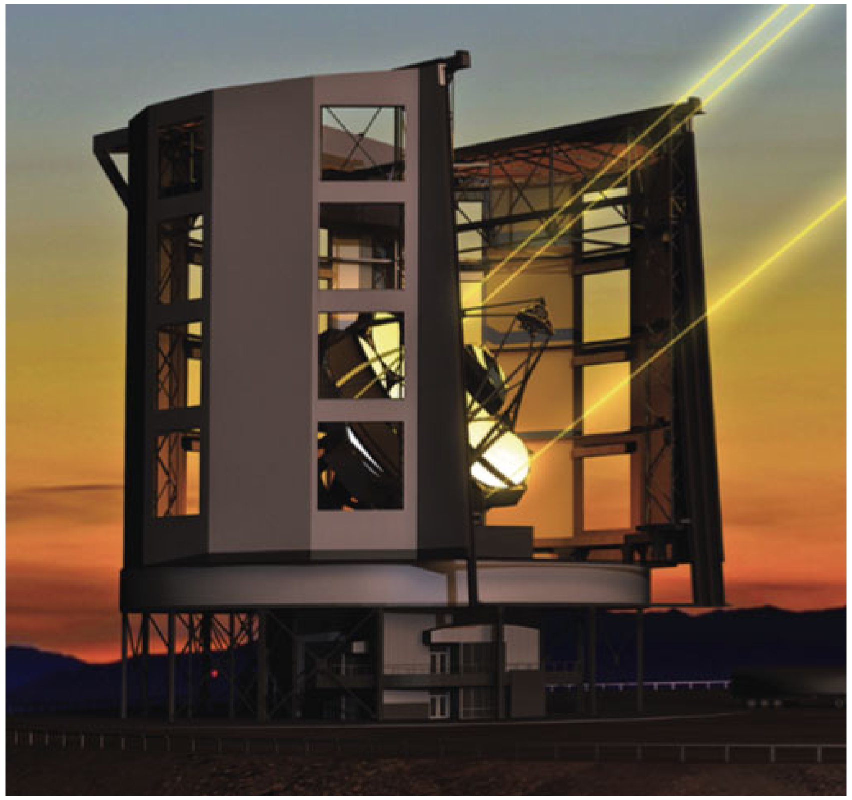
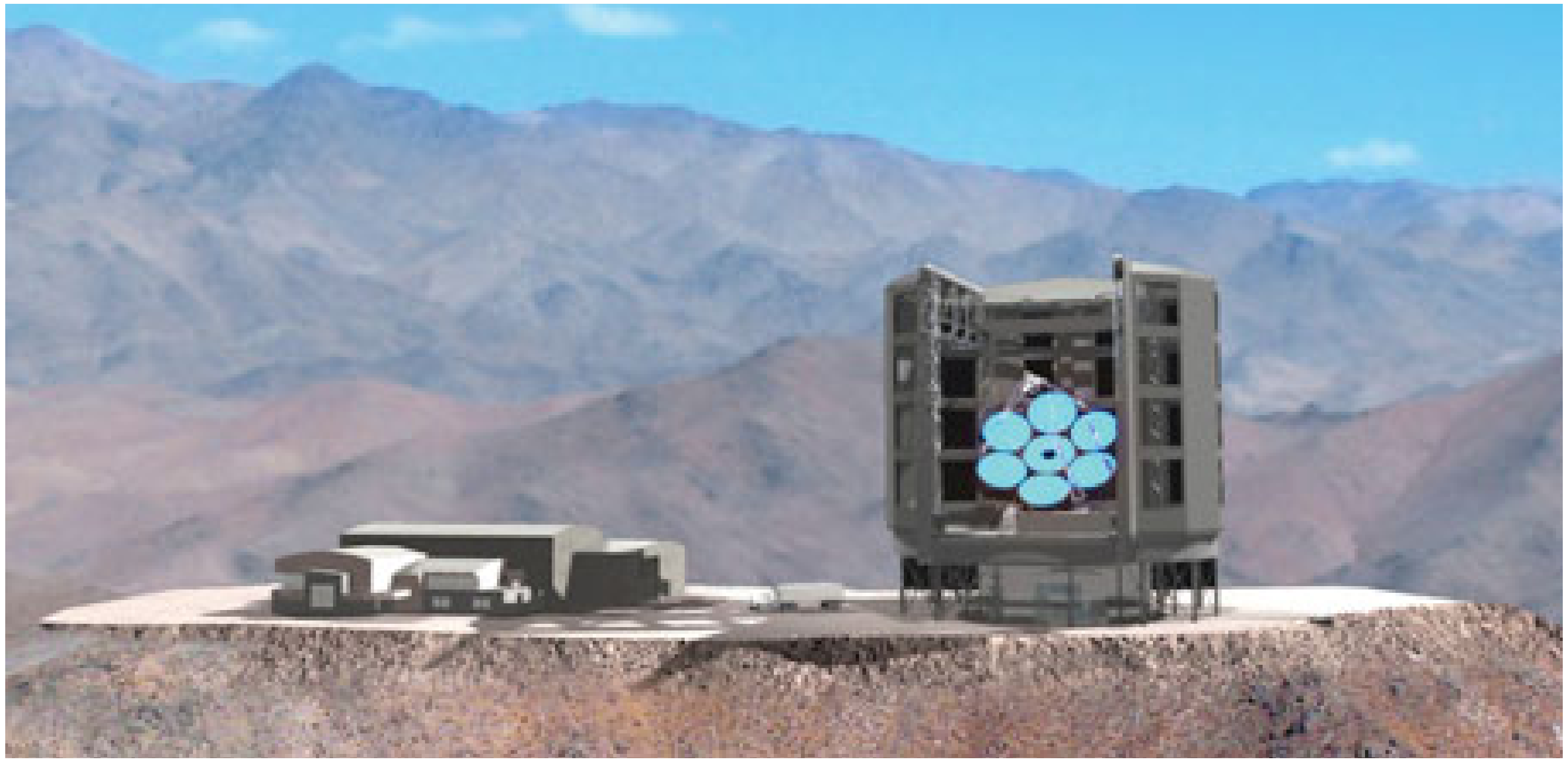
Unlocking the physics of the high-z universe with optical spectroscopy on ELTs





Roderik Overzier

Observatório Nacional, Rio de Janeiro

IAG Advanced School, 28 Feb 2018

Two goals for this talk

1) Provide you with an overview of some of *today's* important topics in the formation of galaxies in the early universe, and the role of ELTs

2) Try to project into the future the (extra-galactic) science we will be most interested in when GMT becomes a reality (>2022–2025)

Important caveats:

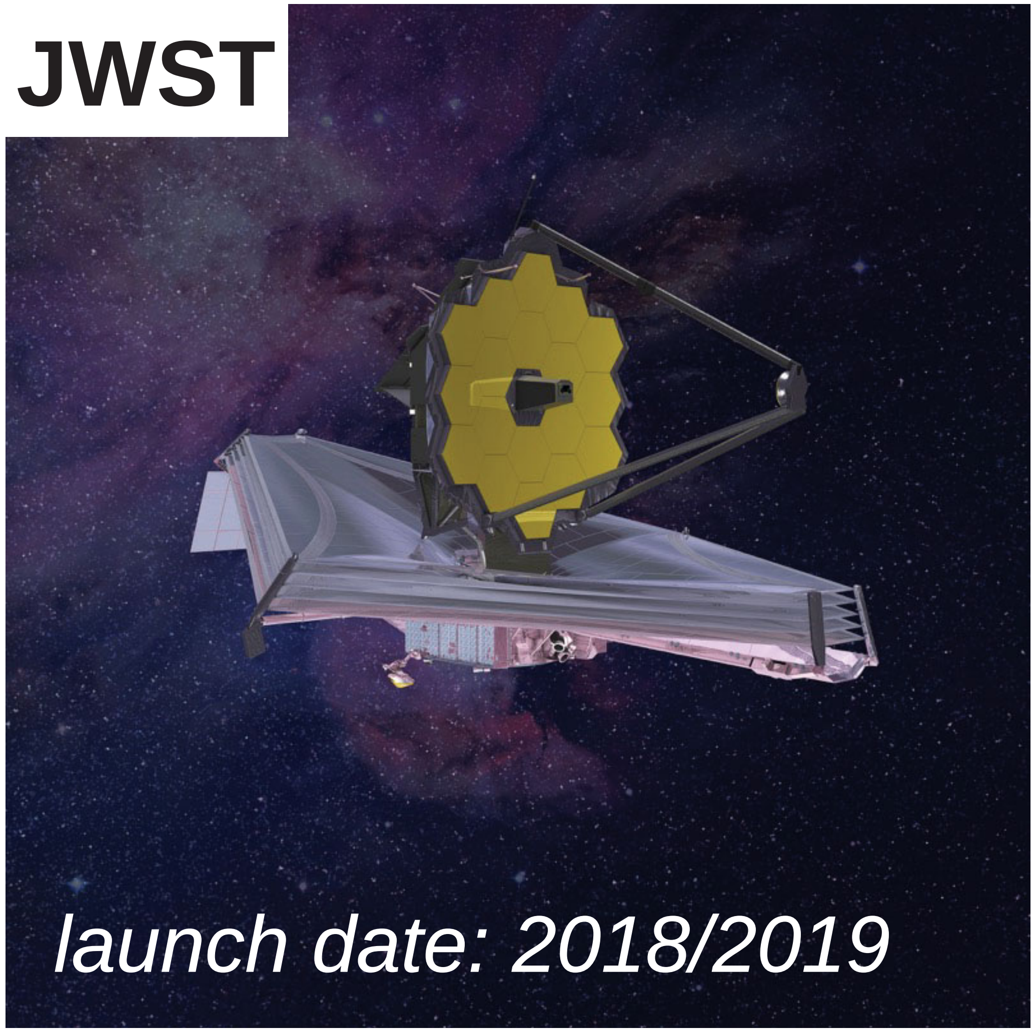
I. Some of the most novel discoveries made by the twin 10m Keck telescopes between 1992 and 2007 were:

- the discovery of galaxies at z = 3 (Steidel et al. 1996)
- the discovery of Gamma Ray Burst hosts (Kulkarni et al. 1998)
- type 1A Supernovae identification (Perlmutter et al. 1997)
- the discovery of extra-solar planets (Marcy et al. 1997)

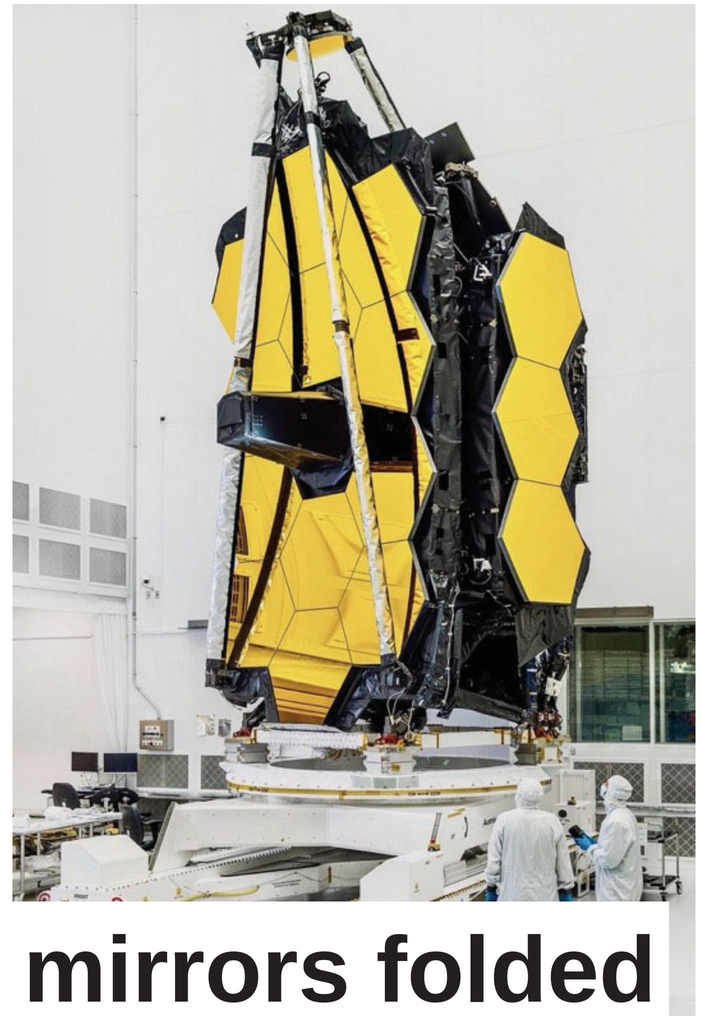
None of these were mentioned in the original 1985 Keck Science case (see Ellis 2011, Depoy et al. 2012)

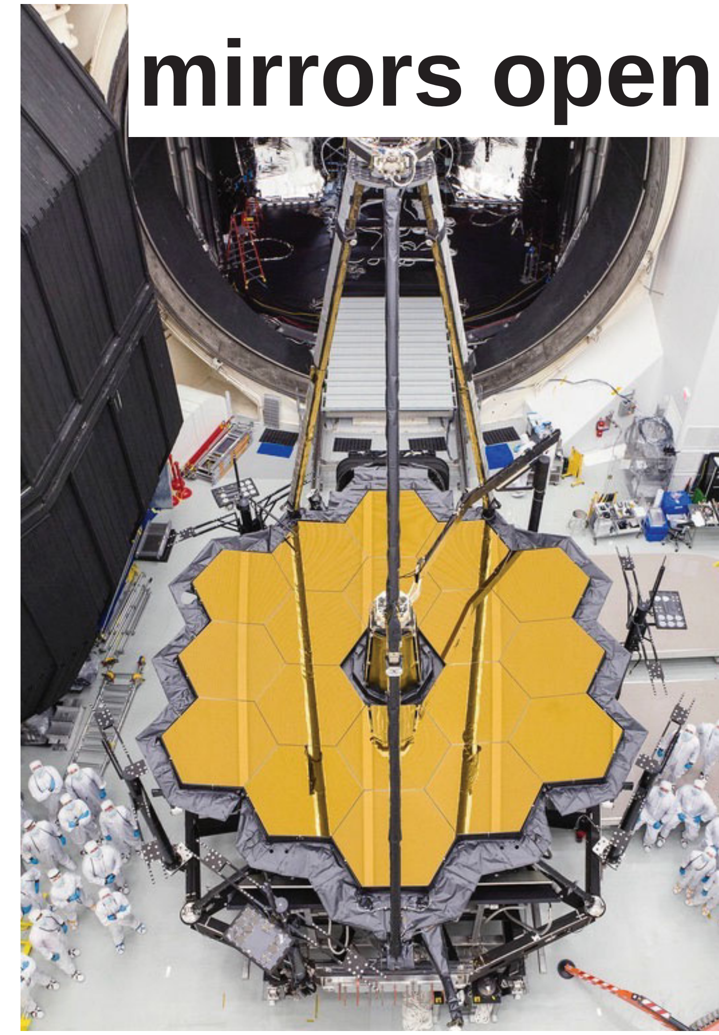
II. The James Webb Space Telescope…

What will the James Webb Space Telescope see?

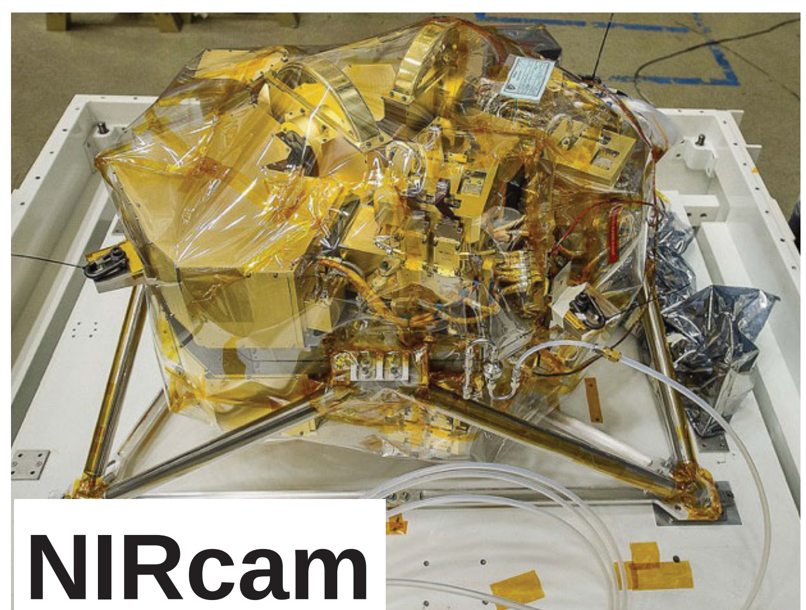


JWST


mirrors folded


mirrors open

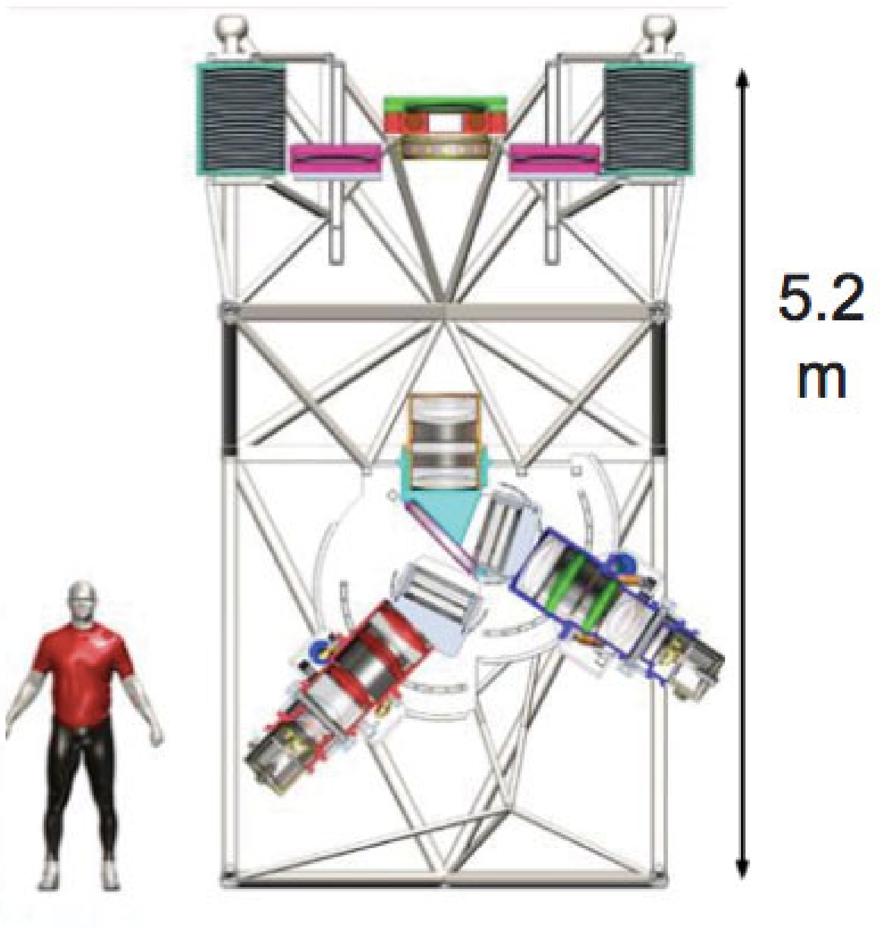

sunshield


NIRcam


NIRspec

GMACS science focus areas

Science = Function(*mirror size, areal coverage, wavelength range, spectral resolution, targeting method, interest*);



- D_{eff} ~ 22 m (~17 m at first light; 3-5x area of Keck)
- ~ 8’ rectangular area on sky (~20’ with MANIFEST)
- 0.3 — 1 micron wavelength range at R ~ 2000 — 5000
- space for tens of masks, each with hundreds of small slits (seeing limited)

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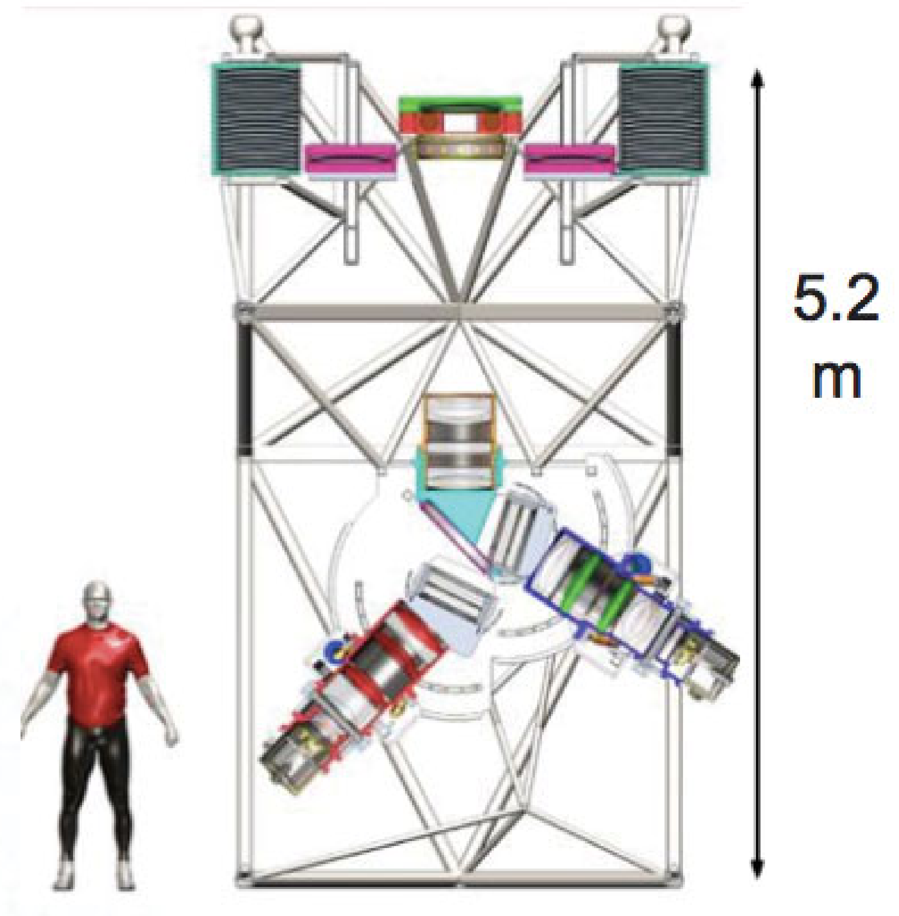

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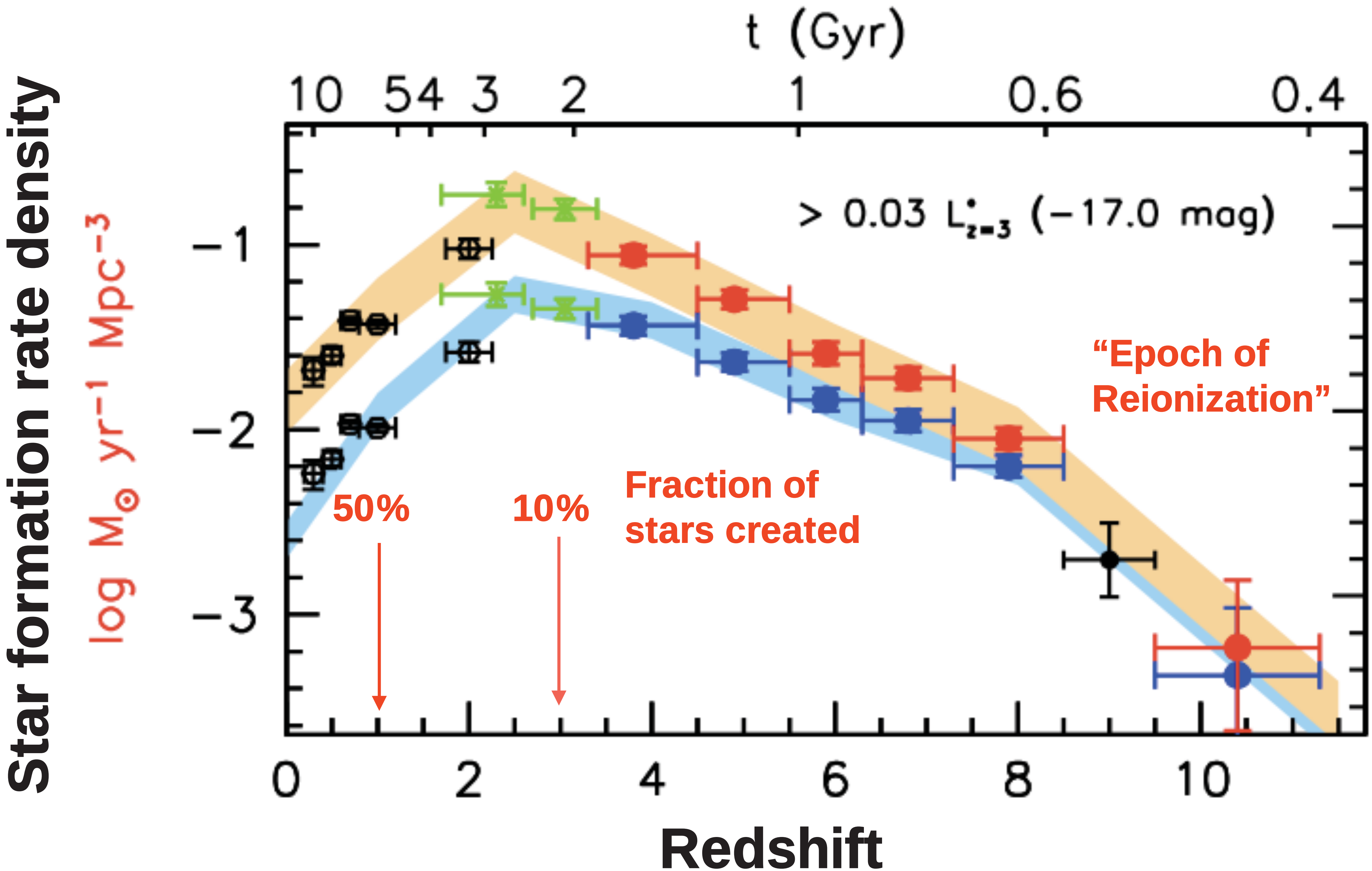
Then you arrive at these main science areas:

1. ISM, MW archaeology, local group dwarfs (exoplanet atmospheres)
2. **galaxy evolution during *"cosmic noon"***
3. **first light and galaxies during *"cosmic dawn"***

From cosmic “dawn” to cosmic “noon”



e.g. see Hopkins & Beacom 2008; Bouwens et al. 2009, 2012, 2014; Overzier et al. 2010; Yan et al. 2011; Madau & Dickinson 2014

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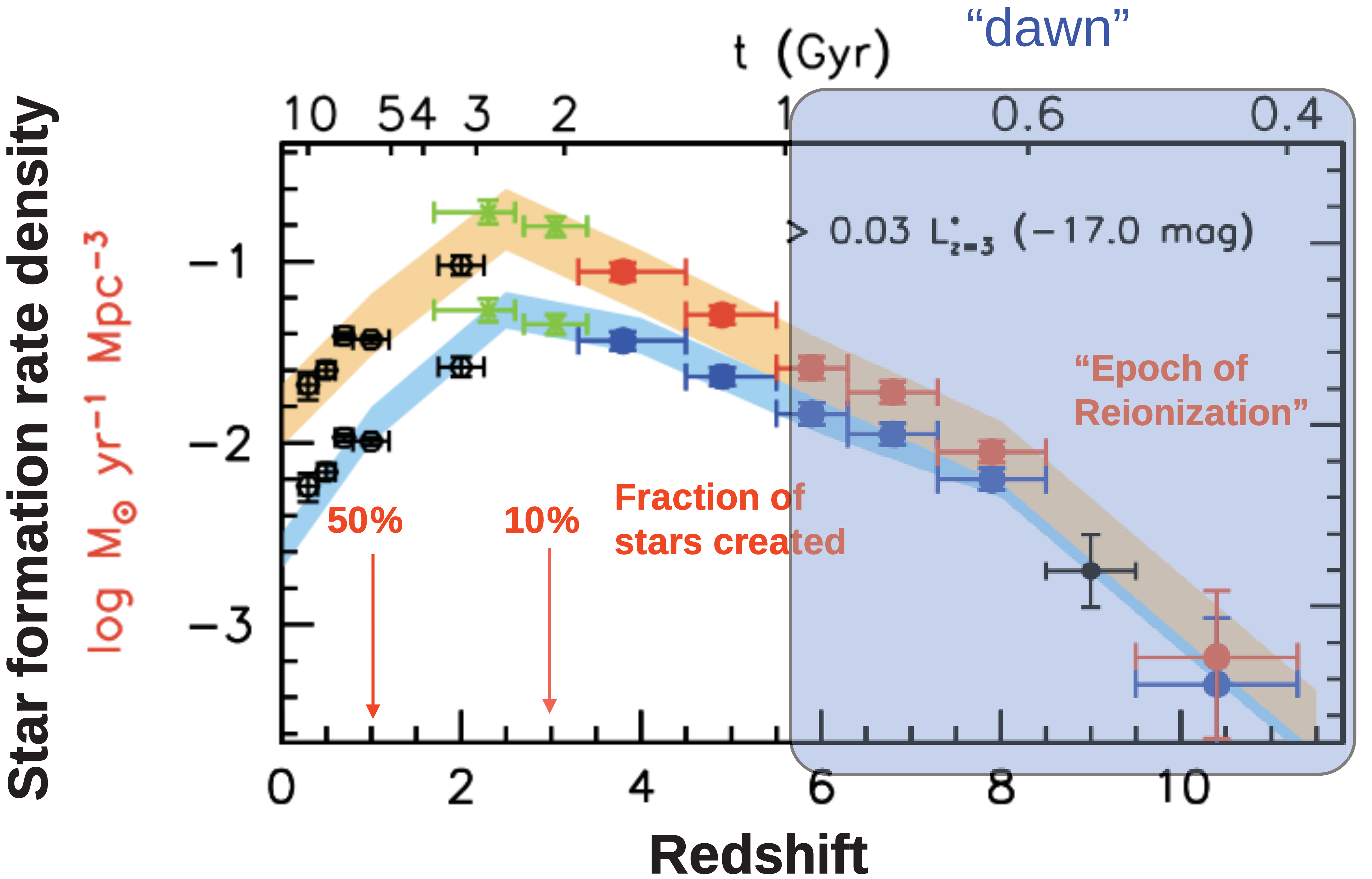

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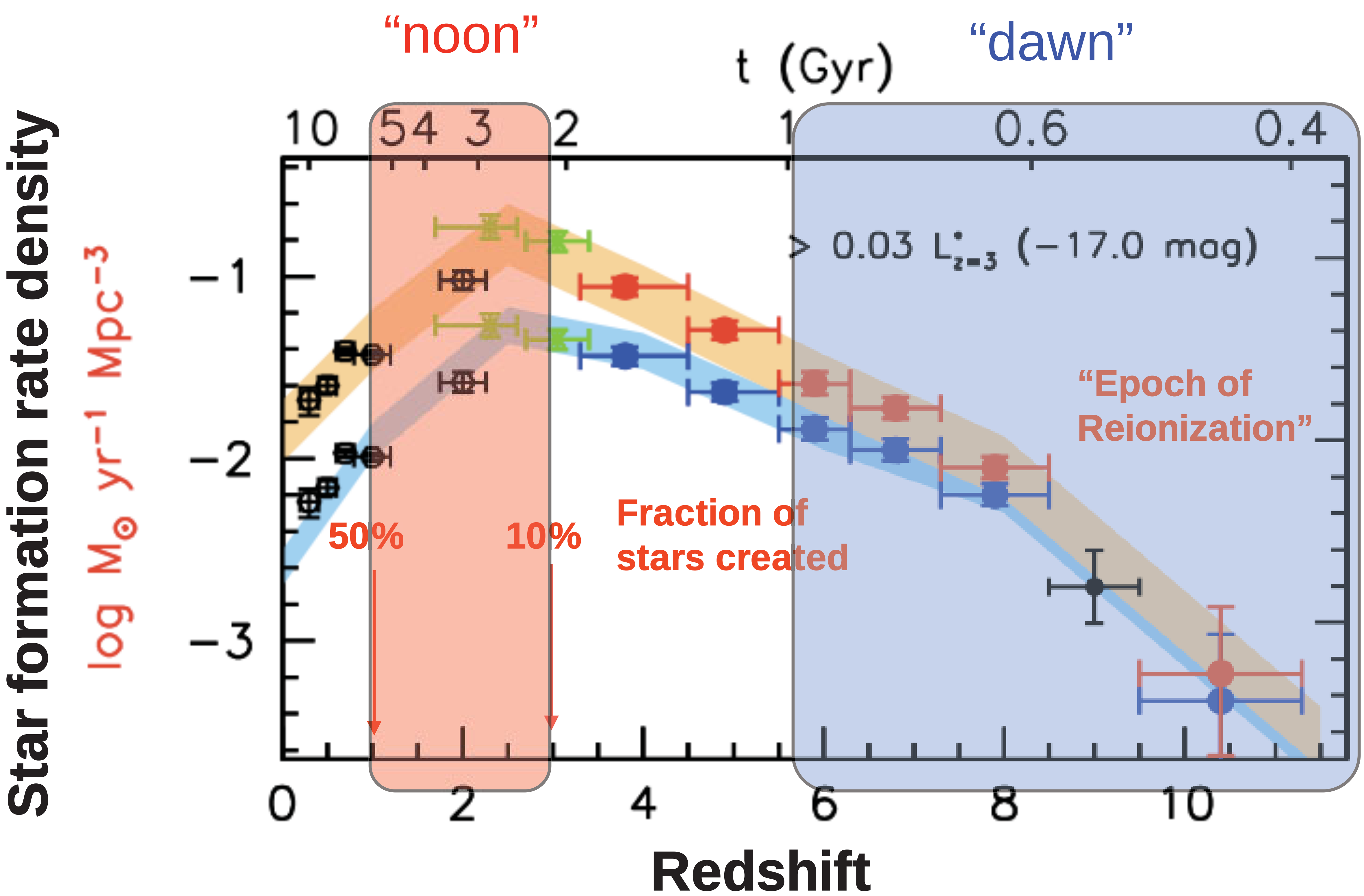

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Cosmic dawn

- epoch of the first stars and galaxies ($z > 6$)
- "seeds" of massive galaxies and supermassive black holes
- "seeds" of massive galaxy clusters and LSS
- period during which the IGM transitioned from being completely neutral ("dark ages") to completely ionized: "**epoch of reionization"**

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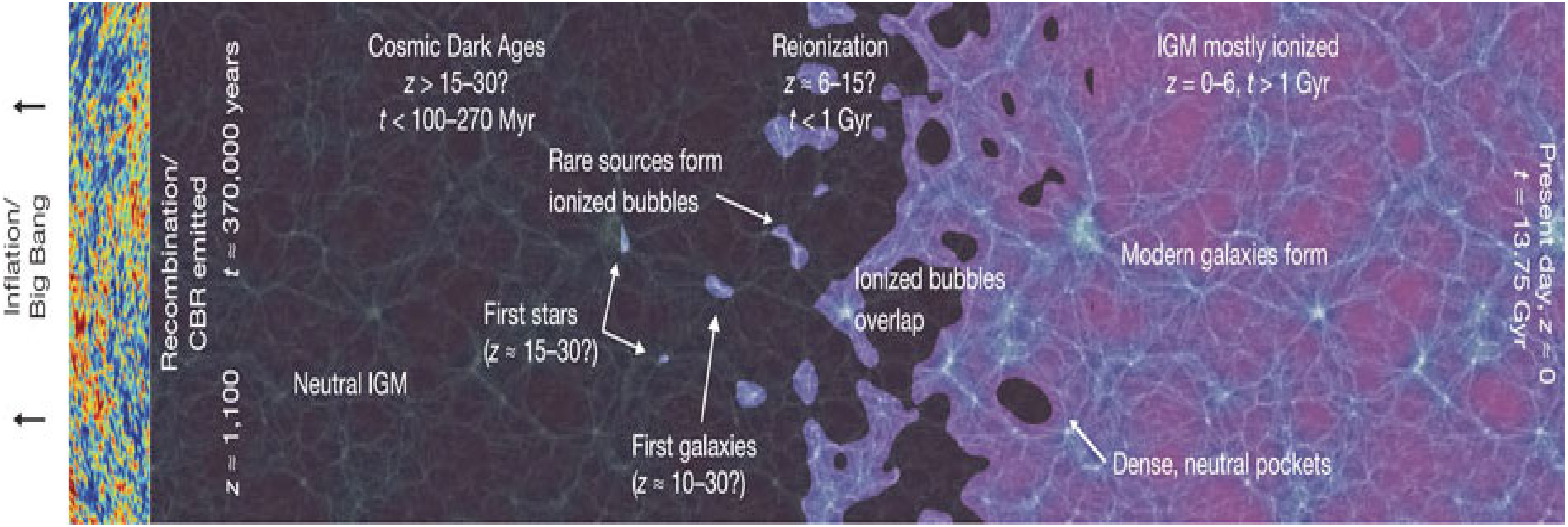
Cosmic noon

- epoch during which today's typical galaxies (satellites, MW-type galaxies and massive galaxies) were most actively forming
- what do we mean by most actively: most of the mass in stars and supermassive black holes was acquired, and reaching present-day morphologies
- $z = 1$—3 for typical (i.e. MW-type) galaxies
- relax somewhat to $z \sim 0.5$ to include lower-mass galaxies, and up to $z \sim 4$ to include very massive galaxies

In the beginning there was… “cosmic dawn”



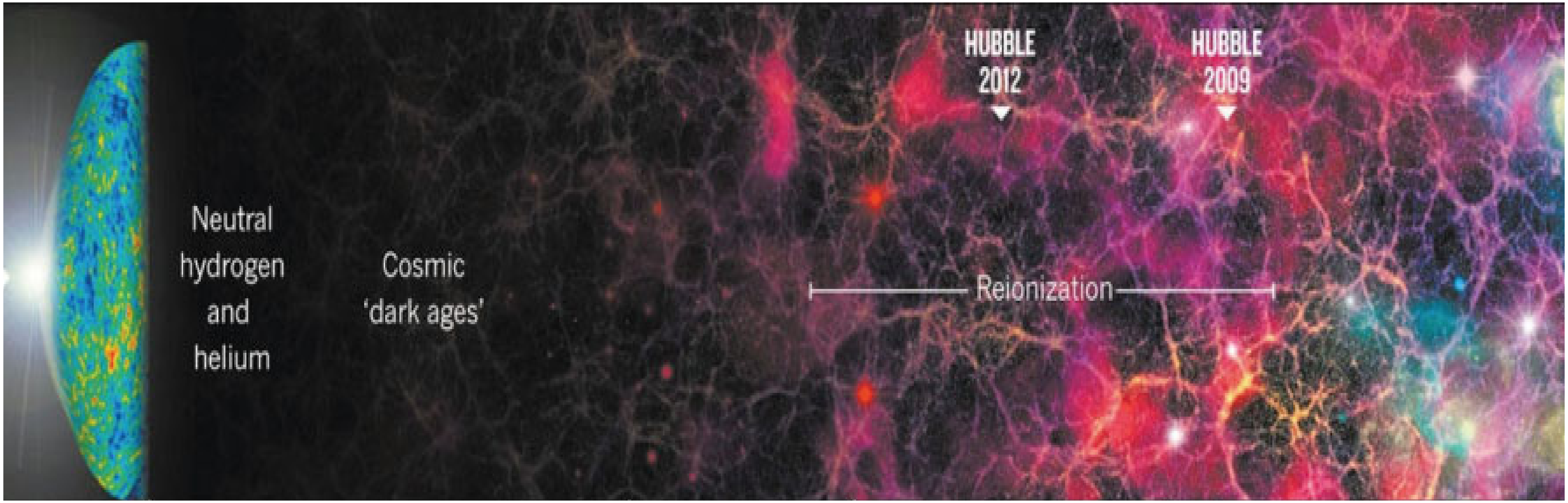
- **Recombination**: nuclei + e- form neutral atoms after about 240,000 yr (z ~ 1370)

- **Photon decoupling** and “**Last scattering**”: photons no longer interact with matter, their temperature decreasing as the universe expands and the neutral IGM becomes fully transparent. This happens at ~350,000 yr (z ~ 1100; images of the CMB)

- **Reionization**: light from the first stars and galaxies “re”-ionizes the neutral hydrogen in **inside-out fashion** (growing “bubbles” of ionized zones that eventually overlap). Starting around z~20-30 and ending at z~6-10 (cosmology dependent!)

Cosmic dawn

- period during which the IGM transitioned from being completely neutral ("dark ages") to completely ionized: "**epoch of reionization**"

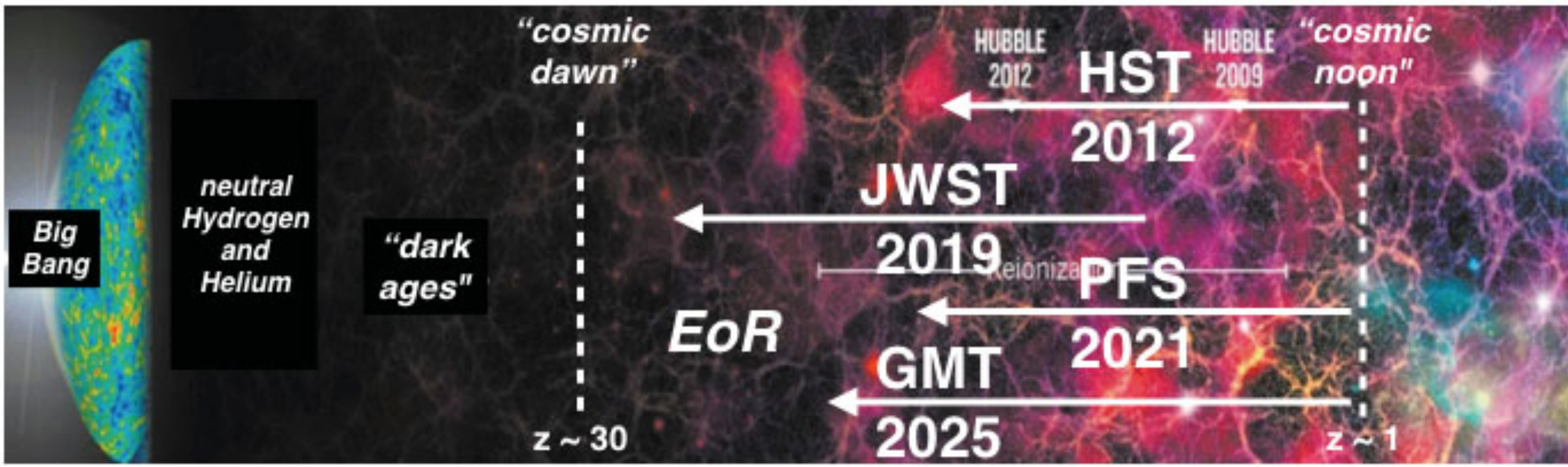


Cosmology sets the **rate of growth of structure** (dark matter, gas cooling, galaxies), and this determines the production **rate of ionizing photons**, which causes the **reionization**

▷ **studying the reionization process is in many ways equivalent to studying the formation of structure in the (early) universe**

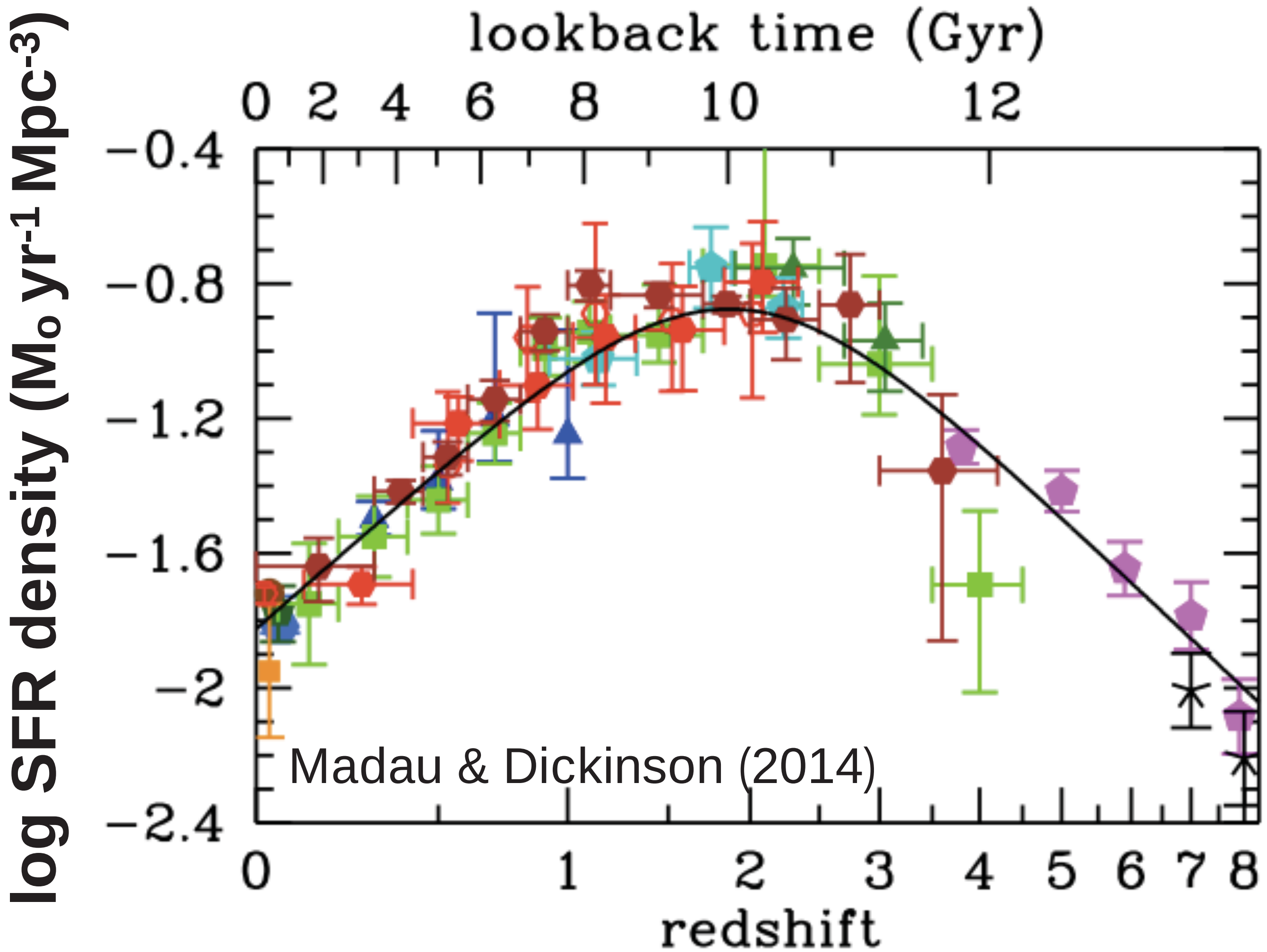
Observing cosmic dawn and reionization

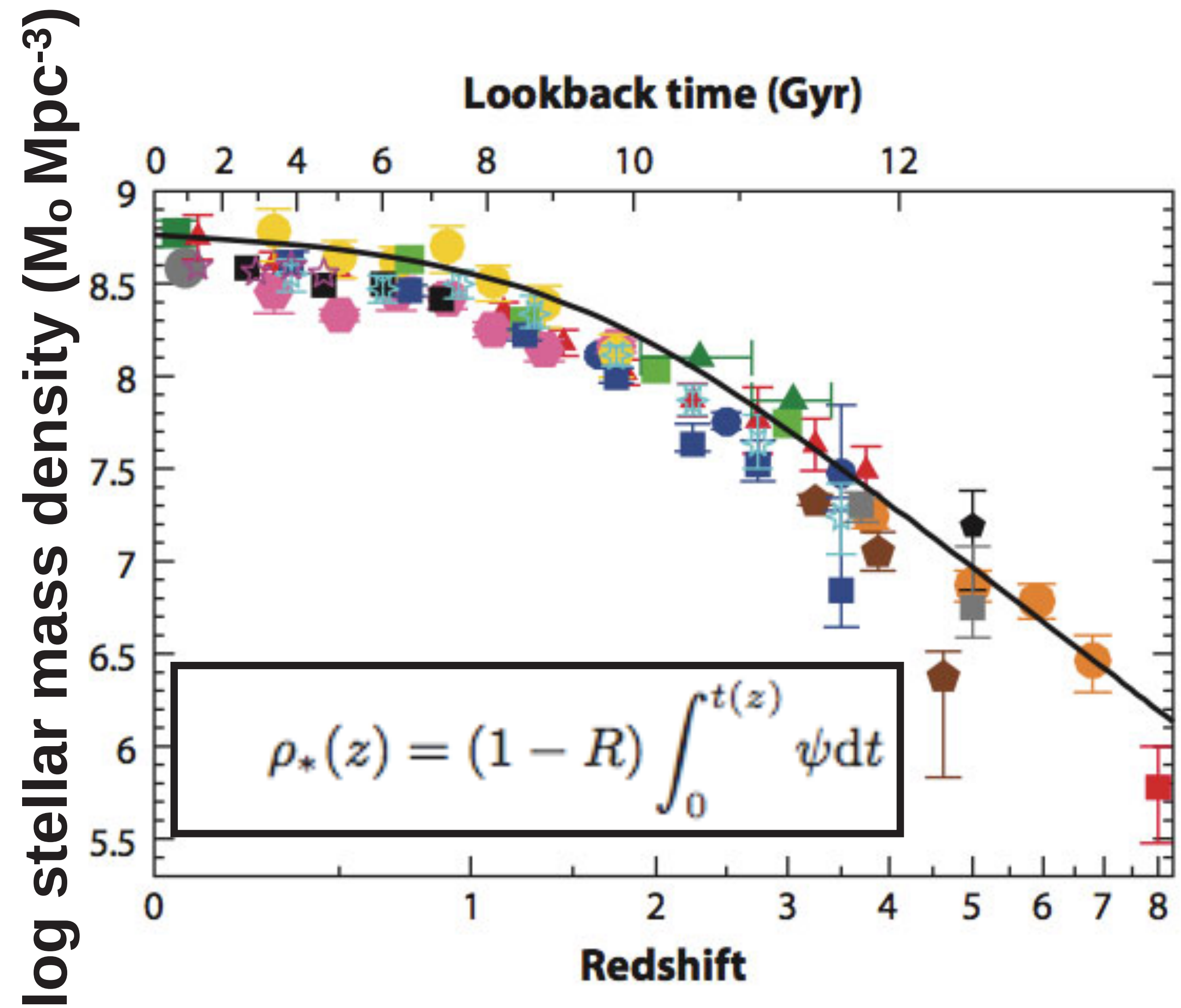
early times can be probed by radio arrays sensitive to the 21 cm neutral hydrogen emission from the neutral IGM…



late times can be probed by optical/infrared telescopes sensitive to the light of the "first" galaxies and the ionized IGM detected in absorption…

Cosmic noon





Main questions:

what physical processes drive or feed the observed relations between:

1. **star formation rate density** (SFRD)
2. **stellar mass density** (SMD),
3. **Hubble sequence** of morphologies
4. **central black holes** (“M_{BH}-σ relation”)

all as a function of dark matter halo mass ?

Observing cosmic noon: key measurements

- most of our current knowledge of the stellar, (ionized) gas and black hole properties of galaxies is based on the physical properties derived from **rest-frame optical** observations, i.e. morphologies, kinematics and spectral diagnostics

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- for this redshift range (z~1-3), nearly all of this happens in the **observed near-infrared**, outside the domain of GMACS (0.3-1 micron):

  - dust-corrected star formation rates (GMTIFS)
  - dynamical galaxy masses from stellar absorption lines (GMTIFS)
  - role of clumpy galaxy formation (AO/GMTIFS)
  - stellar mass—metallicity relation (GMTIFS)
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- however, GMACS **is** perfectly suited for probing the connection between galaxies and the cosmic web through **rest-UV absorption line studies** (observed optical)

From noon ’til dawn: main questions

- How do we interpret the cosmic SFR history ?
- What is the relation between morphology and kinematics of stars and gas ?
- How do the inflows happen? What is the role of outflows?
- How do galaxies evolve to the mass—Z relation?
- How did the seeds of galaxy bulges and black holes form and co-evolve ?
- Which were the first sources that caused re-ionization, and how?
- What is the role of the environment?
- What is the role of the cosmology?

The higher we move in redshift, the younger galaxies become…

➢ “**Starbursts**” are the key to understanding many of these processes

Talk Overview

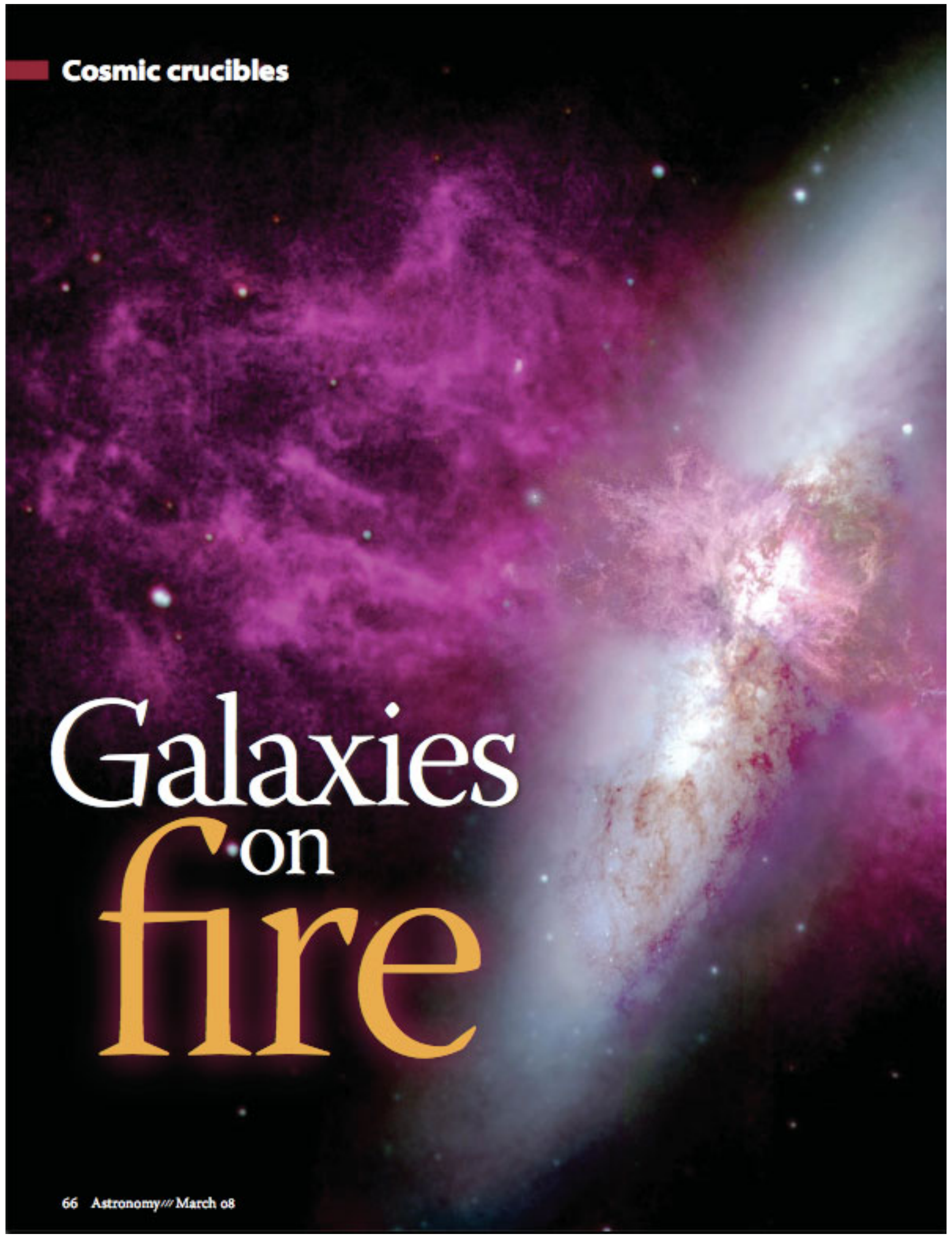
Introduction

The importance of “starbursts”

GMACS at “cosmic noon”

GMACS at “cosmic dawn”

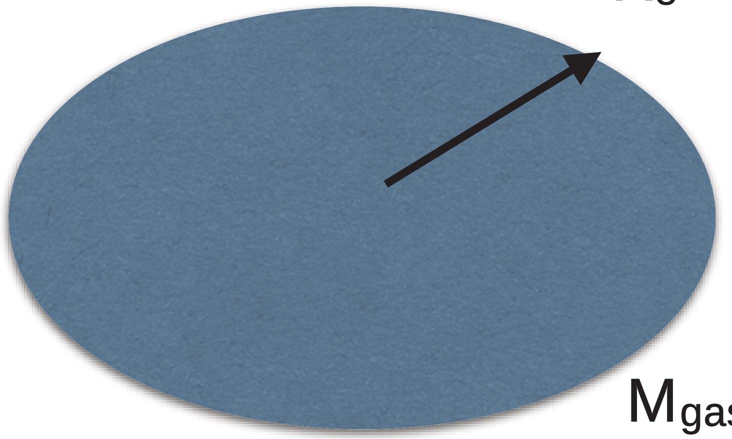
GMACS/GMT synergies



What is a "starburst"; some definitions

#1. Theoretically Maximum achievable SFR in a gas cloud:

$$\mathbf{SFR_{max} \sim M_{gas} / t_{dyn}}$$



with $t_{dyn} \sim R_e / \sigma_v$

and $M_{gas} \sim f_{gas} M_{dyn}$

and $M_{dyn} \sim R_e \sigma_v^2 / G$

$$\mathbf{SFR_{max}} \sim f_{gas} M_{dyn} / t_{dyn} \sim f_{gas} (R_e / t_{dyn}) \sigma_v^2 / G = \mathbf{f_{gas} \sigma_v^3 / G}$$

Example: *Assume a f_{gas} ~ 100% and a R_e = 1 kpc galaxy with velocity dispersion of 100 km/s ➞ SFR_{max} ~ 200 M/yr*

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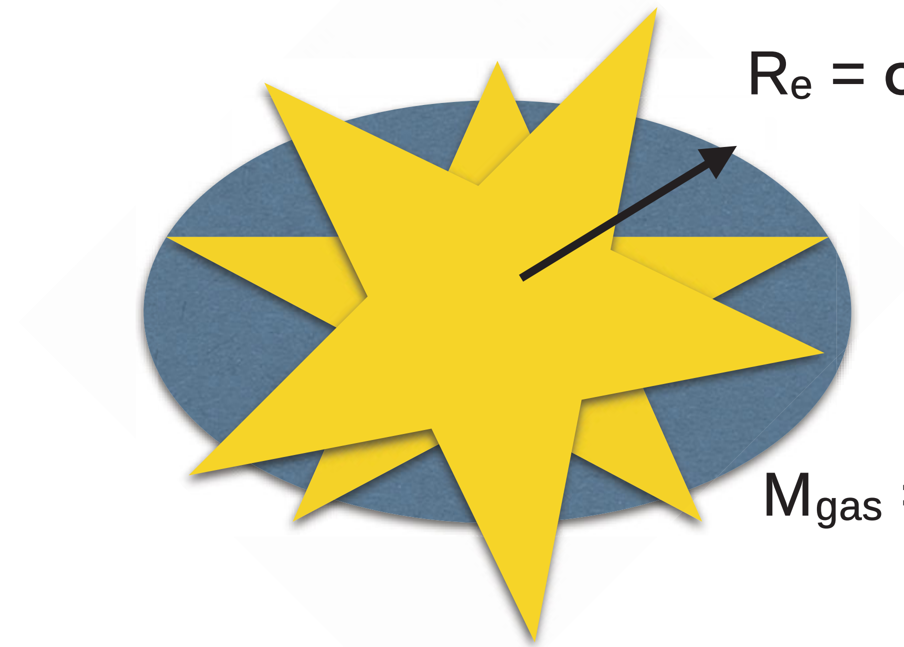

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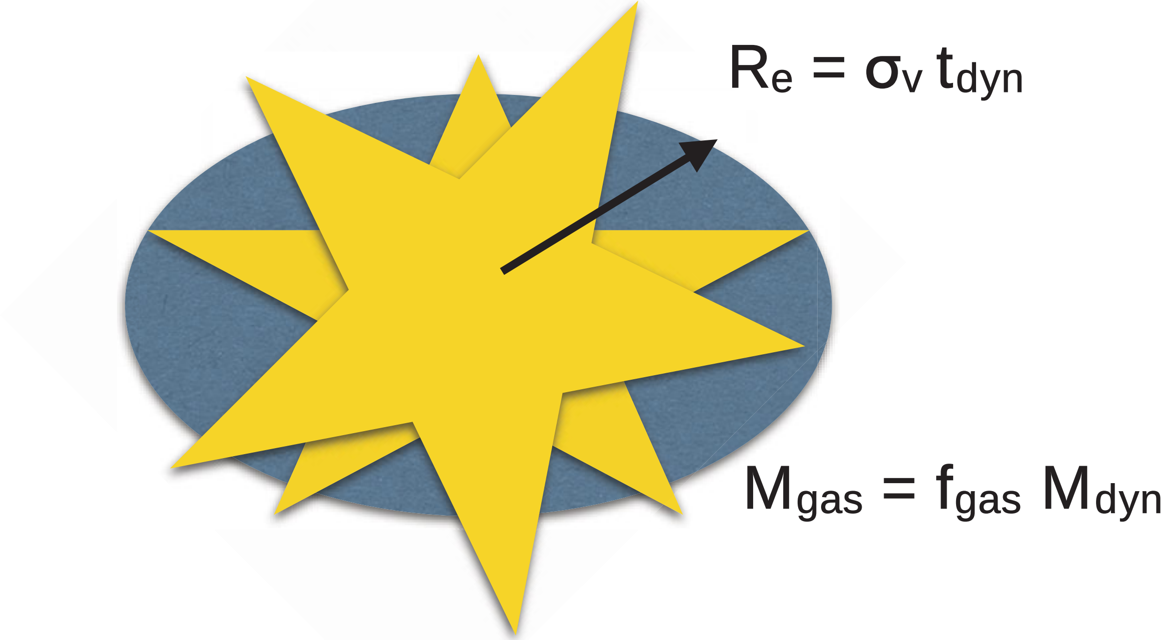

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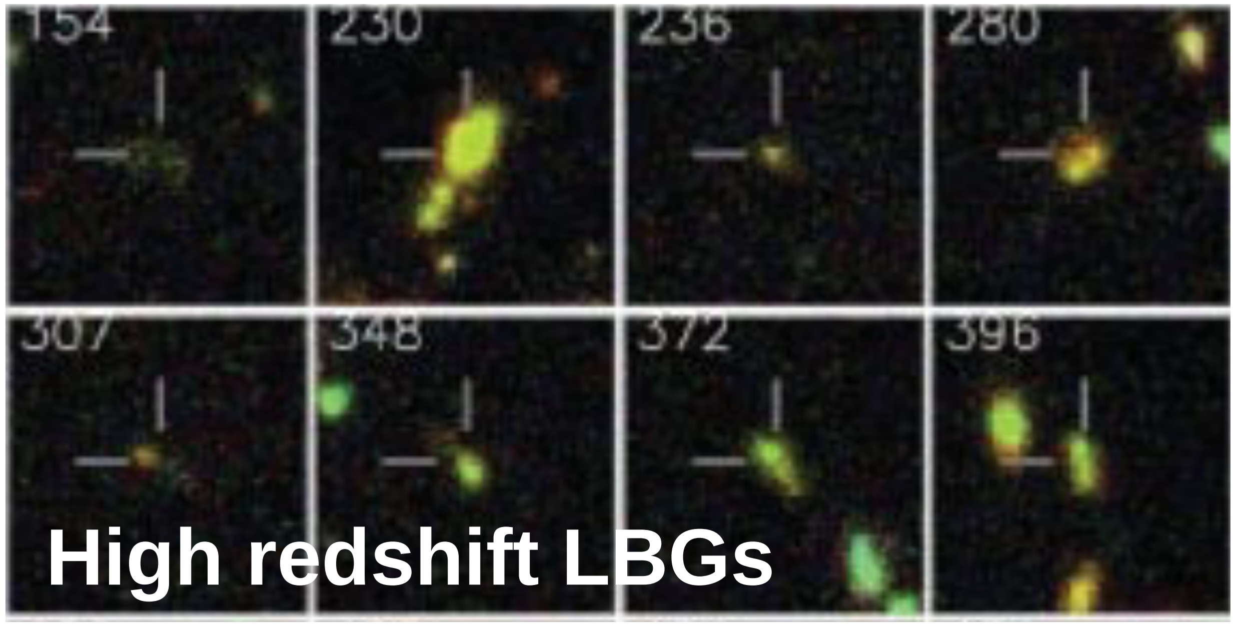


What is a "starburst"; some definitions

#2. Short star formation timescale (*specific* star formation rate)

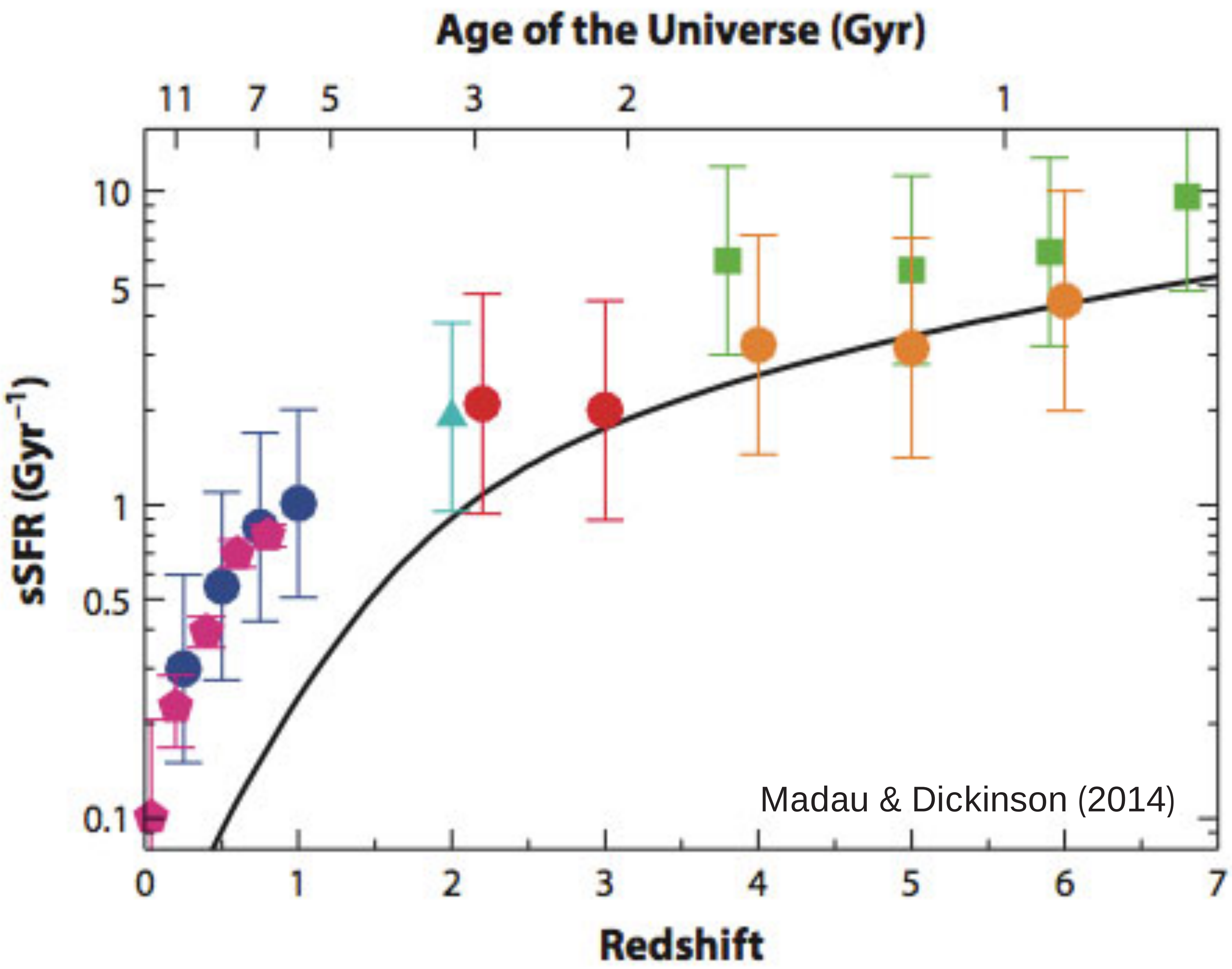
sSFR = SFR / M★ > 1 / t_H for starbursts sSFR >10^{-9} to 10^{-8} yr^{-1}

- sSFR is closely related to the **mass doubling time:**

t_D = M★ / SFR = 1 / sSFR < t_H

- and the **stellar birth rate parameter** b, the ratio of the SFR today to the average past SFR over the age of the galaxy

b = SFR / <SFR>



at high redshift (z > 3), most star-forming galaxies are in this starburst mode

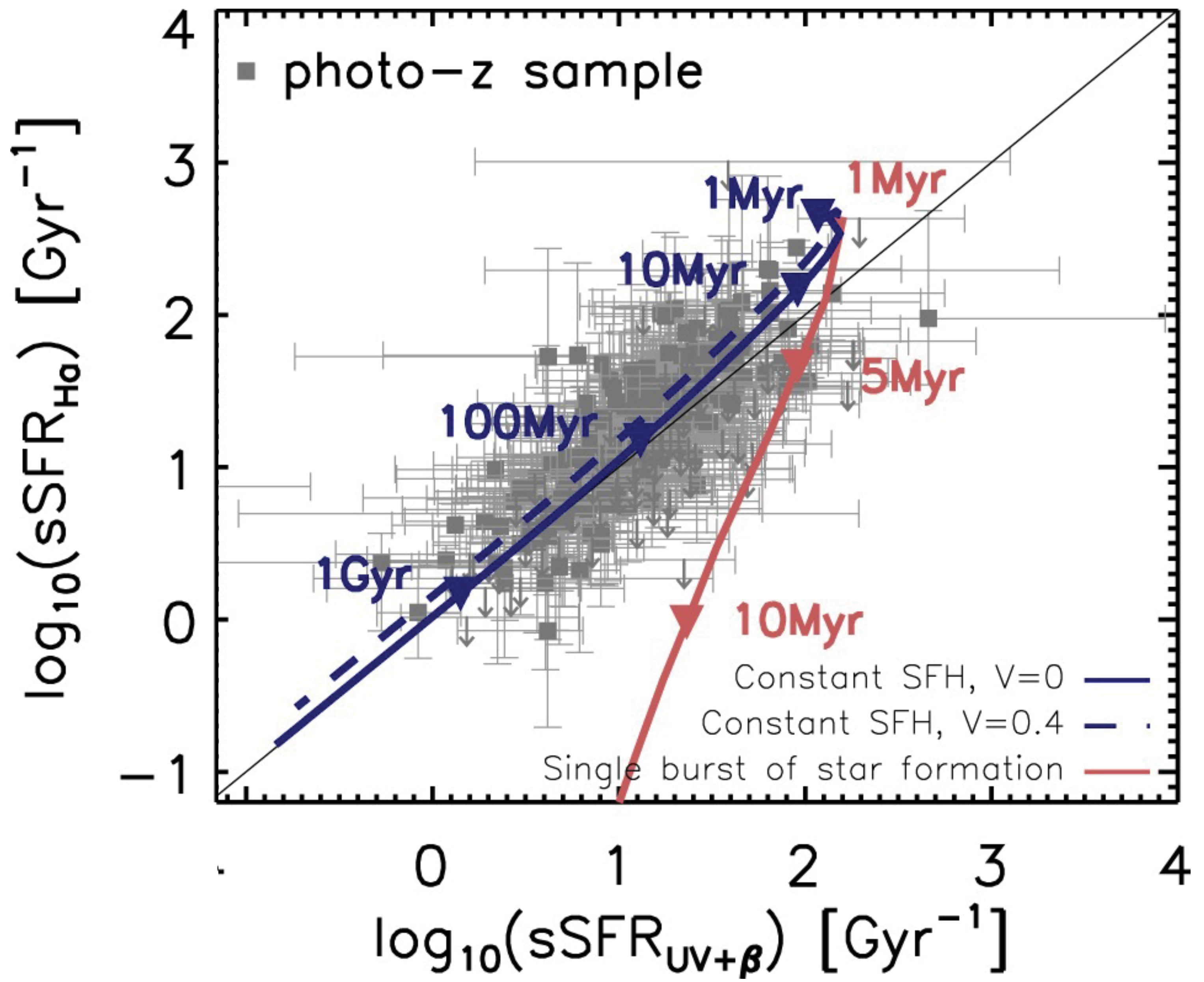
What is a “starburst”; some definitions

#3. Short Gas Depletion Timescale

$t_{depl} = M_{gas} / SFR < t_H$

***Example**:*
Assume a galaxy with a gas mass of 10^{10} M_{sun} and SFR of 100 M_{sun}/yr: the gas would be depleted in only 100 Myr

high-z galaxies are not “bursty”



Smit et al. (2016)

What is a "starburst"; some definitions

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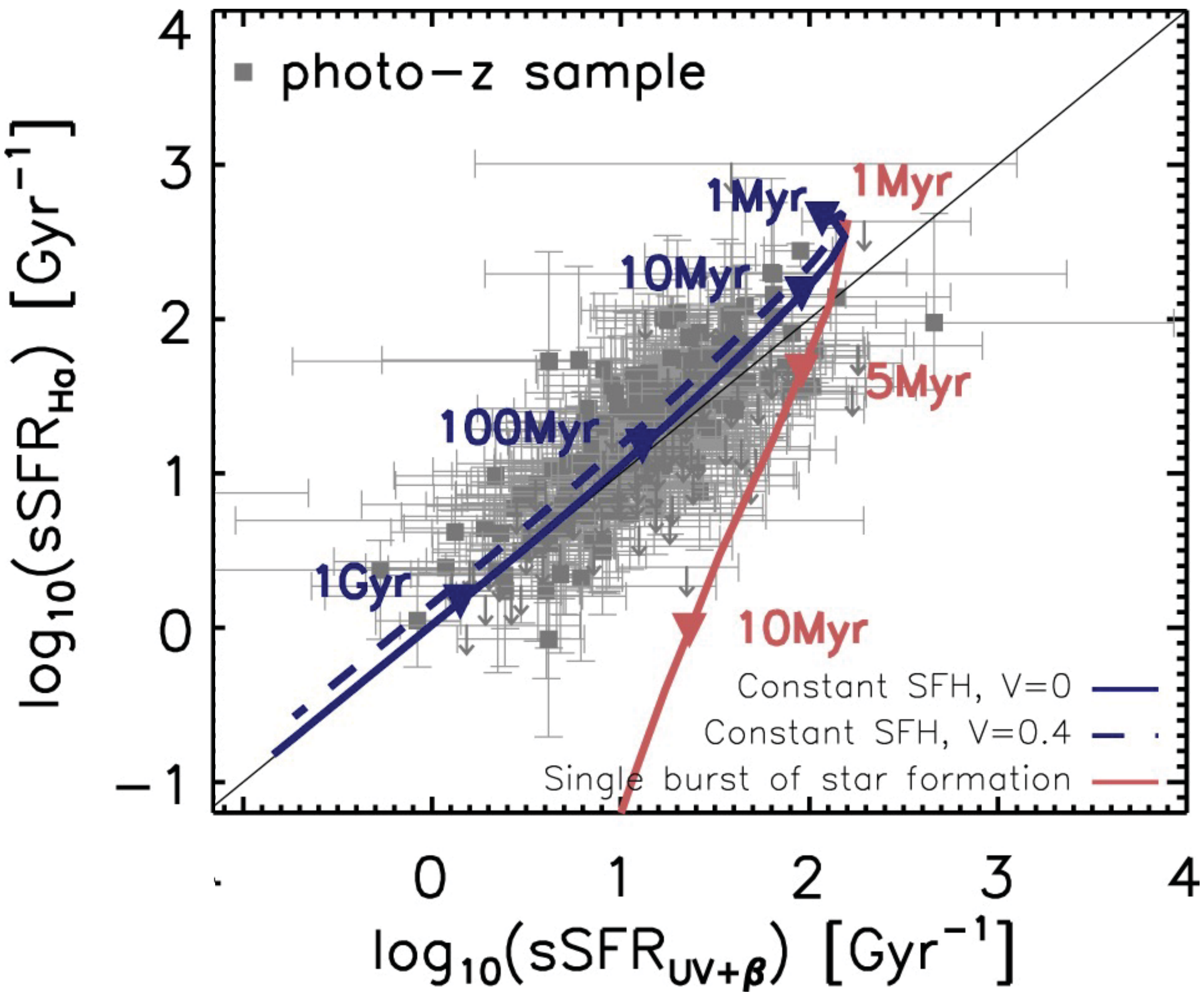
*Starbursts in **high redshift galaxies are not isolated "burst" events; they have relatively constant SFRs***

their SFRs are close to the predicted gas mass accretion rates of their dark matter halos

high-z galaxies are not "bursty"



Smit et al. (2016)

What is a “starburst”; some definitions

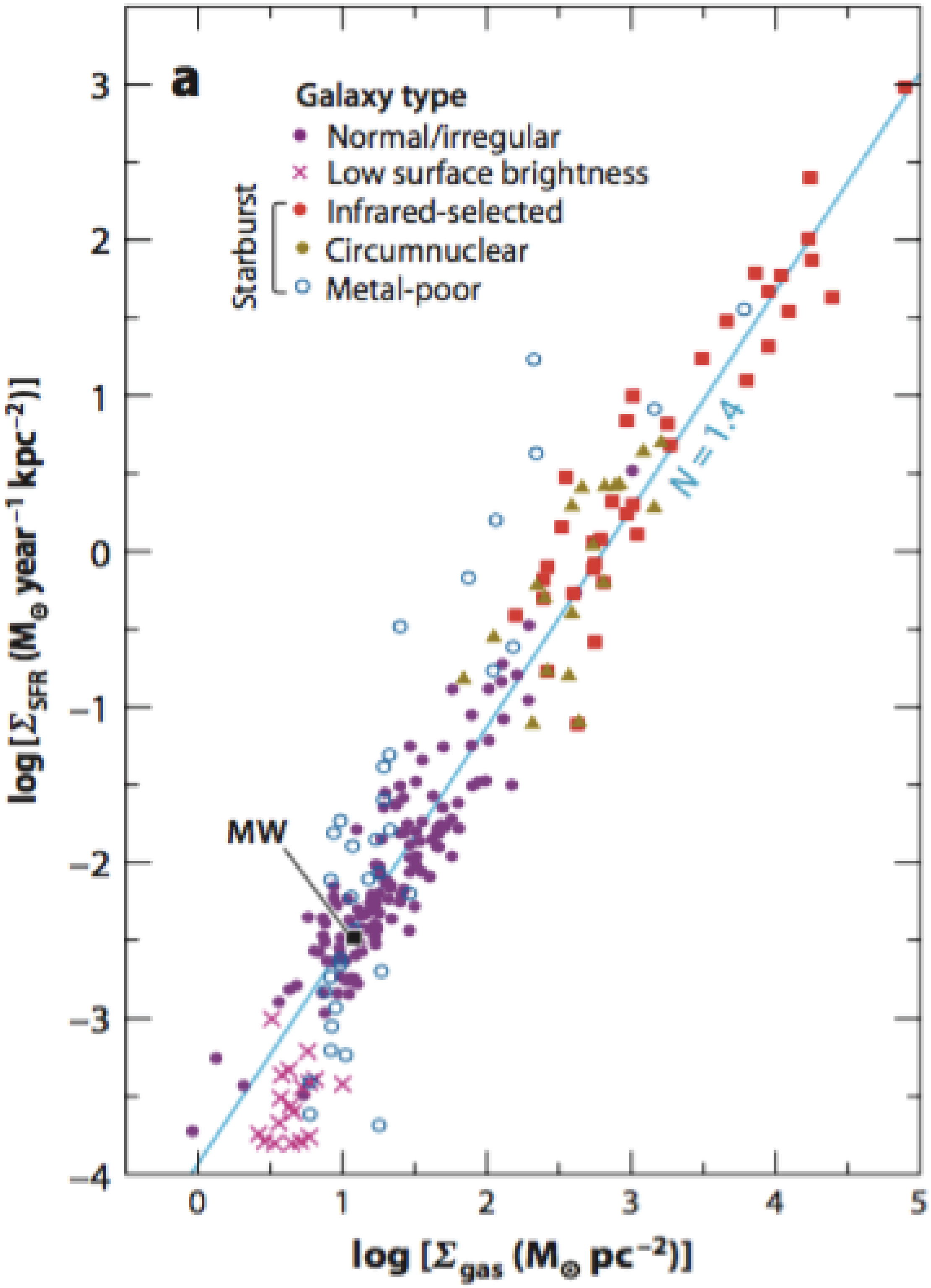
#4. High star formation rate intensity

SFR/area or SFR/volume

***Example**:*

Assume a spherical starburst galaxy with a radius R = 1 kpc and SFR of 100 M_{sun}/yr: the SFR per area will be ~30 M_{sun}/yr/kpc^2

compare this with the Milky Way which has R~10 kpc and SFR~1 M_{sun}/yr: SFR/Area ~ 3x10^{-3} M_{sun}/yr/kpc^2



Evans & Kennicutt (2012)

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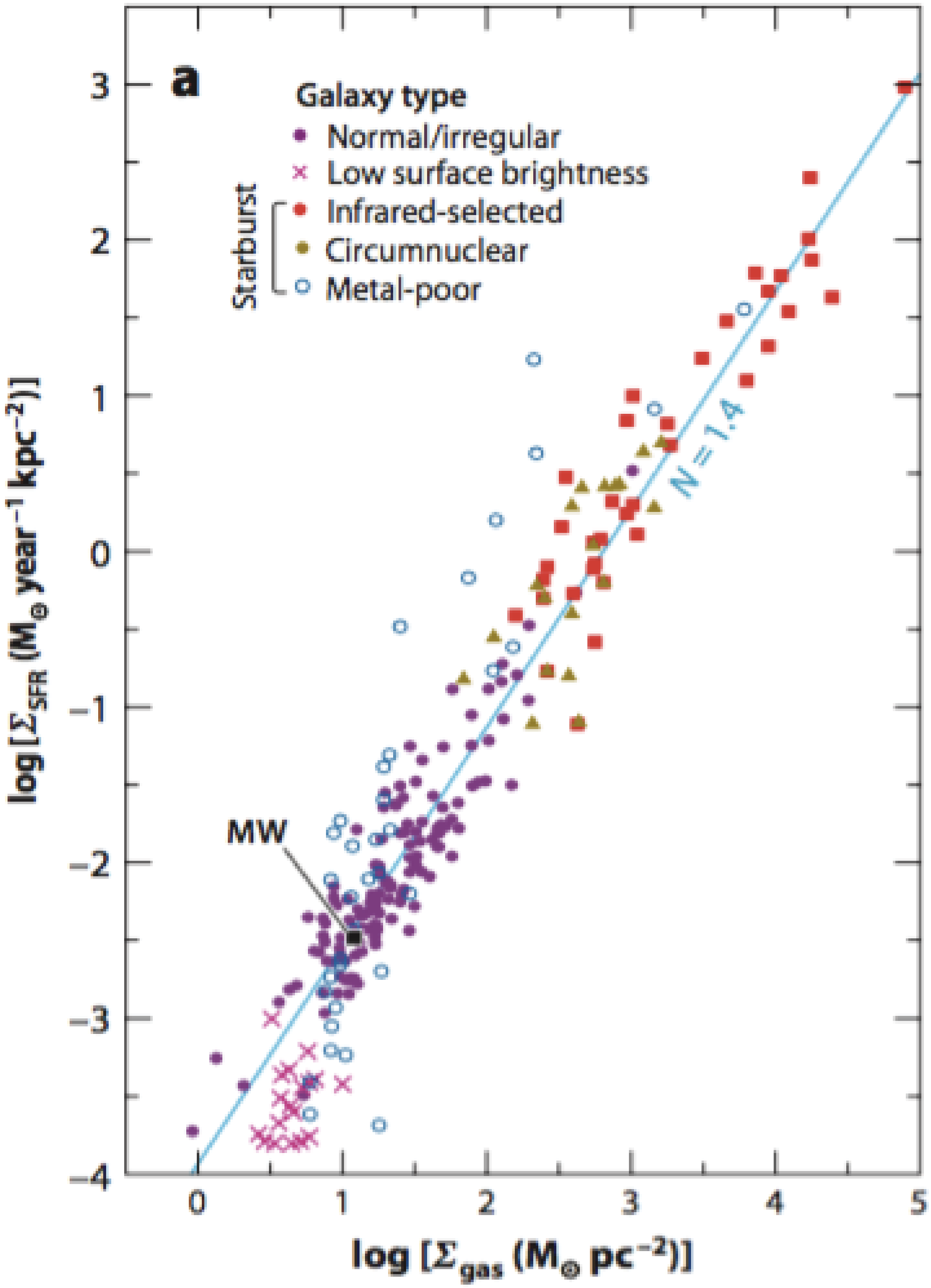
In starbursts, the SFR intensity is ~10,000 higher than that in the Milky Way !



Evans & Kennicutt (2012)

What is a “starburst”; definitions

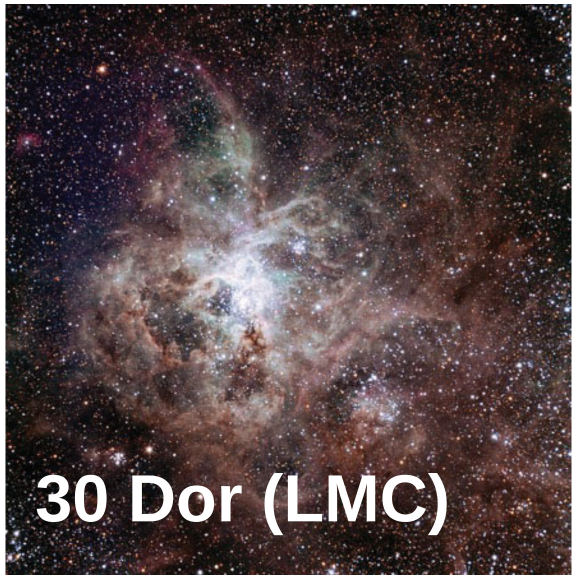
#1. Maximum possible SFR = M_{gas} / t_{dyn} ~ $f_{gas}\,\sigma^3$ / G

#2. SF Timescale (1/specific SFR) = M_{stars} / SFR < t_{Hubble}

#3. Gas Depletion Timescale = M_{gas} / SFR < t_{Hubble}

#4. SFR Intensity (SFR per unit Area or volume) is high

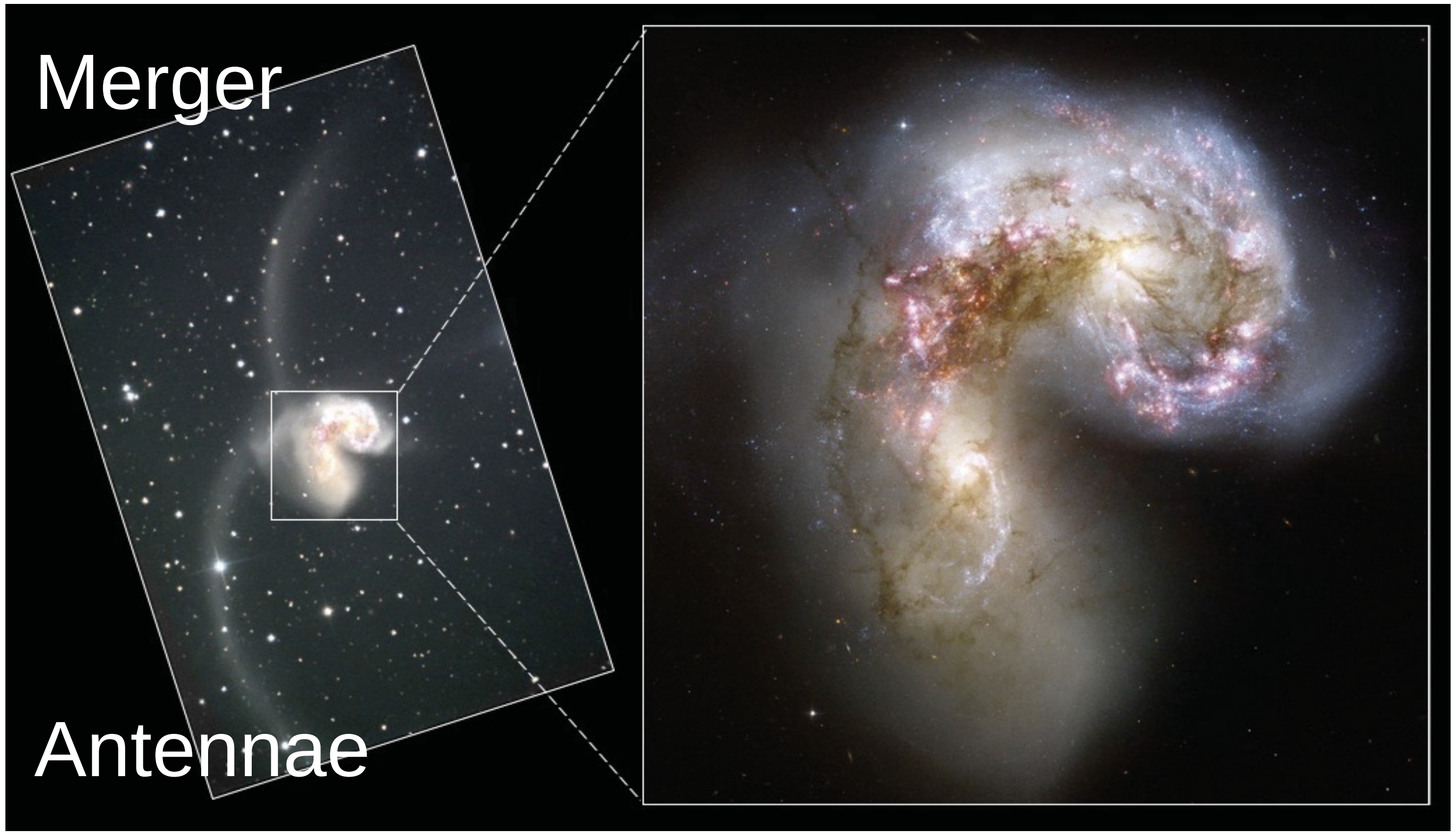
Many localized regions inside the Milky Way and other galaxies qualify as “starbursts”



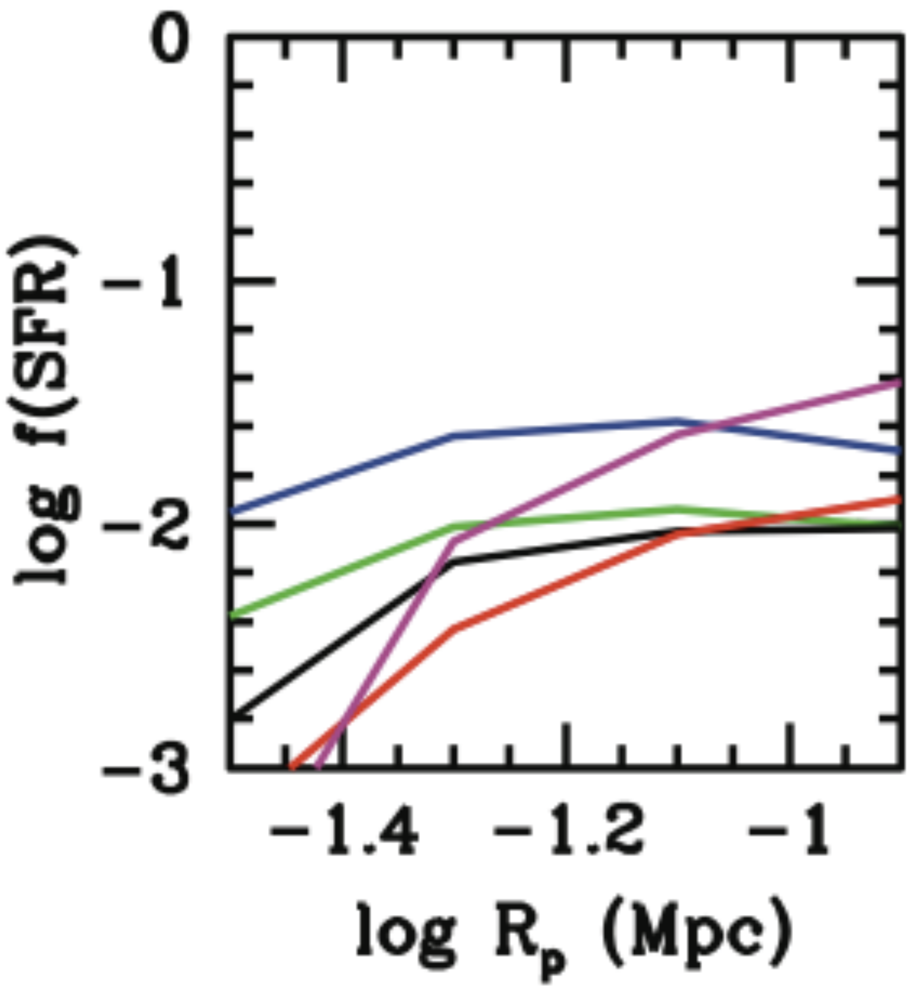
but ***starburst galaxies*** are unique because they satisfy all these criteria as a whole !

Starburst galaxies in a cosmological context

- high star formation activity requires gas ➤ **Inflows**
- Inflows ➤ **Delivery mechanism (nuclear bars, mergers, accretion…)**



Gas accretion by the MW from satellites?

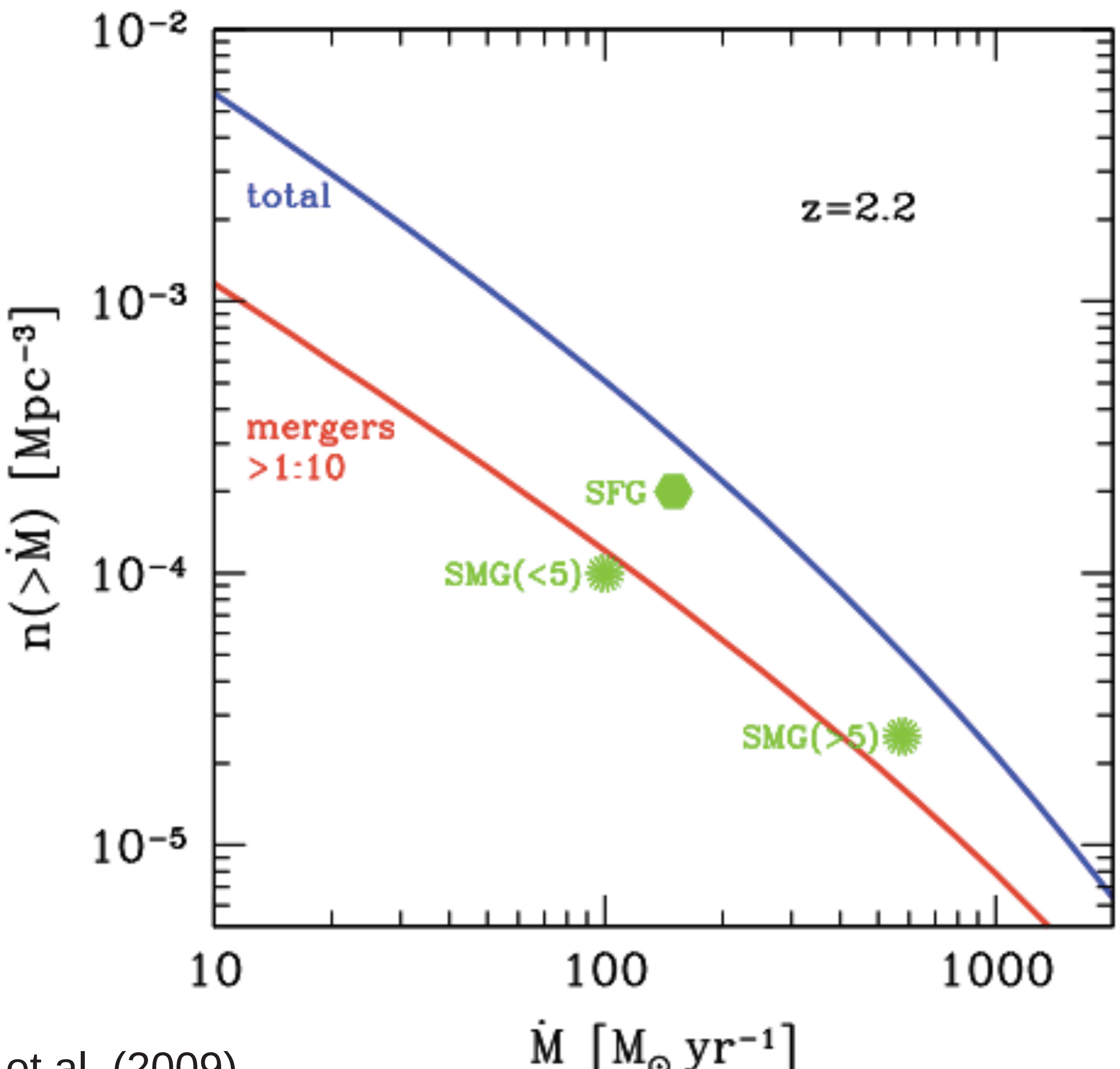


Kauffmann et al. (2008)

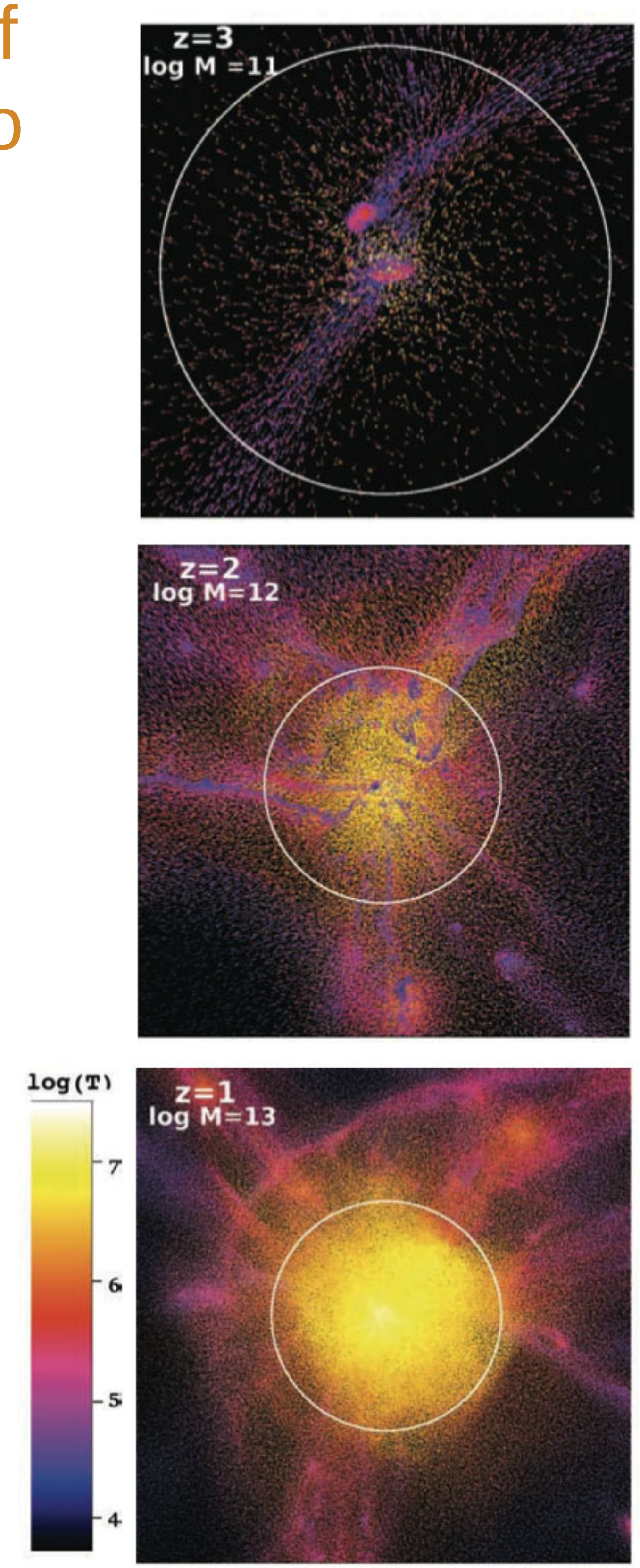
Starburst galaxies in a cosmological context

- the SFR in starburst galaxies ~ SFR_{max} ➤ **Inflows need to be *rapid***

at high redshift (z > 2), the observed SFRs of typical star-forming galaxies are very close to the halo gas accretion rates:



Dekel et al. (2009)



cold accretion

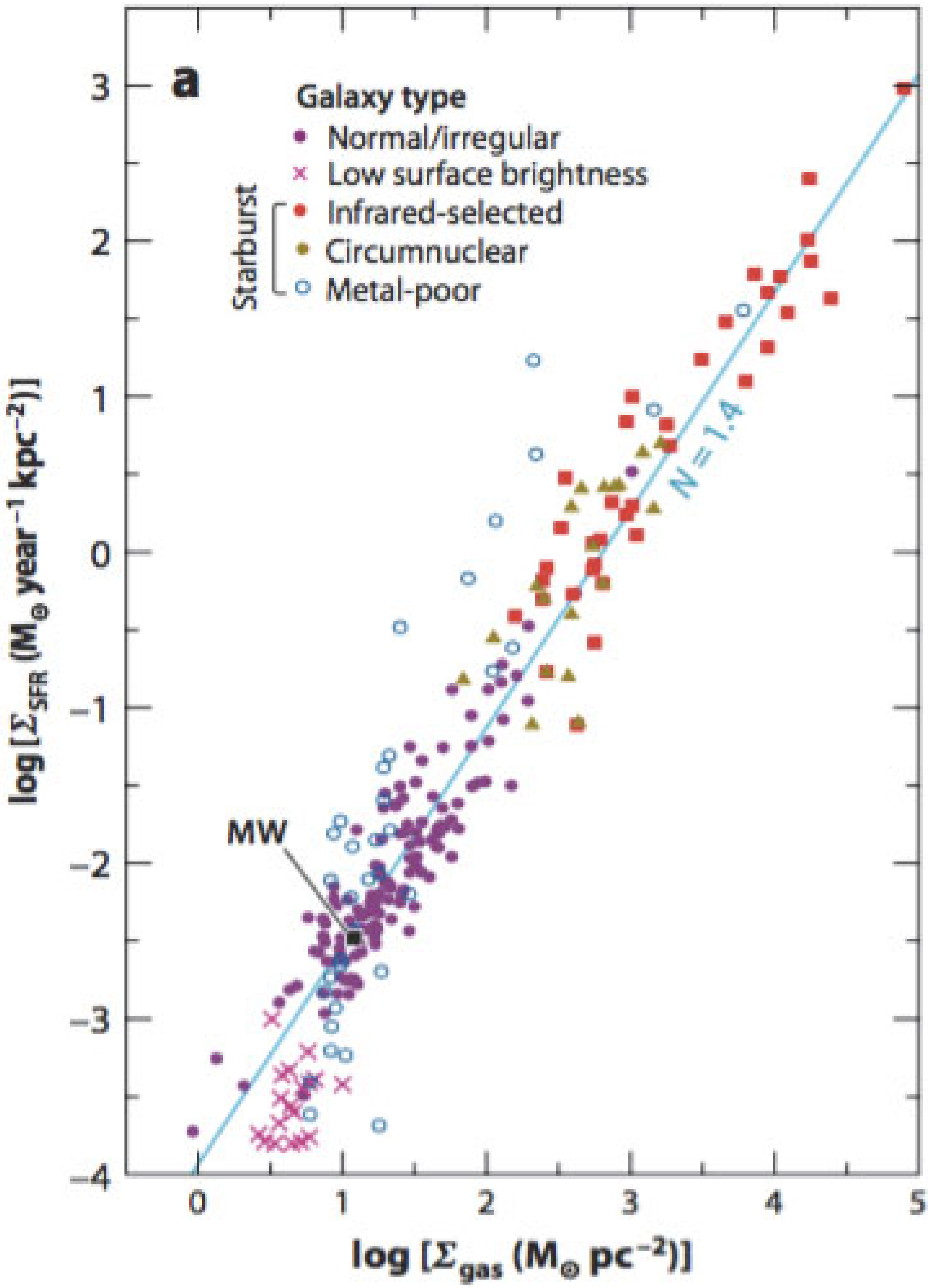
cold+hot accretion

hot accretion

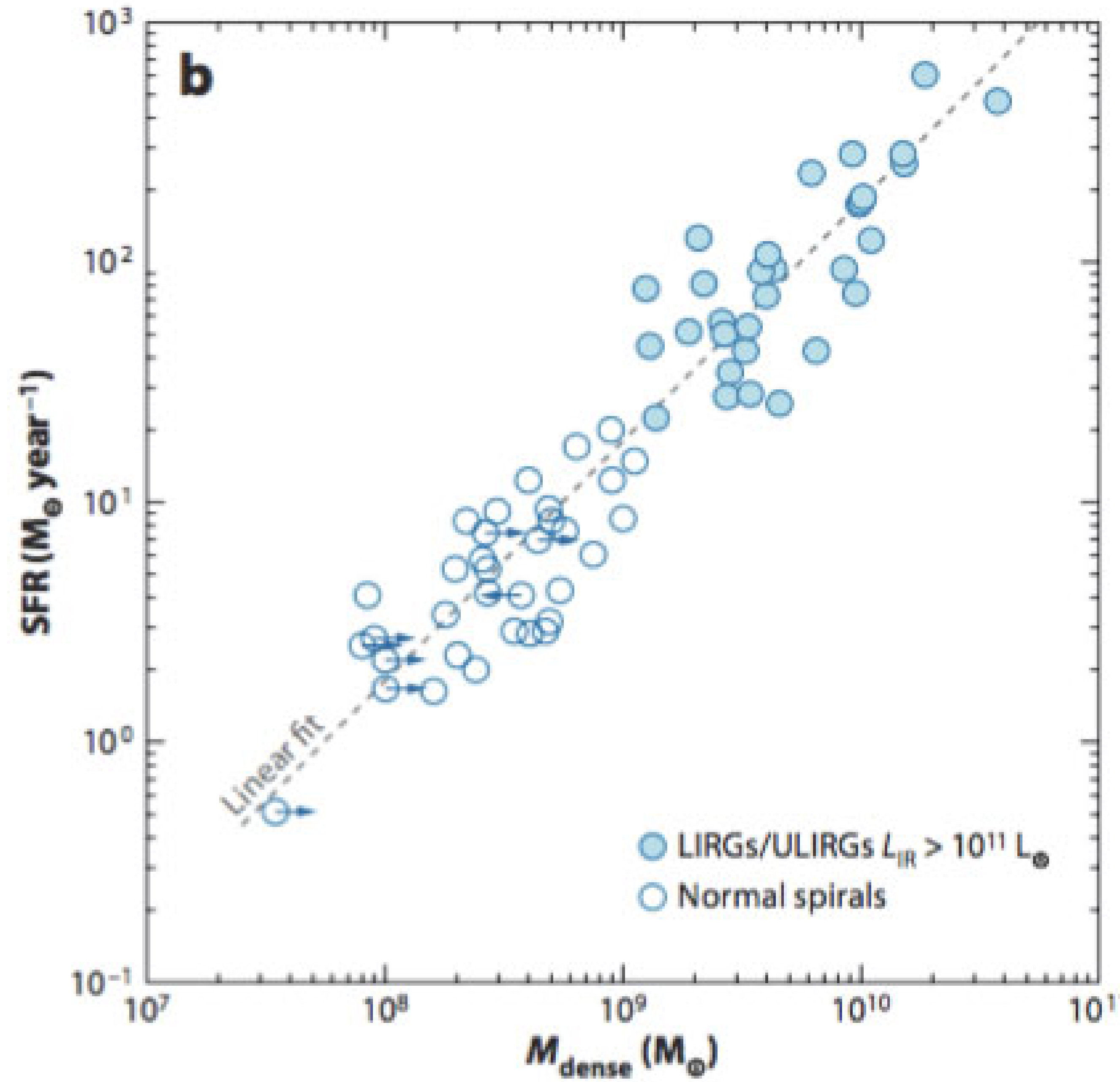
Keres et al. (2005)

Starburst galaxies in a cosmological context

- Larger SFR/area ➤ Higher gas columns ➤ **larger extinction**



Mass in dense molecular clouds



Evans & Kennicutt (2012)

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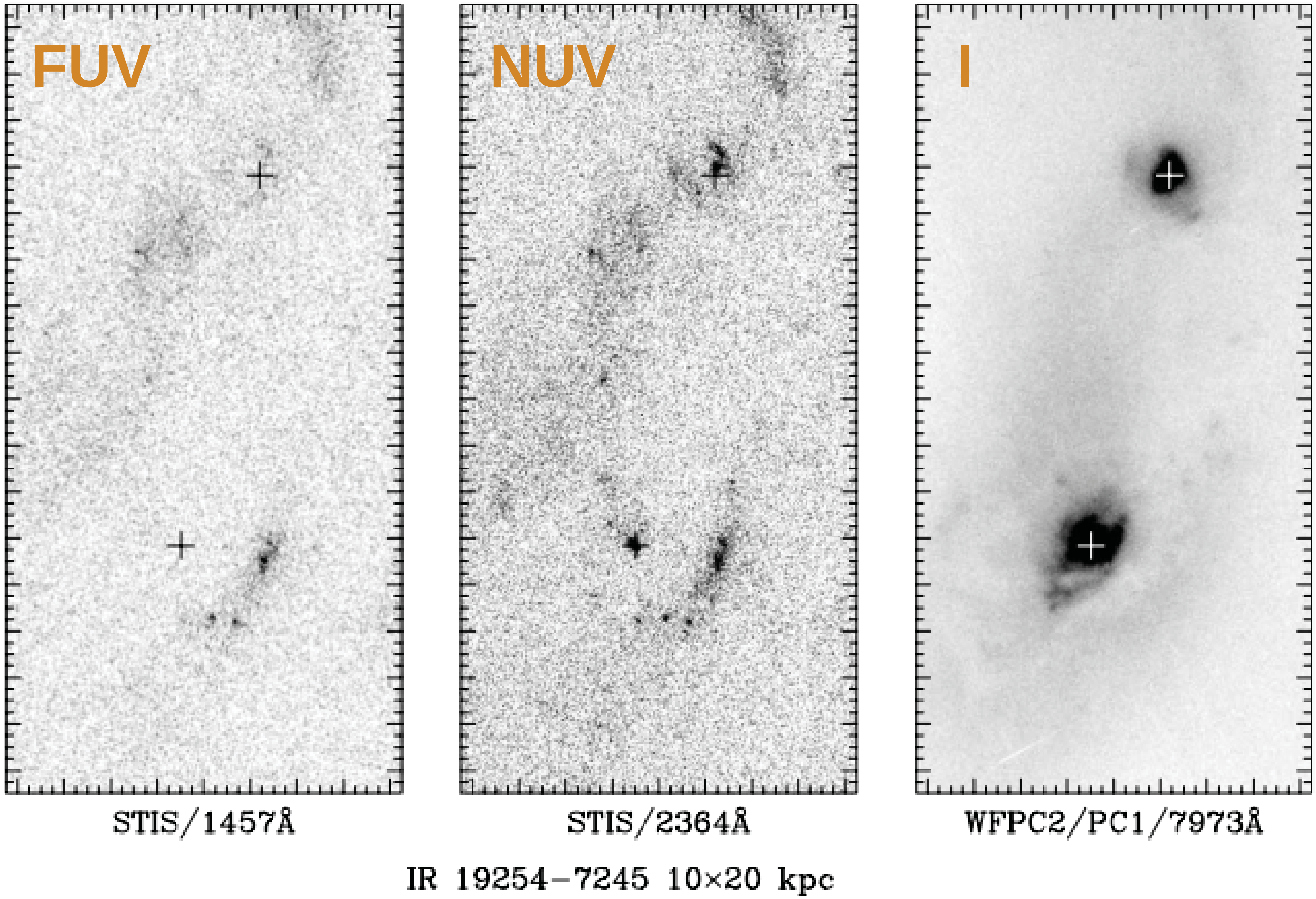
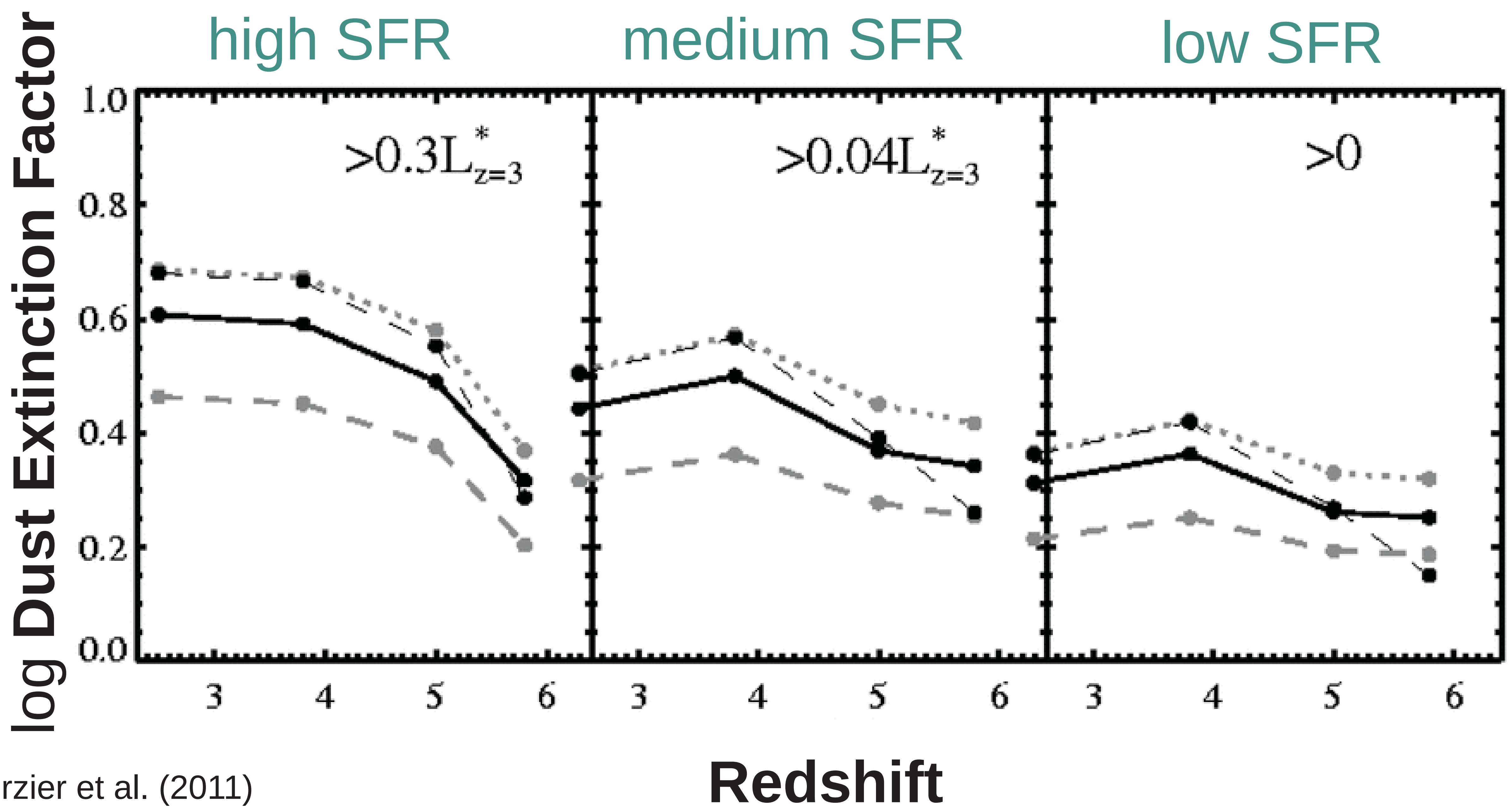
high extinctions can lead to practical observational problems, especially if you are observing in the rest-frame UV (like at high-z):



Ultra-luminous Infrared Galaxy (ULIRG) from Goldader et al. (2002)

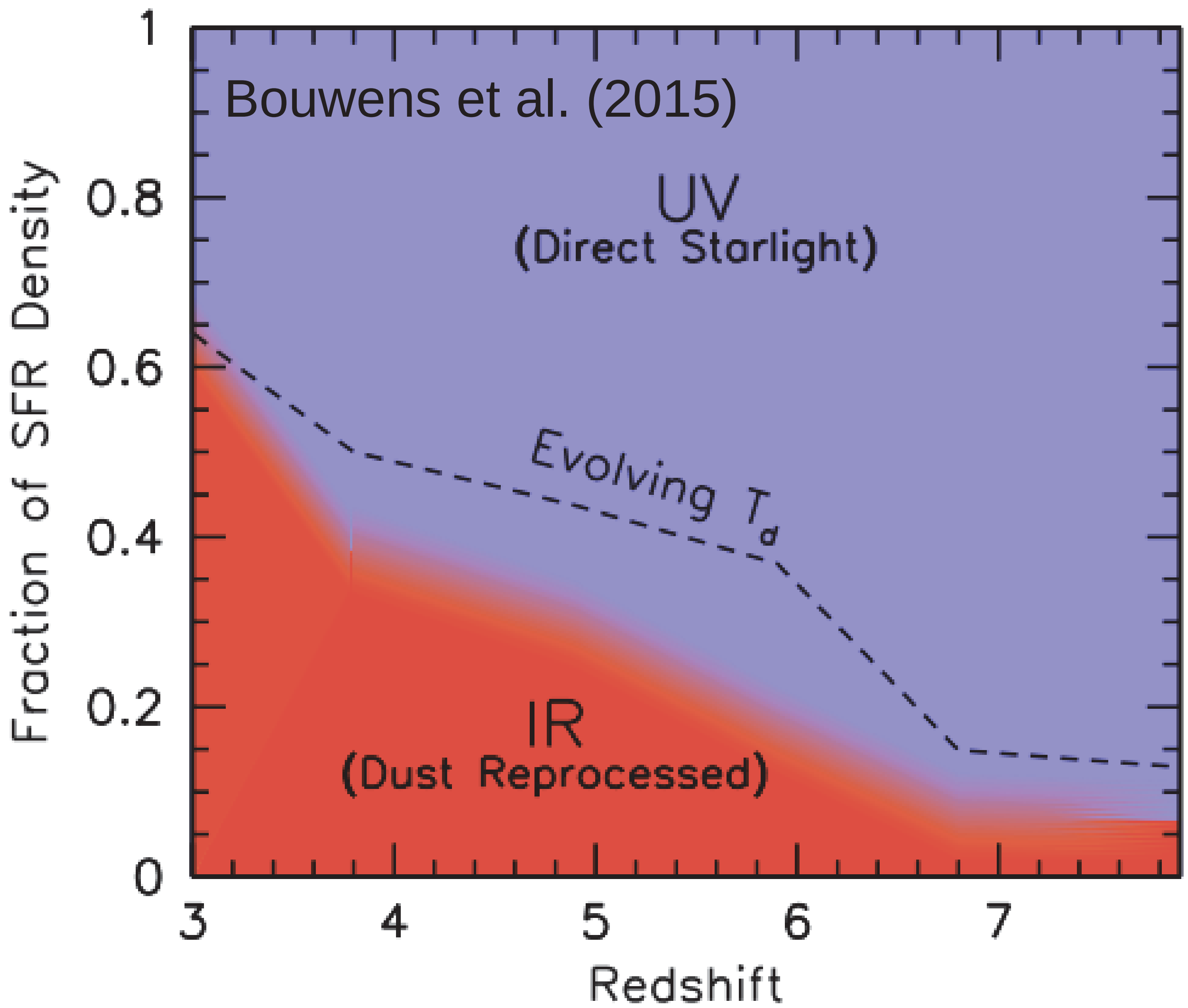
Starburst galaxies in a cosmological context

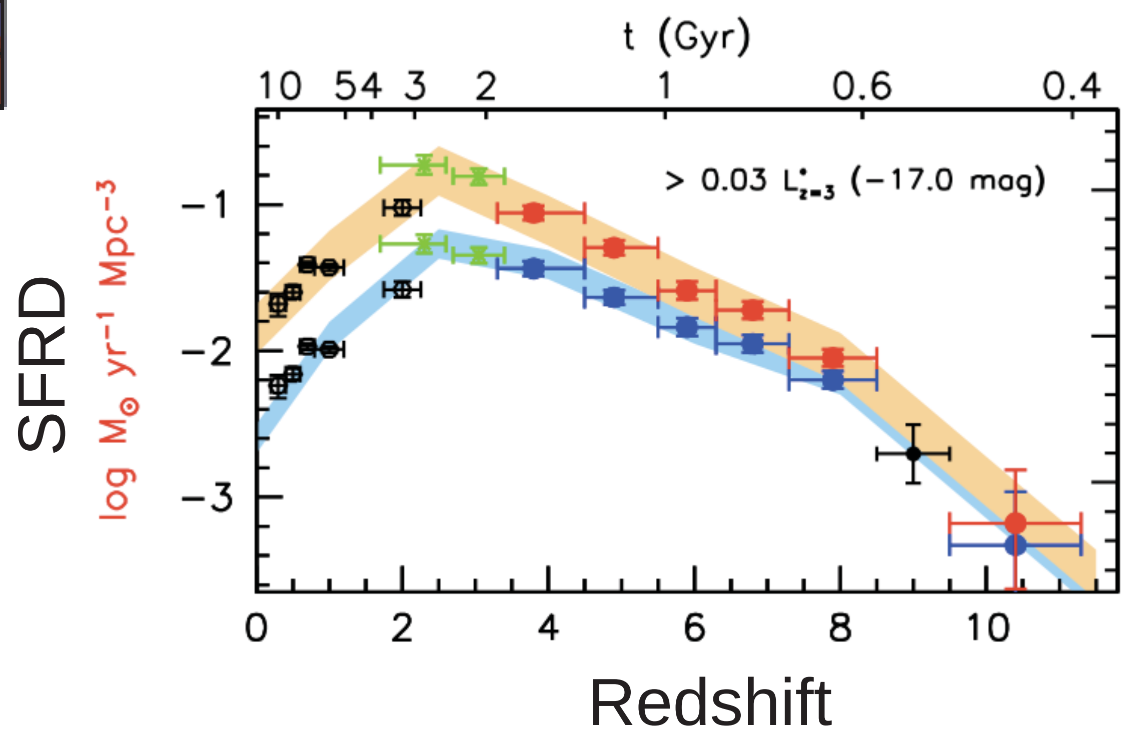
- Larger SFR/area ➤ Higher gas columns ➤ **larger extinction**
- Extinction ➤ Dust production is important at high redshifts!



Overzier et al. (2011)

- very good news for studying galaxies toward cosmic dawn!

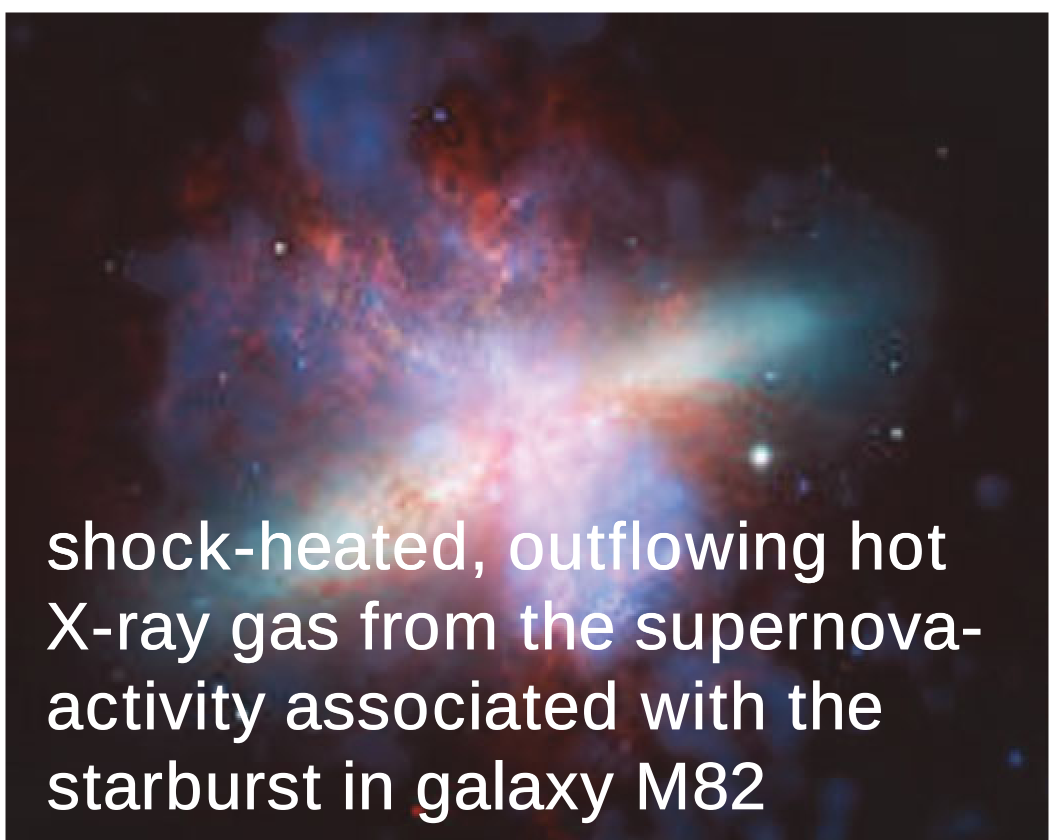




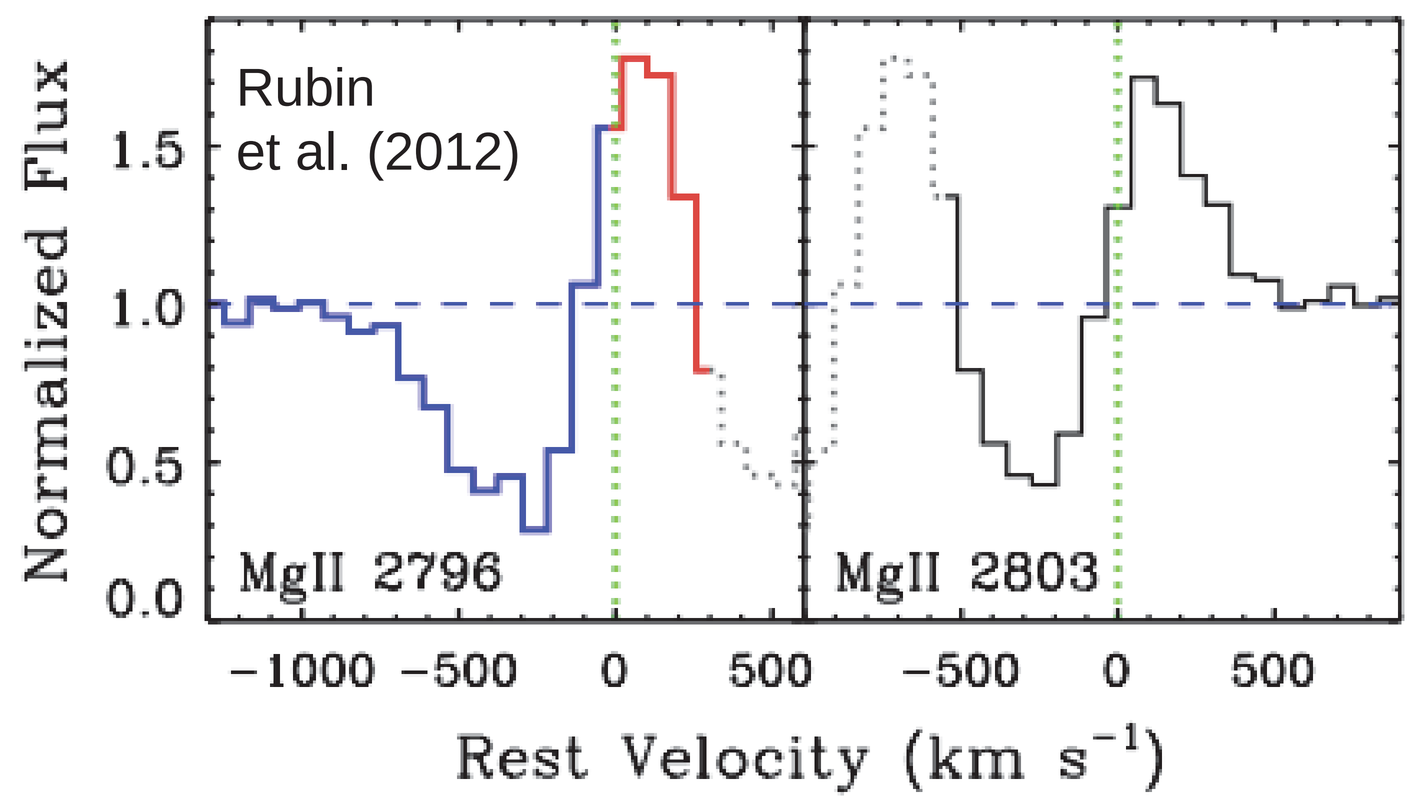
Starburst galaxies in a cosmological context

- Large SFR/area ➤ **high energy density / radiation pressure**
- High SN rate per unit volume ➤ **(Strong) Winds**
- Winds ➤ **gas mixing or *outflows* (if $v_{wind} > v_{escape,galaxy}$)**

maximum wind speed: $v \sim 1800\, \dot{p}_{35}^{1/2}\, (\Omega\, r_{100}\, N_{21} / 4\pi)^{-1/2}$ km/s


shock-heated, outflowing hot X-ray gas from the supernova-activity associated with the starburst in galaxy M82

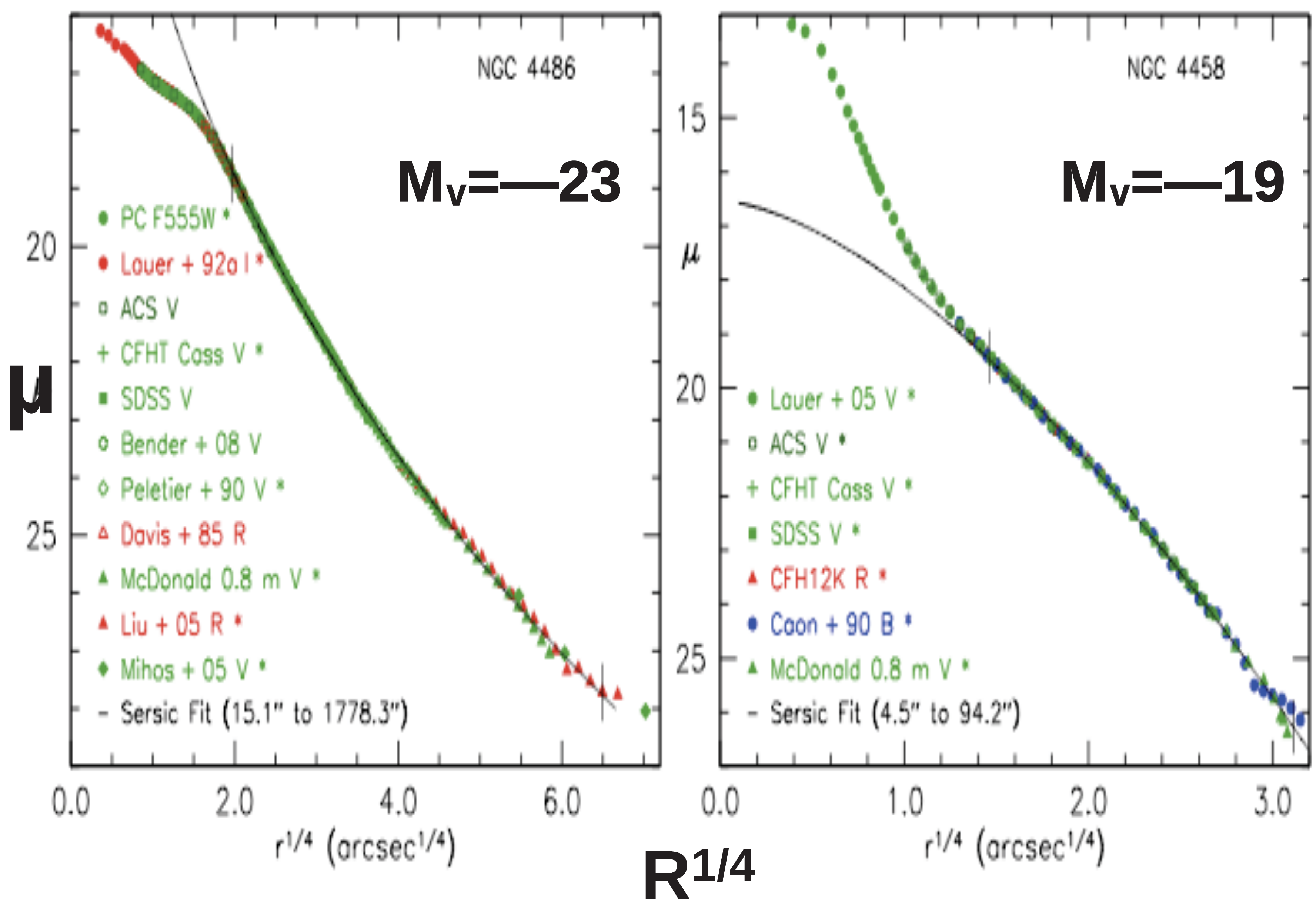
high velocity, outflowing photo-ionized gas as probed by the MgII absorption feature in a starburst galaxy at high redshift:



Starburst galaxies in a cosmological context

- **formed stars ➤ (dense) stellar structures, clusters, black holes**

The "cuspy" nuclear profiles of typical early-type galaxies appear to originate from highly dissipative starburst events at high redshifts:



Overzier et al. (2009)

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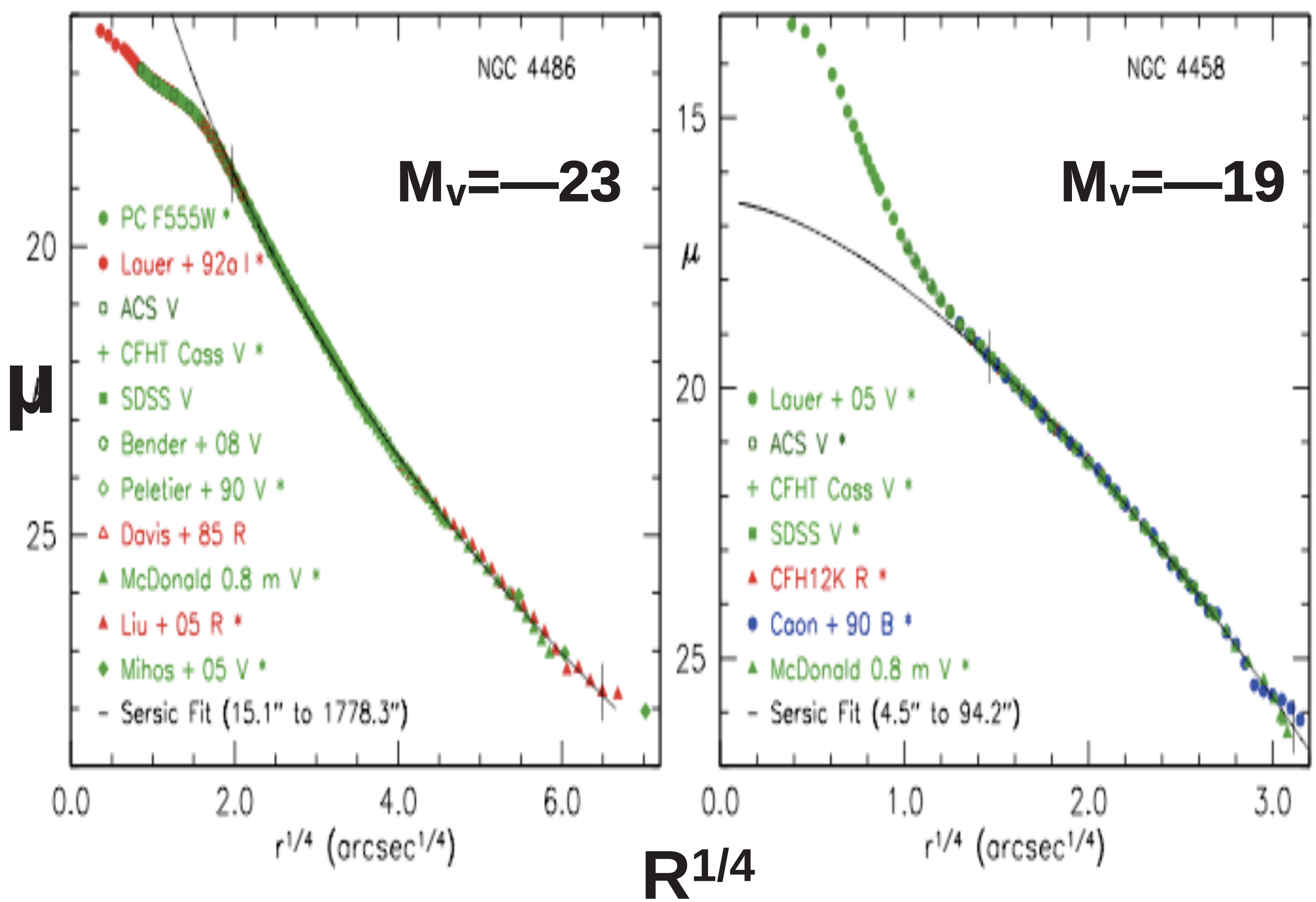
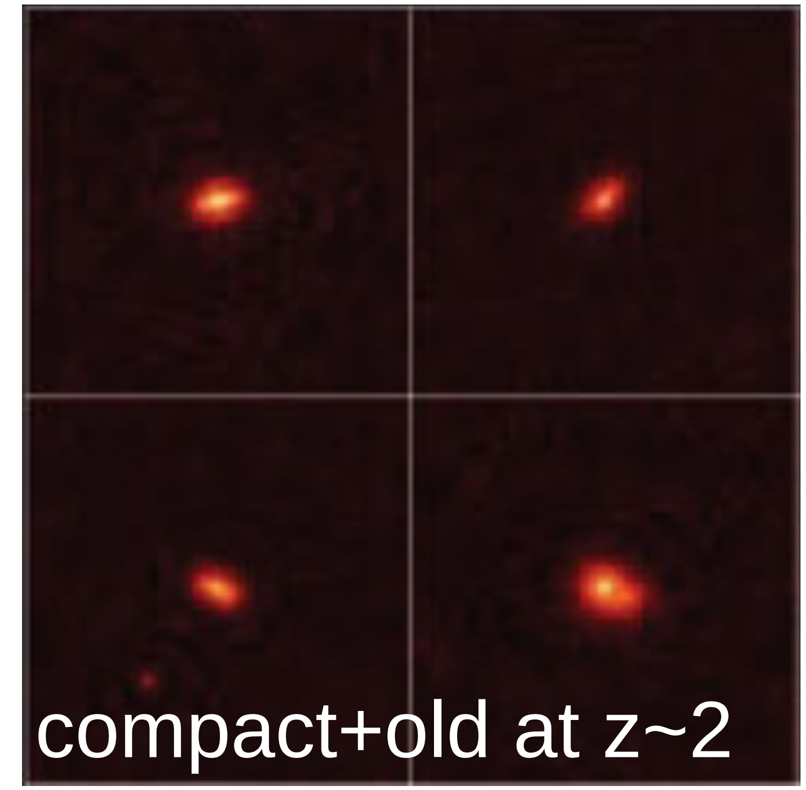
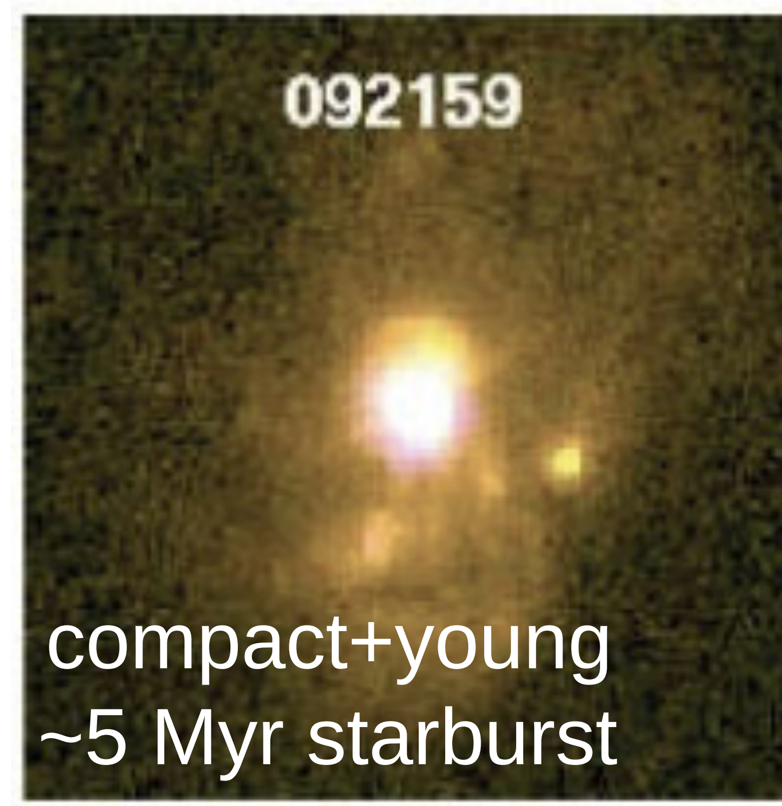


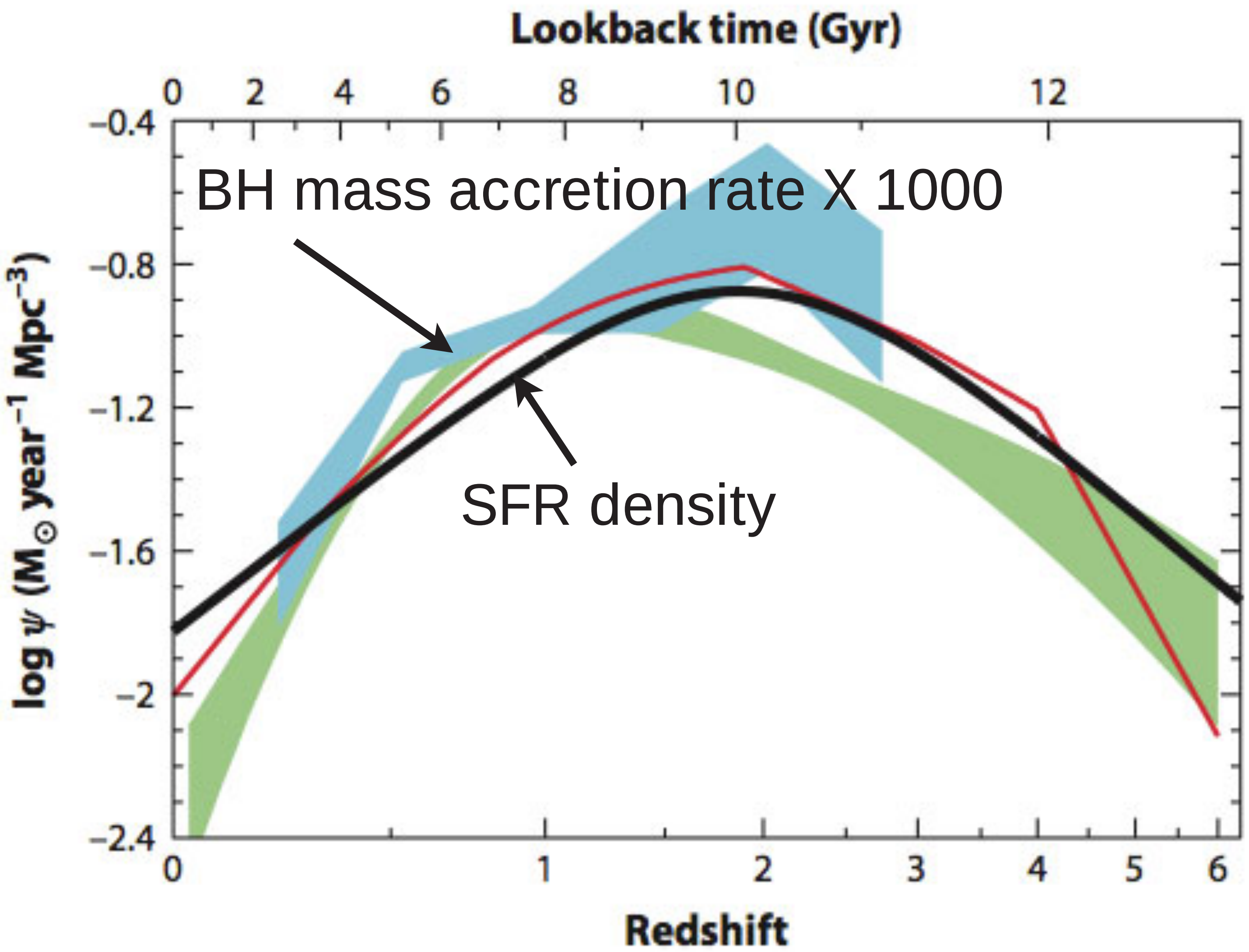




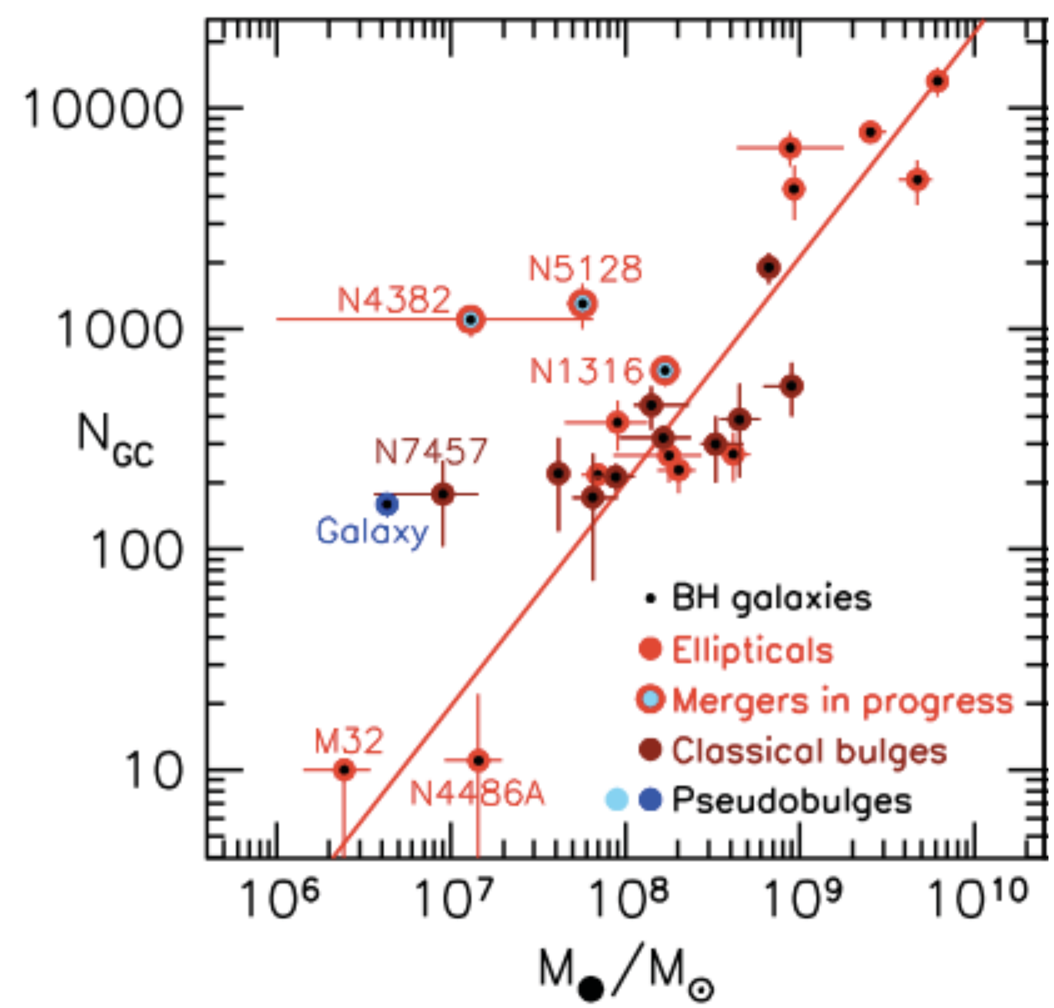
Overzier et al. (2009)

Starburst galaxies in a cosmological context

- formed stars ➤ (dense) stellar structures, clusters, black holes
- black holes + inflows ➤ AGN fueling and BH growth



Madau & Dickinson (2014)

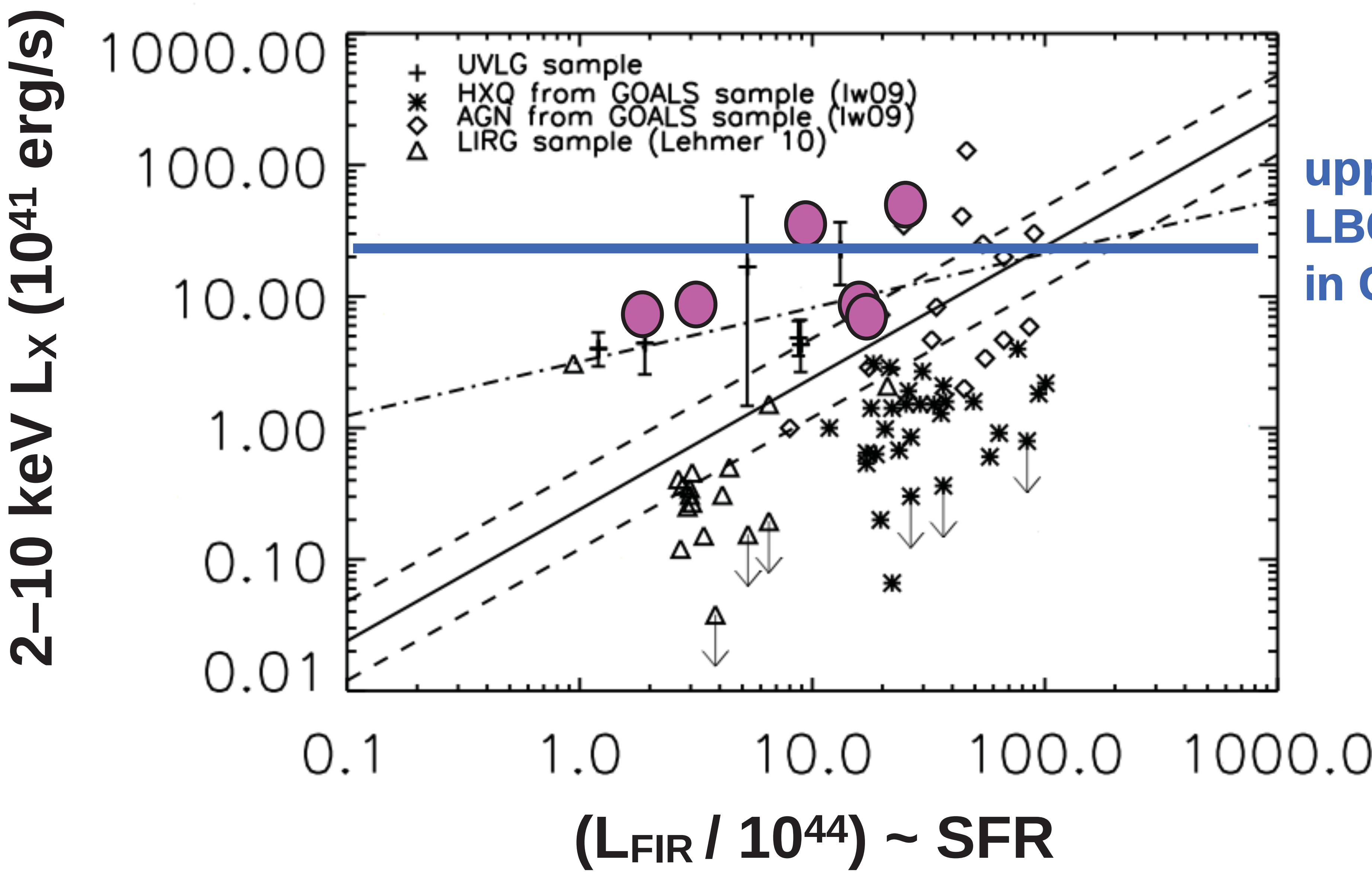


Kormendy (2013)

these figures suggest that the same dissipative events that caused star formation (+globular clusters) are related to those that grew the black holes

Starburst galaxies in a cosmological context

- **black holes + inflows ➤ AGN fueling and BH growth**
- **nuclear inflows ➤ outflows must be weak!**

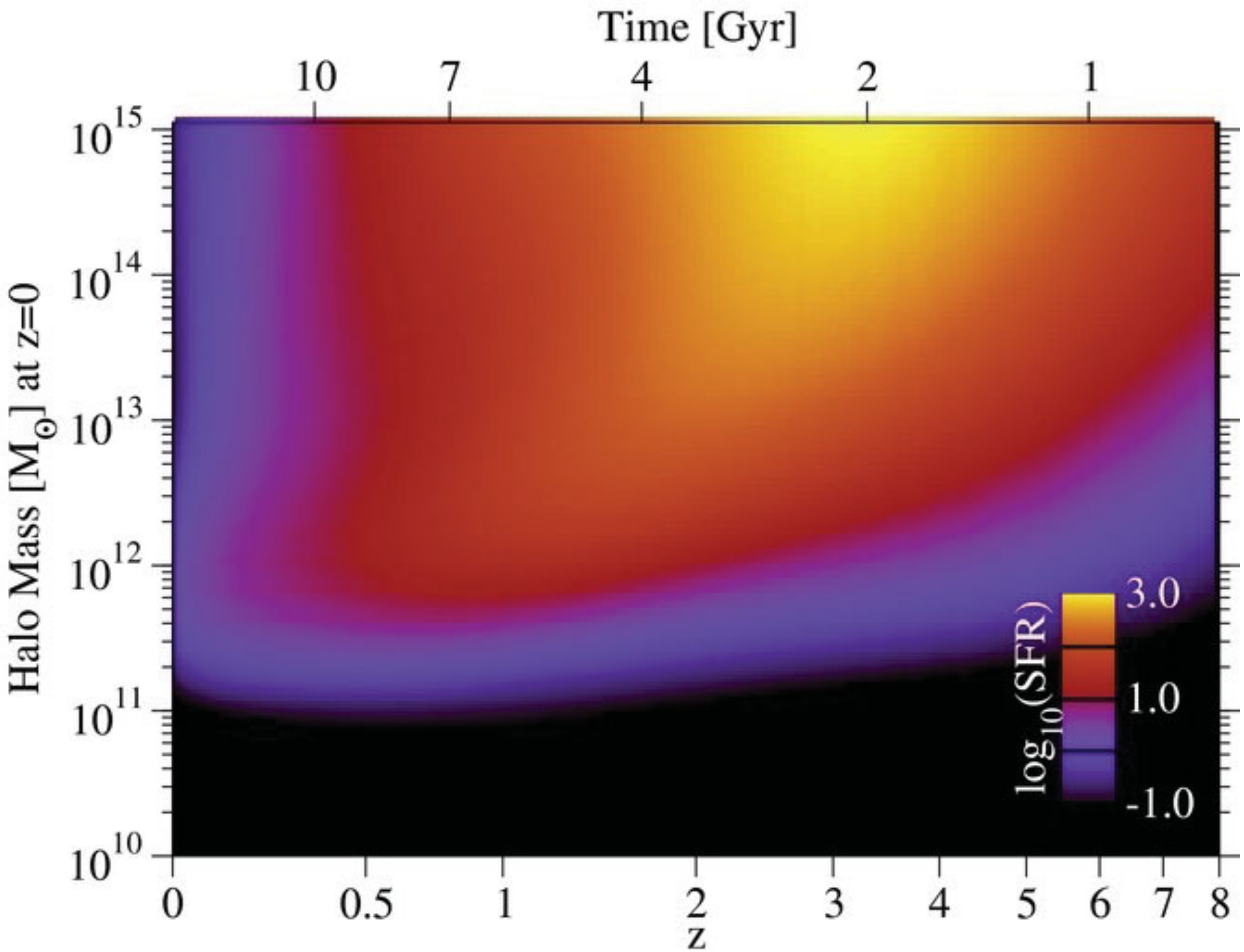


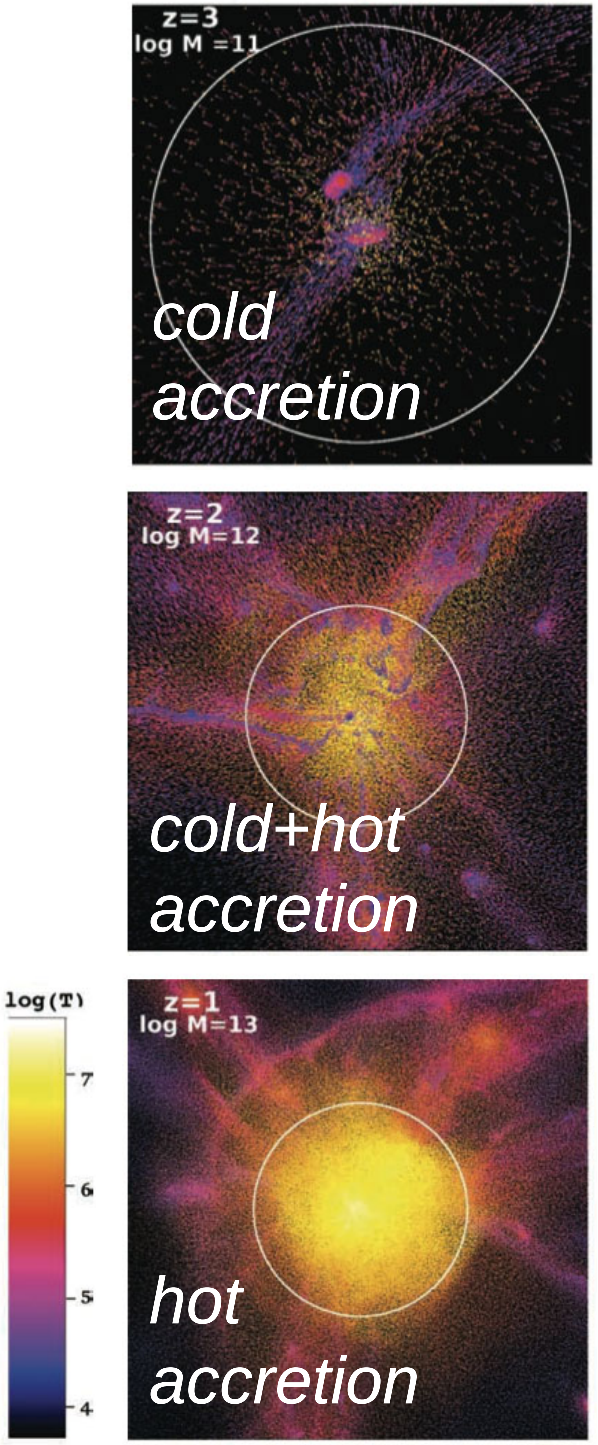
upper limit for LBGs at z = 3-6 in CDFS stack

The fraction of AGN among typical high redshift starburst galaxies is very low (1-3%); is it because they are still in the outflow-dominated, starburst phase?

Starburst galaxies in a cosmological context

- role of environment is important



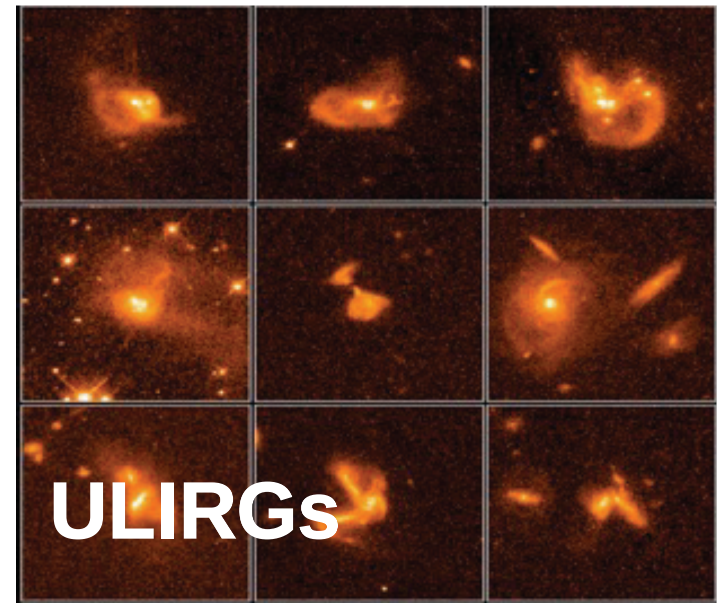


For higher mass halos (e.g., galaxy clusters), star formation peaked earlier than for lower mass halos

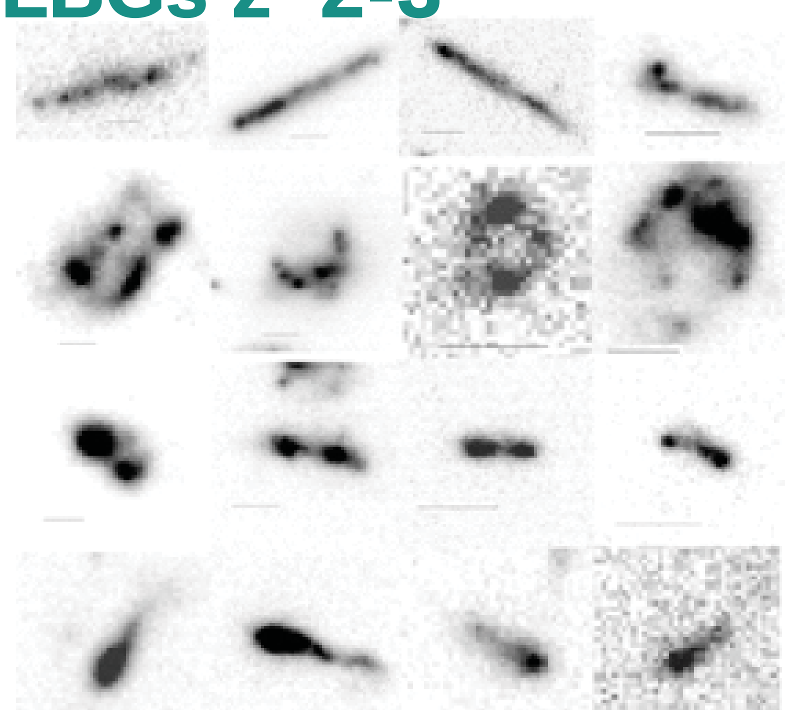
Keres et al. (2005); Behroozi et al. (2013); Overzier (2016); Chiang, Overzier, Gebhardt & Henriques (2017)

Starburst galaxies in a cosmological context

These basic principles govern the evolution of the various types of starbursts at **all** redshifts; their relative importance depends on redshift, mass, etc.

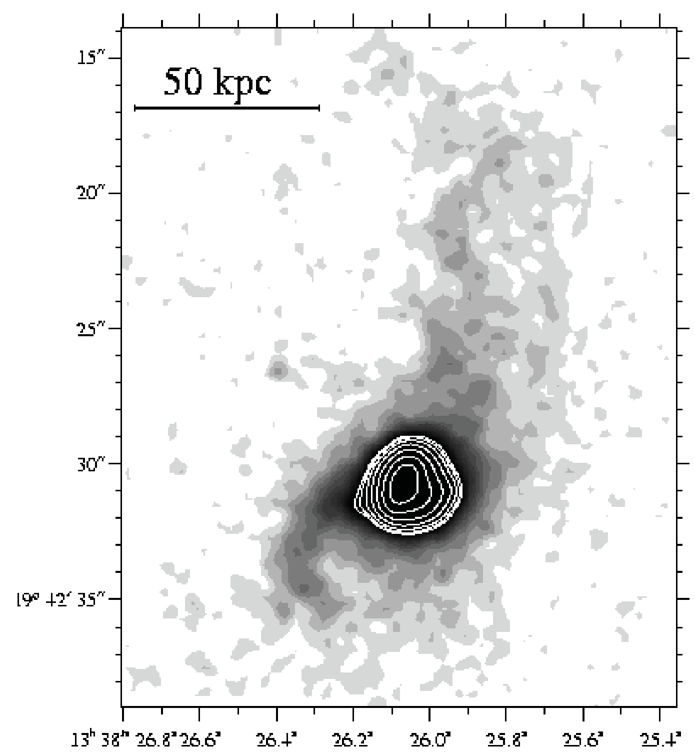


LBGs z~2-3



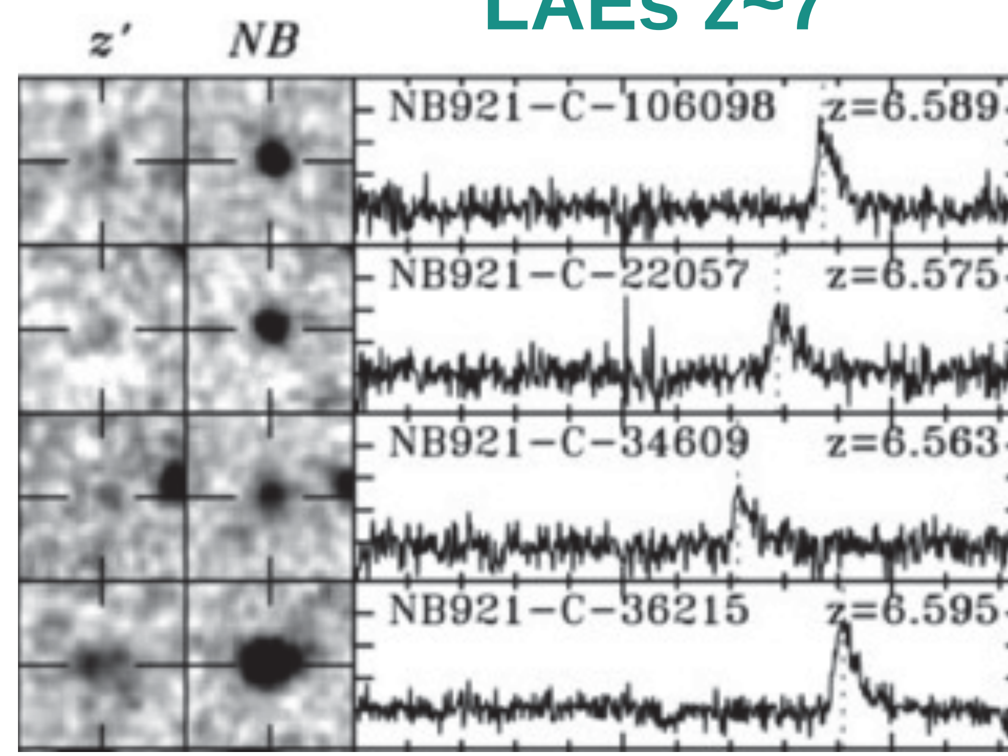
Elmegreen+06

LAB z~4



Zirm+05

LAEs z~7



Ouchi+10

Talk Overview

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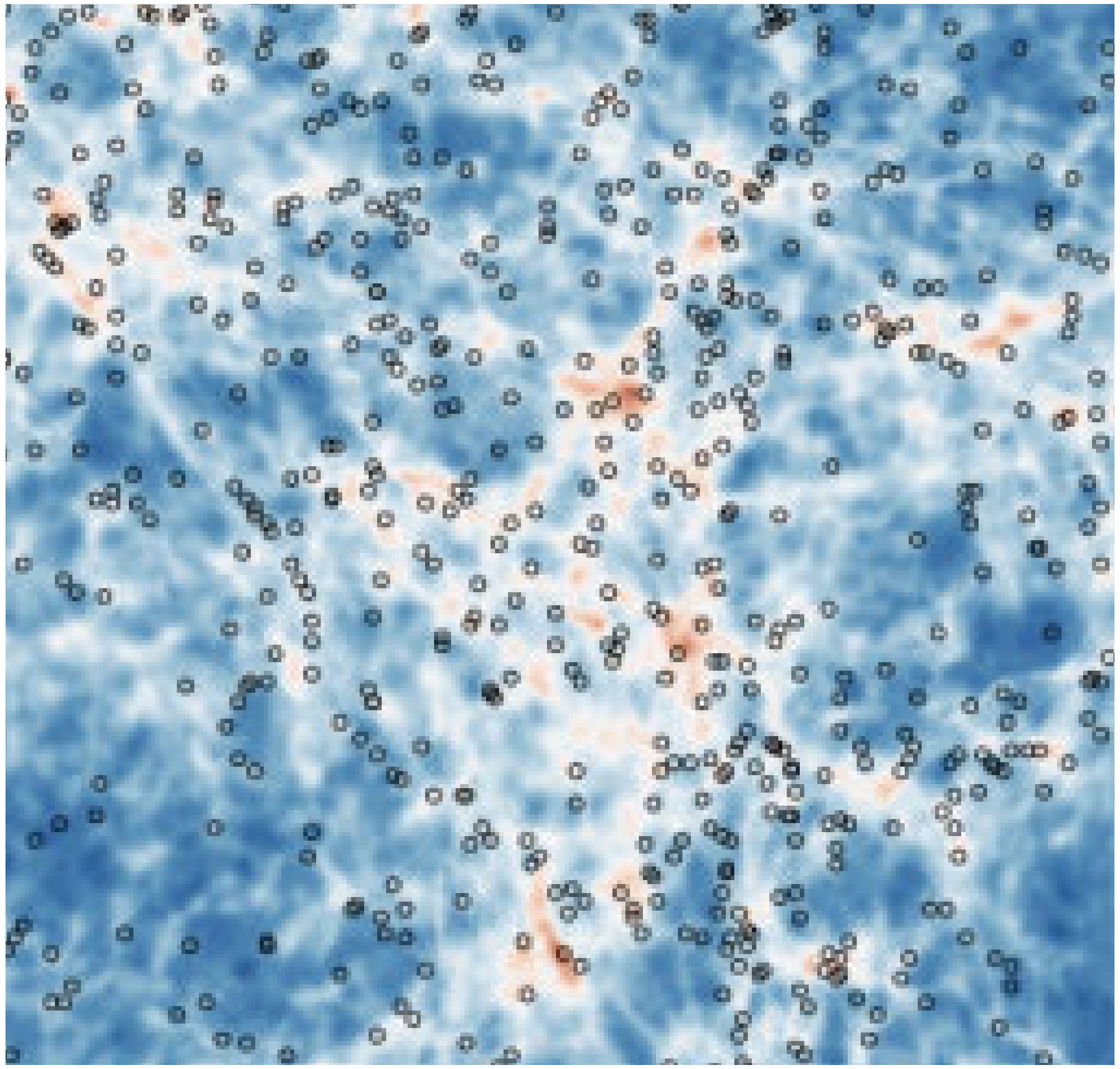
The importance of “starbursts”

GMACS at “cosmic noon”

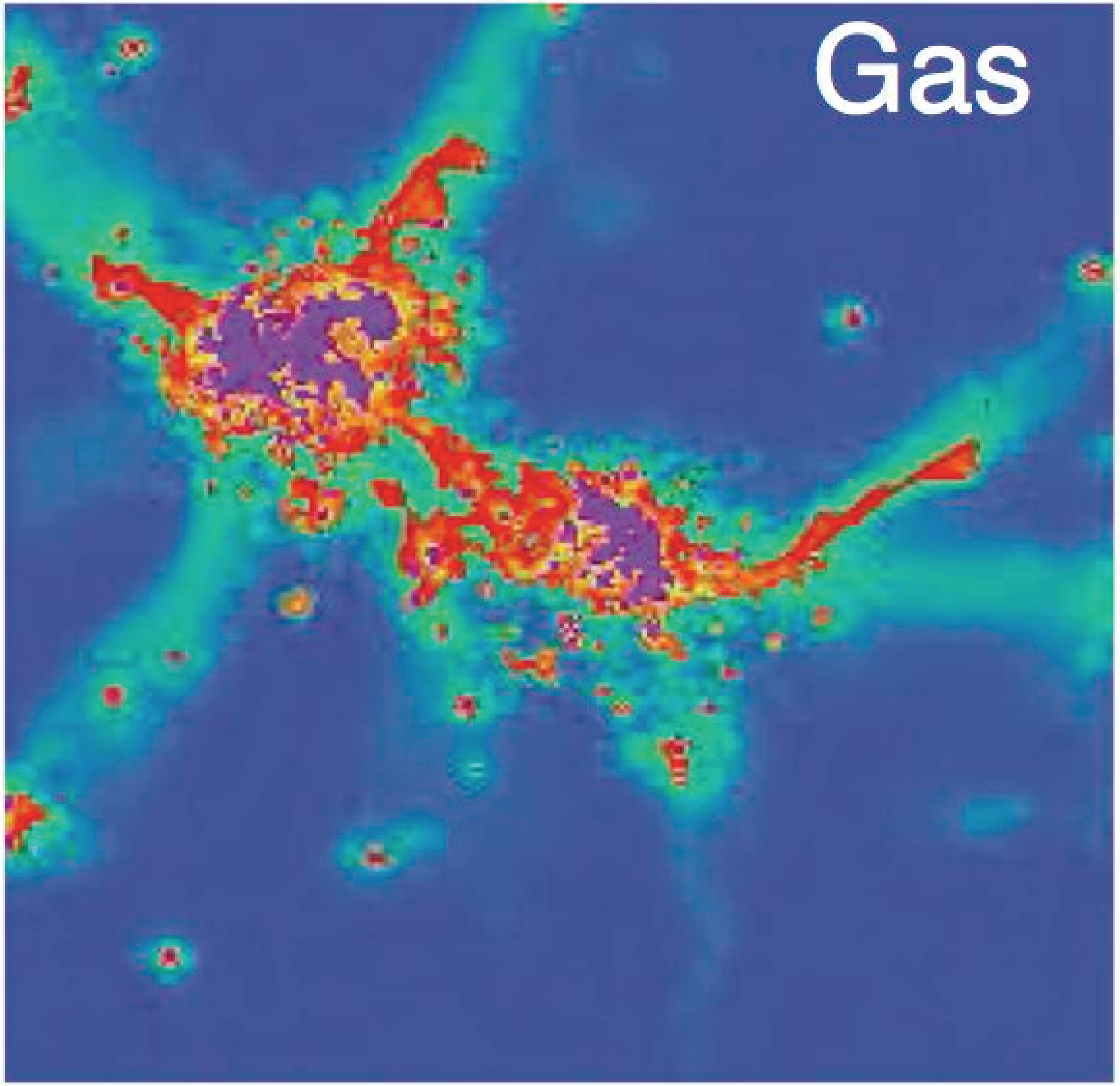
GMACS at “cosmic dawn”

GMACS/GMT synergies



Probing the Galaxy — IGM connection

We know that gas is key to (nearly) everything, but is still an essentially completely unexplored parameter space at any redshift except perhaps for the most local galaxies!



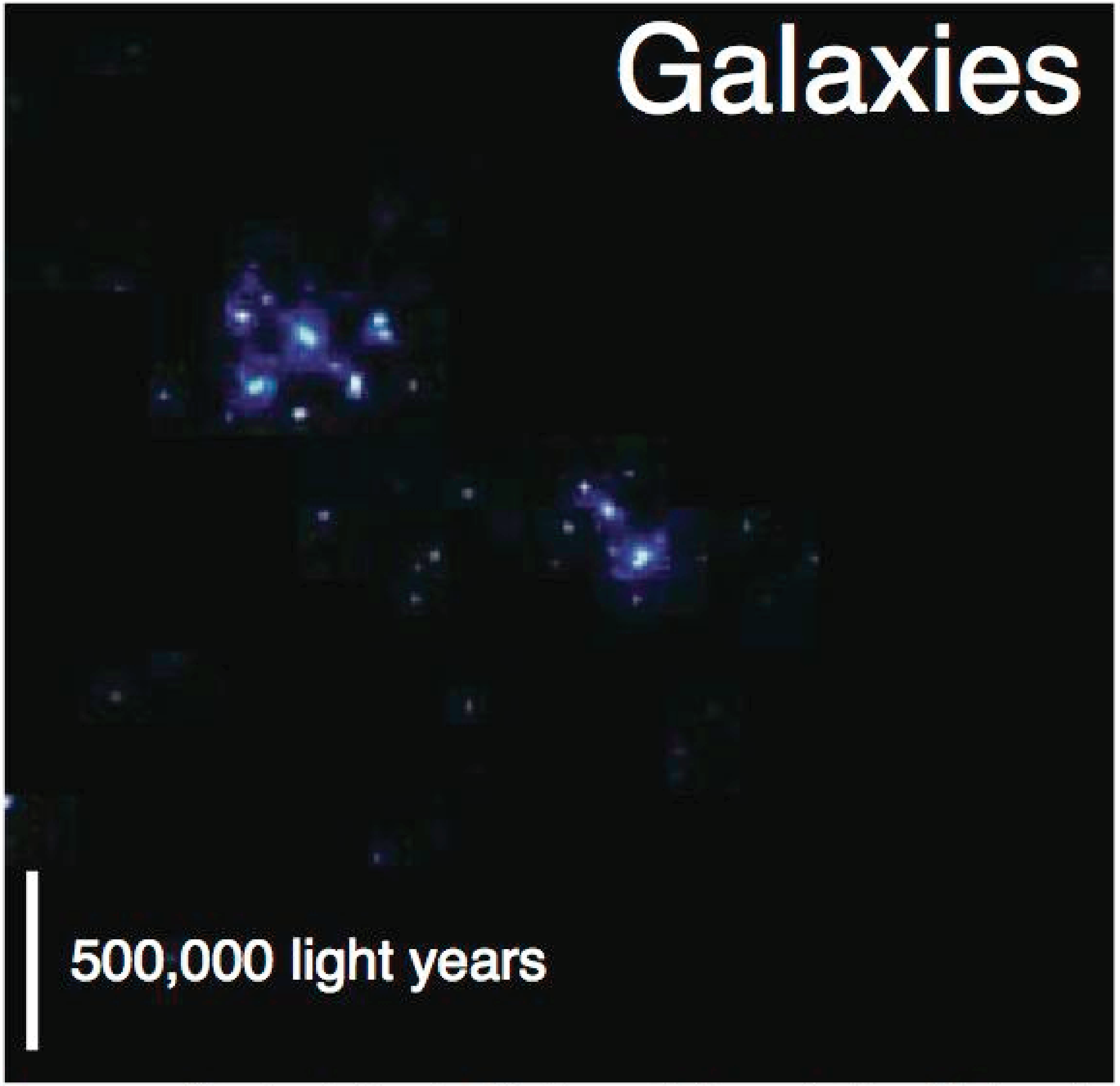
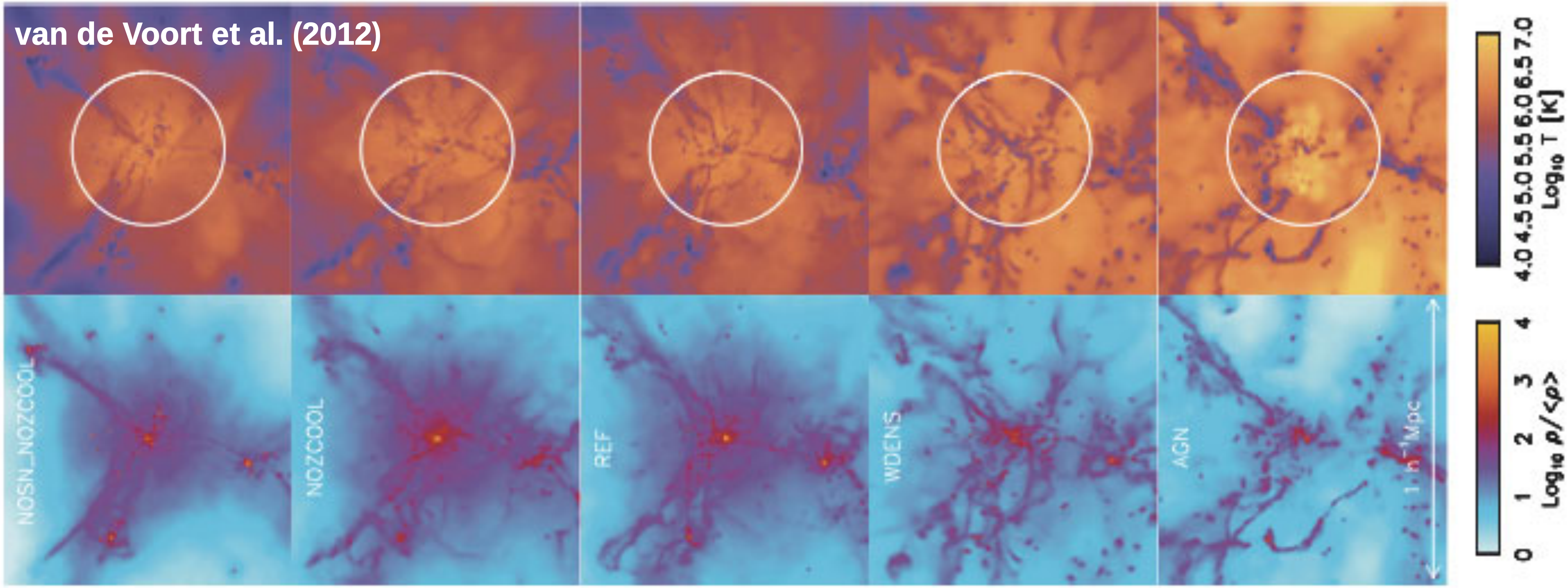


Image credit: simulation by B. Oppenheimer, Leiden University

Probing the Galaxy — IGM connection

the same simulation with 5 different parameter settings:



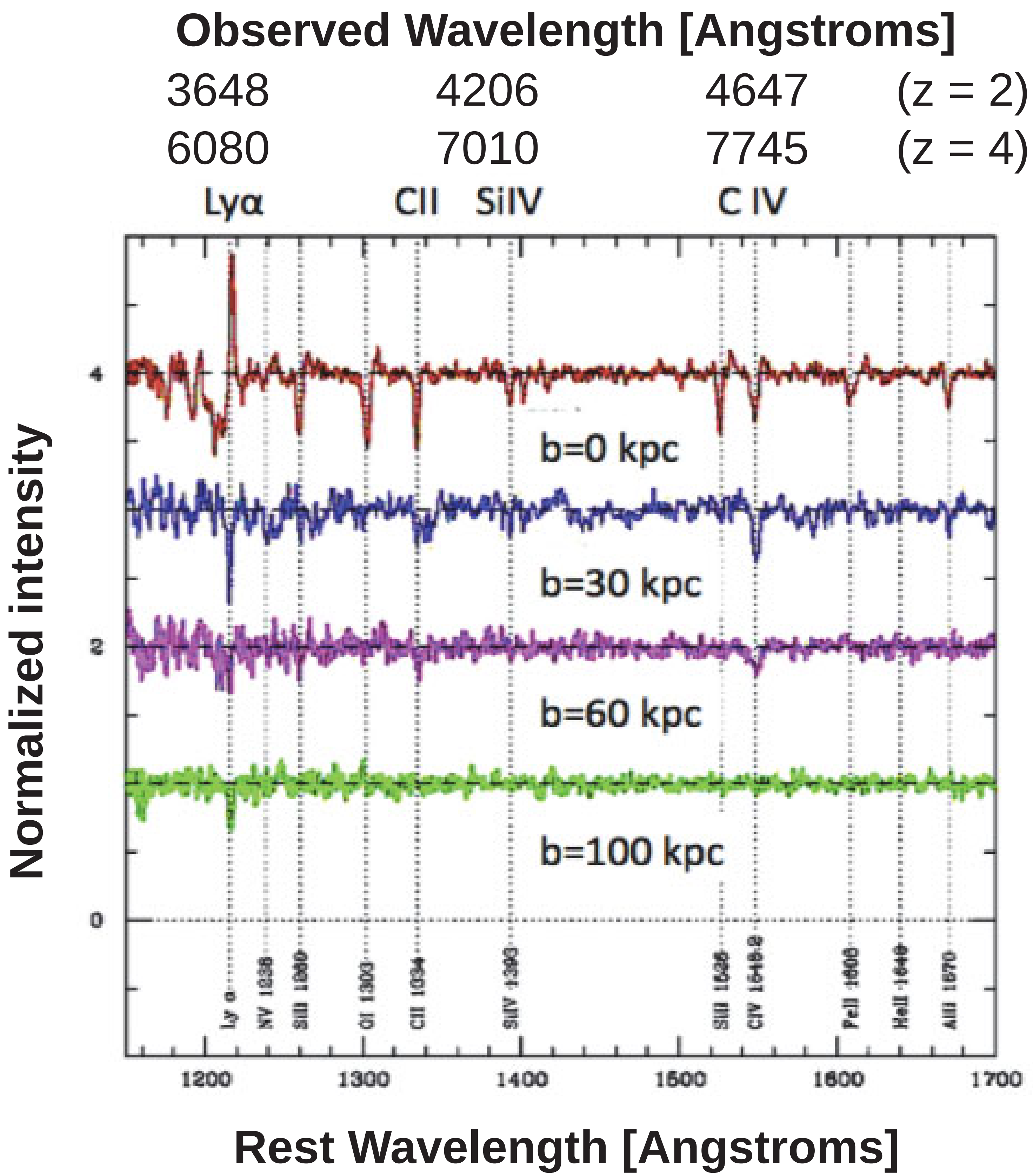
no SN feedback, no metal line cooling	no metal line cooling	metal line cooling + SN feedback	density-dependent SN feedback, no AGN feedback	AGN + SN feedback

- each choice affects the outcome of hot and cold gas accretion rates, and this may have very different behaviour as a function of, e.g, redshift and halo mass

Probing the Galaxy — IGM connection: Starburst galaxies

- current measurements based on stacked pairs of few hundred luminous (L*) LBGs at z=2.2

- metal-enriched gas found in absorption out to ~100 kpc



Steidel et al. (2010)

Probing the Galaxy — IGM connection: Starburst galaxies

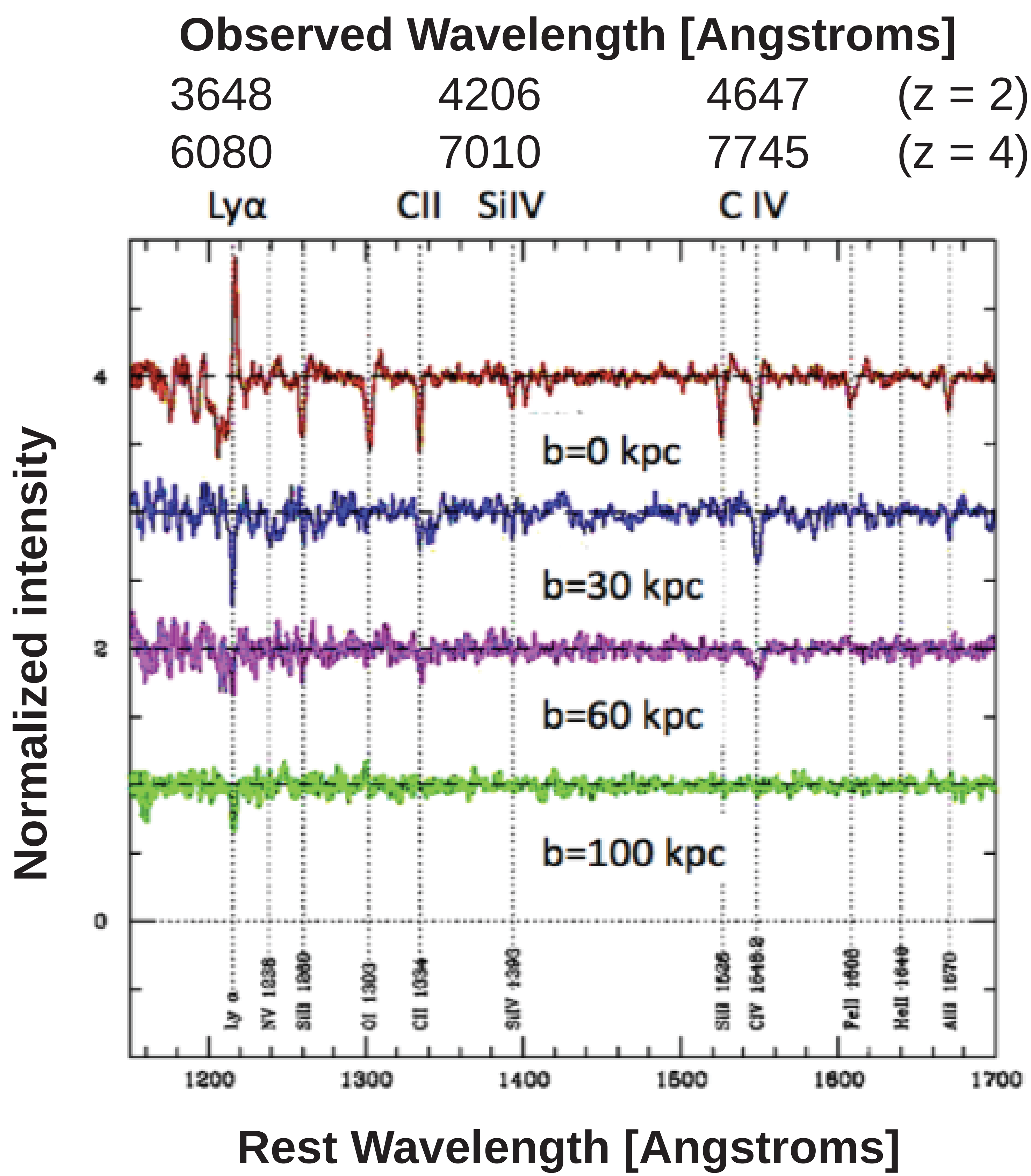
- current measurements based on stacked pairs of few hundred luminous (L*) LBGs at z=2.2

- metal-enriched gas found in absorption out to ~100 kpc

- **evolution of galaxies depends on halo mass**, redshift, and feedback affects systems differently

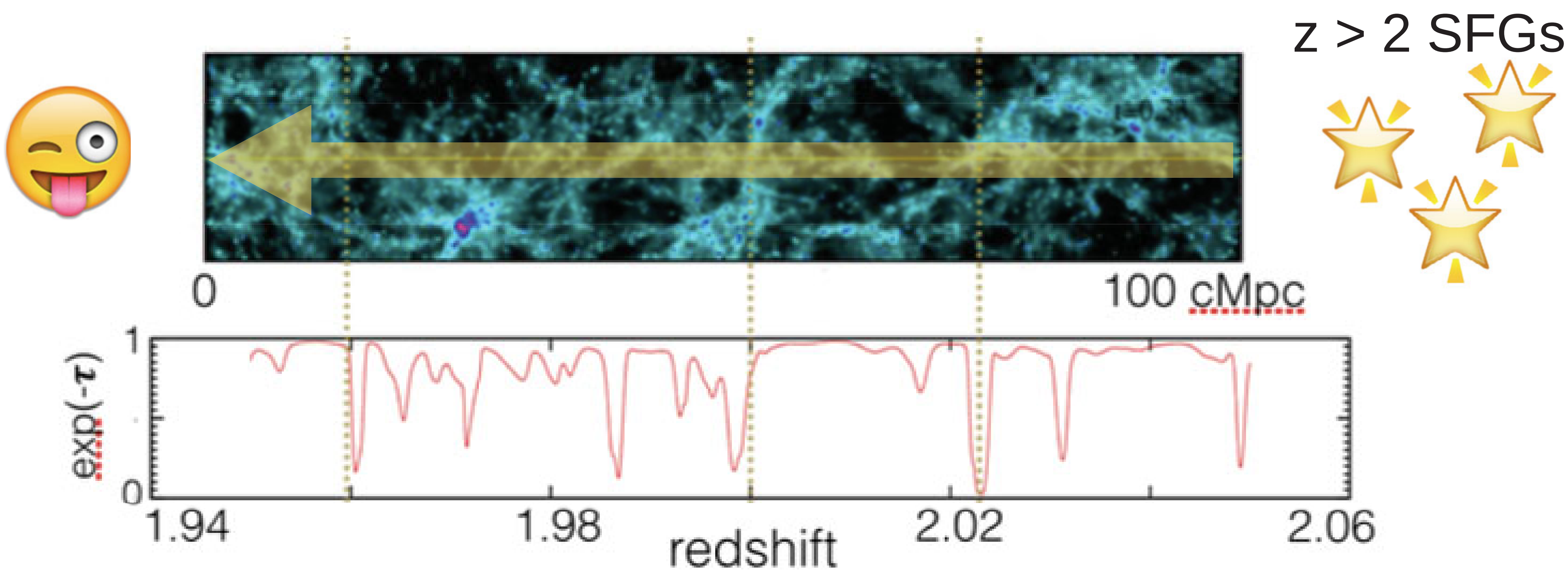
- **local environment should also play some role**: for example, it can remove or limit the gas supply, enhance gas inflows and mergers, or pre-enrich the IGM

- **currently little leverage in redshift, galaxy type and environment —> GMACS**



Steidel et al. (2010)

Probing the Galaxy — IGM connection: “Lyα tomography”



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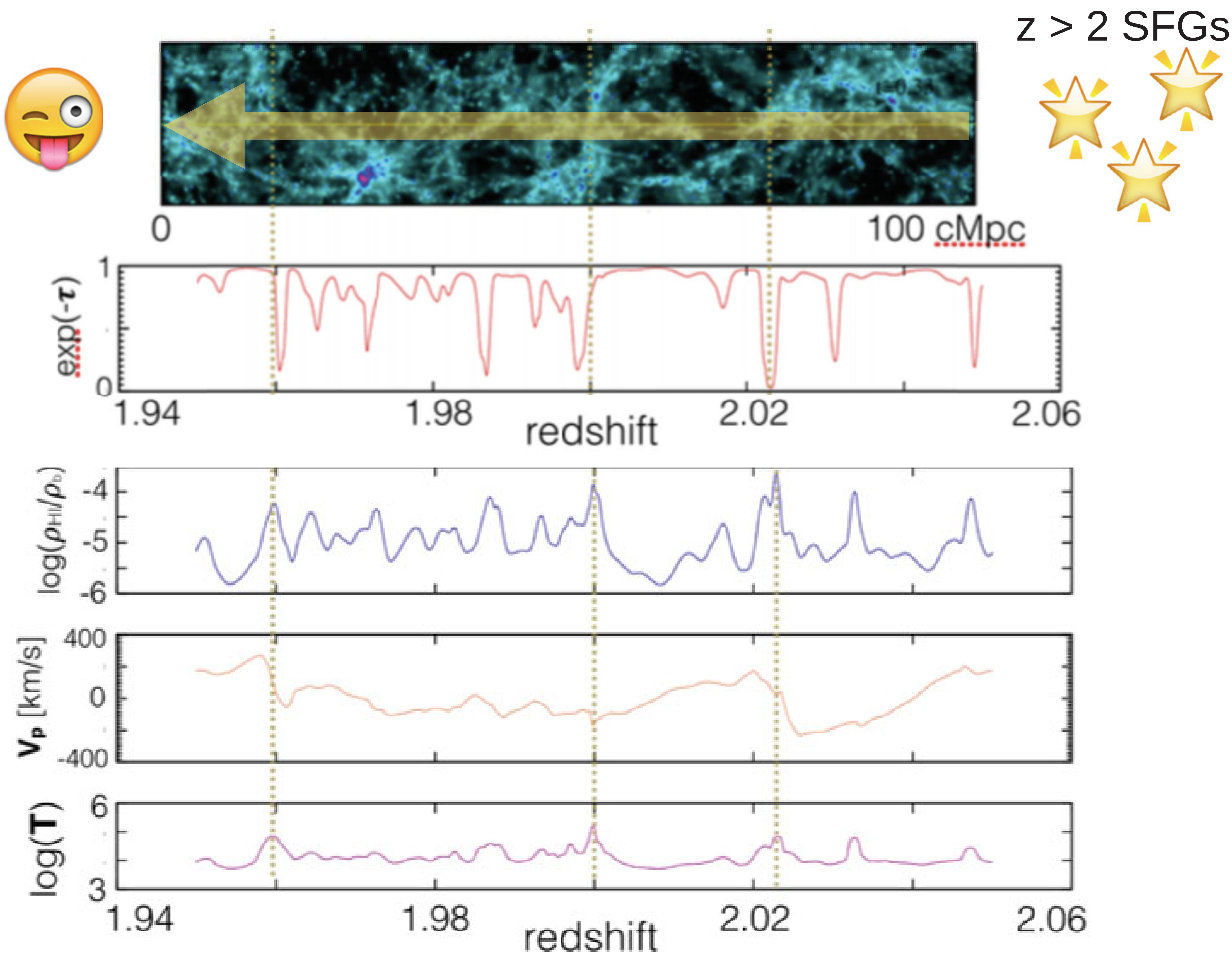
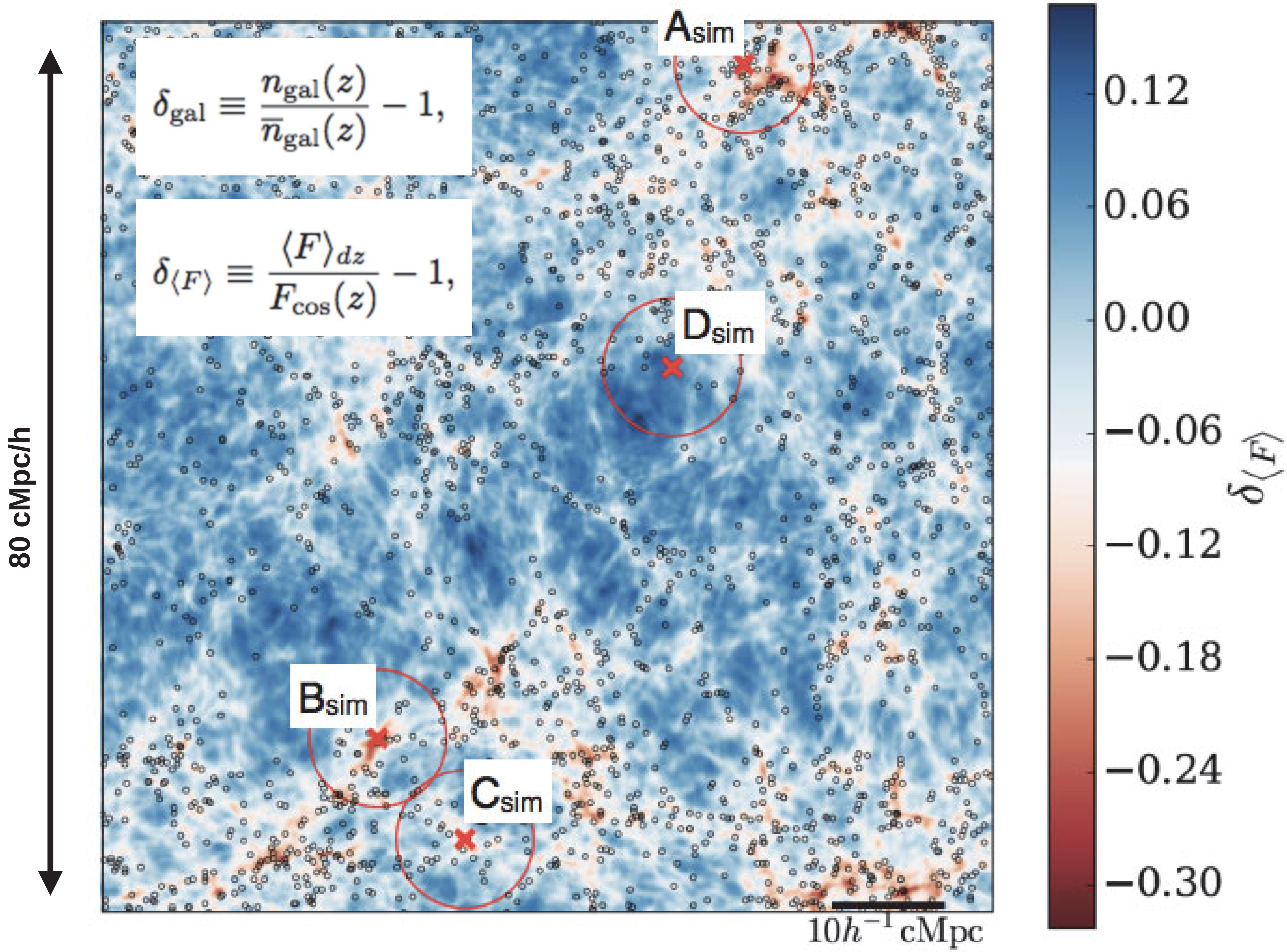
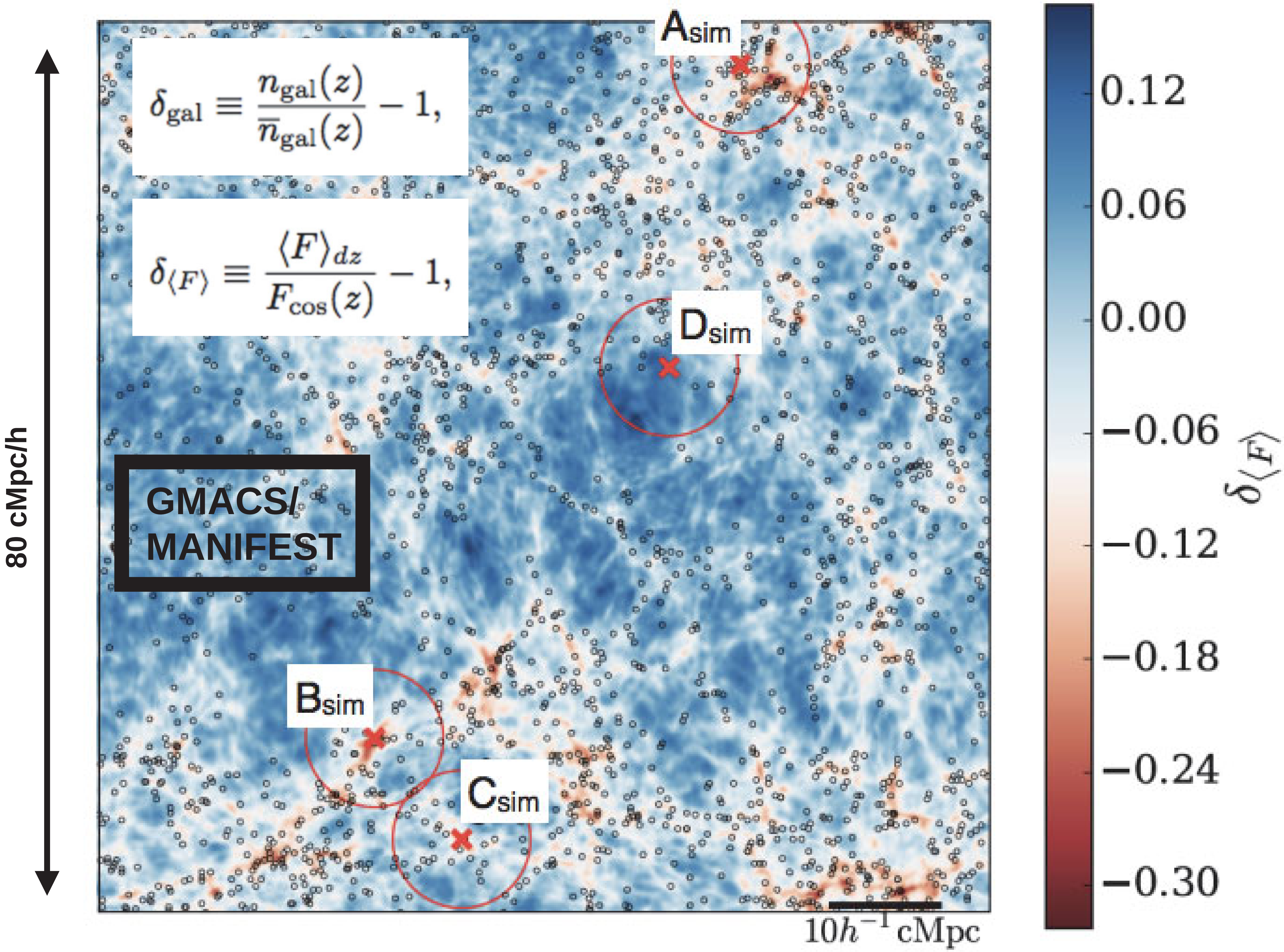


Galaxy — IGM connection: Lyα “tomographic mapping”



Mukae et al. (2017)

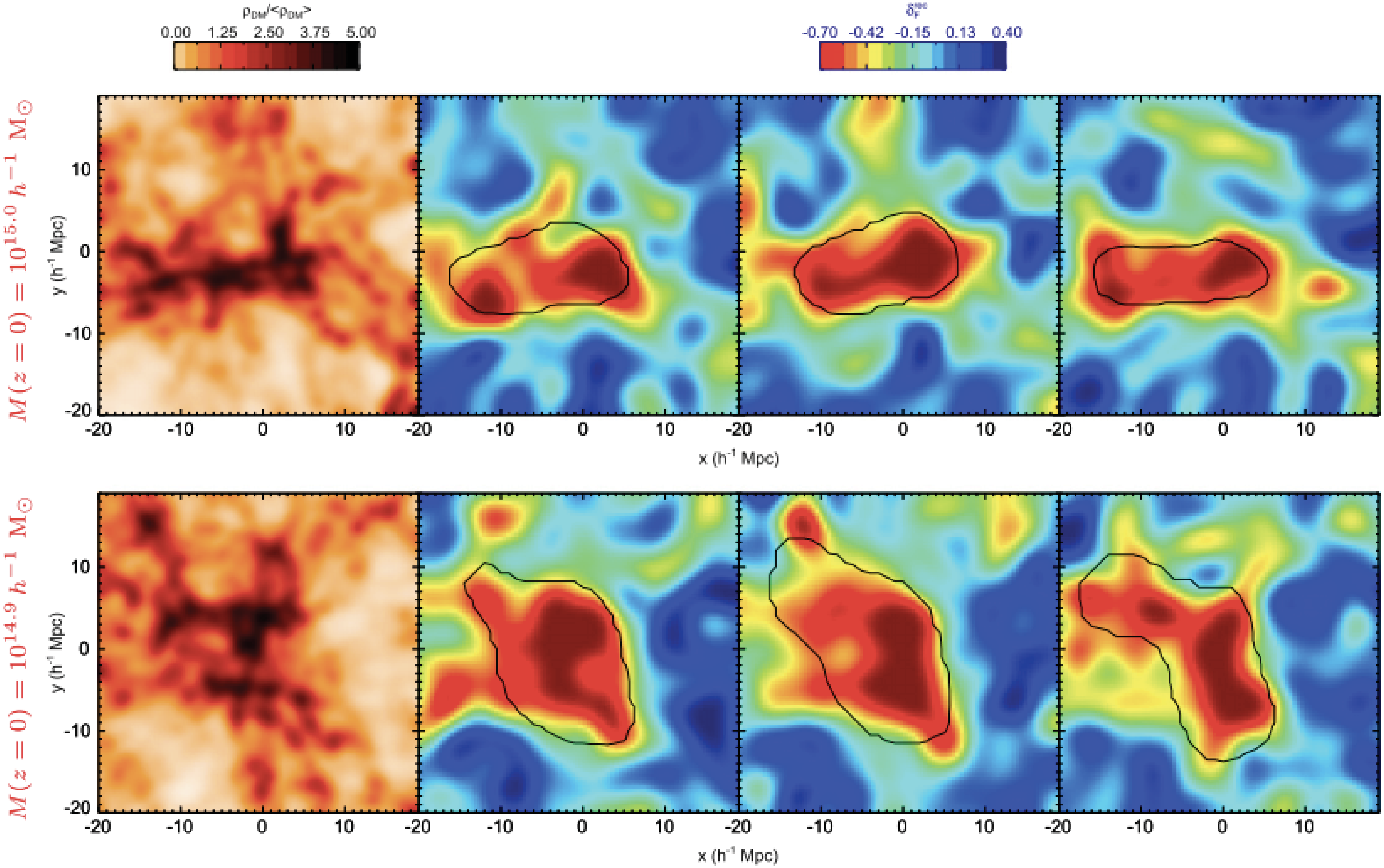
Galaxy — IGM connection: Lyα "tomographic mapping"



Mukae et al. (2017)

Galaxy — IGM connection: Lyα "tomographic mapping"

Massive galaxy protoclusters at z~2.5 (simulations)



Lee et al. (2016); Overzier (2016)

Galaxy — IGM connection: Lyα “tomographic mapping”

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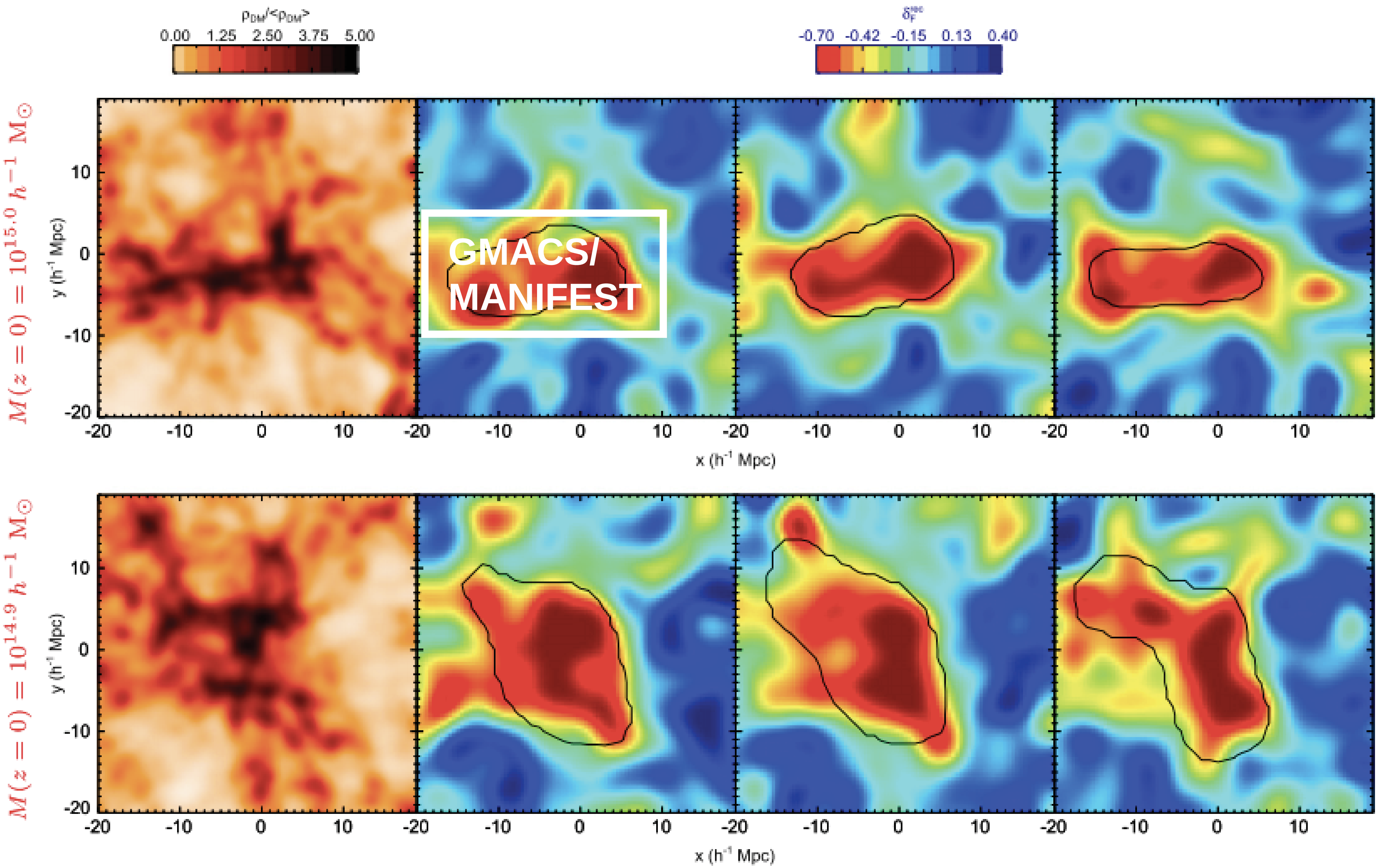


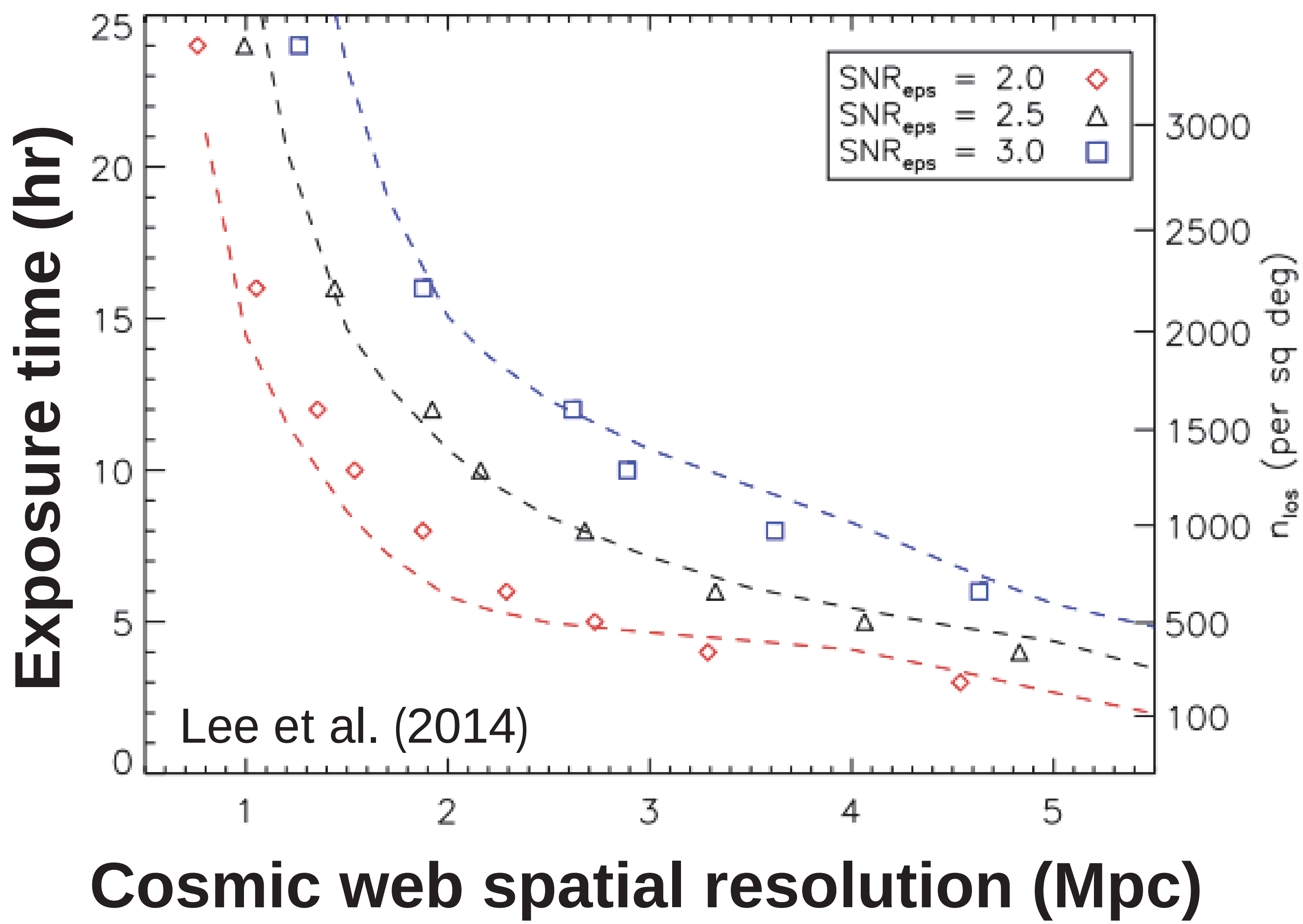
Lee et al. (2016); Overzier (2016)

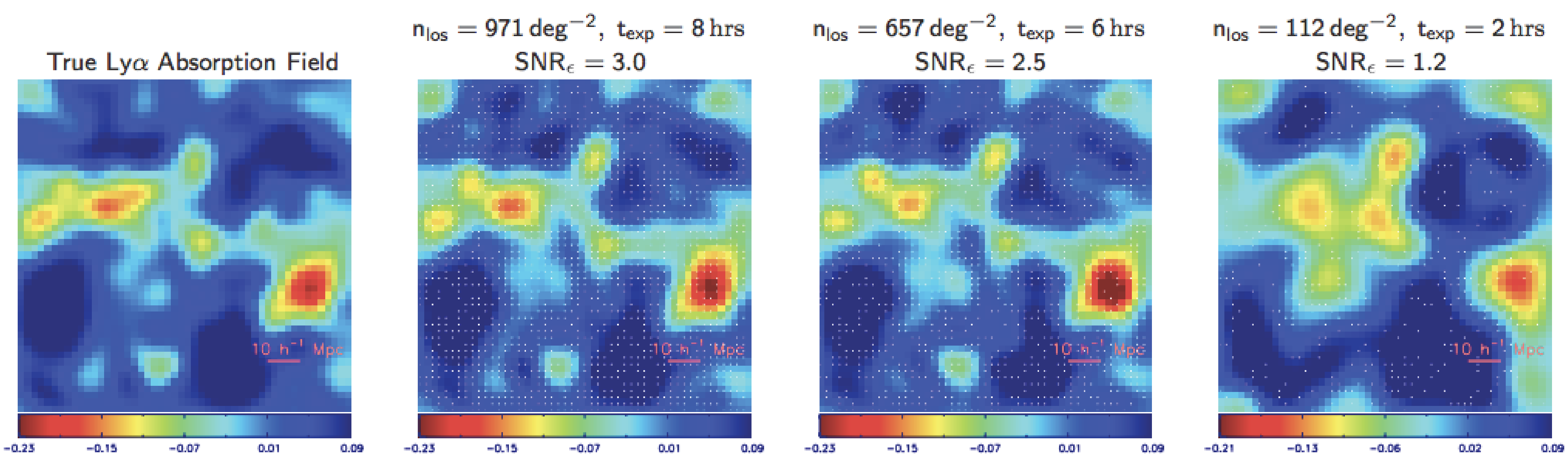
Galaxy — IGM connection: Lyα “tomographic mapping”

The accuracy of cosmic web reconstruction will depend on:

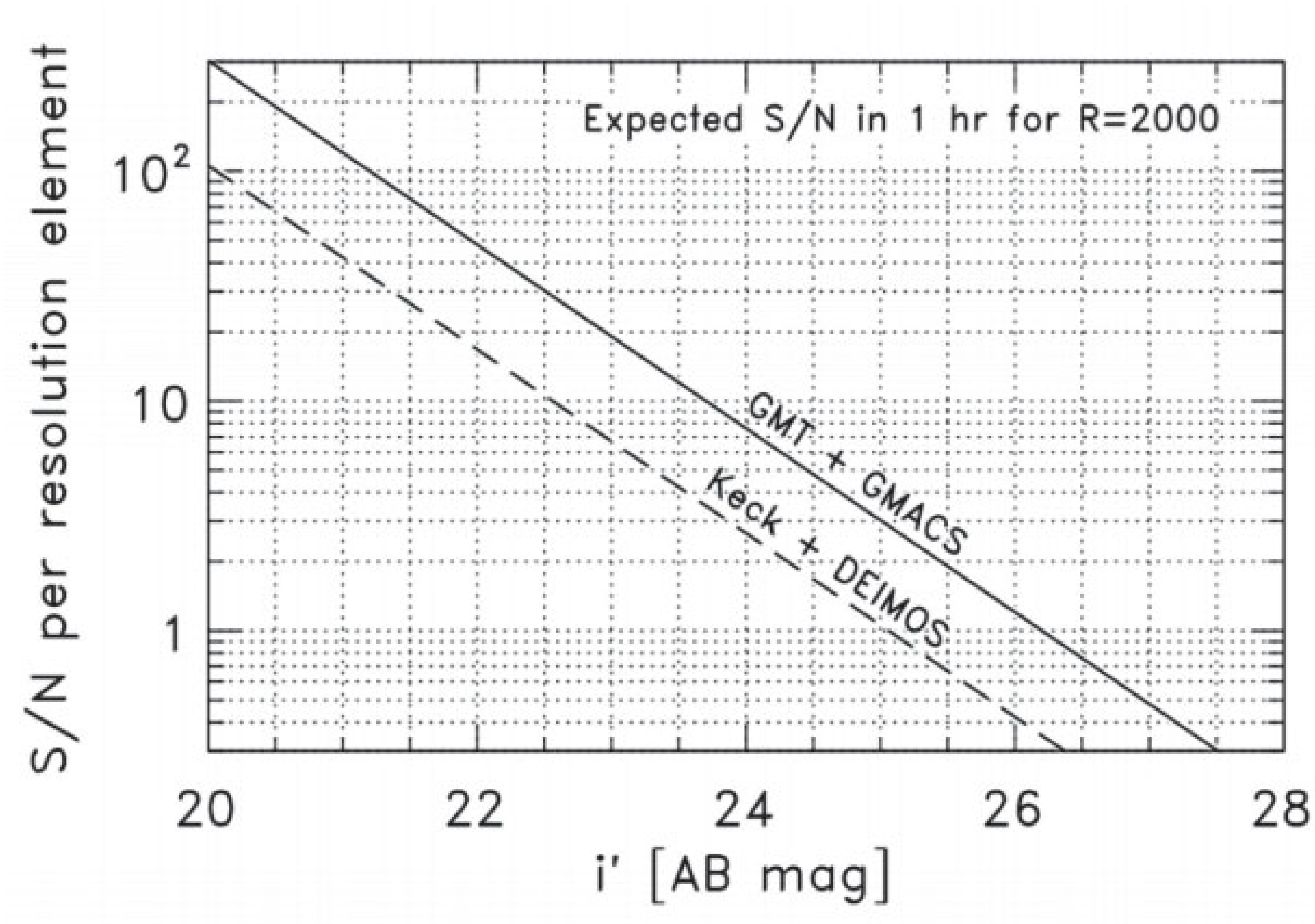
- the number density of background sources observed

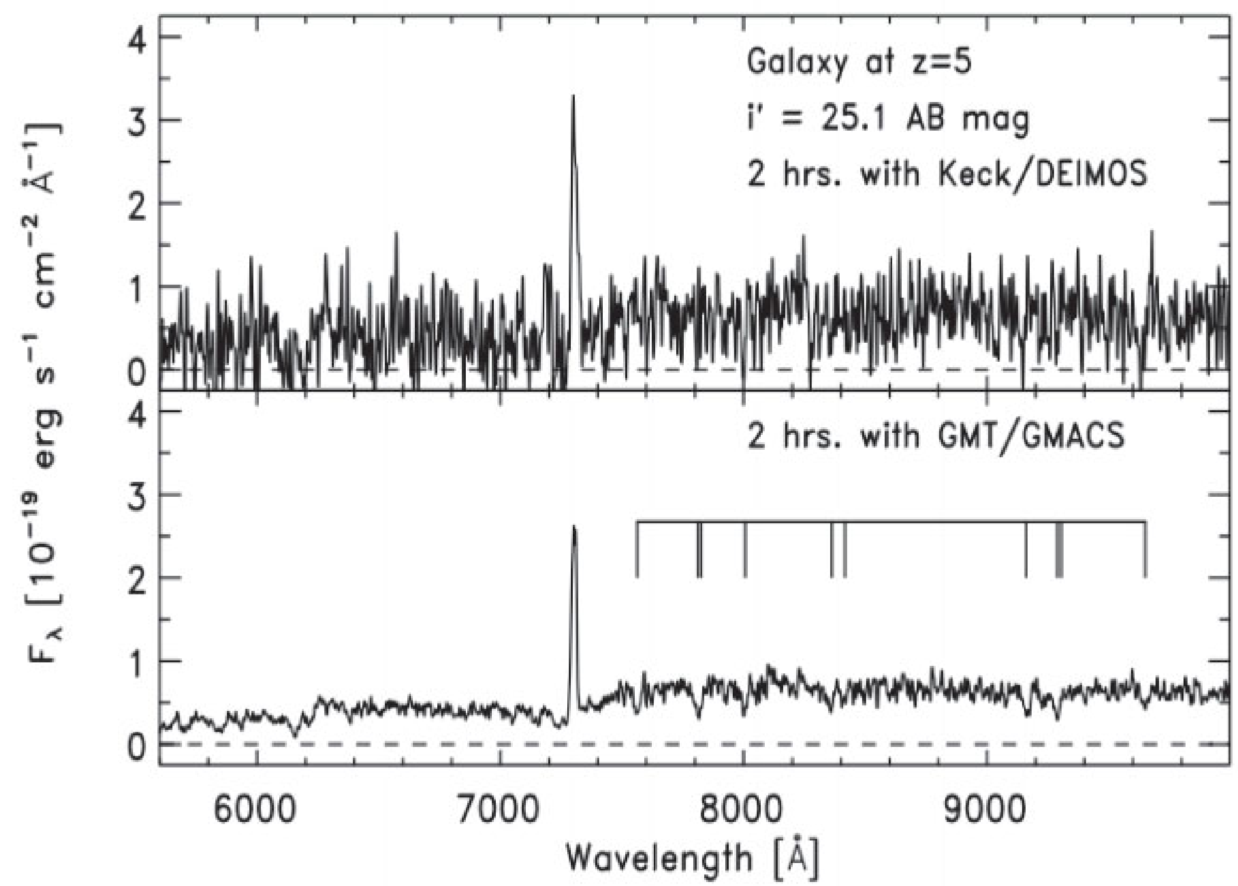
- sufficient spectral S/N in their rest-frame UV continuum





GMACS will significantly speed up the tomographic mapping





Redshift	Surface Density [$arcmin^2$]	No. per GMACS field	Limiting magnitude	Reference
2	5.4	780	R = 25.5 mag	Reddy & Steidel 2009
3	2.3	330	R = 25.5 mag	Reddy & Steidel 2009
4	1.7	240	i = 25.5 mag	Bouwens et al. 2007
5	0.22	30	i = 25.5 mag	Bouwens et al. 2007

GMT Science Book

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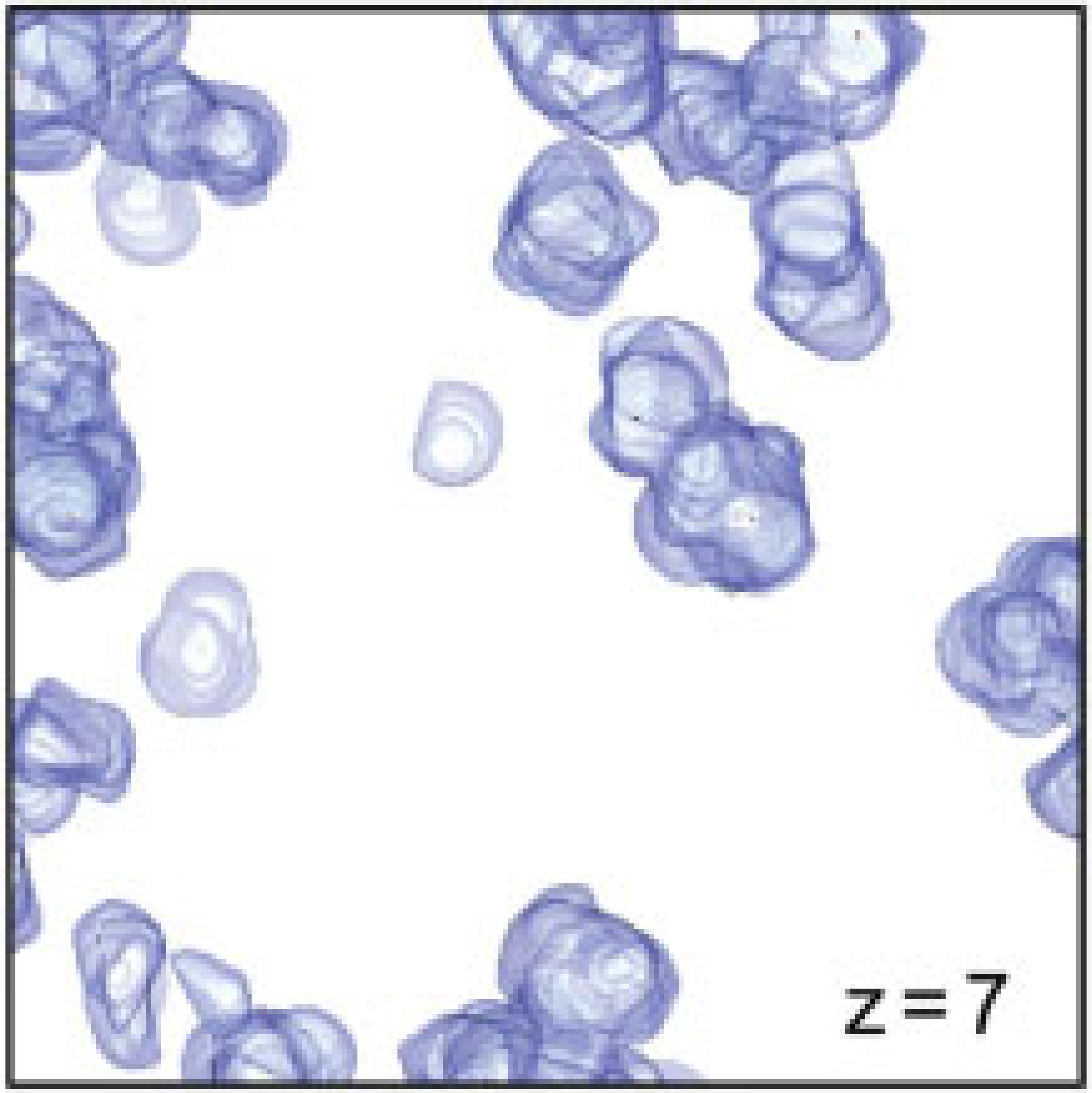
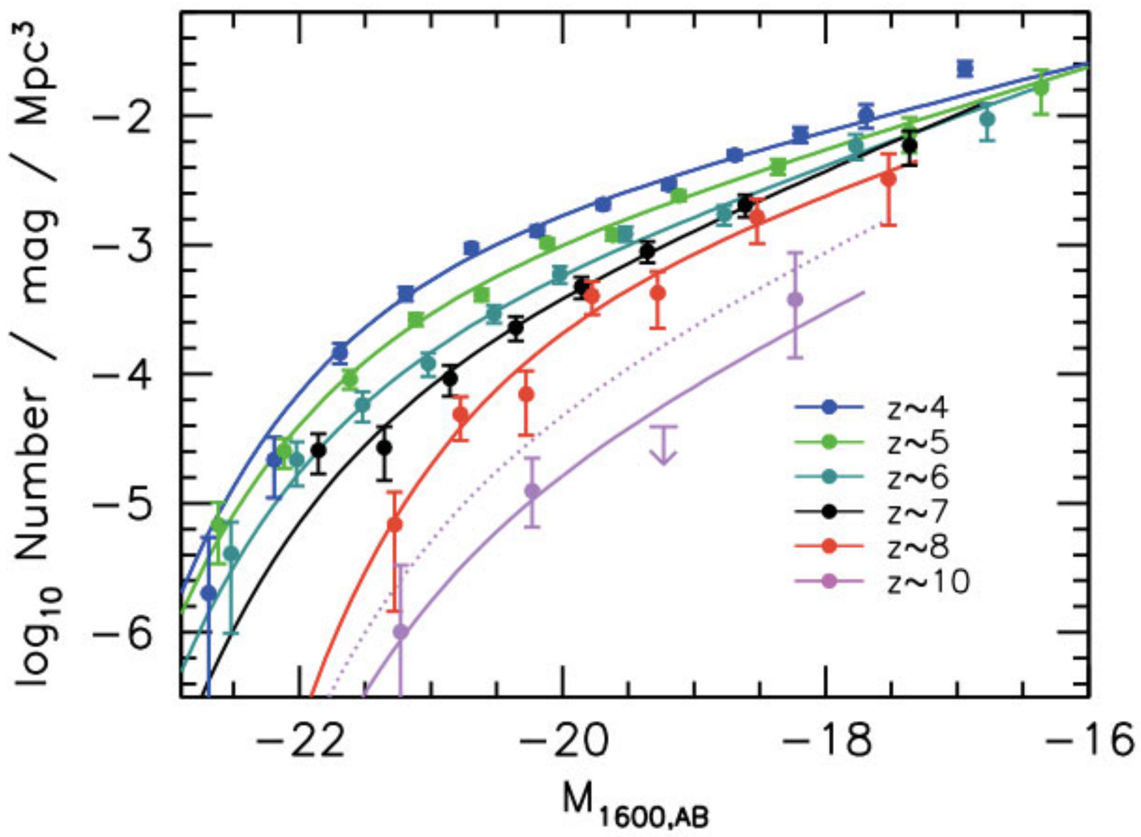


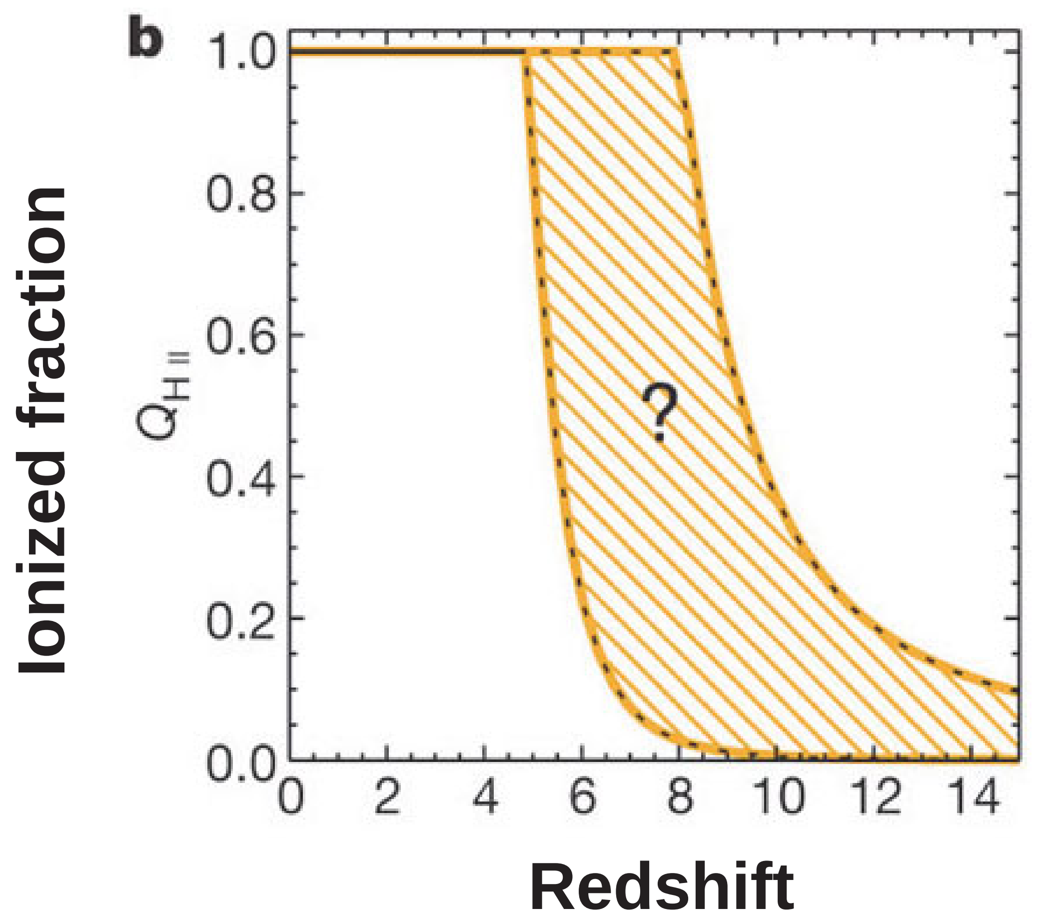
GMACS at "cosmic dawn"

Tracing the process of reionization depends on **two crucial ingredients**:

(1) the production rate of ionizing photons (>13.6 eV; 1 Ry; 912A) from young stars in starburst galaxies (and perhaps a small contribution from quasars)

(2) the *escape fraction* of the ionizing photons from the galaxies into the (neutral) IGM that needs to be (re-)ionized

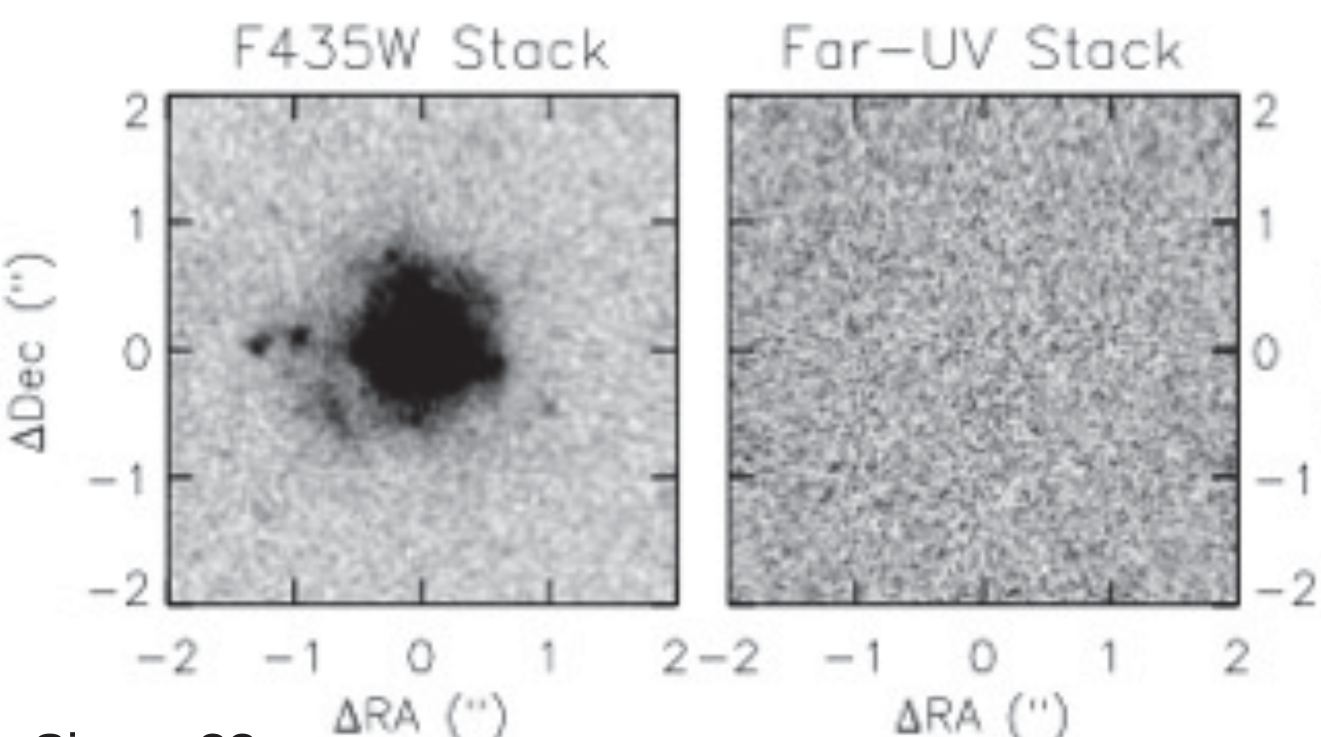




(2) the escape fraction of the ionizing photons from the galaxies into the (neutral) IGM

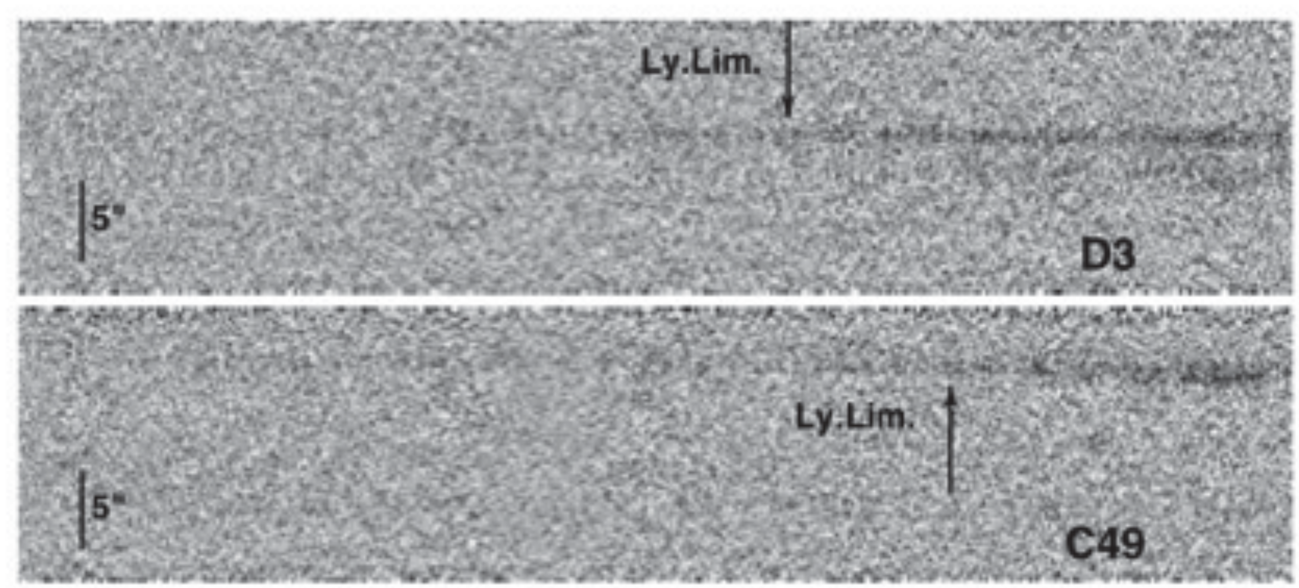
- we do not understand - at all - how those Lyman continuum photons may escape from star-forming galaxies at high redshift
- typical star-forming regions have HI column densities 4–10 orders higher than those needed to absorb all LyC photons produced by the starburst
- little to no evidence for LyC photons from star-forming galaxies at z<4

z = 1



Siana+??

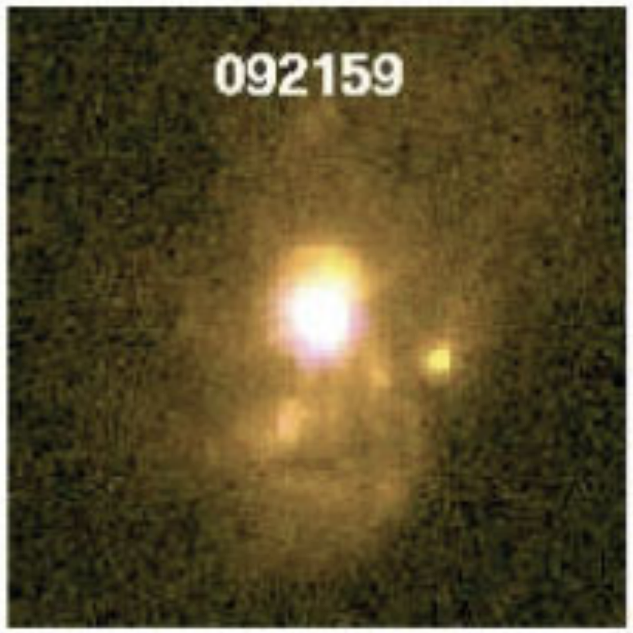
z = 3



Shapley+13

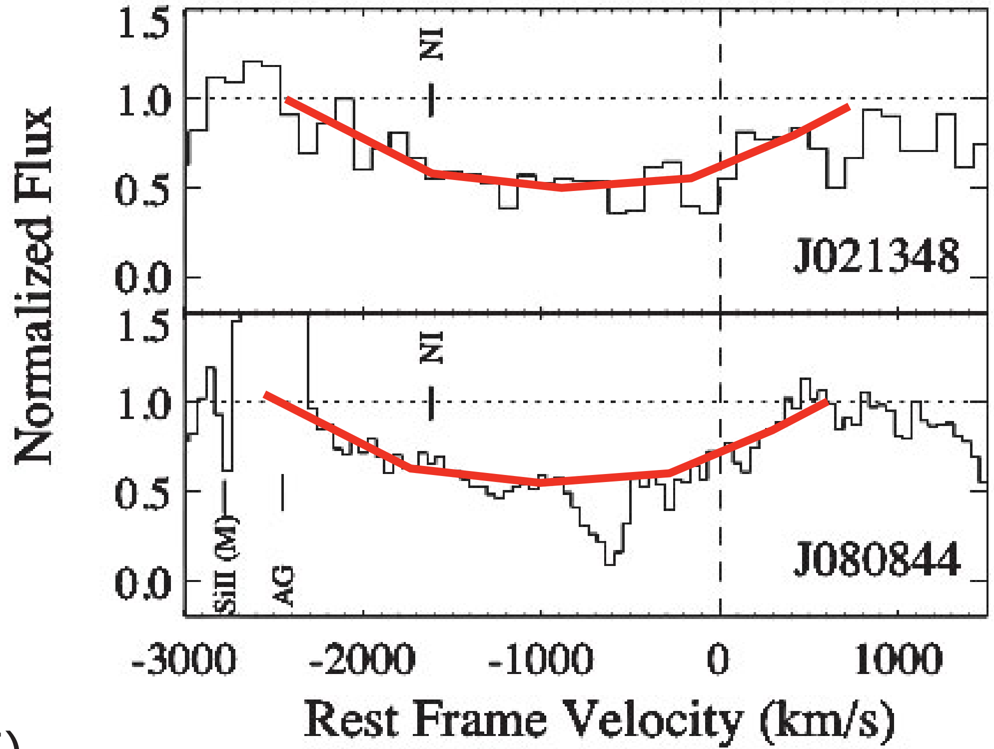
GMACS at “cosmic dawn”: LyC escape fraction

Nearby starburst

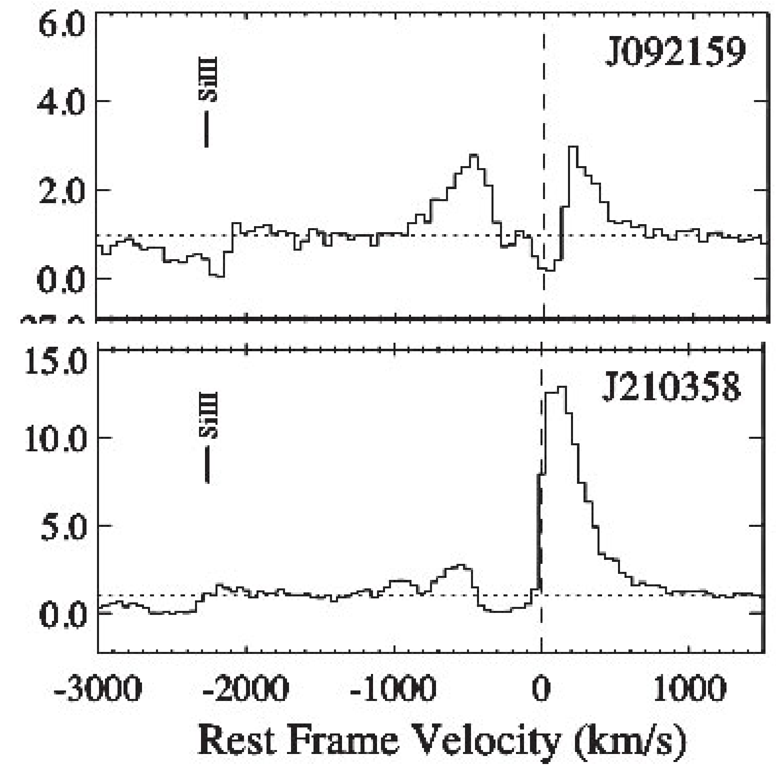


Borthakur et al. (*Science*, 2015)

Extreme outflows in SiII lines



Extreme blue-shifted Lyα



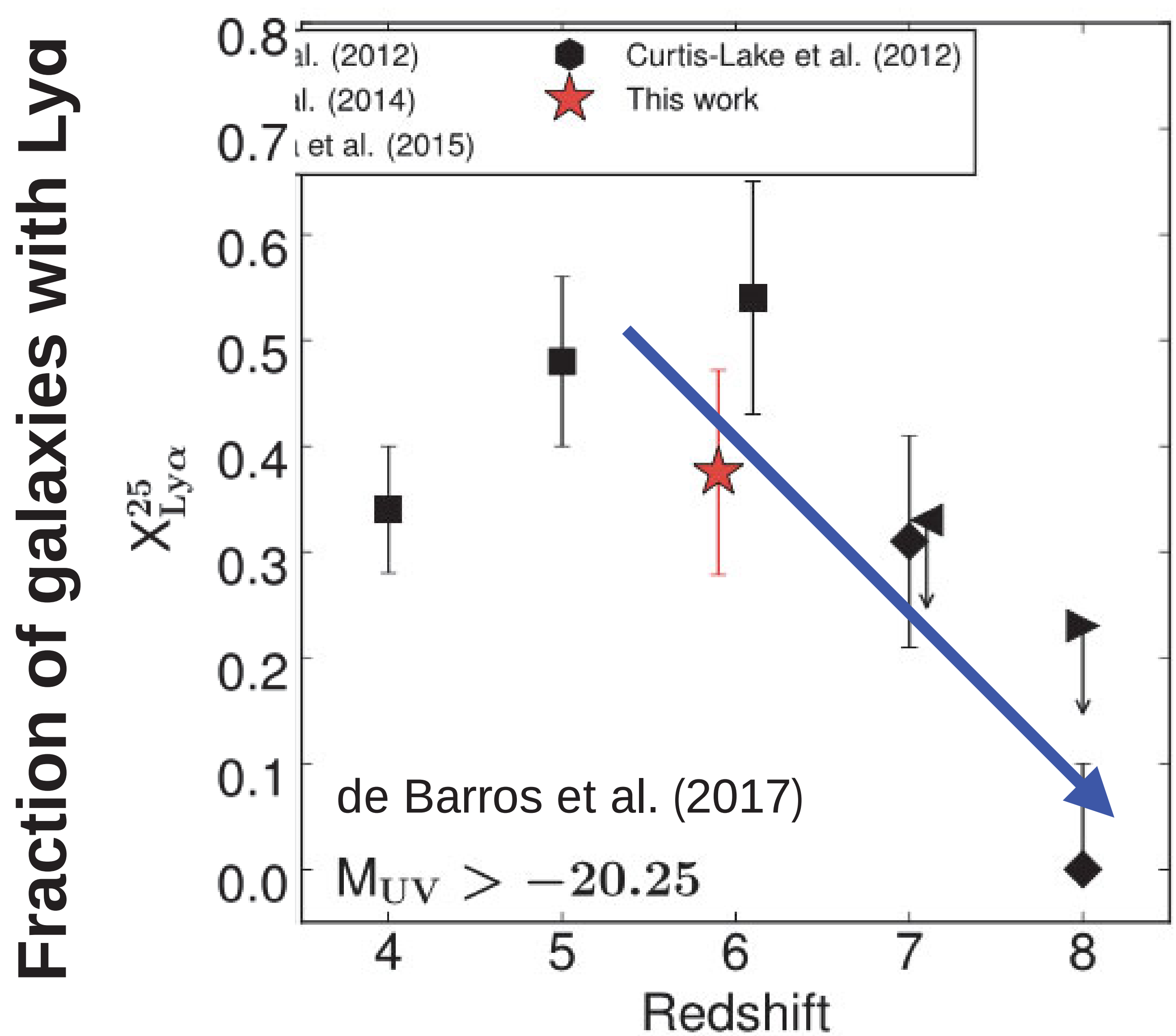
- high SN rates in compact starburst regions lead to high pressures/ densities that drive large-scale Galactic winds

- extreme SN winds blow “holes” into the neutral ISM, completely removing HI gas along certain directions, such that Lyman continuum photons (and Lyα) can escape

- GMACS can easily detect these far-UV signatures in spectra up to z~7

GMACS at “cosmic dawn”: Lyα escape fraction

- Lyα photons in starbursts resonantly scatter off HI atoms, until absorbed by dust
- as the IGM becomes more neutral toward cosmic dawn, we may expect a sharp drop in the fraction of galaxies that are bright in Lyα
- the Lyα fraction of galaxies thus also (indirectly) probes reionization



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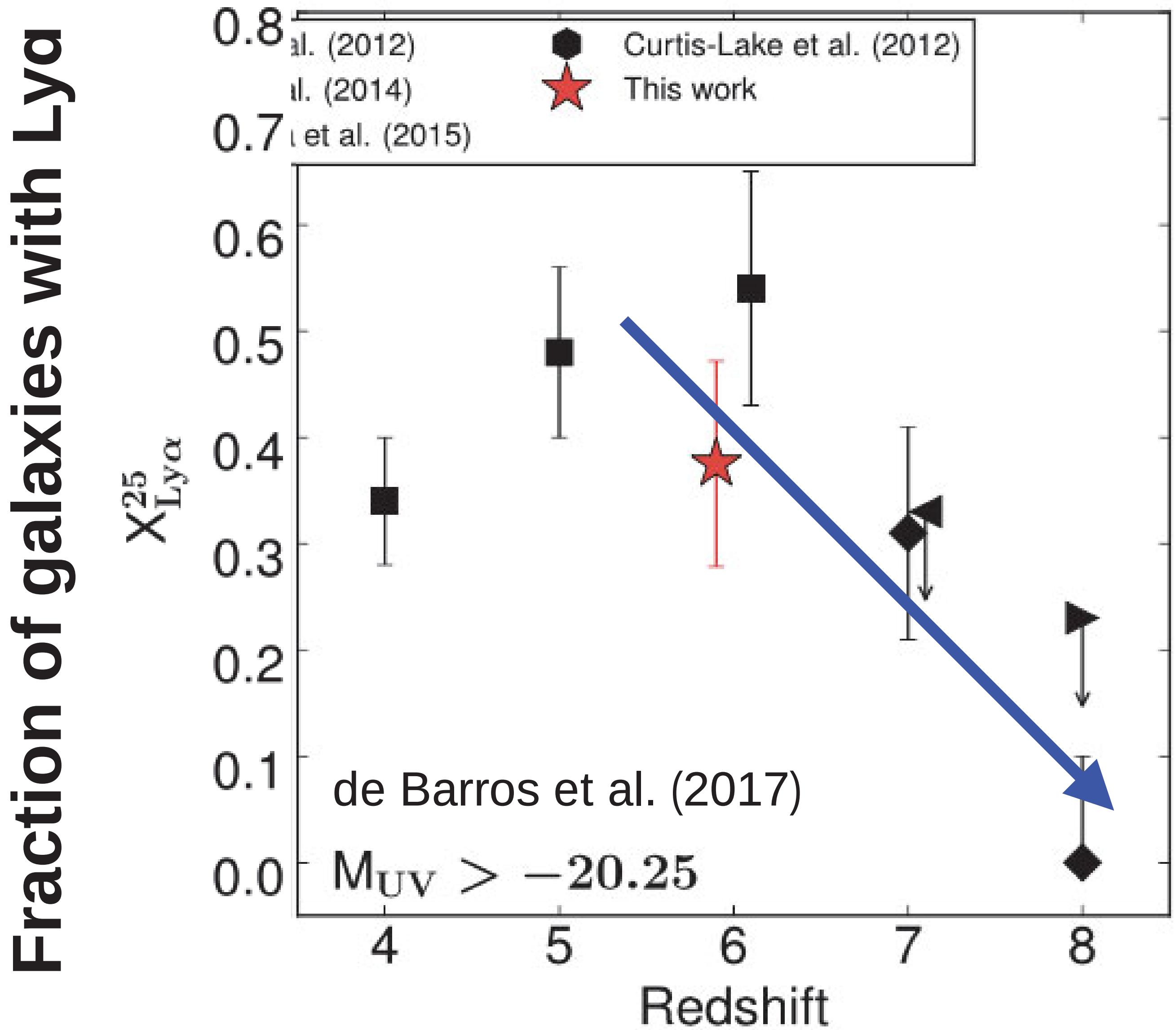
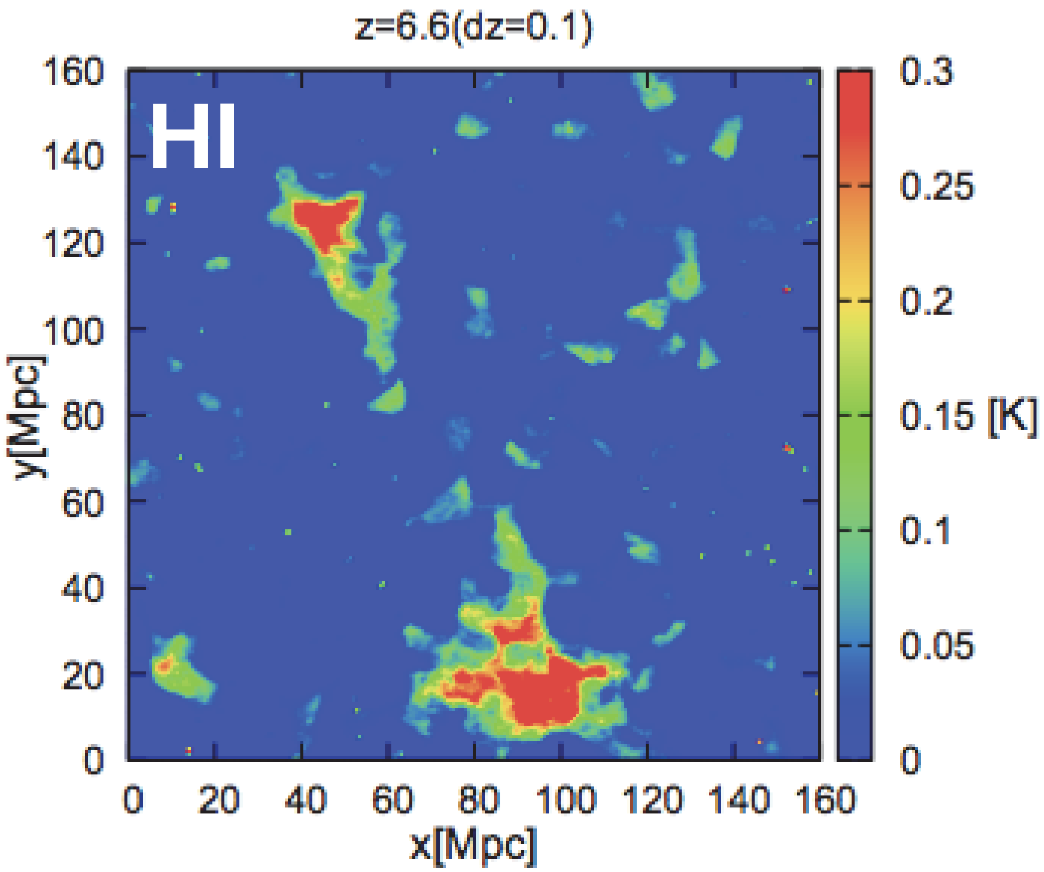


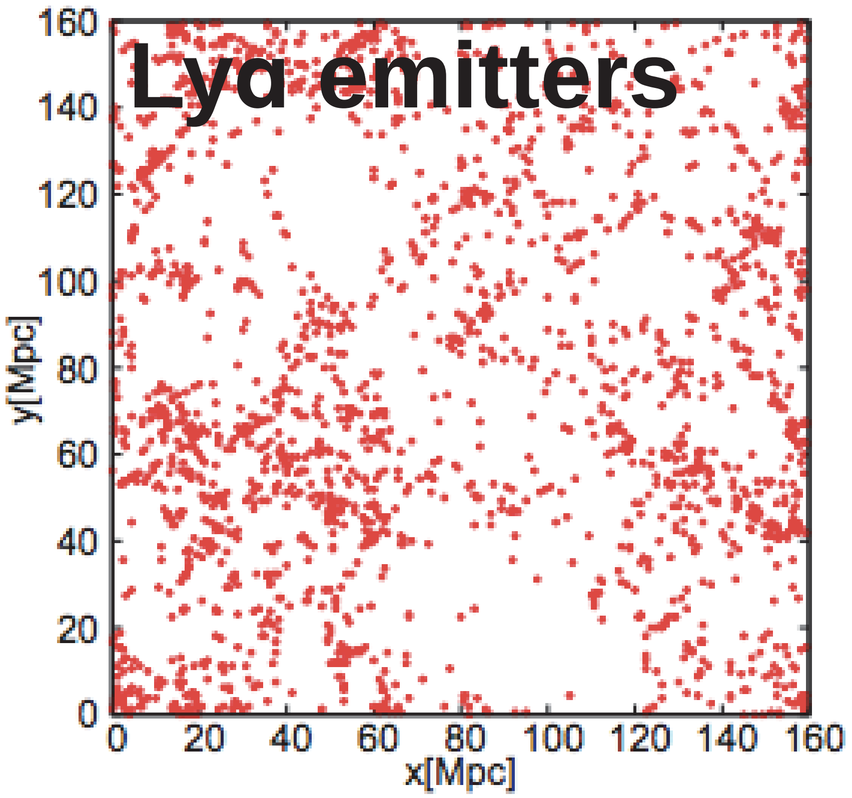
current samples are too small to be conclusive (de Barros et al. 2017)

to target about 300 Lyα galaxies at z~7, one needs about 20 GMACS masks with 2hr/mask,

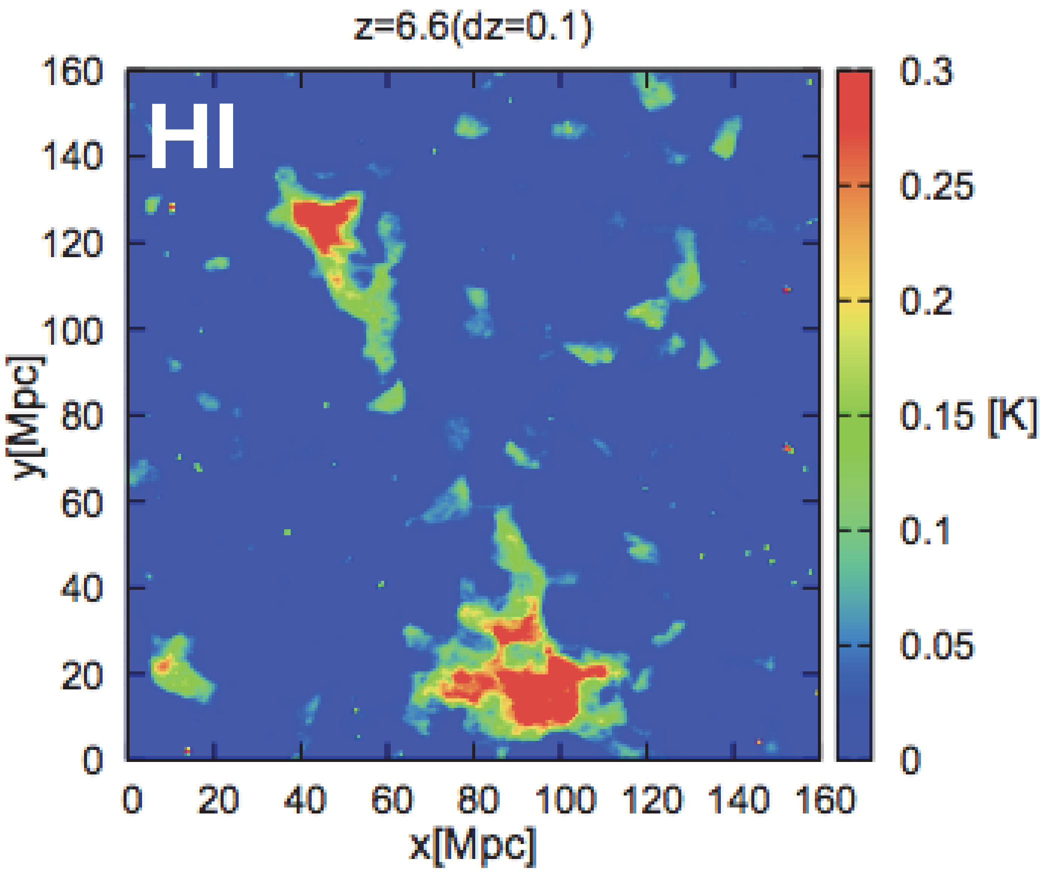
perhaps allowing a robust measurement of this effect for the first time

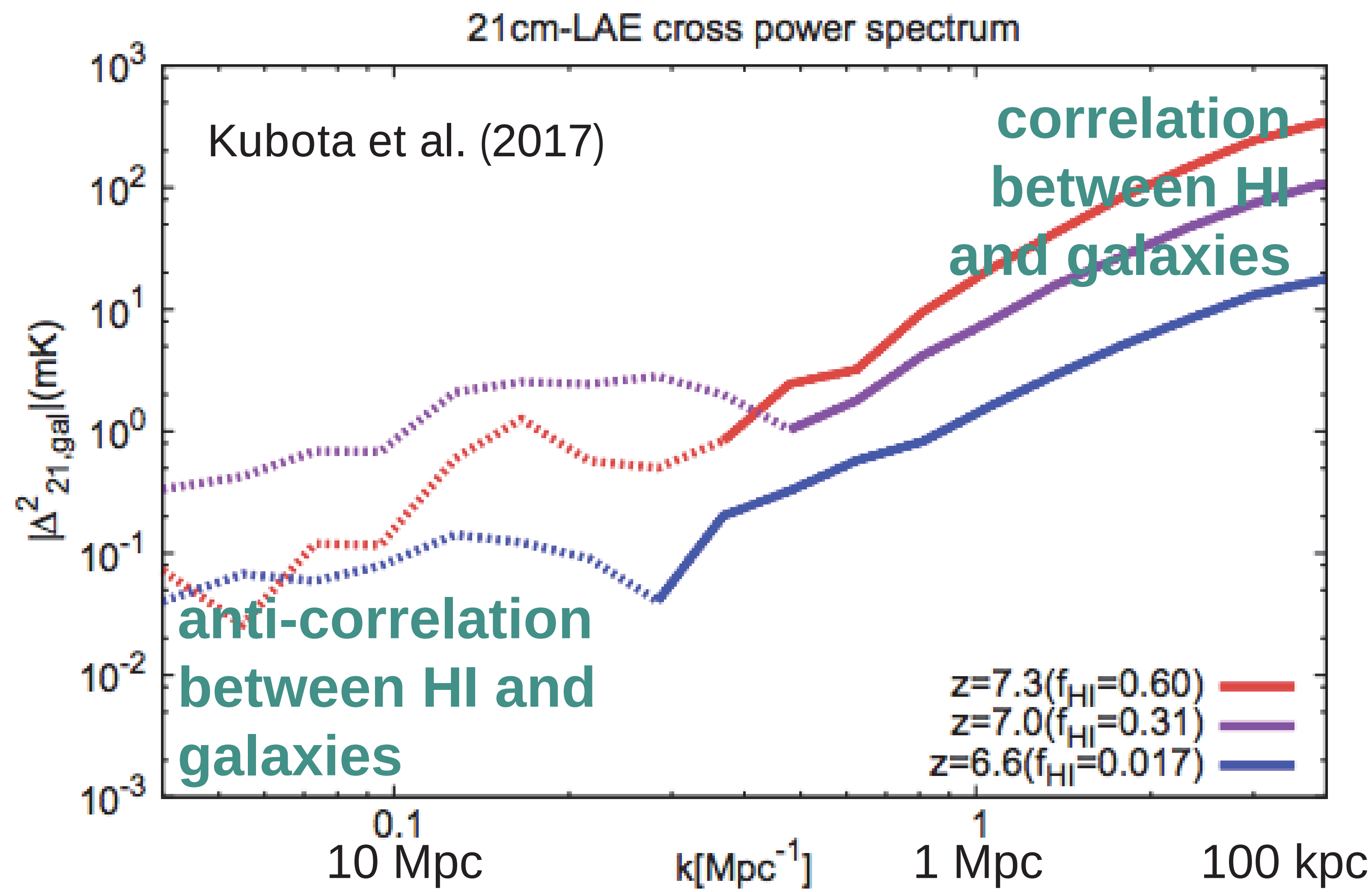
GMACS at “cosmic dawn”: HI — Lyα cross-correlation

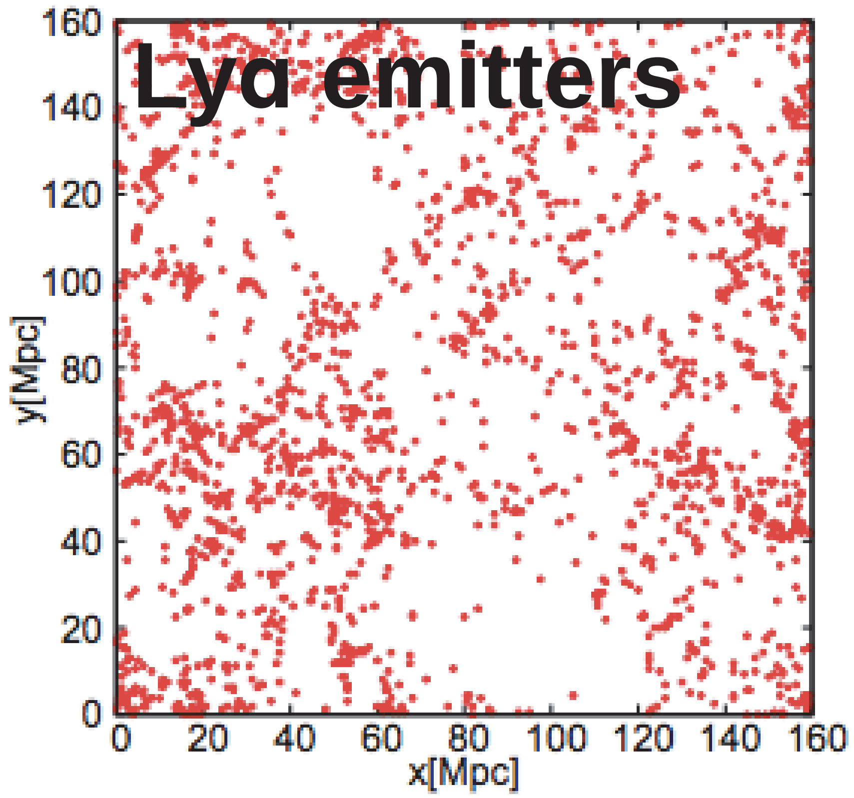


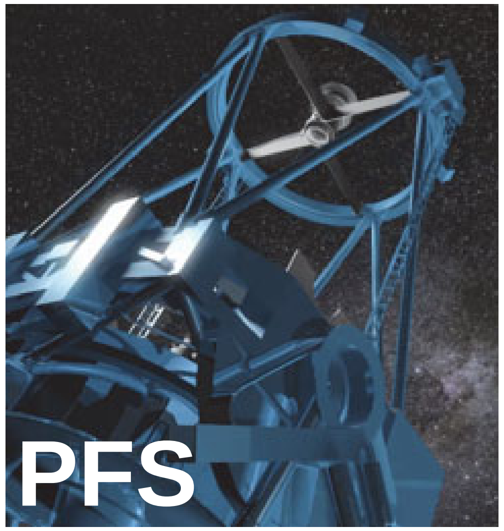


GMACS at “cosmic dawn”: HI — Lyα cross-correlation

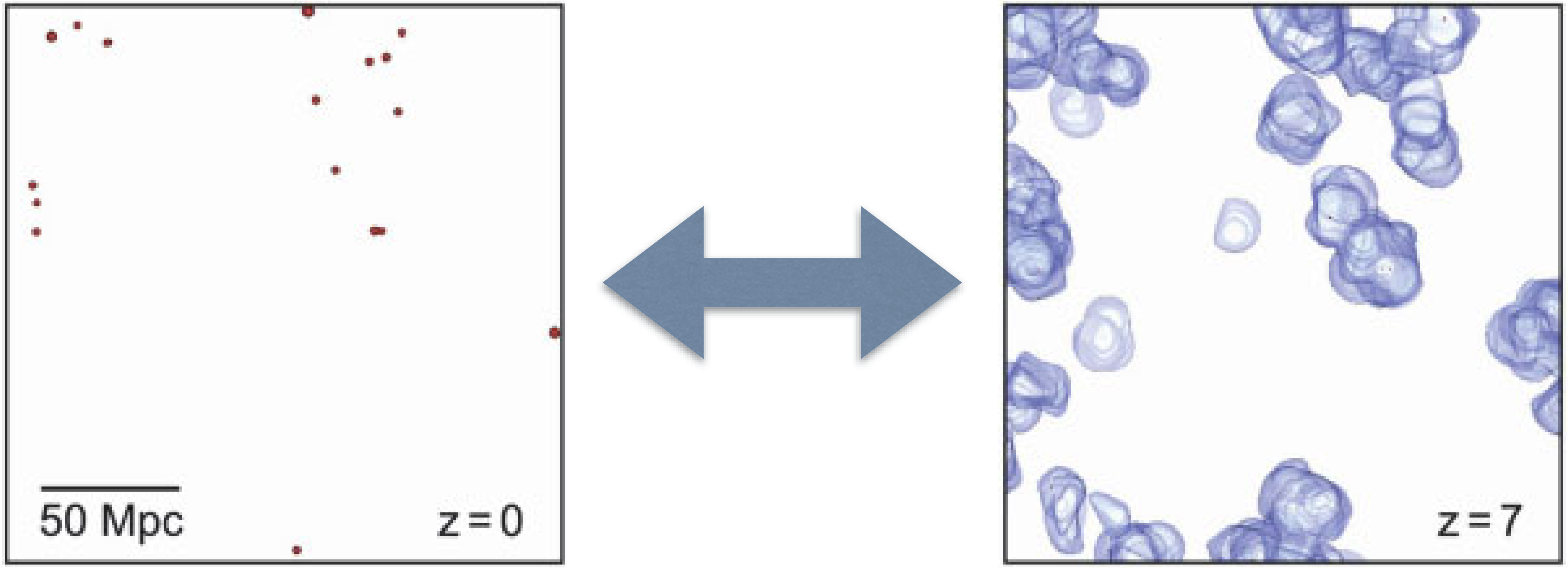








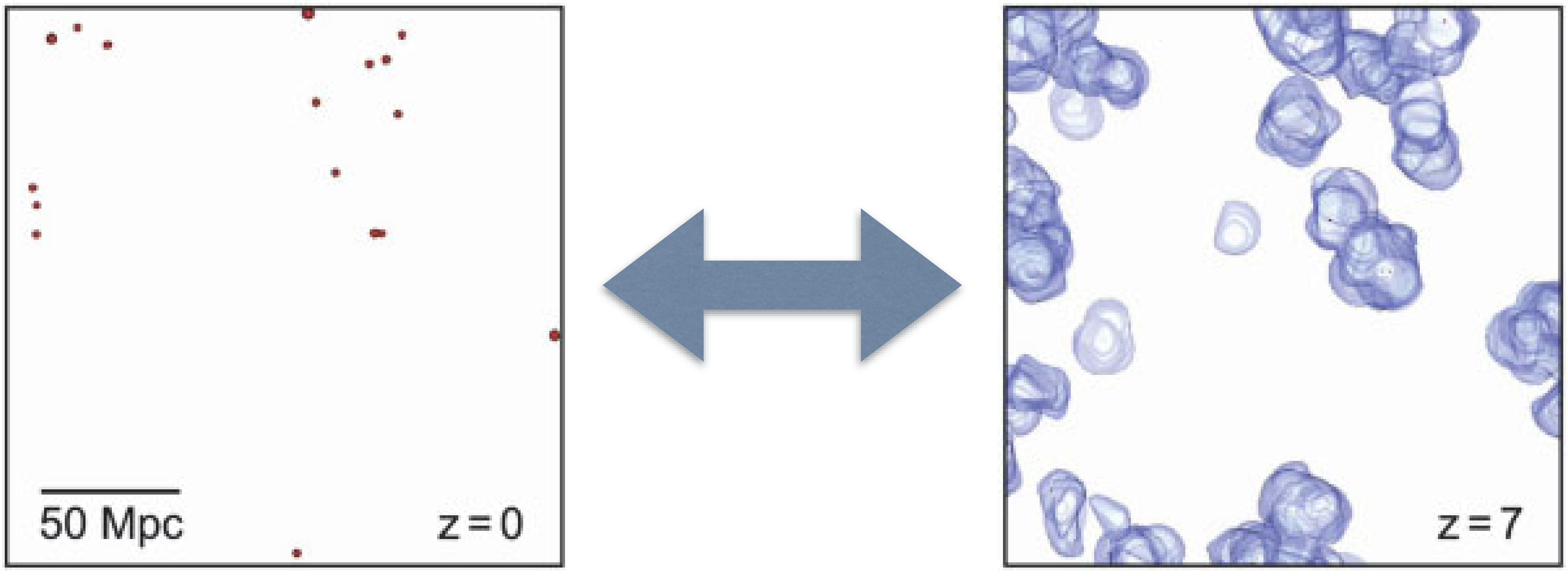
GMACS at “cosmic dawn”: Cluster-forming regions



Chiang et al. (2017)

at z ~ 6–10, the progenitors of *galaxy clusters* make up a significant fraction of the ionizing photon budget (~50%)

GMACS at “cosmic dawn”: Cluster-forming regions



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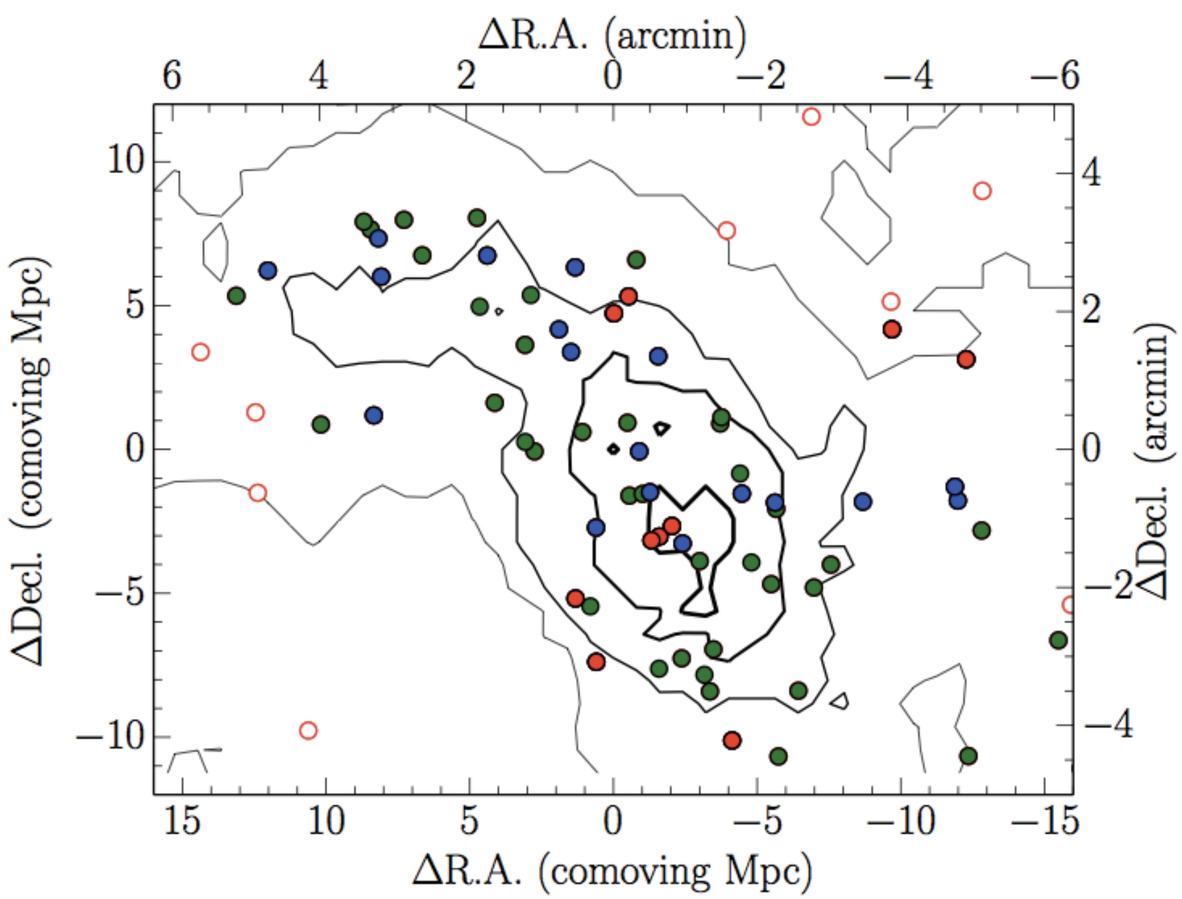
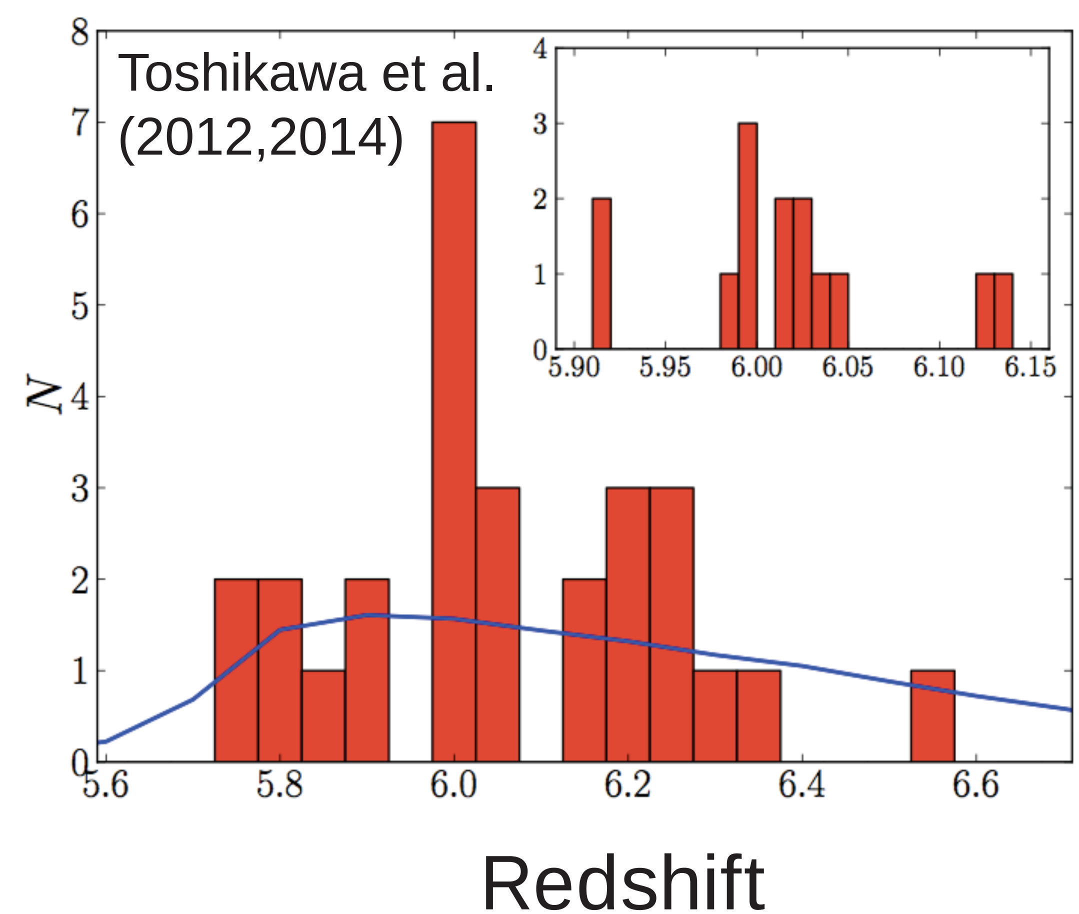
Chiang et al. (2017)





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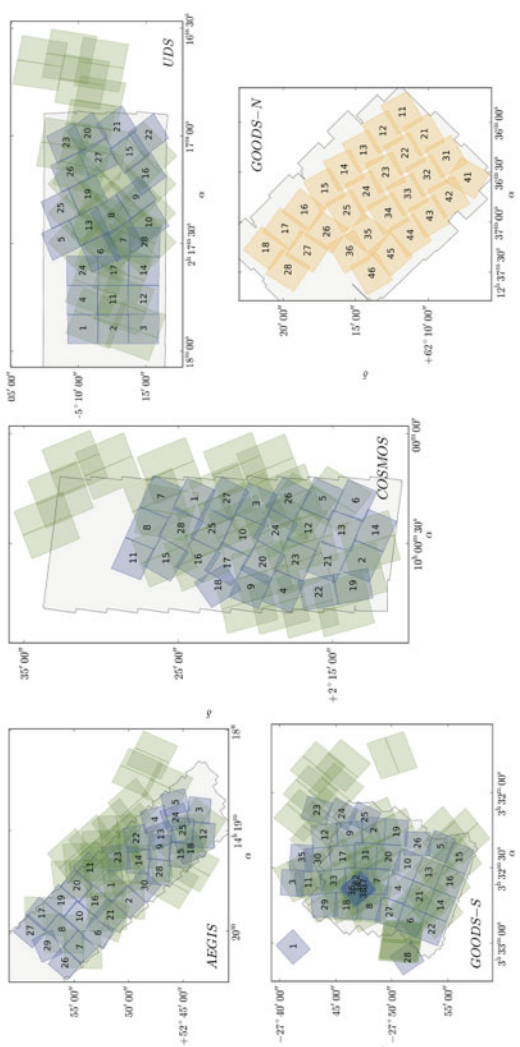
GMACS synergies: target selection

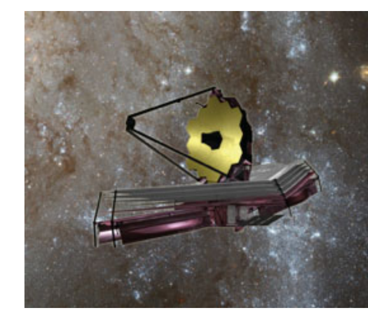
important caveat:

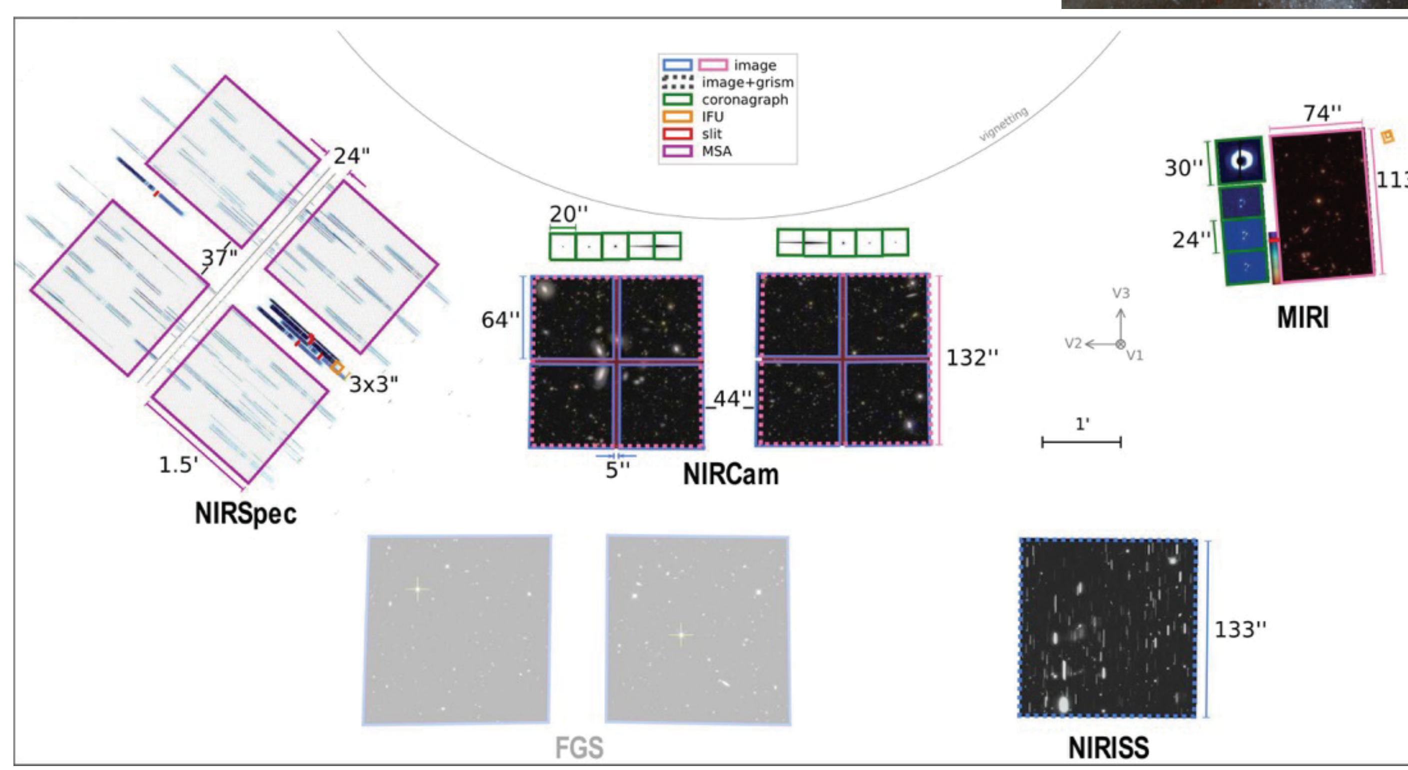
- like most other ELT/TMT/GMT spectrographs, GMACS is NOT a discovery instrument: **it relies on targets provided by other surveys**
- today it is not so easy to find deep enough surveys that can deliver sufficient numbers of targets for GMACS-sized masks

Existing deep/wide surveys with HST:



JWST focal plane instrumentation:





SuMIRe

Subaru Measurement of Images and Redshifts

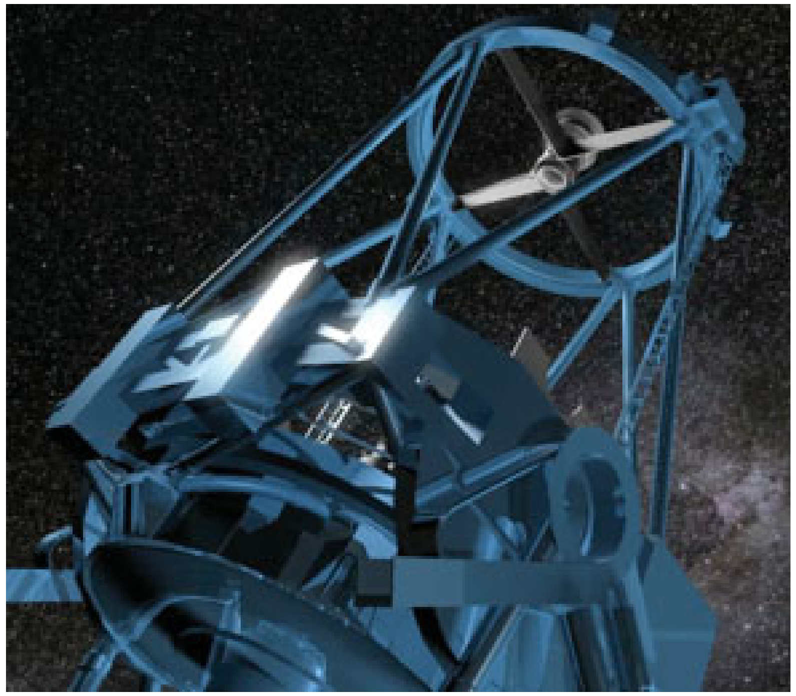
PI: Hitoshi Murayama (IPMU, Tokyo)

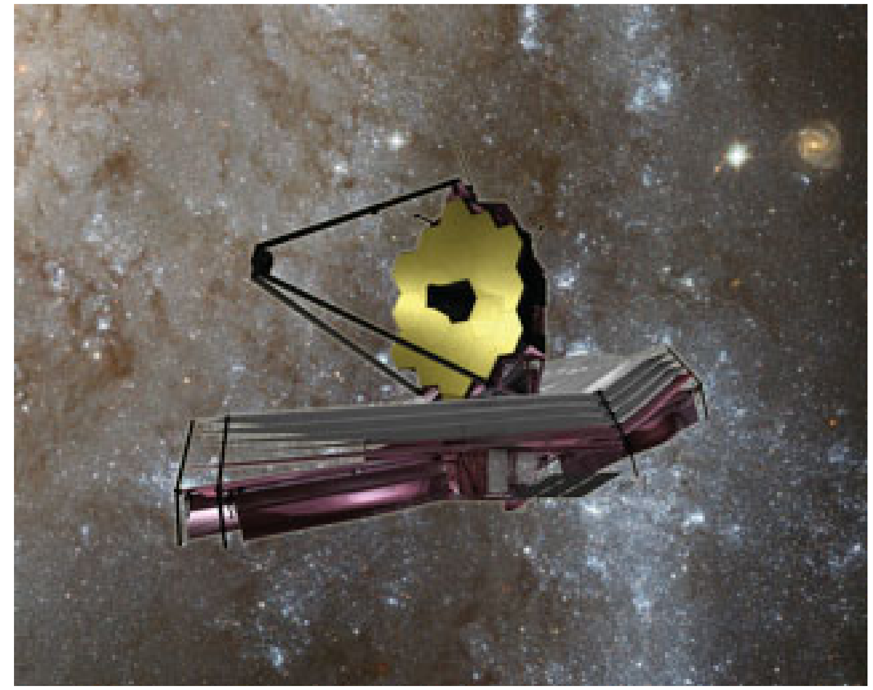
- HyperSuprimeCamera Survey (2014–2019)
- Prime Focus Spectrograph Survey (2020—2024)

Subaru Telescope, Mauna Kea, Hawaii

The Frontiers of Galaxy Evolution: key players

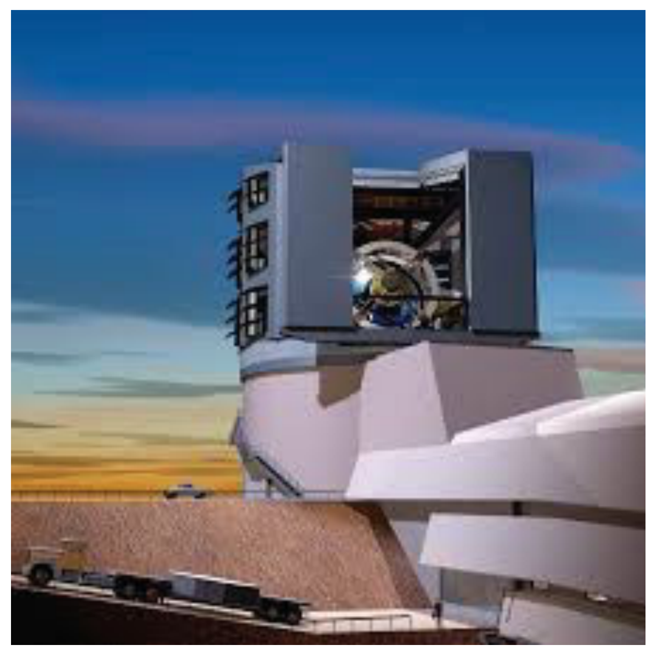
Subaru
large statistical imaging and spectroscopic surveys at z=2-8



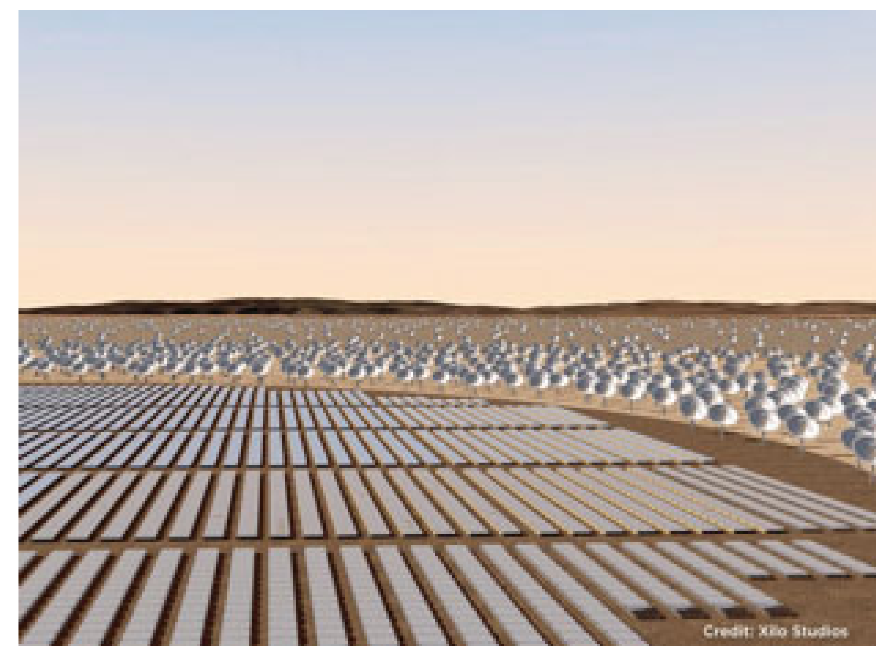


JWST
rest-frame optical diagnostics that are the best indirect probe of escaping LyC radiation

GMT
deep spectroscopy in the rest UV/optical



LSST
deep imaging surveys



SKA
HI and galaxies during reionization

Thank you / roderikoverzier@gmail.com