Excessively High (Fe/O) in Extremely Metal-Poor Galaxies (EMPGs) Suggestive of Hypernovae (HNe) and/or Pair-Instability Supernovae (PISNe)

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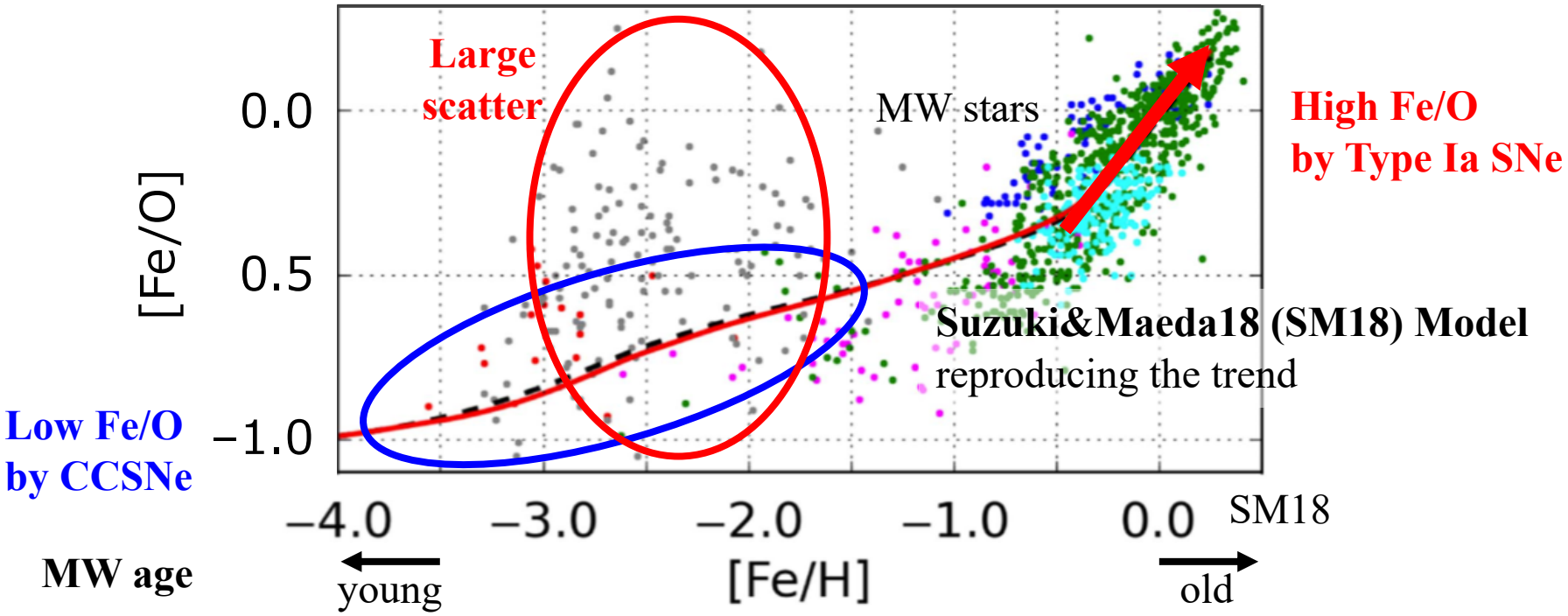
Metal enrichment with age

Milky Way (MW) star: Monotonical increase in Fe/O with Fe/H

O: Massive (~ 9–100 $M_\odot$) stars via core-collapse SNe (CCSNe)

Fe: Low-mass ($\lesssim$ 9 $M_\odot$) stars via Type Ia SNe



→ Fe/O serves as a **cosmic clock**

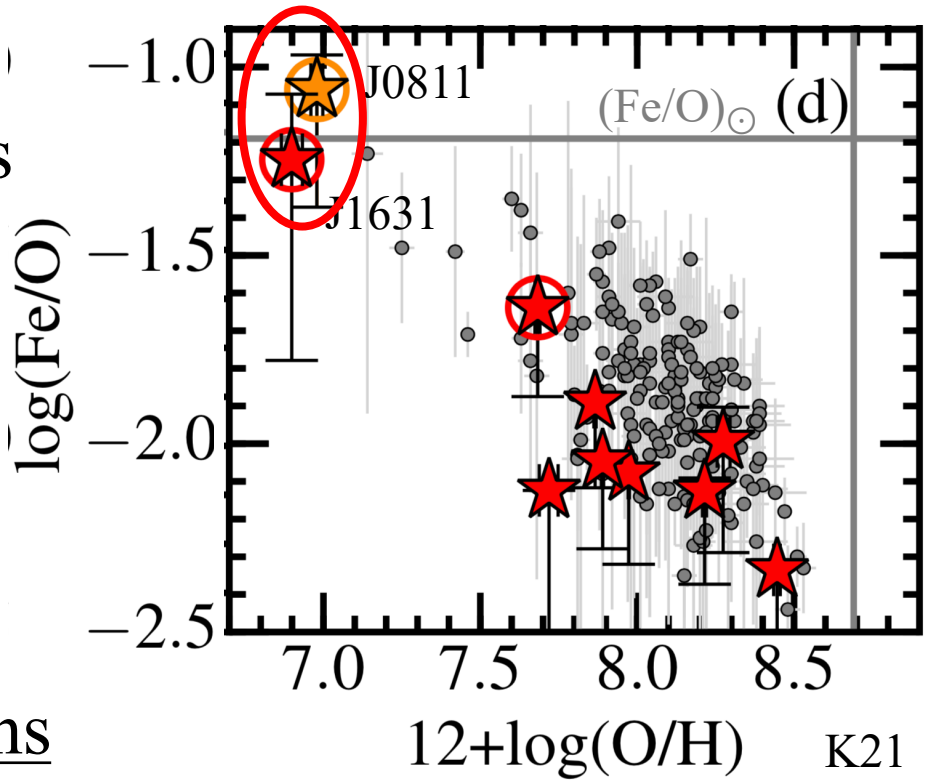
↔ Applicable for galaxies in the early formation phase?

Local early galaxy

Extremely metal-poor galaxy (EMPG)

- Galaxy with O/H ≤ 10% $(O/H)_\odot$, low M_* (10^6–10^9 $M_\odot$)
  → In the **early formation phase**

- Kojima+21: High Fe/O ~ $(Fe/O)_\odot$ in 2 EMPGs
  ↔ Contradictory to the cosmic clock scenario
  Very massive stars? (K21)



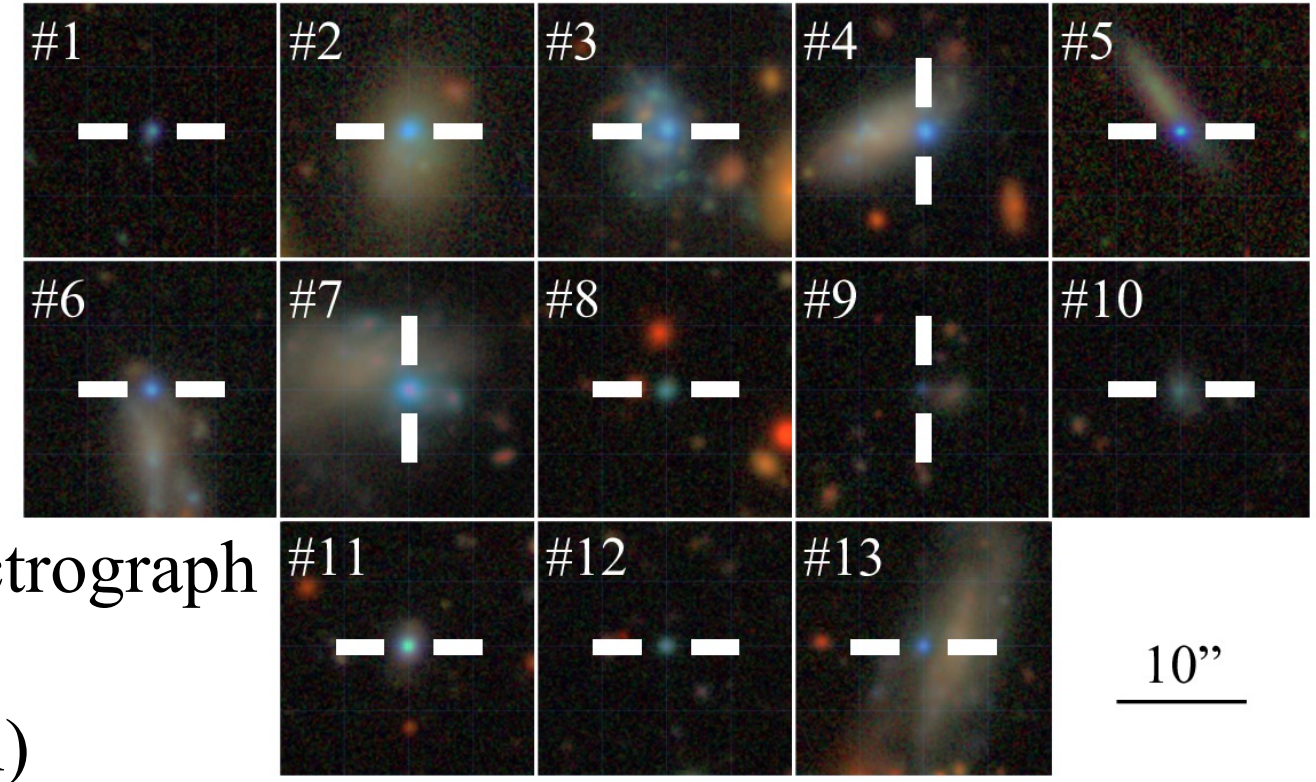
Goals of this study

- To identify more EMPGs with Fe line detections
- To revisit the origin of Fe/O enhancements of EMPGs

Spec. follow-up observations

Target

13 from **faint** (i = 19–24) photometric EMPG candidates selected from HSC-SSP (Kojima+20)

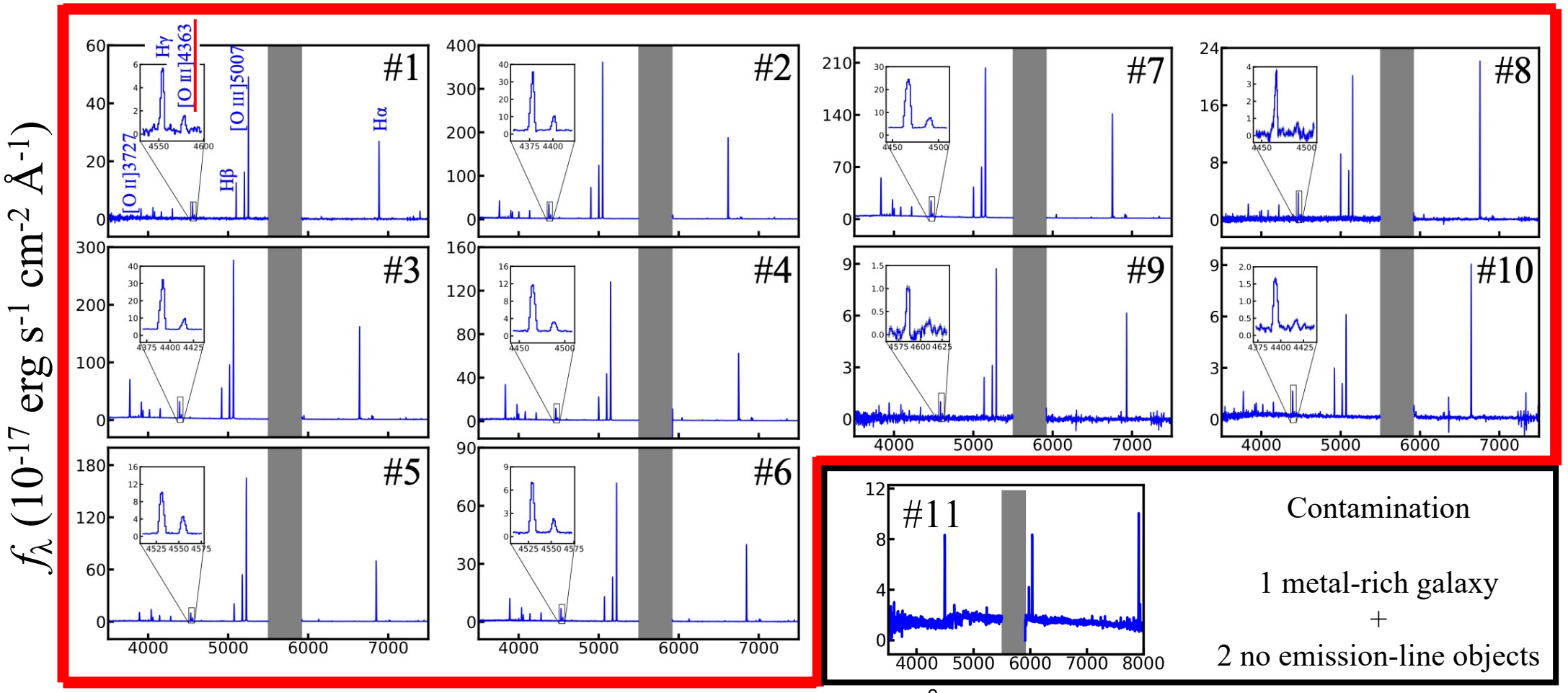


Spectrograph

Keck/Low Resolution Imaging Spectrograph (**LRIS**)

- Wide λ coverage (~ 3000 – 9000 Å)
- **Deep** ($F_{\mathrm{lim},5\sigma} \sim 10^{-16}$ erg s^{-1} cm^{-2})

Reduced spectra

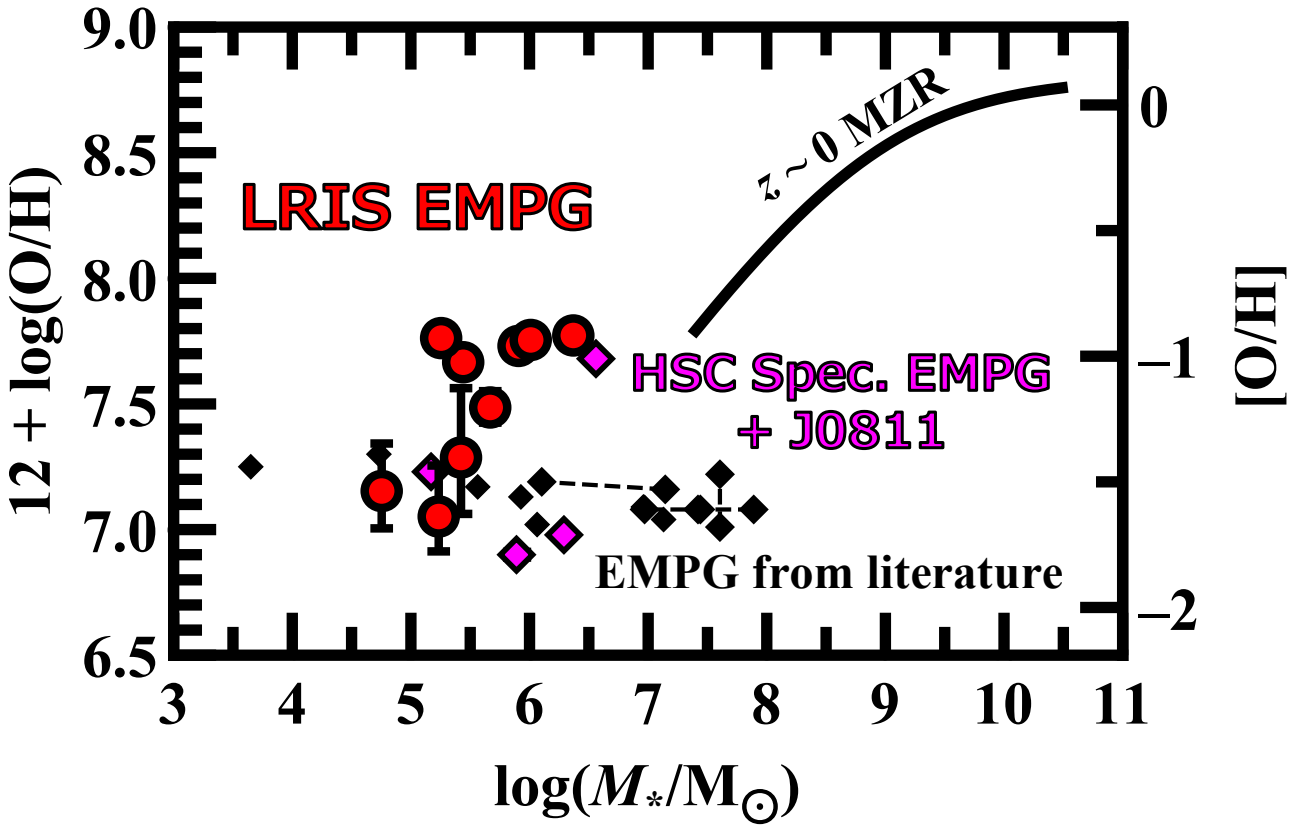


10/13 are local young emission-line galaxies

→ **EMPG candidates**

Metallicity and M_*

- **9**/10 of the EMPG candidates have O/H $\lesssim$ 10% $(O/H)_\odot$
  → LRIS EMPGs
- $M_* = \mathbf{5 \times 10^4} - 3 \times 10^6\ M_\odot$
  → Galaxies in the early formation phase

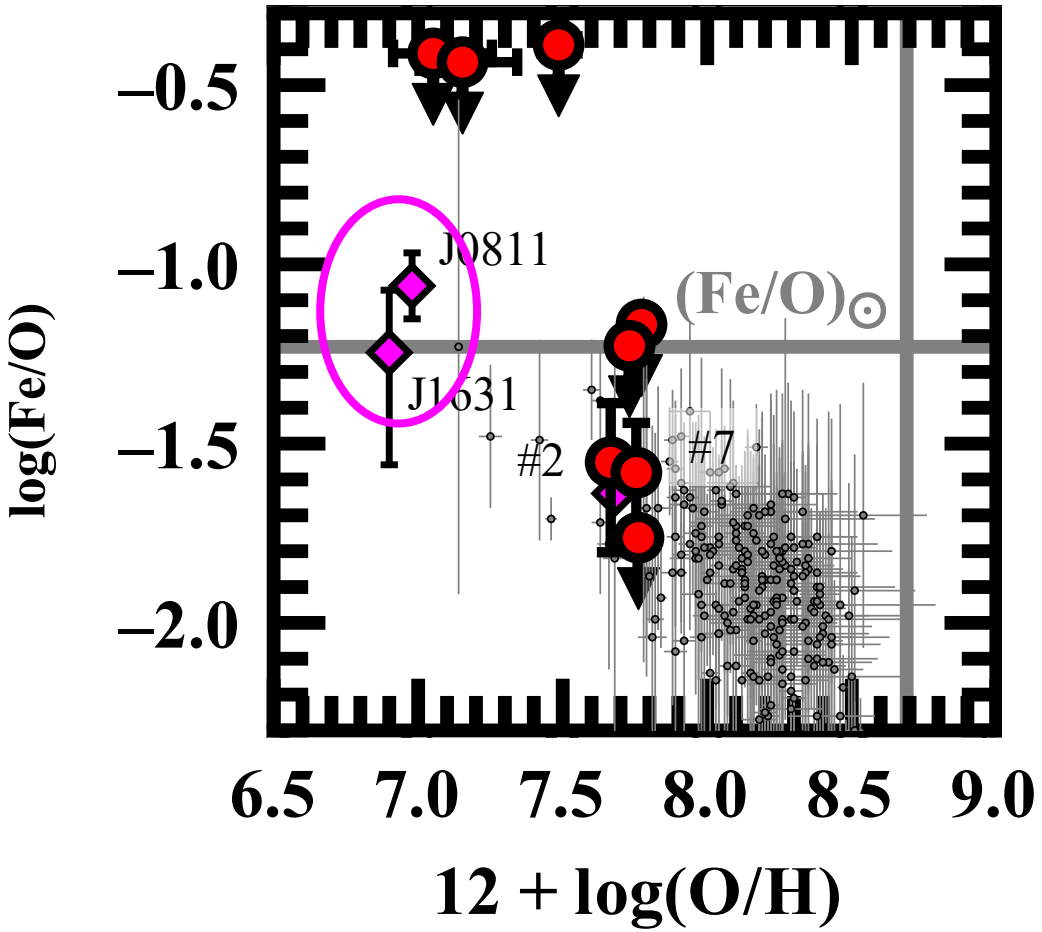


O/H vs. Fe/O

- #2, 7: log(Fe/O) ~ –1.6

  ↔ J1631 and J0811: Very high Fe/O ~ **(Fe/O)$_\odot$**

  High Fe/O in younger EMPGs?



Possible contributors

CCSN

Hypernova (HN)

Progenitor star ~ 30–100 $M_\odot$

CCSN w/ high explosion energy

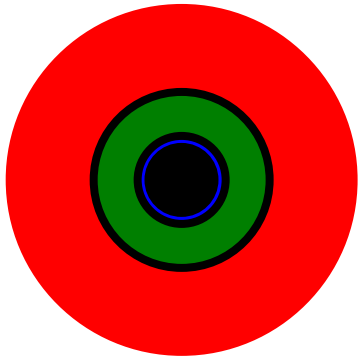
→ Large ^{56}Ni core

Pair-instability SN (PISN)

Progenitor star ~ 140–300 $M_\odot$

Leave no remnant

Around star core

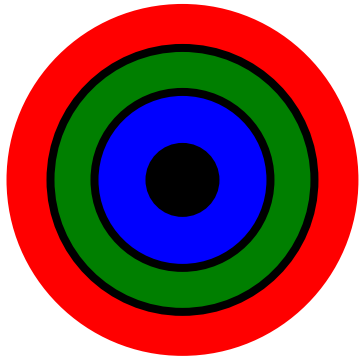


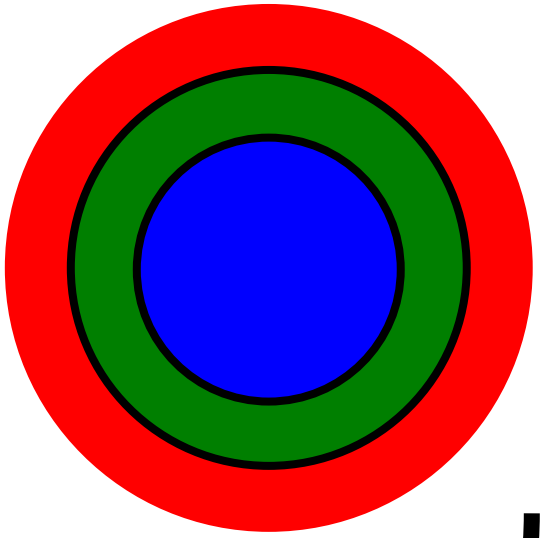
^{16}O

^{28}Si

^{56}Ni → ^{56}Fe

Remnant





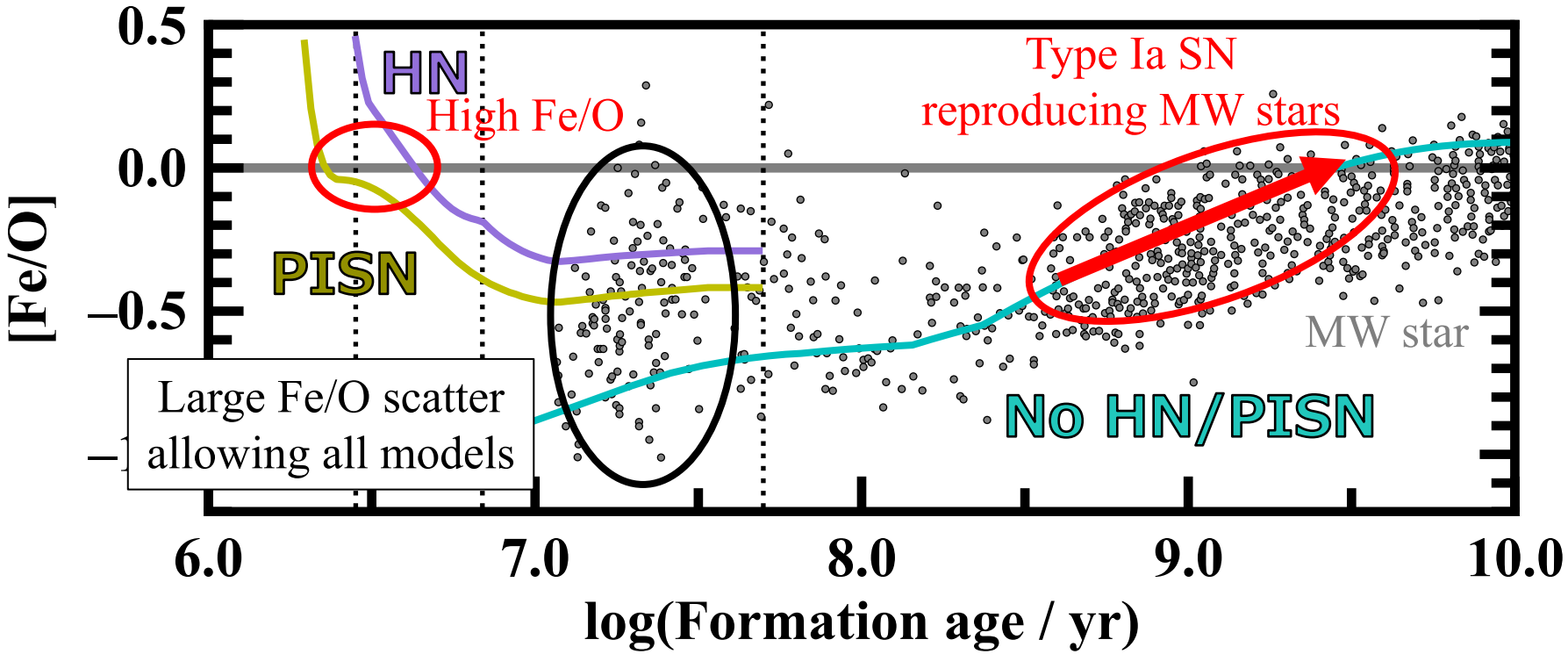
Low Fe/O

High Fe/O

Preferentially born in metal-poor environments

Model construction

	$\leq 8\ M_\odot$	$9–30\ M_\odot$	$30–100\ M_\odot$	$140–300\ M_\odot$
No HN/PISN (SM18)	Type Ia SN	CCSN	CCSN	——
HN	——	CCSN	HN 20%	——
PISN	——	CCSN	CCSN	PISN

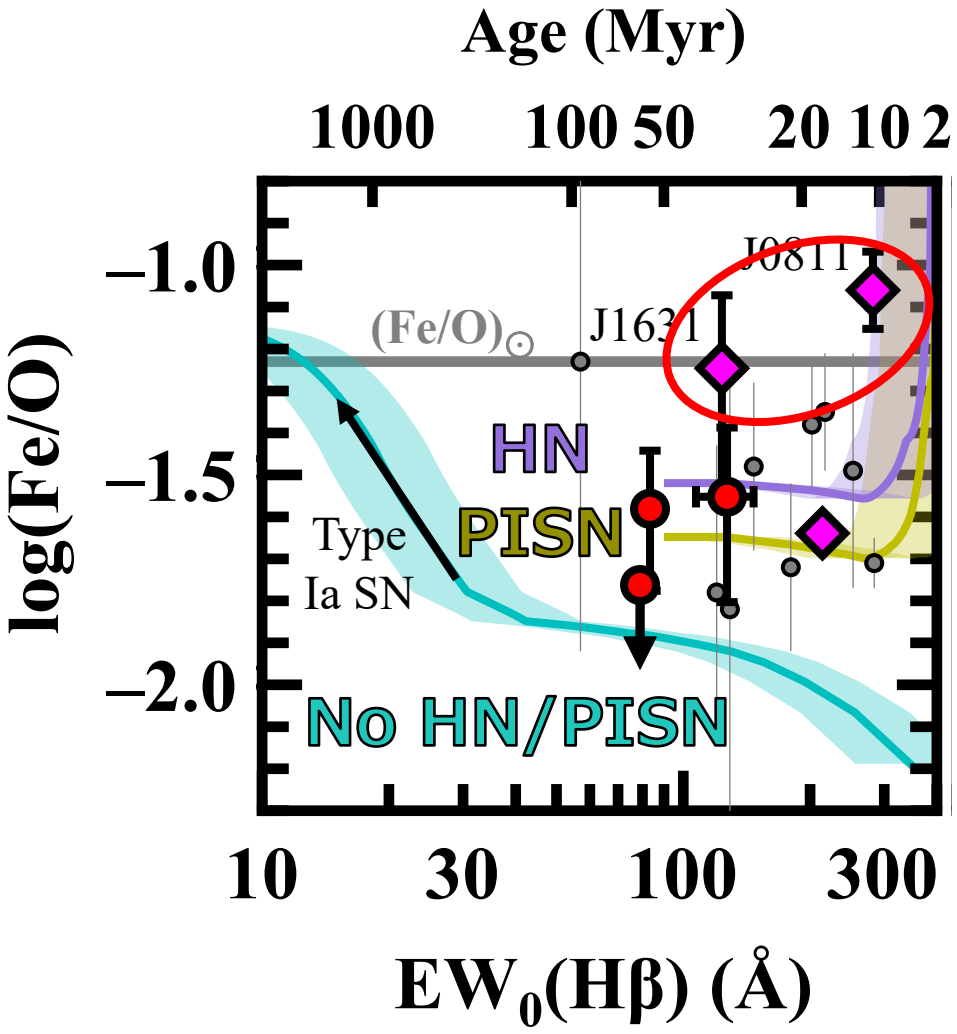


Fe/O vs. EW (age)

- No HN/PISN model cannot
- **HN/PISN models** can
  explain high Fe/O of J1631 and J0811

→ Not Type Ia SNe but **HNe/PISNe** can be responsible for Fe/O enhancements of young EMPGs

→ Fe/O may not serve as a cosmic clock for early galaxies



Summary

- Spectroscopic follow-up observations for 13 **faint** EMPG candidates

  → Identifying 9 EMPGs with M_* down to $\mathbf{5 \times 10^4}$ $M_\odot$

  → Confirming that some young EMPGs have high Fe/O

- Comparing **Fe/O** of EMPGs with **chemical evolution models**

  → **HNe/PISNe** potentially attribute to Fe/O enhancements of young EMPGs

  → Fe/O may not serve as a cosmic clock for early galaxies