

**ASTR 1040: Stars & Galaxies**

**Cosmic Web**

Prof. Juri Toomre TAs: Peri Johnson, Ryan Horton  
Lecture 30 Thur 3 May 2018  
zeus.colorado.edu/astr1040-toomre

**Our Schedule and Topics**

- **Final Exam on Wed May 9, 4:30pm-7:00pm**, here, closed book, 2 crib sheets allowed (4 sides), bring pencils
- All **observatory reports**, "virtual" or actual project, due **D2L dropbox** by 6pm Mon May 7
- **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: First galaxies form.
- 380,000 years: Atoms form, photons fly free and become microwave background.
- 3 minutes: Matter (mostly normal matter: 25% hydrogen, 25% helium, by mass).
- 0.001 second: Matter annihilates.
- 10<sup>-10</sup> second: Electroweak and weak forces become distinct.
- 10<sup>-12</sup> second: Strong force becomes distinct, perhaps causing inflation of universe.
- 10<sup>-43</sup> second: Gravity becomes distinct from other forces?

**Key**

- neutron, proton, electron, neutrino, antiproton, antineutron, antilepton, antiquark, quark

**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**

**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.

Time Since Big Bang

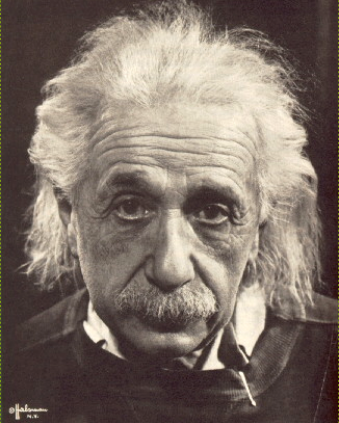
- Present: Humans observe the cosmos.
- 14 billion yrs: Era of Galaxies
- 1 billion years: Era of Atoms
- 380,000 years: Era of Nuclei
- 3 minutes: Era of Nucleosynthesis
- 0.001 seconds: Particle Era
- 10<sup>-10</sup> seconds: Electroweak Era
- 10<sup>-12</sup> seconds: GUT Era
- 10<sup>-43</sup> seconds: Planck Era

Temperatures: 3000 K, 10<sup>9</sup> K, 10<sup>12</sup> K, 10<sup>15</sup> K, 10<sup>29</sup> K, 10<sup>32</sup> K

**Key**

- neutron, proton, electron, neutrino, antiproton, antineutron, antilepton, antiquark, quark

- 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 ...!

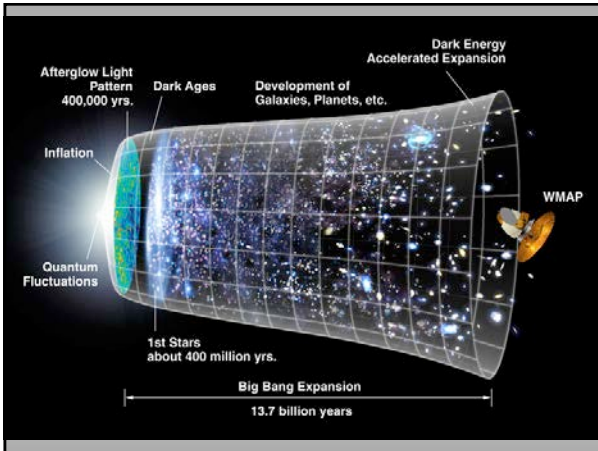


### "Observational Pillars" of Big Bang Theory

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






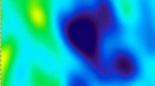
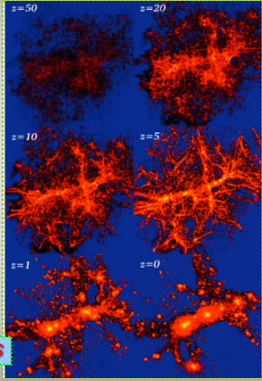


### Era of Galaxies $Z \sim 20$

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

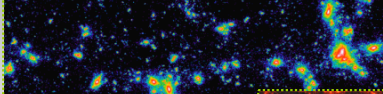
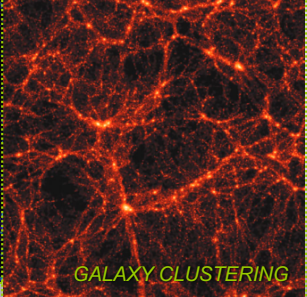


### Forming first stars and galaxies

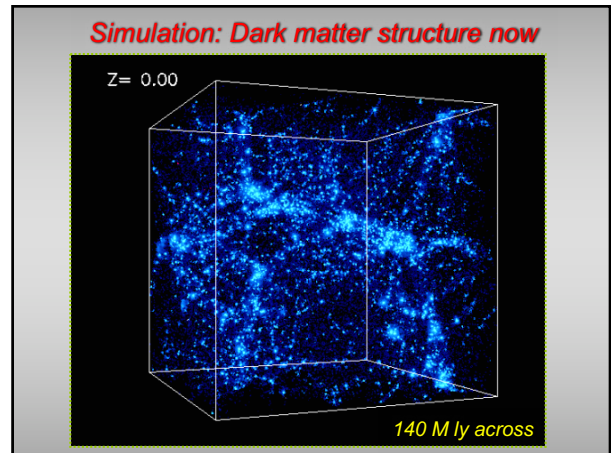
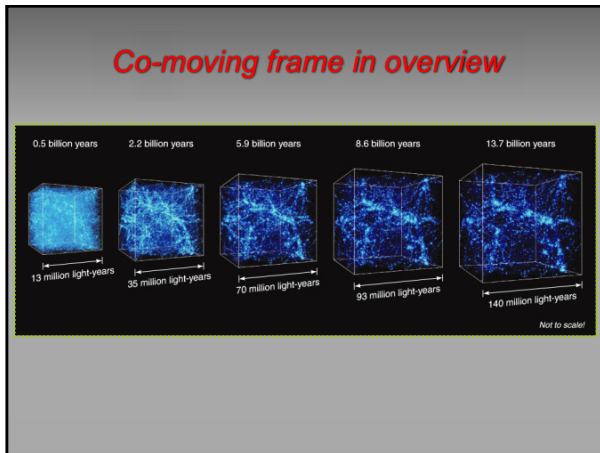
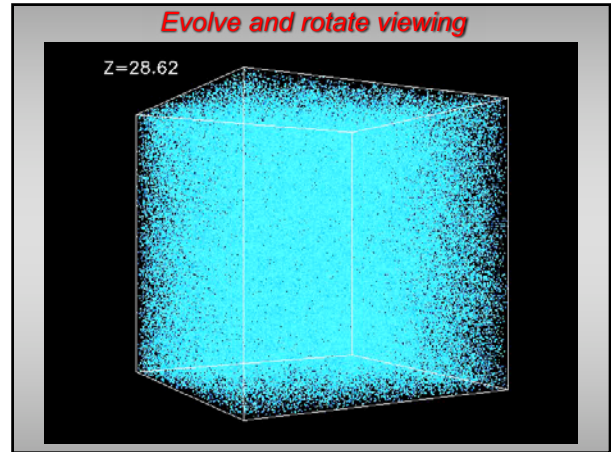
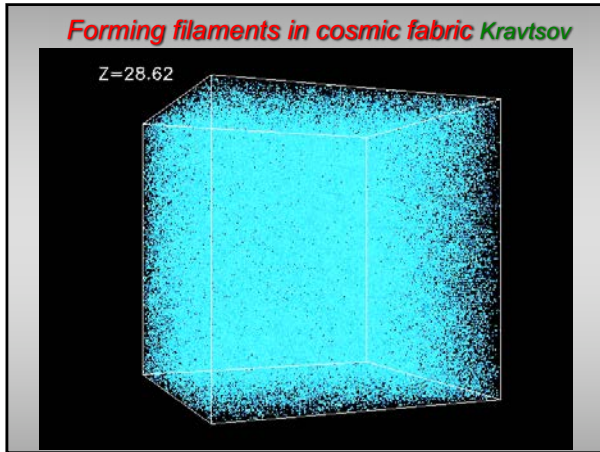



**SIMULATIONS**

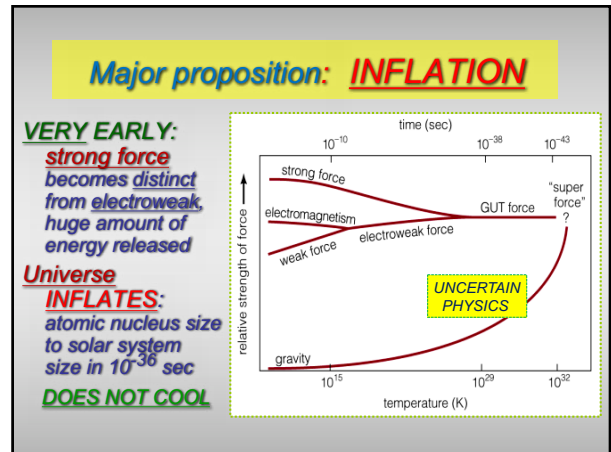
### Simulating large-scale structure

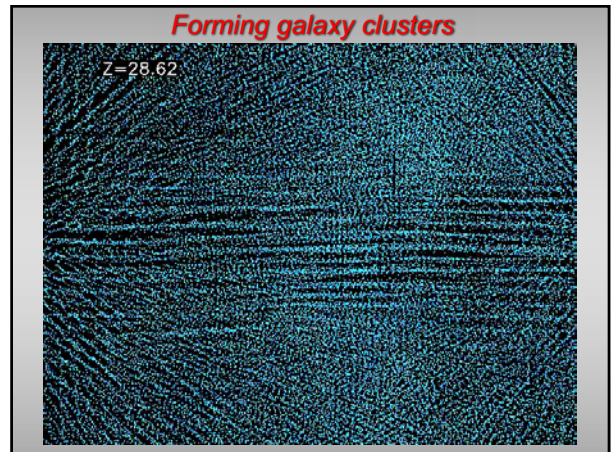
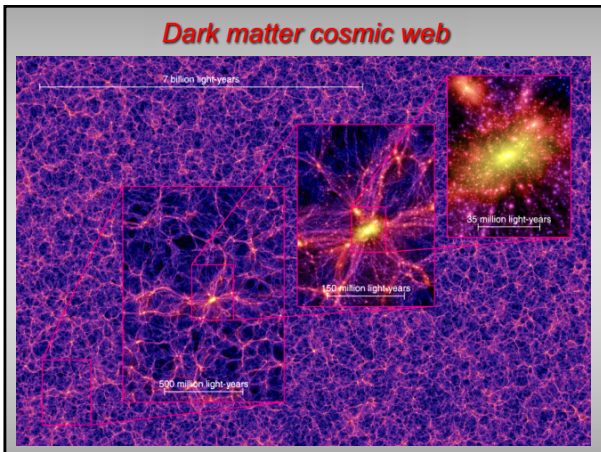
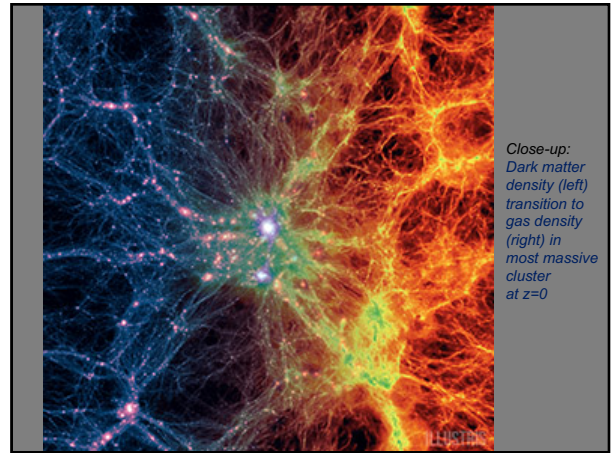
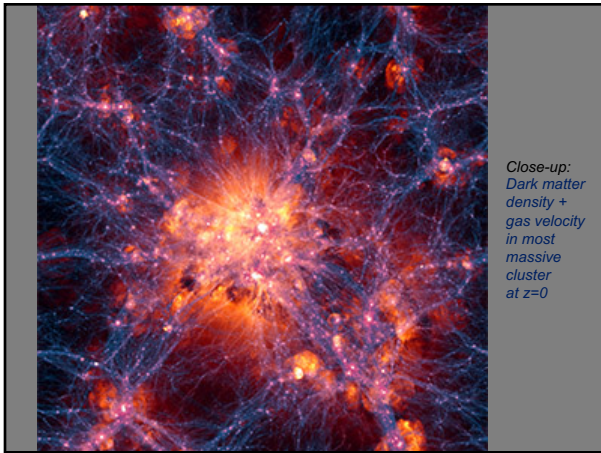
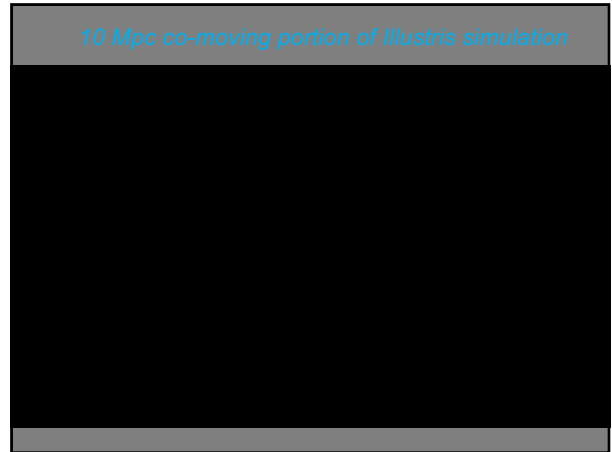



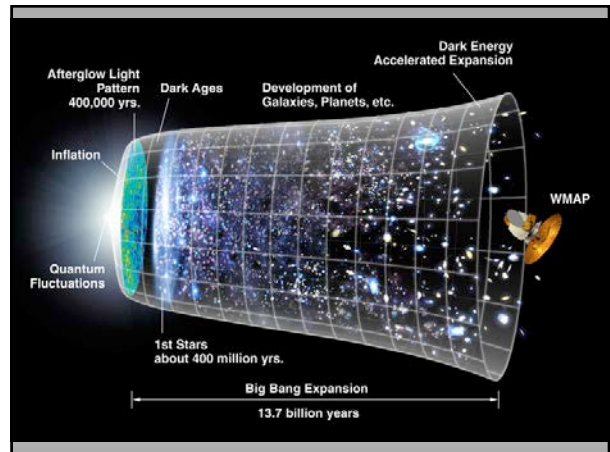
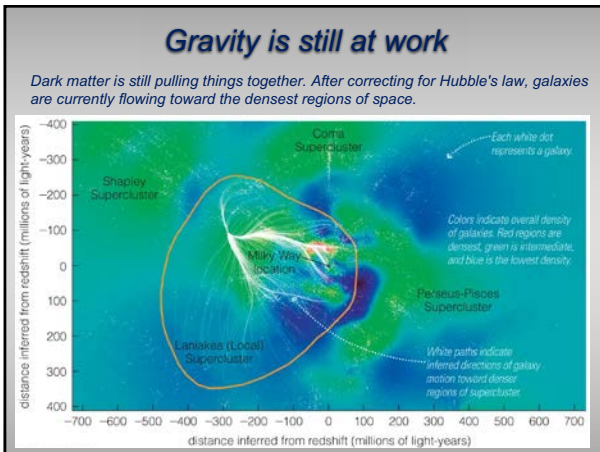
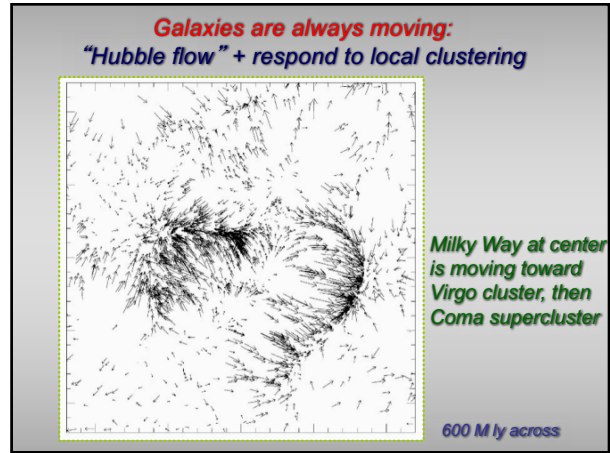
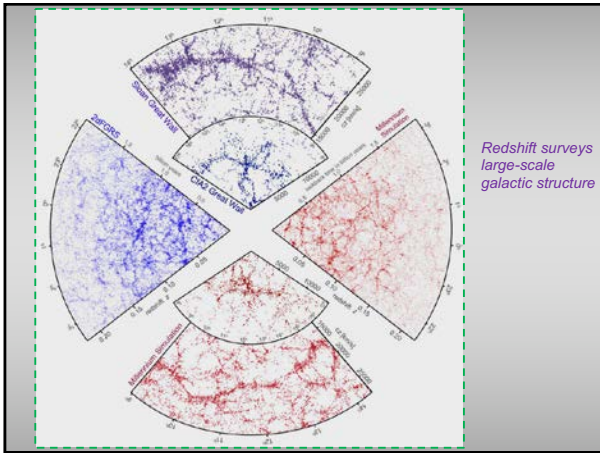
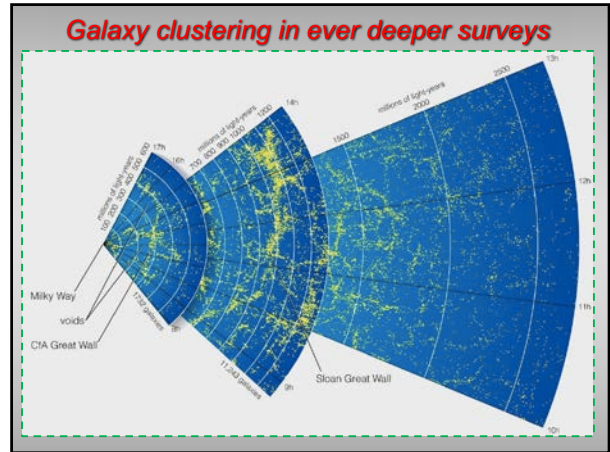
**COLD DARK MATTER**      **GALAXY CLUSTERING**



- 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

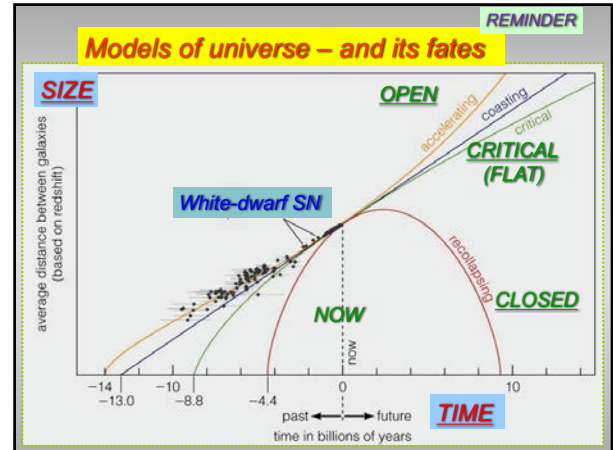






### The Big Mysteries

- 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 ?



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

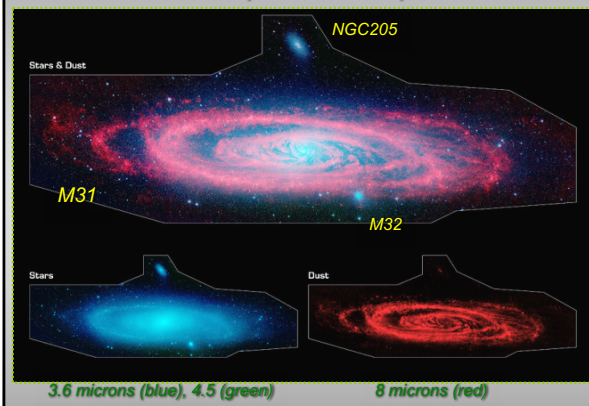
-- **Robert Frost**

National Poet Laureat

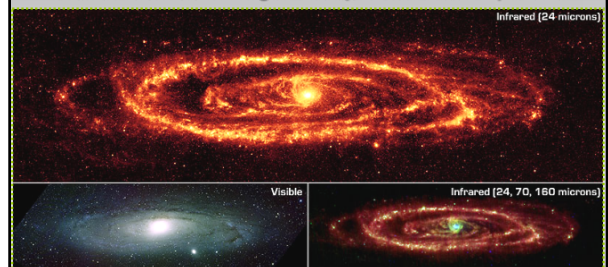
A final visit to our  
 nearest big neighbor:

**Andromeda**

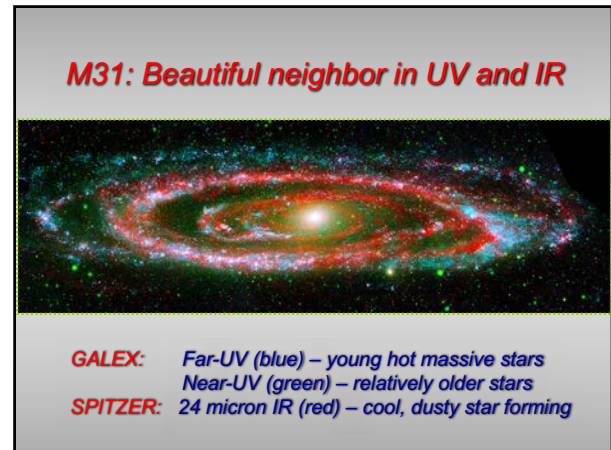
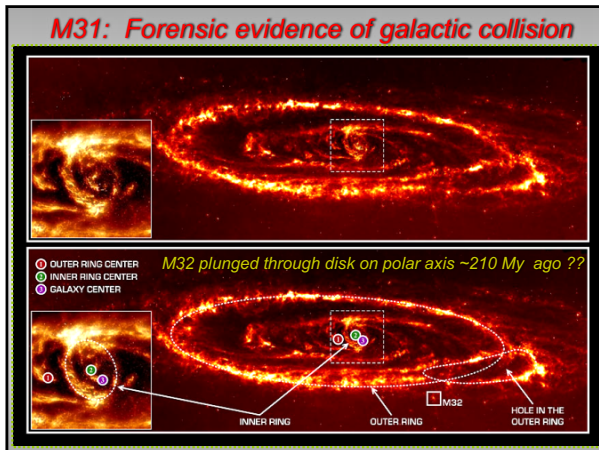
### Andromeda surprises with Spitzer in IR



### M31: 11,000 image composite with Spitzer



- 1 Striking rings of dust and starbirth
- 2 Ring splits into two, forming hole on lower right
- 3 Delicate tracings of spiral arms into very center



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

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