IGM Observation Group

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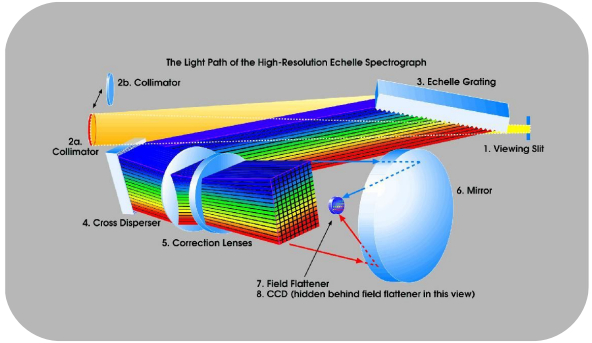
Questions Posed

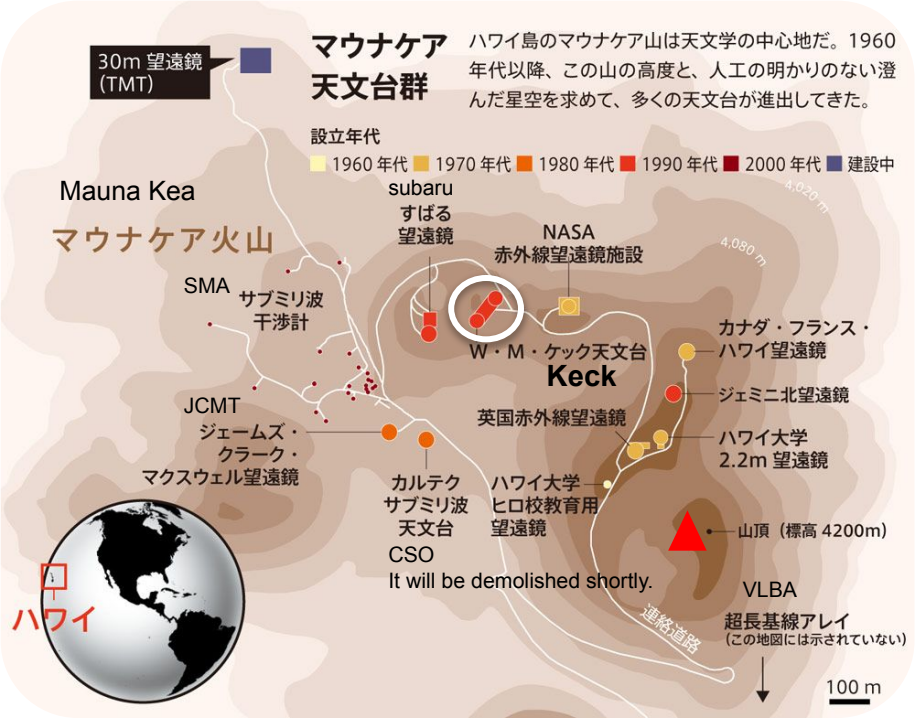
Consider the case for this argument:

- What were the **key technical advances**?
- How did this enable a **fundamental leap** in IGM science?
- What were the **principal discoveries**?

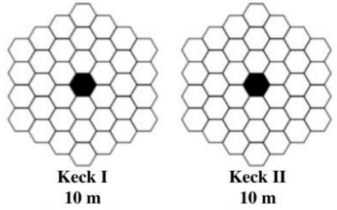


Keck telescope→
←HIRES spectrometer

1. Introduction ~ Keck telescope



1. Introduction ~ Keck telescope I & II

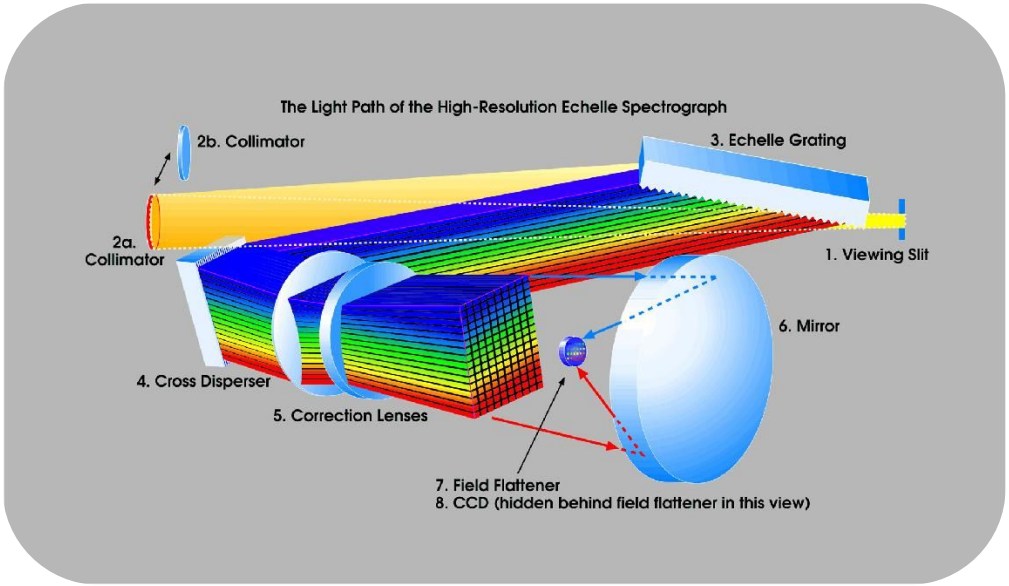


Keck telescope

- **10m** aperture with an effective area of
  - **72.3674 m^2**

Domes in Car Mirror

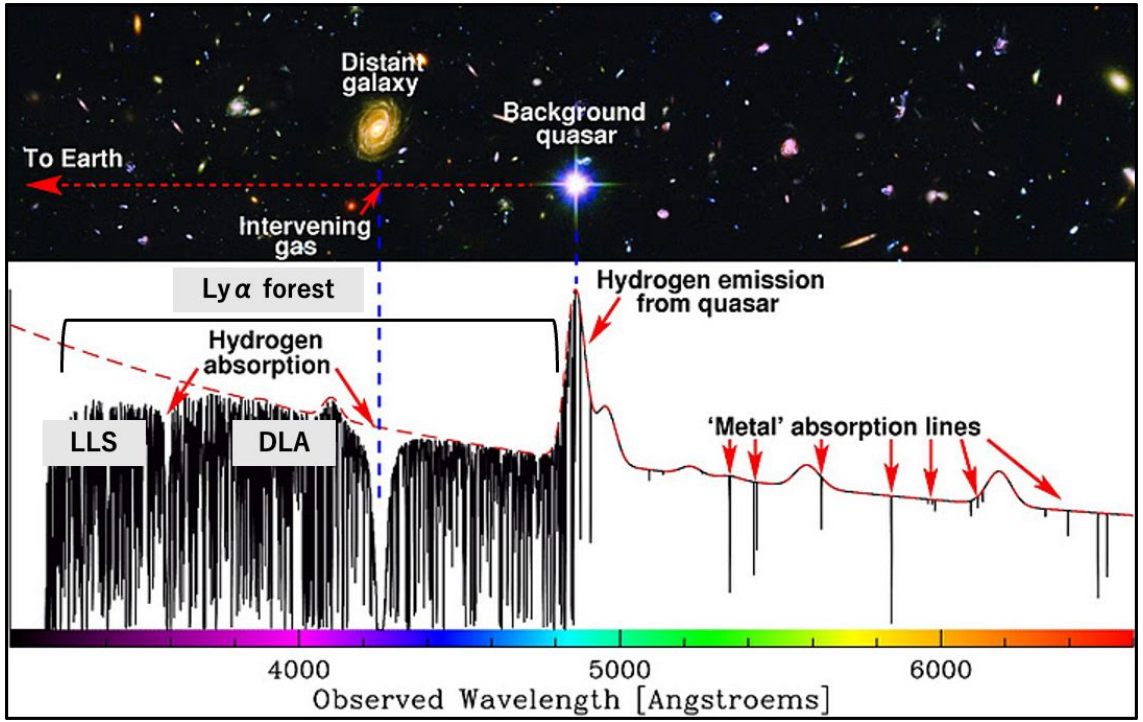
1. Introduction ~ HIRES echelle spectrometer



HIRES

- PI : Steve Vogt
- Specifications
  - **R ~ 40,000**
    - FWHM ~ 8 km/s
  - Wavelengths: **3,000-10,000** Ang
  - Throughout ~5%
  - Detector: readnoise of ~3 electrons

1. Introduction ~ IGM



Background of IGM Study

- we can't see IGM directly
- Strong background light sources show us the IGM figure as **absorption lines**.
- The ability to see absorption lines
  - clearly ← **S/N**
  - finely ← **resolution**

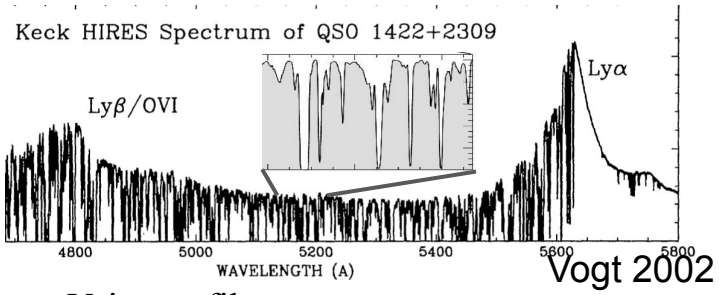
is important for understanding IGM.

- IGM gas is mainly classified and discussed in terms of a quantity called **column density**

2. Fundamental leap

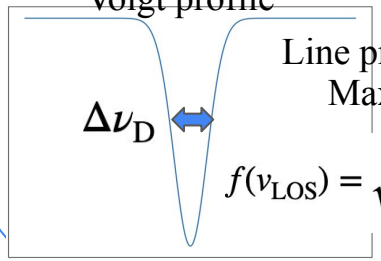
2.1 Spectral Resolution, R ~ 40,000

Thermal Broadening



Vogt 2002

Voigt profile



Line profile is derived from Maxwell distribution

$$f(v_{LOS}) = \sqrt{\frac{m}{2\pi k_B T}} \exp\left(-\frac{m v_{LOS}^2}{2 k_B T}\right)$$

Doppler width (typical T_IGM = 10^4[K])

$$\Delta\nu_D = \frac{\nu_{Ly\alpha}}{c}\sqrt{\frac{2k_B T}{m_p}} \sim 10^{11}[\mathrm{Hz}] \leftrightarrow 12[\mathrm{km/s}]$$

Resolution of frequancy

$$\Delta\nu_{re} = c\Delta\lambda/\lambda = c/R \sim 7.5[\mathrm{km/s}]$$

$$\Delta\nu_{re} < \Delta\nu_D$$

<u>HIRES enabled the first detection of the thermal broadening of IGM</u>

2. Fundamental leap

2.2 Signal-to-noise ratio

Magnitude → Flux : 2.2908677×10−27 erg s^−1 cm^−2 Hz^−1

Assumption

QSO magnitude = 18
QSO redshift = 2.5
Wavelength(rest) = 1100 Å
Time = 1 hour

Instrument

R = 40,000
Aperture = 10 m
ADU(Analog to Digital Unit) = 0.8
CCD readout noise: 5–6 electrons (rms)
CCD dark current: <10 e/pixel/hour
Throughput > 5%

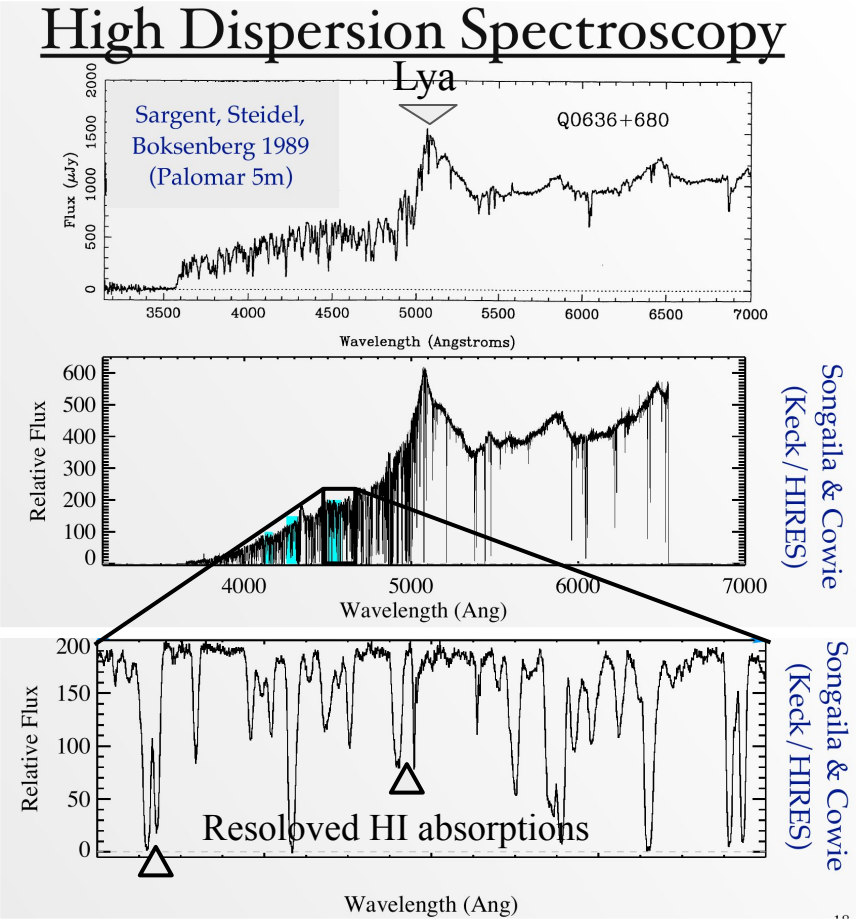
```
flux density=2.29e-27 erg / (cm2 Hz s)
pixel scale [A/pixel]=2.41e-02 Angstrom
flux per pixel=8.76e-12 erg / s
E_photon (lambda=1100 A) =5.16e-12 erg
N_photon=1.70 1 / s
N_electron=1.36 1 / s
S/N=21.86
```

S/N ~ 22

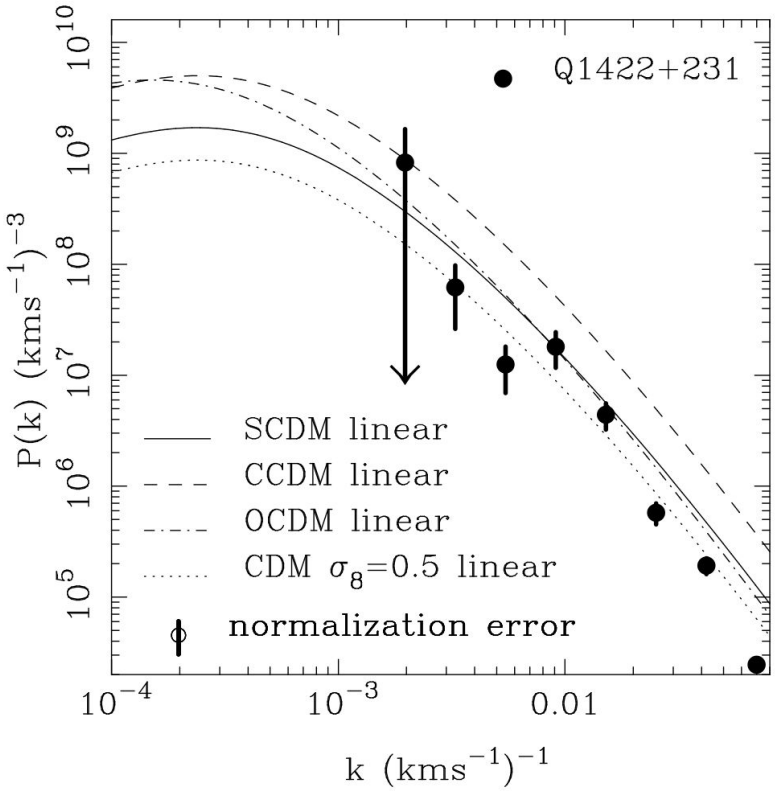
If Aperture = 5m(half), S/N ~ 5(quater)

Aperture is important factor for high-S/N

3. Principle Discovery



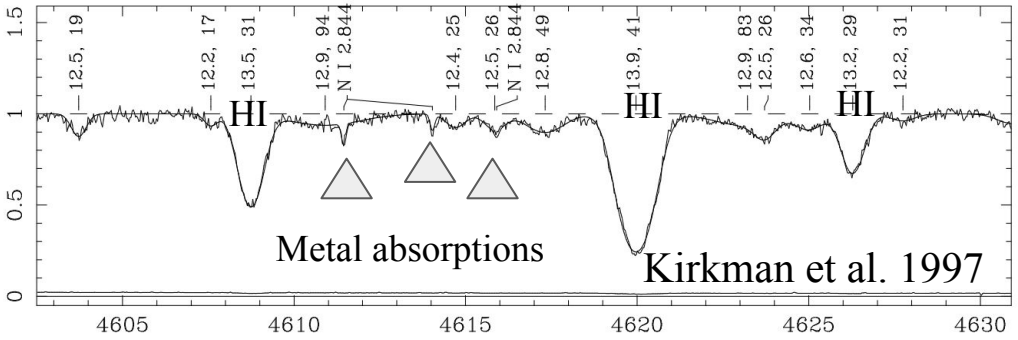
Power spectrum:



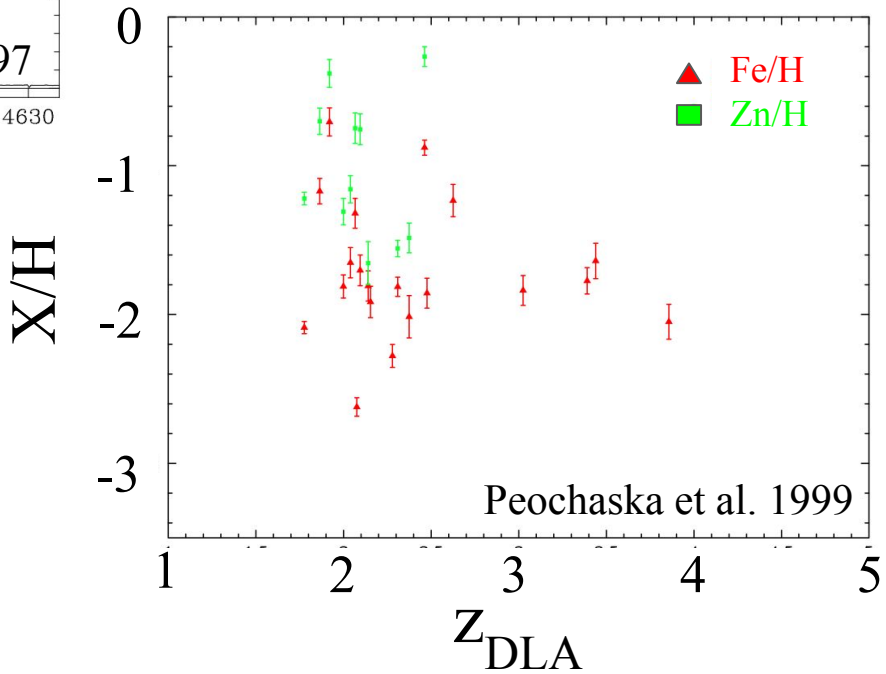
Croft et al.1997

3. Principle Discovery

Metal absorption dectection:



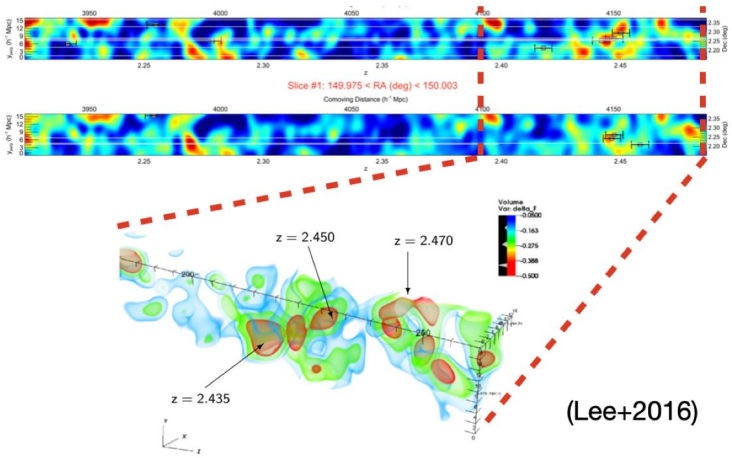
Metal enrichment in Damped Lya System (DLA):



4. Small-scale IGM for Dark Galaxies

- **Motivation from Instrumental Limit**

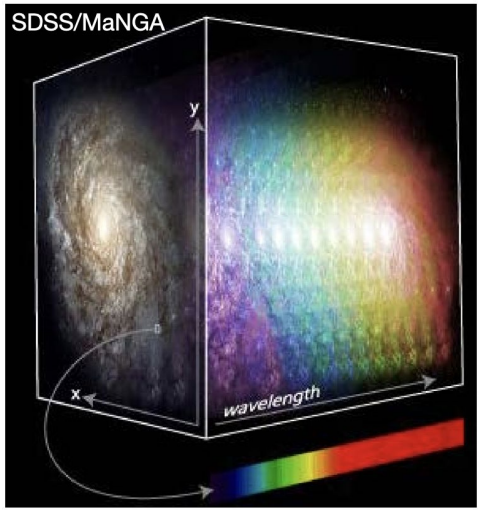
WE have reaced the best resolution of LyA along LoS…
HOW about the projected resolution ?



(Lee+2016)

QSOs/Galaxies as point sources

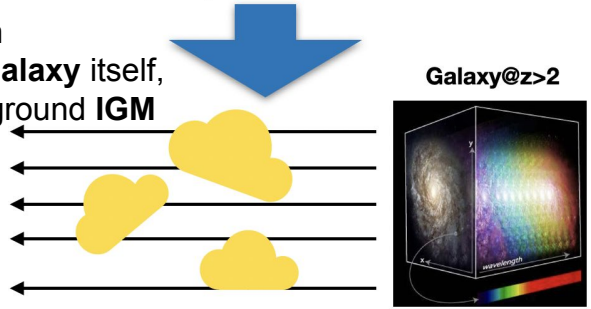
Minimum spatial resolution
~ 3Mpc



Integral Field Spectrometer (IFS)

An Example of Local Galaxies

3D Spectrum
NOT for the **galaxy** itself,
BUT the foreground **IGM**

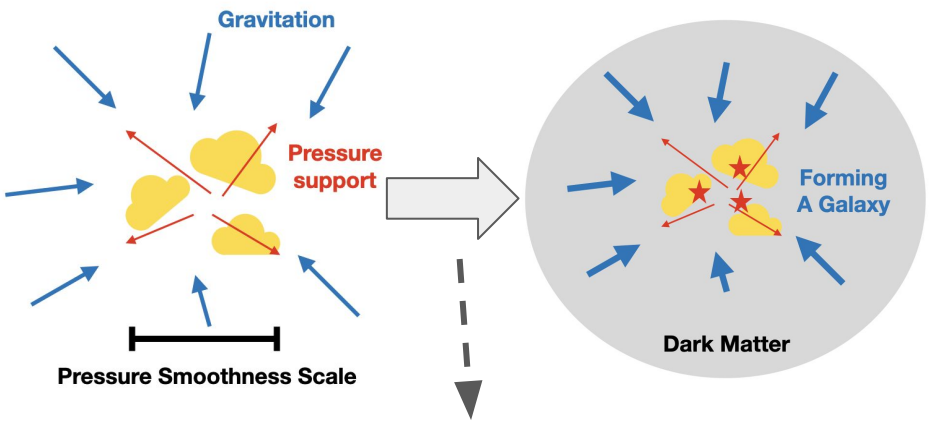


3D HI Distribution on
~ tens kpc?

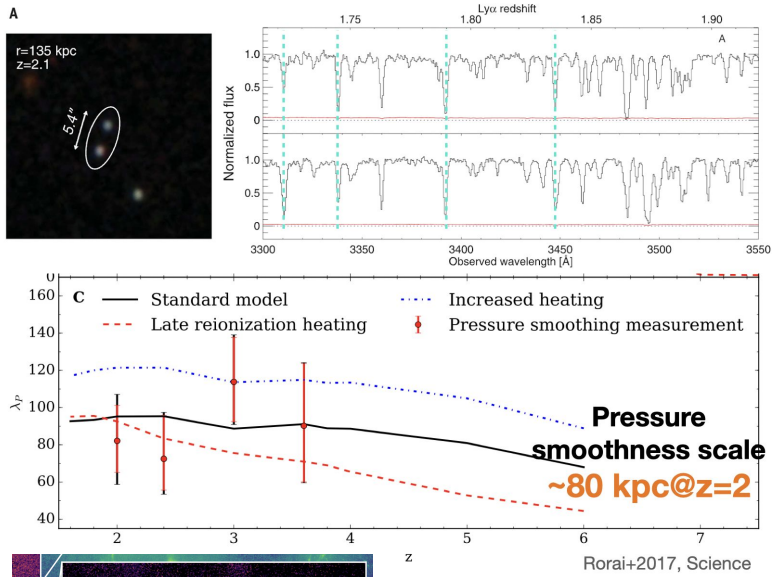
4. Small-scale IGM for Dark Galaxies

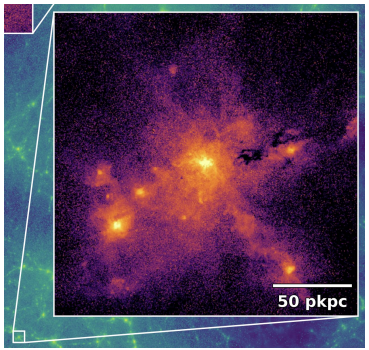
- **Principle Science**

WITNESS the forming of galaxies!!!
– on ~10 kpc scale of IGM (not ISM/CGM)



'DARK' GALAXIES
with NO stellar component YET





Simulation in TNG50
(Byrohl+2021)

Progenitors of such systems

5. Feasibility of New Instrument

1. **Spatially Resolve Background Galaxy:**

bright z~2 SFG, M ~ -23 => Re ~ 4 kpc

lensing magnification of ~ 25 => Re ~ 20 kpc

covered in FoV: 5”×5”

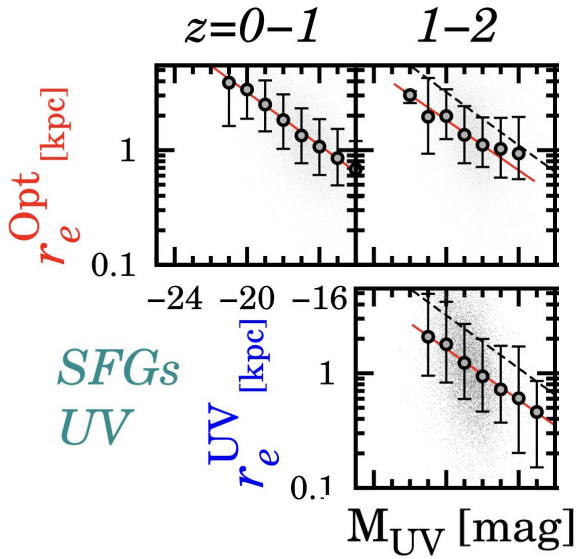
2. **Sensitivity Requirement:**

with a spatial resolution of 0.1” => 50×50 pixels

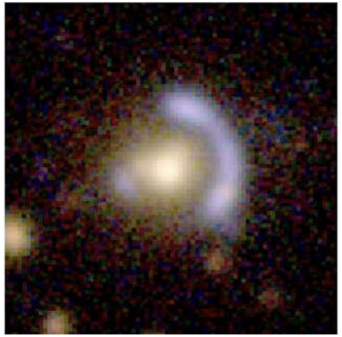
=> F_λ ~ 1e-30 erg/s/cm2/Hz (m~26) in each pixel

3. **Spectral Resolution**

limited by sensitivity (R~20 if assume Keck/HIRES efficiency)



Size-Luminosity relation, Shibuya+15



lensed z~2 galaxies with a magnification of 27, Lin+09

5. Comaprison to existing plan on 30-m telescopes

39m E-ELT/HARMONI

spatial res. ~4 mas

spectral res. ~ 3500

Our inst.

spatial resol. ~ 4 mas

wavelength. 0.4-0.6 μm

What else can be done with our inst.

5. Comaprison to AO design of existing/comming telescopes

Atomospheric coherence length: r_0

$$r_0 \propto \lambda^{6/5}$$

Observing wavelength (μm) ⇒	10	2.2	0.8	0.5
Telescope diam. (m) ⇓				
4	1.1	7.6	22.8	40
10	2.7	18.9	56.9	100
30	8.2	56.8	170.7	300

Wavelength (μm)	r_0	$\tau_0 \approx r_0 / V_w$	$f_0 \equiv 1/\tau_0 \approx V_w / r_0$
0.5	10 cm	5 msec	200 Hz
2.2	53 cm	27 msec	37 Hz
10	3.6 m	180 msec	5.6 Hz

5. Summary

Key **technical advances** of HIRES:

S/N and resolution

Principal discoveries:

Resolved HI absorptions → Power spectrum
Metal absorption → Metal enrichment

New Science: small-scale fluctuation of IGM
use spatially extended galaxy as background source to detect Lyα forest

Required Instrument: high-sensitivity IFU