Exploring Galaxy Evolution from Atomic-Molecular Gas

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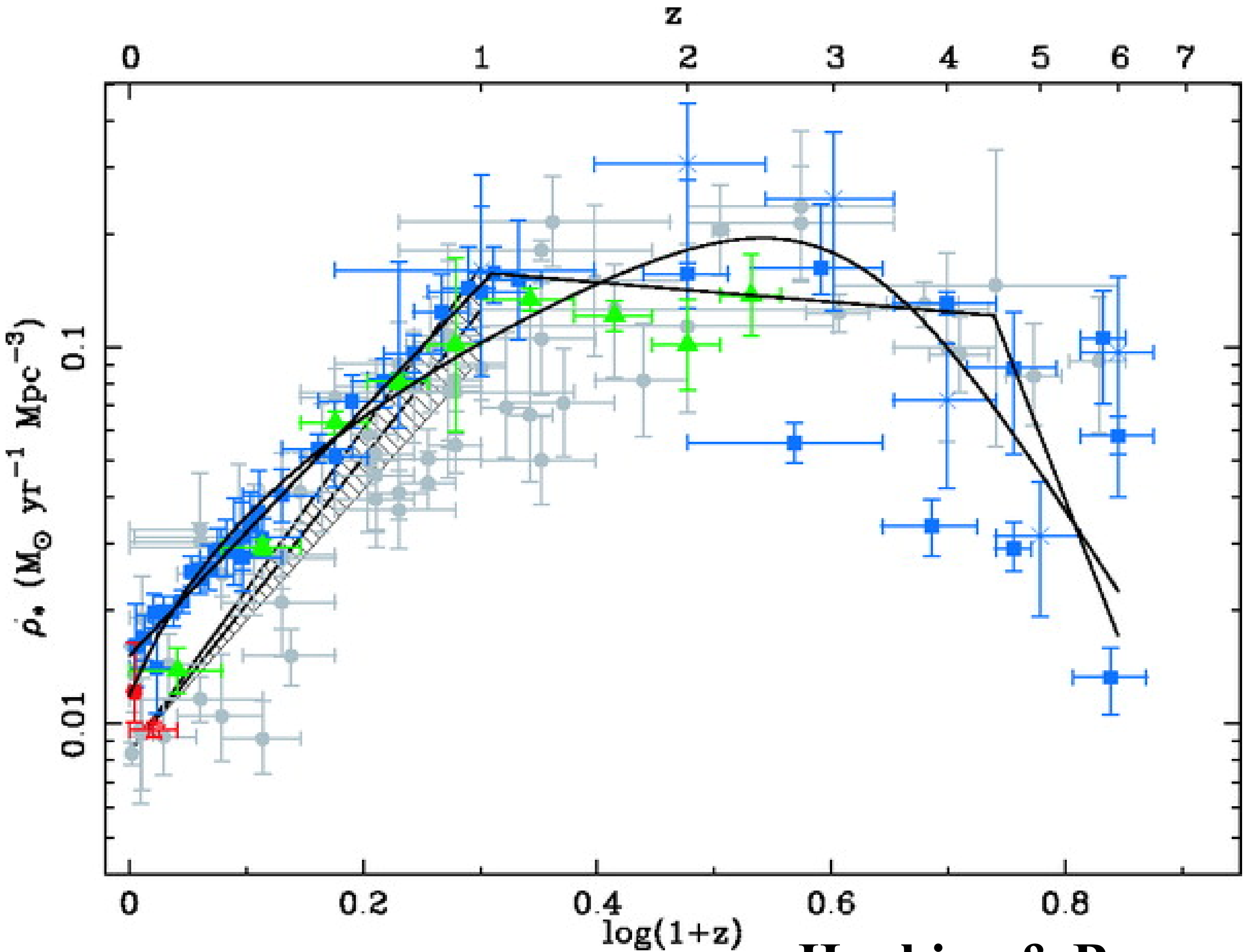
1 Galaxy Evolution in the Evolving Universe

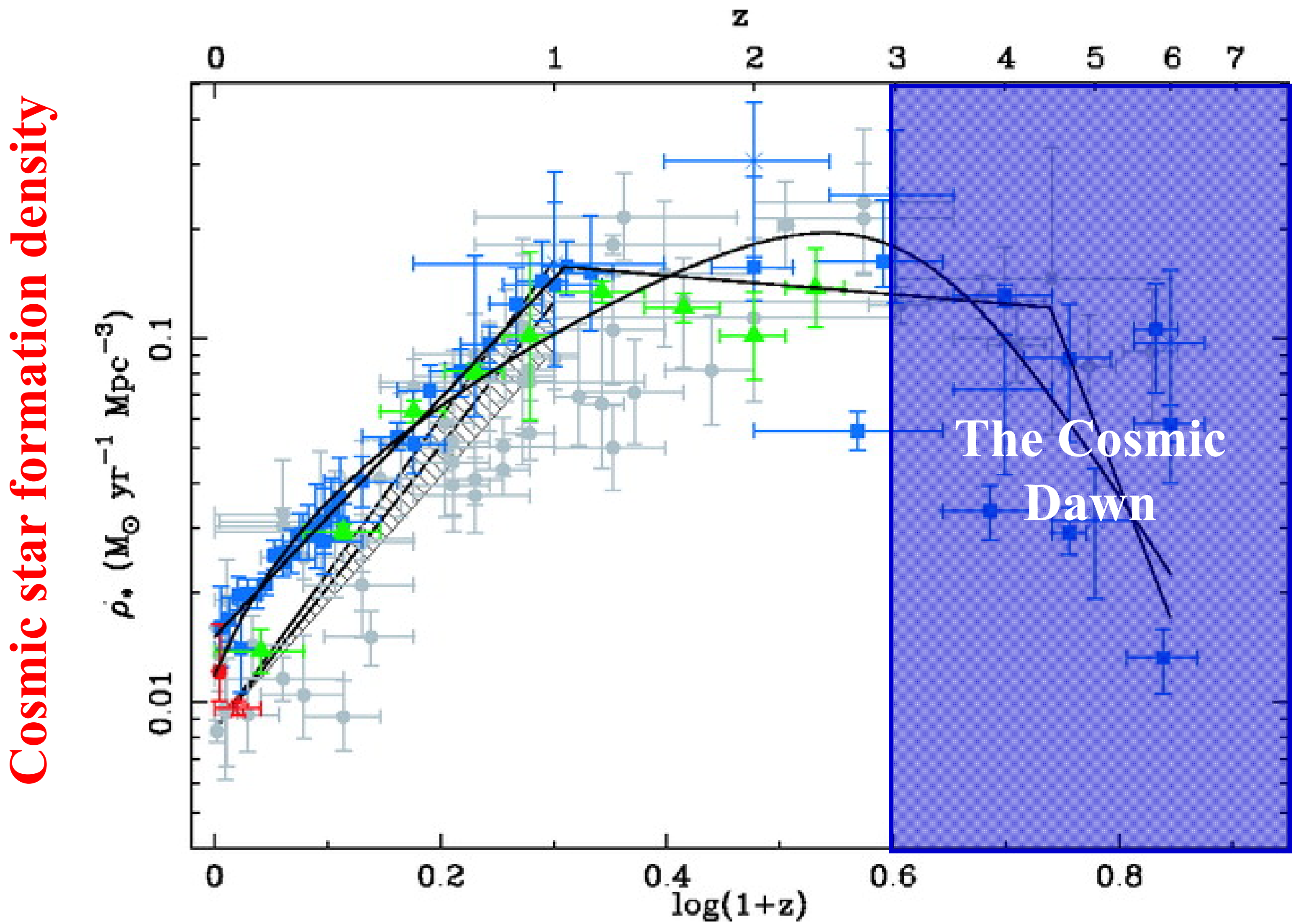
1.1 The cosmic star formation history

Cosmic star formation density



Hopkins & Beacom (2006)

1.1 The cosmic star formation history



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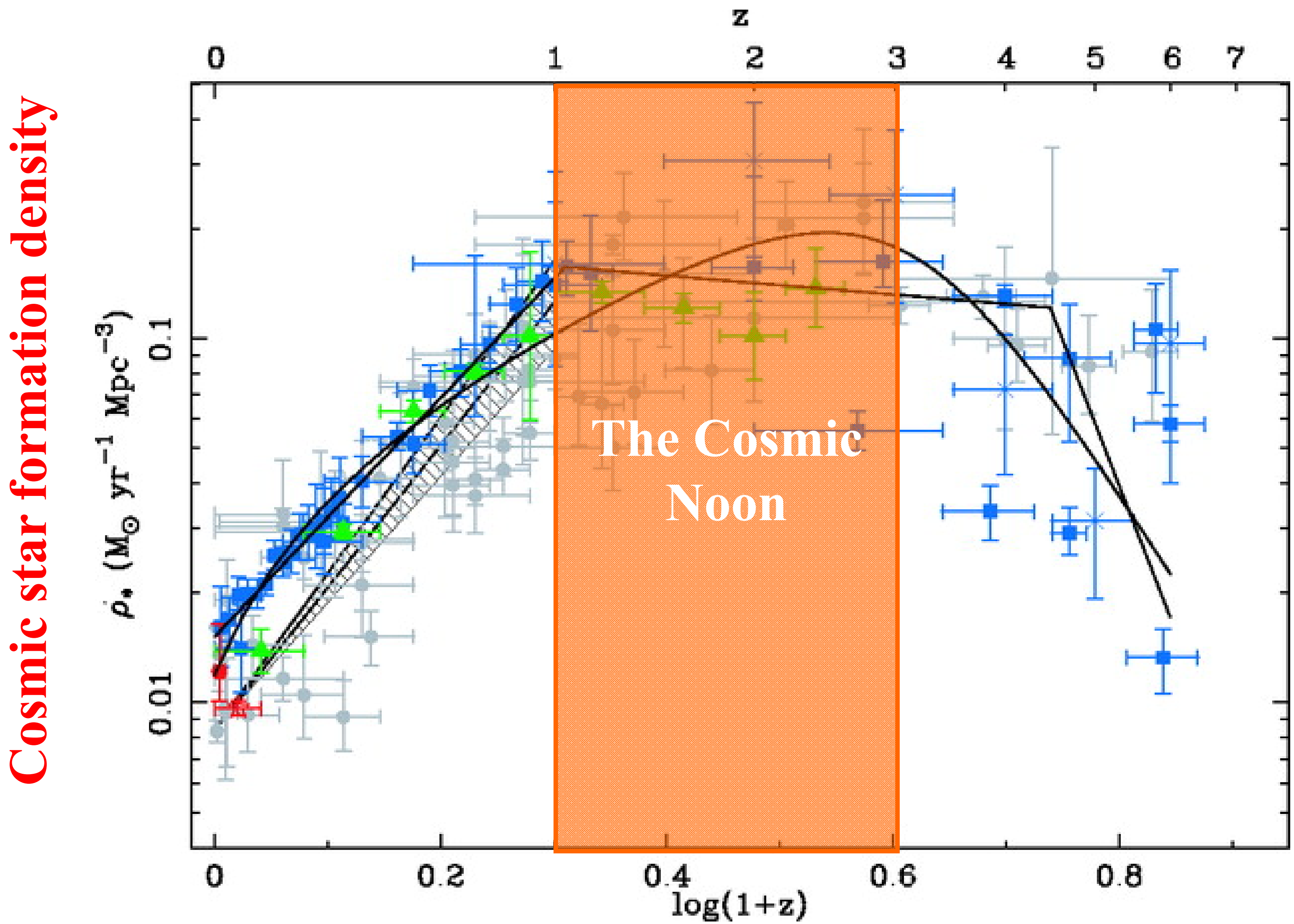

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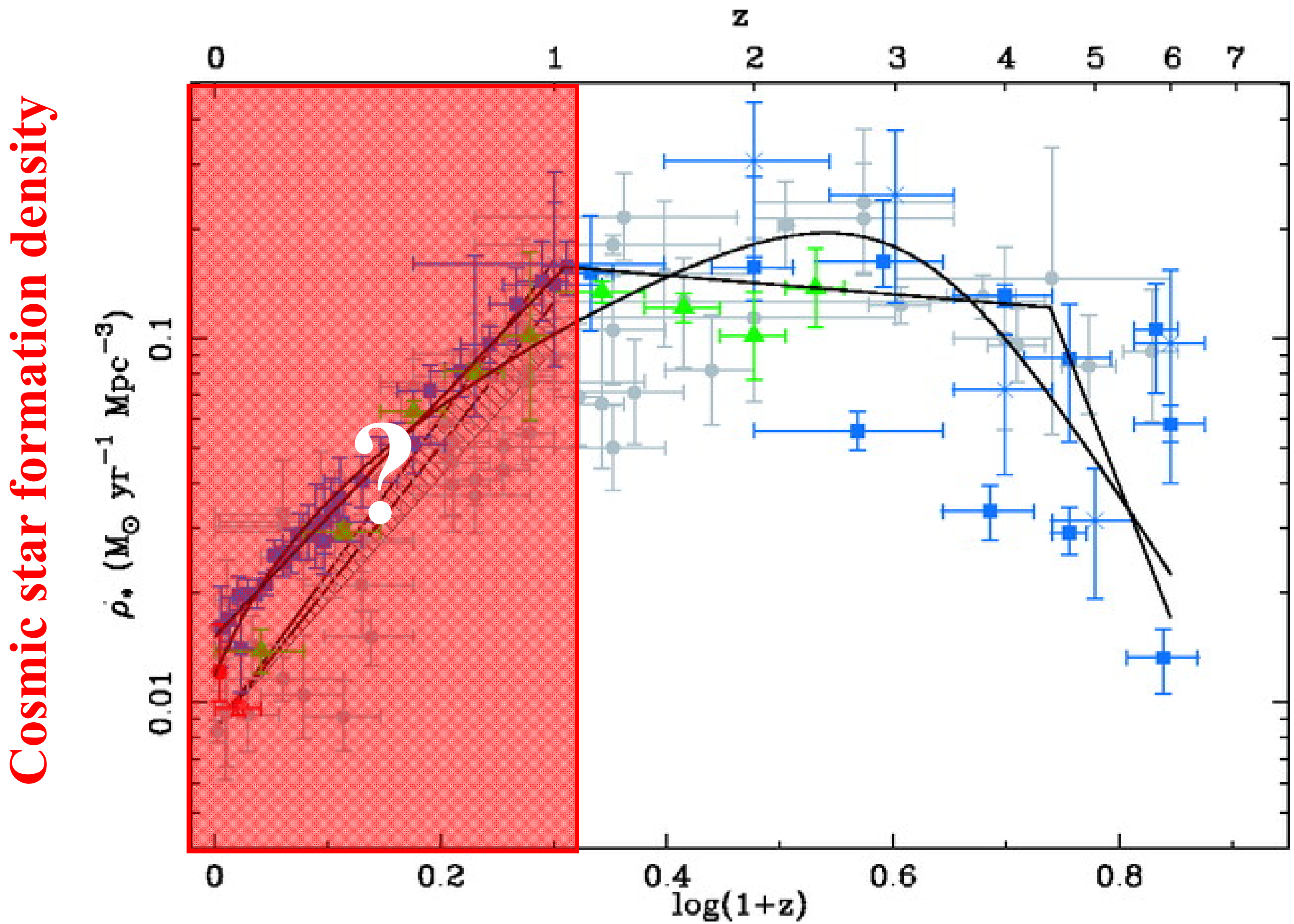

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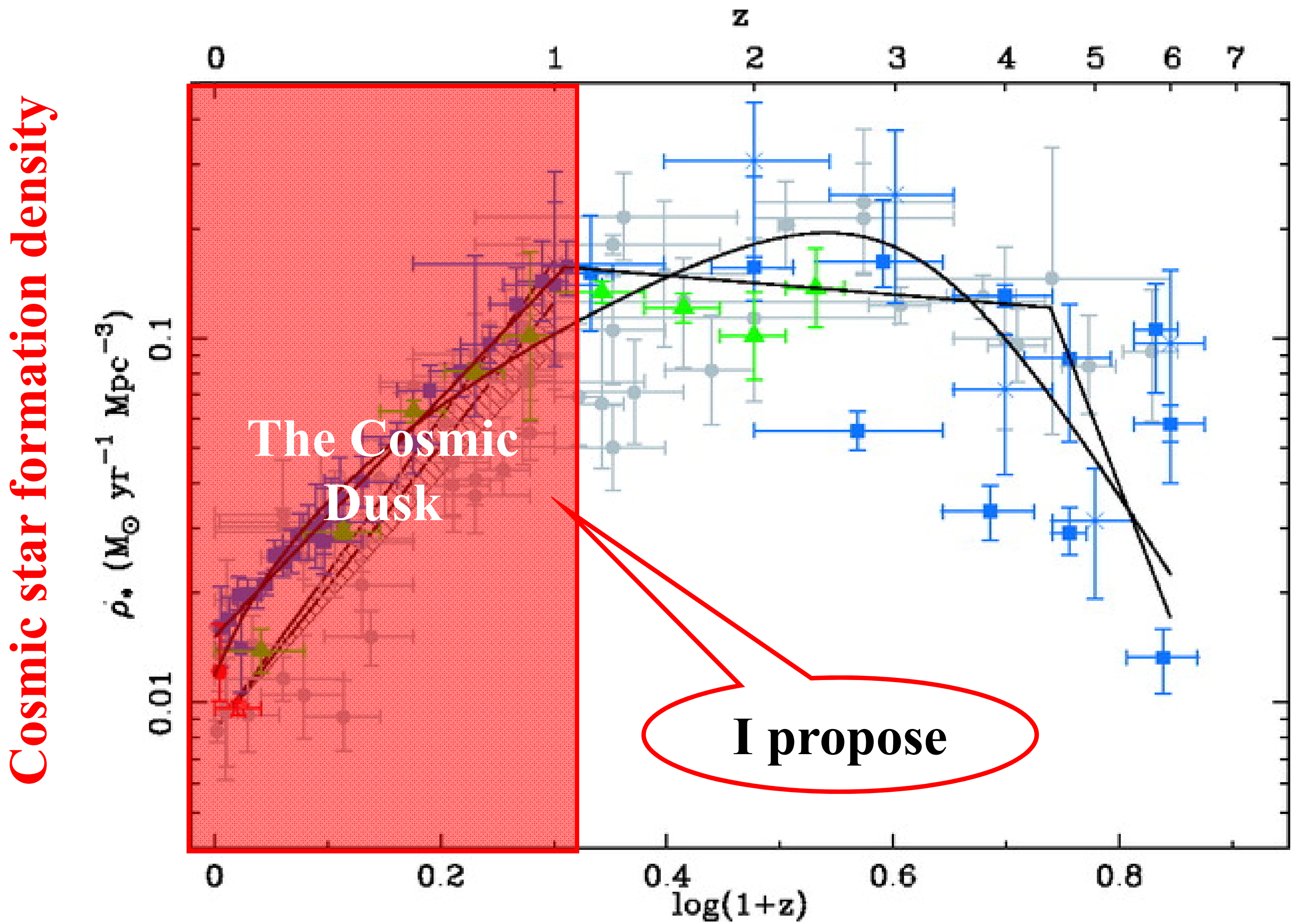

Hopkins & Beacom (2006)

1.2 Cosmic star formation from the gaseous side

Important quantity ever focused: star formation rate (SFR)

Observational SFR indicators

- Ionizing photons from OB stars
- Recombination lines from HII regions
- Forbidden lines from HII regions
- Non-ionizing UV photons
- IR reemission from dust
- PAH band emission from photodissociation regions
- Synchrotron radiation
- X-ray from binaries, etc.

1.2 Cosmic star formation from the gaseous side

Important quantity ever focused: star formation rate (SFR)

Observational SFR indicators

They give information on the SFR, but do NOT tell anything about the transition from gas to stars, which is fundamental in galaxy formation and evolution.
⇒ Importance of gas phase (ISM) observations

Gas will complement the picture of galaxy evolution.

⇨ **We will have a unified picture of the physics of galaxy evolution.**

1.3 Formal goal of the galaxy evolution studies

Galaxy evolution equation in a formal expression:

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Galaxy evolution equation in a formal expression:

$$\begin{aligned}
\mathrm{SFR}(t) &= f_1(\mathrm{SFR}, M_*, M_{\mathrm{mol}}, M_{\mathrm{HI}}, M_{\mathrm{dust}}, M_{\mathrm{halo}}, \delta_{\mathrm{gal}}, \ldots) \\
M_*(t) &= f_2(\mathrm{SFR}, M_*, M_{\mathrm{mol}}, M_{\mathrm{HI}}, M_{\mathrm{dust}}, M_{\mathrm{halo}}, \delta_{\mathrm{gal}}, \ldots) \\
M_{\mathrm{mol}}(t) &= f_3(\mathrm{SFR}, M_*, M_{\mathrm{mol}}, M_{\mathrm{HI}}, M_{\mathrm{dust}}, M_{\mathrm{halo}}, \delta_{\mathrm{gal}}, \ldots) \\
M_{\mathrm{HI}}(t) &= f_4(\mathrm{SFR}, M_*, M_{\mathrm{mol}}, M_{\mathrm{HI}}, M_{\mathrm{dust}}, M_{\mathrm{halo}}, \delta_{\mathrm{gal}}, \ldots) \\
M_{\mathrm{dust}}(t) &= f_5(\mathrm{SFR}, M_*, M_{\mathrm{mol}}, M_{\mathrm{HI}}, M_{\mathrm{dust}}, M_{\mathrm{halo}}, \delta_{\mathrm{gal}}, \ldots) \\
M_{\mathrm{halo}}(t) &= f_6(\mathrm{SFR}, M_*, M_{\mathrm{mol}}, M_{\mathrm{HI}}, M_{\mathrm{dust}}, M_{\mathrm{halo}}, \delta_{\mathrm{gal}}, \ldots) \\
\delta_{\mathrm{gal}}(t) &= f_7(\mathrm{SFR}, M_*, M_{\mathrm{mol}}, M_{\mathrm{HI}}, M_{\mathrm{dust}}, M_{\mathrm{halo}}, \delta_{\mathrm{gal}}, \ldots) \\
&\vdots
\end{aligned}$$

$$x = x(T|T < t)$$

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\end{aligned}
$$

This is the formal and ultimate goal of the studies on galaxy evolution, but clearly it is a substantially complicated problem. New ideas on the methodology are needed to tackle, as well as the physical ideas.

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Galaxy evolution equation in a formal expression:

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&\vdots
\end{aligned}
$$

Especially, the gaseous side should be investigated thoroughly.

1.3 Formal goal of the galaxy evolution studies

Sometimes, some people tend to say

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Sometimes, some people tend to say

Galaxy evolution = high-*z* studies

as if low-*z* studies on galaxy evolution had been completed.

1.3 Formal goal of the galaxy evolution studies

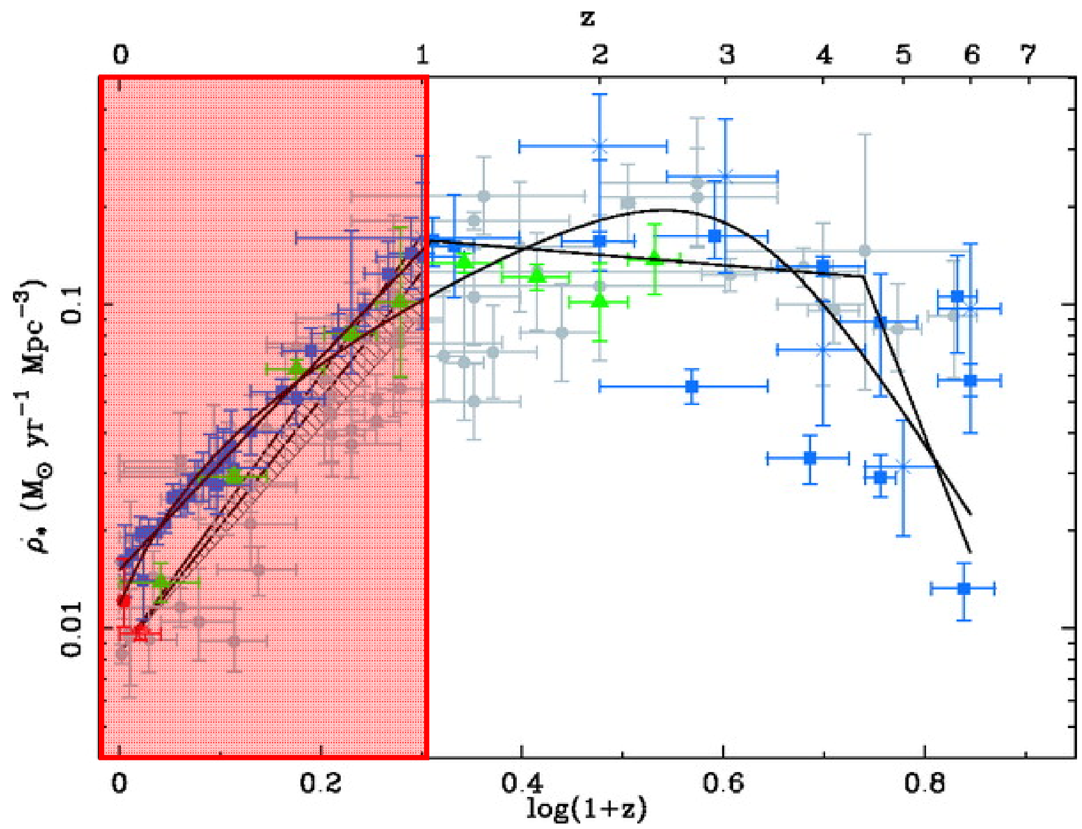
Sometimes, some people tend to say

~~Galaxy evolution = high-z studies~~

DEFINITELY NOT!

We have many fundamental unsolved problems at each redshift (cosmic age).

2 Cosmic Dusk



2 Cosmic Dusk

2.1 Gas mass function

Today, the HI surveys of galaxies are shallow (> mJy), with poor angular resolution.

The HI Parkes All Sky Survey (HIPASS)
The HI Jodrell All Sky Survey (HIJASS)
The Arecibo Legacy Fast ALFA Survey (ALFALFA)
etc.

$< z > \sim 0.01$-0.06
For some dedicated observations, $z < 0.5$ (Kanekar et al. 2016; Fernández et al. 2016)

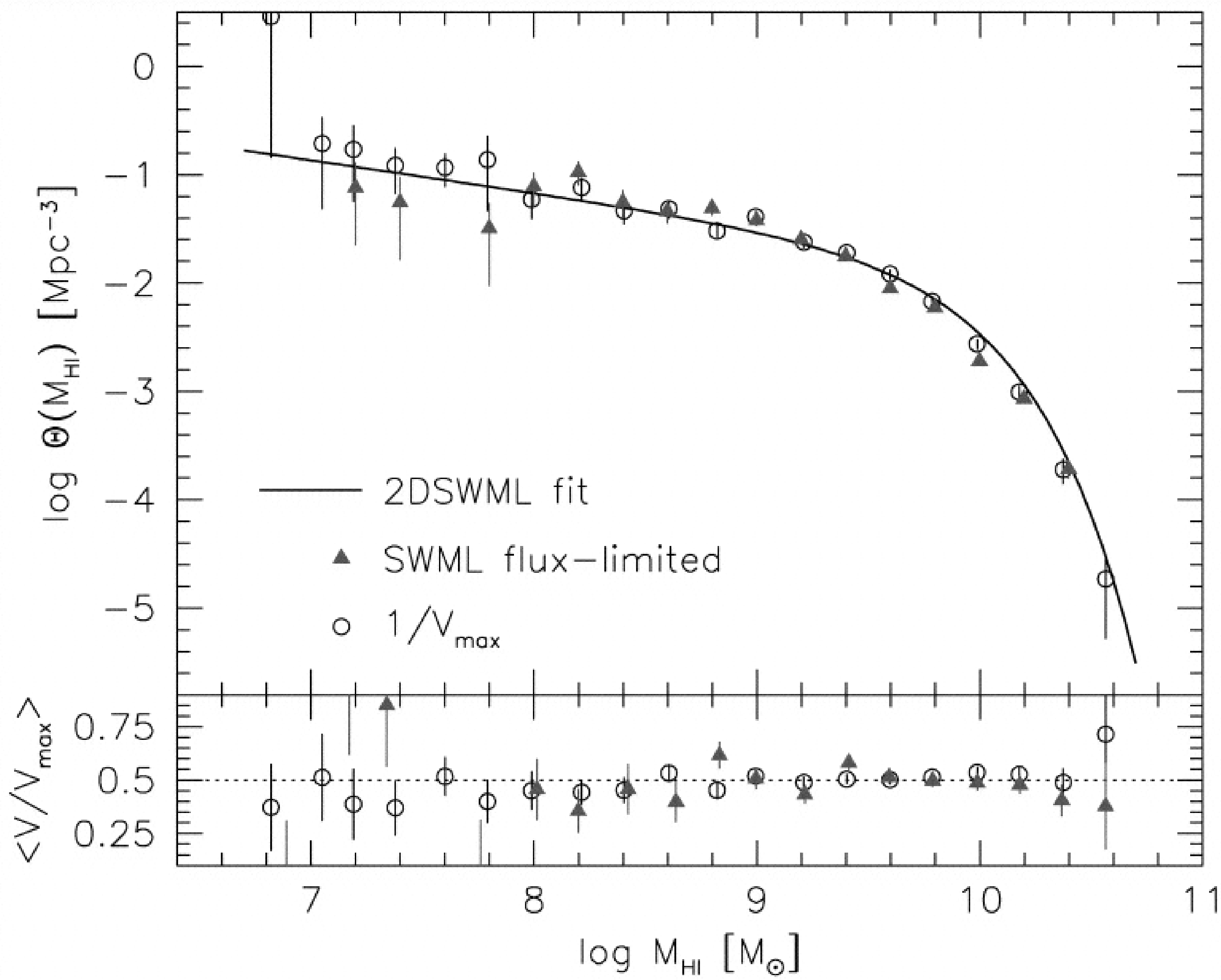
2.1 Gas mass function

The situation for the molecular gas mass function is more serious because of the lack of large-area surveys.

Molecular gas (CO)
Verter et al. (1987): compilation of surveys
Kereš et al. (2003): FCRAO (but optical or FIR selected)
No systematic dedicated survey exists.

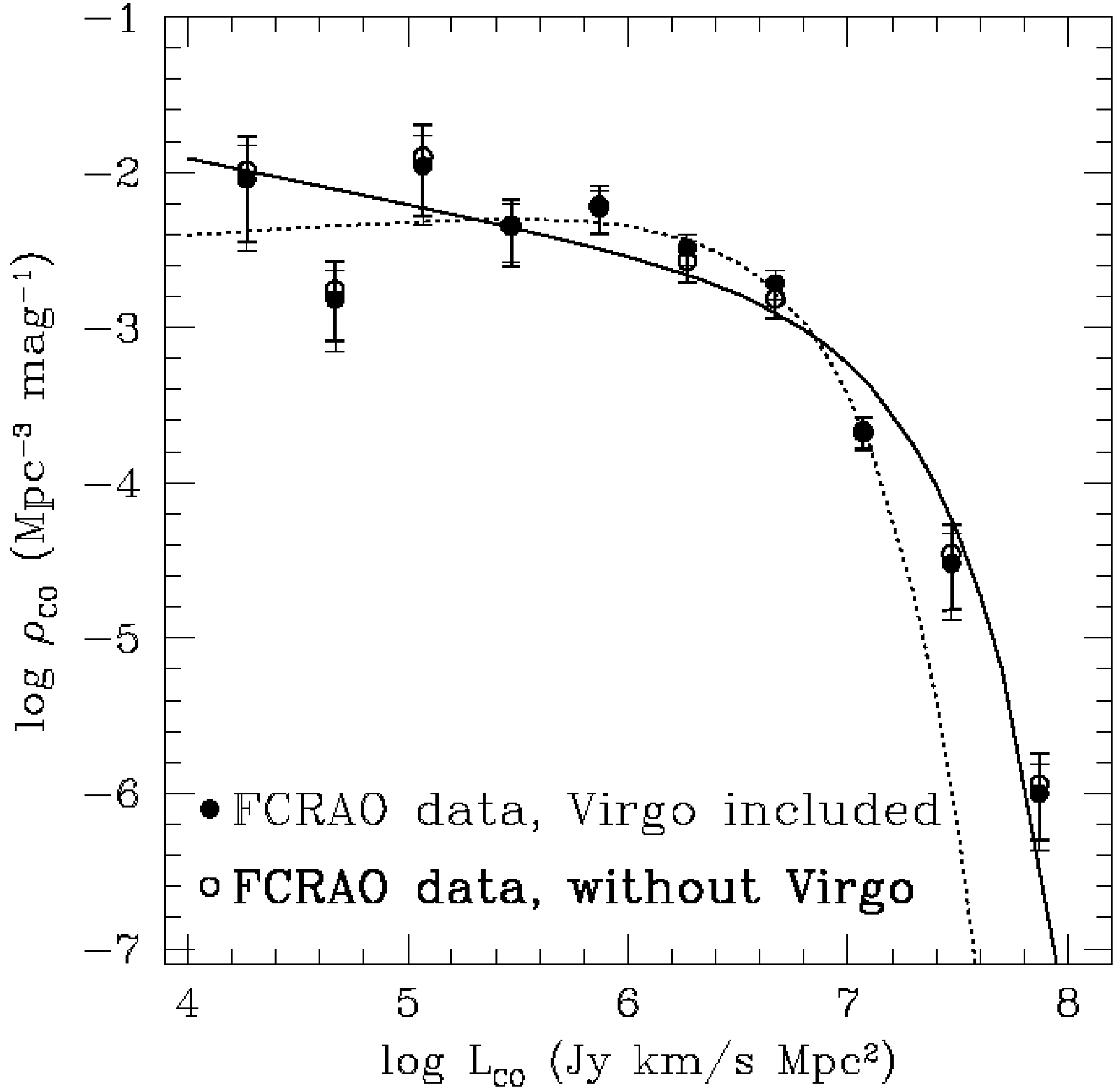
⇒ We can discuss statistically only nearby galaxies, and it is difficult to explore their evolutionary aspects.

HI mass function (HIPASS)



Zwaan et al. (2003)

Molecular (CO) luminosity function



(Kereš et al. 2003)

Need for systematic deep surveys

Only a few systematic studies on the gas mass function have been made mainly because of the limitation from the observational side.

⇩

Need for much larger and deeper surveys, both for atomic and molecular gas!

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Need for much larger and deeper surveys, both for atomic and molecular gas!

Theoretical (semi-analytic) models are studied, but still quite premature to reproduce the gas mass functions.

2.2 Transition from atomic to molecular hydrogen

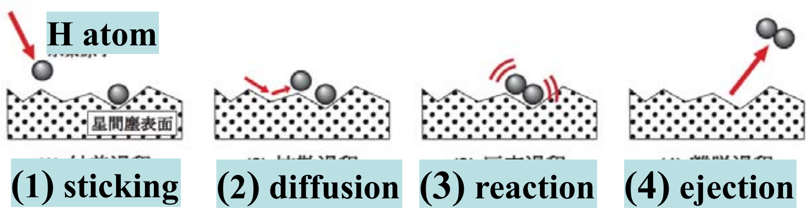
H_2 formation in galaxies is determined by the balance between production and dissociation.

Production

- **2-atom conjugate reaction**
- **3-atom collision reaction**

$$H + H + H \rightarrow H_2 + H.$$

- **Dust surface reaction**
  ⇒most efficient in galaxies



Takahashi (2000)

Dissociation

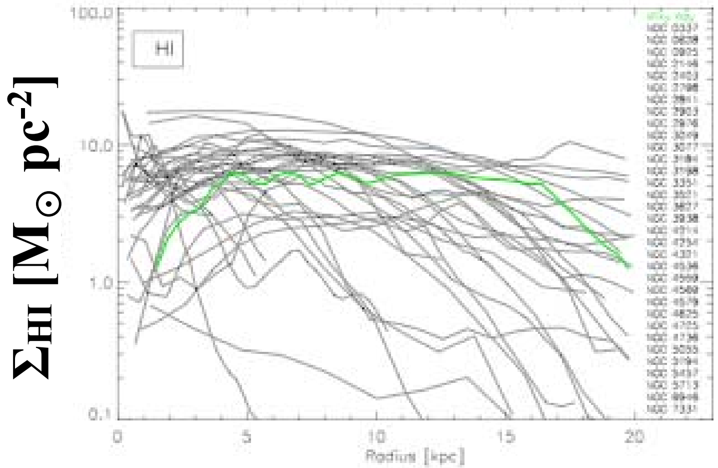
- **Photodissociation by UV**
  Not efficient in a dense dusty molecular clouds because of self-shielding.
- **Dissociation by cosmic rays**
  Dissociate H_2 in molecular clouds.
- **Dissociation by collision**
  Contribution is small.

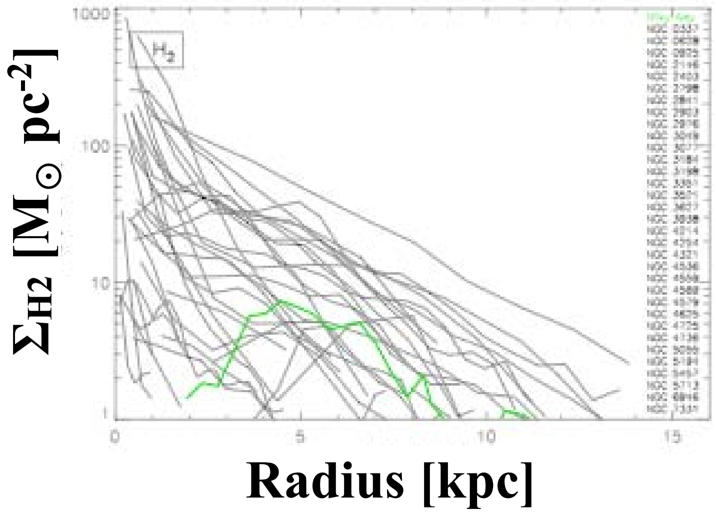
(e.g. Gould & Salpeter 1963; Draine & Bertoldi 1996)

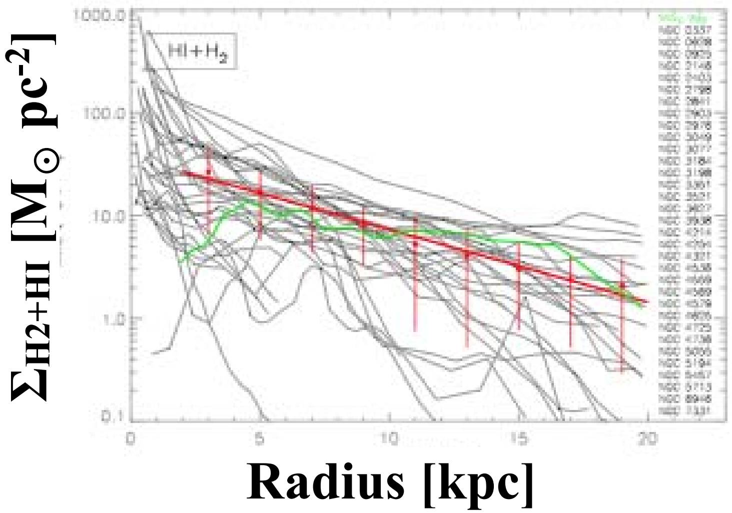
H_2 and HI in galaxies

$$f_{\rm mol} = \frac{\Sigma_{\rm H_2}}{\Sigma_{\rm total}}$$

- **For late types, f_{mol} ~ 25-30 %**
- **Radial decrease.**
  At galactic center, f_{mol} ~1







Bigiel & Blitz (2012); Boselli et al. (2014)

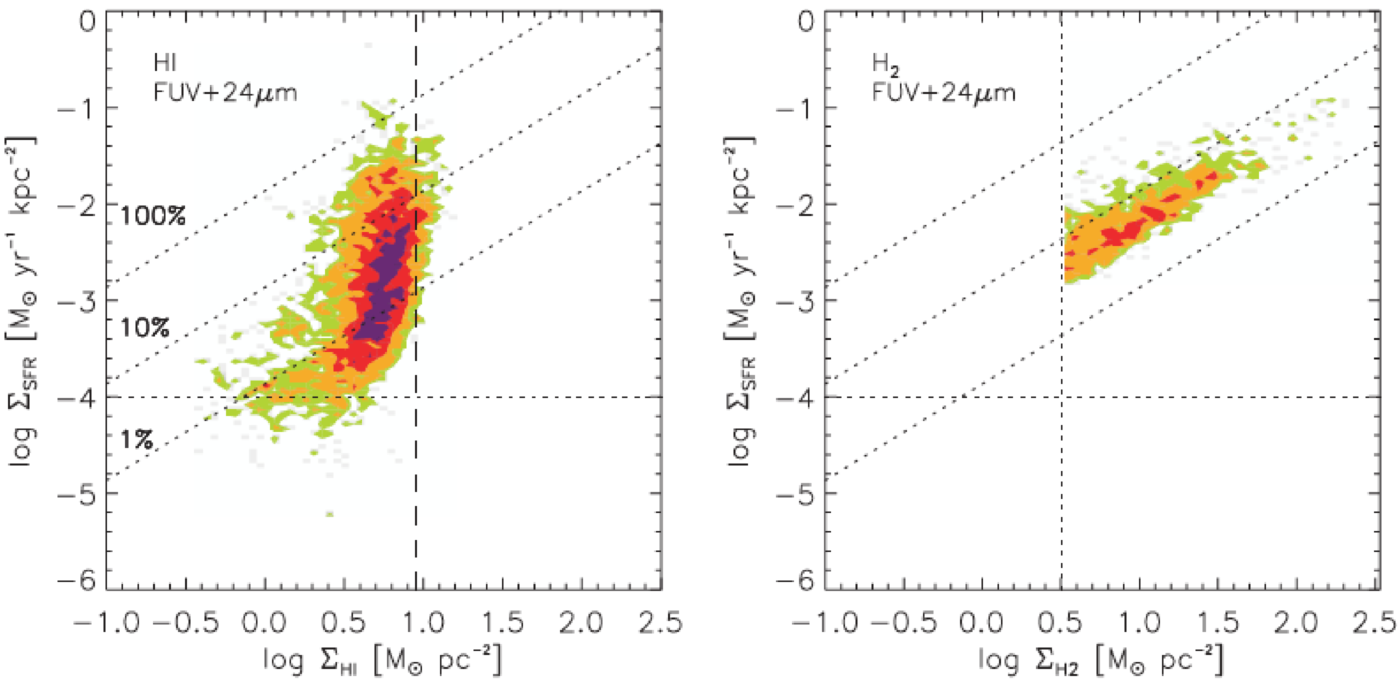
Transition from HI to H_2

Column density of gas required to have enough shielding (assuming $Z = Z_\odot$):

$$\Sigma_{H2} \sim 10\ M_\odot pc^{-2}$$

$$N_{HI} \sim 10^{21}\ cm^2$$

These values agree with observation of nearby late-type galaxies.



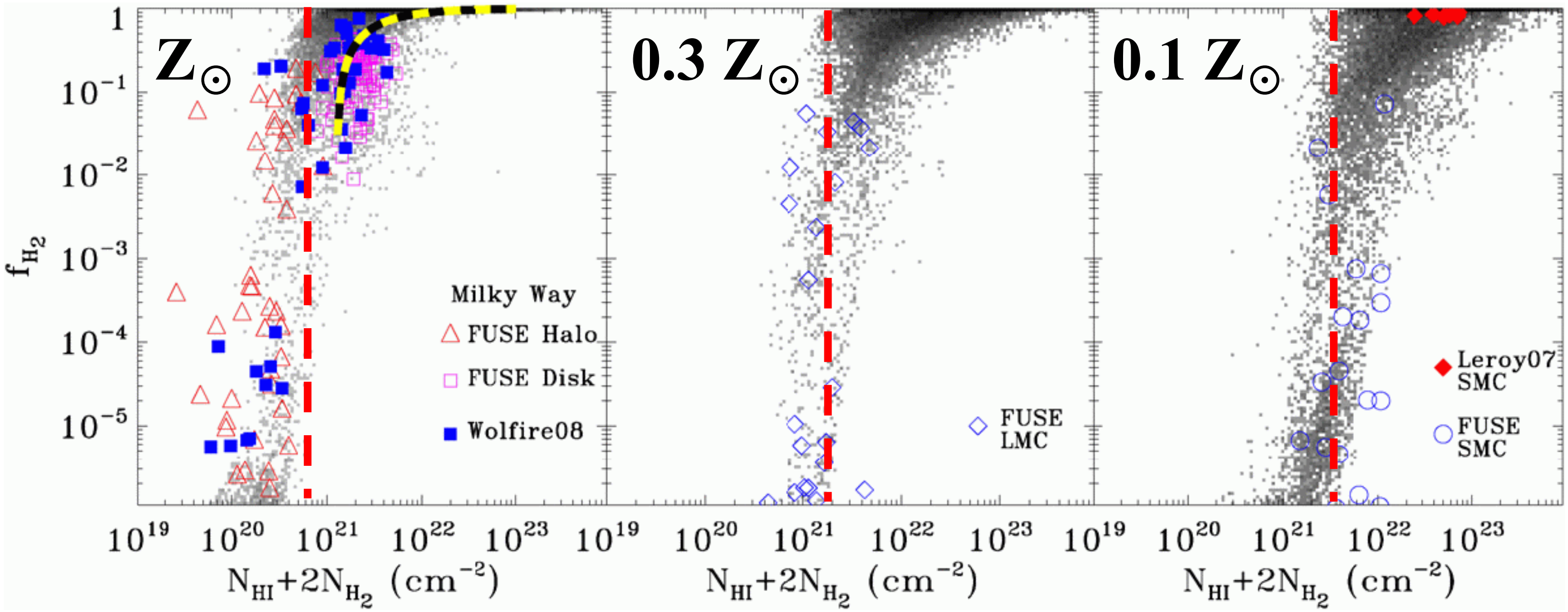
(Bigiel et al. 2008)

Transition from HI to H_2

Transition column density is determined by metallicity (Gnedin et al. 2009): Metal-poor molecular clouds do not contain much dust

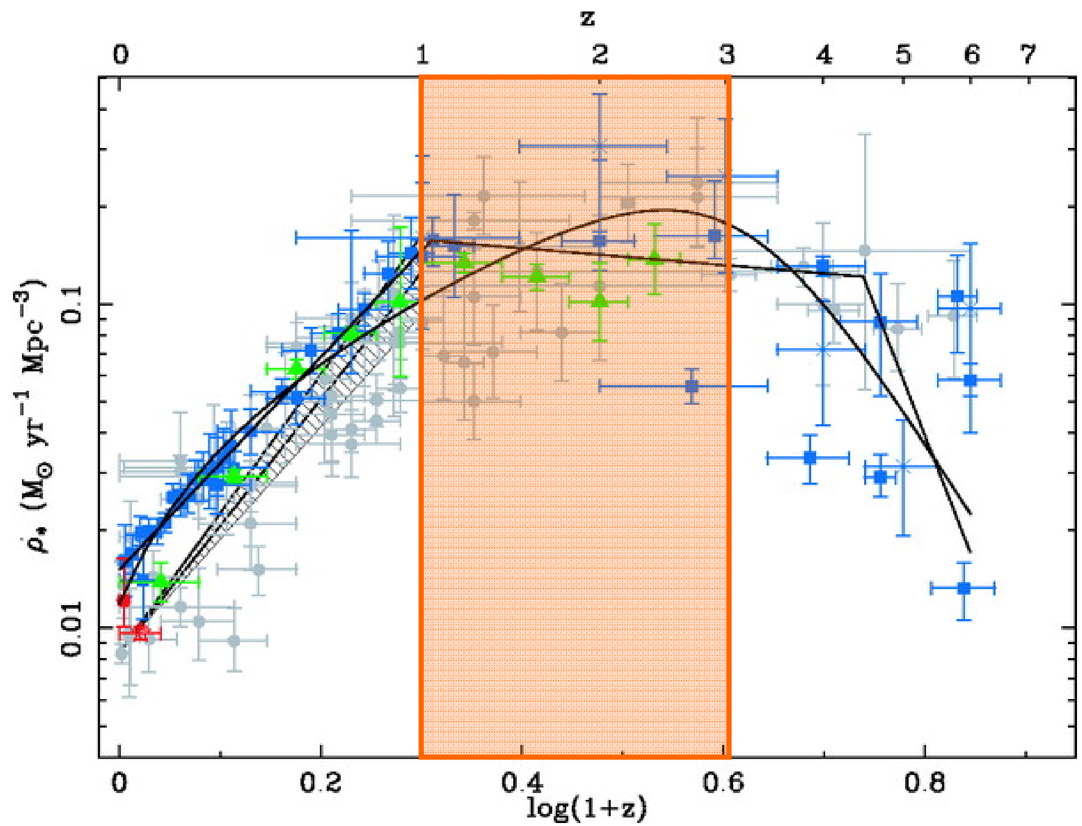
⇒ Critical N_{HI} becomes higher.

Various topics are yet to be solved.



Gnedin et al. (2009)

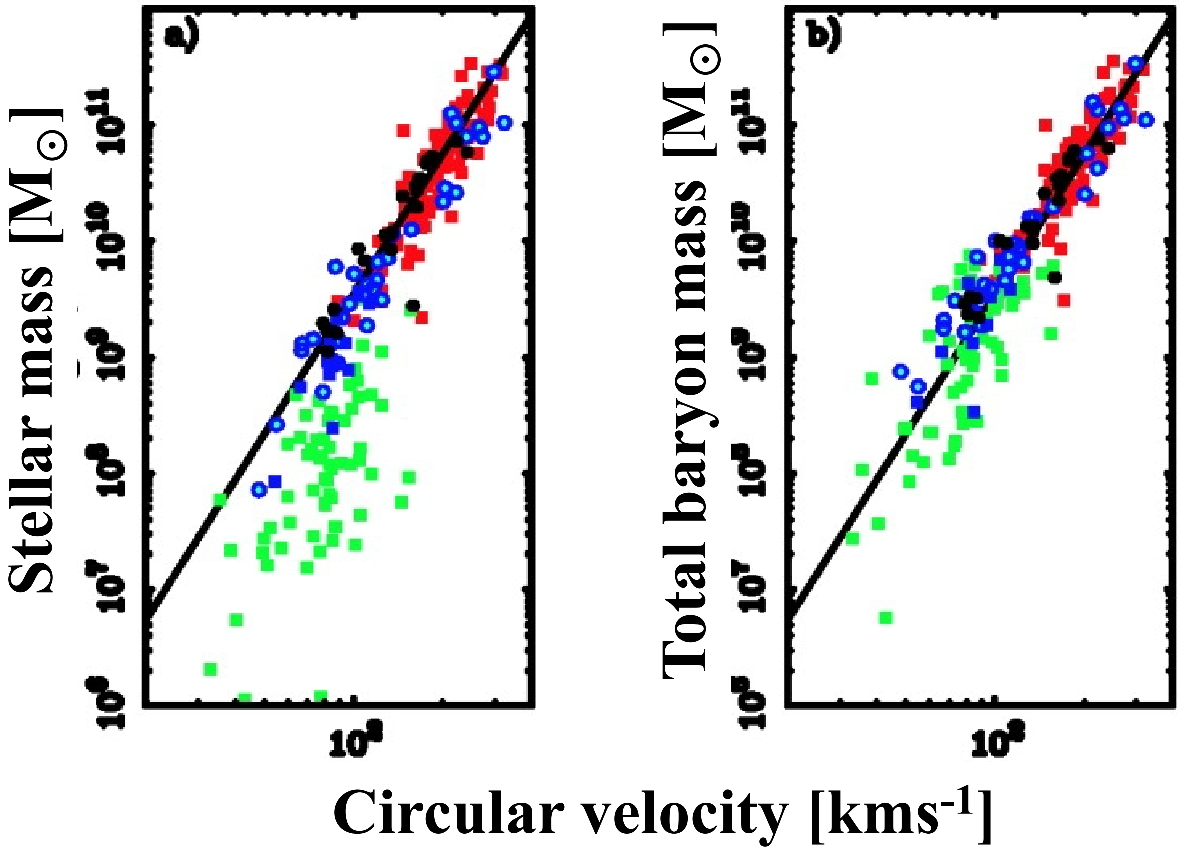
3 Cosmic Noon



3 Cosmic Noon

3.1 Scaling laws including gas properties

Baryonic Tully-Fisher (BTF) relation



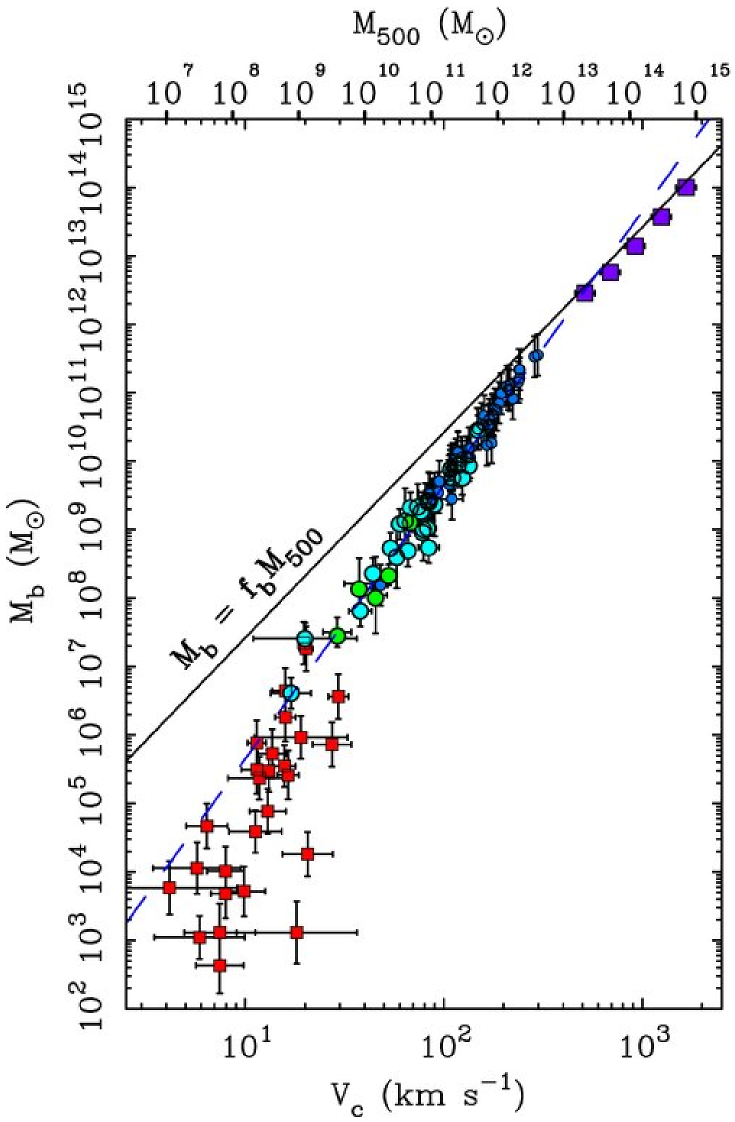
$$M_d = AV_c^b$$

$$b = 3.98 \pm 0.12$$

McGaugh et al. (2000)

If we consider the HI mass and evaluate the TF relation with baryonic mass, the linearity is regained (McGaugh et al. 2000).

The “extended” BTF



McGaugh et al. (2010)

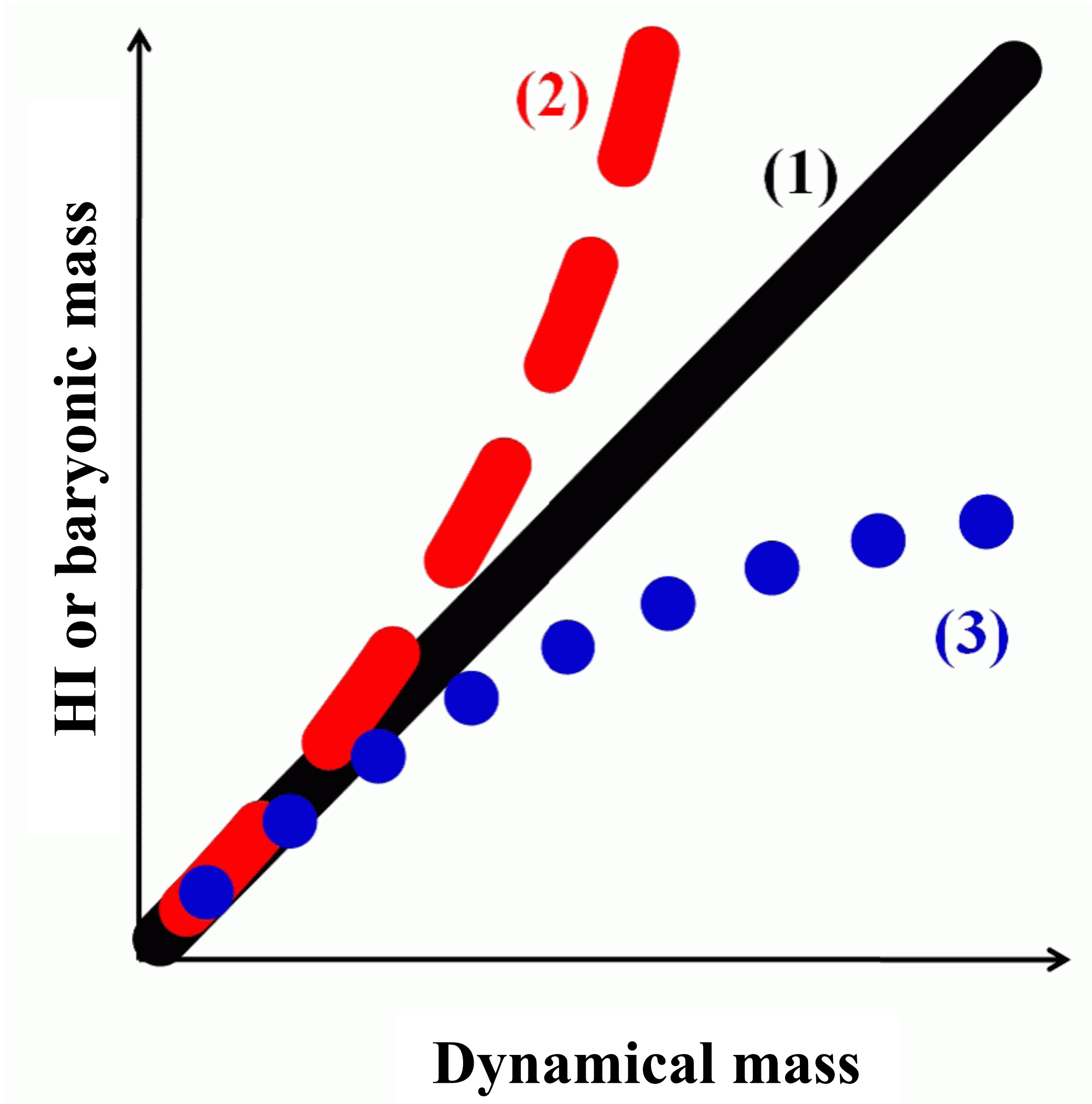
The extended BTF has different slopes for the dSphs, normal galaxies, and galaxy clusters. The slope becomes shallower for larger objects.

⇒ Feedback?

However in current studies, gas-rich dwarfs are missing in the sample.

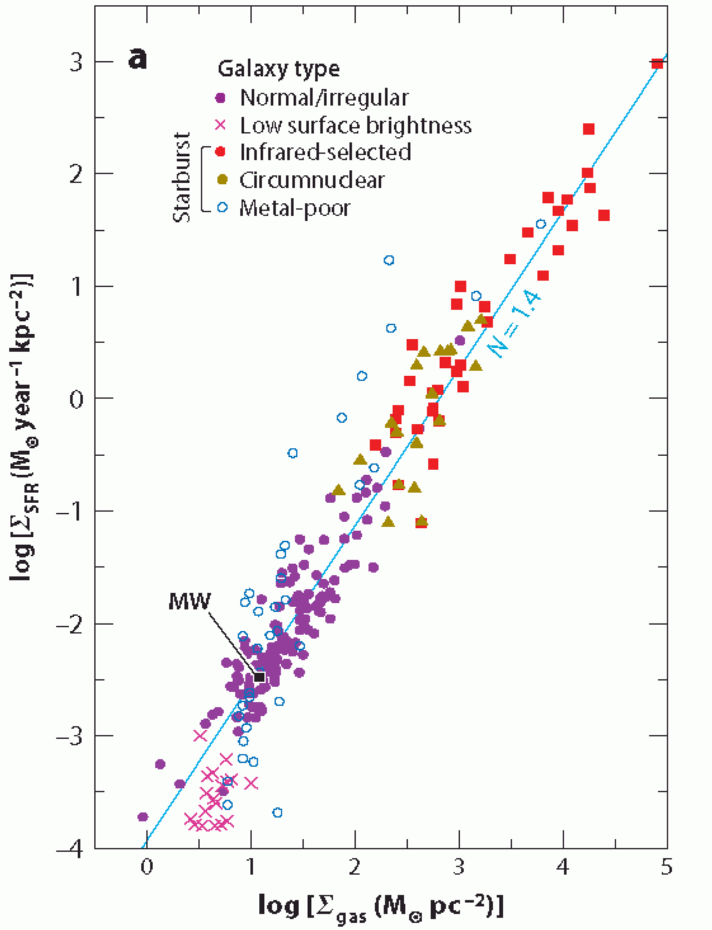
Toward lower HI masses!

BTF as an HI-dynamical bivariate mass function



Kennicutt-Schmidt law

By considering the size of a galaxy, we can discuss the relation between surface densities of gas and SFR. This is know as the Kennicutt-Schmidt law.



The classical Kennicutt-Schmidt law is the relation between the surface densities of gas and SFR.

A single power law is found in a wide range of gas surface density, but the slope is still a matter of debate.

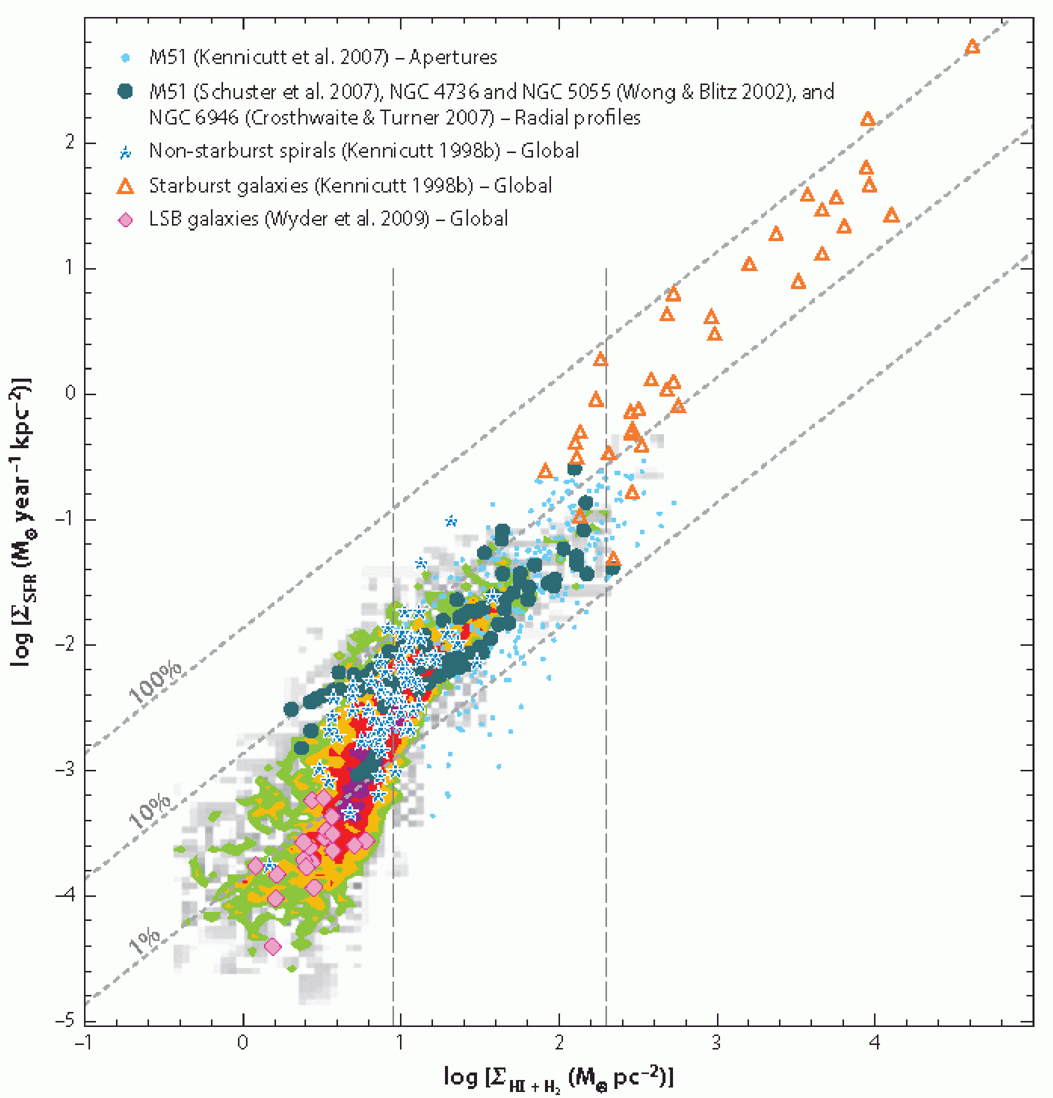
Kennicutt & Evans (2012)

Kennicutt-Schmidt law

What the K-S law shows is the relation between total gas mass (HI + H_2) and SFR.

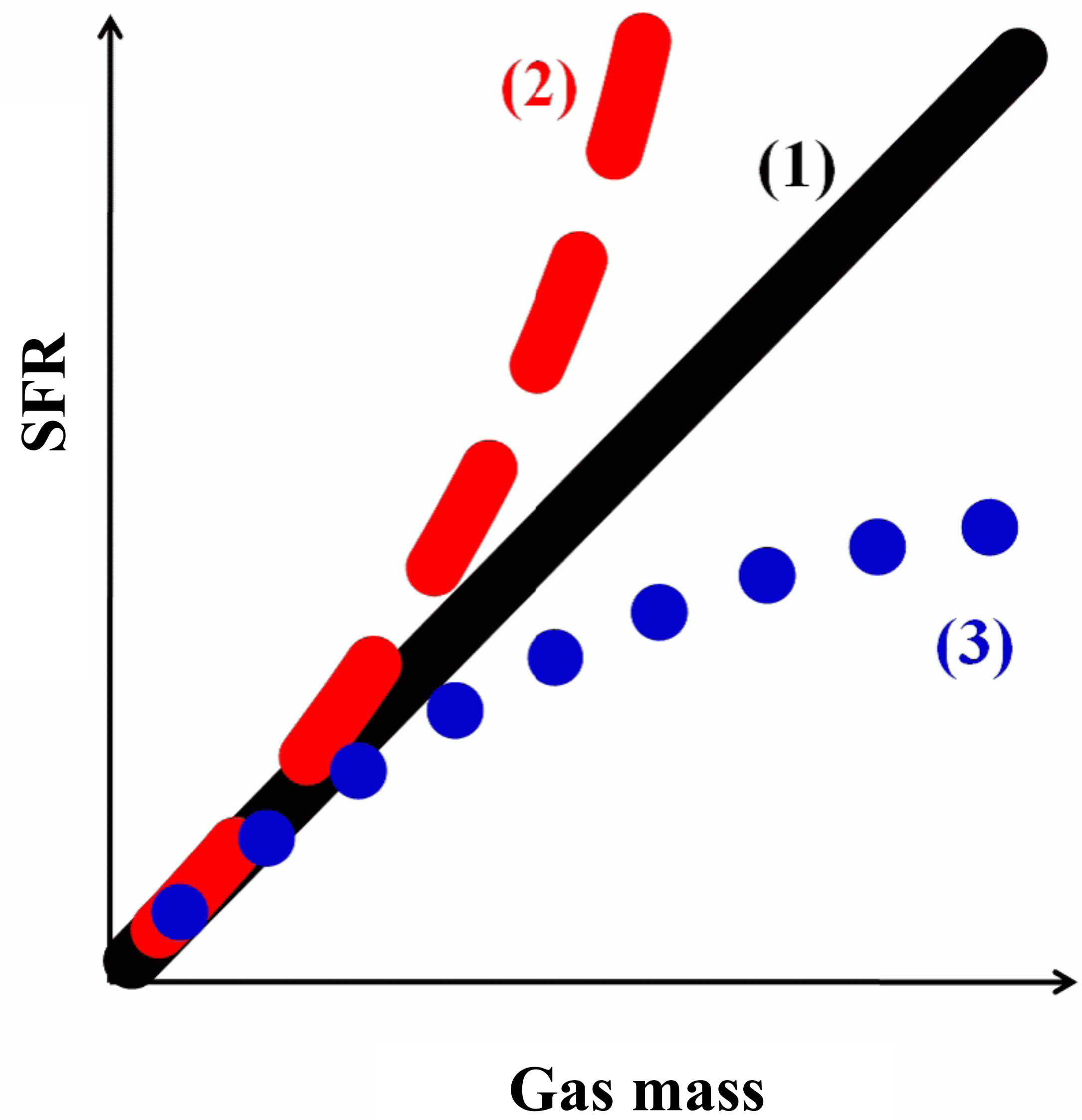
We need observations of HI as deep as CO ($1 < z < 2$), to explore the evolution of the K-S law.

Synergy with observations of molecules is important!



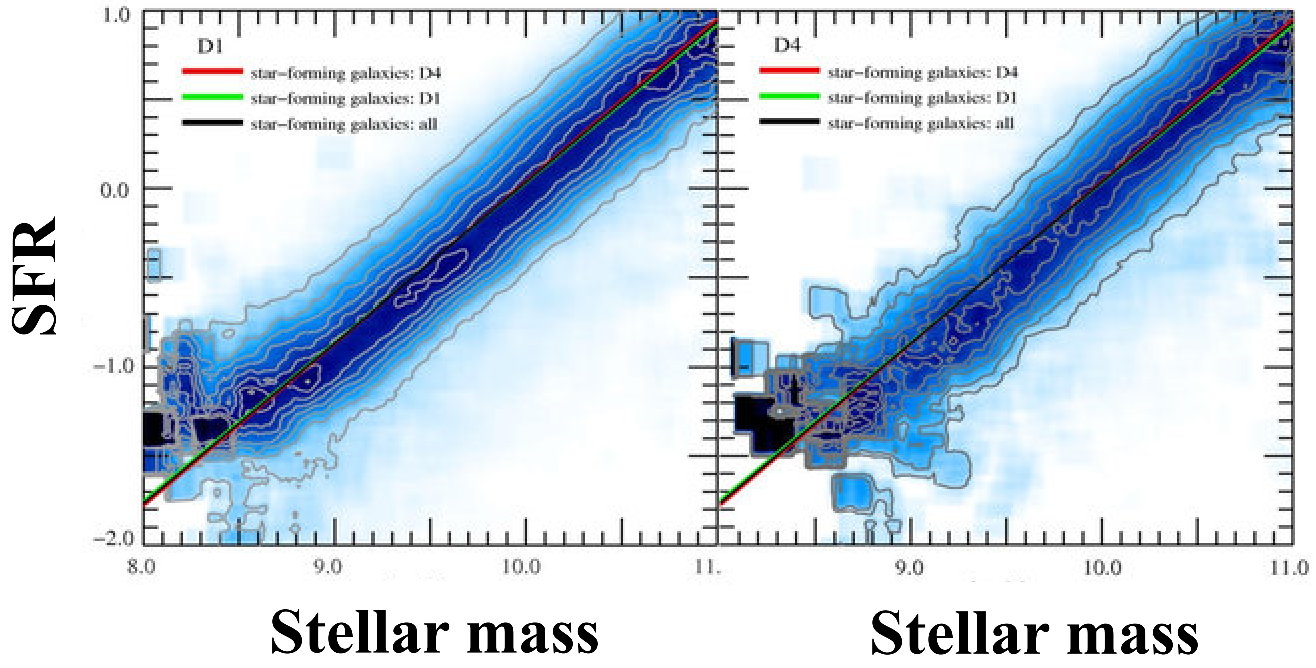
Bigiel et al. (2008)

K-Slaw as an M_{gas}-SFR bivariate function



Star forming galaxy main sequence

Since the SFR is the most interesting quantity, we want to examine the scaling relations including the SFR.



Peng et al. (2010)

A prominent sequence of SF galaxies is found on the stellar mass-SFR plane: star formation main sequence (SFMS).

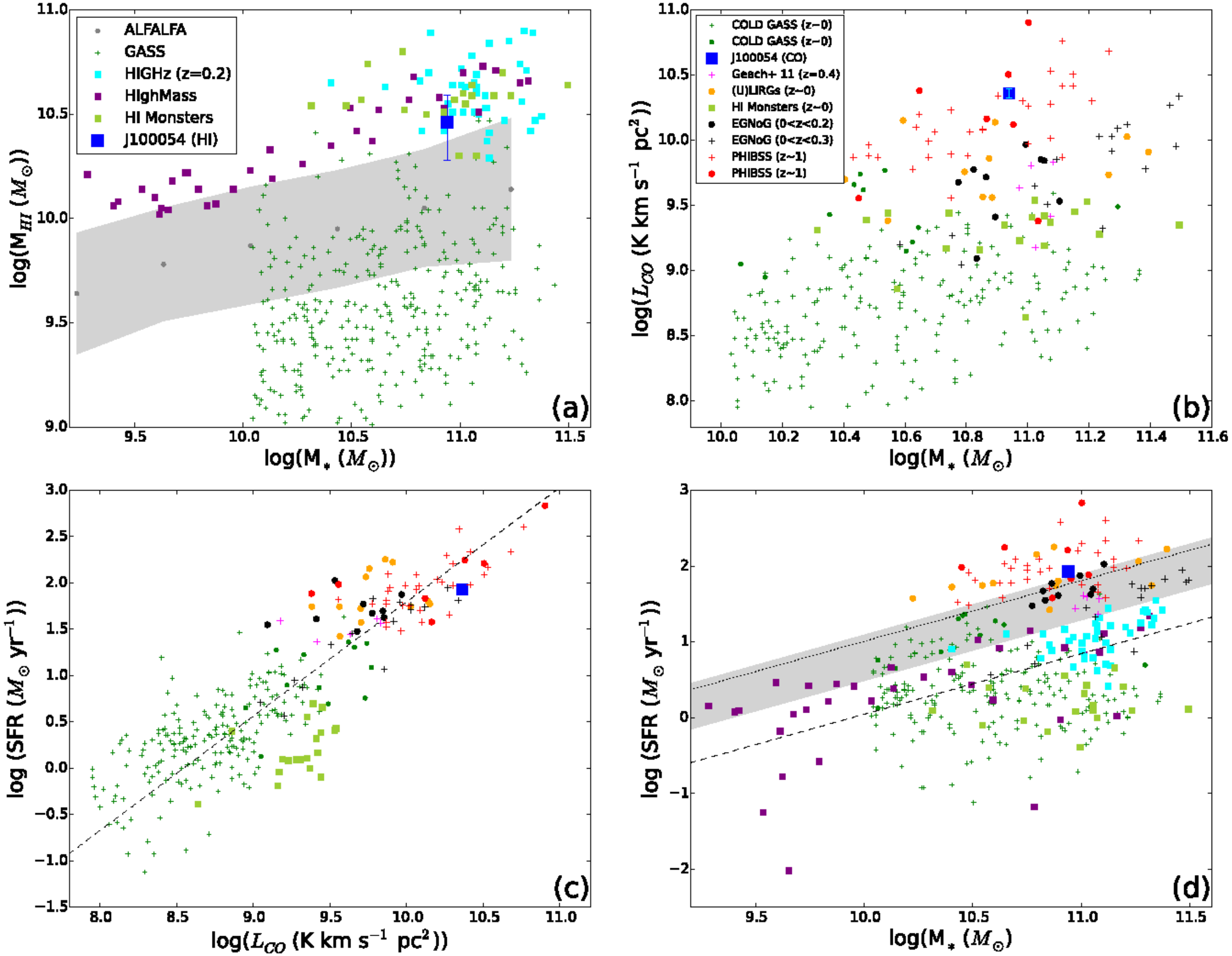
Star forming galaxy main sequence

The star formation main sequence consists of secularly evolving star-forming galaxies (i.e., not merging galaxies).

Relation to various physical properties are examined.
Especially the dependence on the gas amount is of current interest (Genzel et al. 2012; Fernández et al. 2016).

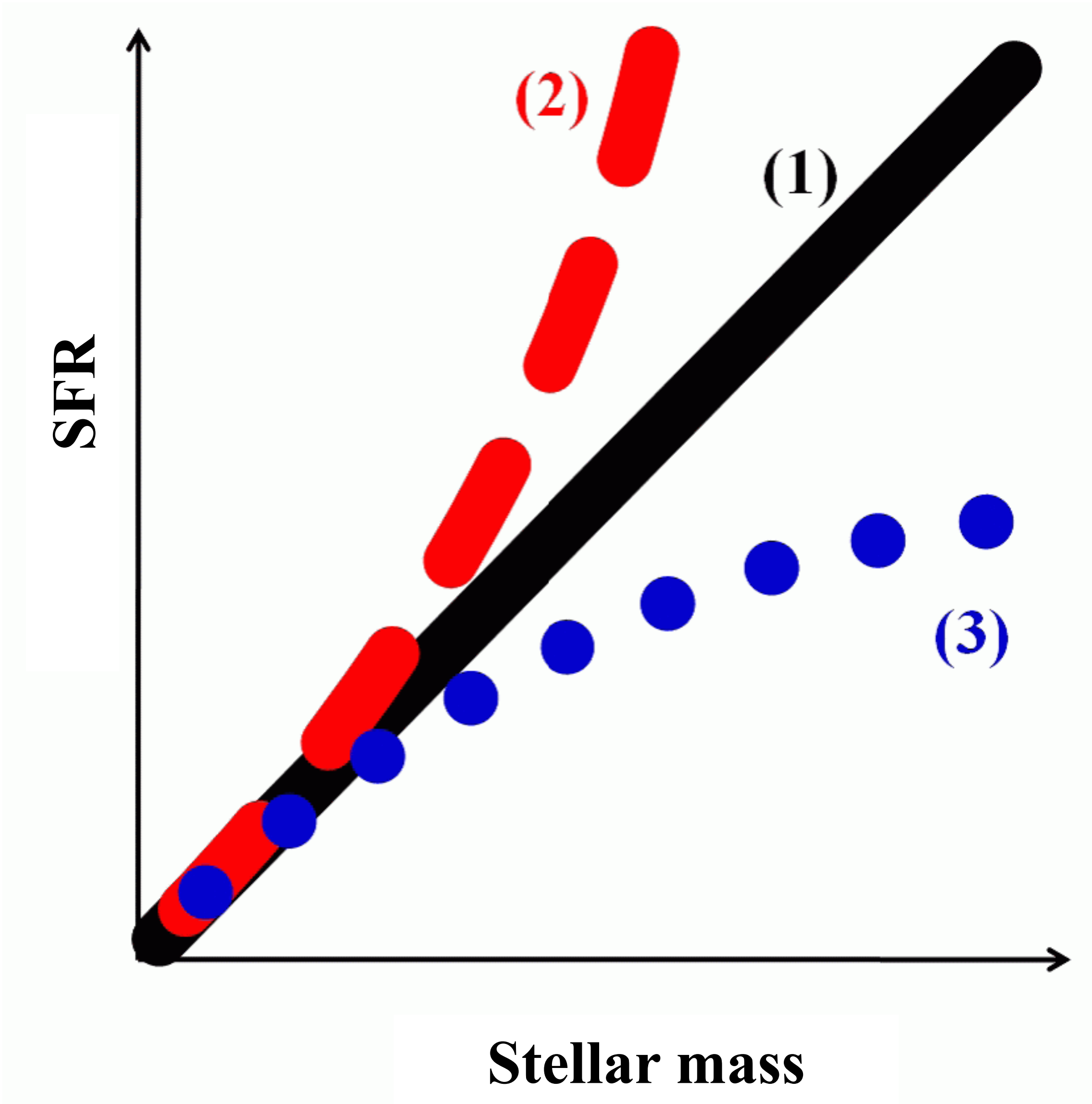
Observations of CO reach $1 < z < 2$, but are not yet a survey.
HI is far from reachable at these redshifts.

Star forming galaxy main sequence



Kanekar et al. (2016)

SFMS as an M_*-SFR bivariate function



A bridge from resolved to global properties

Scaling relations themselves do not tell anything about their governing physics. We need various additional observations and sophisticated analysis to reveal the relevant physical processes (e.g., Kennicutt & Evans 2012).

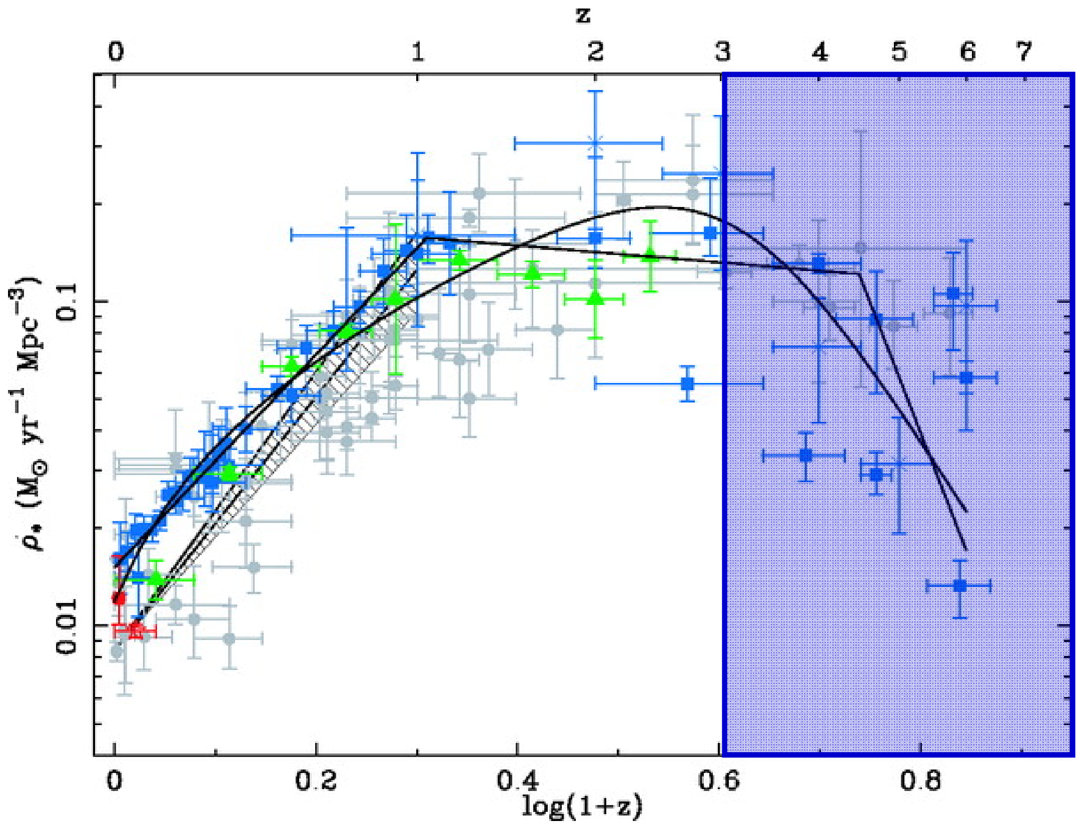
Resolved observation

⇒ HI-H_2 transition
Relation to metallicity (or rather dust amount)
Emerging scale of the global scaling laws

Global scaling laws

⇒ Unification of all the scaling laws as a multivariate distribution function
⇒ Fundamental (multidimensional) relation

4 Cosmic Dawn



4 Cosmic Dawn

4.1 Gas observation of ultra-high redshift galaxies?

Perhaps first galaxies might have formed from halos containing a large amount of HI.

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However…

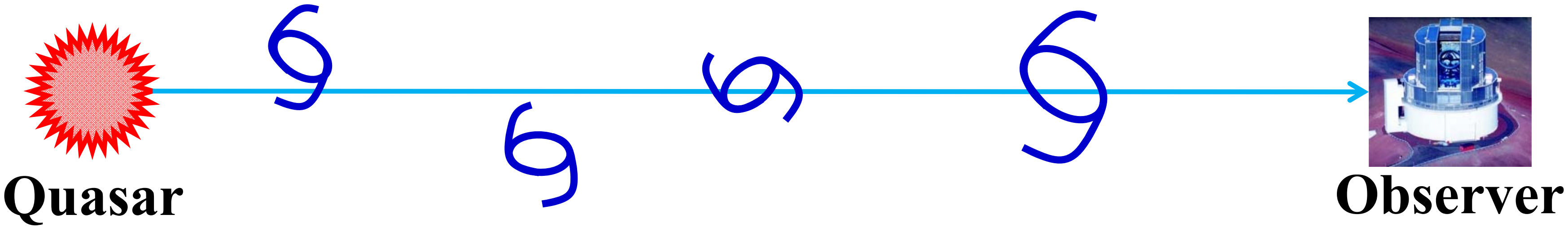
Even with SKA2, it would not be easy to detect emissions from individual galaxies at $z > 4$.

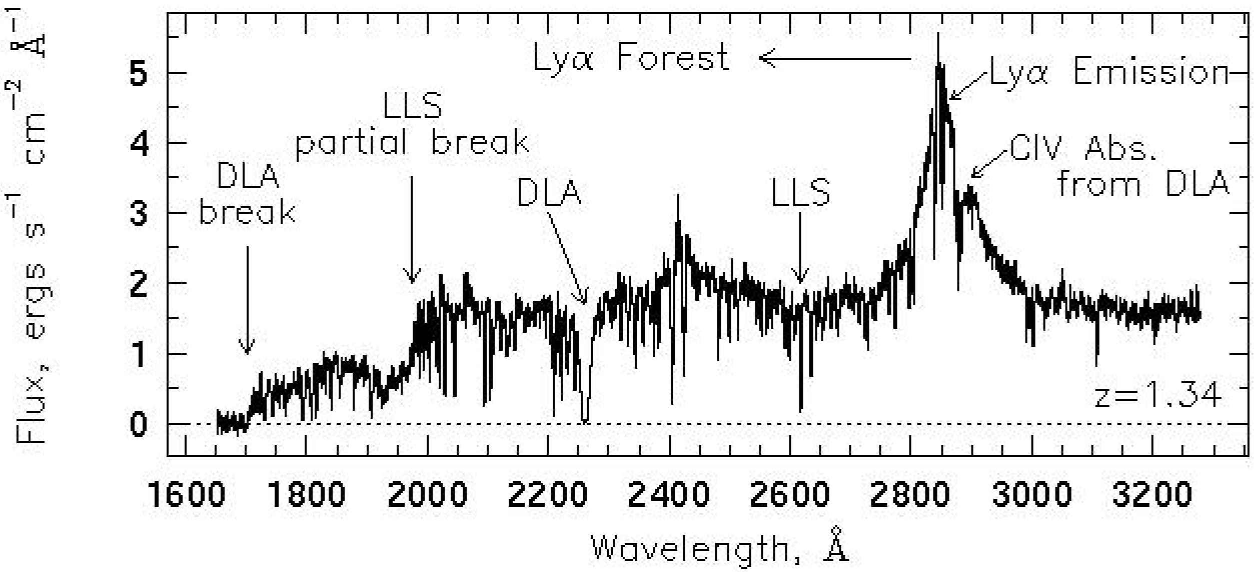
Should we give up a direct observation of such objects?

4.2 Observation of high-z galaxies through absorption

Observation of gas-dominated galaxies

In optical, gas that is not yet turned into galaxies, or gas-dominant young galaxies can be efficiently detected through QSO absorption lines.





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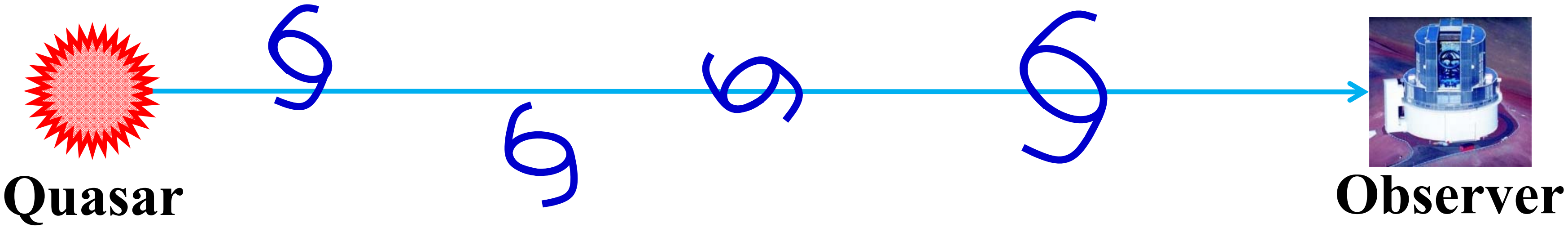
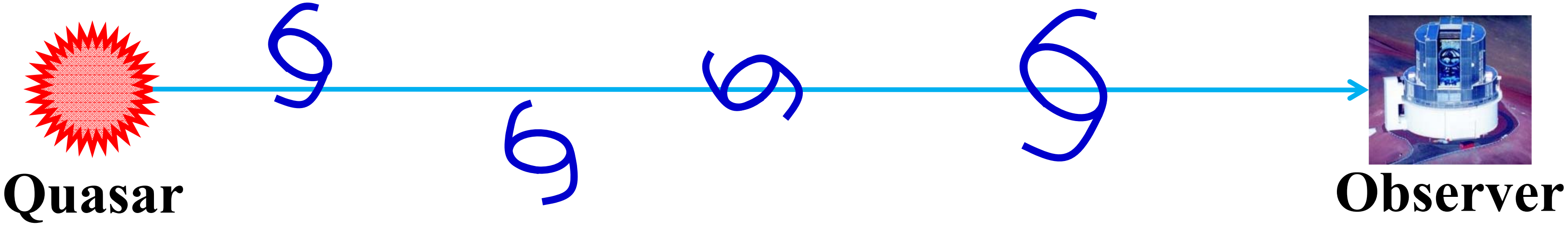


QSO absorption line systems with particularly high HI-column density are observed as damped Lyman α systems (DLAs: $N_{HI} > 2 \times 10^{20}$ cm^{-2}). Such systems are thought to be a progenitor of present-day giant galaxies.

Observation of gas-dominated galaxies

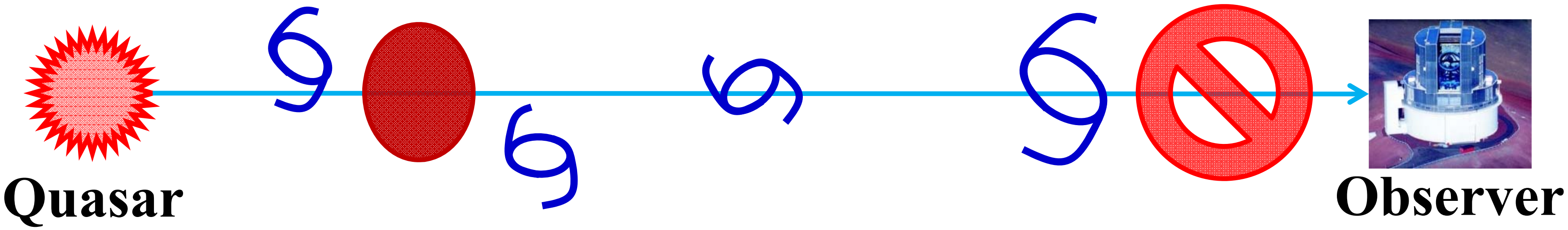


Observations showed that these systems are gas-rich and metal-poor (e.g., Ledoux et al. 2003).

Also, DLAs can be a probe to explore the power spectrum of the large-scale structure at smaller scales.

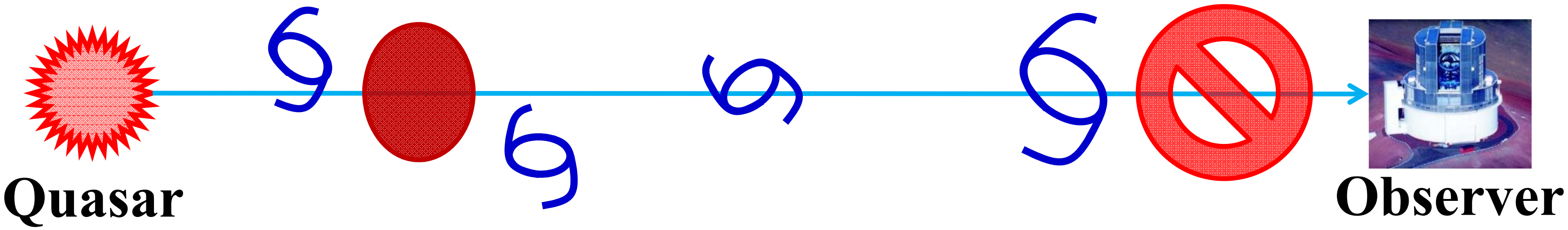
However, a possible fundamental problem in optical/UV-based observation was pointed out.

Observation of gas-dominated galaxies



We want to detect absorption line systems. However, since the continuum emission from background quasars would be very strongly extinguished through the systems with extremely high column density, such systems would be dropped from the initial selection (Vladilo & Péroux 2005).

Observation of gas-dominated galaxies

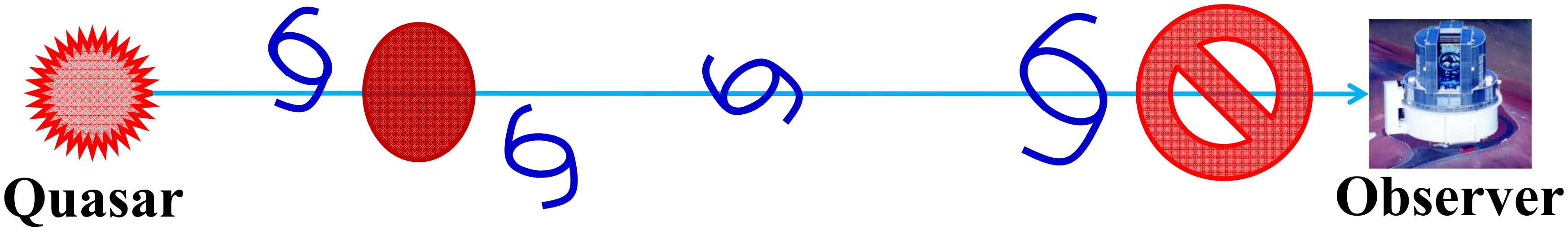


We want to detect absorption line systems. However, since the continuum emission from background quasars would be very strongly extinguished through the systems with extremely high column density, such systems would be dropped from the initial selection (Vladilo & Péroux 2005).

But such a high column density systems are very possibly just before the initial starburst. Namely they are the systems fundamental to understand the cosmic SF history and what we indeed want to observe.

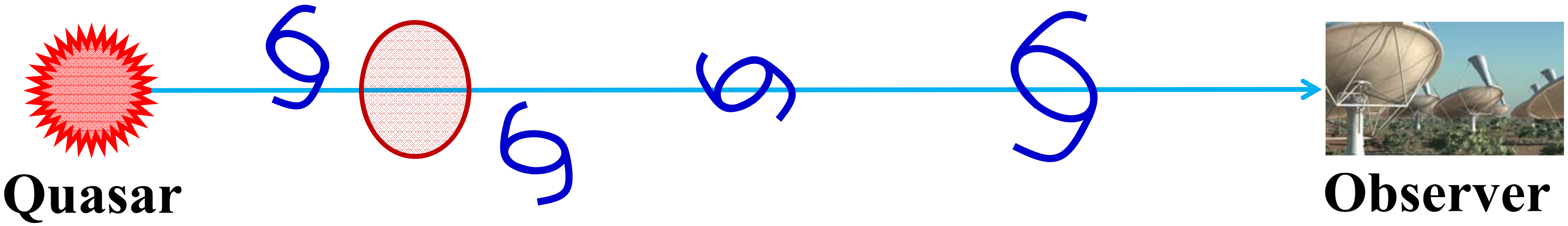
➡ This selection bias is fatal!

Observation of gas-dominated galaxies



How do we solve this fundamental problem?

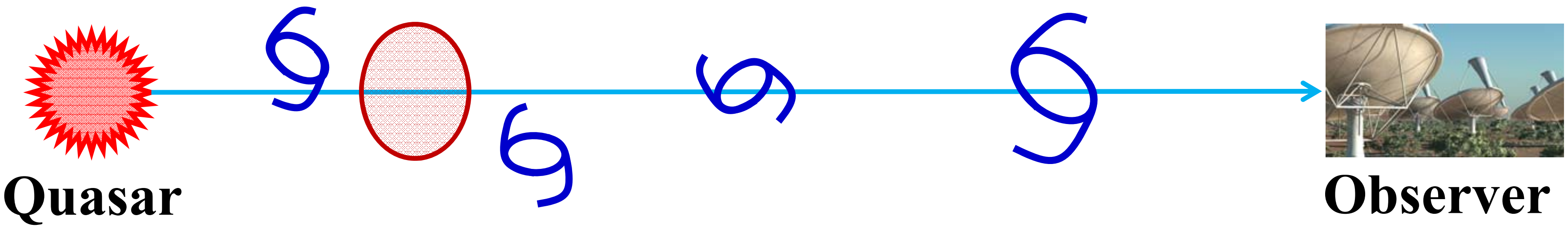
Observation of gas-dominated galaxies



How do we solve this fundamental problem?

Select quasar continuum at radio, and explore 21-cm absorption line systems: best topic for SKA2.

Observation of gas-dominated galaxies



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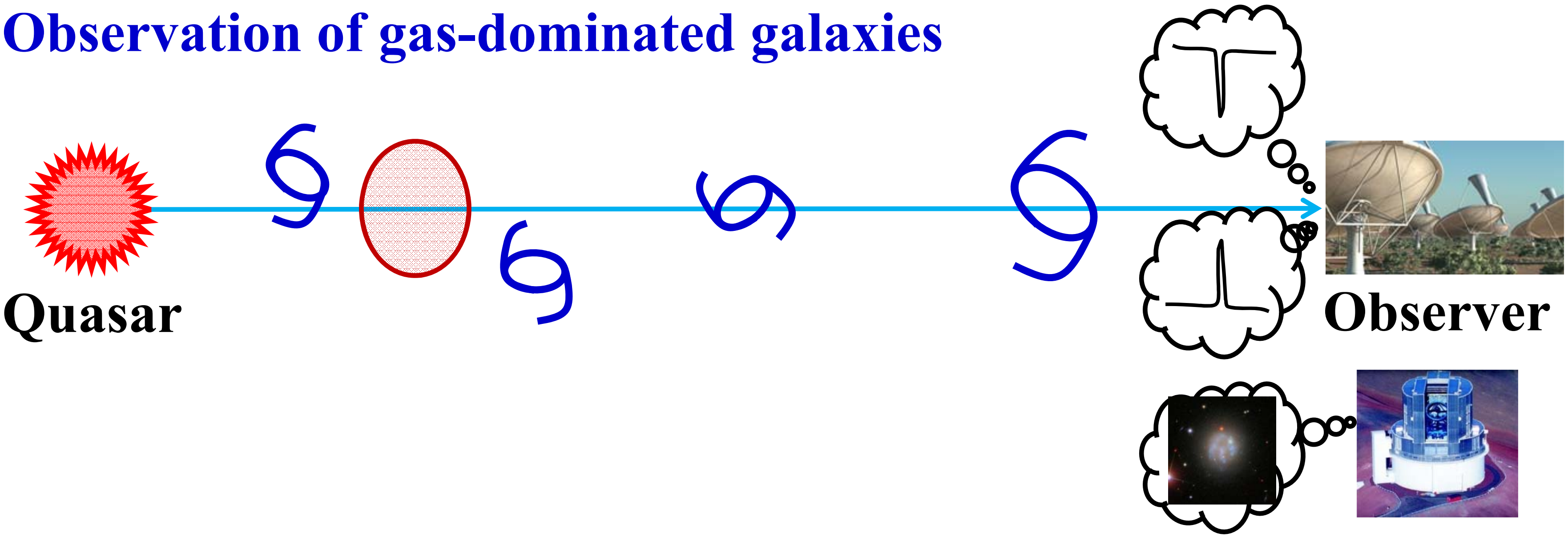
Select quasar continuum at radio, and explore 21-cm absorption line systems: best topic for SKA2.

Advantage to optical/UV absorption line observation:

1. **At radio, dust extinction is negligible.**
2. **Because of small cross section, very high column density systems can be observed.**

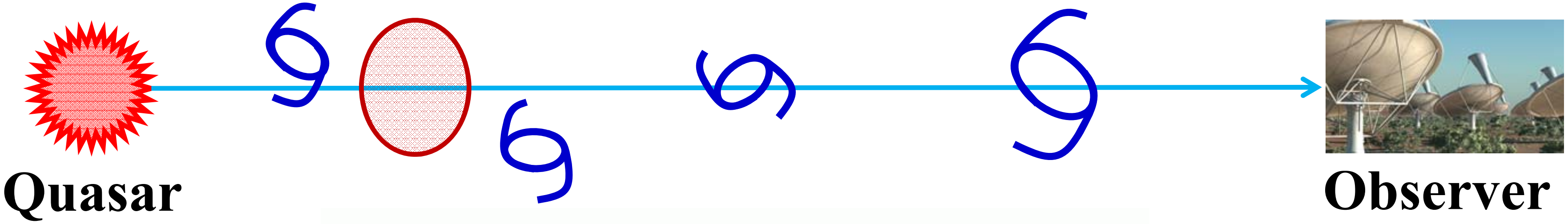
Observation of gas-dominated galaxies

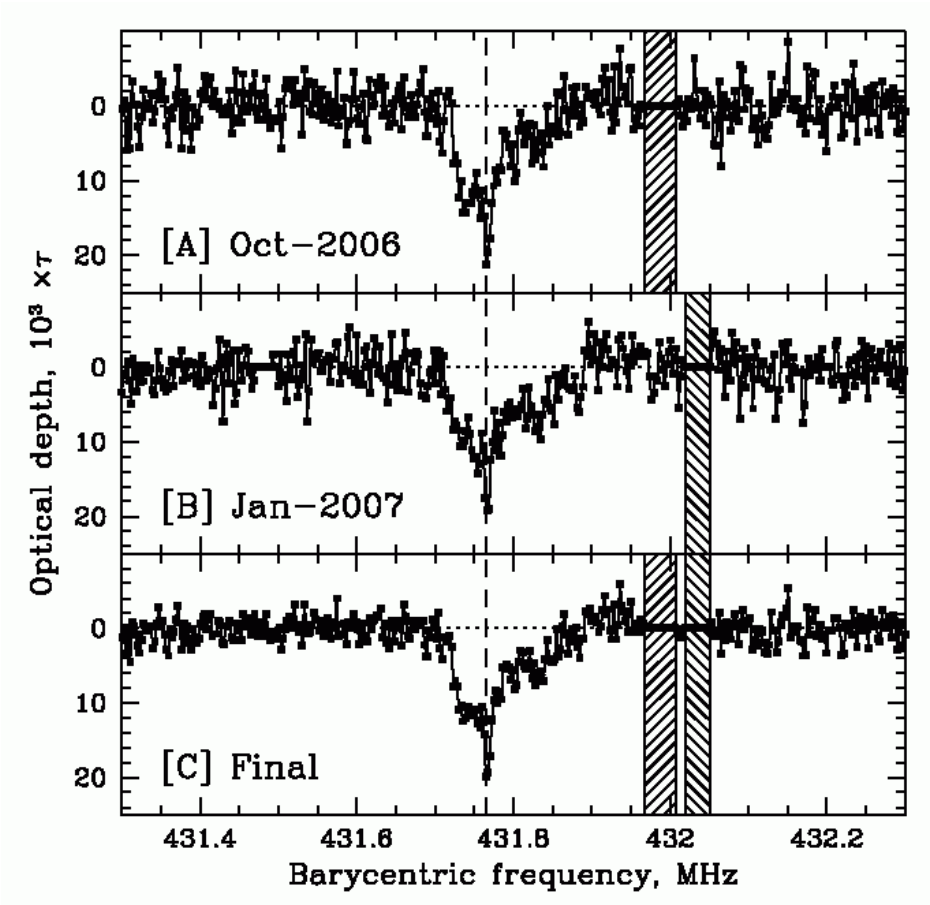


Not only the continuum observation but also ancillary observations like radio emission, optical etc. will provide us with more information on the physics of the systems (e.g., Kanekar et al. 2014; Neeleman et al. 2018).

Theoretical models are also important to compare with the observed results.

Observation of gas-dominated galaxies





York et al. (2007)

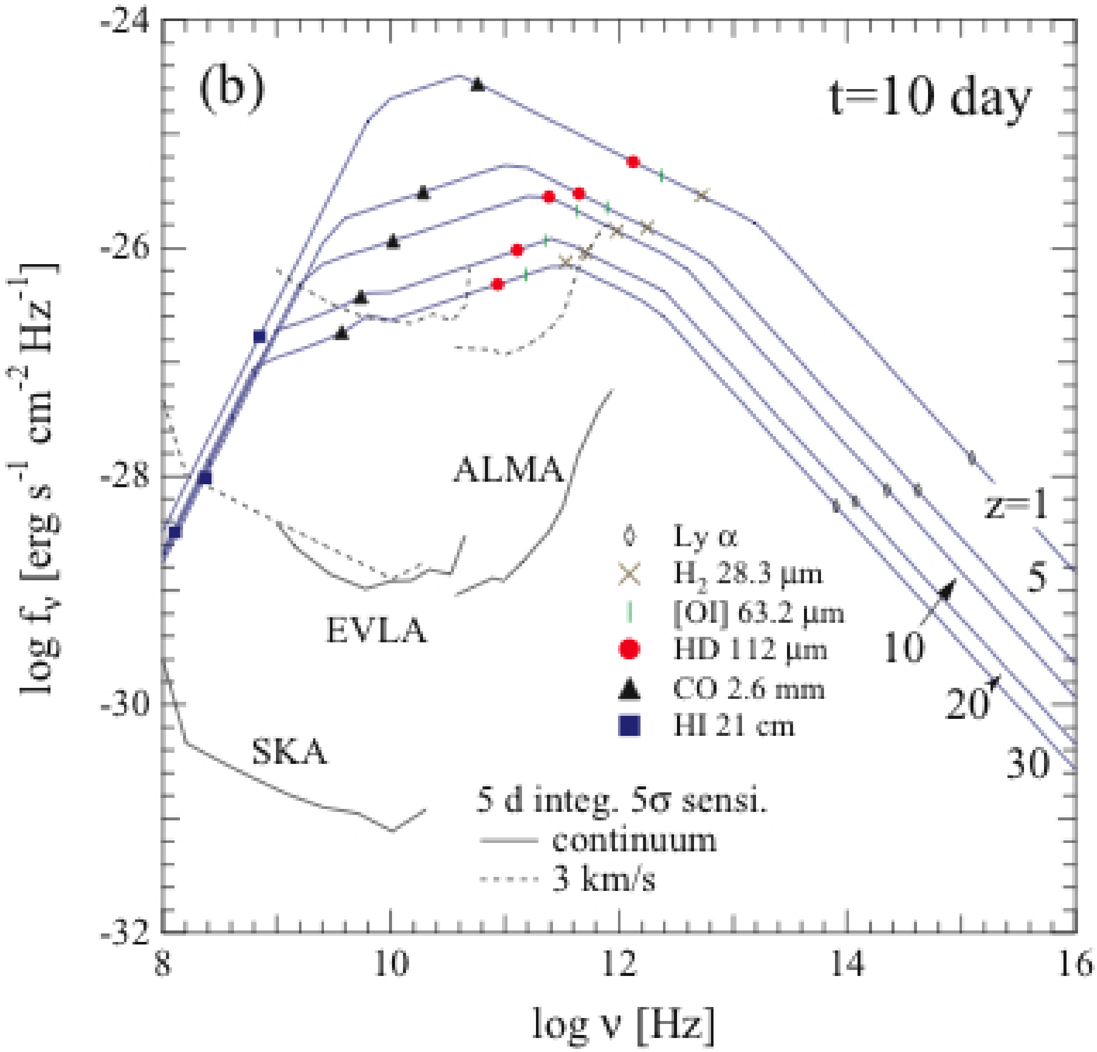
4.3 Background Continuum Sources

We also need to develop a model of the background light continuum sources.

Particularly important is to predict the radio spectra of the background objects, their luminosity function, frequency of occurrence, and observational feasibility.

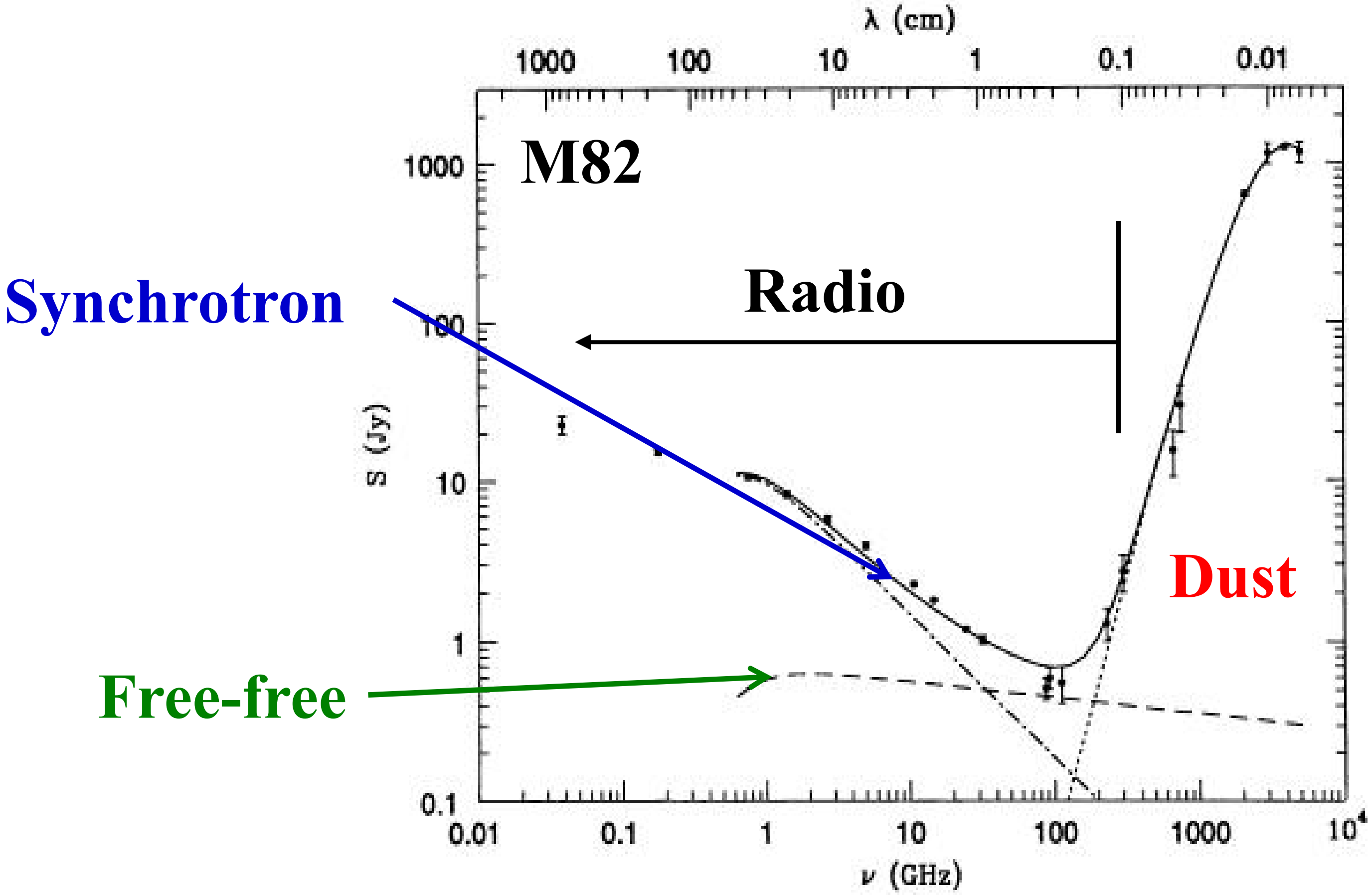
1. **Radio loud quasars are the most natural candidate continuum sources.**
2. **Since at $z > 4$, quasar density is expected to decrease significantly, GRBs are good candidate radio sources.**
3. **Star-forming galaxies are also a good candidate radio continuum sources because of their overwhelmingly large number at high-z.**

GRBs



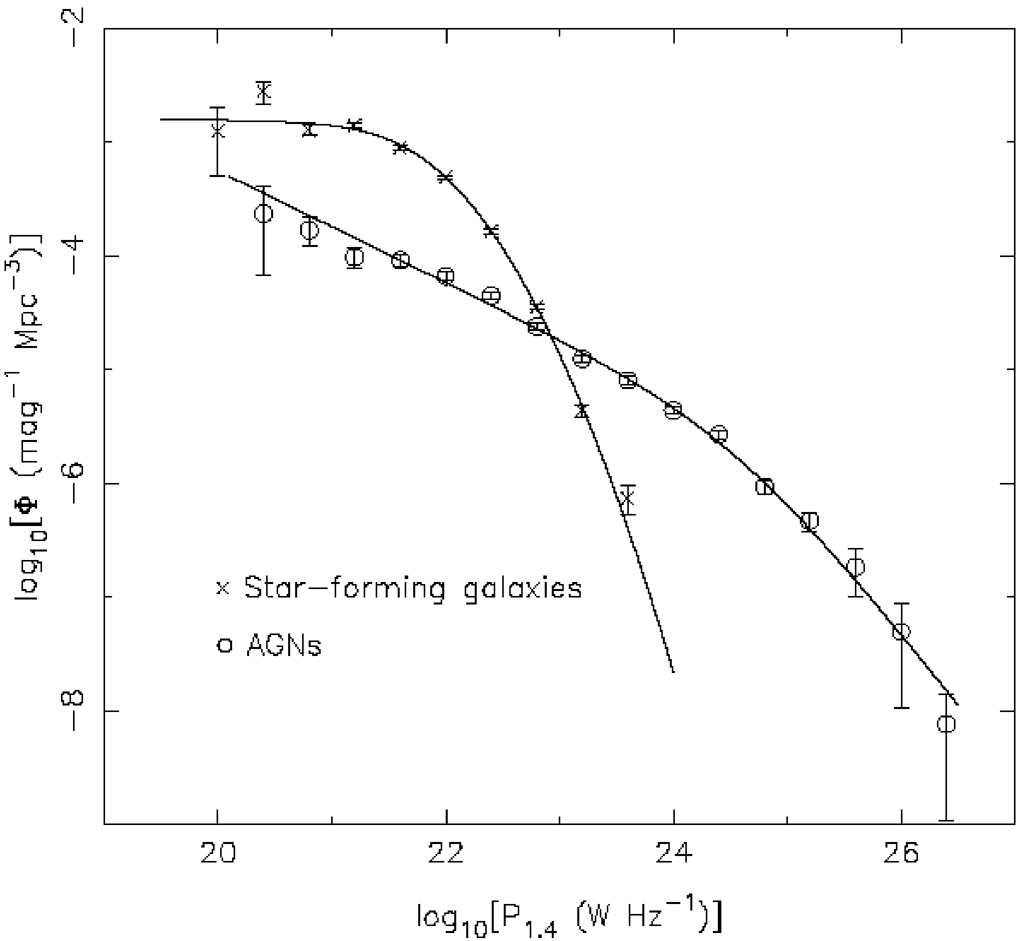
Inoue, Omukai, & Ciardi (2007)

Radio continuum of SF galaxies



(Condon 1992)

The 1.4 GHz LF of SF galaxies and AGNs

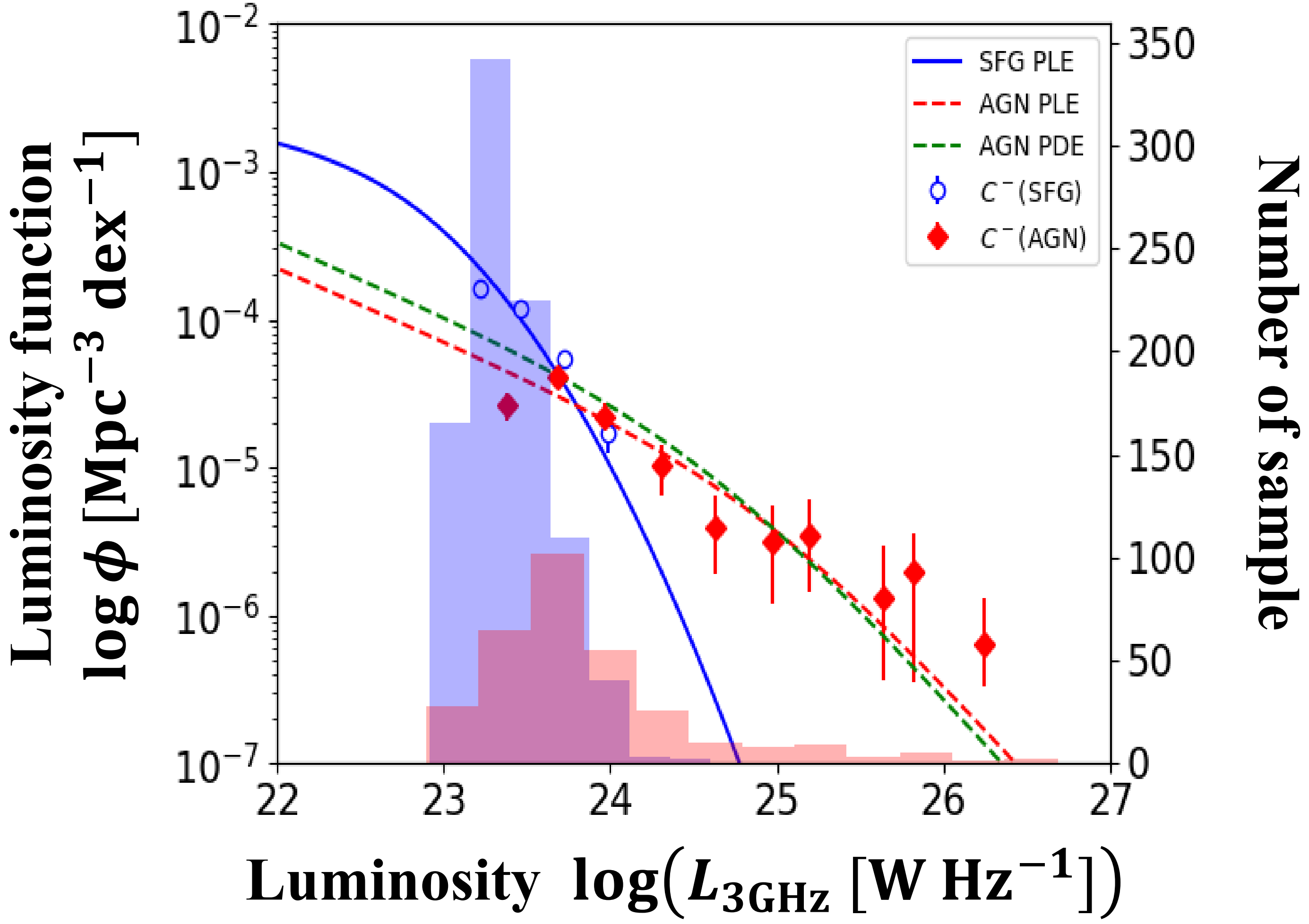


Mauch & Sadler (2007)

The 1.4 GHz LF is divided into two populations: star forming galaxies and AGNs (radio galaxies). The LF of each population can be well approximated by a double power-law like function similar to FIR galaxies. (Machalski & Godlowski 2000; Mauch & Sadler 2007)

⇒ The ratio of the two populations evolve?

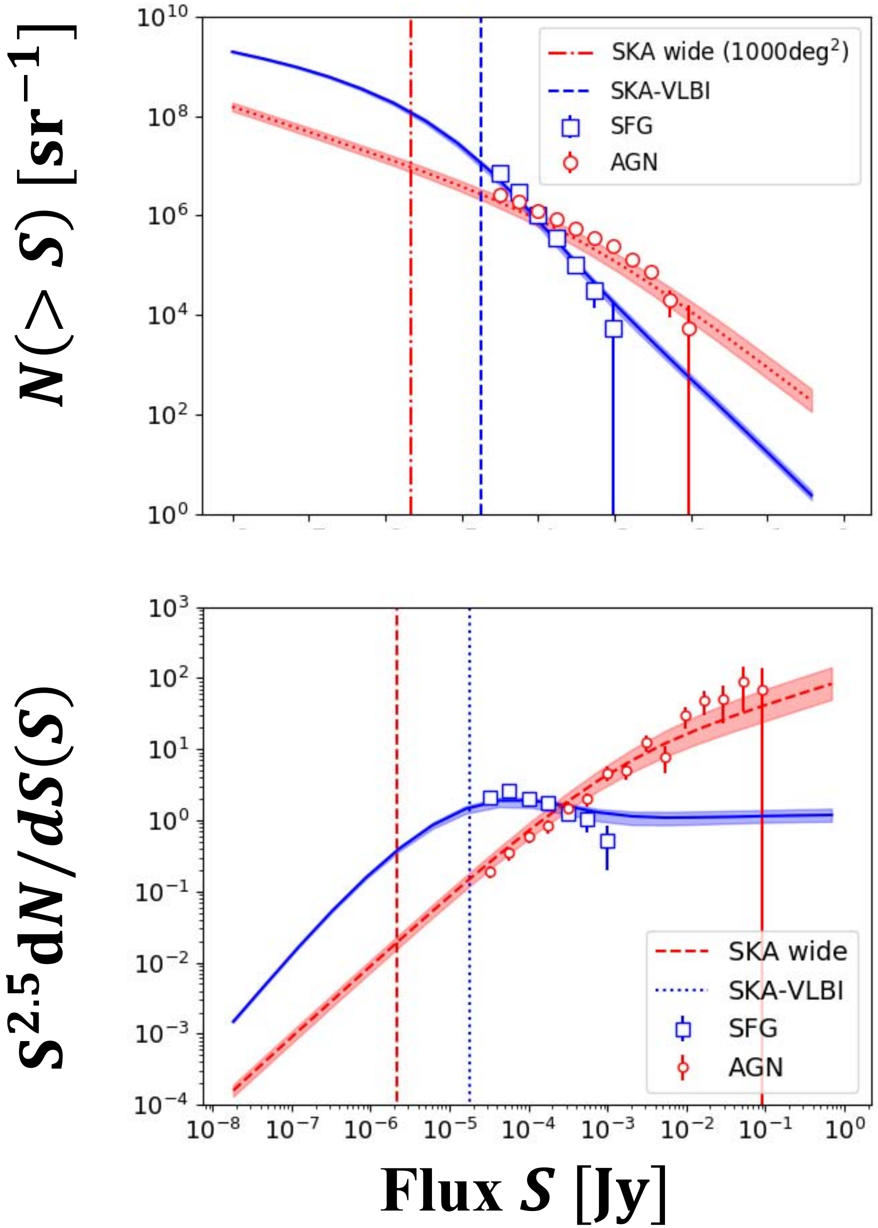
The 3 GHz LF at $z = 1.3$–1.7



Error: bootstrap resampling with 95% confidence interval

Kono et al. (2019)

The 3 GHz number counts of SF galaxies and AGNs



Kono et al. (2019)

(See also Novak et al. 2017)

5 Summary

1. **Galaxy evolution is one of the most important topics in the studies of the cosmic evolution. However, galaxy evolution in terms of gas has just been started. But exact themes on galaxy evolution are not deeply discussed.**
2. **The detection limit of wide surveys of the HI emission by current facilities is of order of mJy, and angular resolution is not sufficient.**
3. **Statistical analysis of galaxies with HI is limited to $z \sim 0$, and the evolution of the HI mass function is not known. The situation for the molecular mass function is even more serious. They will provide the information on the "gaseous side" of galaxy evolution, including the transition from atomic to molecular gas.**

5 Summary

4. **Transition from HI to H_2 in nearby galaxies can be discussed with spatially resolved gas clouds. We expect SKA1 contributes significantly.**

5. **Studies on the scaling relation including gas are also limited to nearby, massive galaxies. Baryon Tully-Fisher relation (BTF) is suggested to deviate from single power law at smallest mass galaxies. It is interesting to clarify what caused this feature.**

6. **The tight correlation between the stellar mass and SFR is referred to as the SF main sequence. The gaseous aspect of the emergence of the SF main sequence is yet to be studied. HI and molecular observation at $1 < z < 3$ is desired.**

5 Summary

7. Kennicutt-Schmidt law is a relation between surface densities of HI+H_2 and SFR in galaxies. Some details are gradually understood through the spatially resolved K-S law. This study is also limited to nearby galaxies up to now. The evolution will be traced by SKA and ALMA.

8. Scaling relations themselves do not tell anything about their governing physics. We need various additional observations and sophisticated analysis to reveal the relevant physical processes.

9. Direct detection of the HI emission line from galaxies at $z > 4$ might be very difficult. Extremely gaseous galaxies and their progenitors can be explored through HI absorption line systems. This is a plausible topic for the SKA2.

5 Summary

10. **Radio-loud QSOs are the first candidate for the radio continuum sources. However since they are expected to be rare at $z > 4$, we should also consider GRBs and star-forming galaxies as a candidate radio sources.**


Are you ready to SKA?
From Tokyo Ska Paradise Orchestra feat. Hiroji Miyamoto