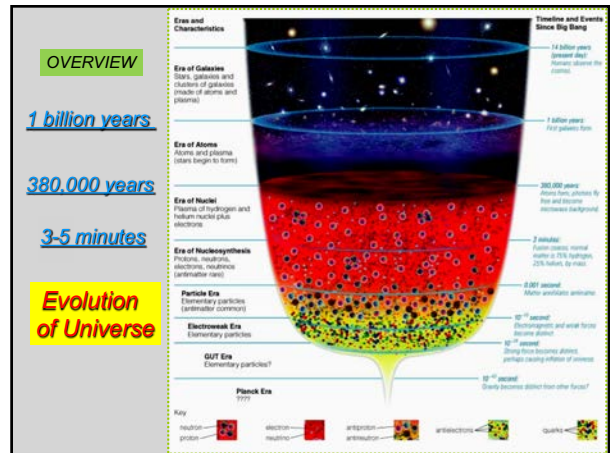
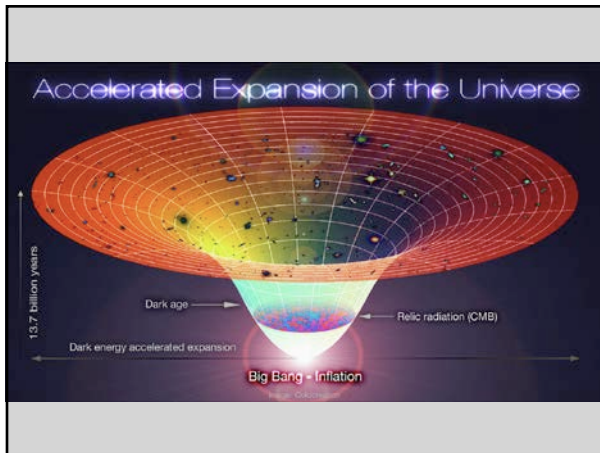


**ASTR 1040: Stars & Galaxies**

Prof. Juri Toomre TAs: Daniel Segal, Max Weiner  
Lecture 30 Thur 30 Apr 2020  
zeus.colorado.edu/astr1040-toomre

**Our Schedule and Topics**

- **Final Exam on Wed, May 6** 4:30pm-7:00pm, on canvas/quizzes, closed book, 2 crib sheets allowed (4 sides). **Review** by Max, **Mon May 4, 4:30pm, zoom.** **Review Set #4** posted
- All **observatory reports** due by 6pm today, **HW# 13 graded**
- **After first 3 to 5 minutes** in our universe
- **Computer models of cosmology in action**
- **Cosmic web of galaxies emerges:** cold dark matter crucial to structure formation
- Current big **outstanding questions or issues in astronomy**



**After "recombination": Era of Atoms**

- Finally **cool enough** for electrons to combine with nuclei to form atoms (**380,000 yrs**)
- Photons now **"decoupled"** = free to become **CMB** of future
- Universe becomes transparent to light

era of atoms

1,500 K

380,000 years

CMB

3,000 K

era of nuclei

6,000 K

temperature

**Major Events Since Big Bang**

Present: Humans observe the cosmos.

14 billion yrs: Era of Galaxies

1 billion years: Era of Atoms

380,000 years: Era of Atoms

3 minutes: Era of Nuclei

3 minutes: Era of Nucleosynthesis

0.001 seconds: Particle Era

10<sup>-10</sup> seconds: Electroweak Era

10<sup>-36</sup> seconds: GUT Era

10<sup>-43</sup> seconds: Planck Era

**Era of Atoms**  
380,000 – 1 billion yr  
< 3000 K

- Cool enough that neutral atoms form through the joining (recombination) of protons and electrons.

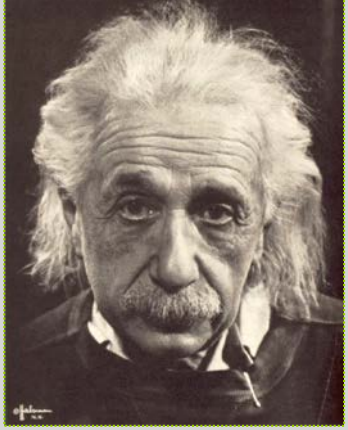
**Matter:** neutral atoms

Once most electrons are not free to scatter photons, the photons could move freely.

Key: neutron, proton, electron, neutrino, positron, antineutrino, antiproton, antineutron, antilepton, quark

# Questions or Comments

- General Theory of Relativity was giant step forward, but then ...
- **Alarming ideas like:**
  - 1: expanding universe (Hubble)
  - 2: CMB (big bang)
  - 3: 1 part in 100,000 uniform (inflation)
  - 4: white dwarf SN (dark energy)
- These could trouble even Einstein ...!



### “Observational Pillars” of Big Bang Theory

1. The universe is aglow with thermal radiation, the Cosmic Microwave Background (CMB)
 

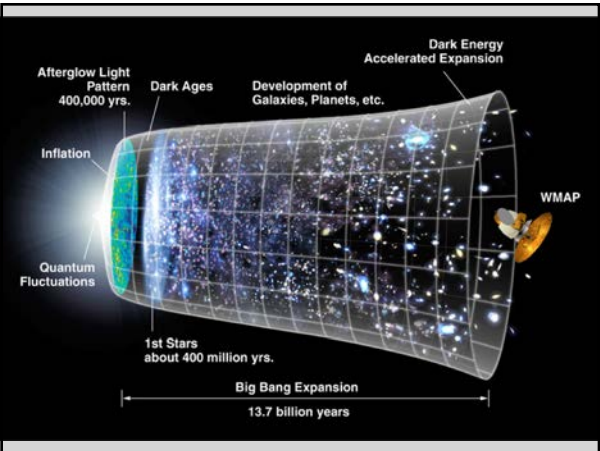


**REMINDER**
2. The observed abundances of light elements agree with Big Bang predictions
 


3. The universe is expanding


4. The night sky is dark

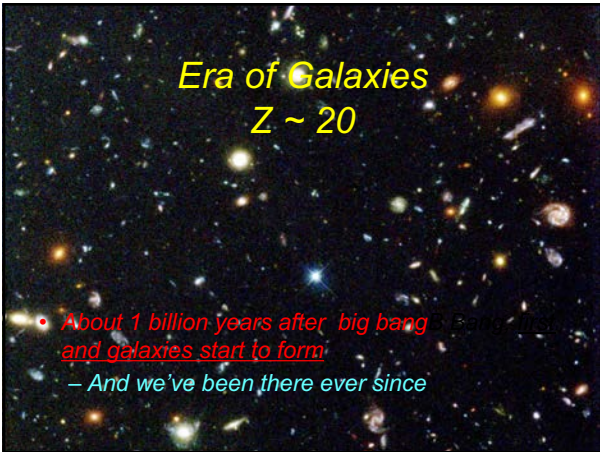




## Era of Galaxies

### Z ~ 20

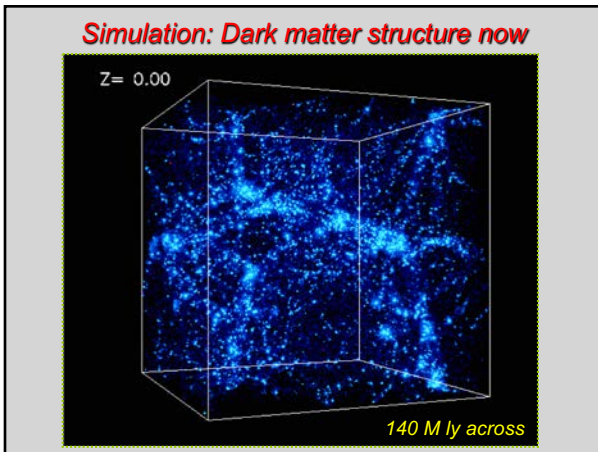
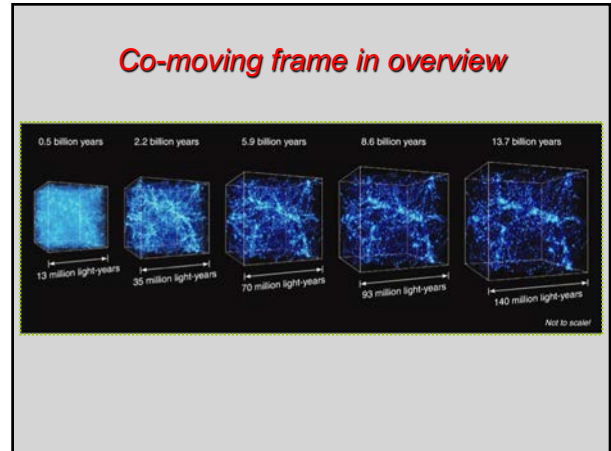
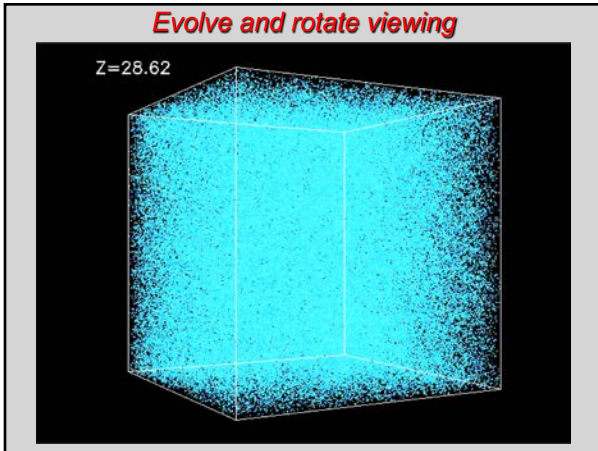
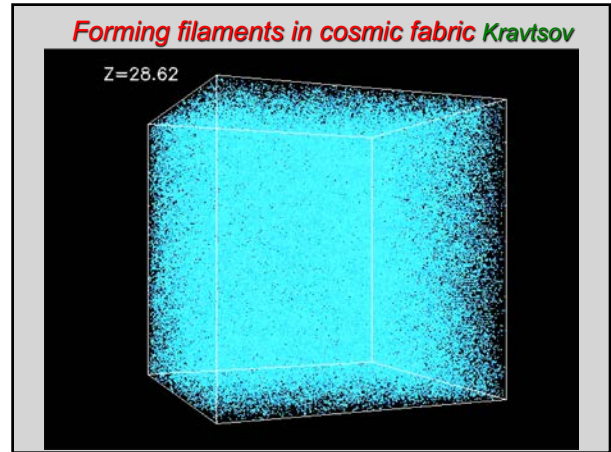
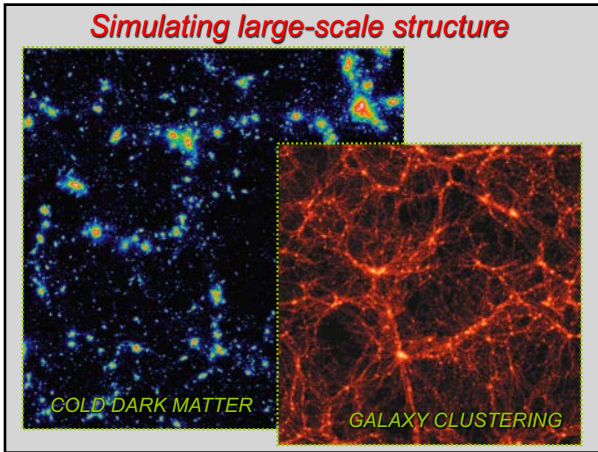
- About 1 billion years after big bang and galaxies start to form
- And we’ve been there ever since



### Forming first stars and galaxies

SIMULATIONS

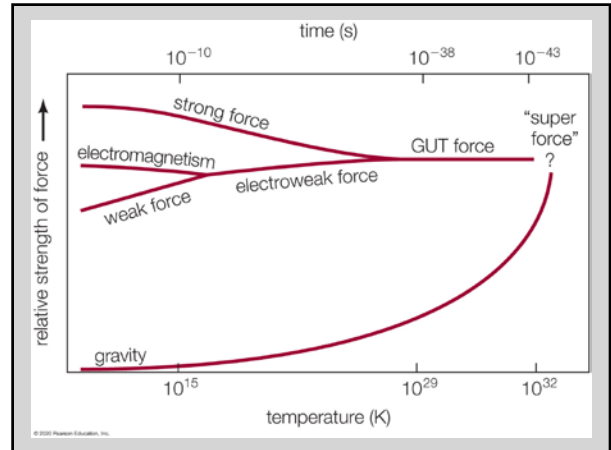




**Questions or Comments**

Poll 1: Which forces have physicists shown to be the same force at very high temperatures or energies, by experiments in particle accelerators?

- A. gravity and the strong force
- B. the electromagnetic and weak forces
- C. the strong and weak forces
- D. gravity and the weak force
- E. the strong and electromagnetic forces



The latest of 4-D N-body simulations in “co-moving frames”

*Illustris, Millennium, Eagle*

Gravity of cold dark matter causes clumping

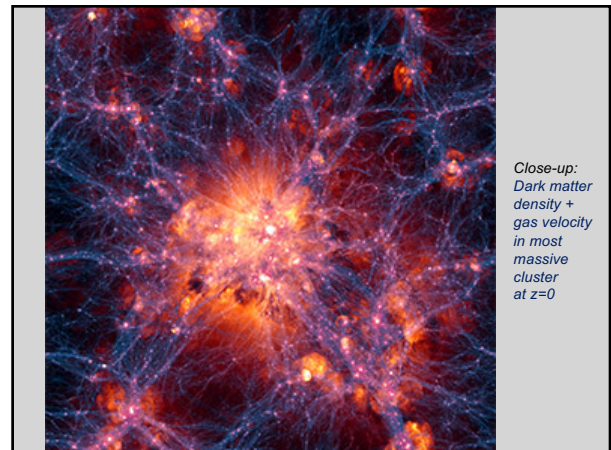
*Illustris: Overdense regions pull in more dark matter*

z = 48.4

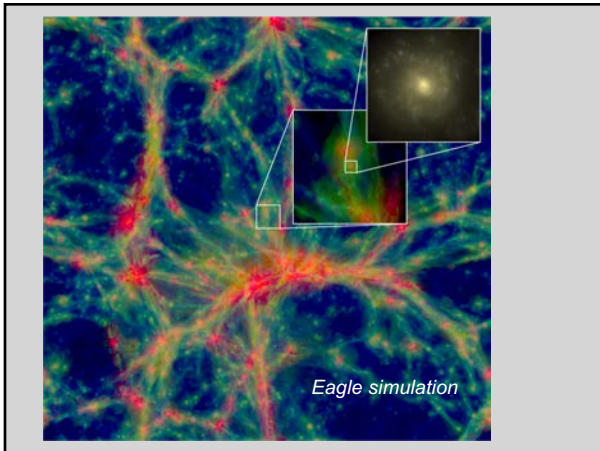
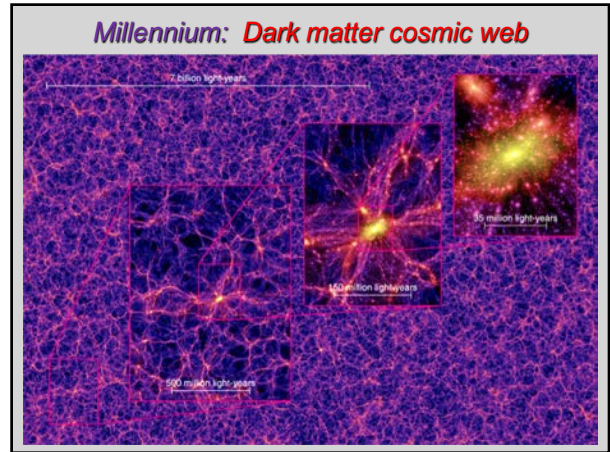
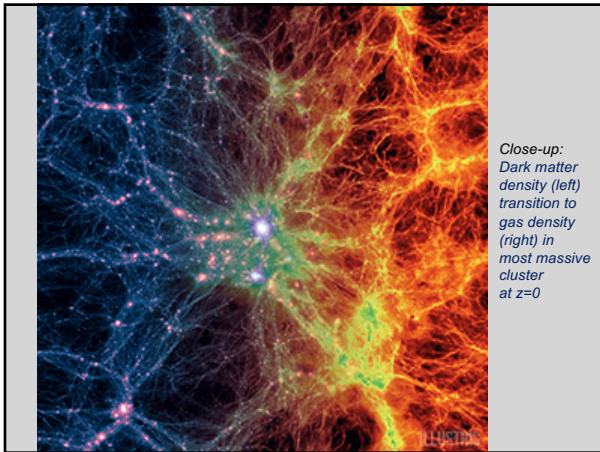
T = 0.05 Gyr

500 kpc

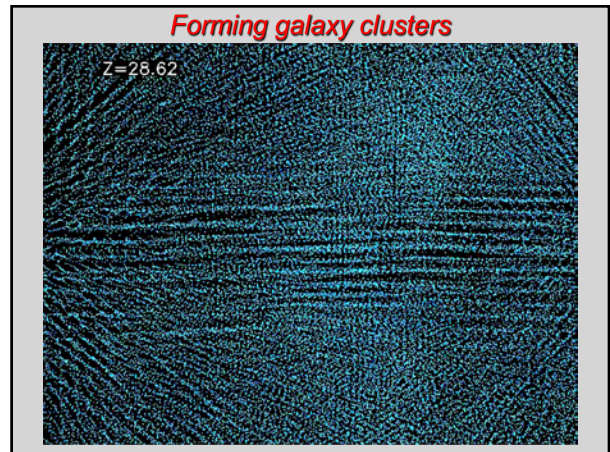
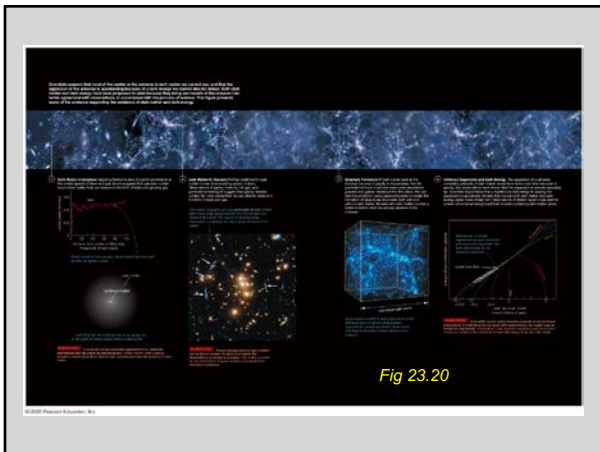
10 Mpc co-moving portion of Illustris simulation



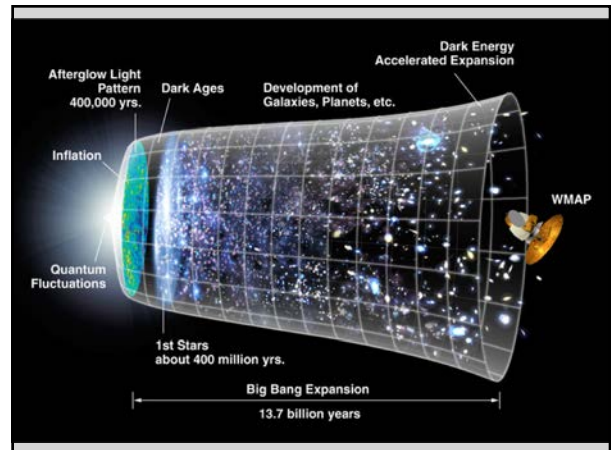
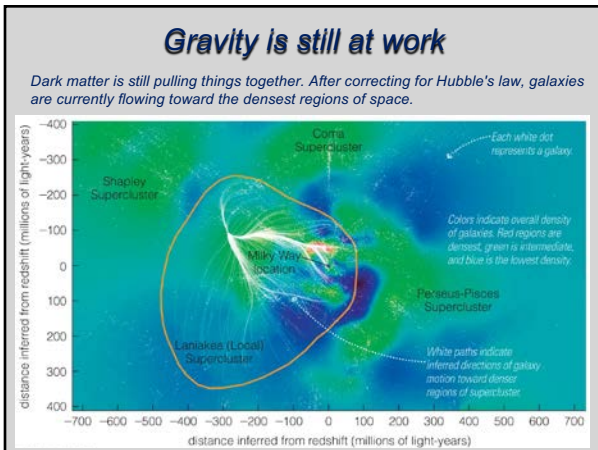
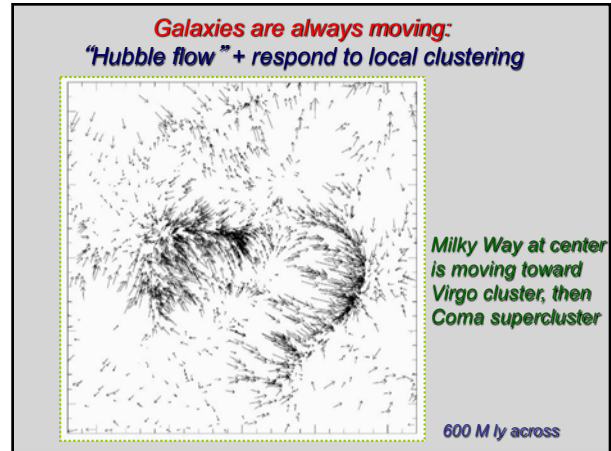
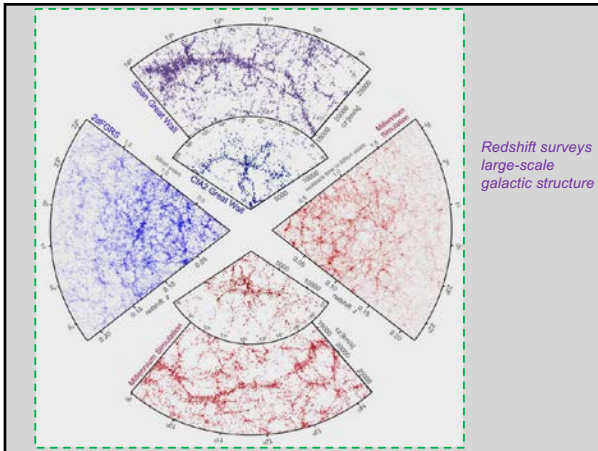
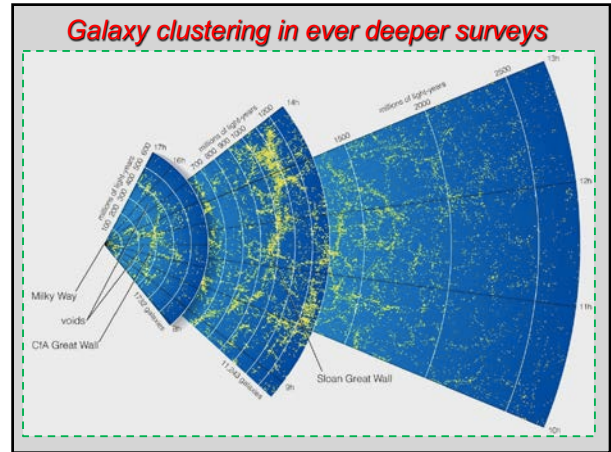
Close-up: Dark matter density + gas velocity in most massive cluster at z=0



Questions or Comments







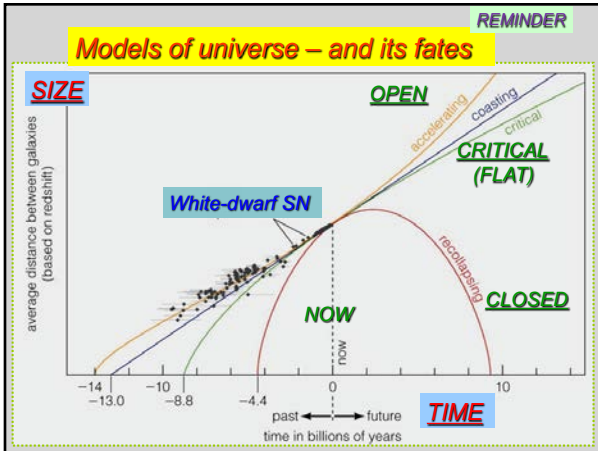
### The Big Mysteries

- What will be the fate of the universe ?
- What is the universe made of ?
- What is the dark matter ?
- Is the theory of inflation correct ?
- What is the dark energy ?
- Which of this, if any, should we believe?

Science is not about belief, it's about exploration...

- Is there life elsewhere ?

## Questions or Comments



Some say the world will end in fire  
Some say with ice  
From what I've tasted of desire  
I hold with those who favor fire  
But if I had to perish twice  
I think I know enough of hate  
To say that for destruction ice  
Is also great  
And would suffice

-- **Robert Frost**

National Poet Laureat

### The best estimates (2018)

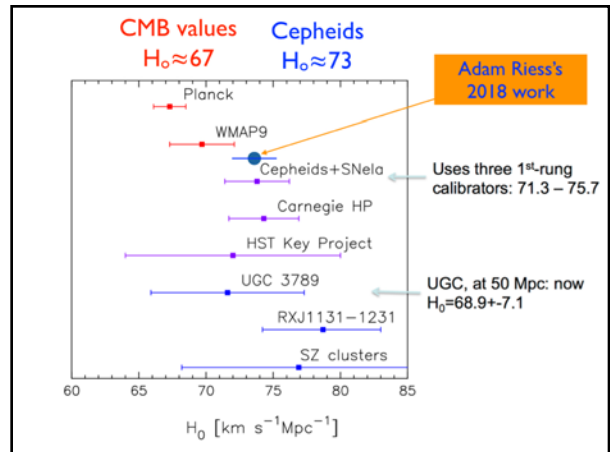
Hubble (Cepheids):  $H_0 = 73.45 \pm 1.66 \text{ km/s/Mpc}$   
 Planck-2017 (CMB):  $H_0 = 66.9 \pm 0.95 \text{ km/s/Mpc}$

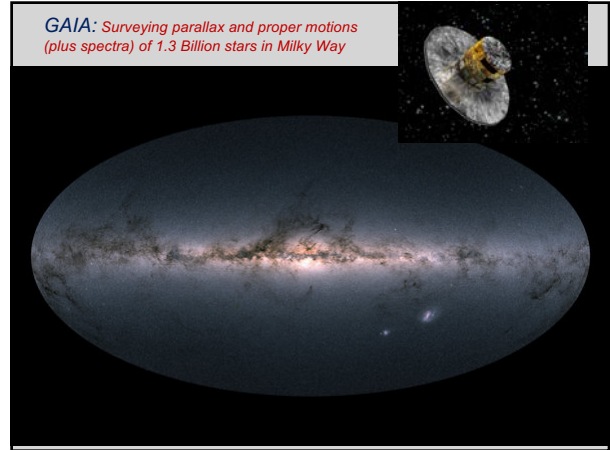
These two independent methods differ in the measured cosmic expansion rate by 10% (a problem?)

Expansion began (in the "Big Bang") approximately 13.8 Gyr ago

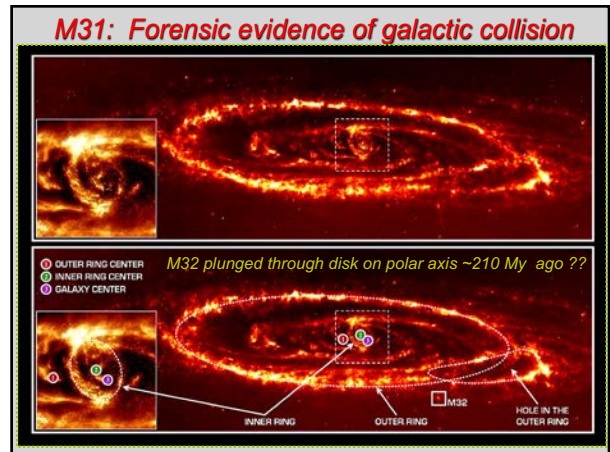
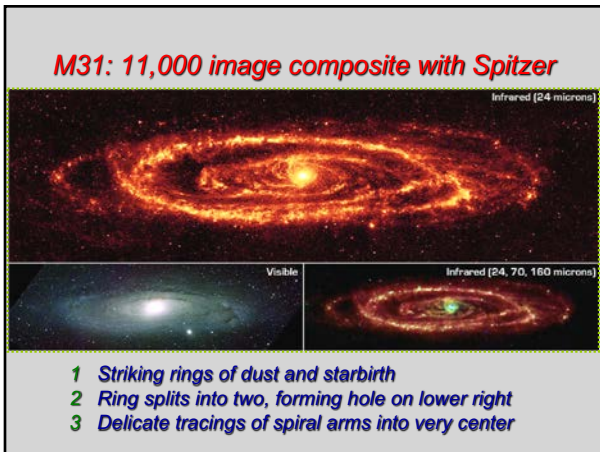
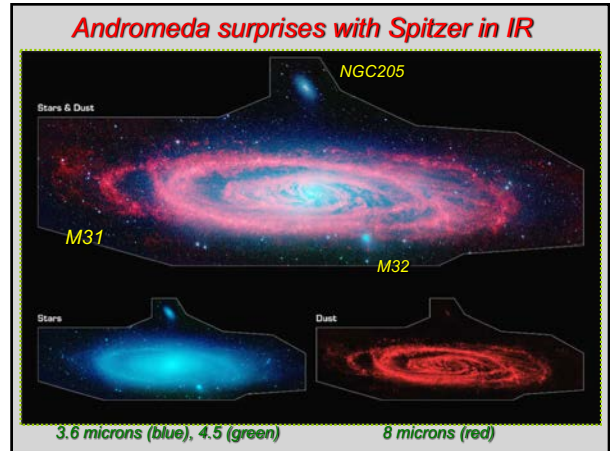
In 1998 astronomers found evidence that the expansion was accelerating !

Expansion slowed down (first 8 Gyr) then began accelerating (in the last 6 Gyr)





A final visit to our nearest big neighbor:  
**Andromeda**





***M31: Beautiful neighbor in UV and IR***



**GALEX:** Far-UV (blue) – young hot massive stars  
Near-UV (green) – relatively older stars  
**SPITZER:** 24 micron IR (red) – cool, dusty star forming

***We wish you good fortunes with the  
Final Exam on Wed May 6 (4:30pm  
on canvas/quizzes)***

***Join Max for zoom review on Mon  
May 4 at 4:30pm***

***... and we hope you've enjoyed this  
course that has touched the universe***