SN1987A の親星モデル

"Progenitor Model of SN 1987A Based on the Slow Merger Scenario"

主に Urushibata, Takahashi, Umeda, T. Yoshida (2018),

MNRAS, 473, L101 (2018), arXiv: 170504084

SN1987 in LMC

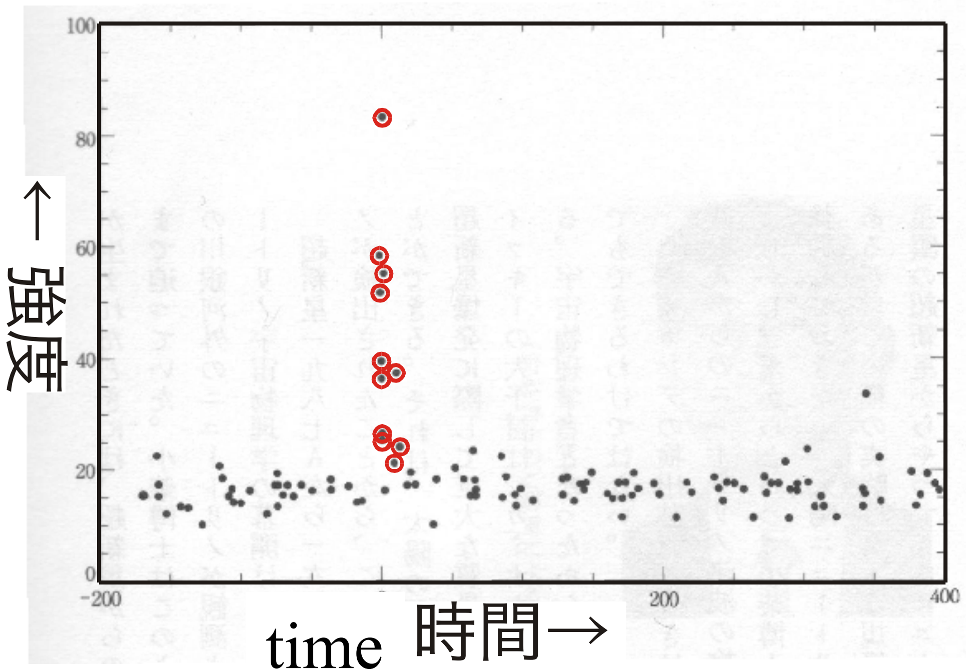
爆発前 (before)
1984年2月5日

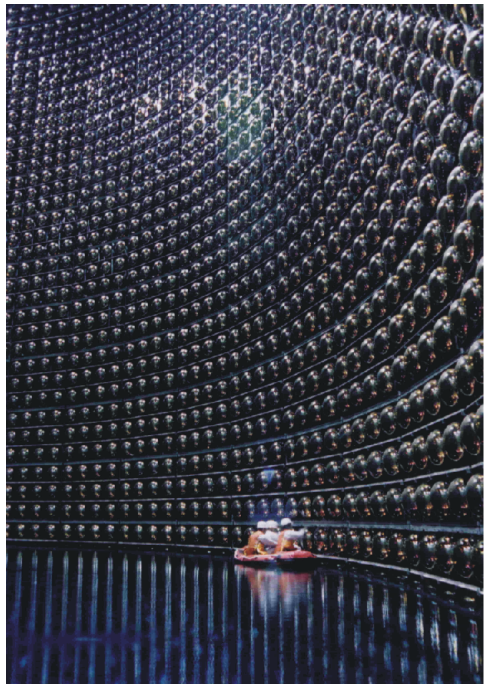
爆発後 (after)
1987年3月8日

Neutrinos from SN1987A

- Kamiokande detected
- 11 in 13 seconds
  10 billion neutrinos per 1cm^2 on the earth
- Supernova explosion theory was roughly confirmed !

Kamiokande





SN 1987A Observations

- The progenitor before the explosion was discovered
  - $\log T_{eff} = 4.12 \sim 4.26$, $\log L/L_{\odot} = 4.89 \sim 5.28$

    → Blue super giant
- Ring like nebula
  - He, N, s-process elements are enriched
  - Velocity structure of the nubula

    → the star used to be a RED super giant

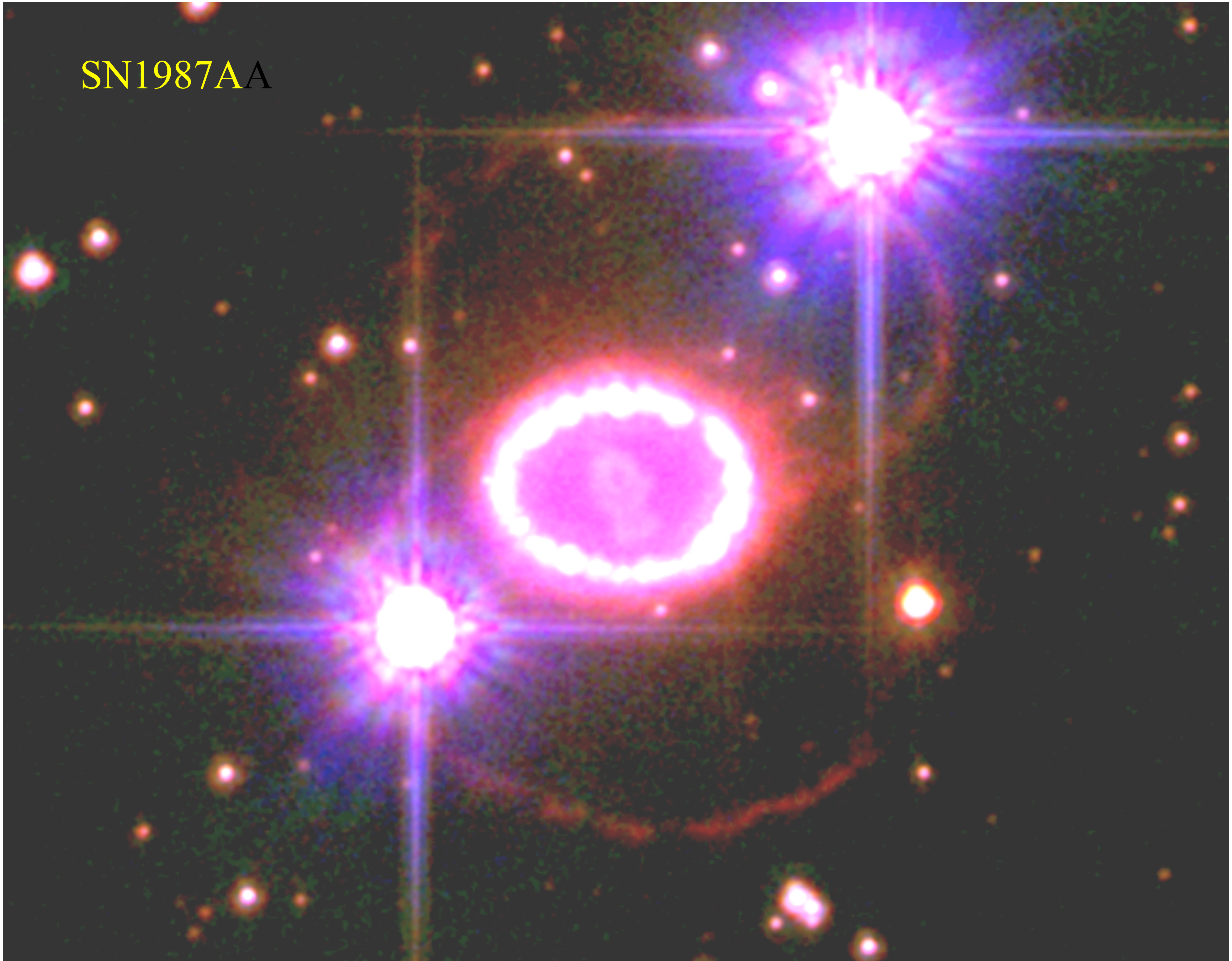
    → time after RED became BLUE

    $\tau_{BSG} < \sim 2 \times 10^4$ yr

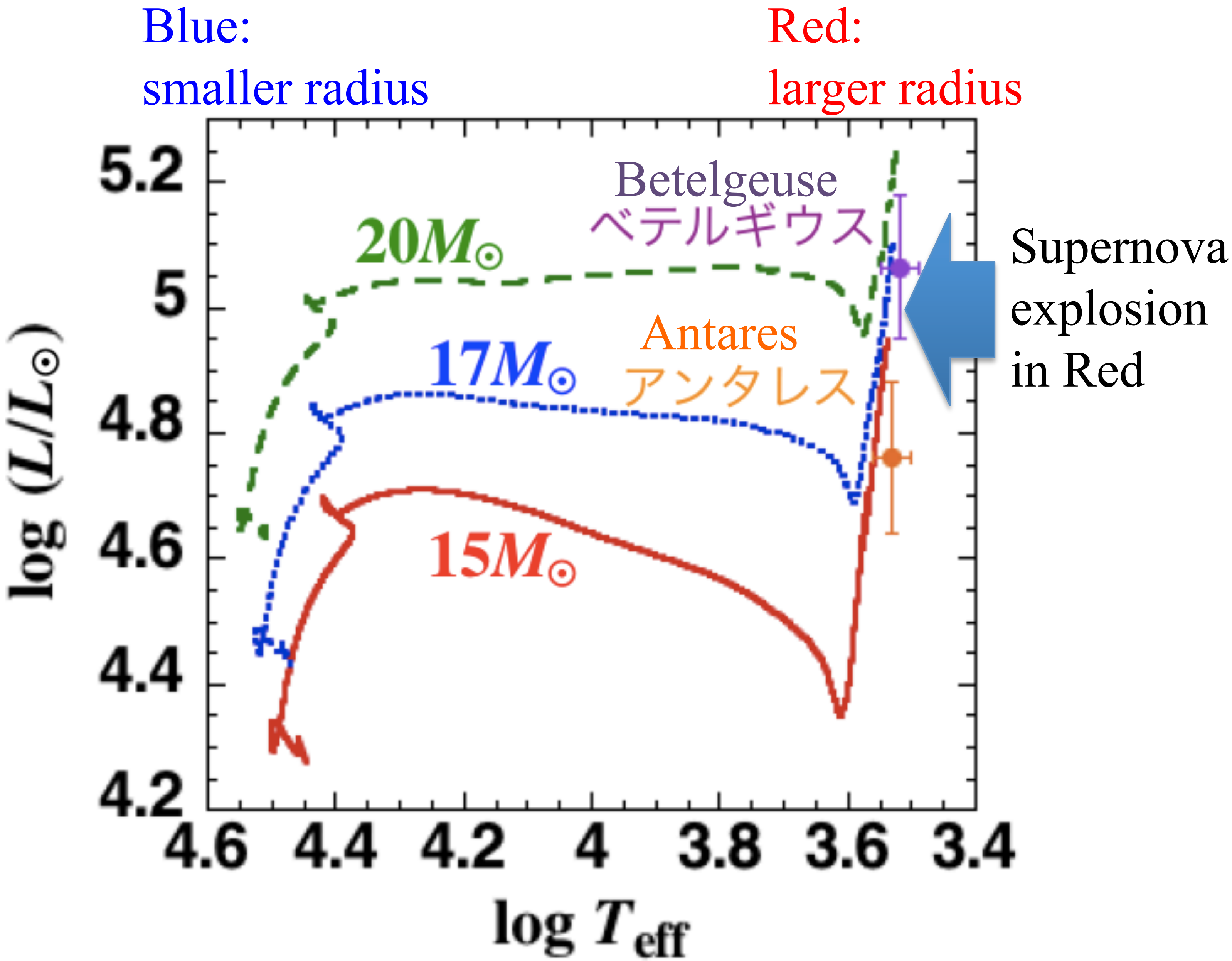
Mysteries about SN1987A progenitor

- It was blue before explosion.
- 3 rings (considered an evidence that the progenitor was once red and turned into blue)
- Ejecta seems to be asymmetric
- Abundance anomary（He-rich

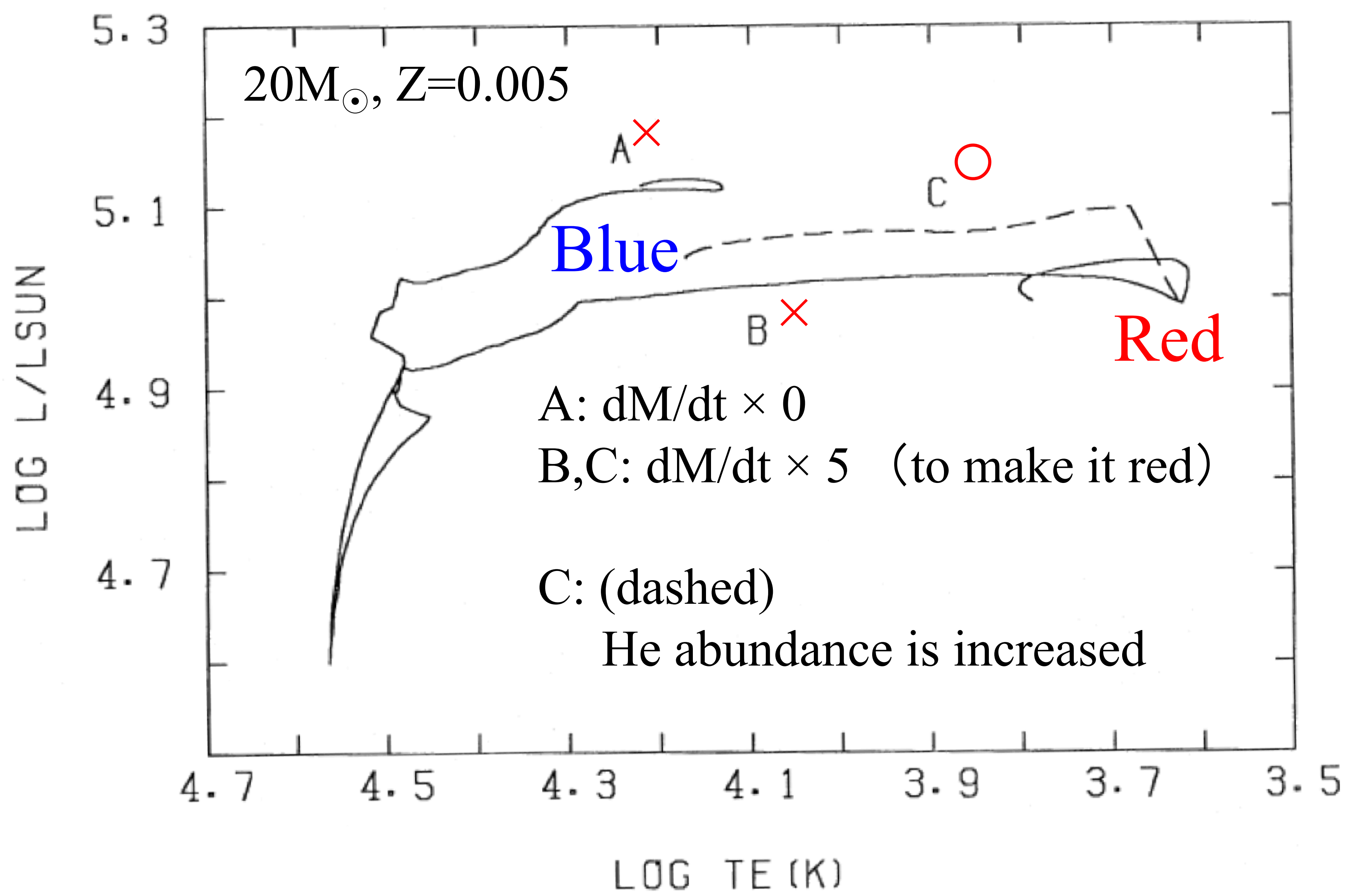
- These peculiarities haven't been fully understood


SN1987AA

HR-diagram: Normal stellar evolution



A single star model (Saio, Nomoto, Kato 1988)



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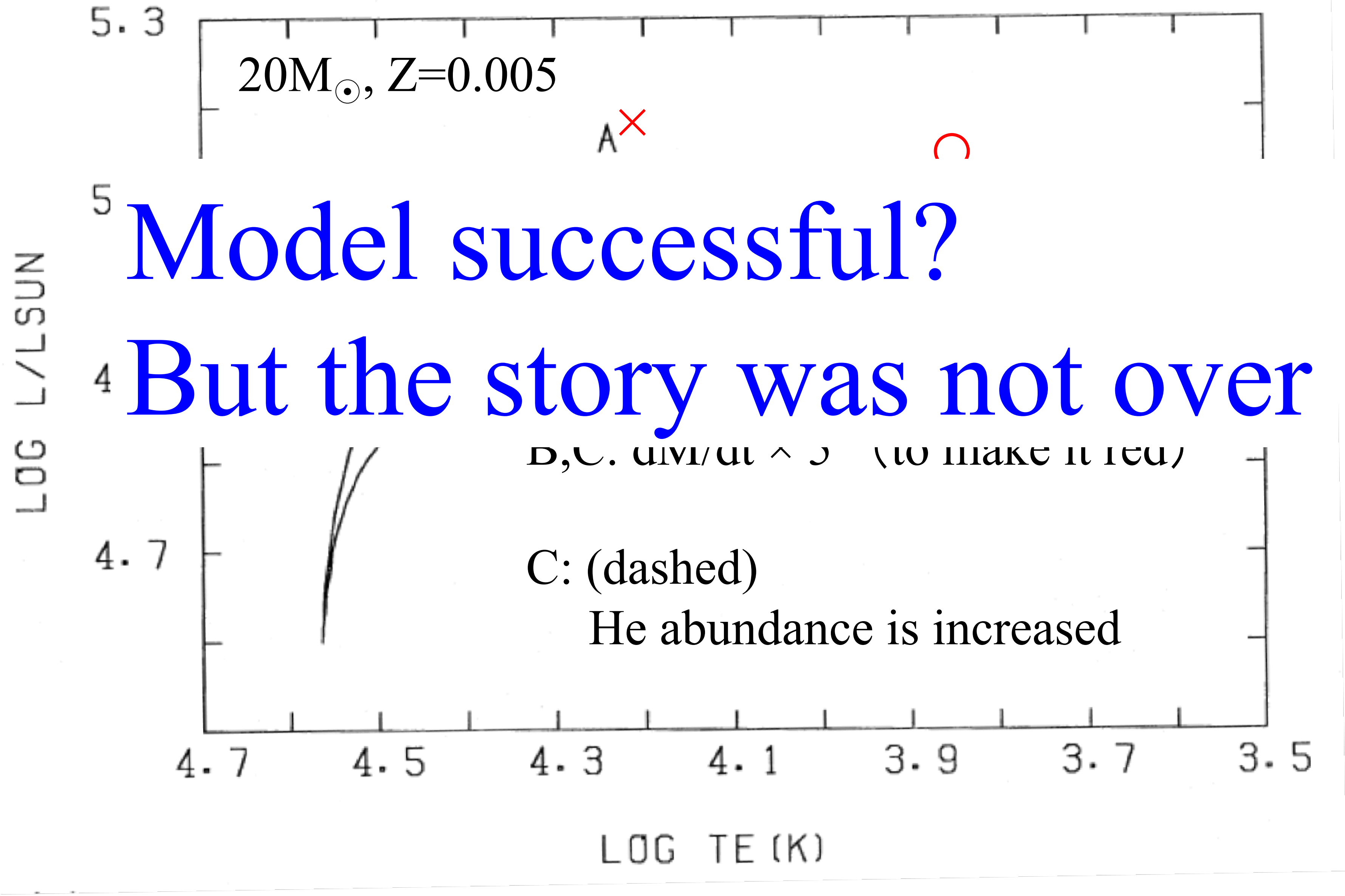


Model successful?

But the story was not over

SN1987A : single or binary?

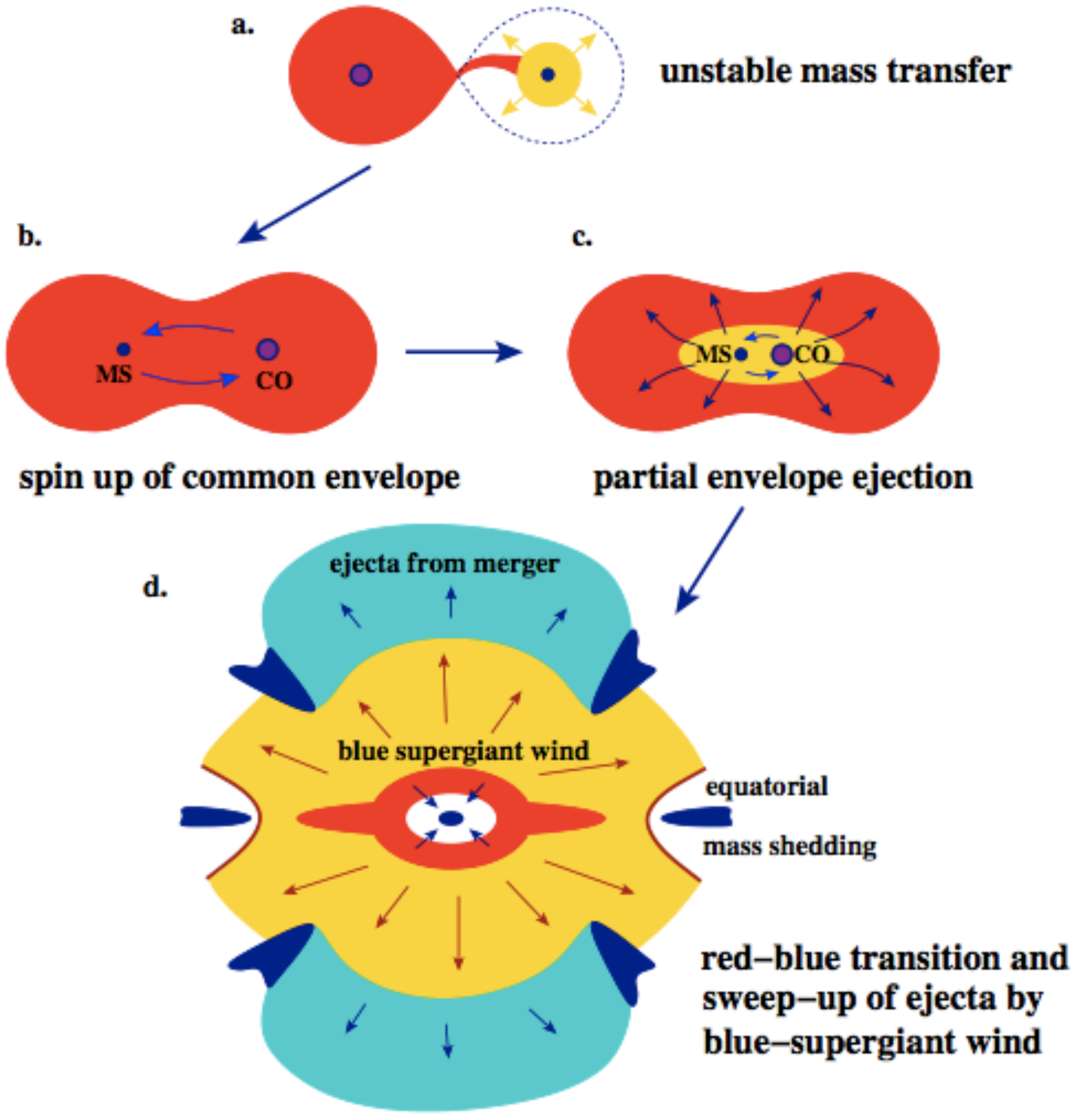
- Saio+1988 result suggested that He-rich may be realized by rotational mixing
  - But no fast-rotating model has been successful
    - Woosley group – conference proceedings
    - Langer group –

      (Most recent one, Petermann et al. 2015

    R to B transition before 2 x 10^4 yr is difficult to explain
- Alternative model : binary merger model
  - Podsiadlowski and collaborators

A merger (spiral-in) model for formation of three rings

(Morris and Podsiadlowski 2007)



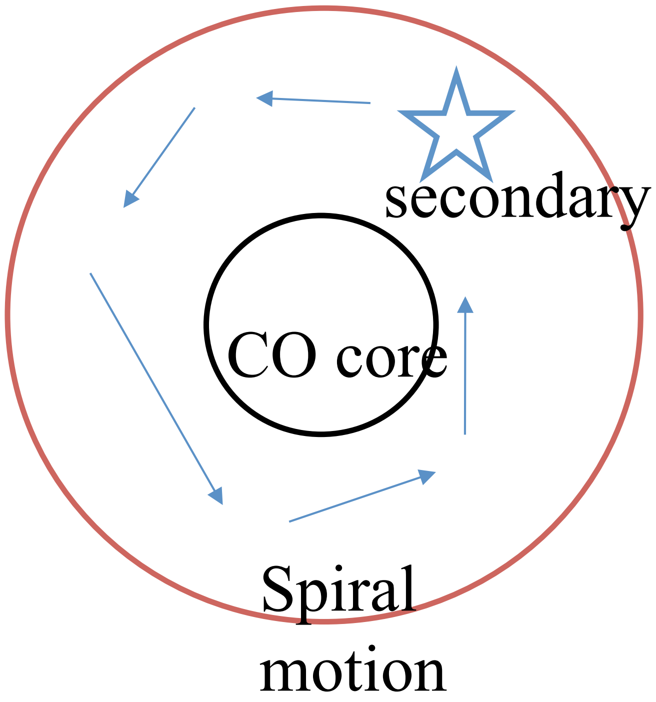
It simultaneously makes the primary turns from Red to Blue
by giving mass, energy and angular momentum.
(Podsiadlowski 1992)

But his stellar evolution code does not include rotation. (also opacity is old)

A Spiral-in Scenario
(Podsiadlowski+92, Ivanova+02, and Morris+07)

// during a common envelope phase.

// The secondary spirals in toward the center due to friction, causing ejection of material due to a transfer of orbital angular momentum.



// a stream flooded from its Roche-lobe flows to the core.

→ the secondary melts in the envelope

⇨ 外層が重くなり重力的に収縮（青くなる）

Aim of our work

(Urushibata et al. 2018, PhD thesis in preparation)

- To decide if it was single or binary
- To construct models which can explain all the observations, especially,
  - Position in the HR-diagram
  - Final stellar mass ~ $19.4 \pm 1.5\ M_{\odot}$
  - Time after Red became Blue, $\tau_{BSG} <\sim 2\text{x}10^4$ yr
  - Chemical anomary in the nebura
    - High He/H = 0.17 ± 0.06 (ratio of number of atoms)
    - N/O = 1.5 ± 0.7 and N/C = 5.0 ± 2.0

c.f., 太陽系組成比: He/H = 0.096 , N/O = 0.13 , N/C = 0.31

Single star model

- 1D stellar evolution code with rotation effects
  - Takahashi, Yoshida, Umeda 2015, + （最近はHOSHI codeと呼んでいるらしい）
  - Commonly adopted method at present
  - Effects of centrifugal force, rotational mixing of matter, rotational mass loss, angular momentum transfer (with magnetic effect --- Spruit –Taylor dynamo)

  - We can basically reproduce other groups' results once similar parameter settings are done

What makes the red to blue evolution?

// The mechanism has been suggested by many researchers.

1. Helium enhanced envelope: Excessive energy flows due to reduced opacity (Saio+88).

   - Rotational mixing and/or enhanced mass loss ?

2. Adding matters to the envelope: Shrinking due to gravity (Podsiadlowski+92).

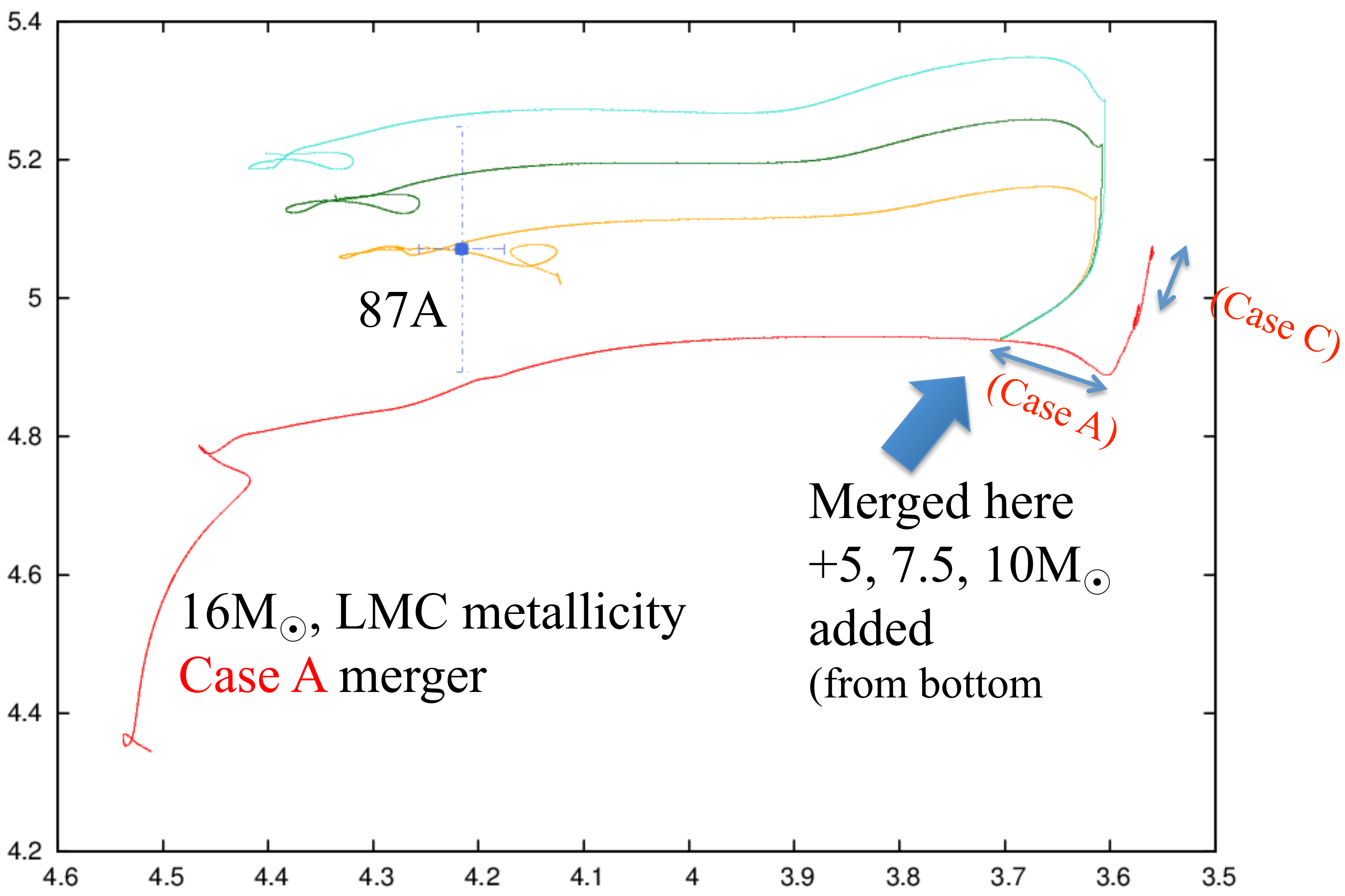
Our conclusion on the single star model

- We tried various calculations, and conclude that
- It is (nearly) impossible to explain the 1987A progenitor.
- Because
  - He and N rich envelope could be made by rotational mixing, but larger core mass is naturally formed
  - Smaller Core/Envelope mass ratio is required to make the star blue (as also suggested by Woosley et al. proceedings)
  - Also, R to B transition time < ~ 2 x 10^4 yr is a very severe constraint. It is nearly impossible to satisfy this by the He enhancement due to rotational mixing.

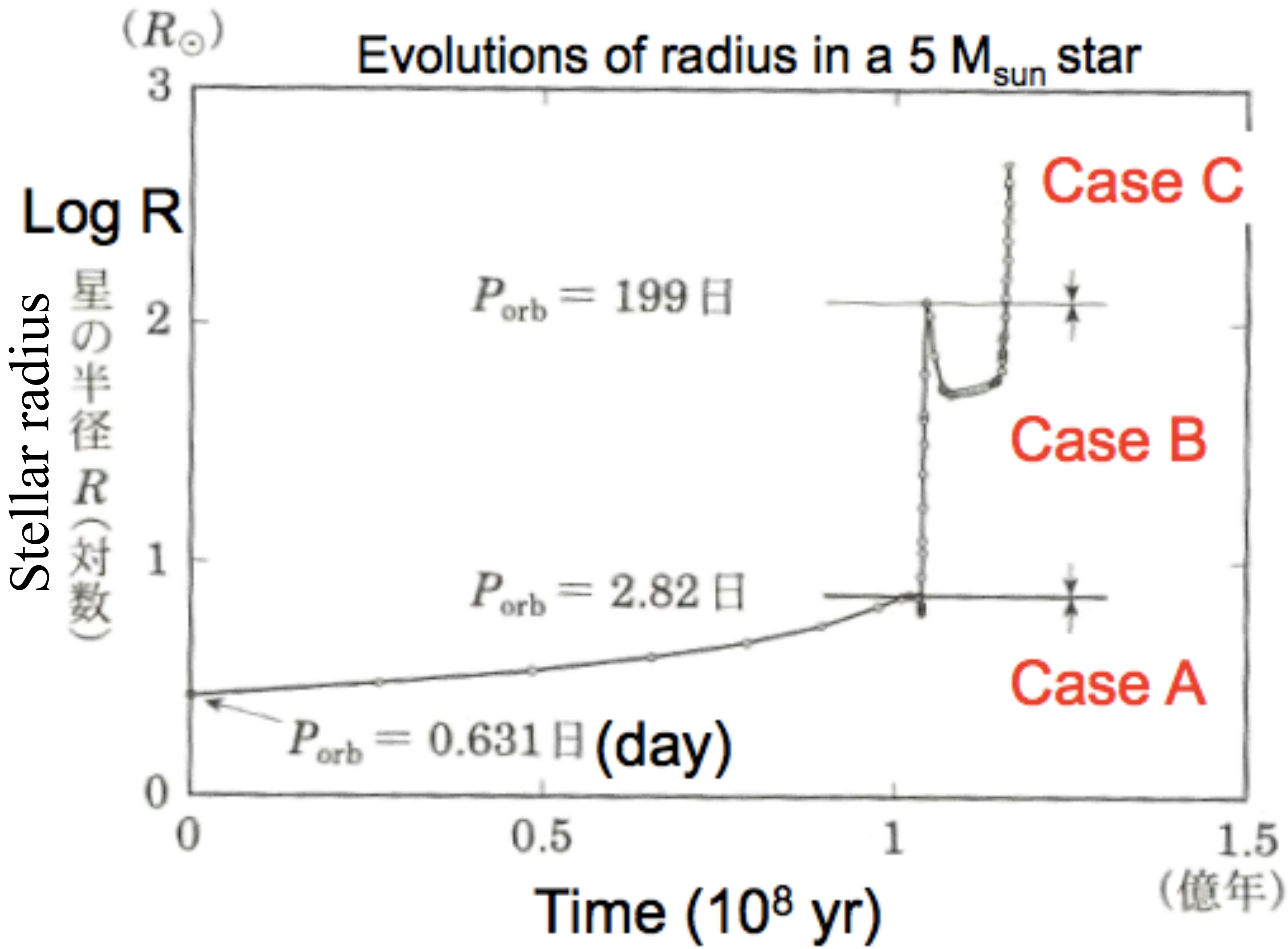
Binary merger model
~ Shrinking due to gravity ?

- We first studied how the model works.

Addition of Mass due to merging (Case A) :



Cases of binary mass transfer



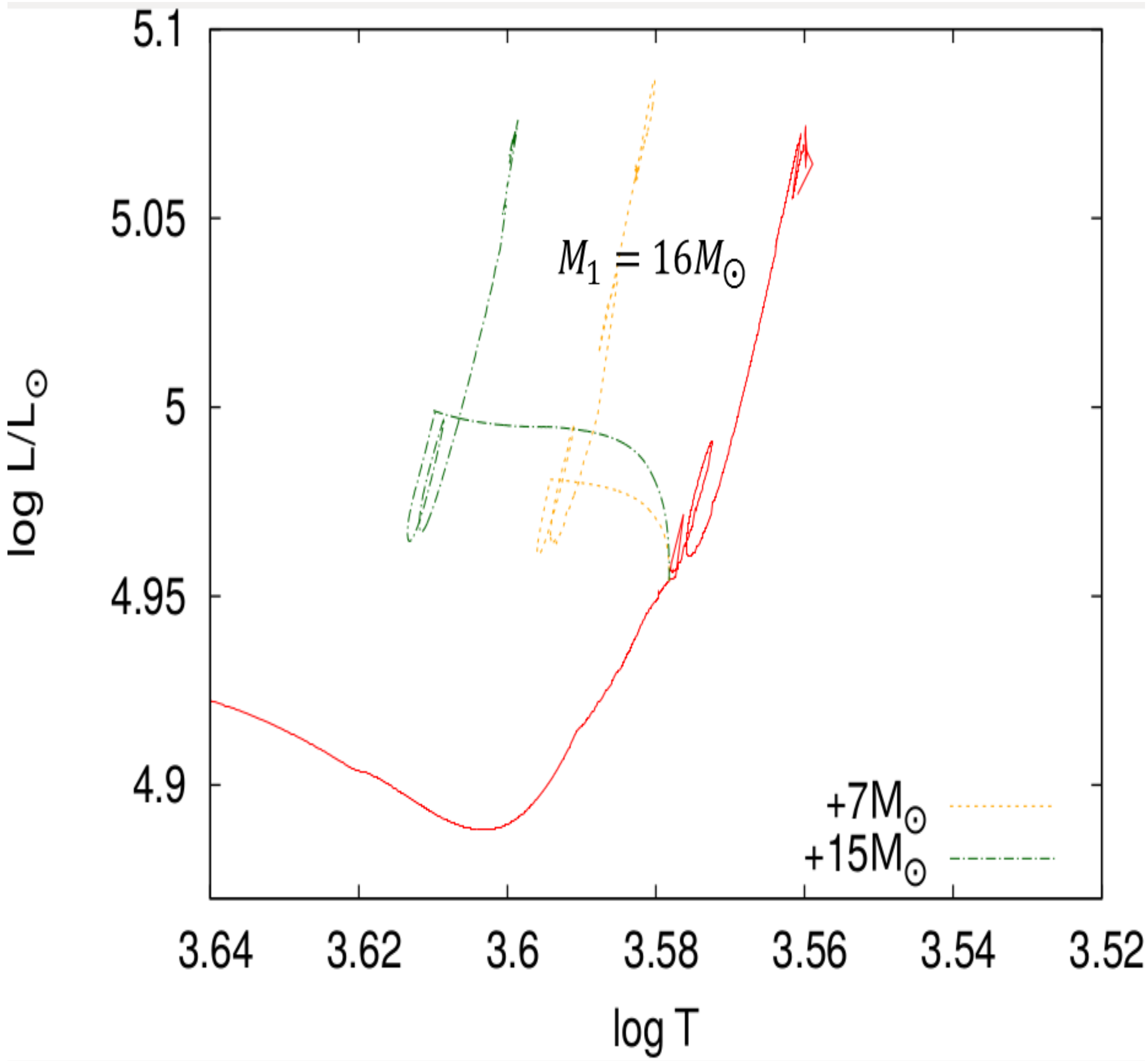
Case C

(To satisfy the $2x10^4$ yr condition, we need Case C)

→ RSGs never become blue !

This means that to explain 87A, just adding mass is not Enough !

We need a more complex model.



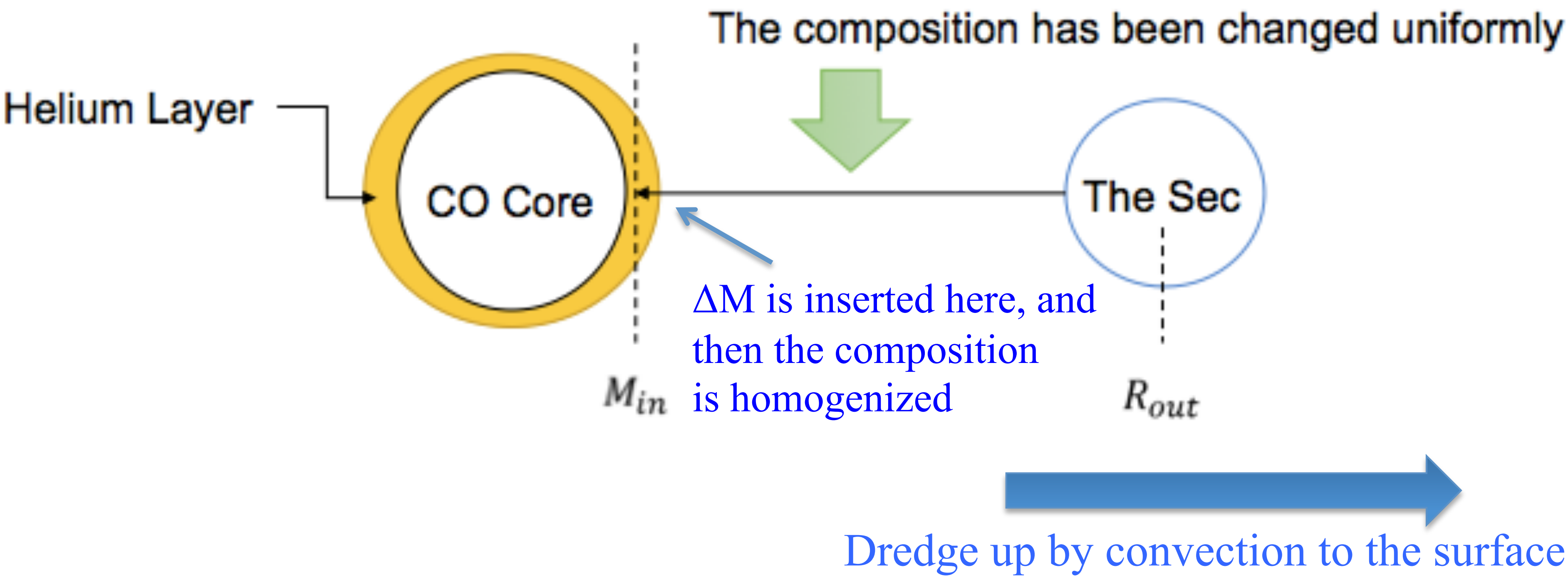
Our binary model

- Binary masses M_1 and M_2 ($M_1 > M_2$)
- Calculate single star evolution of M_1
- Assume that the merger occurs $2x10^4$ yr prior to the core-collapse
- Our model is motivated by the slow merger scenario (Ivanova et al. 2002) in which both the internal mixing and the envelope mass enhancement occur during the merger event.
  - Initial separation ~ 1000 $R_\odot$
  - M_2 melts around R ~ 10R inside the He envelope of M_1

Ivanova et al. (2002)

- Hydrodynamical simulation
- Three rings of 1987A can be explained
- At the end of the merger, a streamline of the melting material can penetrate the H/He boundary.
- The penetration results in rapid H-burning, by which turbulence is powered and mixes the region homogeneously.

Our model for melt



Parameters

M_{in} : the reaching point of the stream (~ $M_{He} - 0.2\ M_{\odot}$

R_{out} : the end point of the turbulent mixing region (~1-3$R_{\odot}$

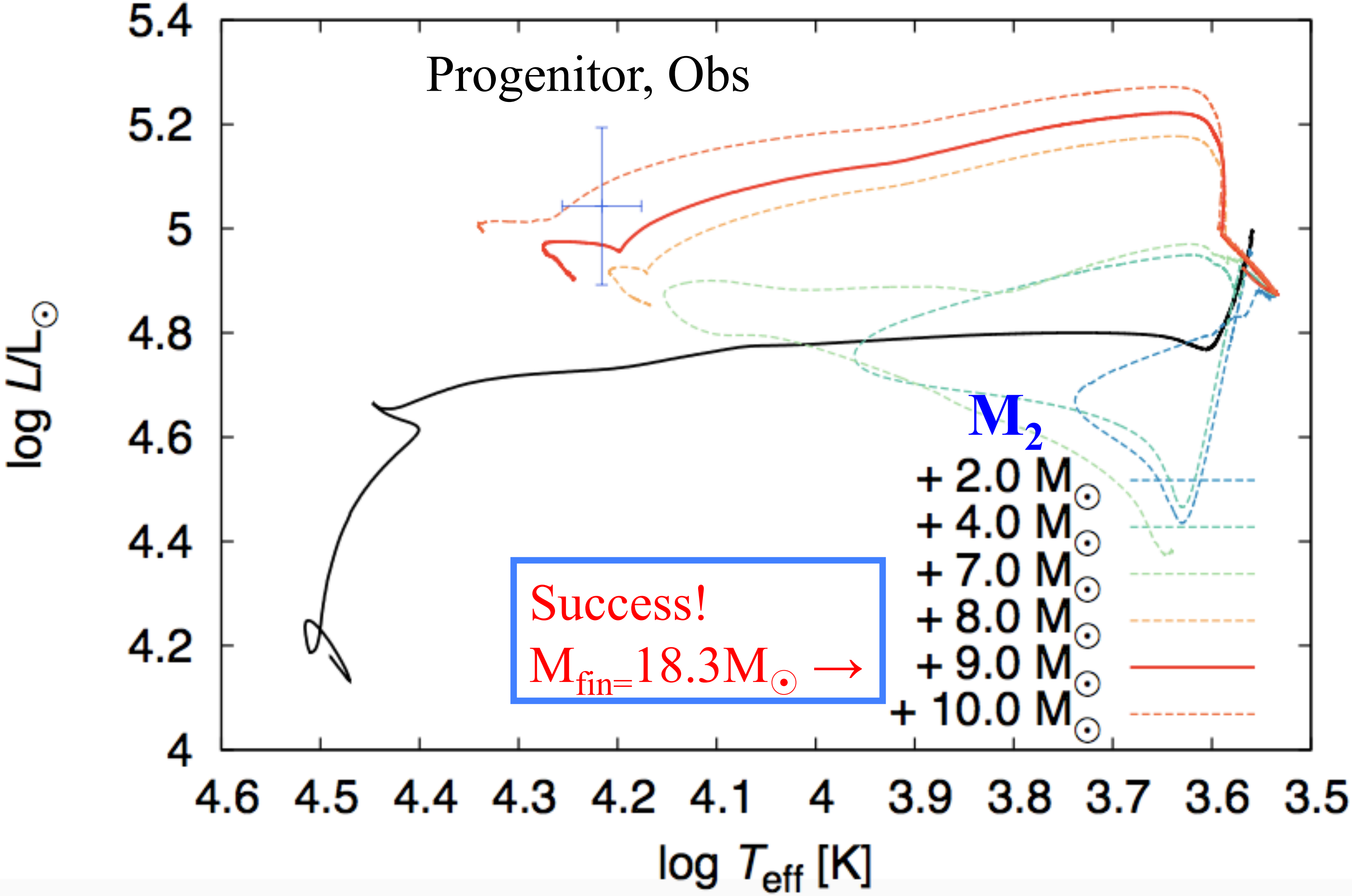
τ_{melt} ~ 100 yr (time scale of the melt)

M_{He} (Helium core mass) = 4.83 $M_{\odot}$ (for M_1=14$M_{\odot}$)

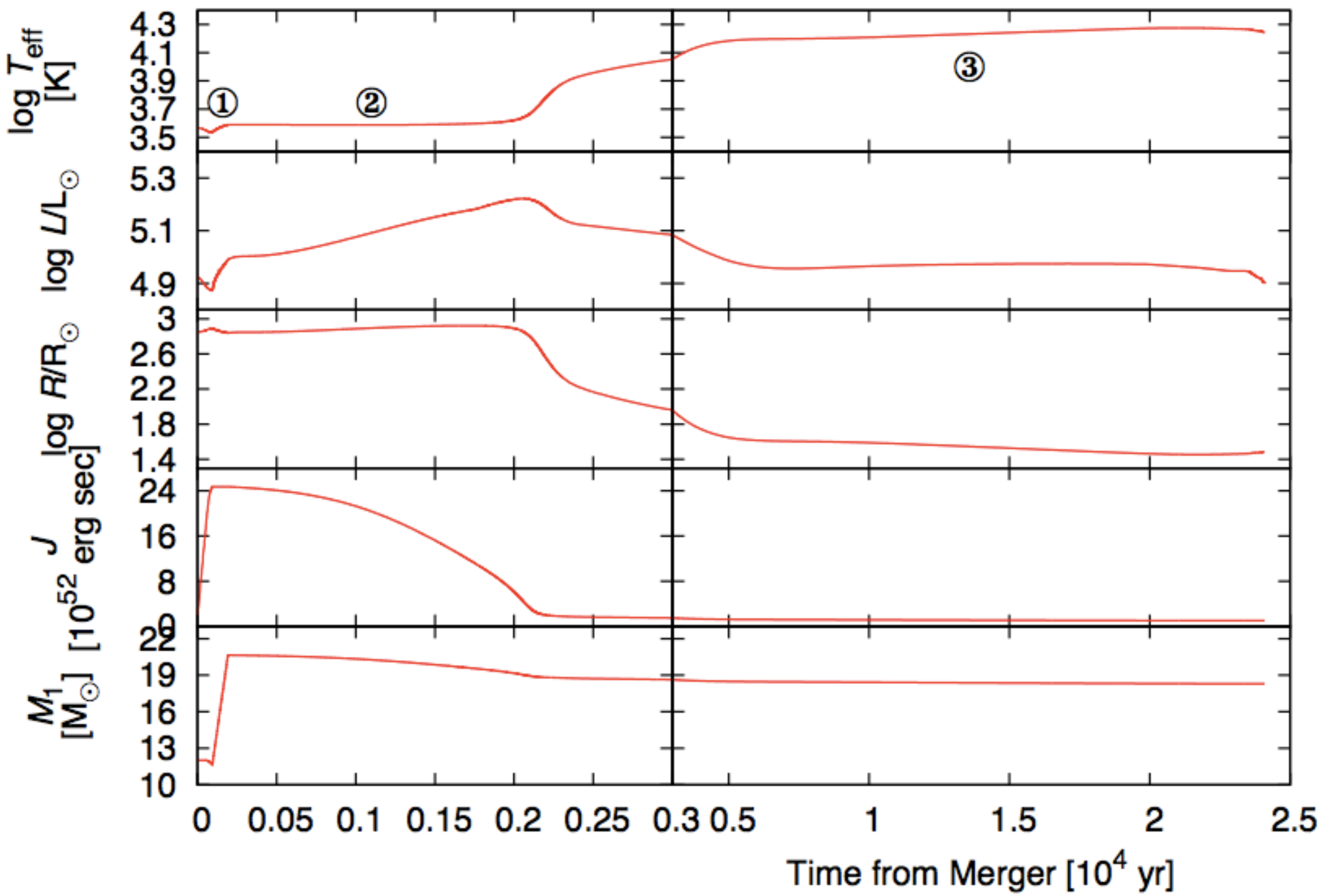
Addition of angular momentum

- The secondary typically has orbital angular momentum $J \sim 3 \times 10^{54}$ erg s, and this is brought into the primary's envelope.
- We find that the most significant effect of the addition is the enhancement of mass loss.
- We take the amount of angular momentum addition as a parameter (in the range of $0.1 \sim 1 \times 10^{54}$ erg s) and the results are discussed.

Results (HR-diagram) : $M_1 = 14M_\odot$,



Time evolution after merger



①: End of the slow merger, ②: High Luminosity phase

③: New thermal equilibrium

Evolution of Angular momentum

- Almost all the angular momentum added is lost during the high luminosity phase
- Since angular momentum is transferred efficiently near the surface, small amount of mass loss induces large angular momentum loss
- In the final stage, surface rotation is not fast, ~ 80 km/s, consistent with observation (Parthasarathy et al. 2006)

- If we add angular momentum more than 10^{54} erg s, mass loss becomes too large to end up as a Blue SG (envelope/core mass ratio too small) – next page for a summary of the results

Summary table of our results

$M_1 = 14\ M_\odot$, $M_{in} = 4.6\ M_\odot$, $\log R_{out}/R_\odot = 2.75$								
J_{add} [$\times 10^{53}$ g cm^2 s^{-1}]	M_2 [$M_\odot$]	M_{fin} [$M_\odot$]	ΔM [$M_\odot$]	$\log T_{eff}$ [K]	$\log L/L_\odot$ -	He/H -	N/C -	N/O -
1.0	6.0	16.87	1.14	4.173	4.861	0.145	3.56	1.23
1.0	7.0	17.92	1.09	4.225	4.900	0.142	3.50	1.22
1.0	8.0	18.96	1.05	4.310	4.957	0.140	3.47	1.21
3.0	7.0	16.07	2.94	3.640	4.381	0.145	4.29	1.29
3.0	8.0	17.27	2.74	4.168	4.854	0.141	3.51	1.22
3.0[1]	9.0	18.29	2.72	4.244	4.902	0.139	3.47	1.21
3.0	10.0	19.35	2.66	4.336	4.994	0.138	3.46	1.21
5.0	8.0	16.09	3.92	3.632	4.423	0.144	5.01	1.34
5.0	9.0	17.20	3.81	4.187	4.872	0.140	3.55	1.23
5.0[2]	9.5	17.69	3.82	4.257	4.915	0.139	3.52	1.23
7.0	8.0	15.43	4.58	3.577	4.946	0.147	3.83	1.29
7.0	9.0	16.40	4.97	4.123	4.821	0.141	3.67	1.25
7.0[2]	10.0	17.41	4.60	4.253	4.890	0.142	3.68	1.26
10.0	10.0	16.83	5.18	3.984	4.773	0.141	3.68	1.26
20.0	10.0	15.90	6.11	3.577	4.955	0.140	3.57	1.25
30.0	10.0	15.72	6.29	3.577	4.954	0.142	3.93	1.29

[1] The satisfactory model. [2] Models match with observational constraints except for the final mass.

Obs : $M_{fin} = 19.4 \pm 1.5\ M_\odot$, $\log T_{eff} = 4.12 \sim 4.26$, $\log L/L_\odot = 4.89 \sim 5.28$
He/H = 0.17 ± 0.06, N/O = 1.5 ± 0.7, N/C = 5.0 ± 2.0

Discussion

- Parameter dependences are not so large
  - Need not much fine tunings (at least compared with single star models)
- Upper limit for the added angular momentum is much smaller than the secondary's orbital angular momentum
  - Disk like mass loss may be necessary for the efficient angular momentum loss
  - Possibly related to the ring formation

Discussion

- Differences with Menon & Heger 2017
  - Worked totally independently and didn't know their work until it appears in arXive
  - (Unfortunately?) our merger model is quite similar to their model
  - We investigated Angular Momentum brought by the Secondary (they didn't)

  - The results might be similar, but all their model in their Table 4 had $\tau_{BSG} > 4 \times 10^4$ yr.
    In some models in Table 5, $\tau_{BSG} < 1.83 \times 10^4$ yr, but the N/C ratios are larger than our observational criterion N/C = 5.0 ± 2.0

結局何が新しい（おもしろい）のか？

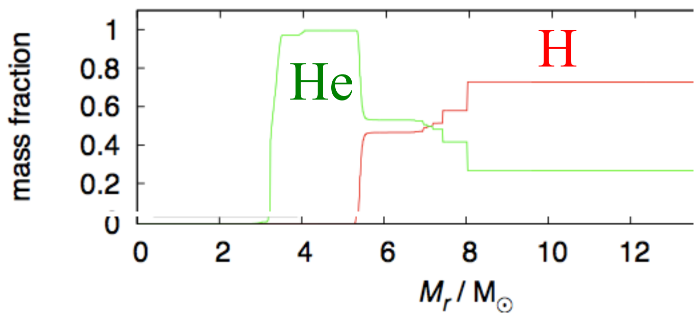
- Single star model と 今回の観測に合う　merger modelとでは親星の構造が違う！
- 表面のヘリウムを増やすために、ヘリウムコアを削って表面に運ぶ必要があった

  ⇨　ヘリウム層が薄くなっている　（質量は半分程度）

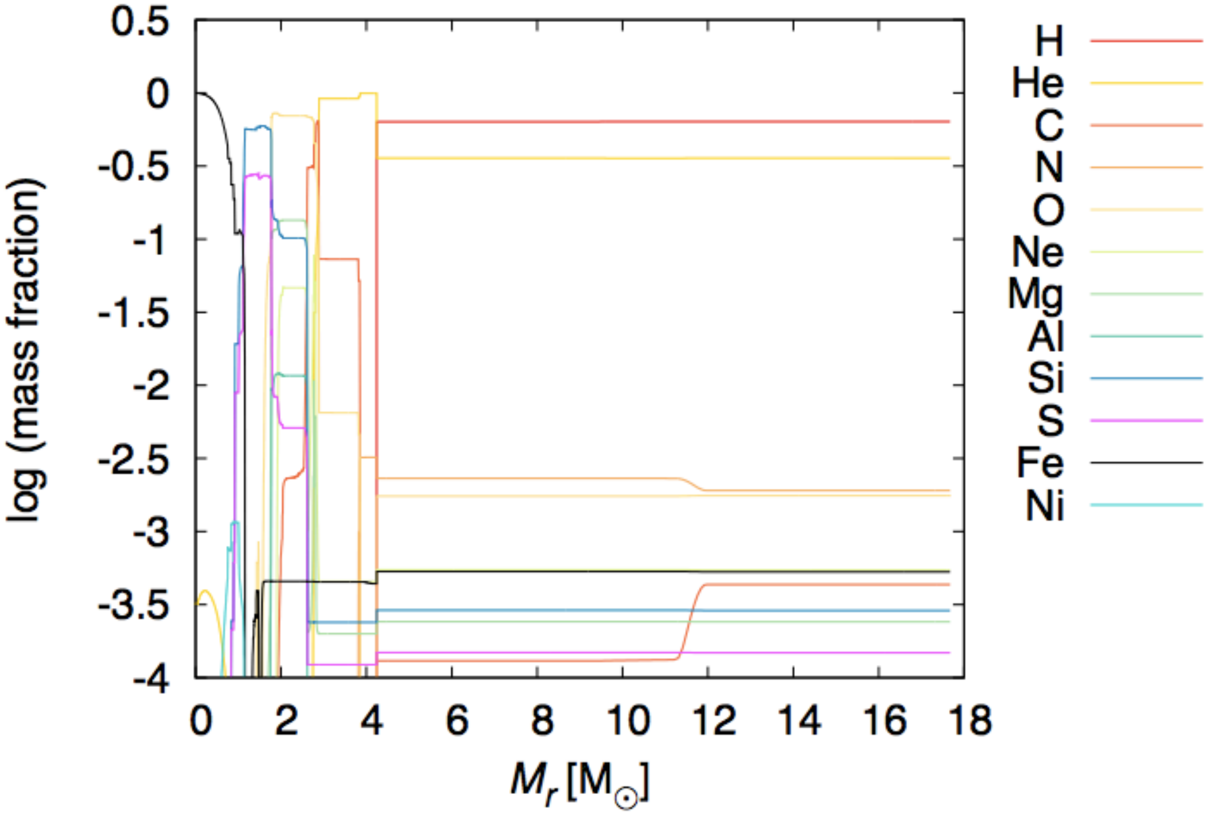
- 爆発後（中）のejectaの非対称性の発達に大きな影響を及ぼす
  - 爆発後のX線光度曲線などの説明に必要であるという示唆（理研グループなどと共同研究進行中）
  - 光度曲線を説明するための^{56}NiやHの混合（これまでは手で人為的に混ぜられていた）と関連する可能性
  - ダスト形成にも影響するであろう
  - 他にも共同研究募集中

Merger model の親星構造

合体前の組成分布



合体後の最終組成分布



単独星モデル

He core : 6~7 $M_\odot$

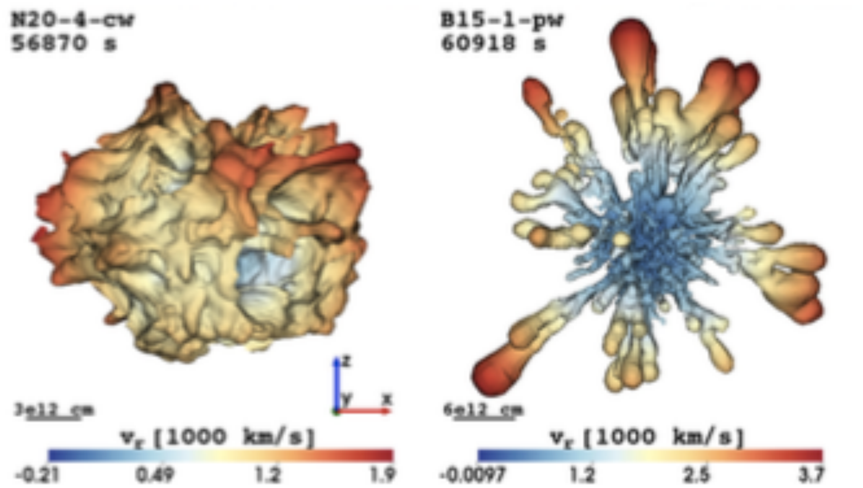
合体モデル

He core : 4.2 $M_\odot$

親星モデルと非対称性の発達度

- A. Wongwathanarat et al. (2015)の爆発シミュレーション例

BSG
20M



BSG
15M

Fig. 10. Same as Fig. 7, but for models N20-4-cw and B15-1-pw at 56870 s and 60918 s, respectively.

BSG15モデルで
外層を変えた効果
左2つ：RSGの外層
右：BSG20Mの外層

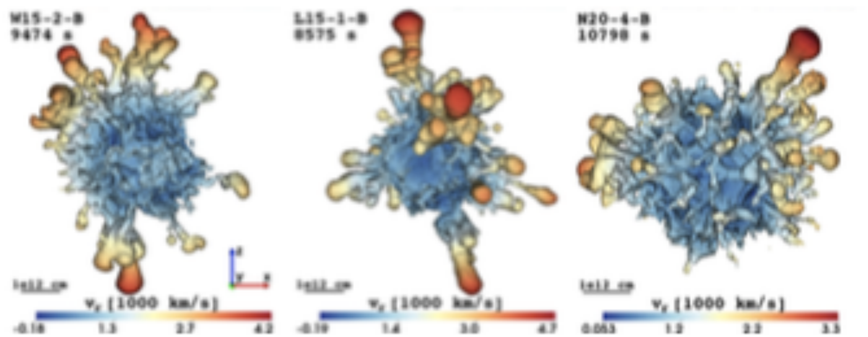


Fig. 11. Same as Fig. 7, but for the additional 3D models W15-2-B, L15-1-B, and N20-4-B, discussed in Sect. 5.4.

Urushibata +2016

- For a Case A merger just adding mass of $5M_{\odot}$ makes the progenitor from Red to Blue
- During the merger, angular momentum also should be added
  - Rotation in general gives negative effects to make the star blue
- From the size of the Ring, Case C merger may be better for the SN1987A model

- Our results revealed that just adding mass is not enough for Case C to make the star blue

Summary

- SN1987A progenitor :
  - Single star model does not work
  - Both the He enhancement and Gravitational contraction due to the binary merger are necessary
  - We found successful models to explain all the observational constraints

  - New model has a thinner He layer