

ASTR 1040: Stars & Galaxies

Cosmic Web

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Lecture 30 Thur 13 Dec 2018
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Our Schedule and Topics

- **Final Exam on Sun, Dec 16 4:30pm-7:00pm**, here, closed book, 2 crib sheets allowed (4 sides), bring pencils
- All **observatory reports**, due in **D2L dropbox** by 6pm today, Thur Dec 13
- **After first three 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**

GAIA: Surveying parallax and proper motions (plus spectra) of 1.3 Billion stars in Milky Way

Evolution of Universe

OVERVIEW

1 billion years

380,000 years

3-5 minutes

Evolution of Universe

Timeline and Events Since Big Bang

- 14 billion years: Present day! Humans observe the cosmos.
- 1 billion years: Era of Galaxies
- 380,000 years: Era of Atoms
- 3 minutes: Era of Nuclei
- 3 minutes: Era of Nucleosynthesis
- 0.001 seconds: Particle Era
- 10⁻¹⁰ seconds: Electroweak Era
- 10⁻²⁸ seconds: GUT Era
- 10⁻⁴³ seconds: Planck Era

Key: neutron, proton, electron, neutrino, antiproton, antineutron, antilepton, quarks

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

time ↑ 380,000 years

temperature ↓ 1,500 K, 3,000 K, 6,000 K

era of atoms, CMB, era of nuclei

Major Events Since Big Bang

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

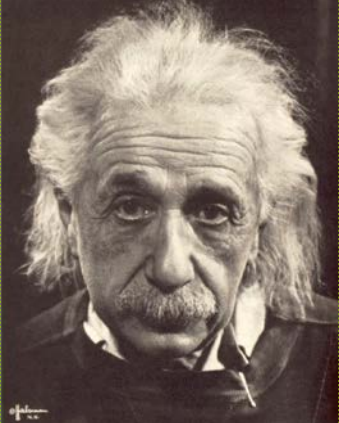
Once most electrons are not free to scatter photons, the photons could move freely.

Temperature Scale: 10³² K, 10²⁹ K, 10¹⁵ K, 10¹² K, 10⁹ K, 3000 K

Time Scale: 10⁻⁴³ seconds, 10⁻²⁸ seconds, 10⁻¹⁰ seconds, 0.001 seconds, 3 minutes, 300,000 years, 1 billion years, 14 billion yrs, Present

Key: neutron, proton, electron, neutrino, antiproton, antineutron, antilepton, quarks

- 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 ...!

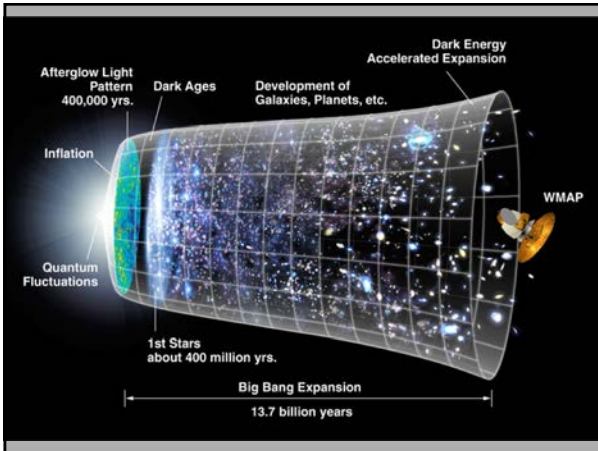


“Observational Pillars” of Big Bang Theory

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





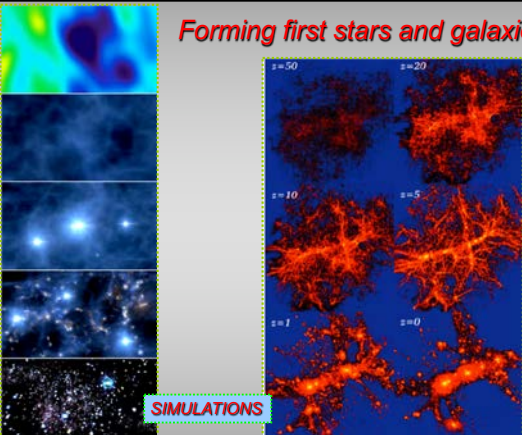


Era of Galaxies $Z \sim 20$

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

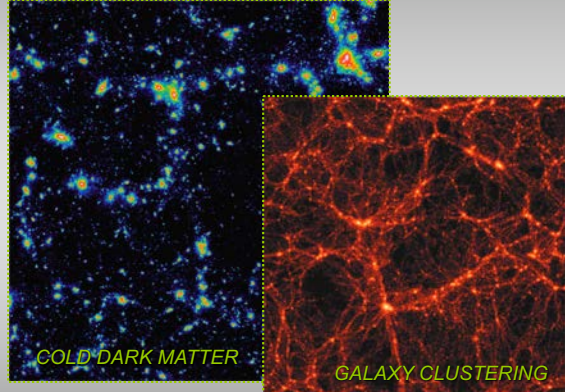


Forming first stars and galaxies

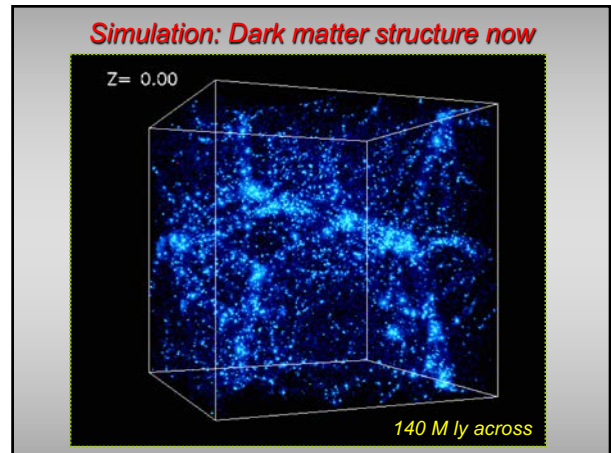
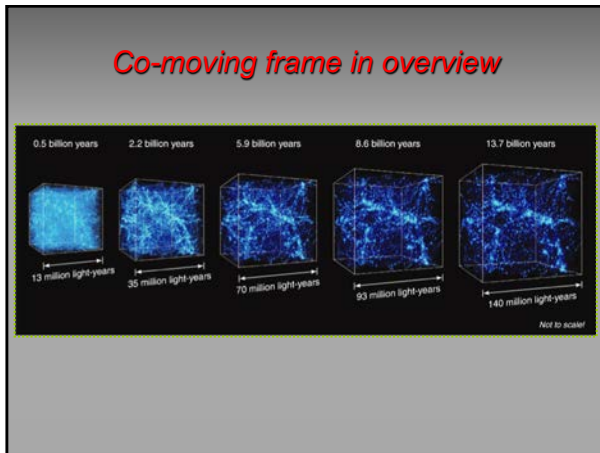
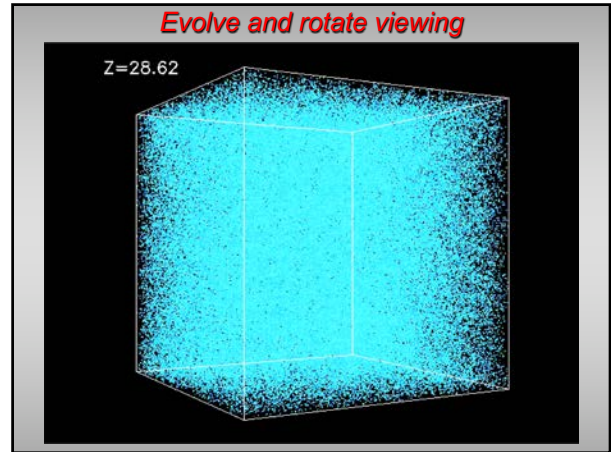
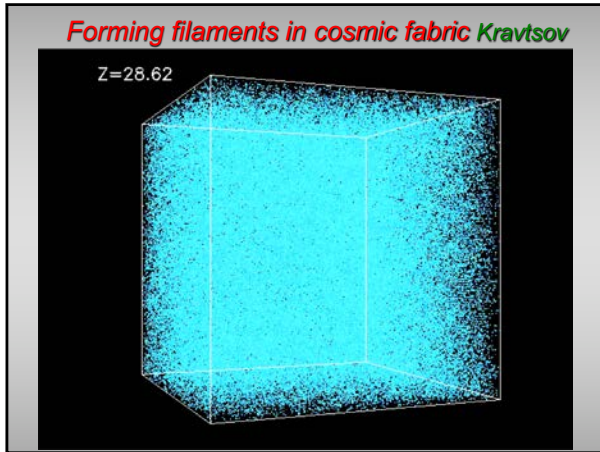


Labels: $z=50$, $z=20$, $z=10$, $z=5$, $z=1$, $z=0$. SIMULATIONS

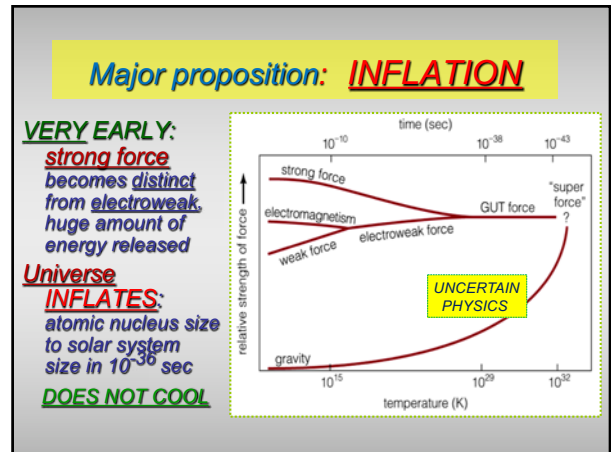
Simulating large-scale structure

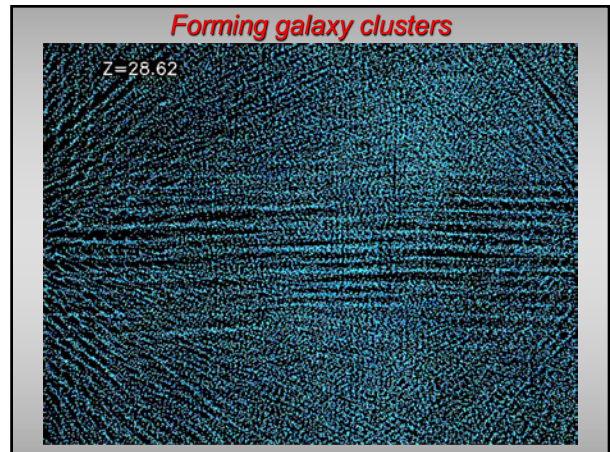
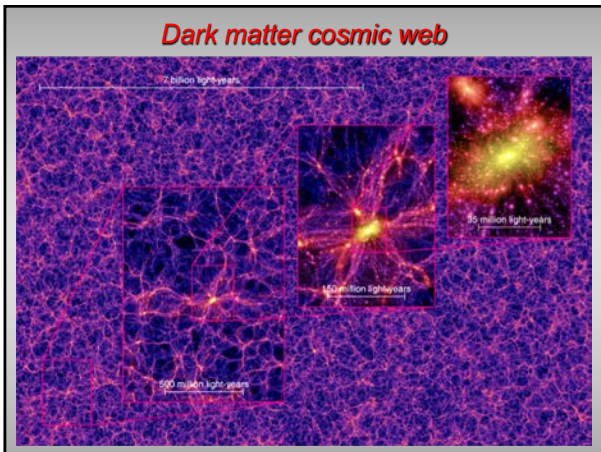
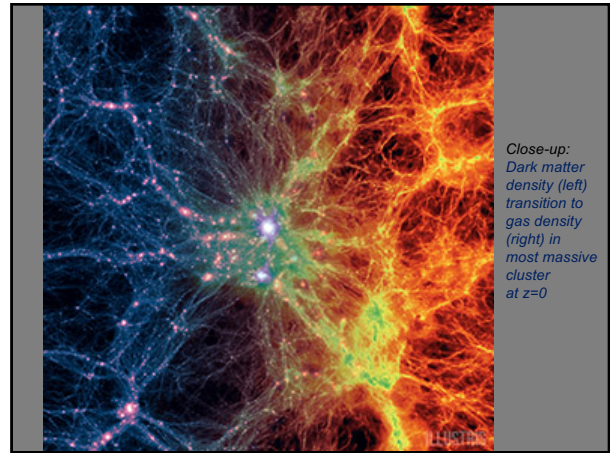
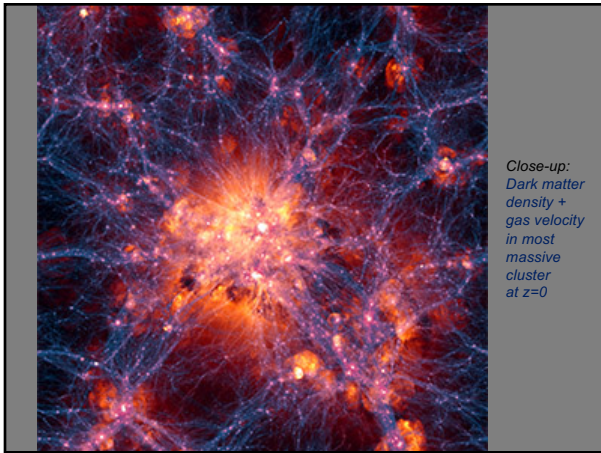
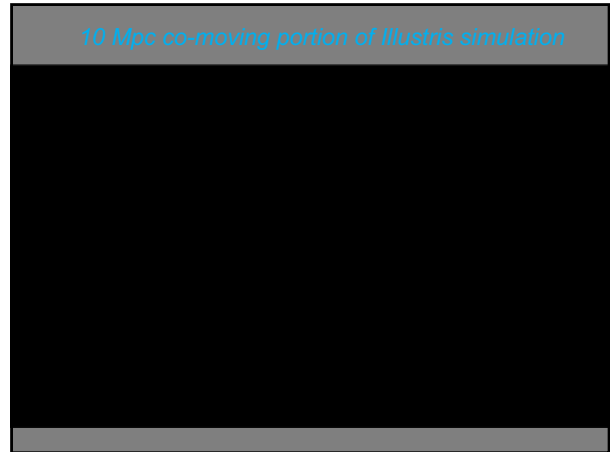


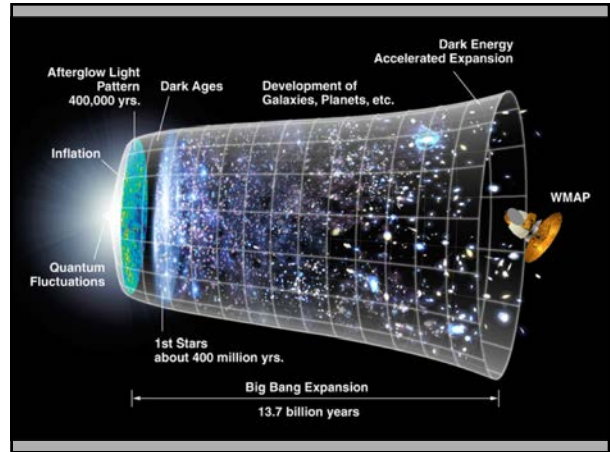
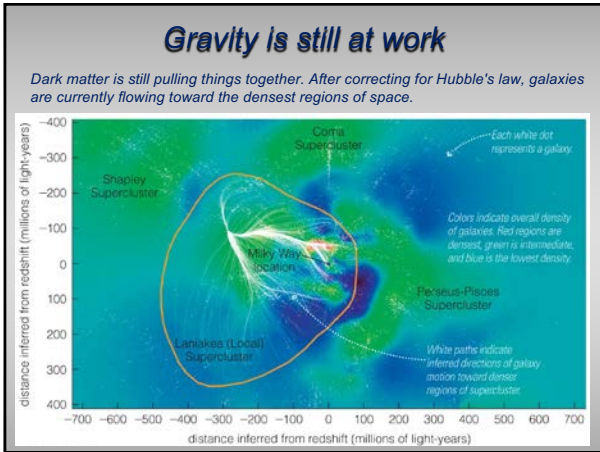
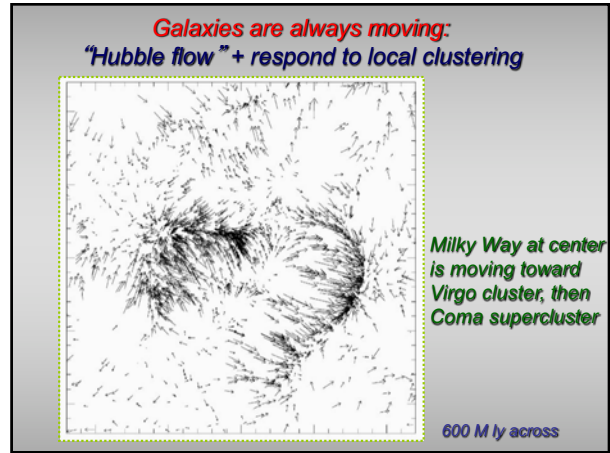
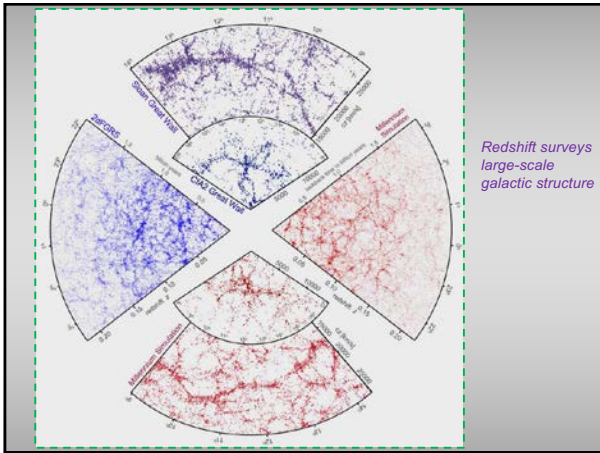
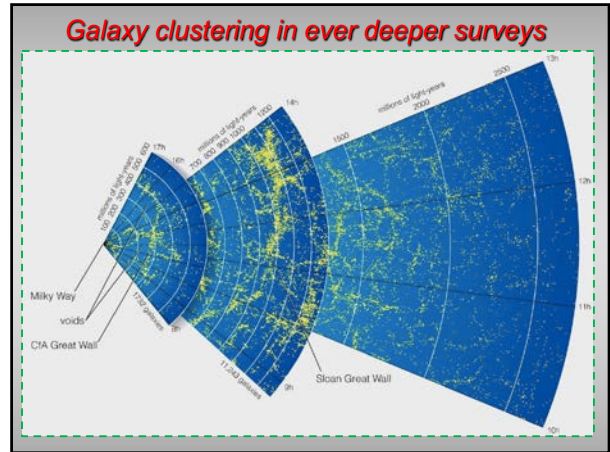
Labels: COLD DARK MATTER, GALAXY CLUSTERING



- Clicker: *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

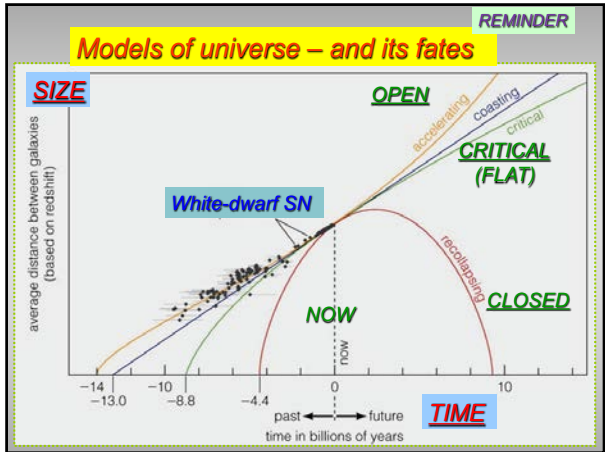






The Big Mysteries

- 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 ?



The best estimates (2018)

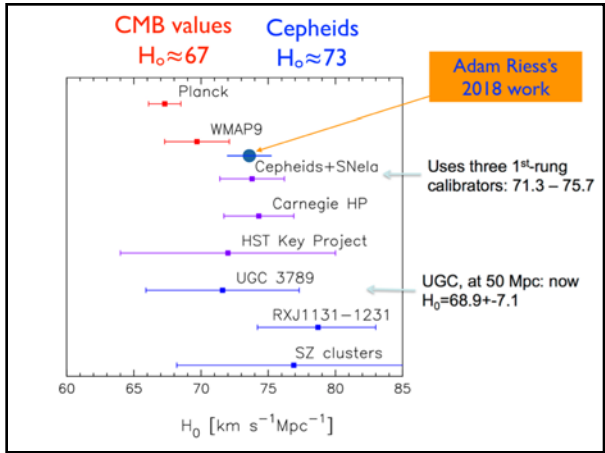
Hubble (Cepheids): $H_0 = 73.45 \pm 1.66 \text{ km/s/Mpc}$
 Planck-2017 (CMB): $H_0 = 66.9 \pm 0.95 \text{ km/s/Mpc}$

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)



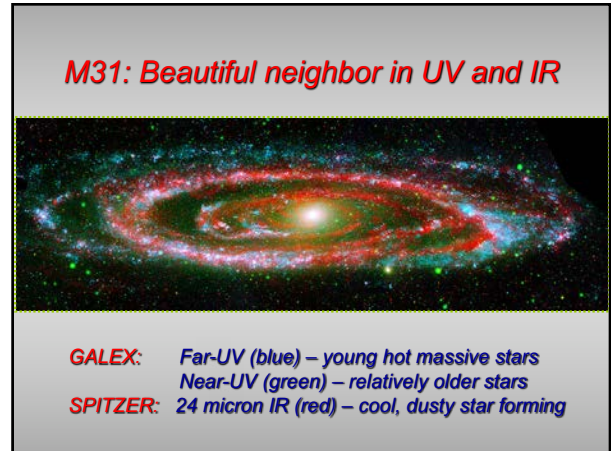
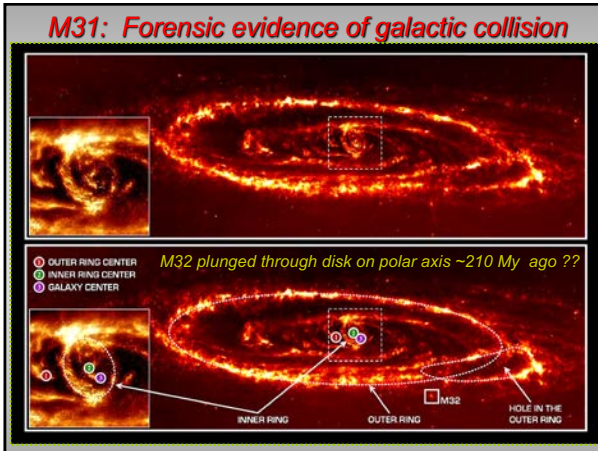
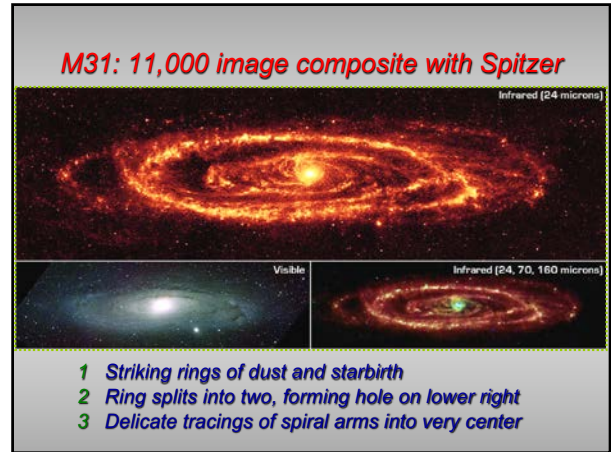
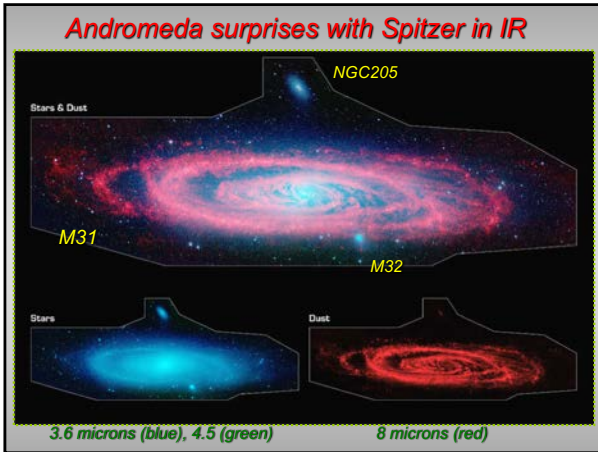
*Some say **the world will end in fire**
 Some say with **ice**
 From what I've tasted of desire
 I hold with those who favor **fire**
 But if I had to perish twice
 I think I know enough of hate
 To say that for destruction **ice**
 Is also great
 And would suffice*

-- Robert Frost

National Poet Laureat

A final visit to our
 nearest big neighbor:

Andromeda



We wish you good fortunes with the Final Exam this Sunday (4:30pm here) – please bring pencils, crib sheets, ID

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