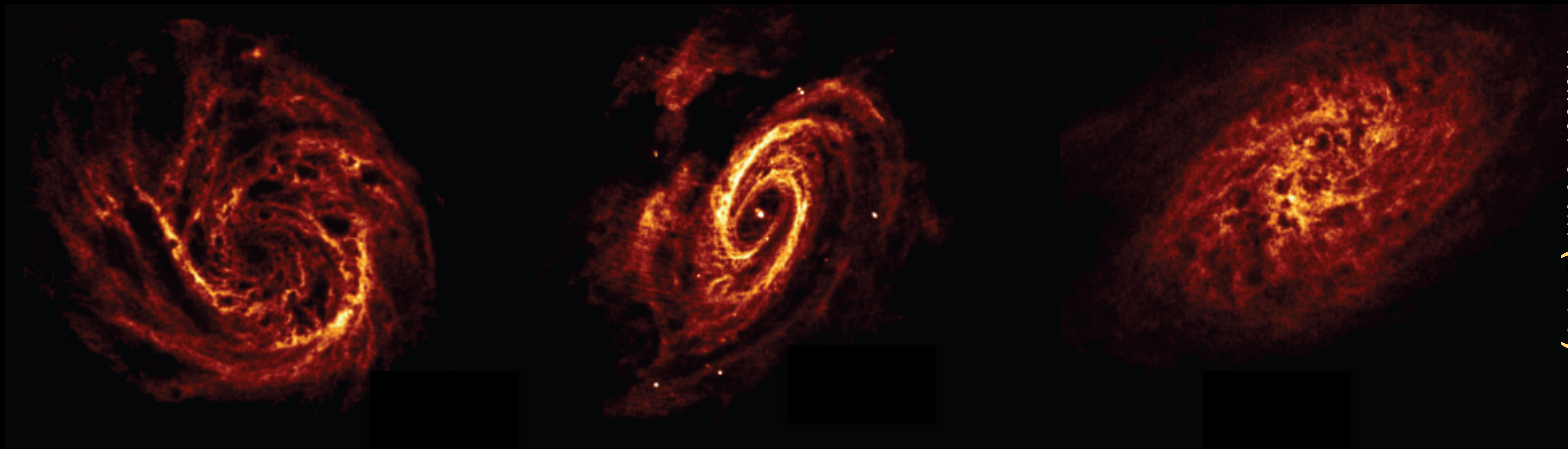

Galaxy Evolution Probed by Extragalactic HI

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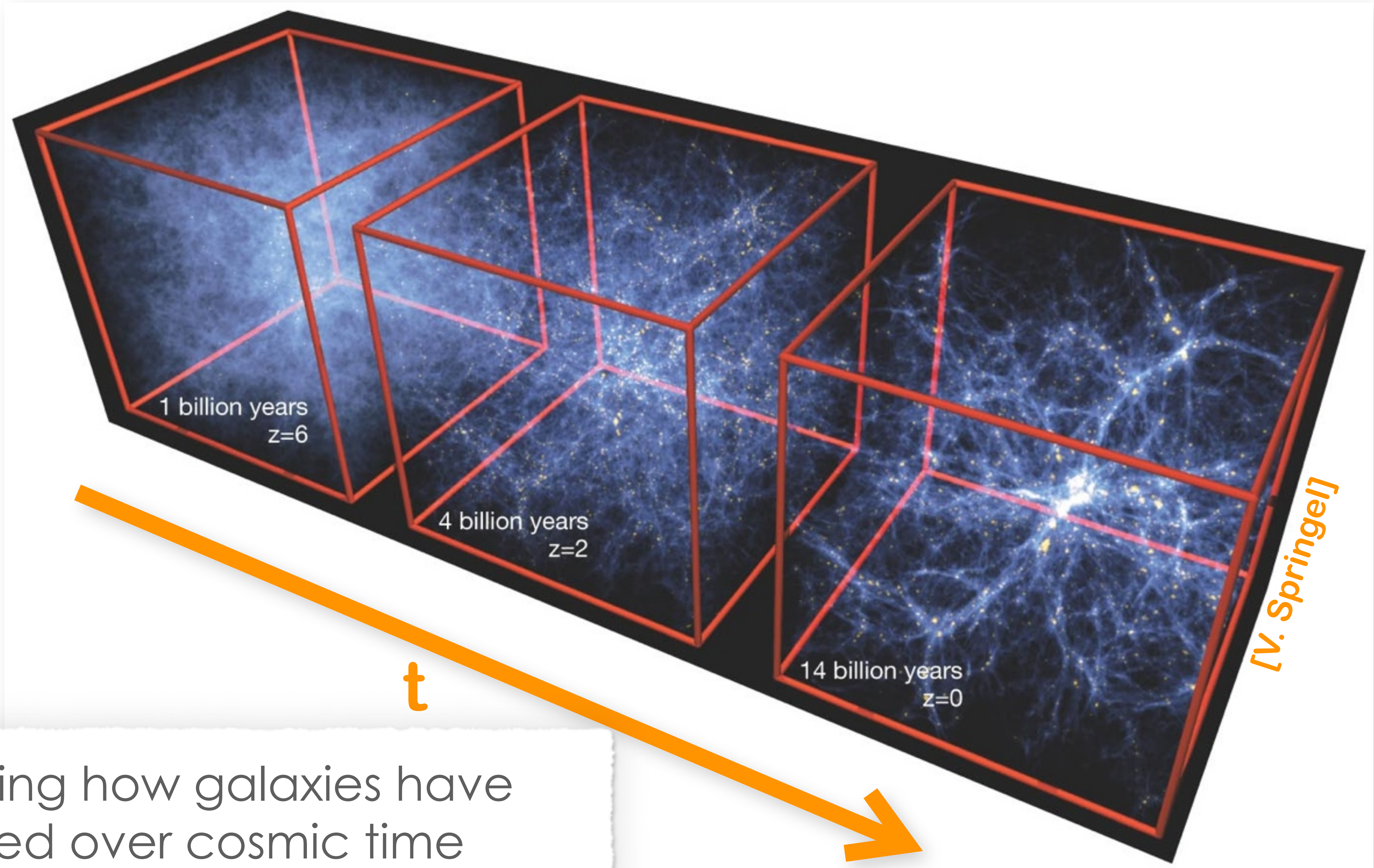
SPES BONA

March 2016

Probing structure formation

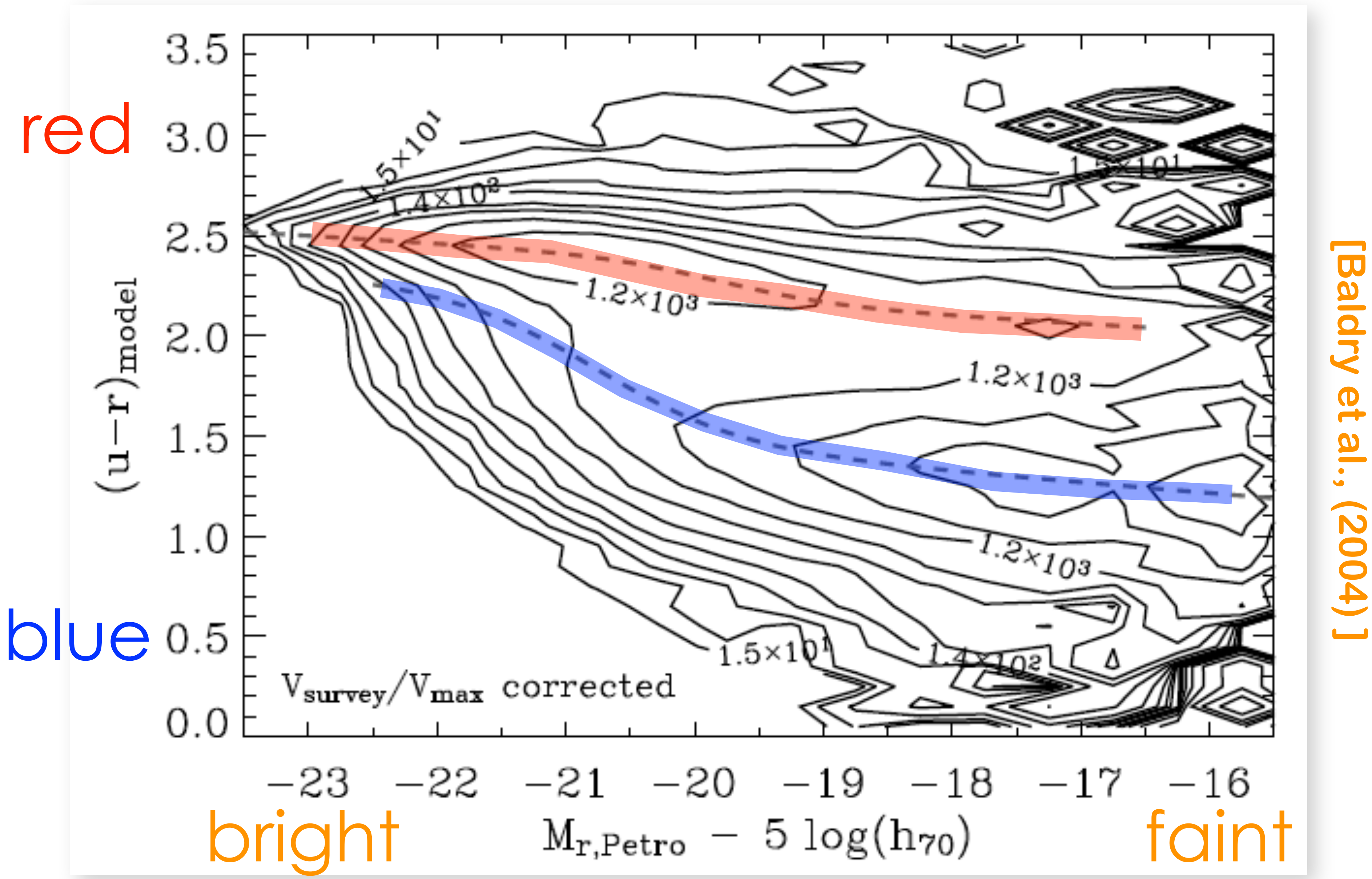
In the ΛCDM framework, galaxies and large scale structure formed hierarchically with the baryonic matter following the DM density distribution...



- Studying how galaxies have evolved over cosmic time enables us to test the models

The landscape

Large optical surveys of the stellar content of galaxies show a bimodal distribution in Col-Mag…

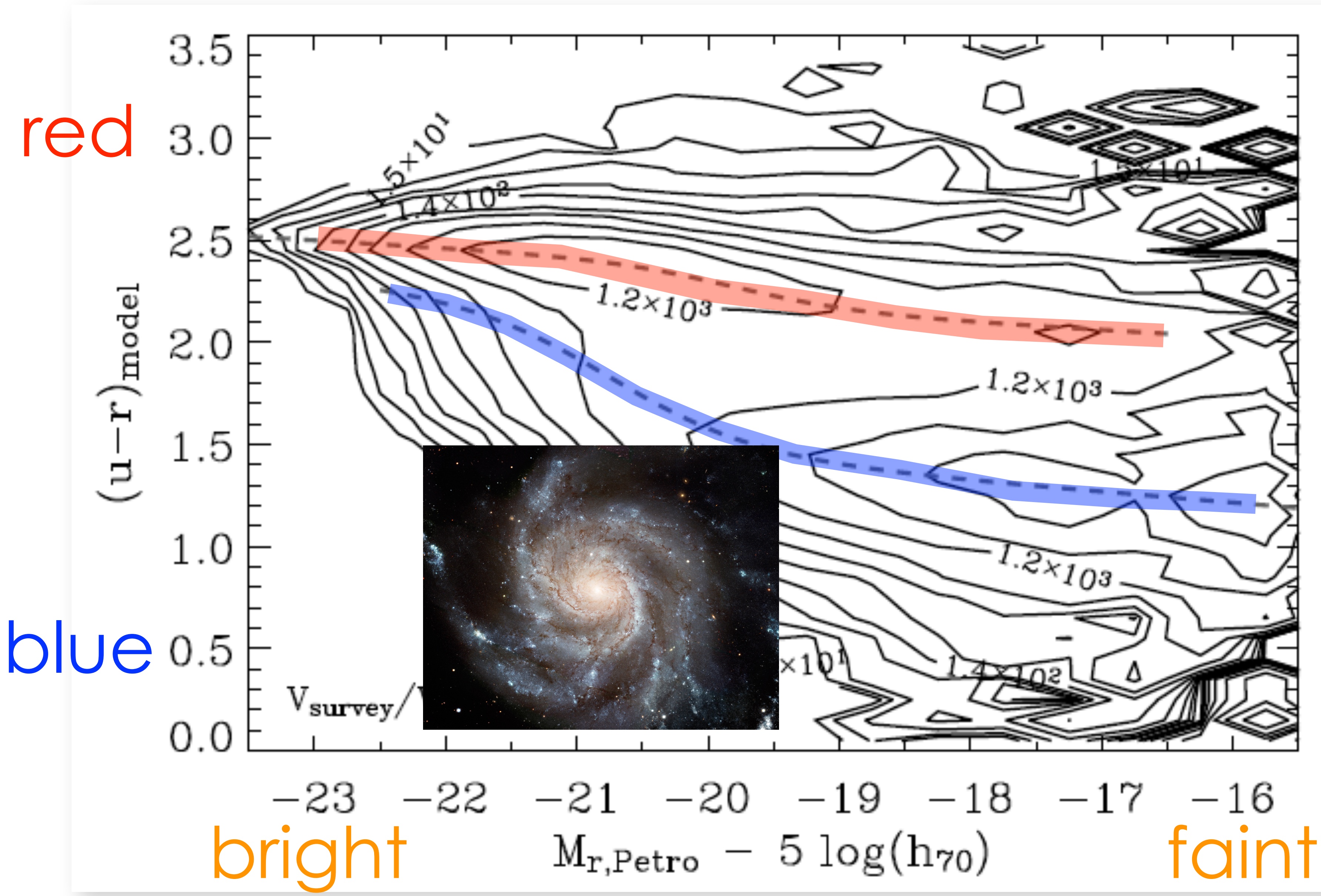


➜ star-formation ongoing OR stopped Gyrs ago…

blue **red**

The landscape

Large optical surveys of the stellar content of galaxies show a bimodal distribution in Col-Mag…



[Baldry et al., (2004)]

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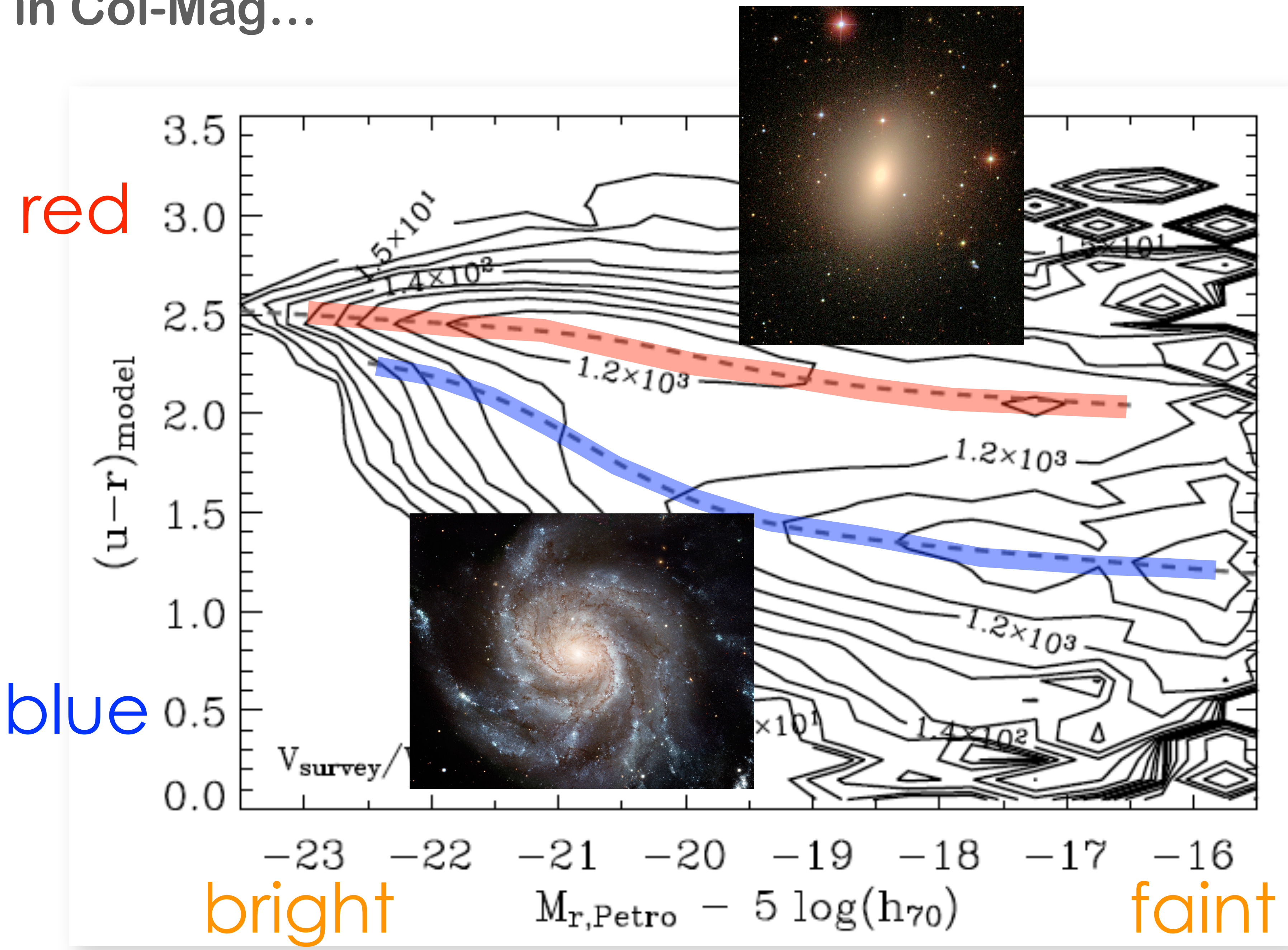
The landscape

Large optical surveys of the stellar content of galaxies show a bimodal distribution in Col-Mag…



[Baldry et al., (2004)]

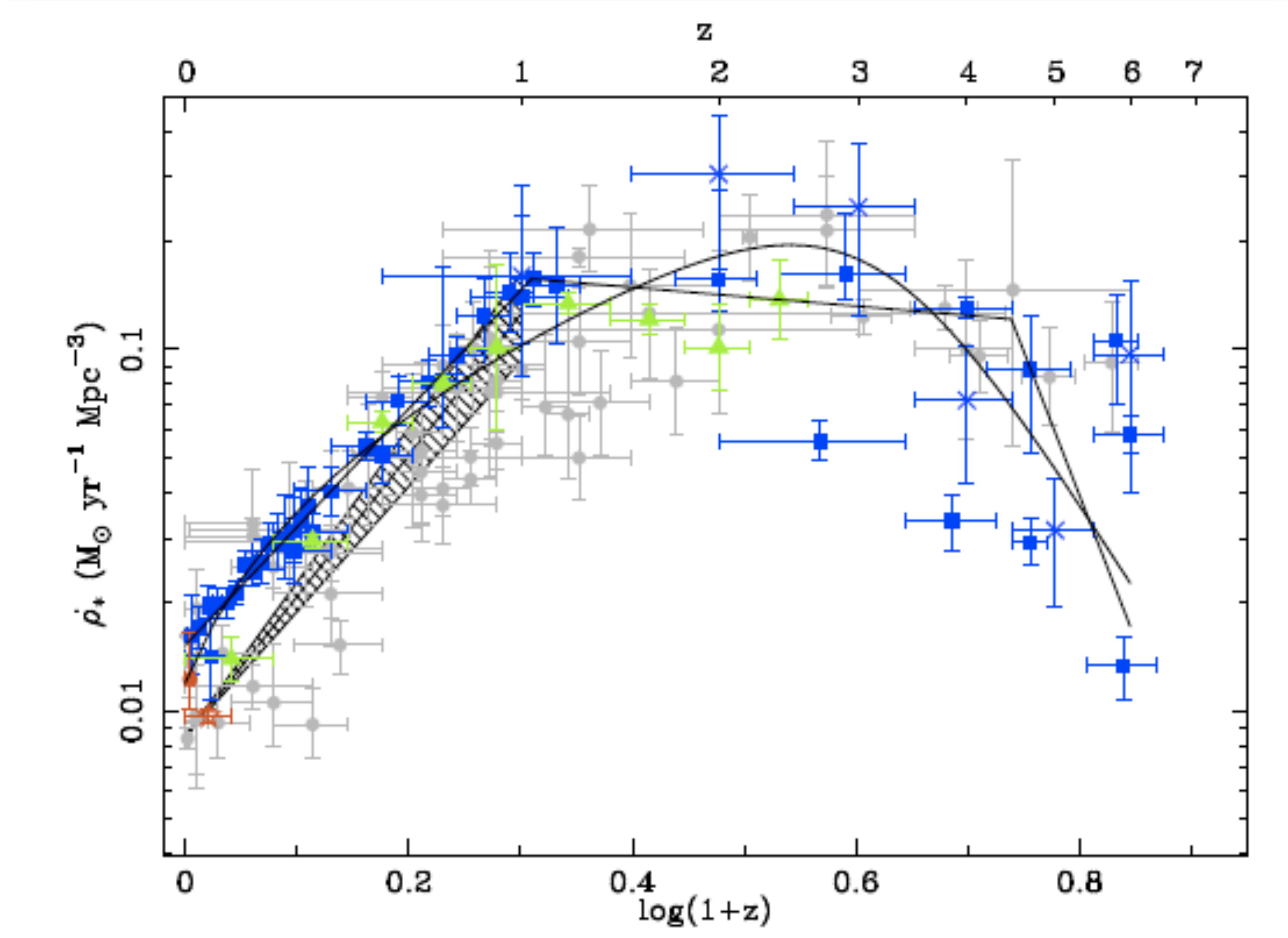
➜ star-formation ongoing <u>OR</u> stopped Gyrs ago…

blue **red**

Star formation

- At z~2, SFRD was an order of magnitude higher than now…

[Hopkins & Beacom (2005)]



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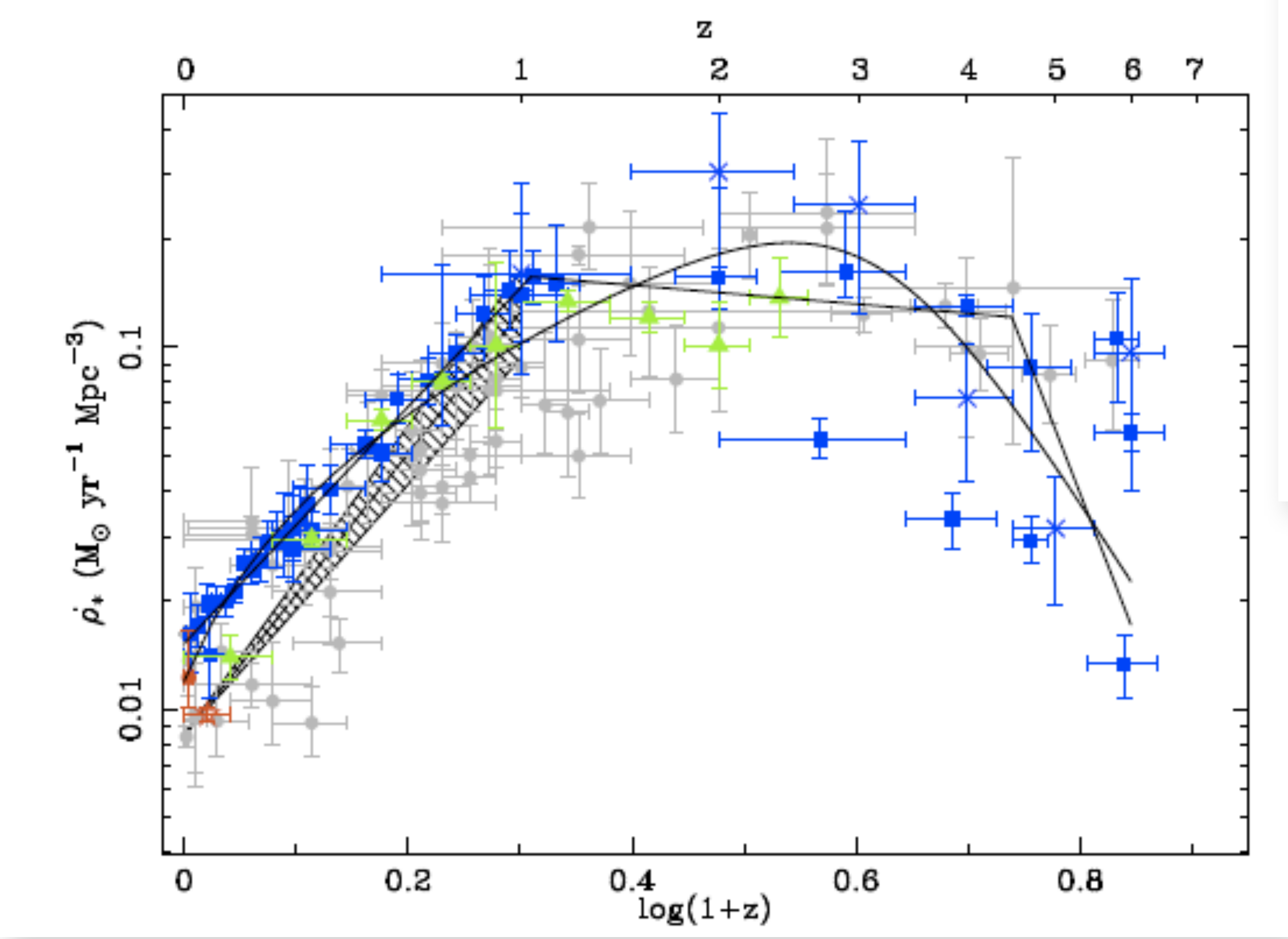
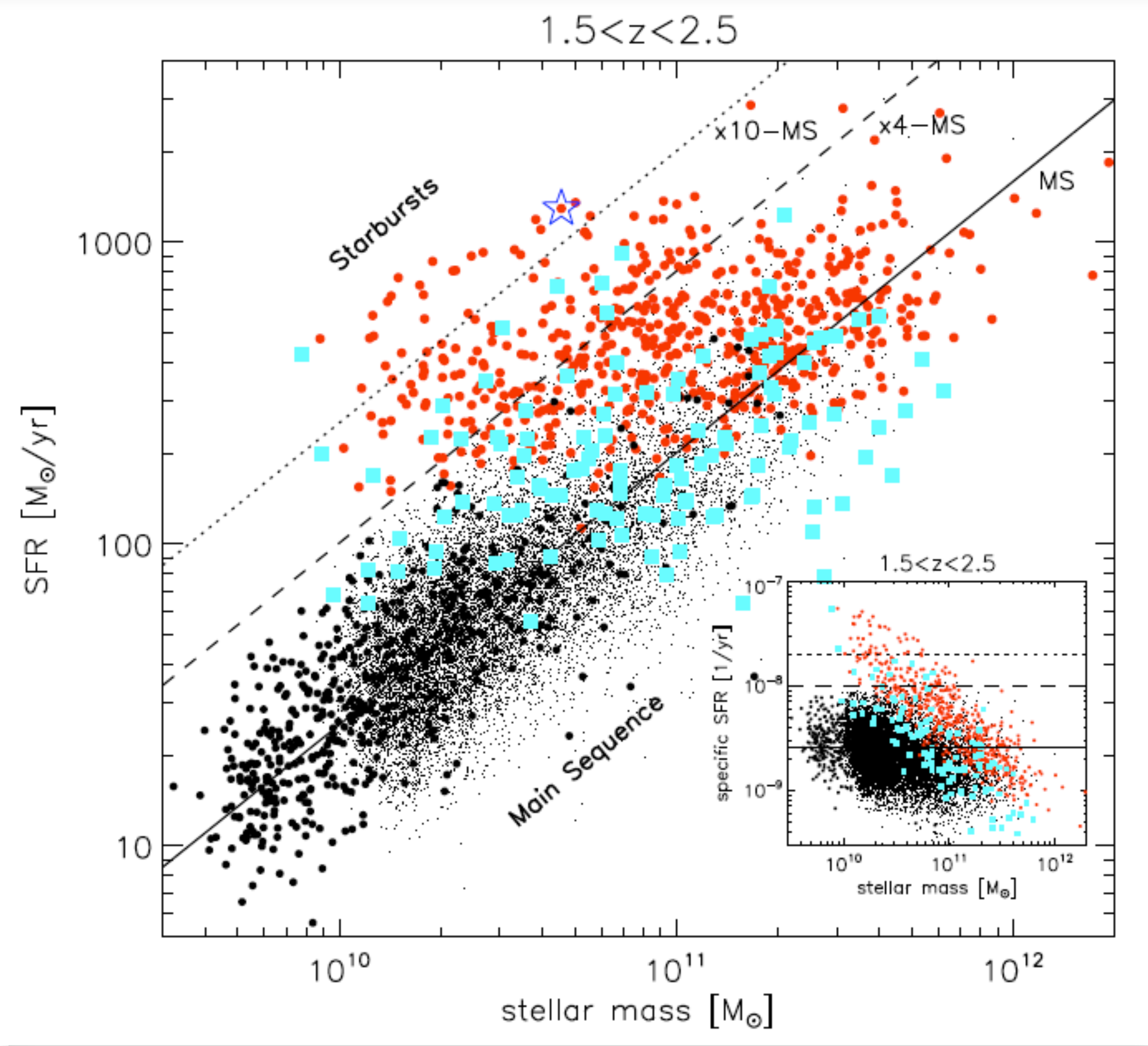




[Rodighiero et al., (2011)]

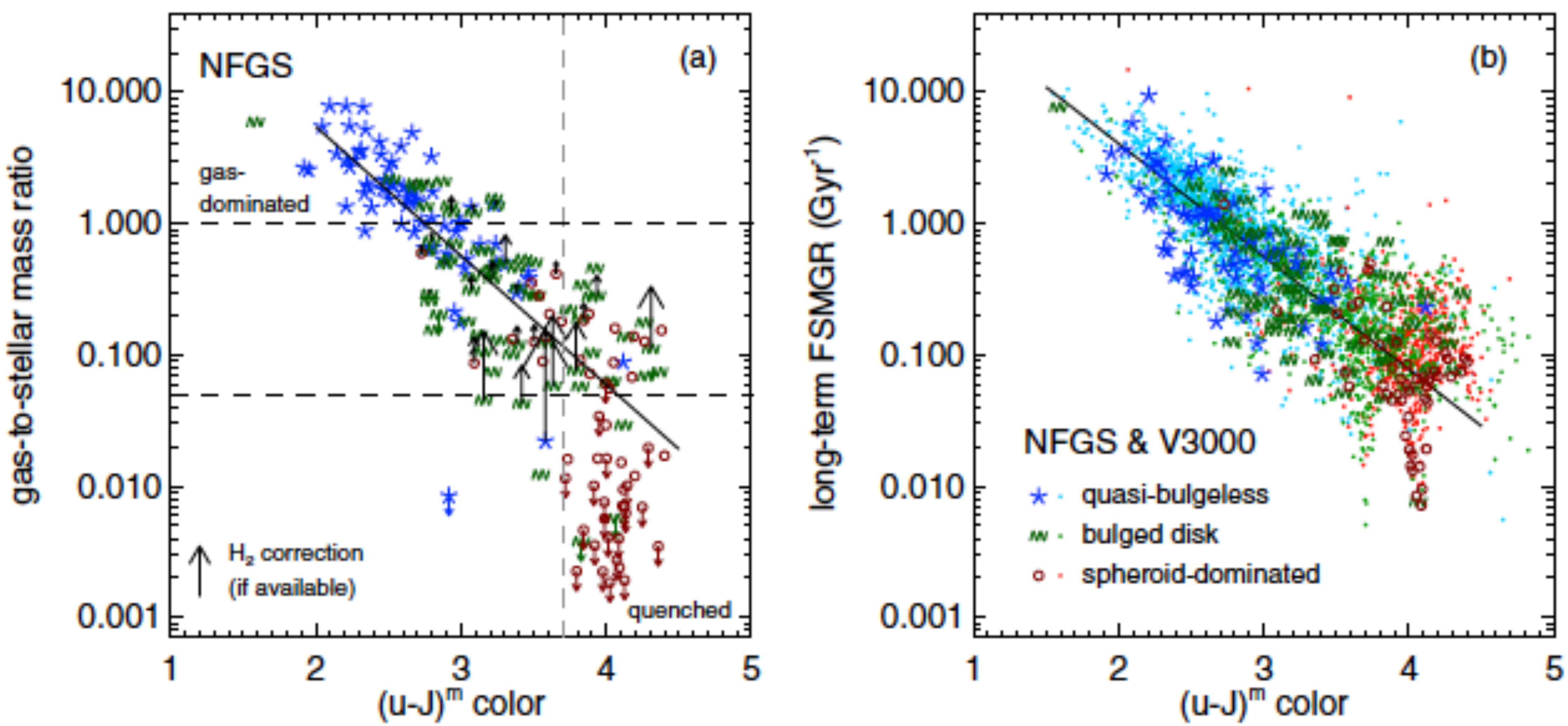
- SFR vs. M* very smooth ➜ mergers only ~10% of SF at z~2
- inflows of gas from IGM to fuel SF

Star formation

- Long term **F**ractional **S**tellar **M**ass **G**rowth **R**ate:

$$FSMGR_{LT} = \frac{mass_{formedinlastGyr}}{1\,Gyr \times (mass_{preexisting})}.$$

[Kannappan et al. (2013)]



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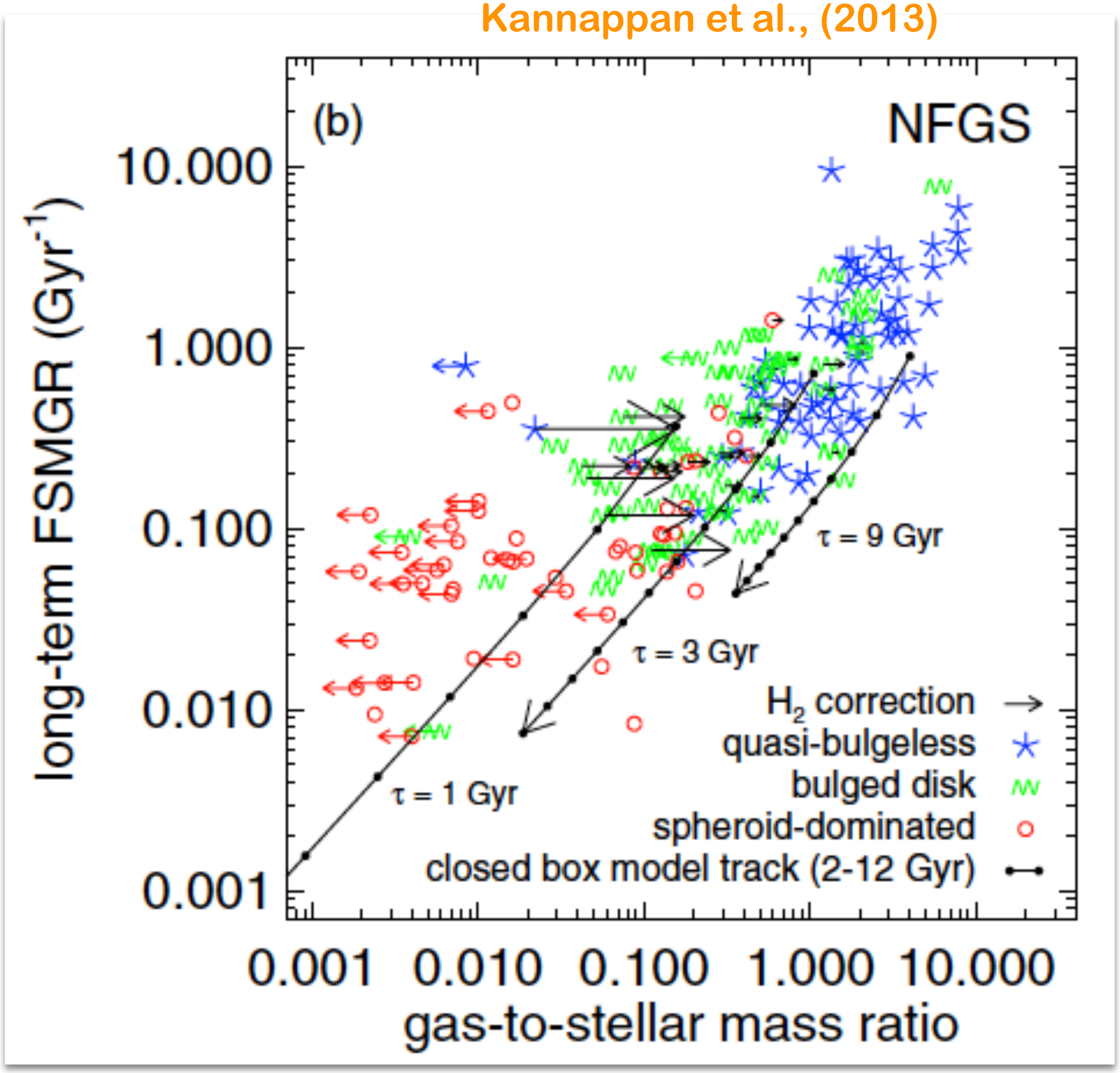
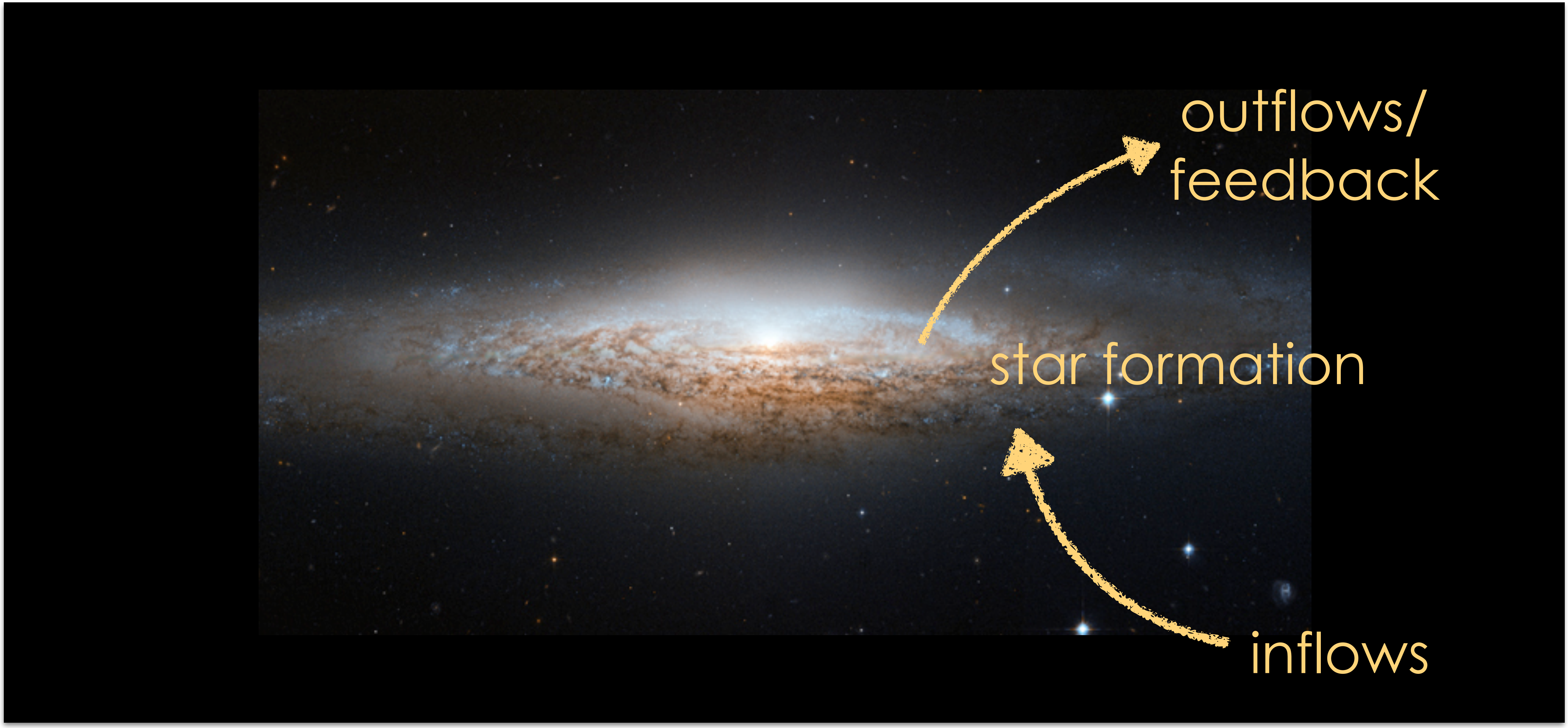


- M_{HI}/M_{*} ~ long term FSMGR!
- closed box models do not work!
  - Implies gas refuelling on Gyr timescales

The baryon cycle

- Since H forms the raw fuel for star formation - vital to study role of HI in galaxies

Observations and models point to a cyclical picture for gas in galaxies:



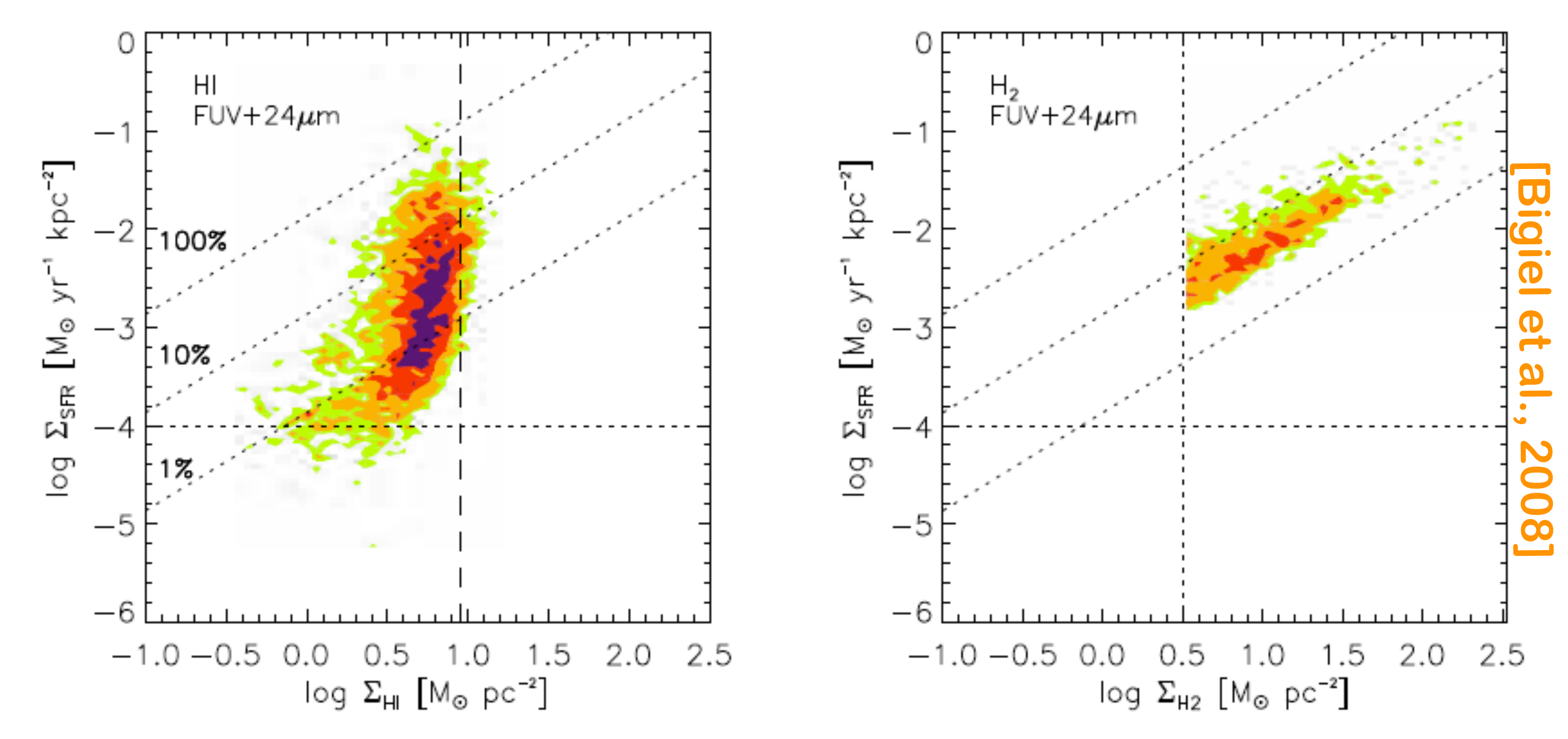
Key questions:

- What are the necessary conditions and processes that govern star formation in galaxies?
- How do galaxies keep forming stars over the age of the universe?
- How is the HI distributed in and around galaxies in different environments (i.e. field/groups/clusters) and over the history of the universe?
- How do galaxies' M_{HI} scale with their stellar/halo masses vs. cosmic time & different environments?
- What is the role of angular momentum in galaxy evolution?

    - *Hope to answer these with SKA, see [Blyth+ 2015, de Blok+ 2015, Popping+ 2015, Staveley-Smith+ 2015, Obreschkow+ 2015,…]*

Key questions

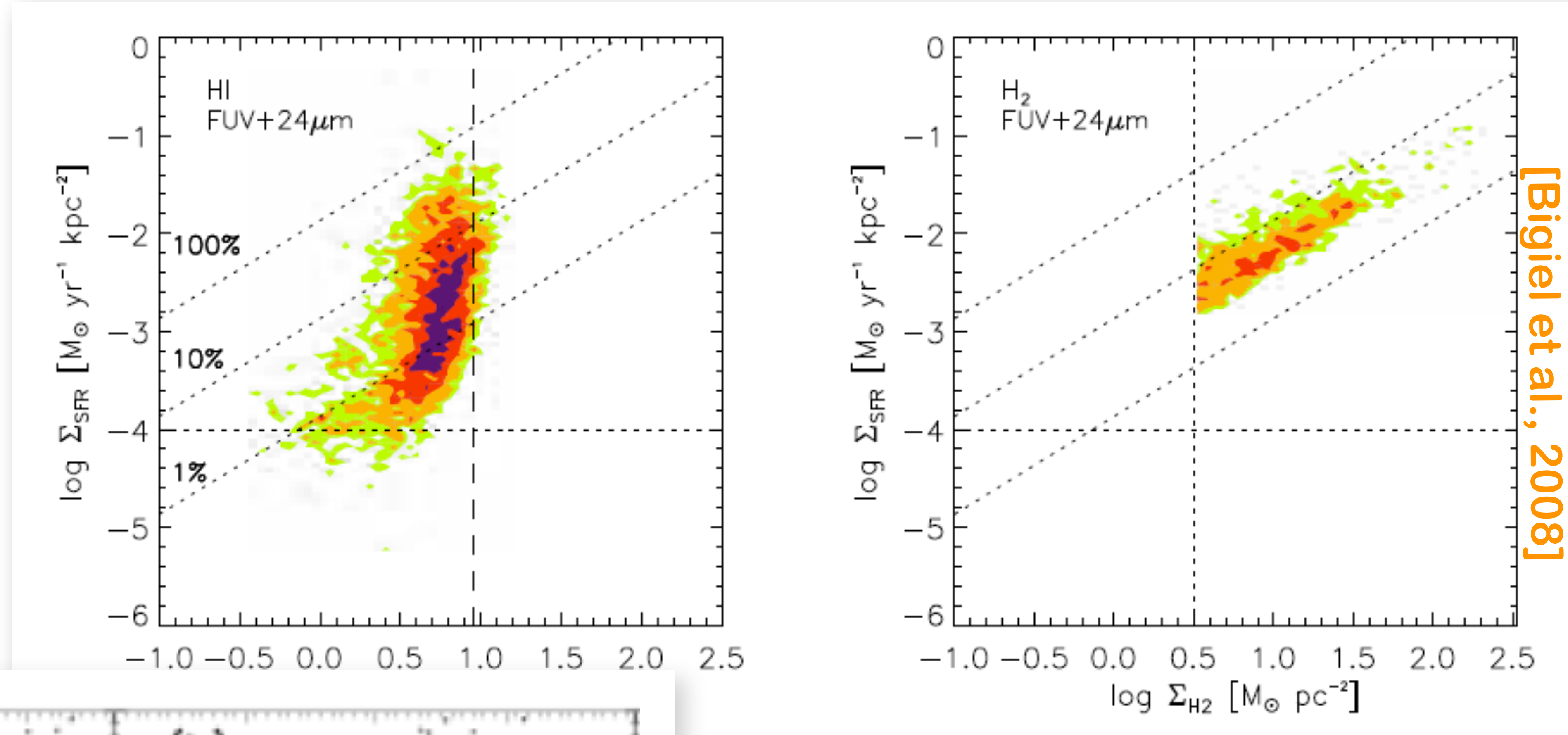
- **How exactly does SF occur in galaxies?**
  - Kennicutt-Schmidt relation:

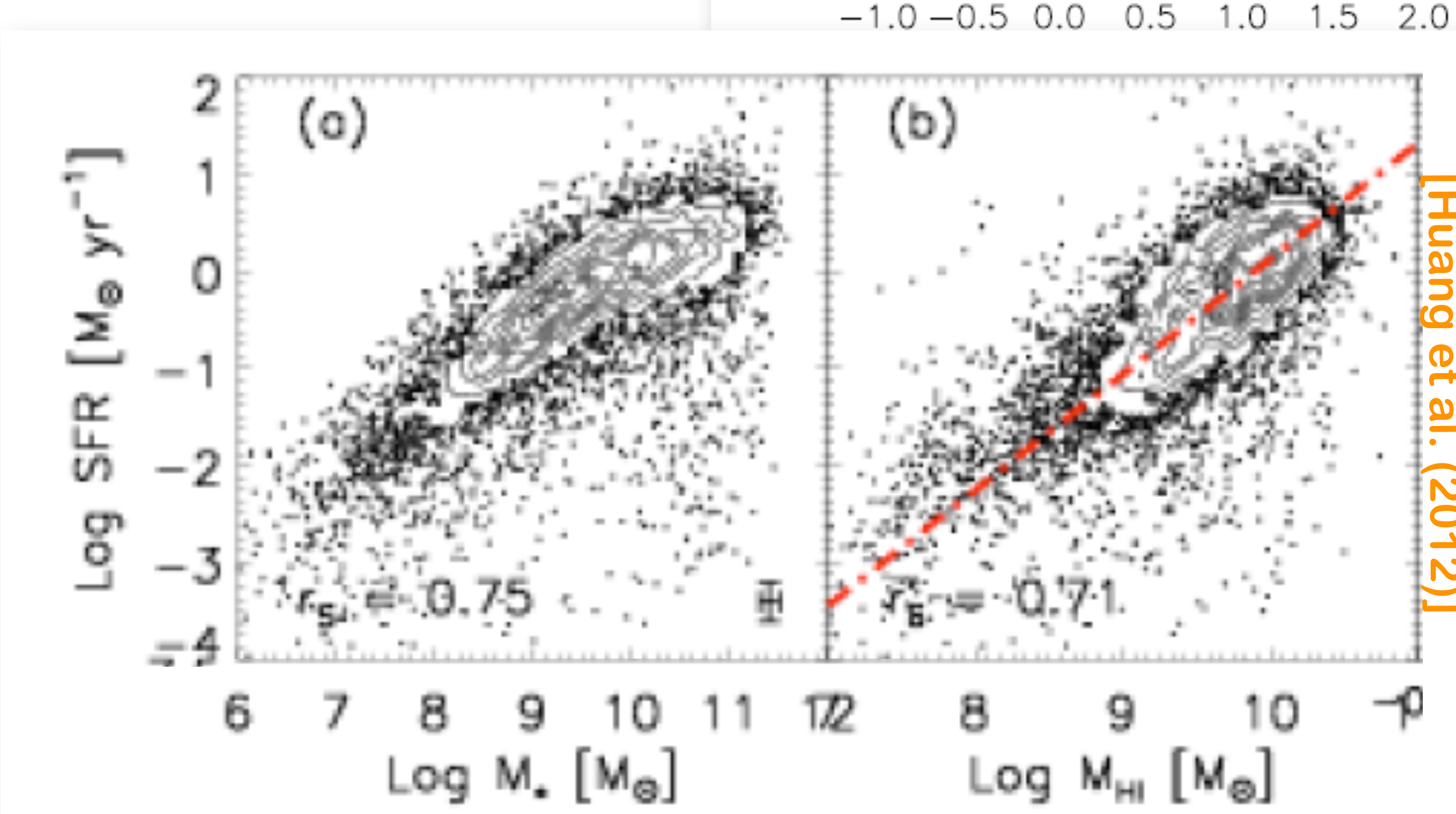


[Bigiel et al., 2008]

Key questions

- **How exactly does SF occur in galaxies?**
  - Kennicutt-Schmidt relation:
  - High gas-mass frac. galaxies follow a different law?





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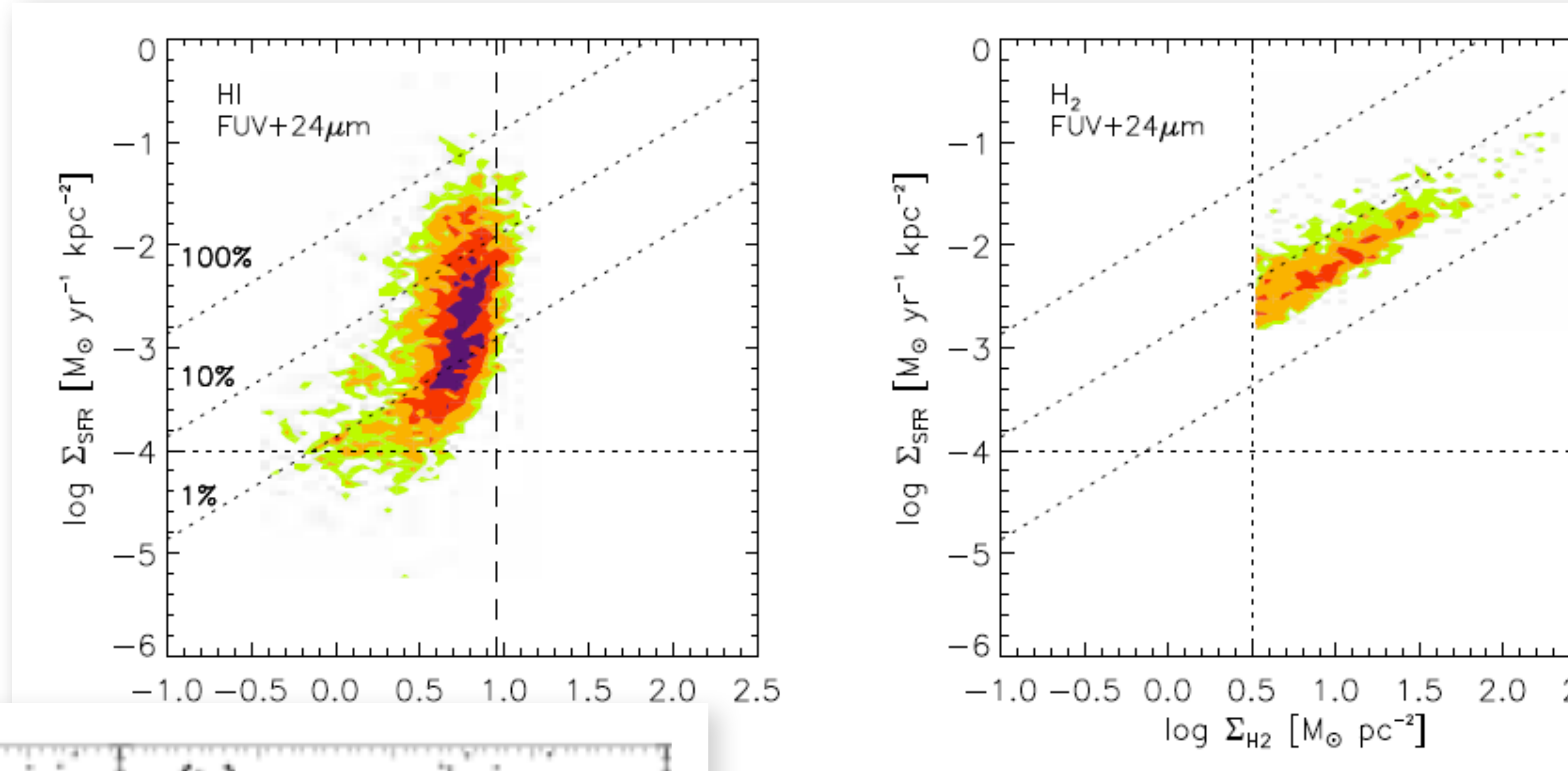
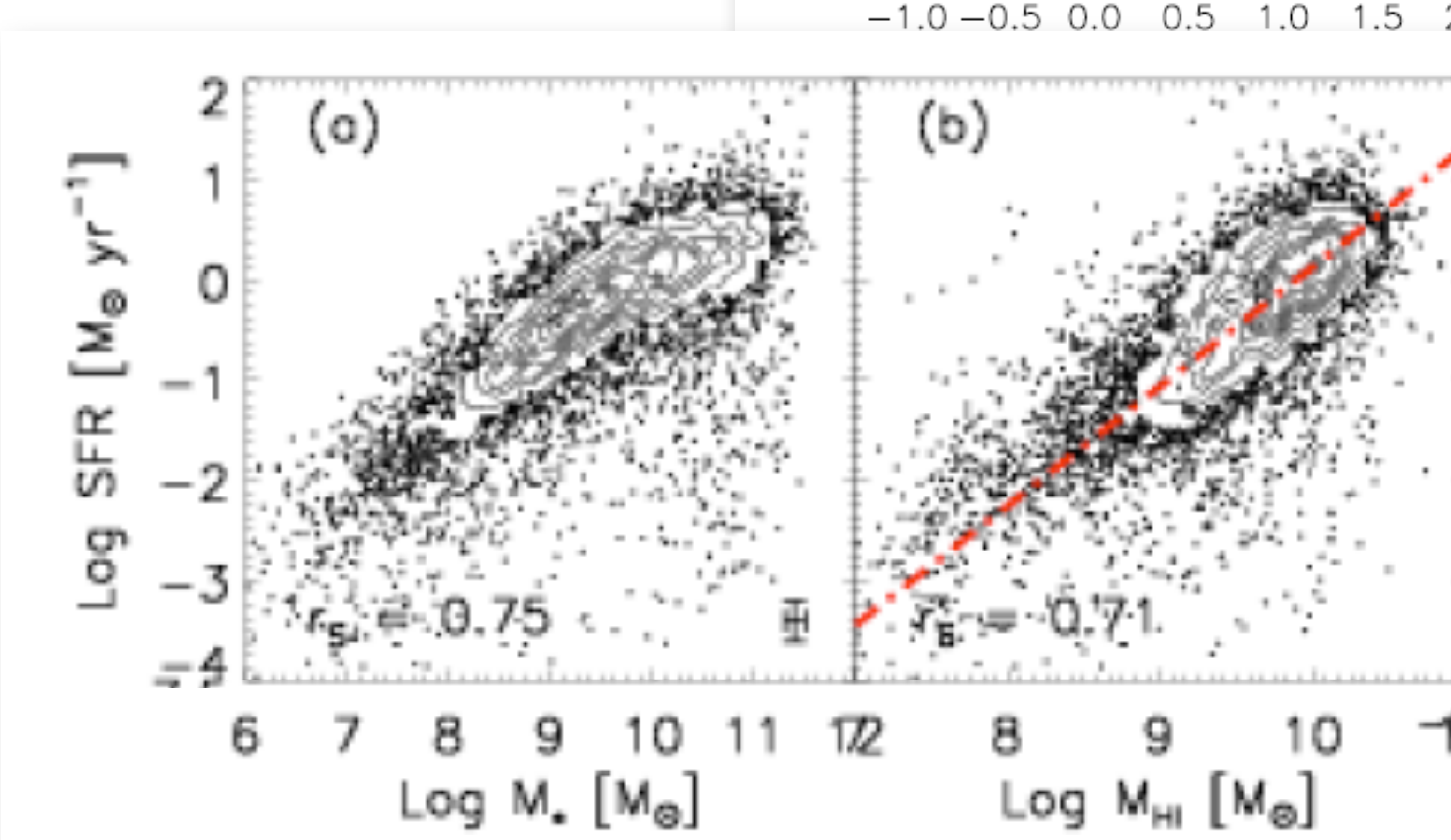


[Bigiel et al., 2008]



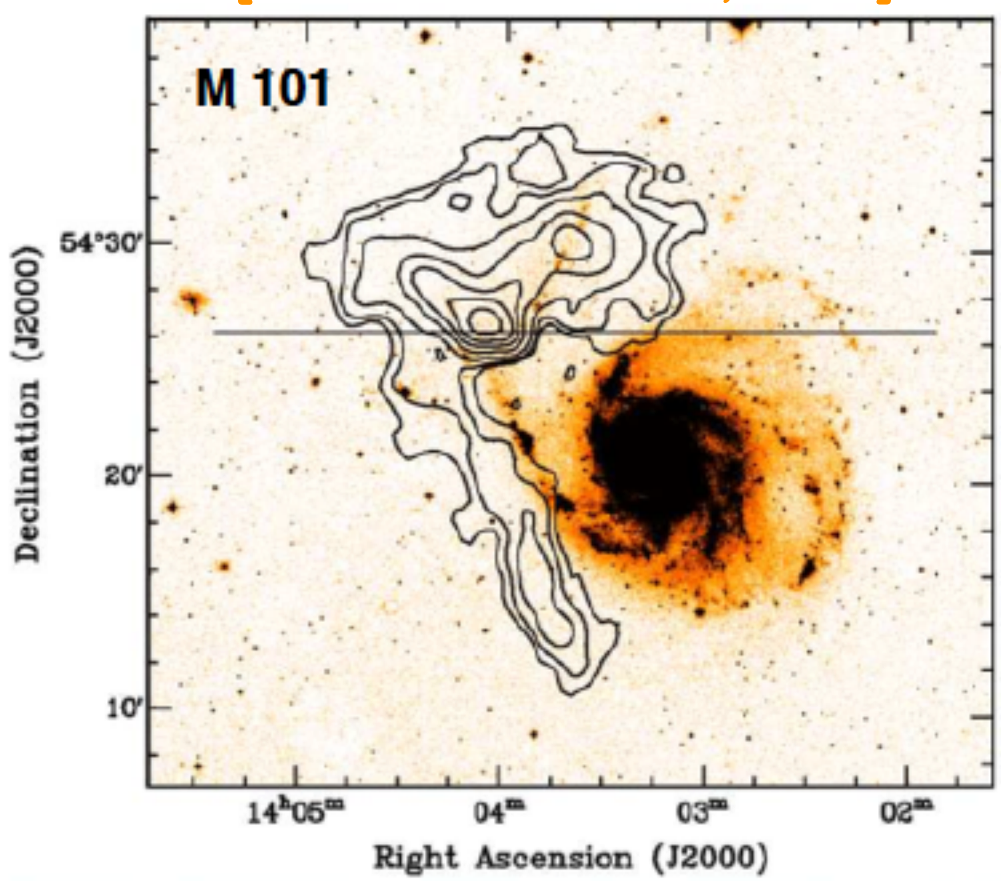
[Huang et al. (2012)]

- What are the processes at the mol. cloud scale level?

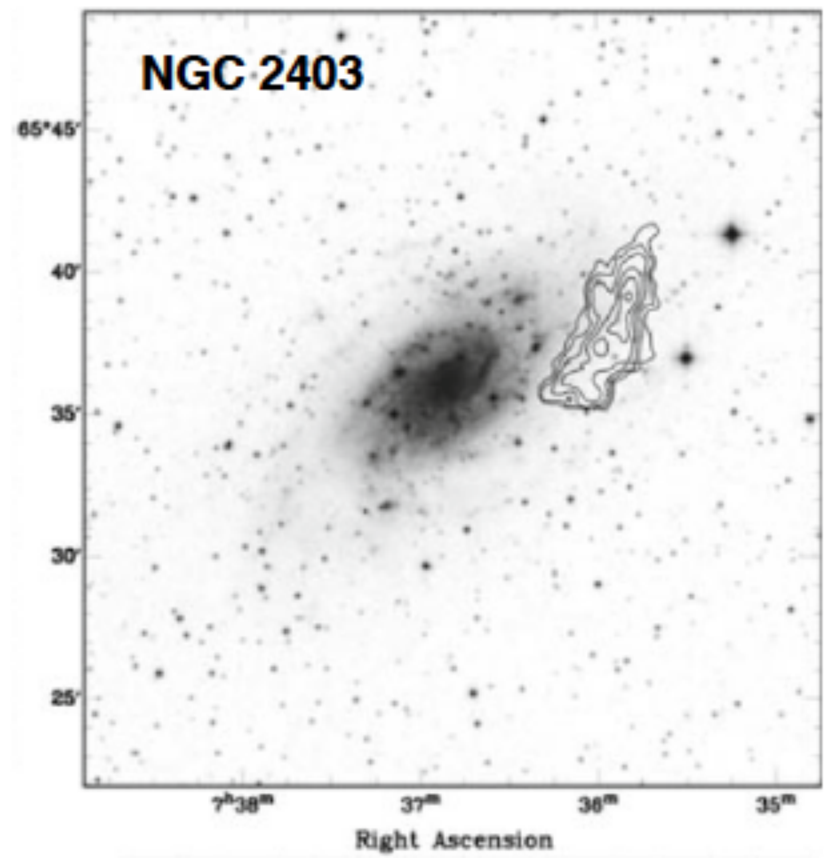
Key questions

- **How do galaxies keep forming stars over a Hubble time?**

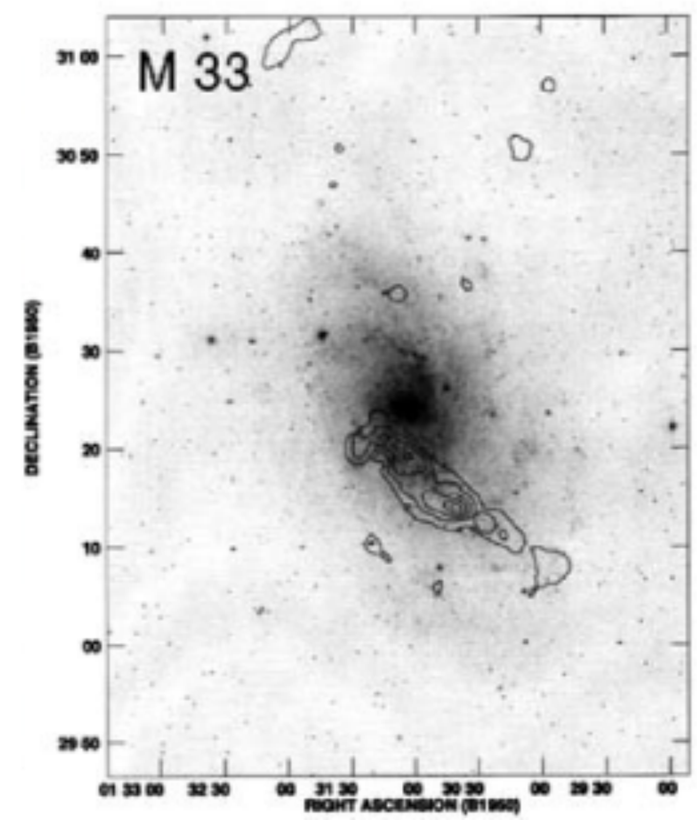
[vd Hulst & Sancisi, 1998]



[Fraternali et al., 2002]



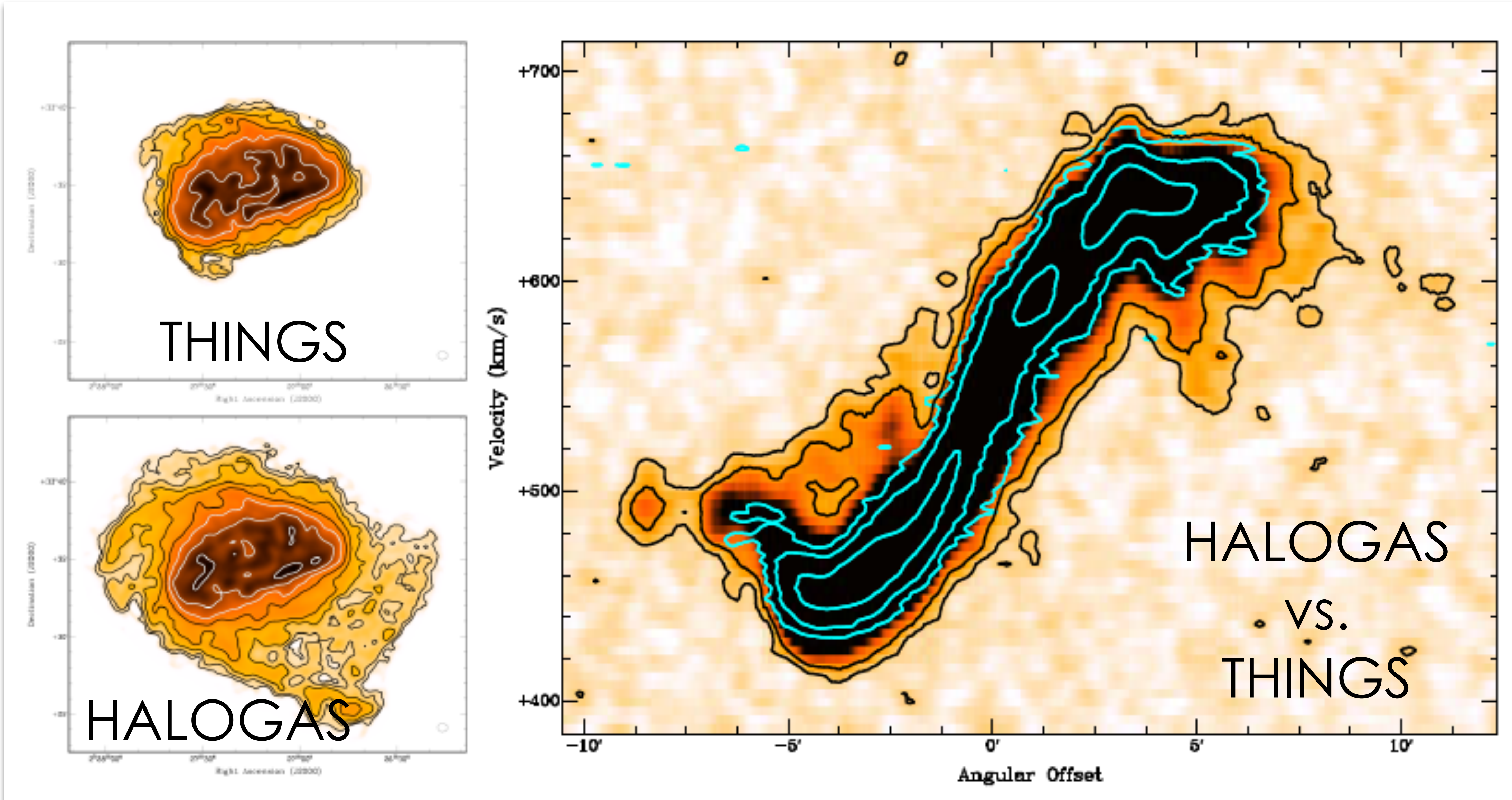
[Sancisi et al., 2008]



- Evidence for accretion of HI around local galaxies

Accretion

To try and find the low column density accreting gas, need to push to lower sensitivities:

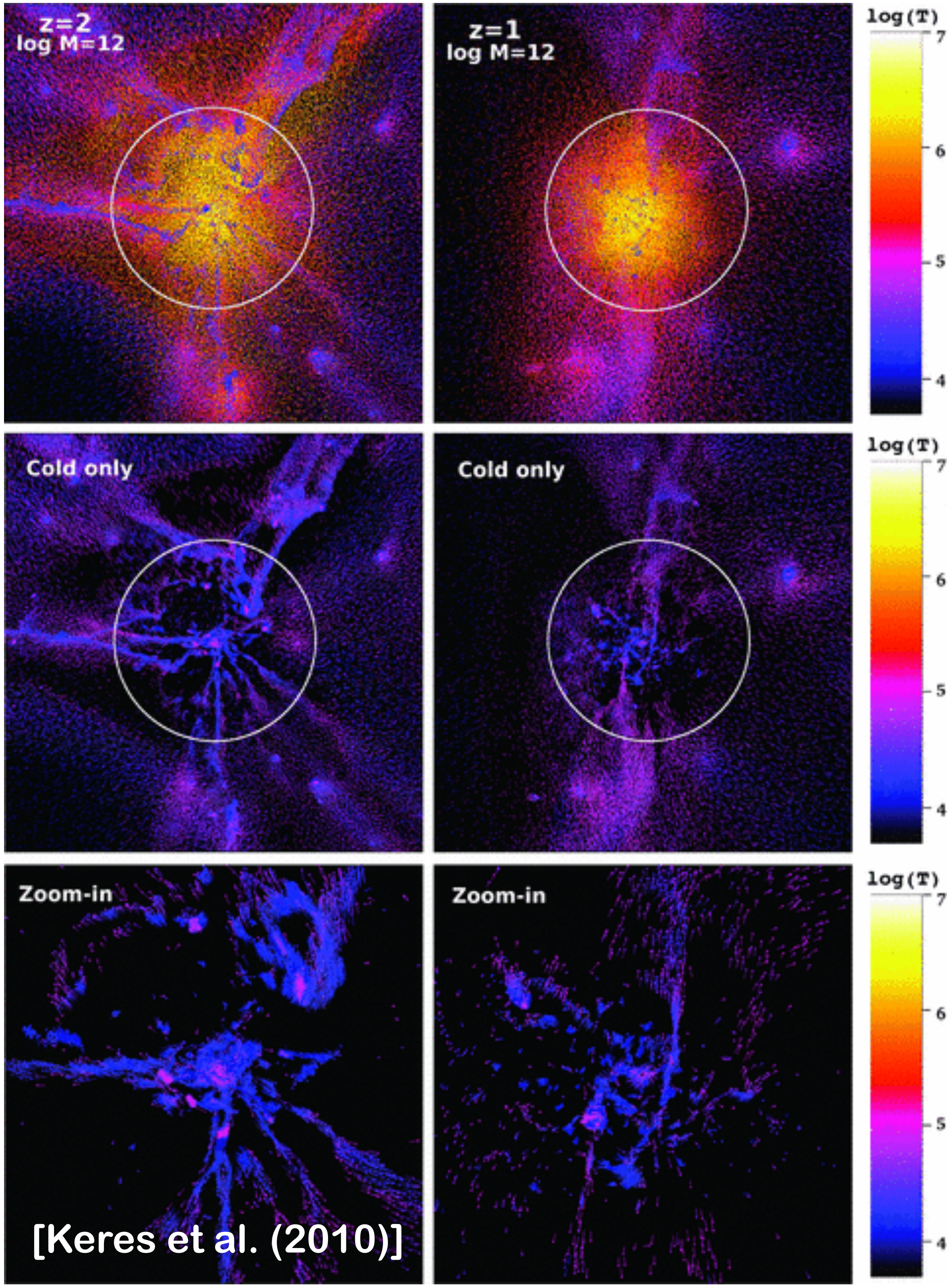


de Blok+ 2015

- But… even down to 10^{19} atoms/cm^2, not enough visible gas to account for SFRs

Accretion

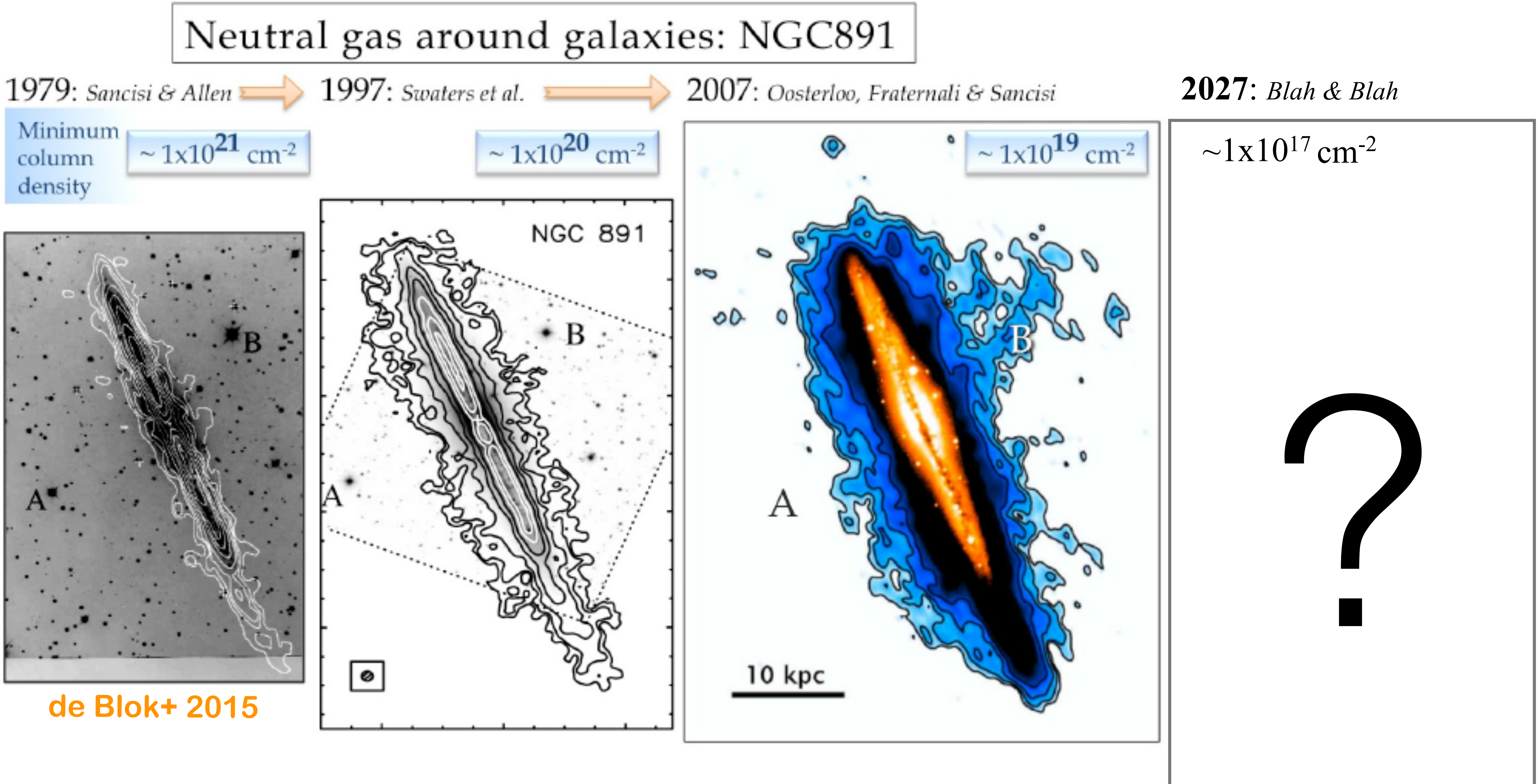
- Simulations by Keres et al. (2010) predict differences in hot/cold accretion based on halo mass and z
- Note: **cold** here means T < $10^{4.5}$ K
- Look for trends in M_{gas}/M_{halo} ratios



Outflows

More sensitive observations reveal the low density gas around galaxies:

- Gas in thick disk likely from stellar outflows (galactic fountain likely)

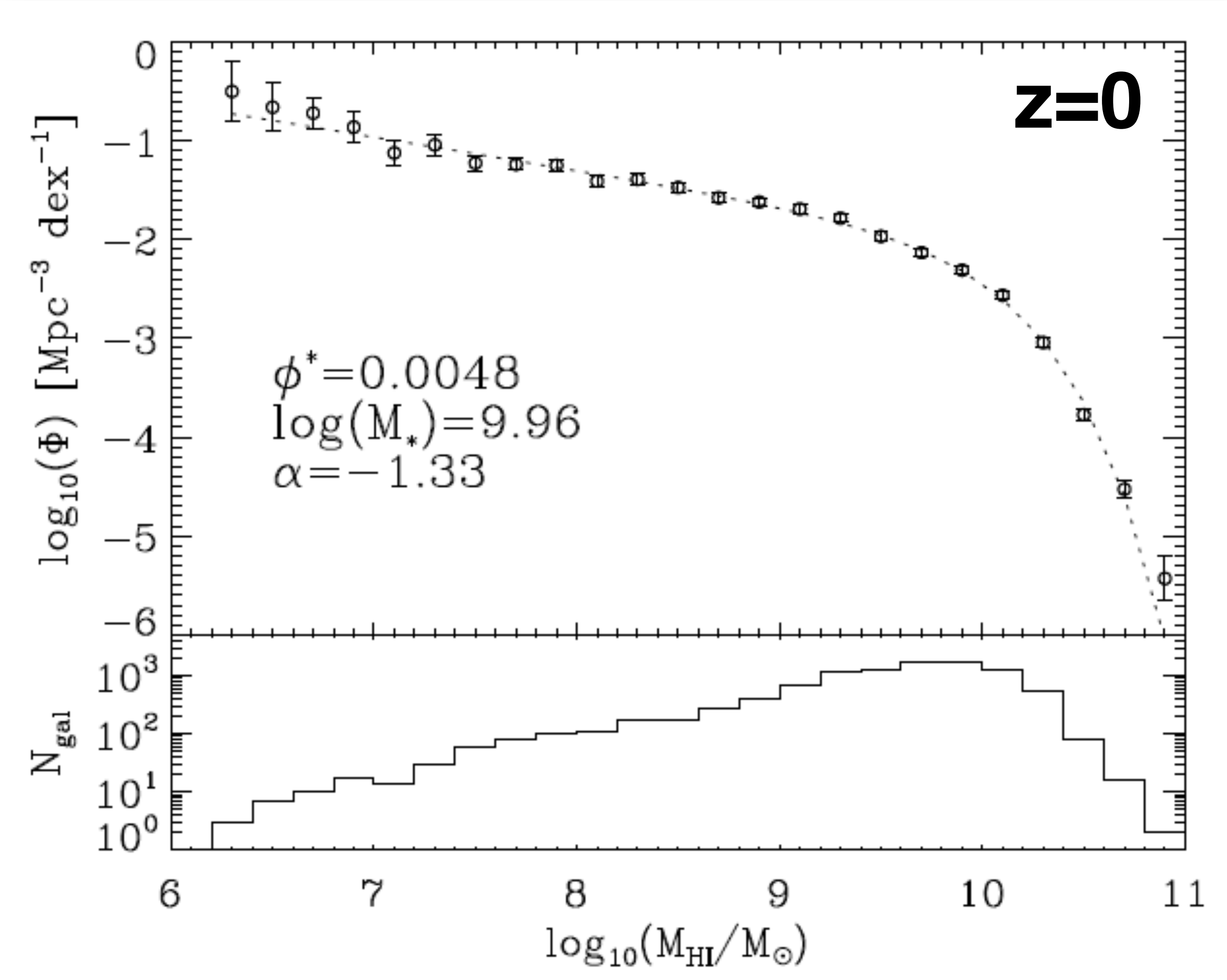


de Blok+ 2015

Key questions

- **How is the HI distributed in and around galaxies in different environments & over the history of the universe?**

HIMF vs. z

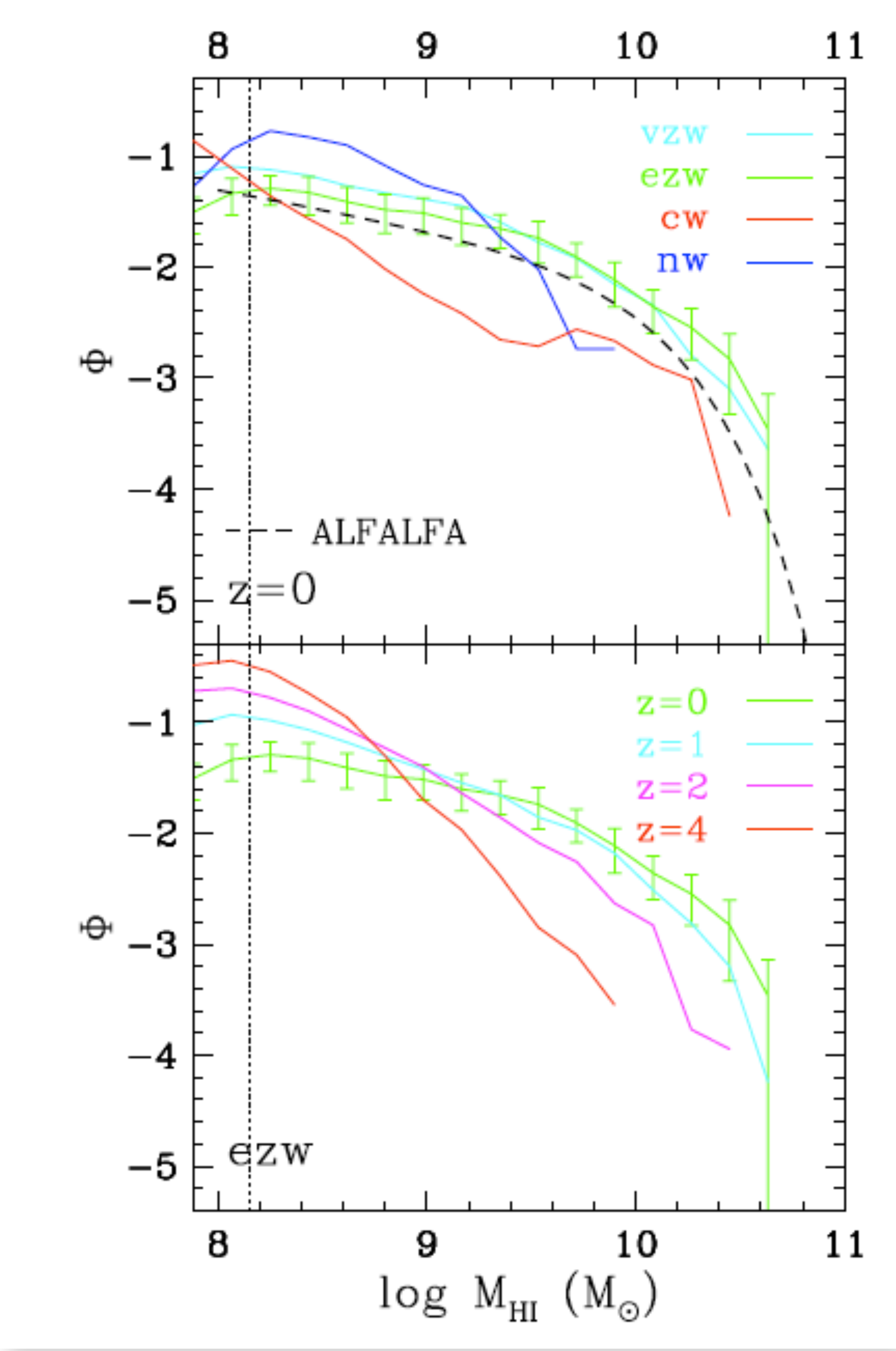


[Martin+ (2010)]

- How do M^*_{HI}, α & normalisation vary vs. z?
- Help to constrain hierarchical galaxy formation models
- Effect of different environments?

Key questions

- Hydrodynamical models including mass-dependent outflows can predict the local HIMF shape well…



[Davé + 2013]

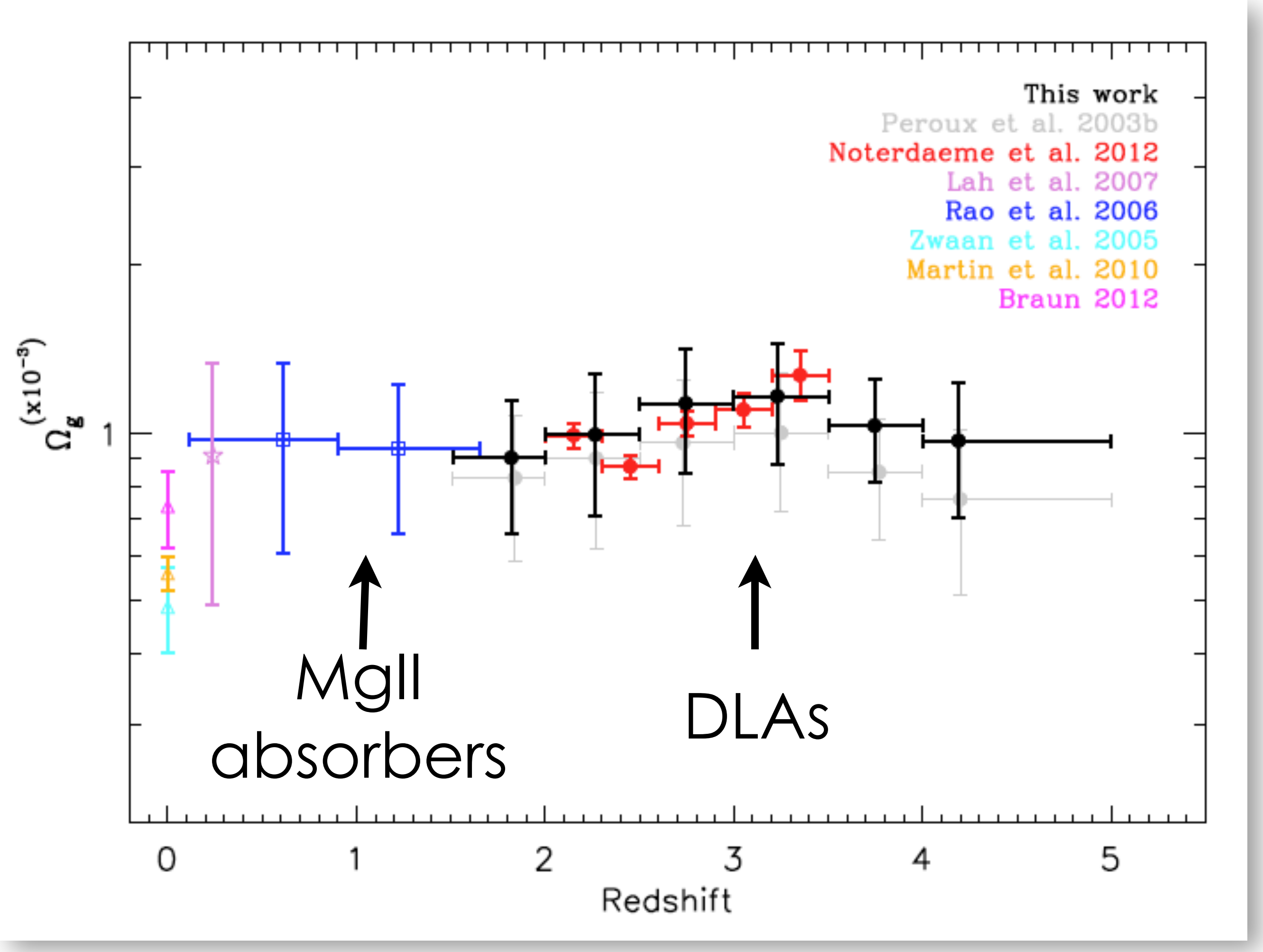
- Also predict evolution with z

Cosmic neutral gas density

What is the average amount of HI vs. z?

- How will HI emission measurements compare to Lyα and MgII absorber results at higher z?

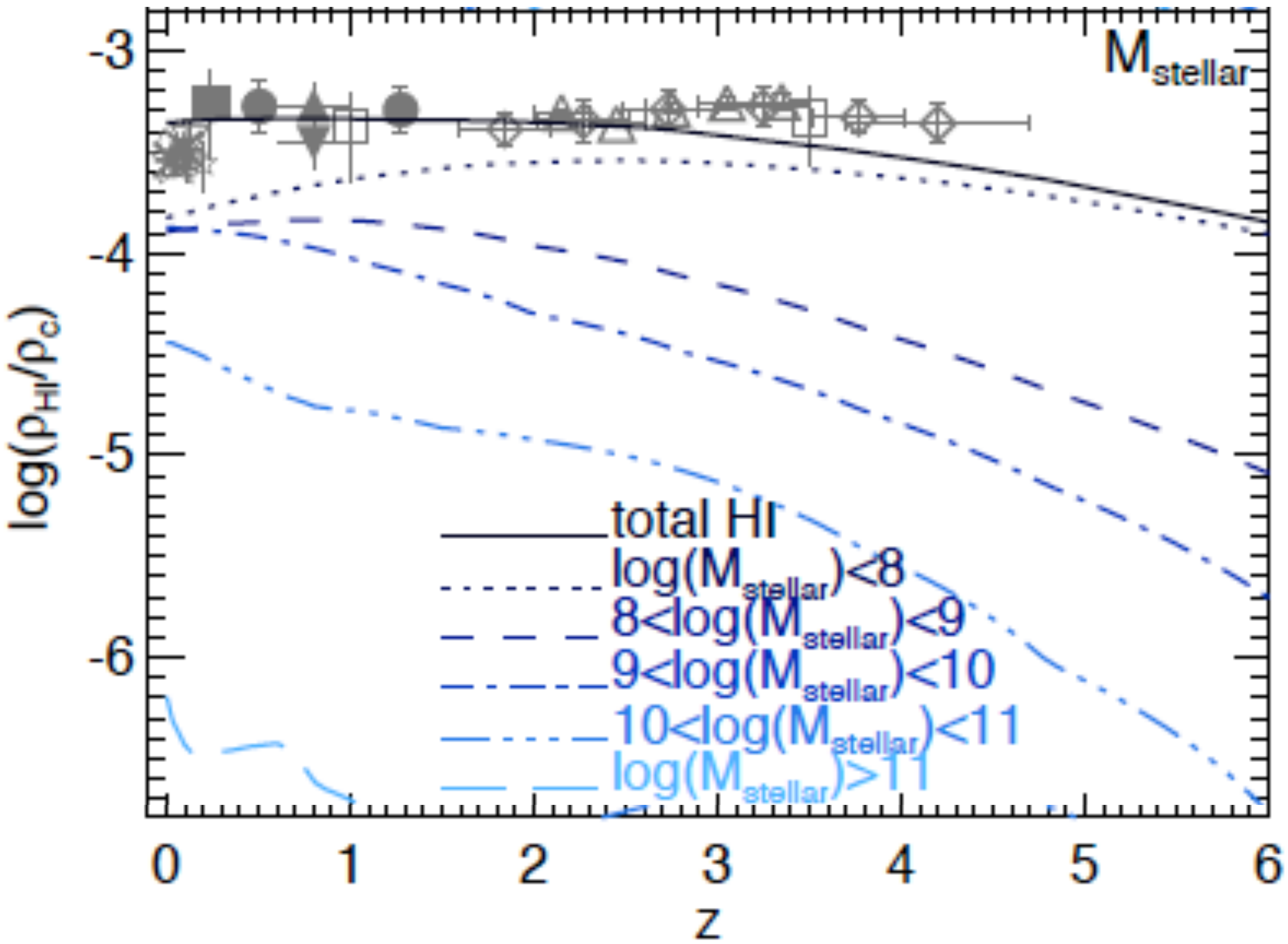
Ω_{HI} vs. z



[Zafar et al. (2013)]

Cosmic neutral gas density

- Semi-analytic models make predictions about the contribution of different mass galaxies to the overall HI gas density:



[Lagos et al. (2014)]

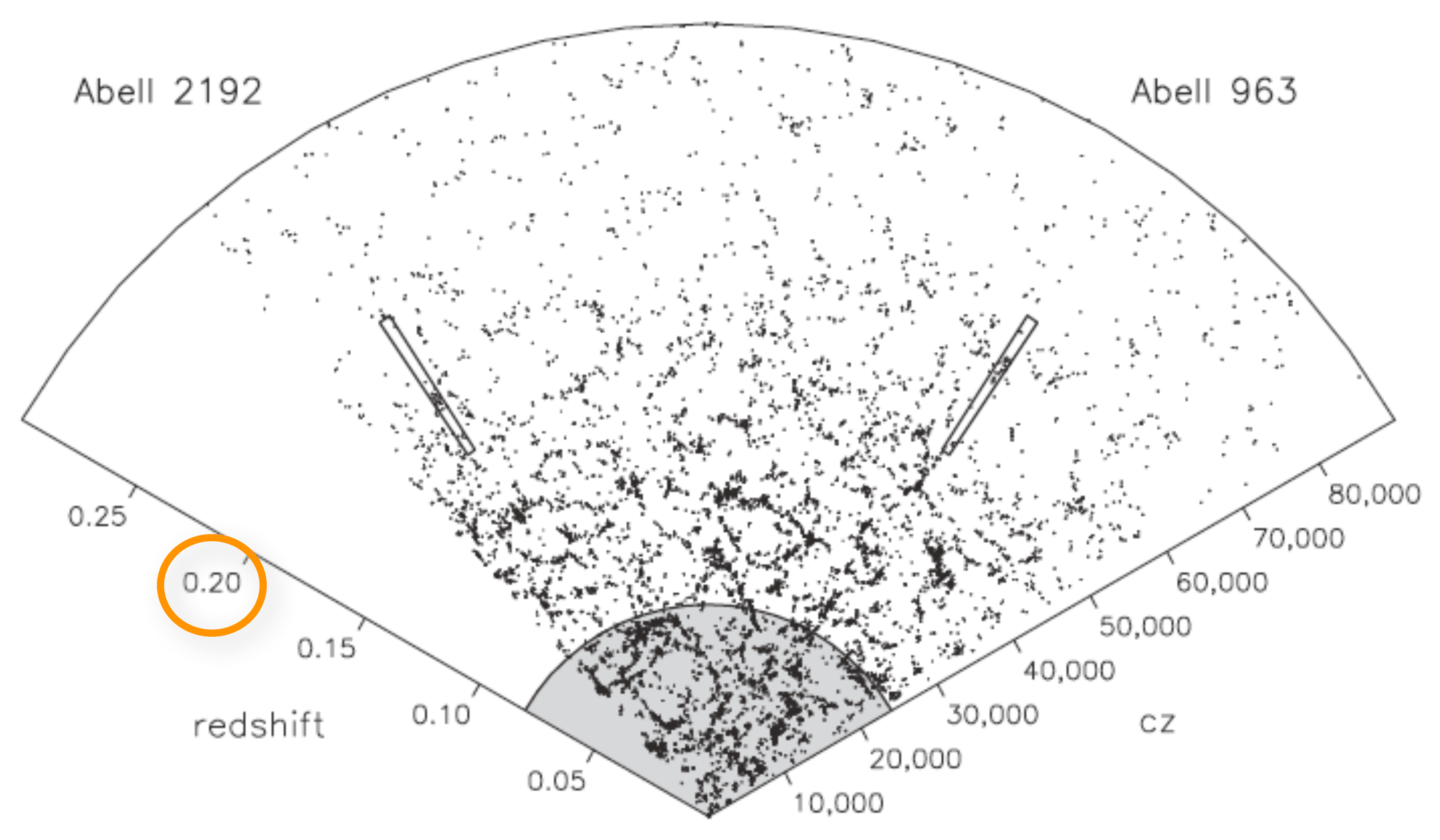
HI at higher z

The BUDHIES (Verheijen et al.) survey on the WSRT has observed 2 clusters at z~0.2 (higher z + environment)

- Observed 150 galaxies in HI

- Find correlations between HI content, and SFR as a function of environment

- Suggests progressive removal of HI as a function of group size

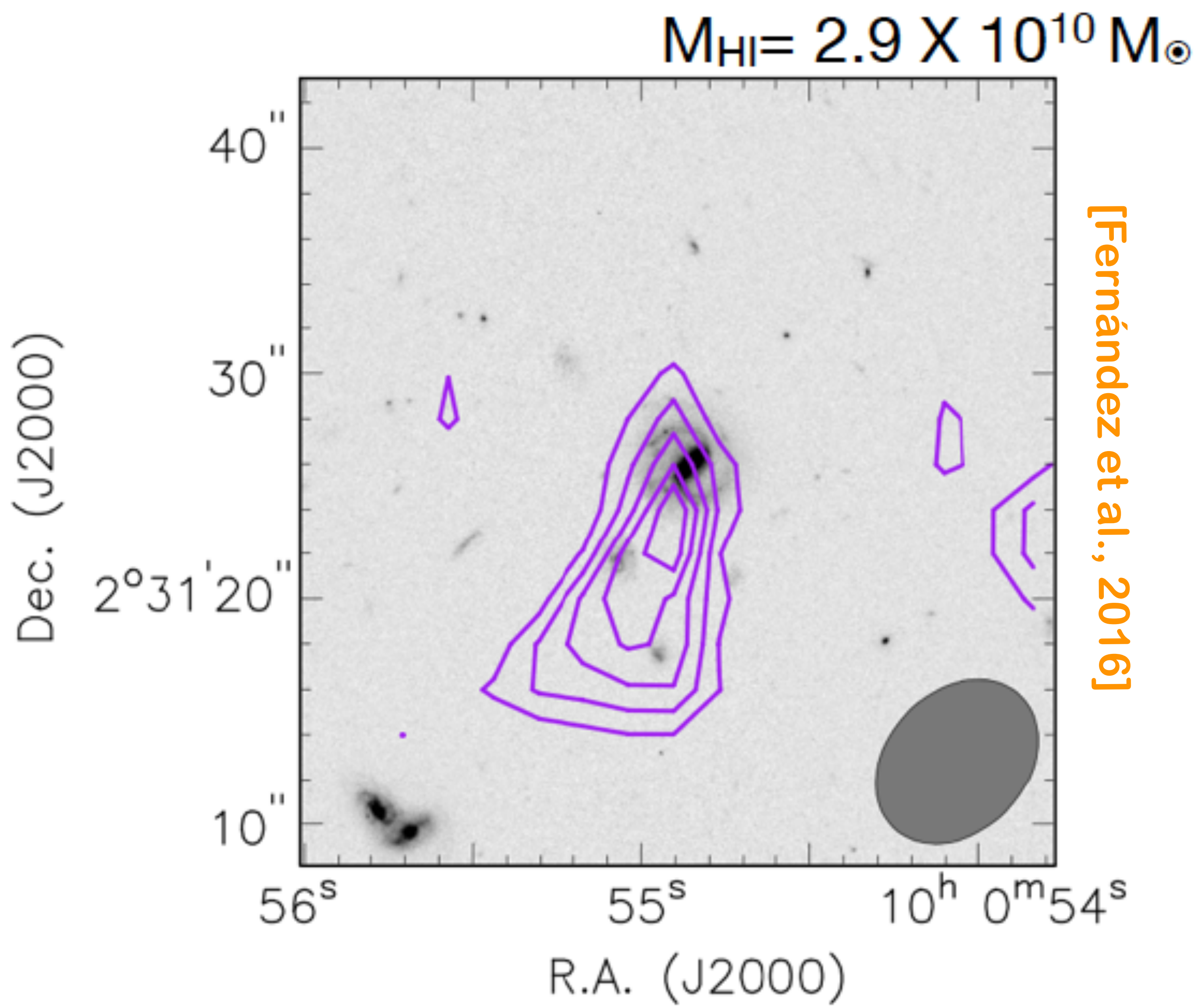


[Jaffe et al., (2013)]

HI at higher z

The JVLA upgrade has made a deep HI survey (CHILES) possible with instantaneous bandwidth covering 0< z< 0.45.

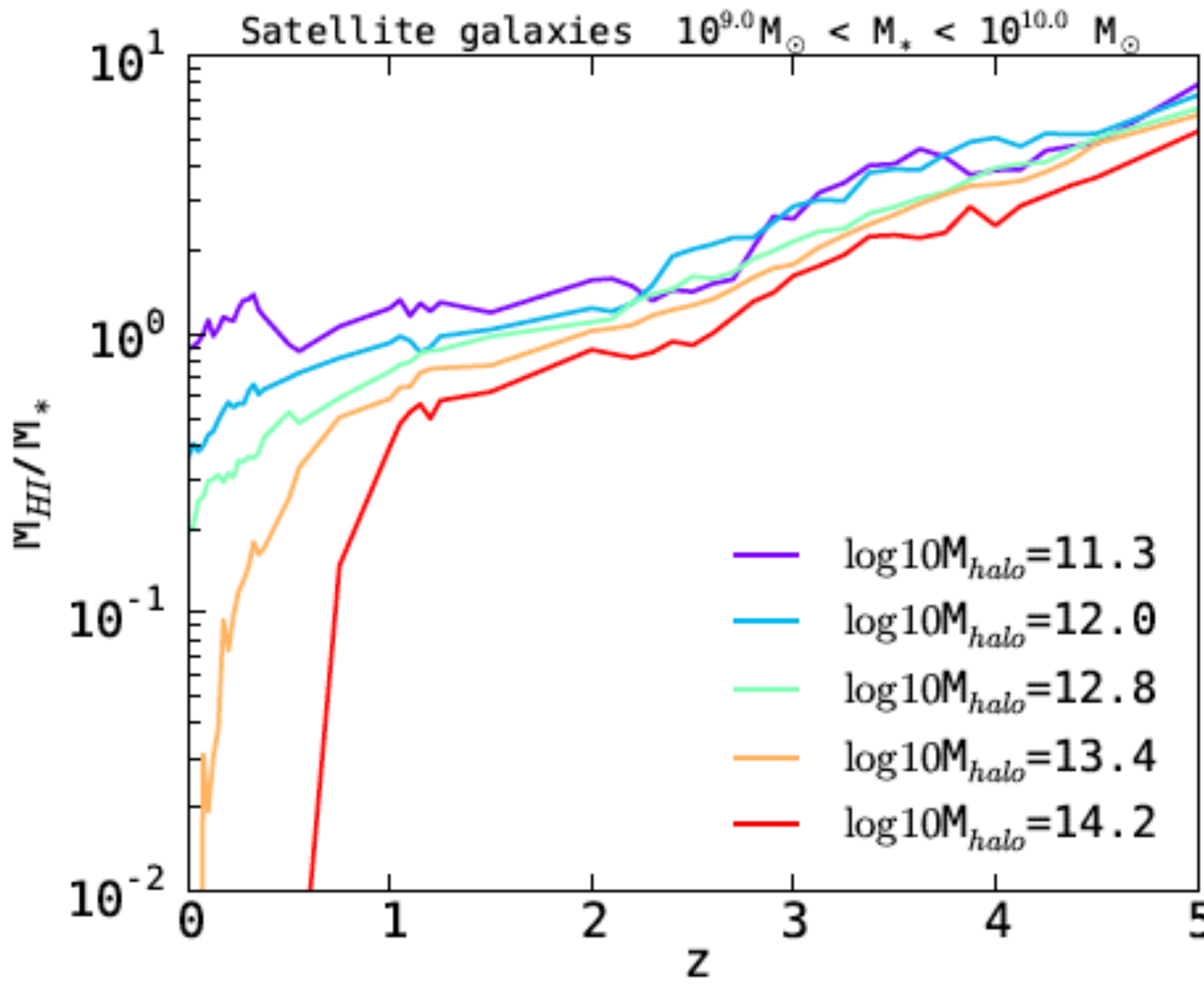
Highest-z HI galaxy image to date: z~0.376



[Fernández et al., 2016]

Key questions

- **How does the M_{HI} scale with stellar/halo mass?**

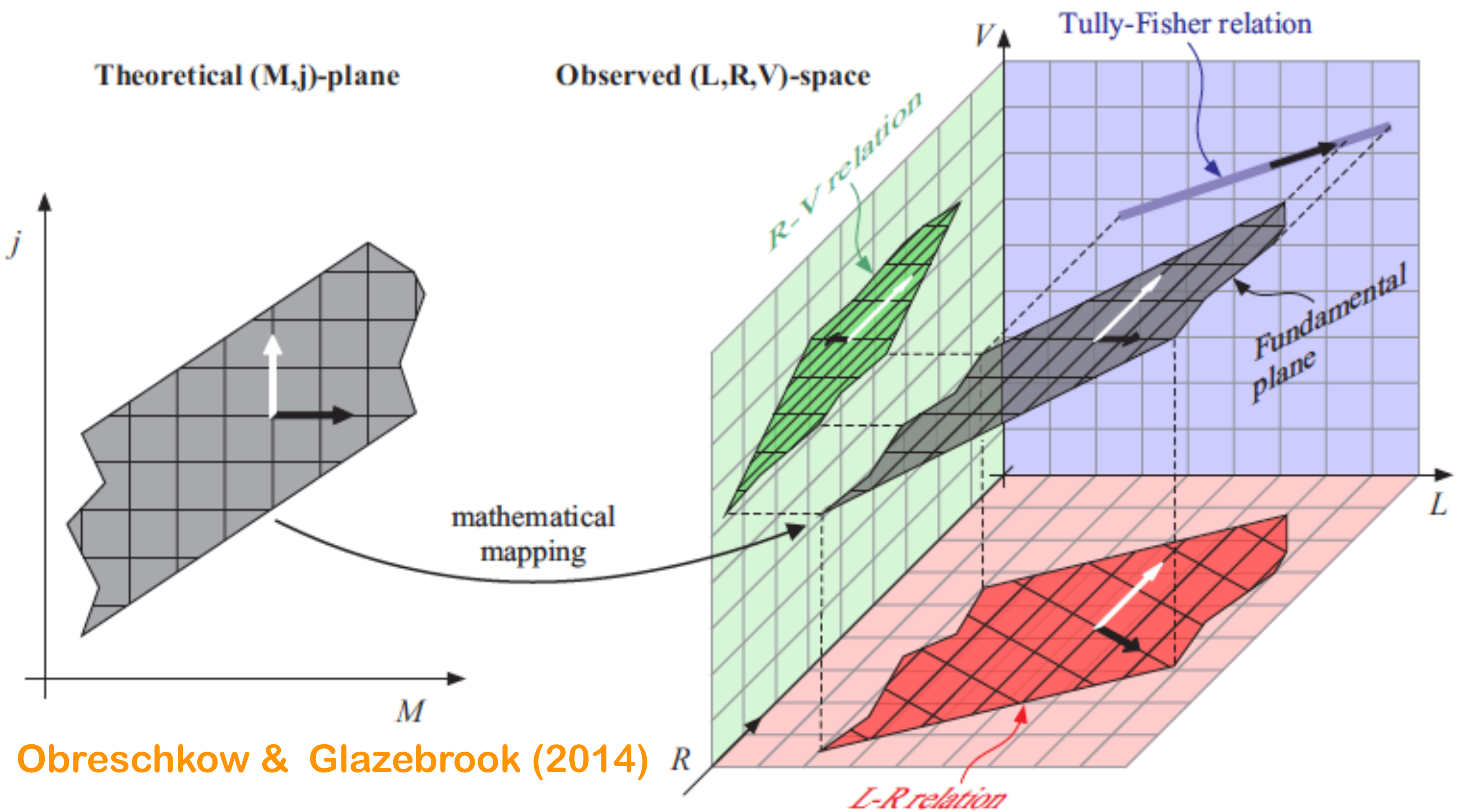


[Rafieferantsoa et al.] (2014)

In hydro. simulations, satellite galaxies follow different z-behaviour. Possibly stripping begins when the halo crosses a mass threshold…

Key questions

- **What is the role of angular momentum in galaxy evolution?**



Modelling a galaxy as an exponential disk inside a spherical halo results in a F.P. in terms of R,L, V

Angular momentum & HI

- HI is an excellent tracer of *j* since most HI found at similar radii as *j* (3-4 Re)
- *j*/*M* regulates star formation since it affects the surface density in the disk and -> conversion of HI to H_2

global HI profiles / HI kinematic maps

specific angular momentum: $j \equiv \frac{J}{M} = \frac{\int_0^\infty dr\, r^2\, \Sigma(r)\, v(r)}{\int_0^\infty dr\, r\, \Sigma(r)}$

Optical images

Past HI surveys

Many HI surveys (using single dishes and interferometers) have probed the gas content of galaxies in different environments in the local universe (z~0):

SKA-pathfinder surveys

Blind surveys: Wide vs. Deep	
CHILES (JVLA)	Single pointing COSMOS field, z<0.45
APERTIF Medium Deep	z<0.25 over 500 deg^2
APERTIF N-sky, shallow HI	z<0.26, DEC>+27°
WALLABY (ASKAP)	z<0.26, -90°<DEC<+30°
DINGO (ASKAP)	z<0.26 over 150 deg^2 0.1 < z < 0.43 over 60 deg^2
LADUMA (MeerKAT)	z<1.4 over ~4 deg^2
Targeted surveys	
MHONGOOSE (MeerKAT)	30 nearby galaxies, N~10^{19} cm^{-2}
FORNAX (MeerKAT)	Fornax cluster 11 deg^2, N~10^{19} cm^{-2}

SKA1

Strawman 1000 h surveys with SKA1:

Survey	Ω deg^2	Freq-ency[1] MHz	Resol-ution[2]	N	$< z >$ (z_{lim})	N_{HI} 10^{20} cm^{-2}
Galaxy/MS	600	1418-1422	$10''$-$1'$			2
Medium wide	400	950-1420	$10''$	34,000	0.1 (0.3)	2
Medium deep	20	950-1420	$5''$	25,000	0.2 (0.5)	0.6
Deep	1	600-1050	$2''$	2,600	0.5 (1)	0.4
Targeted	–	1400-1420	$3''$-$1'$	50	0.002 (0.01)	0.5

Staveley-Smith & Oosterloo 2015

Outlook for SKA2

- ~10x sensitivity of SKA1
- 450 - 1420 MHz -> z<2
- FoV = 100 deg^2

Gas accretion and Cosmic Web:

Targeted survey: Deep, high resolution images of local volume galaxies

- 10 h, N~2.8 x 10^{17} atoms/cm^2 @ 30''
- 100h, N~8.9 x 10^{16} atoms/cm^2 @ 30''

Outlook for SKA2

Revolutionise angular momentum measurements of galaxies:

SKA1: 2000 h, 3 deg^2

Number of line detections, $S_{int} > 5\sigma$	22,000
Median z	0.25
Number of line detections, $s_{peak} > 5\sigma$	9,300
Median z	0.20
... $s_{peak} > 5\sigma$ and $m_R < 20,\ R_e > 1''$	2,100
Median z	0.19
Number of good kinematic maps	30
Optimal beam FWHM ["]	2.5

SKA2: 2000 h, 60 deg^2

Number of line detections, $S_{int} > 5\sigma$	2,800,000
Median z	0.47
Number of line detections, $s_{peak} > 5\sigma$	1,500,000
Median z	0.41
... $s_{peak} > 5\sigma$ and $m_R < 20,\ R_e > 1''$	53,000
Median z	0.21
Number of good kinematic maps	5,700
Optimal beam FWHM ["]	1.2

Obreschkow et al., 2015

Outlook for SKA2

10x more sensitivity + large FoV will drastically increase survey speed and depth possible to do HI surveys (both all-sky and deep):

Compare direct high z detections to stacking results from SKA1

Probe environmental effects much more broadly with large and deep survey

High resolution HI maps at higher z than ever before to study kinematics and star formation processes for ~millions of galaxies…

SKA1-MID t=10h

Resolution (")	d (z=0.2) (kpc)	d (z=0.5) (kpc)	rms noise mJy dV=5 km/s	5 sigma N(HI) dV=5 km/s	5 sigma N(HI) dV=25 km/s	5 sigma M(HI) dV=50 km/s z=0.02	5 sigma M(HI) dV=50 km/s z=0.2	5 sigma M(HI) dV=50 km/s z=0.5
1	3.3	6.1	0.141	3.92E+21	1.96E+22	1.20E+07	1.56E+09	1.32E+10
3	9.8	18.4	0.118	3.65E+20	1.83E+21	1.00E+07	1.31E+09	1.10E+10
10	32.8	61.2	0.091	2.53E+19	1.26E+20	7.72E+06	1.01E+09	8.50E+09
30	98.3	183.7	0.095	2.95E+18	1.47E+19	8.11E+06	1.06E+09	8.92E+09

SKA2 t=10h

Resolution (")	d (z=0.2) (kpc)	d (z=0.8) (kpc)	rms noise mJy dV=5 km/s	5 sigma N(HI) dV=5 km/s	5 sigma N(HI) dV=25 km/s	5 sigma M(HI) dV=50 km/s z=0.02	5 sigma M(HI) dV=50 km/s z=0.2	5 sigma M(HI) dV=50 km/s z=0.5
1	3.3	6.1	0.009	2.53E+20	1.26E+21	7.64E+05	9.99E+07	8.41E+08
3	9.8	18.4	0.009	2.81E+19	1.40E+20	7.64E+05	9.99E+07	8.41E+08
10	32.8	61.2	0.009	2.53E+18	1.26E+19	7.64E+05	9.99E+07	8.41E+08
30	98.3	183.7	0.009	2.81E+17	1.40E+18	7.64E+05	9.99E+07	8.41E+08

Blyth et al., 2015

Summary

High sensitivity, large FoV will be a game changer for HI studies of galaxies:

- will allow direct detections for populations for which stacking results are currently our 'state of the art'!
- insight into the gas in galaxies in different environments, right back to when star formation in the universe was at its peak