Where is the gas in the Universe?
How does it get into galaxies?
Goals for today

1) match gas detection strategies to temperatures and explain why detecting “warm-hot” or ultra-cold gas is so hard
2) define the “missing baryons” problem and candidate solutions to it
3) relate large-scale structure to gas phases and missing baryons
4) identify the two processes that must occur for gas to get into galaxies and form stars
It’s hard to detect gas in the Universe

emission:

- **ultra-cold**
  - CO 2.6mm mm 10-50 K molecular gas with metals
  - HI 21cm radio 50-100 K neutral atomic gas
  - Hα 656nm visible $10^{3-4}$ K ionized-neutral boundary

- **warm-hot**
  - continuum UV/X-ray $10^{6-7}$ K really hot gas

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problems:

* ionized Hydrogen has no lines (why?)
* H$_2$ has no lines until it gets hotter than ~100 K
* continuum from diffuse gas is weak unless very hot
* few/weak emission lines from metals in warm-hot gas
idea for warm-hot (and distant cold) gas: backlight it with something hotter

“quasar absorption line systems”

Local Universe: detect warm-hot gas via trace ionized metal lines (e.g., O$^{+5}$) – *why not H lines?*

Distant Universe: detect high-redshift HI by Ly $\alpha$ absorption – *why not 21cm?*
These spectra have been “de-redshifted” to the quasar rest-frame. The lower panel shows:
A) warm-hot metal lines
B) cold metal lines
C) warm-hot H lines
D) cold H lines
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the Lyman $\alpha$ forest
Hubble’s new Cosmic Origins Spectrograph chases low-redshift warm-hot gas

Chandra observation of X-ray hot halo of gas around spiral galaxy – how much more gas could be in warm-hot phase?

Watch the news!
Missing Baryons Problem

- > ~50% of baryons (normal matter) are not observed in the local universe, compared to (1) Big Bang element production calculations and (2) Lyman $\alpha$ forest observations of gas at high $z$
  
- **Assumed solution:** Warm-Hot Intergalactic Medium (“WHIM”, $10^5$-$10^6$ K) in the cosmic web: barely detectable with HST/COS
  
- **Also could be:** Ultra-cold $\text{H}_2$
  
- *undetected gas also implied by observed star formation rates and non-evolution of HI reservoir over cosmic time*
gas temperatures vary within large-scale structure

Clusters: gas shock-heats as it falls in, reaching X-ray hot temperatures (necessary for support against gravity)

Filaments: gas is cooler and shock-heating mechanism may not work – expected home of warm-hot gas
Think-Pair-Share 2

If someone told you that in a certain type of environment, all the baryons are accounted for and there is no missing baryons problem, which environment would you suspect the person was talking about?
A) cluster
B) filament
C) individual galaxy
D) both A and C
How does gas get into galaxies and form stars?

*Recall stars form only in cold, dense gas.*

**Two steps:**

- **cooling** from the warm-hot phase to HI then H$_2$ (OR: could HI and warm H$_2$ condense from large ultra-cold reservoir? ➔ open question)

- **loss of rotation** ("angular momentum") that would otherwise maintain stable gas orbits – gas inflow is driven by non-circular forces from bars & tidal distortions that help disturb stable gas orbits
The disk problem

• Simulated merging destroys disks and causes too much gas to flow inward to fuel central starbursts
• But the real Universe consists mainly of extended-disk-dominated galaxies (like our own or dwarf disks)
• Possible solution: blow out central gas with supernova and black hole feedback, then let disks regrow from gas fall-back and cosmic gas accretion

→ Would get lots of star formation, but not too much in center

→ If correct, should see merger remnants in the act of rapidly rebuilding disks

(My research…)
GALEX opens our eyes: “invisible” UV disks around spheroid-dominated galaxies

galactic nuclei

active research area for my group at UNC
Before helping to fuel star formation in a galaxy disk, the gas that COS hopes to detect via nearby quasar absorption lines must:
A) cool
B) become HI and then $\text{H}_2$
C) stop orbiting stably in the disk
D) both A and B