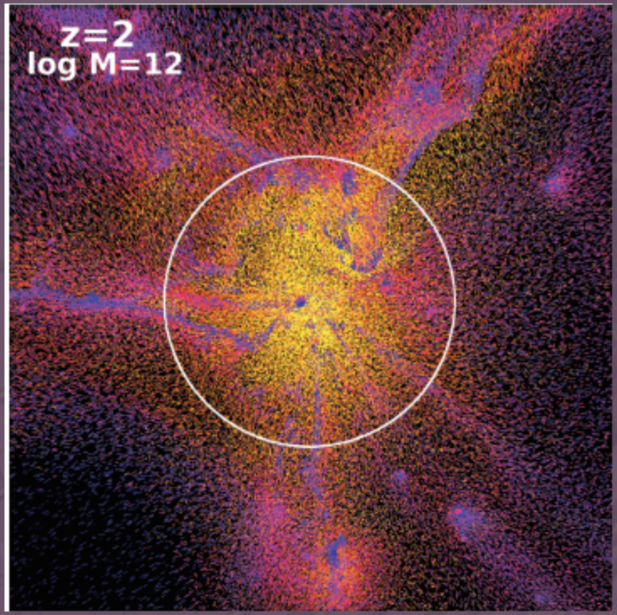
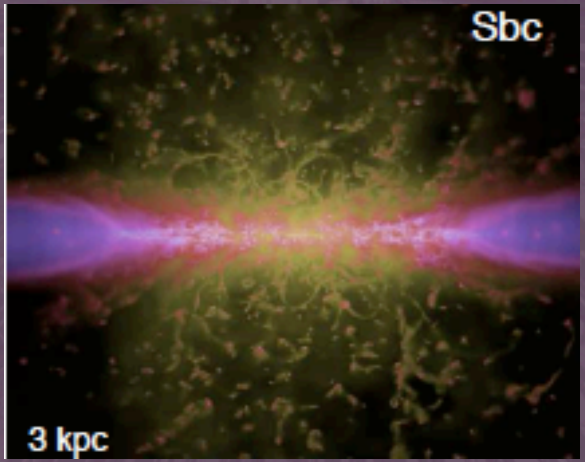
Galaxy and Black Hole Evolution in the 2020s: A High-Energy View

David Weinberg, Ohio State University
Department of Astronomy and CCAPP





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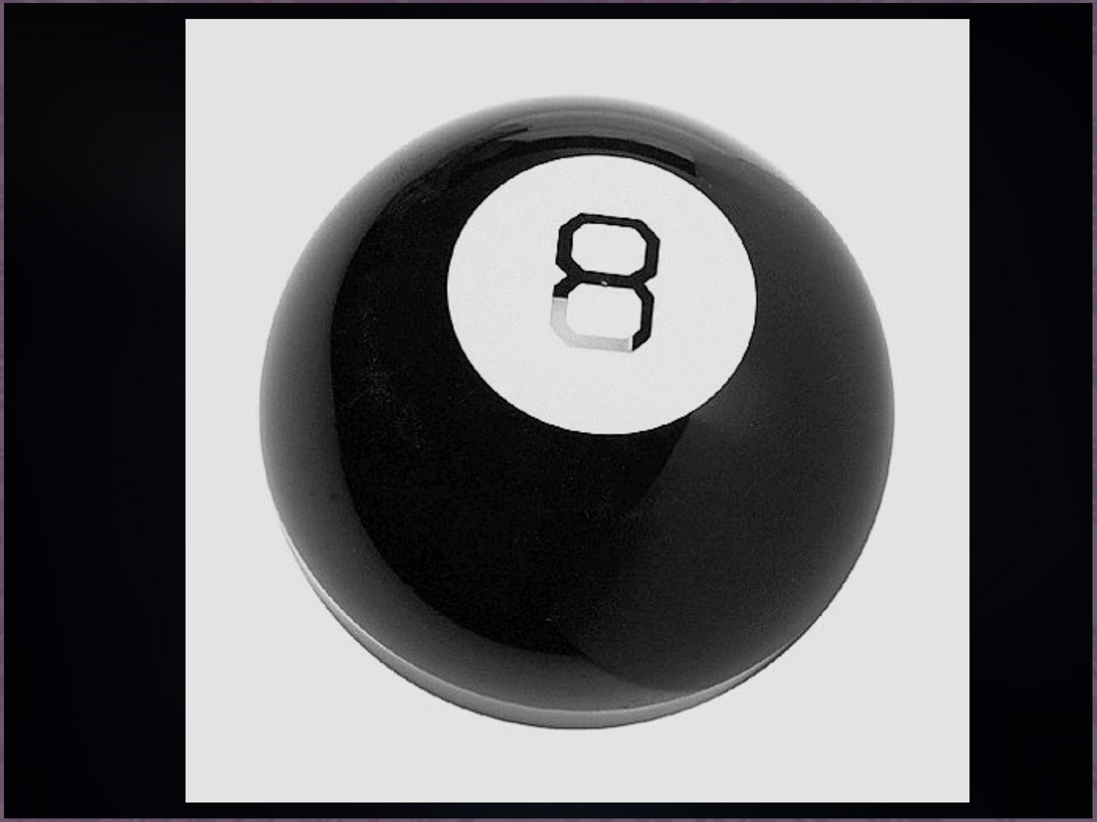
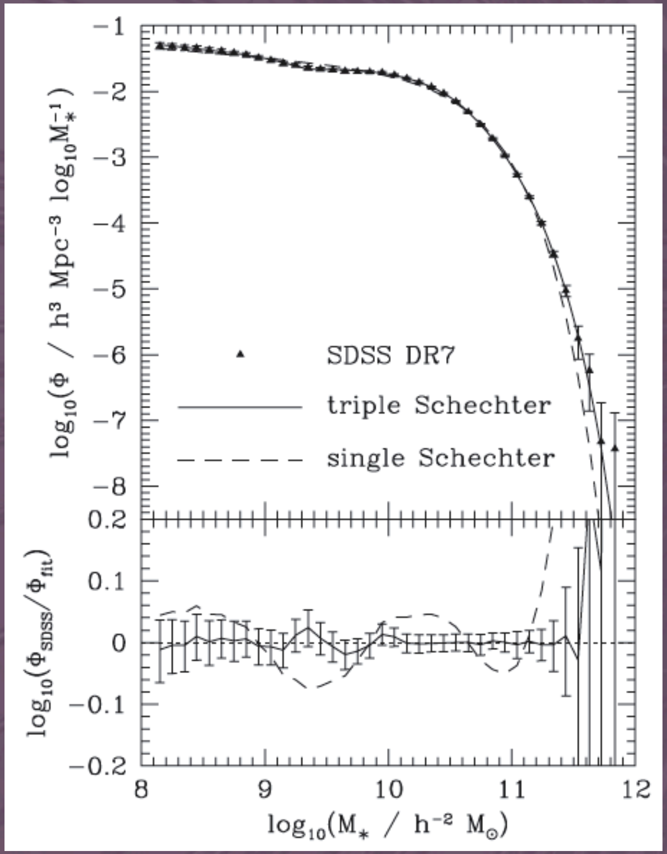


Why is galaxy formation so inefficient?

What physics governs the masses, sizes, morphologies, and star formation histories of galaxies?

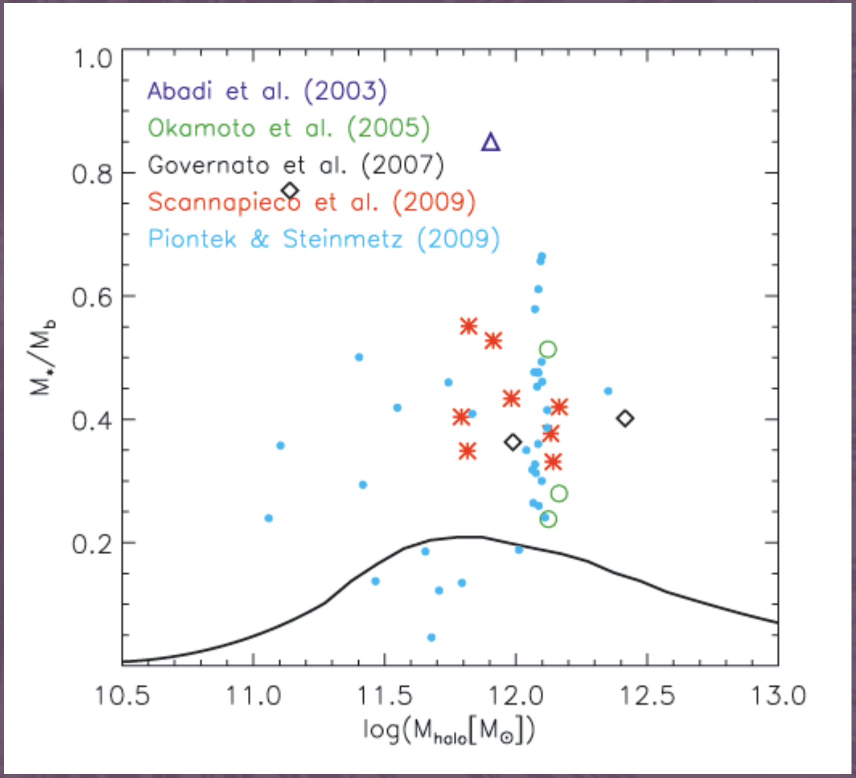
Why is galaxy formation so inefficient?

Global fraction of baryons in stars is ~ 3.5%



Li & White 2009

Conversion of halo baryons to stars of central galaxy *peaks* at ~20%.



Guo, White, Li, & Boylan-Kolchin 2010

Why is galaxy formation so inefficient?

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Conversion of halo baryons to stars of central galaxy *peaks* at ~ 20%.

Probable answer: Feedback.

Open issues:

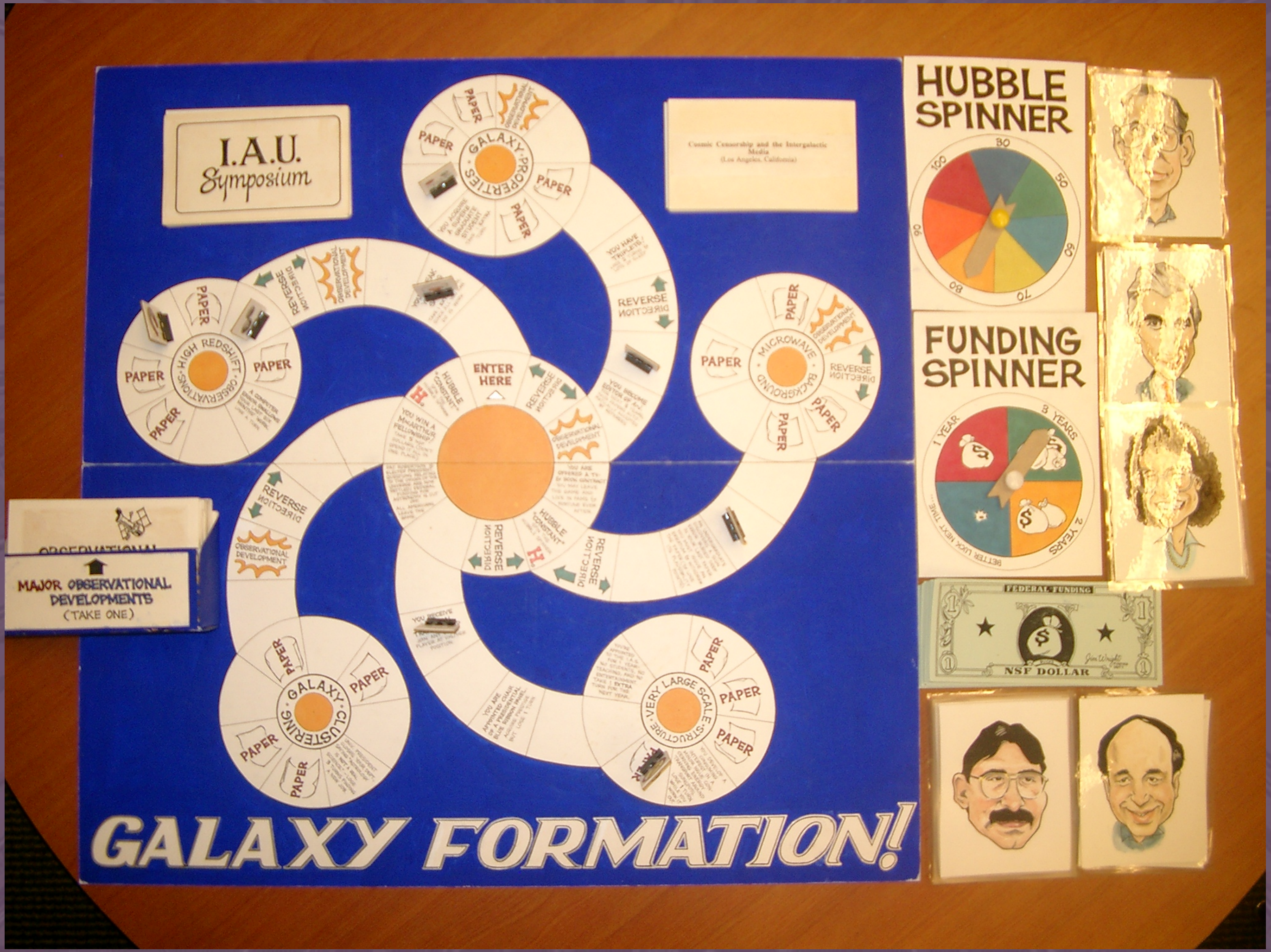
How much feedback is "ejective" vs. "preventive"?

What are the mechanisms of ejective and preventive feedback?

How are the remaining baryons distributed, spatially, and in temperature-density-metallicity? How can they be mapped?

Why is galaxy formation so inefficient?

What physics governs the masses, sizes, morphologies, and star formation histories of galaxies?



A pretty good picture of galaxy formation

Baryon dissipation in DM halos leads to star-forming disks.

Star-formation tracks gas accretion, but
(a) (stellar?) feedback ejects gas, roughly $\eta \sim 1/\sigma$
(b) accretion and recycling shut down for $M_{halo} > 3\times10^{12}\ M_{sun}$ (AGN?)
(c) accretion shuts down in satellites after ~ 1 Gyr

Mergers track mergers of subhalos.
Gas rich mergers preserve disks. Gas poor mergers destroy them.
Late minor mergers grow spheroid diameters.

We don't fully understand all the mechanisms, but does this picture have all of the key ingredients?


REPLY
HAZY. TRY
AGAIN LATER.

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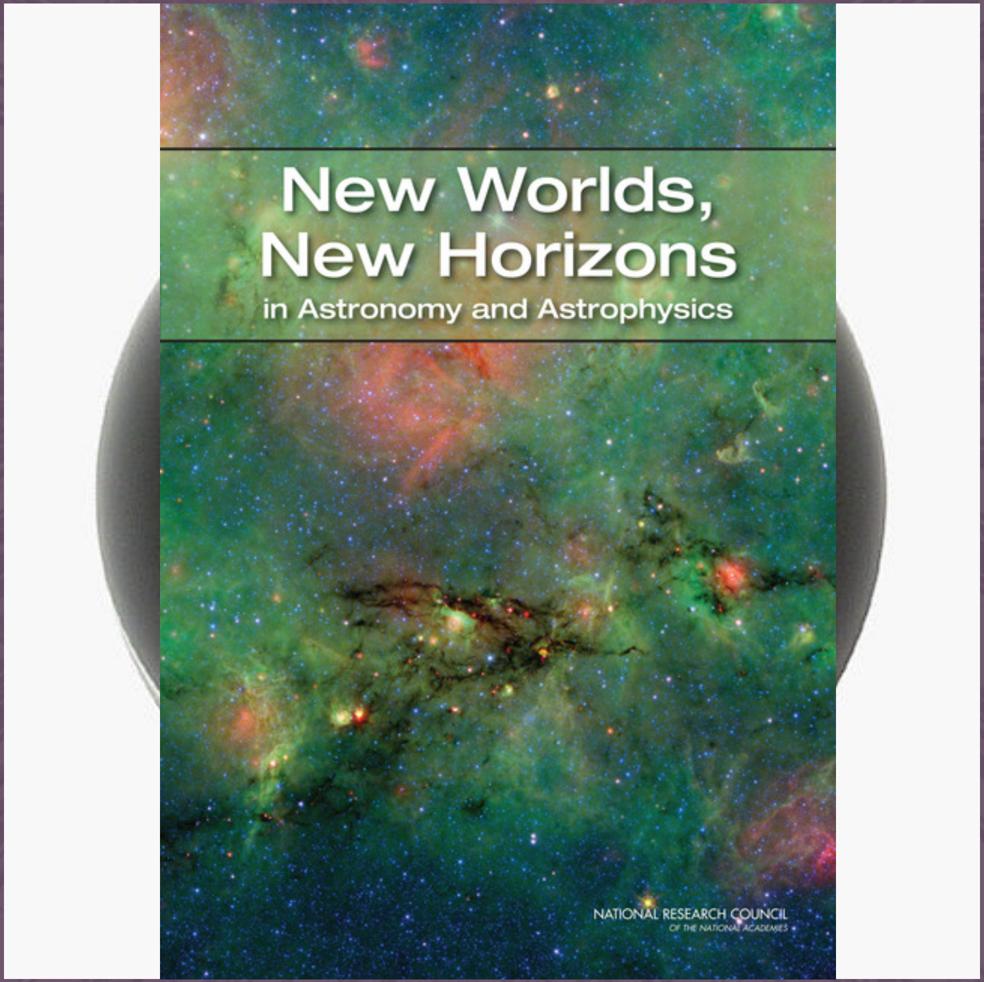


Astro 2010 Questions

Galactic Neighborhood:

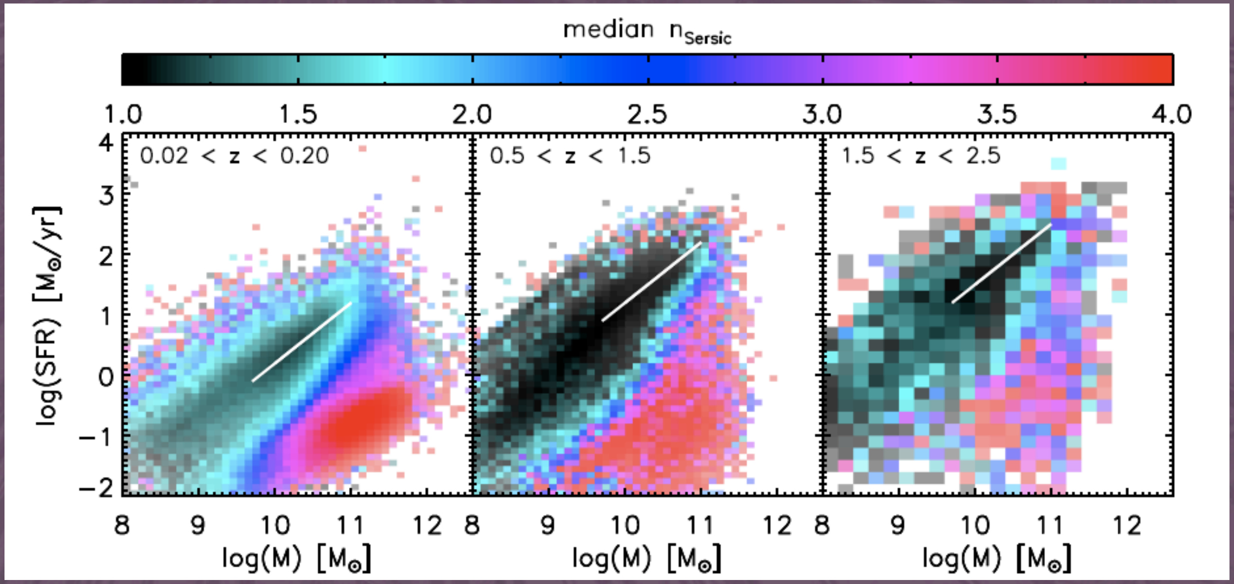
- What are the flows of matter and energy in the circumgalactic medium?
- What controls the mass-energy-chemical cycles within galaxies?

Galaxies Across Cosmic Time:

- How do cosmic structures form and evolve?
- How do baryons cycle in and out of galaxies, and what do they do while they are there?
- How do black holes grow, radiate, and influence their surroundings?

Some recent observational developments

- Cosmic star formation rate out to z = 6, and even beyond
- Distribution of galaxies in the M_* - SFR - Z_{gas} plane over a broad redshift range:
    - "Main sequence" of star-forming galaxies
    - "Red and dead" sequence of passive galaxies
    - mass-metallicity relation and "fundamental plane"
- Size evolution – surprising growth of early-type galaxies since z = 1 – 2



Wuyts et al. 2011

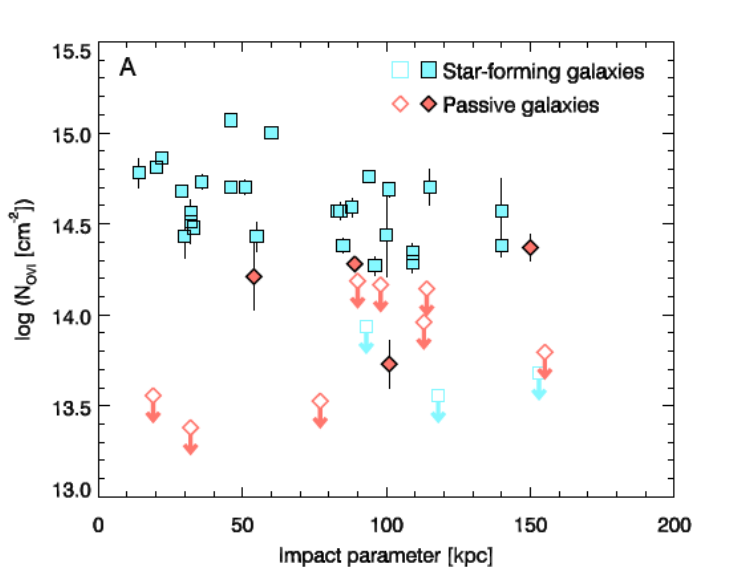
COS-Halos, OVI and low-ionization gas

Tumlinson et al. 2011

OVI absorption ubiquitous around star-forming galaxies out to 150 kpc.

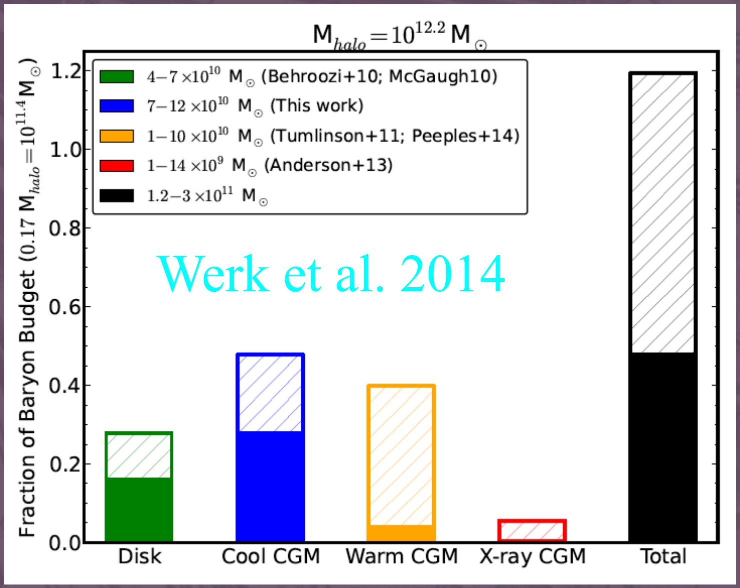
Often absent around passive galaxies.

$M_O = 1.2e7\ M_{sun}\ (f_{OVI} / 0.2)^{-1} \sim M_{O,ISM}$

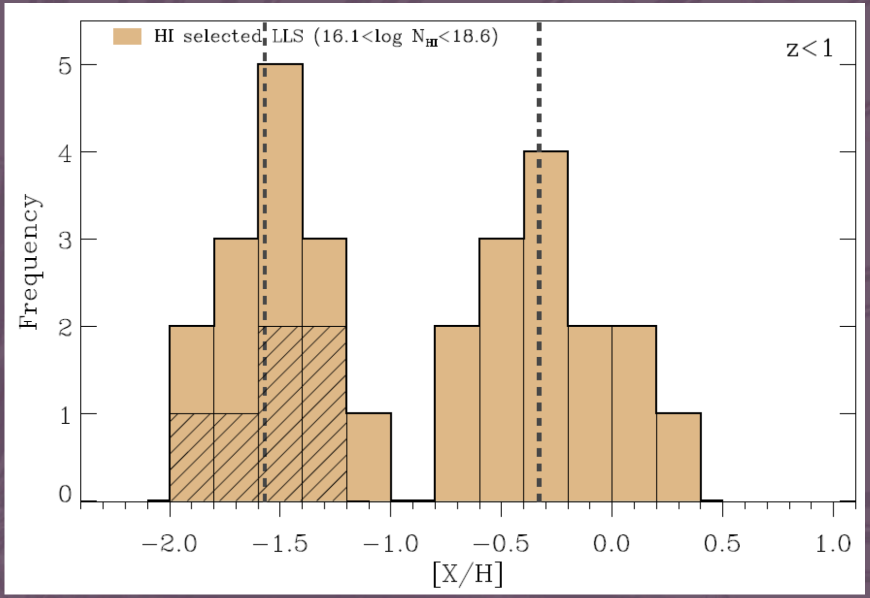


HI absorption ($N_{HI} > 10^{15}\ cm^{-2}$) is ubiquitous around star-forming galaxies, common around passive galaxies.

Inferred mass of cool (few × 10^4 K) gas around star-forming galaxies is comparable to *stellar* mass of disk.

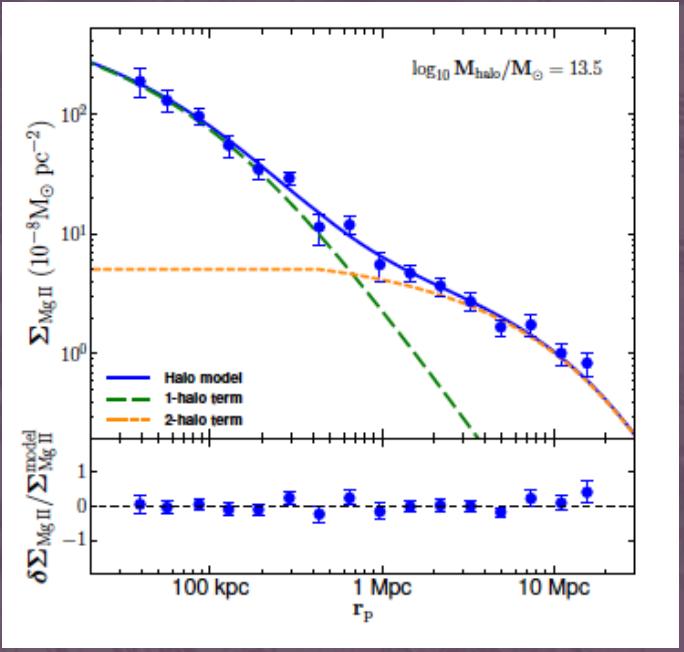


Lehner et al. 2013



High column density HI absorption has bimodal metallicity distribution.

Correlation studies:
MgII absorption in ~ 10^{13} M_{sun} halos of massive galaxies.
Substantial dust survival in IGM/CGM, ~25% of circum/intergalactic metals.

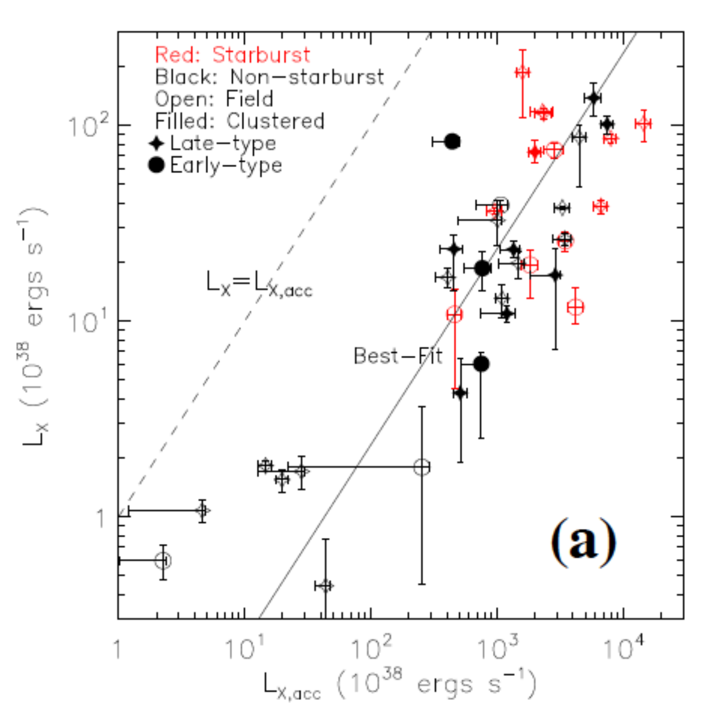


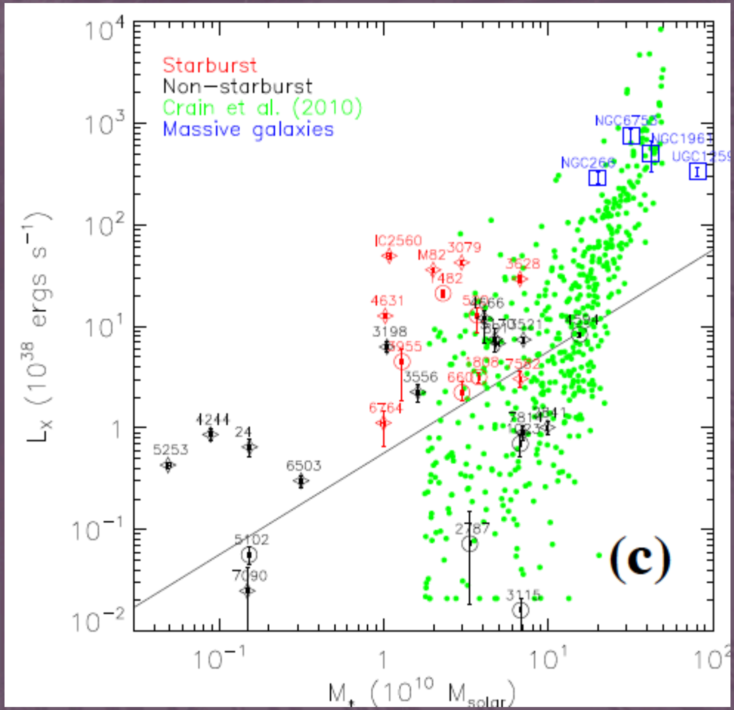
Zhu, Ménard et al. 2013

Hot gas coronae of disk galaxies?

Luminosity well below naïve analytic expectation, though roughly consistent with numerical simulations.
More correlated with SFR than with stellar mass.

Li, Wang, & Crain 2014





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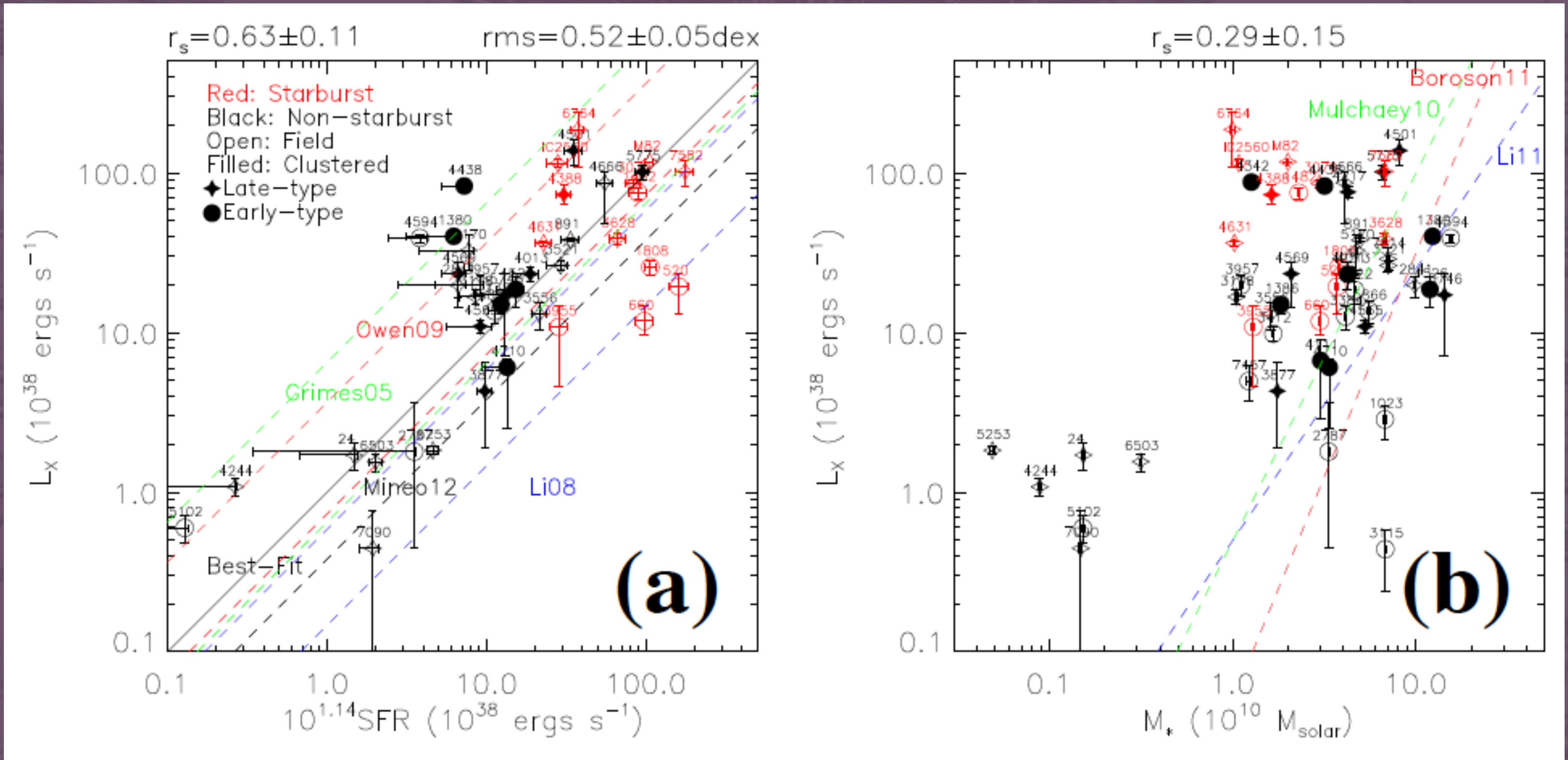
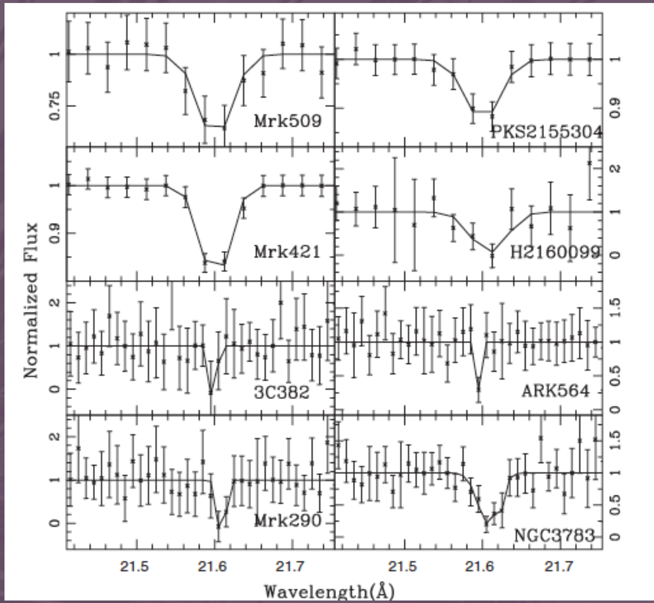


Milky Way Hot Gas Halo

Gupta et al. 2012



Most lines of sight out of MW show OVII and/or OVIII absorption, typical N = 2e16 cm^{-2}.

Emission measure observations yield values of $n_e^2 R$ = 0.0003 – 0.005 cm^{-6} pc, modeled assuming solar metallicity, $f_{OVII} = 0.5$.

For constant density, N = nR,

EM = $n^2R\ (Z/Z_{sun})\ (f\ /\ 0.5)$.

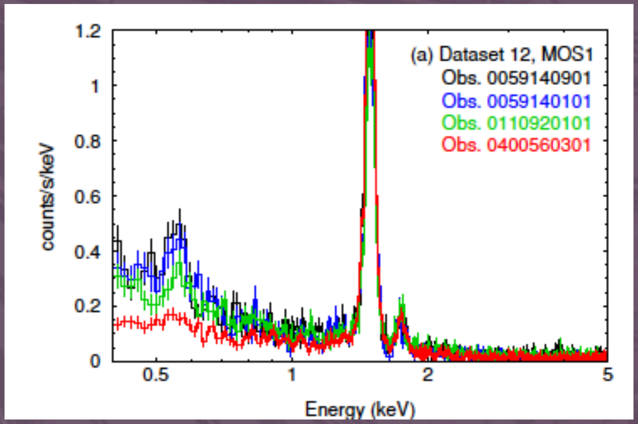
Simultaneous solution yields

R = 90 kpc $(N/2e16)^2\ (EM/0.003)^{-1}\ f_{0.5}^{-1}\ Z_{1.0}^{-1}$ C

M = 1.5e10 $M_{sun}\ (N/2e16)^5\ (EM/0.003)^{-2}\ f_{0.5}^{-3}\ Z_{1.0}^{-3}\ C^2$ where C > 1 is clumping factor.

Note that upper limit on EM = lower limit on R, M.

Changing to constant density core with radius $R_c = x_c R$ boosts implied mass by ~ x_c^{-2} .



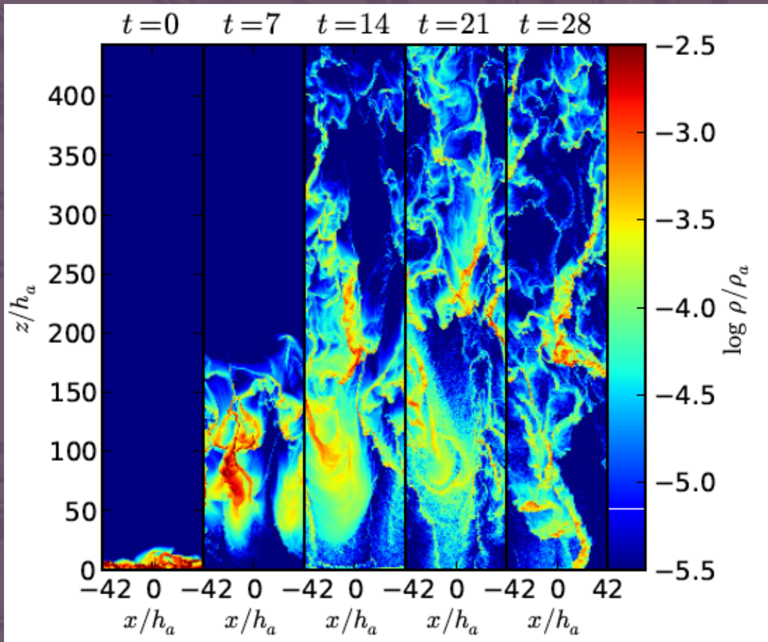
Henley & Shelton 2010

Status of simulations

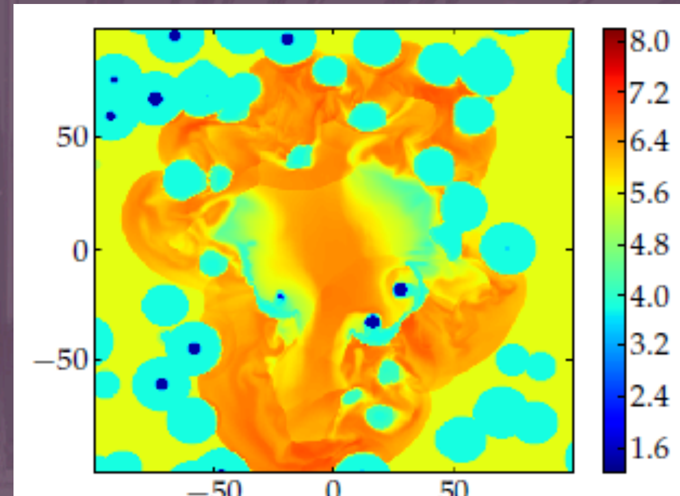
Interesting variety of simulations probing different processes and scales:

Type	Max Res.
ISM or individual clouds/blast waves	sub-pc
Individual galaxies in isolation	few pc
Individual galaxies, cosmological zooms	10s of pc
Cosmological volumes, many galaxies	kpc

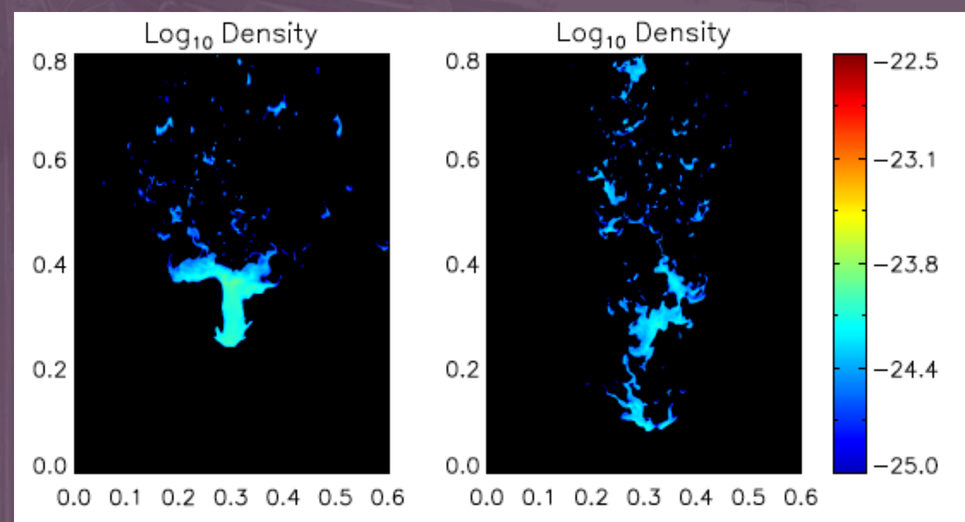
Krumholz & Thompson 2013

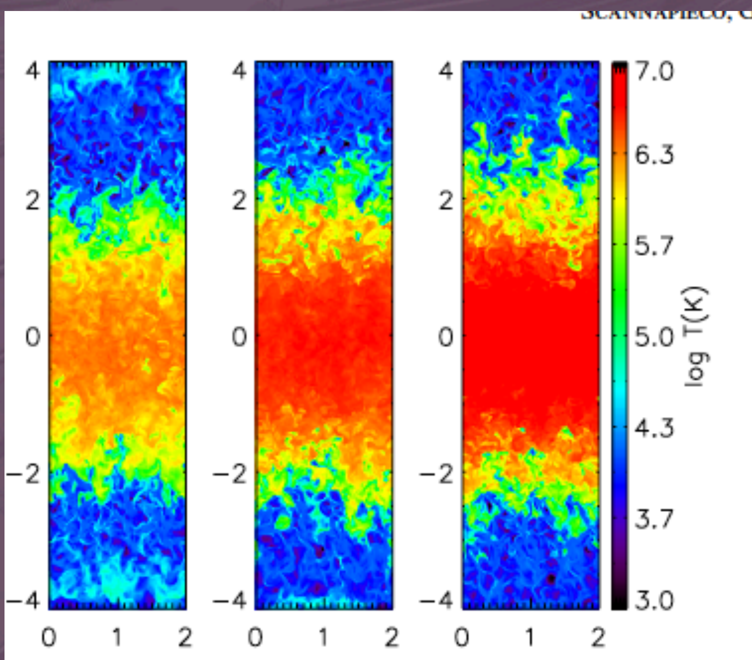


Li et al. 2015



Scannapieco & Bruggen 2015





Scannapieco et al. 2013

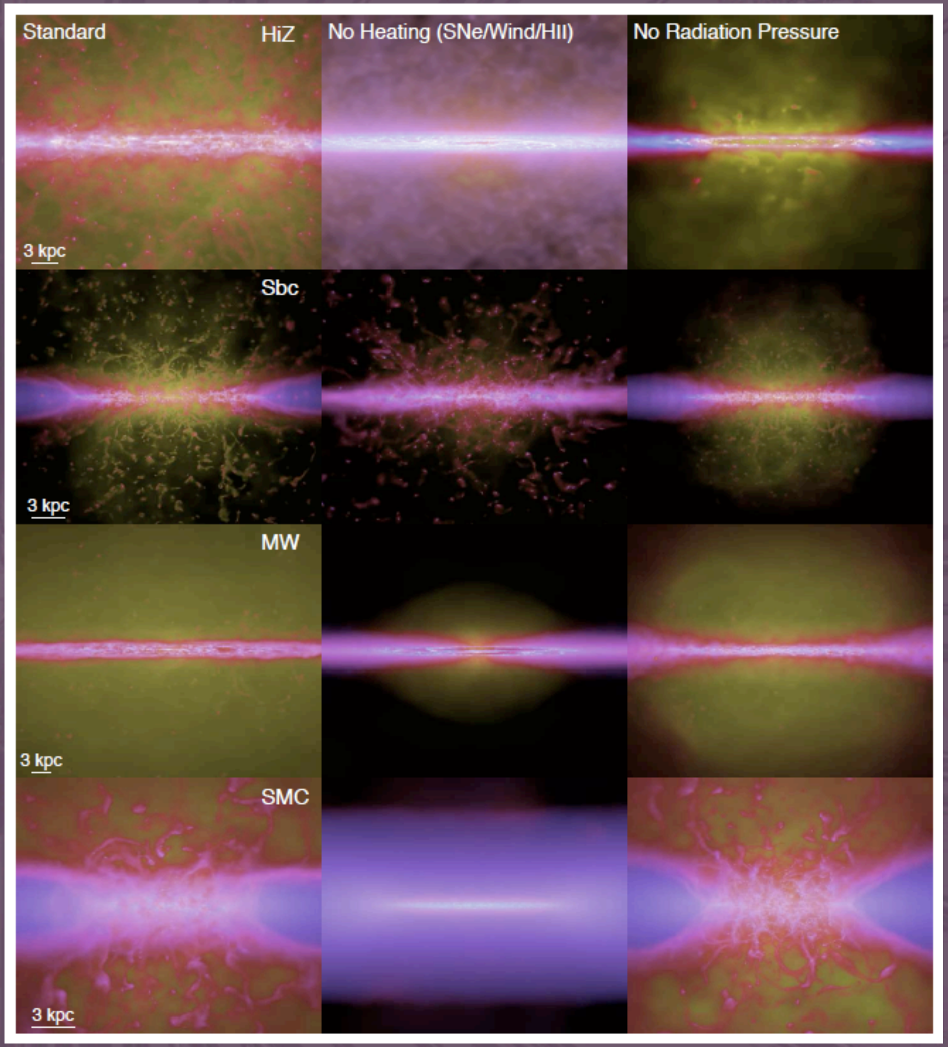
Hopkins, Quataert, Murray 2012

Very high resolution simulations of isolated disks with variety of masses and gas fractions.

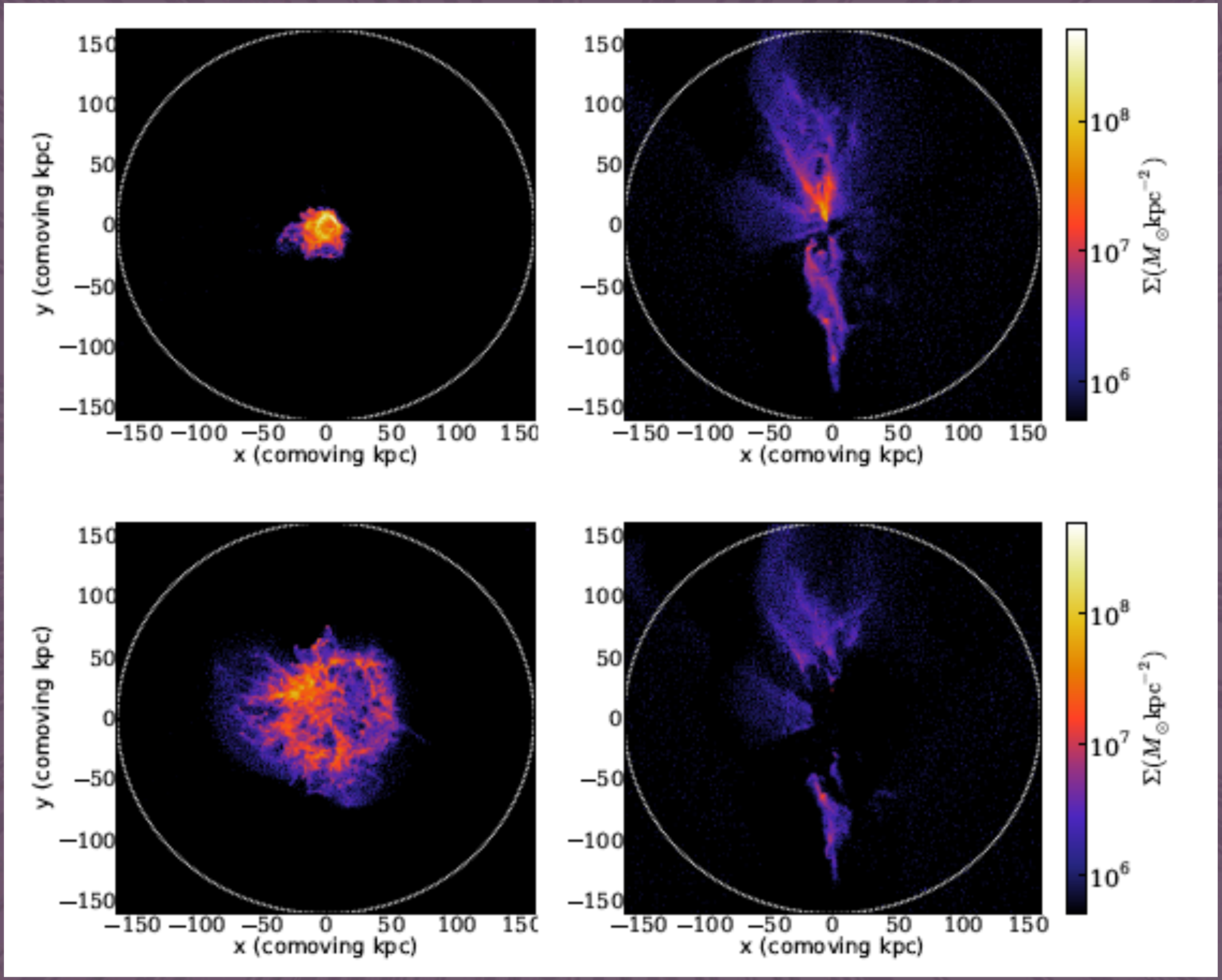
Include heating mechanisms and radiation pressure.

Different mechanisms dominate in different situations.

Sometimes the combined effects are critical; supernovae keep the ISM puffed up, and radiation pressure drives it out.

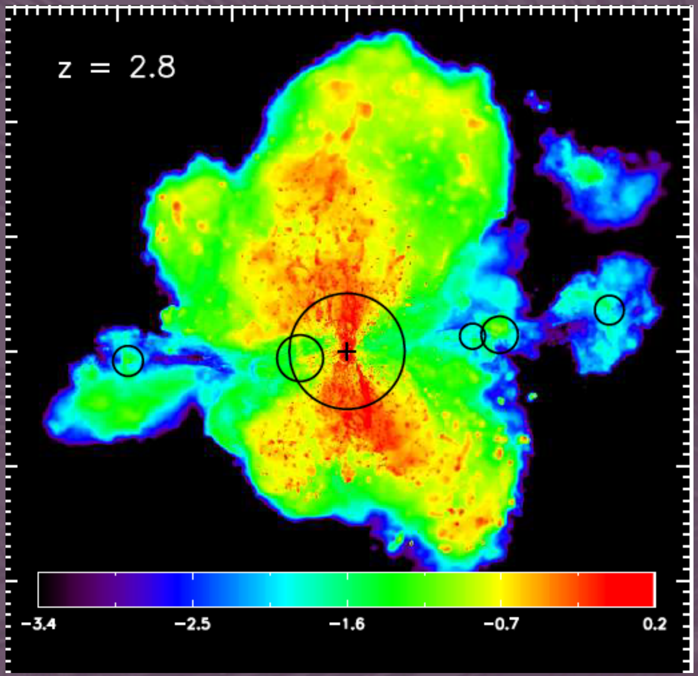


outflow inflow

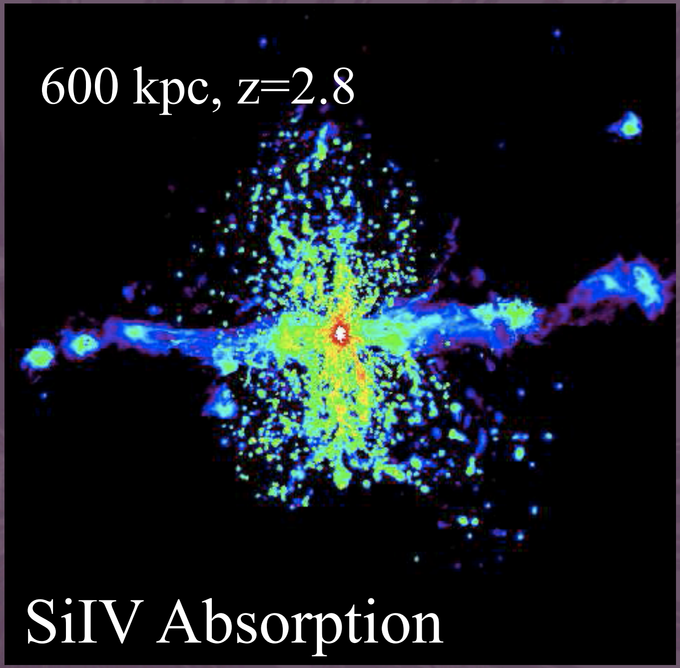


Muratov et al. 2015: "Gusty, Gaseous Flows of FIRE"

Shen, Guedes, Madau, Mayer, Prochaska 2012

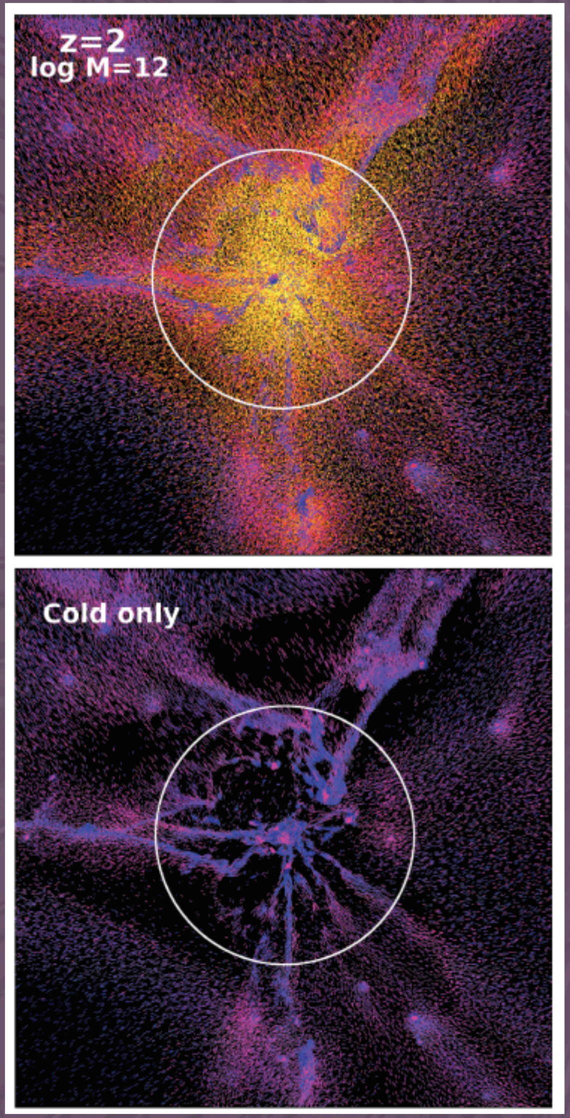


Metallicity



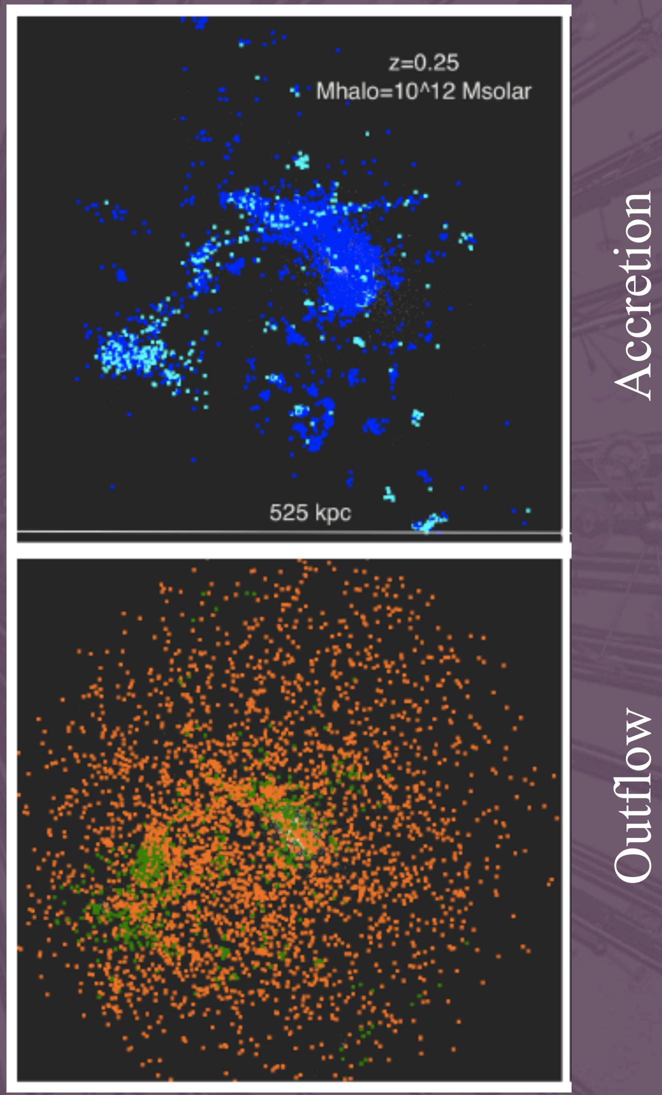
B = density
R = temperature
G = metallicity

Cold & Hot Accretion



Keres et al. 2009

Accretion and Outflow



Ford et al. 2014

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ISM or individual clouds/blast waves	sub-pc
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Cosmological volumes, many galaxies	kpc

Contact with an impressive diversity of observations. But …

Inputs become increasingly "phenomenological"

No simulations have pc-resolution in the circumgalactic medium

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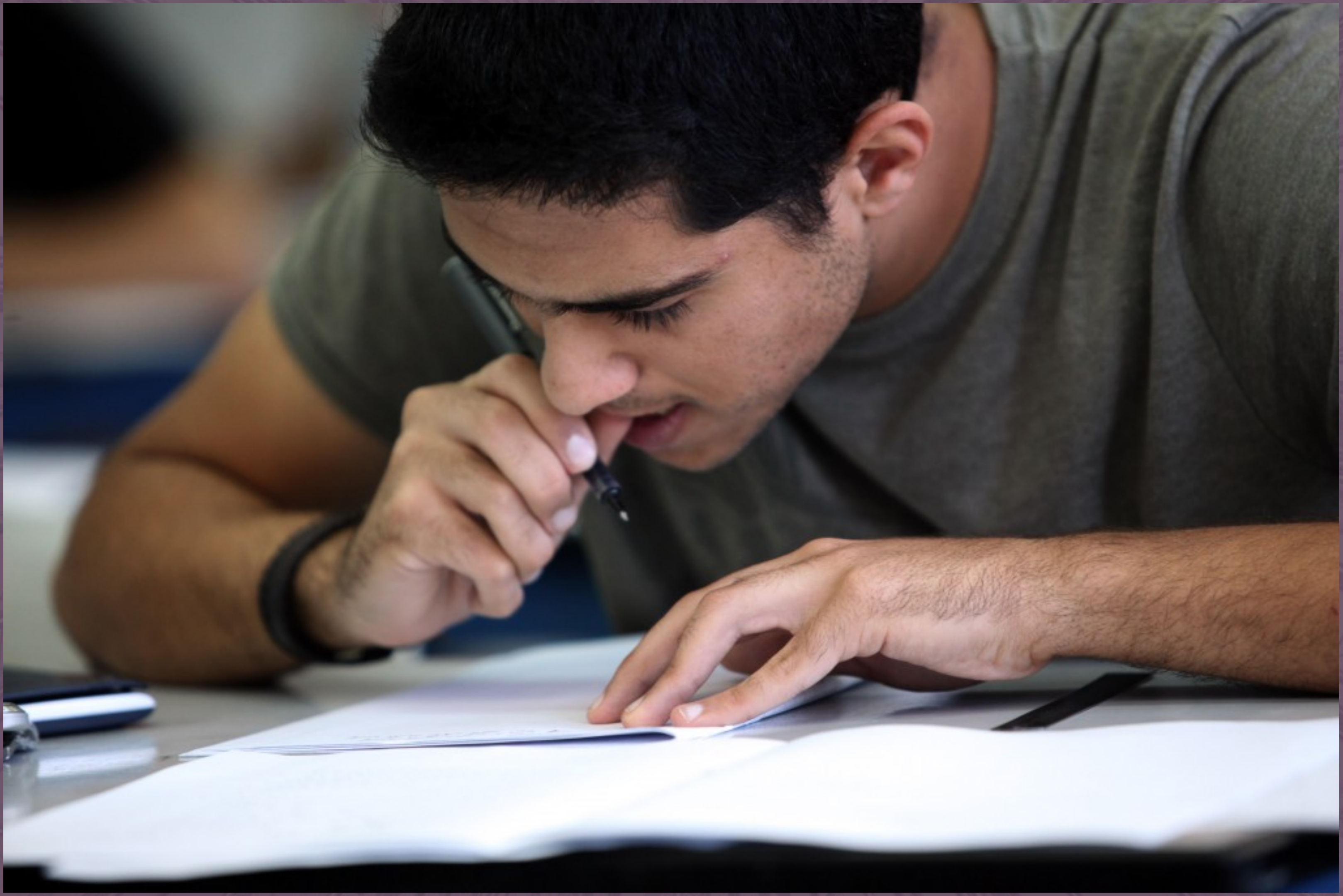
- How do black holes grow, radiate, and influence their surroundings?

Astro 2010 Questions



How do cosmic structures form and evolve?

DM structure grows bottom up, much like ΛCDM predicts.

Possible deviations: modified DM, modified gravity.

Galaxies form by baryon dissipation in DM halos.

How do baryons cycle in and out of galaxies, and what do they do while they are there?

Accrete cold ($M_h<10^{12}$) or hot ($M_h>10^{12}$). Form stars.

Driven from low mass galaxies by star formation. Recycling?

How do black holes grow, radiate, and influence their surroundings?

Stuff happens. Including mergers. Funnels gas to galaxy centers.

Black holes shine as they grow, not so far from thin-disk theory.

AGN suppress accretion by host galaxies in hot gas halos.

What are the flows of matter and energy in the CGM?

See previous answers. (Hope for partial credit.)

What controls the mass-energy-chemical cycles within galaxies?

Supernova heating. Or massive star winds. Or radiation pressure.

Or cosmic rays. Or black hole feedback. Or …

Astro 2020 Questions?

Astro 2020 Questions?

Accounting → Physics

Astro 2020 Questions?

Accounting → Physics

How much gas is coming in and going out?

Why did we lose track of it?

What is the luminosity function of quasars/AGN vs. redshift?

What are the processes governing accretion and outflow?

What is the physical state of the gas?

What is the physics of black hole formation and accretion?

Astro 2020 Questions?

What are the physical mechanisms that regulate accretion and star formation and drive galactic outflows?

What are the physical mechanisms of black hole accretion and AGN-driven outflows?

What are the L/L_{edd} "light curves" of typical BHs over the history of the universe?

What is the physical and dynamical state of interstellar, circumgalactic, and intergalactic gas, on pc, kpc, and Mpc scales?

What do we want?

- Detect the #@&!!?%!-ing hot gas halos of many dozens of normal spiral galaxies, in emission and absorption. (Or severely limit their luminosity.)
- Measure the $%@!<>?!-ing radial profile and mass of the Milky Way's hot gas halo.
- Detect the &$@%%*#-ing WHIM, with good statistics, in absorption and emission.

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- Measure the radial profile and mass of the Milky Way's hot gas halo.
- Detect the WHIM, with good statistics, in absorption, and emission.
- Get M82-like observations for dozens of galaxies, extreme and normal, with a wide range of properties.

- Measure the hot ISM in multiple nearby galaxies.
- X-ray spectra that resolve galactic velocity scales.
- Bolometric L/L_{edd} for thousands of BHs at $z = 0 – 6$.
- High-resolution spectroscopy of many accreting black holes: statistics of spin and physical diagnostics of accretion.

Tricky.

PHOTO: JUSTIN METZ/GETTY


PHOTO: JUSTIN METZ/GETTY


SIGNS
POINT TO
YES

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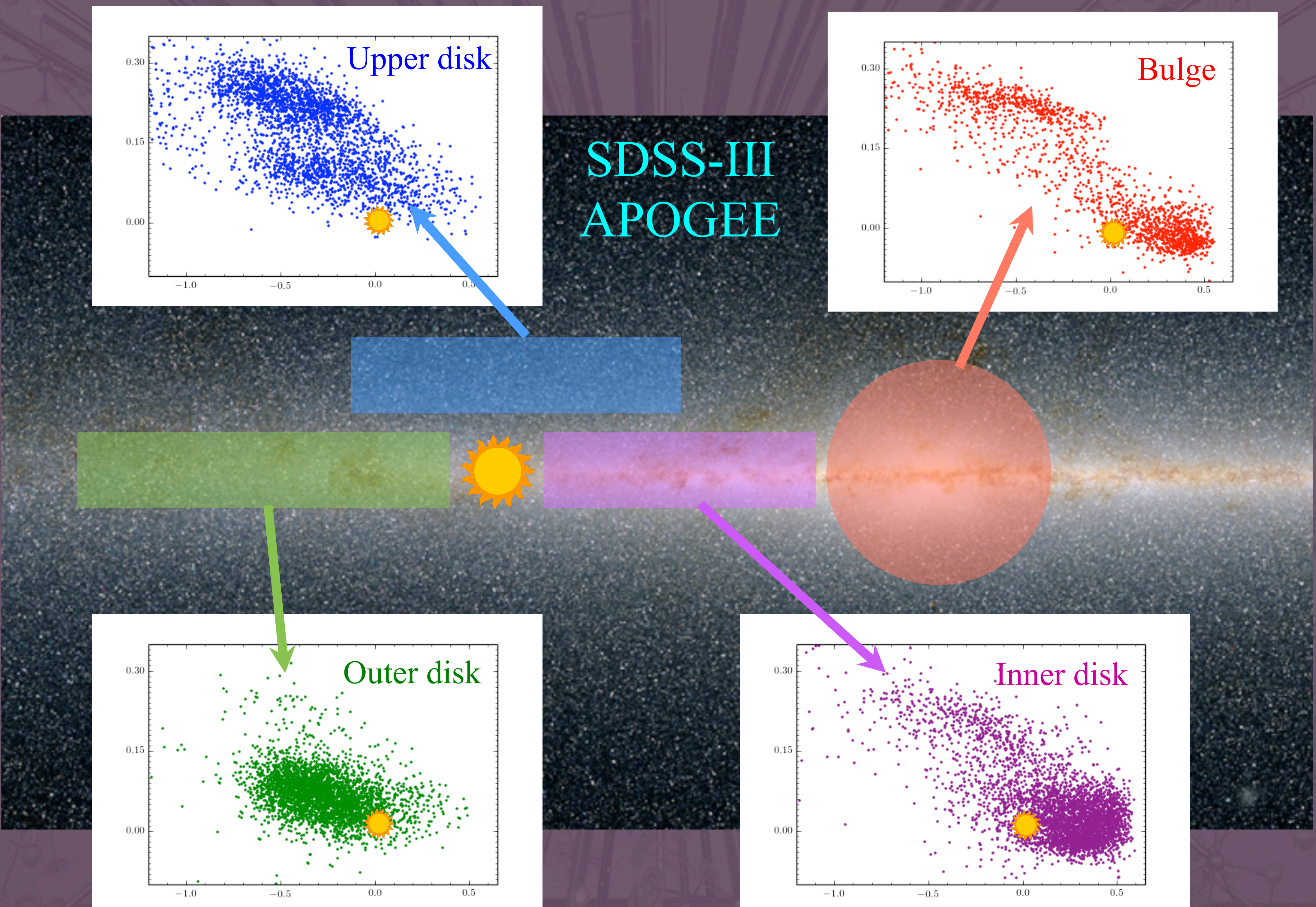
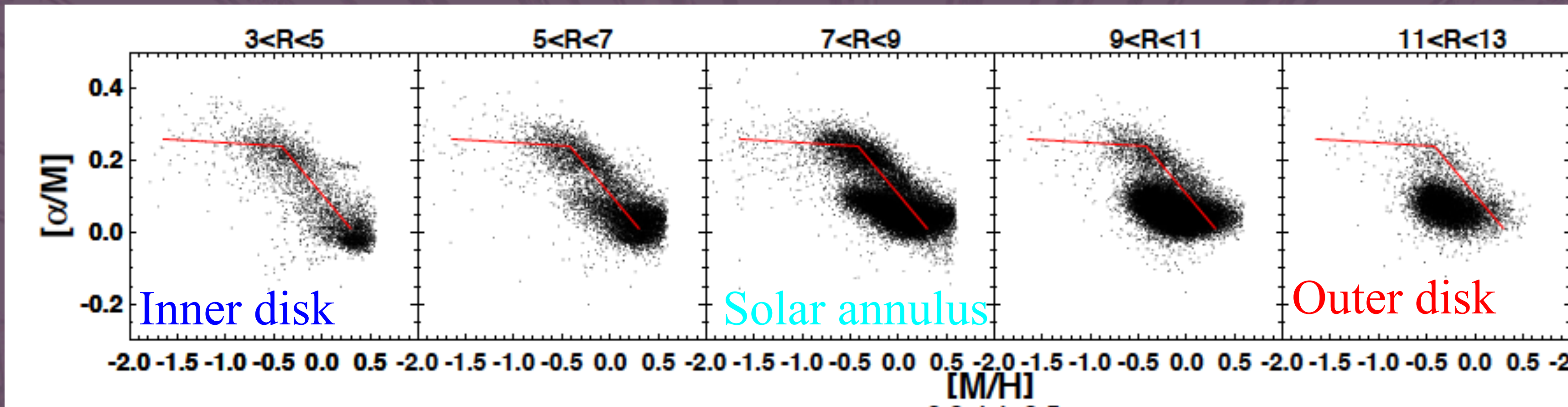
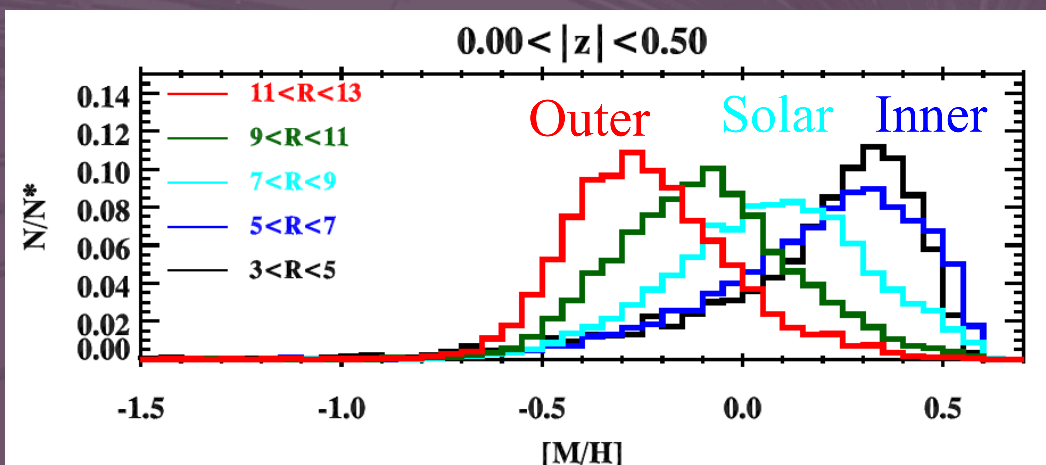
Backup Slides

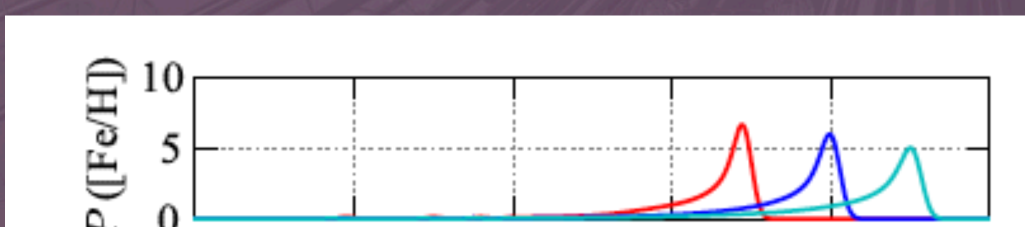
Detailed abundance distributions throughout the Galaxy



Hayden, Holtzman, Bovy et al. 2015 (SDSS-III APOGEE)







"Generic" model predictions, Andrews++

Metallicity distribution function changes shape, from negative skewness at small R to positive skewness at large R.

A signature of radial migration, with metal-rich stars in outer Galaxy originating in the inner Galaxy?

Why is galaxy formation so inefficient?

- What is the balance of ejective vs. preventive feedback?
- What are the primary feedback mechanisms?
- Where are the remaining baryons?

How do galaxies get their gas?

- What is the dynamics of cold accretion? Smooth or clumpy? Where does the gravitational energy go?
- What role does filamentary accretion play in galaxy angular momentum and morphology?
- How much hot accretion is there? What governs it?

Why do galaxies lose their gas?

- What drives galactic winds: heating, radiation pressure, AGN?
- Are outflows episodic or steady? Are they metal-enhanced?
- How do outflows affect accretion, and vice versa?
- Why do quenching and morphology go together? Who's the driver?

Where does ejected gas go?

- How much recycling occurs? What, if anything suppresses it?
- What is the phase structure of the CGM? Are ejected metals mixed?
- Are numerical treatments of gas ejection and the CGM reliable?