

電子捕獲型超新星と鉄コア崩壊型超新星の 多色光度曲線

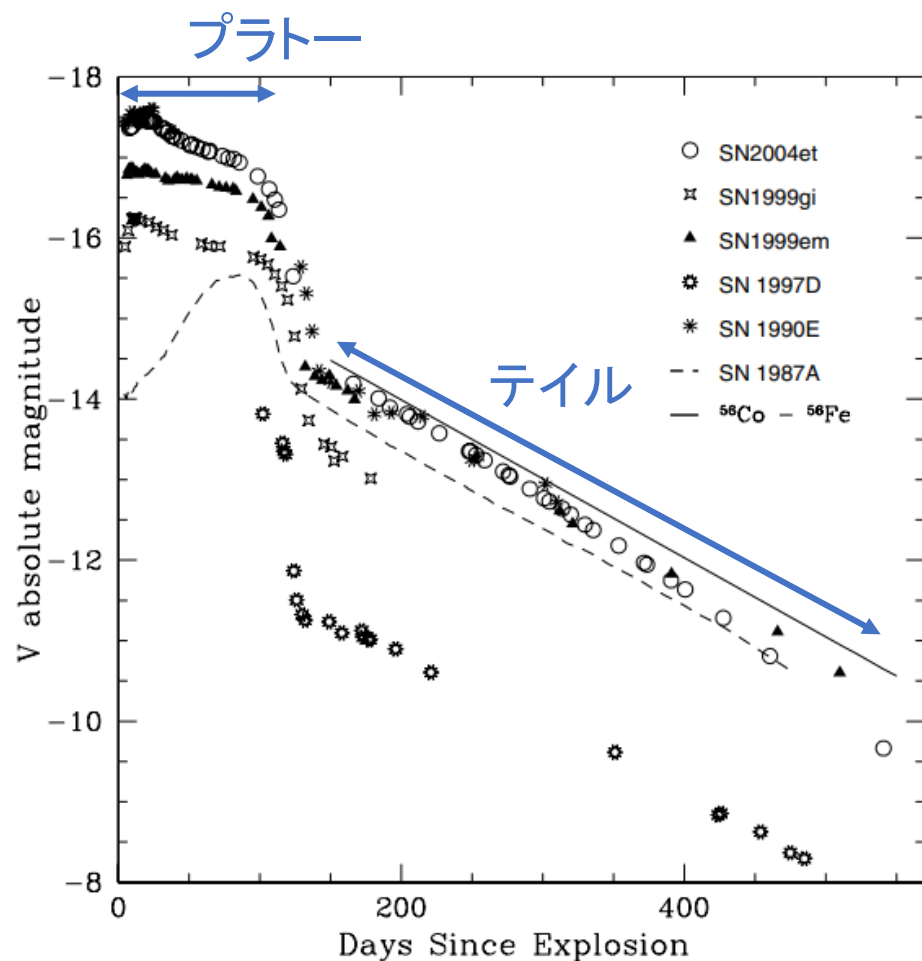
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平松大地 (Center for Astrophysics | Harvard & Smithsonian)

2023年5月30日

木曾シュミットシンポジウム2023

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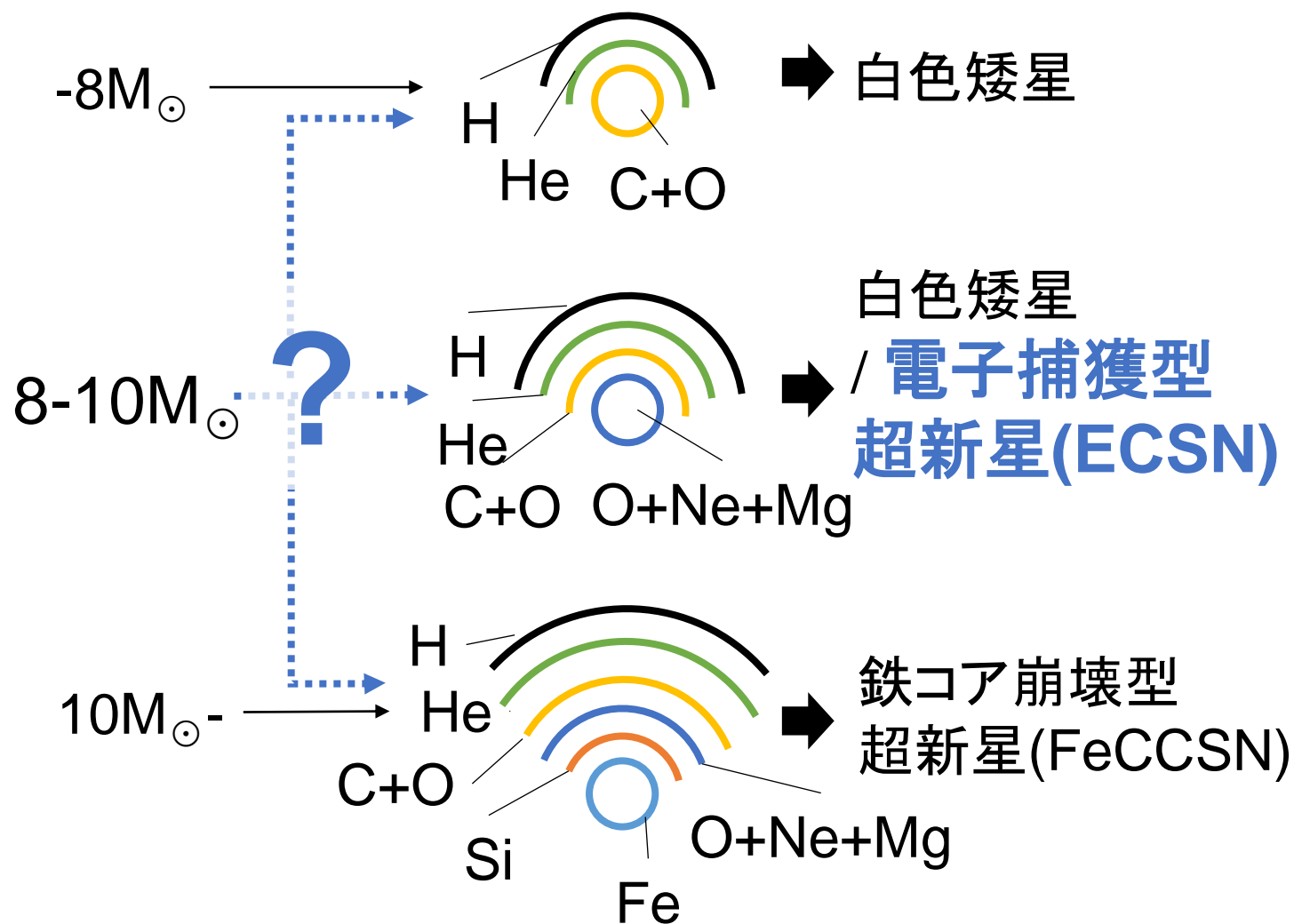
IIP型超新星



Sahu+06

- プラトー:
 - 100日程度明るさがおよそ一定
 - 水素外層の衝撃波加熱による
- テイル:
 - ^{56}Co のdecay
 - ^{56}Ni のejected massが分かる

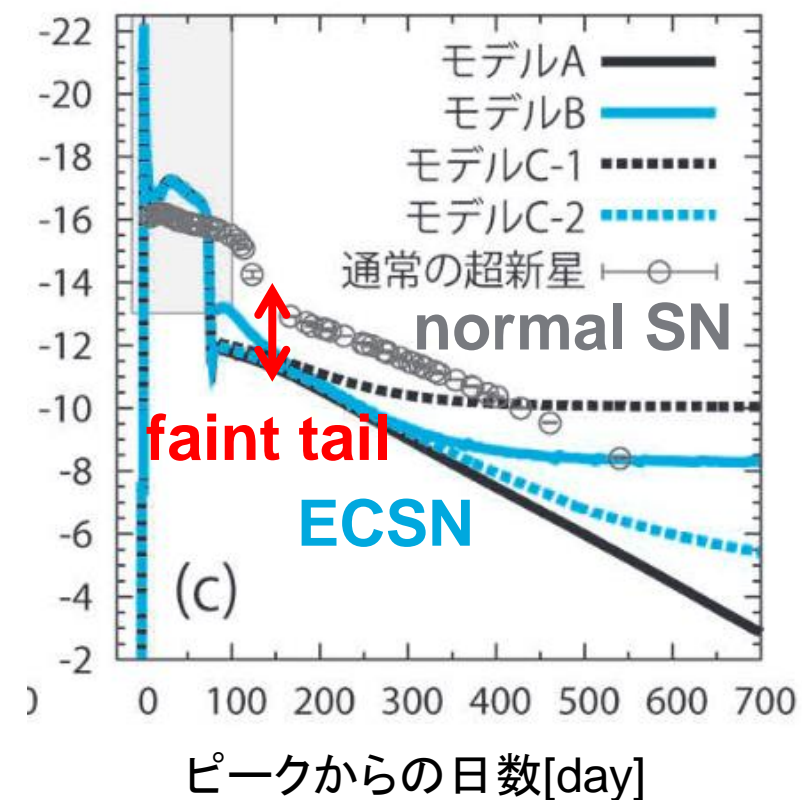
星の進化



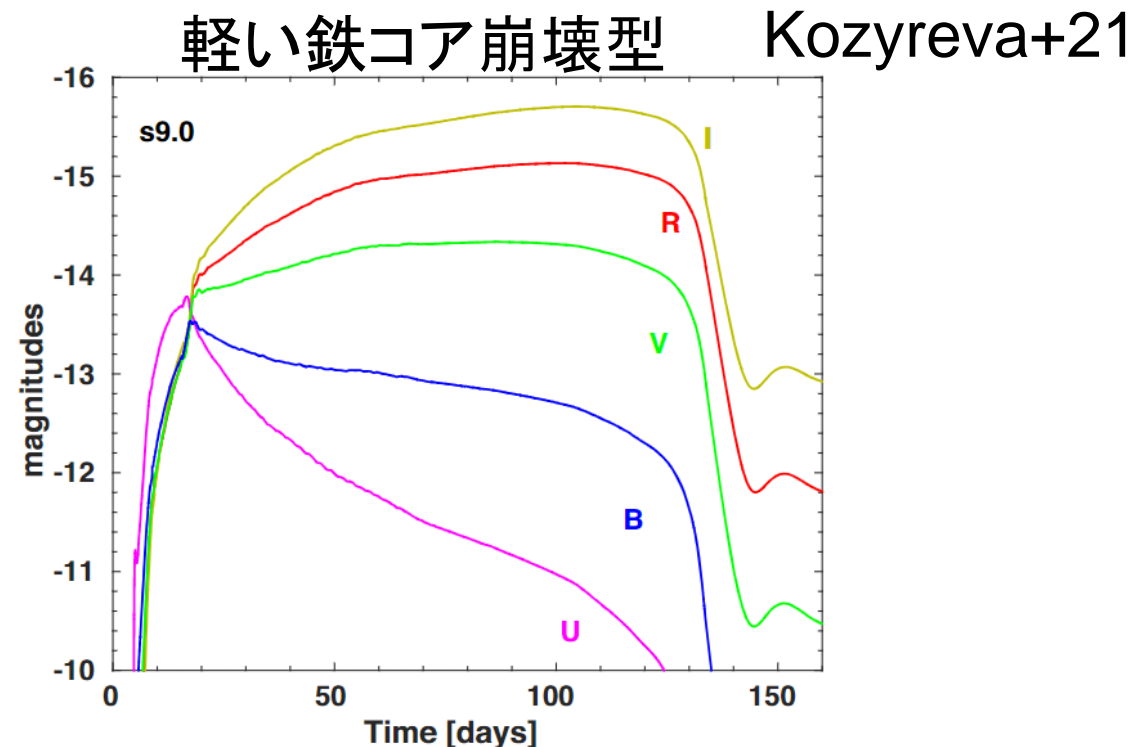
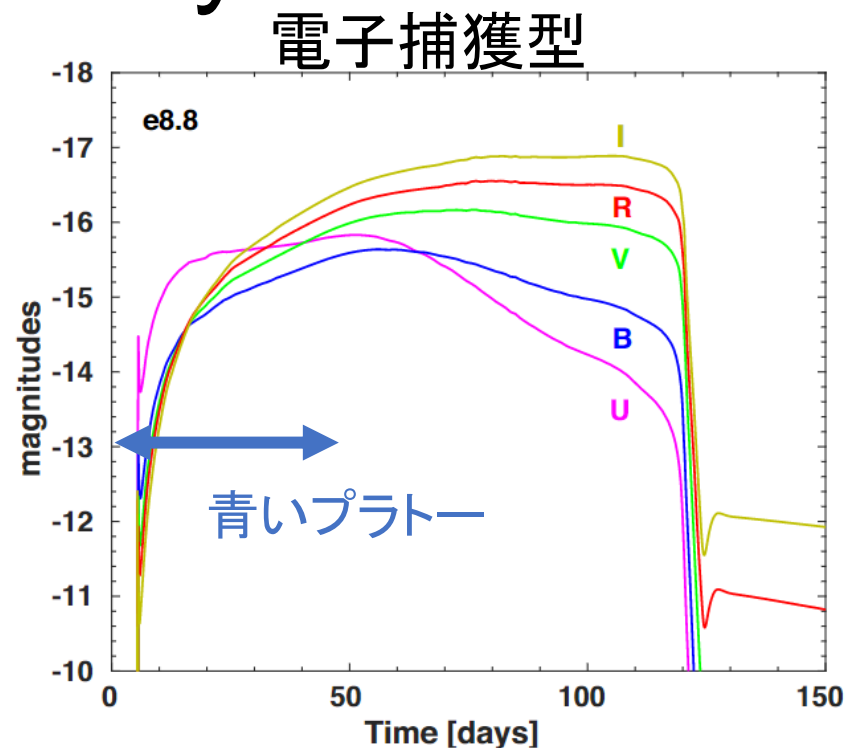
- 星の最期は質量で決まる
- 8-10 M_{\odot} の星の進化の最期は、よくわかっていない
- その最期を明らかにすることは、銀河化学進化や超新星爆発機構などにとっても重要

電子捕獲型超新星(ECSN)

- Super-AGBの爆発 (Miyaji+80, Nomoto 87)
- 爆発: 第一原理計算で爆発、**低い爆発エネルギー**
($\sim 10^{50}$ erg) (Kitauro+06, Janka+08)
- 元素合成: 少ない ^{56}Ni ($0.002-0.004M_{\odot}$)
(Wanajo+09)
- 光度曲線: **II-P型**、暗いtailフェーズ
(Tominaga+13, Moriya+14)
- 候補天体: SN1054(かに星雲)、
SN2018zd (Hiramatsu+21)



電子捕獲型・軽い鉄コア崩壊型の光度曲線 (Kozyreva+21)

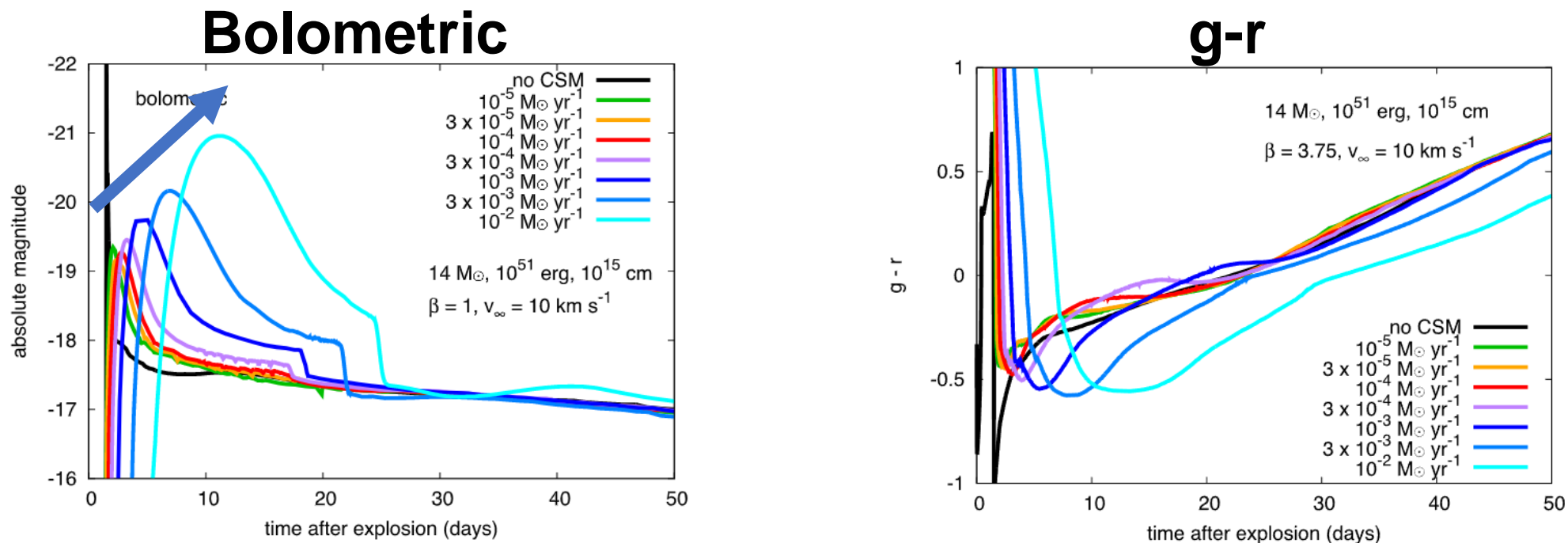


親星: コア(Nomoto 87)+外層(MESA:Jones+13)

親星: $9M_{\odot}$ (Sukhbold+16)

- 電子捕獲型では、**青いプラトー**(~50d)が観測される。
- **星周物質(CSM)との相互作用**は考慮されていない。

CSMがある場合の光度曲線(Moriya+18)



- CSMが十分に濃い場合、**delayed shockbreakout**になる
- CSMが濃いほど、ピークが遅く、明るくなる
- CSMが濃いほど、色進化のタイムスケールが長くなる

Moriya+18

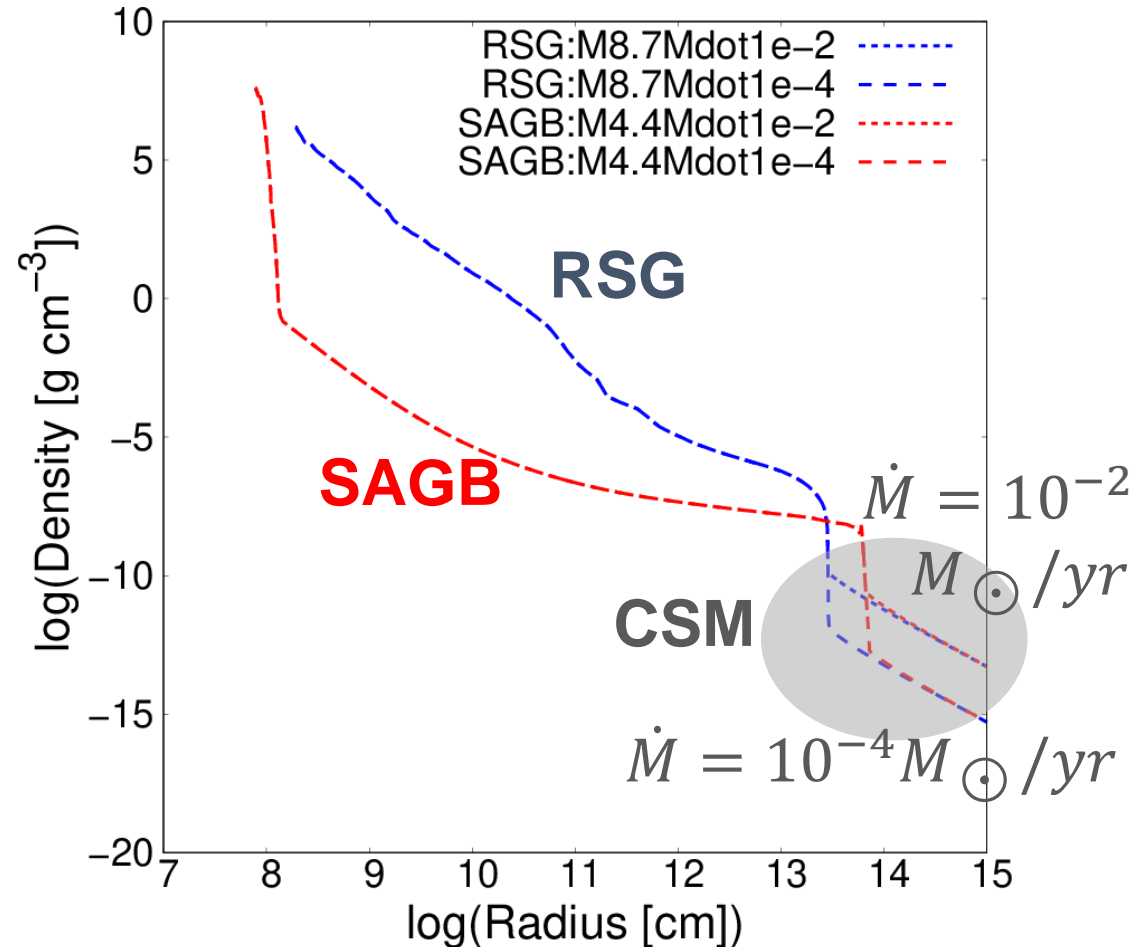
本研究

- モチベーション:
 - **電子捕獲型と軽い鉄コア崩壊型の光度曲線の違い**を明らかにし、観測から電子捕獲型を見分け、8-10M_☉の星の進化を明らかにしたい。
- 手法:
 - STELLA (Blinnikov+00)を用いて光度曲線を計算
 - **CSMなし**の計算を行い、Kozyreva+21の結果を確認
 - **CSMつき**の計算を行い、電子捕獲型の観測的特徴を明らかにする
 - **電子捕獲型を見分ける手法**を提案

親星モデルとパラメータ

- 親星
 - RSG: Sukhbold+16 (s9.0-12.0)
 - SAGB: Tominaga+13
- パラメータ
 - 星の質量 M
 - 外層のH組成 $X(H)$
 - 爆発エネルギー E_{exp}
 - 質量放出率 \dot{M}
 - CSM半径 R_{out}

CSMのパラメータ

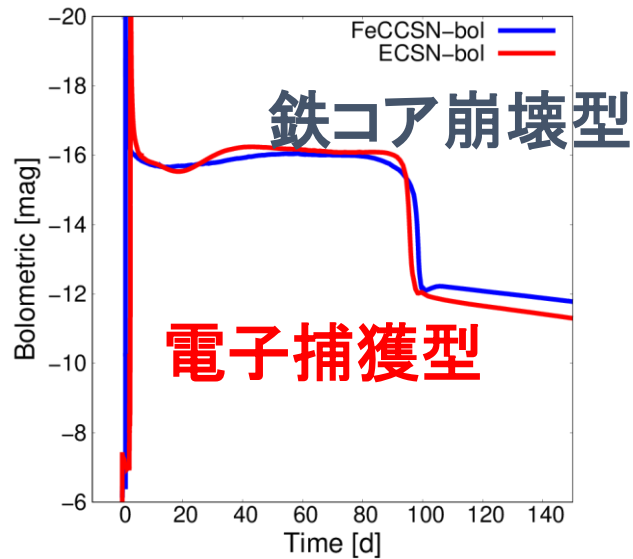


CSMがない場合の光度曲線の比較

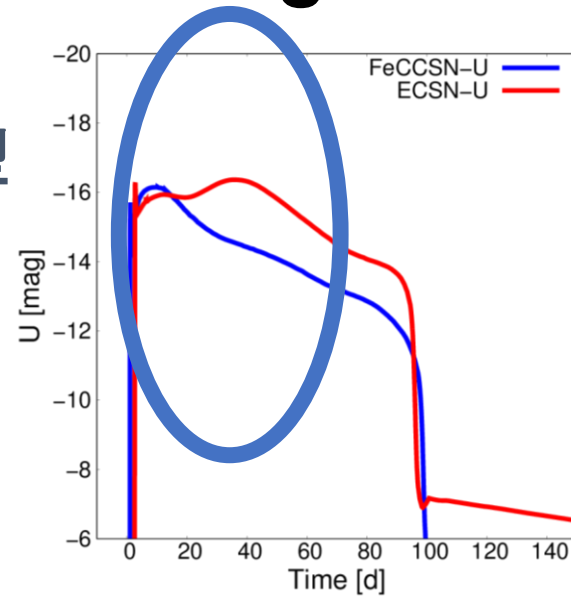
ECSN $M=4.4M_{\odot}$, $X(H)=0.70$, $E_{\text{exp}}=1.1 \times 10^{50}\text{erg}$

FeCCSN $M=8.7M_{\odot}$, $X(H)=0.68$, $E_{\text{exp}}=3.7 \times 10^{50}\text{erg}$

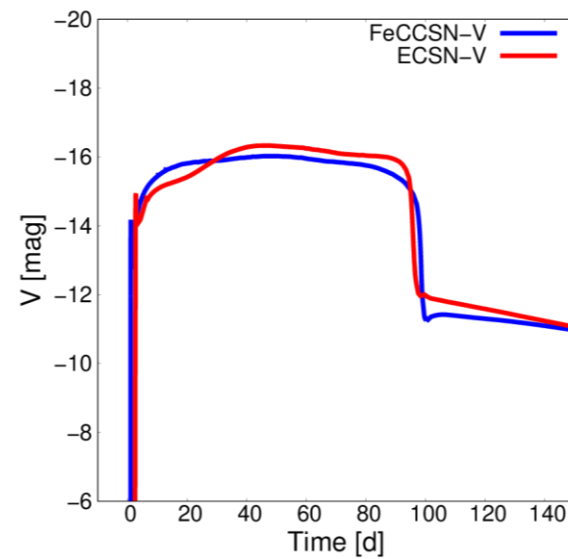
Bolometric



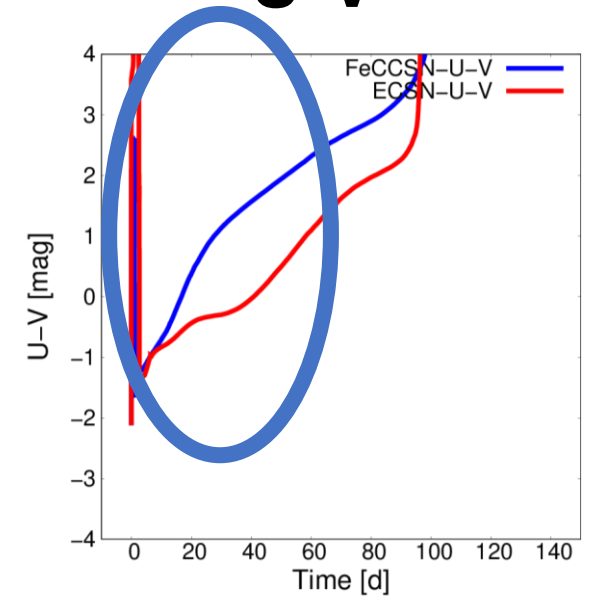
U



V

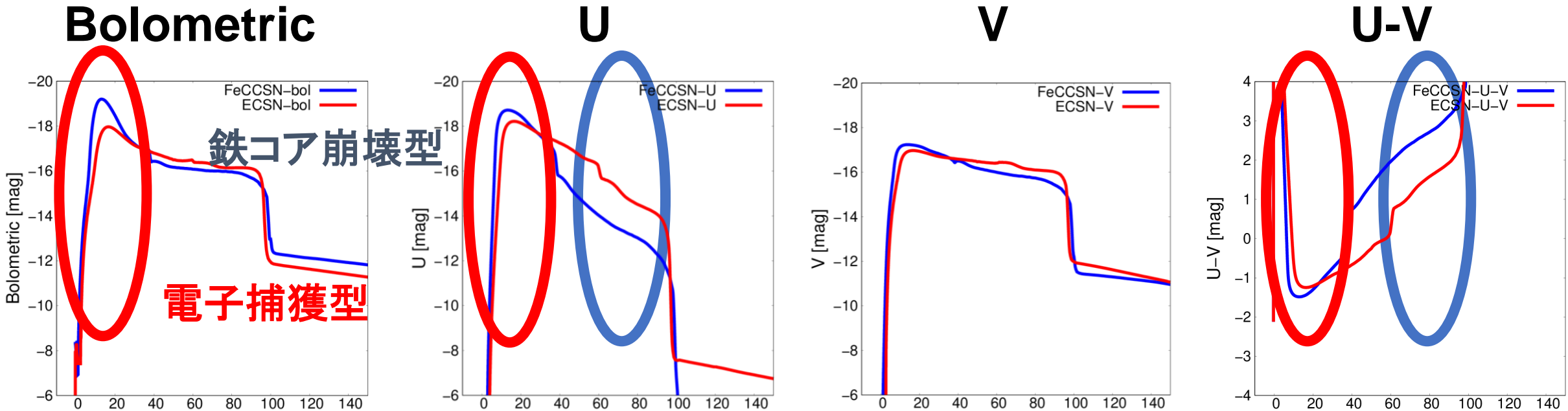


U-V



電子捕獲型で青いプラトーン (~50d)

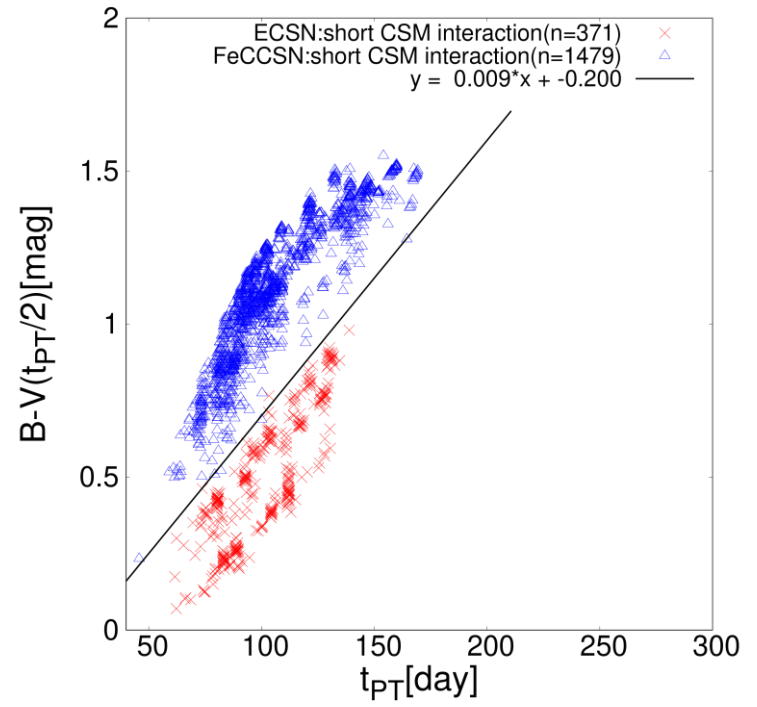
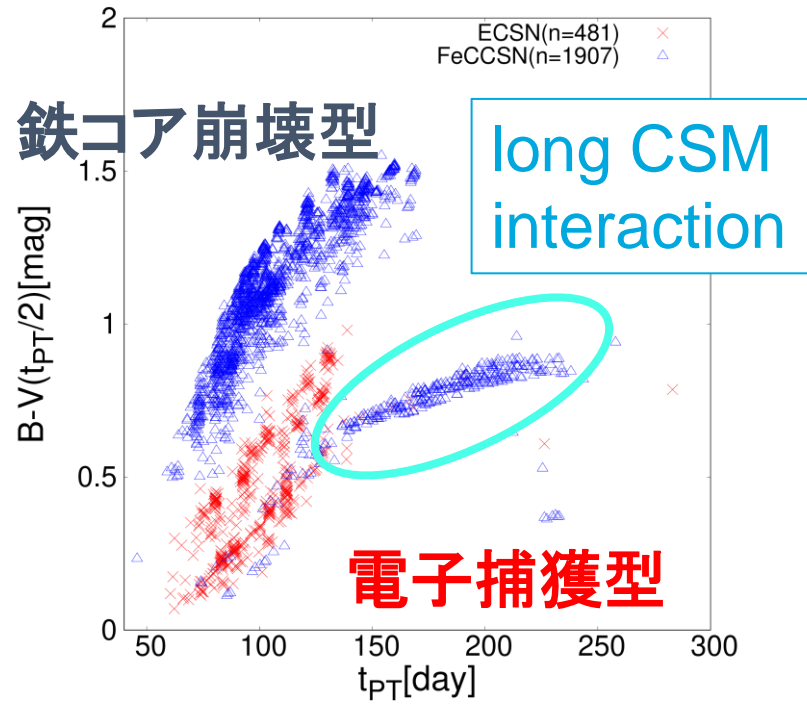
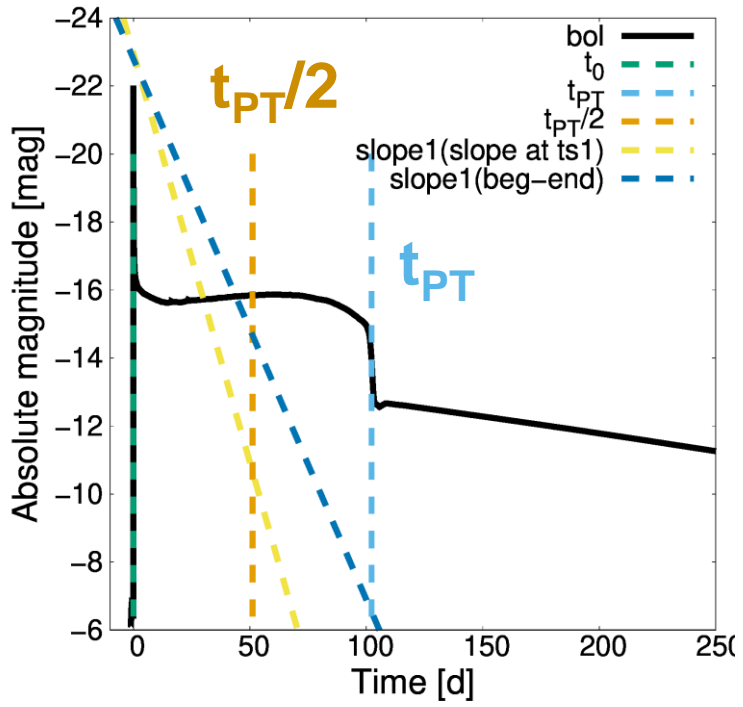
濃い($\dot{M} = 10^{-2} M_{\odot} / yr$) CSMの場合の光度曲線の比較



暗くて赤いdelayed shockbreakout

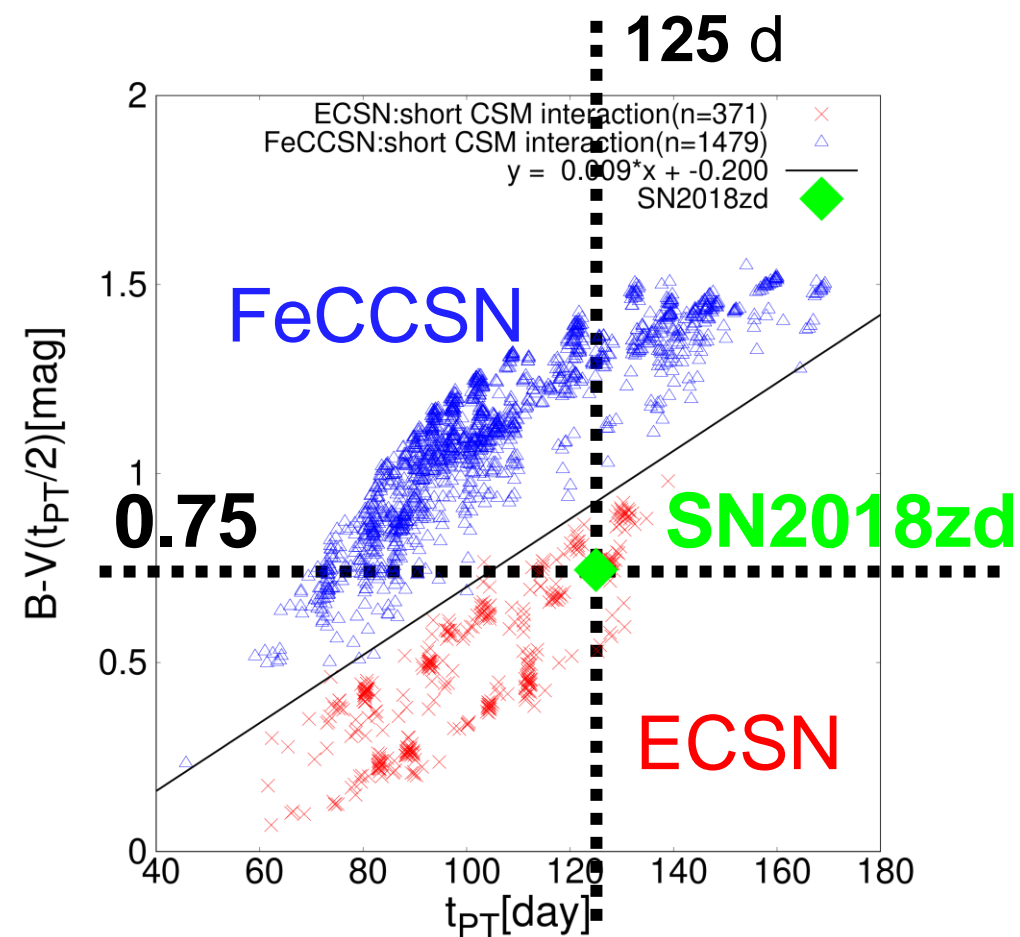
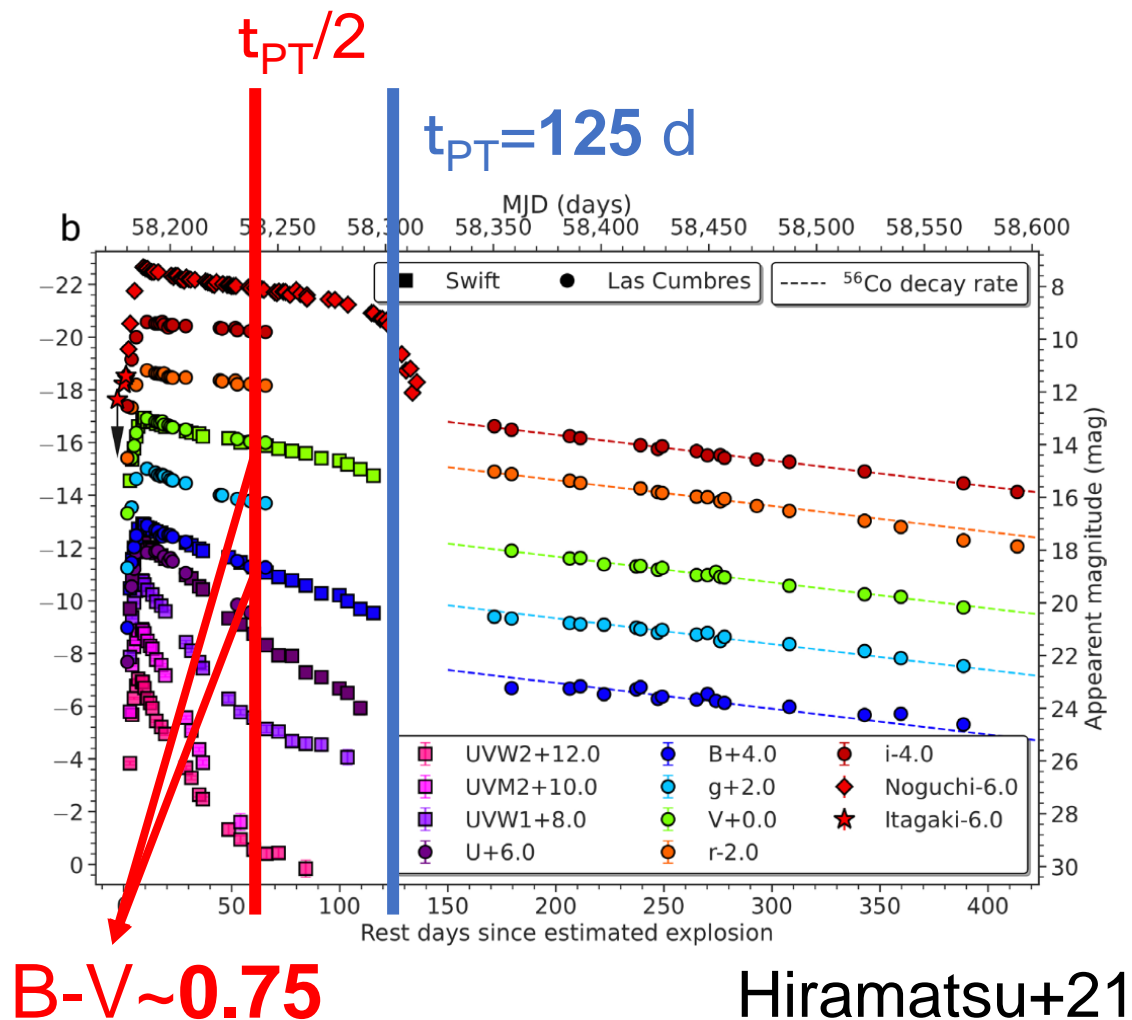
その後、青いプラトー

ECSNの判別手法



- CSM interactionが $t_{PT}/2$ より短い場合に適用可能。
- $B - V \left(\frac{t_{PT}}{2} \right) \lesssim 0.9 \times \left(\frac{t_{PT}}{100} \right) - 0.2$ (ECSN)

SN2018zd



今後

- ECSNの割合: ~0.5-8.5% of all CCSNe (Hiramatsu+21)
- 過去の観測、新規観測からECSNを探す。
- 光度曲線の再現等から、ECSNの親星やCSMなどに制限を与える。
- **爆発初期からの光度曲線、色の情報が必要。**
- **Tomo-e Gozen、せいめい望遠鏡による連携観測を行いたい。**

まとめ

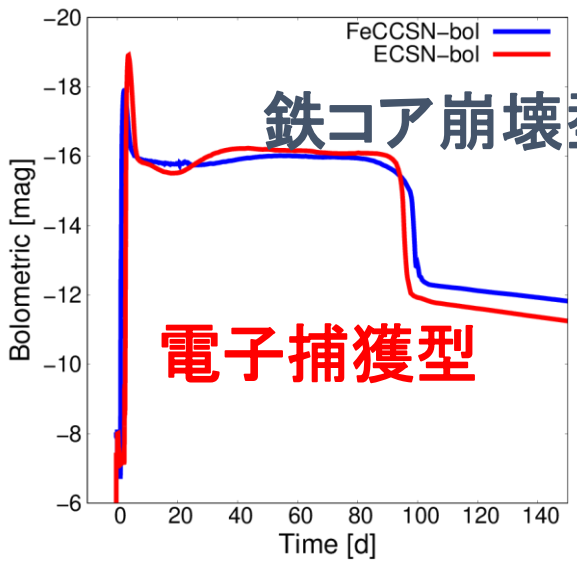
- ECSNの光度曲線
 - CSMがない/薄い ($\dot{M} \leq 10^{-4} M_{\odot} / yr$): **青いプラトー**
 - CSMが濃い ($\dot{M} \geq 10^{-2} \text{ //}$): delayed shockbreakoutの後に**青いプラトー**
- t_{PT} , $B-V(t_{PT}/2)$ を用いた**ECSNの判別手法を提案**した。本手法によれば、SN2018zdはECSNであった可能性が高い。
- 今後、既存の観測結果や、**Tomo-e Gozen**、**せいめい望遠鏡**を用いた**新規観測結果から、ECSNを見つけ、その親星やCSMの情報などを調べていきたい。**

appendix

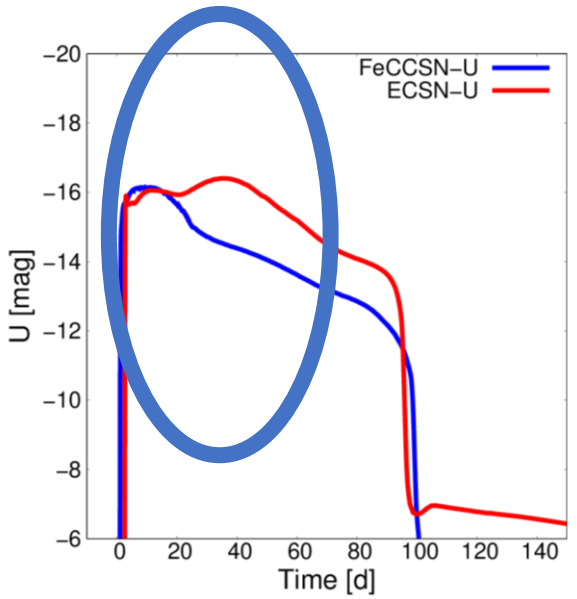
薄い($\dot{M} = 10^{-4} M_{\odot} / yr$) CSMの場合の光度曲線の比較

ECSN $M=4.4M_{\odot}$, $X(H)=0.70$, $E_{exp}=1.1 \times 10^{50}erg$, CSM radius= $10^{15}cm$
FeCCSN $M=8.7M_{\odot}$, $X(H)=0.68$, $E_{exp}=3.7 \times 10^{50}erg$, CSM radius= $10^{15}cm$

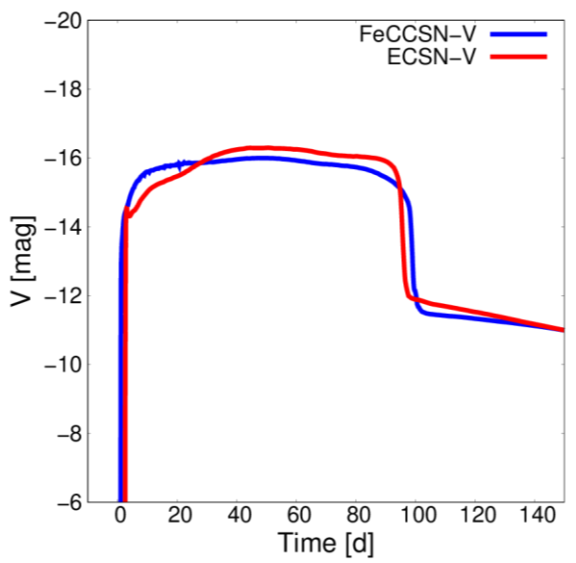
Bolometric



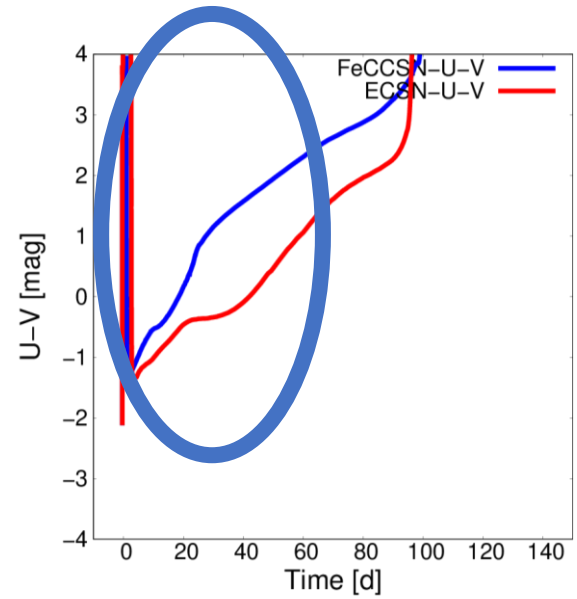
U



V



U-V

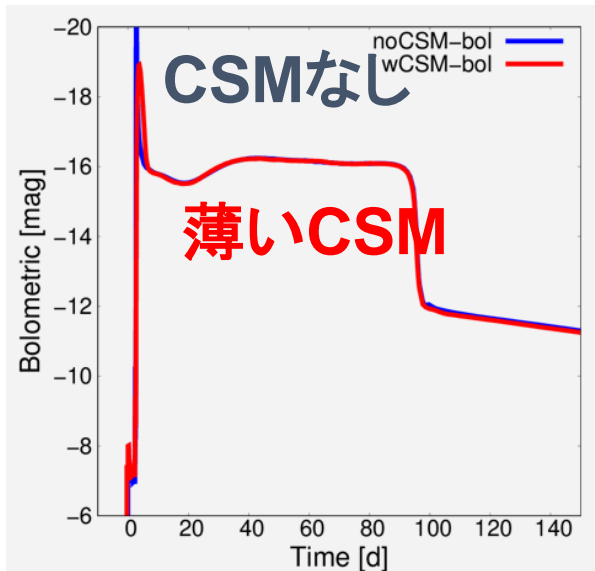


電子捕獲型で青いプラトー (~50d)

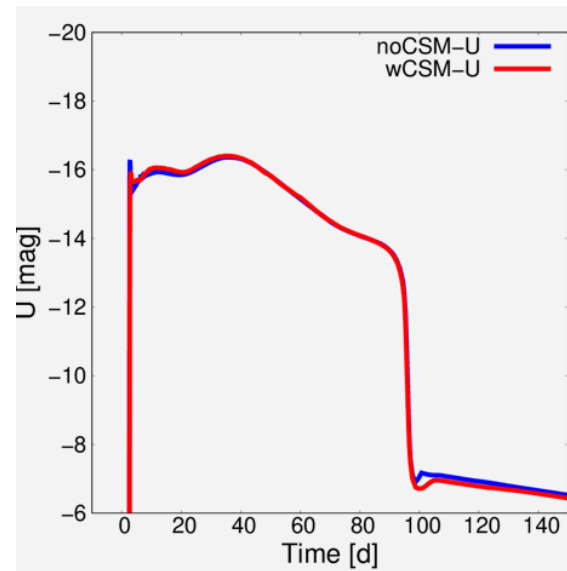
電子捕獲型 CSMの有無($\dot{M} = 10^{-4} M_{\odot} / yr$)

ECSN $M=4.4M_{\odot}$, $X(H)=0.70$, $E_{\text{exp}}=1.1 \times 10^{50}\text{erg}$, CSM radius= 10^{15}cm

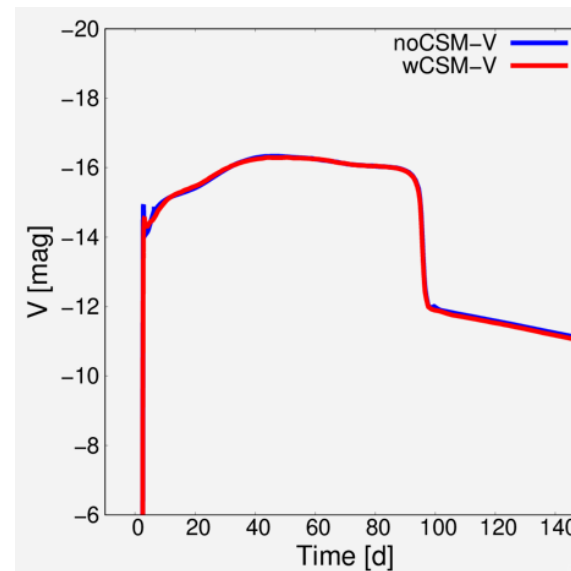
Bolometric



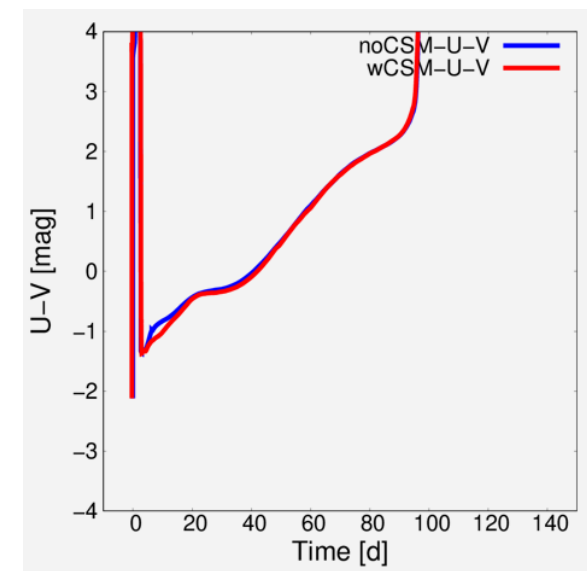
U



V



U-V

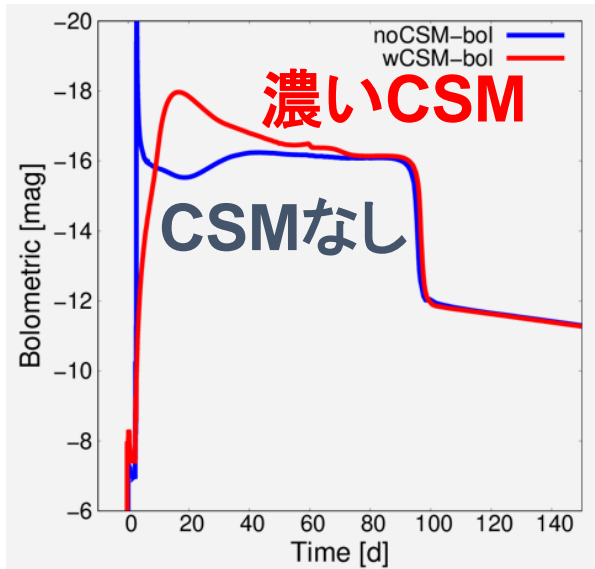


ほとんど、変化なし

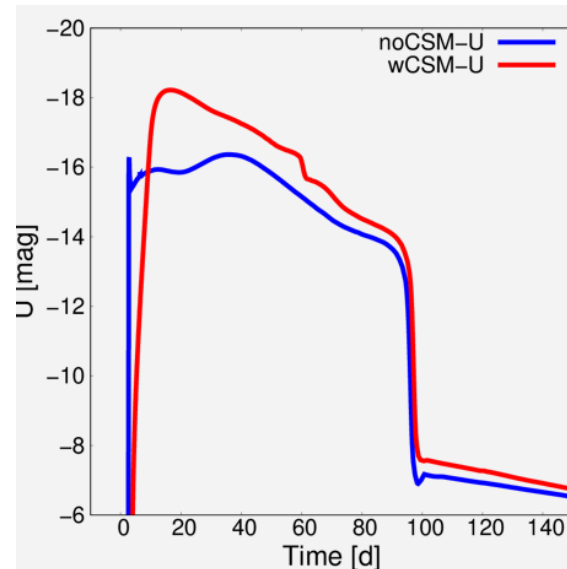
電子捕獲型 CSMの有無($\dot{M} = 10^{-2} M_{\odot} / yr$)

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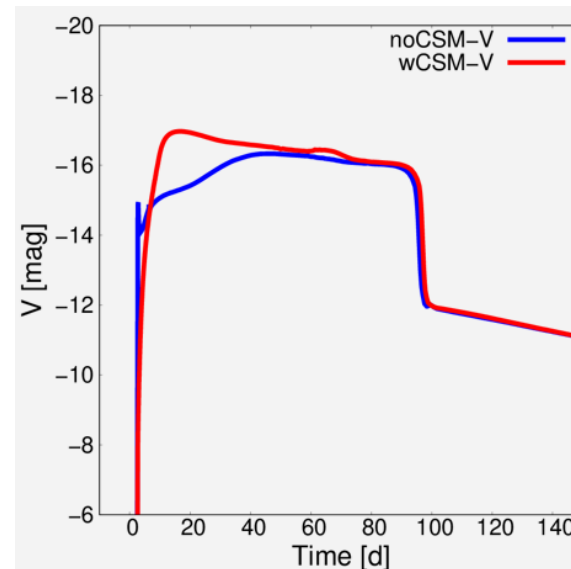
Bolometric



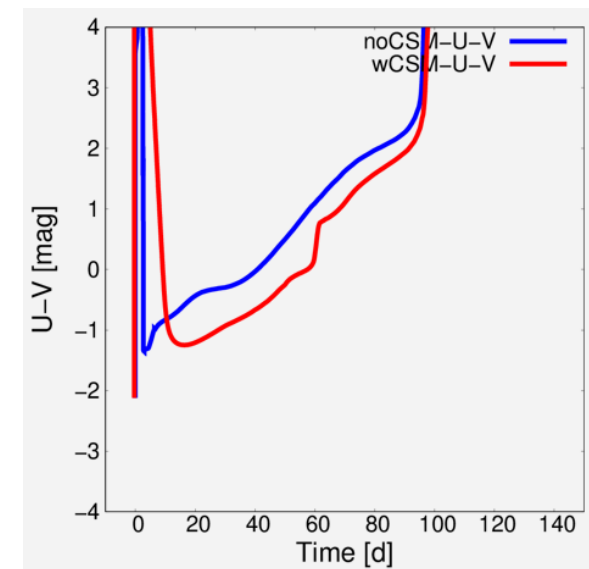
U



V



U-V



同じ爆発エネルギーの場合 ($\dot{M} = 10^{-2} M_{\odot} / yr$)

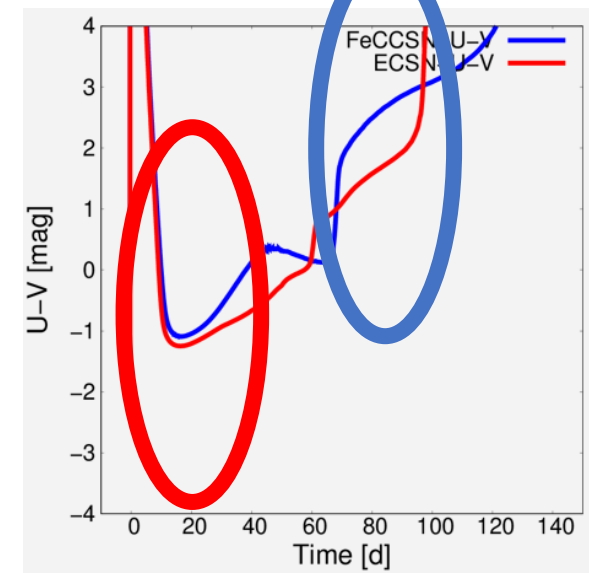
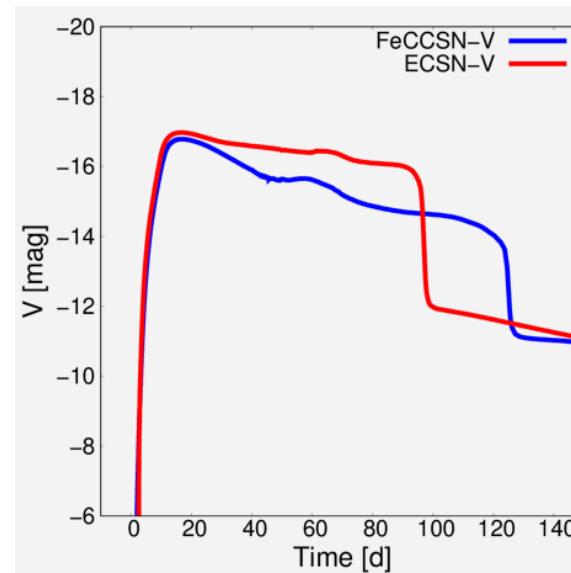
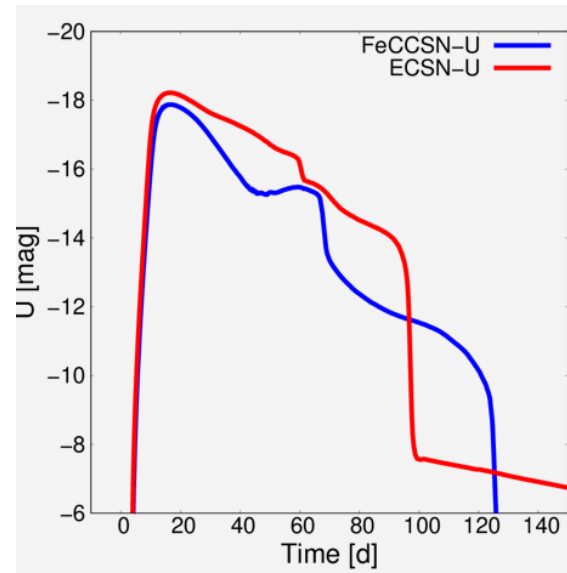
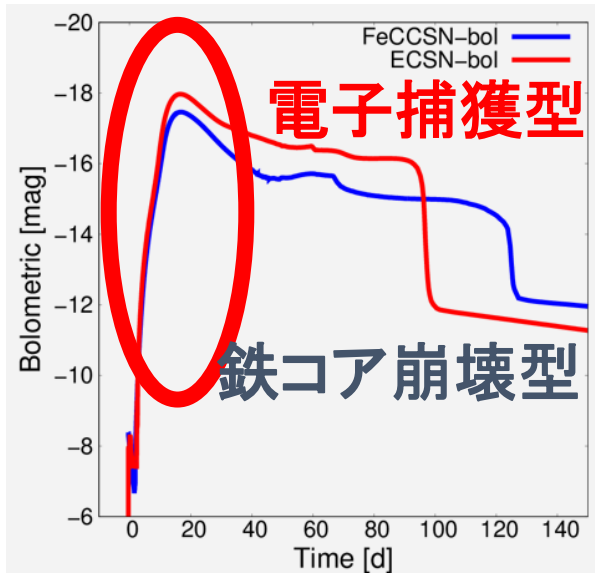
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Bolometric

U

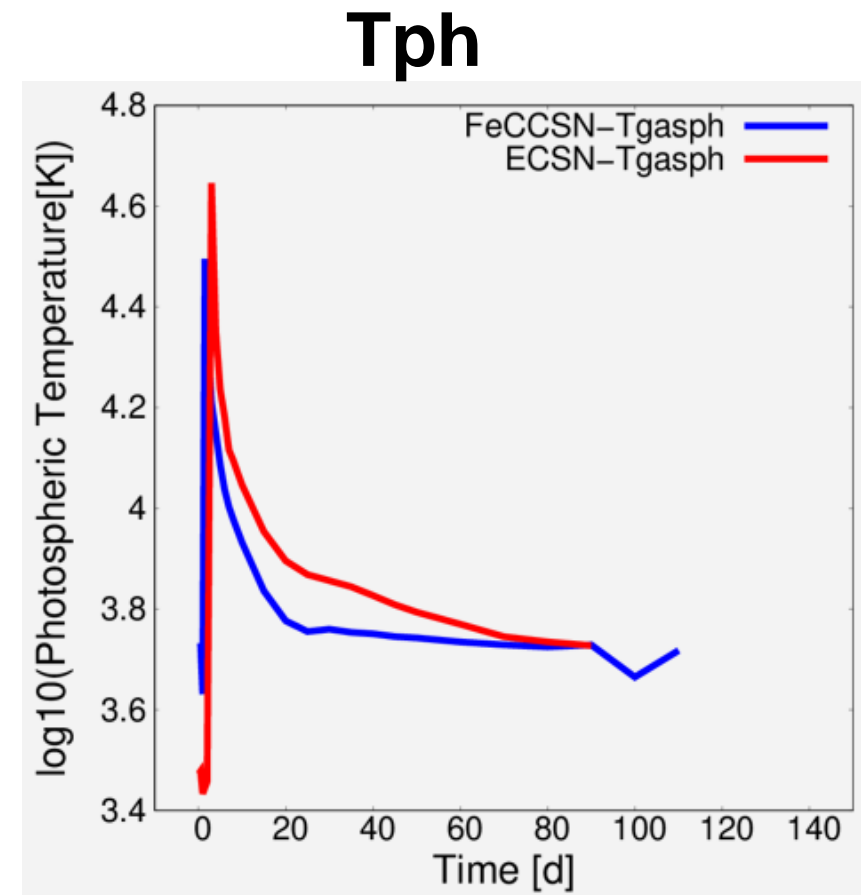
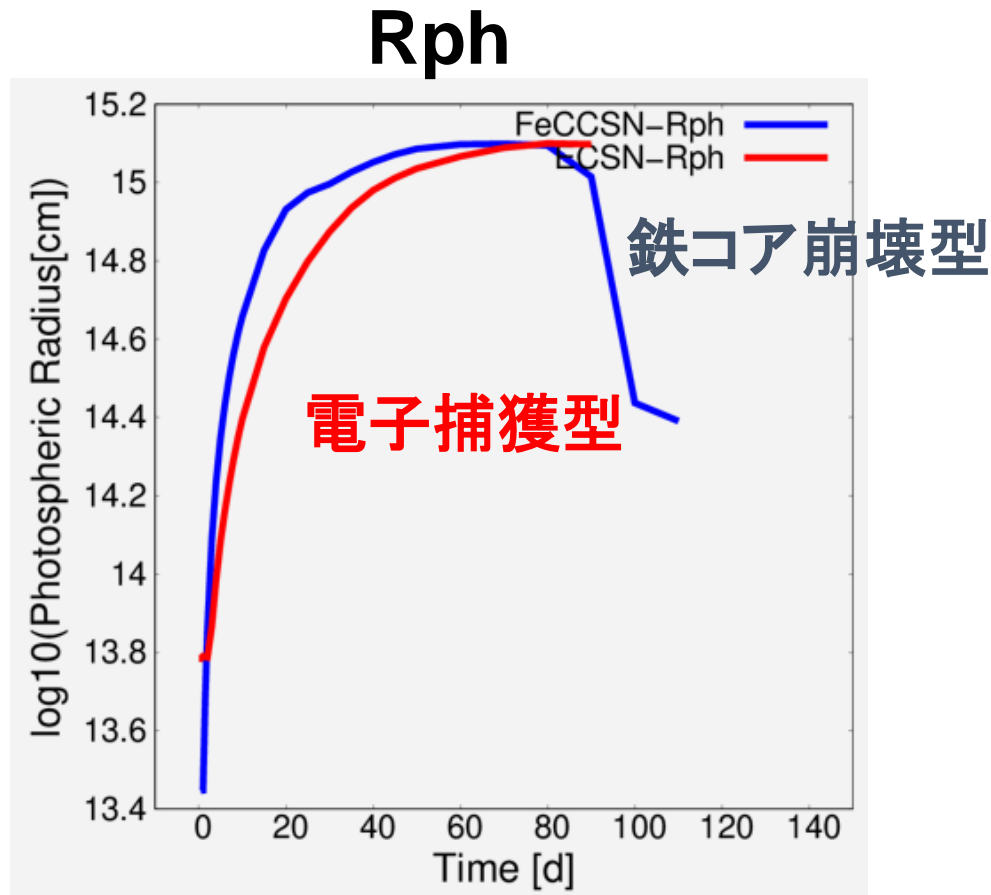
V

U-V

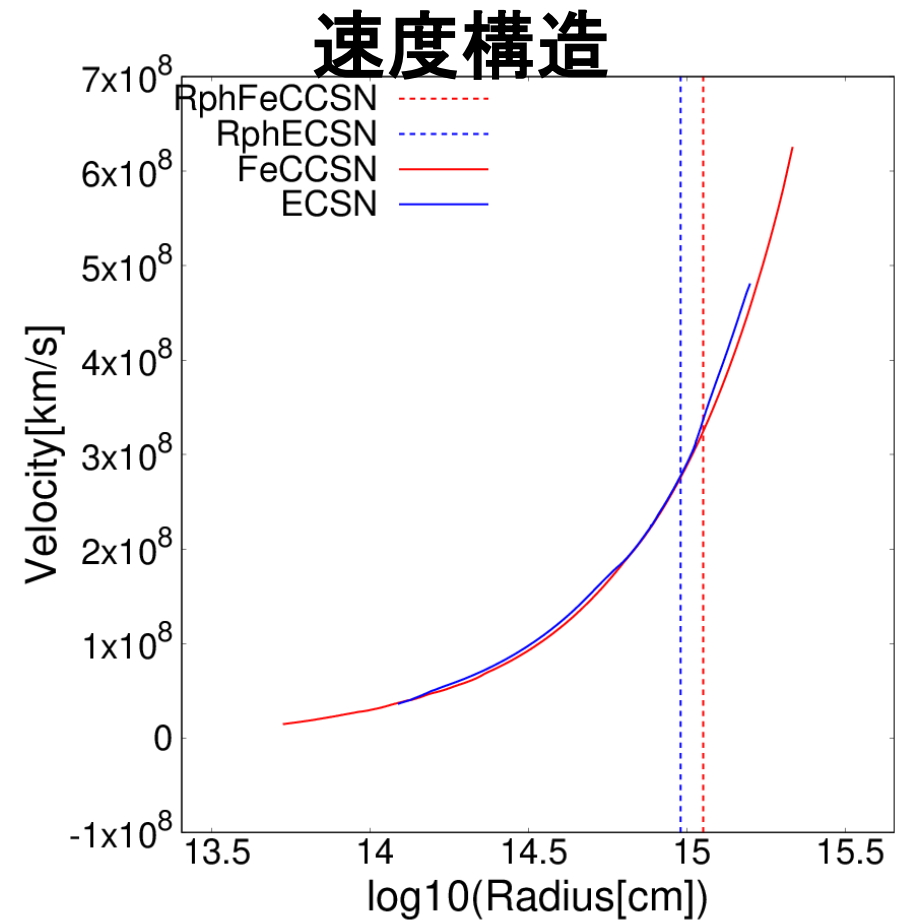
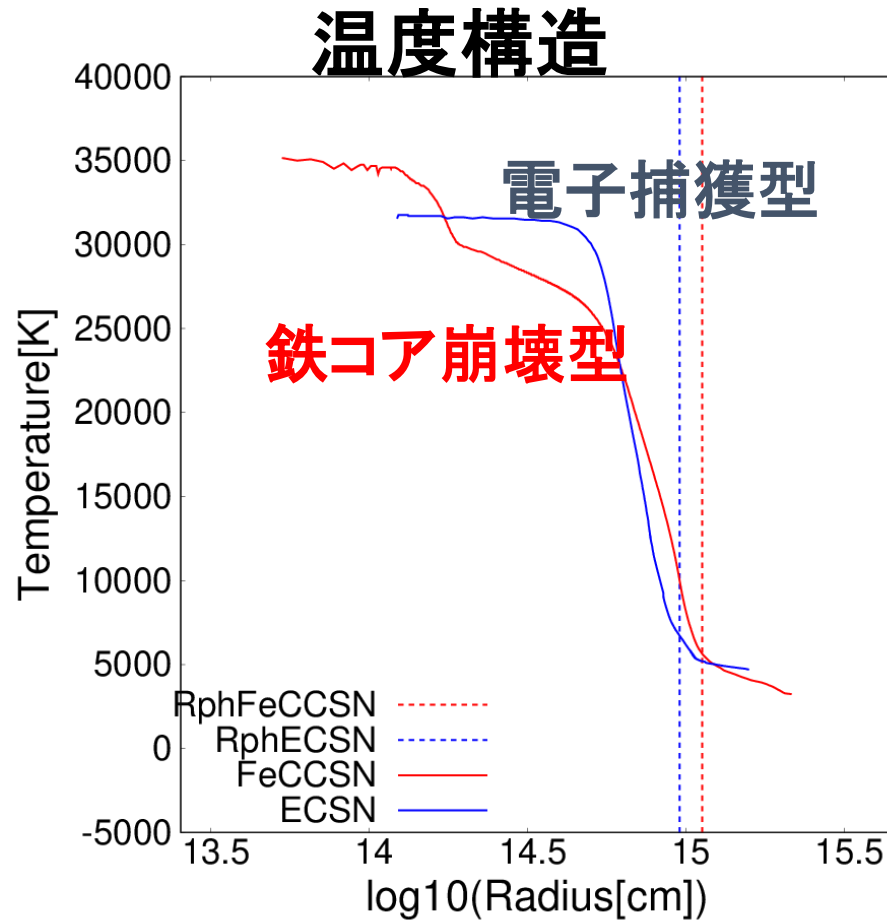


- ・delayed shockbreakoutのピークが同程度の明るさ、色になる
- ・依然、電子捕獲型のプラトー後半は青い

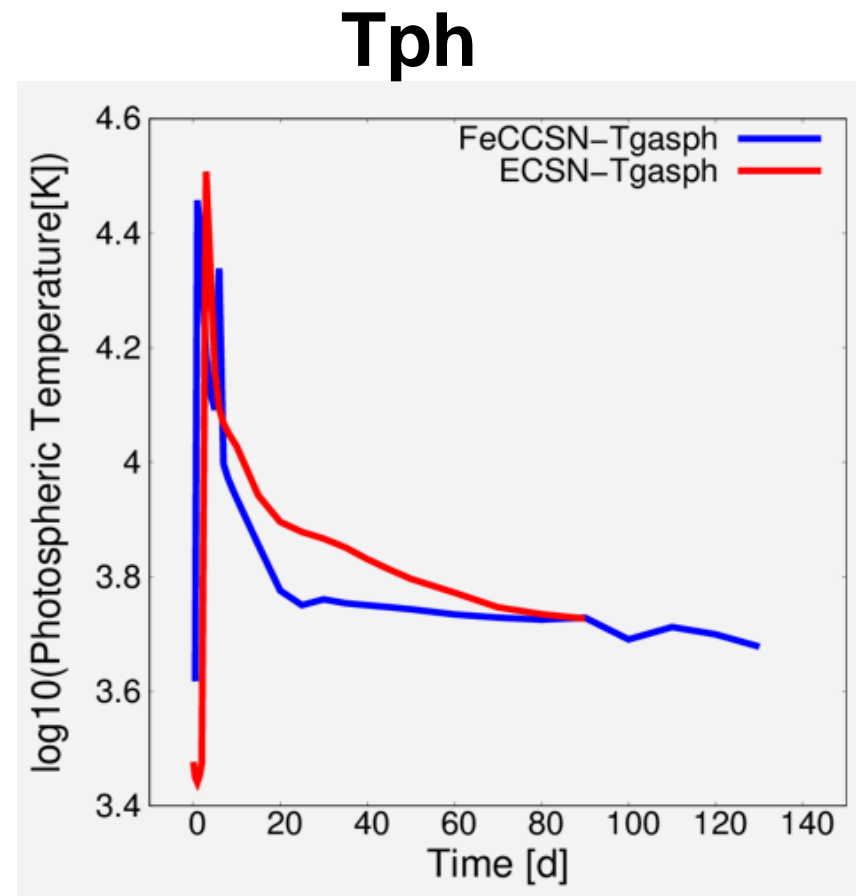
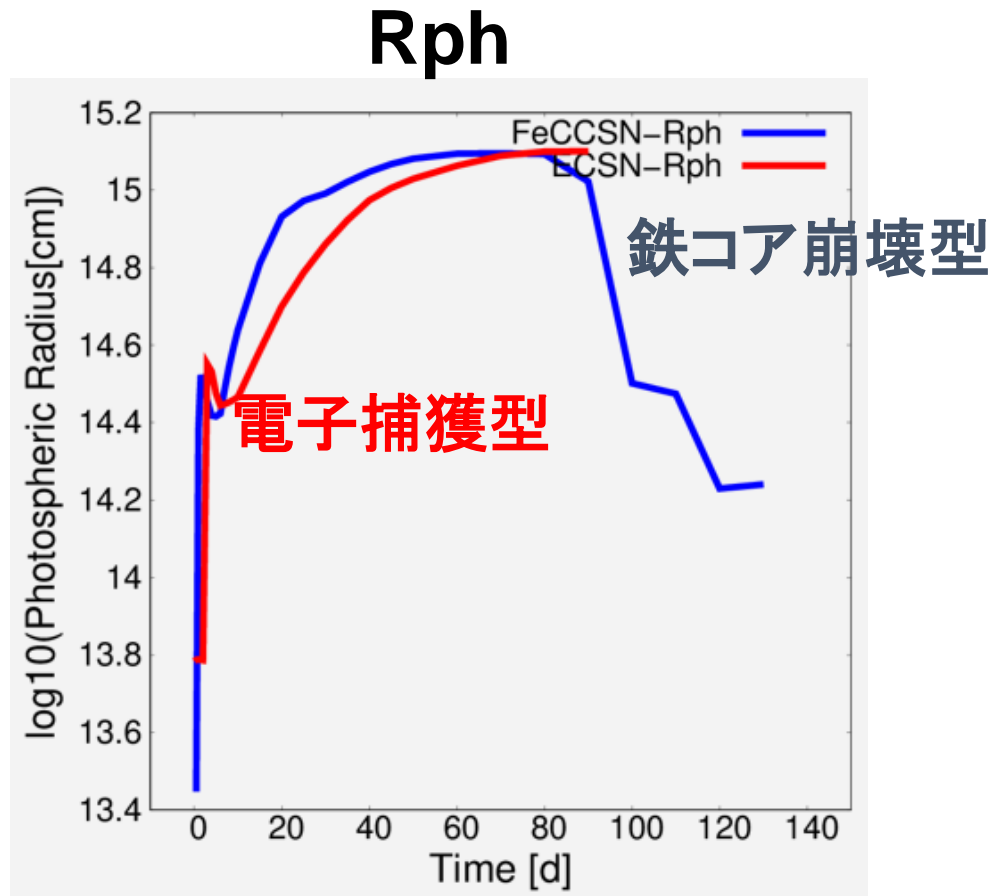
Photosphere evolution (no CSM)



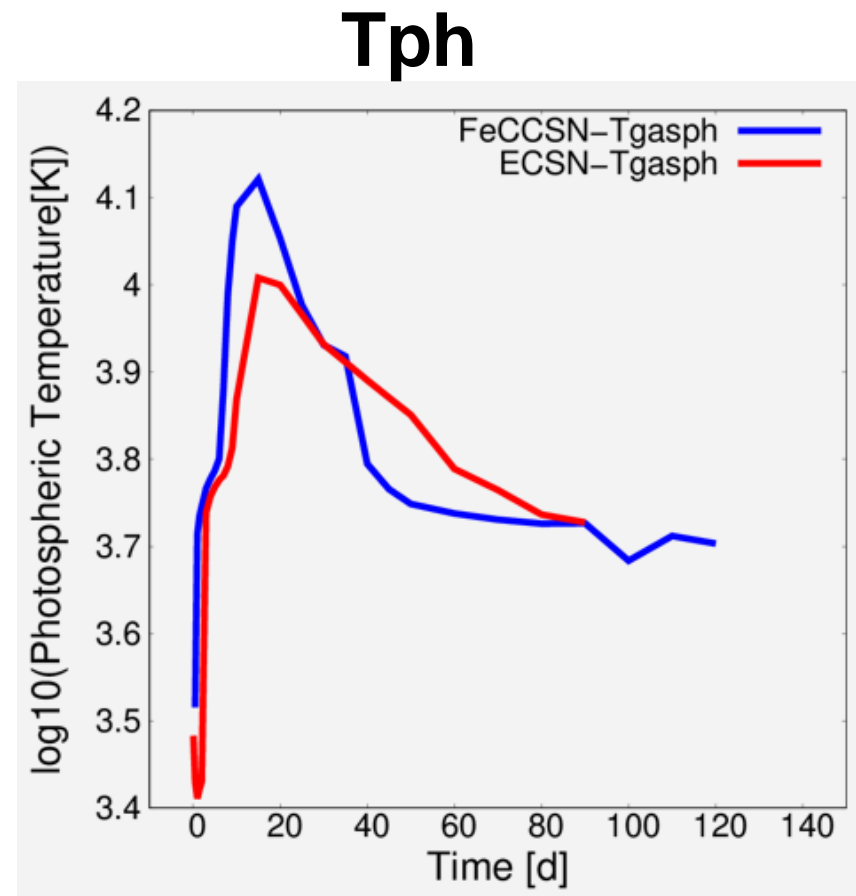
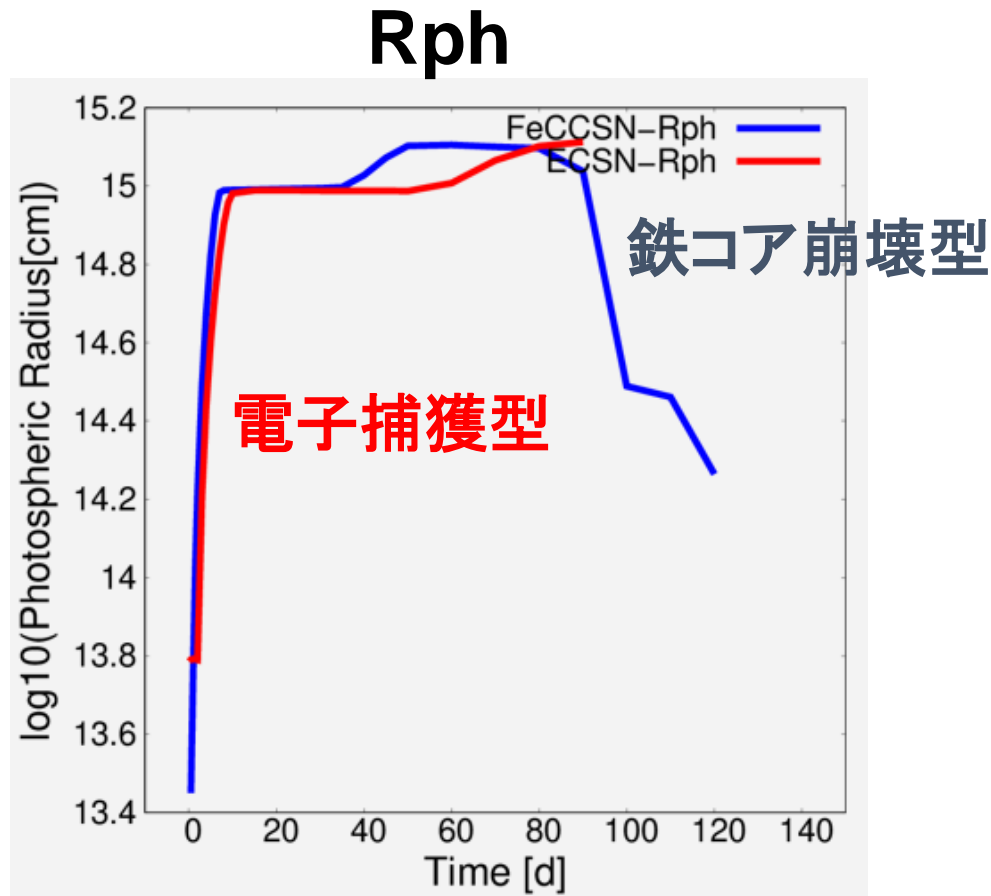
Ejecta evolution (no CSM@40d)



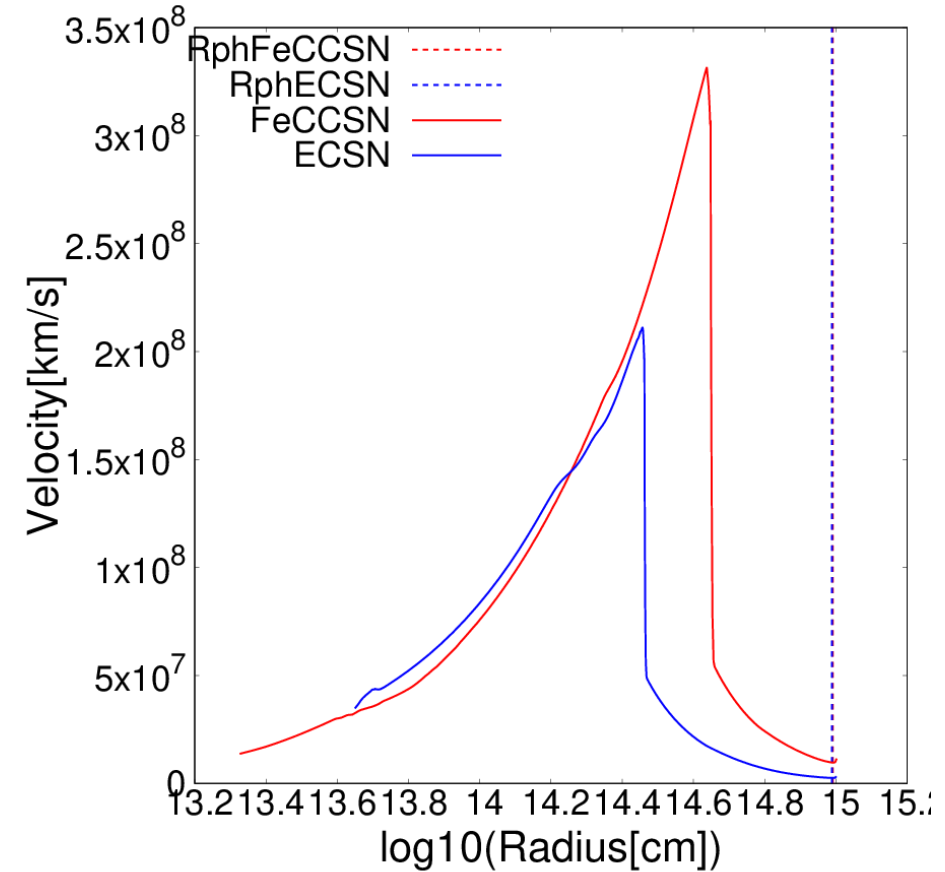
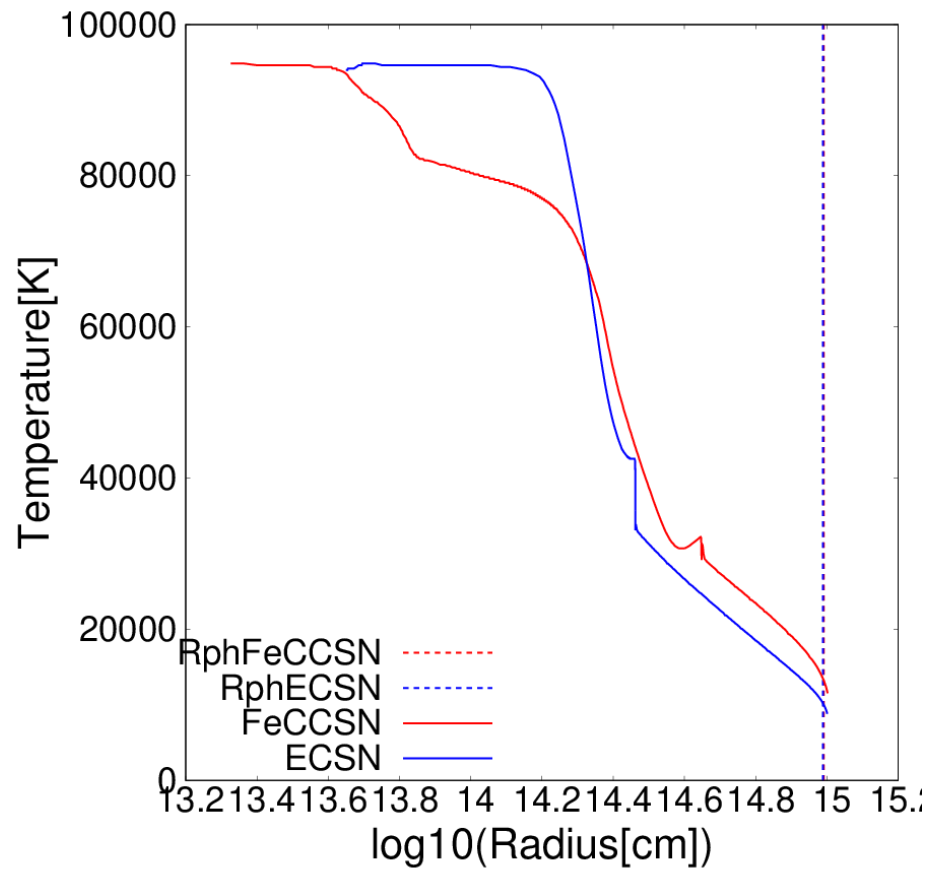
Photosphere evolution ($\dot{M} = 10^{-4} M_{\odot} / yr$)



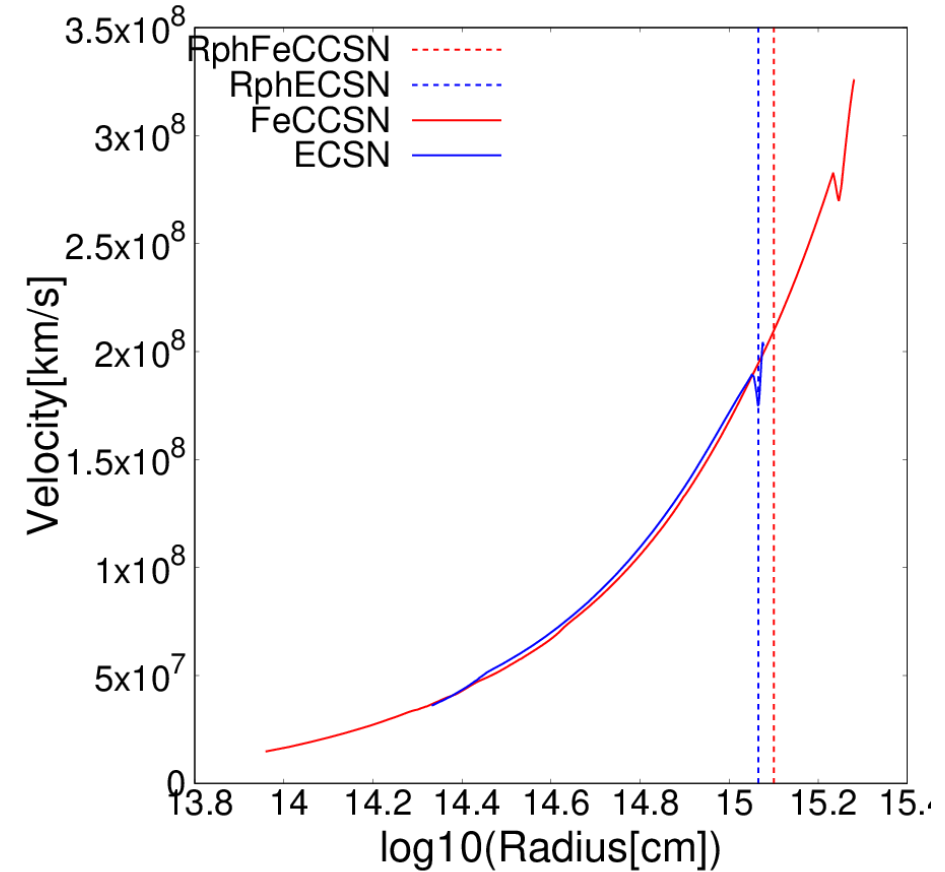
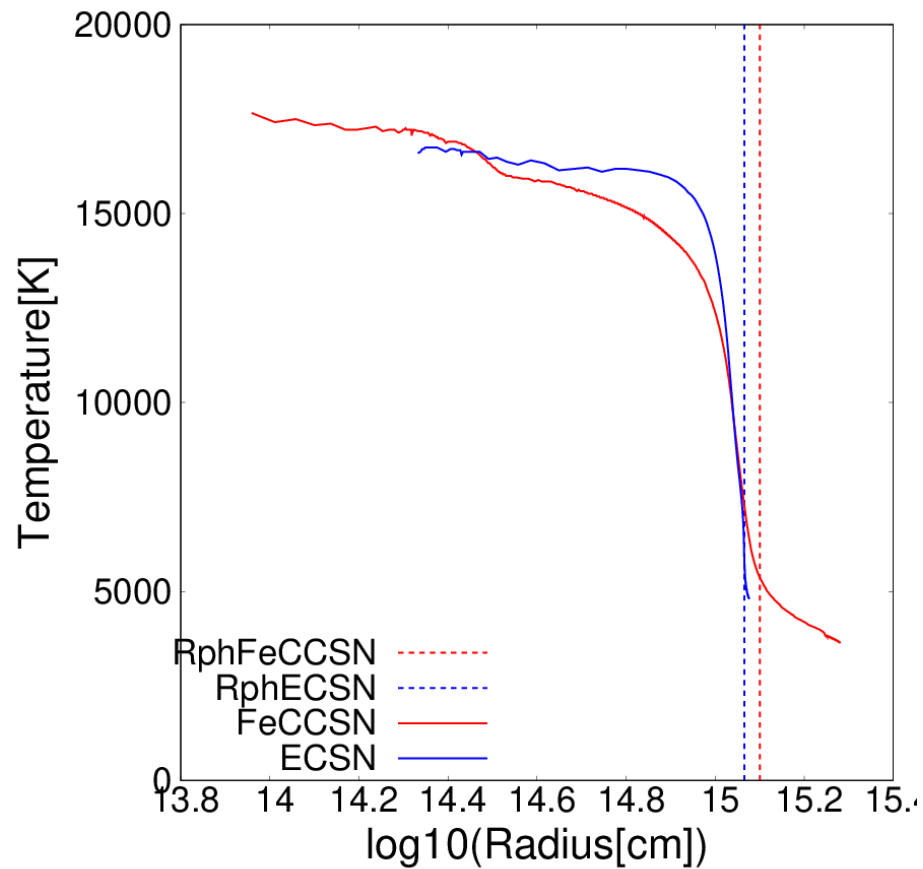
Photosphere evolution ($\dot{M} = 10^{-2} M_{\odot} / yr$)



Ejecta evolution (dense CSM@15d)



Ejecta evolution (dense CSM@70d)

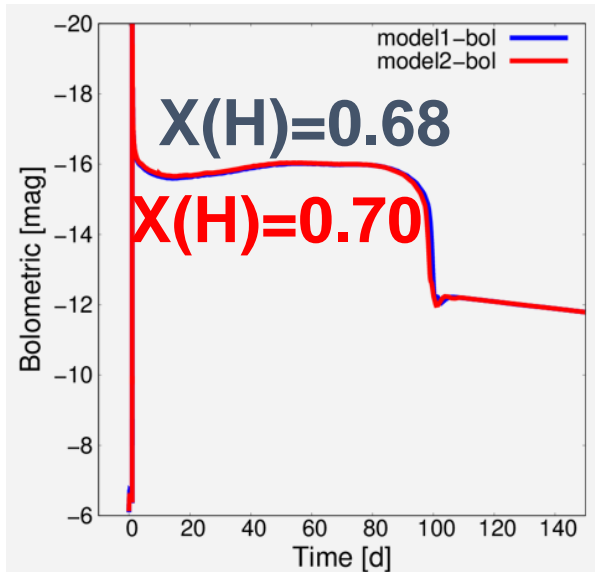


X(H)の影響

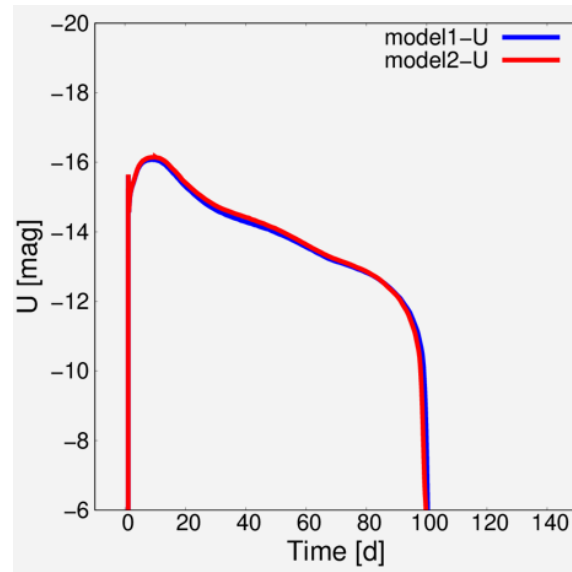
FeCCSN $M=8.7M_{\odot}$, $X(H)=0.68$ $E_{\text{exp}}=3.7 \times 10^{50}$ erg,

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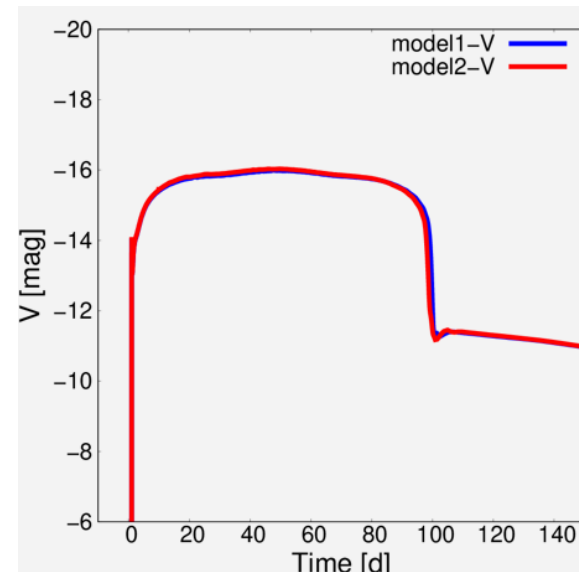
Bolometric



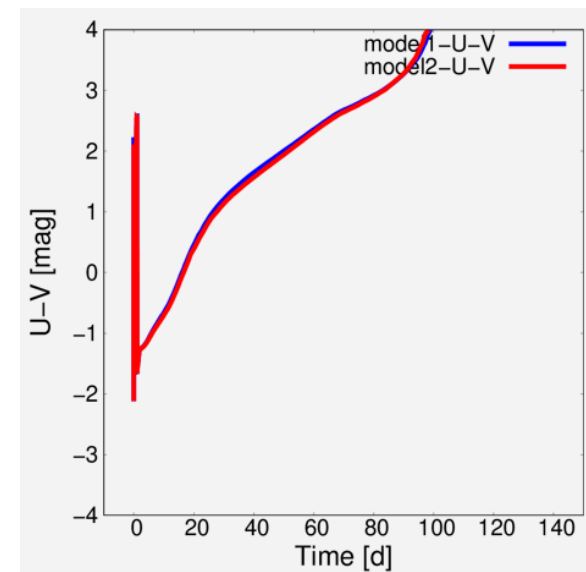
U



V



U-V



今回比較しているモデル程度ならあまり違わない

電子捕獲型のRphが小さい理由①

- $L_{plateau} \sim 1.1 \times 10^{42} \left(\frac{R}{3.5 \times 10^{13} \text{ cm}} \right)^{2/3} \left(\frac{E}{10^{51} \text{ erg}} \right)^{5/6} \left(\frac{M_H}{10 M_{\odot}} \right)^{-1/2} \text{ erg/s}$
- $t_{plateau} \sim 109 \left(\frac{R}{3.5 \times 10^{13} \text{ cm}} \right)^{1/6} \left(\frac{E}{10^{51} \text{ erg}} \right)^{-1/6} \left(\frac{M_H}{10 M_{\odot}} \right)^{1/2} \text{ days}$

(Eastman+94)

- Bolometric degenerateの場合、 $L_{plateau}$ と $t_{plateau}$ が電子捕獲型と鉄コア崩壊型で等しくなり、

$$E_{EC} = (R_{RSG}/R_{SAGB})^{5/4} \times E_{FeCC}$$

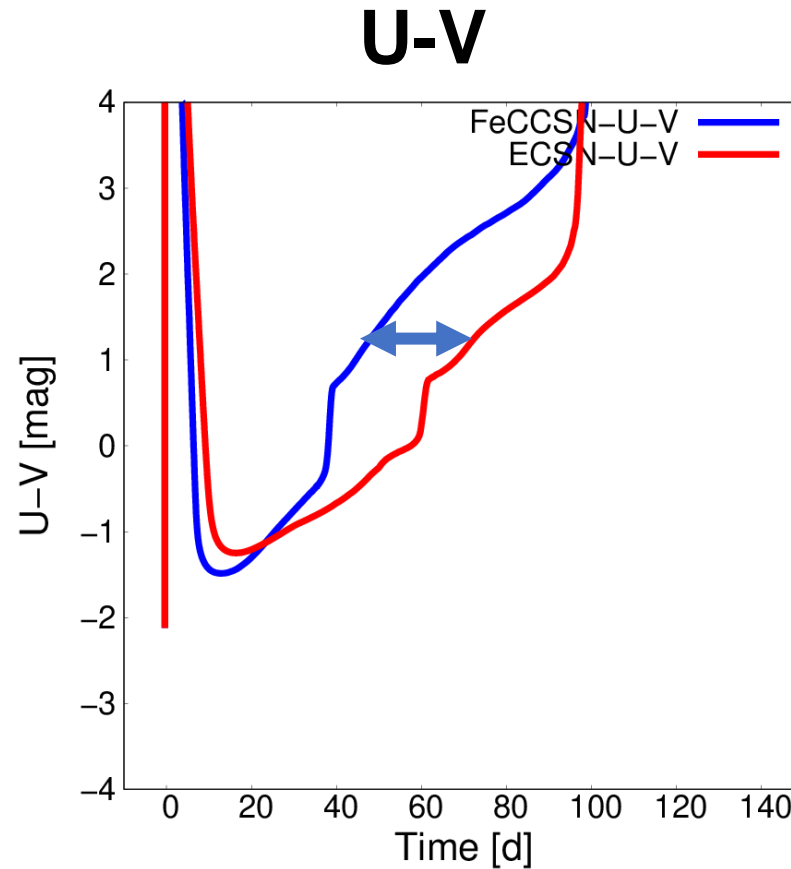
電子捕獲型のRphが小さい理由②

- $R_{\text{RSG}}=10^{13.457}$, $R_{\text{SAGB}}=10^{13.85}$ cmとすると、

$$E_{\text{EC}} = (10^{-0.393})^{5/4} \times E_{\text{FeCC}} \sim 0.32 \times E_{\text{FeCC}}$$
- $M_{\text{ej,FeCC}}=7.7$, $M_{\text{ej,EC}}=3.2M_{\odot}$ とすると、ejectaの典型的な速度は、

$$\frac{v_{\text{EC}}}{v_{\text{FeCC}}} = \sqrt{\frac{E_{\text{EC}}/M_{\text{ej,EC}}}{E_{\text{FeCC}}/M_{\text{ej,FeCC}}}} \sim \sqrt{0.77} \sim 0.88$$
- そのため、電子捕獲型は、鉄コア崩壊型に比べてejectaが広がるスピードが遅く、shockbreakout後、同じタイミングで見ると、鉄コア崩壊型より内側にejectaがあり、高温になっている。

電子捕獲型のRphが小さい理由③



時間がずれているだけで進化はあまり違わない

鉄コアでは早く冷める(半径が小さいため)①

- shockが星表面に到達したときの典型的な温度

$$T_0 \propto \left(\frac{E}{R^3}\right)^{1/4}$$

- 断熱膨張

$$T = T_0 \left(\frac{R_0}{R}\right)^{\frac{3}{4}\gamma}$$

- $T_{FeCC}(R=R_{SAGB})$ は、

$$T_{FeCC}(R_{SAGB}) = T_{FeCC,0} \left(\frac{R_{RSG}}{R_{SAGB}}\right)^{\frac{3}{4}\gamma}$$

鉄コアでは早く冷める(半径が小さいため)②

- よって、同じ場所($R=R_{SAGB}$)での温度は、

$$\begin{aligned} \frac{T_{FeCC}(R_{SAGB})}{T_{EC}(R_{SAGB})} &= \frac{T_{FeCC,0}}{T_{EC,0}} \left(\frac{R_{RSG}}{R_{SAGB}} \right)^{\frac{3}{4}\gamma} = \left(\frac{E_{FeCC}}{E_{EC}} \right)^{1/4} \left(\frac{R_{RSG}}{R_{SAGB}} \right)^{-3/4} \left(\frac{R_{RSG}}{R_{SAGB}} \right)^{\frac{3}{4}\gamma} \\ &= \left(\frac{E_{FeCC}}{E_{EC}} \right)^{1/4} \left(\frac{R_{RSG}}{R_{SAGB}} \right)^{\frac{3}{4}(\gamma-1)} \end{aligned}$$

- 同程度のエネルギー、 $R_{RSG}=10^{13.457}$, $R_{SAGB}=10^{13.85}$ cmとすると、

$$\frac{T_{FeCC}(R_{SAGB})}{T_{EC}(R_{SAGB})} = \left(\frac{R_{RSG}}{R_{SAGB}} \right)^{\frac{3}{4}(\gamma-1)} = 10^{-0.393 \times \frac{3}{4}(\gamma-1)}$$

鉄コアでは早く冷める(半径が小さいため)③

- $\gamma=5/3, 7/5, 4/3$ の場合、

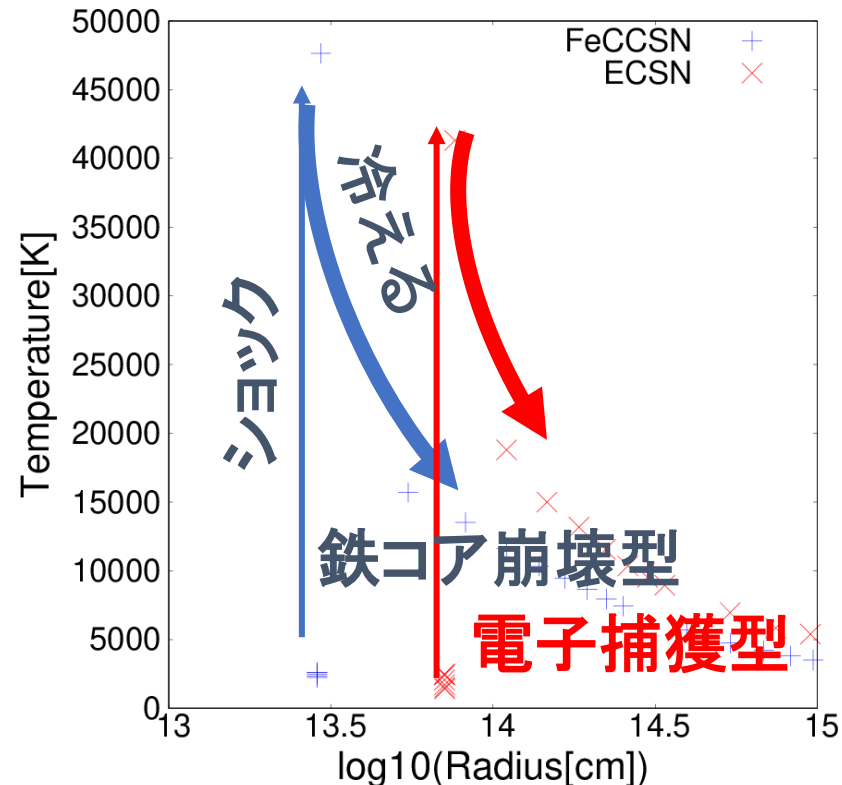
$$\frac{T_{FeCC}(R_{SAGB})}{T_{EC}(R_{SAGB})} \sim \left\{ \begin{array}{ll} 0.64 & (\gamma = 5/3) \\ 0.76 & (\gamma = 7/5) \\ 0.80 & (\gamma = 4/3) \end{array} \right\}$$

となり、鉄コア崩壊型では温度が下がっている。

- CSM付きの場合、断熱膨張にはならないが、密度が低いので、同様に鉄コアで冷たくなっている。

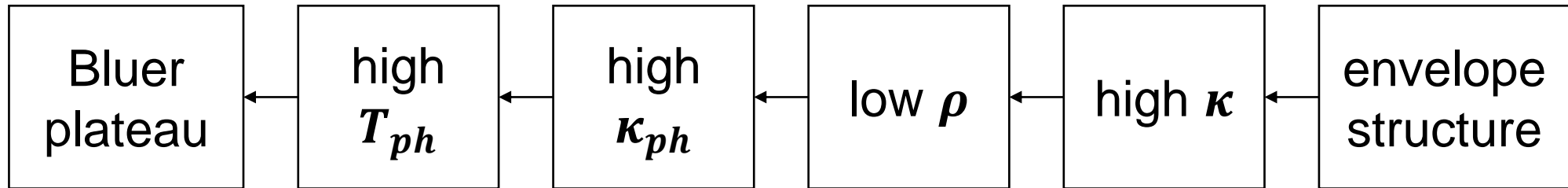
鉄コアでは早く冷める(半径が小さいため)④

ECSN $M=4.4M_{\odot}$, $X(H)=0.70$, $E_{\text{exp}}=1.1 \times 10^{50}\text{erg}$, CSM radius= 10^{15}cm
 FeCCSN $M=8.7M_{\odot}$, $X(H)=0.68$, $E_{\text{exp}}=1.1 \times 10^{50}\text{erg}$, CSM radius= 10^{15}cm



3. Discussion

- 3-1. Bluer plateau of ECSN

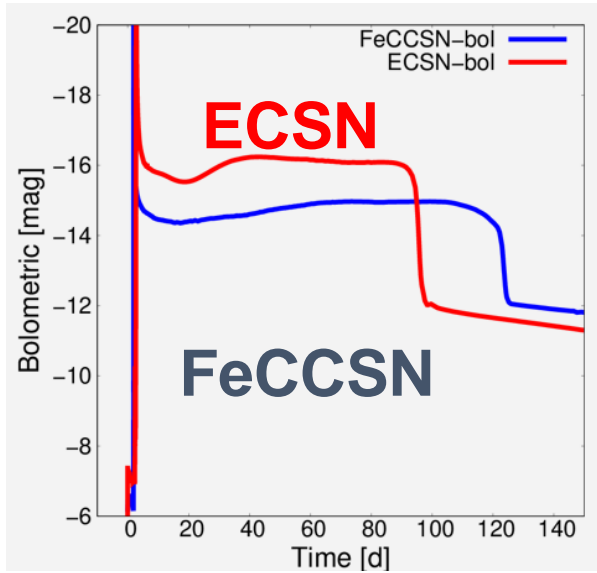


Similar E_{Exp} (no CSM)

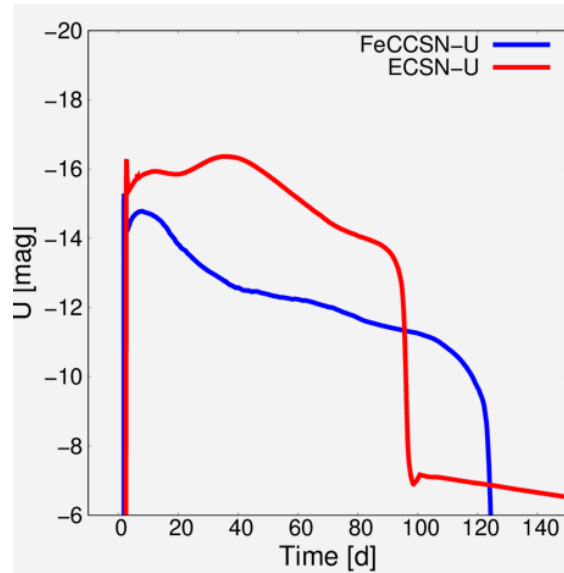
ECSN $M=4.4M_{\odot}$, $X(\text{H})=0.70$, $E_{\text{exp}}=1.1 \times 10^{50}\text{erg}$, CSM radius= 10^{15}cm

FeCCSN $M=8.7M_{\odot}$, $X(\text{H})=0.68$, $E_{\text{exp}}=1.1 \times 10^{50}\text{erg}$, CSM radius= 10^{15}cm

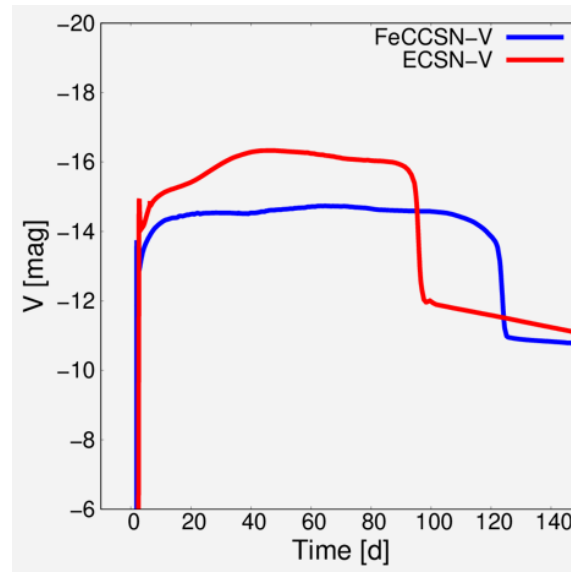
Bolometric



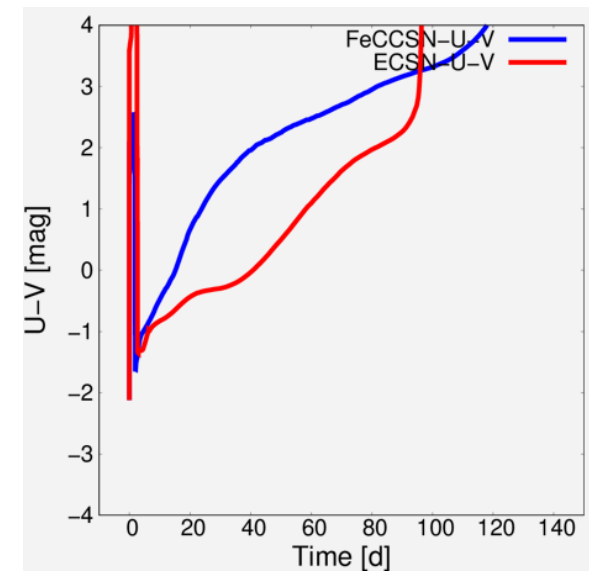
U



V



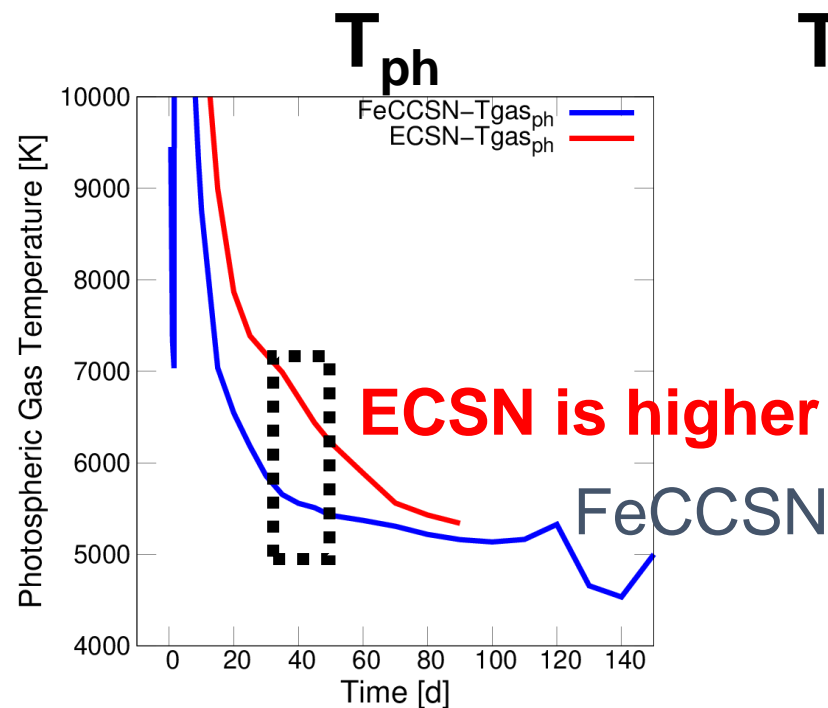
U-V



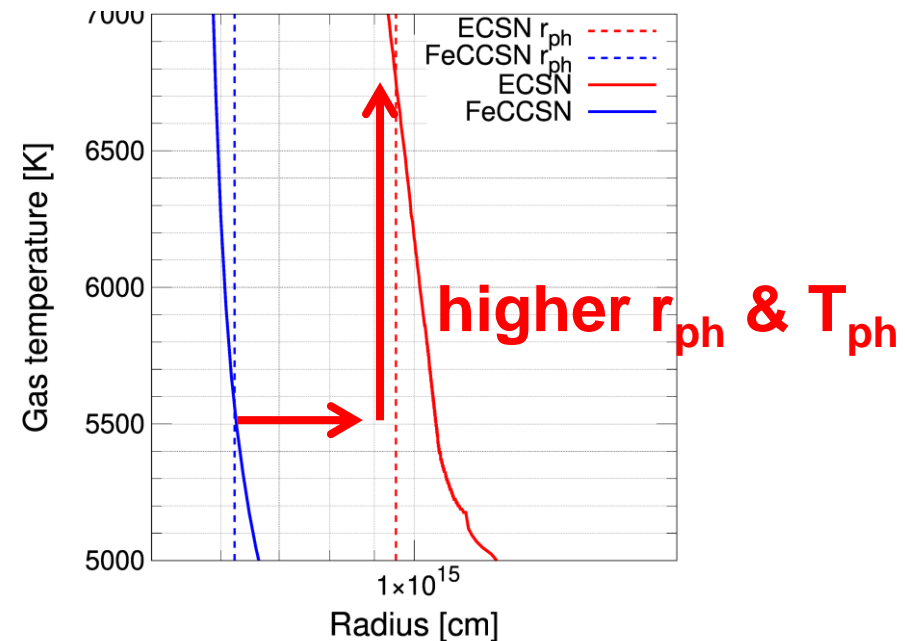
ECSN is still bluer.



Photospheric Temperature (T_{ph})



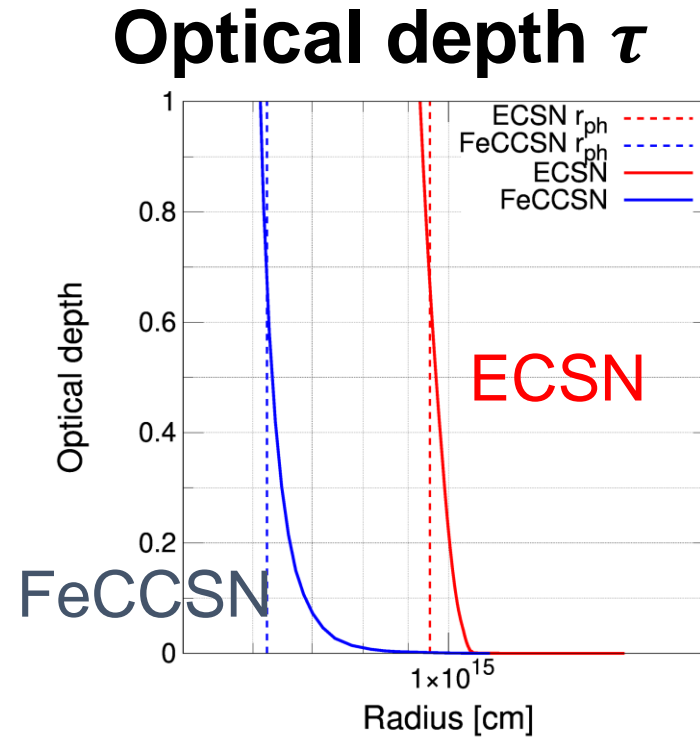
Temperature structure @ 40d



- Higher T_{ph} of ECSN causes the bluer color.
- In spite of larger r_{ph} (photospheric radius), T_{ph} is also higher.
- Photosphere is defined as r_{ph} of: $\tau = \int_{r_{out}}^{r_{ph}} \kappa \rho dr = 2/3$



Optical depth (τ) structure @40 d

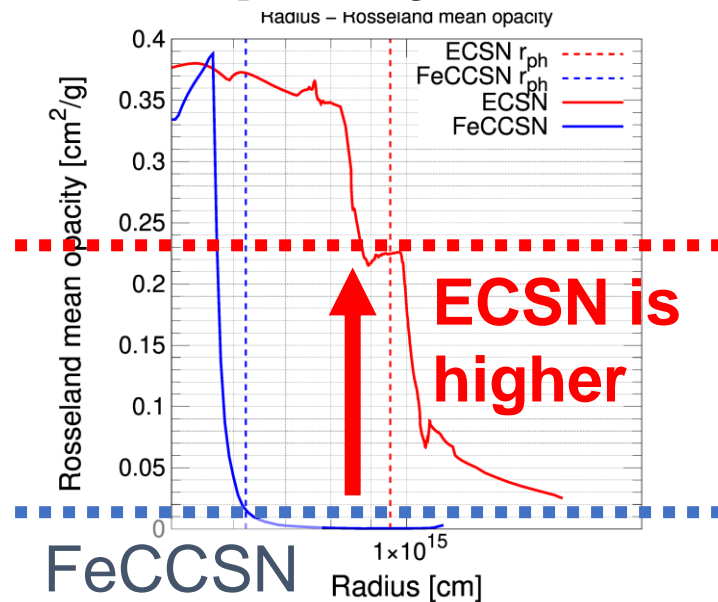


- τ steeply rise around photosphere.
- The main contribution to τ is from very nearby region of photosphere.

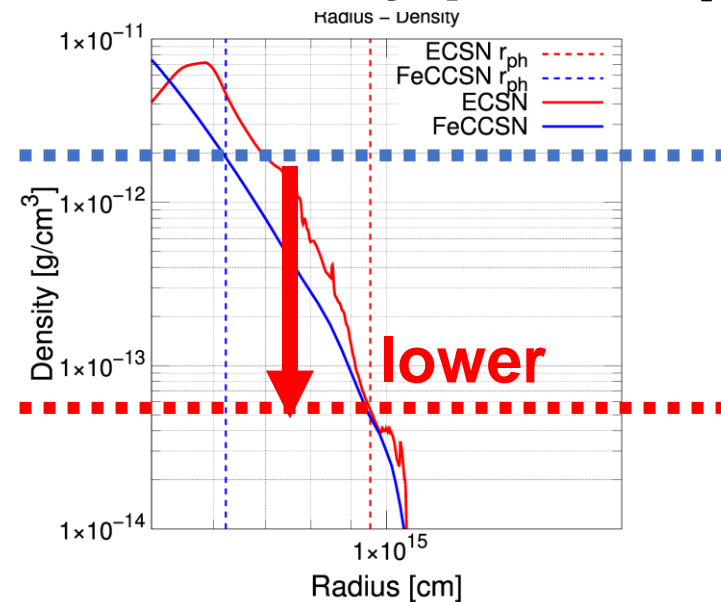


κ (opacity) and ρ (Density)

Opacity κ



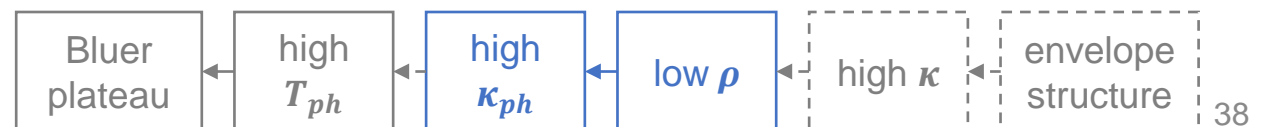
Density ρ



κ and ρ around photosphere

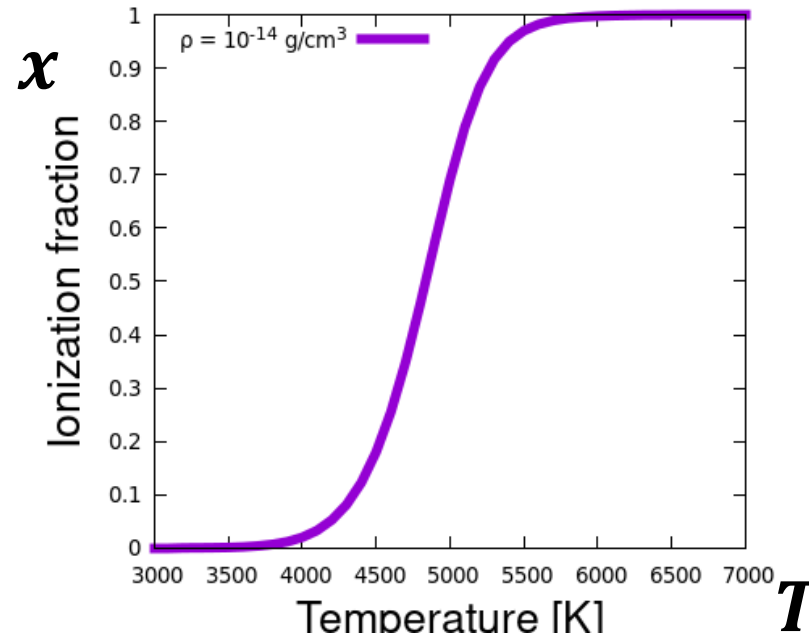
	ECSN		FeCCSN
κ	$\sim 0.05-0.2$	$>$	$\lesssim 0.1$
ρ	$\sim 10^{-14}-10^{-13}$	$<$	$\sim 10^{-13}-10^{-12}$

- ECSN has high κ and low ρ around photosphere.
- κ_{ph} of FeCCSN cannot be high because of high ρ around photosphere.
- High κ_{ph} should be associated with high T_{ph} (next slide).

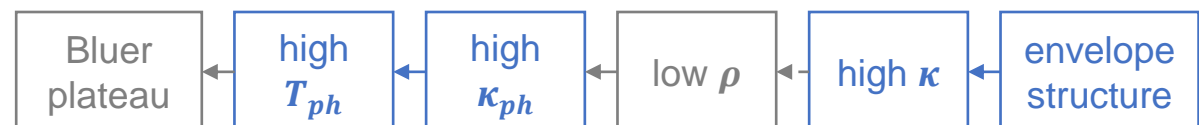


κ , x (ionization fraction), ρ , and T relation

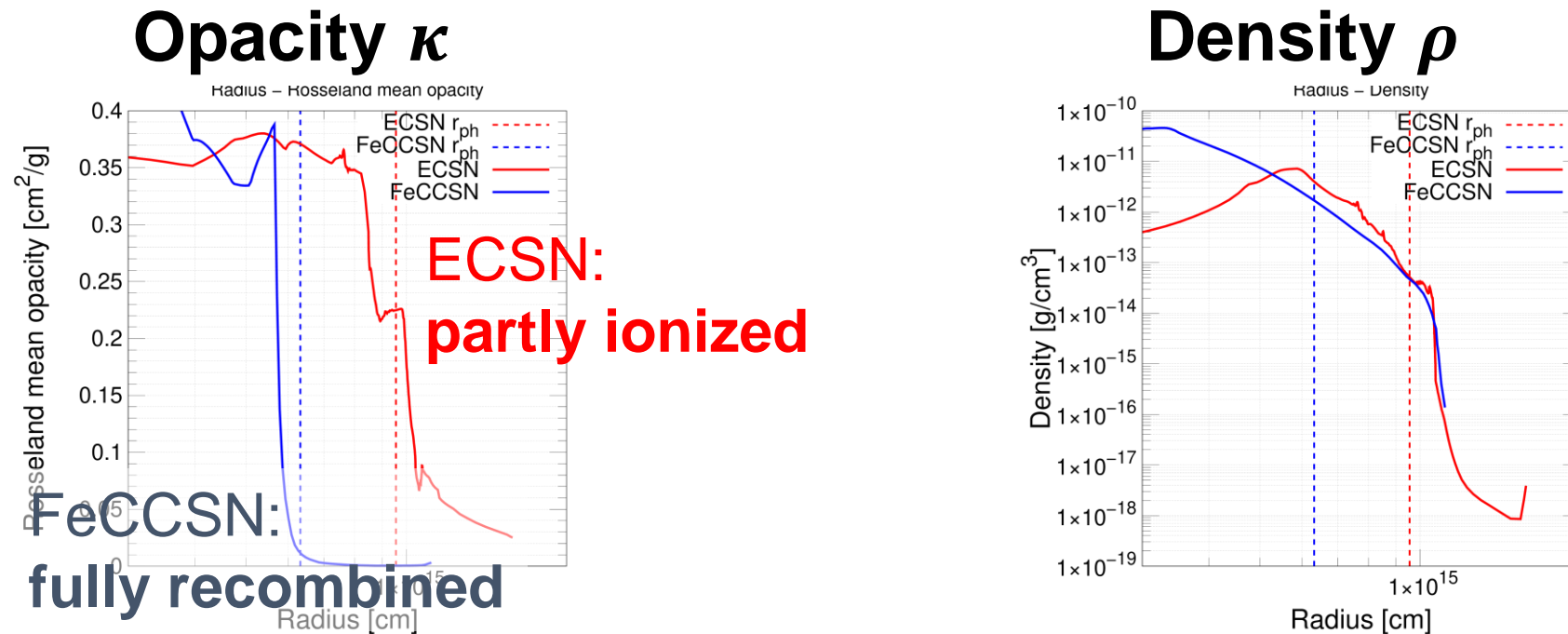
Temperature – Ionization fraction



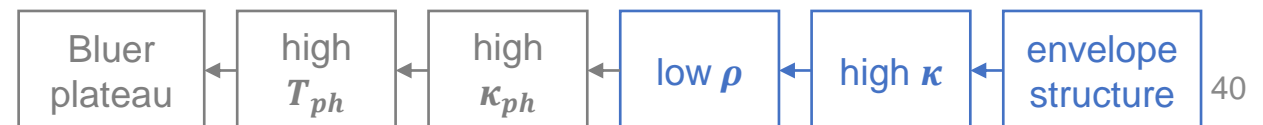
- $\kappa \propto x$ because the opacity around outer ejecta is due to the electron scattering.
- x is positively correlated with T , and negatively with ρ according to Saha eq.



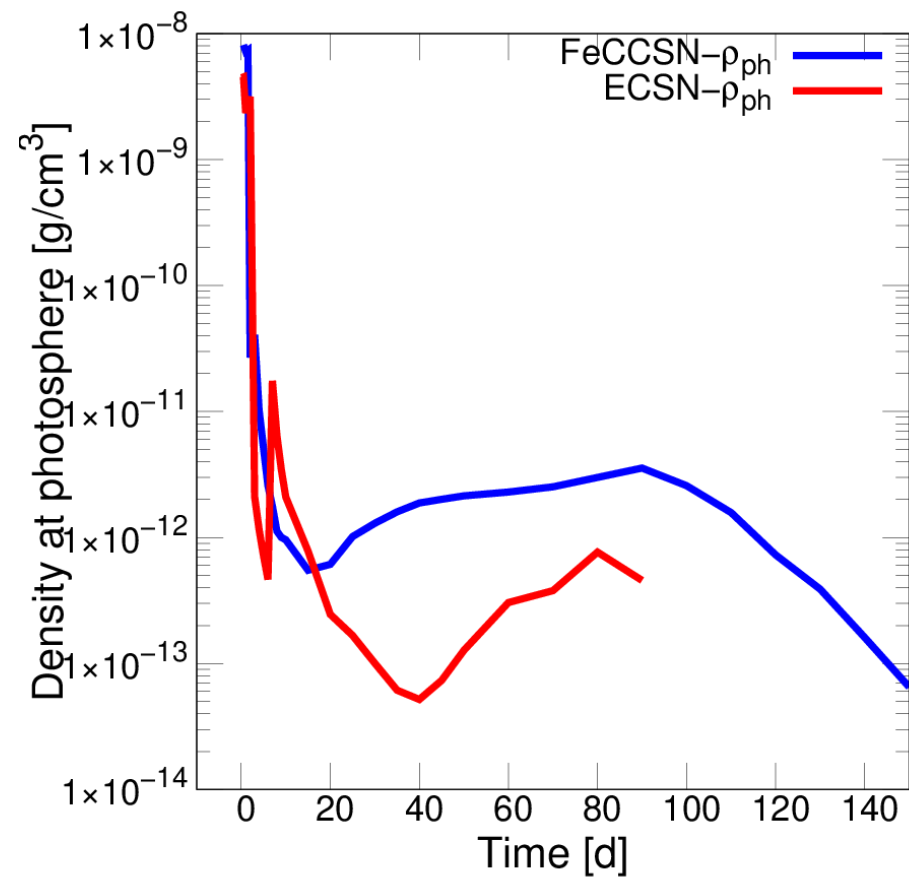
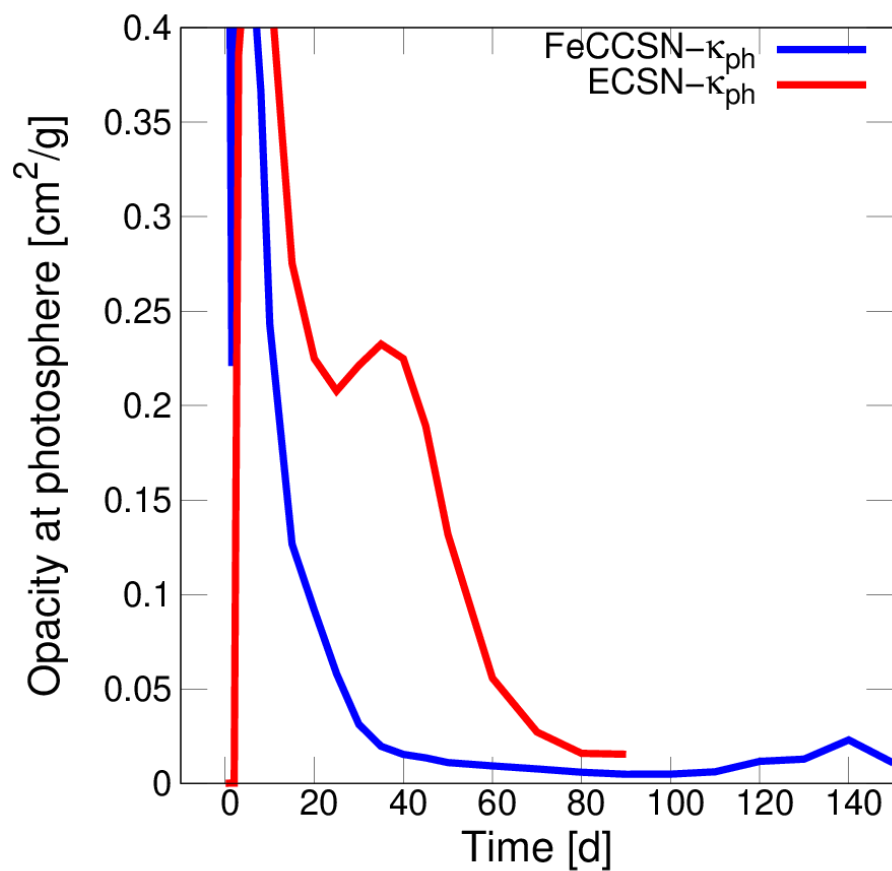
Why FeCCSN has high ρ around photosphere ?



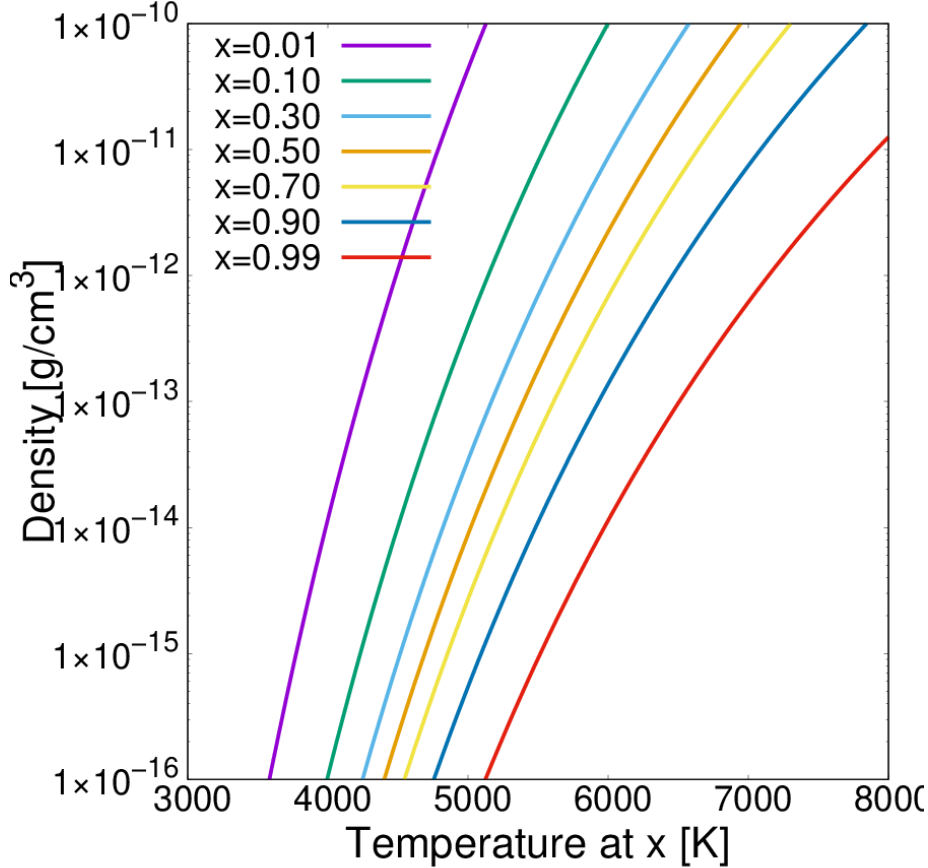
- κ of ECSN is high (partly ionized) at the outer ejecta while that of FeCCSN is almost 0 (fully recombined).
- Because κ of FeCCSN is very low at the outer ejecta, photosphere can be located at inner dense region.
- It is due to the **tenuous and extended envelope structure of ECSN**.



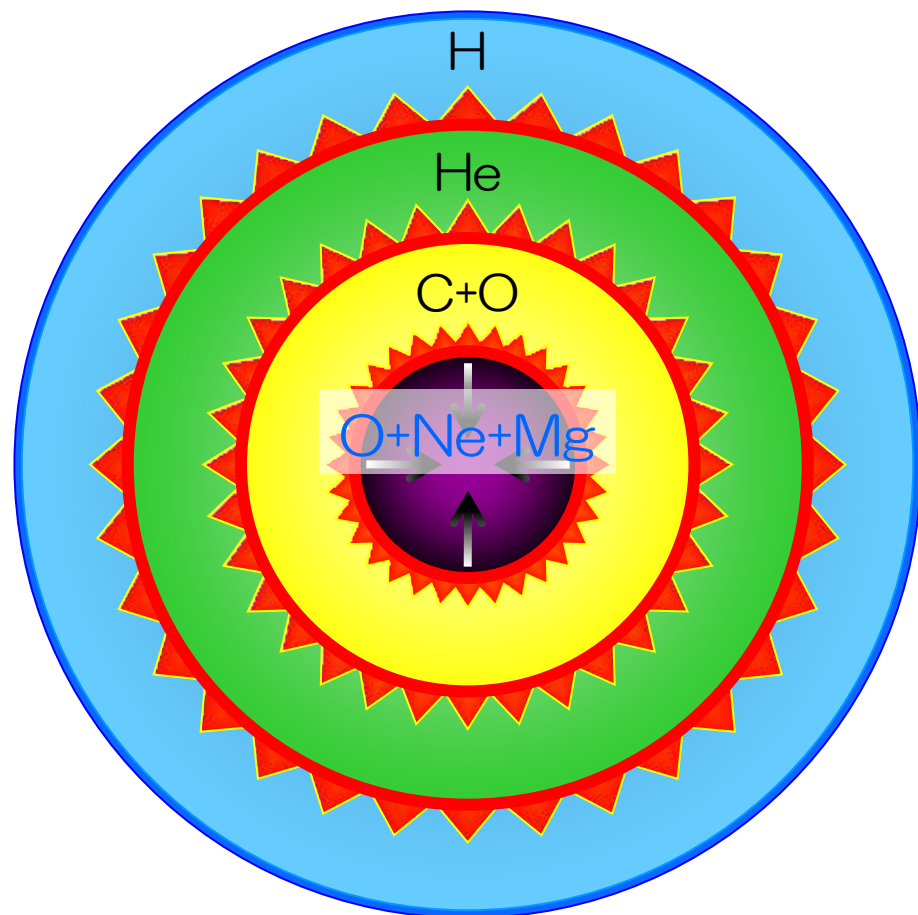
κ_{ph} and ρ_{ph} evolution



ρ, T, x



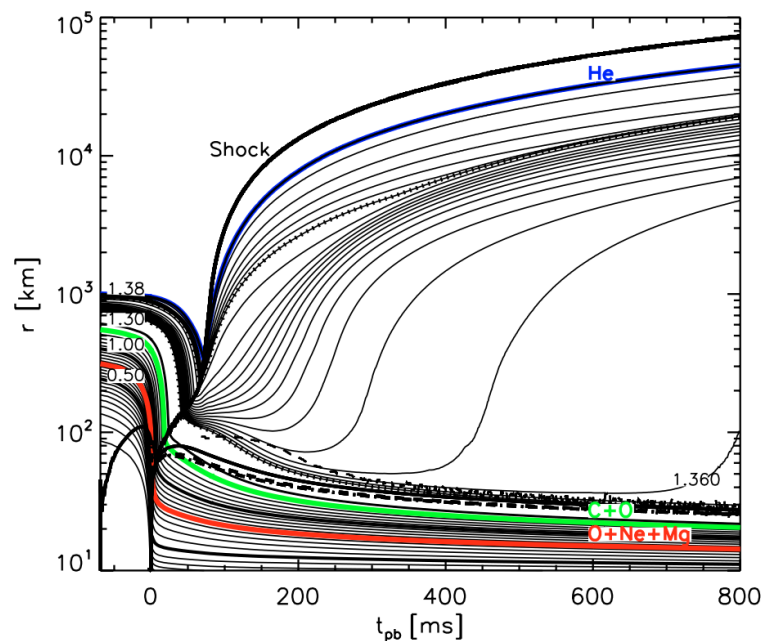
Electron capture ($8M_{\odot} < M < 10M_{\odot}$)



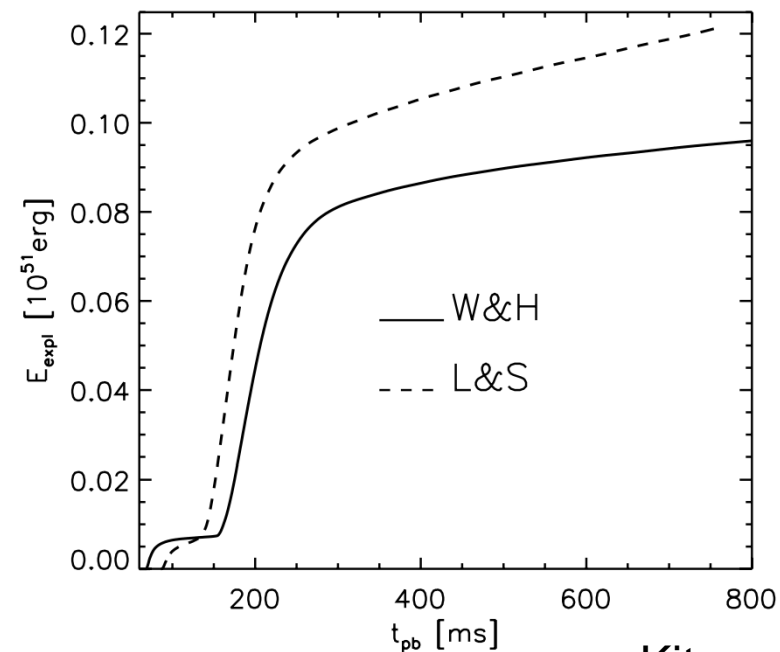
©N. Tominaga

- O+Ne+Mg core is formed. Electron degeneracy pressure support the self-gravity.
- Become super asymptotic giant branch(SAGB).
- When the core density become high and the fermi energy become high enough, electron capture by Mg occurs.
- It makes pressure low, and gravitational contraction proceed.

Explosion of ECSN



Kitaura+06



Kitaura+06

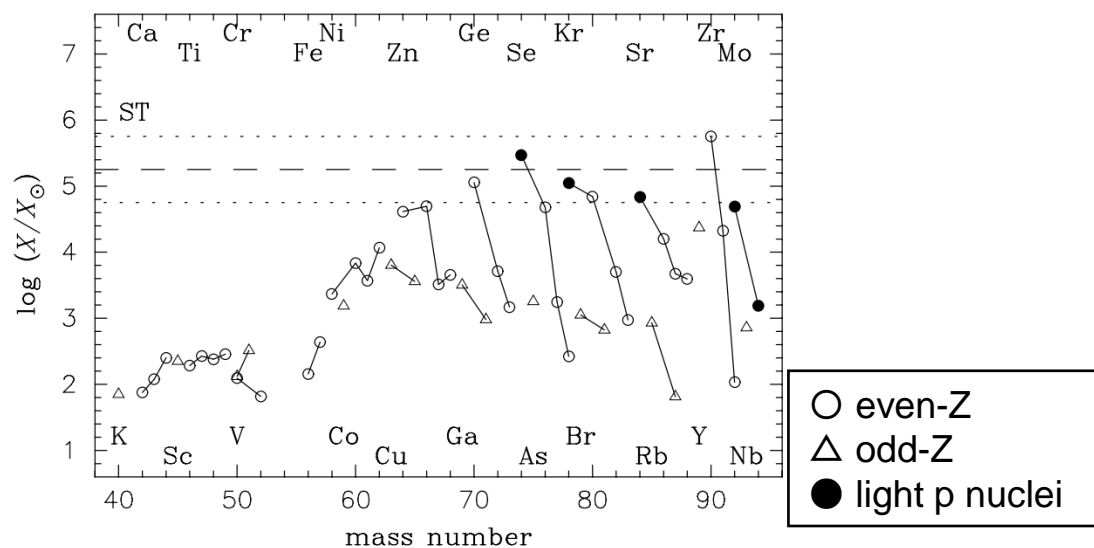
- Explodes in numerical simulation with first principles (Kitaura+06 and Janka+08) in contrast to FeCCSN.
- Explosion energy $\sim 10^{50}$ erg
 - 1 order lower than normal supernovae ($\sim 10^{51}$ erg)

Nucleosynthesis

Table 1
Yields in Units of Solar Masses
Wanajo+09

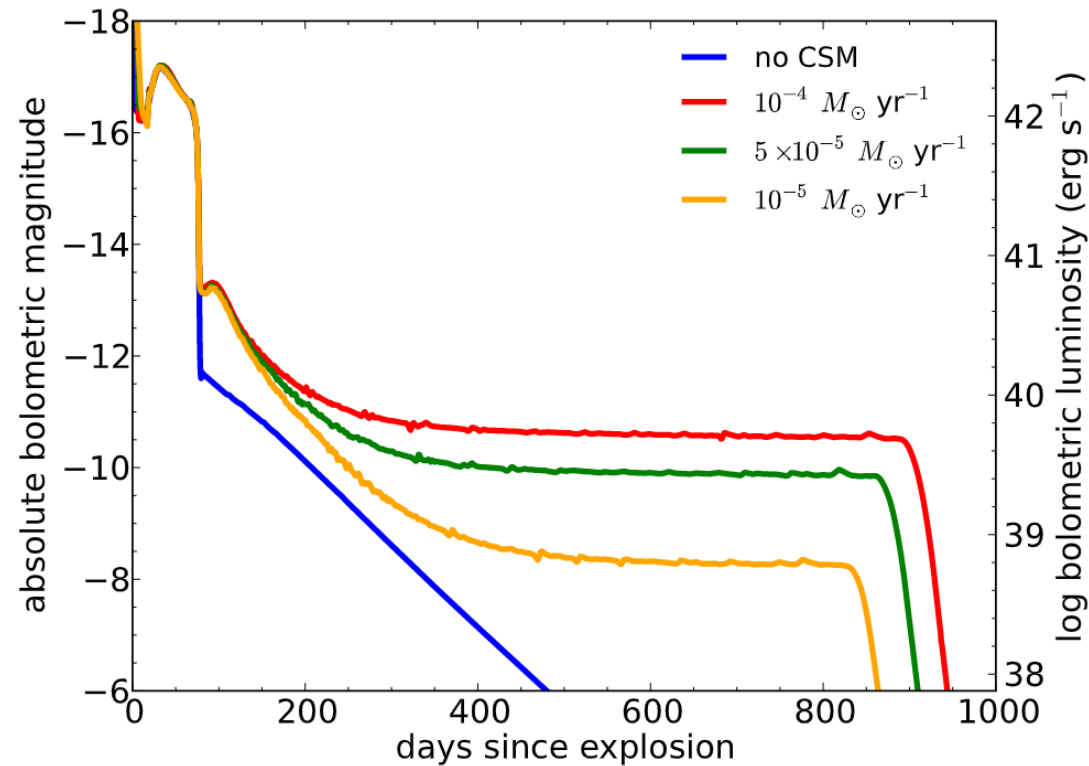
Model	$Y_{e,\min}$	^{56}Ni	^{64}Zn	^{90}Zr	Ni/Fe
ST	0.464	2.50E-03	6.38E-04	1.21E-04	1.65
WH	0.462	4.06E-03	7.31E-04	1.39E-04	1.27
RT	0.464	2.52E-03	6.94E-04	7.83E-05	1.58
MX	0.480	1.67E-03	1.07E-03	3.32E-08	3.01
FP1	0.468	2.62E-03	6.83E-04	5.75E-05	1.55
FP2	0.471	2.76E-03	7.08E-04	1.59E-05	1.46
FP3	0.475	2.91E-03	6.51E-04	8.04E-07	1.36
FM1	0.460	2.41E-03	5.83E-04	1.96E-04	1.73
FM2	0.457	2.32E-03	5.31E-04	2.66E-04	1.82
FM3	0.453	2.24E-03	4.83E-04	3.11E-04	1.92

- nucleosynthesis of ECSN was calculated by Wanajo+09.
- It shows:
 - low ^{56}Ni (0.002-0.004 M_{\odot})
 - large Ni/Fe ratio (1-2)



Wanajo+09

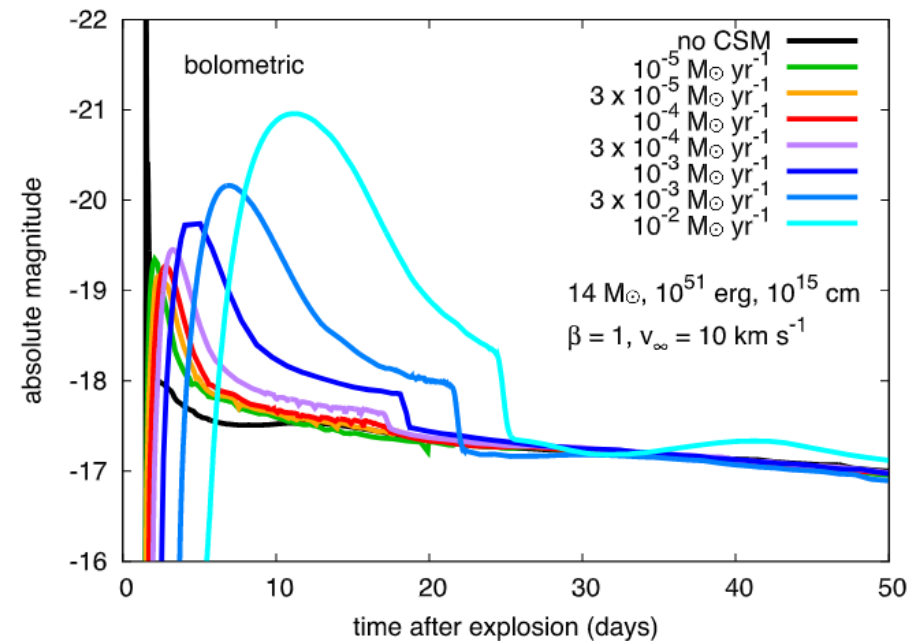
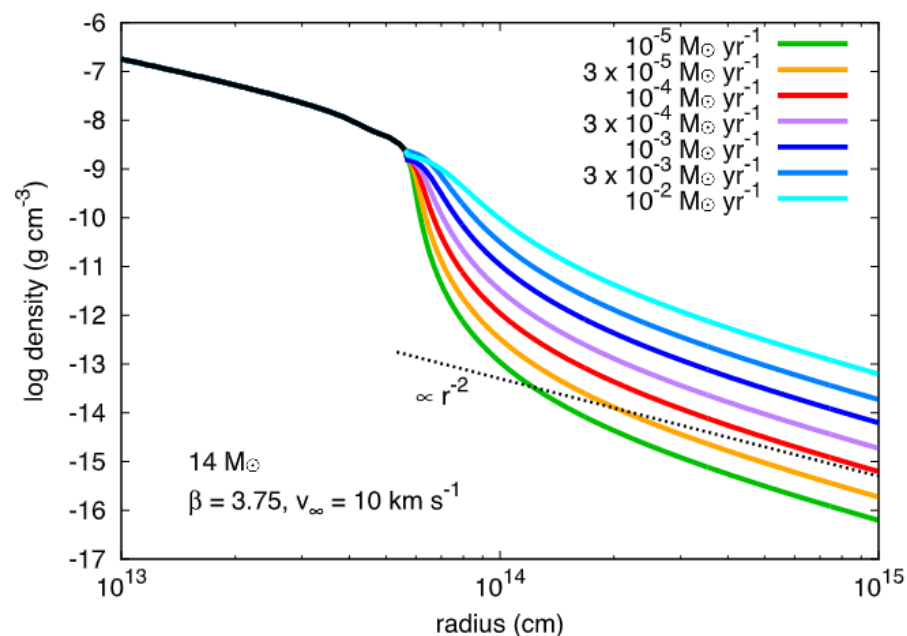
Light Curve of ECSNe



Moriya+14

- Numerical simulations of ECSN light curve are conducted by Tominaga+13, Moriya+14 and Kozyreva+21.
- ECSN light curve is:
 - II-P like
 - large drop (~4mag) to tail phase
 - faint tail (low ⁵⁶Ni) (if no CSM)
- Moriya+14 included circumstellar matter (CSM) interaction.

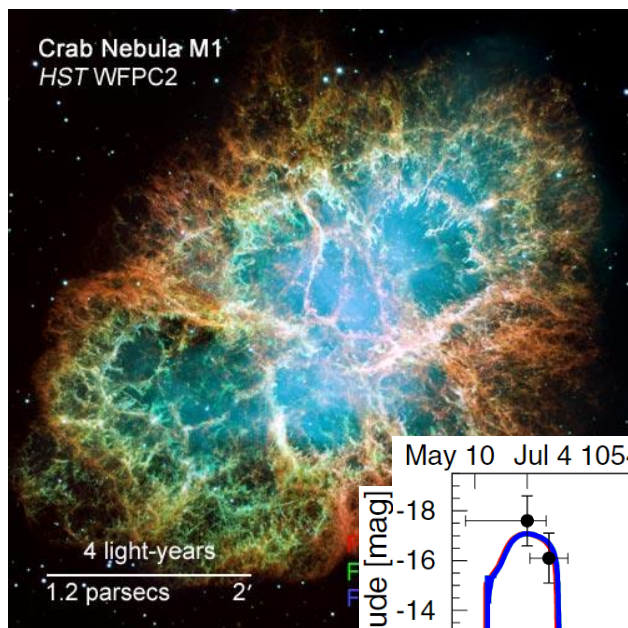
Light curves with CSM interaction



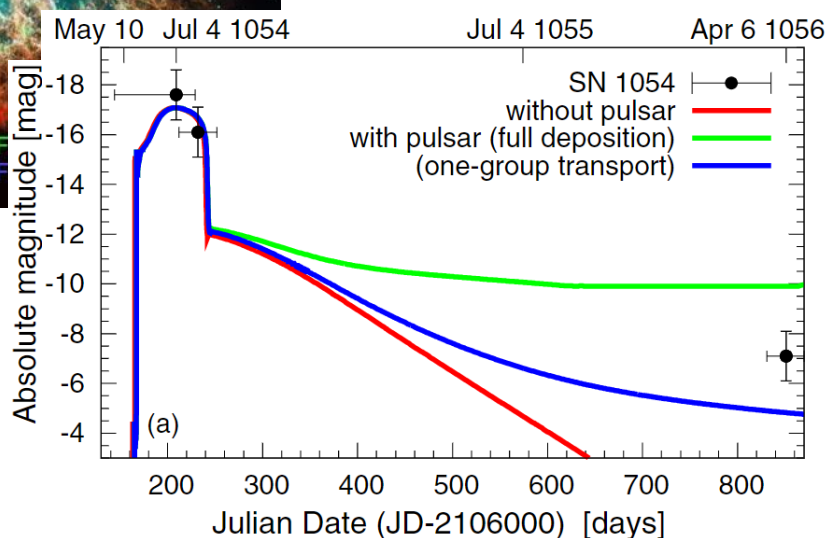
Moriya+18

- Wind acceleration are taken into account on calculating Light curves of FeCCSNe by Moriya+18.
- When CSM is high enough, delayed shock breakout can be seen.

Crab nebula (SN1054)



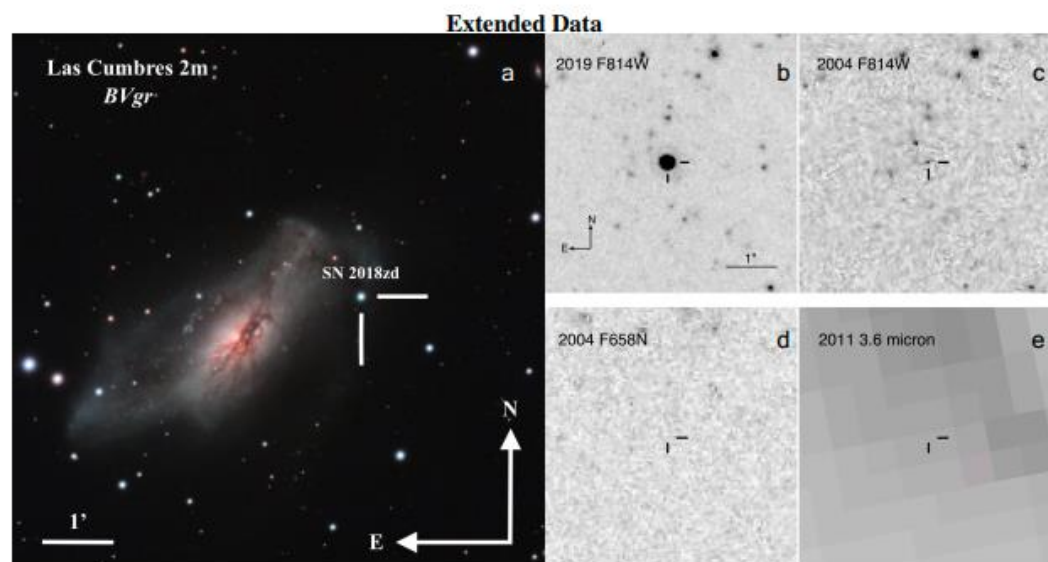
NASA, ESA, J. Hester and A. Loll
(Arizona State University)



Tominaga+13

- Suggested to be a supernova remnant (SNR) of ECSN from observational features:
 - Low energy: $E_{\text{exp}} \sim 3 \times 10^{49} \text{ erg}$ ($M_{\text{ej}} \sim 1-2 M_{\odot}$ (Macalpine+91))
 - High Ni/Fe ratio: $\sim 0.7-3.5$ (Henry84)
- Problem:
 - High peak luminosity as normal supernovae ($\sim 10^{51} \text{ erg}$) although ECSN has low explosion energy ($\sim 10^{50} \text{ erg}$).
- Solved:
 - Large radius and small mass of the envelope can explain. (Tominaga+13)

SN2018zd

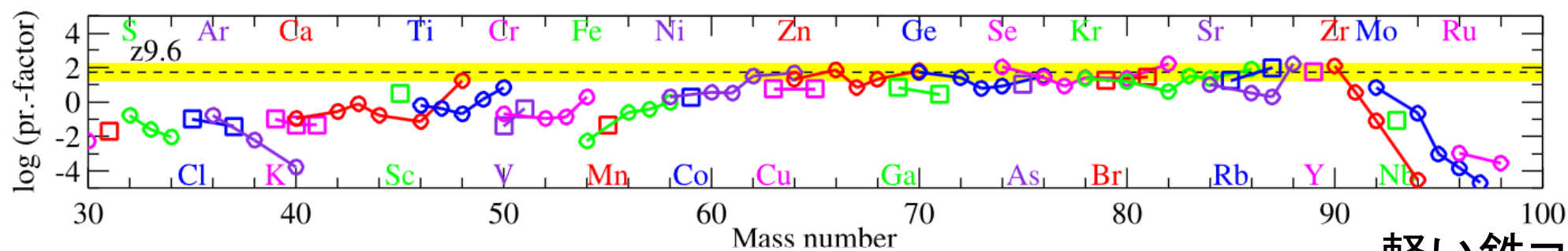
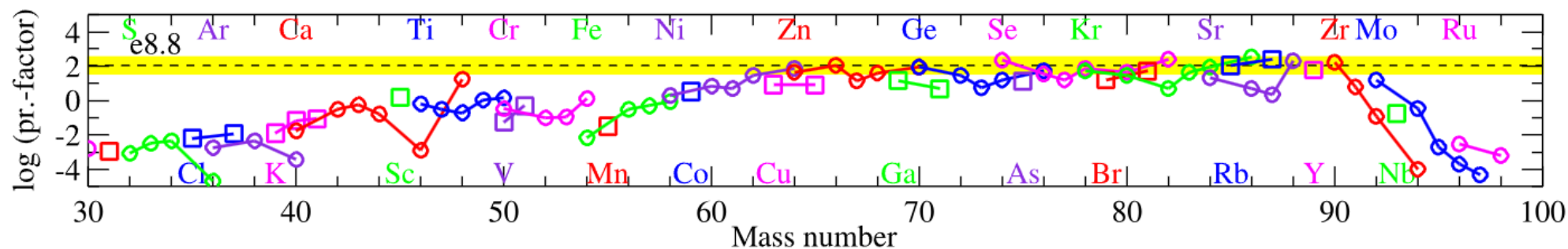


- exploded in March 2018
- Proposed as a ECSN by Hiramatsu+21 from its features:
 - light curve
 - nucleosynthesis
 - explosion energy

Hiramatsu+21

元素合成の違い(Wanajo+18)

電子捕獲型



軽い鉄コア崩壊型

- 電子捕獲型と軽い鉄コア崩壊型では、ほとんど同じ元素合成