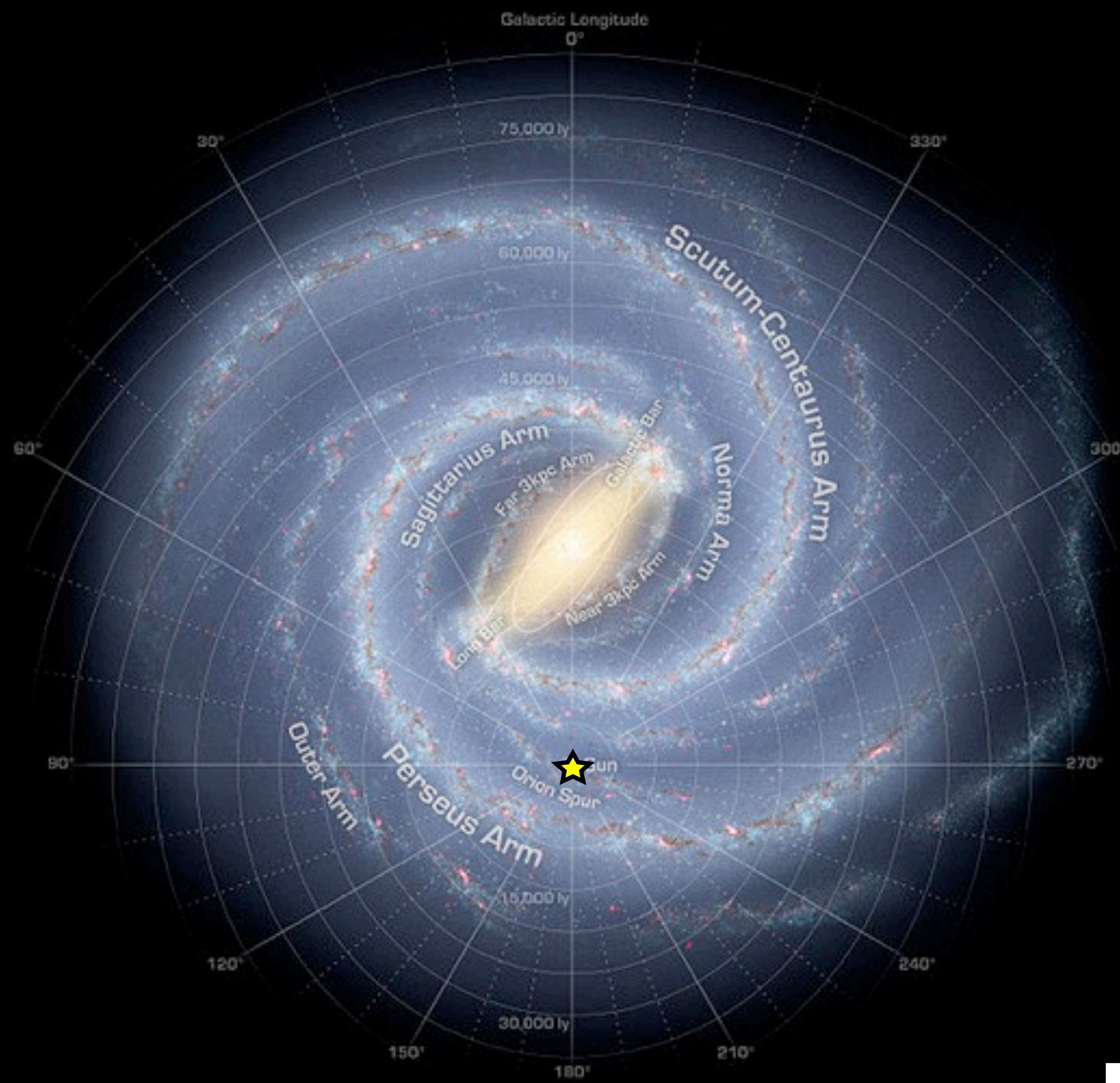
Cosmology & The Milky Way

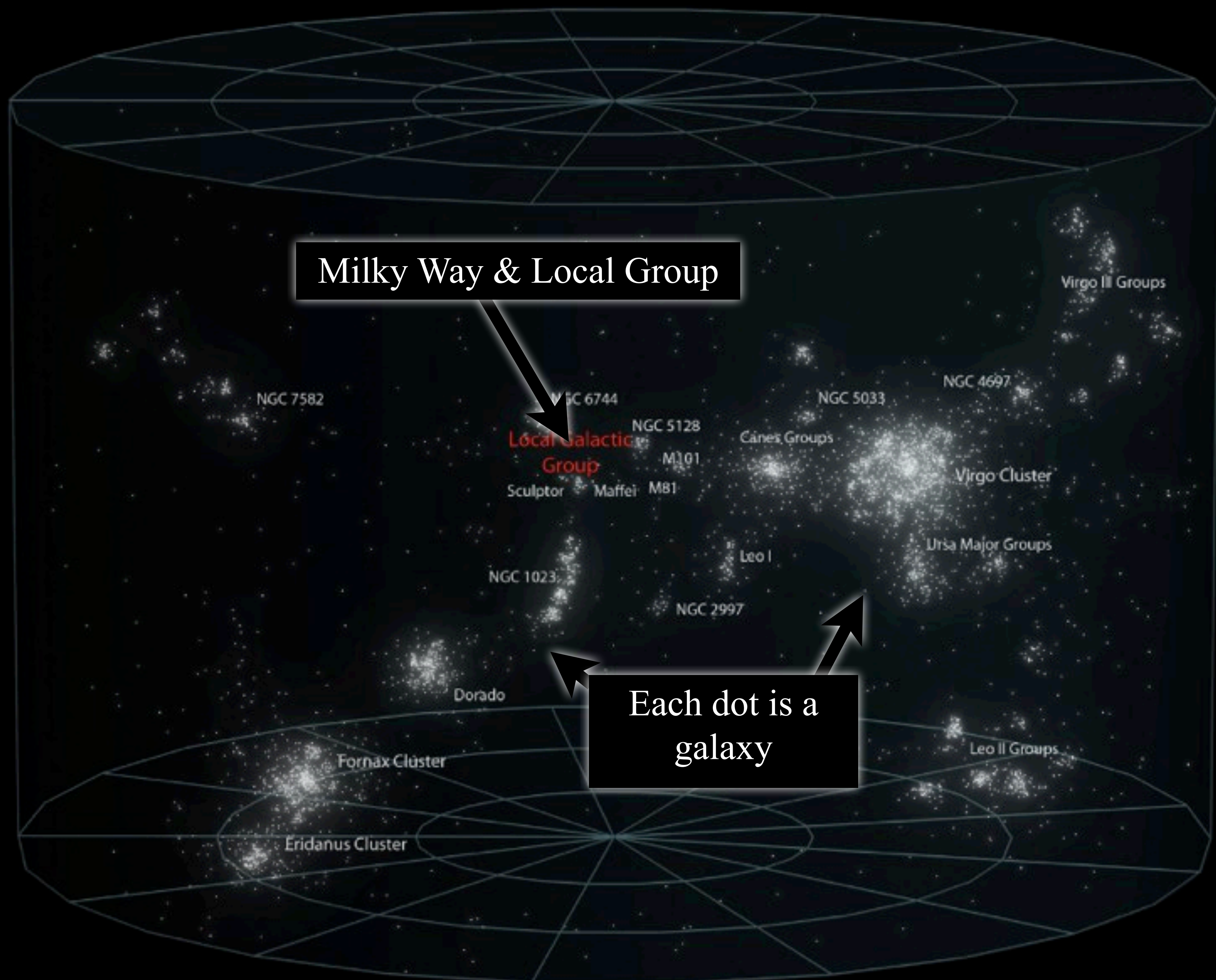


Southern California
SCGE
Center for galaxy evolution

James Bullock
@jbprime

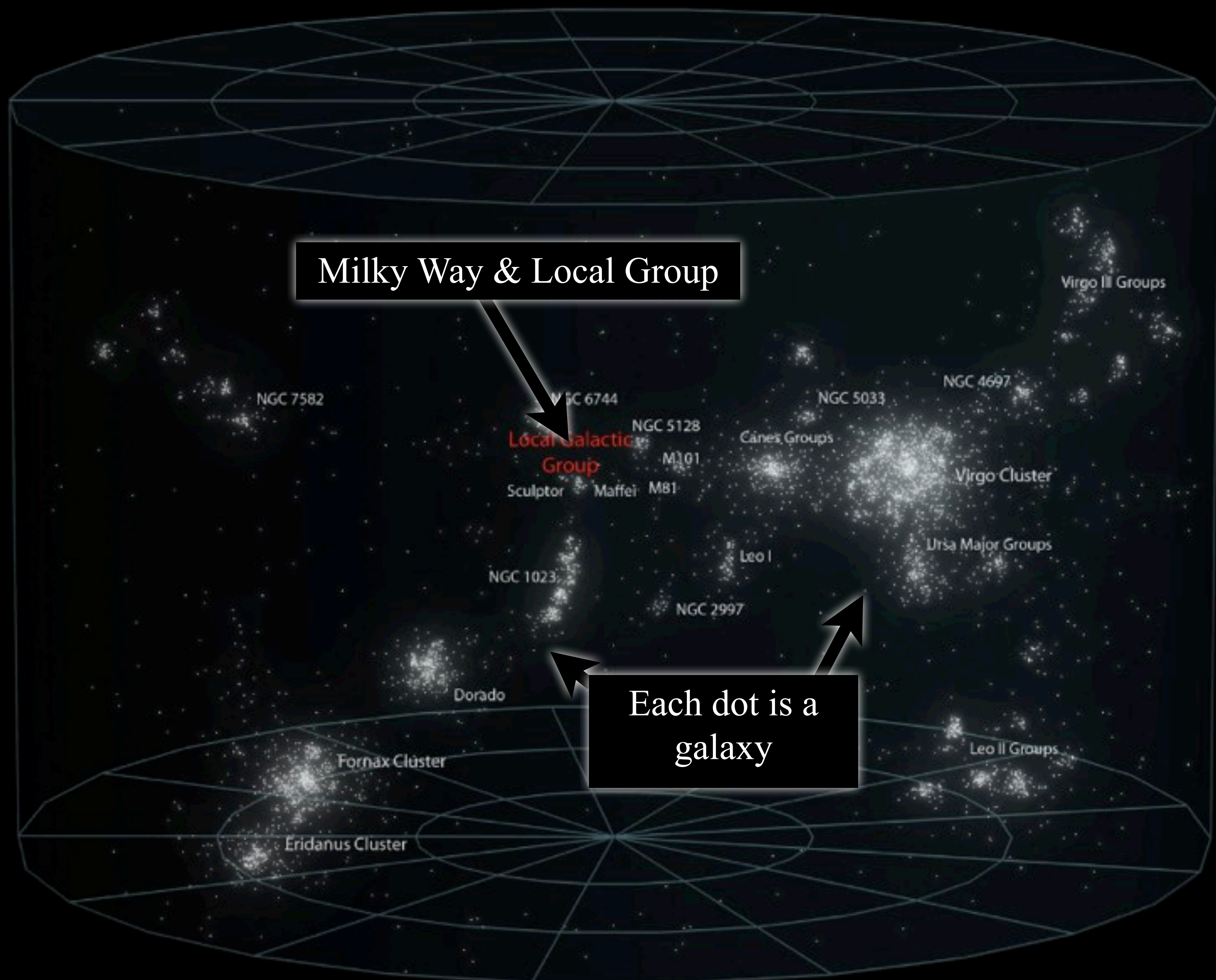
UCIrvine

Universe of Galaxies (~ 10^{-8} of observable part)



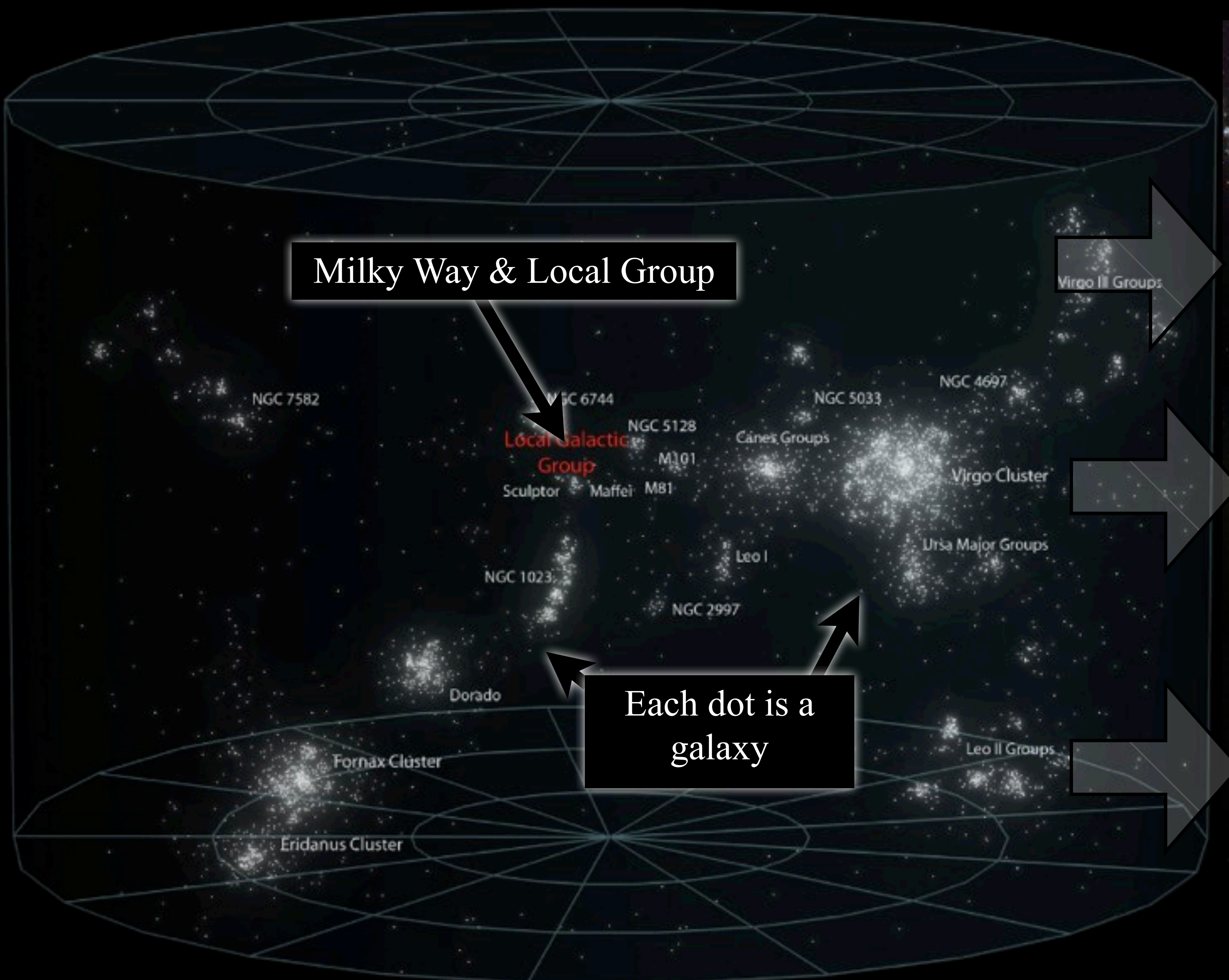
~100 million light years

Why does the Universe look this way?



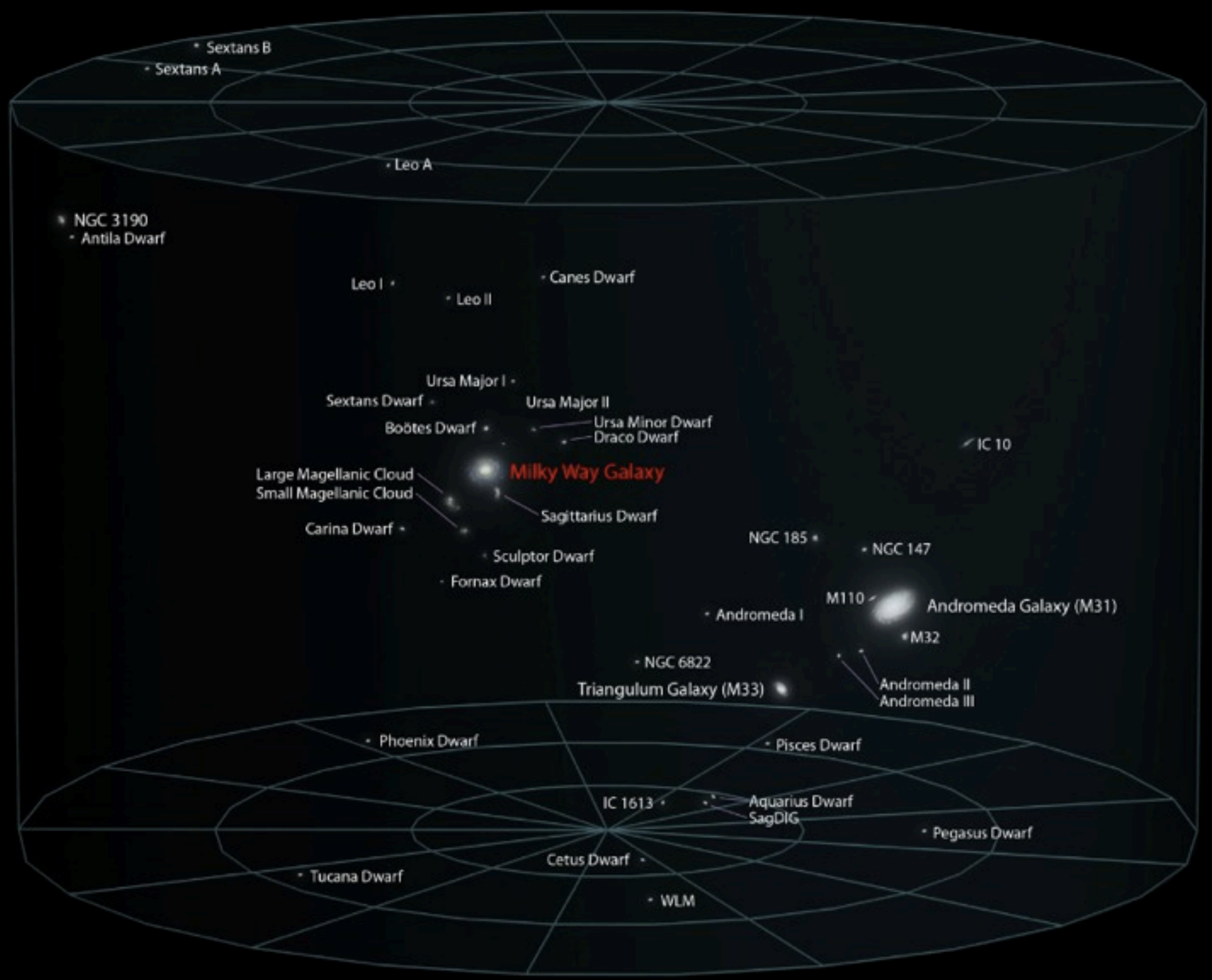
~100 million light years

Why do galaxies have these shapes?



~100 million light years

Our Laboratory: The Local Group



~5 million light years

Wally Pacholka/Astropics.com

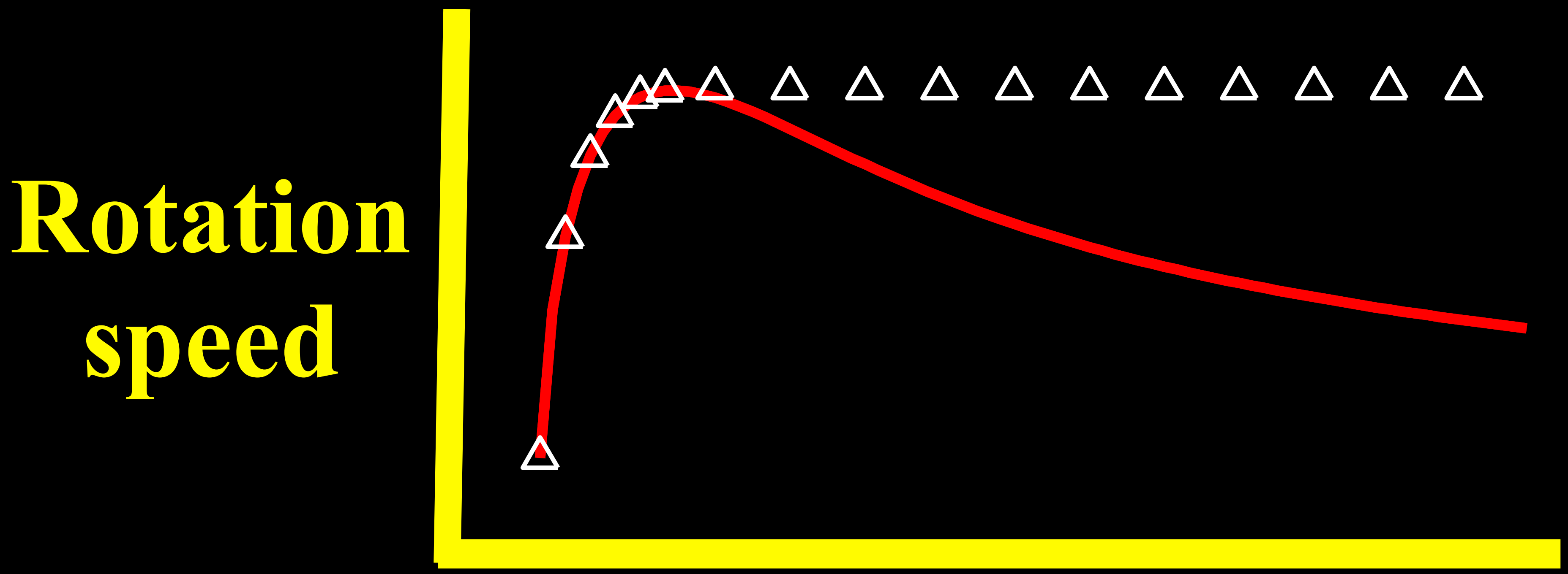
Mauna Kea, Hawaii.

Wally Pacholka/Astropics.com

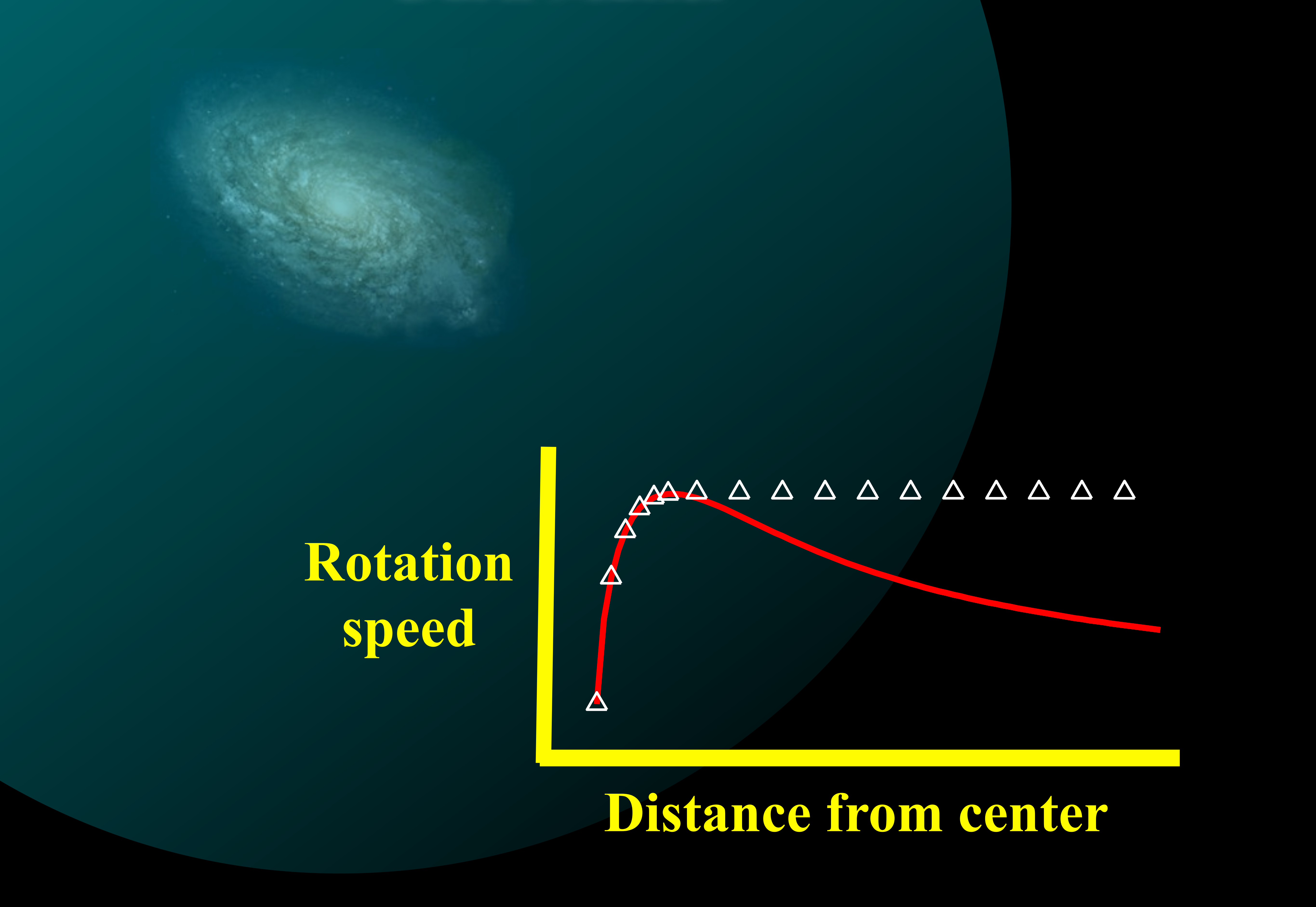
Mauna Kea, Hawaii.

Andromeda (M31)

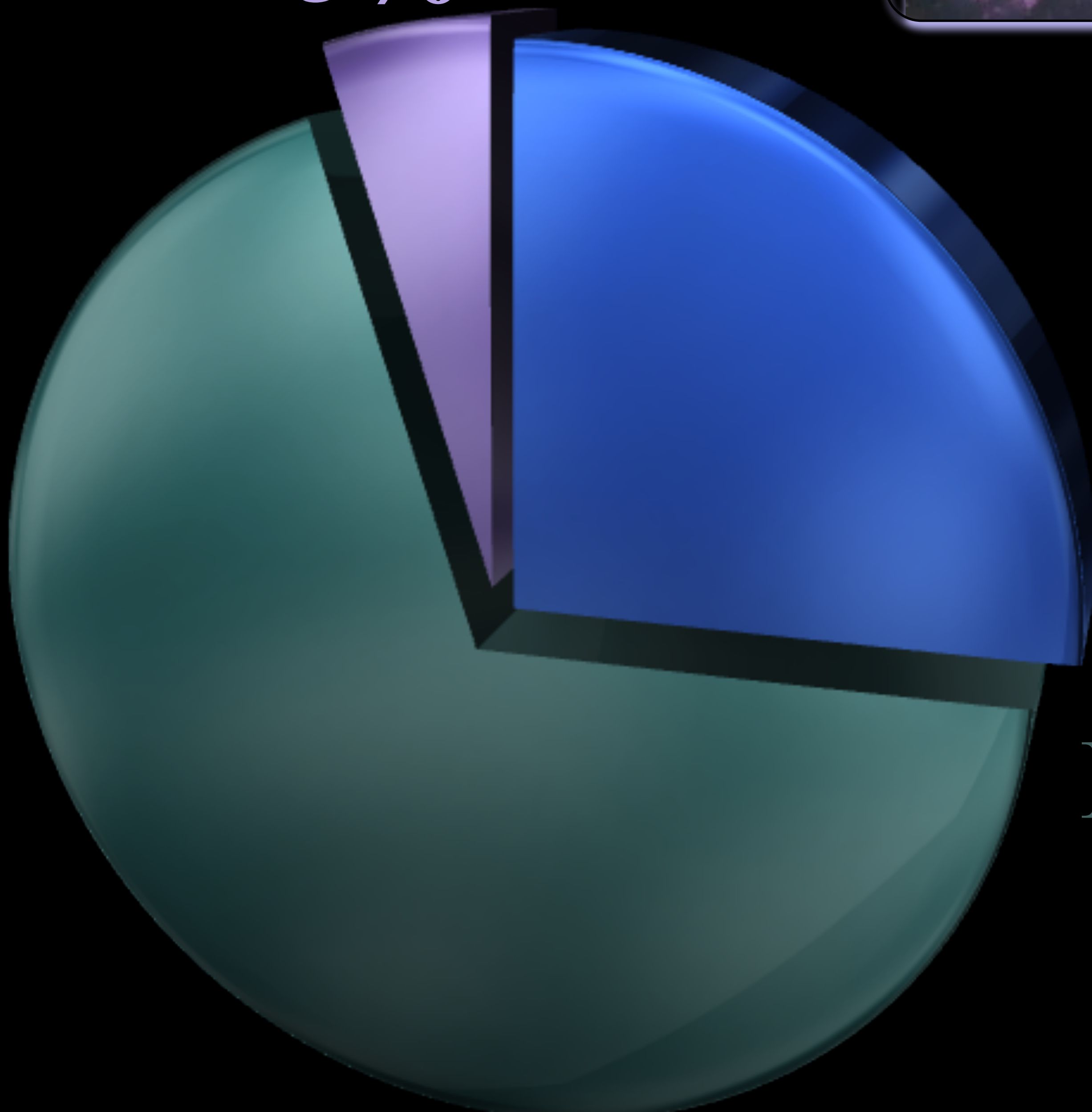
Vera Rubin
1969



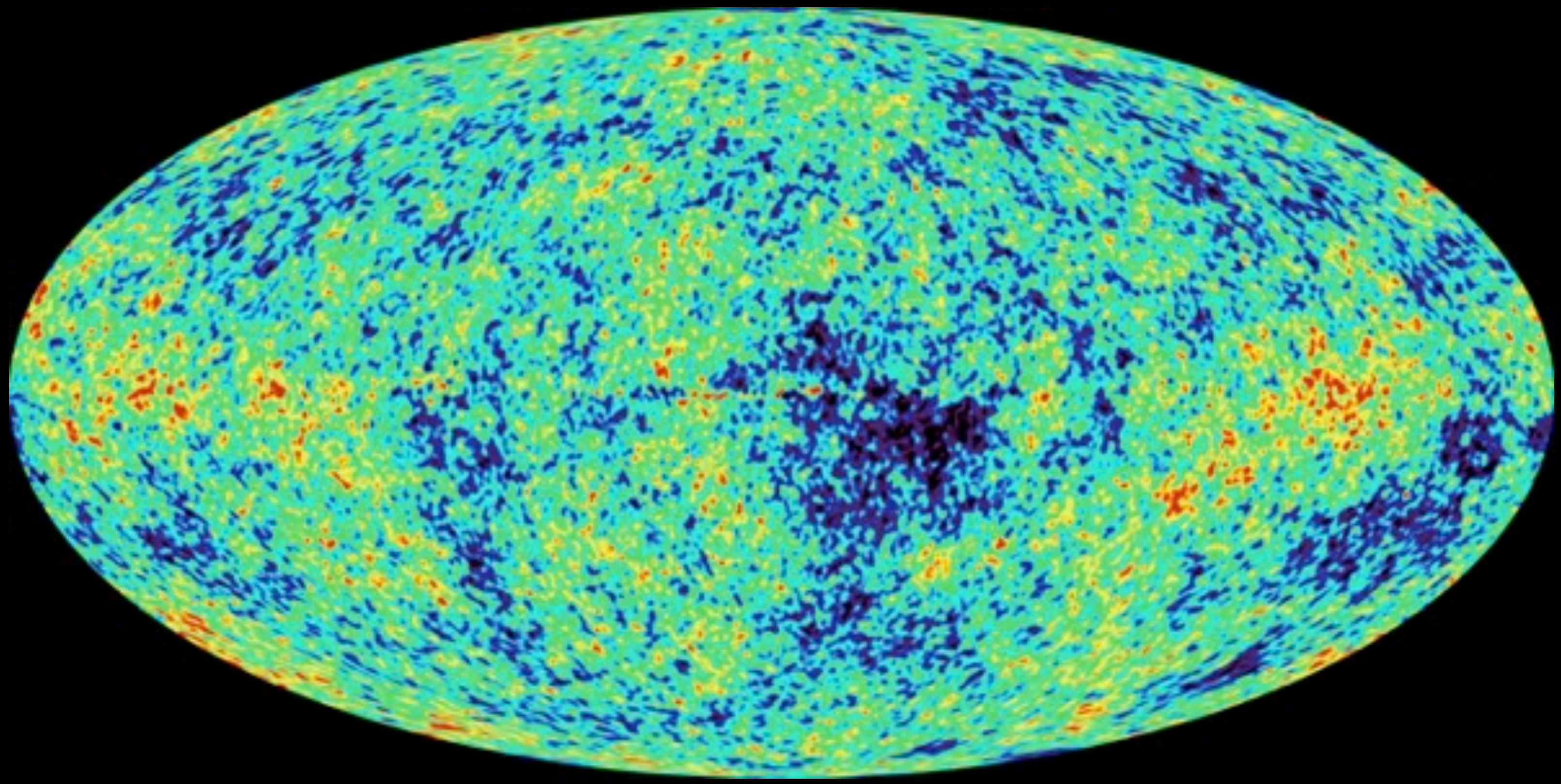
Dark Matter

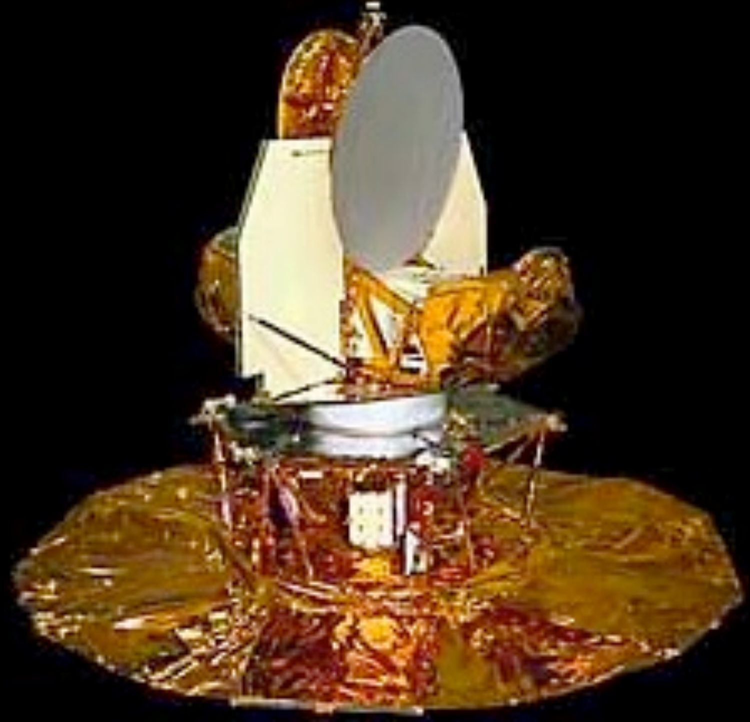


Composition of the Cosmos

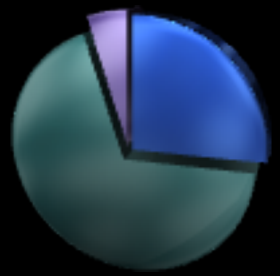


Cosmic Microwave Background 1990-2000's

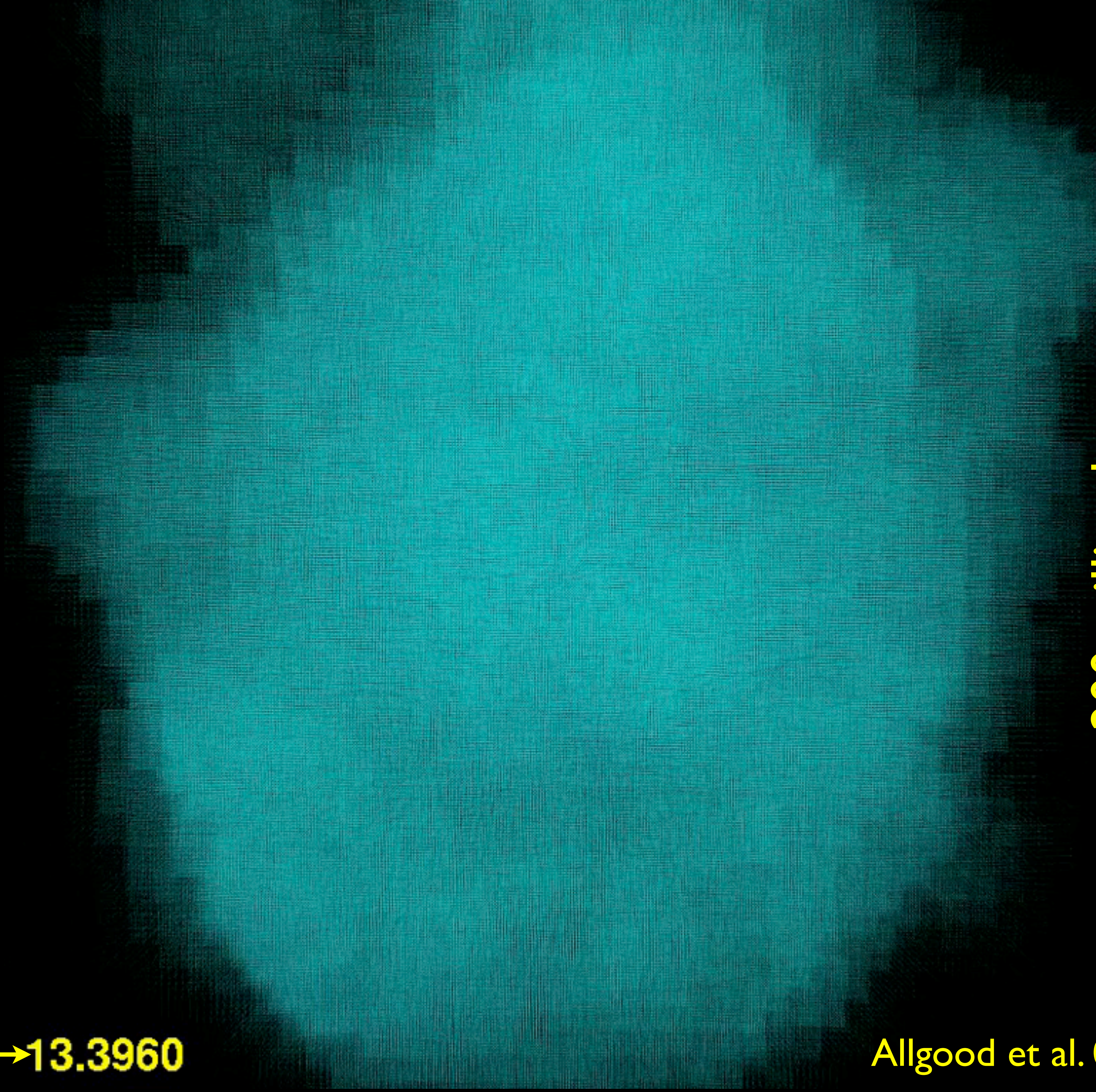




- Temperature map of universe 300,000 yrs after Big Bang
- Universe smooth to 1/100,000
- Need extra mass to get clumpy universe today.



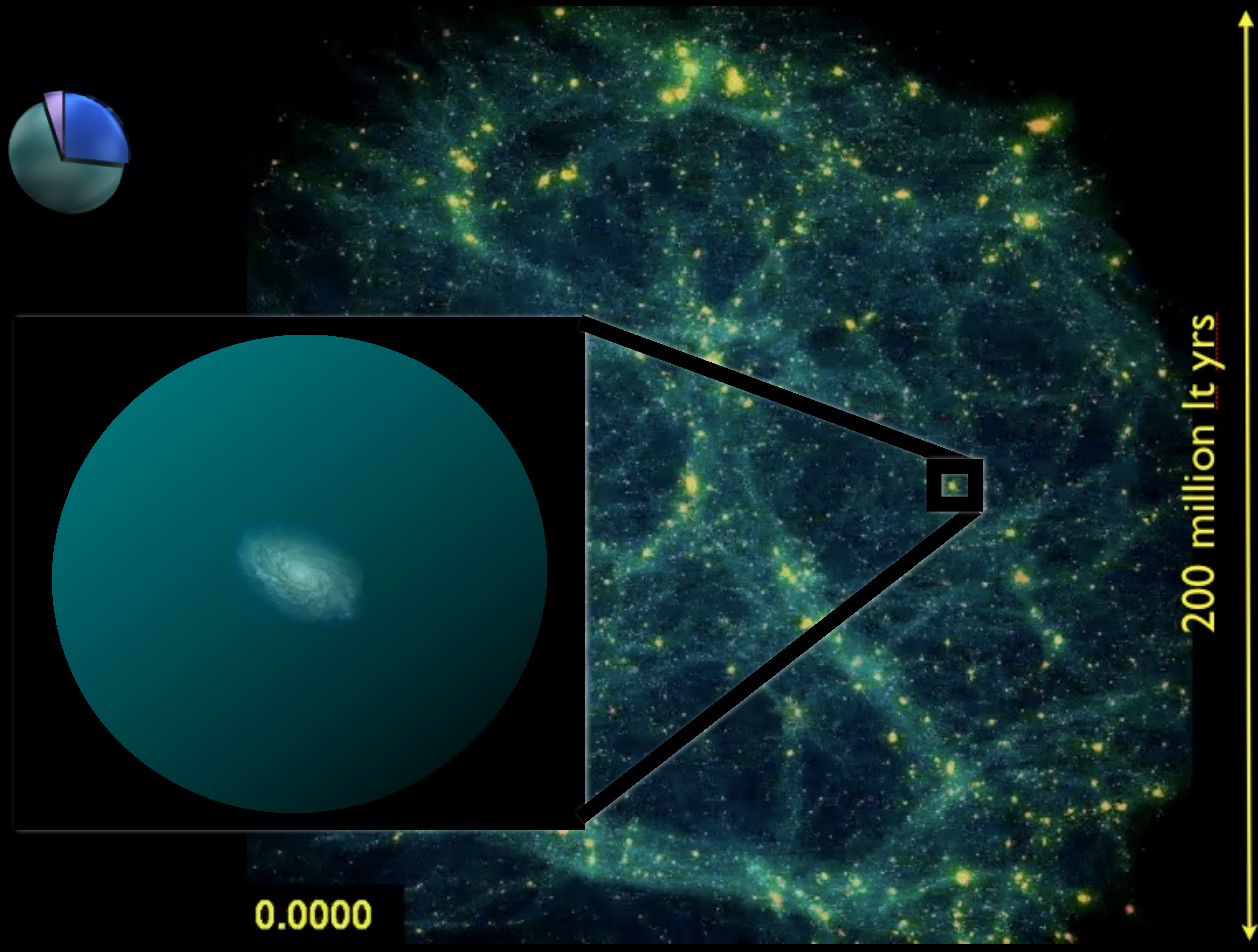
→ Dark Matter allows galaxies to grow:



Look-back time (Gyr) →

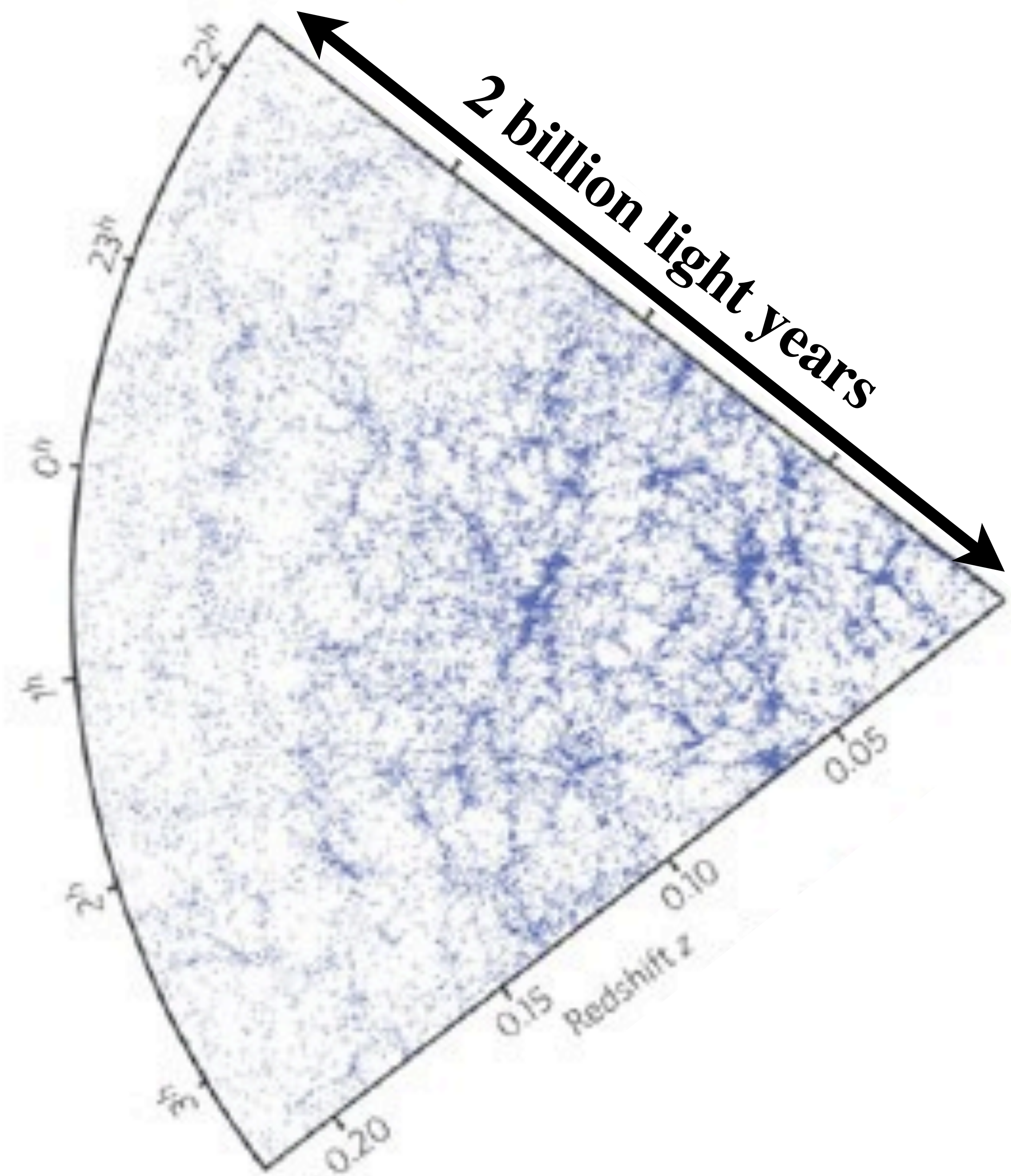
200 million lt yrs

Allgood et al. 06

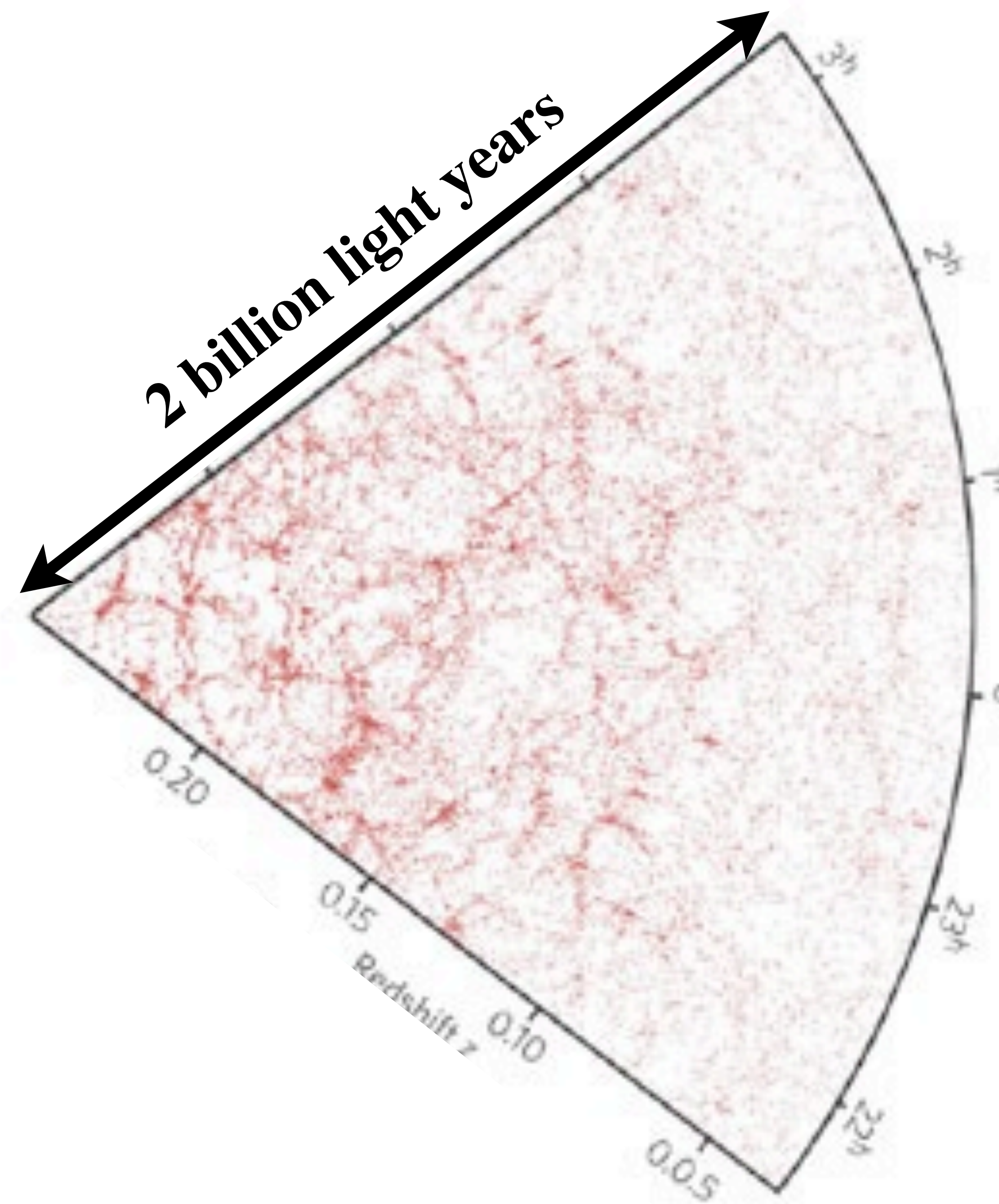


0.0000
200 million lt yrs

Map of real universe



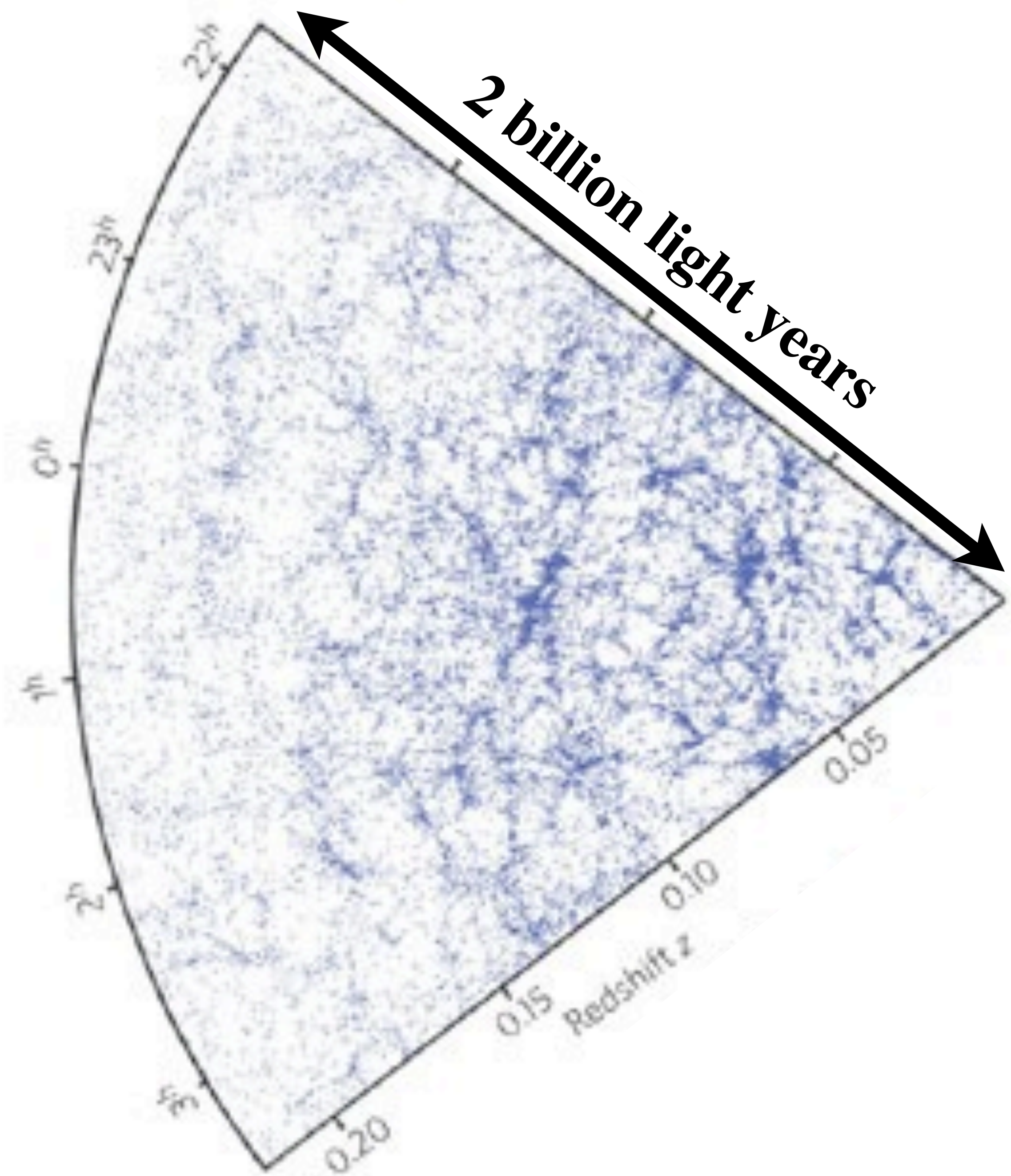
Simulated universe



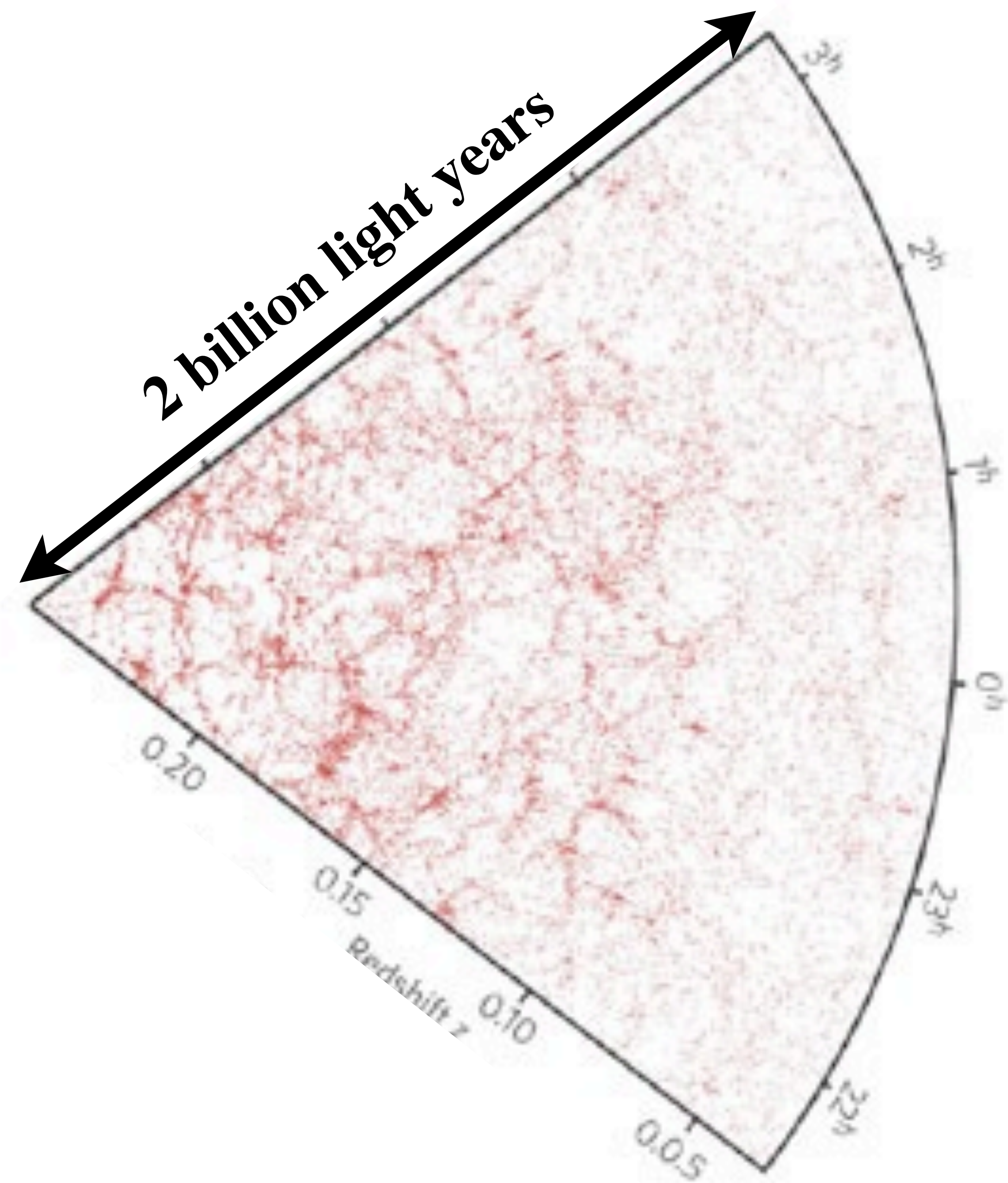
Each point = 1 galaxy

Springel et al.

Map of real universe



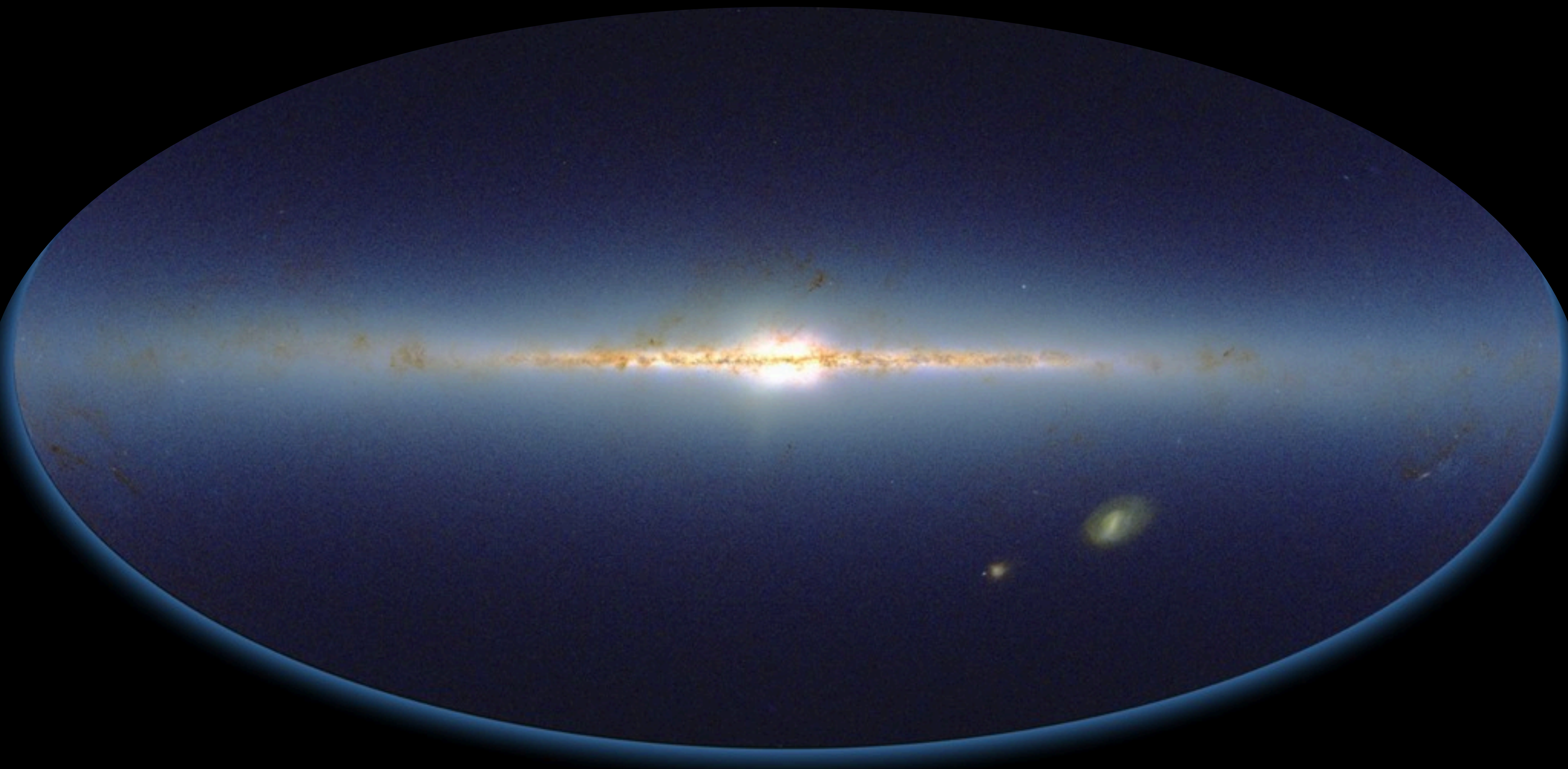
Simulated universe



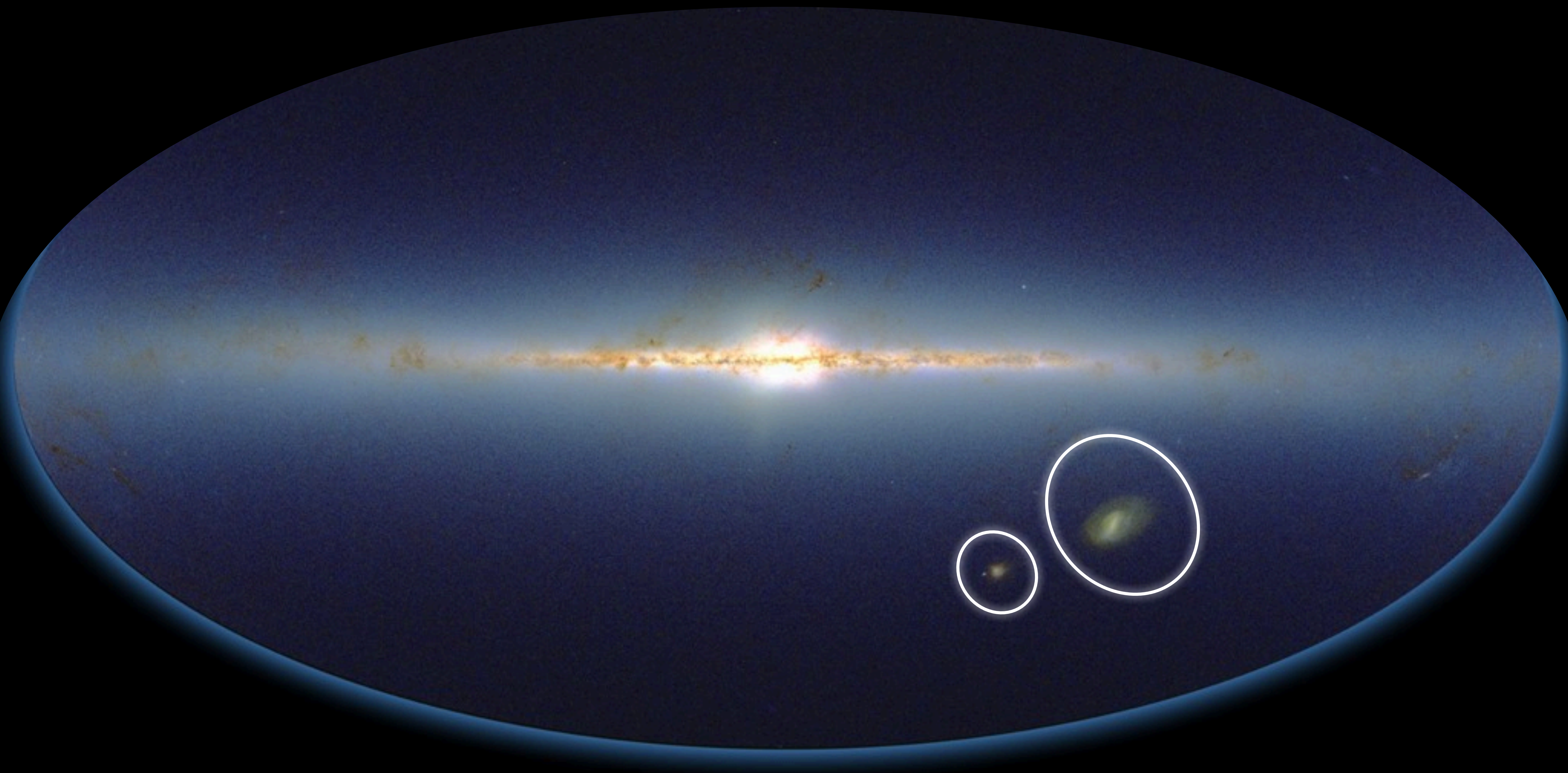
Broad brush: we seem to understand things

What about the details?

The Milky Way in 2micron light

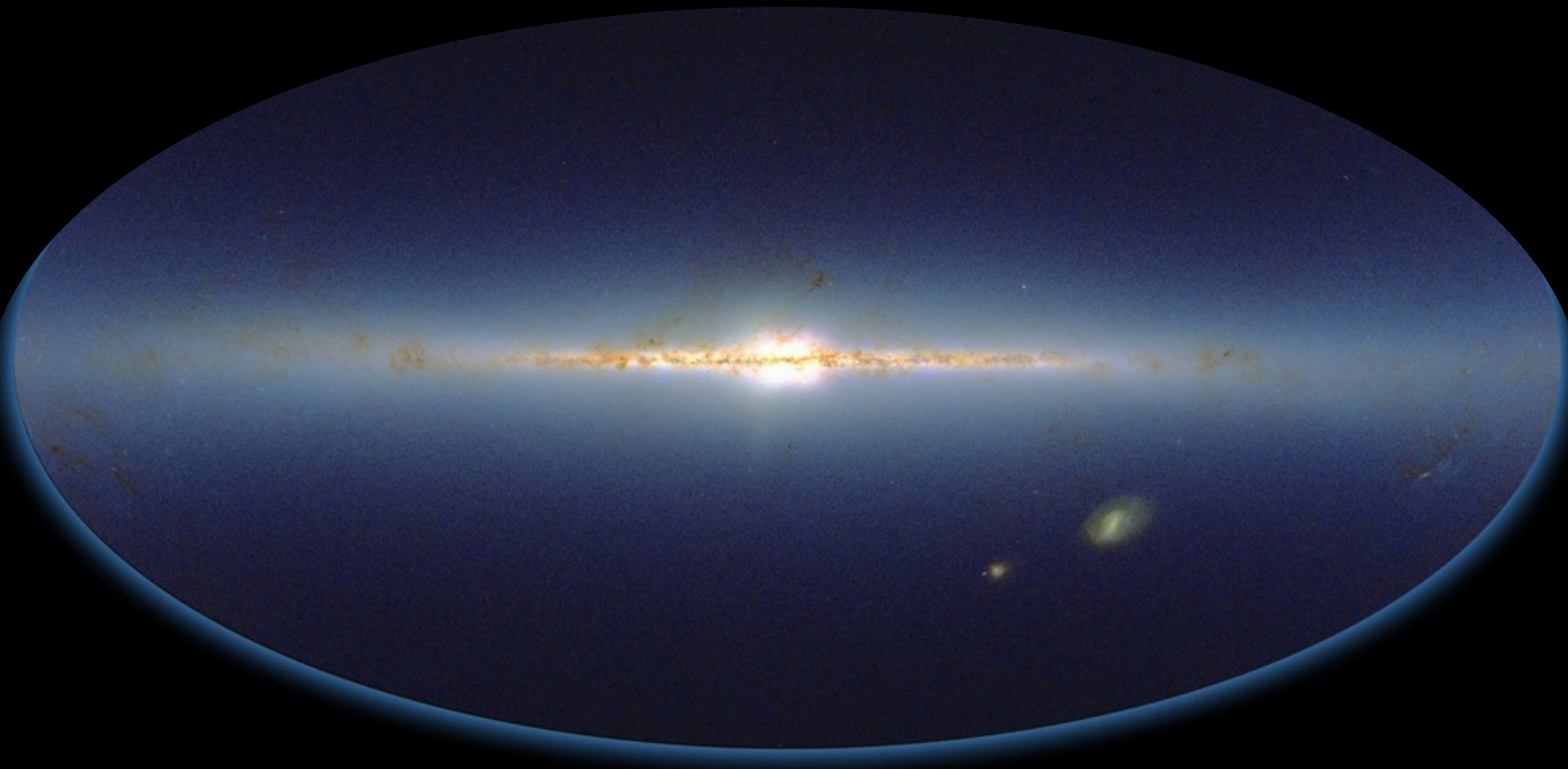


The Milky Way in 2micron light



Satellite galaxies of the Milky Way

The Milky Way in 2micron light



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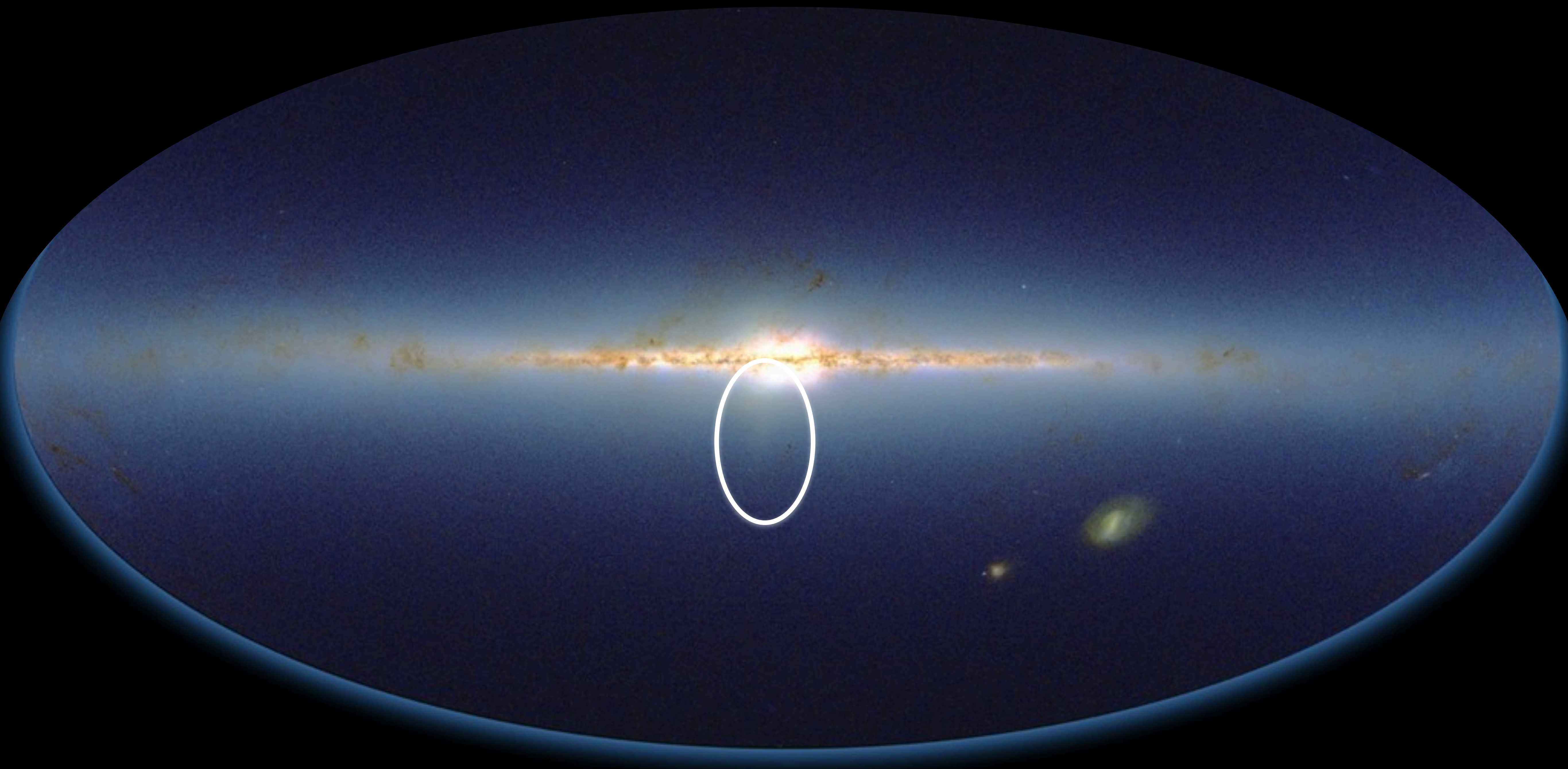
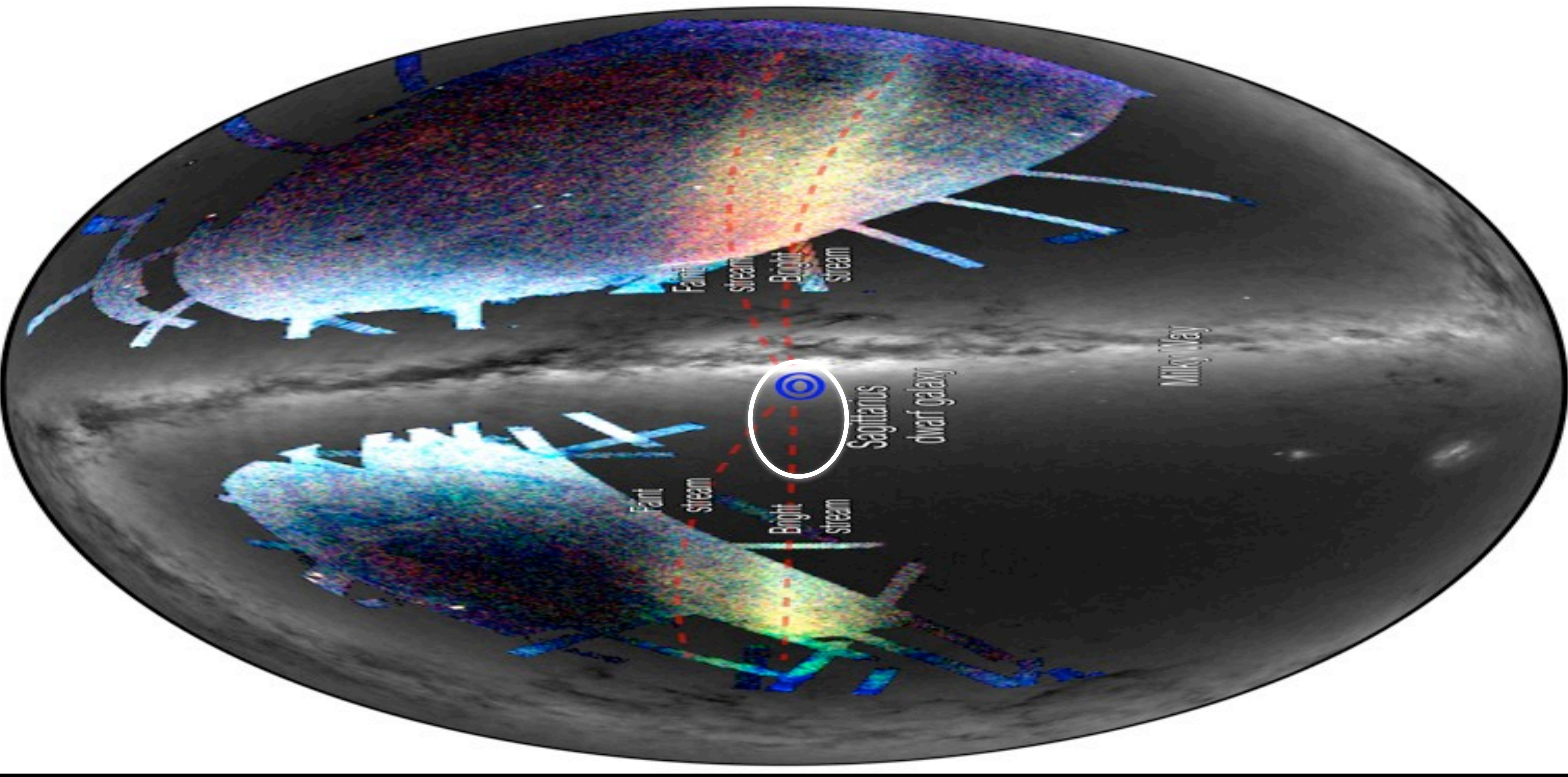
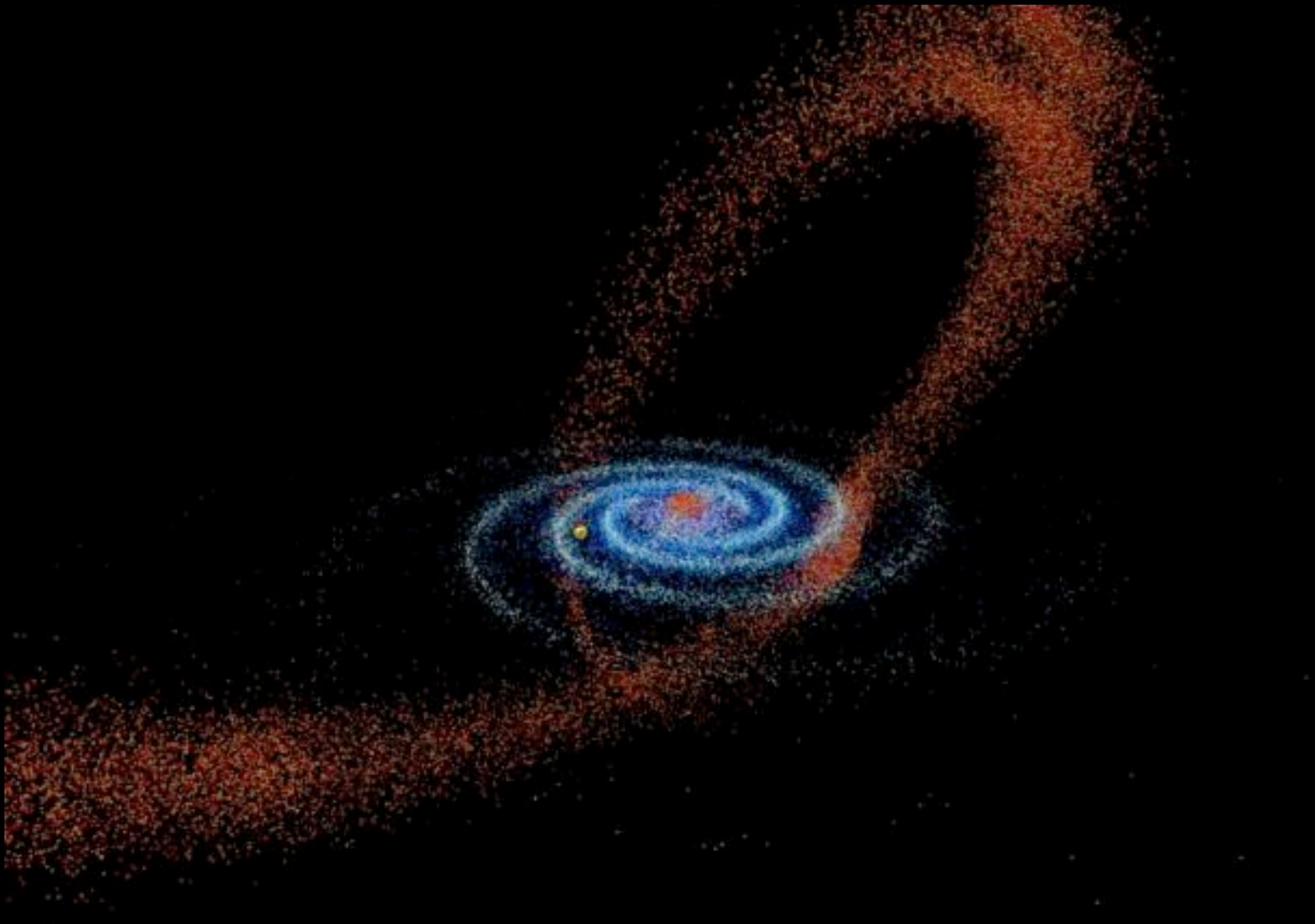


Sagittarius dwarf

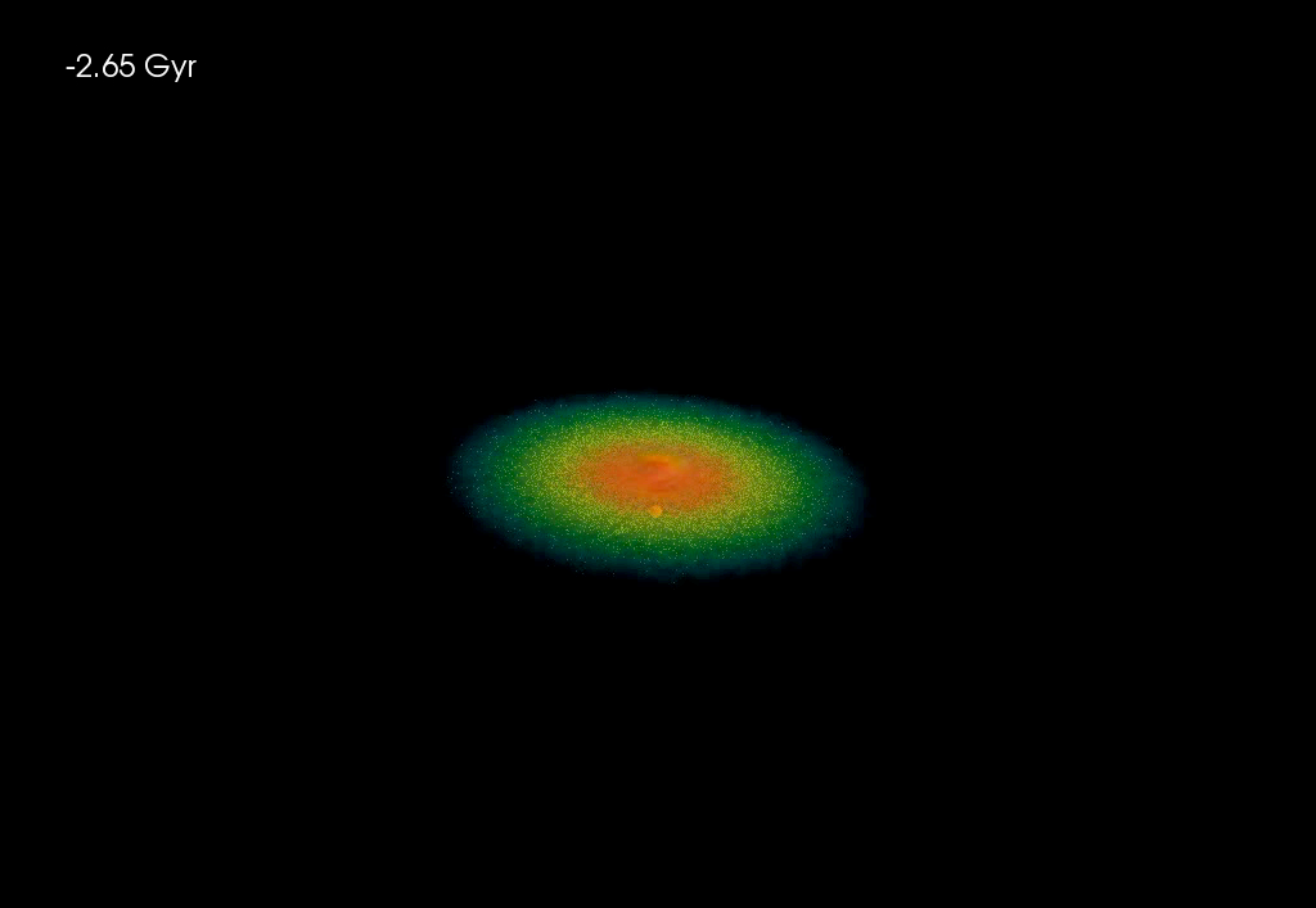
The Milky Way in Star Counts



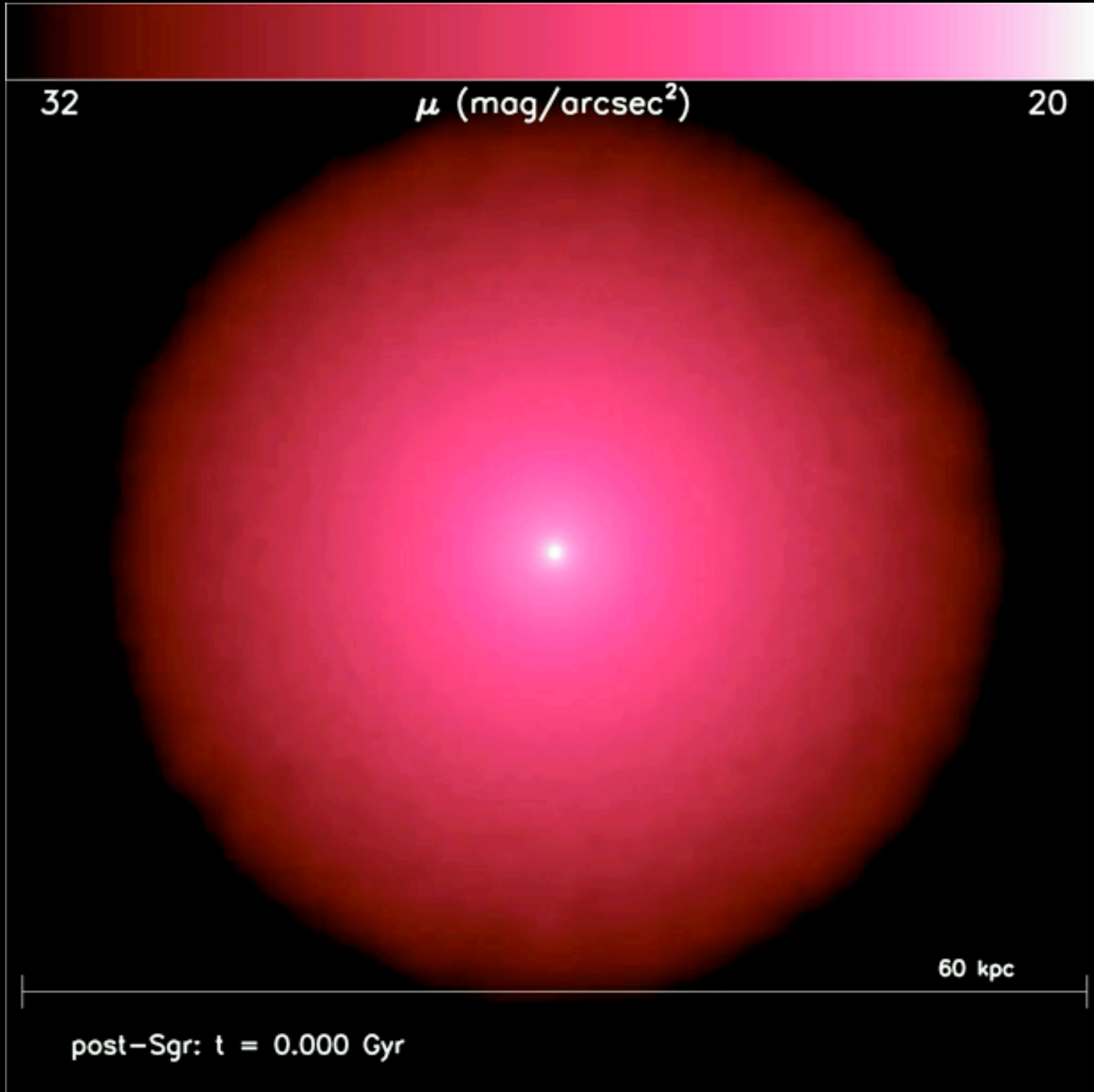
Sloan Digital Sky Ssurvey III (Koposov et al.)



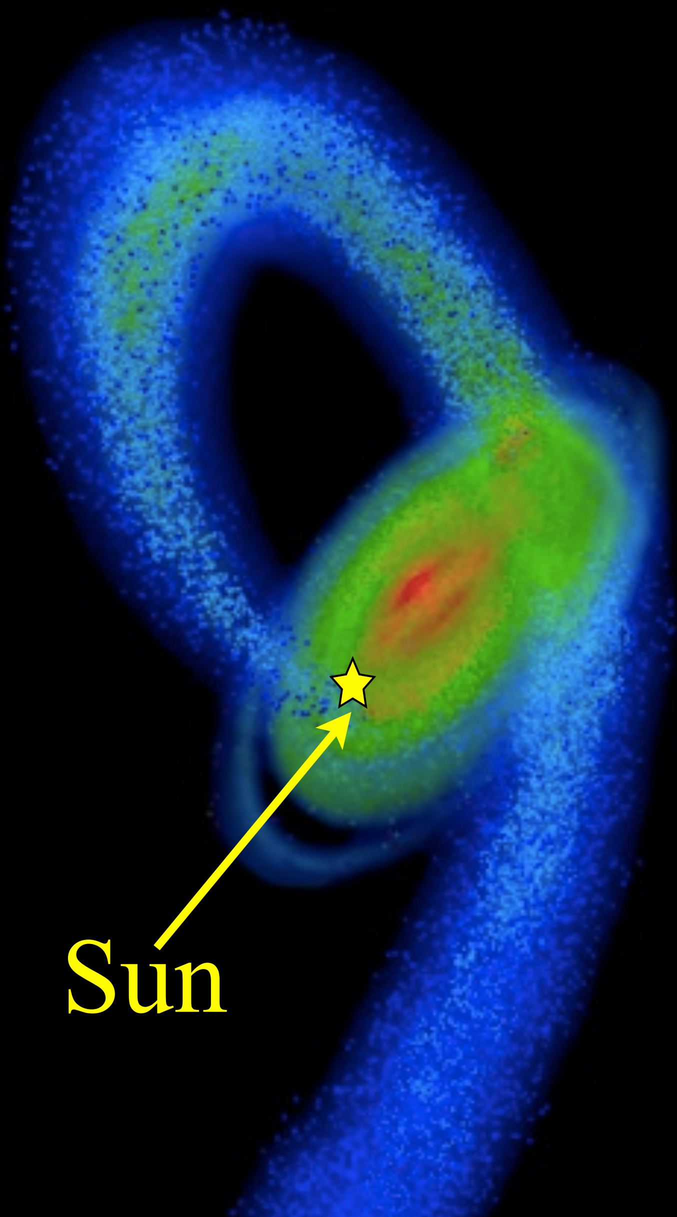
David Law/University of Virginia



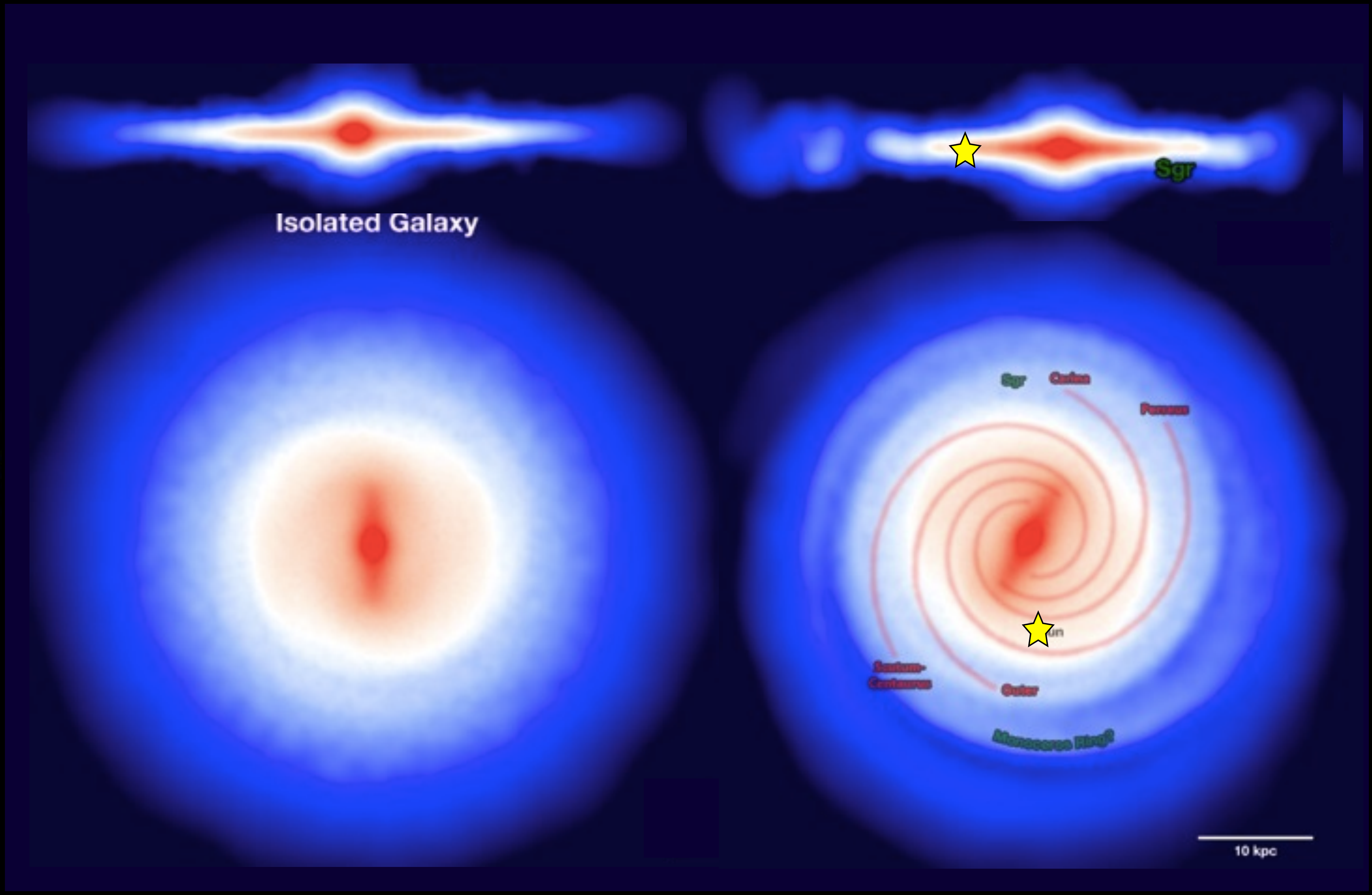
Purcell, JSB, Tollerud, Rocha, Charkrabarti, *Nature*, 2011



Purcell, JSB, Tollerud, Rocha, Charkrabarti, *Nature*, Sept. 2011

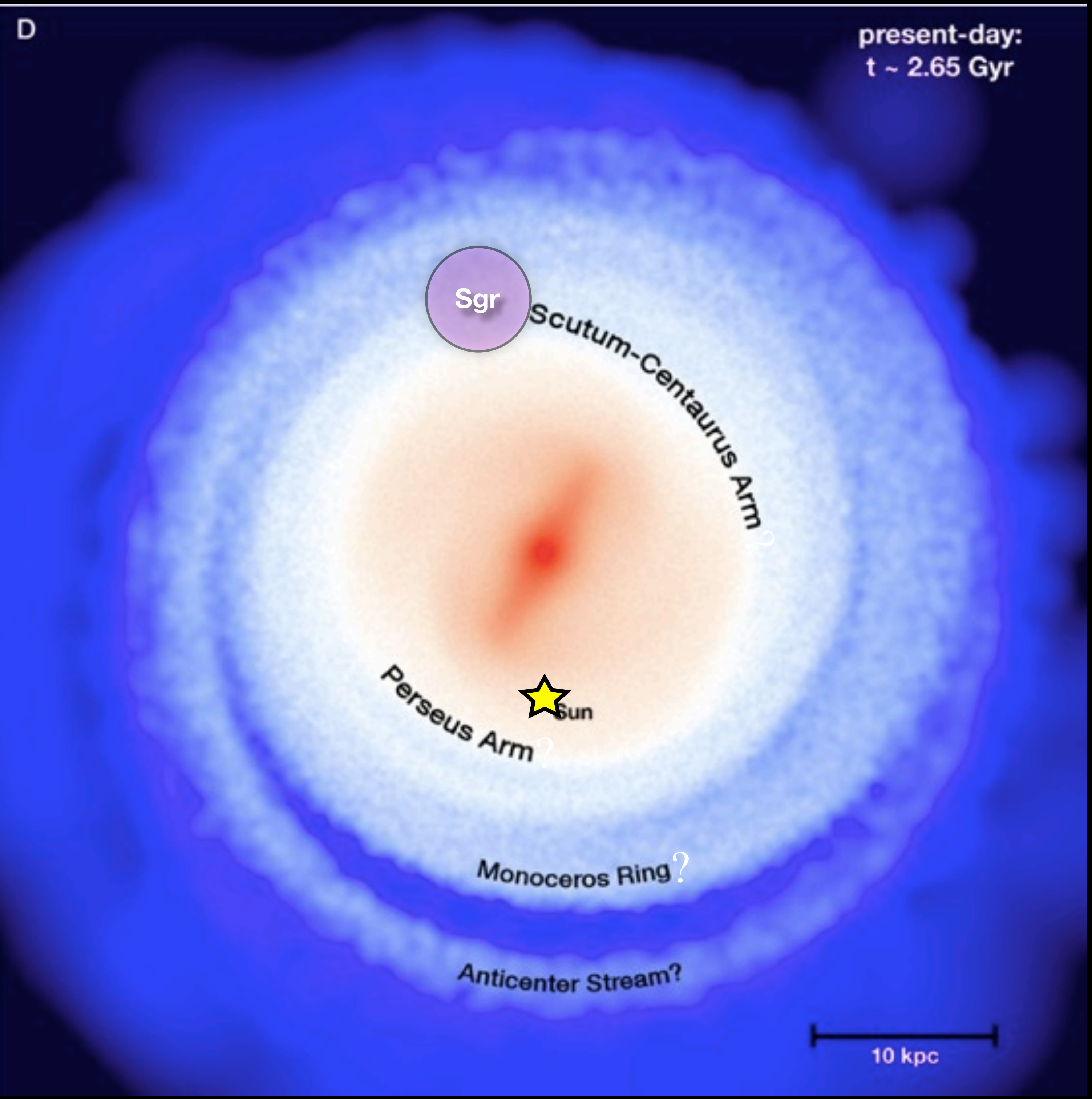


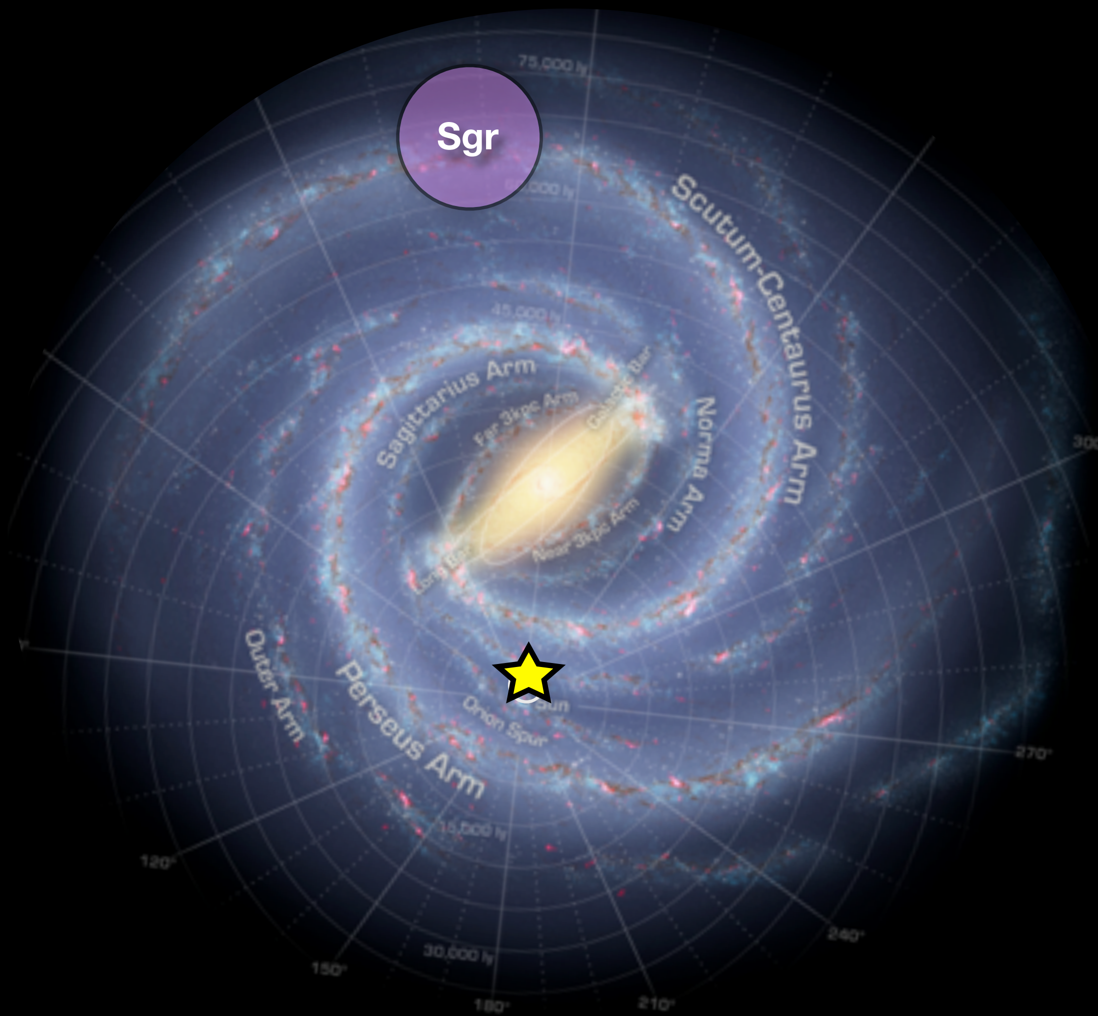
Without Sag. | With Sag.



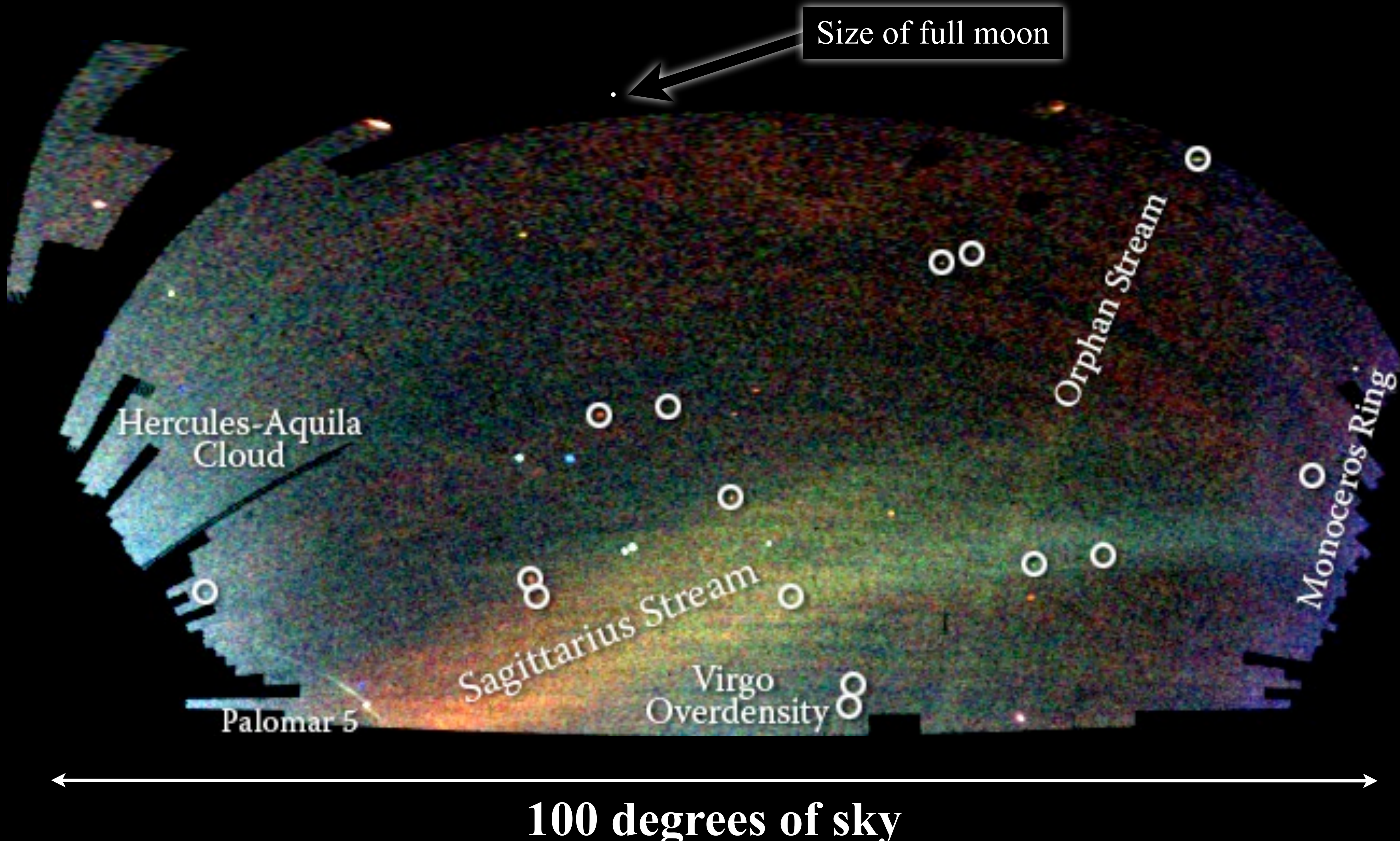
Sagittarius Dwarf ⇒ Spiralilty, Rings, Bar Evolution in the Galaxy

Intermediate-scale spiral structure, similar to MW



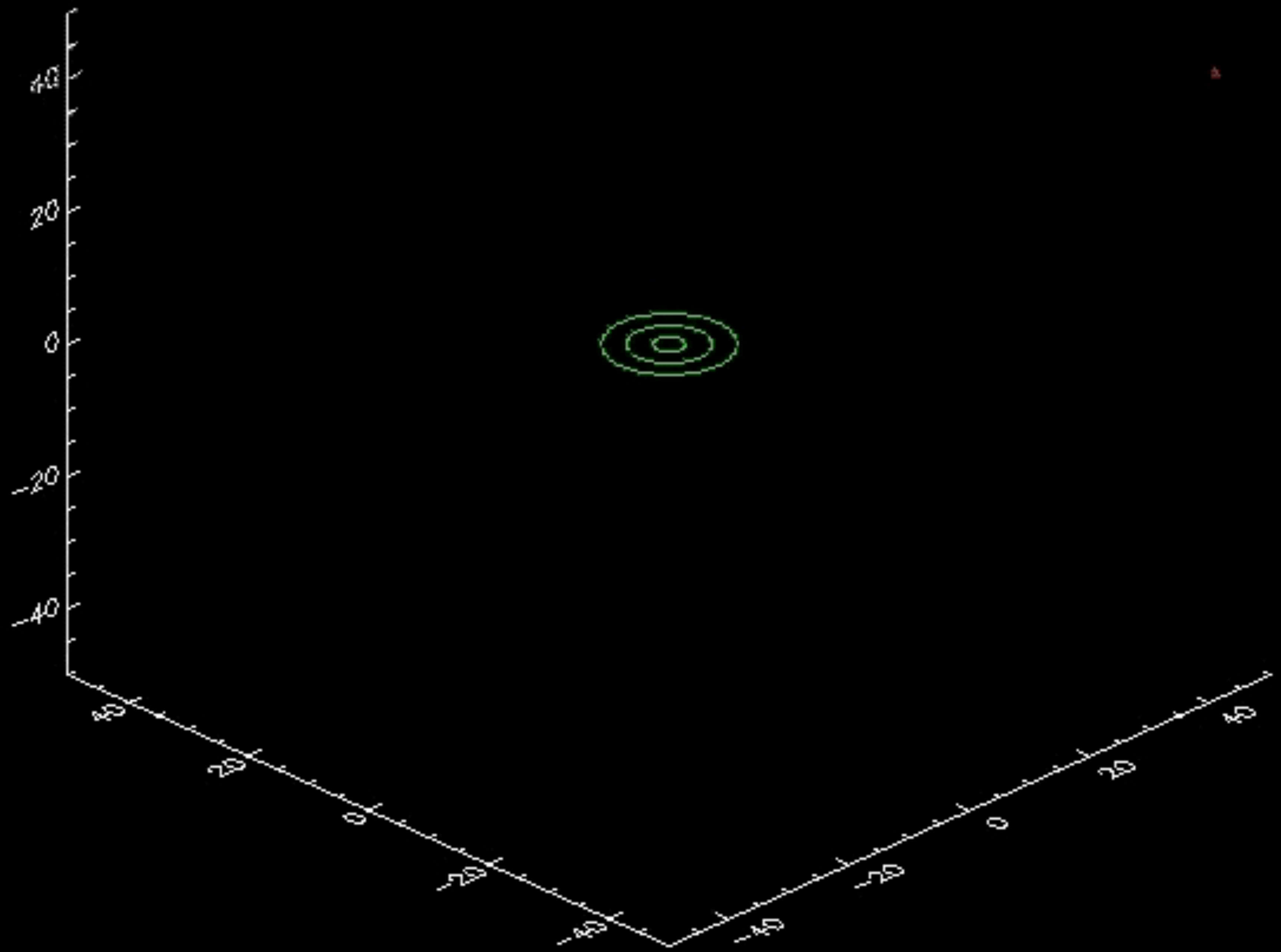


More streams around the Milky Way



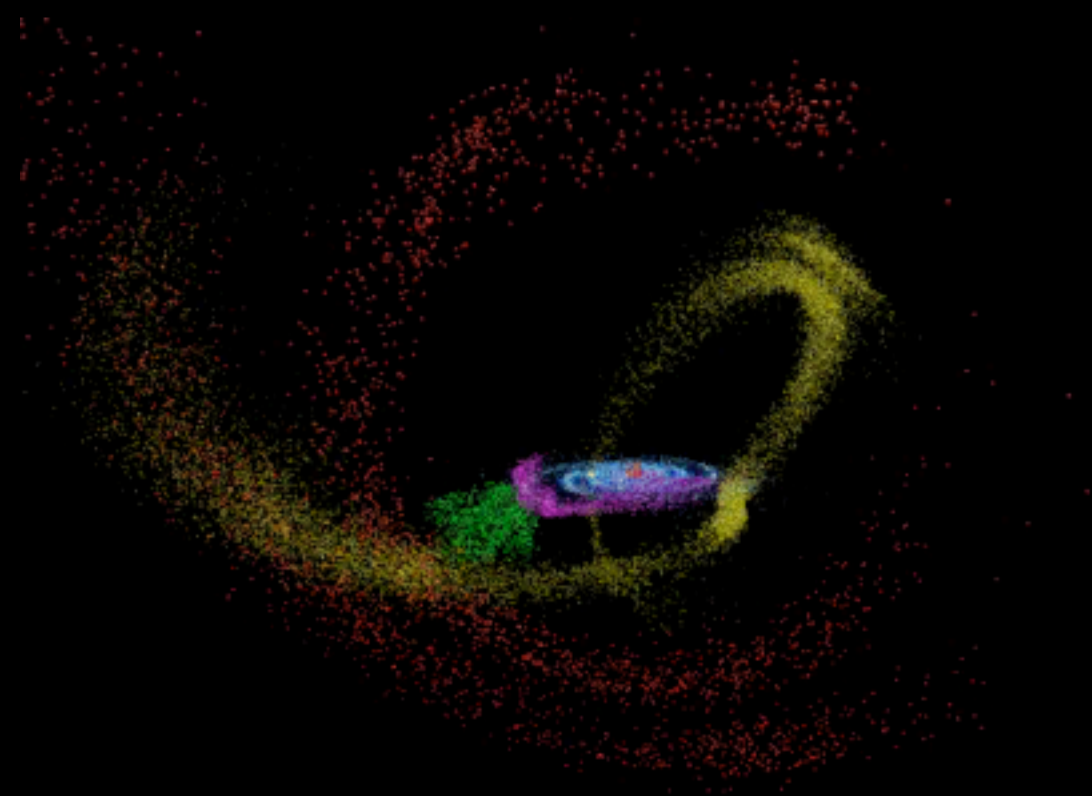
Belokurov et al. 2006

Predicted accretion history of typical galaxy



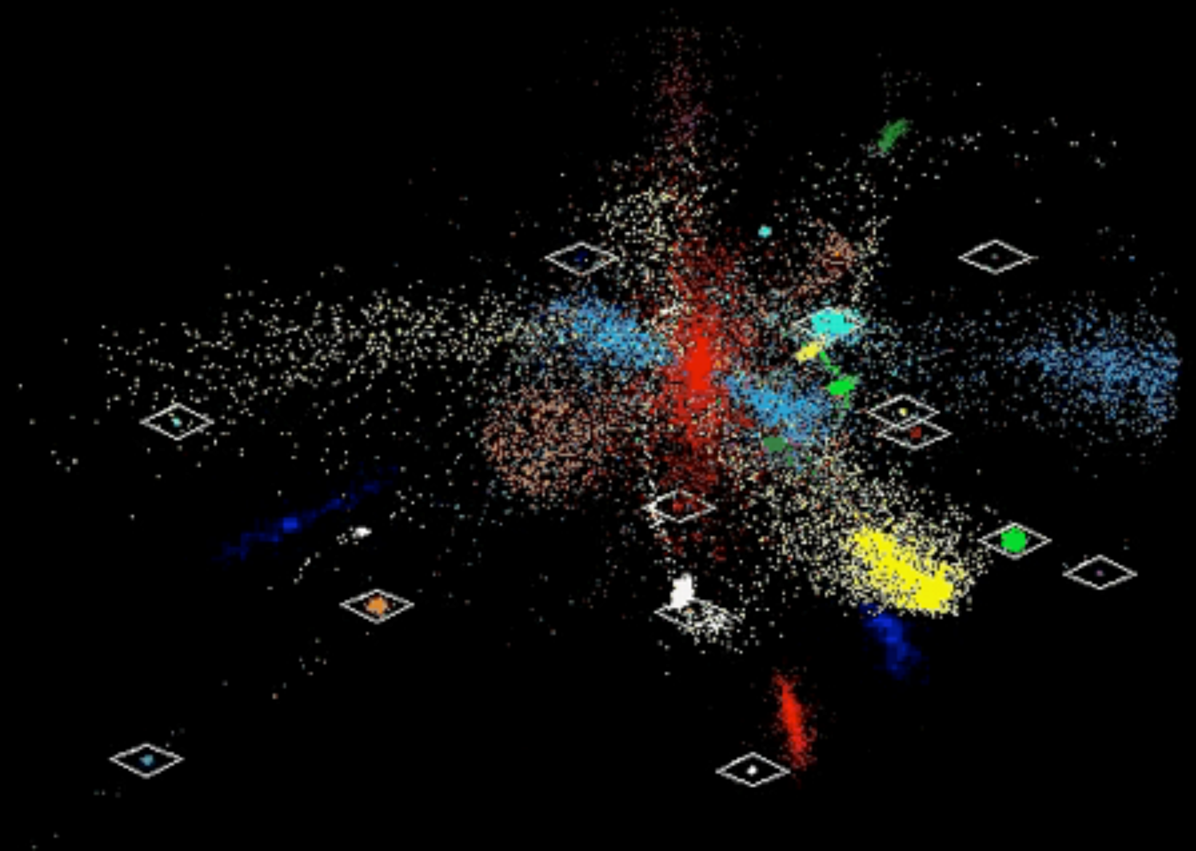
JSB & Johnston 2005

Halo Streams & Substructure



Law & Majewski 06

Data (+ models engineered to match)

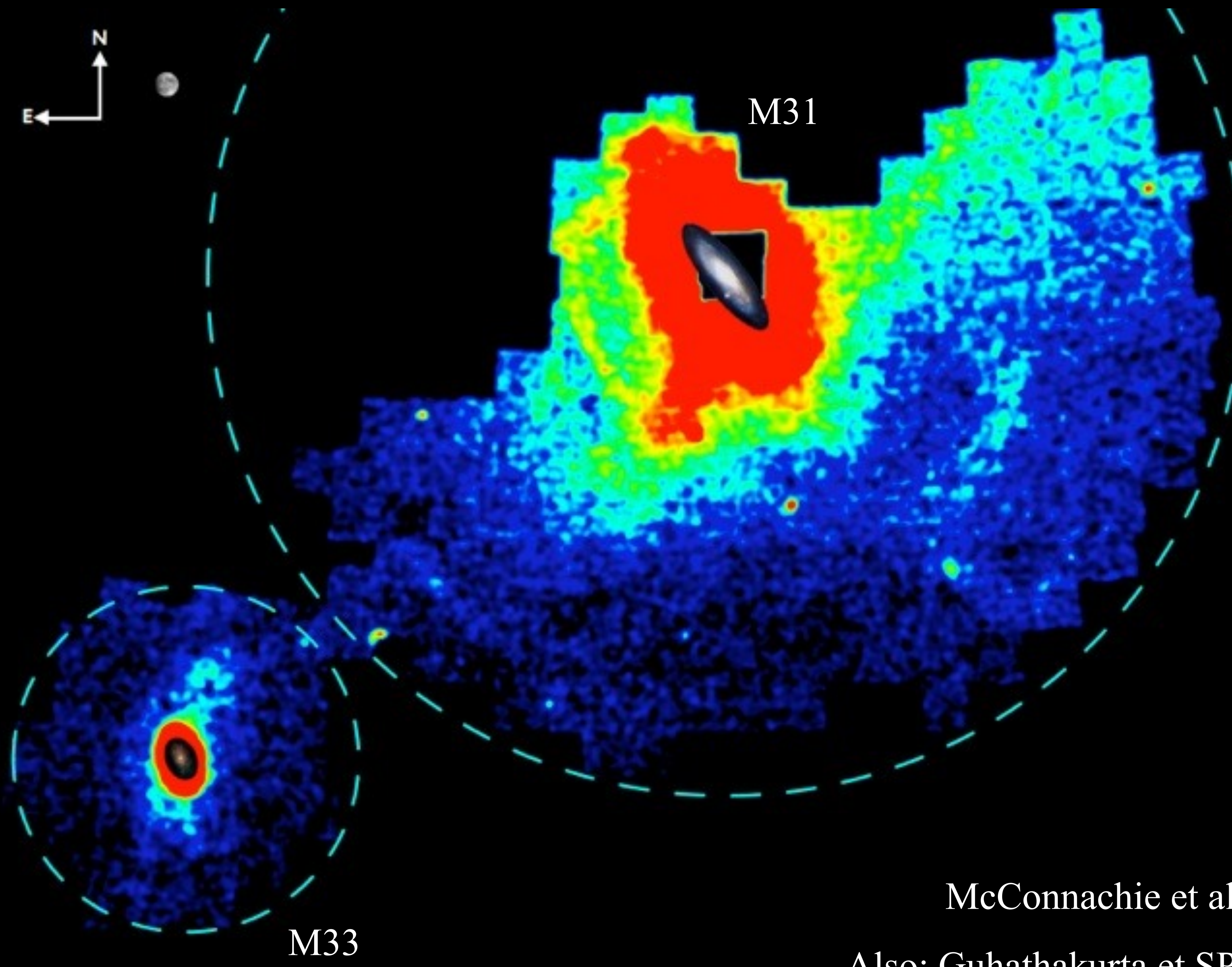


Bullock & Johnston 05

Random LCDM realization

Andromeda Galaxy (M31)

Andromeda galaxy also surrounded by streams

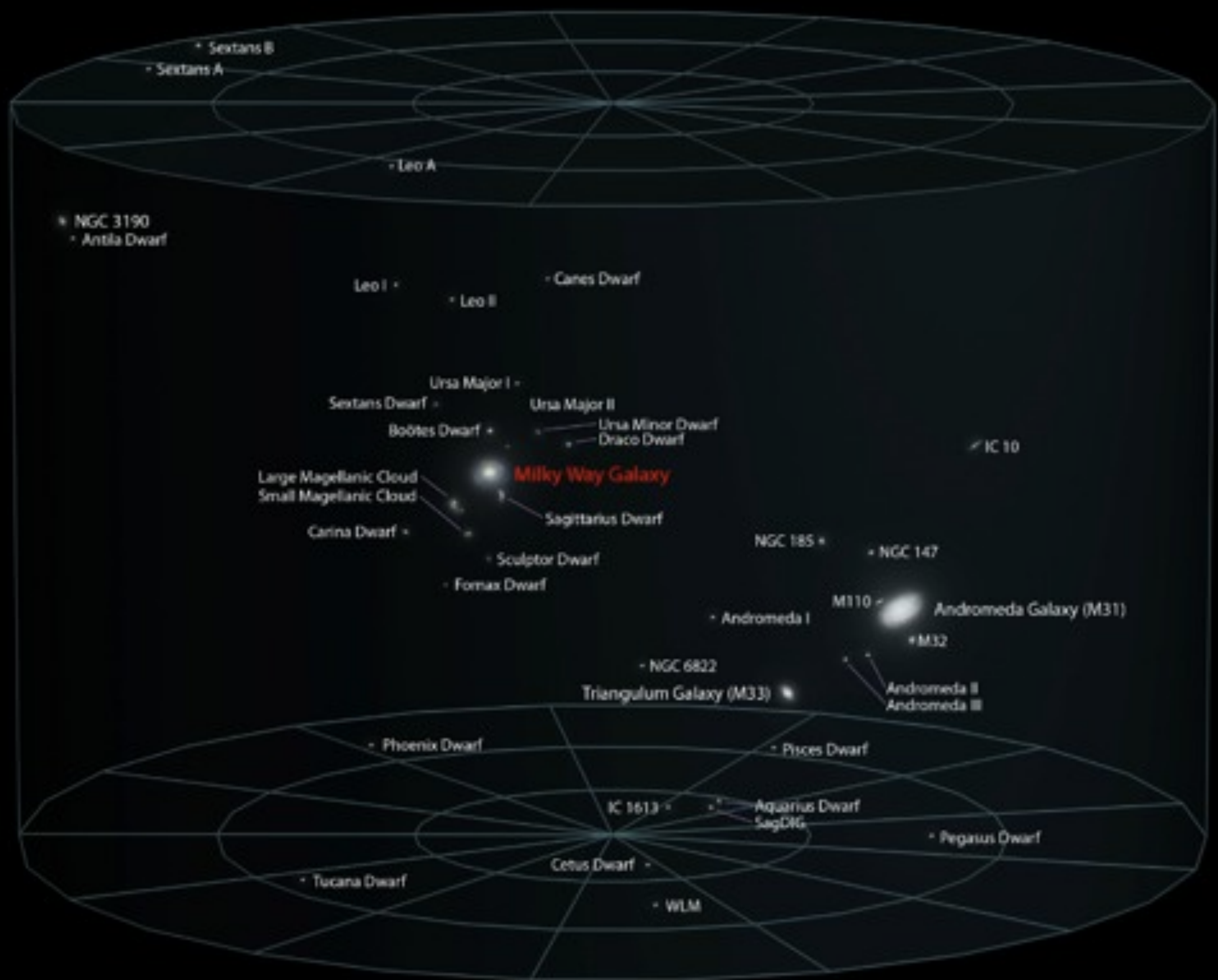


McConnachie et al. 2009

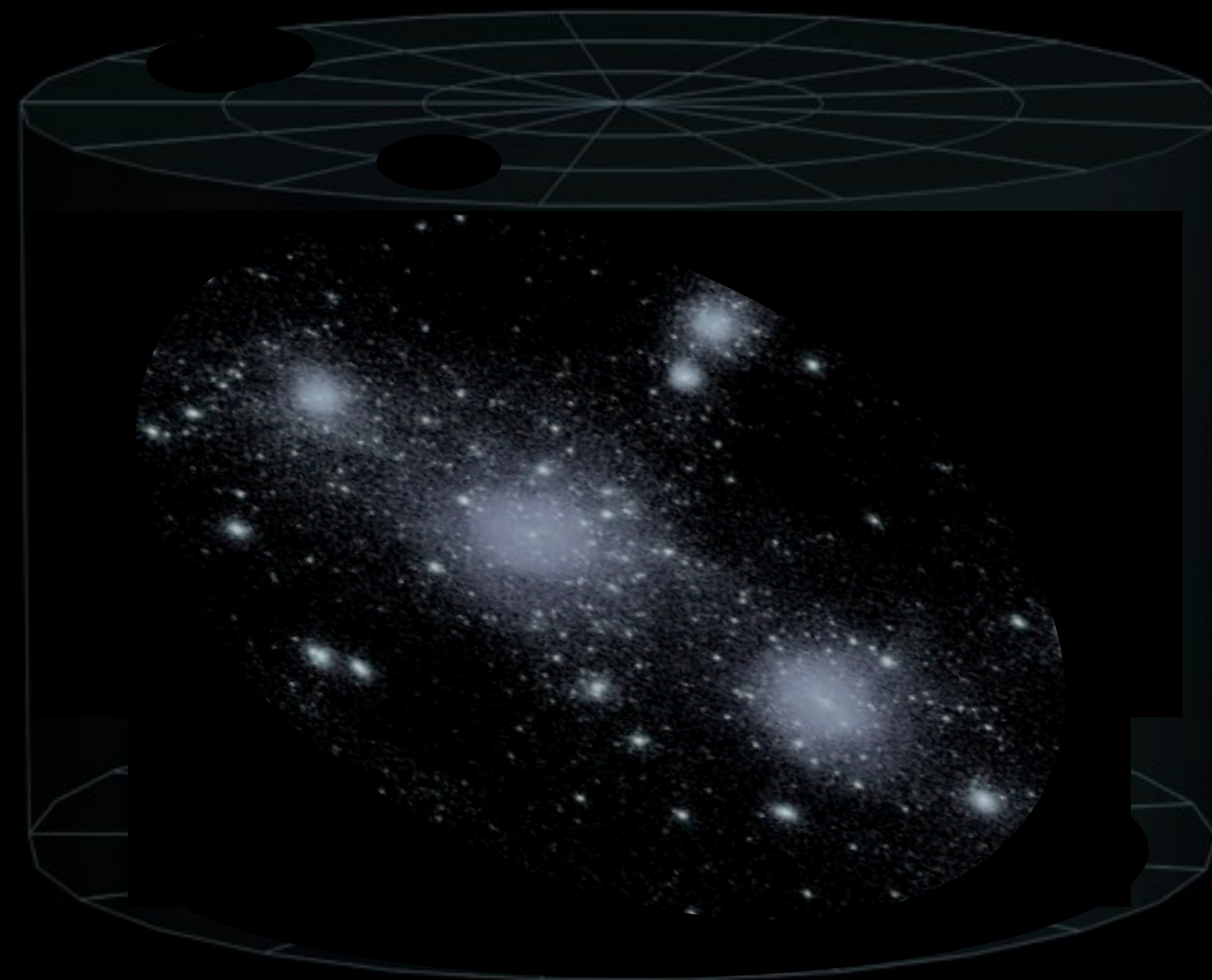
Also: Guhathakurta et SPLASH

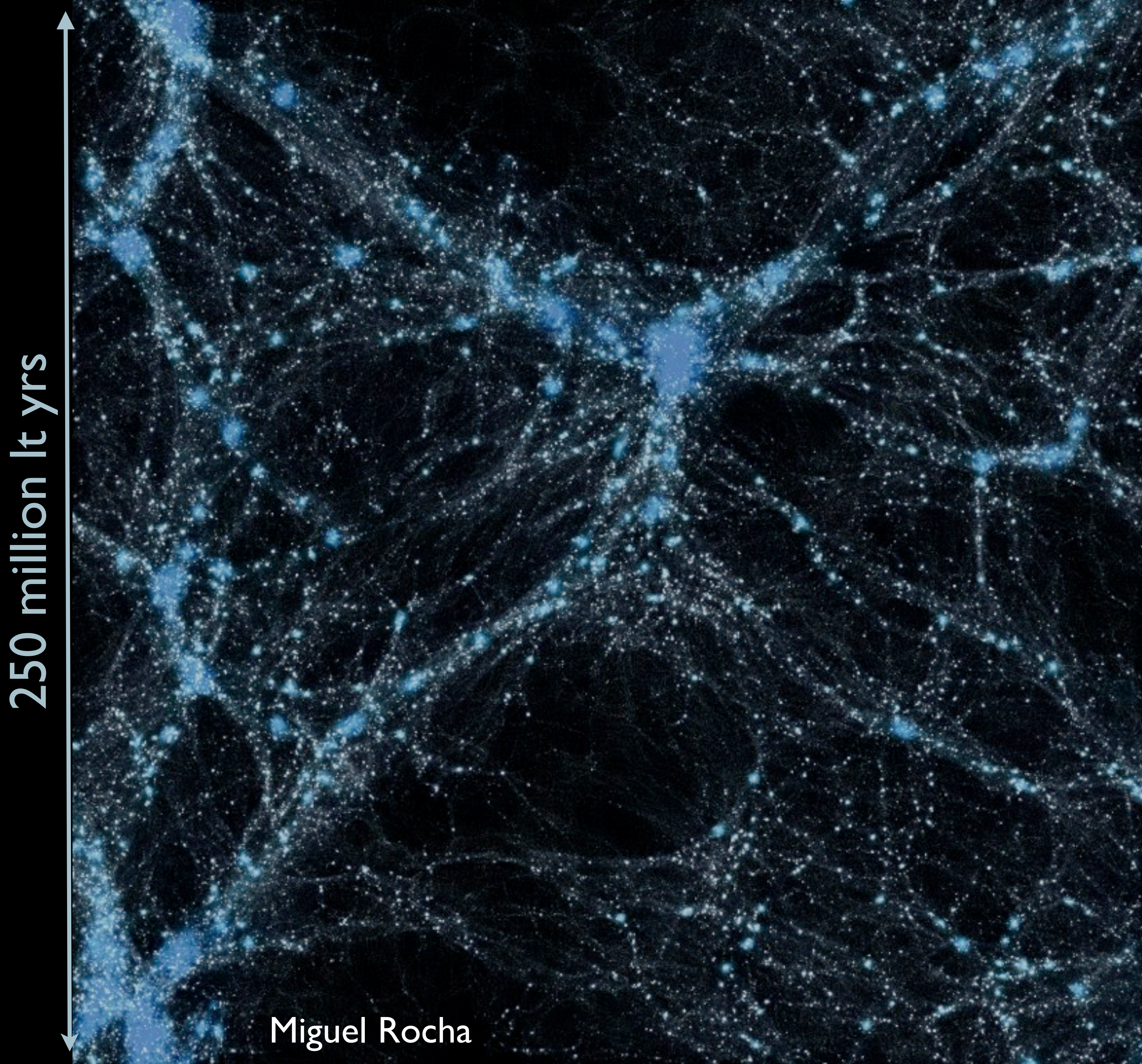
Towards more detailed tests

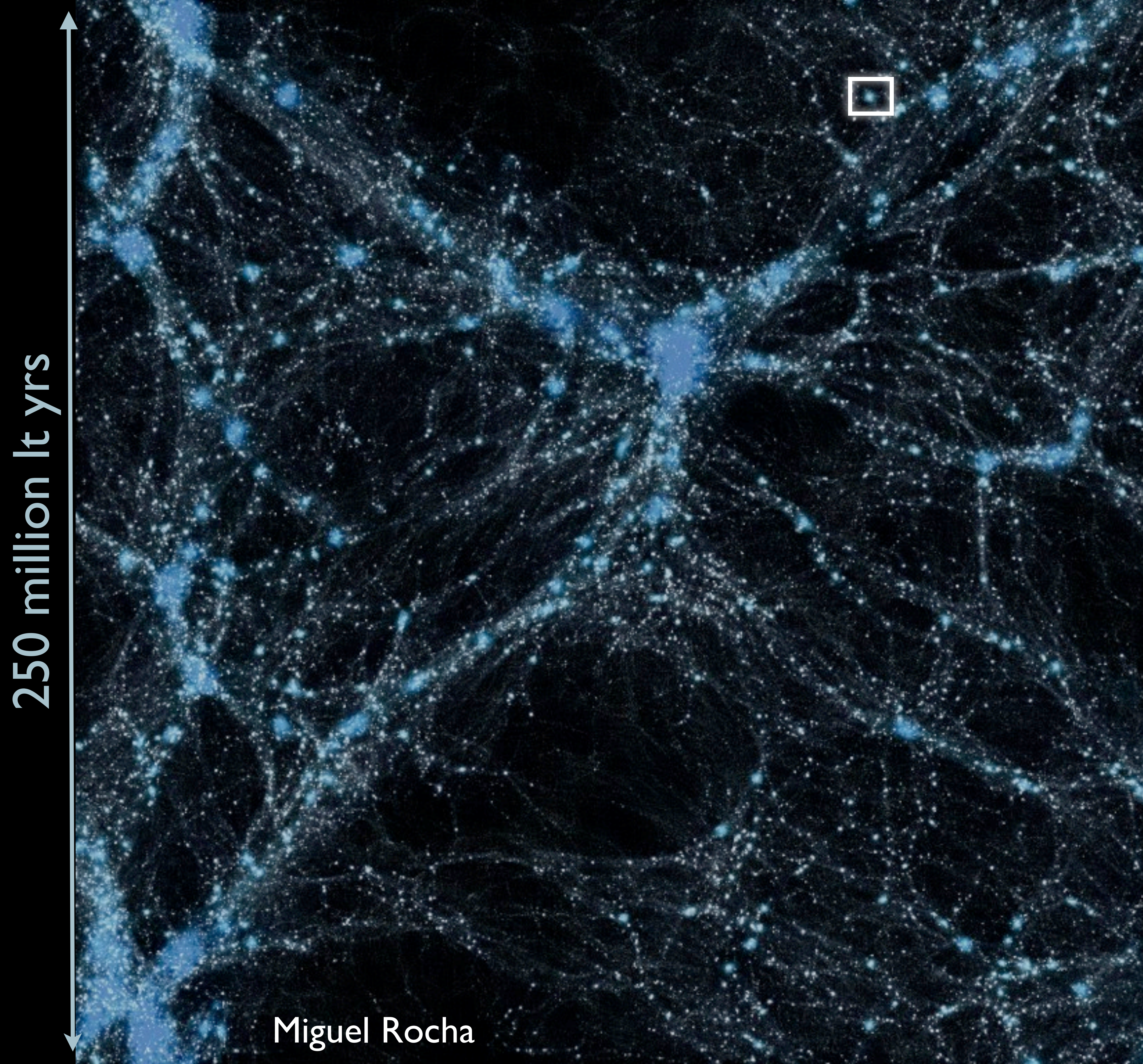
Observed Universe

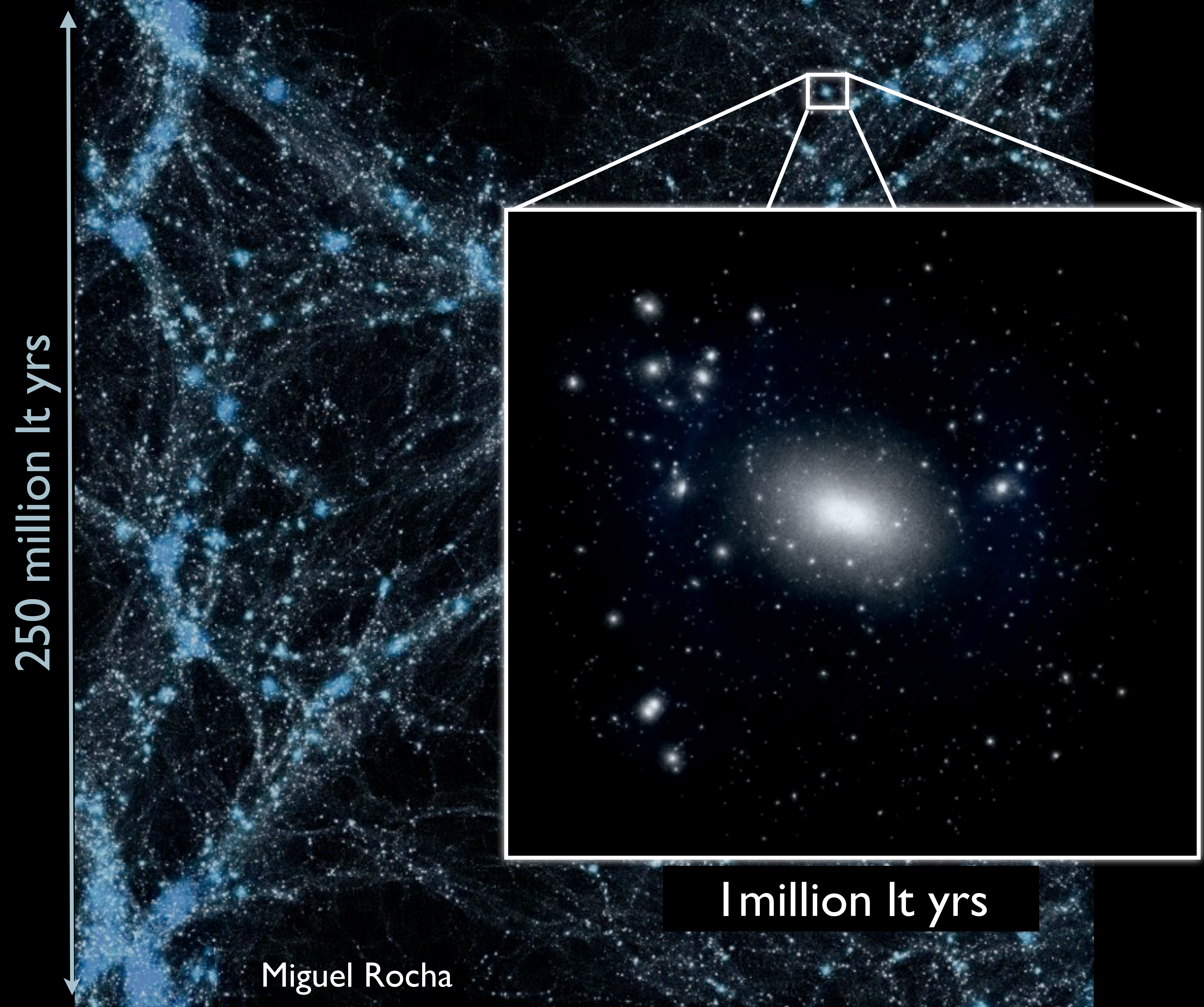


Simulation



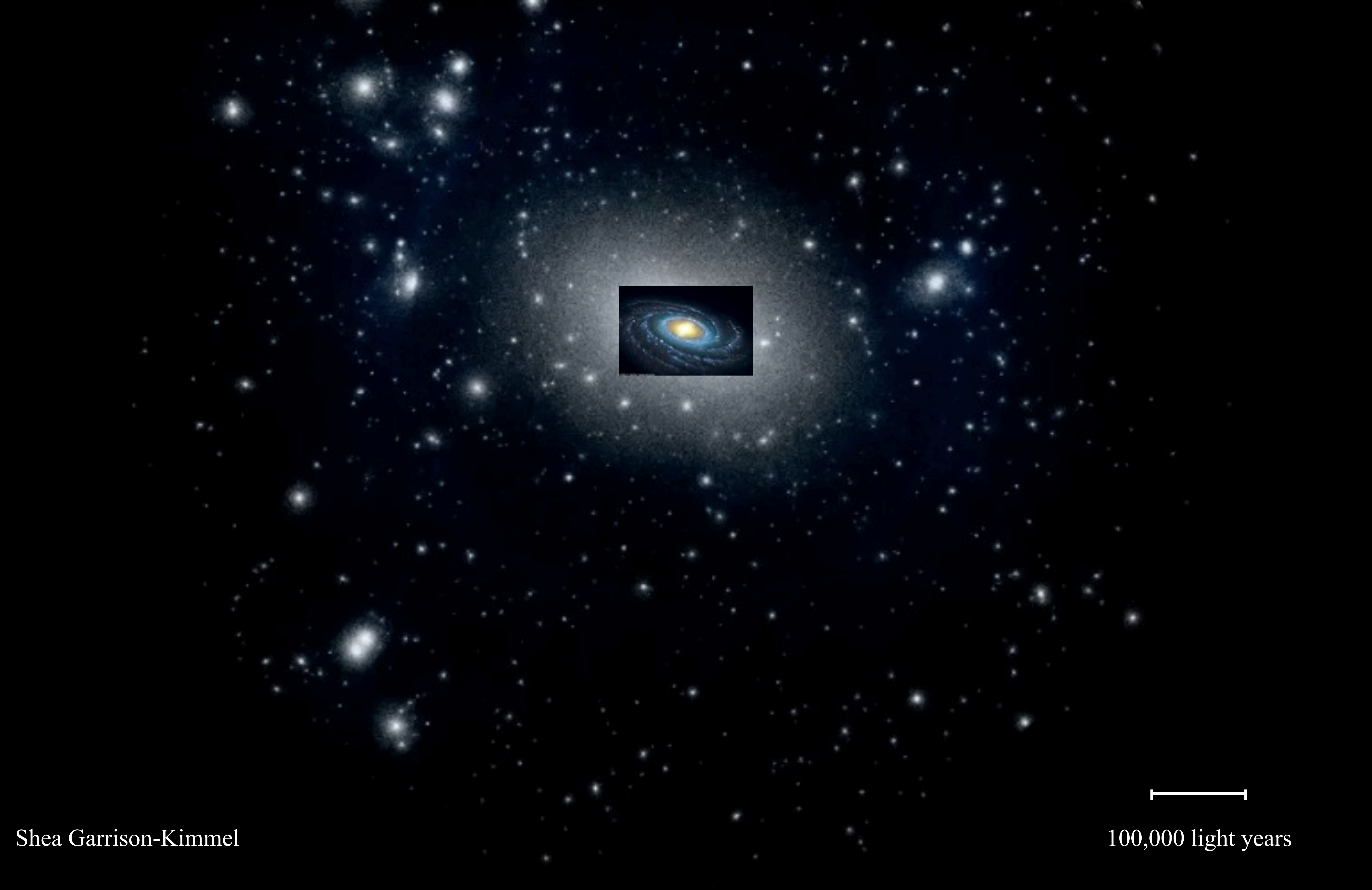

250 million lt yrs
Miguel Rocha


250 million lt yrs
Miguel Rocha


250 million lt yrs
1million lt yrs
Miguel Rocha

Shea Garrison-Kimmel

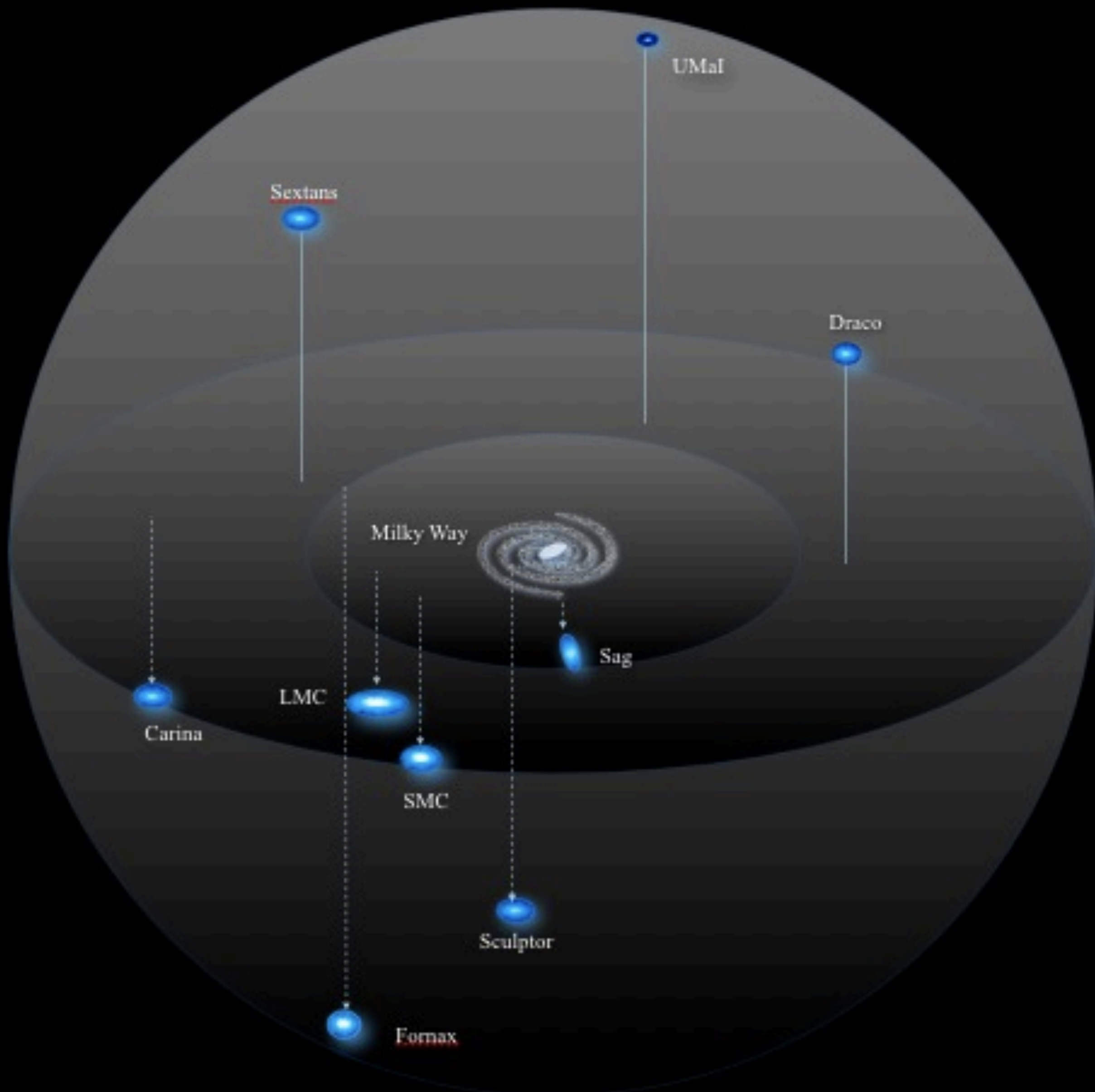
Does the Milky Way look like this?



dark matter clumps
(predicted)

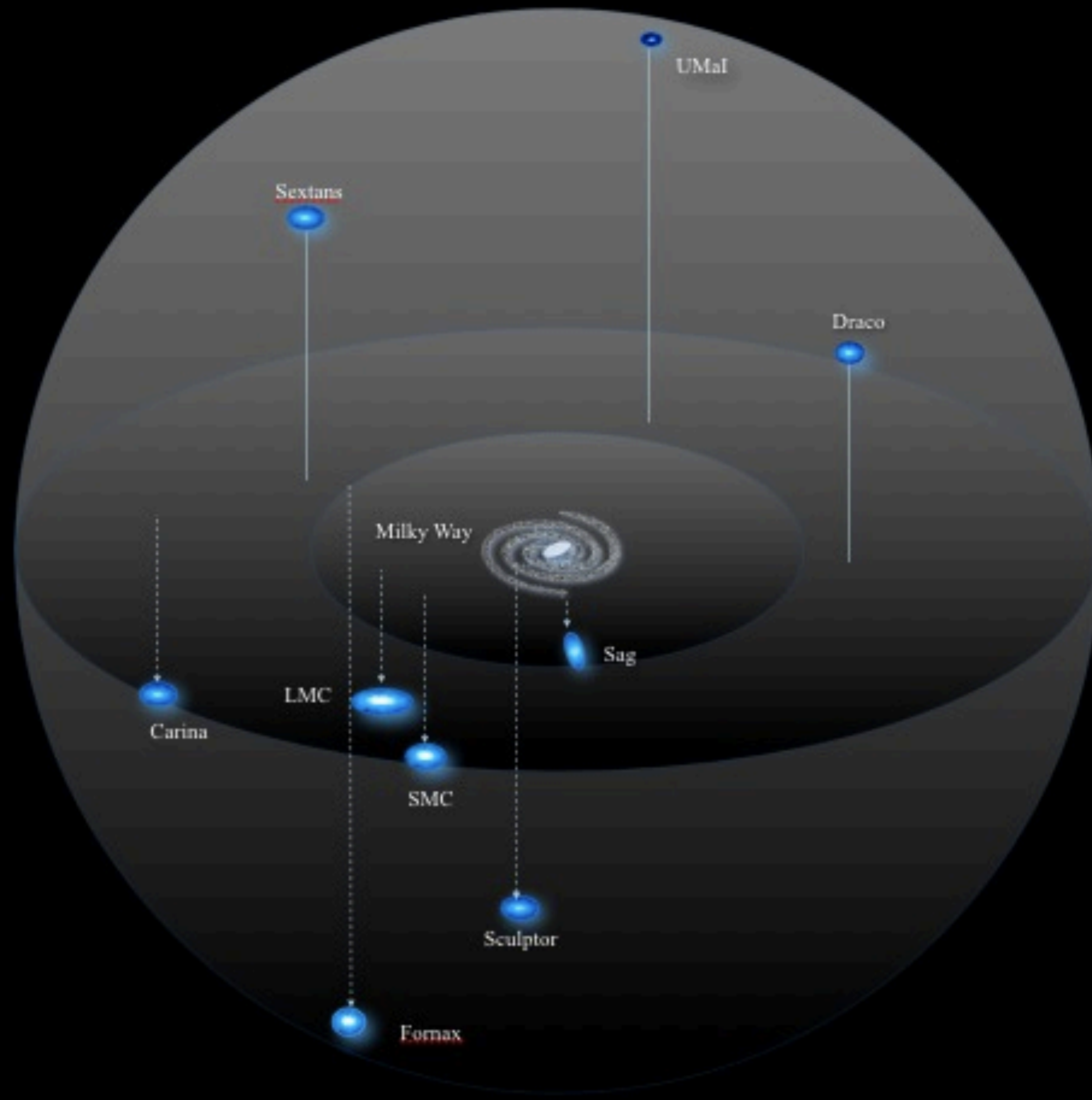
Theory: N>>1000

dwarf galaxies
(observed)



Observation: N_{bright}~10

“Missing Satellites Problem”

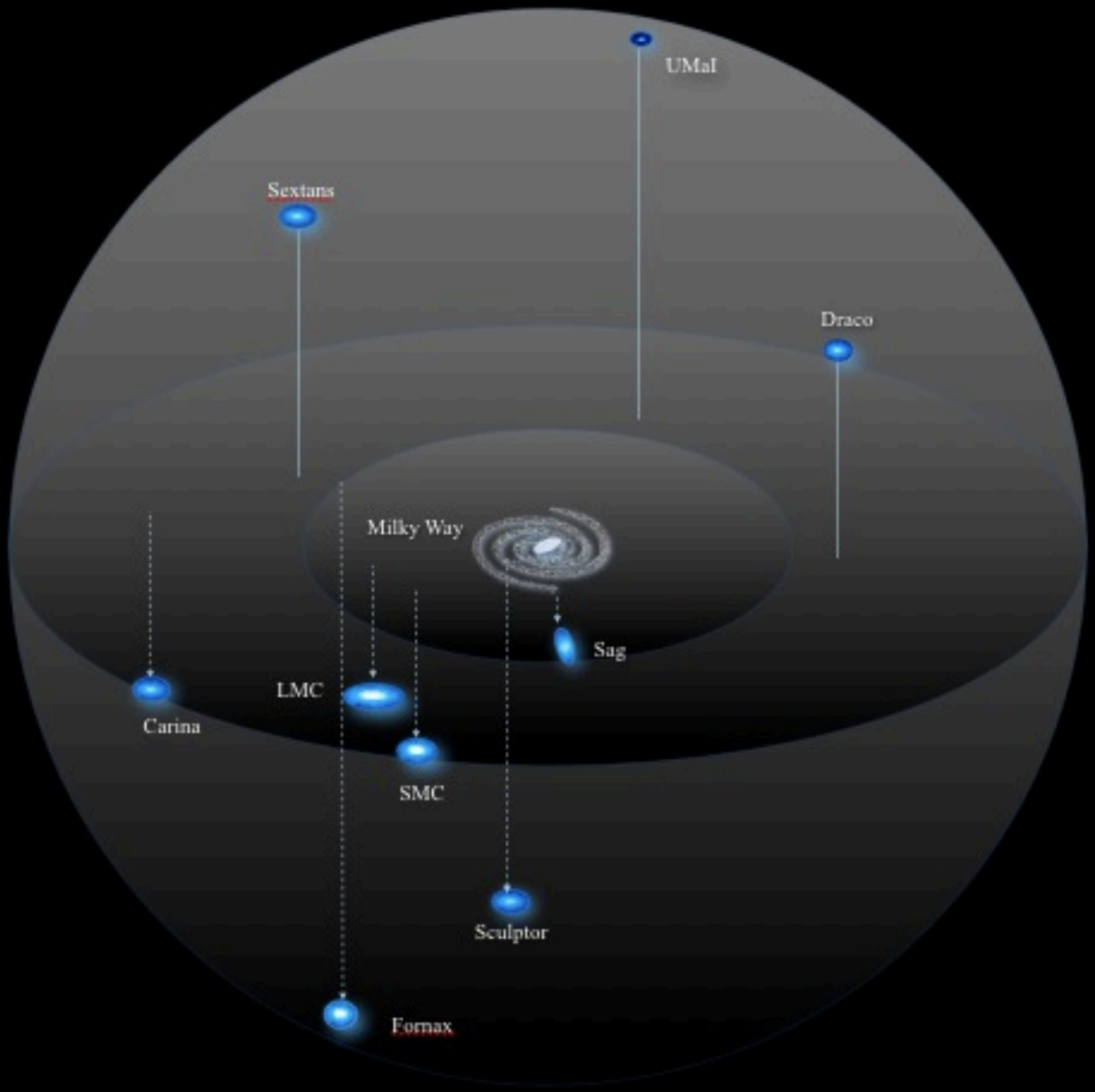


Theory: N>>1000

Observation: N_{bright}~10

Klypin et al. 1999

Maybe... only the biggest clumps have stars?



Theory: N>>1000

Observation: N_{bright}~10

Klypin et al. 1999

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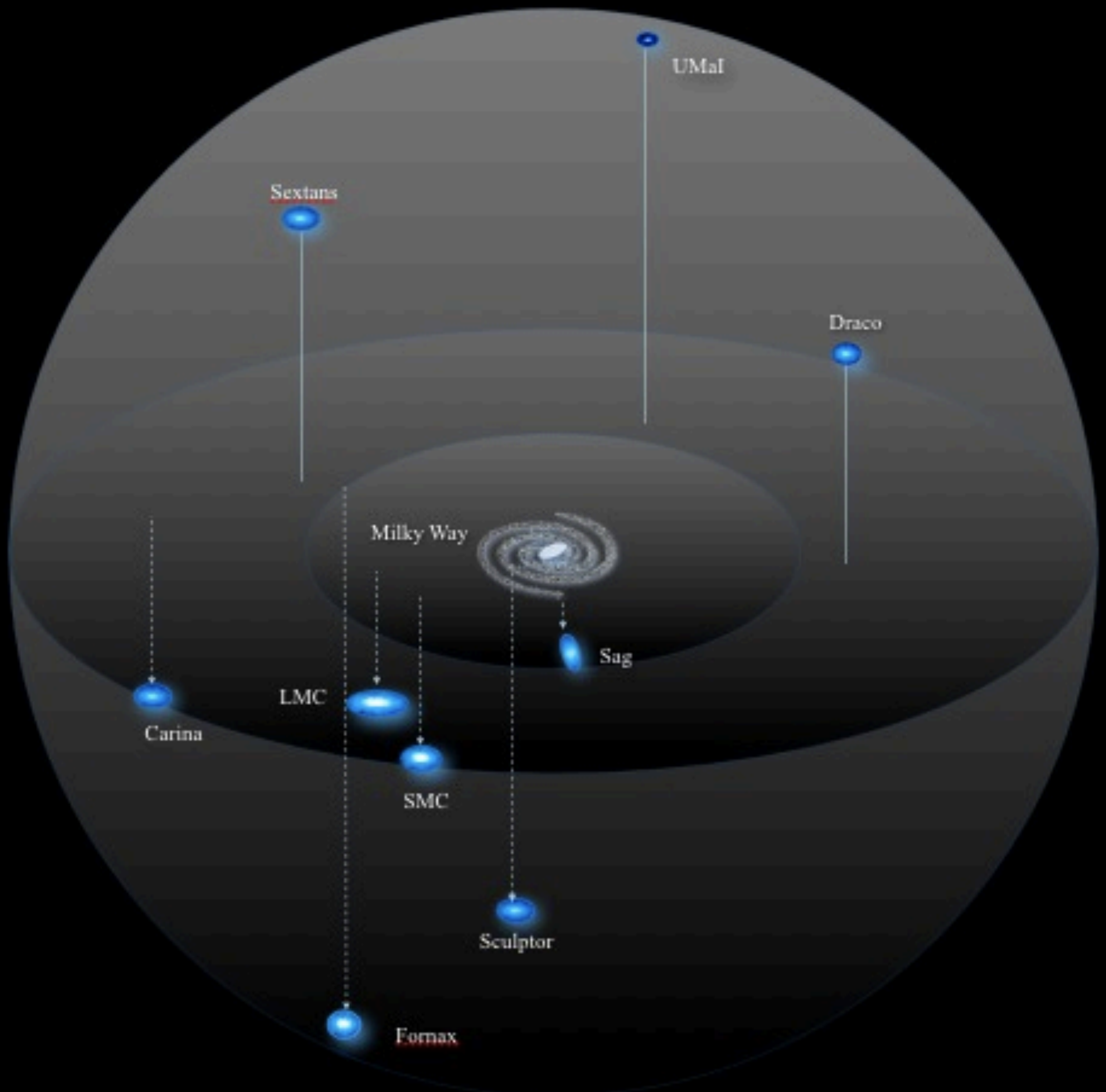

Theory: N>>1000

Observation: N_{bright}~10

Bullock et al. 2000

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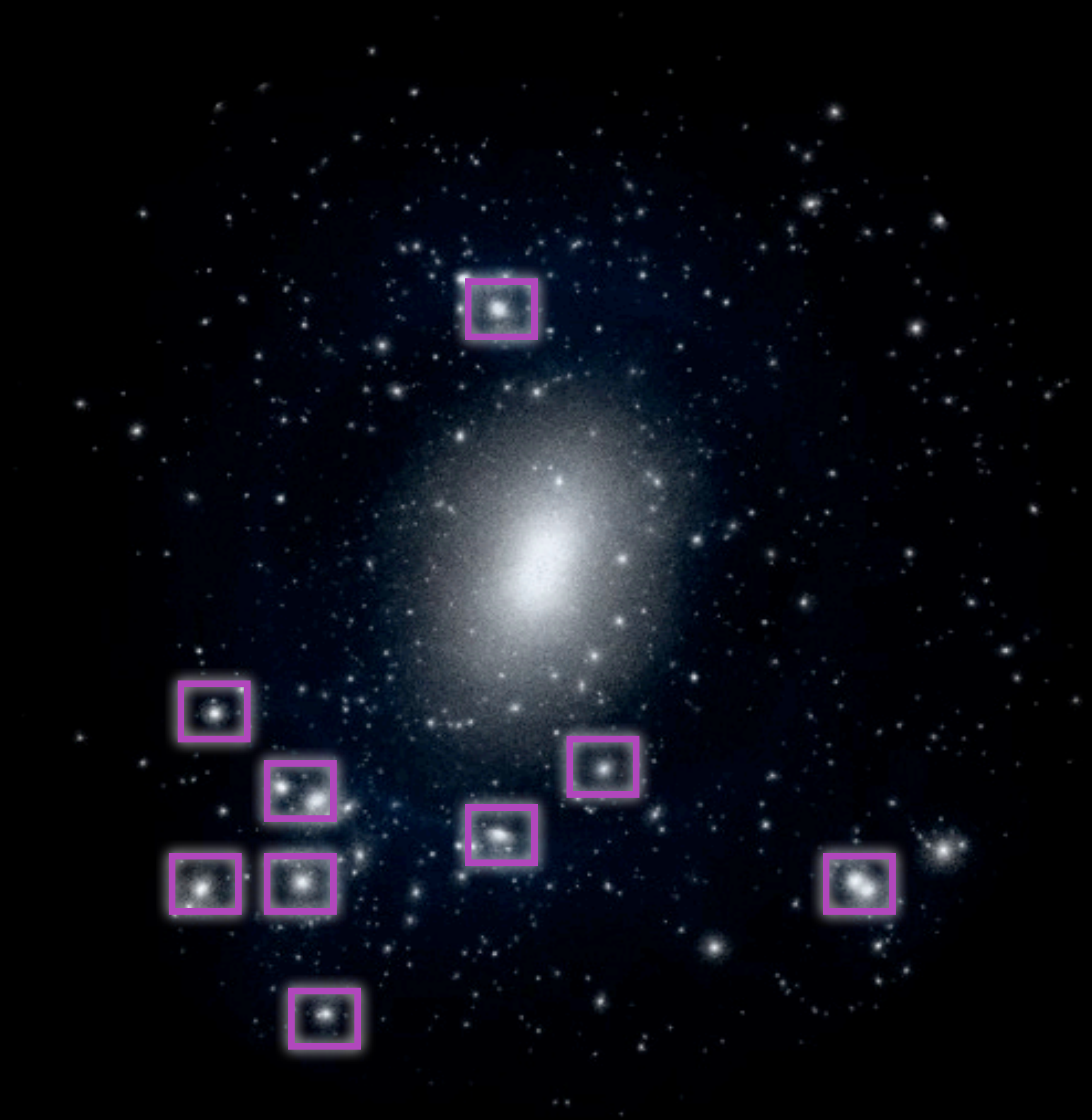
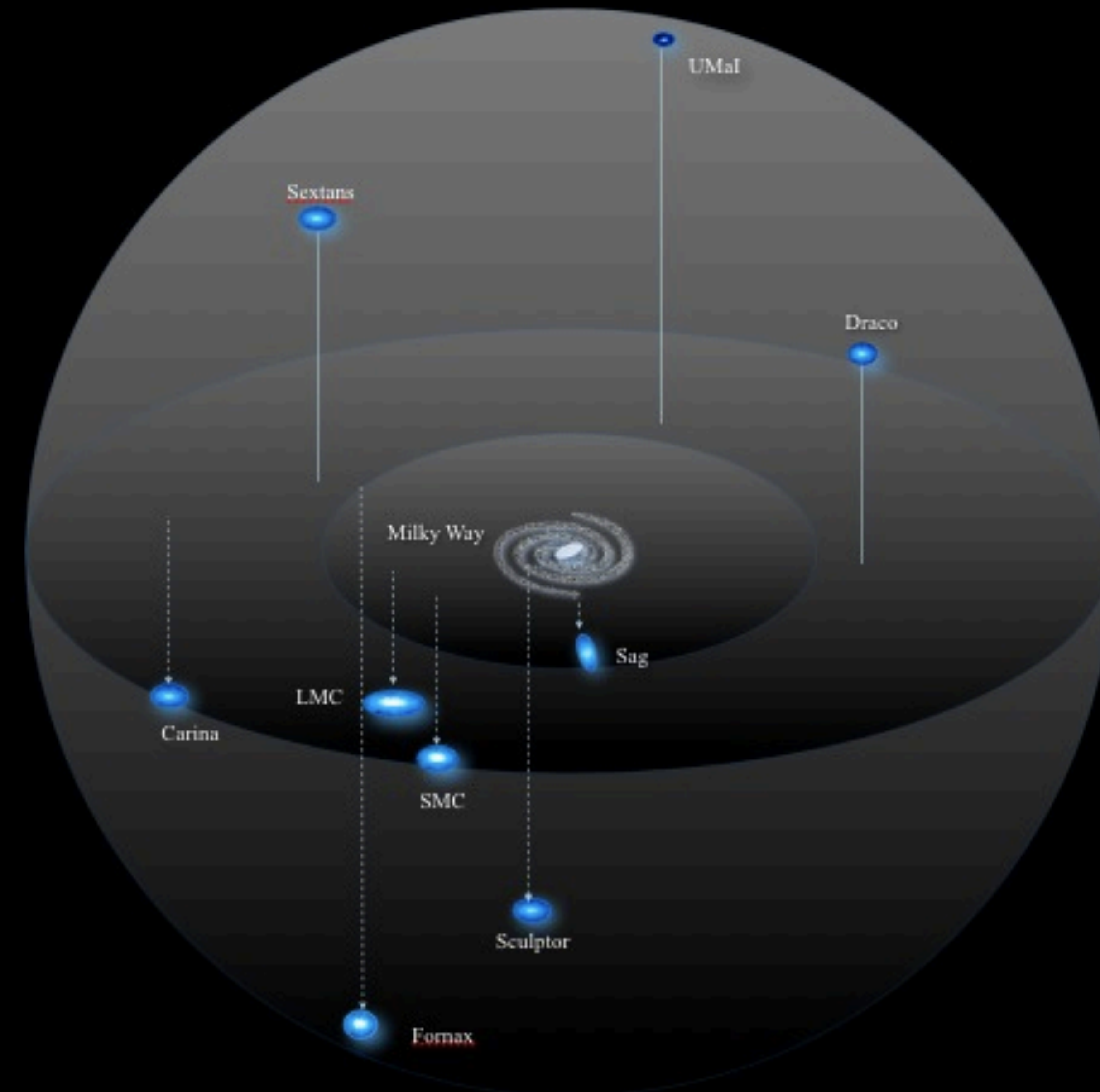
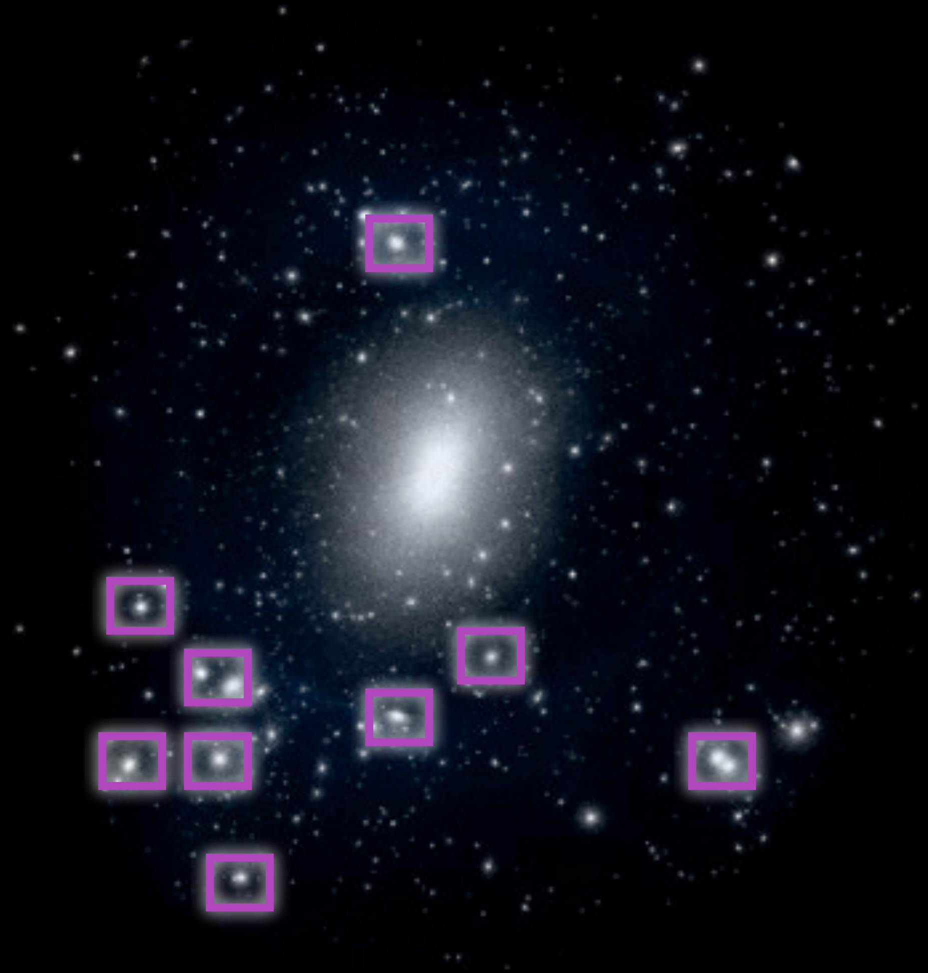


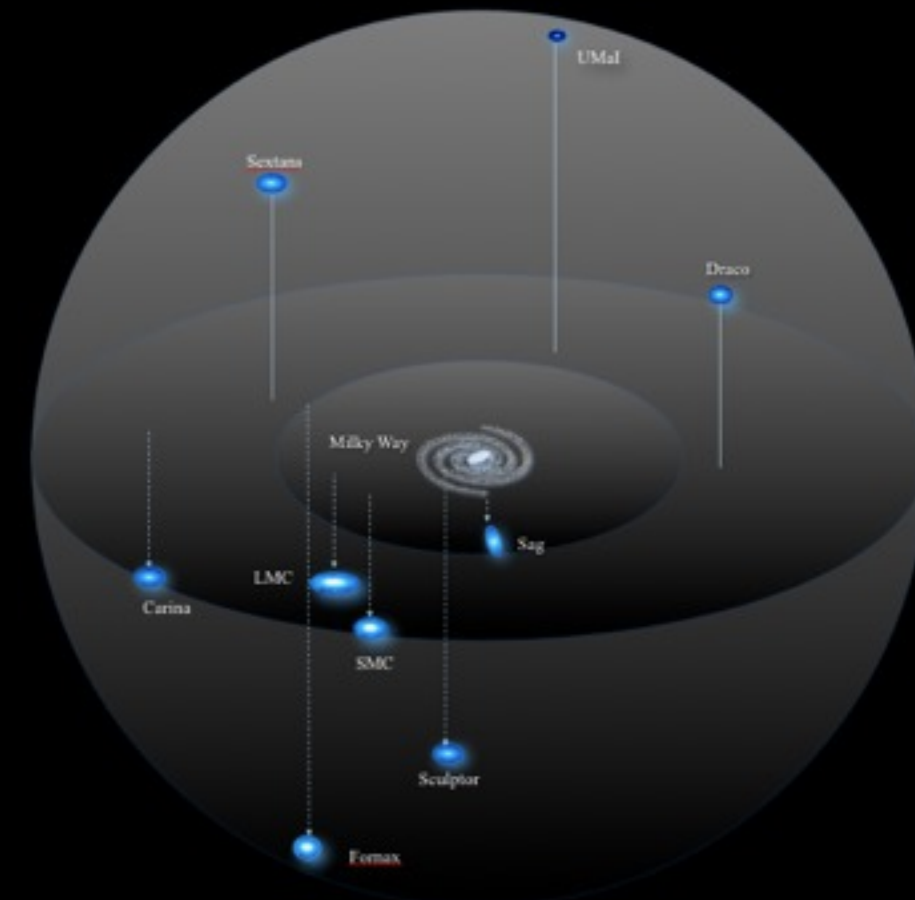


Theory: N>>1000

Observation: N_{bright}~10

Bullock et al. 2000

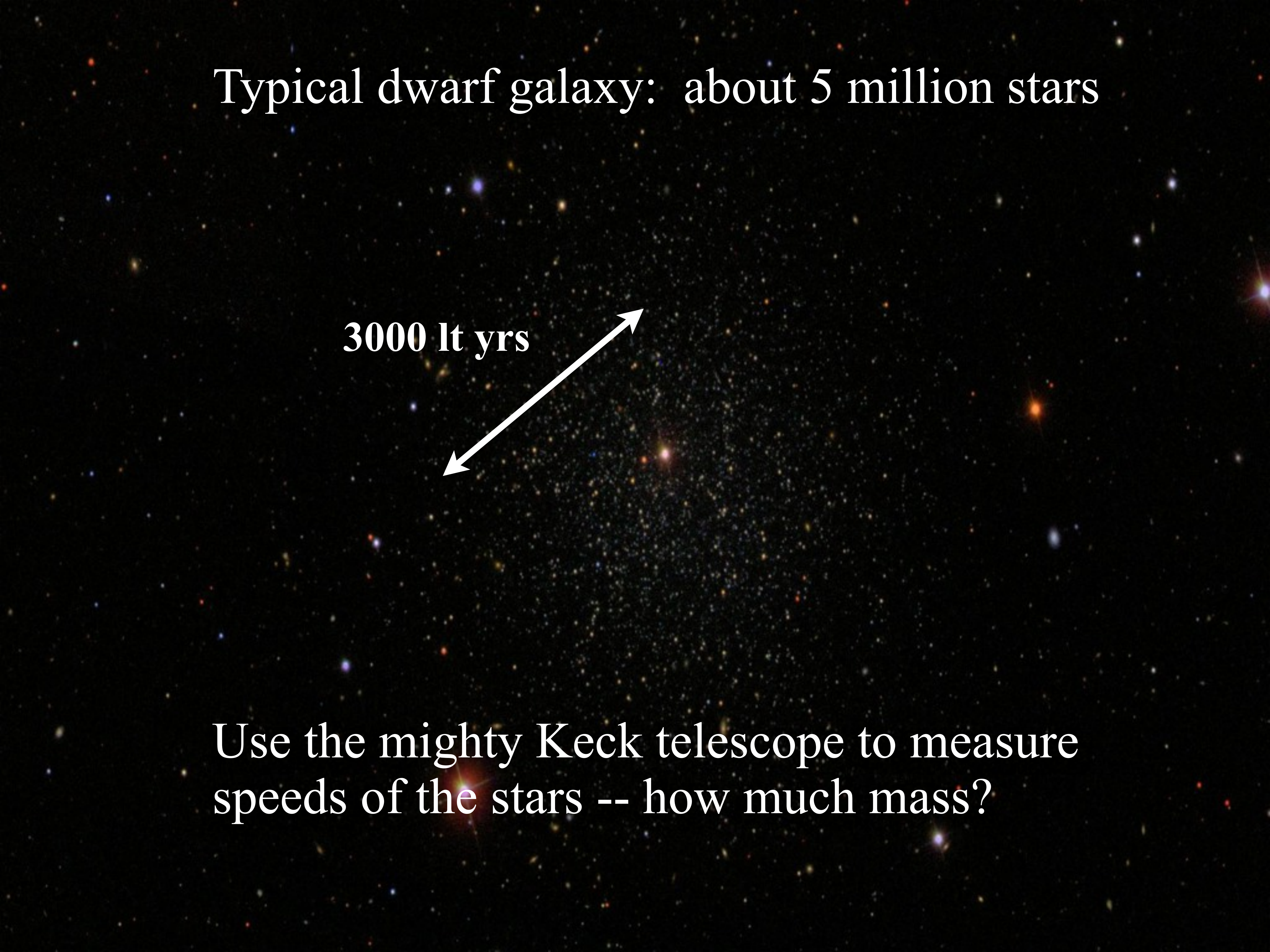




1. Predict dark matter mass in each clump

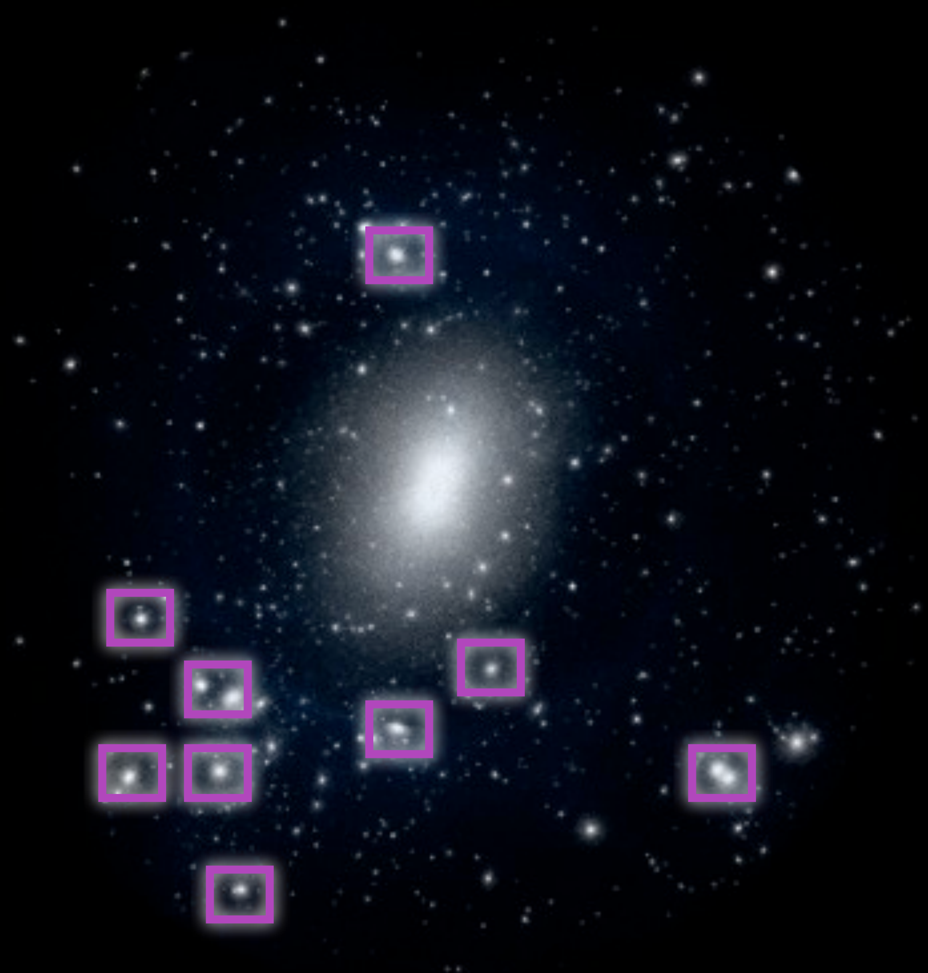
2. Measure dark matter mass in each dwarf galaxy

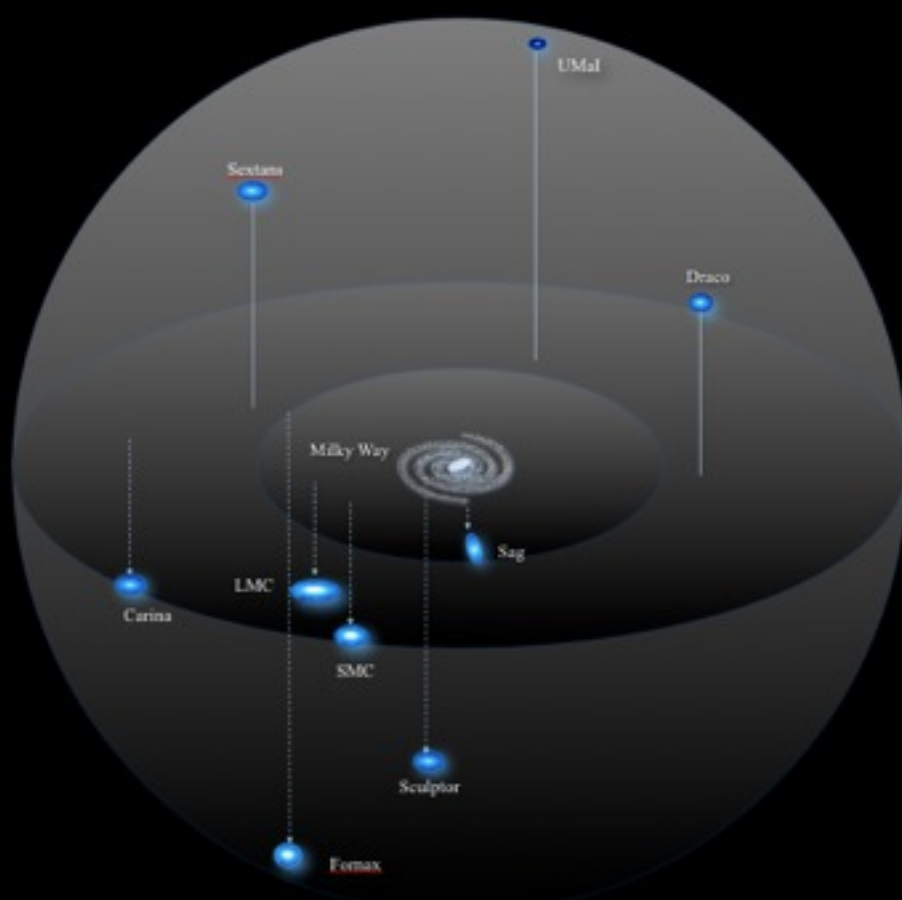
3. Compare

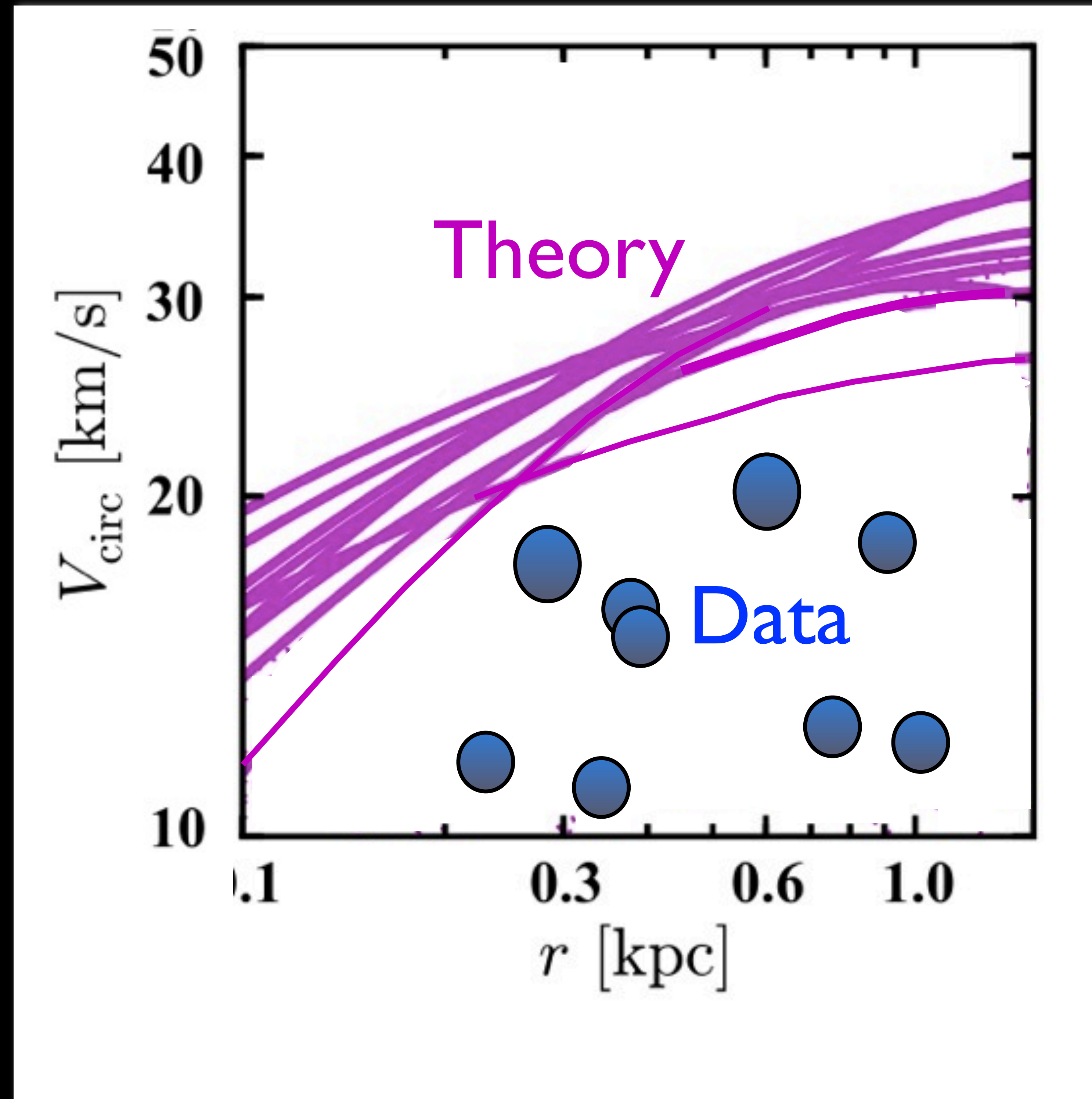

Typical dwarf galaxy: about 5 million stars
3000 lt yrs
Use the mighty Keck telescope to measure speeds of the stars -- how much mass?

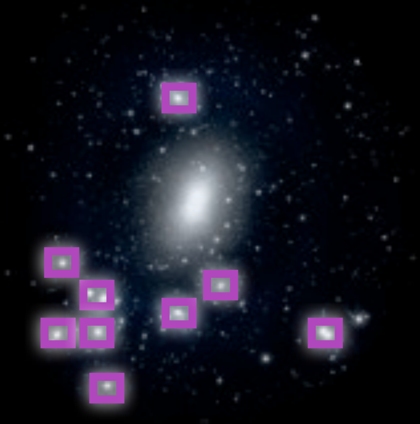
Packed with Dark Matter

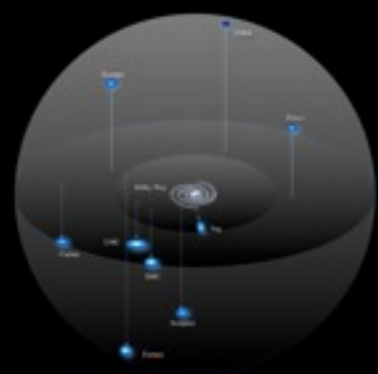
Motions of stars => ~500 times more dark matter than visible!




UMaI
Sextans
Draco
Milky Way
Sag
LMC
Carina
SMC
Sculptor
Fornax

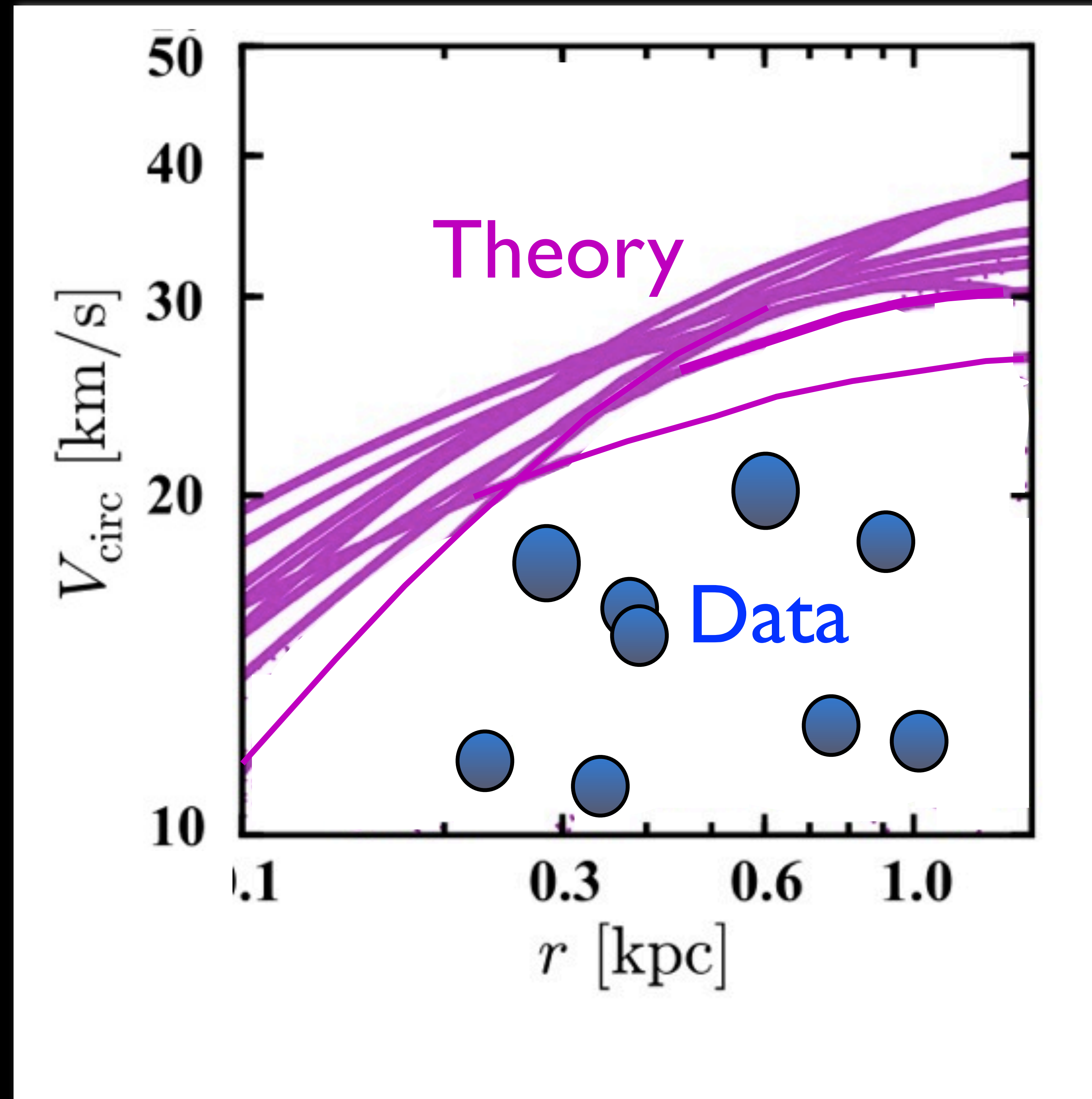

50
40
30
20
10
V_{circ} [km/s]
.1
0.3
0.6
1.0
r [kpc]
Theory
Data





Predicted clumps are too dense to host **any** satellite

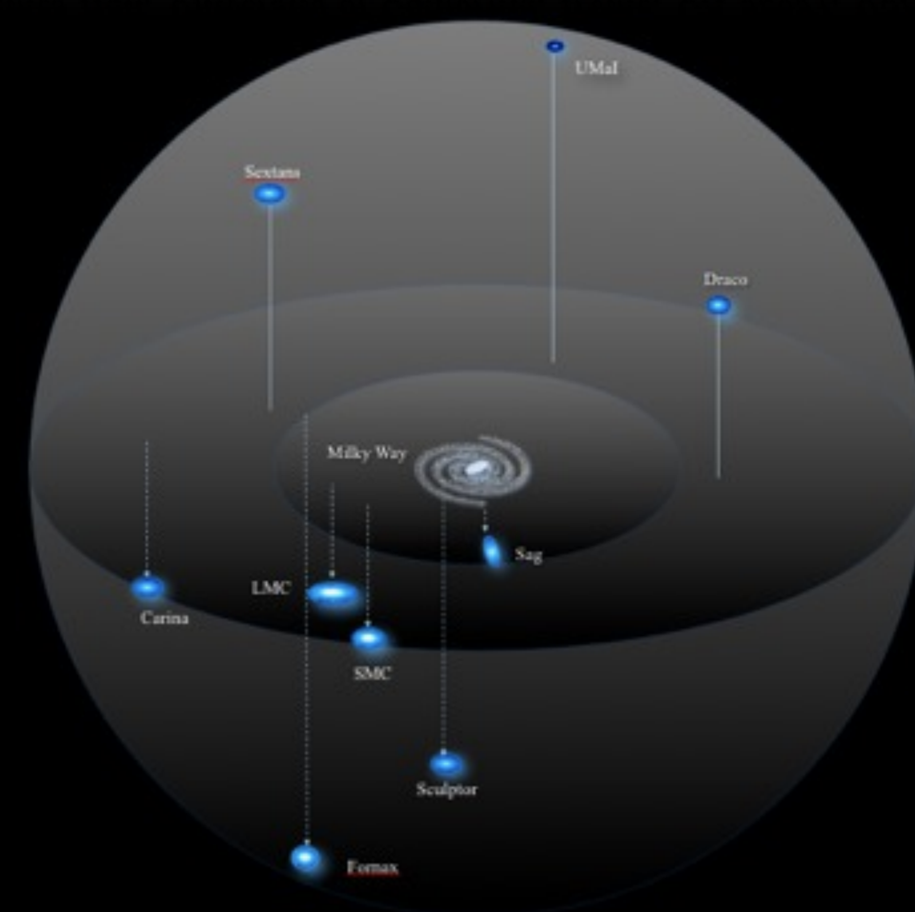
The theory is broken?



The Milky Way's bright satellites as an apparent failure of ΛCDM

Michael Boylan-Kolchin,*† James S. Bullock and Manoj Kaplinghat
Center for Cosmology, Department of Physics and Astronomy, 4129 Reines Hall, University of California, Irvine, CA 92697, USA

10 November 2011



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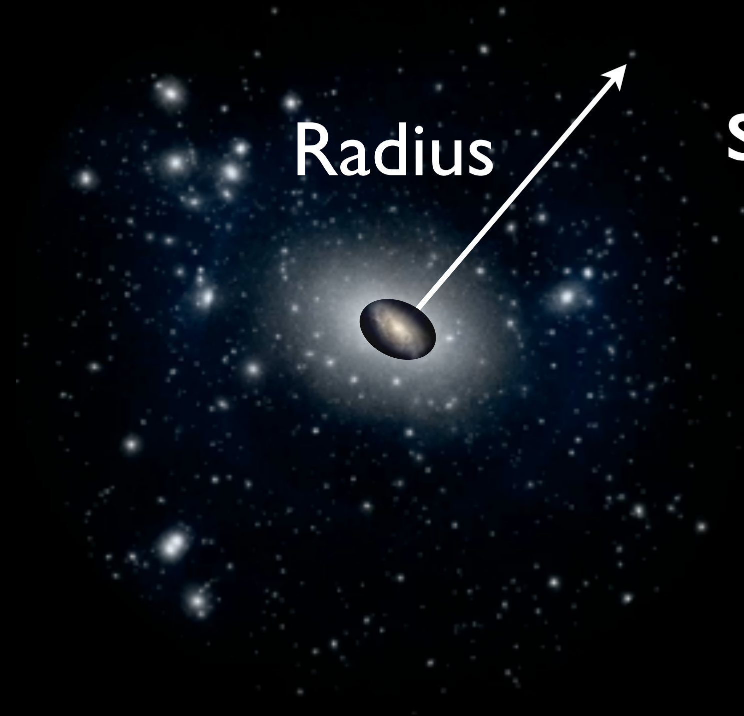
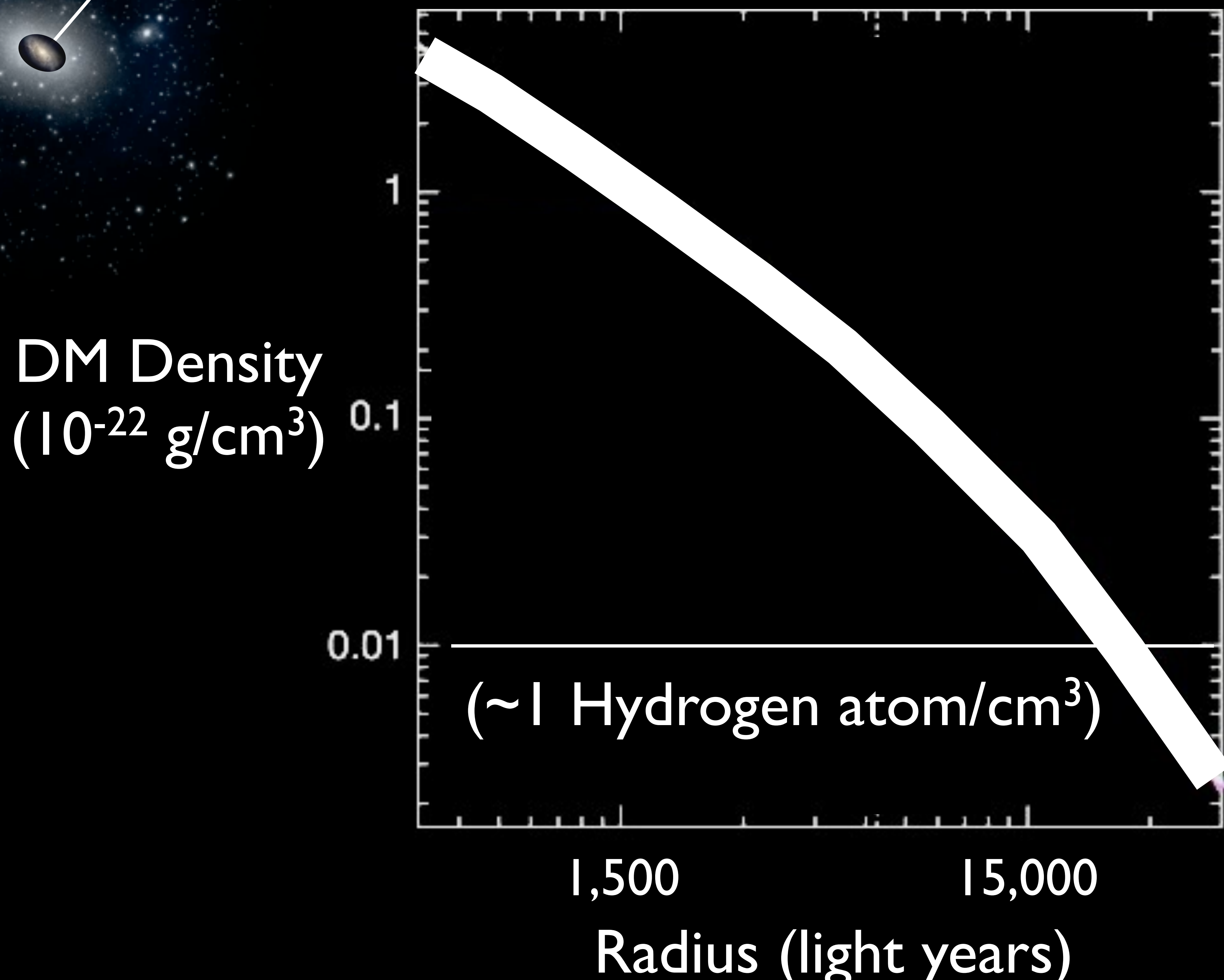
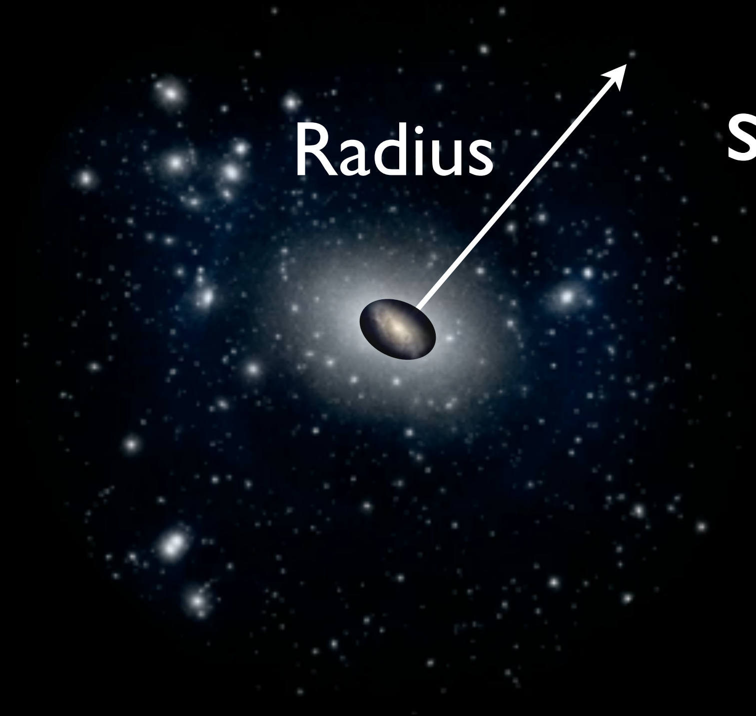
10 November 2011

Maybe Cold Dark Matter is not so simple?

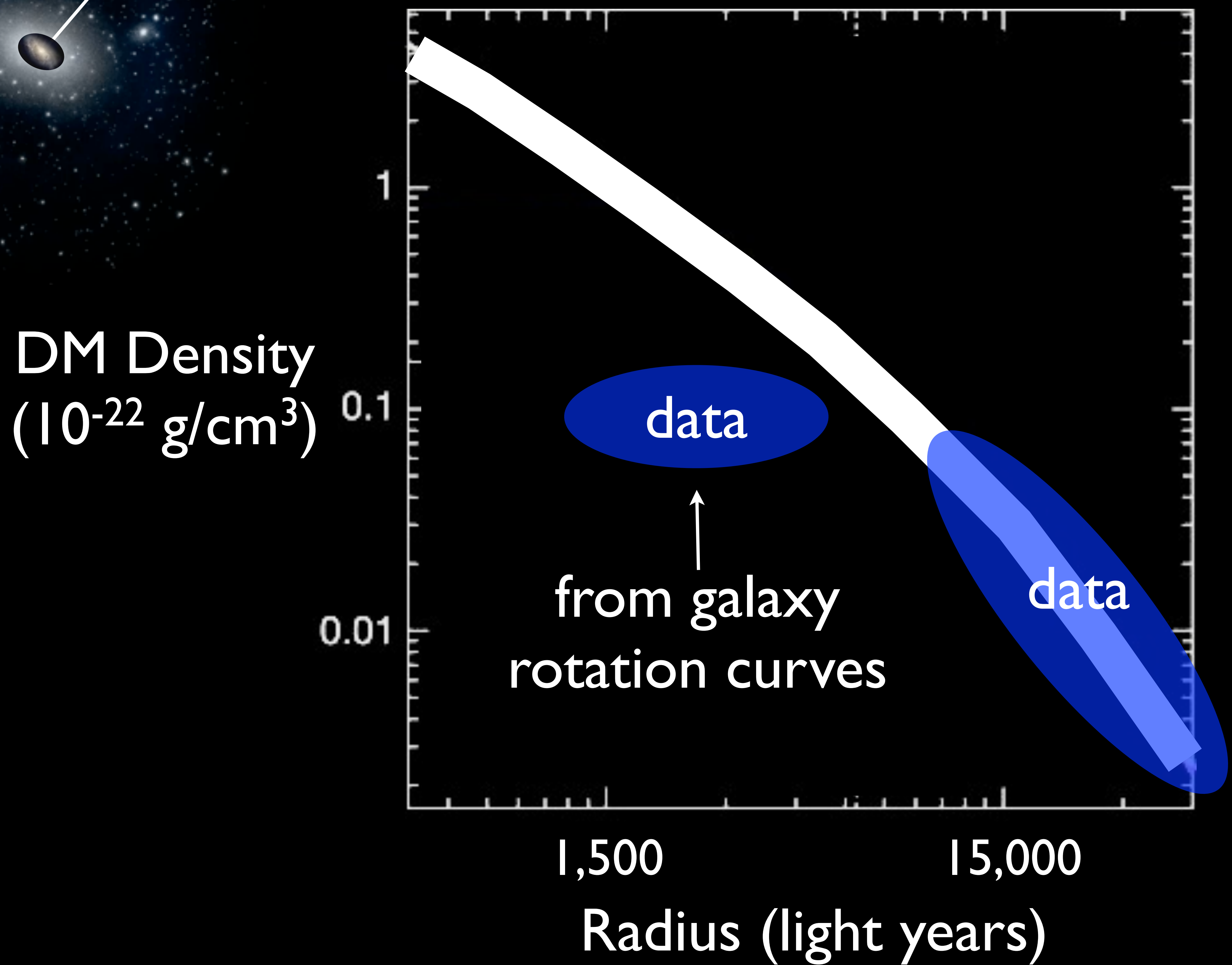


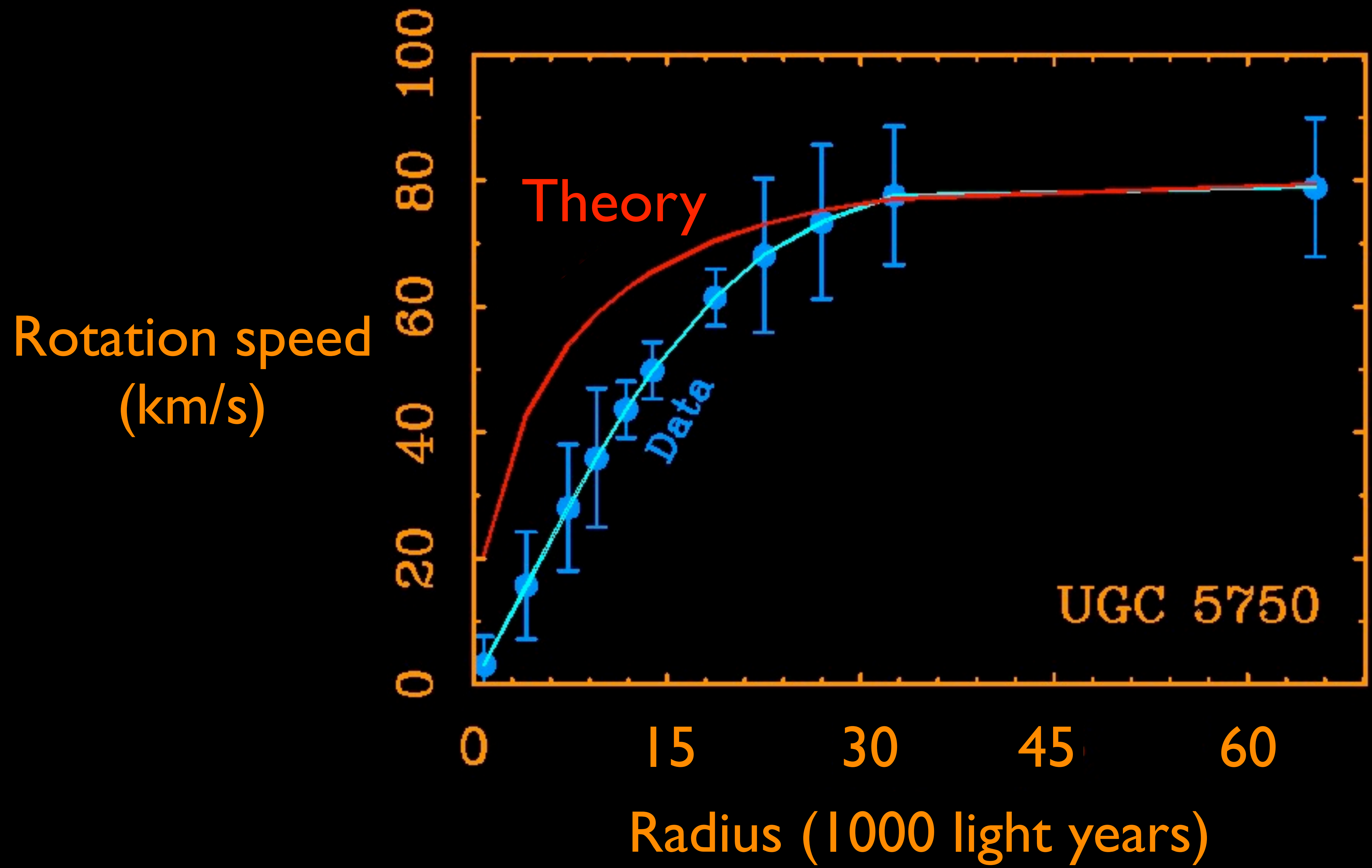
standard dark matter density profile (predicted)



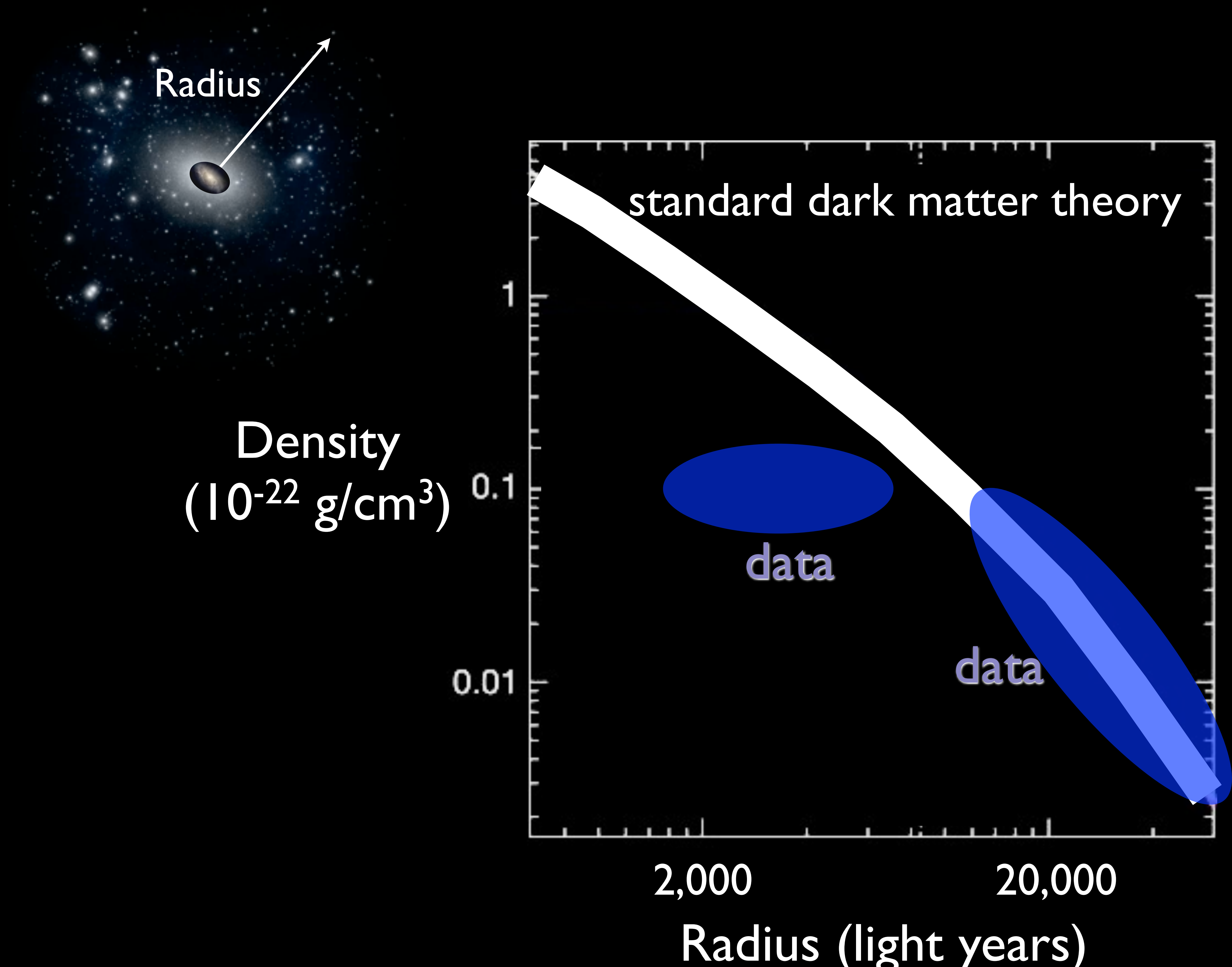


standard dark matter density profile (predicted)

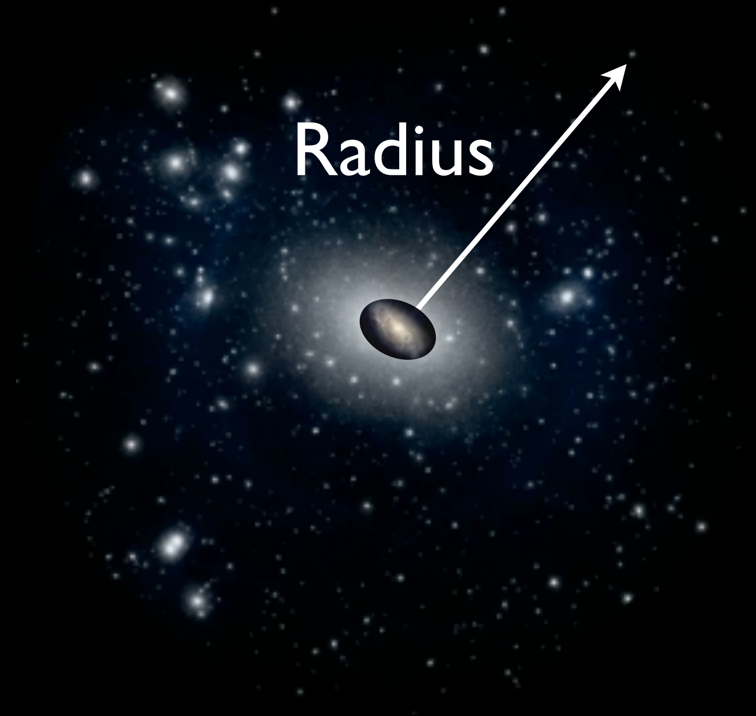


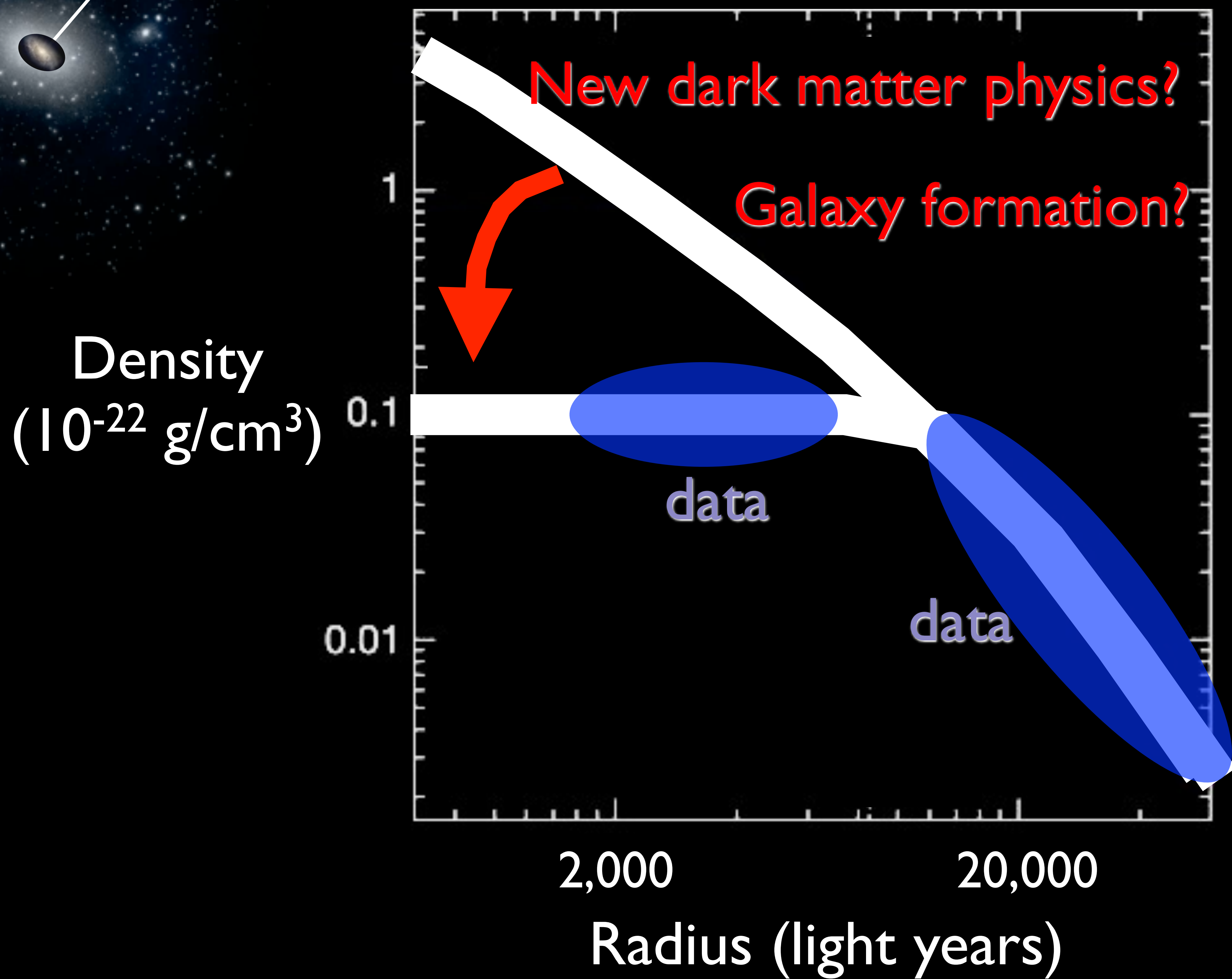


Rotation speed
(km/s)
100
80
60
40
20
0
Theory
Data
UGC 5750
0
15
30
45
60
Radius (1000 light years)



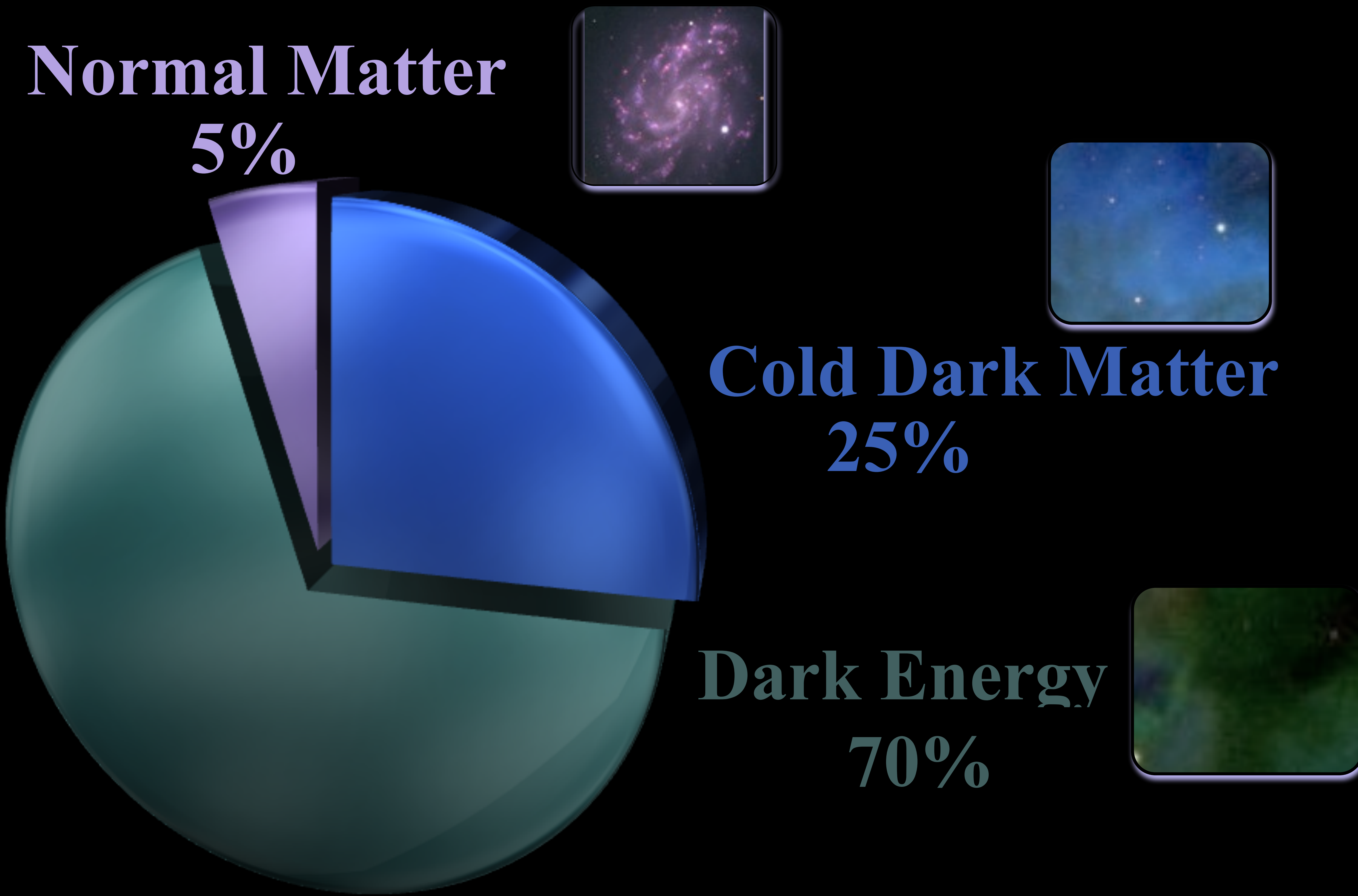
Radius
standard dark matter theory
Density
(10-22 g/cm3)
1
0.1
0.01
data
data
2,000
20,000
Radius (light years)





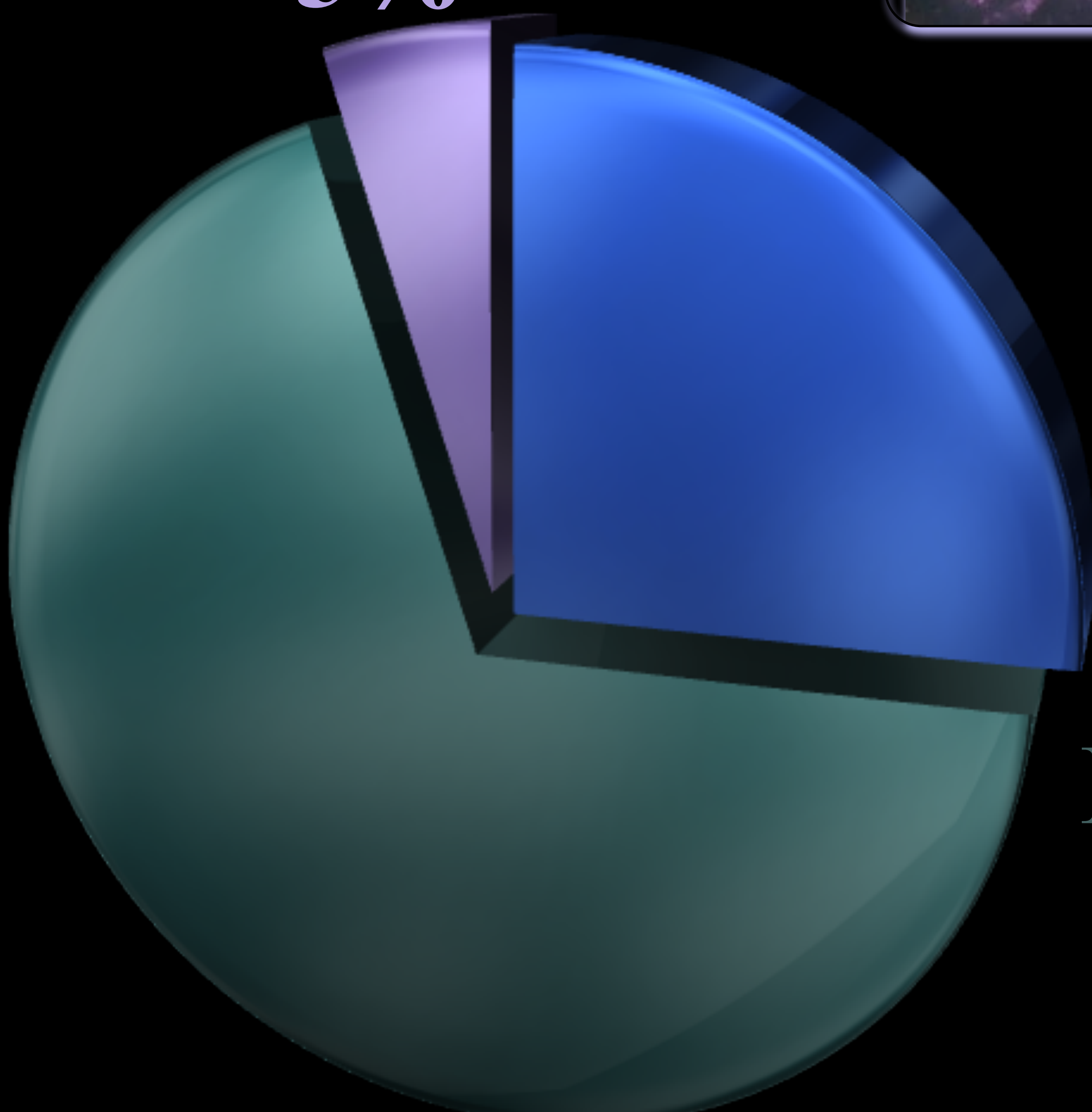
Flores & Primack 94

Composition of the Cosmos



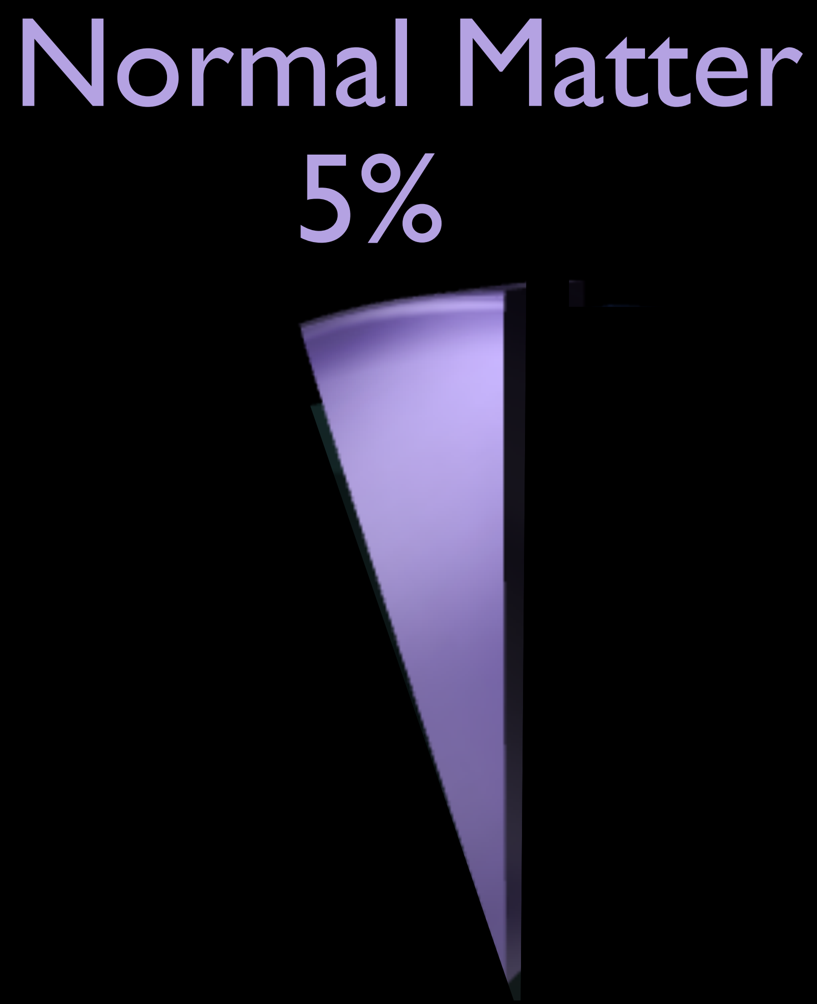
What do we really know?

Normal Matter
5%

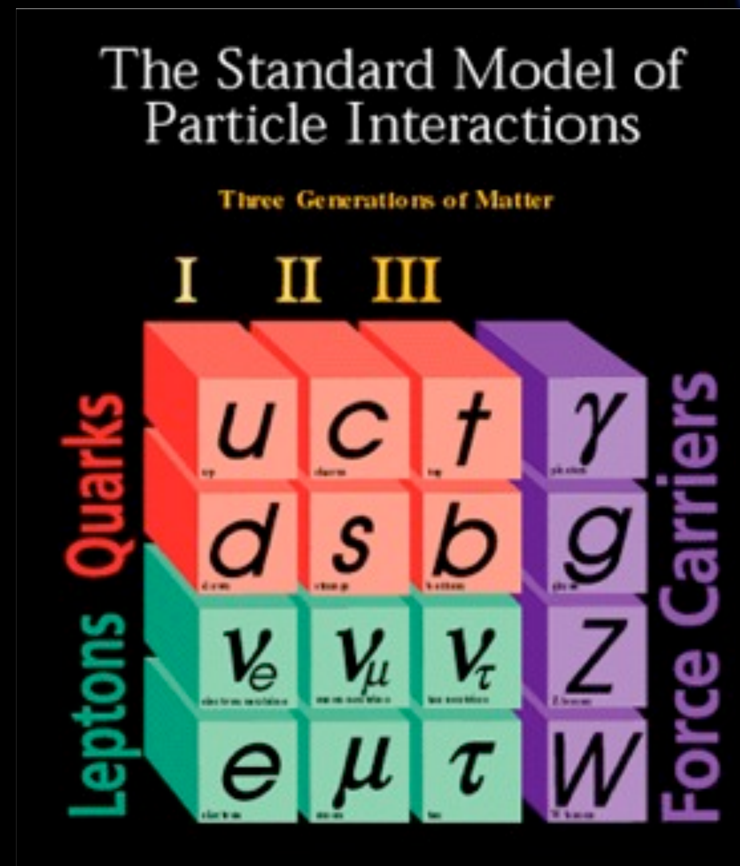


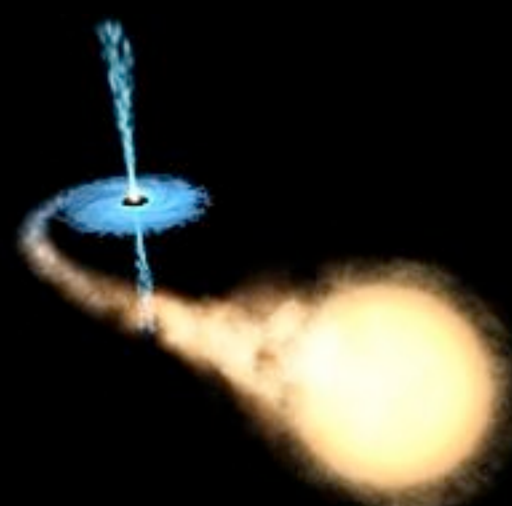
Cold Dark Matter
25%

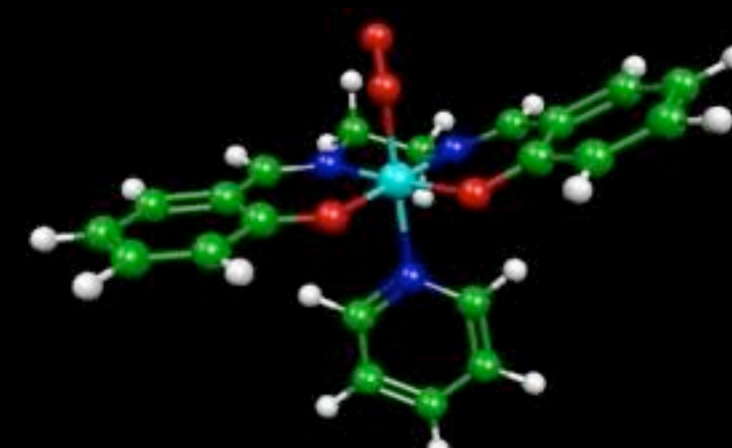
Dark Energy
70%


Normal Matter
5%

Normal Matter
5%

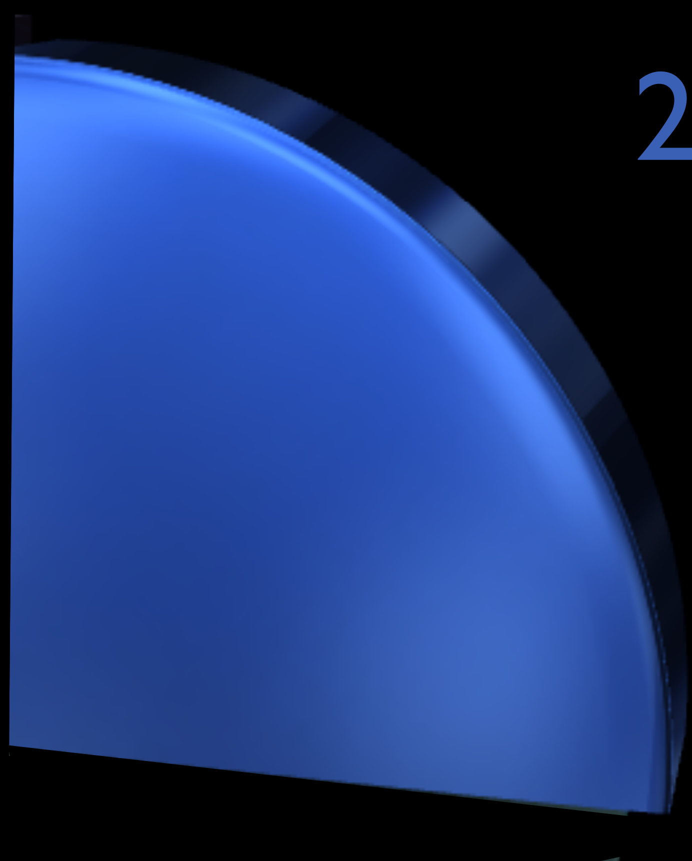






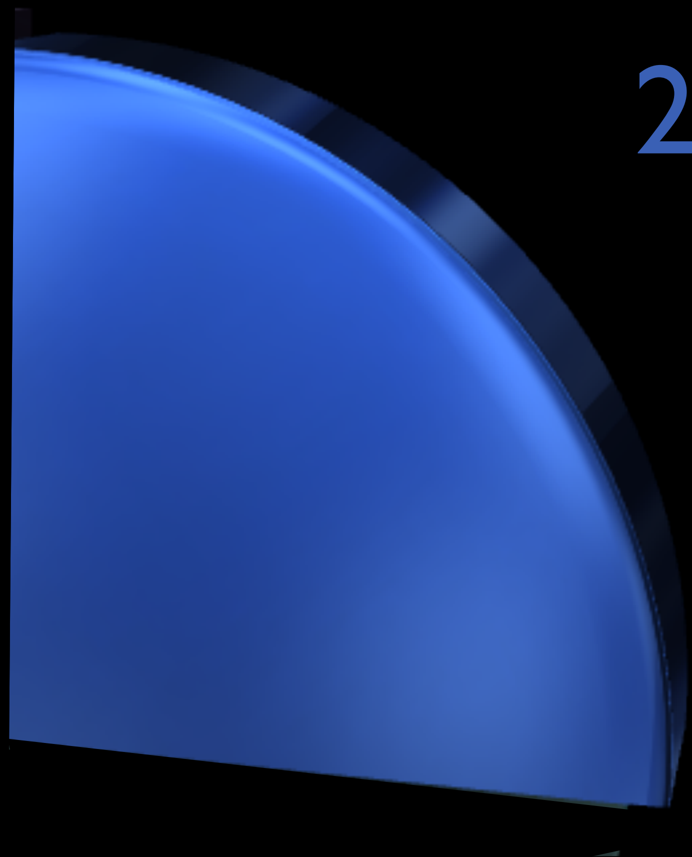
Dark Matter

25%

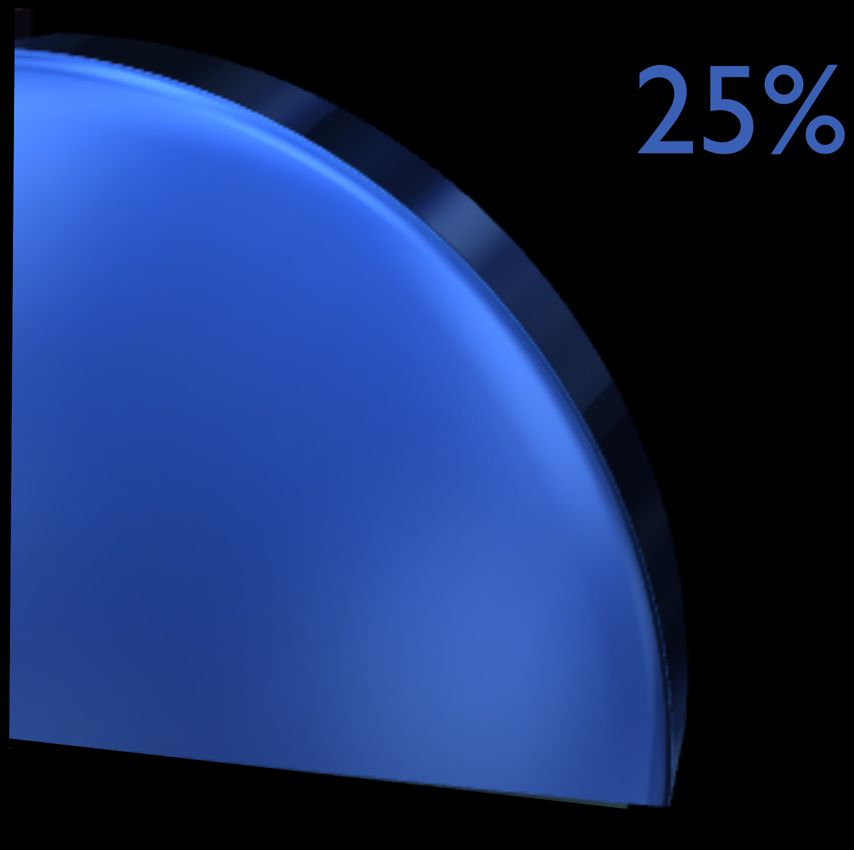


Dark Matter

25%



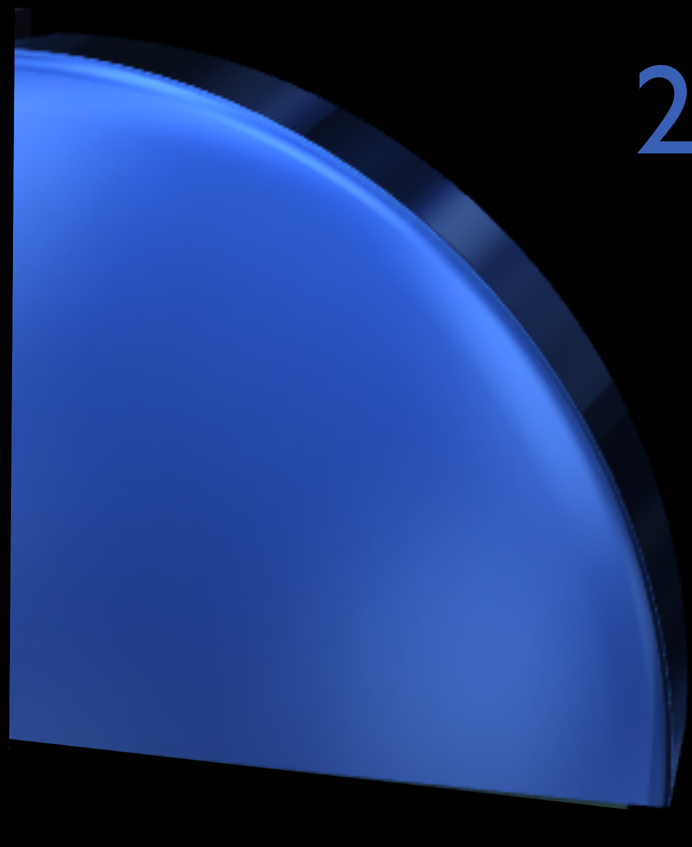
Dark Matter



Matches all large-scale data:

- Single particle.
- Only gravity.
- No other interaction.
- Mass > 10% proton mass

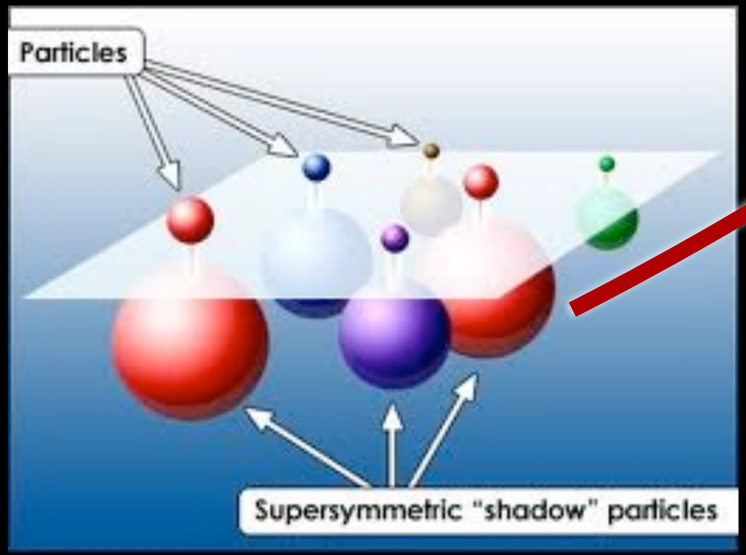
Dark Matter



25%

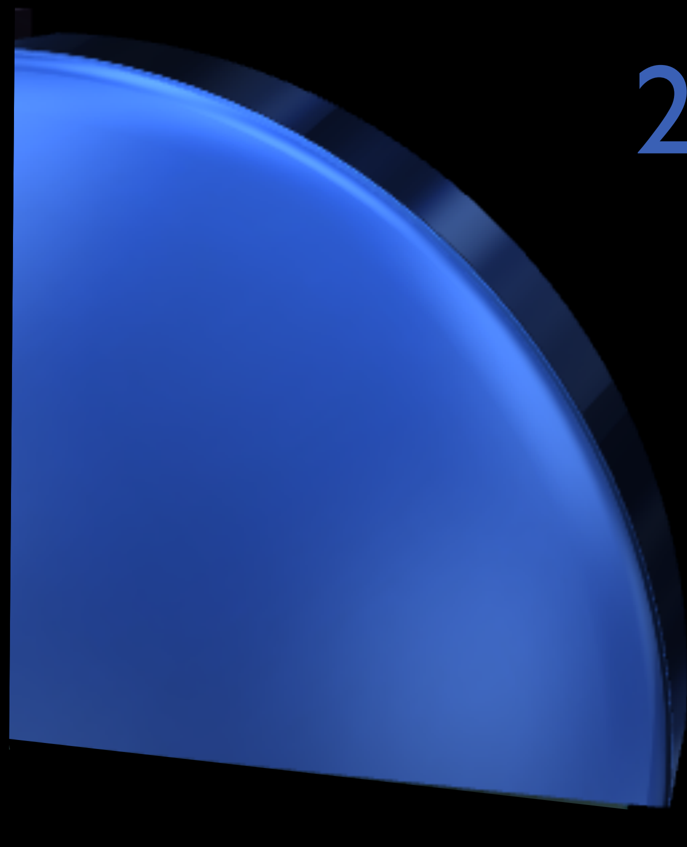
Matches all large-scale data:

- Single (lightest) particle.
- Only gravity.
- No other interaction (weak).
- Mass > 10% proton mass (~100 m_p).



Reasonably well motivated

Dark Matter



25%

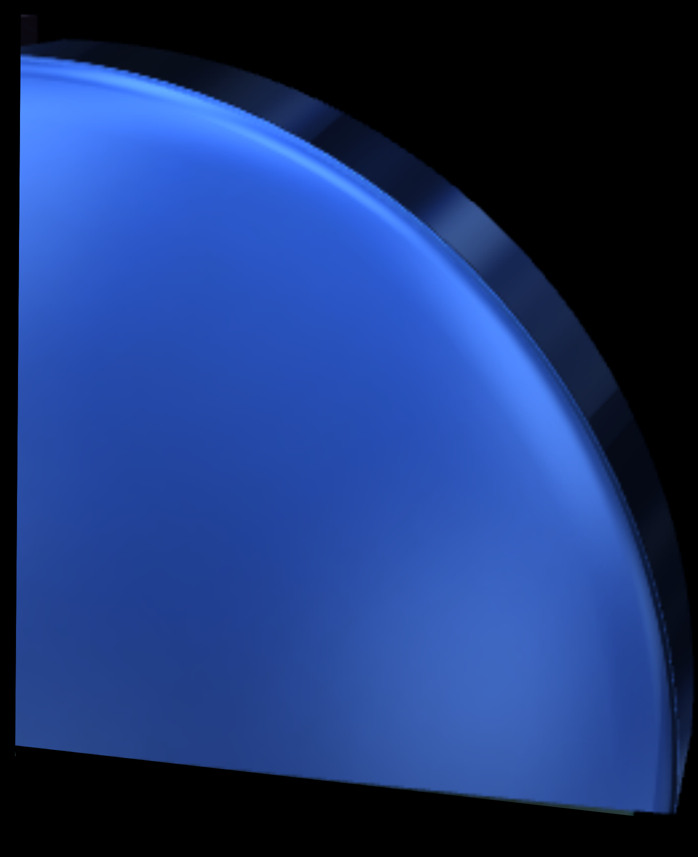
Matches all large-scale data:

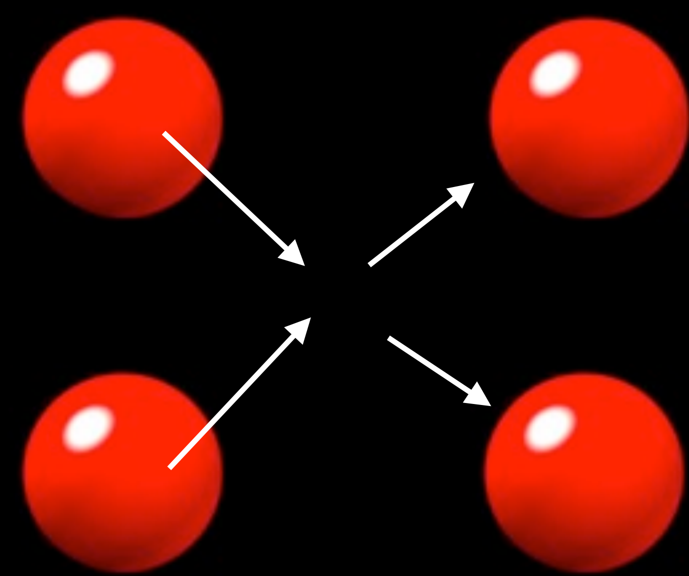
- Single particle.
- Only gravity.
- No other interaction.
- Mass > 10% proton mass

Could it be more complicated?

Toy model:
Self-interacting Dark Matter

25%

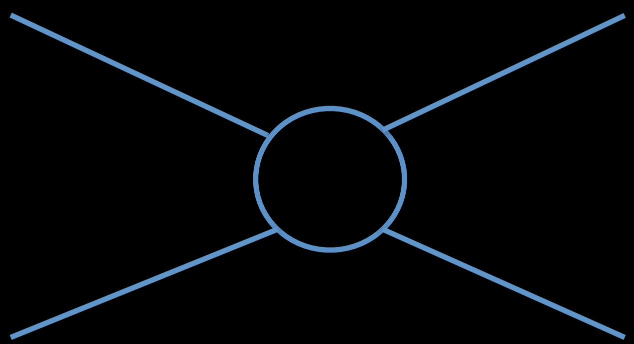




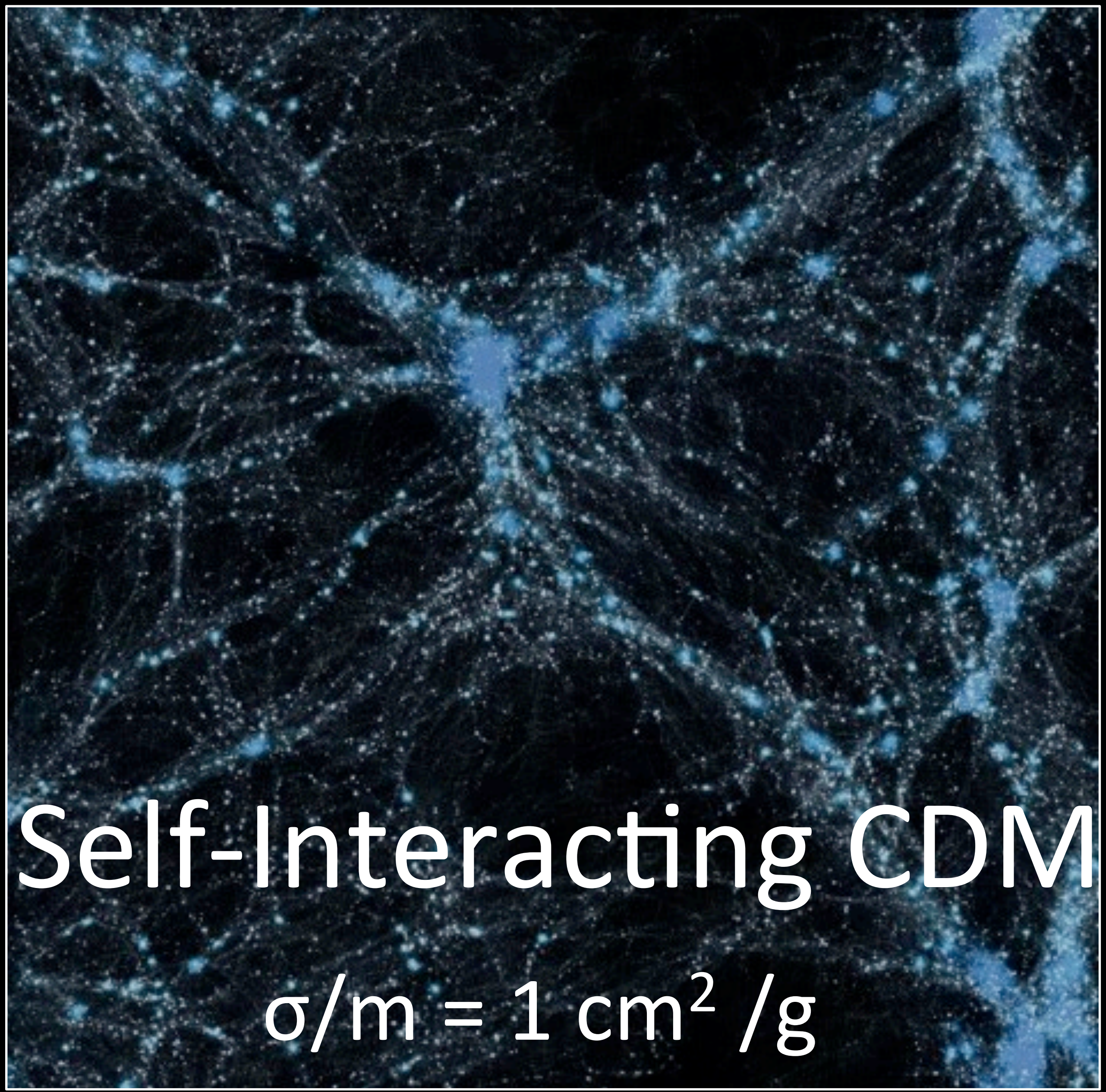
Elastic scattering with: $\sigma/m \sim 1\ \mathrm{cm}^2/\mathrm{g}$ ~ (neutron-neutron scattering)

Scattering rate: $$\Gamma = \rho_{\rm dm}\left(\frac{\sigma}{m}\right) v_{\rm rms}$$

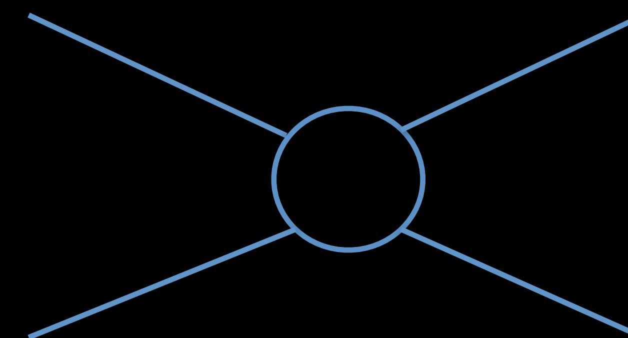
Simulating Self-interacting Dark Matter



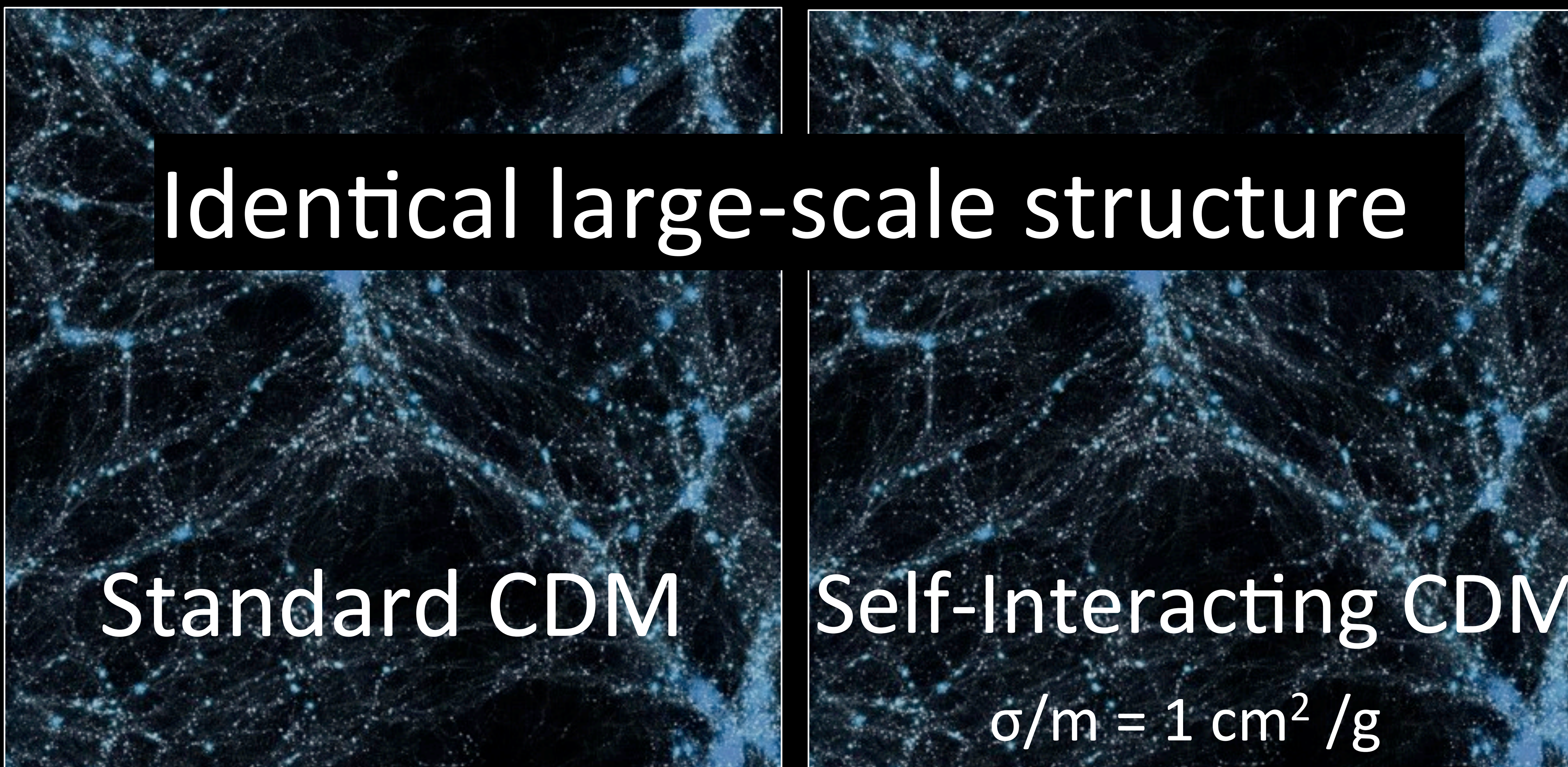
250 million lt yrs

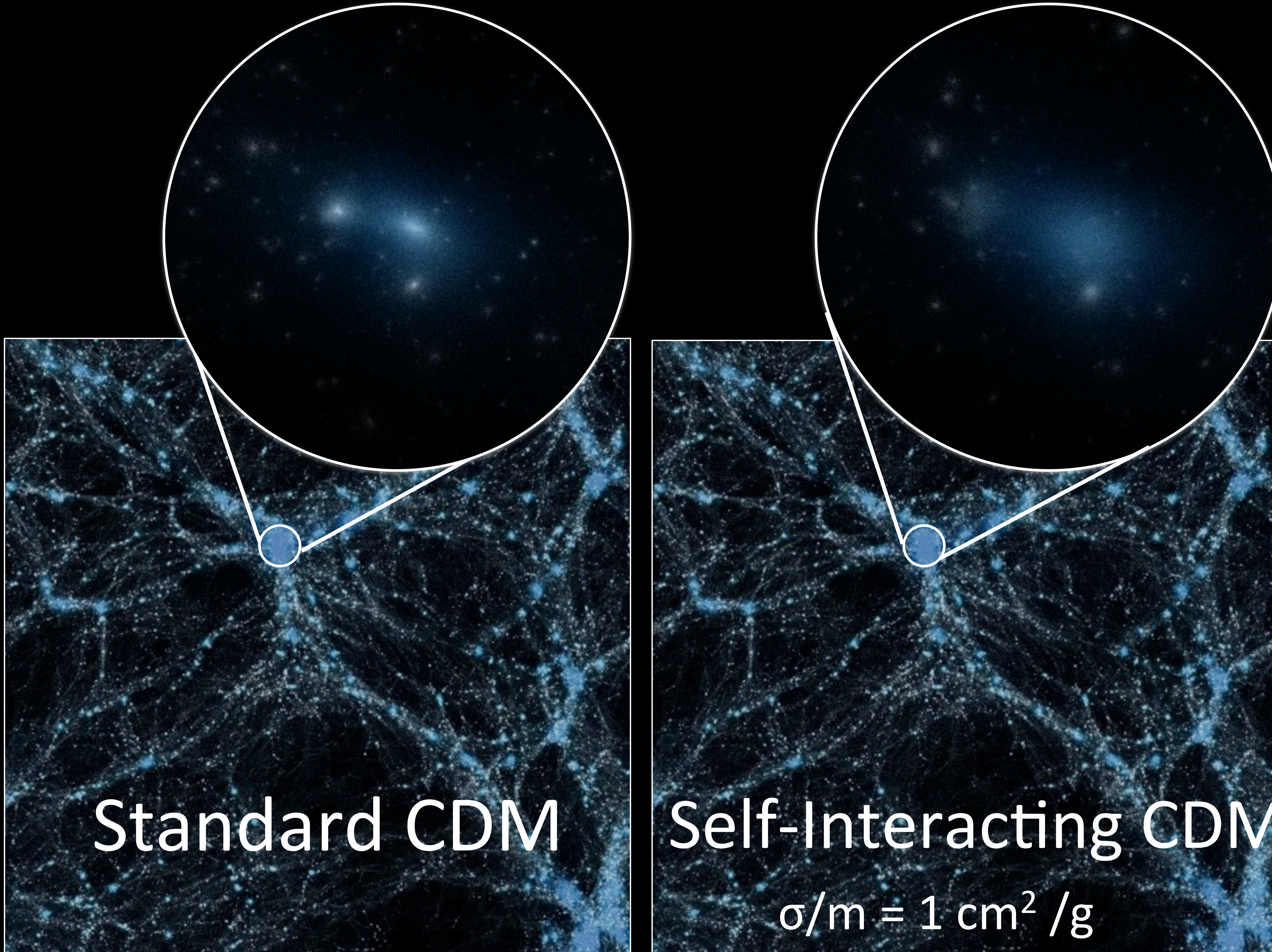


Simulating Self-interacting Dark Matter

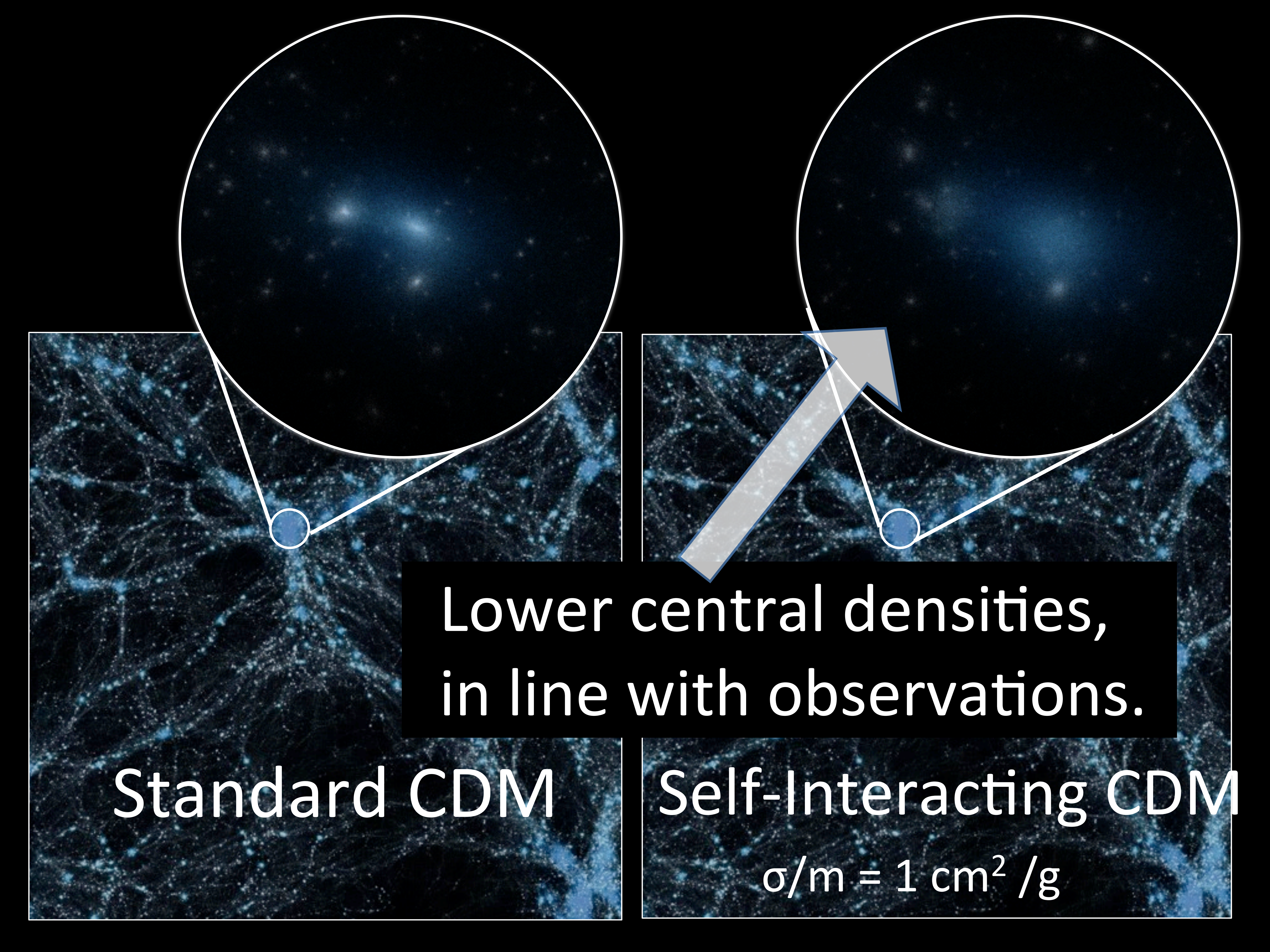


250 million lt yrs



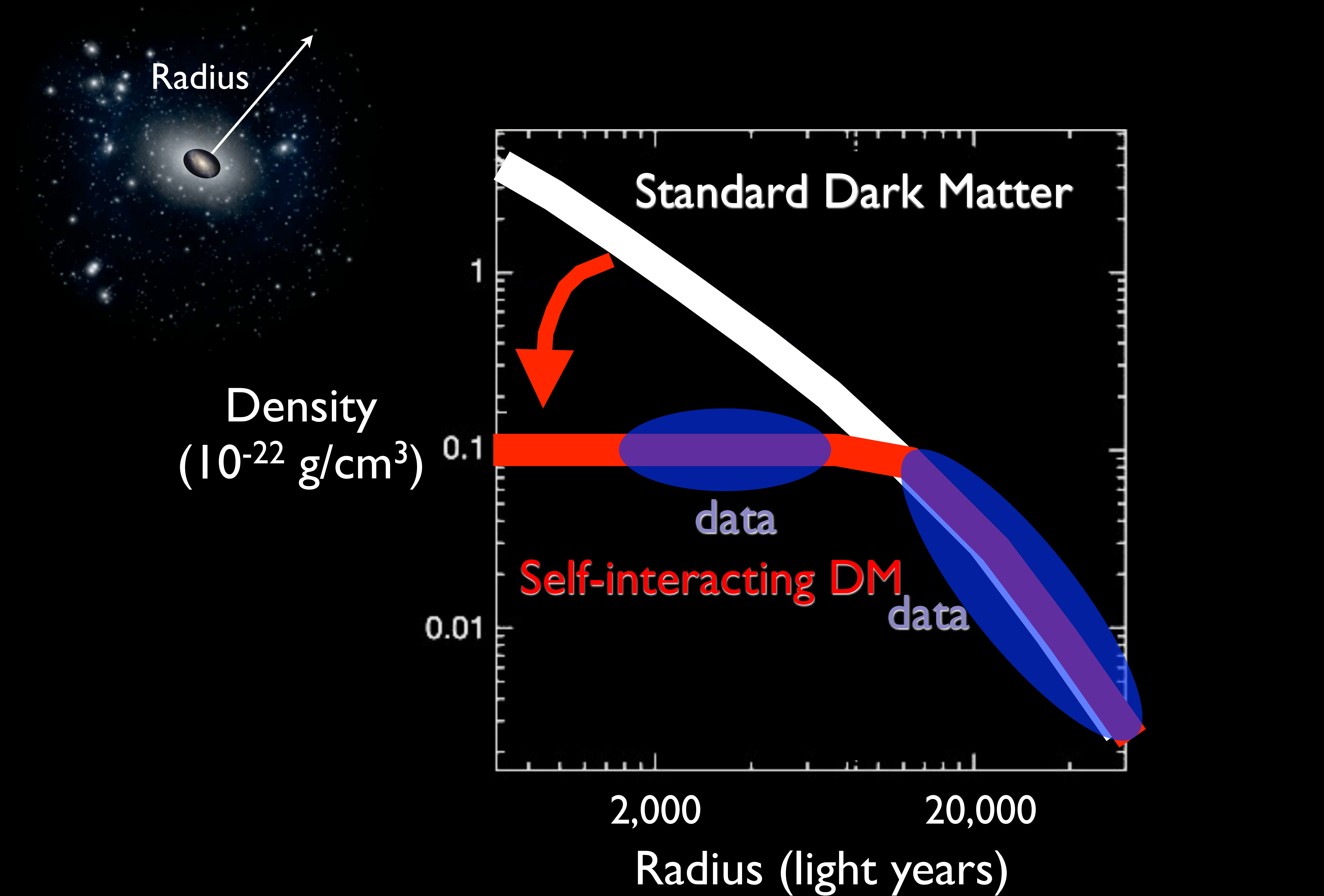


Standard CDM
Self-Interacting CDM
σ/m = 1 cm² /g


Lower central densities,
in line with observations.
Standard CDM
Self-Interacting CDM
σ/m = 1 cm² /g

Standard CDM

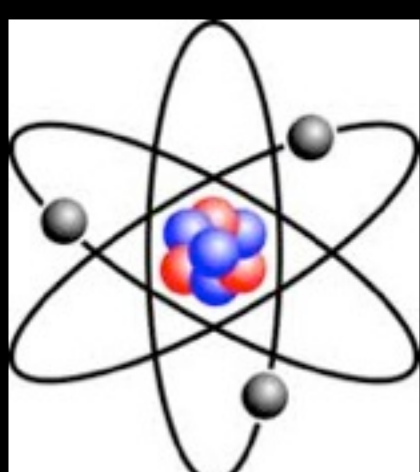
Self-Interacting CDM

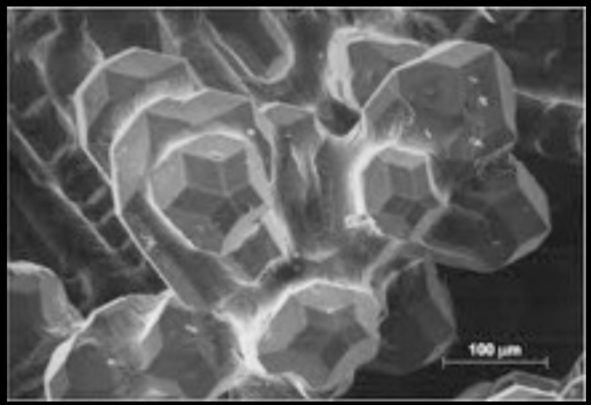


Rocha et al. 12; Peter et al. 12

Normal Matter
5%

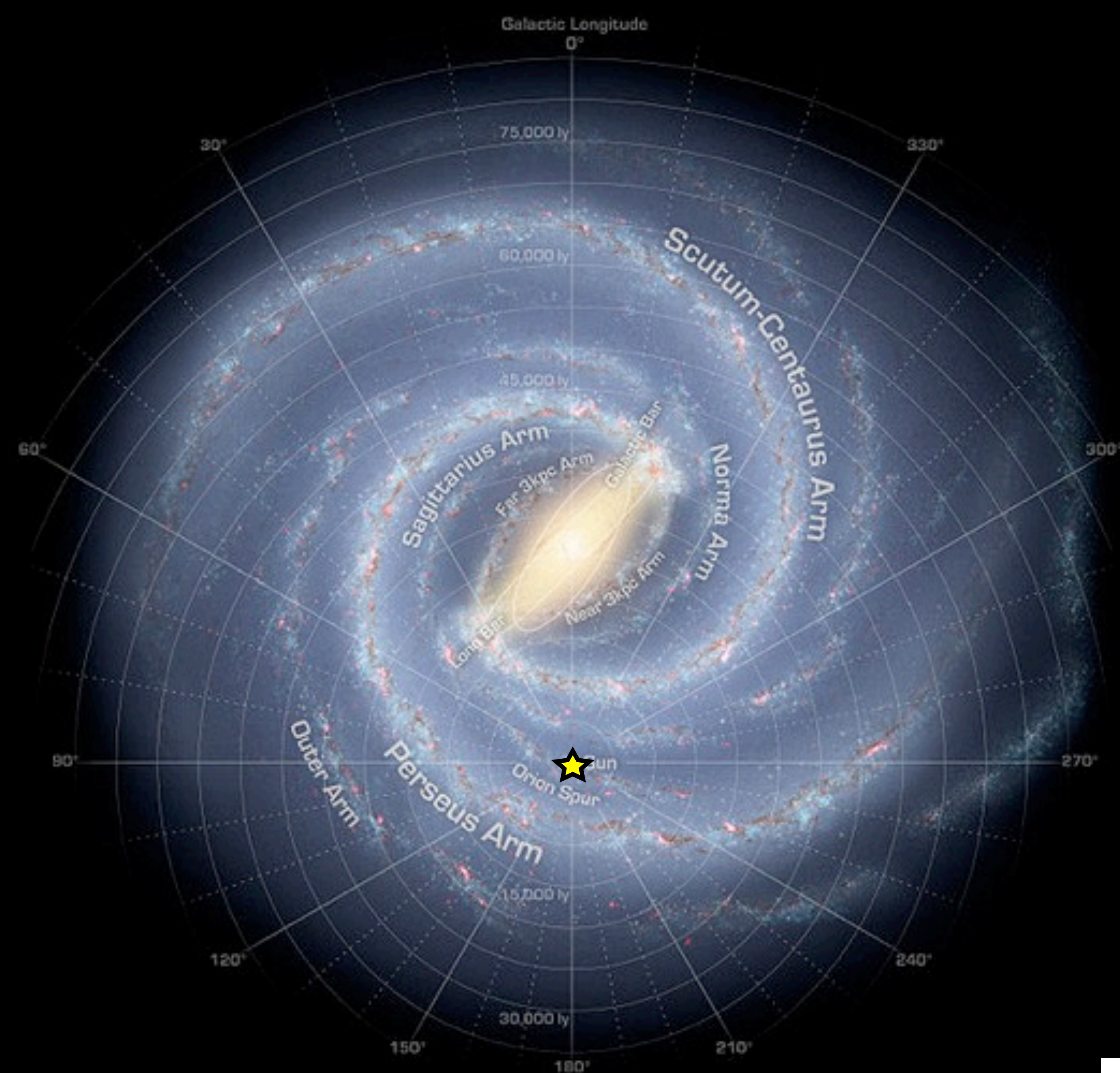
This piece of the pie is very interesting...





Maybe this one is too...

Thanks.

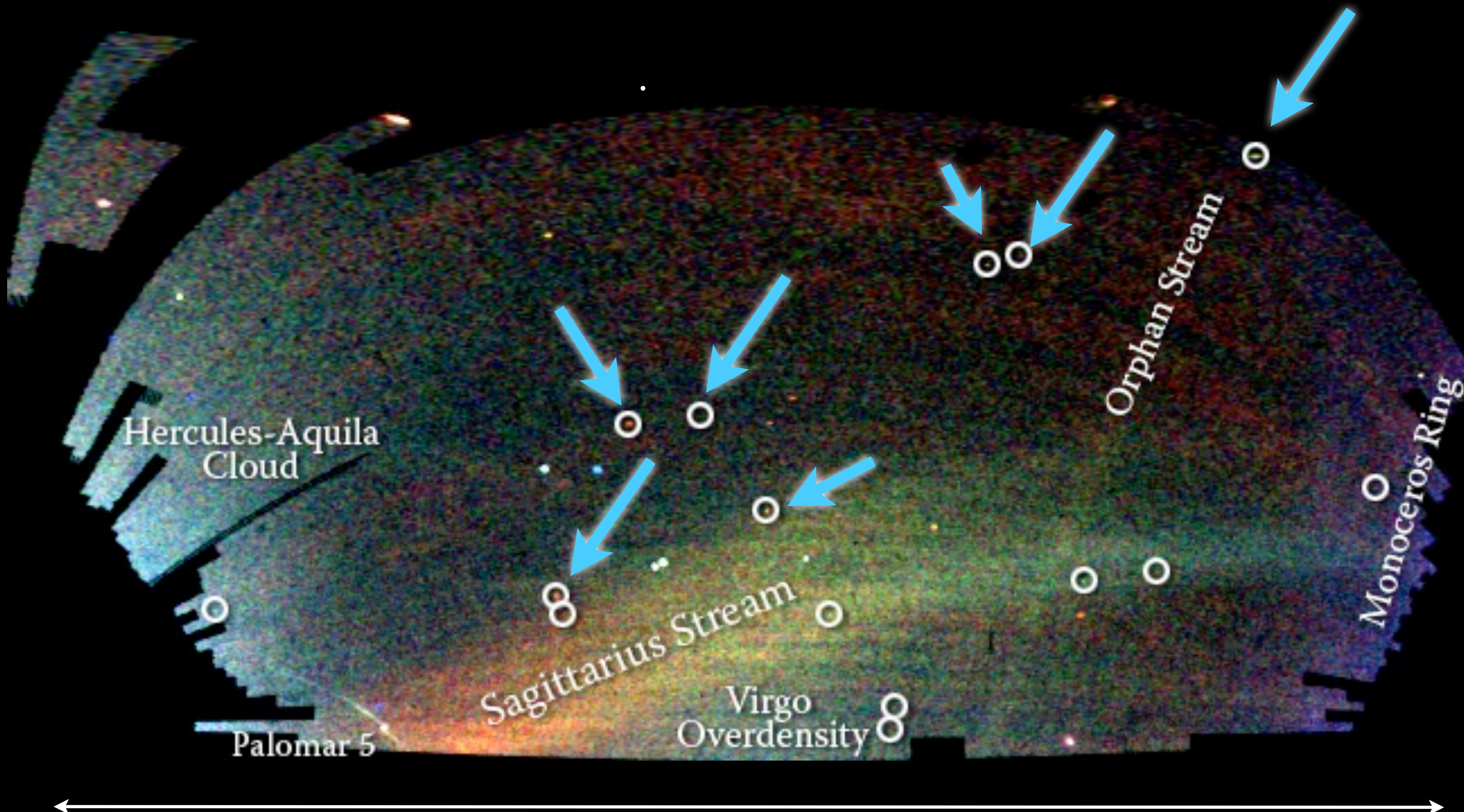


Southern California
SCGE
Center for galaxy evolution

James Bullock
@jbprime

UCIrvine

Not just star streams: new galaxies!



100 degrees of sky

Belokurov et al. 2006

Probably ~100's more faint dwarfs to be discovered