2023/3/20
宇宙線研究所セミナー
13:00- @宇宙線研究所

Theoretical modeling of type Iax SN 1181 remnant

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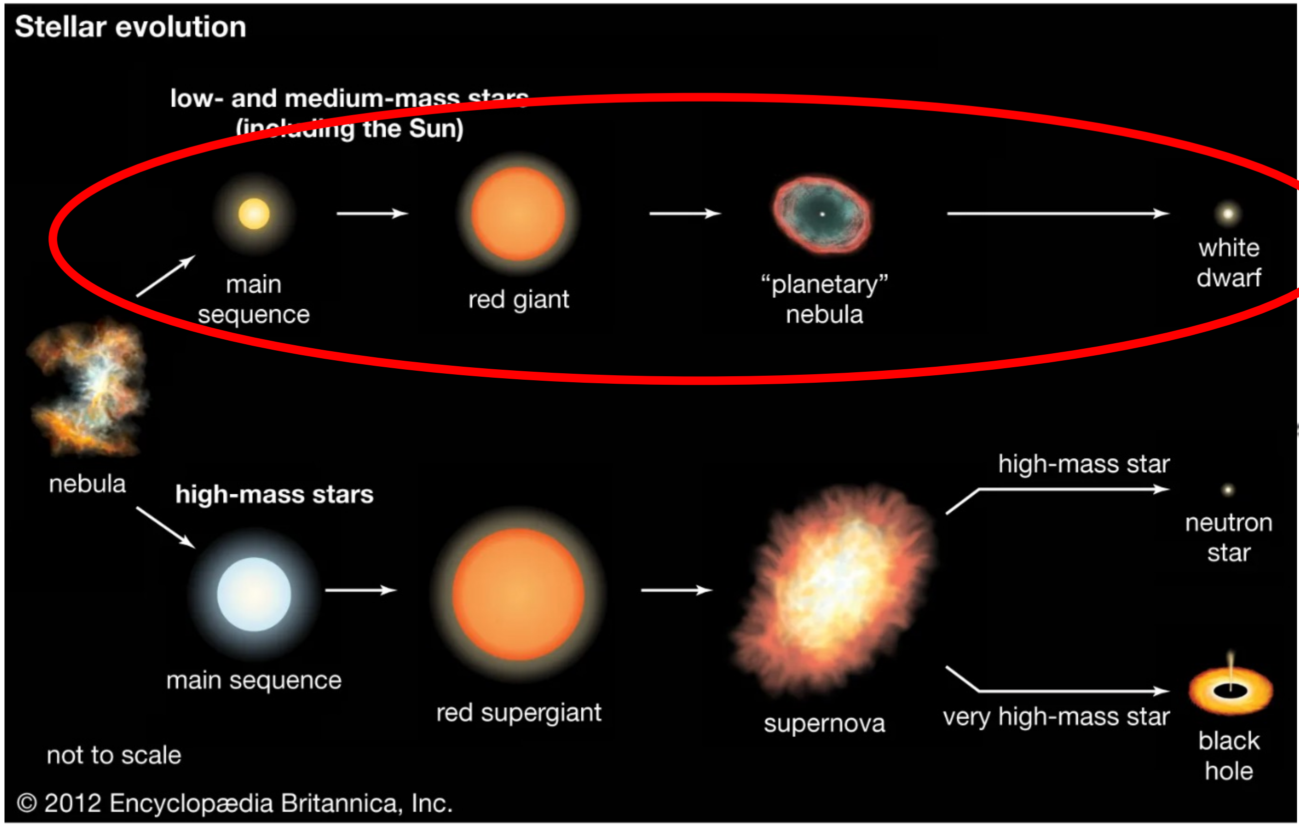
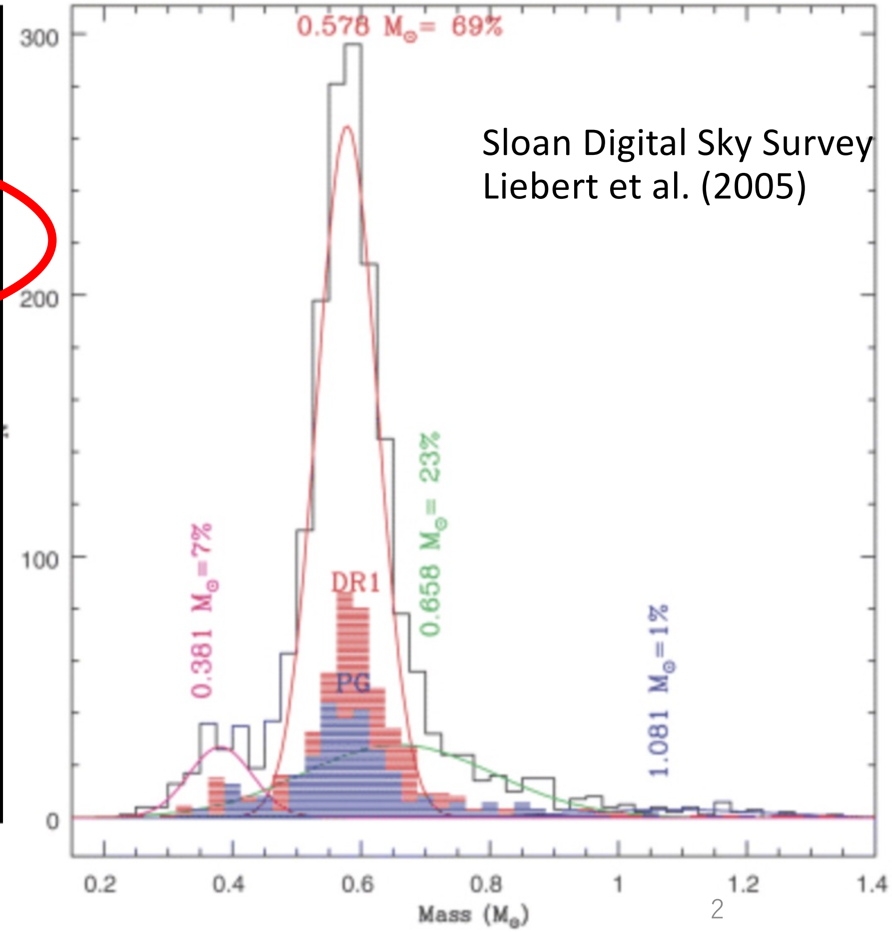
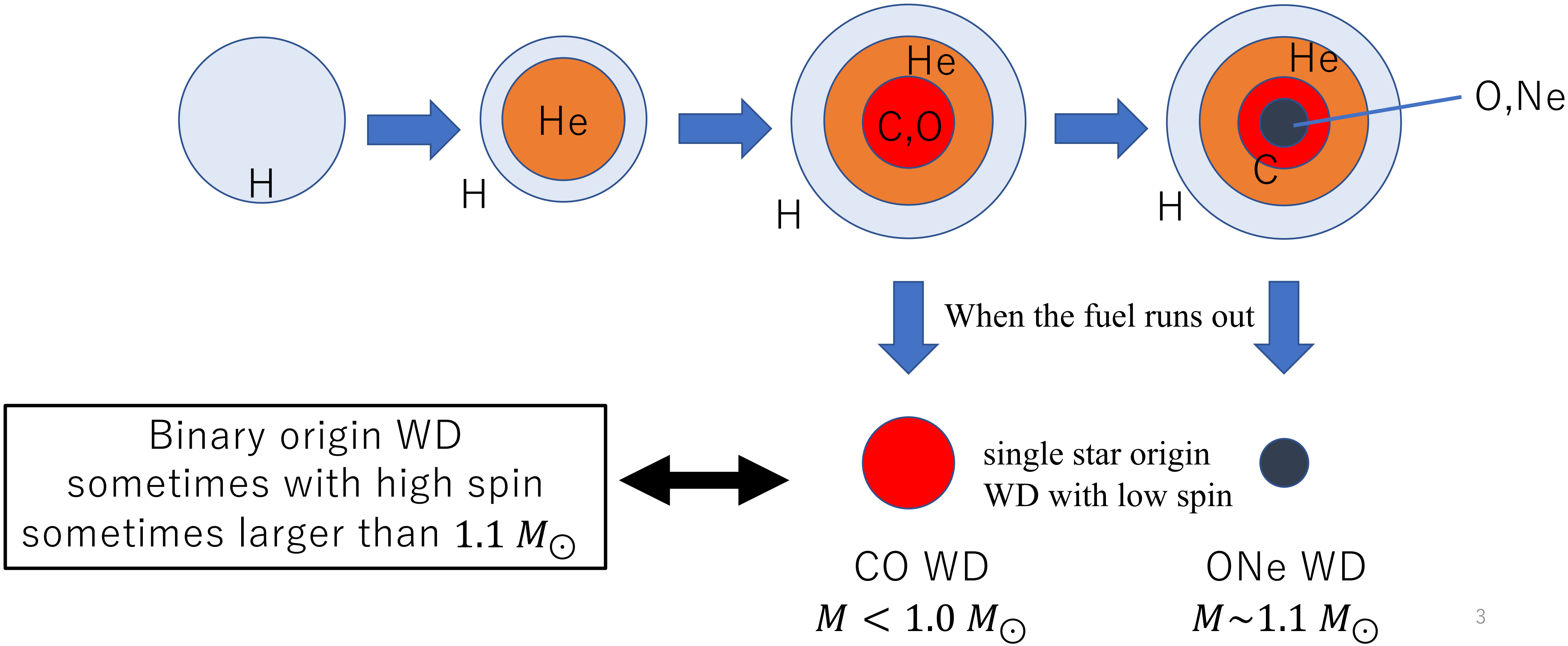
White Dwarf





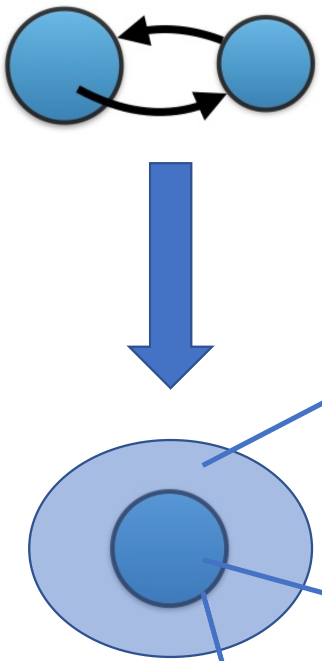
Sloan Digital Sky Survey
Liebert et al. (2005)

White Dwarf



H
He
H
He
C,O
H
He
O,Ne
C
H
When the fuel runs out
Binary origin WD
sometimes with high spin
sometimes larger than 1.1 $M_\odot$
single star origin
WD with low spin
CO WD
$M < 1.0\ M_\odot$
ONe WD
$M \sim 1.1\ M_\odot$

WD + WD → Massive WD in dense nebula ?



CO WD +CO WD
with $1.5 M_{\odot}$ total mass

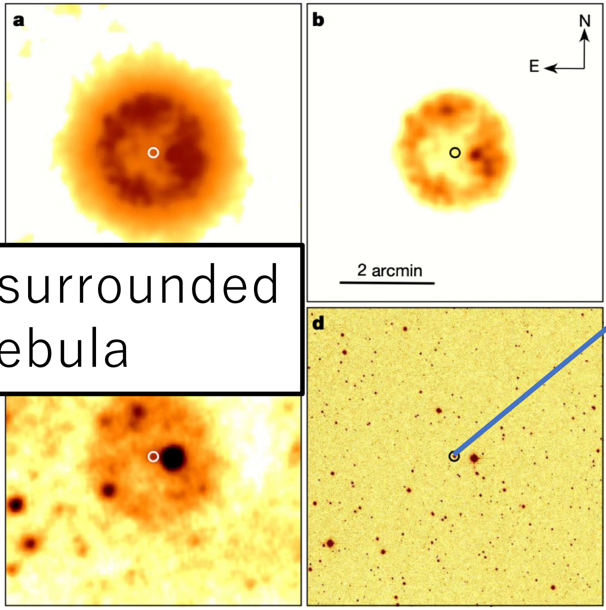
H and He-free nebula
C and O-rich nebula

- hot
- luminous
- rapidly rotating
- highly magnetized massive ONe WD

C burning on the WD surface

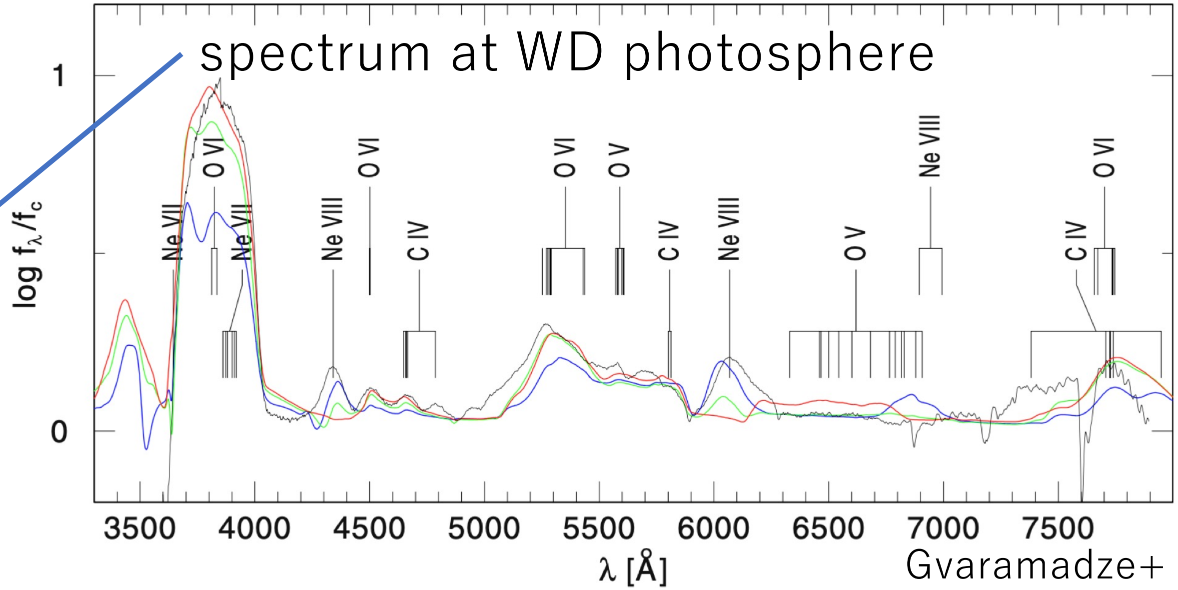
predicted by Schwab+ 2016

Massive White Dwarf WD J005311



WD surrounded by nebula

distance ~ 2.3 kpc (Gaia DR3)



Gvaramadze+ 2019

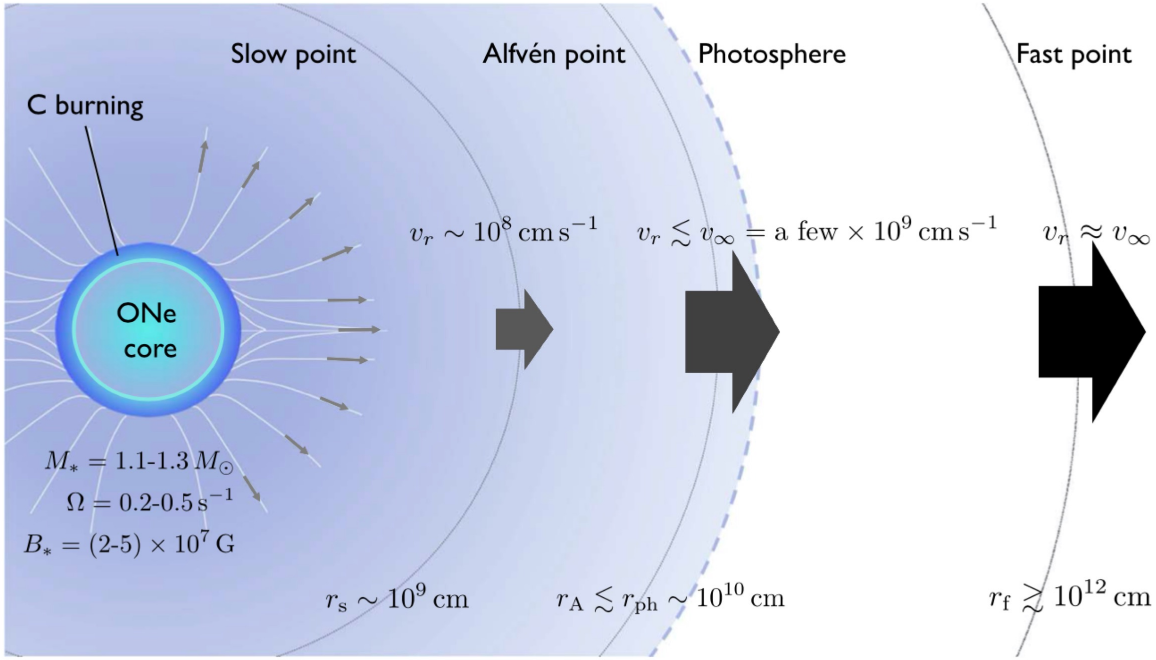
The width & height of the wind line spectrum

$$\dot{M} = (3.5 \pm 0.6) \times 10^{-6}\, M_\odot\, \mathrm{yr}^{-1}$$

$$v_\infty = 16,000 \pm 1,000\, \mathrm{km\, s^{-1}}$$

Similar Features with the predicted massive WD!

Massive White Dwarf WD J005311



Kashiyama+ 2019

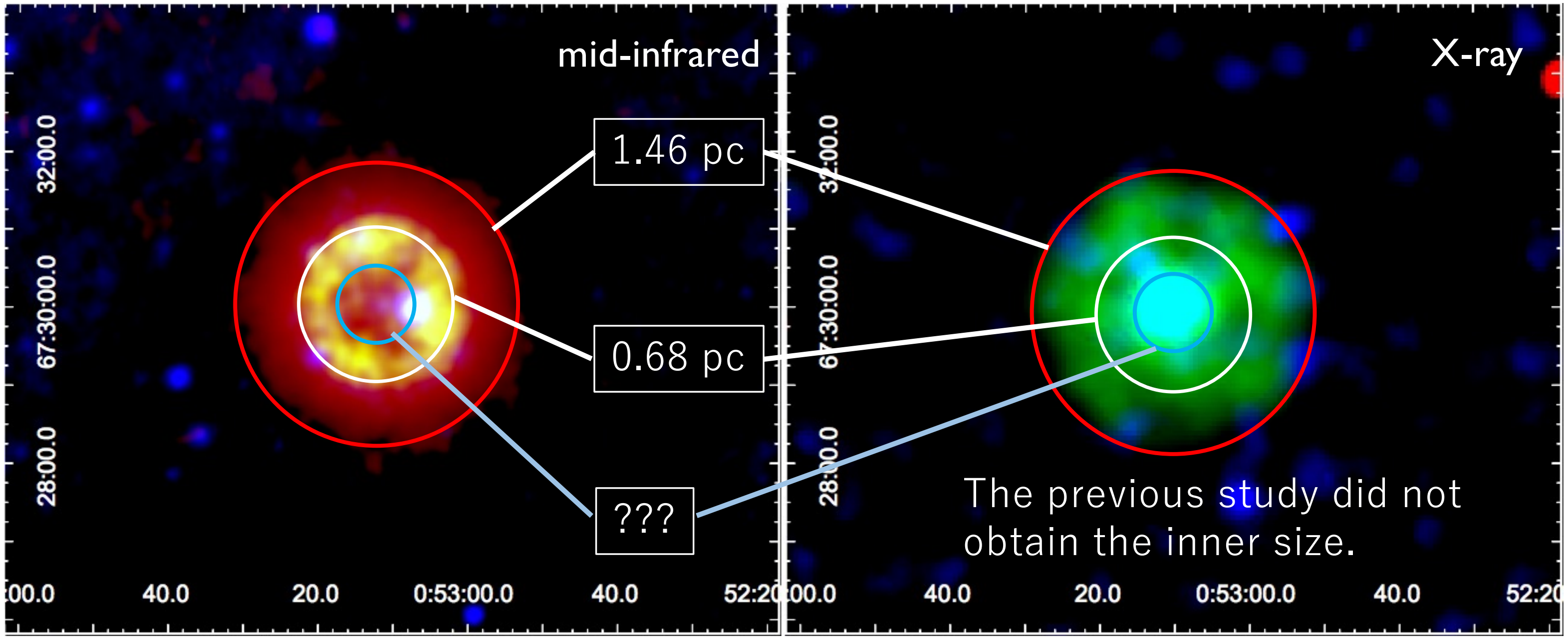
magnetohydro model

⇩

WD mass$\sim 1.1 - 1.3 M_\odot$
fast spinning
highly magnetized
↓
WD Merger Remnant?

X-ray observation of WD J005311

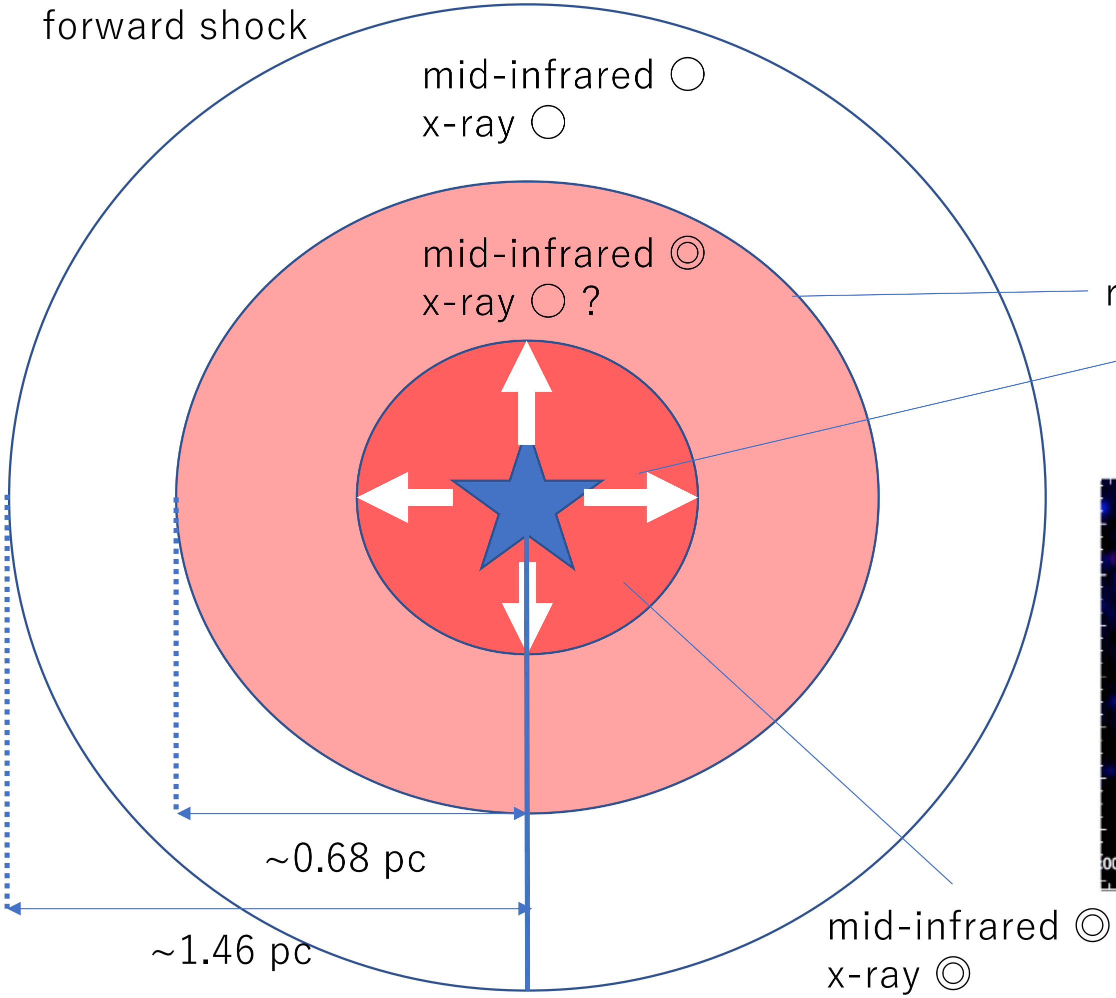
Oskinova+ 2020



Multi layers!

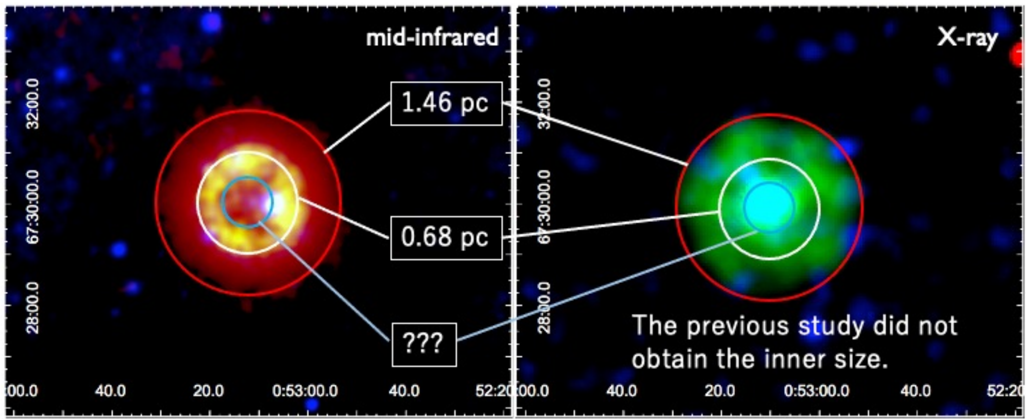
We model the remnant quantitively and gain the progenitor information

Our WD J005311 model



- This multi layer is formed by some explosion?

Oskinova+ 2020

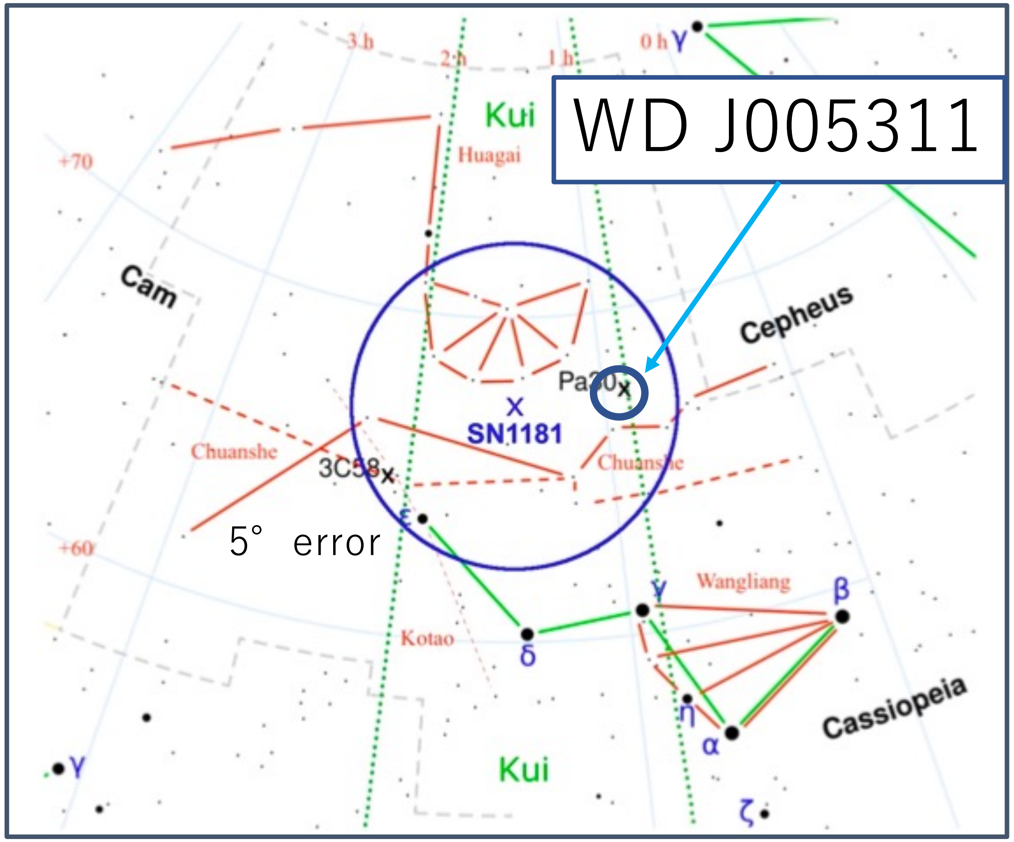


WD J005311 is SN 1181 remnant ?

Fortunately...

- The on-sky location fits historical reports of SN 1181
- Radius and velocity of the remnant
  → WD was formed ~1000 yr ago

- WD J005311 has been a leading candidate of SN 1181 remnant!
- We construct the remnant model assuming that WD J005311 is a SN 1181 remnant.
- Maybe SN Iax which left WD as remnant

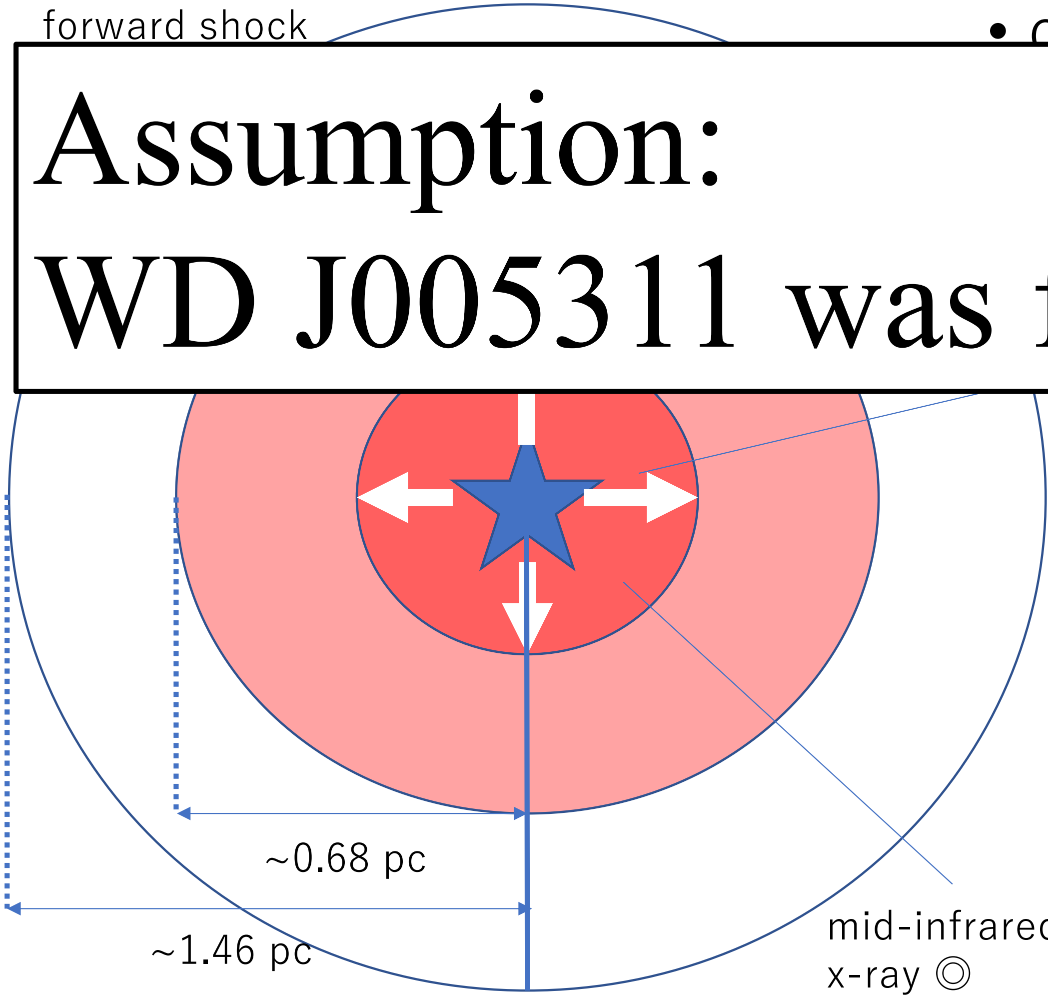


Ritter+ 2021

Our WD J005311 model

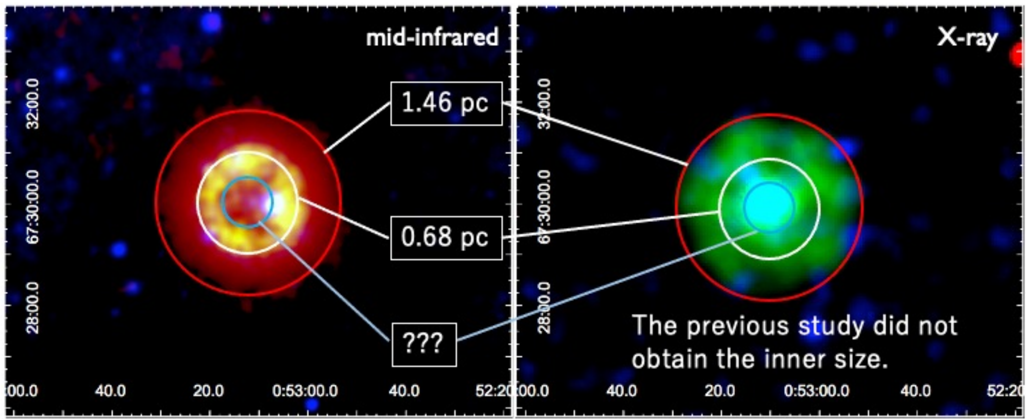
• outer region : ejecta + ISM

Assumption:
WD J005311 was formed in 1181 AD



(thin shell ?)

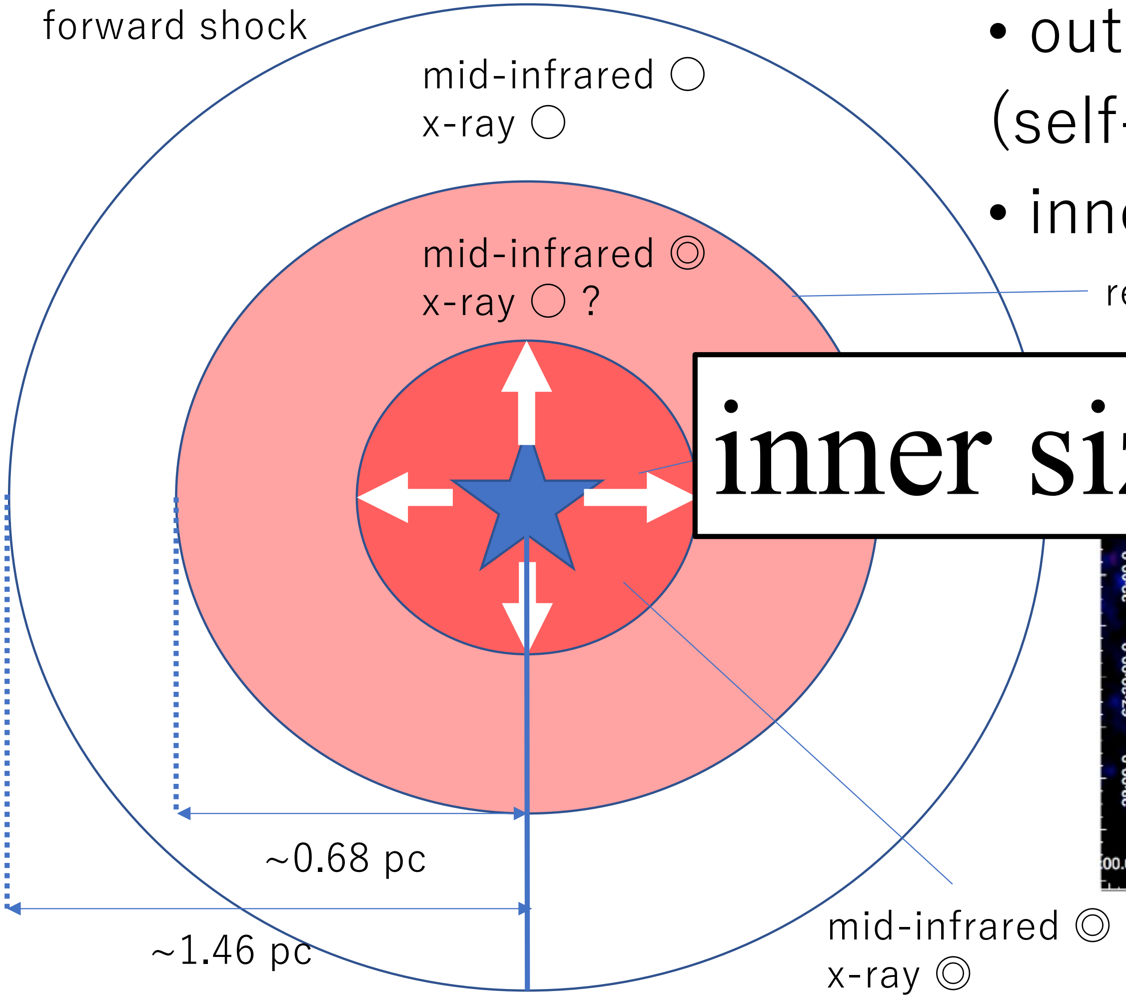
Oskinova+ 2020



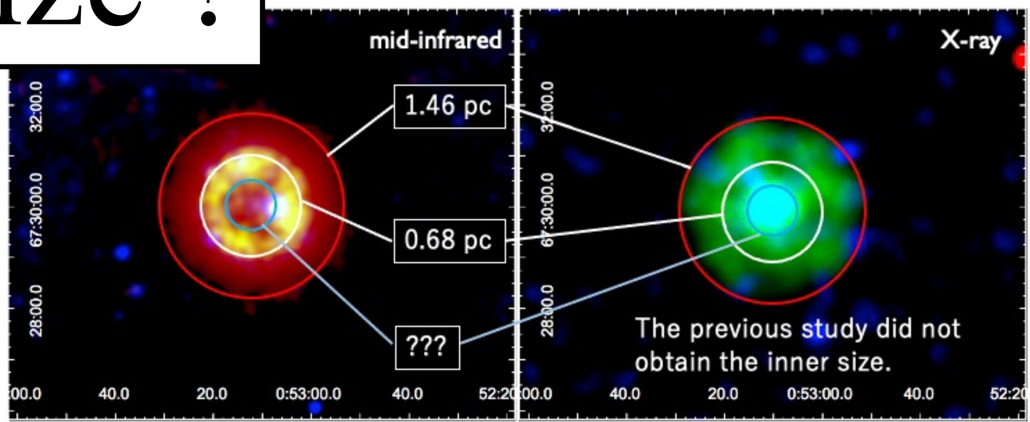
mid-infrared ◎
x-ray ◎

Our WD J005311 model

- outer region : ejecta + ISM
(self-similar solution by Chevalier+82)
- inner region : wind + fallback ejecta



Oskinova+ 2020



Our X-ray analysis by Suzuki-san

鈴木寛大 san at Konan University

表 2.1: XMM での IRAS 00500+6713 の観測ログ

OBSID	観測開始日	露光量 (ks)
0841640101	2019 Jul 8	14.2
0841640201	2019 Jul 24	13.4
0872590101	2021 Jan 8	6.8
0872590201	2021 Jan 10	10.9
0872590301	2021 Jan 14	4.0
0872590401	2021 Jan 16	7.7
0872590501	2021 Jan 20	10.4
0872590601	2021 Jan 18	12.2

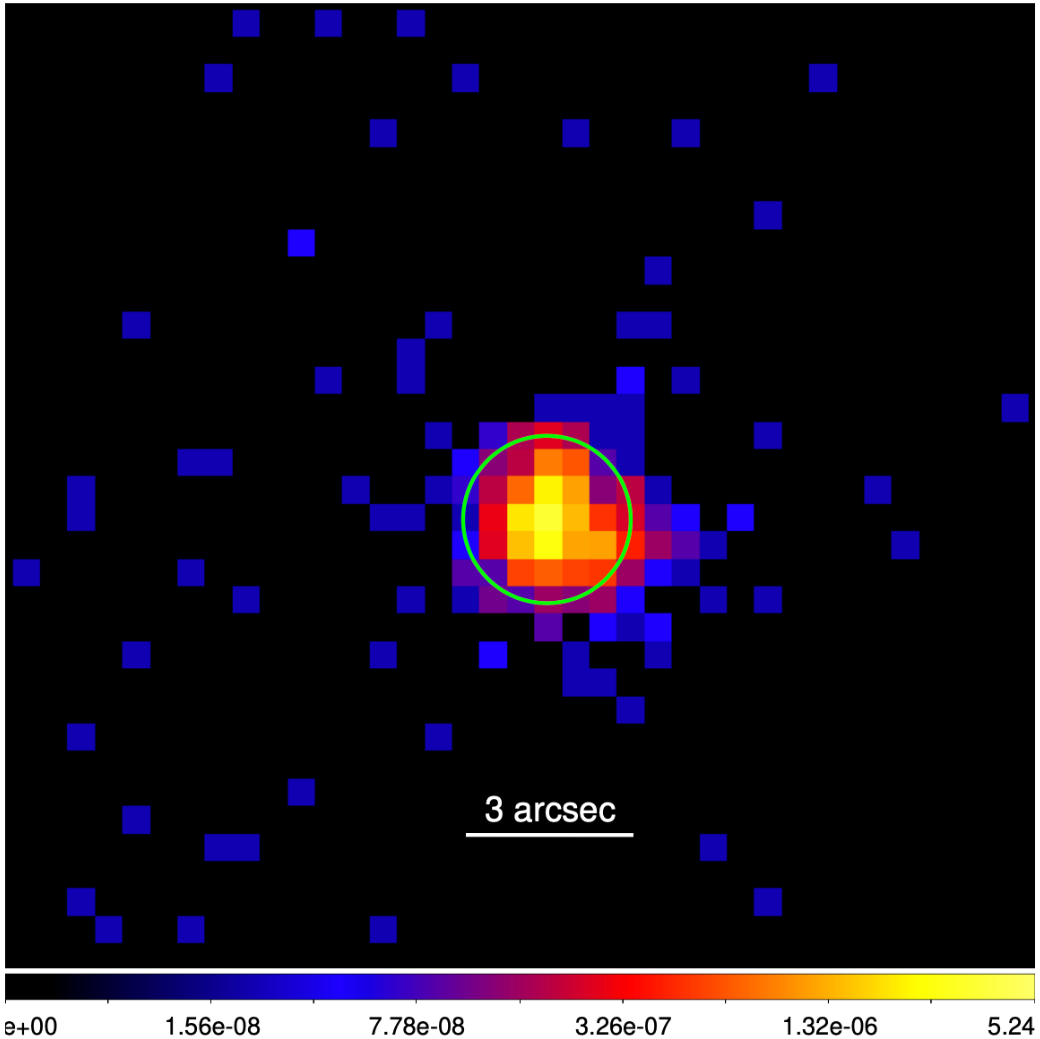
表 2.2: Chandra 衛星での IRAS 00500+6713 の観測ログ

OBSID	観測開始日	露光量 (ks)
23419	2021-05-12T10:02:33	27.7
24342	2021-05-17T02:54:20	14.8
24343	2021-05-14T09:24:33	27.7
24344	2021-10-21T09:03:08	38.0
24345	2021-12-15T09:55:43	20.8
25045	2021-05-17T17:30:09	14.8

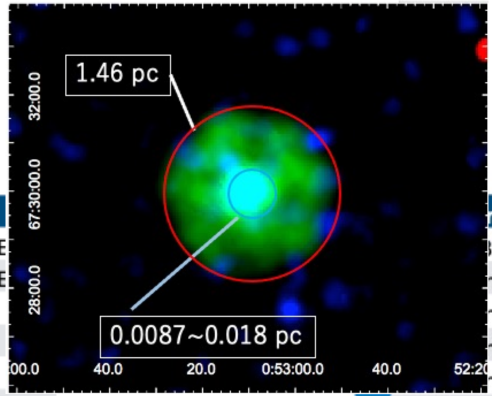
Chandra observation

r = 0.77–1.60 arcsec
→ 0.0087 – 0.018 pc

comparing with
photosphere radius ~10^{10} cm
This region is certainly spread



XMM observation



inner shocked region
(pure metal abundance)

1.2 keV

#	1	1	constant	factor		1.00000	frozen
#	2	2	TBabs	nH	10^22	0.753538	+/- 5.26790E
#	3	3	vnei	kT	keV		.93466E
#	4	3	vnei	H			frozen
#	5	3	vnei	He		0.0	frozen
#	6	3	vnei	C		2800.00	frozen
#	7	3	vnei	N		0.0	frozen
#	8	3	vnei	O		1.10861E+05	+/- 2.62125E+04
#	9	3	vnei	Ne		2800.00	frozen
#	10	3	vnei	Mg		1963.45	+/- 745.727
#	11	3	vnei	Si		2800.00	
#	12	3	vnei	S		2800.00	
#	13	3	vnei	Ar		0.0	
#	14	3	vnei	Ca		0.0	
#	15	3	vnei	Fe		7755.54	+/- 1858.38
#	16	3	vnei	Ni		7755.54	
#	17	3	vnei	Tau	s/cm^3	9.60147E+10	+/- 1.42968E+10
#	18	3	vnei	Redshift		0.0	frozen
#	19	3	vnei	norm		1.0867E-08	+/- 2.19197E-09

Fit statistic : C-Statistic = 4404.76 using 5416 PHA bins and 5409 degrees of freedom.

$n_e n_{ion} V$: 6.3e+52 cm-3

Unabsorbed flux (0.5–5.0 keV) : 3.5e-13 ergs/cm^2/s

outer shocked region
(near solar abundance)

0.3 keV

#			nstant	factor		1.00000	frozen
			abs	nH	10^22	0.448438	+/- 4.74470E-02
			nei	kT	keV		4.26671E-02
			nei	H			frozen
			nei	He		1.00000	frozen
			nei	C		1.00000	frozen
#	7	3	vnei	N		1.00000	frozen
#	8	3	vnei	O		1.00000	frozen
#	9	3	vnei	Ne		2.15916	+/- 0.433043
#	10	3	vnei	Mg		1.11400	+/- 0.330682
#	11	3	vnei	Si		1.00000	frozen
#	12	3	vnei	S		1.00000	frozen
#	13	3	vnei	Ar		1.00000	frozen
#	14	3	vnei	Ca		1.00000	frozen
#	15	3	vnei	Fe		6.57069E-02	+/- 4.11134E-02
#	16	3	vnei	Ni		6.57069E-02	
#	17	3	vnei	Tau	s/cm^3	> 8.9e+11	
#	18	3	vnei	Redshift		0.0	frozen
#	19	3	vnei	norm		2.51439E-04	+/- 8.62767E-05

Fit statistic : C-Statistic = 2077.20 using 1816 PHA bins and 1809 degrees of freedom.

$n_e n_H V$: 1.4e+55 cm-3

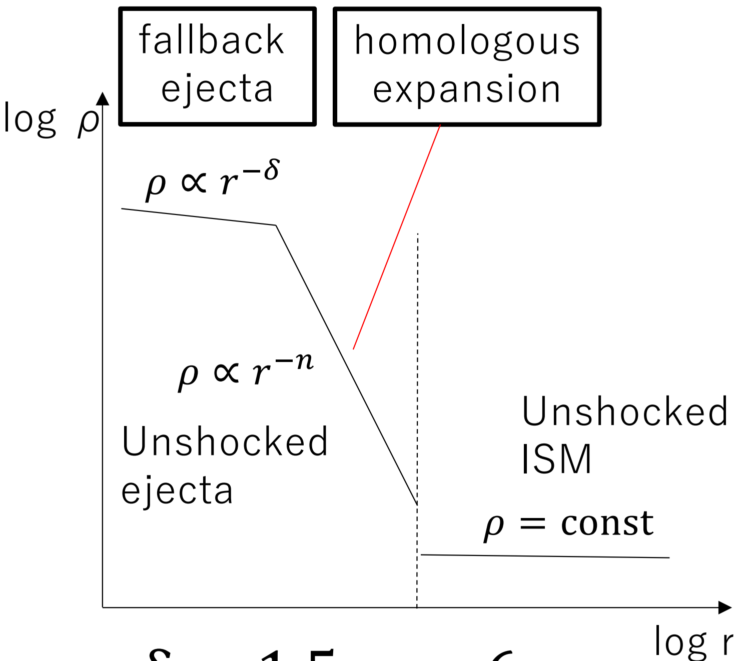
Unabsorbed flux (0.5–5.0 keV) : 9.3e-13 ergs/cm^2/s

temperature

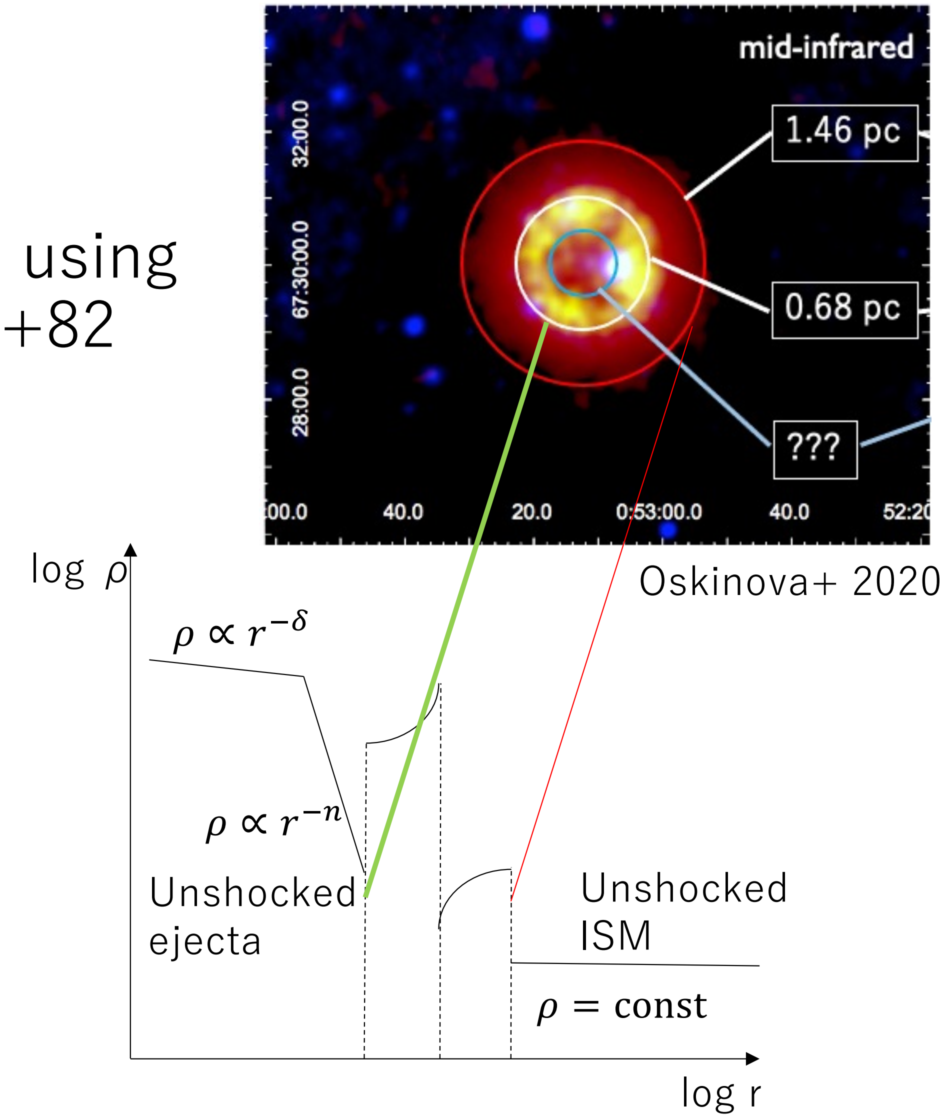
EM

Outer modeling

- We calculate the shock evolution using self-similar solution by Chevalier+82



$$\delta = 1.5, n = 6$$



Oskinova+ 2020

Here we assume explosion occured at 1181

Outer modeling ~Result~

- The radius of the region → $\left(\frac{E_{ej}}{10^{48}\,\mathrm{erg}}\right)^{-0.5}\left(\frac{M_{ej}}{0.5\times10^{33}\,\mathrm{g}}\right)^{0.167}\left(\frac{n_{\mathrm{out}}}{0.1\,\mathrm{cm}^{-3}}\right)^{1/3}=0.922.$
- Emission measure (our model)→ $\mathrm{EM}_f=6.6\times10^{54}\,\mathrm{cm}^{-3}\left(\frac{n_{\mathrm{out}}}{0.1\,\mathrm{cm}^{-3}}\right)^2.$
- X-ray analysis → $\underbrace{EM=n_e n_{ion} V}_{\text{definition of EM}} = 1.74\times10^{55}$ /cm^3
- From above, $n_{out}=0.146$,

n_{out} : number density of CSM

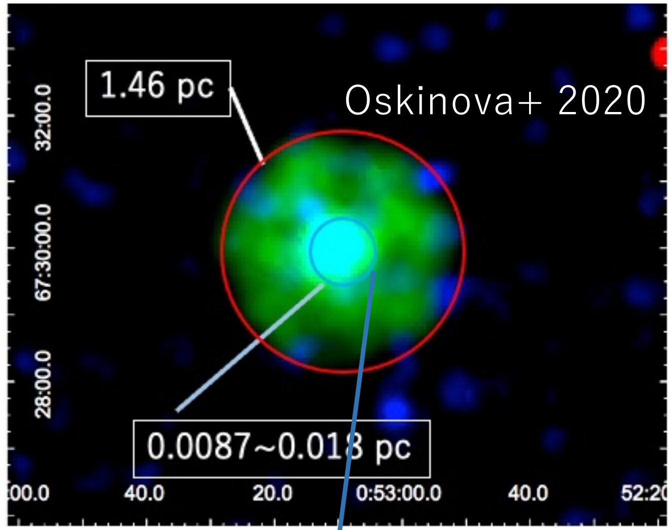
E_{ej} : SN explosion energy

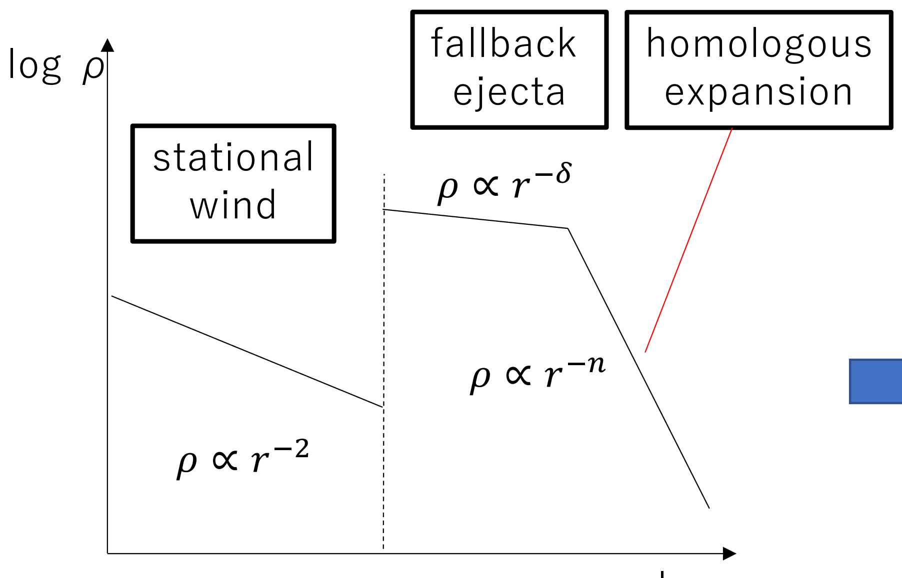
M_{ej} : SN ejecta mass

$$\boxed{\left(\frac{E_{ej}}{10^{48}\,\mathrm{erg}}\right)^{-1/2}\left(\frac{M_{ej}}{0.5\times10^{33}\,\mathrm{g}}\right)^{1/6}=0.81^{+0.06}_{-0.04}.}$$

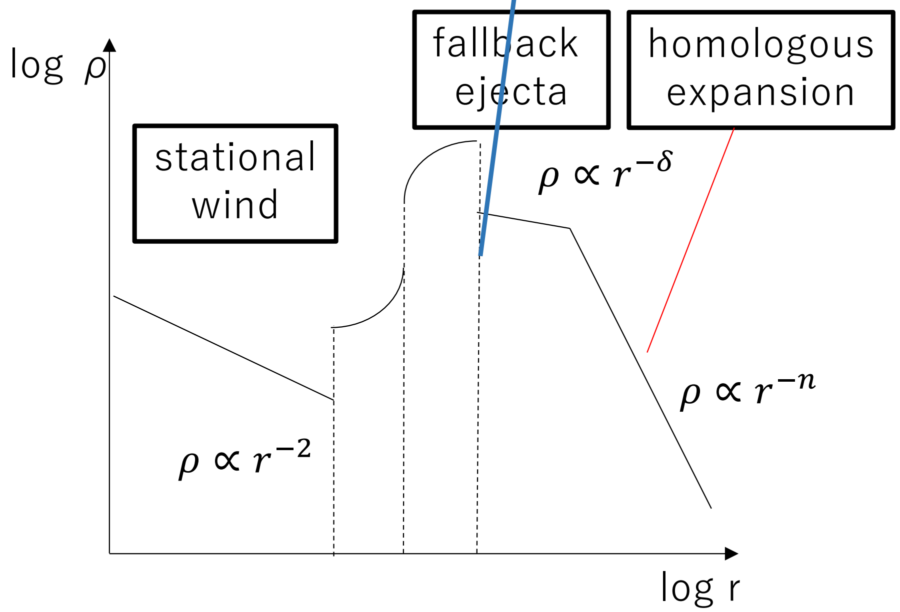
Inner modeling

- We use thin shell approximation.





$$\delta = 1.5, n = 6$$



Inner modeling

- We use thin shell approximation.
- EOM + energy conservation of the shell

$$M_{\rm sh,in}\frac{dv_{\rm sh}}{dt} = 4\pi r_{\rm sh}^2[p_{\rm w} - \rho_{\rm ej}(v_{\rm sh} - v_{\rm ej})^2] - \frac{GM_{\rm sh,in}M_*}{r_{\rm sh}^2},$$

$$\frac{d}{dt}\left[\frac{4\pi r_{\rm sh}^3}{3}\frac{p_{\rm w}}{\gamma - 1}\right] = L_{\rm w} - p_{\rm w} \times 4\pi r_{\rm sh}^2 v_{\rm sh},$$

- If the observed wind is released steadily from the time of merger (1181 AD)

→ r_inner >> 0.018 pc （X-ray analysis）

Wind started blowing recently?

- Wind is produced by the surface burning of the massive WD

- This timescale can be estimated by Kelvin-Helmholtz timescale

$$t_{KH} = \frac{GM^2}{RL} \sim 1000 \text{ years}$$

Schwab+ 2016

- We consider the wind started blowing recently

Wind started blowing recently?

- If the wind started blowing recently

→ inner region becomes smaller

- Our model can constrain when the wind started blowing

- t_{wind} : how many years after the explosion the wind started blowing
- $t_{wind} < 828$ yr

A Swift XRT Observation confirmed a point source
(ID 00358336000, 26th July 2009, Evans+2014)
This means that the wind should begin flowing before 2009.

Our modeling

By giving 5 parameters:

$n_{\mathrm{out}}, E_{\mathrm{ej}}, M_{\mathrm{ej}}, \dot{M}_{\mathrm{wind}}, t_{\mathrm{wind}}$

We can solve this remnant

Outer analysis gives

$$n_{out} = 0.146$$

&

$$\left(\frac{E_{ej}}{10^{48}\,\mathrm{erg}}\right)^{-1/2}\left(\frac{M_{ej}}{0.5\times10^{33}\,\mathrm{g}}\right)^{1/6} = 0.81^{+0.06}_{-0.04}.$$

Inner region calculations

Mass conservation

$$M_{\rm sh,in} = M_{\rm sh,in,w} + M_{\rm sh,in,ej},$$

$$\frac{d}{dt}M_{\rm sh,in,w} = \dot{M}_{\rm w},$$

$$\frac{d}{dt}M_{\rm sh,in,w} = 4\pi r_{sh}^2 \rho(r_{sh})(v_{sh} - v_{ej}).$$

EOM

$$M_{\rm sh,in}\frac{dv_{\rm sh}}{dt} = 4\pi r_{\rm sh}^2[p_{\rm w} - \rho_{\rm ej}(v_{\rm sh} - v_{\rm ej})^2] - \frac{GM_{\rm sh,in}M_*}{r_{\rm sh}^2},$$

Energy conservation

$$\frac{d}{dt}\left[\frac{4\pi r_{\rm sh}^3}{3}\frac{p_{\rm w}}{\gamma - 1}\right] = L_{\rm w} - p_{\rm w} \times 4\pi r_{\rm sh}^2 v_{\rm sh},$$

We solve these 3 equations for each parameter sets:

$M_{\rm ej}, \dot{M}_{\rm wind}, t_{\rm wind}$

compared with

Constraints :

- $5.0 \times 10^{52}\ {\rm cm^{-3}} < {\rm EM_{wind}} < 7.6 \times 10^{52}\ {\rm cm^{-3}}$. at 2021
- **0.0087 < r < 0.018** pc at 2021
- $t_{wind} < 828$ yr

explanation of the parameter sets

- $\dot{M}_{\rm wind}$: mass-loss rate from the central WD

→ Observations have shown that it can take a variety of values.

Table 1. Range of stellar parameters for CMFGEN models. The last two columns show the values from Gvaramadze et al. (2019) and from the hot gas model in the Sect. 3.3.

Parameter	Explored range	Best fit range	Illustrated model	Gvaramadze et al. (2019)	Hot gas model
L_* ($L_\odot$)	10,000 – 200,000	30,000 – 50,000	36,000	$39,810^{+20,144}_{-10,970}$	
T_* (K)	145,000 – 580,000	200,000 – 250,000	237,000	$211,000^{+40,000}_{-23,000}$	
$\dot{M}$ ($M_\odot$/yr)	7.5× 10^{-7} – 2.5× 10^{-6}	$\leq$ 4× 10^{-6}	2.6 × 10^{-6}	3.5(±0.6) × 10^{-6}	
R_* ($R_\odot$)	0.04 – 0.22	$\leq$ 0.2	0.155	0.15±0.04	
v_∞ (kms)	–	~15,000	15,000	16,000±1,000	
Mass fractions					
$X_{\rm H}$	–	–	–	–	–
$X_{\rm He}$	0.017 – 0.135	< 0.4	0.017	< 0.1	$\leq$ 0.44
$X_{\rm C}$	0.0 – 0.261	$\leq$ 0.26	0.13	0.2 ± 0.1	0.13
$X_{\rm O}$	0.414 – 0.697	$\leq$ 0.7	0.41	0.8 ± 0.1	0.39
$X_{\rm Ne}$	0.011 – 0.501	$\leq$ 0.5	0.44	0.01	0.04

Lykou+2022

They tried to fit the infrared spectra using CMFGEN model

Inner region calculations

Mass conservation

$$M_{\rm sh,in} = M_{\rm sh,in,w} + M_{\rm sh,in,ej},$$

$$\frac{d}{dt} M_{\rm sh,in,w} = \dot{M}_{\rm w},$$

$$\frac{d}{dt} M_{\rm sh,in,w} = 4\pi r_{sh}^2 \rho(r_{sh})(v_{sh} - v_{ej}).$$

EOM

$$M_{\rm sh,in}\frac{dv_{\rm sh}}{dt} = 4\pi r_{\rm sh}^2[p_{\rm w} - \rho_{\rm ej}(v_{\rm sh} - v_{\rm ej})^2] - \frac{GM_{\rm sh,in}M_*}{r_{\rm sh}^2},$$

Energy conservation

$$\frac{d}{dt}\left[\frac{4\pi r_{\rm sh}^3}{3}\frac{p_{\rm w}}{\gamma - 1}\right] = L_{\rm w} - p_{\rm w} \times 4\pi r_{\rm sh}^2 v_{\rm sh},$$

We solve these 3 equations for each parameter sets:

$$M_{\rm ej}, \dot{M}_{\rm wind}, t_{\rm wind}$$

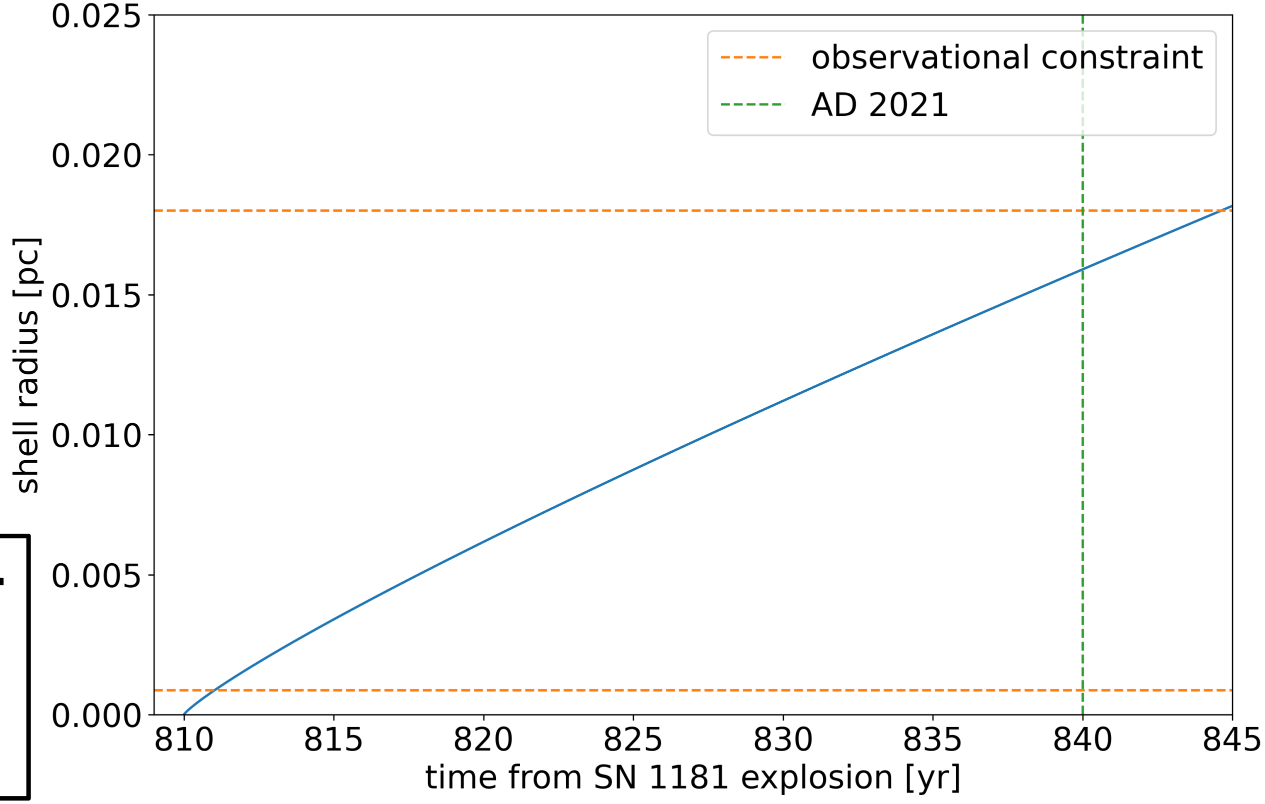
compared with

Constraints :

- $5.0 \times 10^{52}\,{\rm cm^{-3}} < {\rm EM_{wind}} < 7.6 \times 10^{52}\,{\rm cm^{-3}}$. at 2021
- **0.0087 < r < 0.018** pc at 2021
- t_{wind} < 828 yr

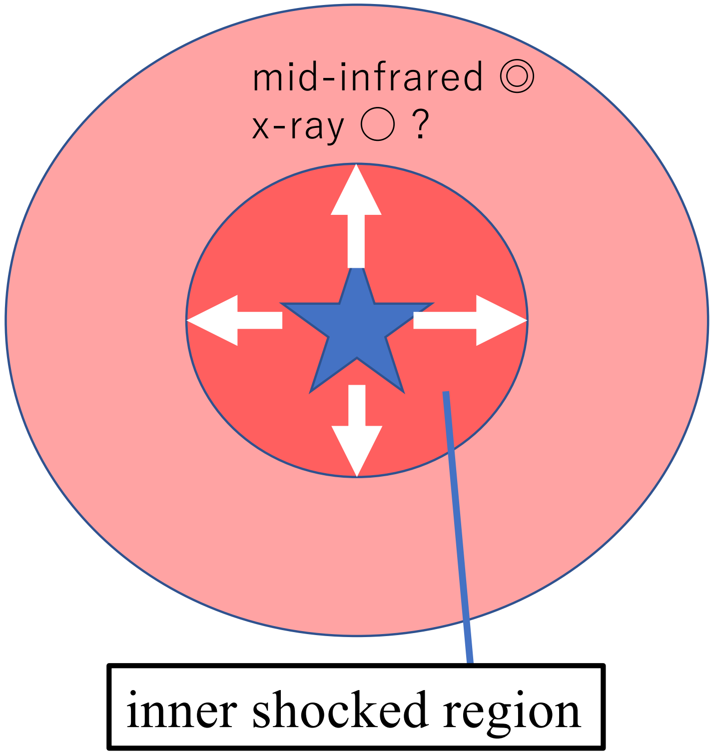
Time evolution of the shell

Time evolution of the shell radius



$$\dot{M}_{\mathrm{wind}} = 3\times10^{-7} M_{\odot}\ /\mathrm{yr}$$
$$M_{\mathrm{ej}} = 0.6 M_{\odot}$$
$$t_{\mathrm{wind}} = 810\ \mathrm{yr}$$

Failure Example



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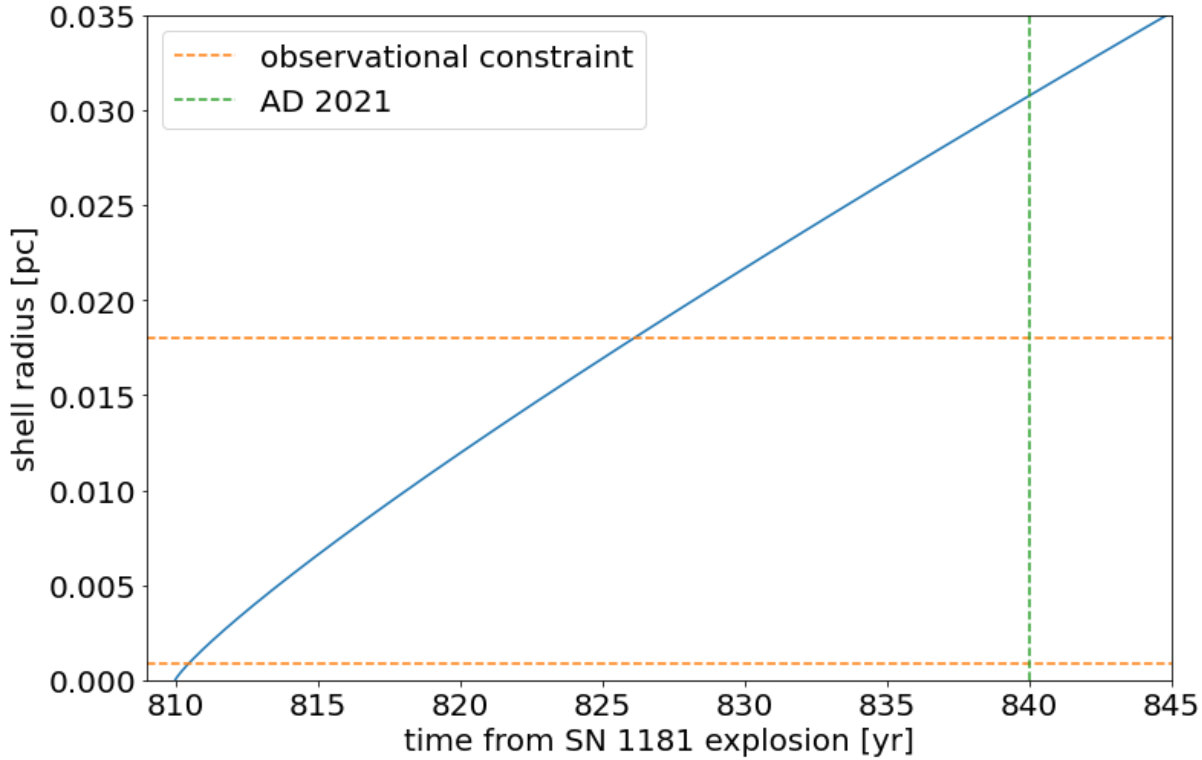
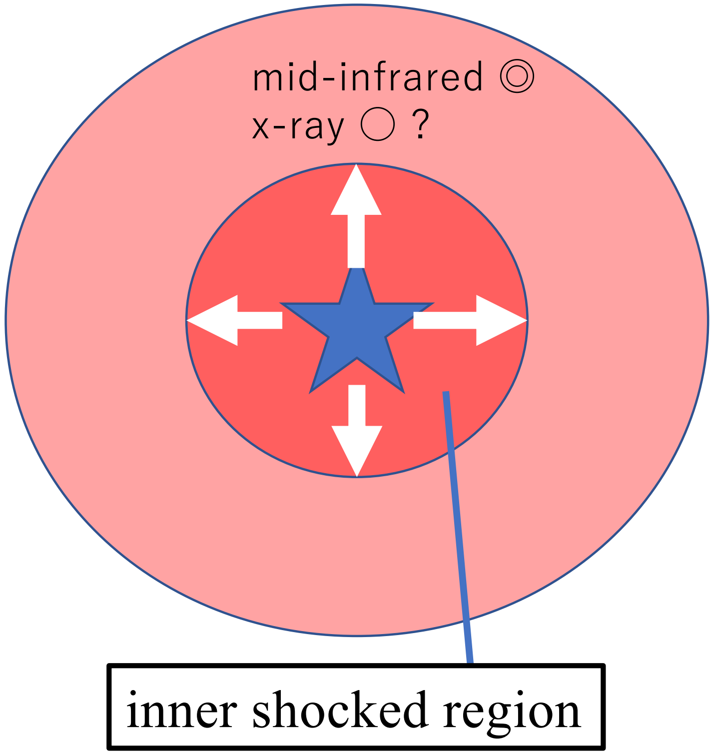
$$M_{\rm ej} = 0.6 M_\odot$$
$$t_{\rm wind} = 810\ {\rm yr}$$

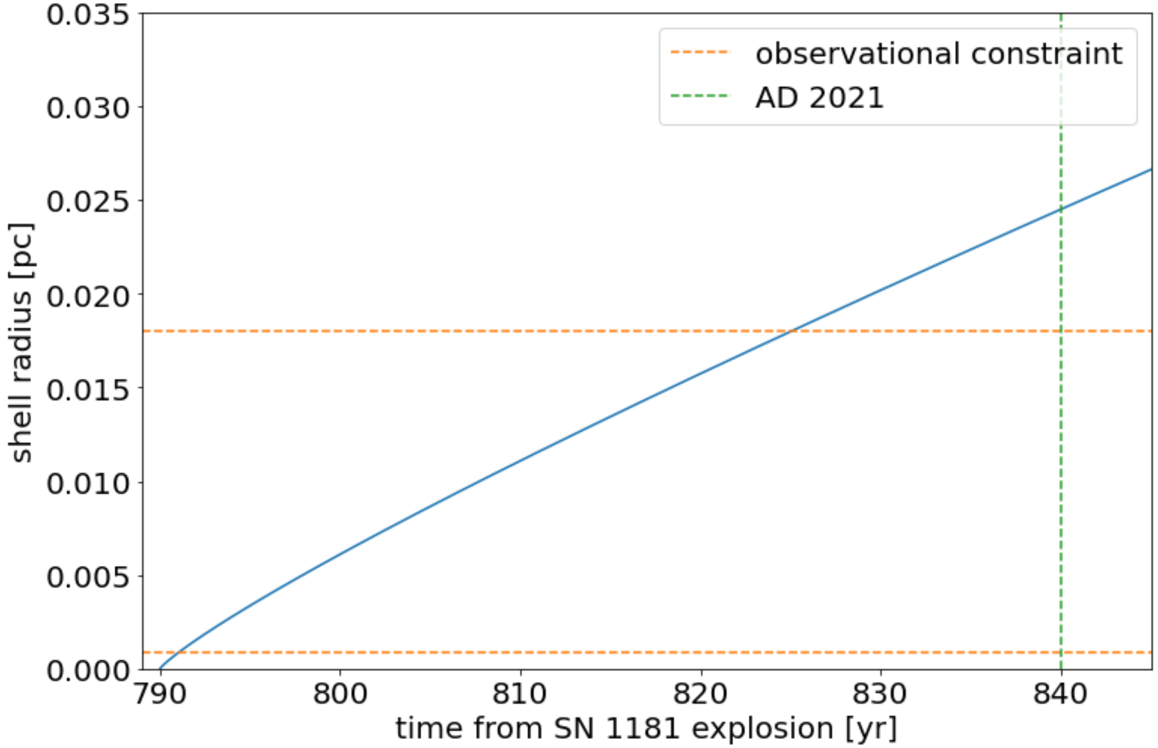


~~0.0087 < r < 0.018 pc at 2021~~

Failure Example

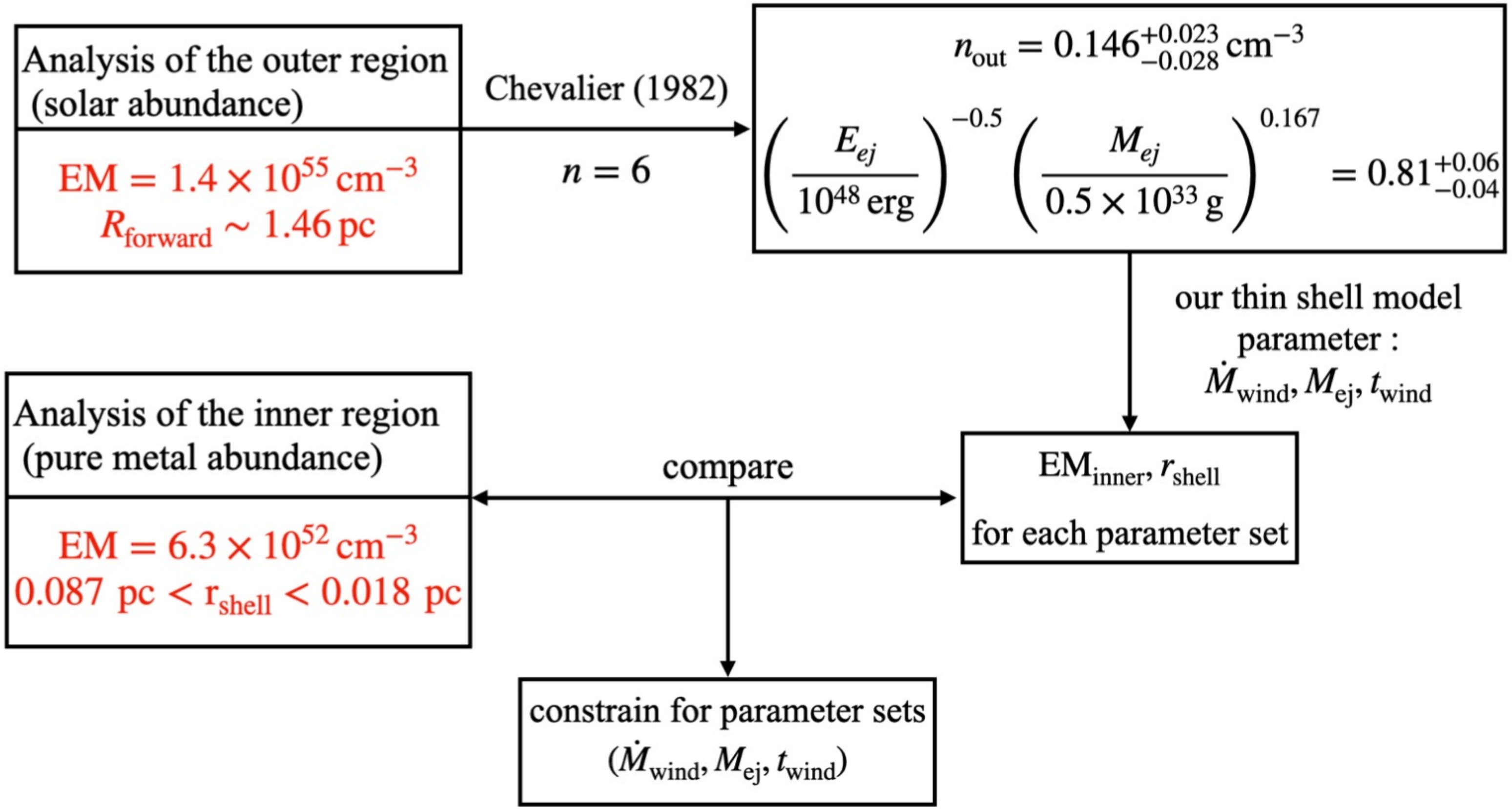


$$\dot{M}_{\mathrm{wind}} = 3\times10^{-7} M_{\odot}\ /\mathrm{yr}$$
$$M_{\mathrm{ej}} = 0.6 M_{\odot}$$
$$t_{\mathrm{wind}} = 790\ \mathrm{yr}$$

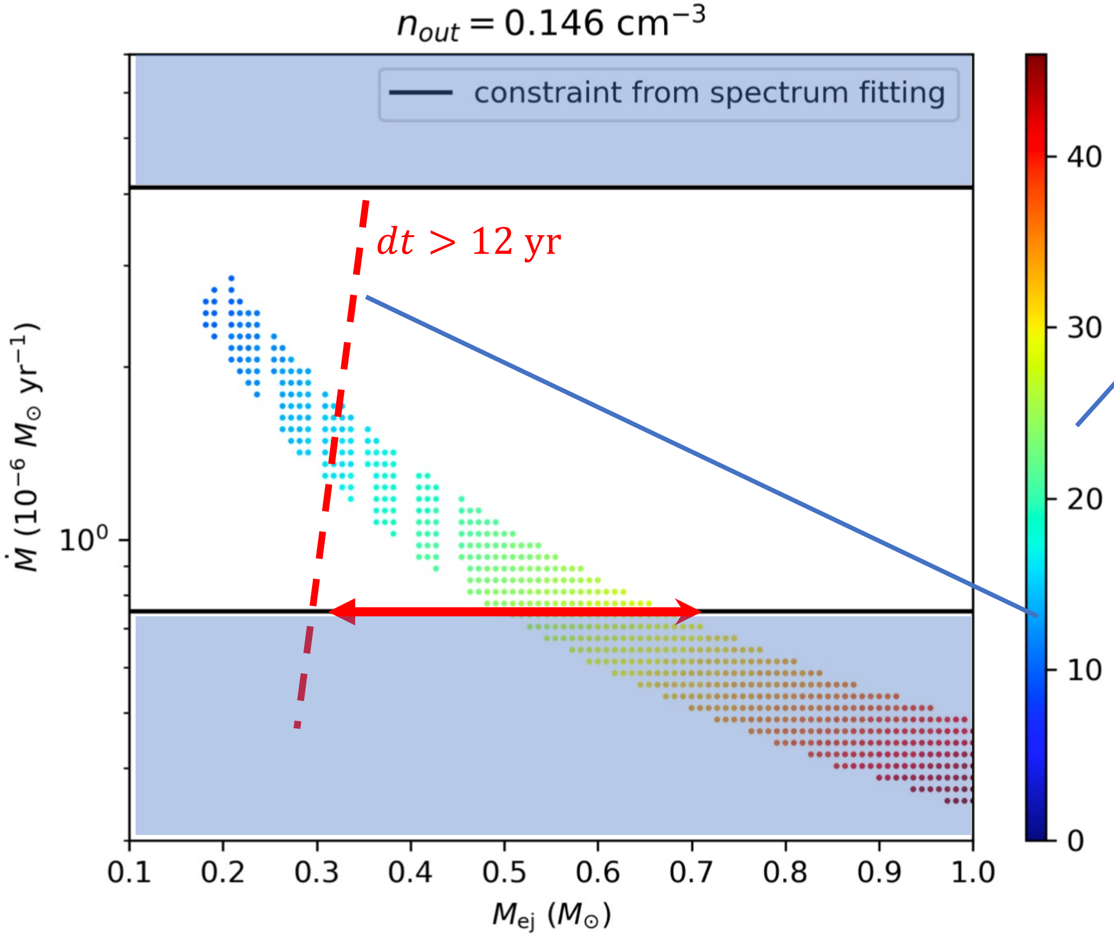


~~0.0087 < r < 0.018 pc at 2021~~

Overview of our model



Results



our thin shell model parameter :
$\dot{M}_{wind}, M_{ej}, t_{wind}$

$dt = 840$ yr - t_{wind}

$t_{wind} < 828$ yr $\rightarrow dt > 12$ yr

$0.3\ M_\odot \lesssim M_{ej} \lesssim 0.7\ M_\odot$

$1.6 \times 10^{48}\ \mathrm{erg} \lesssim E_{ej} \lesssim 2.1 \times 10^{48}\ \mathrm{erg}$

Compared with typical SN Iax

- SN 1181 maximum luminosity is compared to Saturn

→ absolute magnitude of M ~ -14 to -12.5 (fainter than SN Ia)

- SN 1181 left WD J005311 as remnant

↓

SN 1181 is SN Iax?

What is SN Iax?

- Type Iax SN → sub-luminous Type Ia SN
- thought to leave a white dwarf as a remnant
- typical ejecta mass ~ 0.5 solar mass
- rate → ~10% of SN Ia rate
- progenitor → ONe WD + CO WD with super-Chandrasekhar

SN 1181 is SN Iax?

- Type Iax SN → sub-luminous Type Ia SN
- thought to leave a white dwarf as a remnant
- typical ejecta mass ~ 0.5 solar mass
- rate → ~10% of SN Ia rate
- progenitor → ONe WD + CO WD with super-Chandrasekhar

Consistent!

$$0.3\,M_\odot \lesssim M_{\rm ej} \lesssim 0.7\,M_\odot$$

SN 1181 is SN Iax?

- Type Iax SN → sub-luminous Type Ia SN
- thought to leave a white dwarf as a remnant
- typical ejecta mass ~ 0.5 solar mass
- rate → ~10% of SN Ia rate
- progenitor → ONe WD + CO WD with super-Chandrasekhar

We humans are not especially lucky
c.f., one SN Ia per a few hundred years in the Galaxy

Only one SN Iax as historical SN

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1.2 solar mass ONe WD + 1.1 solar mass CO WD
→ SN Iax with 0.1 solar mass ejecta
(Theoretically predicted by Kashyap+2018)

Progenitor mass

- progenitor binary mass = remnant mass +ejecta mass

$1.1 < M_{WD} < 1.3 M_{\odot}$ (Kashiyama +2019)

$0.3\, M_{\odot} \lesssim M_{\rm ej} \lesssim 0.7\, M_{\odot}$ (This work)

- progenitor binary mass : $1.4 - 2.0\, M_{\odot}$

- **ONe WD + CO WD → WD J005311 with SN 1181**
- e.g., 1.1 solar mass ONe WD + 0.5 solar mass CO WD

→ ejecta heavier than 0.1 solar mass ? (Future work)

Conclusion

- ejecta from SN 1181 : $0.3\,M_\odot \lesssim M_{\rm ej} \lesssim 0.7\,M_\odot$
- SN 1181 energy : $1.6 \times 10^{48}\,{\rm erg} \lesssim E_{\rm ej} \lesssim 2.1 \times 10^{48}\,{\rm erg}$
- These values are consistent with the assumption that type Iax SN occurred at 1181

→ strongly supports that WD J005311 is a SN 1181 remnant

- Fast wind started blowing recently!

- WD J005311 was formed by ONe WD + CO WD

and mass of the binary system is $1.4 - 2.0\,M_\odot$

Future work

- 2D simulation of ONe WD + CO WD merger

→ejecta mass, explosion energy, its spherical shape

- Calculating the evolution of the central WD

→**the KH timescale of the WD → when the wind started blowing?**

- XRISM X-ray observation

→precise abundance

- Optical deep survey to find H and He in the outer region

→confirm our calculation

- 2D simulation of this total system including some instabilities