Unveiling Oxygen's Past with Subaru/IRD :

Oxygen Abundance in Very/ Extremely Metal-Poor Stars



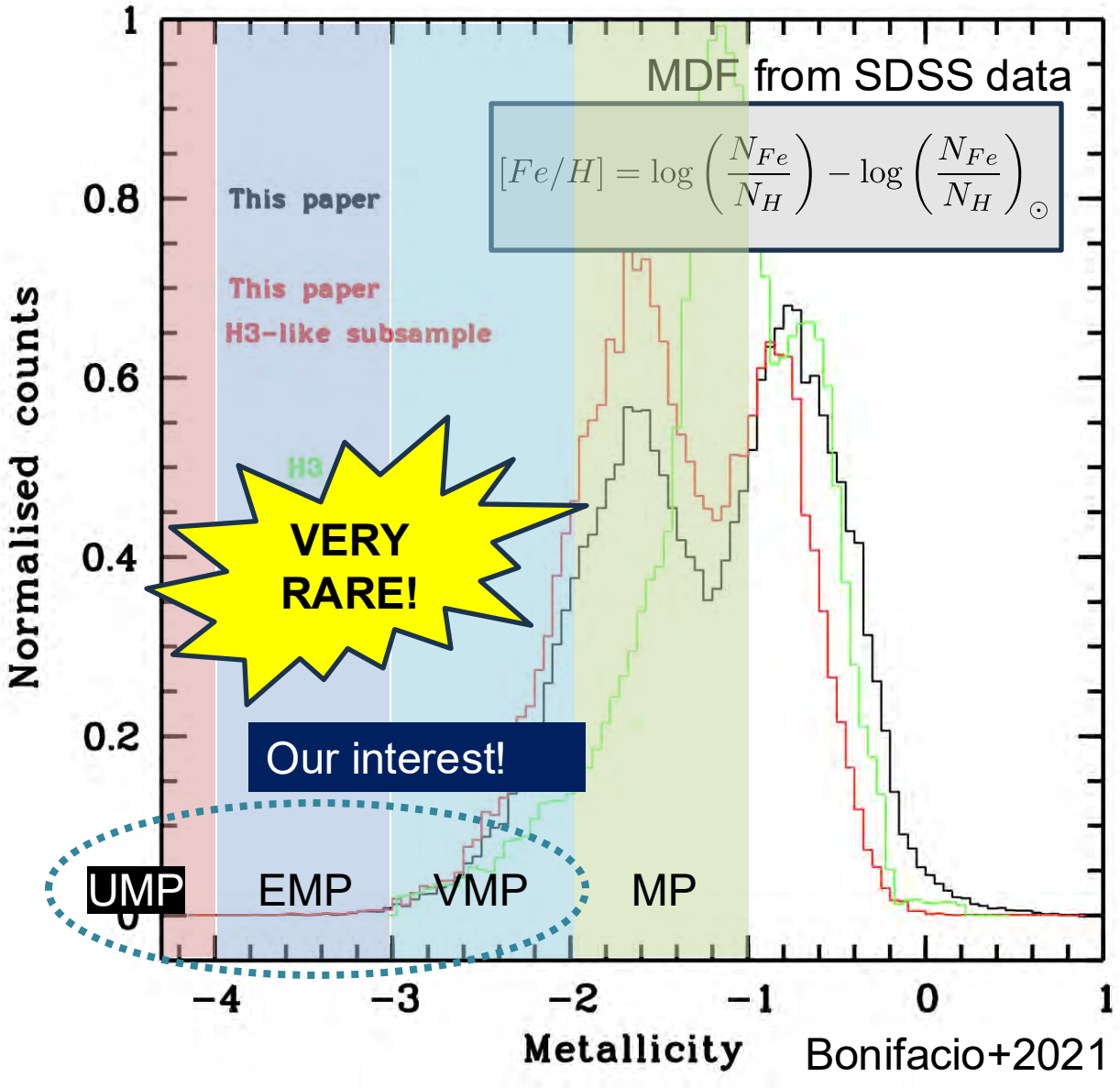
Bakuh **Danang** Setyo Budi - ダナン

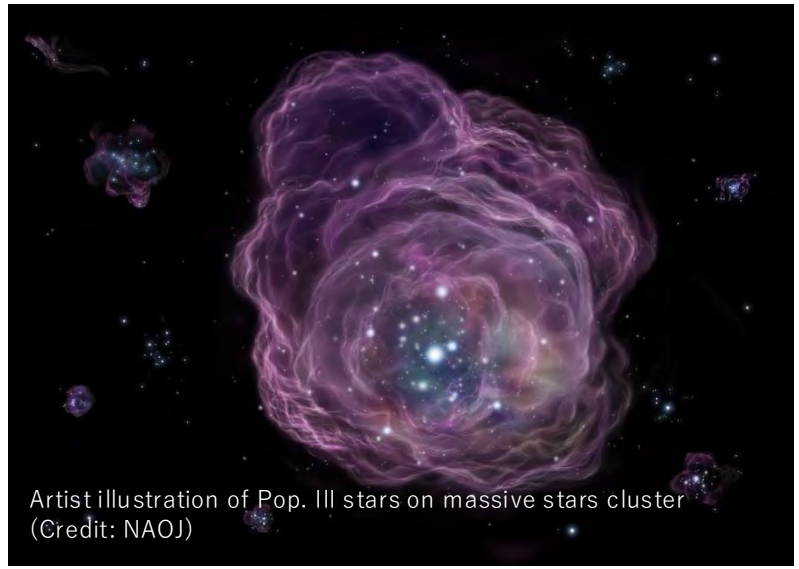
SOKENDAI M2/NAOJ (TMT-Project)

Aoki, Wako (NAOJ/TMT-Project); Nick Storm (MPIA);

Ishigaki, Miho (NAOJ/Subaru Telescope); Matsuno, Tadafumi (Universität Heidelberg), and IRD instrumental team

Quick Introduction about V/EMP





Low-mass Second Generation stars ~ 0.7 – 1 $M_\odot$

- Very long life-span (~10 Gyr)
- [Fe/H] < -4
- Halo stars in Milkyway.
- Preserved the progenitor chemical abundance pattern

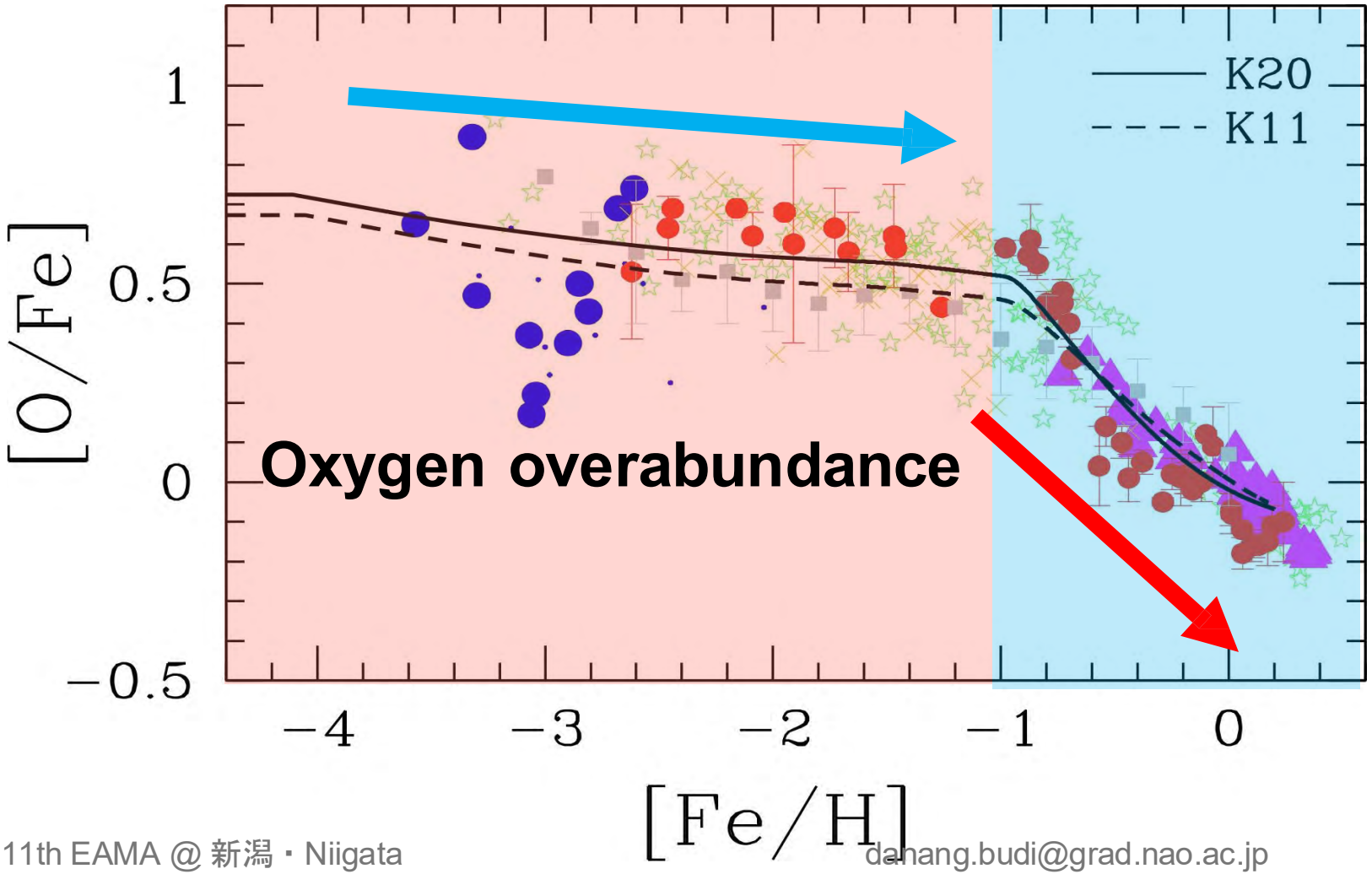
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Oxygen Galactic Chemical Evolution Model

[O/Fe] vs [Fe/H] → Production rate O / Fe, over metallicity (~ stellar ages)

Kobayashi+2020

lower [Fe/H] = metal-poorer ~ older

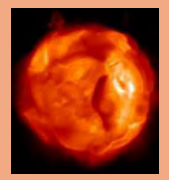


O



SNe II/HNe

+



AGB
(small amount)

Fe



SNe II/HNe

+



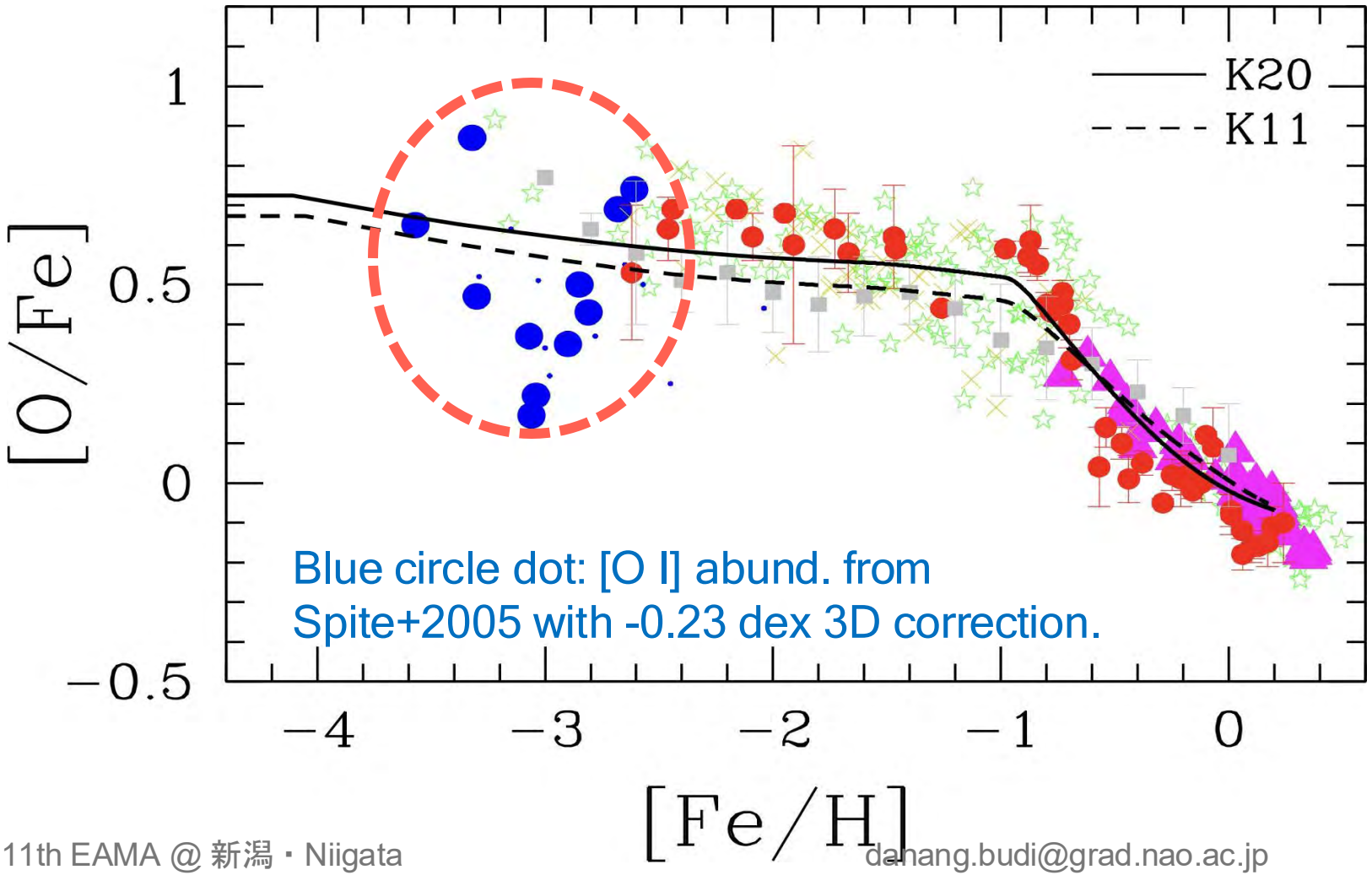
SNe Ia

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Oxygen Galactic Chemical Evolution Model

Why is there large scatter in the Extremely Metal-Poor region?

Kobayashi+2020



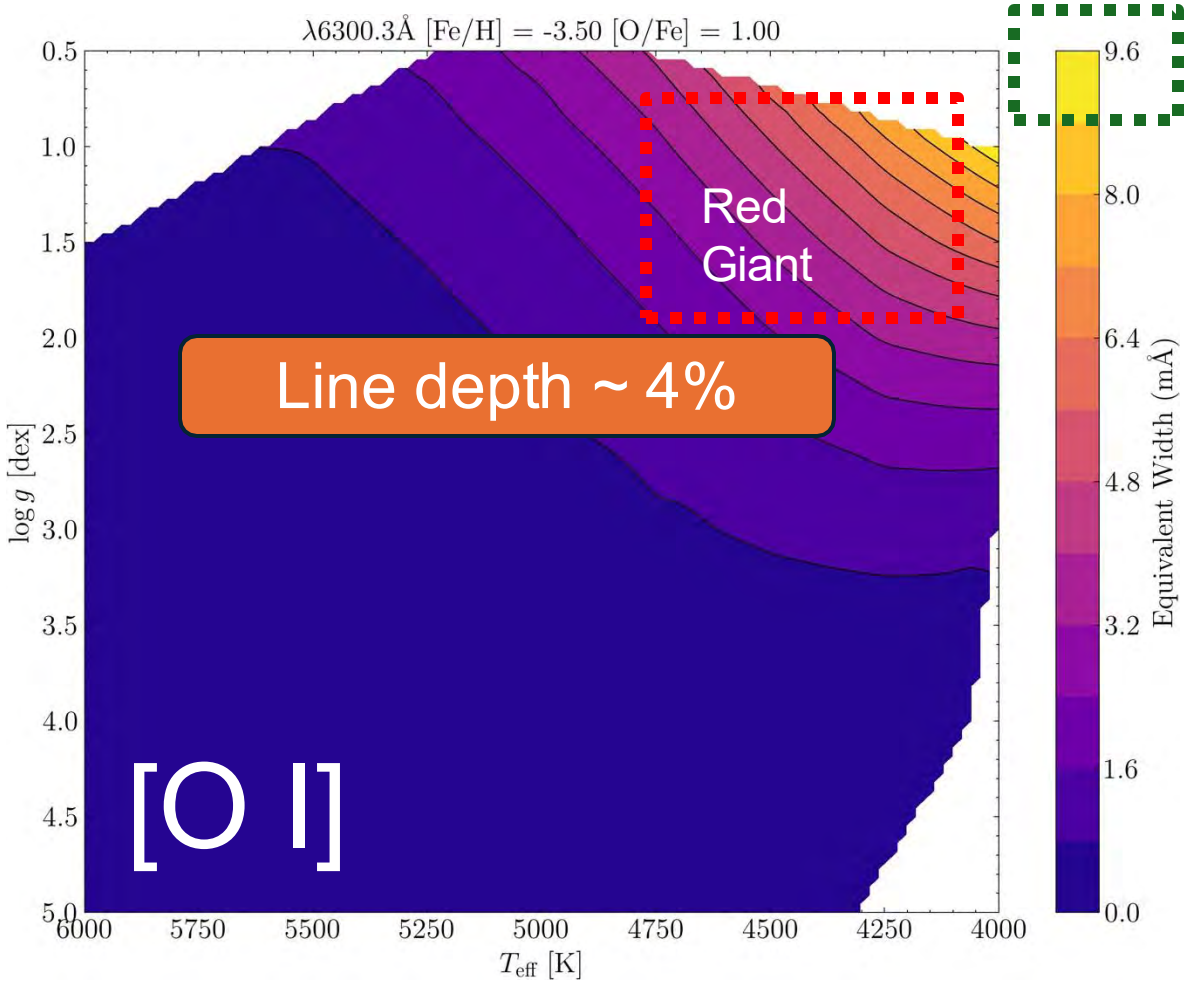
On GCE side :

Different progenitor evidence (unique for each star)?

On observational side :

Measuring O abundance in Very/Extremely Metal-Poor regime is challenging!

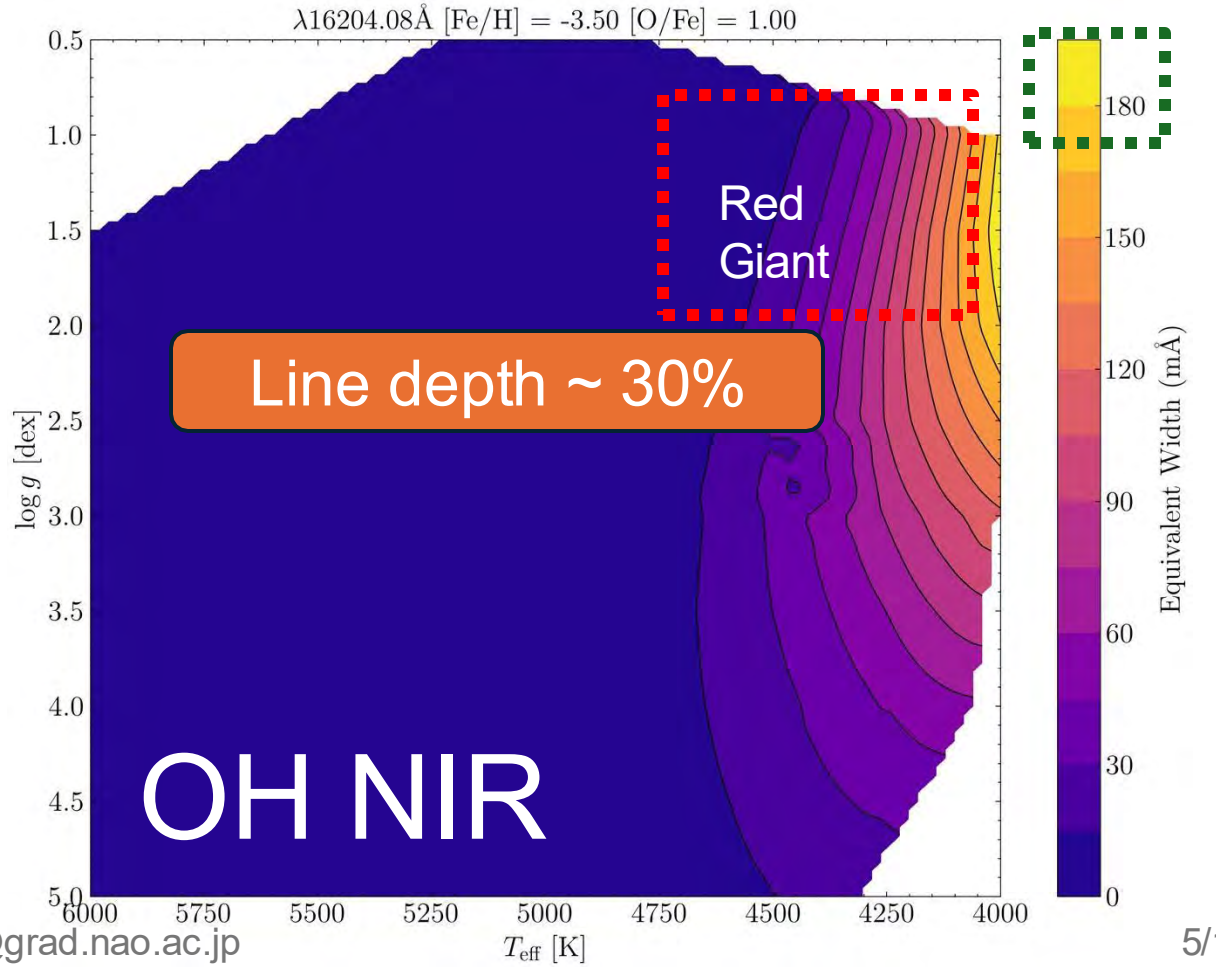
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1D/LTE Simulation Model Color code
= line strength,

Weaker strength = need higher S/N spectra = challenging to measure precisely

Noticed to the scale difference!

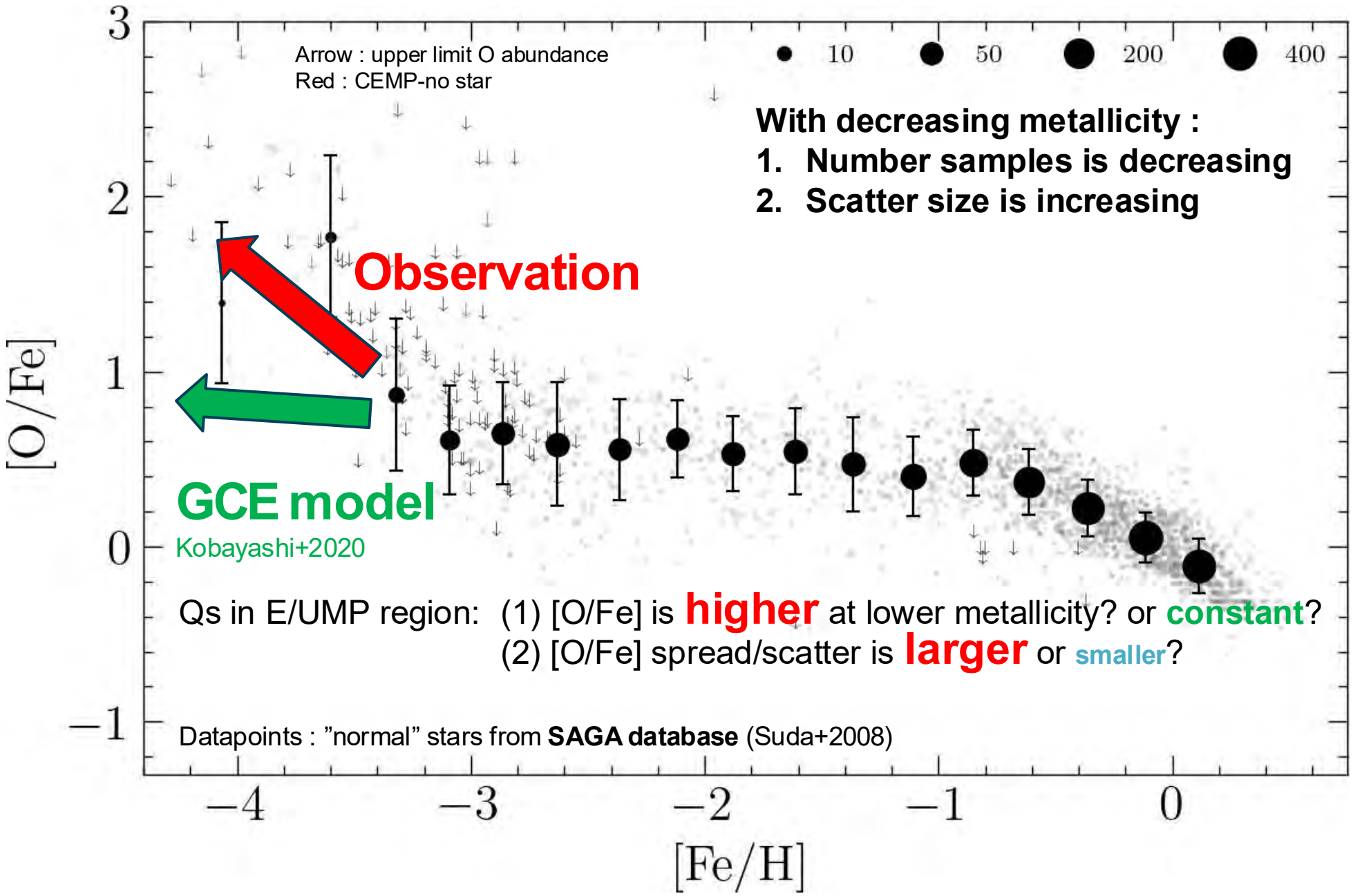


OH lines limitation:

⊗ Only limited to cooler star

⊗ Largely influenced by 3D atm. effects

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Arrow : upper limit O abundance
Red : CEMP-no star
10
50
200
400
With decreasing metallicity :
1. Number samples is decreasing
2. Scatter size is increasing
Observation
GCE model
Kobayashi+2020
Qs in E/UMP region: (1) [O/Fe] is higher at lower metallicity? or constant?
(2) [O/Fe] spread/scatter is larger or smaller?
Datapoints : ”normal” stars from SAGA database (Suda+2008)
[O/Fe]
[Fe/H]
3
2
1
0
−1
−4
−3
−2
−1
0

Project Aims

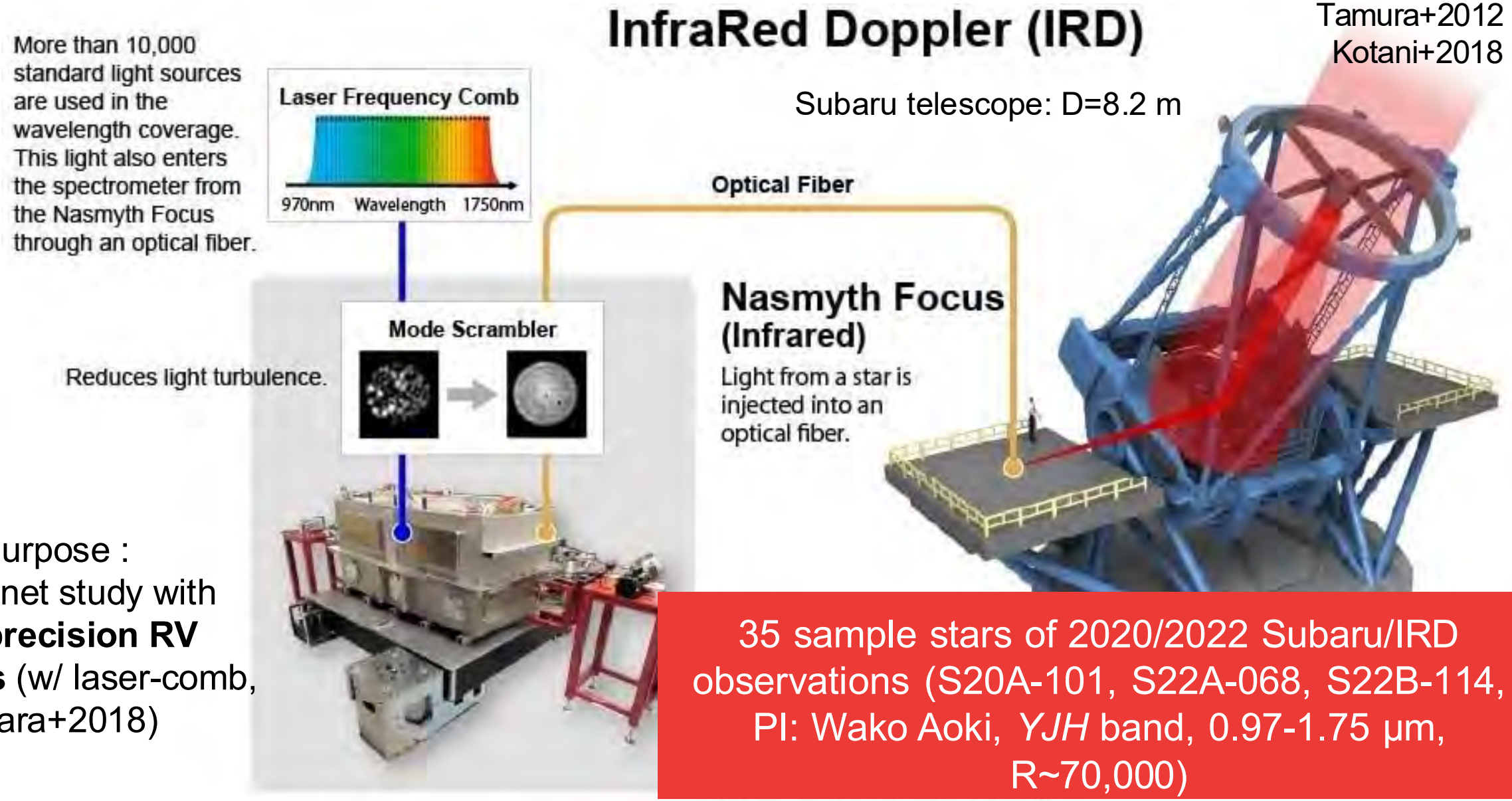
1. **Determine oxygen abundances with high precision** for star in Very/Extremely Metal-Poor regime ($-5 < [Fe/H] < -2$) with **OH lines** in high-resolution near-infrared spectra obtained with **SUBARU/IRD**.

2. **Examine the reliability of OH lines as Oxygen tracers**

   ✓ **Comparing O abundance** from ”reliable” [OI] λ6300 Å line *if available*.

3. **Built & provide a high-resolution Near-IR spectra database** that publicly accessible for future works.

Main Observational Data – *H-band spectra*



Main purpose : exoplanet study with **high-precision RV ~2 m/s** (w/ laser-comb, Kuzuhara+2018)

35 sample stars of 2020/2022 Subaru/IRD observations (S20A-101, S22A-068, S22B-114, PI: Wako Aoki, *YJH* band, 0.97-1.75 μm, R~70,000)

Main Observational Data – *H-band spectra*

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Elemental abundances of 44 very metal-poor stars determined from Subaru/IRD near-infrared spectra

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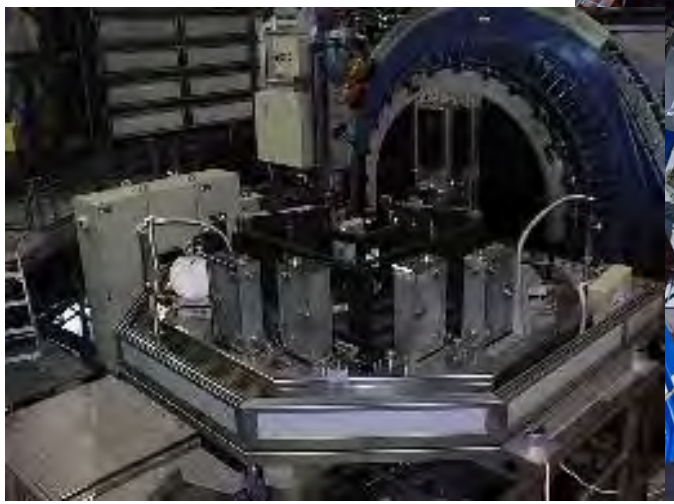
Elemental abundances of Na, Mg, Al, Si, and Sr.

Archival Optical Spectra – [OI] 6300Å line

21 sample have publicly available optical spectra









Subaru/HDS
R~60,000-160,000

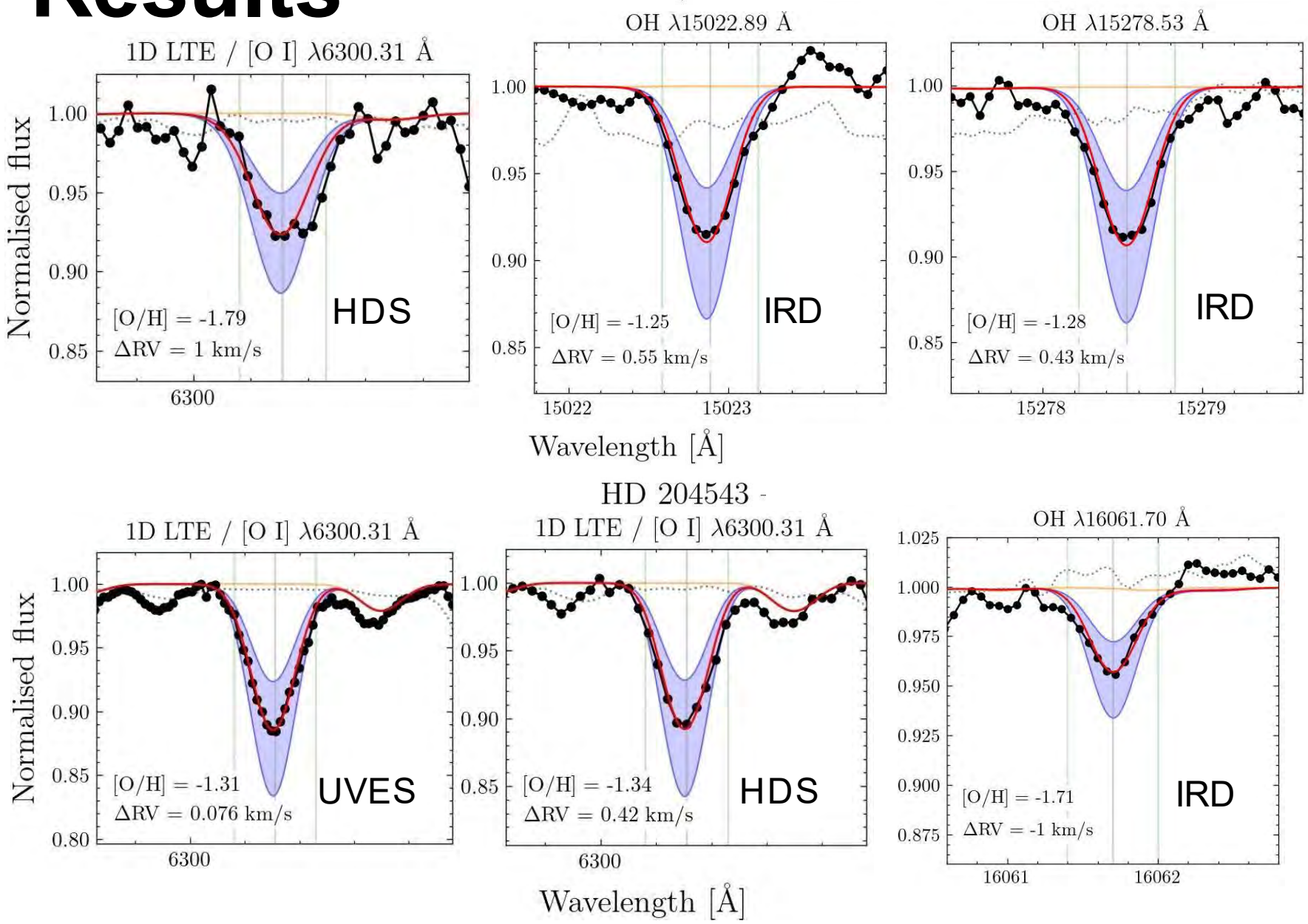
VLT/UVES
R~40,000-60,000

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Methods

- **Recalibrating input parameters**
  - ✓ Effective temperature (color-temperature relation)
  - ✓ Surface gravity (from Gaia DR3 Parallax)
  - ✓ Microturbulance (empirical relation, Dutra-Ferreira+2016)
  - ✓ 1D/~~LTE~~ → **NLTE** Fe abundance (from EW Fe literature data)
- **Spectral synthesis method**
  - 1D `MARCS` atmosphere model grid, LTE assumption
  - `Turbospectrum` (Gerber+2023) / `TSFitPy` (Storm & Bergemann 2023)
  - APOGEE DR17 (*H*-band) and Gaia-ESO linelist (for 1D/LTE [OI] line)
- **Determine 3D/LTE correction of 6300Å [OI] line** (for comparison purpose).
  - 3D RHD `STAGGER` model atmosphere (Magic+2013)
  - `MULTI3D` code (Eitner+2024)

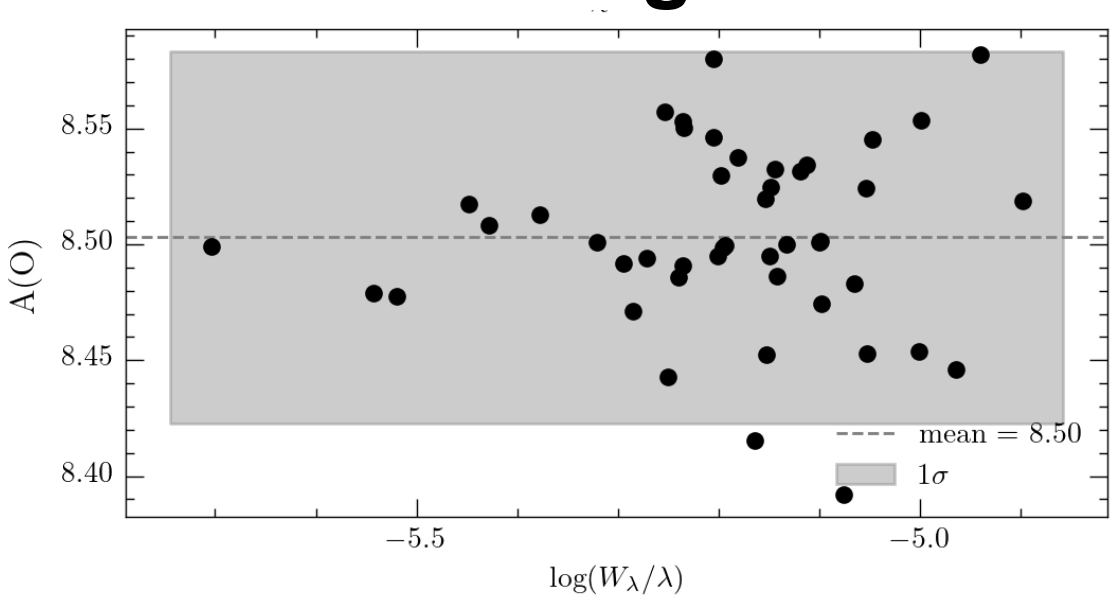
Results



- We found that most stars at least **have three (warm RGB) or >10 (cool RGB) measurable OH lines** (not affected by tellurics).
- We have detected more than 40 OH lines for some targets, **yielding consistent abundance** results between each line **(scatter < 0.1 dex).**

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Results: Testing Consistency

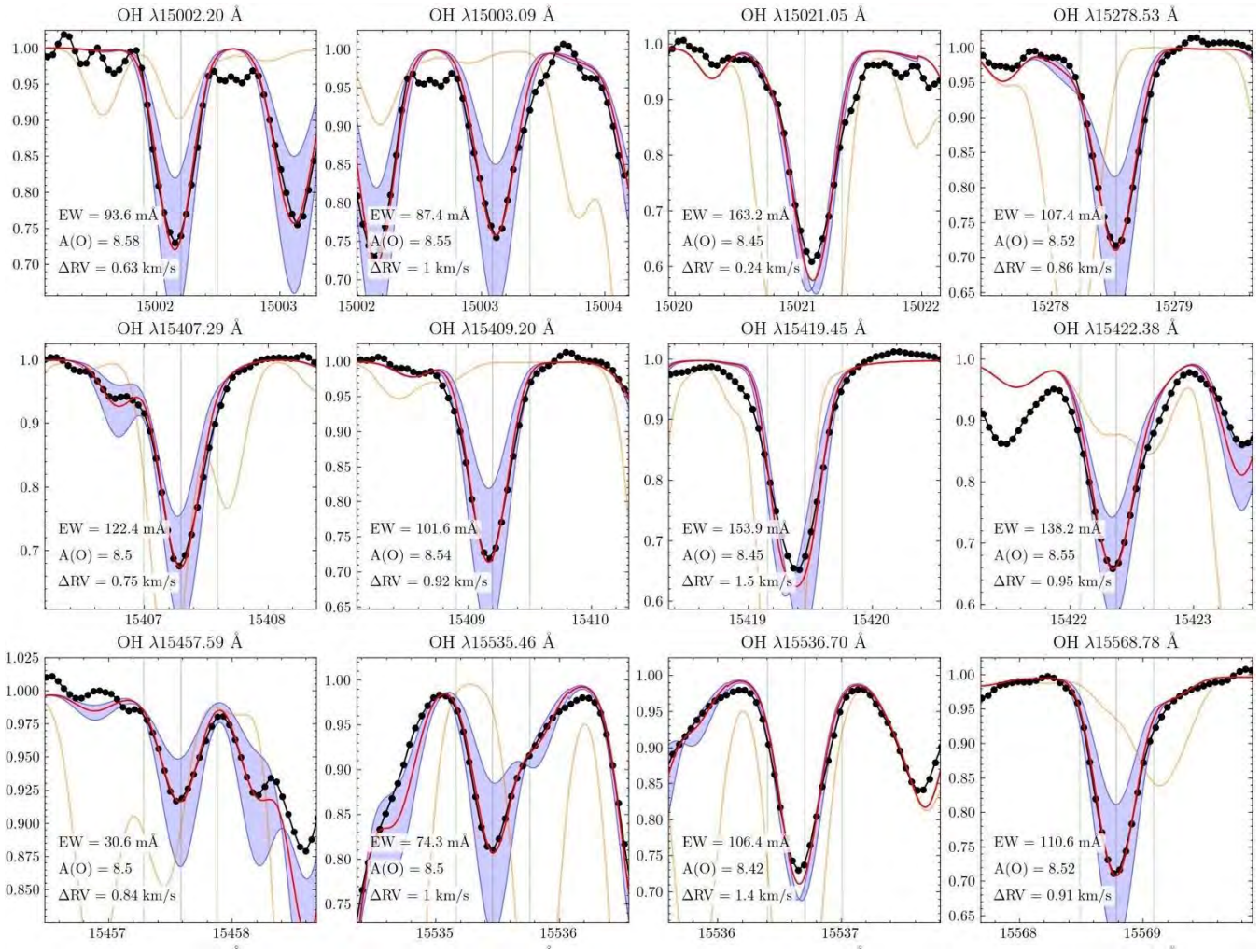


Hawkins+2016
A(O) = 8.52±0.06
OH lines APOGEE spectra

Ramírez & Prieto 2011
A(O) = 8.66±0.02
[OI] line

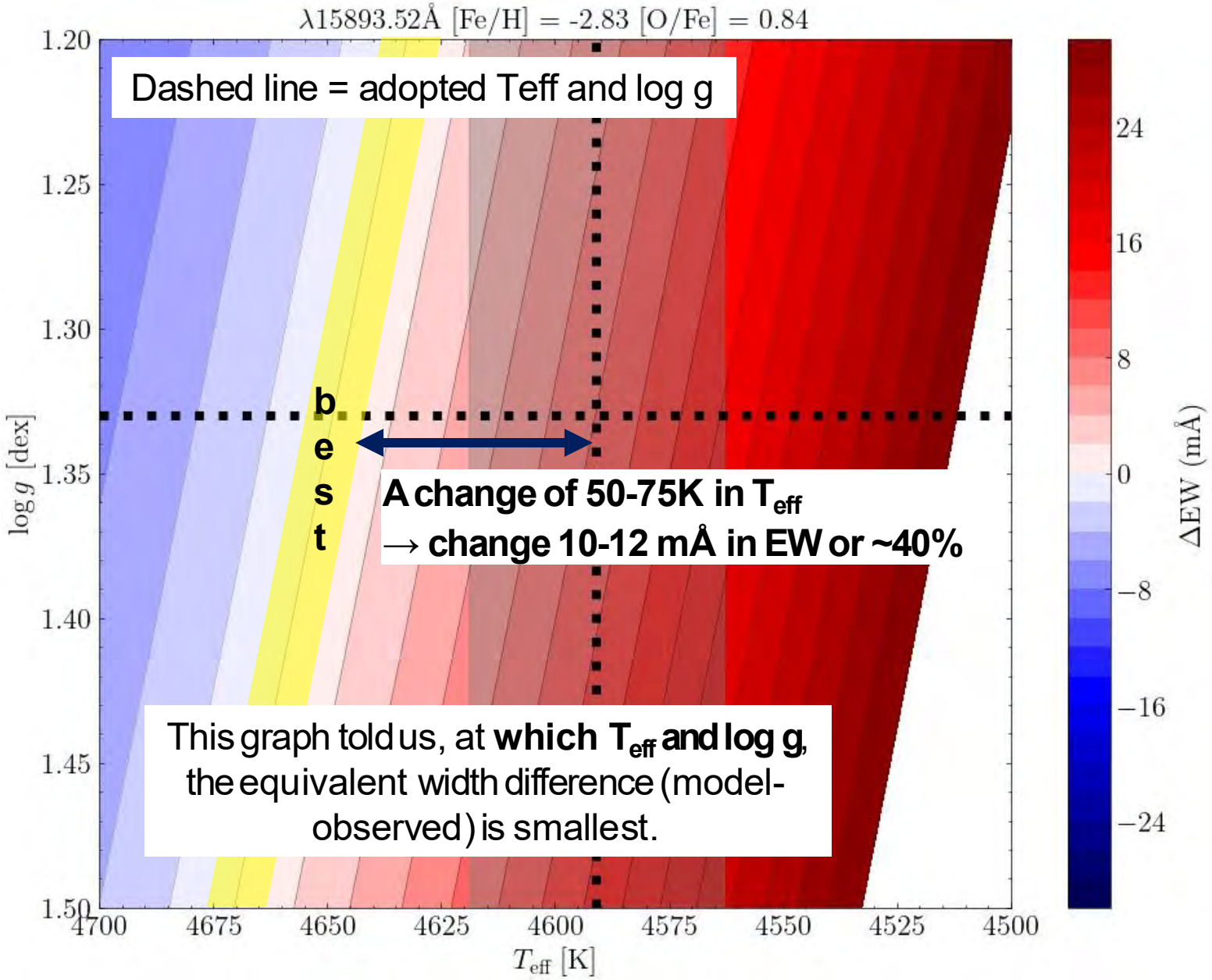
Our works
A(O) = 8.50±0.08

Then we also derived O (OH) abundance using high-res Arcturus NIR spectra.



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Discussion: Problem on Effective Temperature



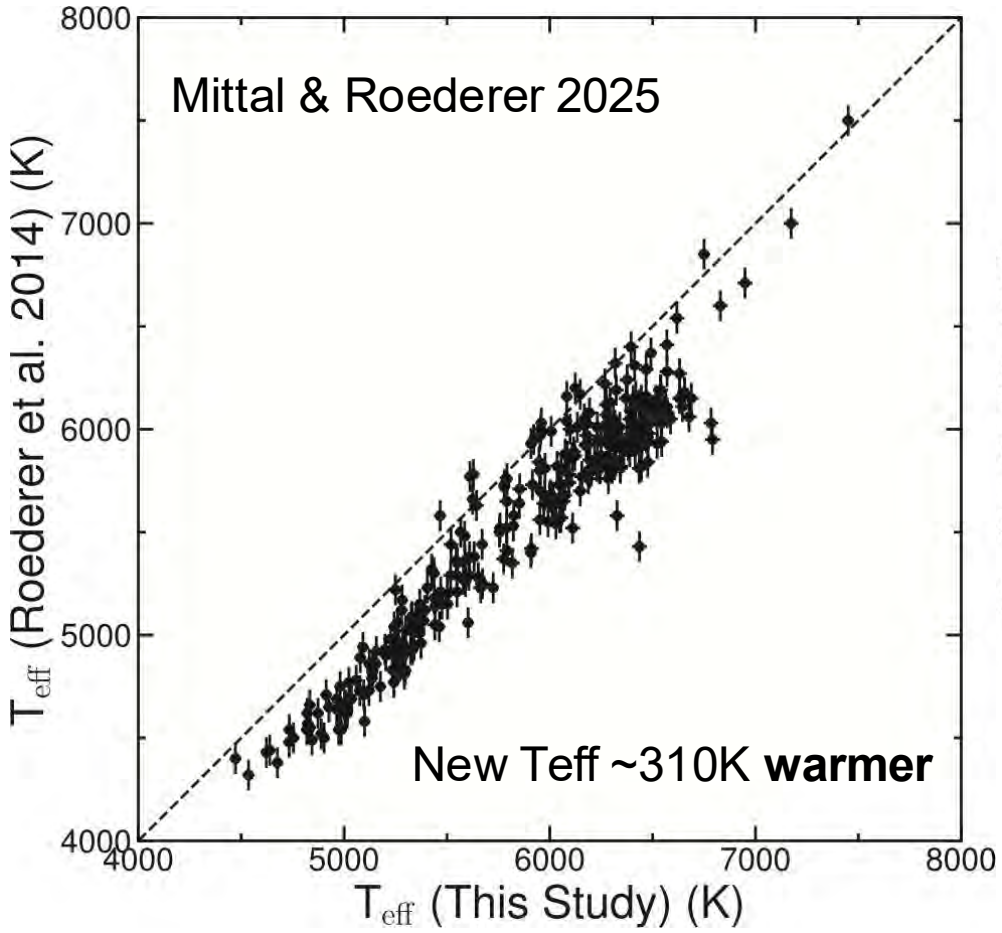
Compared 1D/LTE Oxygen abundance from [OI] opt. line and OH NIR line.

Color coded = equivalent width differences between [OI] and OH line with **same [O/Fe]**.

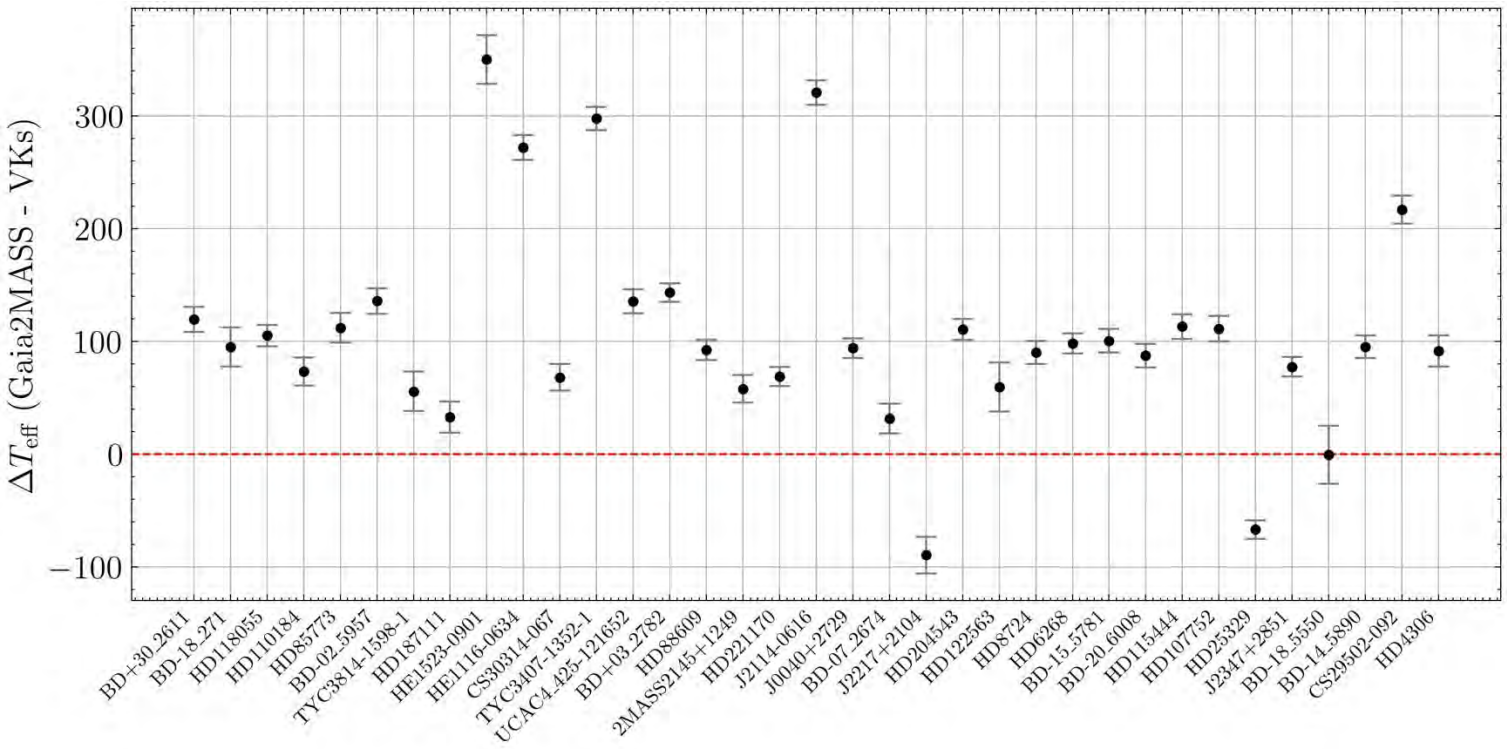
- Oxygen abundances derived from OH lines are **extremely sensitive** to the adopted T_{eff} and log g
- Our previously adopted temperature is **LOWER/COOLER** than ”it should be”.

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Discussion: Problem on Effective Temperature



We updated our method



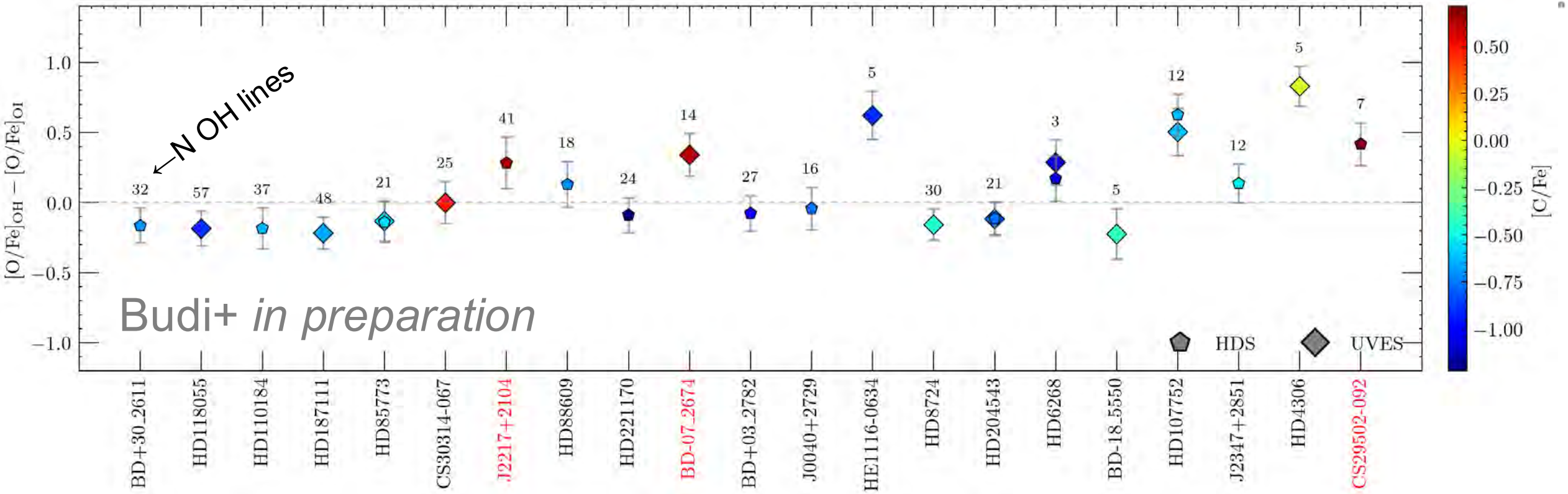
V-K_s (Alonso+1999, Casagrande+2010)

↓

Gaia-2MASS (Mucciarelli+2021)

Newer T_{eff} and log g are **higher** by ~100-300K and ~0.1 dex (not shown here)

Discussion: Problem on Effective Temperature

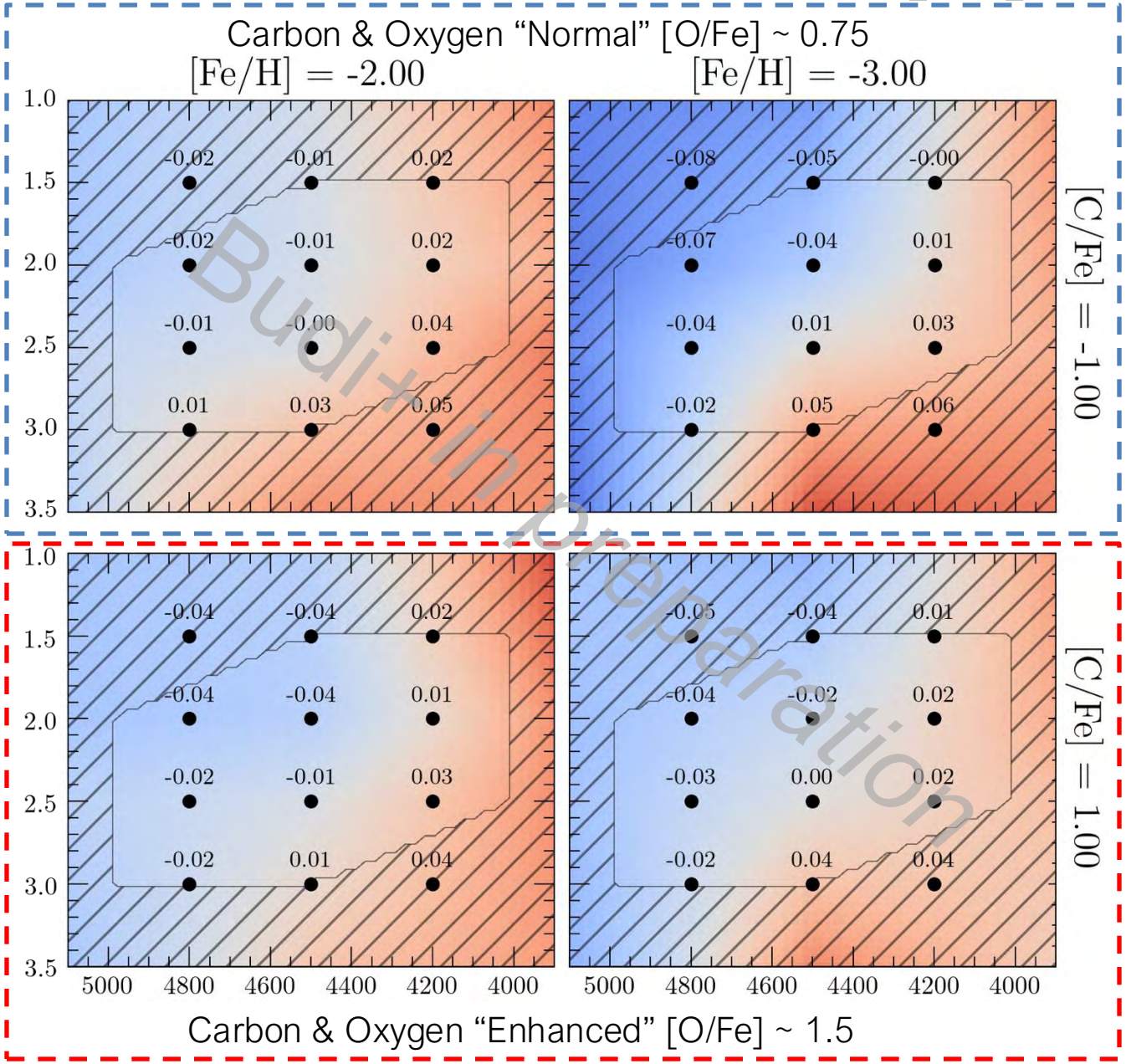


With updated T_{eff} and log g, the discrepancies between [OI] and OH abundances become smaller (~0.4 dex → ~0.1-0.2 dex for cool RGB) **but not vanish completely,** which challenge our understanding of 3D atmospheric effect in cooler RG stars.

Another question is,

does [OI] 1D/LTE could be the best representation for oxygen abundance itself?

Discussion: 3D Effect on [OI] 6300Å



We have built 3D/LTE correction grid for [OI] 6300Å which covers Red Giant stars (T_{eff} > 5000 K & log g > 3, Amarsi+2016)

5 input parameters :

- Temperature (T_{eff}: 4000-5000K)
- Surface gravity (log g: 1.5-3.0)
- **Carbon-abundance** ([C/Fe]: -1.5,...,2.0 dex)
- Microturbulance vel. (v_{mic}: 0.5-2.5 km/s)
- [OI] 1D/LTE abundance ([O/Fe]:0.0-2.5 dex)

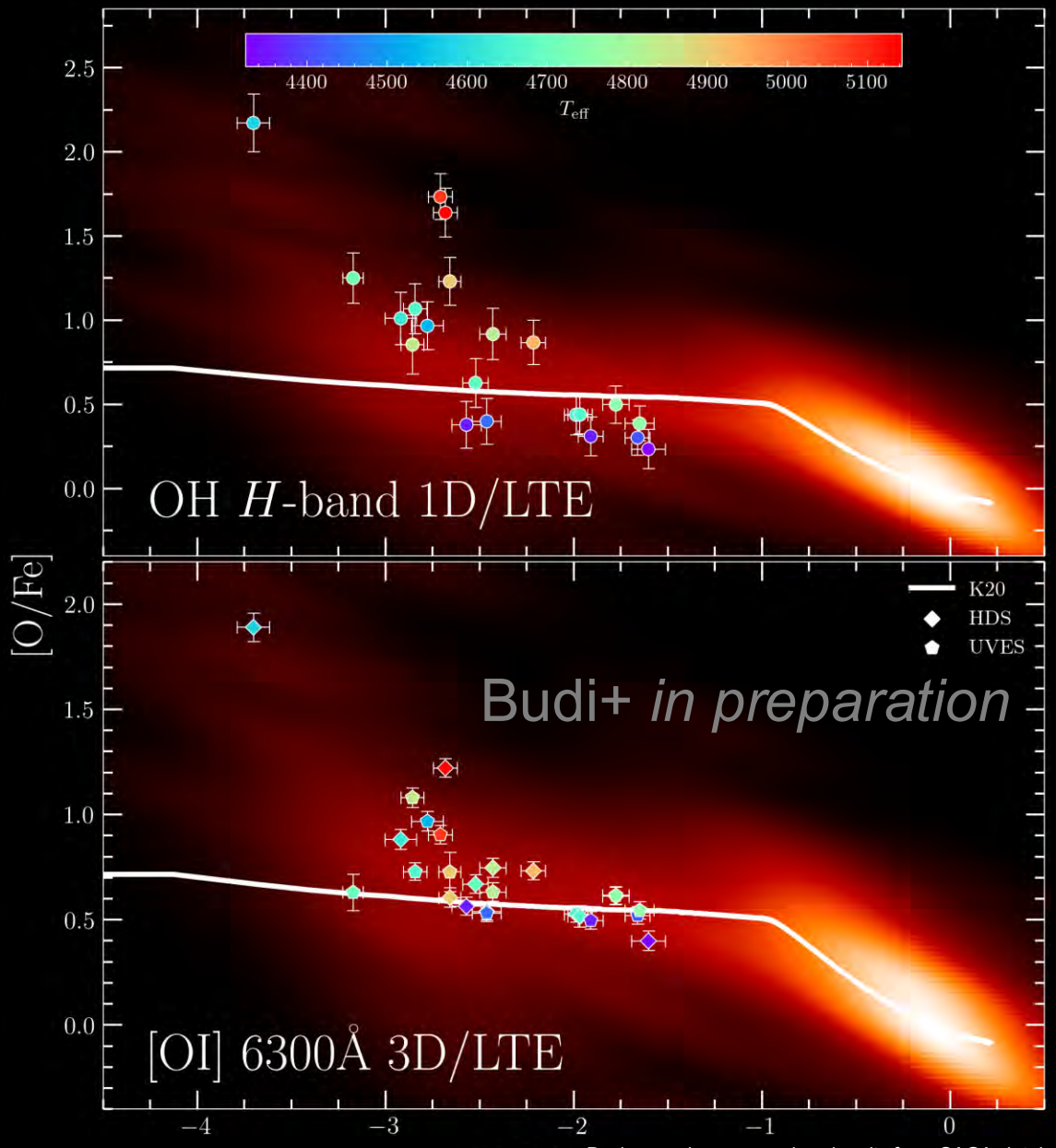
$$\Delta_{3DLTE} = [O/Fe]_{3DLTE} - [O/Fe]_{1DLTE}$$

Towards Red Giant, $|\Delta_{3DLTE}| < 0.1$ dex

✓ [OI] 6300Å is insensitive to both 3D and non-LTE effects (*atleast for Red Giant*)

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Takeway messages : Improving Our Understanding



Background map : number density from SAGA database

- Our results (currently) provide the **largest samples** (35 stars) for O abundance from OH Near-IR lines in Very Metal-Poor regime.
- There is larger scatter of OH abundance (compared to [OI]) and this is **mainly** due to **high temperature sensitivity of OH lines formation**.

Our proposal has been accepted for S25B (this semester), and the observation is scheduled for December 2025 (1 night).

Another **new Subaru/IRD data** will come this semester, add more samples for extremely/ultra metal-poor stars ([Fe/H] < -3).

S25B-118	Bakuh Danang Setyo Budi	Revealing Oxygen's Cosmic Past: IRD observations of EMP/UMP stars	IRD+NGS-AO188 1

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Takeway Messages

- **Are OH lines sufficiently reliable as oxygen tracers?**
  - ✓ **Yes,** when no other optical oxygen lines are available. With a reliable method for deriving T_{eff}, **the abundance differences** (compared to [OI]) **can be less than 0.1 dex**.
  - ⓧ **No,** if [OI] 6300 Å and/or OI 7772 Å lines are **strong**, **uncontaminated** from **tellurics**, and available. Applying 3D/NLTE corrections, if possible, is recommended (e.g., Amarsi+2018)
- Our work provides **the largest dataset** of OH 1D/LTE abundances, alongside a comprehensive, high-resolution, high-quality Near-IR spectral database that **will be publicly available for future studies** using more advanced tools (e.g., 3D/NLTE for OH molecular lines).



Thank you for your attention!

ありがとうございました！

Terima kasih banyak!

Happy to take your questions!

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