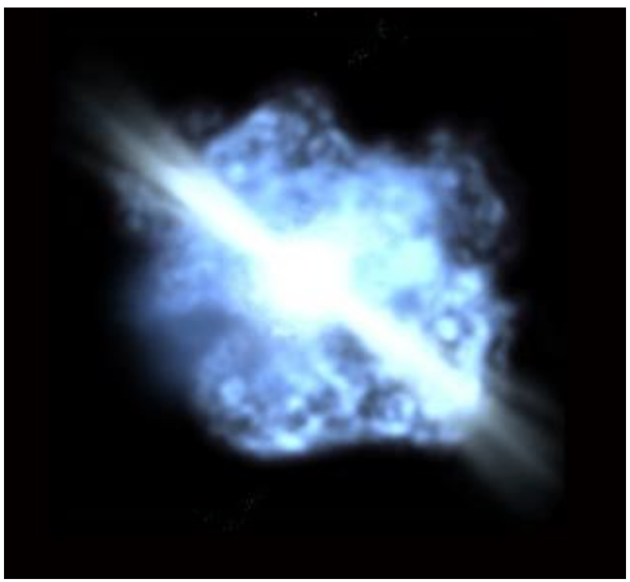
THE UNIVERSITY OF TOKYO

KAVLI IPMU INSTITUTE FOR THE PHYSICS AND MATHEMATICS OF THE UNIVERSE

The first supernovae in the early Universe: radiation hydrodynamics simulations

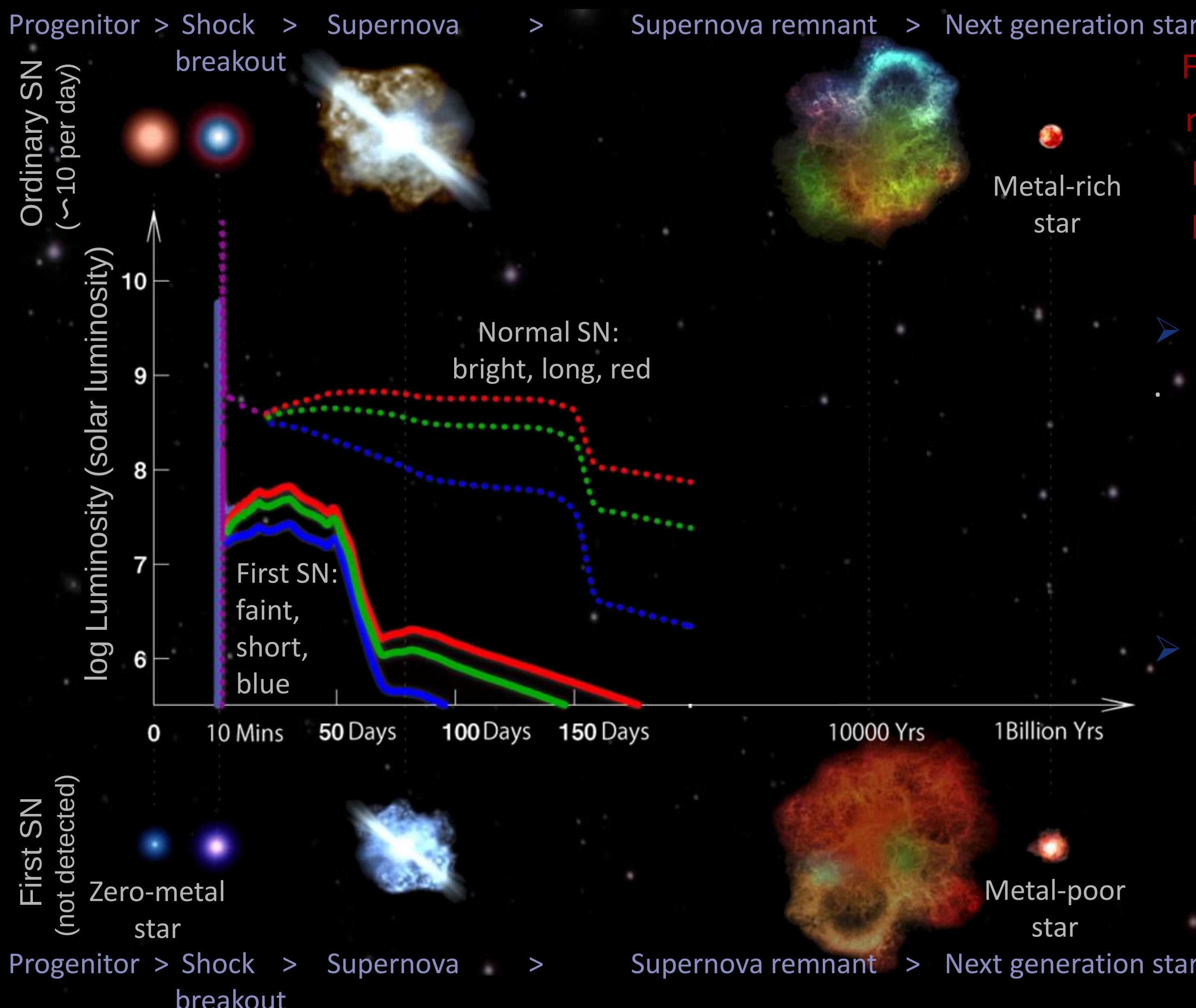


Alexey Tolstov (Kavli IPMU)

Ken'ichi Nomoto (Kavli IPMU)
Miho Ishigaki (Kavli IPMU)
Nozomu Tominaga (Konan Univ)
Sergey Blinnikov (ITEP, Kavli IPMU)
Tomoharu Suzuki (Chubu Univ)

DVU 2017, Playa del Carmen, Mexico, 11-15 Dec 2017

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).

KAVLI IPMU INSTITUTE FOR THE PHYSICS AND MATHEMATICS OF THE UNIVERSE

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**

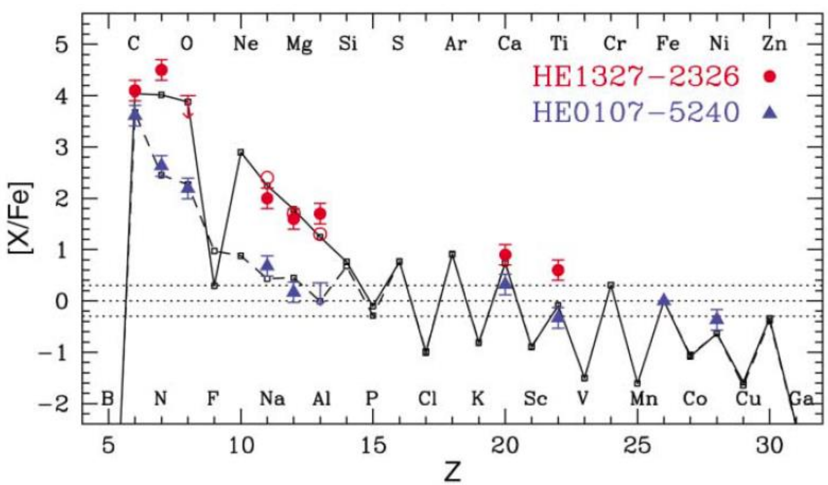
Heger & Woosley 2002, Joggert+11, Joggert+12, Yoon+12, Whalen+13, Whalen+14, Smidt+14, Chen+14, Hirano+15, Chen+16, Hartwig+17

First stars

- **400 million years after Big Bang**
  Direct insight into the age of galaxy formation

Image credit: NASA/WMAP

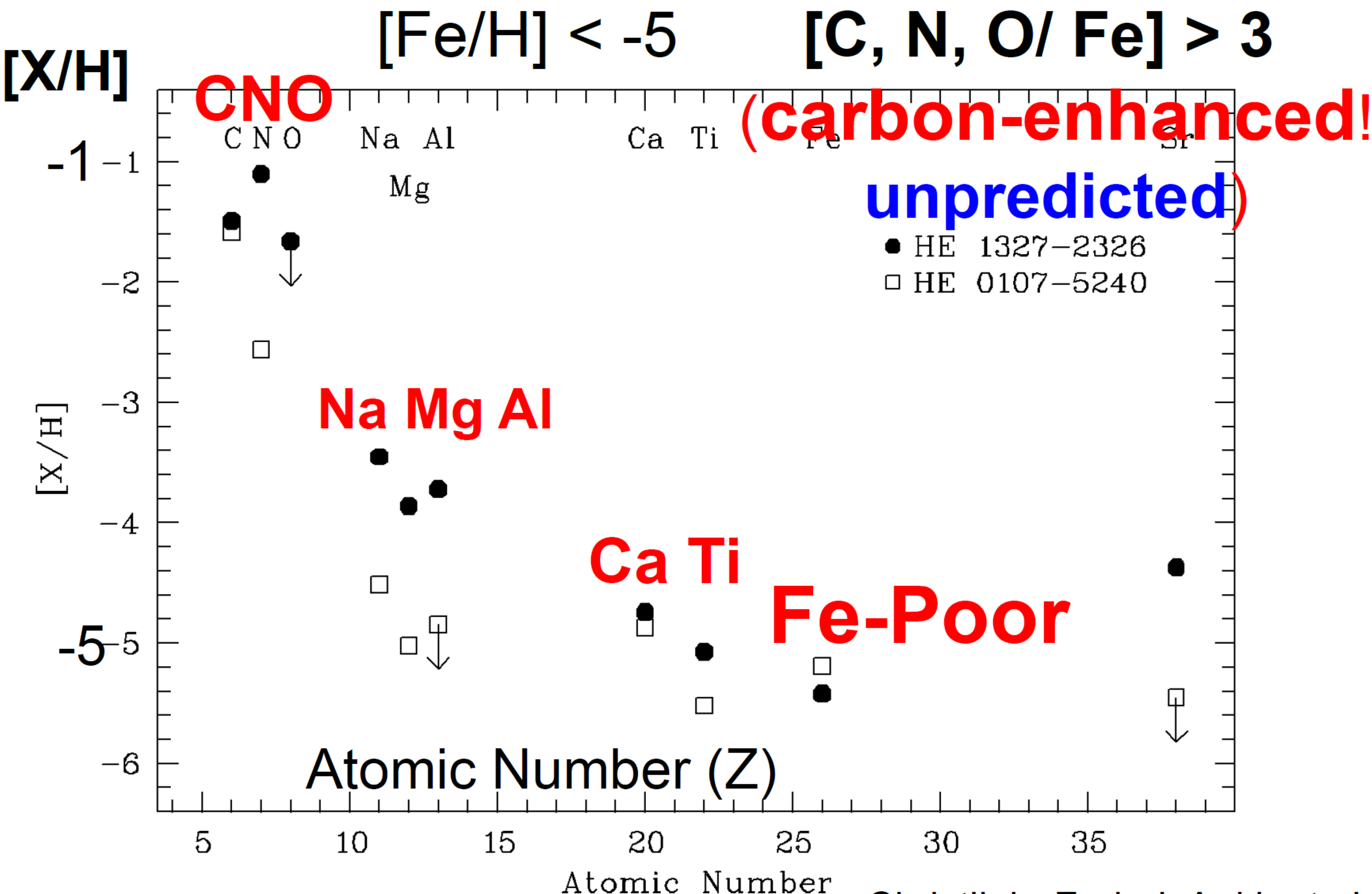
- **Elemental abundance ratio in EMP stars (Iwamoto et al., 2003, 2005)**



- 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

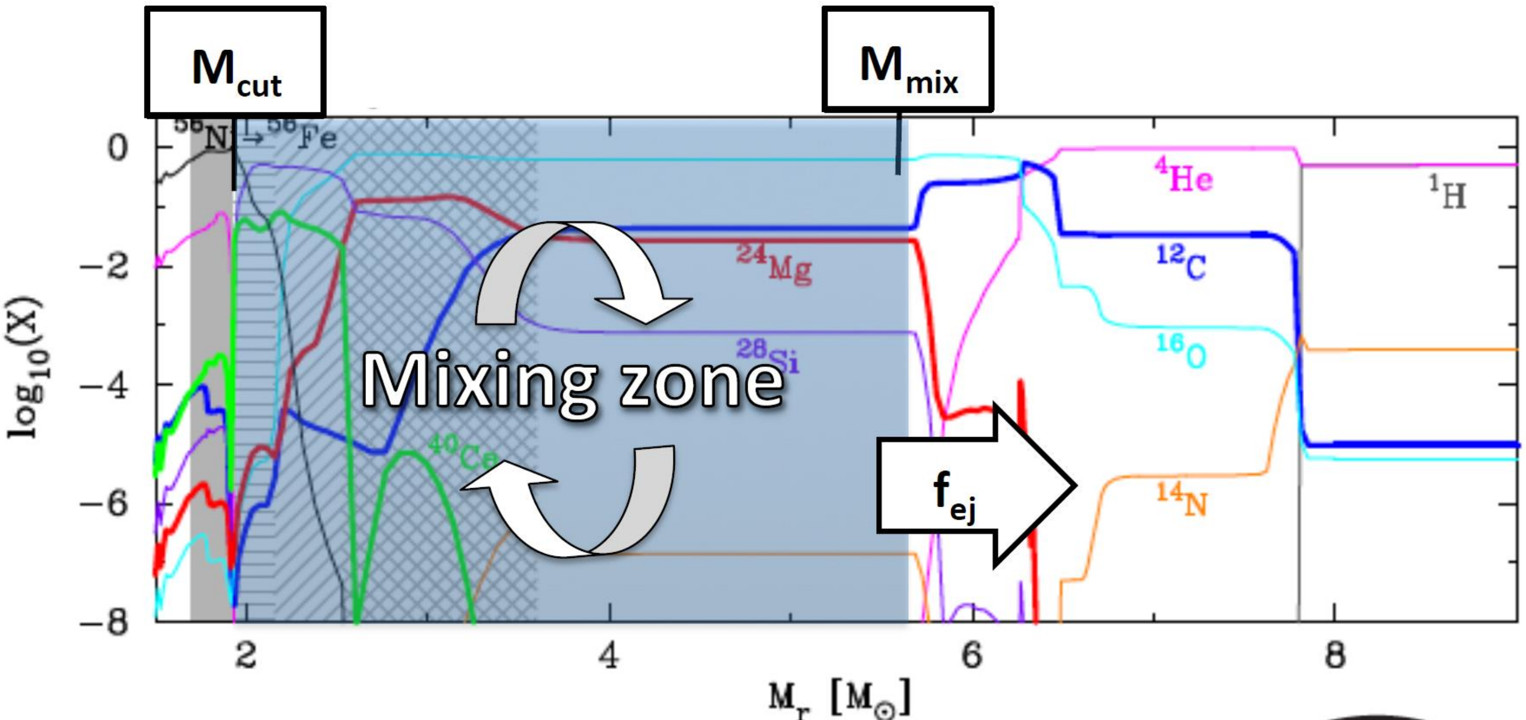
Understanding of the earliest star formation and the chemical enrichment history of the Universe!

Hyper Metal Poor (HMP) stars



Christlieb, Frebel, Aoki, et al.

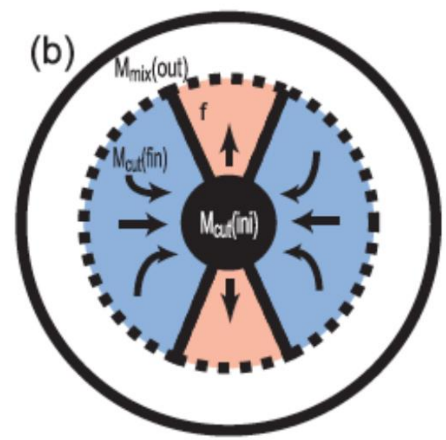
The mixing-fallback model



- ❑ 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):

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

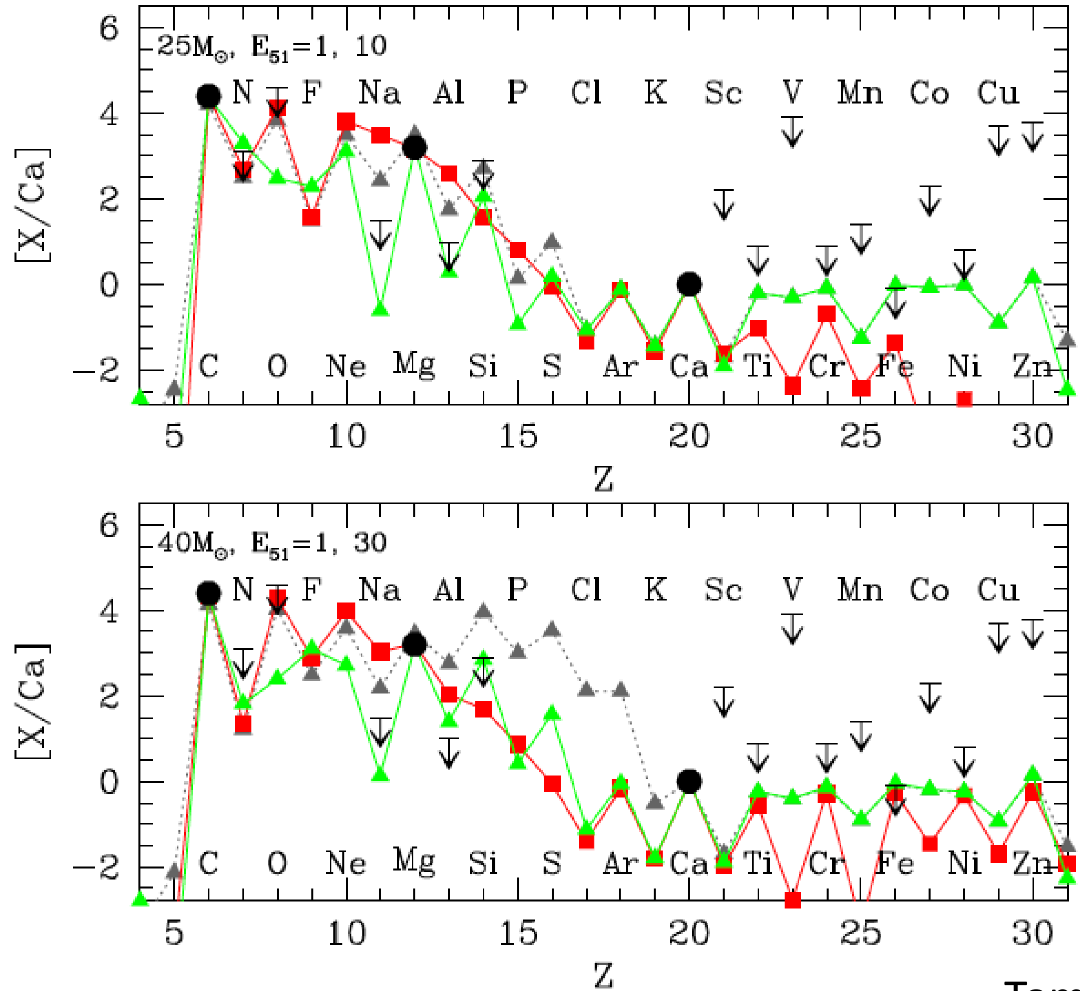


Tominaga et al. 2007

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

■: E_{51}=1 (supernova)

▲: E_{51}= 10 (hypernova)

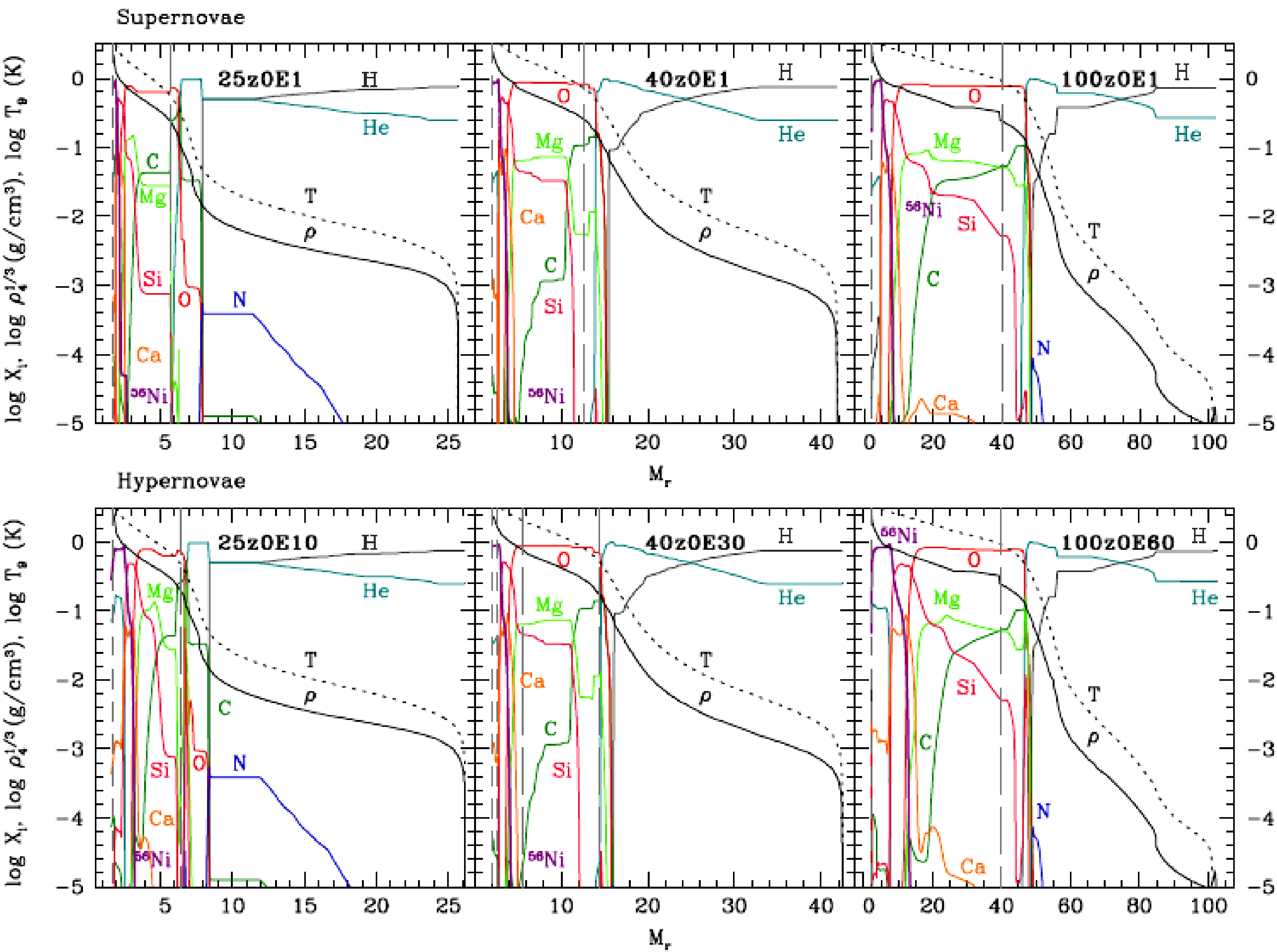


- The majority of the EMP stars are better explained by the Pop III star models with < 40 M$_\odot$
- Jet-like SN explosion or week explosion

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

Tominaga 2007, Ishigaki+ 2015, 2017

Pop III presupernova composition and structure

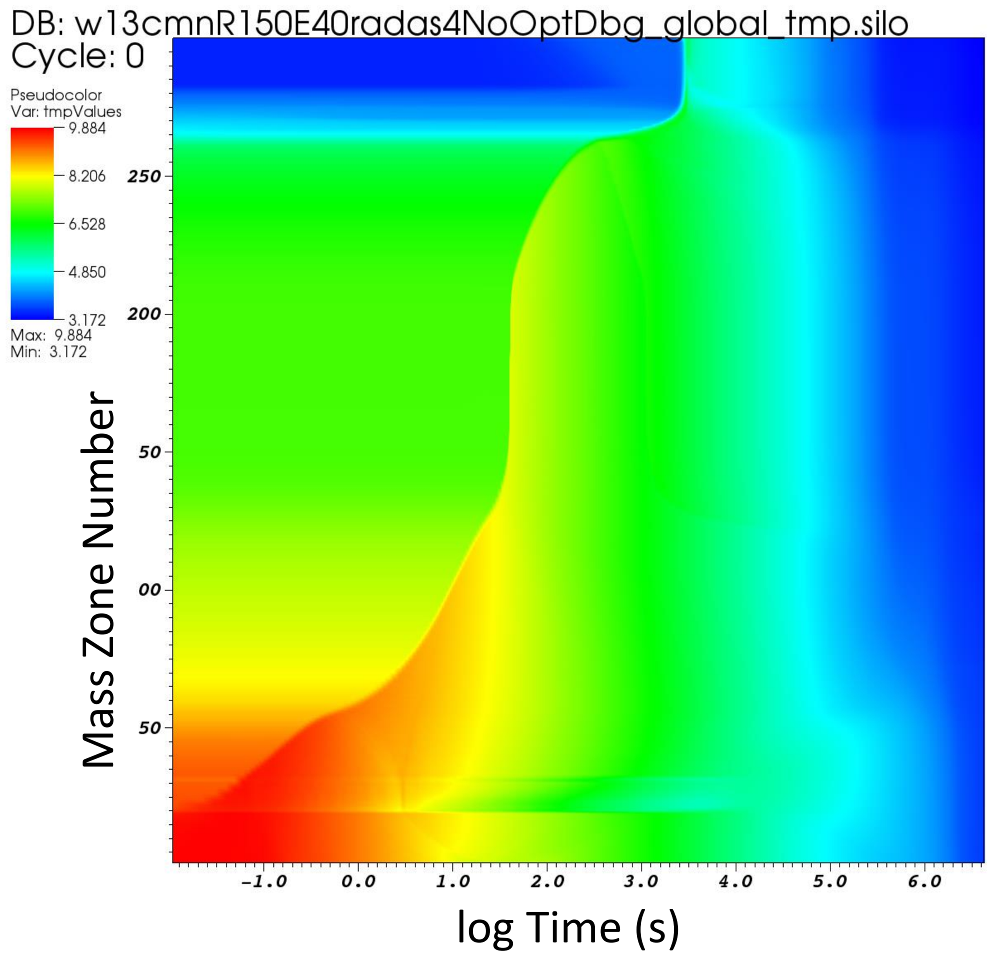


Numerical code STELLA

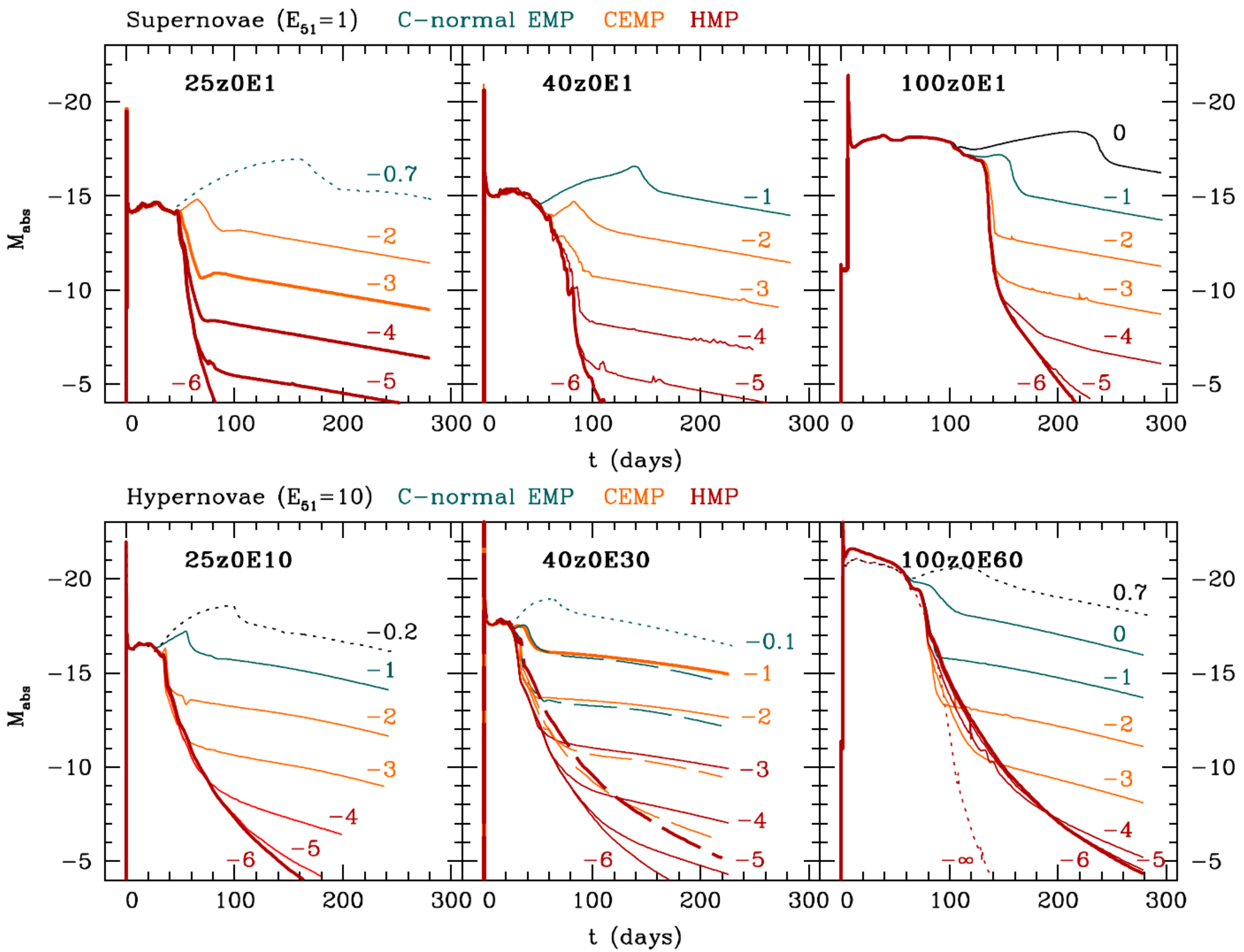
STELLA (STatic Eddington-factor Low-velocity Limit Approximation) (Blinnikov et al. 1998)

- 1D Lagrangian Hydro + Radiation Moments Equations (2D), VEF closure, multigroup (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



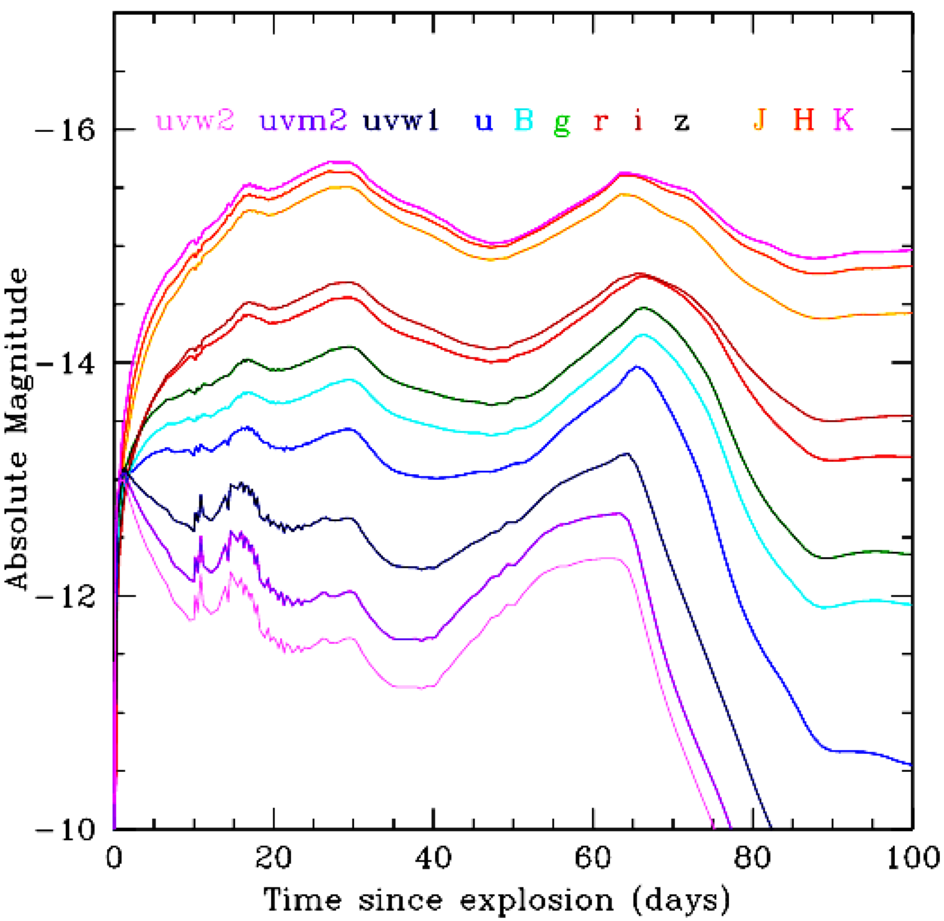
Bolometric light curves of z0 SNe

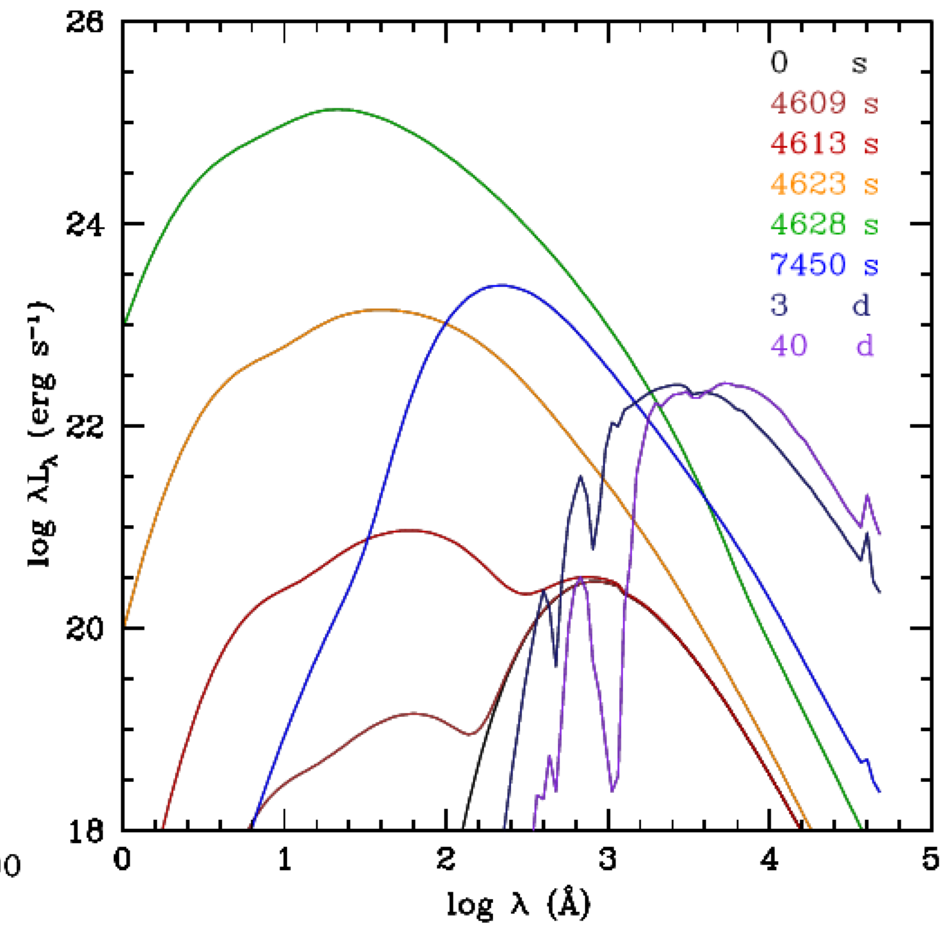


Light curves and spectra M=25$M_\odot$

- Light curves: M(^{56}Ni) = 0.01 $M_\odot$
  Bumps due to zero metallicity

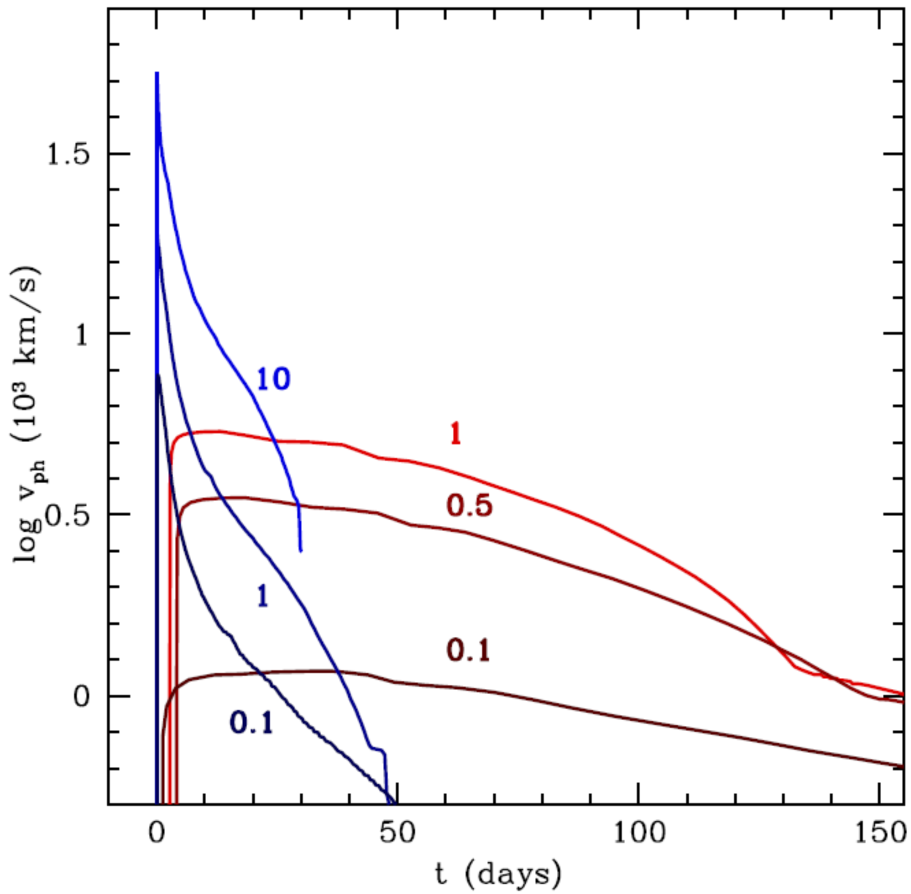
- SED evolution from shock breakout to "plateau" phase



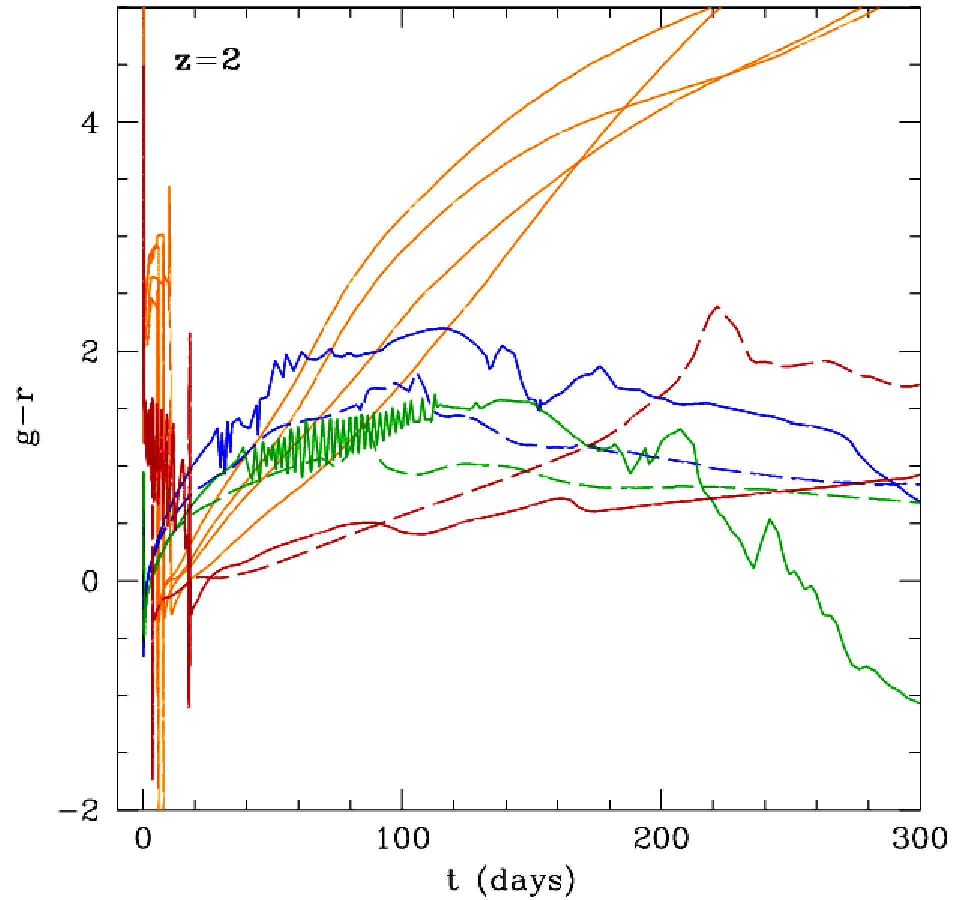


Zero vs solar metallicity

- Photospheric velocities zero-metallicity and solar metallicity progenitors, parametrized by the explosion energy *E*51, M=25M$_\odot$

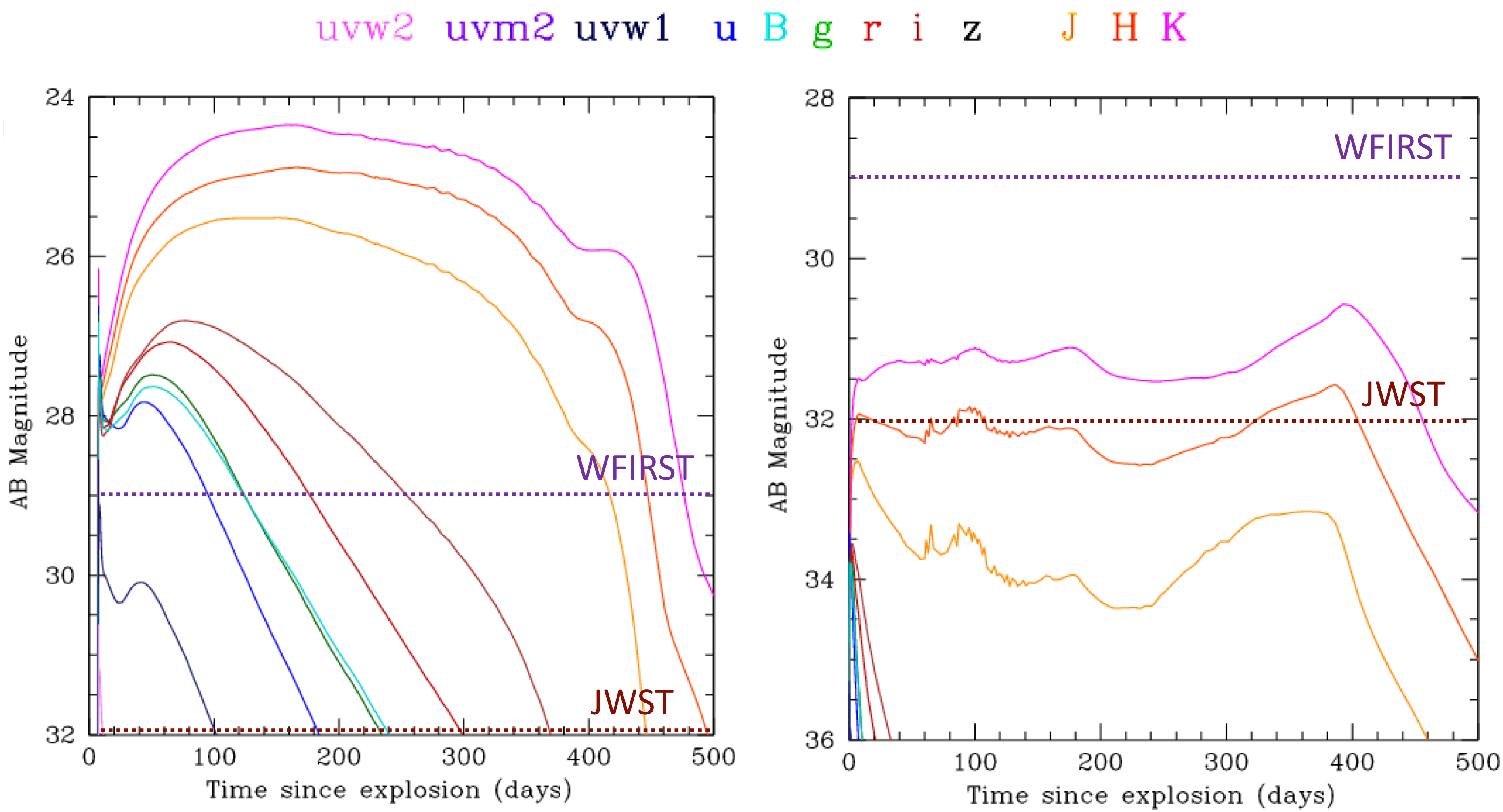


- Color evolution light curves, z=2. Solar metallicity (20-25 M$_\odot$) and zero-metallicity (25 $M_\odot$, 40 $M_\odot$, 100 $M_\odot$) models. SNe -solid lines, HNs - dashed lines.

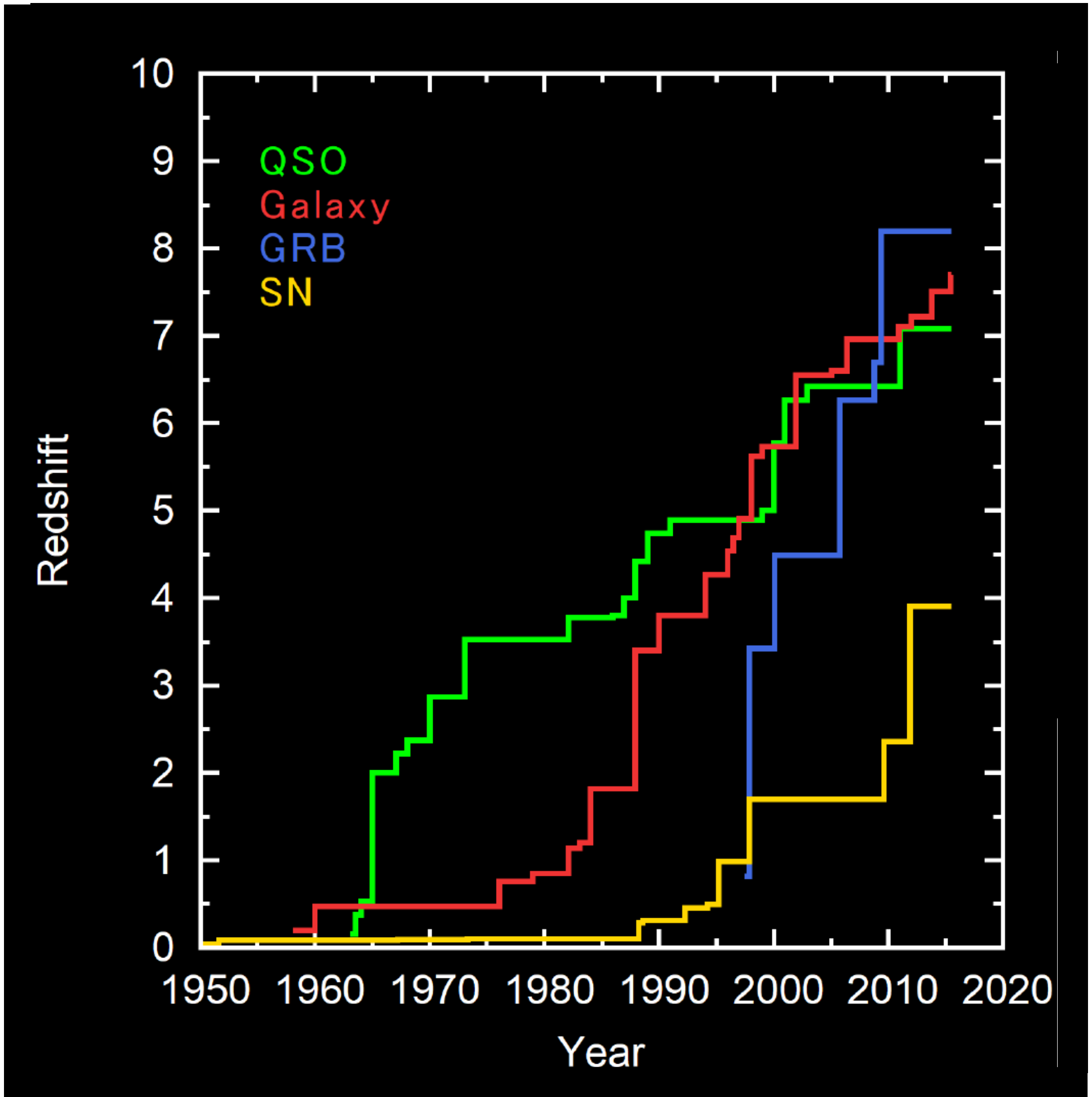


Light curves at redshift z=5, 100$M_\odot$ HN vs 25$M_\odot$ SN

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



Timeline of redshift records



Core collapse supernova	SN 1000+0216	z = 3.8993
Type Ia supernova	SN UDS10Wil	z = 1.914
Type Ia supernova	SN SCP-0401 (Mingus)	z = 1.71

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

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 hypernovae 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.