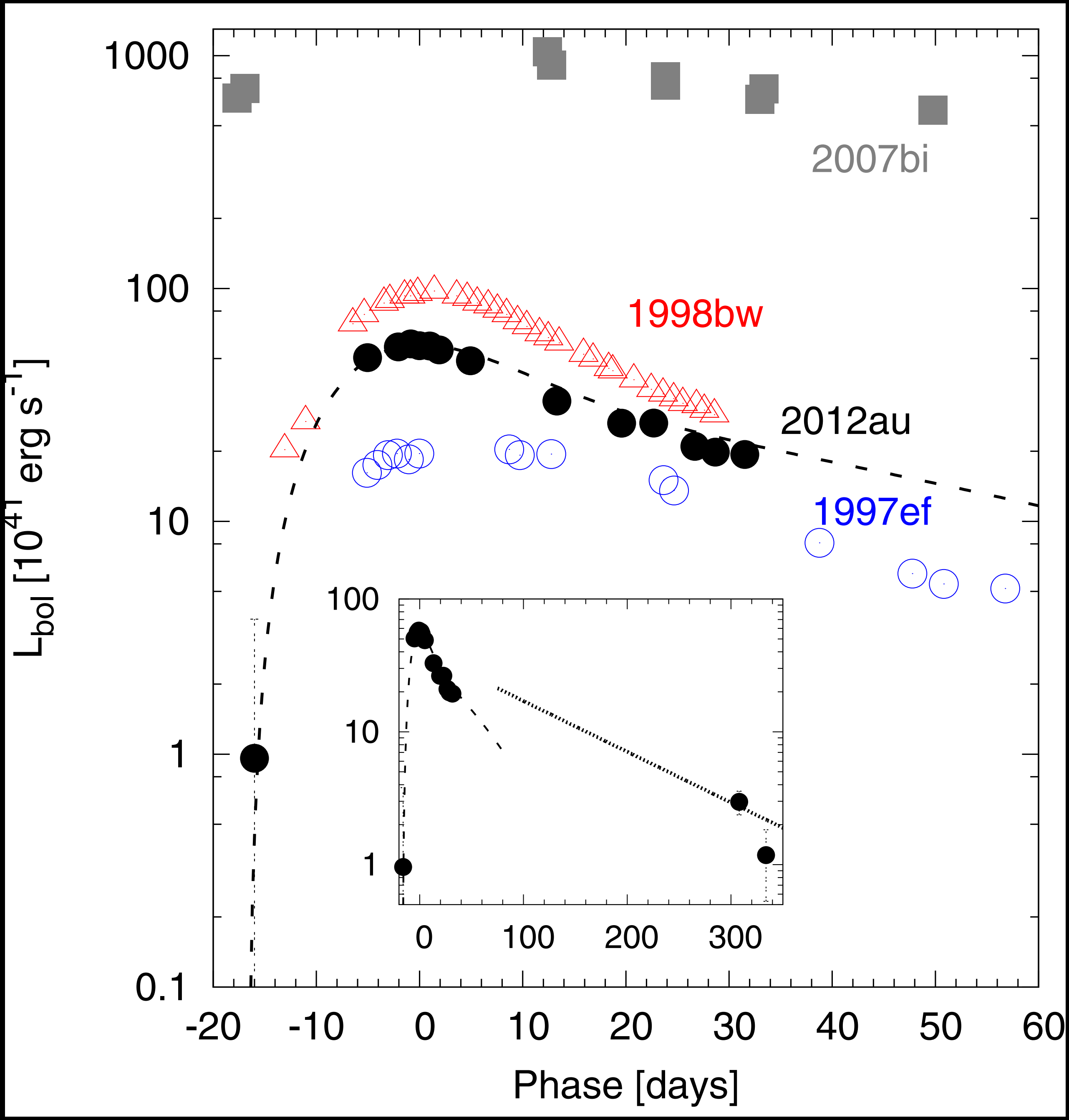
A bright supernova SN 2012au hosting a pulsar

Toshikazu Shigeyama, Miyu Masuyama, and Naoto Kuriyama (RESCEU)

RESCEU 東京大学大学院理学系研究科附属ビッグバン宇宙国際研究センター Research Center for the Early Universe

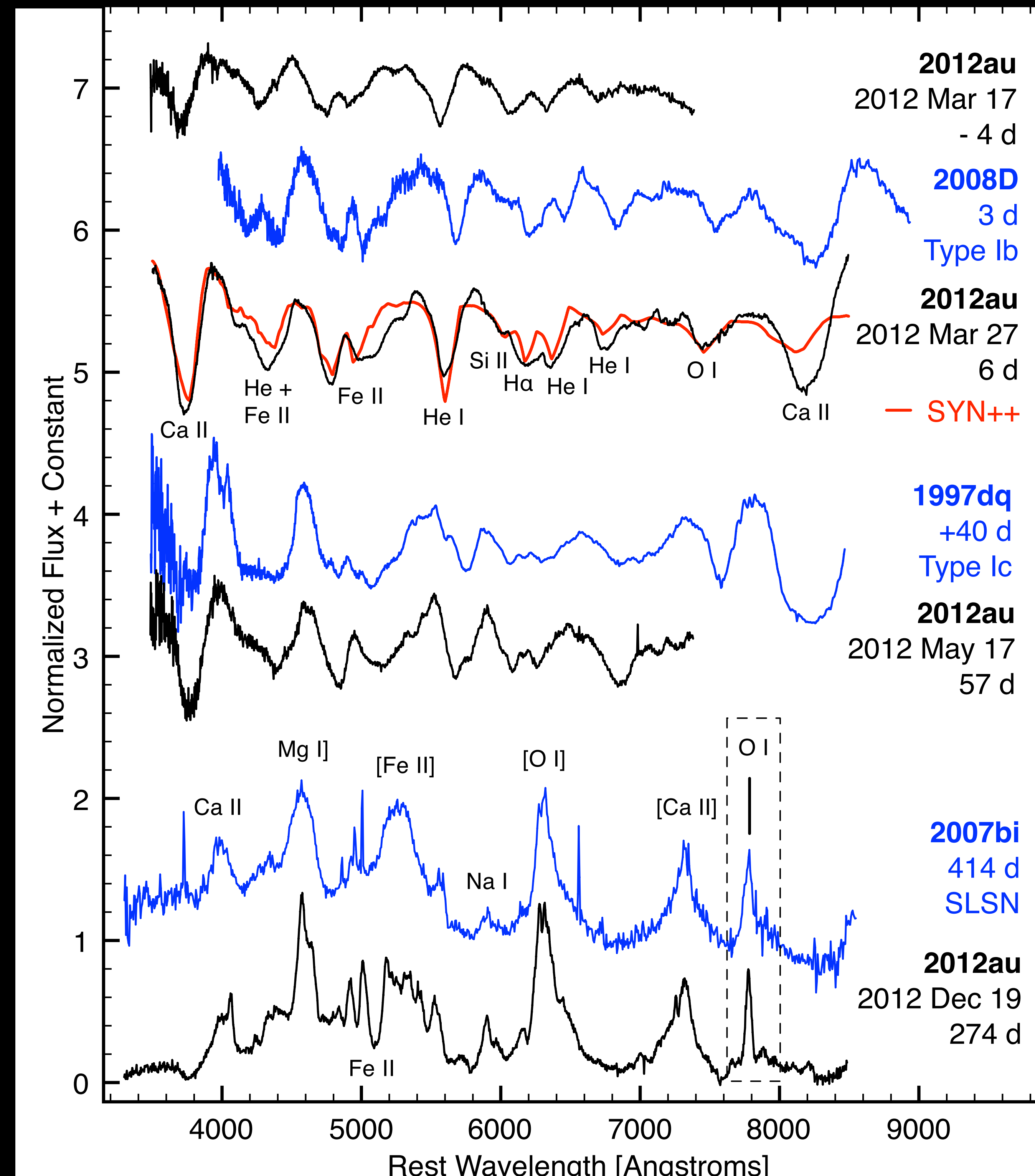
SN 2012au

- Type Ib SN in NGC 4790 (Howerton+ 2012)
  - Distance~23 Mpc
- Light curve and spectra (Takaki+ 2013, Milisavljevic+ 2013)
  - Lpeak~6x10^42 erg/s
    - M_{56Ni} ~ 0.3 M◉
  - Mej ~ 4 M◉
    - Minit~20 M◉
    - Eej~10^52 erg



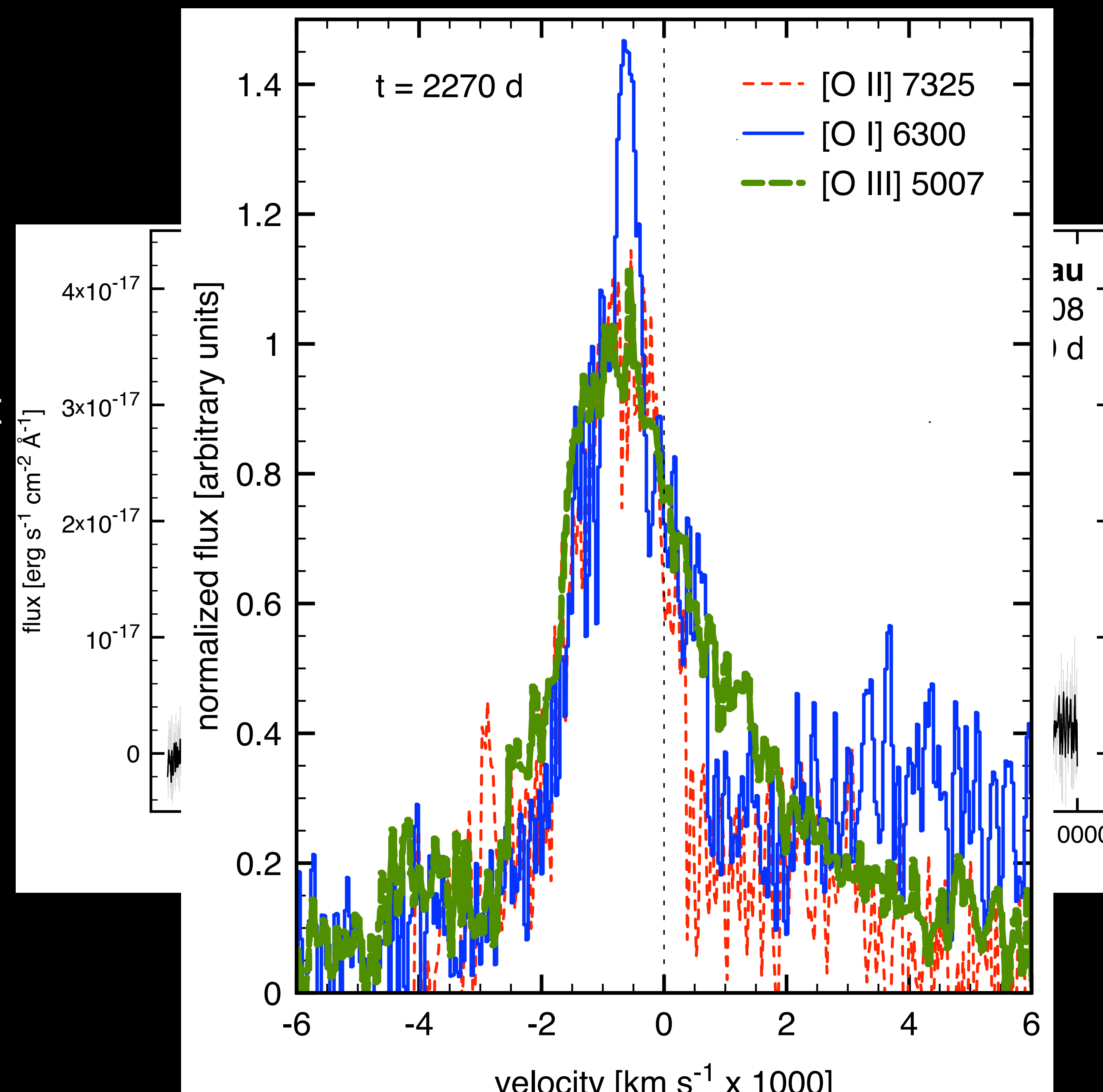
Evolution of the spectra

- Spectra in the photospheric phase
  - He lines and no hydrogen lines=>SN Ib
  - Broad lines=>High energy
- Spectrum in the nebula phase (day 274 d)
  - emission lines from singly ionized or neutral atoms



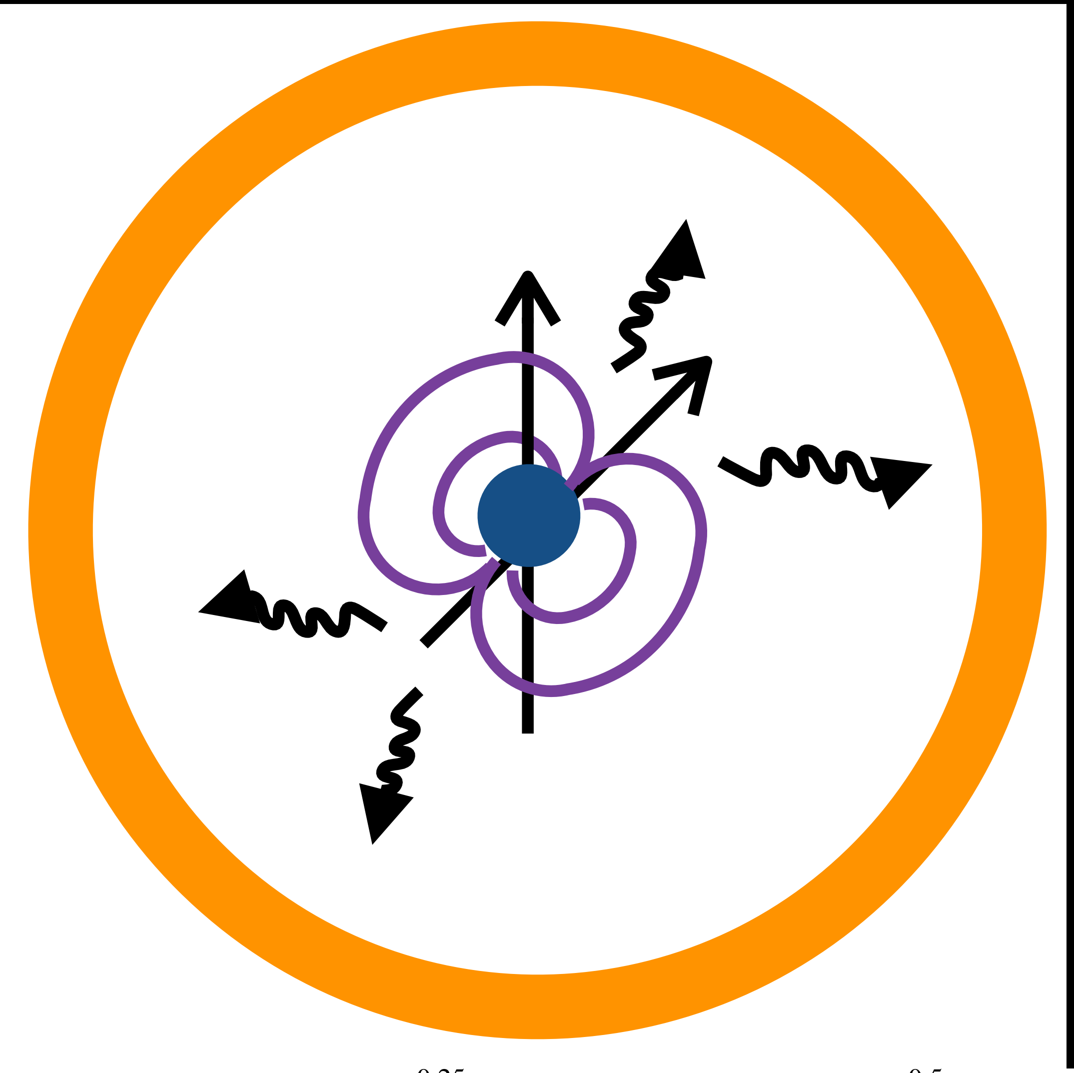
Spectrum 6 yrs later (Milisavljevic+ 2018)

- Emission lines of [OIII] and S[III]
  - Extra energy source
- Line width~2,300 km/s
  - Emission lines from the inner most ejecta=>
    - Shock heating is unlikely
    - Central energy source=pulsar
- Line centers are shifted ~ -700 km/s
  - Pulsar is moving?
  - Kick imparted to the Pulsar



Power of the pulsar (Milisavljevic+ 2018)

- Motion of a thin shell in ejecta pushed by energy injection from the central source (Chevalier and Fransson 1992)
  - ejecta
    - homologous expansion
    - inner region has a uniform density
  - Emission lines originate from the thin shell
    - the power from the pulsar~10^{40} erg/s



$$v = 2{,}300\ \mathrm{km/s} \left(\frac{\dot{E}}{10^{40}\ \mathrm{erg/s}}\right)^{0.25} \left(\frac{E_{\rm ex}}{10^{52}\ \mathrm{erg}}\right)^{0.25} \left(\frac{M_{\rm ej}}{4\ M_\odot}\right)^{-0.5} \left(\frac{t}{6.2\ \mathrm{yr}}\right)^{0.25}$$

Constraints on Magnetic field

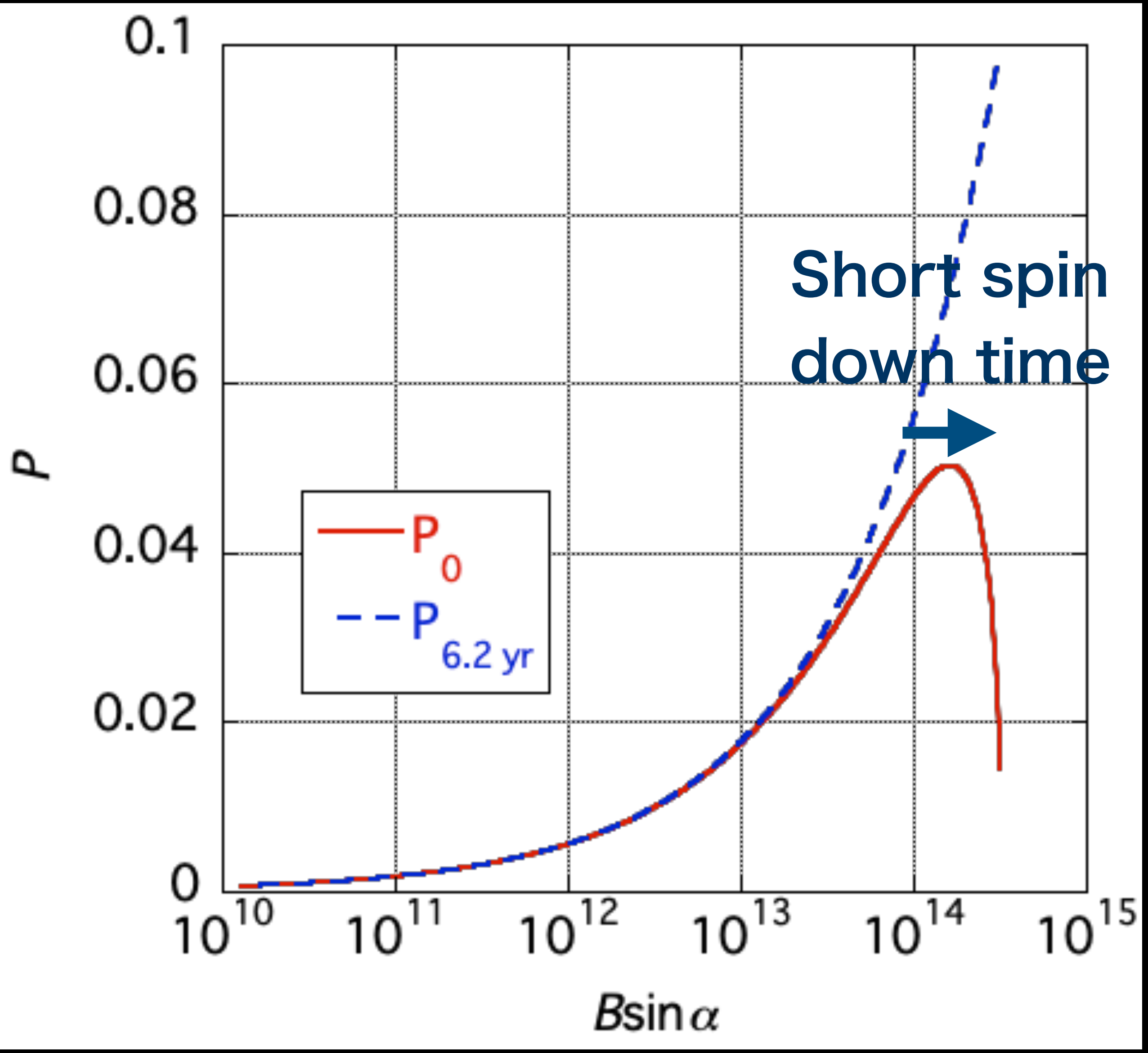
- If the energy is injected by the magnetic dipole radiation, where the spin period P> 1ms.

$$\dot{E} = \frac{8\pi^4 B^2 \sin^2 \alpha R^6}{3c^3 P^4}$$

  - Bsinα should be greater than 3.2×10^{10} G

- The initial spin period P_0 is related to the current spin period by Magnetic braking model.

- P_0>1 ms requires Bsinα< 3.3×10^{14} G

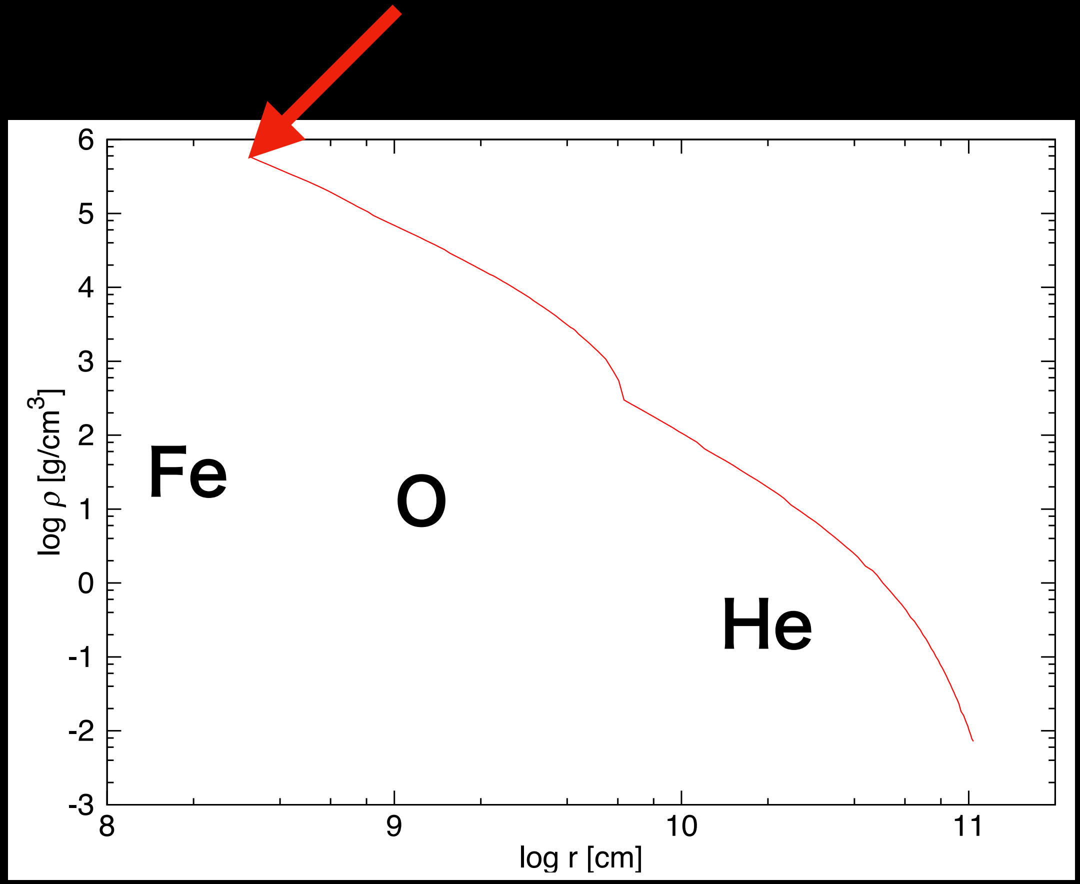


Problems

- High kinetic energy (10^{52} erg) and low velocity (2,300 km/s) emission region
  - The mean velocity of the ejecta~16,000 km/s
  - Is it possible that the inner edge of the ejecta expands slower than 2,300 km/s?
    - Chevalier & Fransson model assumes the existence of slowly expanding ejecta (homologously expanding uniform ejecta)
  - The explosion should produce ~0.3 $M_\odot$ ^{56}Ni

1D Explosion model Masuyama 2019

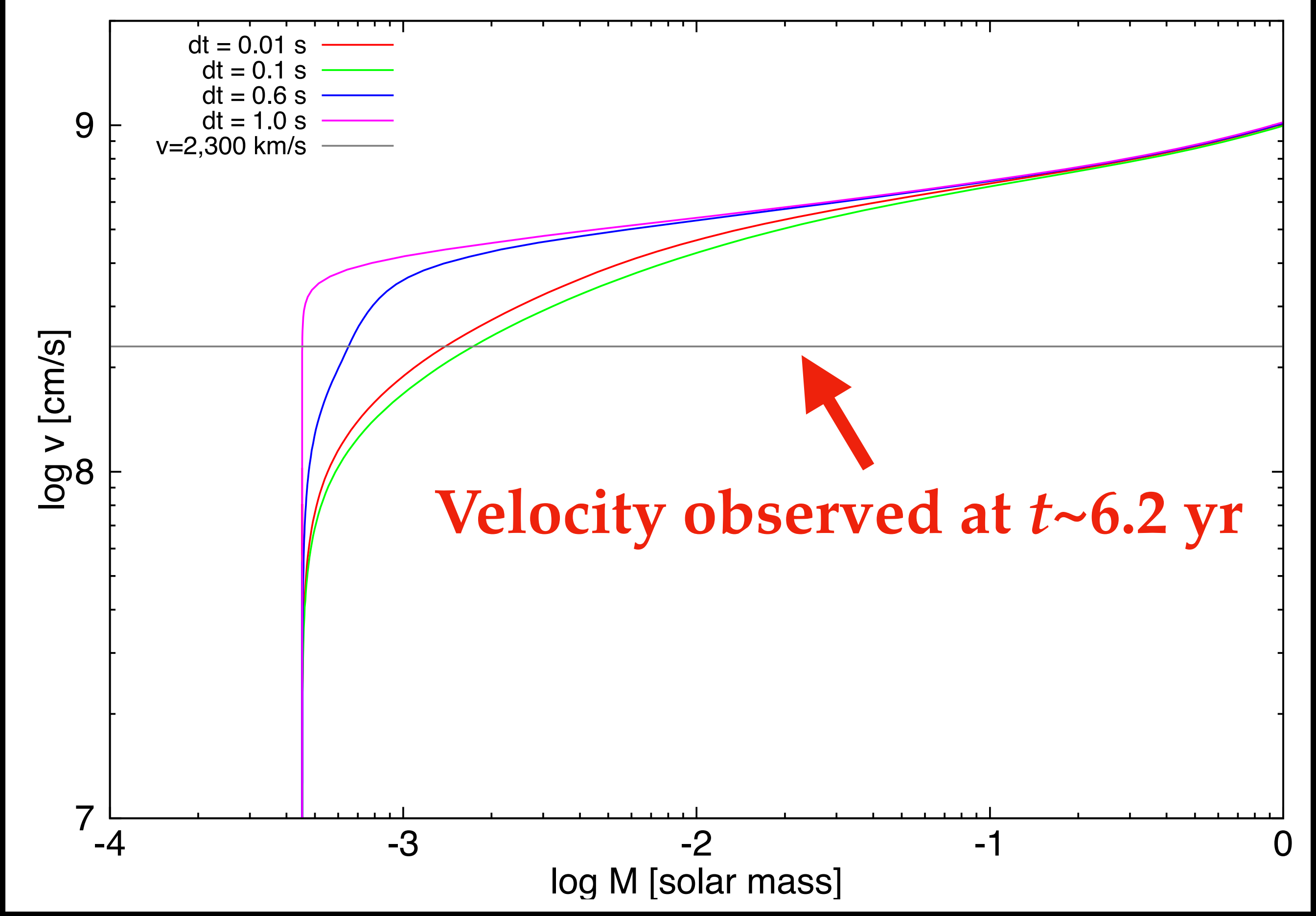
- Initial model=He core (6 M⊙)
- Explosion energy=10^{52} erg
    - Changes the energy input rate or the duration dt of the energy input



Density distribution

Velocity depending on the energy input rates

- Higher rates can reproduce slower ejecta near the inner edge
- If the energy is still supplied when the reverse shock reaches the inner edge, then the matter there can be further accelerated.
- Quick explosion is preferred.
    - Matter of 10^{-3} $M_\odot$ has slow velocities.
    - Magnetic braking requires $B\sin\alpha > 10^{16}$ G=>inconsistent



Velocity distribution

Luminosity of [OIII] line

- Observed luminosity of [OIII] line ~10^{38} erg/s
  - Line ratios of different ionization stages=>T~6,300K
  - From the mass and the expansion velocity=>N~10^2 / cm^3, ΔV ~ 3×10^{50} cm^3
  - $L(\lambda = 500.7\,\mathrm{nm})\ 8.63 \times 10^{-10} N_\mathrm{e} N_\mathrm{i} T^{-1/2} \frac{\Omega(1,2)}{\omega_1} \exp\left(-\frac{h\nu_{21}}{kT}\right) \times \Delta V \sim 10^{41}\,\mathrm{erg/s}$

^{56}Ni production

- Estimate Ni mass from the maximum temperature T_{max} attained in each cell
- Assume matter with T_{max}>5x10^9 K becomes Ni (Thielemann+ 1986)
  - Quick explosion can produce more than 0.2 $M_\odot$ Ni

Summary

- SN 2012au
  - energetic and quick explosion of a stripped envelope star
  - $E \sim 10^{52}$ erg, $M_{Ni} \sim 0.3\ M_\odot$, $M_{init} \sim 20\ M_\odot$
  - Pulsar ionizes O and S in the inner ejecta
    - 3×10^{10} G < $B \sin\alpha$ < 3×10^{14} G
  - Pulsar might be kicked

Other topics in Nuclear astrophysics group in RESCEU

- Dynamical mass ejection from massive stars a few years prior to supernovae: Kuriyama
- Fallback Accretion onto Neutron star: Iwata, Kashiyama
- Ejection of free neutrons from binary neutron star merger: Ishii
- SN IIn Light curve: Takei, Tsuna, Kashiyama
- Supernovae in close binary systems: Suda