Common Envelope Physics

Natasha Ivanova

University of Alberta

“Merging Visions:
Exploring Compact-Object Binaries with Gravity and Light”
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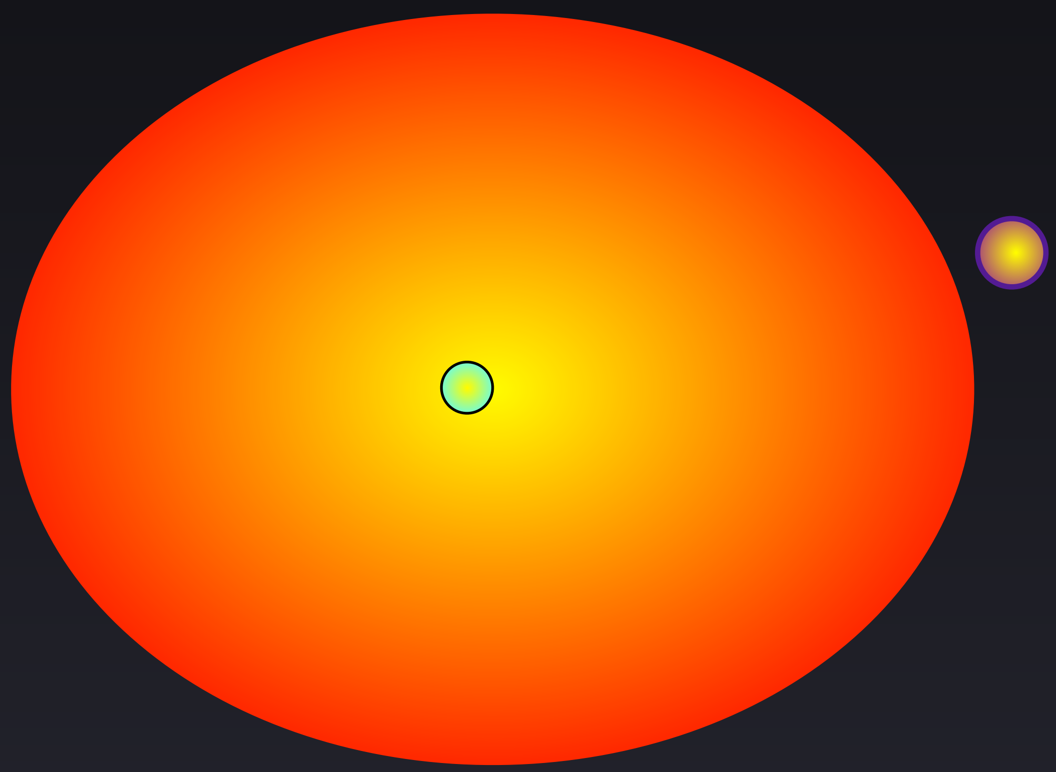
Common envelope event

Unstable mass transfer (1976: Webbink, Paczynski, Ostriker).

- ➡ It is a rapid phase, during which a smaller companion spirals inward through the extended envelope of the larger (often more massive primary) donor.
- ➡ The common envelope event is terminated upon **ejection** of the common envelope (when a binary with much smaller orbital separation than in the initial binary is formed) or **merger.**
- ➡ CEE is an ultimate tool of transforming of initially wide binaries in close interacting binaries



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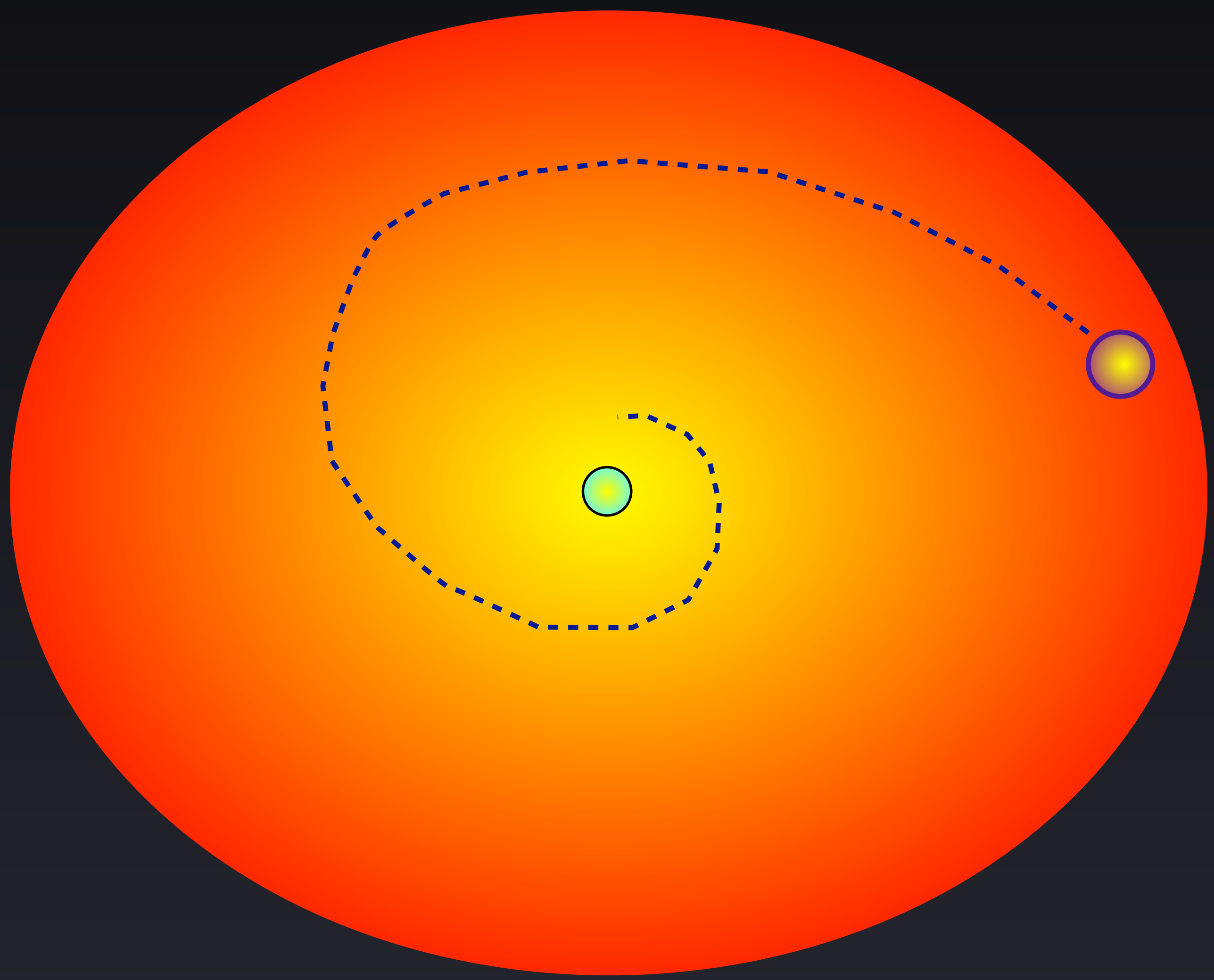

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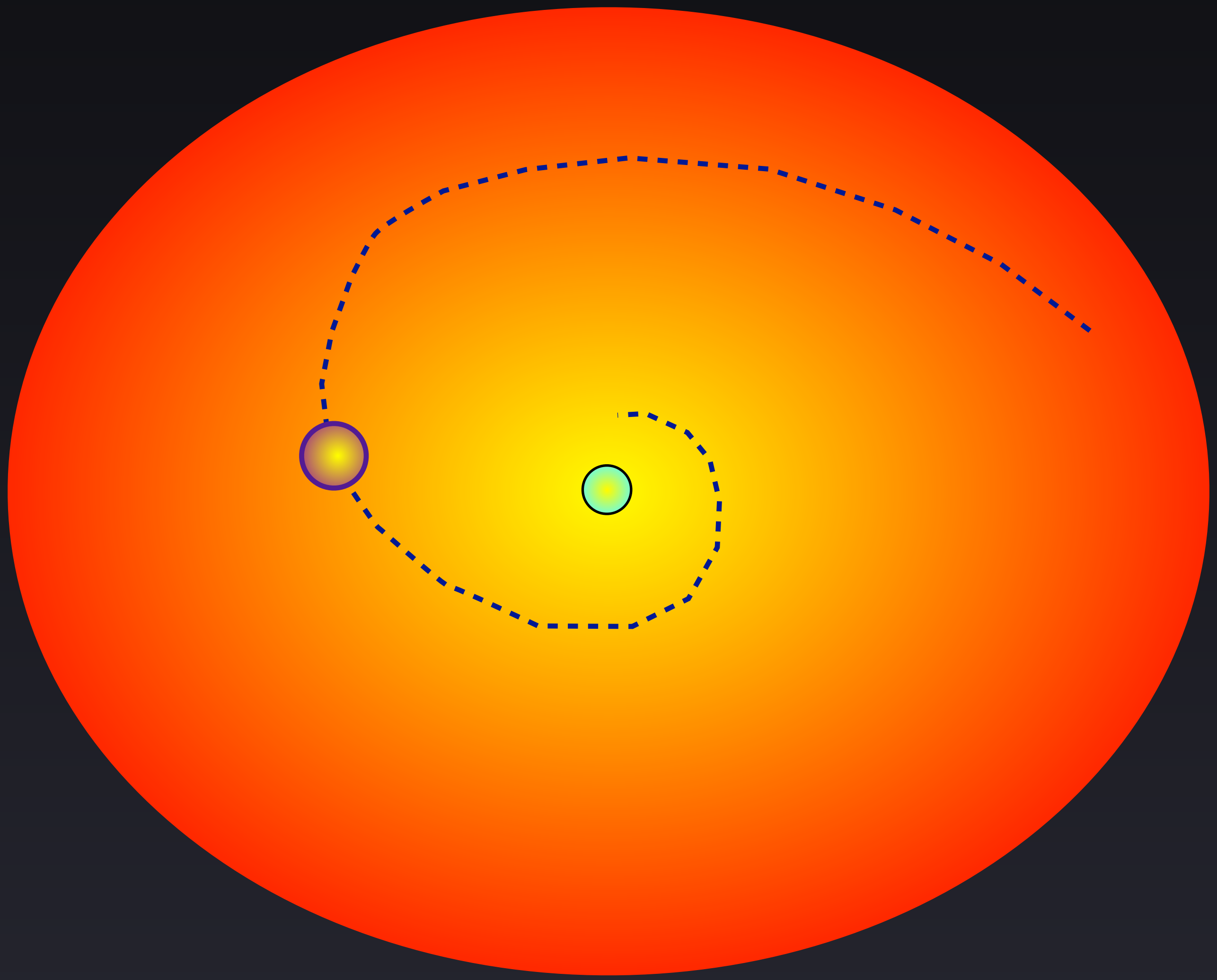

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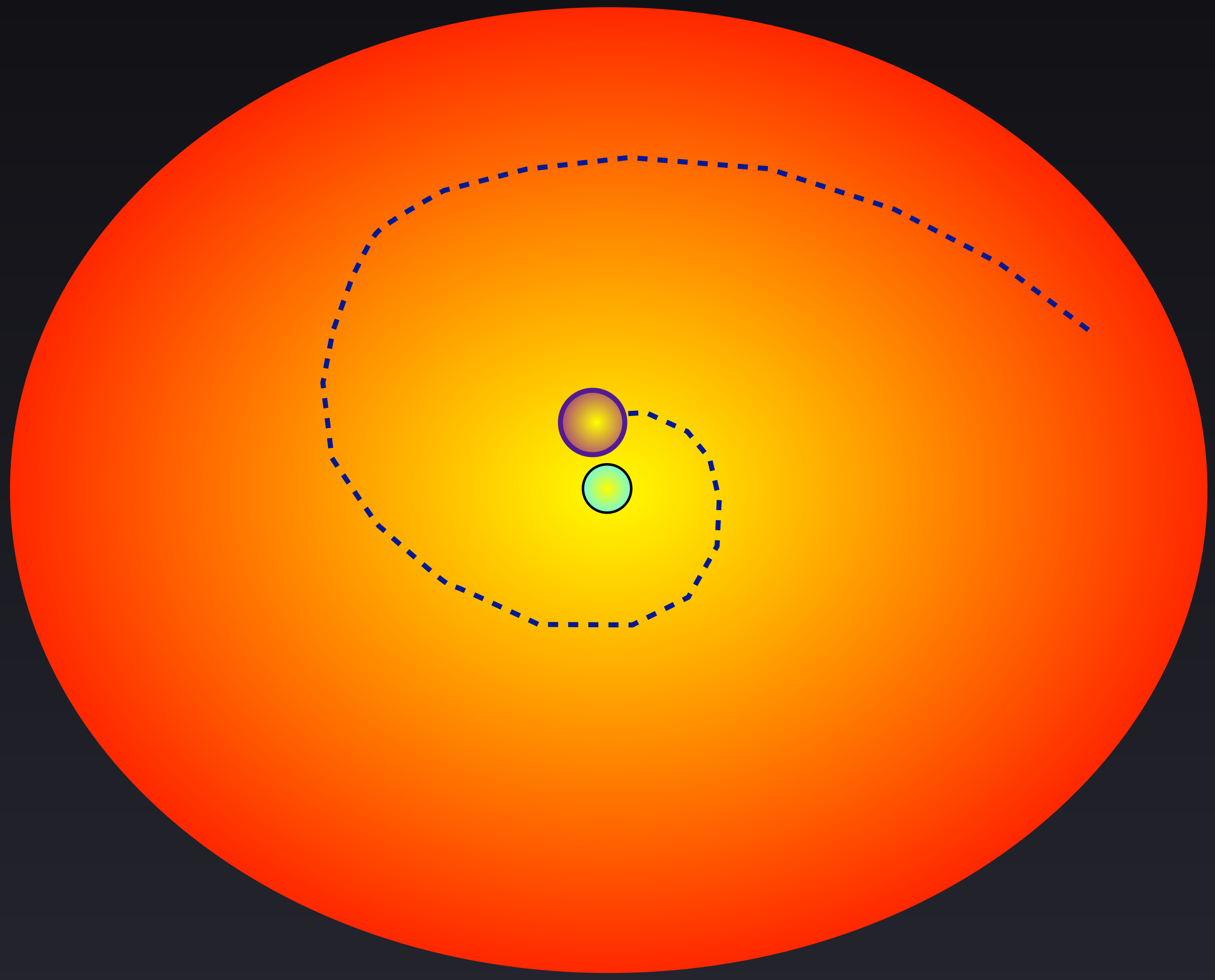

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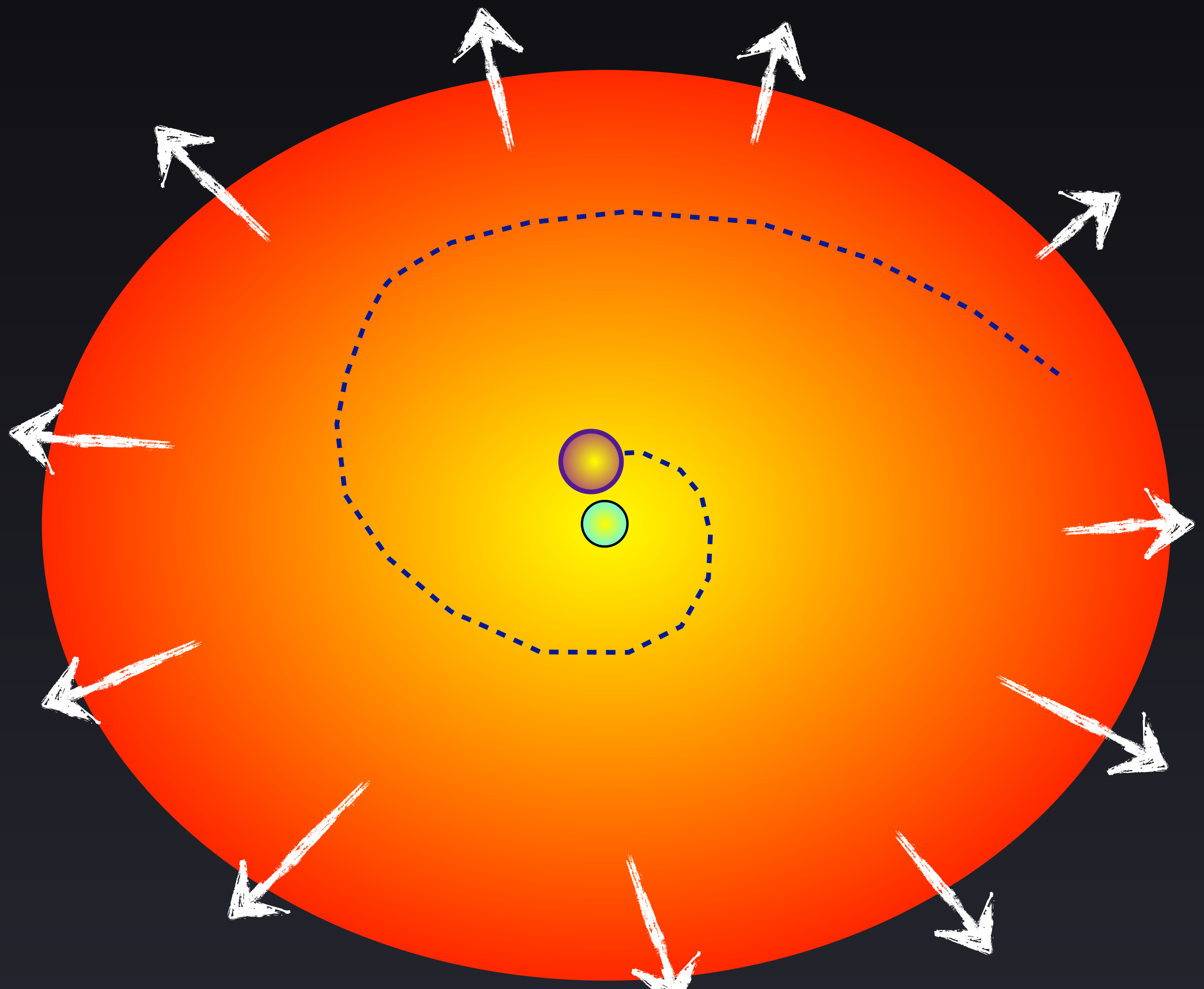

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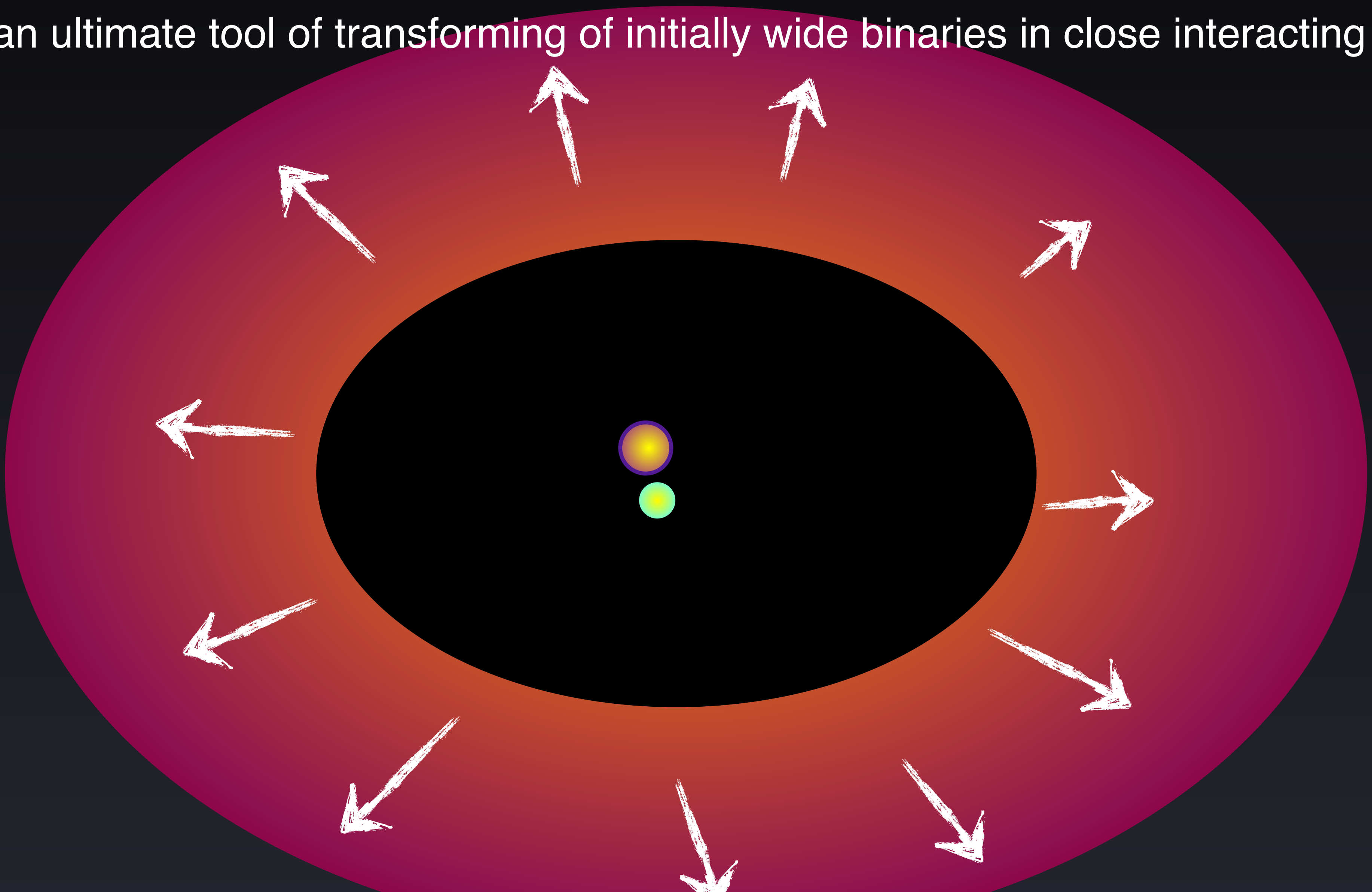
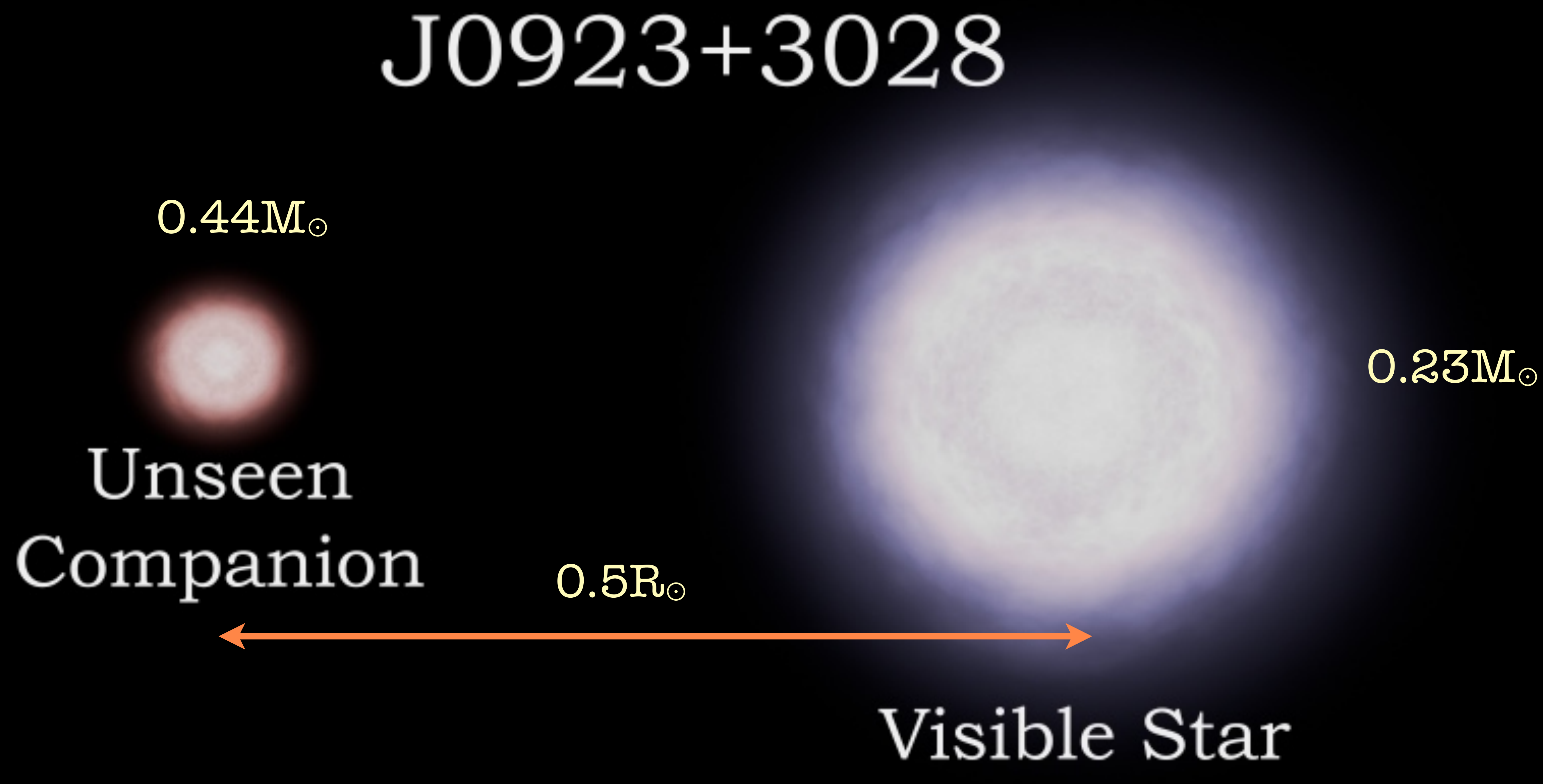


Double White Dwarf



Credit: Clayton Ellis (CfA)

In the past, each of these stars was at least 10R⊙

I am doing super-cool DBH or DNS mergers
Why should I care about boring double WDs?

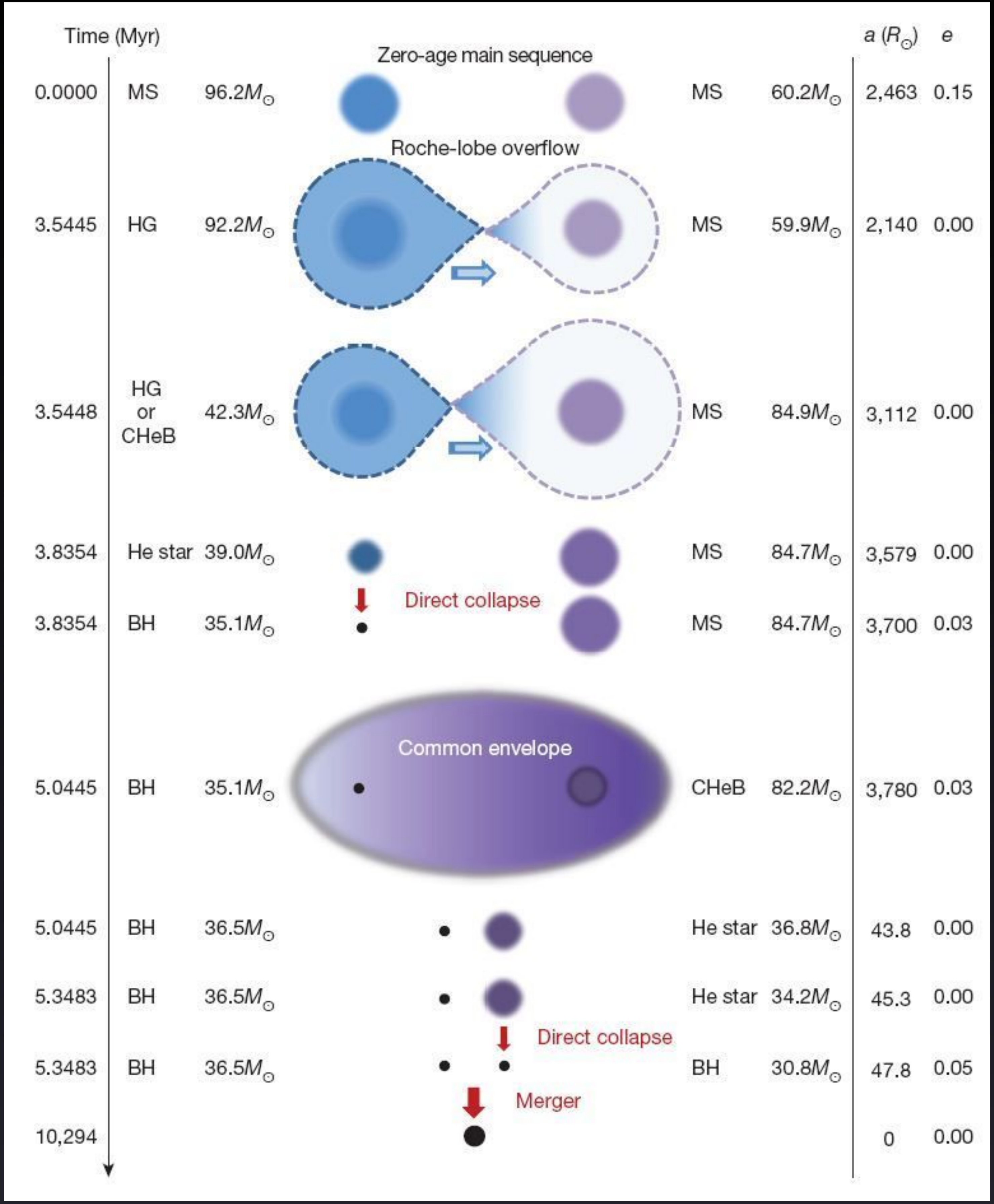
I am doing super-cool DBH or DNS mergers
Why should I care about boring double WDs?

The bad news in that CE is effective in making the binaries you are interested in. It is also effective in killing a bunch of potential DBHs and DNSs!

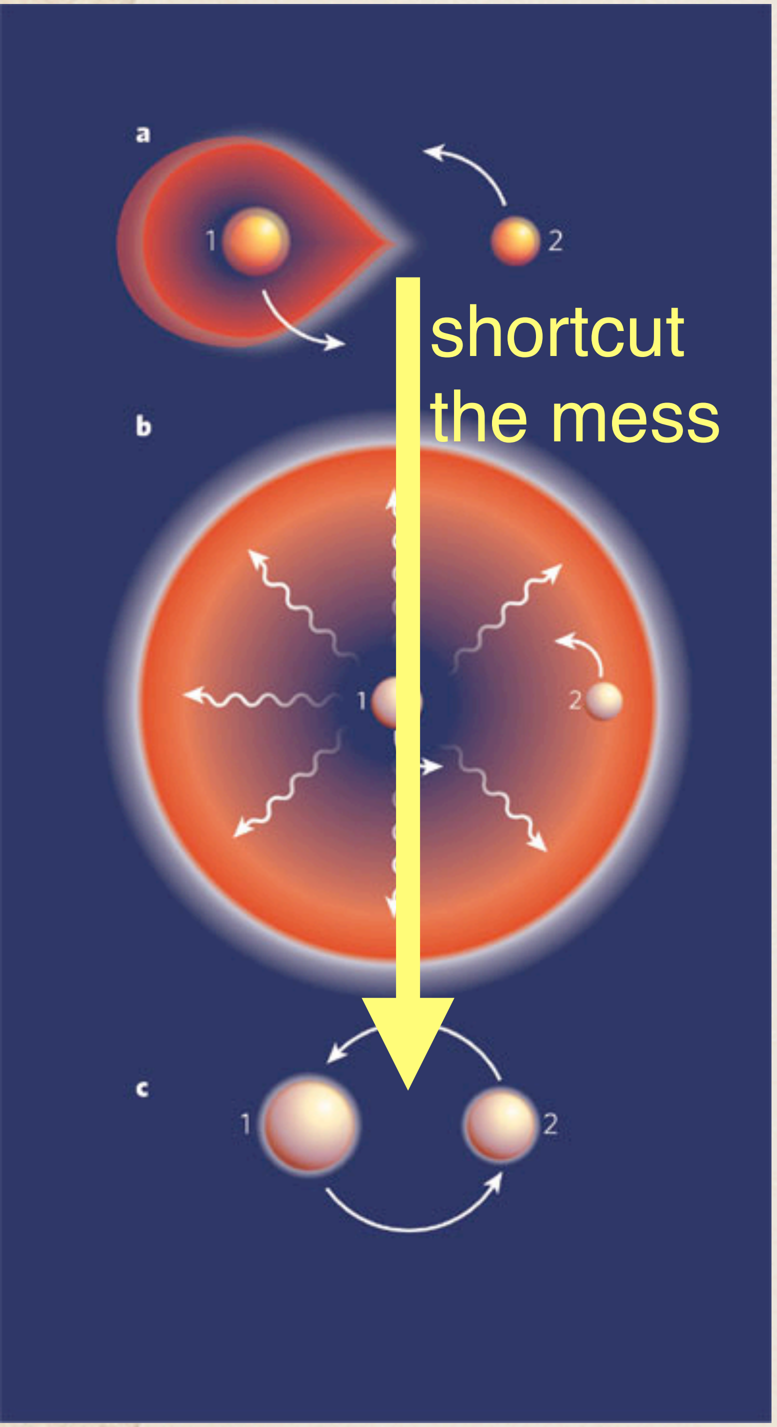
All those complicated scenarios will be discussed by others!

Example binary evolution leading to a BH–BH merger similar to GW150914

K Belczynski *et al.* *2016*



CE: αλ - energy formalism



$$\alpha\,\Delta E_{\rm orb} < E_{\rm bind,env} = \frac{GM_1 M_{1,\,\rm env}}{\lambda R_{\rm RL}}$$

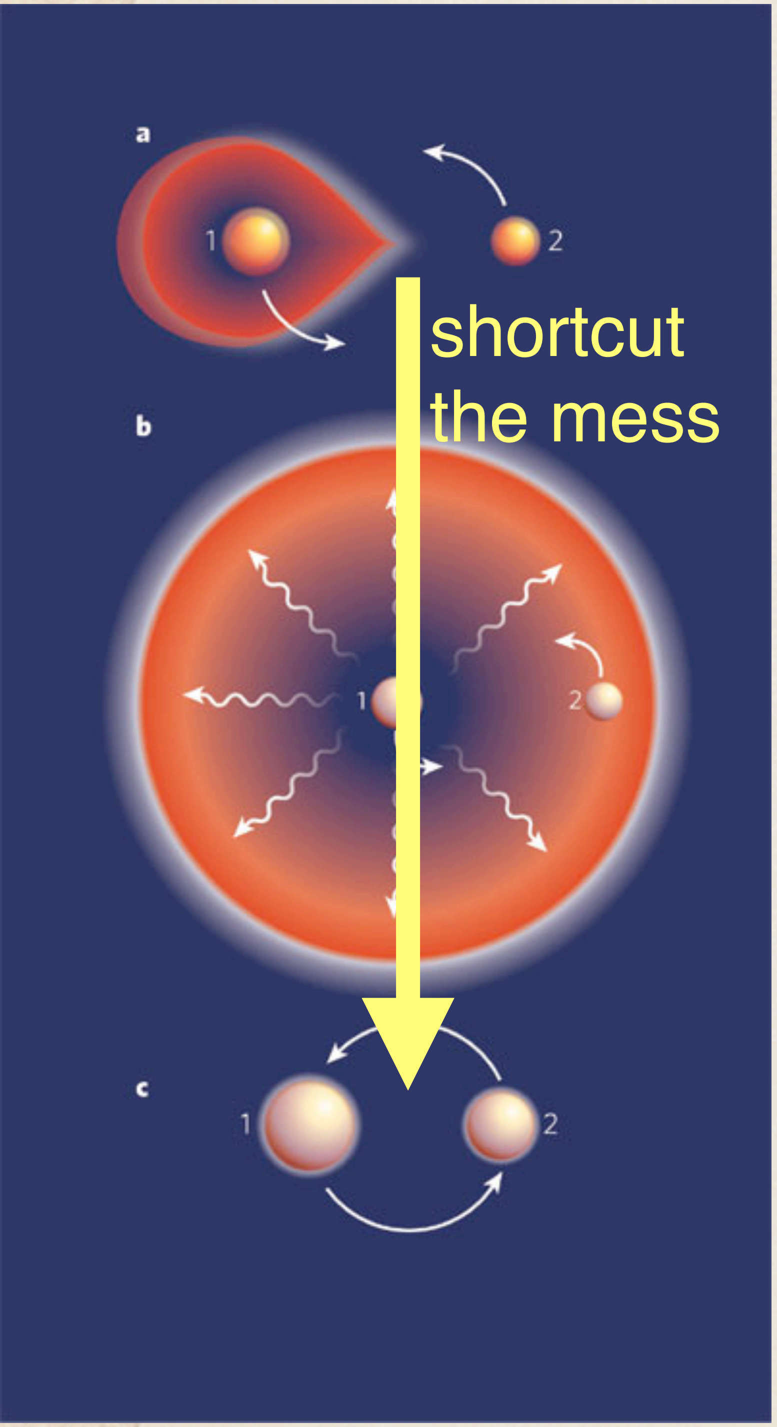
$$\Delta E_{\rm orb} = \frac{GM_{1,\rm core} M_2}{2a_{\rm fin}} - \frac{GM_1 M_2}{2a_{\rm ini}}$$

standard: $\alpha\lambda = 1$

Webbink 1984,
Livio & Soker 1988

α - “efficiency” of the energy re-use, can not be more than 1
λ - envelope structure parameter

CE: αλ - energy formalism



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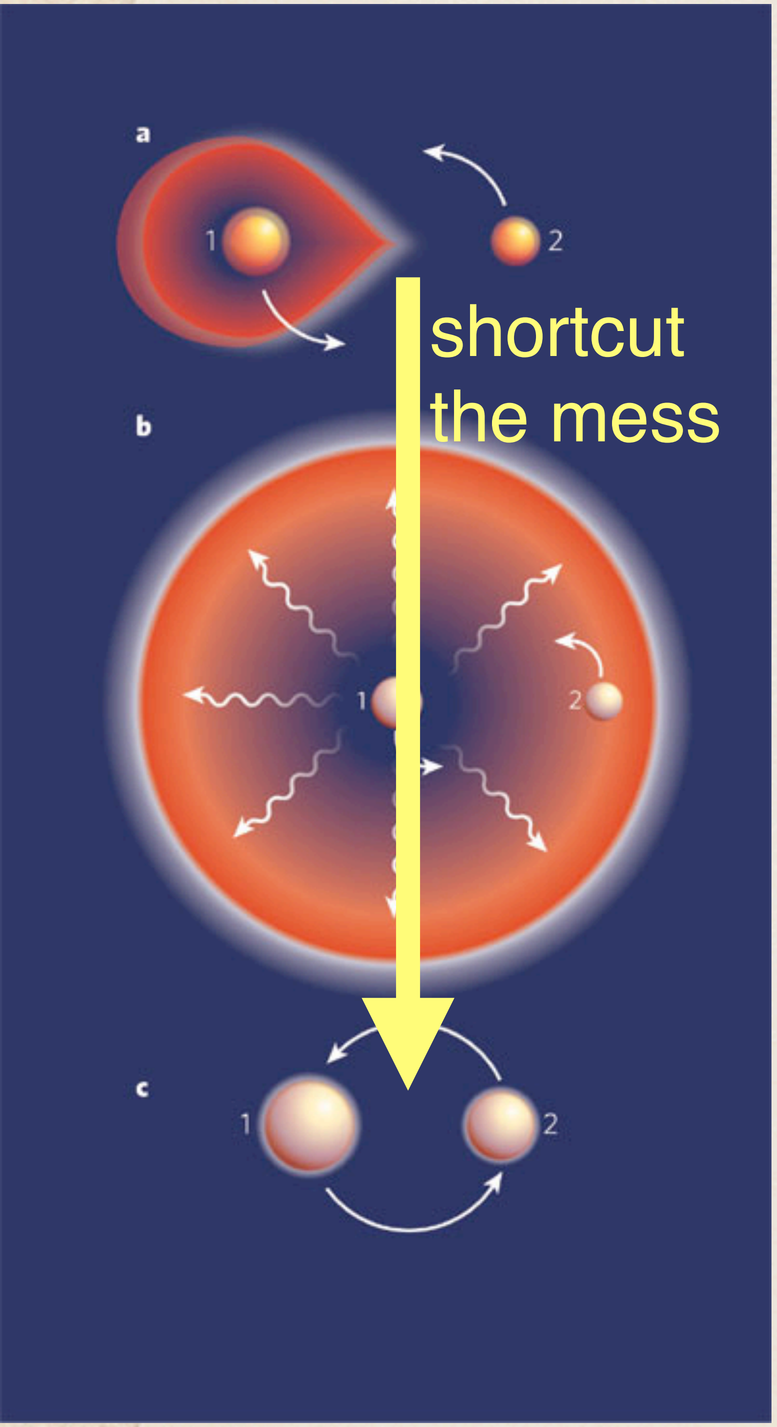
Energy formalism is loved by BPS codes.
Its fast, its numerical super rigid.

CE: αλ - energy formalism



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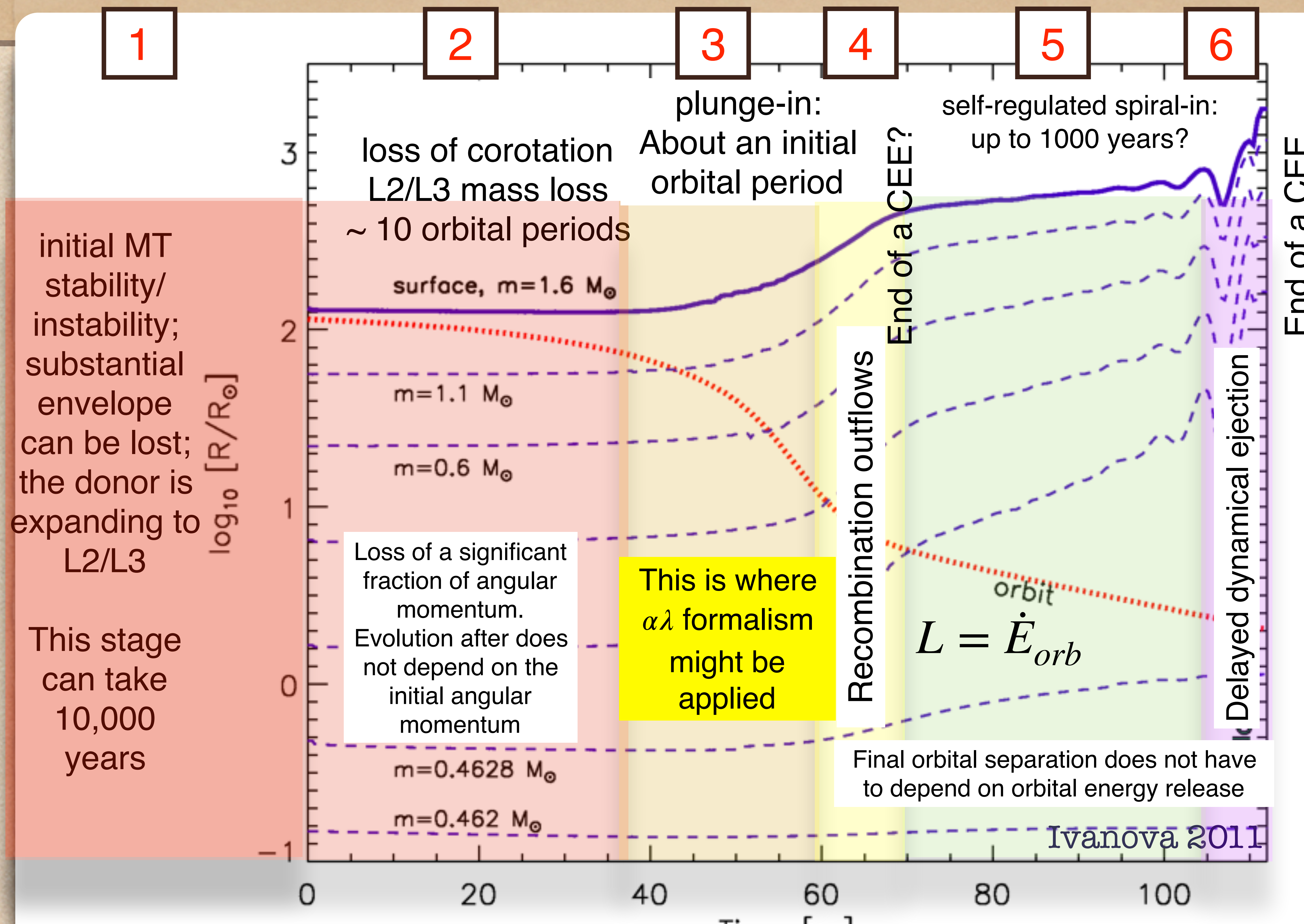
This event is so straightforward. You do not need even to use Einstein's equations. EOS are easy. Why is CE not done yet?

CE Event: main qualitative phases and timescales



Not to scale

- Different physics, different numerical codes
- Range in time-scales: 10^{10} - from 1 sec to 1000 yr
- Range in length-scale: 10^8 - from 10km to 1000 Rsun

Energies

Energy conservation as adopted in the energy formalism

$$-\frac{GM_1 M_{comp}}{2a^{ini}} + E_{tot,env} = -\frac{GM_{core} M_{comp}}{2a^{fin}}$$

Generic form of energy conservation

"source": accretion, jets, MF, nuclear

"sink"

$$U^{ini} + \Omega^{ini} + K^{ini} + \boxed{E_{extra}} = U^{fin} + \Omega^{fin} + K^{fin} + \boxed{E_{rad}}$$

EF: some components are ignored (for $U^{ini} + \Omega^{ini} + K^{ini}$)

EF: ignored (for E_{extra})

EF: some components are ignored (for $U^{fin} + \Omega^{fin}$)

EF: ignored (for K^{fin})

EF: ignored (for E_{rad})

K_{ej}^{fin} and $U_{env,rec}$ are comparable to final orbital energy

$$K_{env3D,orb},\ \Omega_{env3D},\ \Delta U_{remnants},\ K_{cm}^{fin},\ U_{ej}^{fin},\ \Omega_{ej}^{fin}, \ldots$$

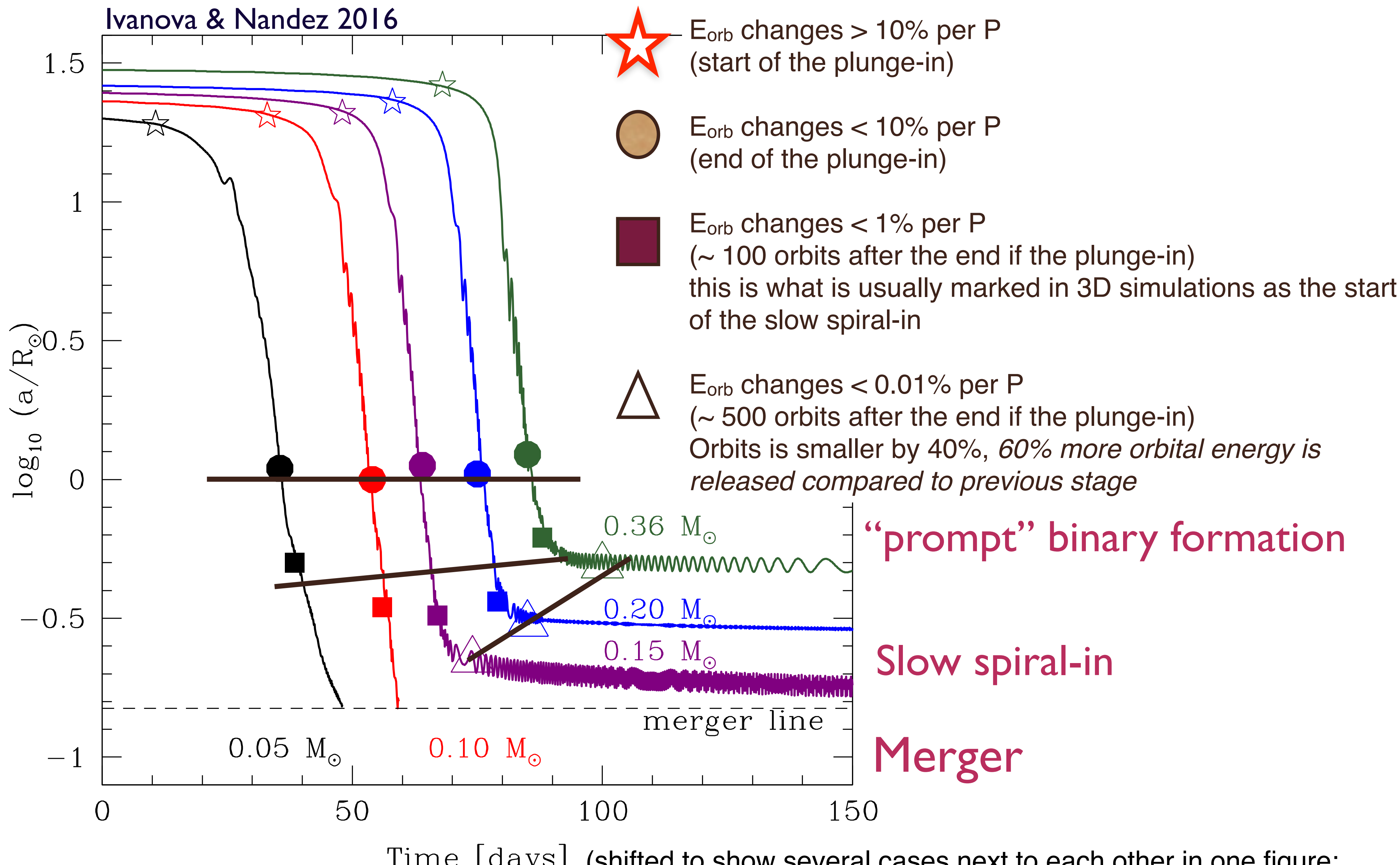
If things are so complicated, is there any hope or any progress? Let's just use the energy formalism!

Vocabulary

Doing well: We (CE modelling community) think that we have done solid calculations at least for some stages and some sets of initial conditions. We believe that for those calculations most of relevant physics is included and physics of outcomes is understood. We hope that complete understanding only requires way more brutal computing force.

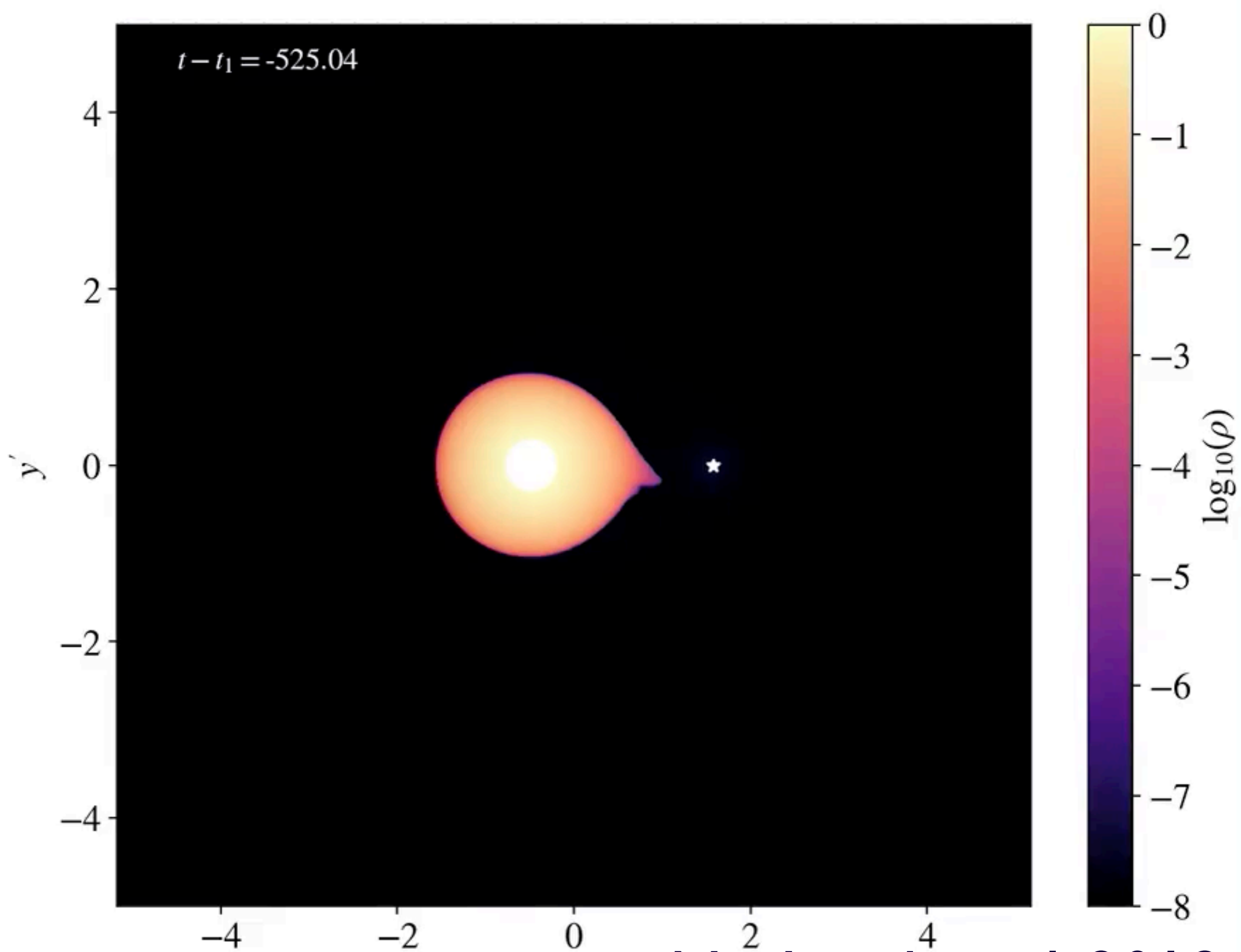
Work in progress: solid calculations are advertised to be on the way, or some preliminary simplified calculations are done, some physics is understood, complete set of physics is not yet included by anyone, published results are more speculative.

Doing well: as was predicted, we can get different kinds of CEEs

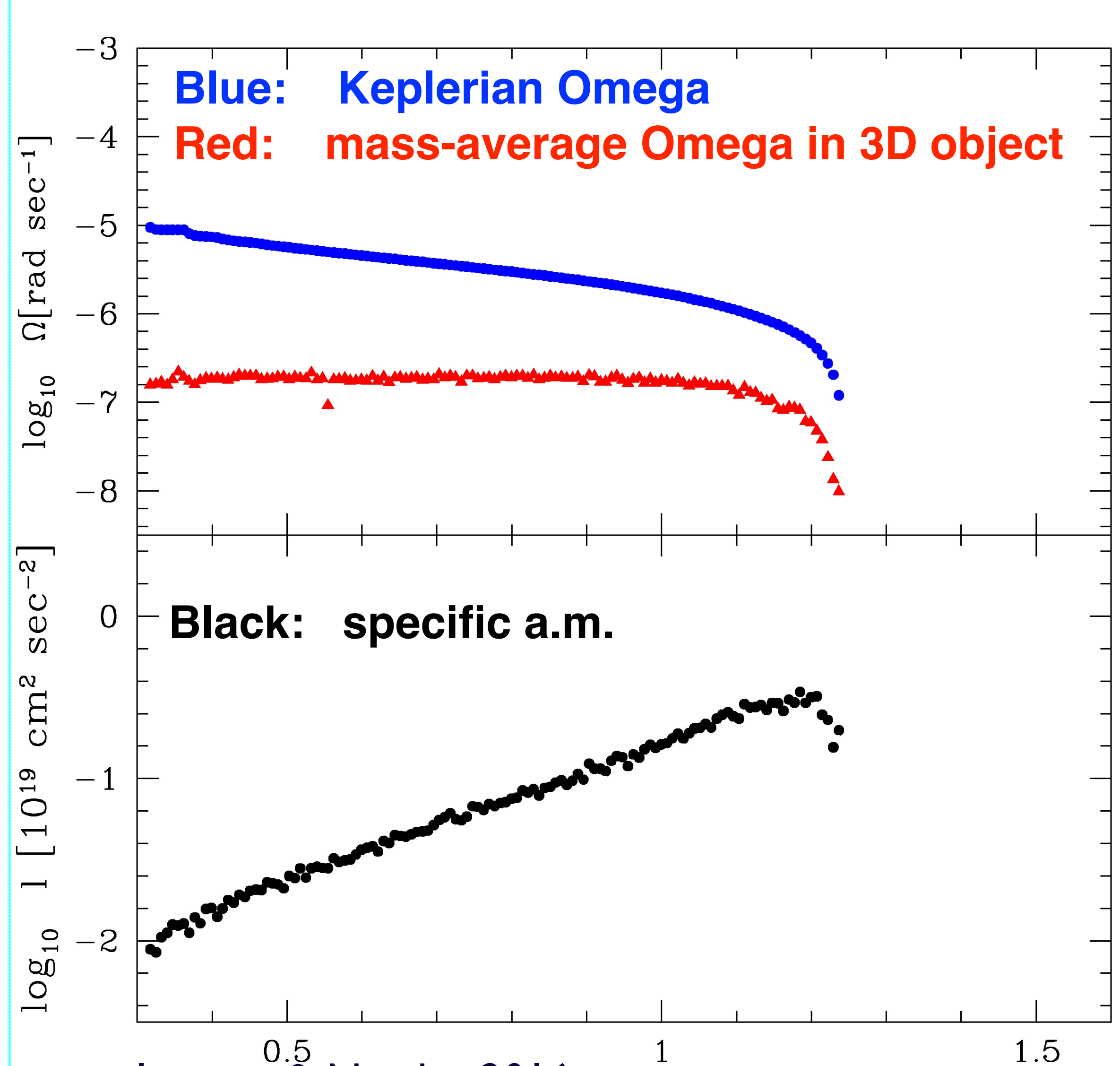


(shifted to show several cases next to each other in one figure; simulations started 300-500 days before the shown time)

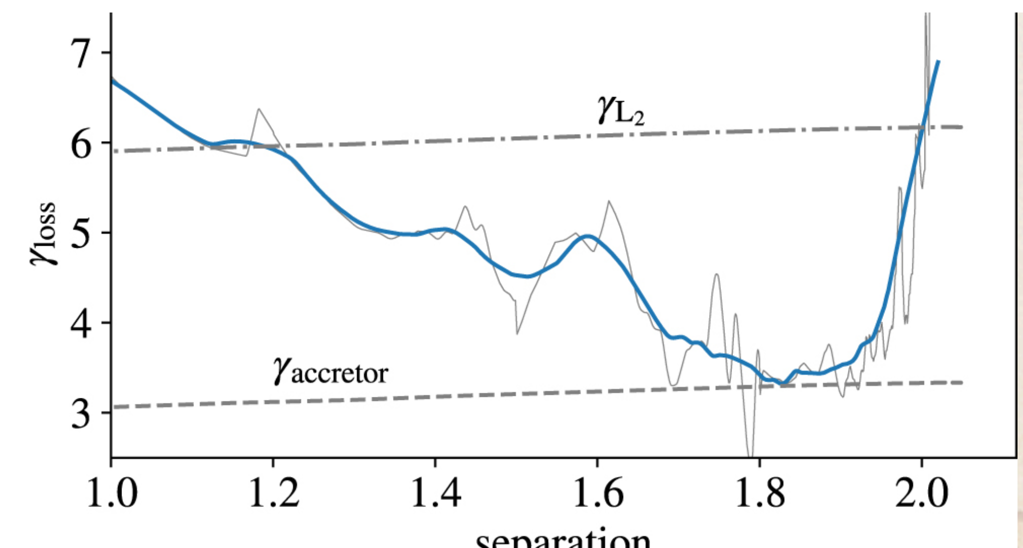
Doing well: understand A.M. loss



MacLeod et. al. 2018



Ivanova & Nandez 2016

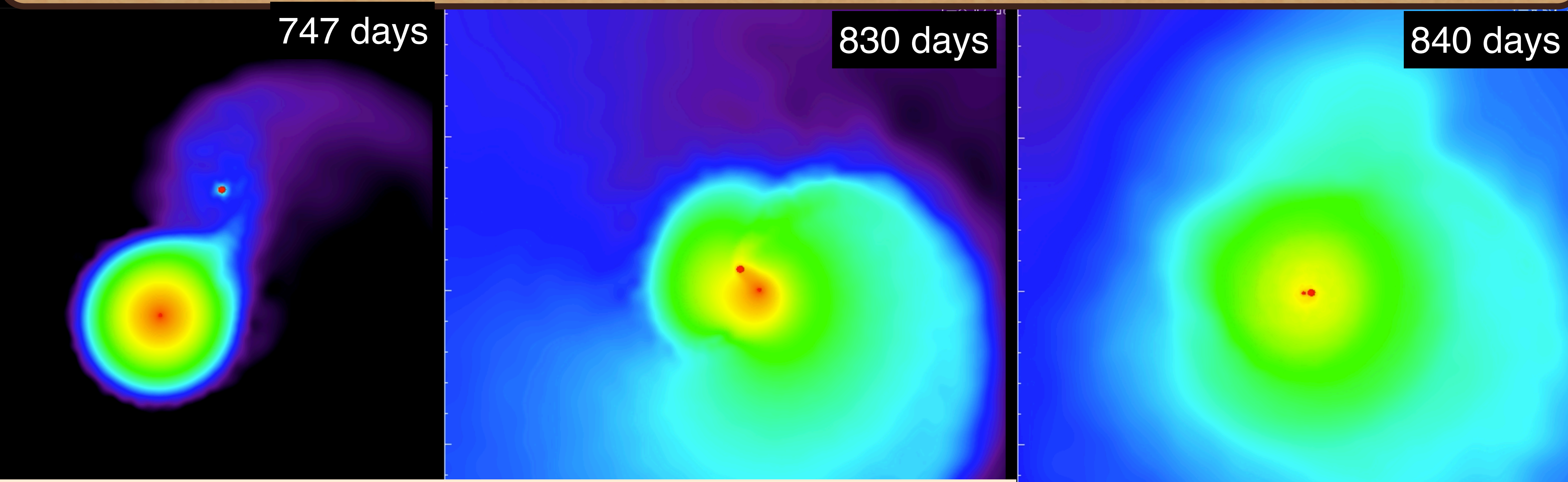


L2 outflows have specific a.m. that differs from that of L2

State after the plunge:

- there is no corotation with the binary during any stage
- most of a.m. is lost

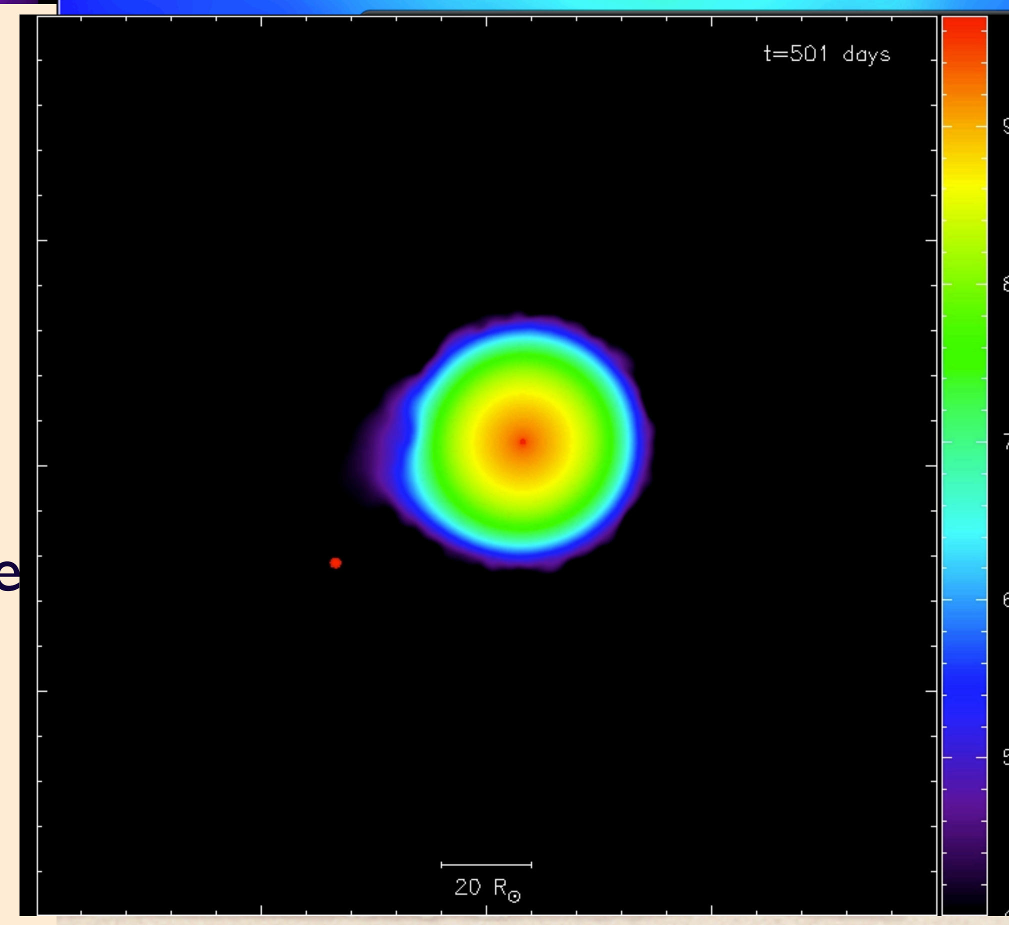
Doing well: model a complete CE ejection for low-mass systems



In the shown simulation (1.6Msun RG with 0.32Msun core + 0.36Msun WD), ~1/3 of the final orbital energy is in the kinetic energy of the ejecta. Range: 17-47% of the finial orbital energy.

Internal energy is non-zero, and is 20-50% when compared to kinetic energy. Potential energy is non-zero though by magnitude 5-10 times less than thermal energy. Few km/s - the binary COM.

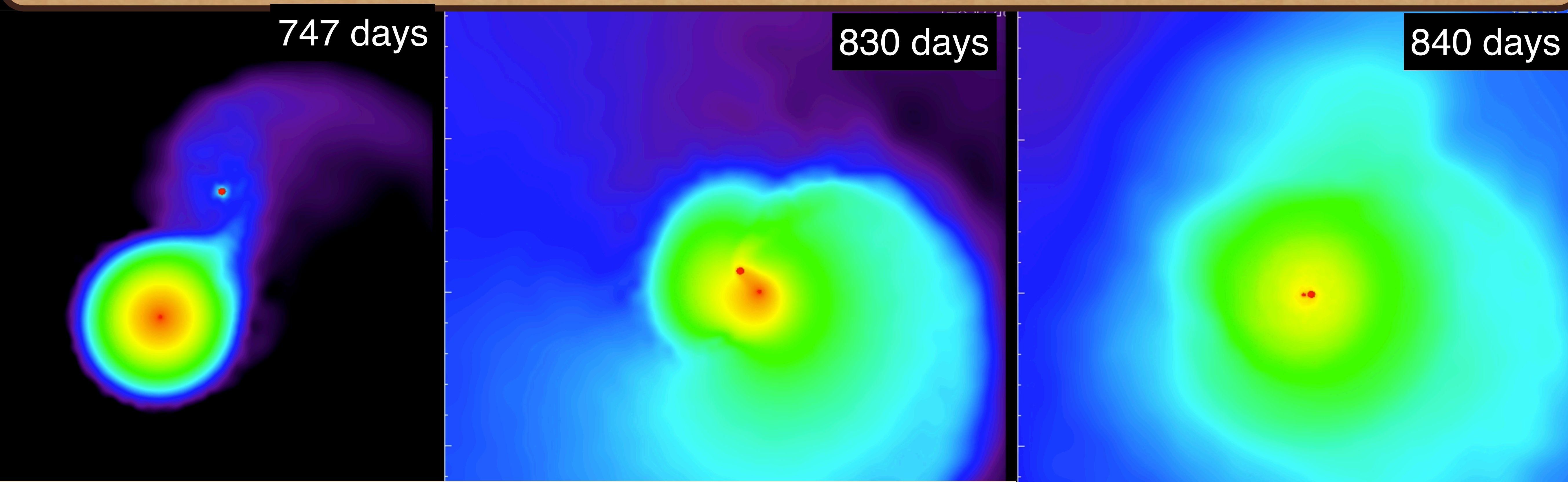
Updated energy formalism with fits for the final kinetic energy are in Nandez & Ivanova 2016



$$(E_{\mathrm{orb,ini}} - E_{\mathrm{orb,fin}})(1 - a^{\infty}_{\mathrm{unb}}) + E_{\mathrm{bind,env}} + hM_{env} = 0$$

h: 1.5×10^{13} erg/g – specific recombination energy

Doing well: model a complete CE ejection for low-mass systems



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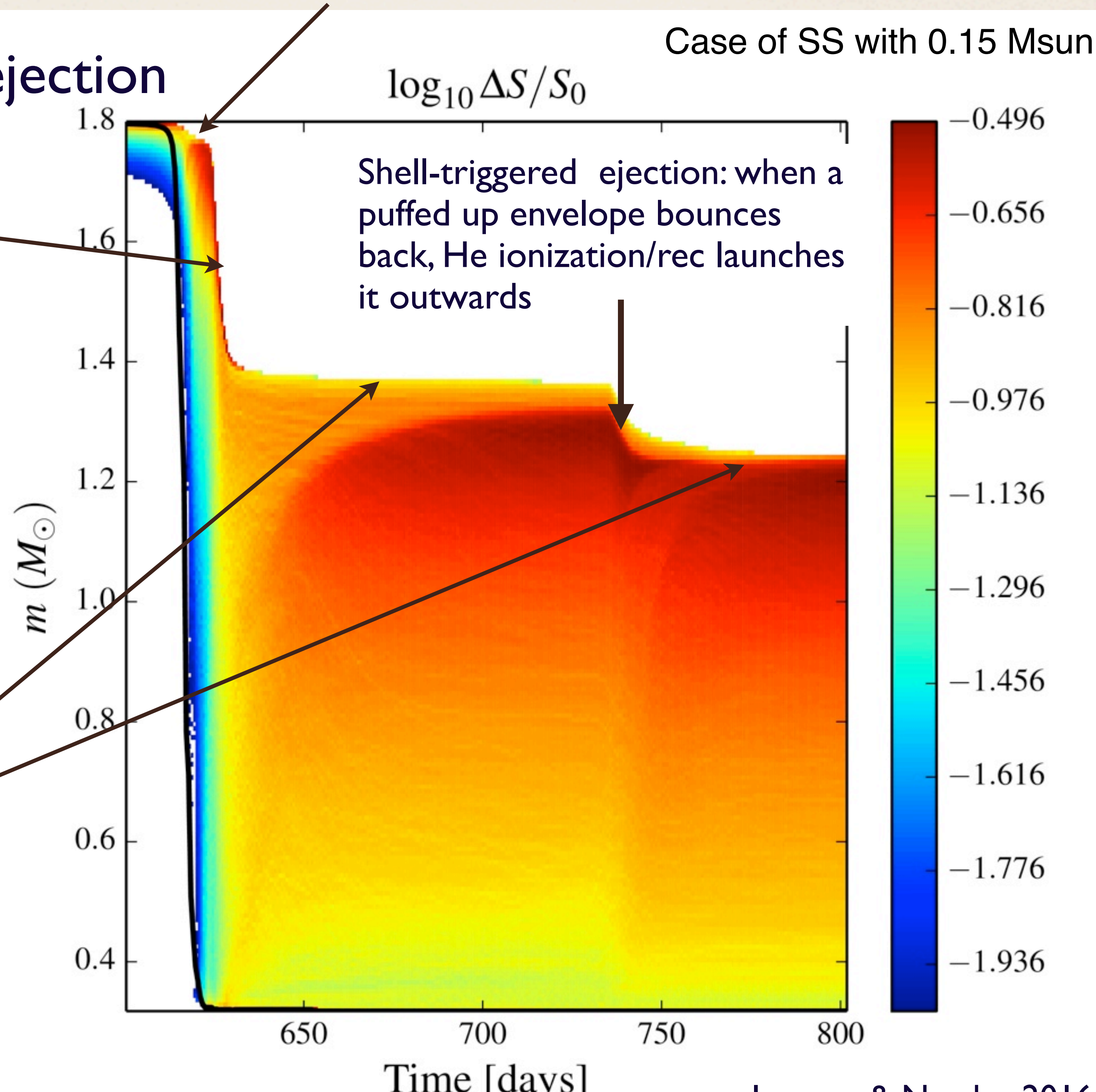
Work in progress:CE in massive stars
e.g., Pail Ricker's group
see also poster by A. Miguel Holgado

Doing well: distinguish several different CE mass ejections

Most of initial orbital J is lost by the end of the plunge-in.

Initial ejection

Plunge-in ejecta: always takes place



Recombination outflow 0.15 Msun/yr

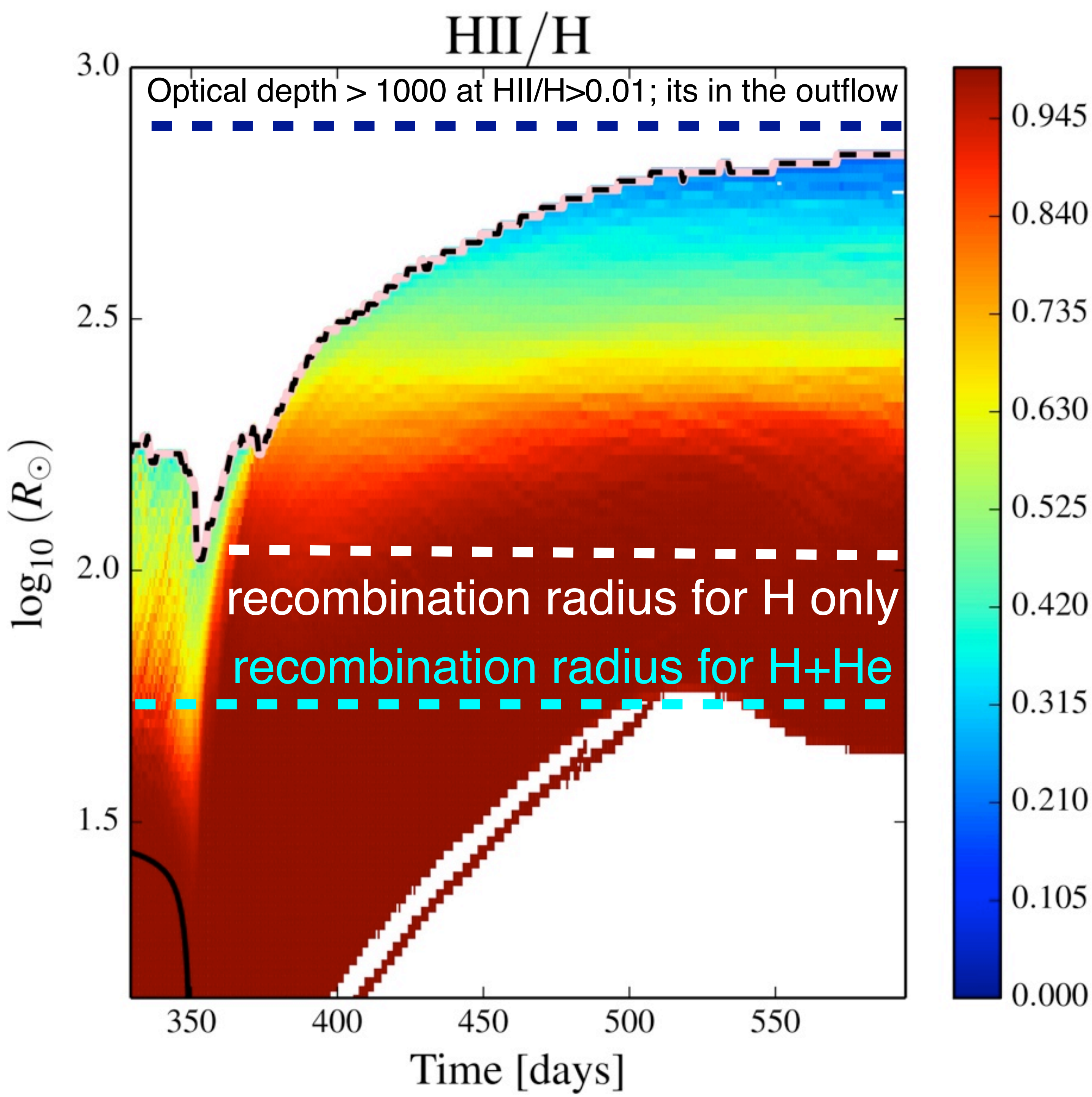
Here 3D simulation is converted in 1D representation, an analogy of Kippenhahn diagram

Ivanova & Nandez 2016

There are always several ejection episodes, and each is powered differently, and matter carries away different specific kinetic energy.

Doing well: understand how CE outflows works

This is the envelope that is outflowing at a rate of 2 Msun/yr.
Only remaining bound envelope is shown.



Ivanova & Nandez 2016

Hydrogen recombination starts at a radius where the *released recombination energy* is larger than *the local potential energy*: material starts to outflow

Recombination:
it can remove the entire envelope during several dynamical timescales, via *steady recombination outflows*

Important: its the trigger. The location - *where* it starts - is more important than the initial energy value.

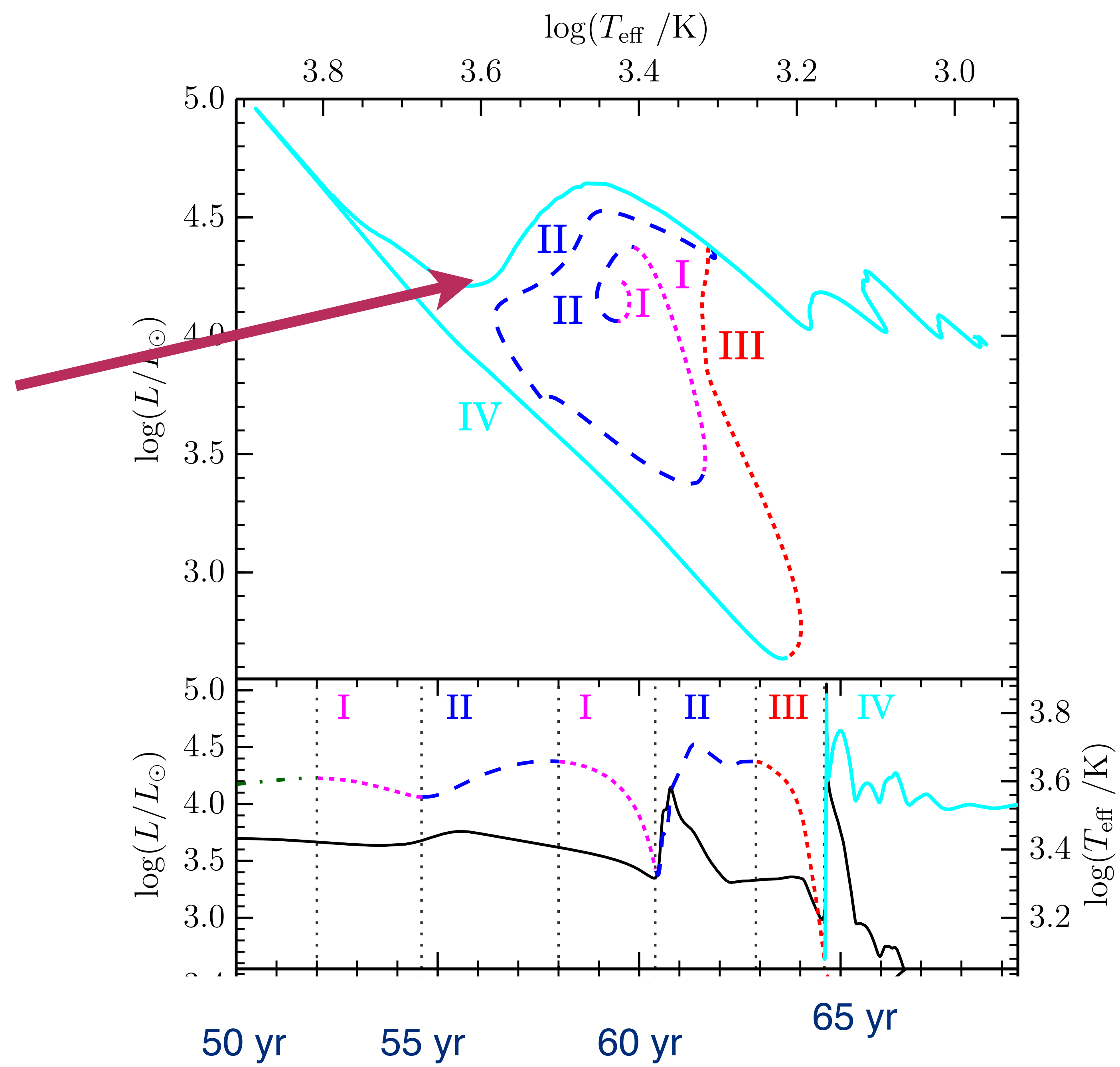
This does not take into account neutral—> molecular transition

Here 3D simulation is converted in 1D representation

Doin well: physics during self-regulated spiral-in

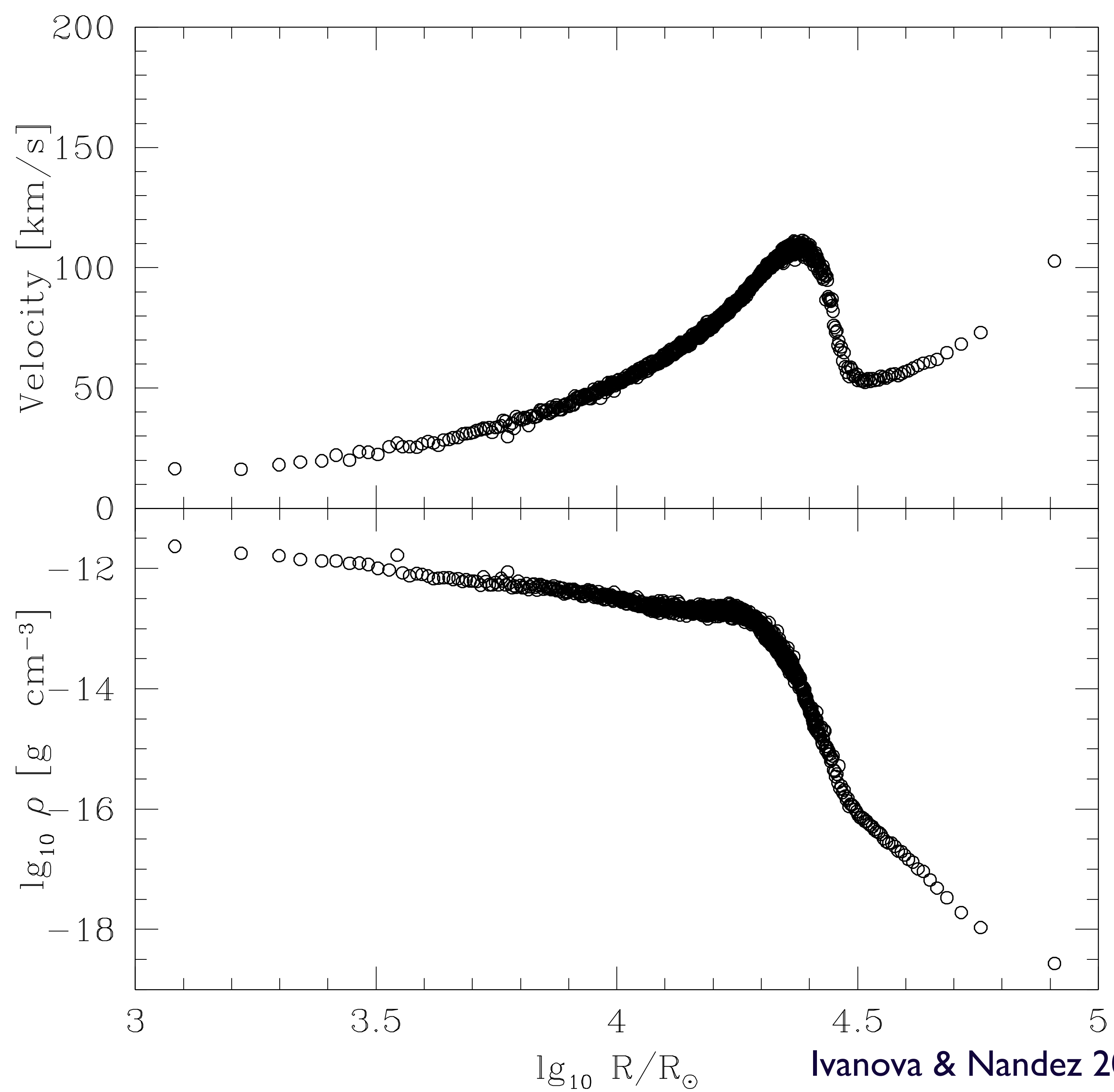
During “slow spiral-on”, the CE object looks like as a very luminous and cold pulsing variable: almost the entire envelope is recombined and has $\Gamma_1 < 4/3$

~10% of the envelope mass is unbound with each pulse, every 5-10 years Similar Principe as to shell triggered ejection found independently in 3D models. He ionization/recombination drives it.



Clayton et al 2017

Work in progress: linking CE mass ejections to observations



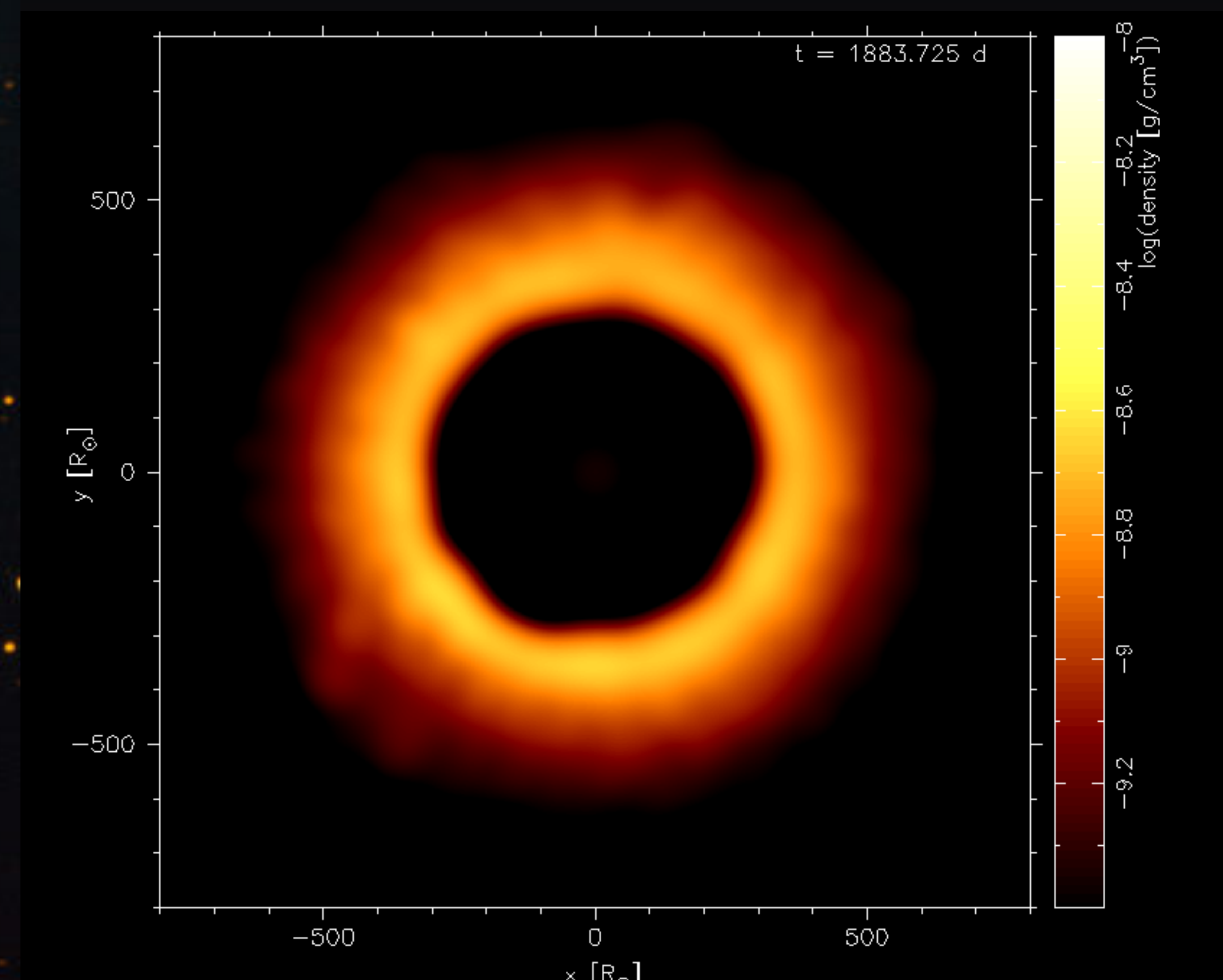
Ivanova & Nandez 2018

There are always several ejection episodes, and each is powered differently, and matter carries different kinetic energy. Ejection imprint.

Work in progress: linking CE mass ejections to observations

Fine ring nebula (Shepley 1) almost perfectly pole on with a binary inside

~1000 days after a plunge.
Clearing ~600Rsun in a middle

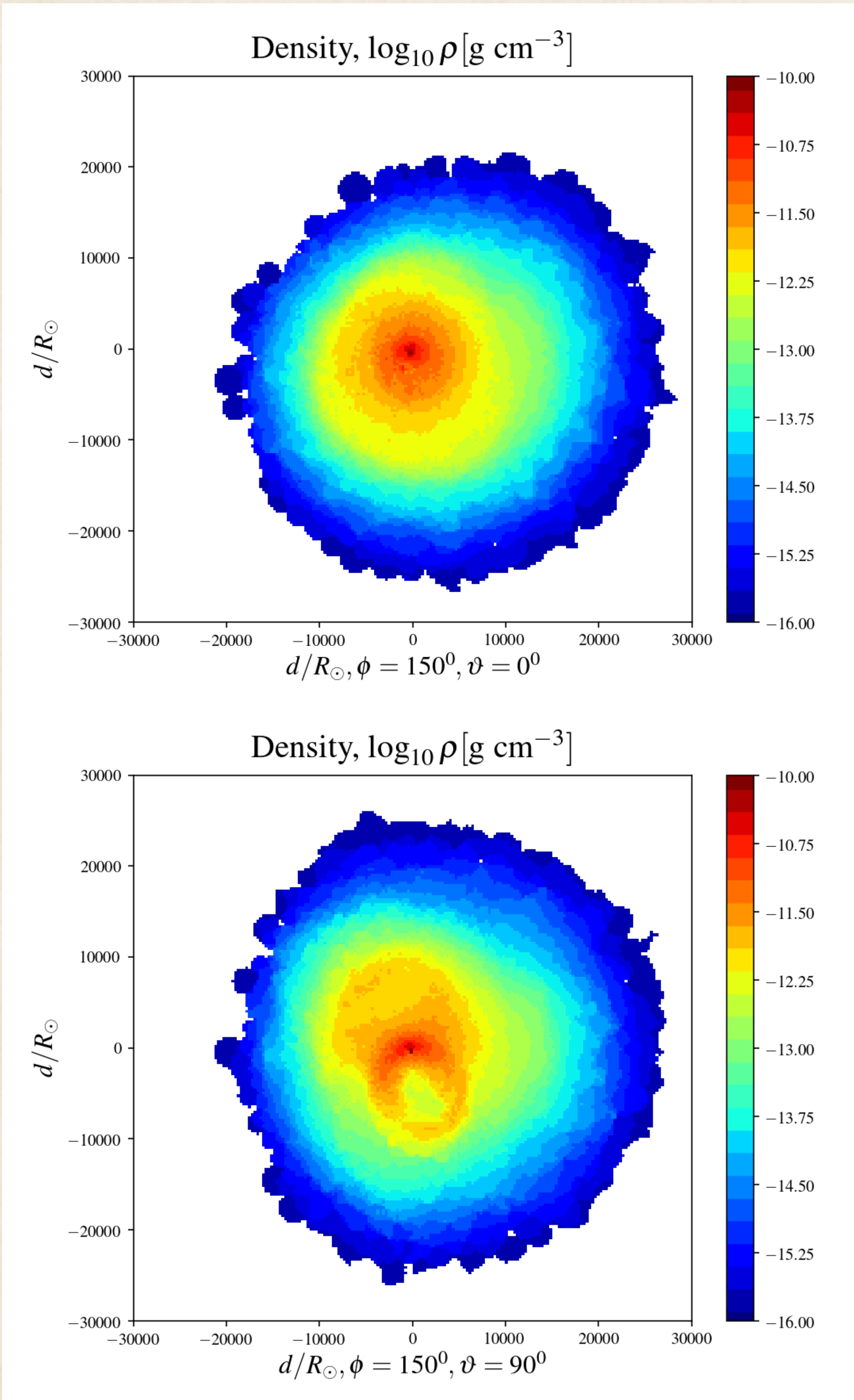


A “simple” post-CE nebula from simulations

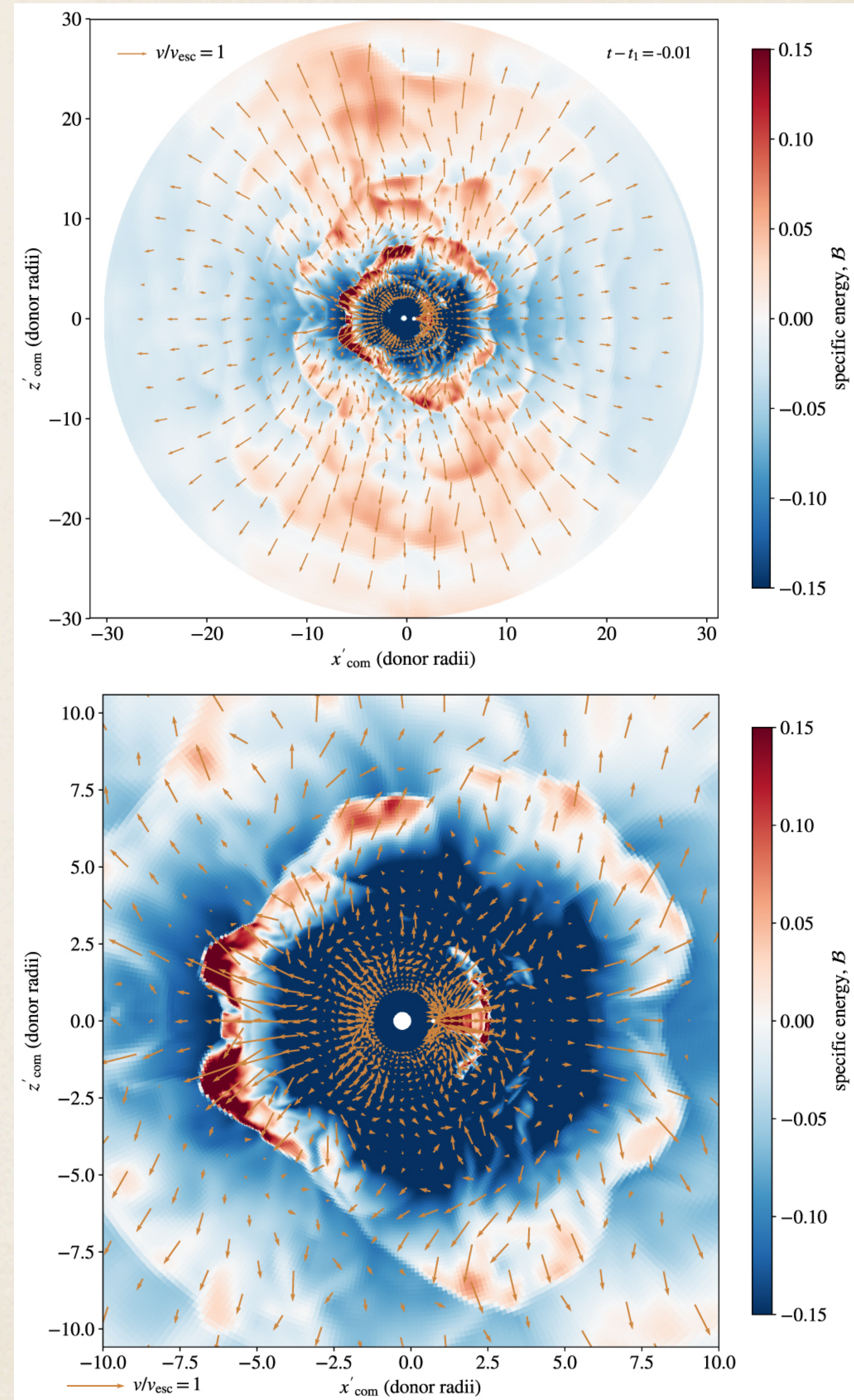
the case of 1.6Msun RG with 0.32Msun core and 0.36Msun WD

But the devil is in the details

Work in progress: making PNe. More additional physics needed to be included.

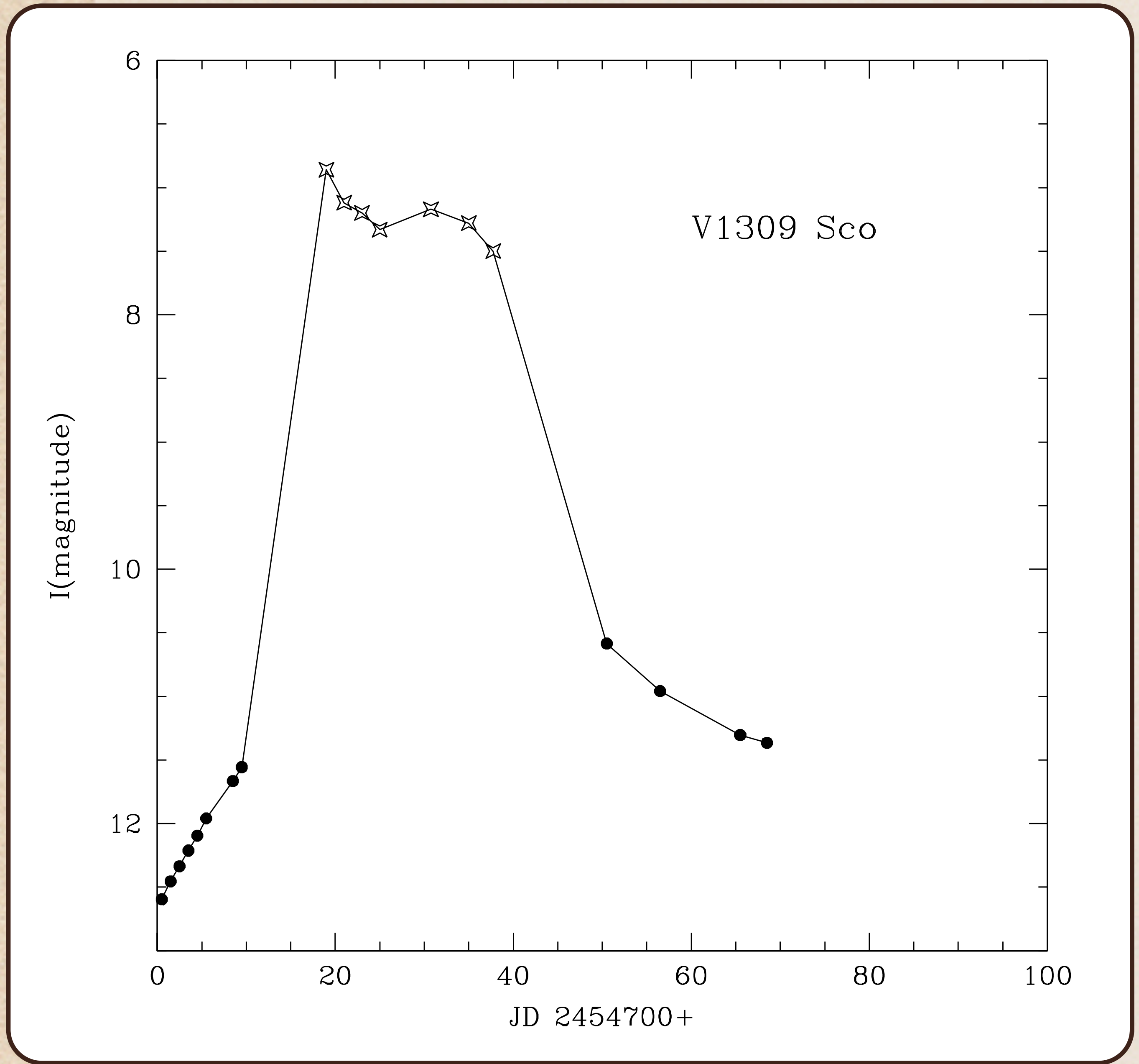


Ivanova & Nandez 2018

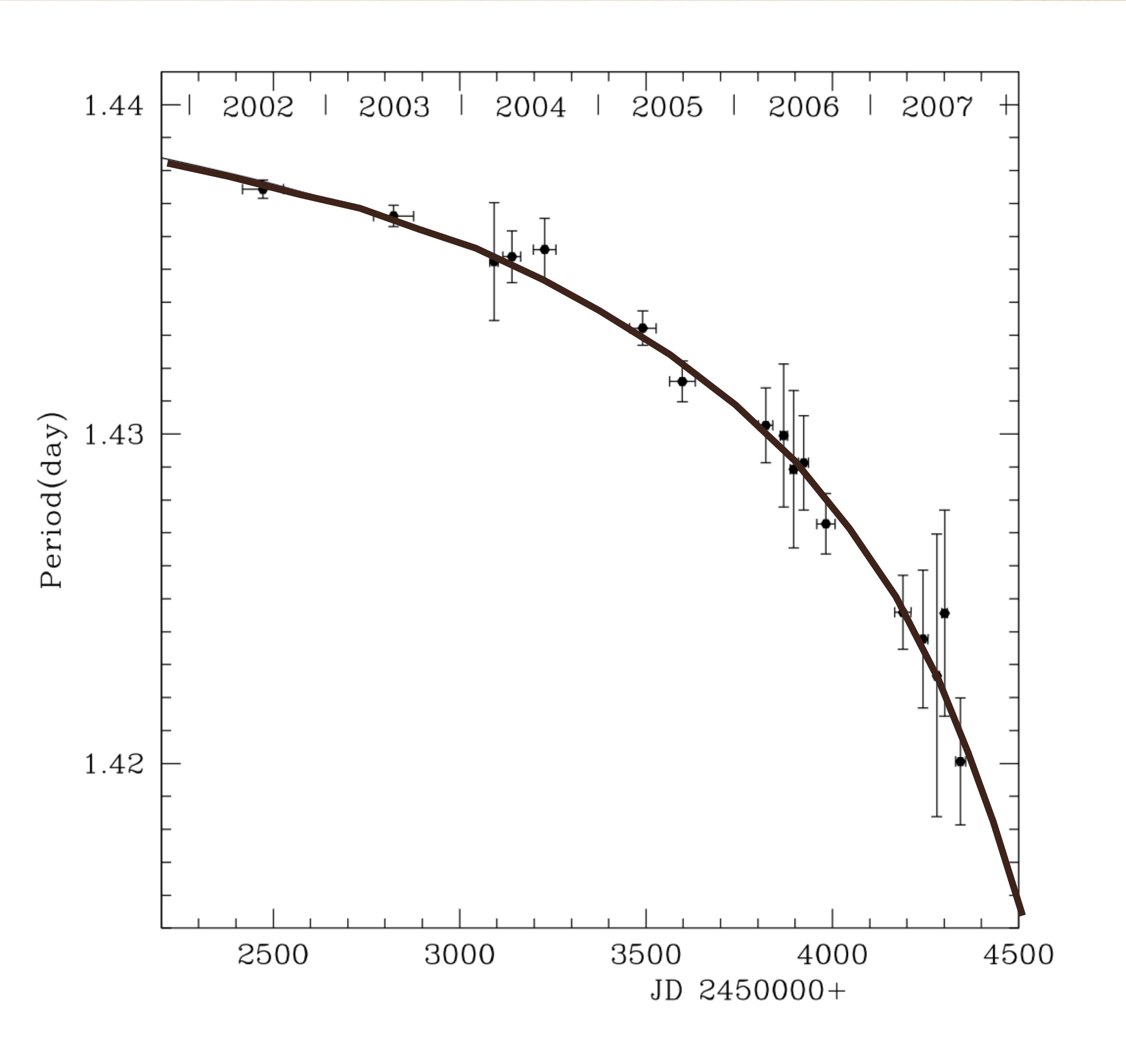


MacLeod et. al. 2018

V1309 Sco outburst

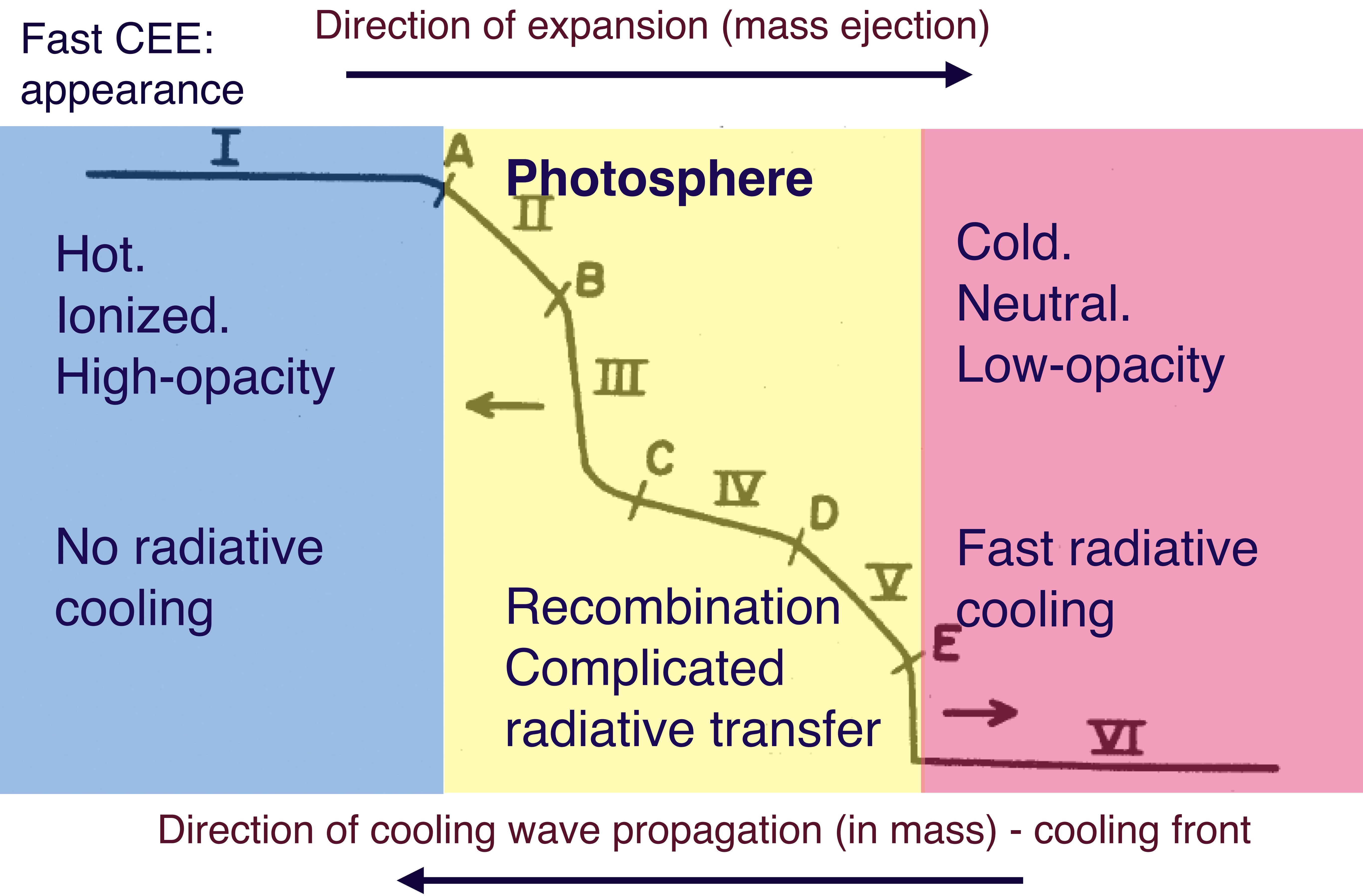


Nakano 2008



Tylenda et al. 2011

1.5+0.16 Msun binary (Stepien 2011)


Fast CEE:
appearance
Direction of expansion (mass ejection)
I
A
Photosphere
II
Hot.
Ionized.
High-opacity
B
III
Cold.
Neutral.
Low-opacity
C
IV
D
V
No radiative
cooling
Recombination
Complicated
radiative transfer
E
Fast radiative
cooling
VI
Direction of cooling wave propagation (in mass) - cooling front

Fast CEE: appearance

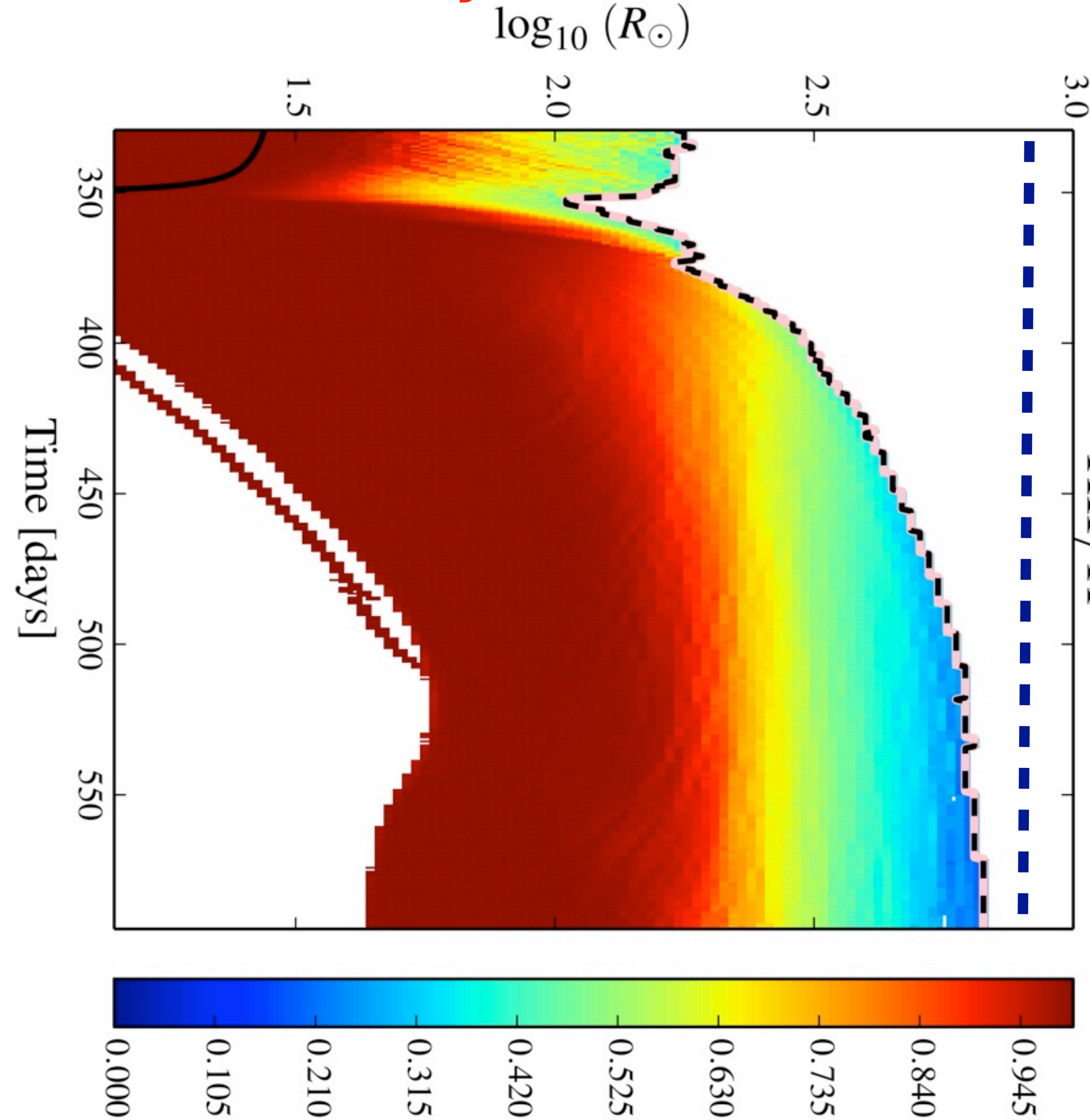
Direction of expansion (mass ejection)

We can not see directly into recombination/into bound mass

I

Hot.
Ionized.
High-opacit

No radiativ
cooling



Optical depth > 1000 at HII/H>0.01; its in the outflow

l.
pacity

diative

II

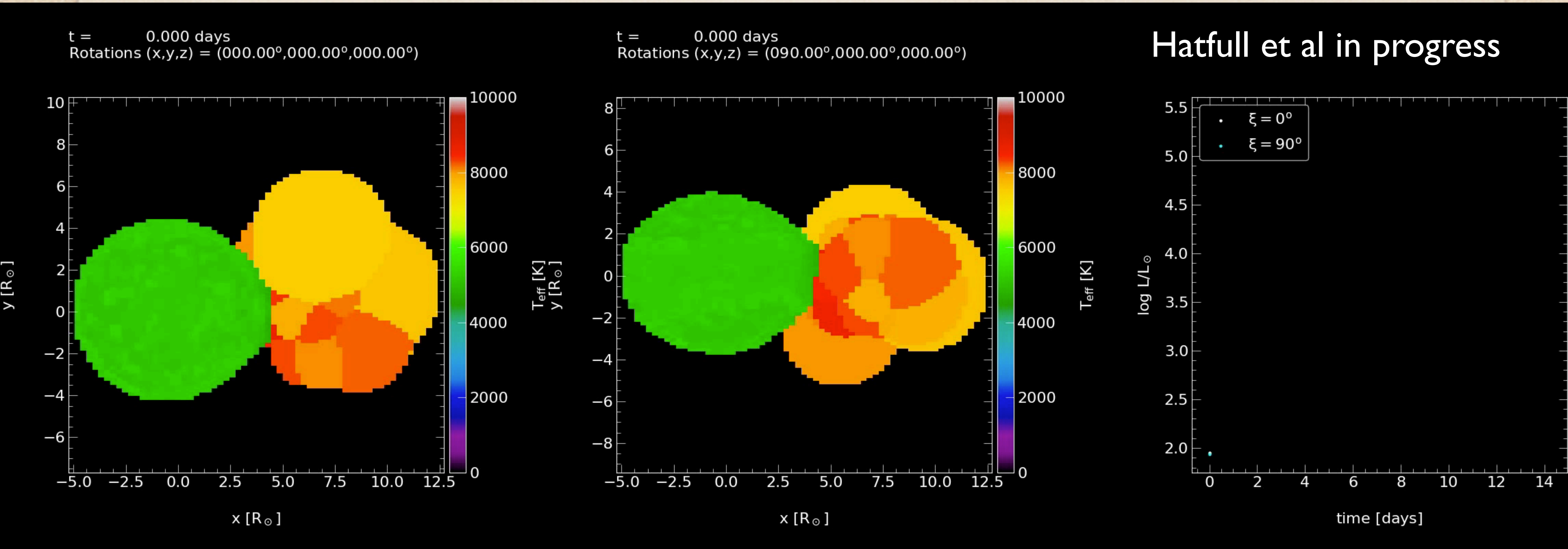
Directior

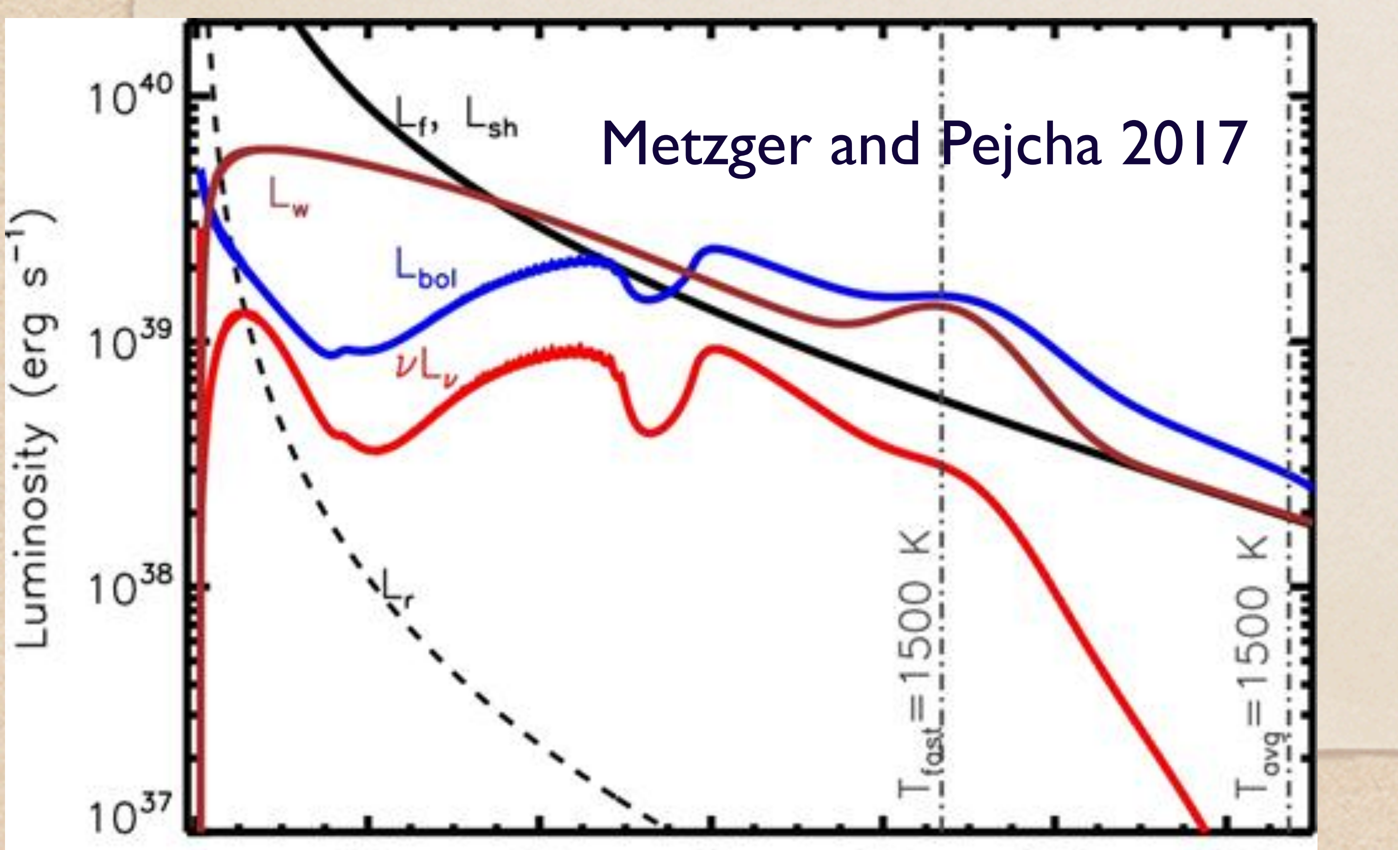
ing front

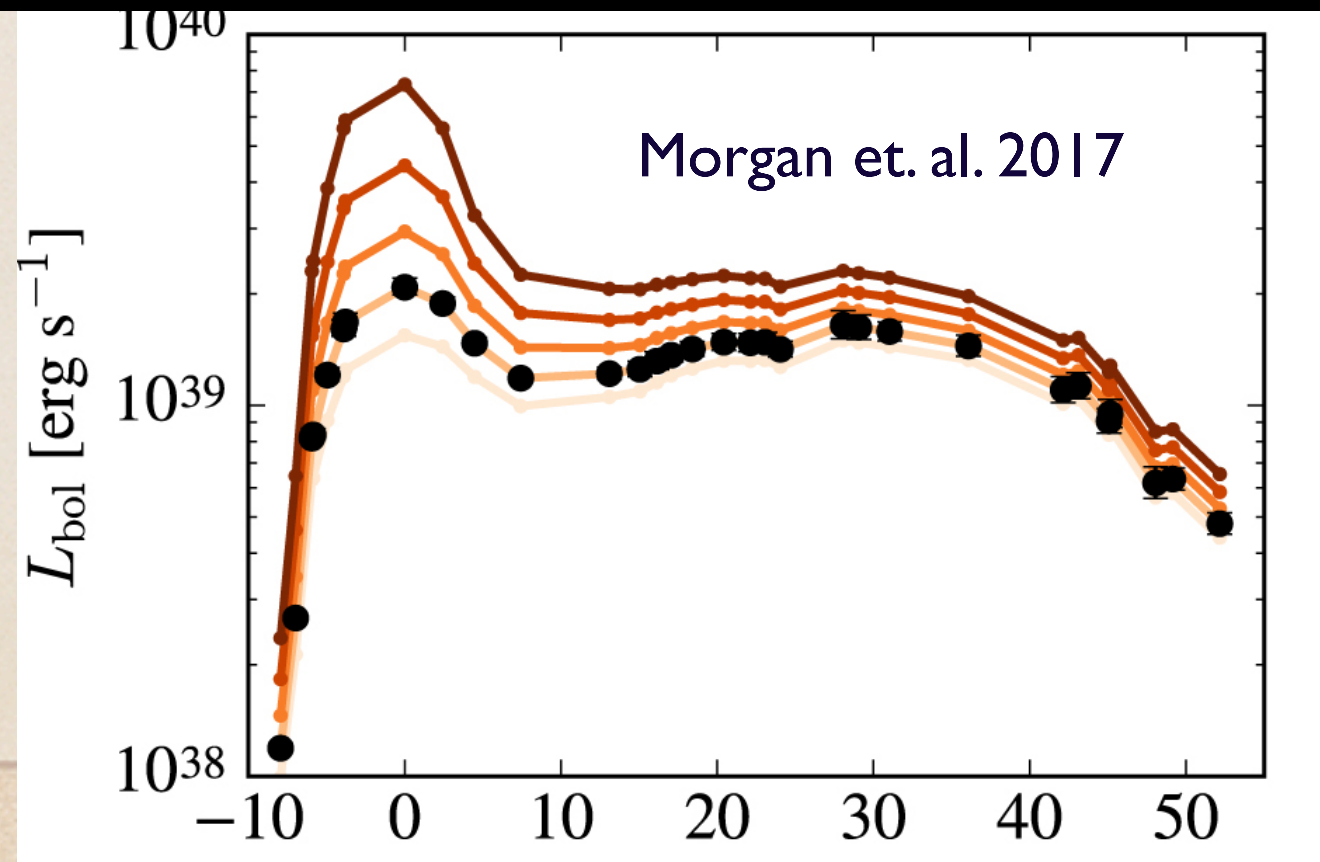
⇒The radius and temperature of the photosphere remains roughly constant.

Photosphere is what you observe. It is not where recombination has to take place.

Work in progress: making light curves, comparing it to LRNe







The current state of CE physics

- αλ-formalism is to be gone. This is a global agreement within CE-modelling community and post-CE observers community. No single alpha rules them all. Sorry, BPS community.
- An entire common envelope ejection can be modelled for low-mass stars. Recombination helped in studied cases, but is not expected to guarantee the ejection in all the CE cases. Complete CE ejection in massive stars: in progress.
- Substantial mass can be lost even before the CE/merger event has started. L2/L3 and pre-CE mass loss are important for CE outcomes.
- CE outflows shape up PNe
- Modelling light curves of CEEs and mergers by different groups and methods, and comparison of them to LRN/etc may provide an enormous amount of details on how CEEs take place in reality.