$^{12}\mathrm{C}(\alpha,\gamma)^{16}\mathrm{O}$反応率の不定性が対不安定型超新星における元素合成とニュートリノ放出に与える影響

第11回超新星ニュートリノ研究会 11th Supernova Neutrino Workshop
@東京大学駒場キャンパス The University of Tokyo, Komaba 2025/03/04

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With
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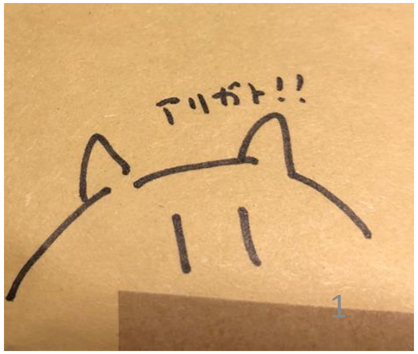
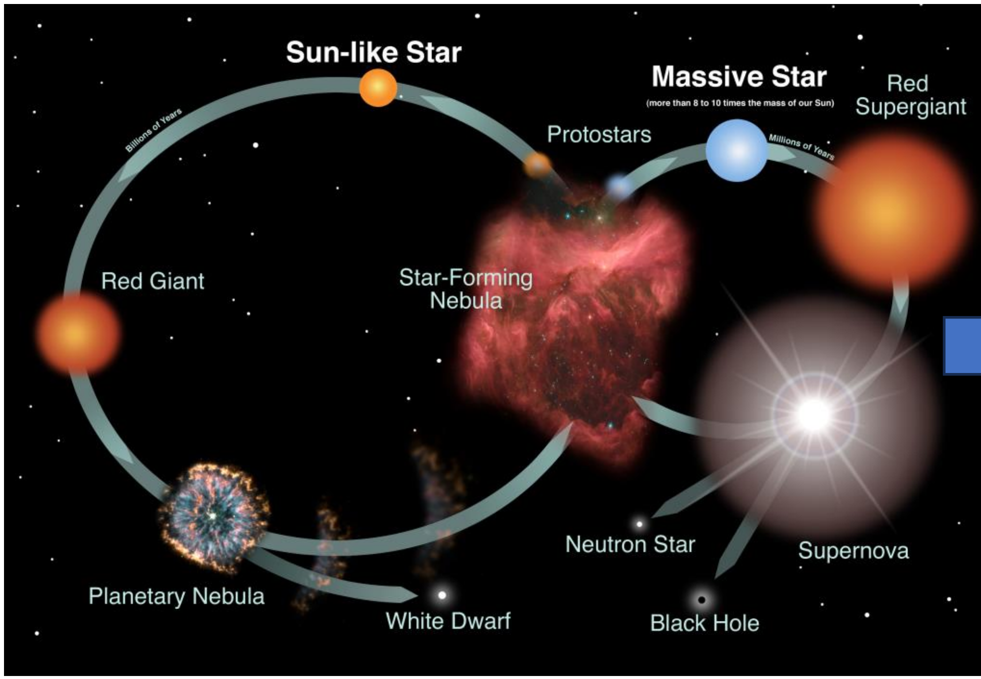
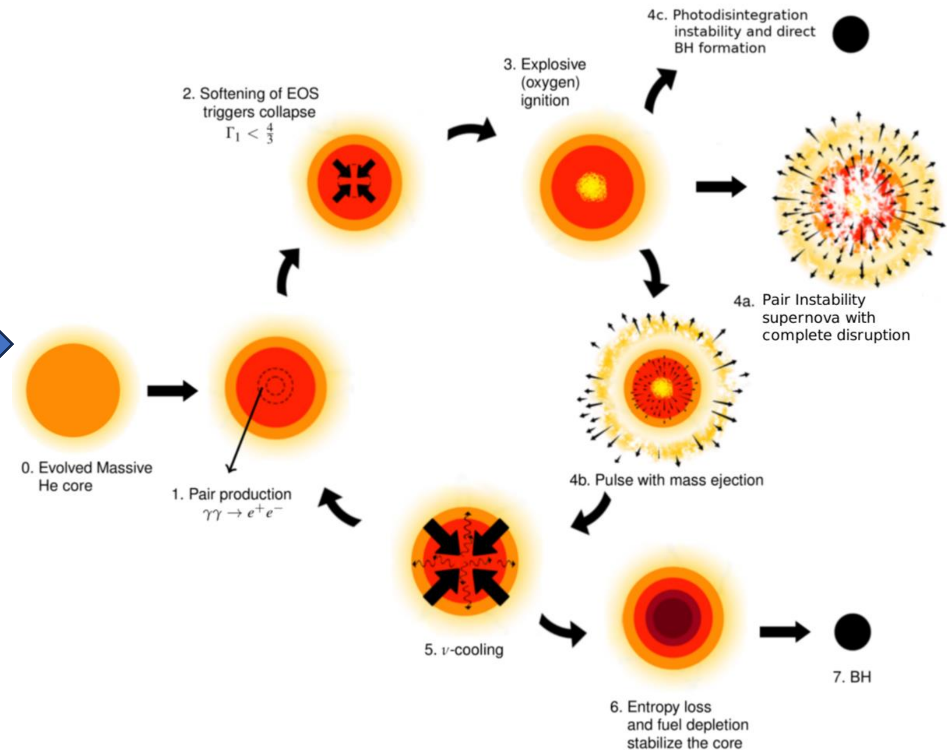
芦田洋輔 Yosuke Ashida (Tohoku Univ.)
澤田涼 Ryo Sawada (ICRR, UTokyo Komaba)



Introduction
Final fates of stars





NASA

M. Renzo *et al.* A&A **640**, A56 (2020)

~8$M_\odot$: White dwarf

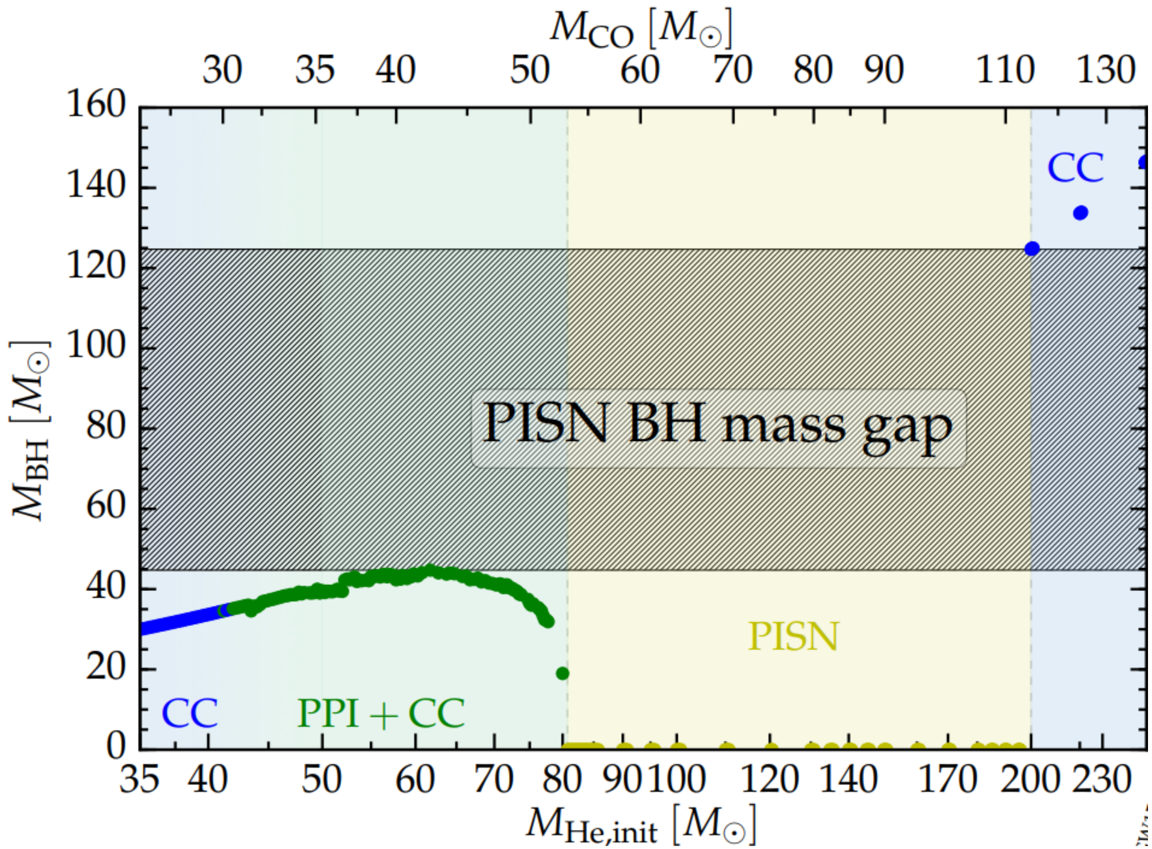
~30(?)$M_\odot$: Core-Collapse supernova (Neutron star, Black hole)

~140$M_\odot$: Black hole (Direct collapse/ Falied supernova)

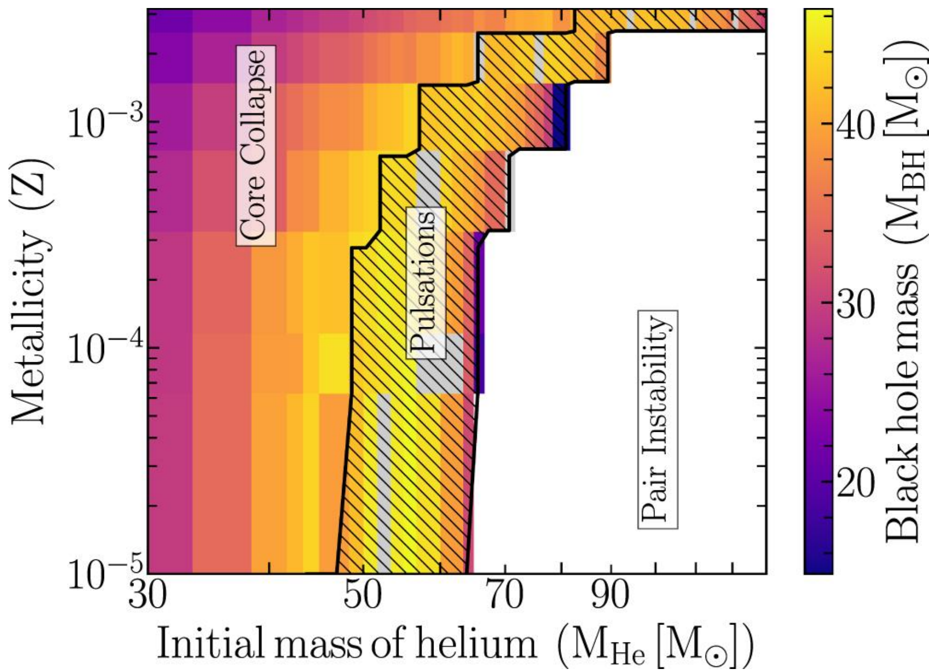
~260$M_\odot$: Pair-instability supernova

260$M_\odot$~ : Black hole (Direct collapse?)

Introduction
Final fates of stars



M. Renzo *et al.* A&A **640**, A56 (2020)



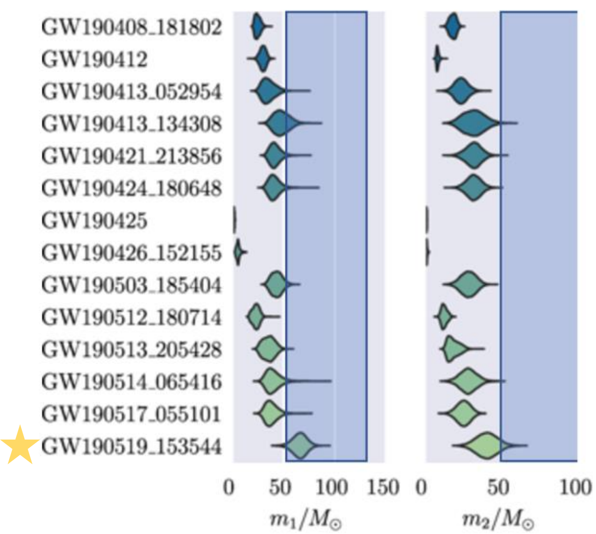
R. Farmer *et al.* ApJ. **887**, 53 (2019)

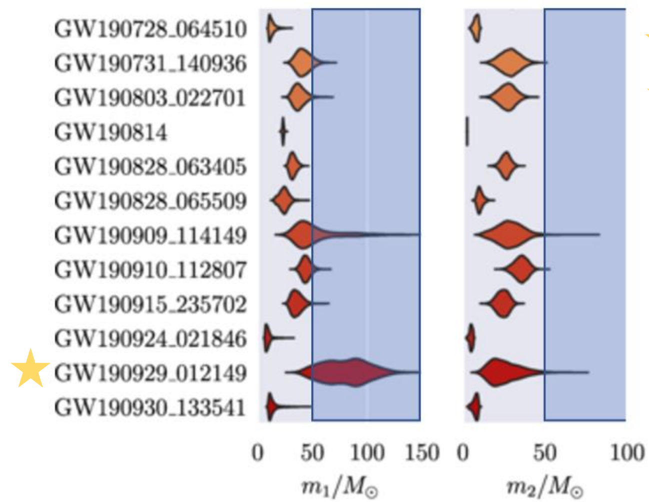
Final fate of ZAMS 140-260$M_\odot$ low metal very massive star

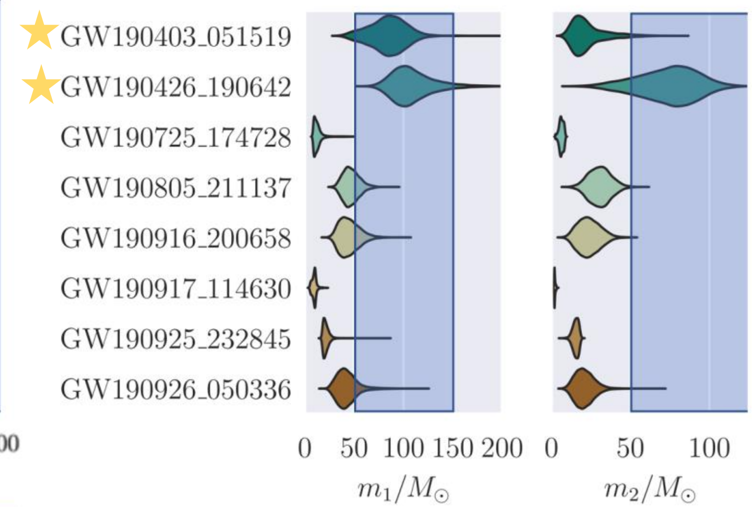
→Pair-instability supernova

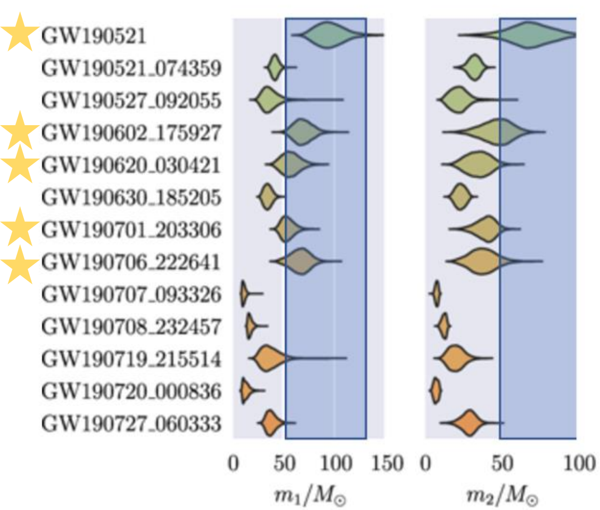
Complete destruction →No compact object (remnant)

Introduction
GW events in PI mass gap





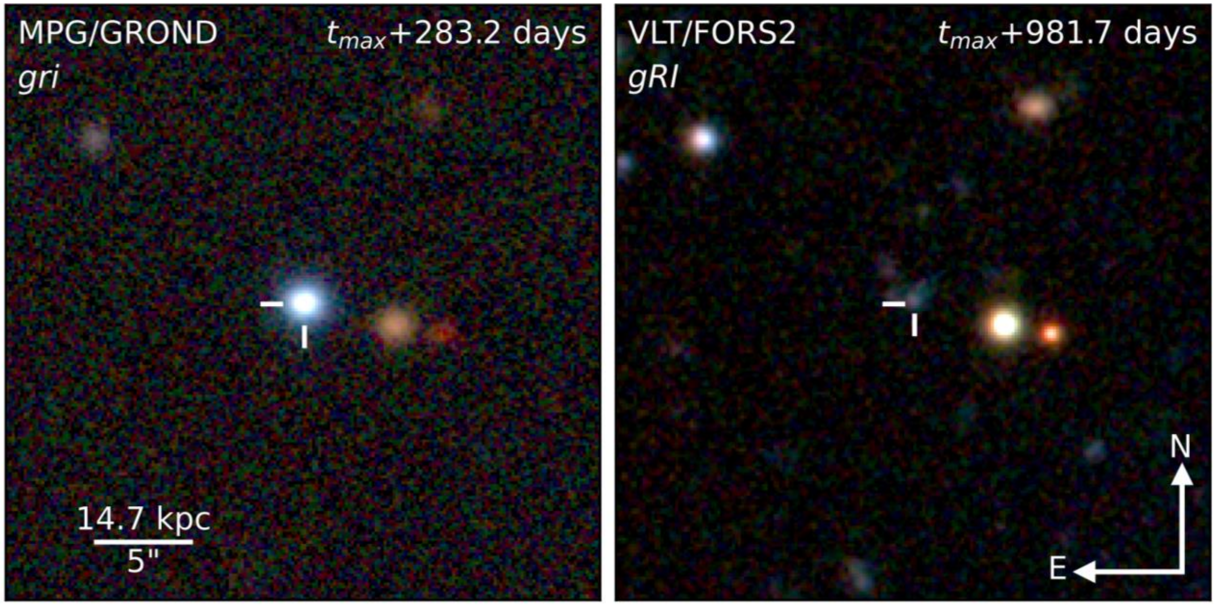


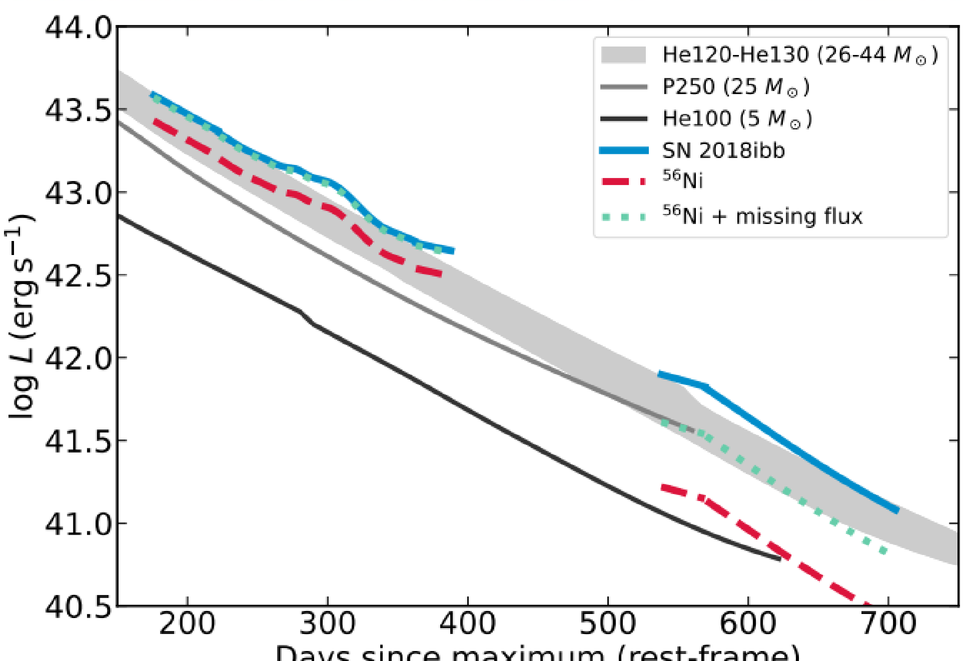


GW event	M_{rem} [$M_\odot$]	$M_{BH,1}$ [$M_\odot$]	$M_{BH,2}$ [$M_\odot$]
GW190403_051519	$105.2^{+29.1}_{-24.1}$	$88.0^{+28.2}_{-32.9}$	$22.1^{+23.8}_{-9.0}$
GW190426_190642	$175.0^{+39.4}_{-34.3}$	$106.9^{+41.6}_{-25.2}$	$76.6^{+26.2}_{-33.6}$
GW190519_153544	$101.0^{+12.4}_{-13.8}$	$66.0^{+10.7}_{-12.0}$	$40.5^{+11.0}_{-11.1}$
GW190521	$156.3^{+36.8}_{-22.4}$	$95.3^{+28.7}_{-18.9}$	$69.0^{+22.7}_{-23.1}$
GW190602_175927	$110.9^{+17.7}_{-14.9}$	$69.1^{+15.7}_{-13.0}$	$47.8^{+14.3}_{-17.4}$
GW190620_030421	$87.2^{+16.8}_{-12.1}$	$57.1^{+16.0}_{-12.7}$	$35.5^{+12.2}_{-12.3}$
GW190701_203306	$90.2^{+11.3}_{-8.9}$	$53.9^{+11.8}_{-8.0}$	$40.8^{+8.7}_{-12.0}$
GW190706_222641	$99.0^{+18.3}_{-13.5}$	$67.0^{+14.7}_{-16.2}$	$38.2^{+14.6}_{-13.3}$
GW190929_012149	$101.5^{+33.6}_{-25.3}$	$80.8^{+33.0}_{-33.2}$	$24.1^{+19.3}_{-10.6}$
GW191109 010717	107^{+18}_{-15}	65^{+11}_{-11}	47^{+15}_{-13}
GW191127_050227	76^{+39}_{-21}	53^{+47}_{-20}	24^{+17}_{-14}
GW200220_061928	141^{+51}_{-31}	87^{+40}_{-23}	61^{+26}_{-25}

R. Abbott *et al.* Phys. Rev. X **11**, 021053 (2021).
R. Abbott *et al.* arXiv:2108.01045 (2021)
E. Moreno-Méndez *et al.* MNRAS **522**, 1686 (2023).

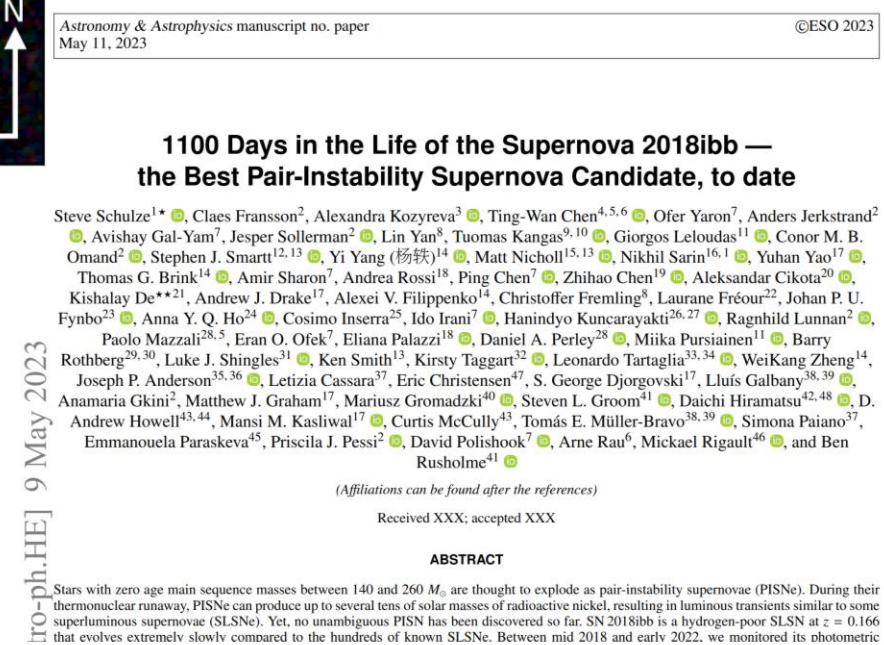
Introduction
PISN best candidate





SN 2018ibb

S. Schulze *et al.* A&A **683**, A223 (2024)



Astronomy & Astrophysics manuscript no. paper
May 11, 2023

1100 Days in the Life of the Supernova 2018ibb — the Best Pair-Instability Supernova Candidate, to date

Steve Schulze[1★], Claes Fransson[2], Alexandra Kozyreva[3], Ting-Wan Chen[4,5,6], Ofer Yaron[7], Anders Jerkstrand[2], Avishay Gal-Yam[7], Jesper Sollerman[2], Lin Yan[8], Tuomas Kangas[9,10], Giorgos Leloudas[11], Conor M. B. Omand[2], Stephen J. Smartt[12,13], Yi Yang (杨轶)[14], Matt Nicholl[15,13], Nikhil Sarin[16,1], Yuhan Yao[17], Thomas G. Brink[14], Amir Sharon[7], Andrea Rossi[18], Ping Chen[7], Zhihao Chen[19], Aleksandar Cikota[20], Kishalay De[★★21], Andrew J. Drake[17], Alexei V. Filippenko[14], Christoffer Fremling[8], Laurane Fréour[22], Johan P. U. Fynbo[23], Anna Y. Q. Ho[24], Cosimo Inserra[25], Ido Irani[7], Hanindyo Kuncarayakti[26,27], Ragnhild Lunnan[2], Paolo Mazzali[28,5], Eran O. Ofek[7], Eliana Palazzi[18], Daniel A. Perley[28], Miika Pursiainen[11], Barry Rothberg[29,30], Luke J. Shingles[31], Ken Smith[13], Kirsty Taggart[32], Leonardo Tartaglia[33,34], WeiKang Zheng[14], Joseph P. Anderson[35,36], Letizia Cassara[37], Eric Christensen[47], S. George Djorgovski[17], Lluís Galbany[38,39], Anamaria Gkini[2], Matthew J. Graham[17], Mariusz Gromadzki[40], Steven L. Groom[41], Daichi Hiramatsu[42,48], D. Andrew Howell[43,44], Mansi M. Kasliwal[17], Curtis McCully[43], Tomás E. Müller-Bravo[38,39], Simona Paiano[37], Emmanouela Paraskeva[45], Priscila J. Pessi[2], David Polishook[7], Arne Rau[6], Mickael Rigault[46], and Ben Rusholme[41]

(Affiliations can be found after the references)

Received XXX; accepted XXX

ABSTRACT

Stars with zero age main sequence masses between 140 and 260 $M_\odot$ are thought to explode as pair-instability supernovae (PISNe). During their thermonuclear runaway, PISNe can produce up to several tens of solar masses of radioactive nickel, resulting in luminous transients similar to some superluminous supernovae (SLSNe). Yet, no unambiguous PISN has been discovered so far. SN 2018ibb is a hydrogen-poor SLSN at z = 0.166 that evolves extremely slowly compared to the hundreds of known SLSNe. Between mid 2018 and early 2022, we monitored its photometric

Introduction
$^{12}C(\alpha,\gamma)^{16}O$ reaction rate uncertainty

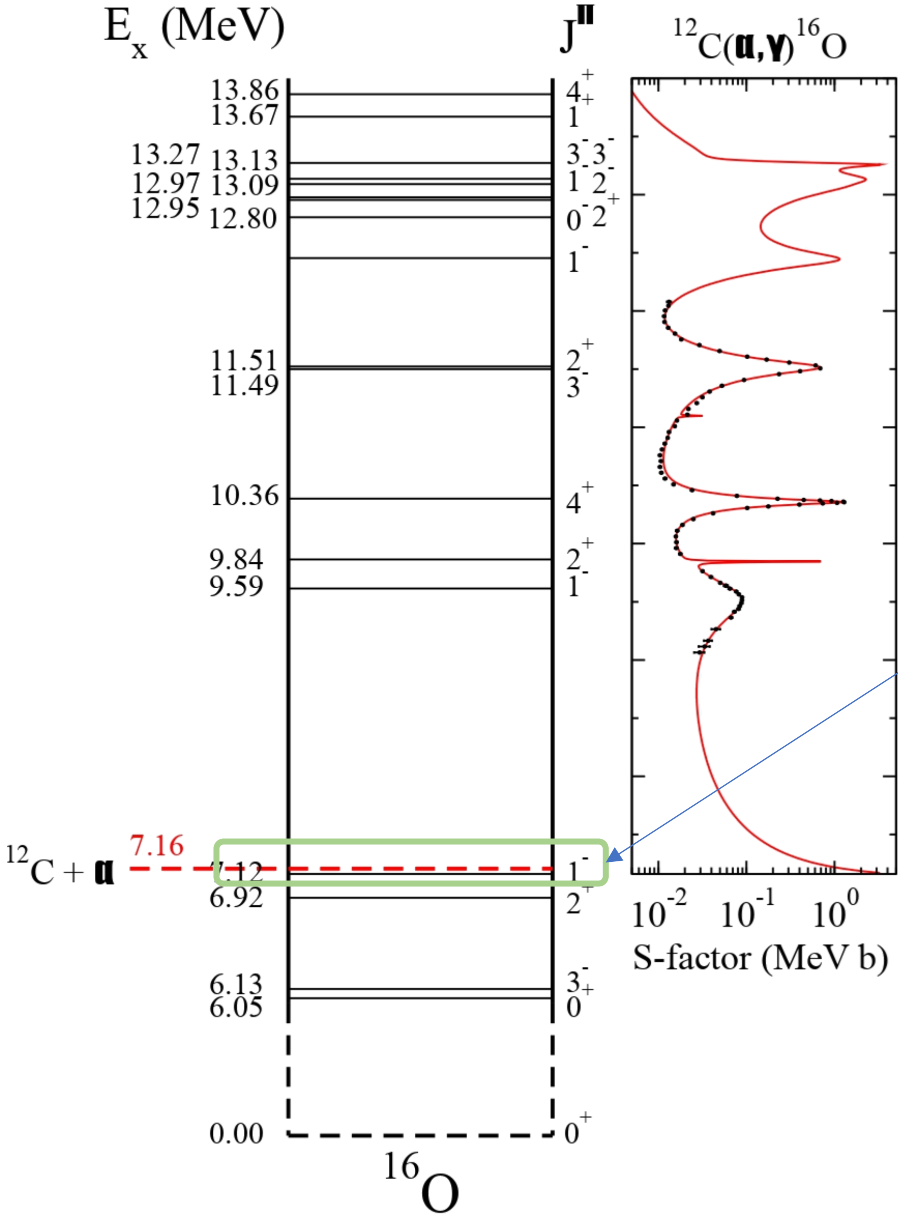
Fuel	Main Product	Secondary Product	T (10^9 K)	Time (yr)	Main Reaction
H	He	^{14}N	0.02	10^7	$4\,H \xrightarrow{CNO} {}^{4}He$
He	O, C	^{18}O, ^{22}Ne s-process	0.2	10^6	$3\,{}^{4}He \rightarrow {}^{12}C$ $^{12}C(\alpha,\gamma)^{16}O$
C	Ne, Mg	Na	0.8	10^3	$^{12}C + {}^{12}C$
Ne	O, Mg	Al, P	1.5	3	$^{20}Ne(\gamma,\alpha)^{16}O$ $^{20}Ne(\alpha,\gamma)^{24}Mg$
O	Si, S	Cl, Ar, K, Ca	2.0	0.8	$^{16}O + {}^{16}O$
Si,S	Fe	Ti, V, Cr, Mn, Co, Ni	3.5	0.02	$^{28}Si(\gamma,\alpha)$...

$^{12}C(\alpha,\gamma)^{16}O$ reaction
(this work's target)

$^{16}O+{}^{16}O$ reaction
(PISN main energy)

https://www2.yukawa.kyoto-u.ac.jp/~nuc2021/slides/heger_a.pdf

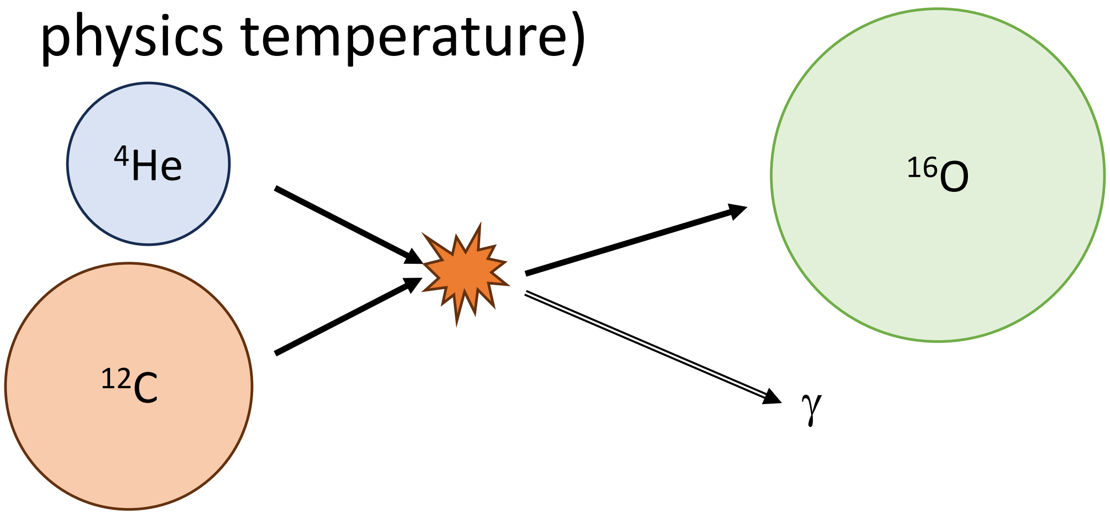
Introduction
$^{12}C(\alpha,\gamma)^{16}O$ reaction rate uncertainty



deBoer *et al.* Rev. Mod. Phys. **89**, 035007 (2017).

$$S(E) = \sigma(E)E\left(\exp\frac{2\pi Z_1 Z_2 e}{\hbar v}\right)$$

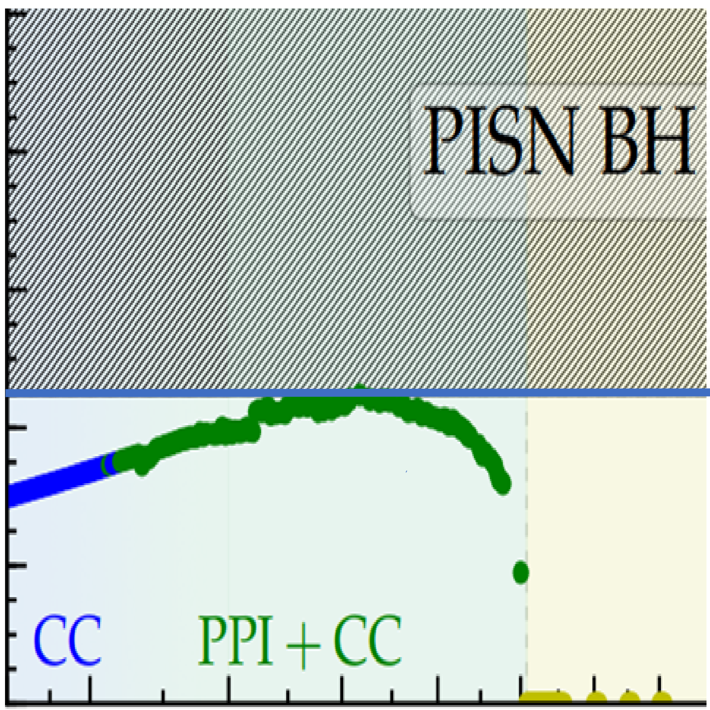
Too difficult to id. Astronomical S-factor (convert: 0.1MeV ~ 10^9 K: typical stellar physics temperature)



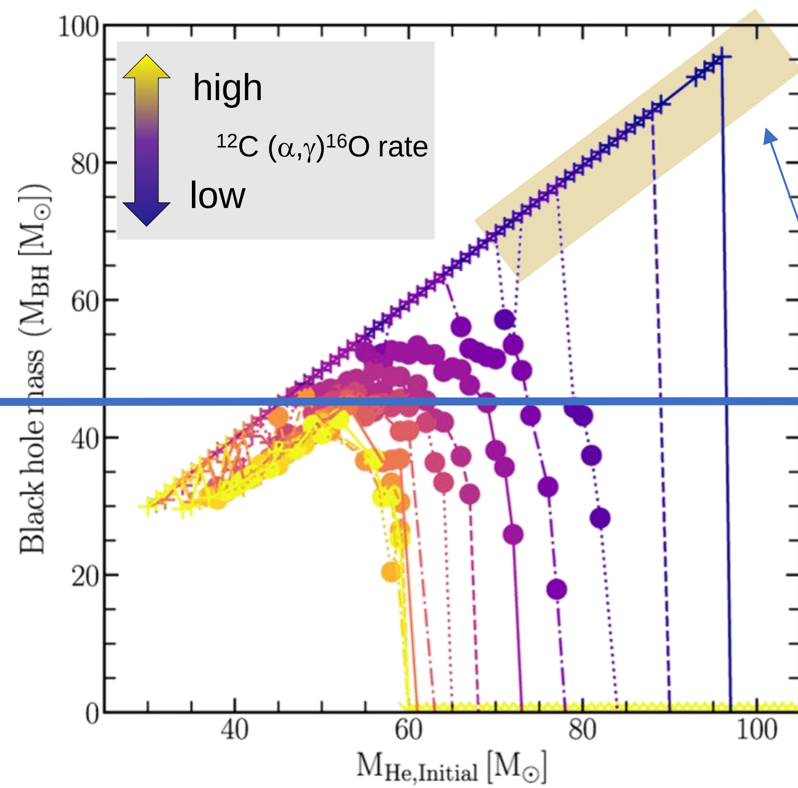
Introduction

PI mass gap and $^{12}C\ (\alpha,\gamma)^{16}O$ rate

M. Renzo *et al.* A&A **640**, A56 (2020)



R. Farmer *et al.* ApJL. **902**, L36 (2020).

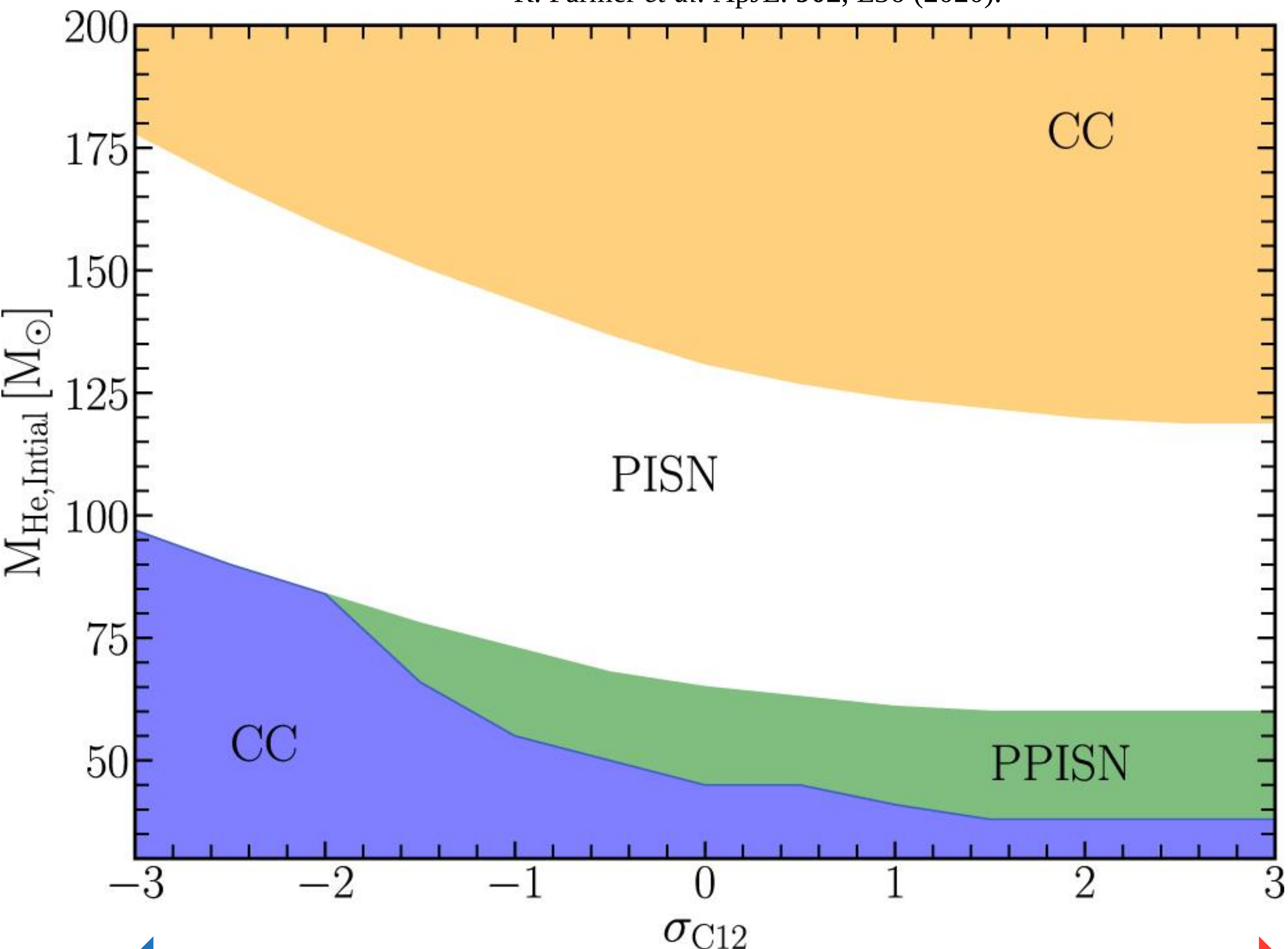


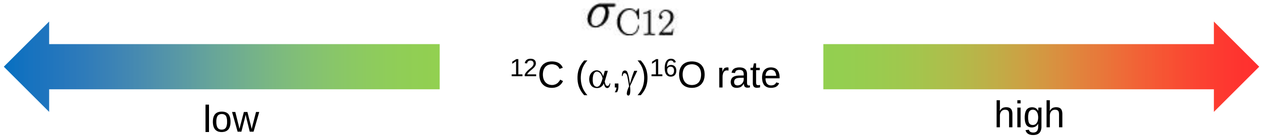
Lower limit of PI mass gap is affected by Nuclear reaction（especially $^{12}C(\alpha,\gamma)^{16}O$）

（GW190521 like）
Massive BH formation

Introduction
PISNe details (final fate) with rate

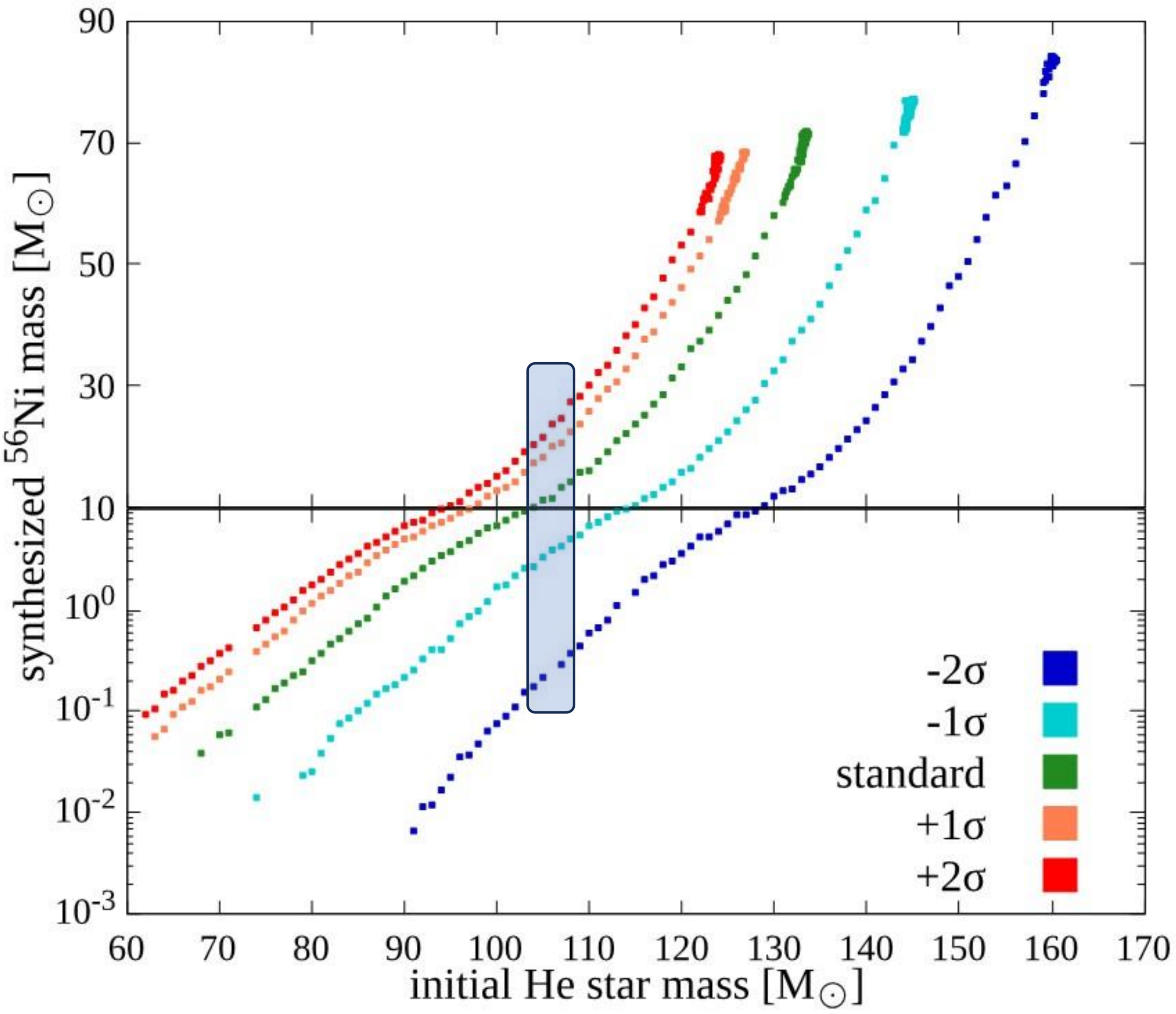
R. Farmer *et al.* ApJL. **902**, L36 (2020).





PISN final fate → strongly effected from $^{12}C(\alpha,\gamma)^{16}O$ reaction rate

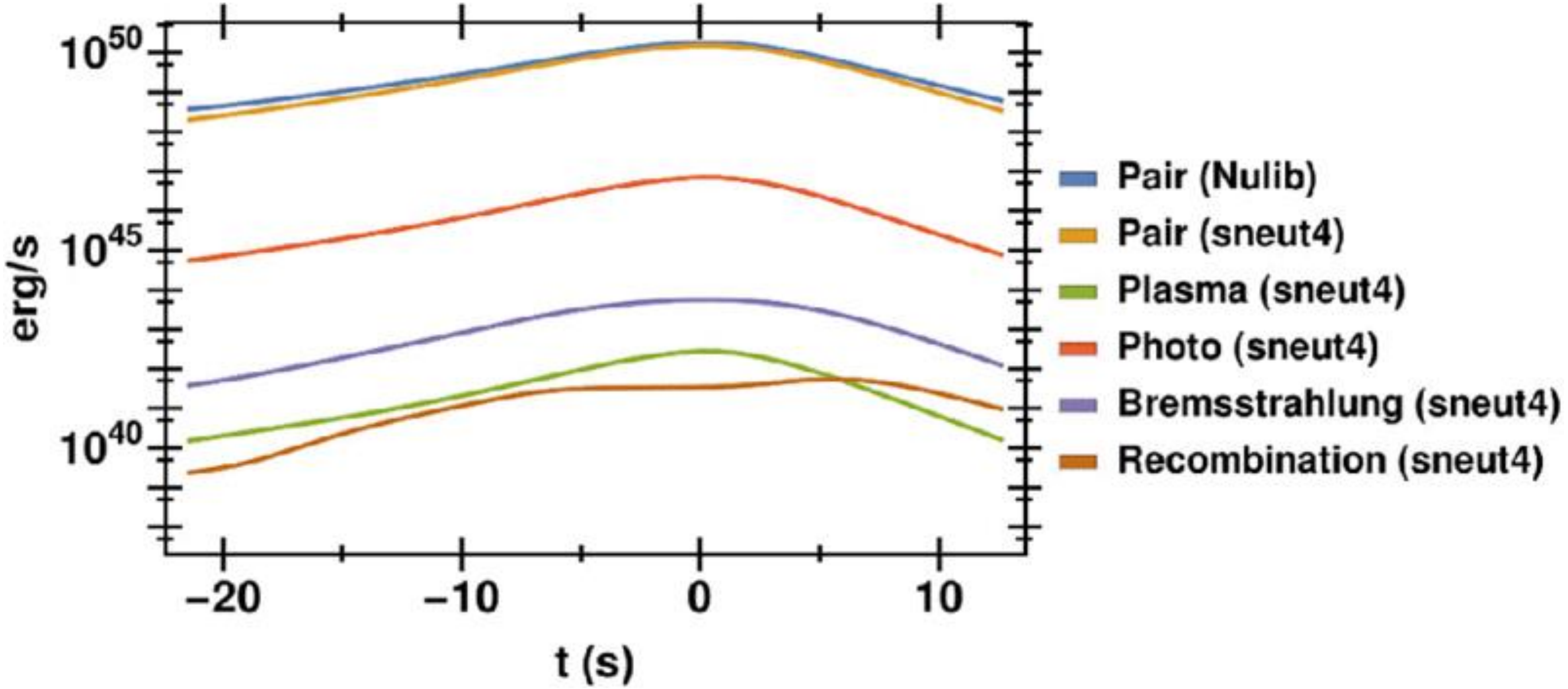
Introduction
^{56}Ni synthesis



H. Kawashimo *et al.* MNRAS **531**, 2786 (2024)

Focusing on the same initial mass,
high $^{12}C(\alpha,\gamma)^{16}O$ reaction rate series makes more ^{56}Ni

Motivation
Previous work



W. P. Wright *et al*. Phys. Rev. D **96**, 103008 (2017)

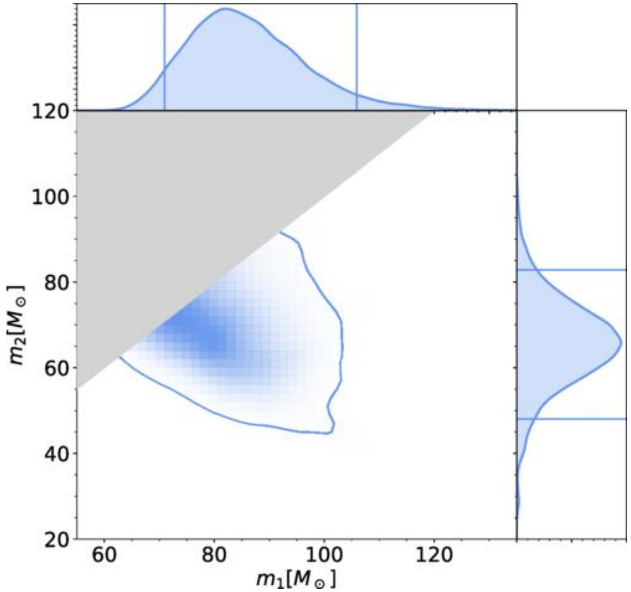
$M_{\mathrm{ZAMS}} = 250\ M_{\odot}$
$(M_{\mathrm{final}} = 126.7\ M_{\odot})$
$Z = 0.001$

Neutrino emission from PISN:
Pair process, ~ 10^{49} erg/s

In this work…

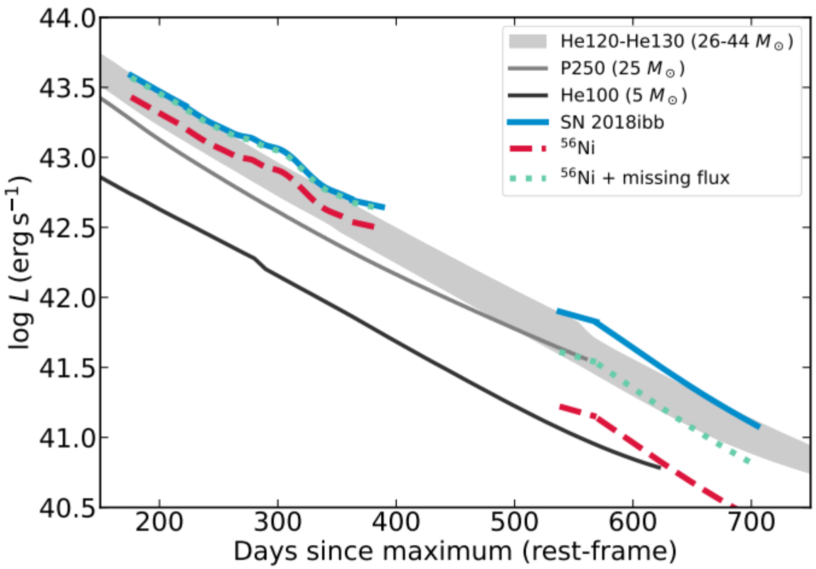
PISN emission =>

GW (mass gap BBH)



A. Abbott *et al.* PRL. **125**, 101102 (2020)

optical (e.g. 2018ibb)



H. Kawashimo *et al.* MNRAS **531**, 2786 (2024)

We investigate VMSs stellar evolution focusing on neutrino luminosity with changed $^{12}C(\alpha,\gamma)^{16}O$ reaction.

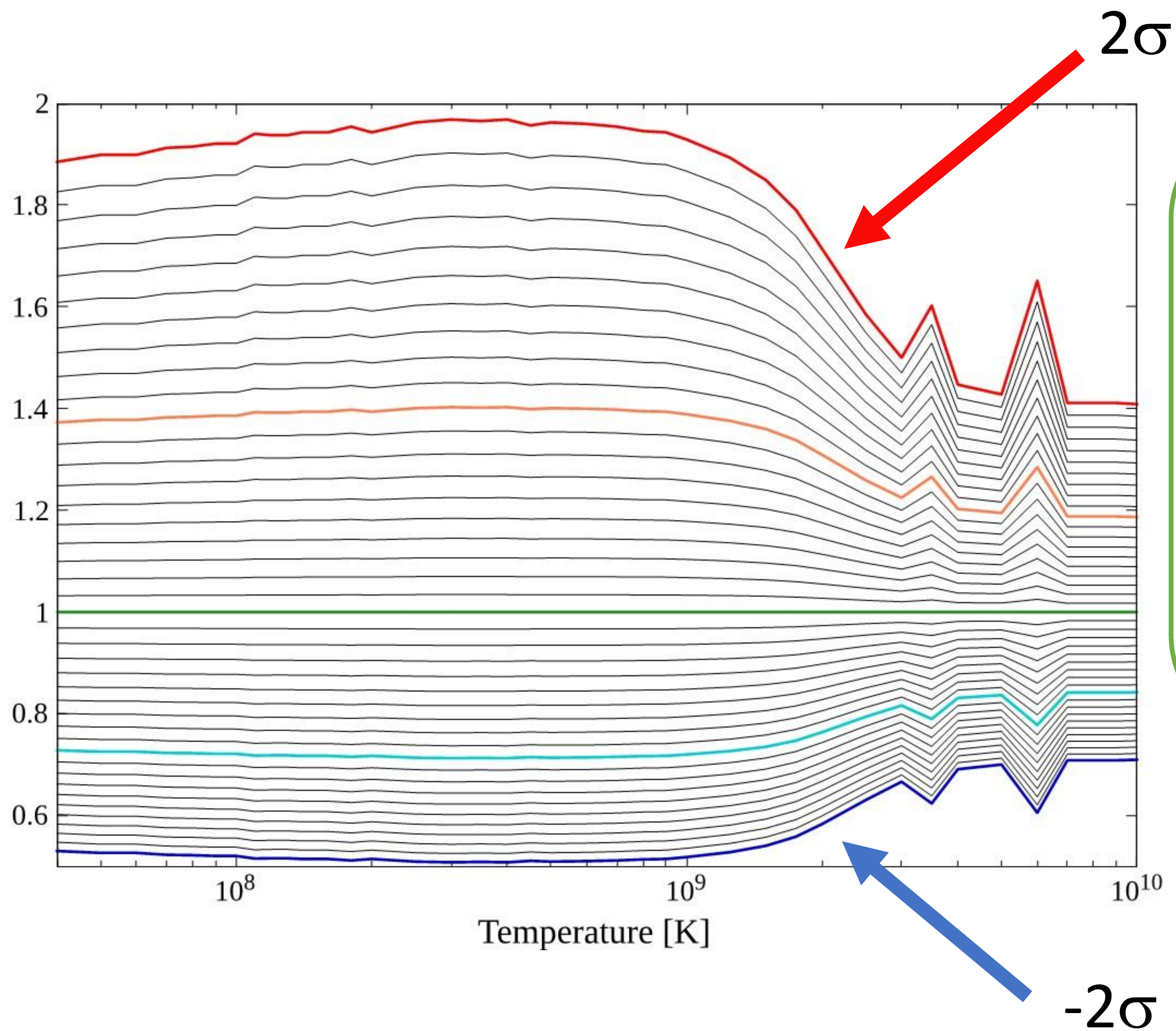
Method
Stellar evolution

MESA r24.08.1 (Paxton+ 2011 etc.)

Initial conditions and setups: Marchant+ 2019

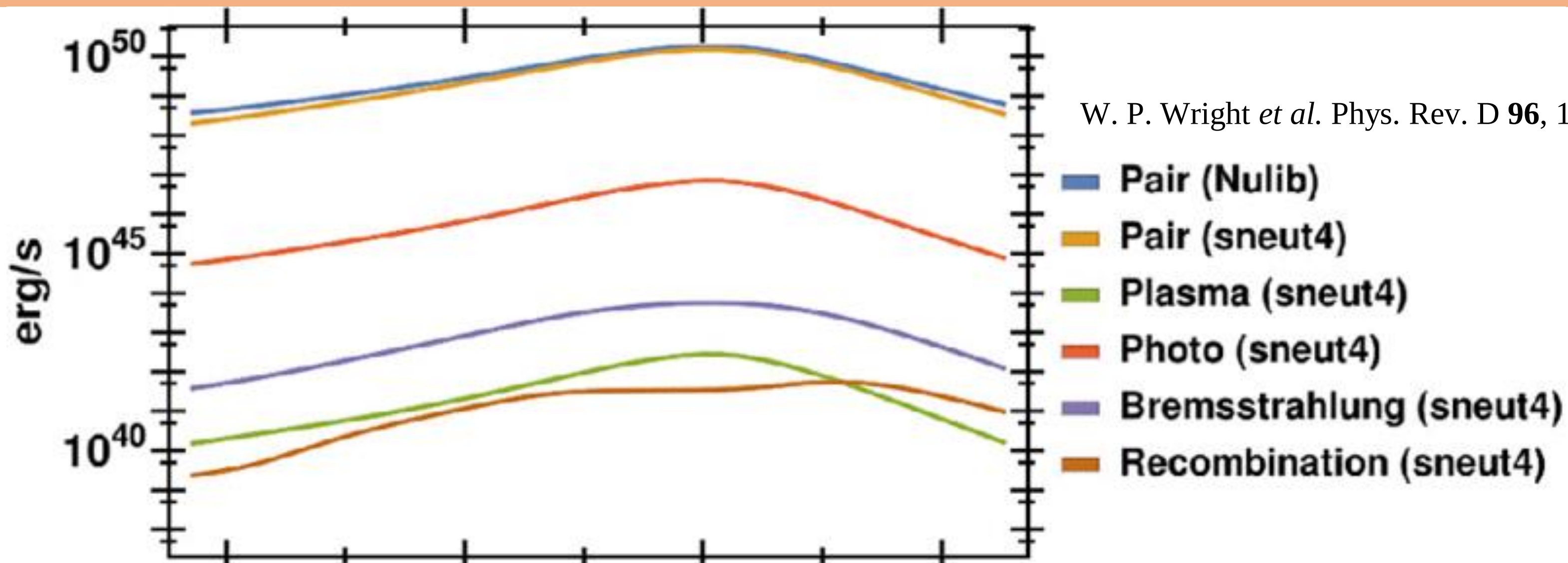
- He star (Main sequence terminated + H envelope removed)
- Metallicity $Z = 10^{-3}$
- Initial mass M_{He} => $60\ M_{\odot}$ to $160\ M_{\odot}$ (step $5\ M_{\odot}$)

Method
Reaction rate

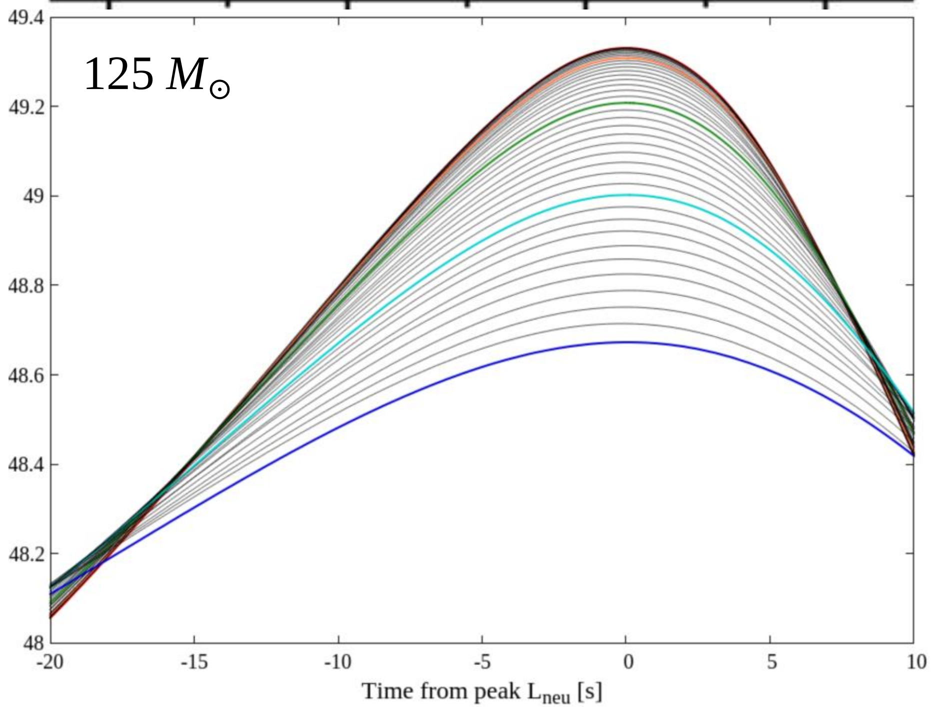


$^{12}C(\alpha,\gamma)^{16}O$ reaction:
Kunz+ 02 and
STARLIB (Sallska+ 14)
-2σ to 2σ (0.1σ step)

Consistency with previous work



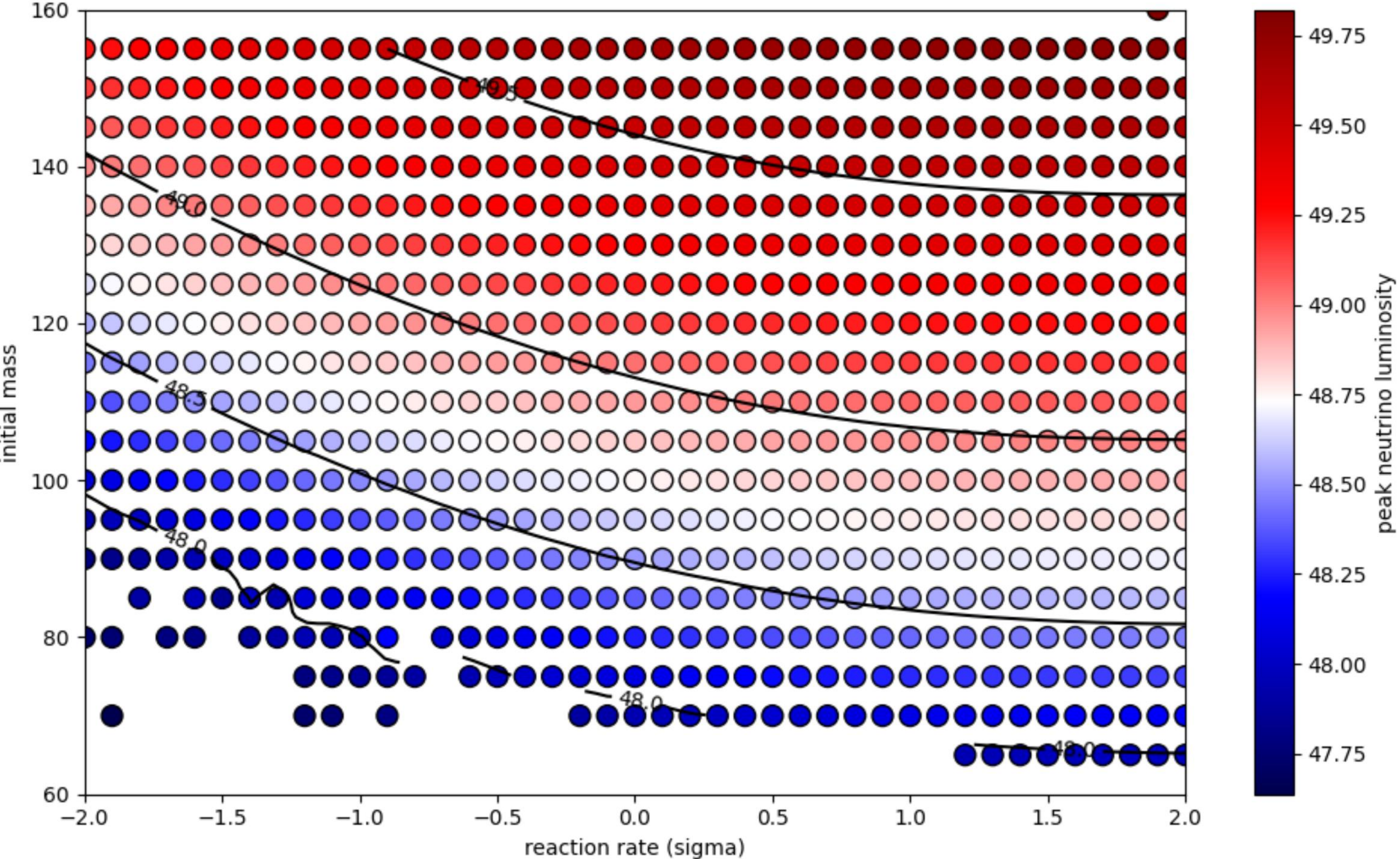
W. P. Wright *et al.* Phys. Rev. D **96**, 103008 (2017)



Our result provided more emission?
(see -20s & +10s)

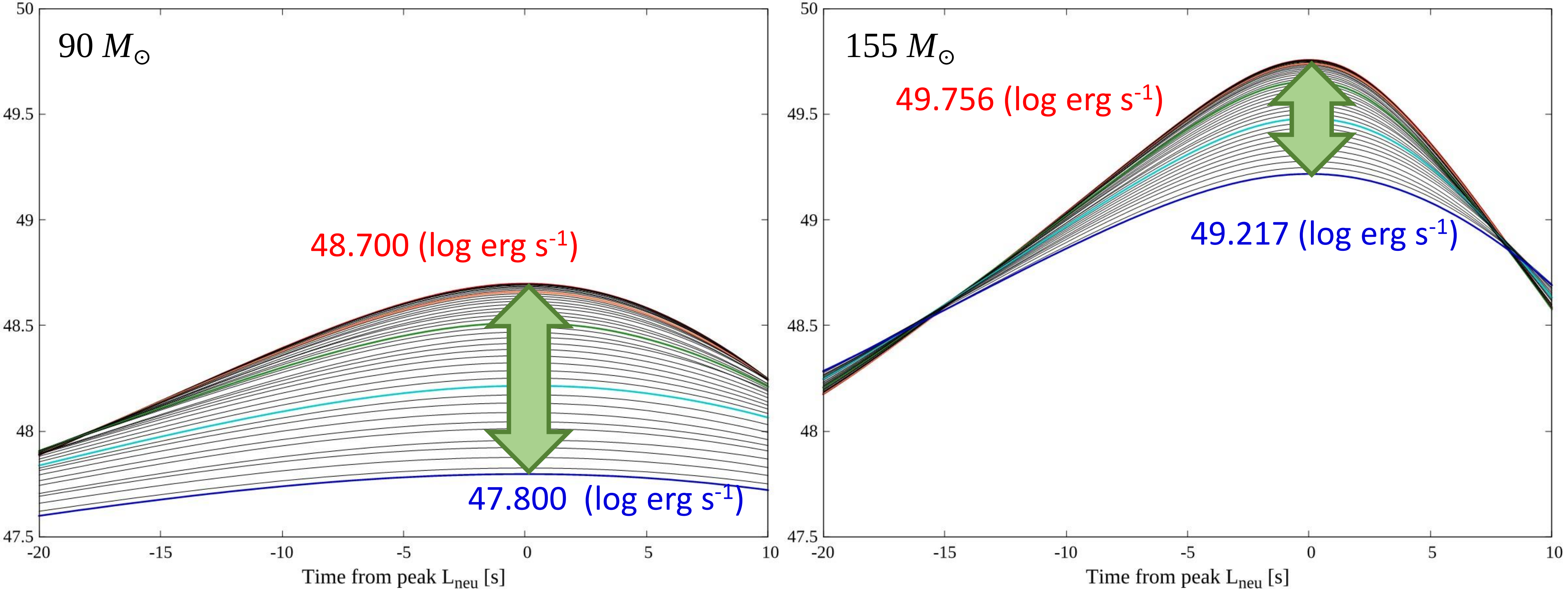
Results

Peak neutrino luminosity map



Discussion

Error range shifting



Massive case
=> Reaction rate induced error
will be smaller

Future work

Observation estimation

TABLE II. Numbers of interactions per detector for each mass ordering and a PISN at 10 kpc. These event counts are for the whole neutrino burst. The last two columns represent the number of interactions observed when neutrino oscillations are not taken into account.

		NMO		IMO		Unoscillated	
Mass	Detector	Helm	SFHo	Helm	SFHo	Helm	SFHo
P150	Hyper-Kamiokande	1.77	1.78	1.74	1.75	3.02	3.05
	Super-Kamiokande	0.24	0.24	0.23	0.23	0.40	0.41
	DUNE	0.14	0.14	0.15	0.15	0.25	0.25
	JUNO	0.10	0.10	0.10	0.10	0.17	0.17
P250	Hyper-Kamiokande	52.23	50.08	43.32	41.98	85.70	84.19
	Super-Kamiokande	6.98	6.69	5.79	5.61	11.46	11.26
	DUNE	2.95	2.78	3.17	3.06	5.30	5.20
	JUNO	3.13	3.00	2.48	2.40	5.06	4.97

W. P. Wright *et al.* Phys. Rev. D **96**, 103008 (2017)

How will be changed by reaction rate uncertainty?
(for future work)

Summary

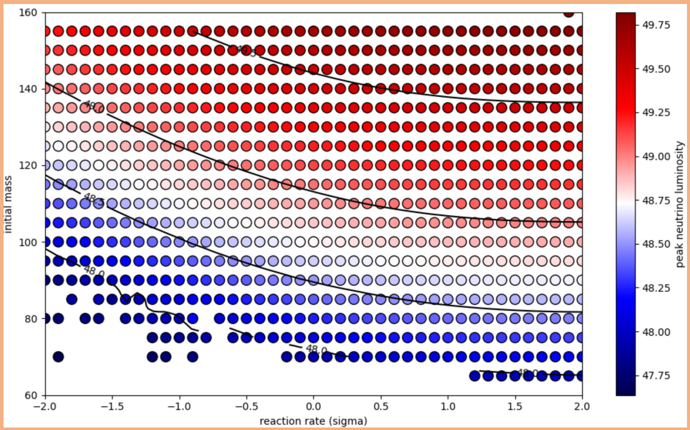
Introduction

- PISN is interested in the context of GW obs. (e.g. GW190521) and optical obs. (SN 2018ibb)
- $^{12}C(\alpha,\gamma)^{16}O$ plays an important role for PISN explosion

In our work…

- He star evolution with $^{12}C(\alpha,\gamma)^{16}O$ reaction (x0.5 ~ x2)
- Neutrino emission time evolution

Result



Discussion

- Error range will be smaller in high mass region