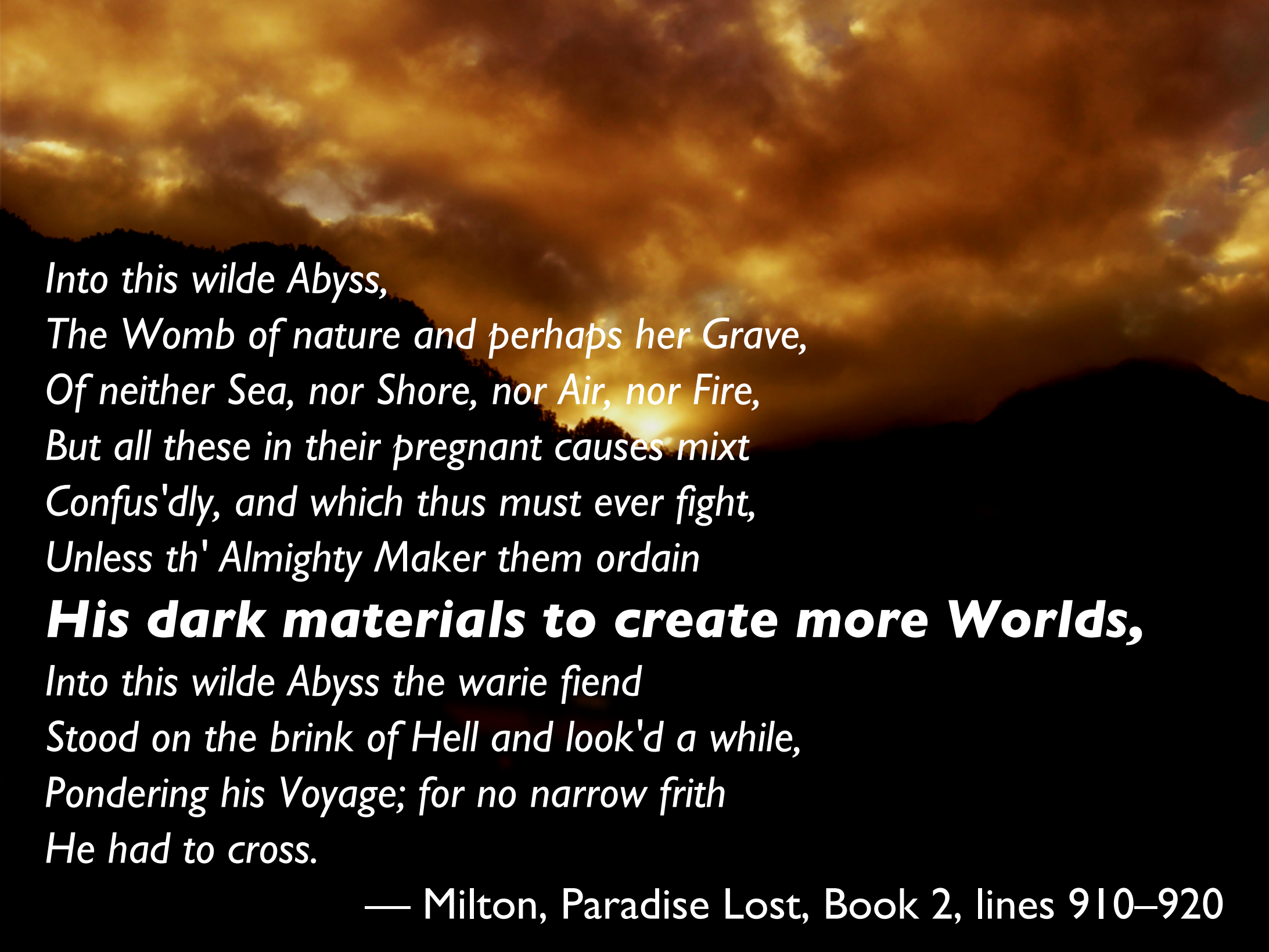

Into this wilde Abyss,
The Womb of nature and perhaps her Grave,
Of neither Sea, nor Shore, nor Air, nor Fire,
But all these in their pregnant causes mixt
Confus'dly, and which thus must ever fight,
Unless th' Almighty Maker them ordain
His dark materials to create more Worlds,
Into this wilde Abyss the warie fiend
Stood on the brink of Hell and look'd a while,
Pondering his Voyage; for no narrow frith
He had to cross.
— Milton, Paradise Lost, Book 2, lines 910–920

Dark Matter

&

Dark Energy

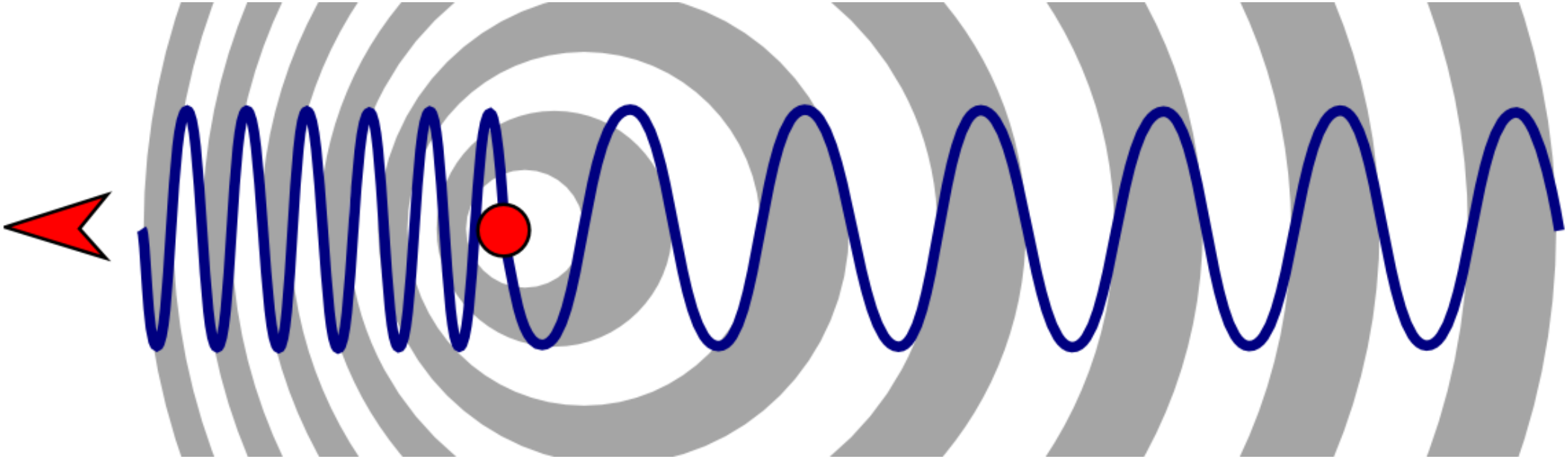
Kevin Huffenberger, Physics Department, U. Miami

Dark Matter Clues

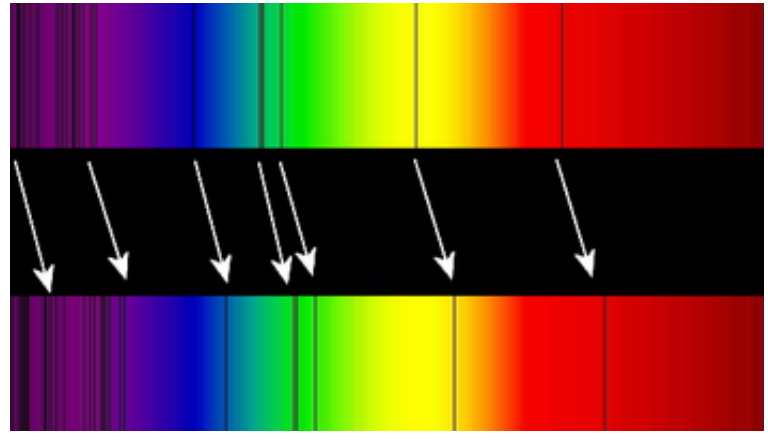
1. Galaxies in the galaxy clusters move faster than expected


Coma cluster
~ 1000 galaxies
320 Mly away
10^14-10^15 solar masses

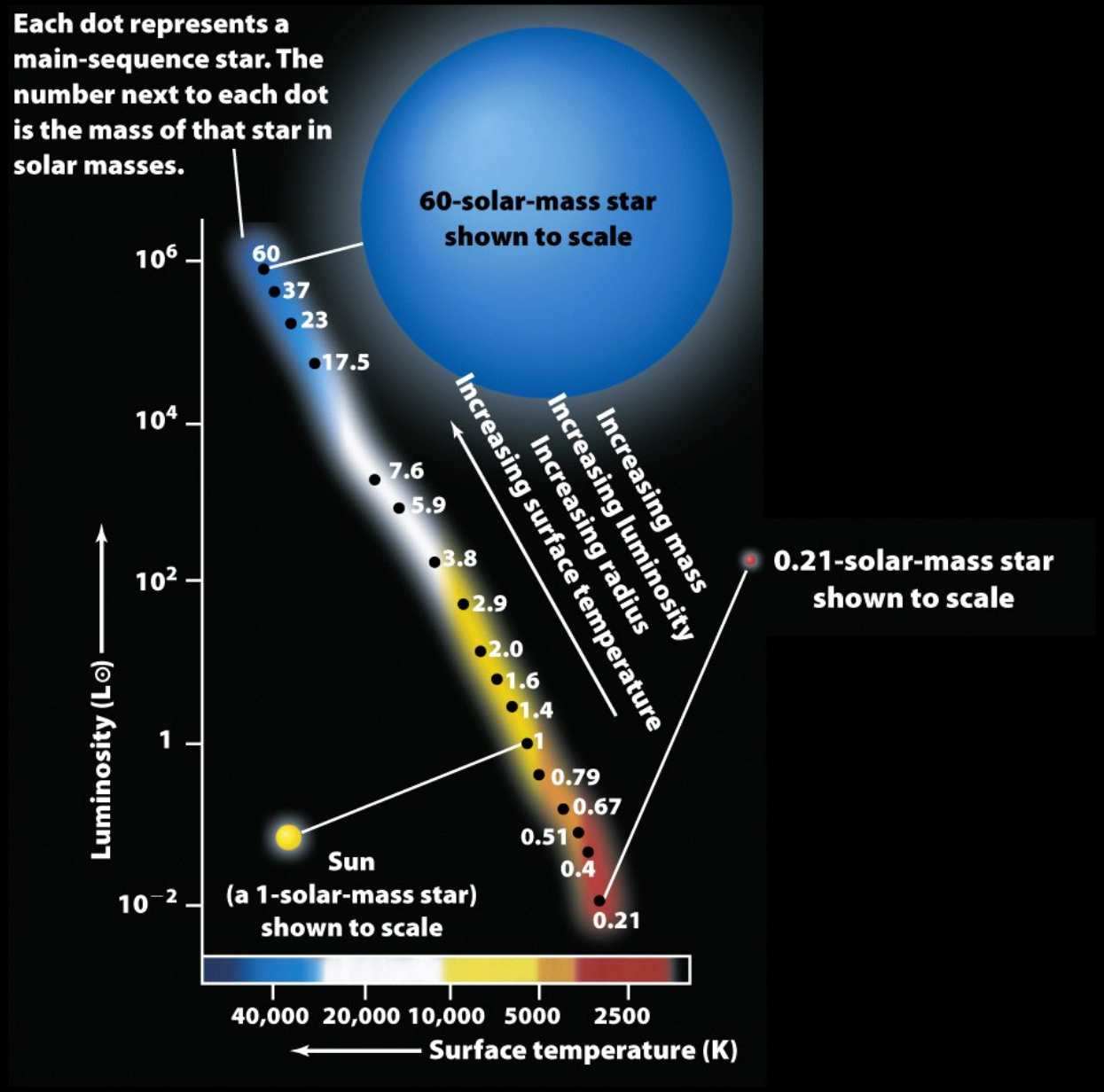
Motion of those galaxies from Doppler effect.

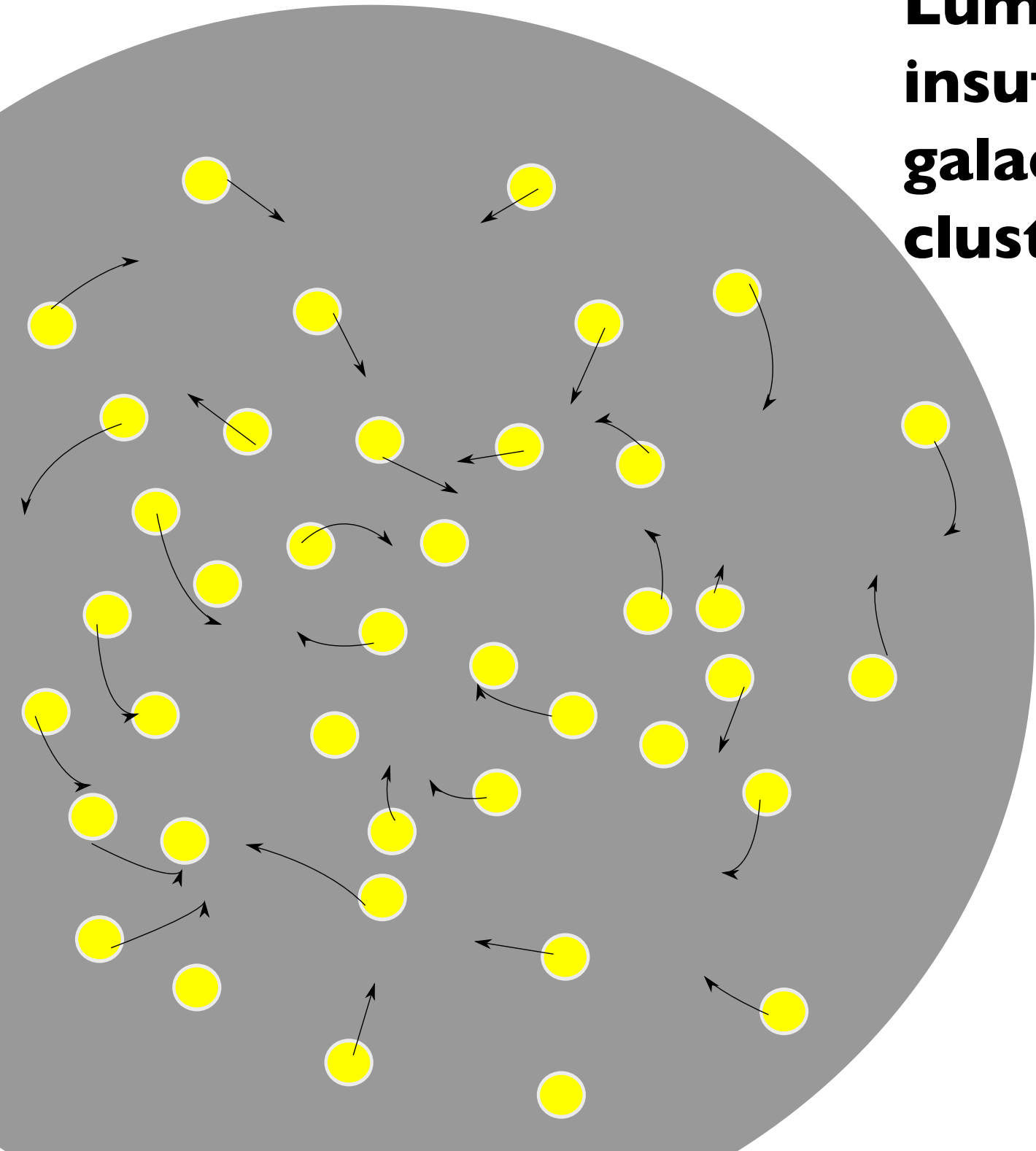


"blue-shift" "red-shift"



Main sequence masses





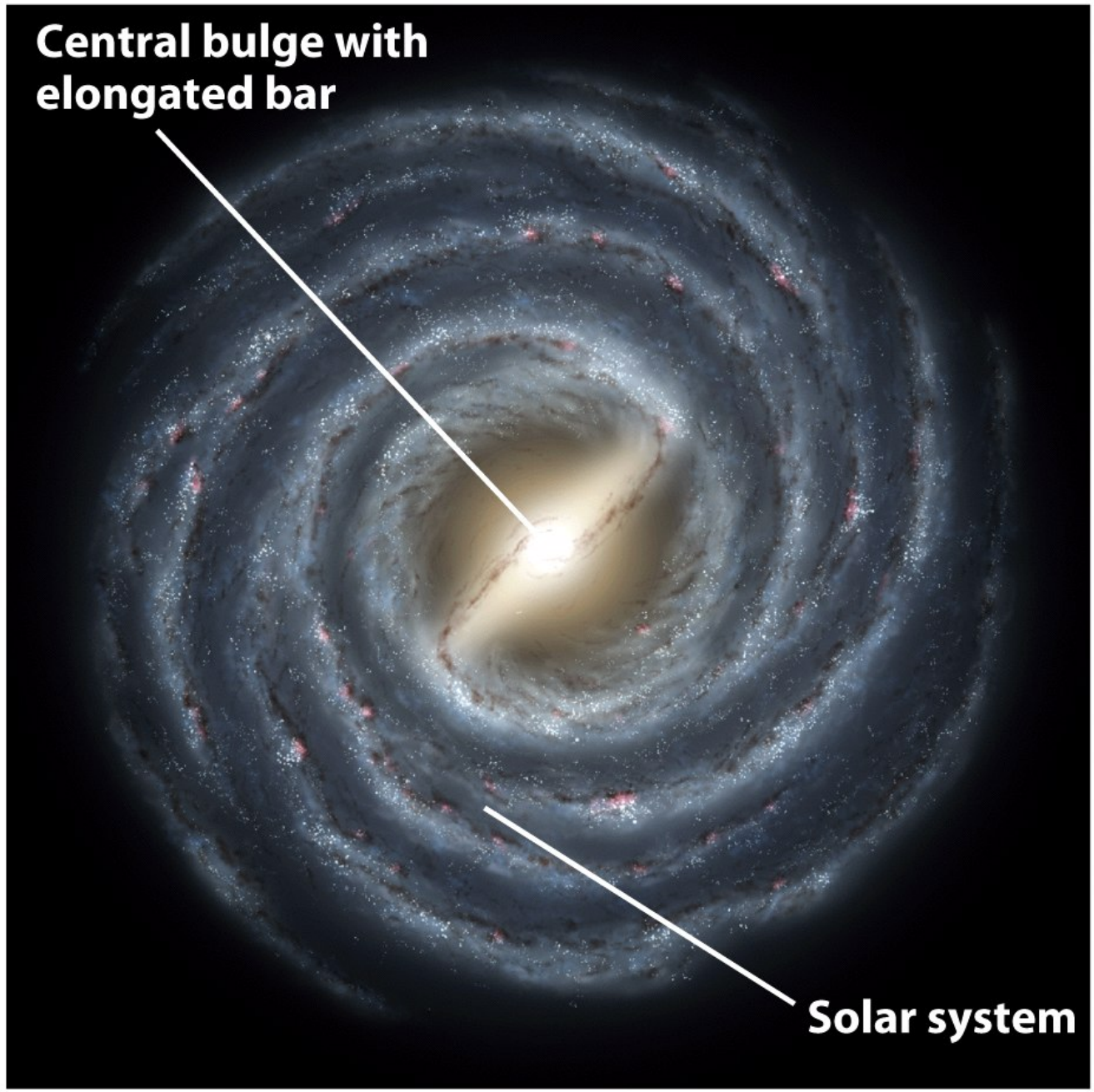
Luminous matter insufficient to explain galactic motions in clusters

Dark Matter Clues

1. Galaxies in the galaxy clusters move faster than expected

2. The outer parts of spiral galaxies rotate faster than expected

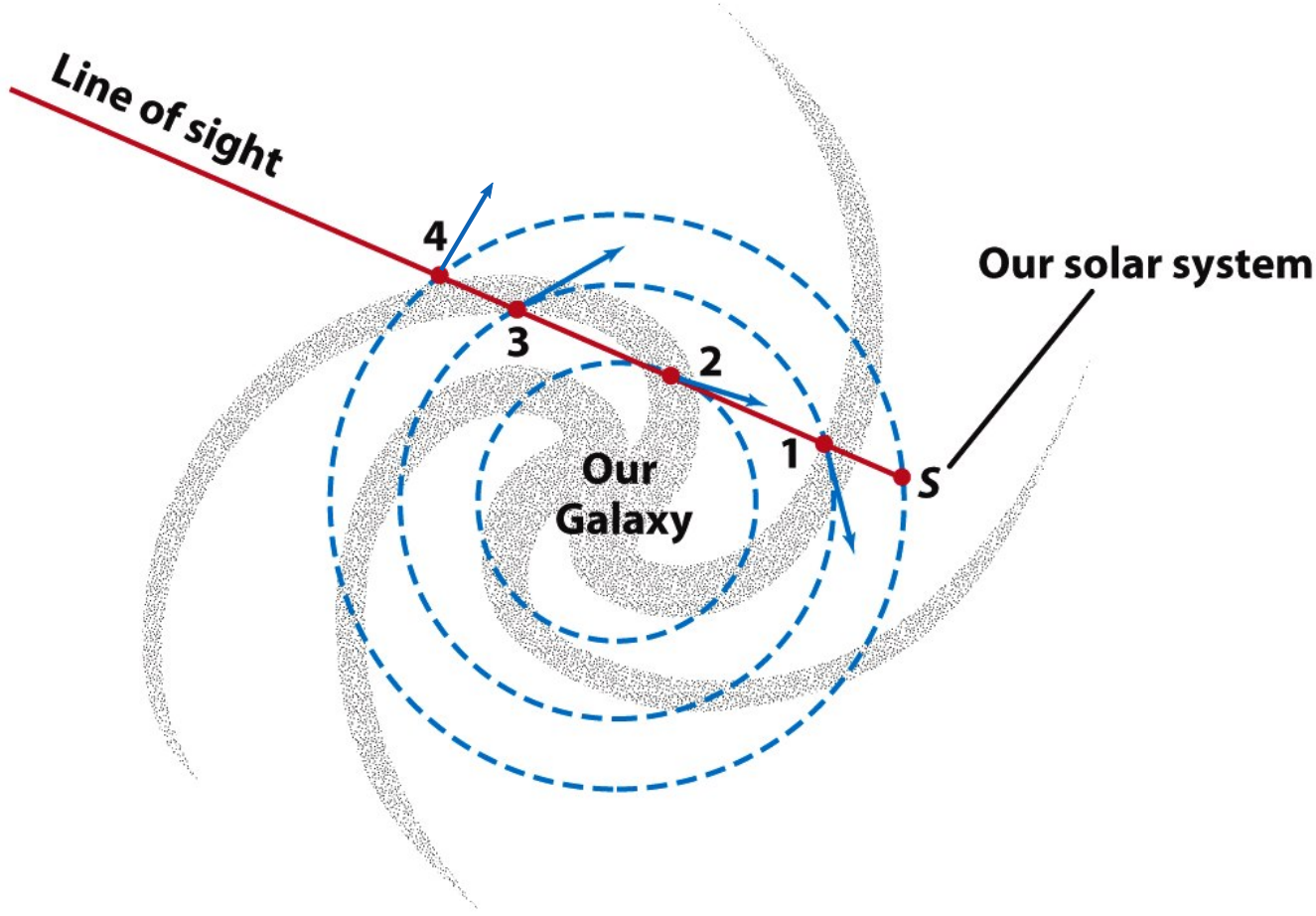
Disk's spiral structure



The structure of the Milky Way's disk

Figure 23-16a

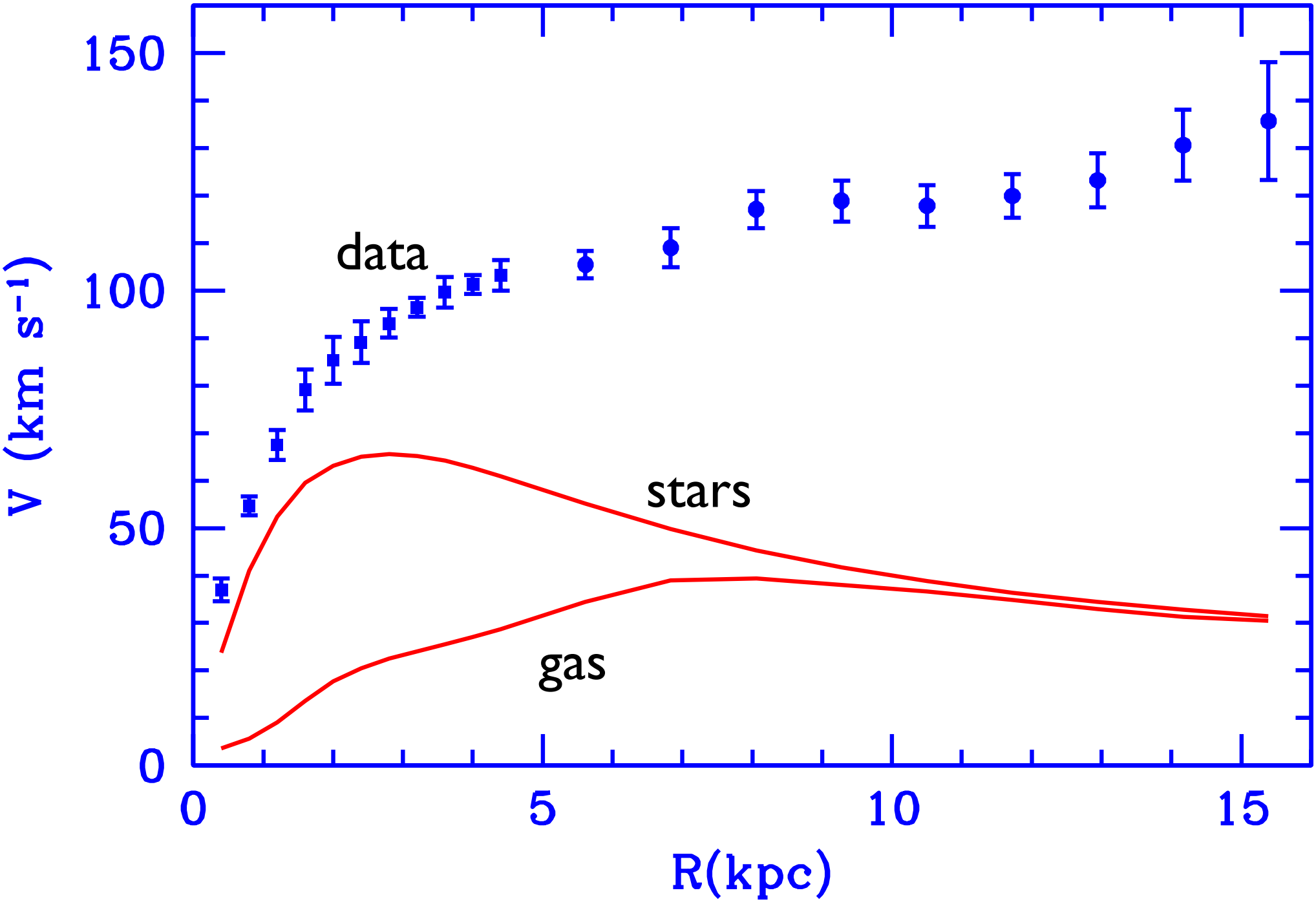
Reconstructing spiral arms from 21cm



- Hydrogen clouds 1 and 3 are approaching us: They have a moderate blueshift.
- Hydrogen cloud 2 is approaching us at a faster speed: It has a larger blueshift.
- Hydrogen cloud 4 is neither approaching nor receding: It has no redshift or blueshift.

Figure 23-13
Universe, Eighth Edition

M33 Rotation Curve



Galaxy rotation curves

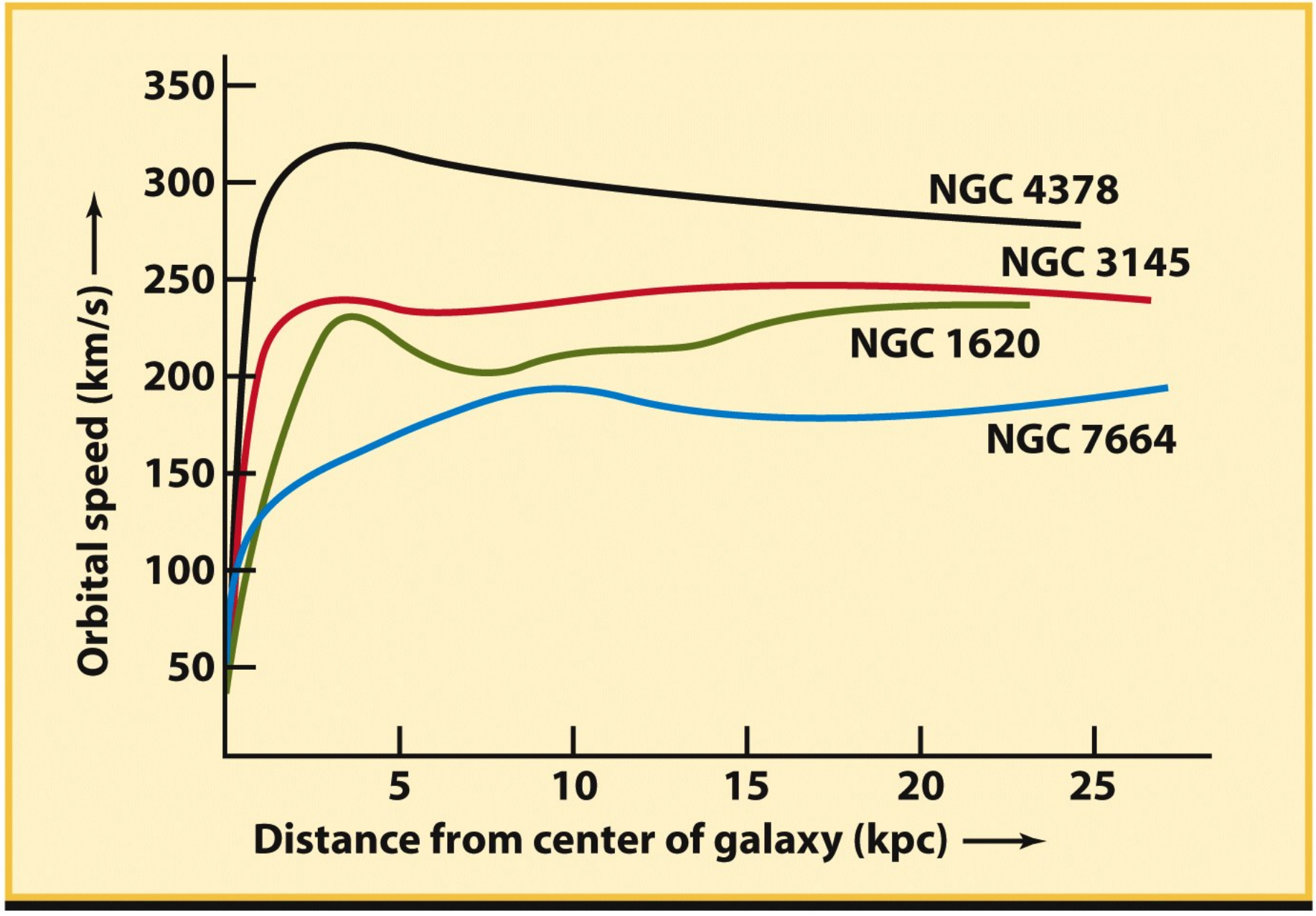


Figure 24-29
Universe, Eighth Edition

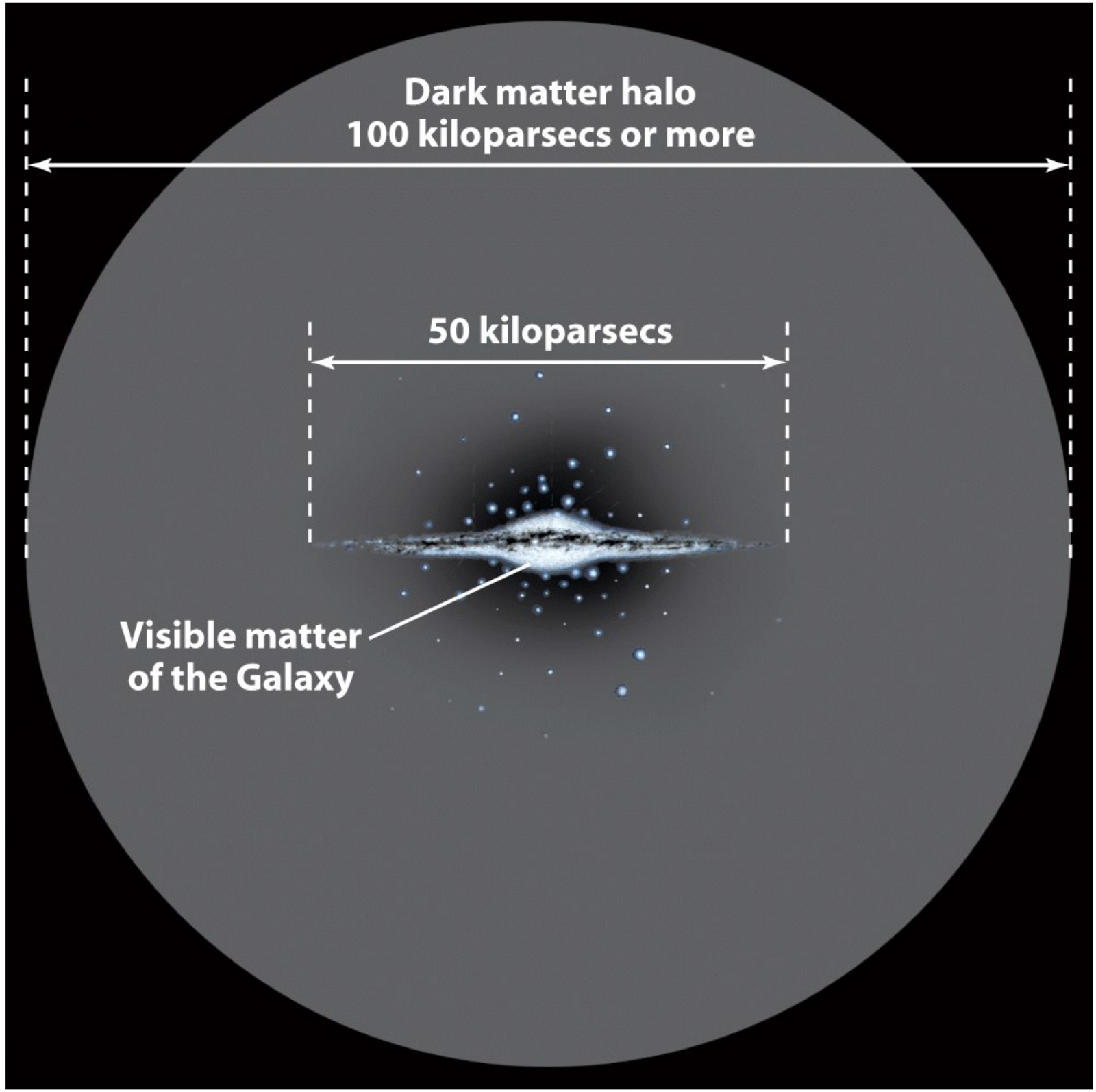
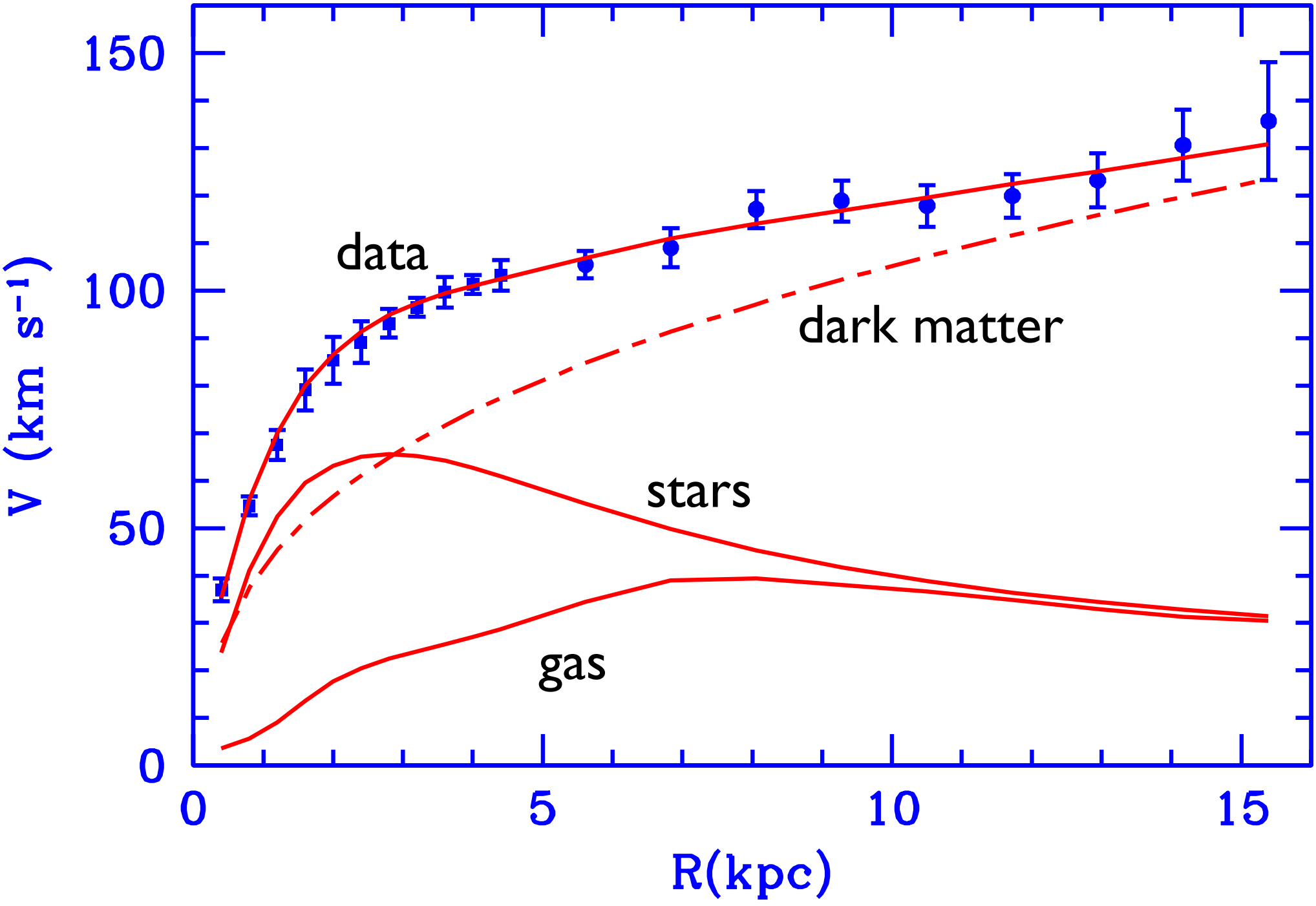

Dark matter halo
100 kiloparsecs or more
50 kiloparsecs
Visible matter
of the Galaxy

Figure 23-19

M33 Rotation Curve



Dark Matter Clues

1. Galaxies in the galaxy clusters move faster than expected

2. The outer parts of spiral galaxies rotate faster than expected

3. Dark matter doesn't form compact objects.

MACHO = MAssive Compact Halo Object

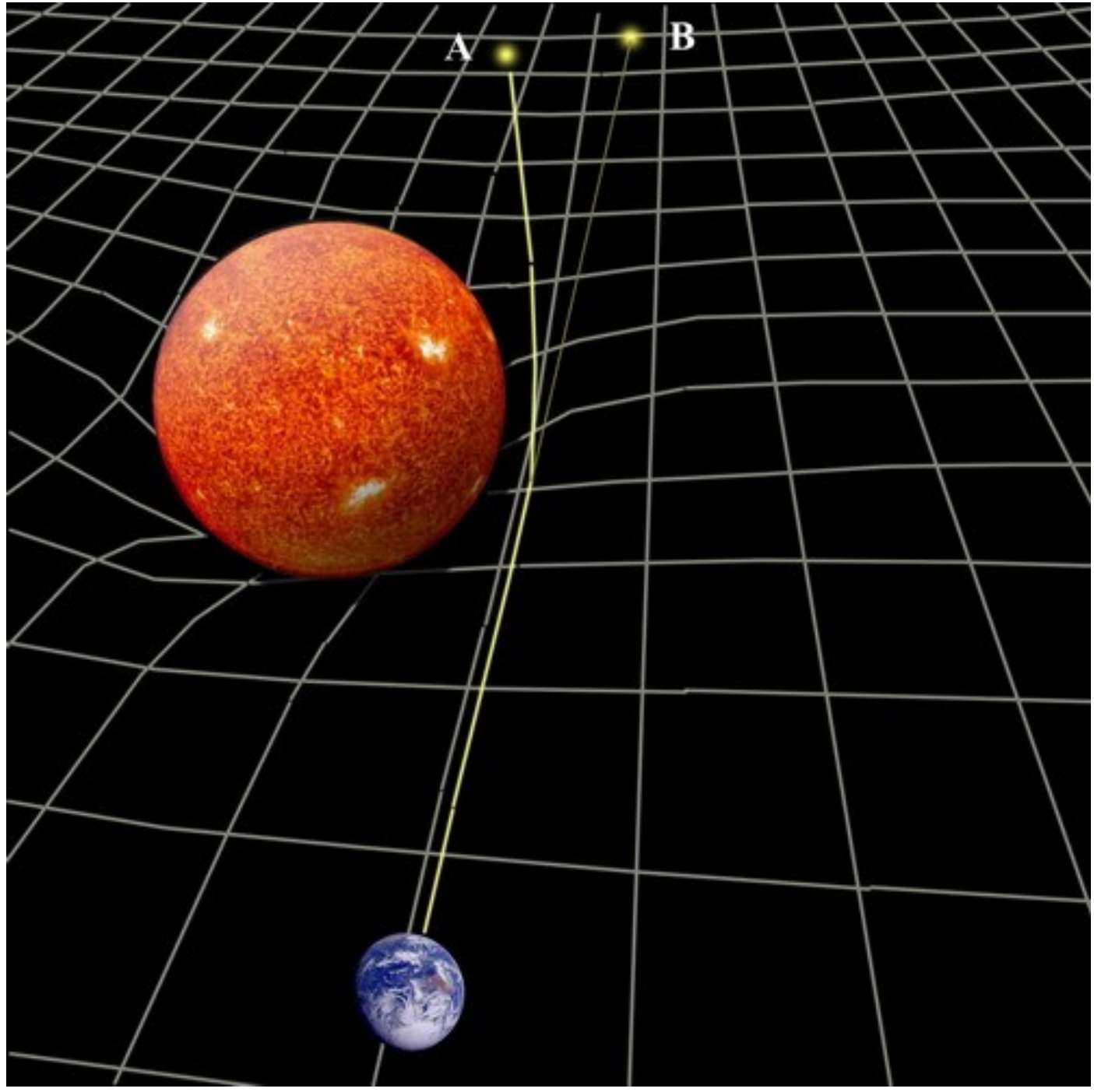
"big objects" : brown dwarfs, black holes, old white dwarf or neutron stars, rogue planets

... observe with gravitational lensing

WIMP = Weakly Interacting Massive Particle

subatomic particle yet unknown to physics

Gravity = curvature of spacetime.



Looking for MACHOs

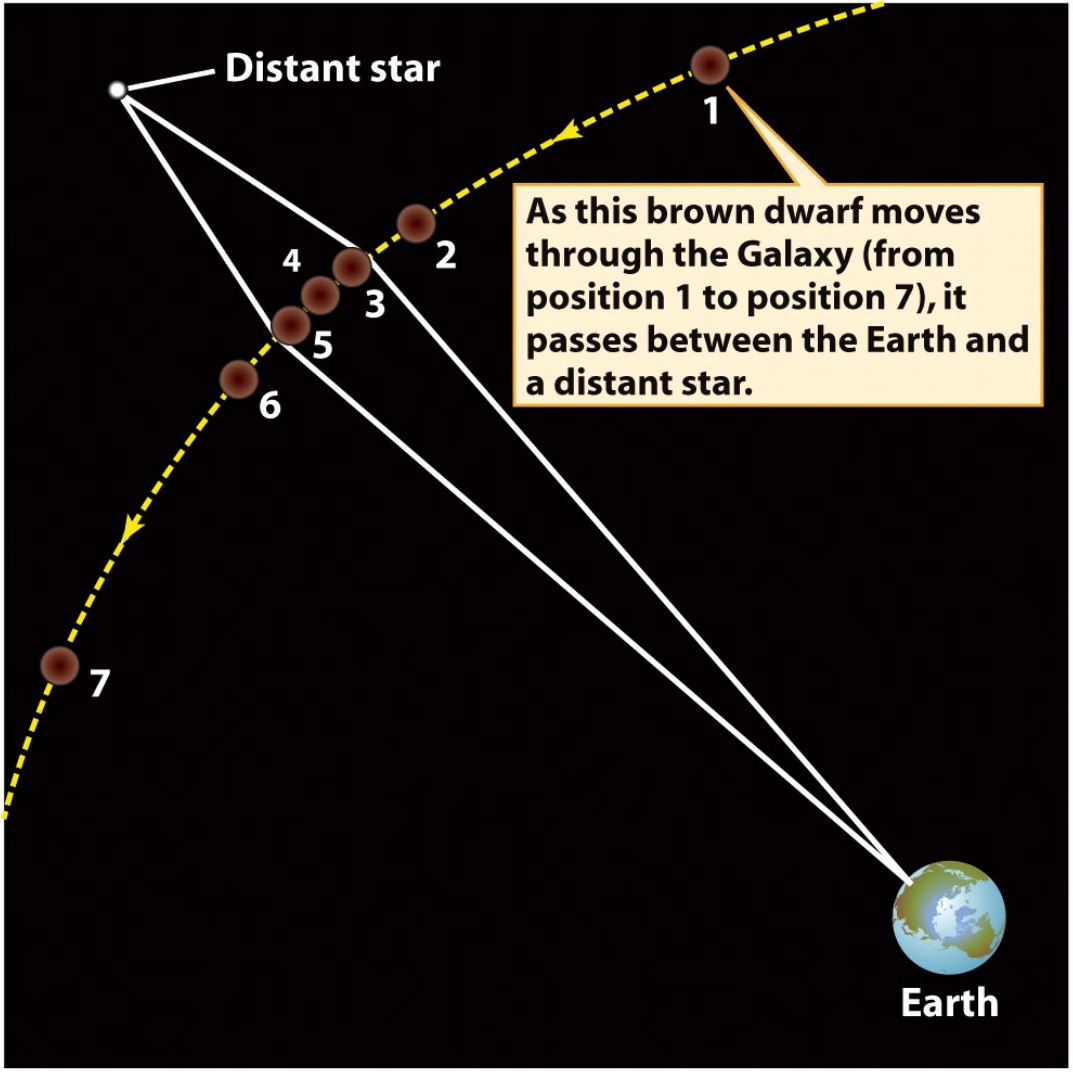


Figure 23-20a
Universe, Eighth Edition

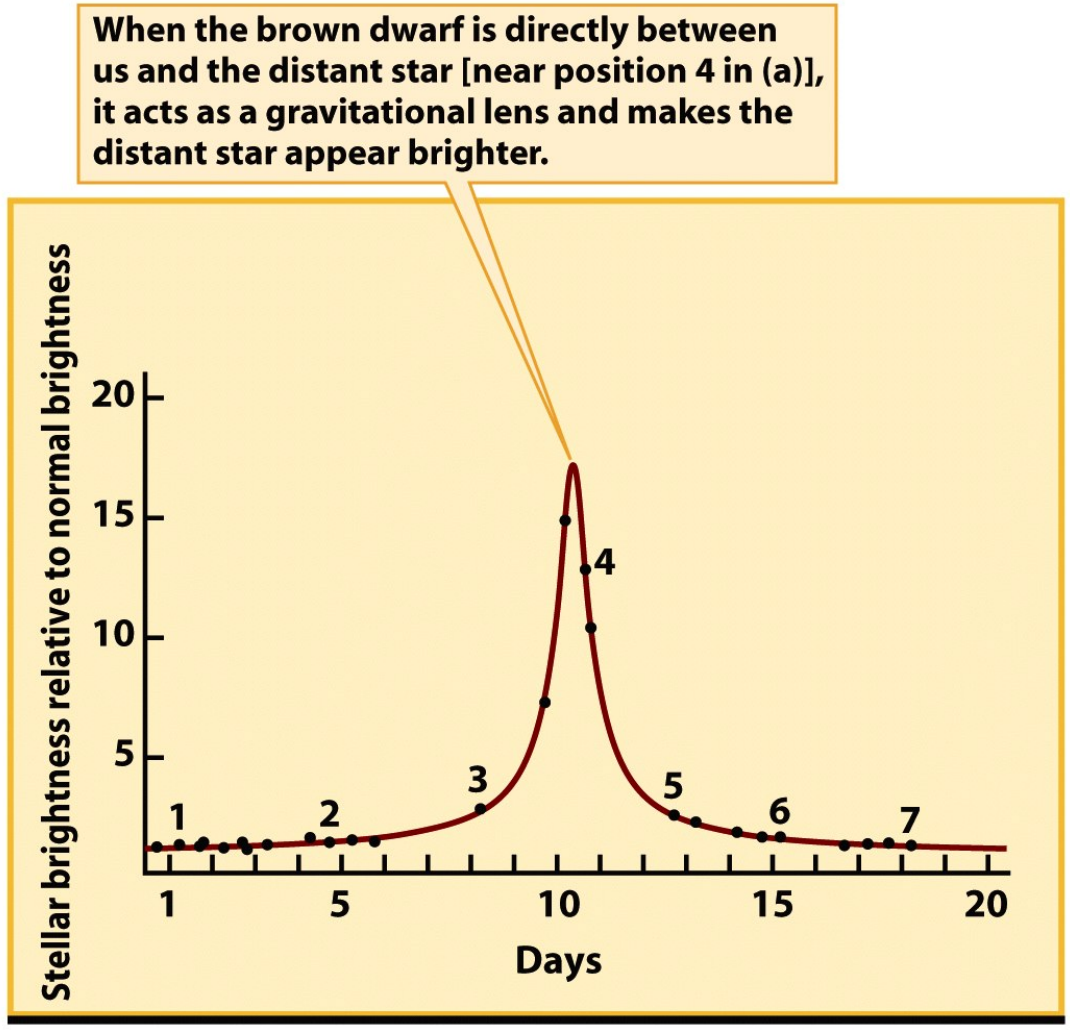


Figure 23-20b
Universe, Eighth Edition

Microlensing is observed, but...

... is too rare and too small for MACHOs to be a significant portion of the dark matter

Dark Matter Clues

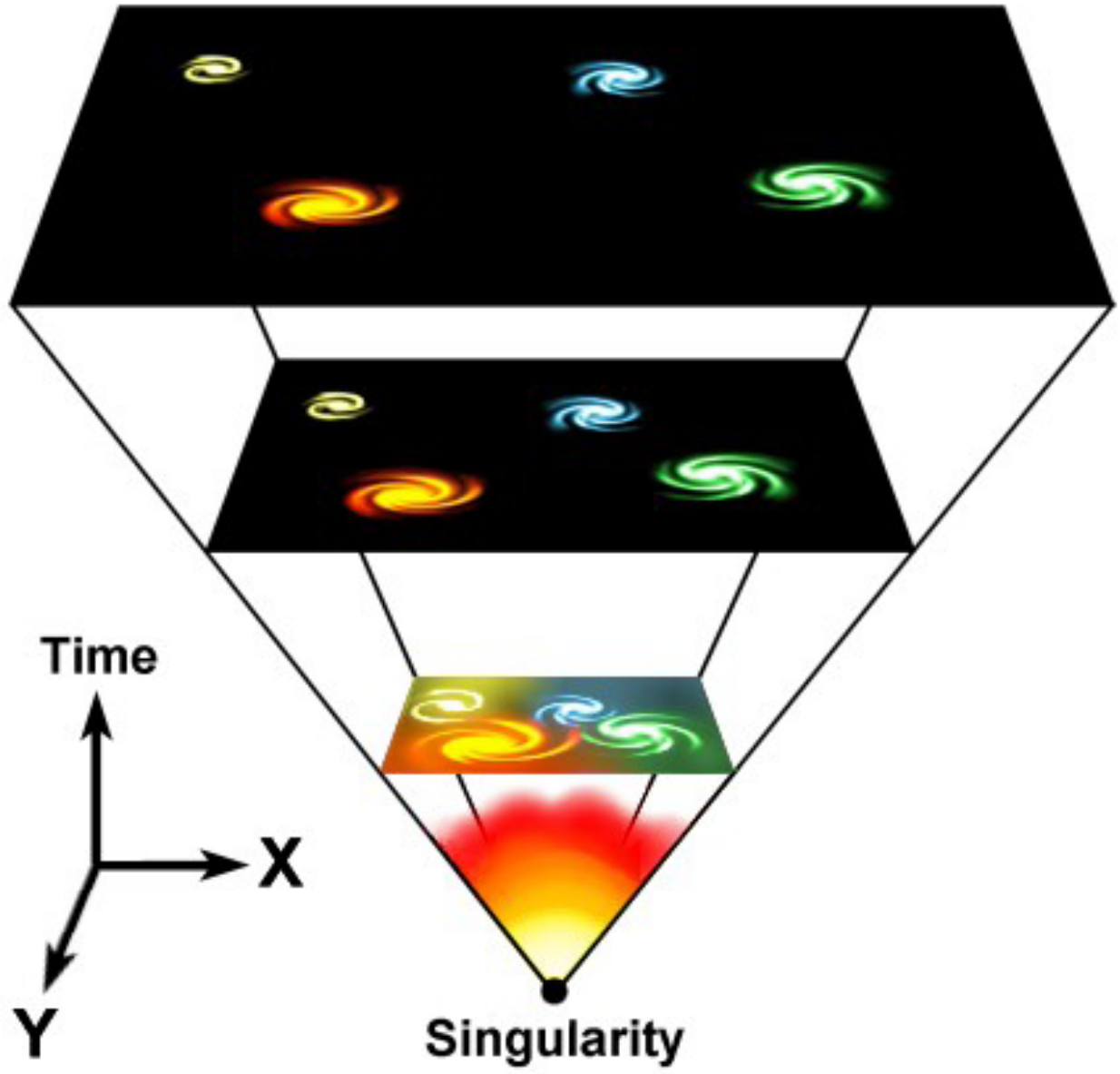
1. Galaxies in the galaxy clusters move faster than expected

2. The outer parts of spiral galaxies rotate faster than expected

3. Dark matter doesn't form compact objects.

4. Dark matter doesn't interact with gas (it's not atoms!)

Expanding universe & the Big Bang



Thermal history of the Universe

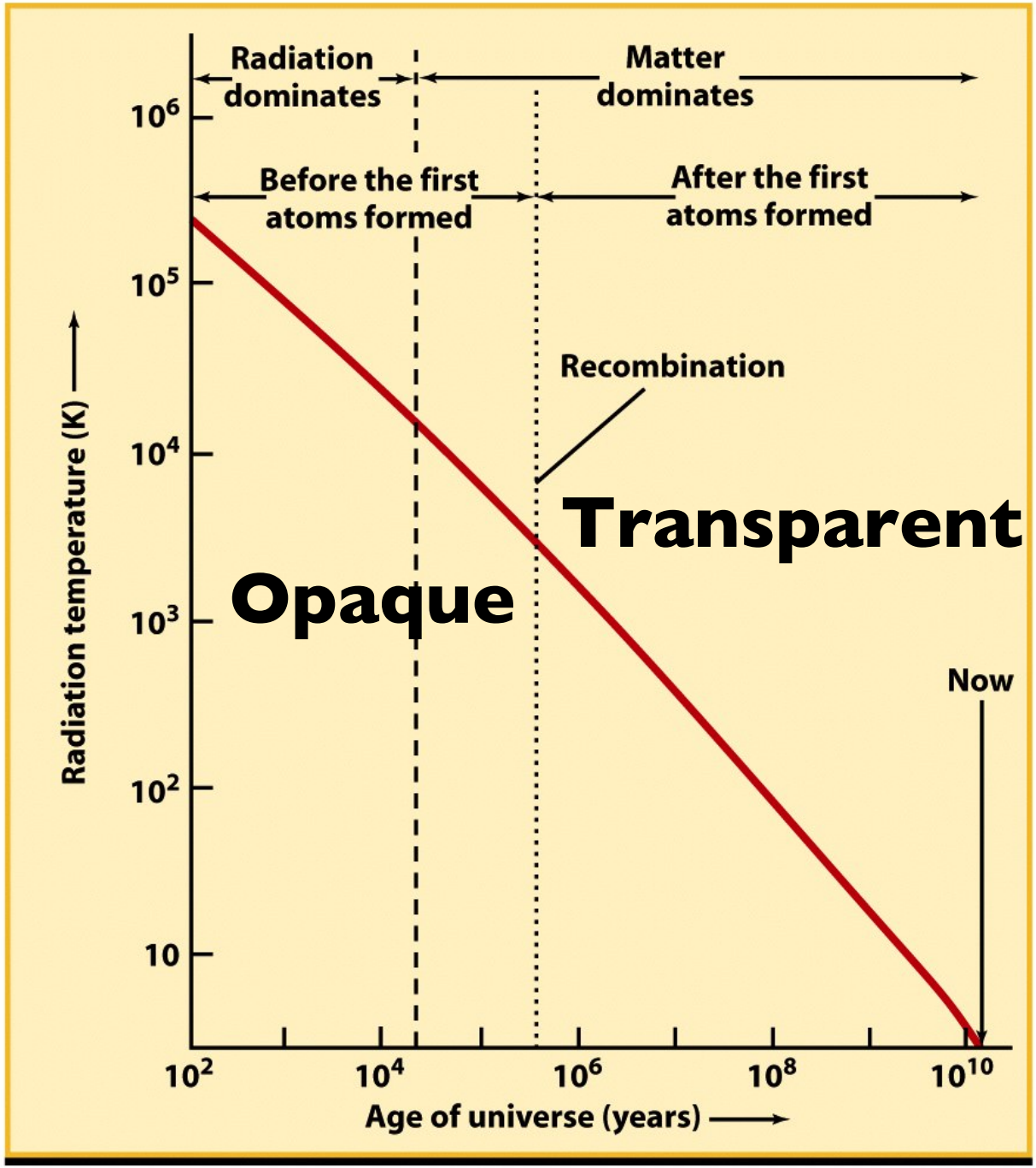
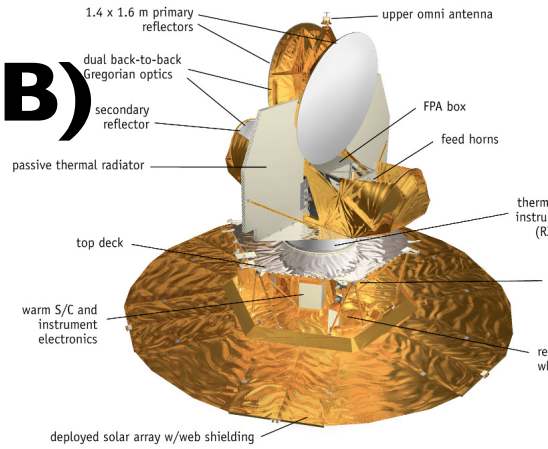


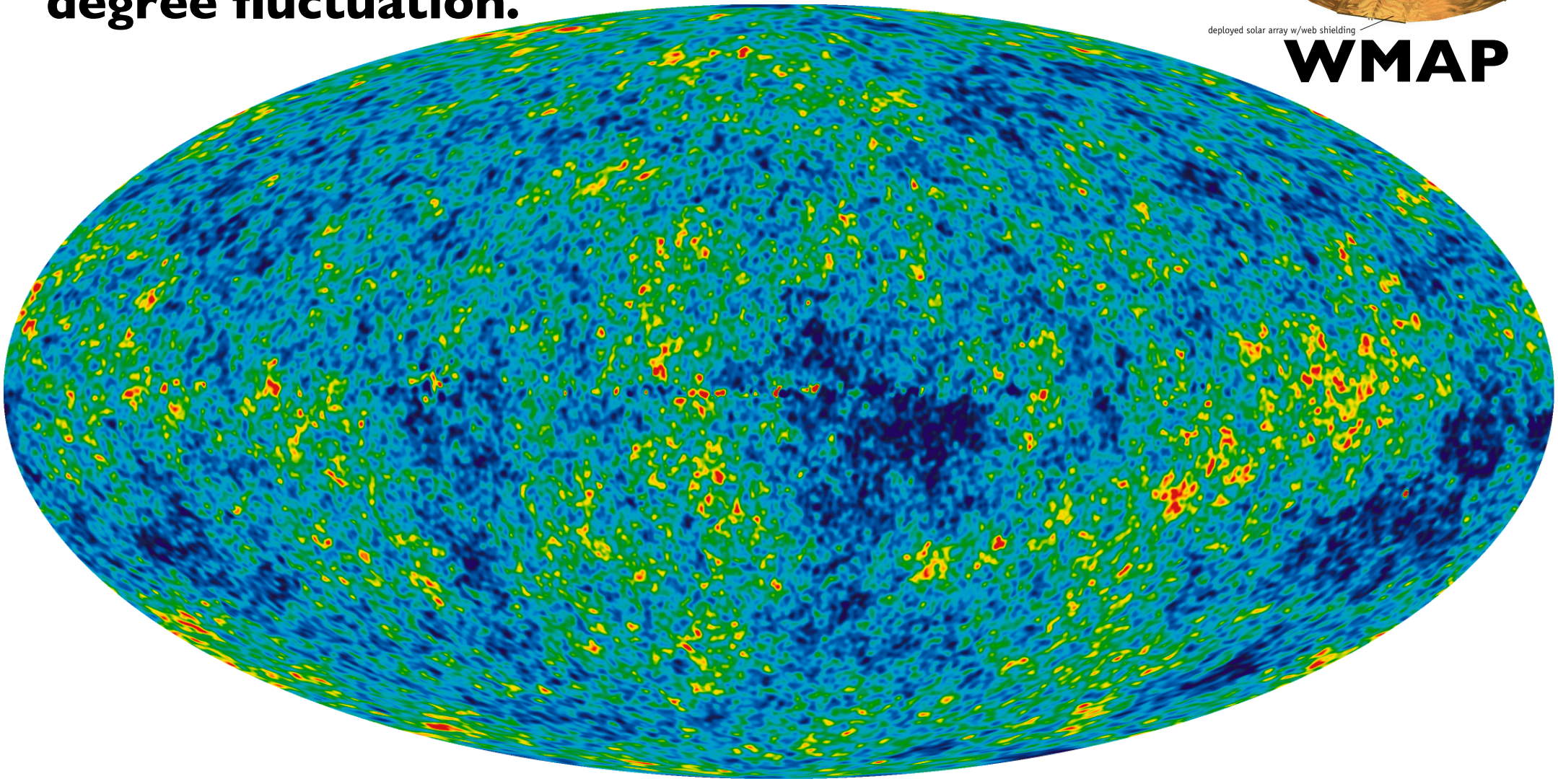
Figure 26-11
Universe, Eighth Edition

Cosmic Microwave Background (CMB)



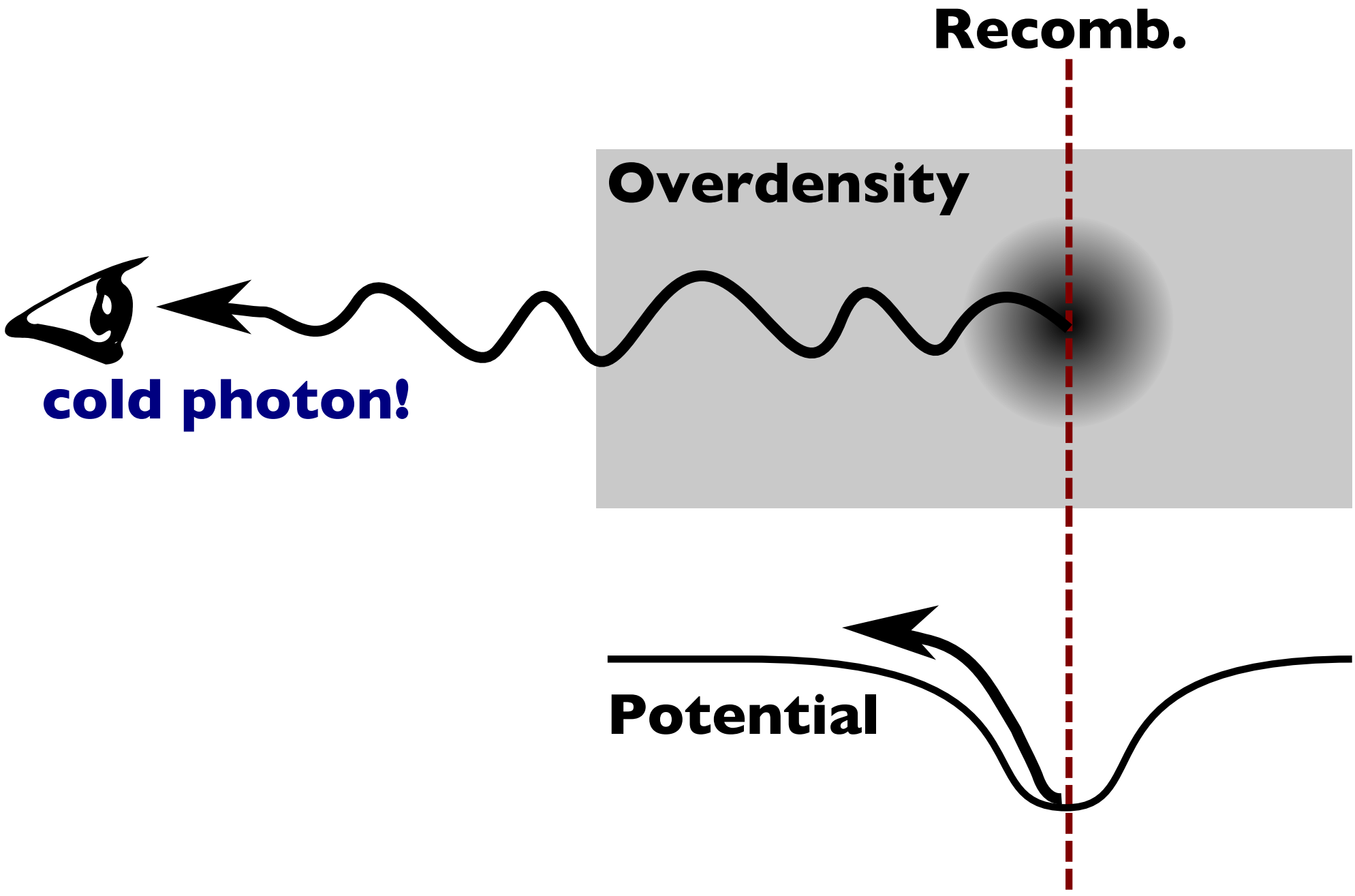
WMAP

Few ten-thousands of a degree fluctuation.

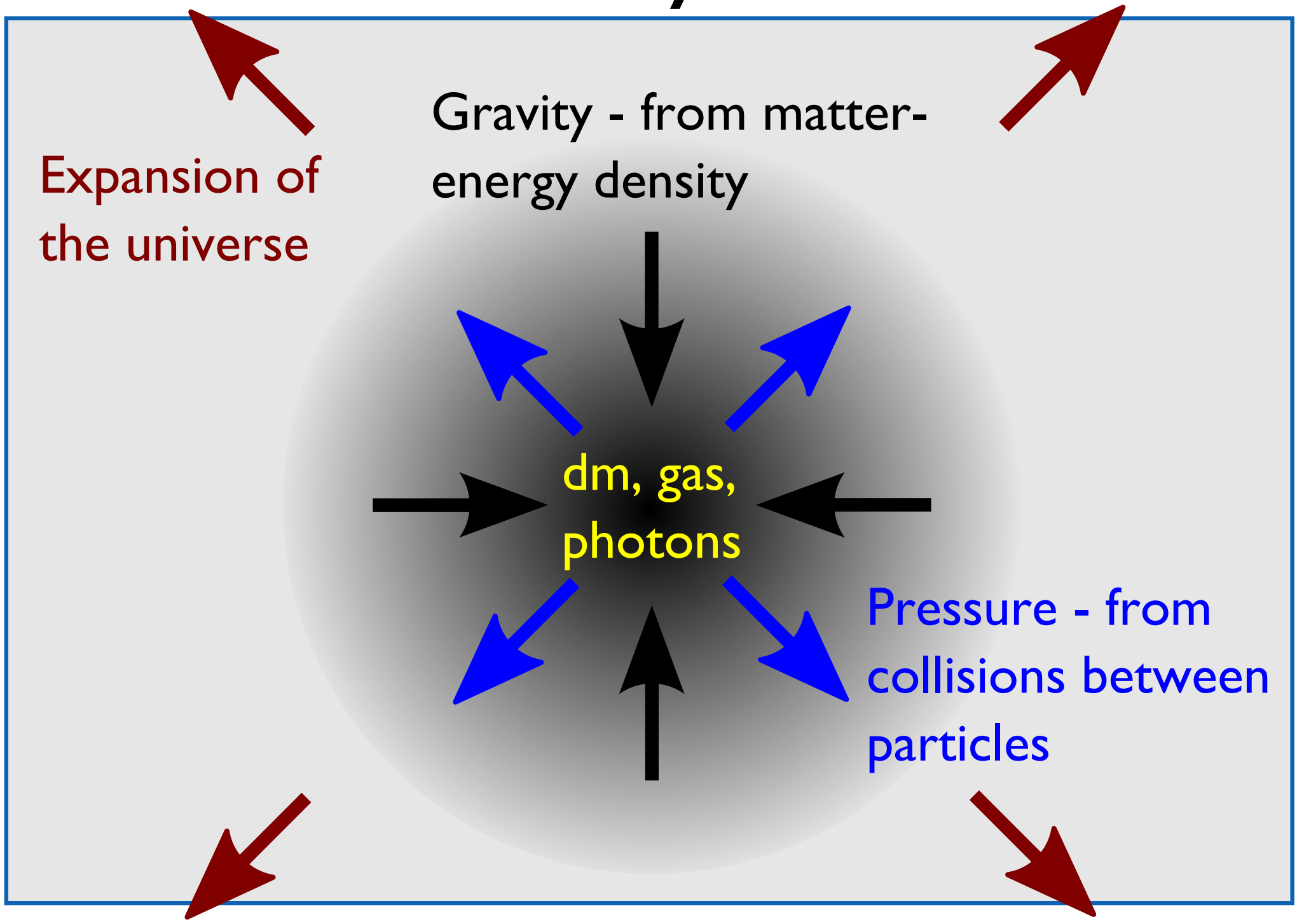


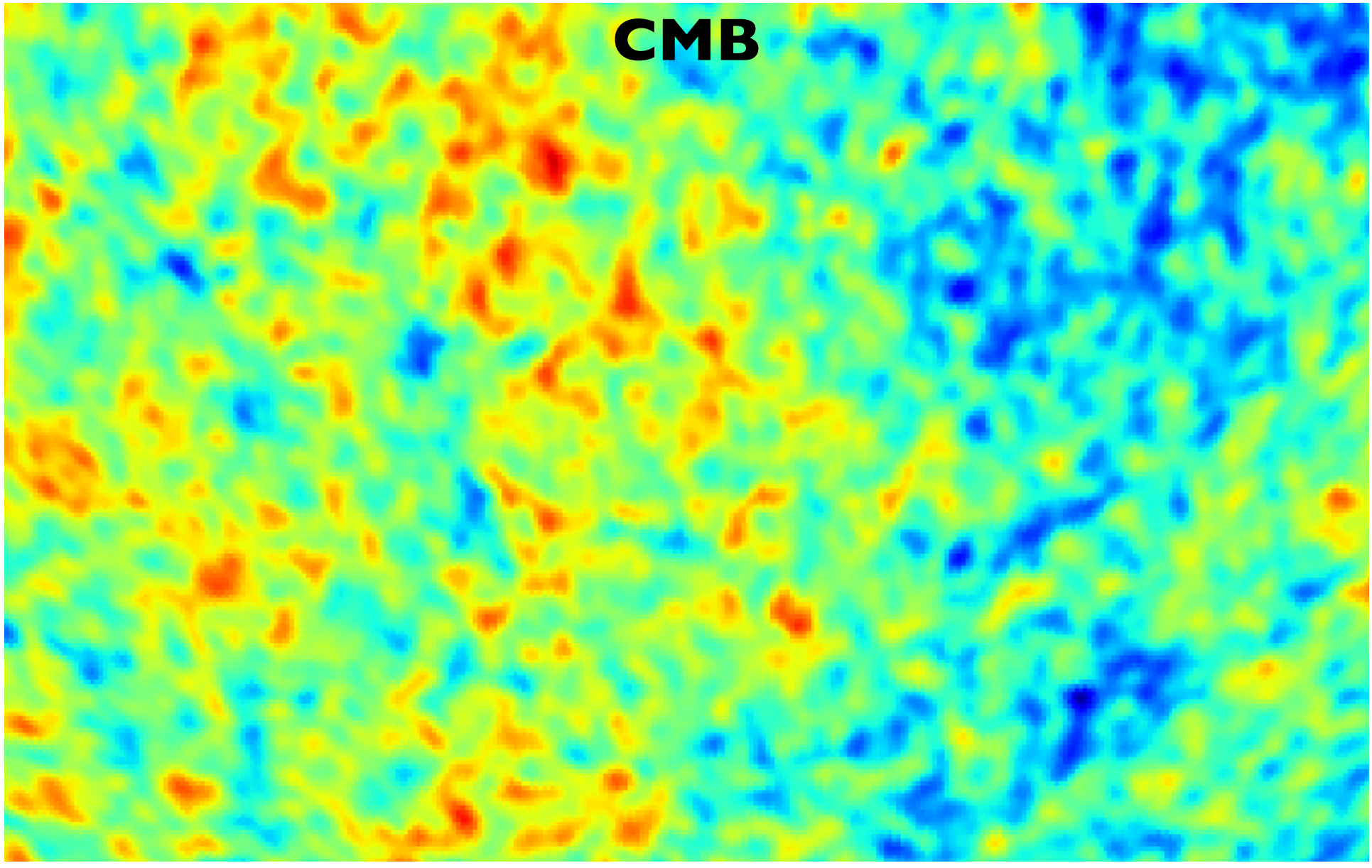
info on grav. potential @ recombination

Probing gravitational potential



Forces on an overdensity





Statistics of hot/cold spots

Normal matter has gravity, exerts pressure

Dark matter has gravity, no pressure

Dark Matter Clues

1. Galaxies in the galaxy clusters move faster than expected.

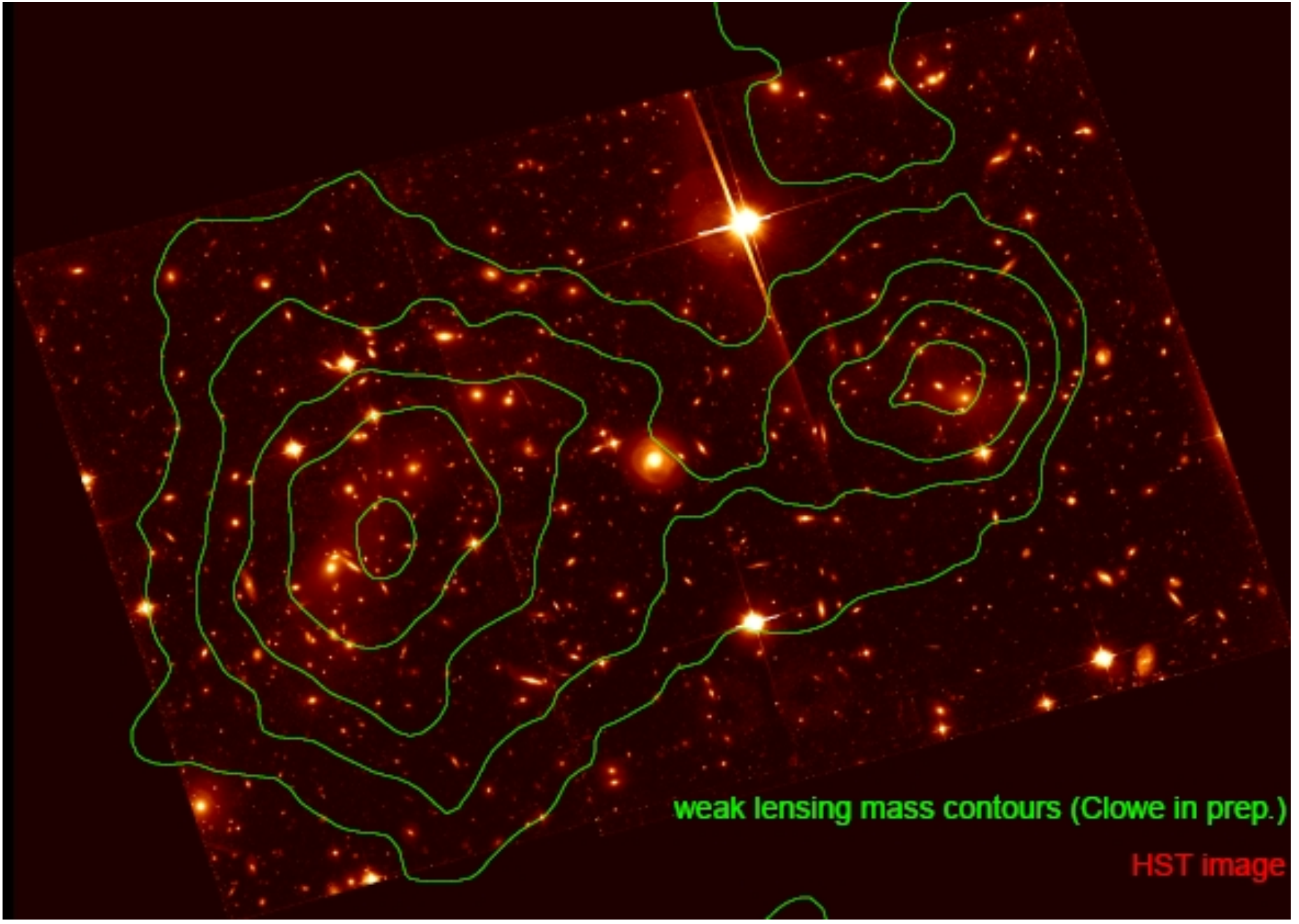
2. The outer parts of spiral galaxies rotate faster than expected.

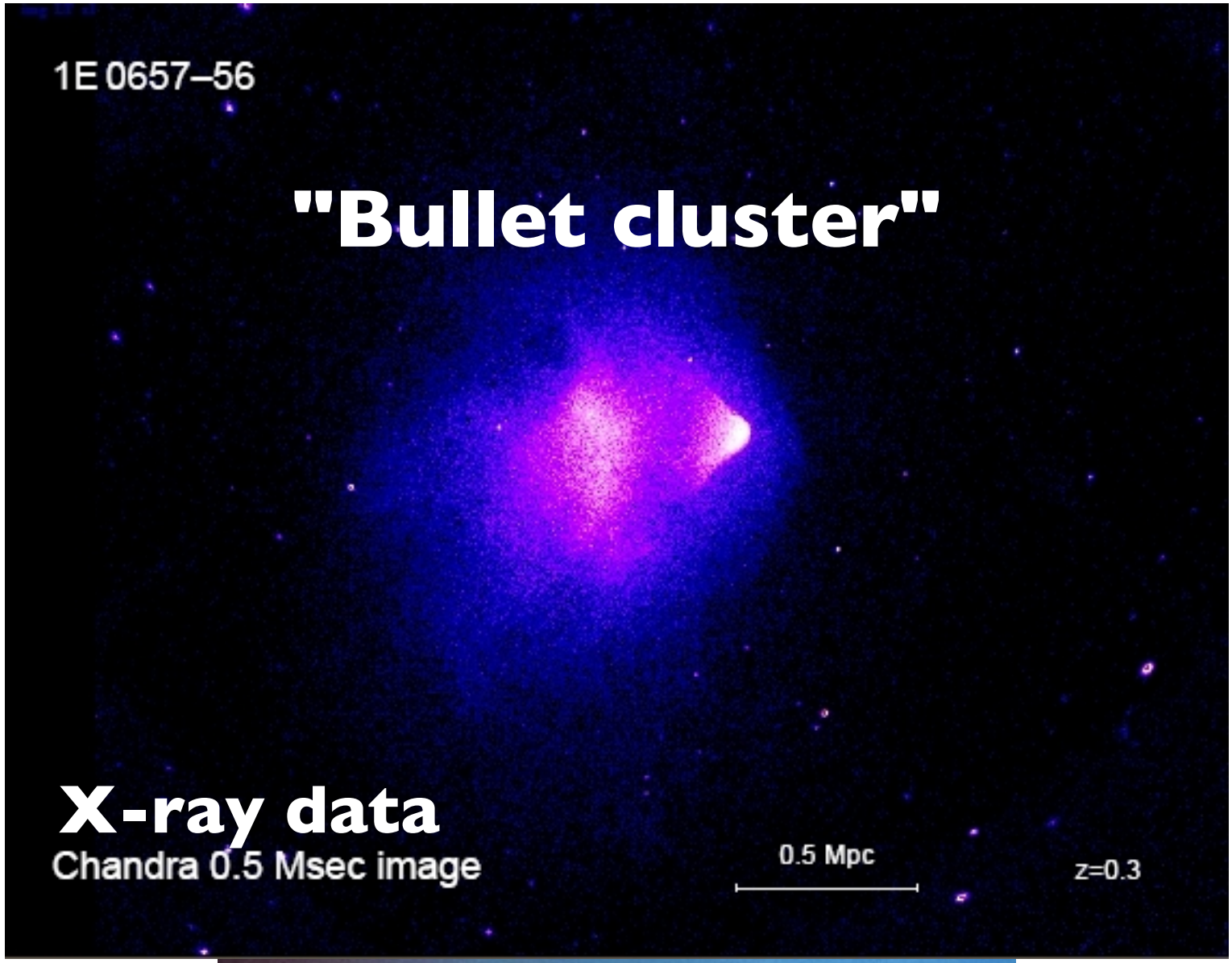
3. Dark matter doesn't form compact objects.

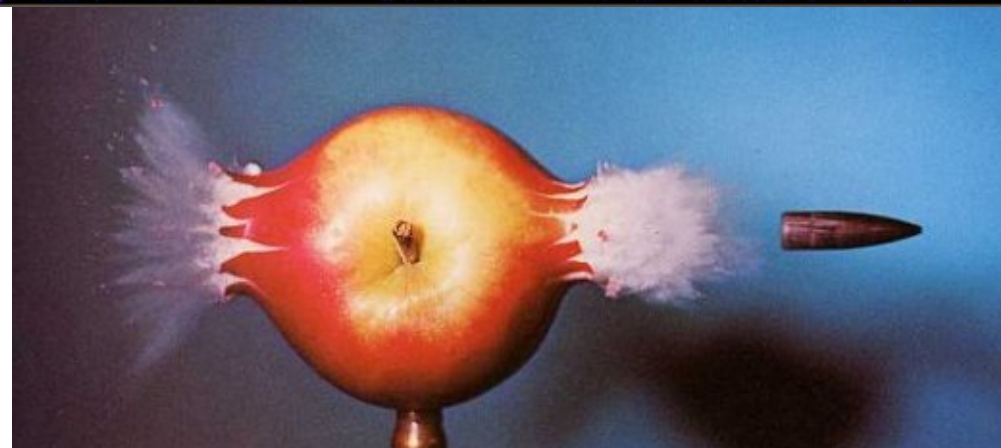
4. Dark matter doesn't interact with gas (it's not atoms!)

5. Dark matter hardly interacts with itself, if at all.

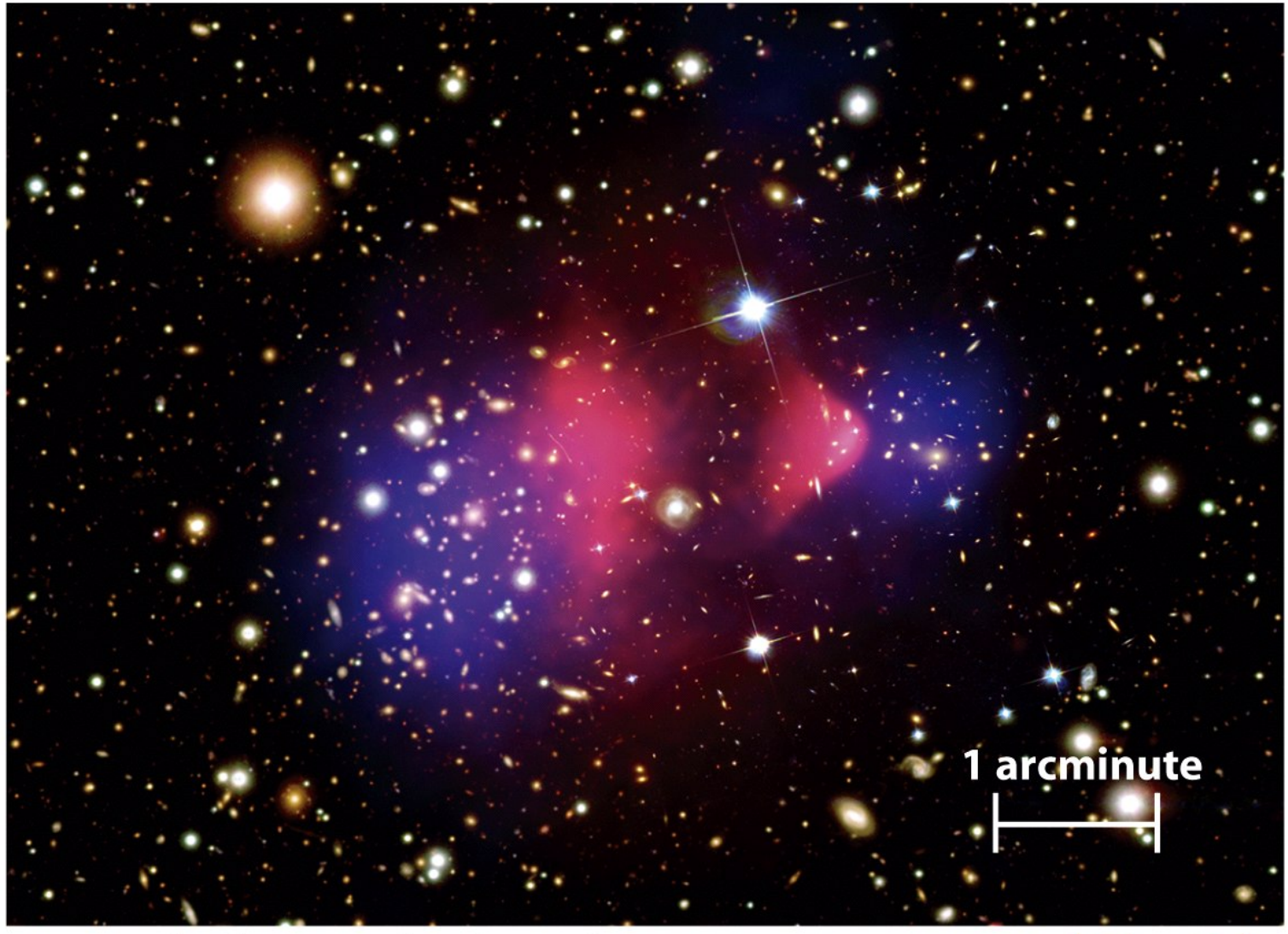
Lensing mass map




1E 0657–56
"Bullet cluster"
X-ray data
Chandra 0.5 Msec image
0.5 Mpc
z=0.3



Bullet cluster



Composite image of galaxy cluster 1E0657-56 showing visible galaxies, X-ray-emitting gas (red) and dark matter (blue)

R I V U X G

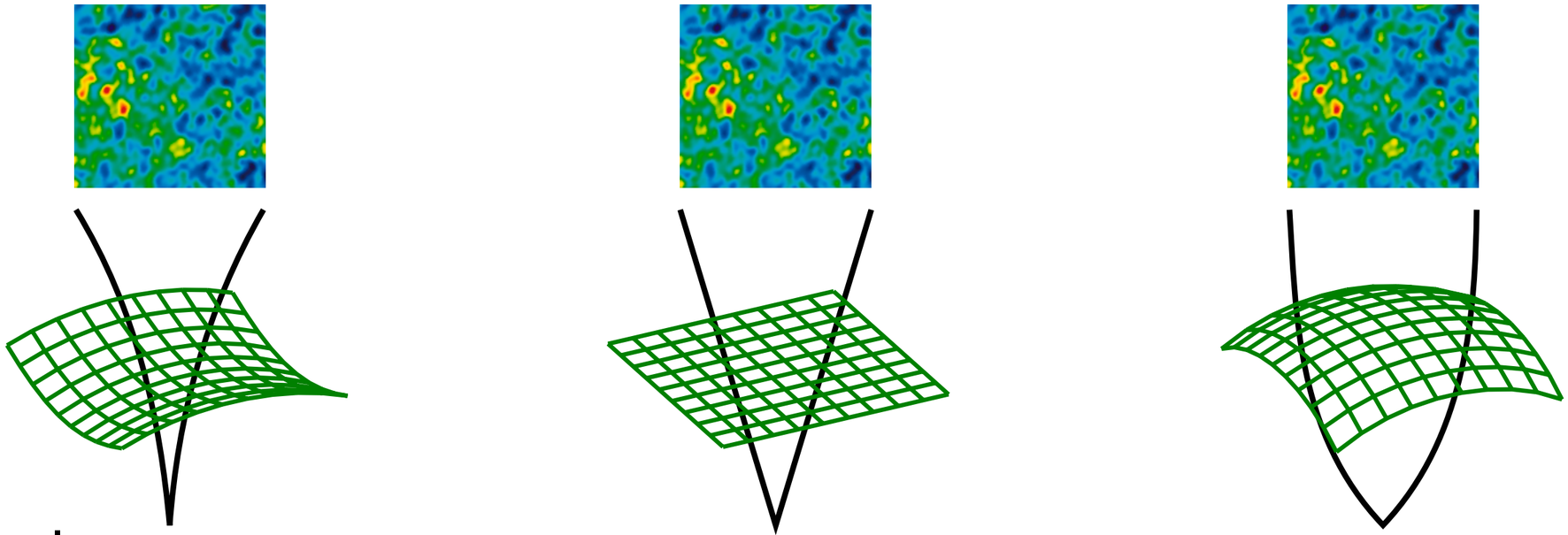
Figure 24-32a
Universe, Eighth Edition

Dark Energy Clues

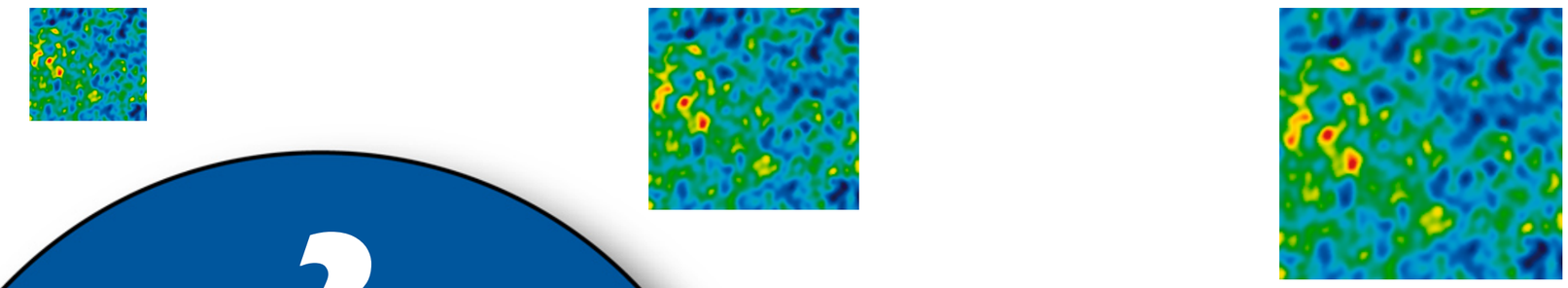
1. The universe contains much more mass-energy density than just normal and dark matter

Measuring curvature (= weighing the universe)

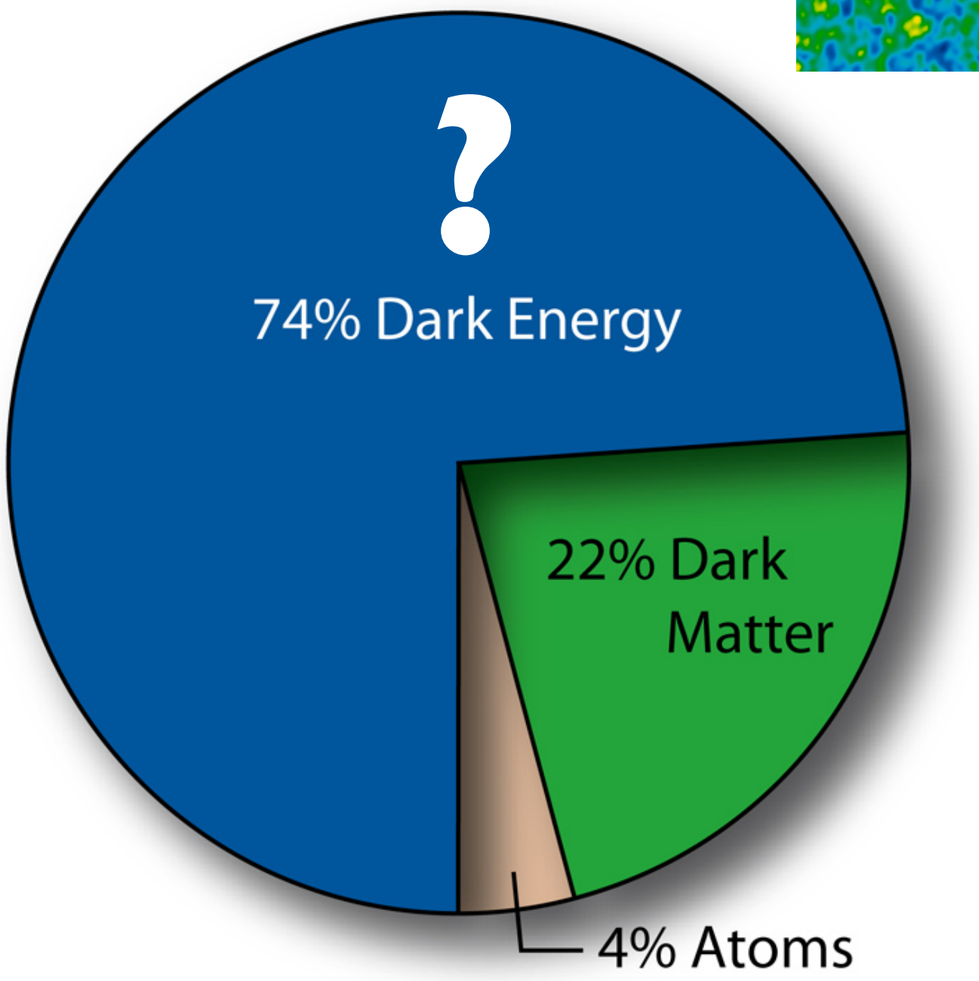
CMB surface



CMB observed



CMB Data:



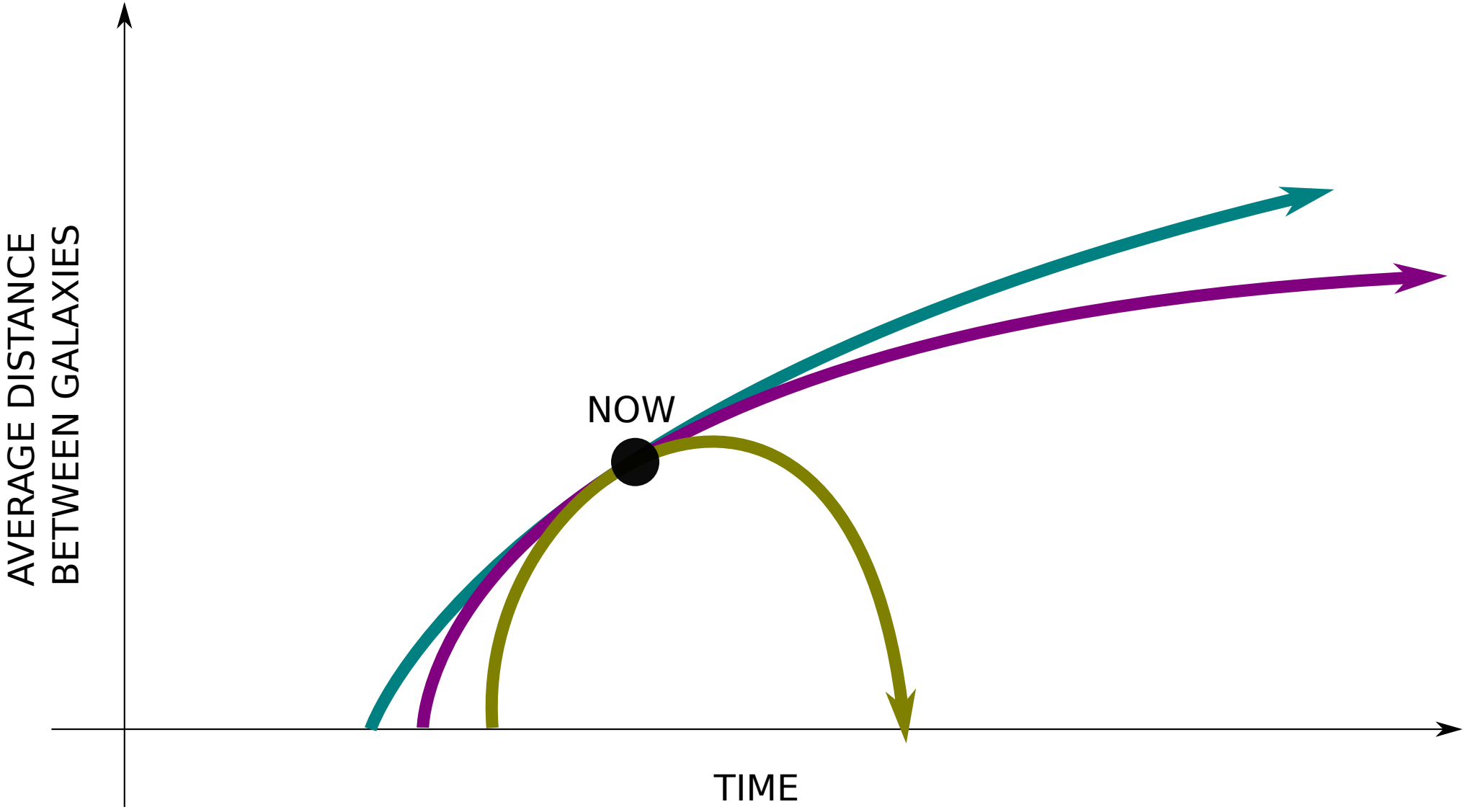
Dark Energy Clues

1. The universe contains much more mass-energy density than just normal and dark matter

2. The universe's expansion is accelerating!

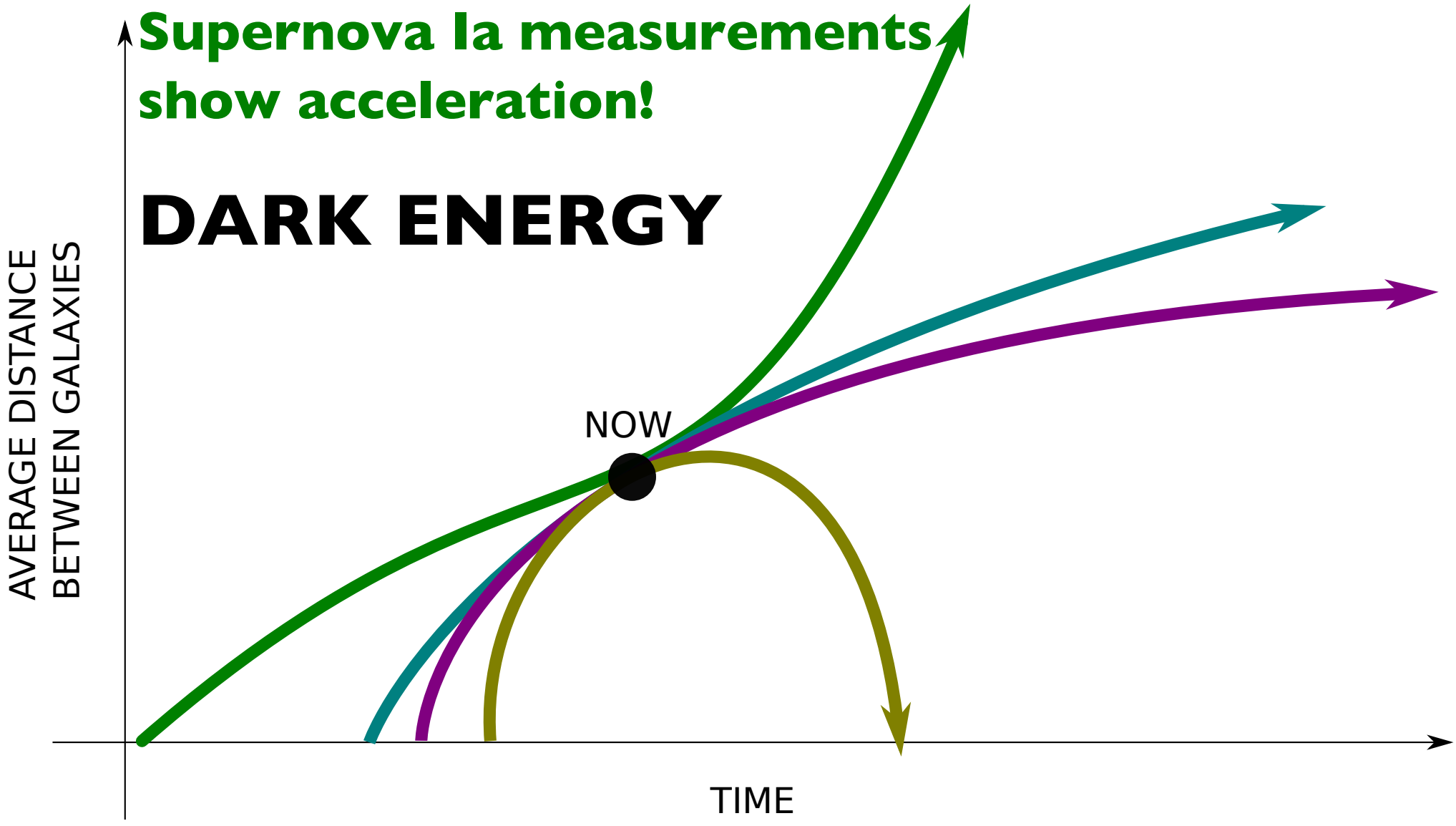
Expansion history/future

... based on Einstein's model for gravity.



Expansion history/future

... based on Einstein's model for gravity.



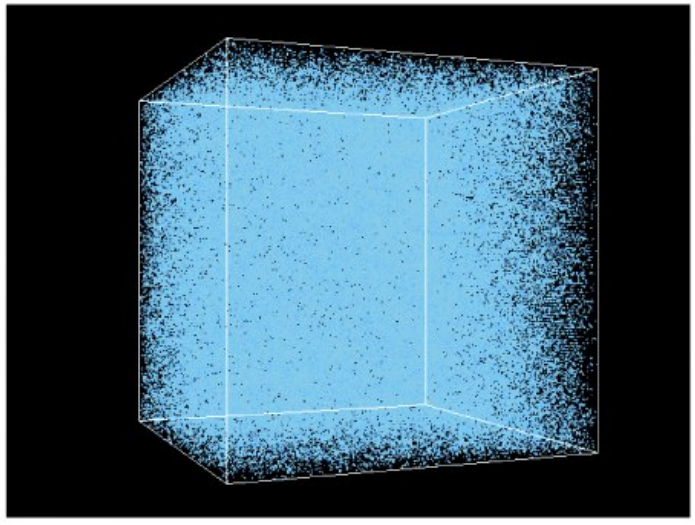
Dark Energy Clues

1. The universe contains much more mass-energy density than just normal and dark matter

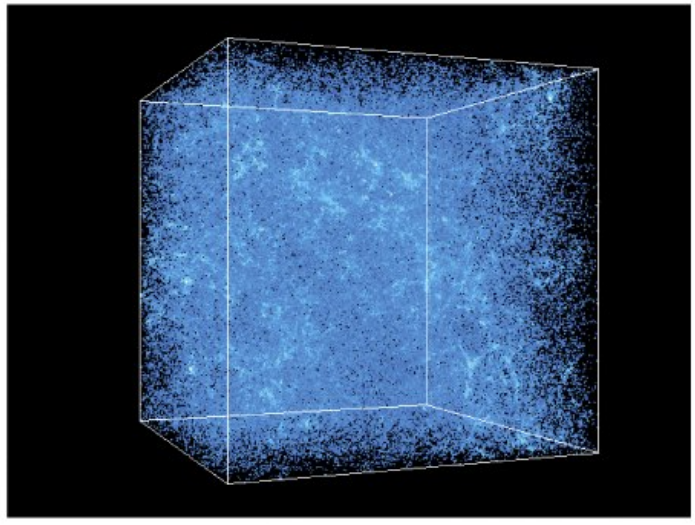
2. The universe's expansion is accelerating!

3. Structure formation slows down as the universe starts to accelerate.

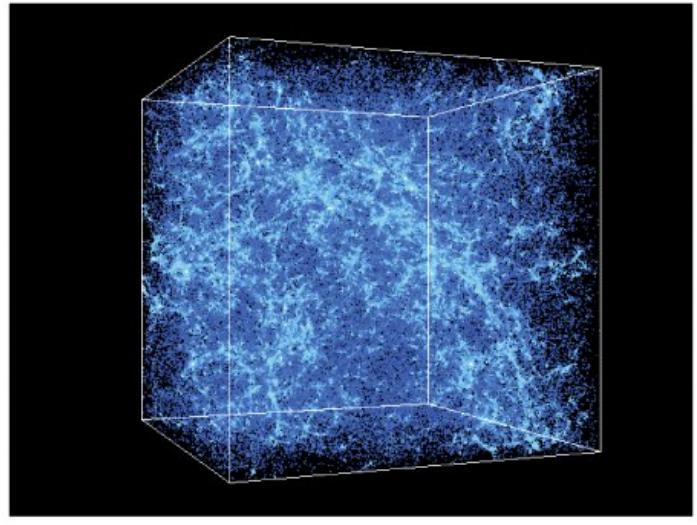
Cosmological matter simulation



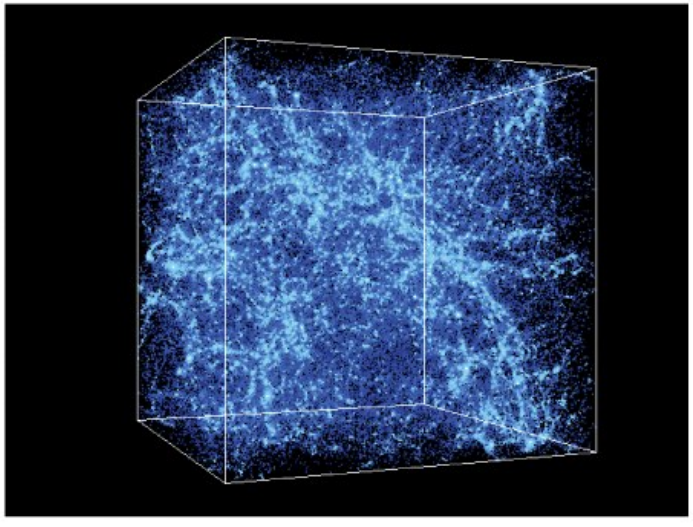
$z = 27.36$ Universe 120 million years old



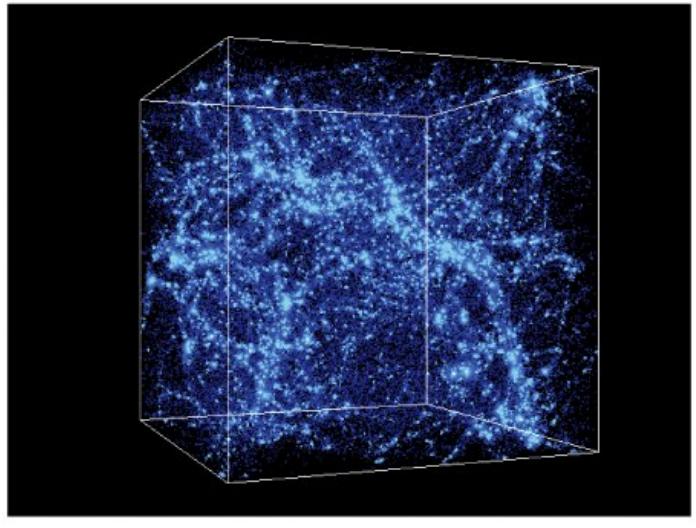
$z = 9.83$ Universe 490 million years old



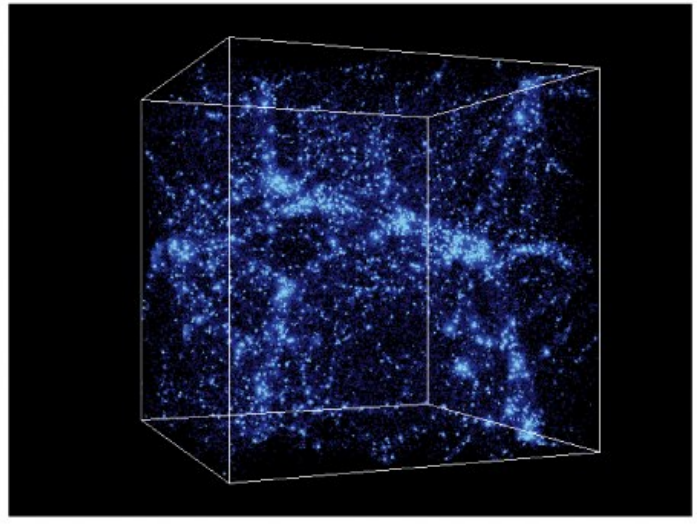
$z = 4.97$ Universe 1.2 billion years old



$z = 2.97$ Universe 2.2 billion years old



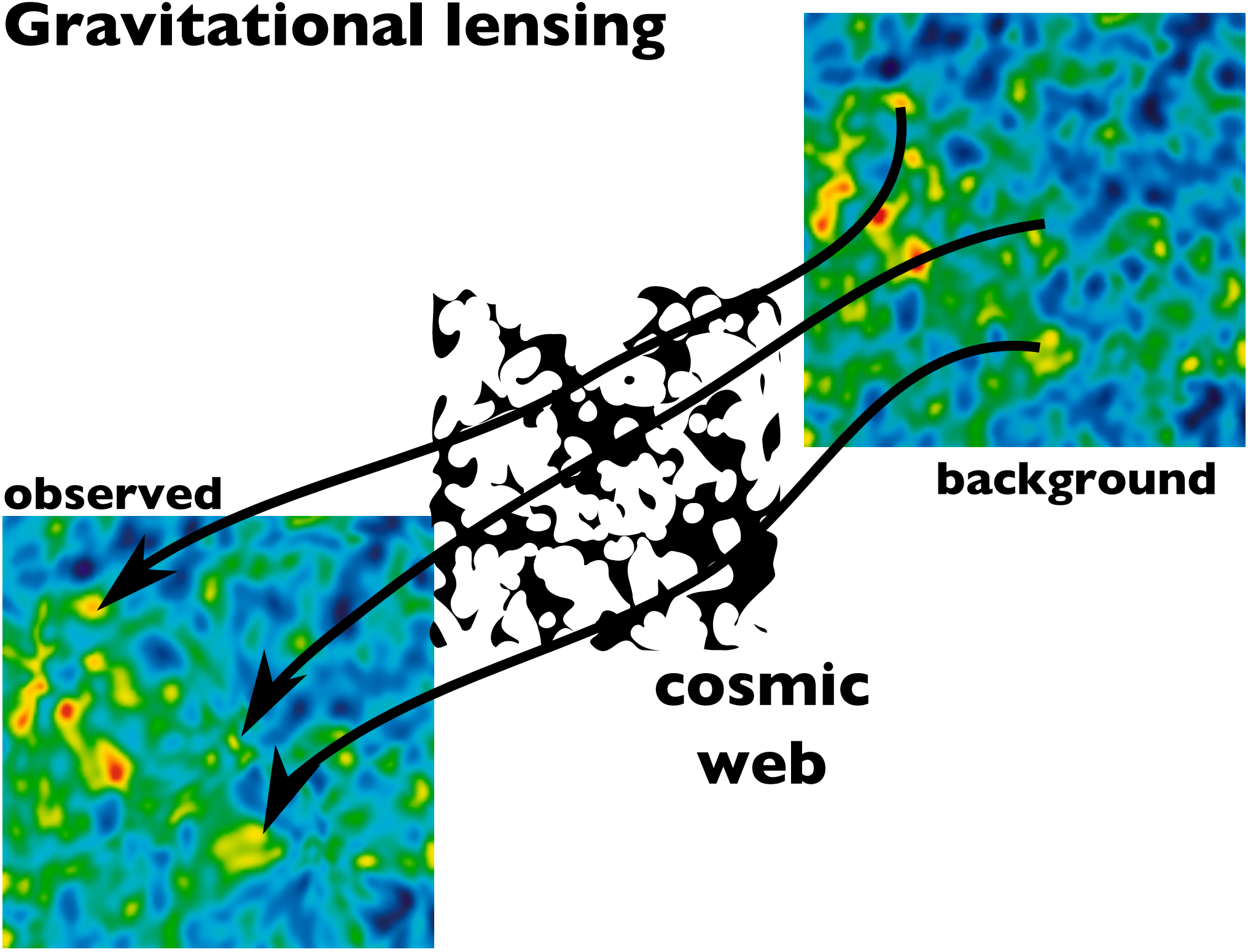
$z = 0.99$ Universe 6.0 billion years old



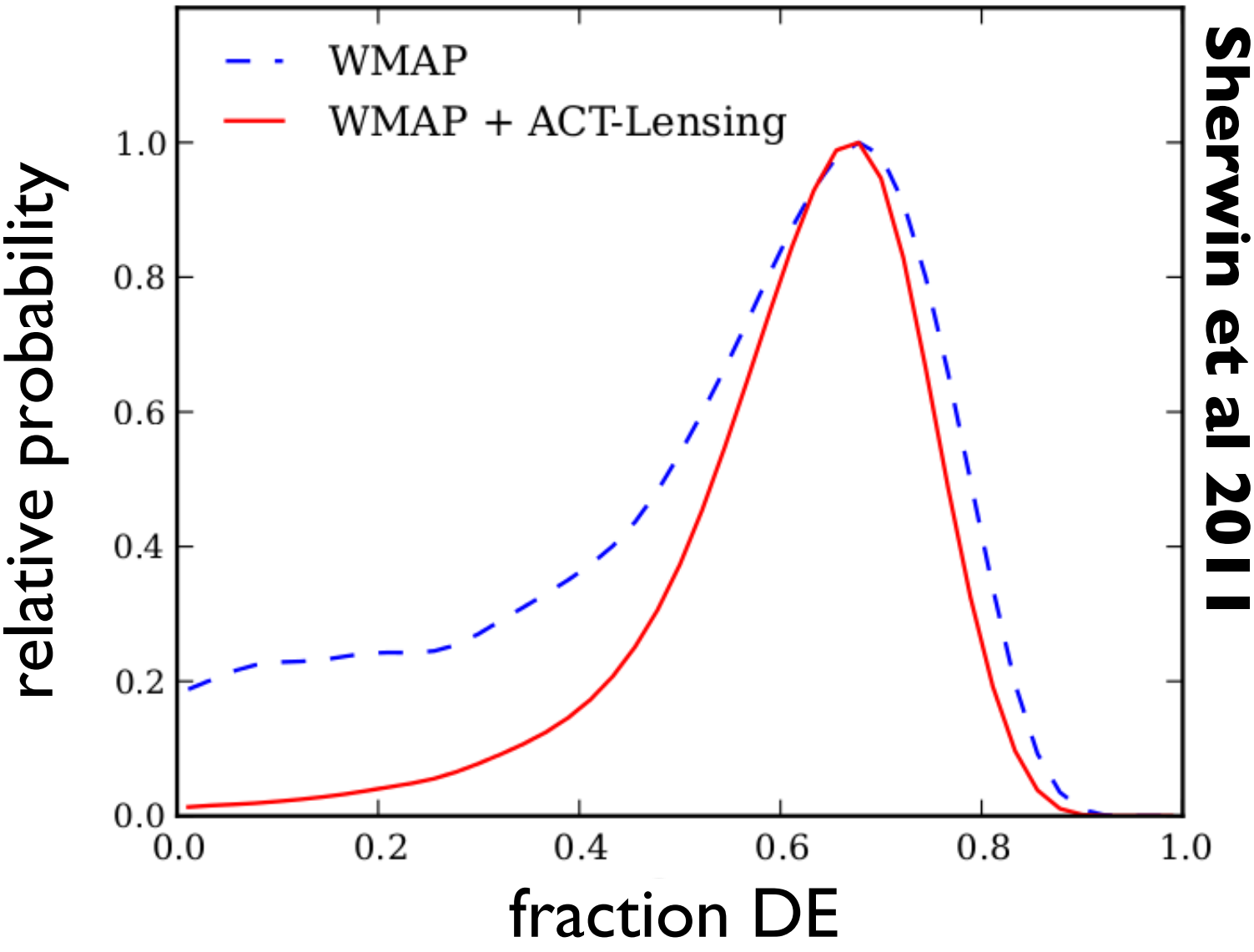
$z = 0.00$ Universe 13.7 billion years old

Figure 27-15
Universe, Eighth Edition

Gravitational lensing



CMB-lensing result



Evidence for Dark Energy from CMB alone (w/out SN)

Conclusions

The universe is mostly (95%) made of unknown substances

Dark matter (20%) has normal gravity but no pressure or substantial interactions. Observed in galaxies, clusters, and the microwave background.

Dark energy (75%) has repulsive gravity but is otherwise mysterious. Observed in the expansion of the universe and in the suppression of structure.