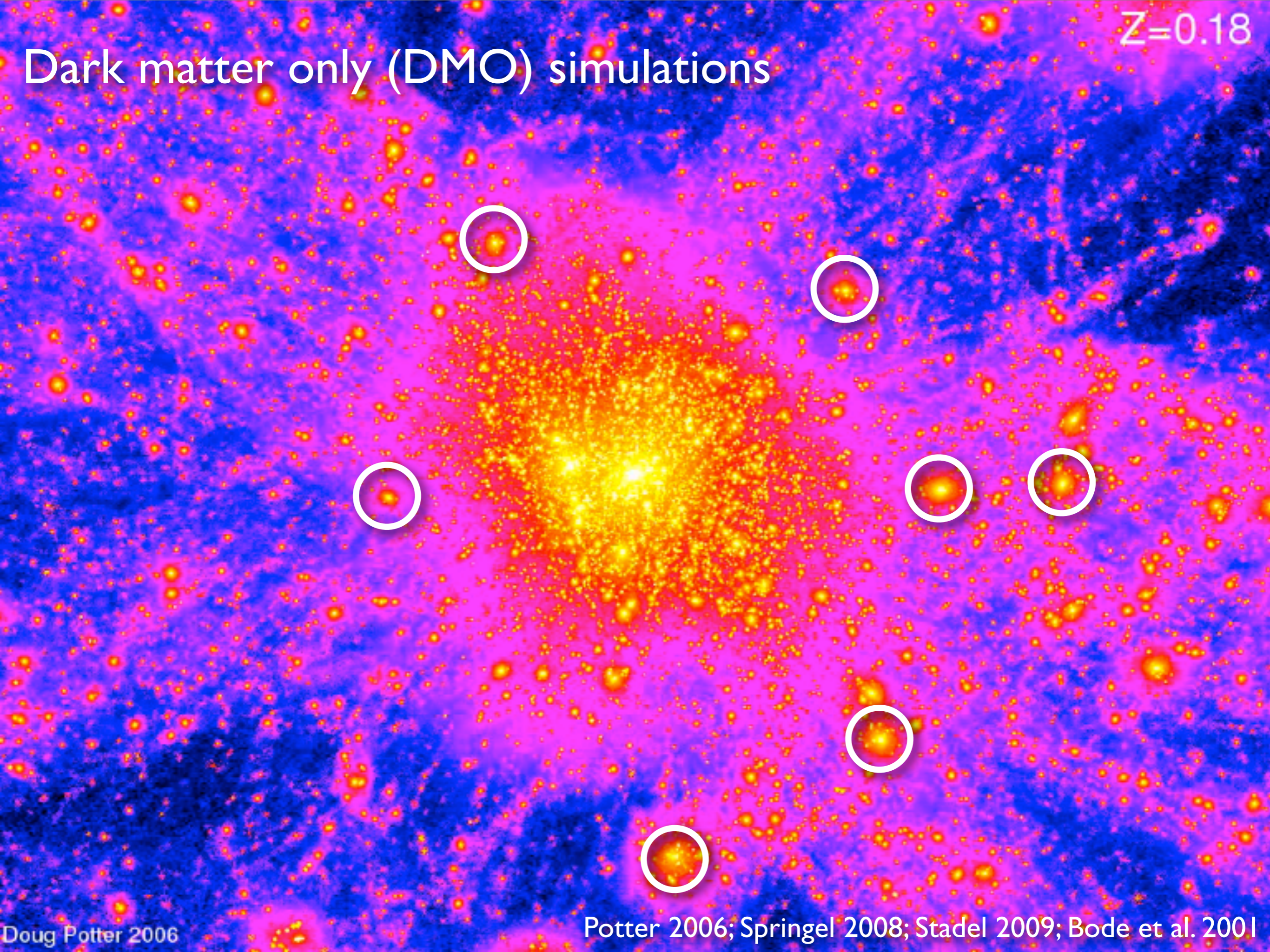
$Z=0.18$

Dark matter only (DMO) simulations



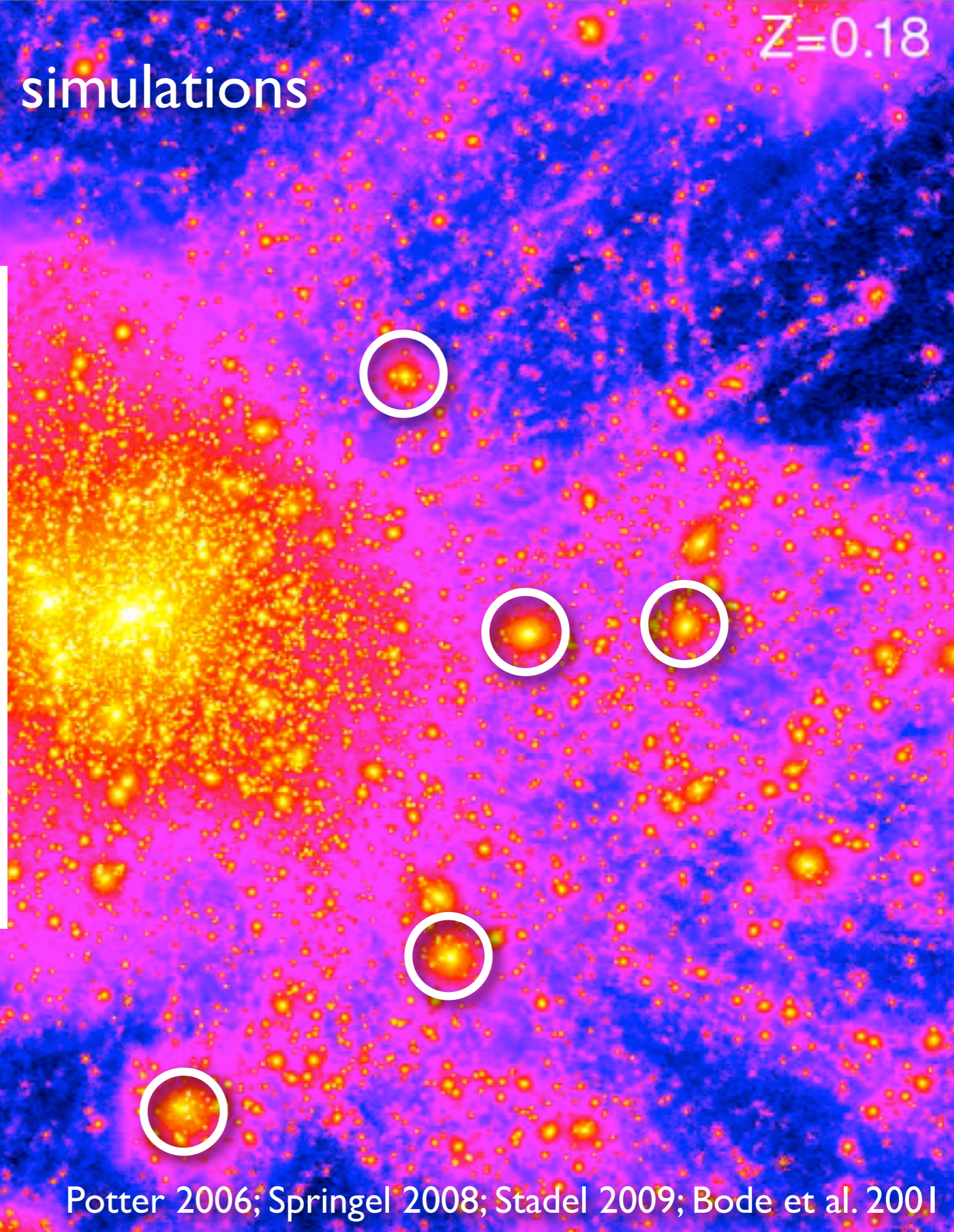
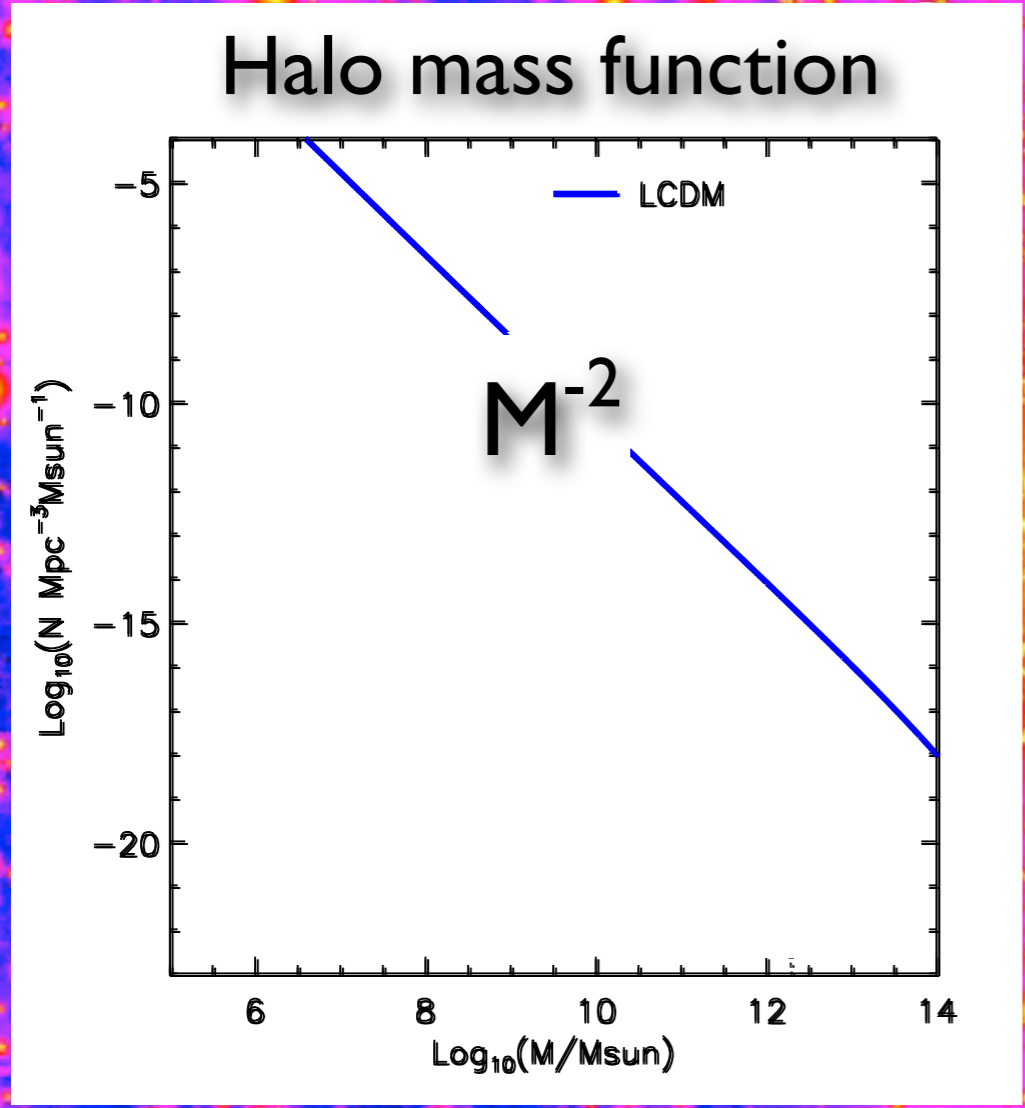
$Z=0.18$

Dark matter only (DMO) simulations



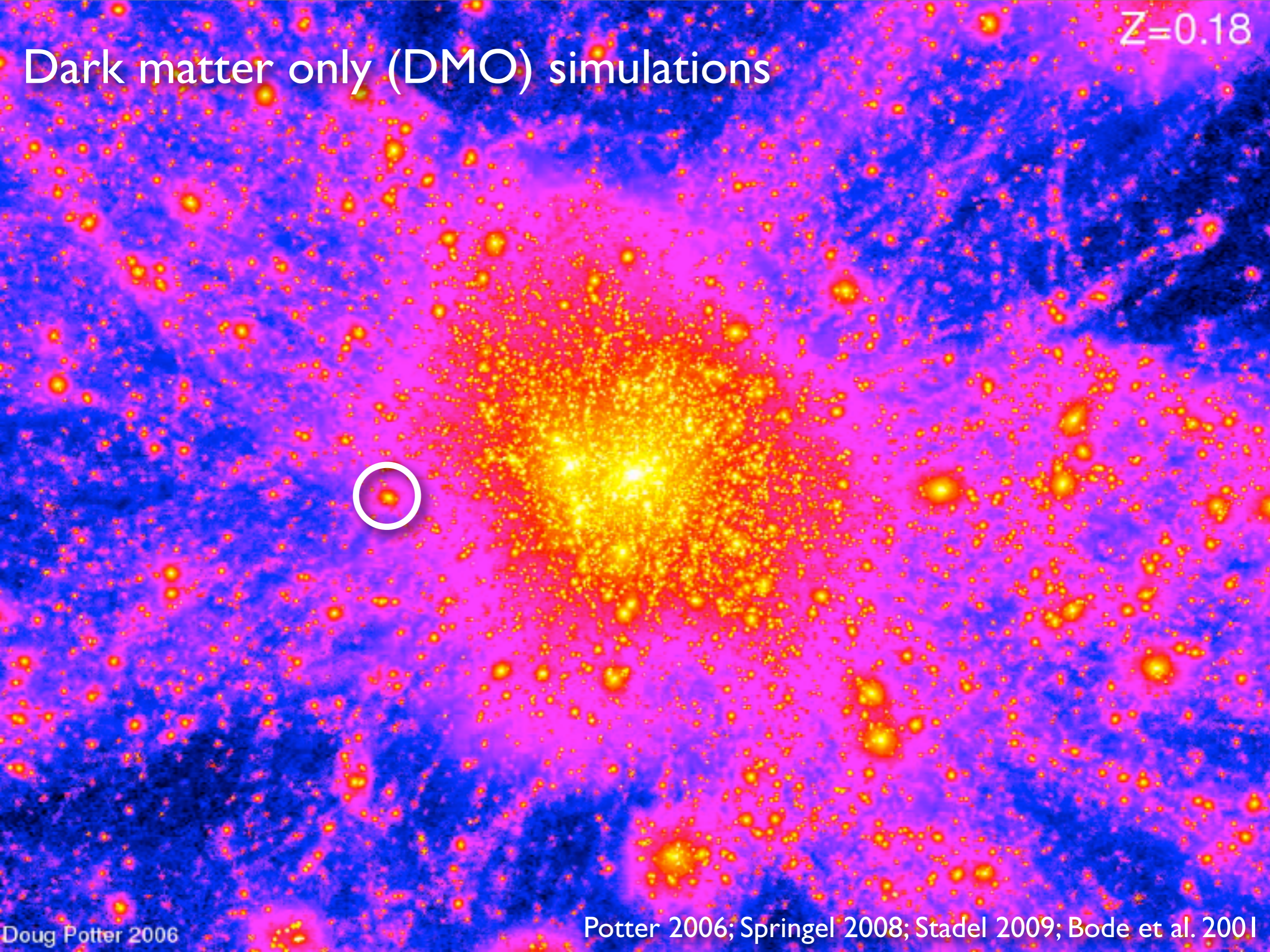
$Z=0.18$

Dark matter only (DMO) simulations



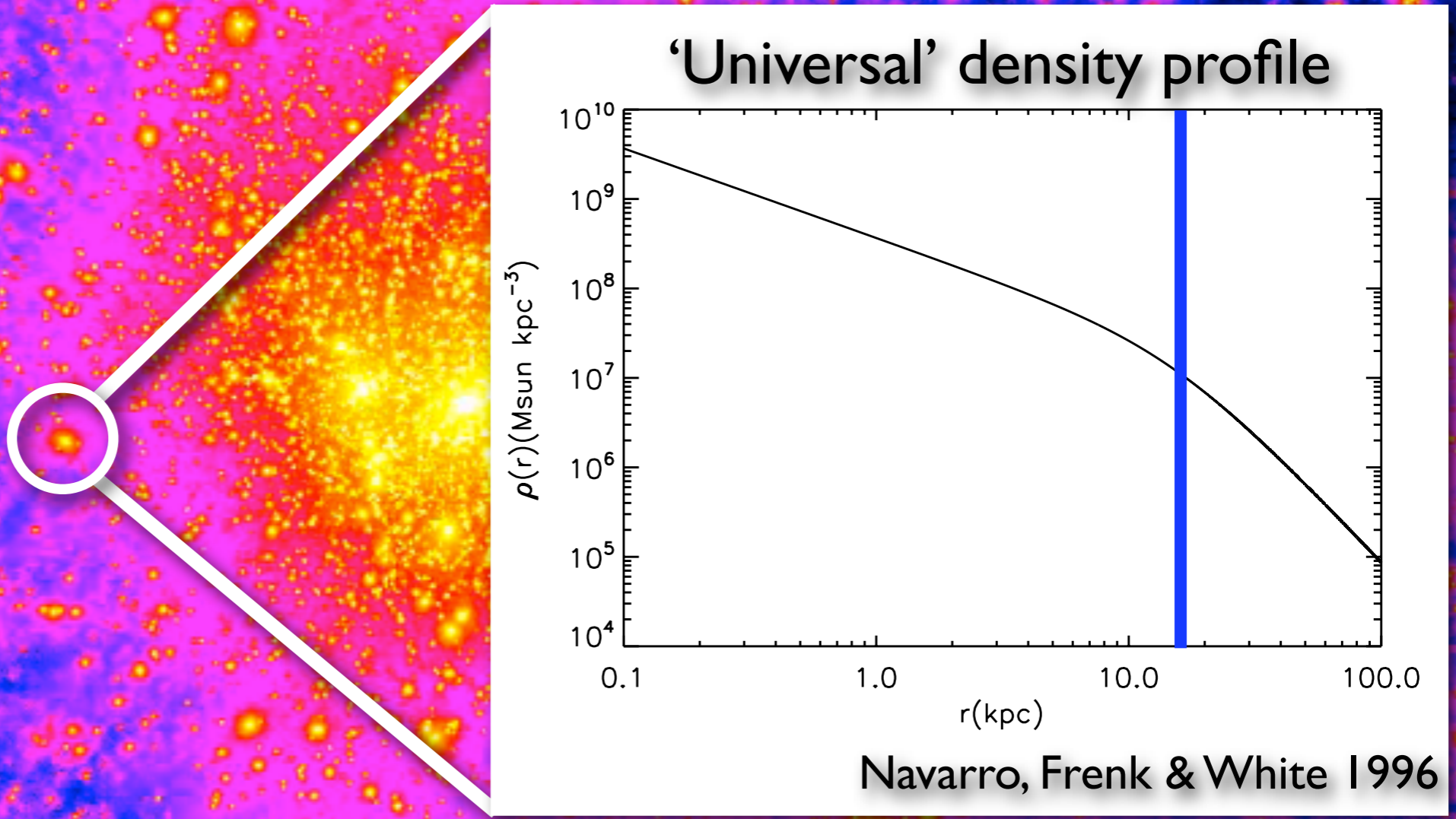
$Z=0.18$

Dark matter only (DMO) simulations



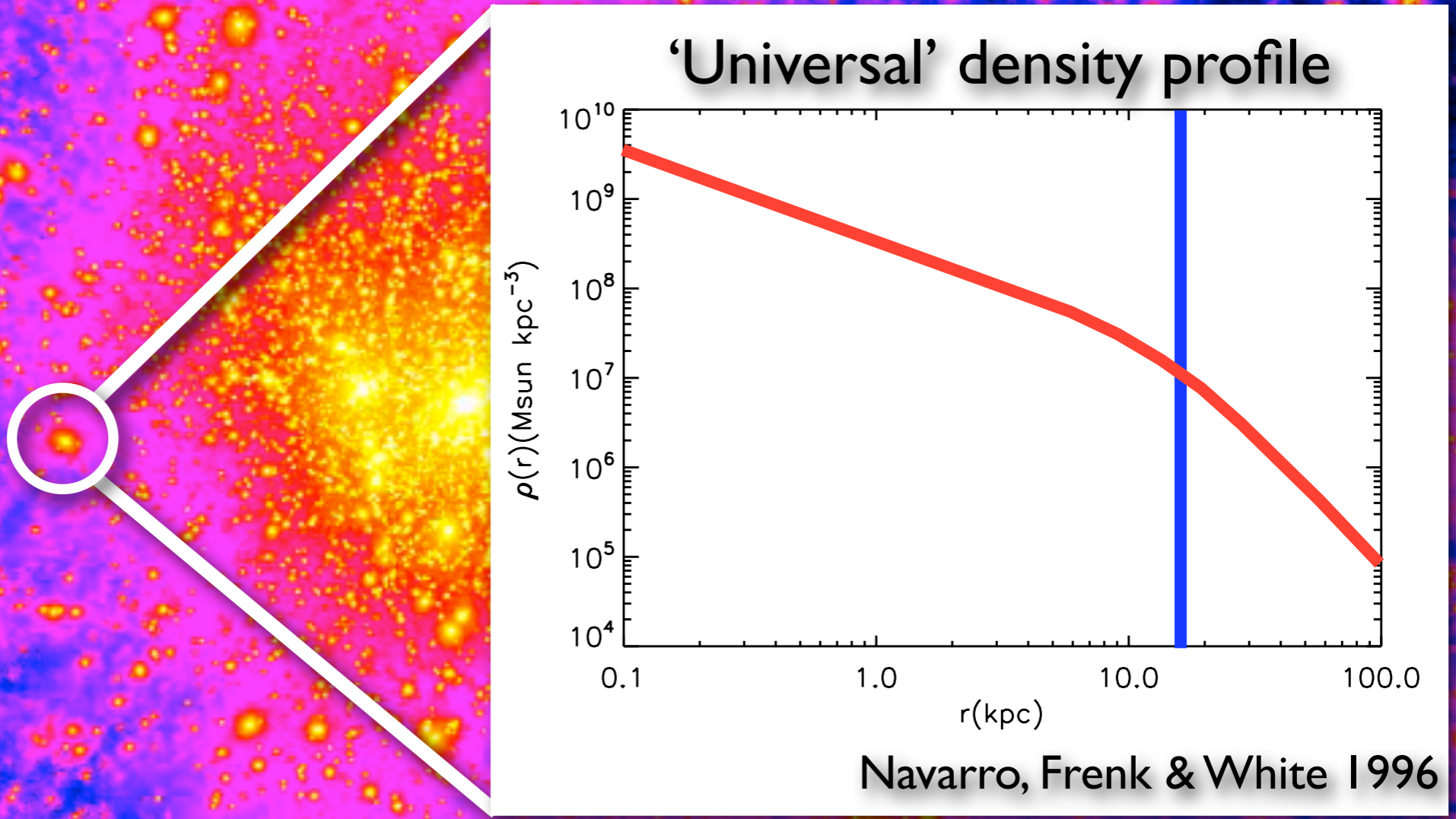
$Z=0.18$

Dark matter only (DMO) simulations

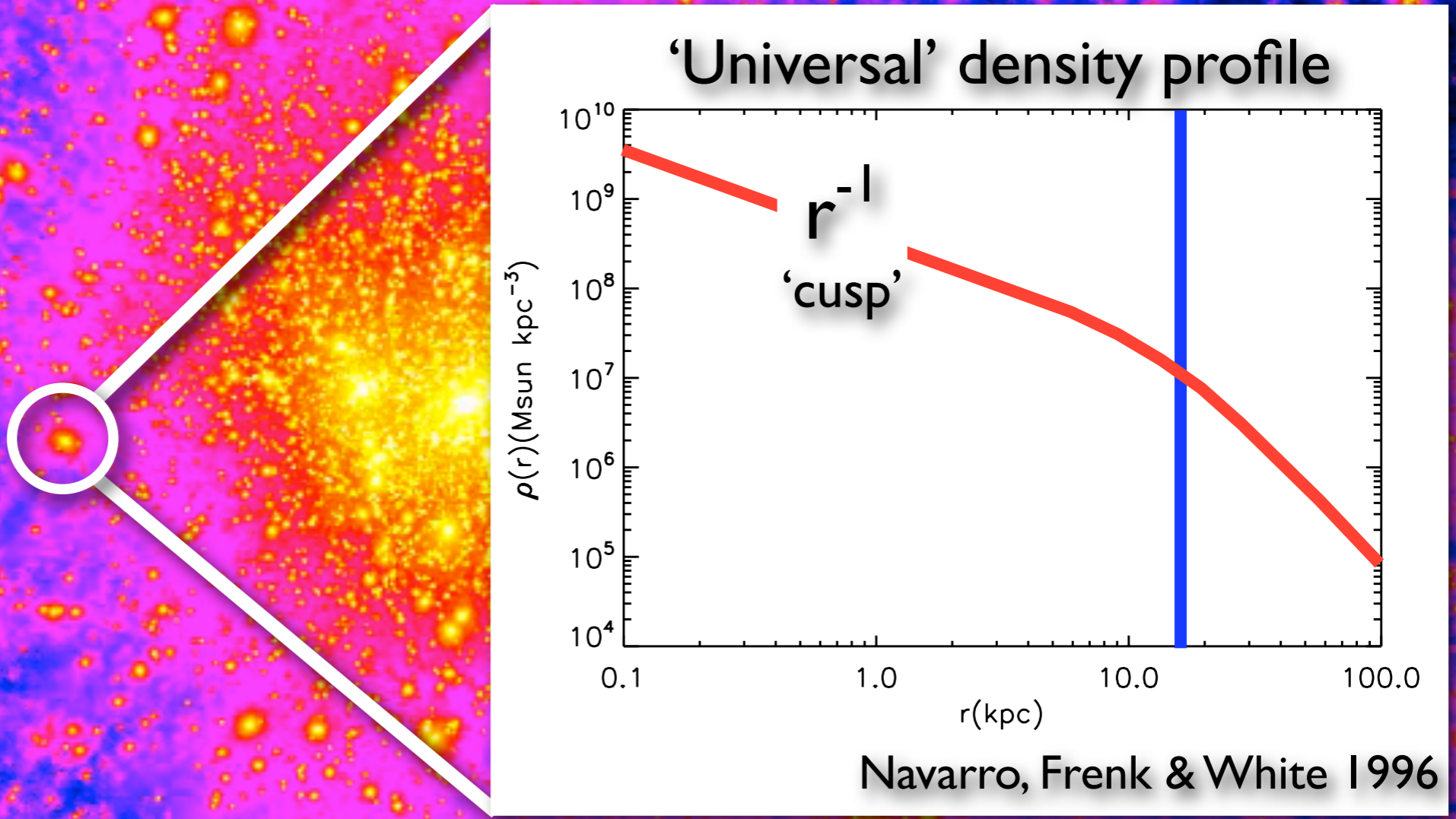


$Z=0.18$

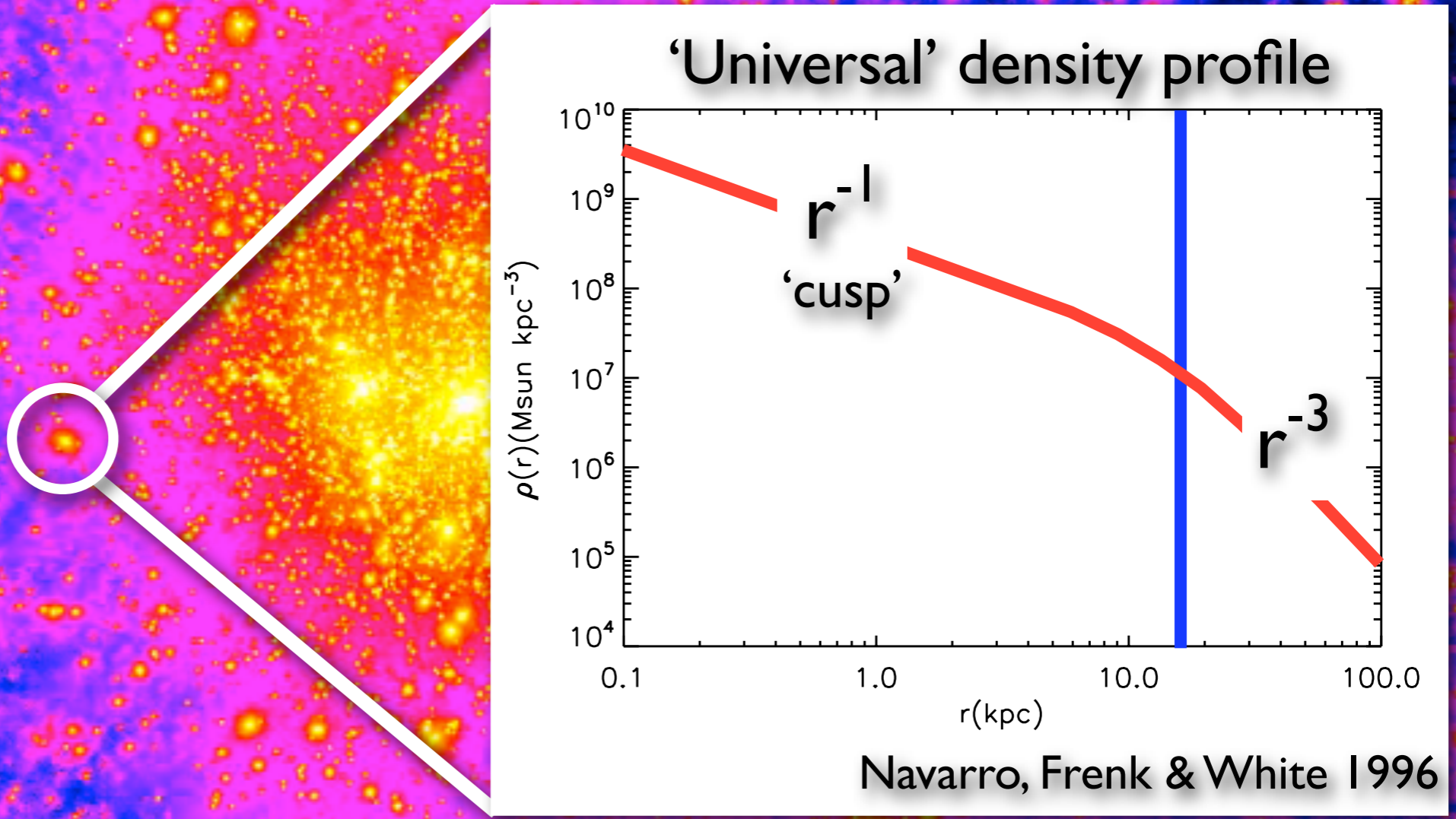
Dark matter only (DMO) simulations



Dark matter only (DMO) simulations

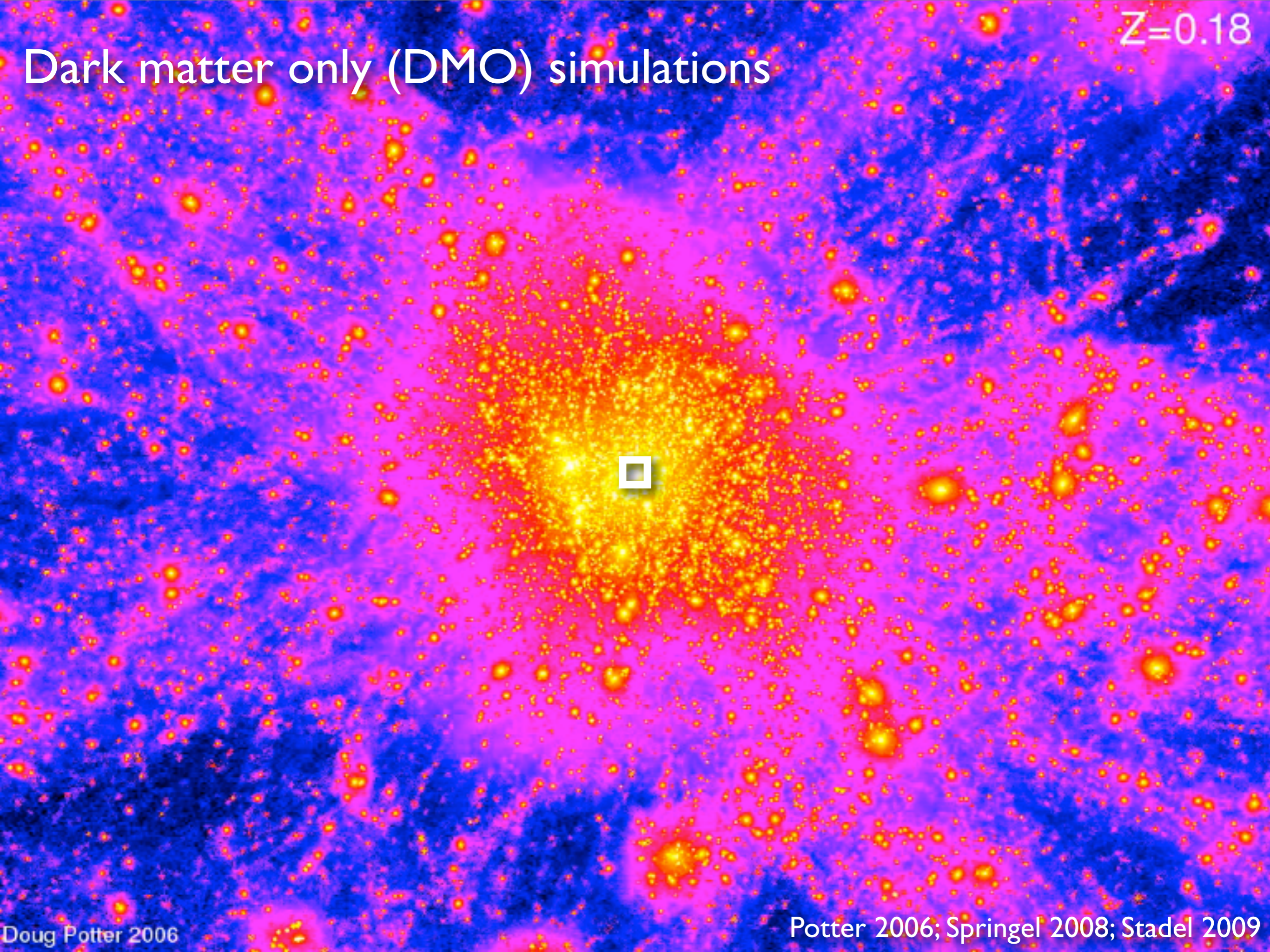


Dark matter only (DMO) simulations

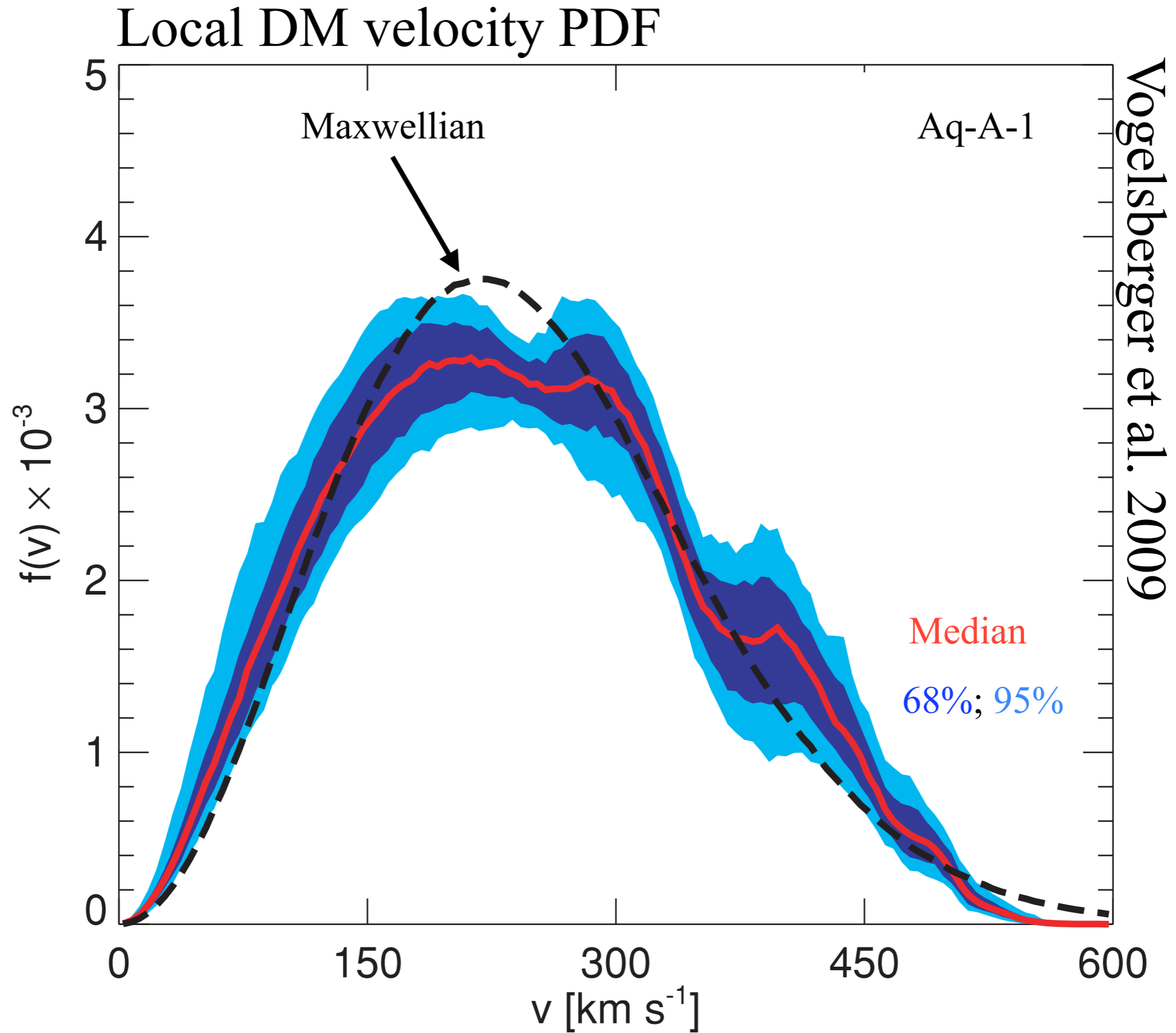


$Z=0.18$

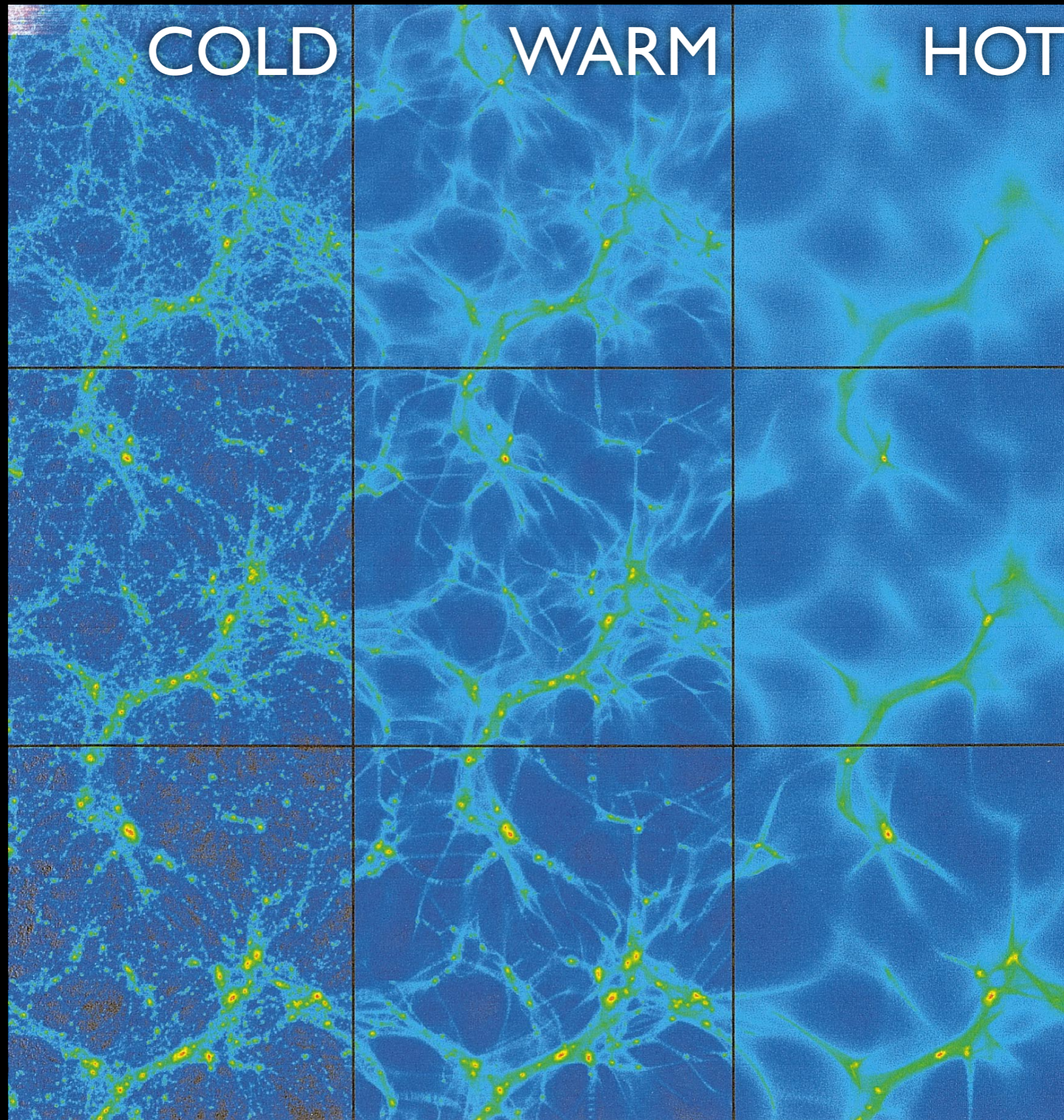
Dark matter only (DMO) simulations



Dark matter only (DMO) simulations



Dark matter only (DMO) simulations



Dark matter only (DMO) simulations



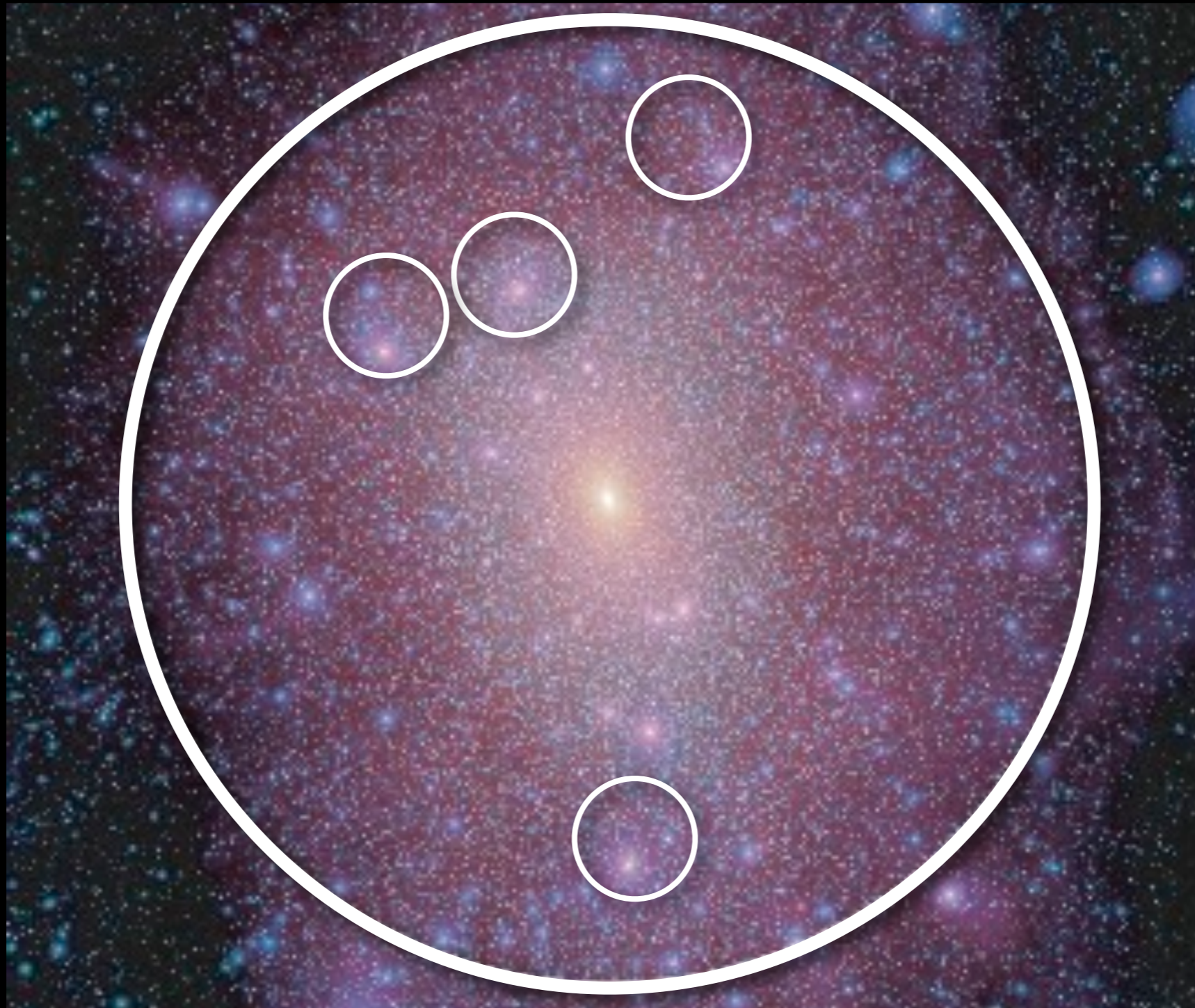
$$N_{\text{hr}} = 18,535,972$$

Dark matter only (DMO) simulations



$$N_{\text{hr}} = 18,535,972$$

Dark matter only (DMO) simulations



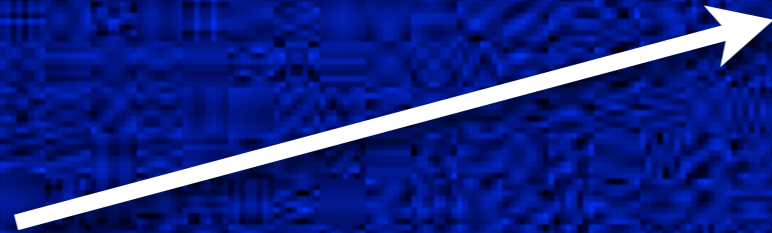
$$N_{\text{hr}} = 4,252,607,000$$

Dark matter only (DMO) simulations | Warm Dark Matter

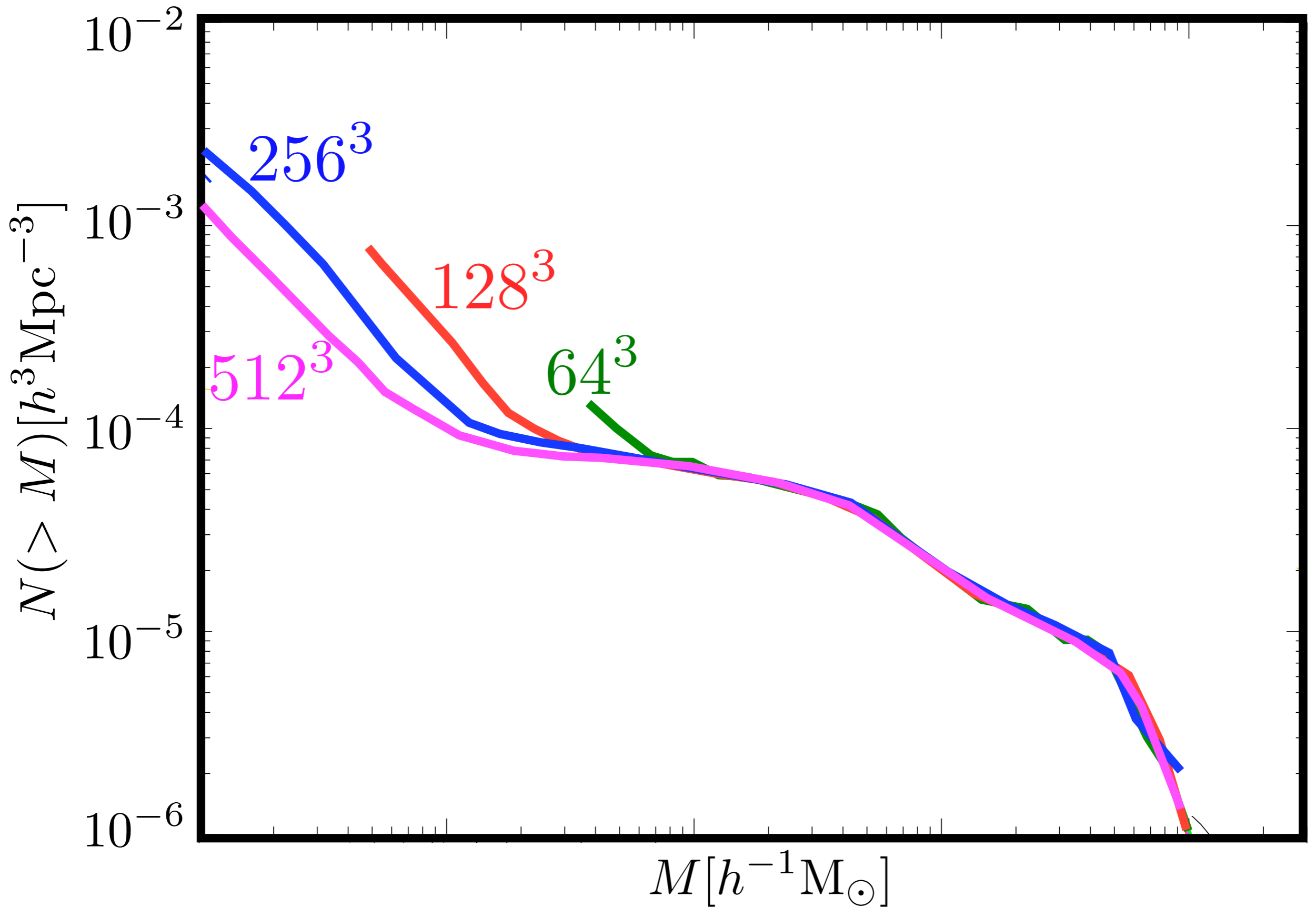
Dark matter only (DMO) simulations | Warm Dark Matter

Dark matter only (DMO) simulations | Warm Dark Matter

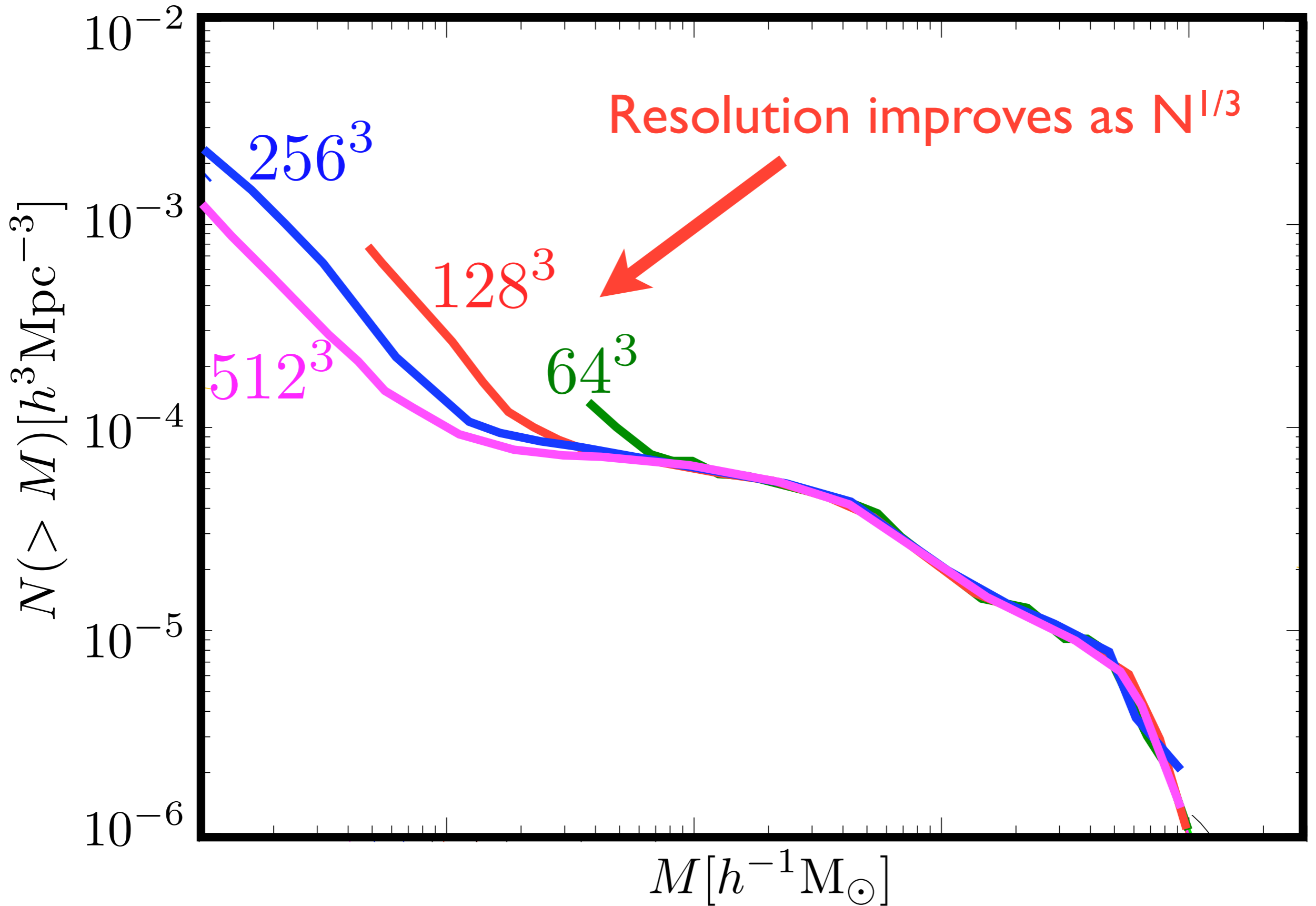
Spurious halos?



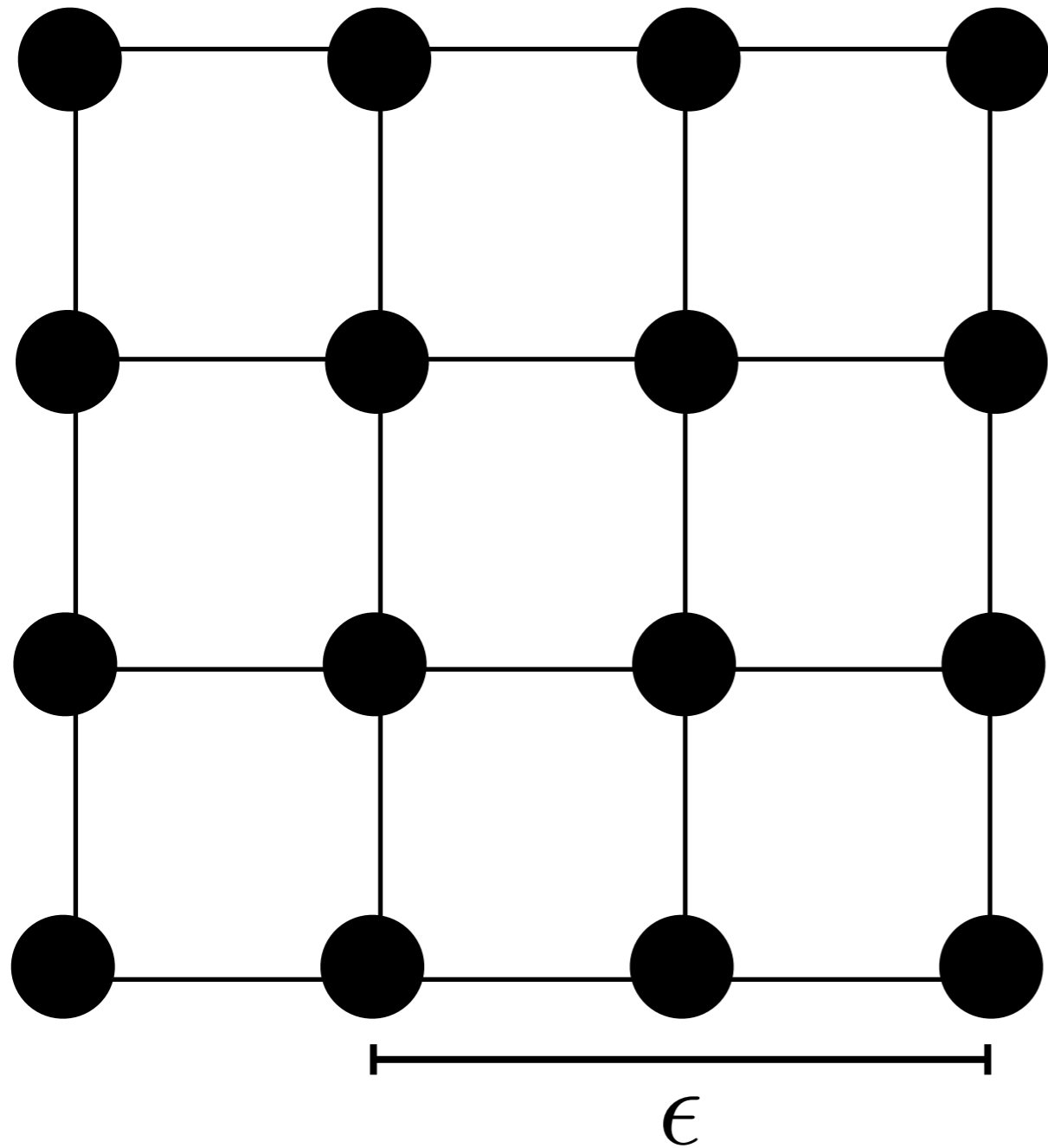
Dark matter only (DMO) simulations | Warm Dark Matter



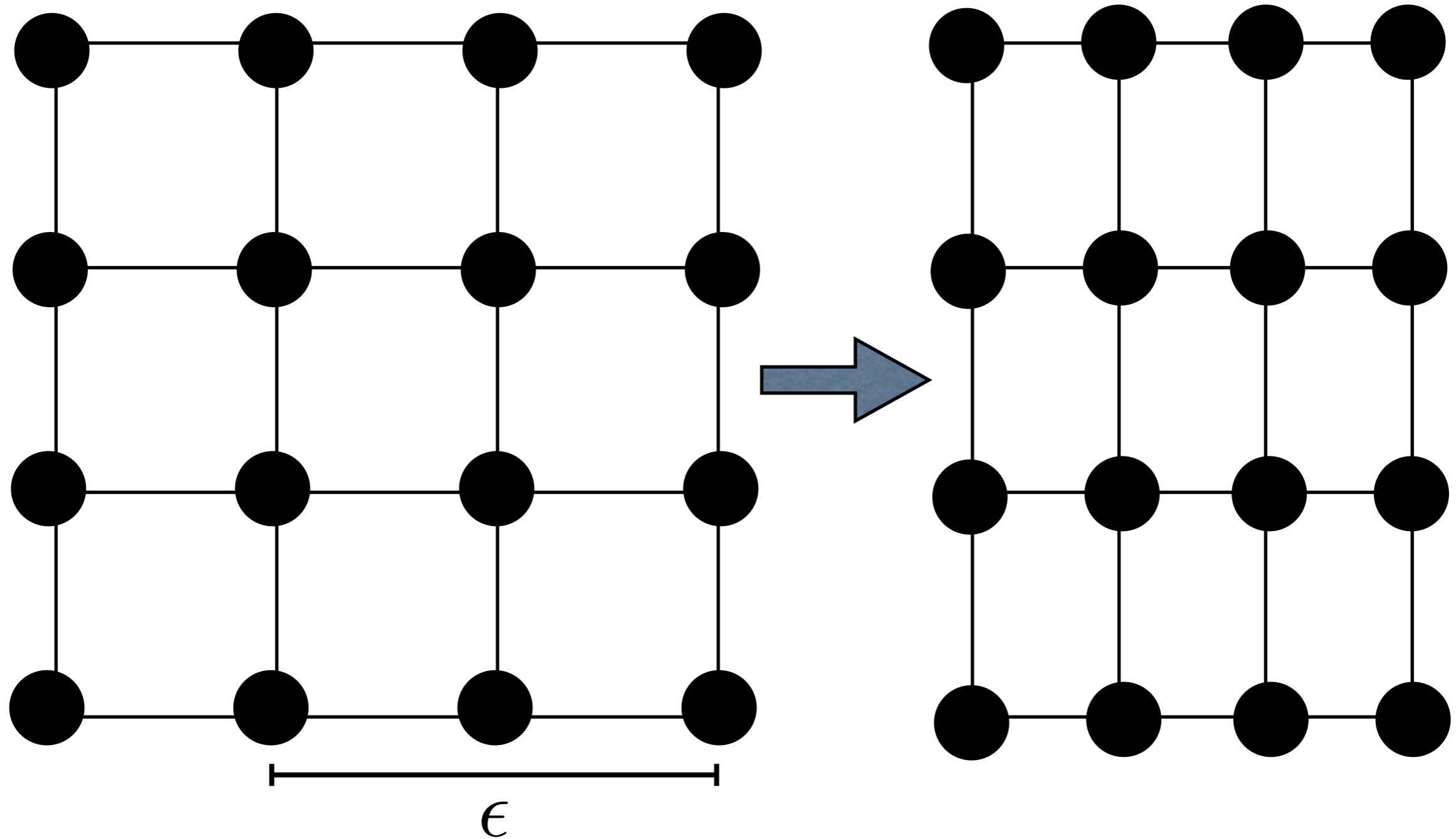
Dark matter only (DMO) simulations | Warm Dark Matter



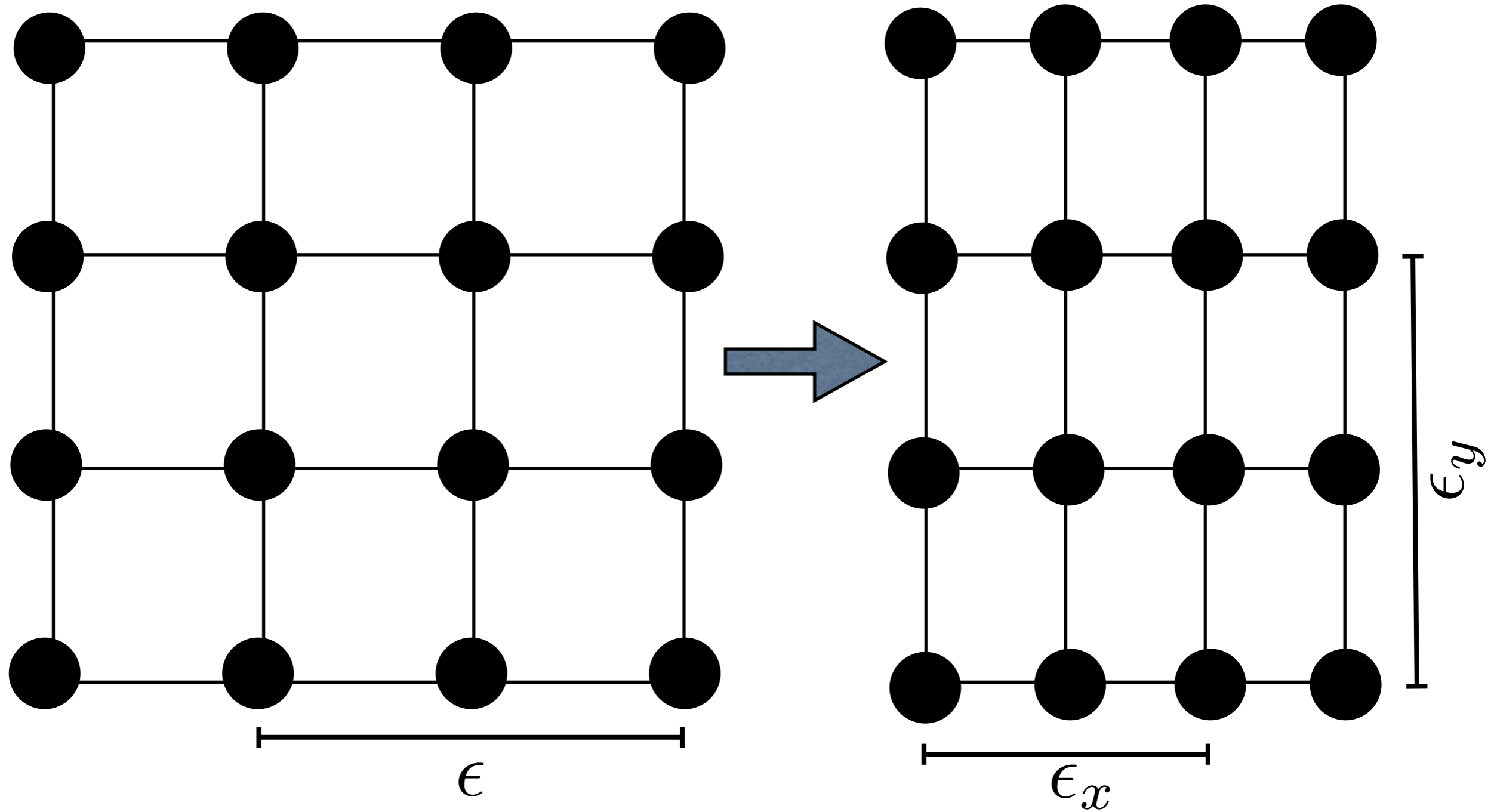
Dark matter only (DMO) simulations | Warm Dark Matter



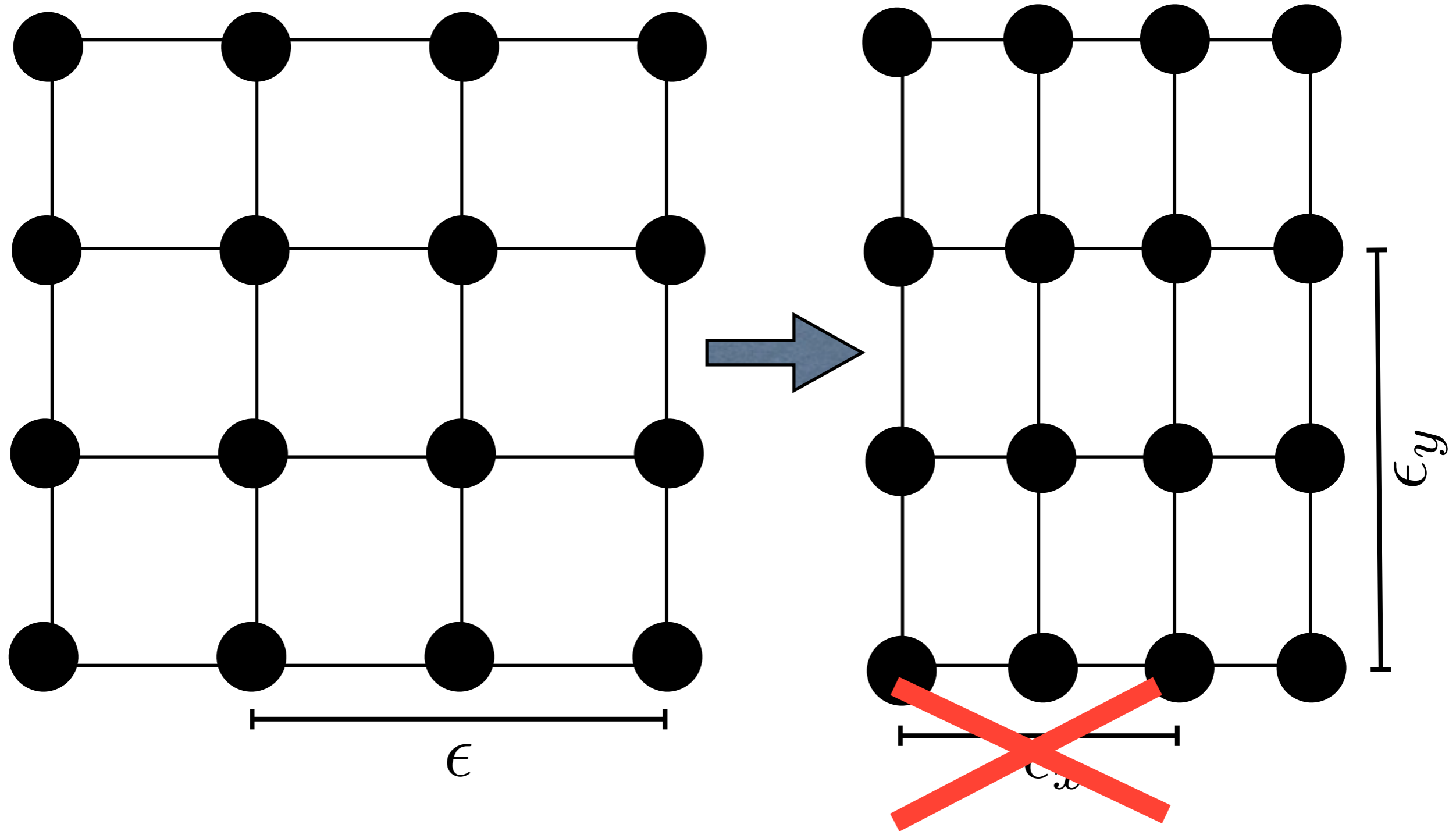
Dark matter only (DMO) simulations | Warm Dark Matter



Dark matter only (DMO) simulations | Warm Dark Matter



Dark matter only (DMO) simulations | Warm Dark Matter



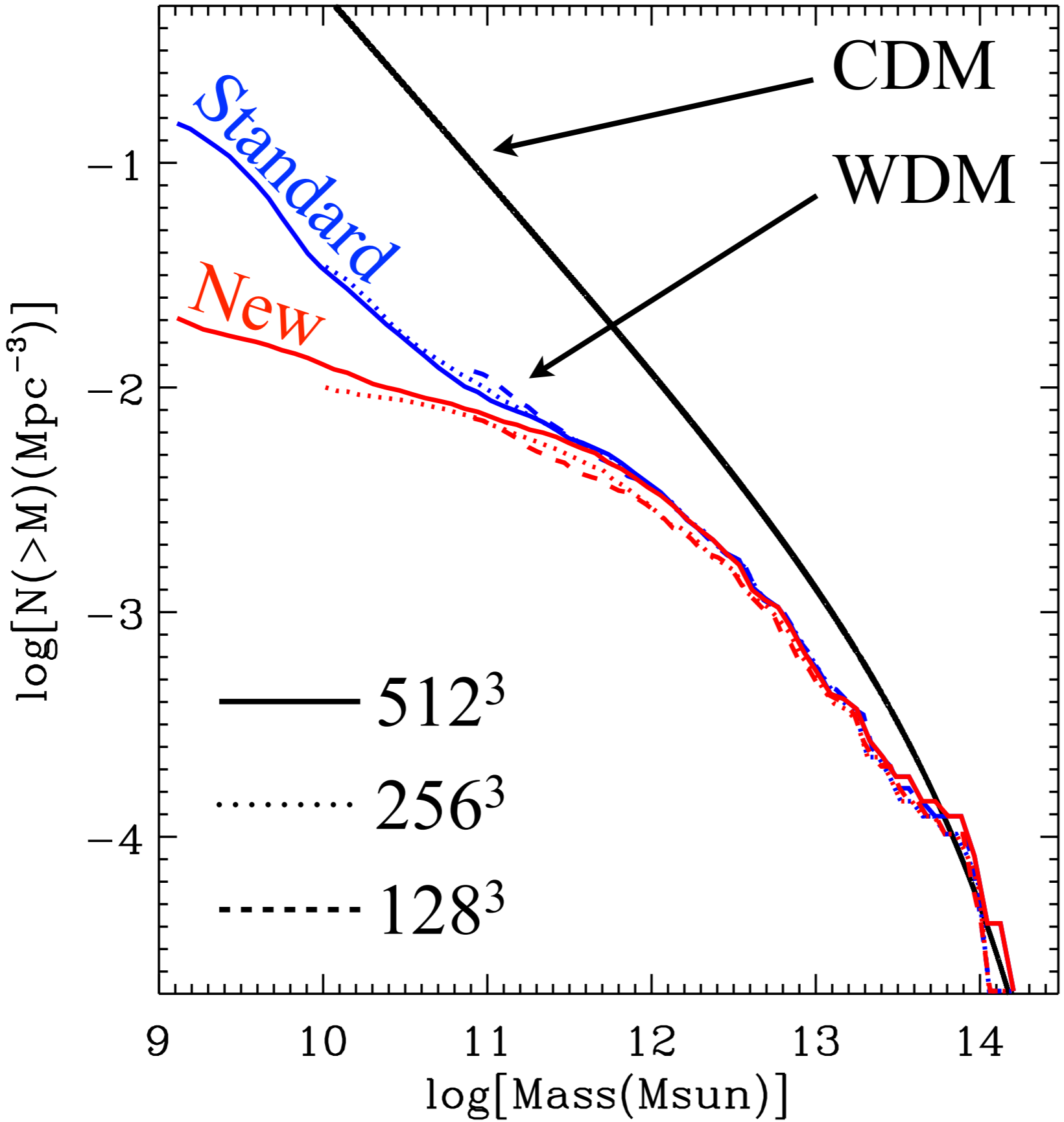
Dark matter only (DMO) simulations | Warm Dark Matter

$$\epsilon = 2\Delta x$$

Dark matter only (DMO) simulations | Warm Dark Matter

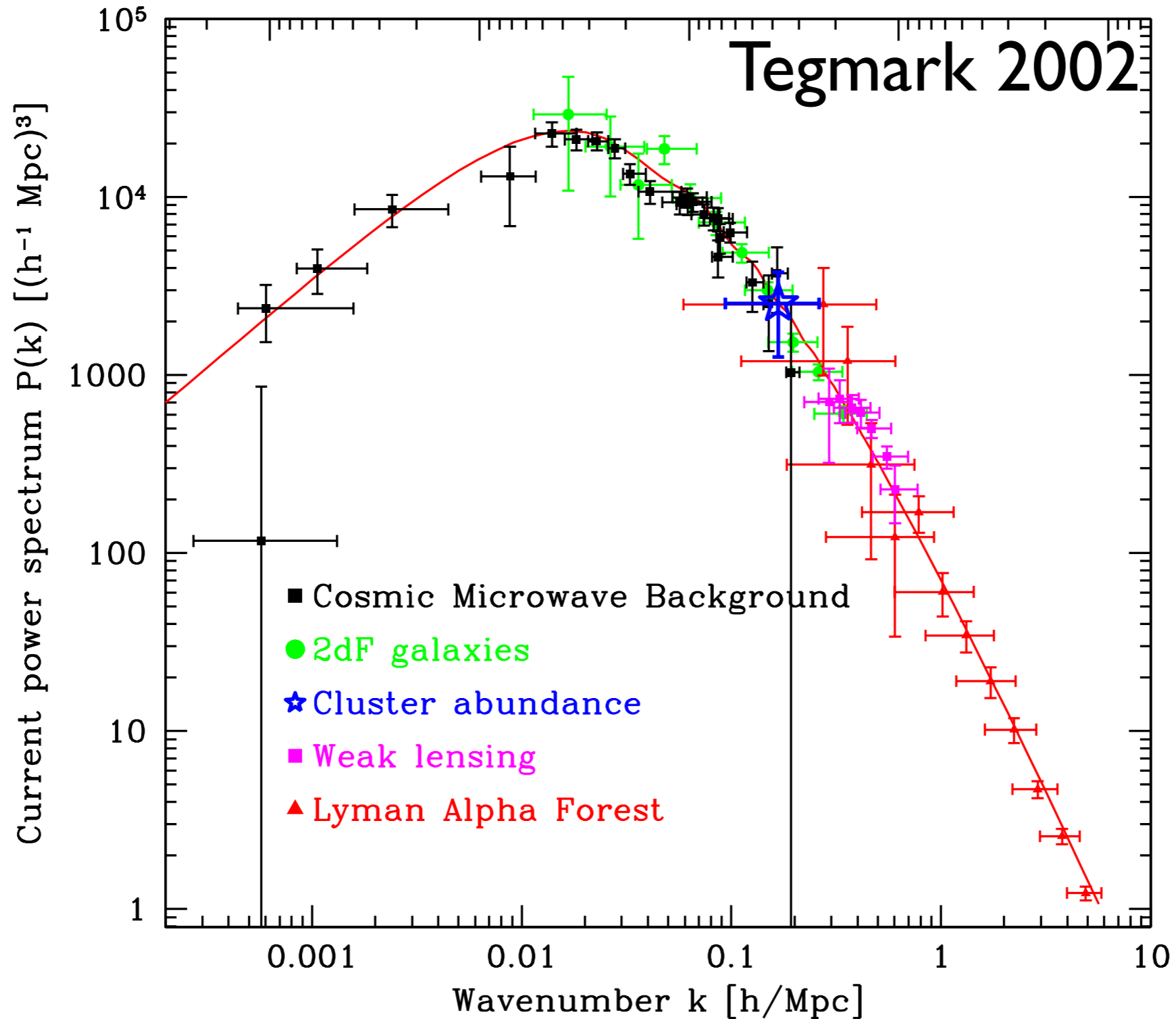
$$\epsilon = 2 \max[\Delta x]$$

Dark matter only (DMO) simulations | Warm Dark Matter



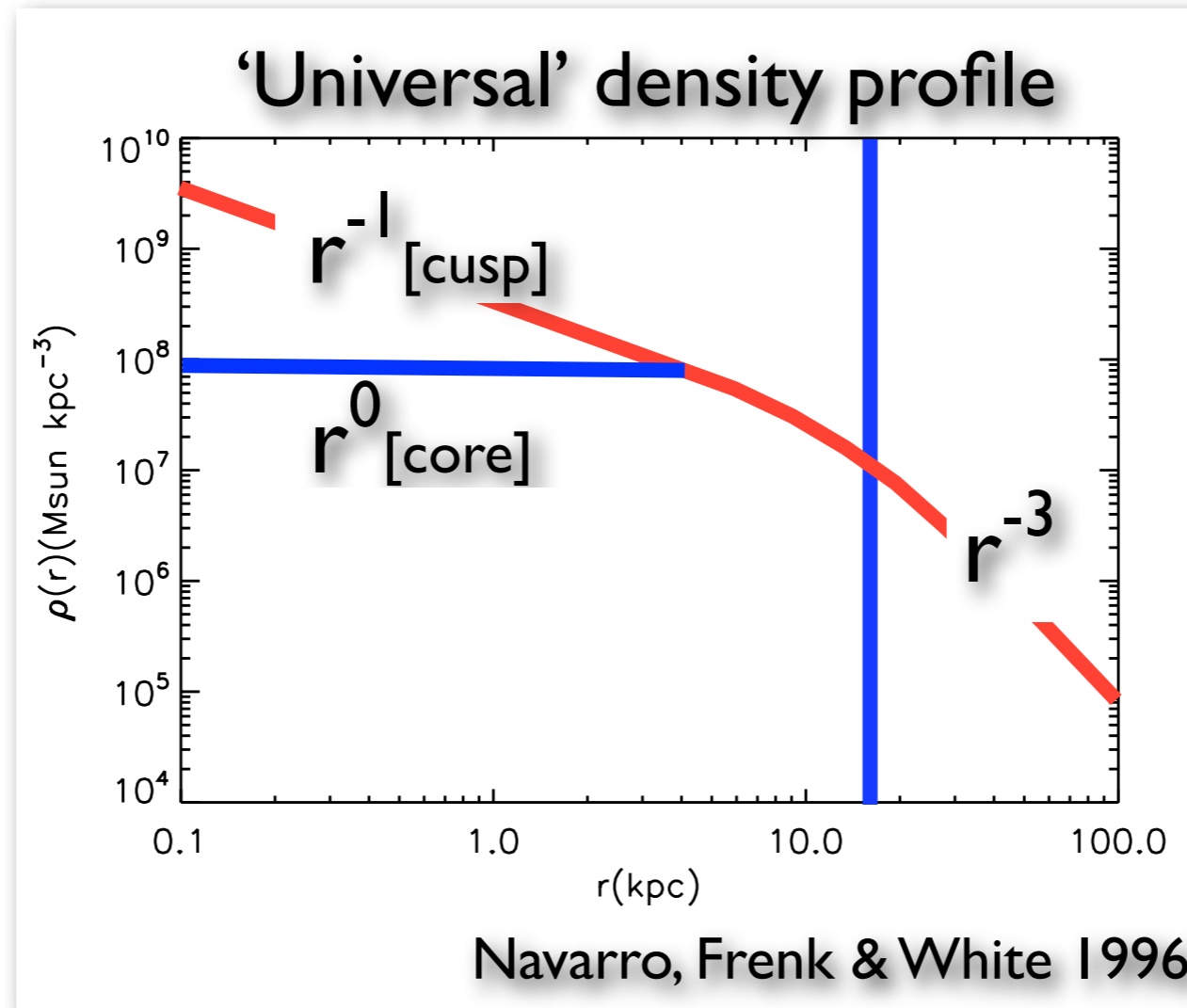
DMO simulations | The “Small Scale Crisis”

LCDM [DMO] \Rightarrow Excellent match to large scale structure



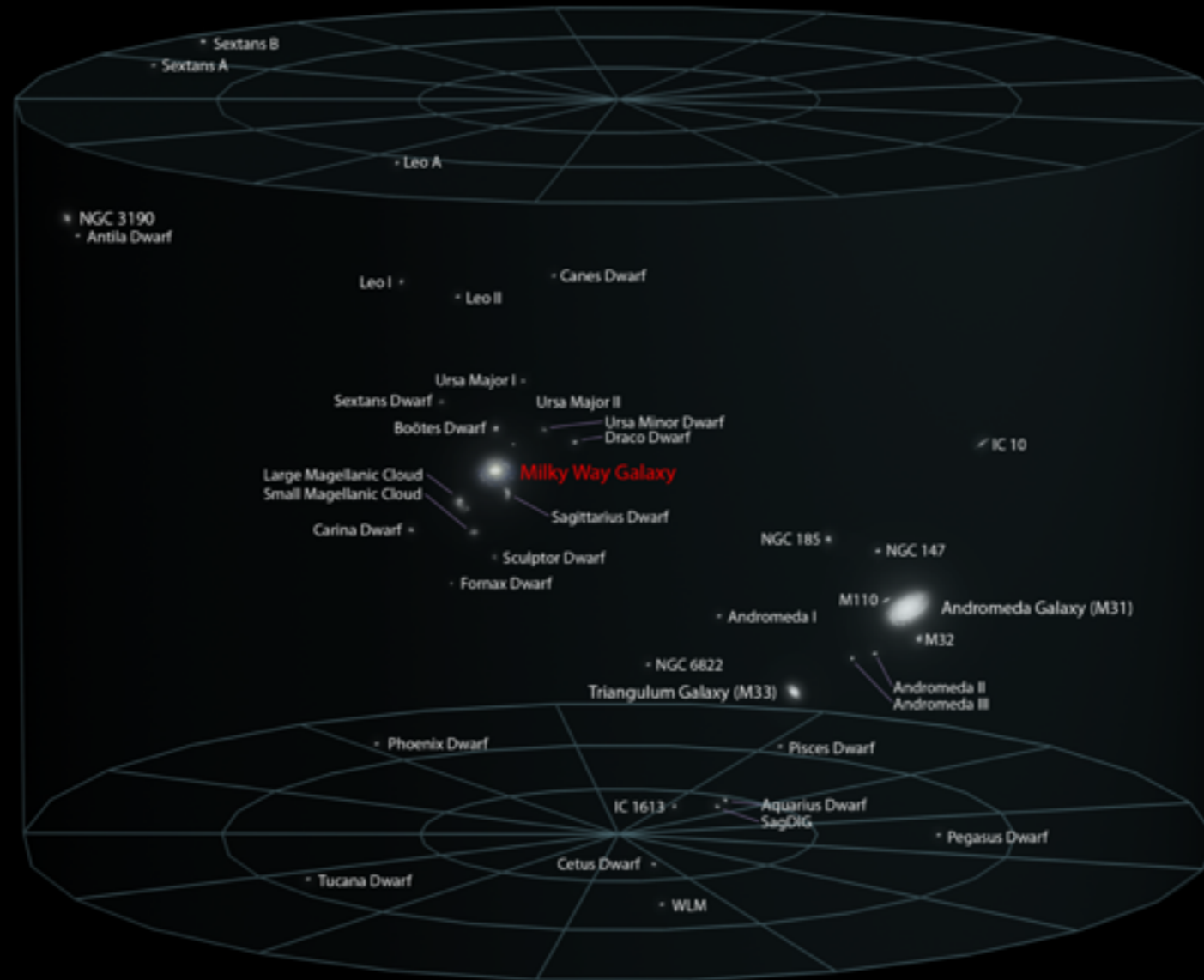
DMO simulations | The “Small Scale Crisis”

a) The ‘cusp-core’ problem



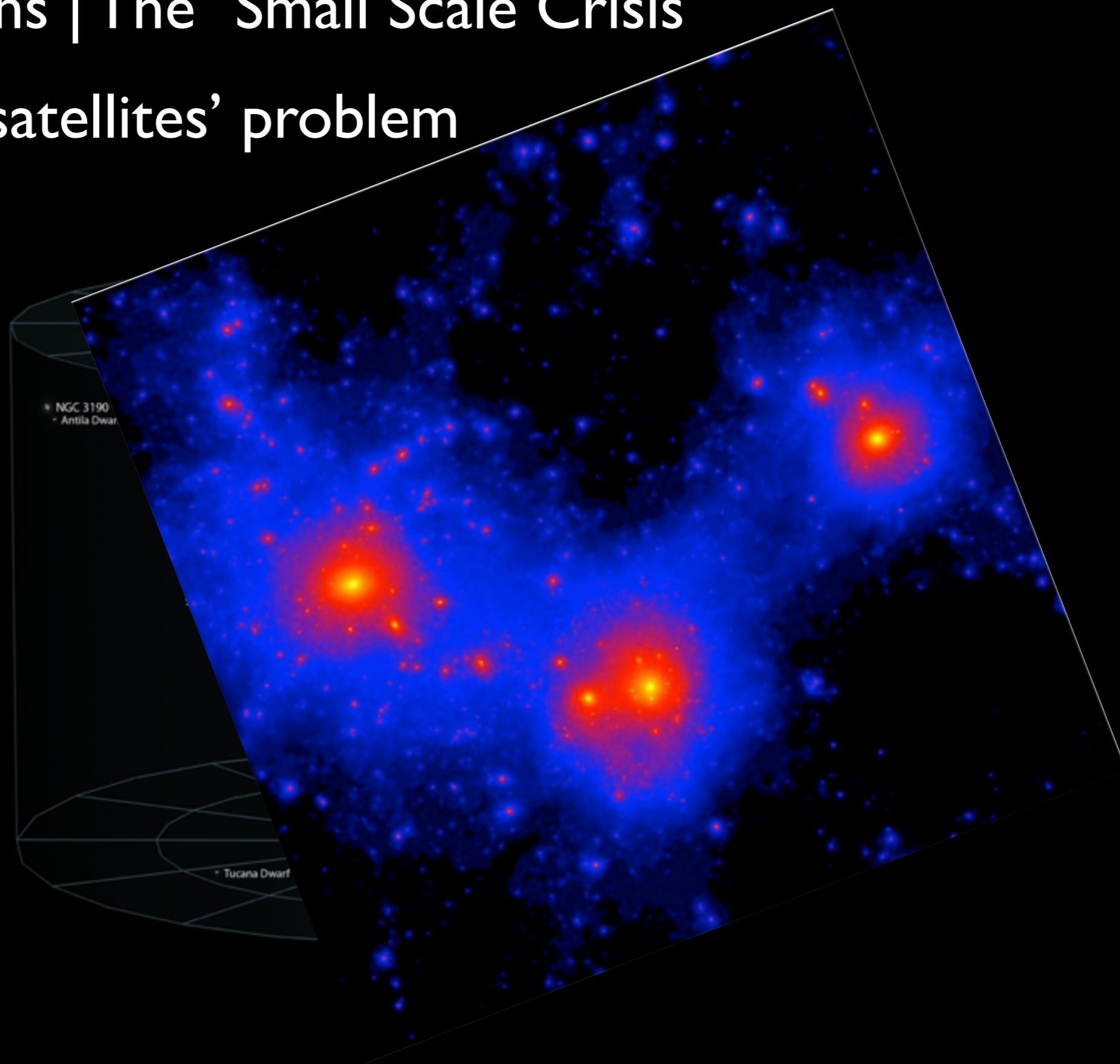
DMO simulations | The “Small Scale Crisis”

b) The ‘missing satellites’ problem



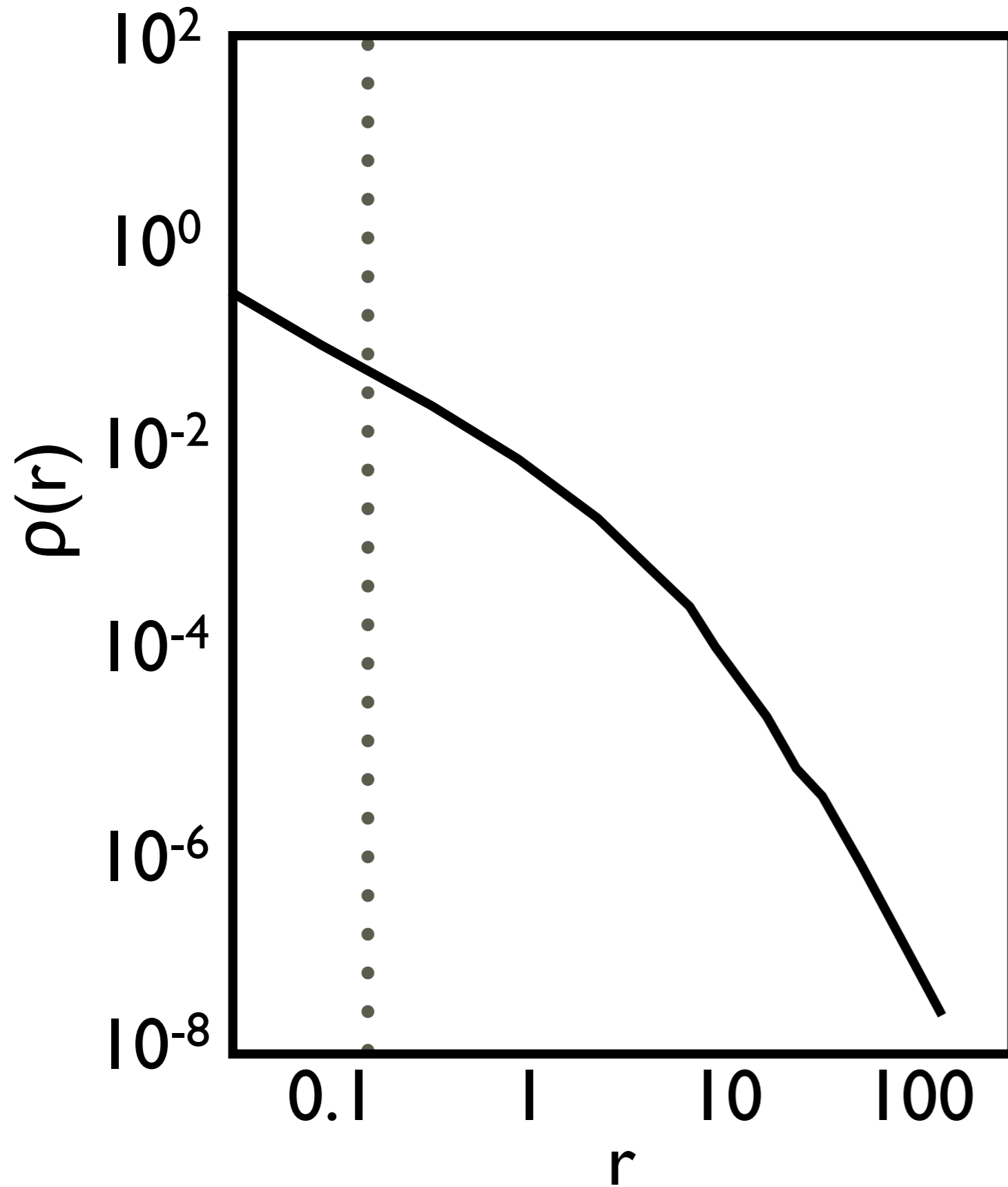
DMO simulations | The “Small Scale Crisis”

b) The ‘missing satellites’ problem

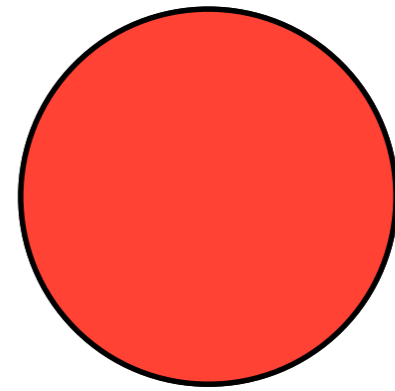


Baryons

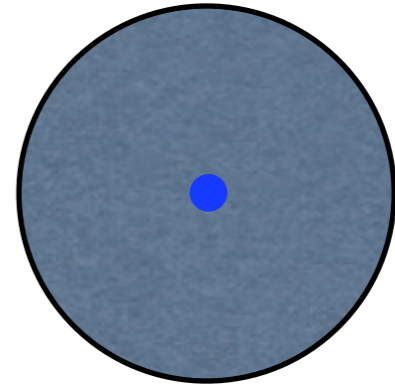
Including baryons (stars and gas)



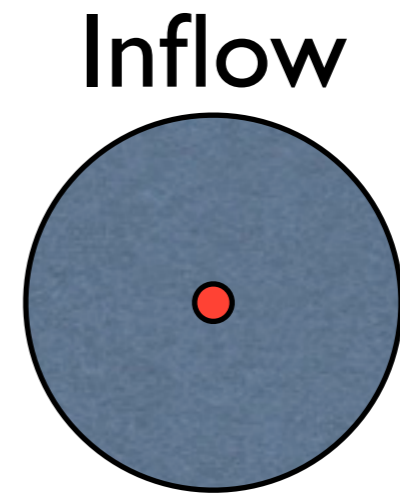
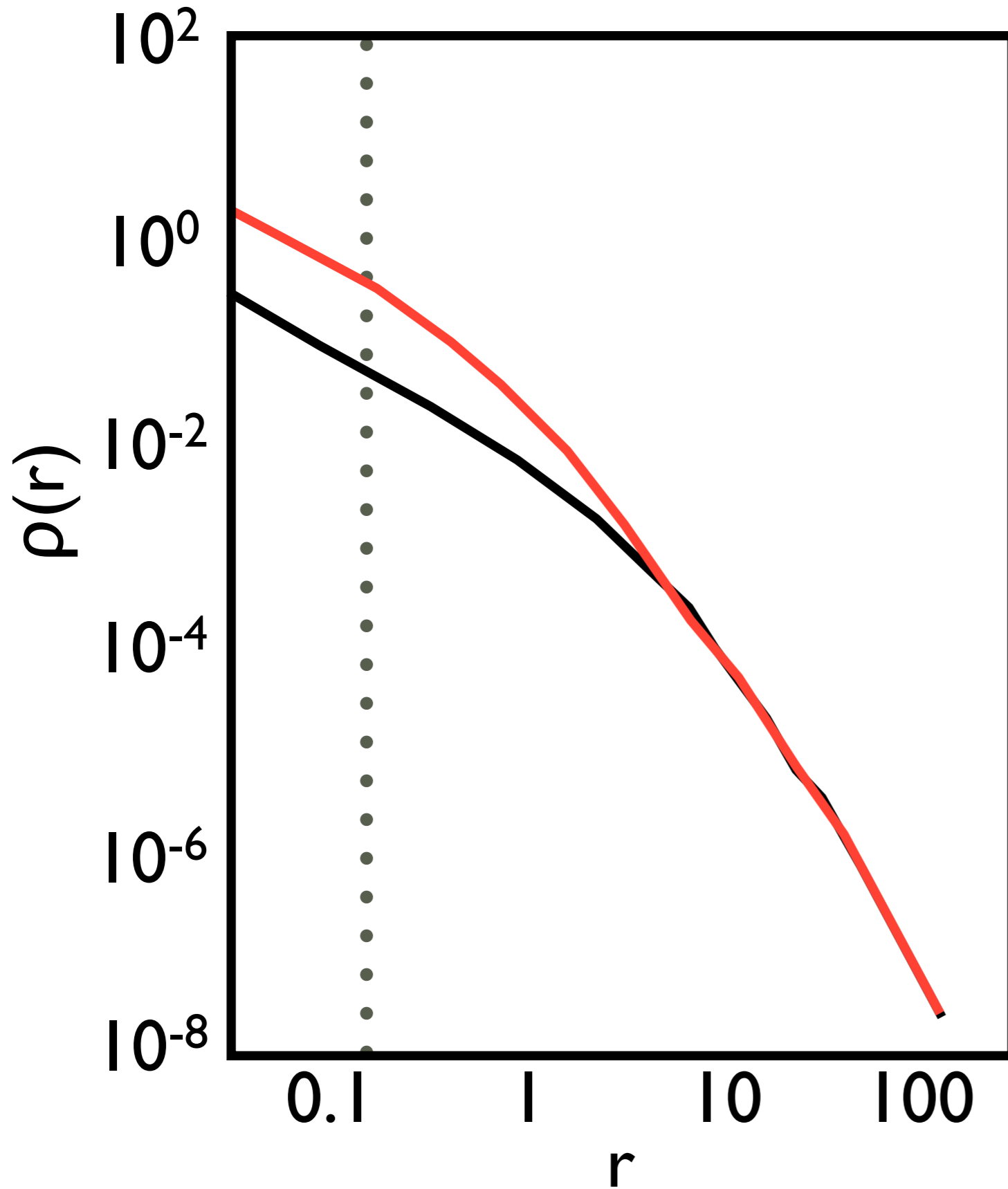
Inflow



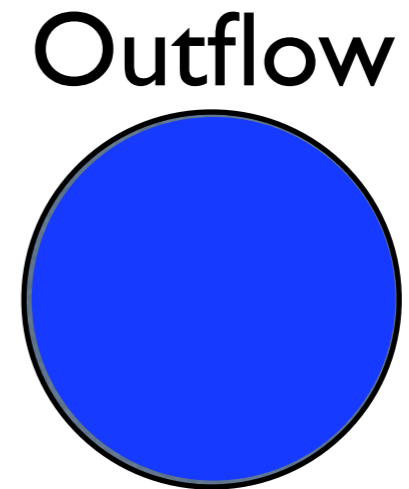
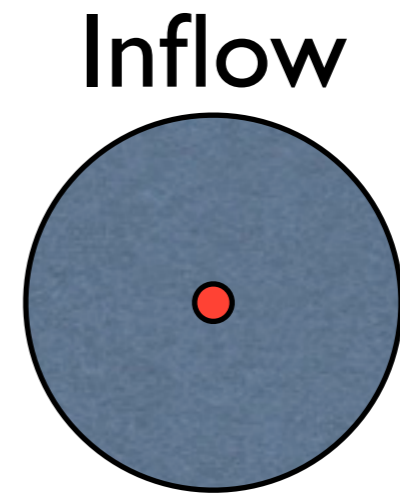
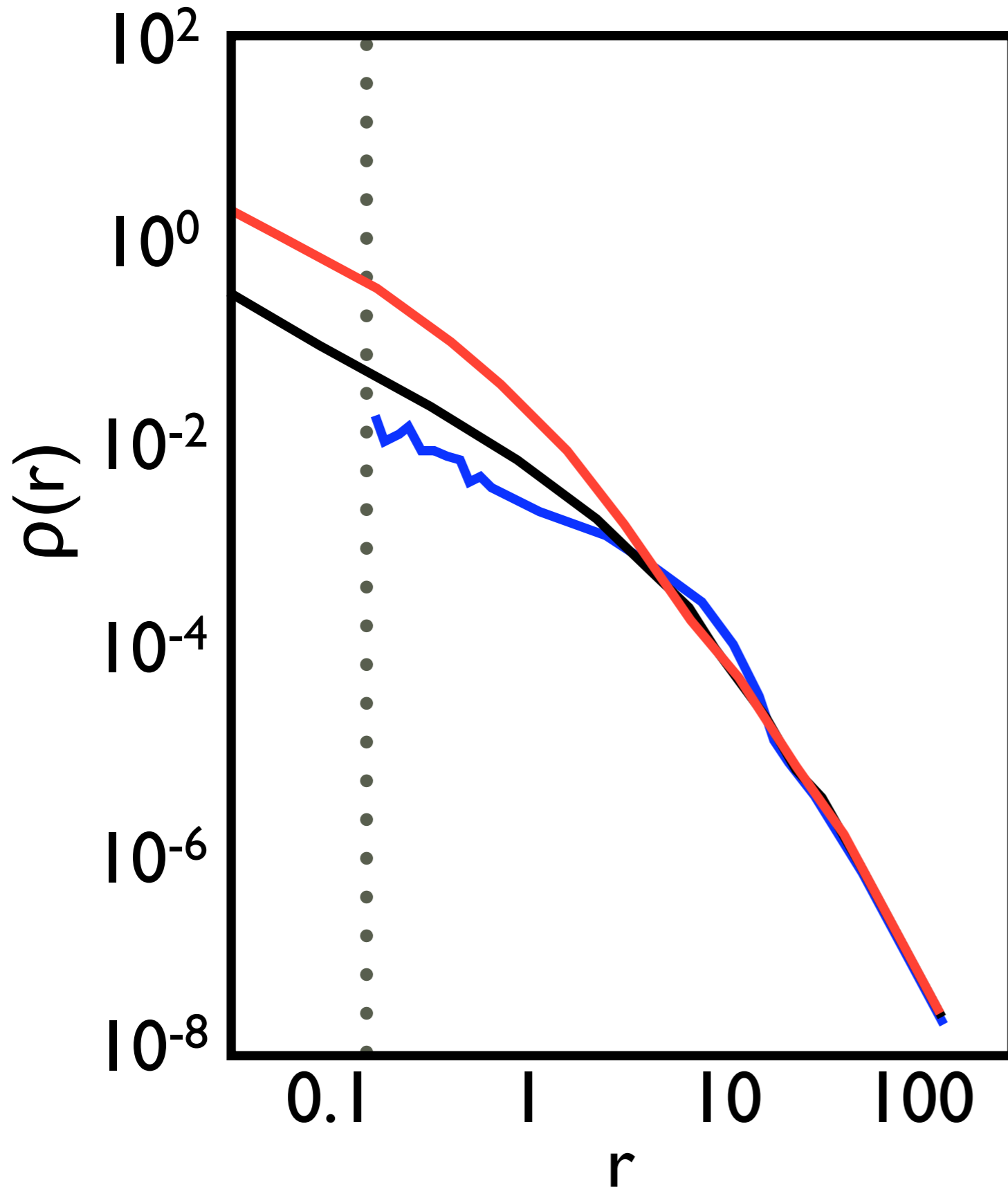
Outflow



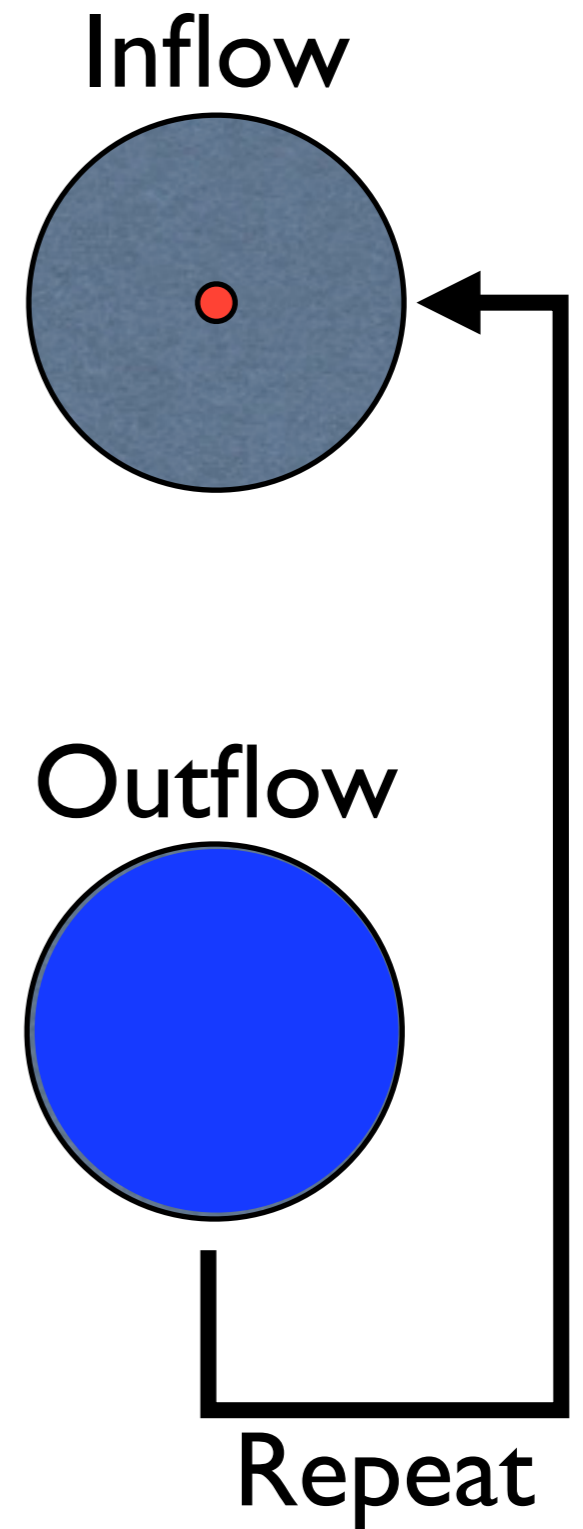
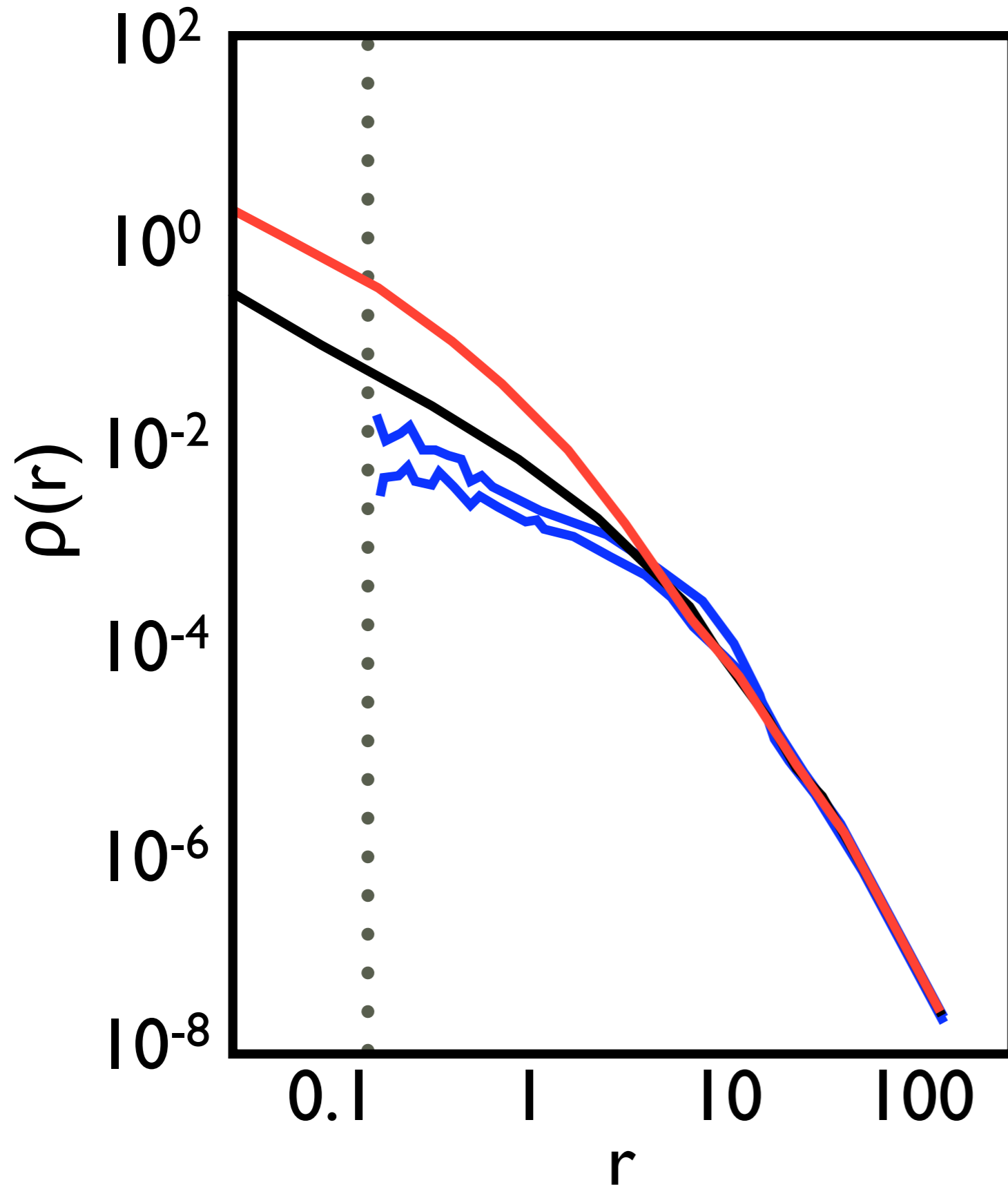
Including baryons (stars and gas)



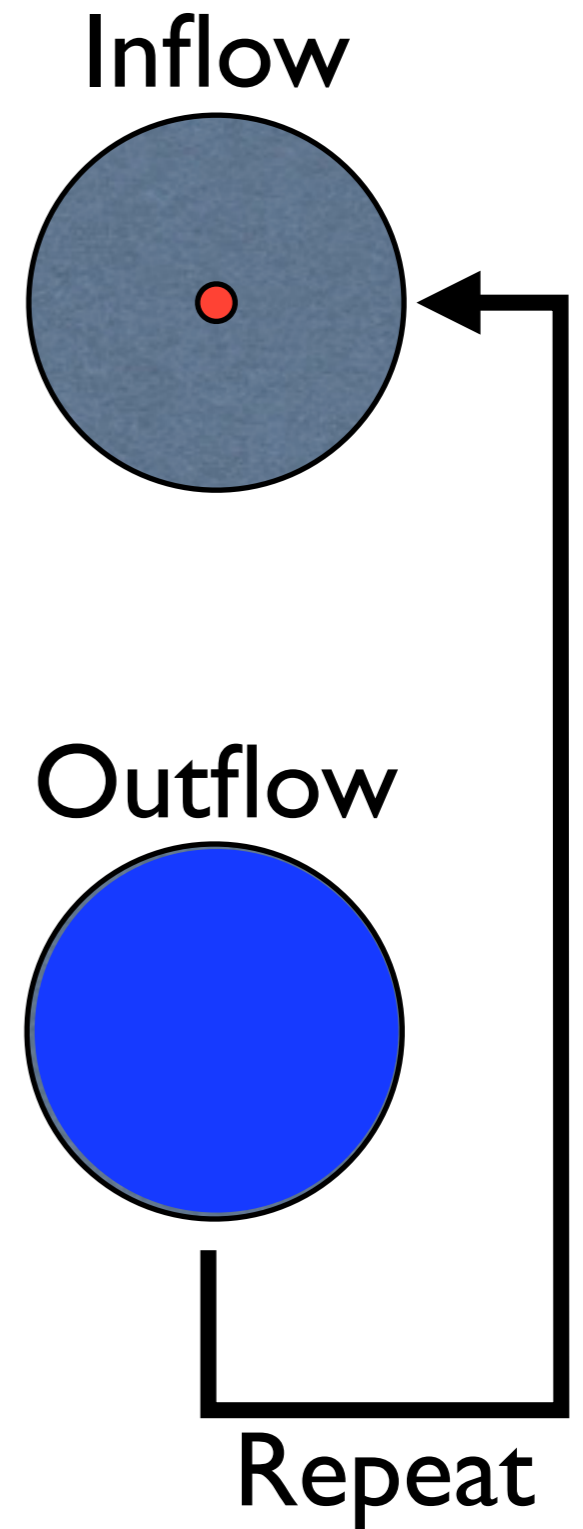
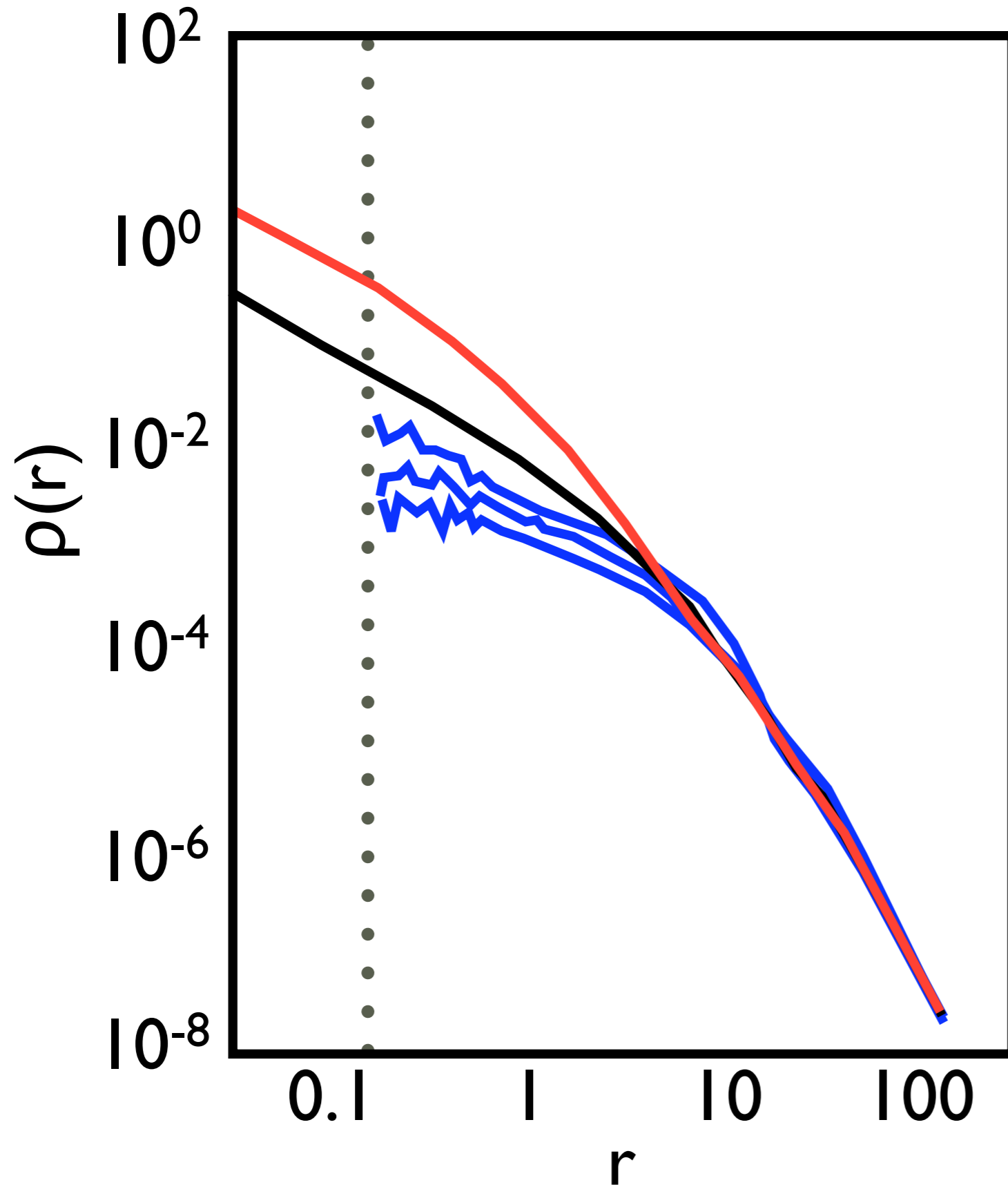
Including baryons (stars and gas)



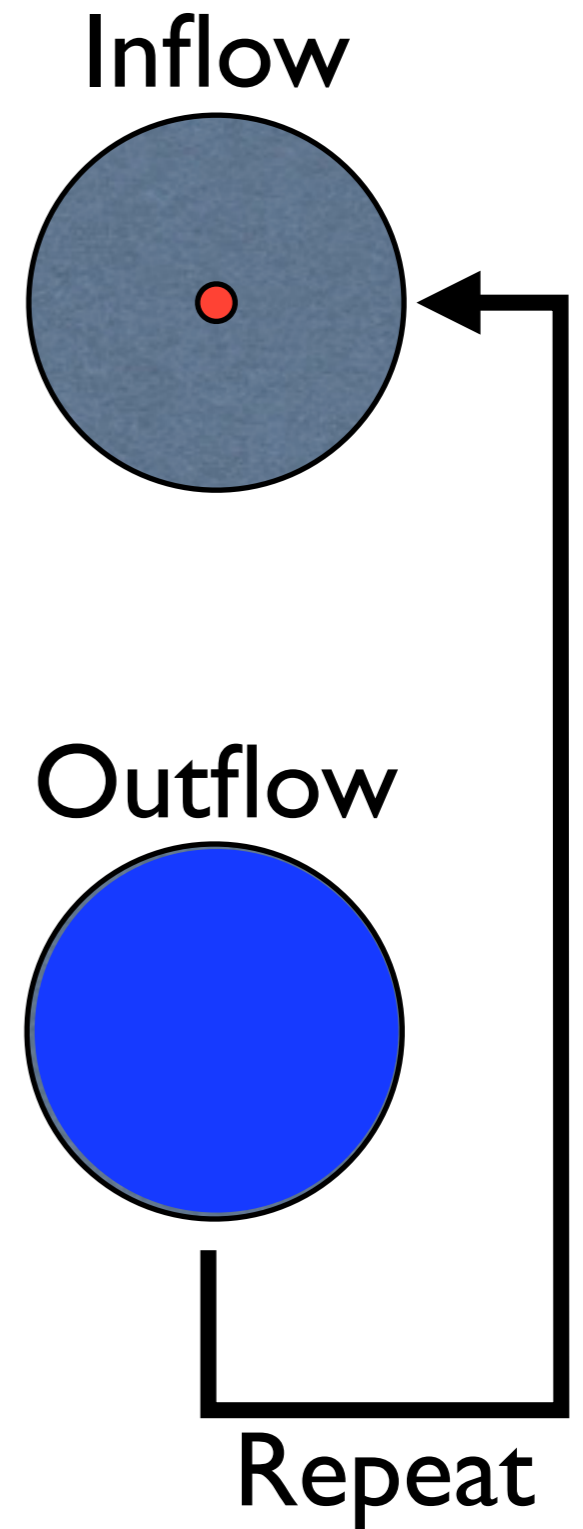
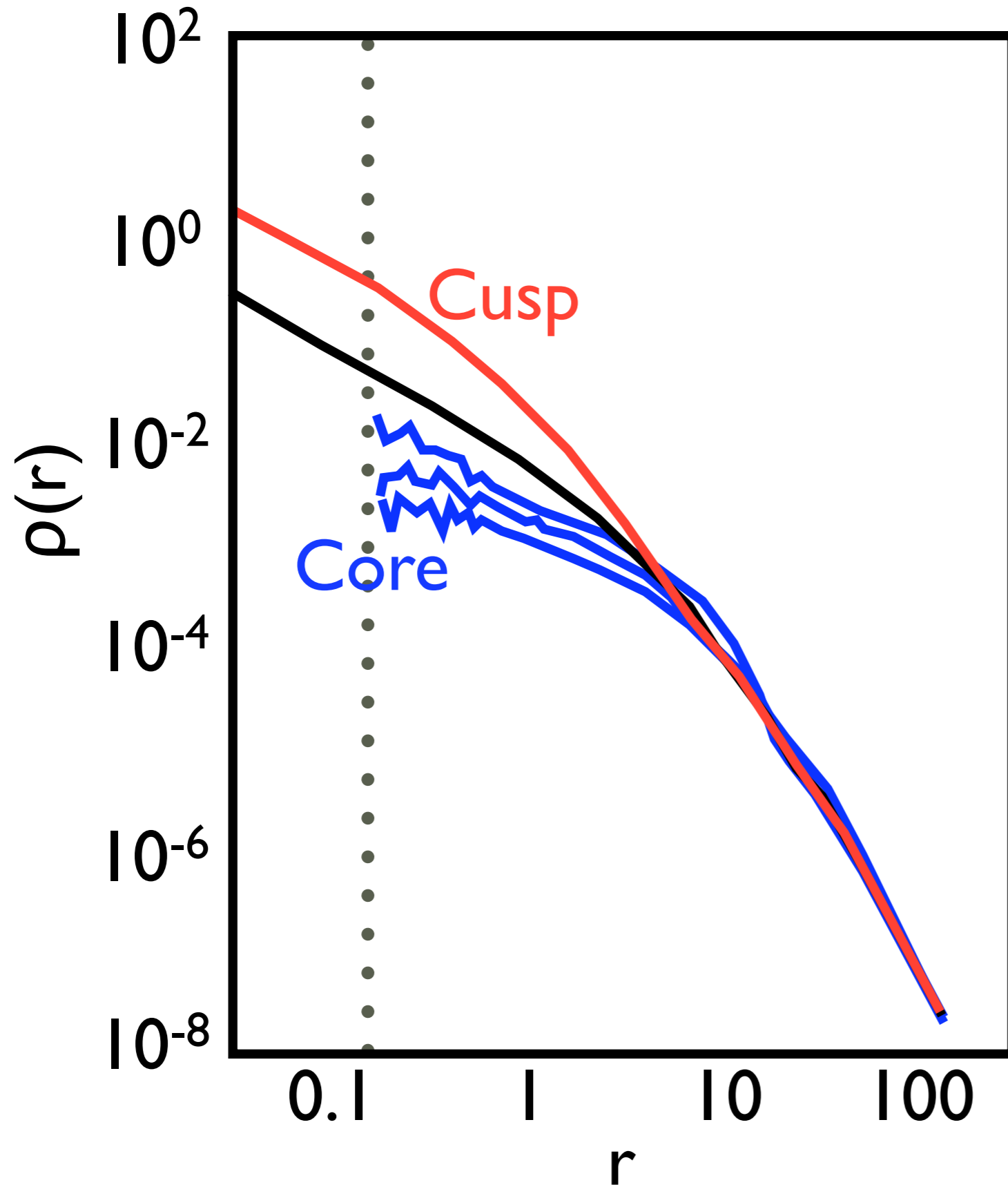
Including baryons (stars and gas)



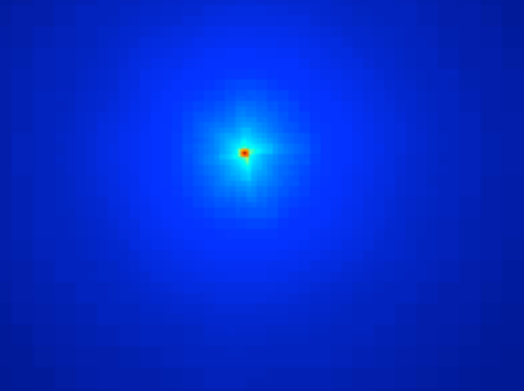
Including baryons (stars and gas)



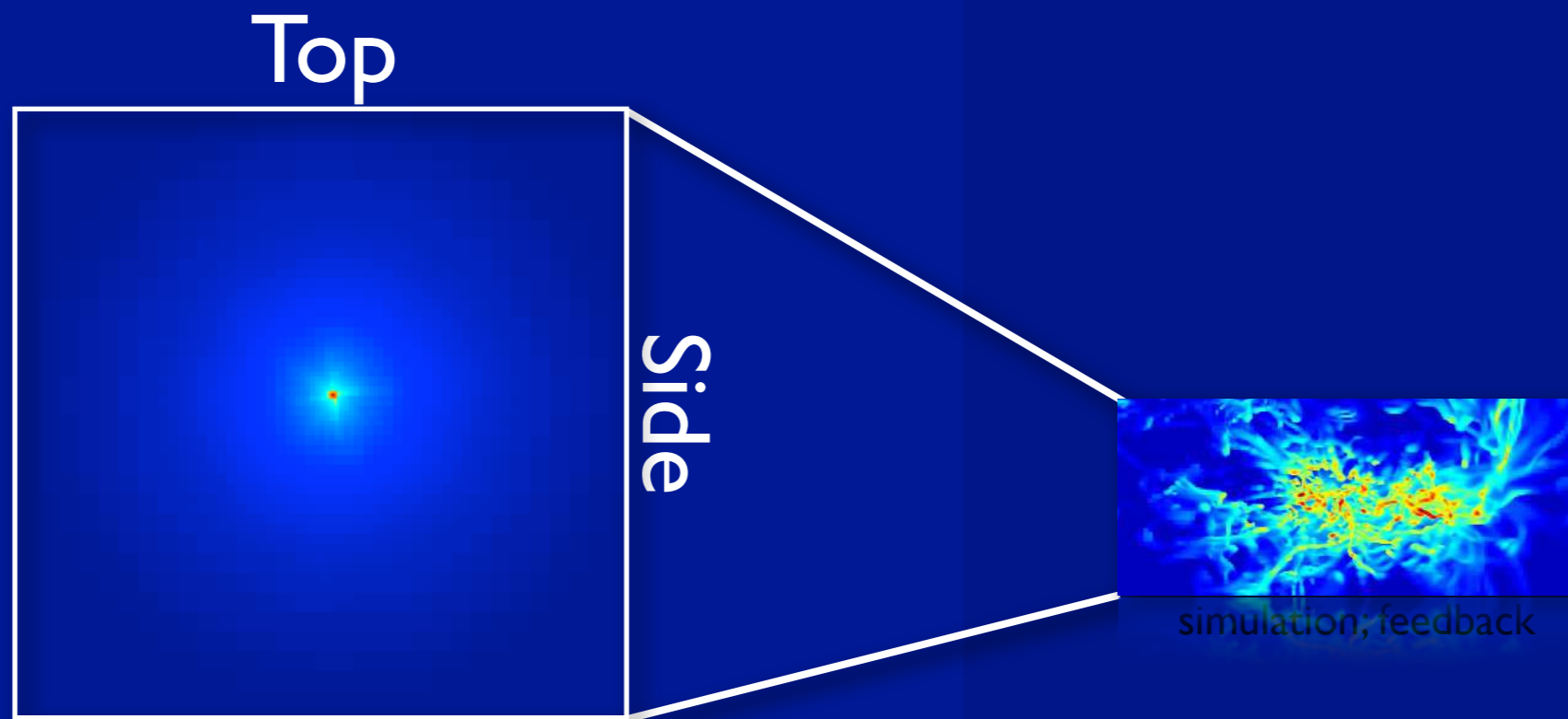
Including baryons (stars and gas)



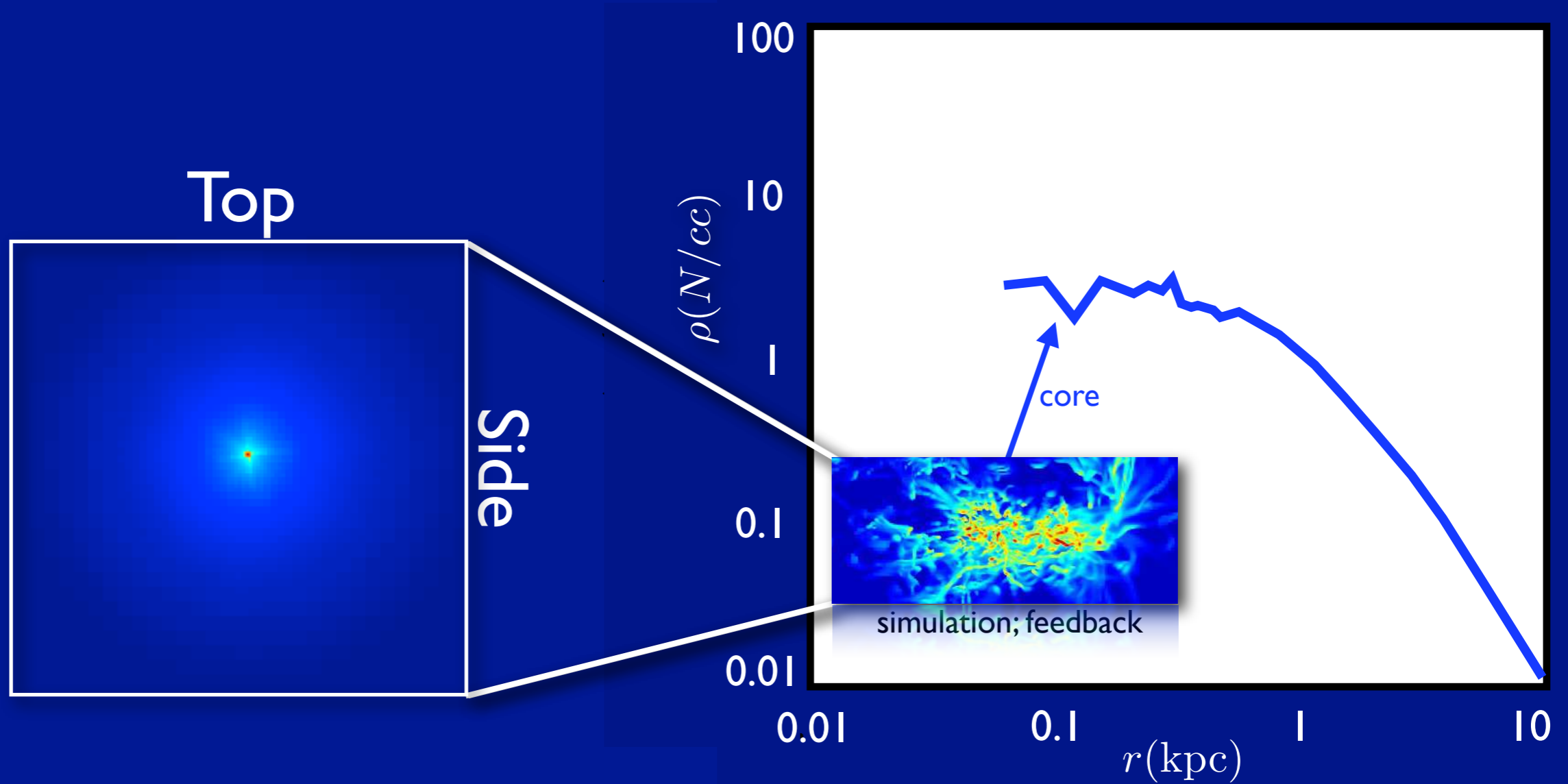
Including baryons (stars and gas)



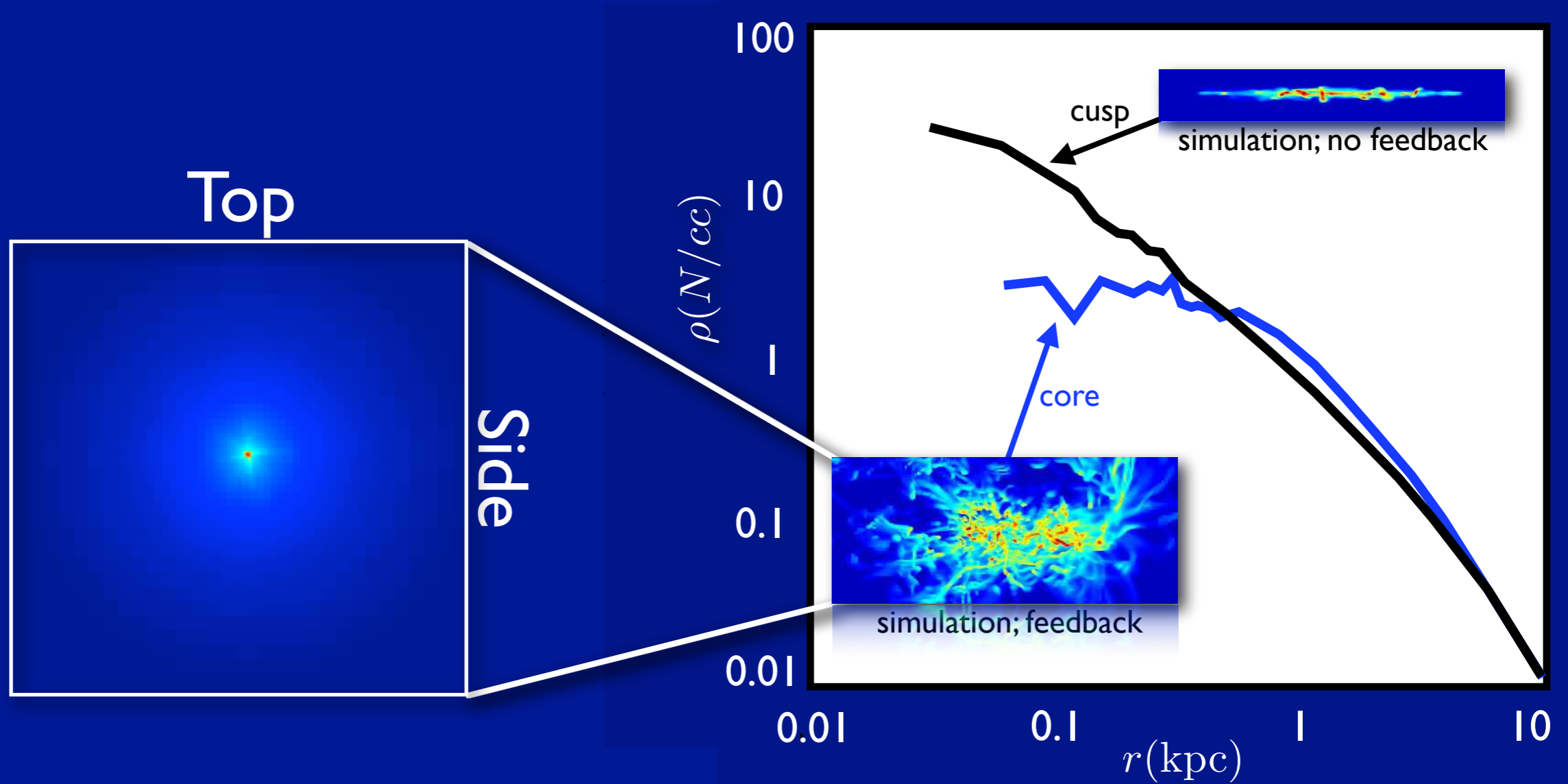
Including baryons (stars and gas)



Including baryons (stars and gas)



Including baryons (stars and gas)



Including baryons | The “Small Scale Crisis” ...

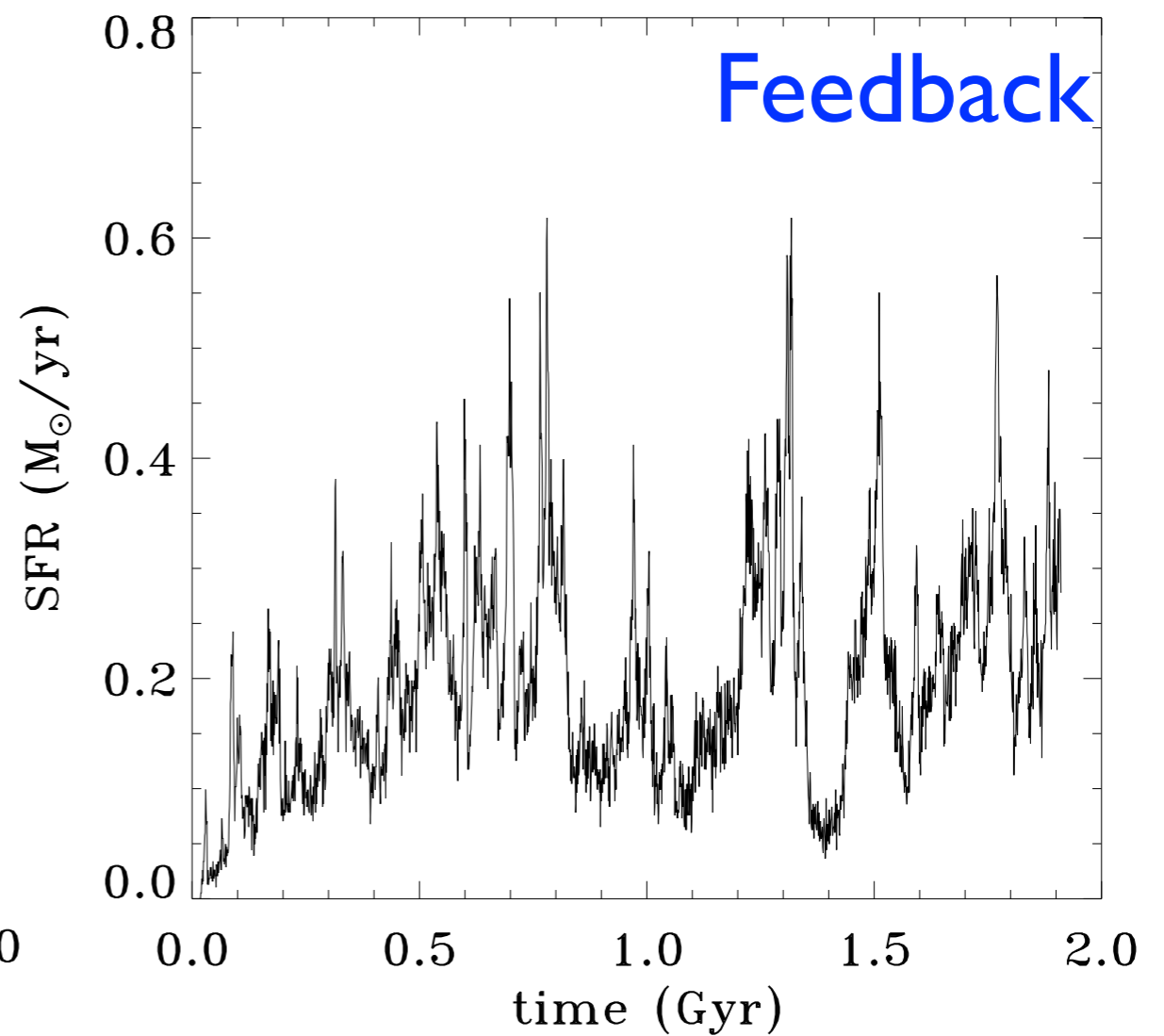
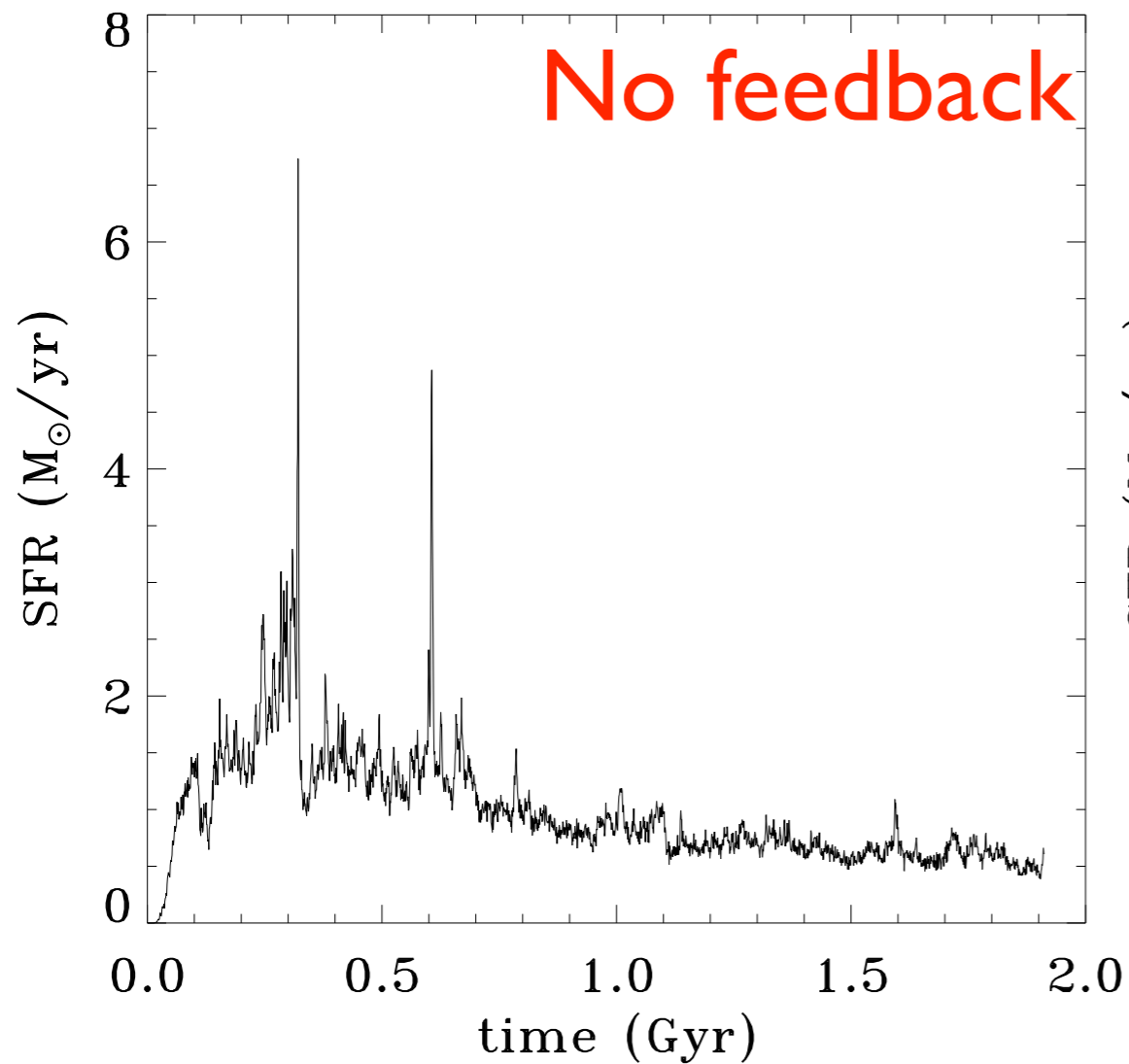
Including baryons | **The “Small Scale Crisis” ...**

T13  **2 key observational predictions:**

Including baryons | The “Small Scale Crisis” ...

T13 \Rightarrow 2 key observational predictions:

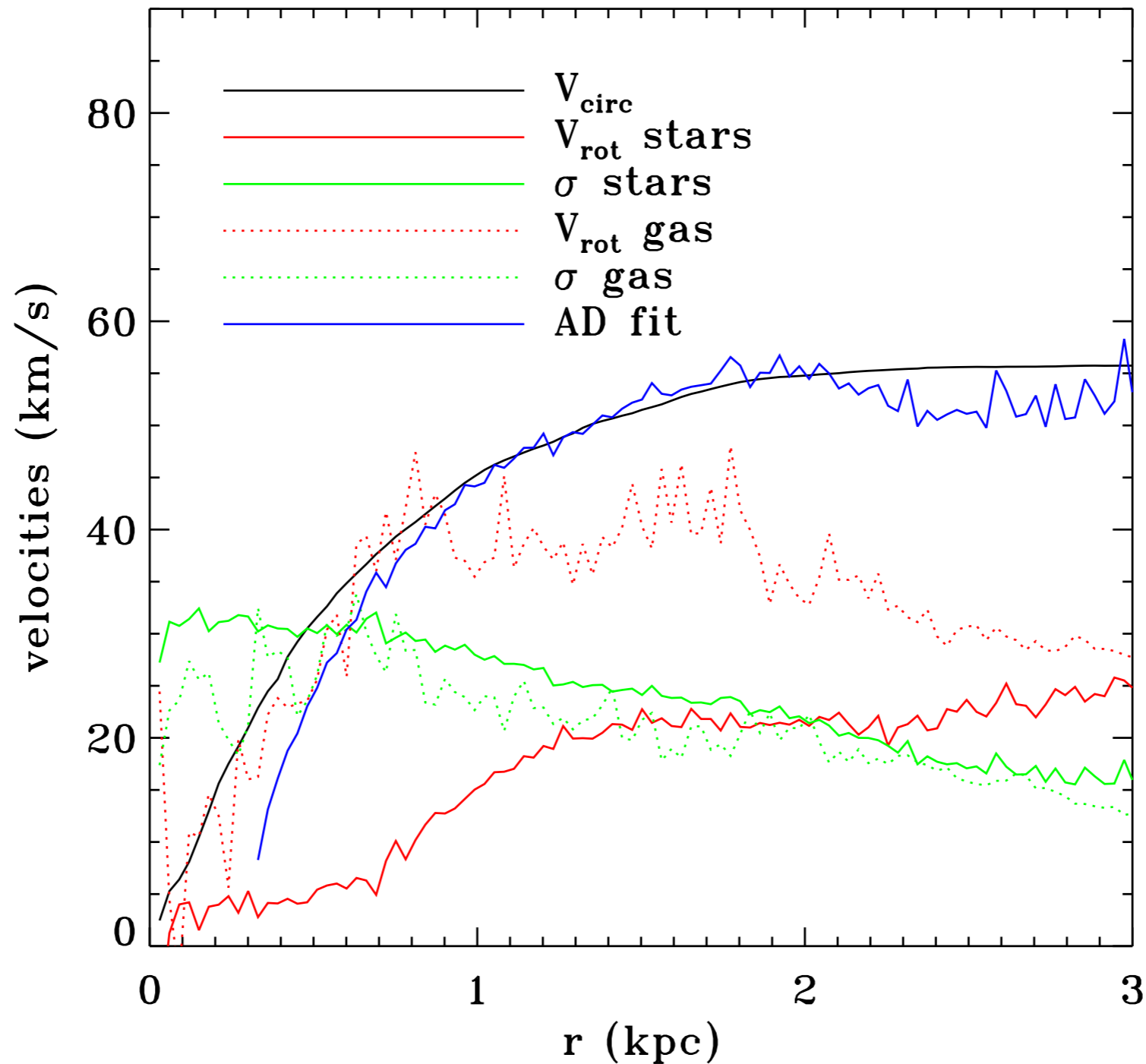
i) Star formation should be bursty



Including baryons | The “Small Scale Crisis” ...

T13 \Rightarrow 2 key observational predictions:

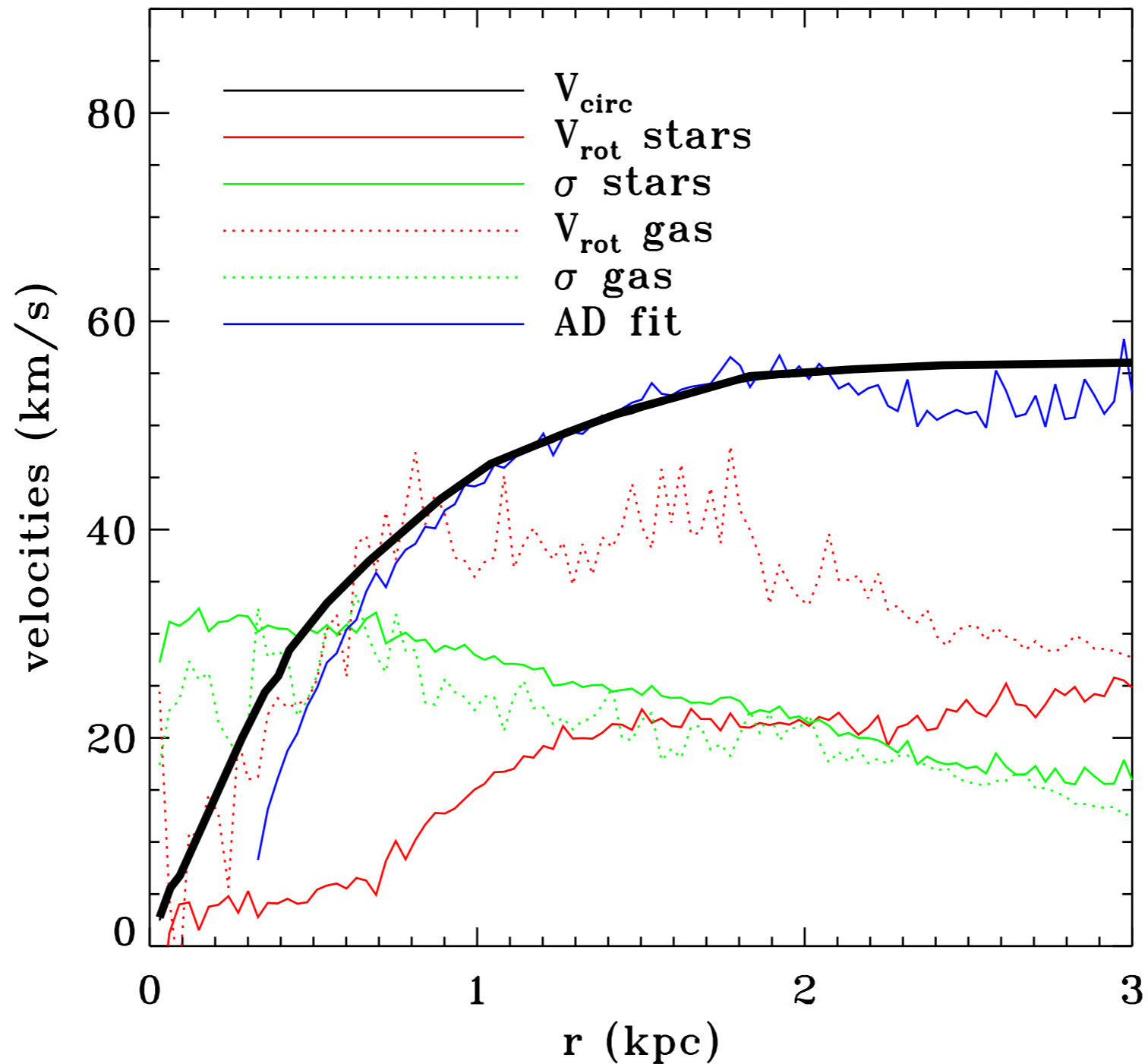
ii) Stars should be heated too



Including baryons | The “Small Scale Crisis” ...

T13 \Rightarrow 2 key observational predictions:

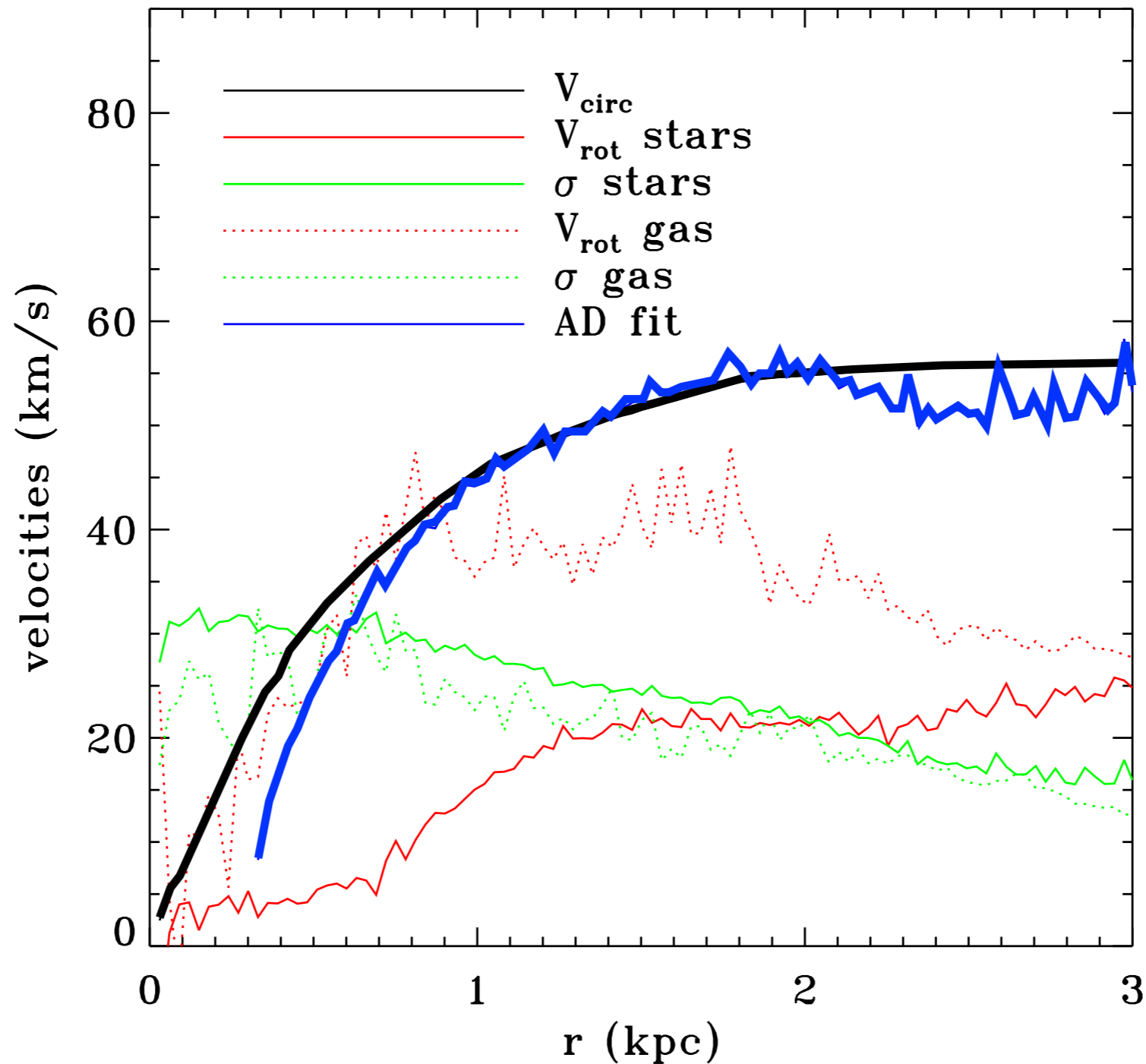
ii) Stars should be heated too



Including baryons | The “Small Scale Crisis” ...

T13 \Rightarrow 2 key observational predictions:

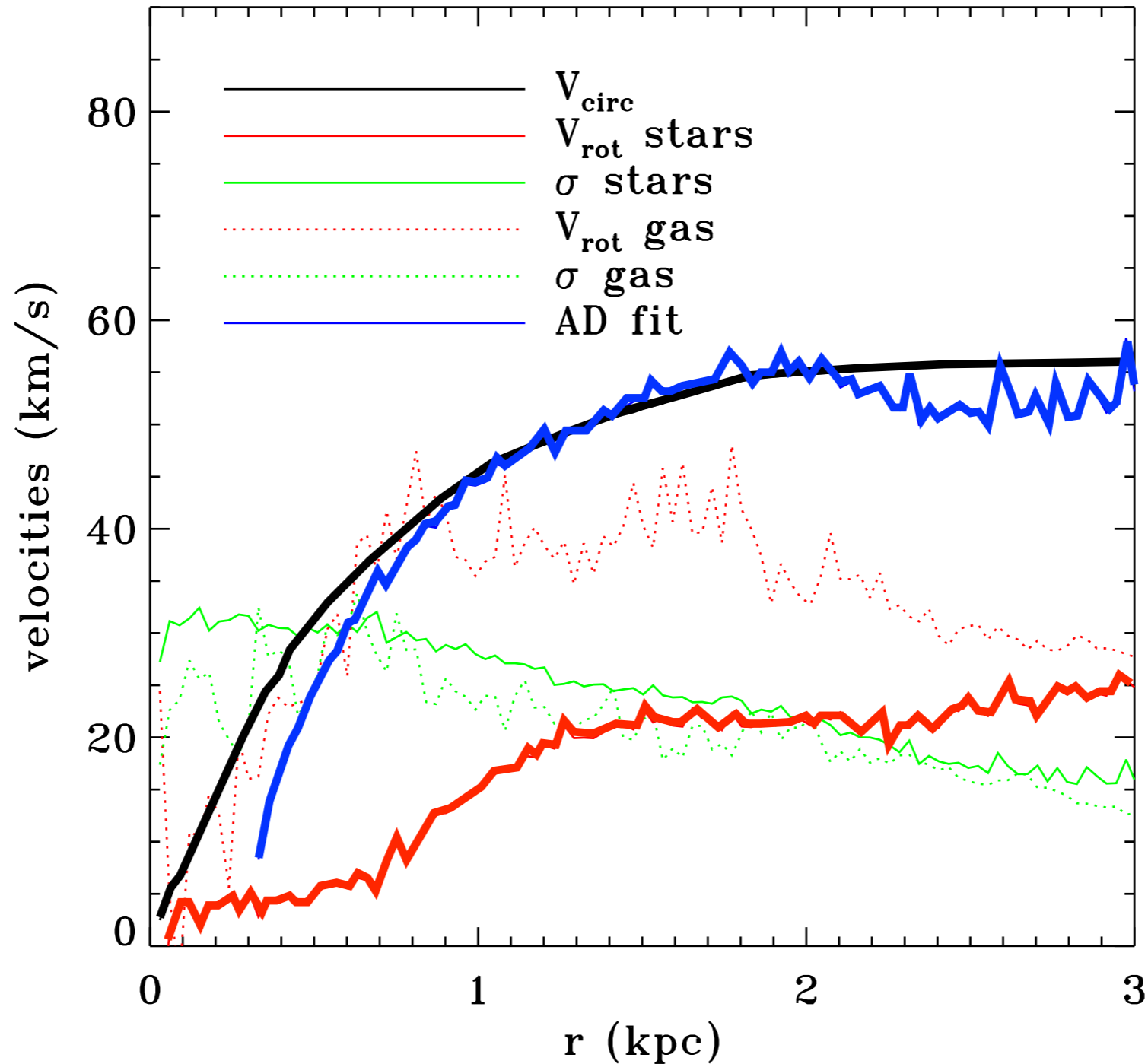
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Including baryons | The “Small Scale Crisis” ...

T13 \Rightarrow 2 key observational predictions:

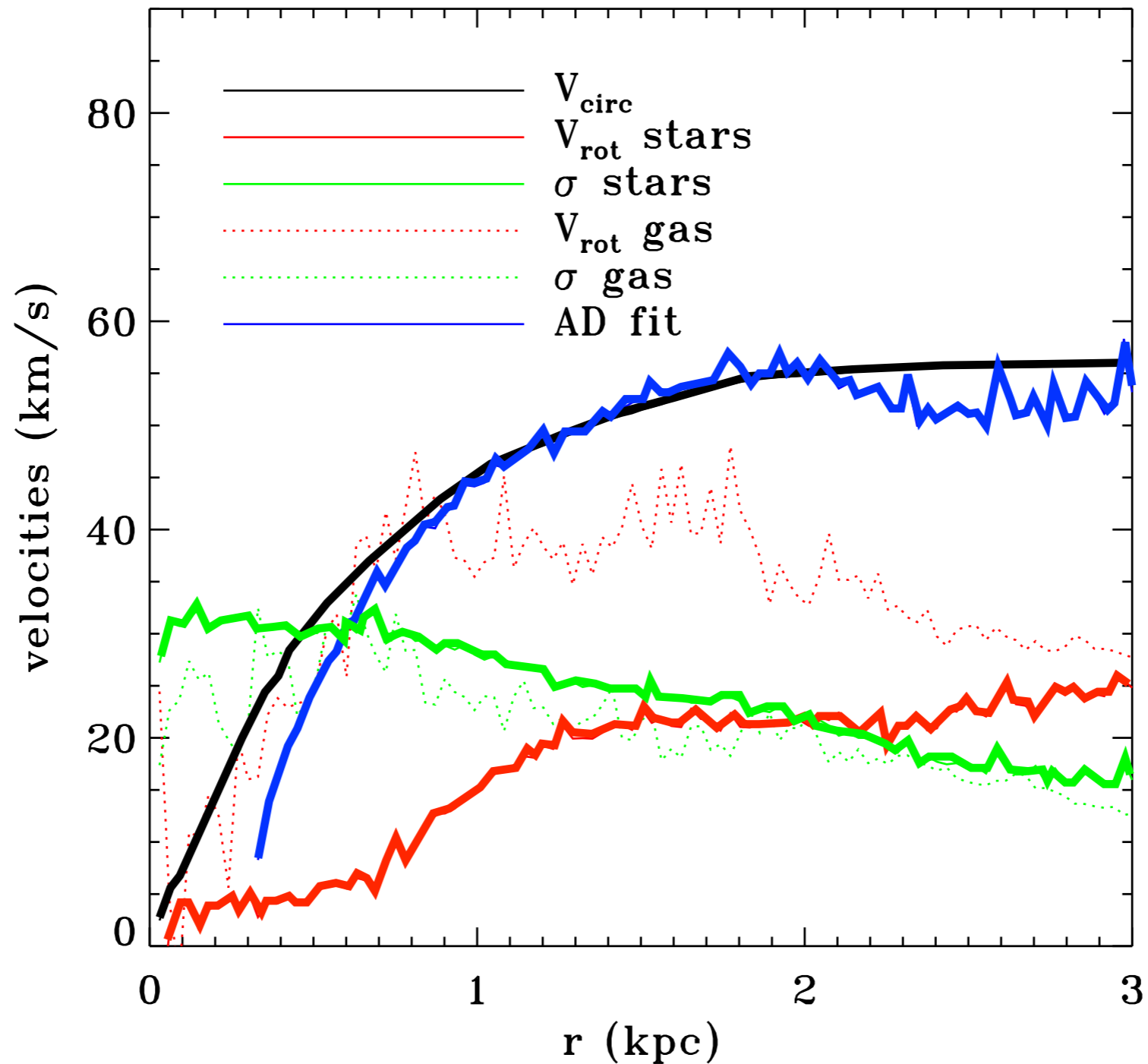
ii) Stars should be heated too



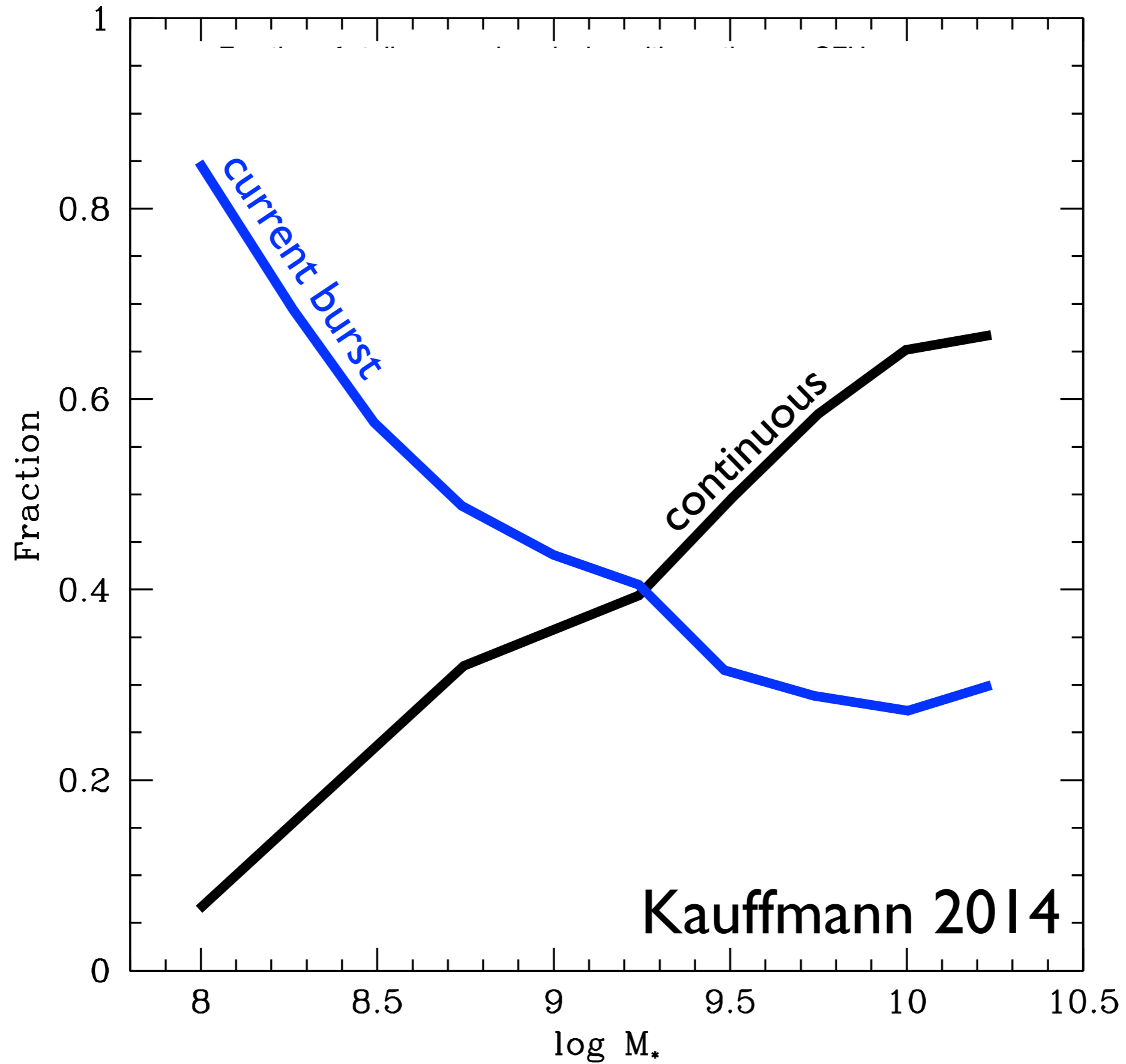
Including baryons | The “Small Scale Crisis” ...

T13 \Rightarrow 2 key observational predictions:

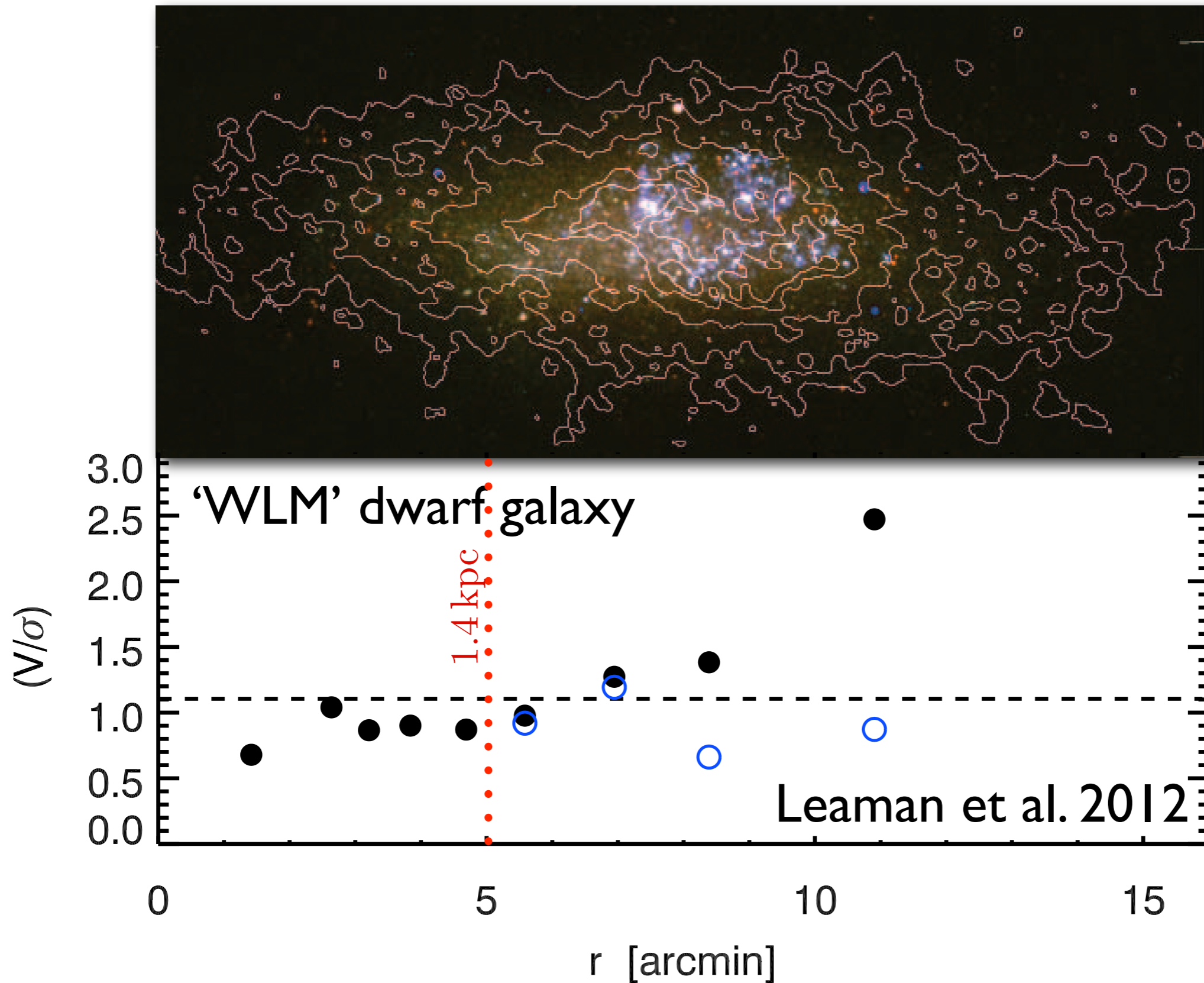
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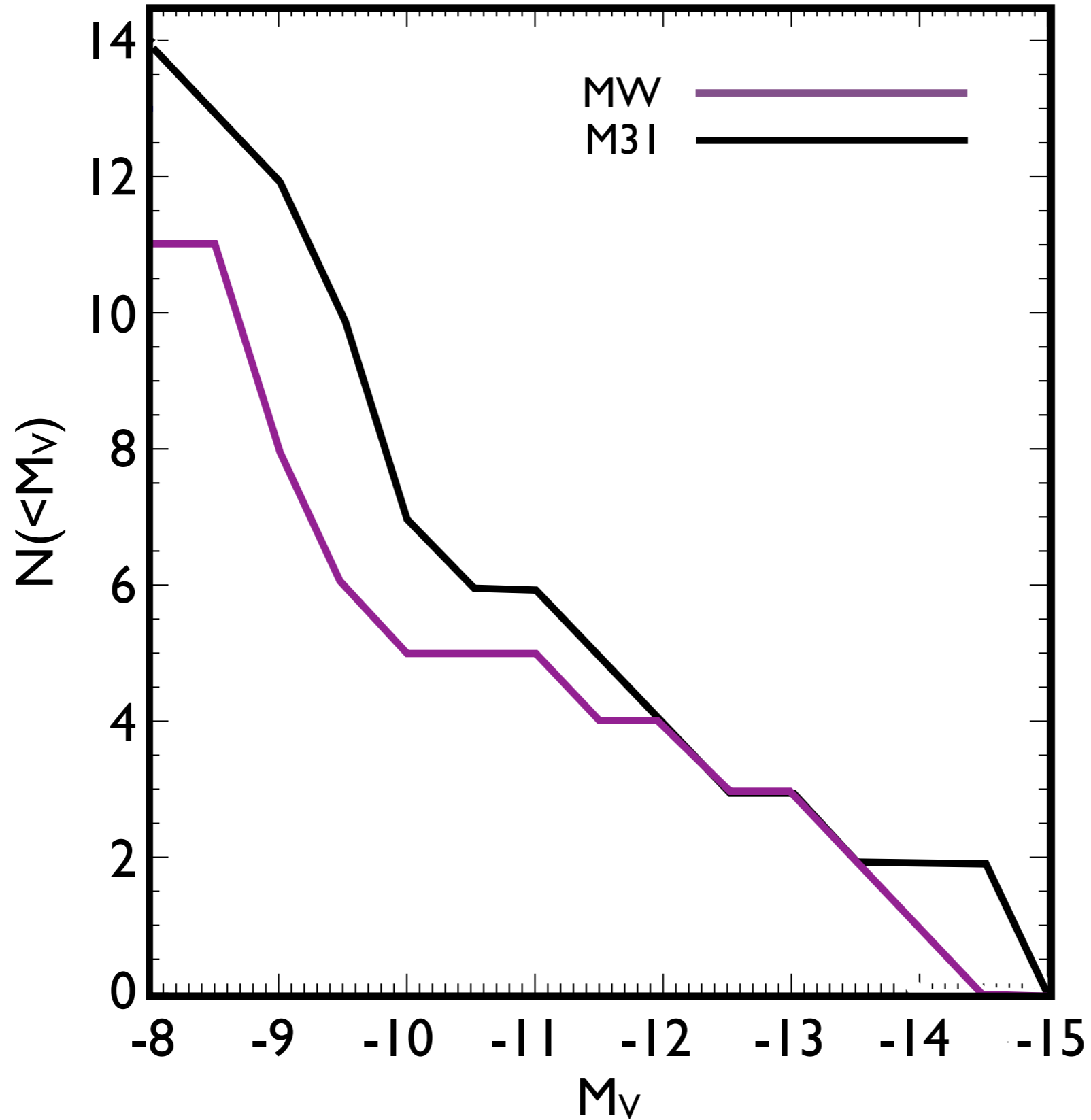
Including baryons | The “Small Scale Crisis” ...



Including baryons | The “Small Scale Crisis” ...

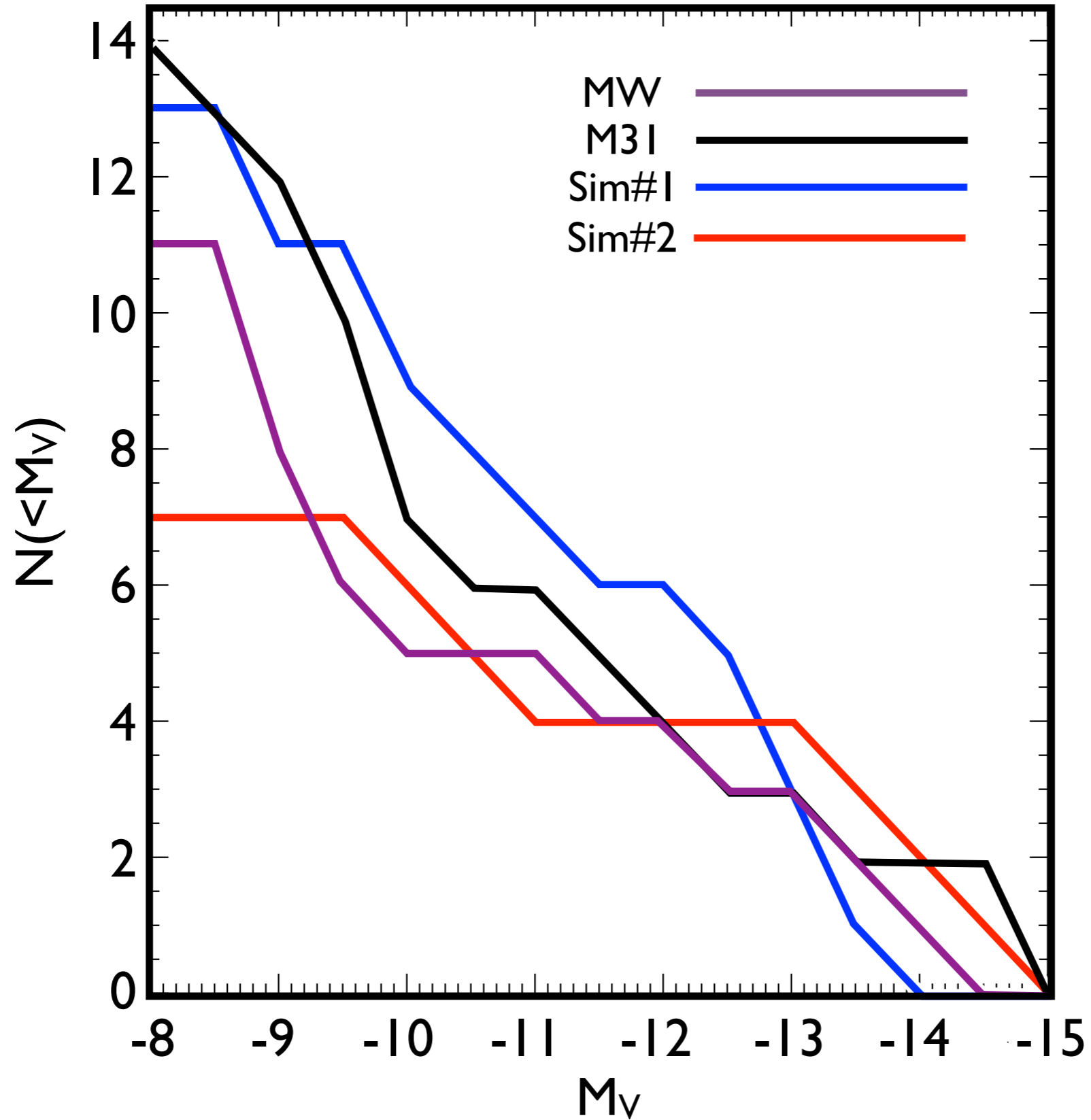


Including baryons | The “Small Scale Crisis” ...



Zolotov, Brooks et al. 2012/13; and see Read et al. 2006; Peñarrubia et al. 2010

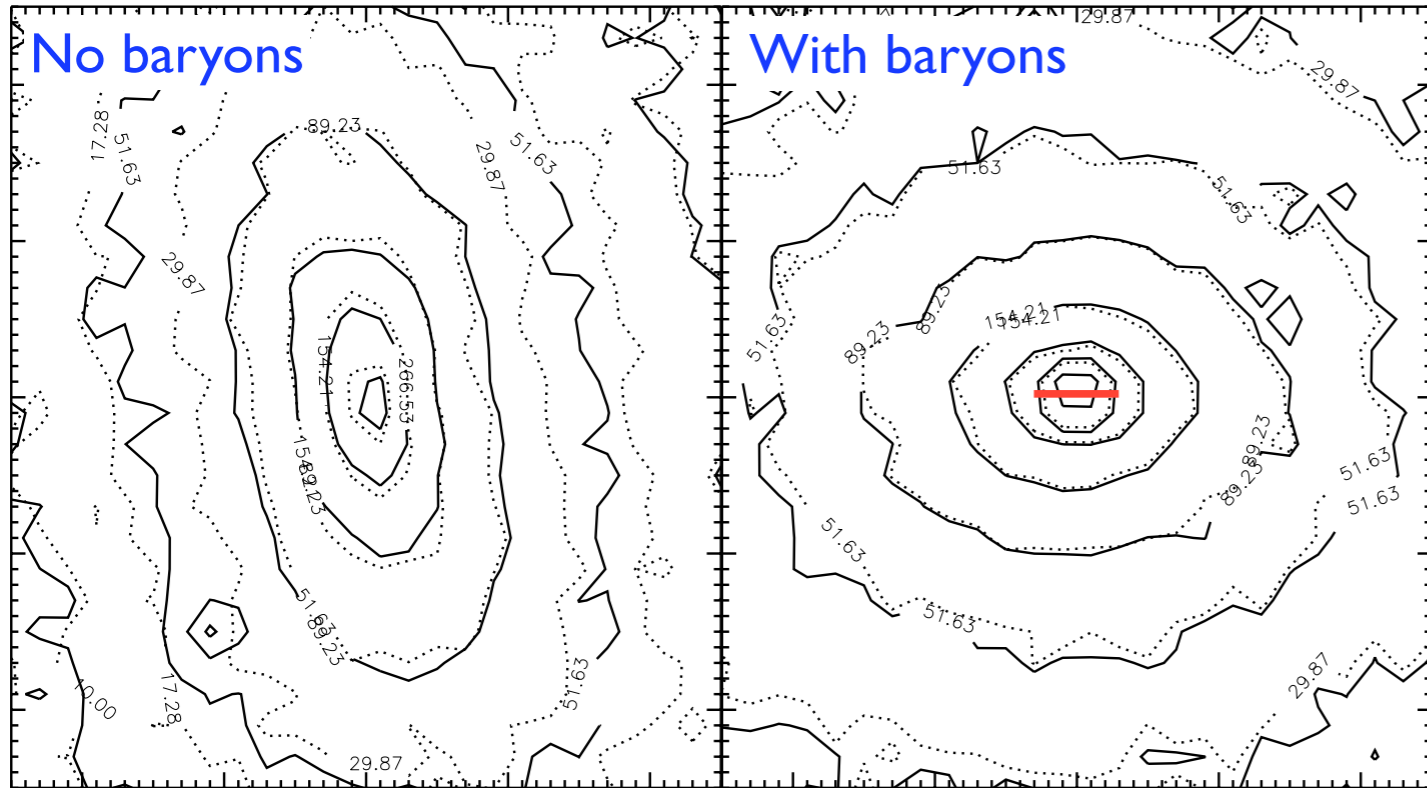
Including baryons | The “Small Scale Crisis” ...



Including baryons | Other changes

Including baryons | Other changes

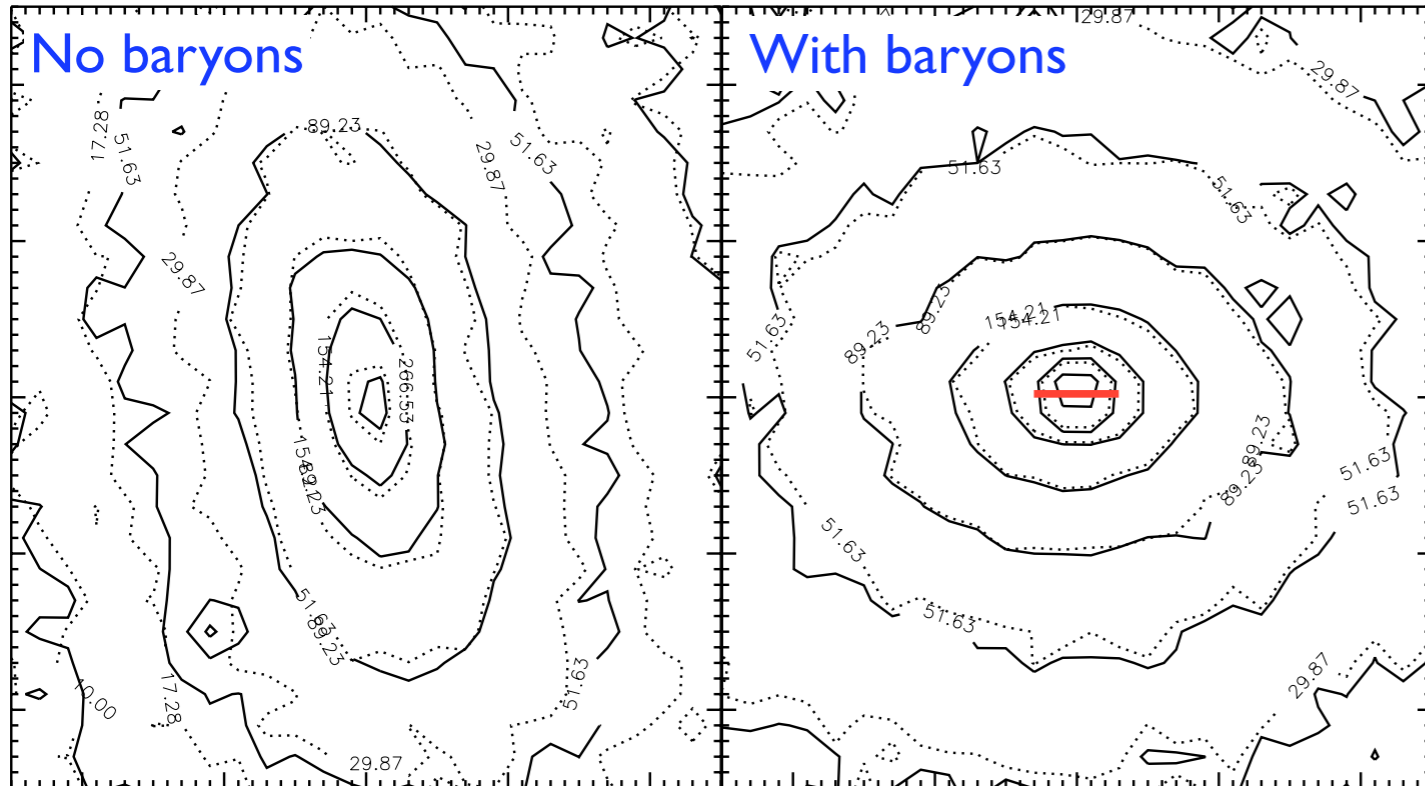
Shape change



Katz & Gunn 1991; Dubinski 1994; Debattista et al. 2008; Read et al. 2009

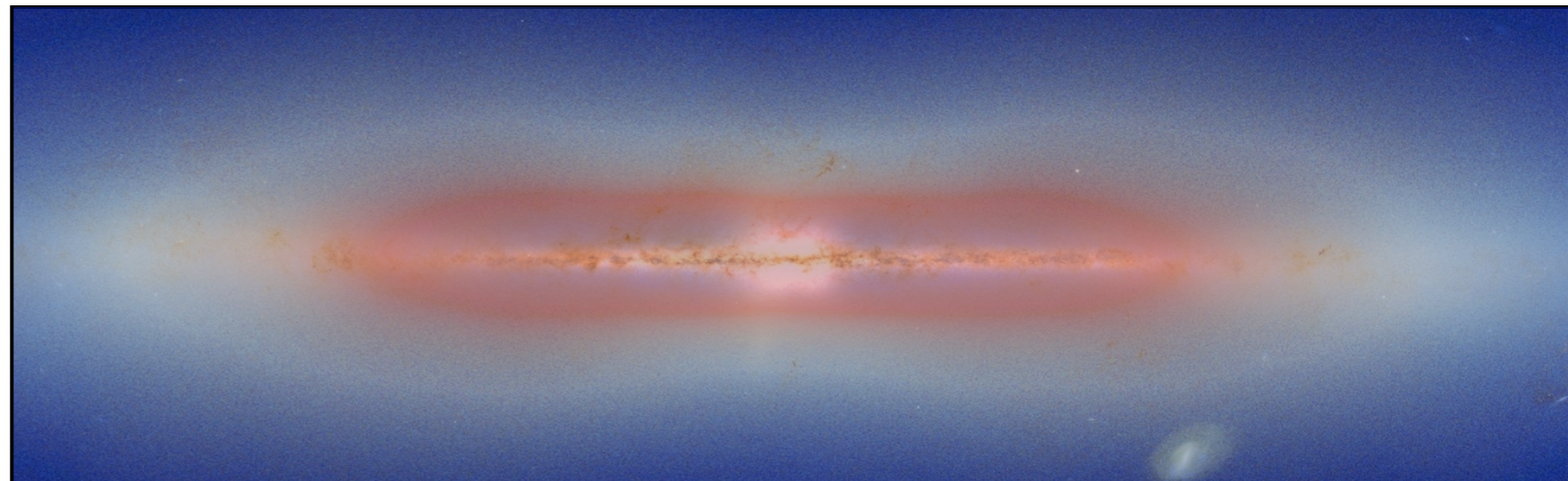
Including baryons | Other changes

Shape change



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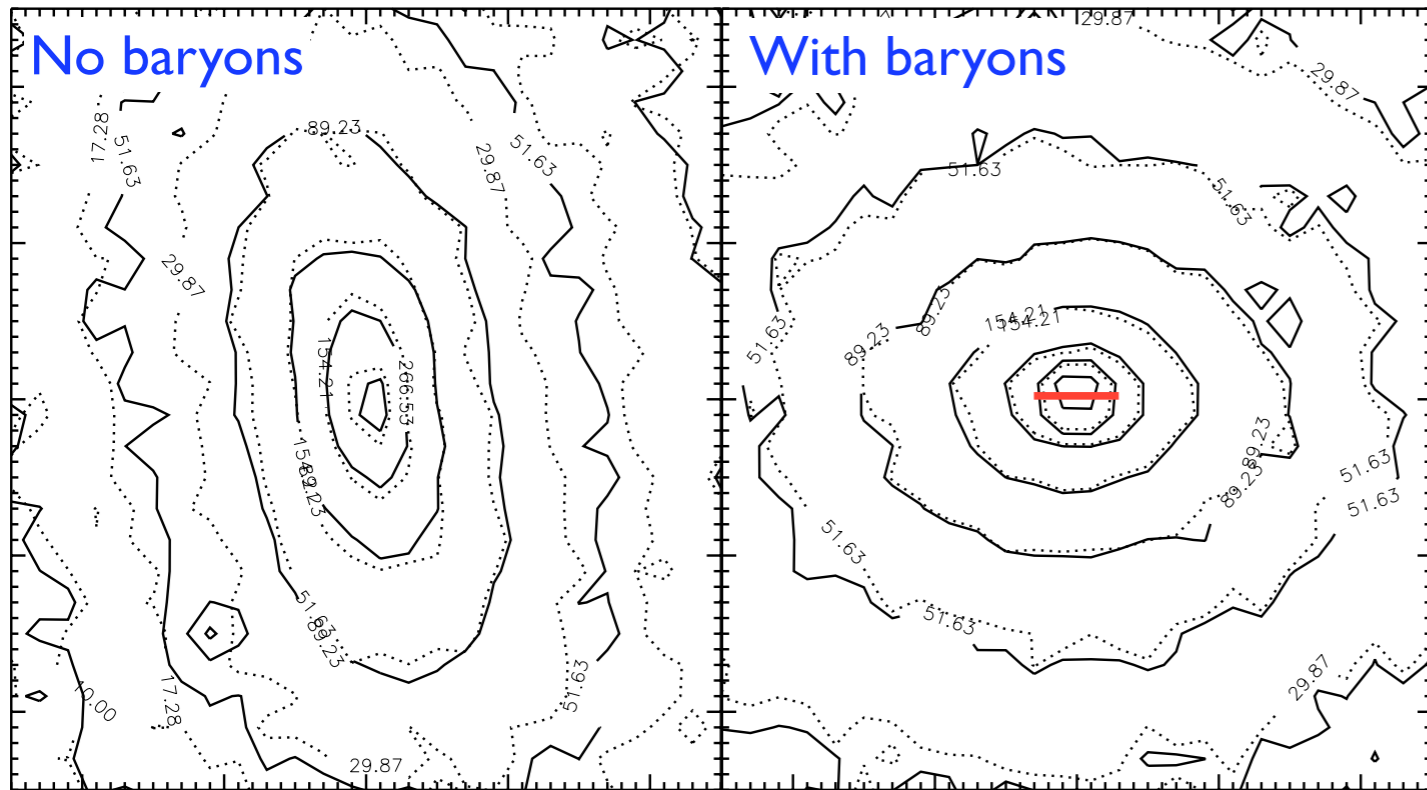
Dark discs



Lake 1989; Read et al. 2008/9

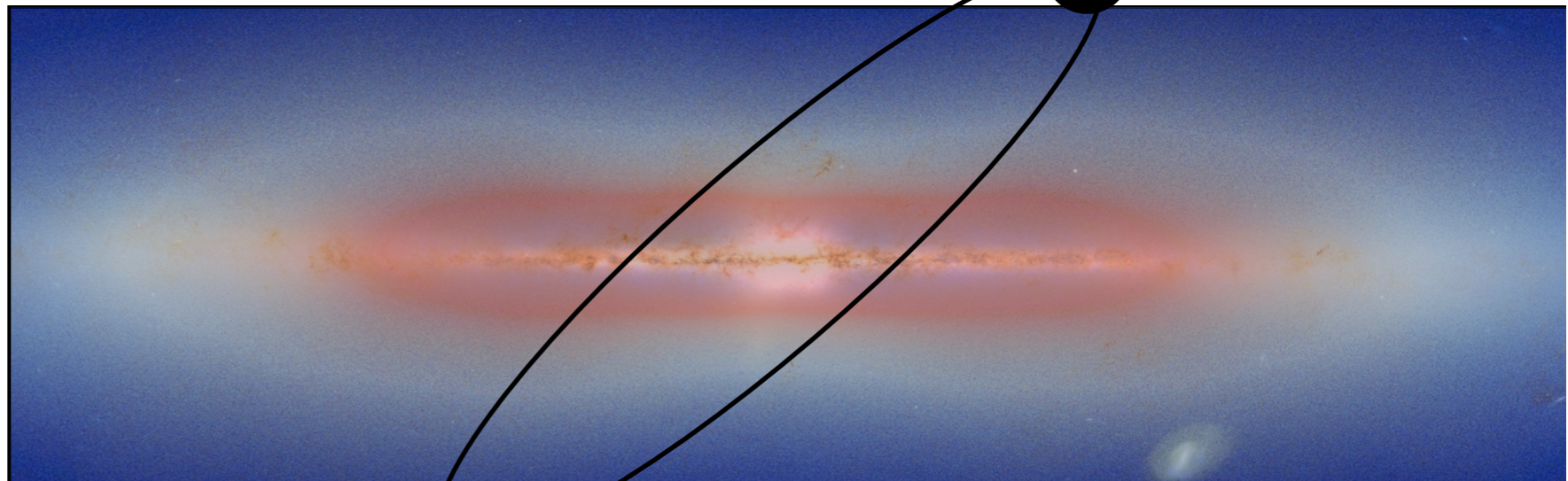
Including baryons | Other changes

Shape change



Katz & Gunn 1991; Dubinski 1994; Debattista et al. 2008; Read et al. 2009

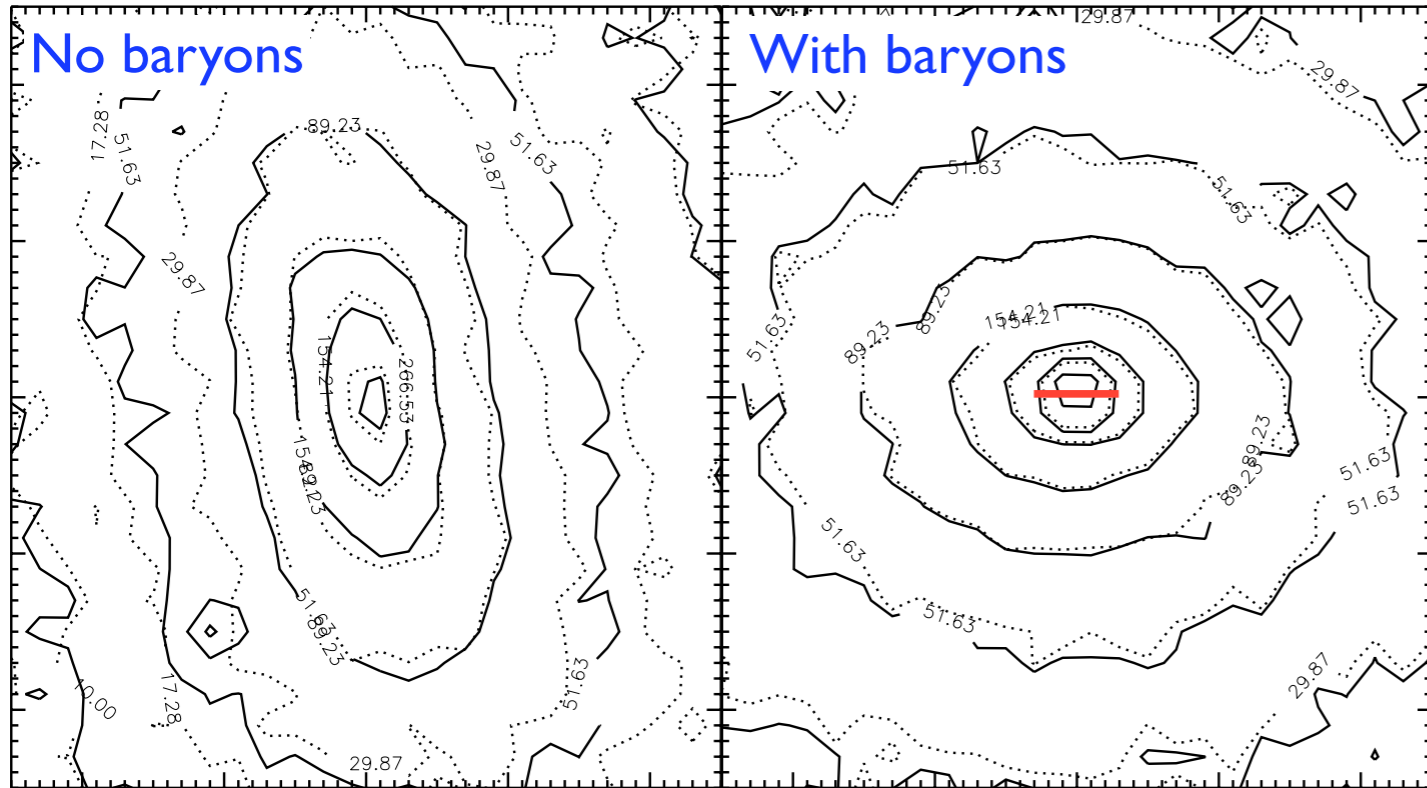
Dark discs



Lake 1989; Read et al. 2008/9

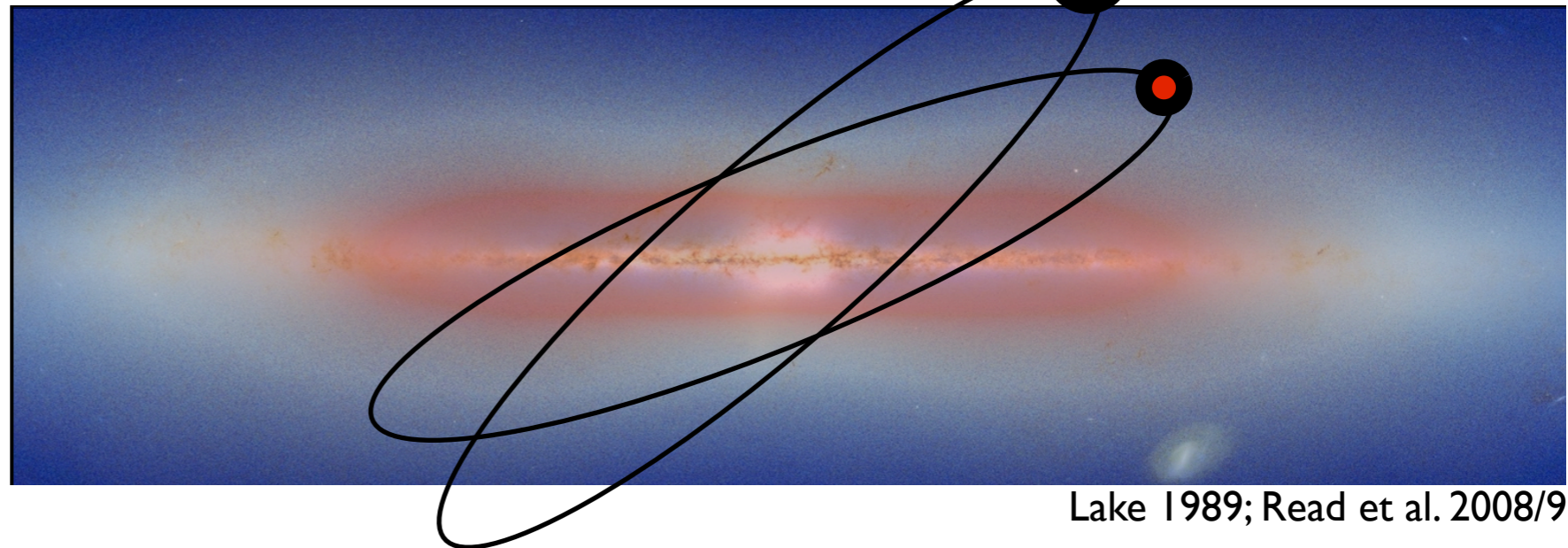
Including baryons | Other changes

Shape change



Katz & Gunn 1991; Dubinski 1994; Debattista et al. 2008; Read et al. 2009

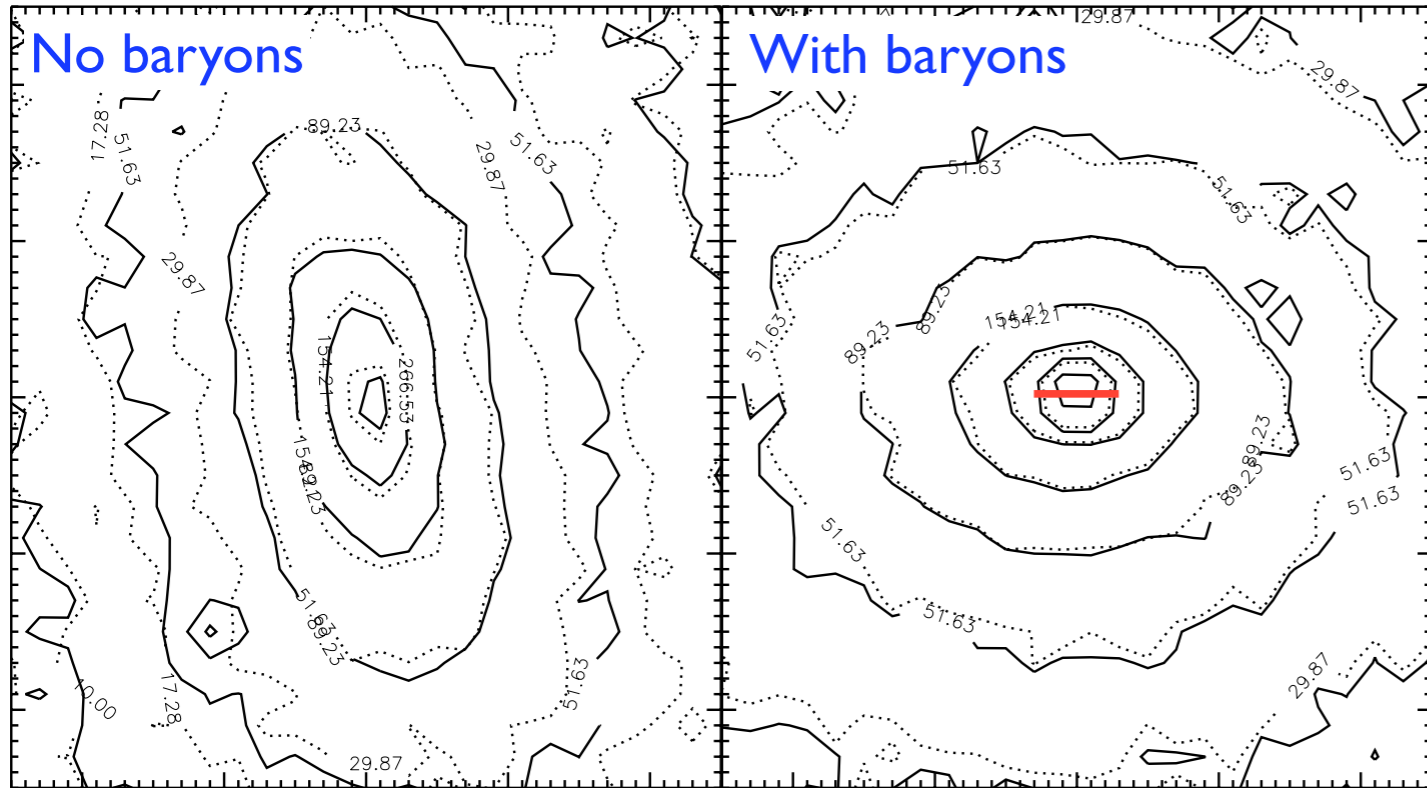
Dark discs



Lake 1989; Read et al. 2008/9

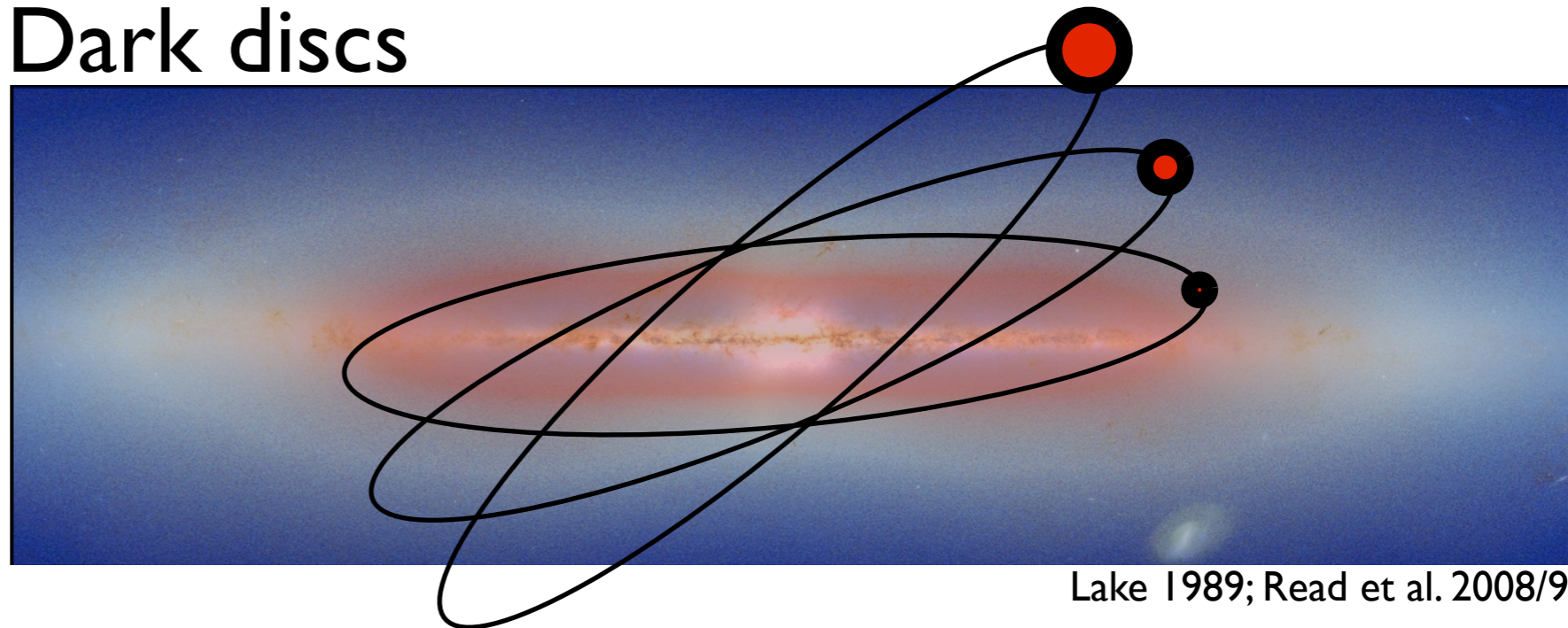
Including baryons | Other changes

Shape change



Katz & Gunn 1991; Dubinski 1994; Debattista et al. 2008; Read et al. 2009

Dark discs

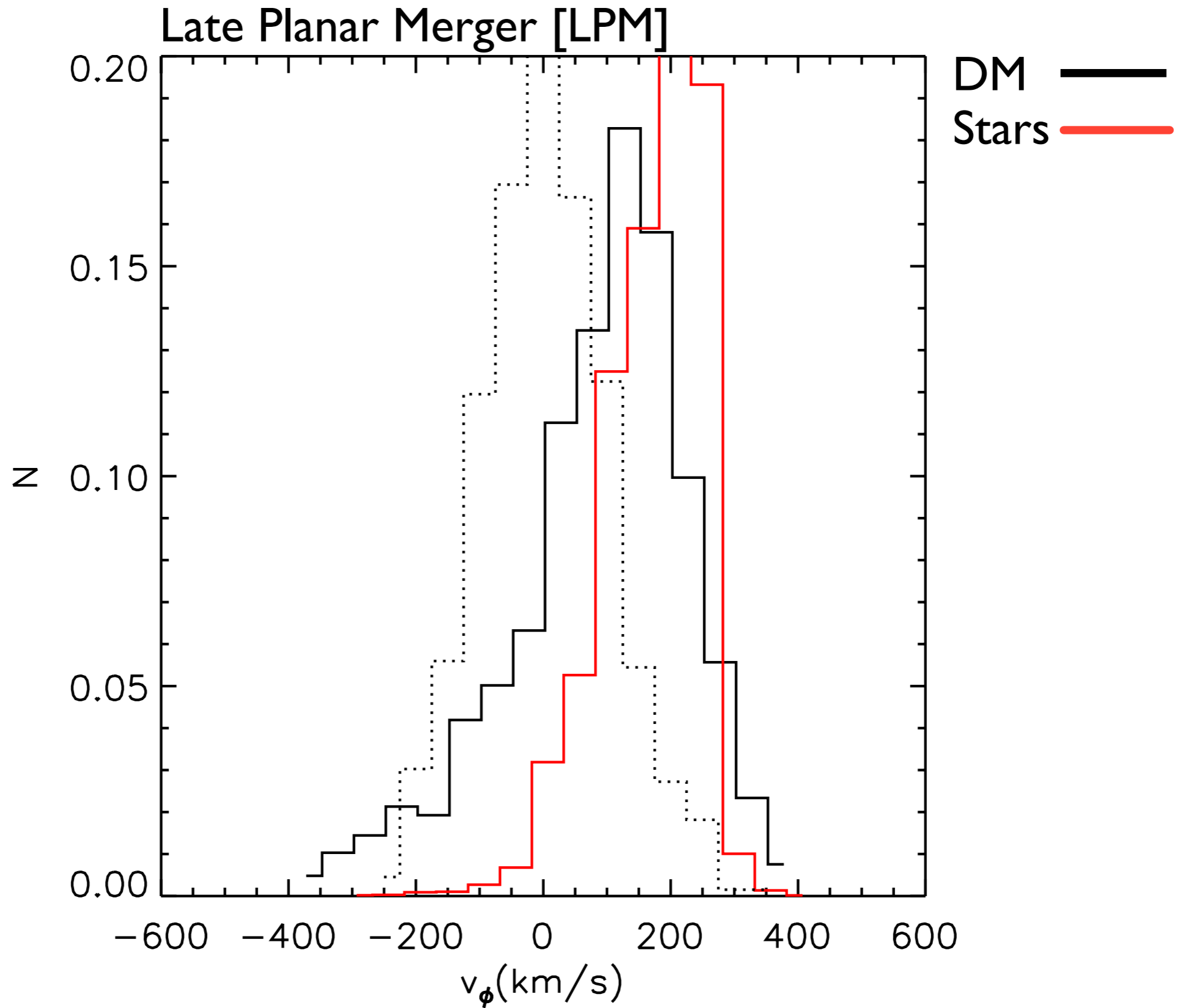


Lake 1989; Read et al. 2008/9

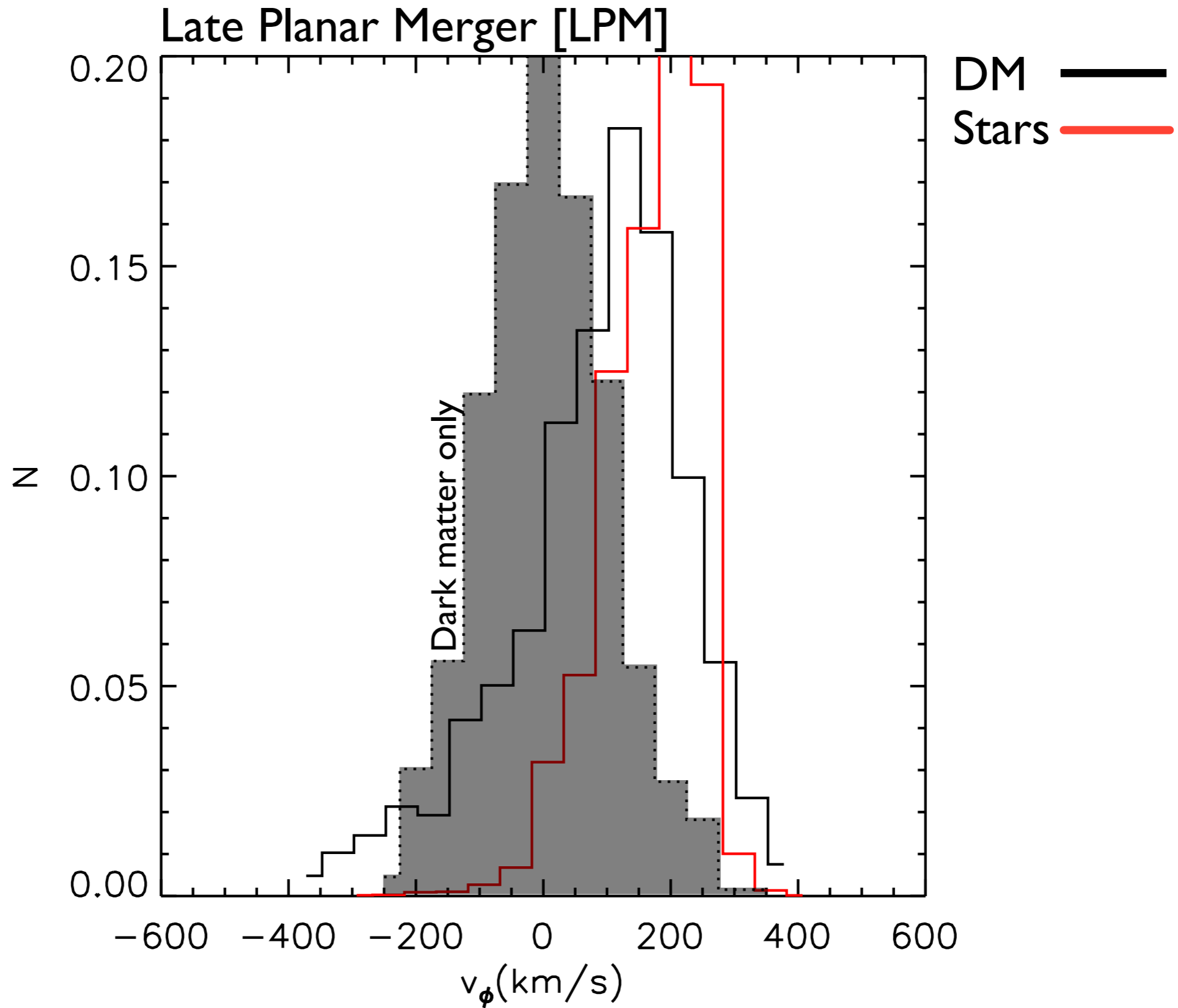
Including baryons | Dark discs

Stellar disc

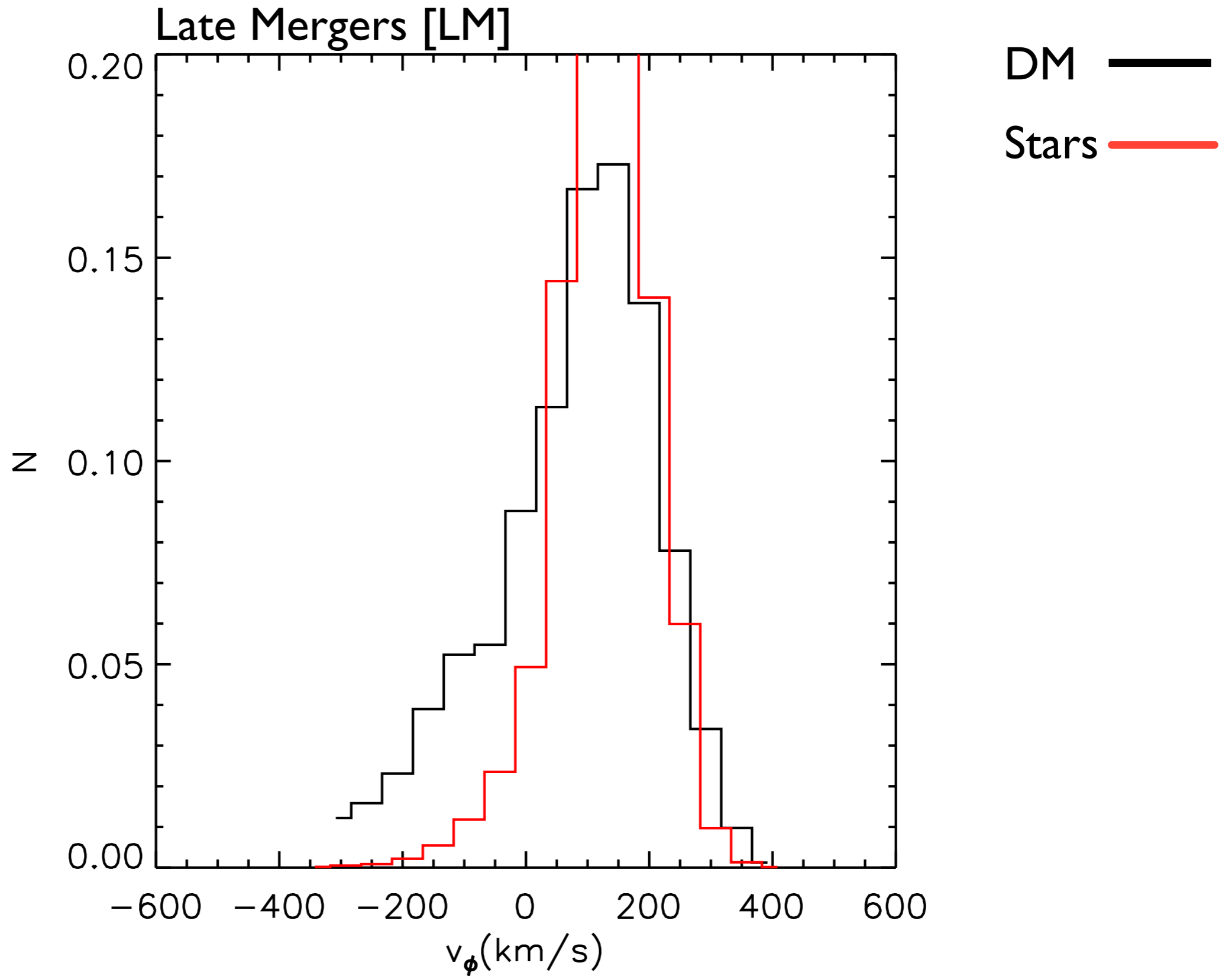
Including baryons | Dark discs



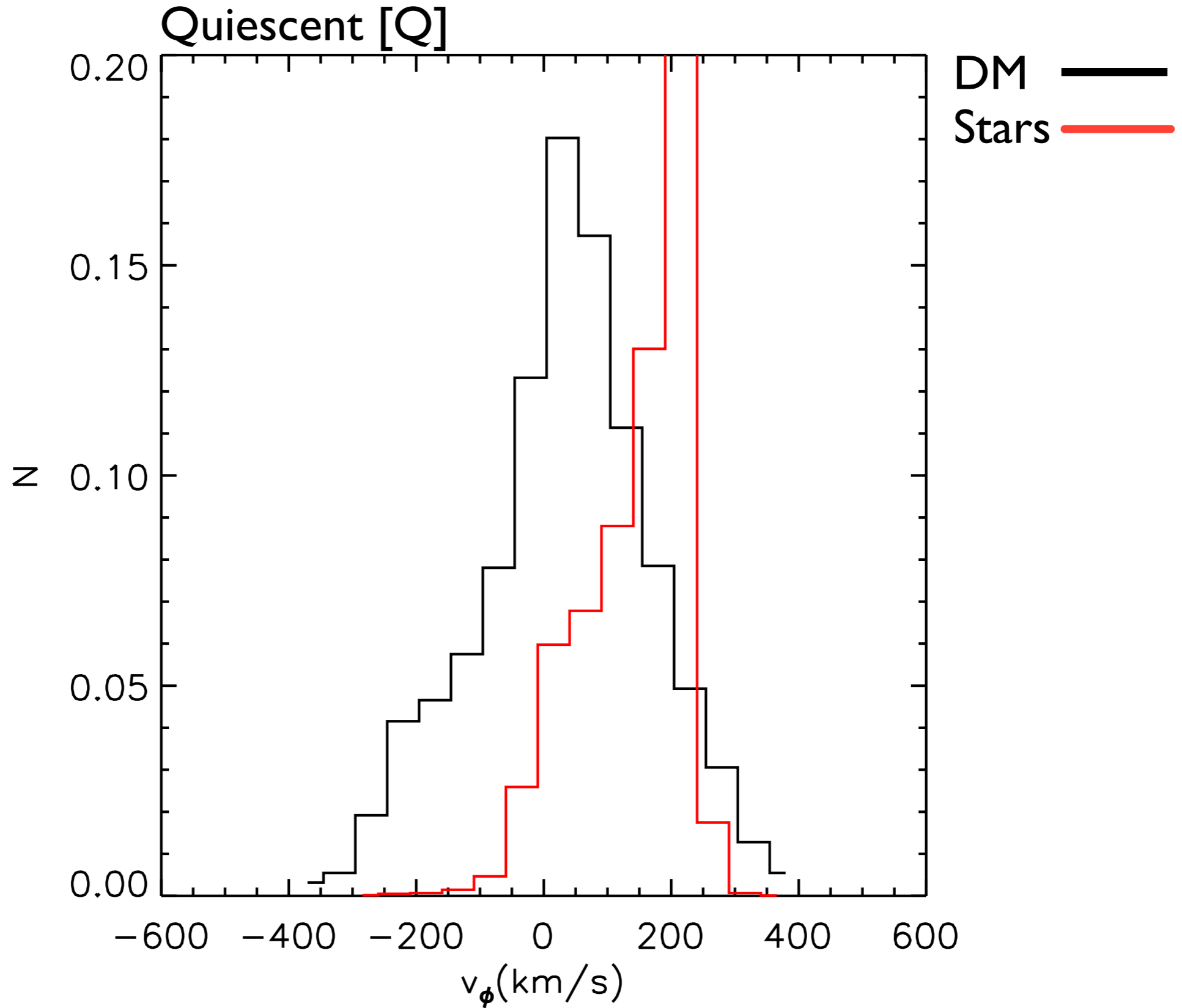
Including baryons | Dark discs



Including baryons | Dark discs



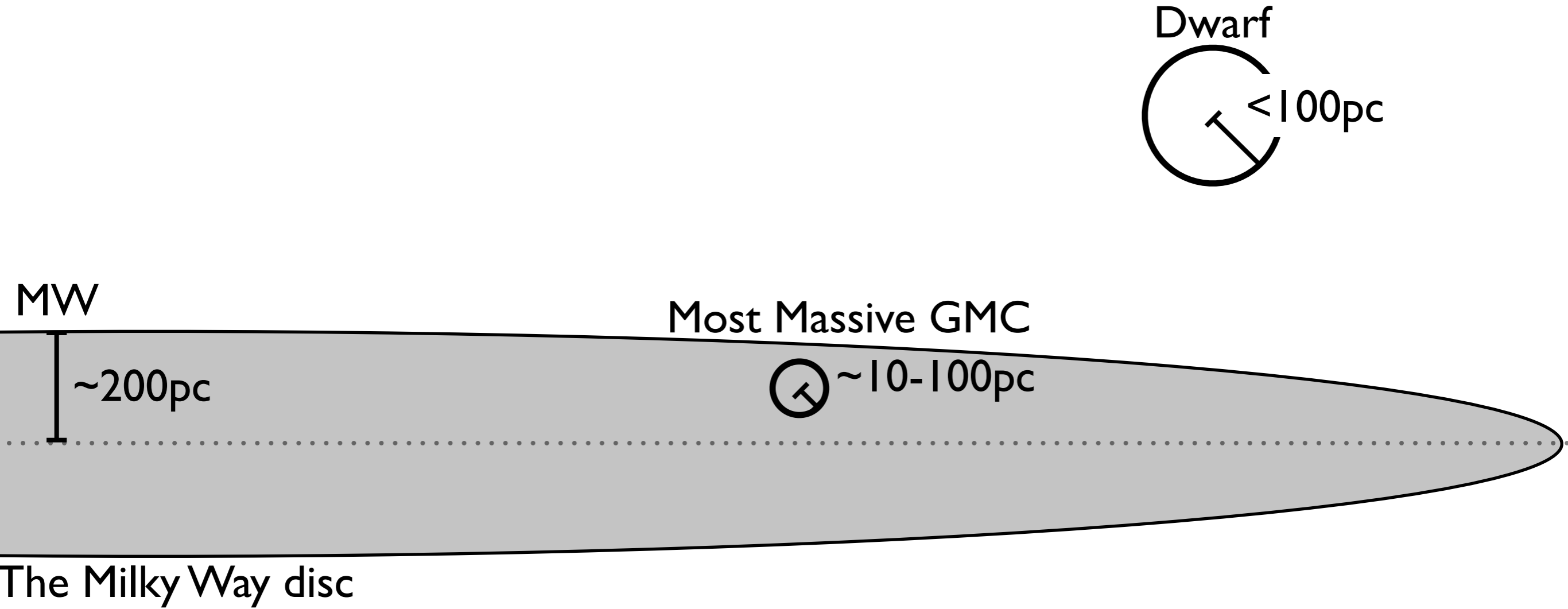
Including baryons | Dark discs



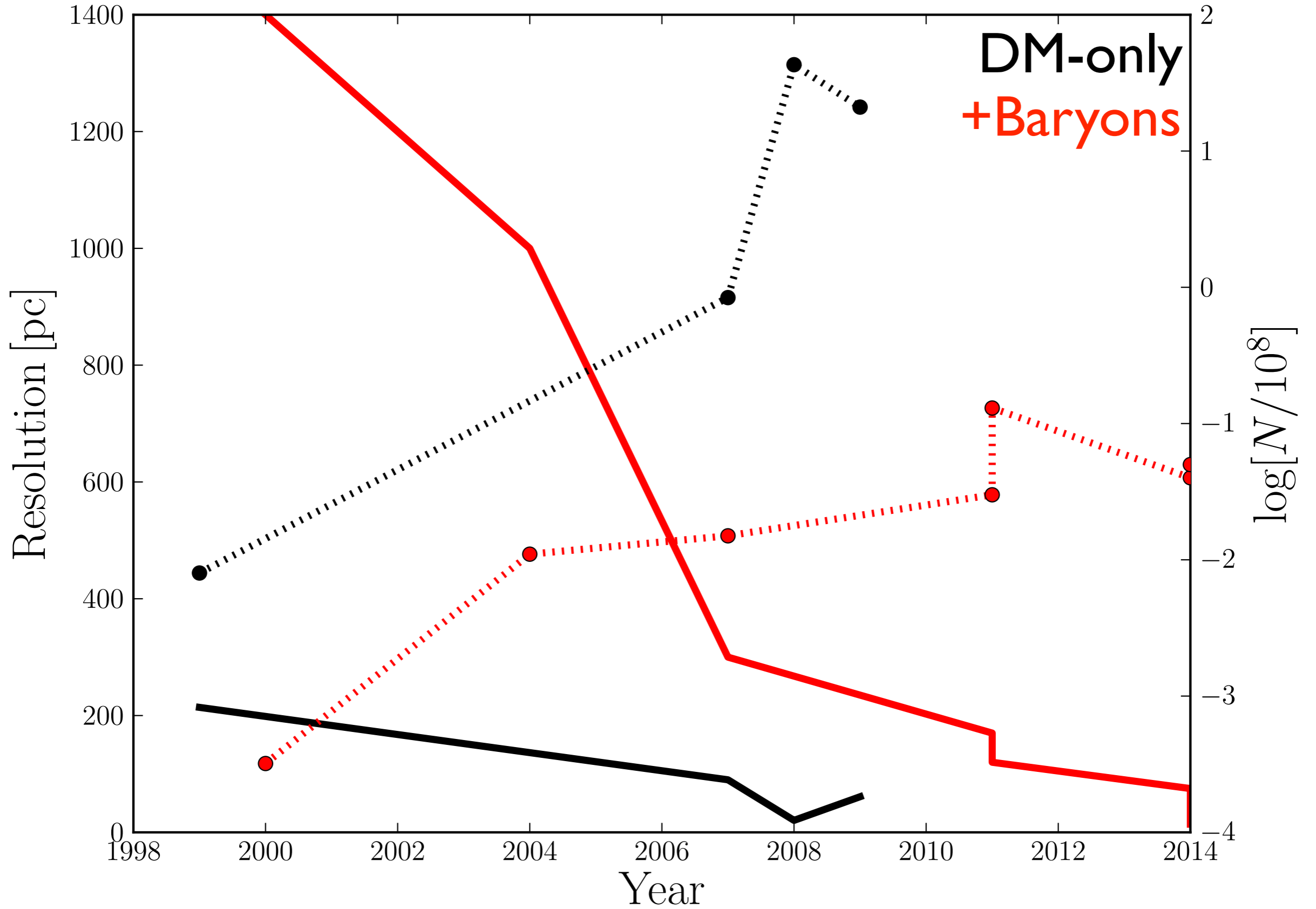
Ab Initio

[Towards *predictive* simulations with baryons]

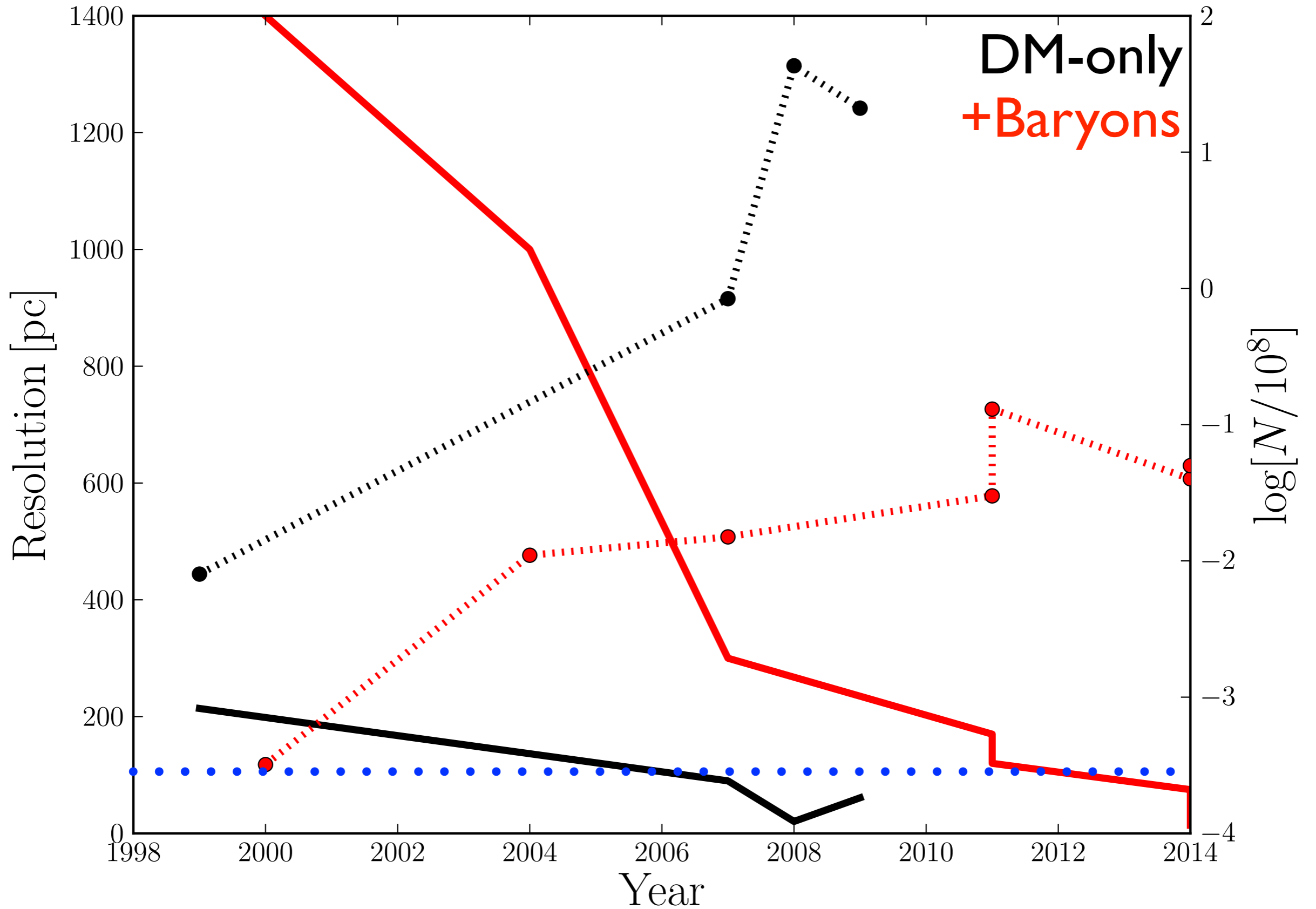
Towards *predictive* simulations with baryons



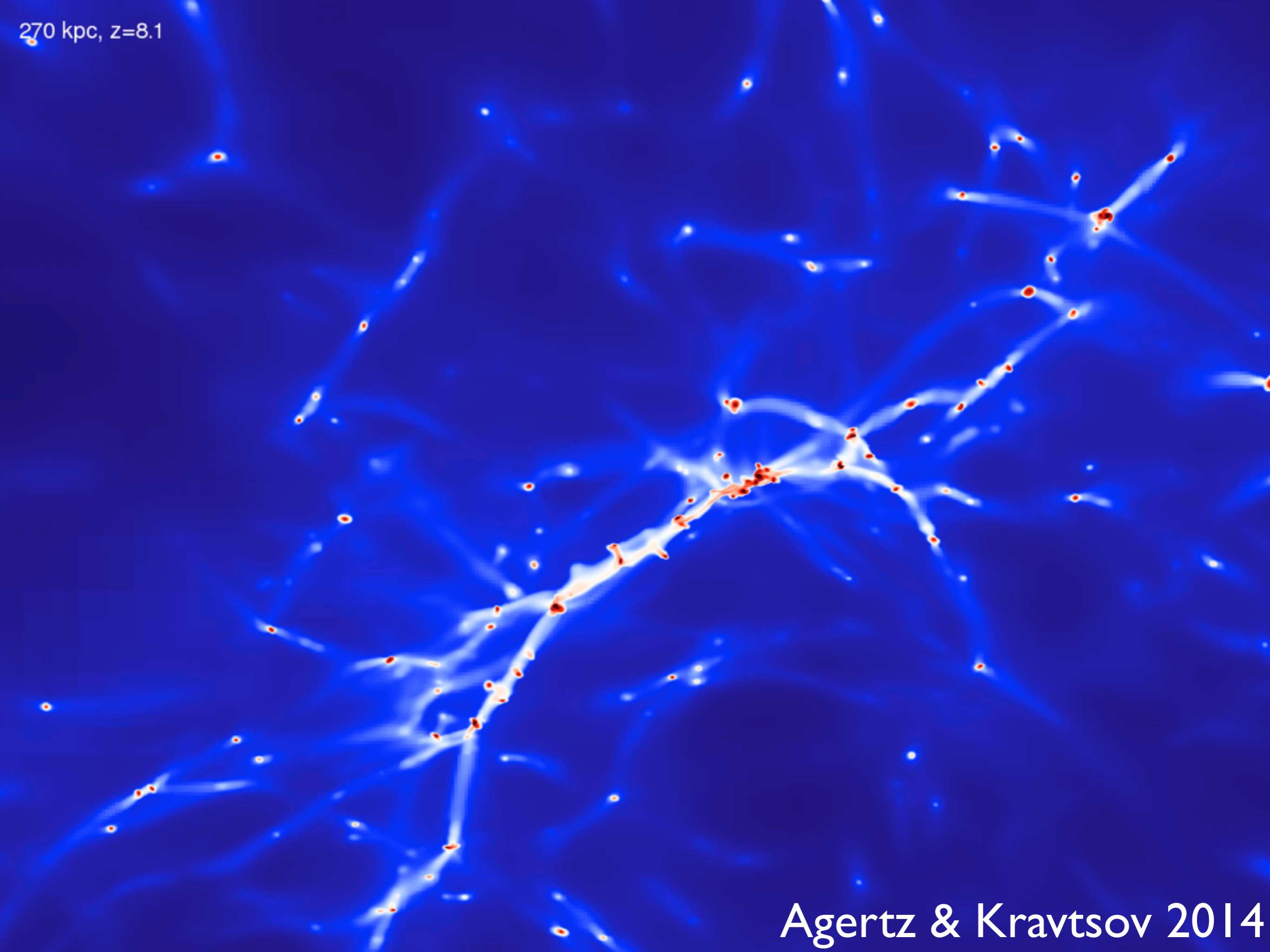
Towards *predictive* simulations with baryons



Towards *predictive* simulations with baryons

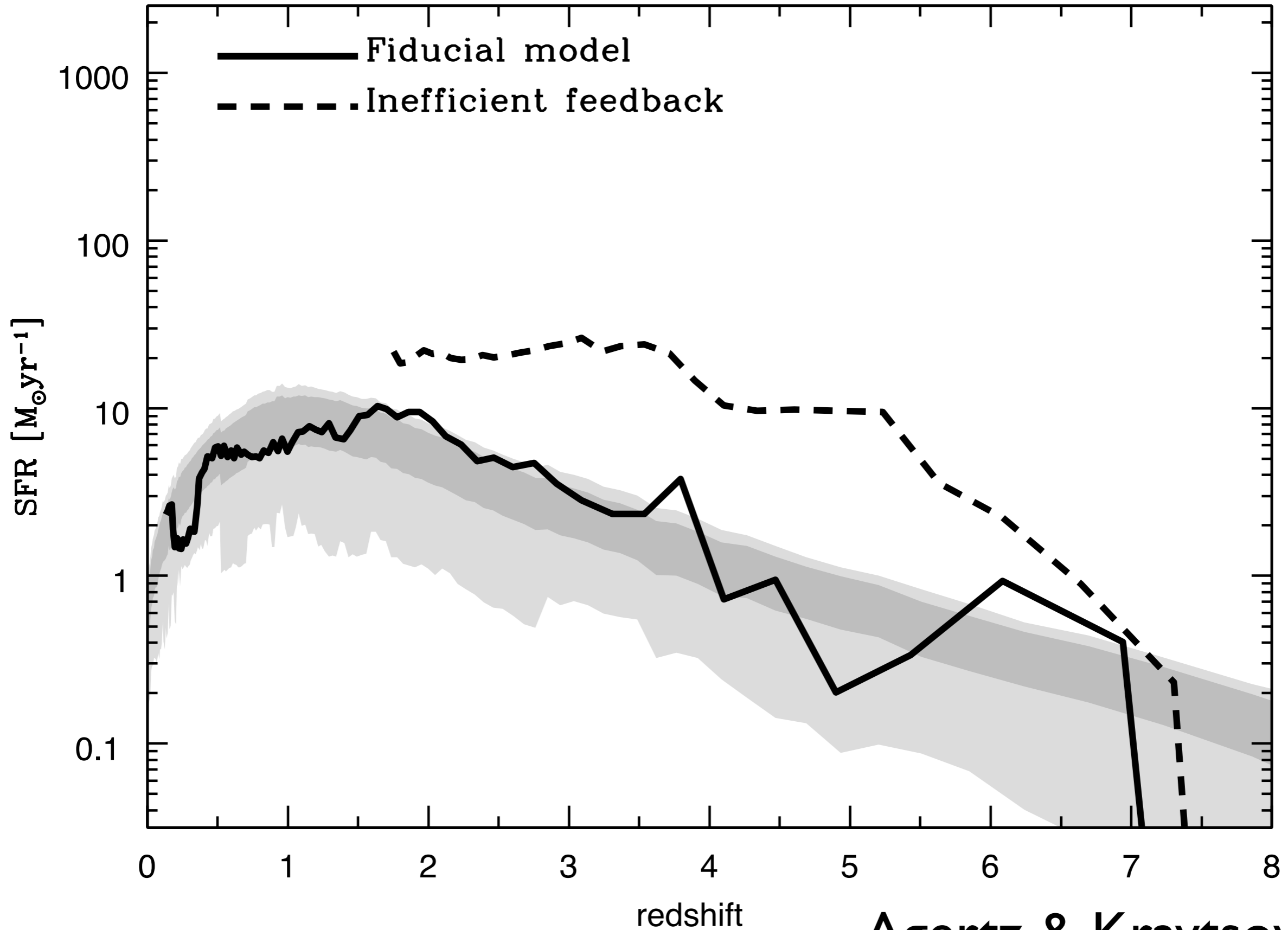


270 kpc, $z=8.1$

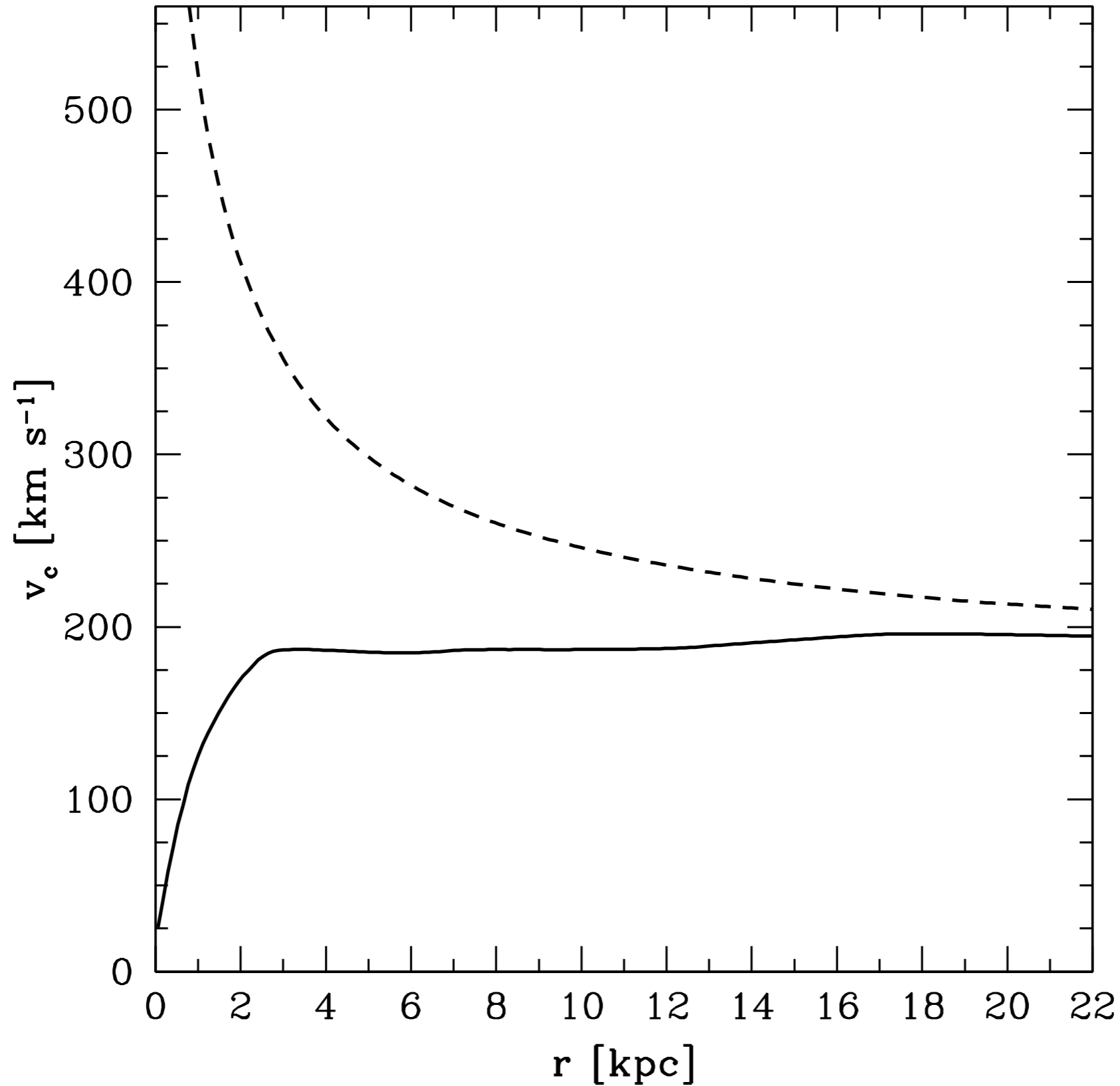


Agertz & Kravtsov 2014

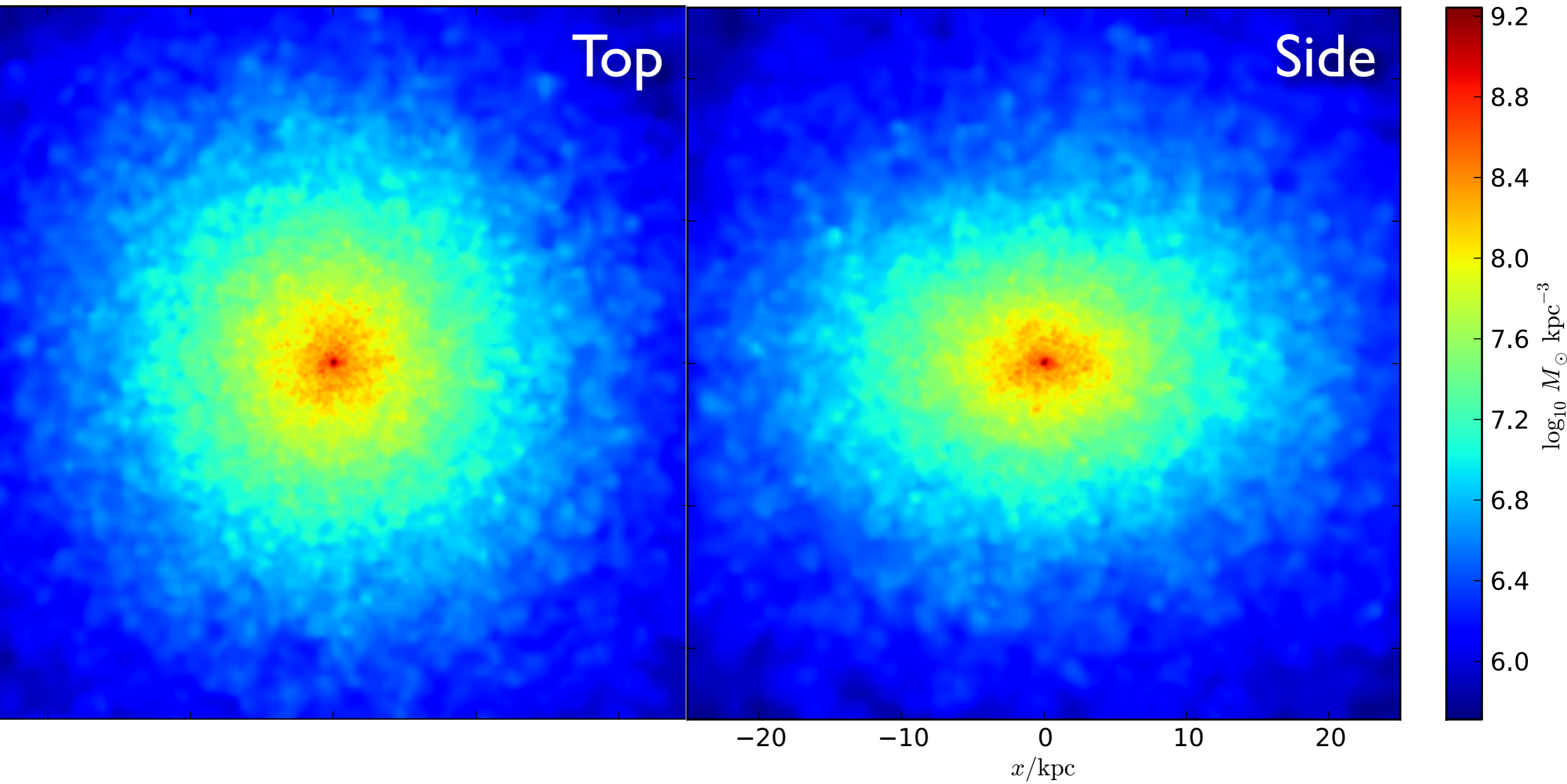
Towards *predictive* simulations with baryons



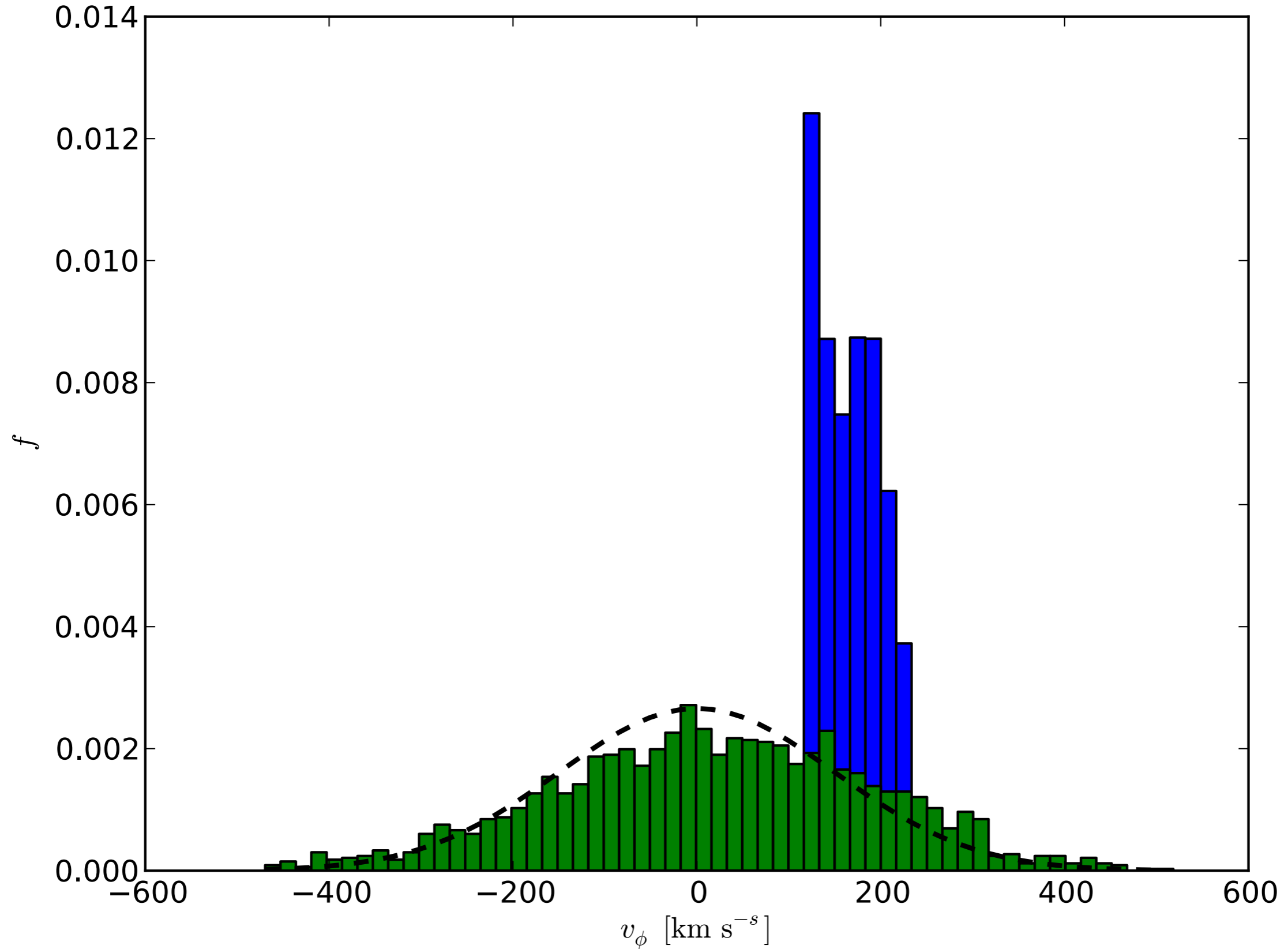
Towards *predictive* simulations with baryons



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Towards *predictive* simulations with baryons



Conclusions

- Cold Dark Matter “DM-only” simulations are well converged across different codes \Rightarrow excellent match to large scale structure
- WDM simulations are more problematic, but solutions are on the way ... watch this space!
- Including models for baryons in the Universe can significantly alter the results from structure formation simulations:
 - Triaxial “halos” \Rightarrow Oblate/round halos.
 - Cuspy dark matter profiles \Rightarrow Cored dark matter profiles.
 - Cored halos are more easily tidally disrupted \Rightarrow Fewer satellites.
 - An existing stellar disc \Rightarrow An accreted “dark disc”.
- Simulations are rapidly improving and have passed a critical resolution threshold \Rightarrow expect more predictive simulations including baryons soon!