Circumstellar properties of Type Ia supernovae with helium star donors *(work in progress)*

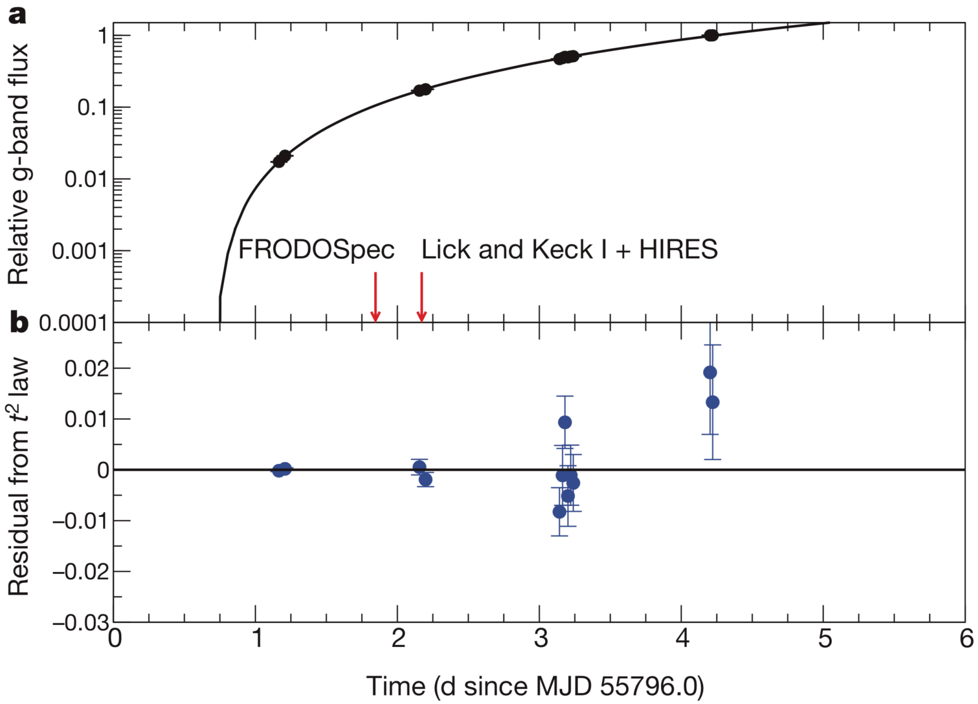
Takashi Moriya (NAOJ)

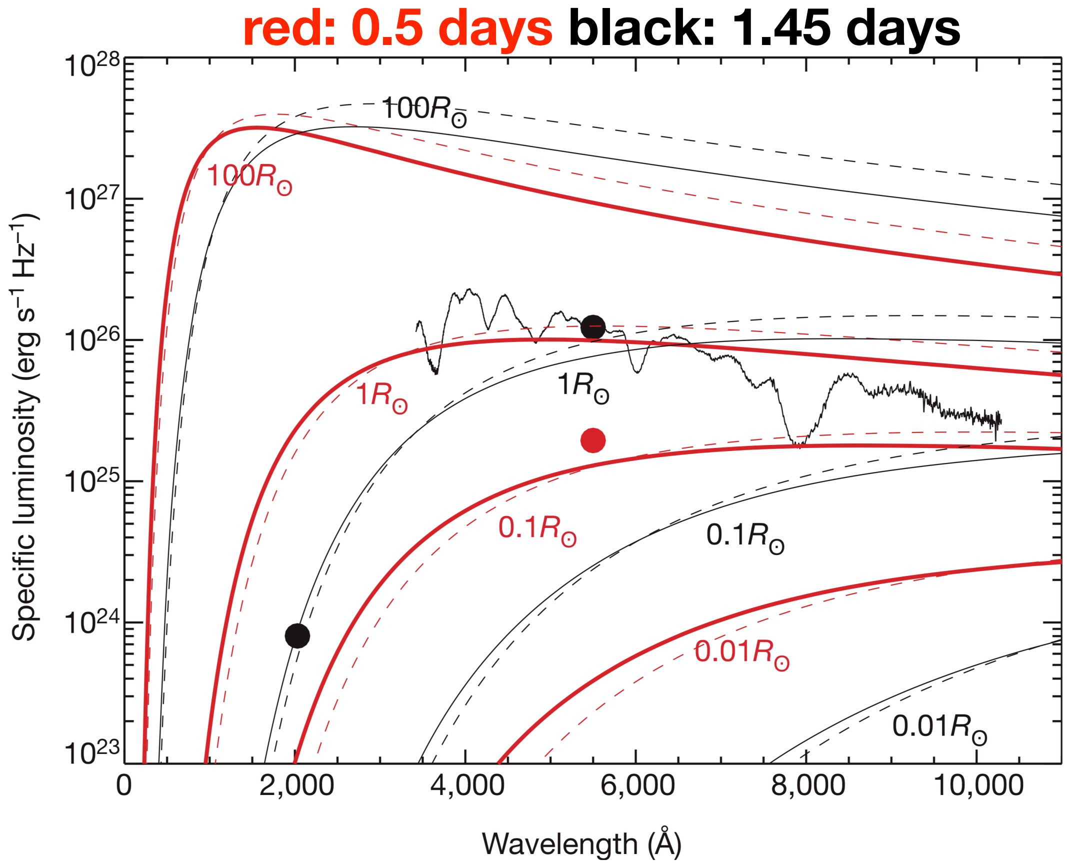
Dongdong Liu, Bo Wang, Zhengwei Liu (Yunnan Observatories)

国立天文台
NAOJ
National Astronomical Observatory of Japan

Type Ia SNe

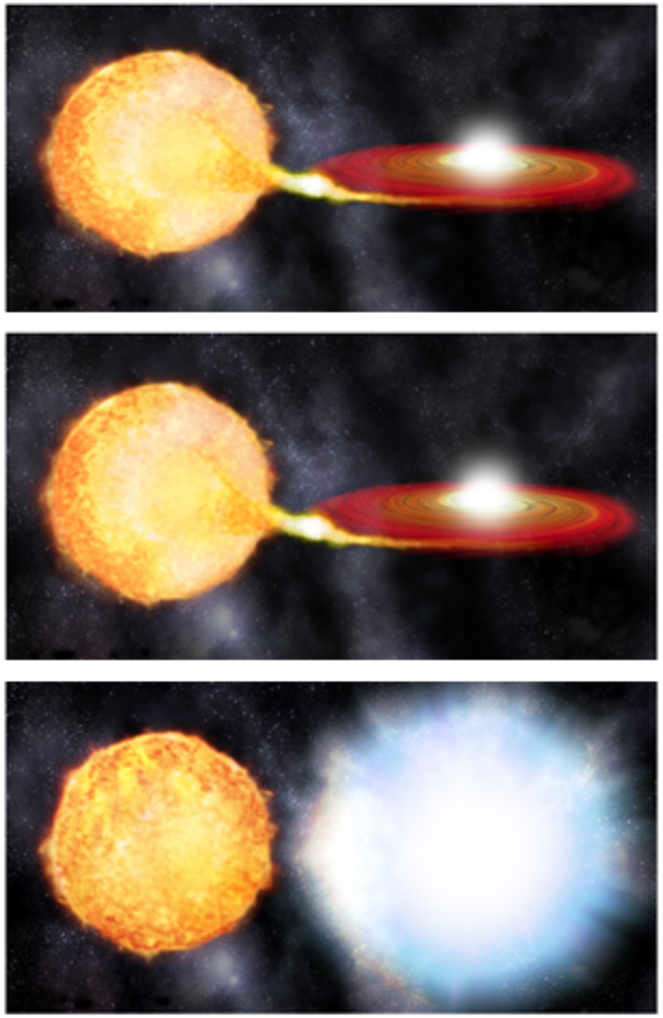
- explosions of C+O WDs
  - early observations of SN 2011fe (Nugent et al. 2011)



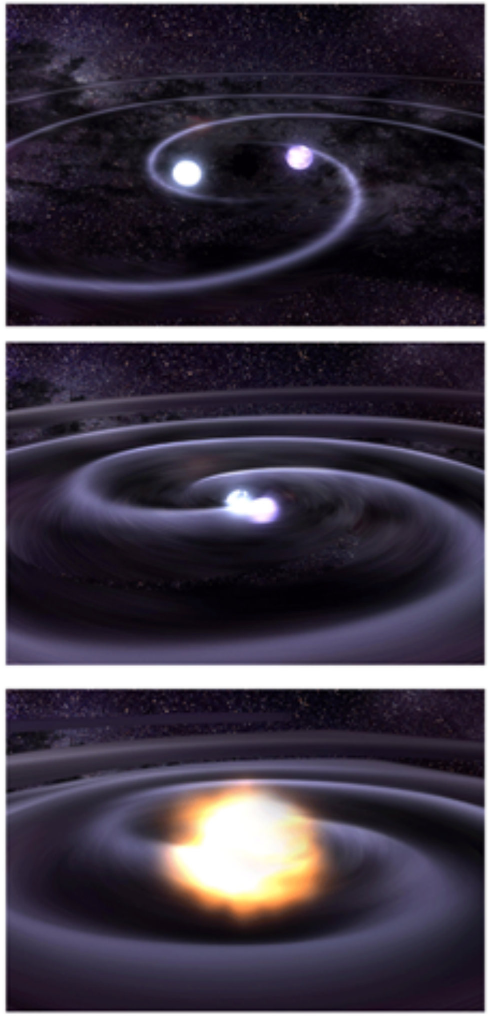


Companion stars

single degenerate (SD)

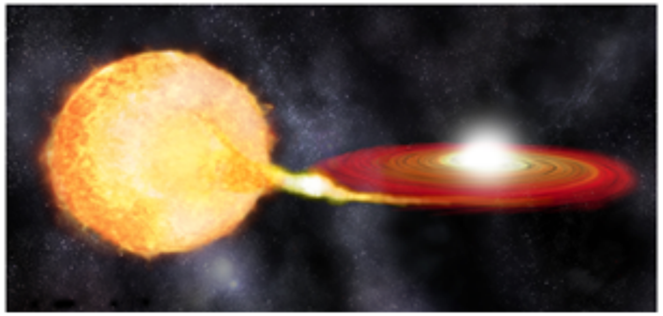


double degenerate (DD)

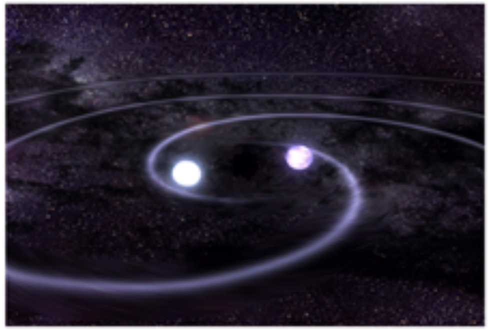


How to distinguish two channels by observations?

single degenerate (SD)



double degenerate (DD)



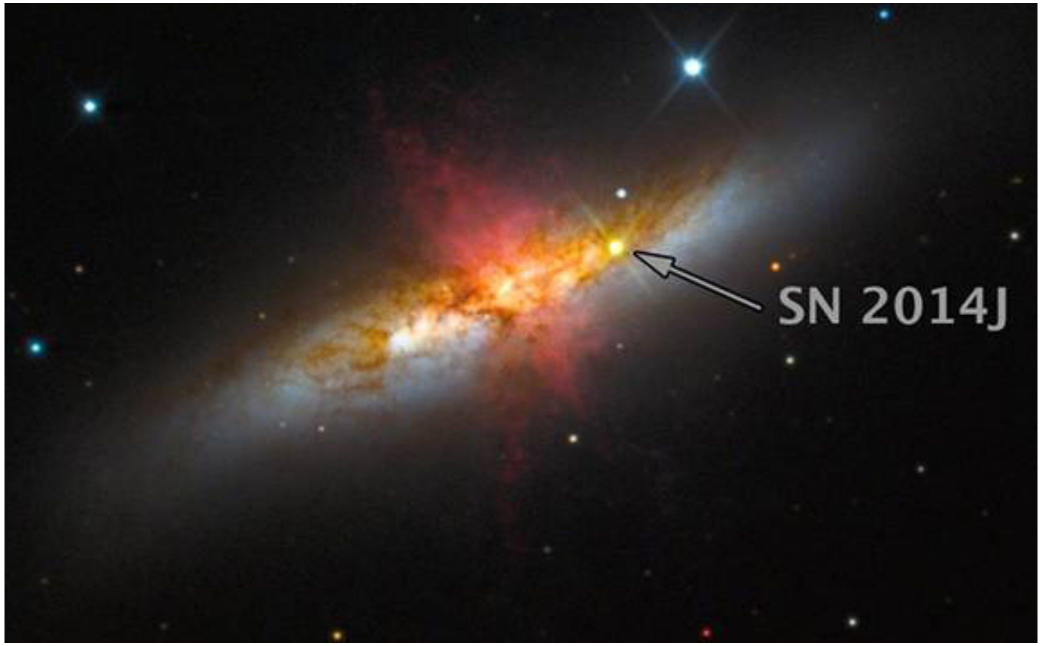
bright star

“dirty” environment

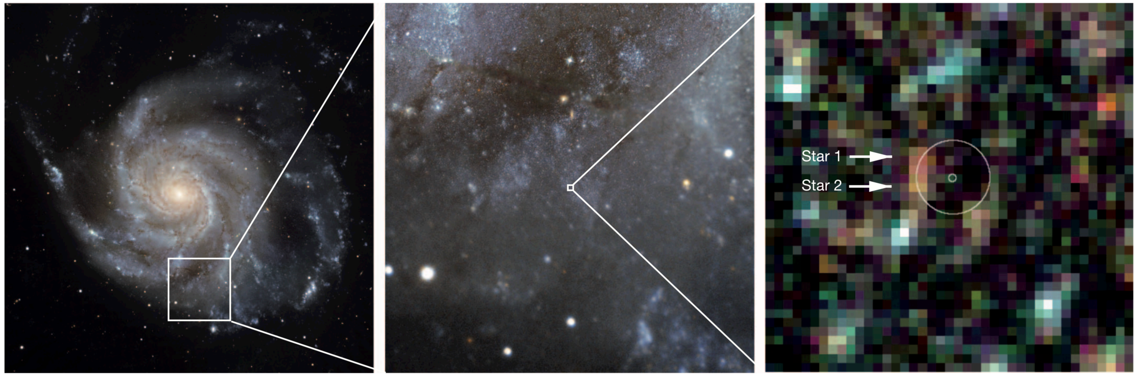
SN 2011fe & SN 2014J — two nearest SNe Ia

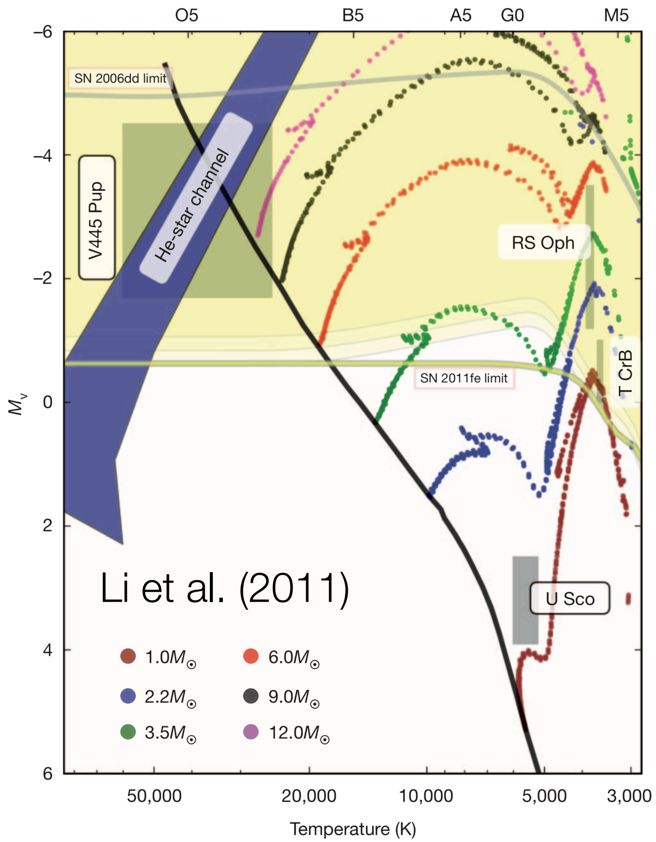
6.5 Mpc

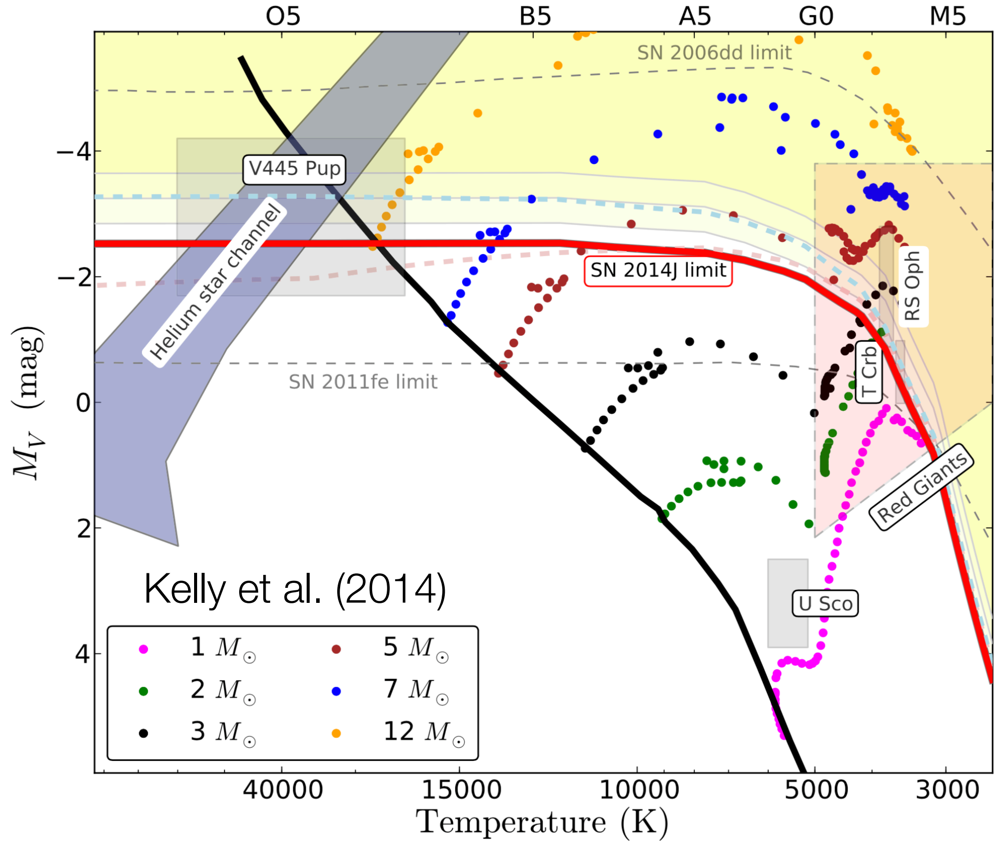
3.5 Mpc



Searching for companion stars



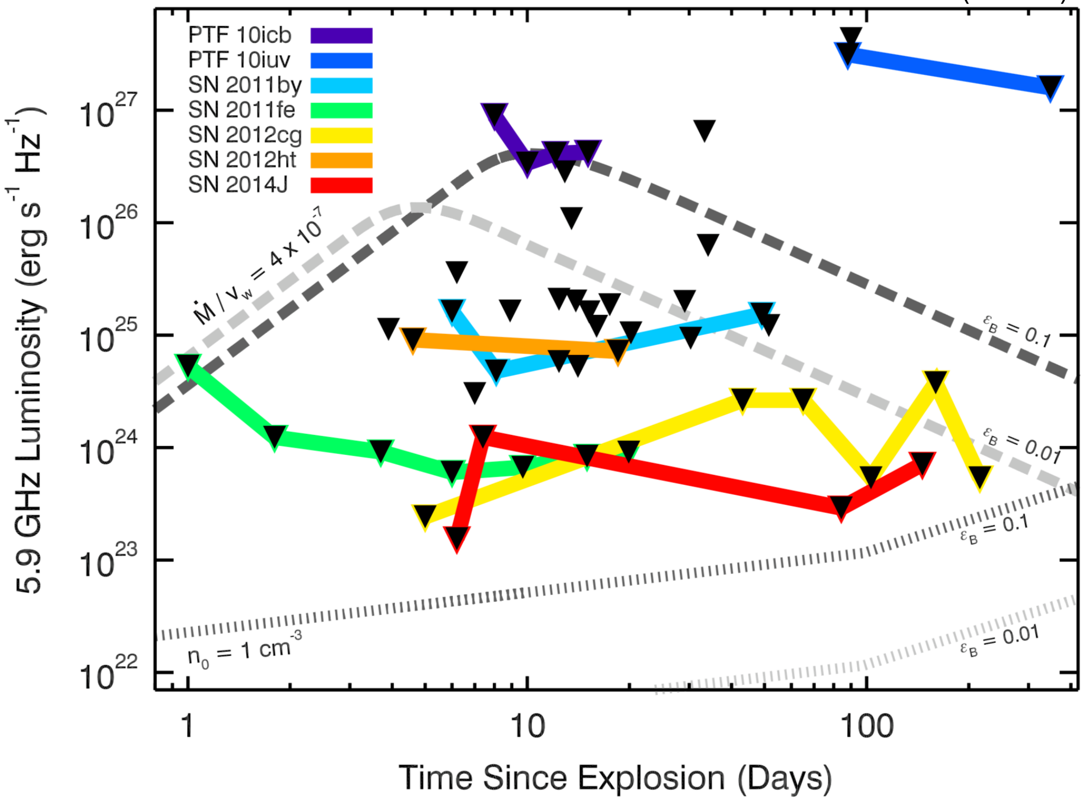




Circumstellar density

- CSM density $$\rho = \frac{\dot{M}}{4\pi v_{\rm wind}} r^{-2}$$
- constrained by radio observations
  - no radio signal has ever detected from SNe Ia

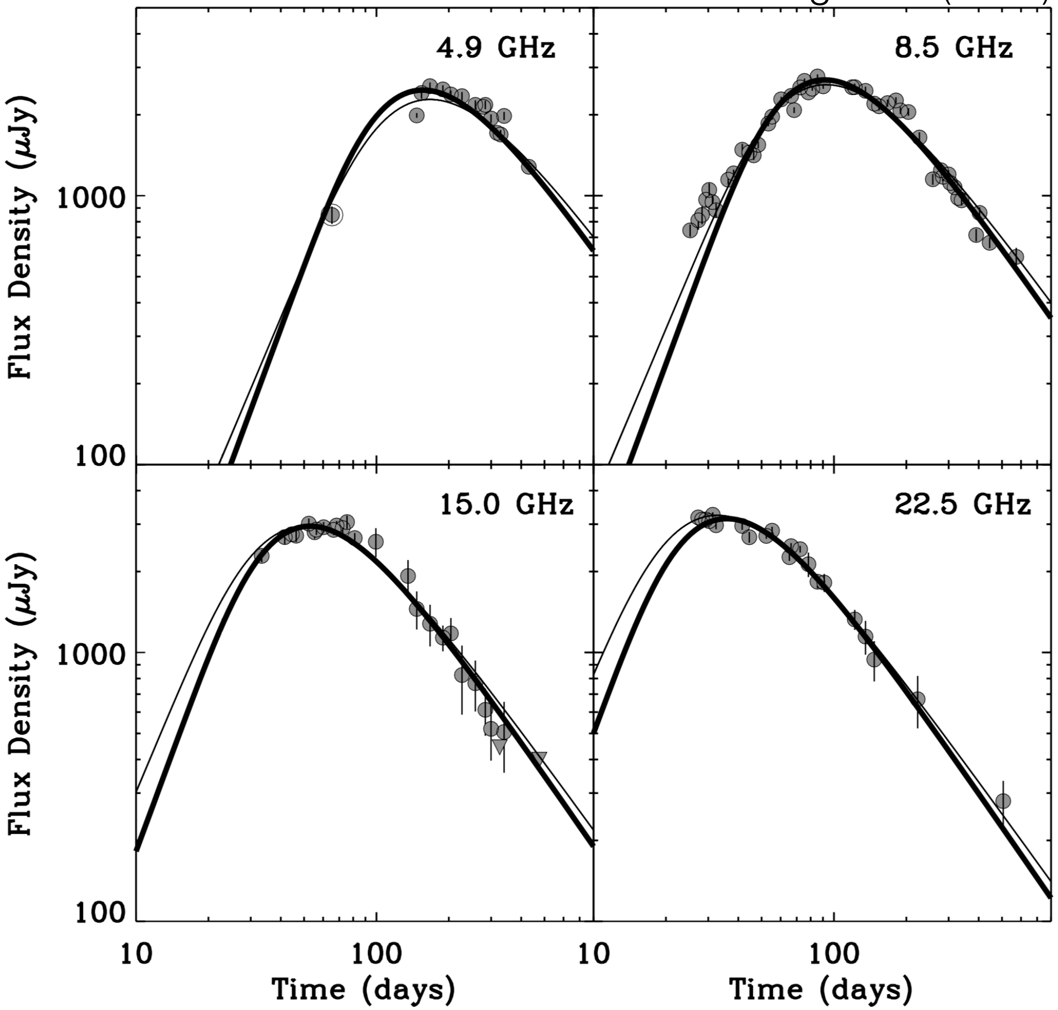
Chomiuk et al. (2016)



Radio emission from SN ejecta + CSM interaction

- synchrotron emission from relativistic electrons accelerated at the forward shock

Soderberg et al. (2005)



Radio luminosity

$$L_\nu \propto \epsilon_e \epsilon_B^{\frac{p+1}{4}} E_{ej}^{\frac{3(n-3)}{2(n-2)}} M_{ej}^{-\frac{3(n-5)}{2(n-2)}} \left(\frac{\dot{M}}{v_\infty}\right)^{\frac{p+5}{4} - \frac{3}{n-2}}$$

$$\mathrm{d}n_{\mathrm{rel}}(\gamma)/\mathrm{d}\gamma \propto \gamma^{-p} \qquad \rho \propto r^{-n}$$

p ~ 3, Eej ~ 1e51 erg, Mej ~ 1.4 Msun, n ~ 7

- two major uncertain parameters: ε_B and ε_e
  - ε_B : a fraction of shock energy converted to B energy
  - ε_e : a fraction of shock energy used to relativistic electron acceleration

ε_B & ε_e (microphysics at shock)

- We can use core-collapse SN observations to constrain them
- it is very often assumed $\varepsilon_B = \varepsilon_e = 0.1$
  - not likely — in consistent with X-ray observations when available

- combined analysis of radio and X-ray observations gives…
  - SN 1993J (Fransson+ 1998): $\varepsilon_B = 0.14,\ \varepsilon_e = 0.0005$
  - SN 2002ap (Bojornsson+ 2004): $\varepsilon_B = 0.002,\ \varepsilon_e = 0.1$
  - SN 2011dh (Maeda 2012): $\varepsilon_B = 0.006,\ \varepsilon_e = 0.05$
  - SN 2013df (Kamble+ 2016): $\varepsilon_B = 0.001,\ \varepsilon_e = 0.2$

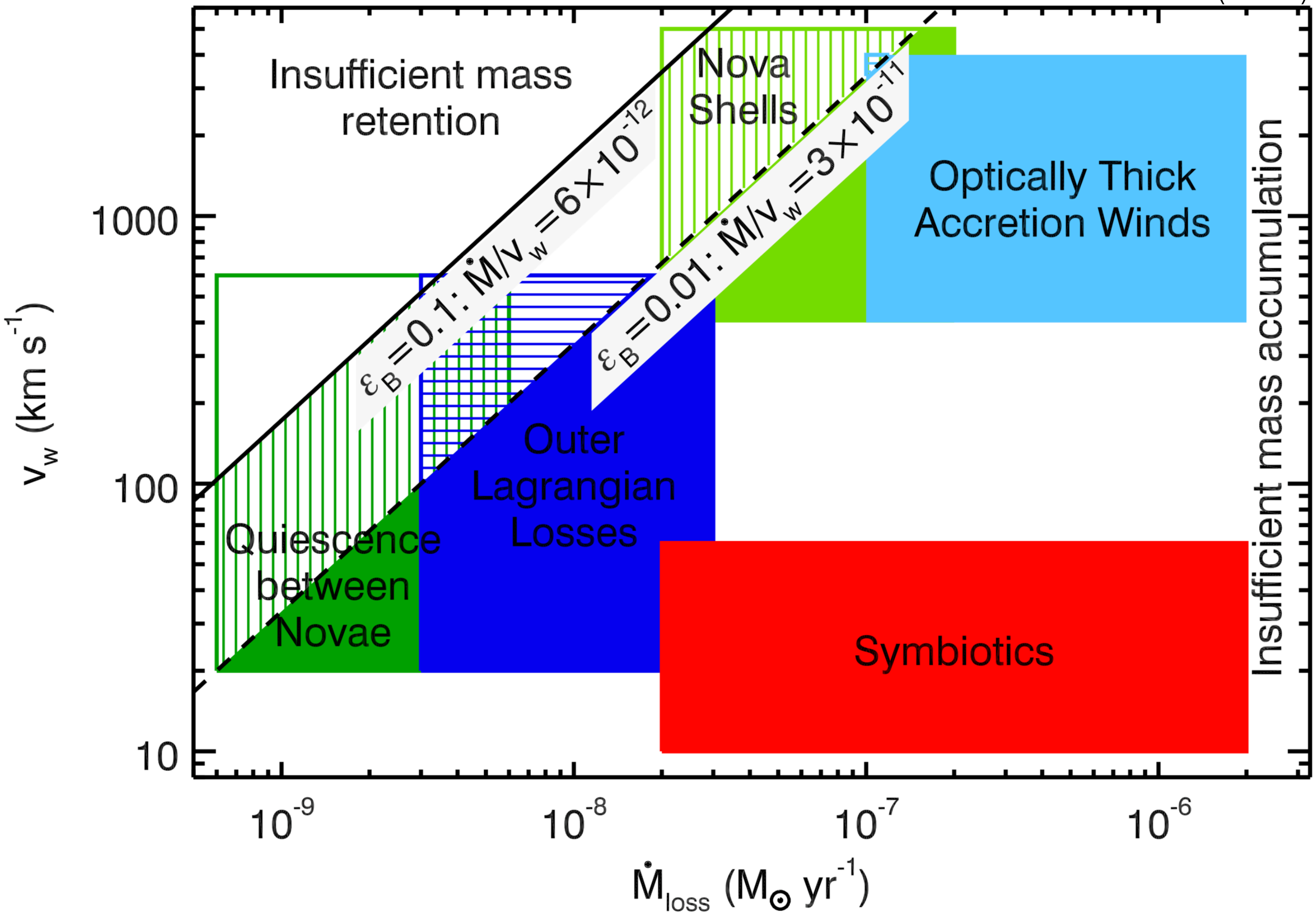
- for CSM density estimate, $\varepsilon_B \varepsilon_e$ matters (when p ~ 3)

$$L_\nu \propto \epsilon_{\rm e} \epsilon_B^{\frac{p+1}{4}} E_{\rm ej}^{\frac{3(n-3)}{2(n-2)}} M_{\rm ej}^{-\frac{3(n-5)}{2(n-2)}} \left(\frac{\dot{M}}{v_\infty}\right)^{\frac{p+5}{4}-\frac{3}{n-2}}$$

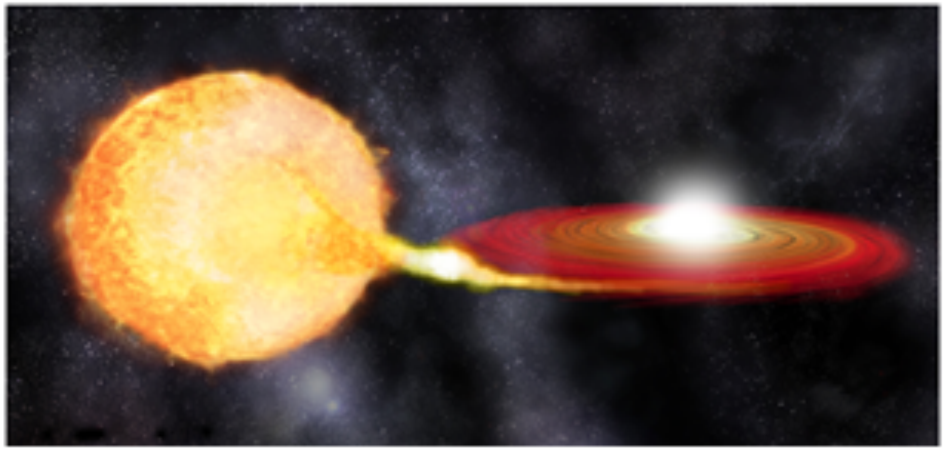
Deepest constraints for SNe Ia

- from SN 2011fe

Chomiuk et al. (2012)



He star donor channel for SNe Ia

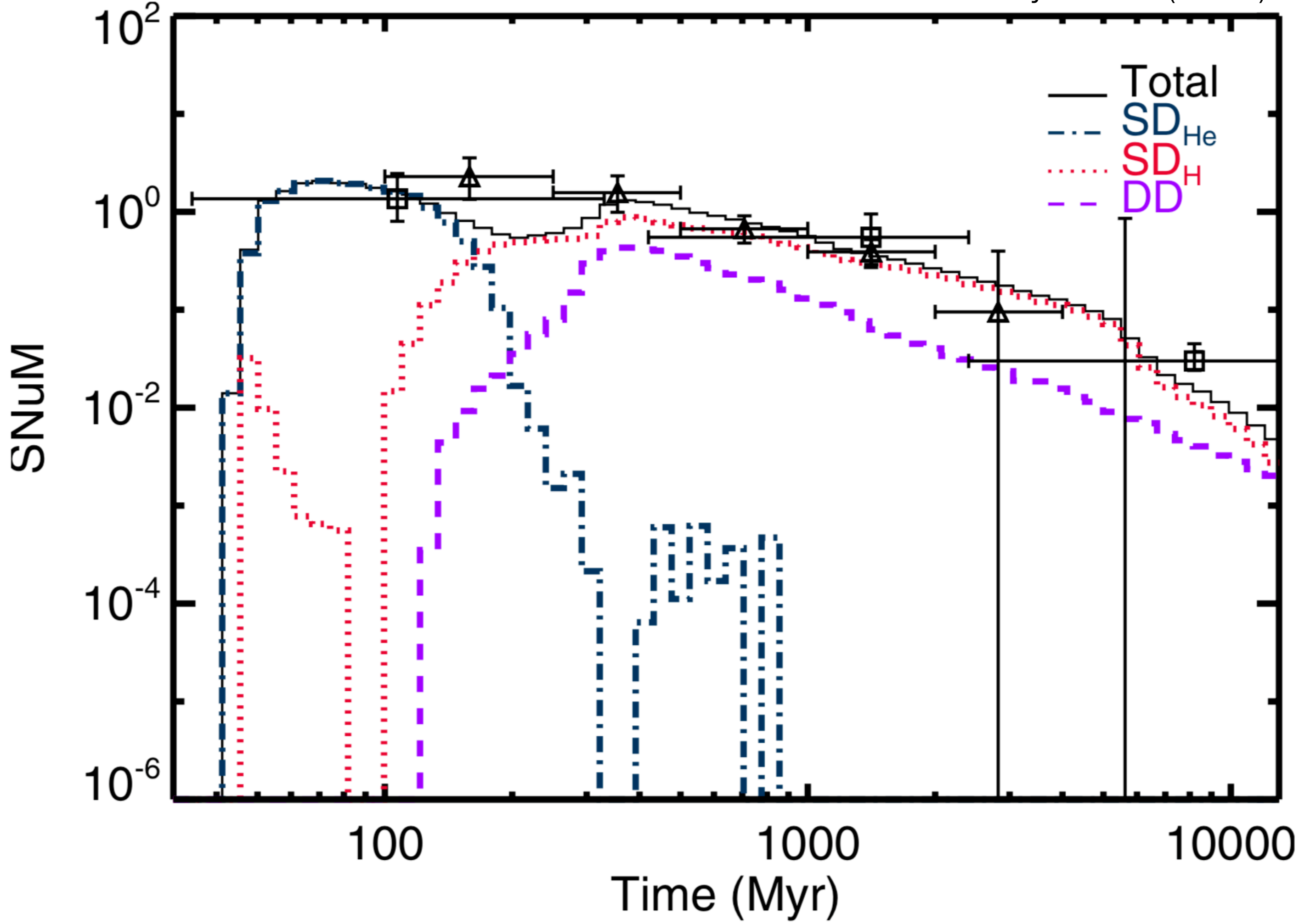


- donor stars can be He stars (e.g., Yoon & Langer 2003)
- we assume SNe Ia occur when WDs reach the Chandrasekhar limit

Early SNe Ia are likely from the He star donor channel

- He star donor channel dominates early SN Ia population

Claeys et al. (2014)

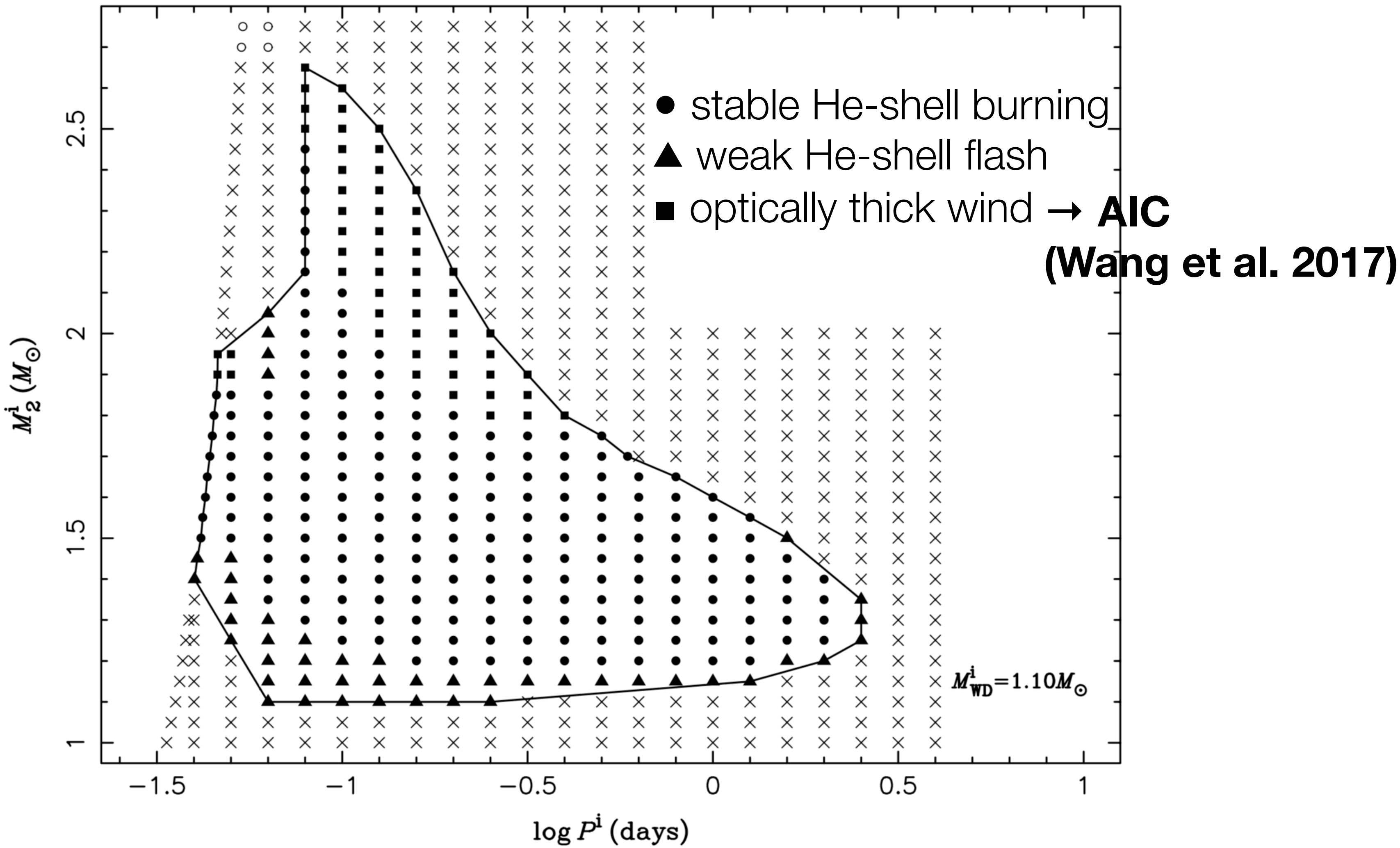


This work

Can the helium star donor channel avoid the current constraints on CSM density?

Evolution model

- Wang et al. (2009)
  - calculated ~ 2400 evolution models of He star + WD binaries

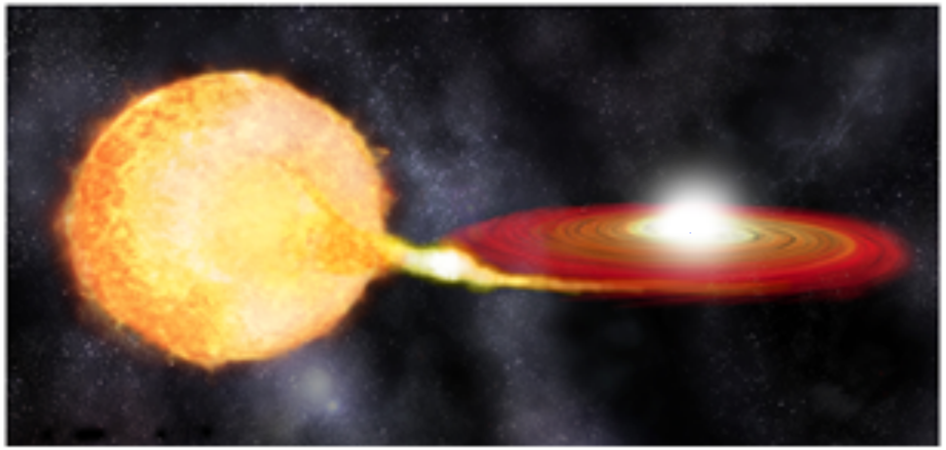


He shell burning on C+O WDs

- maximum He burning rate on C+O WDs (Nomoto 1982)

$$\dot{M}_{\rm max} \simeq 7.2 \times 10^{-6} (M_{\rm WD}/{\rm M}_\odot - 0.6)\ {\rm M}_\odot\ {\rm yr}^{-1}$$

- if the mass transfer rate exceeds $\dot{M}_{\rm max}$, the mass accretion doesn't catch up with the He burning
  - extended envelope is formed and "optically thick wind" blows

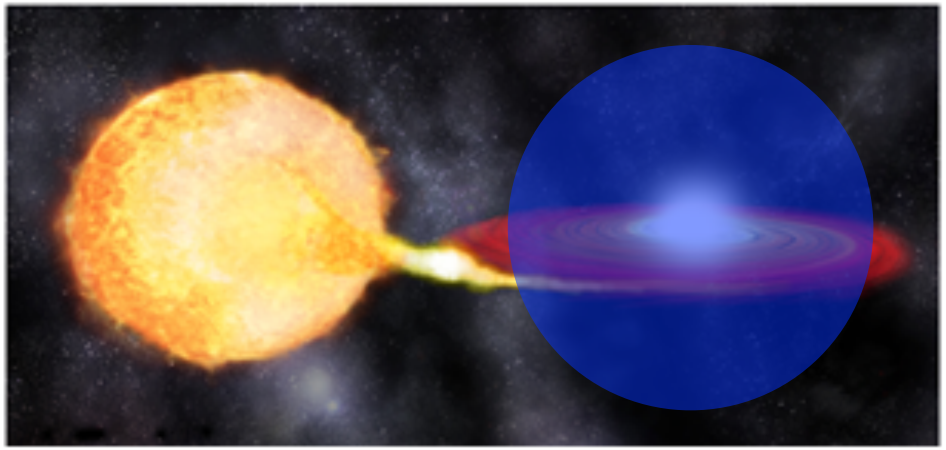


He shell burning on C+O WDs

- maximum He burning rate on C+O WDs (Nomoto 1982)

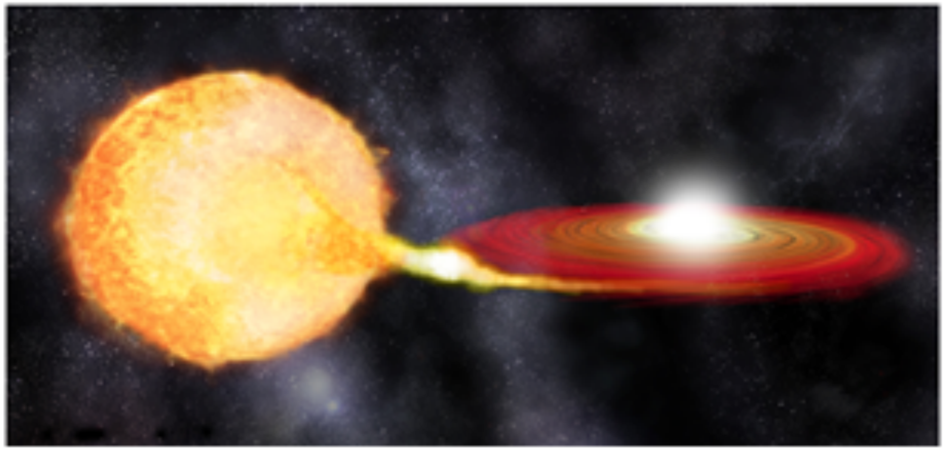
$$\dot{M}_{\rm max} \simeq 7.2 \times 10^{-6} (M_{\rm WD}/{\rm M}_\odot - 0.6)\ {\rm M}_\odot\ {\rm yr}^{-1}$$

- if the mass transfer rate exceeds $\dot{M}_{\rm max}$, the mass accretion doesn't catch up with the He burning
    - extended envelope is formed and "optically thick wind" blows



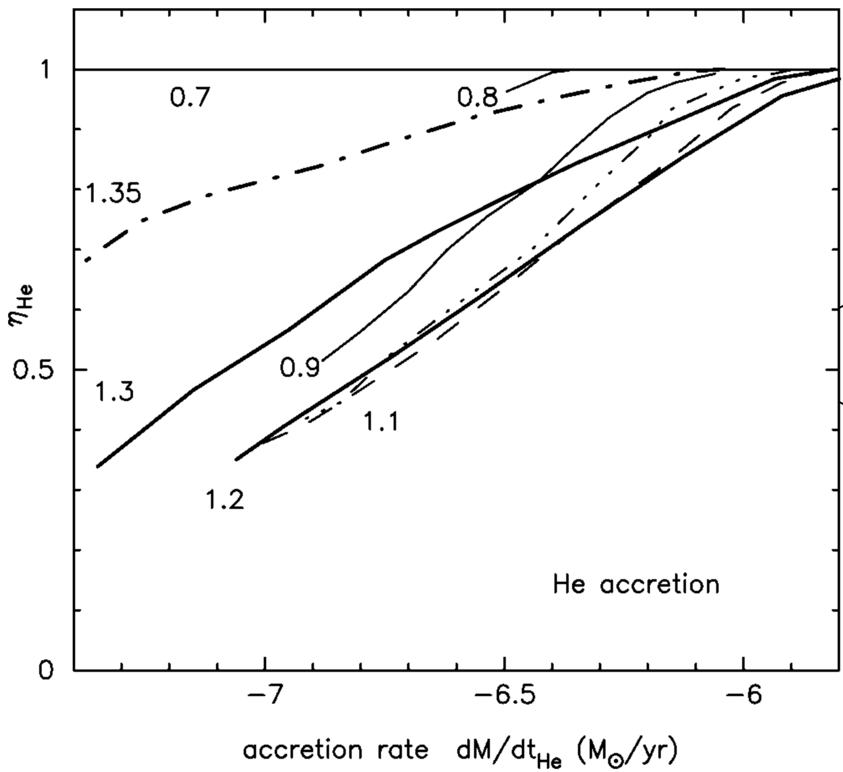
He shell burning on C+O WDs

- below $\dot{M}_{\rm max}$, stable He shell burning occurs down to a certain accretion rate
  - theoretically, all the transferred He is burned on WDs
    - but some mass loss is observed in stable burning systems
  - we assume 1% of transferred mass is lost from the outer Lagrangian point



He shell burning on C+O WDs

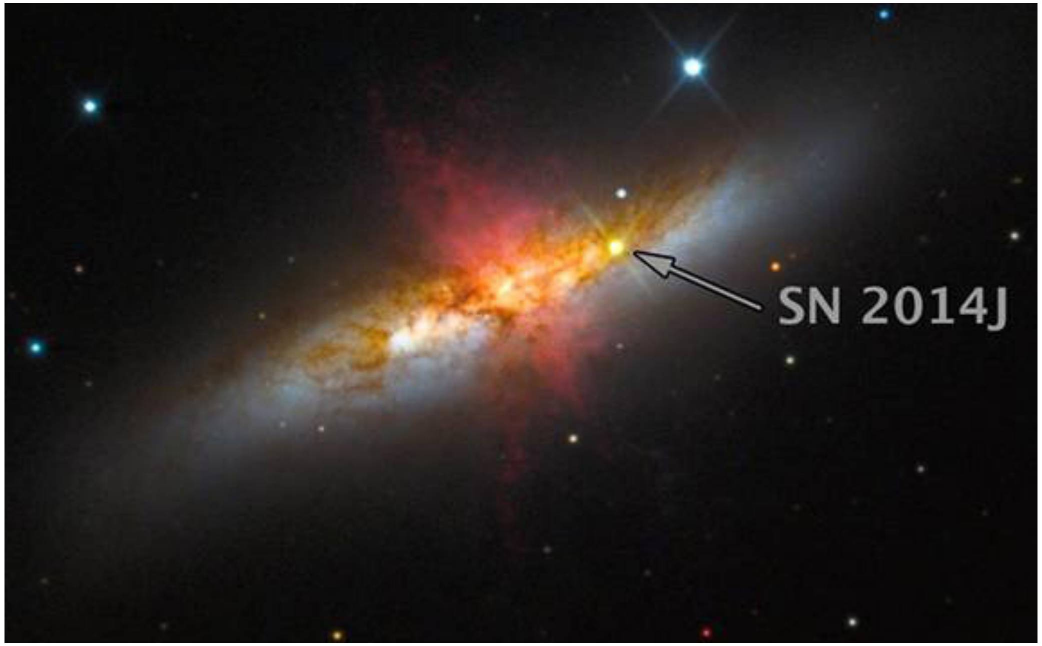
- below a certain mass accretion rate, He shell burning gets unstable
- if accretion rate is below ~ 4e-8 Msun/yr, He shell flash is strong enough to decrease the WD mass (Woosley et al. 1986)
    - No SN Ia explosions at this phase
- WD mass grows if the He shell flash is “weak”



Kato & Hachisu (2004)

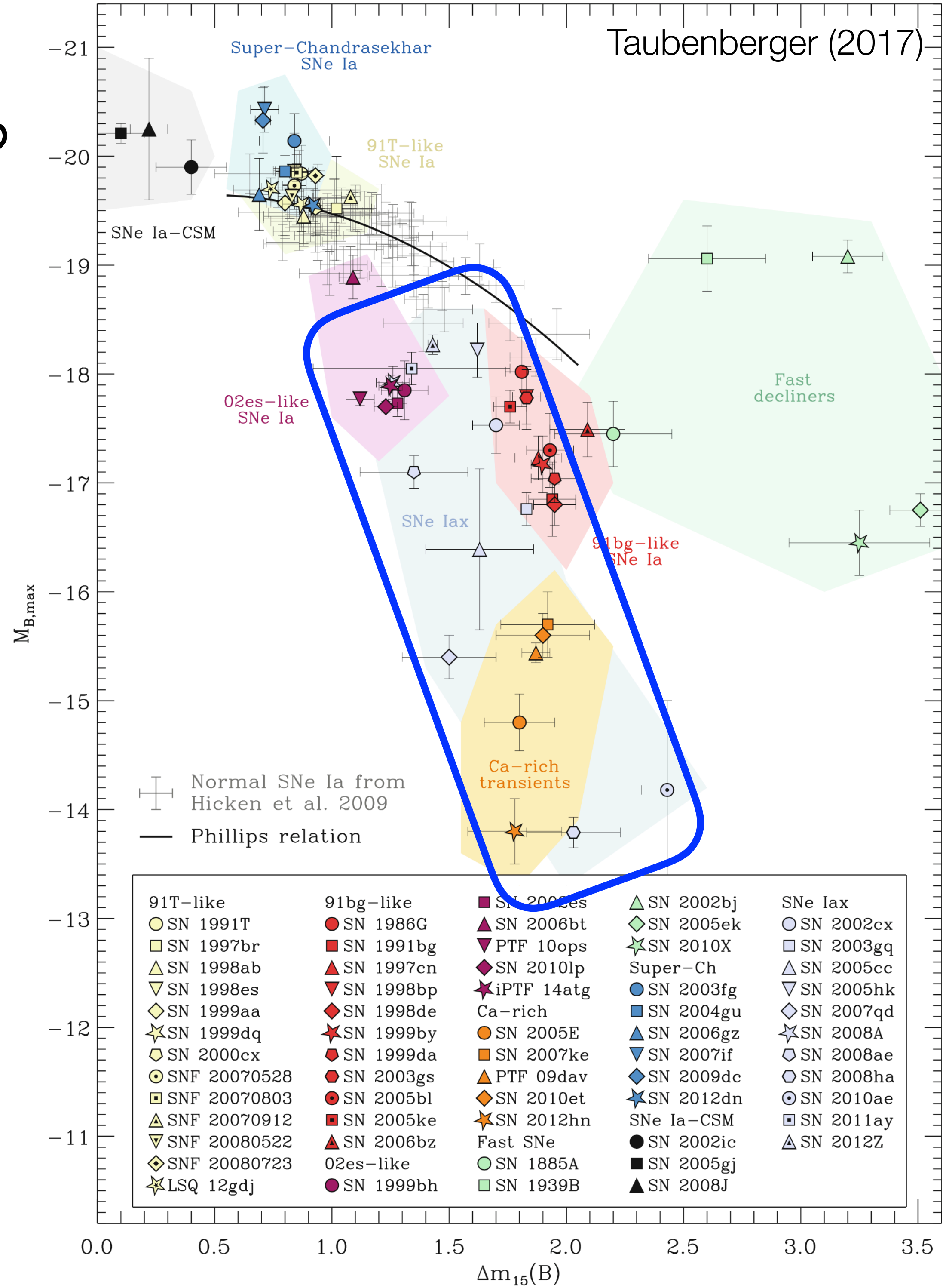
SN 2011fe & SN 2014J explosion sites

- likely from star forming regions — young SNe Ia?



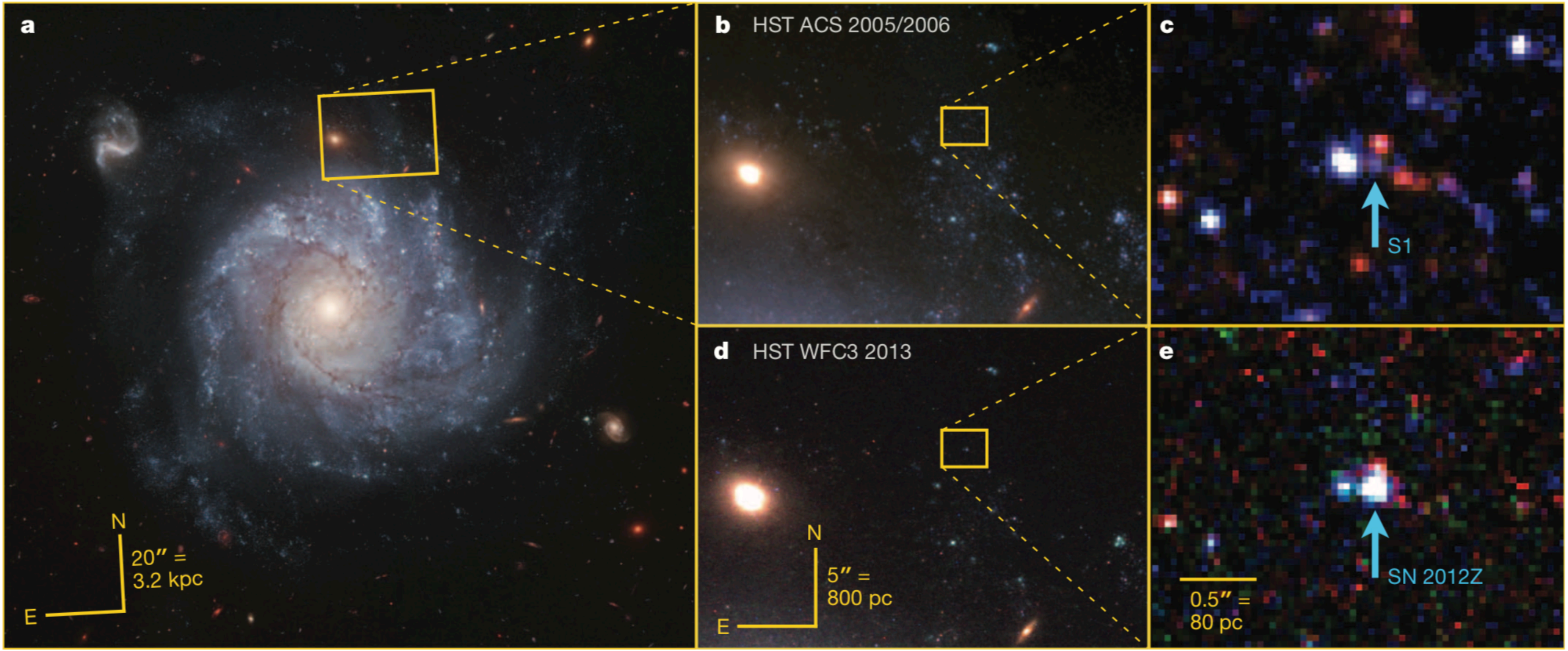
SNe Iax and He donors?

- a peculiar kind of SNe Ia



Possible blue star detected at SN 2012Z

McCully et al. (2014)



- SNe Iax would be interesting targets for radio & X-ray follow-up

Conclusions

- SD He star donor channel is not excluded with current deep limits for CSM density and companion brightness from SN 2011fe and SN 2014J

- SN 2011fe and SN 2014J could be both from young SNe Ia population

- We need nearby old SNe Ia to exclude the SD scenario

- SNe Iax may be related to this channel
    - radio & X-ray observations would be interesting