

# *Galaxies on FIRE:*

## Burning up the small-scale crises of $\Lambda$ CDM

Observed Starlight

Molecular



X-Rays

Star Formation

Cosmic evolution

BLUE WATERS

Shea Garrison-Kimmel (Einstein Fellow, Caltech)  
on behalf of Phil Hopkins (Caltech) and the FIRE Collaboration



# What is ~~FIRE~~?

galaxy formation?

## ***Standard paradigm:***

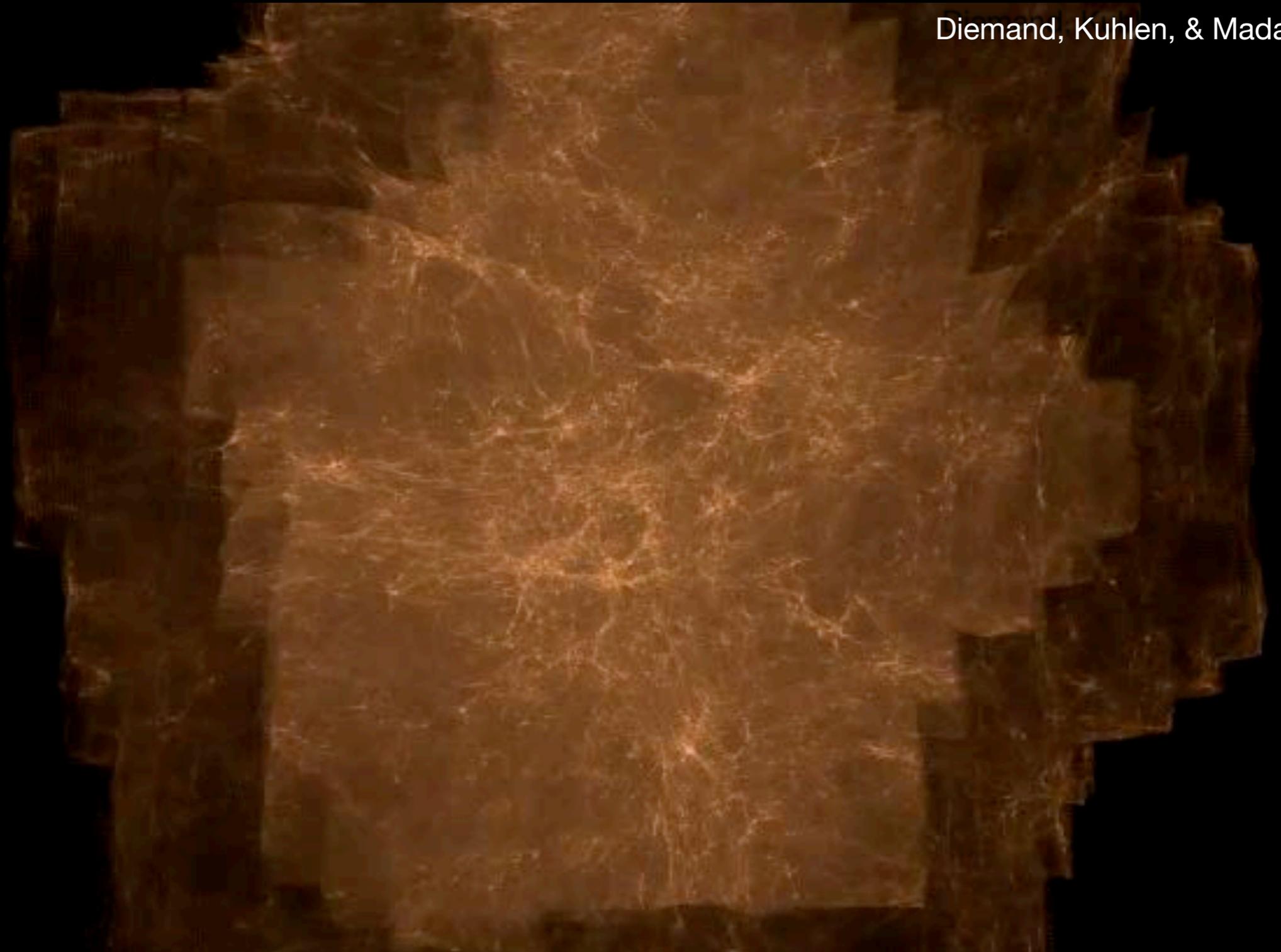
- Dark matter dominates the total mass
  - ↳ Some type of mass that only (strongly) interacts via gravity (*i.e., collisionless: no EM forces, no pressure*)
- Density field is initially **very** smooth, with only tiny fluctuations seeded during inflation
- Gravity causes these fluctuations to grow, starting with the smallest ones

***This is (physically) easy to simulate!***

# *Evolution of a Milky Way-like object*

**$z=11.9$**

Diemand, Kuhlen, & Madau 2006



*But this is **only gravity**, and we **know** there's other physics important for galaxy formation*

# Galaxy formation

Gas

Gas

**feedback**  
(e.g. supernovae)

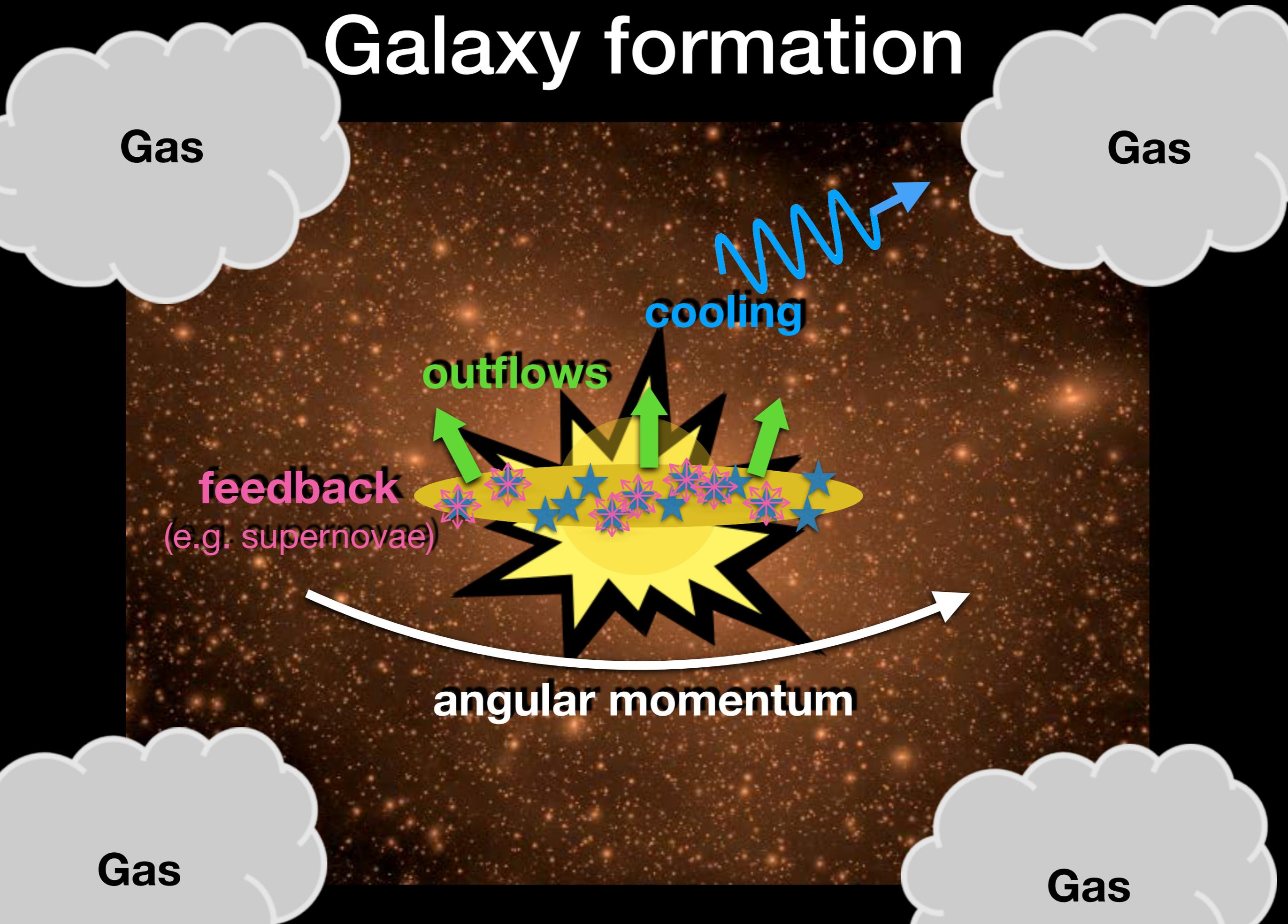
**outflows**

**cooling**

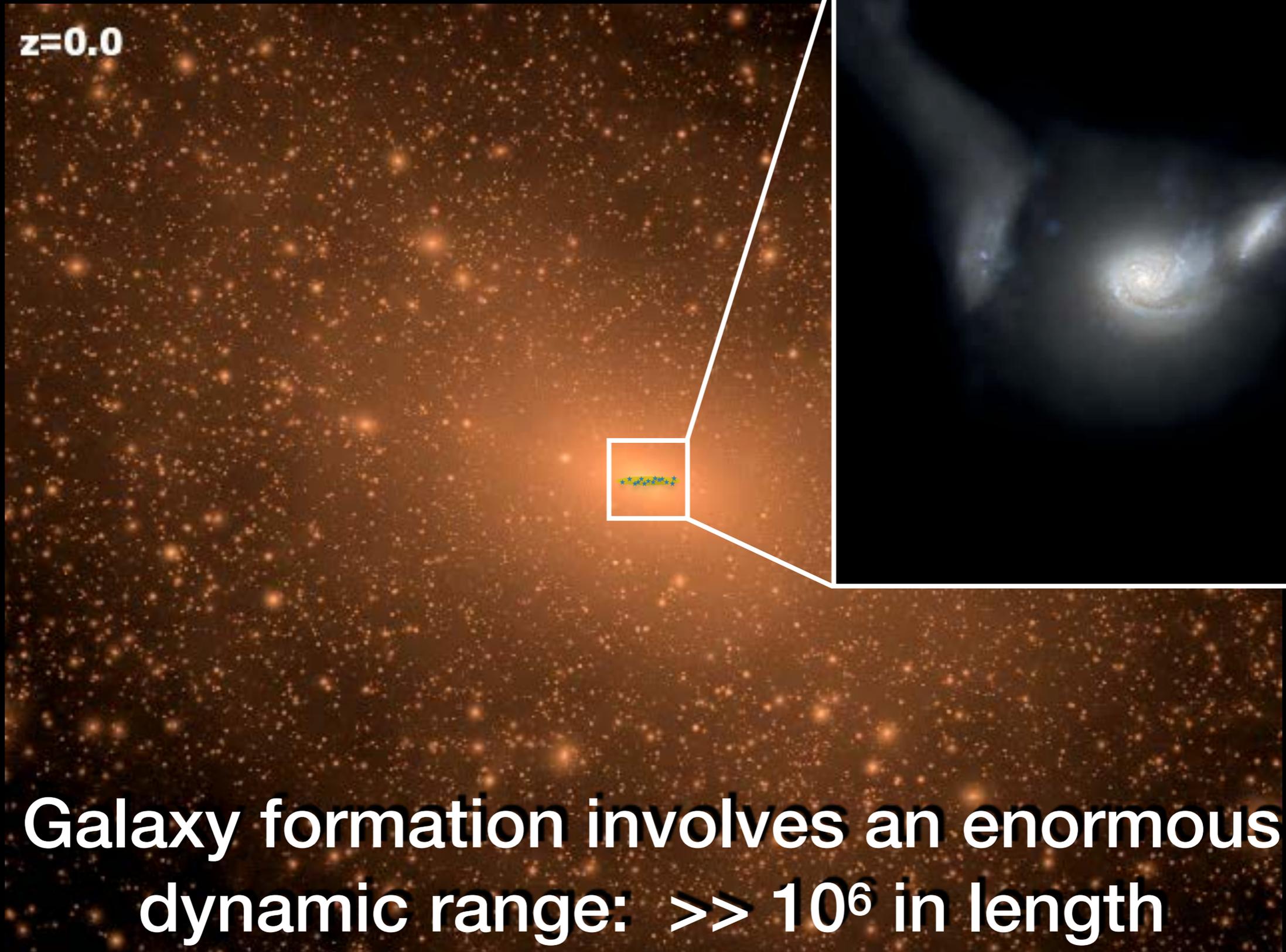
**angular momentum**

Gas

Gas

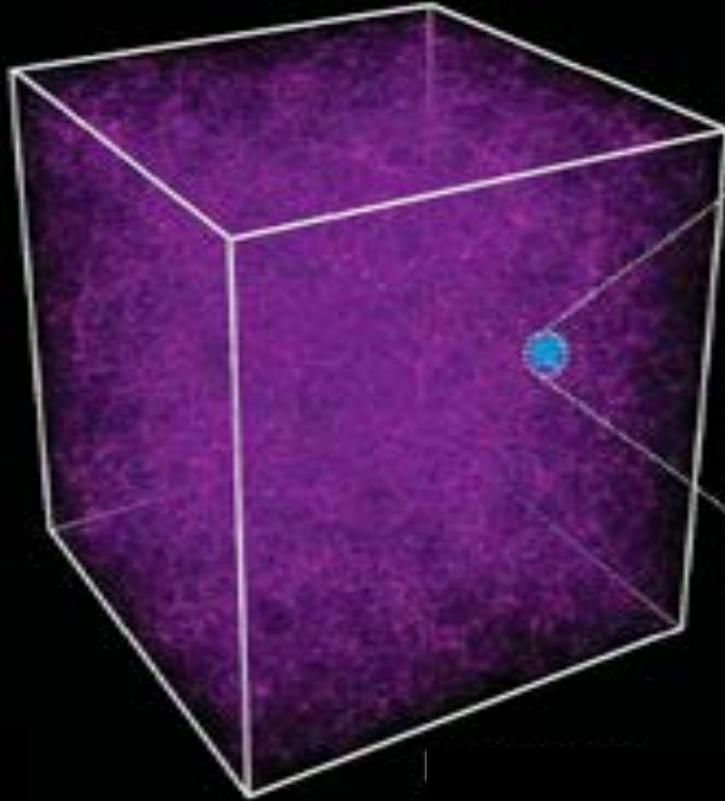


# Galaxy formation



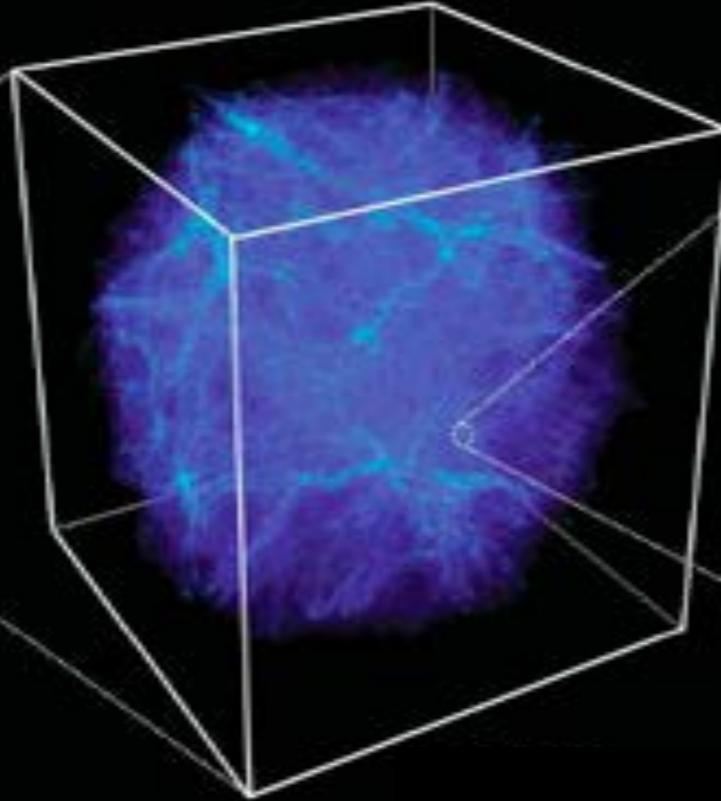
$\sim 10^{10}$  pc

Hubble volume



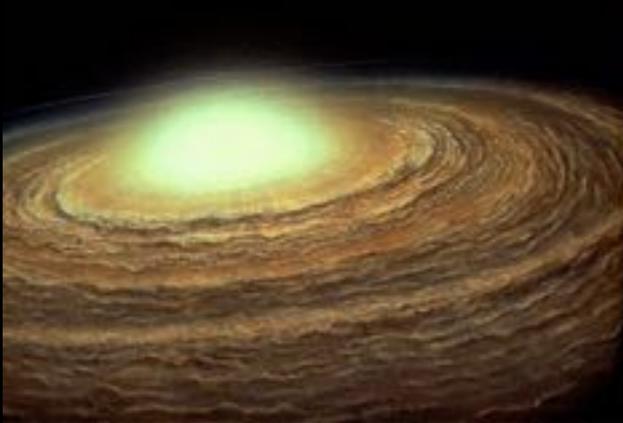
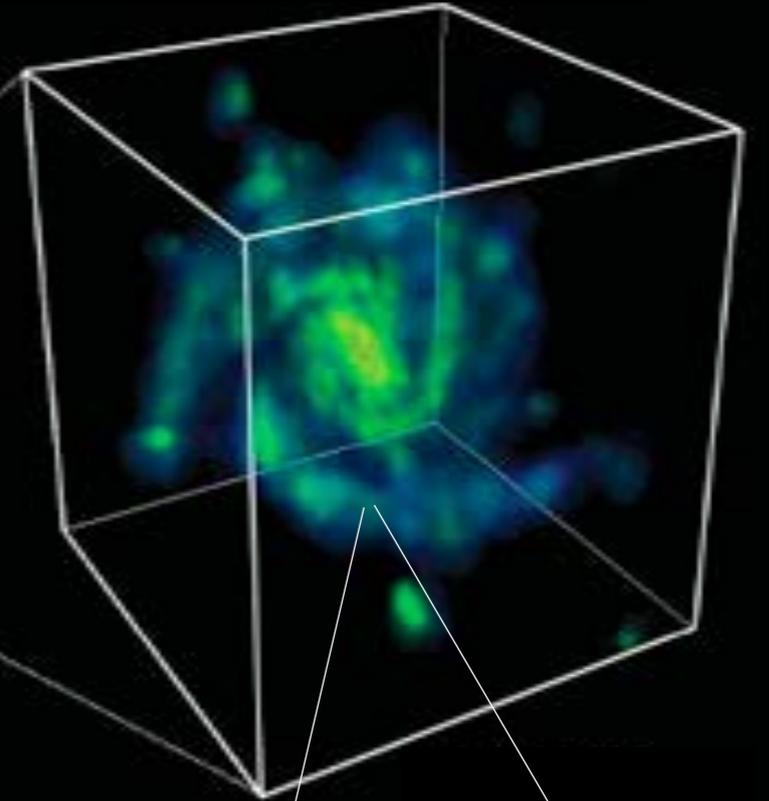
$\sim 10^7 - 10^8$  pc

Clusters, Large-scale structure



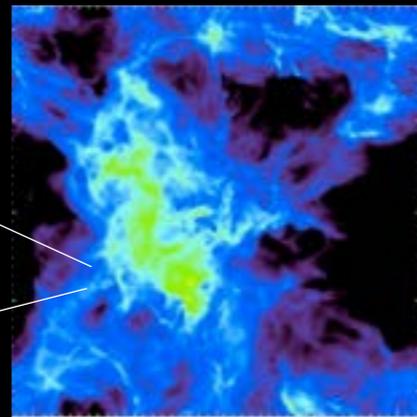
$\sim 10^{4-5}$  pc

Galaxy



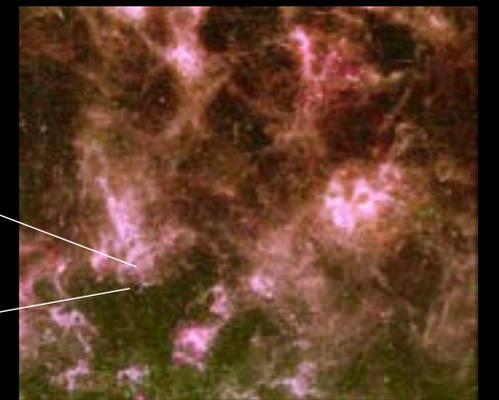
$\sim 10^{-5}$  pc

Stars, protostellar disks



$\sim 10^{-2} - 10^0$  pc

Cores, clusters,  
Supernovae blastwaves

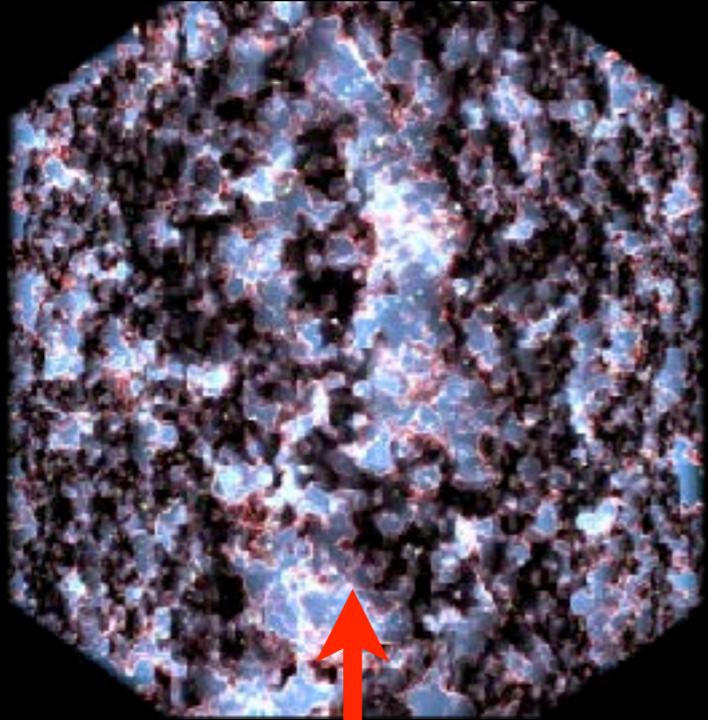


$\sim 10^1 - 10^2$  pc

Molecular clouds,  
Star-Forming Regions

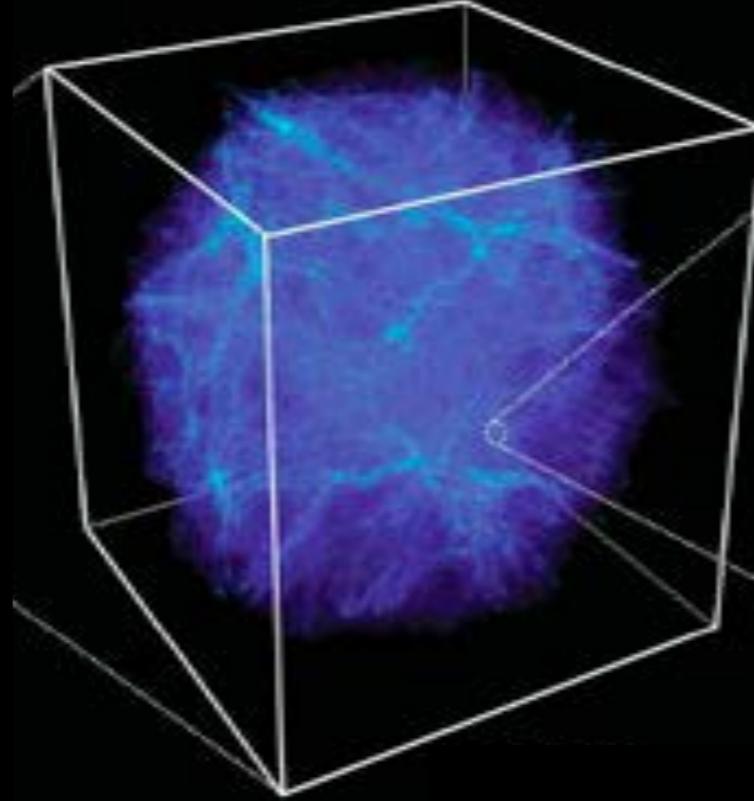
$\sim 10^{10}$  pc

Hubble volume



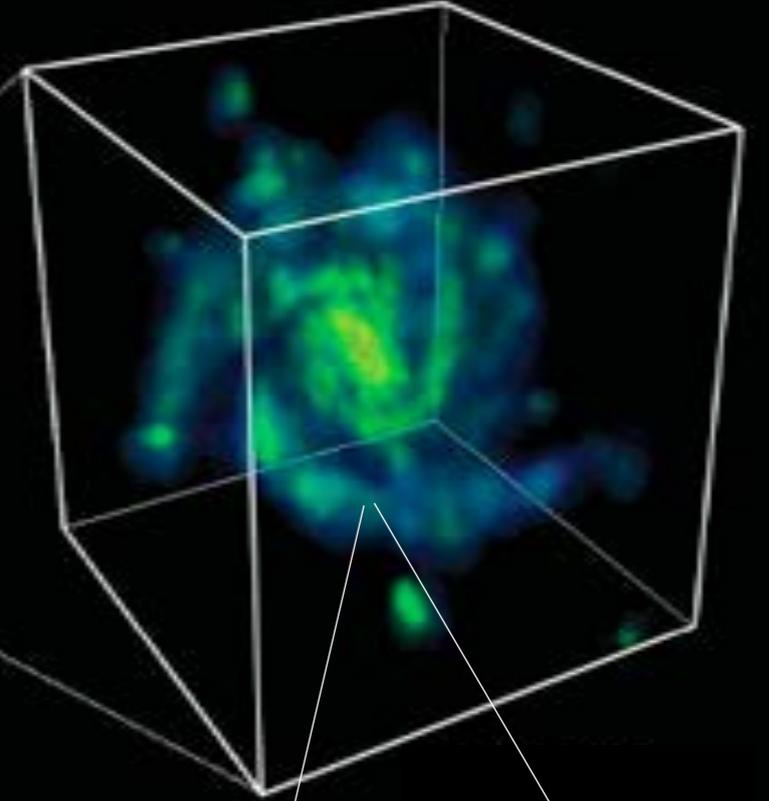
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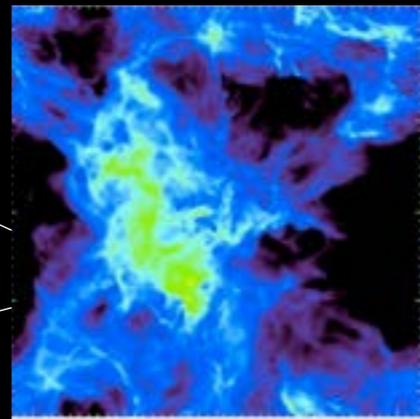
$\sim 10^{4-5}$  pc

Galaxy



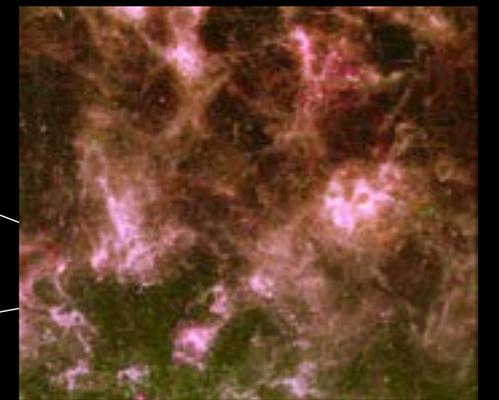
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$\sim 10^{-2} - 10^0$  pc

Cores, clusters,  
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Molecular clouds,  
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# ***FIRE*** (tries to) model the physics driving galaxy formation

***cosmological collapse***

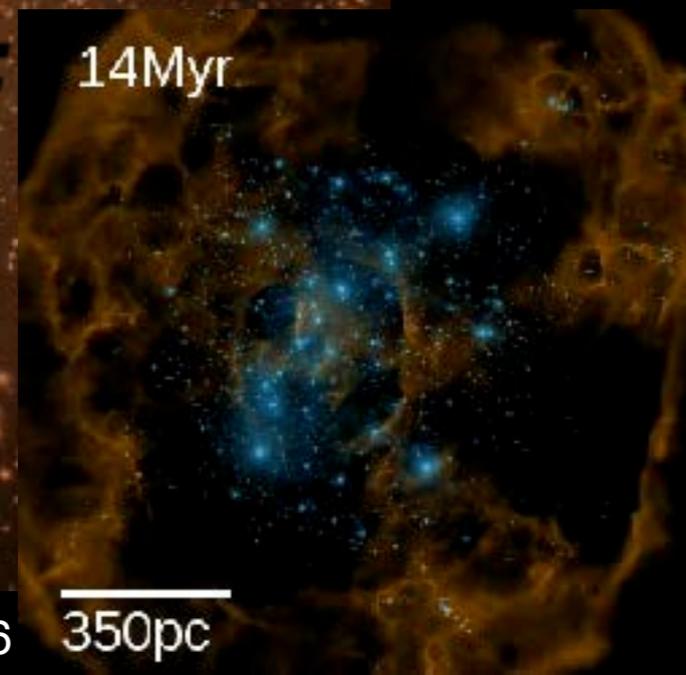
***hydrodynamics and gas cooling***

***star formation in self-gravitating gas***



***energy return from stars (feedback), based on the results of stellar evolution studies:***

- stellar winds***
- radiative feedback***
- supernovae types Ia and II***



# What are we studying with FIRE?

*galactic winds and  
the circumgalactic medium*

*what are the  
smallest galaxies?*

*high-redshift galaxy  
formation (JWST)*

*the role of cosmic rays  
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*drivers of galaxy  
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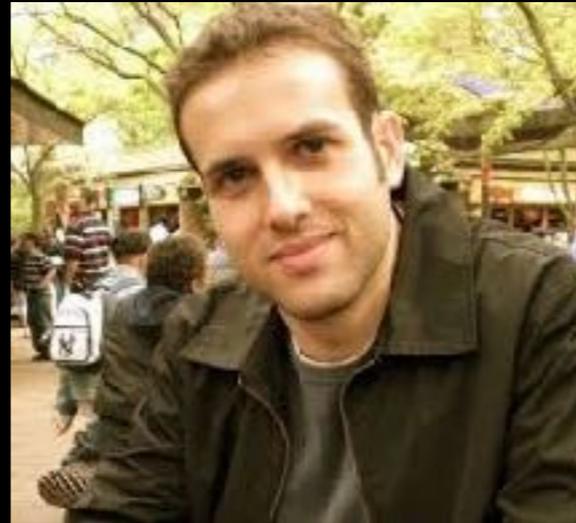
# Who is FIRE?

*Pls at ten institutions:*

**Phil Hopkins, Caltech**



**Dusan Keres  
UC San Diego**



**C.A. Faucher-Giguère  
Northwestern**

**Norm Murray, CITA**



**Andrew Wetzel  
UC Davis**

**Eliot Quataert  
UC Berkeley**



**James Bullock  
UC Irvine**



**Mike Boylan-Kolchin  
UT Austin**



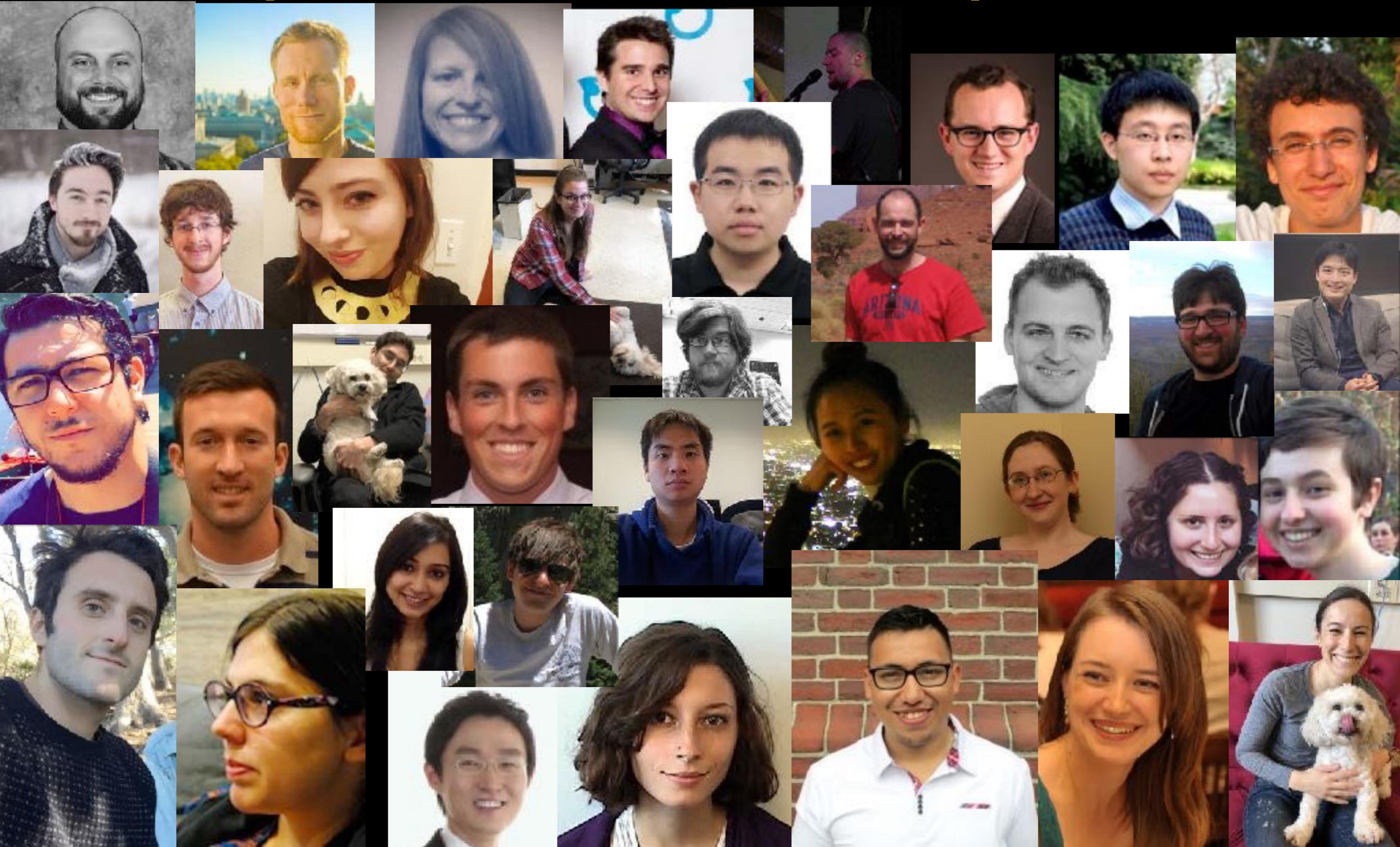
**Chris Hayward  
CCA**

**Robert Feldmann  
ETH Zurich**



# Who is FIRE?

*plus 35 - 45 students and postdocs*

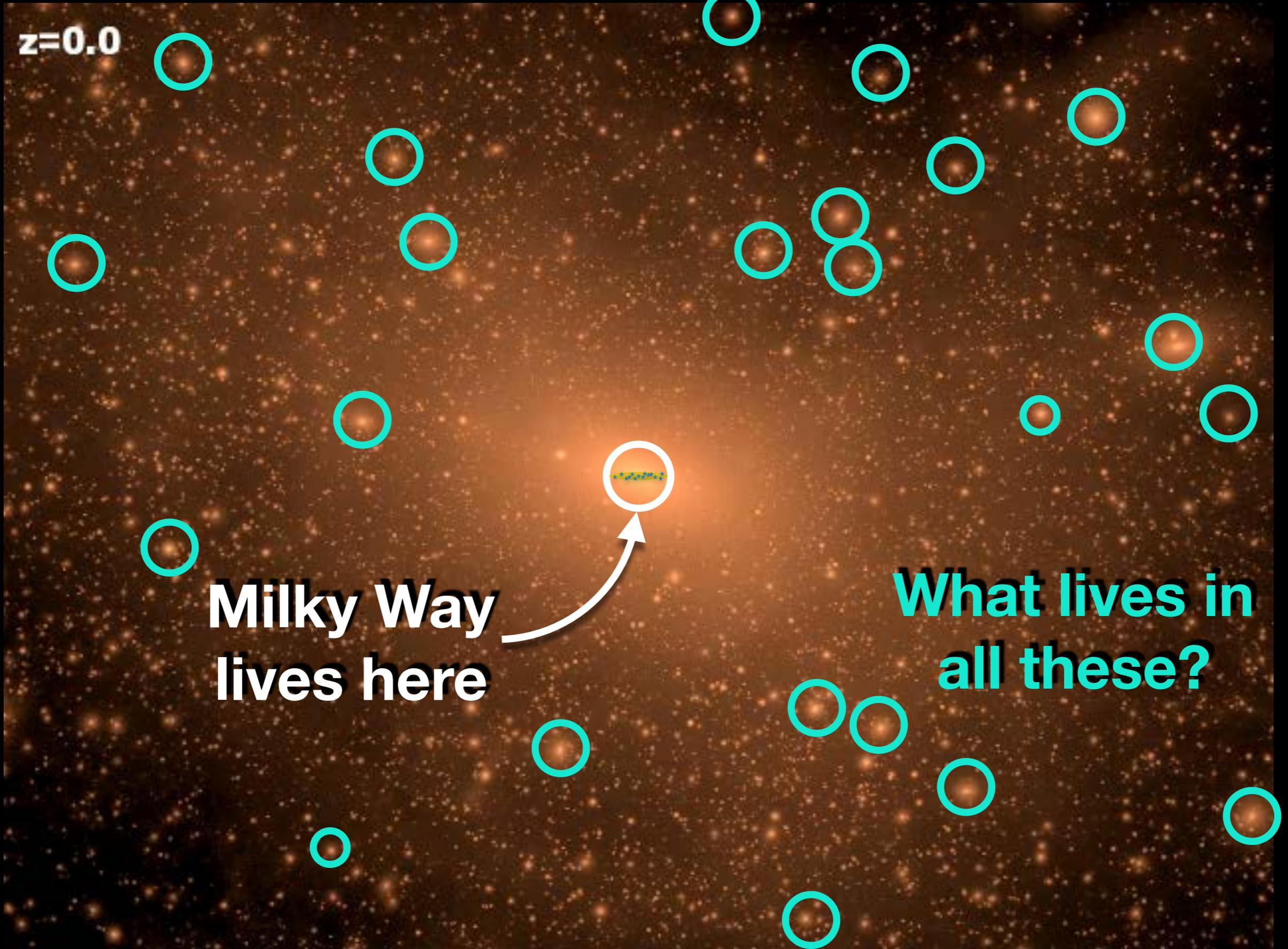


# Small-scale problems

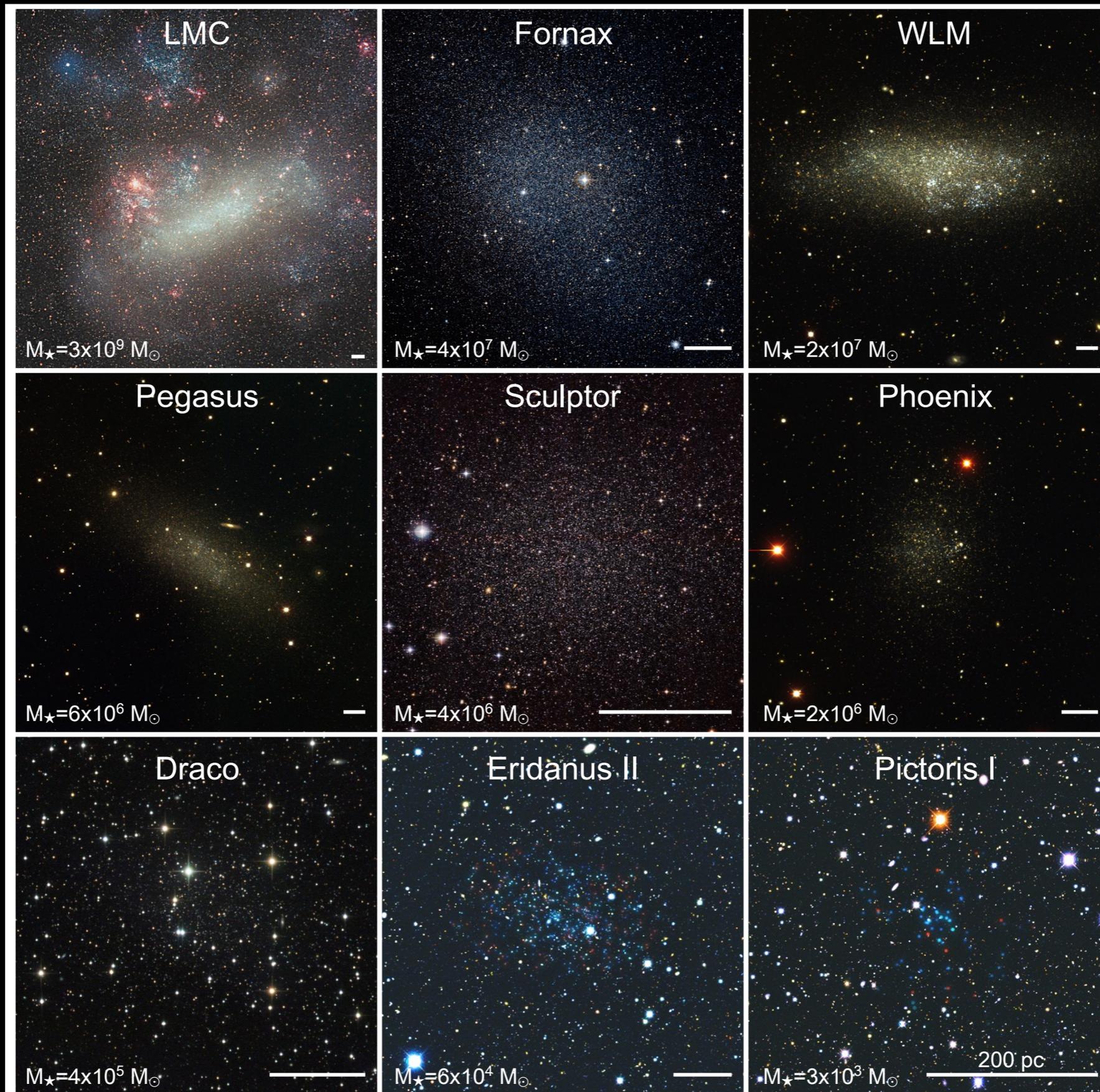
$z=0.0$

**Milky Way  
lives here**

**What lives in  
all these?**



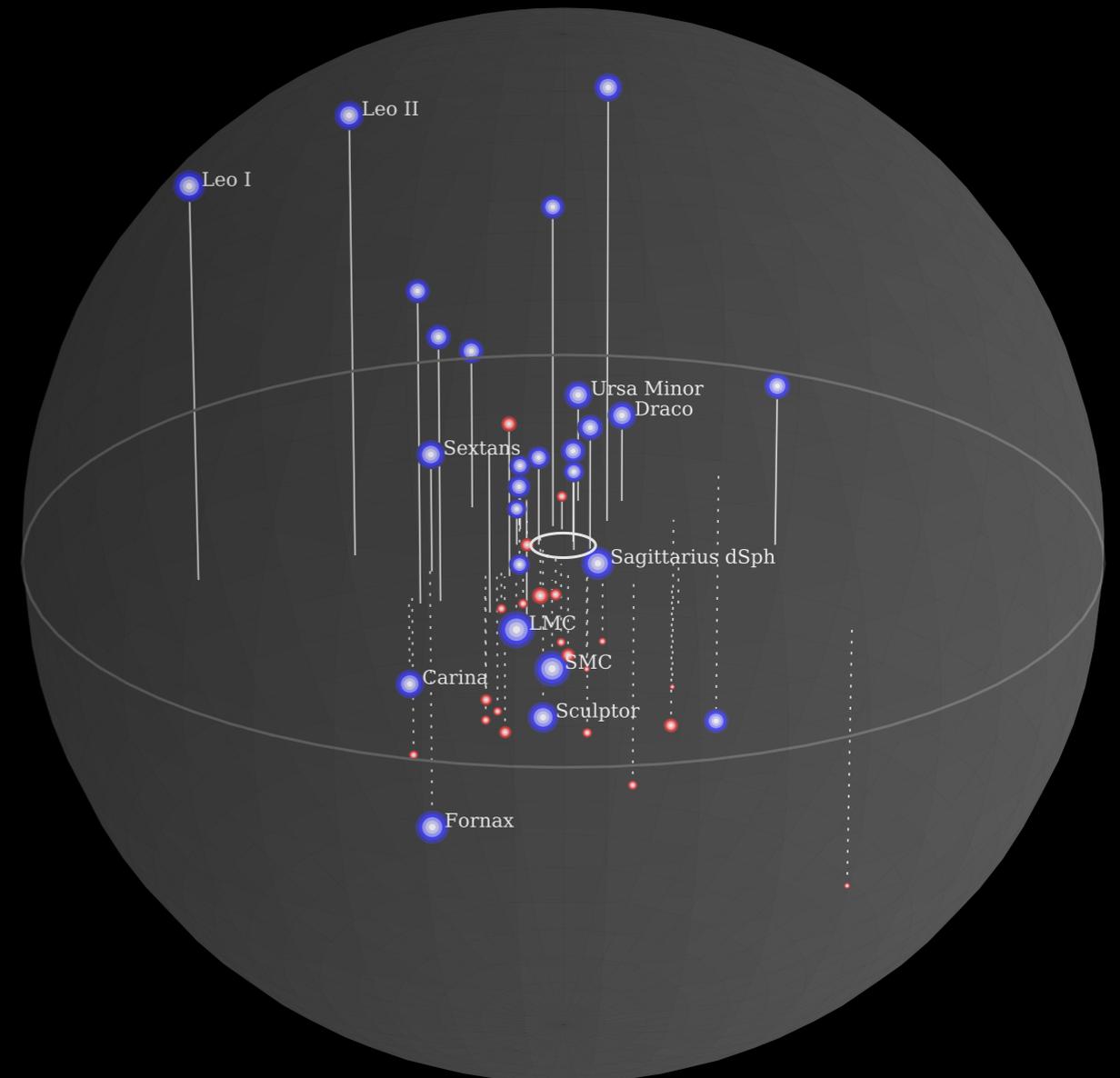
# Dwarf galaxies!



# Dwarf galaxies...but not enough



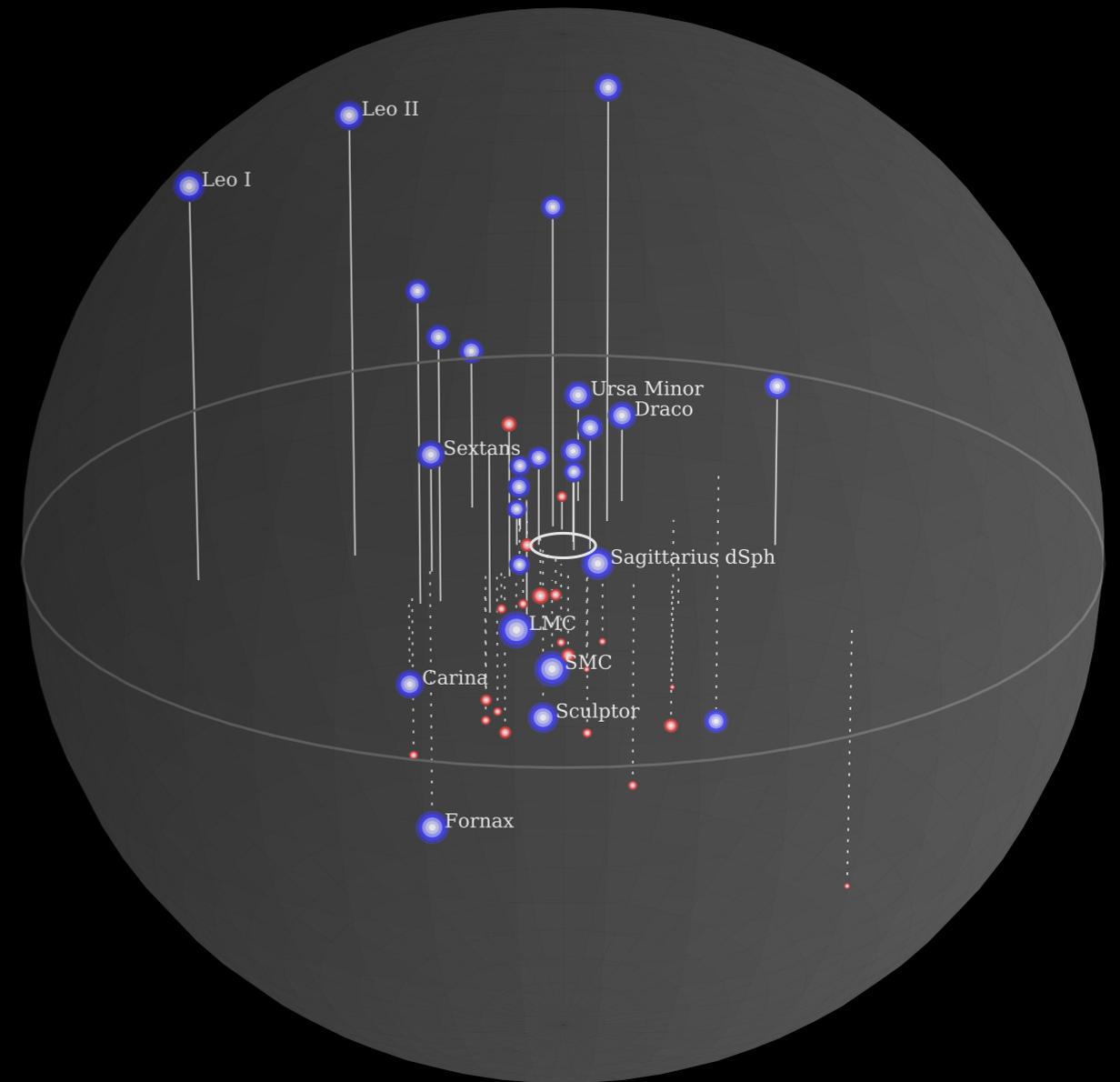
*Theory:* thousands of  
“subhalos”



Pawlowski/Bullock/Boylan-Kolchin

*Observations:* tens of  
“satellite galaxies”

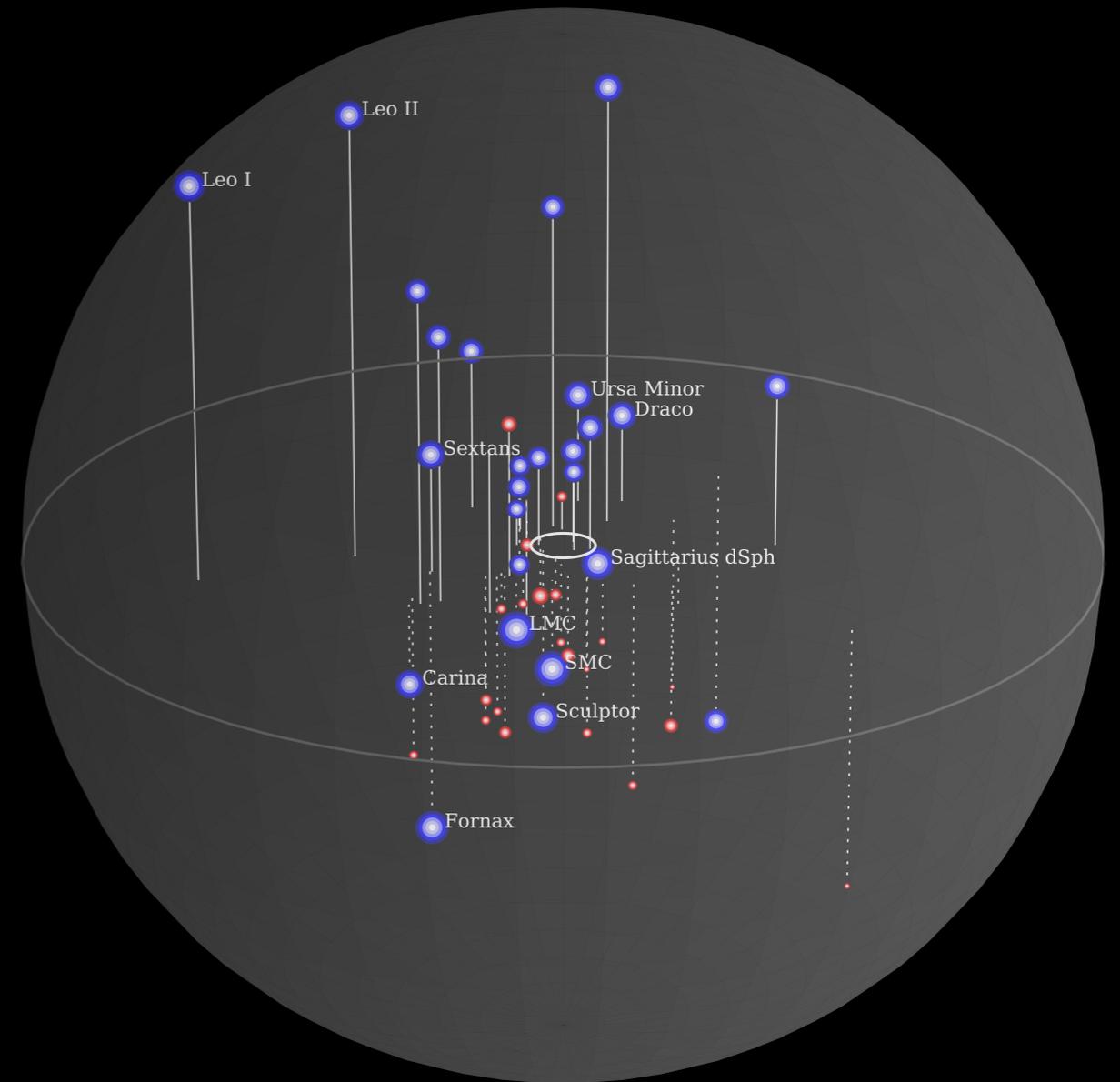
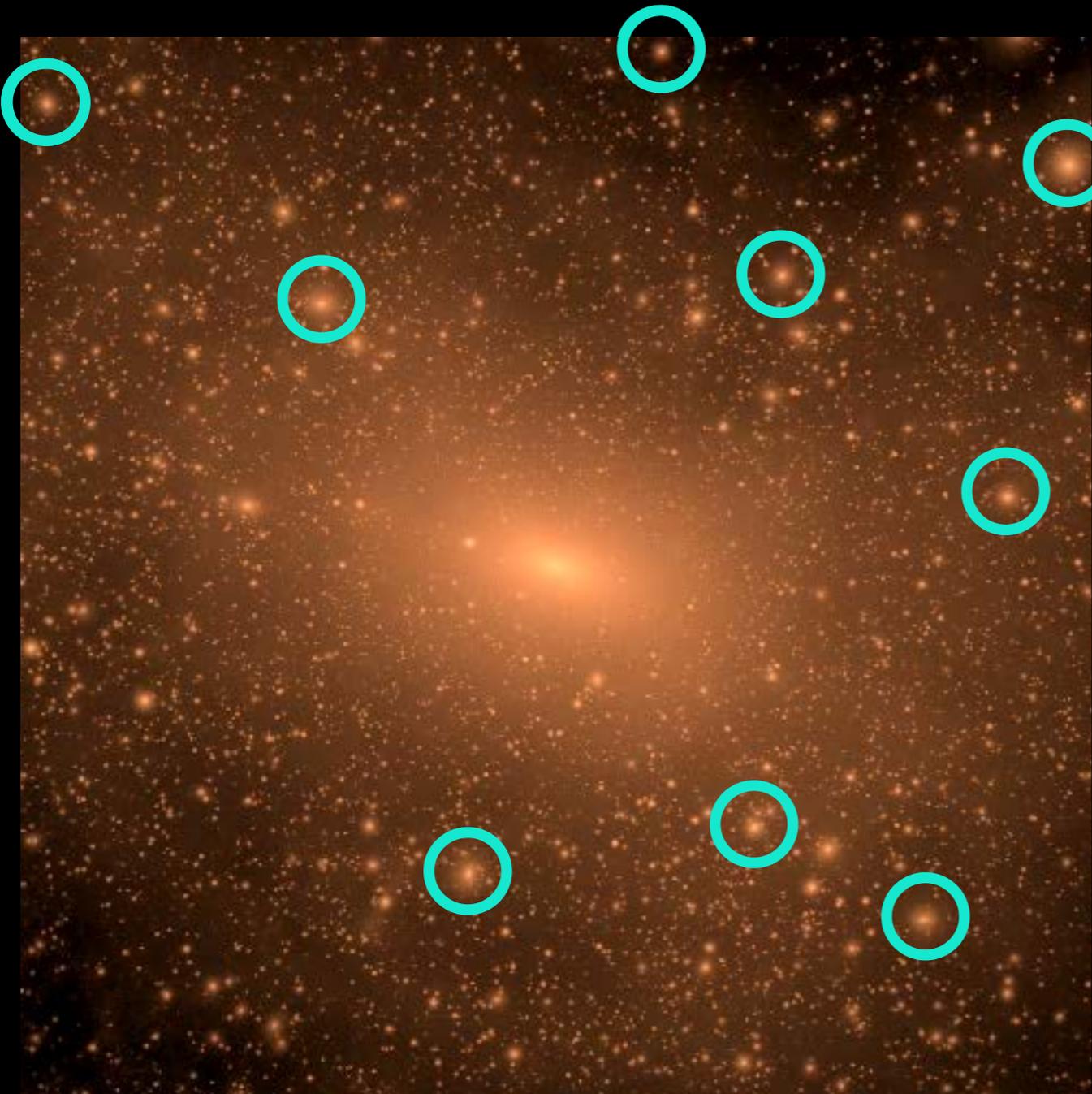
# The missing satellites problem



Pawlowski/Bullock/Boylan-Kolchin

***Postulate:*** Maybe only the biggest dark matter clumps host (detectable) galaxies?

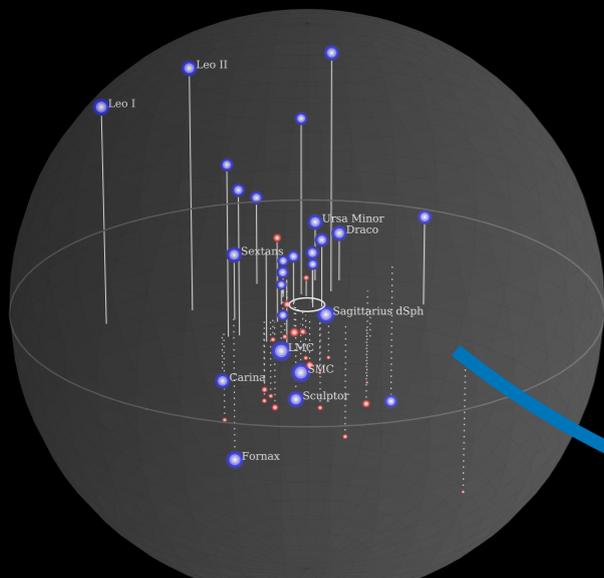
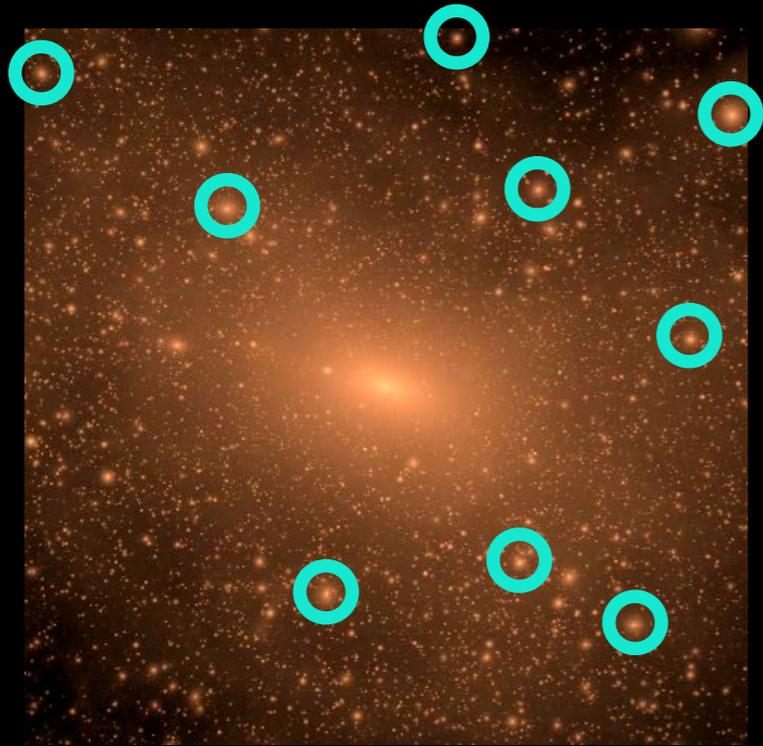
# The missing satellites problem



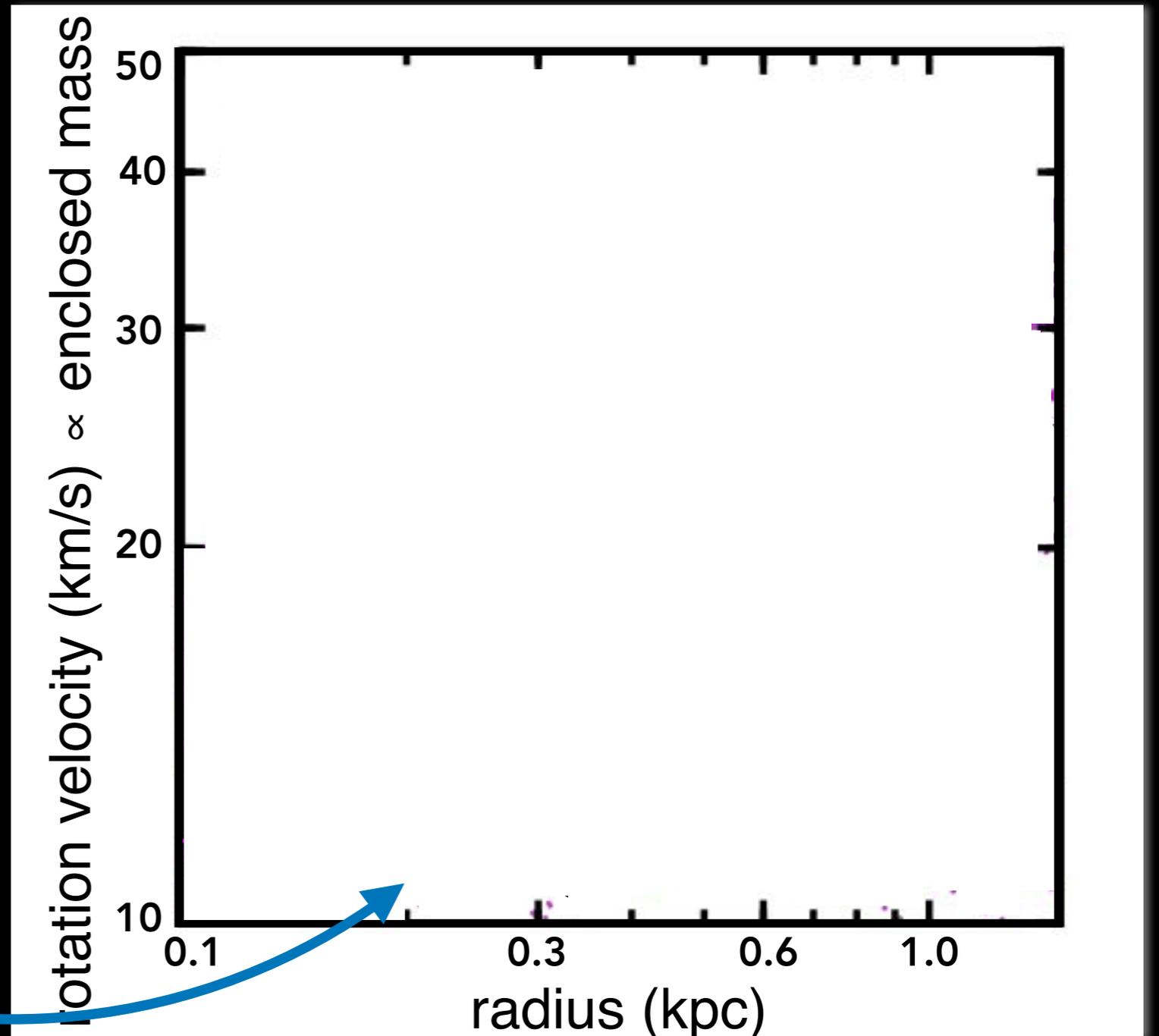
Pawlowski/Bullock/Boylan-Kolchin

***Corollary:*** The known galaxies should be compatible with the biggest clumps

# The central mass problem



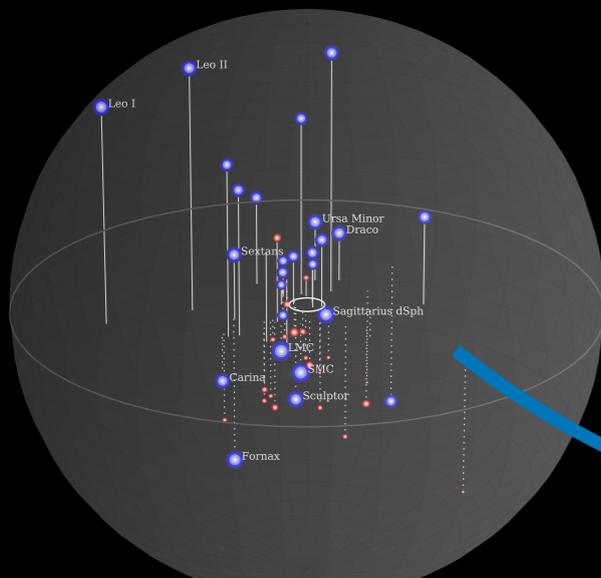
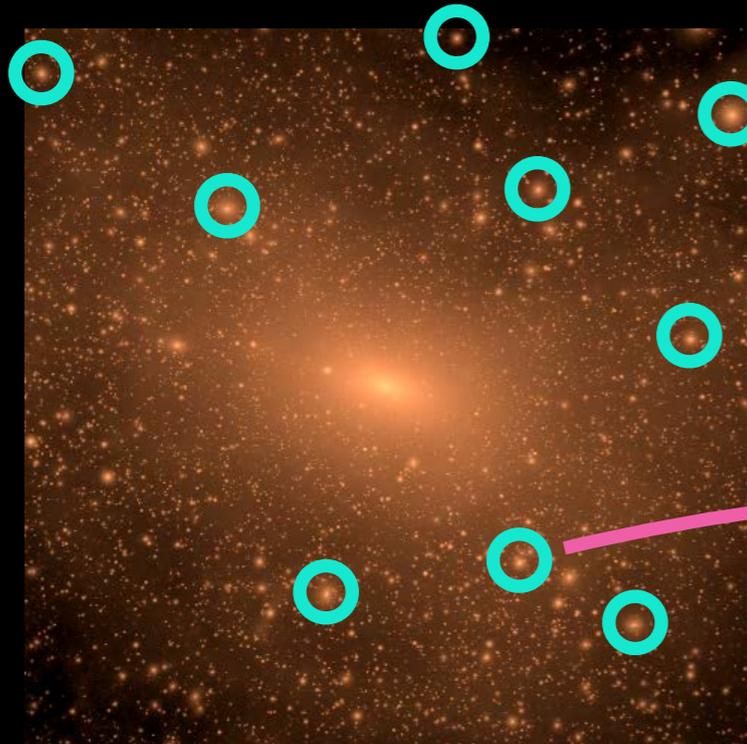
Pawlowski/Bullock/Boylan-Kolchin



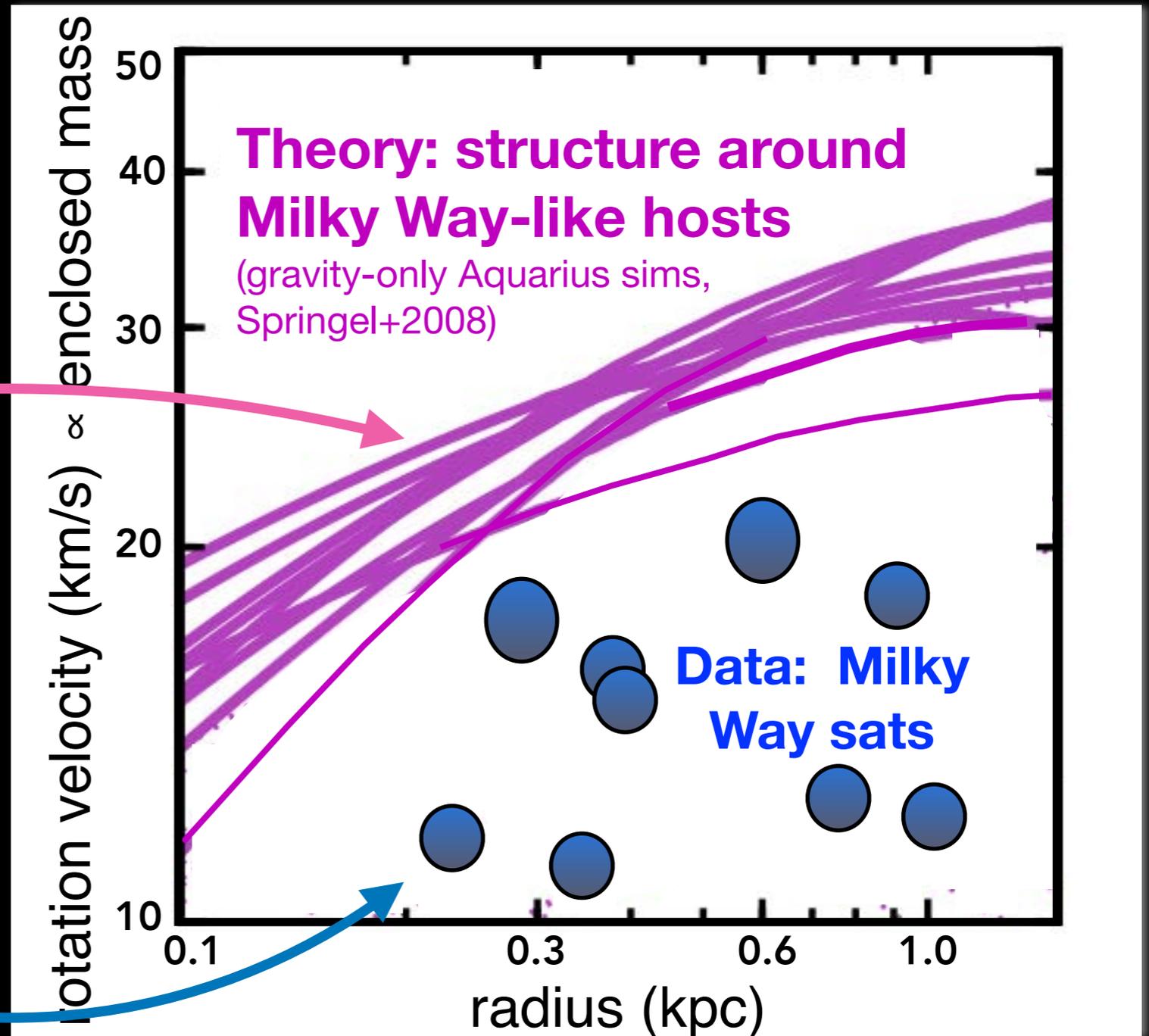
$$\text{rotation velocity} = \sqrt{G M(<r)/r}$$

Compare *dynamical* (total) masses to check

# The central mass problem

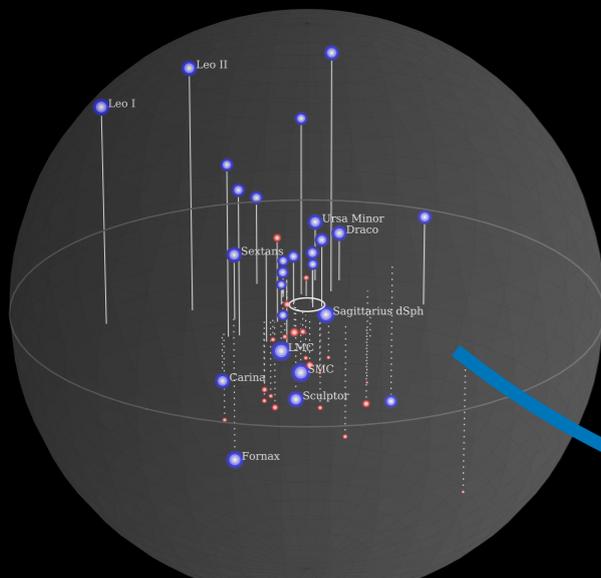
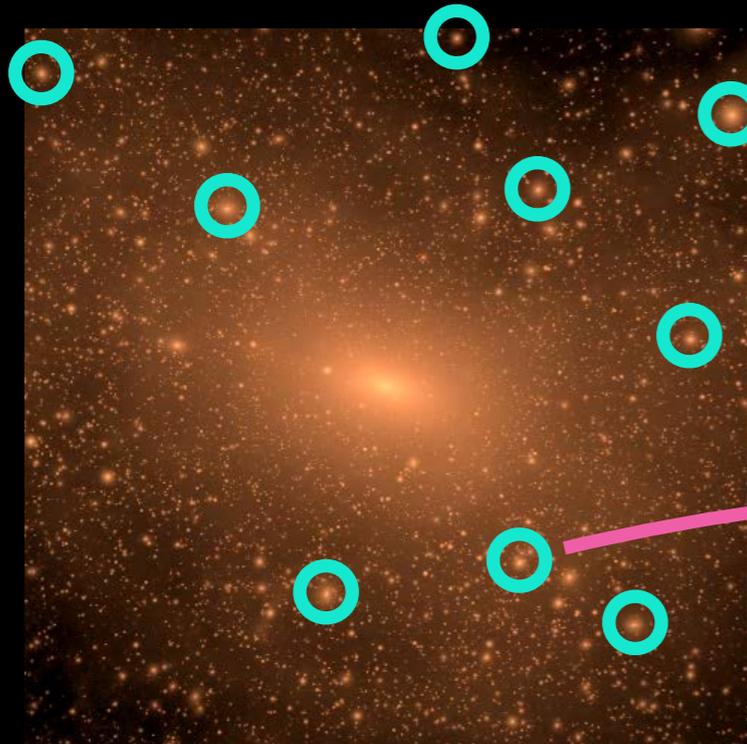


Pawlowski/Bullock/Boylan-Kolchin

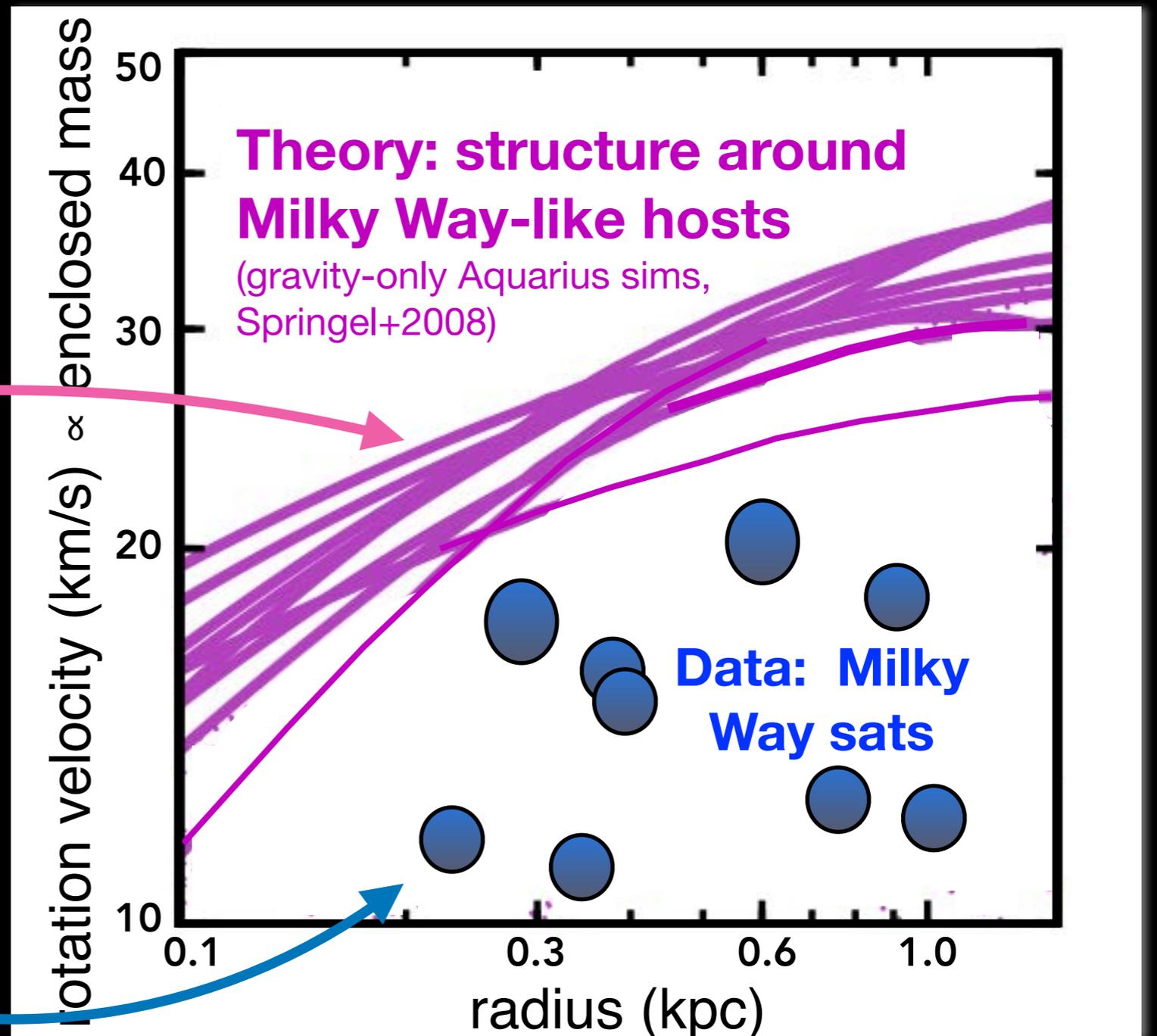


**Big clumps** (which are “too big to fail” to form stars) have **too much central mass** to host the **bright galaxies**

# The central mass problem



Pawlowski/Bullock/Boylan-Kolchin



**CAVEAT: these curves are from a gravity-only sim that ignores known physics (i.e. galaxy formation)**

Can known, standard model physics that aren't included in gravity-only simulations resolve the “missing satellites” and “central mass” problems?

*...or do we need to invoke “new physics”?*

# What are we studying with FIRE?

*galactic winds and  
the circumgalactic medium*

*what are the  
smallest galaxies?*

*high-redshift galaxy  
formation (JWST)*

*the role of cosmic rays  
in galaxy formation*

*drivers of galaxy  
morphology*

*impact of baryons  
on dark matter*

*what can we  
learn from Gaia?*

*importance of  
magnetic fields*

*radiation/matter  
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*growth of  
supermassive  
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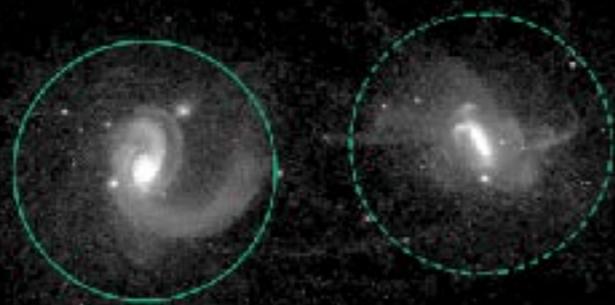
# Tackling small-scale problems with the FIRE simulations

*ELVIS* on *FIRE* and the *Latte* suites

Isolated dwarf galaxies at ludicrous resolution

Triple Latte

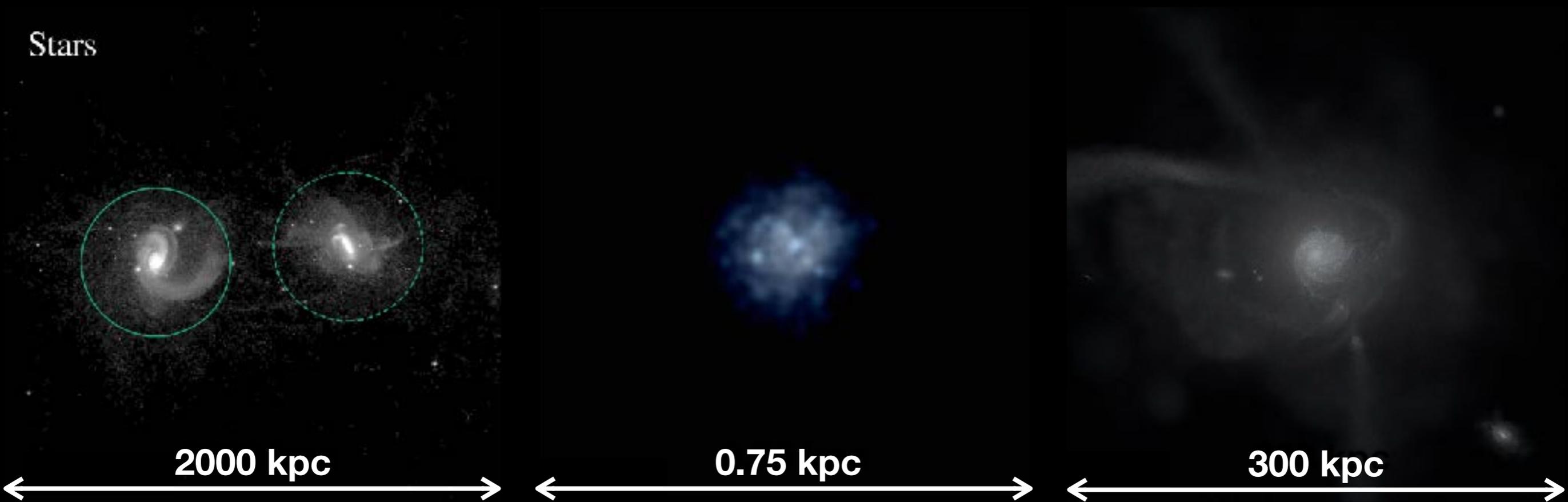
Stars



2000 kpc

0.75 kpc

300 kpc

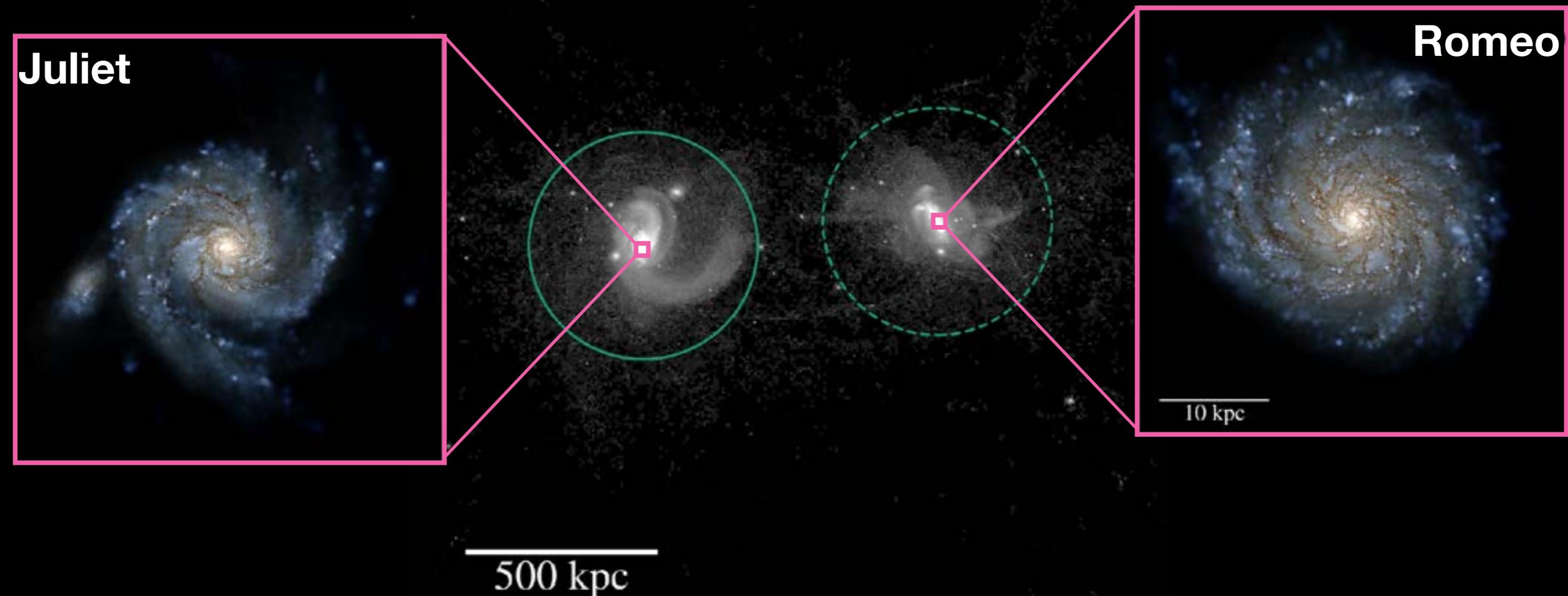


# ELVIS on FIRE and the Latte suite

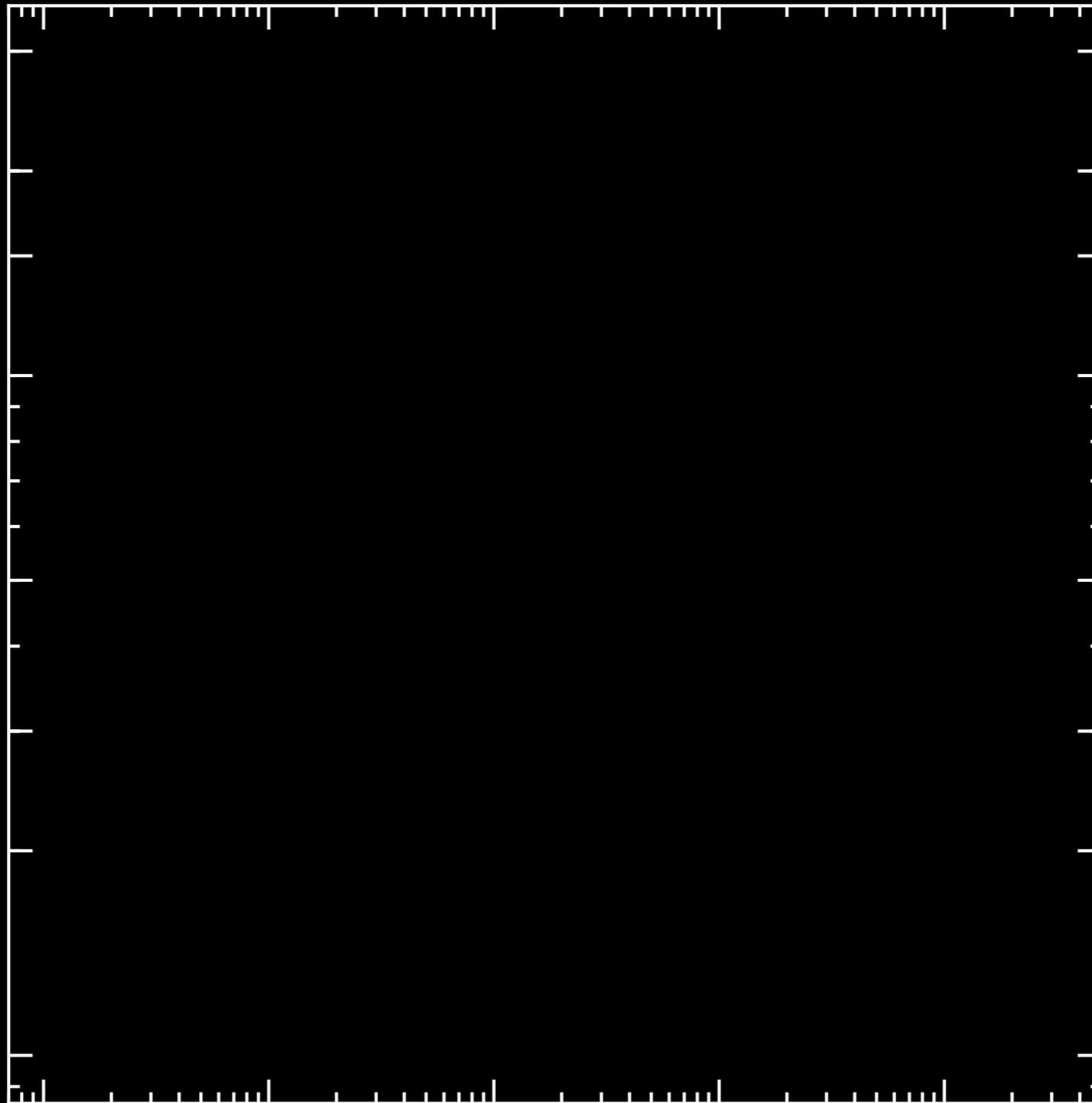
*Ten Milky Way-mass galaxies, each with a population of nearby dwarf galaxies (within  $\sim 1$  Mpc of each host)*

Each simulation spans  $\sim 10^6$  parsecs while resolving  $\sim 1$  pc scales

Stars

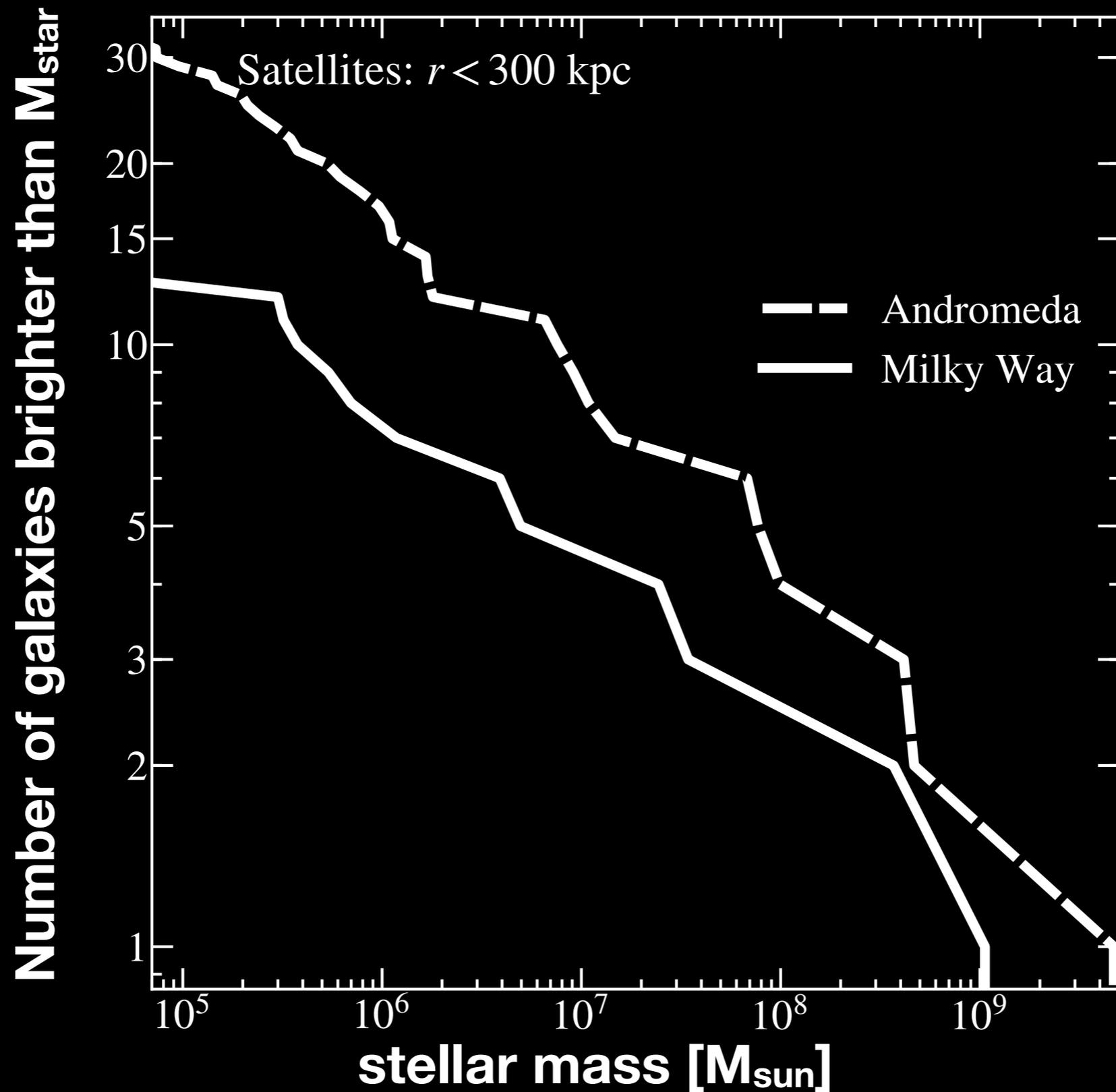


# The missing satellites problem

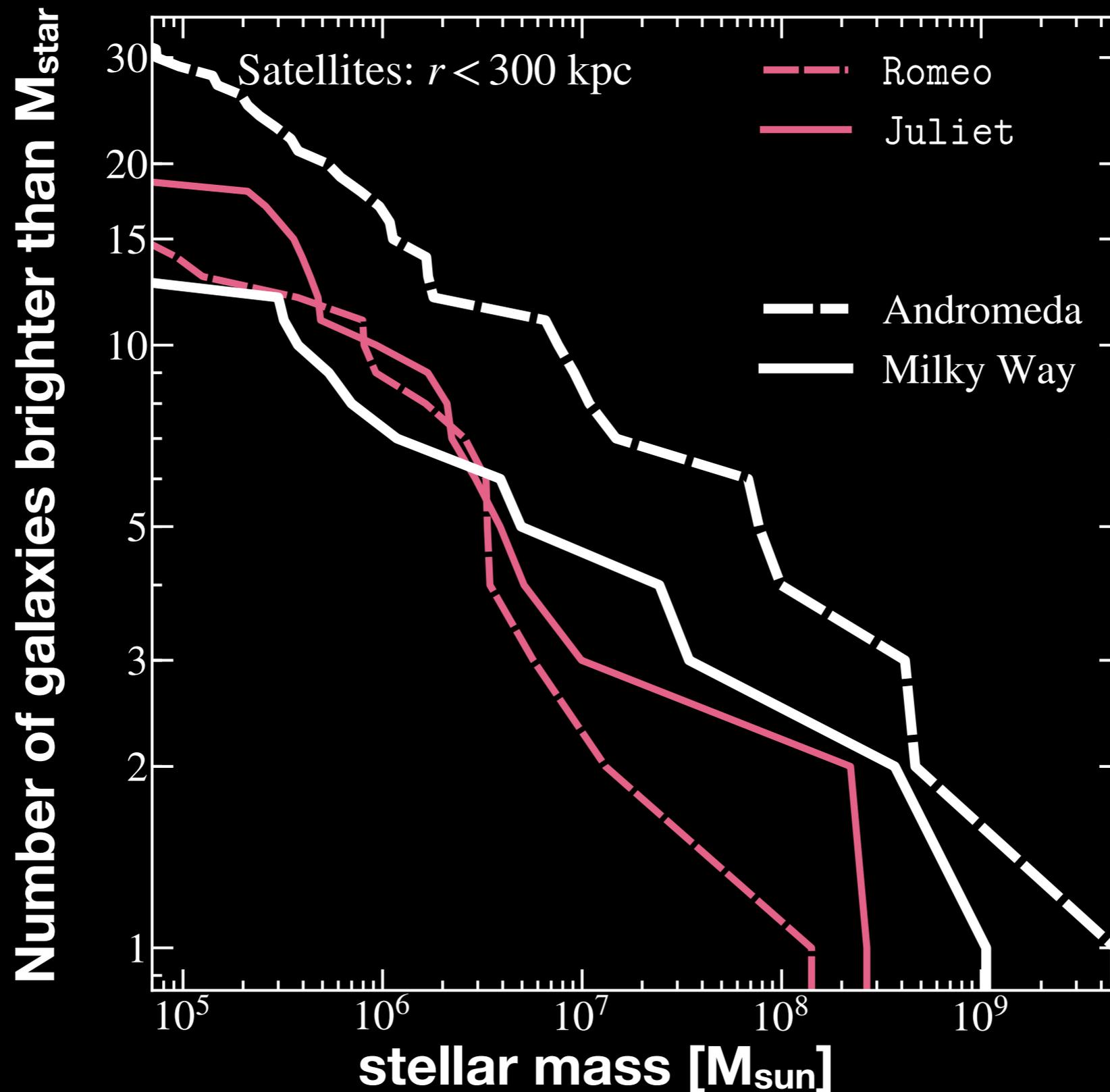




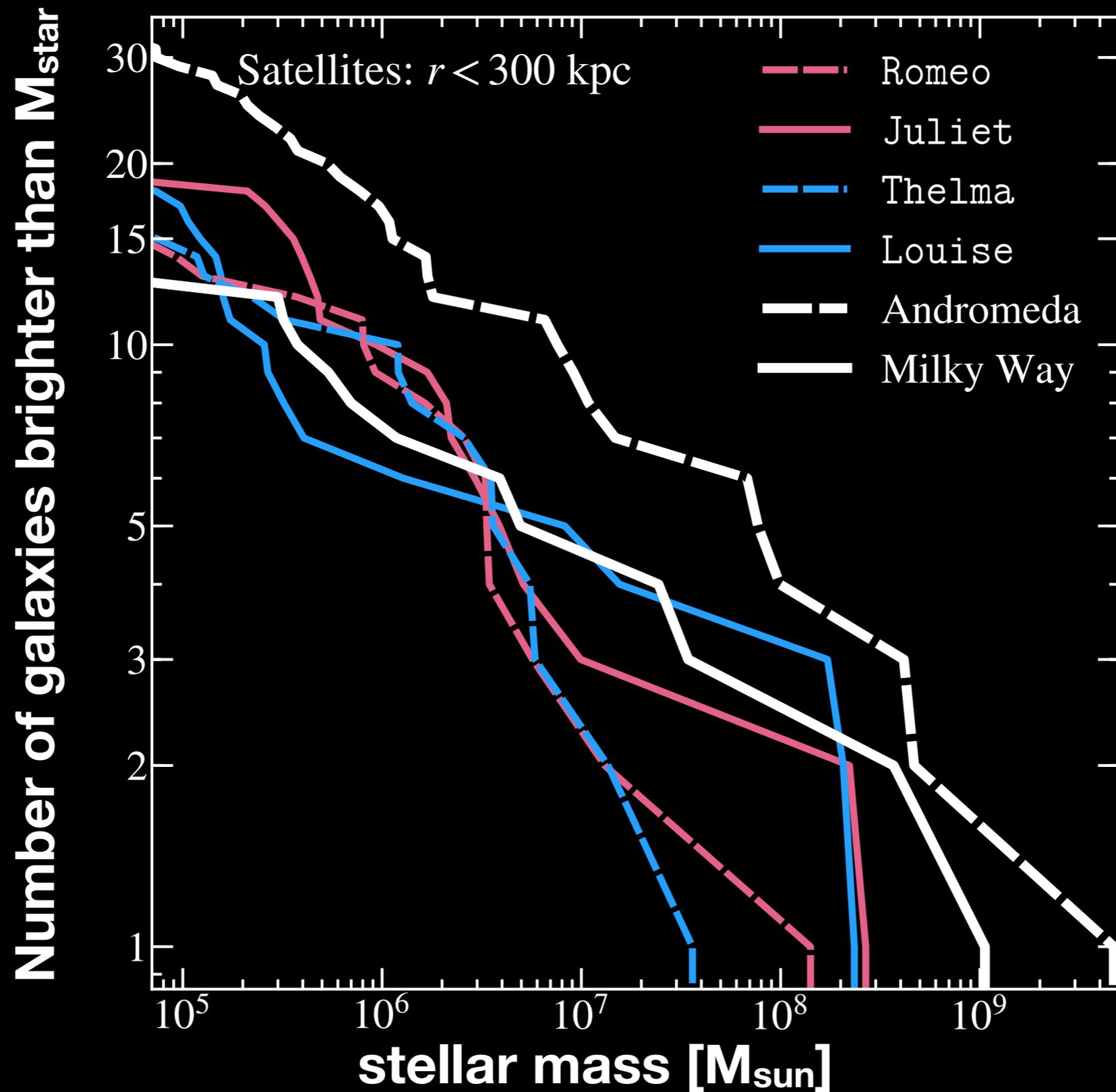
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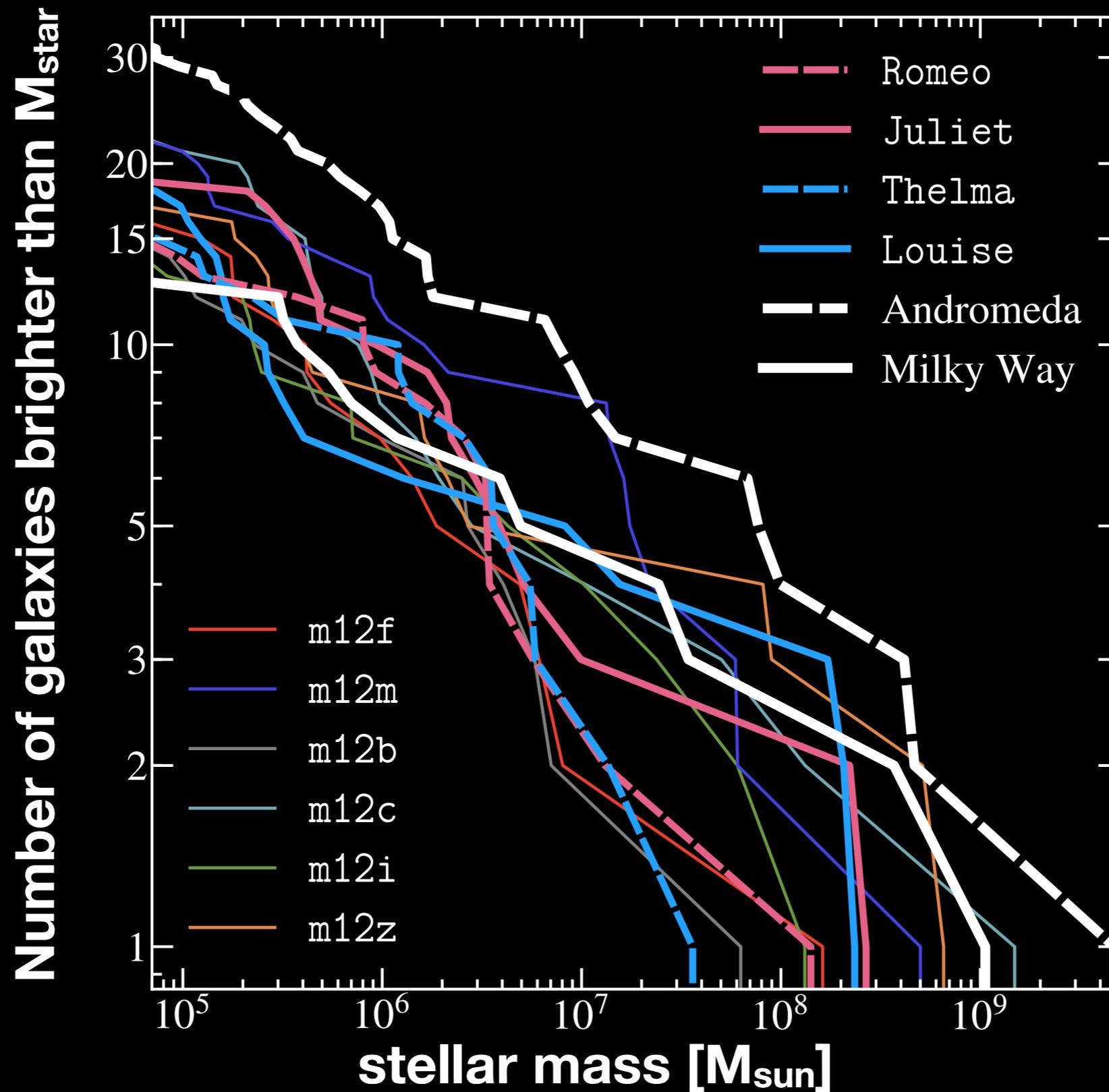
# The missing satellites problem



# The missing satellites problem



# No missing satellites problem!



# What about the central masses?

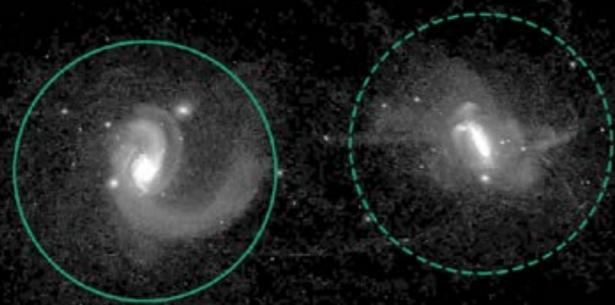
*Is the internal structure of the simulated dwarfs consistent with those observed?*

***ELVIS on FIRE and the Latte suites***

**Isolated dwarf galaxies at ludicrous resolution**

**Triple Latte**

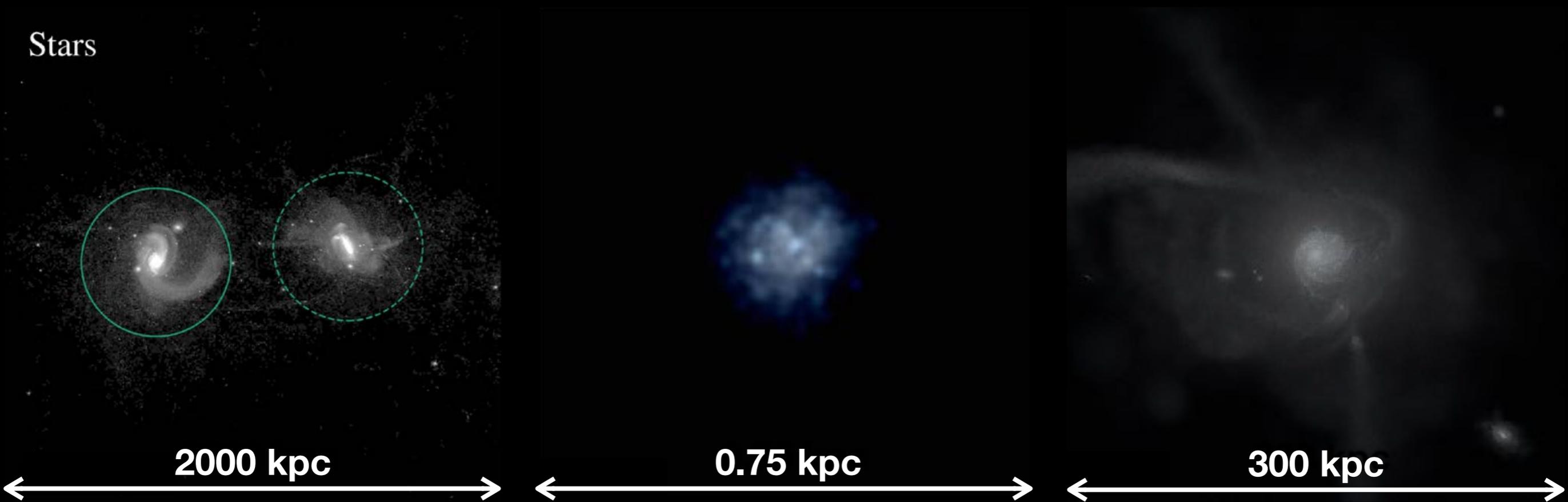
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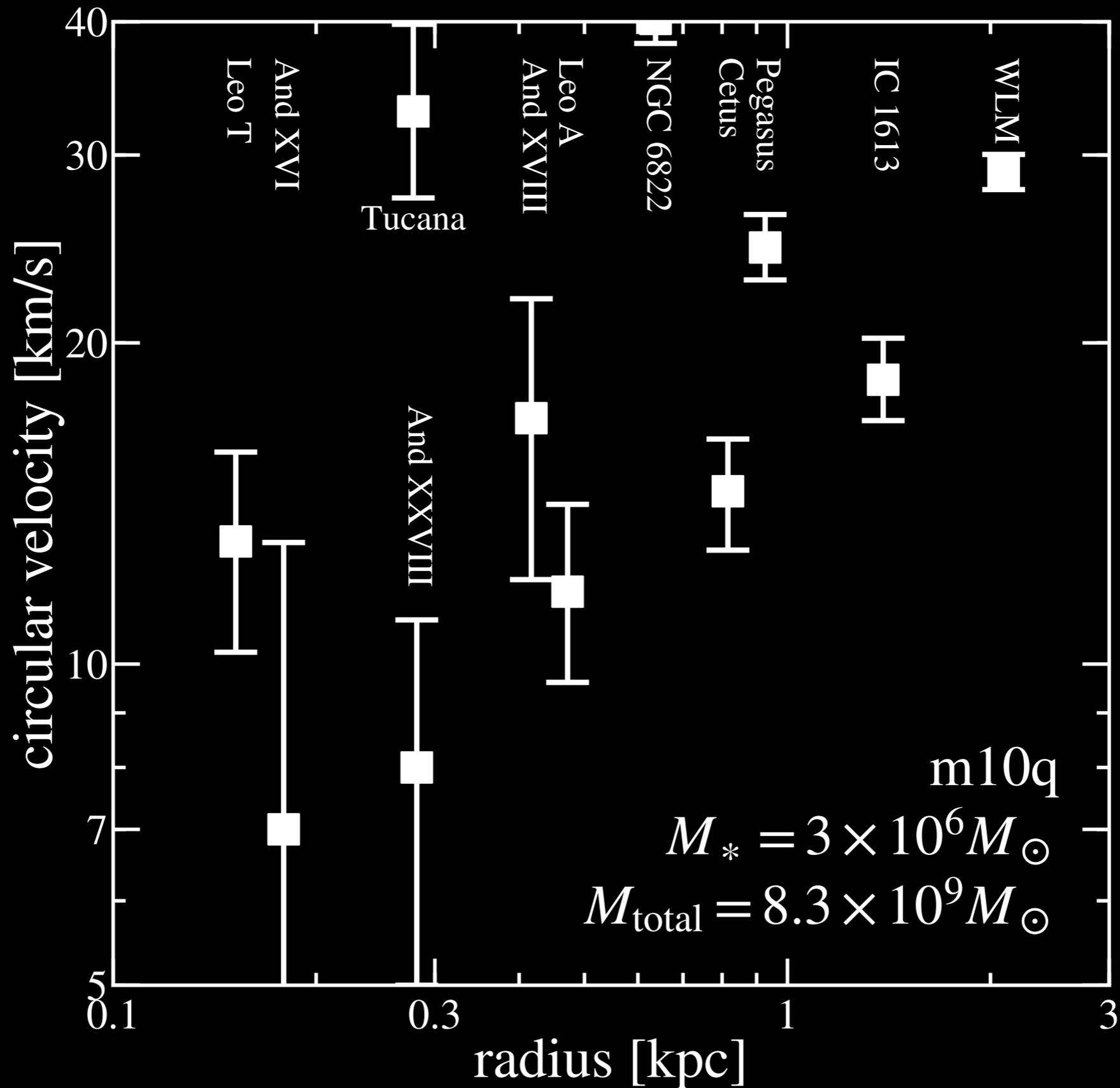


# Ultra-high resolution isolated dwarf galaxies

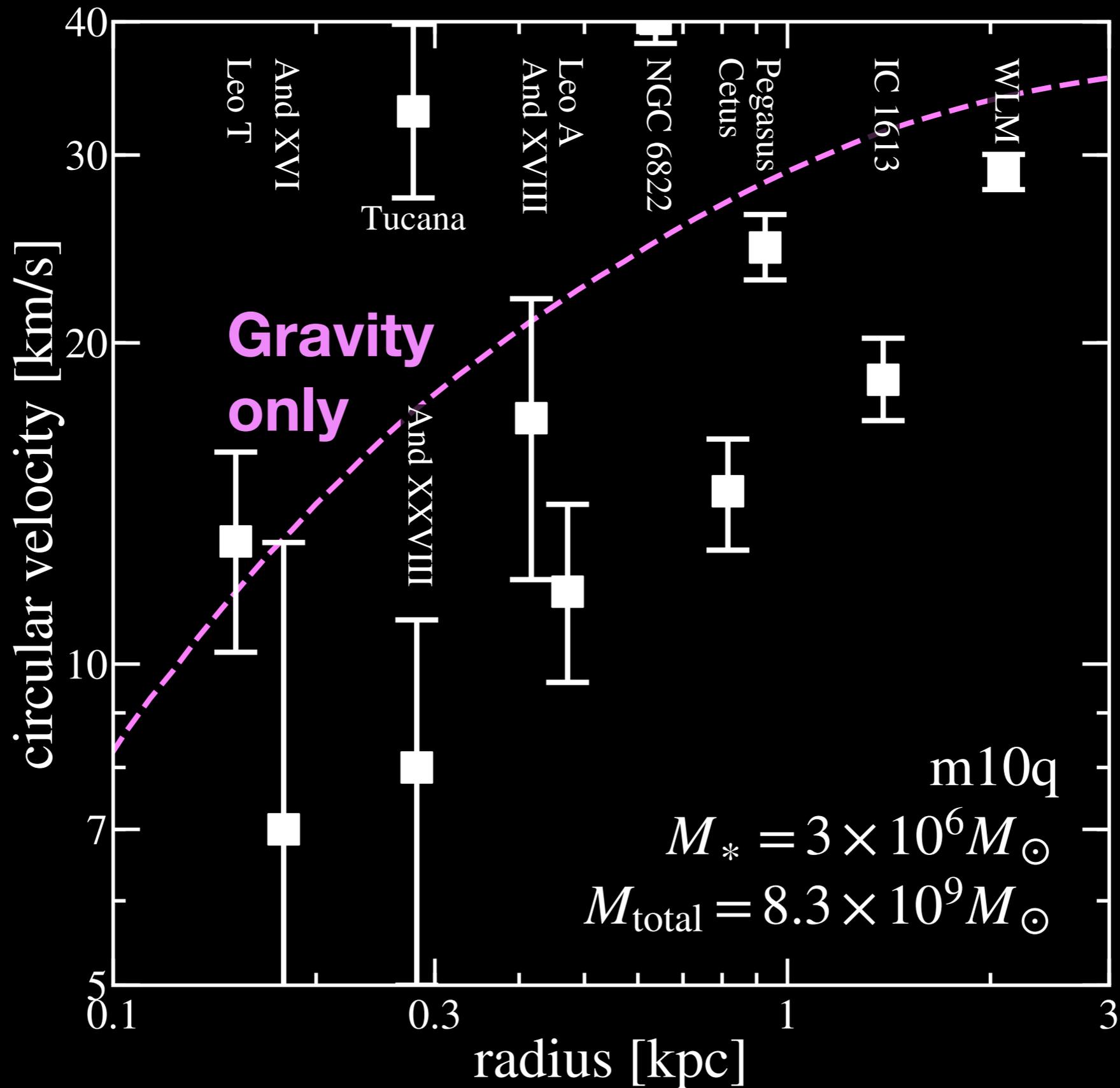
- $m_{\text{gas}} \approx 30 M_{\text{sun}}$  — equivalent to a single high mass star!
- First cosmological simulations (run to  $z = 0$ ) to resolve the cooling radii of individual supernovae
- Density profiles resolved beyond  $\sim 30$  parsecs
- Target *isolated* dwarfs — systems in a void, far from any MW-mass galaxies



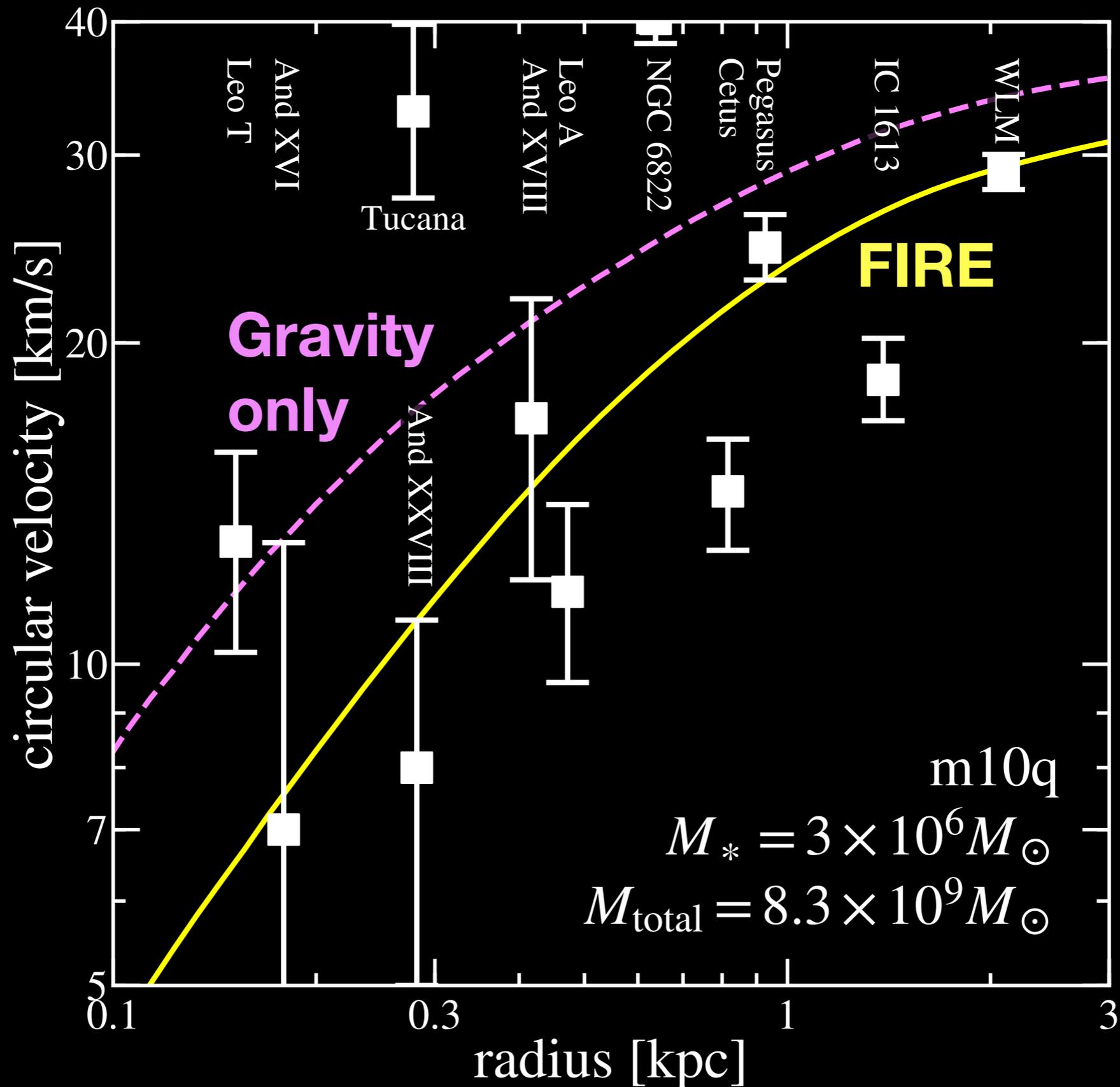
# Internal structure of FIRE dwarfs



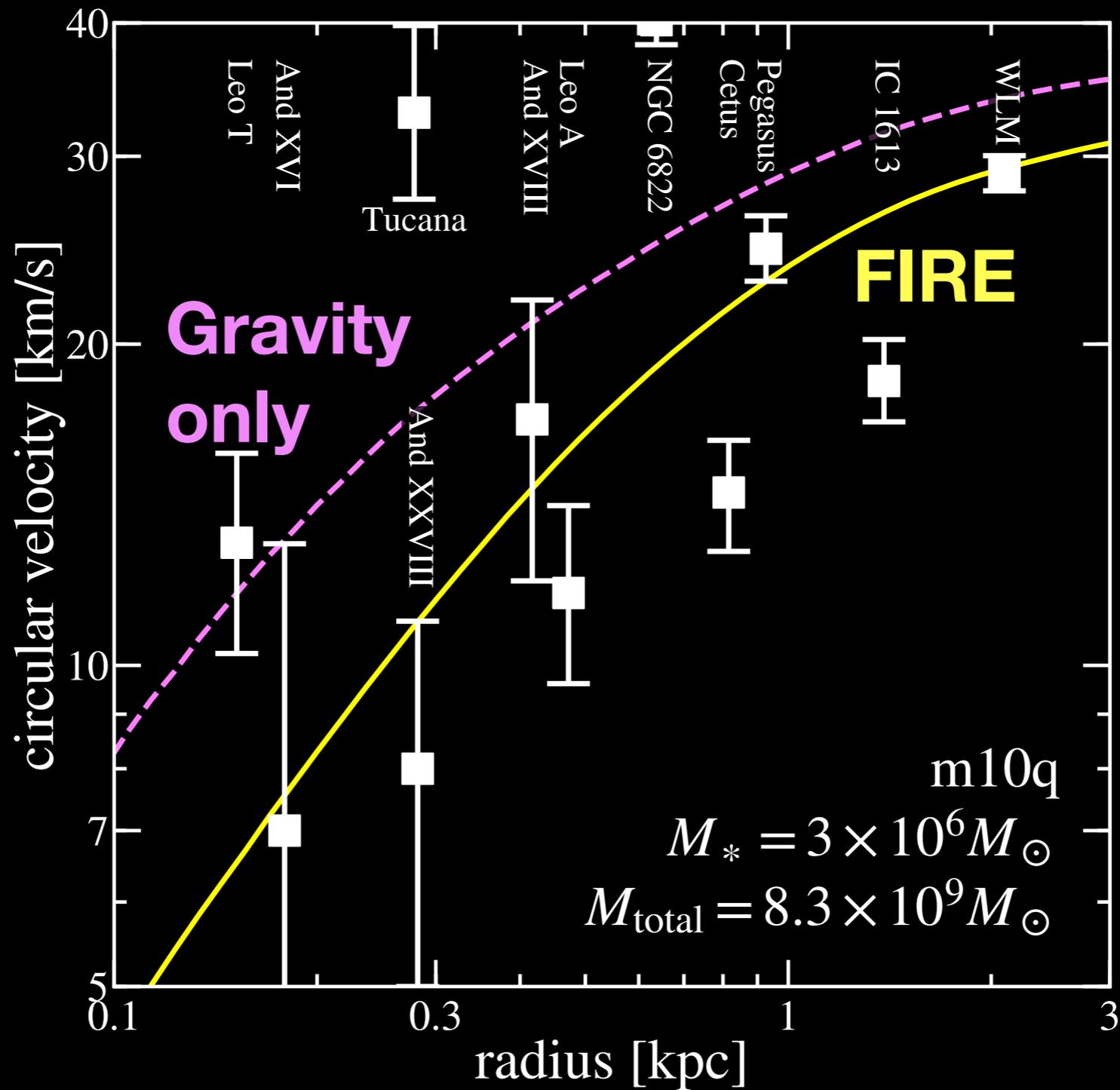
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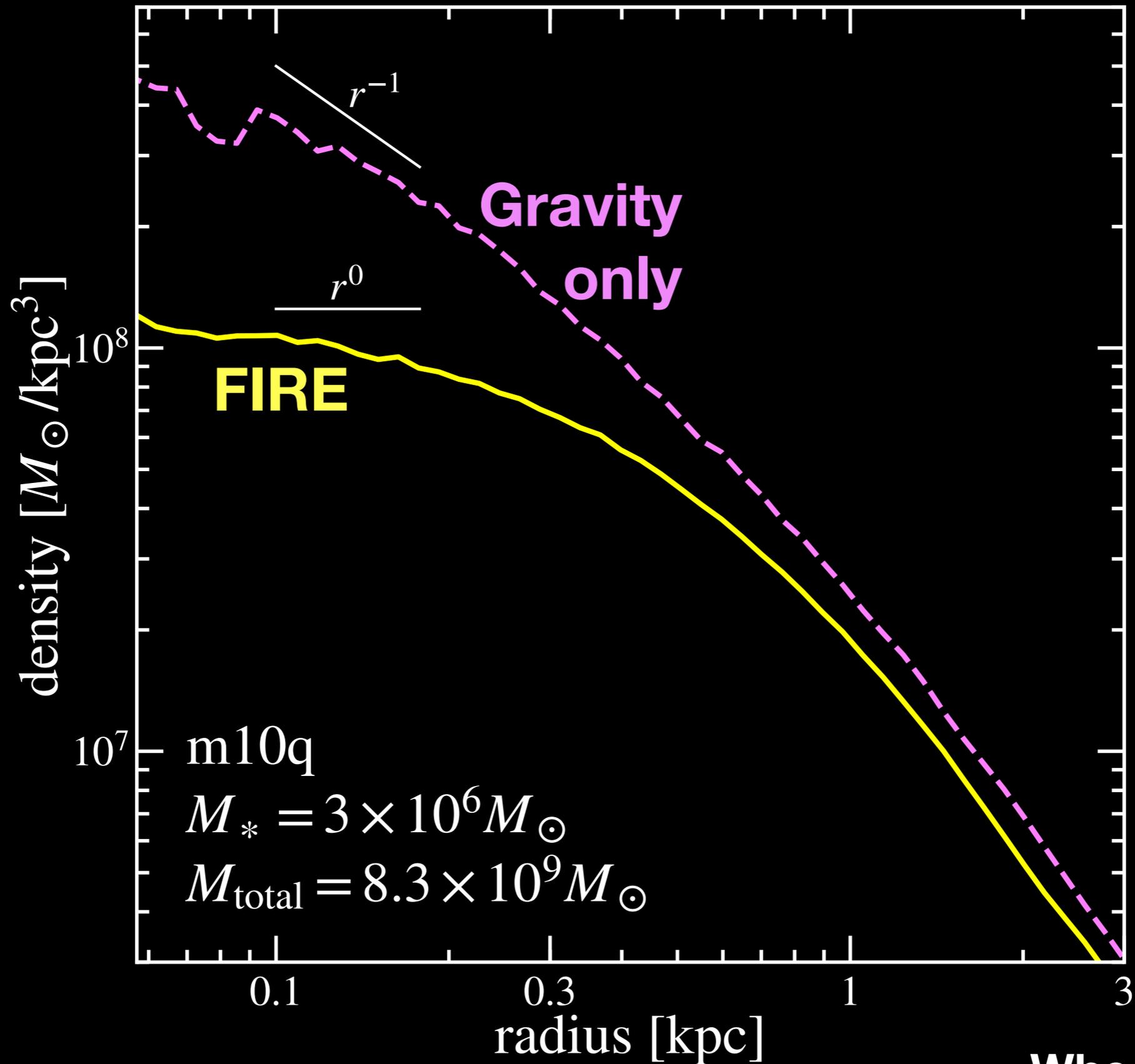


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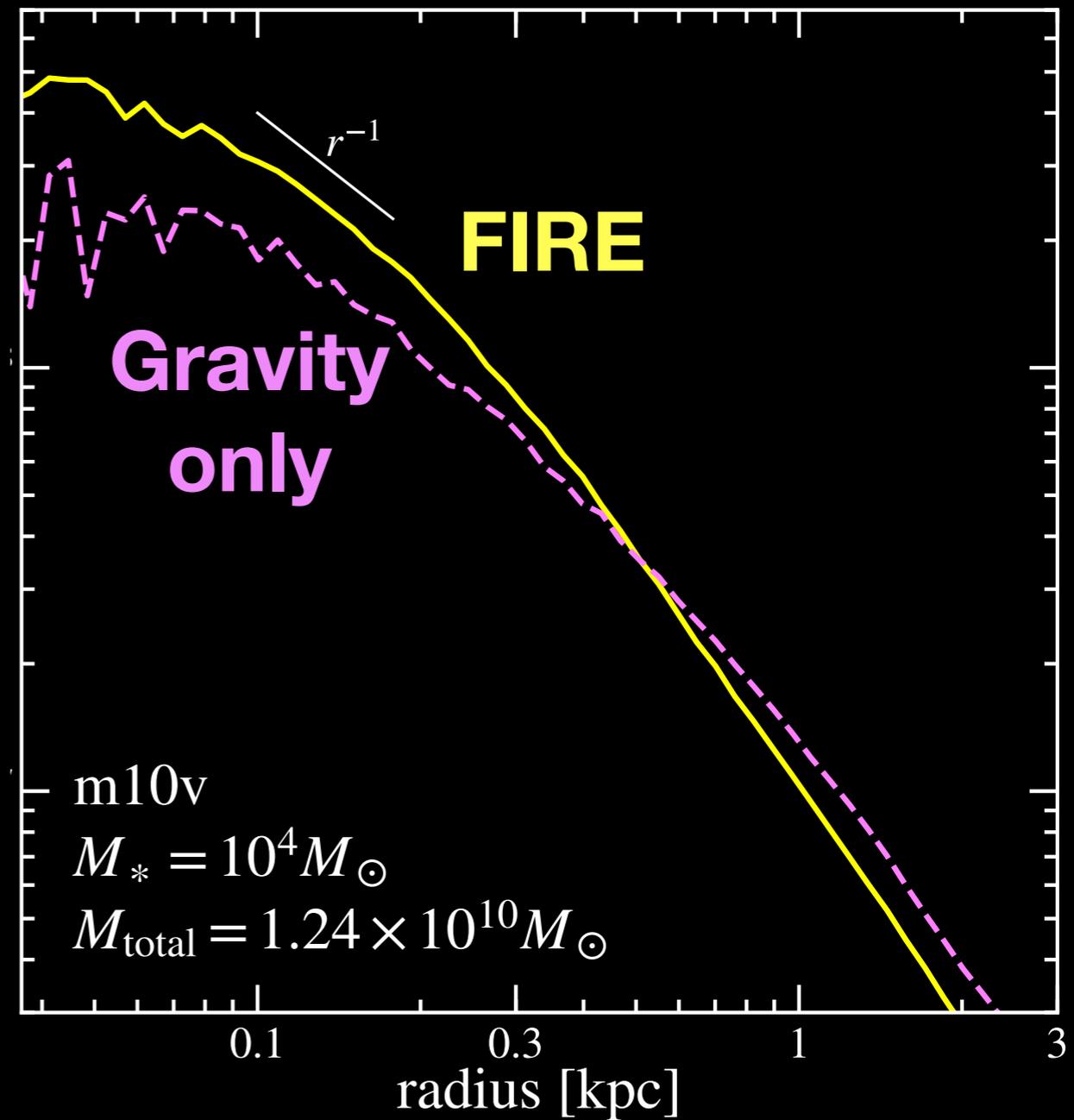
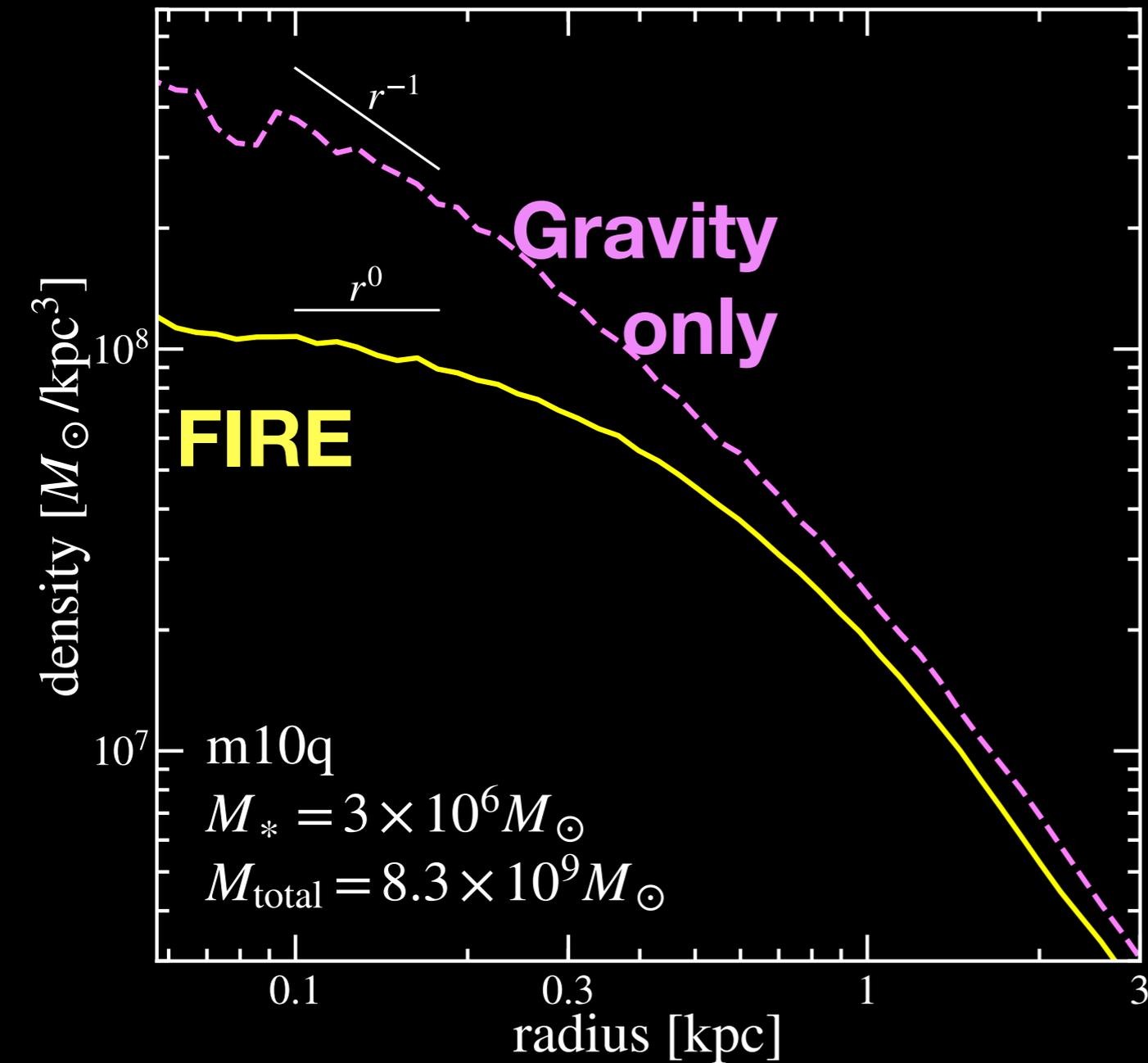


The MW-mass hosts of *ELVIS* on *FIRE* and *Latte* are also free of the central mass problem

# Feedback induced “cores”



# Feedback induced “cores,” *if there’s enough energy*



# What about smaller galaxies?

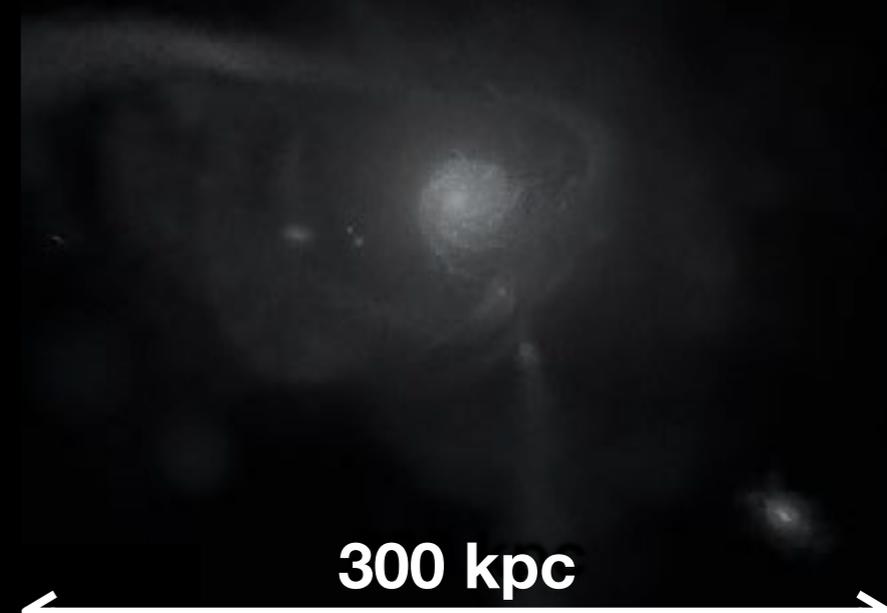
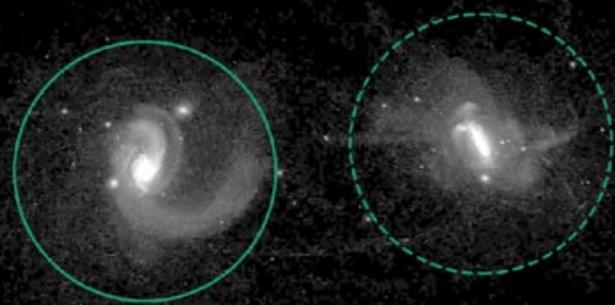
*How do we push make predictions for the ultra-faint population around the Milky Way?*

***ELVIS on FIRE and the Latte suites***

**Isolated dwarf galaxies at ludicrous resolution**

**Triple Latte**

Stars



2000 kpc

0.75 kpc

300 kpc



# Triple Latte: a billion particles in the Milky Way

Current: ELVIS on FIRE + Latte

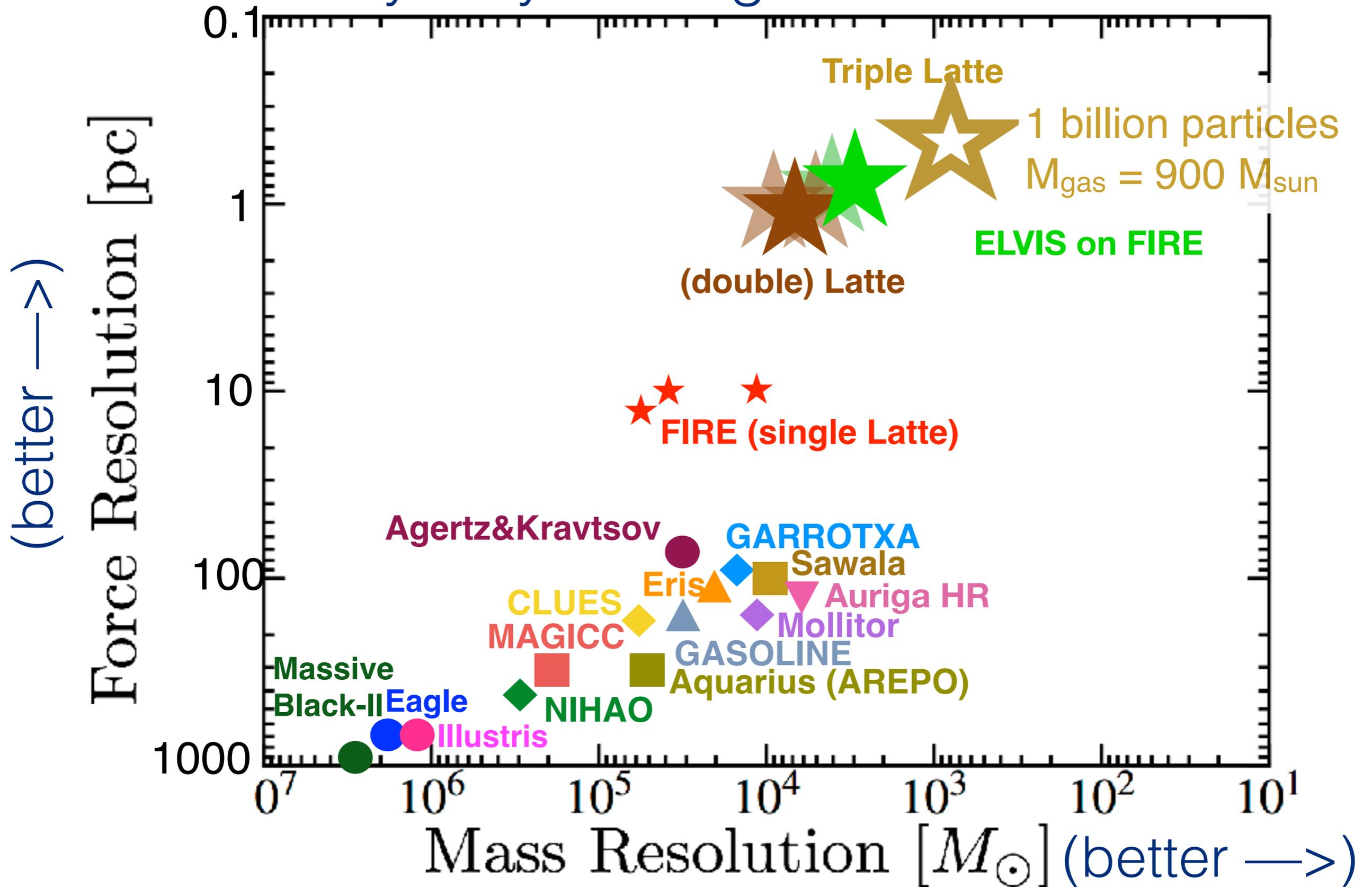
- $m_{\text{gas}} \approx 3,500 - 7,070 M_{\text{sun}}$
- $\sim 100$  million particles in the halo  
(and 300 million in the Local Group)
- 1-5 million core-hours for Latte,  
10-20 million for ELVIS on FIRE

Upcoming: Triple Latte

- $m_{\text{gas,star}} = 880 M_{\text{sun}}$
- 1.1 billion particles
- $\sim 25$  million core-hours
- now running (at  $z=2.5$ )



# cosmological hydrodynamic simulations of Milky Way-mass galaxies to $z = 0$



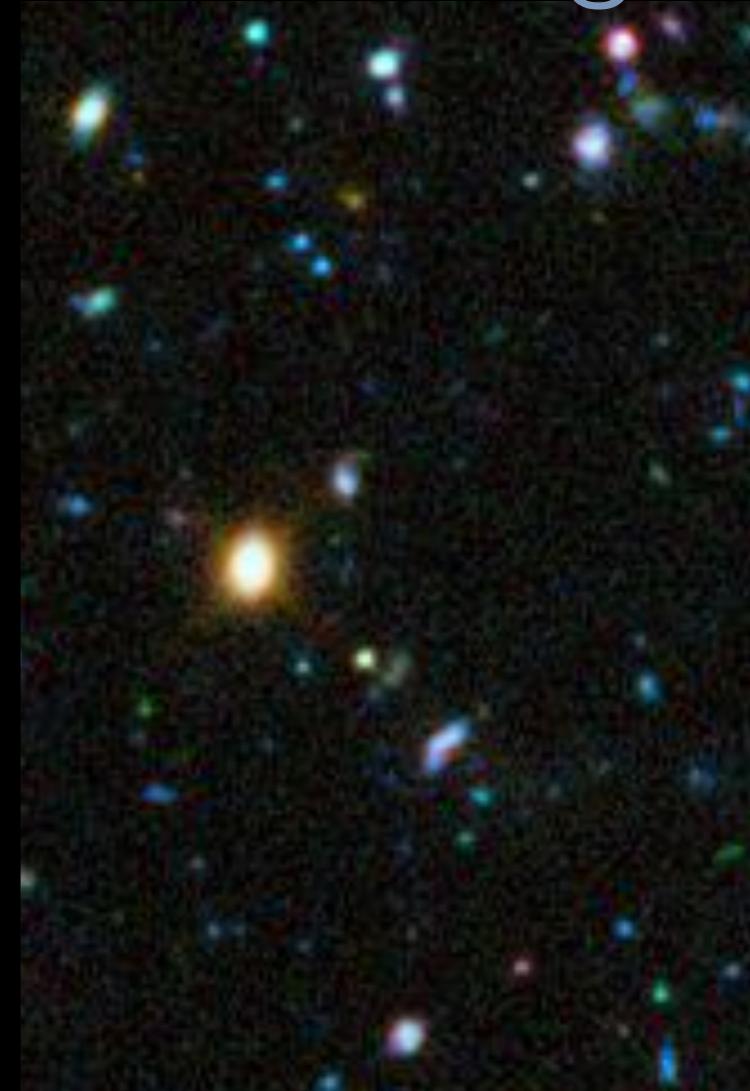
# MW-mass progenitor at $z = 2.5$

300 kpc (physical)

$$\Sigma_{\min} = 10^6 M_{\odot} / \text{kpc}^2$$

# MW-mass progenitor at $z = 2.5$

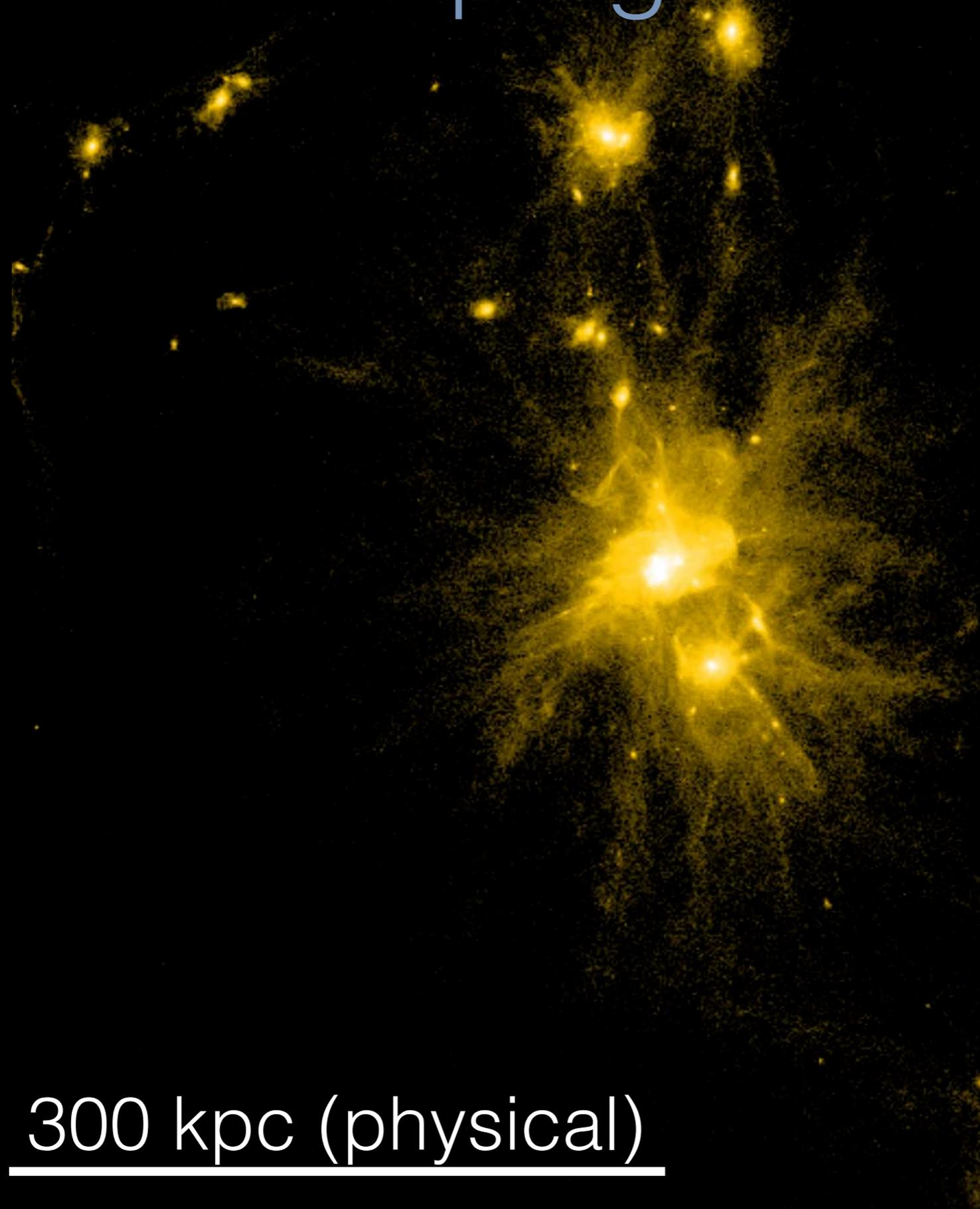
HST image



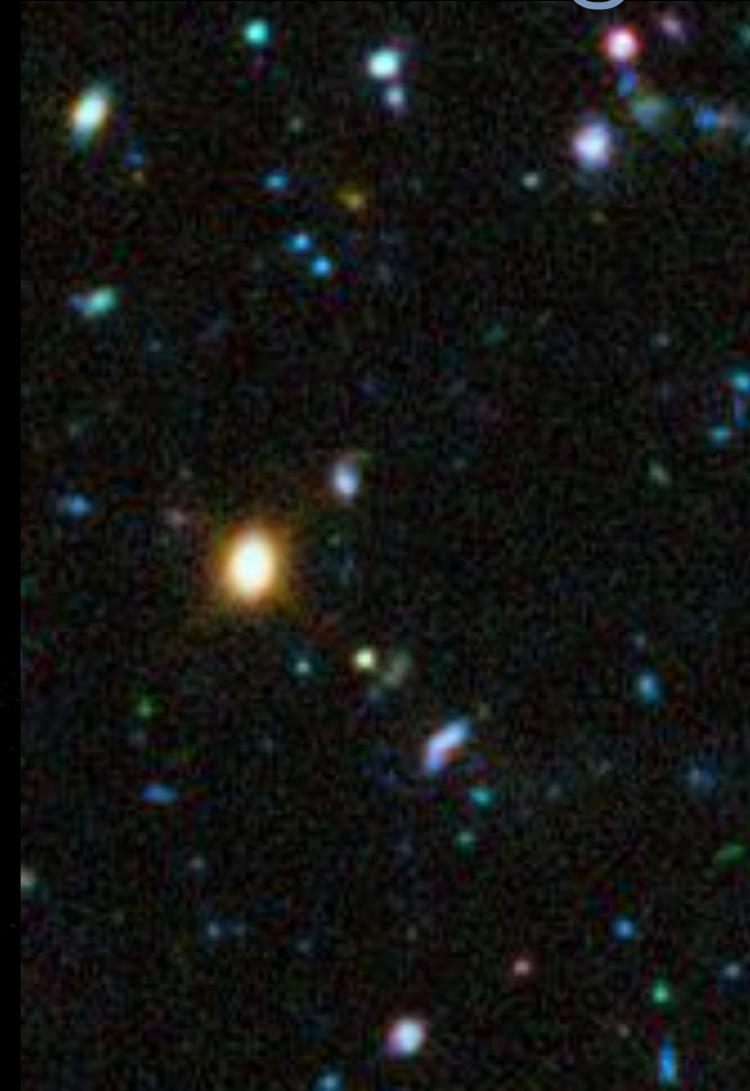
300 kpc (physical)

$$\Sigma_{\min} = 10^6 M_{\odot} / \text{kpc}^2$$

# MW-mass progenitor at $z = 2.5$



HST image



300 kpc (physical)

$$\Sigma_{\min} = 10^3 M_{\odot} / \text{kpc}^2$$

# Conclusions



FIRE simulations **realistically capture the evolution of dwarf galaxies** near the MW and in the Local Group

Together with ultra-high res ( $\sim 30 M_{\text{sun}}$ ) sims of *isolated* dwarfs, our results indicate that **baryonic physics can explain the “small-scale problems”**

Triple Latte (currently running) will provide **self-consistent predictions for ultra-faint dwarfs** around the MW for the first time



**[this slide intentionally left blank]**

[the above statement is a lie]

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James Bullock (UC Irvine)

Mike Boylan-Kolchin (UT Austin)

Andrew Wetzel (UC Davis)

Chris Hayward (CCA)

Robert Feldmann (ETH Zurich)

***~30 - 40 graduate students***

***and postdocs***



Sarah Wellon



Ammond Fielding



Cameron Hummels

Shea Garr



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dark matter*

*predictions for  
next-gen telescopes*

*gravitational  
wave sources (LISA)*

# What are we studying with FIRE?



# What are we studying with FIRE?

## ***Titles***

magnetic medium massive  
local way-mass satellites  
physics masses assembly  
sizes neutral metal  
morphologies versus  
baryons **simulations**  
reconciling low-mass  
mass reionization hydrogen neutrino  
realistic haloes view merging  
gradients complicates testing disc  
proto-galaxies dynamical  
population using diagnostics  
soft scaling photons effects  
drives instability sub-1 quiescent  
bursty halo fires  
lumpy **galaxies** noon  
binary nuclei stars origin  
missing **formation** radial  
angular black high flows impact mergers  
effect emergence evolution resonant  
difficulty strongly individual  
dark rapid **stellar** r-process  
diffusion dwarf outflows cosmic  
diffuse diverse milky **fire** fluctuations  
simulated fields structure  
efficiency **galaxy**  
simulating momentum environments

## ***Abstracts***

realistic project  
find galactic accretion  
population histories metallicity  
galaxy form msun within cent  
**stellar** interstellar  
observed  
haloes  
mass even winds present  
because radius suite simulation around clumps  
central properties reproduce include  
including surface model **star**  
range disc large scale physics scatter  
redshift study size outflows most  
radii **galaxies** black  
mergers milky zoom-in fractions  
over relation more rate times  
show similar between formed masses  
dwarfs small using processes  
baryonic lower **massive** distribution  
dark high **stars** matter covering  
high-resolution resolution simulated  
effects isolated density gradients medium  
**halo simulations**  
dwarf environments fraction  
**fire** evolution observations time  
m star models clusters  
consistent  
**cosmological**

# Galaxy formation

Gas

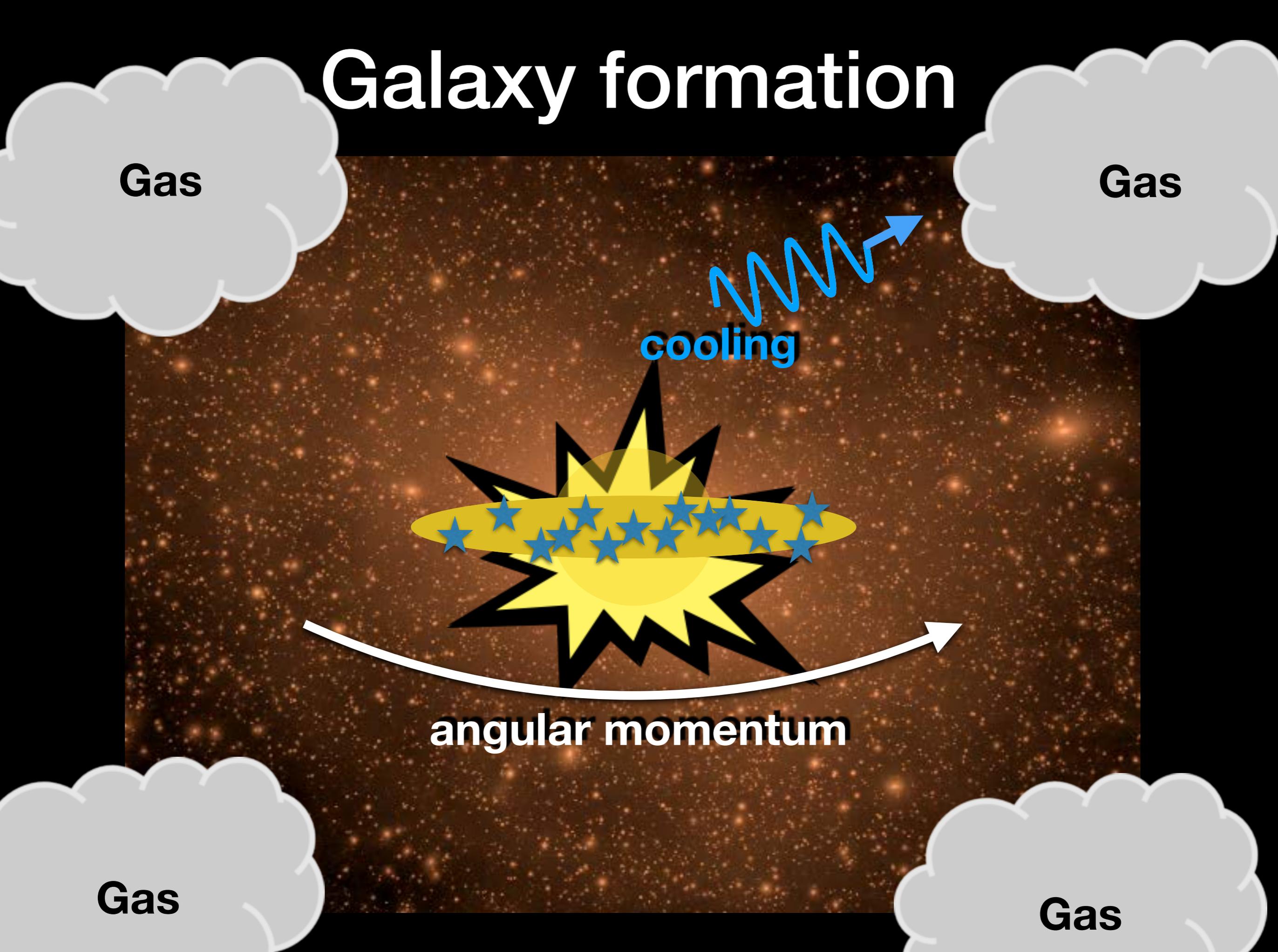
Gas

cooling

angular momentum

Gas

Gas



# Galaxy formation

Gas

Gas

**feedback**  
(e.g. supernovae)

**outflows**

**cooling**

**angular momentum**

Gas

Gas

