The multi-phase gas in the semi-analytic model GAEA

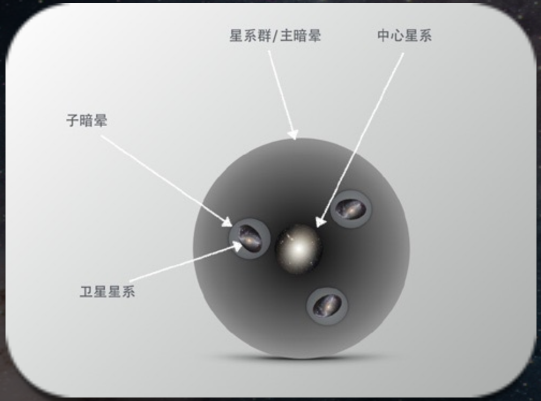
Lizhi Xie

2023-6-5 @ IFPU

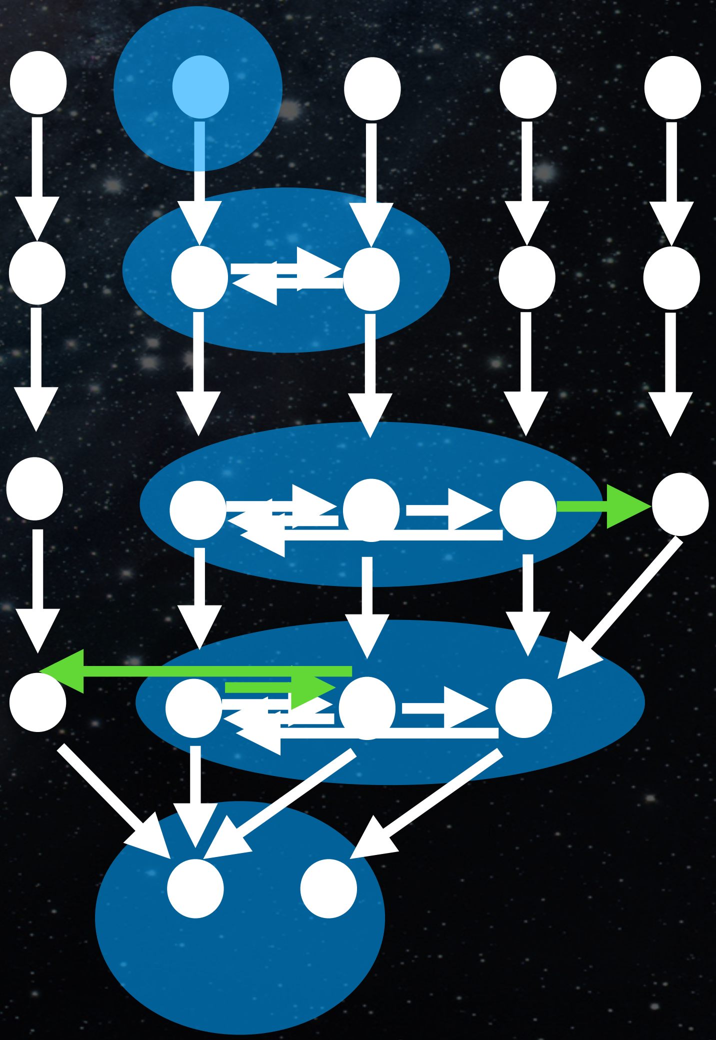
Collaborators: Gabriella De Lucia; Fabio Fontanot; Michaela Hirschmann

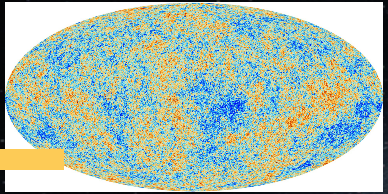
Simulate the Universe

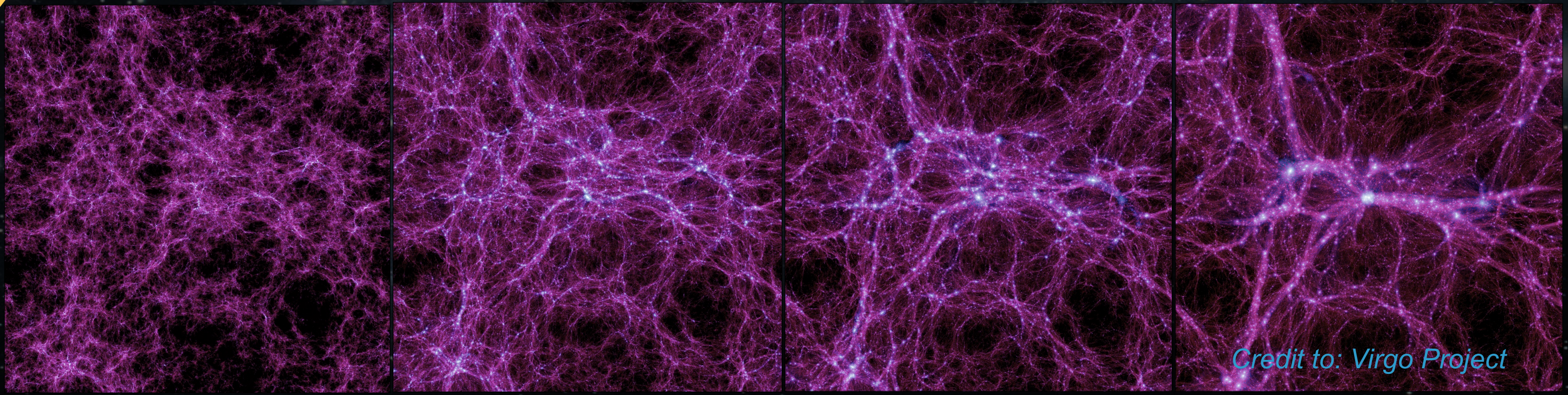
N-body simulation
- Solve gravity between multiple dark matter particles
- Output the hierarchical assembly of the cosmic structure



merger tree

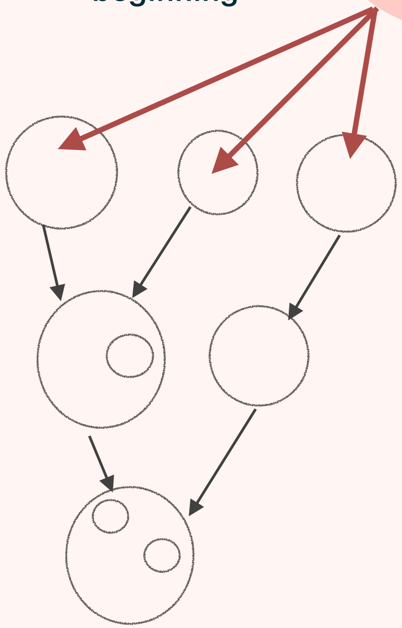


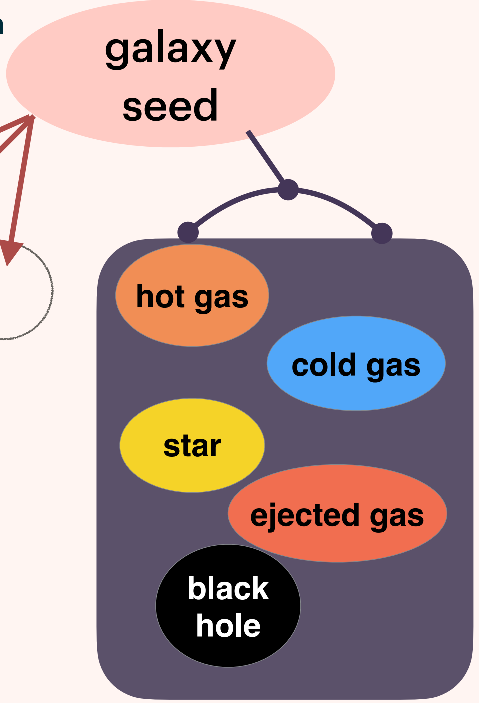




SEMI-ANALYTIC GALAXY FORMATION MODEL

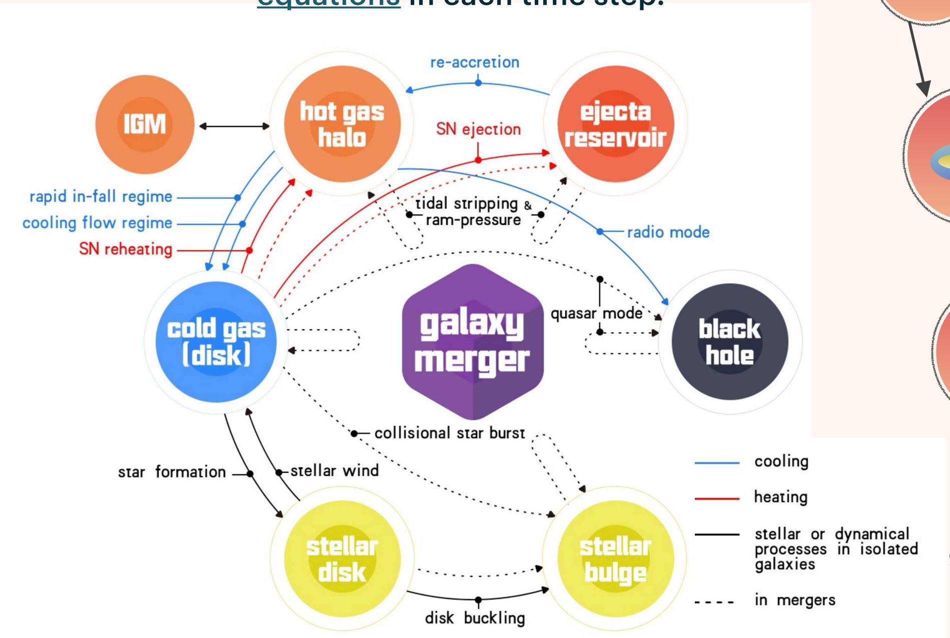
put a galaxy seed in each dark matter halo at the beginning



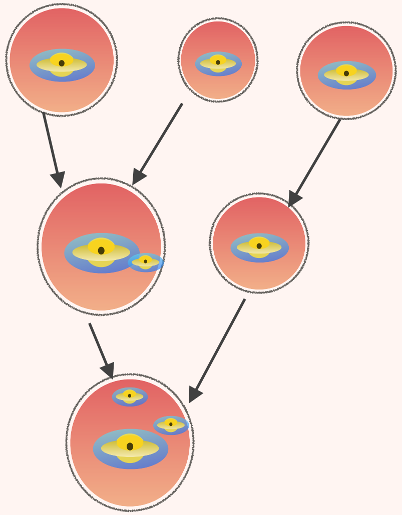


Each galaxy is divided into several discrete components

Evolve a galaxy by counting the mass increase/decrease of each component while calculating physically/empirically motivated equations in each time step.



Jiang et al. 2019



knowing the properties of each galaxy at different times, merge galaxies when time is up, now you get the galaxy merger tree

Sub-grid physics

A dark matter particle equals to $\sim 10^6 M_\odot - 10^8 M_\odot$
Cosmological simulation is not able to
- resolve earth, solar system
- simulate the interactions between stellar clouds or stars
- not even the nuclear activities inside stars

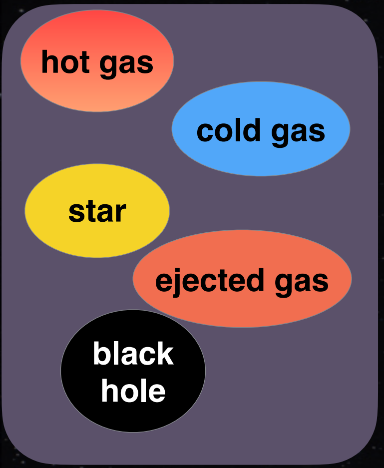
The time resolution is ~15,000,000 years
- Cosmological simulation can not simulate interactions between atoms and ions within stars, ISM, and IGM.

Sub-grid physics

Empirical equations or theoretical models for physical processes that are too small to be handled in simulations

Unknown physical details

- Test the impact of each individual physical processes
- Modifying details of hypothetical theories using observational constraints
- Implement with new theories

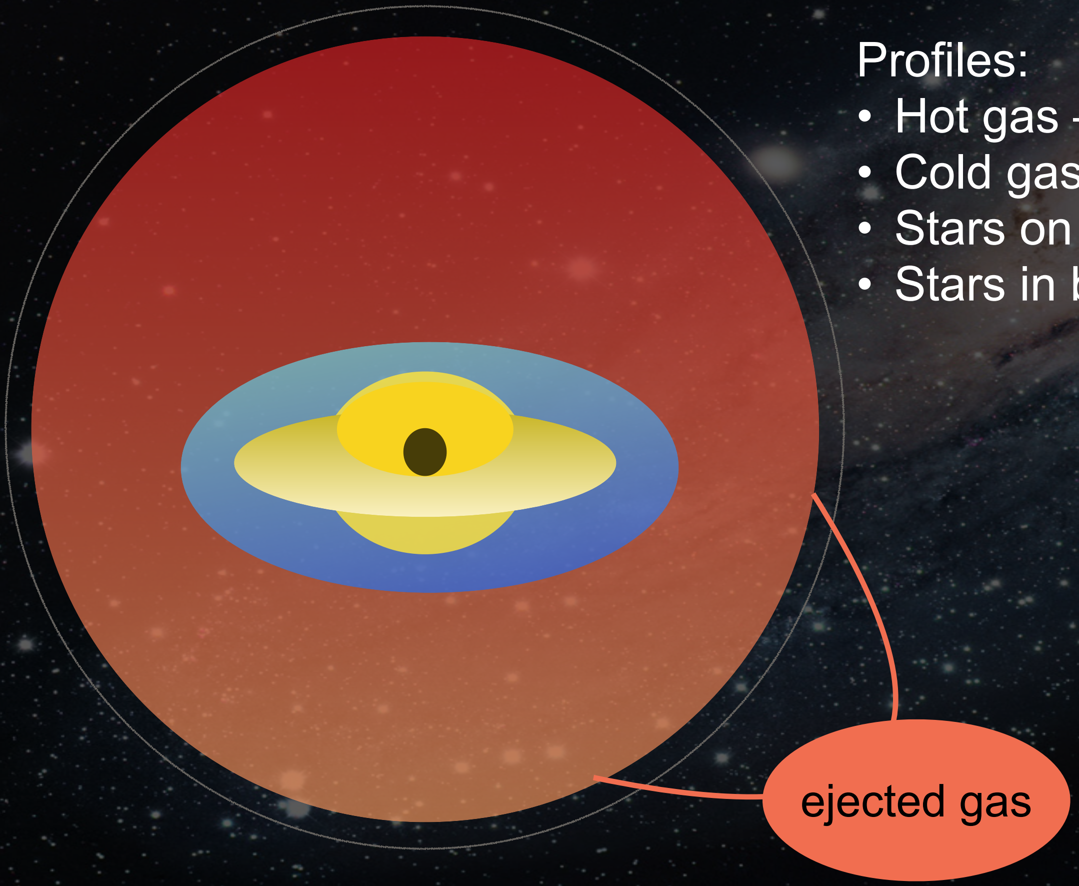


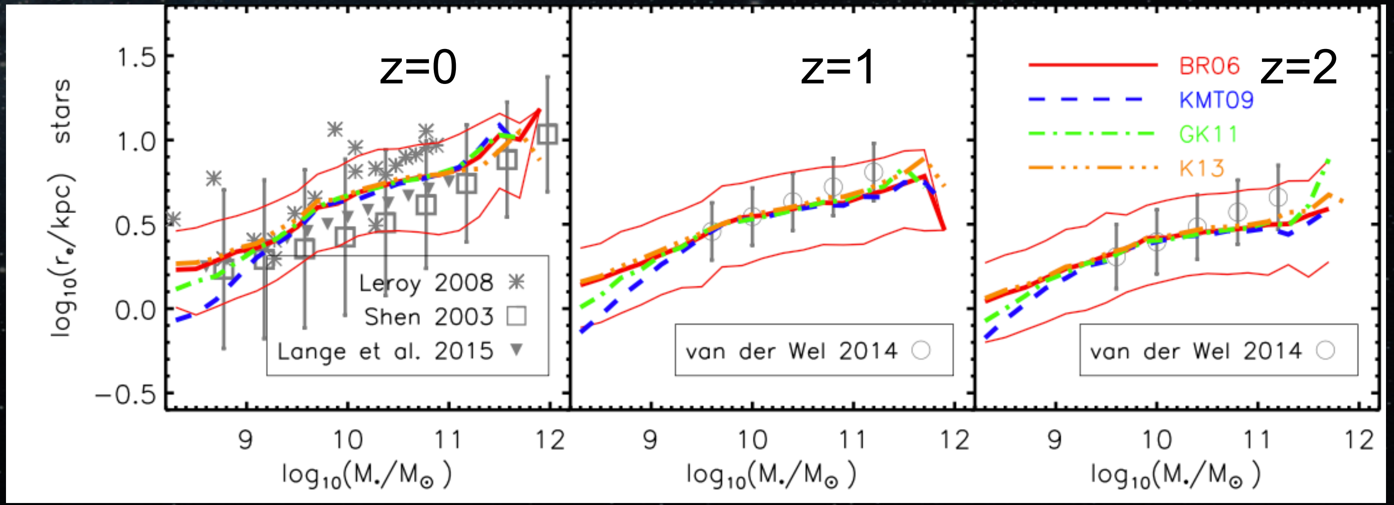
A galaxy in SAM

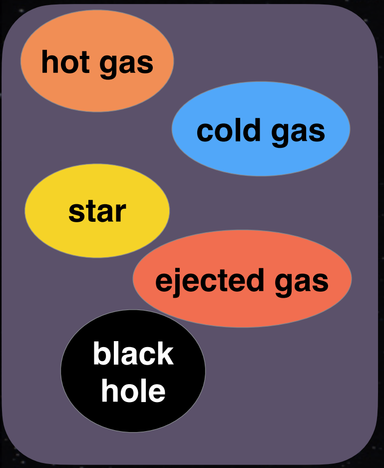
Sizes — angular momentum $\overset{\text{Accretion}}{j_{\rm DM} \rightarrow} j_{\rm hotgas} \overset{\text{Cooling}}{\rightarrow} j_{coldgas} \overset{\text{SF}}{\rightarrow} j_{\star}$

Profiles:

- Hot gas — isothermal sphere
- Cold gas — exponential
- Stars on the disc — exponential
- Stars in bulge — Jaffe law



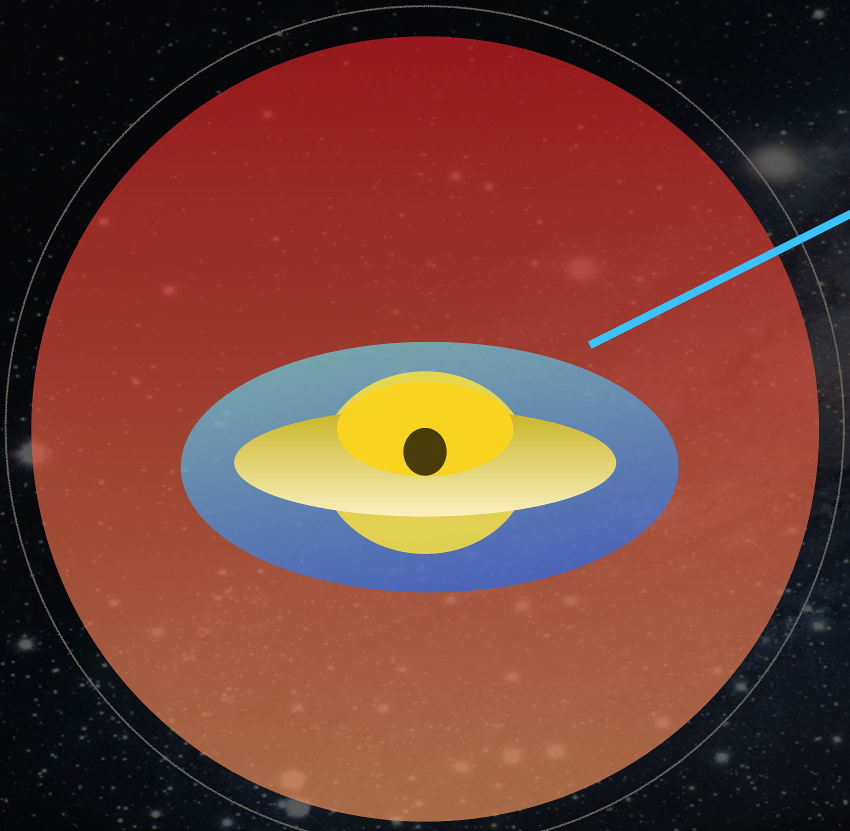


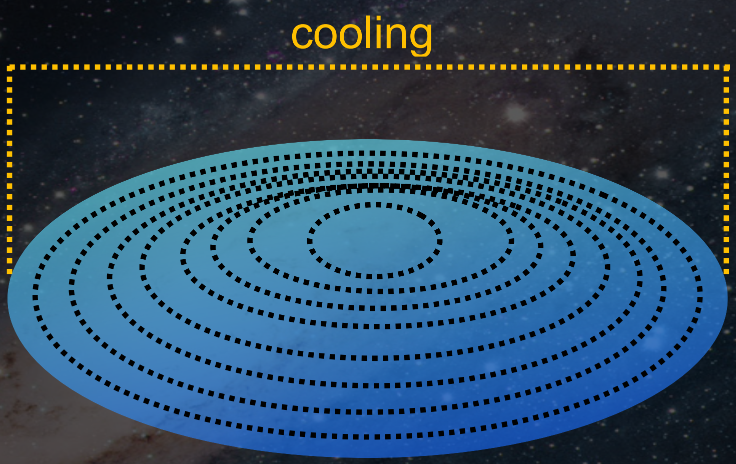


Gas on the cold gas disk

20 annuli, $r_i = [0.2, 10] r_g$

r_g - scale length

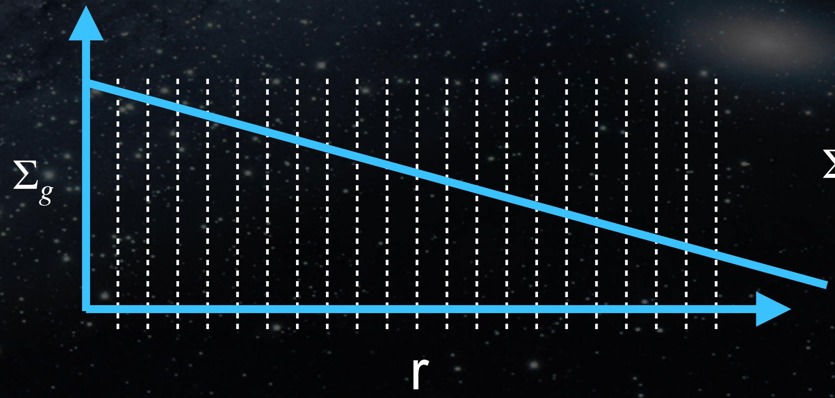


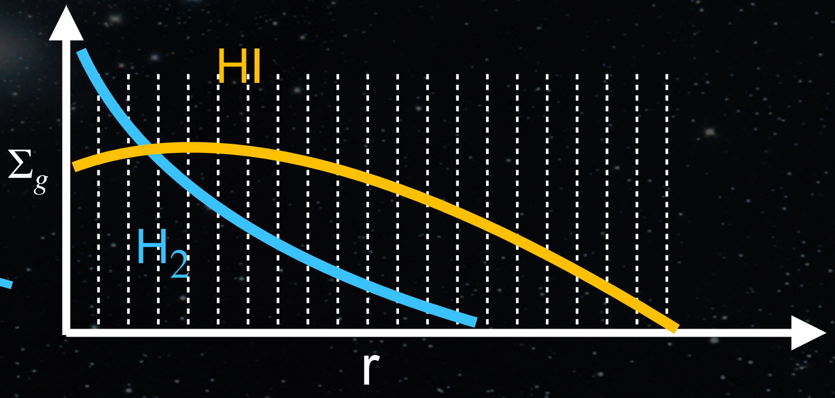


$$r_g = \frac{j_g}{2V_{max}}$$

$$\Sigma_{g,i} = \frac{M_g}{2\pi r_g^2} e^{-r_i/r_g}$$

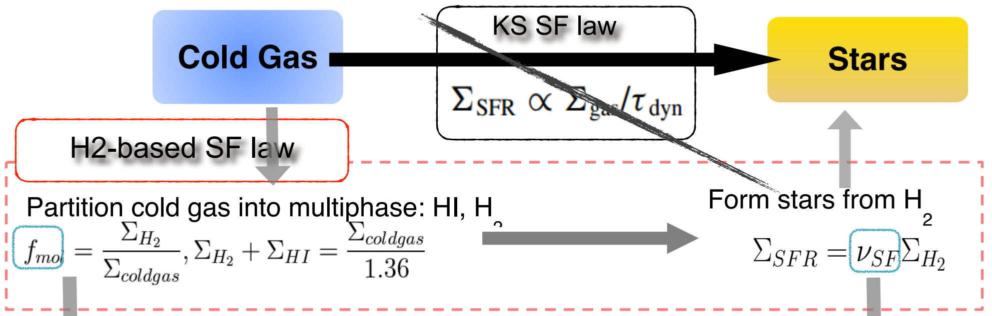
Cold gas density profile
— exponential





Multi-phase cold gas — star formation laws

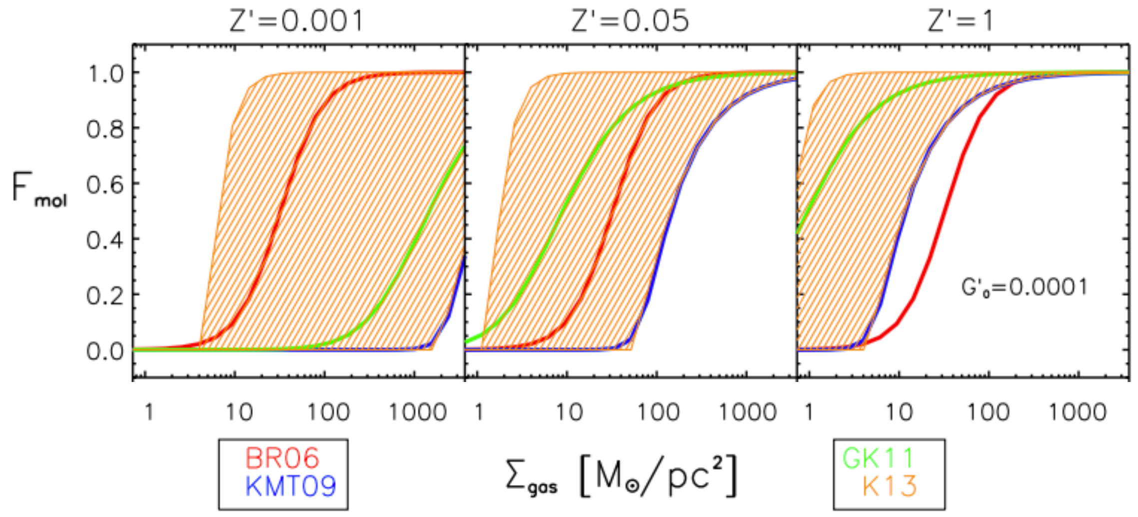
We tested four H2-based star formation laws to partition HI and H2

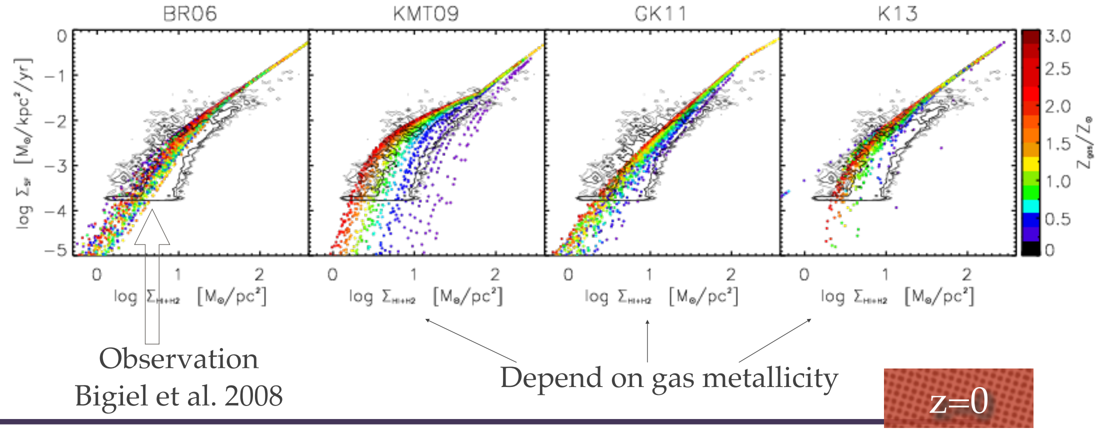


H2-based SF law

- **Fitting functions of nearby galaxies:** Blitz & Rosolowsky 2006 (BR06) .
- **Theories:** Krumholz, Mckee & Tumlinson 2009 (KMT09); Krumholz 2013 (K13)
- **Fitting functions of hydro-simulations:** Gnedin & Kravtsov 2011 (GK11)

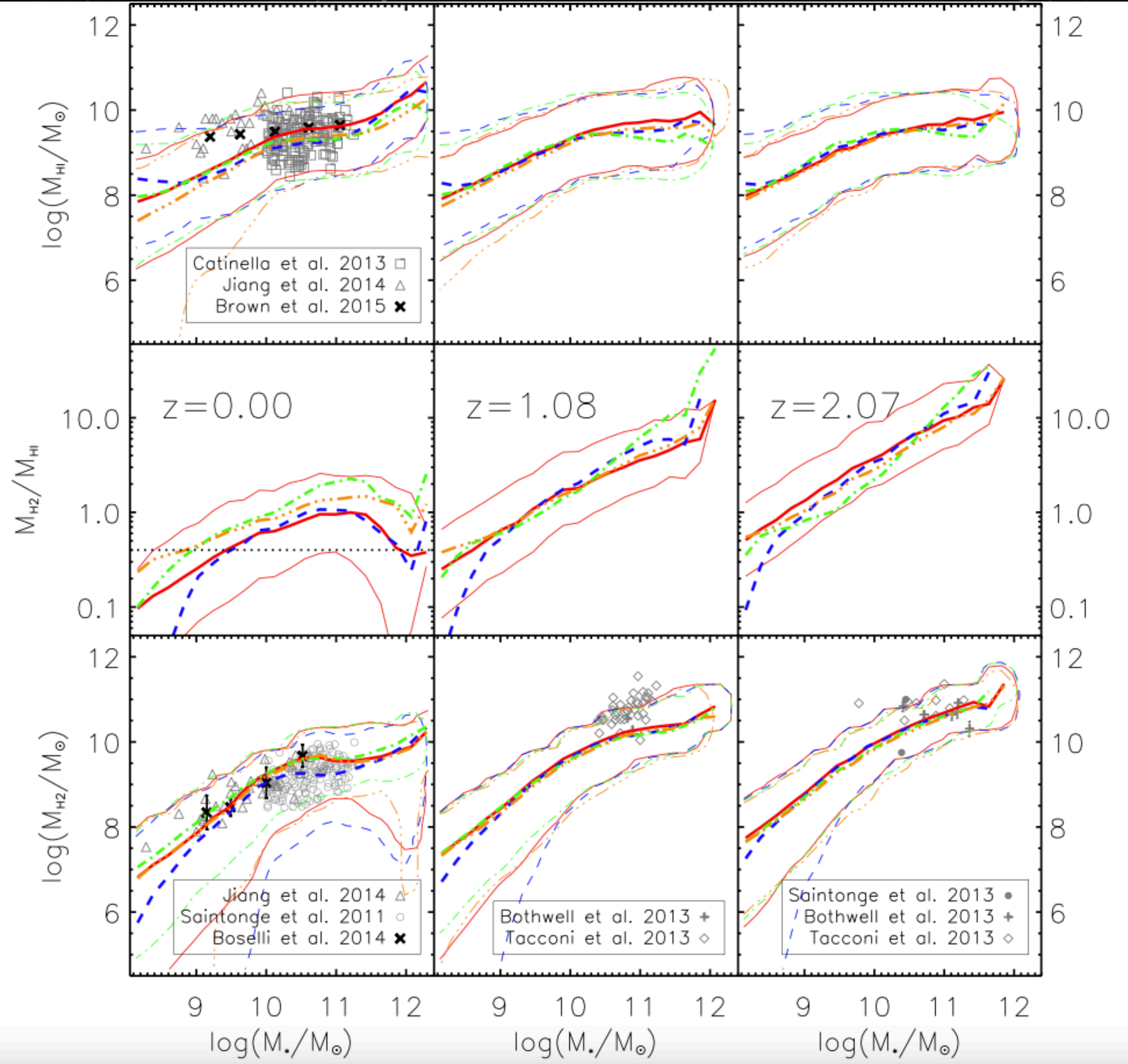
Cold Gas = HI + H2 + (He+metals)





z=0

Xie et al. 2017, arXiv: 1611.09372

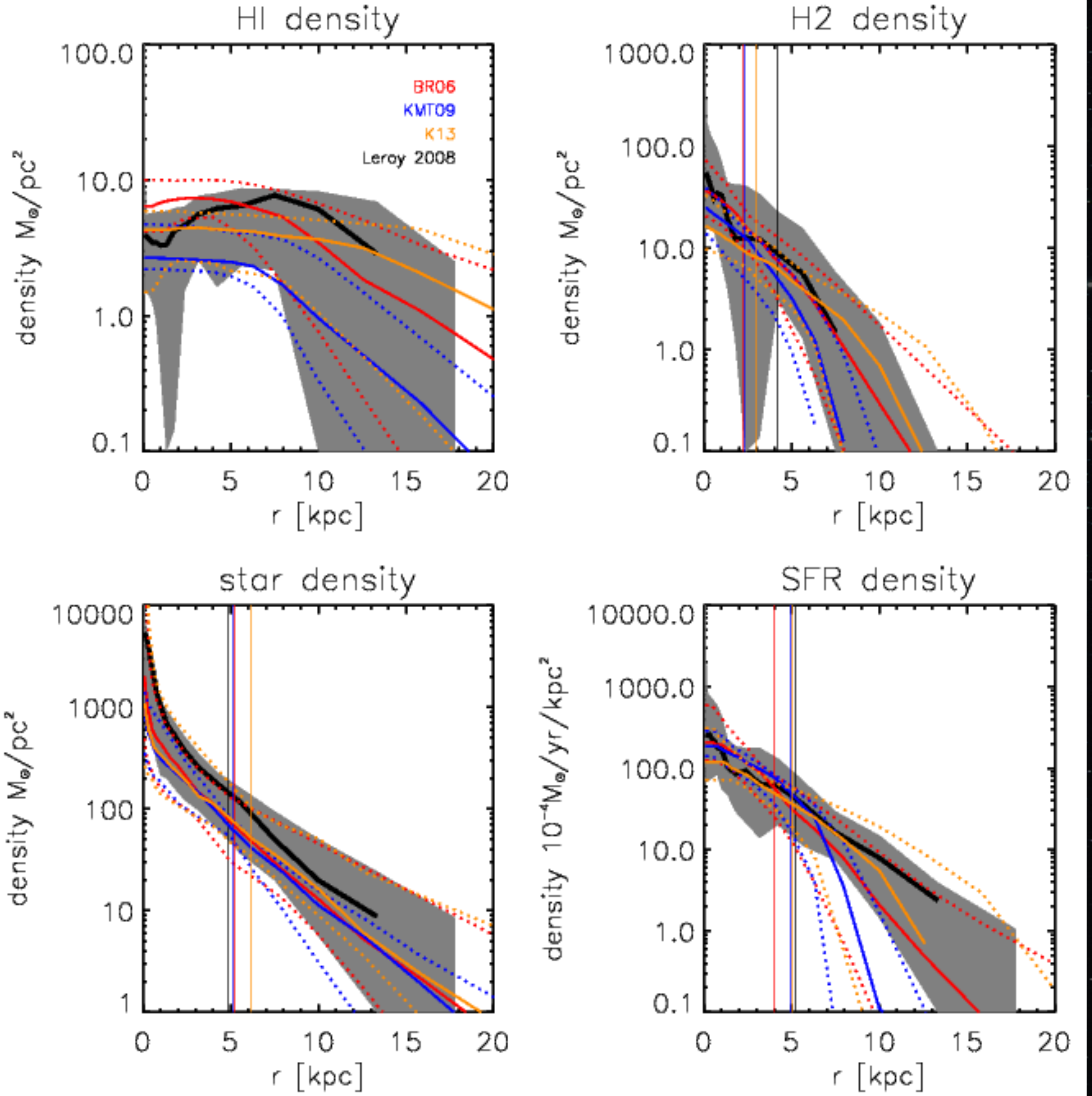


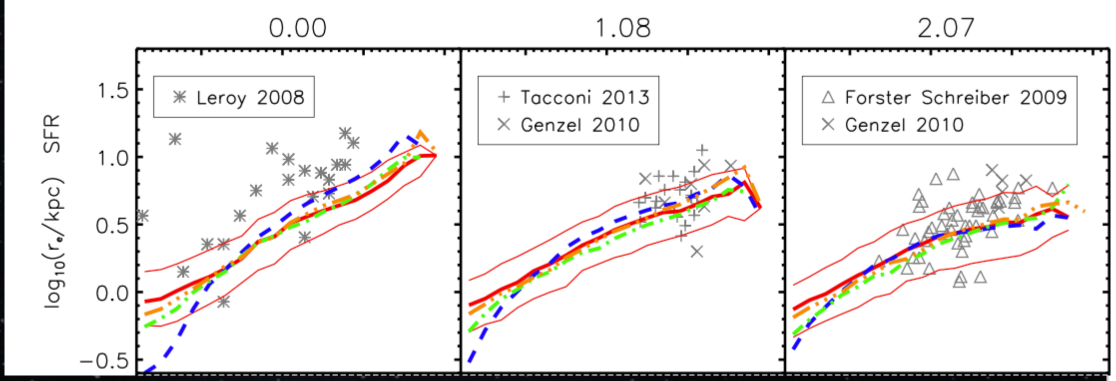
Modifying star formation laws does not significantly affect the HI or H2 fractions

$$cooling \rightarrow f_{mol} \rightarrow SFR \rightarrow feedback \rightarrow f_{mol}$$

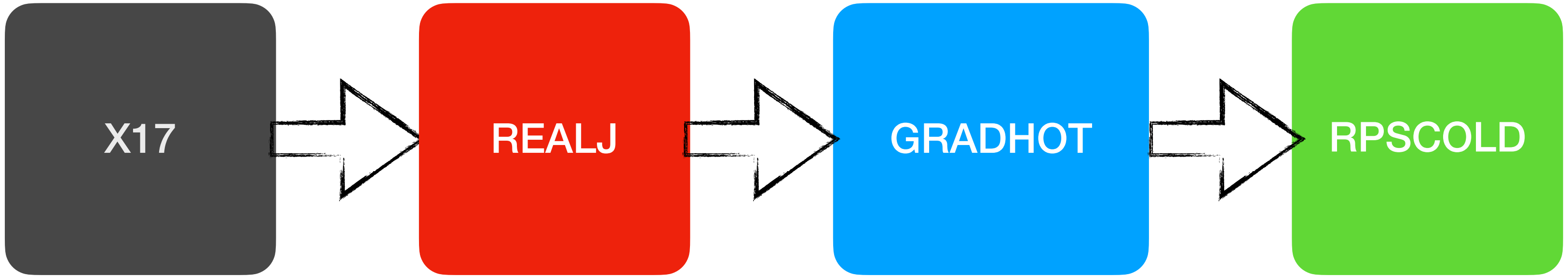
Density Profiles

Our model can reproduce the HI, H2, SFR, and stellar density profiles of near by galaxies.
Waiting to compare with more data.





Update environmental effects —



REALJ :

Cooling: $j_{cooling} = 3j_{\rm dm}$ during cold flow; $j_{cooling} = 1.4j_{\rm dm}$ while hot-mode cooling

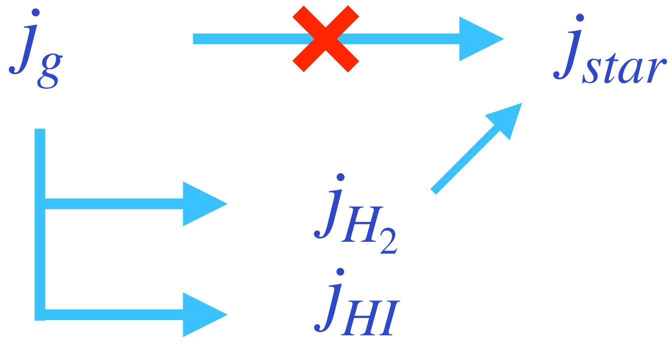
Star formation: stars form in 20 annuli on the disk, $j_{\rm sf} = j_{\rm SFgas} < j_{gas\ disk}$

GRADHOT :

tidal stripping + ram-pressure stripping to remove hot gas, stripping time-scale 400 Myr

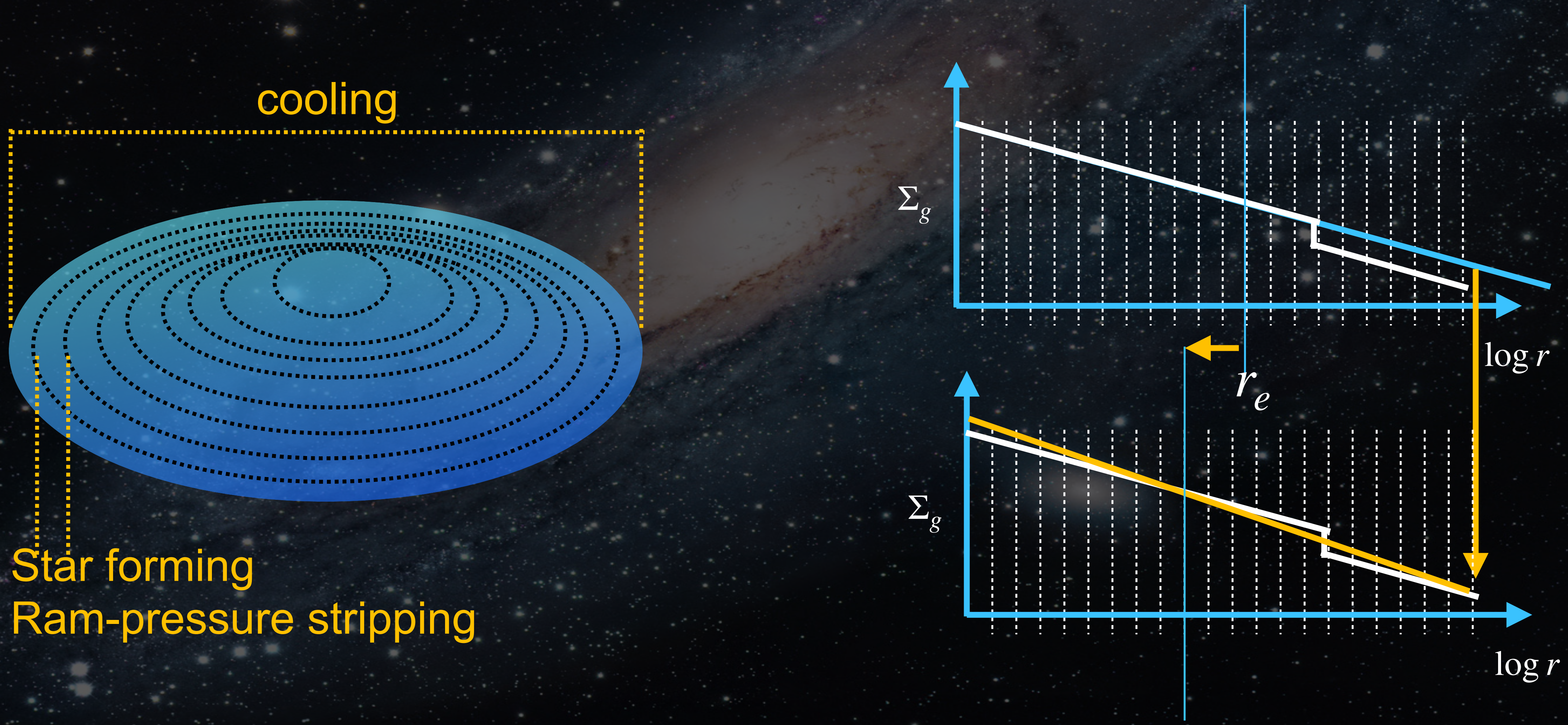
RPSCOLD:

ram-pressure stripping of cold gas in each annulus if $r_{g,i} < r_{\rm hot}$, stripping time-scale 400 Myr



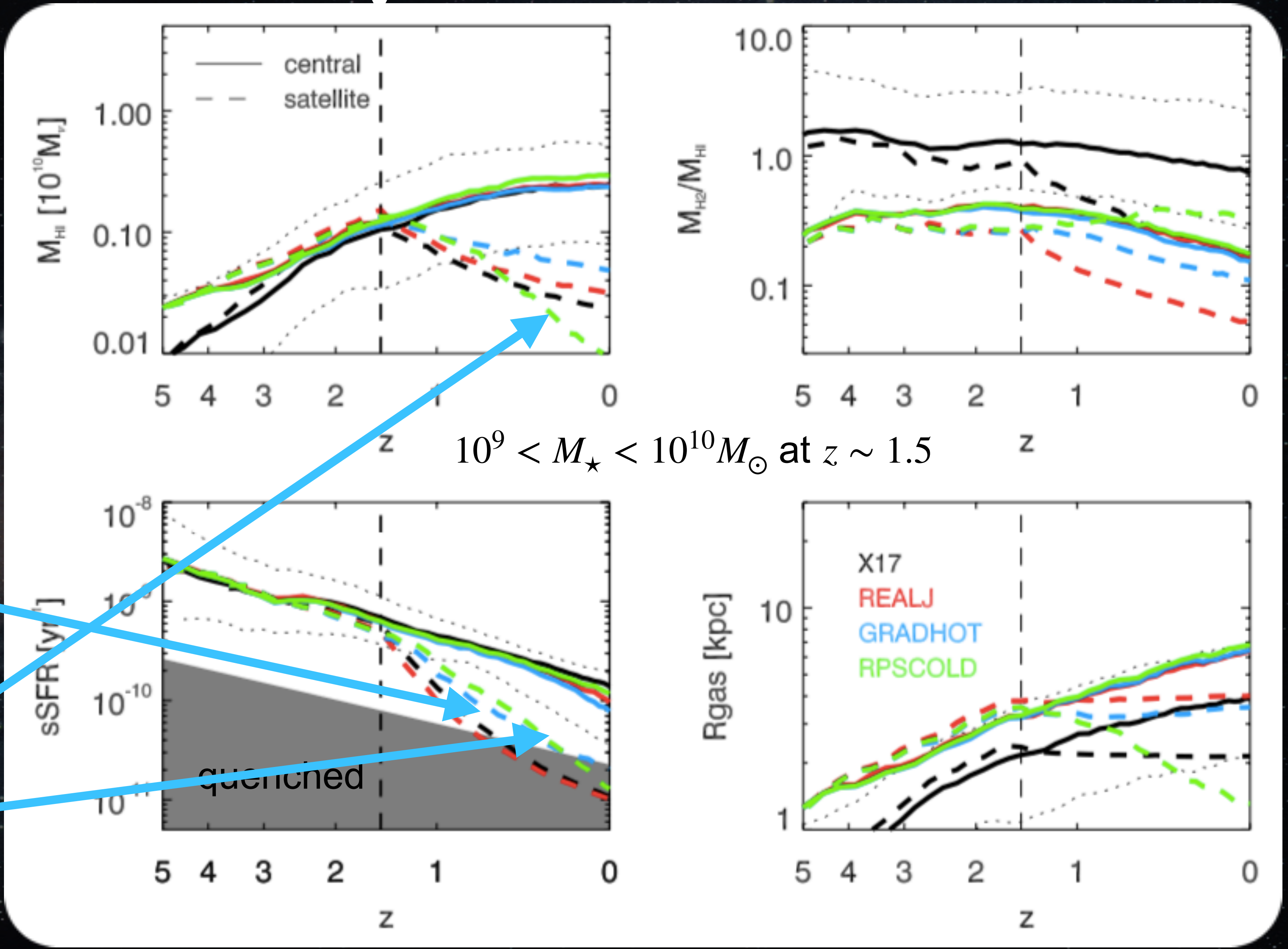
specific angular momentum in annulus i $\quad j_{\rm g,i} = \frac{r_{\rm i}}{2r_{\rm g}} j_{\rm g}$

Environmental stripping remove gas, mostly HI, at large radii



- X17 = original model
- REALJ = X17 + angular momentum updates
- GRADHOT = REALJ + gradual hot gas stripping
- RPSCOLD = GRADHOT + cold gas stripping

infall time



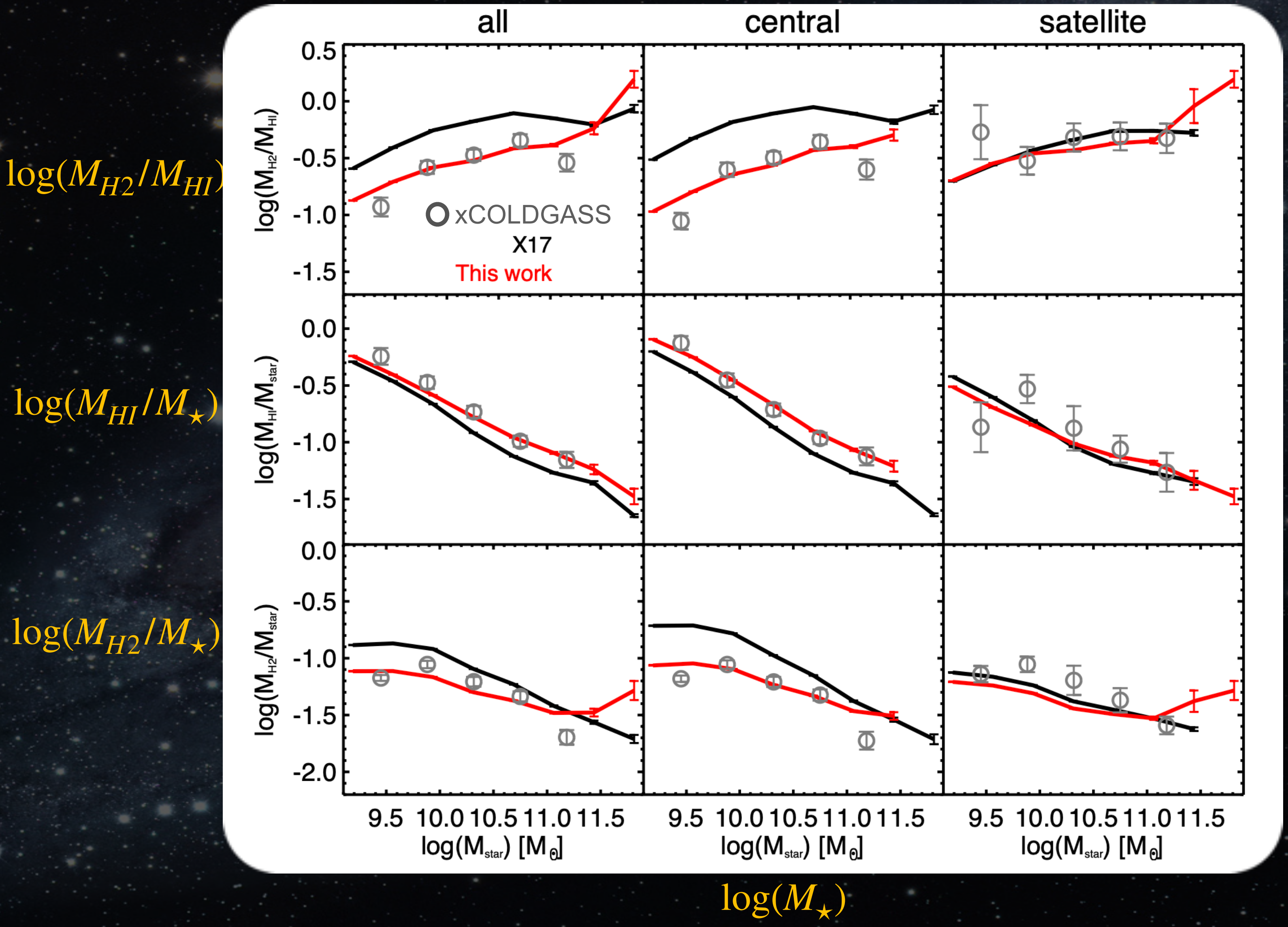
$10^9 < M_\star < 10^{10} M_\odot$ at $z \sim 1.5$

With gradual stripping of hot gas, the quenching of star formation in satellite galaxies is delayed

With RPS of cold gas, the HI mass decreases rapidly, while SFR is not obviously affected.

Xie et al. 2020

Calibration — gas fractions of central and satellite galaxies at $z \sim 0$

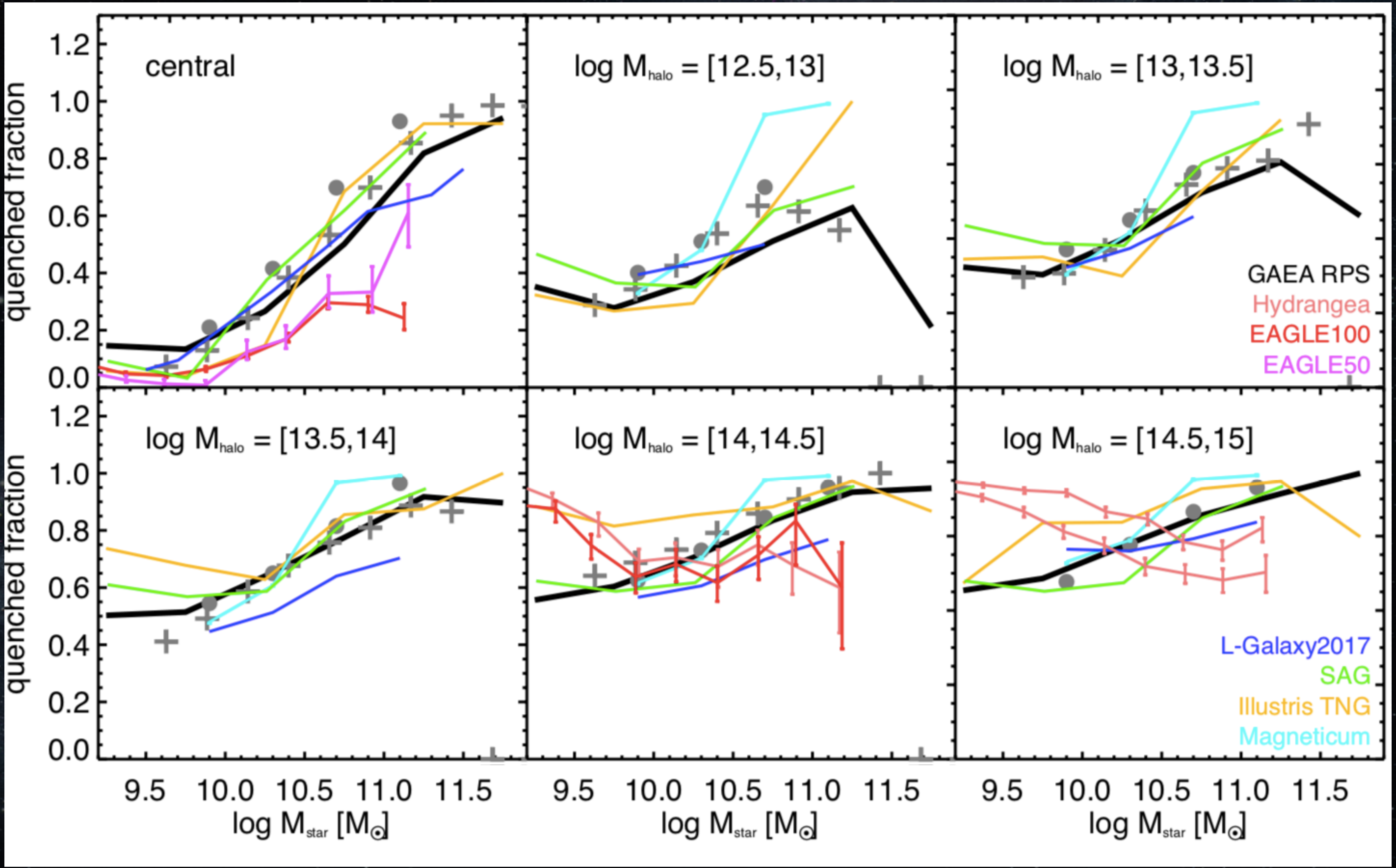


Xie et al. 2020

Compare with other state-of-the-art models and simulations

SDSS ● +

This work — black



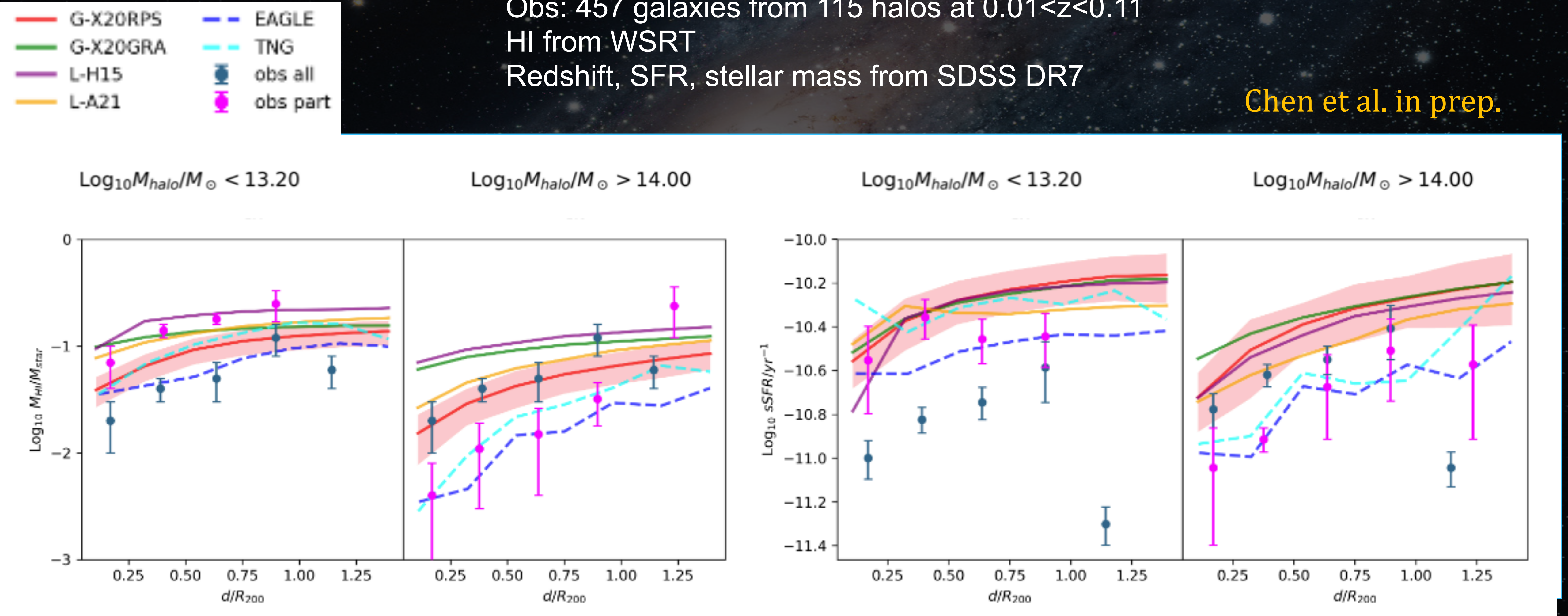
z~0

Xie et al. 2020

Compare with other state-of-the-art models and simulations

Obs: 457 galaxies from 115 halos at 0.01<z<0.11
HI from WSRT
Redshift, SFR, stellar mass from SDSS DR7

Chen et al. in prep.



Conclusion

- Our model can reproduce the HI and H2 scaling relations at z=0.
- The profiles of HI, H2 and stars are also consistent with observational measurements for nearby galaxies.
- Varying star formation laws have minor impact on the global properties of model galaxies.
- The ram-pressure stripping of cold gas can decrease the HI in satellite galaxies rapidly.