Interacting Massive Binaries

https://billwolf.space/projects/massive_binaries_2021/

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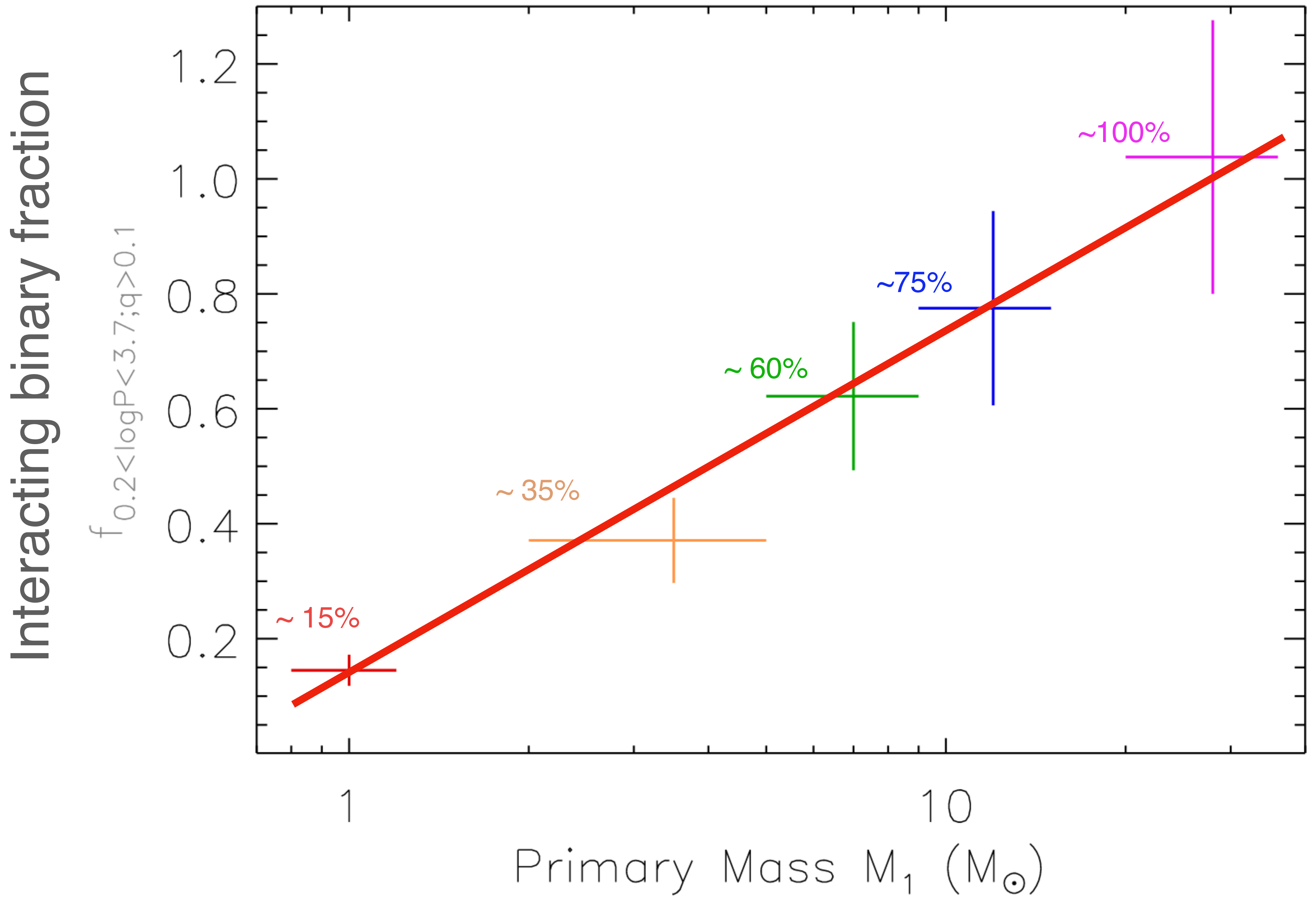
In collaboration with **Ebraheem Farag** & **William Wolf**

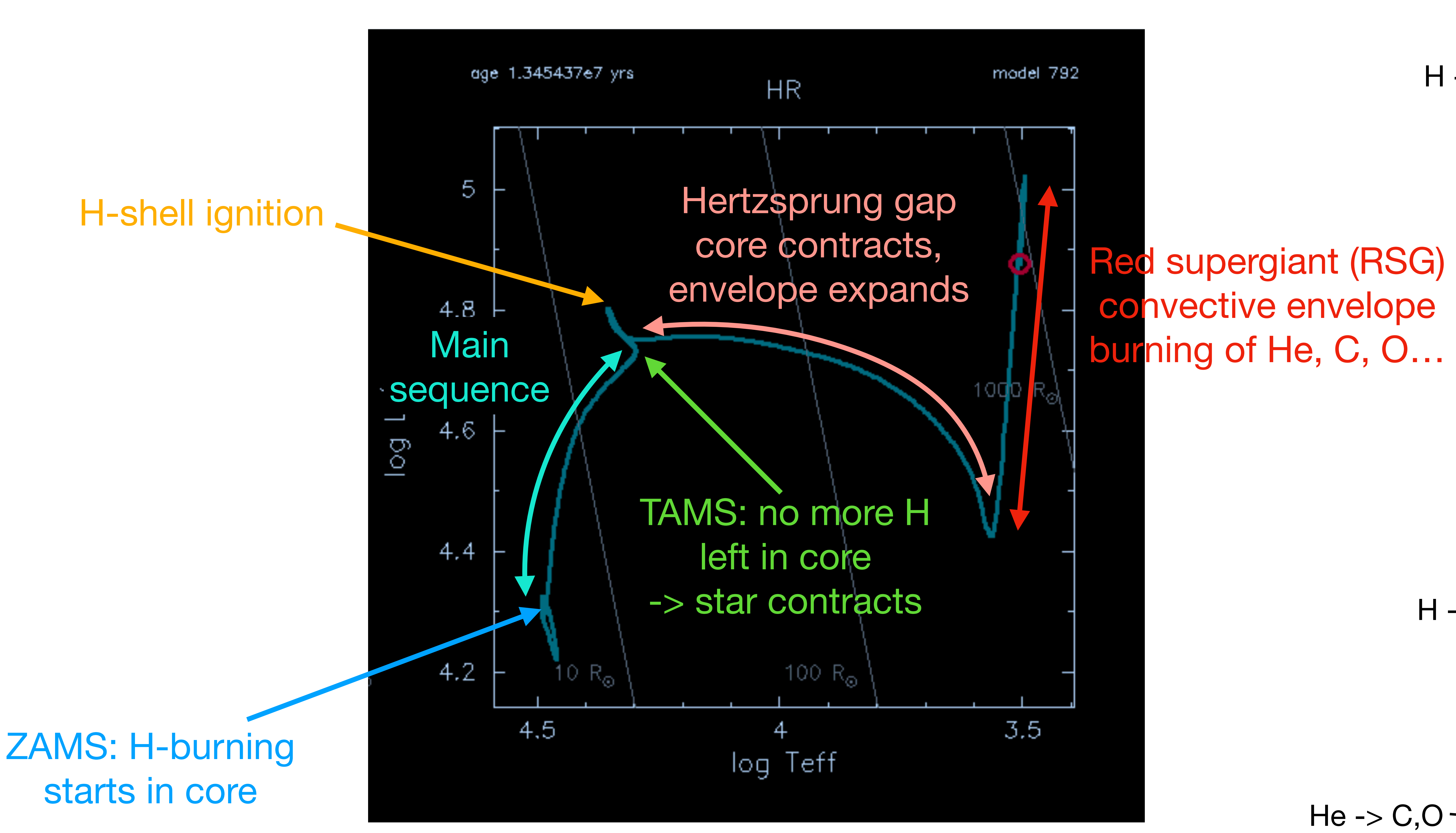
Most massive stars will interact in a binary

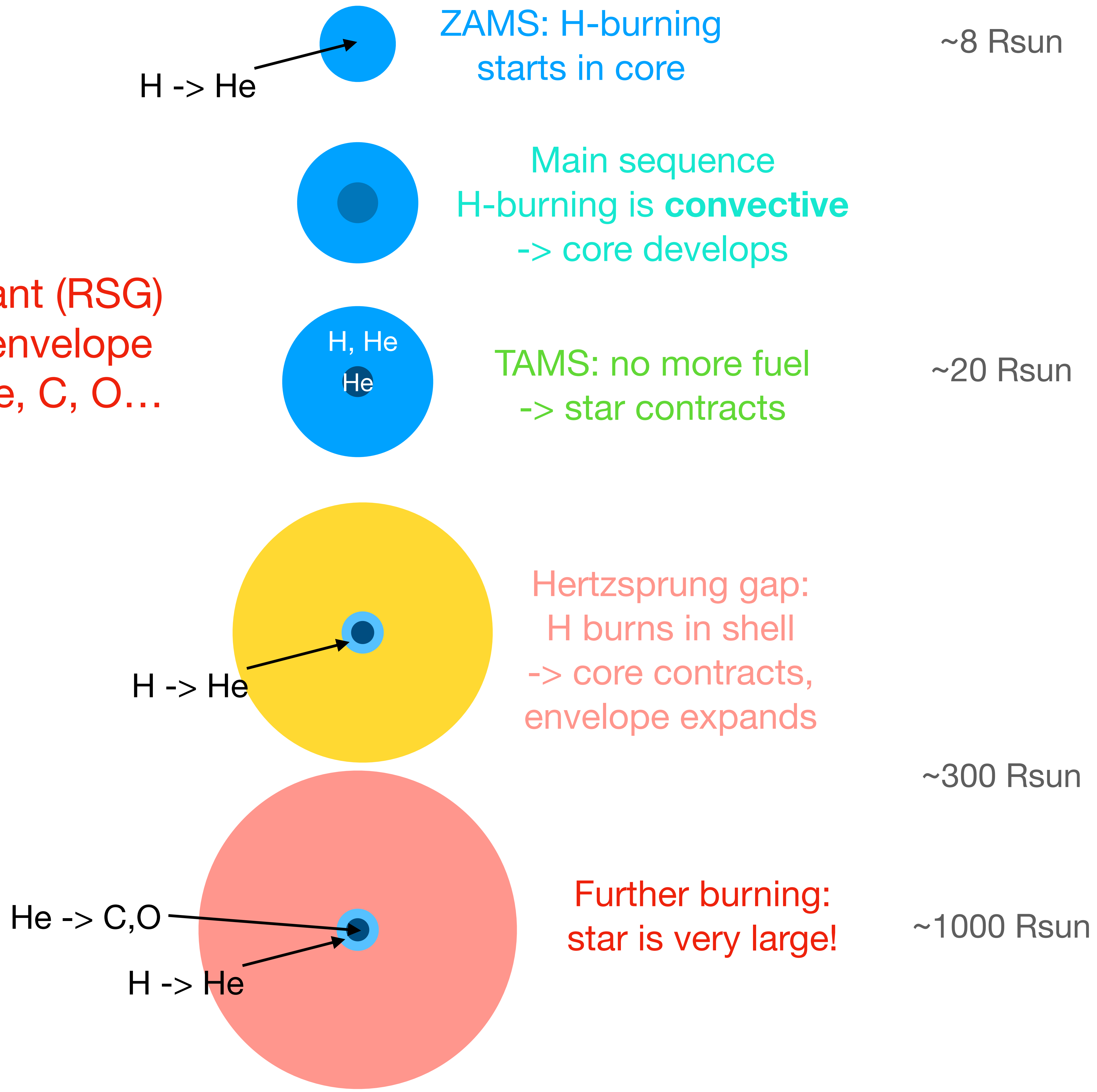
The fraction of binaries that will interact is high
(Moe & DiStefano, 2017)



(cf. Sana et al. 2012, Chini et al. 2012, Kudritzski et al. 2014, Raghavan et al. 2010)

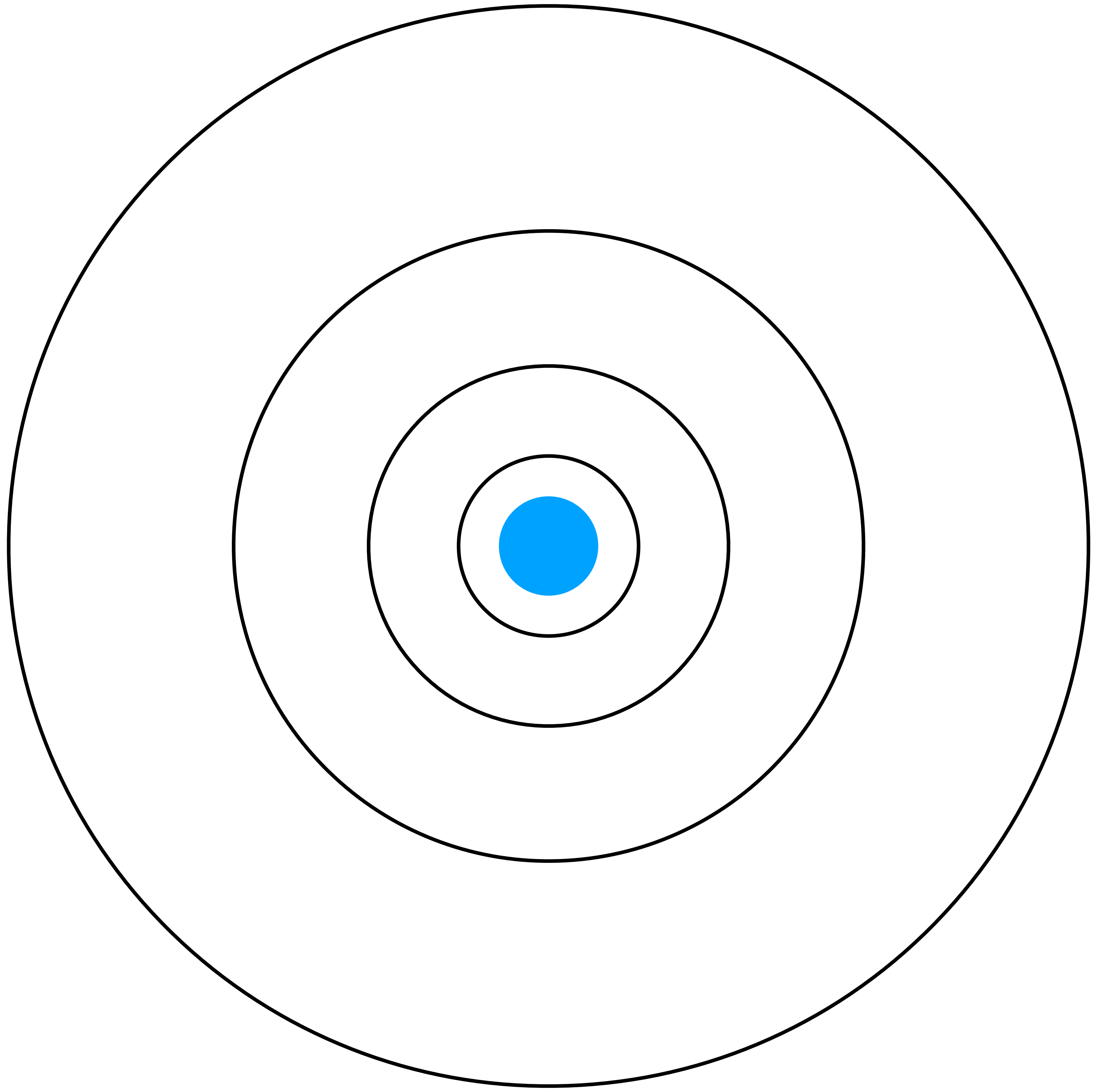
Recap: evolution of a **single** massive star





Initiating interaction

Equipotential surfaces surrounding a single star:



Initiating interaction

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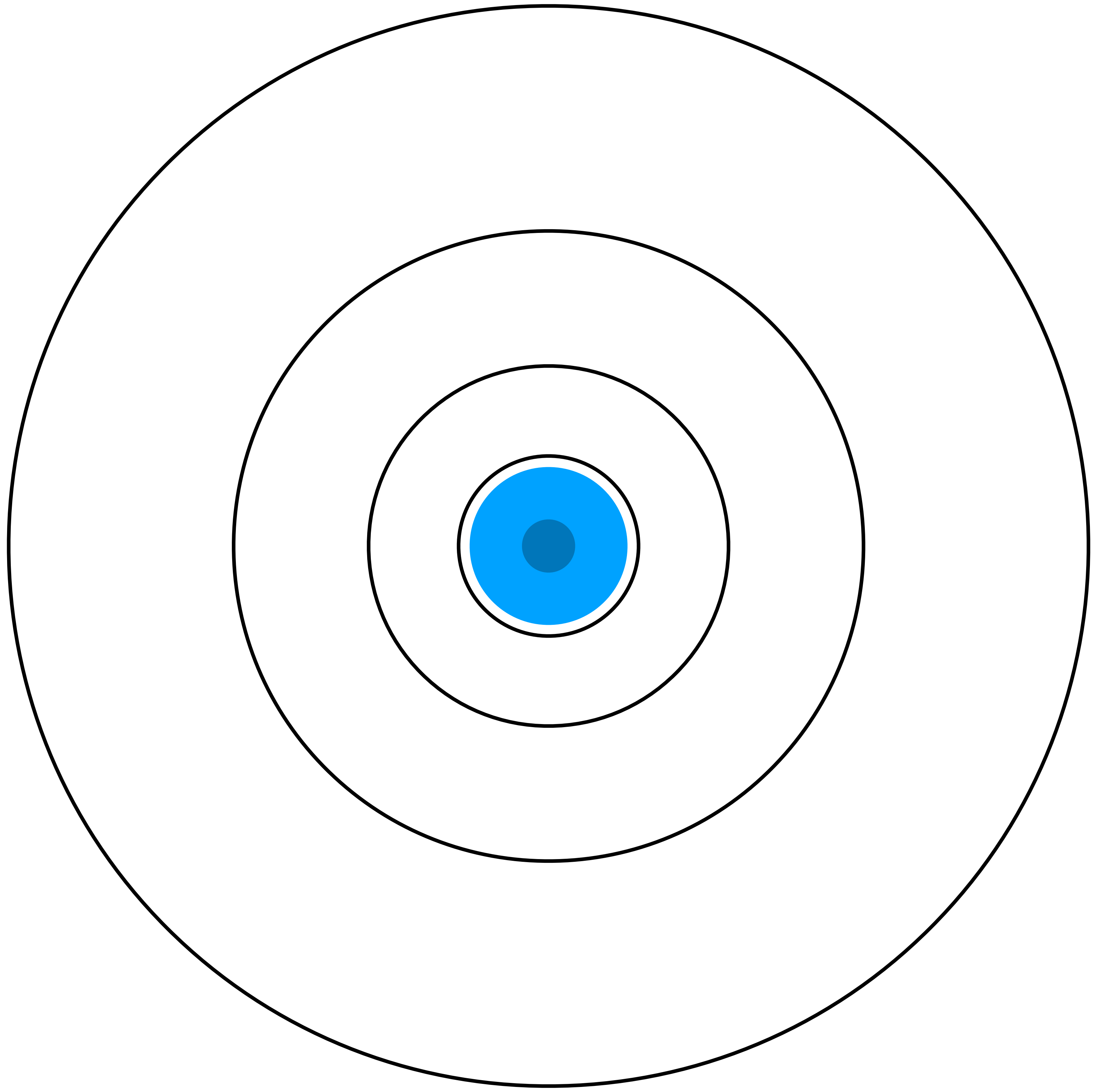

Initiating interaction

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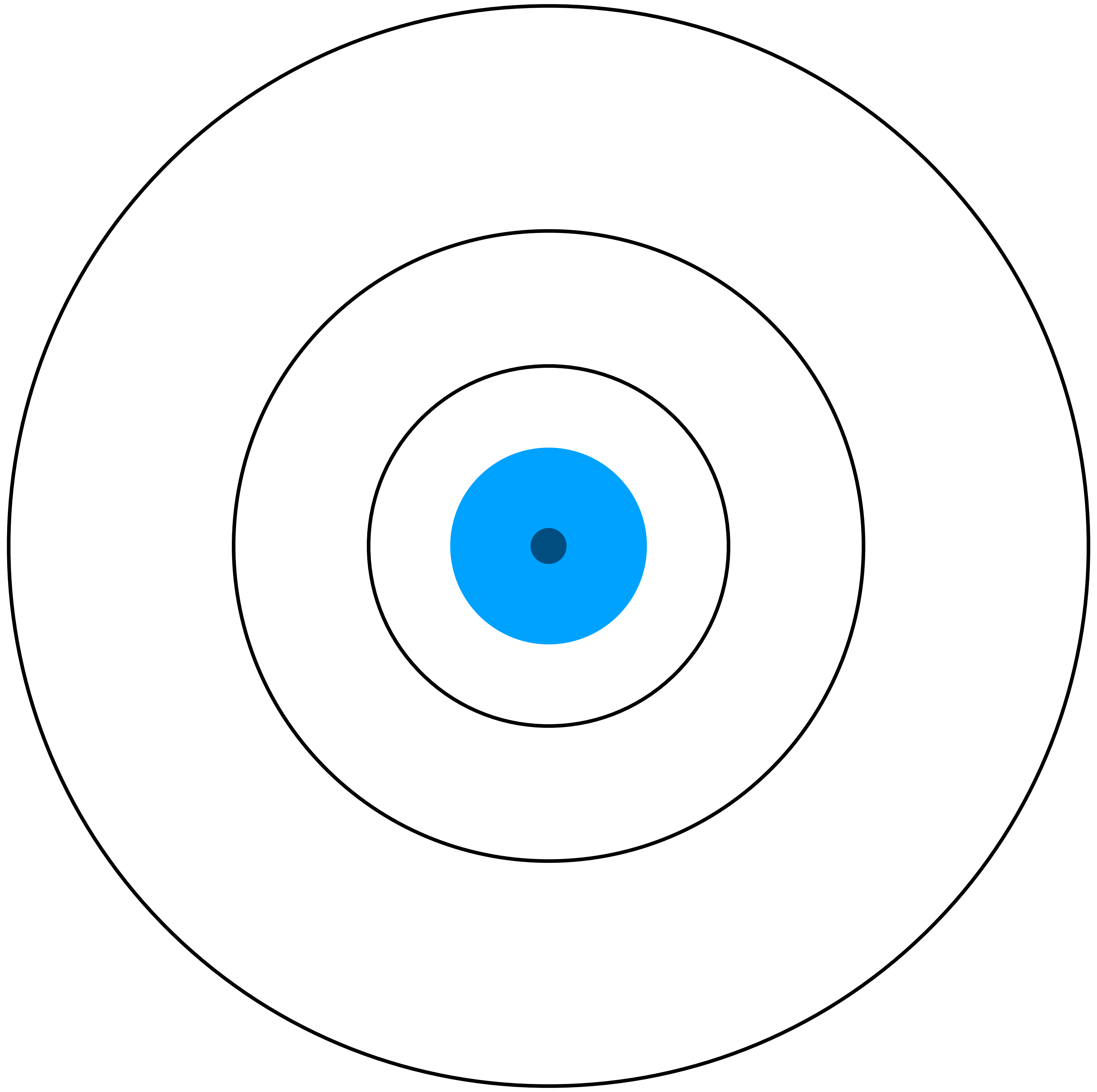

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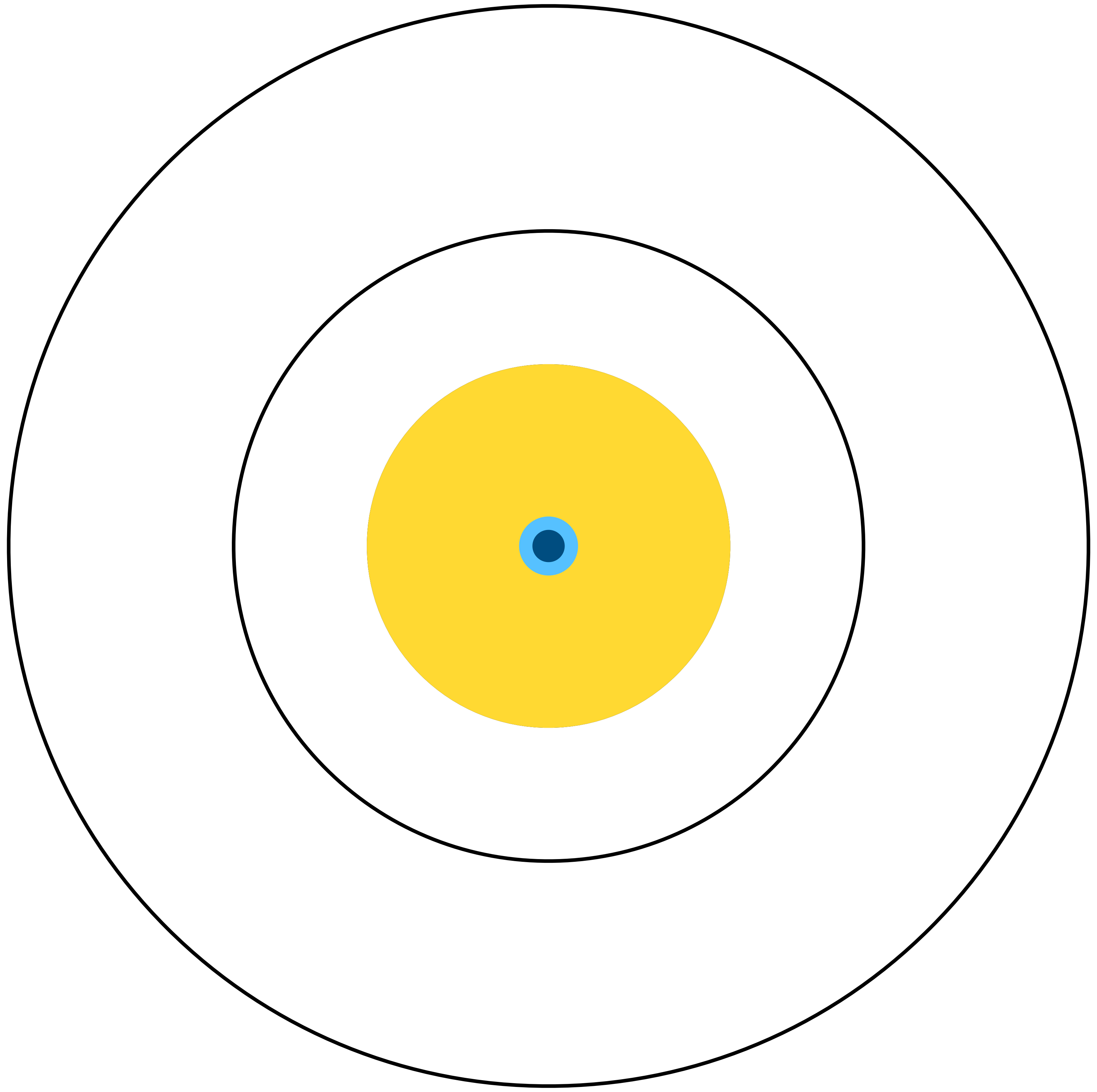

Initiating interaction

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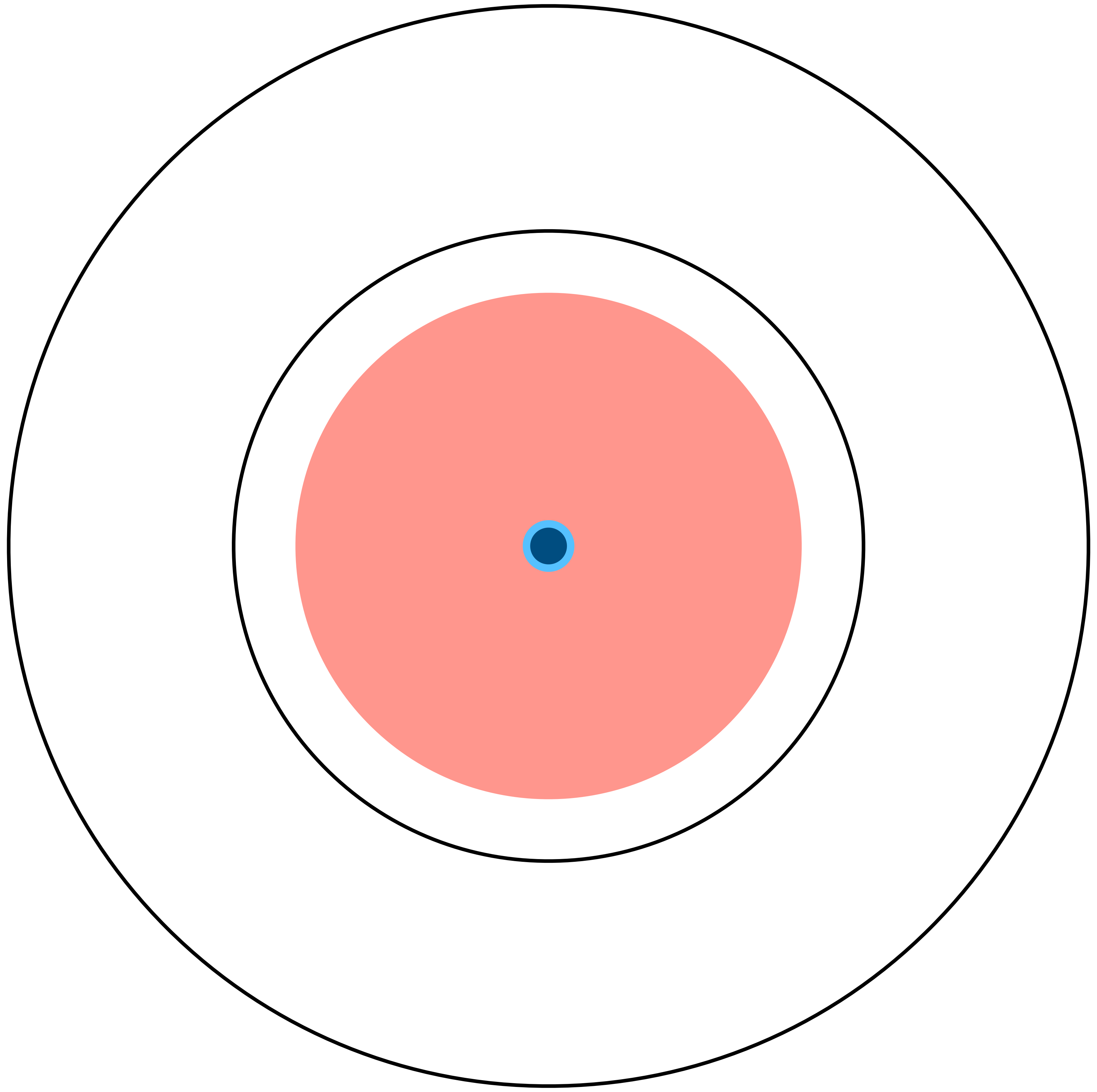
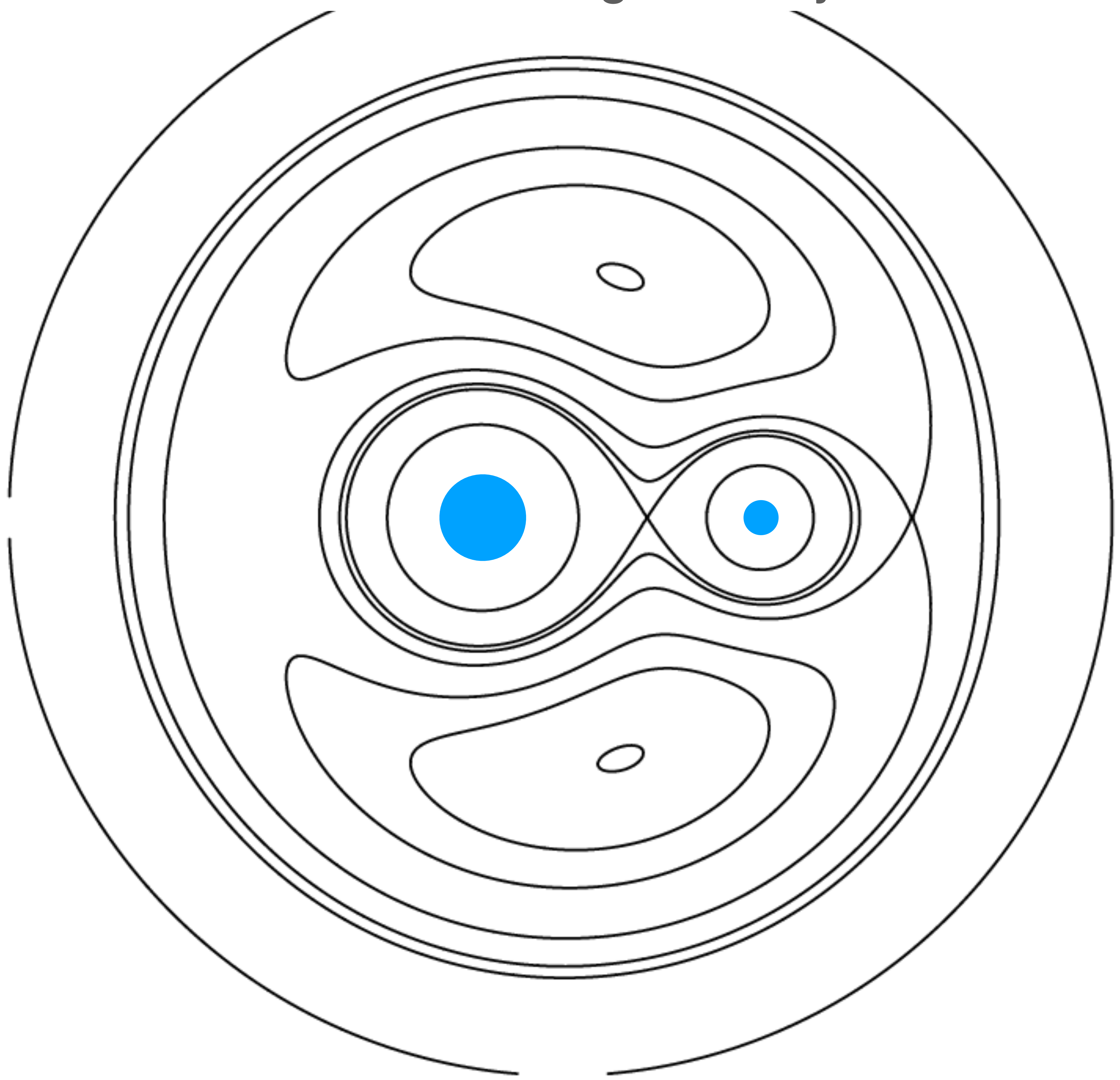


The Roche potential

Equipotential surfaces surrounding a binary star:



The Roche potential

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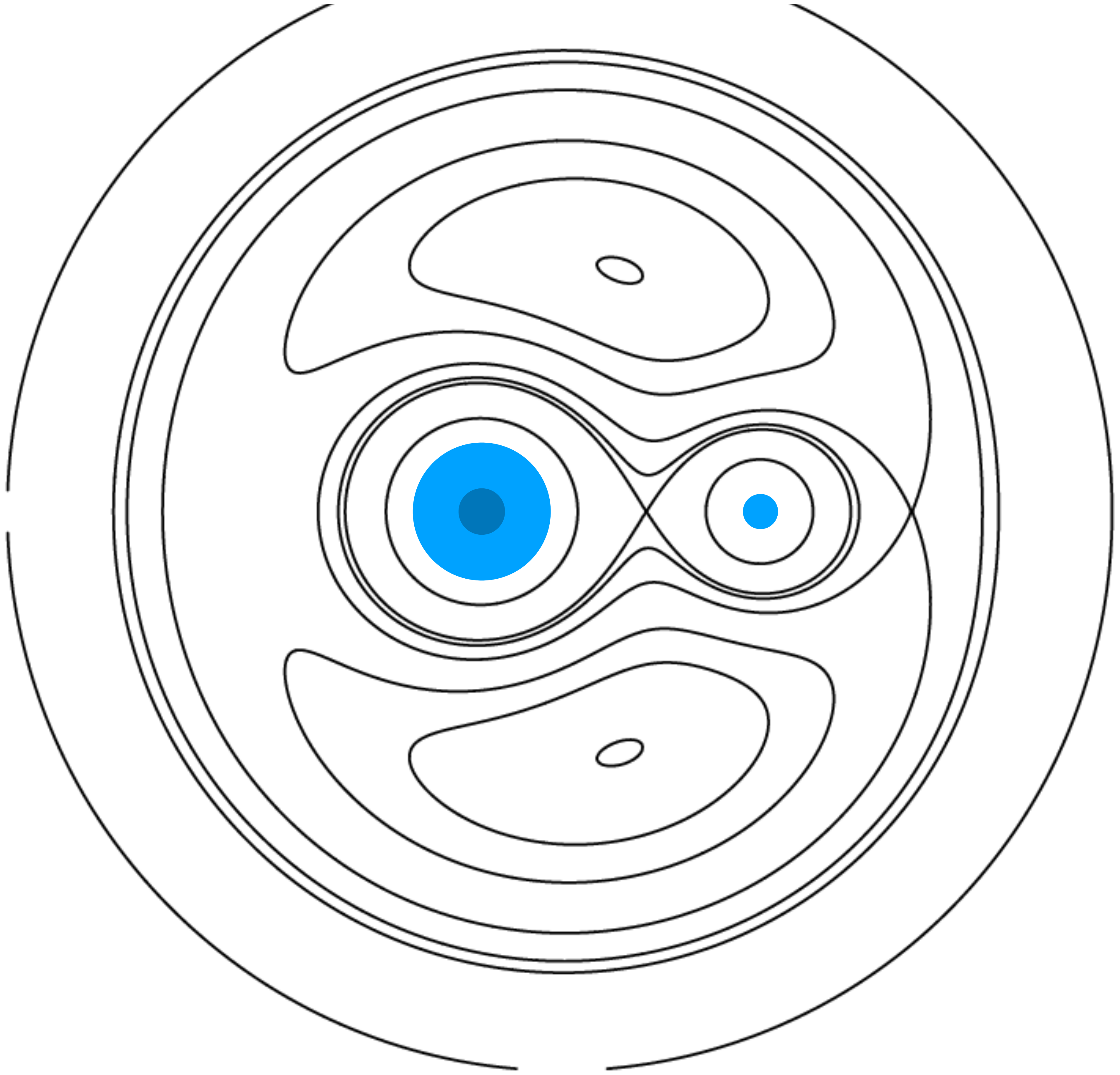

The Roche potential

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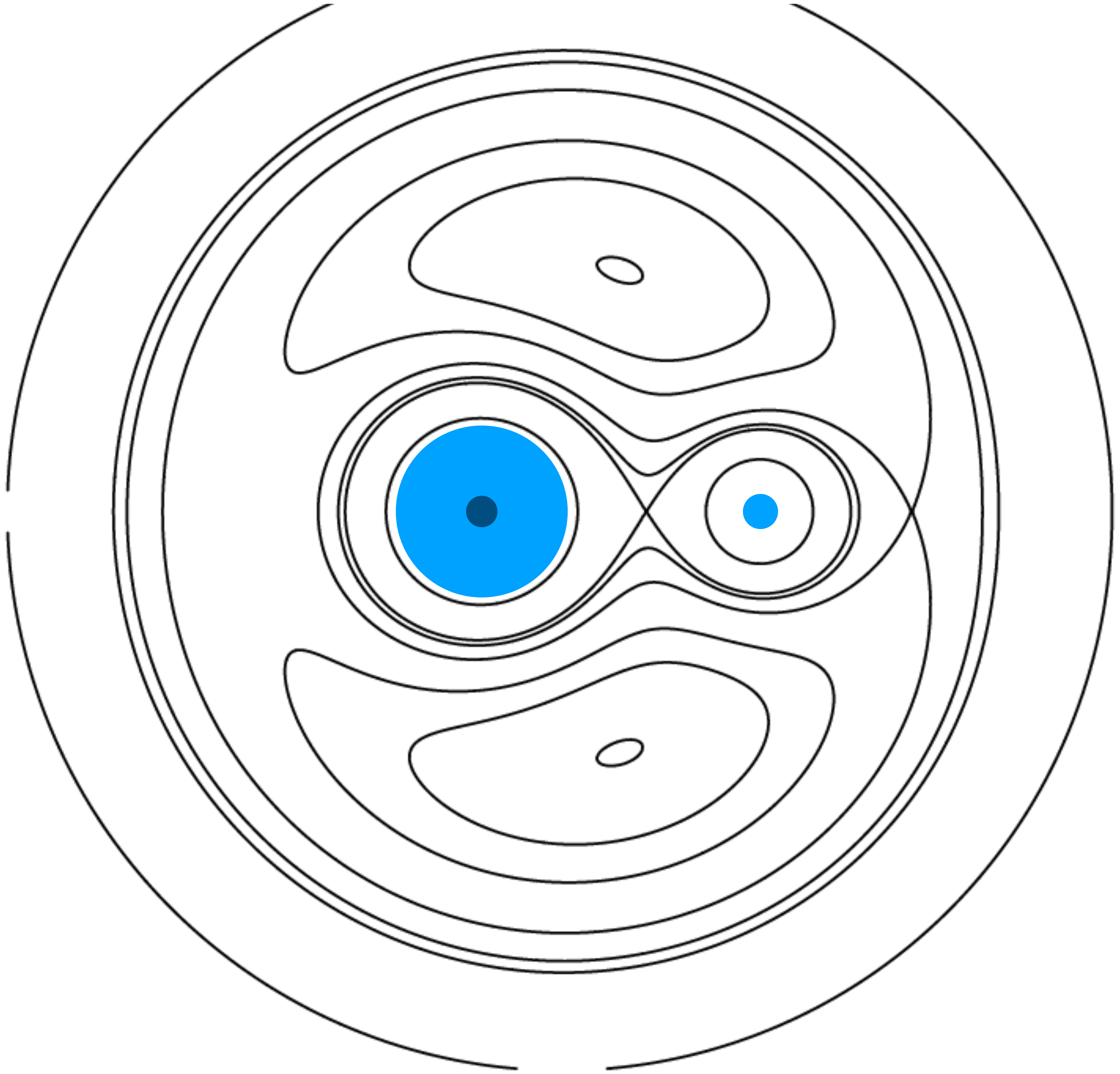

The Roche potential

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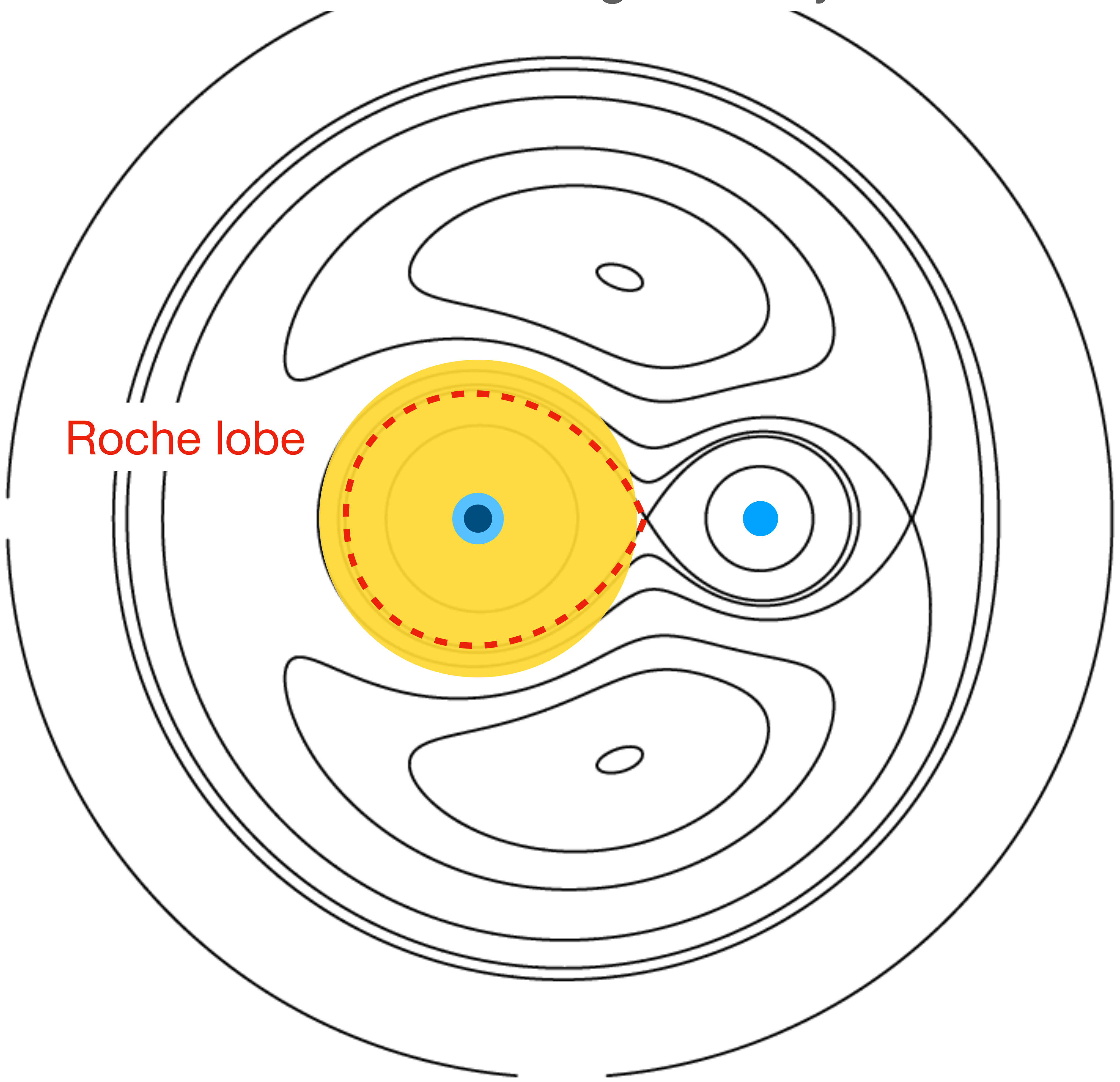
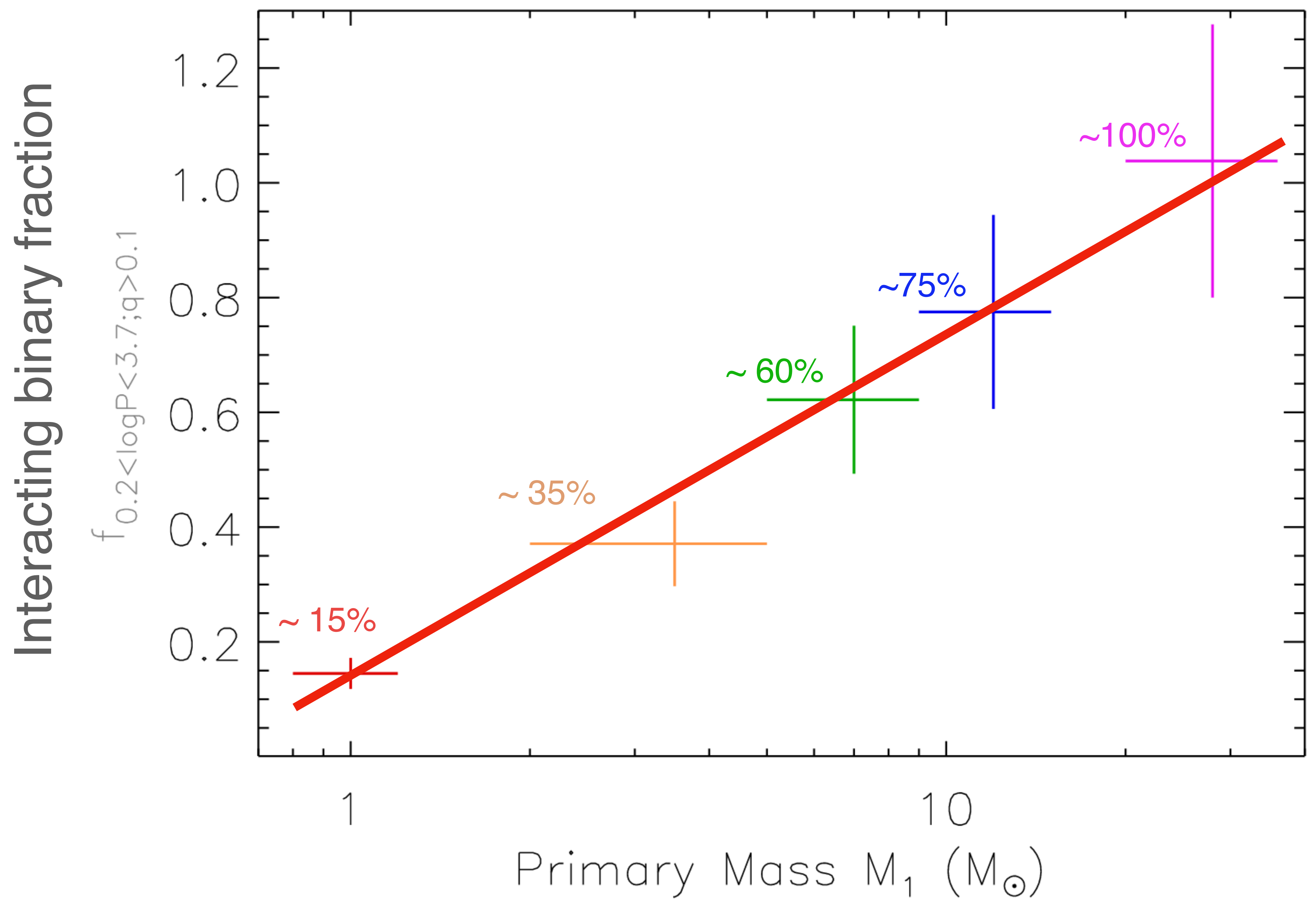


Star does not fit
inside its Roche lobe

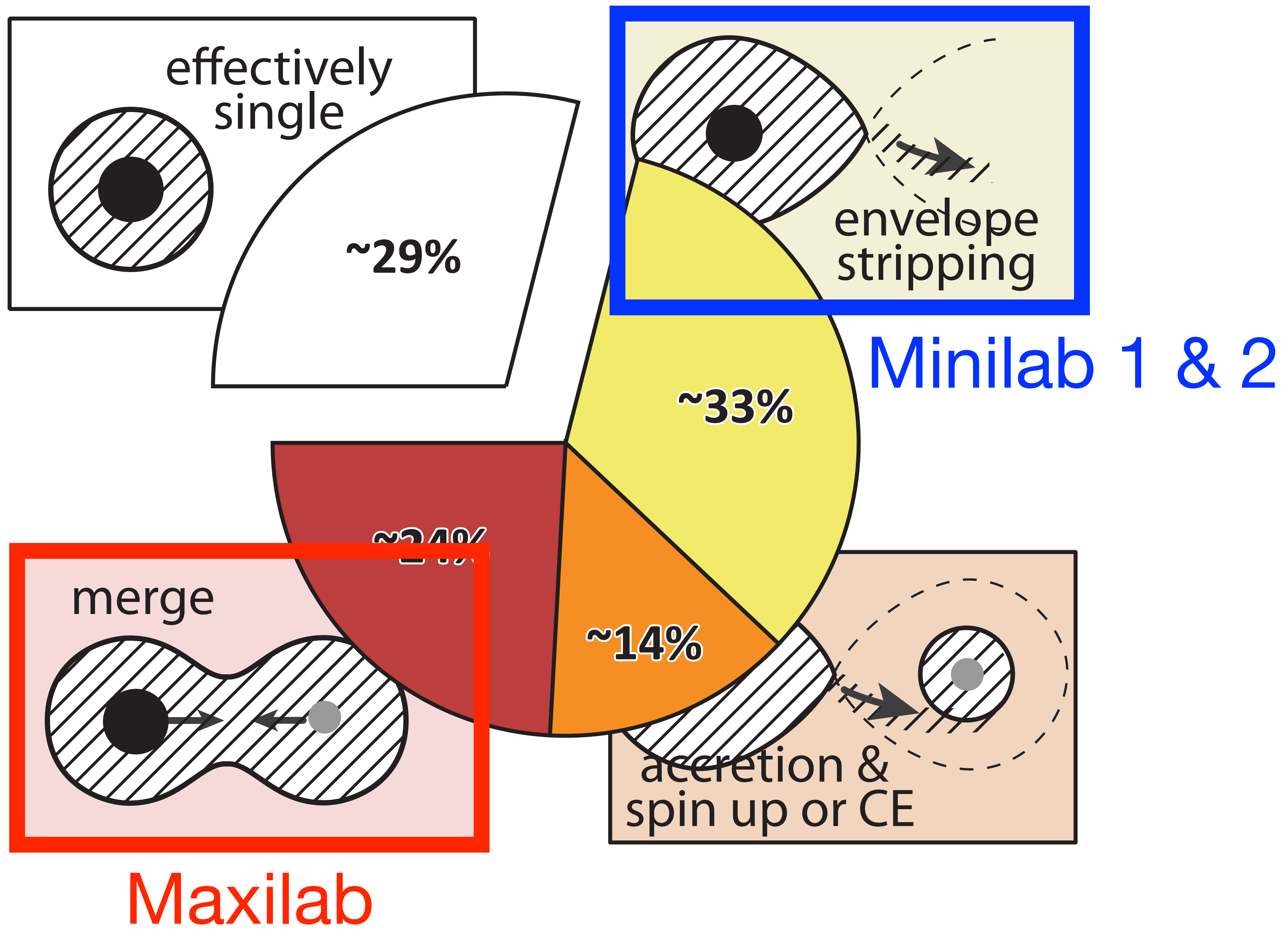
Binary interaction starts

Most massive stars will interact in a binary

The fraction of binaries that will interact is high
(Moe & DiStefano, 2017)



Envelope-stripping, mass accretion and mergers are common binary interactions
(Sana et al. 2012, figure credit: S.E. de Mink)

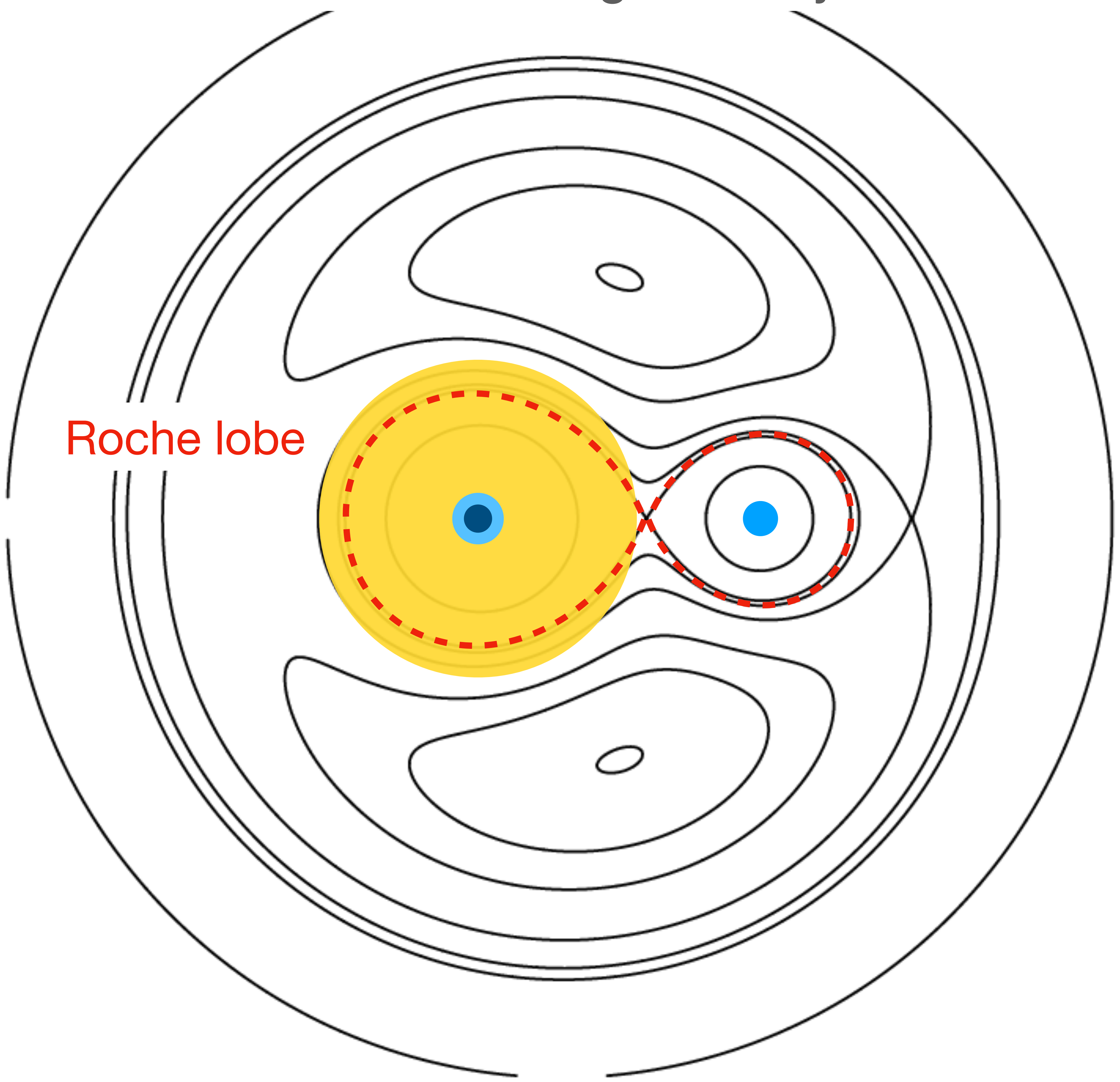


(cf. Sana et al. 2012, Chini et al. 2012, Kudritzski et al. 2014, Raghavan et al. 2010)

Minilab 1
Envelope-stripping

Roche-lobe overflow

Equipotential surfaces surrounding a binary star:



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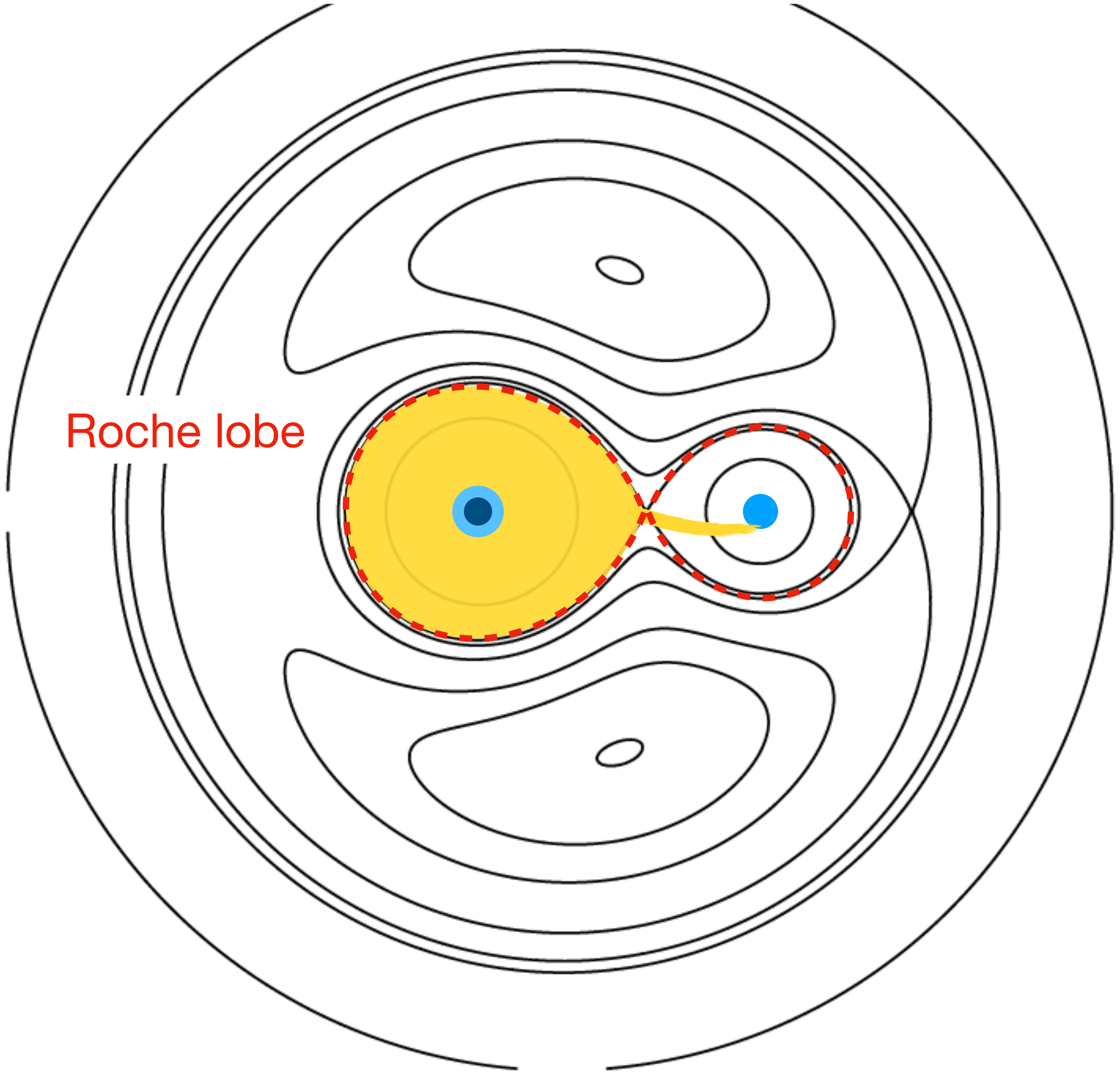

Roche-lobe overflow

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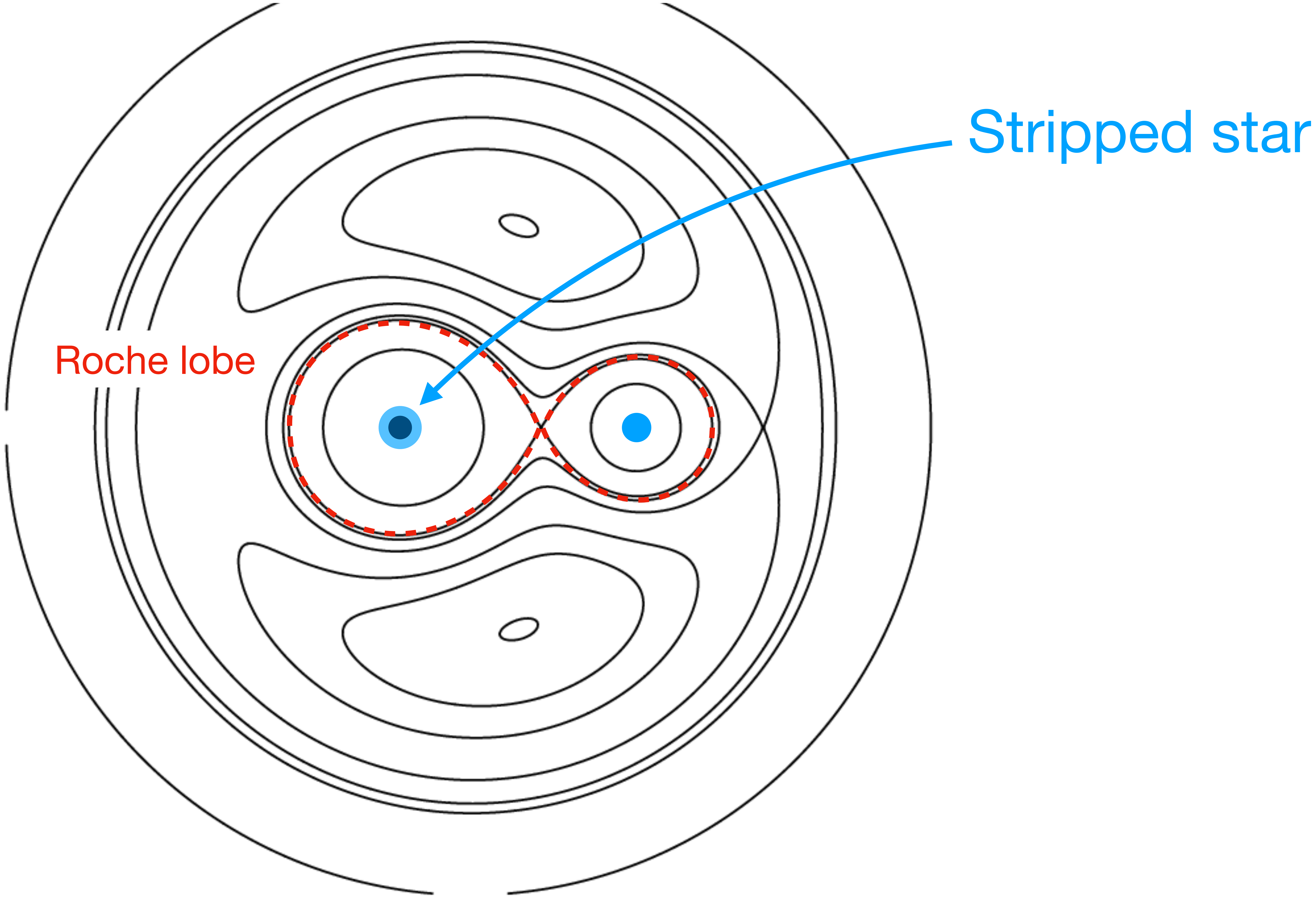


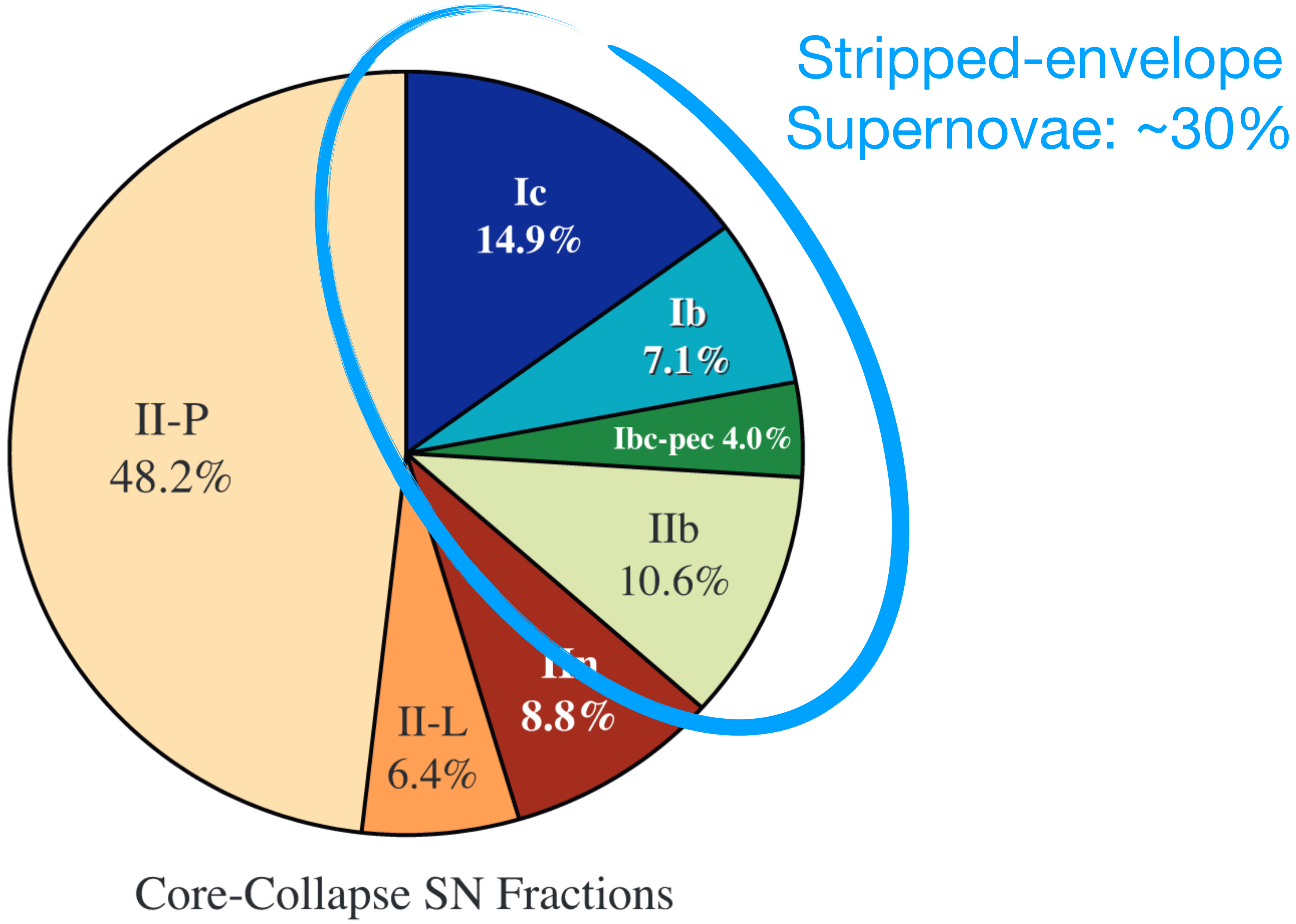
Ongoing mass transfer observed

Zhao et al. (2008) on the CHARA array

300 pc distance
13 day orbit
Donor: 3 $M_\odot$
Accretor: 13 $M_\odot$

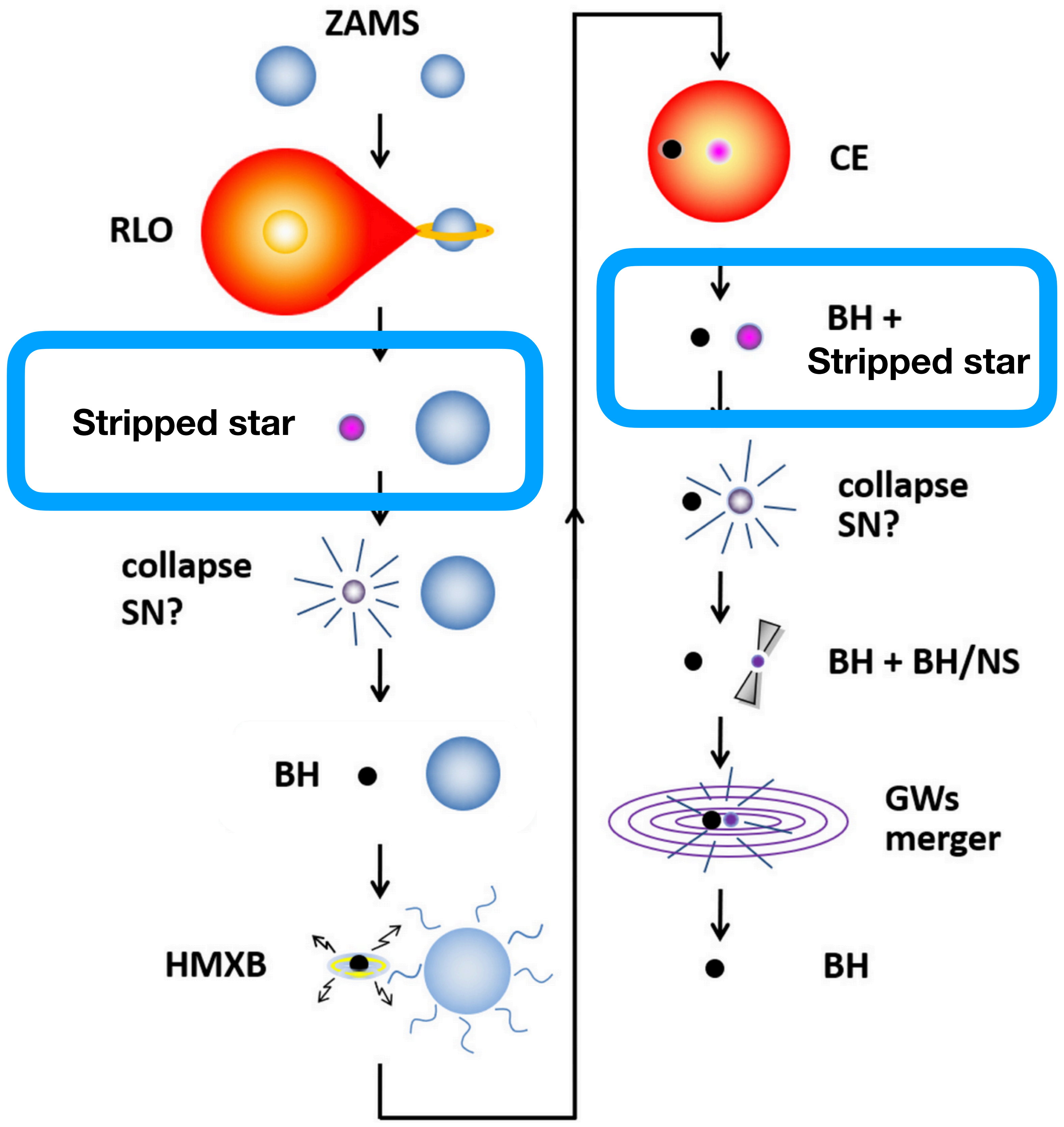
Importance of stripped stars

1/3 of all core-collapse supernovae are stripped



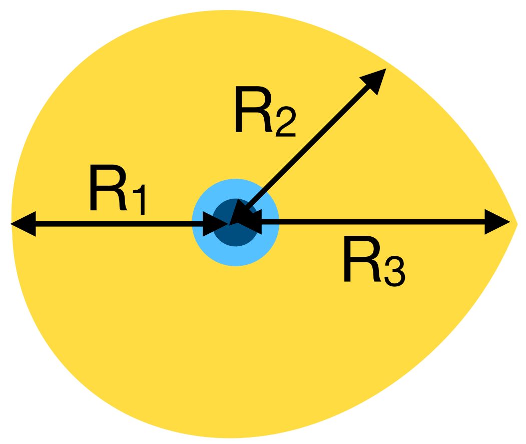
Smith et al. (2011),
see also Graur et al. 2017

2 stripped stars needed for GW mergers
(isolated binary evolution case)



Kruckow et al. (2018), Langer et al. (2020), Tauris et al. (2017), …

Roche-lobe overflow - implementation



Star in reality — 3D

Star in MESA — 1D

How to know when the star fills its Roche lobe?

1. The Roche radius, R_L, is the radius of a sphere with the same volume as the Roche lobe

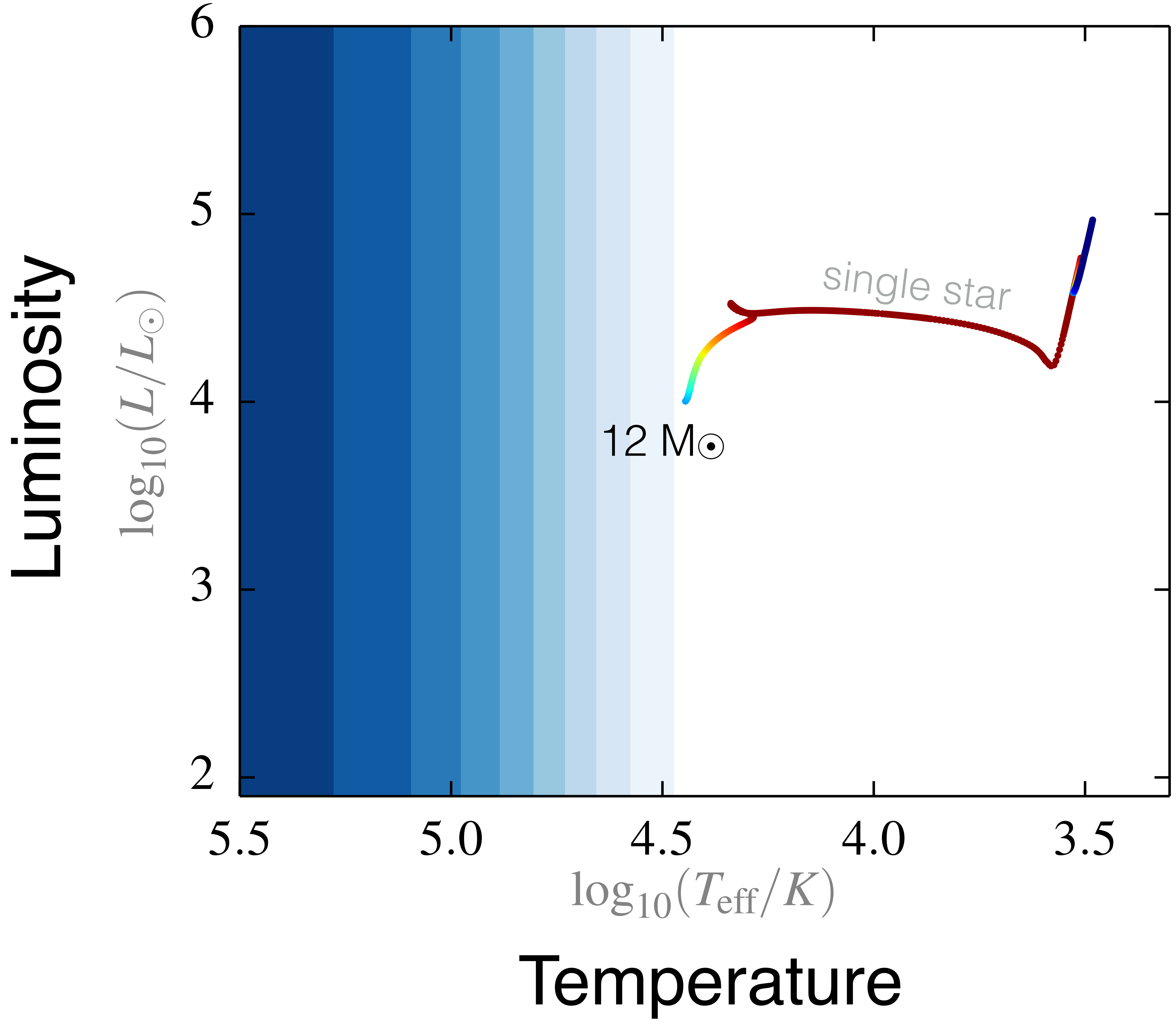
$$V = \frac{4\pi R_L^3}{3}$$

2. Eggleton (1983) found an approximate relation (accuracy: ~1%) for the Roche radius using the mass ratio, q=M1/M2, and the separation between the two stars, a.

$$\frac{R_{\mathrm{L}}}{a} = \frac{0.49q^{2/3}}{0.6q^{2/3} + \ln(1 + q^{1/3})}$$

3. Roche-lobe overflow starts when R > R_L

The creation of a stripped star



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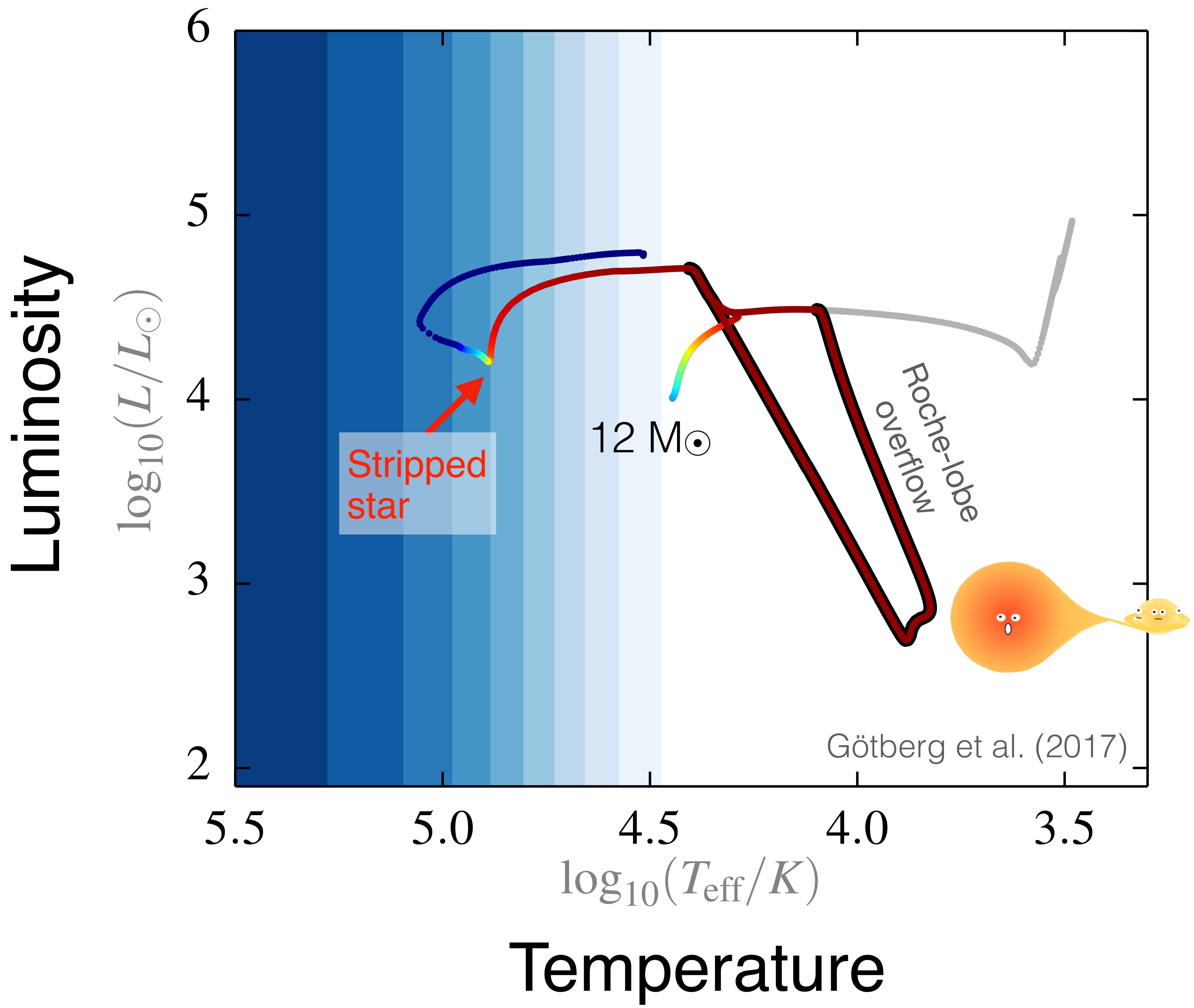

(cf. Kippenhahn & Weigert 1967, Paczyński 1971, Podsiadlowski et al. 1992, Smith et al. 2011, Graur et al. 2017)

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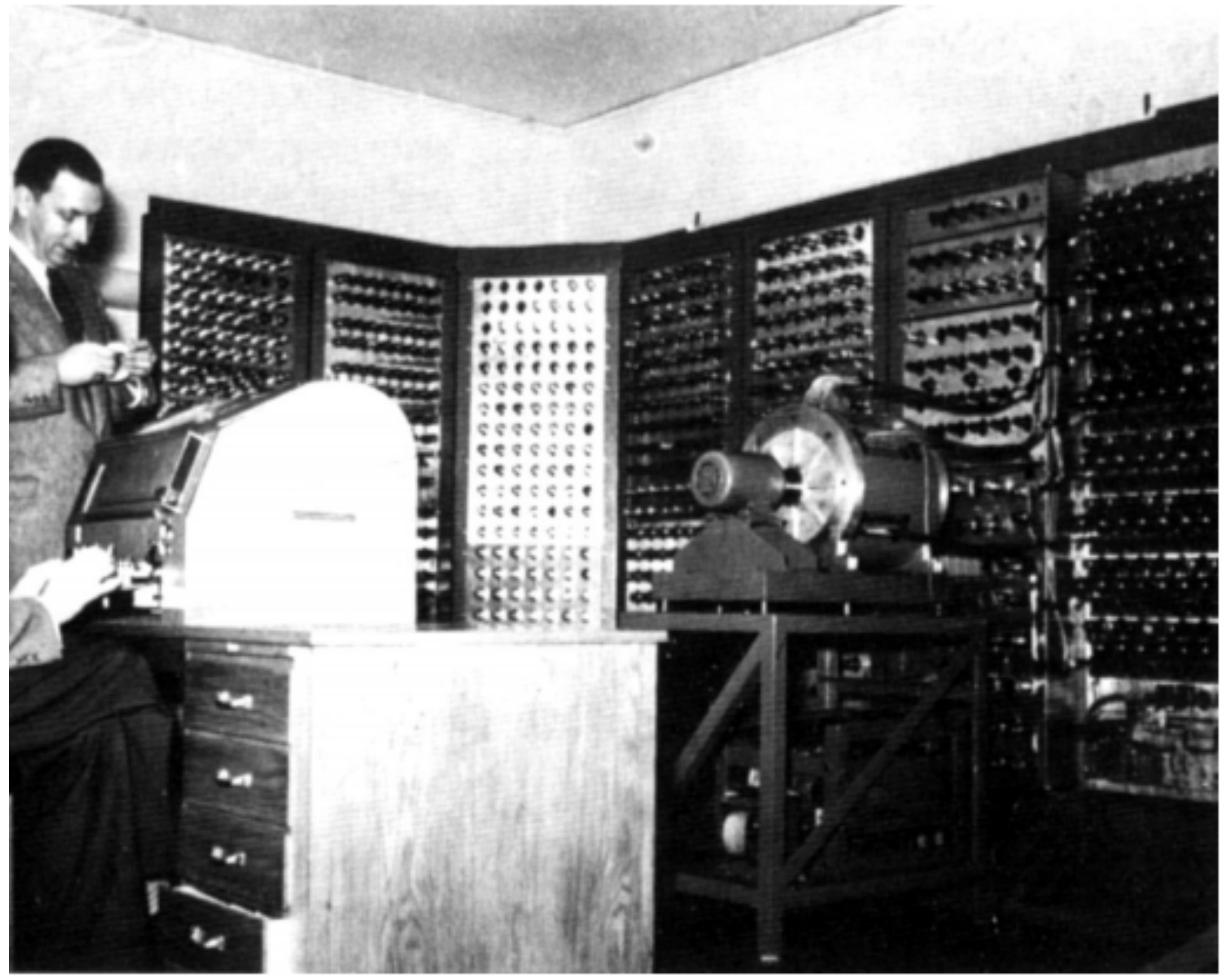
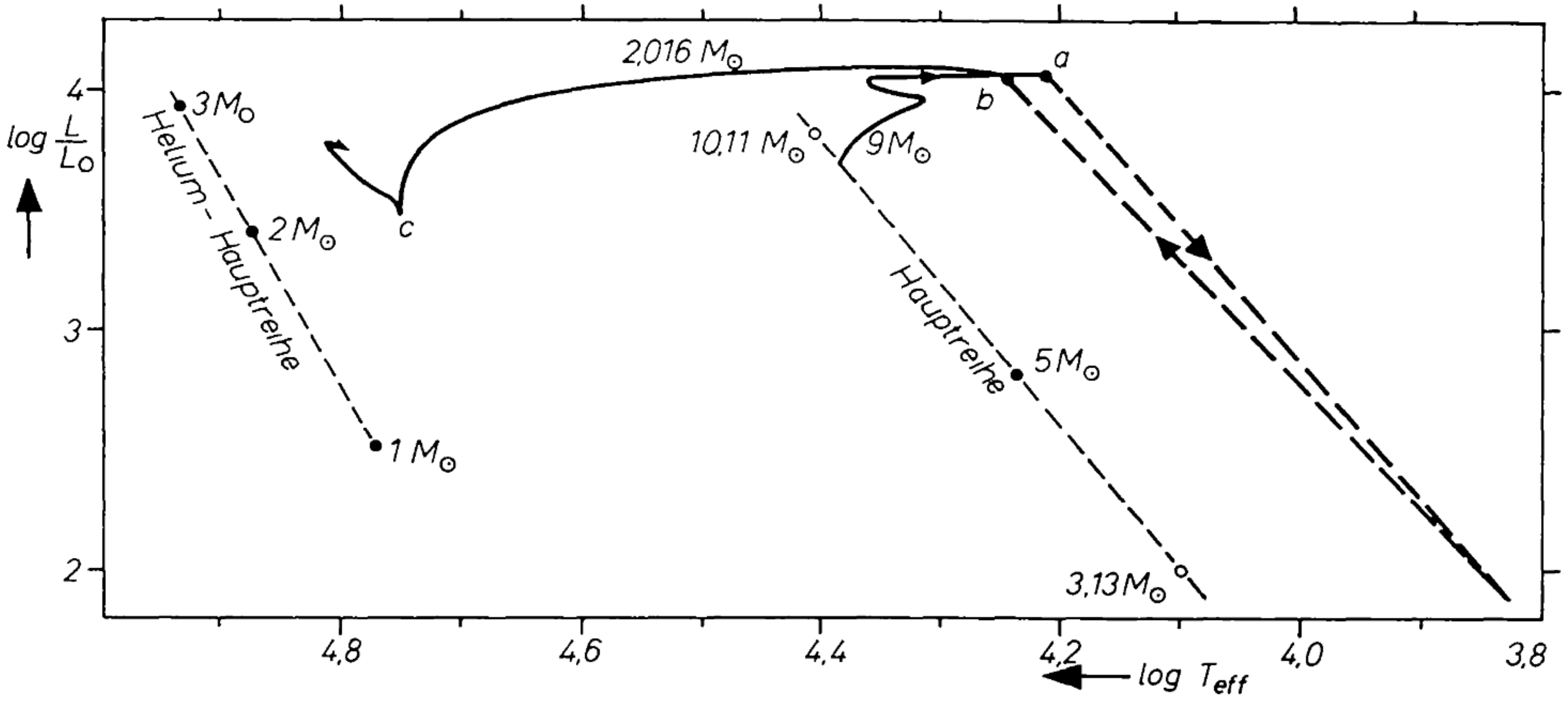


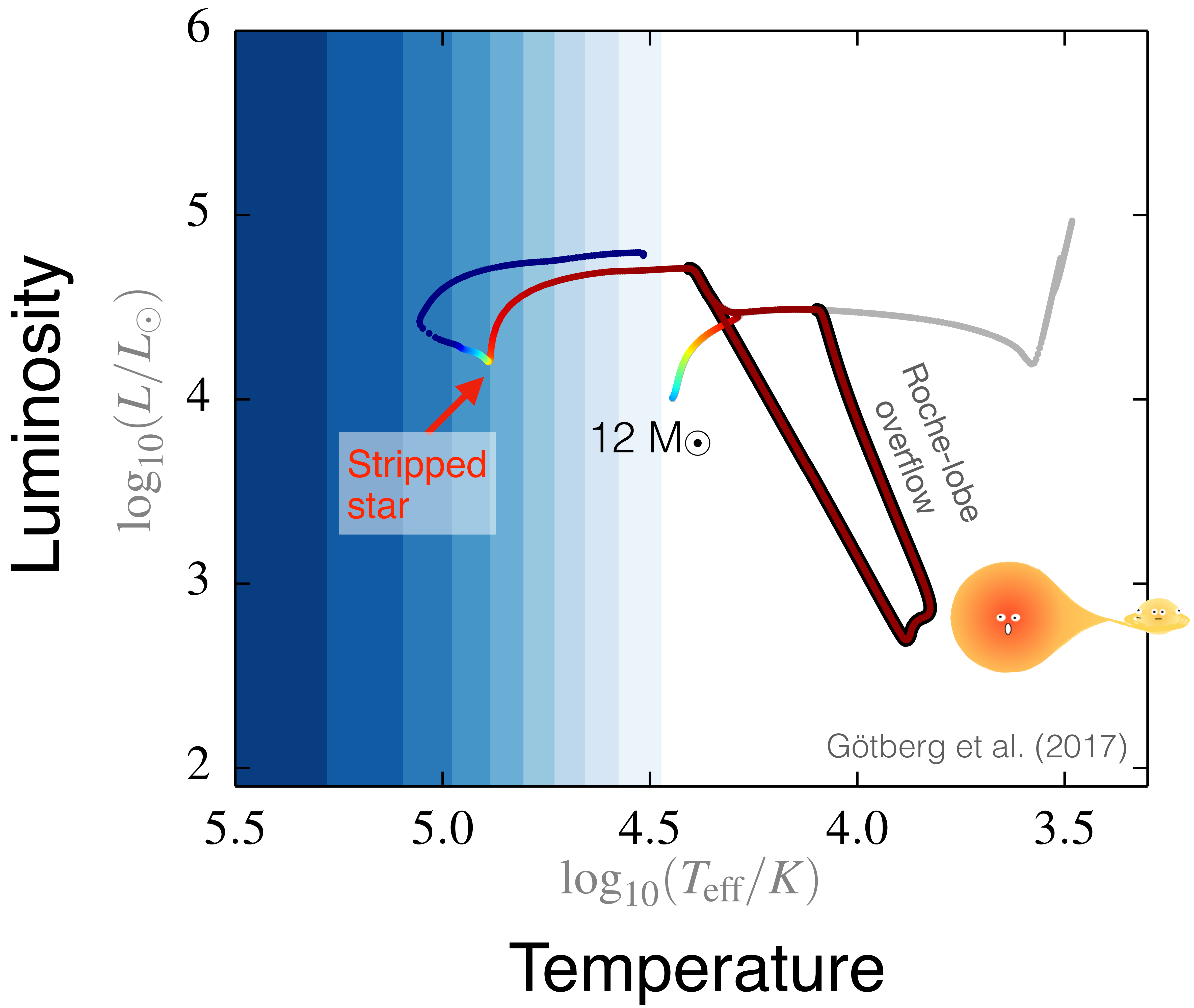
Computing stellar evolutionary models in Göttingen, 1957



(Kippenhahn & Weigert, 1967)

(cf. Smak 62, Paczyński 71, Yungel'Son 73, Massevitch+76, van den Heuvel+76, van der Linden 87, Podsiadlowski+92, Pols+98, Dewi+02/03, Eldridge+08, Yoon+10, Claeys+11, …)

The creation of a stripped star



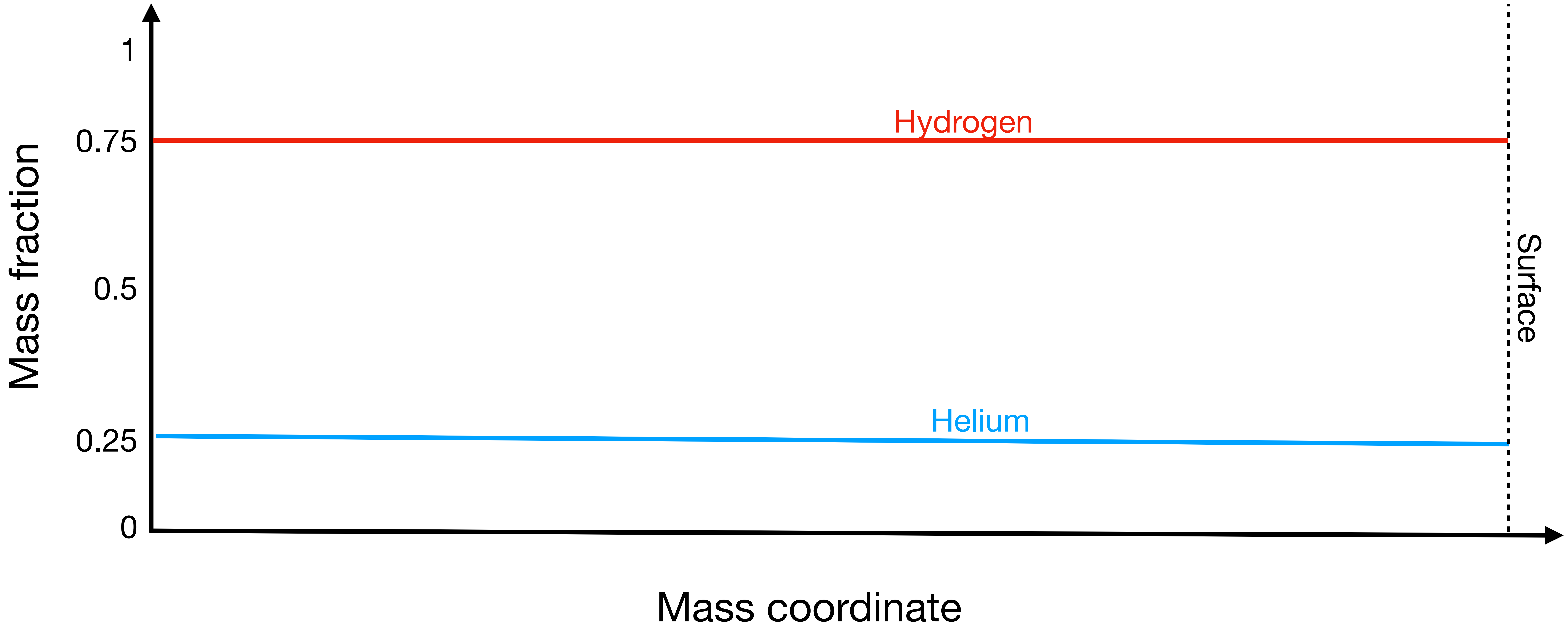
Minilab 1
(Task 1 & 2)

- Model mass transferring binary
- Identify Roche-lobe overflow phase
- Find stellar properties of a stripped star during He-burning

(cf. Kippenhahn & Weigert 1967, Paczyński 1971, Podsiadlowski et al. 1992, Smith et al. 2011, Graur et al. 2017)

Stellar winds affect leftover hydrogen

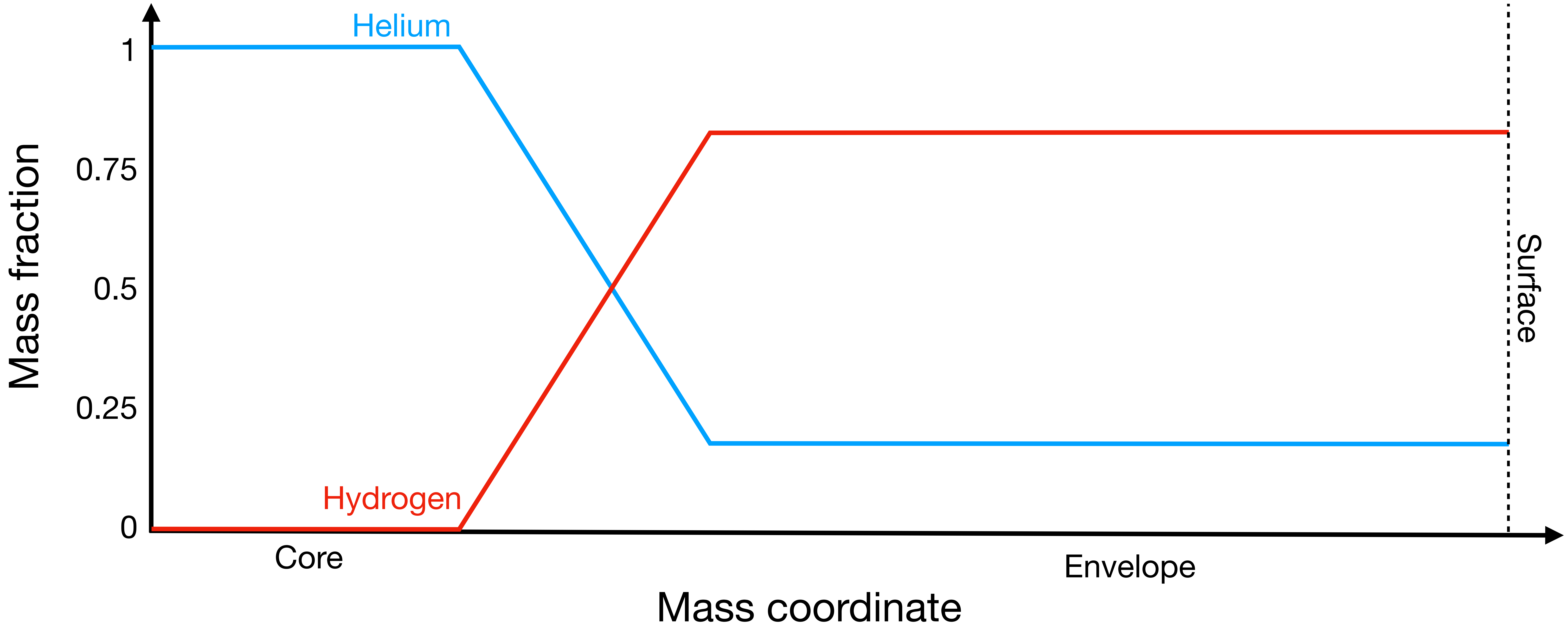
At zero-age main-sequence:



(Vink 2017, Gilkis et al. 2019, Shenar et al. 2020, Sander & Vink 2020)

Stellar winds affect leftover hydrogen

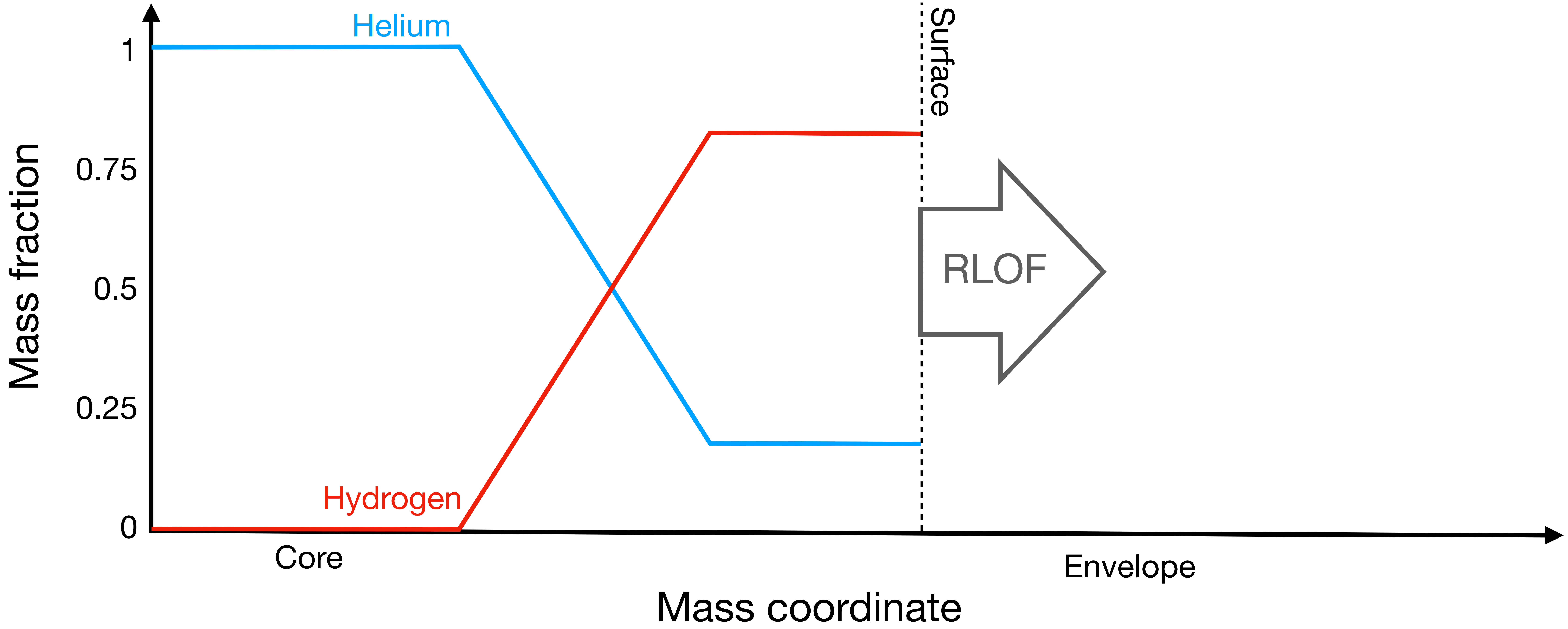
After main sequence:



(Vink 2017, Gilkis et al. 2019, Shenar et al. 2020, Sander & Vink 2020)

Stellar winds affect leftover hydrogen

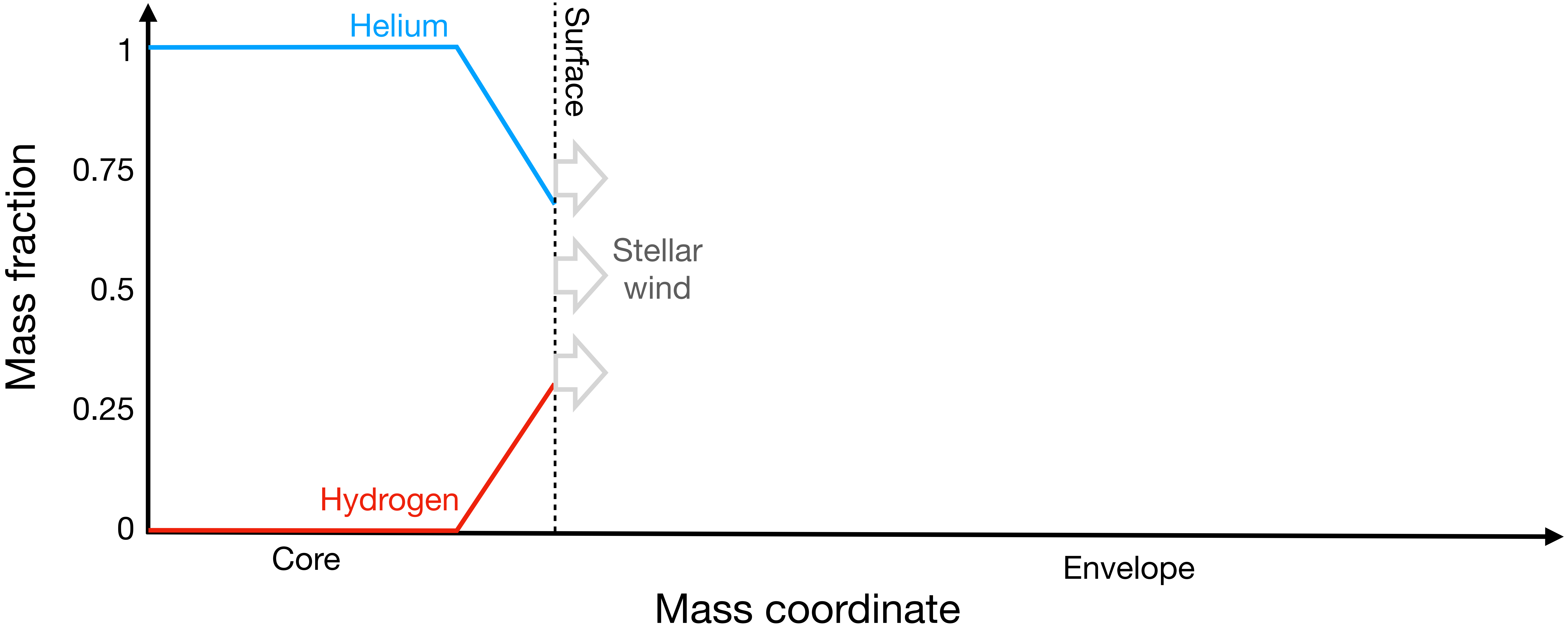
During Roche-lobe overflow:



(Vink 2017, Gilkis et al. 2019, Shenar et al. 2020, Sander & Vink 2020)

Stellar winds affect leftover hydrogen

After Roche-lobe overflow — a stripped star:



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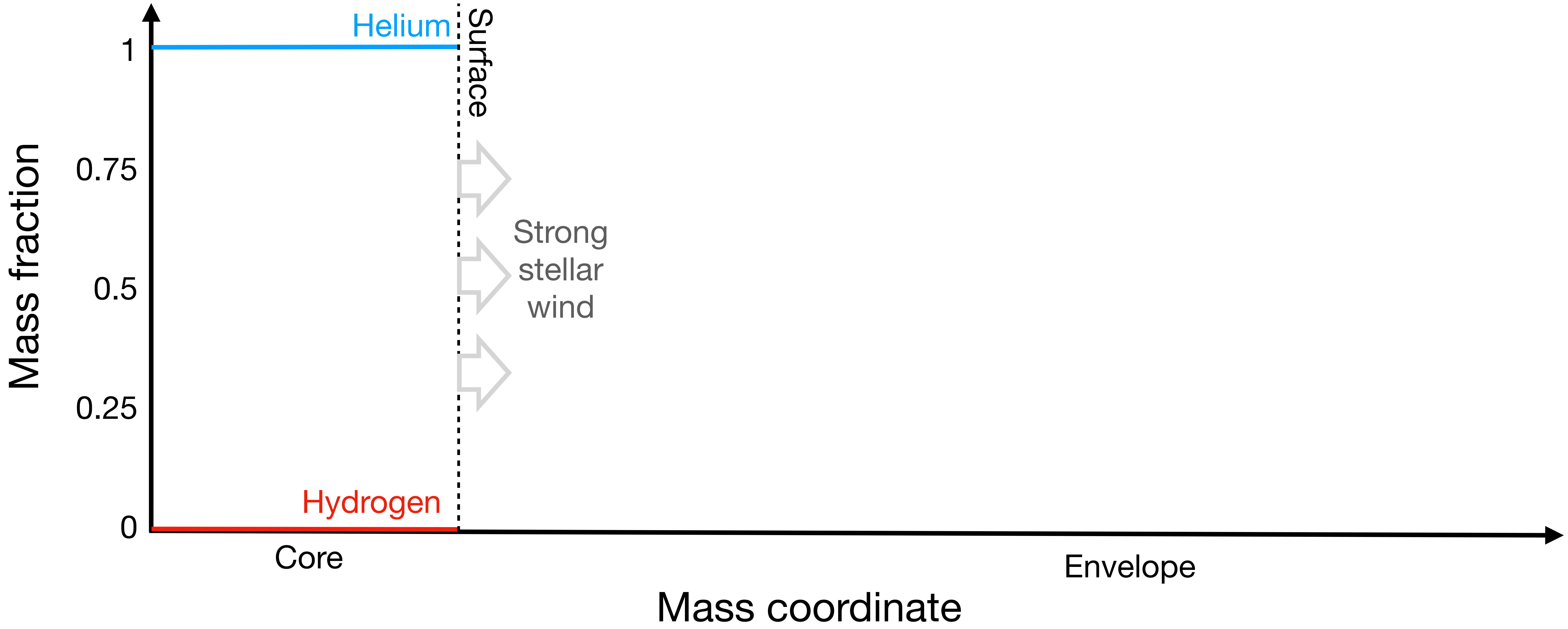

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Stellar winds affect leftover hydrogen

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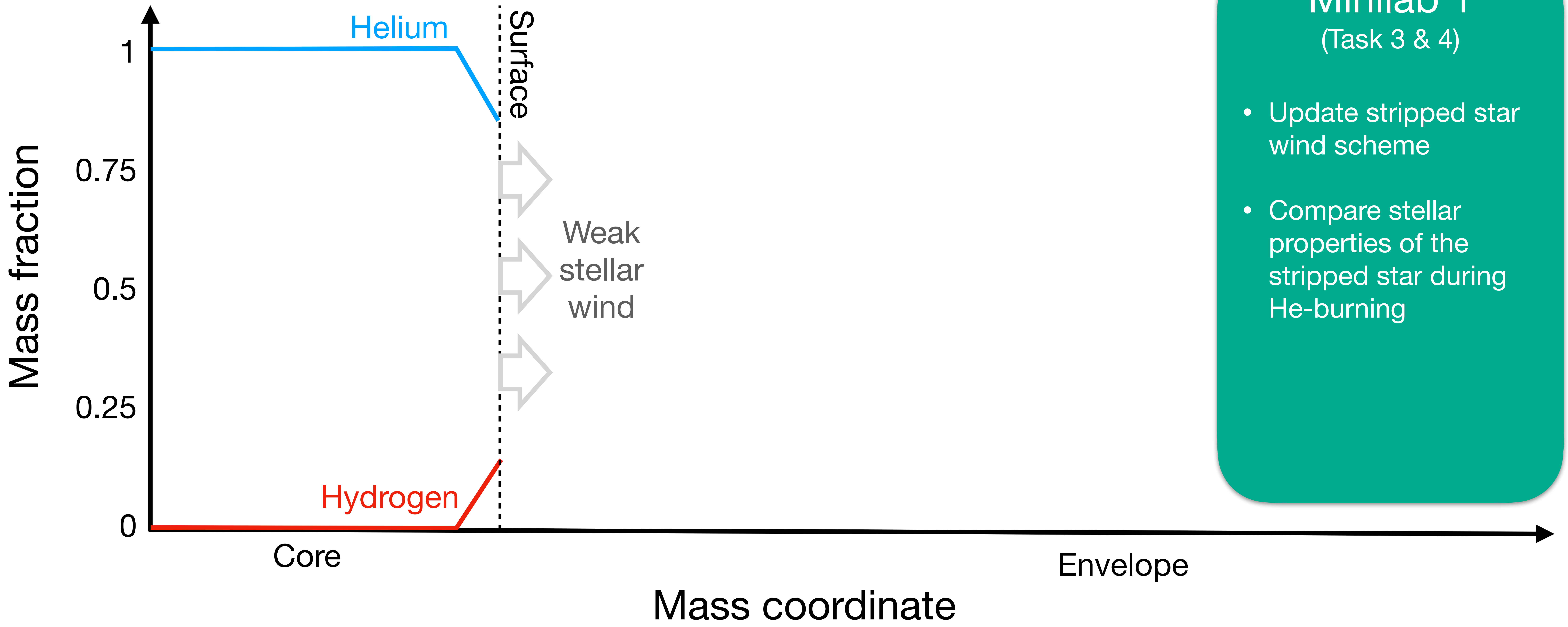
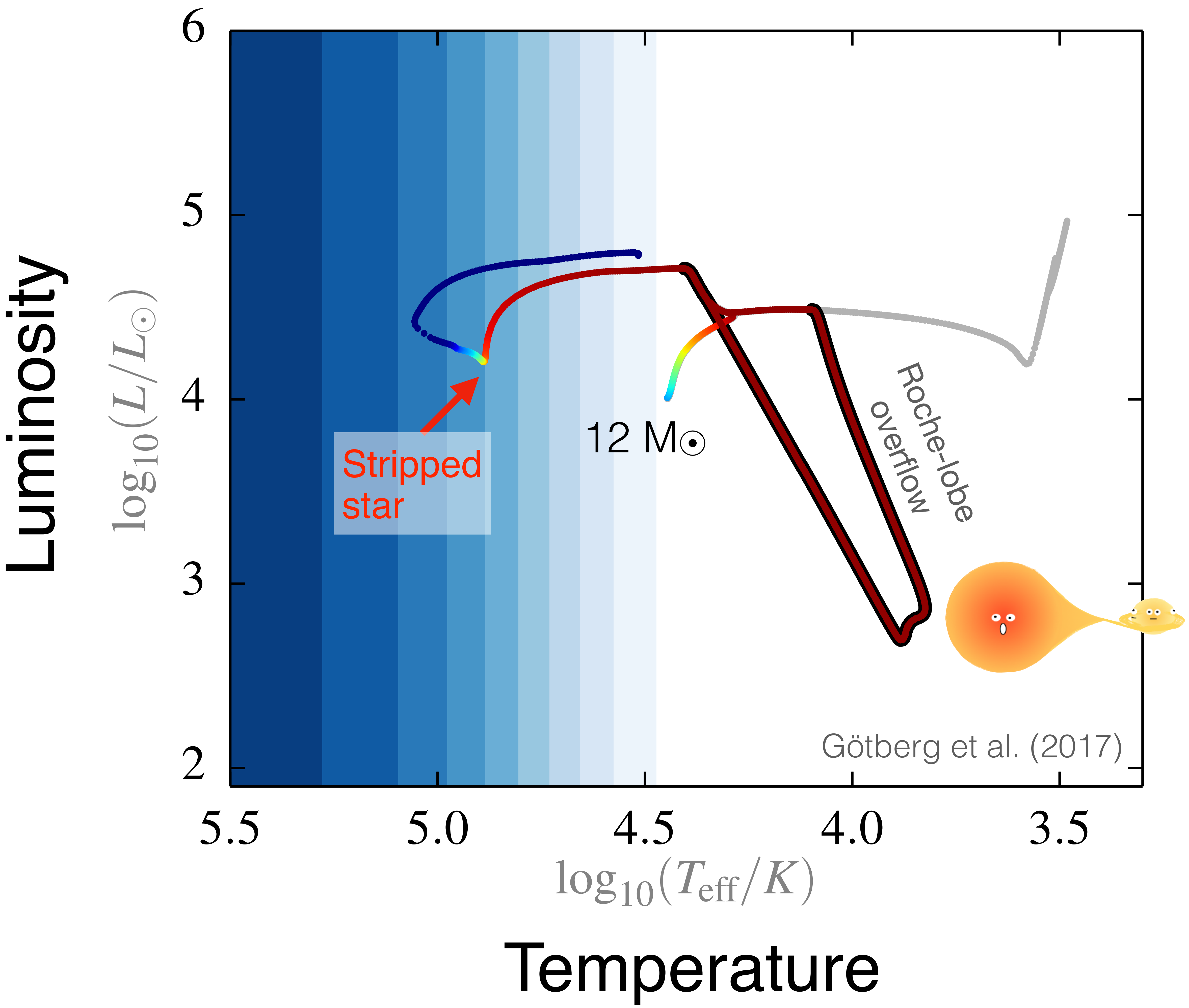


Minilab 1
(Task 3 & 4)

- Update stripped star wind scheme
- Compare stellar properties of the stripped star during He-burning

(Vink 2017, Gilkis et al. 2019, Shenar et al. 2020, Sander & Vink 2020)

Ionizing emission



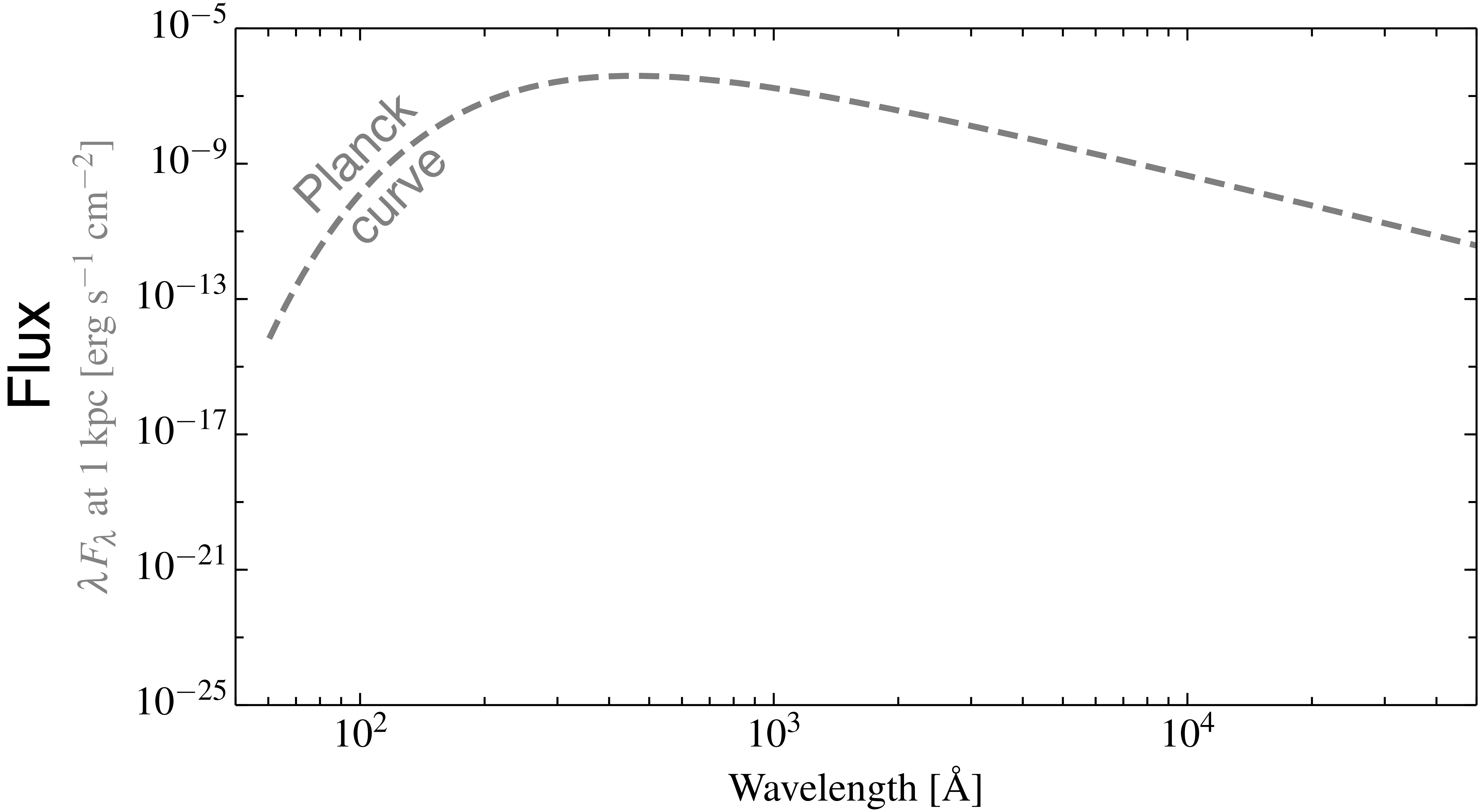
(cf. Kippenhahn & Weigert 1967, Paczyński 1971, Podsiadlowski et al. 1992, Smith et al. 2011, Graur et al. 2017)

BONUS

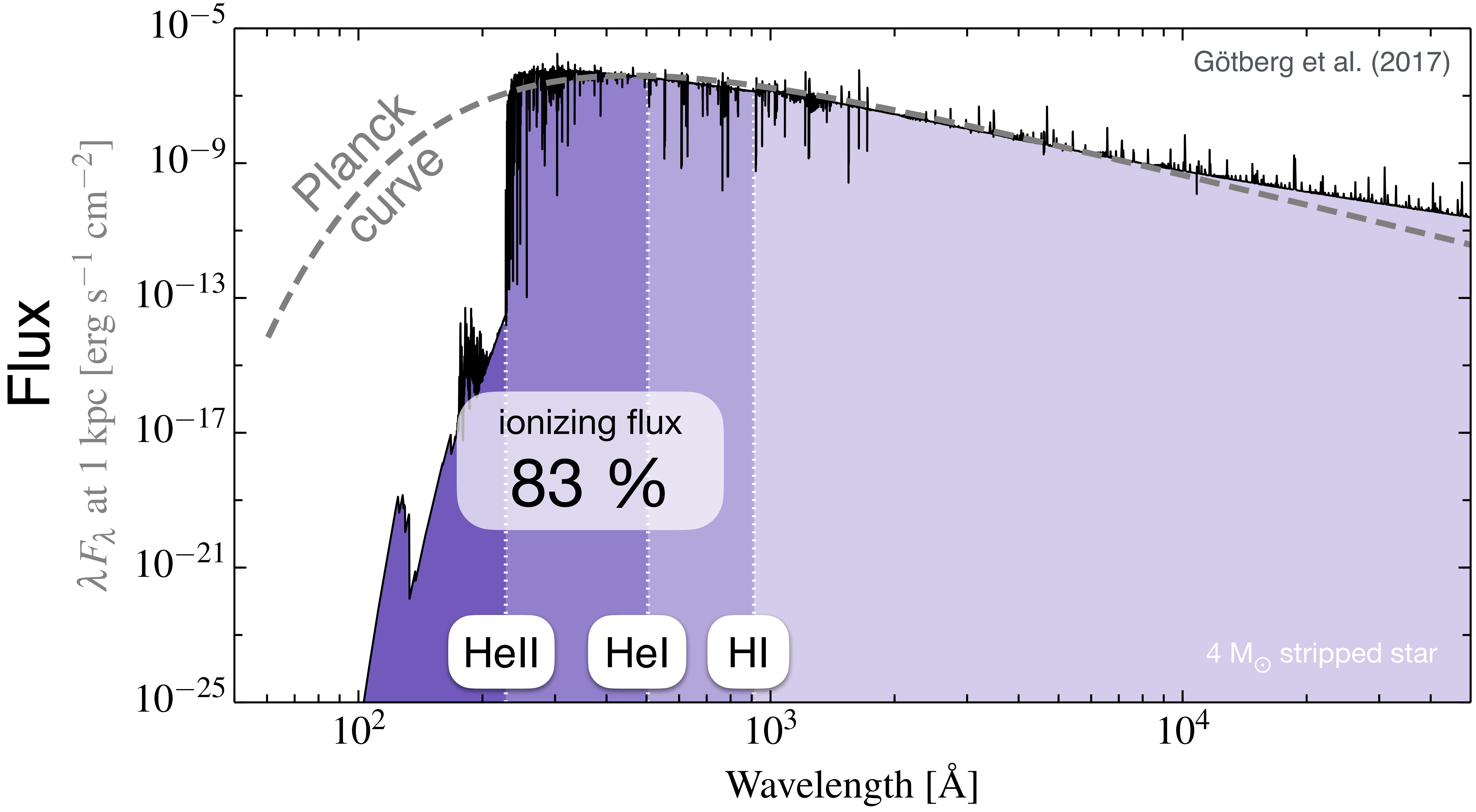
Minilab 1
(Bonus)

- Compare emission rate of H-ionizing photons with massive OB-type stars.

Ionizing emission



Ionizing emission



CMFGEN

Planck curve

$$B(\lambda, T) = \frac{2hc^2}{\lambda^5} \frac{1}{e^{\frac{hc}{\lambda k_B T}} - 1},$$

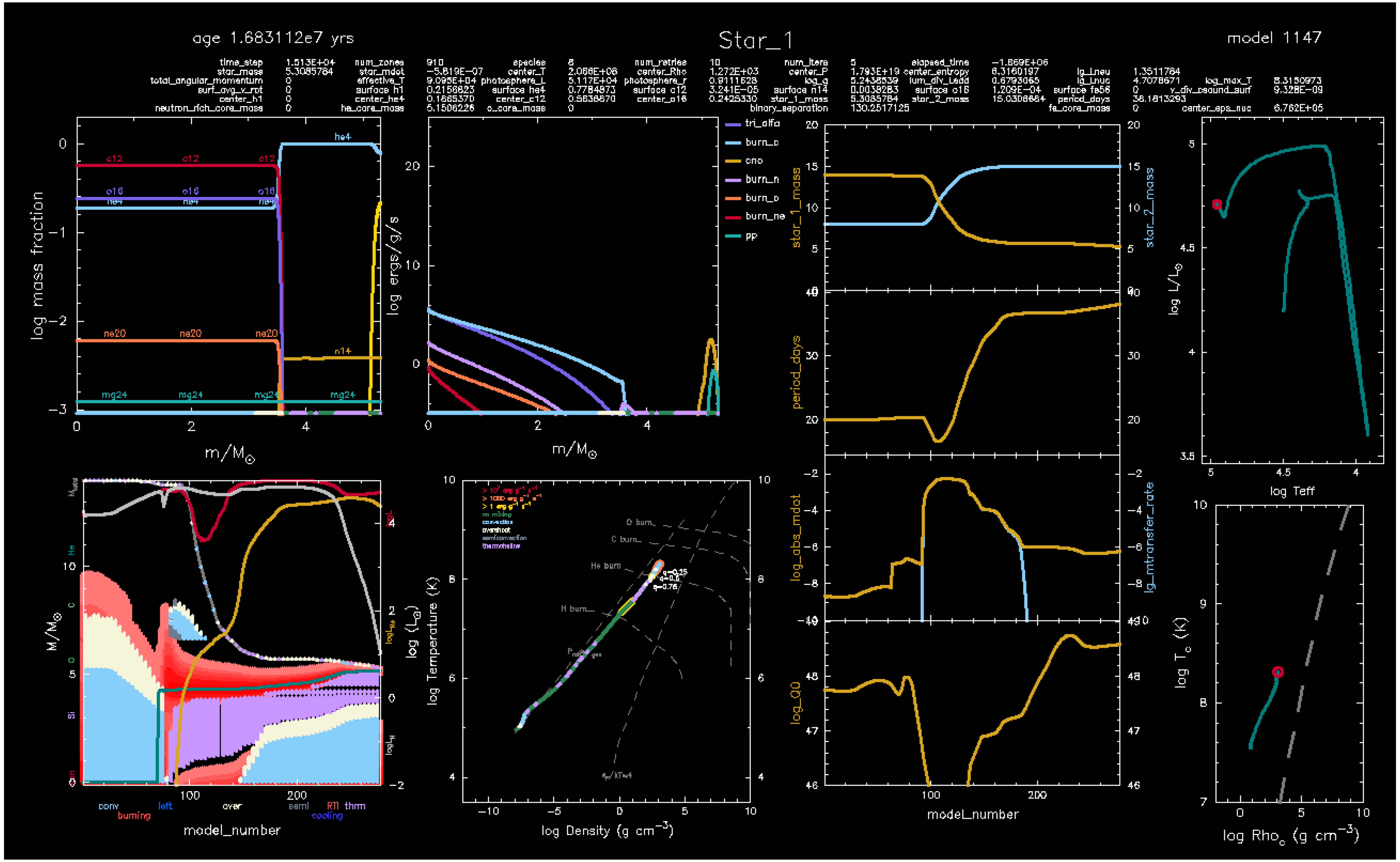
- Reasonably accurate for H-ionizing photons
- In-accurate for He+ ionizing photons

(see also Groh et al. 2008, Kim et al. 2015)

Time to have fun!

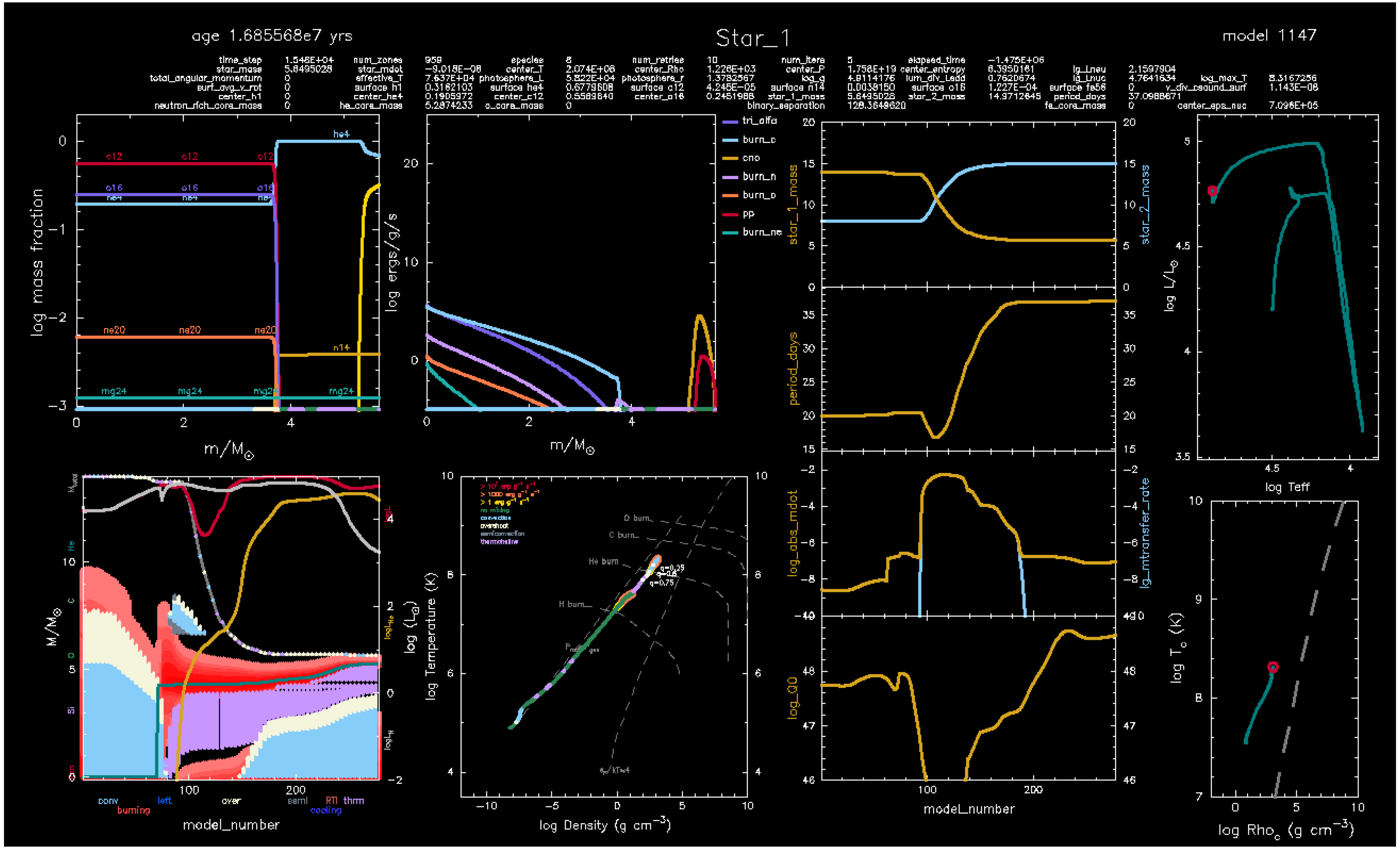
Minilab 1

Standard wind



Minilab 1

New wind
(Vink 2017)

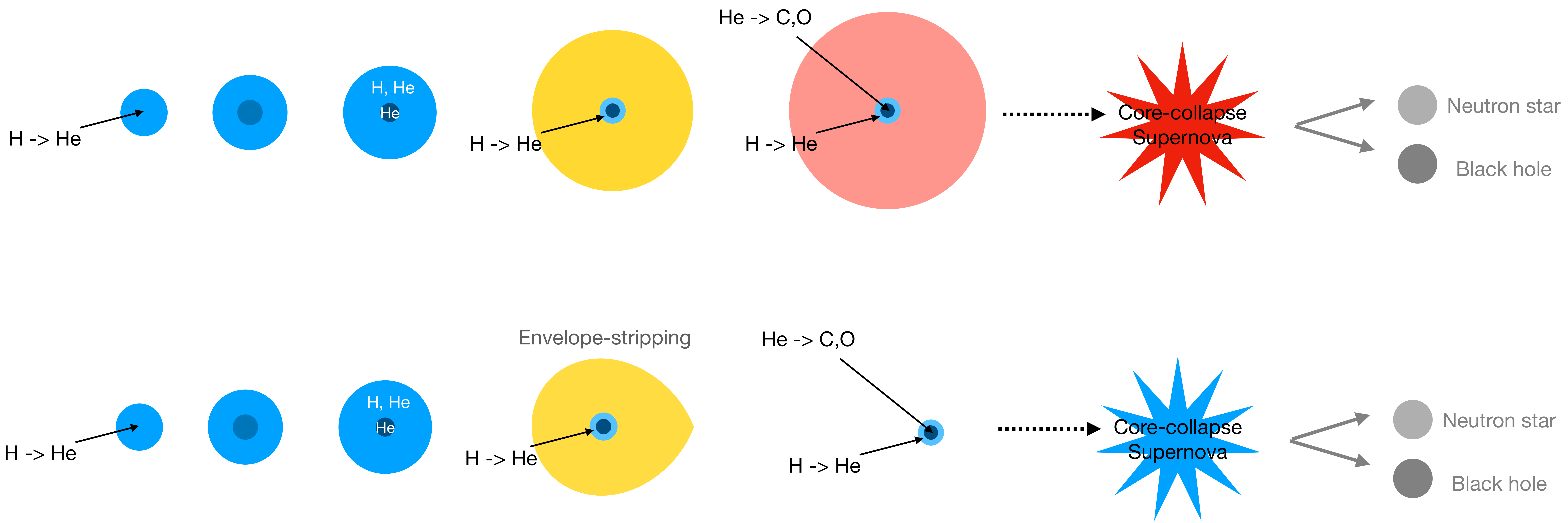


Break

Minilab 2

Stripped-envelope supernovae

Evolution to stellar death

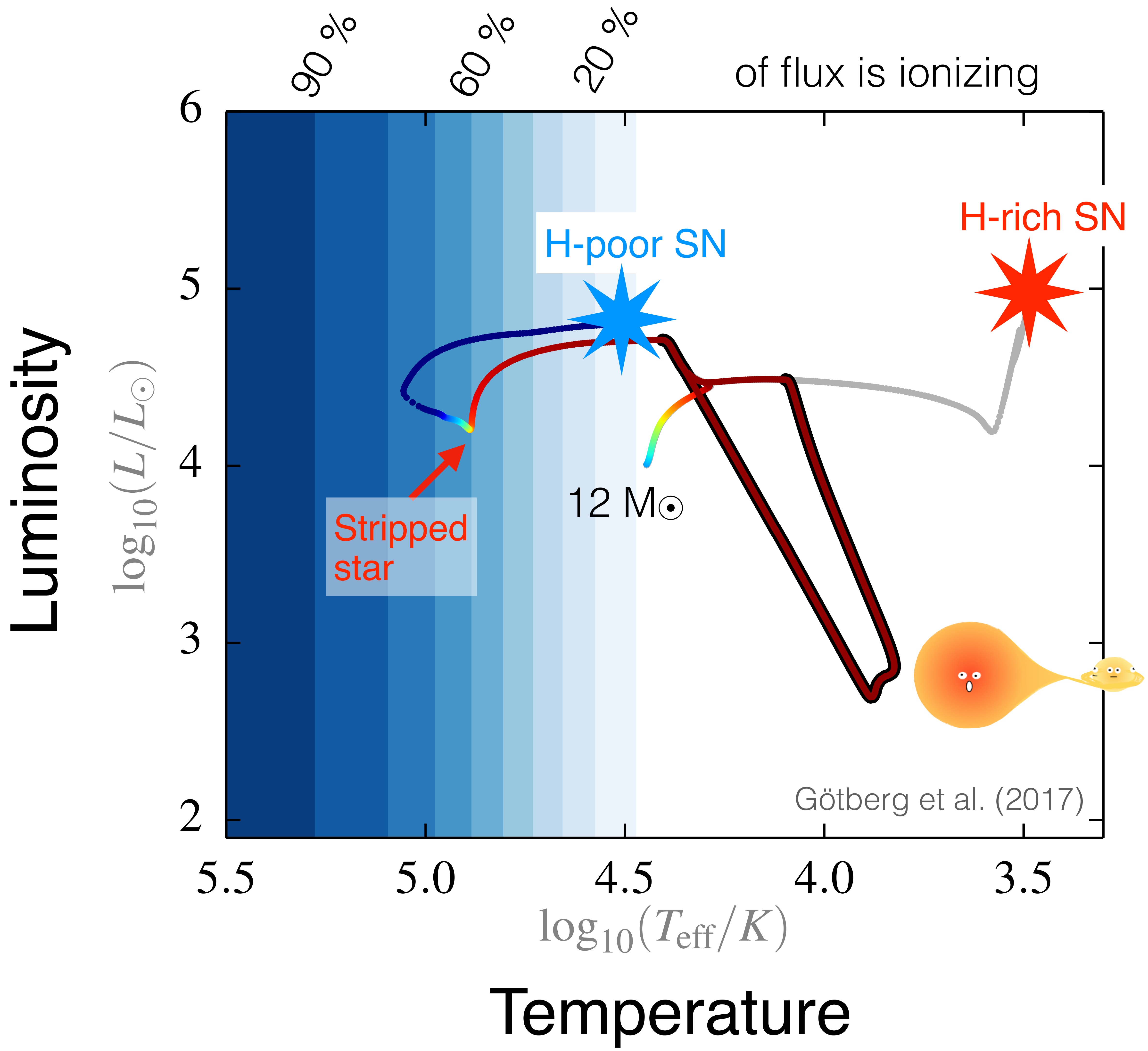


Supernova types

H-poor SNe

(Haichinger et al. 2012)

- **Type IIb**
  H-poor (> 0.03 Msun)
  He-rich (> 0.14 Msun)
- **Type Ib**
  H-free (< 0.02 Msun)
  He-rich (> 0.14 Msun)
- **Type Ic**
  H-free (< 0.02 Msun)
  He-free (< 0.06 Msun)



Minilab 2

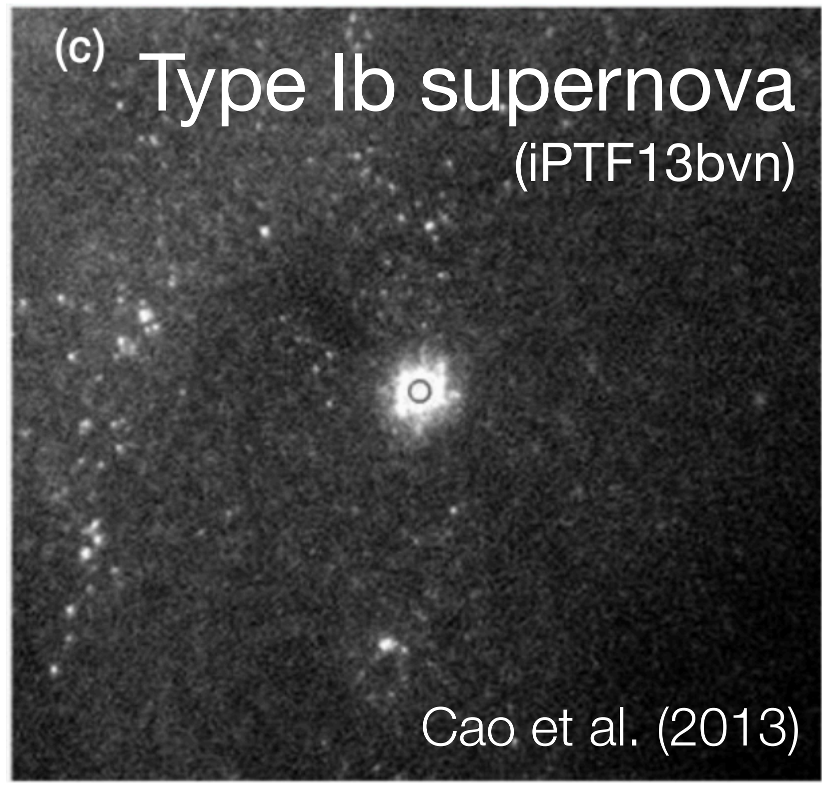
(Task 1-5)

- Predict what supernovae your strong and weak wind models should give rise to.
- Note: In weak wind case, do not wait for C-depletion, analyze the model once it enters 2nd RLOF.

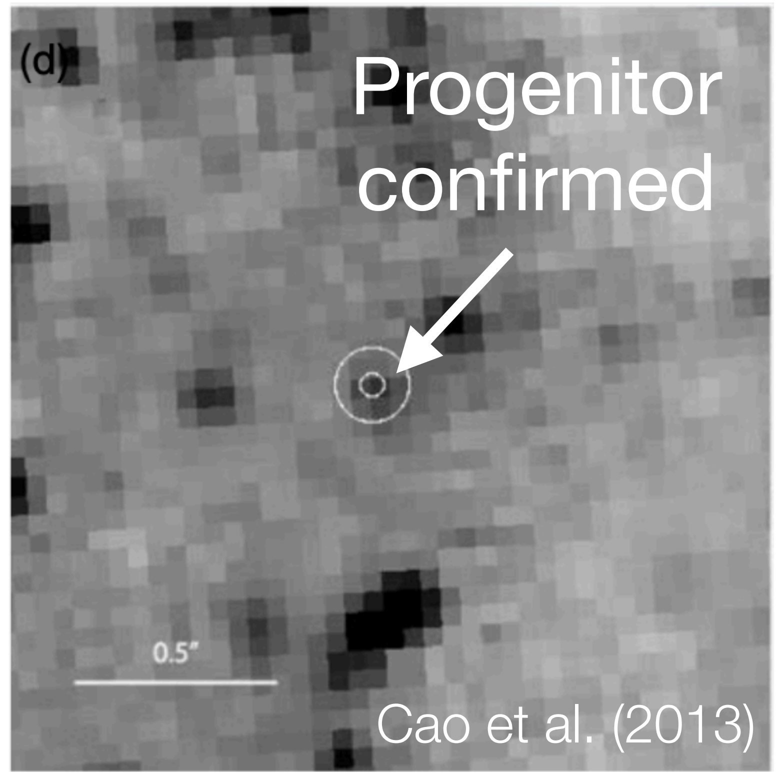
(Dessart et al. 2012, Smith et al. 2011, Graur et al. 2017)

Can stripped stars be confirmed as progenitors?

1. H-poor supernova is found



2. Is the progenitor visible in archival images?



About iPTF13bvn:
- Type Ib supernova
- Distance: 22.5 Mpc
- Apparent V-band magnitude: ~26 mag

Minilab 2
(Task 6-7)

- Assuming an apparent magnitude limit of V=25 mag, out to what distance can your SN progenitor be detected?
- Pick a different binary (spreadsheet) and record progenitor and SN properties.

MESA provides absolute magnitude

$$M = m - 5\log_{10}(d_{\rm pc}) + 5$$

Apparent magnitude

Distance in pc

Spreadsheet: Ylva - Minilab 2

Fill in your name to pick a binary:

M1_init	M2_init	Pinit=3 days	5 days	10 days	15 days
9 Msun	6 Msun	Student 1	Student 9	Student 17	Student 25
10 Msun	6 Msun	Student 2	Student 10	Student 18	Student 26
11 Msun	6 Msun	Student 3	Student 11	Student 19	Student 27
12 Msun	8 Msun	Student 4	Student 12	Student 20	Student 28
13 Msun	8 Msun	Student 5	Student 13	Student 21	Student 29
14 Msun	8 Msun	Student 6	Student 14	Student 22	Student 30
15 Msun	8 Msun	Student 7	Student 15	Student 23	Student 31
16 Msun	10 Msun	Student 8	Student 16	Student 24	Student 32

Record the absolute V-band magnitude the model has when it enters mass transfer dur

M1_init	M2_init	Pinit=3 days	5 days	10 days	15 days
9 Msun	6 Msun				
10 Msun	6 Msun				
11 Msun	6 Msun				
12 Msun	8 Msun				
13 Msun	8 Msun				
14 Msun	8 Msun				
15 Msun	8 Msun				
16 Msun	10 Msun				

Record the total H1 mass (total_mass_h1)

M1_init	M2_init	Pinit=3 days	5 days	10 days	15 days
9 Msun	6 Msun				
10 Msun	6 Msun				
11 Msun	6 Msun				
12 Msun	8 Msun				

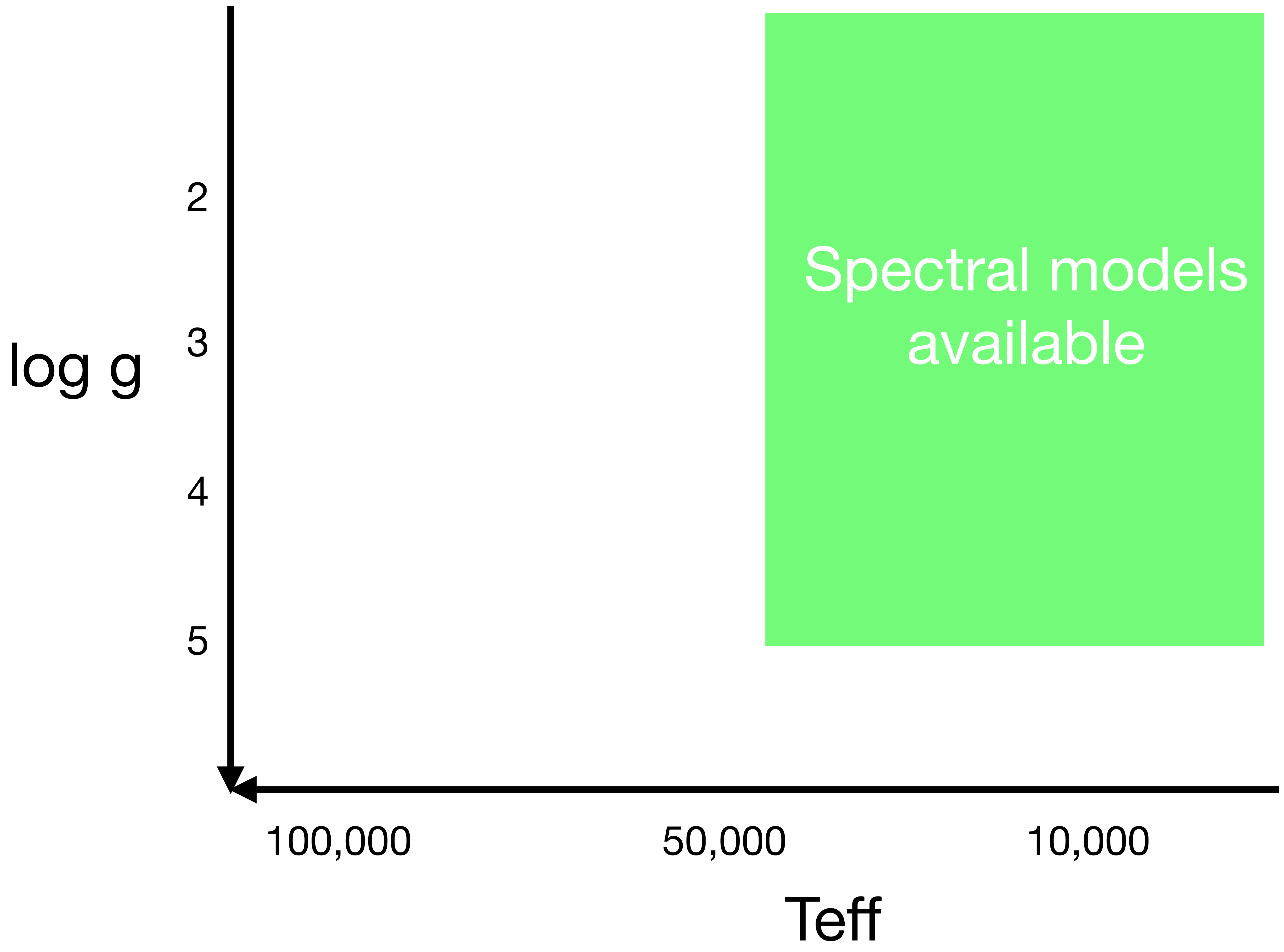
Obtaining magnitudes

Standard colors in MESA from matching stellar properties to spectral models ($MESA_DIR/colors module):

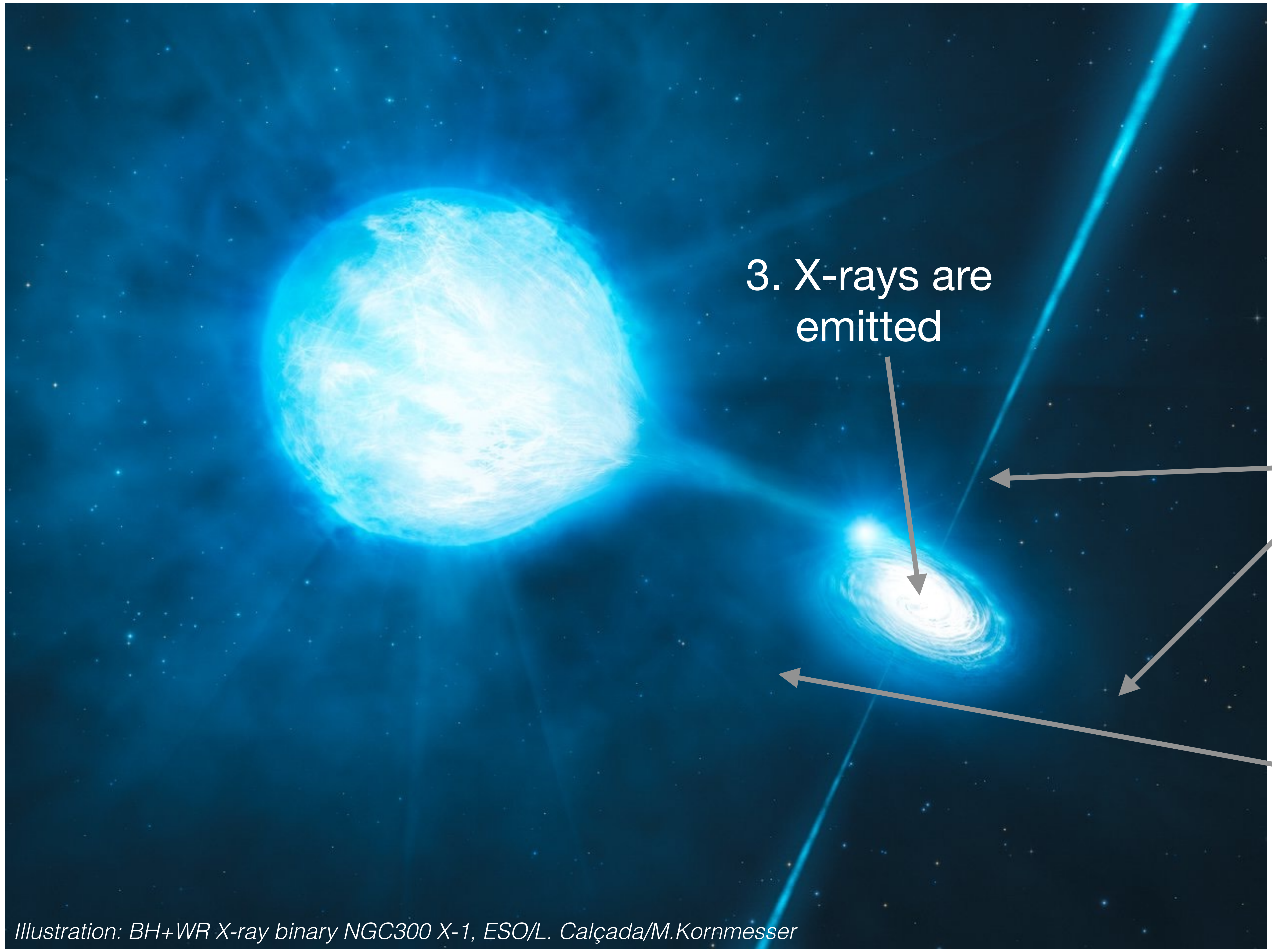
```
#Teff logg M_div_H   U  B  V  R  I  J  H  K  L  Lprime  M
2000.0 4.0 -0.1 -13.443 -11.39 -7.895 -4.464 -1.831 1.666 3.511 2.701 4.345 4.765 5.68
2000.0 4.5 -0.1 -13.402 -11.416 -7.896 -4.454 -1.794 1.664 3.503 2.728 4.352 4.772 5.687
2000.0 5.0 -0.1 -13.358 -11.428 -7.888 -4.431 -1.738 1.664 3.488 2.753 4.361 4.779 5.685
2000.0 5.5 -0.1 -13.22 -11.079 -7.377 -4.136 -1.483 1.656 3.418 2.759 4.355 4.753 5.638
2200.0 3.5 -0.1 -11.866 -9.557 -6.378 -3.612 -1.185 1.892 3.294 2.608 3.929 4.289 4.842
```

...

```
30000.0 4.0 1.0 -1.431 -2.509 -2.769 -2.915 -3.077 -3.496 -3.745 -3.628 -3.852 -3.869 -4.161
30000.0 4.5 1.0 -1.485 -2.548 -2.805 -2.953 -3.115 -3.533 -3.778 -3.663 -3.885 -3.901 -4.189
30000.0 5.0 1.0 -1.529 -2.582 -2.834 -2.982 -3.141 -3.557 -3.8 -3.686 -3.905 -3.921 -4.206
31000.0 4.0 1.0 -1.495 -2.585 -2.848 -2.994 -3.158 -3.583 -3.835 -3.716 -3.945 -3.962 -4.258
31000.0 4.5 1.0 -1.542 -2.618 -2.88 -3.03 -3.195 -3.62 -3.869 -3.752 -3.978 -3.994 -4.287
31000.0 5.0 1.0 -1.587 -2.653 -2.91 -3.061 -3.224 -3.646 -3.893 -3.777 -3.999 -4.016 -4.306
32000.0 4.5 1.0 -1.603 -2.69 -2.956 -3.108 -3.275 -3.704 -3.957 -3.838 -4.067 -4.084 -4.381
32000.0 5.0 1.0 -1.644 -2.722 -2.984 -3.137 -3.303 -3.731 -3.982 -3.864 -4.089 -4.106 -4.401
33000.0 4.5 1.0 -1.665 -2.762 -3.032 -3.184 -3.353 -3.785 -4.042 -3.921 -4.153 -4.17 -4.472
33000.0 5.0 1.0 -1.702 -2.791 -3.057 -3.211 -3.38 -3.813 -4.067 -3.947 -4.176 -4.193 -4.491
34000.0 4.5 1.0 -1.73 -2.836 -3.111 -3.263 -3.432 -3.866 -4.126 -4.003 -4.238 -4.255 -4.561
34000.0 5.0 1.0 -1.762 -2.861 -3.132 -3.287 -3.457 -3.893 -4.151 -4.029 -4.261 -4.278 -4.581
35000.0 4.5 1.0 -1.799 -2.912 -3.191 -3.343 -3.513 -3.949 -4.209 -4.086 -4.323 -4.341 -4.647
35000.0 5.0 1.0 -1.826 -2.933 -3.208 -3.364 -3.535 -3.973 -4.233 -4.11 -4.344 -4.362 -4.667
37500.0 5.0 1.0 -1.996 -3.118 -3.403 -3.559 -3.731 -4.17 -4.433 -4.308 -4.546 -4.564 -4.873
40000.0 5.0 1.0 -2.173 -3.304 -3.6 -3.756 -3.93 -4.37 -4.633 -4.508 -4.747 -4.765 -5.075
```



Black hole companions



1. Some mass is ejected

2. BH moves through stellar wind -> can accrete

BONUS

Minilab 2
(Bonus)

- Model X-ray luminosity as the donor star evolves
- When is the system bright in X-rays?

Time for explorations!