Dark Matter & Dark Energy

Astronomy 1101

Key Ideas:

Dark Matter

- Matter we cannot see directly with light
- Detected only by its gravity (possible future direct detection in the lab)
- Most of the matter in the Universe

Dark Energy

- Vacuum energy of the Universe
- Responsible for acceleration of the Universe's expansion.

Galaxy Rotation Curves Revisited

Spiral Galaxies rotate such that:

- Speed rises from the center to the inner disk
- Speed becomes constant (flat) in the outer disk

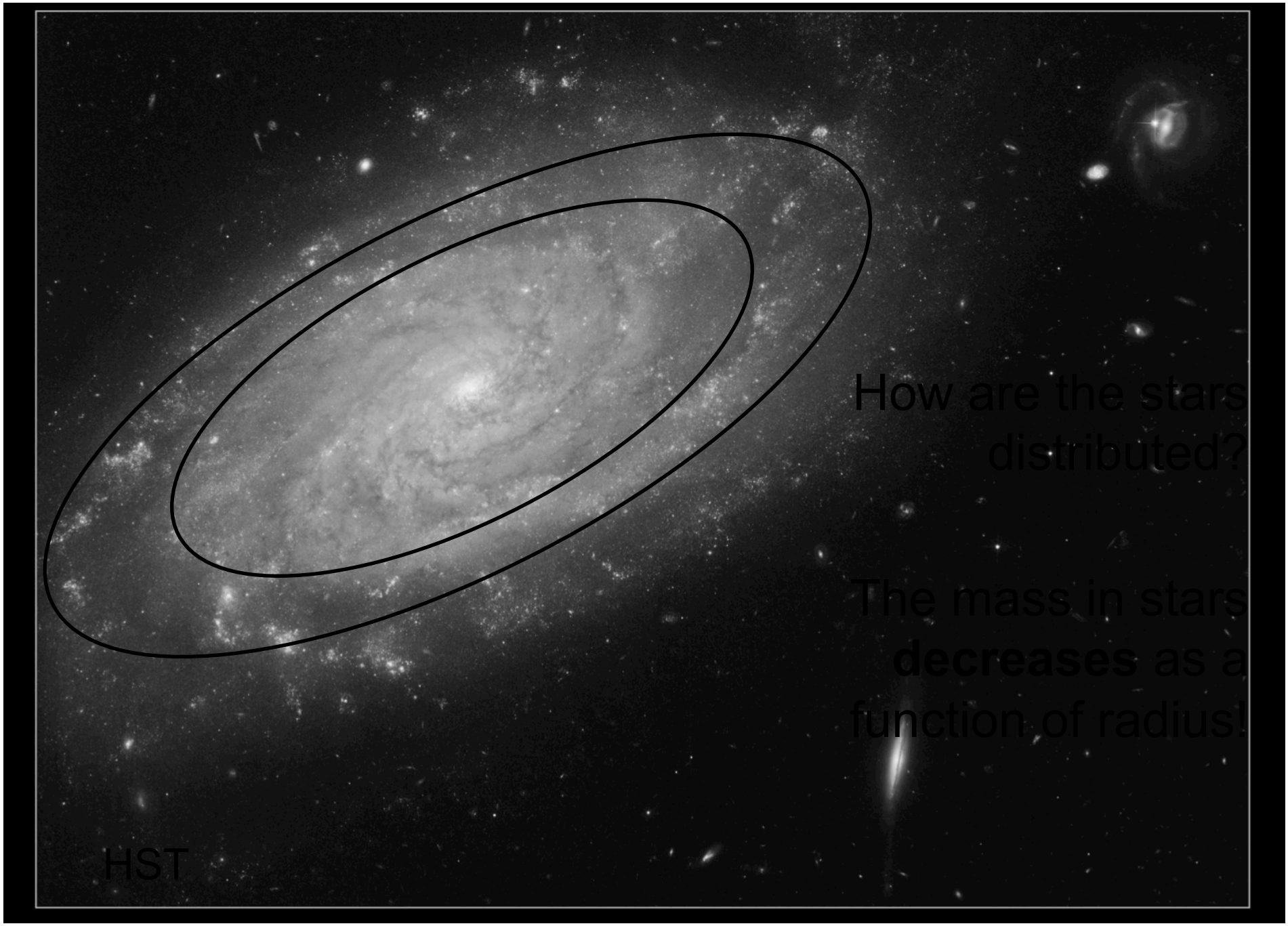
Weighing Galaxies

Stars & gas clouds in a galaxy are held in their orbits by the gravity of the mass *interior* to its orbit.

$$M(R) = \frac{V_{rot}^2 R}{G}$$

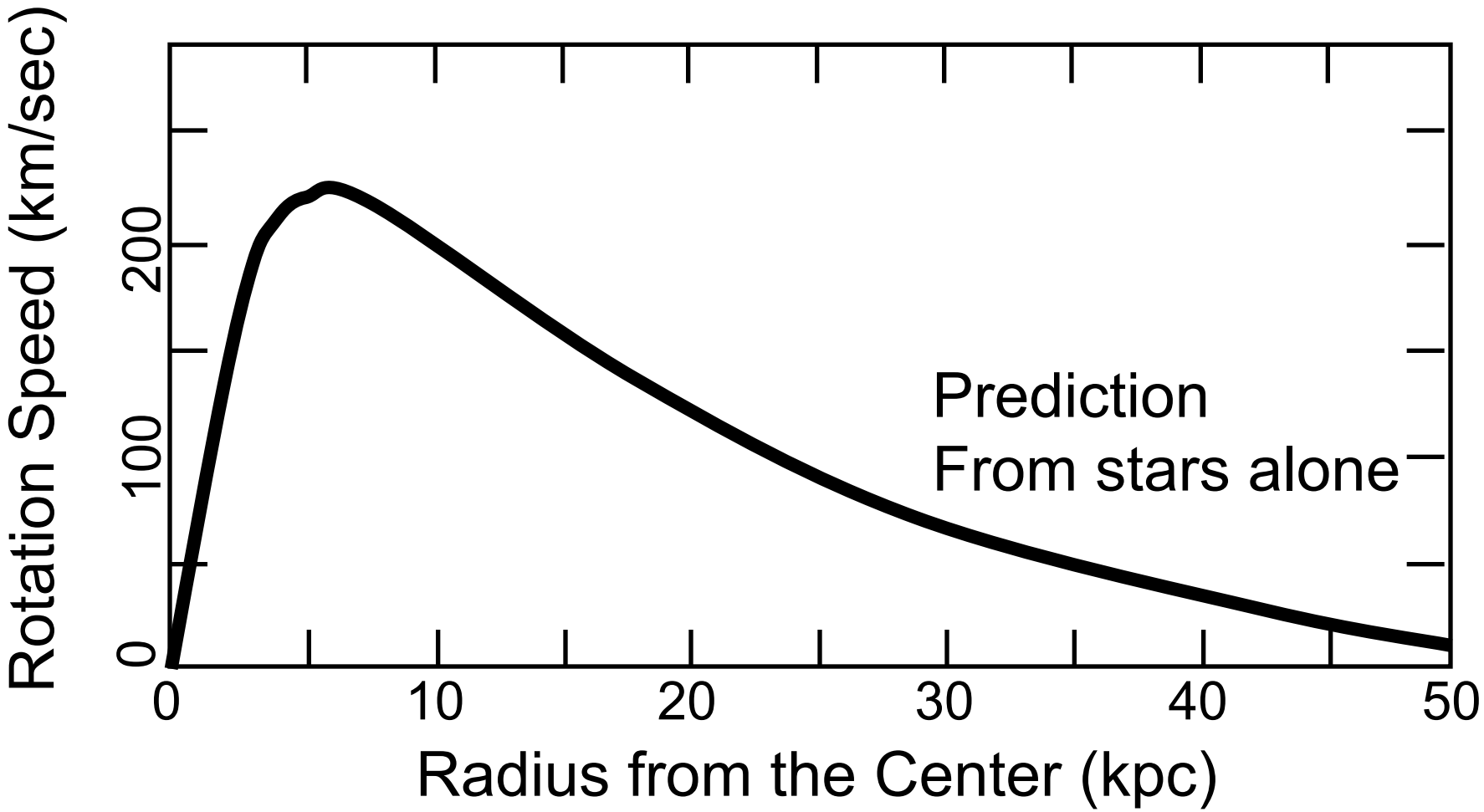
M(R) = mass interior to radius R

V_{rot} = rotation speed


How are the stars distributed?
The mass in stars **decreases** as a function of radius!
HST

Prediction From Stars

$$V_{rot}^2 = \frac{GM(R)}{R}$$



Mass Distribution in Galaxies

Most of the stars are in the inner 10 kpc

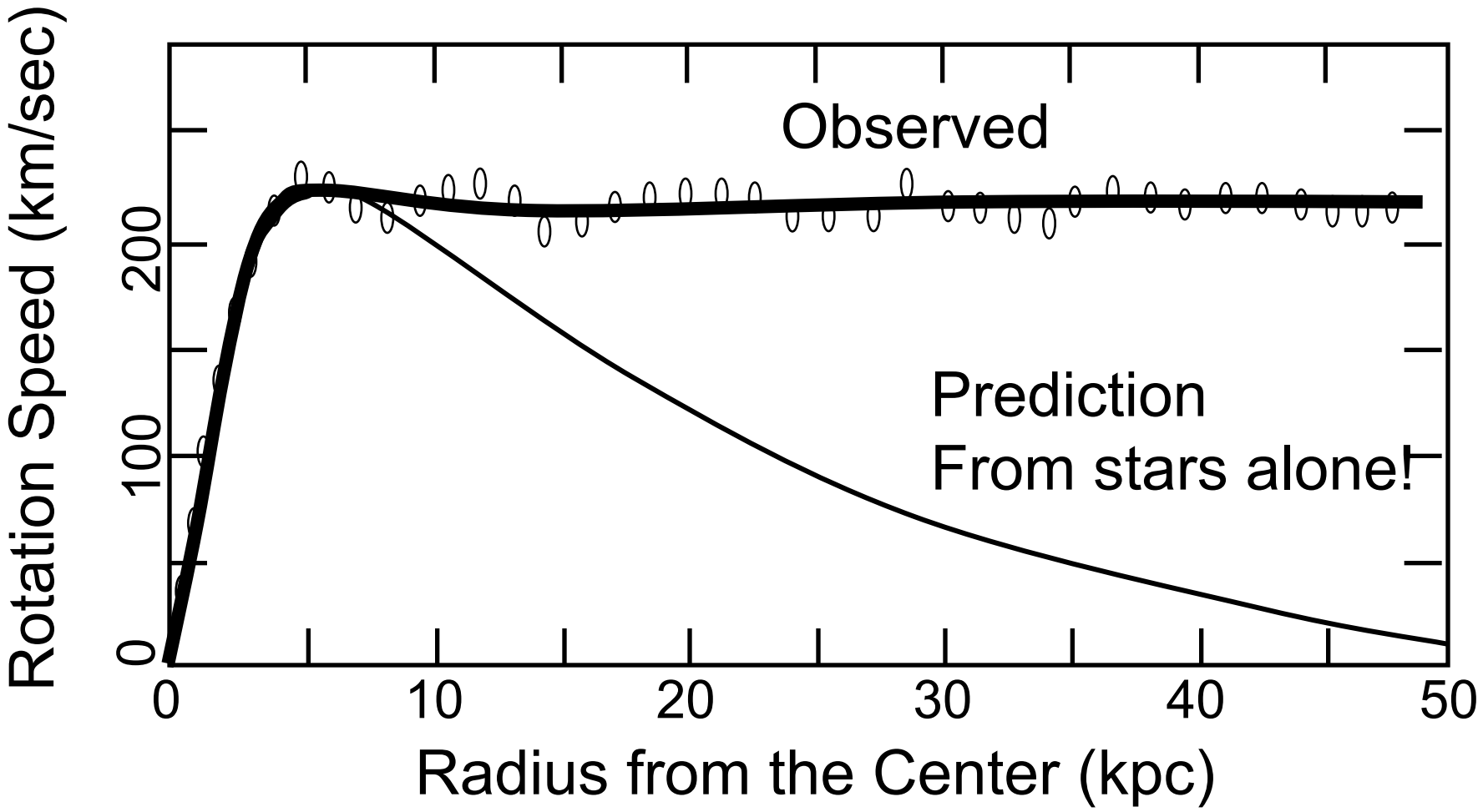
If stars provided all of its mass we expect:

- rotation speed should rise to a maximum in the inner parts
- Then fall steadily with radius outside R > 10 kpc because there are no more stars, no more mass.

What do the observations say?

Observed *vs.* Predicted From Stars

$$V_{rot}^2 = \frac{GM(R)}{R}$$



Lots of unseen mass in galaxies!

The rotation velocity stays flat!

- Outer parts are rotating *faster* than expected.

Need *more mass at large radii* than is observed in the stars and gas alone...

If V_{rot} = constant, then $M(R) \sim R$! The mass must be increasing in radius even though there are less and less stars….

$$M(R) = \frac{V_{rot}^2 R}{G}$$

Mass Distribution in Galaxies

Another way to say it:

If the stars at the outskirts of galaxies were **only** orbiting the stars & gas we see interior to them, should be unbound (!).

Galaxies should be flying apart. They're not. Thus, some form of non-luminous (dark) matter must be present, holding them together.

Dark Matter Halos

Question:

What is the extra mass if it is not stars & gas?

Answer:

Galaxies must have extended ***dark matter halos***

Properties of Dark Halos:

- Contain ~90% of the galaxy's mass
- More extended than the starlight component
- The orbits of satellite galaxies (like the LMC) suggest halos may extend out as far as 200 kpc!

Dark Matter in Galaxy Clusters

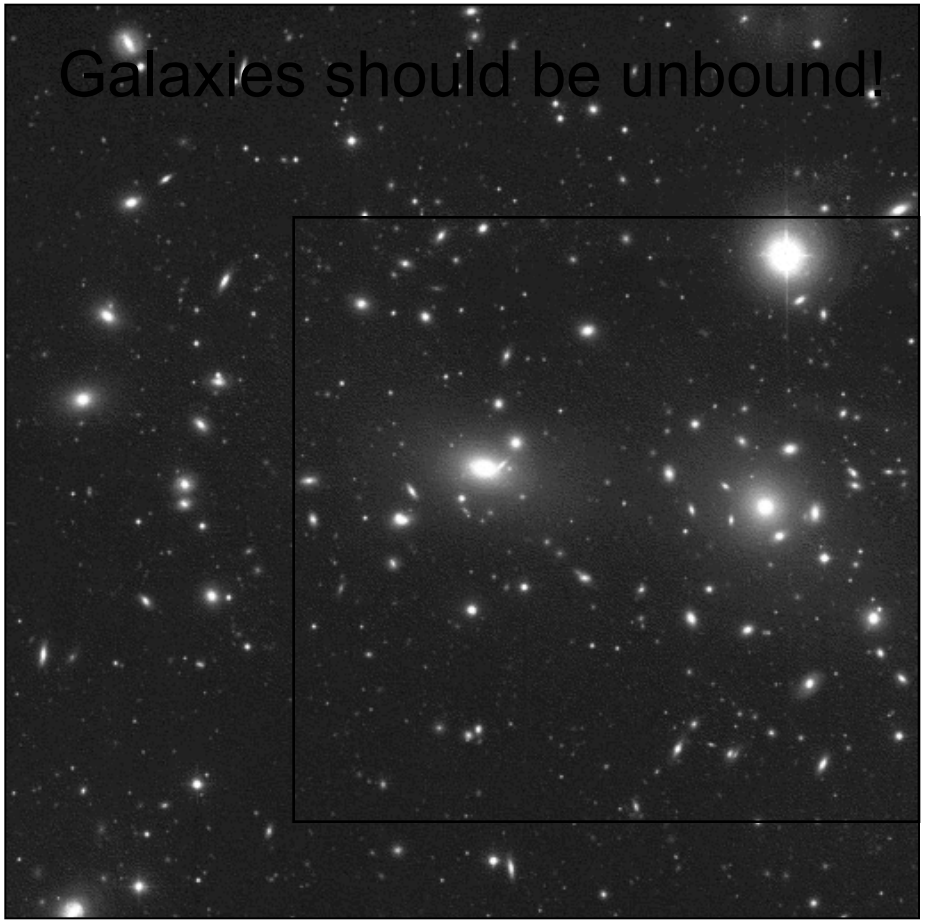
1933: Fritz Zwicky measured the motions of galaxies in the Coma cluster

- Found velocities of *>1000 km/sec* relative to the cluster center.
- This is greater than the escape velocity computed by adding up the light of the cluster!

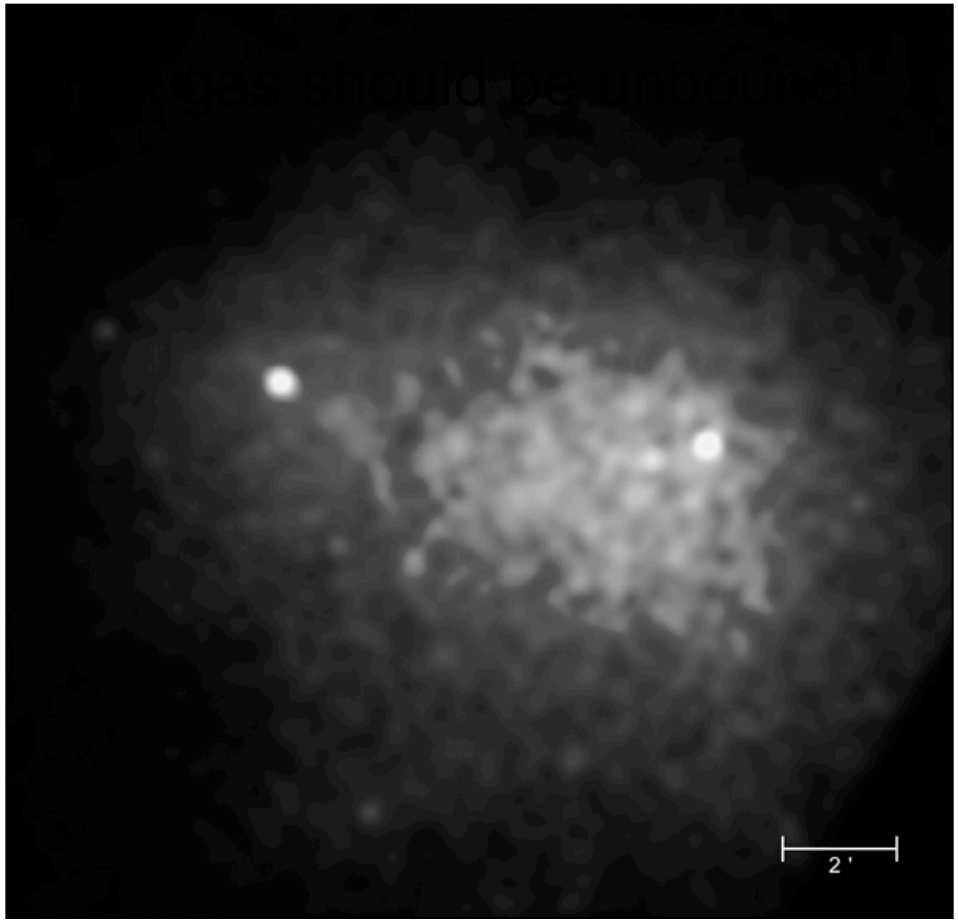
Zwicky suggested that "dark matter" adds extra gravity to hold the cluster together.

Subsequent observations show that galaxy clusters are 90–99% dark matter.

Coma Cluster

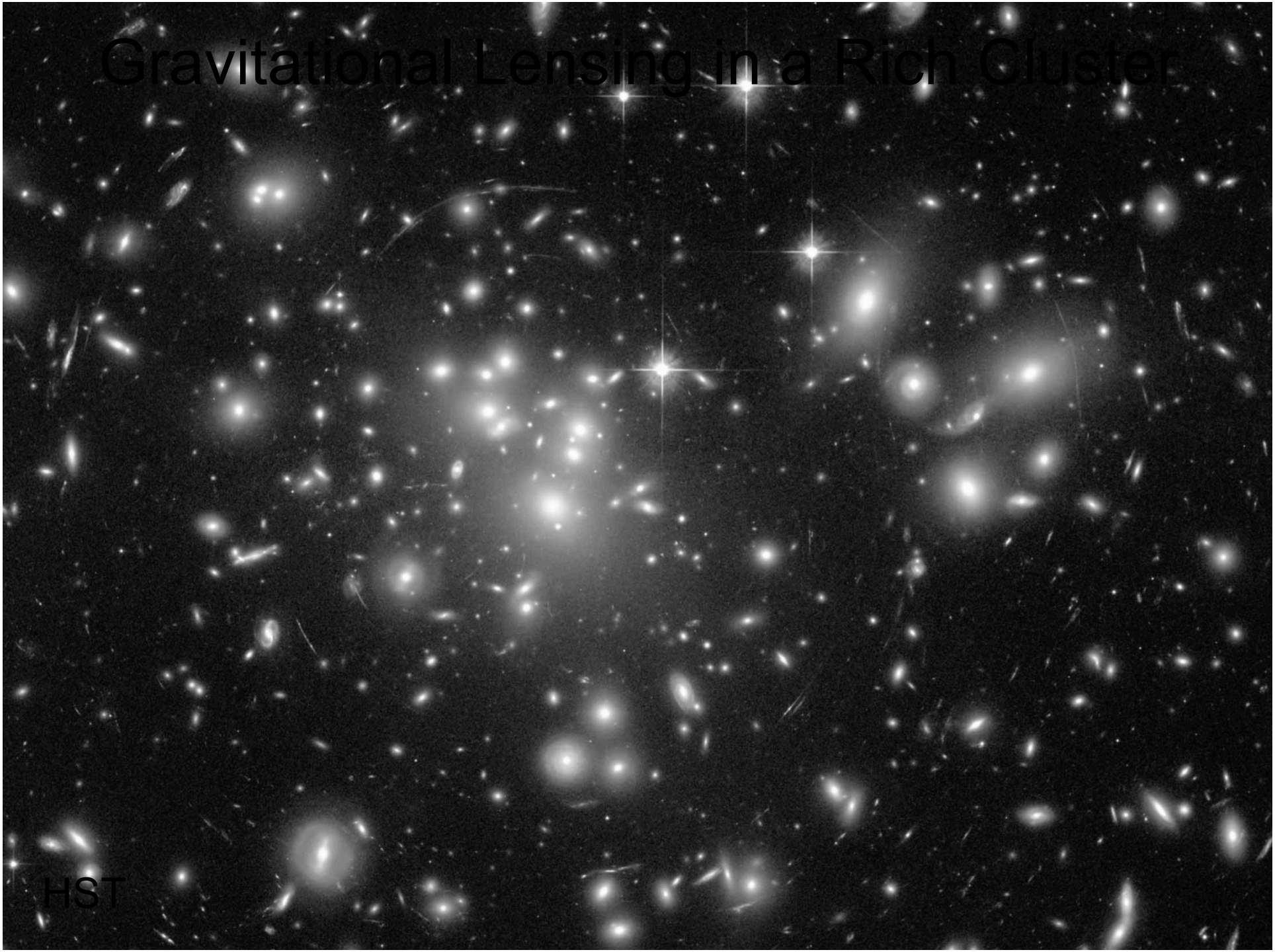


Visible Light
(NOAO)

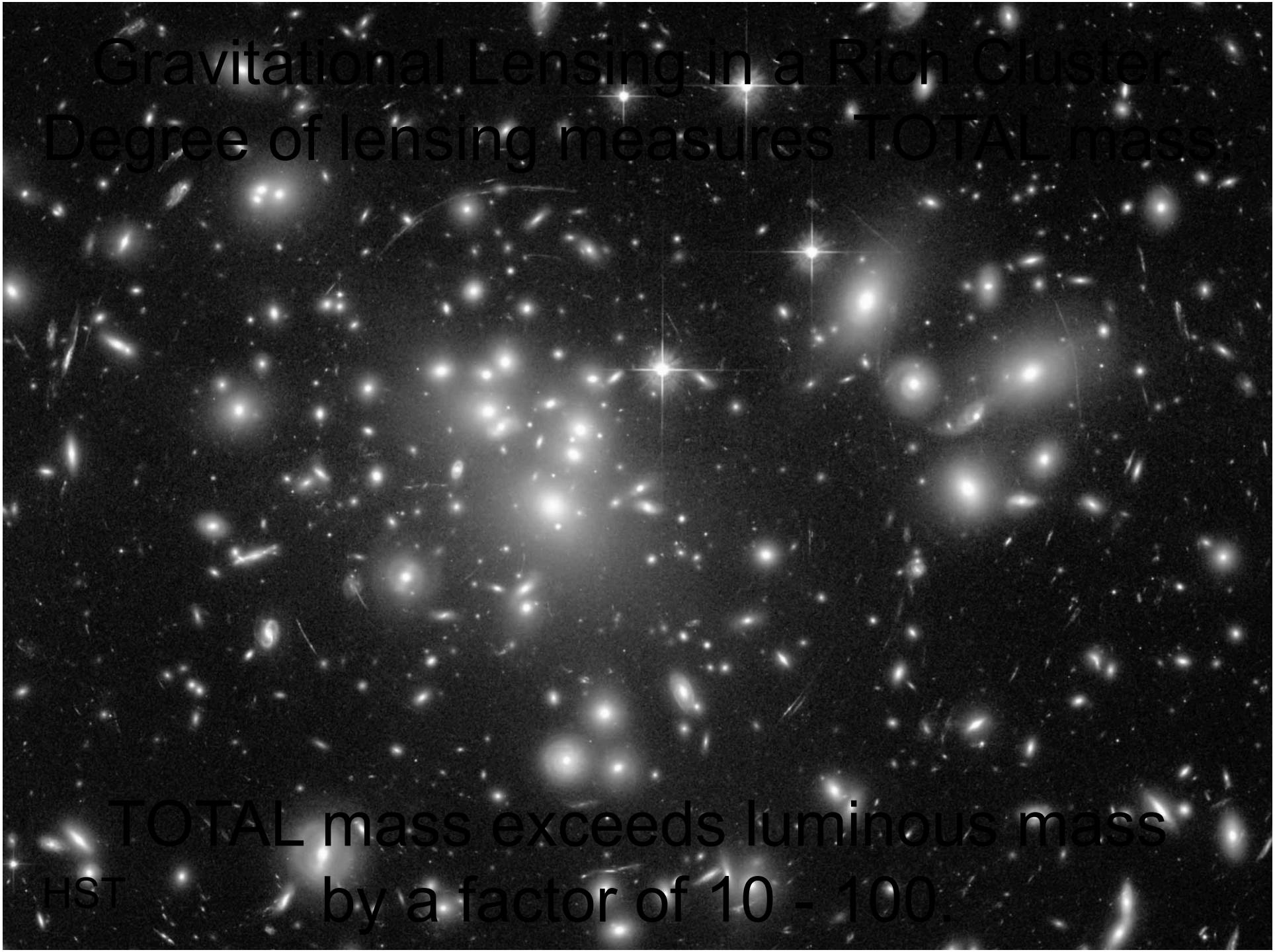


X-rays
(Chandra)

Gravitational Lensing in a Rich Cluster



HST


Gravitational Lensing in a Rich Cluster:
Degree of lensing measures TOTAL mass.
TOTAL mass exceeds luminous mass
by a factor of 10 - 100.
HST

Dark matter

1 – Rotation curves
2 – Galaxies moving too fast in clusters
3 – Hot gas in clusters
4 – Strong lensing

Dark Matter

Called “Dark Matter” because it cannot be detected directly using light.

It is only detected by its *Gravitational Effects*:

- Outer parts of galaxies *rotate faster than expected* from the starlight.
- Galaxies in clusters *orbit/move faster than expected* from the starlight.
- Hot X-ray gas that would otherwise evaporate from a galaxy cluster stays confined.

What is Dark Matter made of?

Is Dark Matter Just Ordinary Stuff?

Ordinary matter ("baryons") made of protons and neutrons

Candidates:

- Brown Dwarfs & Jupiter-sized planets
- Cold stellar remnants (black holes, neutron stars, & white dwarfs) Trillions!
- Primordial black holes (Big Bang leftovers)
- Frozen hydrogen snowballs, comets, ??

Collectively called:

Massive Compact Halo Objects (MACHOs)

Gravitational Microlensing

If a MACHO passes between Earth & a more distant background star:

- GR predicts that the MACHO's mass bends the starlight of the more distant star.
- Get a "*Gravitational Microlens*" that briefly magnifies the background star.

Chance alignments are very rare.

- Most should last only for a few weeks
- Must monitor millions of stars for many years

Microlensing Searches

Monitoring of LMC & SMC to search for microlensing from MACHOs:

- Watched ~12 Million stars for 6 years.
- Found only 13-17 halo microlensing events
- Most likely mass range ~0.15 – 0.9 M_{sun} making them Jupiters up to white dwarfs

MACHOs can make up only at most ~1-10% of the halo of the Milky Way

Dark matter is not MACHOs.

Is Dark Matter **not** Ordinary Stuff?

Fundamental particles that only interact via gravitation and (possibly) the weak force.

Massive neutrinos:

- Produced in large numbers in the Big Bang??

Exotic new particles:

- Predicted by some particle theories.

Weakly Interacting Massive Particles:

WIMPs

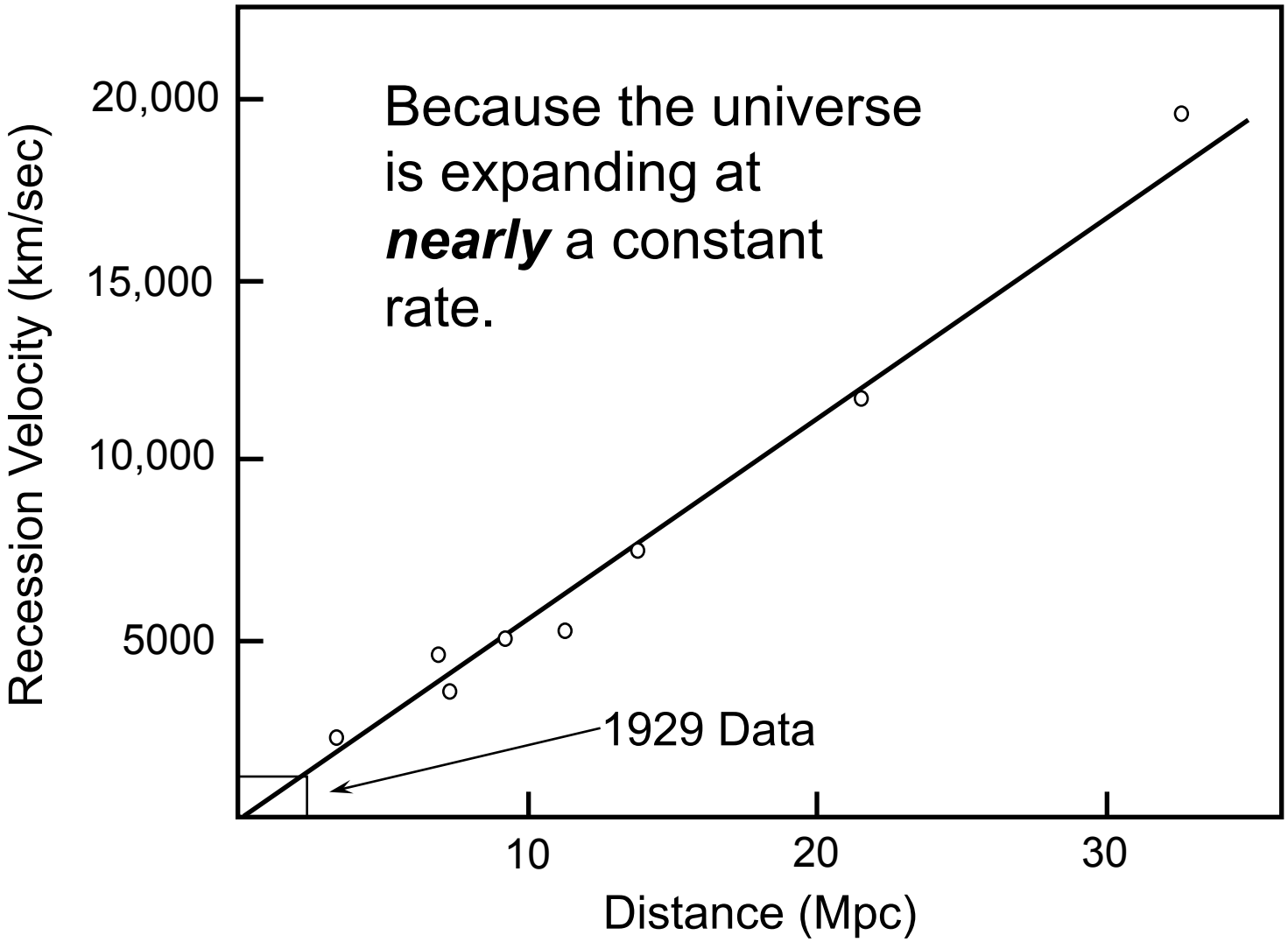
Particle Dark Matter Searches

Attempts to directly detect dark matter.

- Particle accelerator experiments searching for new massive particles in collisions.
- Searches for “cold dark matter” particles hitting the Earth from space.

So far, no convincing detections have been reported, but the searches go on. Best chance may be new particle accelerators (LHC) and other new experiments.

Hubble & Humason (1931)



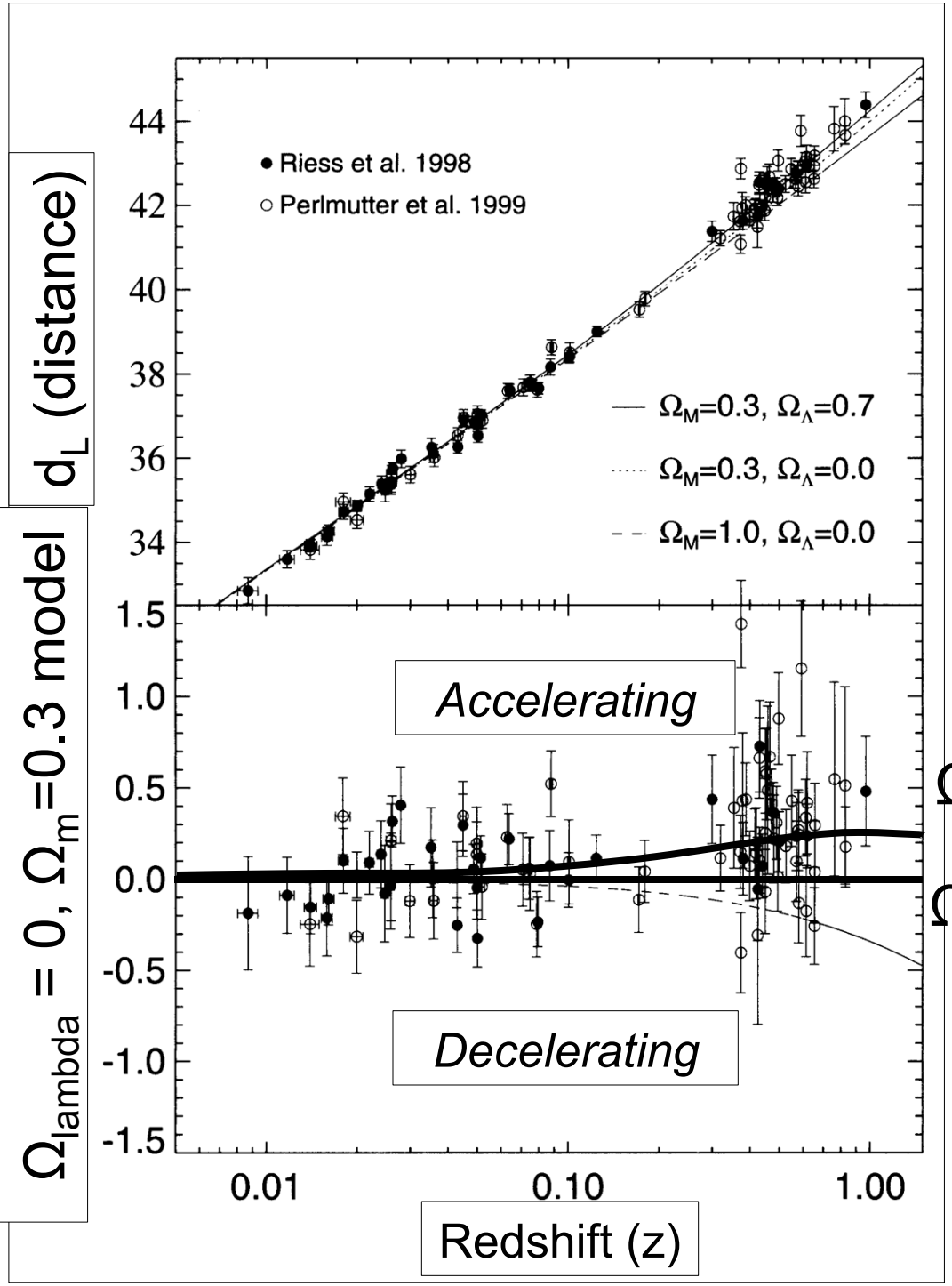
The Universe is accelerating in its expansion, not slowing down.

Nobel prize to Riess, Perlmutter, & Schmidt for discovery in 1998.

New way to get distances to very distant galaxies: Type Ia supernova explosions

Thermonuclear detonation of white dwarf.

They find that our universe has total energy density $\Omega_0 \sim 1$, that it is accelerating, and that $\Omega_\Lambda \sim 0.7$ and $\Omega_m \sim 0.3$.



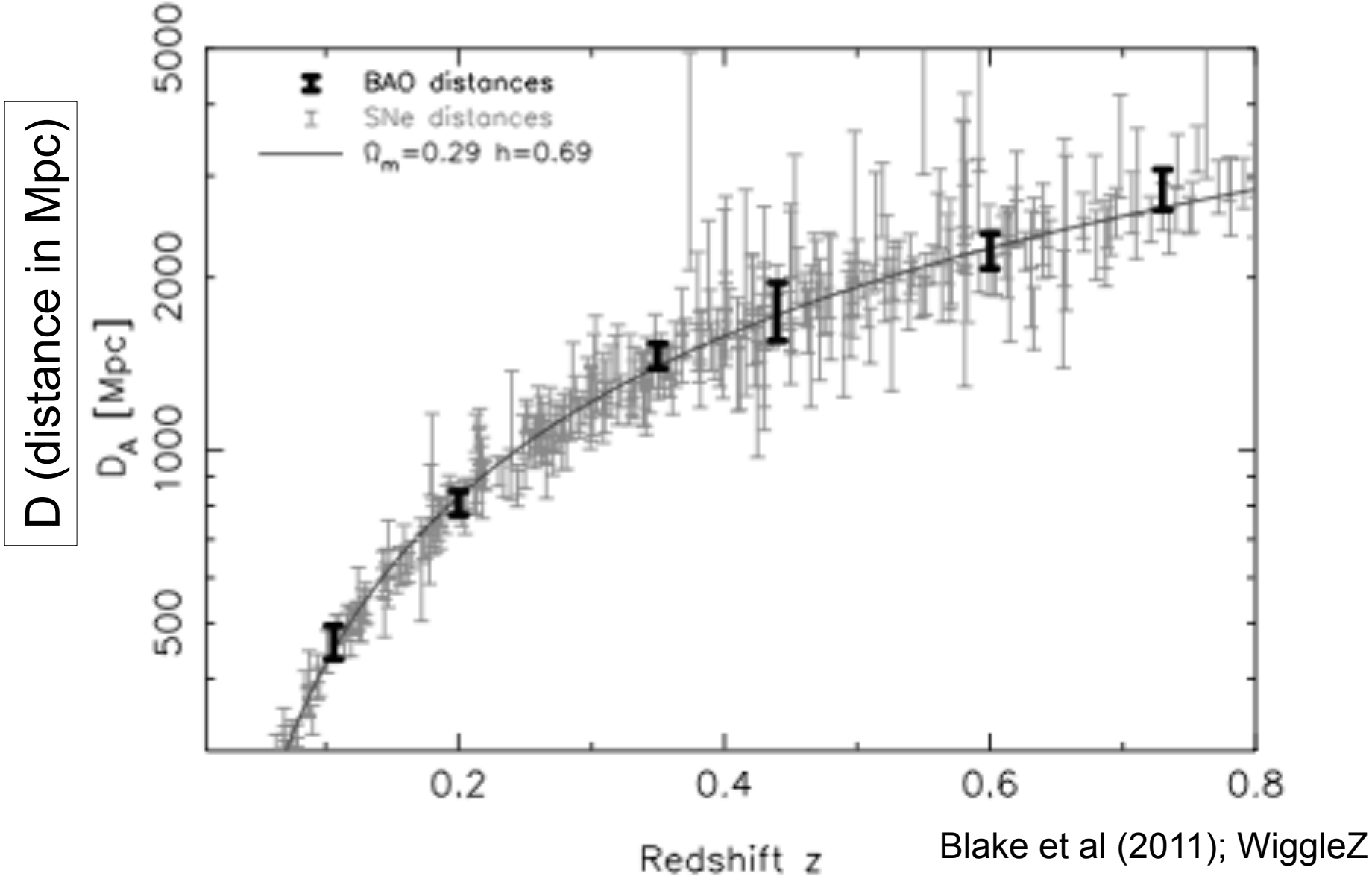
Linear nearby, but then not linear at high redshift (great distance, long ago).

Thus, acceleration.

Ω_m =0.3, $\boldsymbol{\Omega_\Lambda}$=0.7

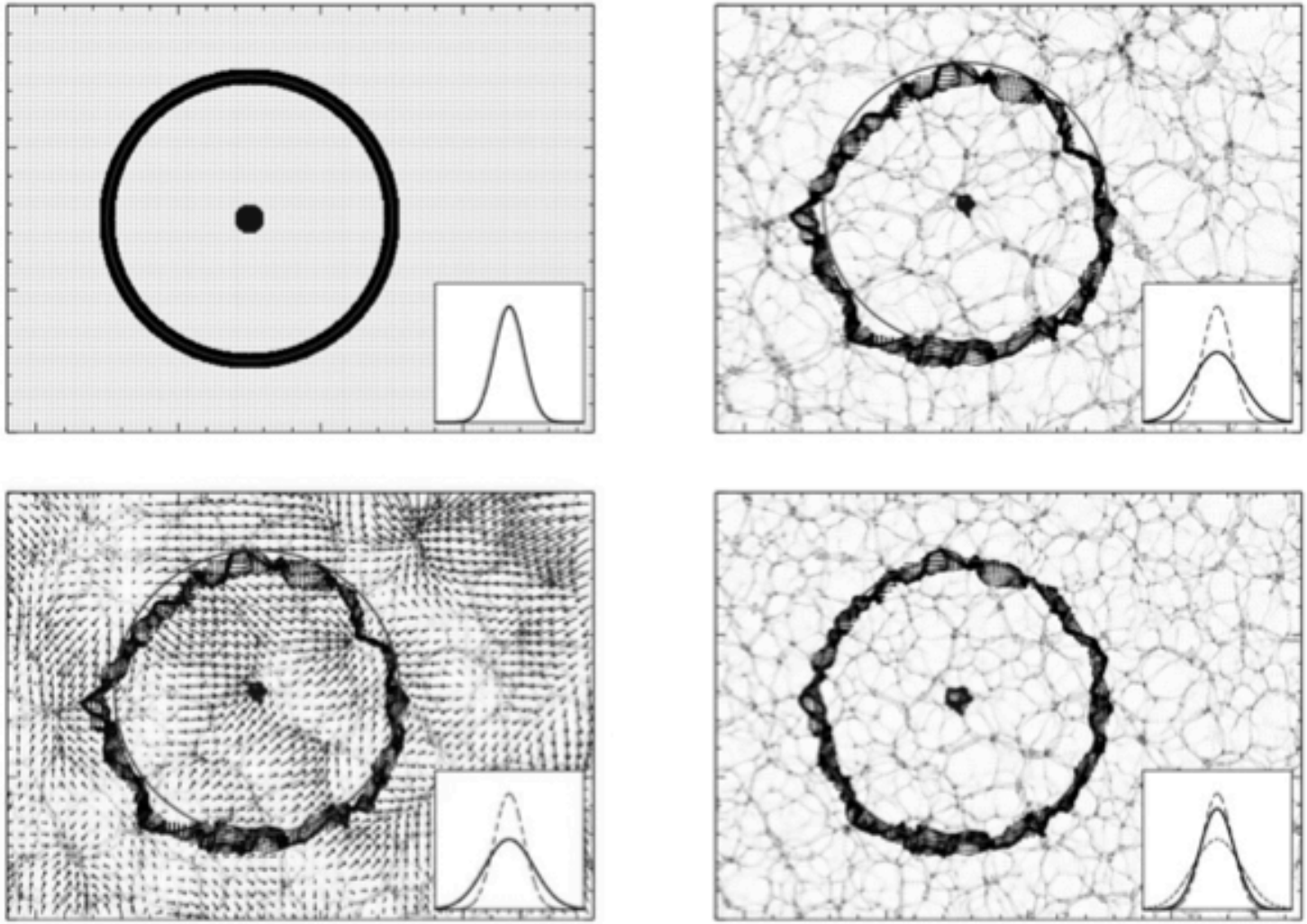
Ω_Λ =0.3, $\boldsymbol{\Omega_\Lambda}$=0

Baryon Acoustic Oscillations (BAO): Ripples in the primordial fluid imprint on cosmic structure.



Blake et al (2011); WiggleZ

Baryon Acoustic Oscillations (BAO): Ripples in the primordial fluid imprint on cosmic structure.



Weinberg et al 2013; Padmanahban et al 2012

Physics Reports 530 (2013) 87–255

Contents lists available at ScienceDirect

Physics Reports

journal homepage: www.elsevier.com/locate/physrep

Observational probes of cosmic acceleration

David H. Weinberg [a,b,*], Michael J. Mortonson [b], Daniel J. Eisenstein [c,d], Christopher Hirata [e], Adam G. Riess [f], Eduardo Rozo [g]

[a] *Department of Astronomy, Ohio State University, Columbus, OH, United States*

[b] *Center for Cosmology and Astro-Particle Physics, Ohio State University, Columbus, OH, United States*

[c] *Steward Observatory, University of Arizona, Tucson, AZ, United States*

[d] *Harvard College Observatory, Cambridge, MA, United States*

[e] *California Institute of Technology, Pasadena, CA, United States*

[f] *Department of Physics and Astronomy, Johns Hopkins University, Baltimore, MD, United States*

[g] *Kavli Institute for Cosmological Physics, University of Chicago, Chicago, IL, United States*

We know less about dark energy than dark matter.

"Extra" energy density that does not dilute. **Not** like normal energy!

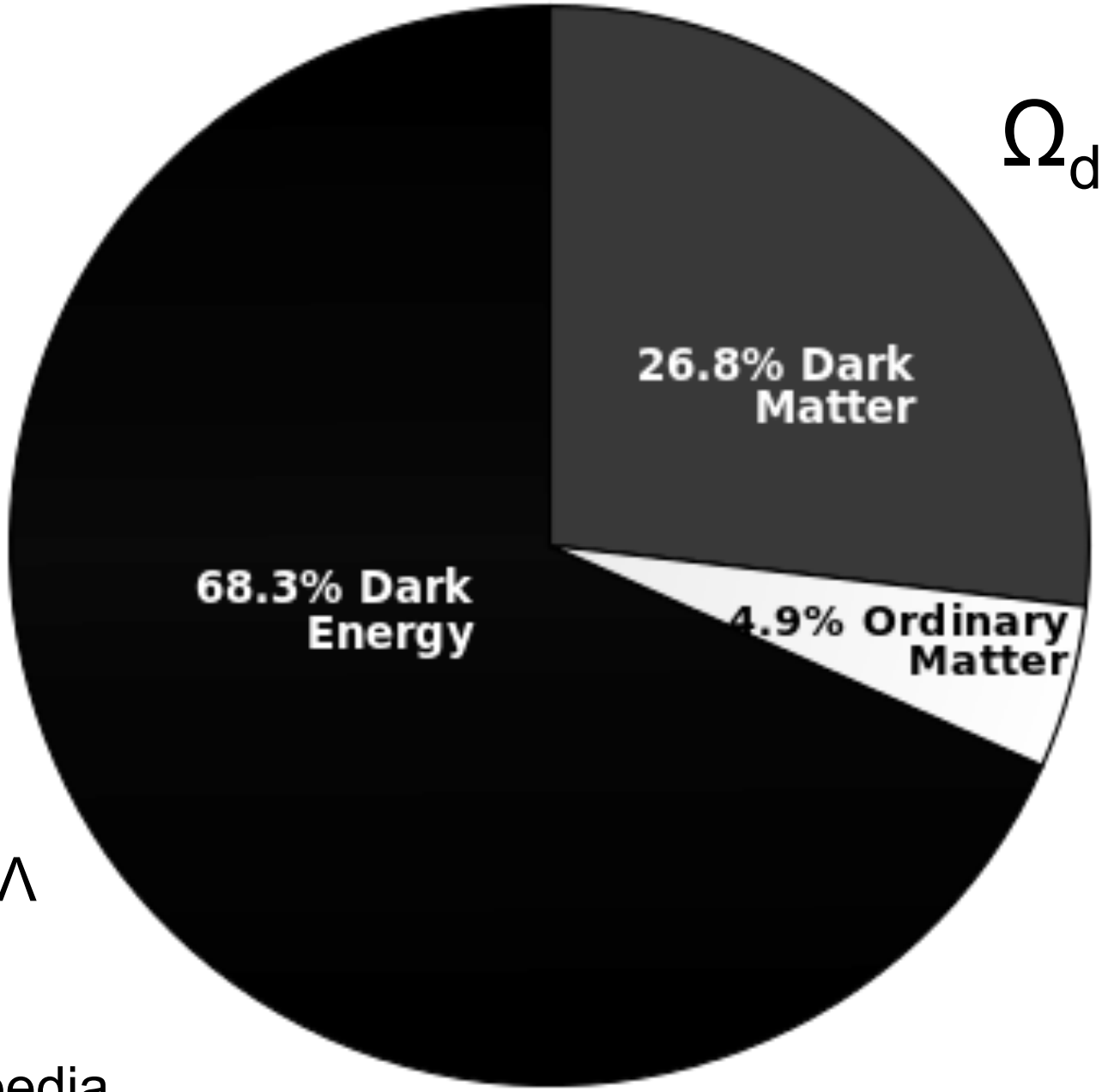
Cosmological **Constant** (Λ):

- Vacuum energy component whose density is constant over cosmic history
- Problem: theories predict 10^{100} times too high…

Generic Dark Energy

- Could vary in density over cosmic time
- Candidates include exotic particle physics objects like scalar fields, quintessense, phantom energy...

Why doesn't it affect things right here?

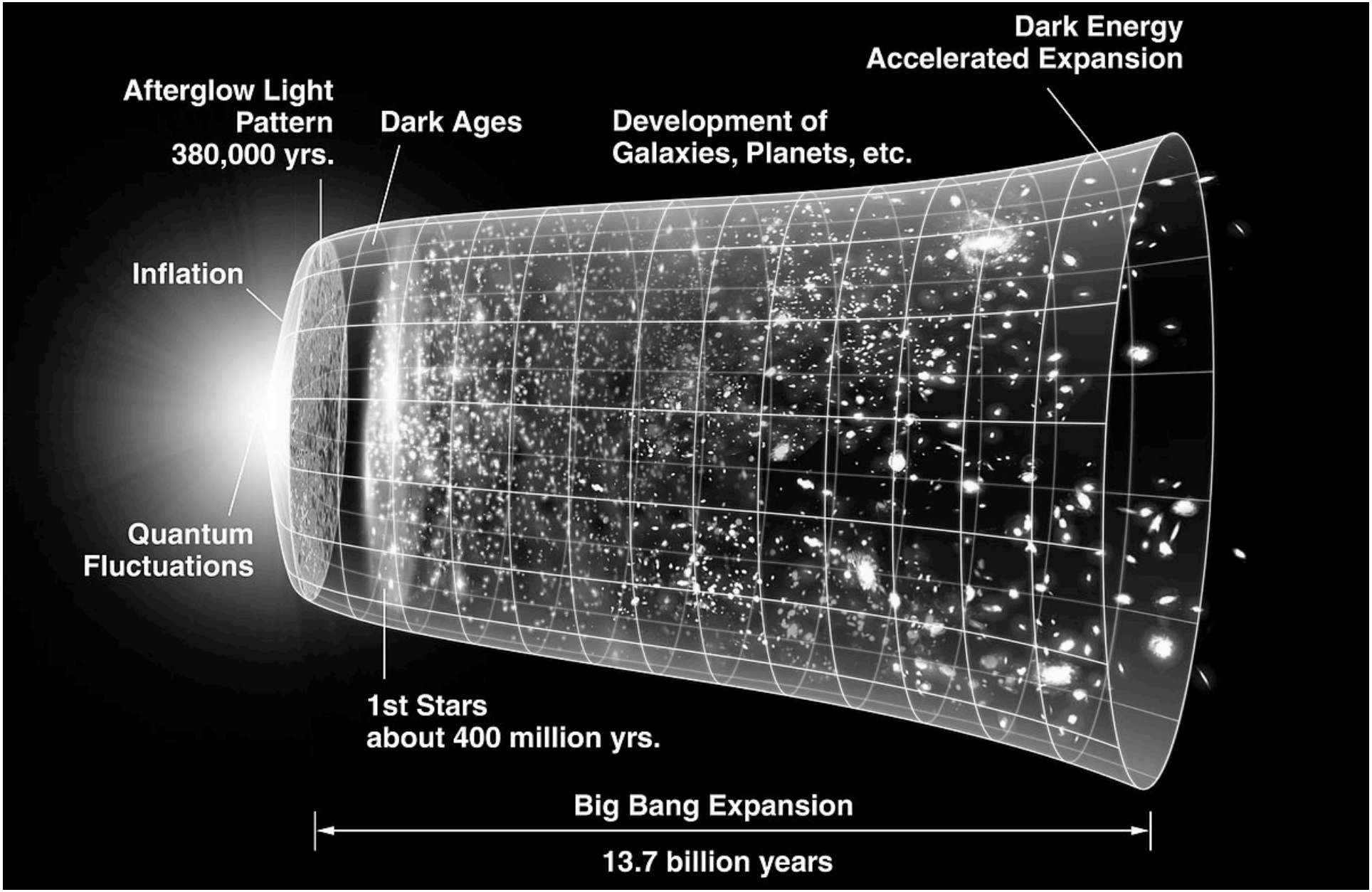


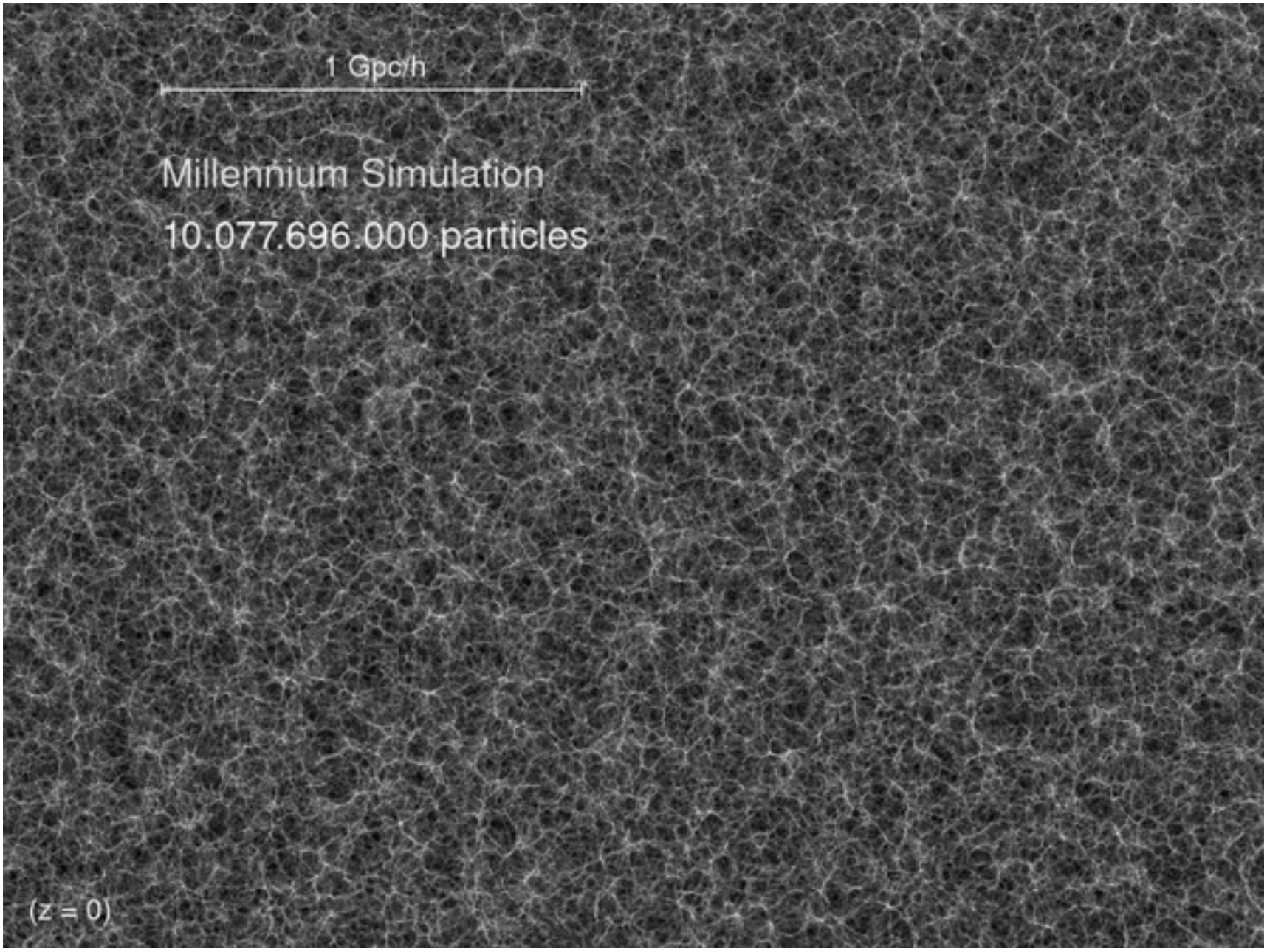
Ω_{dm}

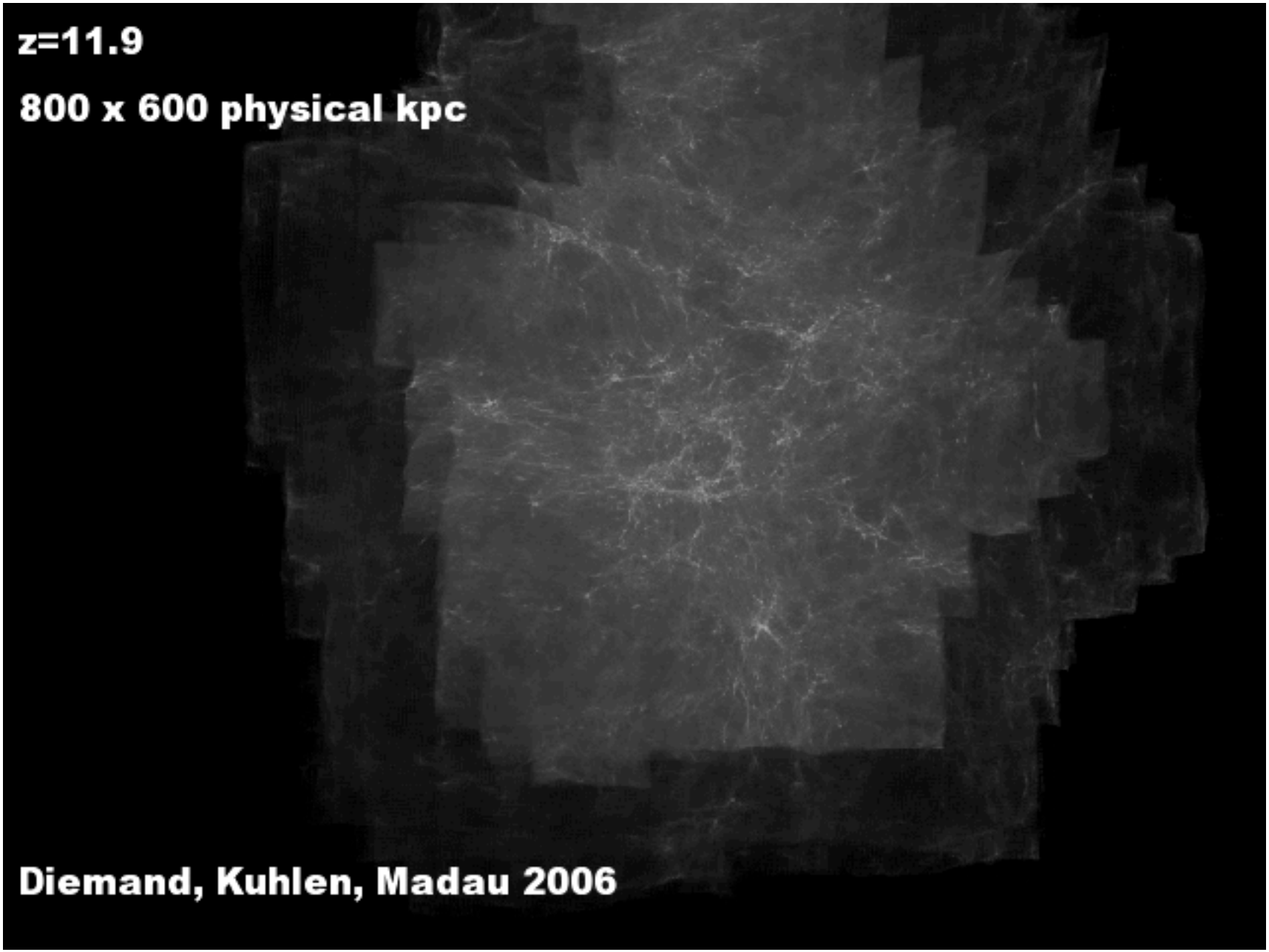
Ω_b

Ω_Λ

Wikipedia


Dark Energy
Accelerated Expansion
Afterglow Light
Pattern
380,000 yrs.
Dark Ages
Development of
Galaxies, Planets, etc.
Inflation
Quantum
Fluctuations
1st Stars
about 400 million yrs.
Big Bang Expansion
13.7 billion years


1 Gpc/h
Millennium Simulation
10.077.696.000 particles
(z = 0)


z=11.9
800 x 600 physical kpc
Diemand, Kuhlen, Madau 2006

A (Very) Radical Suggestion:

Maybe Dark Matter & Dark Energy don't exist at all!

Is our theory of gravity *wrong* on large scales?

MoND: Modified Newtonian Dynamics

Problems:

- None of the alternative theories of gravity have survived key tests of detailed predictions.
- Hard to reconcile these theories with the observed gravitational lensing.