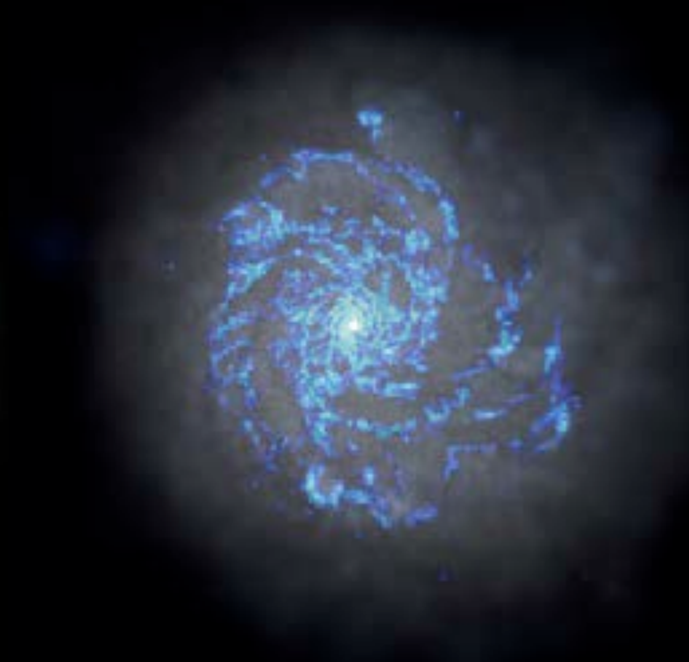
Galaxies on FIRE:
Burning up the small-scale crises of ΛCDM

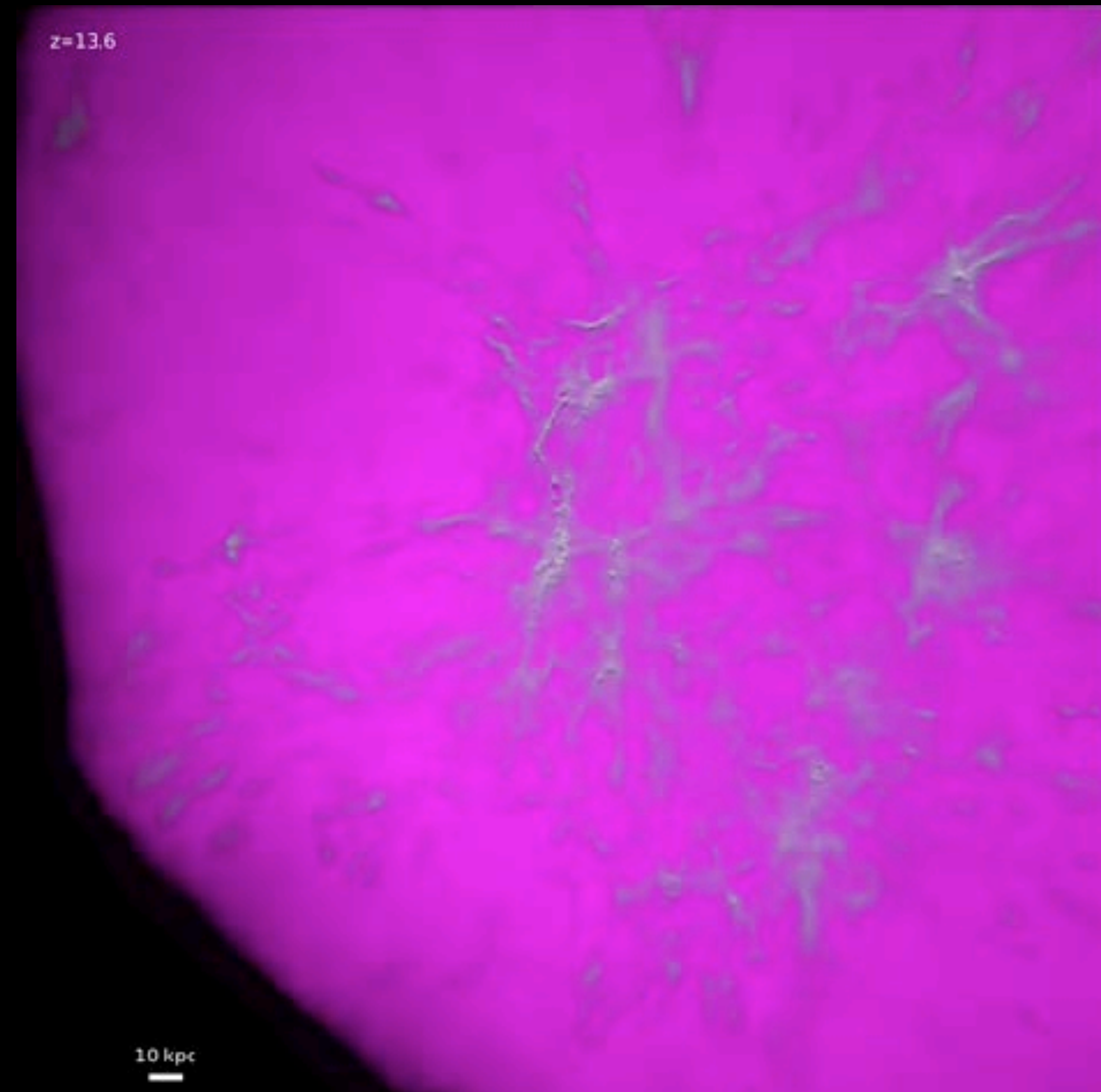
Observed Starlight

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

FIRE Feedback In Realistic Environments

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

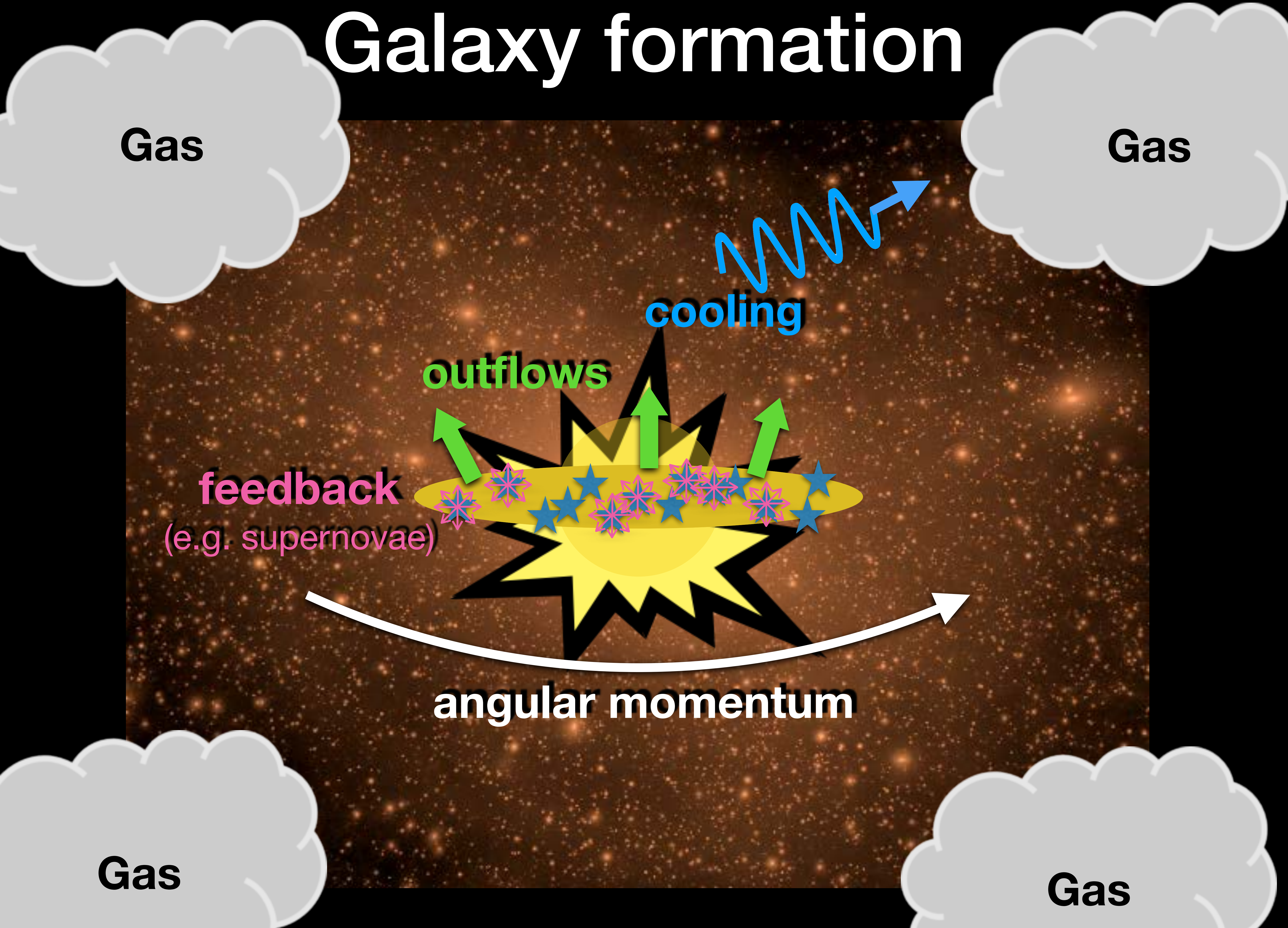
This is (physically) easy to simulate!

Evolution of a Milky Way-like object

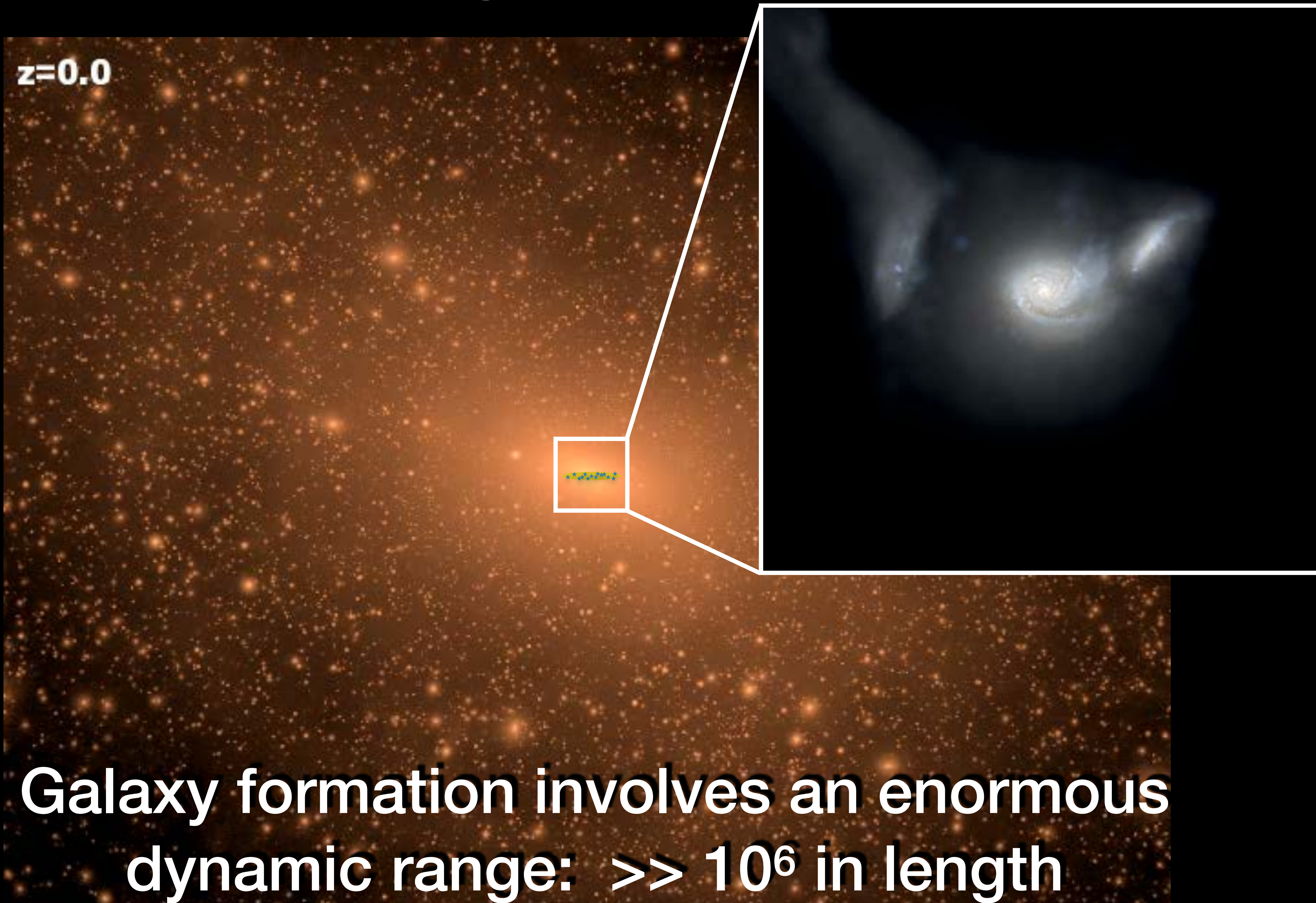
Diemand, Kuhlen, & Madau 2006

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

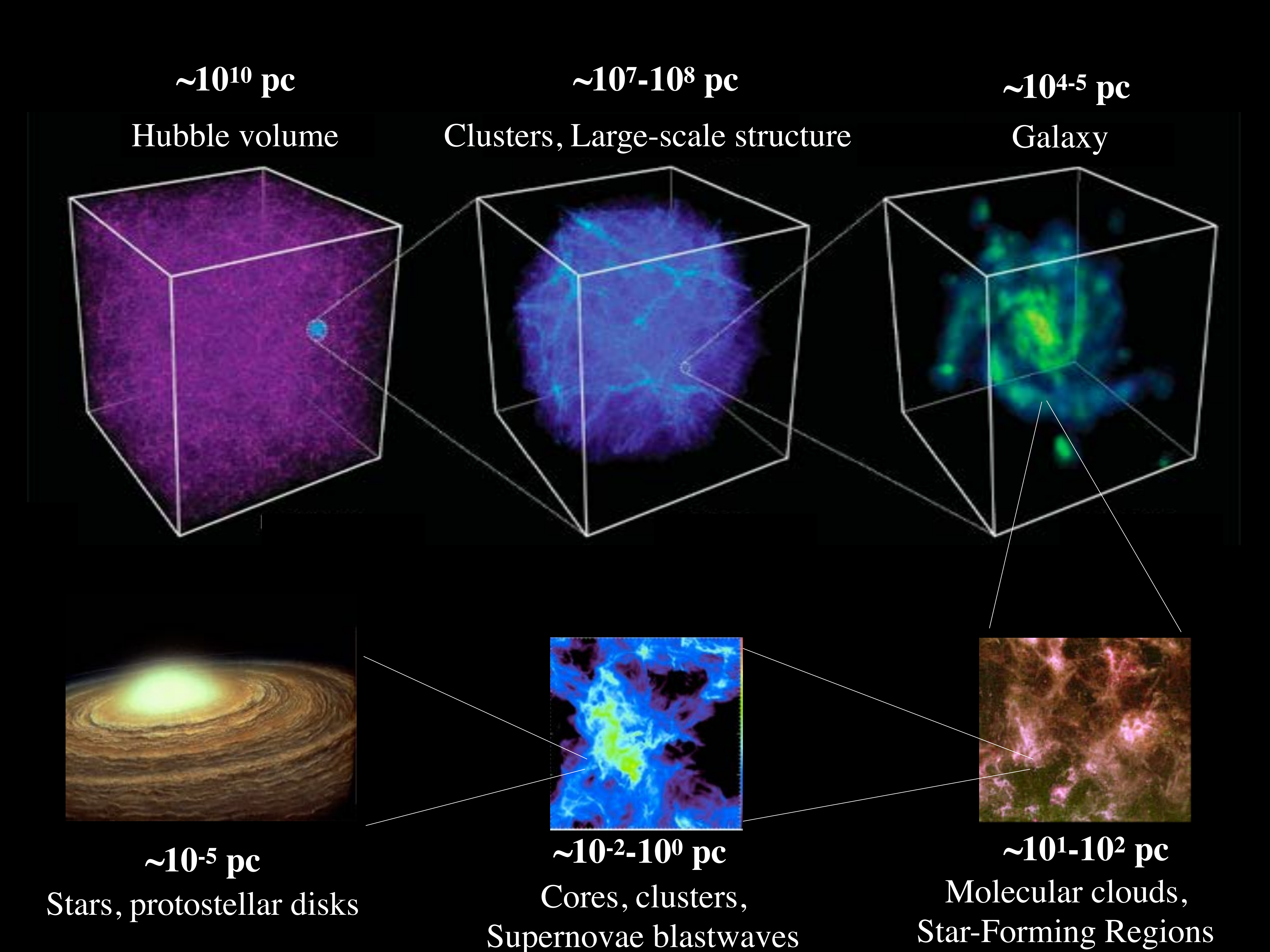
Galaxy formation



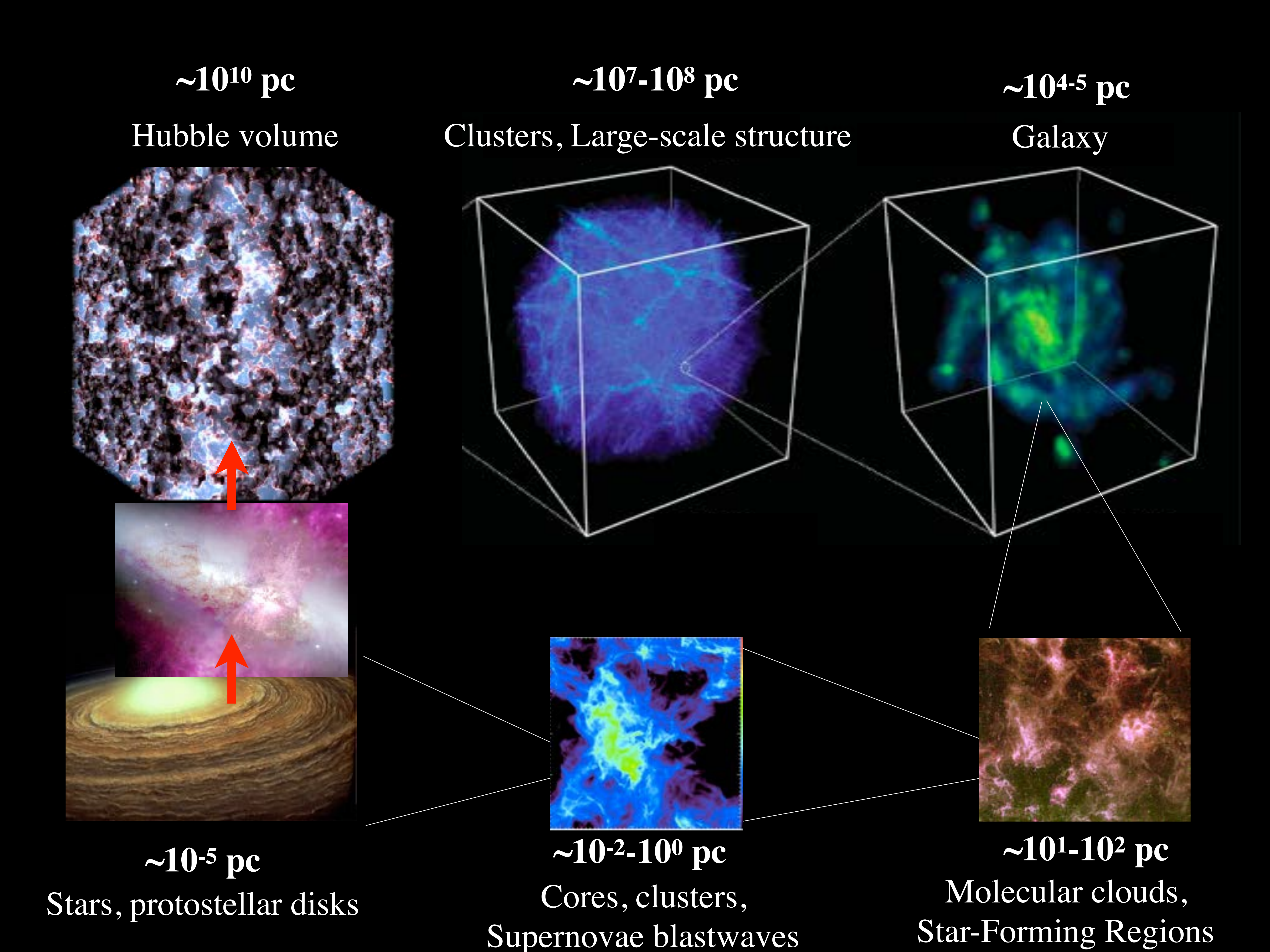
Galaxy formation



Galaxy formation involves an enormous dynamic range: >> 10^6 in length



~10^10 pc
Hubble volume
~10^7-10^8 pc
Clusters, Large-scale structure
~10^4-5 pc
Galaxy
~10^-5 pc
Stars, protostellar disks
~10^-2-10^0 pc
Cores, clusters,
Supernovae blastwaves
~10^1-10^2 pc
Molecular clouds,
Star-Forming Regions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~10^{-2}-10^{0} pc
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~10^{1}-10^{2} pc
Molecular clouds,
Star-Forming Regions

FIRE (tries to) model the physics driving galaxy formation

cosmological collapse

hydrodynamics and gas cooling

star formation in self-gravitating gas

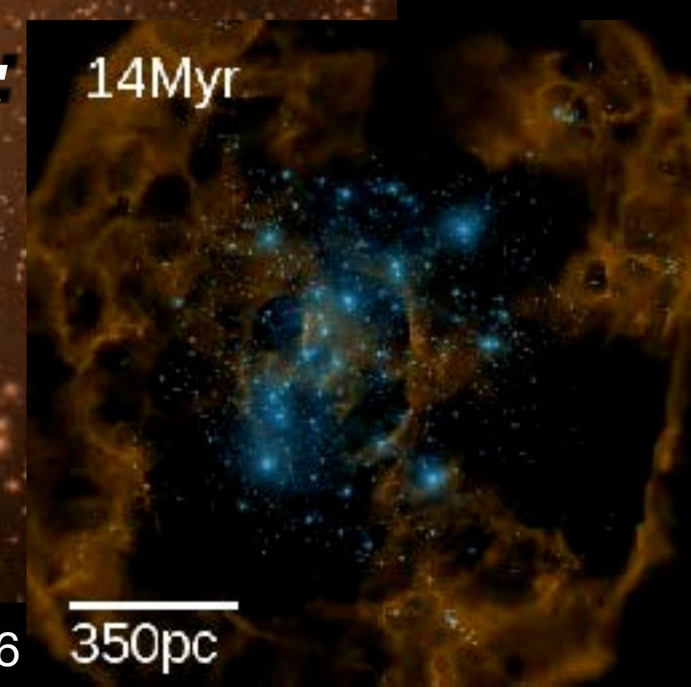
not to scale!

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

— stellar winds

— radiative feedback

— supernovae types Ia and II



M. Grudic+2016

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

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Who is FIRE?

PIs 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

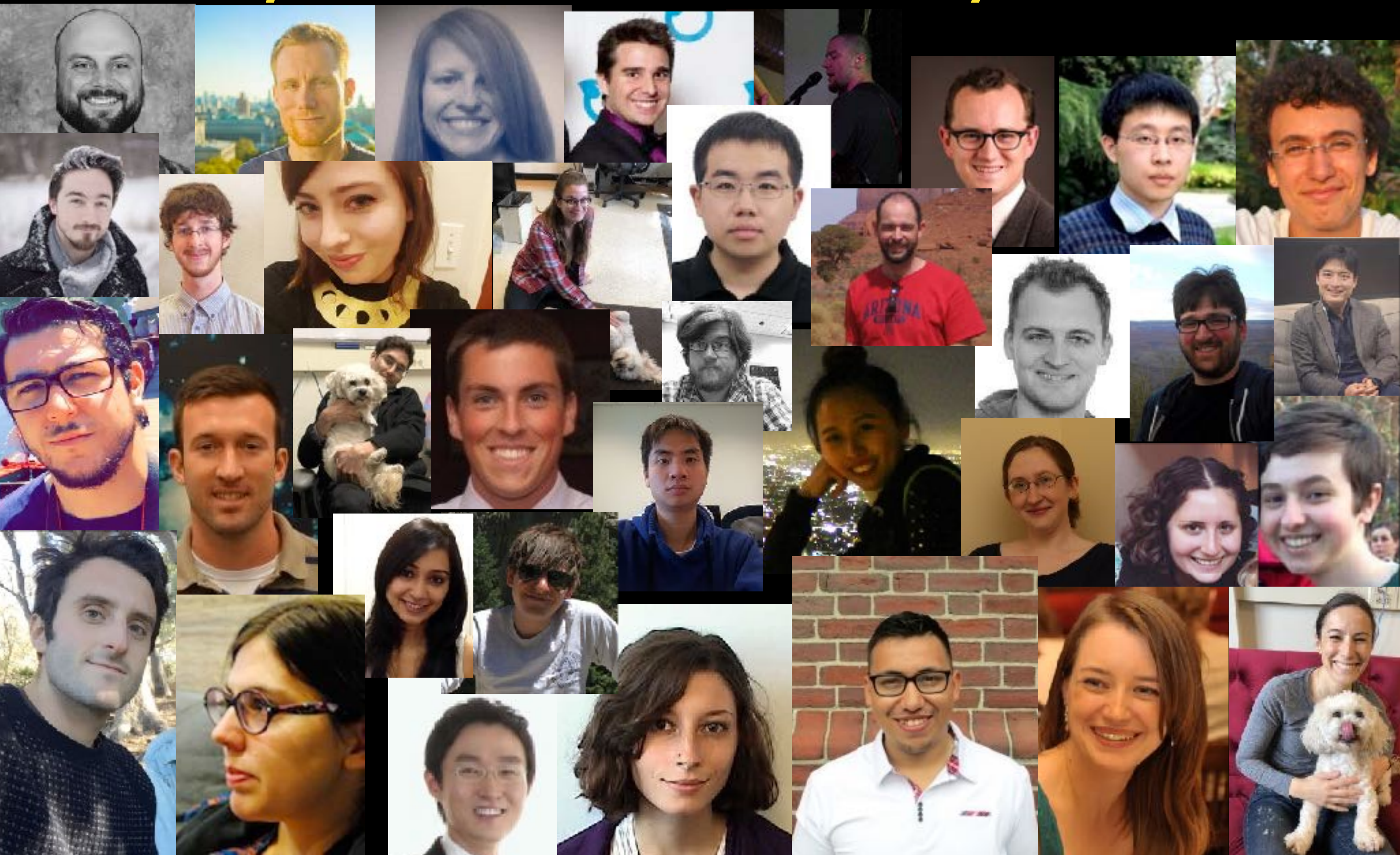
Mike Boylan-Kolchin
UT Austin

Chris Hayward
CCA

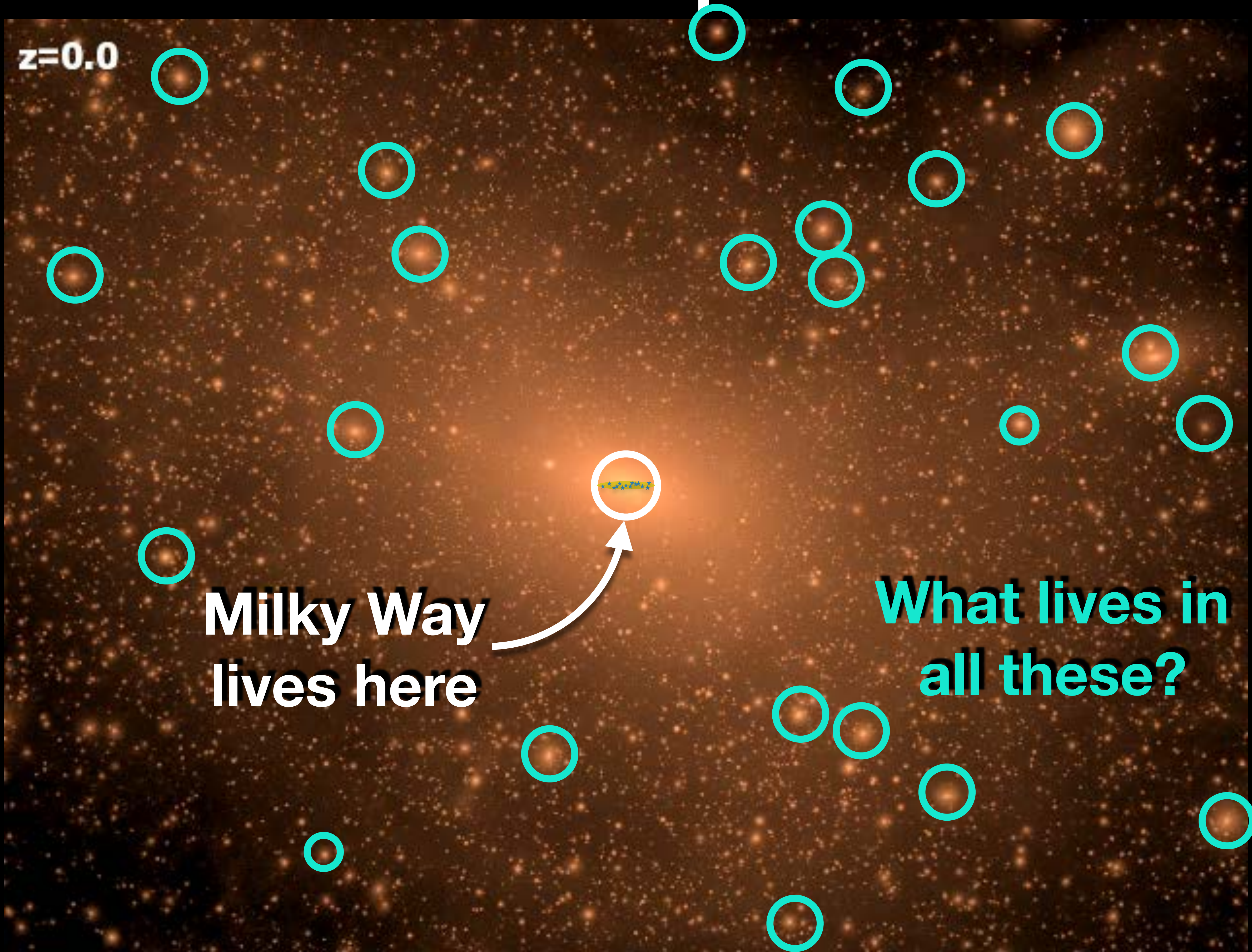
Robert Feldmann
ETH Zurich

Who is FIRE?

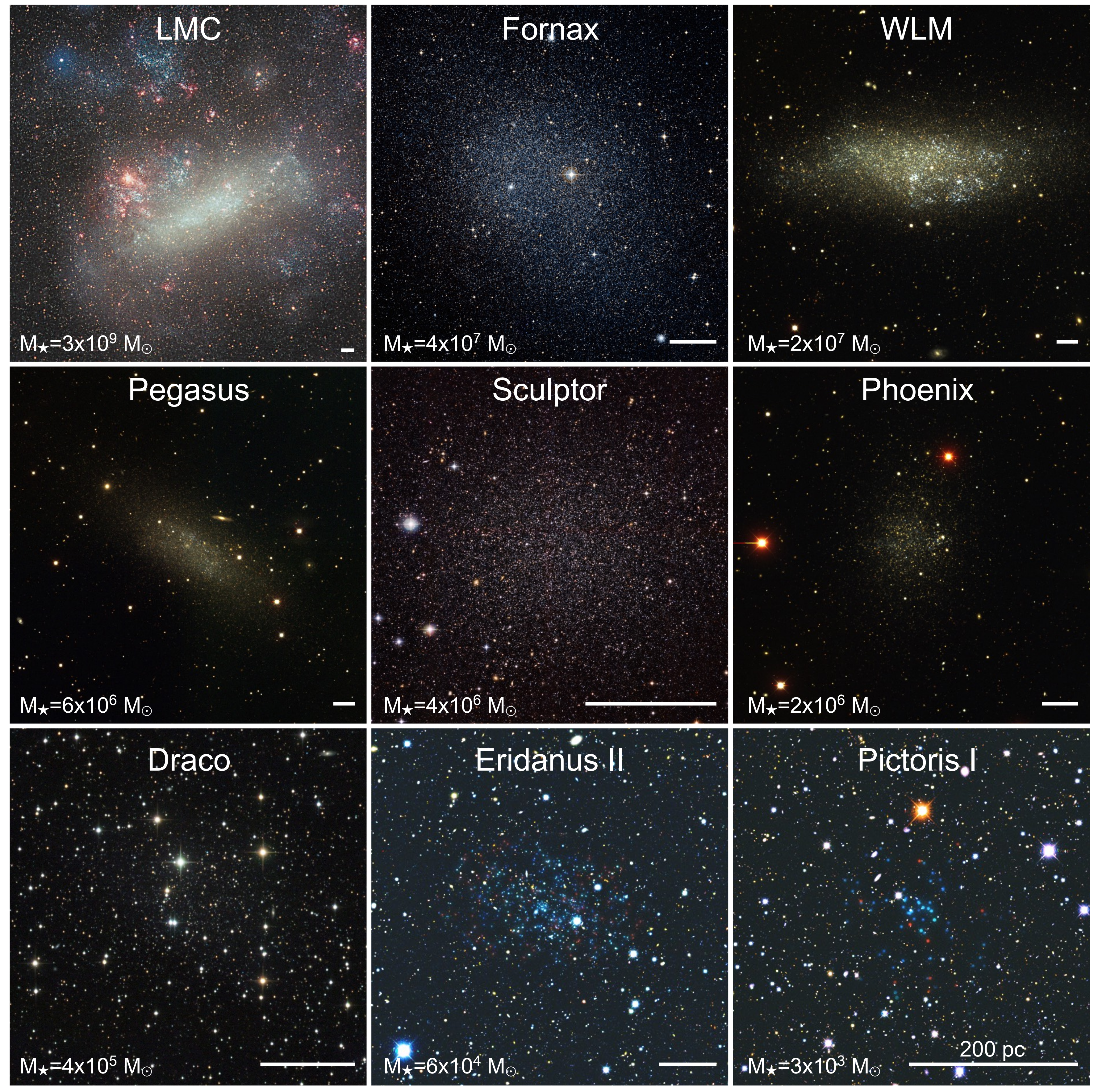
plus 35 - 45 students and postdocs



Small-scale problems



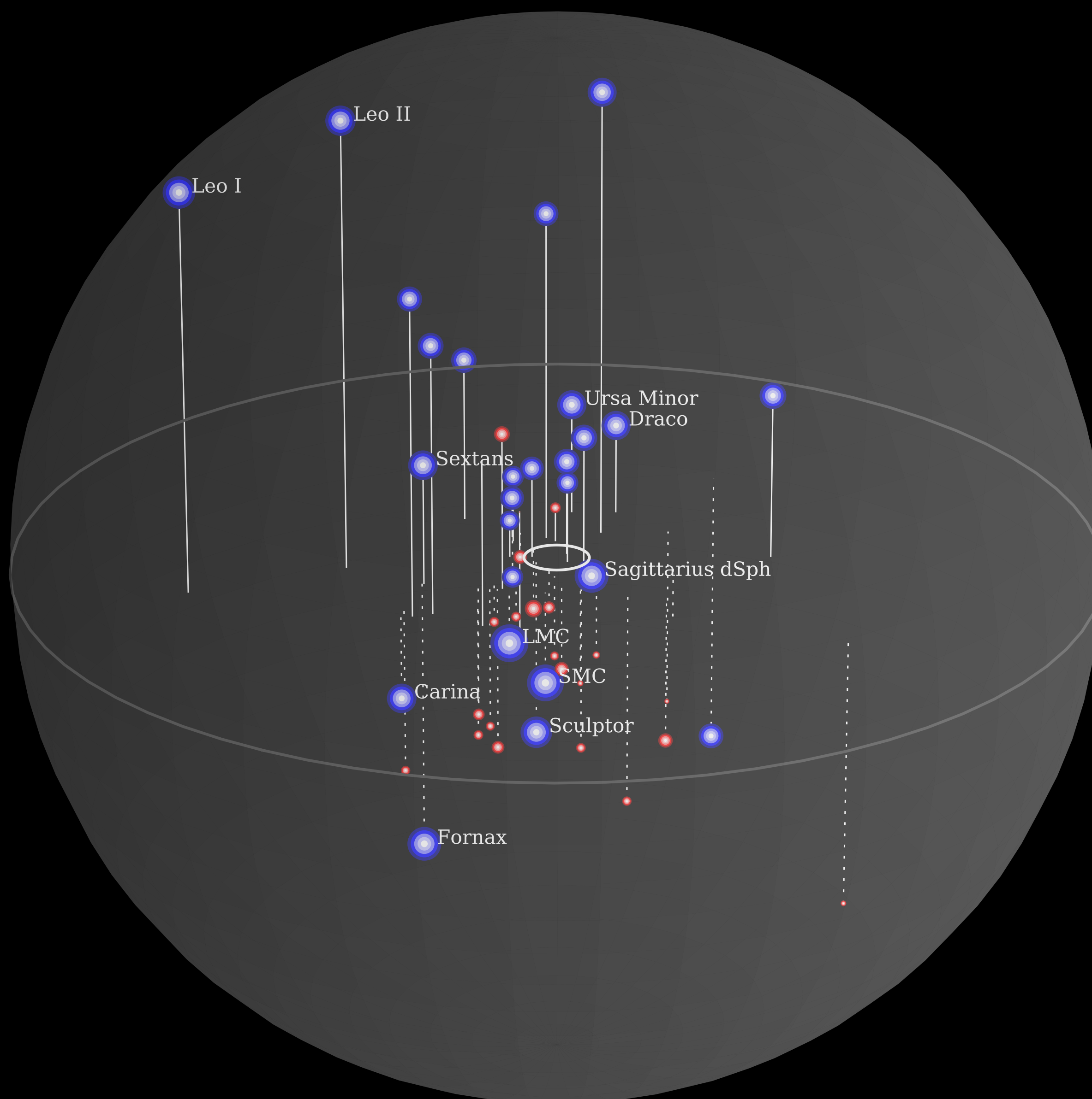
Dwarf galaxies!



Bullock & Boylan-Kolchin, 2017

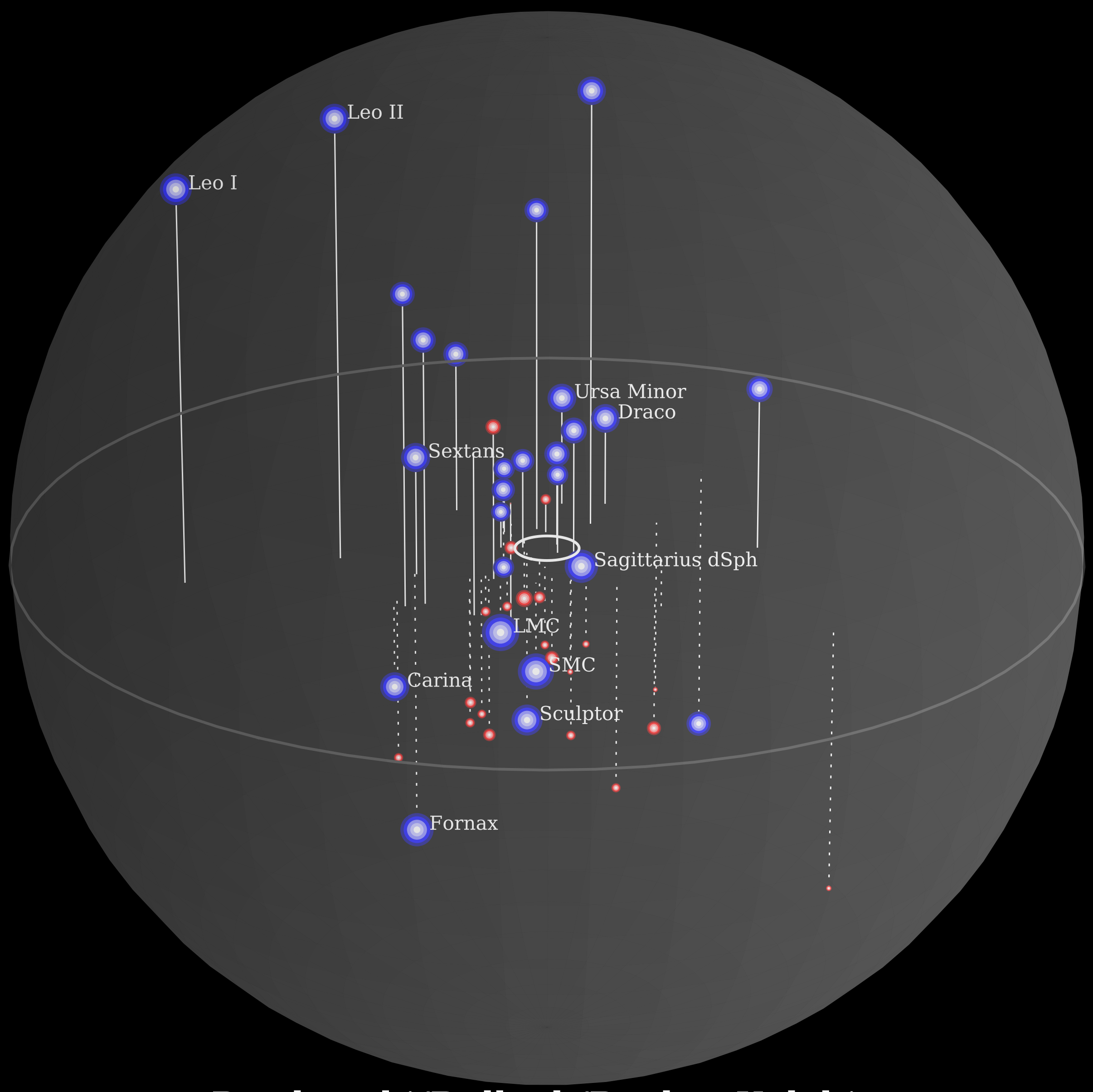
Dwarf galaxies…but not enough

Theory: thousands of "subhalos"



Observations: tens of "satellite galaxies"

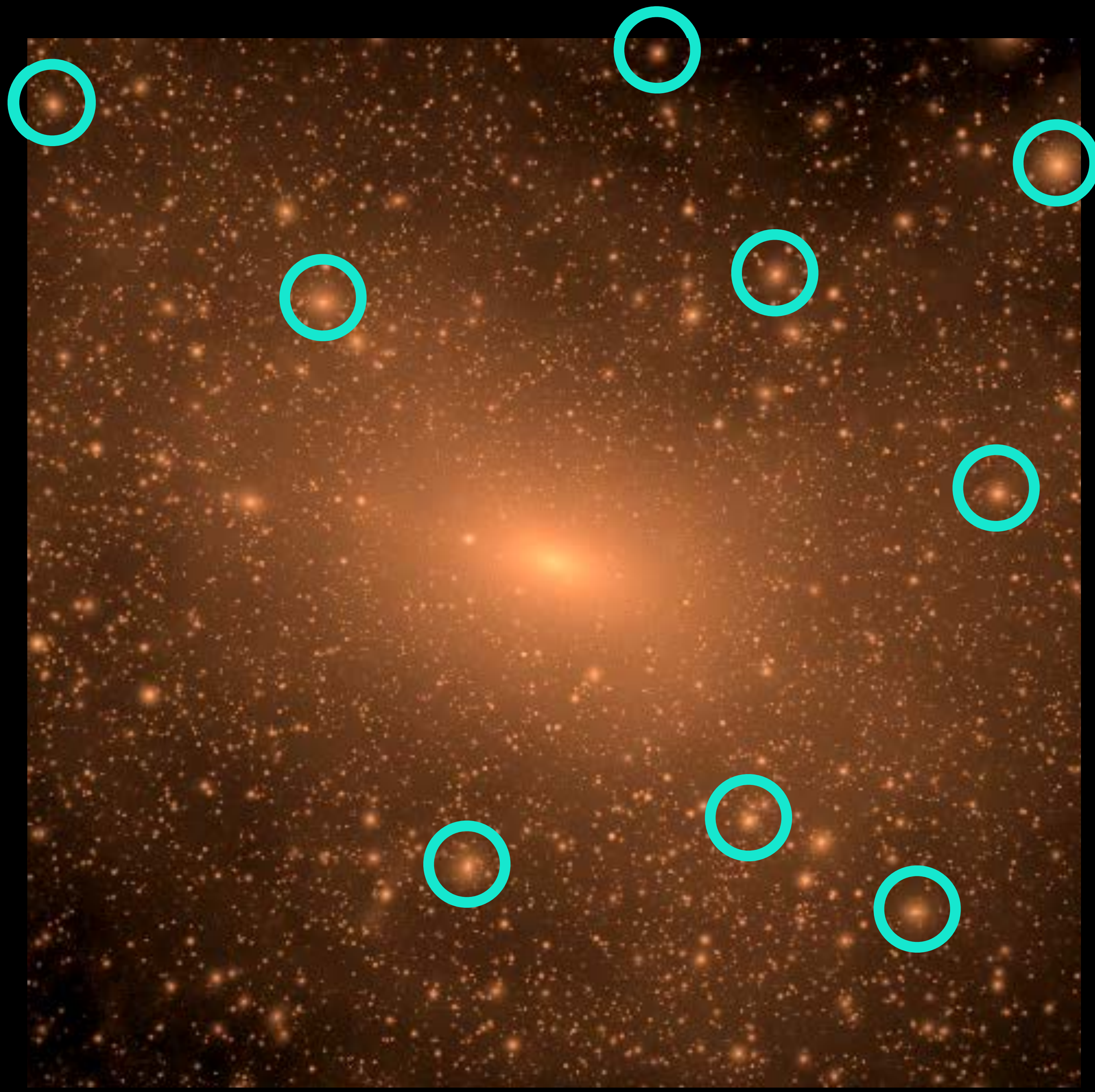
The missing satellites problem

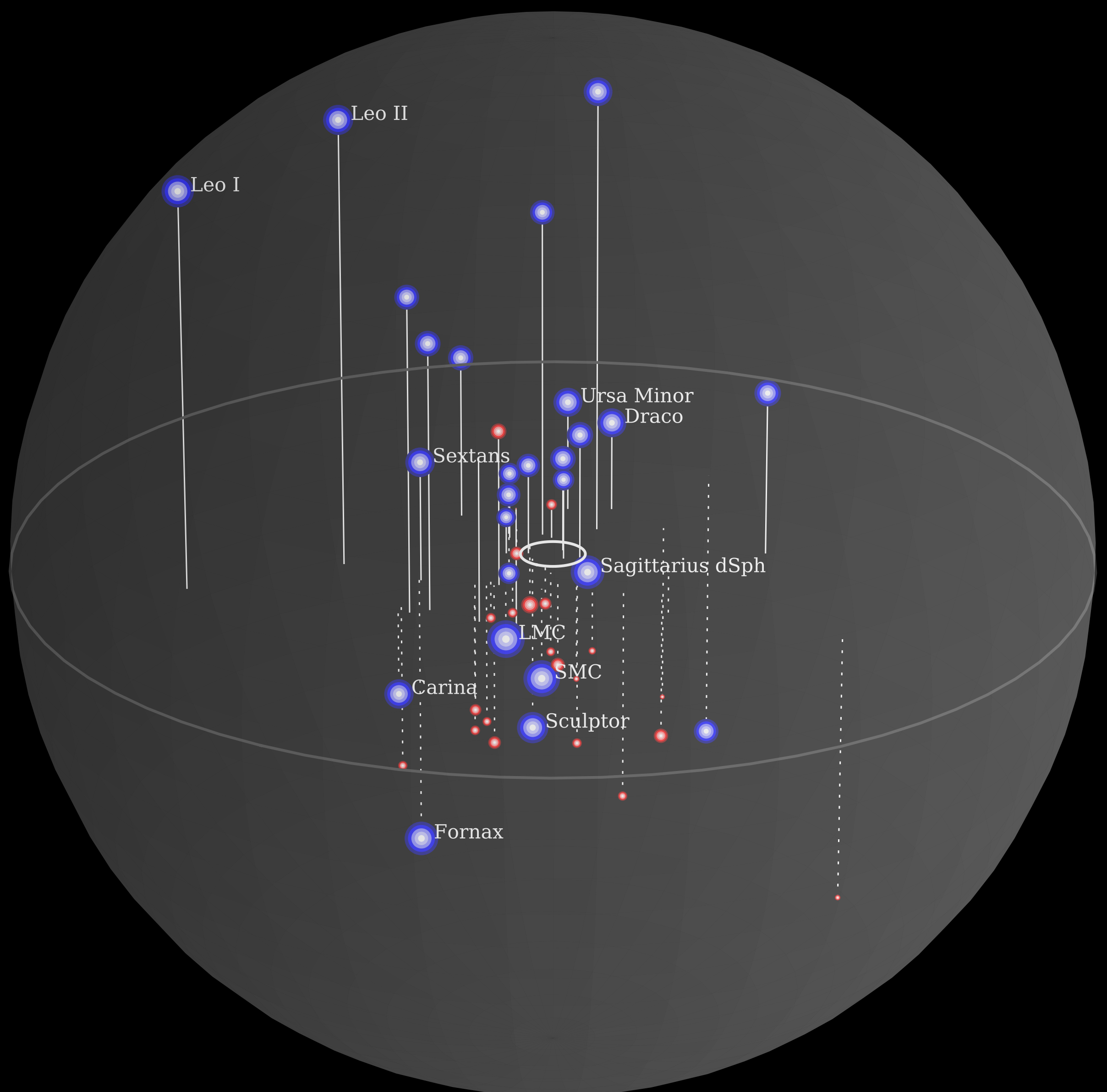


Pawlowski/Bullock/Boylan-Kolchin

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

The missing satellites problem

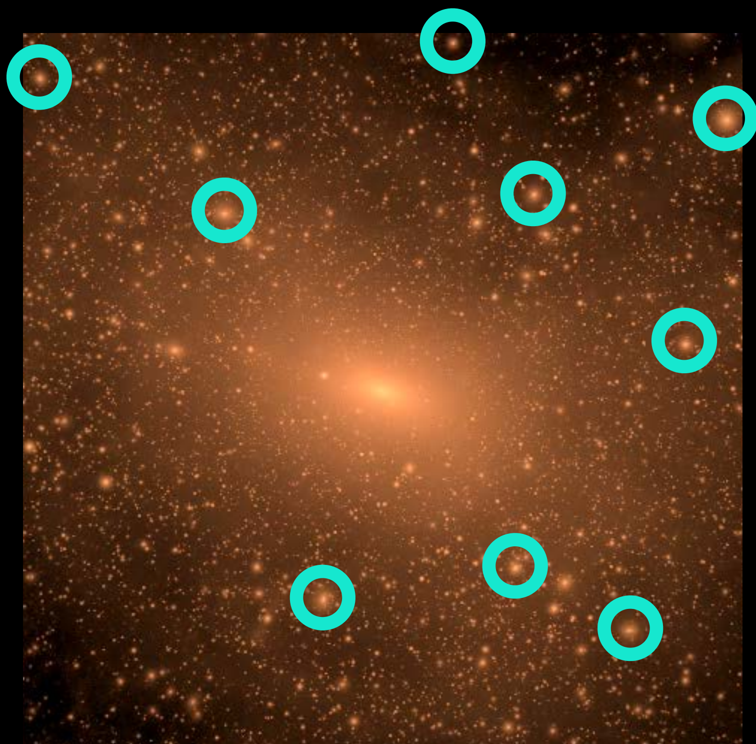


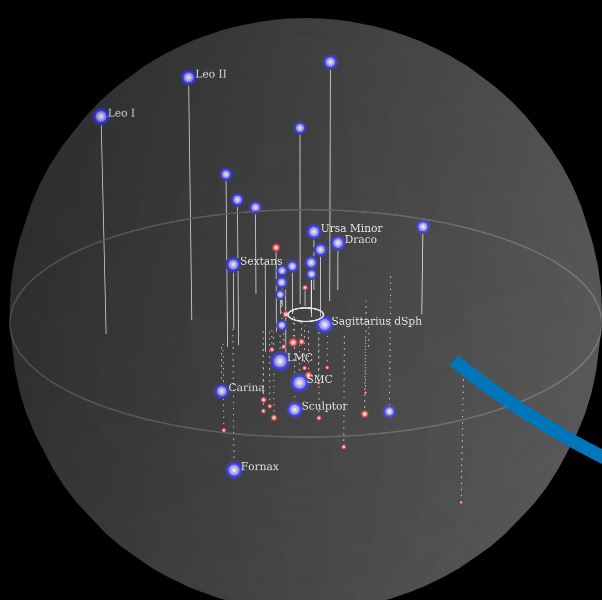


Pawlowski/Bullock/Boylan-Kolchin

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

The central mass problem





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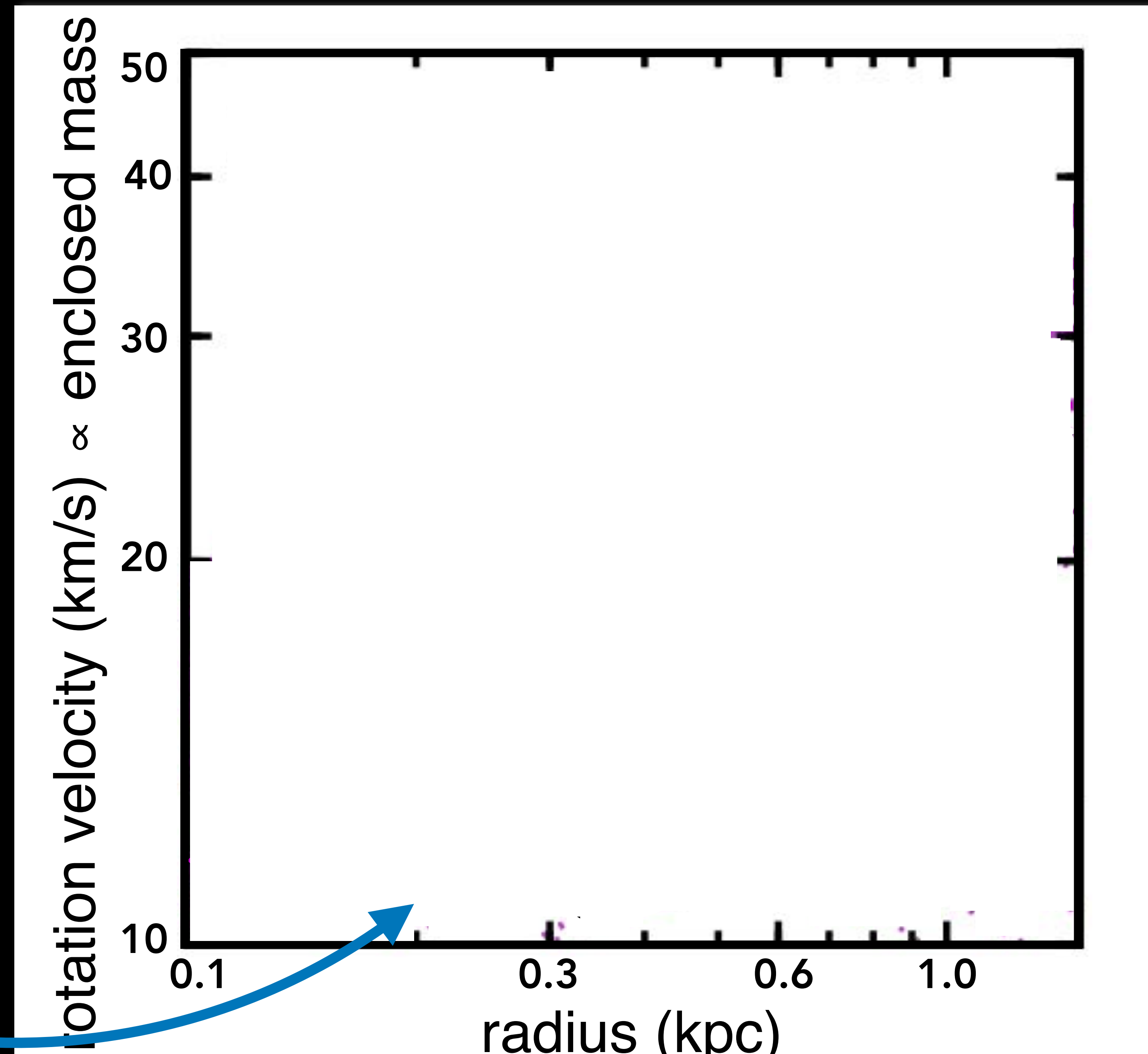
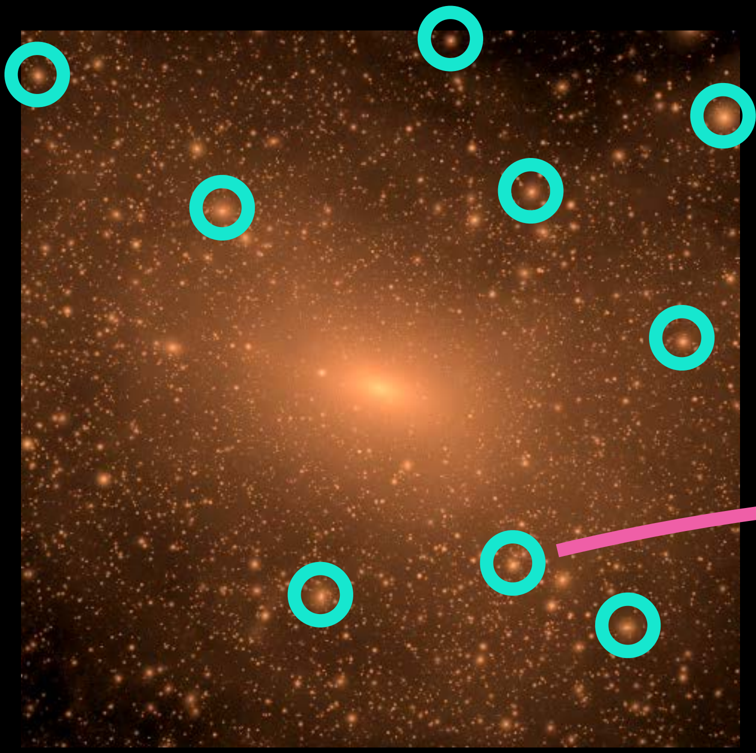
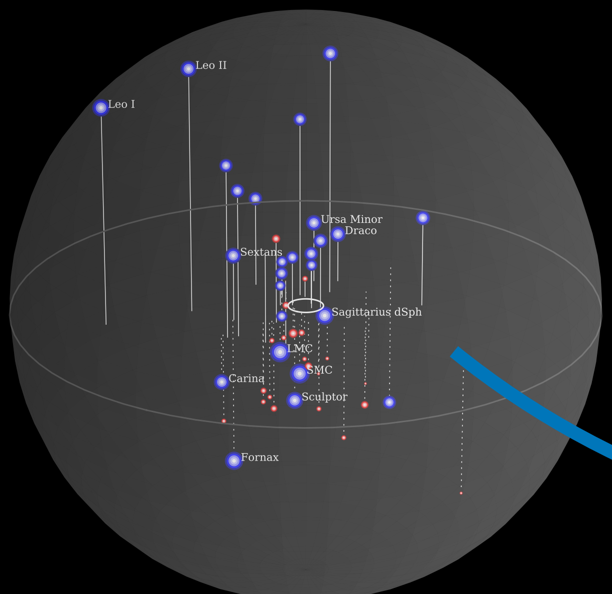


rotation velocity = sqrt[G M(<r)/r]

Compare *dynamical* (total) masses to check

The central mass problem





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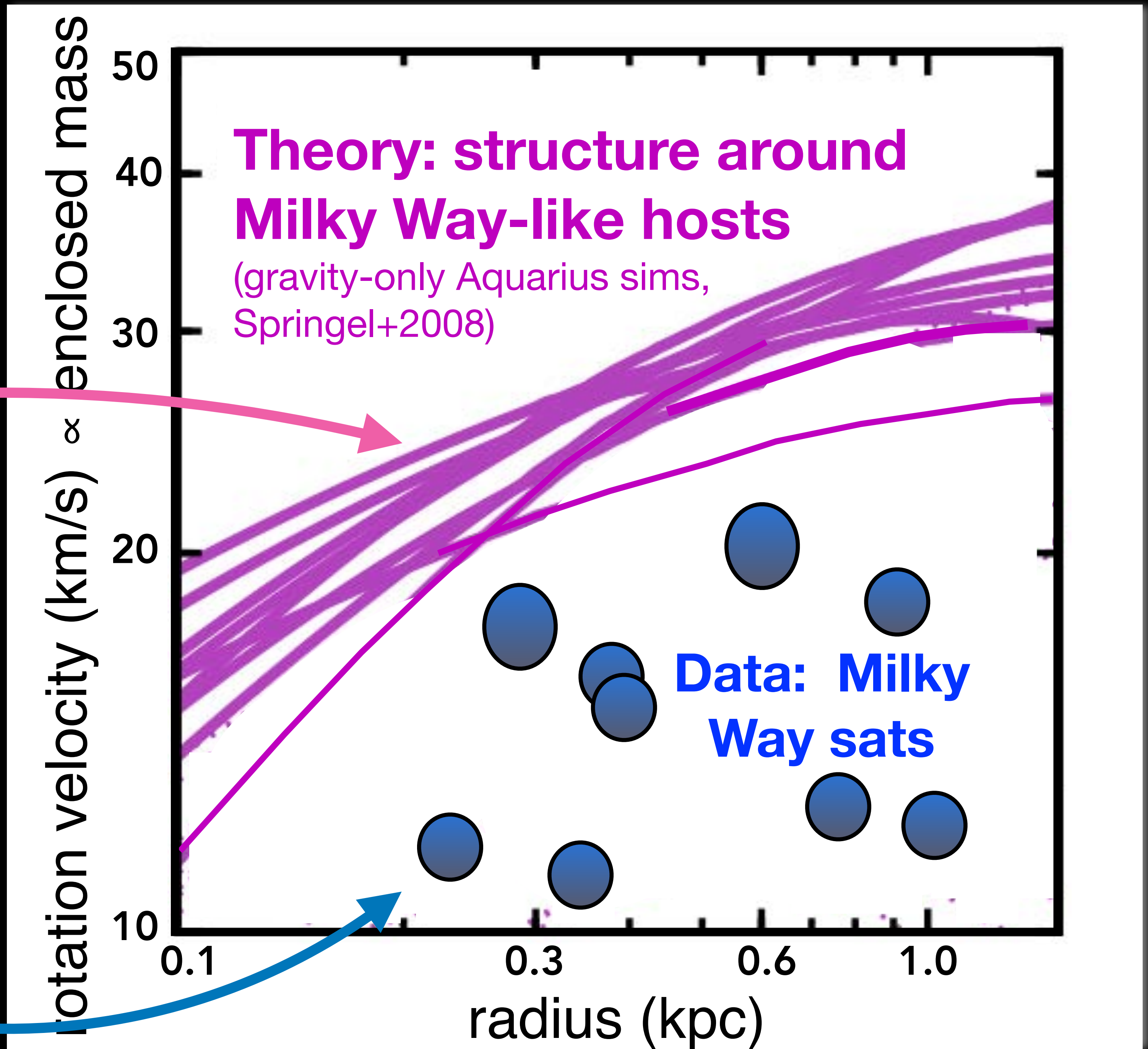
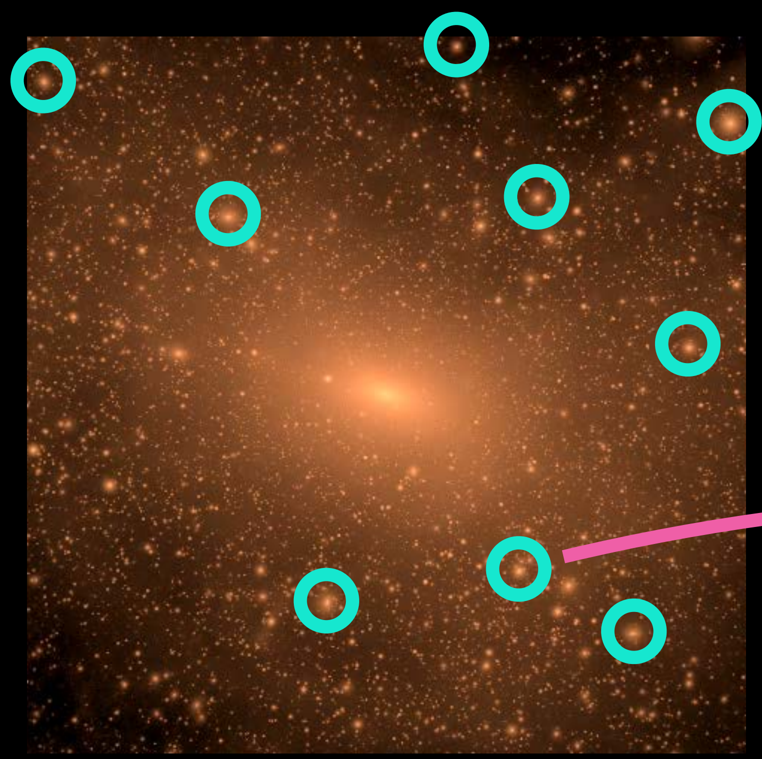
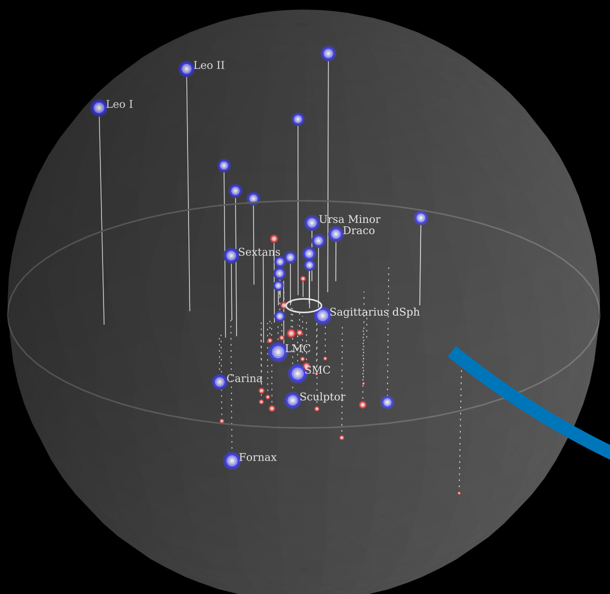


rotation velocity = sqrt[G M(<r)/r]

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





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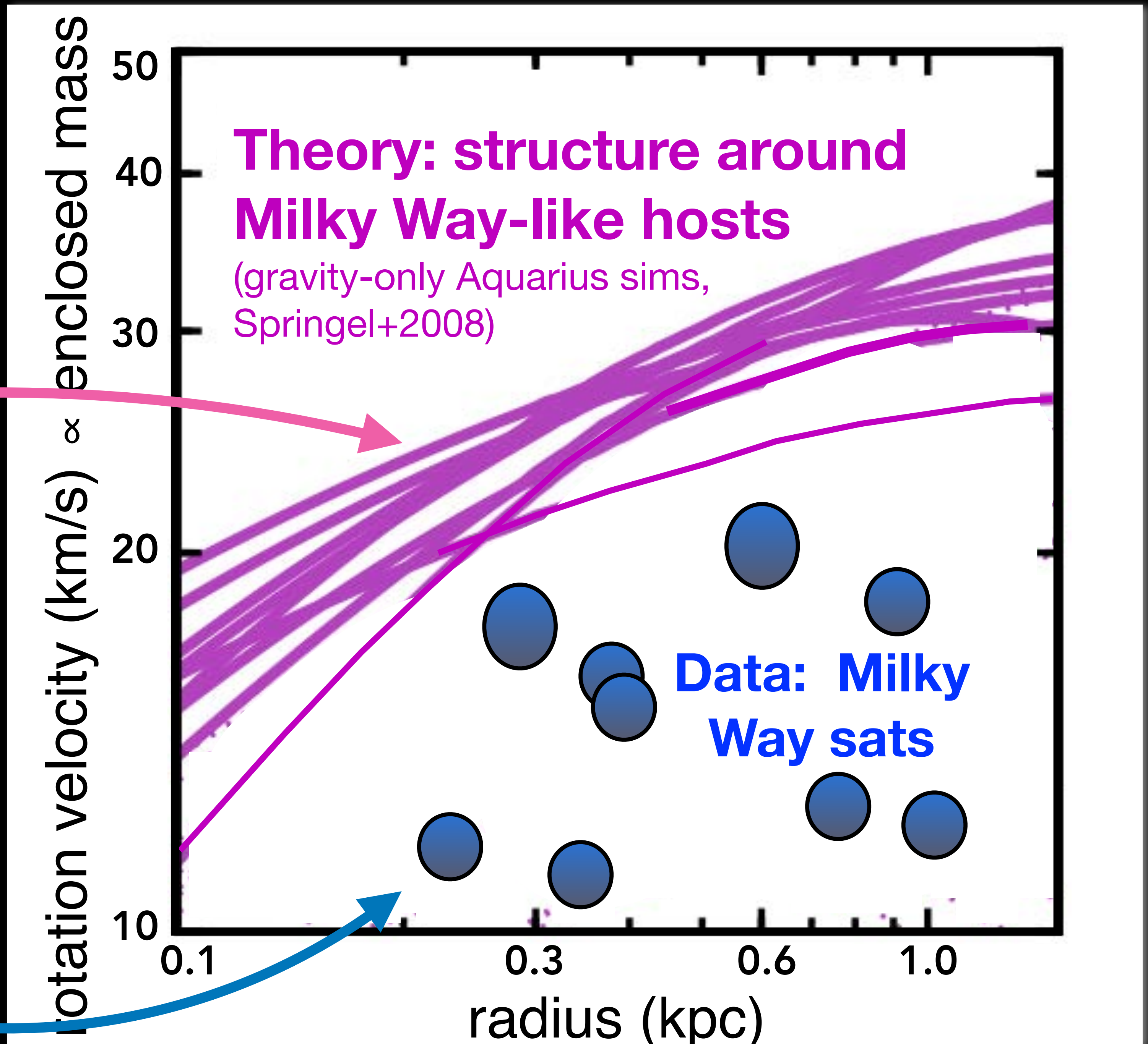

rotation velocity = sqrt[G M(<r)/r]

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"?

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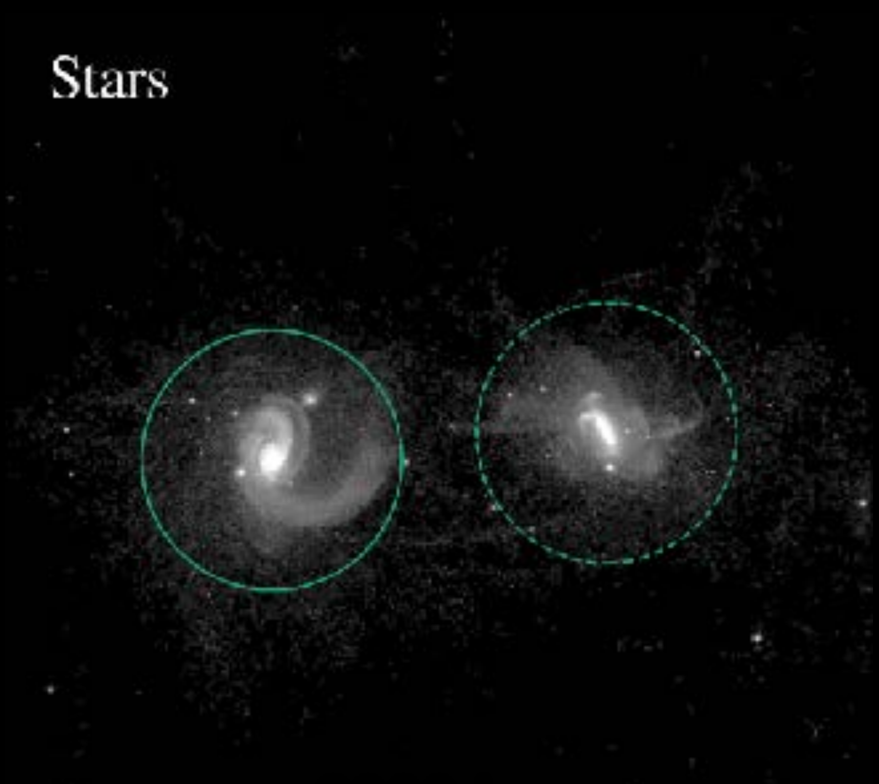
Tackling small-scale problems with the FIRE simulations

ELVIS on FIRE and the _Latte_ suites



2000 kpc

Isolated dwarf galaxies at ludicrous resolution

0.75 kpc

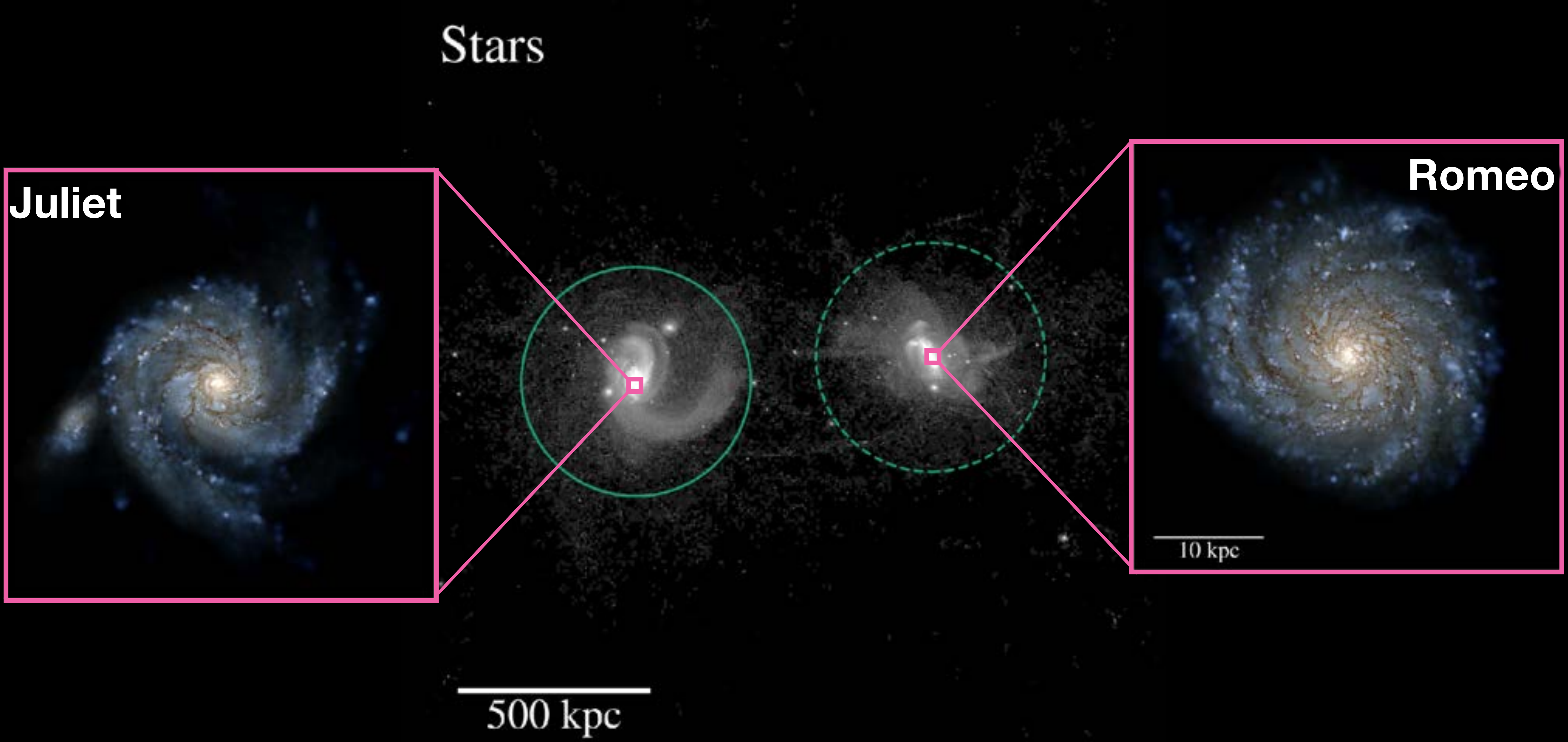
Triple Latte

300 kpc

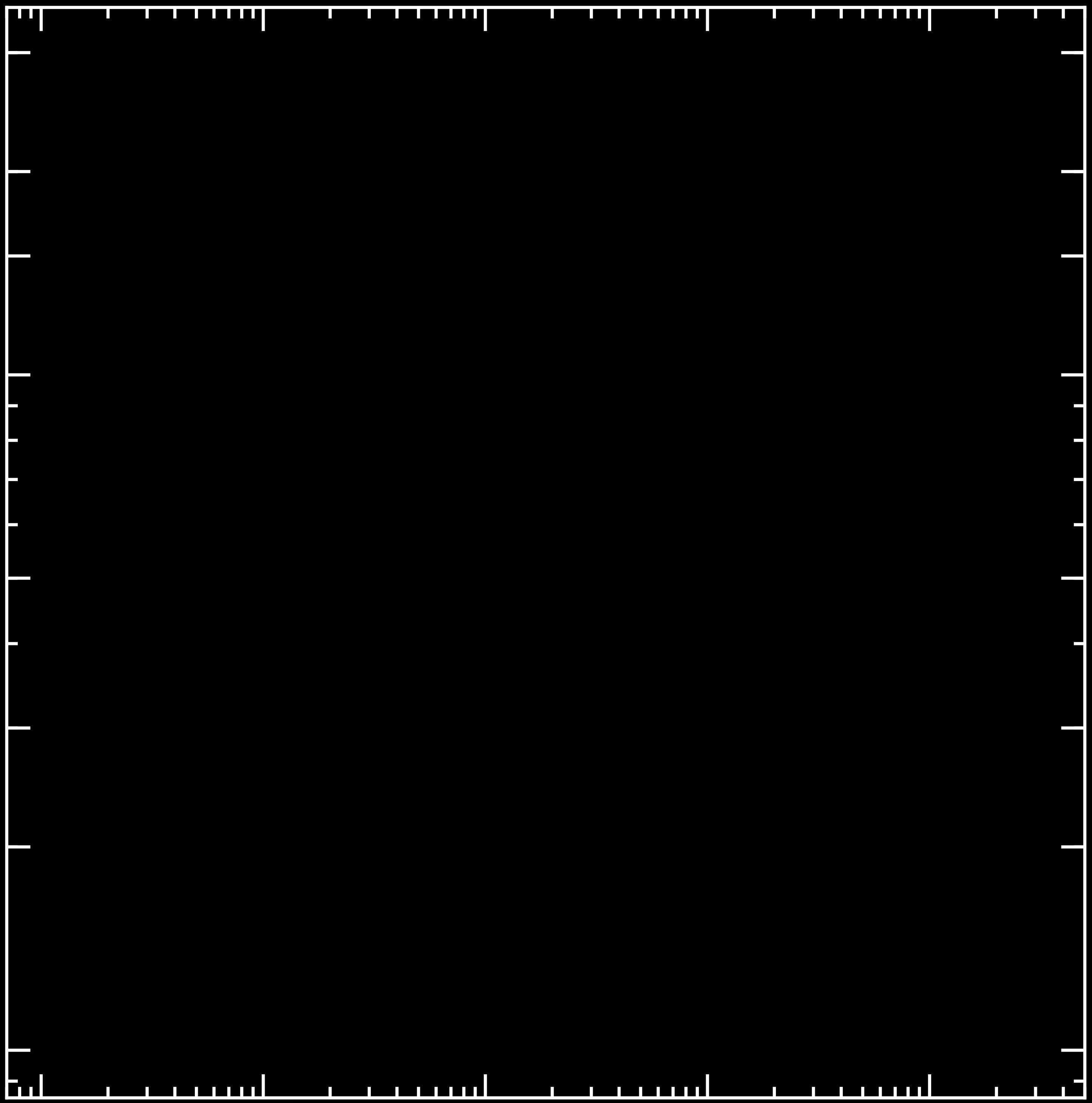
ELVIS on FIRE and the Latte suite

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

Each simulation spans ~10^6 parsecs while resolving ~1 pc scales

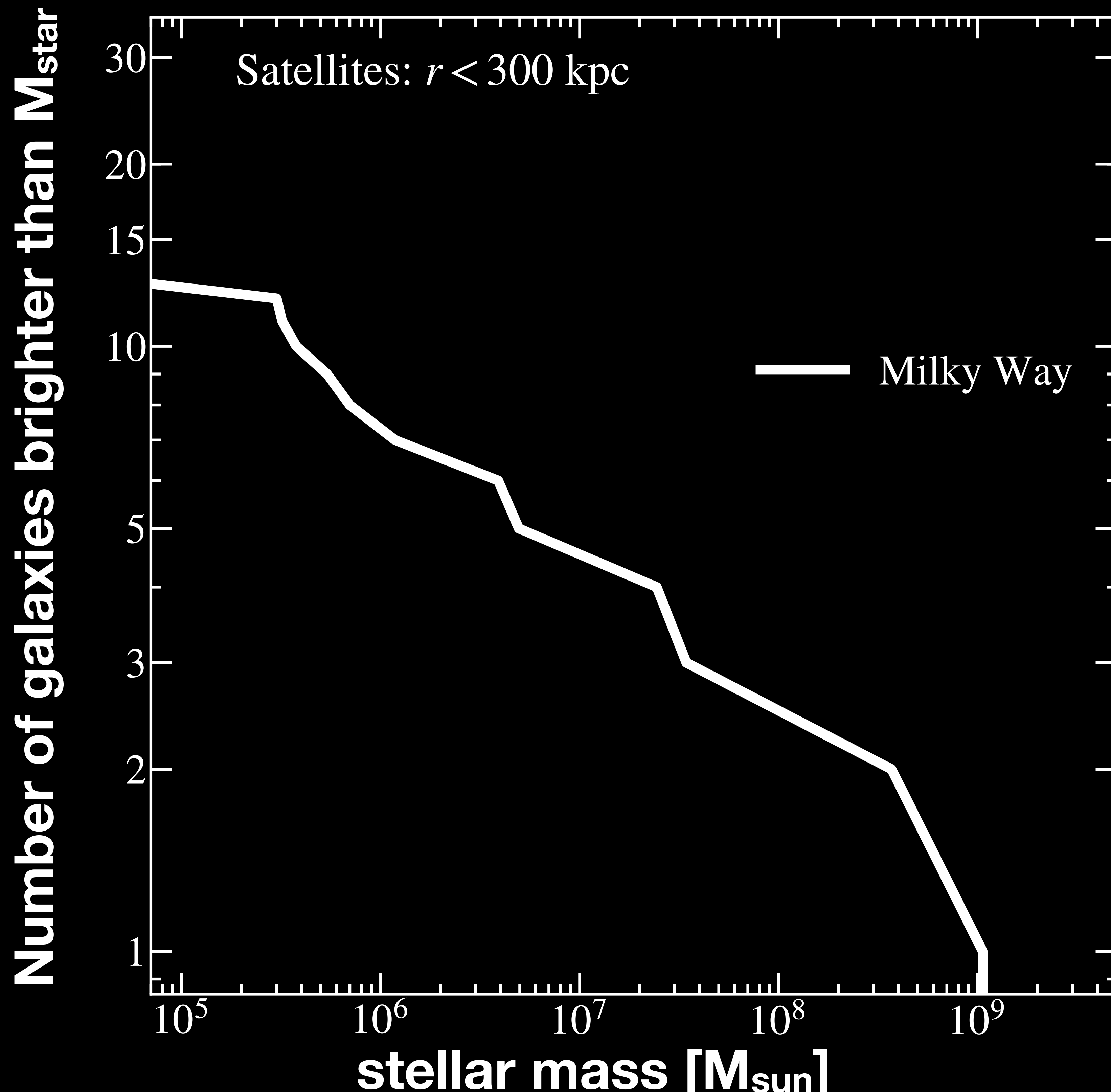


The missing satellites problem



SGK+, in prep

The missing satellites problem



SGK+, in prep

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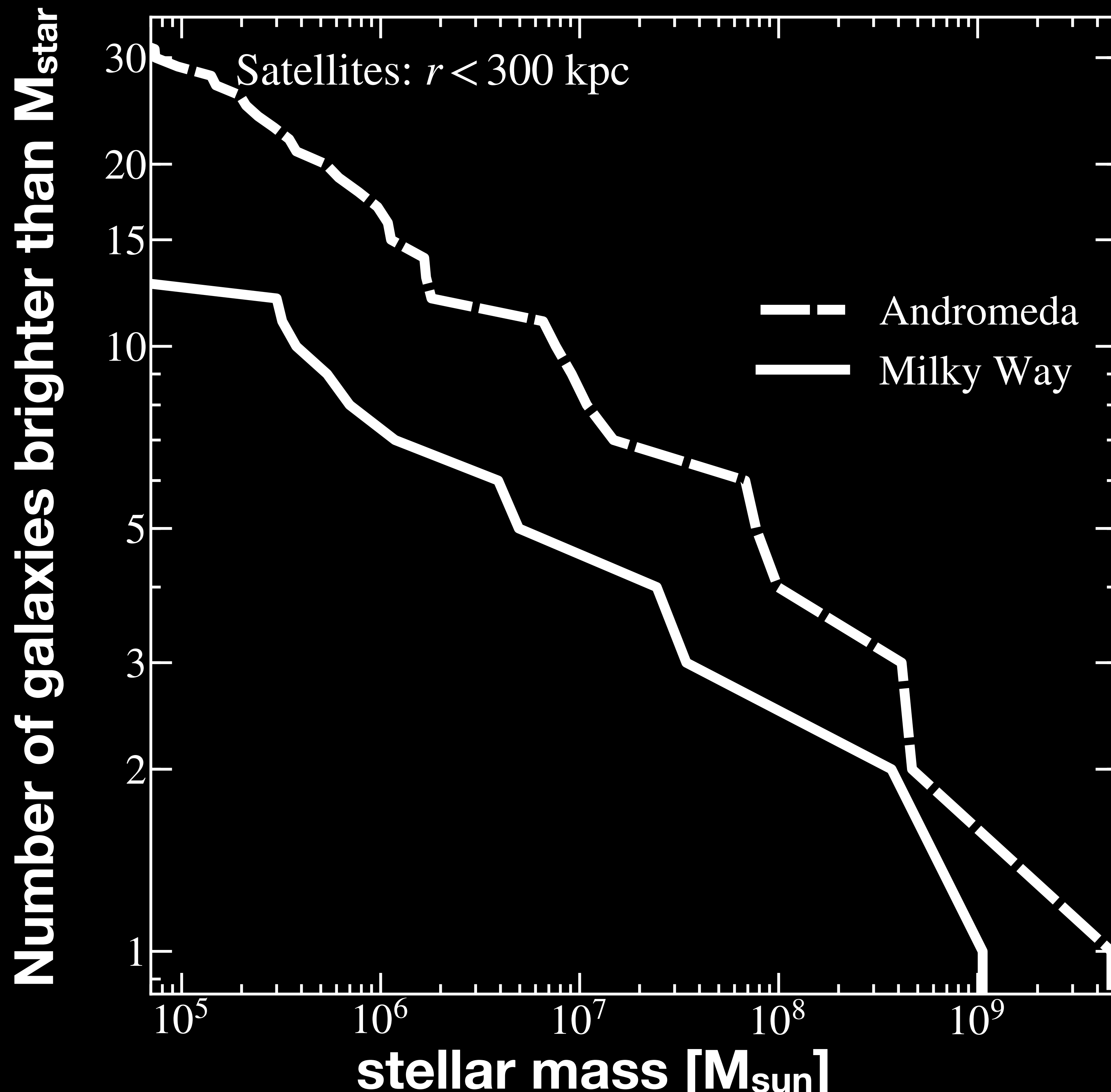

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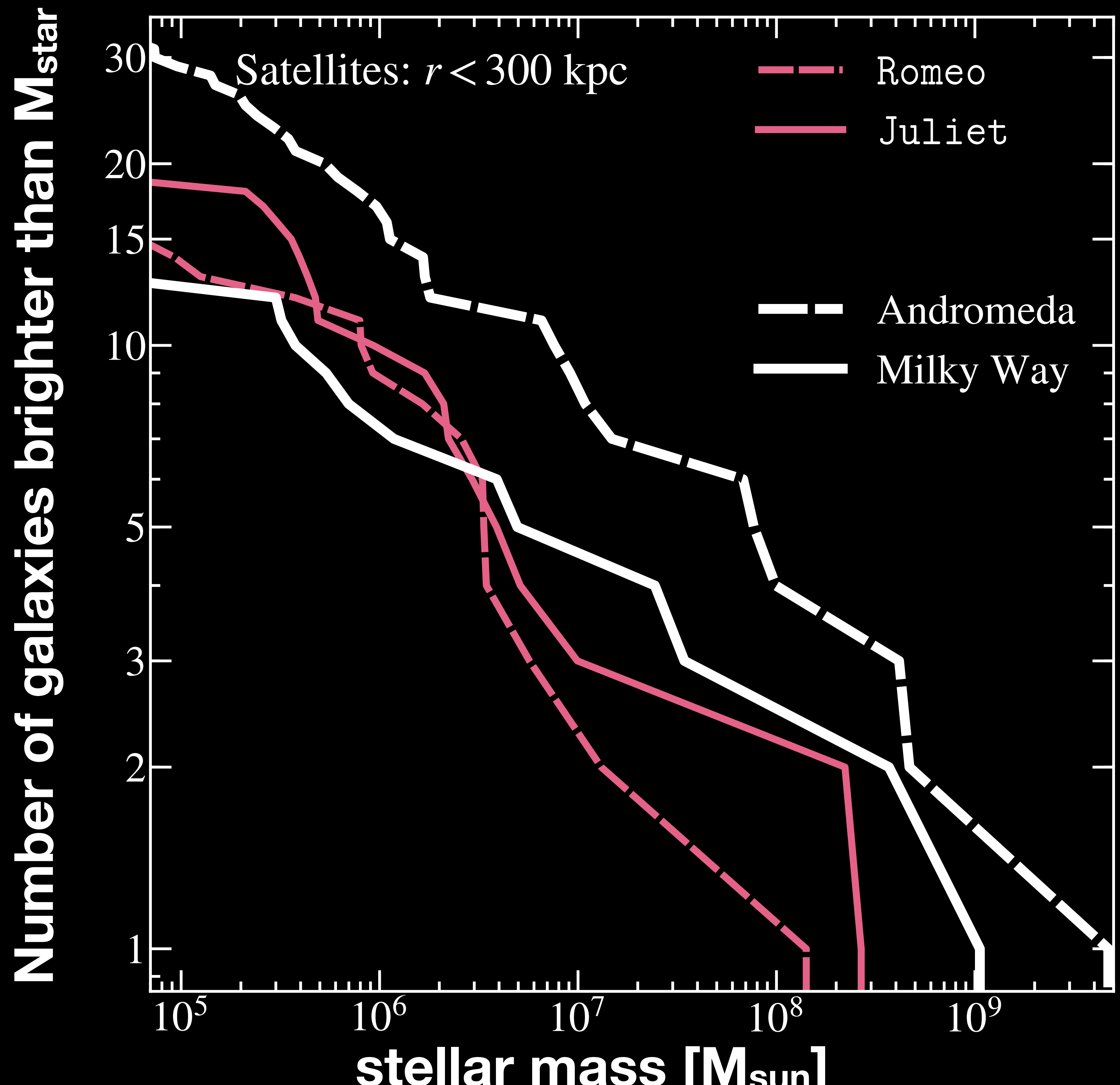
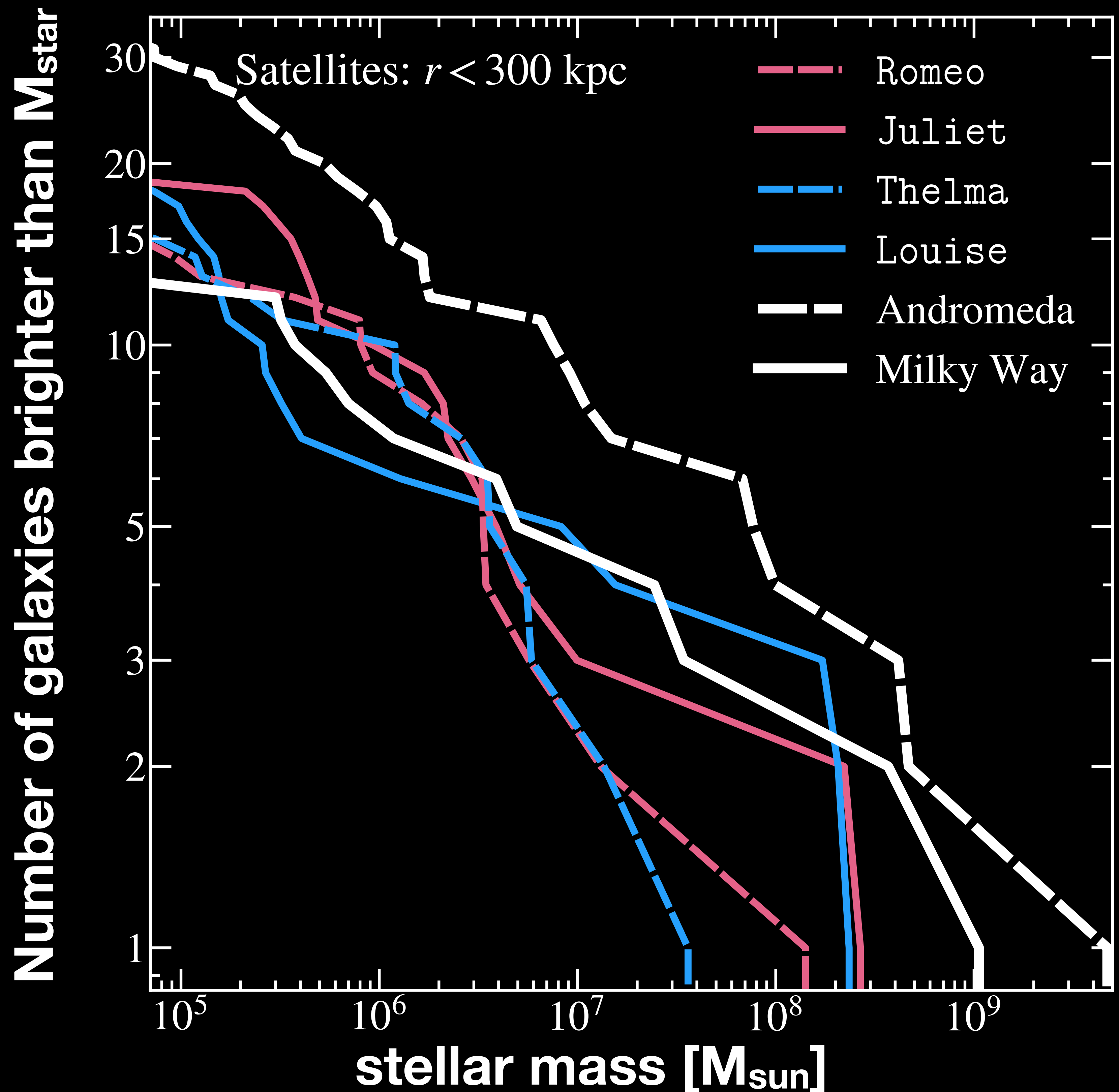


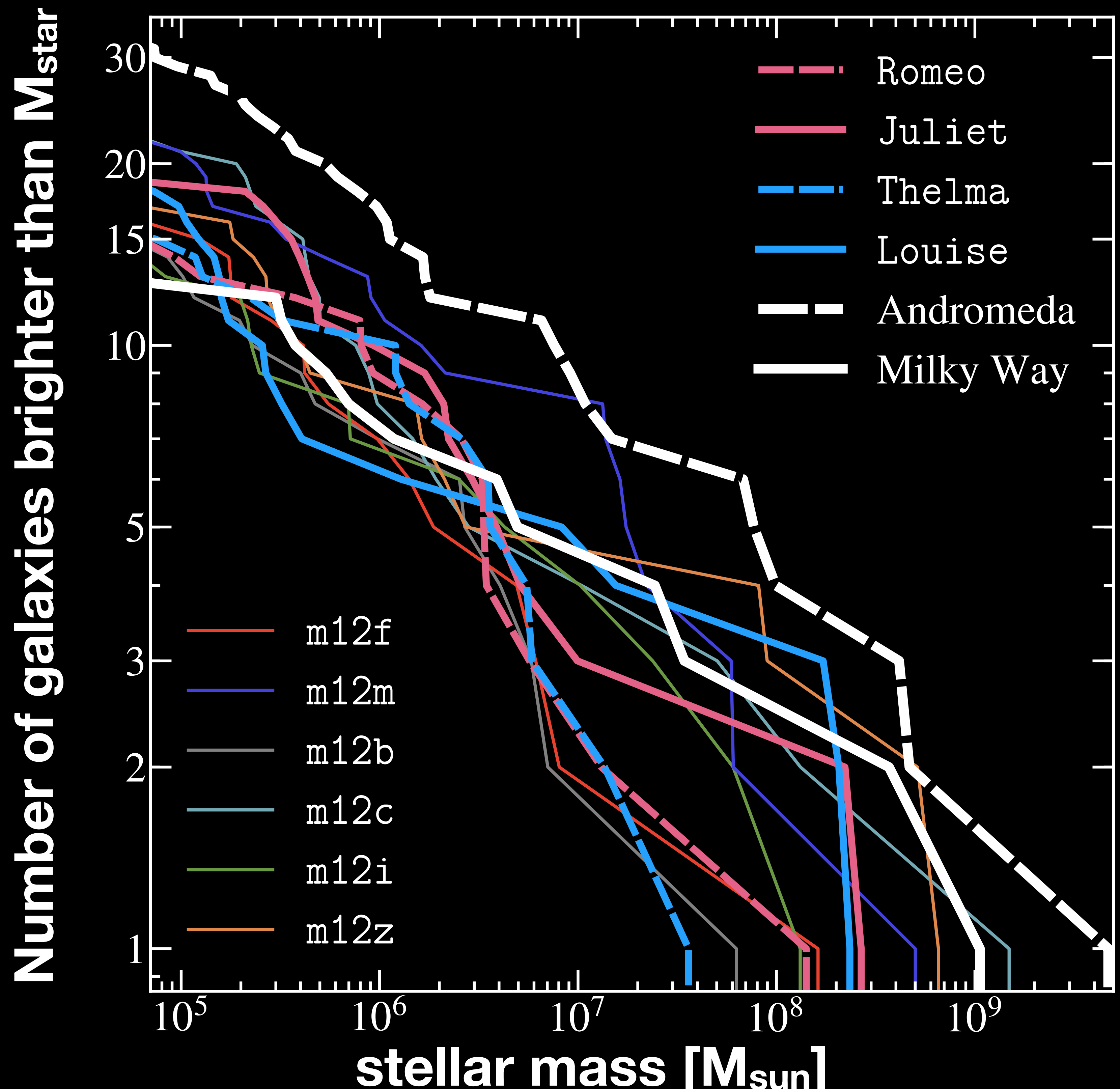
SGK+, in prep

The missing satellites problem



SGK+, in prep

No missing satellites problem!

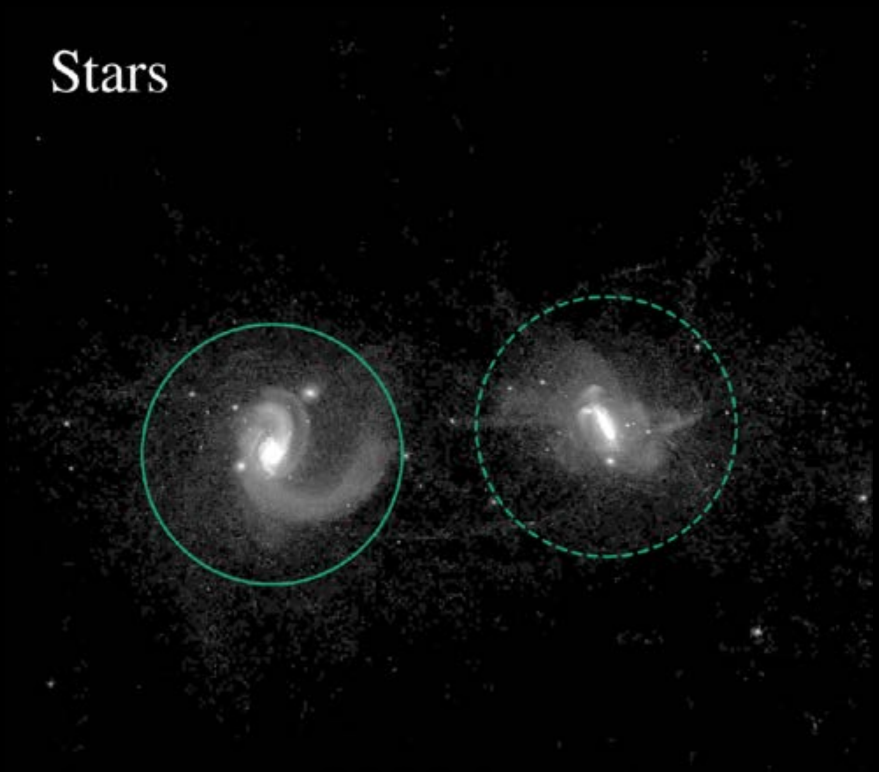


SGK+, in prep

What about the central masses?

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

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



2000 kpc

Isolated dwarf galaxies at ludicrous resolution

0.75 kpc

Triple Latte

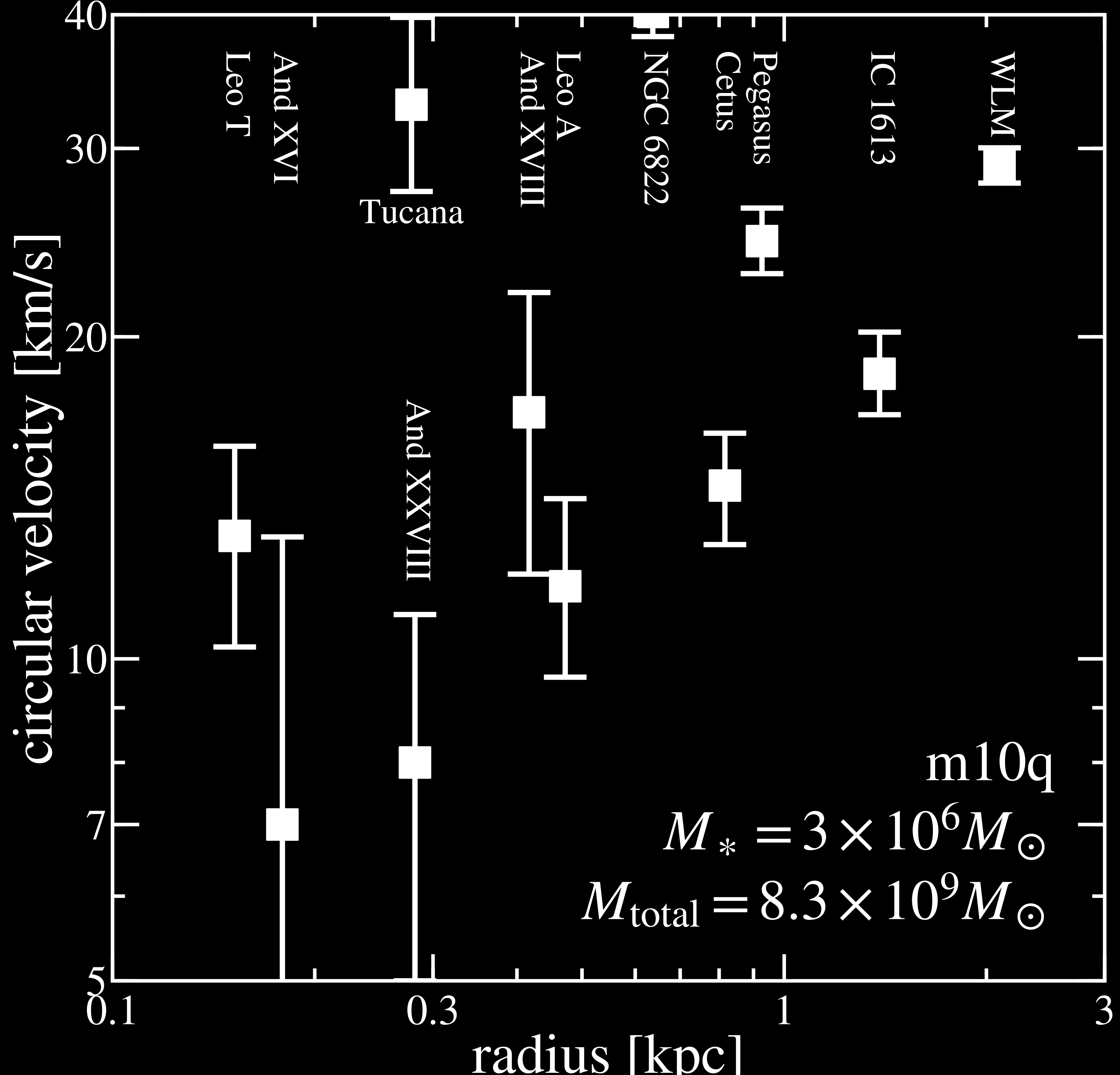
300 kpc

Ultra-high resolution isolated dwarf galaxies

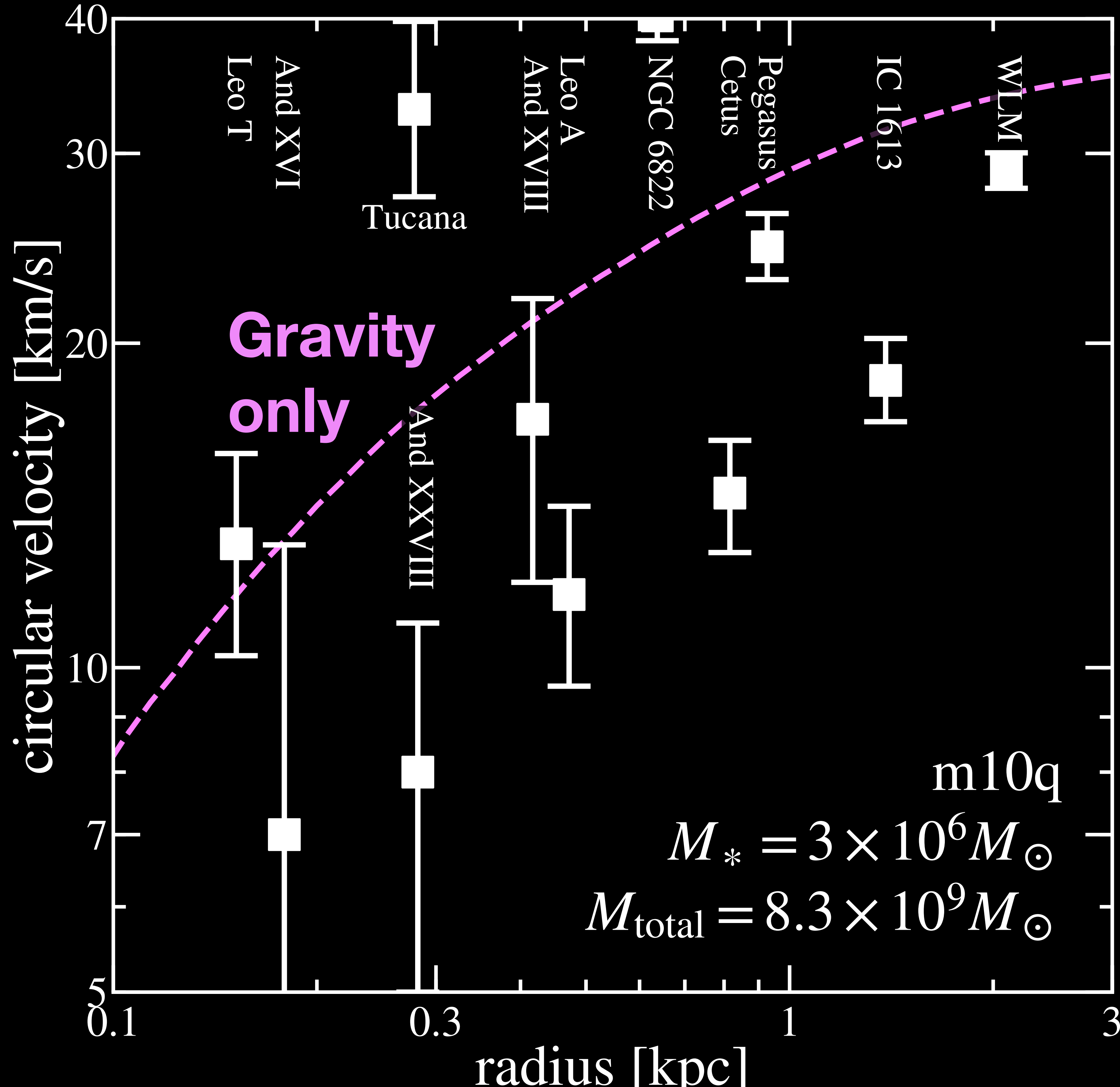
- $m_{gas} \simeq 30\ M_{sun}$ — equivalent to a single high mass star!
- First cosmological simulations (run to *z* = 0) to resolve the cooling radii of individual supernovae
- Density profiles resolved beyond ~30 parsecs
- Target *isolated* dwarfs — systems in a void, far from any MW-mass galaxies

Wheeler+, in prep

Internal structure of FIRE dwarfs



Internal structure of FIRE dwarfs



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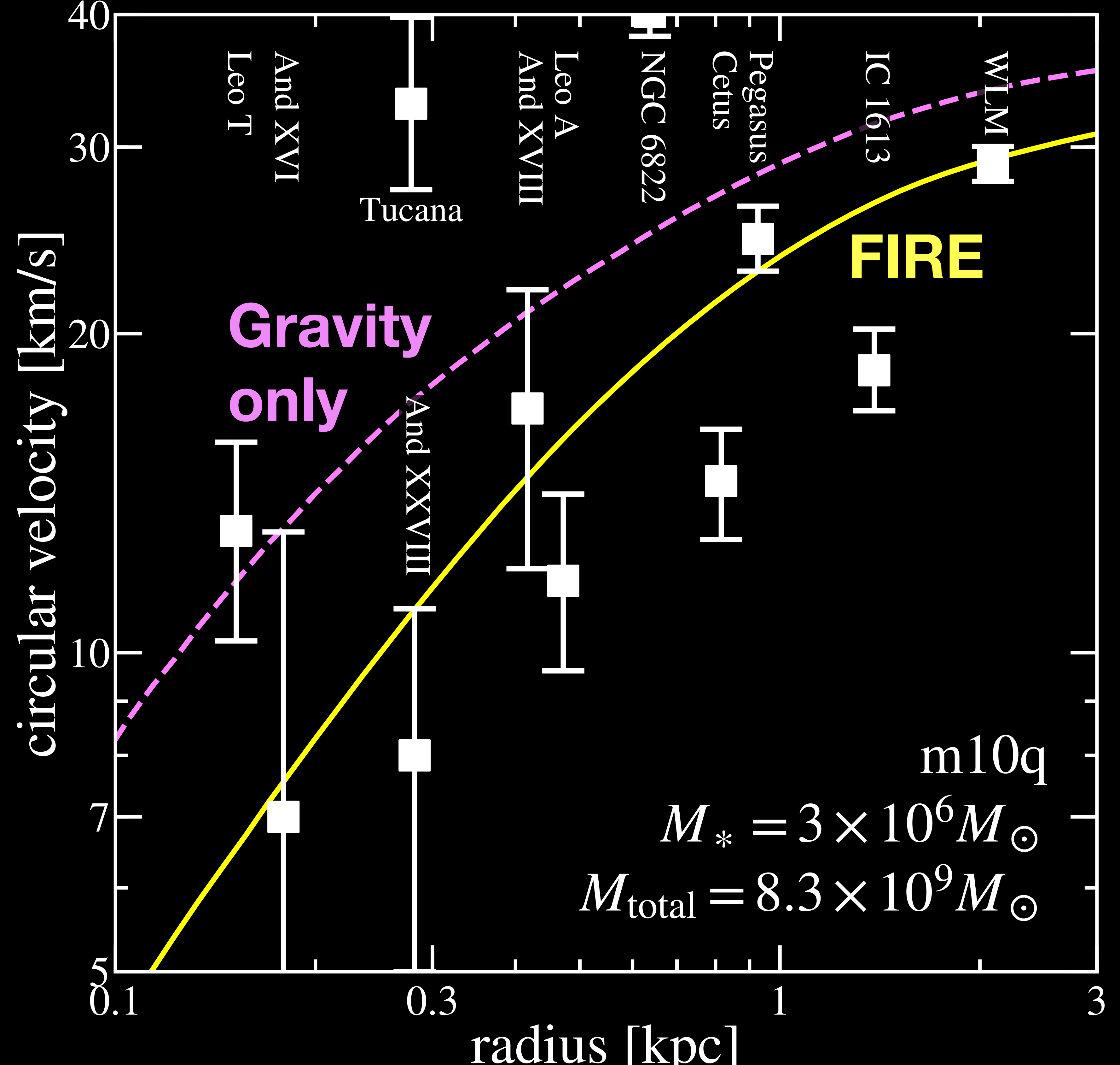

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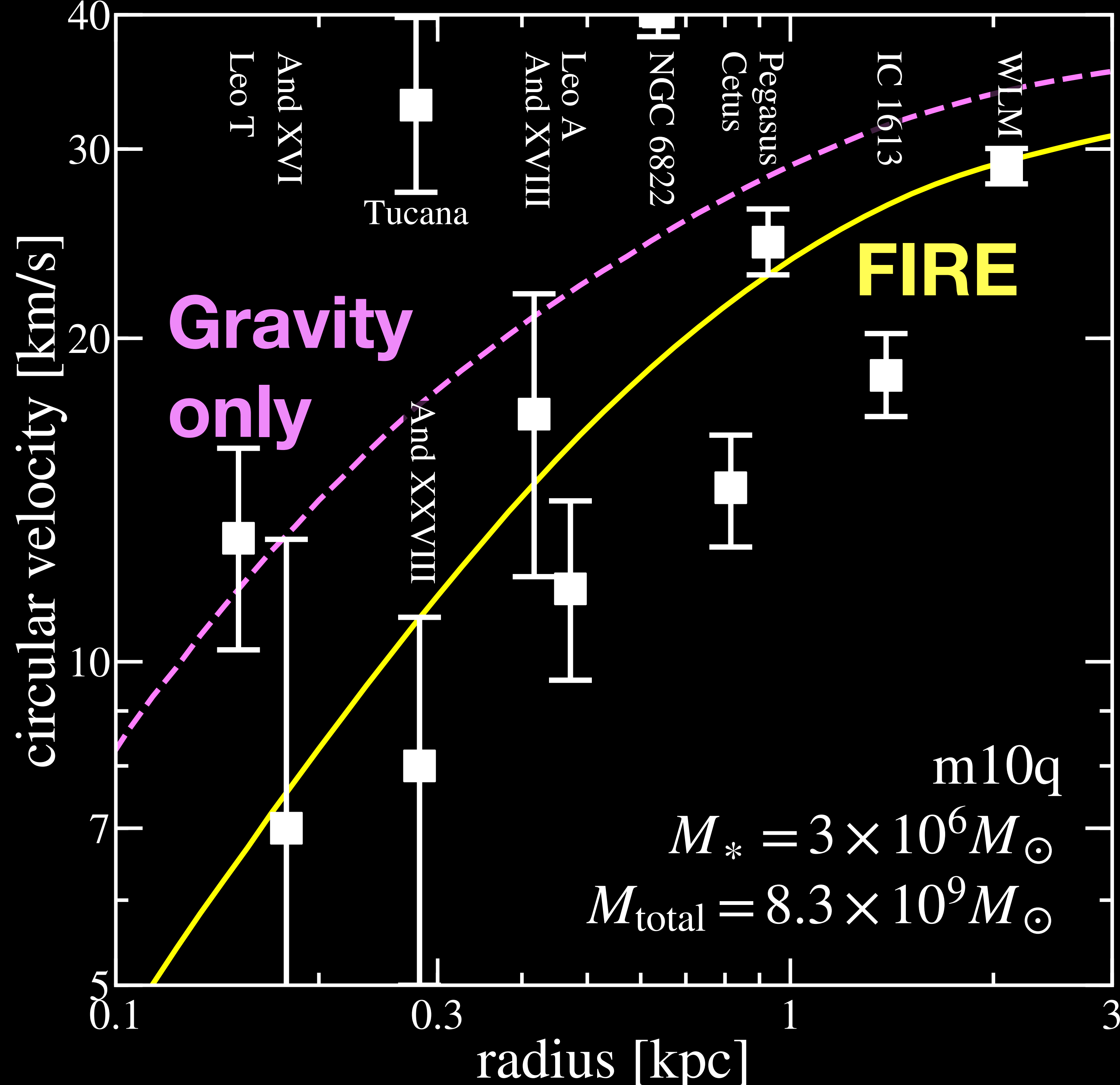
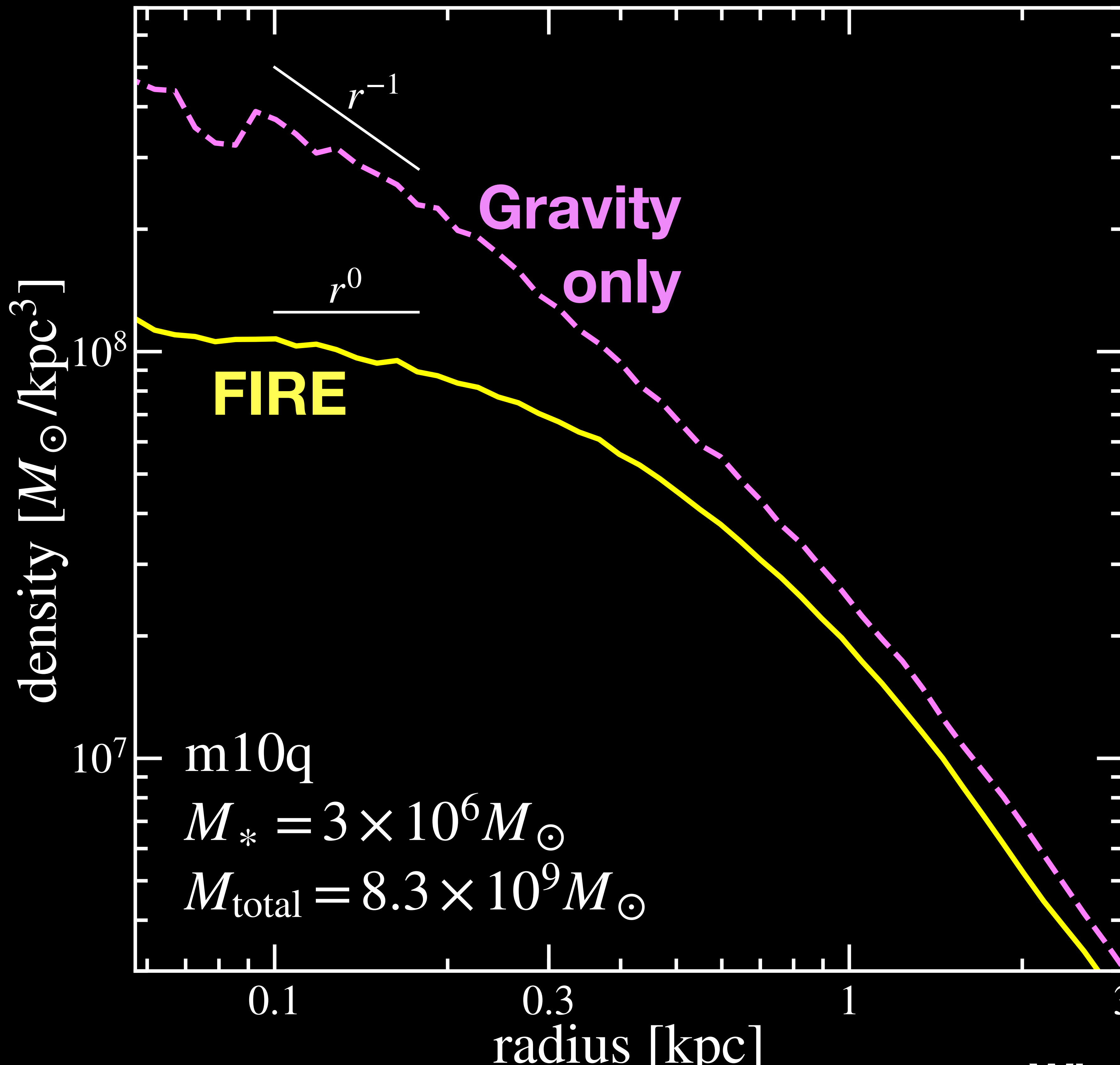


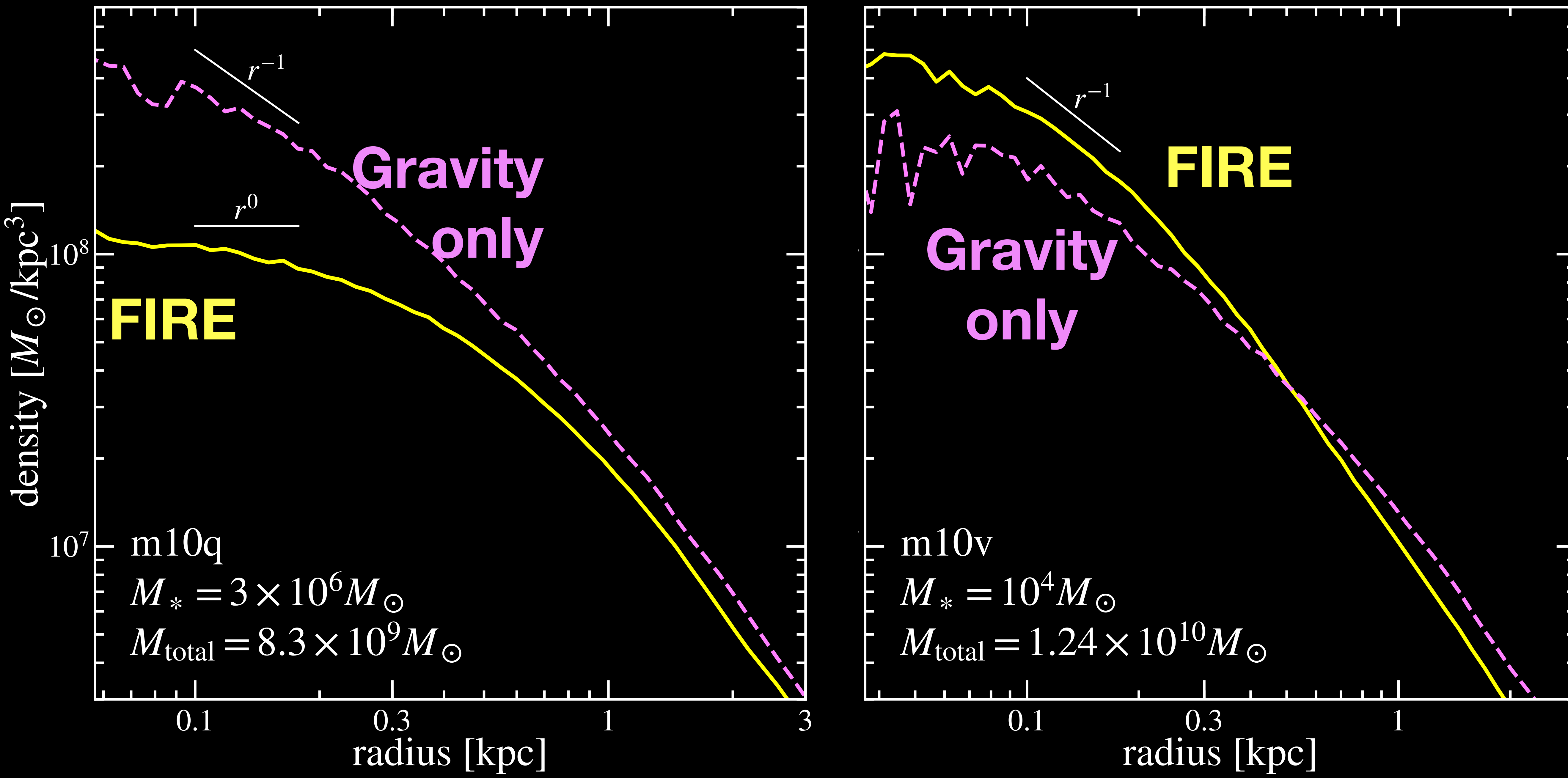
The MW-mass hosts of *ELVIS on FIRE* and *Latte* are also free of the central mass problem

Feedback induced “cores”



Wheeler+, in prep

Feedback induced "cores,"
if there's enough energy

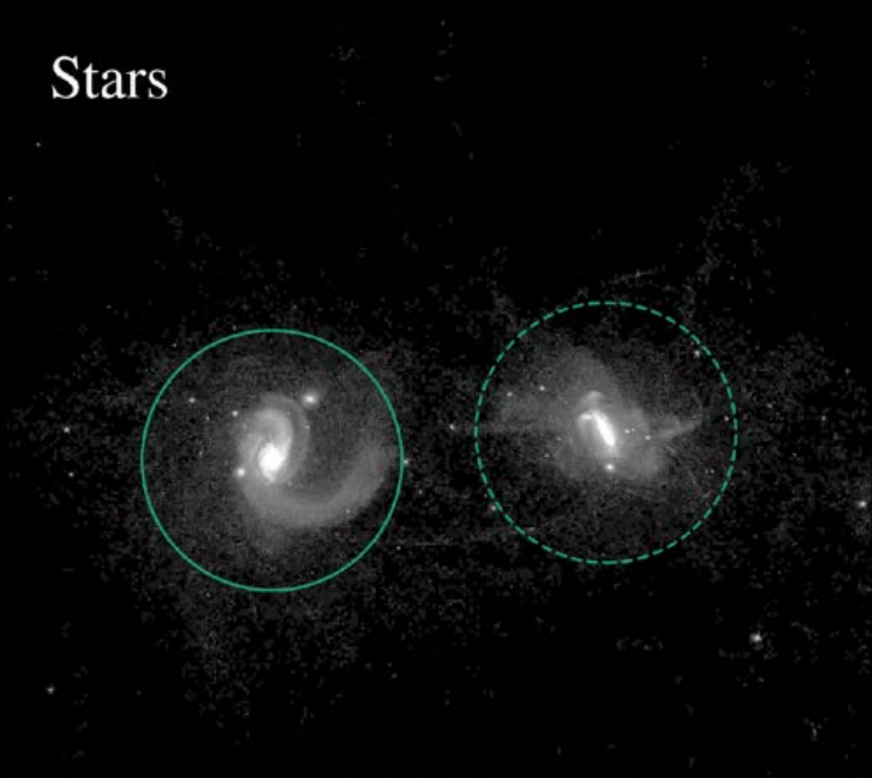


Wheeler+, in prep

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**



2000 kpc

Isolated dwarf galaxies at ludicrous resolution

0.75 kpc

Triple Latte

300 kpc

Triple Latte: a billion particles in the Milky Way

Current: ELVIS on FIRE + Latte

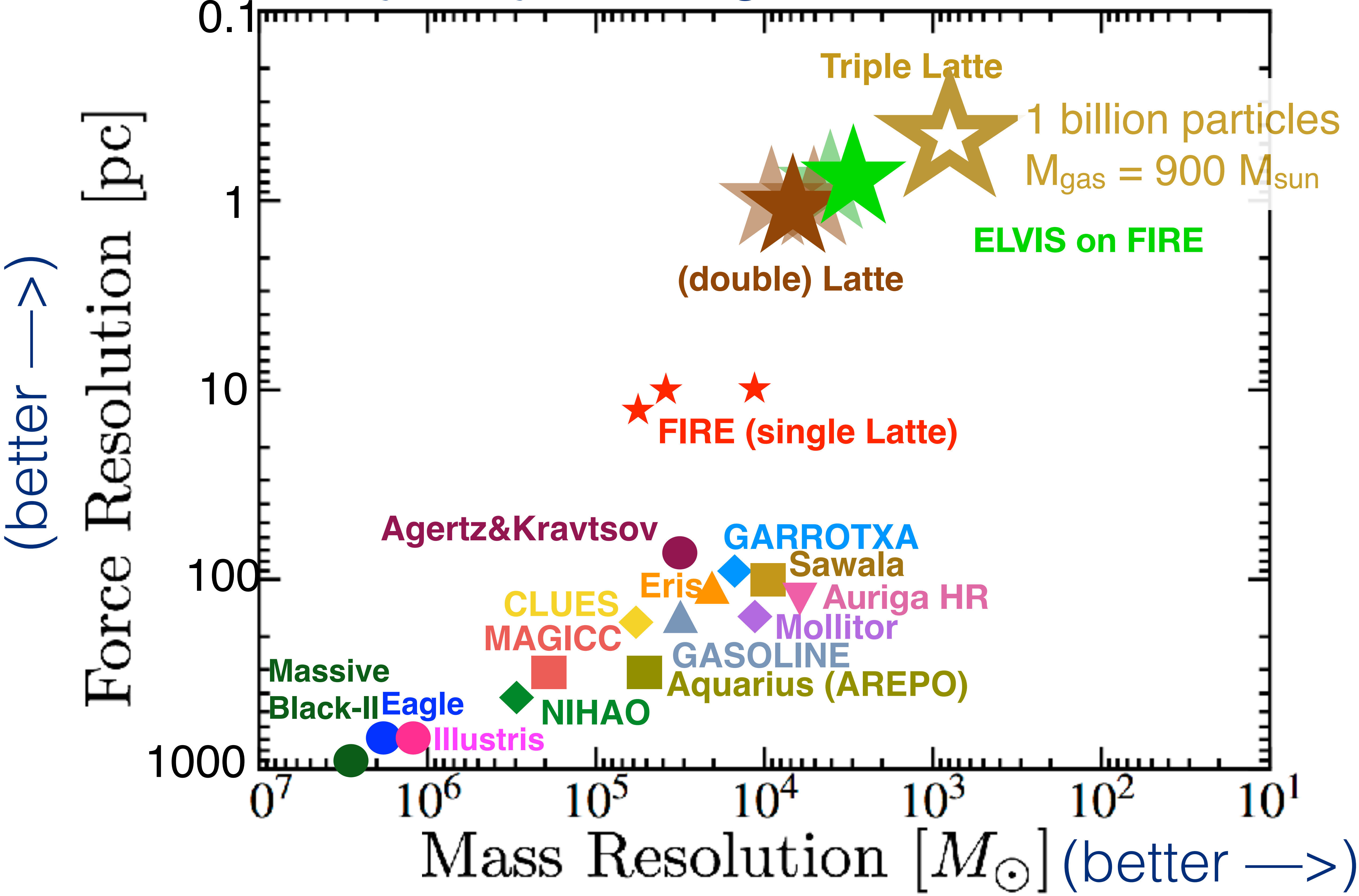
- $m_{gas} \simeq 3{,}500 - 7{,}070\ M_{sun}$
- ~100 million particles in the halo (and 300 million in the Local Group)
- 1-5 million core-hours for Latte, 10-20 million for ELVIS on FIRE

Upcoming: Triple Latte

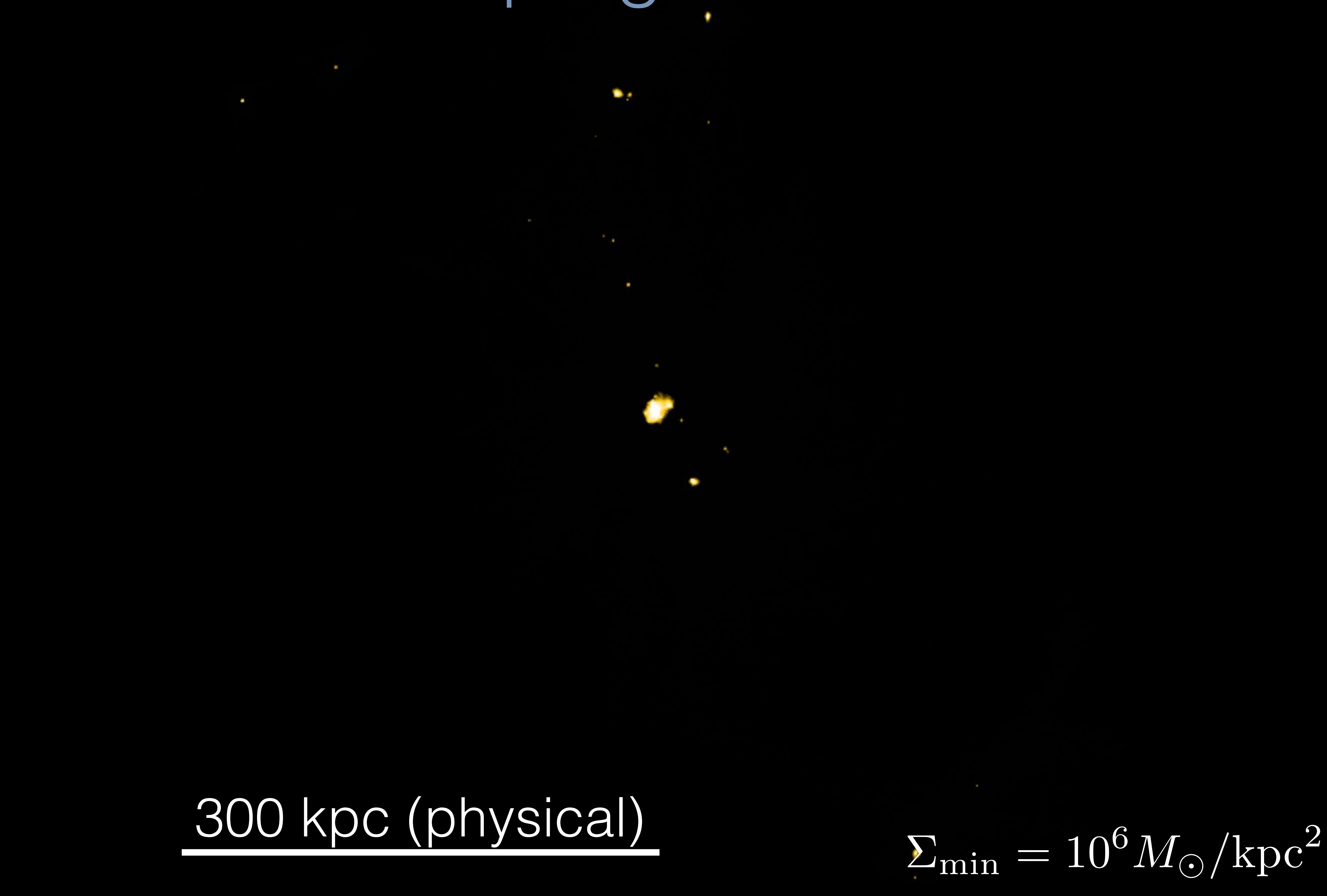
- $\mathbf{m_{gas,star} = 880\ M_{sun}}$
- **1.1 billion particles**
- **~25 million core-hours**
- **now running (at z=2.5)**

FIRE
Feedback In Realistic Environments

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

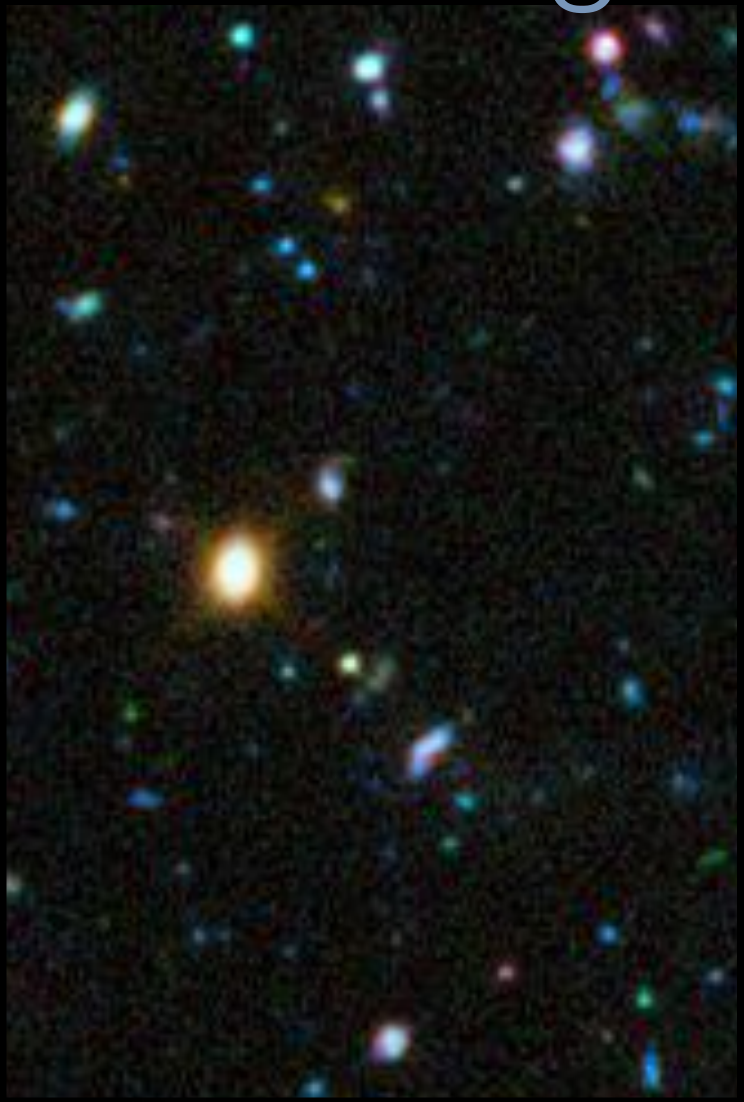


MW-mass progenitor at z = 2.5



MW-mass progenitor at z = 2.5

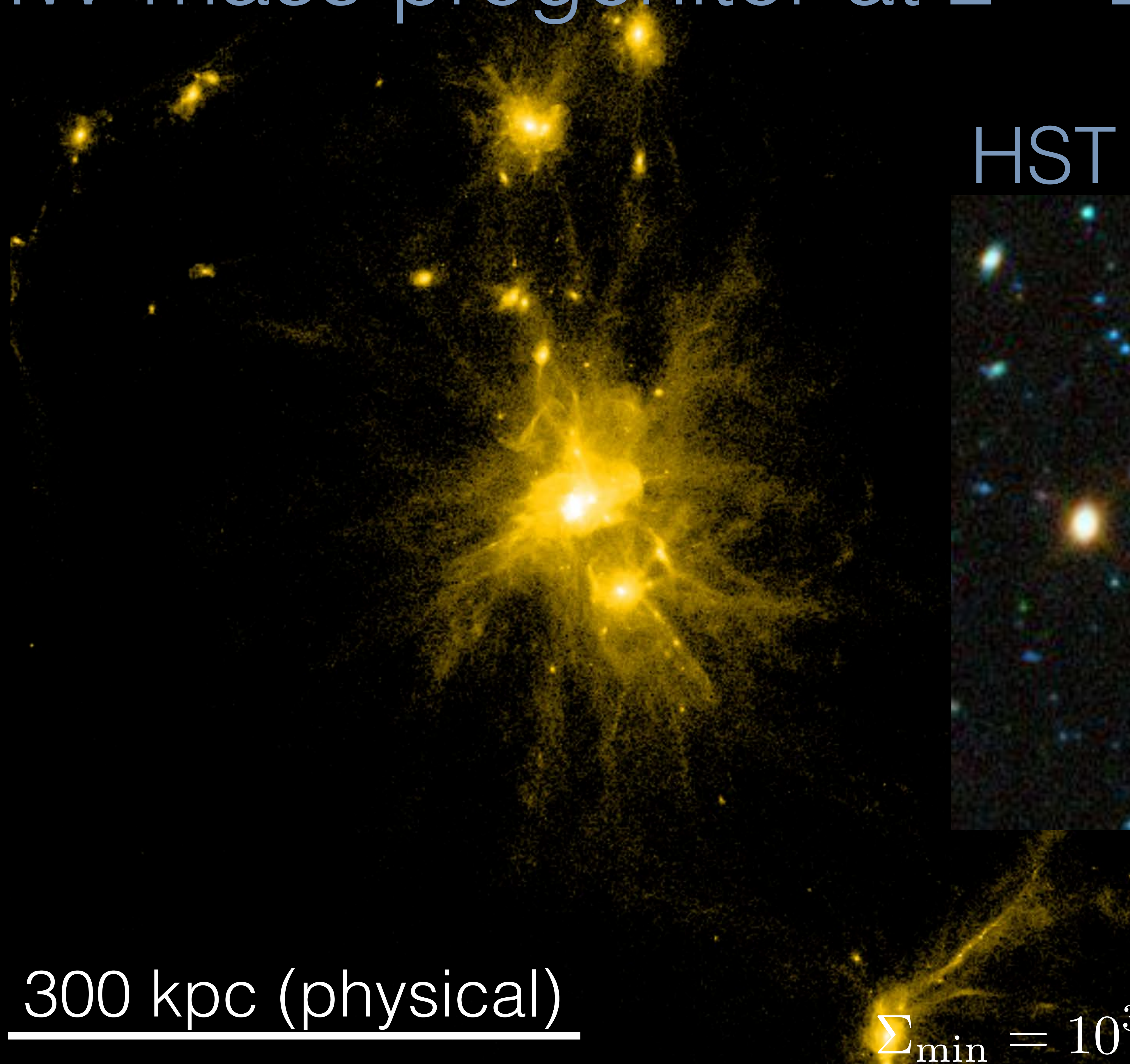
HST image



300 kpc (physical)

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

MW-mass progenitor at z = 2.5



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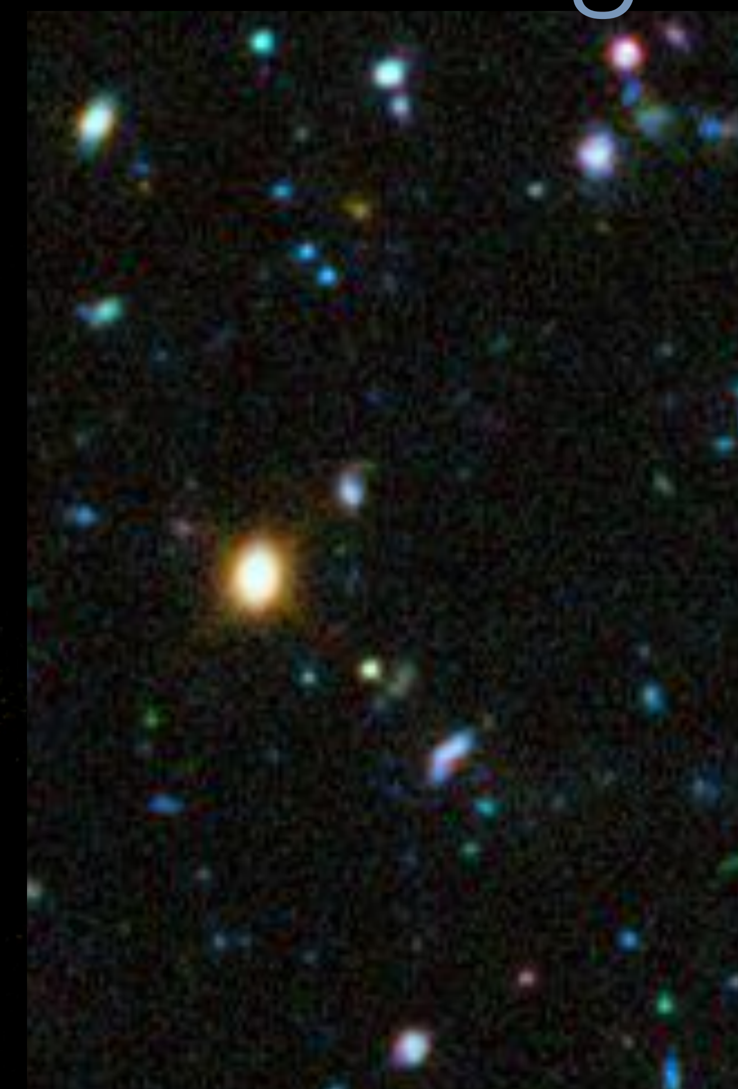

Conclusions

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

Together with ultra-high res (~30 M_{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

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[the above statement is a lie]

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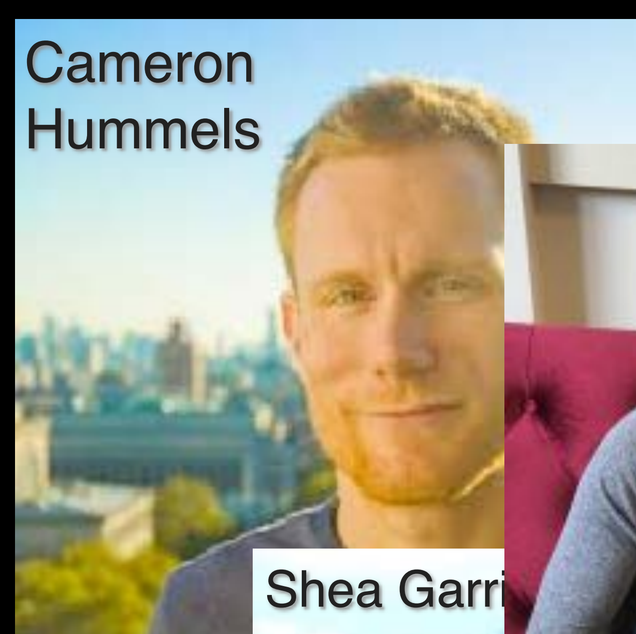
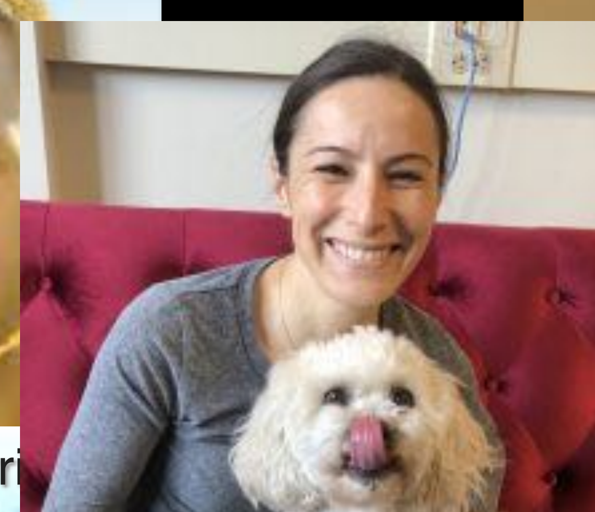
obert Feldmann (ETH Zurich)

~30 - 40 graduate s and postdocs





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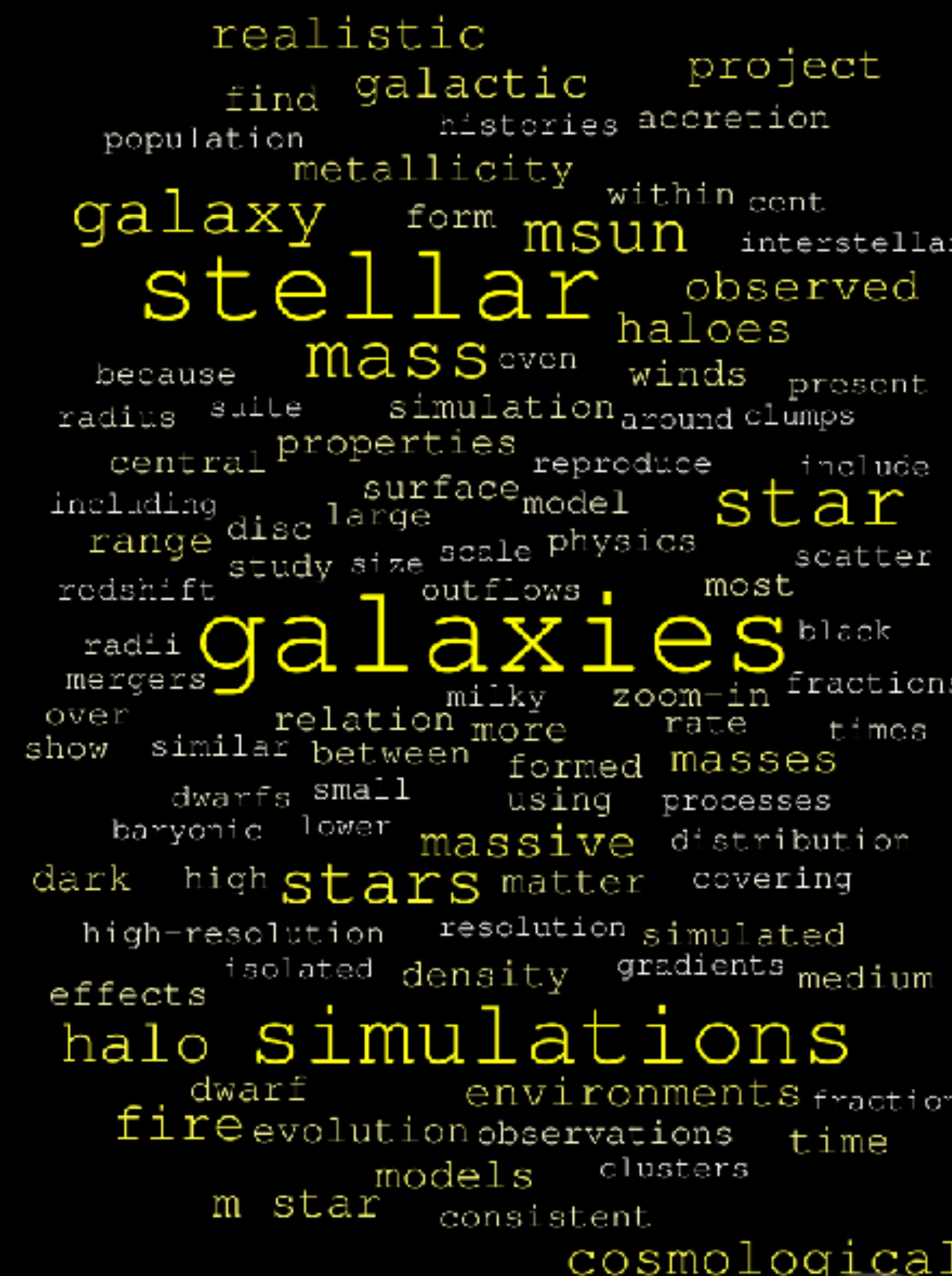
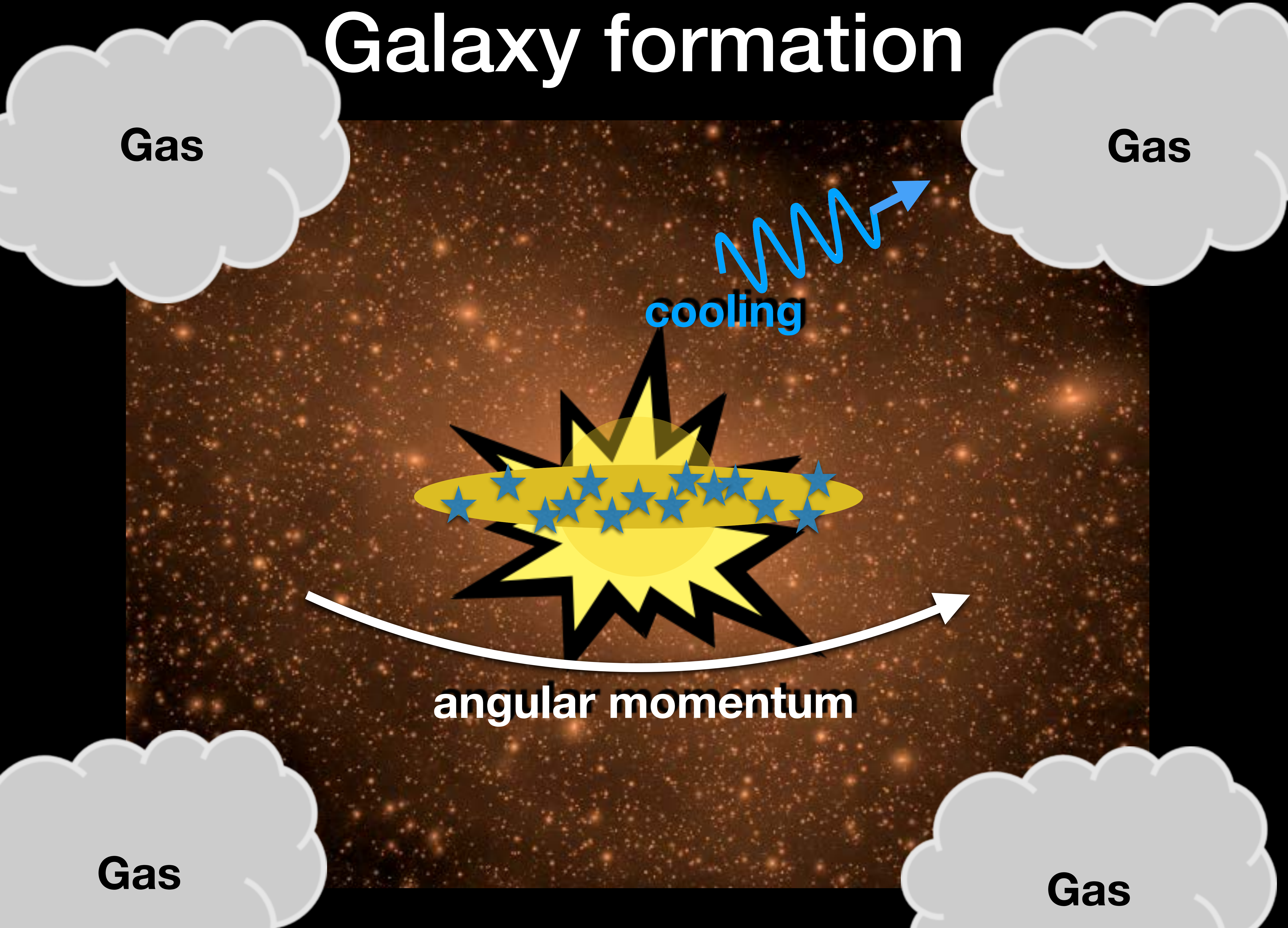
What are we studying with FIRE?

Titles

Abstracts



Galaxy formation



Galaxy formation