From Galaxy Evolution to the Eve of Galaxy Formation through the 21-cm Shadow

Tsutomu T. TAKEUCHI
Division of Particle and Astrophysical Science, Nagoya University, Japan

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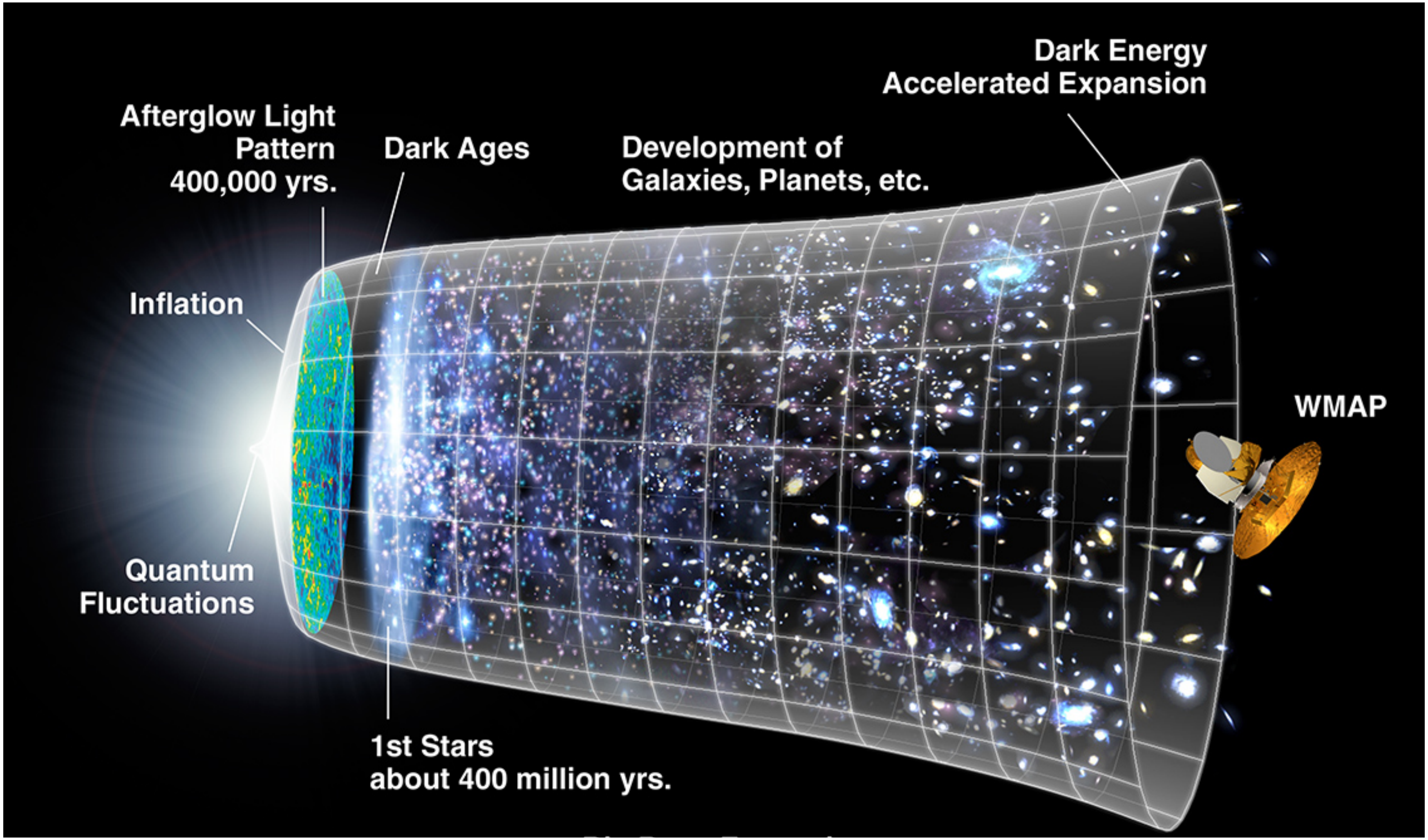
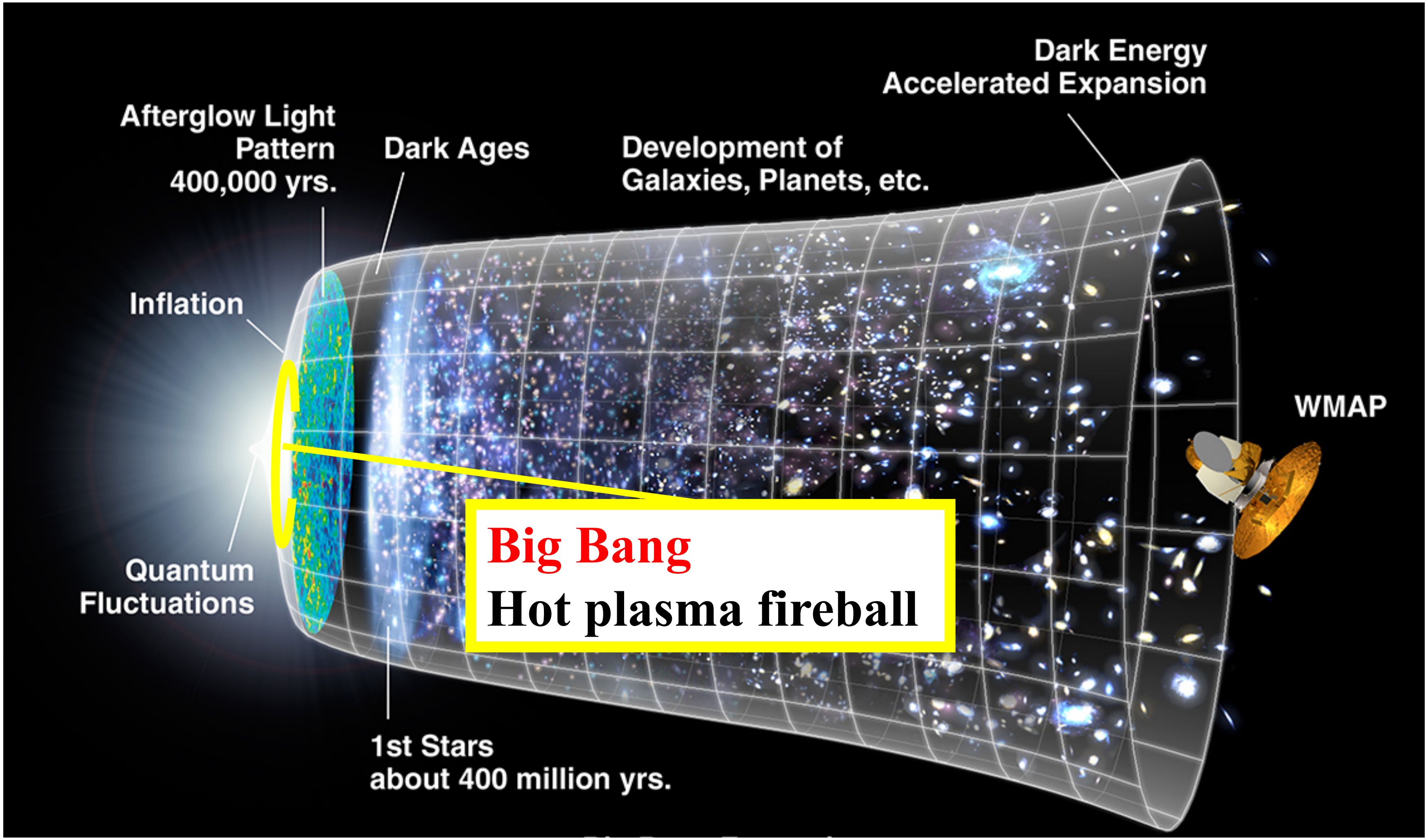
1 Galaxies in the Global Evolution of the Universe

1.1 Global Evolution of the Universe



http://map.gsfc.nasa.gov/m_mm.html

1.1 Global Evolution of the Universe



Big Bang

Hot plasma fireball

http://map.gsfc.nasa.gov/m_mm.html

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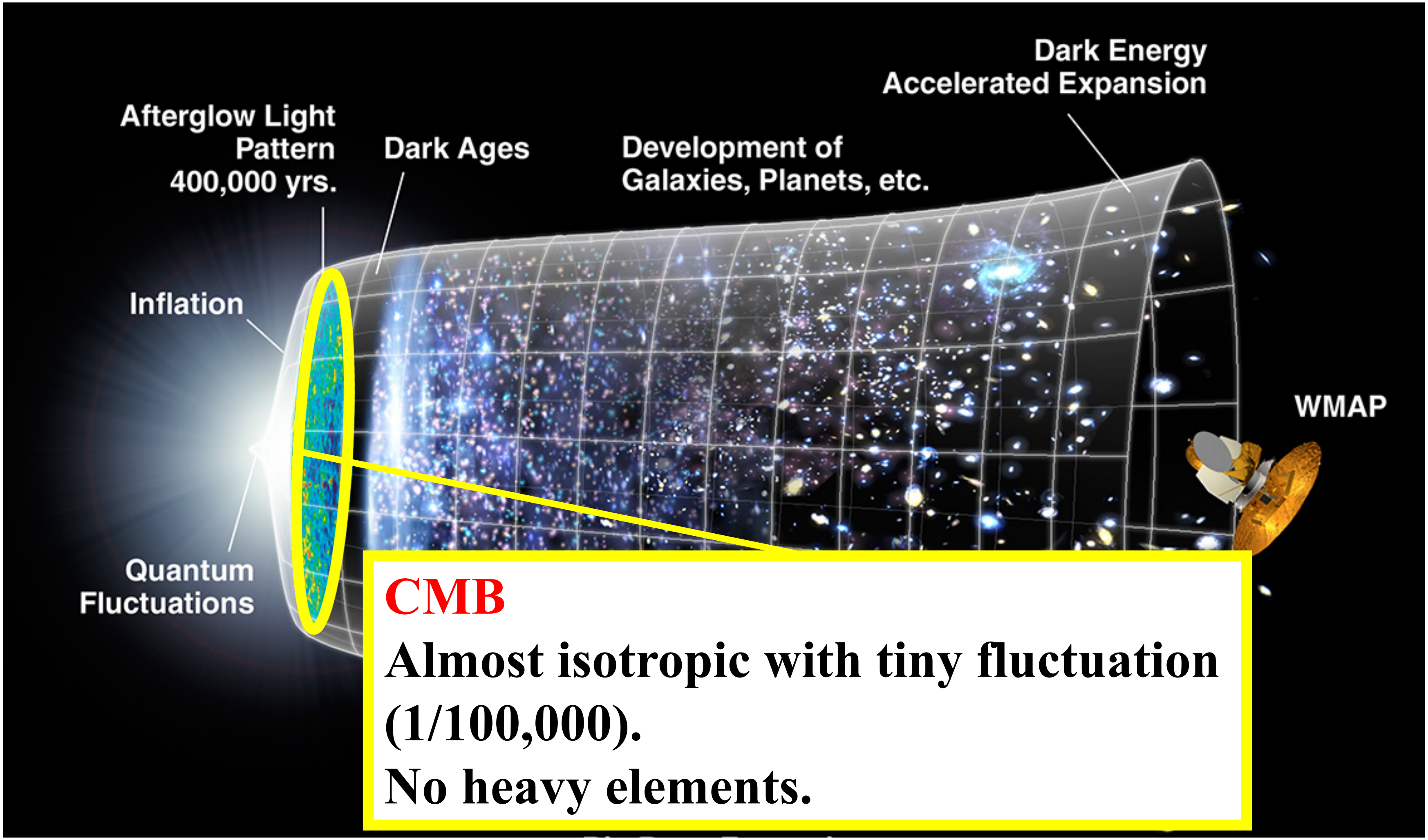


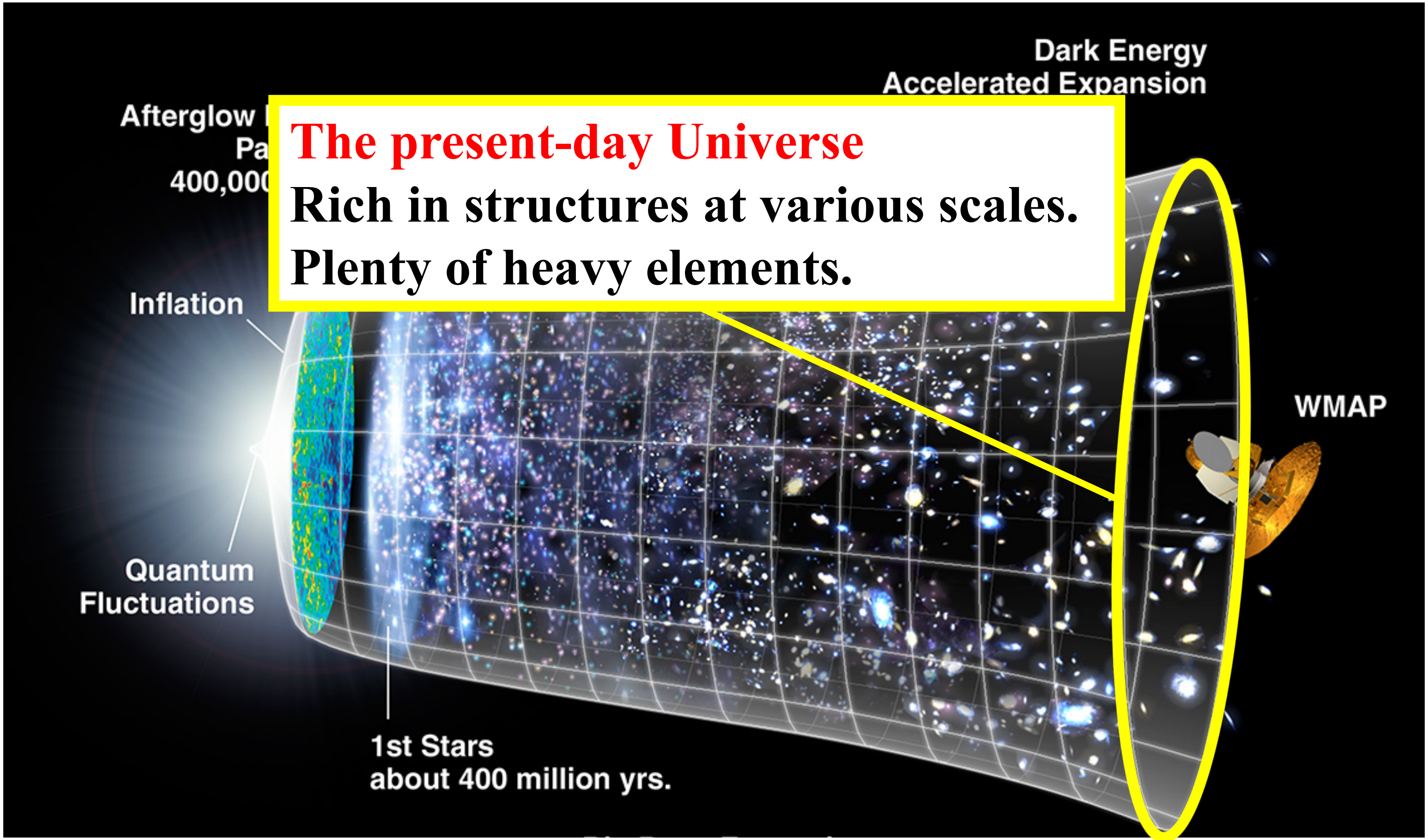
CMB

Almost isotropic with tiny fluctuation (1/100,000).

No heavy elements.

http://map.gsfc.nasa.gov/m_mm.html

1.1 Global Evolution of the Universe



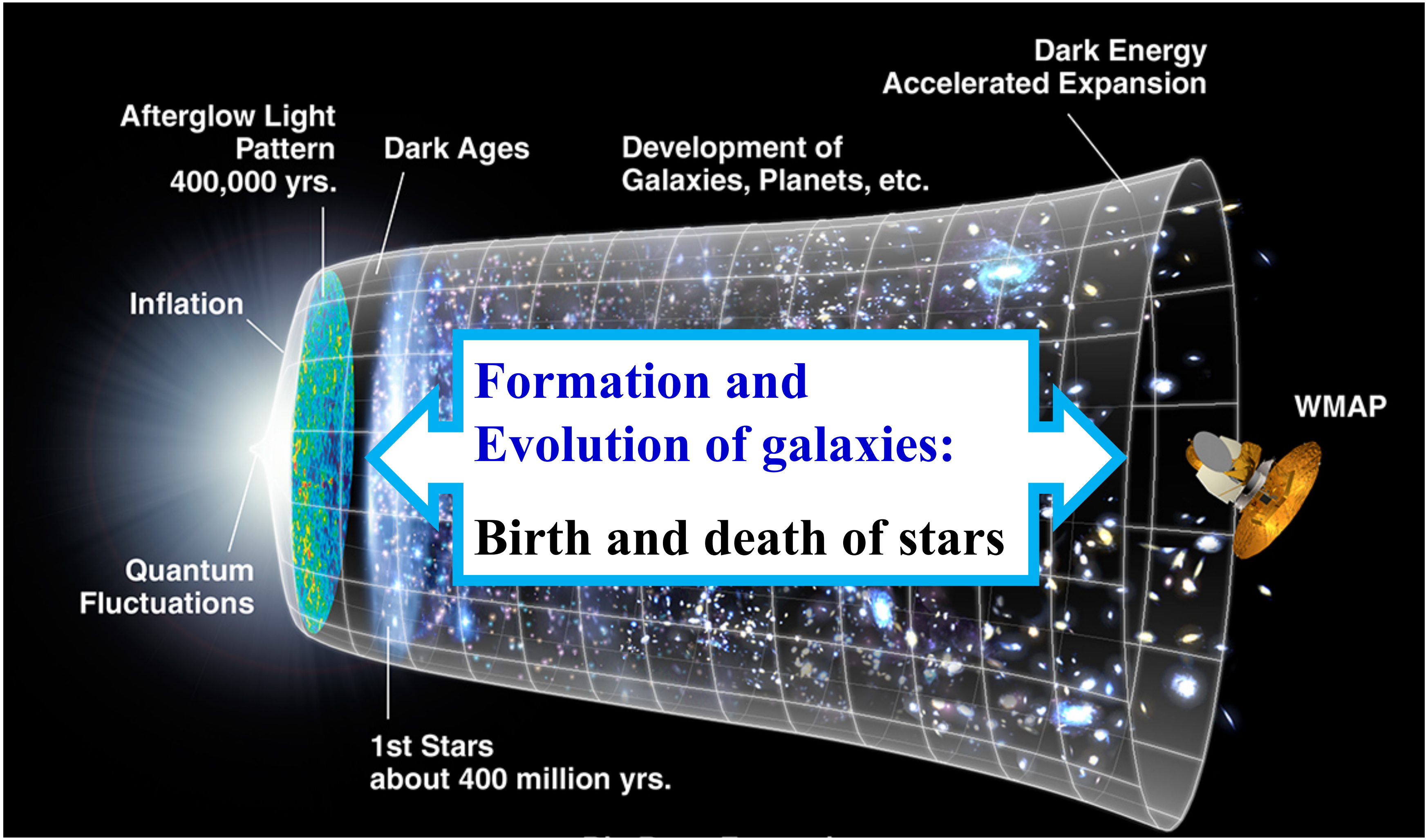
The present-day Universe

Rich in structures at various scales.

Plenty of heavy elements.

http://map.gsfc.nasa.gov/m_mm.html

1.1 Global Evolution of the Universe



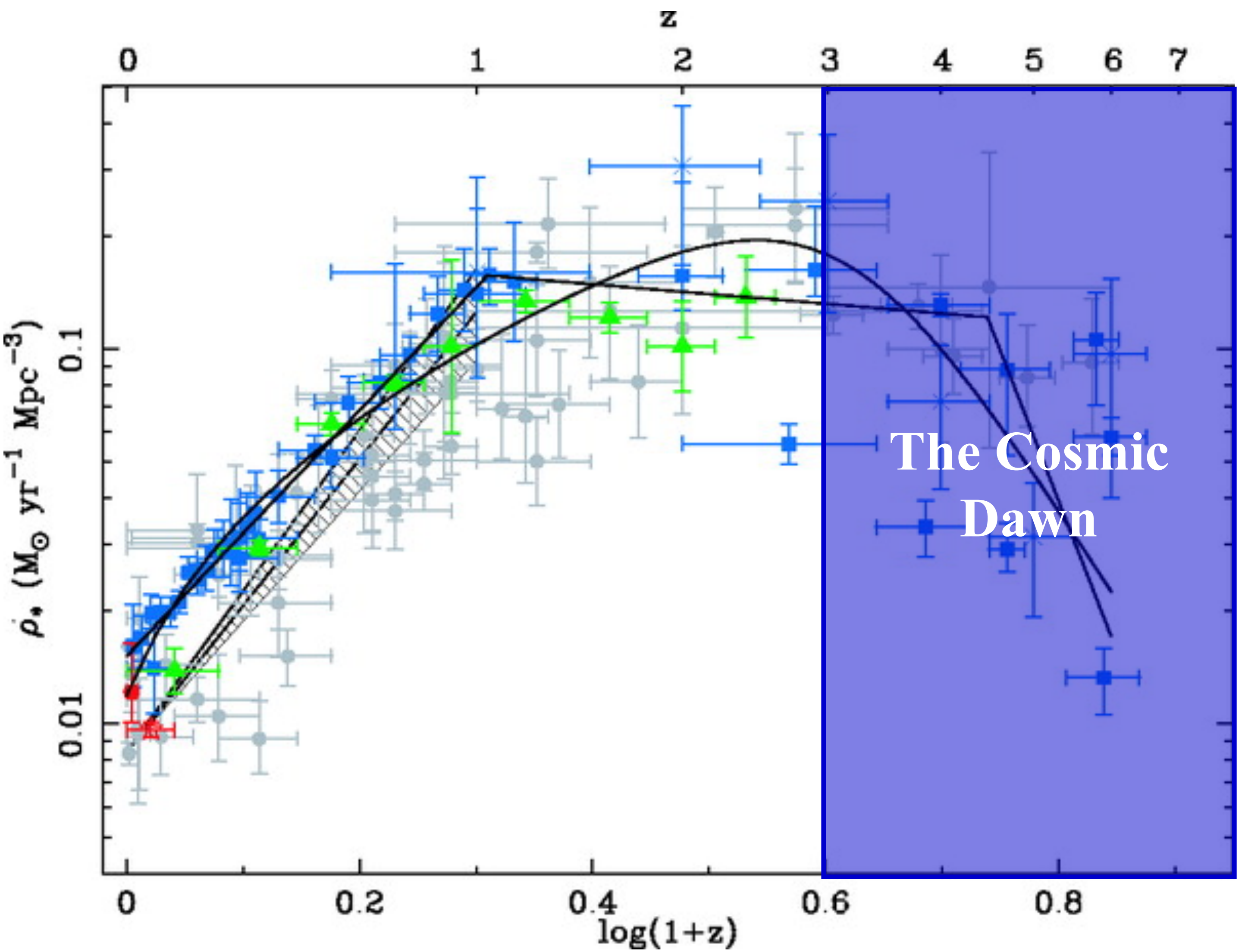
Formation and Evolution of galaxies:

Birth and death of stars

http://map.gsfc.nasa.gov/m_mm.html

1.2 The cosmic star formation history

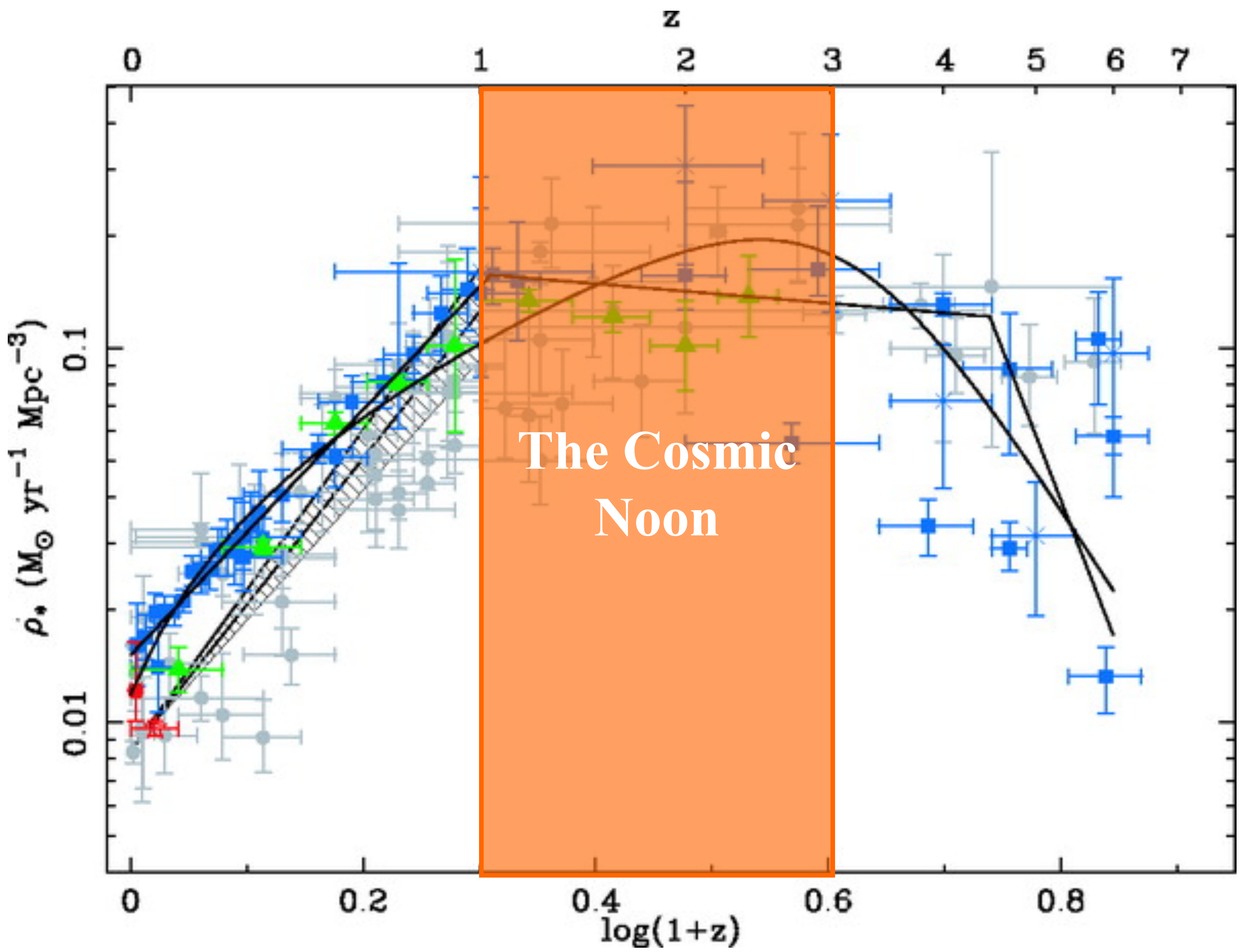
Cosmic star formation density



Hopkins & Beacom (2006)

1.2 The cosmic star formation history

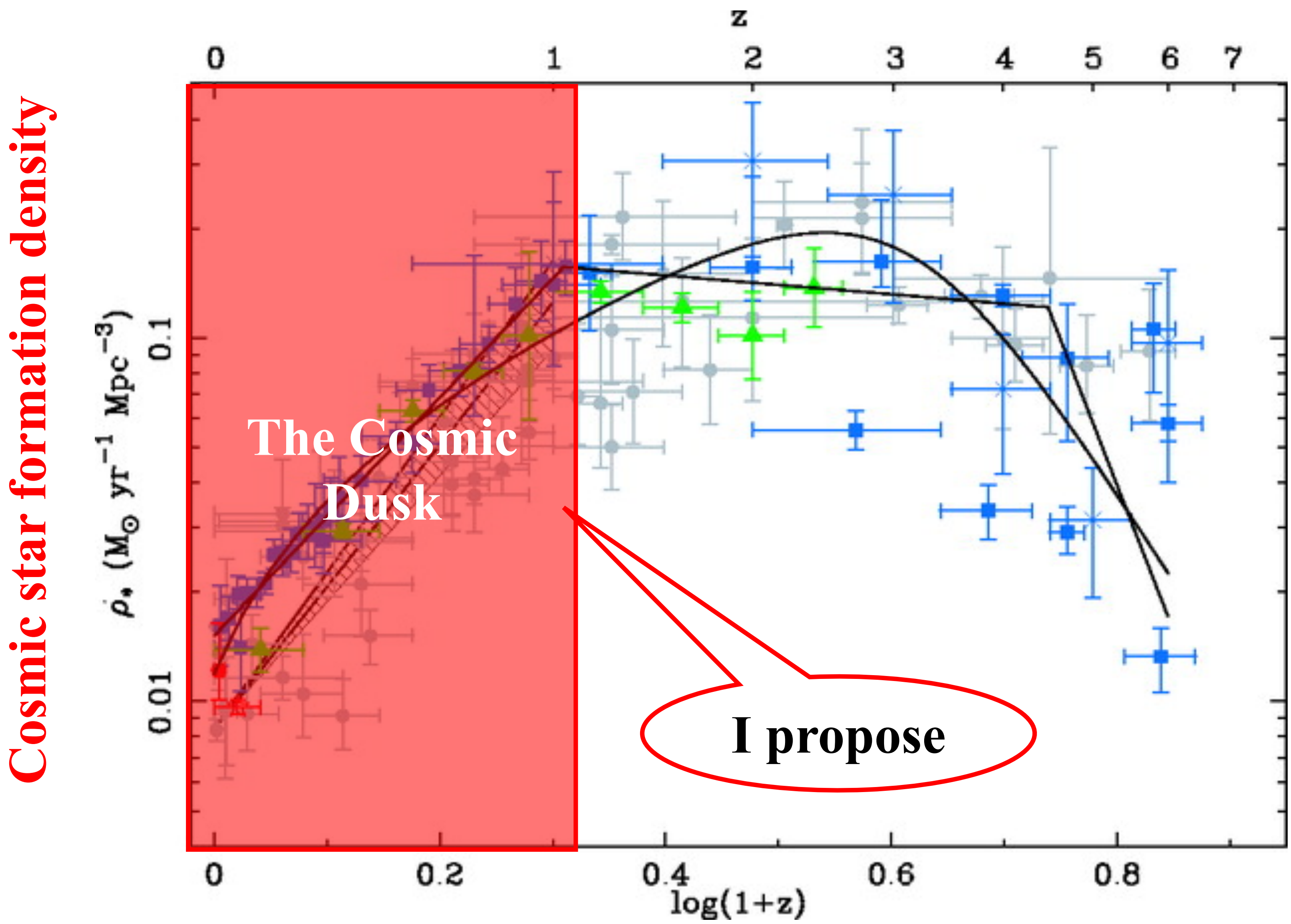
Cosmic star formation density



The Cosmic Noon

Hopkins & Beacom (2006)

1.2 The cosmic star formation history



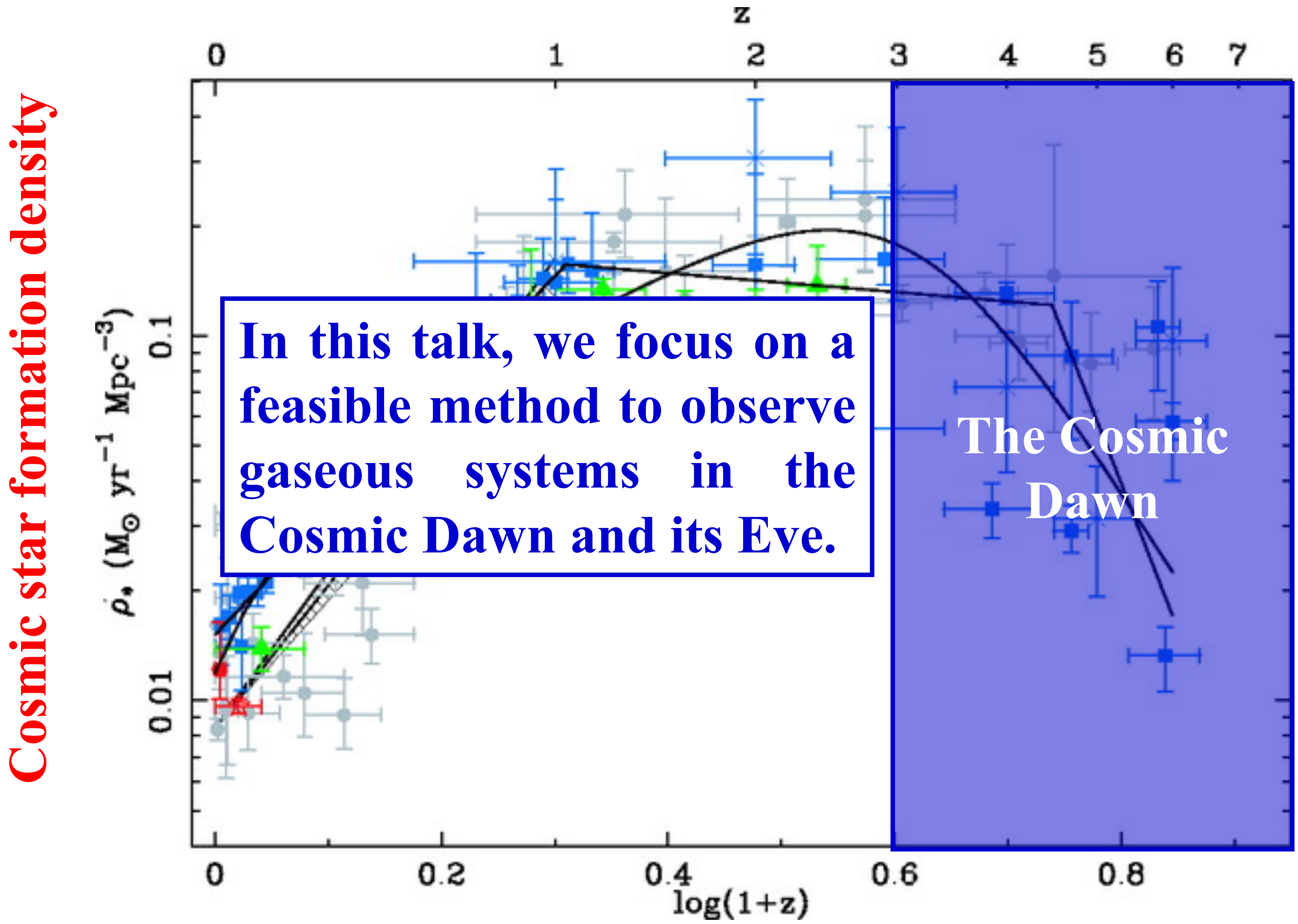
Cosmic star formation density

The Cosmic Dusk

I propose

Hopkins & Beacom (2006)

1.2 The cosmic star formation history

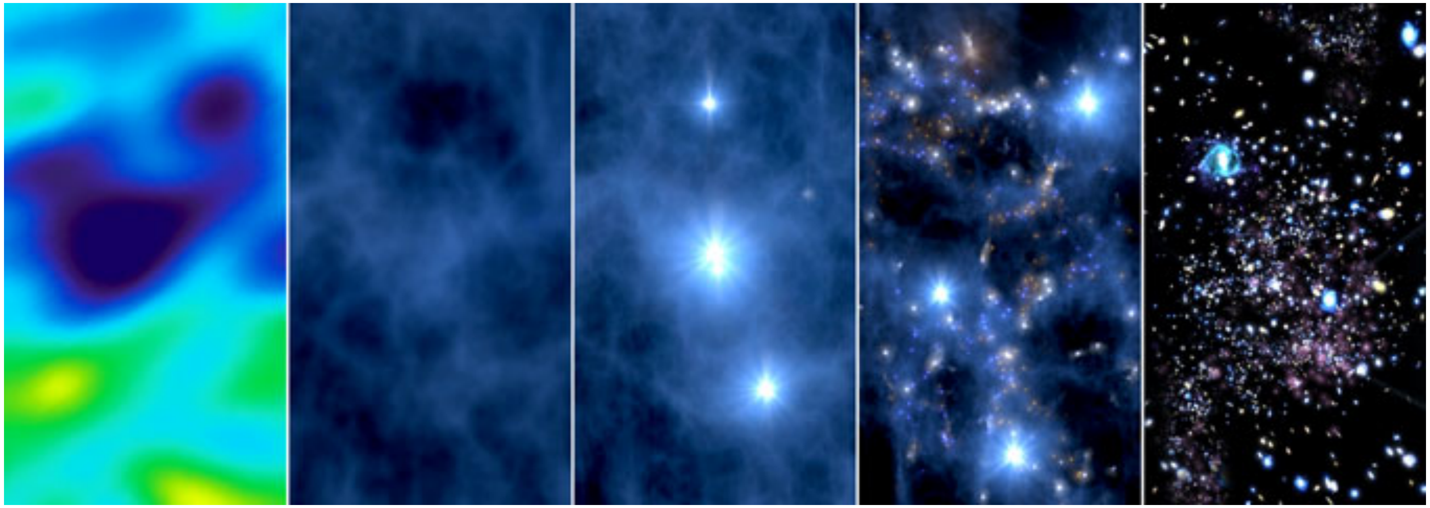


In this talk, we focus on a feasible method to observe gaseous systems in the Cosmic Dawn and its Eve.

Hopkins & Beacom (2006)

1.3 From the Dark Ages to the Cosmic Dawn

The transition epoch from the Dark Ages, first object formation, and collective star formation (galaxy formation) mode is the growing phase of galaxies.

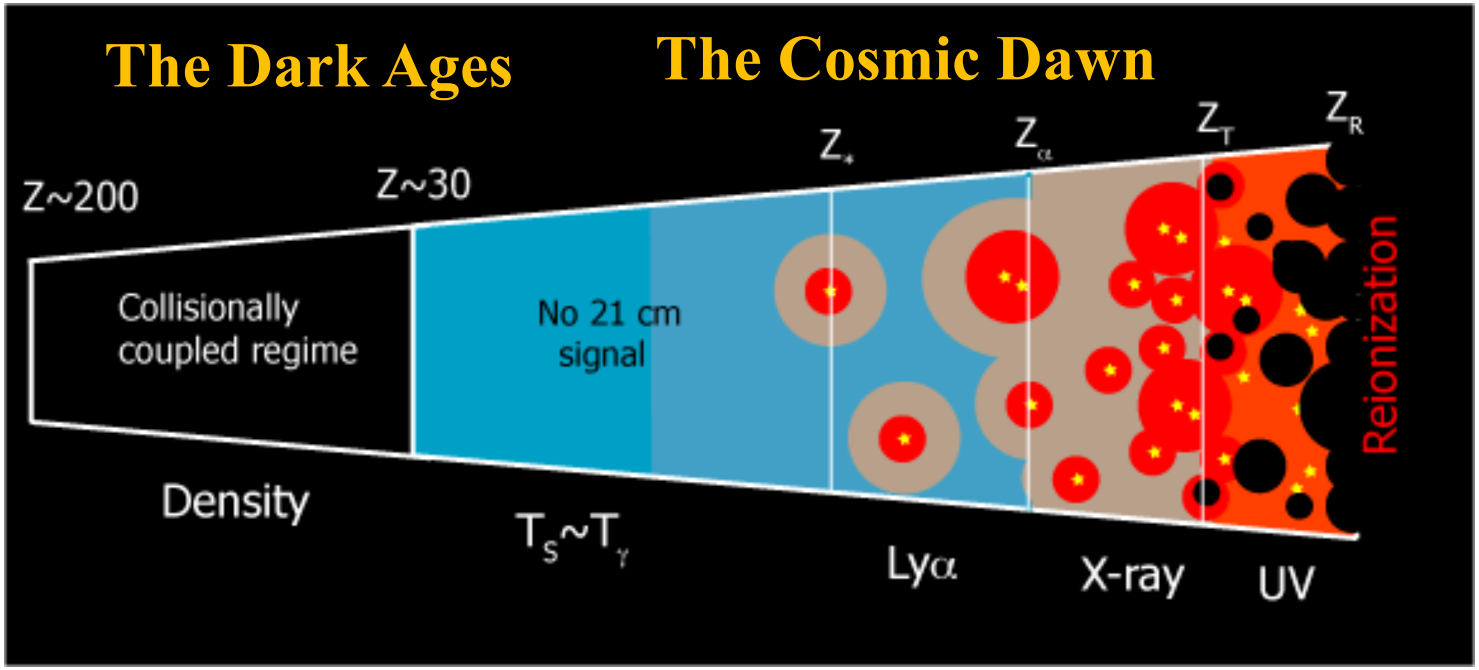


1. **Gravitational growth from almost homogeneous matter**
2. **Formation of dark halos**
3. **Free fall of baryons onto halos.**
4. **First star formation.**
5. **First metal enrichment by first supernovae**
6. **Onset of burst of star formation and galaxy formation**

Epoch of reionization (EoR)

At the end of the dark age, first objects started to ionize their surrounding regions, and the ionized regions overlapped with each other. Finally the whole Universe was ionized.

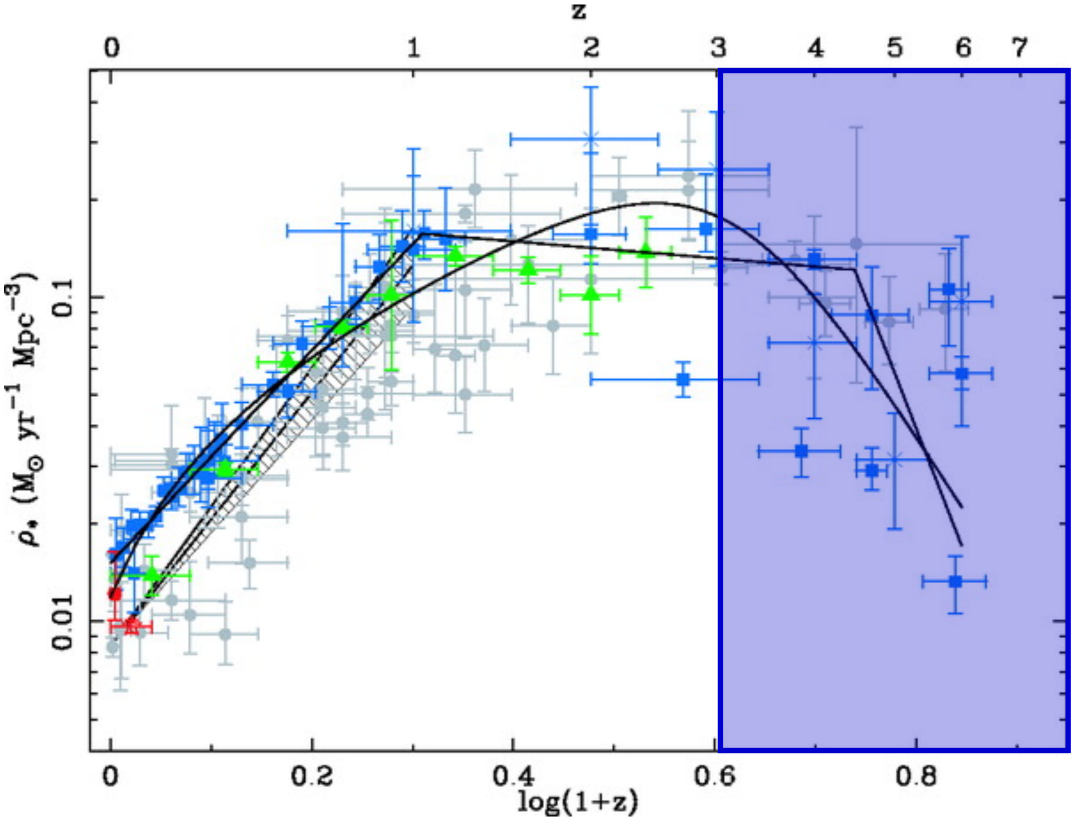
⇒ **The history of reionization is important**



From the Dark Ages to the Cosmic Dawn

The growing phase of galaxies from tiny fluctuations of neutral hydrogen is at $3 < z < 20$

The unique probe of baryons in the Dark Ages and the Cosmic Dawn is HI. Perhaps first galaxies might have formed from halos containing a large amount of HI.



1.4 Cosmic star formation probed by HI

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.**

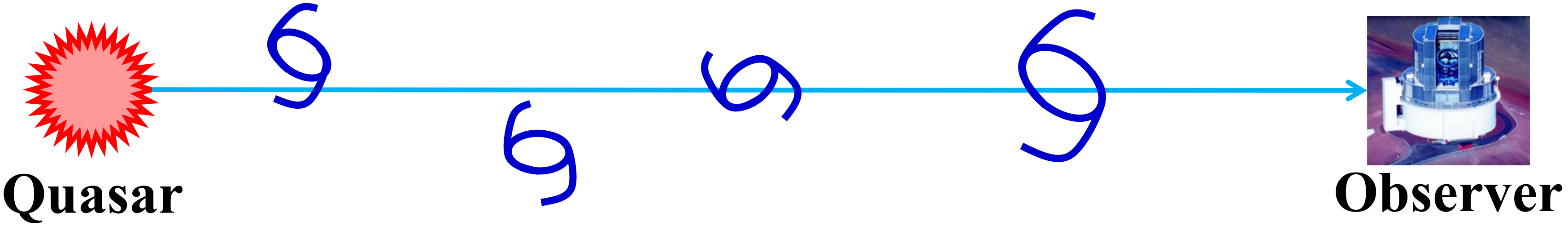
They give information on the SFR, but do NOT tell anything about the transition from gas to stars, which is fundamental in galaxy formation and evolution.

⇒ Importance of SKA!

2 Exploration of galaxy formation via absorption

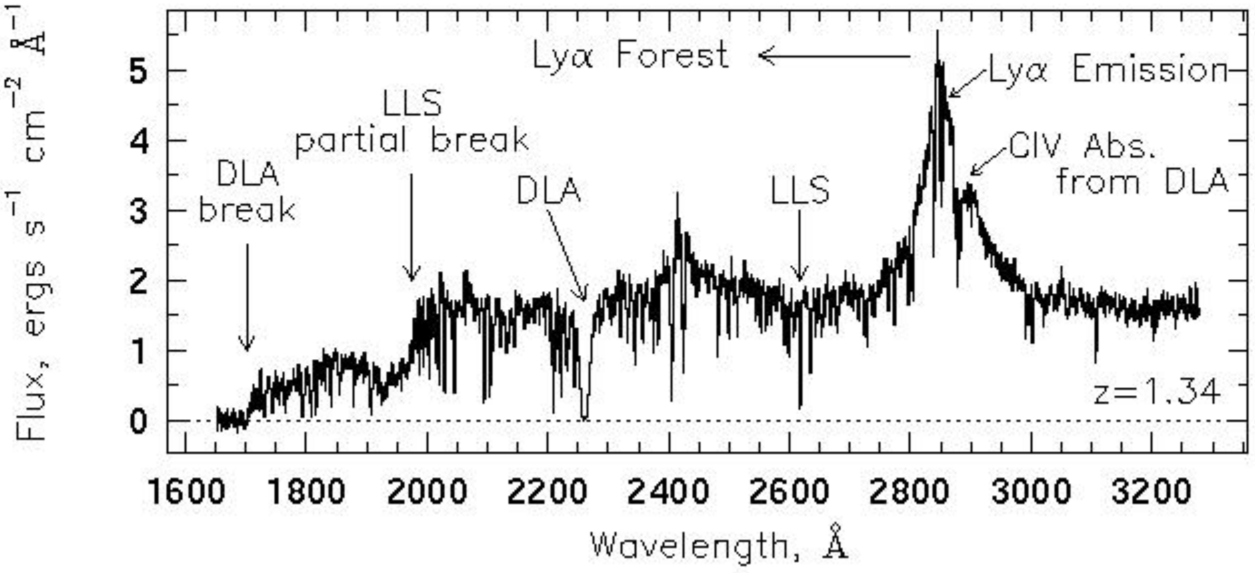
Observation of gas-dominated galaxies

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



Quasar

Observer



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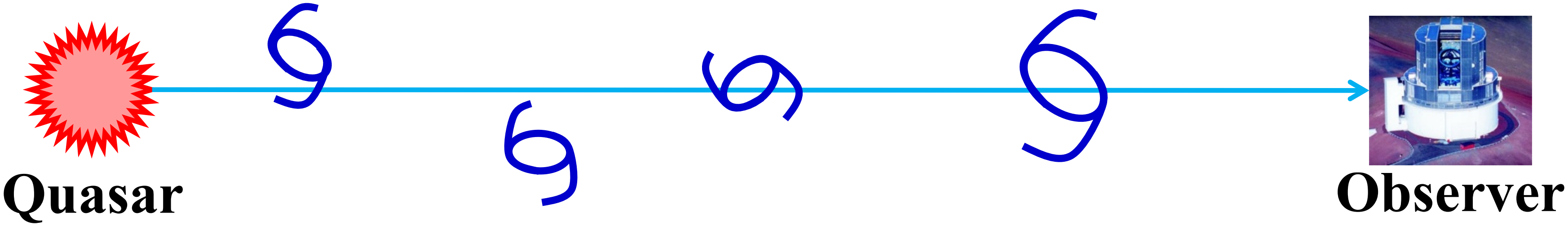
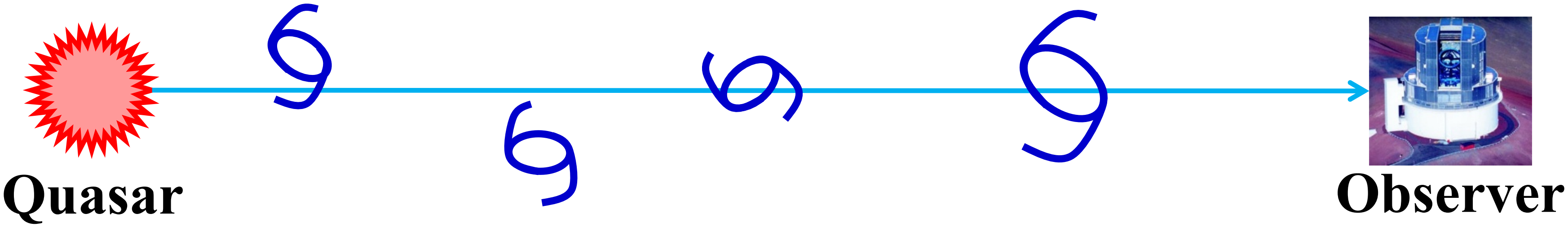


QSO absorption line systems with particularly high HI-column density are observed as damped Lyman α systems (DLAs: $N_{\mathrm{HI}} > 2 \times 10^{20}$ cm^{-2}). Such systems are thought to be a progenitor of present-day giant galaxies.

Observation of gas-dominated galaxies

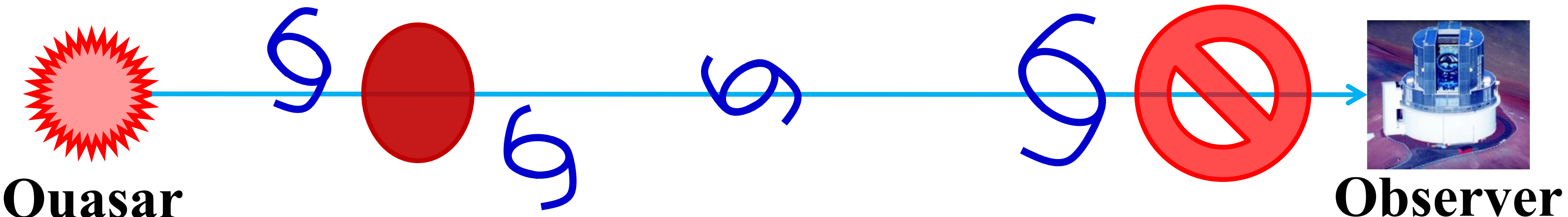


Observations showed that these systems are gas-rich and metal-poor (e.g., Ledoux et al. 2003).

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

However, there is a fundamental problem in optical/UV-based observation!

Observation of gas-dominated galaxies

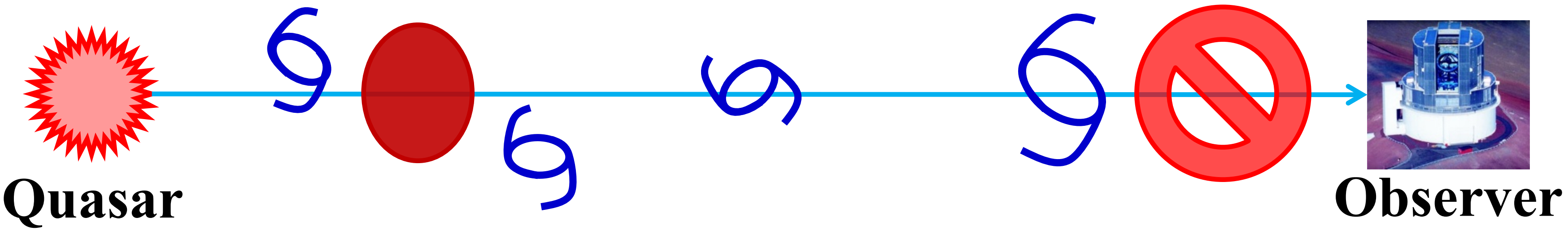


We want to detect absorption line systems. However, since the continuum emission from background quasars would be very strongly extinguished through the systems with extremely high column density, such systems would be dropped from the initial selection (Vladilo & Péroux 2005).

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.

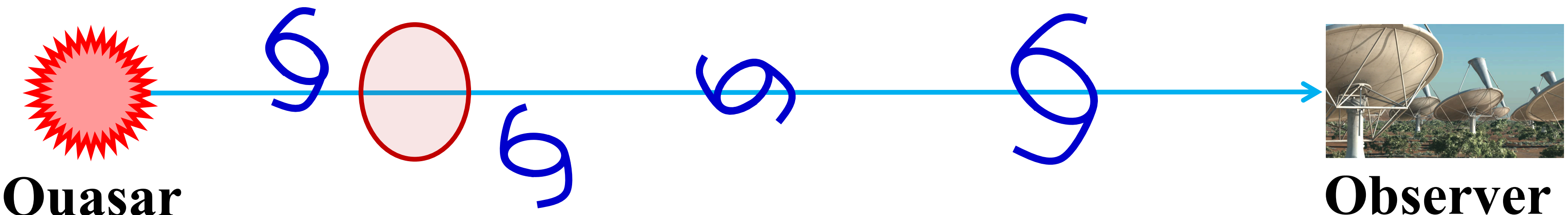
→ This selection bias is fatal!

Observation of gas-dominated galaxies



How do we solve this fundamental problem?

Observation of gas-dominated galaxies



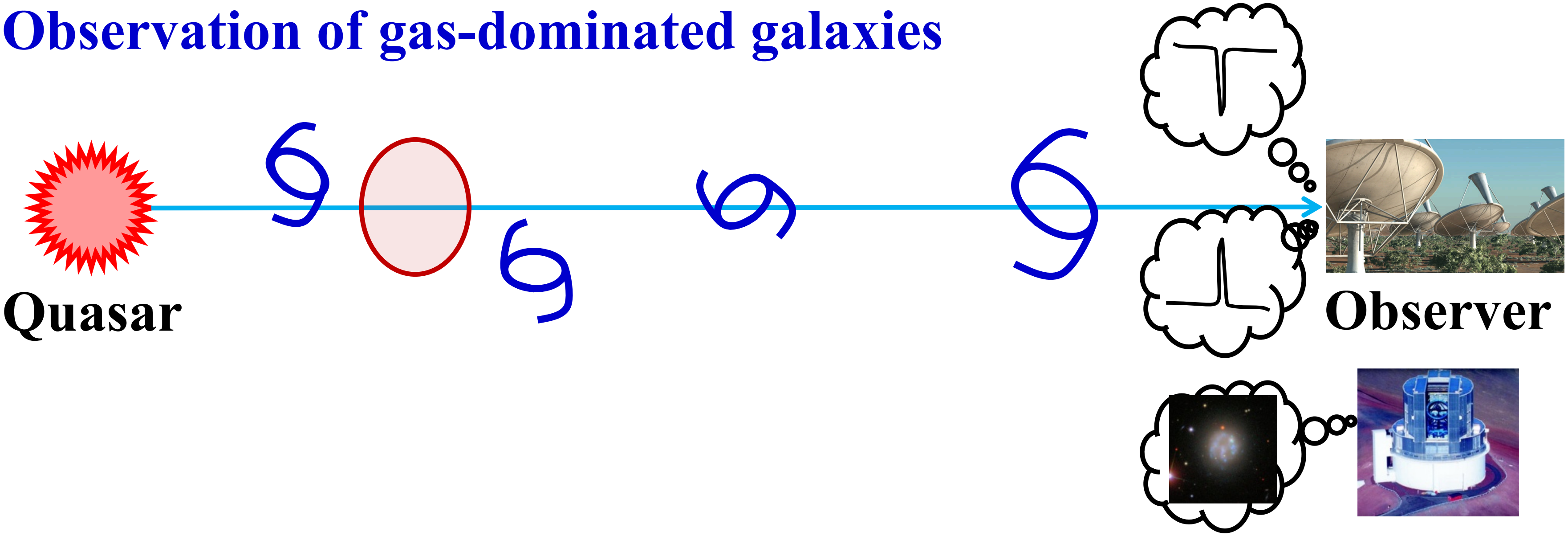
How do we solve this fundamental problem?

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

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.**

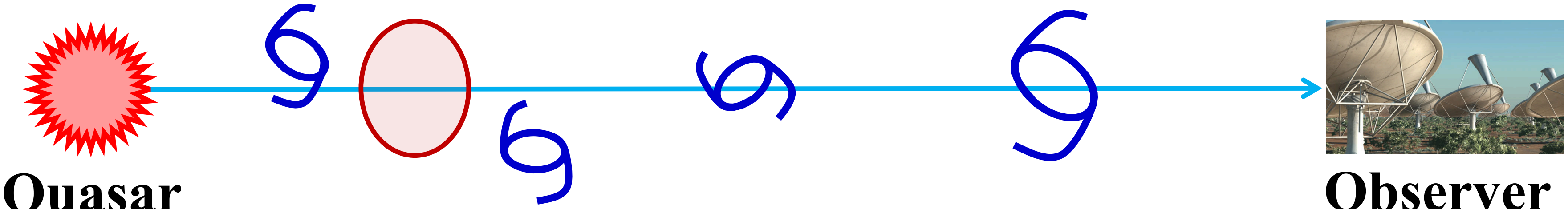
Observation of gas-dominated galaxies



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.

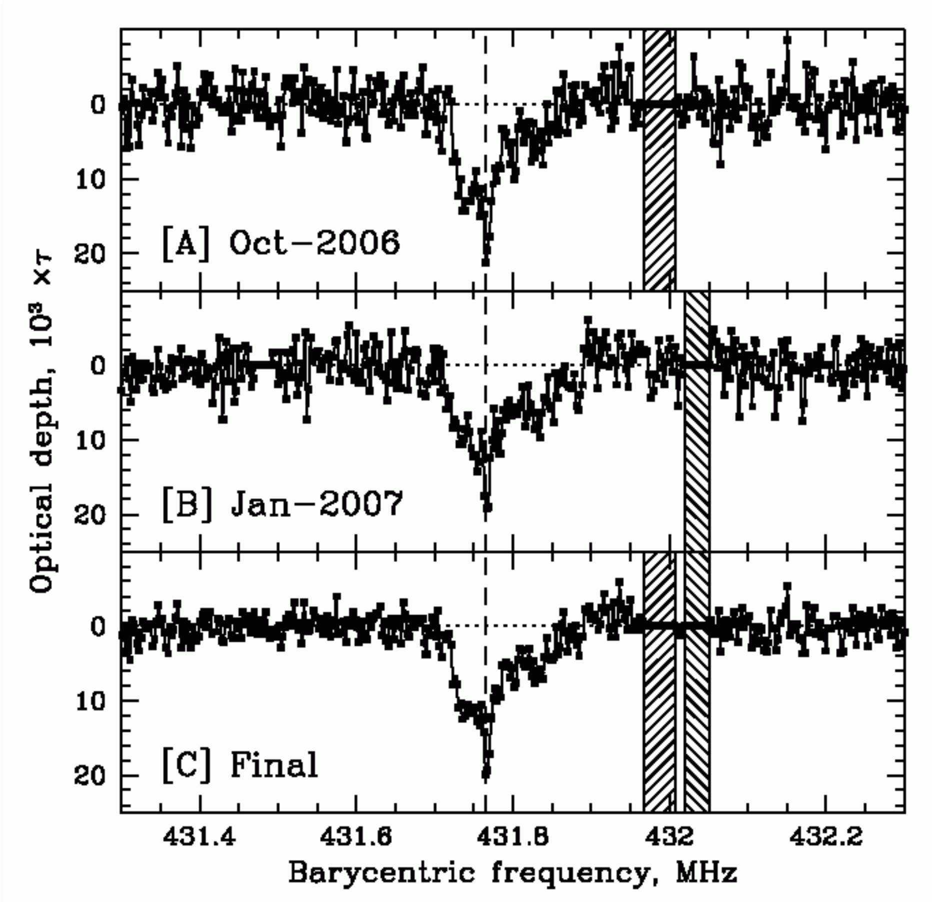
Theoretical models are also important to compare with the observed results.

Observation of gas-dominated galaxies



Quasar

Observer



York et al. (2007)

3 Toward the 21-cm Shadows

3.1 Physical state of primeval galaxies

There have been some attempts of detecting 21 cm absorption in DLA, but most of the DLAs were not detected, suggesting a small τ_{21cm}. Also, a deficiency of H_2 has been reported.

The ISM structures, in which dense regions are localized while most of the volume is occupied by the warm diffuse medium, provide a common interpretation for the lack of detections both in HI 21 cm absorption and H_2 in DLAs.

3 Toward the 21-cm Shadows

3.1 Physical state of primeval galaxies

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⇒ State-of-the-art simulations are desired to examine the feasibility of 21-cm absorption line systems!

Statistics of HI absorption line systems

We show a pilot theoretical study on the statistics of HI absorption line system based on Hirashita et al. (2003).

The 21-cm optical depth, τ_{21cm}, depends on the spin temperature (e.g., Furlanetto et al. 2006) as:

$$\tau_{21\,\mathrm{cm}} = 0.54\left(\frac{\Delta v}{10\ [\mathrm{km\,s^{-1}}]}\right)^{-1}\left(\frac{T_{\mathrm{s}}}{10^{3}\ [\mathrm{K}]}\right)^{-1}\left(\frac{N_{\mathrm{HI}}}{10^{21}\ [\mathrm{cm^{-2}}]}\right) \qquad (1)$$

where T_s is the spin temperature of hydrogen atoms and Δv is the velocity dispersion, assumed to be 10 kms^{-1}.

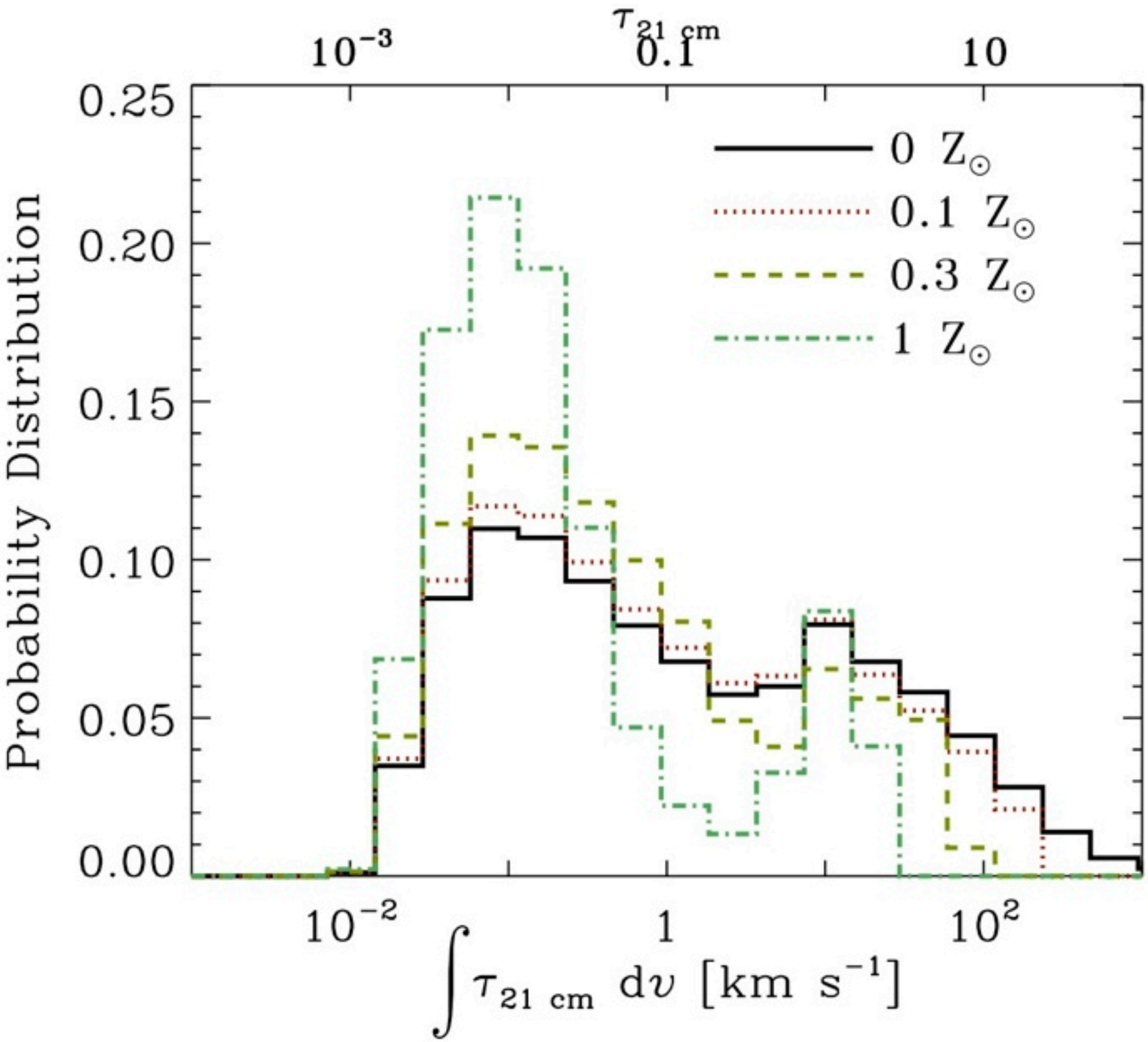
The spin temperature $T_s = T_{gas}$ is assumed, since the density is high enough for the spin temperature to approach the kinetic temperature (Field 1958).

Statistics of HI absorption line systems

A quantity free from the assumptions on Δv is also calculated by integrating 21 cm over the entire line profile, τ_{LP}:

$$\tau_{\mathrm{LP}} \equiv \int \tau_{21\,\mathrm{cm}} \mathrm{d}v = 0.54 \left(\frac{T_{\mathrm{s}}}{10^3\ [\mathrm{K}]} \right)^{-1} \left(\frac{N_{\mathrm{H}}}{10^{21}\ [\mathrm{cm}^{-2}]} \right)\ [\mathrm{km\,s^{-1}}] \qquad \mathbf{(2)}$$

Statistics of HI absorption line systems



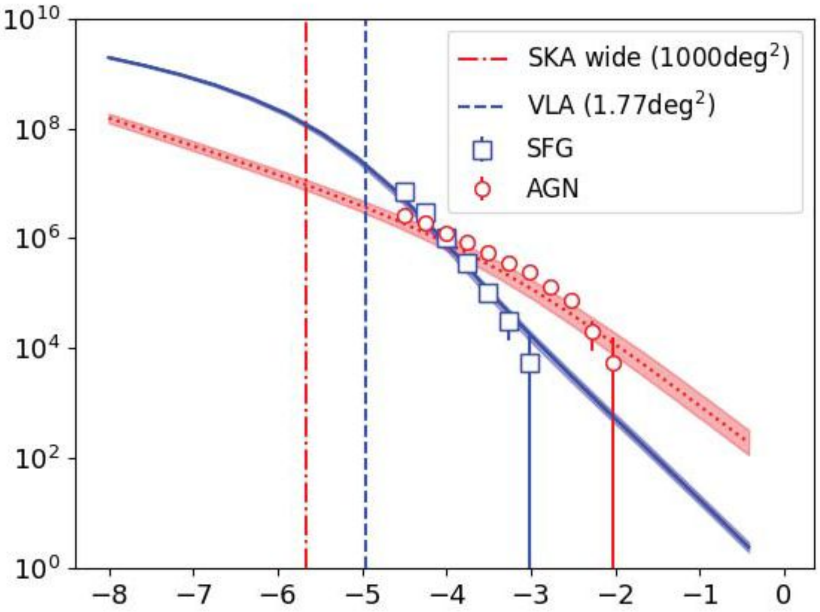
Takeuchi et al. (2019): work lead by Tee & Hirashita

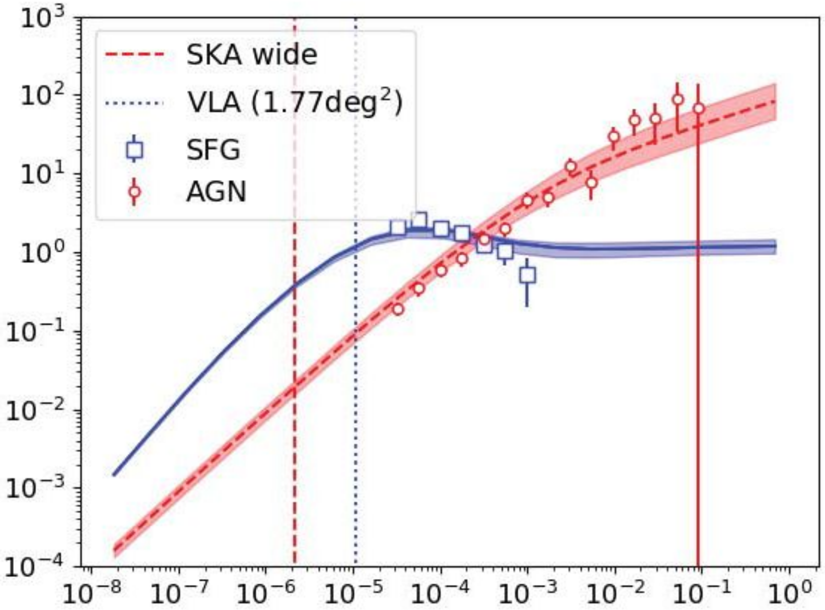
Statistics of HI absorption line systems

For the case without extinction, we clearly find two peaks around τ_{LP} = 0.1 and 10. The peak at higher τ is originated from the warm diffuse medium where column density is relatively small (but larger than $2 \times 10^{20}\,\mathrm{cm}^{-2}$) with a high temperature ($T_{gas} > 10^3$ K), while the peak at lower τ is due to cool and dense regions.

The effect of dust extinction is clearly seen. The abundance dramatically decreases at large 21 cm originating from high column density regions, since the extinction is large. The peak at $\tau \sim 0.01$ is relatively enhanced as the extinction bias becomes stronger.

Statistics of HI absorption line systems





Kono et al. (2019)

Statistics of HI absorption line systems

Requirement for unbiased detection of DLAs:

1. **For a typical QSO (100 mJy), rms ~ 33 nJy is needed to detect τ ~ 0.001.**
2. **Since the noise level should be 1/3000 for a continuum, the dynamic range must be 35 dB.**
3. **Pointed observation: to detect τ ~ 0.001, a pointed observation with ~ 10 hr per one DLA by SKA-LOW is ideal.**

3.2 Background Continuum Sources

We also need to develop a model of the background light continuum sources like quasars and early gamma-ray bursts (GRBs).

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

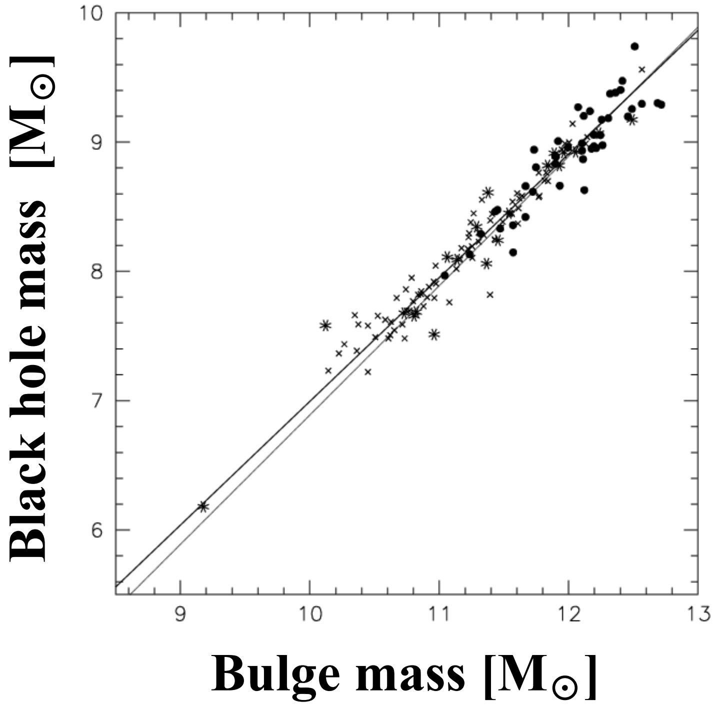
1. **Assuming that the fraction of radio loud quasars are constant with time, we can adopt the Local bulge-black hole mass relation to high-z Universe.**
2. **At $z > 10$, quasar density is expected to decrease significantly, and GRBs are good candidate radio sources**

Quasars

Radio loud quasars are only a small fraction among all. Observationally it is well known that they are associated with strong jets, and having elliptical galaxies as their host (in the low-*z* Universe).

It is suggested that the merger history of their hosts and/or angular momentum of gas around the central BHs are relevant to their properties.

We should model quasars with some empirical relations, as well as their *environments*.



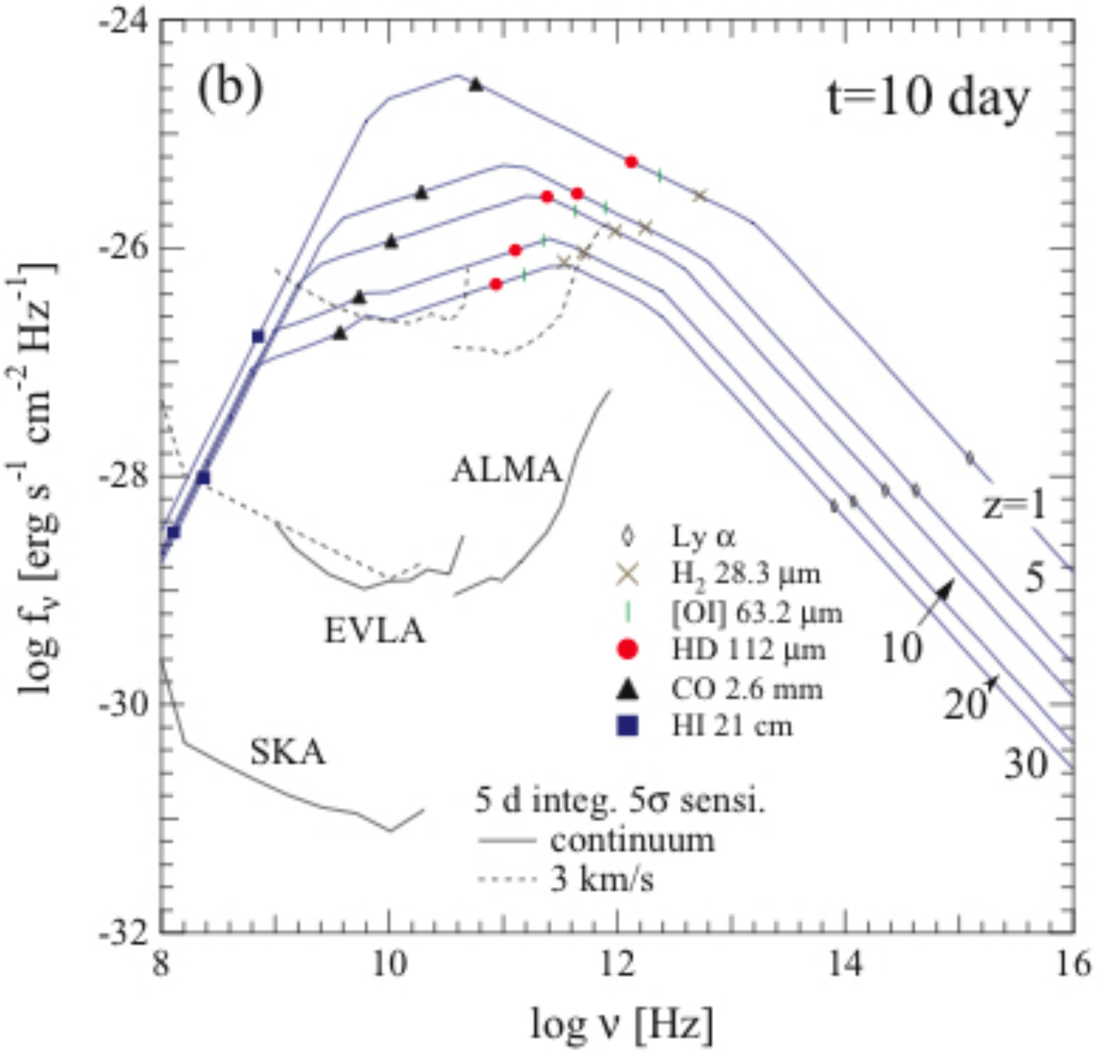
Bettoni et al. (2003)

Gamma-Ray Bursts

We can estimate the density of surrounding ISM by connecting the radio spectrum and the light curve of the GRBs. It may be also possible to detect the molecular absorption lines like CO on their spectra.

Through these observations, we can expect information of the physics of first stars (Inoue et al. 2007).

Gamma-Ray Bursts



Inoue, Omukai, & Ciardi (2007)

4. Summary

1. Optical/UV QSO absorption line systems are a useful tool for exploring gaseous systems, a very high column density system drops the background quasar itself from the original selection because of its strong extinction.
2. To avoid this fatal bias, we can select a quasar sample by radio continuum emission, and survey the absorption systems by 21cm lines.
3. The feasibility of such systems on the QSO radio continuum depends on their metallicity, ISM structure, and spatial abundance.
4. The distribution of $\tau_{21\mathrm{cm}}$ strongly depends on metallicity. Without extinction (Z = 0), the PDF has double peaks that stem from warm and cold dense regions. With increasing extinction, the contribution from higher-density regions diminishes.

4. Summary

5. For a typical QSO, rms ~ 33 nJy is needed to detect τ ~ 0.001. Since the noise level should be 1/3000 for a continuum, the dynamic range must be 35 dB. To detect τ ~ 0.001, a pointed observation with ~ 10 hr per one DLA by SKA-LOW is ideal.
6. To estimate the abundance and spatial distribution of primeval galaxies, dedicated simulations with N-body + SPH and radiative transfer may be needed to treat especially the structure in the early Universe at small scales.
7. It is important to include the effect of star formation, but still many problems remain unsolved. State-of-the-art simulations are still waited.

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You are always welcome to join us!

Hirashita et al. (2003)

A 2-dimensional hydrodynamical simulation of a galactic disc based on Wada & Norman (2001).

Parameter values appropriate for formation redshift $z_{\mathrm{vir}} = 3$ and virial mass $M_{\mathrm{vir}} = 8.0 \times 10^{10}\ M_{\odot}$ were taken. A 1 kpc × 1 kpc area was simulated with 2048 × 2048 grids.

To choose the possible lines of sight for DLAs, only grids with $N_{\mathrm{HI}} > 2 \times 10^{20}\ \mathrm{cm}^{-2}$ were adopted.

Hirashita et al. (2003)

Dust extinction was considered, since if the extinction is so large that the background QSO is obscured, such a line of sight cannot sample DLAs.

Vladilo & Péroux (2005) showed strong lack of DLAs with zinc column density $N_{\mathrm{Zn}} > 10^{13.2}$ cm−2, which they explained with the effect of extinction in metal-rich environments.

⇒ Grids with $N_{\mathrm{Zn}} > 10^{13.2}$ cm−2 were omitted to be consistent with the observed extinction bias mentioned above.

Hirashita et al. (2003)

Under a given N_H and Tgas at each grid, we evaluate $f_\mathrm{H2} = 2n_\mathrm{H2}/n_\mathrm{H}$, where $2n_\mathrm{H}$ and n_H2 are the number densities of hydrogen nuclei and H_2, respectively. The formulae are summarized in Section 2.1 of Hirashita & Ferrara (2005).

The equilibrium condition is set to be $R_\mathrm{dust} = R_\mathrm{diss}$ (R_dust and R_diss are the rates of H_2 formation on dust grains and H_2 dissociation by UV radiation per unit volume, respectively). We adopt a dust grain radius of 0.1 μm, a dust material density of 3 g cm^{-3}, and the typical UV radiation field in the solar neighborhood.

The local hydrogen number density is related to the column density as $n_\mathrm{H} = N_\mathrm{H}/H_\mathrm{disk}$ (the thickness of disk is assumed to be $H_\mathrm{disk} = 100$ pc).

Hirashita et al. (2003)

Since the dependence of Rdust on the dust temperature (Td) is weak, we simply adopt $T_{\mathrm{d}} = 20$ K.

For the dust-to-gas ratio, we adopt a scaling relation with the metallicity as $D = 0.01(Z/Z_{\odot})$.

***N.B.* These simplifying assumptions should be replaced by more sophisticated theoretical treatment like Asano et al. (2013a, b).**

All hydrogen is assumed to be in atomic form; i.e. $N_{\mathrm{HI}} = N_{\mathrm{H}}$. The velocity dispersion is set to be $\Delta v = 10$ km s^{-1} based on the typical nonthermal velocity dispersions observed in galaxies (Braun et al. 2009).