Type Ic Core-Collapse Supernovae Evolved from Very Massive Stars

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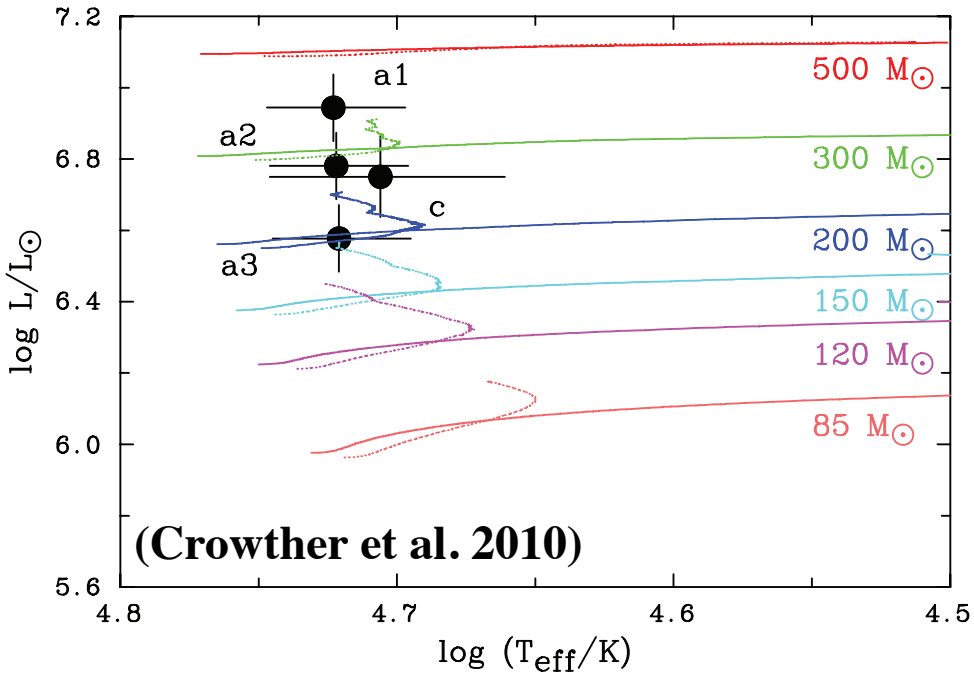
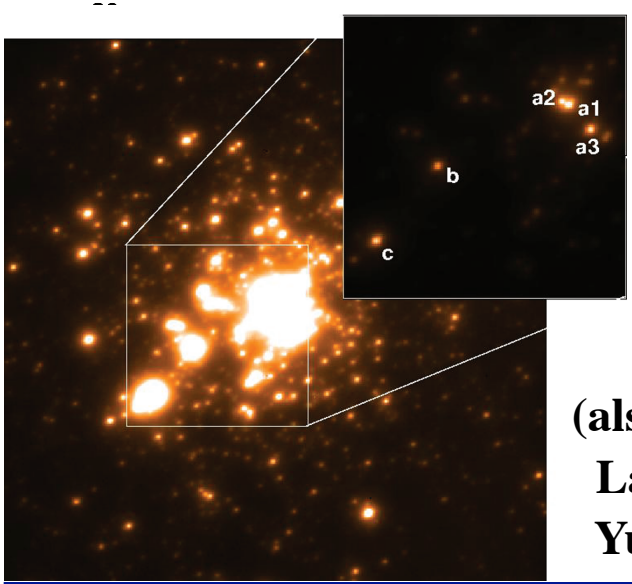
Very Massive Stars

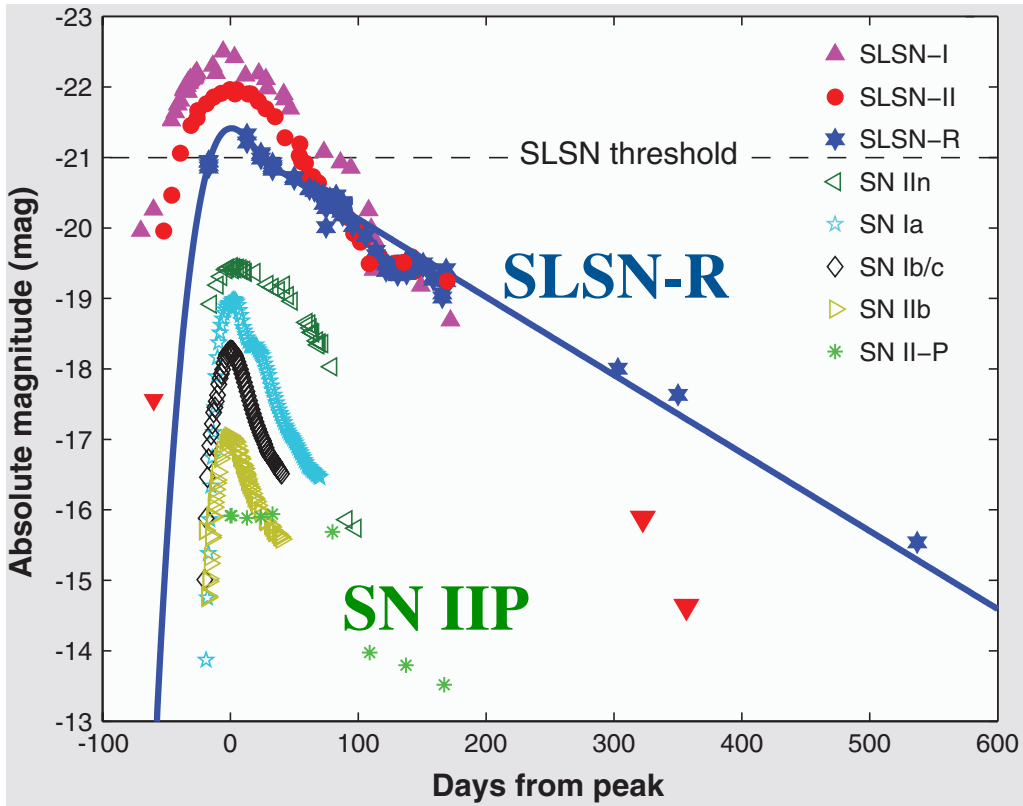
- M_{MS}~$320M_{\odot}$ stars in R136





(also e.g.,
Langer et al. 2007,
Yusof et al. 2013)

- Super-luminous SN-R



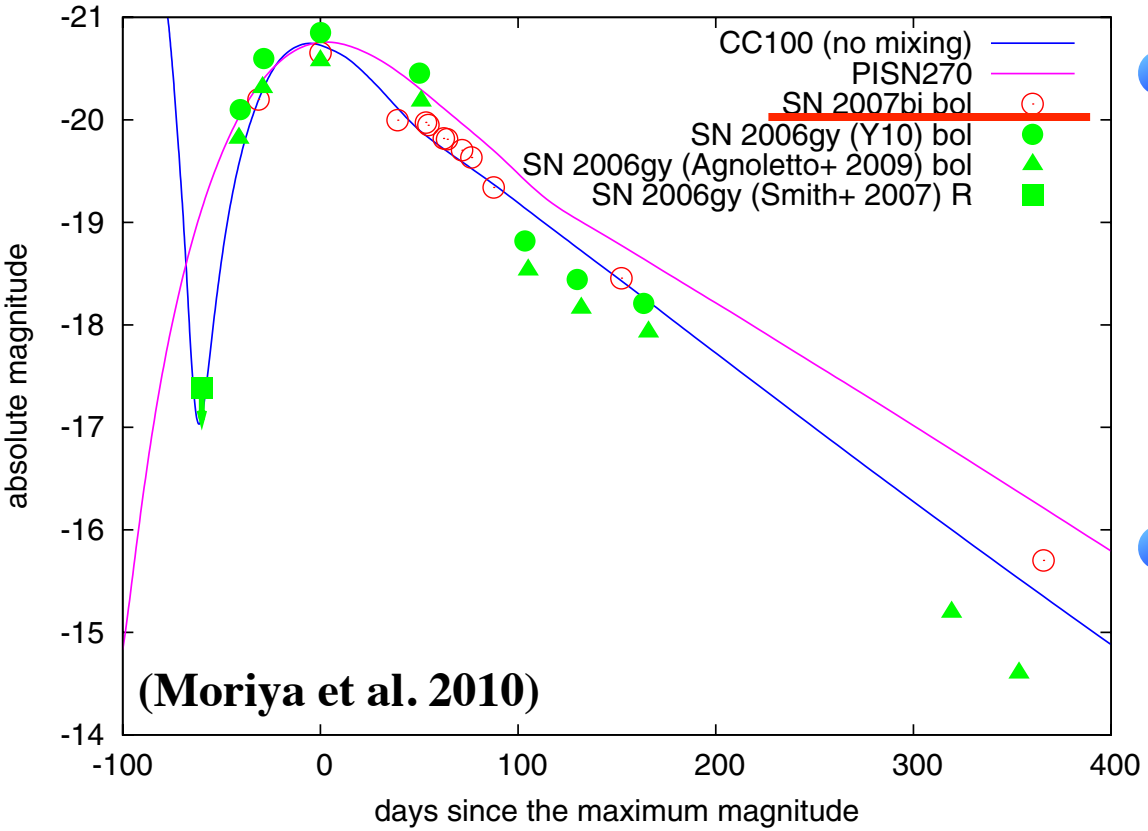
(Gal-Yam 2012)

SN 2007bi

→ **Pair-instability SN?**

(Gal-Yam et al. 2009)

SN 2007bi



- **Type Ic SLSN**
  $M_{R,max}$ = -21.3 mag
  (Gal-Yam et al. 2009)
  Z = 0.2-0.4 $Z_\odot$ host galaxy
  (Young et al. 2010)

- **Ejected ^{56}Ni amount**
  → **$M(^{56}\mathrm{Ni}) \sim 3.5\text{-}7.4\ M_\odot$**

Possibilities of explosion mechanism

- **Pair-instability SN (PISN)**
  → **$M_{CO} \sim 95 - 105\ M_\odot$**
  (Gal-Yam et al. 2009)

- **Core collapse SN (CCSN)**
  → **$M_{CO} \sim 43\ M_\odot$**
  (Moriya et al. 2010)

- **Interaction with CSM**
  (Chatzopoulos et al. 2013)

- **Magnetar-energized ejecta**
  (e.g., Nicholl et al. 2013)

Evolution and SNe of Very Massive Stars

- **Progenitors for SNe Ic with large ^{56}Ni production**

  Massive Star evolution (TY & Umeda 2011; Umeda, TY & Takahashi 2012)

  $M_{\rm MS}$ = (13 -) 100 - 500 $M_\odot$, Z=0.004

  - **Mass loss rate**

    Main-sequence → Vink et al. (2001) $\propto Z^{0.69}$, $Z^{0.64}$

    Red giant → de Jager et al. (1988) (Z dependence: $\propto Z^{0.64}$)

    Wolf-Rayet stars → Nugis & Lamers (2000)
    (Z dependence: Vink & de Koter 2005)

  → **Final mass, CO-core mass, stellar type**

- **^{56}Ni production in aspherical core-collapse SNe Ic**

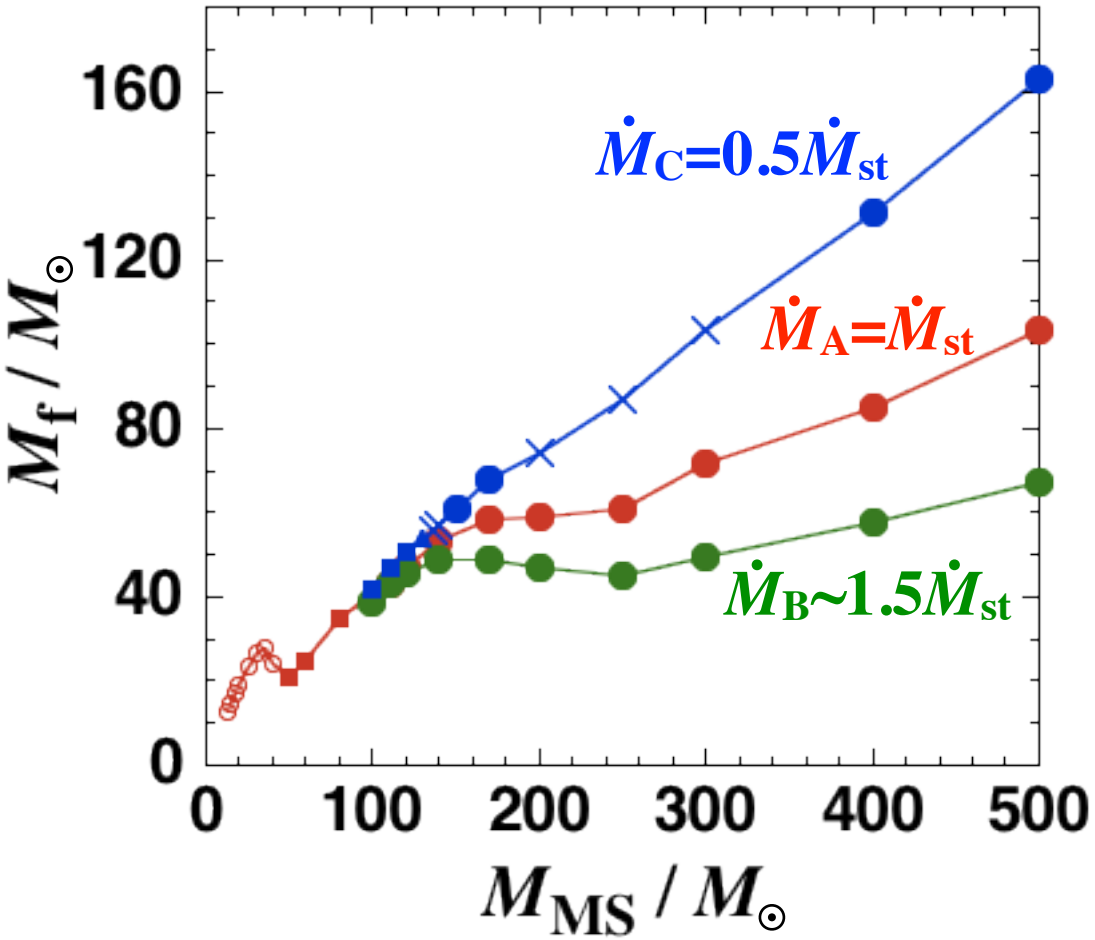
  - Aspherical SN explosions of 110 and 250 $M_\odot$ stars (Z=0.004) with various opening angles $\theta_{\rm op}$

    → Dependence of $M(^{56}{\rm Ni})$ and ejecta amount on $\theta_{\rm op}$

    Constraints from the observations of SN 2007bi

Final Mass of Very Massive Stars

(TY & Umeda 2011)



- $Z = 0.004$
- $\dot{M}_A$: standard ($\dot{M}_{st}$)

  $\dot{M}_B \sim 1.5\ \dot{M}_{st}$

  (WR stars: Crowther 2007)

  $\dot{M}_C = 0.5\ \dot{M}_{st}$

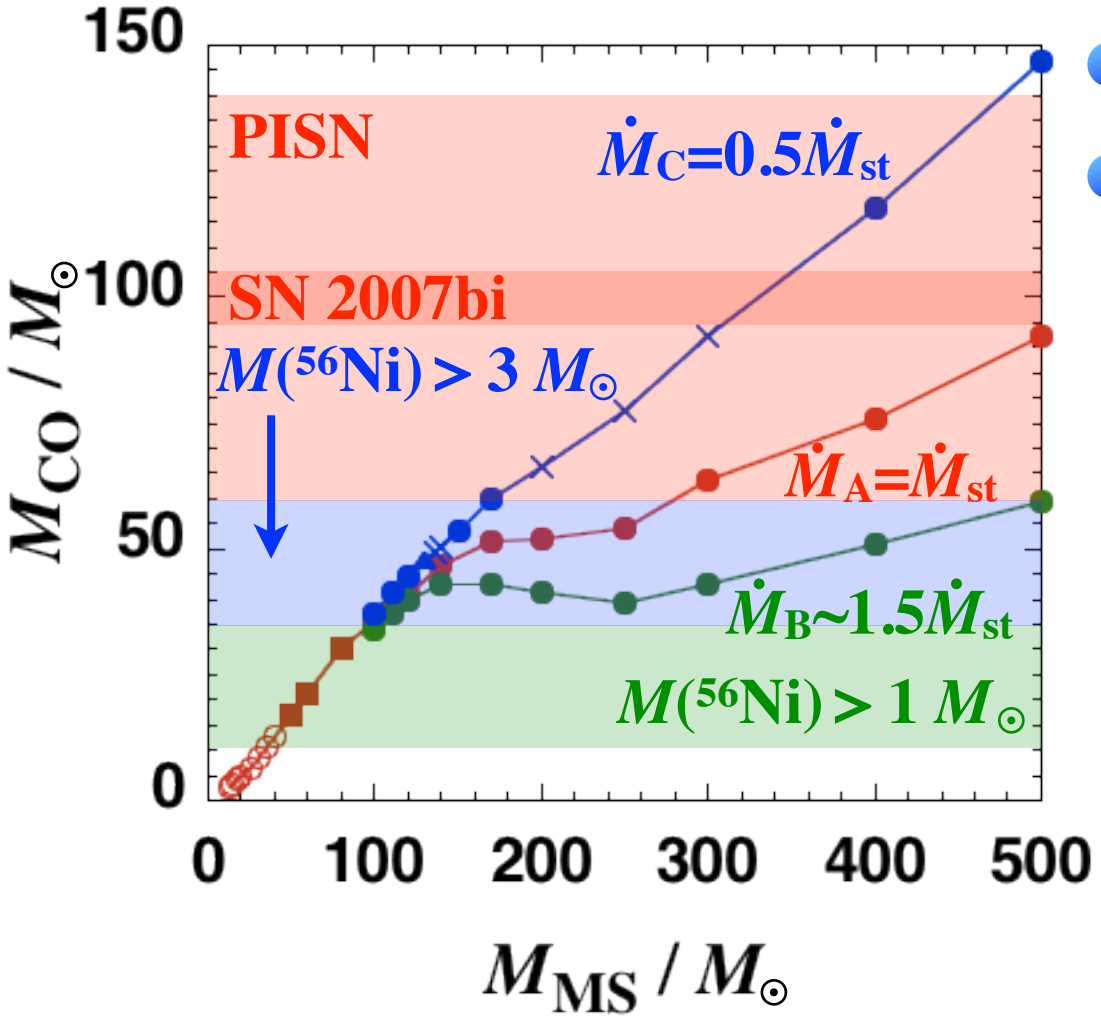
  (e.g., Discussion in Hirschi 2008, Pulse et al. 2008)
- Stellar types

  ○RG star, ■WN star

  × WC star, ●WO star

- Final mass M_f depends on mass loss rate.
- $M_{MS} > 100$ - $140\ M_\odot$ ➡ WO or WC stars ... SNe Ic

CO Core Mass of Very Massive Stars



(TY & Umeda 2011)

- $Z = 0.004$
- Available ^{56}Ni amount from CCSN (Umeda & Nomoto 2008)

$M(^{56}\mathrm{Ni}) \gtrsim 1\,M_\odot$

$M_{CO} \gtrsim 10\,M_\odot, E_{51} \gtrsim 10$

$M(^{56}\mathrm{Ni}) \gtrsim 3\,M_\odot$

$M_{CO} \gtrsim 30\,M_\odot, E_{51} \gtrsim 20$

PISN ➡ $M_{CO} > 60\,M_\odot$

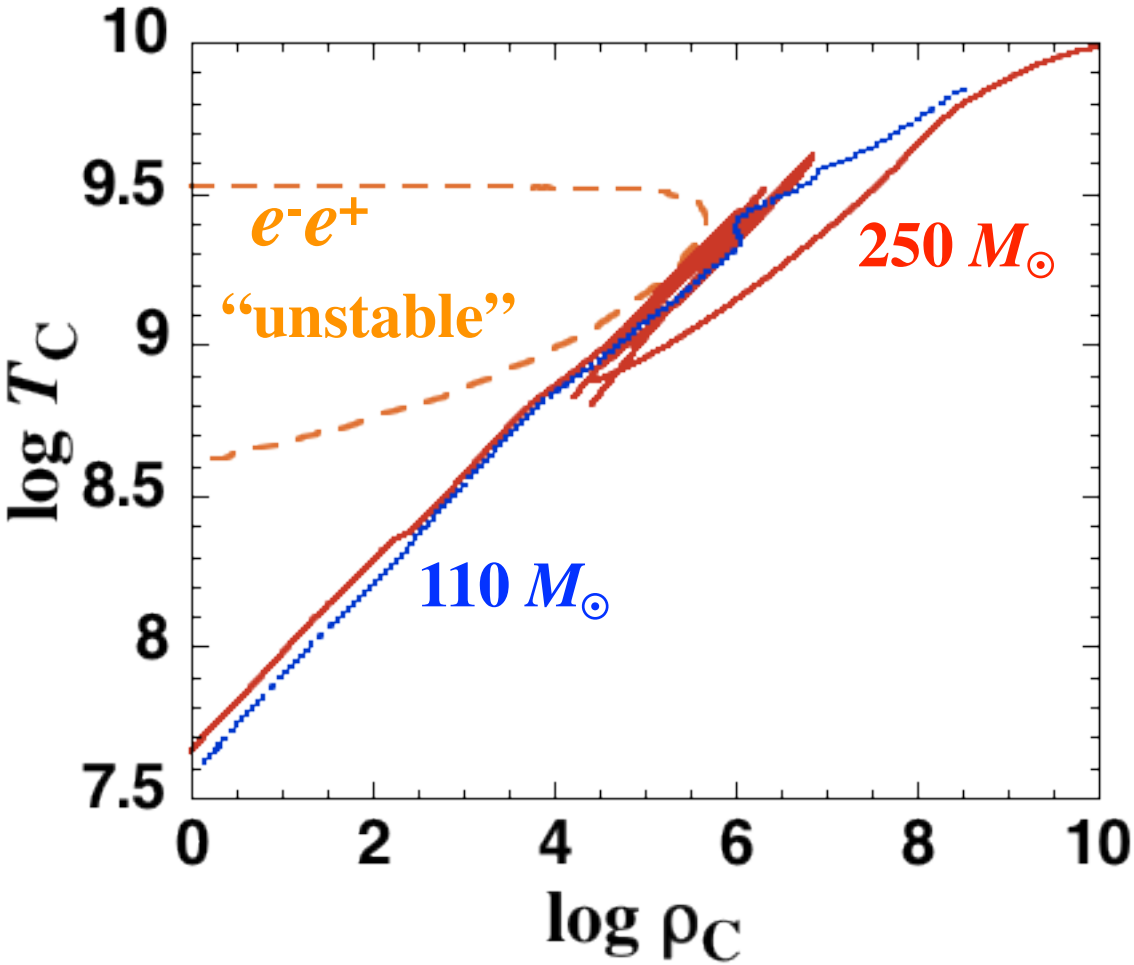
(Heger & Woosley 2002, Umeda & Nomoto 2002)

- CC SN Ic with $M(^{56}\mathrm{Ni})>3M_\odot$ ➡ A: $110 < M_{MS} < 280\,M_\odot$
- Small mass loss rate ➡ PISN is possible for SN 2007bi

Pulsational Pair-Instability SNe

- **Pulsational pair-instability (PPI) SNe**

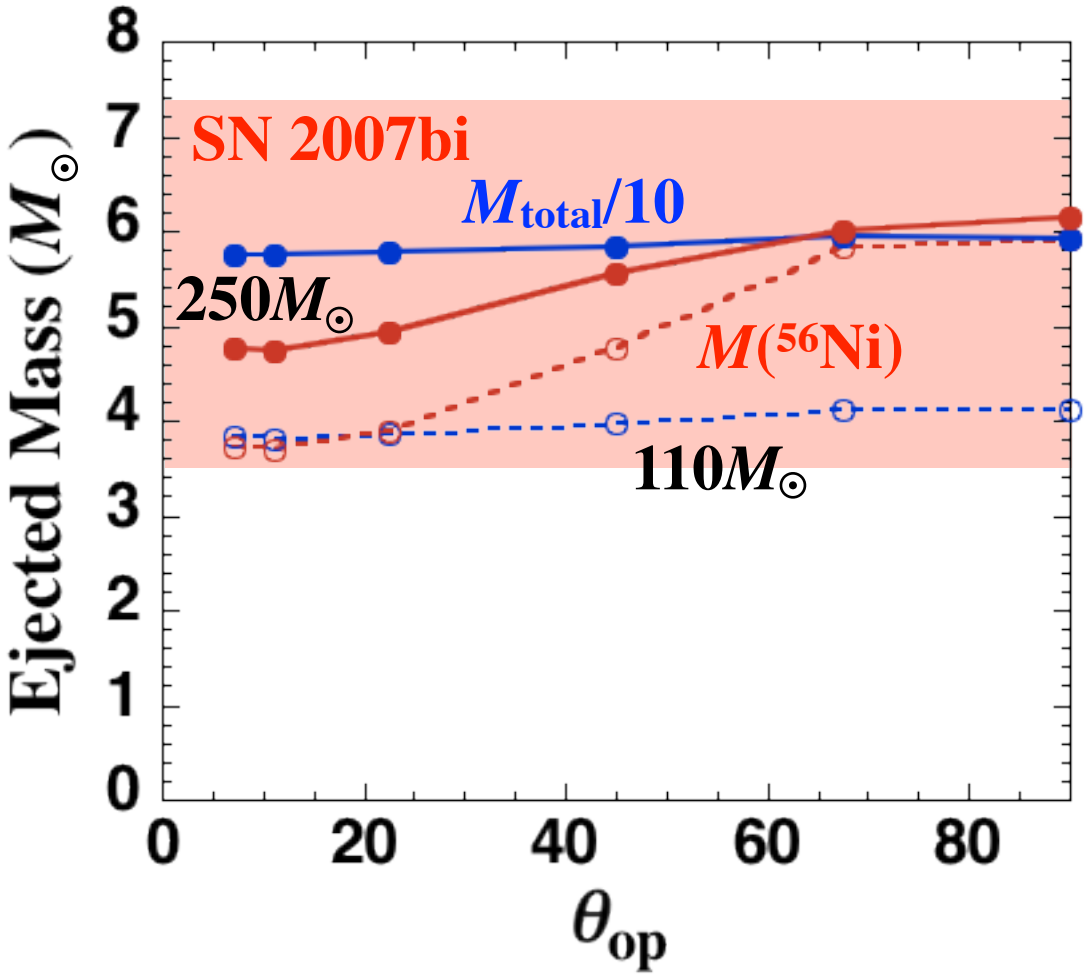
➡ **Pulsations by pair-instability** ➡ **Core-collapse**



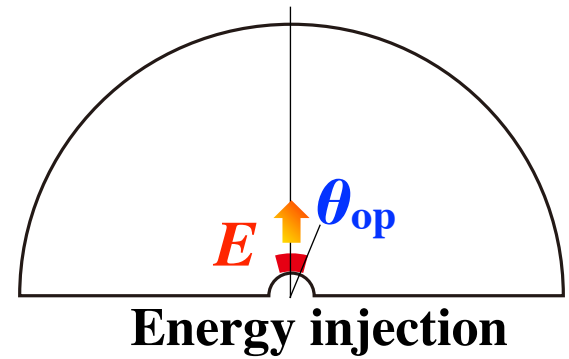
- **250 $M_\odot$ → 61 $M_\odot$ WO**
  M_{CO}=56 $M_\odot$
  ($40 \lesssim M_{CO} \lesssim 60\ M_\odot$)
  (Heger & Woosley 2002)
  ➡ **PPI SN (CCSN)**
- **110 $M_\odot$ → 43 $M_\odot$ WO**
  M_{CO}=39 $M_\odot$
  ($M_{CO} \lesssim 40\ M_\odot$)
  ➡ **CCSN**

^{56}Ni Production of Aspherical CC SNe

- Dependence on opening angle θ_{op}



(TY, Okita, Umeda, submitted)



- Mass cut: 2.0 $M_\odot$
- 250 $M_\odot$ model (solid lines)
  - ➡ $E = 7\times10^{52}$ erg
- 110 $M_\odot$ model (dashed lines)
  - ➡ $E = 5\times10^{52}$ erg

- Aspherical explosion ➡ Reproducing ^{56}Ni mass in SN 2007bi

One possibility for explosion mechanism of SN 2007bi

Conclusions

- **Very massive stars in Z=0.004**
  - **Final mass and CO-core mass strongly depend on the mass loss rate.**
  - **Progenitor of SNe Ic → $M_{\rm MS} > 100$ - 140 $M_\odot$**

- **SNe Ic with large ^{56}Ni production**
  - **CCSN (PPI SN) with $M(^{56}\mathrm{Ni}) \gtrsim 3\ M_\odot$**
    → **$110 \lesssim M_{\rm MS} \lesssim 280\ M_\odot$, $E \gtrsim 2\times10^{52}$ erg**
  - **PISN with $M(^{56}\mathrm{Ni}) \gtrsim 3\ M_\odot$**
    → **$M_{\rm MS} \gtrsim 500\ M_\odot$**
    ($M_{\rm MS} \gtrsim 300\ M_\odot$ with small mass loss rate)

- **Aspherical CC (PPI) SN models**

  $M_{\rm MS}$=250$M_\odot$ and E=7×10^{52} erg, $M_{\rm MS}$=110$M_\odot$ and E=5×10^{52} erg

  → **One possibility for explosion mechanism of SN 2007bi**