Observation of Extremely Metal-poor Galaxies by Subaru：

Probe of Early Universe

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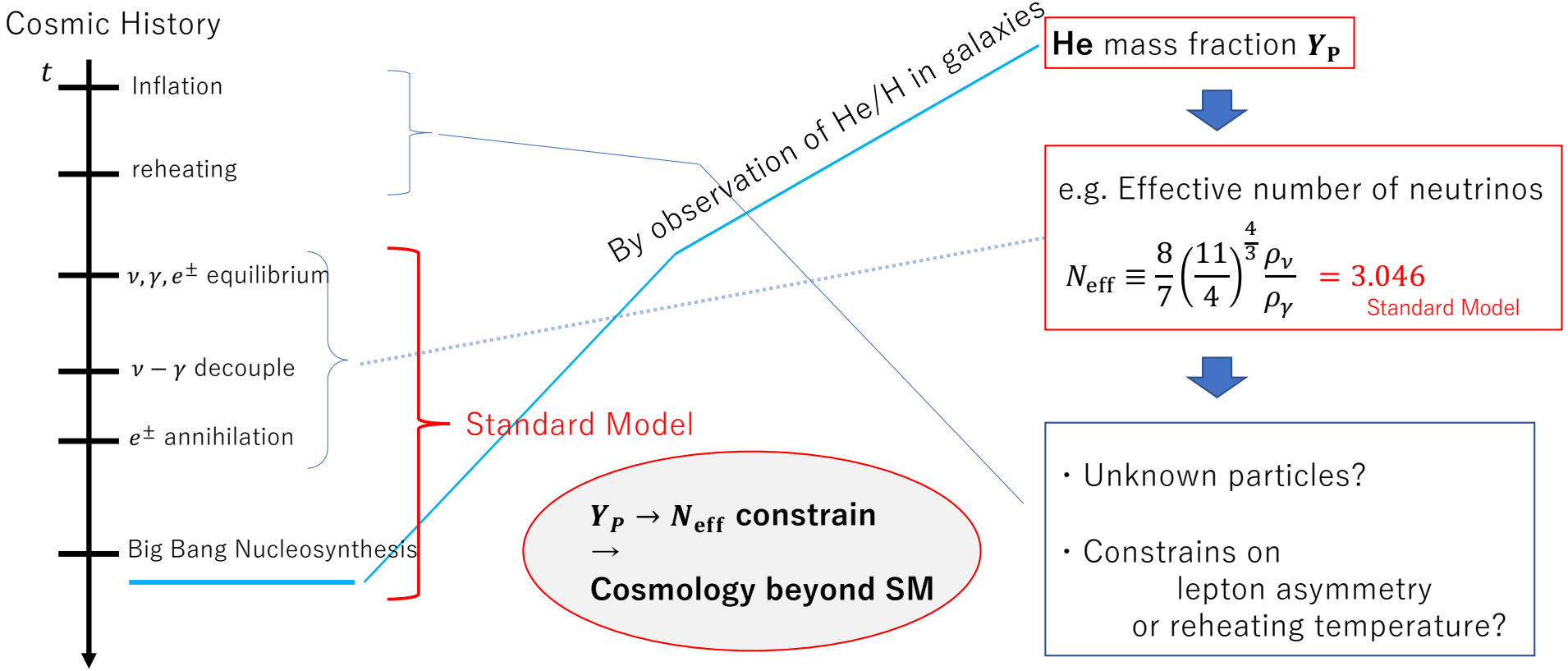
Big Bang Nucleosynthesis



Uncertainty of Y_P

Previous results Y_P are not yet accurate enough

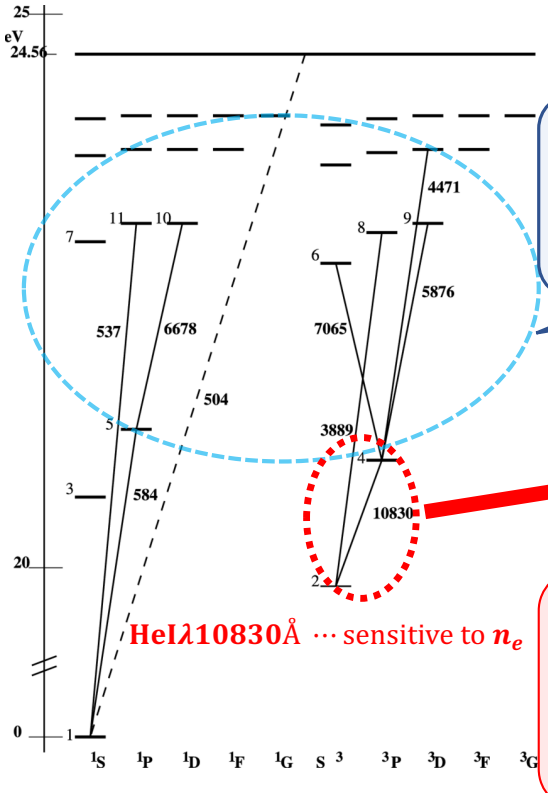
(Hsyu et al. (2020) : $Y_P = 0.2436^{+0.0040}_{-0.0039}$, $N_{\mathrm{eff}} = 2.85^{+0.28}_{-0.25}$)

Main sources of error

1. Systematic errors in He/H determination of galaxies
2. Statistical errors due to small sample size

We aim at overcoming these problems and determing Y_P with high accuracy

Importance of **HeIλ10830Å**



Helium energy levels

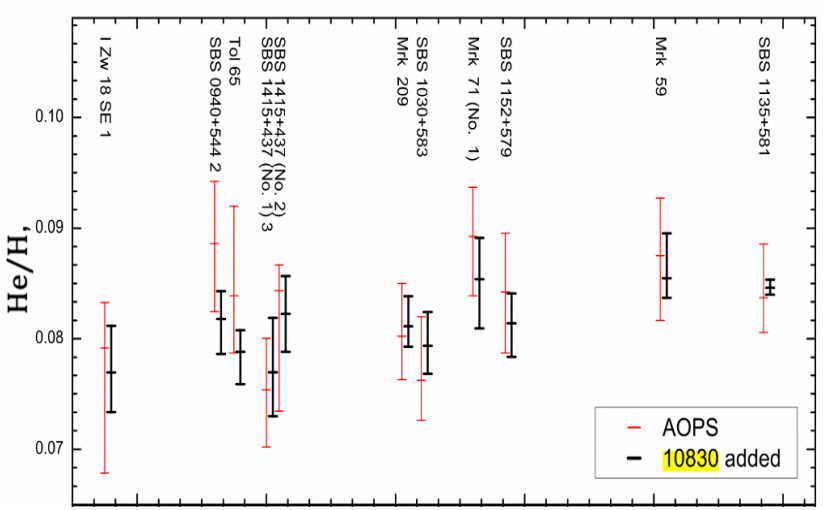
Labrosse,Gouttebroze+04

With only optical lines

→ He/H uncertainty due to degeneracy of n_e, T_e

Including HeI10830λÅ

→ **Potentially breaking the degeneracy**



Aver+15

New Observations - EMPRESS 3D -

Sample of Hsyu et al. (2020)

48 galaxies with metallicity of $0.1 - 0.4Z_{\odot}$
&
7 **EMPGs** ($\equiv Z < 0.1Z_{\odot}$)

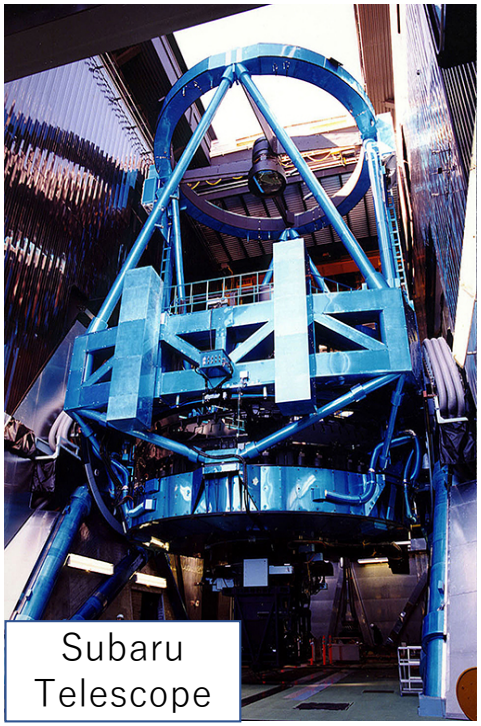
+

EMPRESS 3D Survey

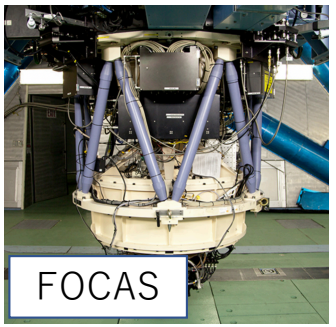
-We observe 30 EMPGs in 10 nights of 2021 – 2023, using Subaru
  -Targets: Low metallicity and available during observation periods

- Optical lines (by FOCAS) & NIR lines (IRCS+SWIMS)

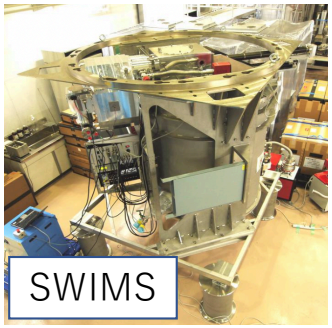
-We have already observed 7 EMPGs



(https://subarutelescope.org/jp/about/)



(https://subarutelescope.org/jp/about/instrument/)



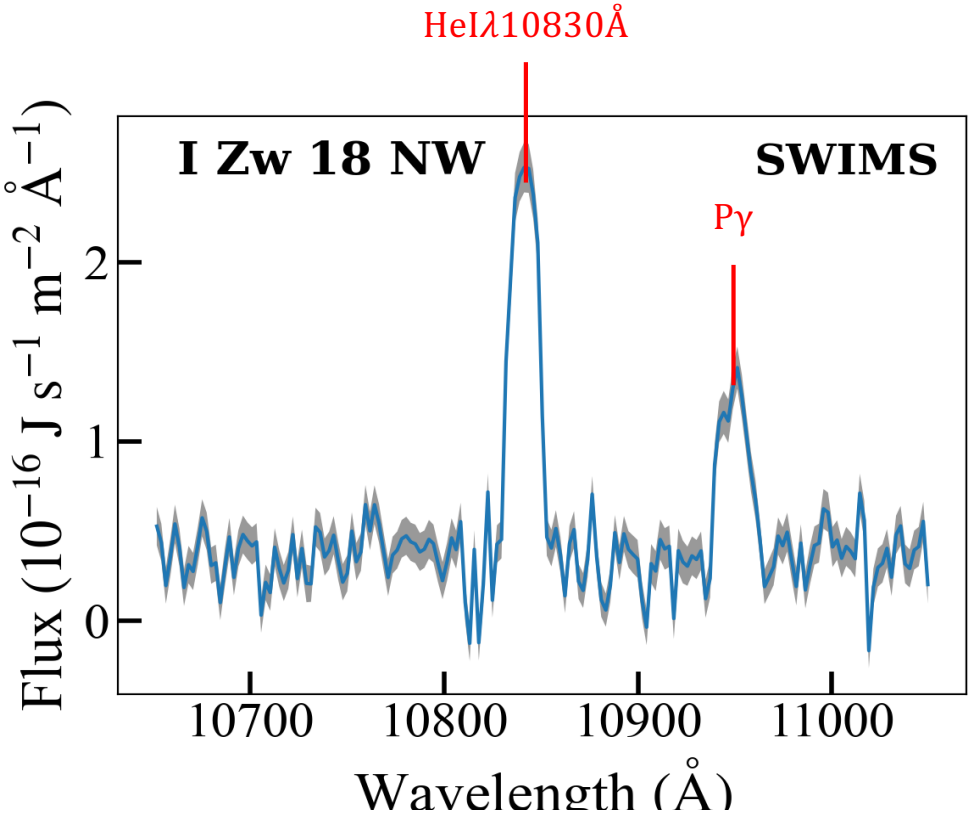
(http://www.ioa.s.u-tokyo.ac.jp/TAO/swims/)

Observation Results

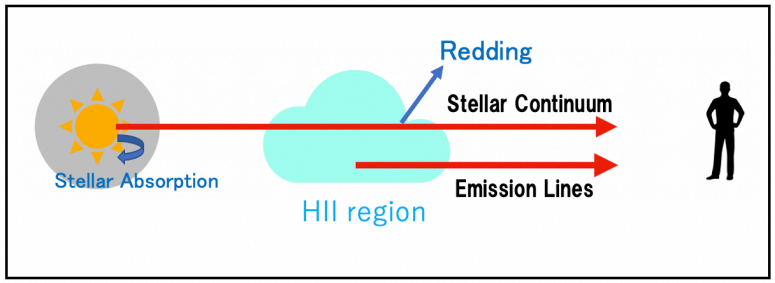
Object	$(O/H)\times10^5$	$F(HeI10830)/F(P\gamma)$
J1631+4426	0.794 ± 0.057	1.45 ± 0.21
Magellan/MOIRCS (7/23/2020, integration time 1800sec × 2)		

Object	$(O/H)\times10^5$	$F(HeI10830)/F(P\gamma)$
J1253-0312	12.303 ± 0.851	7.15 ± 0.01
J1016+3754	4.365 ± 0.101	1.43 ± 0.59
SUBARU/IRCS (4/1/2021, integration time 300sec × 4)		

Object	$(O/H)\times10^5$	$F(HeI10830)/F(P\gamma)$
I Zw 18 NW	1.34 ± 0.15	2.19 ± 0.27
J1201+0211	3.126 ± 0.230	7.23 ± 0.65
J1119+5130	3.199 ± 0.399	2.44 ± 0.53
J1243+3901	3.126 ± 0.230	4.87 ± 0.81
SUBARU/SWIMS (5/29/2021, integration time 300sec × 3)		



He/H Determination



$$\frac{F(\lambda)}{F(\mathrm{H}\beta)_{\mathrm{p}}} = y^{+}\frac{E(\lambda)}{E(\mathrm{H}\beta)}\frac{\frac{EW(\mathrm{H}\beta)+a_{\mathrm{H}}(\mathrm{H}\beta)}{EW(\mathrm{H}\beta)}}{\frac{EW(\lambda)+a_{\mathrm{He}}(\lambda)}{EW(\lambda)}}f_{\tau}(\lambda) \times \frac{1+\frac{C}{R}(\lambda)}{1+\frac{C}{R}(\mathrm{H}\beta)}10^{-f(\lambda)\ c(\mathrm{H}\beta)},$$

$$\chi^2 = \sum_{\lambda}\frac{\left(\frac{F(\lambda)}{F(H\beta)} - \frac{F(\lambda)}{F(H\beta)_{meas}}\right)^2}{\sigma(\lambda)^2}$$

H8, Hδ, Hγ, Hβ, Hα, Pγ, HeI3889, HeI4026,

HeI4472, HeI5016, HeI5876, HeI6678, HeI7065, **HeI10830**

Input

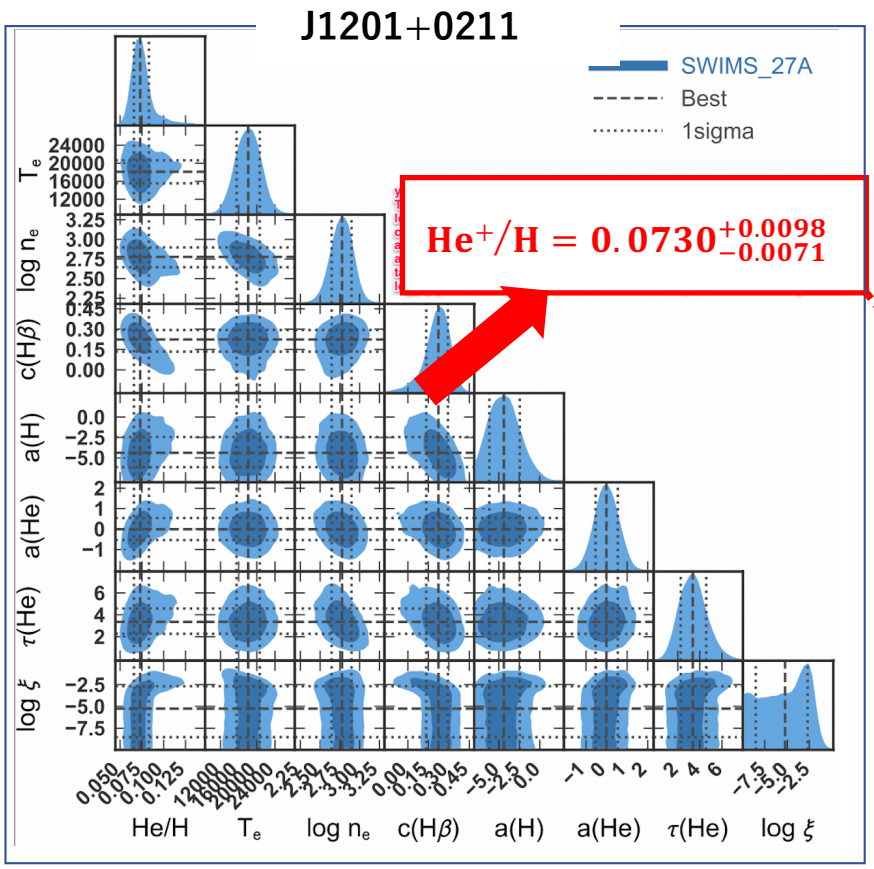
Output

He^{+}/H, T_e [K], n_e [cm^{-3}], $c(H\beta)$ a_H [Å] , a_{He} [Å] , τ, ξ

Searching best parameters which reproduce observed fluxes

$$\log(p) = -\frac{\chi^2}{2} - \frac{(T_{\mathrm{e}} - T_{\mathrm{m}})^2}{2\sigma^2}$$

He/H Determination



Doubly ionized He is also considered

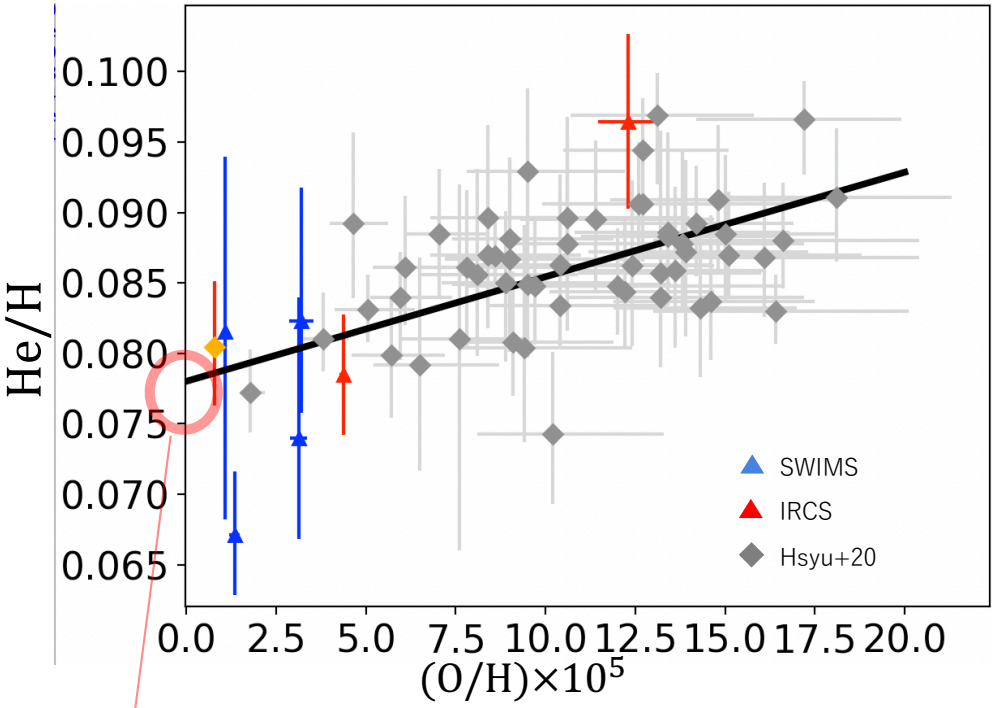
using

$y^{++} = 0.084t^{0.14}(\mathrm{HeII4686Å/H\beta})$ (Pagel 1992)

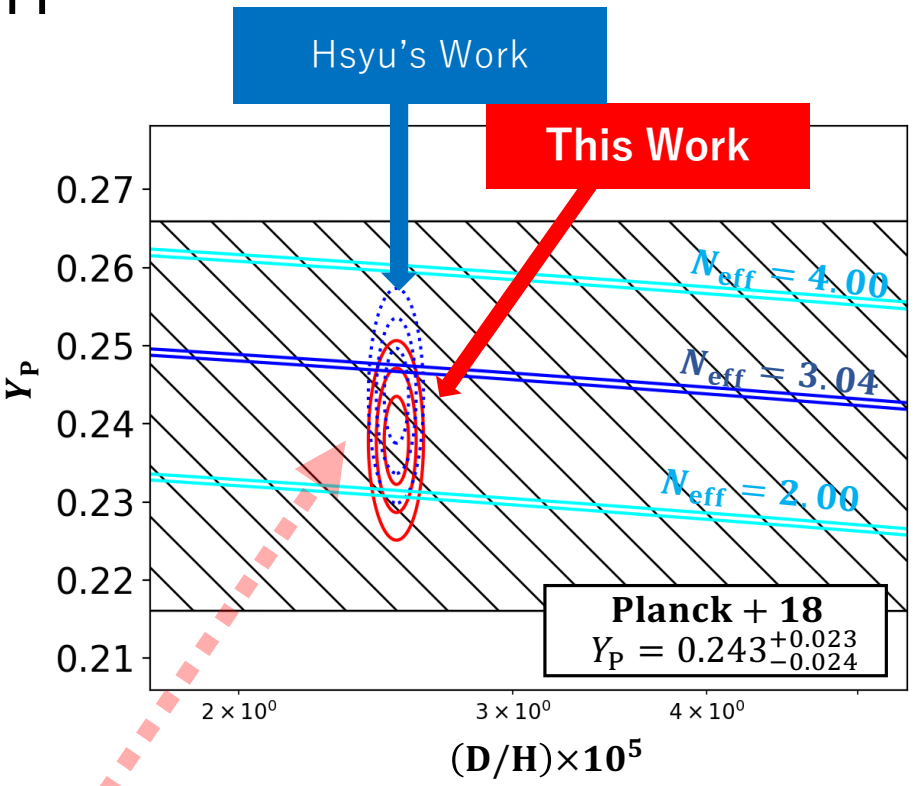
$$y = \frac{\mathbf{He^+}}{\mathbf{H^+}} + \frac{\mathbf{He^{++}}}{\mathbf{H^+}}$$

For J1201+0211, $y = 0.0740^{+0.0099}_{-0.0072}$

Yp, Neff Determination

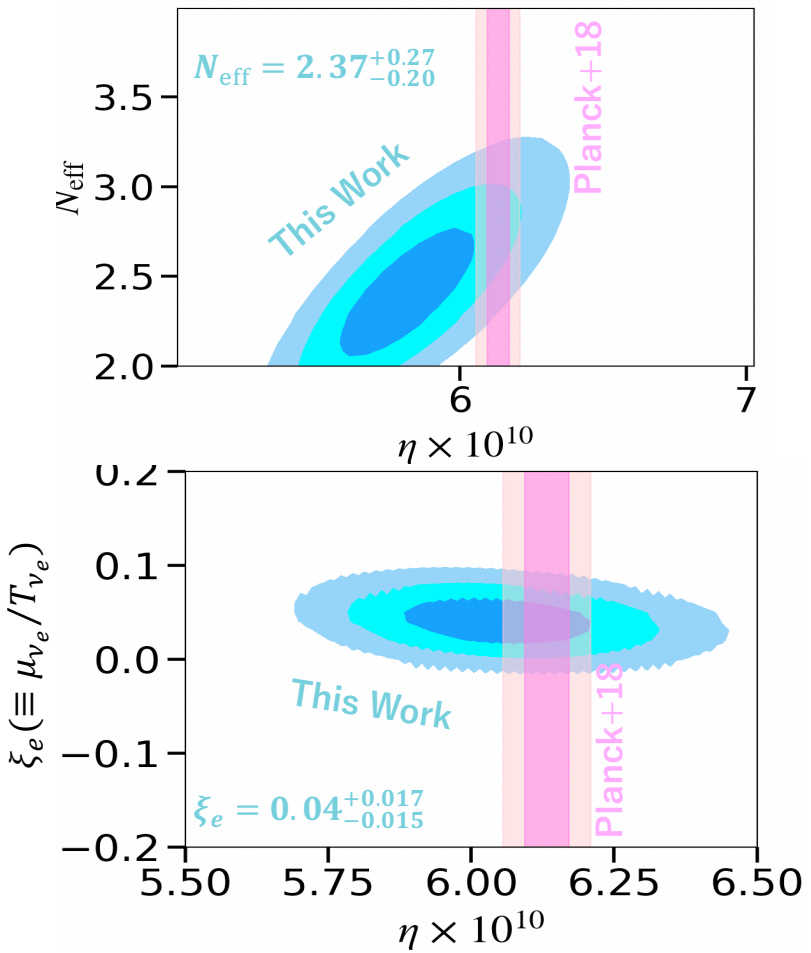


$y_P = 0.0780 \pm 0.0016$ → $Y_P = \frac{4y_P}{1+4y_P}$ → $Y_P = 0.2379^{+0.0037}_{-0.0037}$



※ We used Cooke (2018)'s results for (D/H)

Discussion



- **$N_{\rm eff} < 3.046$?**

  -Agreement with Planck+18 in 2 σ

- **Implication for lepton asymmetry, etc ?**

e.g. Lepton asymmetry ($n_l < n_l$)

↳ $n_{\bar{\nu}} < n_{\nu}$

↳ $p + e^- \leftrightarrow n + \nu_e$

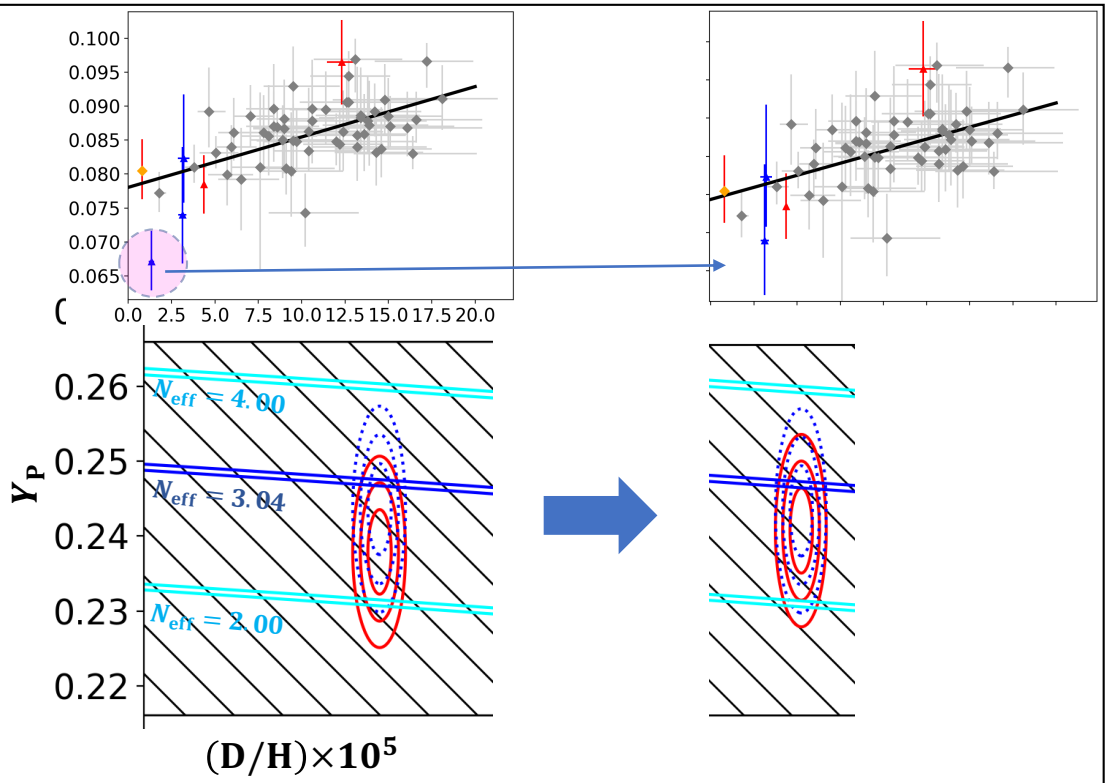
$p + \bar{\nu}_e \leftrightarrow n + e^+$

Less neutron

$n \rightarrow p + e^- + \bar{\nu}_e$

$n + p \rightarrow D + \gamma$ (Start of BBN)

Discussion



Left: Results shown in the previous slide
Right: Results excluding IZw 18 NW, with particularly low He/H

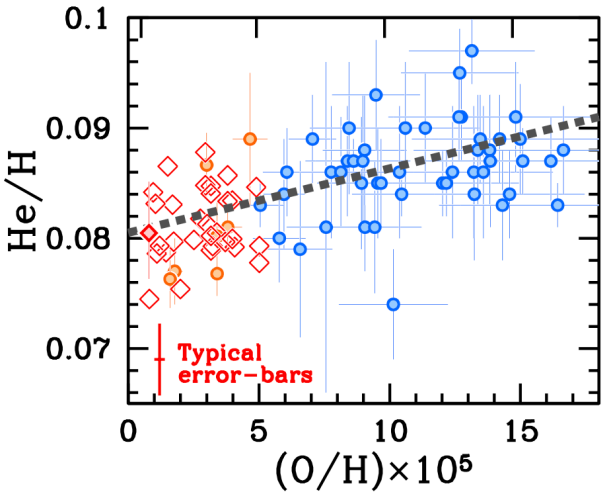
Due to low He/H of **IZw 18 NW ?**

- Problem of measurement accuracy ?
- Unknown mechanism for decreasing He/H ?

Future Prospects

- **Increase the sample size**
  - -30 EMPGs by 2023
  - -Subaru Prime Focus Spectrograph will adds thousands of galaxies($O/H \times 10^5 \lesssim 20$)

- **Reduction & evaluation of systematic errors**
  - -Improve the fitting function to be more realistic
  - (CELib; Saitoh et al. (2018))
  - - Temperature, density structure
  - - Fitting methods



Star formation history potentially changes He/H – O/H relation

(Fukushima, Nagamine+ '21)

Summary

- We are aiming at constraining Y_{P}, N_{eff} by observation of galaxies

  - Addition of 7 EMPGs to a previous sample
    → Smaller Y_{P} than the value of standard model by 2 σ

⇒ We need

- To increase the sample size

- To investigate the theoretical He-O relationship

- To find out what causes the low He/H of I Zw 18 NW