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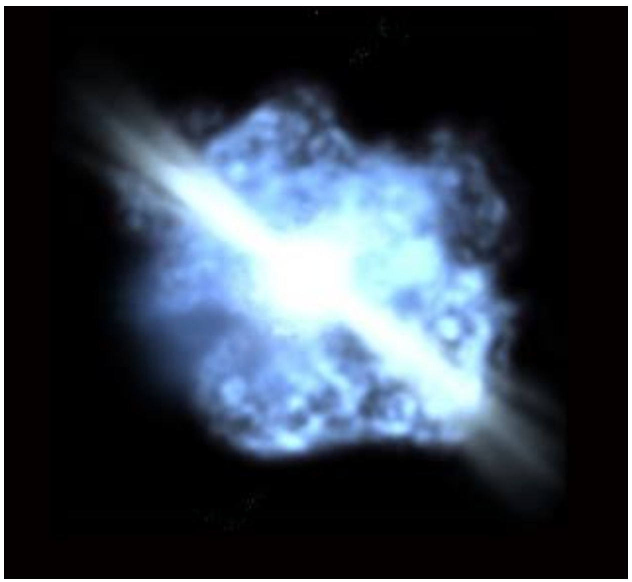
# Photometric indicators of first supernovae: radiation hydrodynamics simulations

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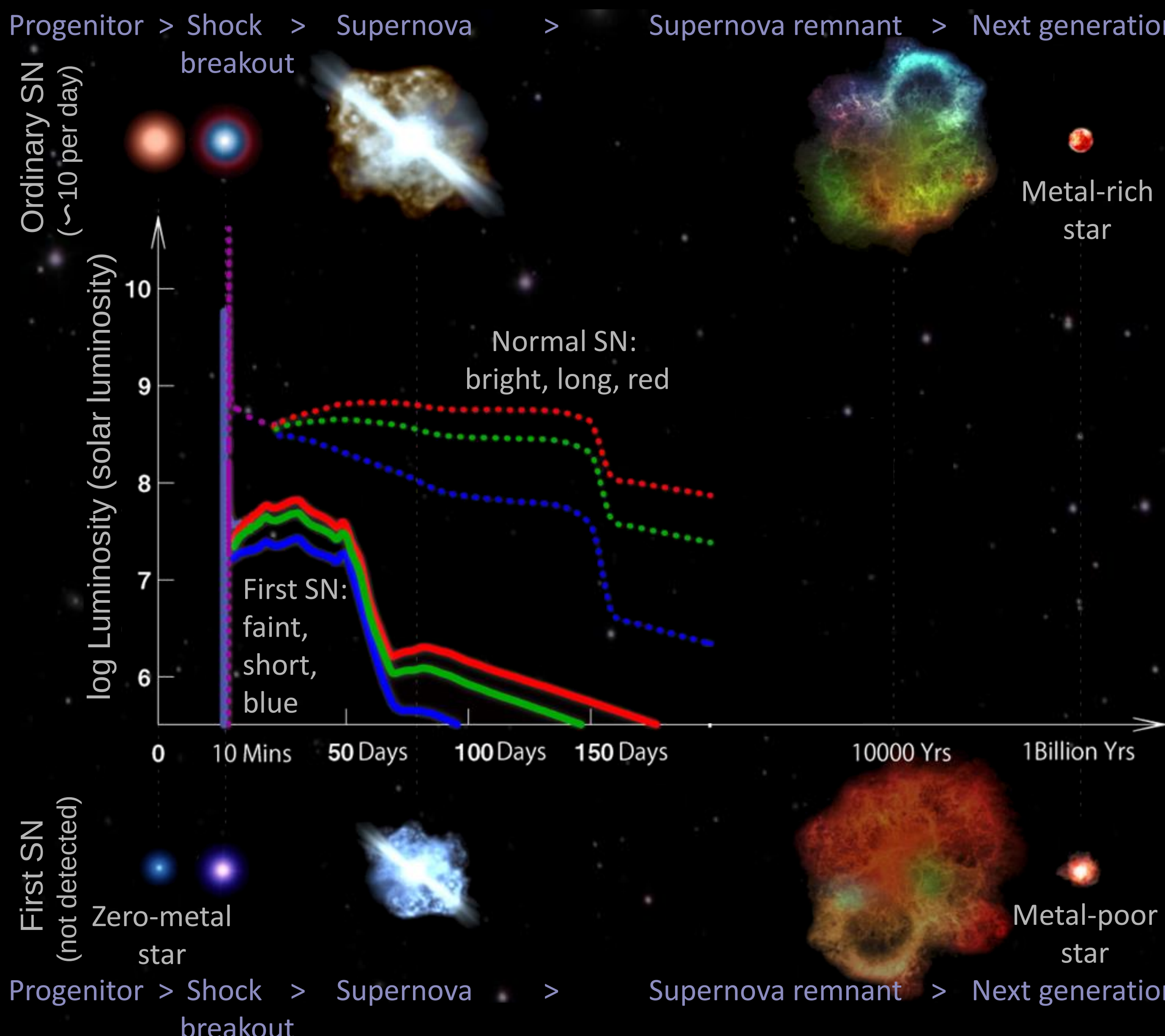
**Stellar Archaeology as a Time Machine to the First Stars, IPMU, 3-7 Dec 2018**

# The first supernova explosions




First supernovae (SNe): near future detections!
How do they explode?
How to identify them?

- Simulations:
  - first supernovae - explosions of first stars (compact, zero-metal stars)
- Purpose:
  Photometric easy-to-use indicator of first SN explosions for current and future surveys (HSC/Subaru, LSST, WFIRST, JWST).

# Pop III stars – Pop III GRB – Pop III SNe

$M > 10^5 M_\odot$:SMS (Super Massive Stars)

→ GR instability → Collapse

$M \sim 300 - 10^5 M_\odot$:

→ Collapse (& Explosion ) → IMBH → SMBH ?

→ **Pop III GRBs ?**

$M \sim 140 - 300 M_\odot$:

→ **Pair Instability SNe** → Complete Disruption

$M \sim 8 - 140 M_\odot$:

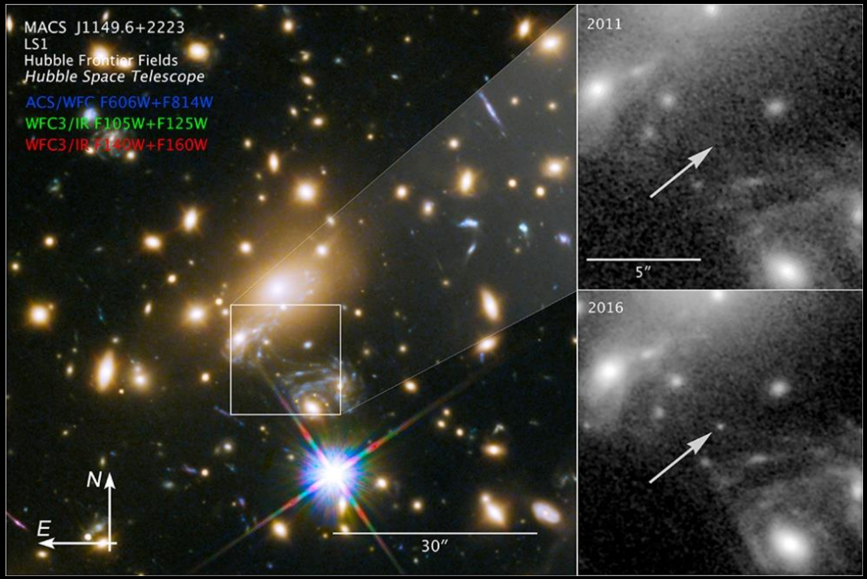
→ Core Collapse → **Pop III GRBs, Hypernovae**

→ **SNe II**

Heger & Woosley 2002, Joggert+11, Joggert+12, Yoon+12, Whalen+13, Whalen+14, Smidt+14, Chen+14, Hirano+15, Chen+16, Hartwig+17

# The First Stars

Image: NASA



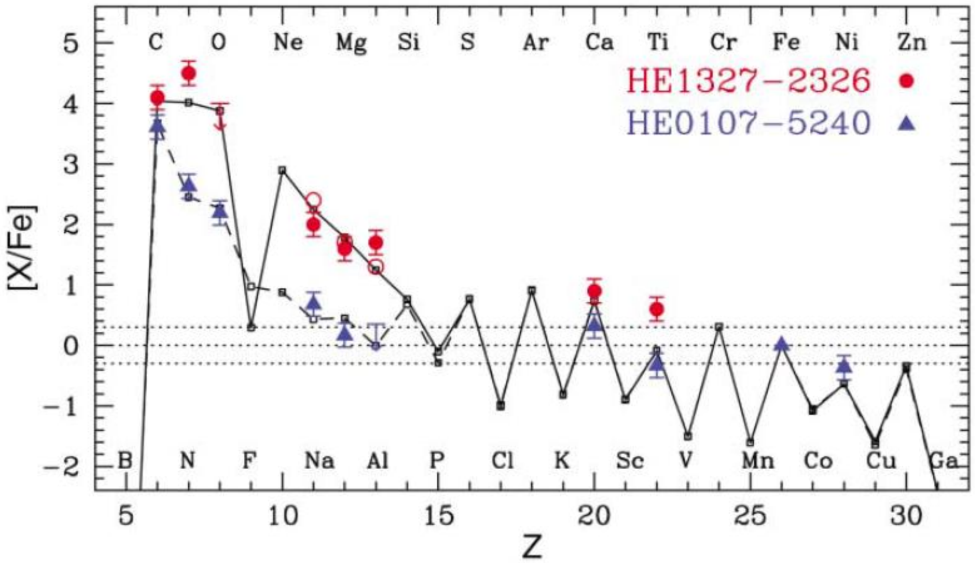

- Direct detection of Pop III stars not possible now or even with 30 – 40 m class telescopes

- MACS J1149 Lensed Star 1, also known as Icarus (Kelly+2018), z=1.49, μ > 2000

- Need a magnification μ > 300 (Rydberg et al. 2013)

# The First Stars. Stellar Archeology.

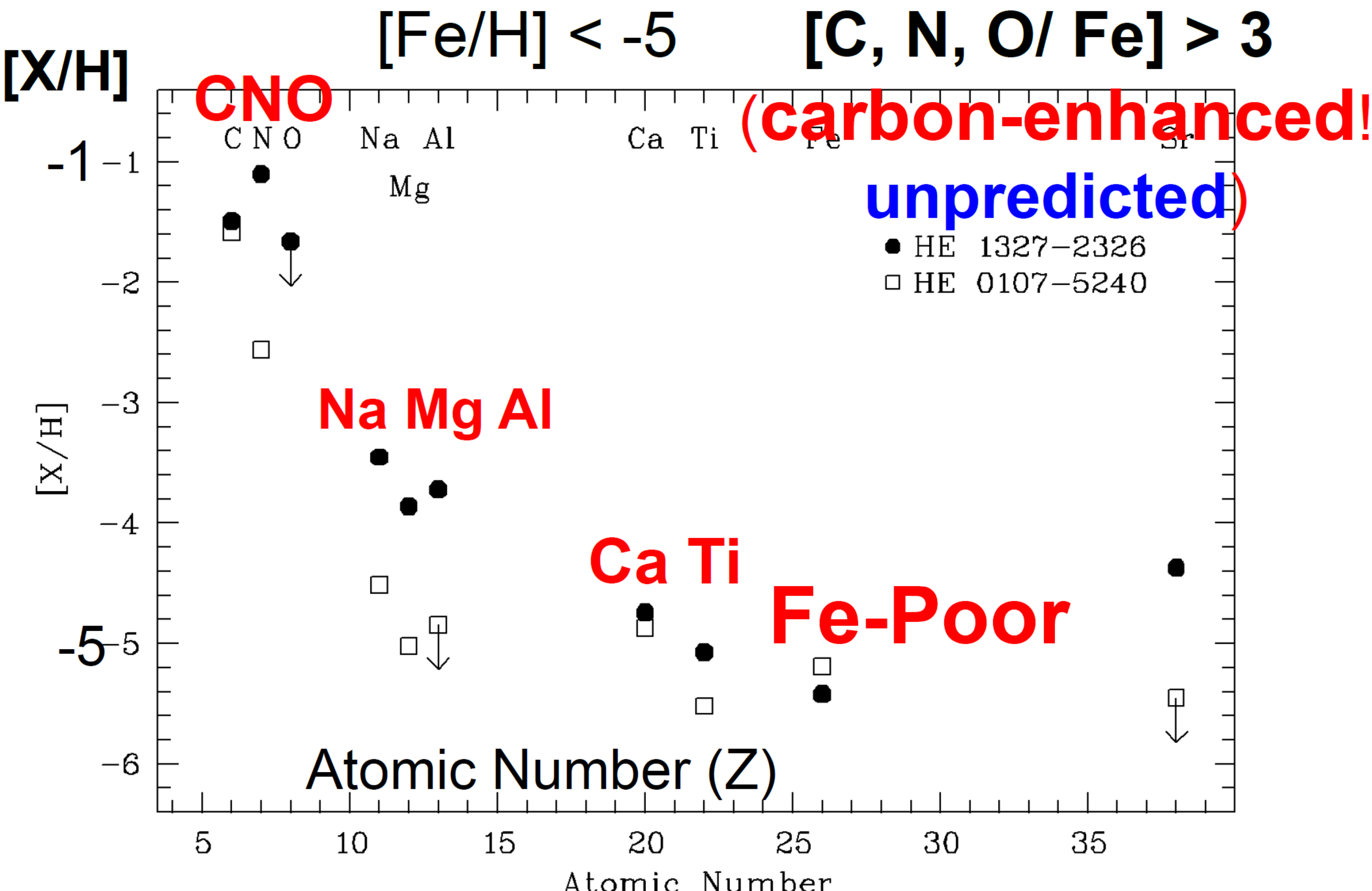
- **Elemental abundance ratio in EMP stars (Iwamoto et al., 2003, 2005)**




- 2nd generation (low mass) extremely metal-poor (EMP, [Fe/H]<-3) stars: abundance pattern and distribution (mixing)
- Abundance pattern of EMP stars provides constraints on mass, explosion energy of first supernovae
- Light curves and spectra of first supernovae (including shock breakout)
- Observational signature of first supernovae (M, E, abundance) expected from 1st stars
- Rough IMF and constraints on star formation rate

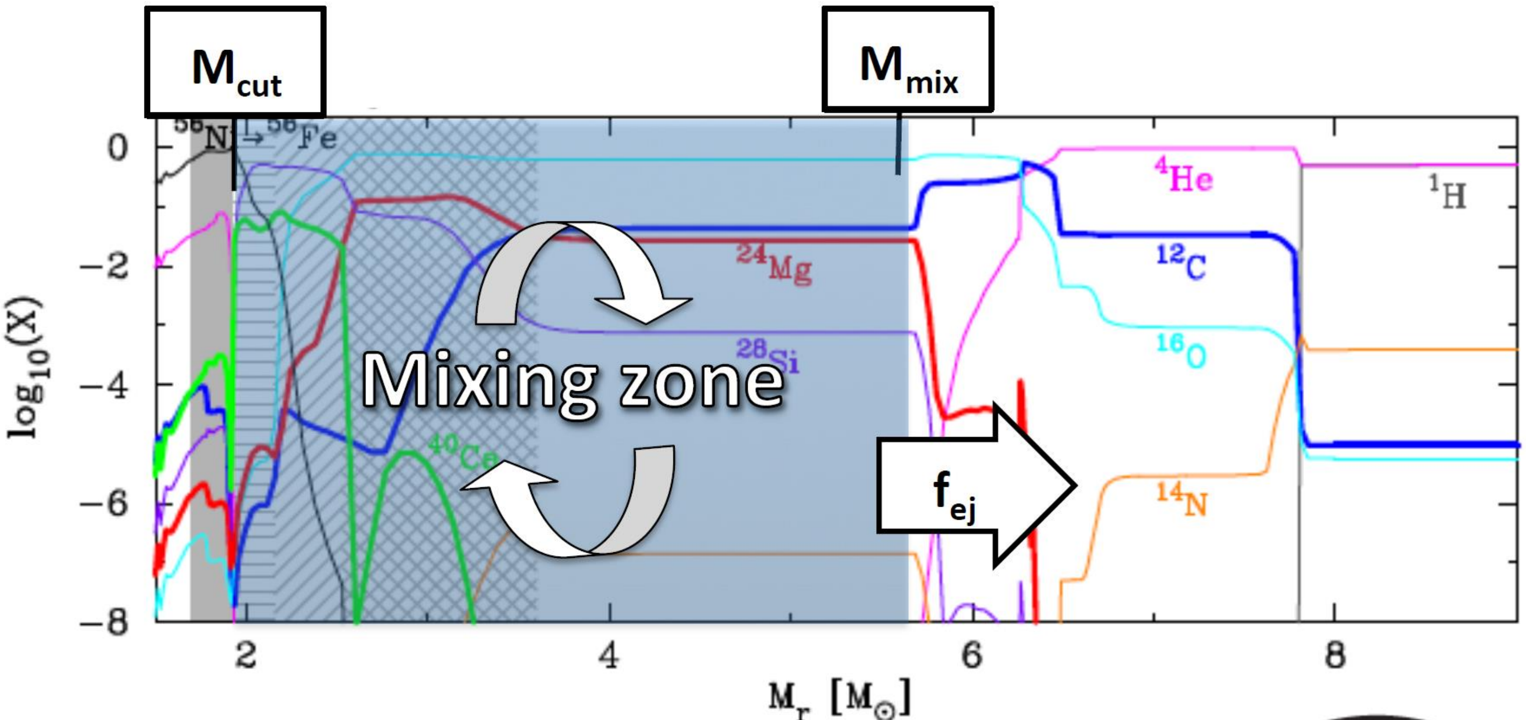
**Understanding of the earliest star formation and the chemical enrichment history of the Universe!**

# Hyper Metal Poor (HMP) stars




Christlieb, Frebel, Aoki, et al.

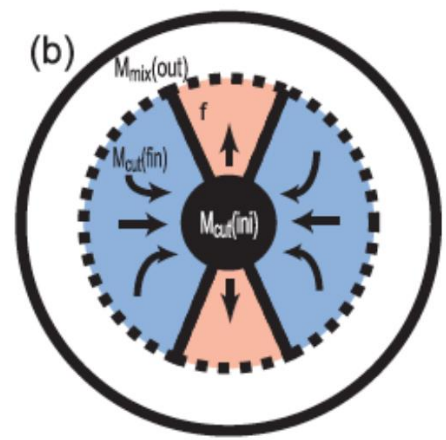
# The mixing-fallback model




- ❑ $M_{cut}$: Inner boundary of the mixing zone
- ❑ $M_{mix}$: Outer boundary of the mixing zone
- ❑ $f_{ej}$: ejected fraction (fraction of mass ejected in the mixing zone)

➡ Mass of a compact remnant (e.g. NS or BH):

$$M_{rem}=M_{cut}+(1-f_{ej})(M_{mix}-M_{cut})$$

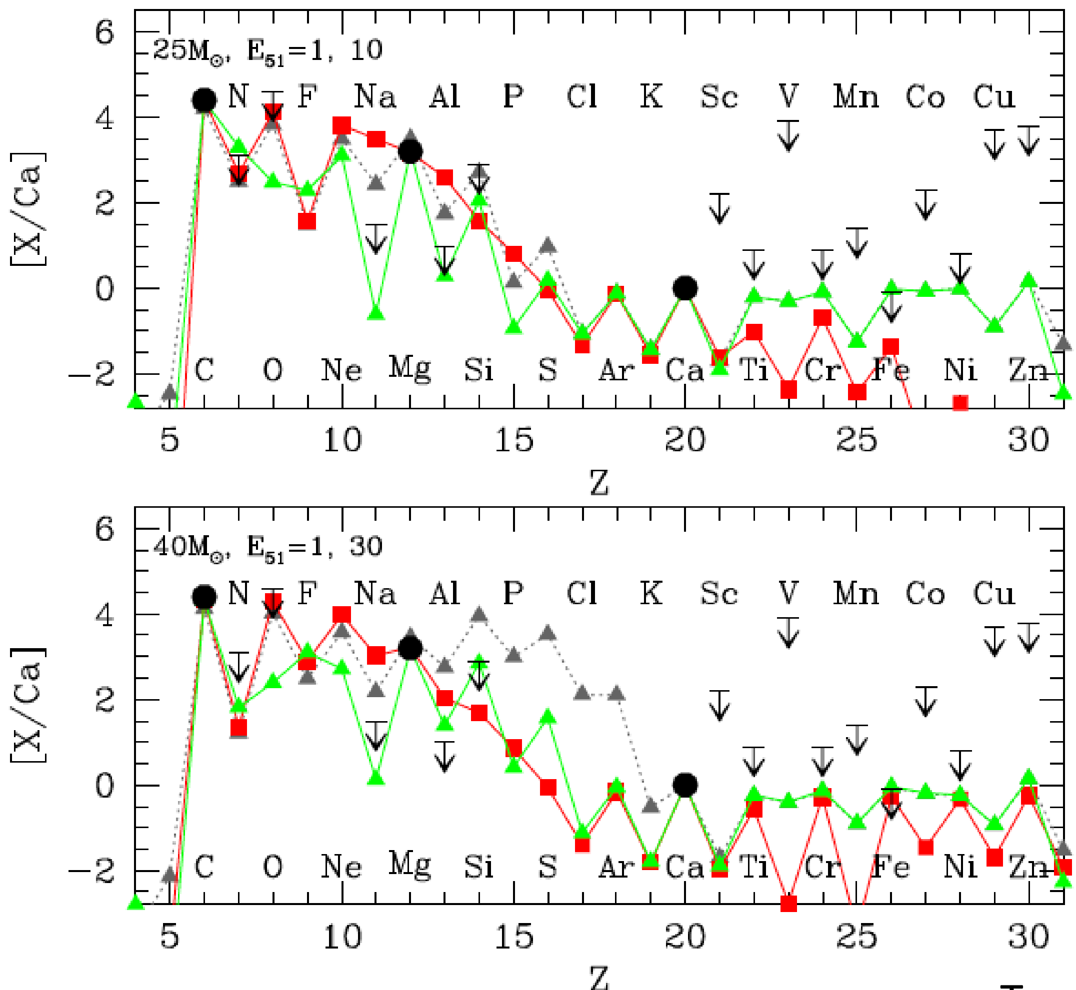



Tominaga et al. 2007

# Nucleosynthesis signatures. SM 0313-6708 vs. Pop III SN yields $M=25M_\odot$ and $40M_\odot$

■: $E_{51}=1$ (supernova)

▲: $E_{51}=10$ (hypernova)

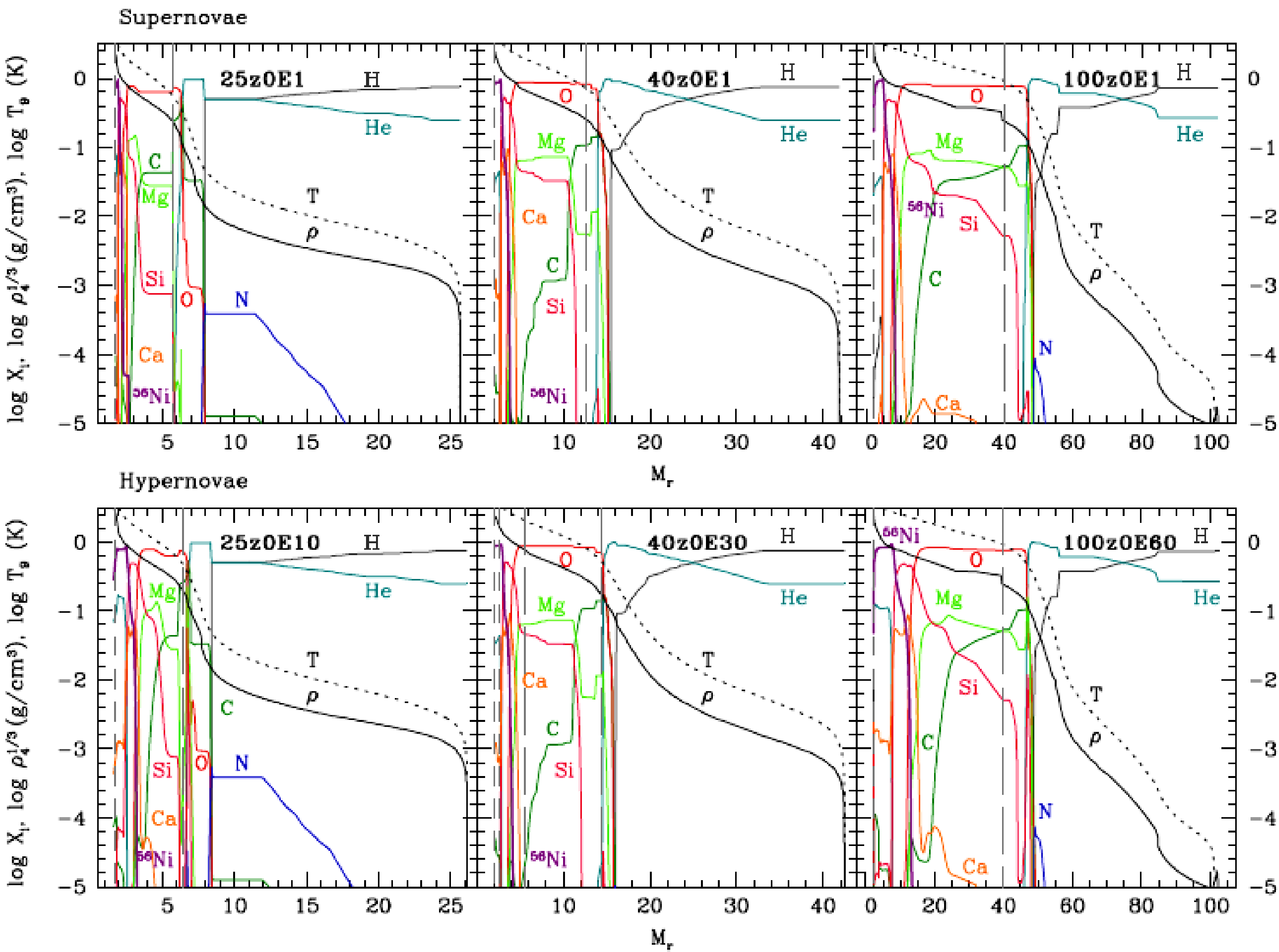



- The majority of the EMP stars are better explained by the Pop III star models with < 40 $M_\odot$
- Jet-like SN explosion or week explosion

$$[\mathrm{Fe/H}] = \log_{10}\left(\frac{N_{\mathrm{Fe}}}{N_{\mathrm{H}}}\right)_{\mathrm{star}} - \log_{10}\left(\frac{N_{\mathrm{Fe}}}{N_{\mathrm{H}}}\right)_{\mathrm{sun}}$$

Tominaga 2007, Ishigaki+ 2015, 2017

# Pop III presupernova composition and structure

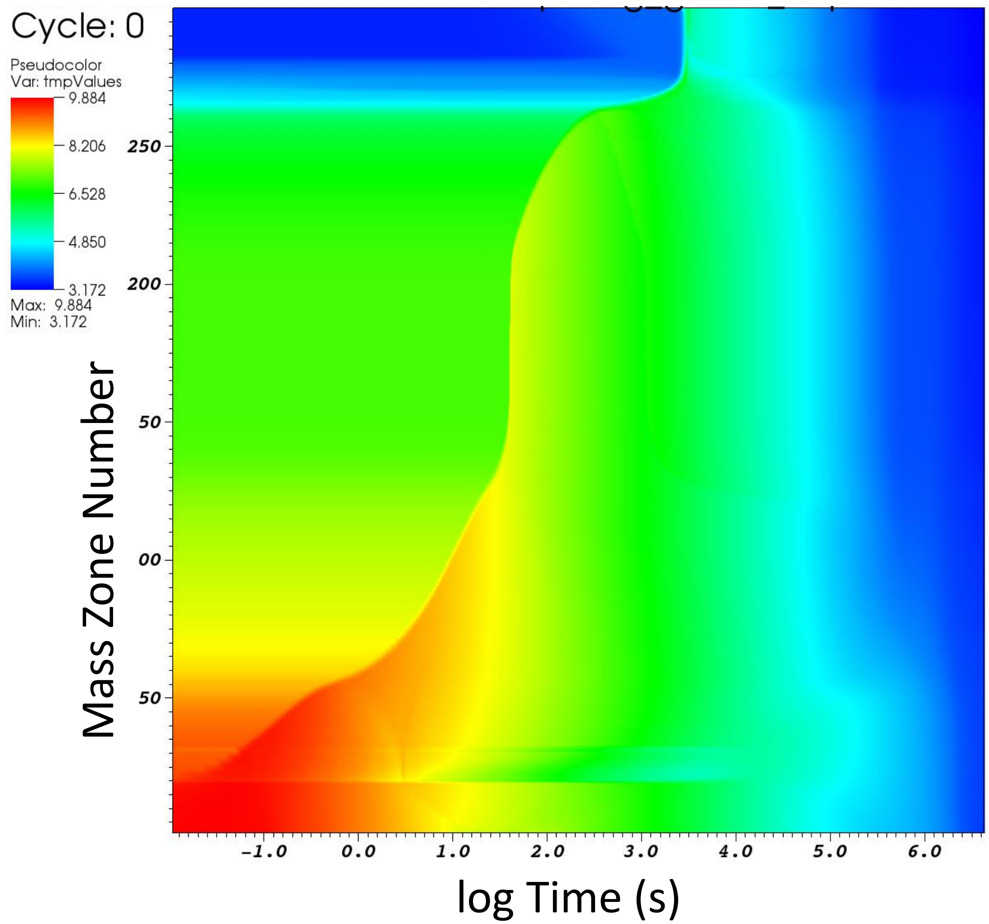


# Numerical code STELLA

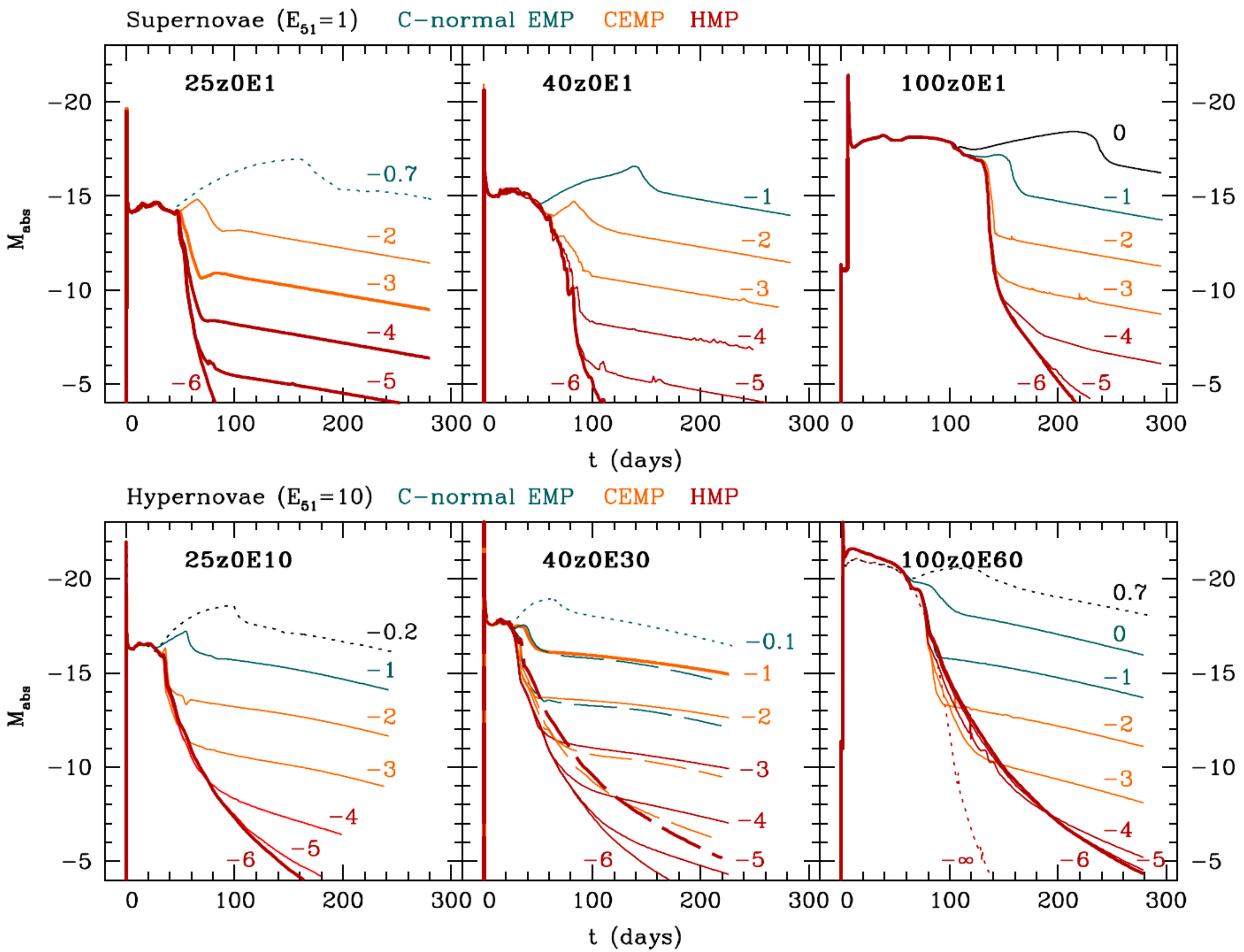
**STELLA (STatic Eddington-factor Low-velocity Limit Approximation) (Blinnikov et al. 1998)**

- 1D Lagrangian Hydro + Radiation Moments Equations (+1D), VEF closure, multigroup (+1D) (100-300 groups, up to 1000), implicit scheme
- Opacity includes photoionization, free-free absorption, lines and electron scattering (Blandford & Payne 1981). Ionization – Saha's approximation
- STELLA was used in modeling of many SN light curves: SN 1987A, SN 1993J and many others (Blinnikov et al. 2006)

Temperature evolution

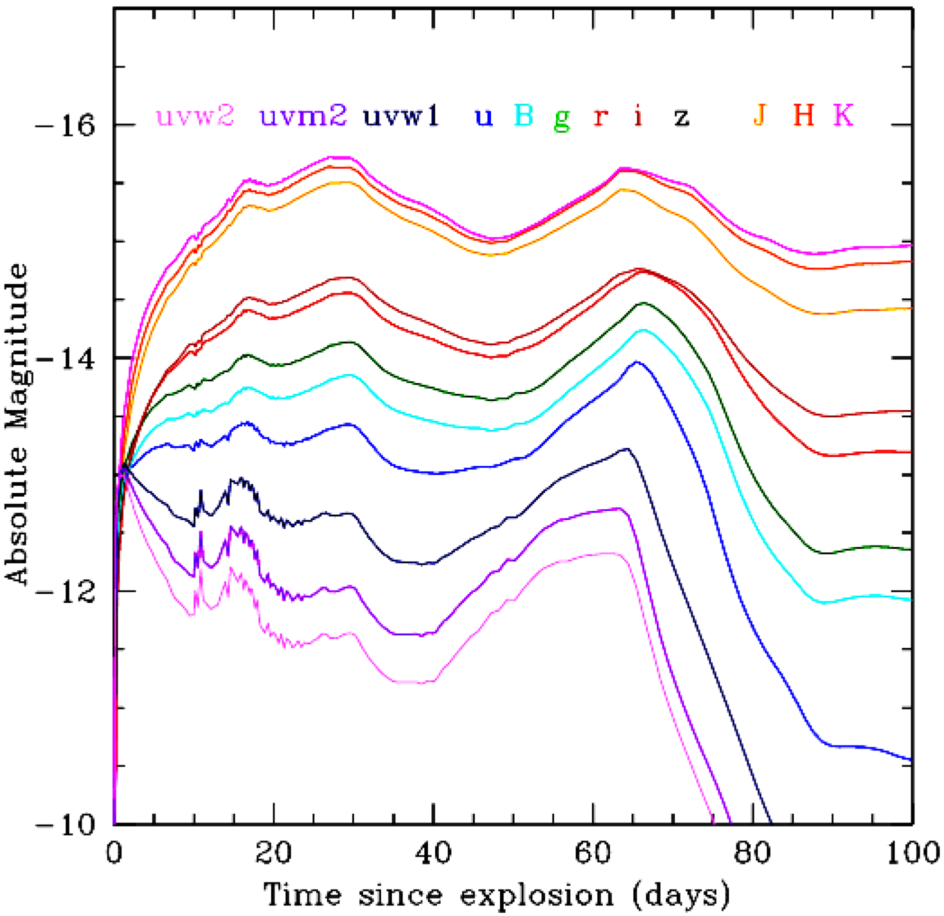


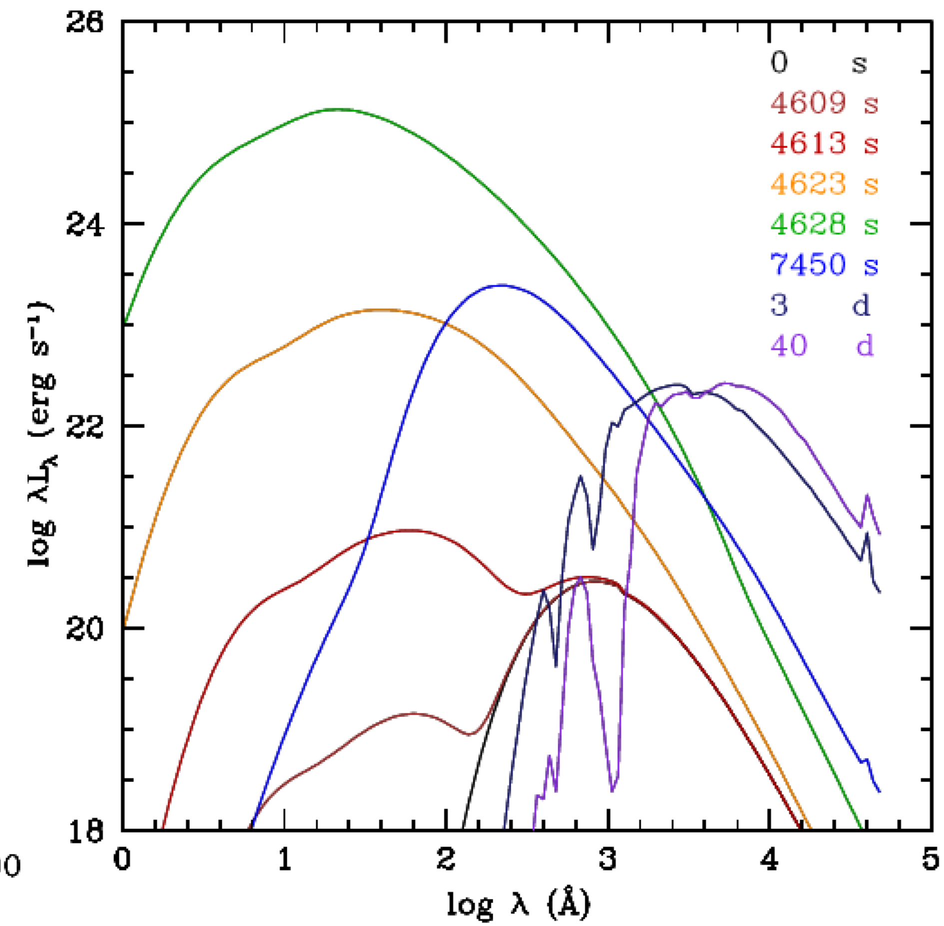
# Bolometric light curves of z0 SNe



# Light curves and spectra M=25$M_\odot$

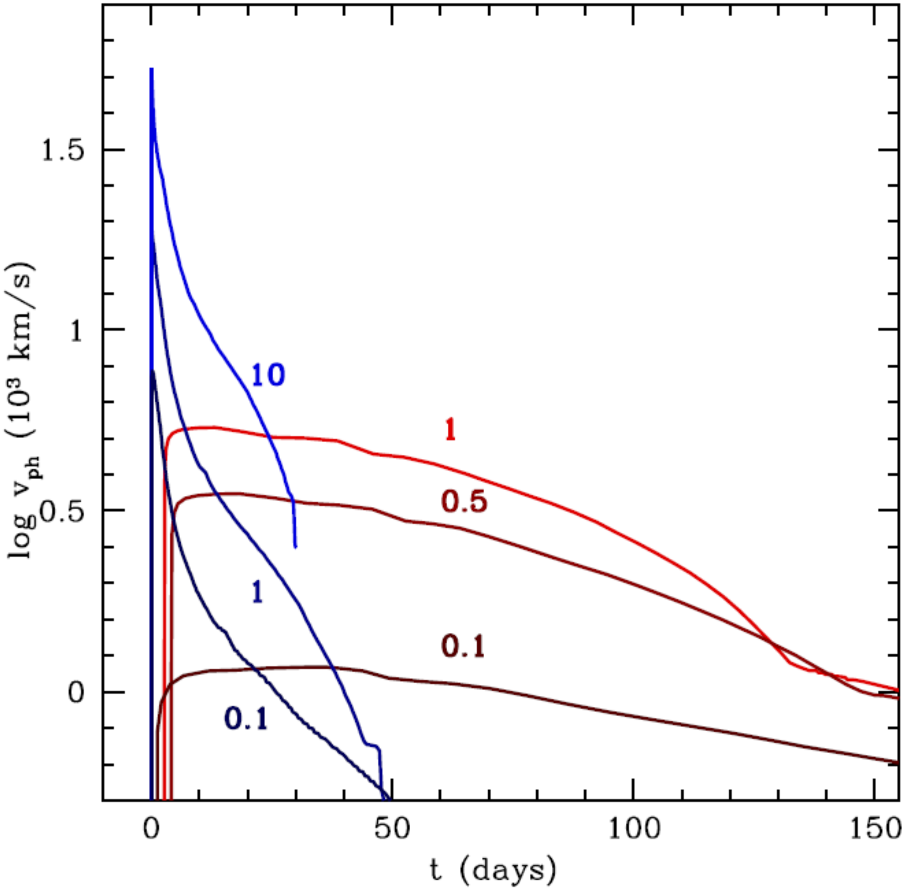
- Light curves: $M(^{56}Ni) = 0.01\ M_\odot$
  Bumps due to zero metallicity
- SED evolution from shock breakout to "plateau" phase



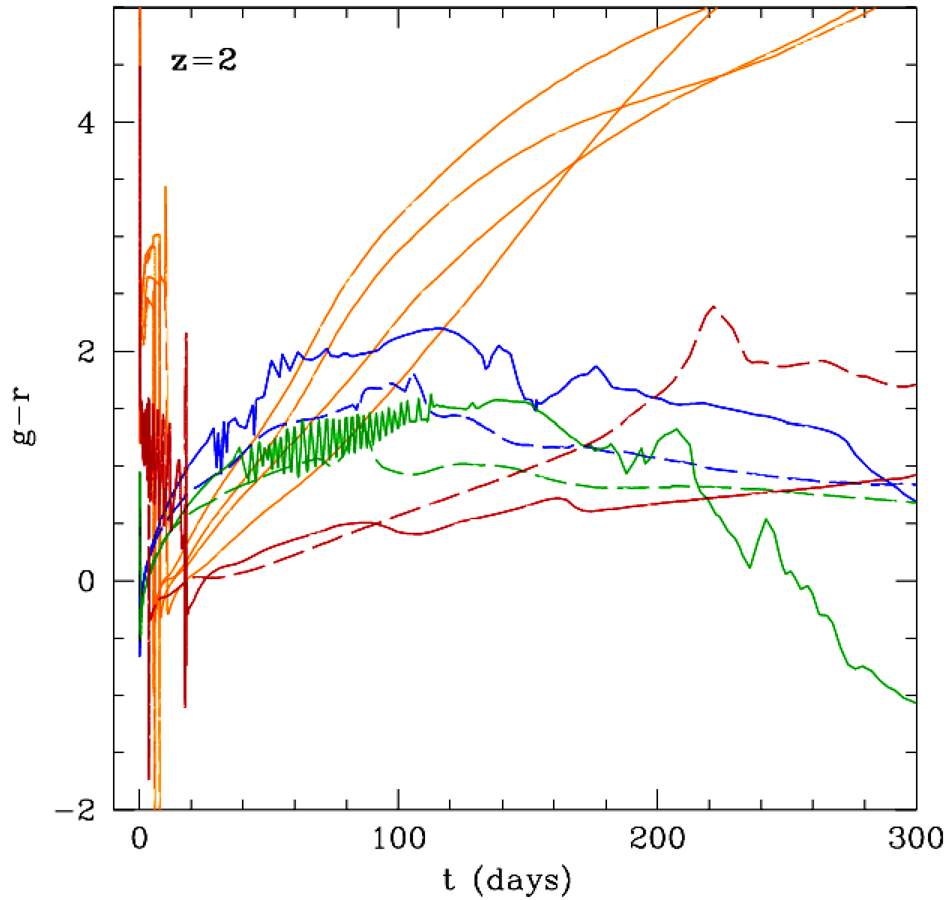



# Zero vs solar metallicity

- Photospheric velocities of zero-metallicity and solar metallicity progenitors, parametrized by the explosion energy $E51$, M=25$M_\odot$

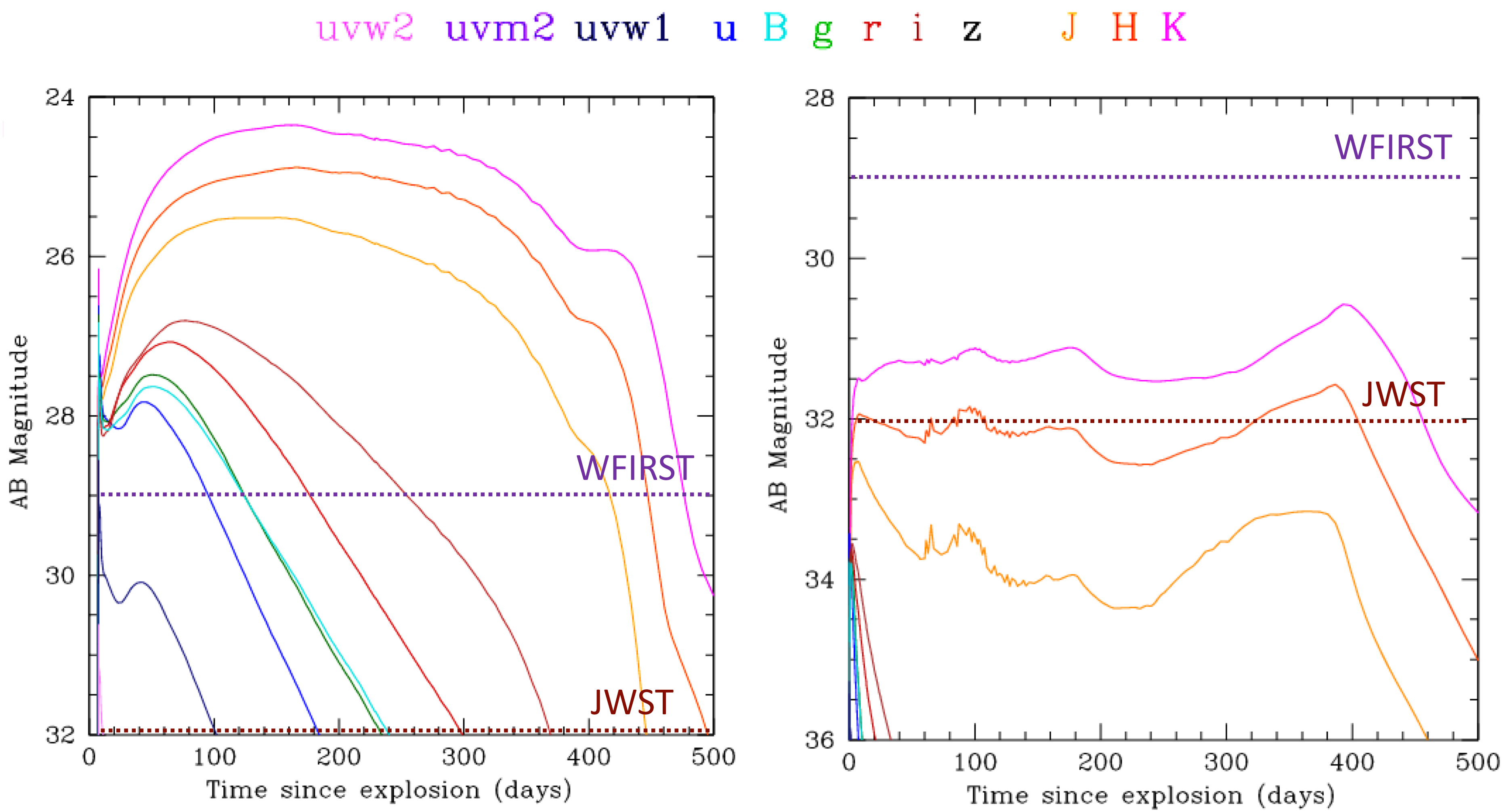



- Color evolution light curves, z=2. Solar metallicity (20-25 $M_\odot$) and zero-metallicity (25 $M_\odot$, 40 $M_\odot$, 100 $M_\odot$) models. SNe -solid lines, HNs - dashed lines.



# Light curves at redshift z=5, 100$M_\odot$ HN vs 25$M_\odot$ SN

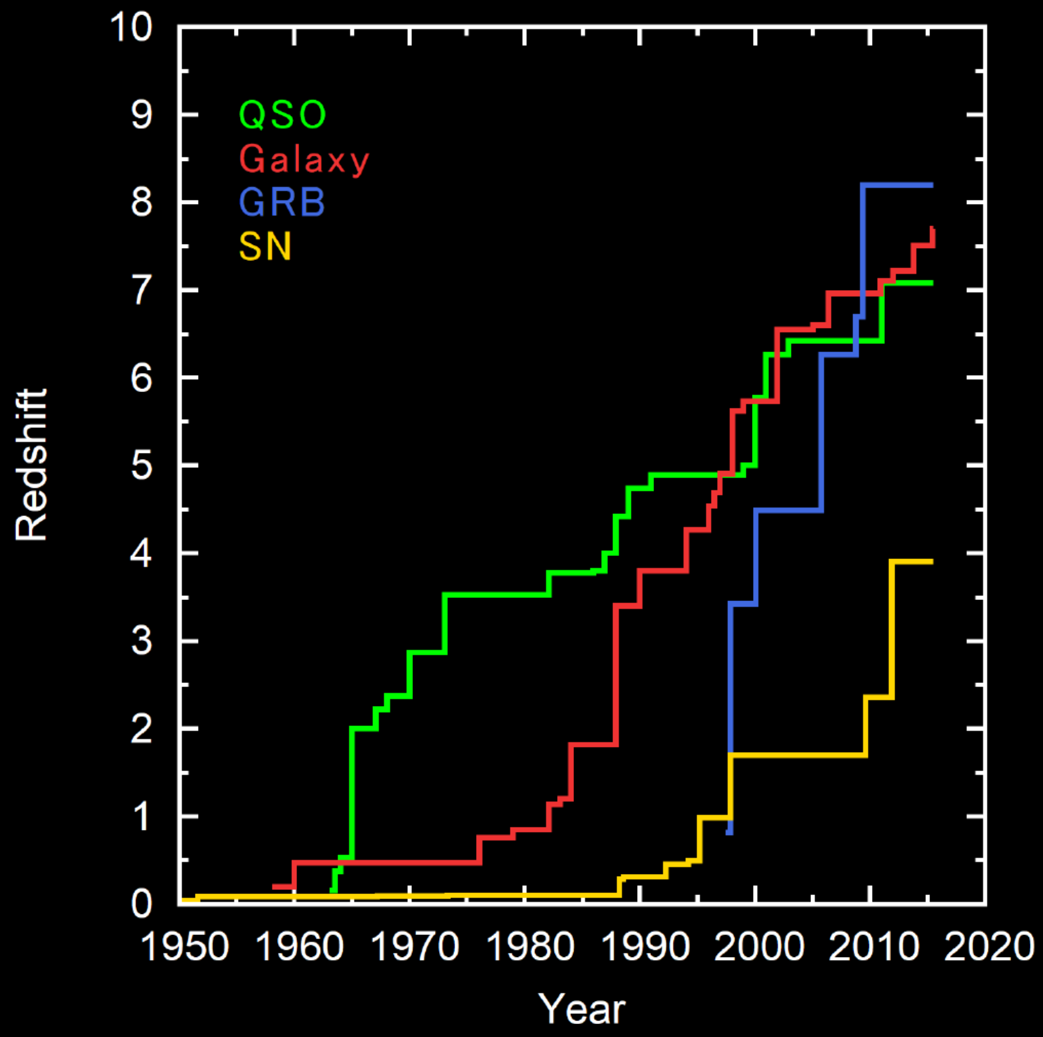
- Light curves: M(56Ni)=0.01 $M_\odot$



# The First Supernovae in the decade (by D. Whalen)

- WFIRST and Euclid will detect Pop II and Pop III SNe out to z ~ 7 (CC SNe) and z ~ 14 -17 (PI SNe) in the coming decade
- JWST and the ELTs will directly detect PI SNe at z > 30 and CC SNe at z = 10 – 15
- Future dedicated surveys of cluster lenses similar in scope to CLASH and FF by JWST and the ELTs could push CC SN detections out to z ~ 18 because their filters will go down to longer wavelengths (3.5 – 4.5 μm)
- In the next 10 – 15 years, SN detections will probe the properties of stars out to z ~ 18, cosmic SFRs and the nature of dark matter (Mattis et al 2016)

# Timeline of redshift records




High-Redshift SNe

- High Redshift SNe z = 3.9 (Cooke+ 2012)
- Superluminous SNe?
- CSM interaction?

- CC SN 1000+0216, z=3.8993
- Type Ia SN UDS10Wil, z=1.914

# Summary

## *Pop III CCSN light curve simulations*

- BSGs are typical presupernovae for Pop III core-collapse SNe with $M_{MS} \lesssim 40$–60 $M_{\odot}$: shorter, bluer, and fainter than ordinary SNe.

  Shock breakout: shorter duration (100s) and soft X-ray spectrum (0.1–0.3 keV) of lower luminosity compared to RSG progenitors.
- The plateau phase is common to both BSG and RSG, but can be bumpy.

  The flat color evolution curve B - V during the plateau phase can be used as an indicator of Pop III and low-metallicity SNe.

## *Detectability*

- The direct detection of Pop III core-collapse SNe is hardly possible at high redshift (Whalen et al. 2013), but Pop III HNe and PPISNe will be visible to the James Webb Space Telescope (JWST) at $z \sim 10$–15 (Smidt et al. 2014). HSC/Subaru, LSST can detect Pop III SNe in metal-free gas pockets($z \sim 2$).
- The results of our simulations are suitable for identification of low-metallicity supernovae in the nearby universe in galaxies with $Z \sim 10^{-5}$–$10^{-4}$.
- Both searches of local faint SNe and very luminous SNe at high z should be performed.


Thank you!