

# 狭帯域フィルターを用いた金属欠乏星探査

富永望(国立天文台/甲南大学)

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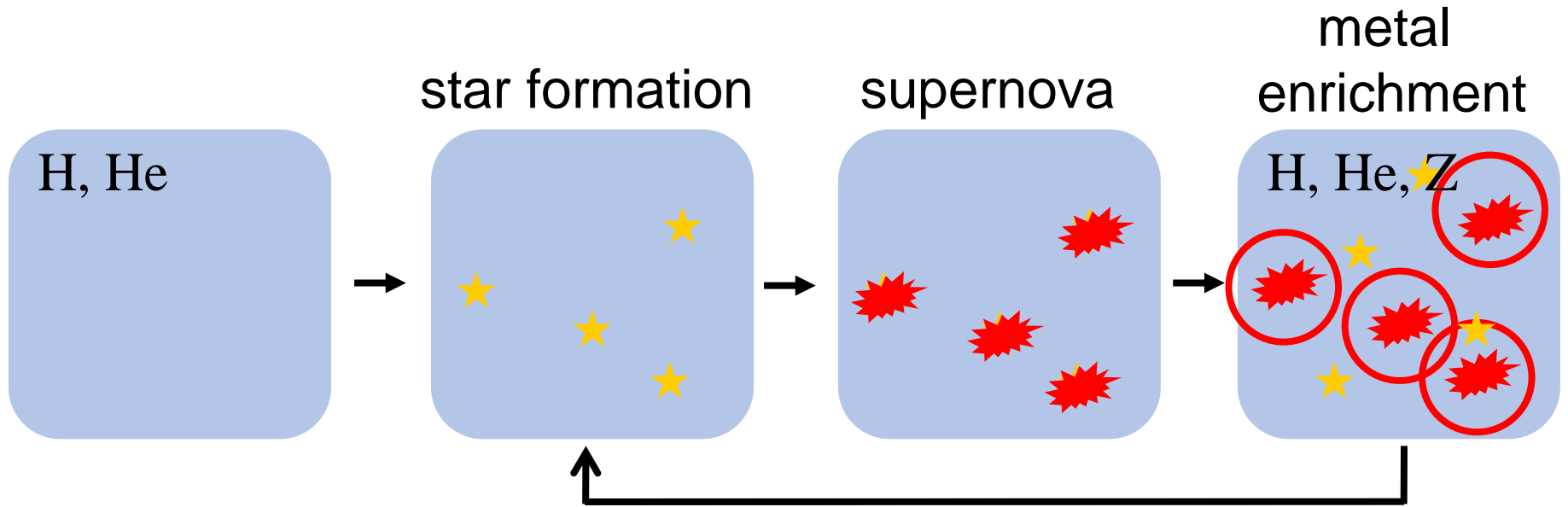
諸隈智貴(千葉工業大学/東京大学),

青木和光, 金子慶子, 福嶋美津広, 神澤富雄,

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酒向重行, 高橋英則(東京大学)

# Metal-poor stars



**Metallicity** increases with time

$$[\text{Fe}/\text{H}] = \log(\text{Fe}/\text{H}) - \log(\text{Fe}/\text{H})_{\odot}$$



# Metal-poor stars

(e.g., Cayrel + 04; Honda + 04)

$[\text{Fe}/\text{H}] < -5$

Hyper Metal-Poor (HMP)

$[\text{Fe}/\text{H}] < -4$

Ultra Metal-Poor (UMP)

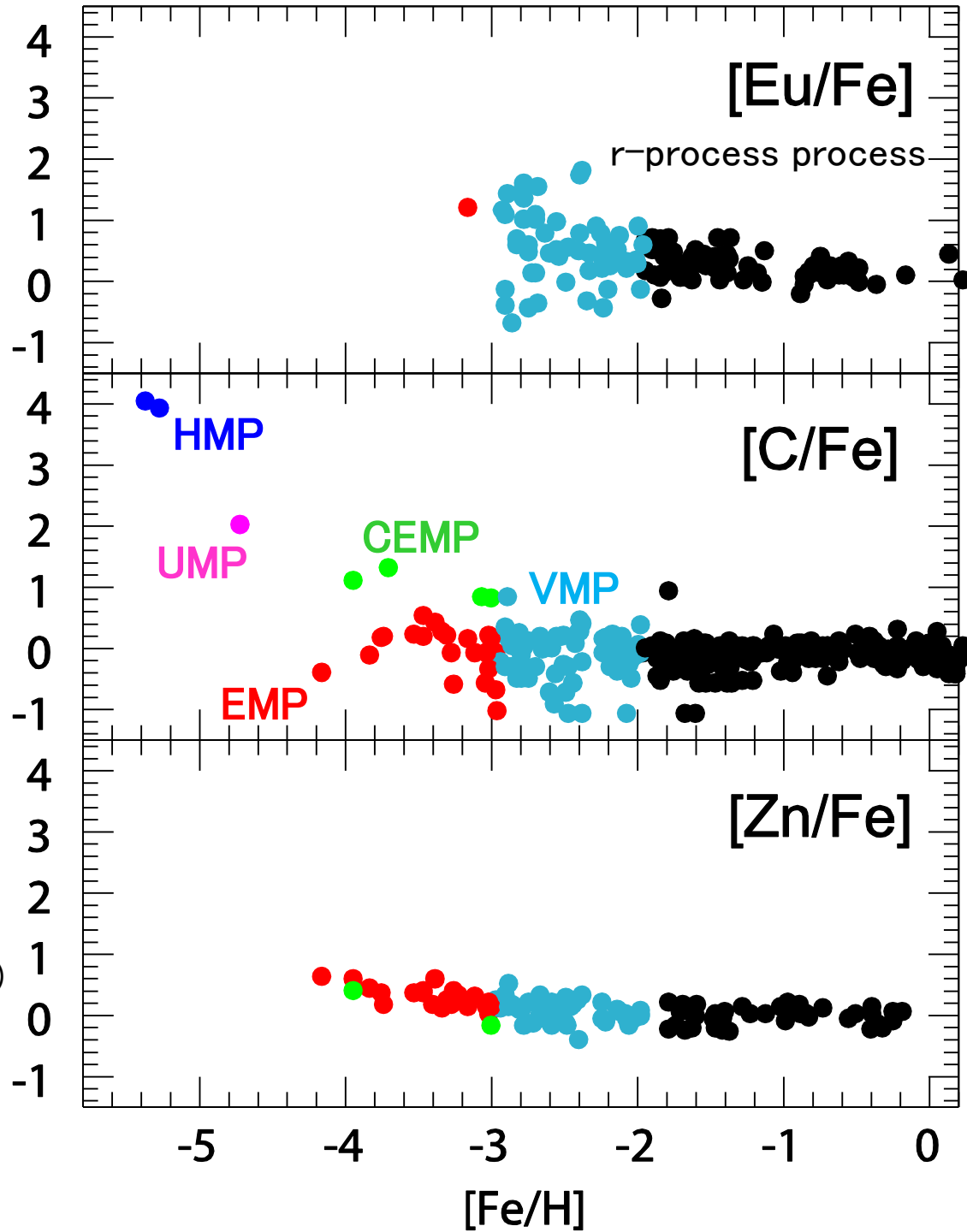
$[\text{Fe}/\text{H}] < -3$

Extremely Metal-Poor (EMP)

$[\text{Fe}/\text{H}] < -2$

Very Metal-poor (VMP)

(Beers & Christlieb 05)

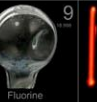



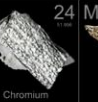



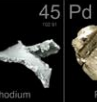
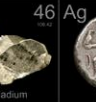



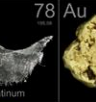
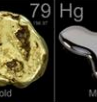

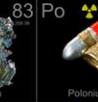
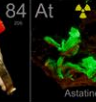




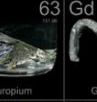
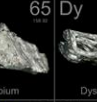

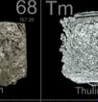





# What we can learn from MP stars

- Origin of elements
- First supernovae
- First stars
- Chemical evolution
- Galaxy formation

# Origin of elements

## THE ELEMENTS

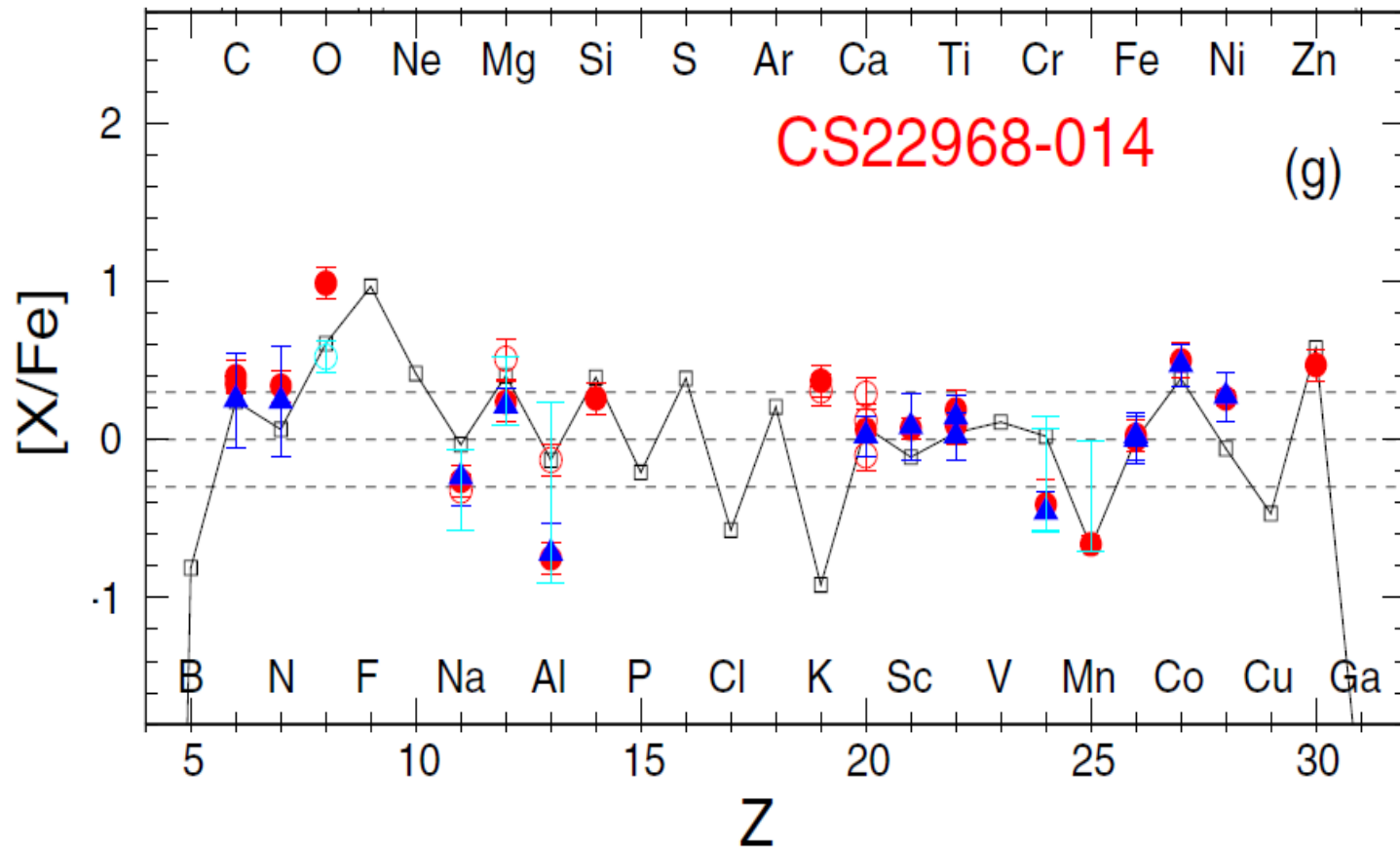
 1 Hydrogen																	 2 Helium						
 3 Lithium	 4 Beryllium																	 5 Boron	 6 Carbon	 7 Nitrogen	 8 Oxygen	 9 Fluorine	 10 Neon
 11 Sodium	 12 Magnesium																	 13 Aluminum	 14 Silicon	 15 Phosphorus	 16 Sulfur	 17 Chlorine	 18 Argon
 19 Potassium	 20 Calcium	 21 Scandium	 22 Titanium	 23 Vanadium	 24 Chromium	 25 Manganese	 26 Iron	 27 Cobalt	 28 Nickel	 29 Copper	 30 Zinc	 31 Gallium	 32 Germanium	 33 Arsenic	 34 Selenium	 35 Bromine	 36 Krypton						
 37 Rubidium	 38 Strontium	 39 Yttrium	 40 Zirconium	 41 Niobium	 42 Molybdenum	 43 Technetium	 44 Ruthenium	 45 Rhodium	 46 Palladium	 47 Silver	 48 Cadmium	 49 Indium	 50 Tin	 51 Antimony	 52 Tellurium	 53 Iodine	 54 Xenon						
 55 Cesium	 56 Barium	 57 Lanthanum	 72 Hafnium	 73 Tantalum	 74 Tungsten	 75 Rhenium	 76 Osmium	 77 Iridium	 78 Platinum	 79 Gold	 80 Mercury	 81 Thallium	 82 Lead	 83 Bismuth	 84 Polonium	 85 Astatine	 86 Radon						
 87 Francium	 88 Radium	 104 Rutherfordium	 105 Dubnium	 106 Seaborgium	 107 Bohrium	 108 Hassium	 109 Meitnerium	 110 Darmstadtium	 111 Roentgenium	 112 Ununbium	 113 Ununtrium	 114 Ununquadium	 115 Ununpentium	 116 Ununhexium	 117 Ununseptium	 118 Ununoctium							
<p> radioactive elements</p> <p>Photographs show samples of the pure or nearly pure element except in Francium, Ra, Po, At, Pa, and Bi, whose radioactive minerals containing minute traces of the element. Po, Ra, Po, Pb, and Bi show artificial elements containing measurable amounts of the element. Technetium shows a 1-cm scale. Hydrogen shows a Rutherford backscattering image of the single isotopes, which is mostly hydrogen. 86-111 show the person or place after which the element is named. 112-118 had not been named yet in 2009.</p> <p>Photos and photography by Theodore W. Gray and Nick Meehan.</p> <p>All images copyright © 2009 Theodore W. Gray and Nick Meehan. All rights reserved. No part of this publication may be reproduced, stored in a retrieval system, or transmitted, in any form or by any means, electronic, mechanical, photocopying, recording, or by any information storage and retrieval system, without the prior written permission of Theodore W. Gray and Nick Meehan.</p> <p>Other sizes of this poster: <a href="http://periodictable.com">periodictable.com</a></p> <p>Real samples like these: <a href="http://element-collection.com">element-collection.com</a></p>		 57 Lanthanum	 58 Cerium	 59 Praseodymium	 60 Neodymium	 61 Promethium	 62 Samarium	 63 Europium	 64 Gadolinium	 65 Terbium	 66 Dysprosium	 67 Holmium	 68 Erbium	 69 Thulium	 70 Ytterbium	 71 Lutetium							
 89 Actinium	 90 Thorium	 91 Protactinium	 92 Uranium	 93 Neptunium	 94 Plutonium	 95 Americium	 96 Curium	 97 Berkelium	 98 Californium	 99 Einsteinium	 100 Fermium	 101 Mendelevium	 102 Nobelium	 103 Lawrencium									

PERIODICTABLE.COM

On the other side of this poster you will find a version with smaller pictures but with detailed technical data on each of the elements, plus trend plots.

More images and complete technical data can be found at [periodictable.com](http://periodictable.com)

# Abundance pattern of a MP star

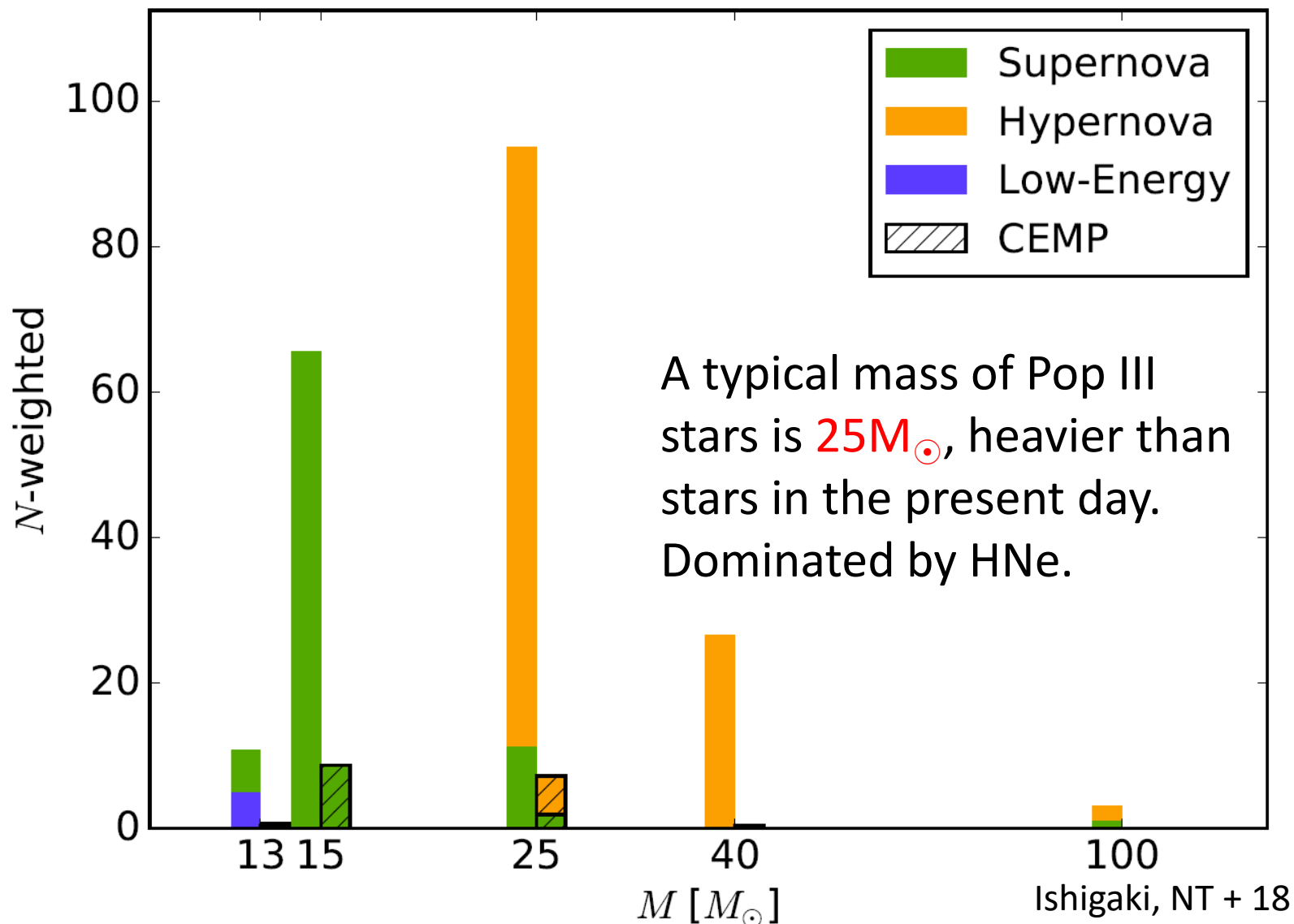


NT+14

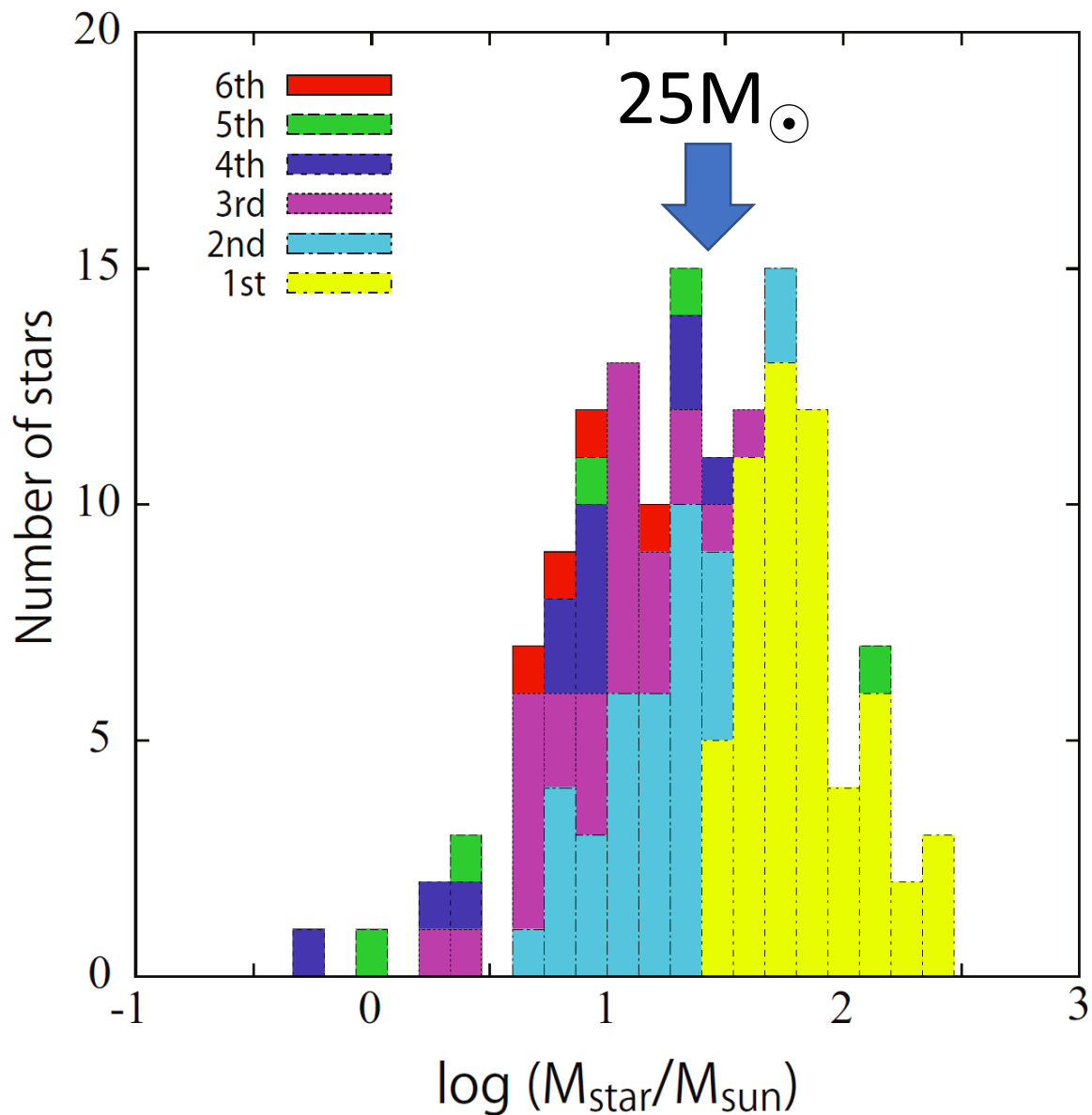
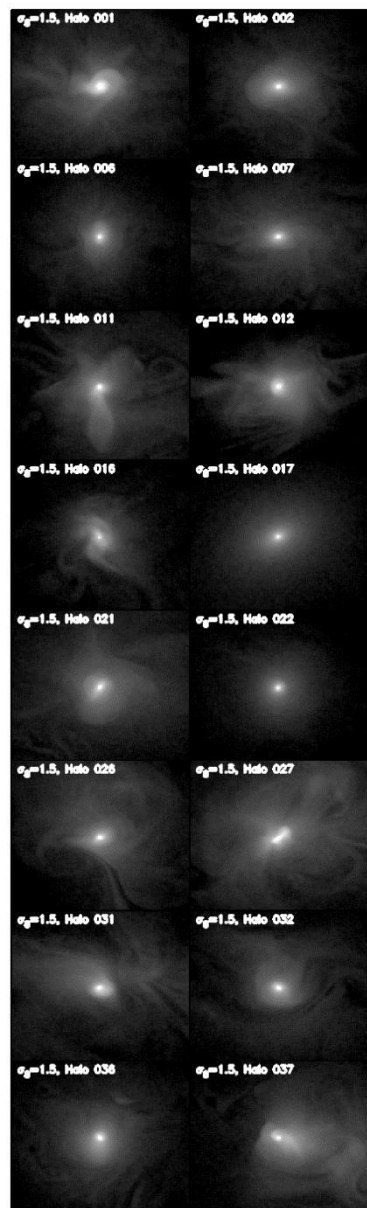
- Main-sequence mass: 25Msun
- Ejected Fe mass:  $8.61 \times 10^{-2}$ Msun
- Explosion energy:  $2 \times 10^{52}$ ergs
- Remnant mass: 3.84Msun

# Initial mass function of Pop III stars

- $\chi^2$  fitting of 218 stars with  $[\text{Fe}/\text{H}] < -3$

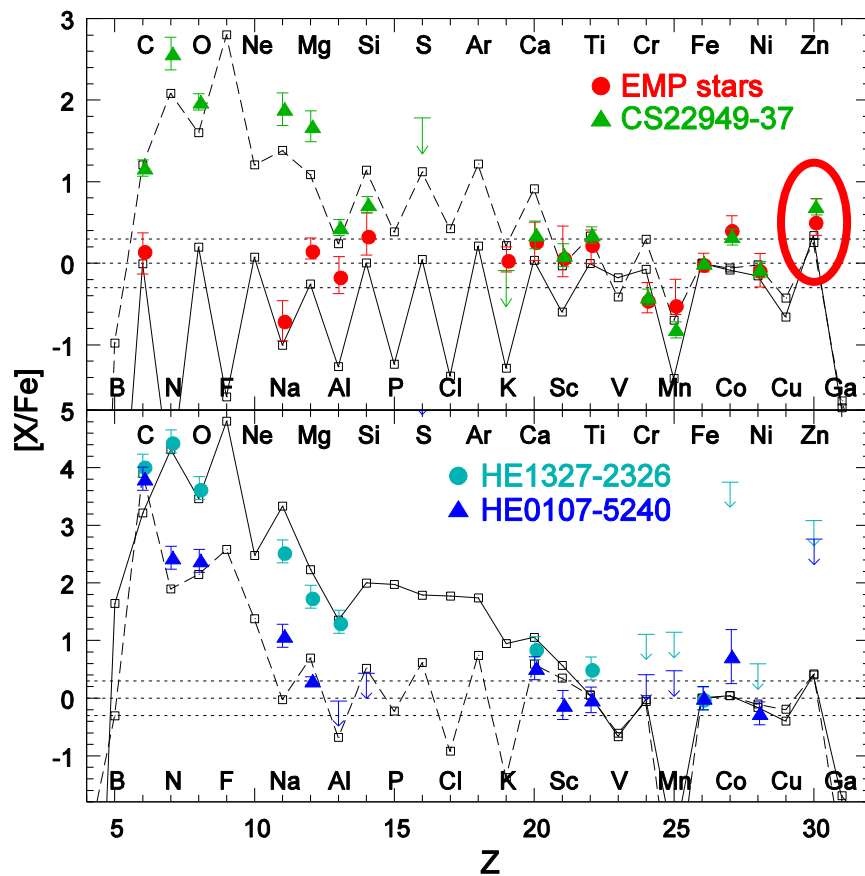
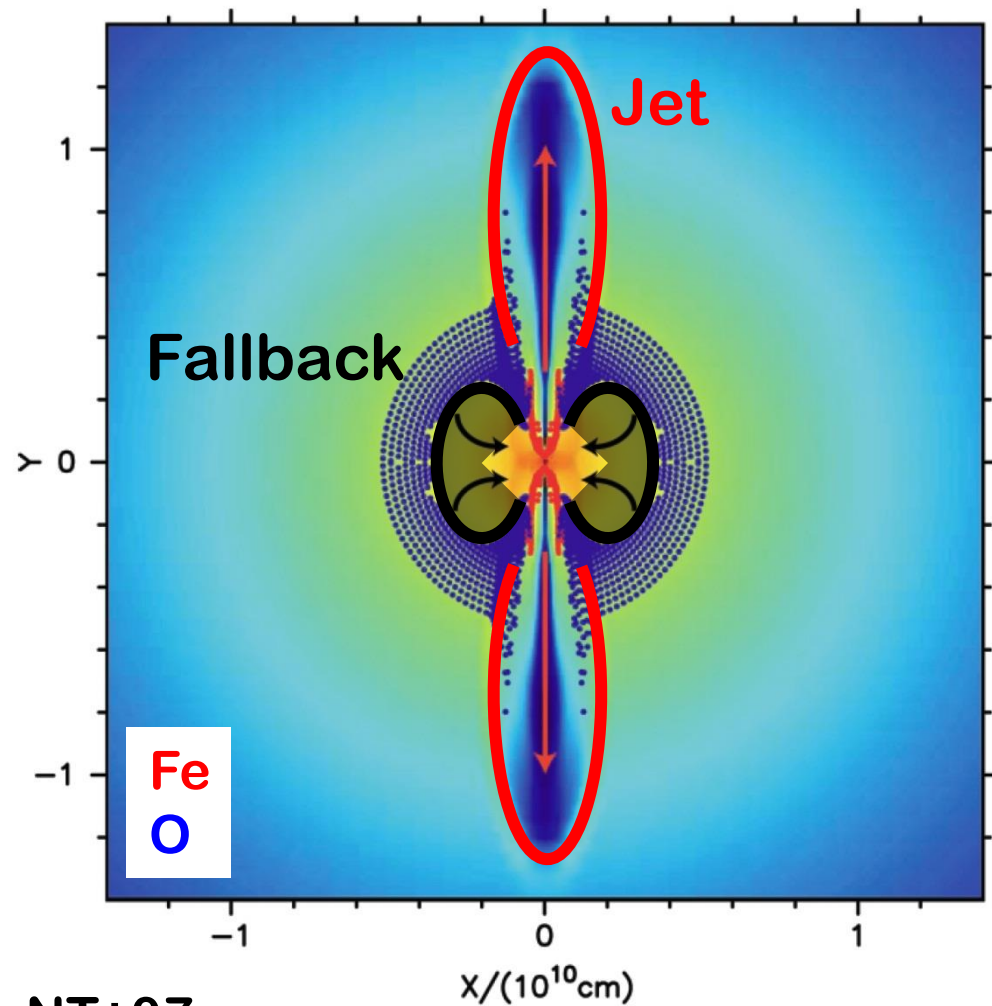


# IMF from cosmological simulation





# Aspherical supernova explosion



# Stellar fates depend on their masses

Type Ia supernova

Brown dwarf

White dwarf

Neutron star or black hole

Pair instability supernova

Supernovae

Mass loss

Core collapse

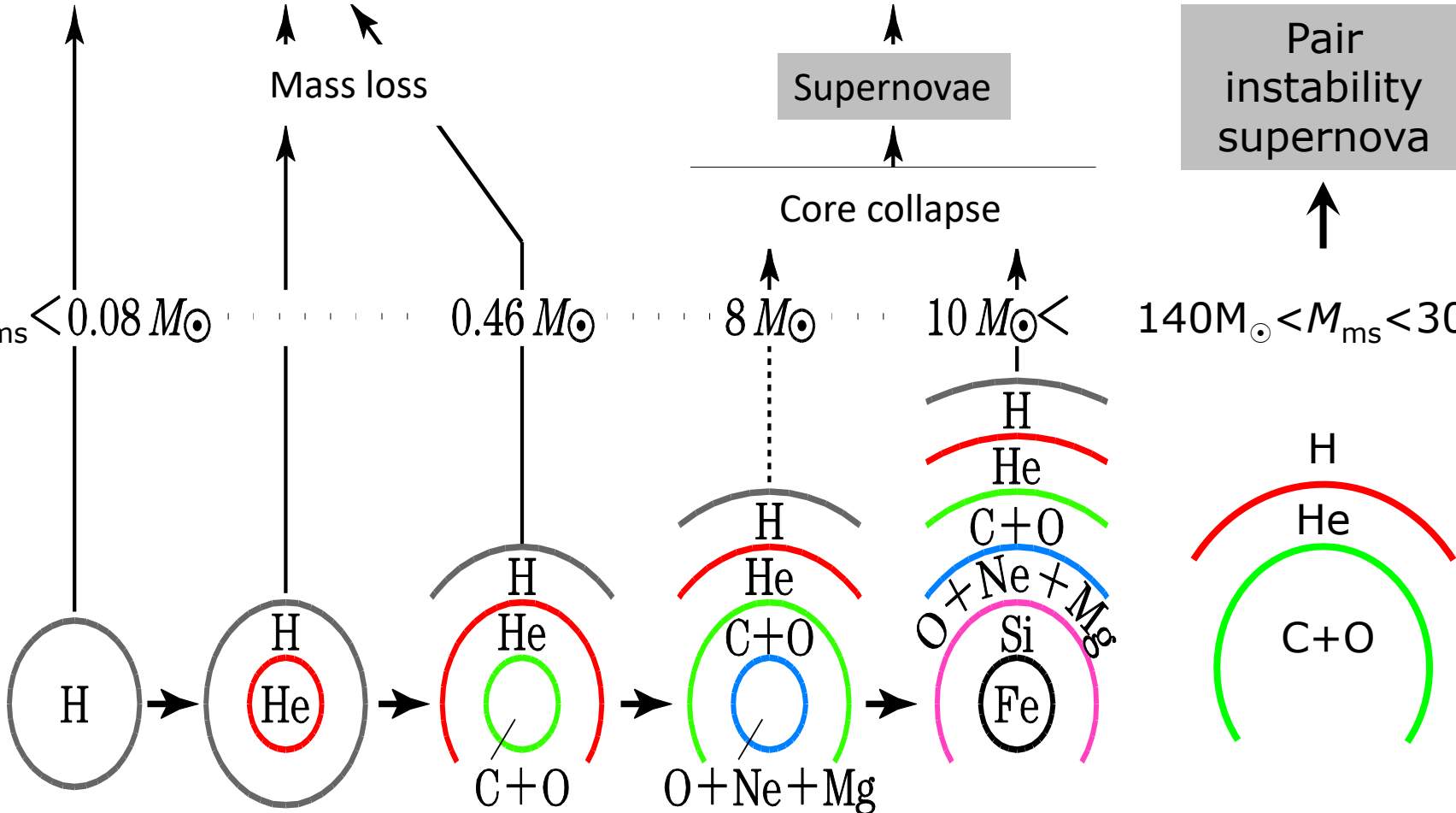
$$M_{\text{ms}} < 0.08 M_{\odot}$$

$$0.46 M_{\odot}$$

$$8 M_{\odot}$$

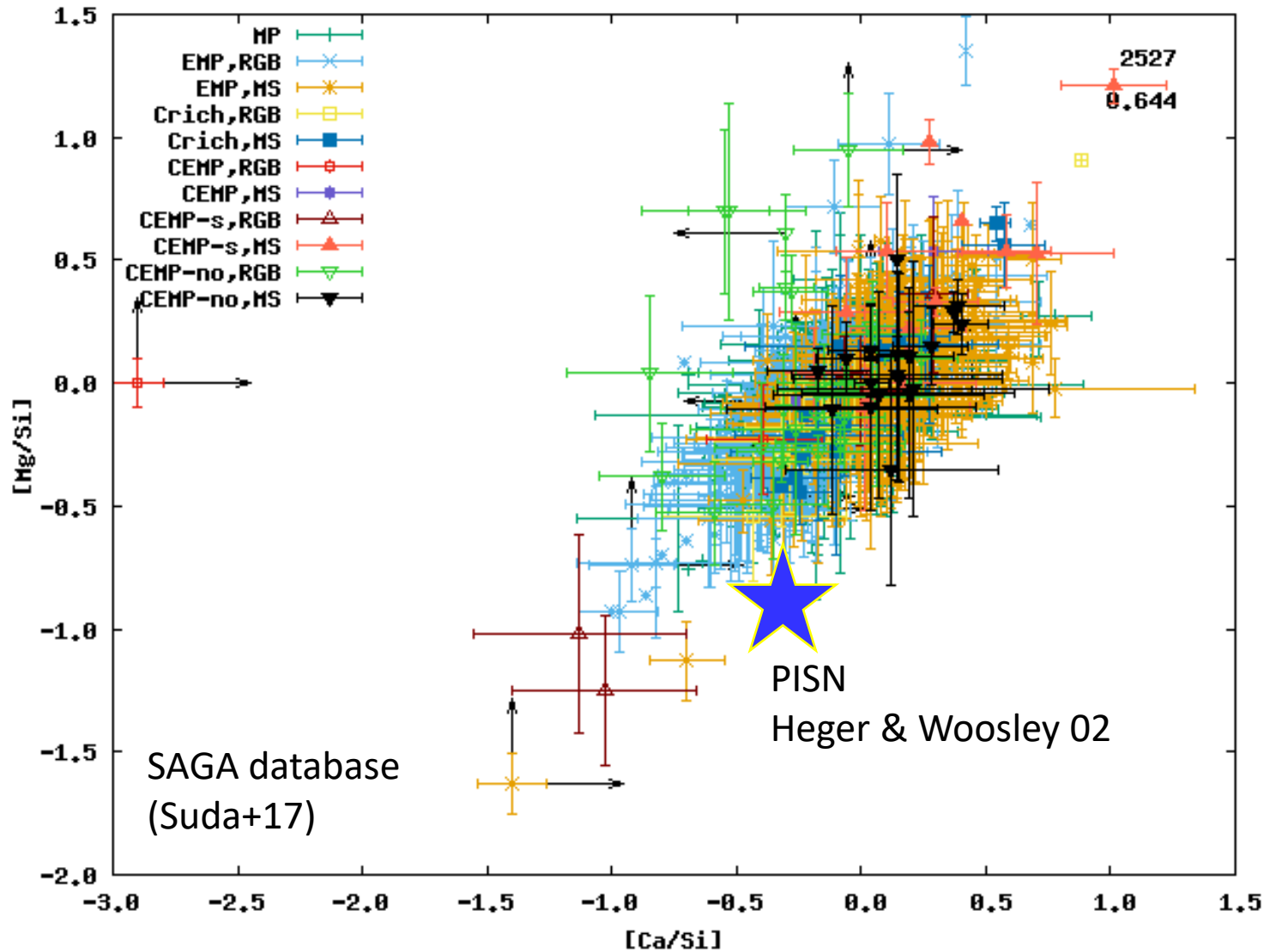
$$10 M_{\odot} <$$

$$140 M_{\odot} < M_{\text{ms}} < 300 M_{\odot}$$



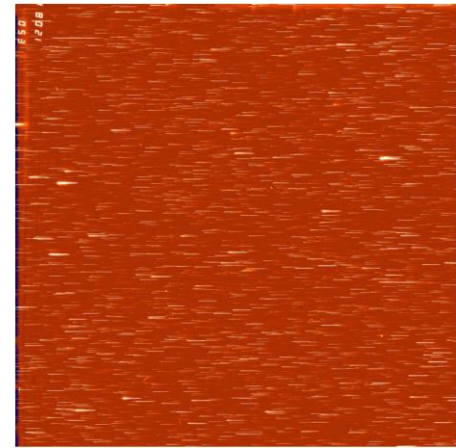
元素はいかにつくられたか(野本憲一編)

# [Ca/Si] vs. [Mg/Si]



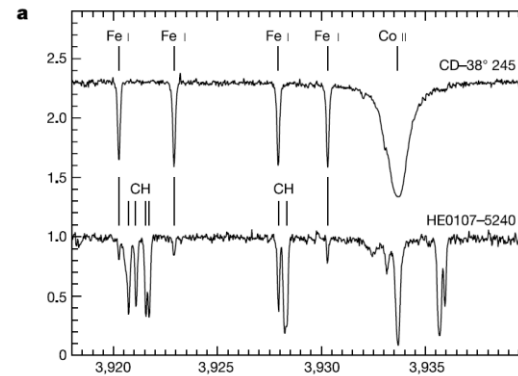
# Past surveys

- Objective prism survey
  - HK survey (Beers+)
  - Hamburg/ESO survey (Christlieb+)



## A stellar relic from the early Milky Way

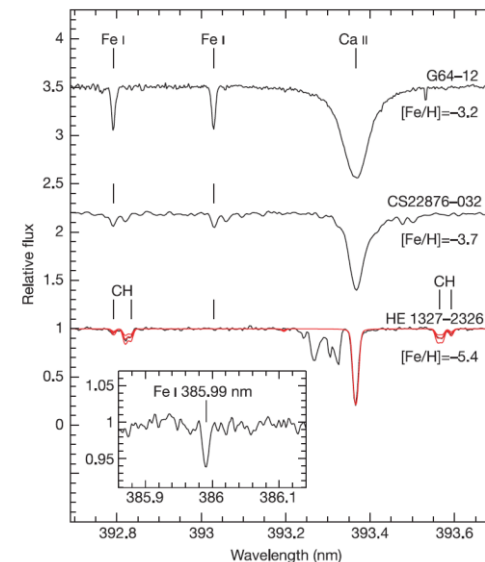
N. Christlieb<sup>\*†</sup>, M. S. Bessell<sup>‡</sup>, T. C. Beers<sup>§</sup>, B. Gustafsson<sup>\*</sup>, A. Korn<sup>||</sup>, P. S. Barklem<sup>\*</sup>, T. Karlsson<sup>\*</sup>, M. Mizuno-Wiedner<sup>\*</sup> & S. Rossi<sup>¶</sup>



[Fe/H] ~ -5.2

## Nucleosynthetic signatures of the first stars

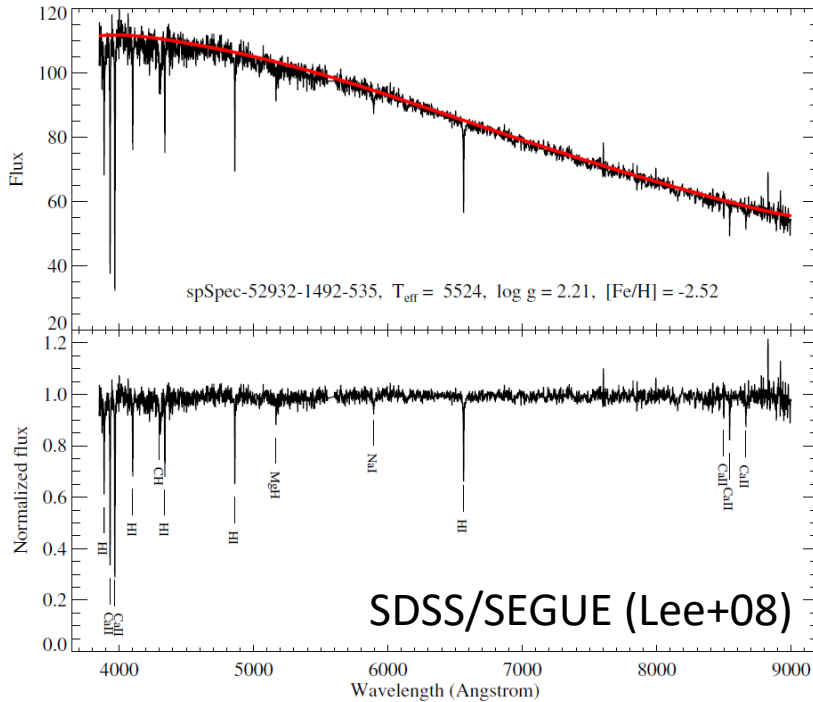
Anna Frebel<sup>1</sup>, Wako Aoki<sup>2</sup>, Norbert Christlieb<sup>2,3</sup>, Hiroyasu Ando<sup>2</sup>, Martin Asplund<sup>1</sup>, Paul S. Barklem<sup>4</sup>, Timothy C. Beers<sup>5</sup>, Kjell Eriksson<sup>4</sup>, Cora Fechner<sup>3</sup>, Masayuki Y. Fujimoto<sup>6</sup>, Satoshi Honda<sup>2</sup>, Toshitaka Kajino<sup>2</sup>, Takeo Minezaki<sup>7</sup>, Ken'ichi Nomoto<sup>8</sup>, John E. Norris<sup>1</sup>, Sean G. Ryan<sup>9</sup>, Masahide Takada-Hidai<sup>10</sup>, Stelios Tsangarides<sup>9</sup> & Yuzuru Yoshii<sup>7</sup>



[Fe/H] ~ -5.4

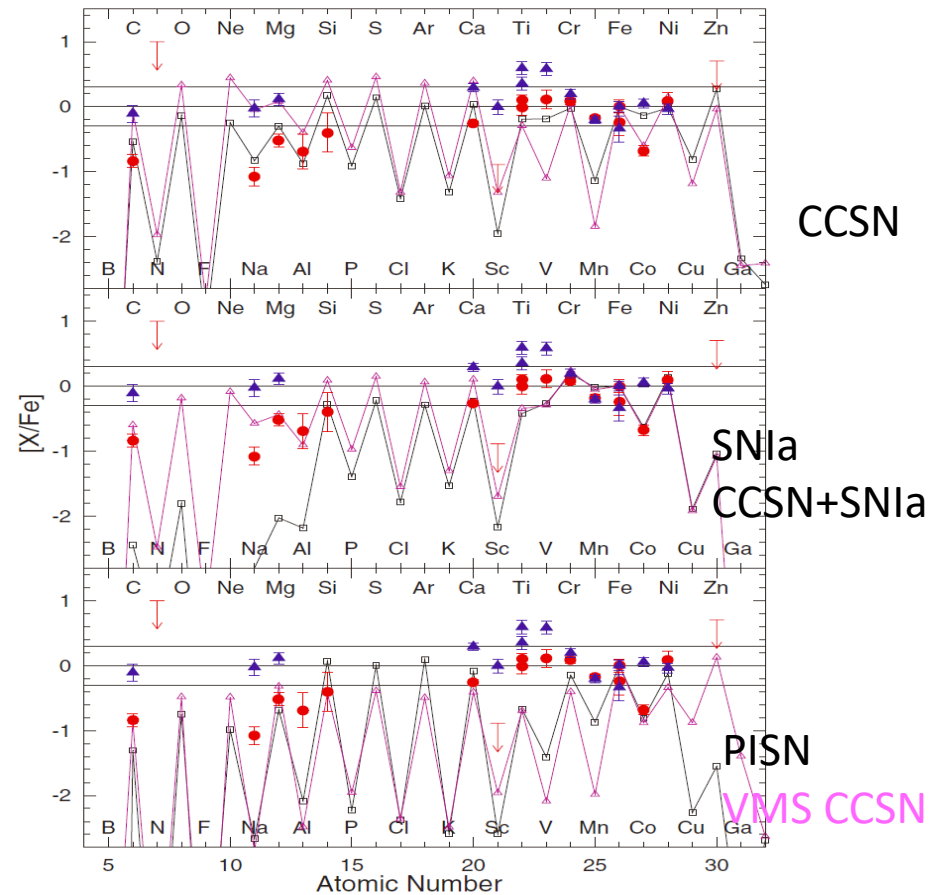
# Past surveys

- Low-resolution multi-object spectroscopic survey



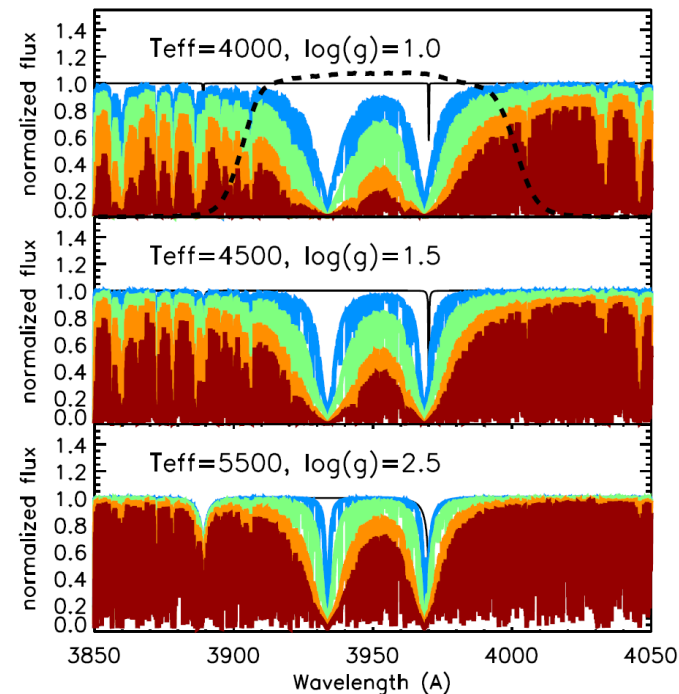
## A chemical signature of first-generation very massive stars

W. Aoki,<sup>1,2\*</sup> N. Tominaga,<sup>3,4</sup> T. C. Beers,<sup>5,6</sup> S. Honda,<sup>7</sup> Y. S. Lee<sup>8</sup>



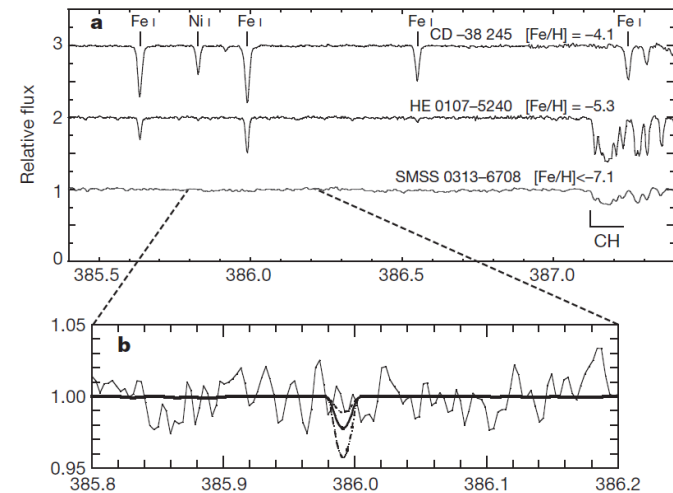
# Past surveys

- Narrow-band photometric survey
  - Skymapper survey (Keller+)
  - Pristine survey (Starkenburg+)
    - 26 papers in 5 years
  - ZERO survey (Chiba+)

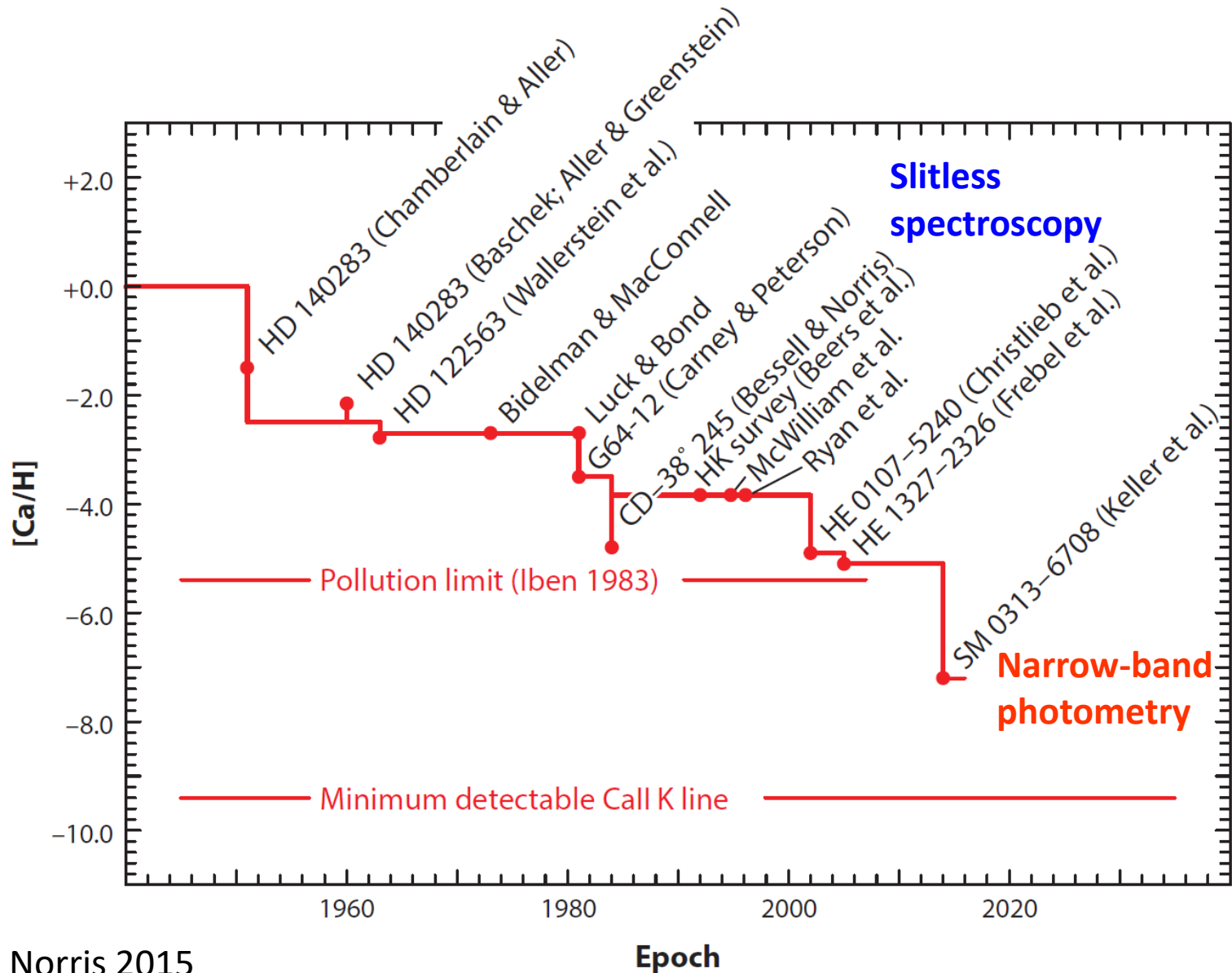


## A single low-energy, iron-poor supernova as the source of metals in the star SMSS J031300.36–670839.3

S. C. Keller<sup>1</sup>, M. S. Bessell<sup>1</sup>, A. Frebel<sup>2</sup>, A. R. Casey<sup>1</sup>, M. Asplund<sup>1</sup>, H. R. Jacobson<sup>2</sup>, K. Lind<sup>3</sup>, J. E. Norris<sup>1</sup>, D. Yong<sup>1</sup>, A. Heger<sup>4</sup>, Z. Magic<sup>1,5</sup>, G. S. Da Costa<sup>1</sup>, B. P. Schmidt<sup>1</sup> & P. Tisserand<sup>1</sup>



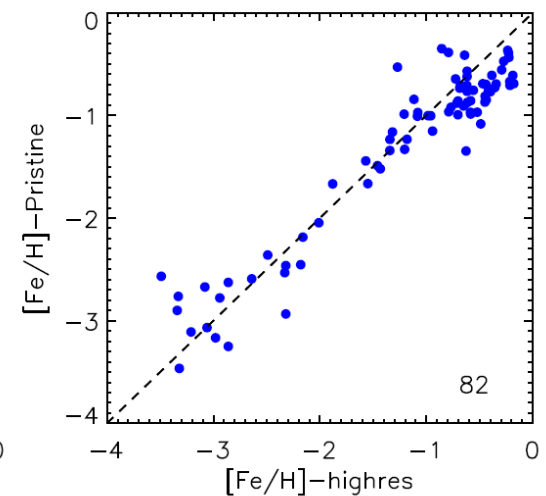
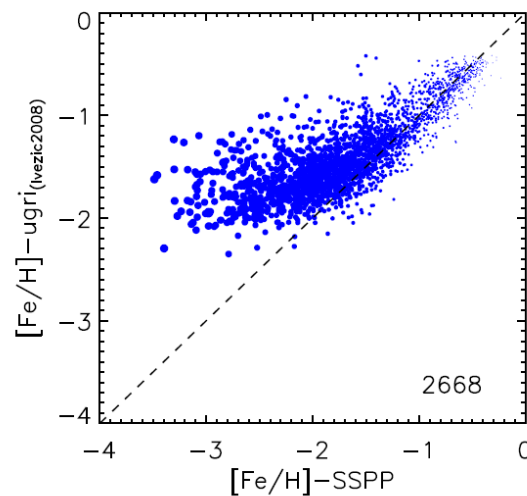
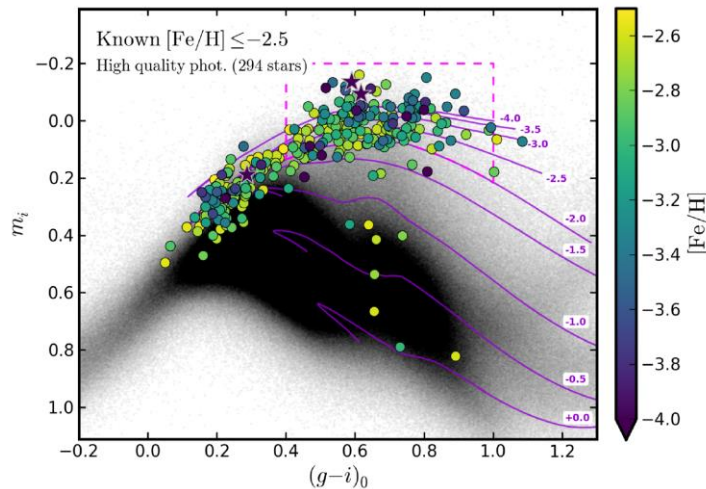
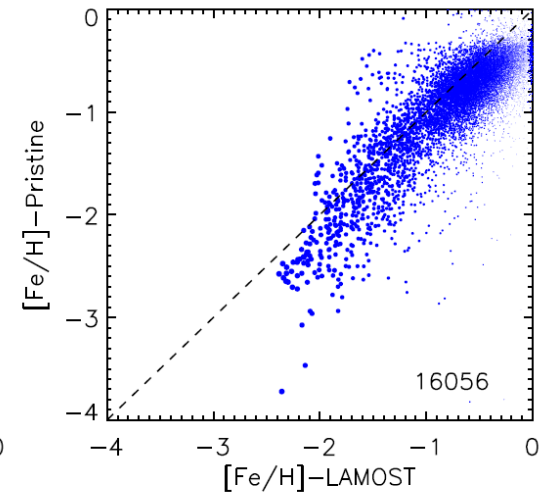
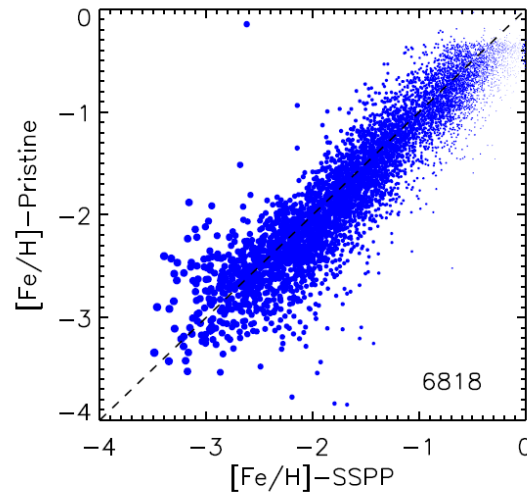
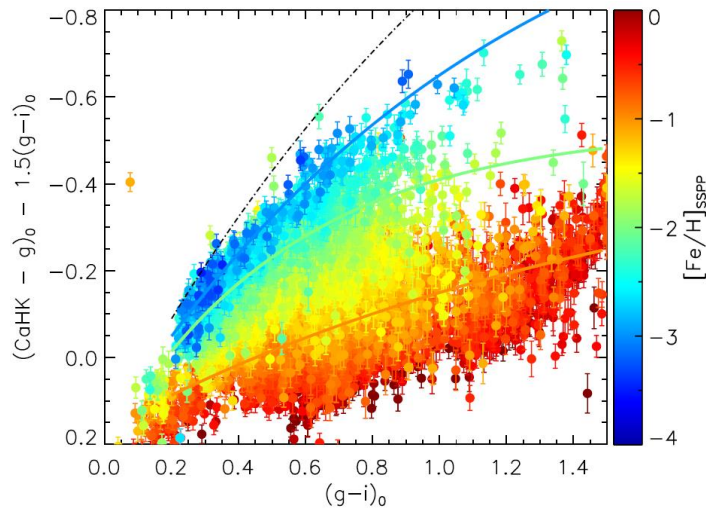
# Ca abundance of Fe-poor stars





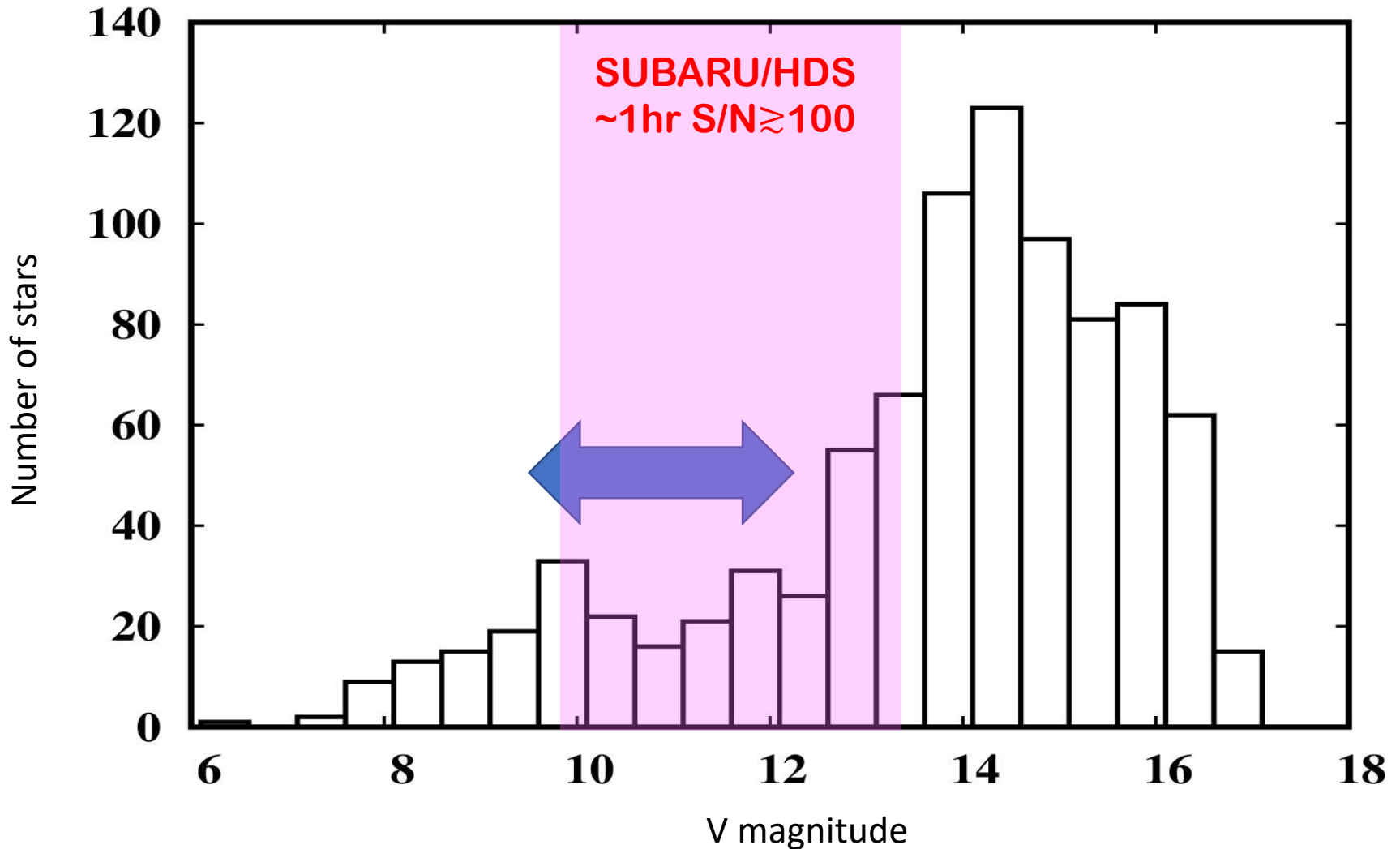
# Narrow band surveys

## Pristine survey & Skymapper survey





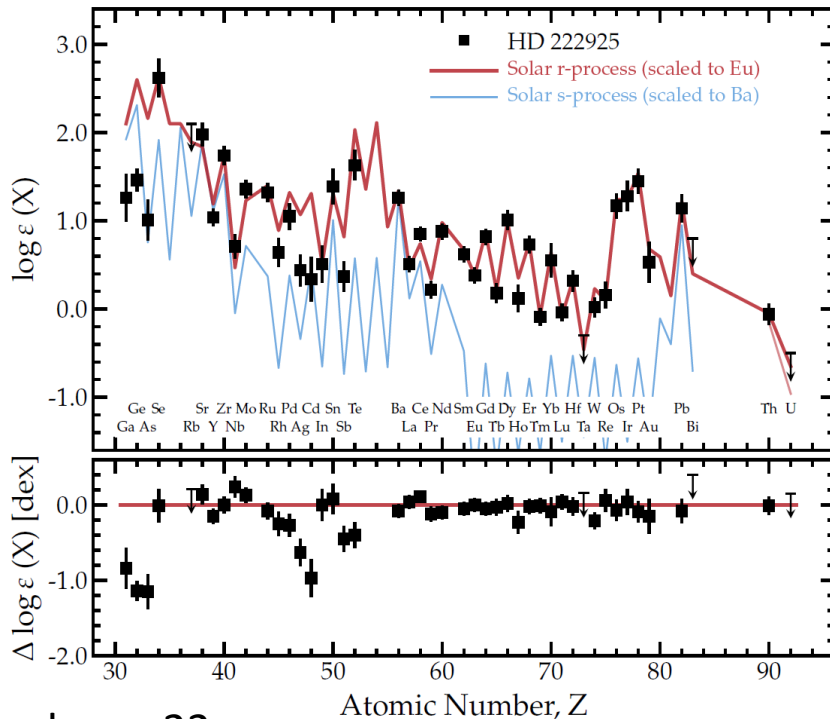
# Number of metal-poor stars with $[Fe/H] < -2$



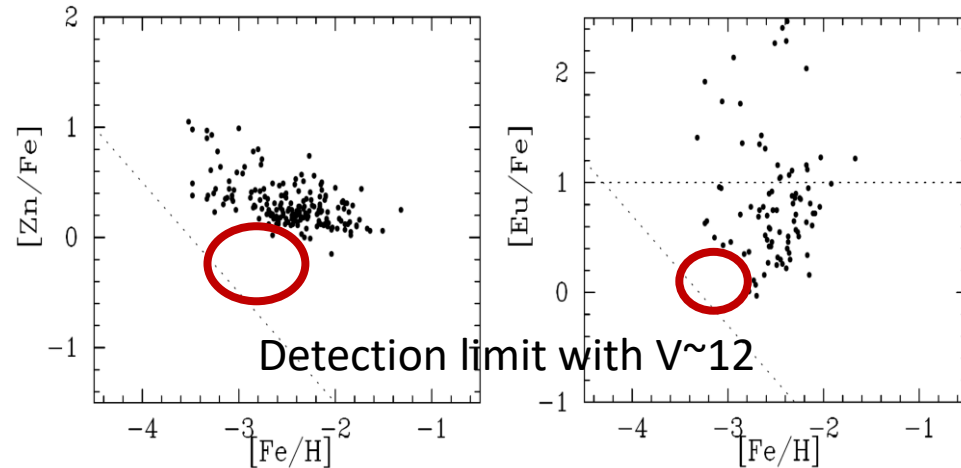
# Profits from bright metal-poor stars

- Measurement of rare elements

UV spectroscopy



- Measurement of low abundance or stringent upper limit



# 基盤研究A (2021~2024年度)

## 明るい金属欠乏星の全北天域探査による 初代星元素合成と初期銀河系形成の解明

既製品フィルターを用いたパイロット観測+追観測の結果 -> 岡田さん (甲南大)

「北半球から観測可能な明るい金属欠乏星を網羅的に探査」

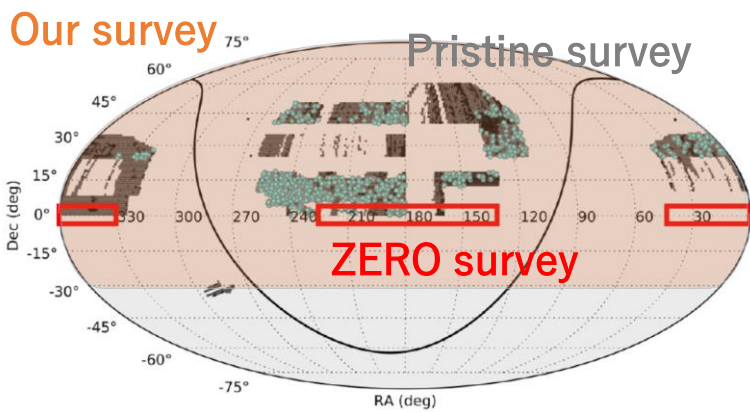
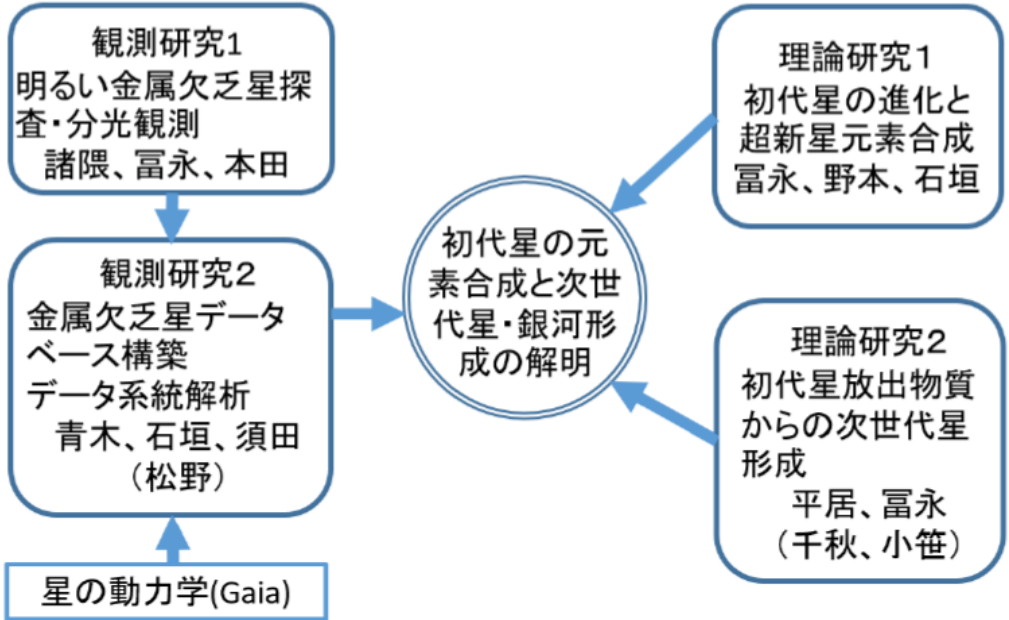
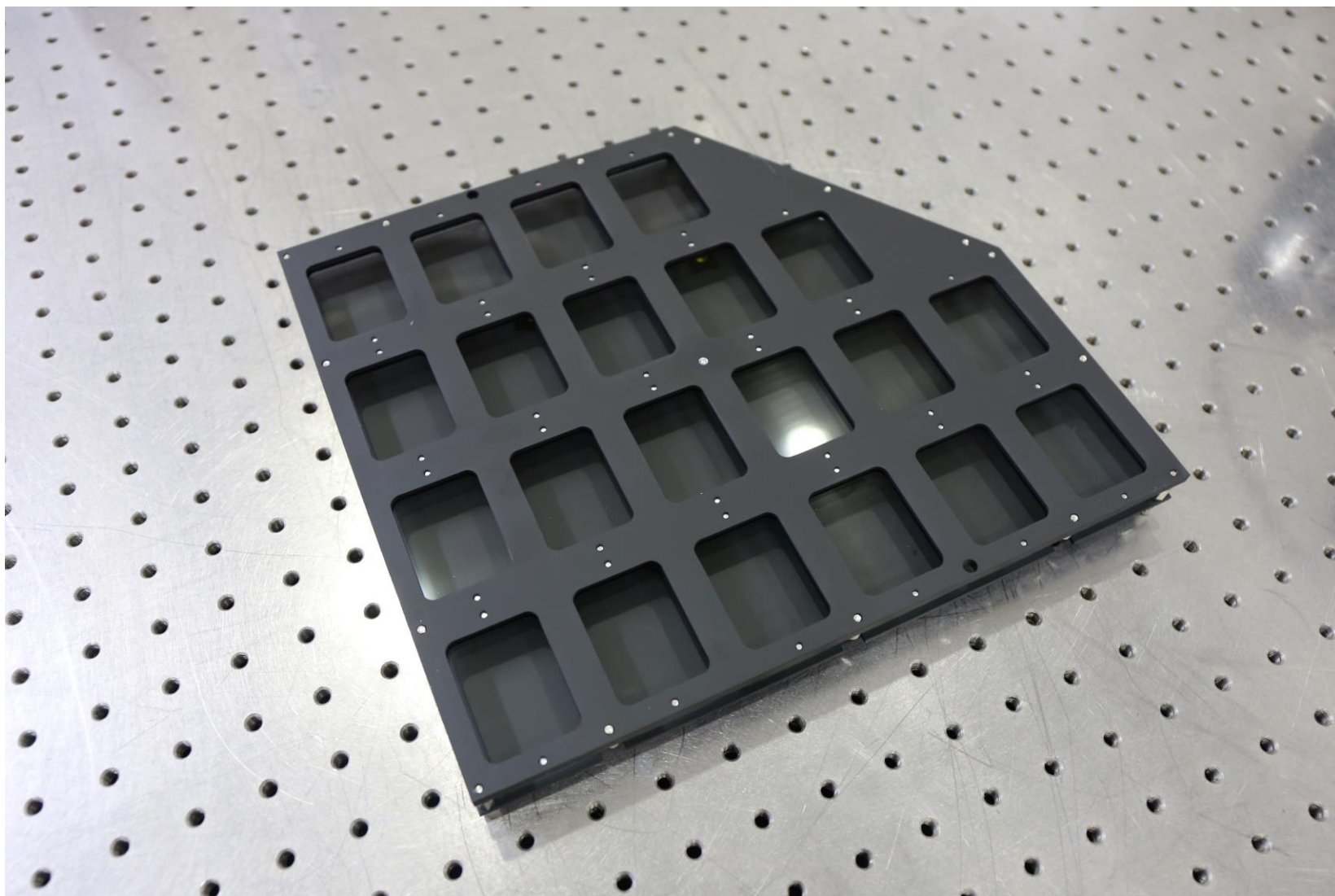


図2

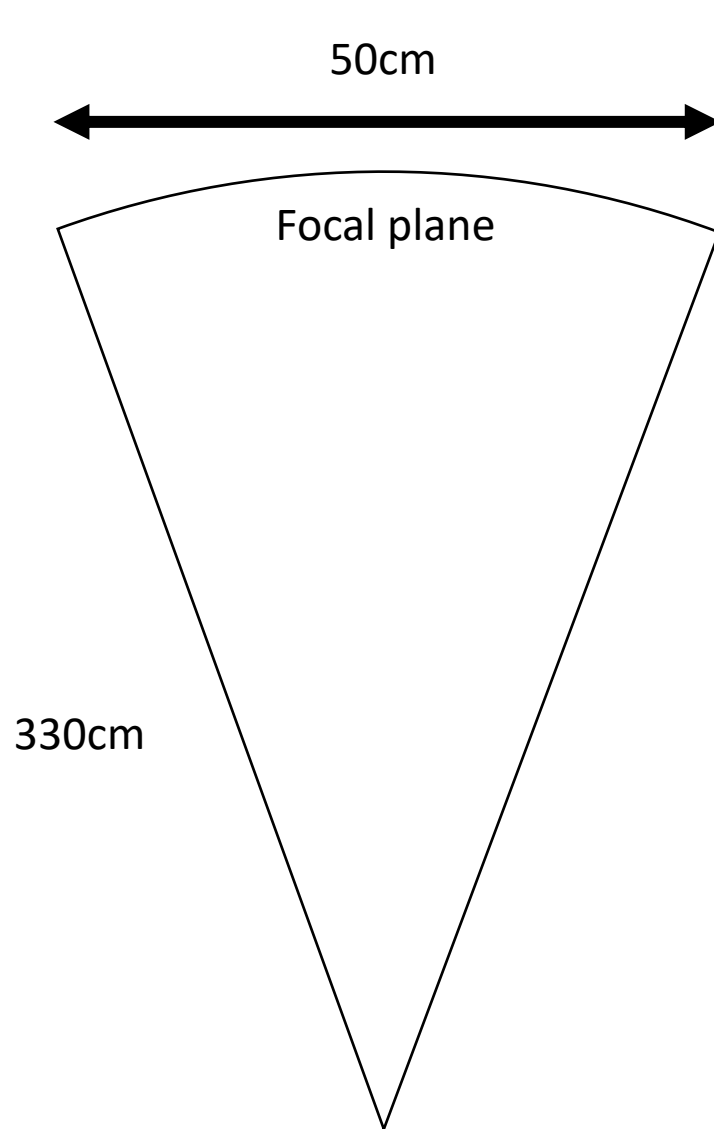
- 研究代表者: 青木和光
- 研究分担者: 富永望、本田敏志、諸隈智貴、石垣美歩、平居悠、須田拓馬、野本憲一
- 研究協力者: 千秋元、小笹隆司、松野允郁



# Current filter holder



# Tomo-e Gozen Camera



$$\lambda = \lambda_0 \sqrt{1 - \left(\frac{\sin \theta_0}{n^*}\right)^2}$$

[https://www.thorlabs.co.jp/NewGroupPage9\\_PF.cfm?Guide=10&Category\\_ID=134&ObjectGroup\\_ID=3880](https://www.thorlabs.co.jp/NewGroupPage9_PF.cfm?Guide=10&Category_ID=134&ObjectGroup_ID=3880)

$$\sin \theta = 0 - 0.076$$

$$\lambda/\lambda_0 = 1 - 0.9971 \quad (n^*=1)$$

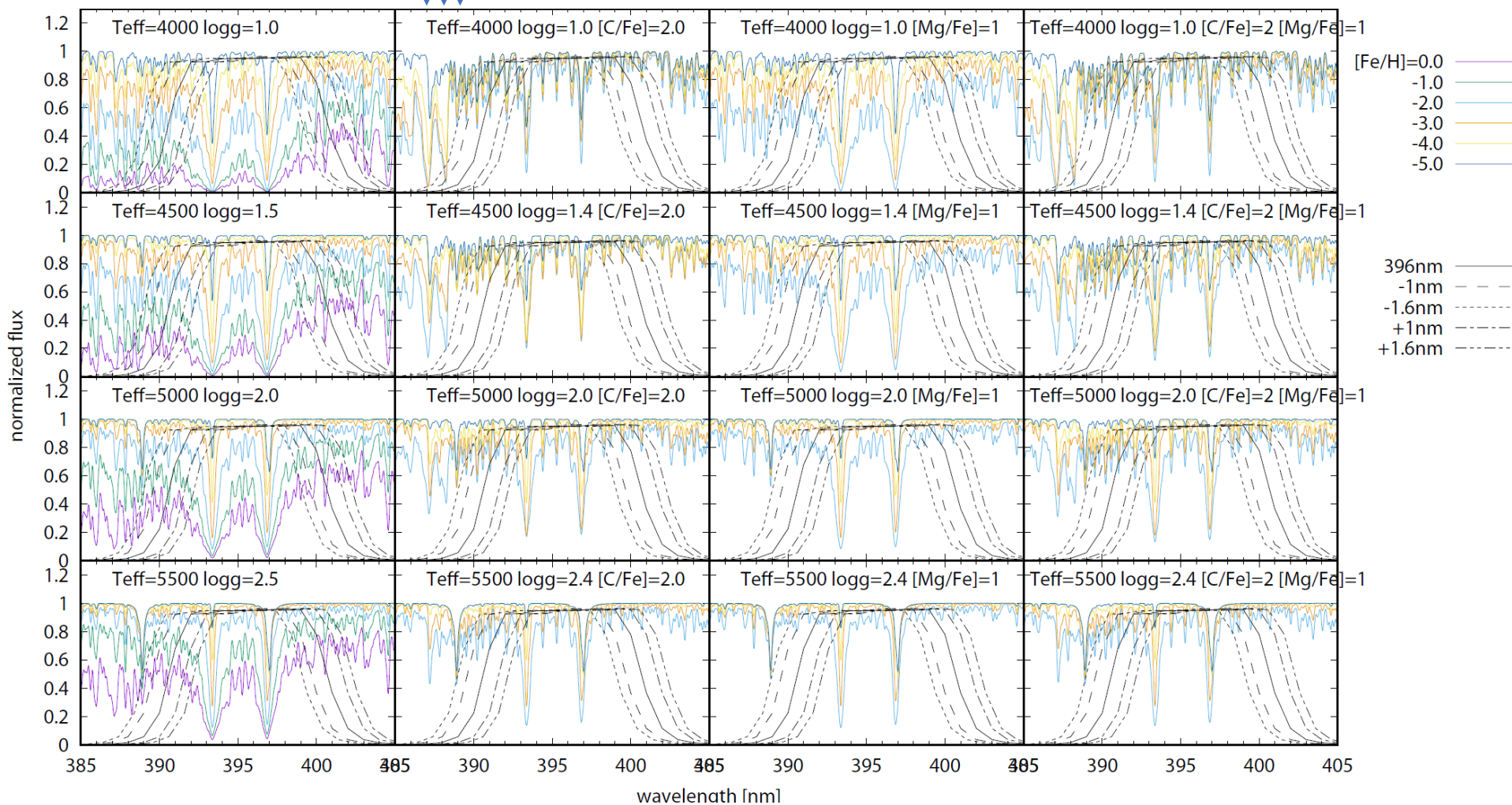
Fused silica  $n^*=1.46-1.47$

$$\Delta\lambda = \pm 0.6\text{nm} \quad (\lambda_0=400\text{nm})$$

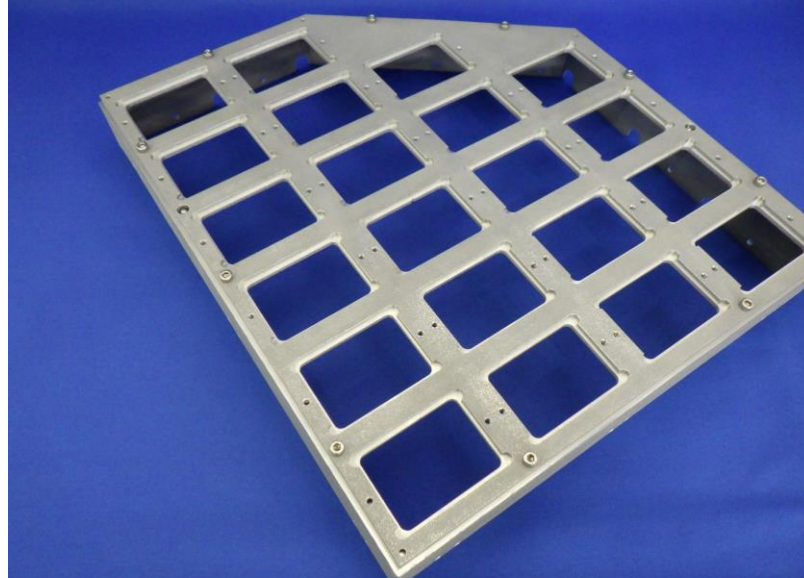
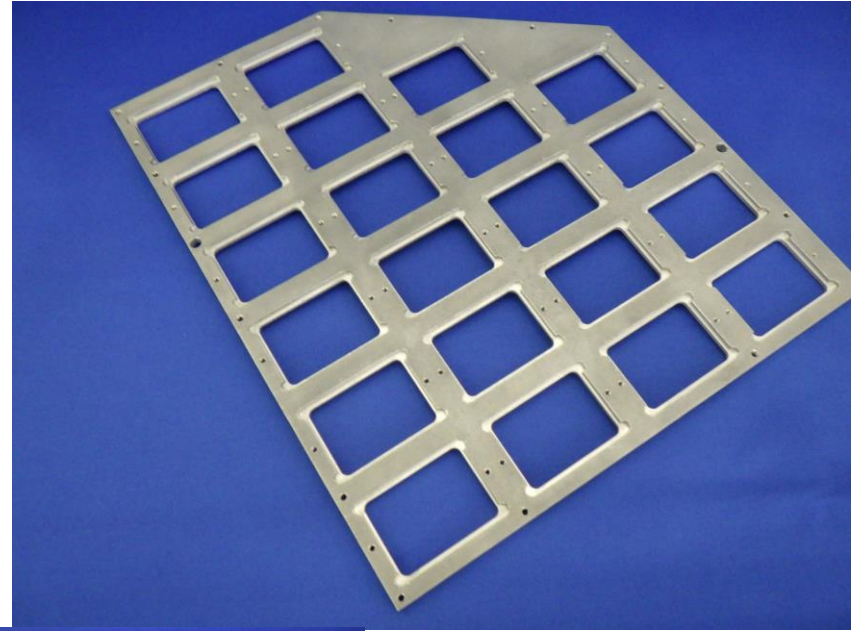
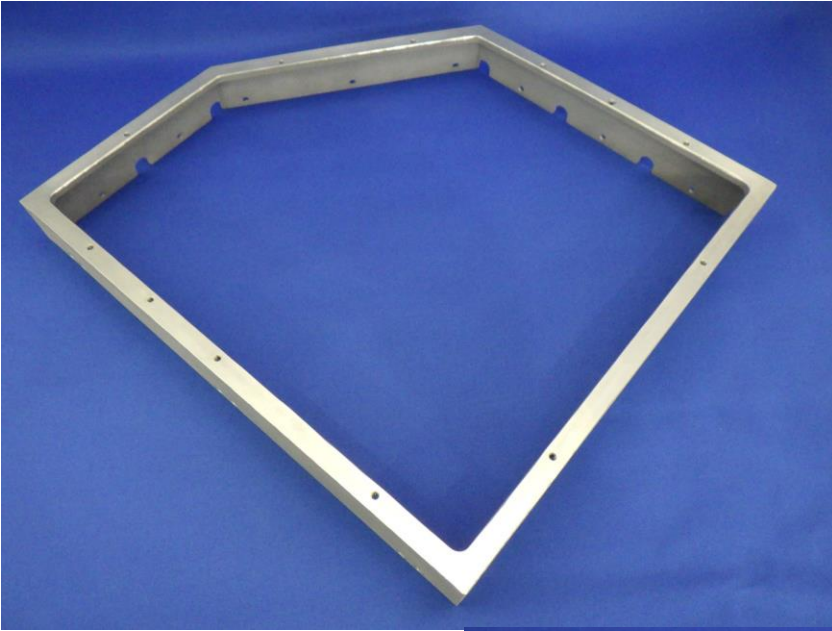


# Narrow-band for CaHK (395nm)

CH, CN, H $\zeta$



# New filter holder produced by ATC



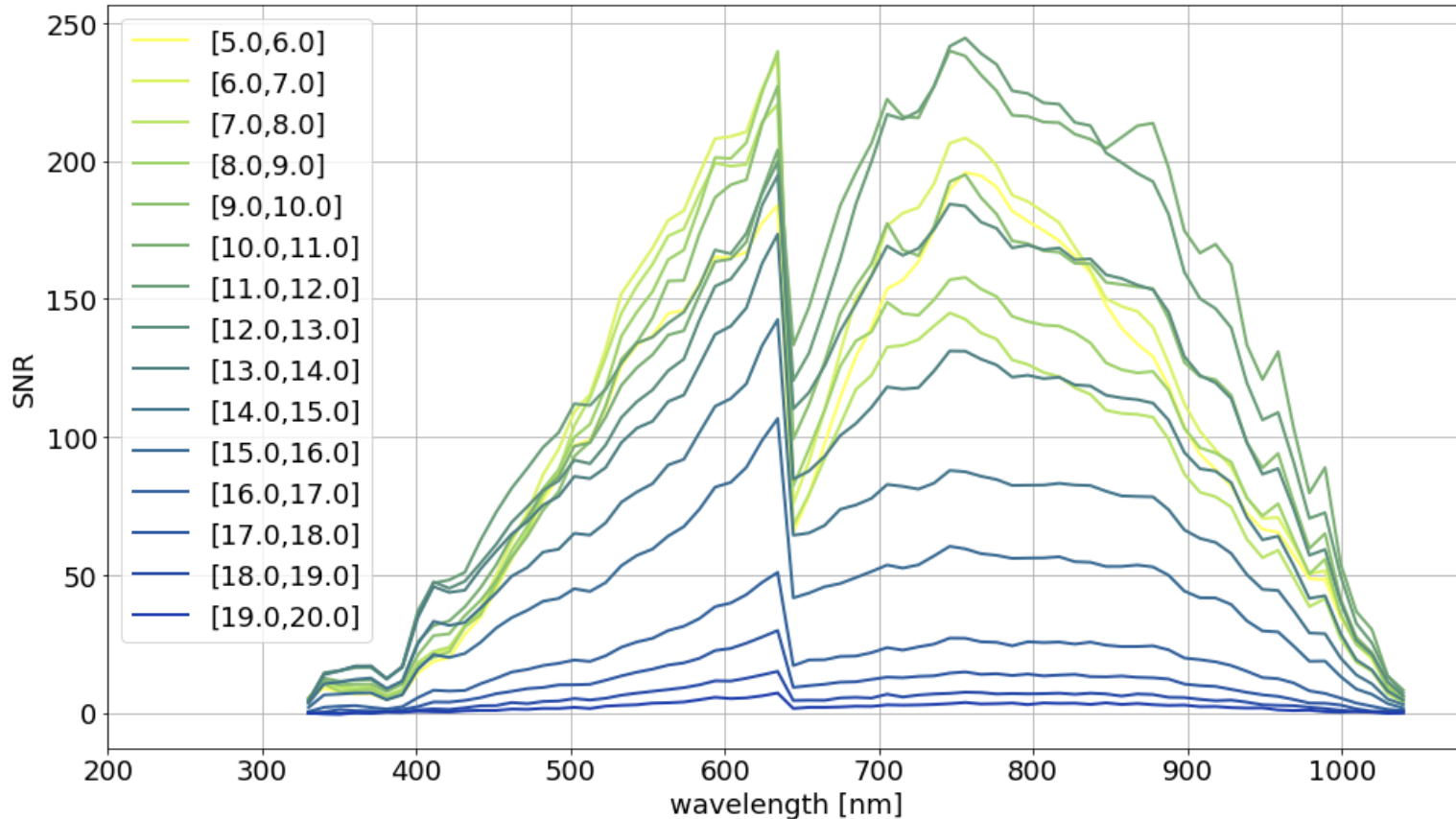


# Gaia DR3

- Astrophysical parameters ( $T_{\text{eff}}$ ,  $\log g$ ,  $[M/H]$ , AG, distance, etc.) from BP/RP spectra for 470 million objects
- Astrophysical parameters ( $T_{\text{eff}}$ ,  $\log g$ ,  $[M/H]$ ,  $[X/M]$  for 12 elements, etc.) from RVS spectra for 5.5 million objects
- Mean BP/RP spectra for 219 million sources, most of them with  $G < 17.6$  mag
- Mean RVS spectra for 1 million well-behaved objects

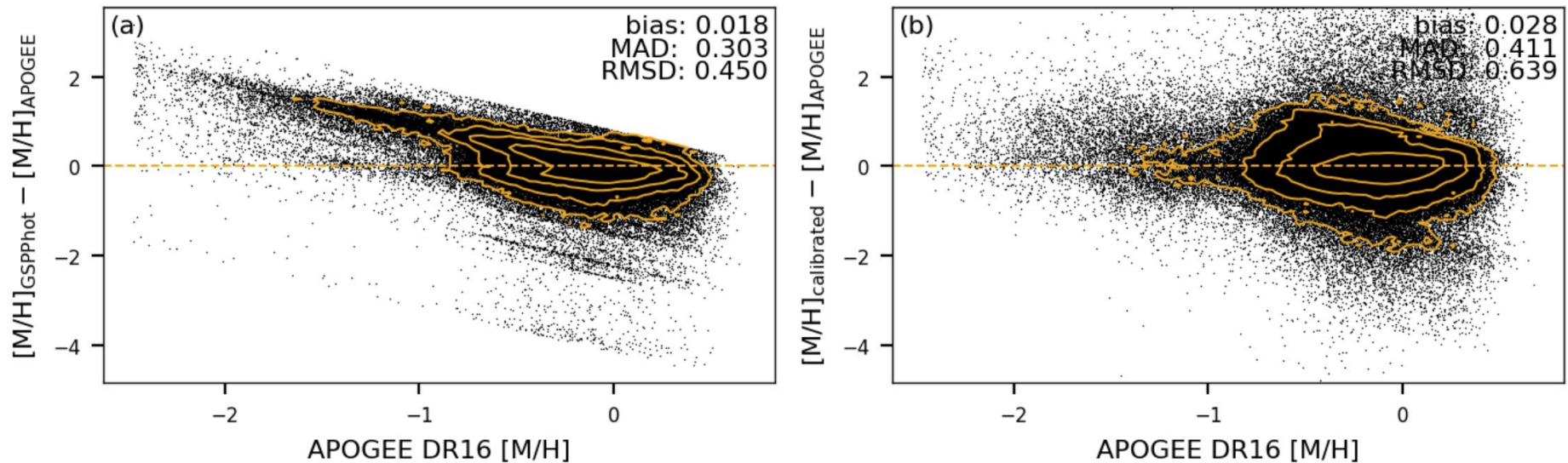


# Gaia DR3 BP/RP Mean Spectra



Metallicity estimates exhibit substantial biases compared to literature values and are only useful at a qualitative level. However, we provide an empirical calibration of our metallicity estimates that largely removes these biases.

# Metallicity estimate with BP/RP spectra



Metallicity estimates from GSP-Phot are generally very poor, being  $\sim 0.1$  dex too low and exhibiting additional strong systematics. Therefore, we do not recommend to use the  $[M/H]$  estimates from GSP-Phot. However, GSP-Phot  $[M/H]$  estimates can be calibrated empirically, e.g. using LAMOST data.

[https://gea.esac.esa.int/archive/documentation/GDR3/Data\\_analysis/chap\\_cu8par/sec\\_cu8par\\_apsis/ssec\\_cu8par\\_apsis\\_gspphot.html](https://gea.esac.esa.int/archive/documentation/GDR3/Data_analysis/chap_cu8par/sec_cu8par_apsis/ssec_cu8par_apsis_gspphot.html)



# Requirements and survey plan

- Two narrow band filters (NB395, 10nm width, NB433 20nm width, NB518?, NB857x)
  - Magnitude at 395nm: <15 mag @ 395nm (cool red)
  - Efficiency at 395nm: x 0.5
  - Signal-to-noise ratio: **>20-50?**
- Required number of nights:
  - 1 night for no filter survey for 12,000 deg<sup>2</sup> for ~<18mag (5sigma)
  - **??** clear nights x 2 to cover whole northern sky
- Observing plans:
  - Observations are not time critical
  - (probably) need to avoid GW O4 (Mar 2023-)
  - Test observation: (hopefully) **Sep 2022?**
  - Main survey: during breaks of GW O4?, after GW O4?, before the end of FY2023?
- Follow-up spectroscopy
  - With Nishi-Harima, Subaru, etc.
  - Collaboration with US team to study r-process-enhanced stars (RPA: R-Process Alliance) through IReNA
- Byproducts
  - Searches for stellar activities using Ca H-K lines
  - Others?