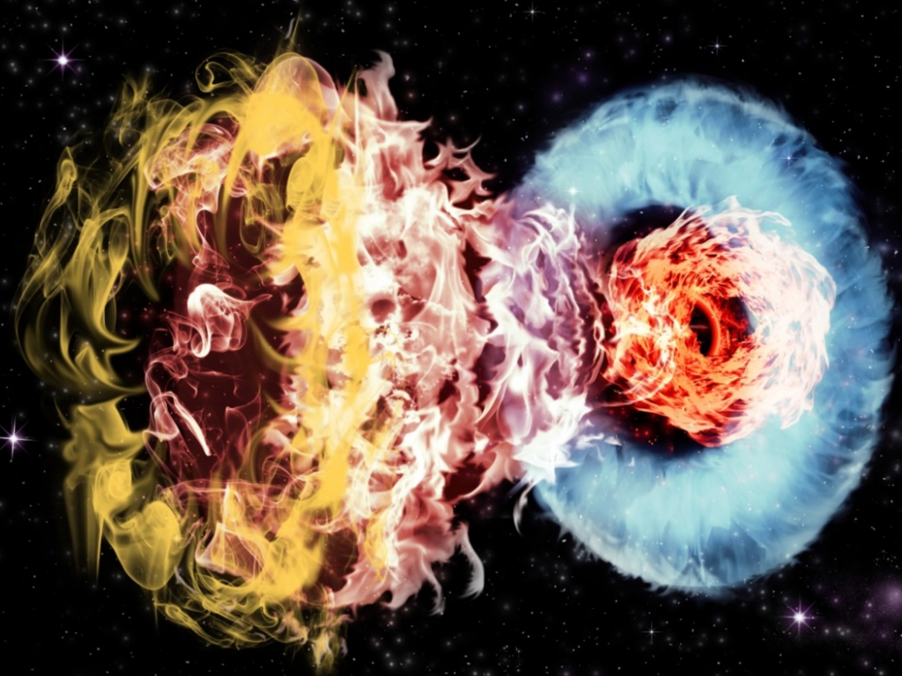
Are Pop III supernovae unusual ?



Ken Nomoto
Shing-Chi Leung
Alexey Tolstov
Miho Ishigaki
Sergei Blinnikov
(Kavli IPMU, U. Tokyo)

Are Pop III supernovae unusual ?

- **First (Pop III) Stars :** How massive ?
- **Unusual Supernovae (SNe) ??**

→ **Peculiar Abundance Patterns ?**

Hypernovae (incl. GRB-SNe: ~20-40 $M_\odot$)

Faint Supernovae (Fallback SNe)

Superluminous Supernovae (~80-140 $M_\odot$)

Fast-Evolving Luminous Transients (FELTs)

(8-10 $M_\odot$; 80-140 $M_\odot$)

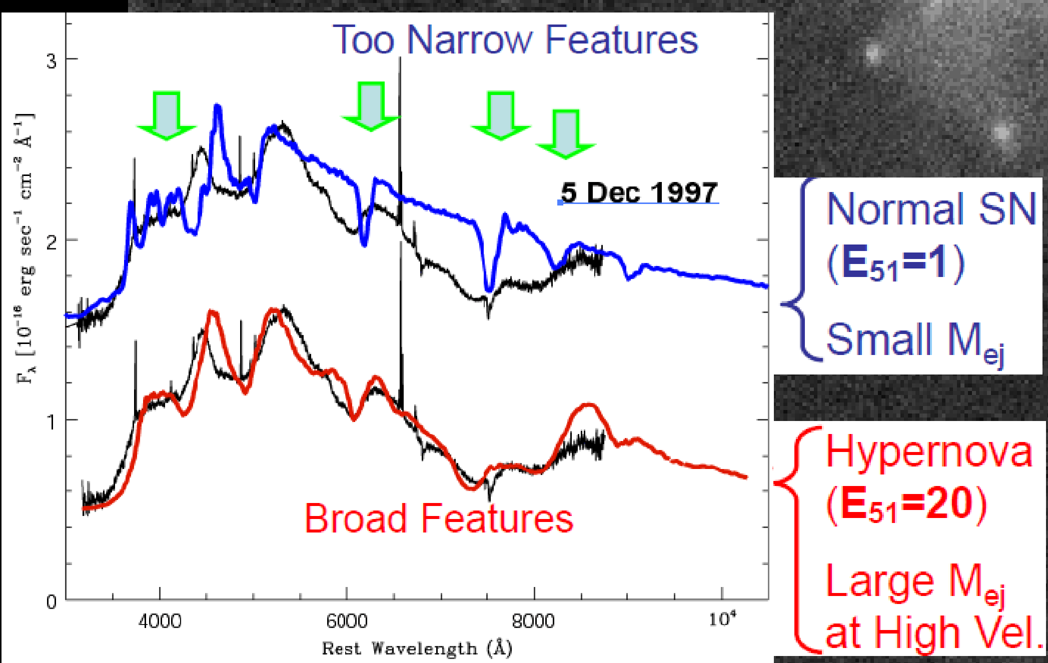
Hypernova – GRB Connection

Three GRB－SNe = all Type Ic Hypernovae

$E > 10^{52}$ erg (～10 × normal SN)

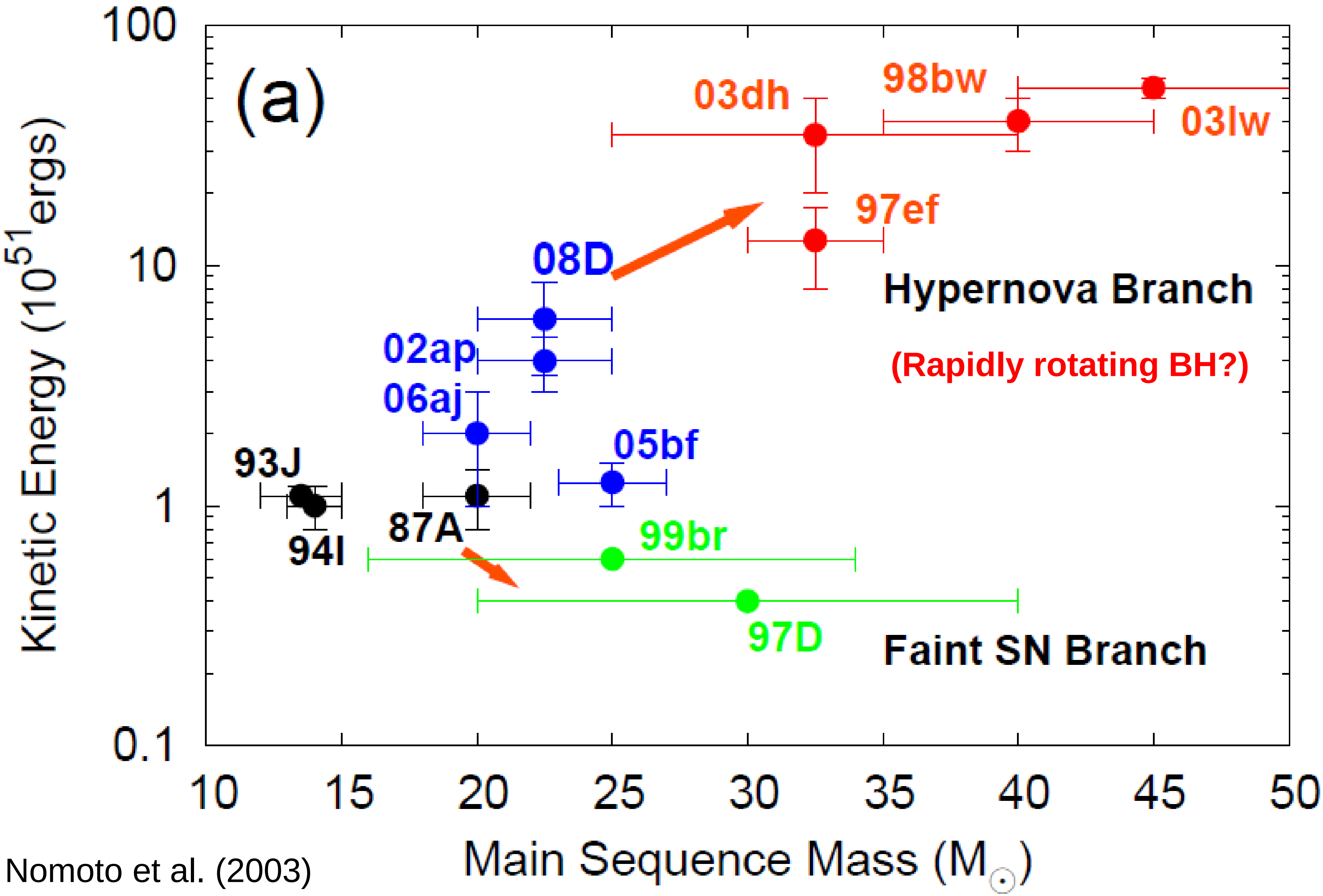
Large M_{ms} →Black Hole Forming SNe

Aspherical



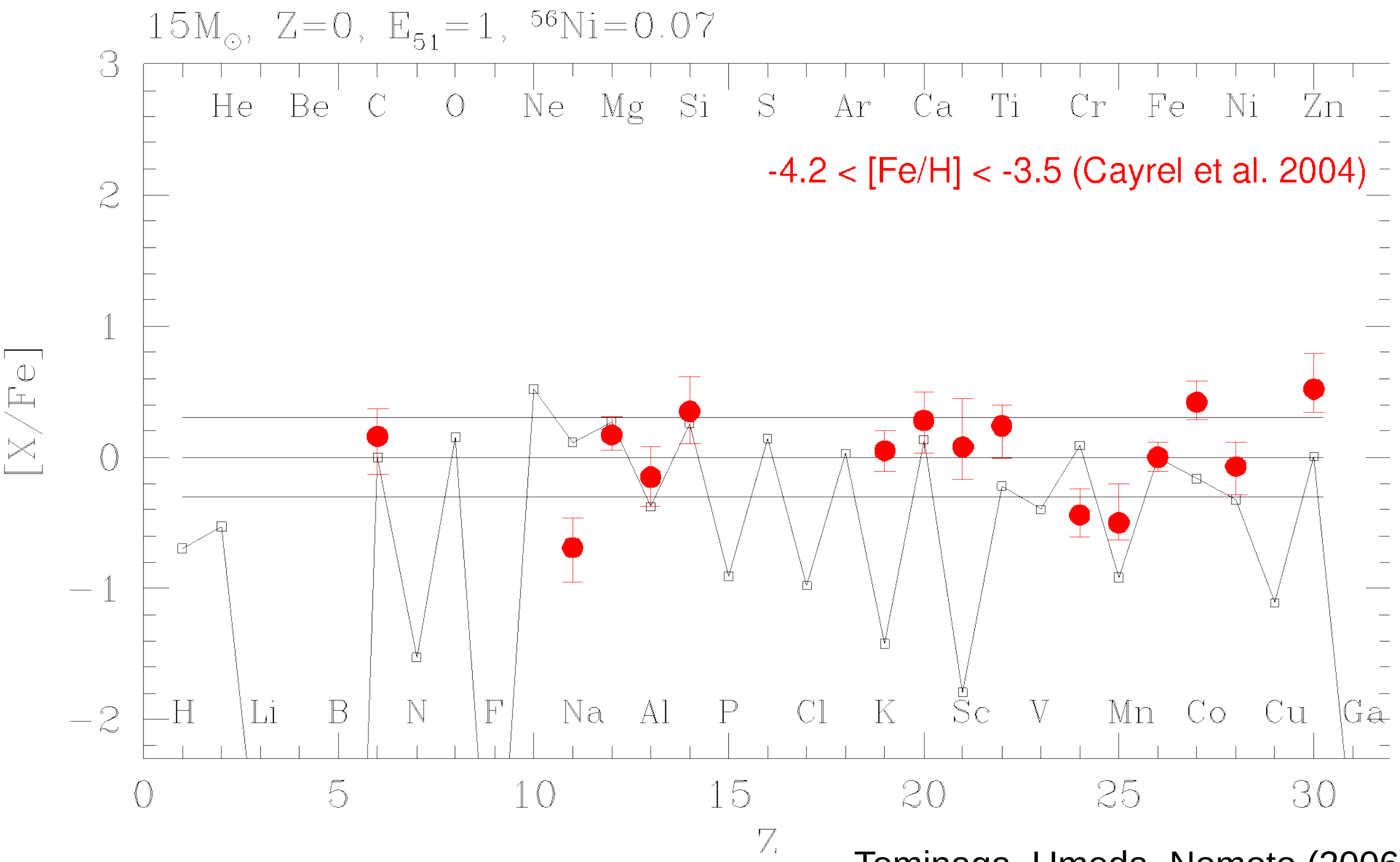
$E_{51}=E/10^{51}$ erg

SNe [M_{ms}-E relation]



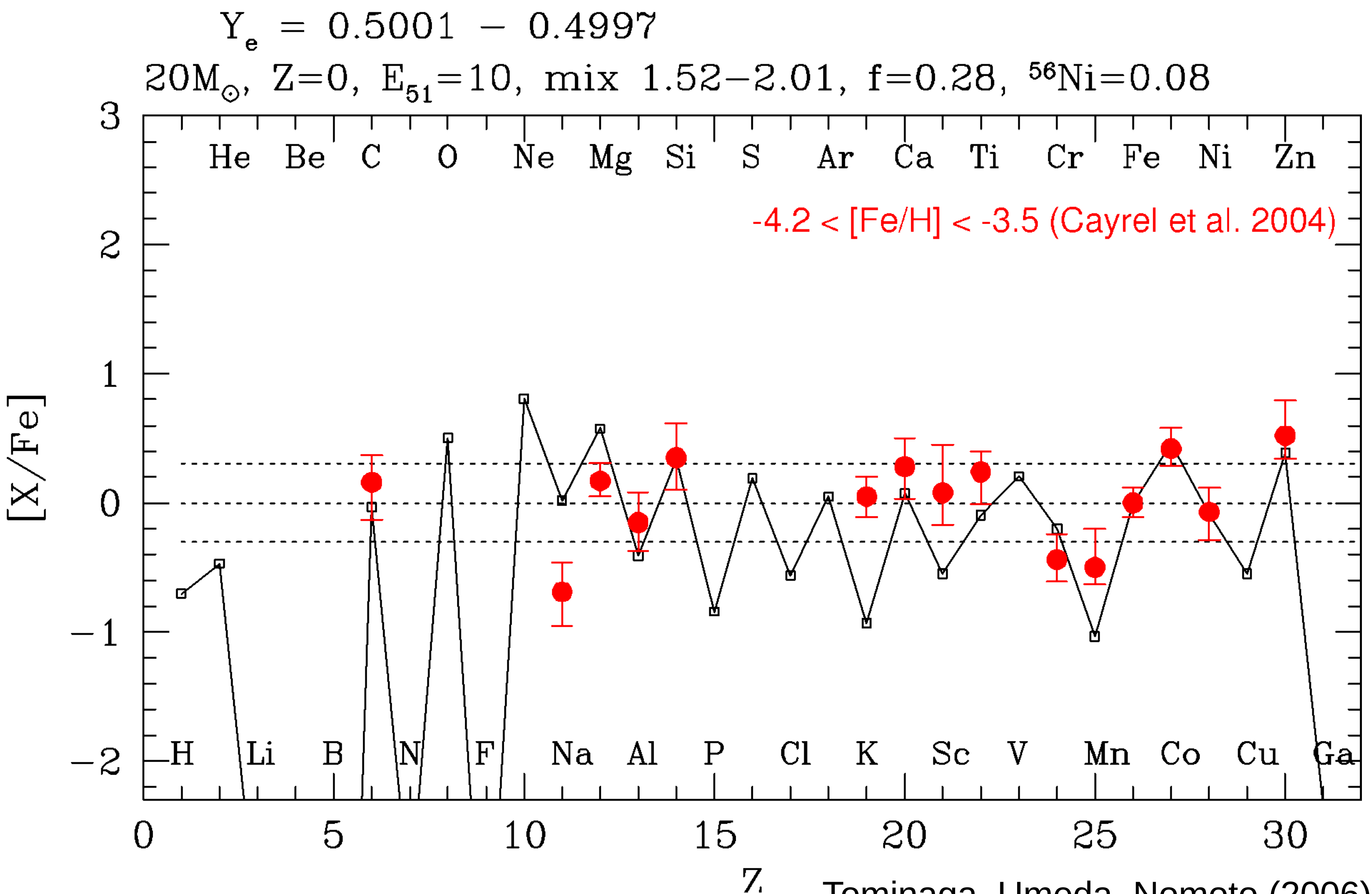
Nomoto et al. (2003)

EMP stars vs. **Normal** SN II: Poor Fit



Tominaga, Umeda, Nomoto (2006)

EMP stars vs. **Hypernova** (E_{51}=10)



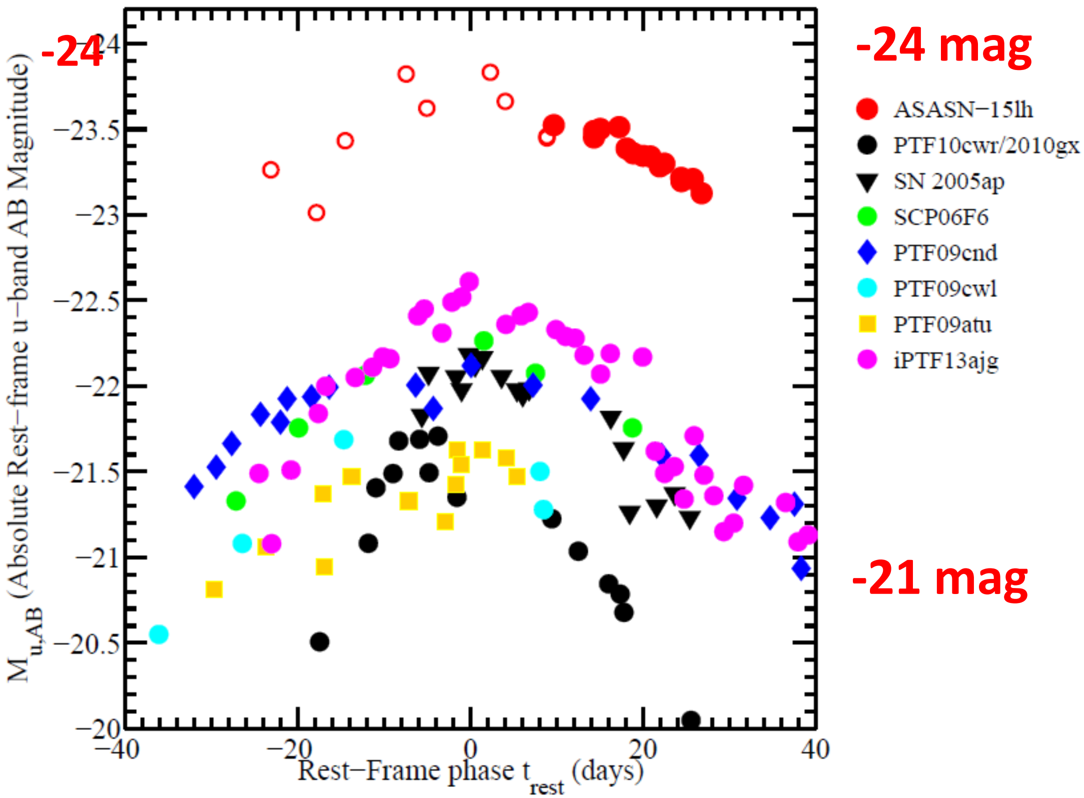
Tominaga, Umeda, Nomoto (2006)

Superluminous Supernovae (SLSNe)

Type I SLSNe (SLSNe-I): no Hydorgen

U-band

-24 mag



-21 mag

-20 days 20

(Dong+15)

32 SLSNe from PTF (2009-2012)

* (Perley, Quimby+16)

Host galaxies

- **Low mass** galaxies
  (M* < 2 x 10⁹ M⊙)
- **Low metallicity** galaxies
- (12+log [O/H] < 8.4)
  (Z < 0.5 Z⊙)

Rate ~ 1 SLSN/10^3 – 10^4

Core collapse SNe

(De Cia+16)

Superluminous Supernovae
(Progenitors, Mechanisms??)

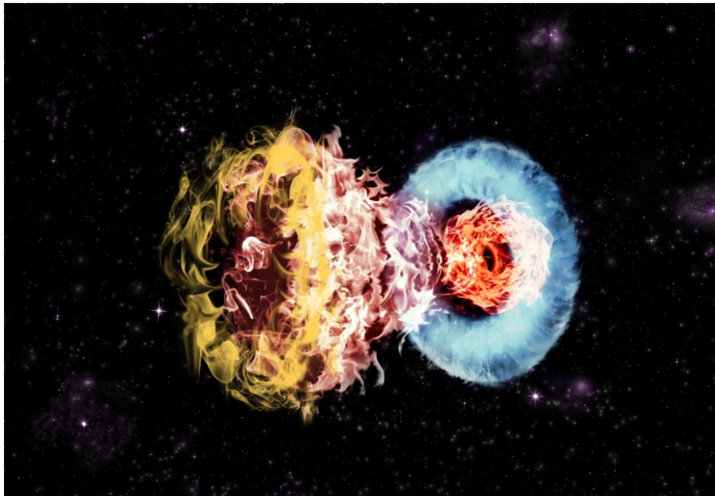
Type I SLSNe: No Hydrogen

*__Radioactive Decays__ (Core-Collapse SN
Pair Instability SN)

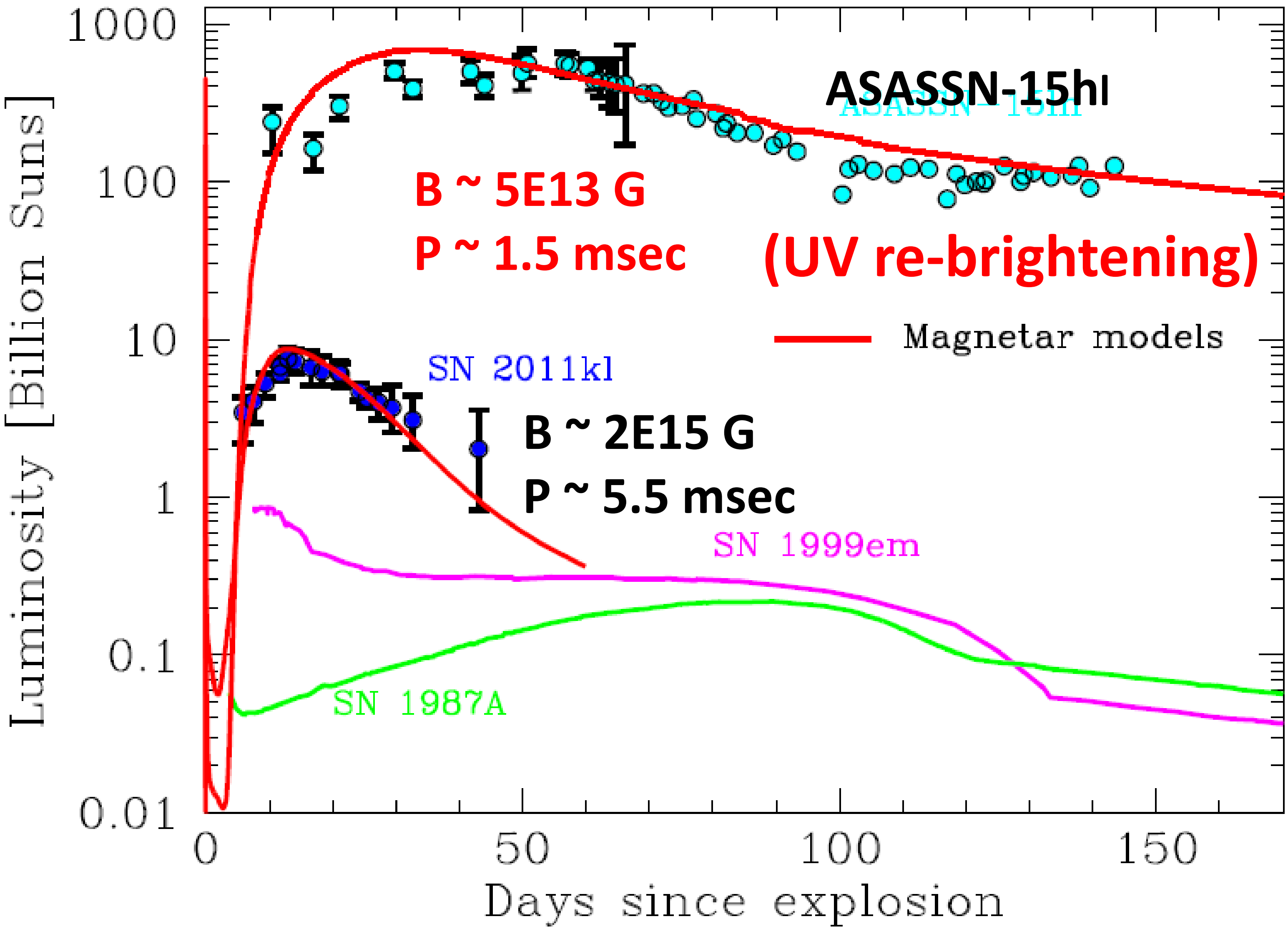
*__Magnetar__

*__Black Hole Accretion__

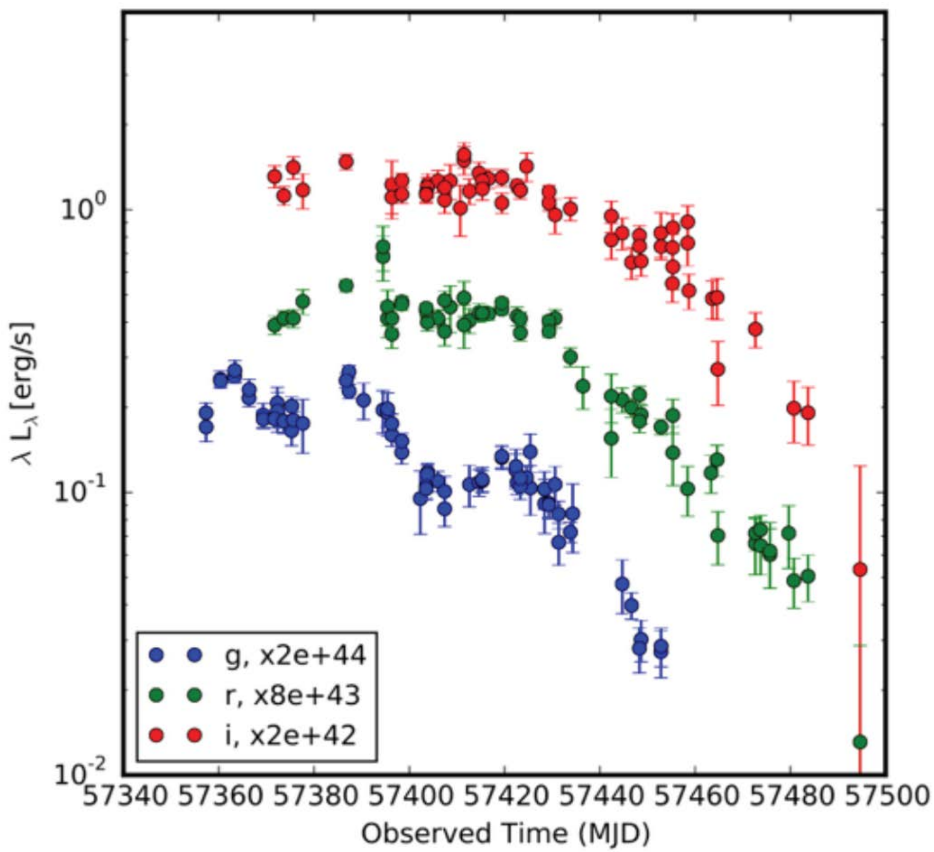
*__Circumstellar Interaction__



Magnetar models for ASASSN-15hl & SN 2011kl (Radiation-Hydro Models: Bersten, KN+16)



SLSN-I PTF15esb: Bumpy Light Curve

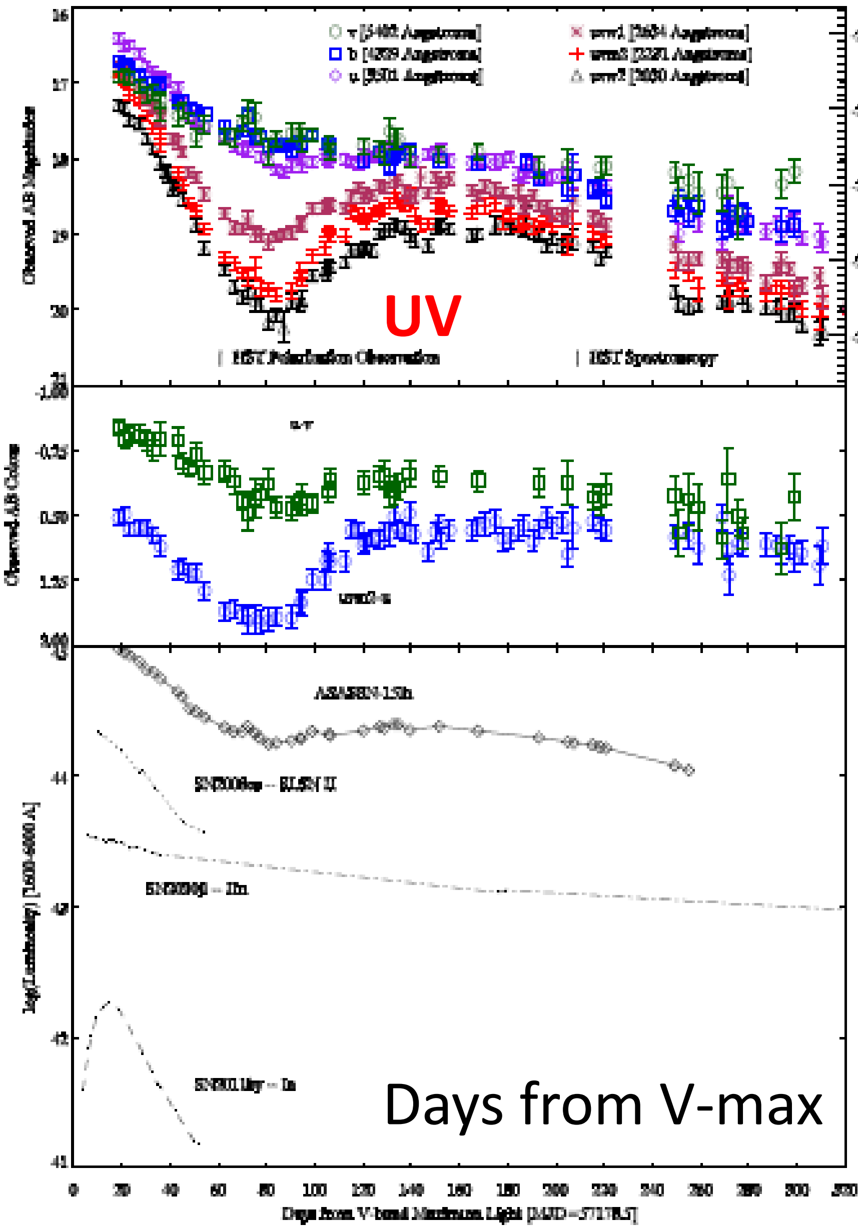


(Yan+16)

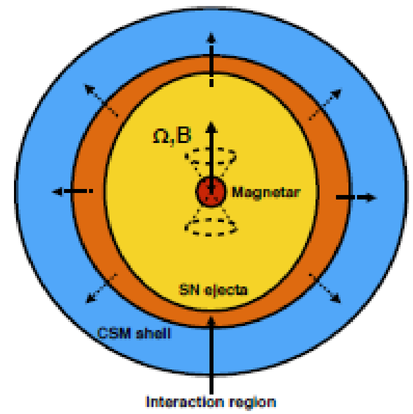
Light Echo from a CSM shell around SLSN-I (iPTF16eh)

(Lunnan+18)

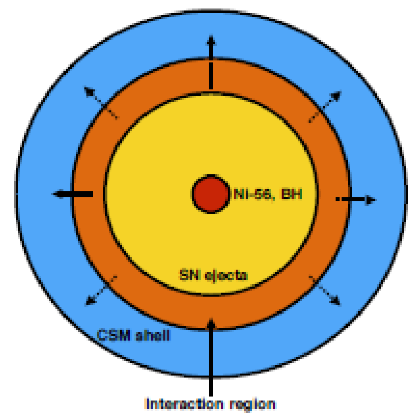
UV re-brightning : Double power sources?



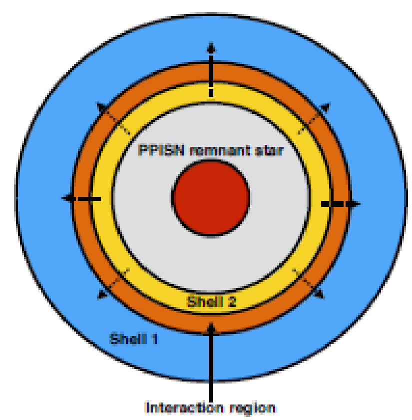
(Chatzopoulos+16)



Magnetar
+ CS interaction
(Chatzopoulos+16)

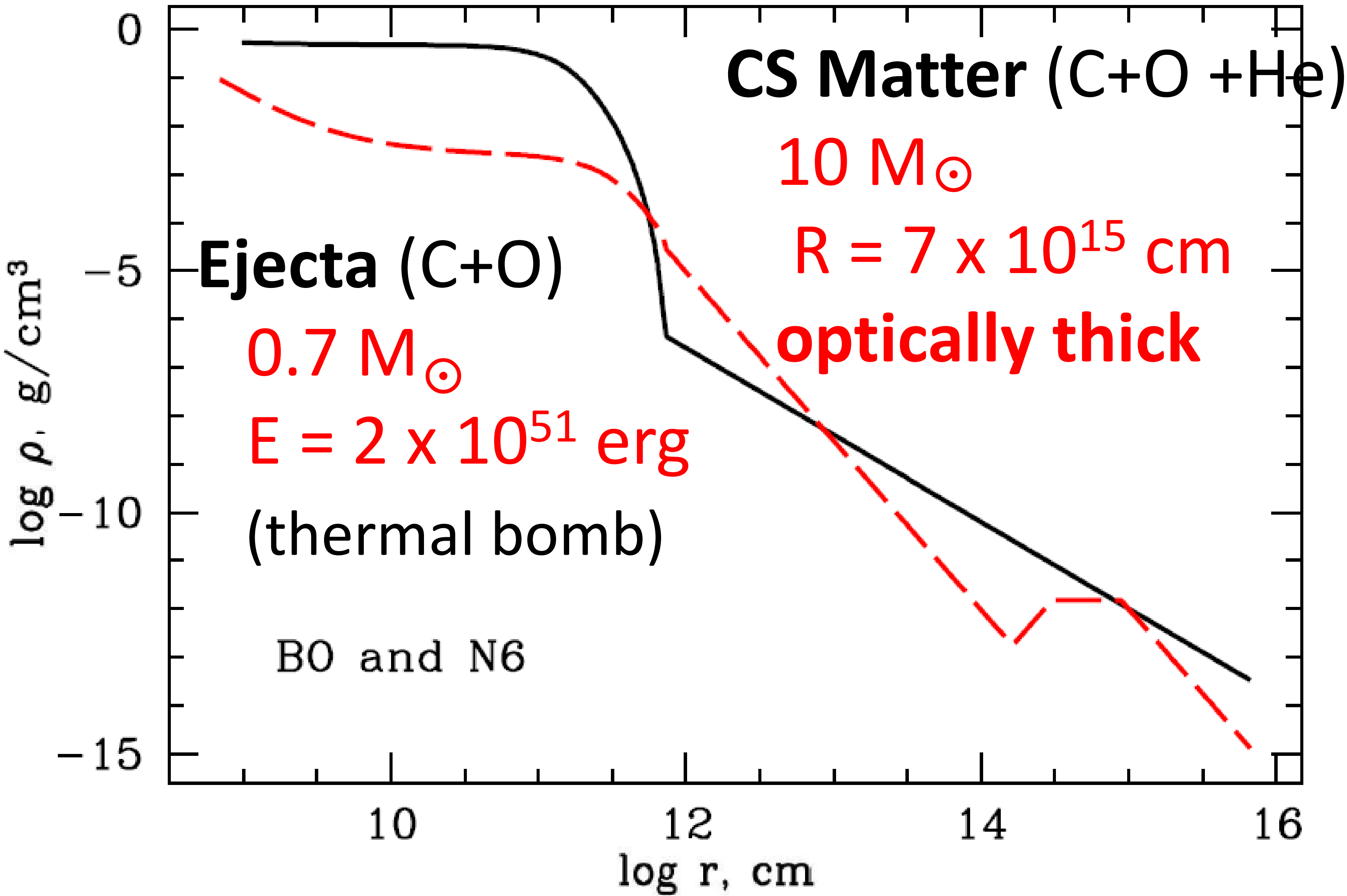


Radioactive Decay
+ CS interatction



Multiple CS Interactions
(Sorokina, KN+16 with STELLA)

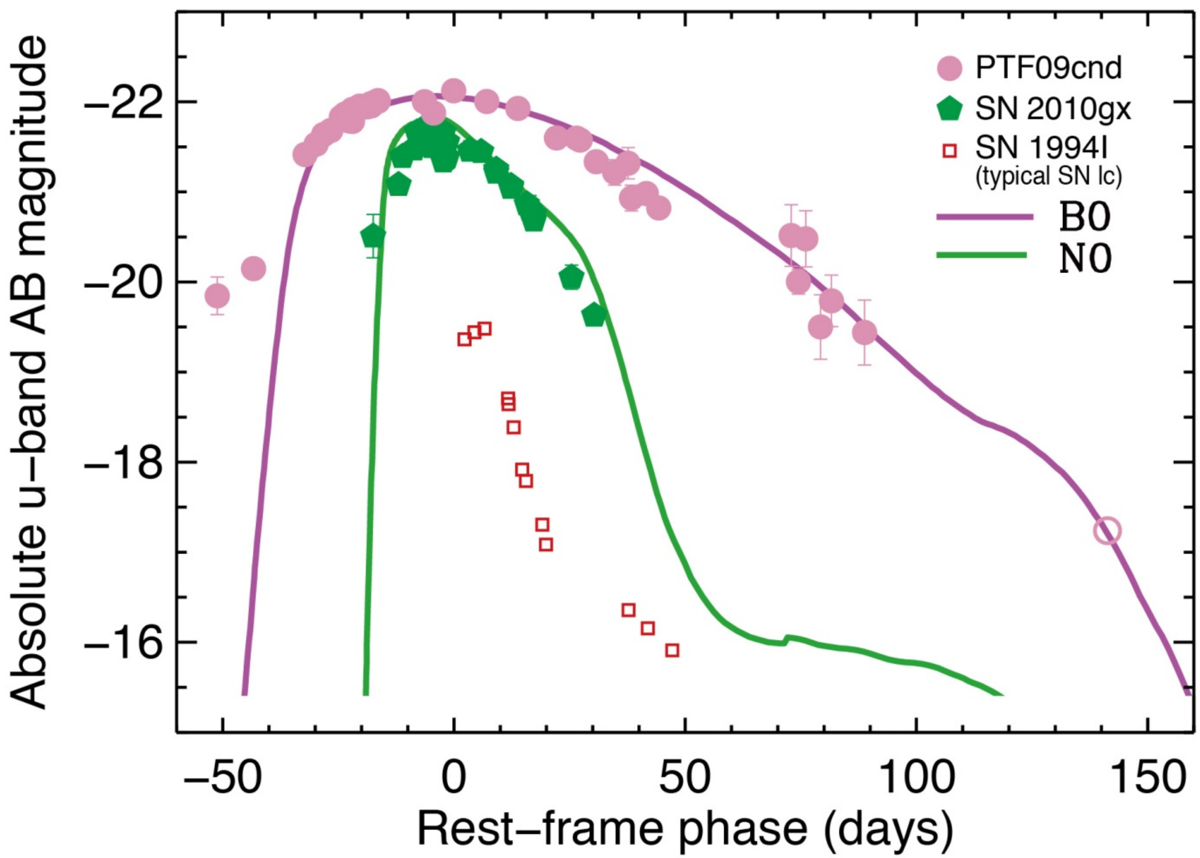
Circumstellar Interaction model for SN 2010gx (with STELLA: Sorokina, KN+16)



Interaction Light Curves: Narrow & Wide

	SN 2010gx (N0)	PTF09cnd (B0)
M(CSM)/M⊙	**10**	**50**
M(ejecta)/M⊙	0.7	5
E (10^{51} erg)	2	5

u-band



Circumstellar Interaction Models

- Interaction between the SN ejecta and optically thick circumstellar matter (CSM) reproduces both narrow and wide LCs of SLSNe-I.
- Massive (~10-50 $M_\odot$) and extended ($R \sim 10^5$ $R_\odot$) non-H (C+O +He) CSM is suggested.

~80 – 140 $M_\odot$ Stars

M(He) ~ 50 – 62 $M_\odot$

Pulsational Pair-Instability (PPI)

* → Pulsational Mass Ejection

→ Dense Circumstellar Matter

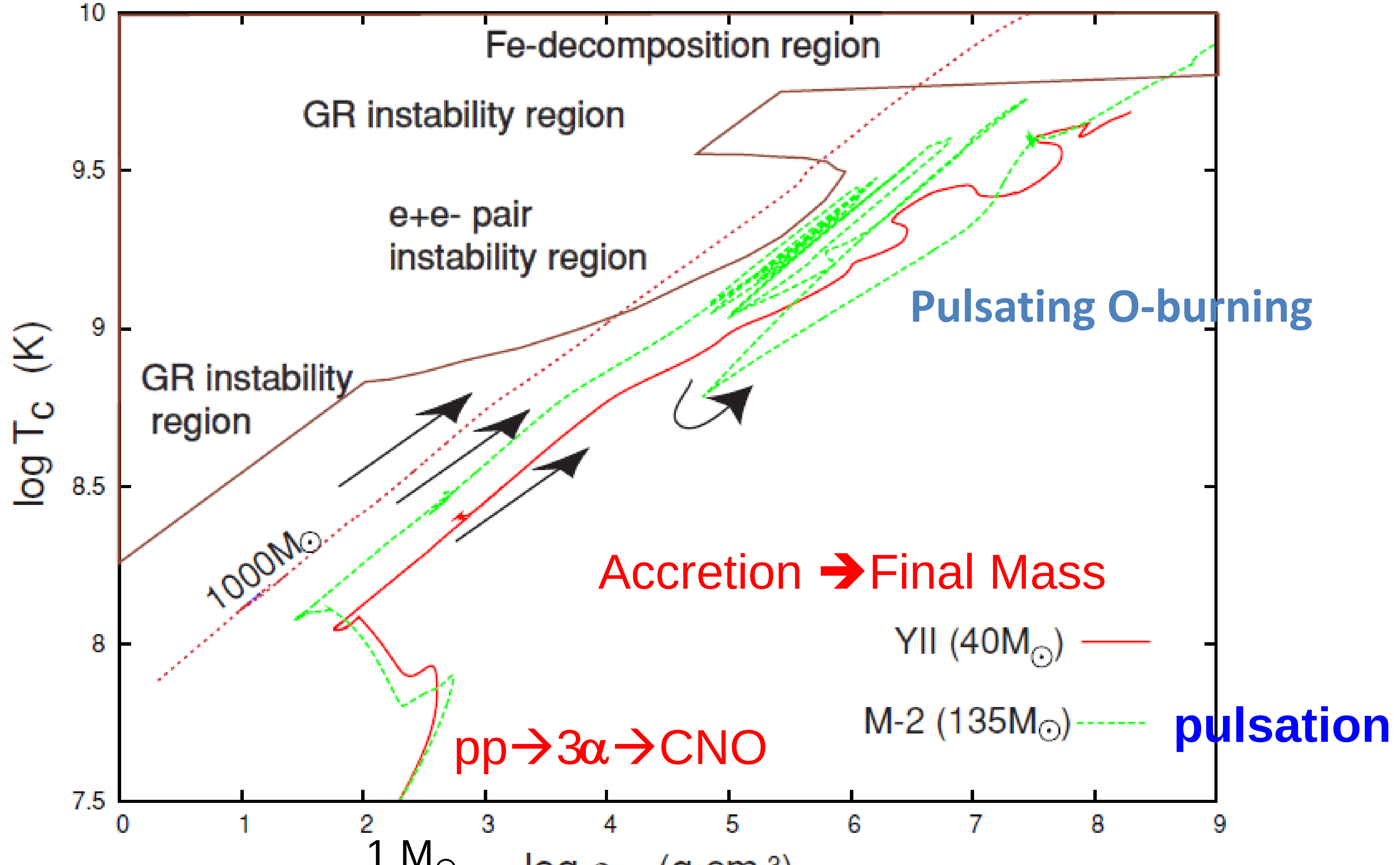
M(ej) ~ 4 – 40 $M_\odot$

* → **Collapse (BH formation):** $M(^{56}Ni) < 10\ M_\odot$

e.g., Barkat et al. (1967)
Heger & Woosley (2002)
Ohkubo, Nomoto et al. (2009)
Yoshida et al. (2016)
Woosley (2017)

Pulsating O & Si Burning ➔ CSM ?

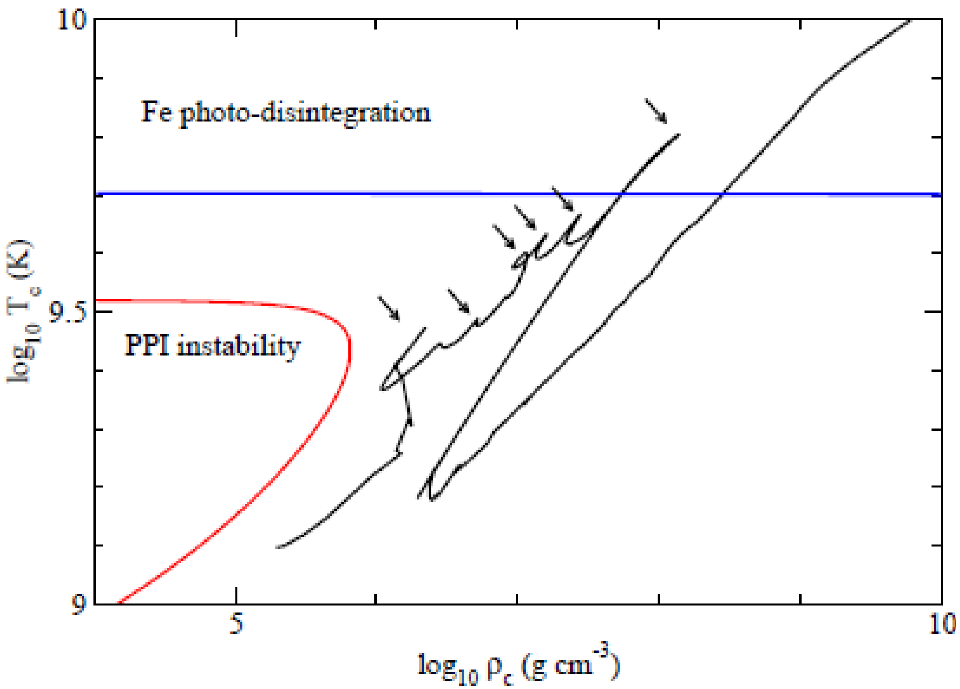
Pulsational Pair-Instability (80-140 M$_\odot$)

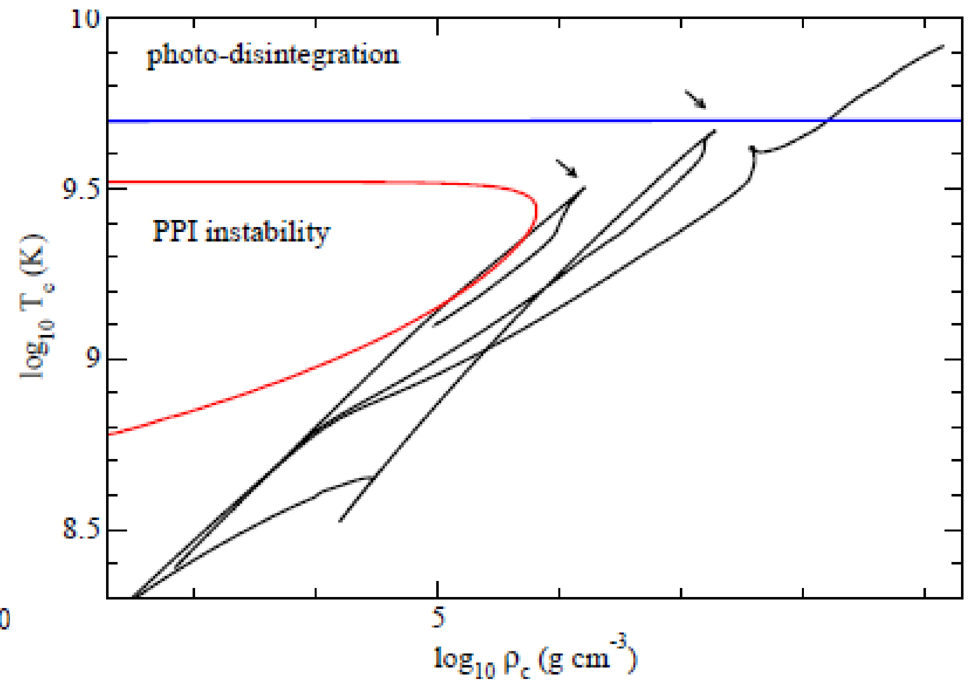


Ohkubo et al. (2009)

Pulsational Pair-Instability and Mass Loss

(Leung, KN+18)





Small scale pulse (Small mass ejection)
Time to collapse ~1 year

Large pulse (Large mass ejection)
Time to collapse ~100 - 1000 year

40 solar mass

64 solar mass

Pulsational Pair-Instability Models

- Main-sequence stars:

  $M = 80 - 140\ M_\odot$

- He cores:

  $M_{He} = 40 - 64\ M_\odot$

* Pulsational Mass Ejection

  ➔ Dense CSM

  $M(ej) \sim 2 - 23\ M_\odot$

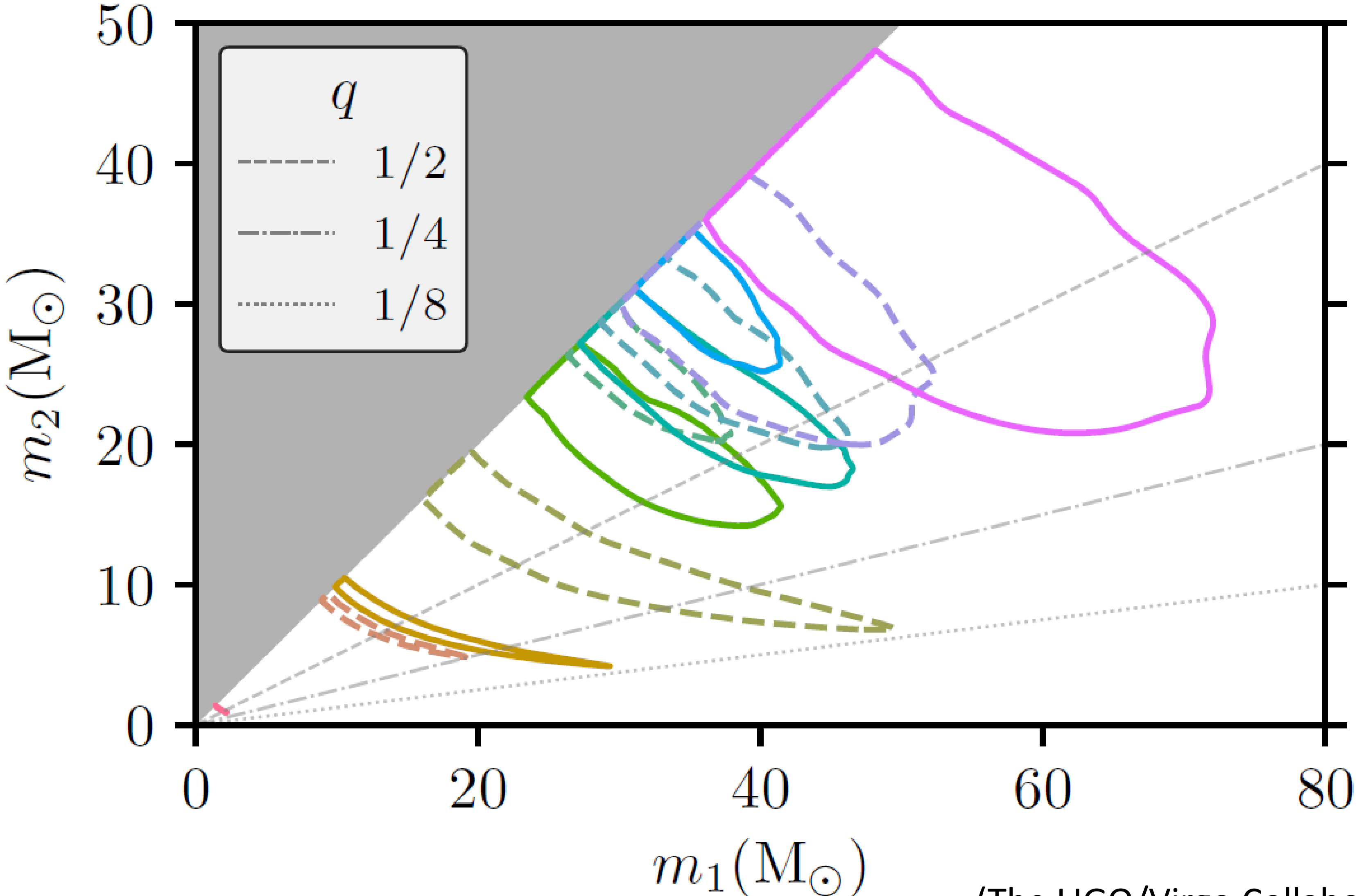
  (Woosley 2017)
  (Leung, KN+2018)

M(He)	M(final)	Mass Loss	Pulse
40	38	2	6
45	39	6	4
50	47	3	3
55	48	7	3
60	51	9	2
63	40	23	2
64	0 (PISN)	64	1

➔ Collapse (BH formation) ➔ $M(BH, Max) = 51\ M_\odot$

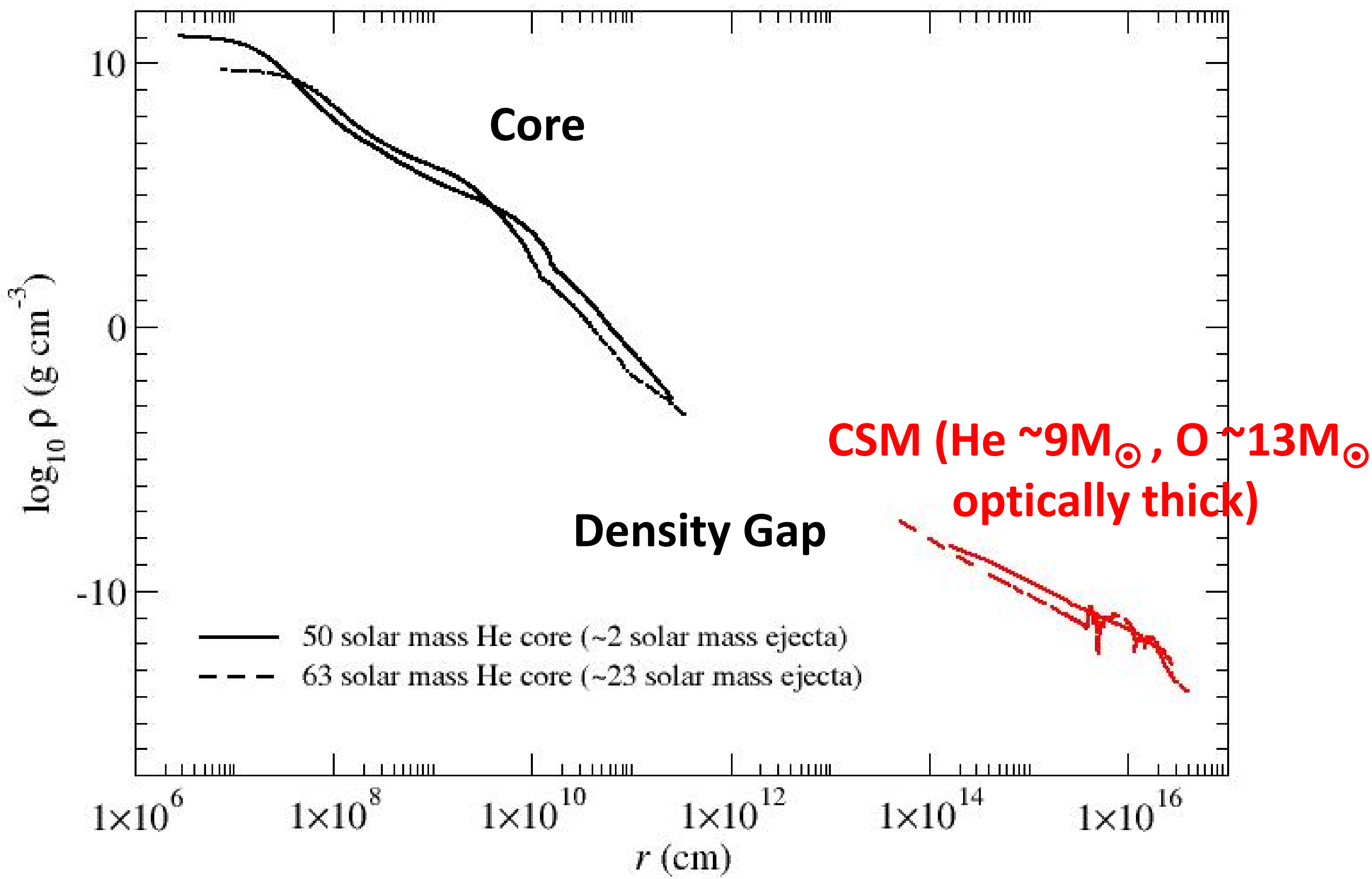
➔ ?? $M(^{56}Ni) < 10\ M_\odot$

$M(BH)/M_{\odot} = 50.6^{+16.6}_{-10.2}$ (GW 170729)



(The LIGO/Virgo Collaboration)

Pre-Collapse Core and CSM after PPI



(Leung, KN+18)

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

M(ZAMS) = 100 $M_\odot$

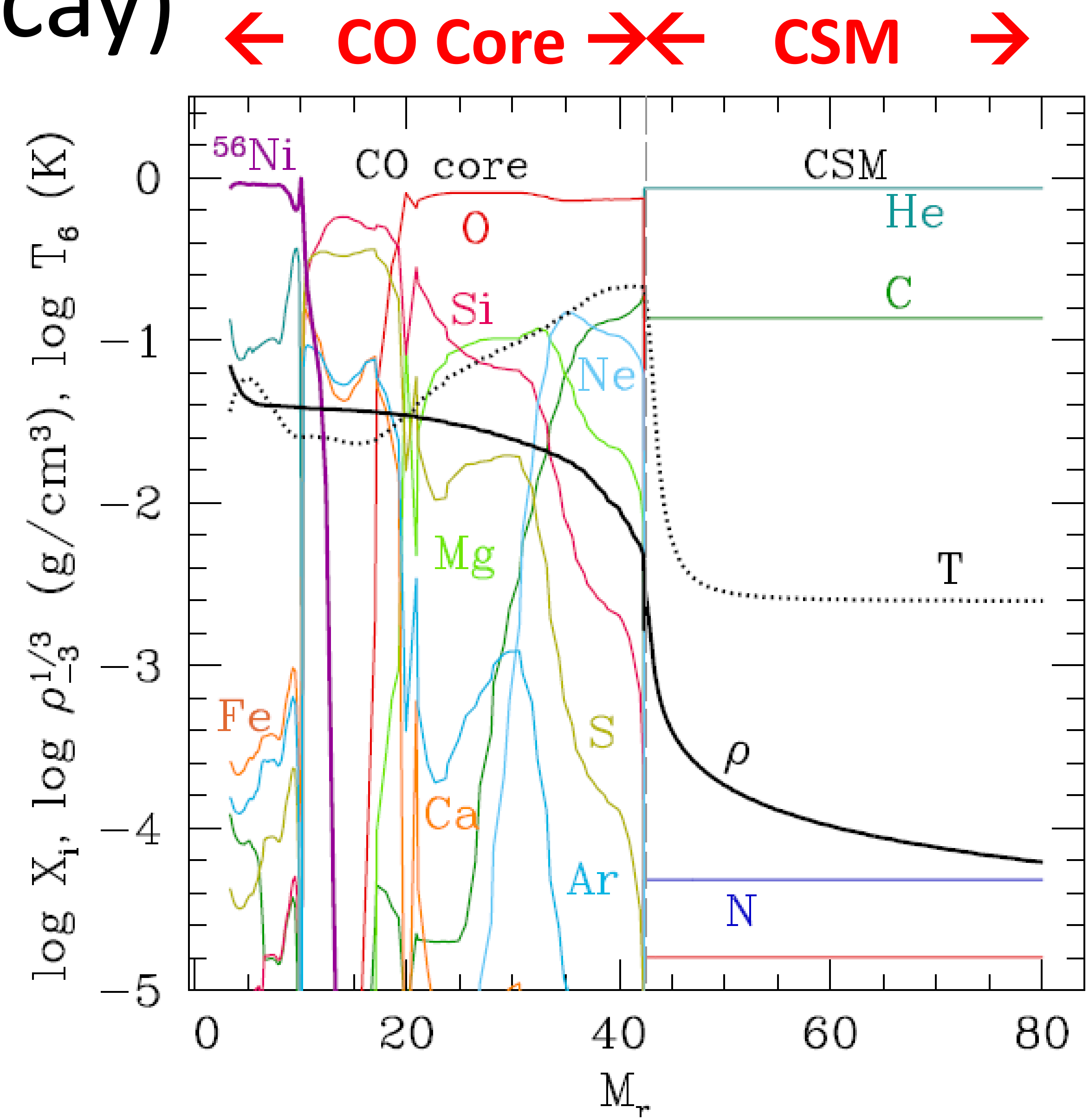
M(ejecta) = 40 $M_\odot$

M(CSM) = 37 $M_\odot$

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

E = 2 x 10^{52} erg

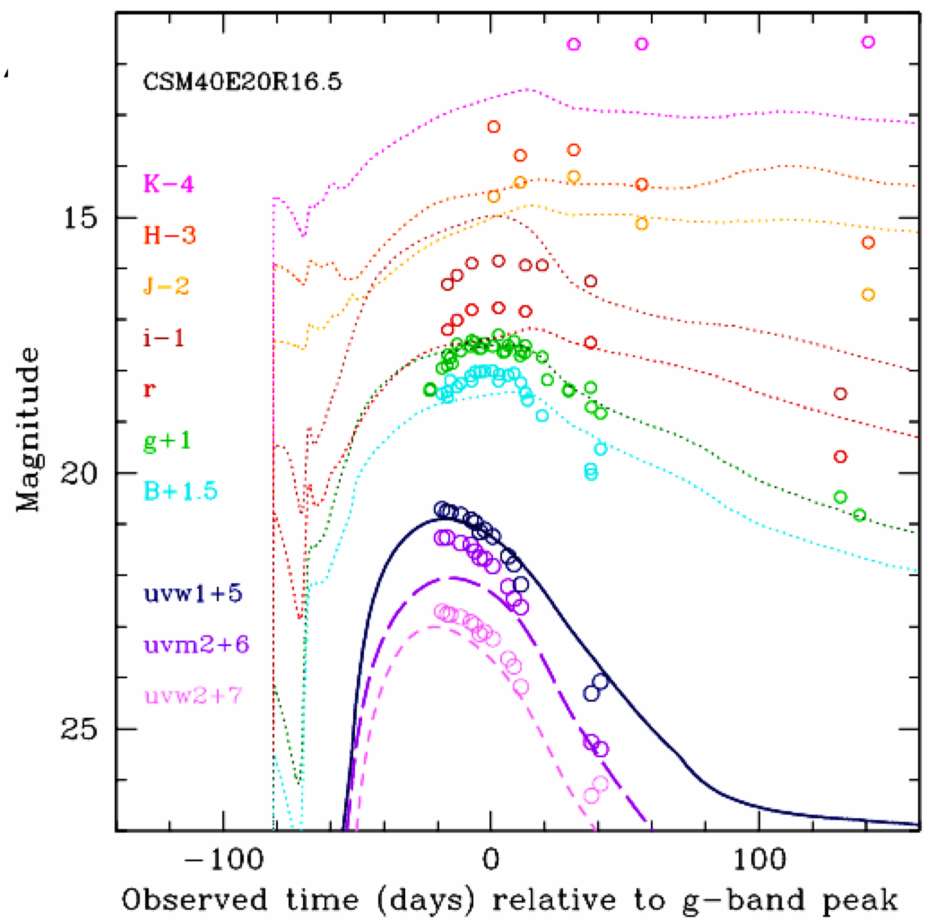
(Tolstov, KN+16)



Gaia16apd: CS interaction models better than magnetar, Ni-decay

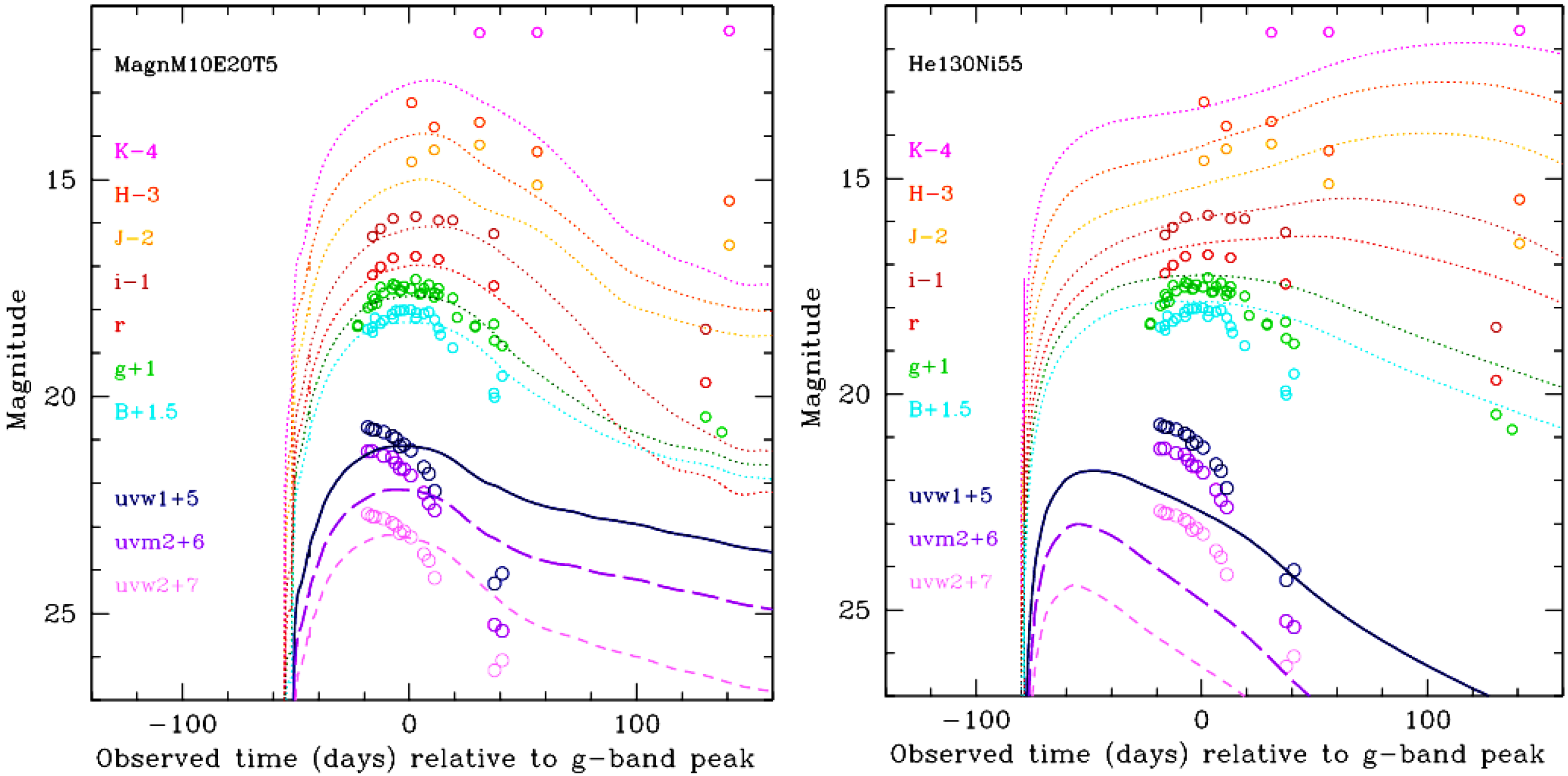
- $E_{51} = 20$, $M_{ej} = 40\ M_\odot$, $M_{CSM} = 40\ M_\odot$, He+C+O

(Tolstov, KN+16)



Gaia16apd: Magnetar and PISN models

- Magne: $E_{51, magn} = 20$, $E_{51, ej} = 1$, $T_{spindown} = 5$ d, $M_{ej} = 10\ M_{\odot}$
- PISN: $E_{51} = 40$, $M(^{56}Ni) = 5.5\ M_{\odot}$, $M_{ej} = 57\ M_{\odot}$



(Tolstov, KN+16)

Fast-Evolving Luminous Transient **(FELT)**:KSN 15K

Circumstellar Interaction Model with a Super-AGB star

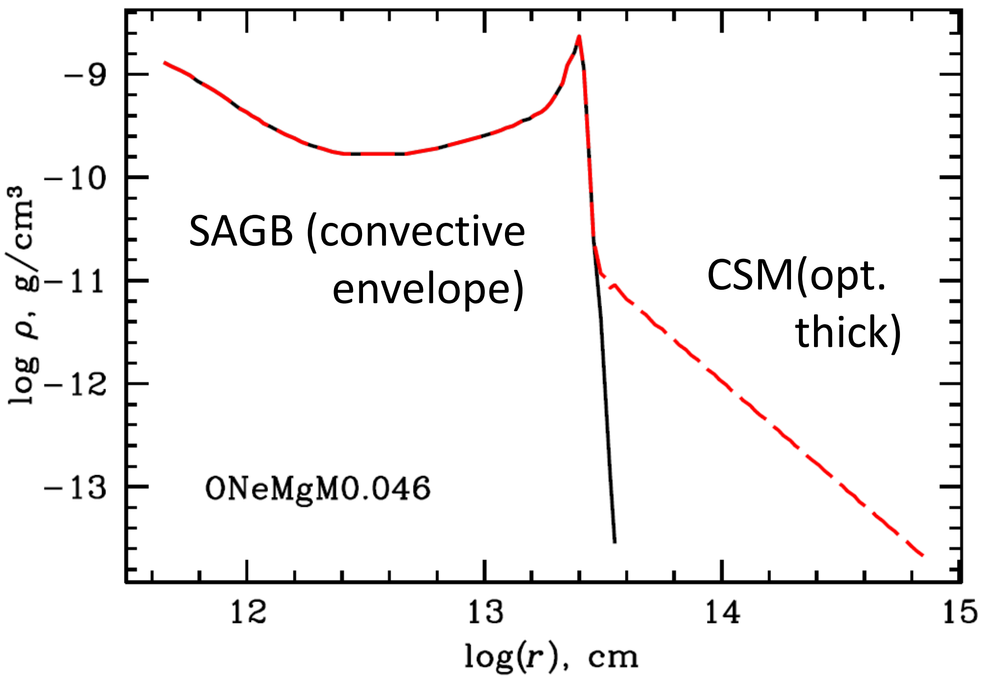
Near the border between Electron-Capture SN and an ONeMg White Dwarf

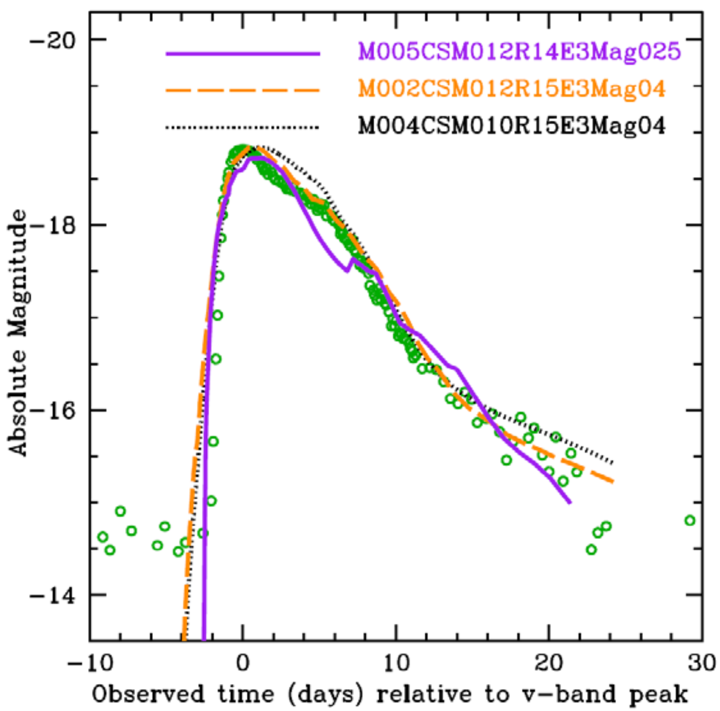
M(ONeMg core) = 1.37 $M_\odot$ M(H/He envelope) = 0.046 $M_\odot$

M(CSM) = 0.12 $M_\odot$

Electron Capture SN: Weak explosion ➔ CS Interaction (early LC) + Crab-like Pulsar (late LC)

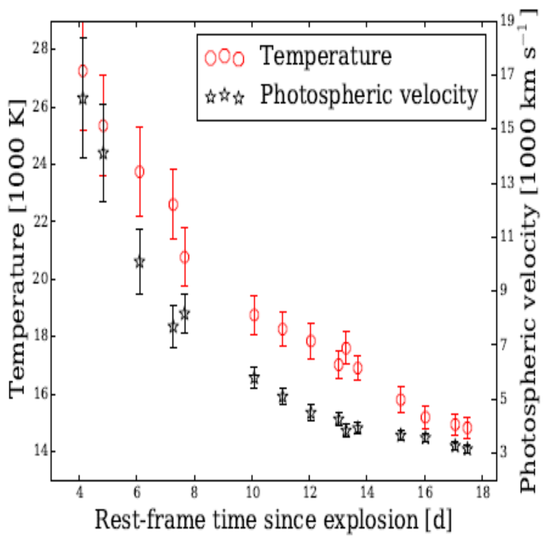
(Tolstov, KN+18)

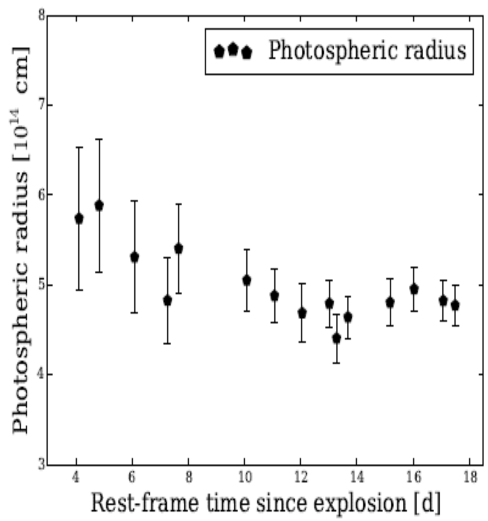


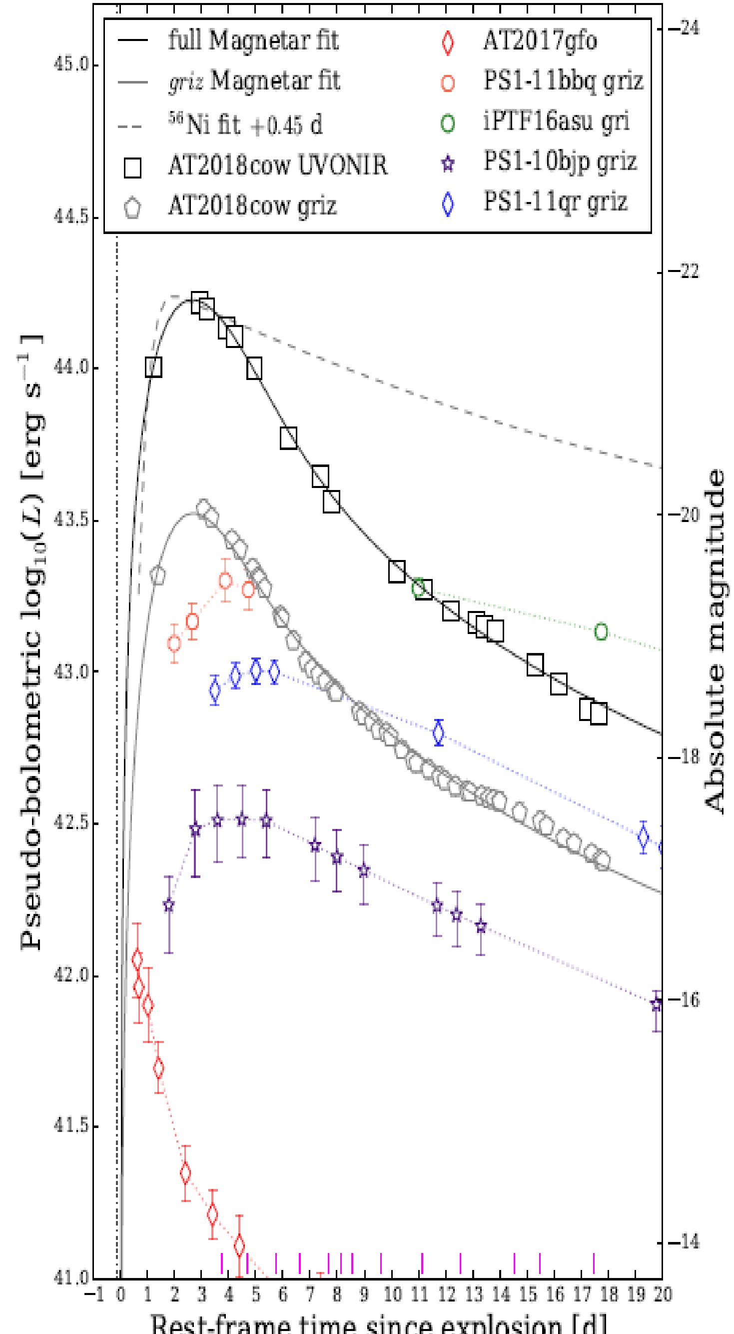


AT2018cow (COW)

- A rapid transient with 3-day (!) rise
- Superluminous event (10^{44} erg s^{-1})
- Rapid drop after 5 days
- Unusual photosphere radius and velocity



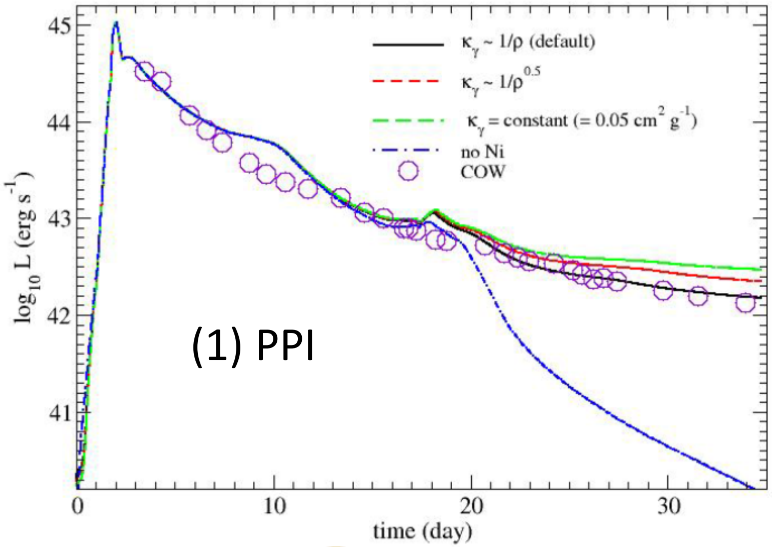




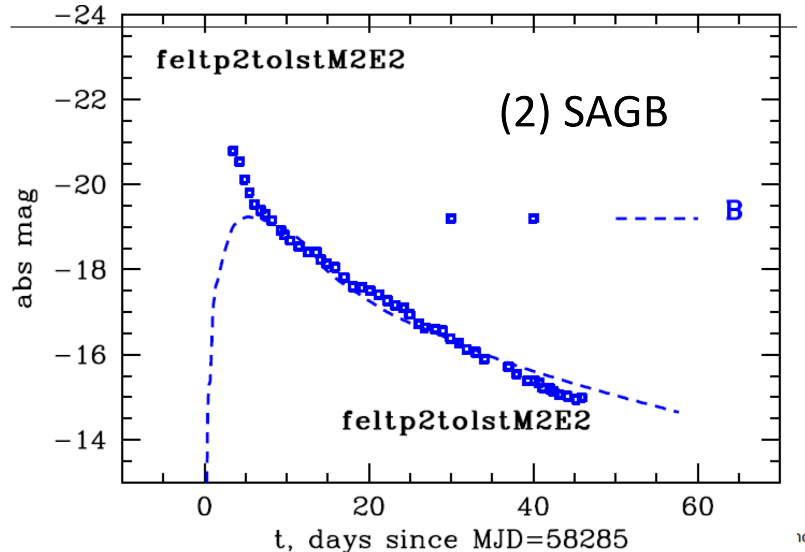
Prentice et al., ApJ (2018)

AT2018cow

(1) PPI model = CS interaction + Ni-decay
(2) Super-AGB model = CS interaction + pulsar

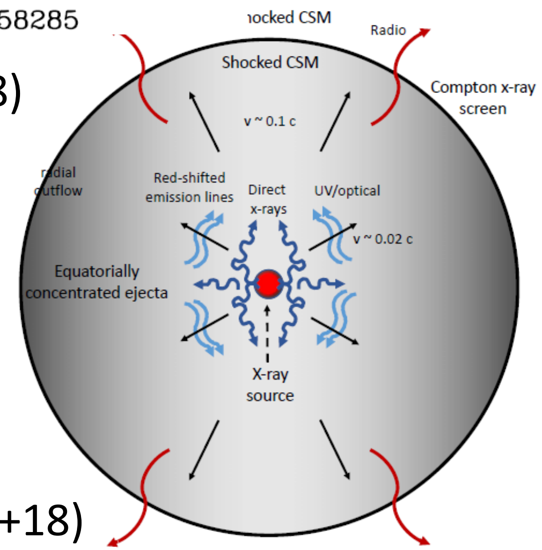


(Leung+18)



(Blinnikov, Sorokina+18)

M(He core) = 43 $M_\odot$
M(CSM) = 0.5 $M_\odot$



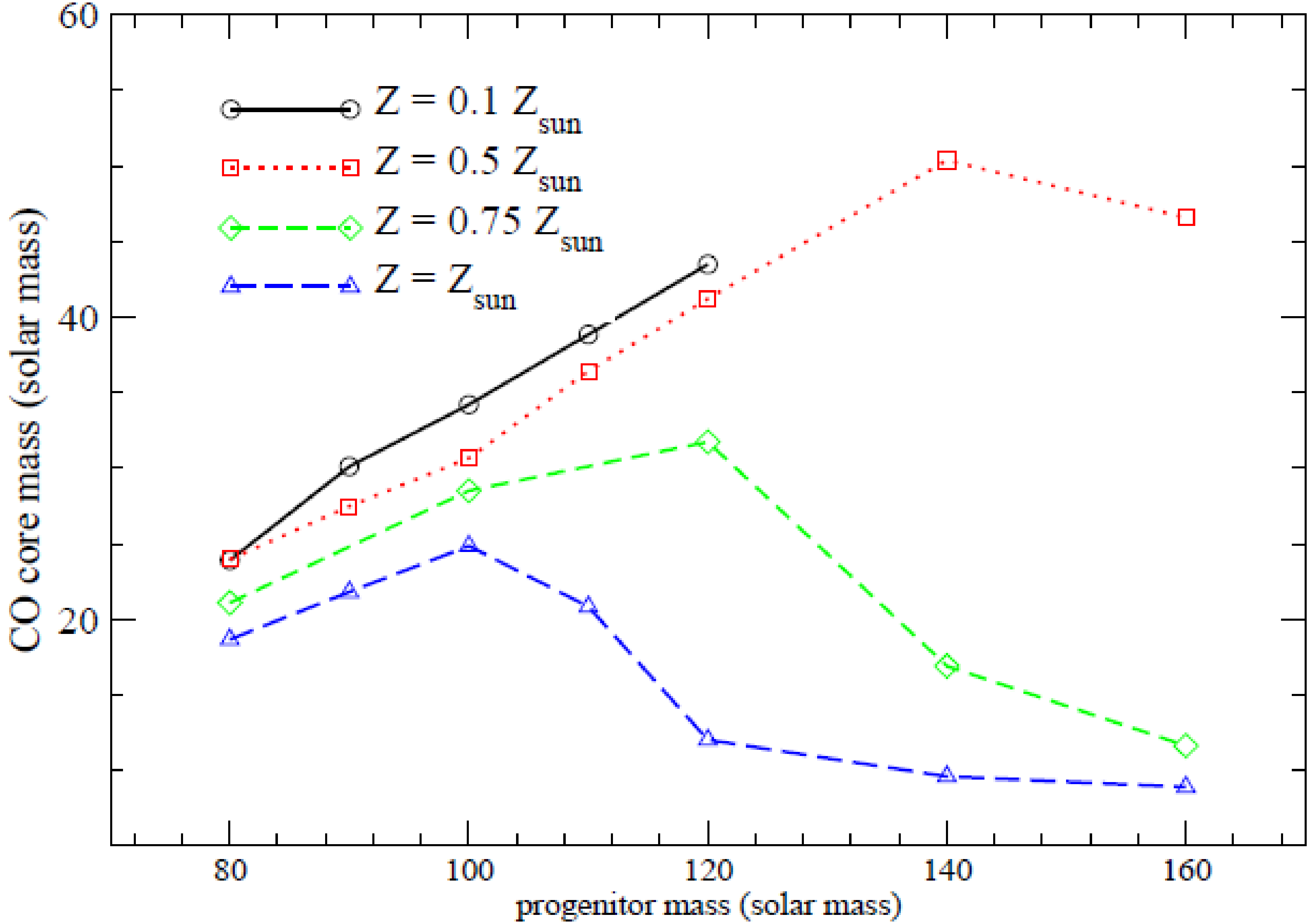
(Margutti+18)

Unusual SNe: Superluminous SNe-I

- Double Power Source Models ➔ good for UVLCs
  Circumstellar Interaction
  + Pulsar or Radioactive decay
- The origin of massive non-H (He, O-rich) CSM can be **Pulsational Pair-Instability.**
- Metallicity constraint ($Z < 0.7\ Z_{\odot}$)
- Ejected mass and the remaining core mass are
- consistent with the observed BH mass (~50 $M_{\odot}$)
- Nucleosynthesis in 80 – 140 $M_{\odot}$ stars
  vs. Abundance Patterns of EMP stars ?

CO Core Mass: PPISN: $Z < 0.7 Z_\odot$

(Leung, KN+18)



Unusual SNe: Fast-Evolving Luminous Transients (e.g., KSN 15K)

- Double power source models for light curves:
  Circumstellar Interaction
  + Pulsar or Radioactive decay
- 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 ??)

Progenitor Mass

- Combined mechanisms for re-brightning
  & mutiple peaks ?
- If Pulational Pair-Instability ➔ COHe CSM,
  progenitors : 80 $M_\odot$ < M < 140 $M_\odot$

➔ CSM + BH accretion

➔ CSM + Radioactive decay (core collapse)

➔ CSM (multiple ejection)

or: M(magnetar) > 80 $M_\odot$?? (CSM + Magnetar)