Galaxy Formation: Cosmological Framework and Observational Challenges

Romeel Davé

ROYAL OBSERVATORY EDINBURGH

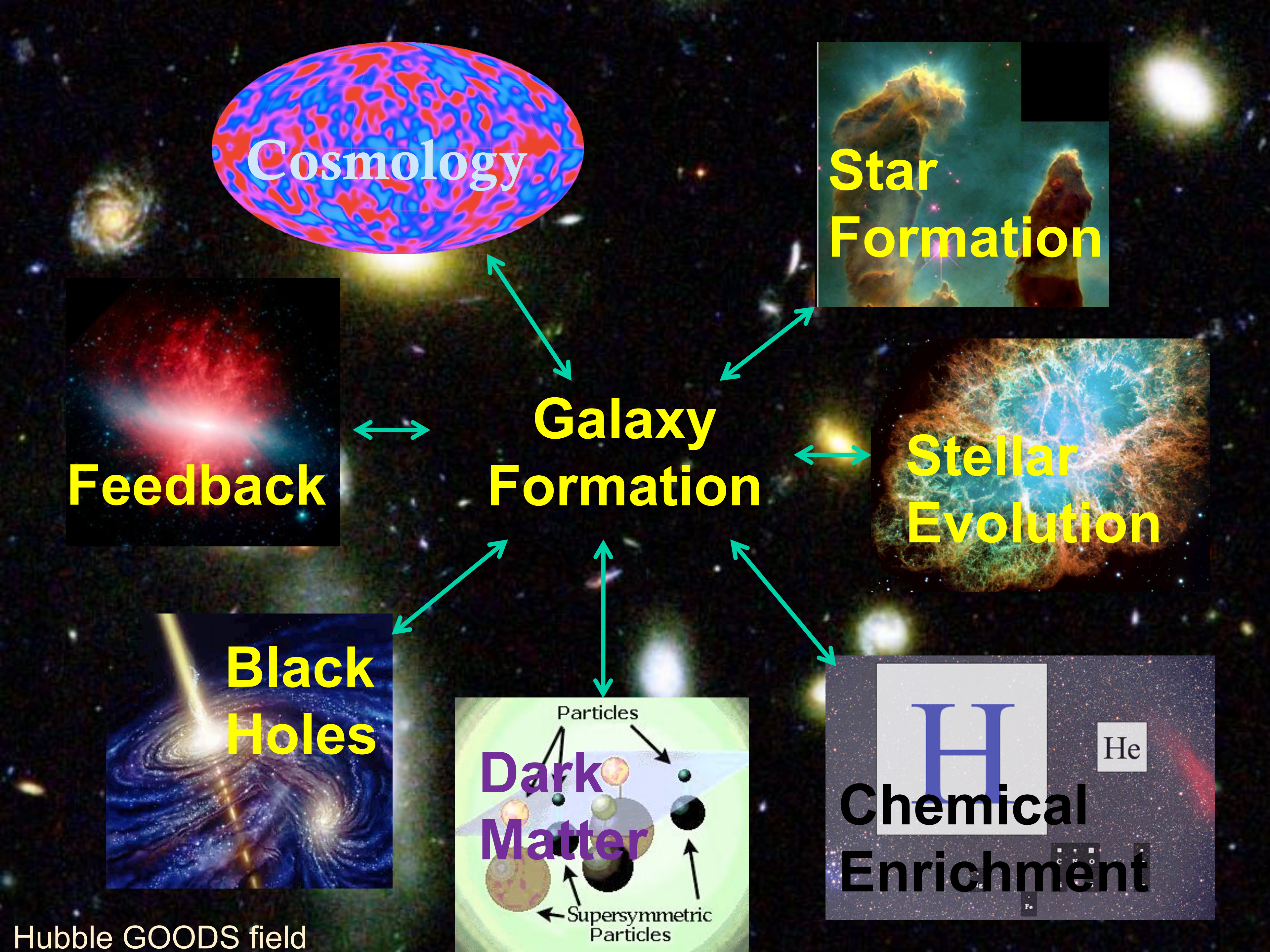
UNIVERSITY of the WESTERN CAPE

NRF National Research Foundation | SAAO South African Astronomical Observatory

Outline

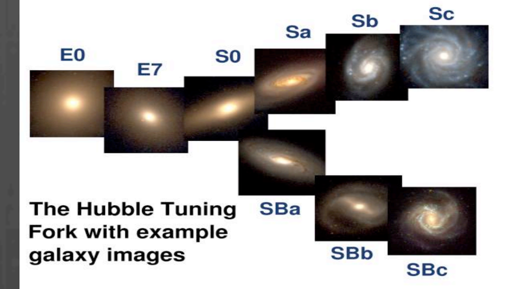
1. Setting the stage: What is galaxy evolution?
2. Galaxy components and how we observe them
3. The modern galaxy formation paradigm
4. The role of black holes in galaxy evolution
5. Circum-galactic gas and how it governs galaxy growth

Please ask questions! I have plenty of slides but I'd prefer discussion!


Cosmology
Star Formation
Feedback
Galaxy Formation
Stellar Evolution
Black Holes
Particles
Dark Matter
Supersymmetric Particles
H
He
Chemical Enrichment
Hubble GOODS field

Properties Along Hubble Sequence

NOTE: These are only ***trends***; many exceptions!

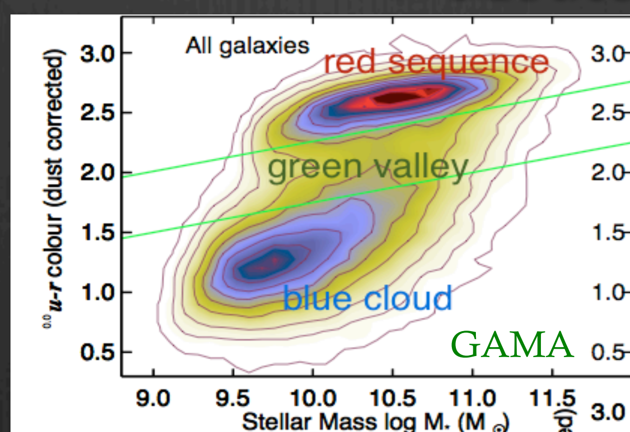


<u>Ellipticals (early types)</u>

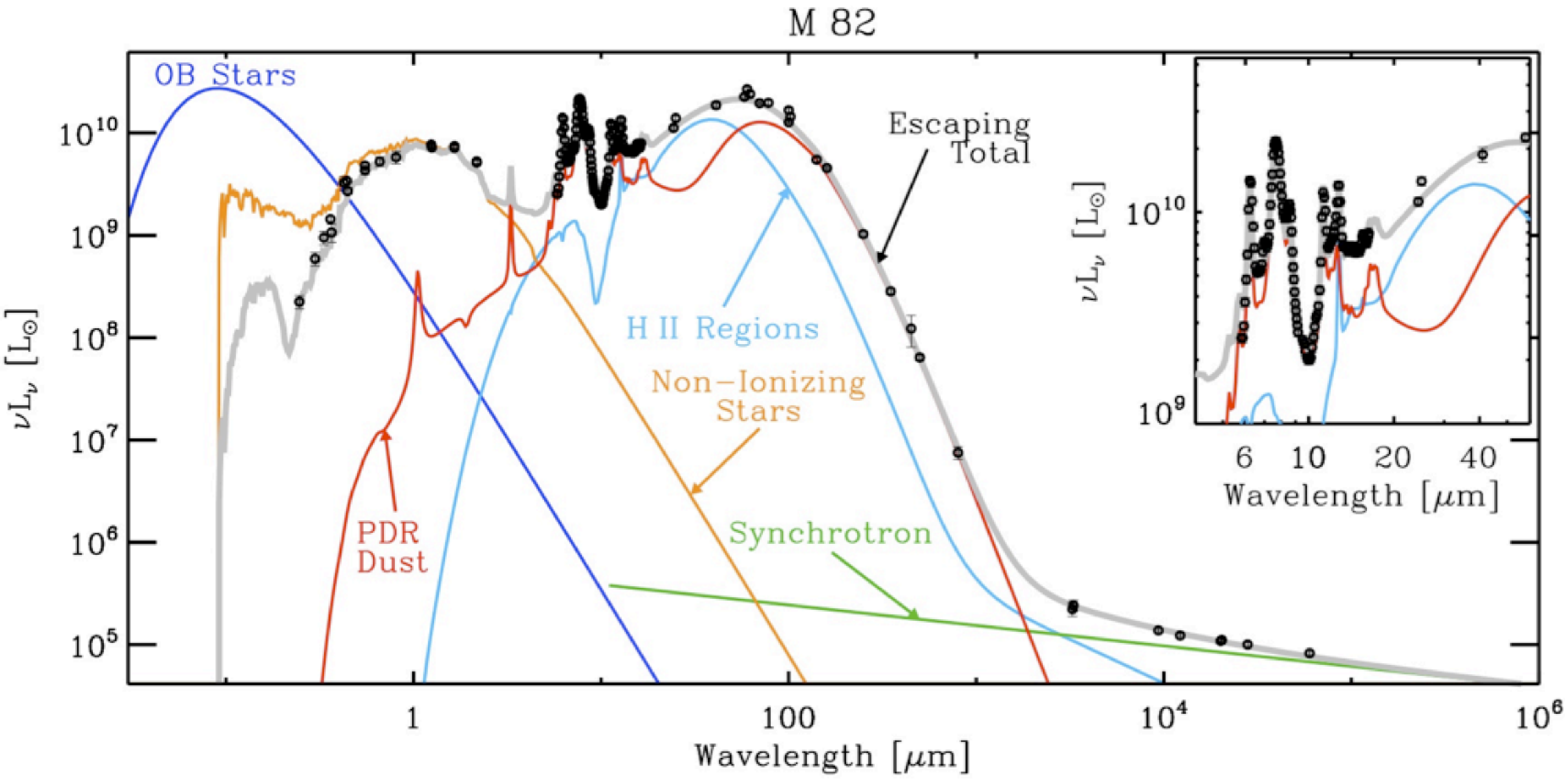
- Red & dead
- Dominate @massive end
- In dense regions; clustered
- Lots of hot gas
- More strongly clustered
- Very little dust
- Large black hole

<u>Spirals (late types)</u>

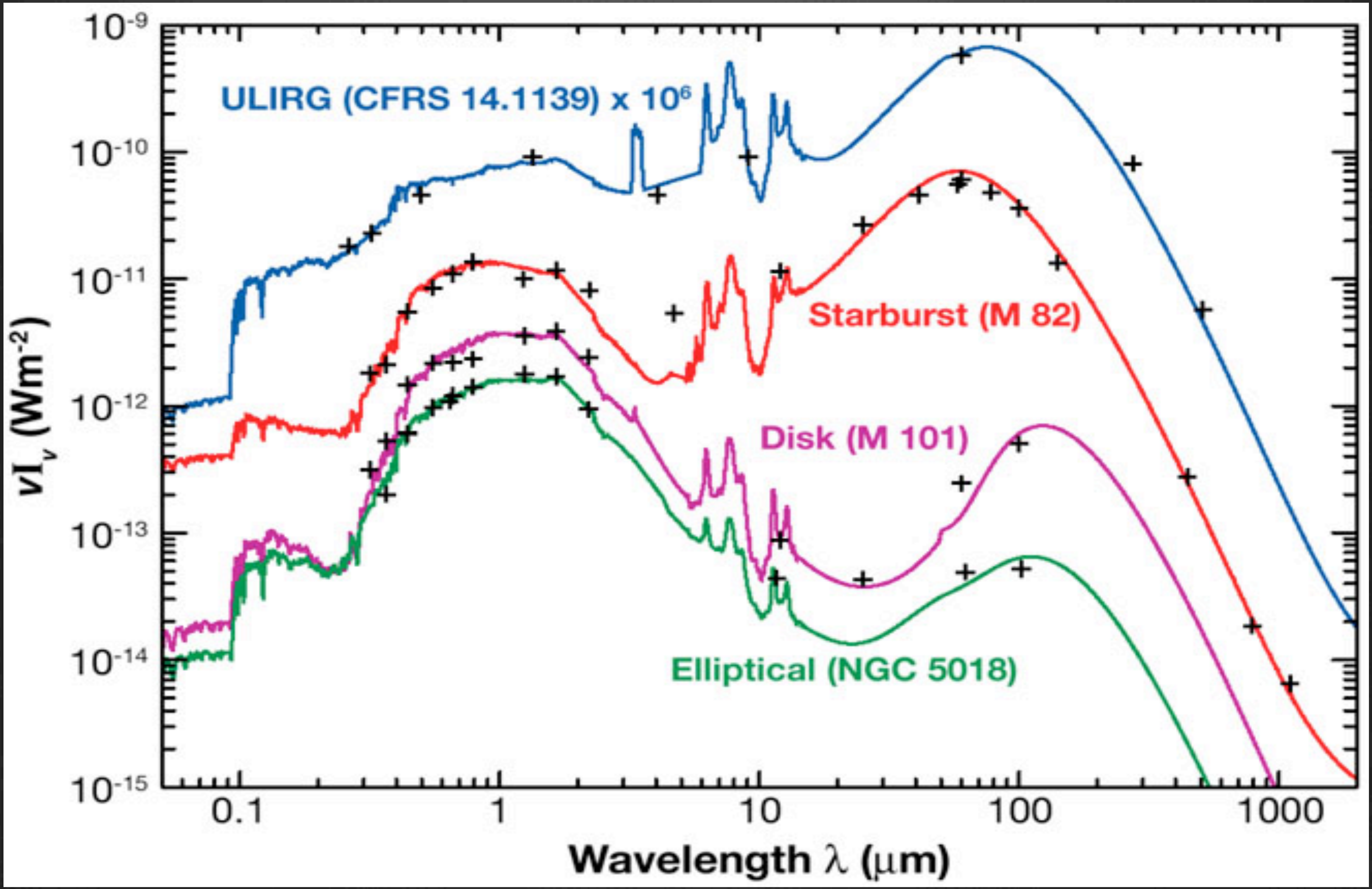
- Blue & star-forming
- Dominate @<~L*
- In field & poor groups
- Lots of cold gas
- Less strongly clustered
- Dust correlates with mass
- Modest black hole



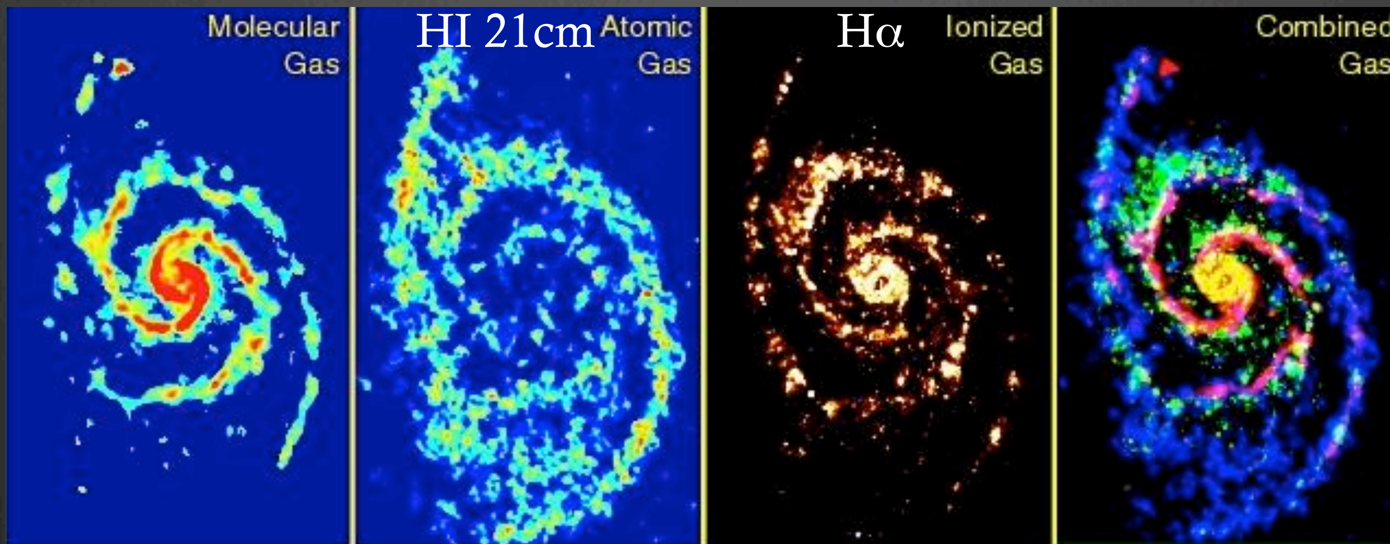
Starlight across the E/M spectrum



SEDs vs galaxy type



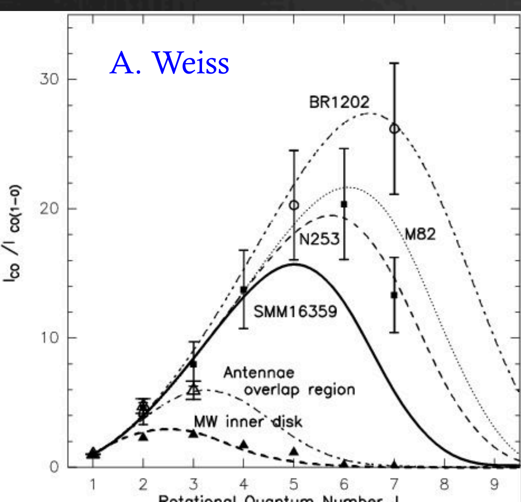
Gas: Ionized, Molecular, Atomic

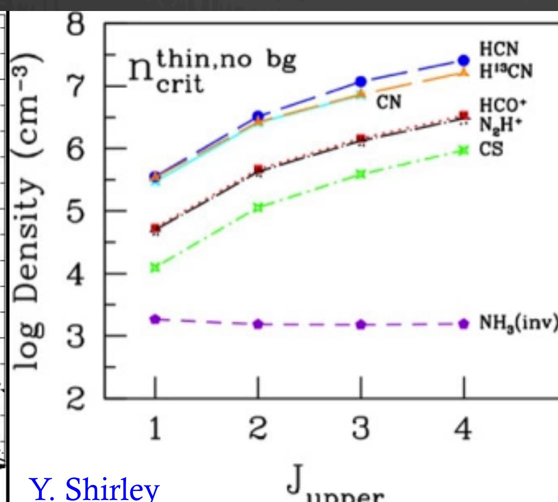


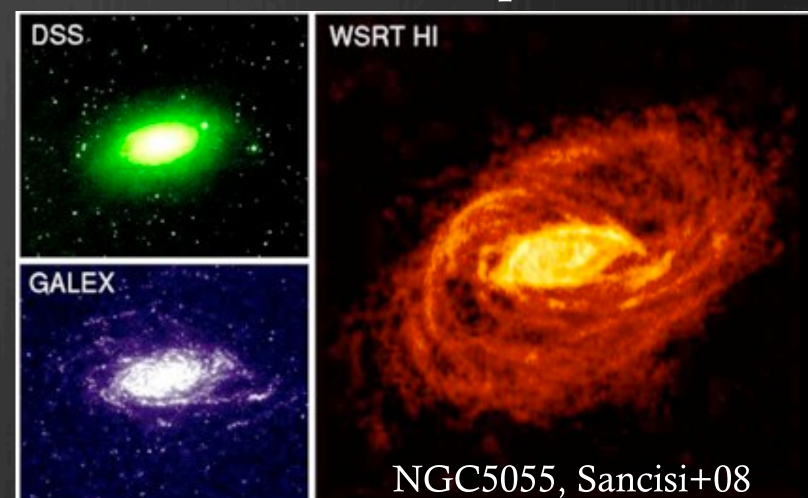
M51 (from Eve)

Molecular: Want H_2, have CO line(s) & dense gas.
Conversion is tricky! Z, ISRF, (n,T)

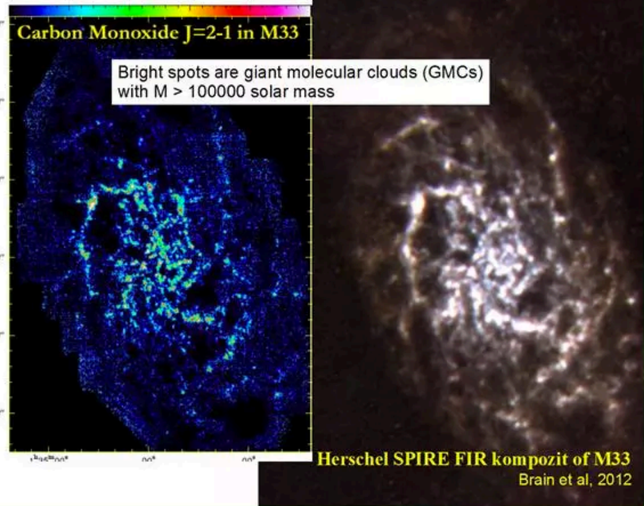
HI extends to 10's-100+ kpc.
Warps? SF w/o H_2? CGM abs?

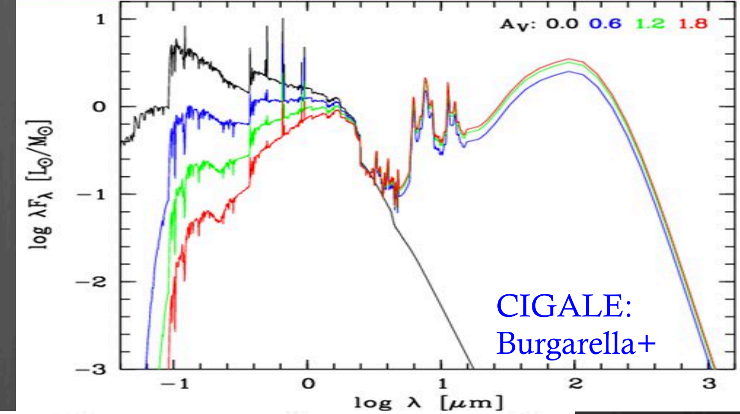


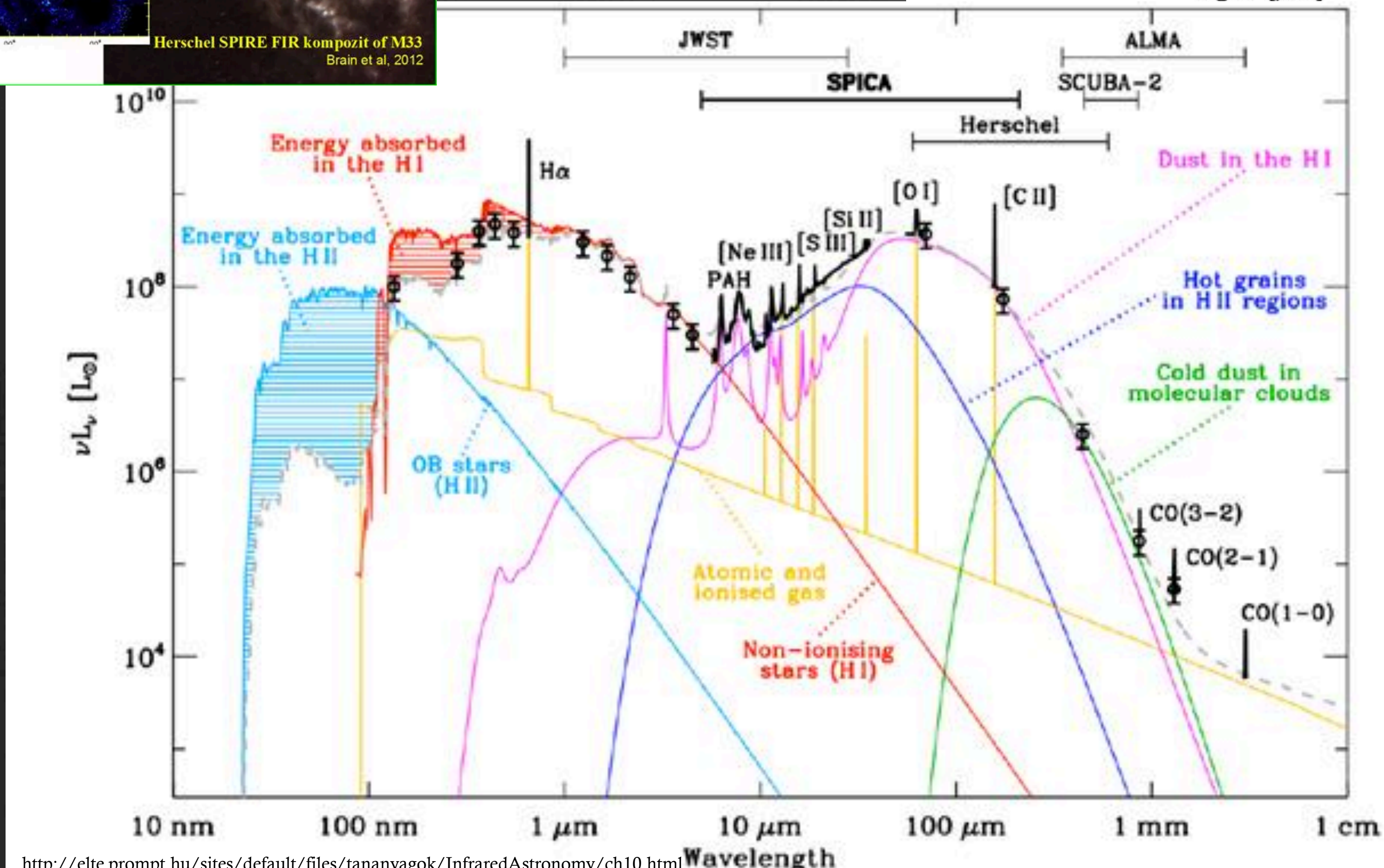




Dust

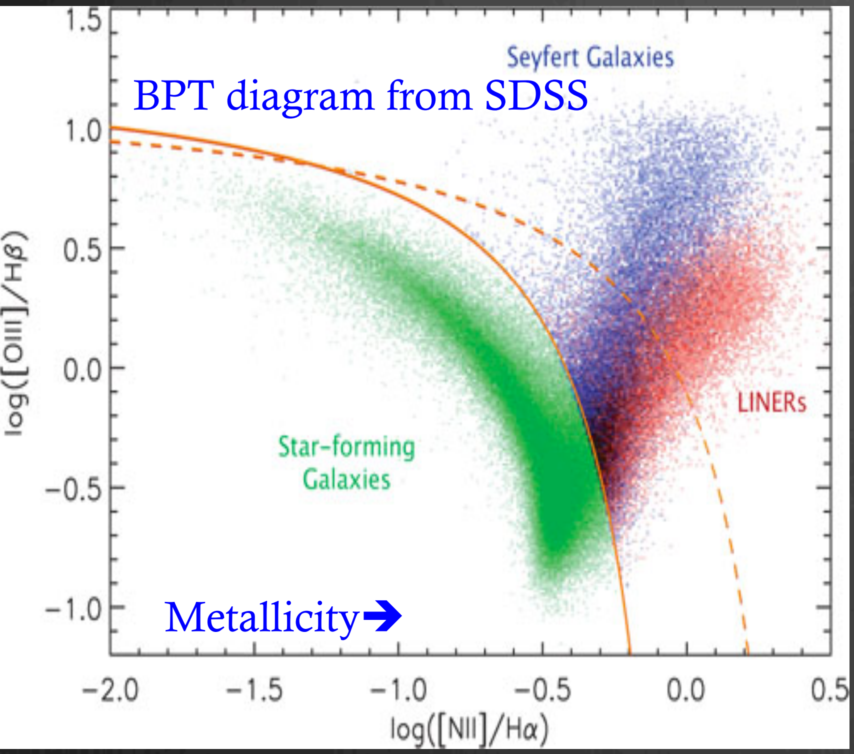


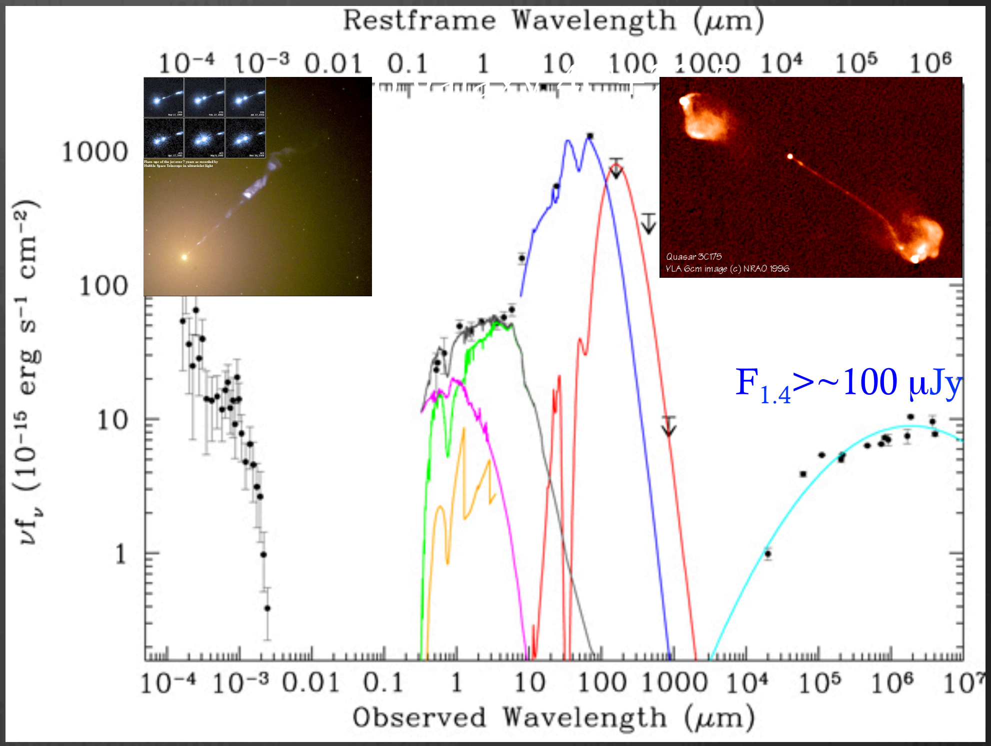


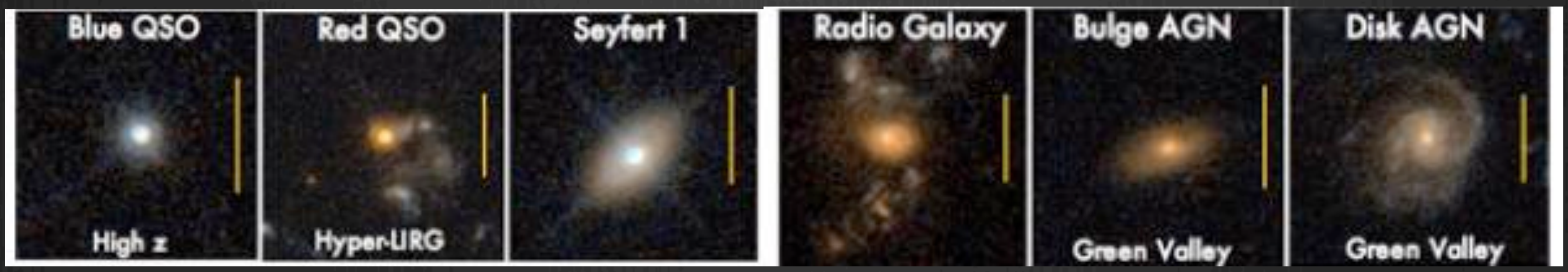


http://elte.prompt.hu/sites/default/files/tananyagok/InfraredAstronomy/ch10.html

AGN: Emission Lines, X-ray, Radio





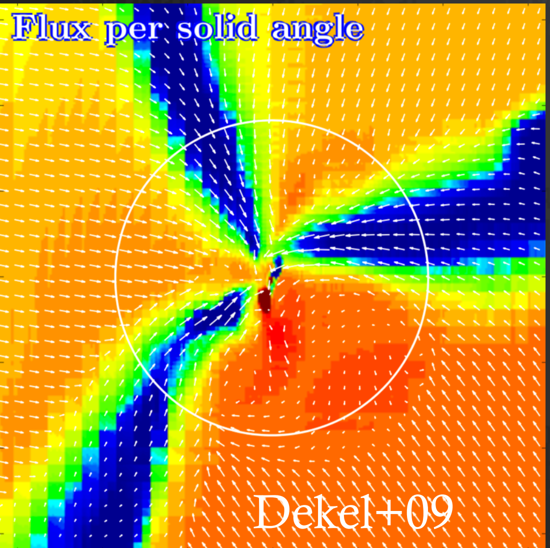


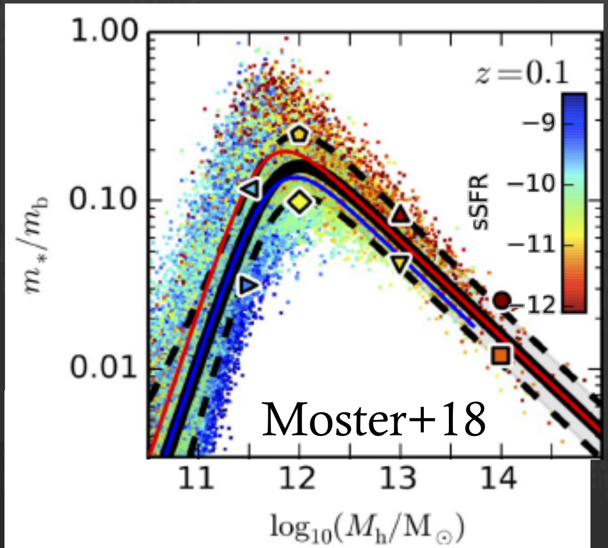
The Modern View of Galaxy Formation

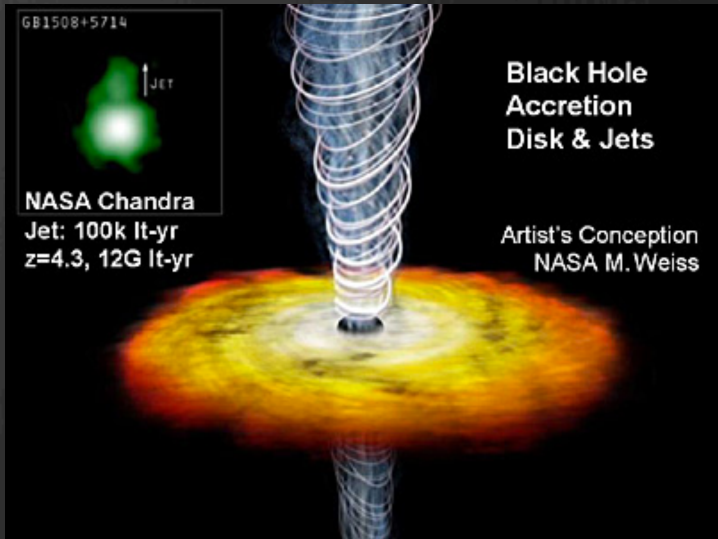
- Cold gas accretion from IGM, suppressed at low and high M_{halo}.
- Inefficient conversion into stars within ISM; ~constant gas reservoir
- Galactic outflows regulate stellar mass + metal growth
- Outflows recycle back into galaxies; dominant at low-z
- Black holes grow roughly along with galaxies
- AGN feedback starves massive galaxies (also expels gas)
- Variations in co-growth driven by inflow fluctuations & mergers

Baryon Cycle

Quenching







Feedback in Realistic Environments (FIRE) Simulation (Hopkins+)

$\eta/(1+\eta)$ $+\dot{M}_{rec}(t_{rec})$

$\zeta\dot{M}_{grav}$

$\dot{M}_{grav}$
(from IGM)

$1/(1+\eta)$

Galaxies = Gas Processing Factories

$$SFR = (\zeta\dot{M}_{grav}+\dot{M}_{recyc})/(1+\eta)$$

$$Z = y\ SFR/\zeta\dot{M}_{grav}$$

Finlator, RD 08
RD+12

BARYON CYCLING PARAMETERS

Equilibrium Model: Analytic Galaxy Formation

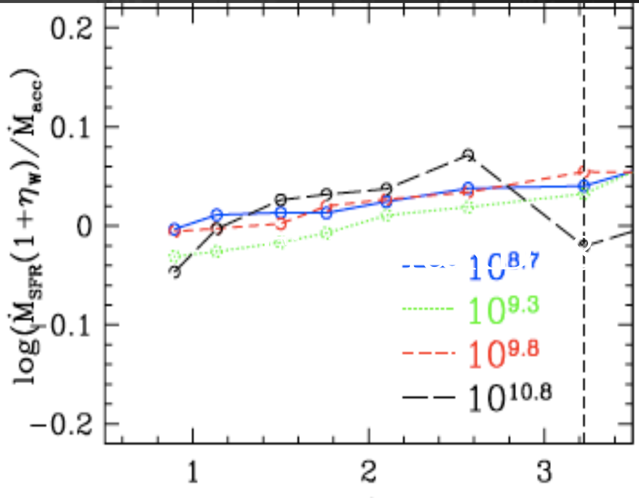
RD+12

Inflow = SFR + Outflow + ~~dReservoir/dt~~

- SFR = $(\zeta \dot{M}_{grav} + \dot{M}_{recyc})/(1+\eta)$
- $Z = y$ SFR / $\zeta \dot{M}_{grav}$
- $f_{gas} = (t_{dep}$ sSFR)

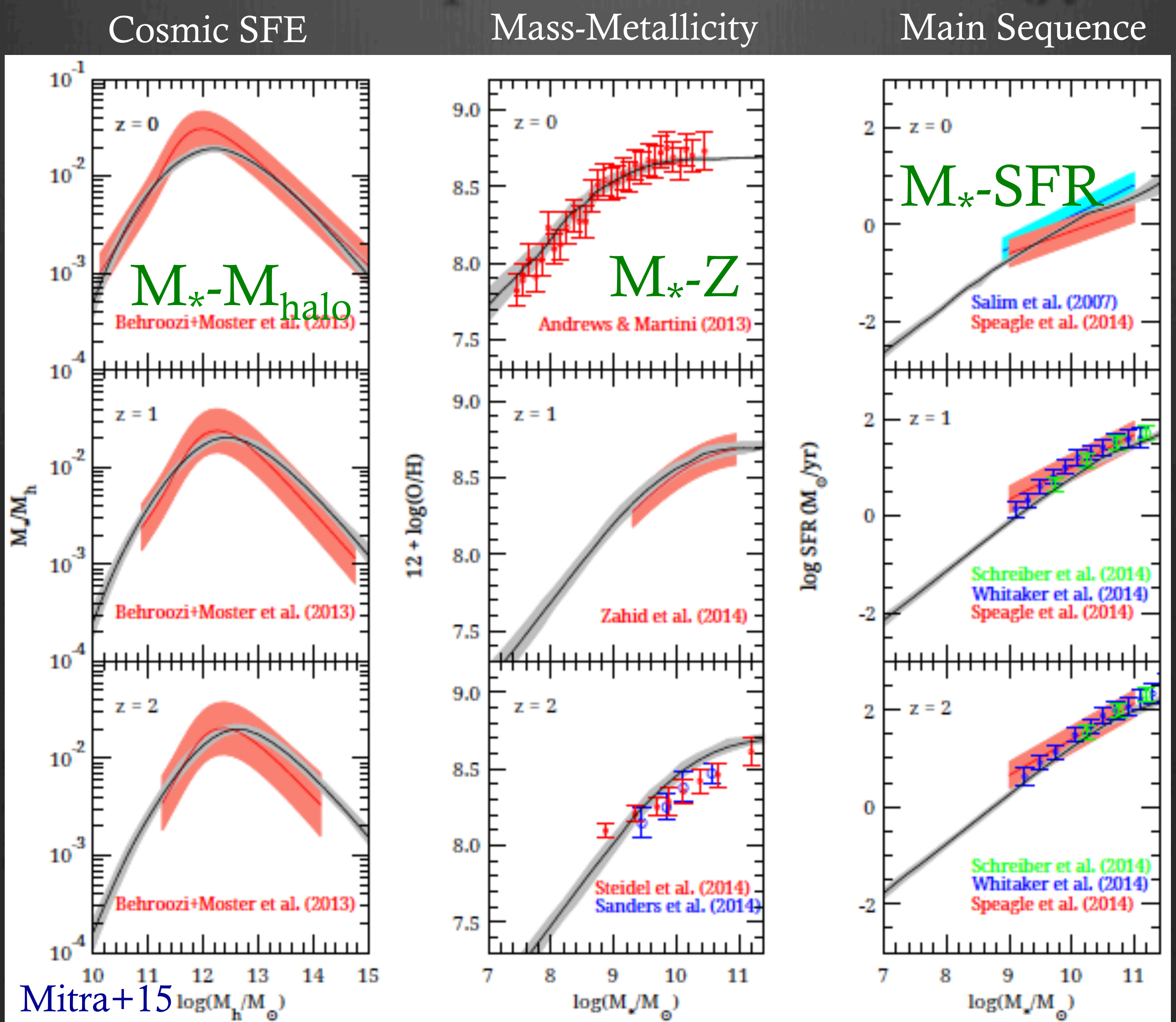
where

$\dot{M}_{grav} \sim f_b M_{halo}^{1.1} (1+z)^{2.25}$ [Dekel+09]



Finlator&RD08

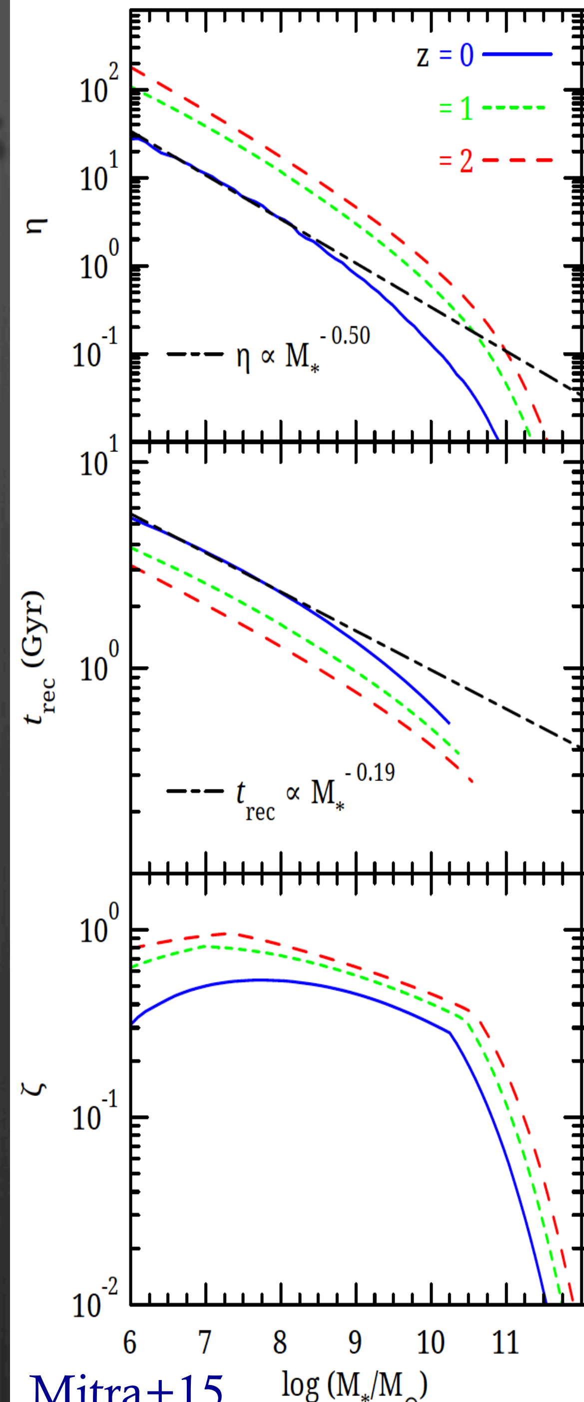
The Best-Fit Equilibrium Model (χ^2~1.6)



Feedback: Generic Constraints

- Mass loading factor strongly drops with mass; dwarfs eject more!
- Preventive feedback is required to truncate SF in massive galaxies.
- Recycling time is ~few 10^8-10^9 yrs, faster at high mass.

Most current galaxy formation models yield or employ scalings qualitatively similar to these.



Mitra+15

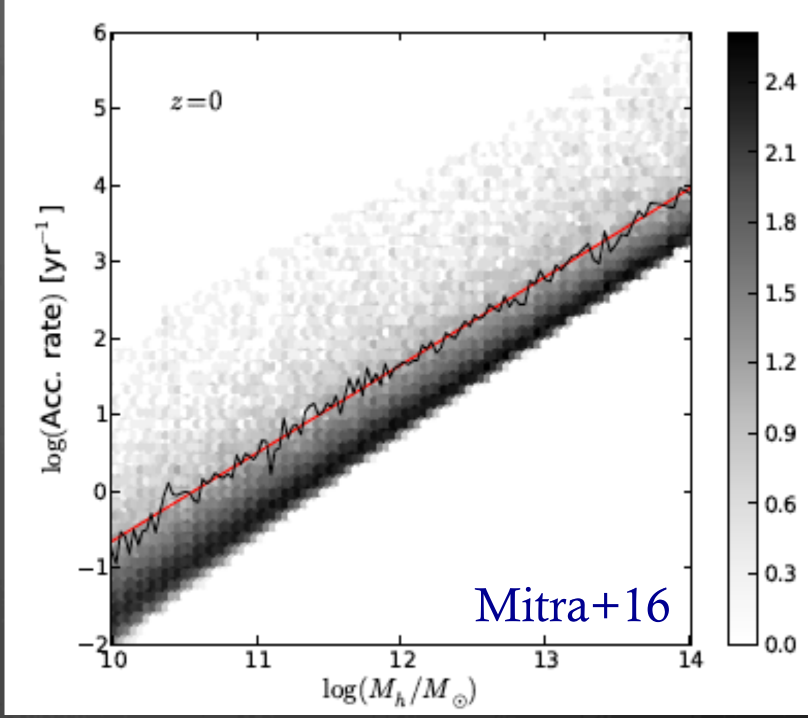
The role of Merging: Scatter

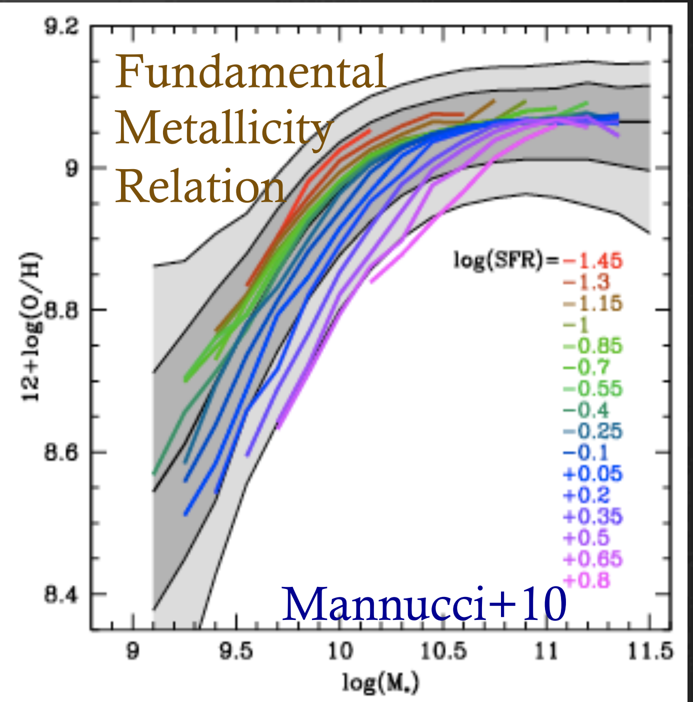
- *First order: Smooth accretion*

  Overall smooth accretion sets the form of scaling relations.

  $Z = y\ SFR/(dM_{grav}/dt)$

- *Second order: Stochasticity*
  - Mergers, environment, gas reservoir, etc. are 2nd order effects.
  - Accrete a "lump" (merger) ➔ higher SFR (&f_{gas}), lower Z.



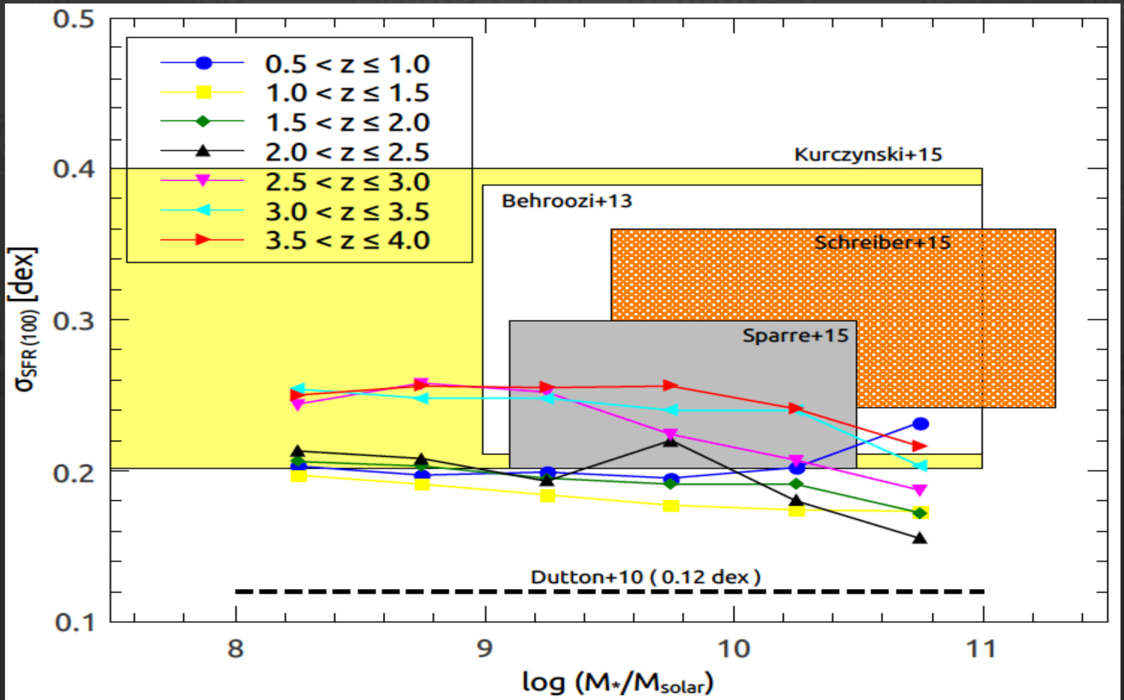


Main Sequence Scatter from Inflow Fluctuations

- Scatter in IGM inflow gives scatter in SFR.

$$\mathrm{SFR} = \frac{\zeta \dot{M}_{\mathrm{grav}} + \dot{M}_{\mathrm{recyc}}}{1+\eta}$$

- Predicts roughly the observed scatter! This means little/no room for scatter in η, t_{rec} (but correlated scatter OK).



Mitra+16

Gas Fractions

- Set by consumption vs inflow:

$$\mathrm{SFR} = 0.02\ M_{gas}/t_{dyn} \sim t_H^{-1} \sim (1+z)^{1.5}$$
$$\text{vs. Inflow} \sim (1+z)^{2.25}$$

- At high-z (z>~4-6), *gas accumulation phase:*

$$1 + z_{\mathrm{eq}} \approx \left[5 f_{\mathrm{gas}}(1+\eta)\right]^{4/3} \left(\frac{M_{\mathrm{halo}}}{10^{12} M_{\odot}}\right)^{-0.2}$$

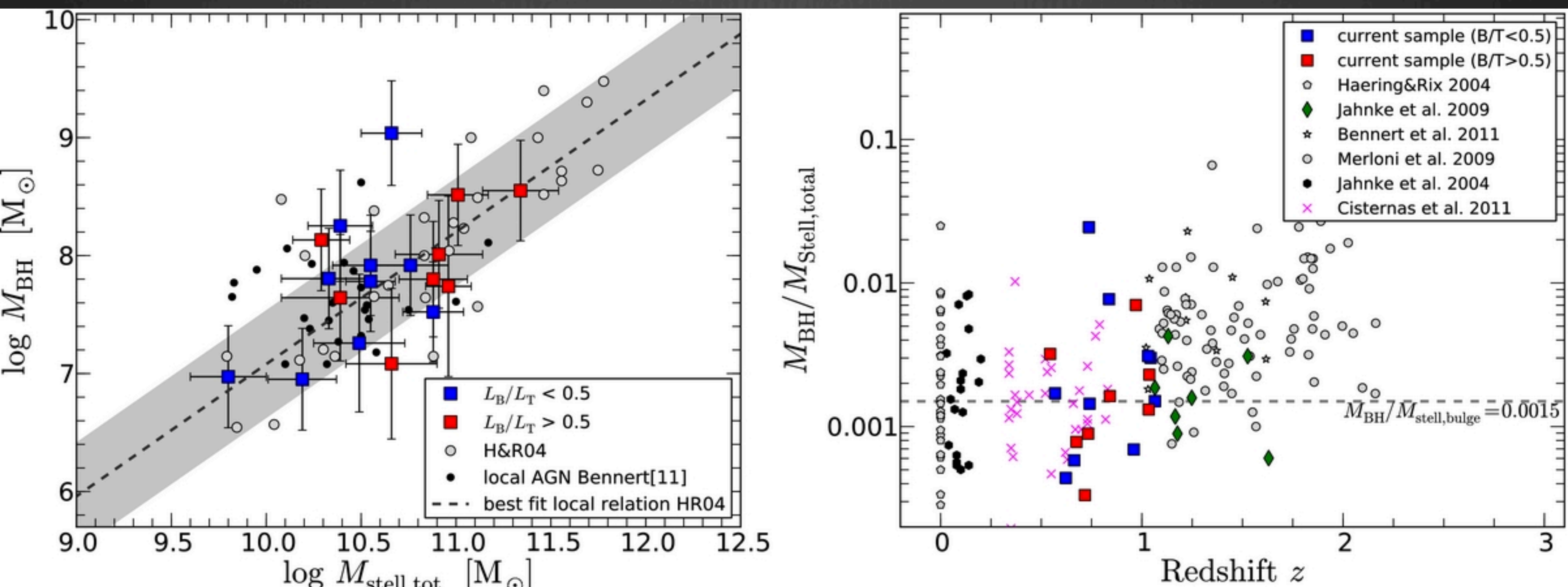
- After this, get a slowly evolving gas frac:

$$f_{gas} \sim t_{Hubble}\, M_*^{-0.3}\, (1+z)^{2.25}\, M_*^{\beta} \sim M_*^{-0.5} (1+z)^{\sim 1}$$

This is close to what is observed.

Black Holes and Galaxies Co-evolve

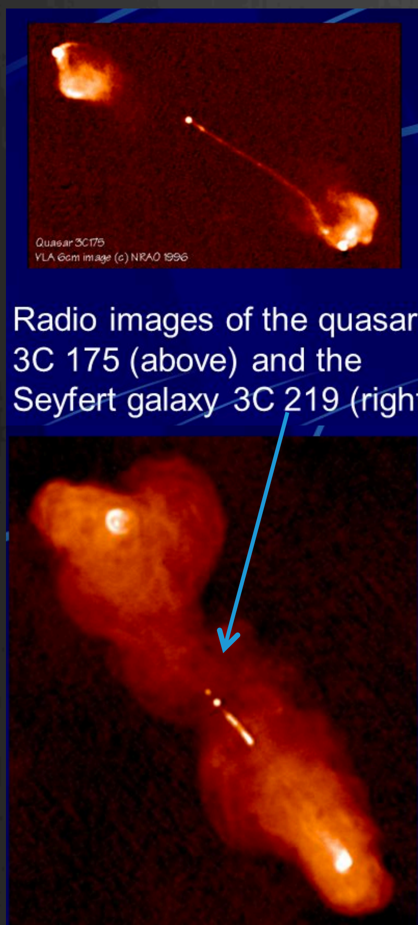
- Magorrian relation and its cousins: M_{BH} correlates with σ / M_{bulge} / M_{*} / M_{halo}.
- Large scatter, but no strong variation with redshift.
- *What physics connects BH and galaxy growth?*

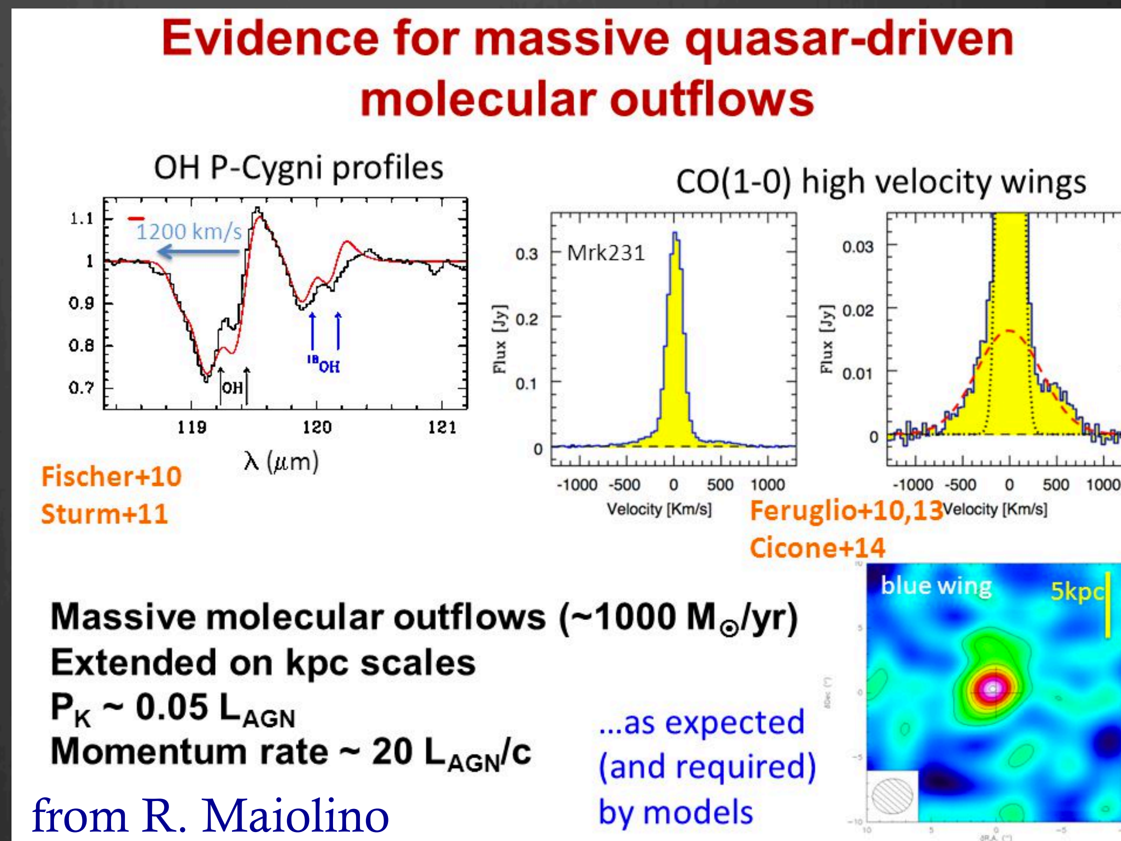


Schramm & Silverman 2013

BH Feedback Is Observed

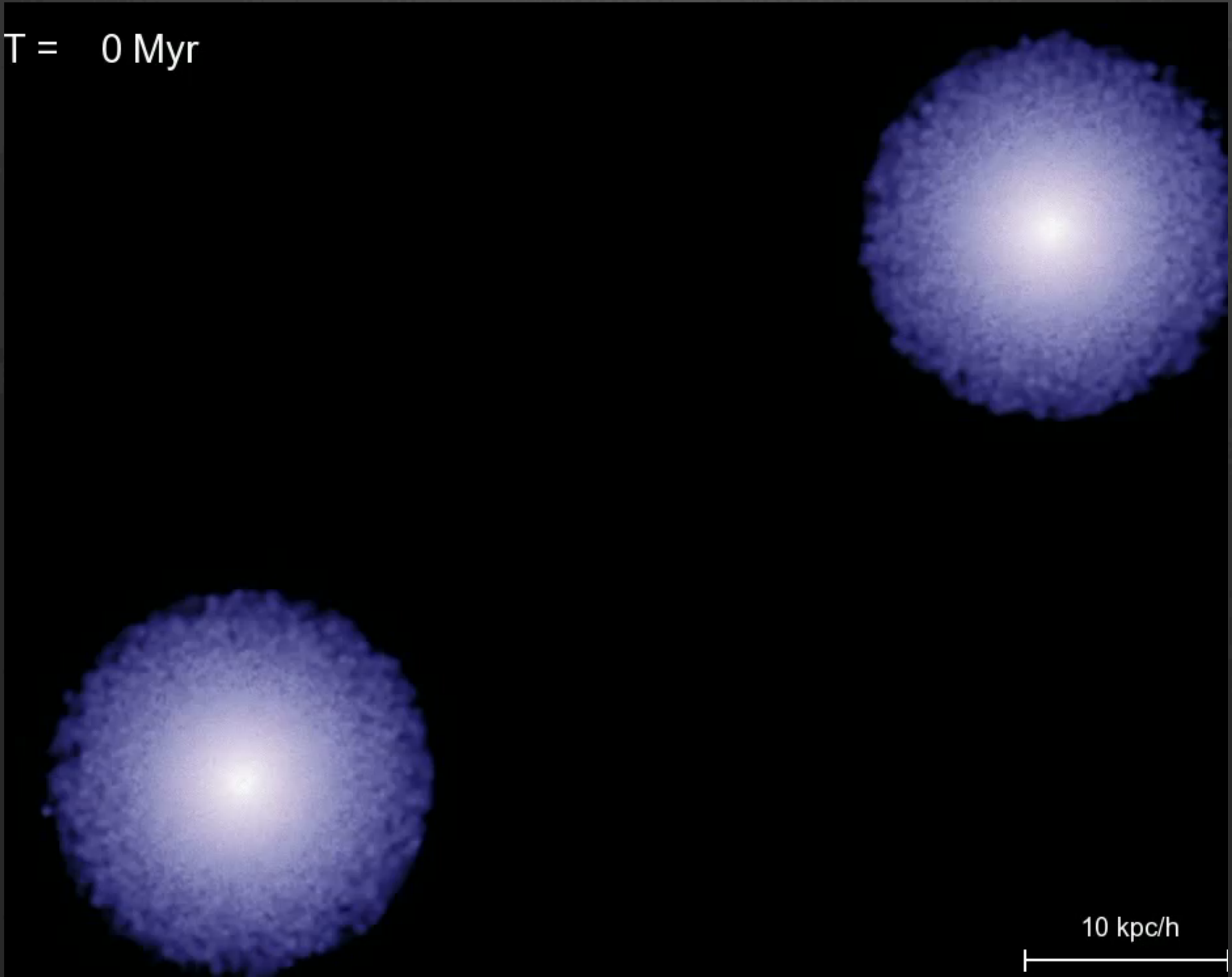
- Jets: Red & dead, λ_{Edd}<~0.02, v~10^4 km/s, p>~few L/c
- Molecular outflows: ULIRGs, λ_{Edd}>~0.02, v~10^4 km/s, p~20L/c





Modeling BH Growth+Feedback

- Pioneering models with thermal feedback: Mergers drive rapid central inflow, causes heating that expels gas.



Springel, di Matteo, Hernquist 2005

The Merger-Starburst-Quasar Scenario

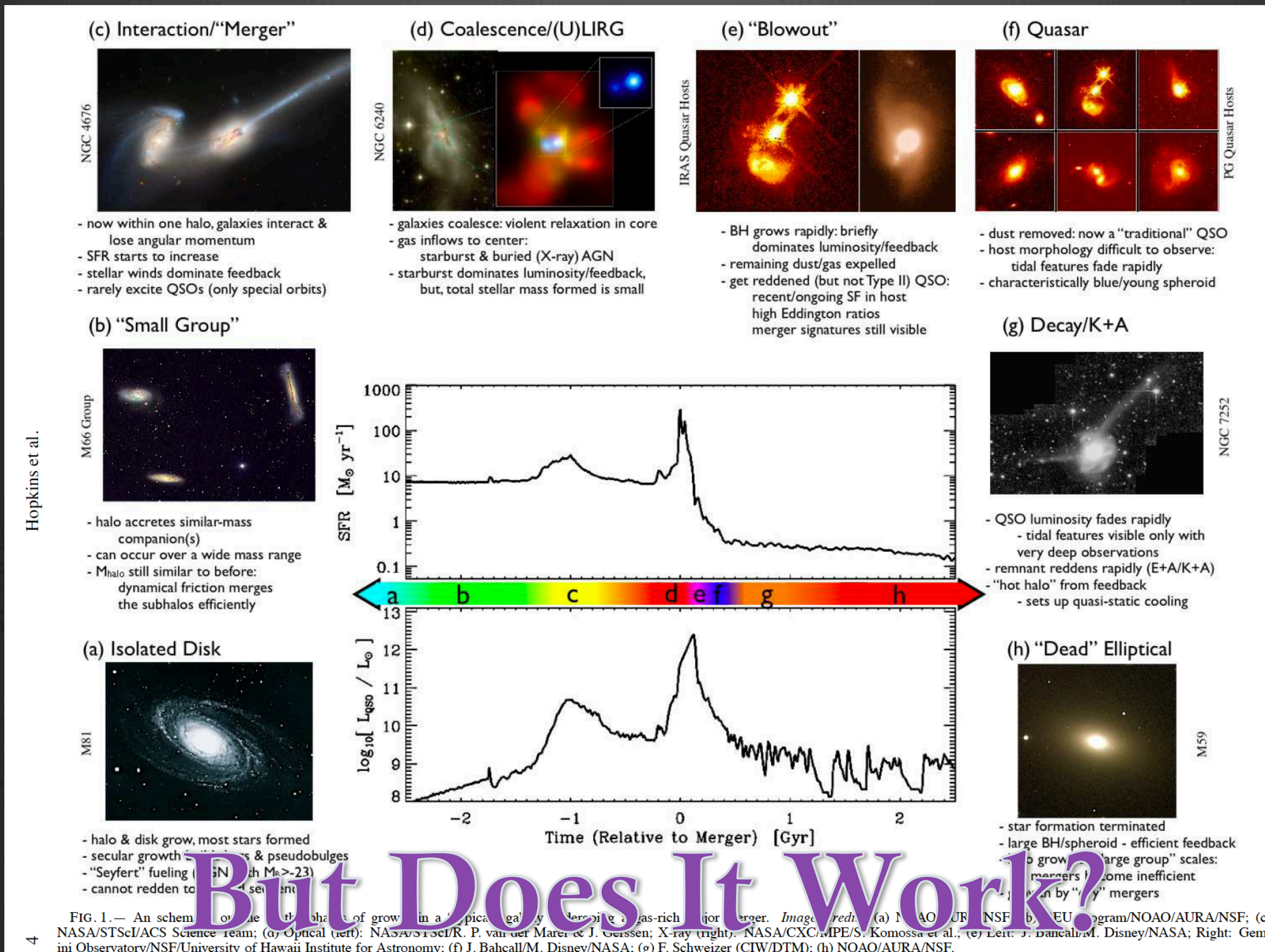
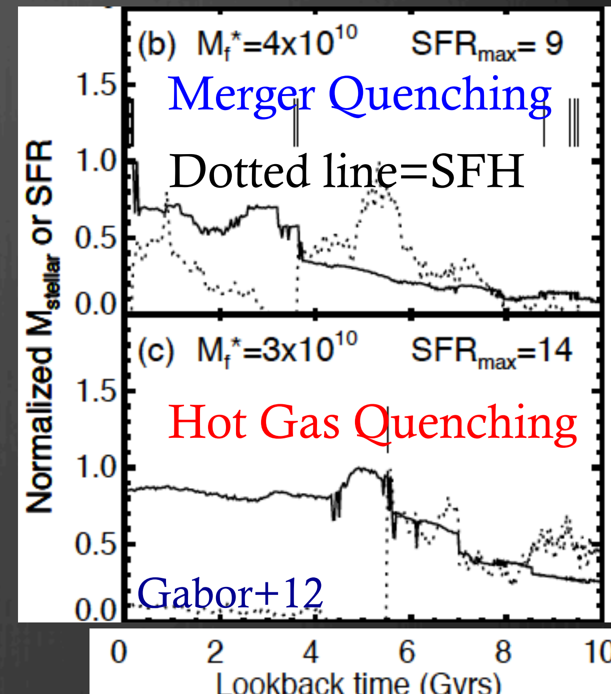


FIG. 1.— An schem ... of grow ... gas-rich ... erger. *Image credi...* (a) N ... AO ... NSF ... EU ... gram/NOAO/AURA/NSF; (c) NASA/STScI/ACS Science Team; (d) Optical (left): NASA/STScI/R. P. van der Marel & J. Gerssen; X-ray (right): NASA/CXC/MPE/S. Komossa et al.; (e) Left: J. Bahcall/M. Disney/NASA; Right: Gemini Observatory/NSF/University of Hawaii Institute for Astronomy; (f) J. Bahcall/M. Disney/NASA; (g) F. Schweizer (CIW/DTM); (h) NOAO/AURA/NSF.

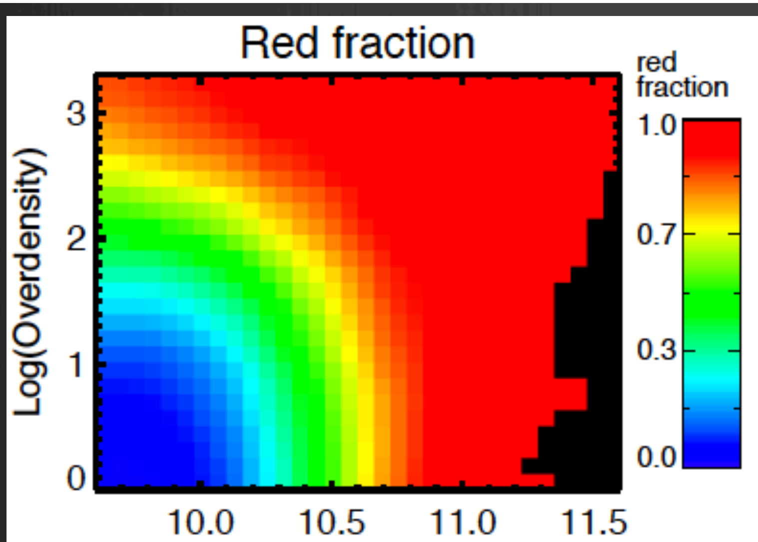
But Does It Work?

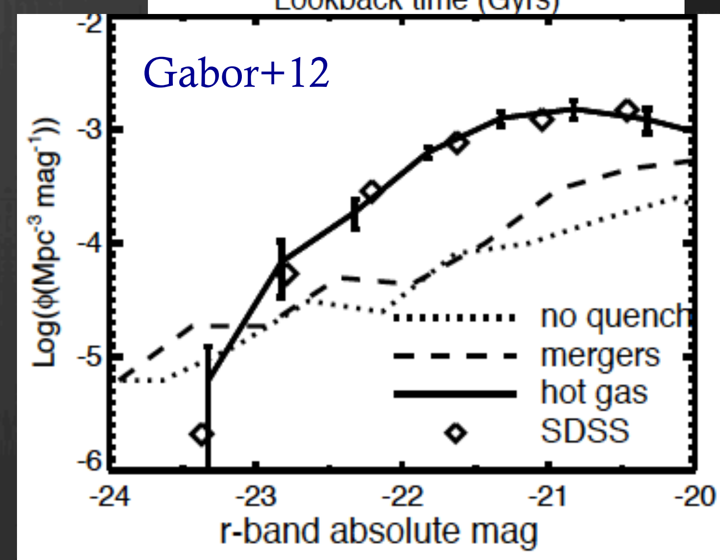
Need "Radio Mode"

- Croton+06 (SAMs): Keeping halo gas reservoir hot can quench galaxies.
- Gabor+12 (hydro sims): Gas evacuated in merger, SF restarts in 1-2 Gyr.
- Gabor+RD 15:



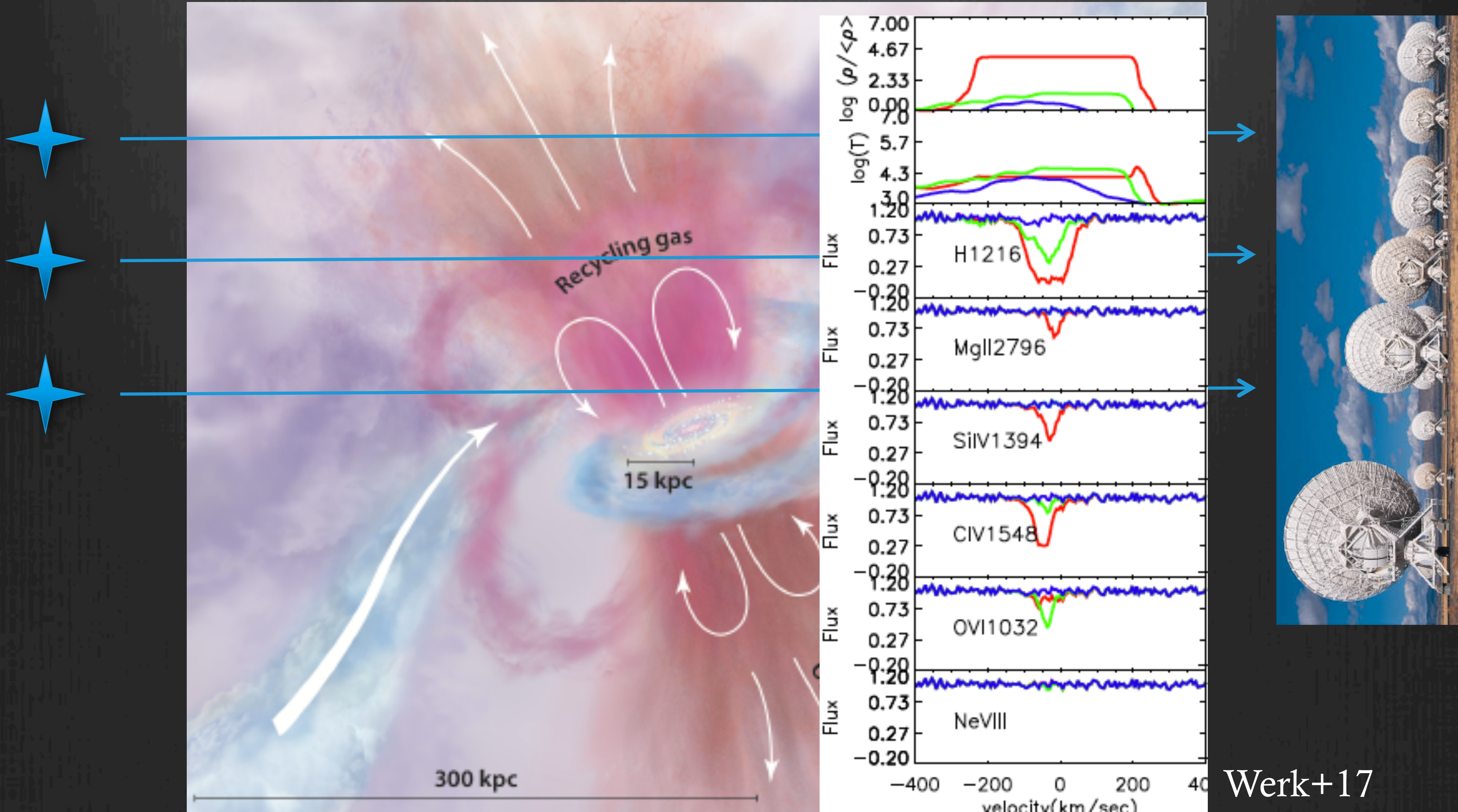
Hot gas in massive halos drives both mass quenching and environment quenching





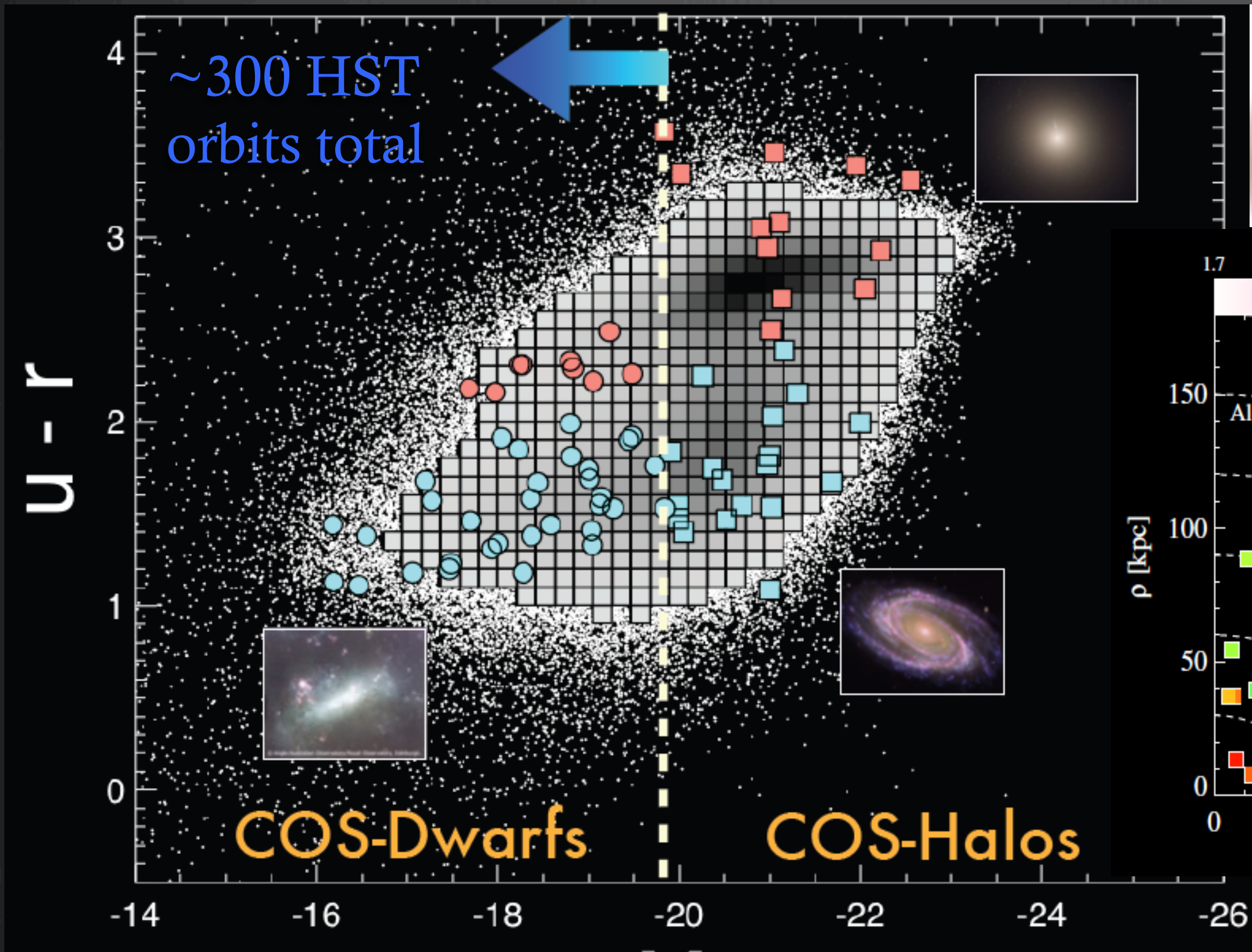
CGM: Observing the Baryon Cycle

Absorption lines can probe $\{\rho, T, Z, J_{UV}, v_{los}\}$



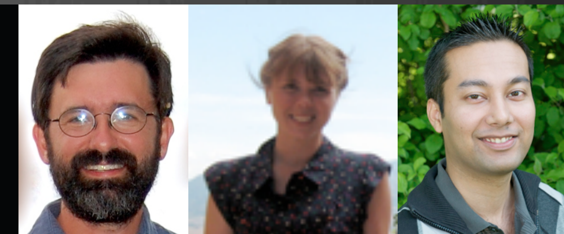
Werk+17

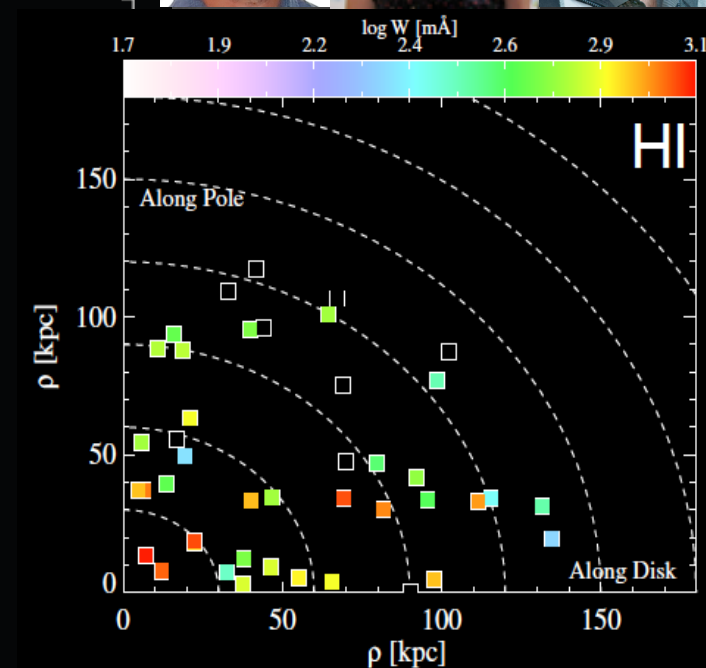
COS-Halos+COS-Dwarfs



z = 0.02 - 0.10
logM* = 8 - 10
optimal for CIV

z = 0.15 - 0.35
logM* = 10 - 11.5
optimal for OVI





Detect:
HI, OVI, CII, CIII, {CIV}, SiII, SiIII, SiIV, MgII (from Keck), …

CGM: Birth

protogalaxies (z>~6):

- massive first stars quickly disseminate metals into the CGM/IGM ➔ Pop II SF. *[What is IMF of first stars?]*

- CGM ionization suppresses galaxy growth in photo-sensitive halos $M_{halo} <\sim 10^{9\text{-}9.5}\,M_{\odot}$. *[Is this where MW dE's come from?]*

- EoR CGM probed by metal absorbers, 21cm emission. *[Can we see UV/IR line emission?]*

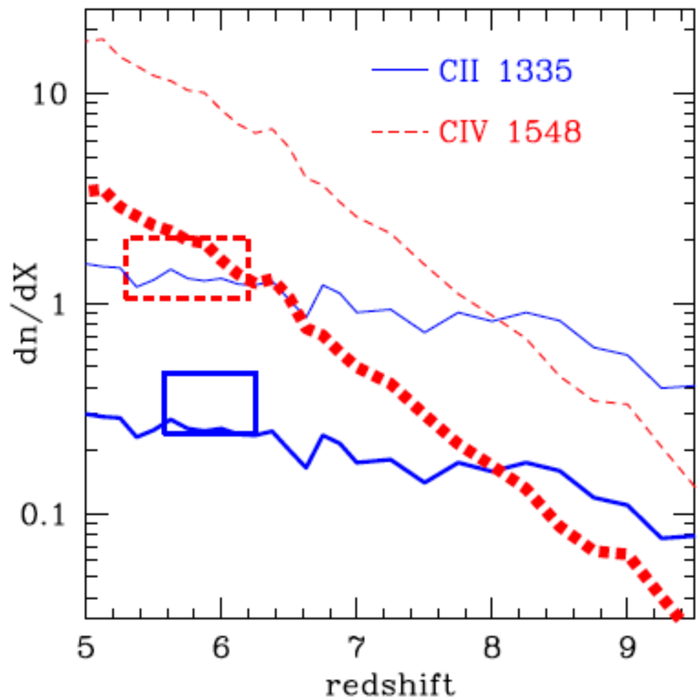
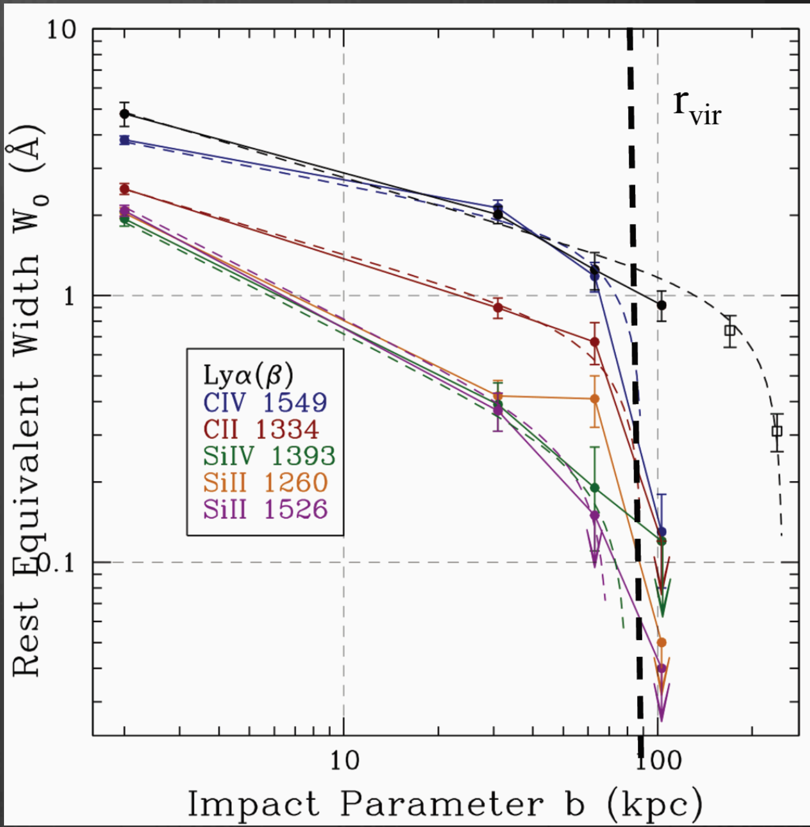


Figure 9. The predicted number of C II (solid blue) and C IV (dashed red) systems per unit absorption path length as a function of redshift. Heavy curves indicate the expected number of systems in the column density range 10^{13}–$10^{15}\mathrm{cm}^{-2}$, whereas thin curves correspond to a next-generation survey encompassing 10^{12}–$10^{15}\mathrm{cm}^{-2}$. All curves include an extrapolation as described in the text. The predicted number of C II systems evolves slowly while the predicted C IV abundance decreases strongly with increasing redshift. The solid blue and dashed red boxes indicate C II and C IV observations, respectively.

CGM: Adolescence

peak galaxy growth (2<z<6)

- Strong ubiquitous outflows, higher mass loading in lower-mass galaxies. *[How much preventive feedback from winds?]*
- Powerful AGN appear, and first quenched galaxies. *[Can radio mode alone quench early galaxies fast enough?]*
- Accretion via cold filaments. *[When does the hot CGM/proto-ICM appear?]*

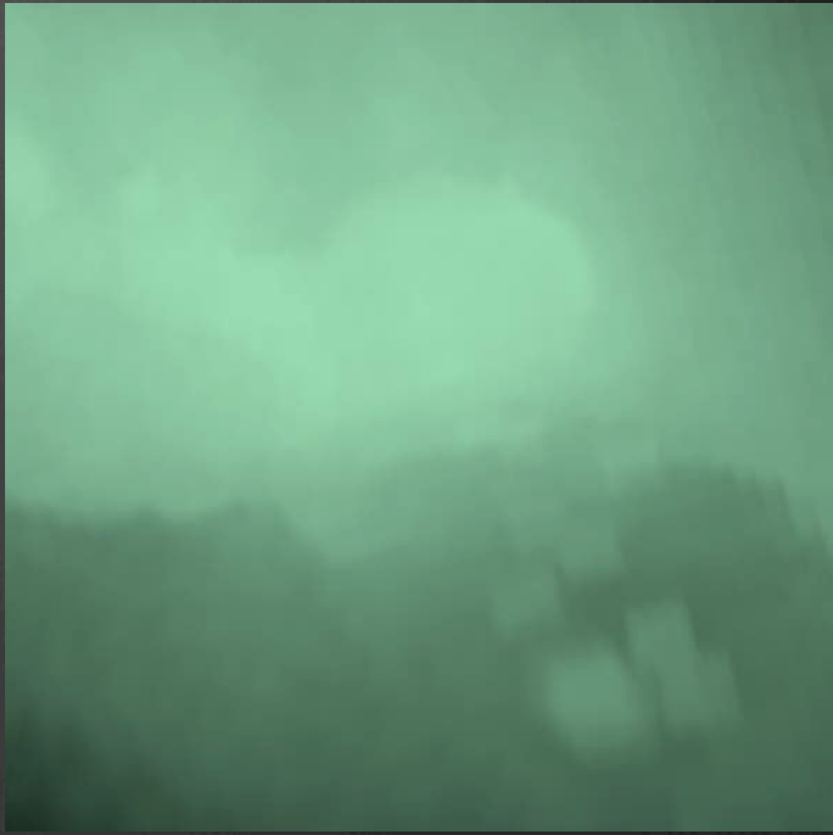


Steidel+10: Stacked galaxy-galaxy abs

CGM: Settling

hubble sequence emerges (0.5<z<2)

- Slower accretion, lower SF means thin disks can form. *[Abundance gradients established?]*
- BHs get frisky and start quenching centrals above a given halo mass. *[Does this only depend on mass?]*
- Weaker winds means IGM metals start migrating back towards galaxies. *[How do we measure the extent of IGM metals?]*



GASOLINE sim by F. Governato

CGM: Present-day Galaxies

the boring life (z<~0.5)… or is it?

- Big disks slowly moving towards quiescence. *[Is accretion from IGM still happening? necessary?]*
- Outflows are rare, mostly fountains. *[Is this because of SFR or ISM morphology?]*
- AGN maintenance mode is keeping massive galaxies quenched. *[How does AGN energy couple to hot CGM?]*

Chandra image of NGC5813 Group

Summary

- Galaxies grow in a balance between environmentally-regulated inflows, star formation in dense ISM gas, and ubiquitous outflows driven by star formation processes. None of these physical processes are well understood.
- Galaxies likely quenched by AGN feedback, the main impact of which is to keep CGM gas hot. However, expulsion also happens, and could drive quenching in some (most?) cases. None of these physical processes are well understood.
- Many frontiers where galaxy formation models can make an impact, as numerical experiments that can guide and interpret observations and provide new testable predictions.