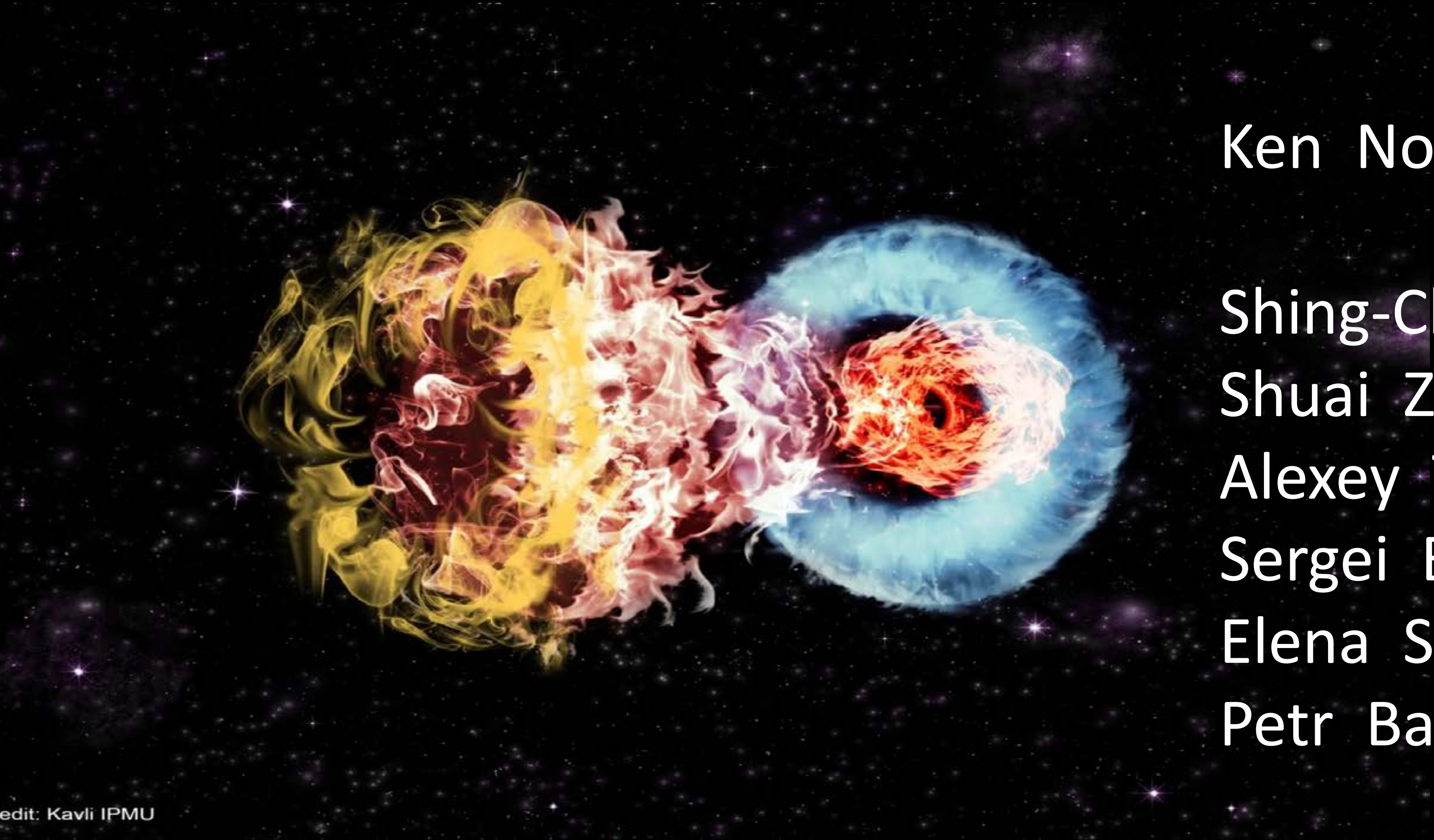
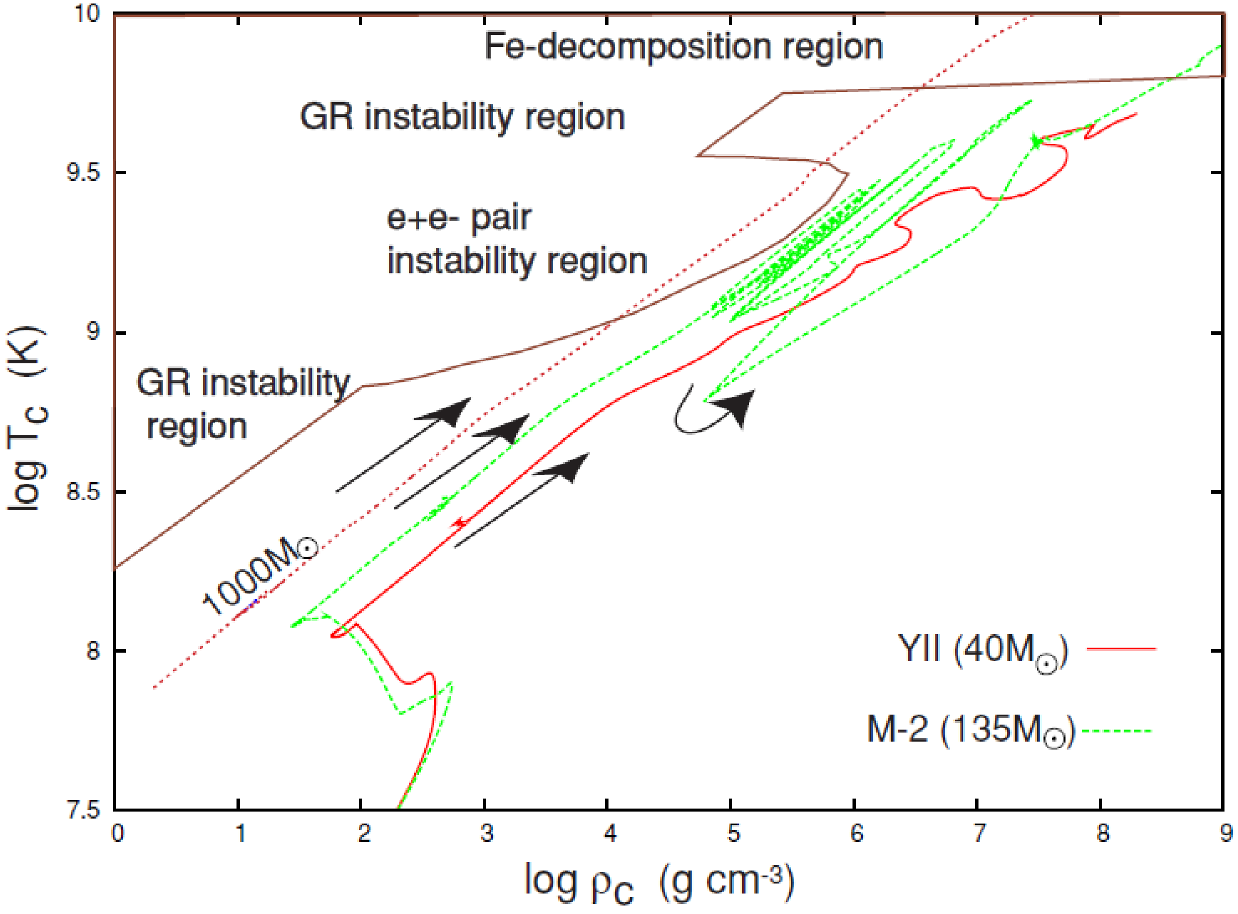
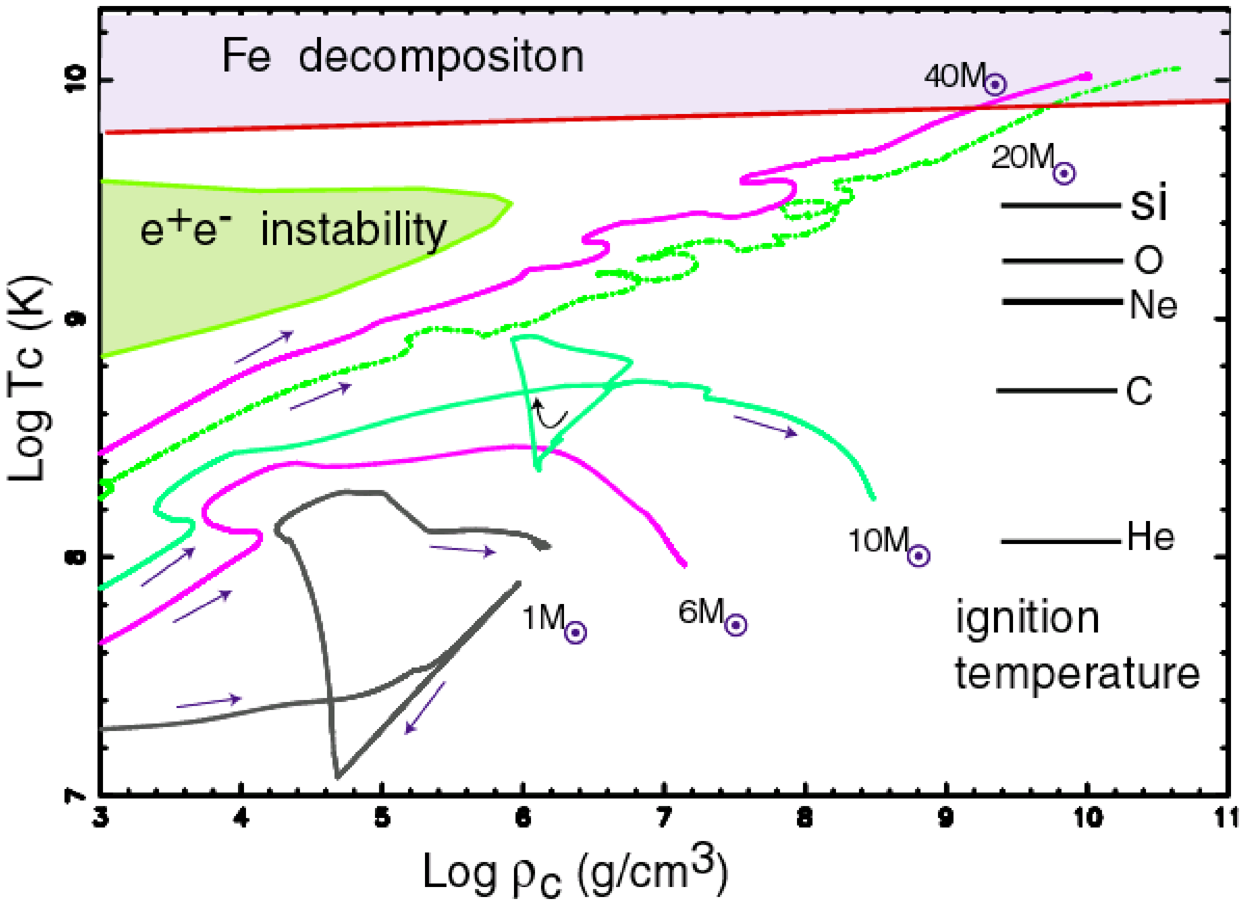
Circumstellar Interaction & Unusual Supernovae (FBOT, SLSN)



Ken Nomoto (Kavli IPMU, U. Tokyo)
Shing-Chi Leung (IPMU → Caltech)
Shuai Zha (Hong Kong → Stockholm)
Alexey Tolstov (IPMU → Moscow)
Sergei Blinnikov (ITEP, Moscow & IPMU)
Elena Sorokina (ITEP)
Petr Baklanov (ITEP)

Stellar Evolution (Mass Dependence)





Diversities of Optical Properties of CC Supernovae

Collapsing **Core** + H-rich **Envelope** + Circumstellar Matter (**CSM**)

Explosion Energy, M(ejecta) **M(env)** **M(CSM)**

Energy Source of Late Light Curve Shock Heating Circumstellar Interaction

Radioactivity, Pulsar/Magnetar, BH ➔ II-P, II-L, II-b ➔ Shock breakout

8–10 $M_\odot$: Degenerate ONeMg Core + Super-AGB Envelope

(**slow** evolution) ➔ **Mass Loss**

➔ ONeMg White Dwarf + Planetary Nebula

➔ **Electron Capture SN** (ECSN) + SAGB Envelope + CSM (He-rich, C-dust)

10–80 $M_\odot$: Fe-core collapse Wolf-Rayet wind

80–140 $M_\odot$: O-core: **Pulsational Pair Instability** ➔ **Mass Ejection** ➔ CSM (**He, CO**)

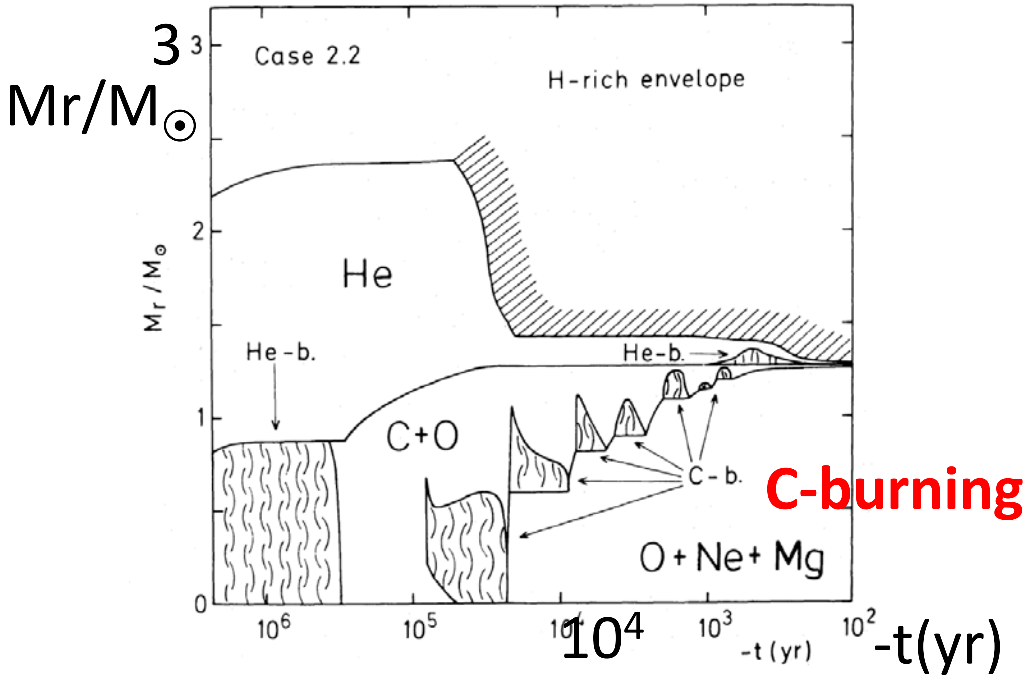
➔ Fe core collapse ➔ BH

140–400 $M_\odot$: O-core: Pair Instability Supernovae > 400 $M_\odot$: Collapse

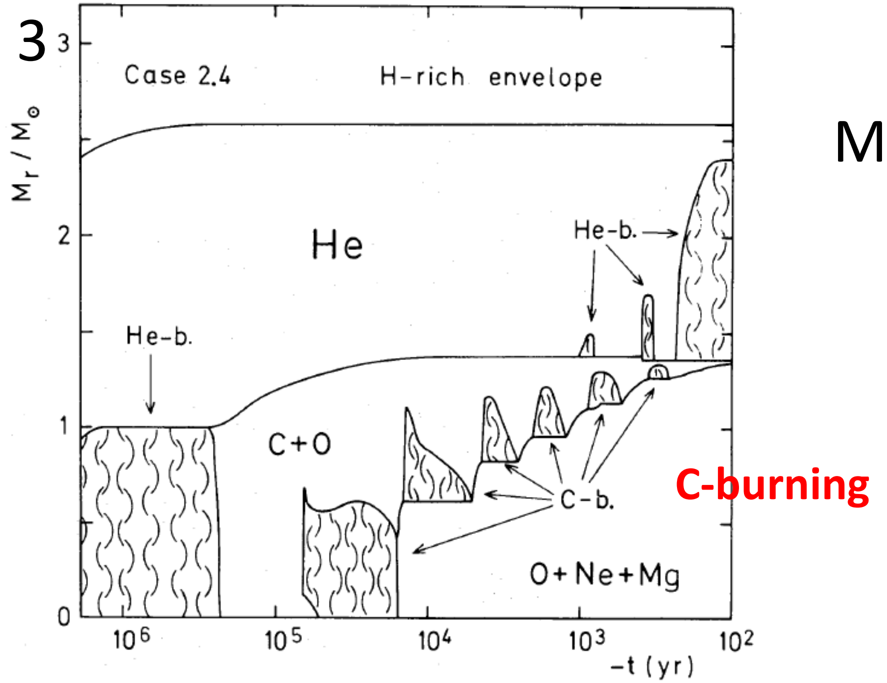
Evolution of 8-10 $M_\odot$ Stars:

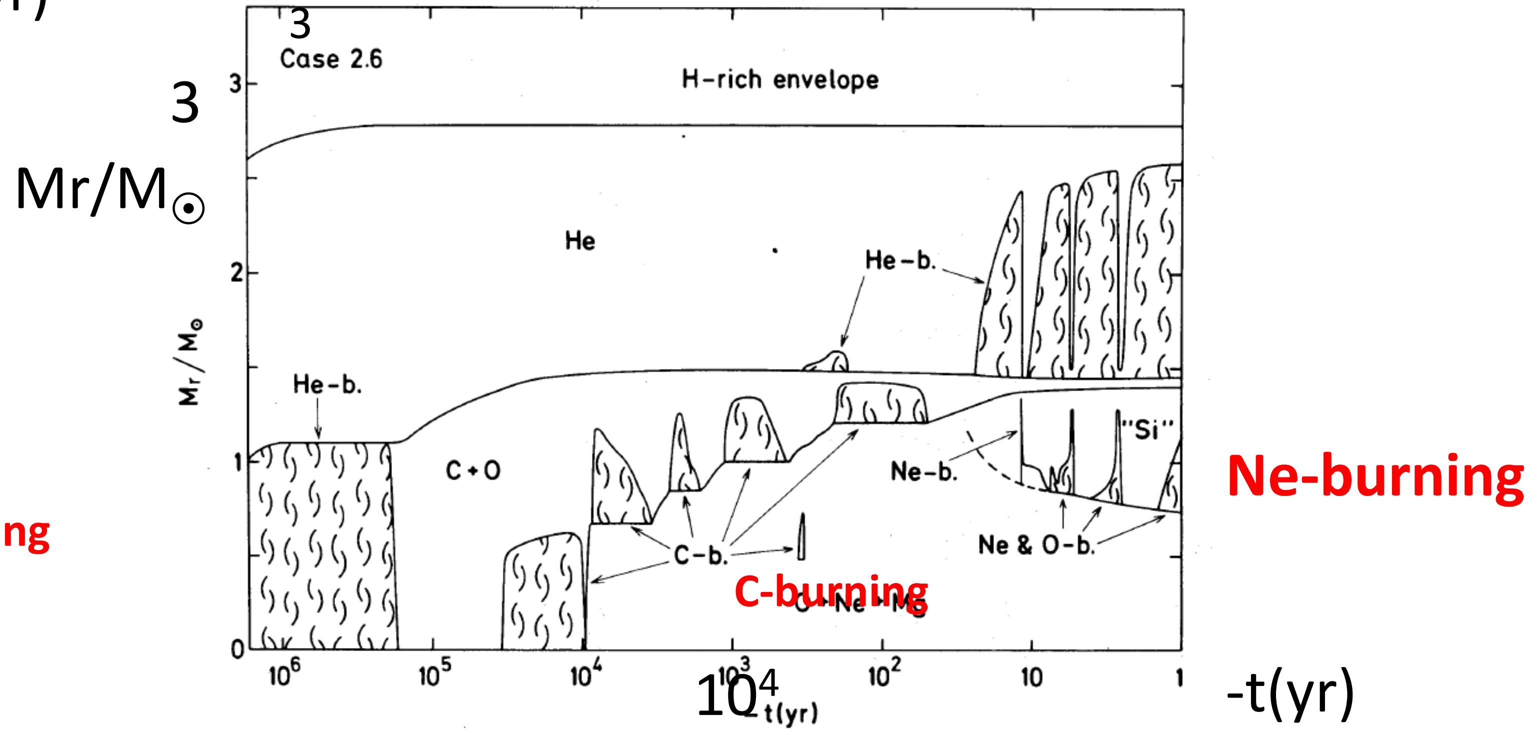
Formation of an electron degenerate ONeMg core

(Nomoto 1982, 84, 87)



Slow Evolution (nuclear timescale)
➔ Importance of Mass Loss



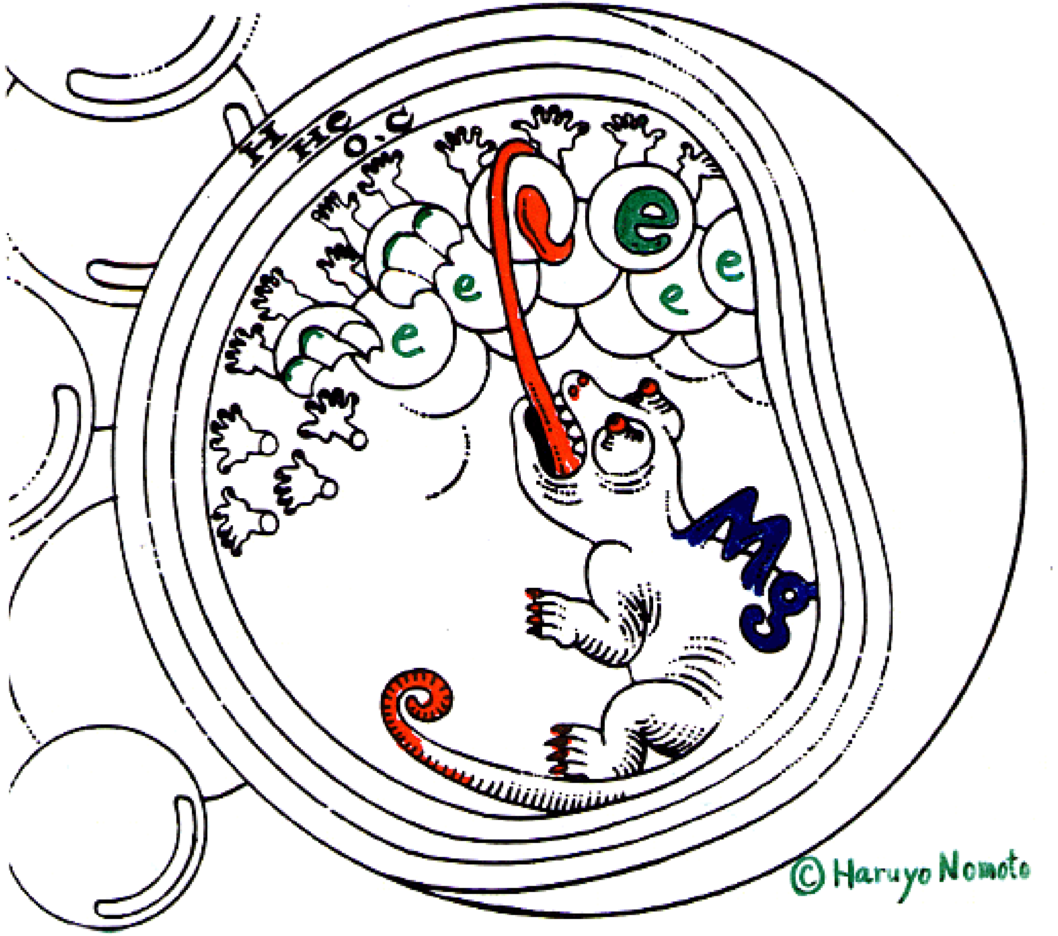


Electron Capture (EC) in 8-10 $M_\odot$ Stars

Electron-degenerate O+Ne+Mg Core

- ^{24}Mg(e$^-$,ν)^{24}Na (e$^-$,ν)^{24}Ne
- $\rho > 4.0 \times 10^9$gcm^{-3}
- →collapse

(Nomoto 1984)



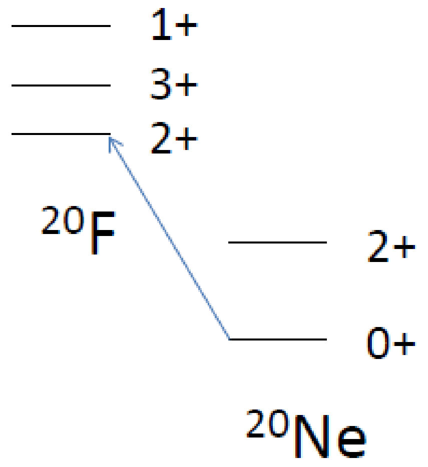
New Electron Capture Rate

Electron capture **(1) decrease in Ye ➔ Collapse**

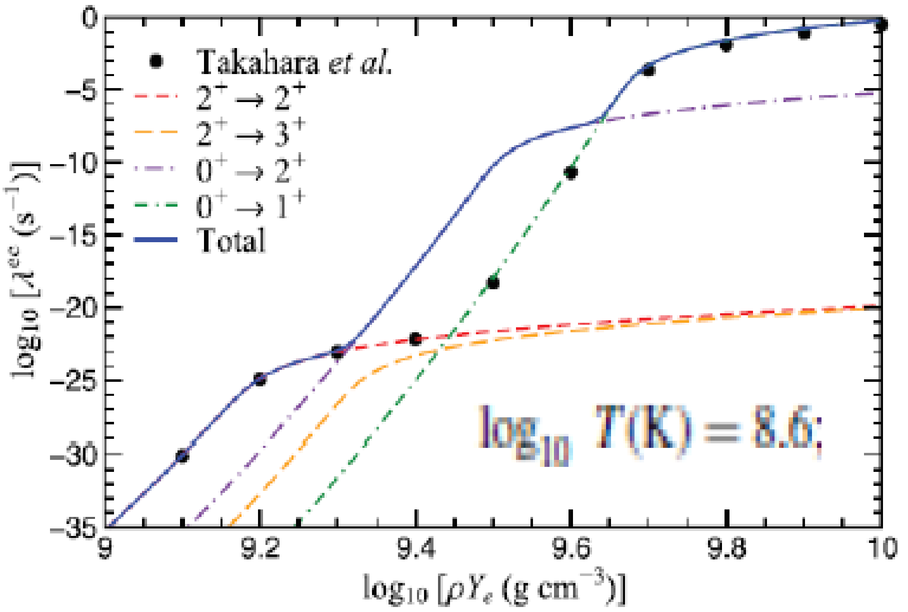
(2) heating ➔ Ne, O deflagration (➔SN Iax; Jones+19)

$^{24}\mathrm{Mg}(e^-,\nu_e)^{24}\mathrm{Na}(e^-,\nu_e)^{24}\mathrm{Ne}$

$^{20}\mathrm{Ne}(e^-,\nu_e)^{20}\mathrm{F}(e^-,\nu_e)^{20}\mathrm{O}$



$^{20}\mathrm{Ne}\ (e^-, \nu)\ ^{20}\mathrm{F}$



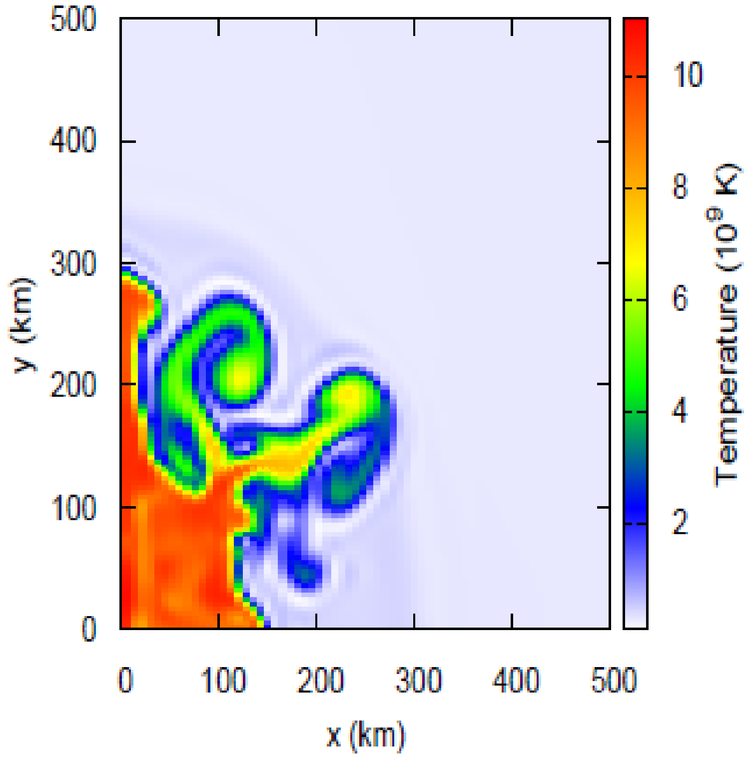
New Rate: 0+ ➔ 2+: 2nd forbidden transition (Suzuki+19, Kirsebom+19)

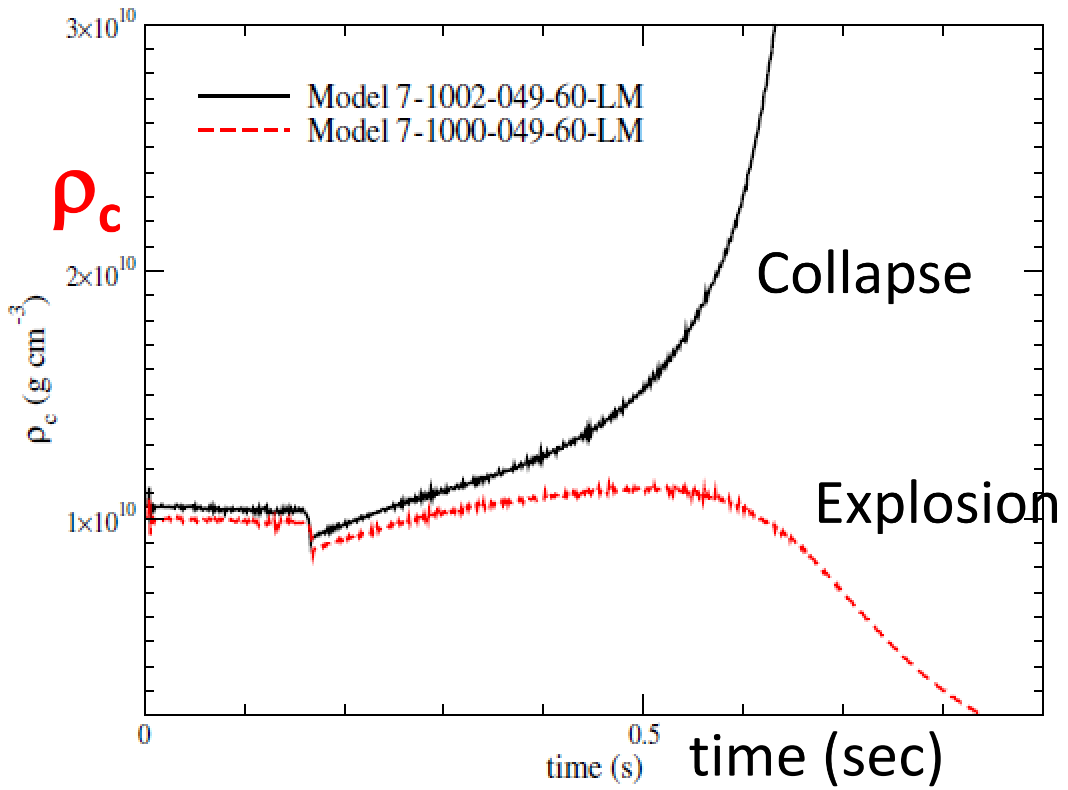
➔ Heating starts at lower density but slow ➔Contraction

➔ Oxygen deflagration starts at **ρ_c ~ $10^{10.1-10.2}$** g cm^{-3} (Zha+19)

Electron capture in O-Ne-Mg Core

- Heating starts at lower density but slow ➔ Contraction
  ➔ Oxygen deflagration starts at ρ_c ~ $10^{10.1-10.2}$ g cm^{-3}
- ➔ **Collapse** (Zha+19: ApJ) **: AIC**





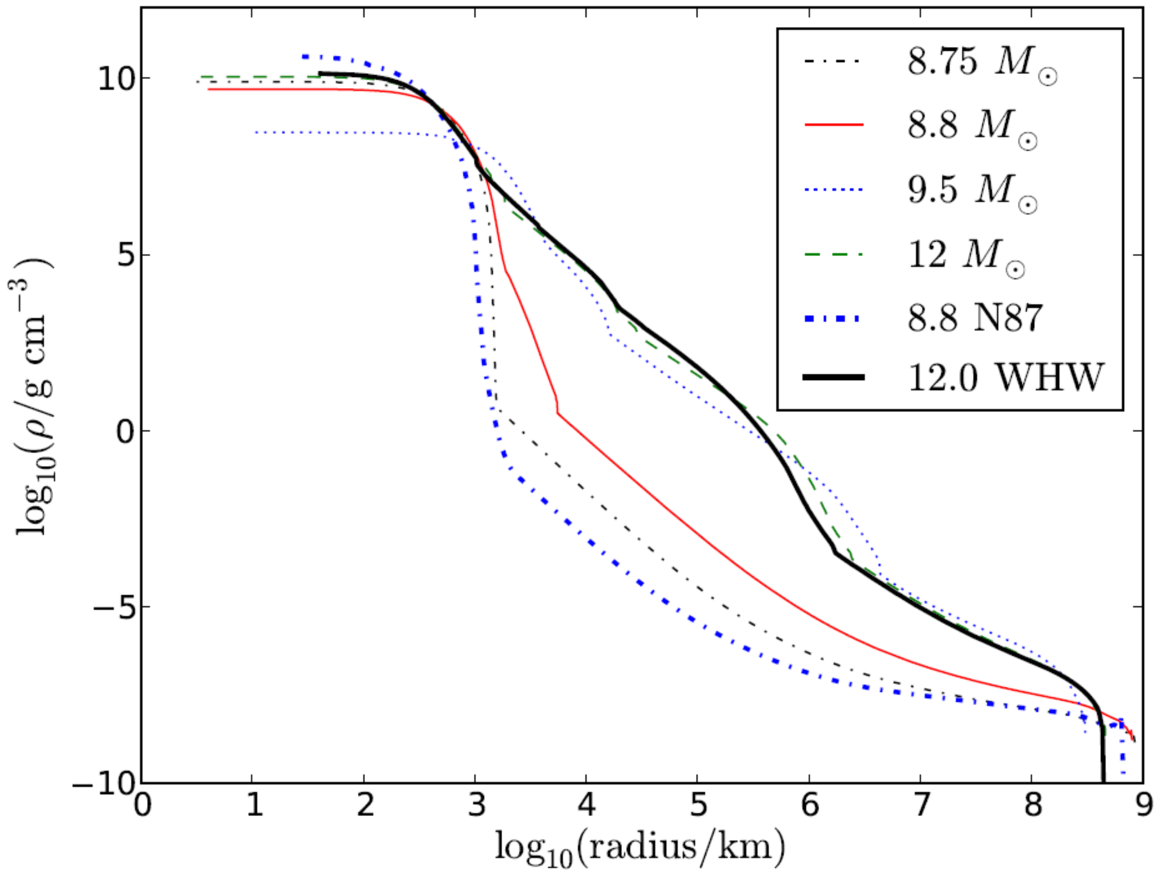
2D simulations: Oxygen deflagration starting from ρ_c > (<) $10^{10.0}$ g cm^{-3}

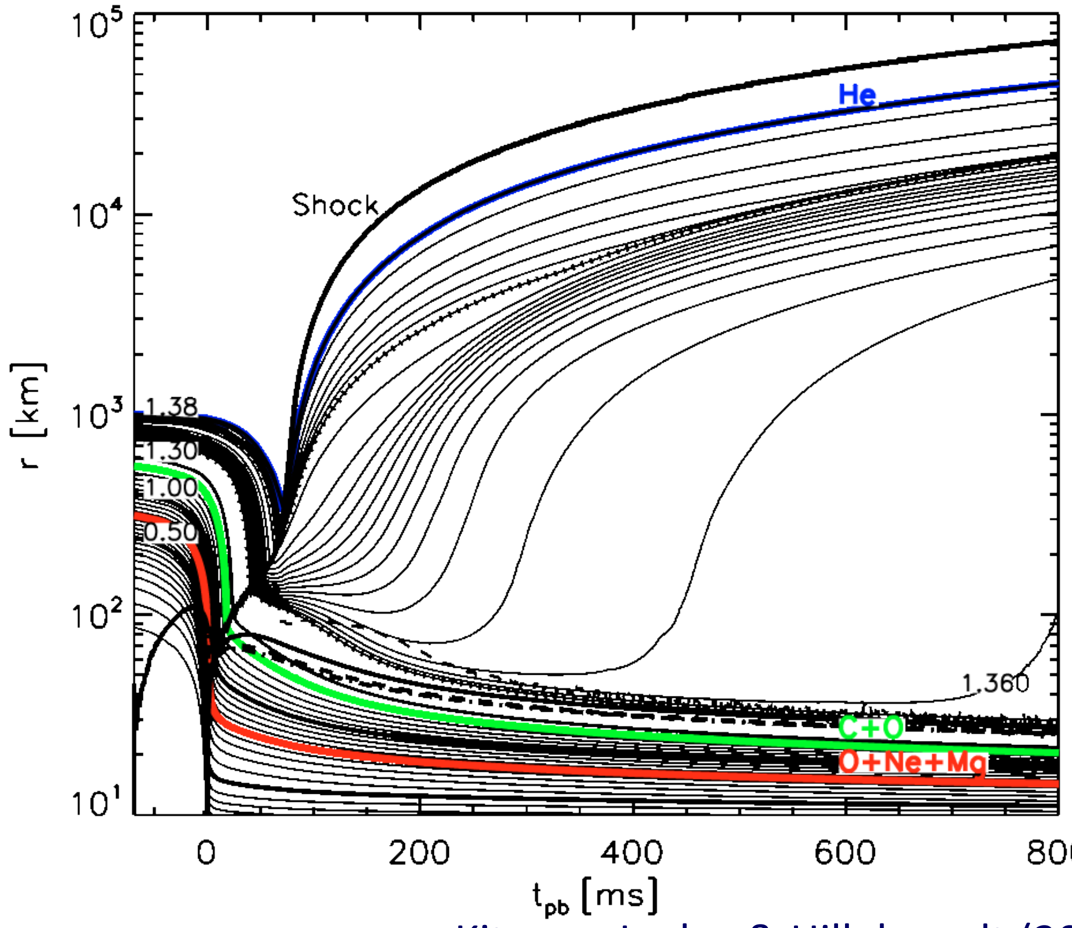
➔ **Collapse** **(Explosion)** (Zha+19)

8.8 $M_\odot$ Star: Neutrino Heating → Weak Explosion

E_{exp} =1×10^{50}erg ; M_{ej}=0.011$M_\odot$; M (^{56}Ni) = 0.003 $M_\odot$

Neutron Star: M_B ~ 1.36 $M_\odot$ → M_G ~ 1.22 $M_\odot$





Kitaura, Janka, & Hillebrandt (2006)

Diversities of Optical Properties of CC Supernovae

Collapsing Core + H-rich Envelope + Circumstellar Matter (CSM)

Energy Source of Late Light Curve Shock Heating Circumstellar Interaction

Radioactivity, Pulsar/Magnetar, BH ➔ II-P, II-L, II-b ➔ Shock breakout

8–10 $M_\odot$: Degenerate ONeMg Core + Super-AGB Envelope

(**slow** evolution) ➔ **Mass Loss**

➔ ONeMg White Dwarf + Planetary Nebula

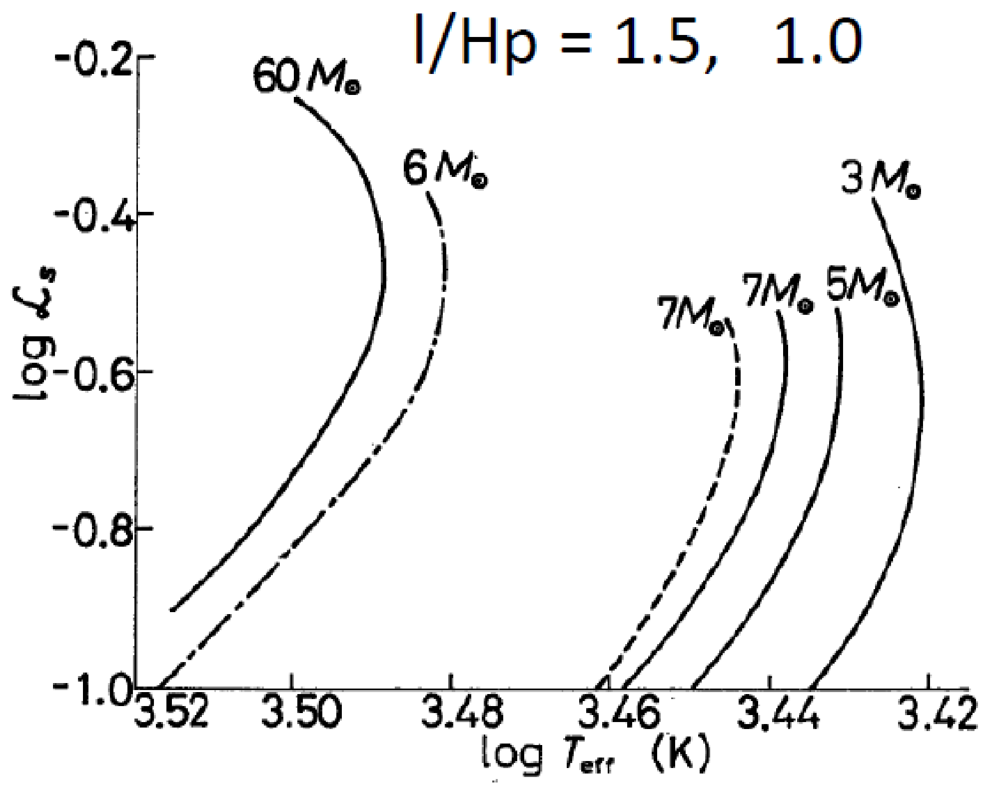
➔ Electron Capture SN (ECSN) + SAGB Envelope + CSM (He-rich, C-dust)

H-rich Envelope of Super-AGB Stars

- Thin He shell
  - ➔ Thermal pulses of He shell burning (C, s-process synthesis)
  - ➔ 3rd Dredge-up of the He layer

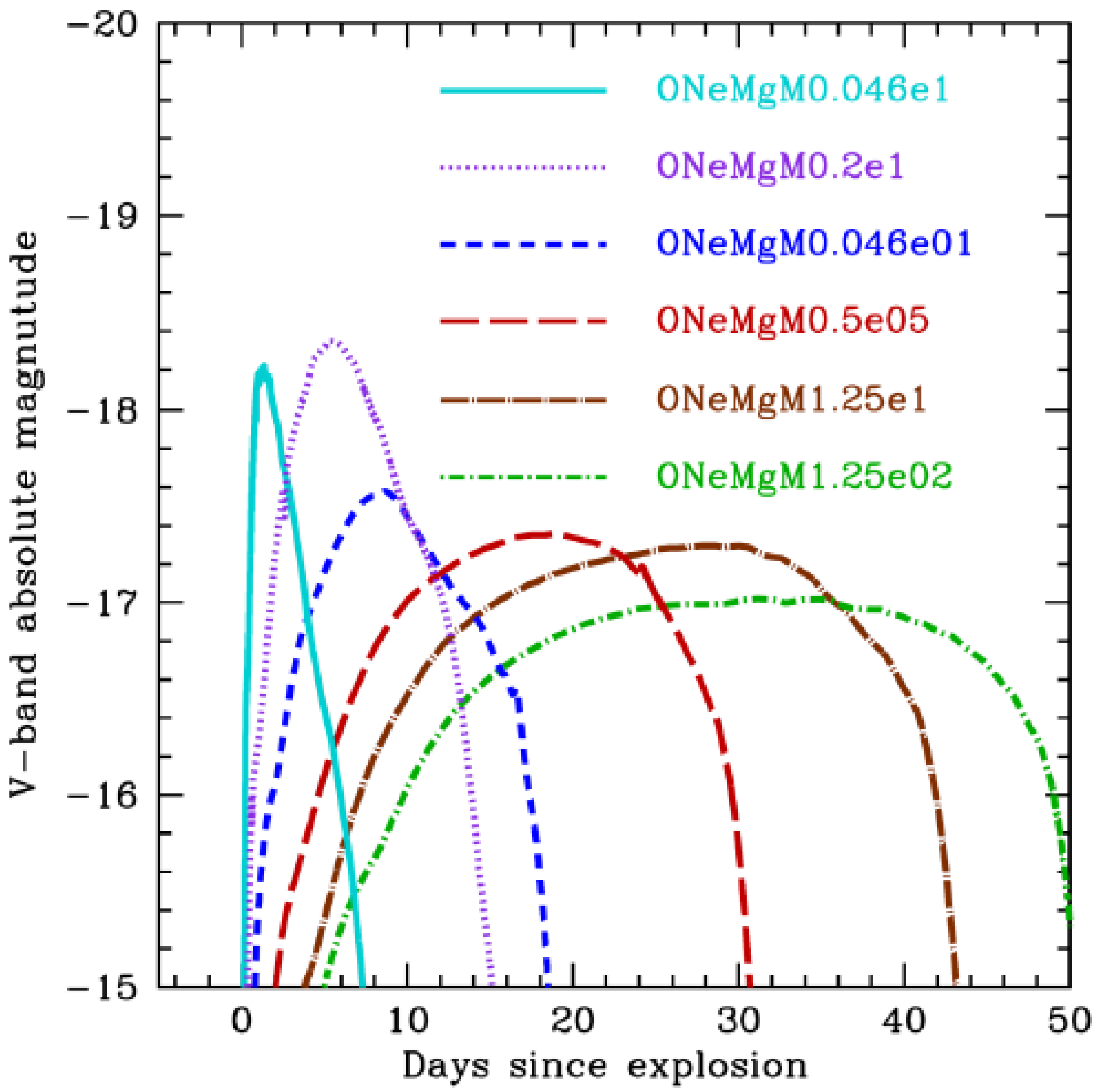
- **Extensive mass loss** (C-dust ?)
  - ➔ Small mass H-rich envelope and Dense Circumstellar Matter (dusty)

  - ➔ SN IIn ? II-L ?? II-pec ??



(Nomoto et al. 1972)

V-band light curve simulations (M ~ 0.05 – 1.25 $M_\odot$)

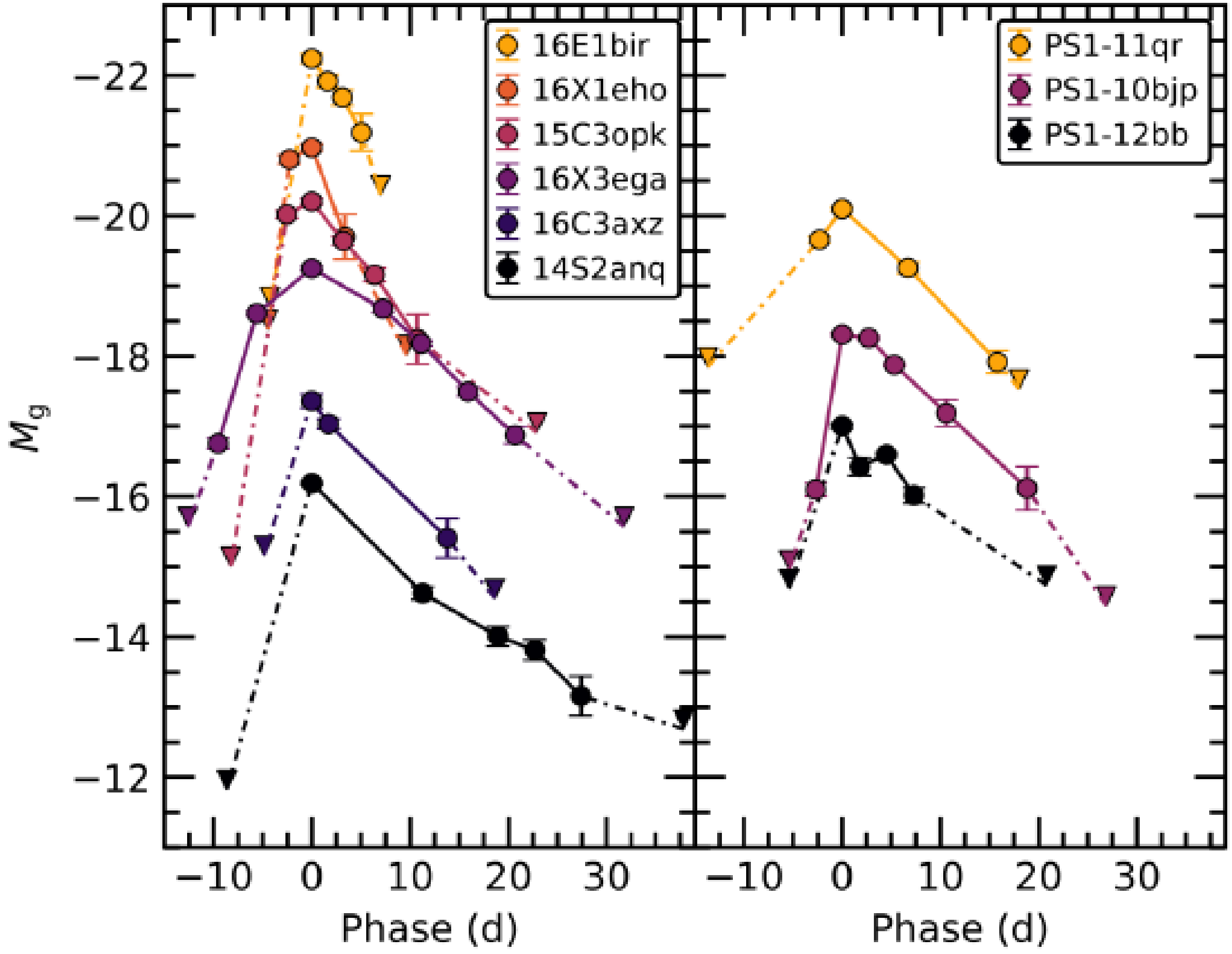


- Rise-time t_{rise} versus width of the peak Δ
- M ~ 1 $M_\odot$:
  t_{rise} > 10 d
  Δ ~ 10 – 30 d
- M ~ 0.1 $M_\odot$:
  t_{rise} ~ 2-5 d
  Δ < 10 d

(Tolstov , KN +19, ApJ)

Fast Evolving Luminous Transients (FELT)

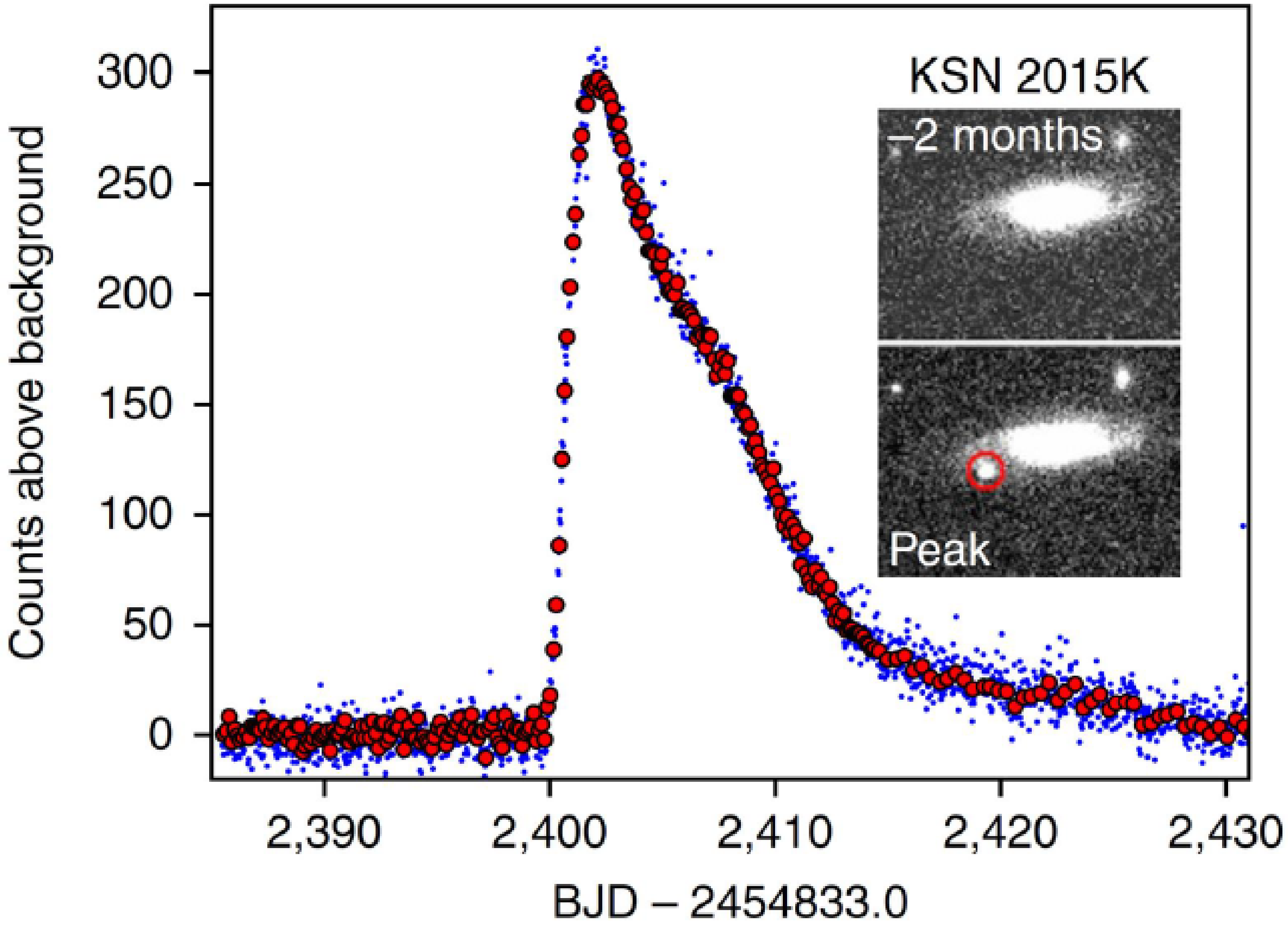
Fast Blue Optical Transients (FBOT)



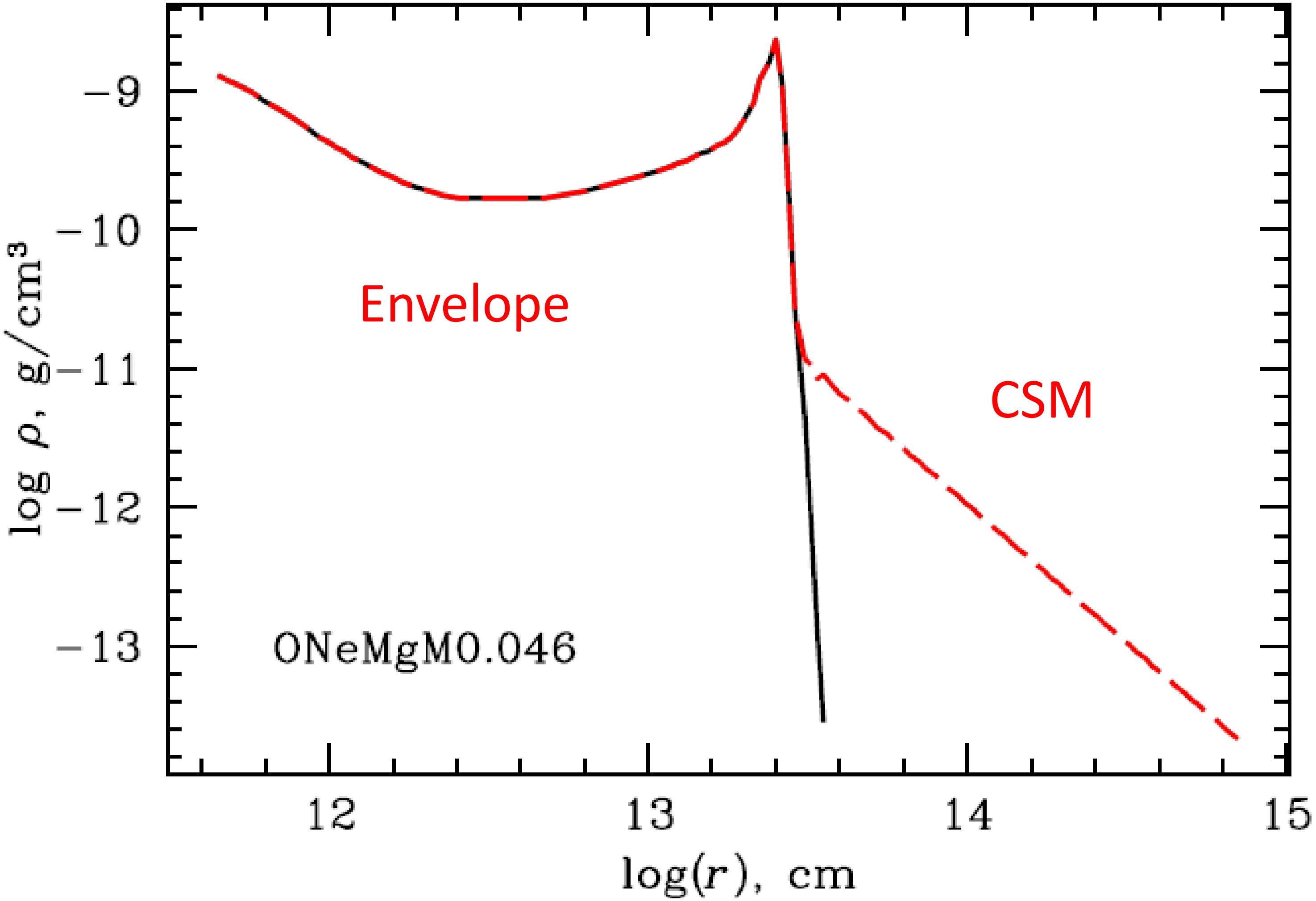
- KSN 2015K (Rest+2018), AT 2018cow (Prentice+2018)

K2/Kepler light curve of KSN 2018K

Rest+ 2018



Super AGB H-rich Envelope + Circumstellar Matter

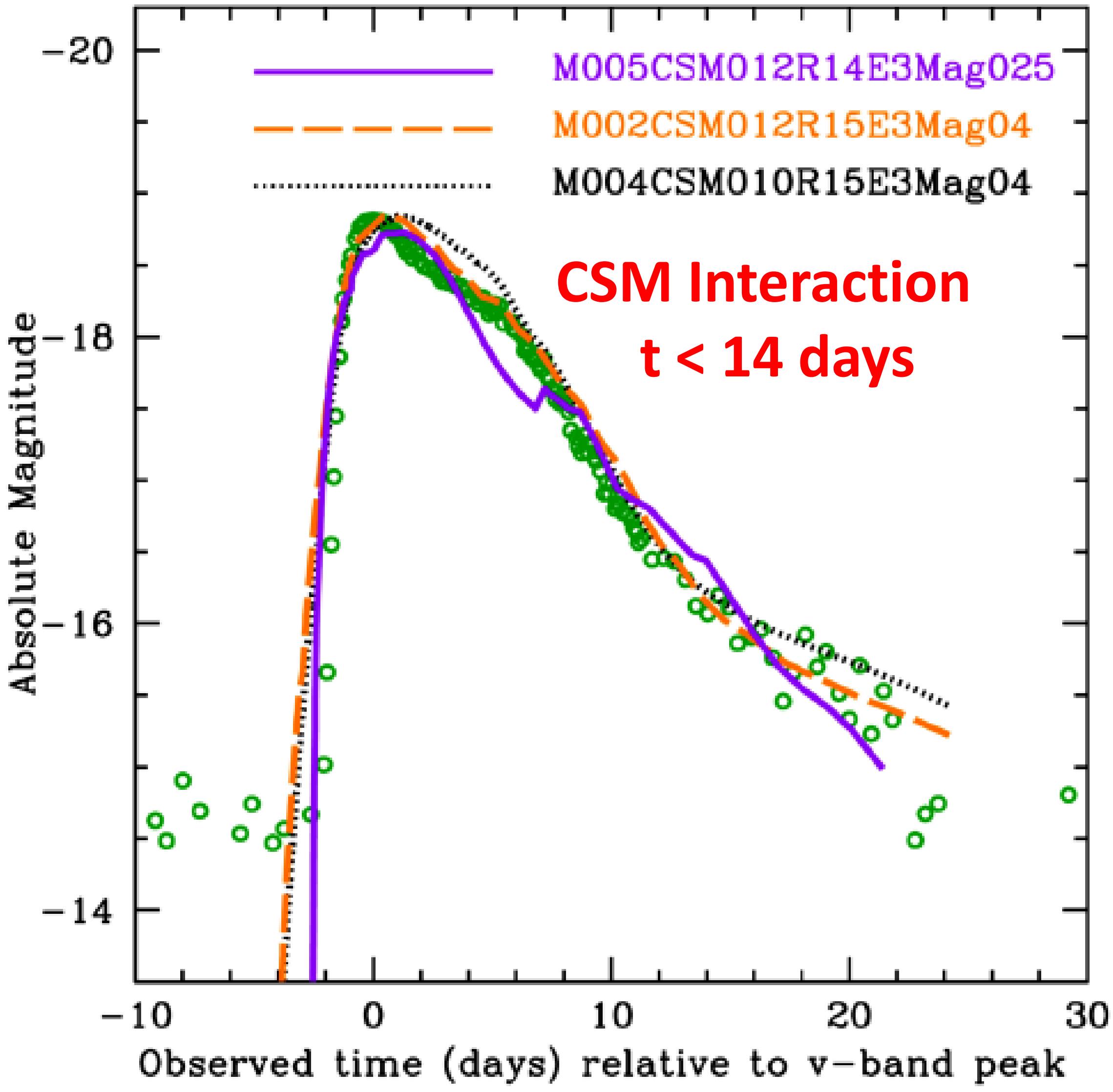


- $M_{ej} \sim 10^{-2} M_\odot$
- $M_{CSM} \sim 0.10\text{-}0.12\ M_\odot$
- $R_{ph} \sim 10^{14}$ cm
- $E_{kin} \sim 10^{50}$ erg
- Pulsar(?):
  $P \sim 20$ ms
  $B \sim 2 \cdot 10^{12}$ G

CSM formation ~ a few years

(Tolstov , KN +19, ApJ)

KSN 2015K V-band light curve simulations



- $M_{ej} \sim 10^{-2}\, M_\odot$
- $M_{CSM} \sim 0.10\text{-}0.12\, M_\odot$
- $R_{ph} \sim 10^{14}$ cm
- $E_{kin} \sim 10^{50}$ erg
- Pulsar(?): **t > 14 days**

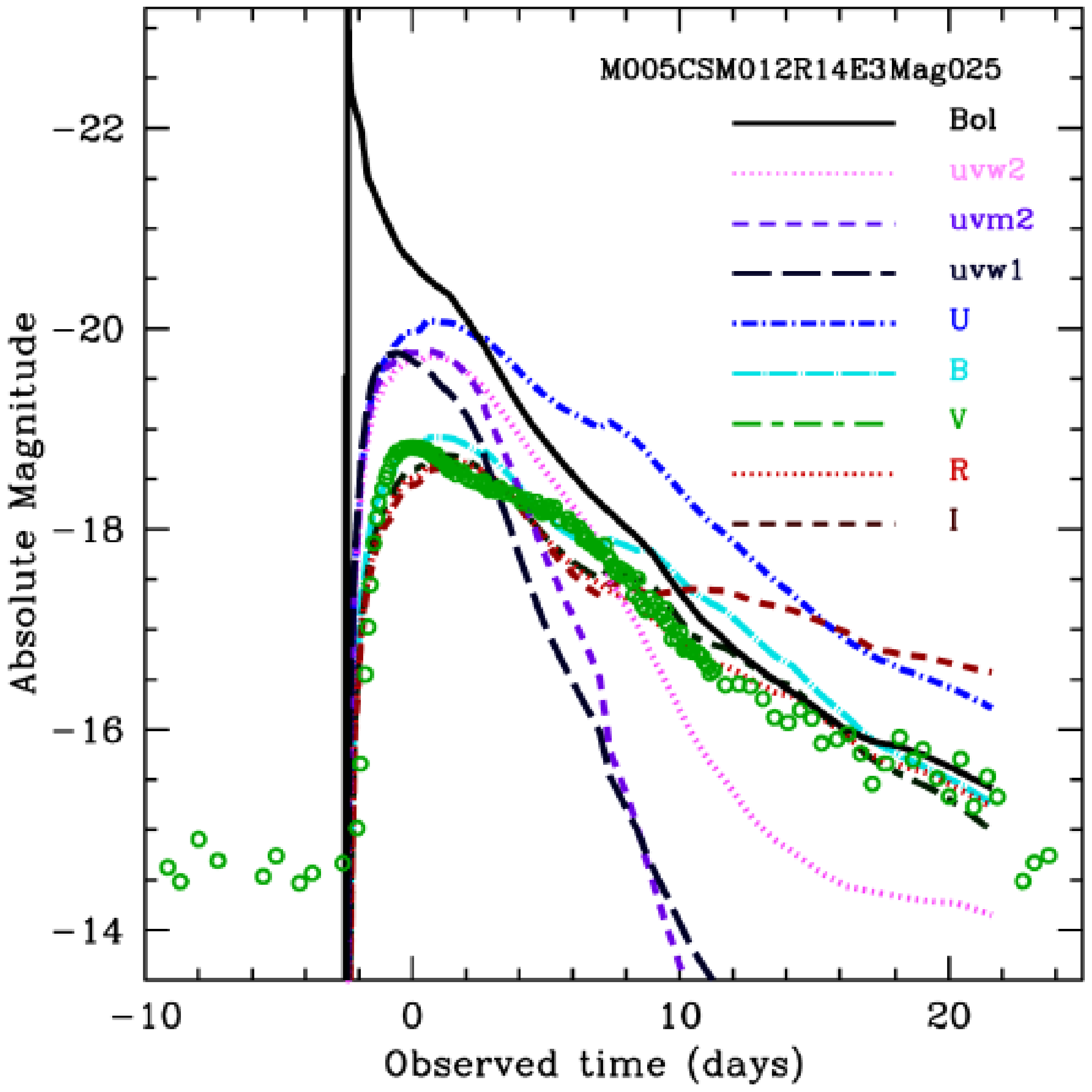
  $P \sim 20$ ms

  $B \sim 2{\cdot}10^{12}$ G

- Smearing term: Multi-D is required

(Tolstov , KN +19, ApJ)

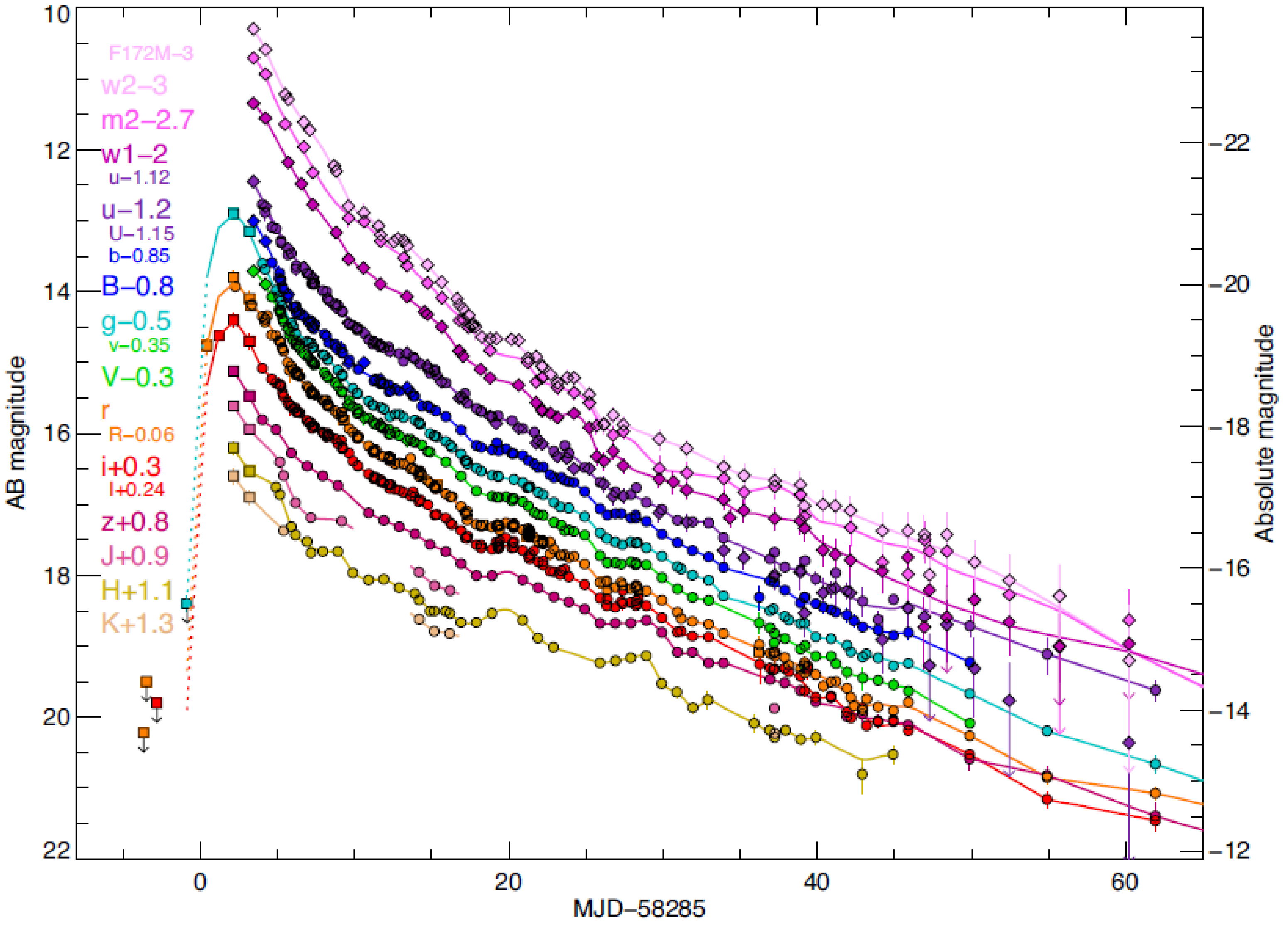
KSN 2015K multiband LC simulations



- Peak: soft X-rays (100 eV)
- Bright U-band and UV emission
- g-r ~ - 0.3 (peak)
  g-r ~ - 0.2 (+8 d)
- $V_{ph} \geq 10{,}000$ km/s

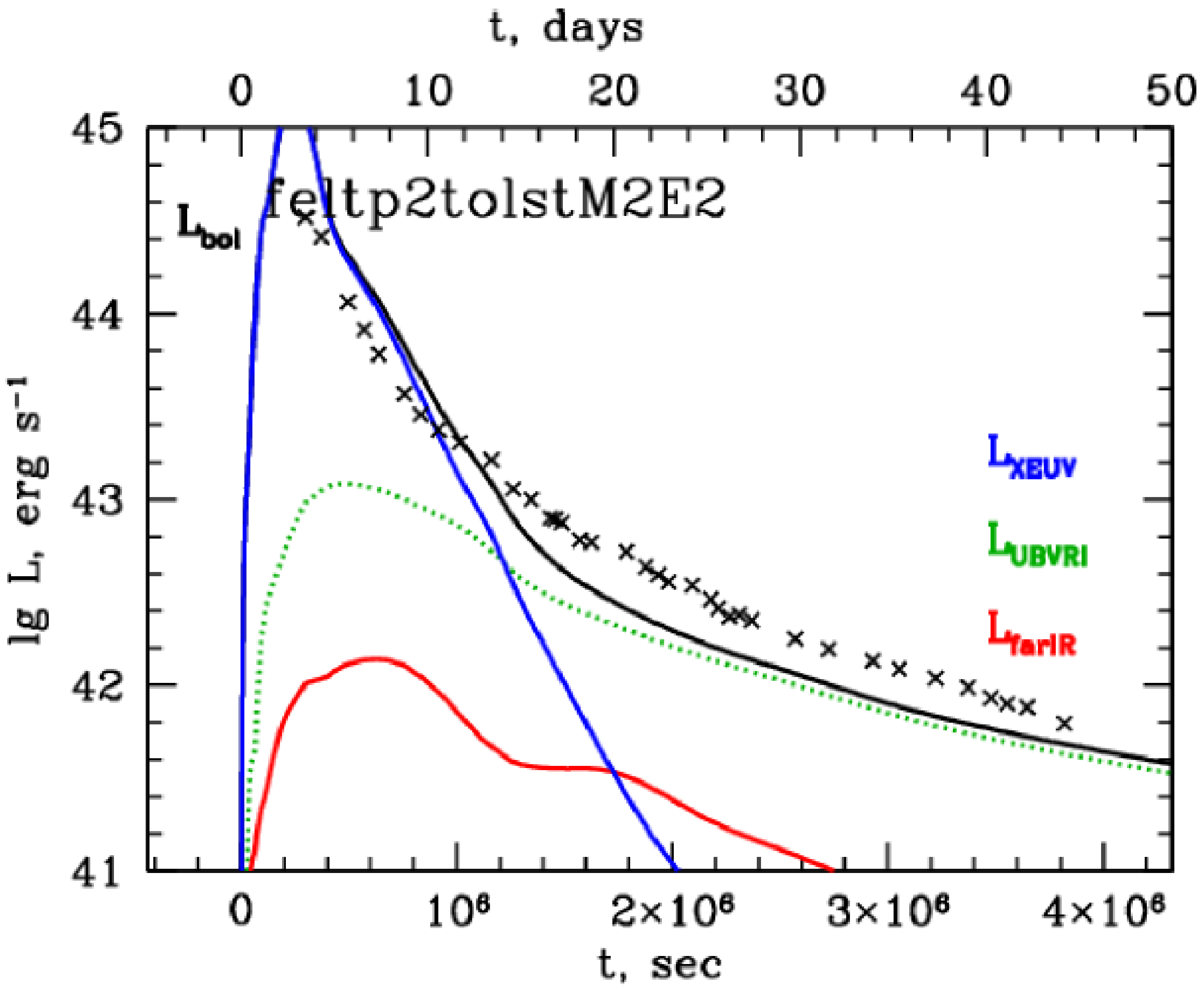
(Tolstov , KN +19, ApJ)

AT2018cow (Fast Blue Optical Transient)



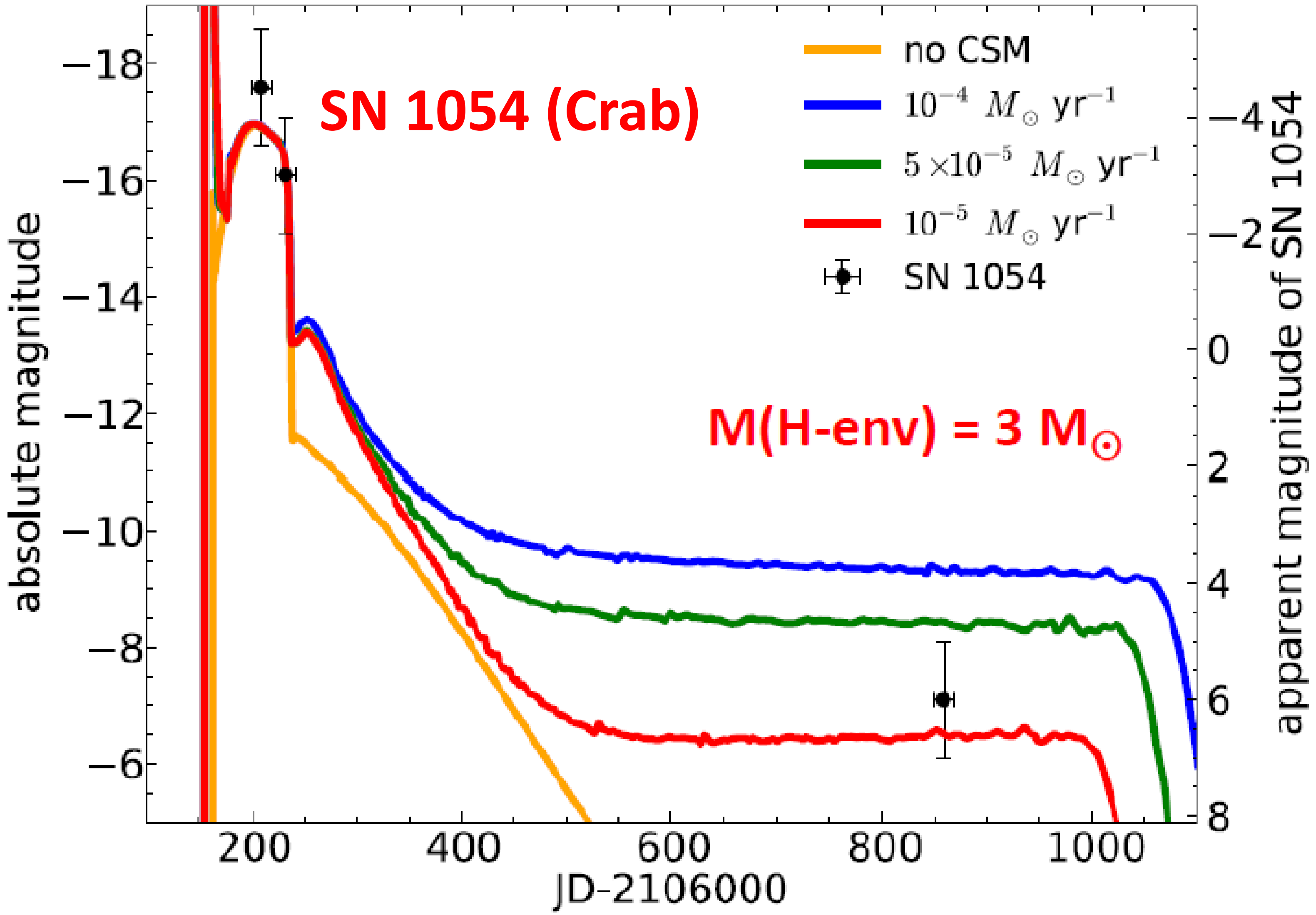
Perley+19

Multiband LC simulations for AT 2019cow



(Tolstov +19)

Light Curves of ECSNe with CSM Interaction



Moriya, Tominaga, Langer, Nomoto, Blinnikov, Sorokina (2014)

Diversities of Electon Capture Supernovae

Collapsing ONeM Core + He-rich Envelope + CSM → SN

M(core) = 1.36 $M_\odot$ M (env) < 0.1 $M_\odot$ **Fast Blue Optical Transient**

KSN 2015K, AT2018cow

M (env) ~ 0.1 - 7 $M_\odot$ SN II-L. II-P ?

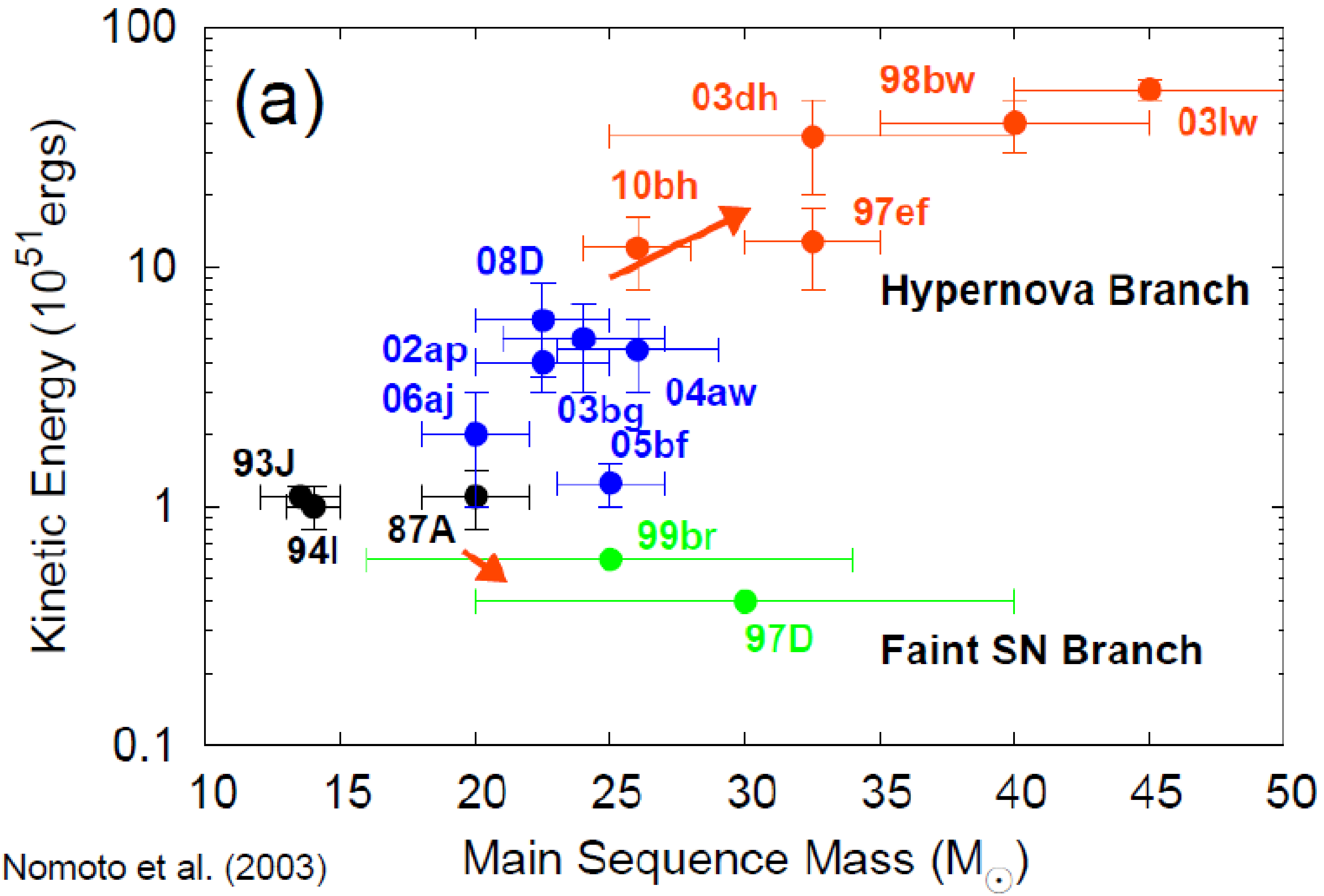
M (env) ~ 1 - 3 $M_\odot$ **Crab-like** SN

Energy Source of Late Light Curve

Pulsar, Circumstellar Interaction

M = 10 – 50 $M_\odot$: GRB Supernovae

SNe [M_{ms}-E relation]



Nomoto et al. (2003)

Diversities of Optical Properties of CC Supernovae

Collapsing Core + H-rich Envelope + Circumstellar Matter (CSM)

Energy Source of Late Light Curve Shock Heating Circumstellar Interaction

Radioactivity, Pulsar/Magnetar, BH ➔ II-P, II-L, II-b ➔ Shock breakout

10–80 $M_\odot$: Fe-core collapse Wolf-Rayet wind

80–140 $M_\odot$: O-core: Pulsational Pair Instability ➔**Mass Ejection** ➔CSM (**He, CO**)

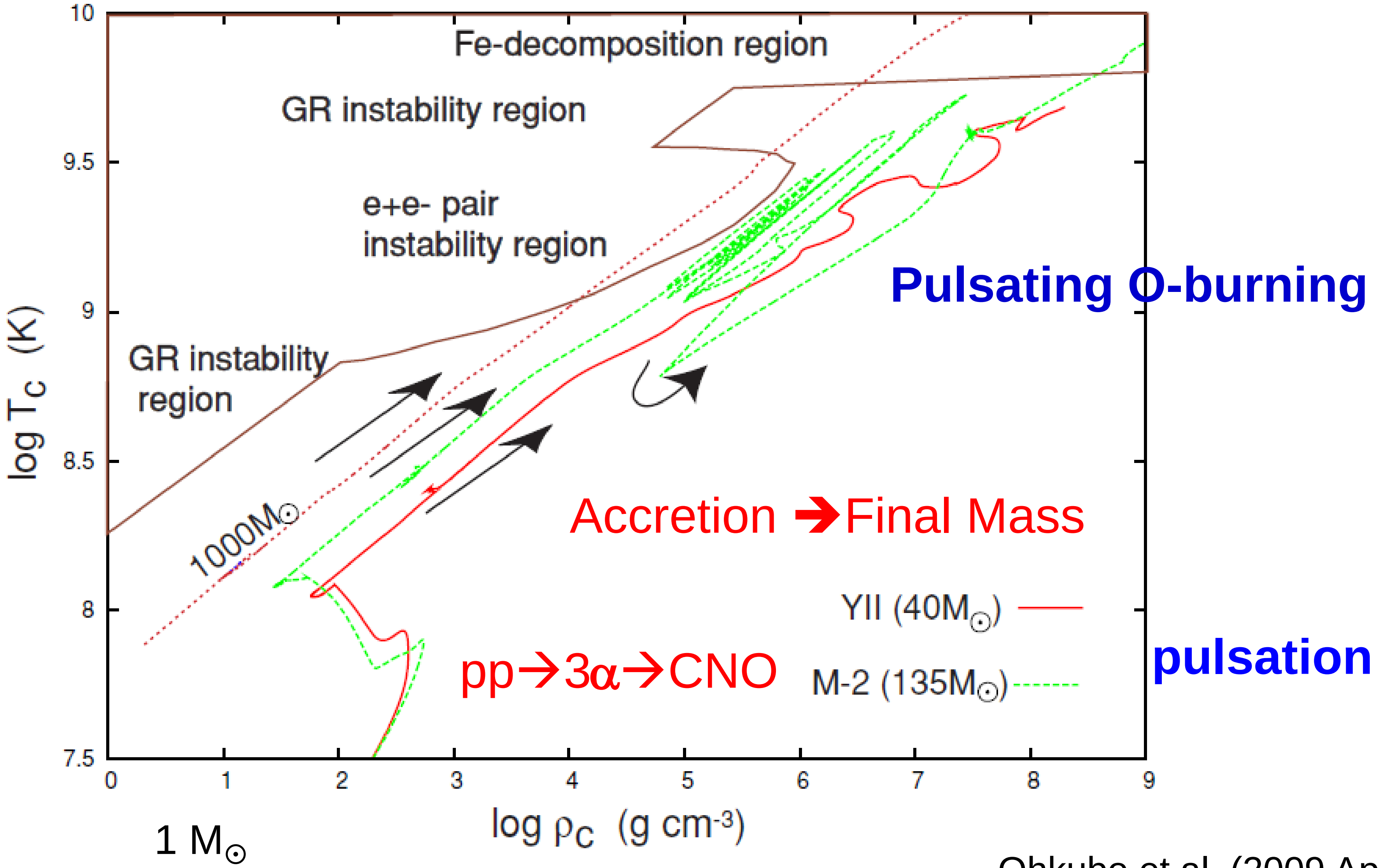
➔ Fe core collapse ➔ BH

140–400 $M_\odot$: O-core: Pair Instability Supernovae

> 400 $M_\odot$: Collapse

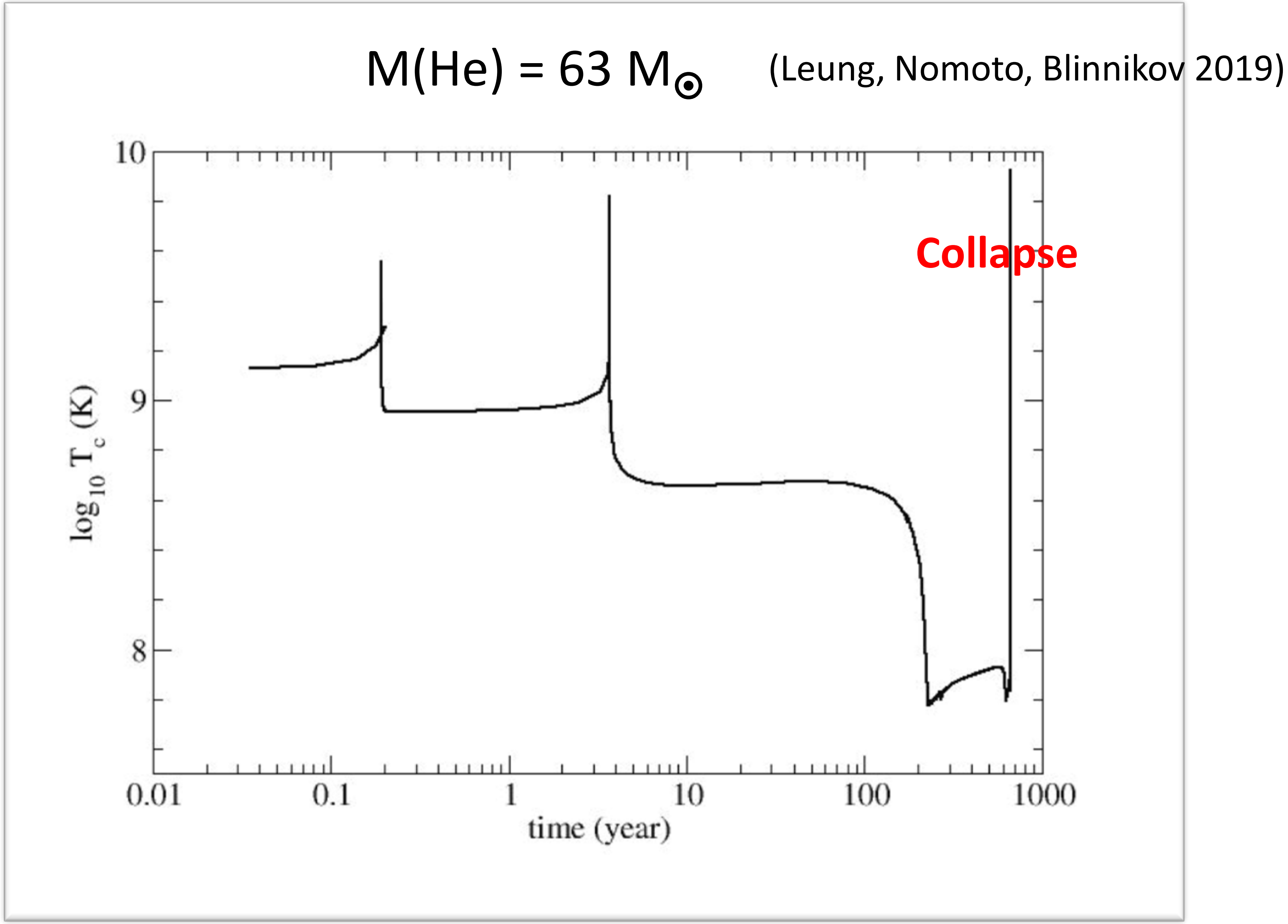
Pulsating O & Si Burning ➔ CSM ?

Pulsational Pair-Instability (80-140 $M_\odot$)

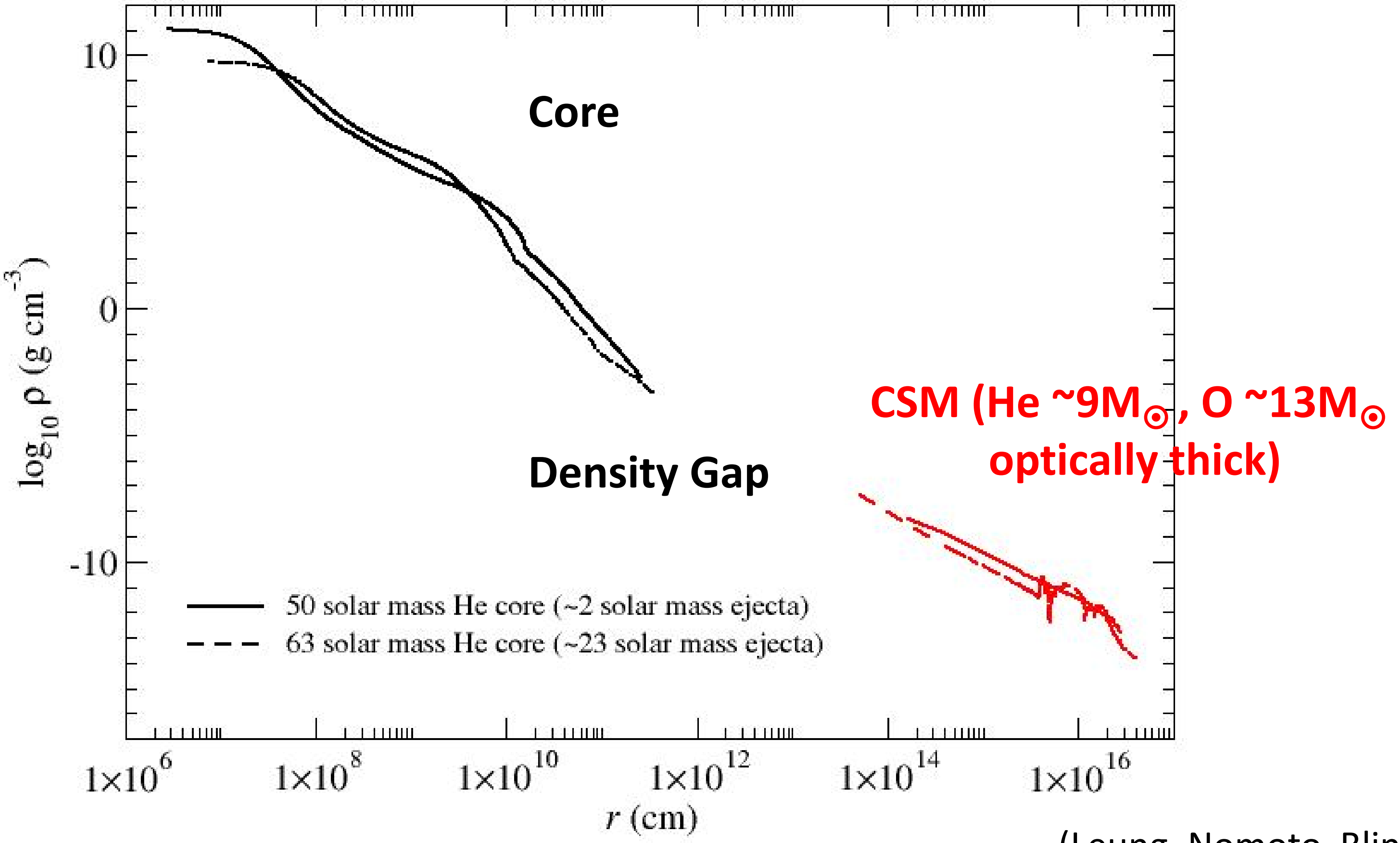


Ohkubo et al. (2009 ApJ)

Pulsational Pair-Instability (PPI)

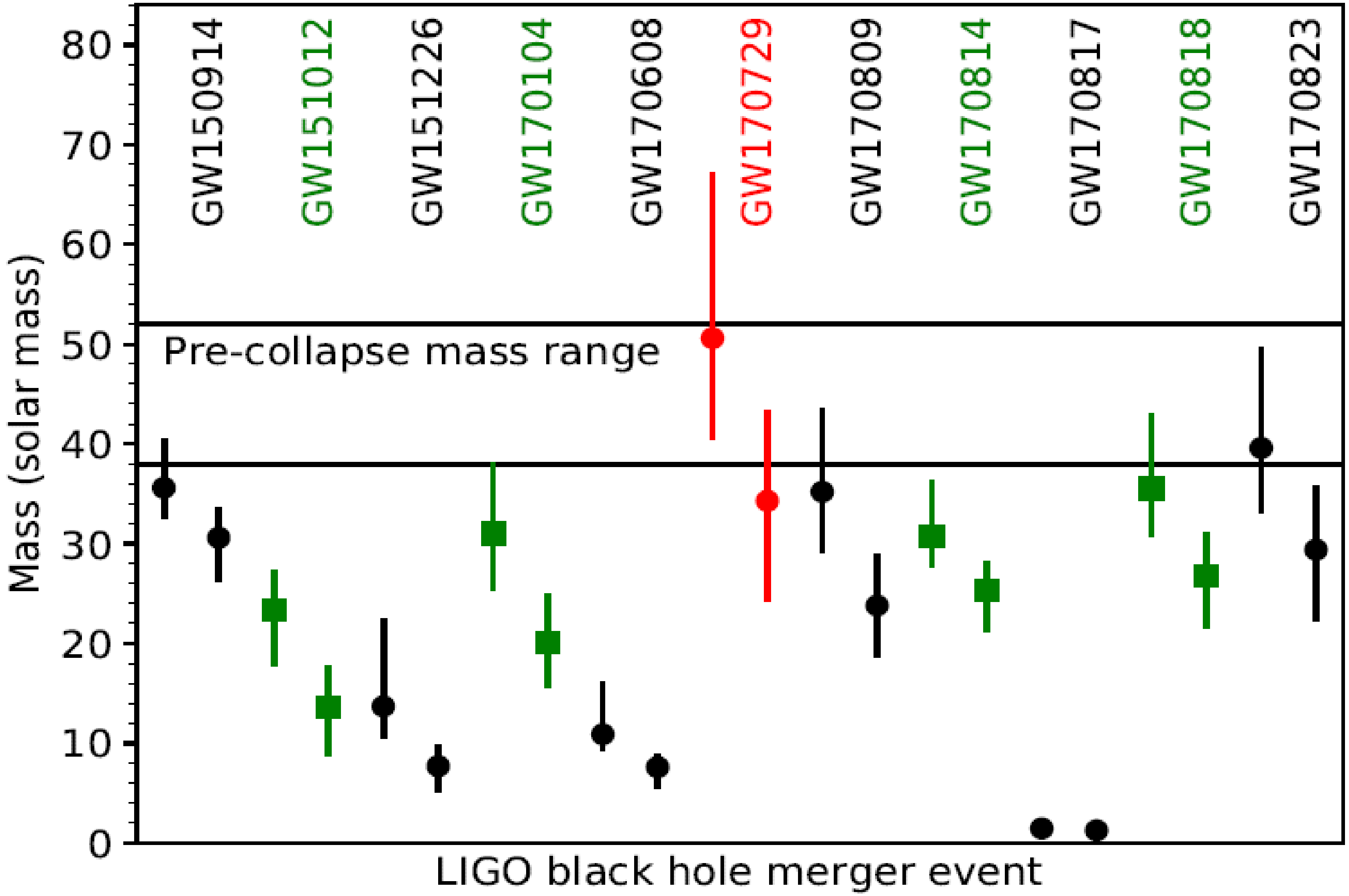


Pre-Collapse Core and CSM after PPI



(Leung, Nomoto, Blinnikov 2019)

LIGO BH masses vs. PPISN masses



(Leung, Nomoto, Blinnikov 2019)

~80 – 140 $M_\odot$ Stars

Pulsational Pair-Instability (PPI: Barkat+)

➔ Pulsational Mass Ejection (Woosley, Marchant+, Leung-KN)

➔ Dense Circumstellar Matter

M(CSM: He, C, O) ~ 4 – 40 $M_\odot$

Circumstellar Interaction ➔

Type I Superluminous Supernovae ?

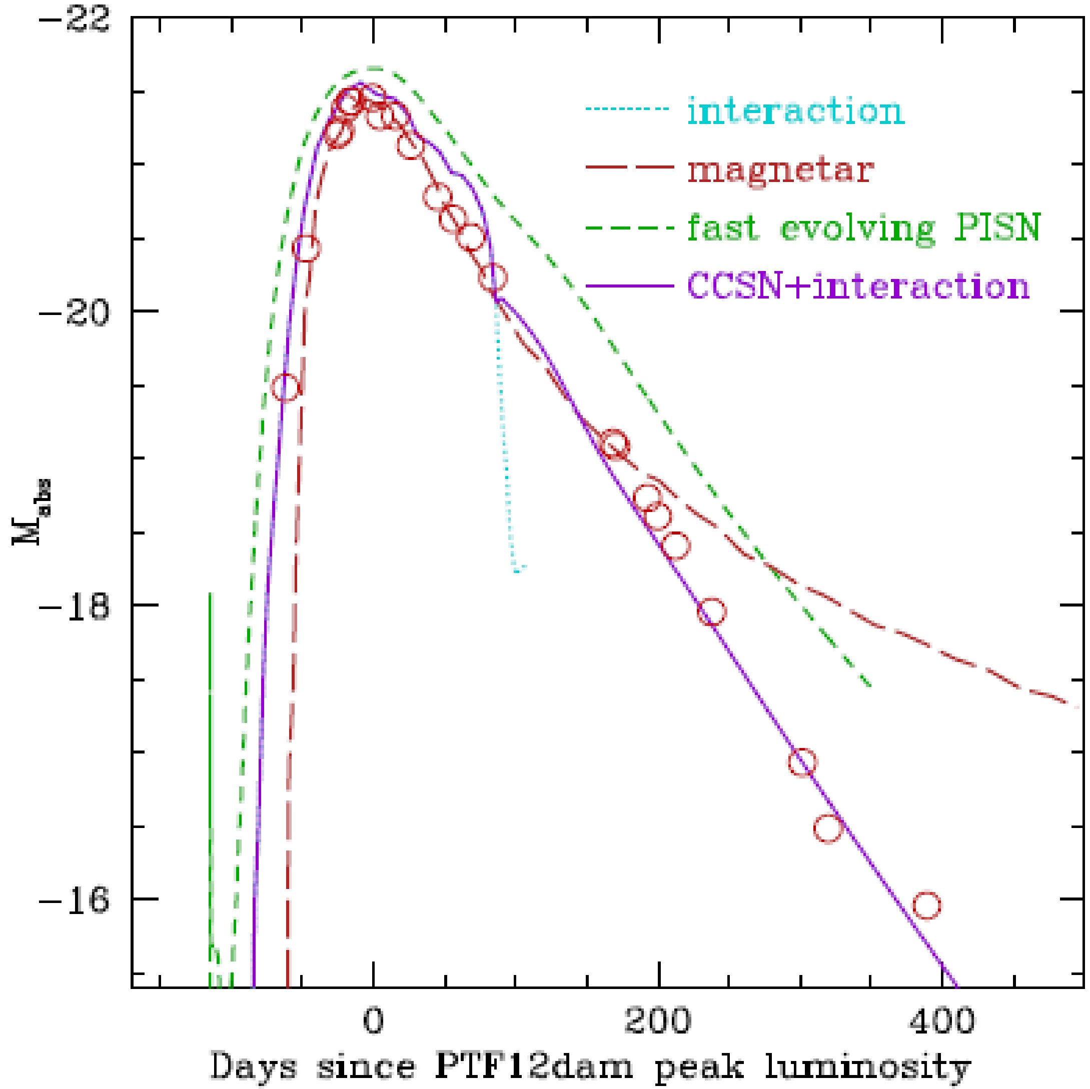
➔ Collapse (BH formation):

M(BH) = 38 – 51 $M_\odot$ if no-mass ejection (e.g., Leung-KN)

(cf. Binary BH masses from GW)

r-process in accretion disk, if jet-induced ejection ??

SLSN PTF12dam



(Tolstov, KN+17, ApJ)

Pulsational Pair-Instability Supernova : BH spinning
(CSM+ ^{56}Ni decay)

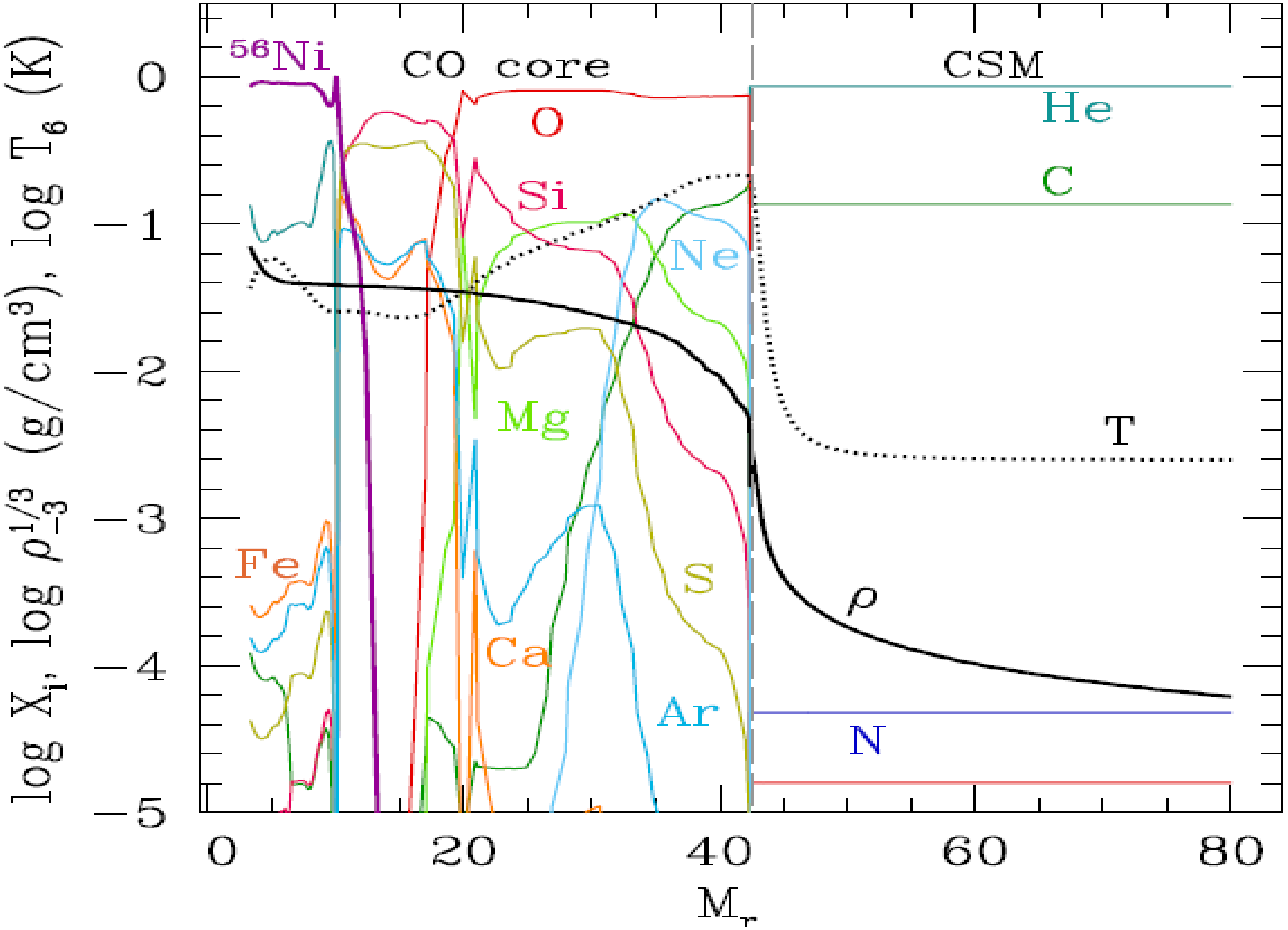
M(ZAMS) = 100 $M_\odot$
M(ejecta) = 40 $M_\odot$
M(CSM) = 37 $M_\odot$

M(^{56}Ni) = 6 $M_\odot$

E = 2 x 10^{52} erg

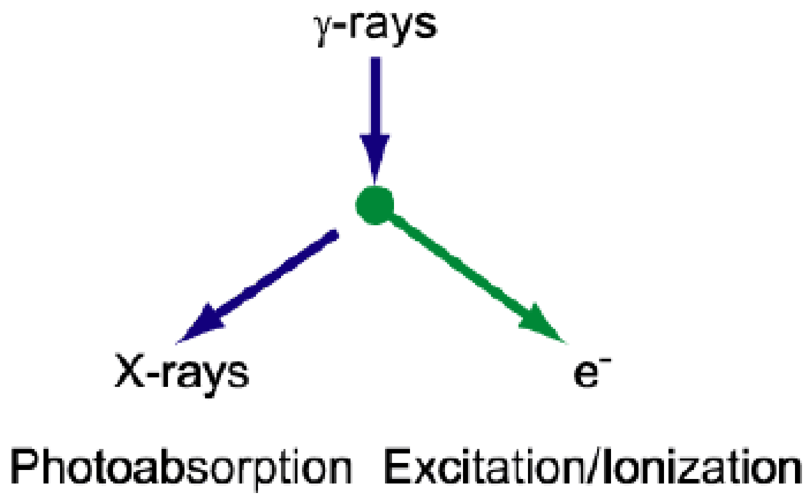
(Tolstov, KN+17, ApJ)

← CO Core → ← CSM →



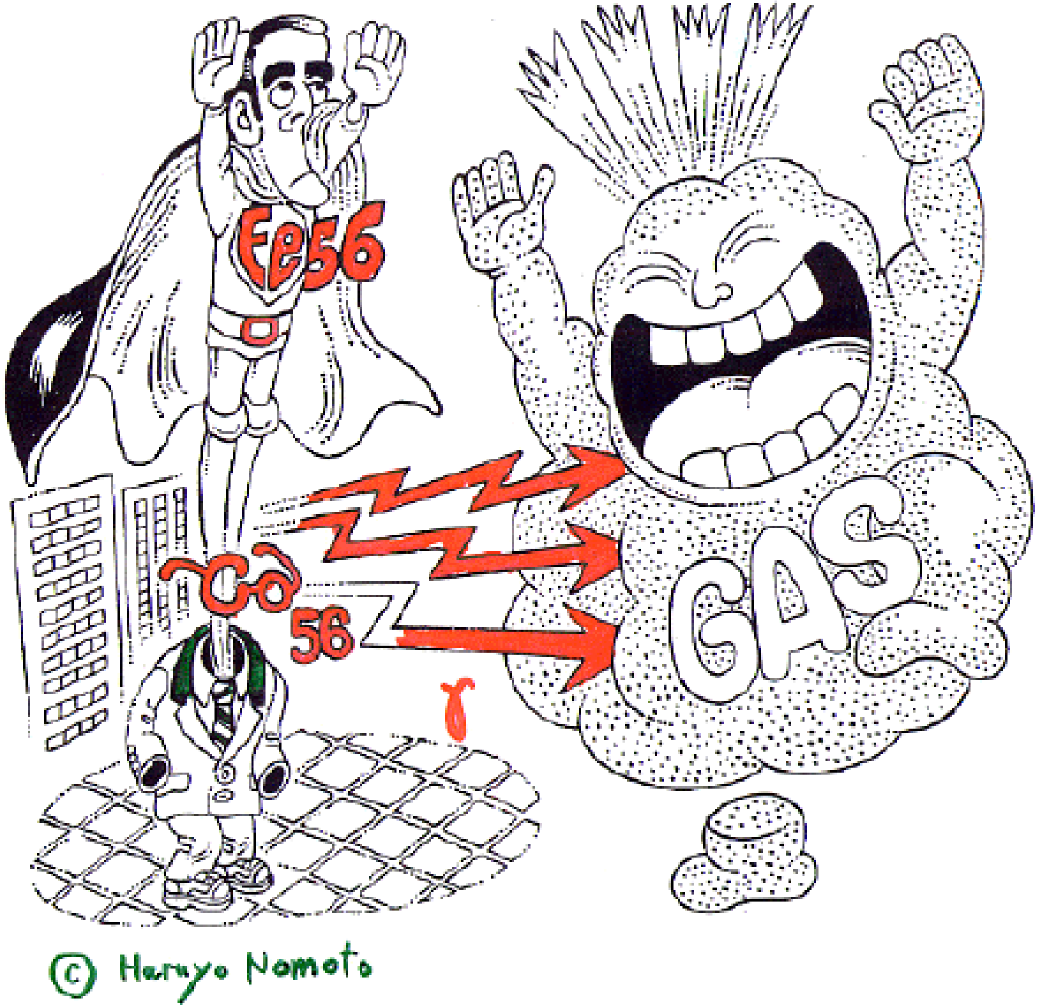
^{56}Co-decay

$$^{56}\mathrm{Ni} \xrightarrow[6.6\mathrm{d}]{\gamma} {}^{56}\mathrm{Co} \xrightarrow[78\mathrm{d}]{\gamma} {}^{56}\mathrm{Fe}$$

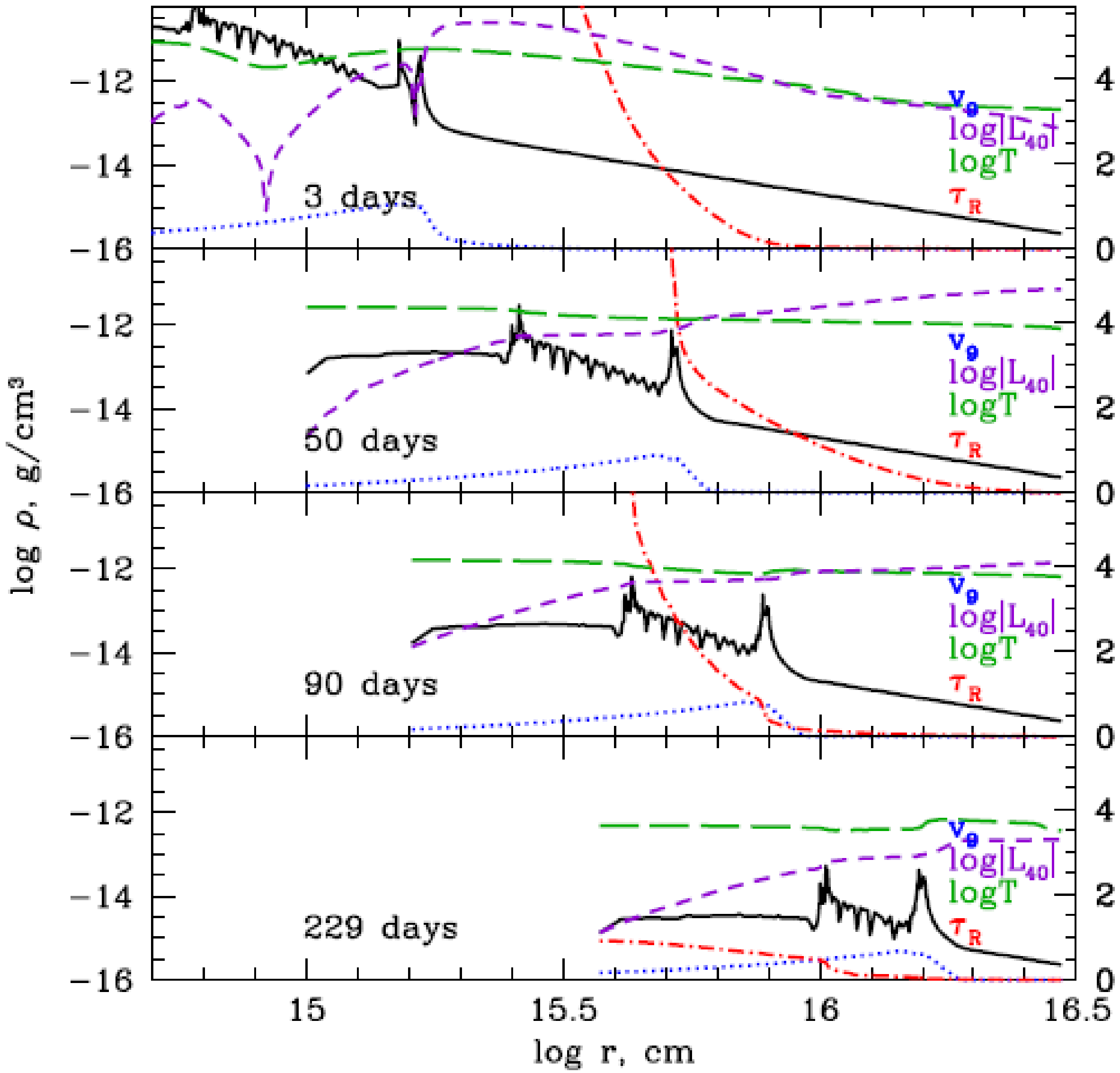


$L \propto M(^{56}\mathrm{Ni})$

Shape: M_{ej}



PPI SN ➔ Circumstellar Interaction



(Tolstov, KN+17, ApJ)

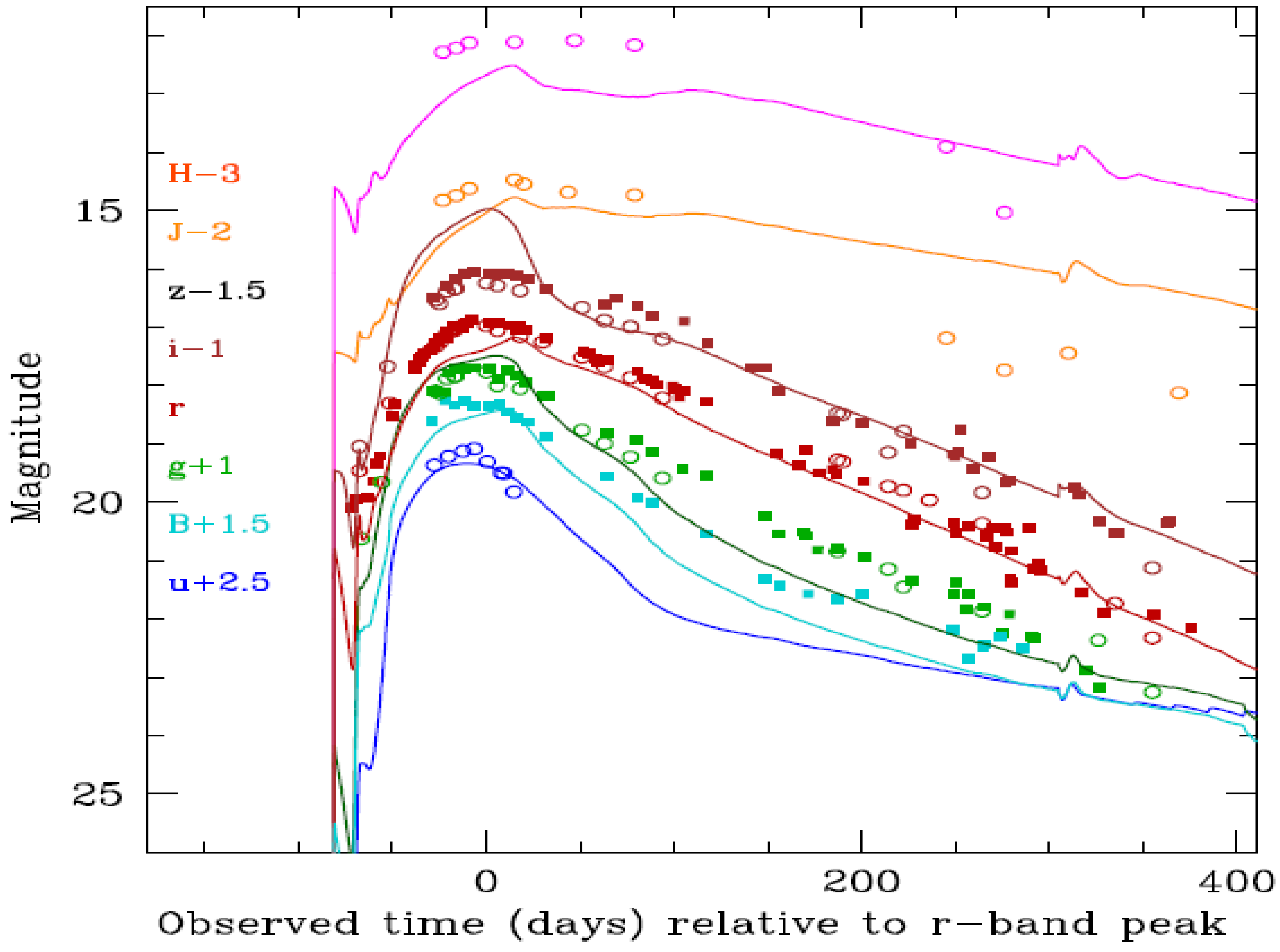
Pulsational Pair-Instability Model for PTF 12dam (Interaction + Radioactive Decays)

M(ZAMS) = 100 $M_\odot$
M(ejecta) = 40 $M_\odot$
M(CSM) = 37 $M_\odot$
R(CSM) = 5 x $10^5 R_\odot$

M(^{56}Ni) = 6 $M_\odot$

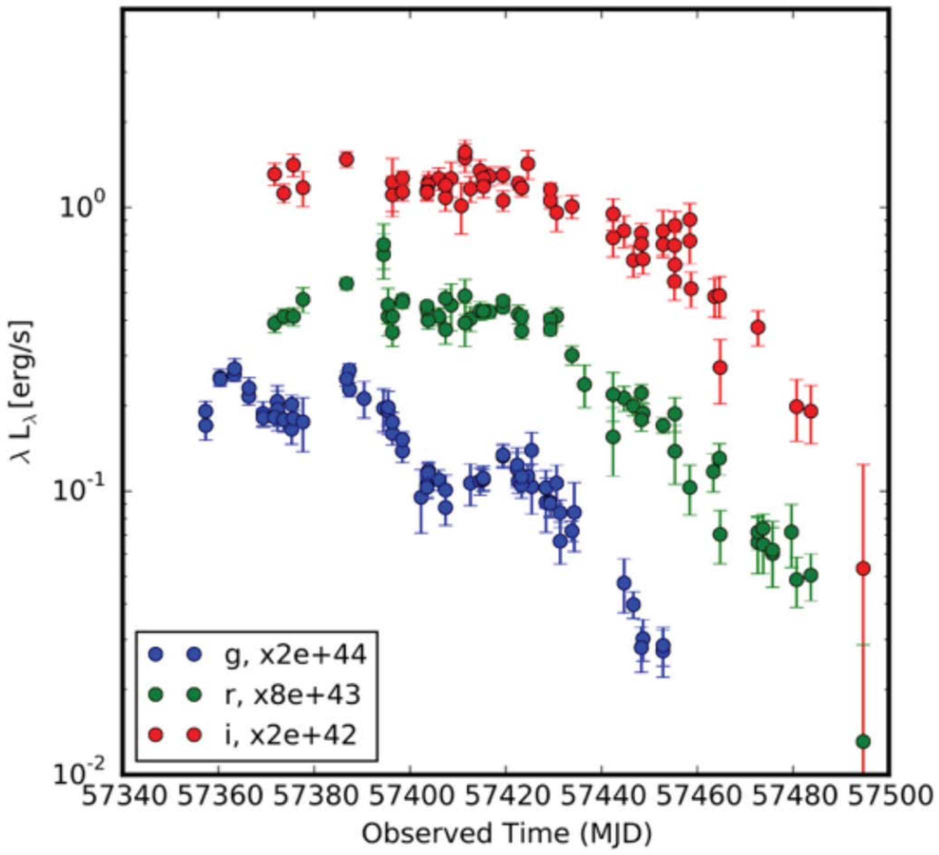
E = 2 x 10^{52} erg

(STELLA: Tolstov, KN+17, ApJ)

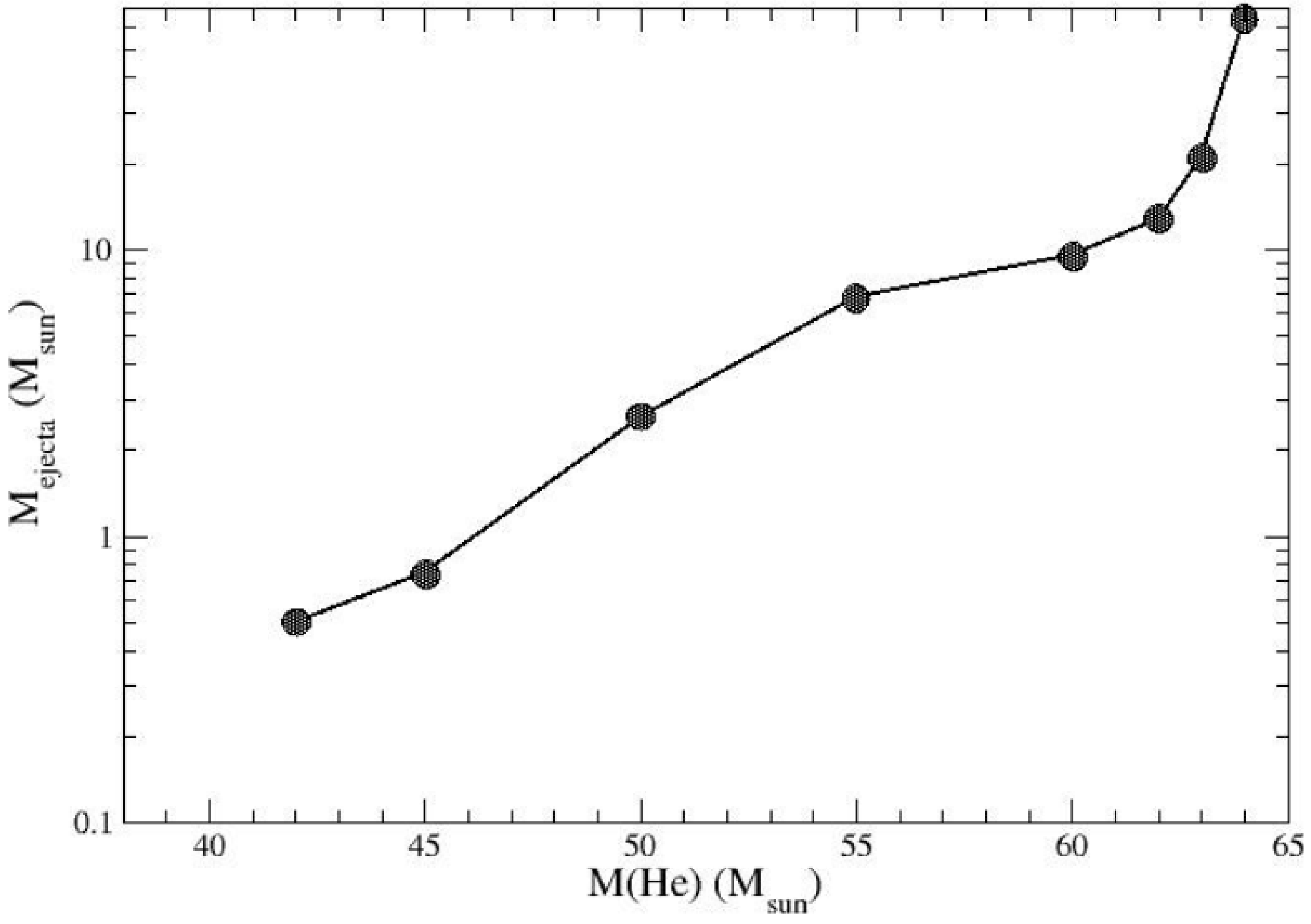


SLSN-I: CSM signature?

SLSN-I PTF15esb:
Bumpy Light Curve

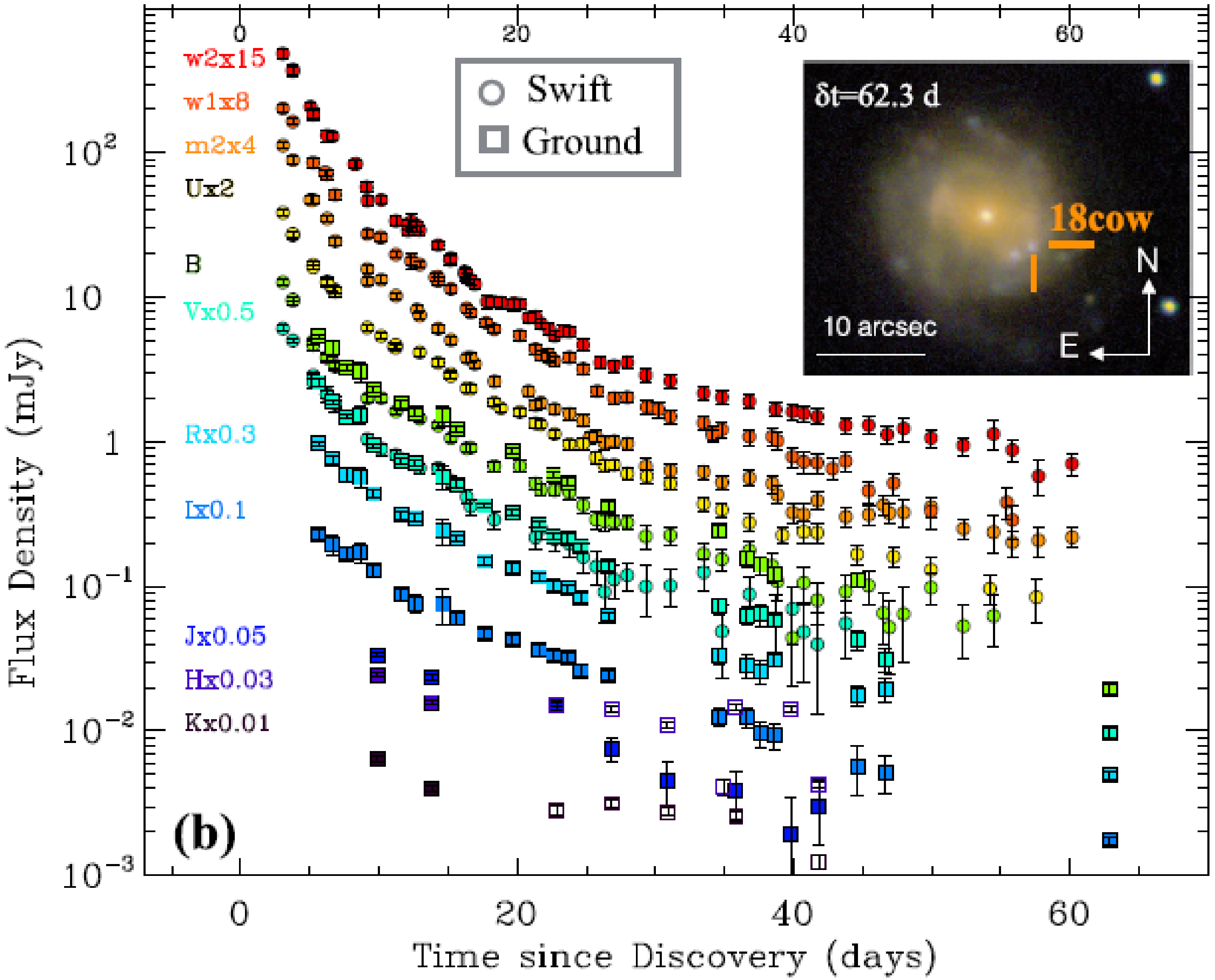


Ejected Mass (He+CO) from PI Pulsation



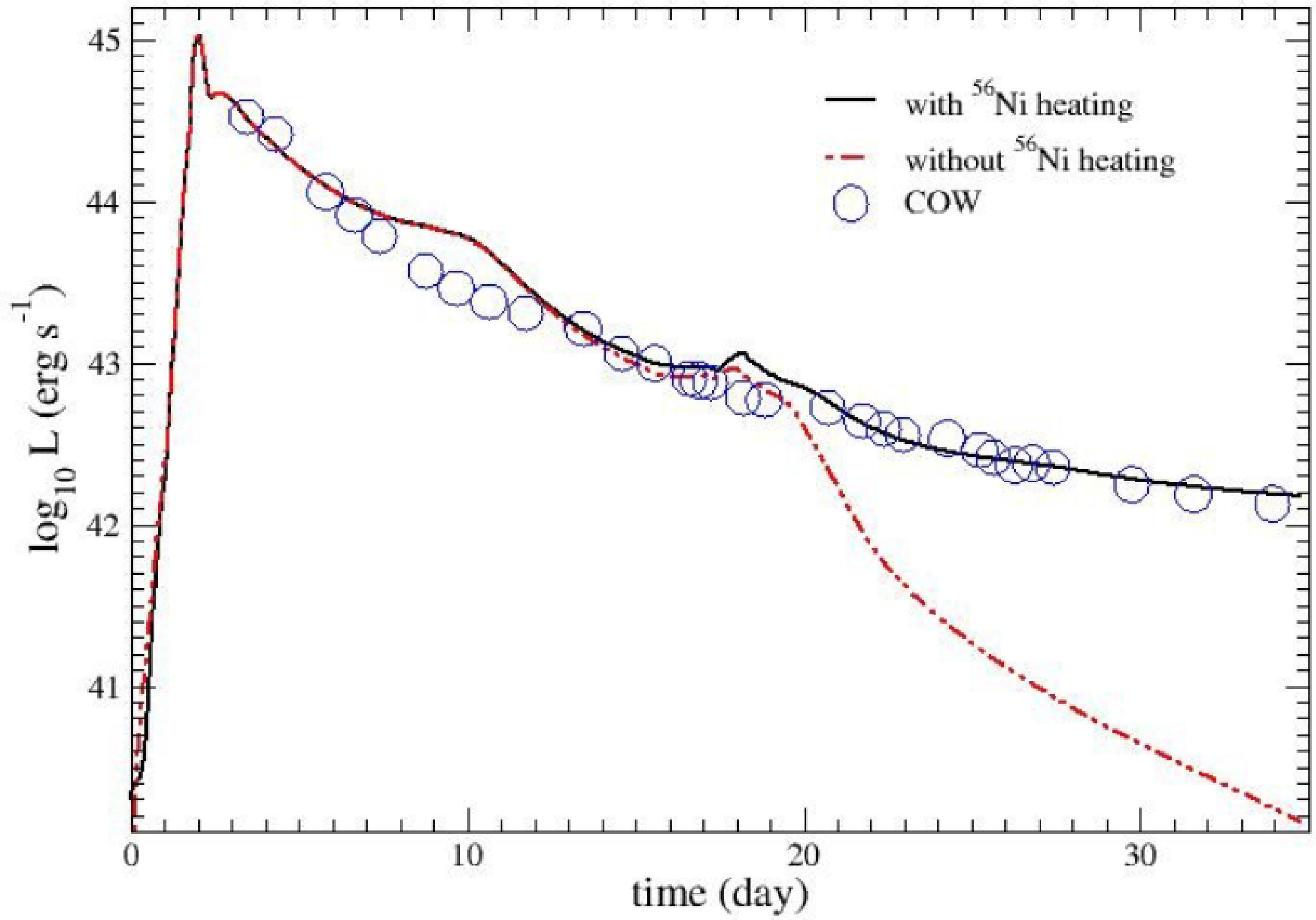
(Leung+20)

AT2018cow (FBOT)



(Margutti+19)

Pulsational Pair Instability Model for AT2018cow



$M(\text{He core}) = 43\ M_\odot$

$M(\text{CSM}) = 0.5\ M_\odot$

$M(^{56}\text{Ni}) = 0.06\ M_\odot$

$E = 5 \times 10^{51}$ erg

t < 20 d : CS interaction

t > 20 d : BH accretion ?

Magnetar ?

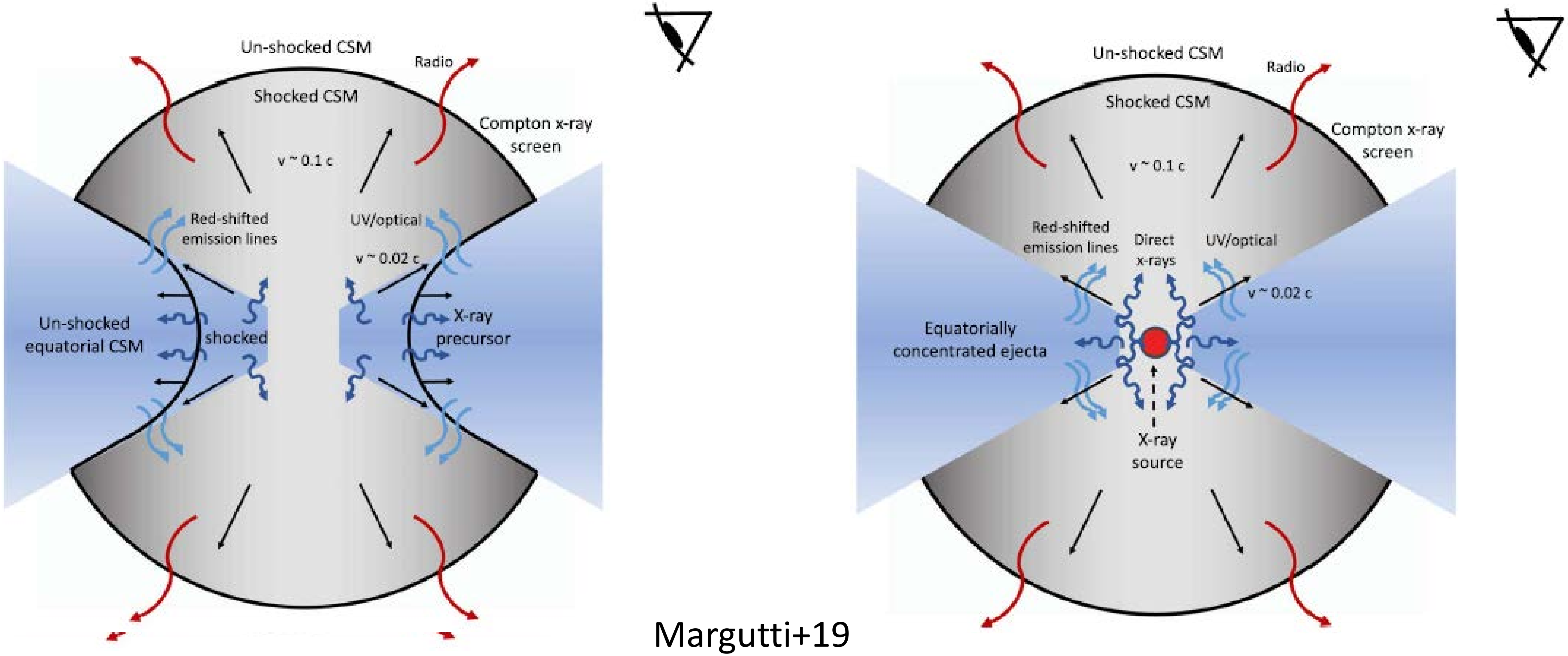
Radioactivity ?

(Leung+20)

Fast Blue Optical Transients (e.g., AT2018cow; KSN 15K)

- Double power source models for light curves:
  Circumstellar Interaction (peak)
  + Pulsar or Radioactive decay (tail)
- Progenitors with dense CSM can be Super-AGB stars or PPI (or Wolf Rayet) stars ??
- Mass loss just before SNe in other mass range ??
- Nucleosynthesis ?
- AT2018cow (CS interaction:
  PPISN or ECSN in Super-AGB or Binary Merger ??)

AT2018cow : High Energy Emissions & Gemetry



Margutti+19

Diversities of Electon Capture Supernovae

Collapsing ONeM Core + He-rich Envelope + CSM → SN

M(core) = 1.36 $M_\odot$ M (env) < 0.1 $M_\odot$ **Fast Blue Optical Transient**

KSN 2015K, AT2018cow

M (env) ~ 0.1 - 7 $M_\odot$ SN II-L. II-P ?

M (env) ~ 1 - 3 $M_\odot$ **Crab-like** SN

Energy Source of Late Light Curve

Pulsar, Circumstellar Interaction

Diversities of Pulsational Pair-Instability Supernovae

Collapsing He Core + Optically Thick CSM → SN

M(He) = 40 – 42 $M_\odot$ M (CSM) < 1 $M_\odot$ **Fast Blue Optical Transient**

e.g., AT2018cow

M(He) = 50 - 64 $M_\odot$ M(CSM) > 10 $M_\odot$ **Superluminous Supernova**

Energy Source of Late Light Curve

Radioactivity, Pulsar/Magnetar, BH, Circumstellar Interaction