ASTEROID FROM ANOTHER STAR!

- An asteroid has passed through the solar system, diving in from way above the ecliptic and shooting back out
  - Currently zooming along at 98,400 mph (158,360 km/h)
  - Named “’Oumuamua”
  - About 100m long and cigar shaped
  - Read more in Scientific American or the BBC
  - An animation of an artist’s impression from the ESO

HOW DO WE KNOW IT'S INTERSTELLAR?

- It's orbit: given that speed, it's got escape velocity from the solar system

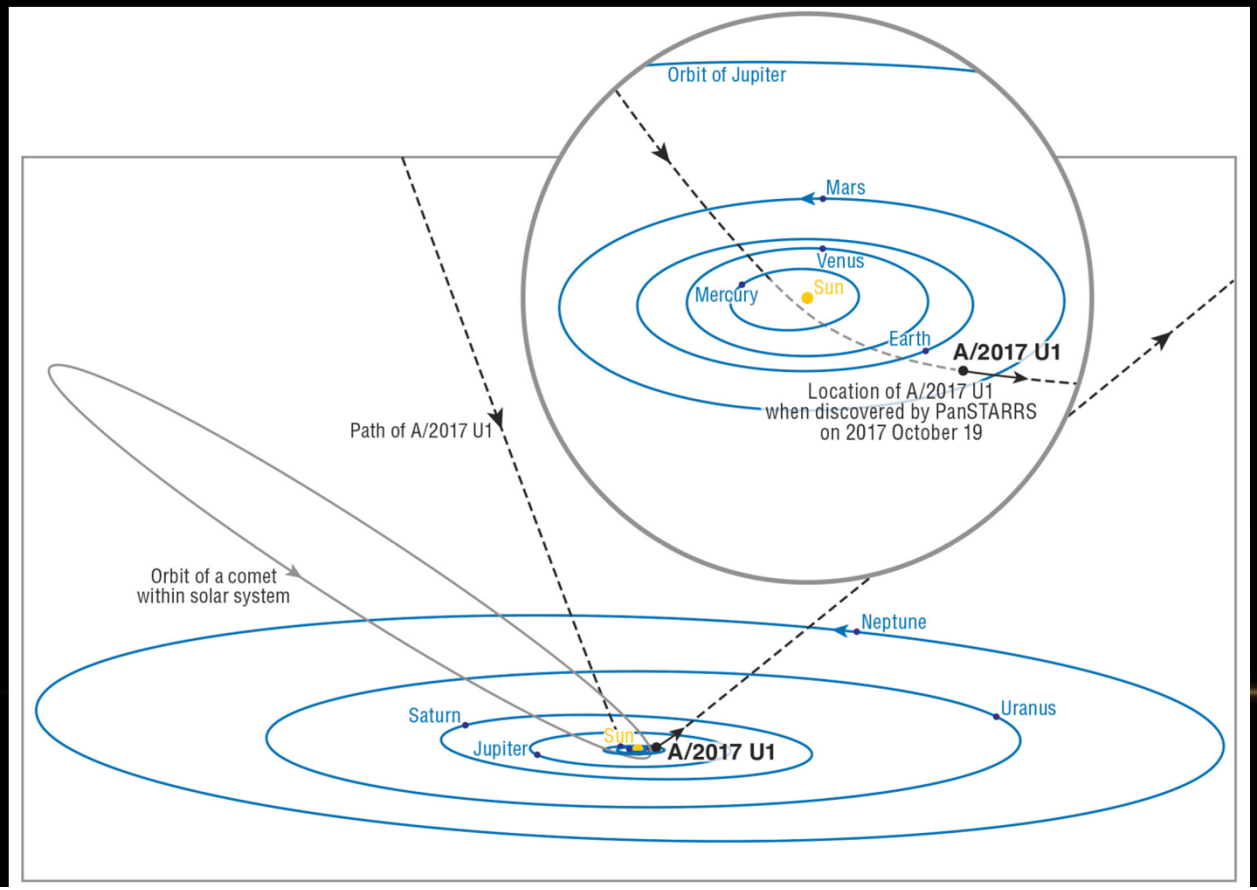


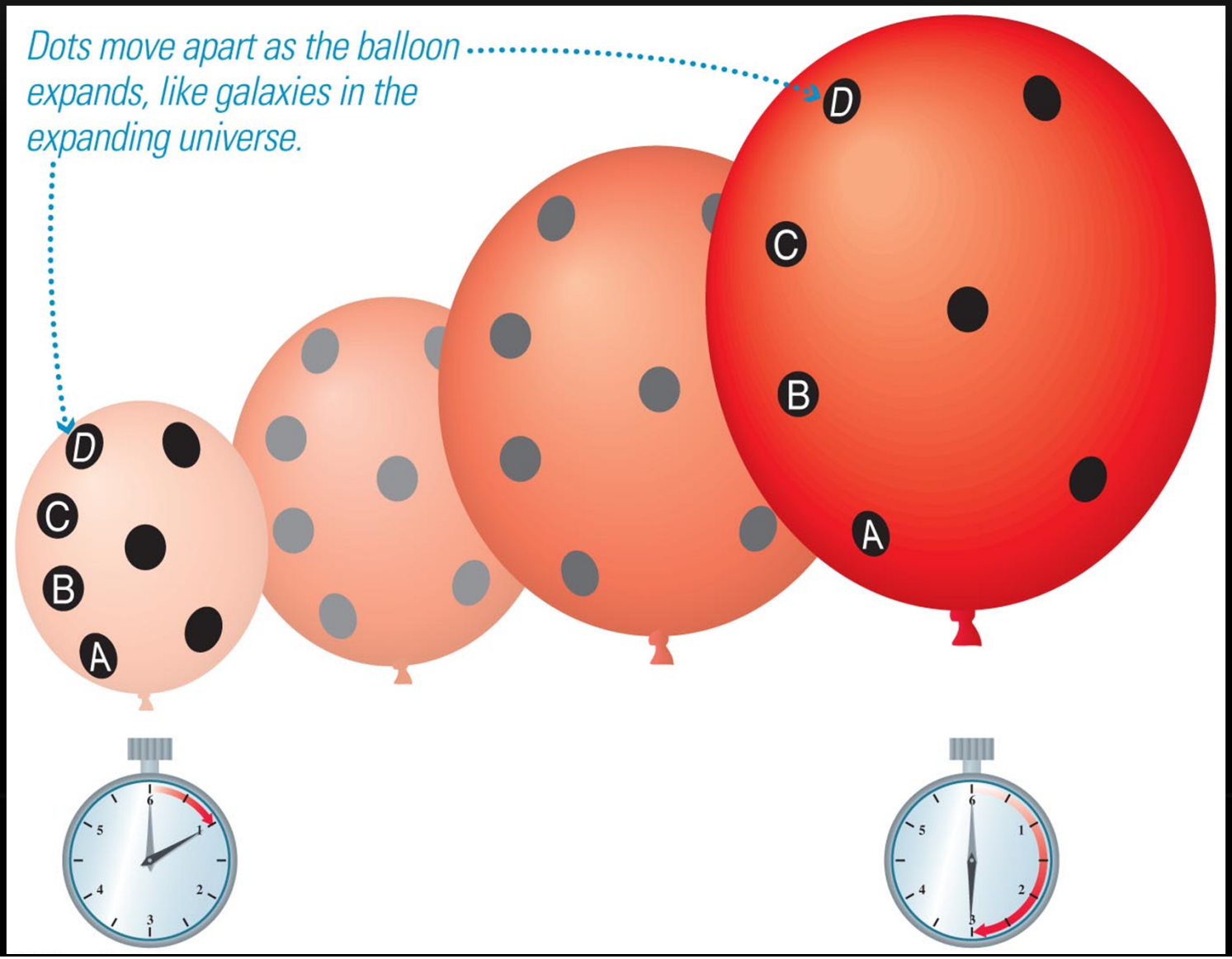
Figure #2 from *Nature* 25020

HOW DID IT GET HERE?

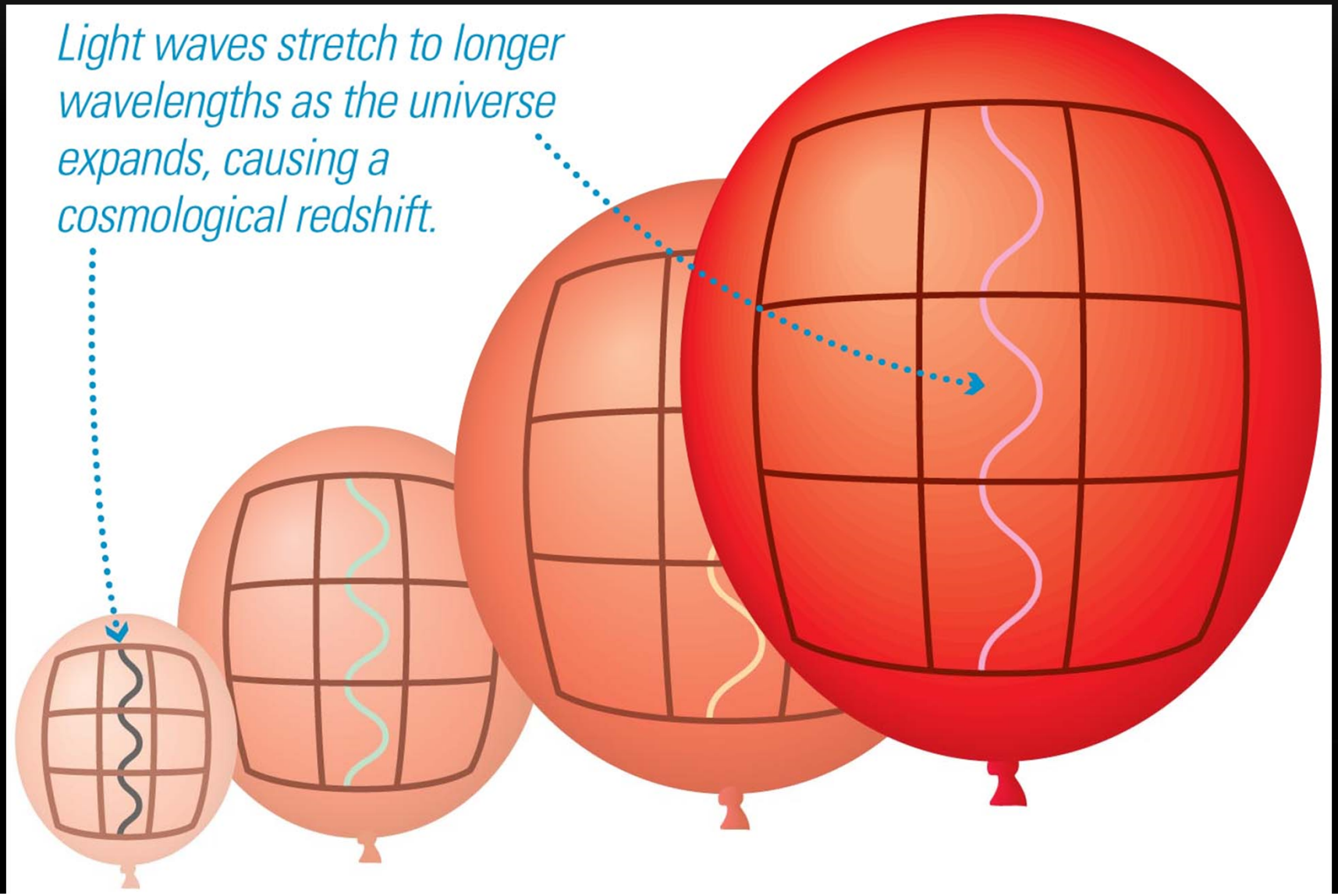
- In our solar system, asteroids which formed inside the frost line (so were rocky not icy) also could get tossed out of the solar system by a close encounter with a planet
  - just like comets headed to the Oort cloud
  - We see a few such asteroidy-comets, called “Manx Comets”
- Other solar systems should have the same thing going on
  - So interstellar space is likely home to a lot of such wandering leftover star-system bits: sometimes one must come cruising through
  - This is the first one discovered

EXPANDING UNIVERSE

Fig.16.19



EXPANDING UNIVERSE

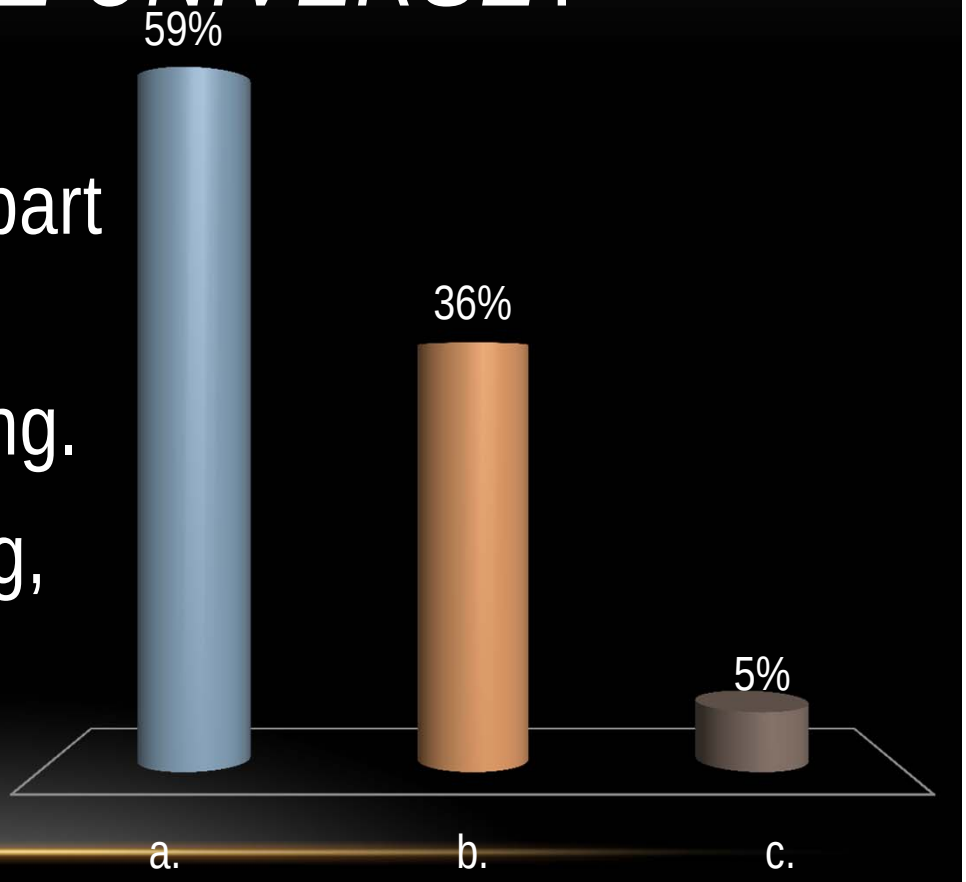


WHAT DO WE MEAN BY THE *EXPANSION OF THE UNIVERSE*?

a. Galaxies are moving apart through space.

✓ b. Space itself is expanding.

c. Everything is expanding, including Earth, our bodies, etc.



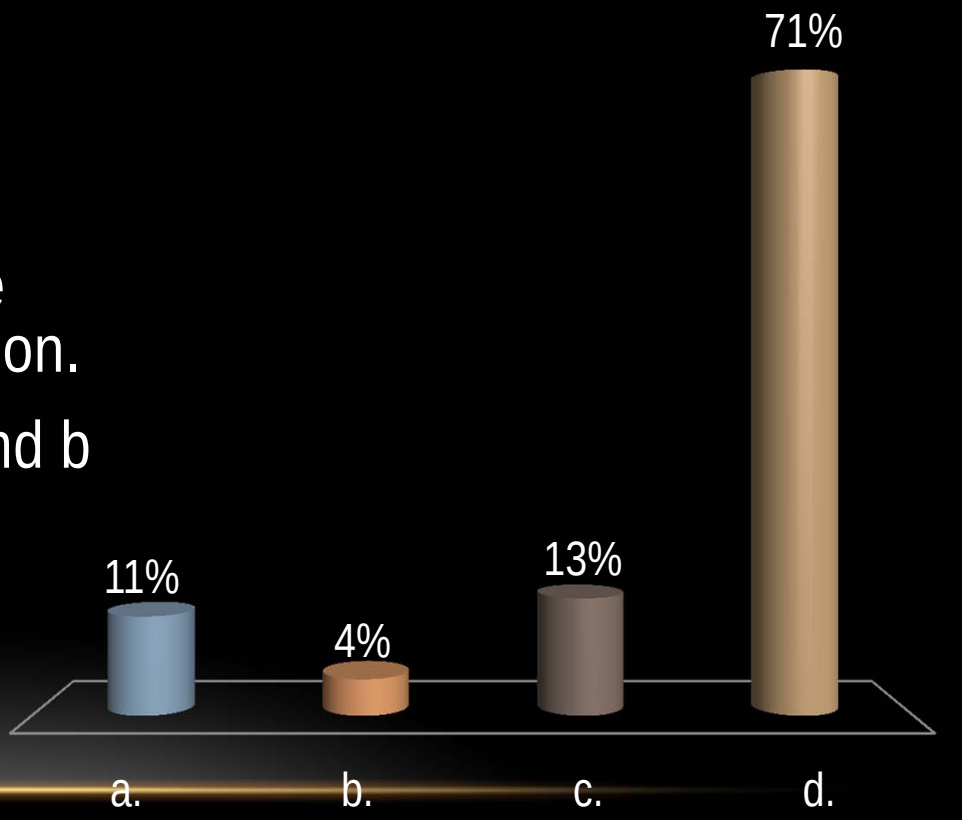
WHAT *MODEL* HELPS UNDERSTAND THAT ALL GALAXIES COULD BE RECEDING FROM EACH OTHER DUE TO THE EXPANSION OF SPACE, BUT SEEING THIS DOES NOT MEAN YOU'RE IN THE CENTER?

a. Galaxies are like raisins in an expanding cake.

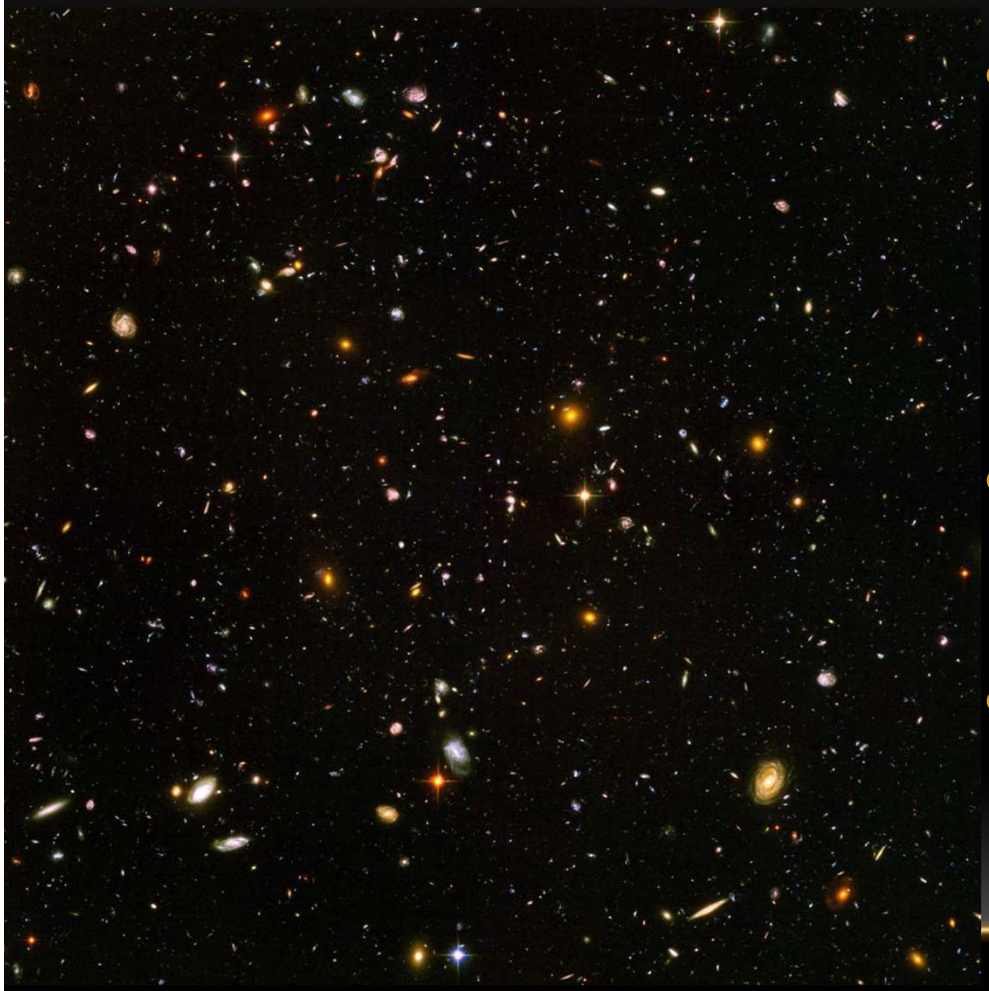
b. Galaxies are like spots on the surface of an expanding balloon.

c. Like all scientific models, a and b have some features of the universe, but not all.

✓ d. All of the above.



GALAXY EVOLUTION



- We can learn how galaxies formed and changed simply by looking back in time…
- Looking far away is also looking long ago
- (*that's the Hubble Ultra-deep field again*)

BASIC IDEA

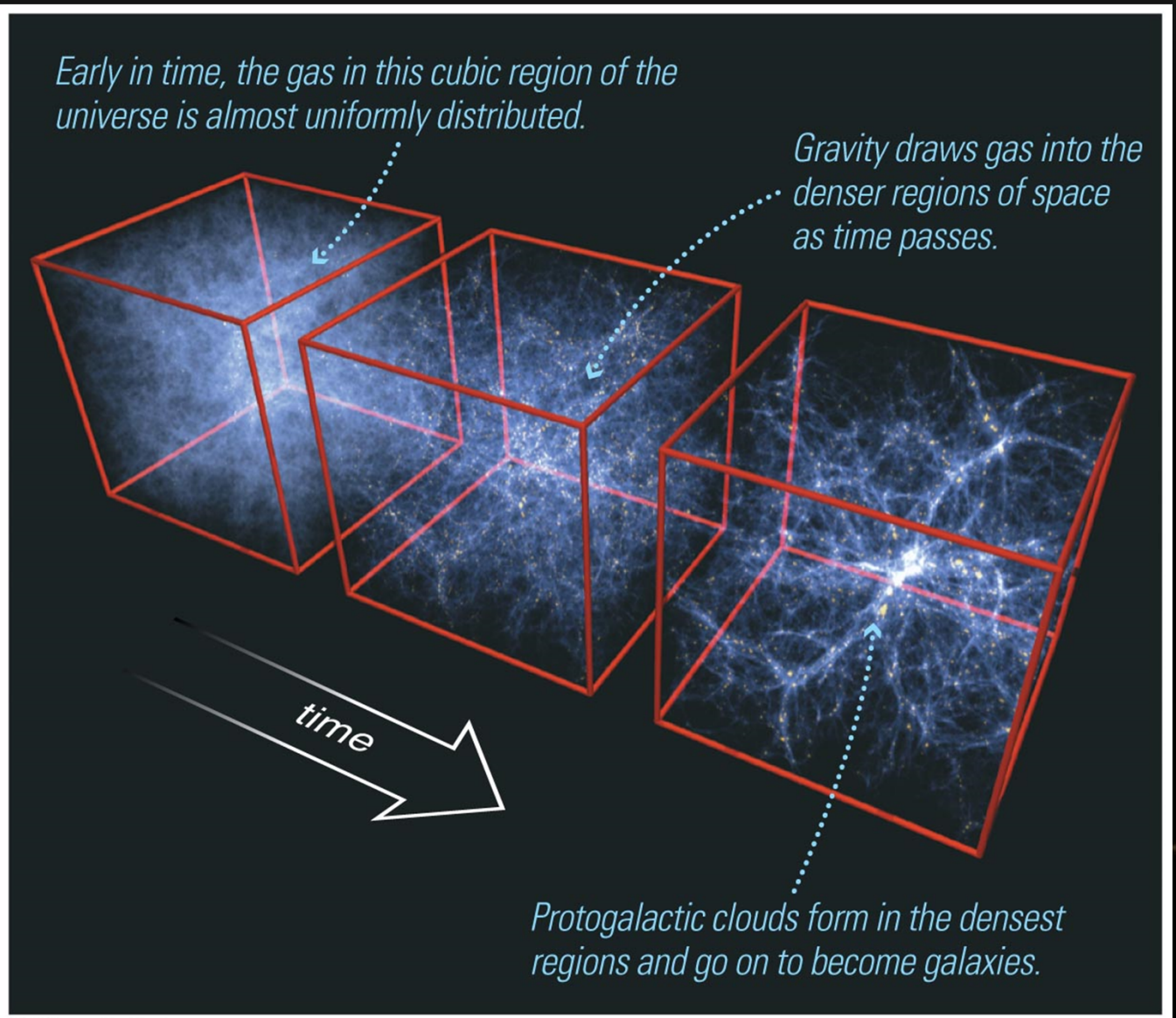


Fig.16.23

SPIRAL GALAXY FORMATION

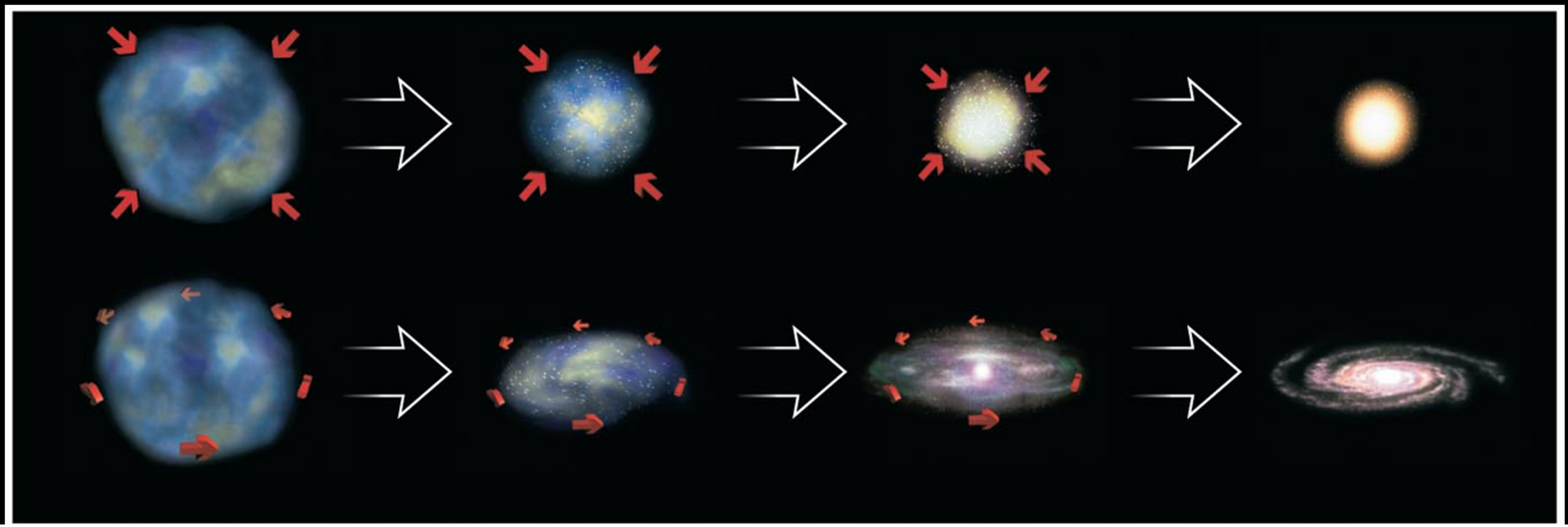
- We talked about how the Milky Way might have formed
  - Same story is likely true for other spiral galaxies
- But what about the other sorts?
  - Ellipticals (dwarf and giant)
  - Irregulars

TWO THINGS PLAY A ROLE

- Different initial conditions
  - Much like different conditions would affect how different solar systems would form
- Interactions with other galaxies
  - Galaxies are fairly big compared to the distances between them, so (unlike stars) have a decent chance to collide
  - Even more so earlier in the universe, before things expanded to where they are now

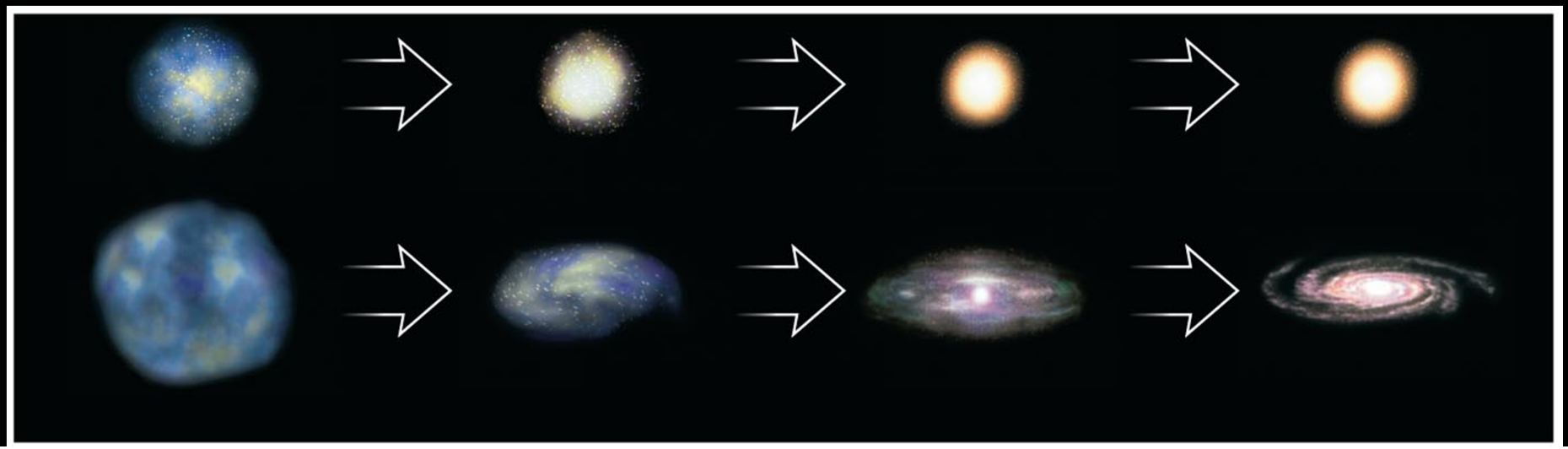
INITIAL CONDITIONS: SPIN

- If the initial cloud has more spin, it'll do the Milky Way thing: it's more likely to get a disk
- Less spin, more even collapse, more elliptical



INITIAL CONDITIONS: DENSITY

- More density, stars form faster, use up gas & dust before it gets into a disk
  - So no disk, no recent star formation
    - Two things elliptical galaxies are known for



DISTANT RED ELLIPTICALS

- Some distant elliptical are redder than comparable spirals
- Star formation has stopped, only older, smaller, redder stars are left

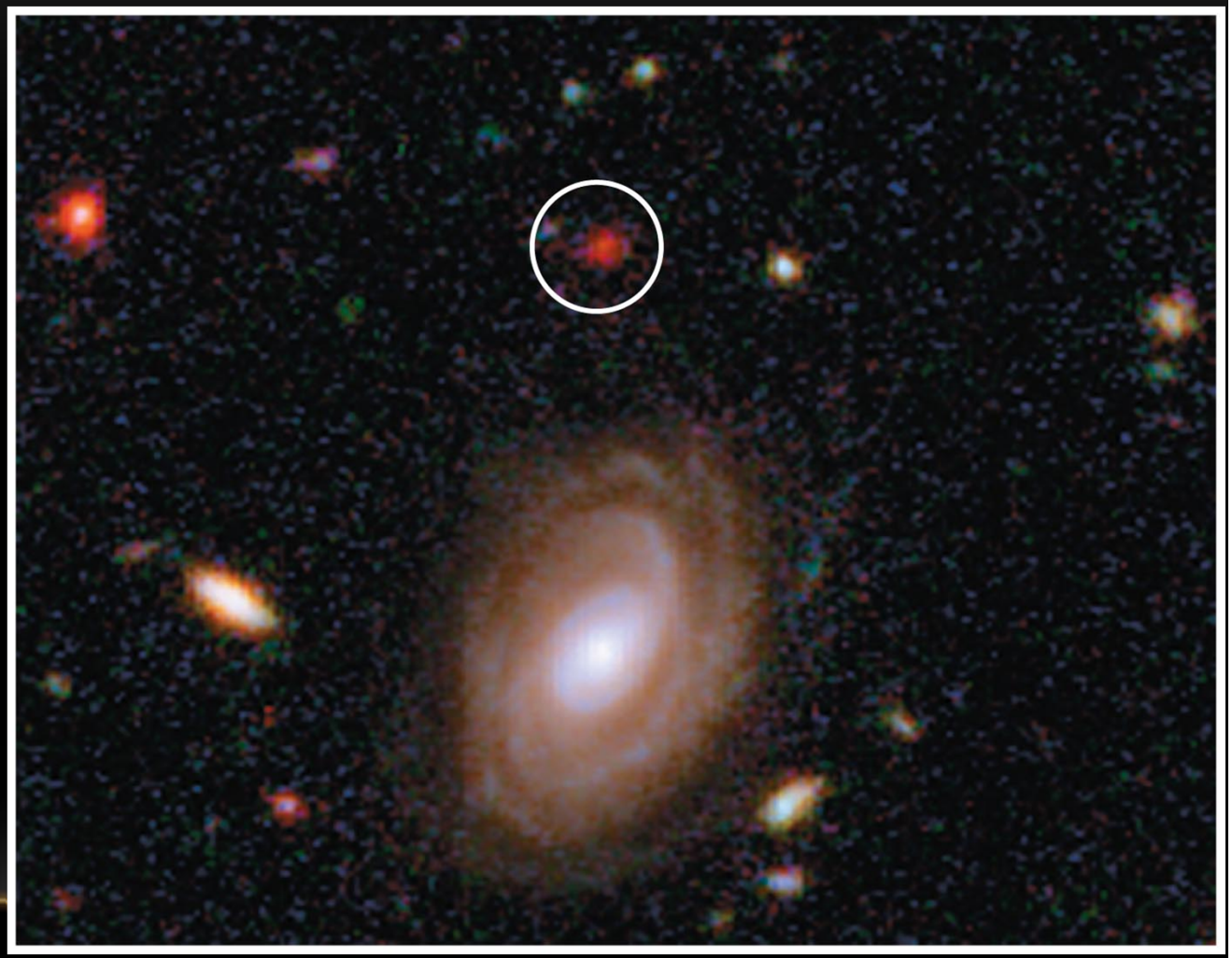
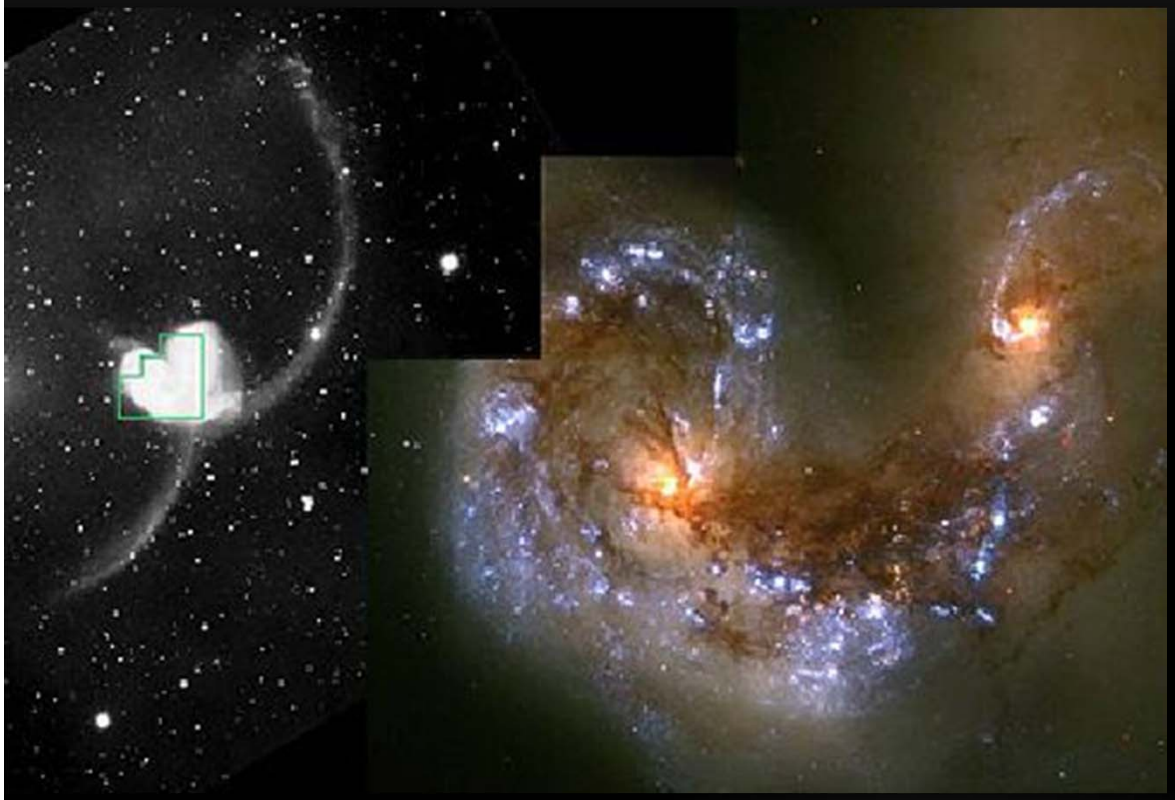


Fig.16.24

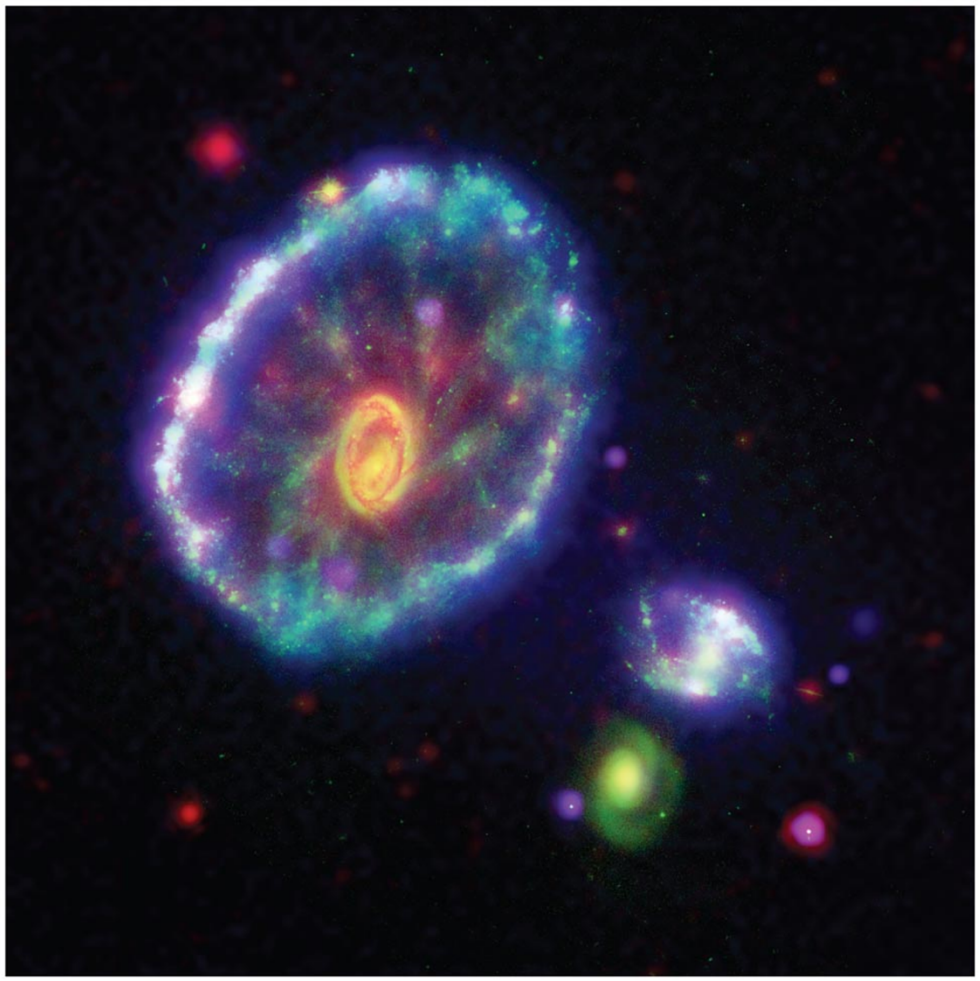
GALAXY COLLISIONS



- We see galaxies colliding
- Not too surprising – they are big compared with the distances between them
- Triggers lots of star formation

HST image of “Antennae Galaxies” by B. Whitmore, F. Schweizer

HEAD-ON



- The Cartwheel Galaxy
- Note star formation!
  - *(False colors: R=IR, G=Visual, B=UV, P=X-ray)*
  - Where are stars forming and why?

STARBURST GALAXIES

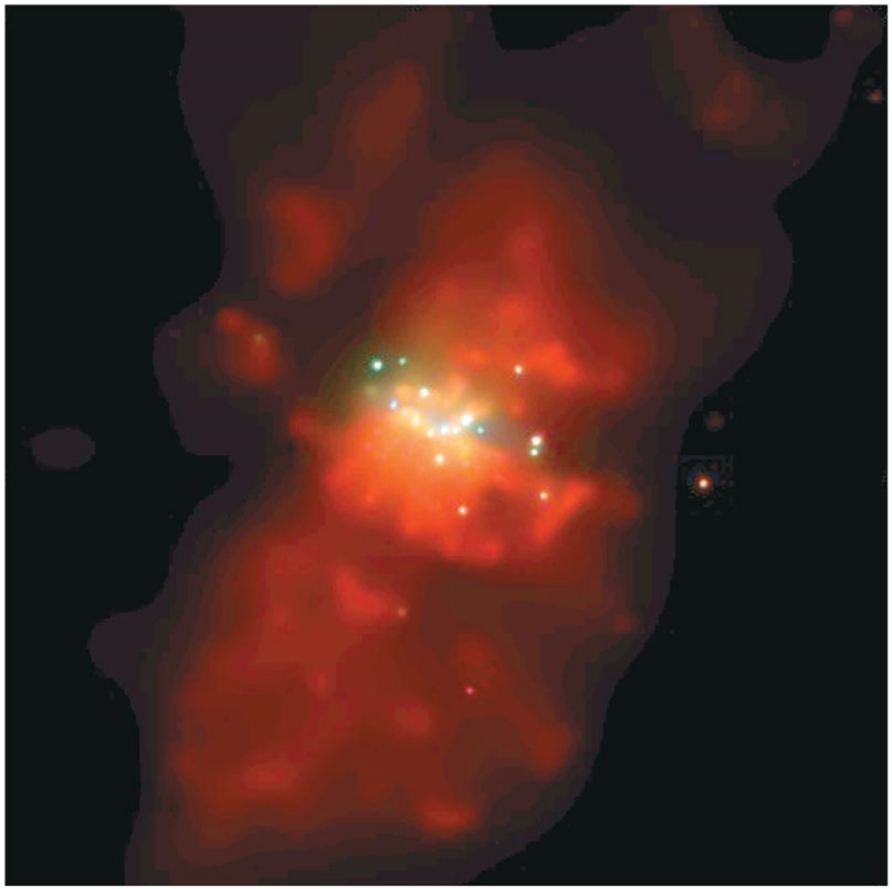
- Collisions are better than a simple Spiral Density Wave for bumping clouds and getting them to collapse to form stars
- A whole galaxy's worth of star formation all at once

a This visible-light photograph (from the Hubble Space Telescope) shows violently disturbed gas (red) blowing out both above and below the disk.

Fig.16.30a

STARBURST GALAXIES

- Lots of star formation means lots of massive stars
- Lots of Supernovae: blows hot gas out of the whole galaxy
- Leaves behind neutron stars, black holes



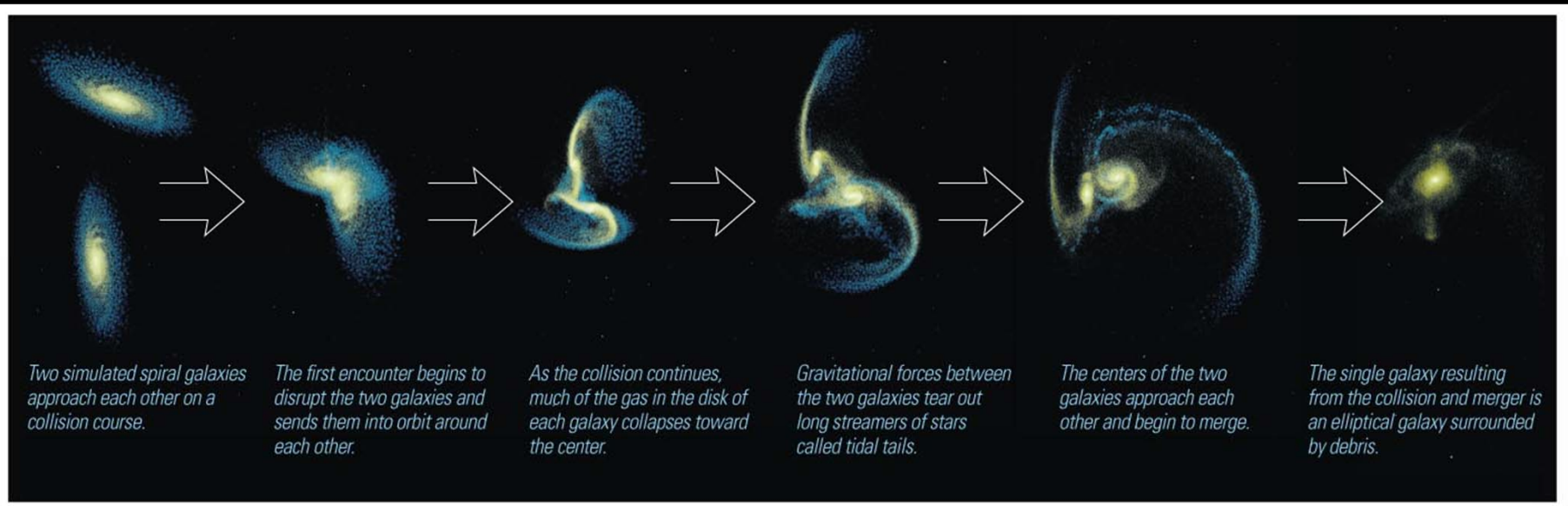
b This X-ray image from the Chandra X-Ray Observatory shows the same region as the visible-light photograph in (a). The reddish region represents X-ray emission from very hot gas blowing out of the disk. The bright dots in the galactic disk probably represent X-ray emission from accretion disks around black holes or neutron stars produced by recent supernovae.

Fig.16.30b

MERGERS

- Run computer simulations of what happens when two spiral galaxies collide
  - After orbiting each other closely a few times, and spraying stars everywhere, you're left with a large elliptical galaxy

Fig.16.26

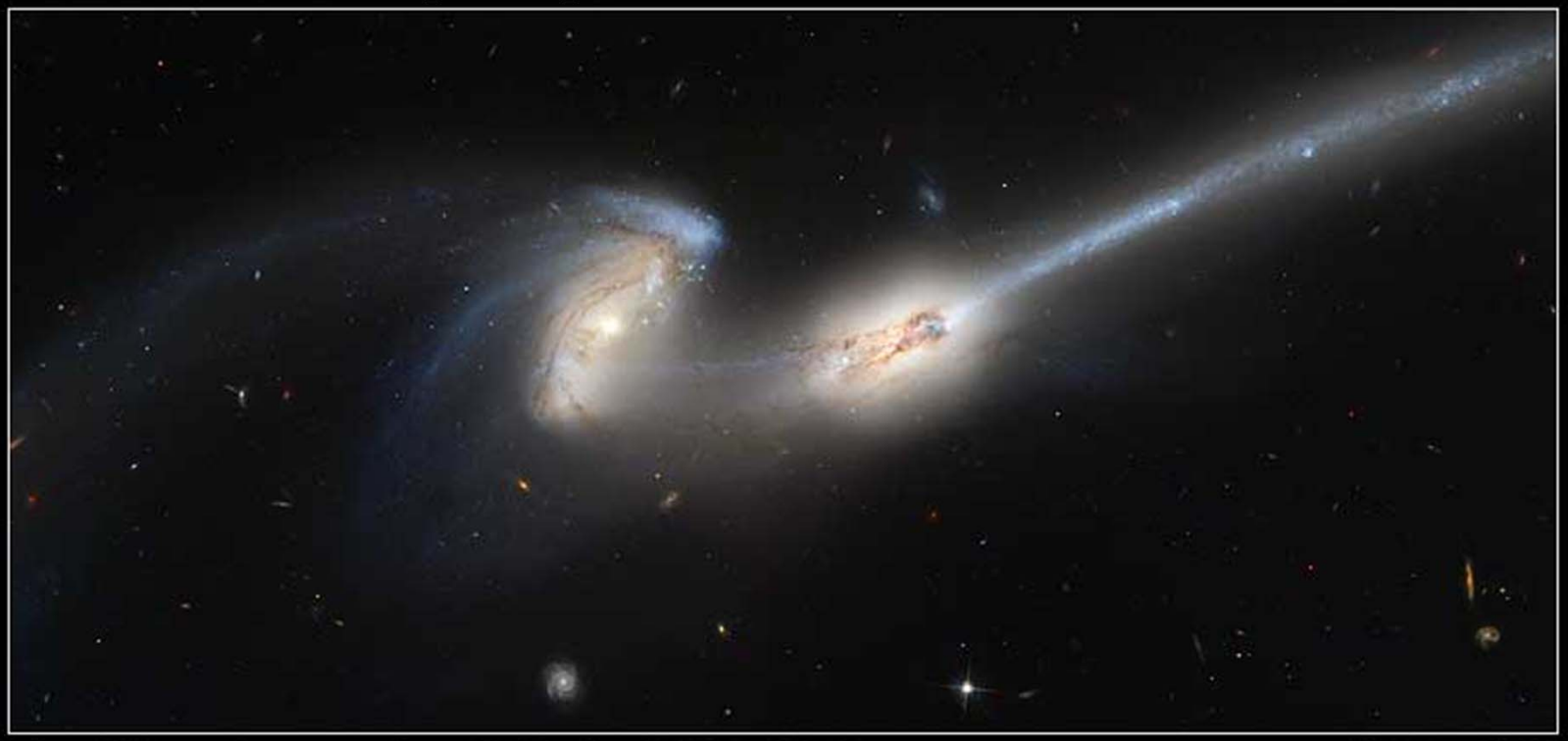


ONE NEAR THE START

- The first pass of such an inspiral?

THE MICE

- Merging galaxies 300 million ly away
- Fate of Milky Way and Andromeda?



The Mice • Interacting Galaxies NGC 4676 **HST • ACS**

NASA, H. Ford (JHU), G. Illingworth (UCSC/LO), M. Clampin (STScI), G. Hartig (STScI) and the ACS Science Team
STScI-PRC02-11d

JUMBLED UP

ESO image of “Atoms for Peace” Galaxy

- After several passes, everything comes together

CLUSTERS

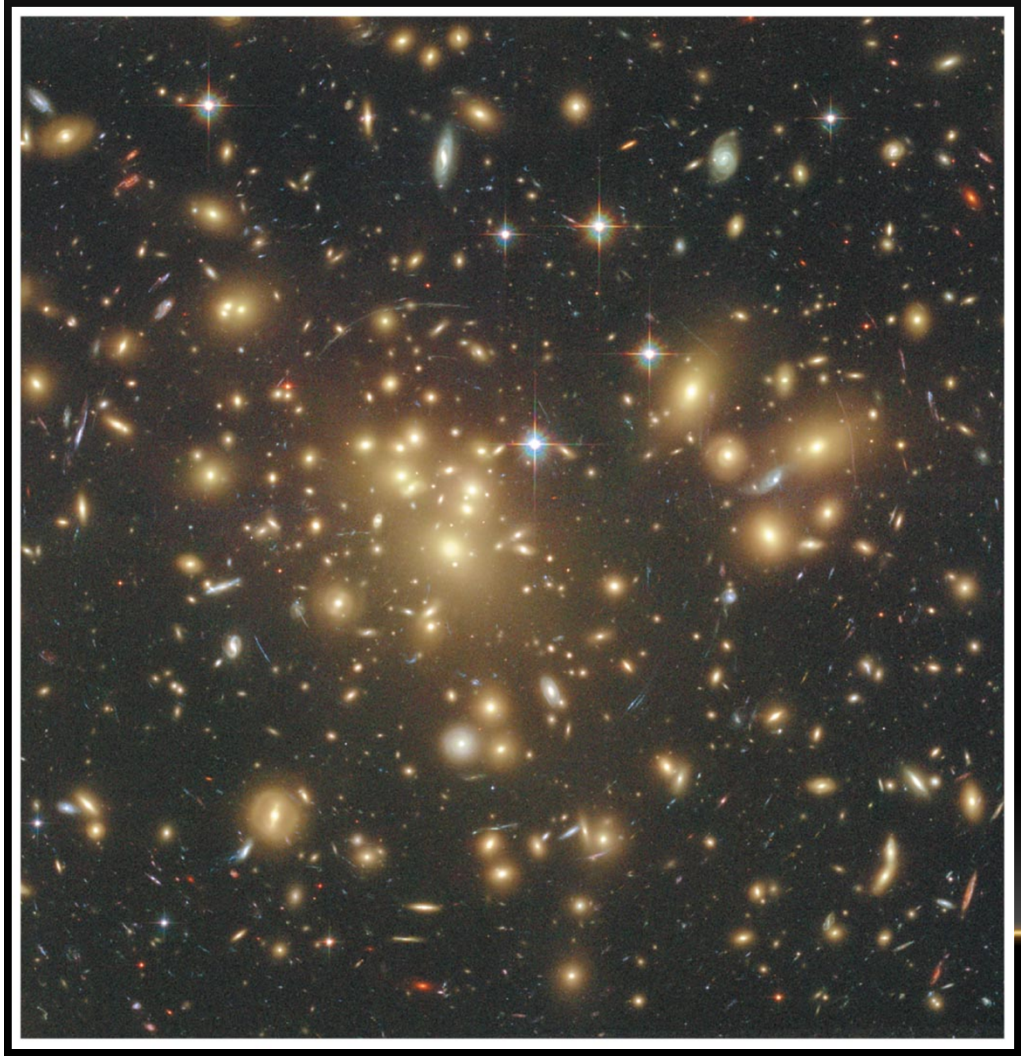
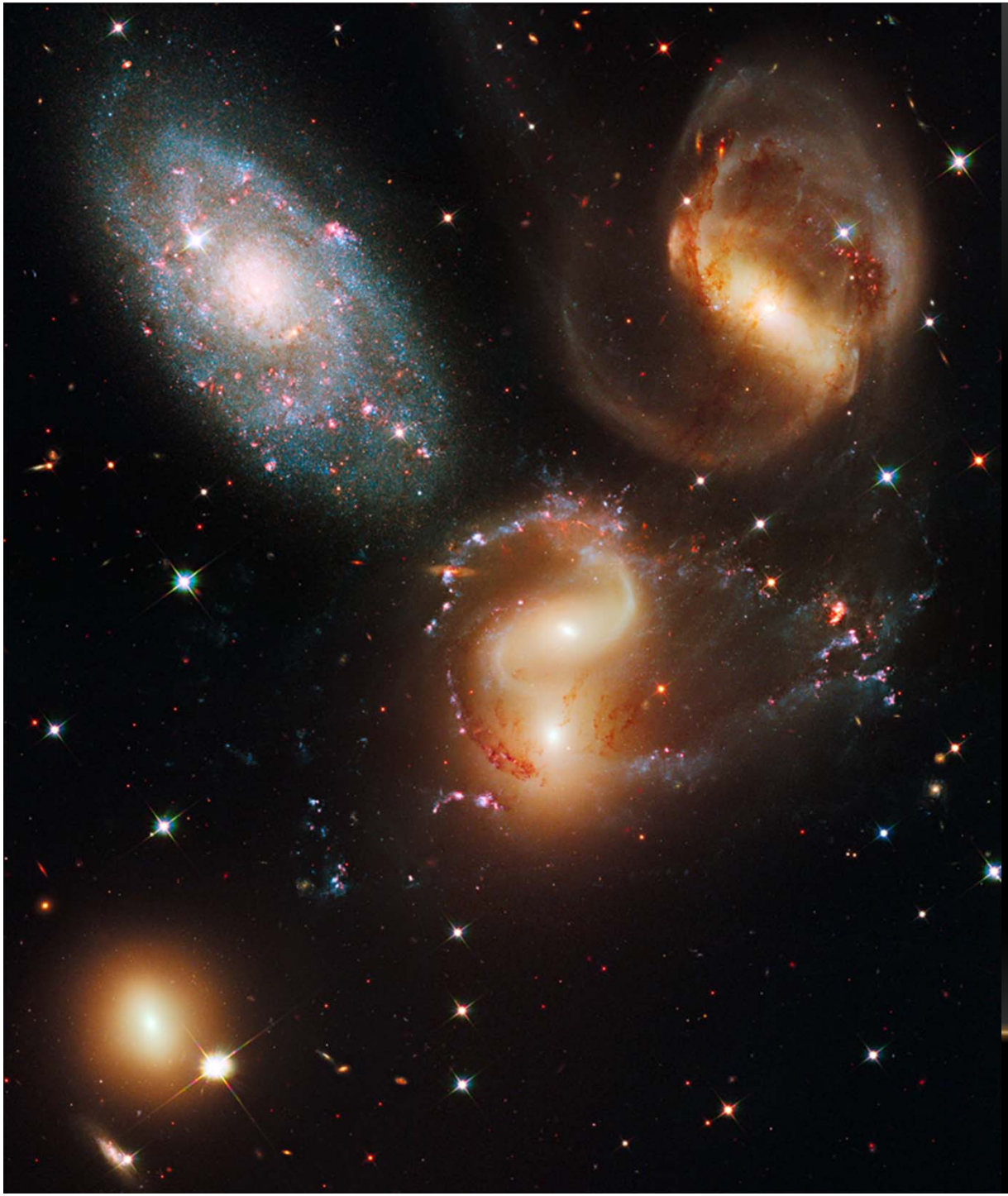


Fig.16.10

- Elliptical galaxies are more common in “clusters” of galaxies
- Because collisions would be more common where there are more galaxies?



STEPHAN'S QUINTET

- Four of these are 300 Mly away and interacting
- One is only 40 Mly away
  - Which one?

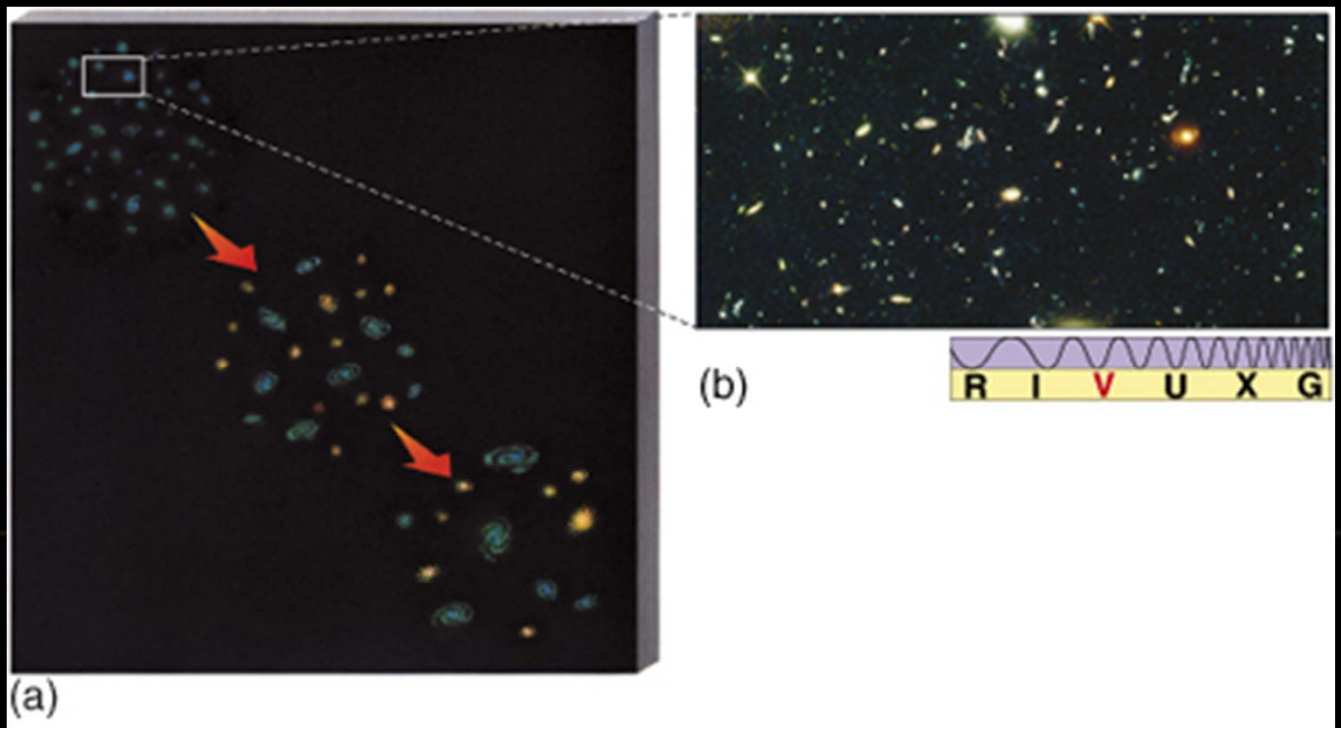
The Hubble SM4 ERO Team

“TOP-DOWN” FORMATION

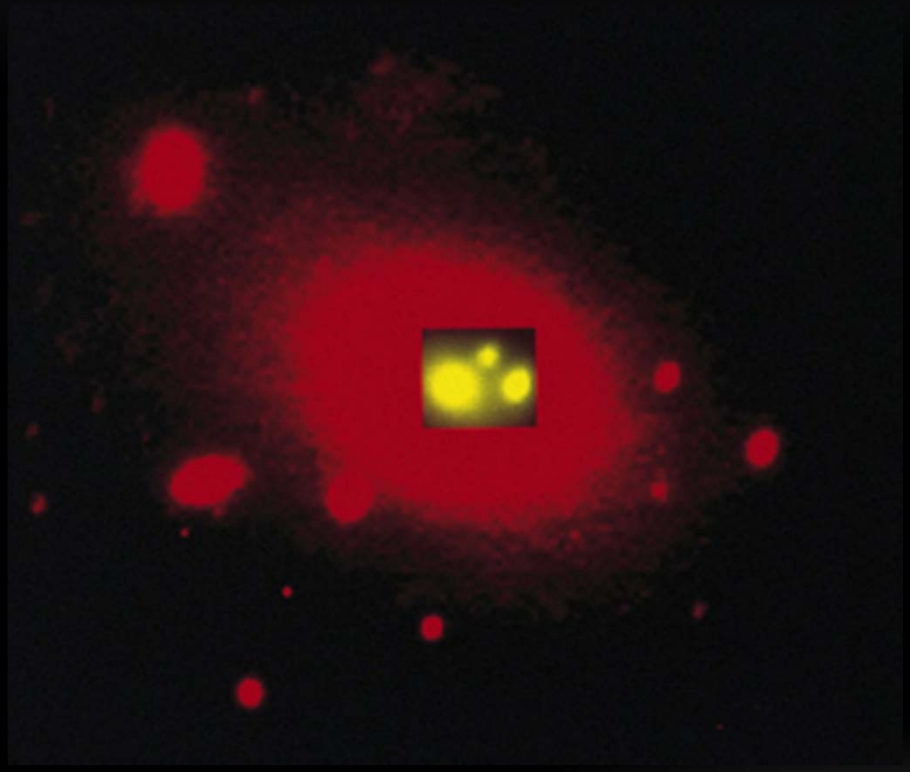
- Big collapsing cloud of gas

“BOTTOM UP” FORMATION

- Do smaller globs of stars (“dwarf galaxy” sized) form first, them merge to make bigger galaxies?
- Pictures very far away (and thus long ago) appear to be showing us this in action



MMM, TASTY



- Nearby evidence is seen that this is happening
- The central giant elliptical in cluster Abell 2199 can be seen absorbing smaller galaxies

UNDIGESTED REMNANTS

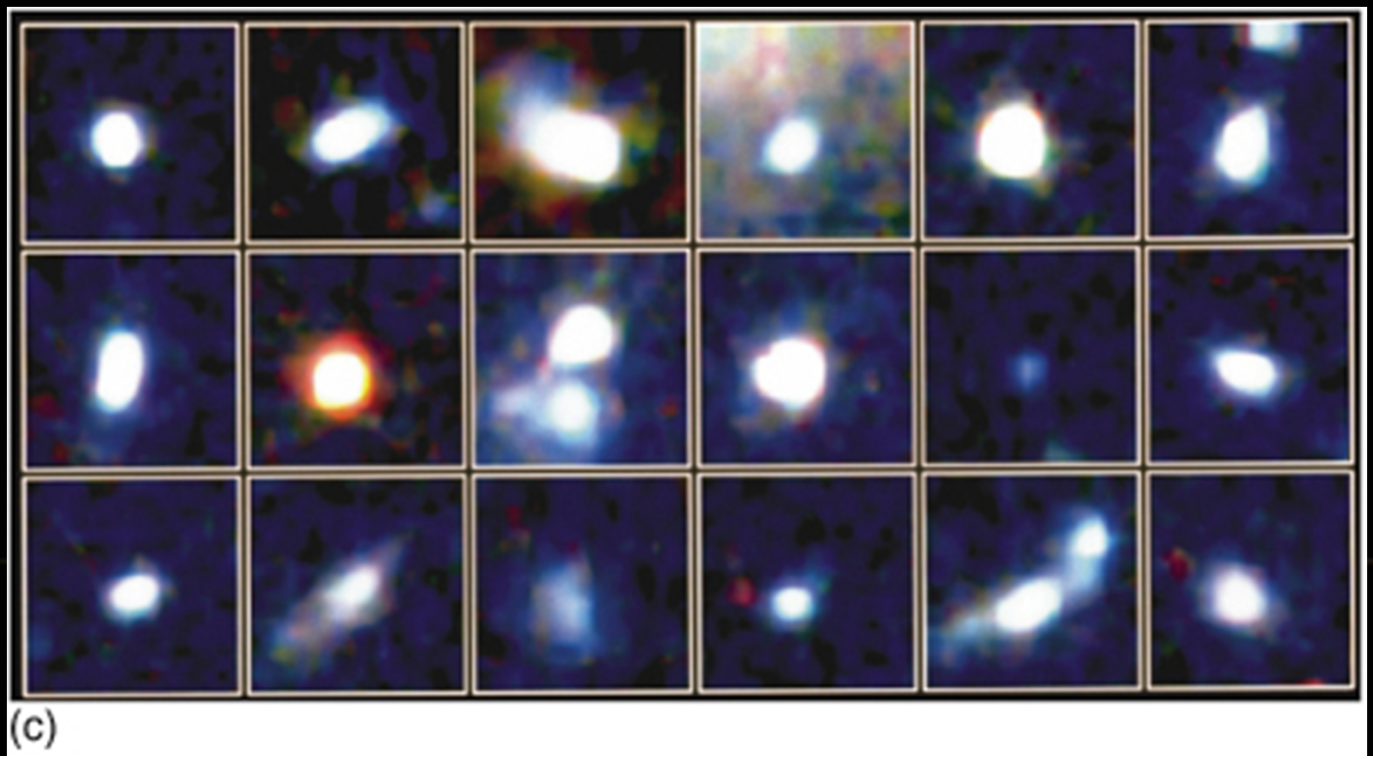
- Another one (Abell 3827)
- This process would also explain why giant ellipticals don't have much gas and current star formation
  - It all got used up in the merger

Fig.16.28 is much like this picture

THE “FOSSIL EVIDENCE”

- Small, billion-star clusters all in the same tight area
  - They are very much like the dwarf galaxies we see today
- This is a more gradual process, akin to planetoid formation via colliding clumps

10 billion year old light!



LOOK BACK TIME

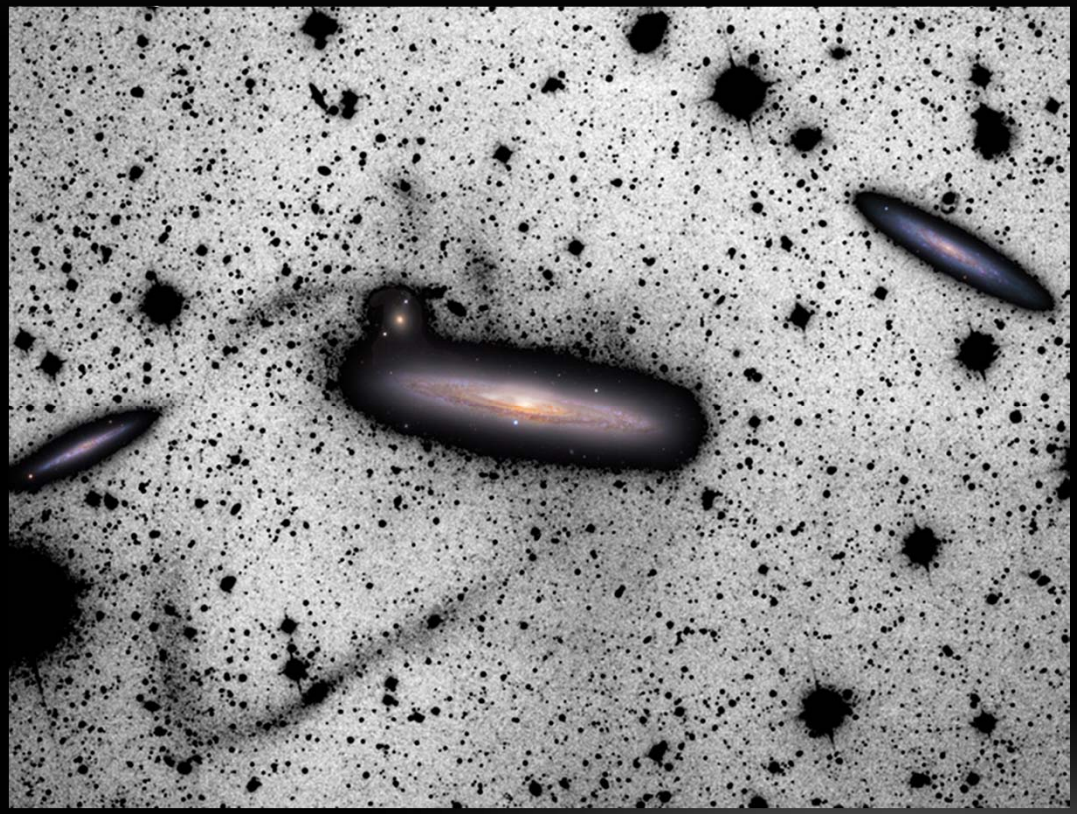
- If something is 10 billion light years away…
  - we are seeing light which was made 10 billion years ago
  - we are “Looking Back” 10 by in the past
- Way back when, we do see evidence of such merging of smaller into larger galaxies

THE MILKY WAY?

- Perhaps our galaxy was formed via smaller galaxies colliding?
- We see this happening elsewhere
- Models and data hint at least some of this has happened
  - Some part being “Bottom-up” probably true
- Proposed Webb Space Telescope is designed to be able to see this

M51 Whirpool Galaxy
Image by Todd Boroson (NOAO)

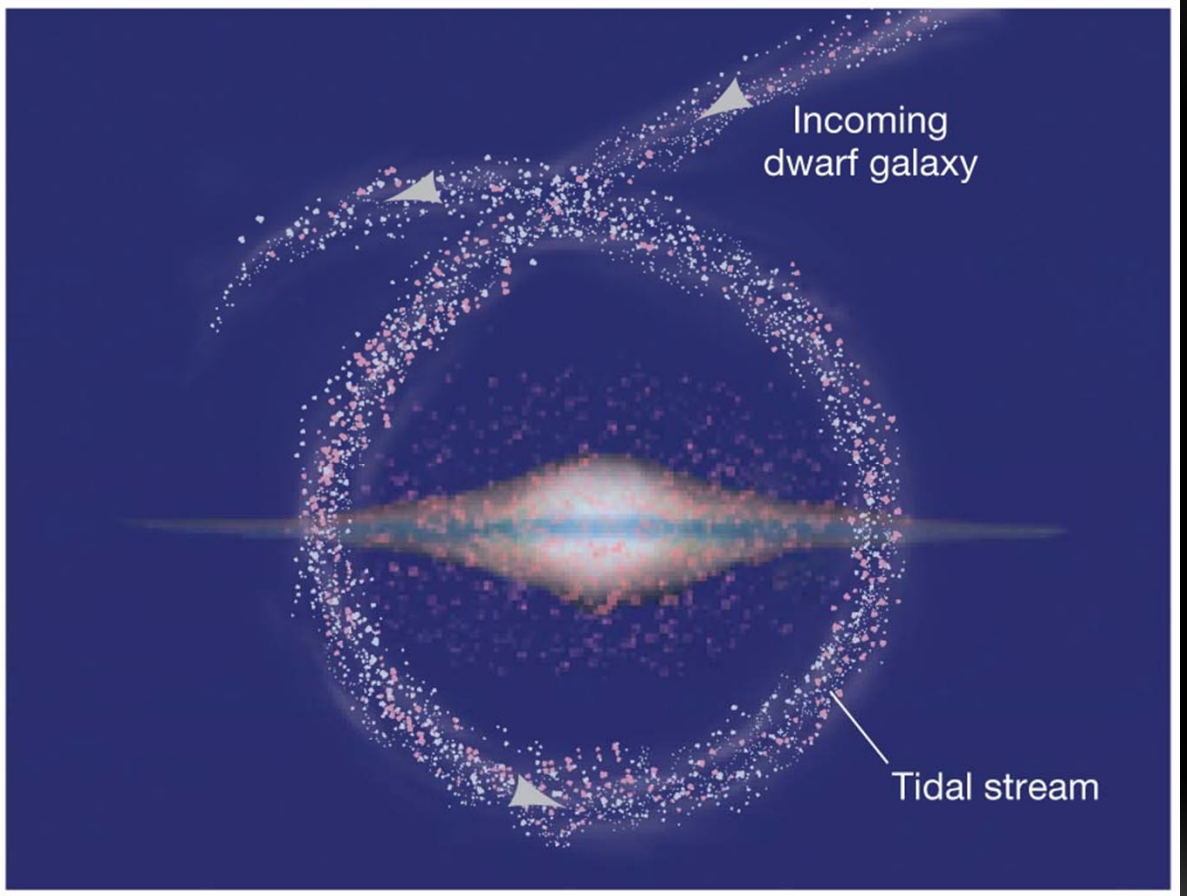
STAR STREAMS



- Late in the merger action, all that's left are tidal streams of stars

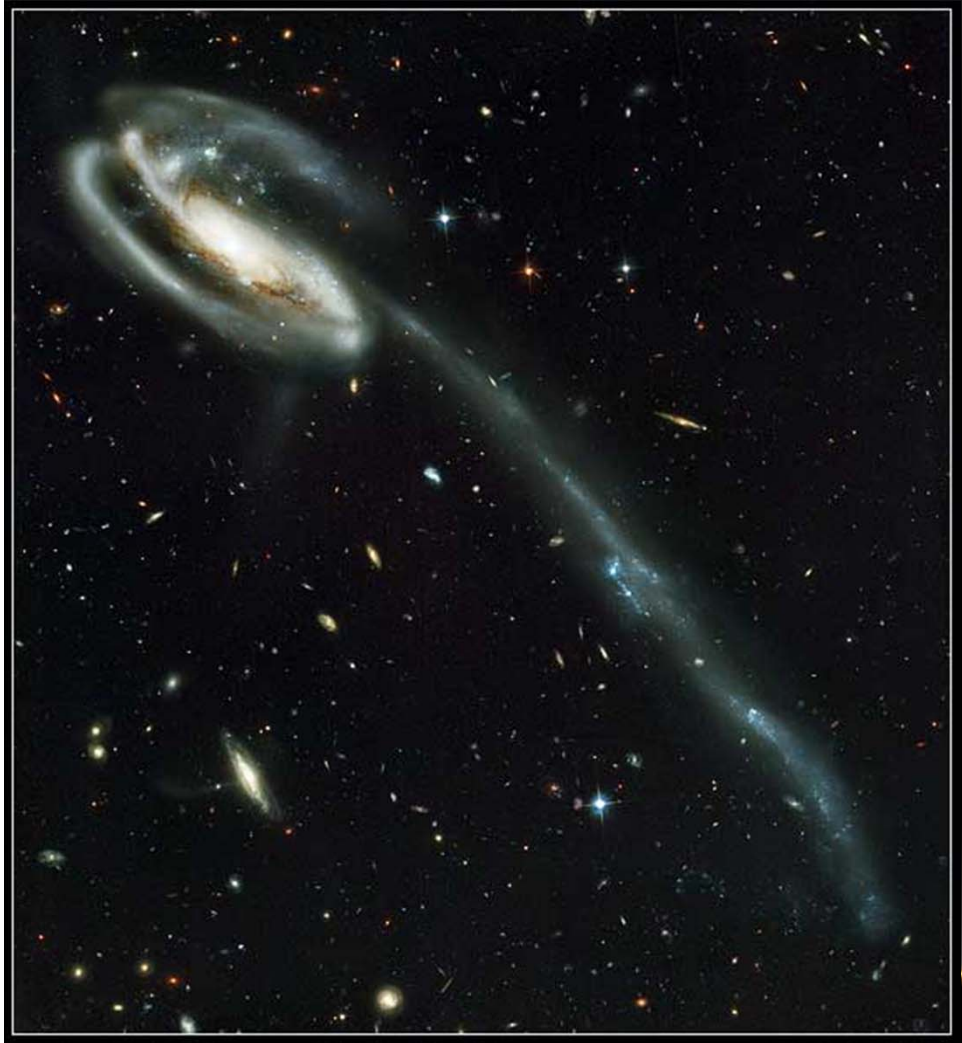
NGC 4216
Ken Crawford (Rancho del Sol Obs.)

STAR STREAMS



- We see evidence of these around the Milky Way

TADPOLE GALAXY



Tadpole Galaxy • UGC 10214 **HST • ACS**

NASA, H. Ford (JHU), G. Illingworth (UCSC/LO), M. Clampin (STScI), G. Hartig (STScI) and the ACS Science Team • STScI-PRC02-11a

- Small galaxy at upper left zipping through larger spiral 420 Mly away
- Leaves 280,000 ly long trail of stars as gravity zings some stars out of their usual orbits
- Note blue star formation
- Note backdrop of faint galaxies, like the Deep Field pictures

SO, WHICH IS IT?

- Likely a mixture between “top down” and “bottom up”
  - *eg*, Giant ellipticals formed from merging of many smaller galaxies (each of which formed “top down” from a cloud of gas)
  - Dwarf ellipticals: mostly top-down
  - Smaller spirals: more “top down”, larger ones probably ate stuff too