Close binary evolution and Gravitational Wave Sources

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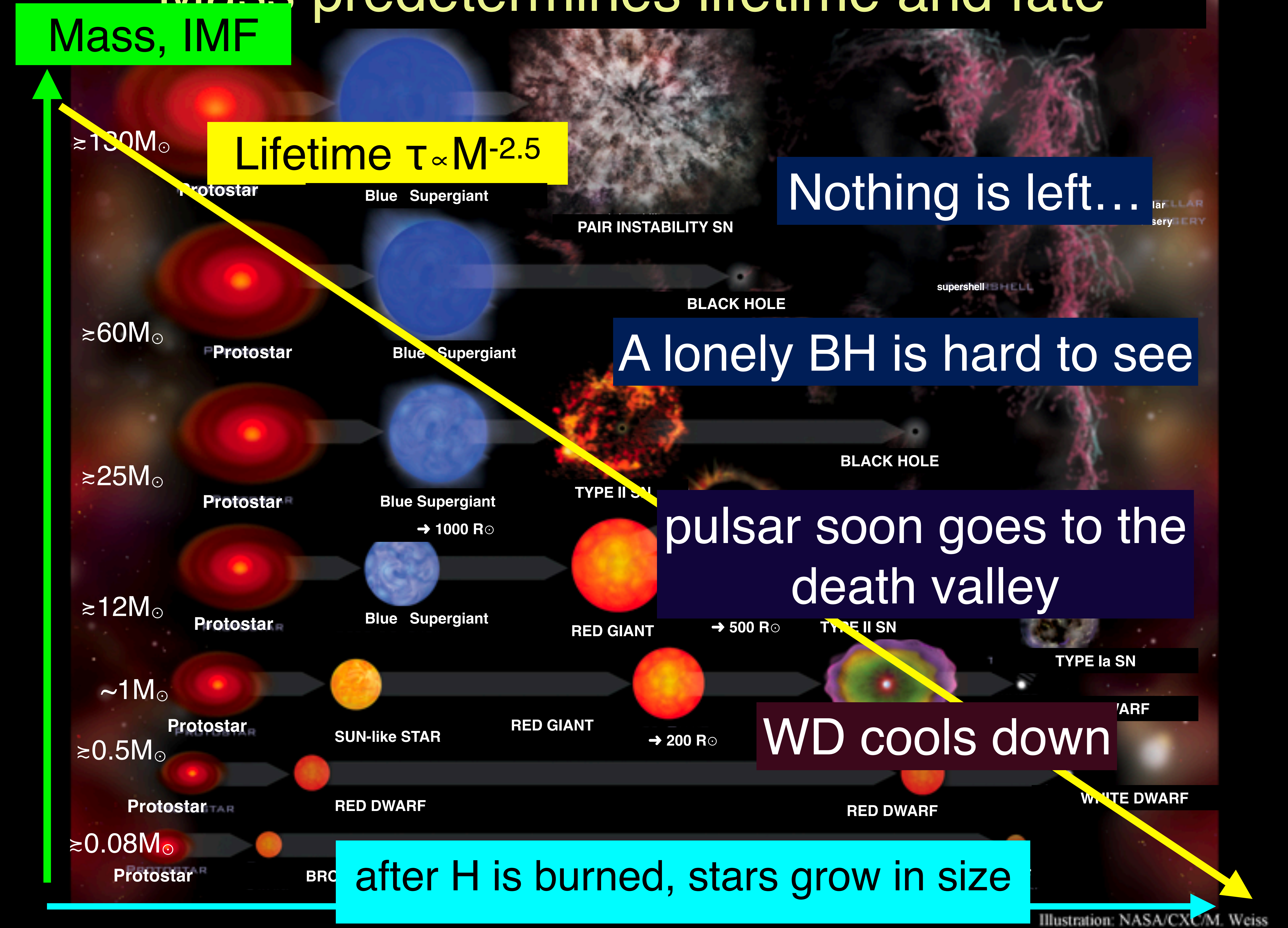
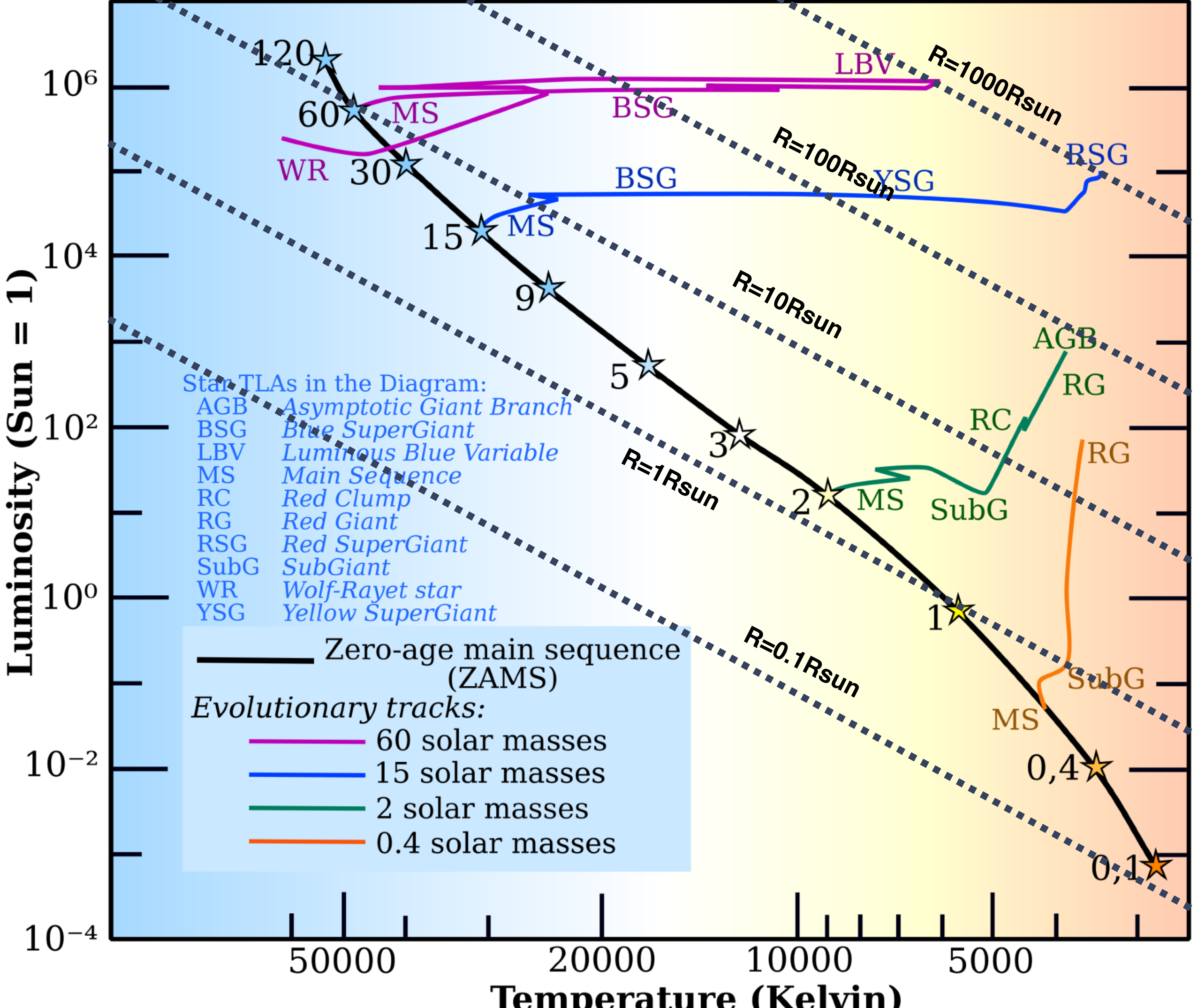
IPMU, Jan 22, 2020

Mass predetermines lifetime and fate





Prialnik 2000

on the life of a single star:

The life is to grow

The death is to shrink or blow

leave nothing behind

Main Sequence (few to a dozen Rsun) ⇒

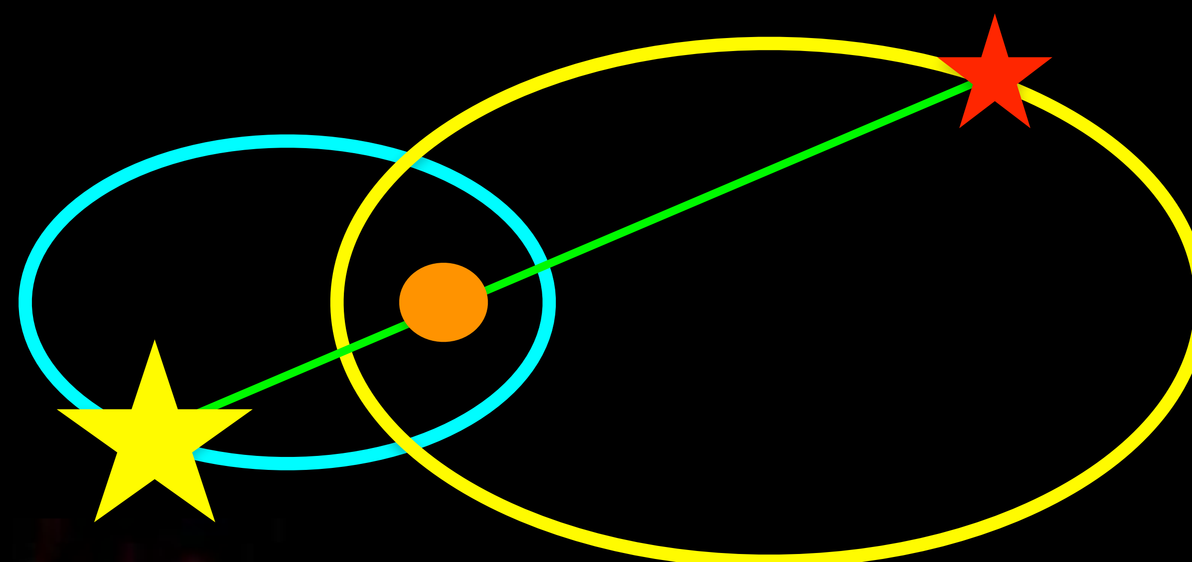
(various) Giants (100-1000 Rsun) ⇒

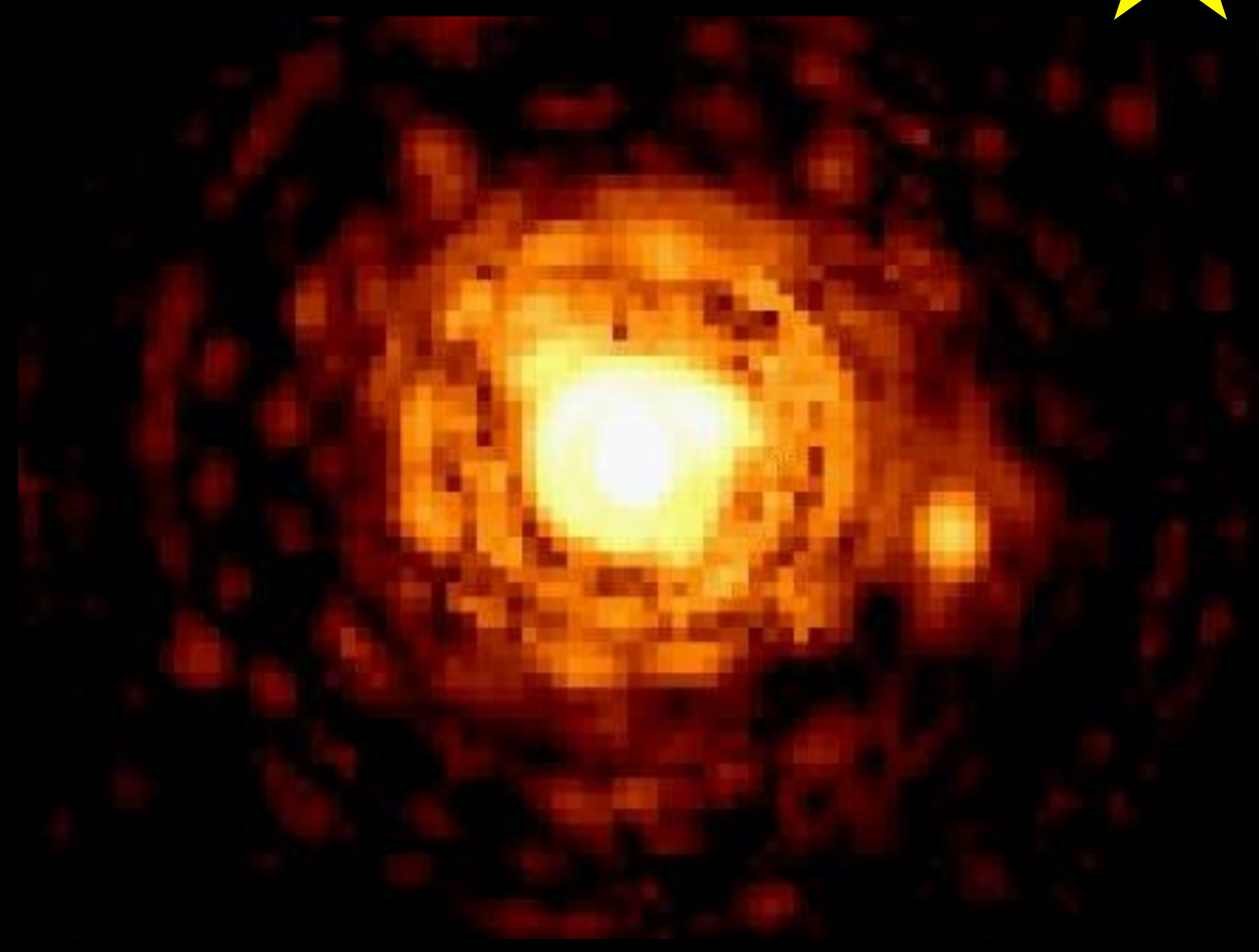
Various compact remnants (≪Rsun)

Being more massive brings the end of life sooner

But sometime stars are not born isolated.

In a multiple star system, the stars all orbit about the common centre-of-mass of the system.

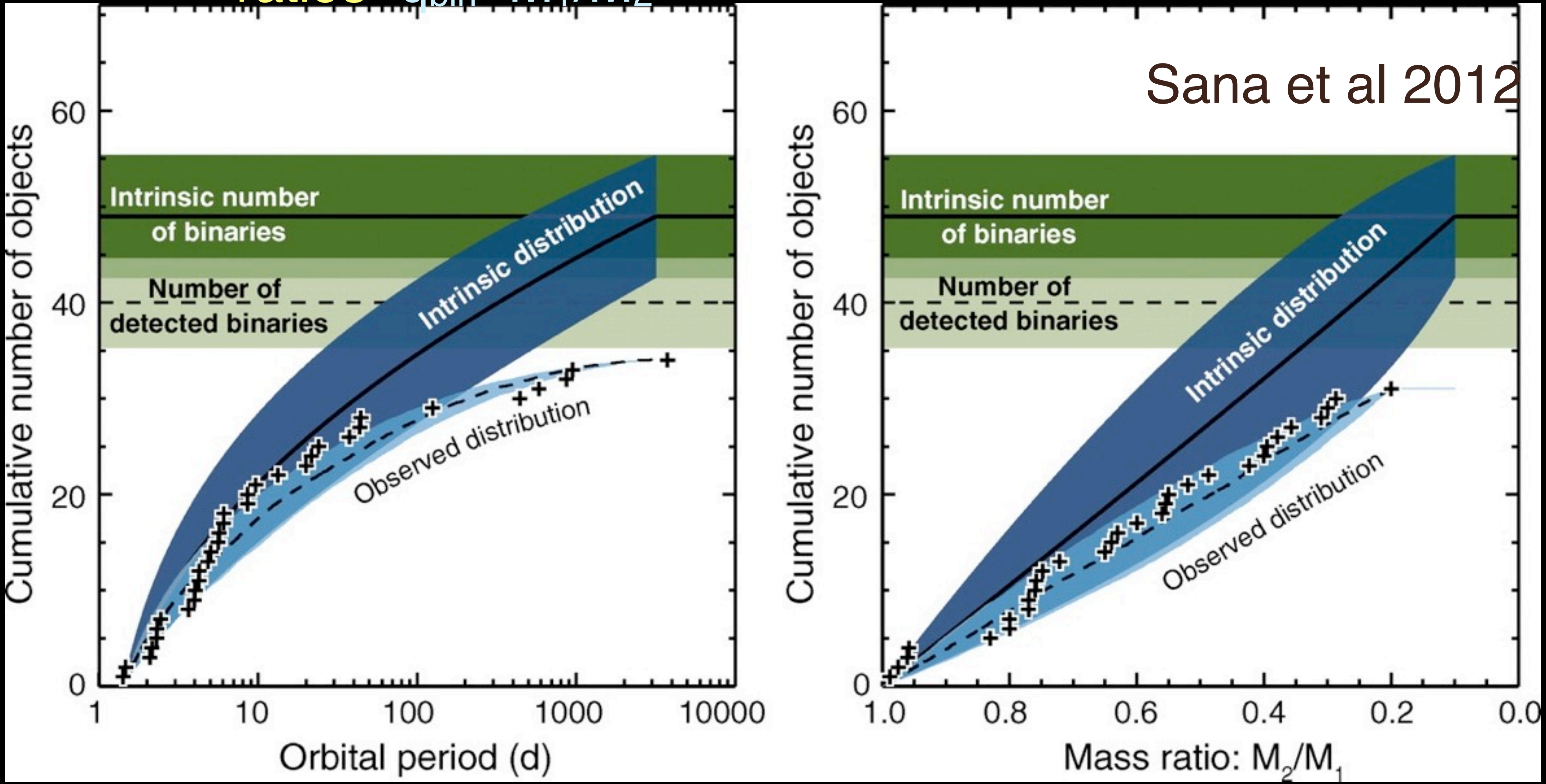




Hubble Space Telescope image of Gliese 623, two stars separated by 2 AU.

Binary Stars: why do we care?

binary fraction for stars like our Sun $f_{bin} \sim 0.5$
intrinsic binary fraction for massive O stars
$f_{bin} = 0.69 \pm 0.09$ (Sana et al 2012) Many are triples, quadruples,…
The binaries could have all kinds of
periods and binary mass ratios=$q_{bin}=M_1/M_2$



Binary Stars

In a nutshell:

if two stars have the same age,

then a more massive one is more evolved;

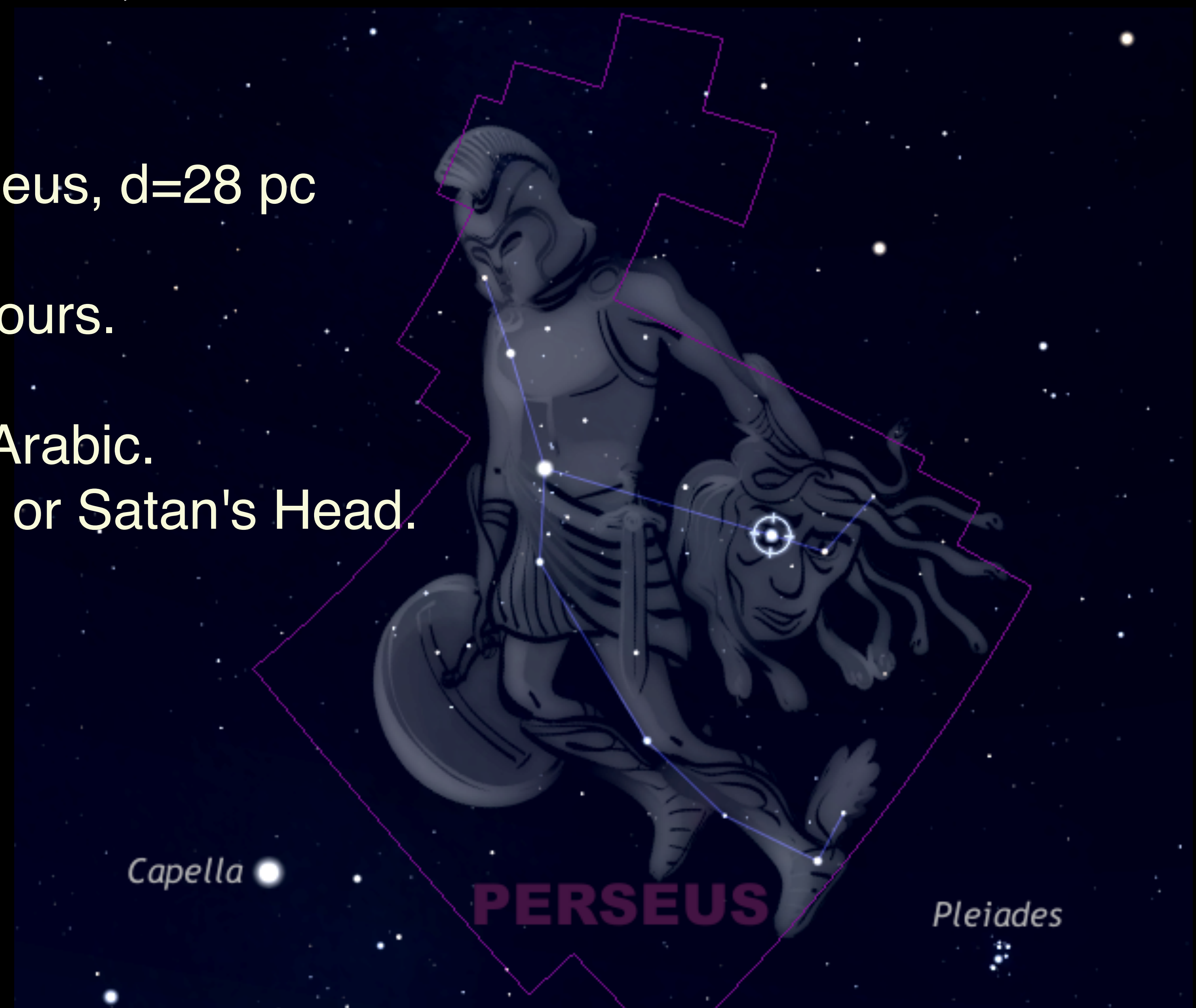
a more massive is expected to have a larger radius

Algol　アルゴル

Algol is a star in the constellation Perseus, d=28 pc

Every 2.87 days it dims for about 10 hours.

Algol means "Demon Star" in ancient Arabic.
The Hebrew name is "Rosh ha Satan" or Satan's Head.



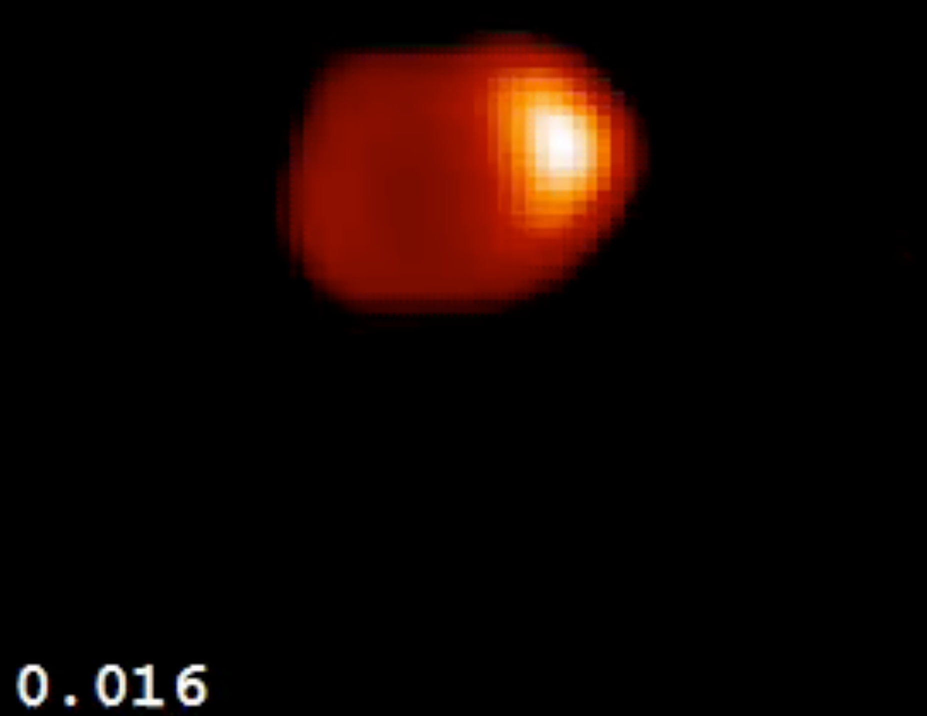
AN graphic by Ade Ashford / Stellarium.

It's a triple!
3.6+0.8+1.7Msun,
P_1= 2.87d (a_1=13 Rsun),
P_2=680d (a_2=560Rsun)

Algol　アルゴル

Algol A is a MS star, and Algol B is a subgiant

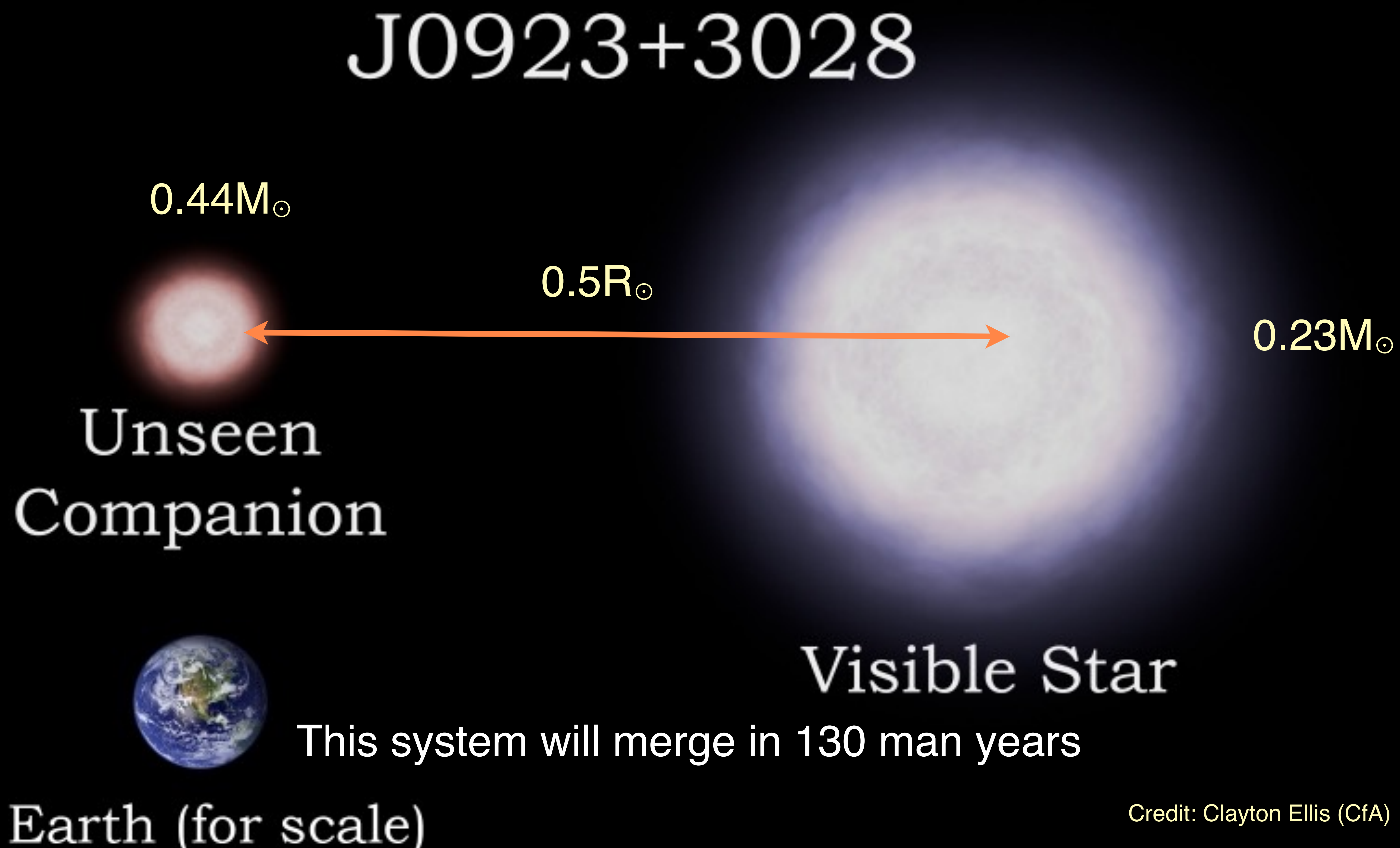
A more evolved star (Algol B) is less massive!



Algol B orbits Algol A.
This animation was assembled from 55 images of the CHARA interferometer in the near-infrared H-band, sorted according to orbital phase. (Baron et al 2012)
CHARA: resolution is 0.0005 arcsec

Inner binary:
3.6+0.8Msun,
P_1= 2.87d (a_1=13 Rsun),

Double White Dwarf



This system will merge in 130 man years

Credit: Clayton Ellis (CfA)

In the past, each of these stars was at least 10$R_\odot$

credit: ESO

Henize 2-428:

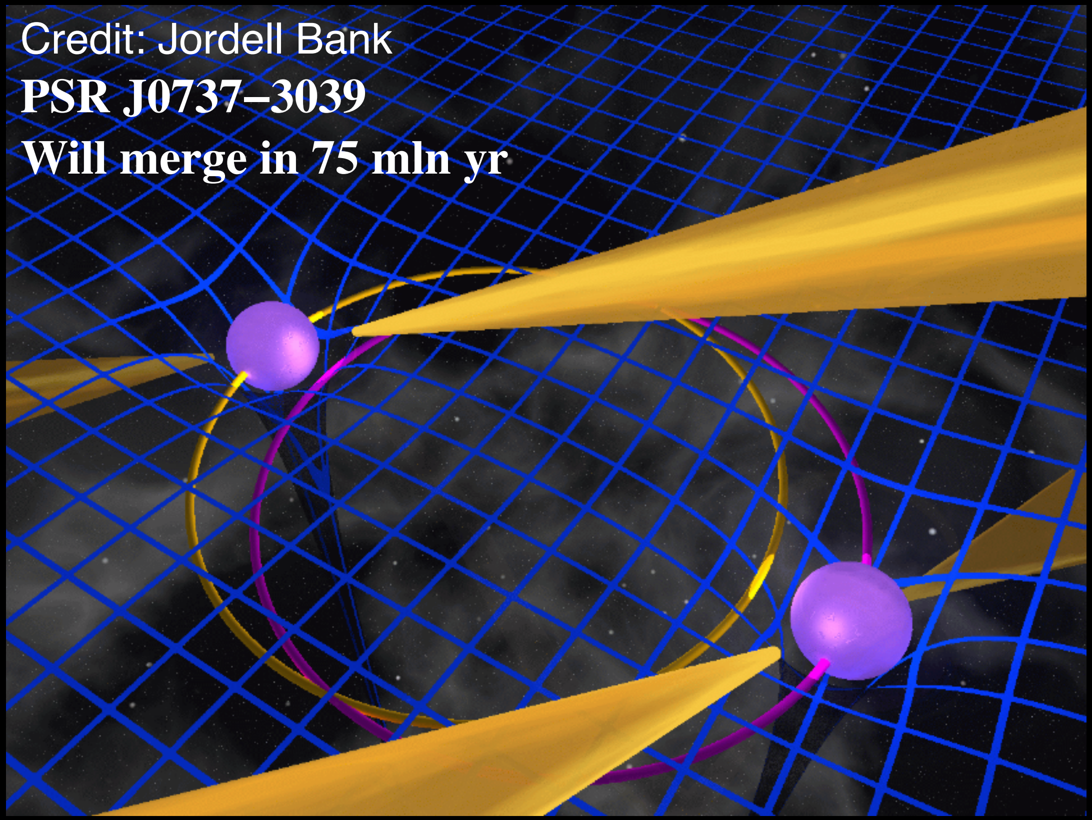
total mass 1.8Msun,

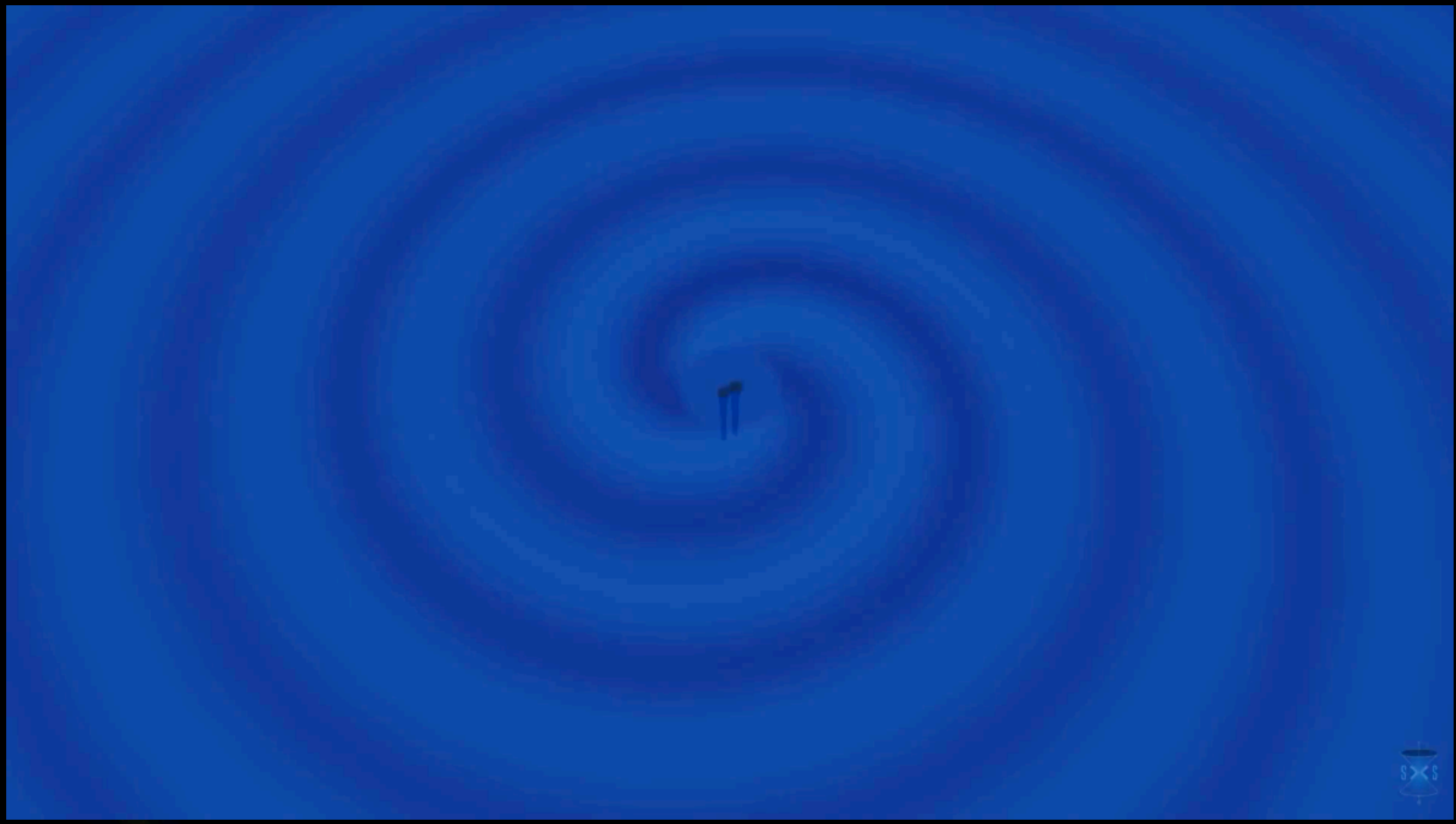
distance between the WDs is about 1.5Rsun

In about 700 man year they will merge and explode as Ia SN

At least one of the stars was > 200 Rsun before

Double Neutron Stars, double Black Holes





Credit: LIGO, SXS

In the past, each of these stars was > $500 R_\odot$

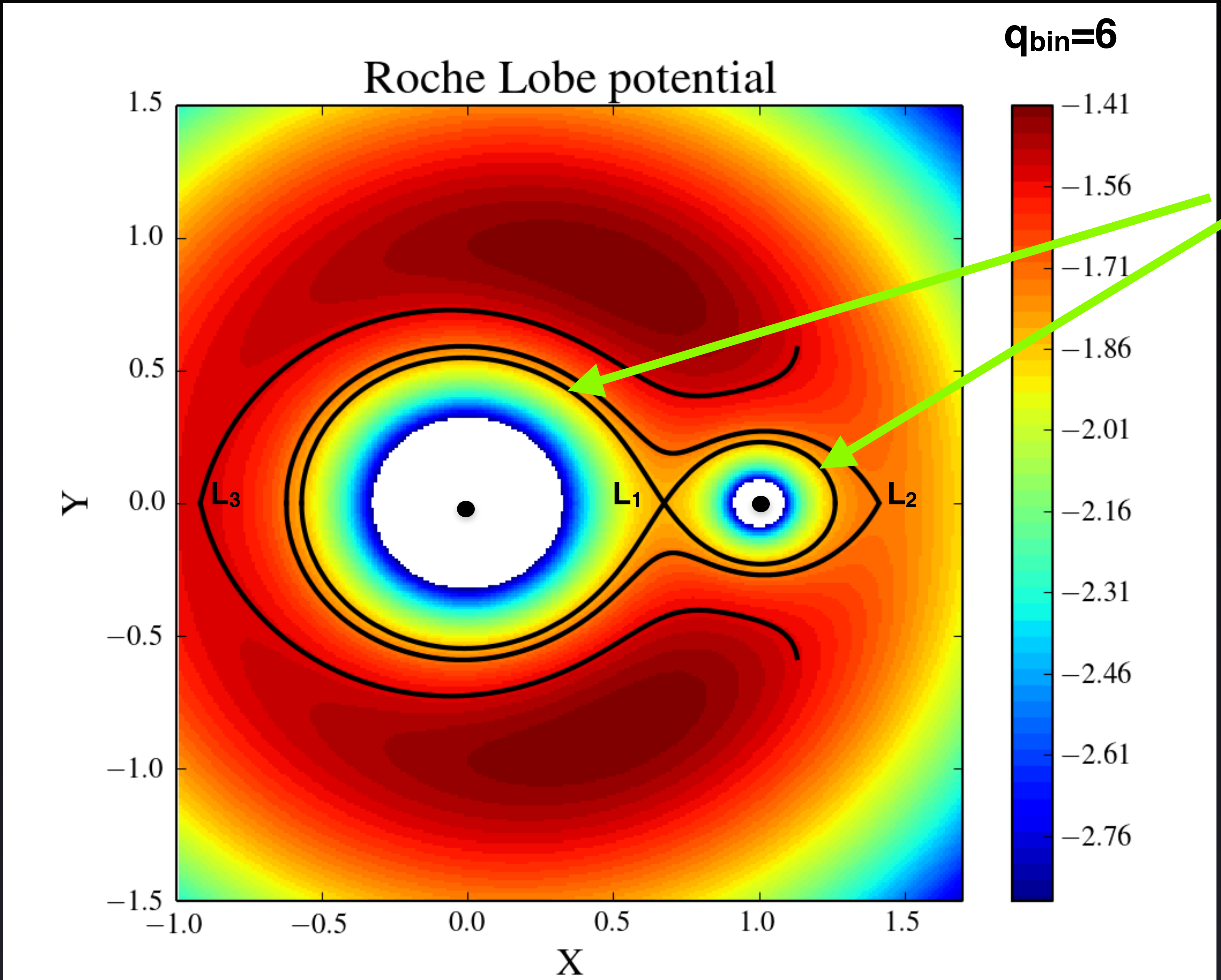
Questions we ask:

How come these close binaries could exist?

How could they be formed?

What has happened to them in the past?

Understanding hard life in a binary

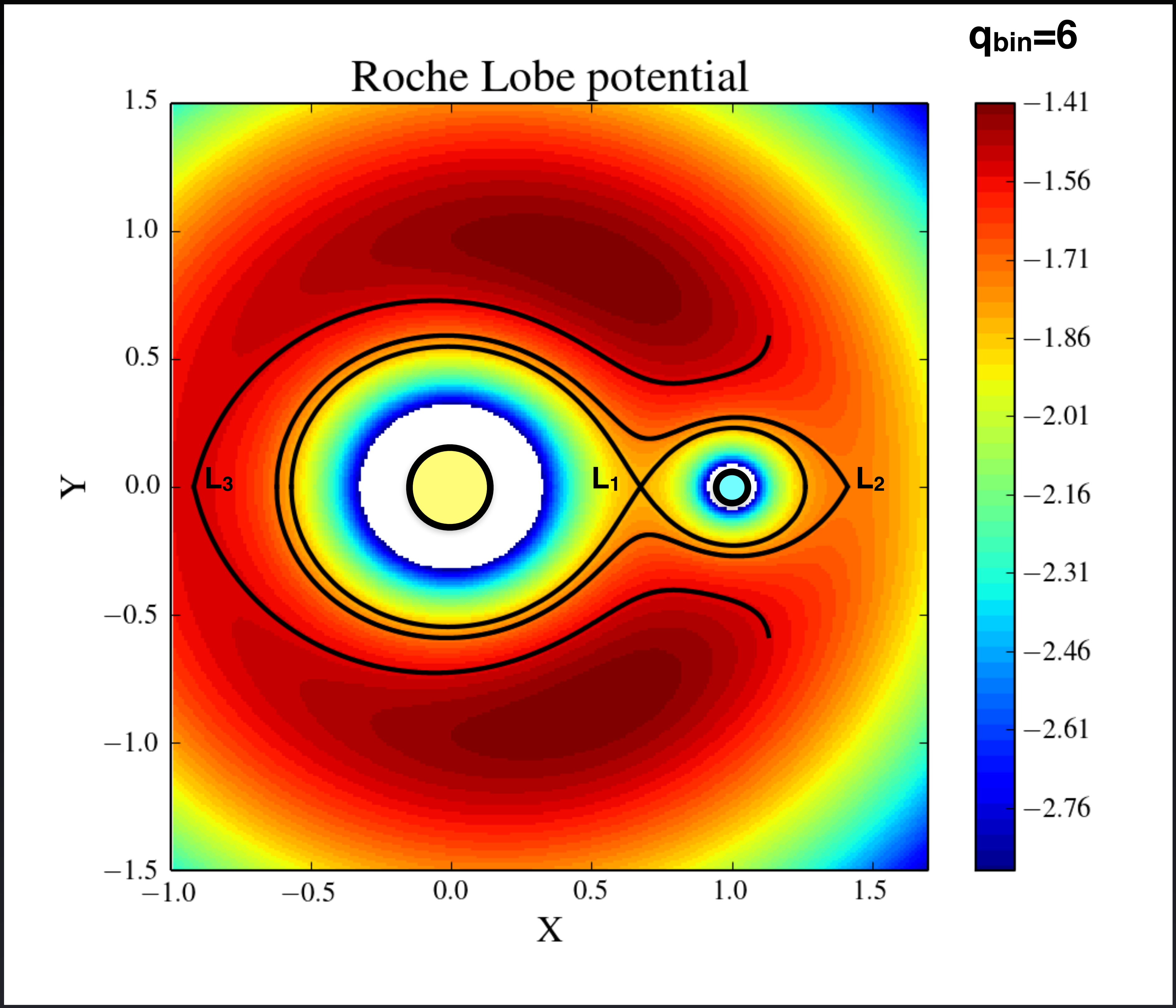


Orbital plane, corotation frame

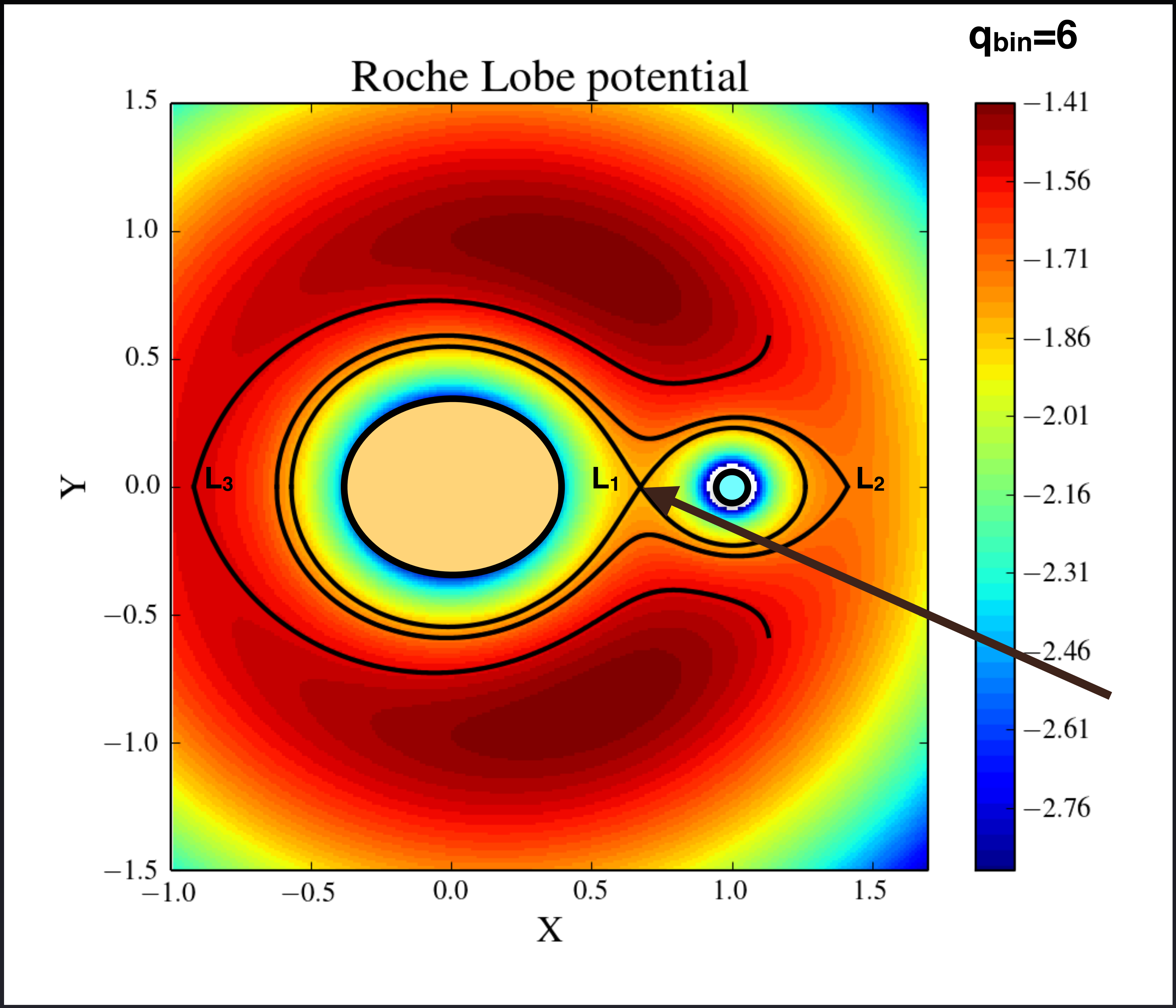
Roche lobe is the volume around a star within which orbiting material is gravitationally bound to that star

Colors indicate surfaces of the same potential (regions in 3D space where every point is at the same potential)

Understanding hard life in a binary



Understanding hard life in a binary

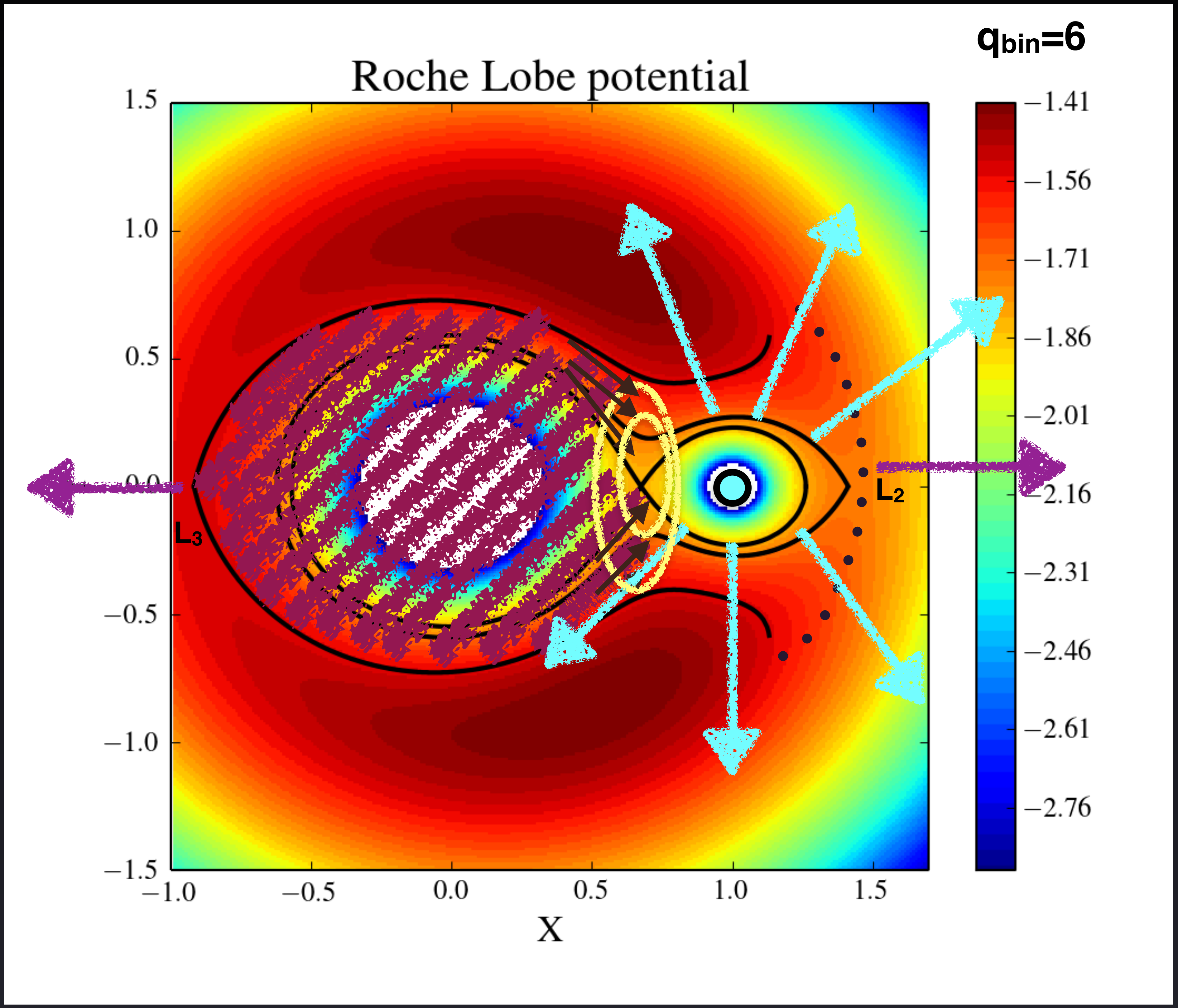


If two stars get too close (distance between them is becoming comparable to their size), tidal forces from one star can deform the larger star into a tear-drop shape

Either initially close binaries, or a star is growing in its size with time

L_1 - saddle point, such that gas bound to one star in vicinity of L_1 finds it easier to pass through L_1 into the RL of the another star than to escape completely.

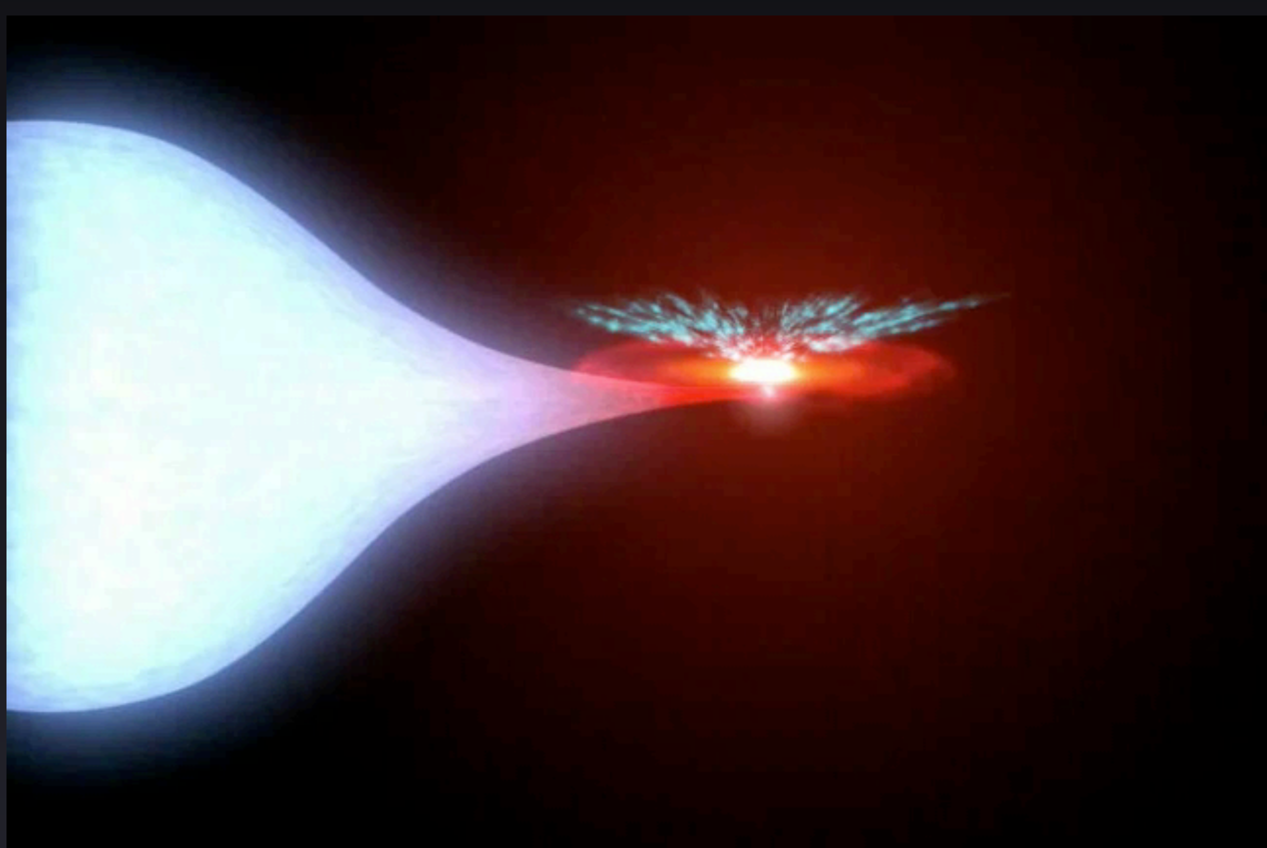
Understanding hard life in a binary

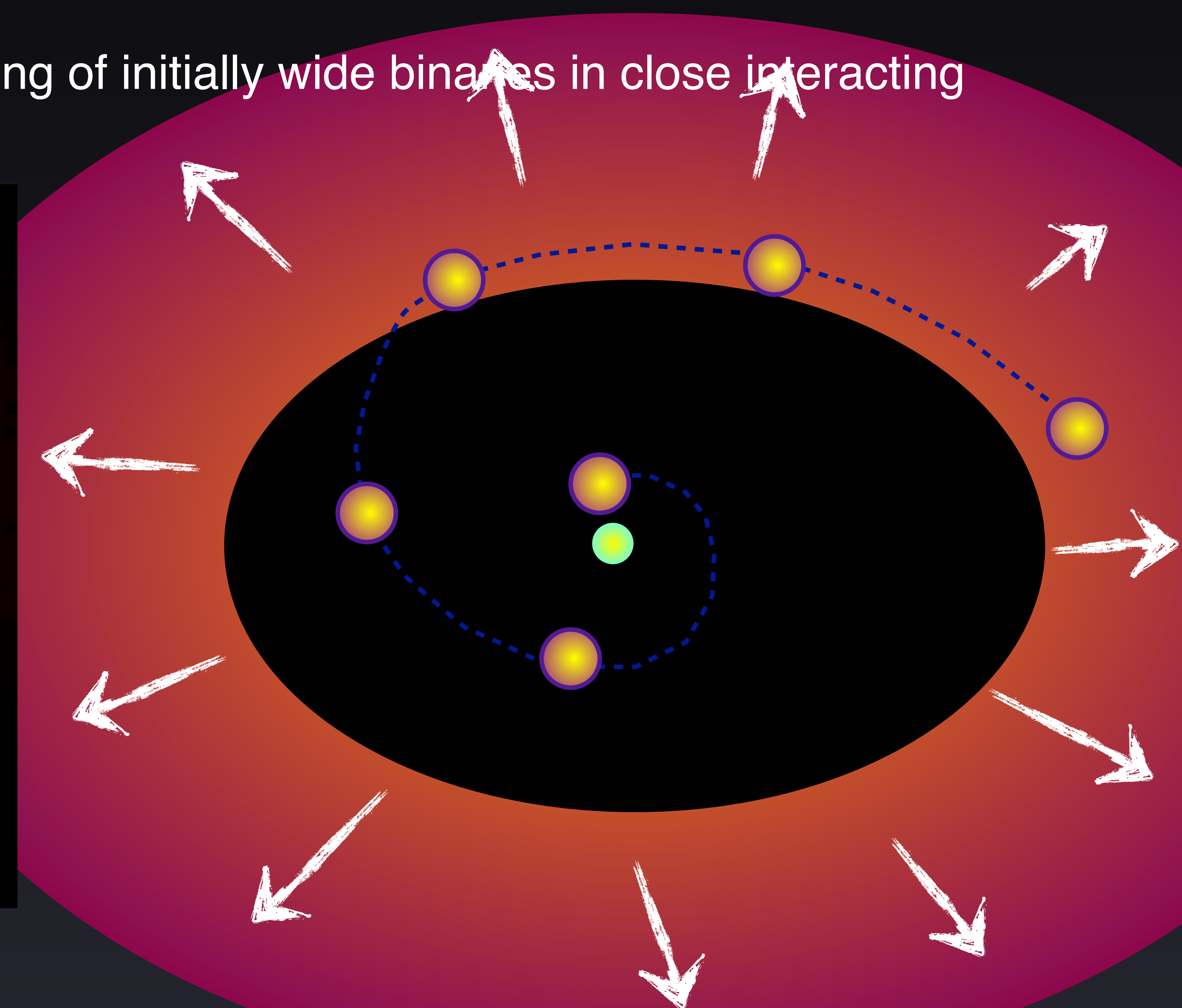


If star evolves and become bigger than its Roche lobe, its material gets to RL of the another star – MASS TRANSFER VIA ROCHE LOBE OVERFLOW STARTS!

Stability at RLOF decides the fate of the binary

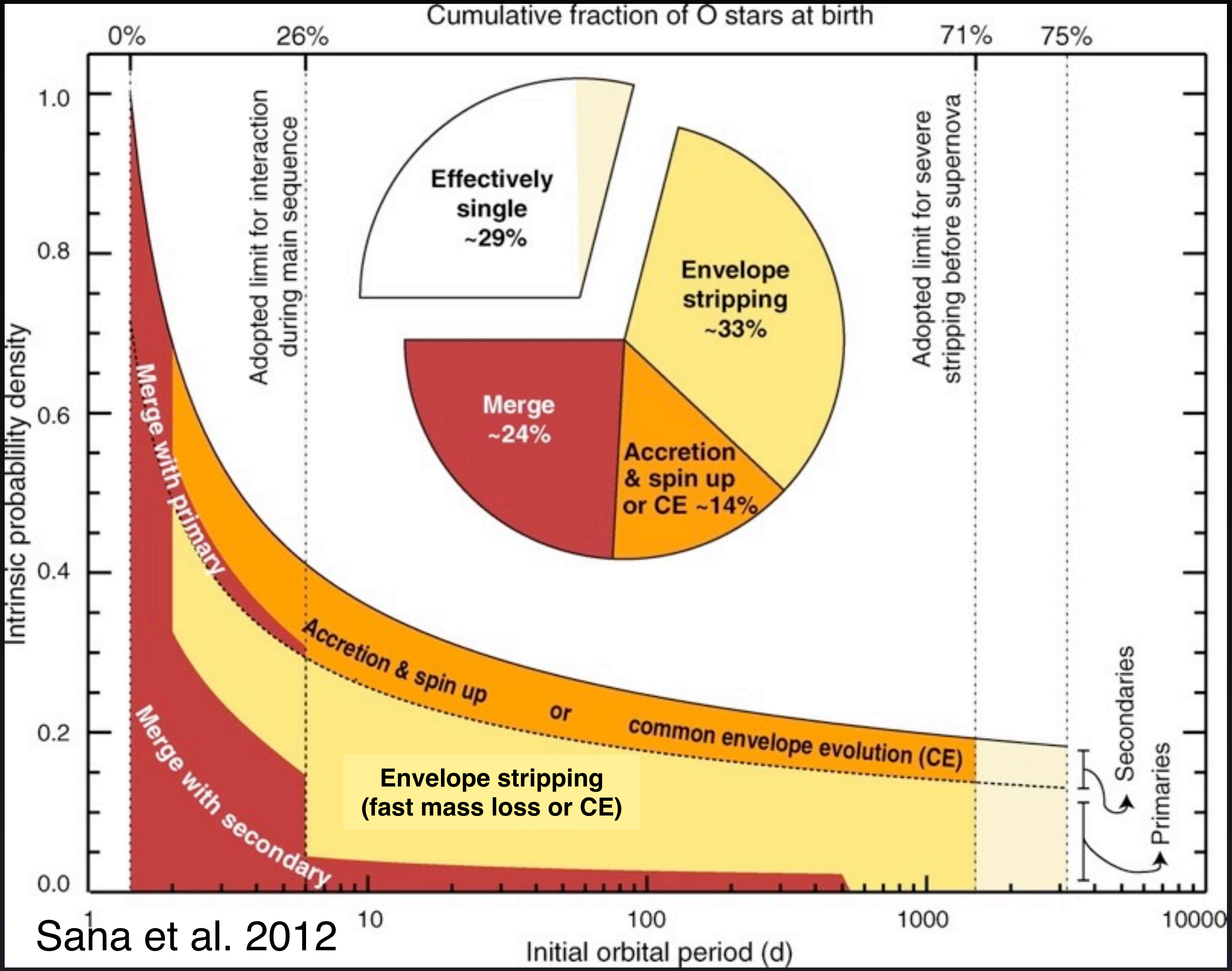
- ➡ Stable, long-term mass transfer (e.g. X-ray binaries)
- ➡ Unstable, AKA Common Envelope event (1976: Webbink, Paczynski, Ostriker).
  - ➡ It is a rapid phase, during which a smaller companion spirals inward through the extended envelope of the larger (often more massive primary) donor. Can end as a merger or as a binary formation
  - ➡ CEE is an ultimate tool of transforming of initially wide binaries in close interacting binaries





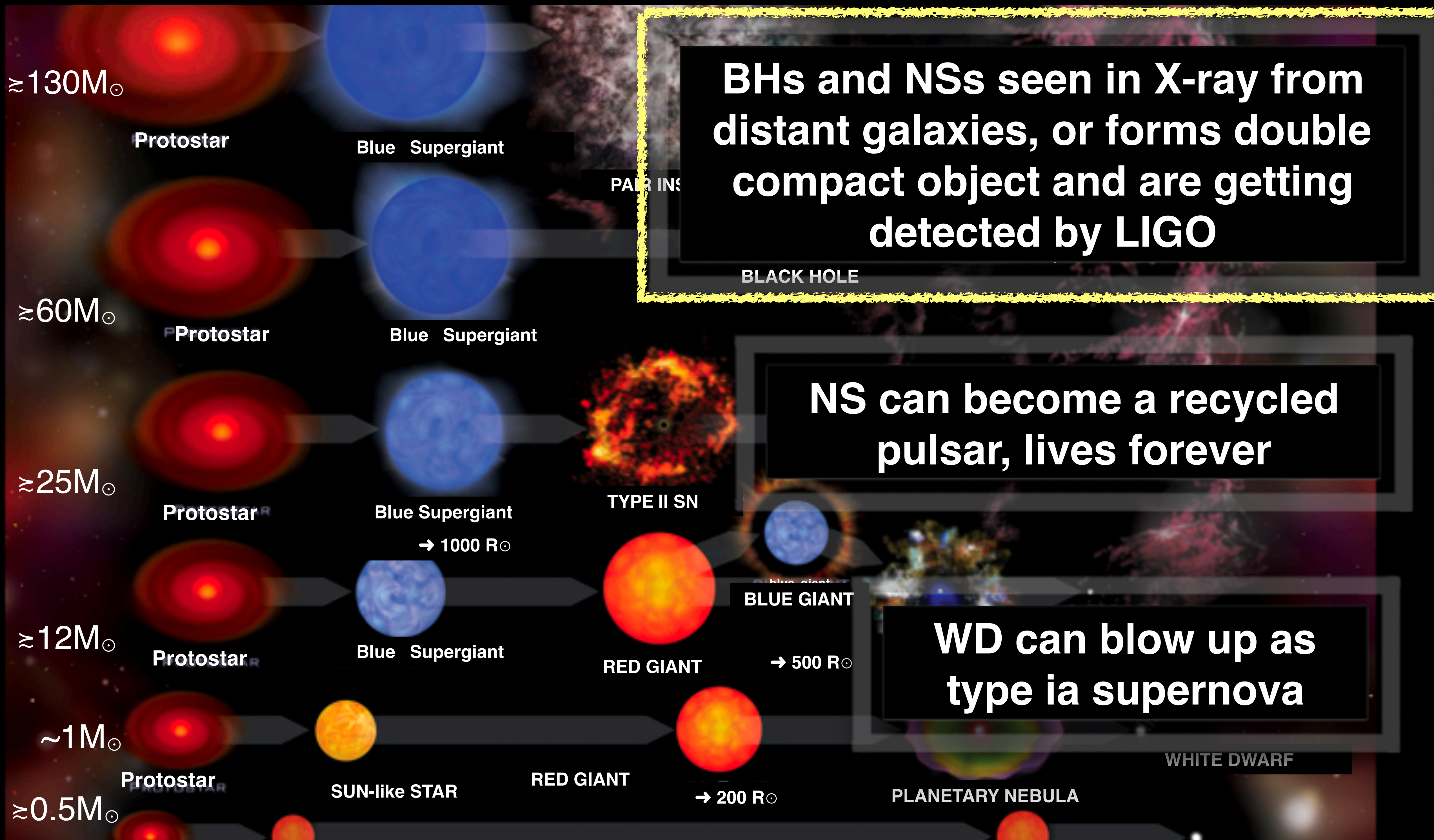
How often stars do that?

Input: IMF + q + periods -> Most of massive stars interact!



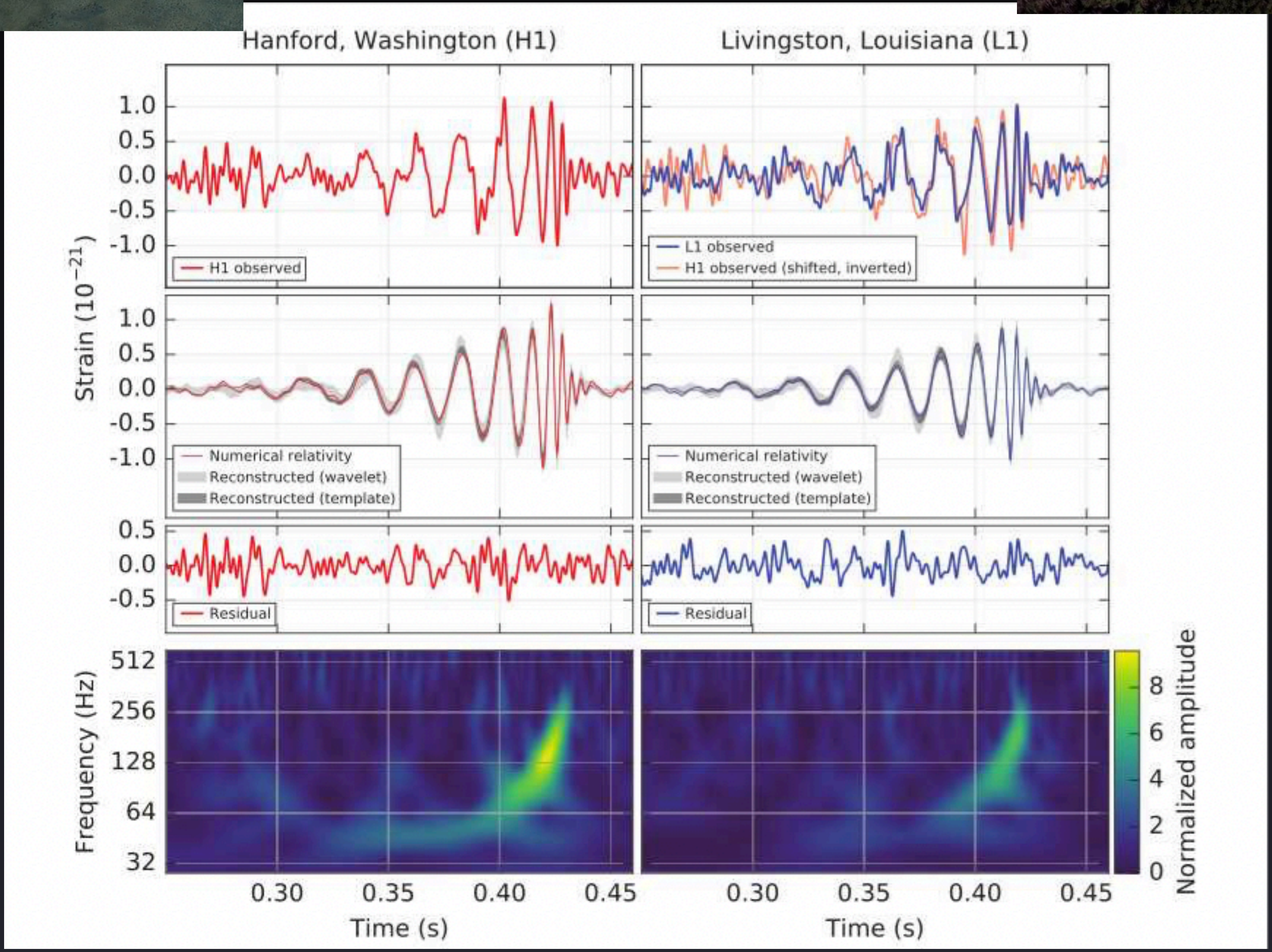
The pie chart above is proper to indicate what fraction would interact, but is the subject of great uncertainties on what kind this interaction will be!

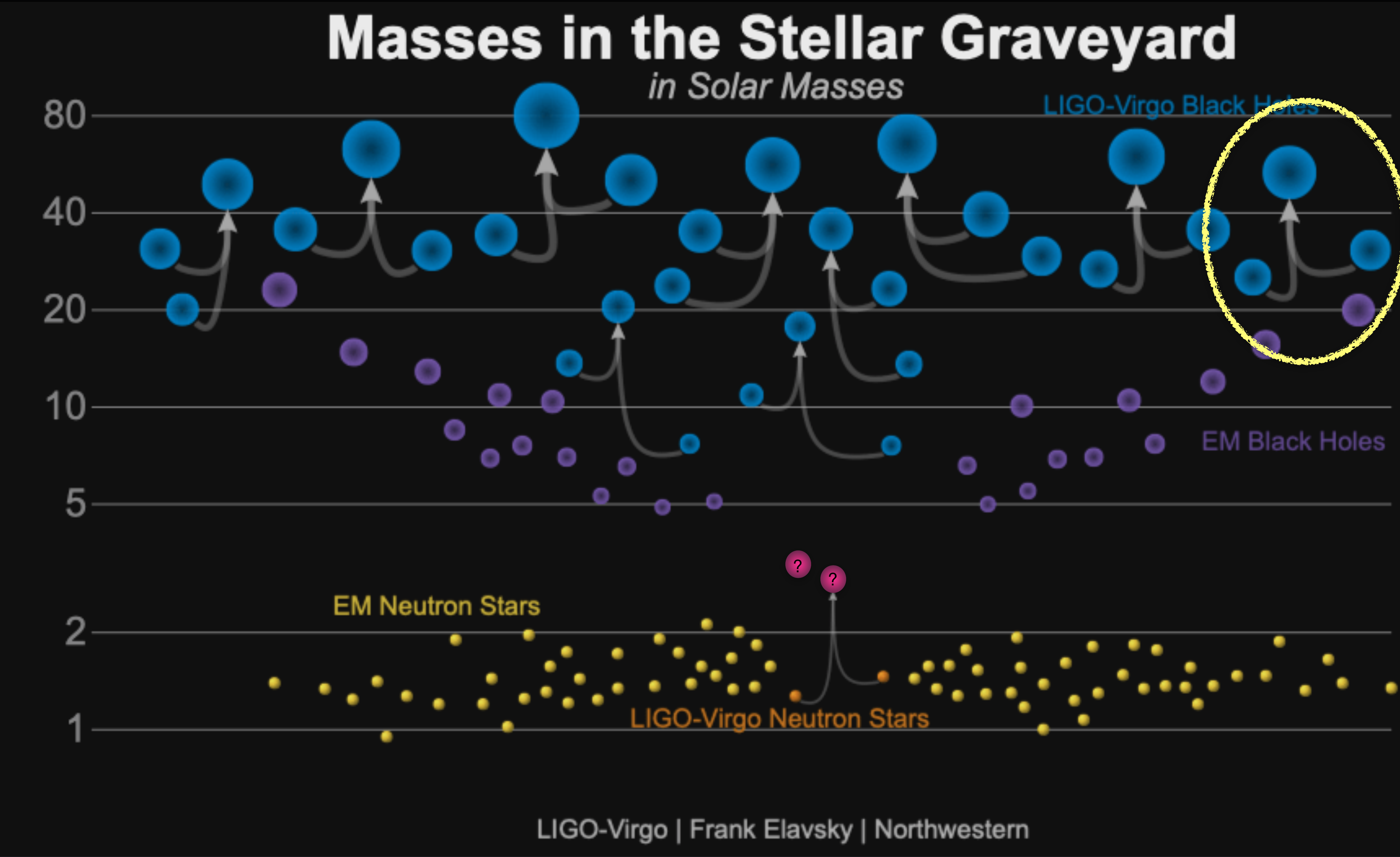
Interactions: CHANGE Mass, Lifetime and Fate



Interactions between stars are responsible for the formation of many high-energy objects and events, including supernovae, X-ray binaries, gamma-ray bursts, gravitational-wave sources, and more!

The First One! GW150914: 36 + 29 Msun




Masses in the Stellar Graveyard
in Solar Masses
80
40
20
10
5
2
1
LIGO-Virgo Black Holes
EM Black Holes
EM Neutron Stars
LIGO-Virgo Neutron Stars
?
?
LIGO-Virgo | Frank Elavsky | Northwestern

Three schools of thought

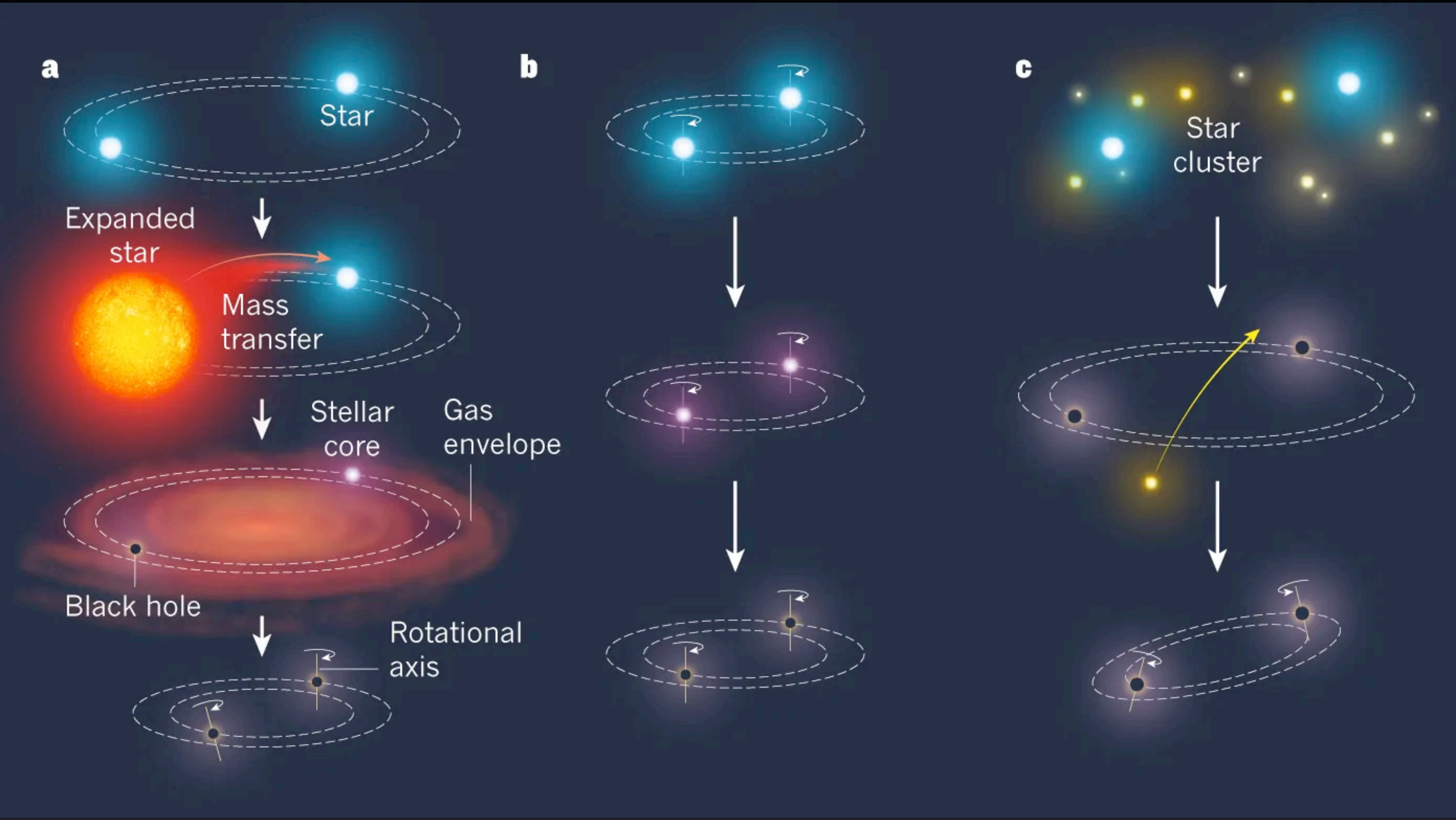
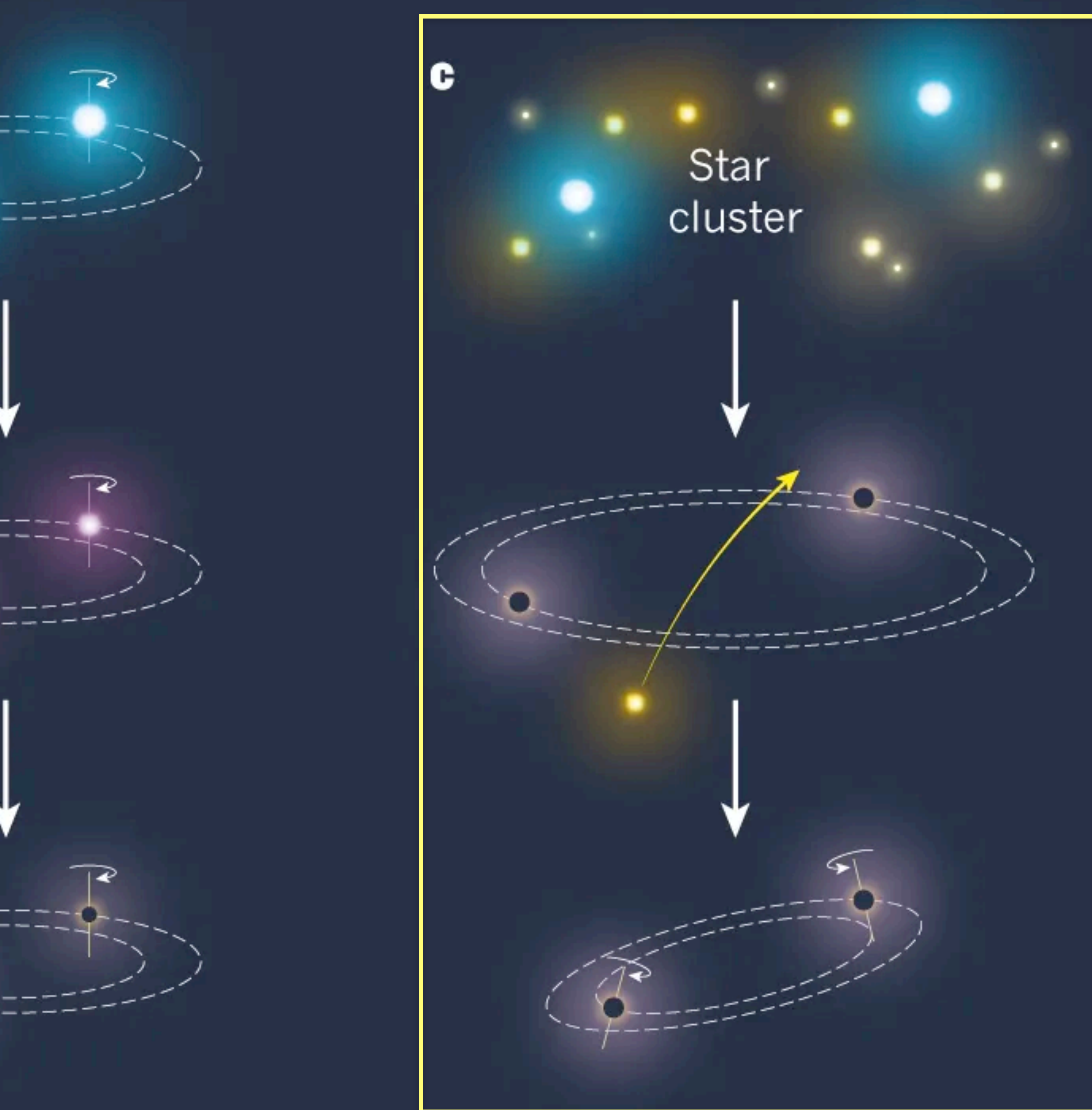


Image credit:
Mandel & Farmer, 2017


c
Star
cluster

- Mass ratio distribution
- Period distribution
- Mass transfer
- Common envelope

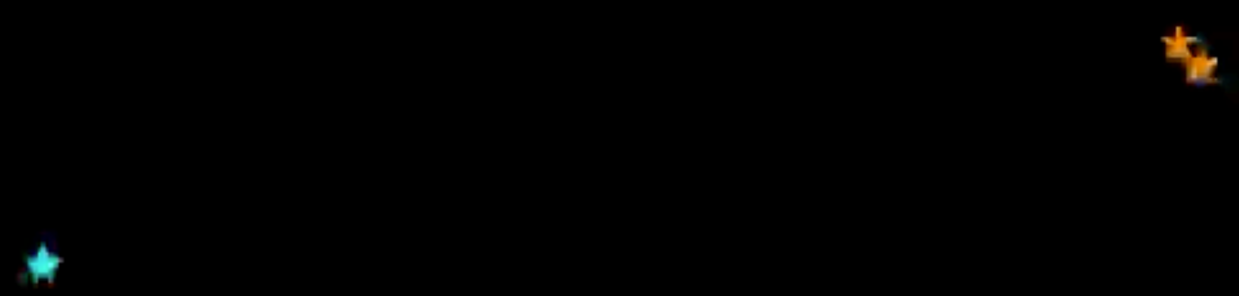
(it still can play a role, but not formative)

- IMF
- “BH IMF”
- Kicks
- All possible stellar physics and related uncertainties

Dynamical BH (NS) binary formation

- Dense environment with a high chance of stellar encounters
  - Globular clusters - spherical system of 10^4-10^6 stars with high stellar density of 10^4-10^6 stars per pc^3
- Formation:
  - “IMF” for BHs/NSs as for normal stars
  - Natal kick - retention problem; changes “IMF” (ECS NSs!)
  - Most become single upon formation
- Evolution:
  - Due to dynamical friction BH/NSss quickly concentrate in the centre.
  - BH sub-cluster (Spitzer instability)
  - Central BH clouds is an ideal place for their further interactions
  - In the past it was thought that this interaction would quickly all BHs away. Detailed simulations show significant fraction of BHs remains.

Dynamical BH (NS) binary formation



Seed binary is formed via exchange BS or BB encounter.
A more massive star is replacing a lighter companion.

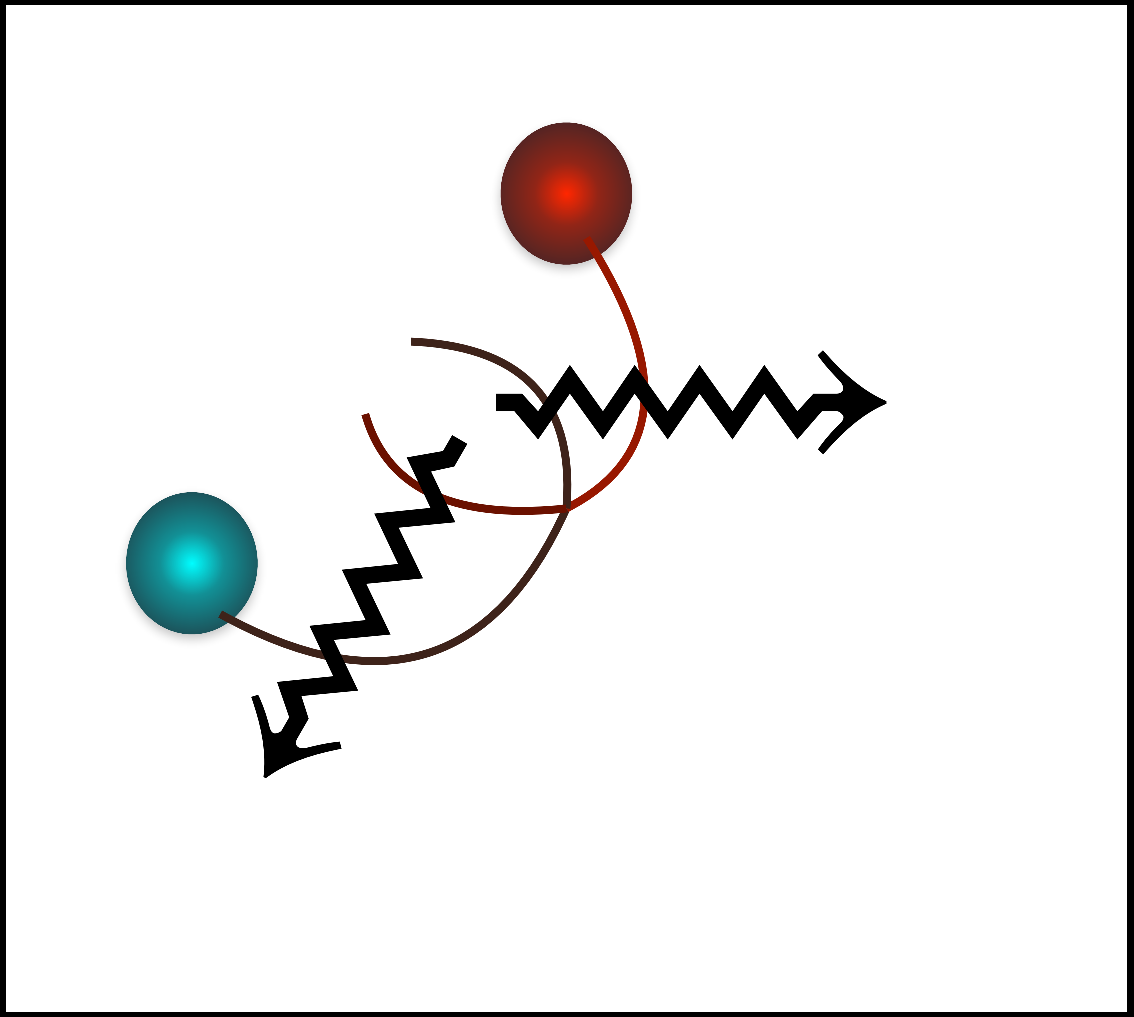
Rates: simple cross-sections

Fantastic tool to study encounters:
FewBody by Fregeau et al.

movie: Rodrigues

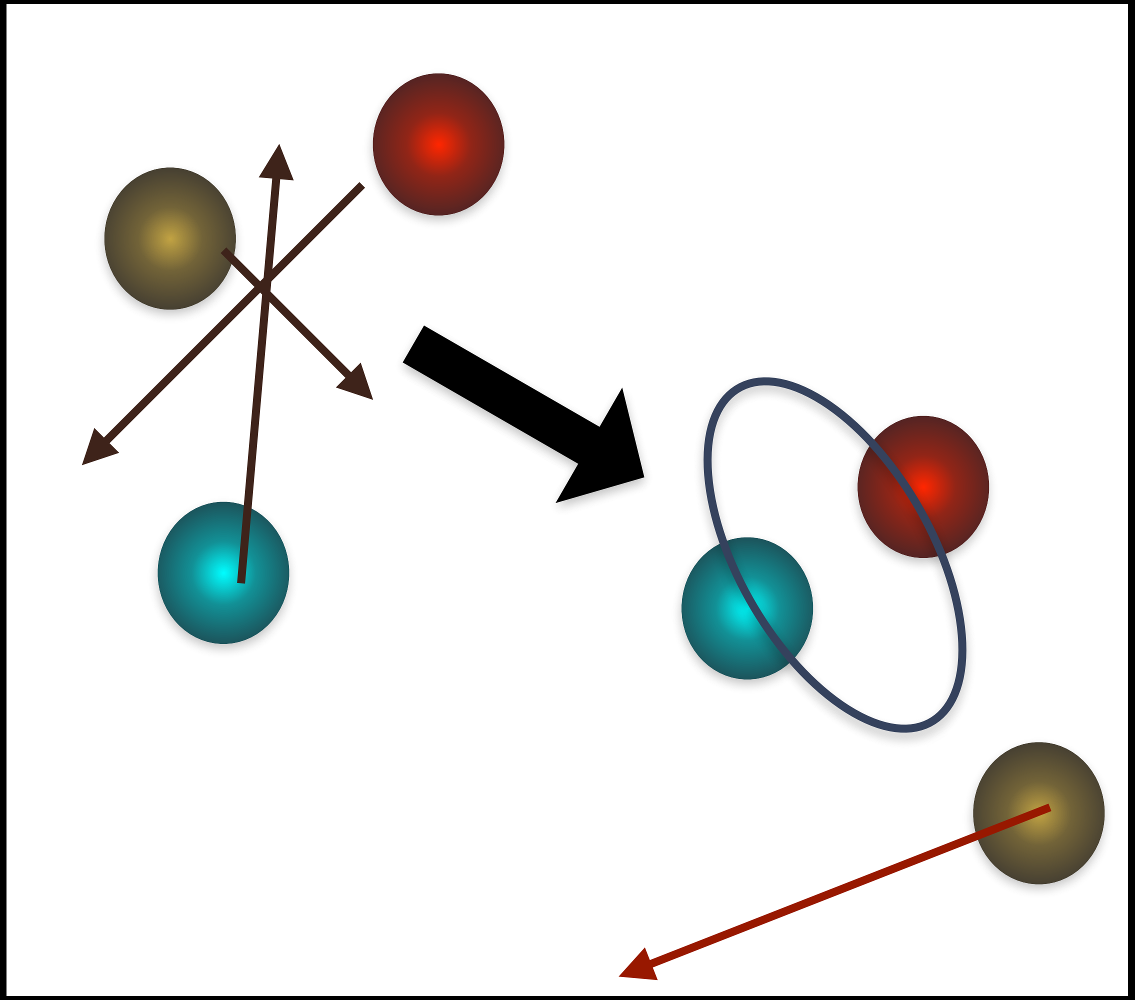
Dynamical BH (NS) binary formation

Two body: GW capture



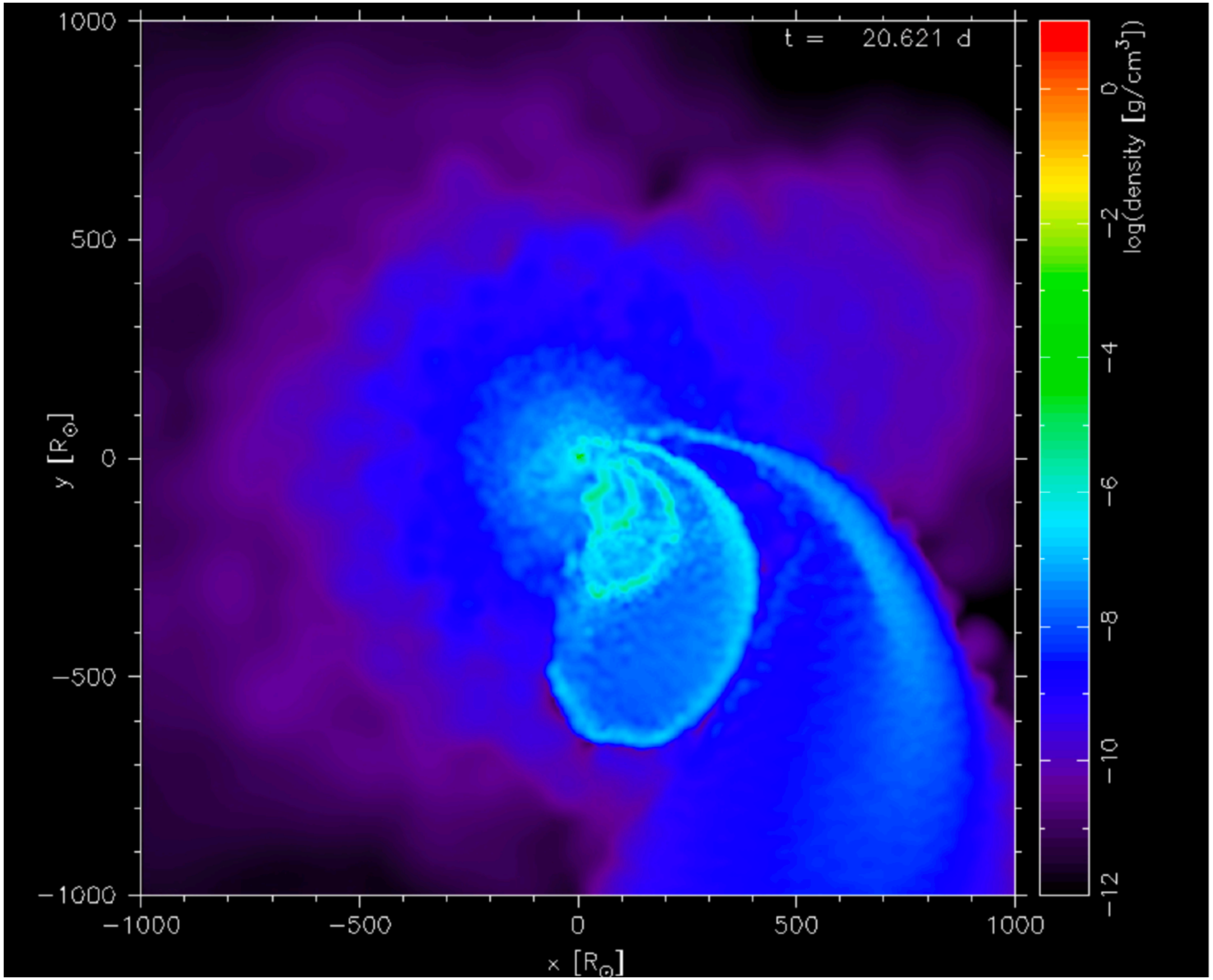
Two body gravitational focusing with energy loss by GW emission.
Rates: Quinlan & Shapiro 1987

Tree body



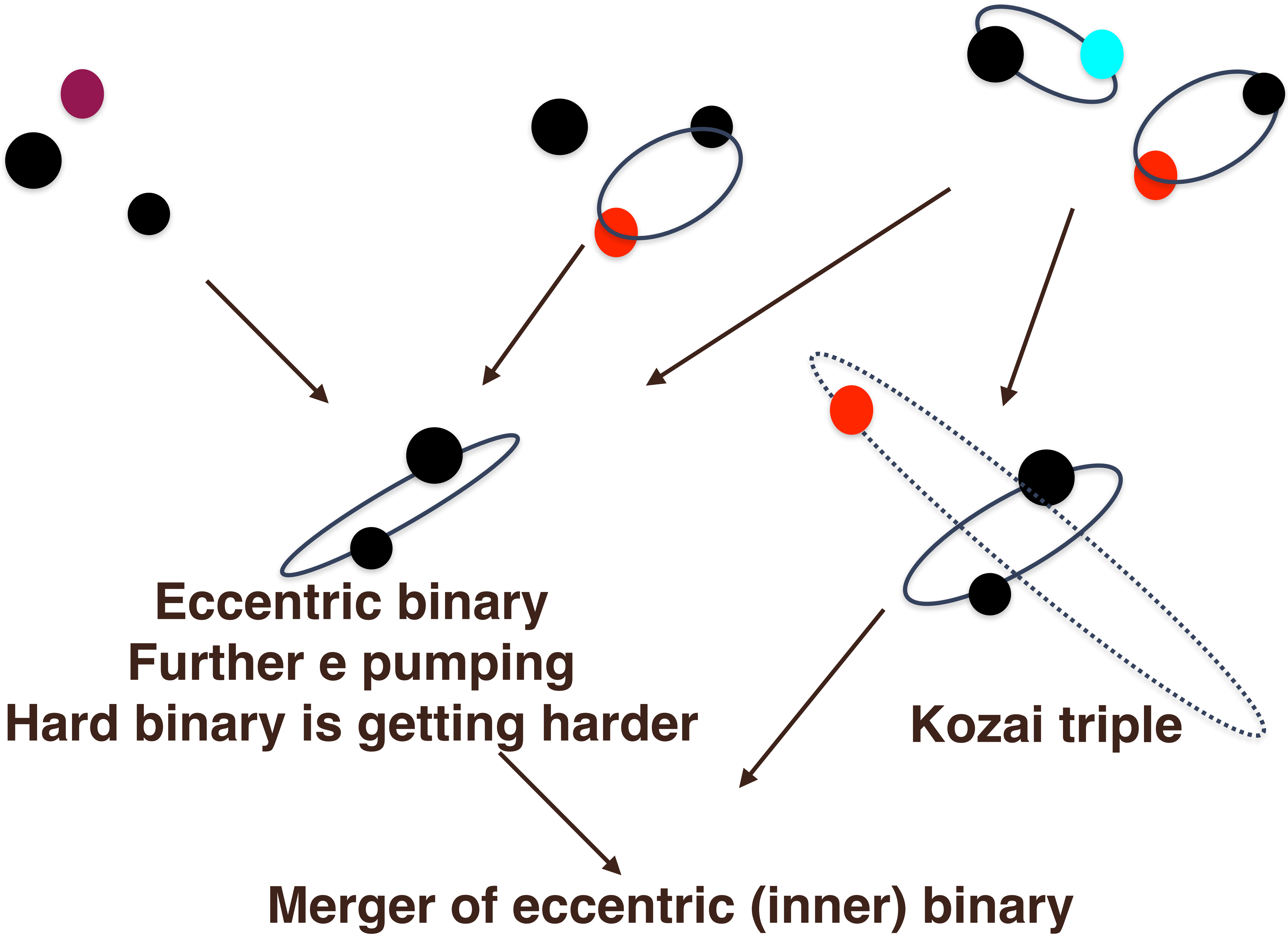
Temporary formation of a triple system which become a bound binary by ejecting the third star at a high velocity.
Rates for non-equal masses: Ivanova et al 2010

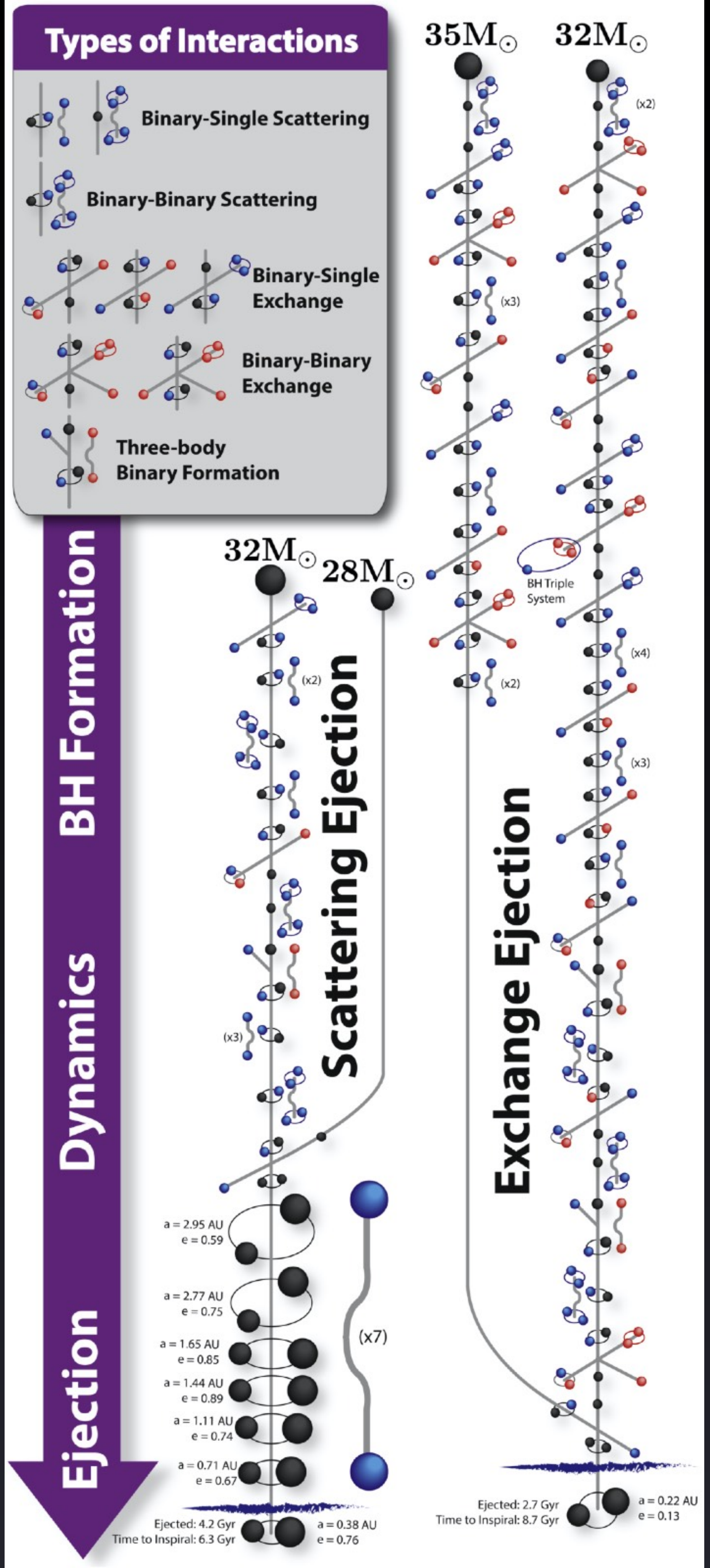
Dynamical BH (NS) binary formation



Ivanova et al 2017

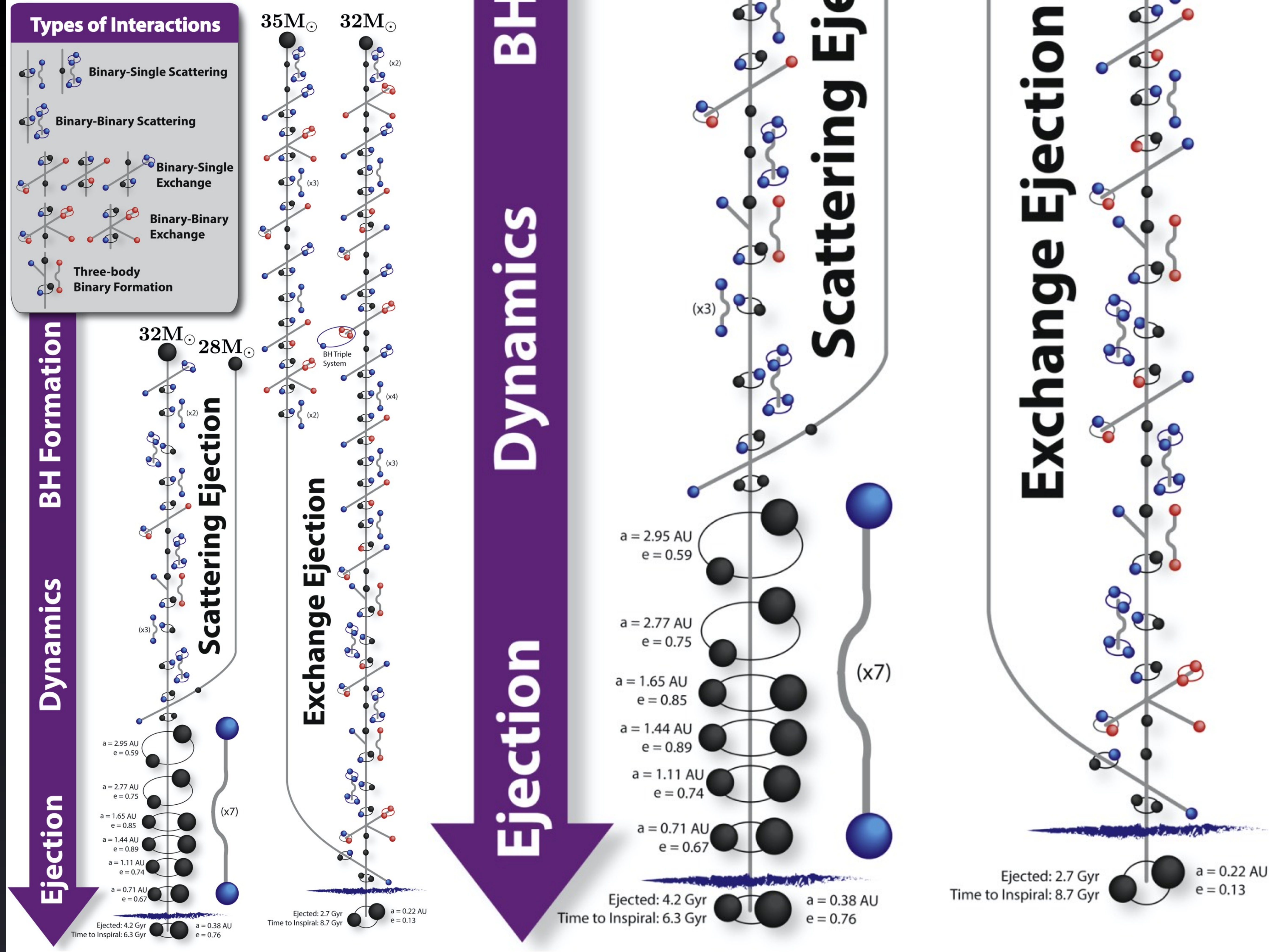
Dynamical BH-BH binary formation





Dynamical BH-BH binary formation: the tree

Rodriguez et al 2016

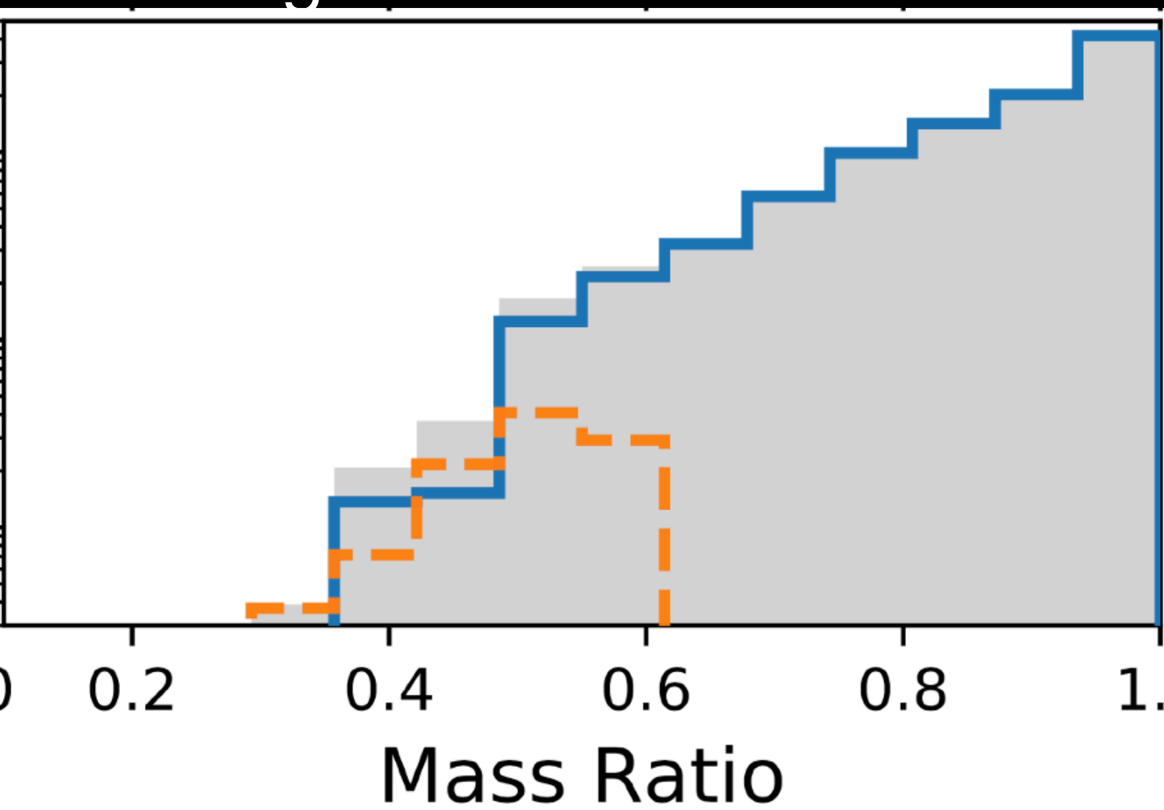

Types of Interactions
Binary-Single Scattering
Binary-Binary Scattering
Binary-Single Exchange
Binary-Binary Exchange
Three-body Binary Formation
35M$_\odot$
32M$_\odot$
32M$_\odot$
28M$_\odot$
BH Formation
Dynamics
Ejection
Scattering Ejection
Exchange Ejection
BH Triple System
(x2)
(x3)
(x4)
(x7)
a = 2.95 AU e = 0.59
a = 2.77 AU e = 0.75
a = 1.65 AU e = 0.85
a = 1.44 AU e = 0.89
a = 1.11 AU e = 0.74
a = 0.71 AU e = 0.67
Ejected: 4.2 Gyr
Time to Inspiral: 6.3 Gyr
a = 0.38 AU e = 0.76
Ejected: 2.7 Gyr
Time to Inspiral: 8.7 Gyr
a = 0.22 AU e = 0.13

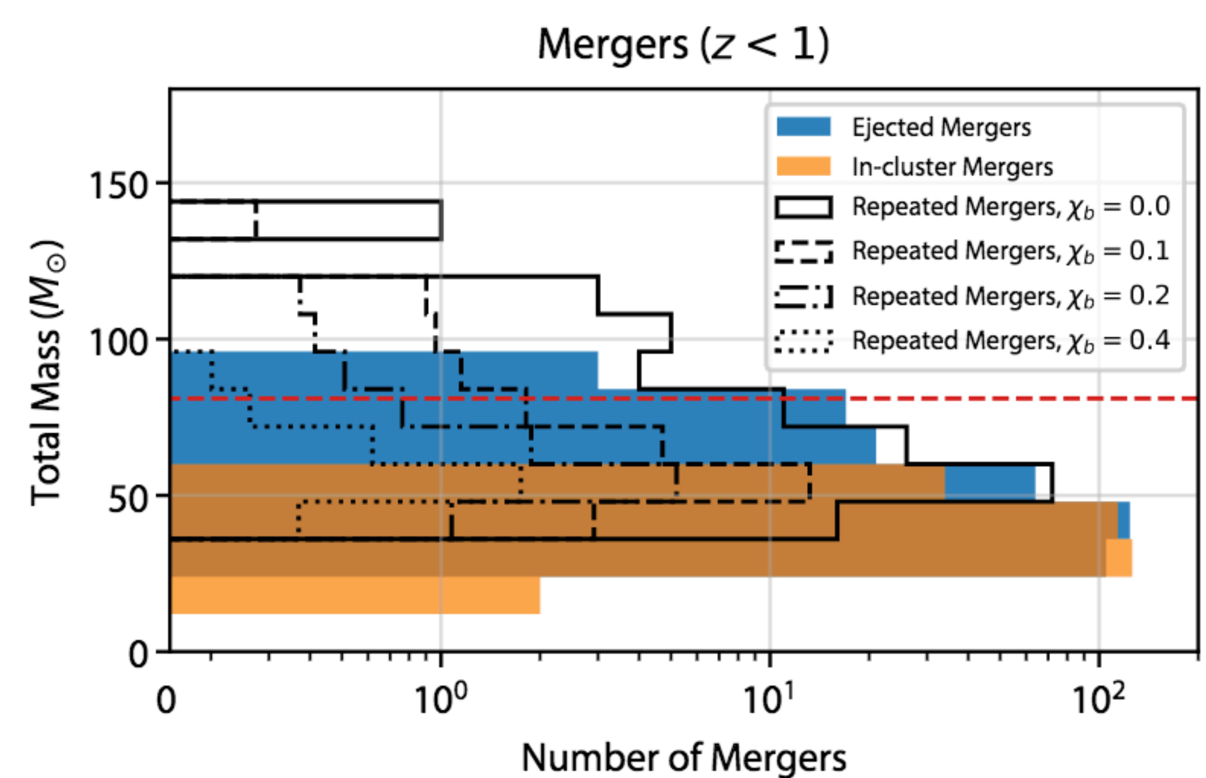
Dynamical BH-BH binary formation: Predictions

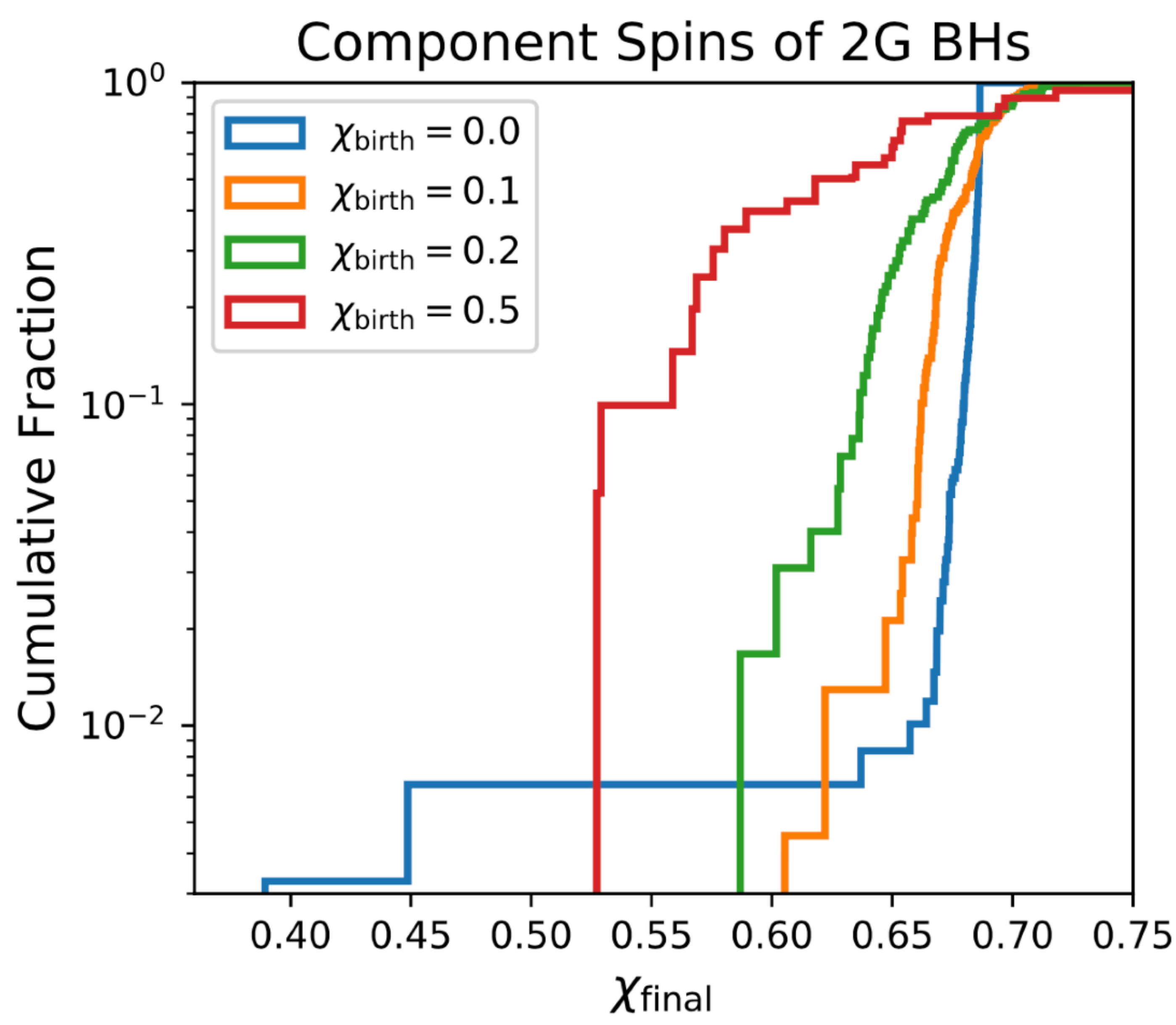
Rodriguez et al 2017

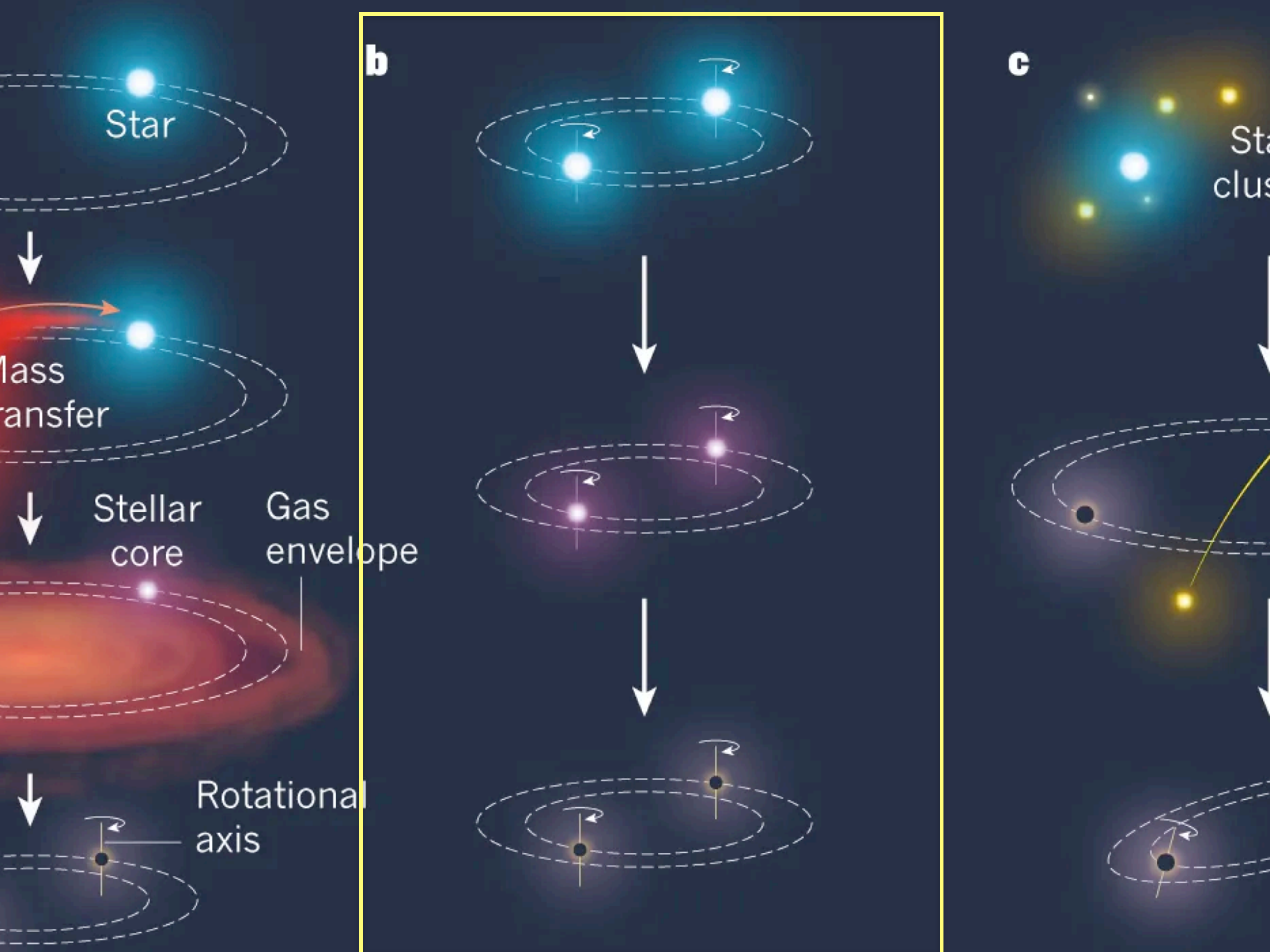
Rodriguez et al 2019

Spins are not aligned
Could be high spins
Mass ratio - almost any if >0.3
High eccentricity is OK



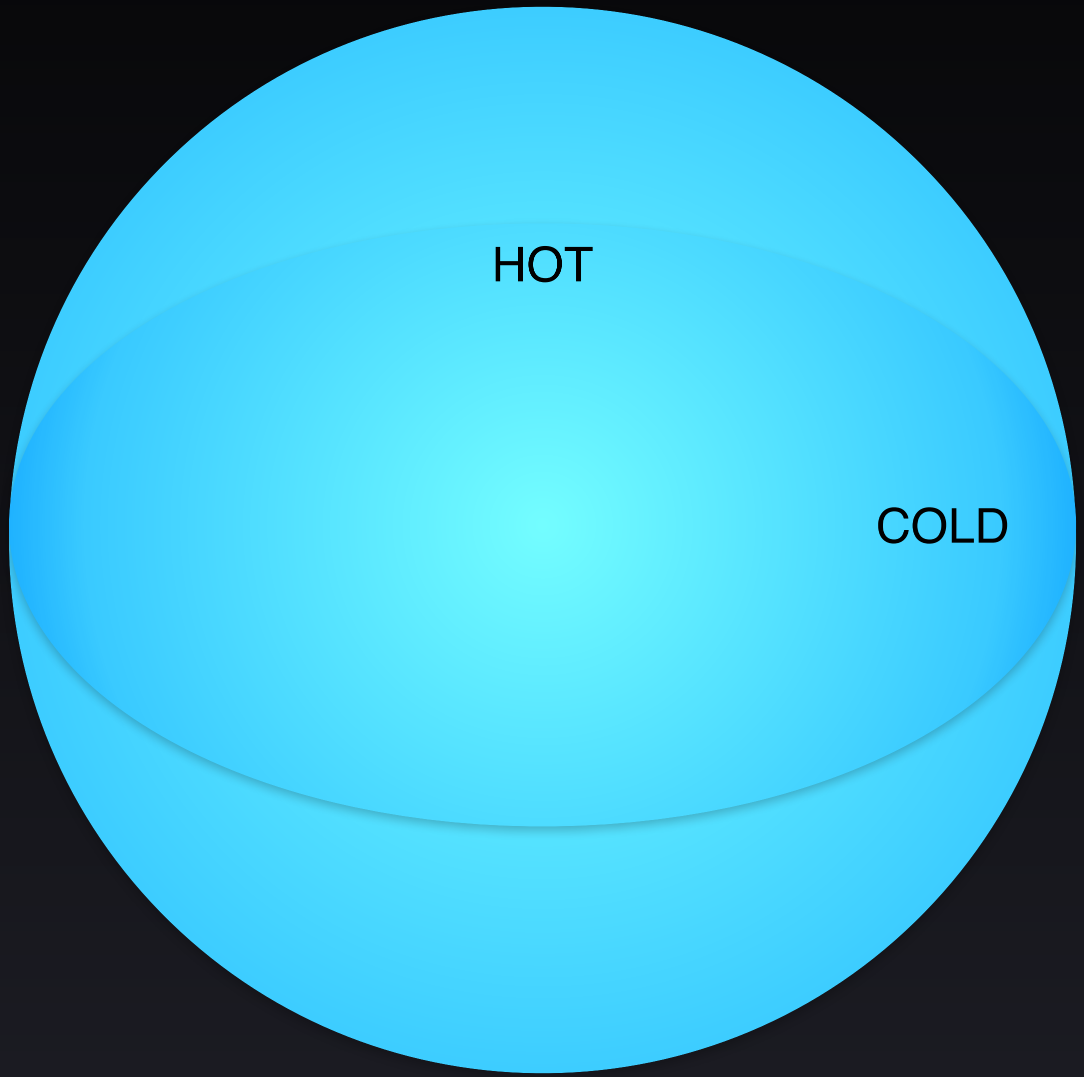


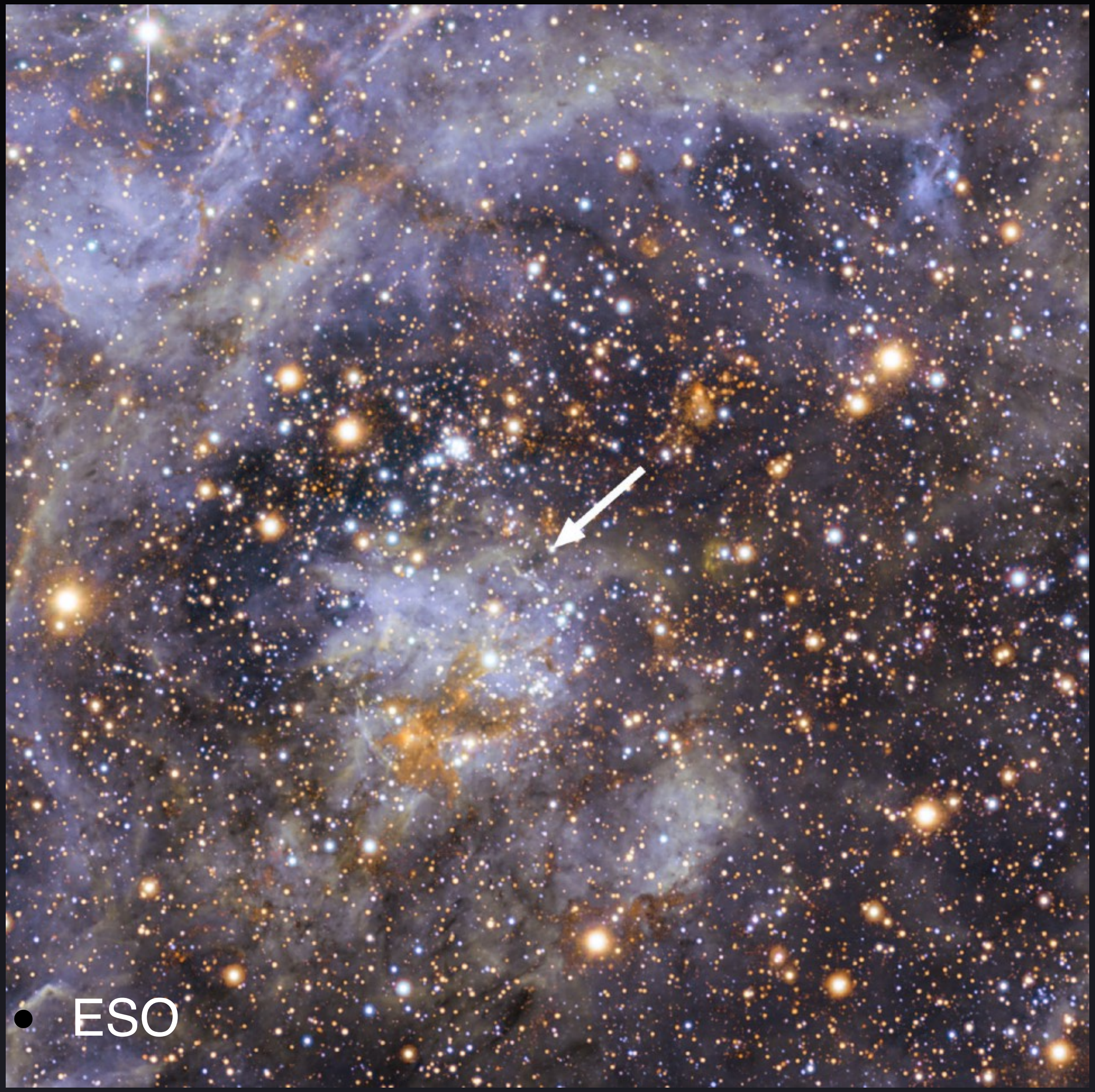




Star
Stellar
core
Gas
envelope
Rotational
axis
b
c

Fast rotating stars

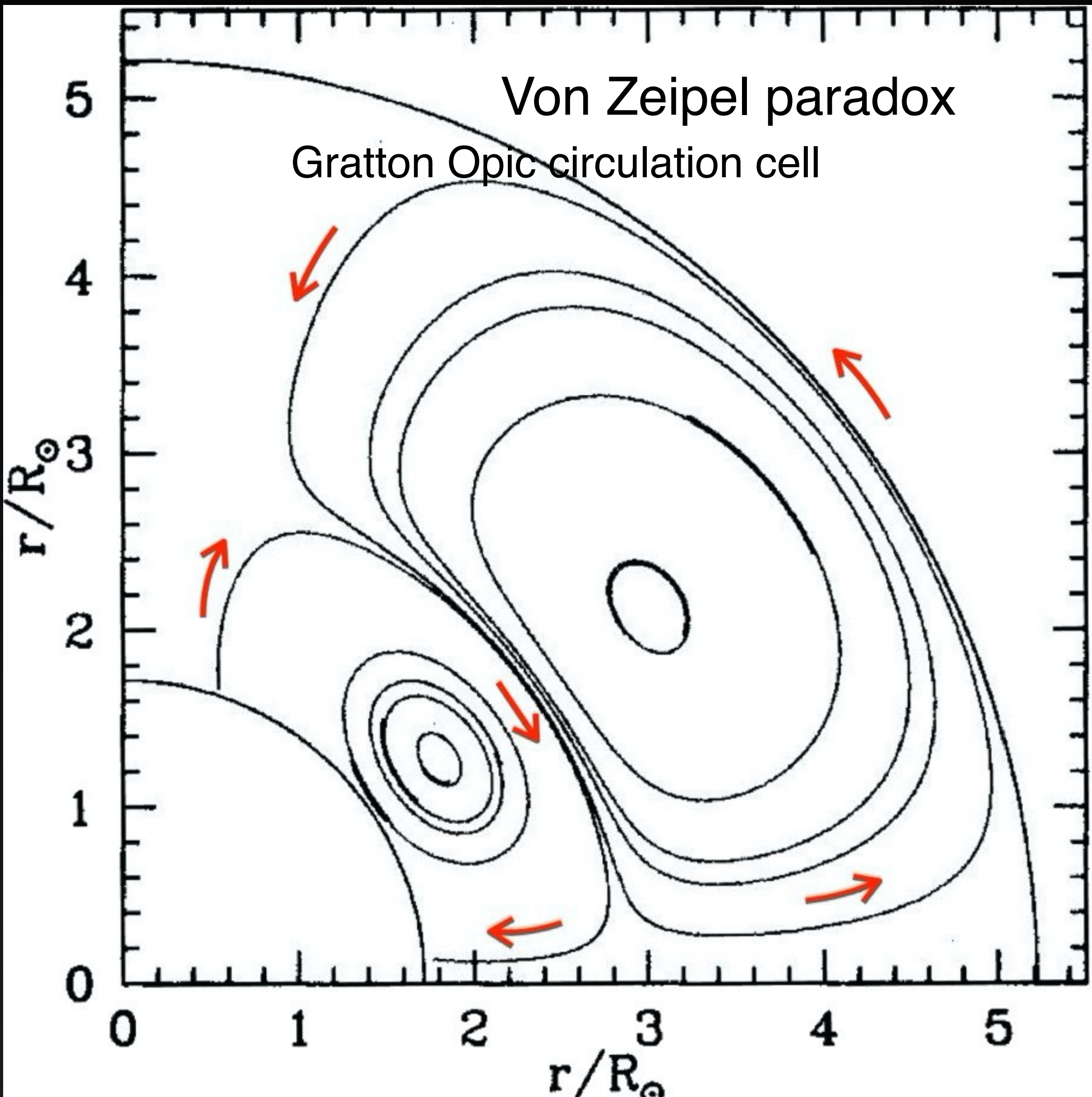




- VFTS 102
- 25 Msun star that rotates near critical, 600 km/s at equator

Oblateness (interior, surface)
New structure equations

Fast rotating stars



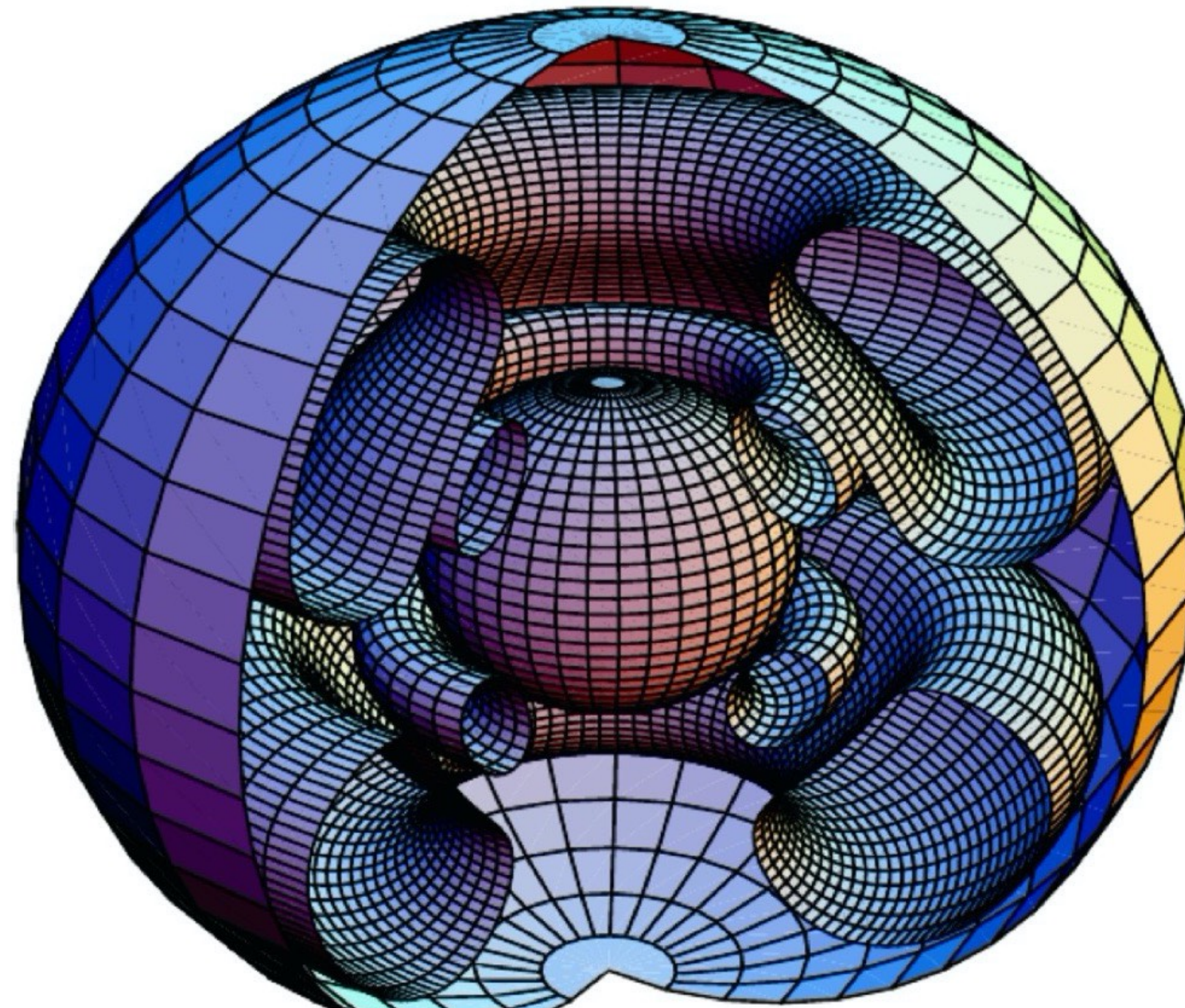
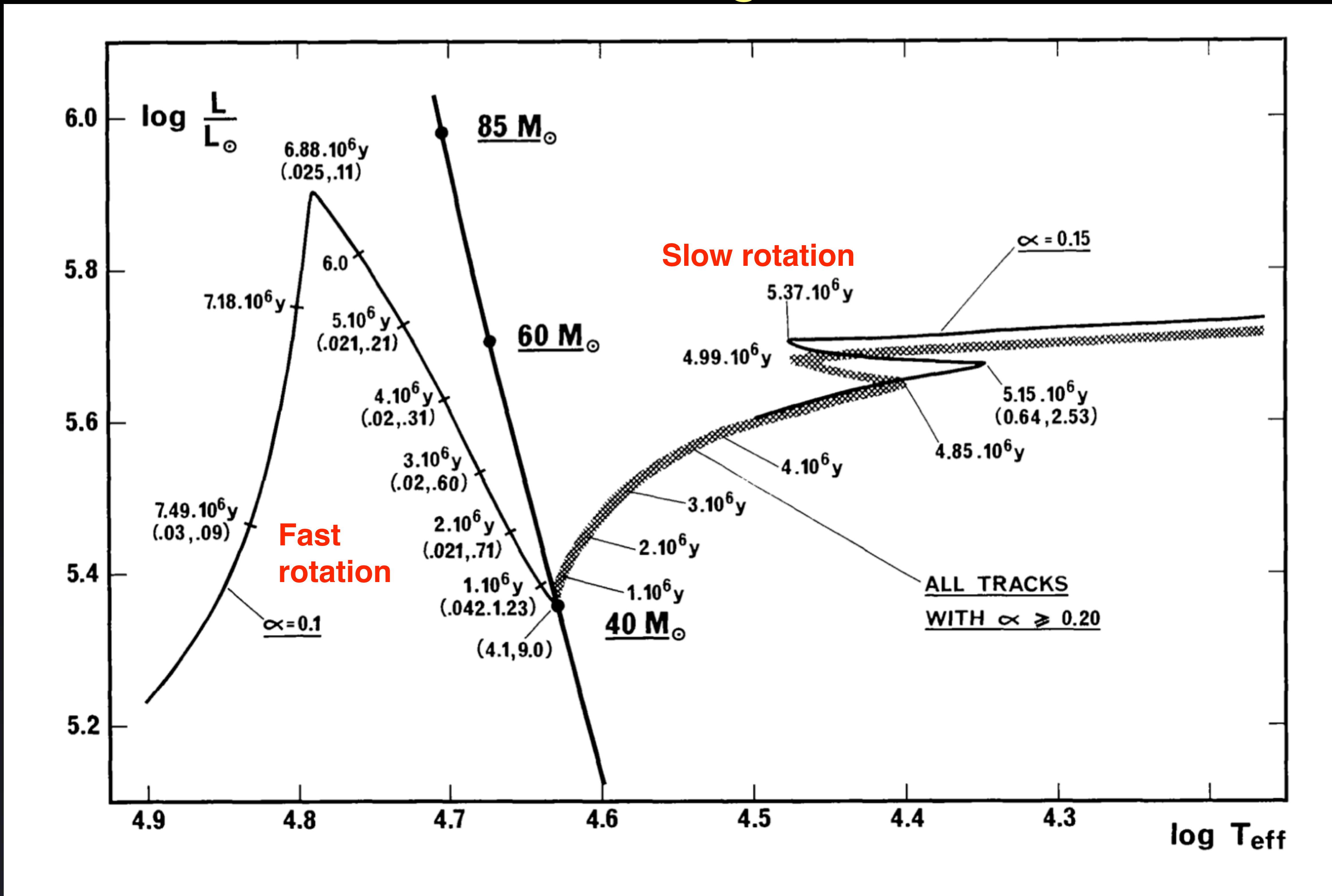


image: Meynet and Maeder2002

- Rotation: if the rotational velocity of a star depends only on the radius, it cannot simultaneously be in thermal and hydrostatic equilibrium.
- This leads to creation of meridional circulation, then to differential rotation, and to shear instabilities, to diffusion of angular momentum and altogether to additional mixing.
- Expected: Increase of mass loss by rotation, mass loss would be anisotropic

Fast rotating stars

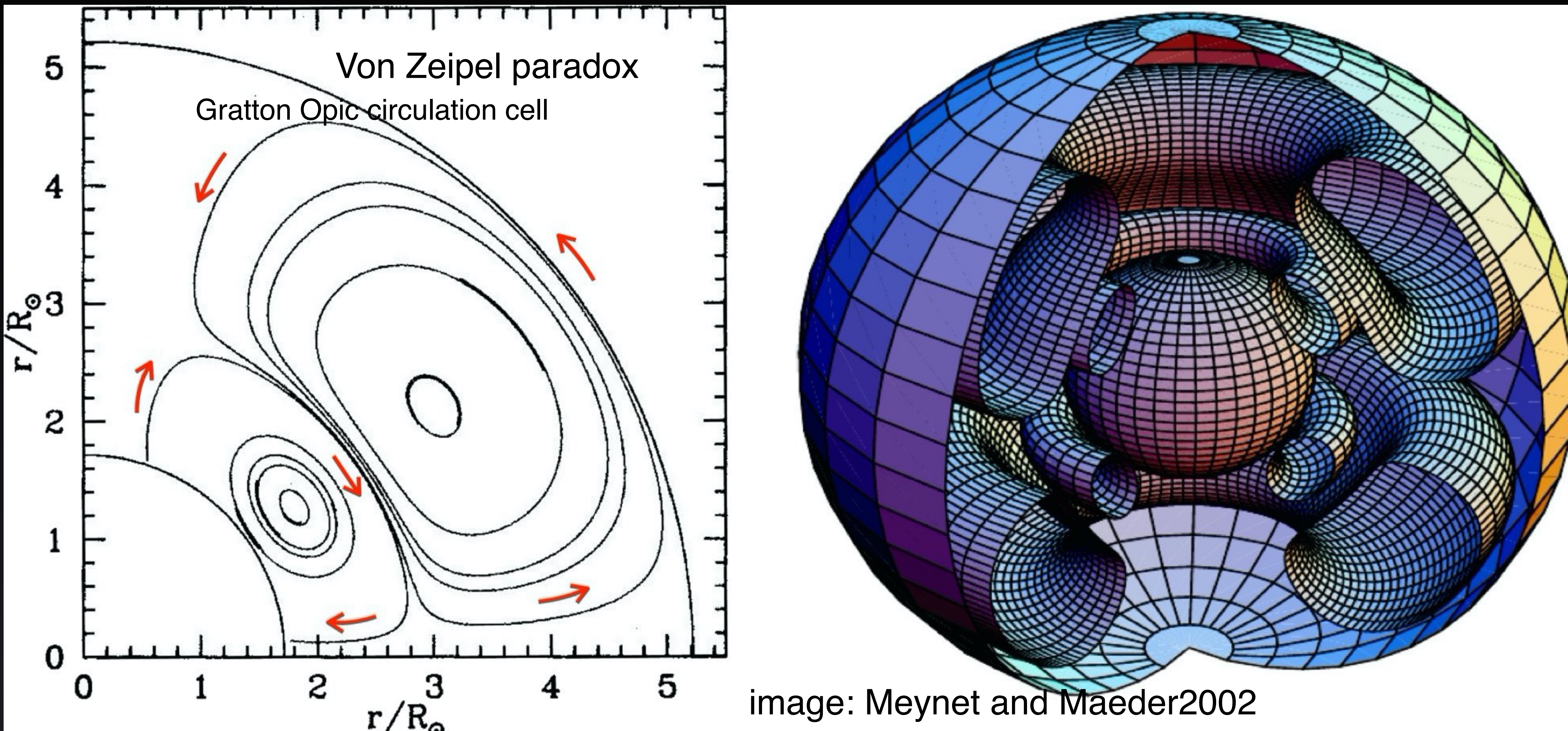


Maeder 1987

- Rotation induced mixing will result in a more chemically homogeneous structure than in a non-rotating star.

Initial homogeneous evolution can be enforced by tidal locking in a very close massive binary (de Mink et al. 2009)

Fast rotating stars



- In low Z massive stars, Gratton Opic cell does not develop due to one of the term in the equation for the speed of meridional circulation! That results in an extreme differential rotation and extreme mixing. (Maeder 2009)
-

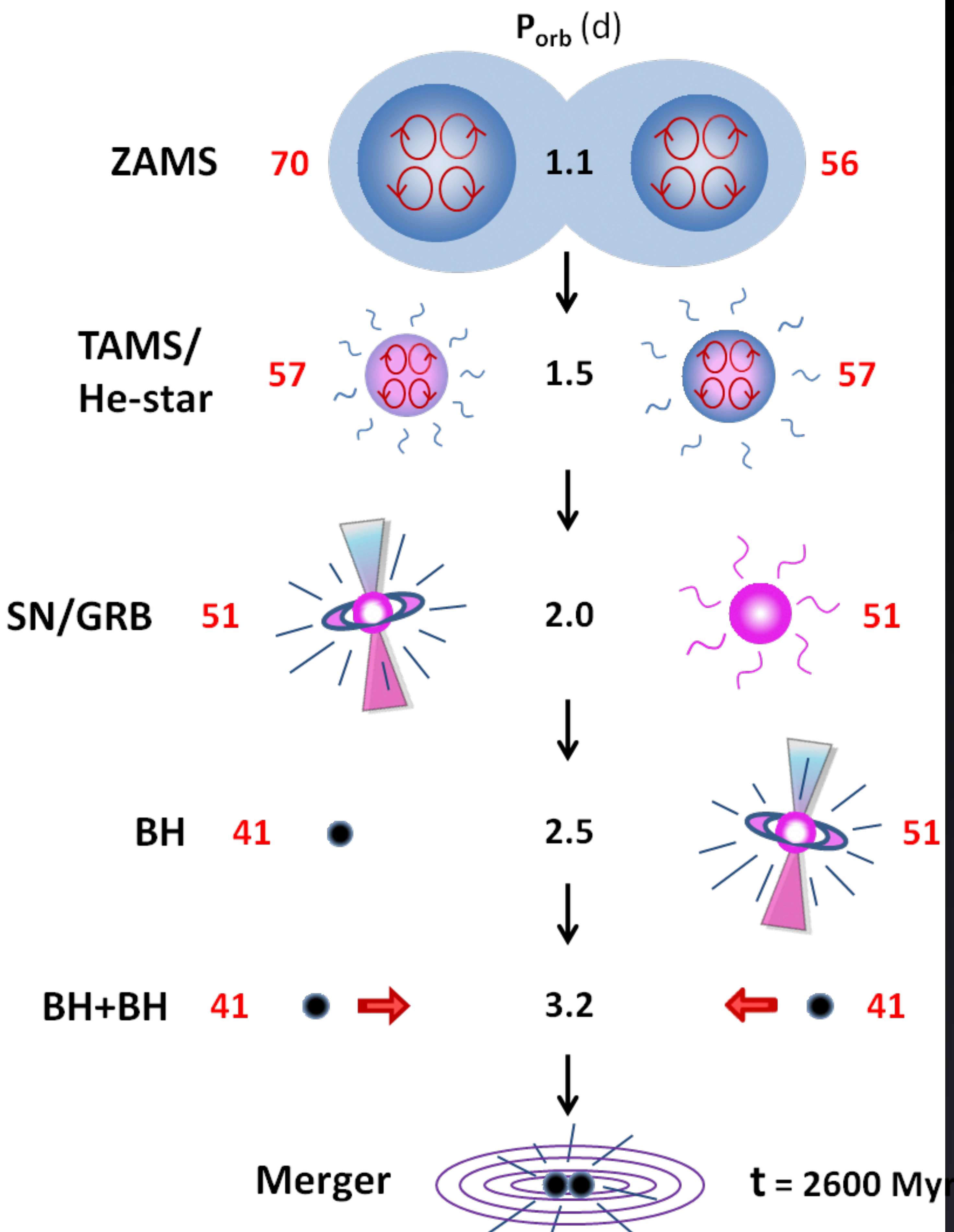


Image: Marchant et al 2016

Fast rotating stars and BH-BH Formation AKA **Massive Overcontact Binary** (MOB) Model

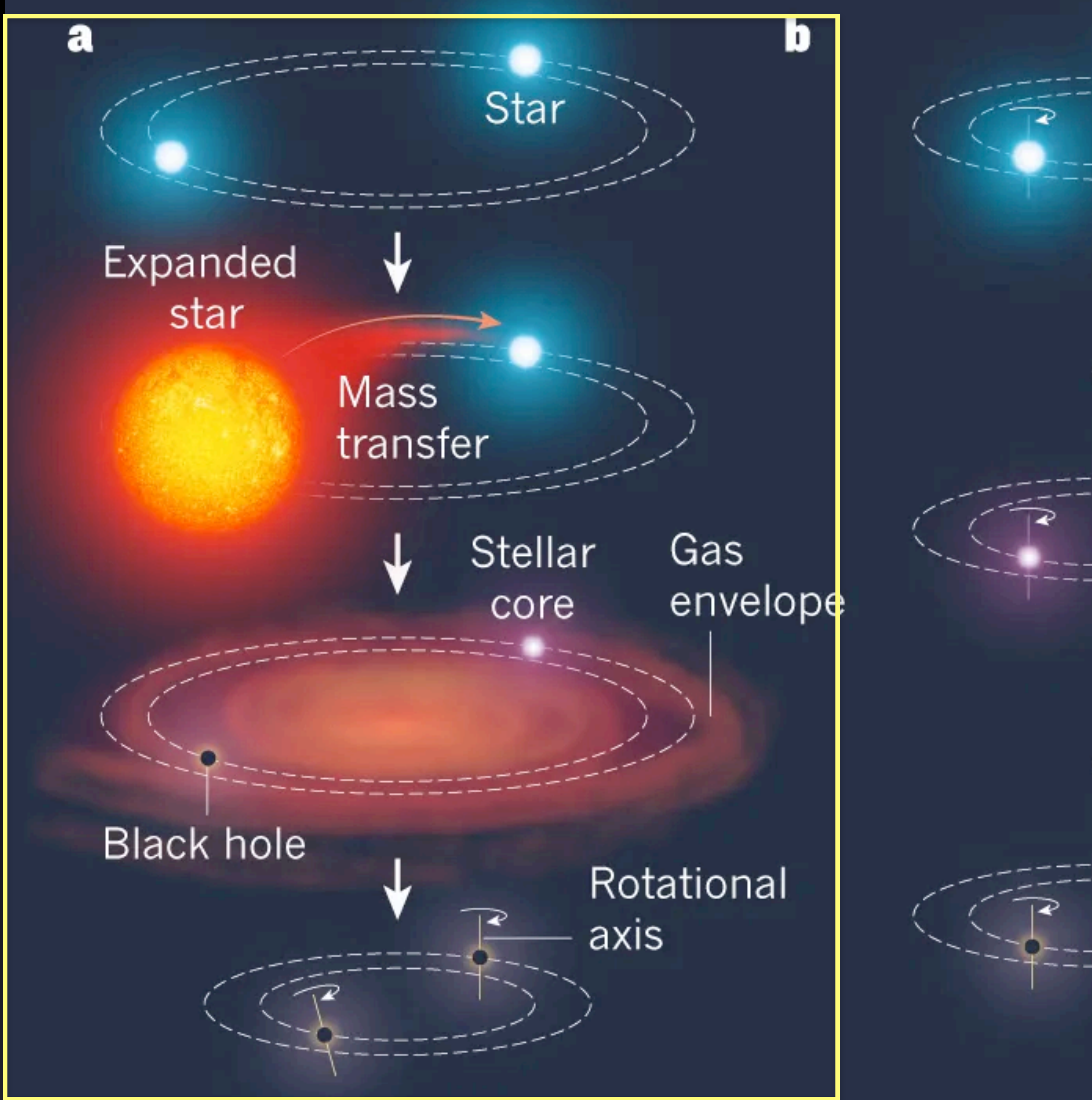
- Marchant et al 2016
- Mandel & de Mink 2016, de Mink & Mandel 2016

Scenario needs:

- rotation > 40% of critical. Uses baroclinic instability in this regime
- Uses diffusion coefficient D which is highly uncertain
- Very low metallicity, Z<1/50Zsun
- Initial mass ratio q>0.8
- Neglects rotationally induced mass loss

Outcome:

- Very massive with a mass ratio ⇨ 1
- Aligned spins unless affected by collapse
- Non-eccentric


a
b
Star
Expanded
star
Mass
transfer
Stellar
core
Gas
envelope
Black hole
Rotational
axis

Which binaries become MT binaries and which go into CEE:

<u>defined by understanding instability</u>

How close binaries will be formed:

<u>defined by understanding of CEE physics</u>

➡ Resulting population of the observed MT binaries
➡ Resulting population of post-CE binaries inclusive of LIGO sources

1. The basics of theory on MT instability
   i. What is a standard treatment
   ii. What has been recently questioned and revised
   iii. what BPS codes cannot do (yet)
2. The basics of CE physics
   i. What is a standard treatment
   ii. What has been recently questioned and revised
   iii. what BPS codes cannot do (yet)

Roche Lobe Overflow: (simplified) treatment in stellar codes

Standard assumption:
Donor radius must stay ~ within Roche lobe radius

Compare responses to determine stability, at RLOF:

$$R_{\mathrm{RL}} \propto M_{\mathrm{d}}^{\zeta_{\mathrm{RL}}}$$

$$R_{\mathrm{d}} \propto M_{\mathrm{d}}^{\zeta_{\mathrm{d}}}$$

All we know about how conservative MT is, GW, MB, CB disk, tides...

All we know about a donor's response on ML

$$\zeta_{\mathrm{d}} \geq \zeta_{RL} \quad \text{stability}$$

$$\zeta_{\mathrm{d}} < \zeta_{RL} \quad \text{instability}$$

Mass-radius response exponents & fate of the system

Consequence: A fully conservative MT with MT mass ratio

$$q_{MT}=m_{donor}/m_{accretor} > q_{crit}=0.8$$

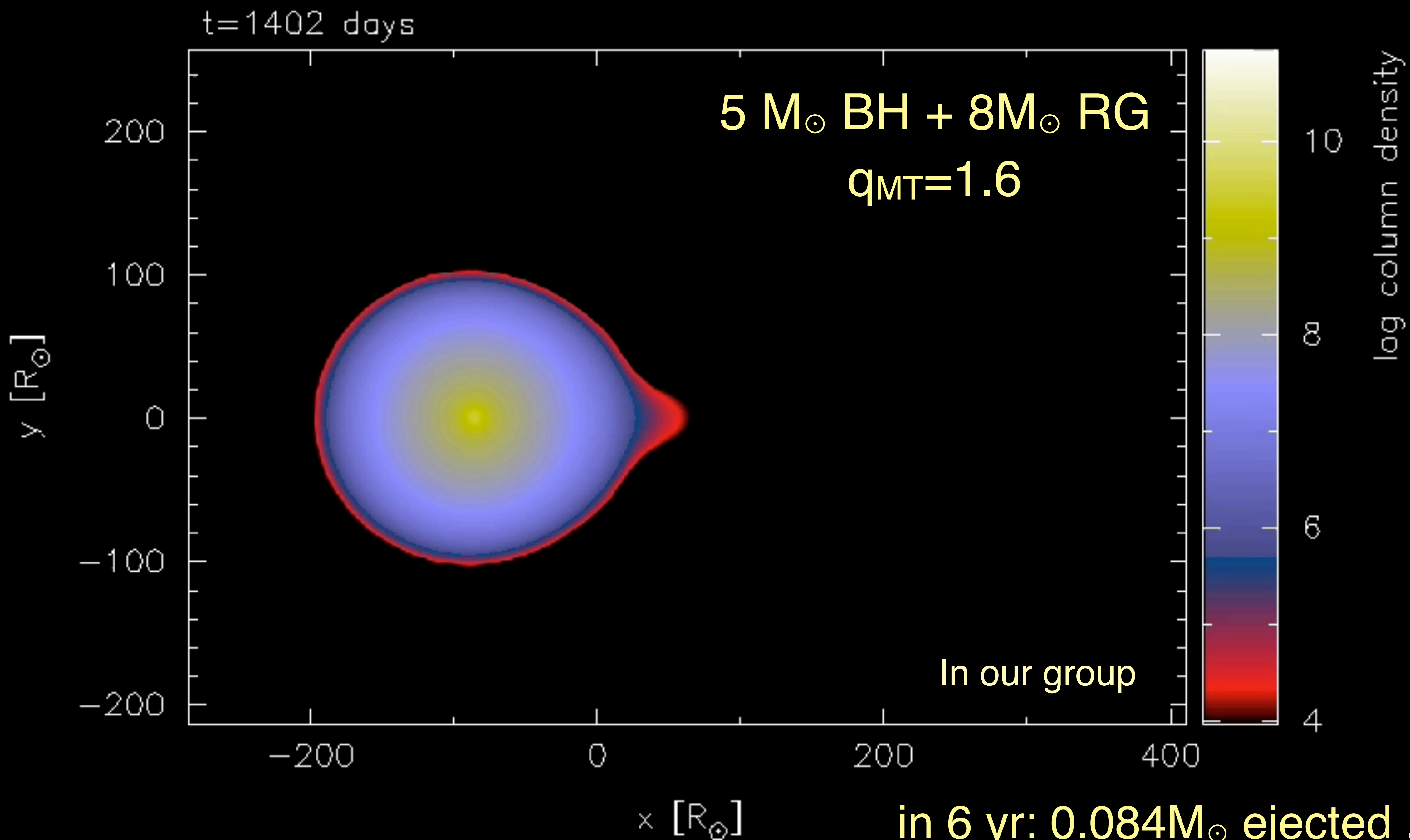
and a convective donor is deemed to be unstable ⇒

Any first episode of conservative MT with a convective donor is unstable. CEE.
Radiative donors deem to produce (initially) dynamically stable M,T unless q>10 (Darwin instability).

MT can also become unstable when thermal timescale response is considered. This is known as Delayed Dynamical Instability in radiative donors (e.g., Ge et a 2010)

$q_{crit}=3.5$

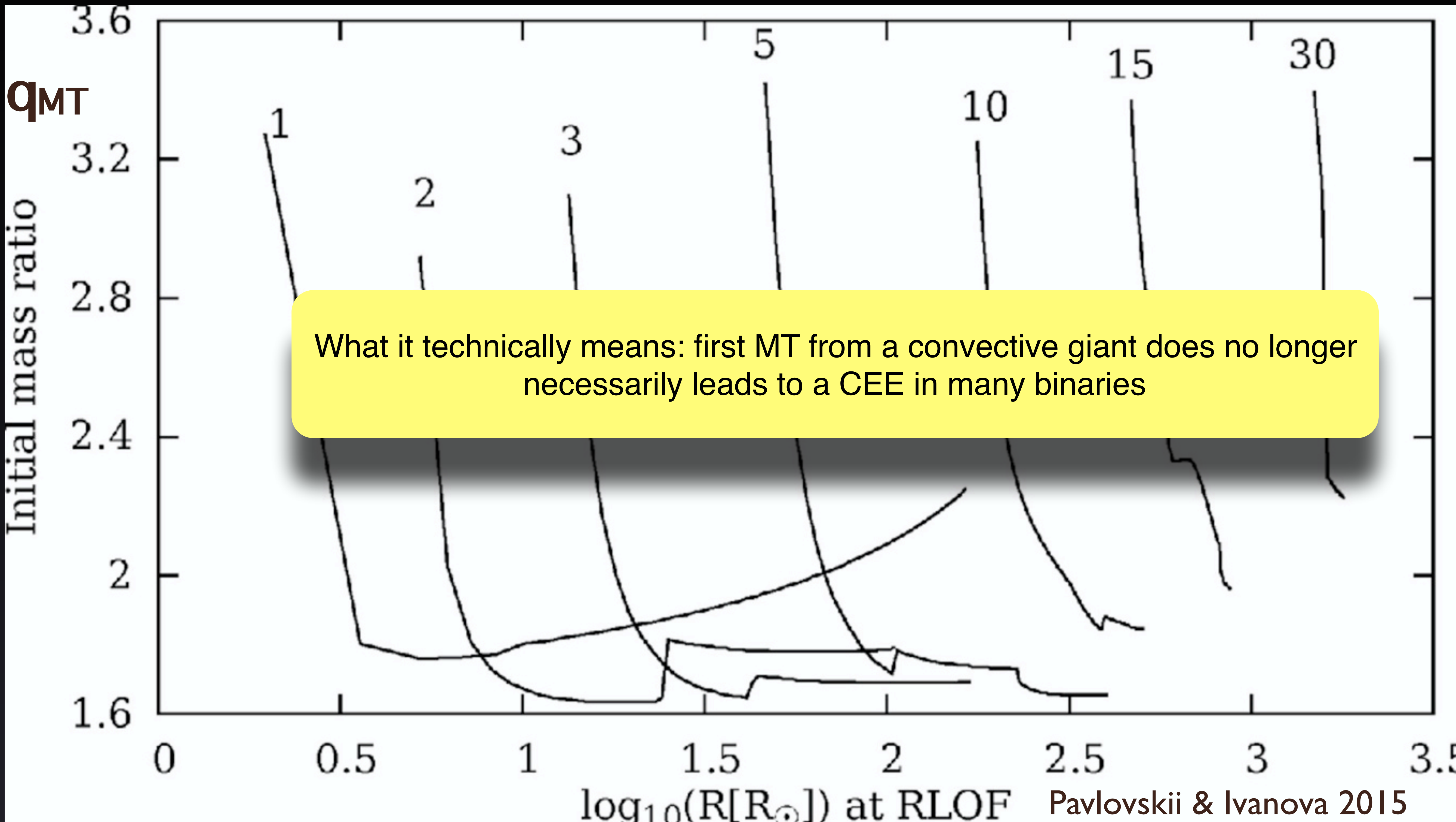
$q_{MT}!=q_{bin}$



in 6 yr: 0.084$M_\odot$ ejected ,
0.025 $M_\odot$ went to circumbinary disk,
Effective ML about 0.02 $M_\odot$/yr

really hard to make MT been dynamically unstable,
presumably till L_2 /L_3 overflow
Stream is very wide

New stability: stream-limited MT, convective donors

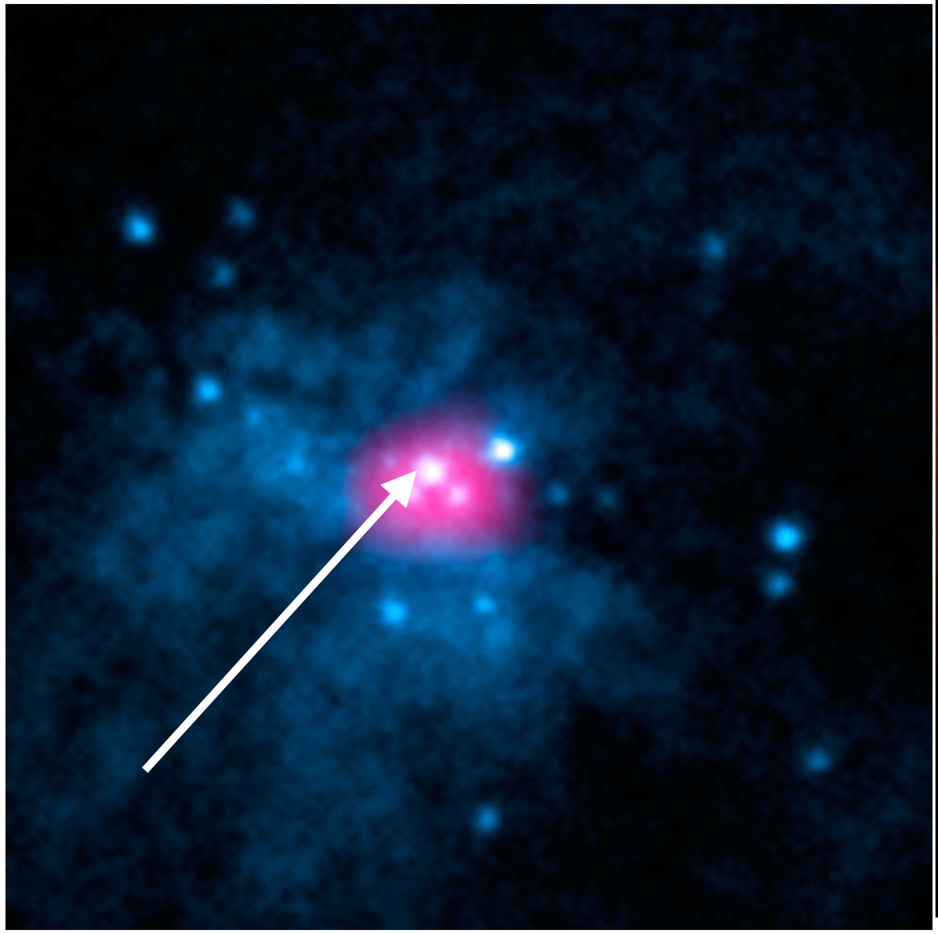


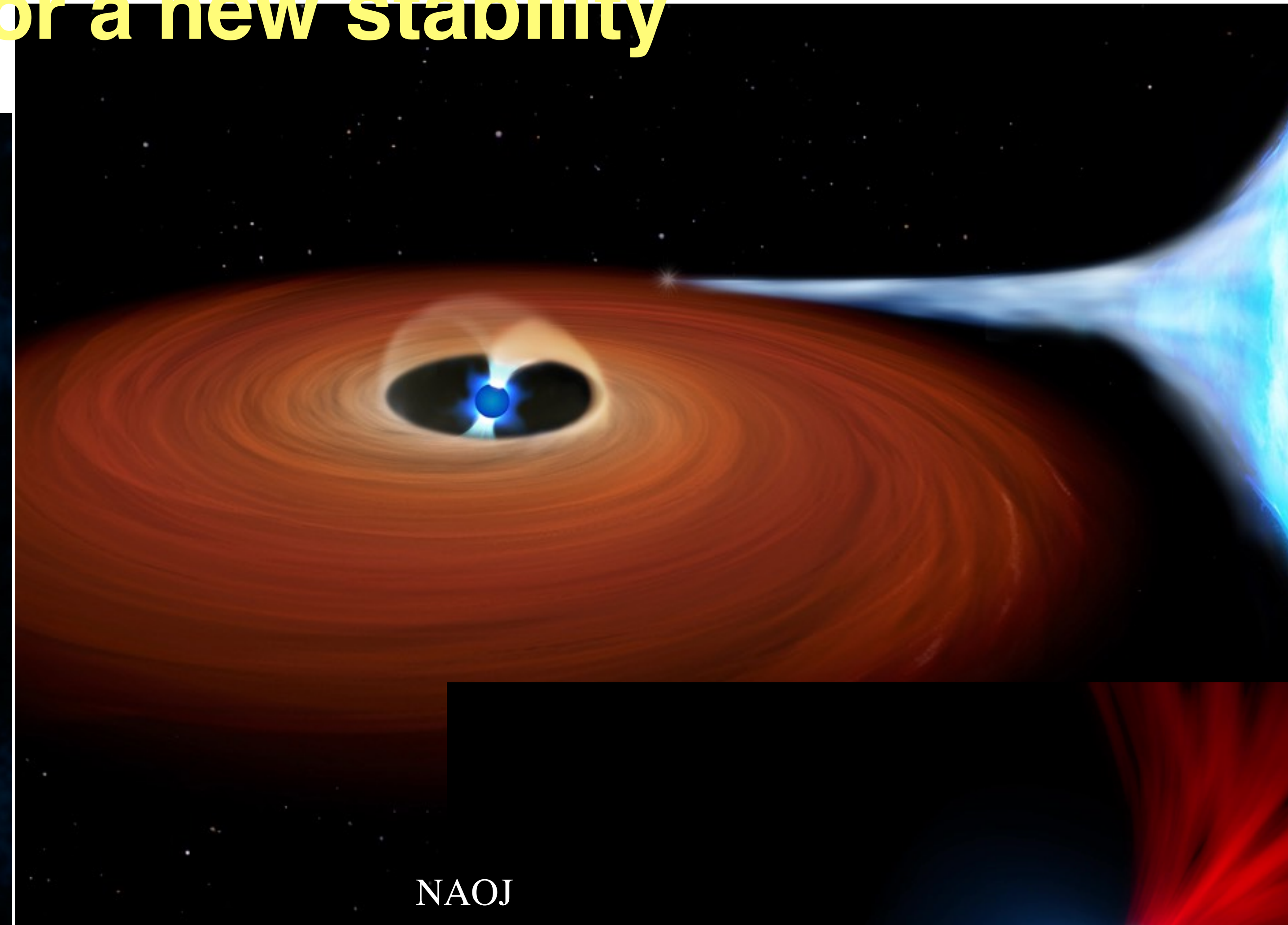
What it technically means: first MT from a convective giant does no longer necessarily leads to a CEE in many binaries

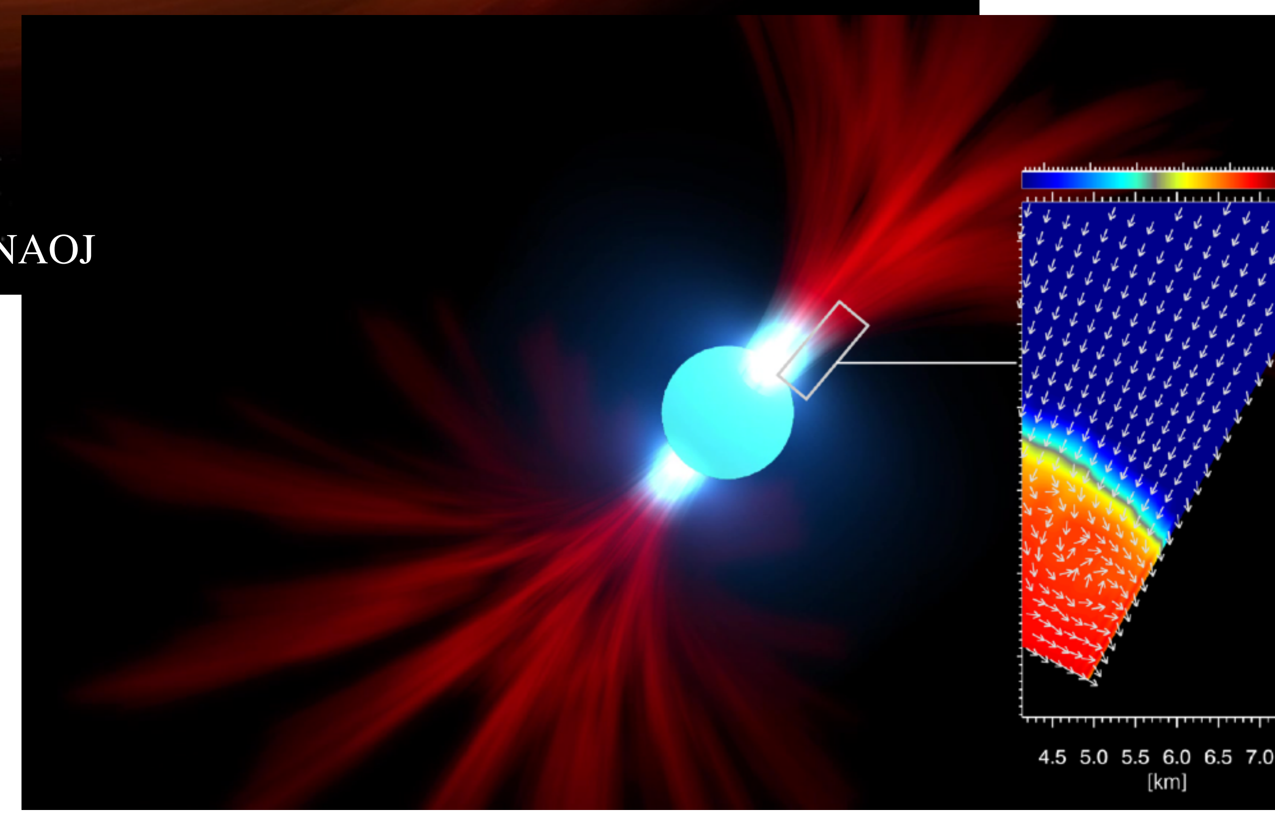
when convective envelope is shallow, critical mass ratio q_{crit} ~3.5 (as for DDI)

while convective envelope develops, q_{crit} is decreasing, saturating at ~1.6

Nature's request for a new stability







New stability: stream-limited MT, radiative/early convective donors

This system can be explained with the donor that was initially 8-10 $M_\odot$ (Fragos et al 2015):

effectively, initial $q_{crit} \Rrightarrow 7$. Non-conservative MT.

Pavlovskii et al 2017:

Massive donors are very rarified in their outer envelopes

stable conservative MT could take place for a large range of radii and for **as large q_{MT} as 8**

This apparently affects the formation of BH-BH via CEEs, decreasing the formation rates (though making it consistent with the the empirical rate obtained by LIGO, 9-240 Gpc^{-3} yr^{-1})

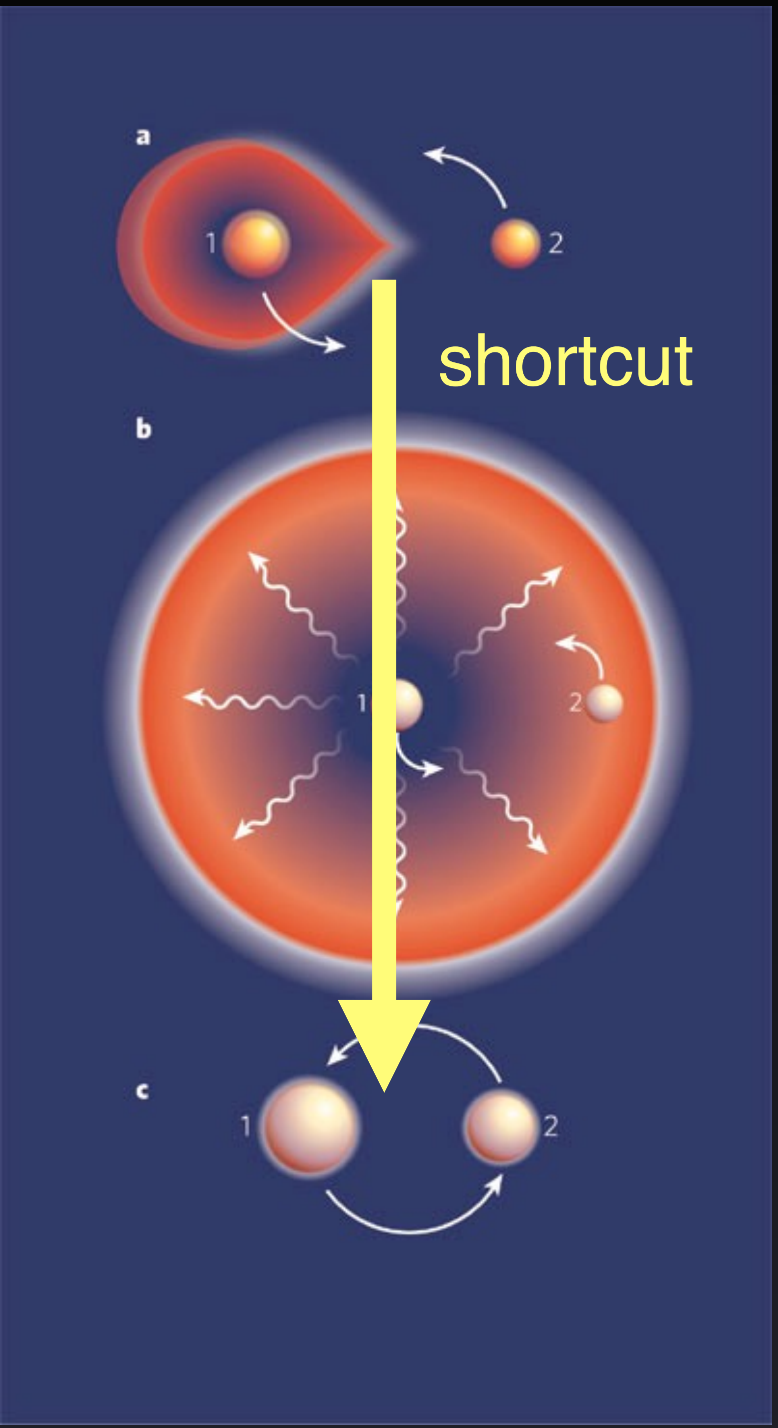
The punchline:

- Systems with a much larger mass ratios are expected to be stable

- Significantly less of initial binaries are expected to start a CEE and instead follow stable MT.

- Stream-limited MT is not yet easy to introduce into BPS codes. And radius is not equal to R_{RL}

Common envelope: *αλ* energy-formalism



The CEE phase 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.** Both ends lead to an ejection of at least a fraction of the envelope matter.

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

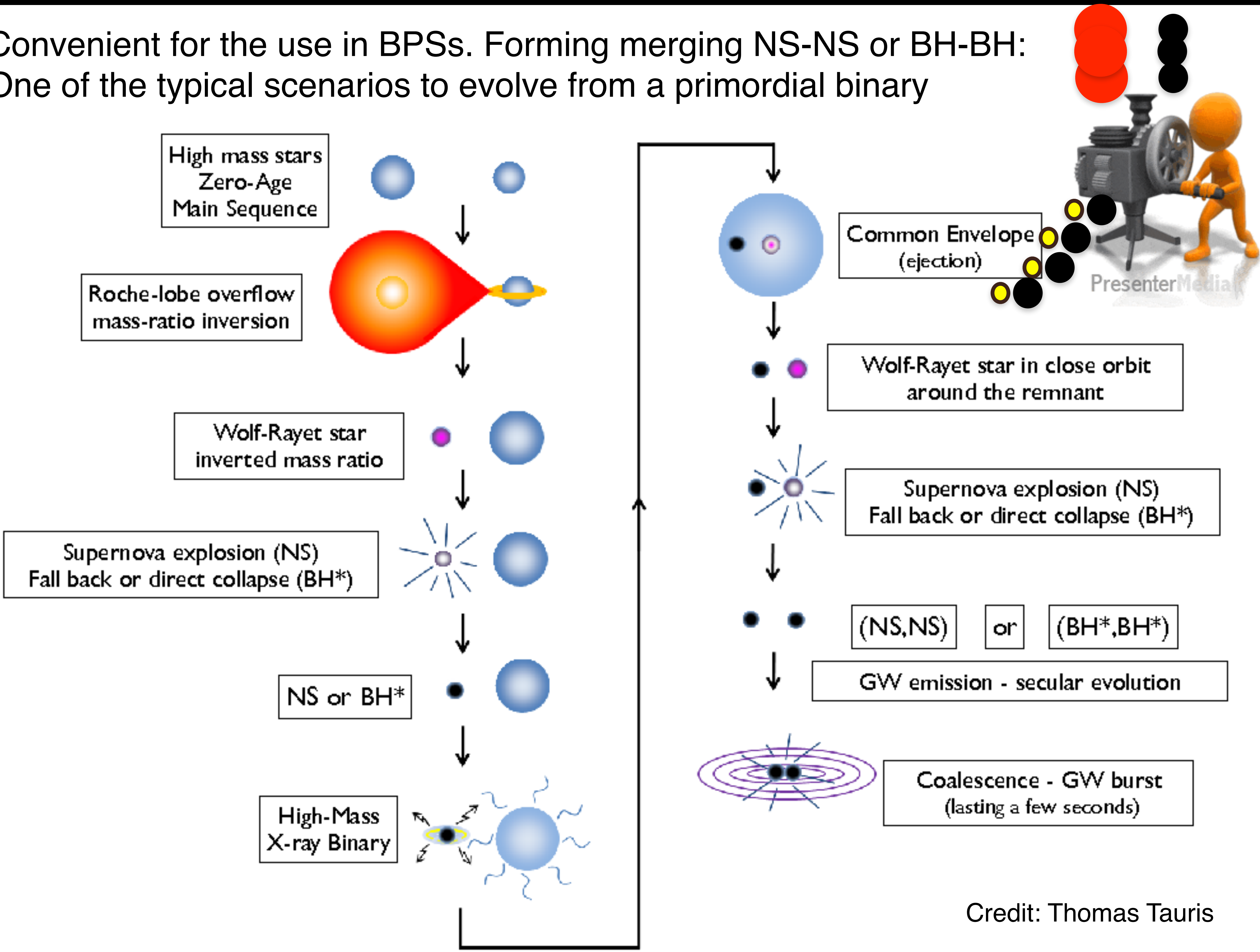
$$\Delta E_{\rm orb} = \frac{GM_{1,\rm core} M_2}{2a_{\rm fin}} - \frac{GM_1 M_2}{2a_{\rm ini}}$$

standard: $\alpha\lambda = 1$

Webbink 1984,
Livio & Soker 1988

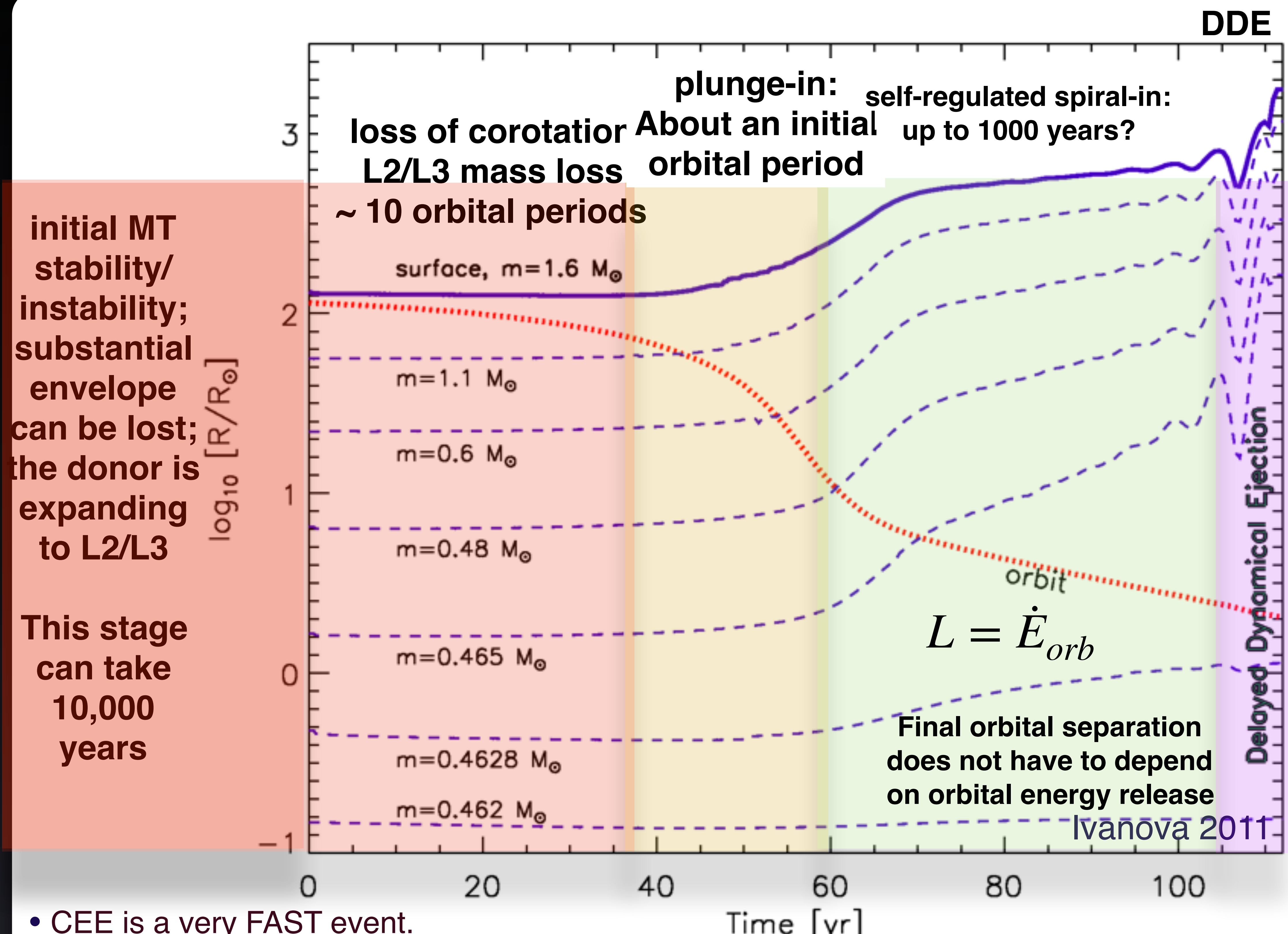
α - efficiency of the energy re-use, can not be more than 1
λ - envelope structure parameter

Convenient for the use in BPSs. Forming merging NS-NS or BH-BH:
One of the typical scenarios to evolve from a primordial binary



Credit: Thomas Tauris

CE Event: main qualitative phases and timescales



- CEE is a very FAST event.
- Theory uses indirect constrains based on observations of systems that only can be formed by a CE.
- Range in time-scales: 10^{10} - from 1 sec to 1000 yr
- Range in length-scale: 10^8 - from 10km to 1000 Rsun

VALIDATION: Double White Dwarfs

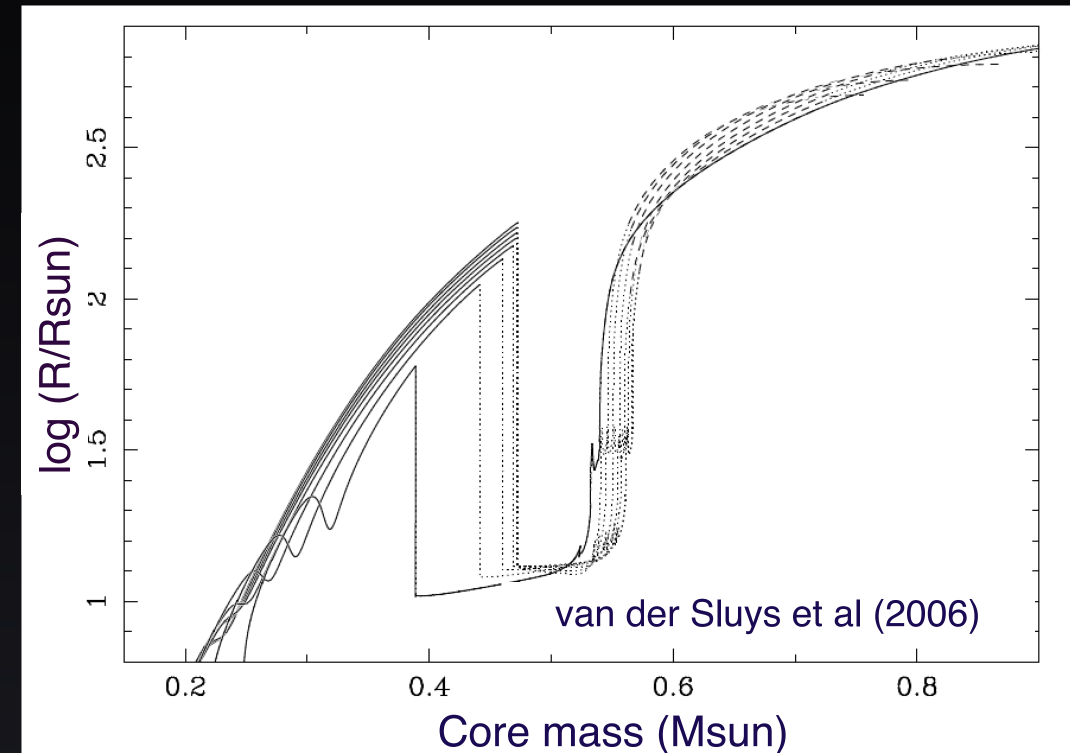
Test with Observations:
DWD systems.

- Theory: for low-mass giants, core mass and R are related

- Observations: several DWDs with well identified masses and orbits

- pre-CE state is constrained

⇒ Best astrophysical sites to test!

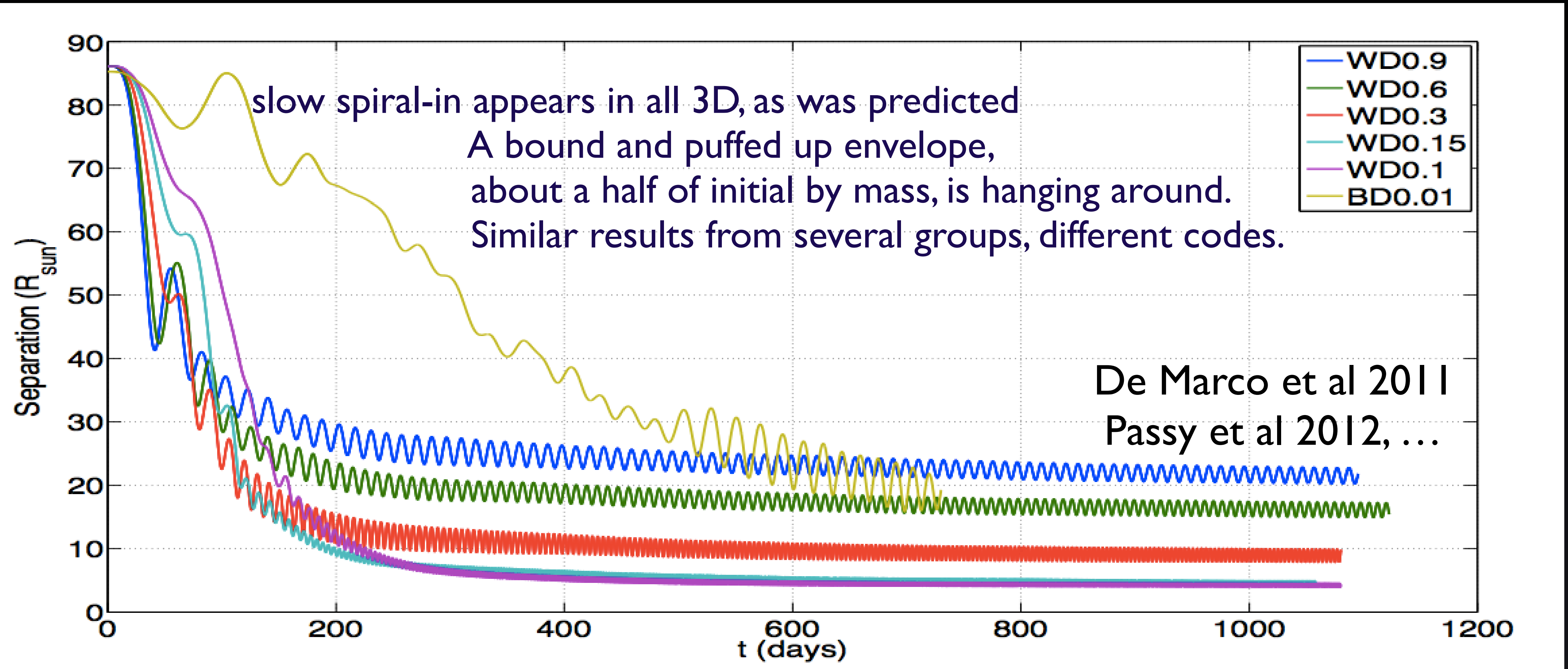


Double White Dwarfs with Known Masses and Periods

System	M_1 ($M_\odot$)	M_2 ($M_\odot$)	Period (days)
WD 0136+768	0.37 ± 0.02	0.47 ± 0.03	1.407227
WD 0957−666	0.32 ± 0.02	0.37 ± 0.02	0.06099
WD 1349+144	0.44	0.44	2.2094
WD 1101+364	0.36	0.31	0.14458
	older	younger	

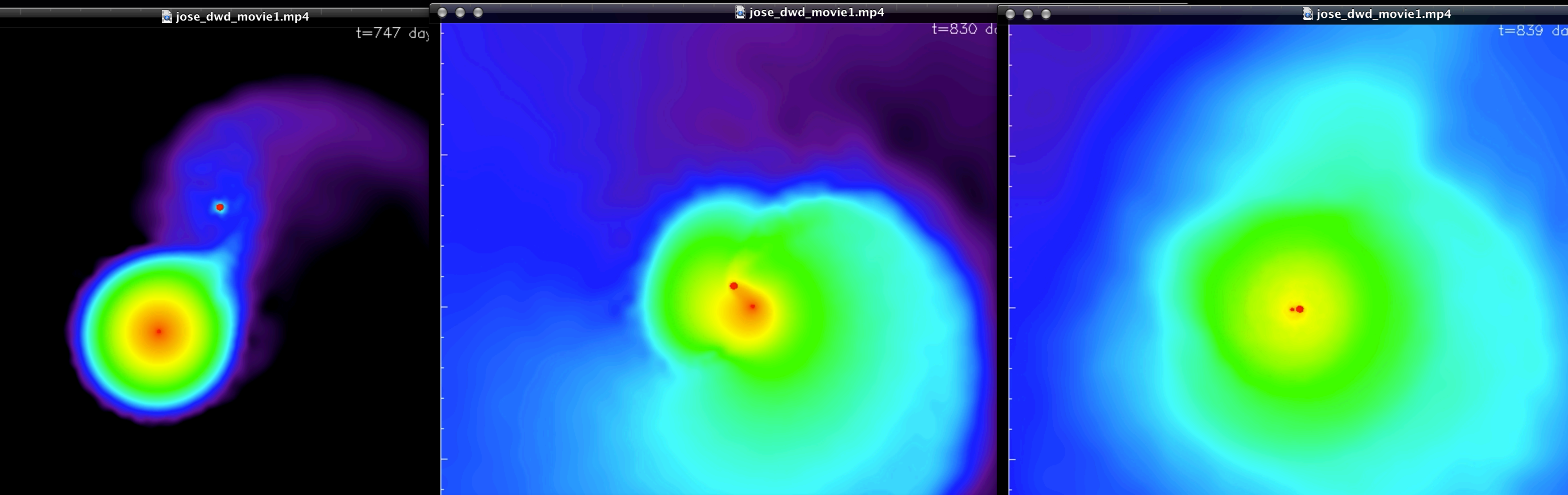
table from Woods et al 2011

“Dynamical” CEE vs self-regulated



No efficient drug forces between the binary and the envelope.
Dynamical codes can not treat long-term CEE!
Is self-regulated regime natural and mandatory for all CEE?
What will happen to that puffed up envelope?
Does it fall back?

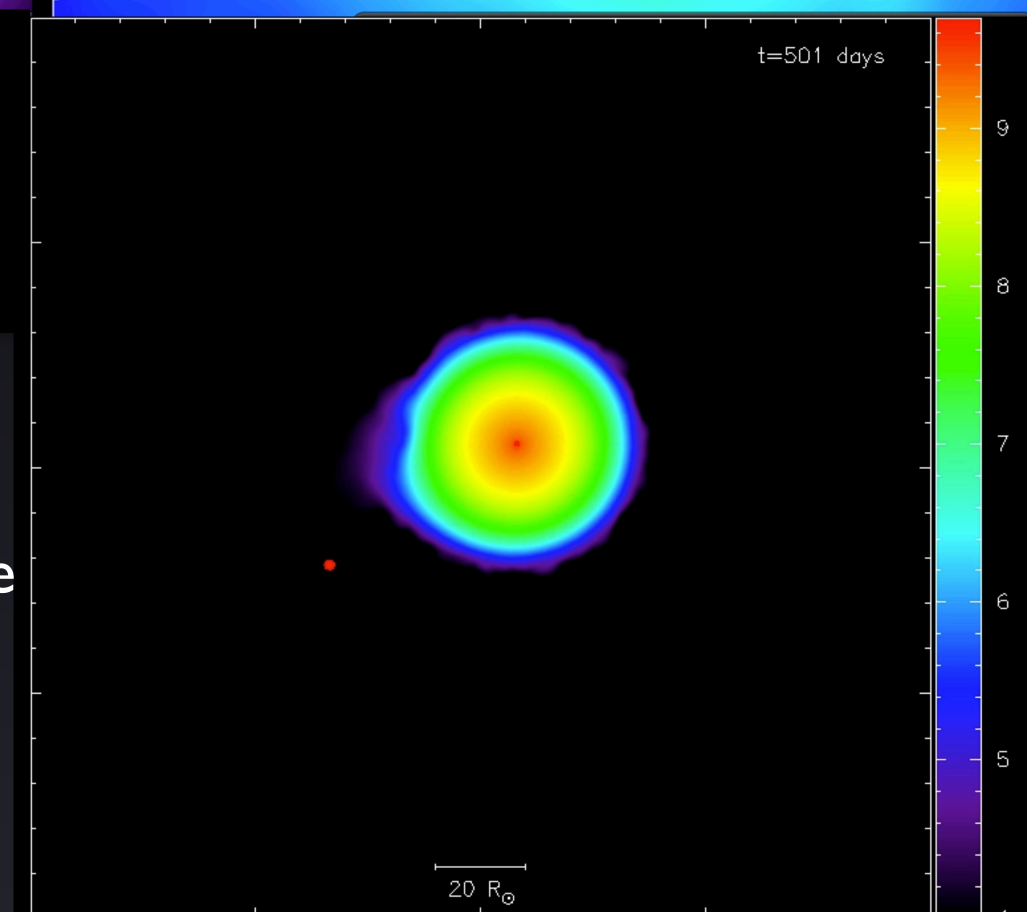
Modelling complete CE ejection: EOS and ejecta's kinetic energy



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

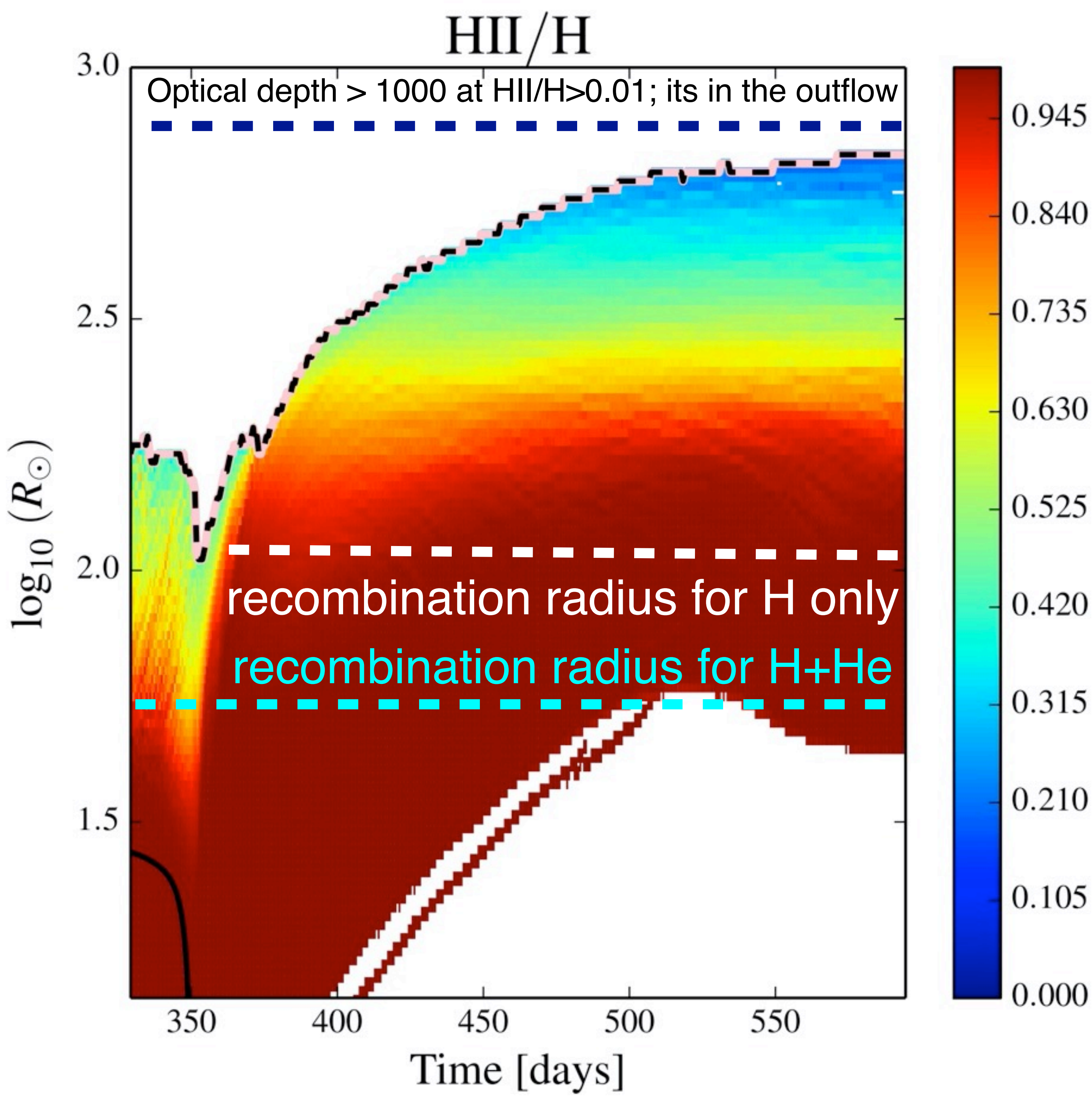


$$(E_{\rm orb,ini} - E_{\rm orb,fin})(1 - a^{\infty}_{\rm unb}) + E_{\rm bind,env} + hM_{env} = 0$$

$$h:\ 1.5 \times 10^{13}\,{\rm erg/g} - \text{specific recombination energy}$$

How does recombination-powered ejection work?

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

Understanding CE mass ejections

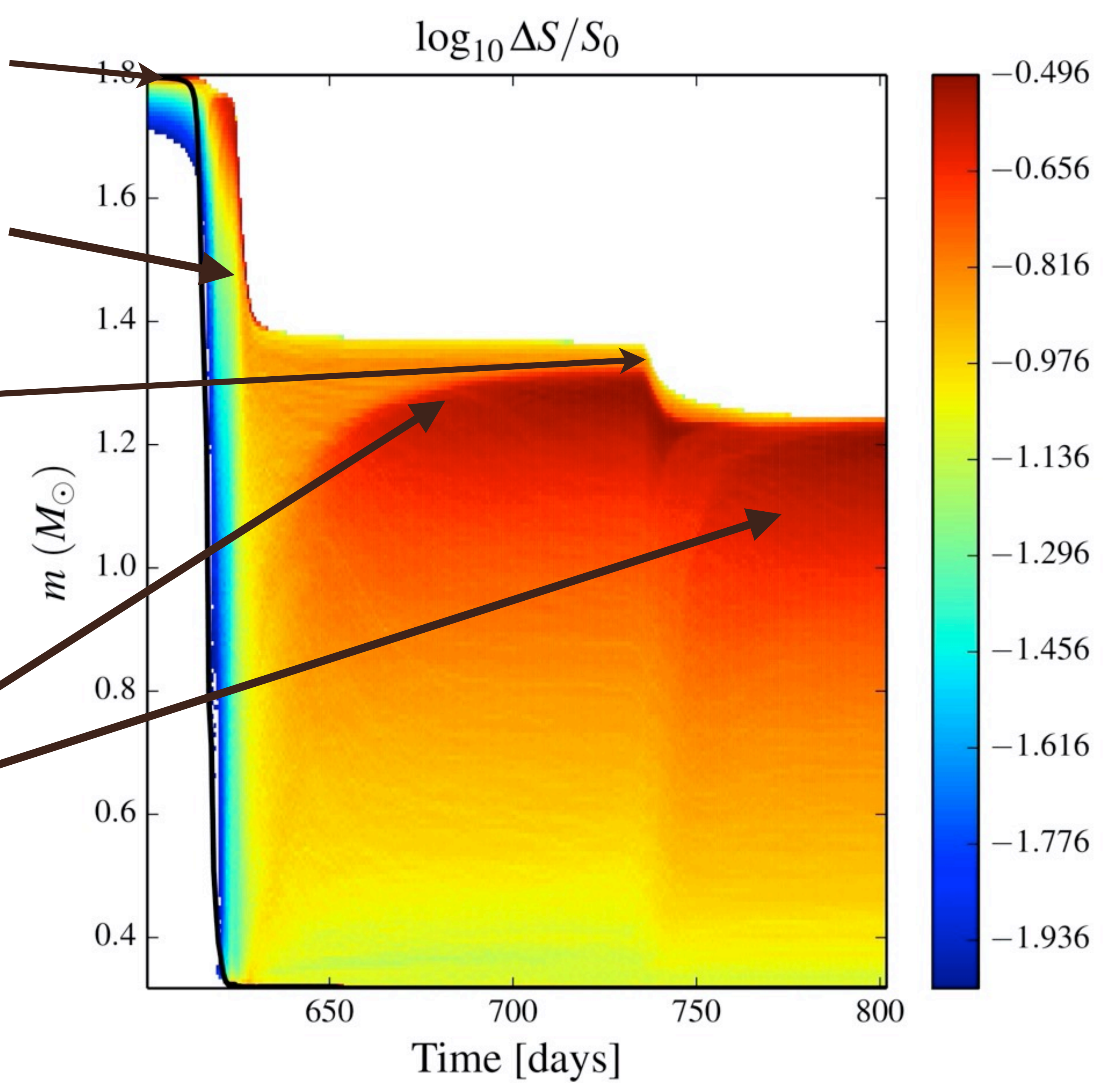
Initial ejection
Most of initial orbital J is lost by the end of the plunge-in.

Plunge-in ejecta
Driven by mechanical energy

Shell-triggered ejection
when a puffed up envelope bounces back

Recombination Outflows
Here 0.15 Msun/yr, can be several Msun/yr

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



Ivanova & Nandez 2016

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

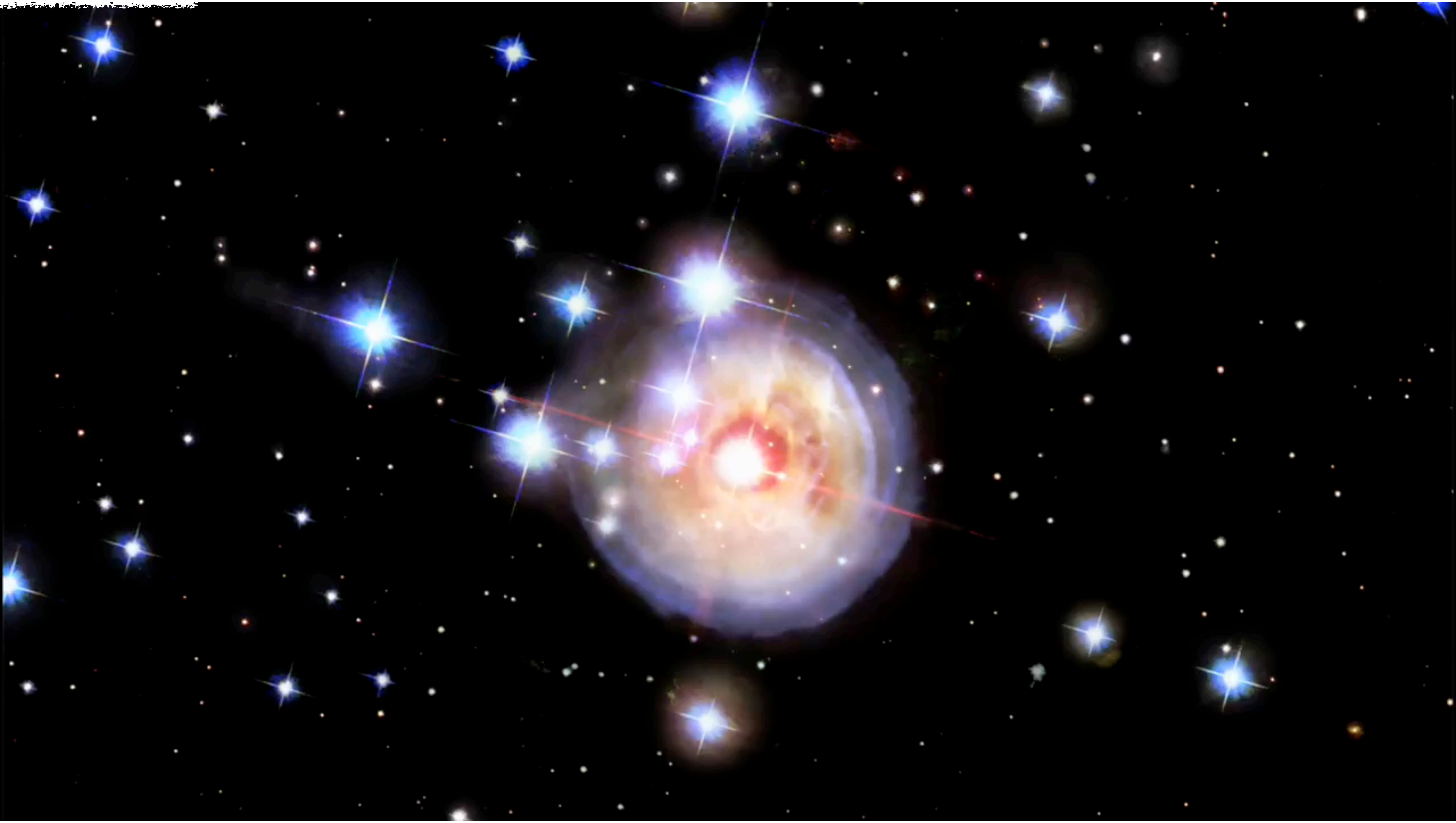
The punchline:

- There is no single alpha that make them all

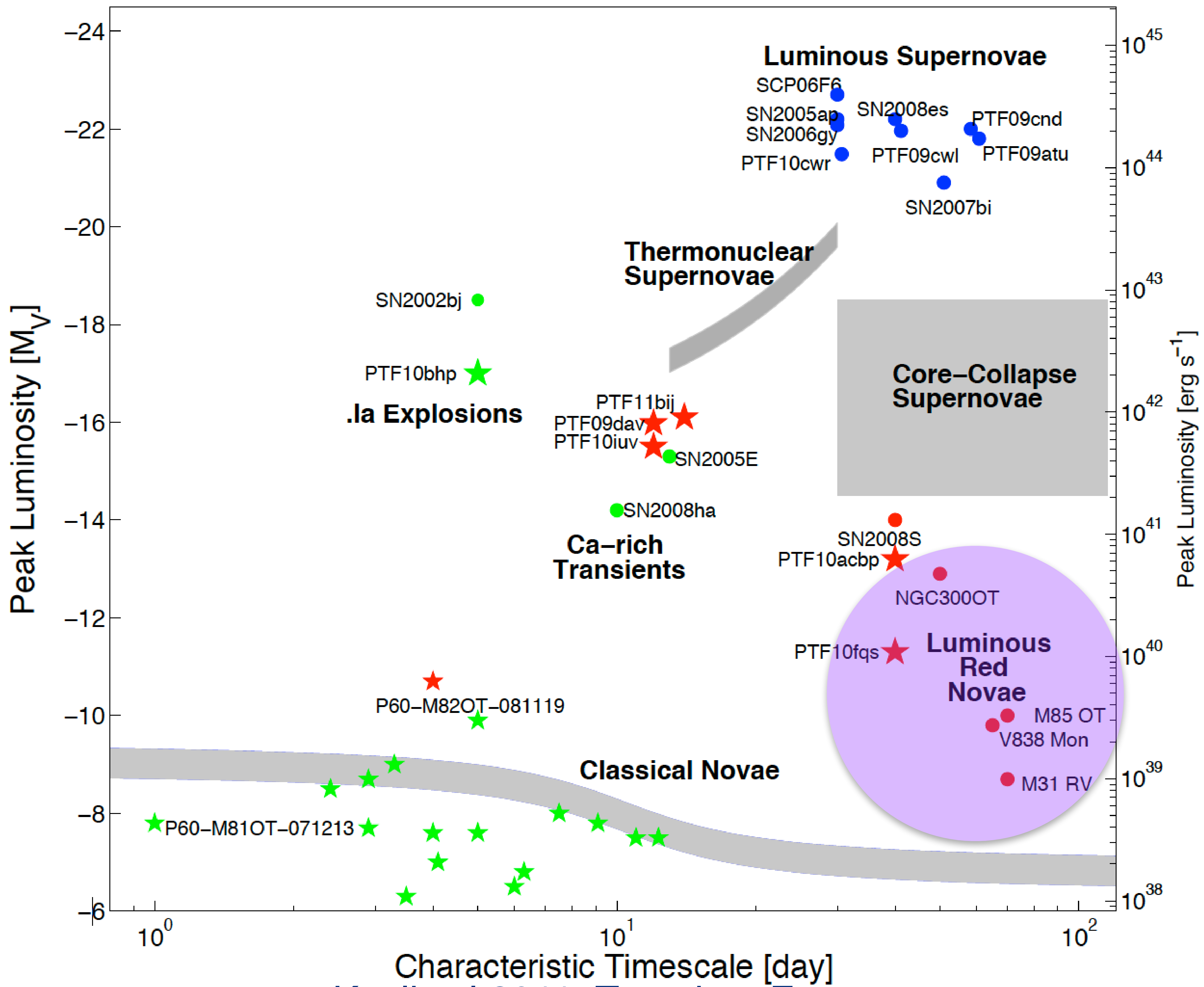
- No complete prescription exists to be reliably used in BPS codes

- Only some ranges of donors have been explored and have their CE calculated

V838 Monocerotis: light echo 2002-2006

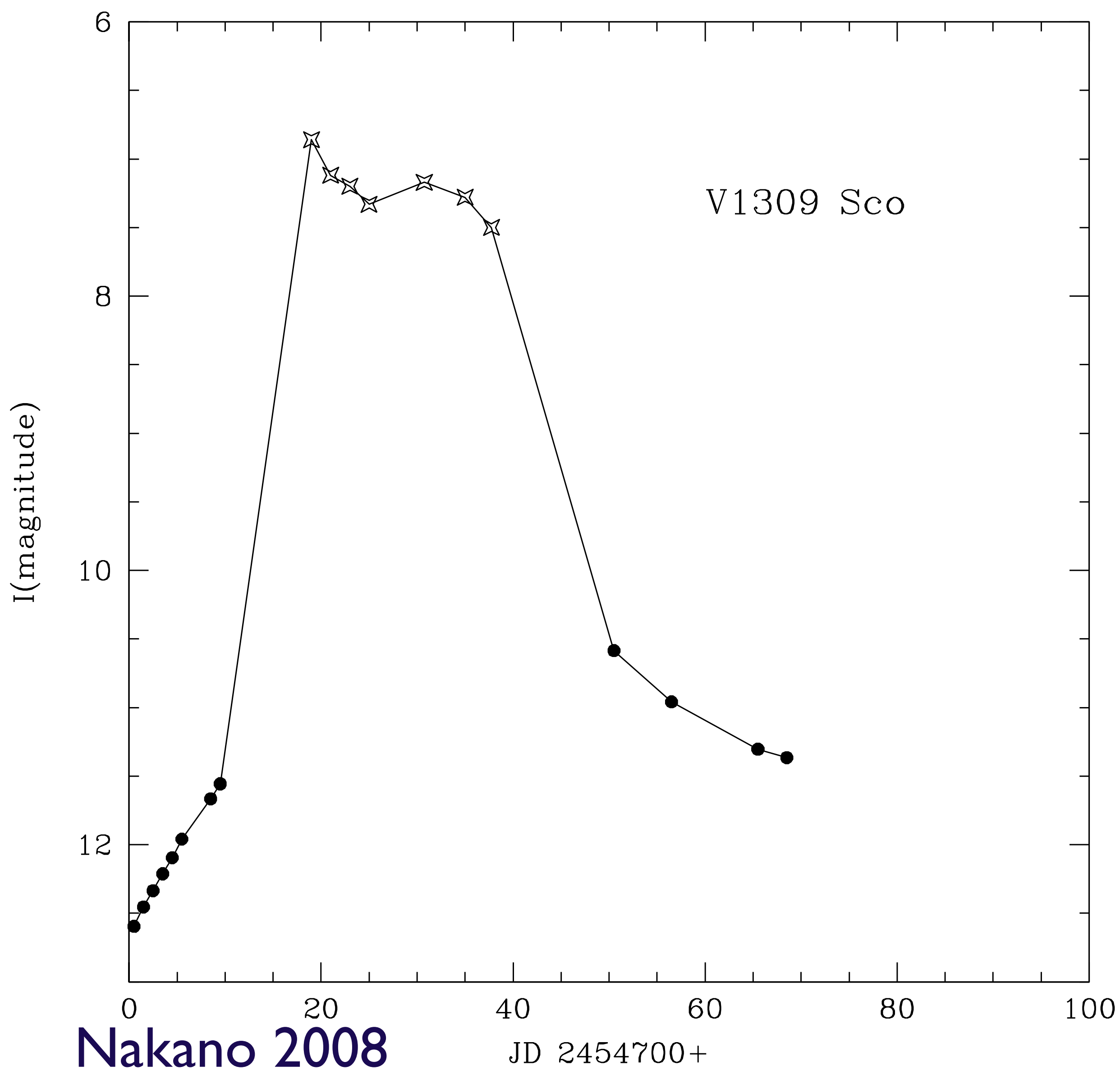


Luminous Red Novae

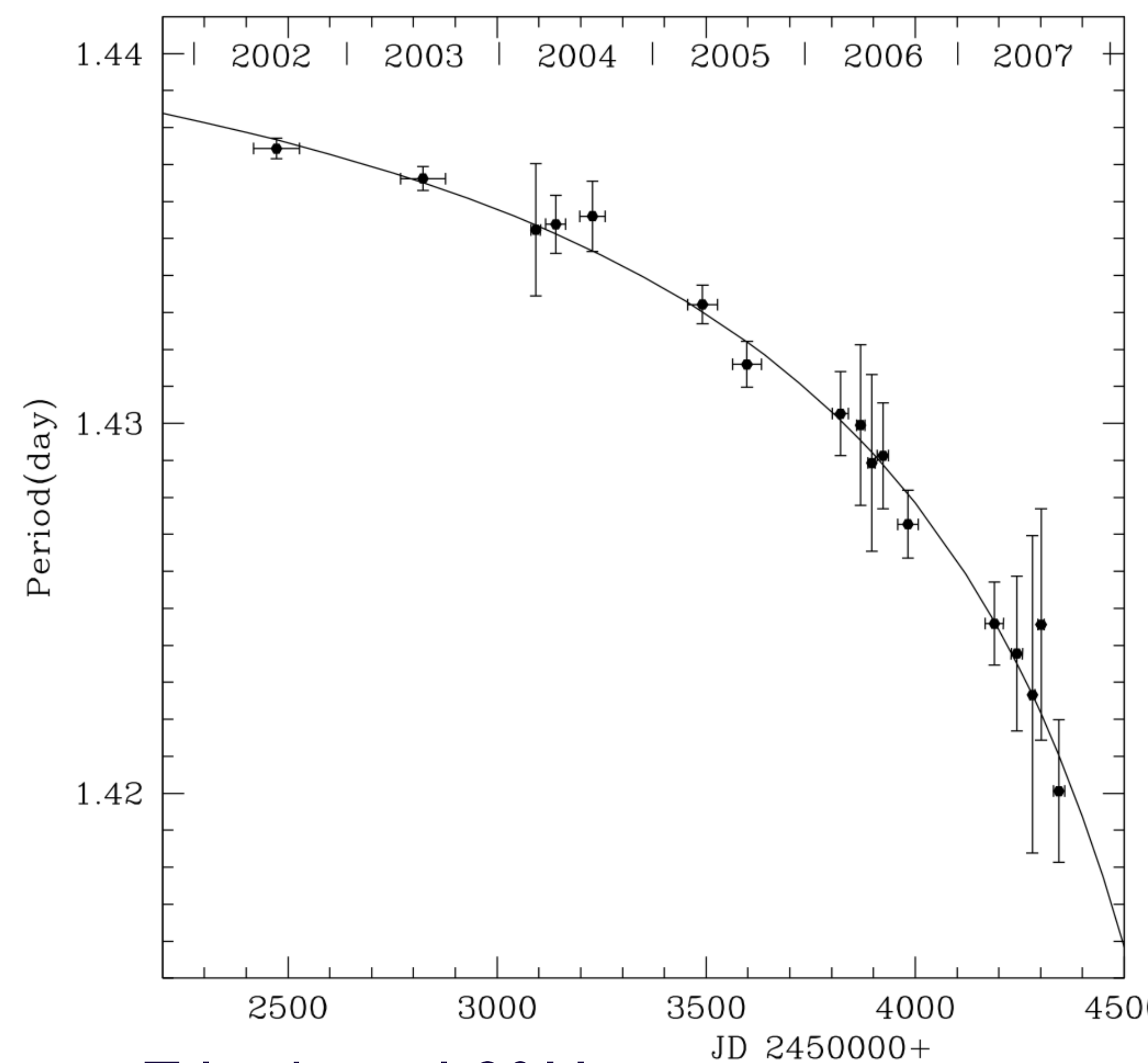


Kasliwal 2011: Transient Factory

V1309 Sco outburst



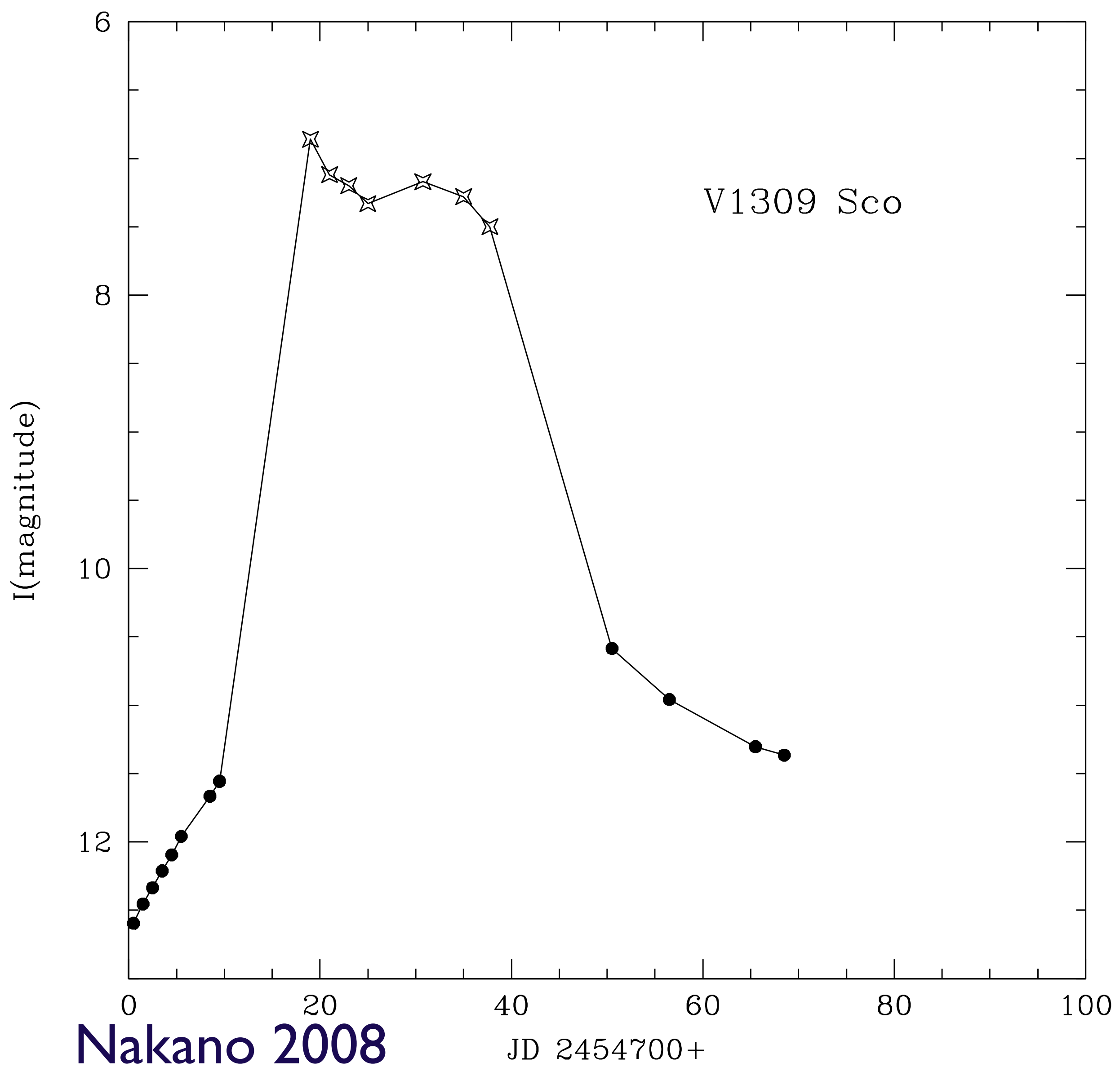
Nakano 2008



Tylenda et al. 2011

1.5+0.16 Msun binary (Stepien 2011)

V1309 Sco outburst



Nakano 2008

Observational clues:

- Large increase in R (x100) & L (x1000)
- Plateau Phase
- Extremely rapid decline (<< τ_{dyn})
- Inconsistent velocities

LOS ALAMOS SCIENTIFIC LABORATORY
OF THE UNIVERSITY OF CALIFORNIA LOS ALAMOS NEW MEXICO

REPORT WRITTEN: February 1964

REPORT DISTRIBUTED: June 17, 1964

THEORY OF THE FIREBALL

by

Hans A. Bethe

Hans A. Bethe

[...]

5. THE COOLING WAVE

a. Theory of Zel'dovich et al.

Zel'dovich, Kompaneets, and Raizer [10] (quoted as Z) have considered the loss of radiation by hot material when the absorption coefficient for the radiation increases monotonically with temperature. They have shown that in this case a cooling wave proceeds into the hot material

The appearance is mainly controlled by how the energy stored in the ejecta is radiated away

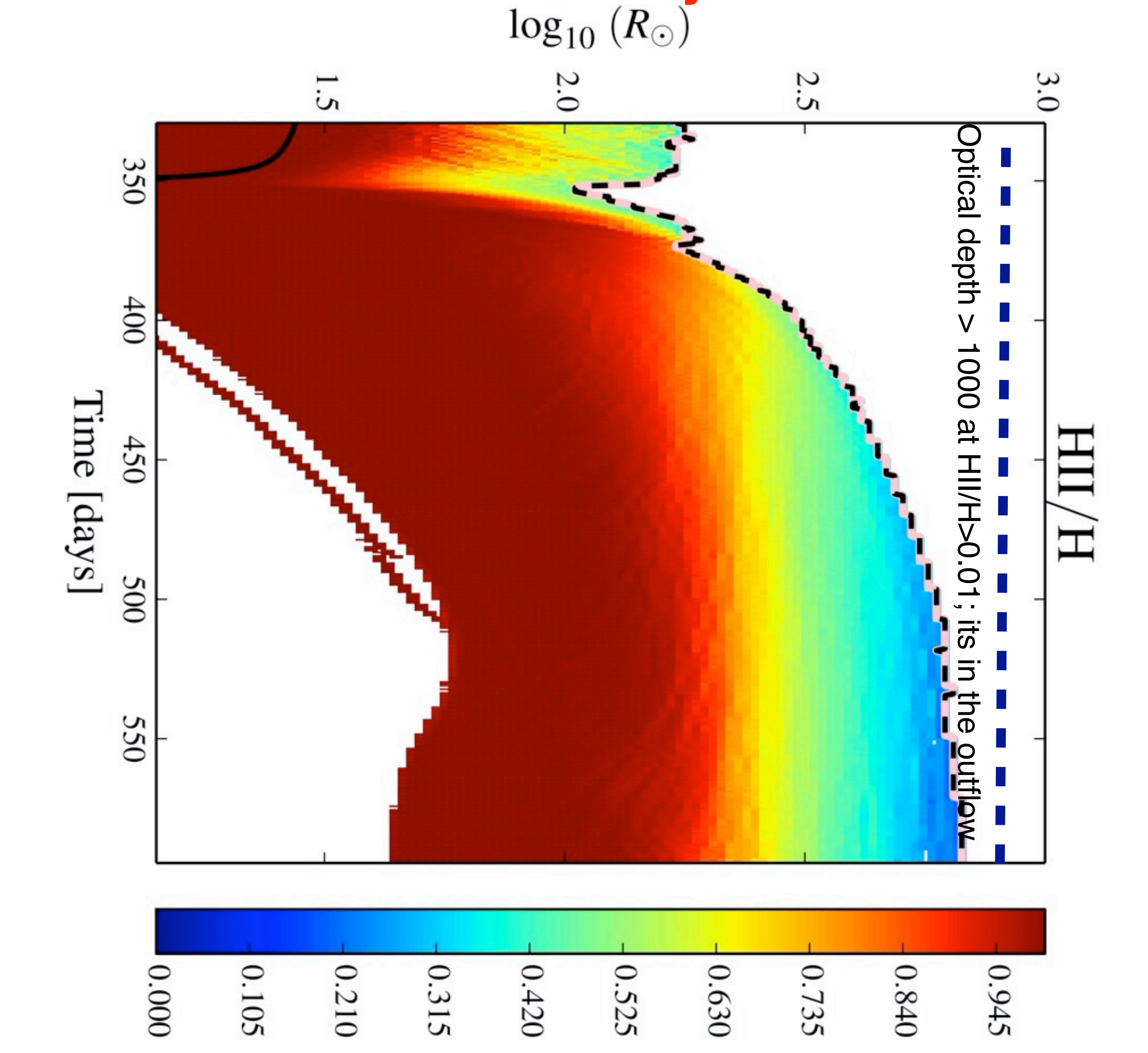
Fast CEE:
appearar

Direction of expansion (mass ejection)

We can not see directly into recombination

Hot.
Ionize
High-c

No rac
coolin



old.
eutral.
ow-opacity

ast radiative
ooling

VI

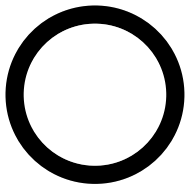
Di) - cooling front

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

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

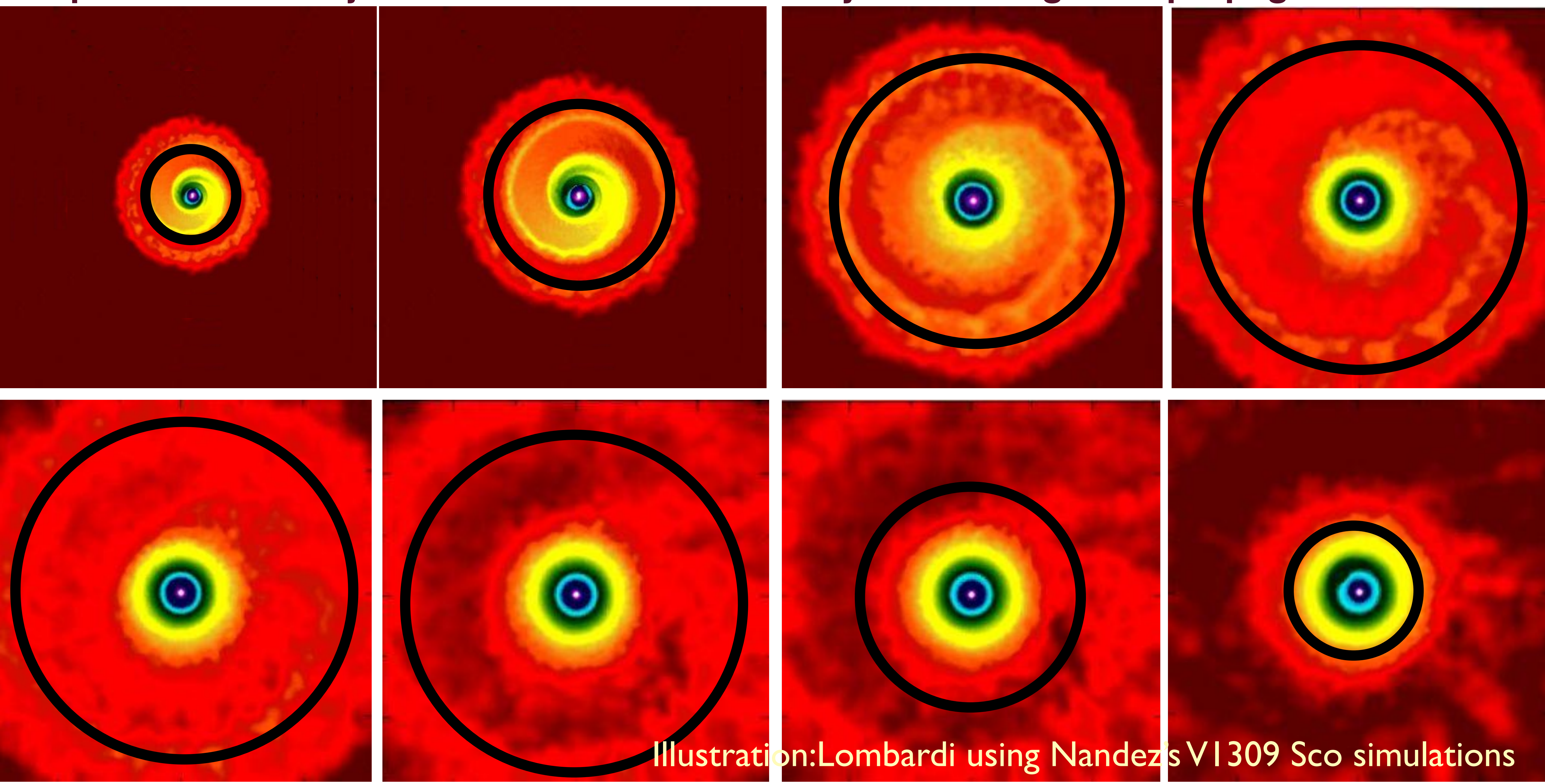
Red Transients

WCR - Wavefront of Cooling and Recombination



= recombination front / photosphere

Expansion of the ejecta outwards is balanced by the cooling front propagation inwards



Red Transients

- Large size and luminosities, plateau phase
- Red color (T~5000K)
- fast decline ($\tau_{decline}$~ a fraction of plateau time)
- Spectroscopic velocities (few x100 km/s) are larger than the expansion rate of the "effective" radius (<100km/s)

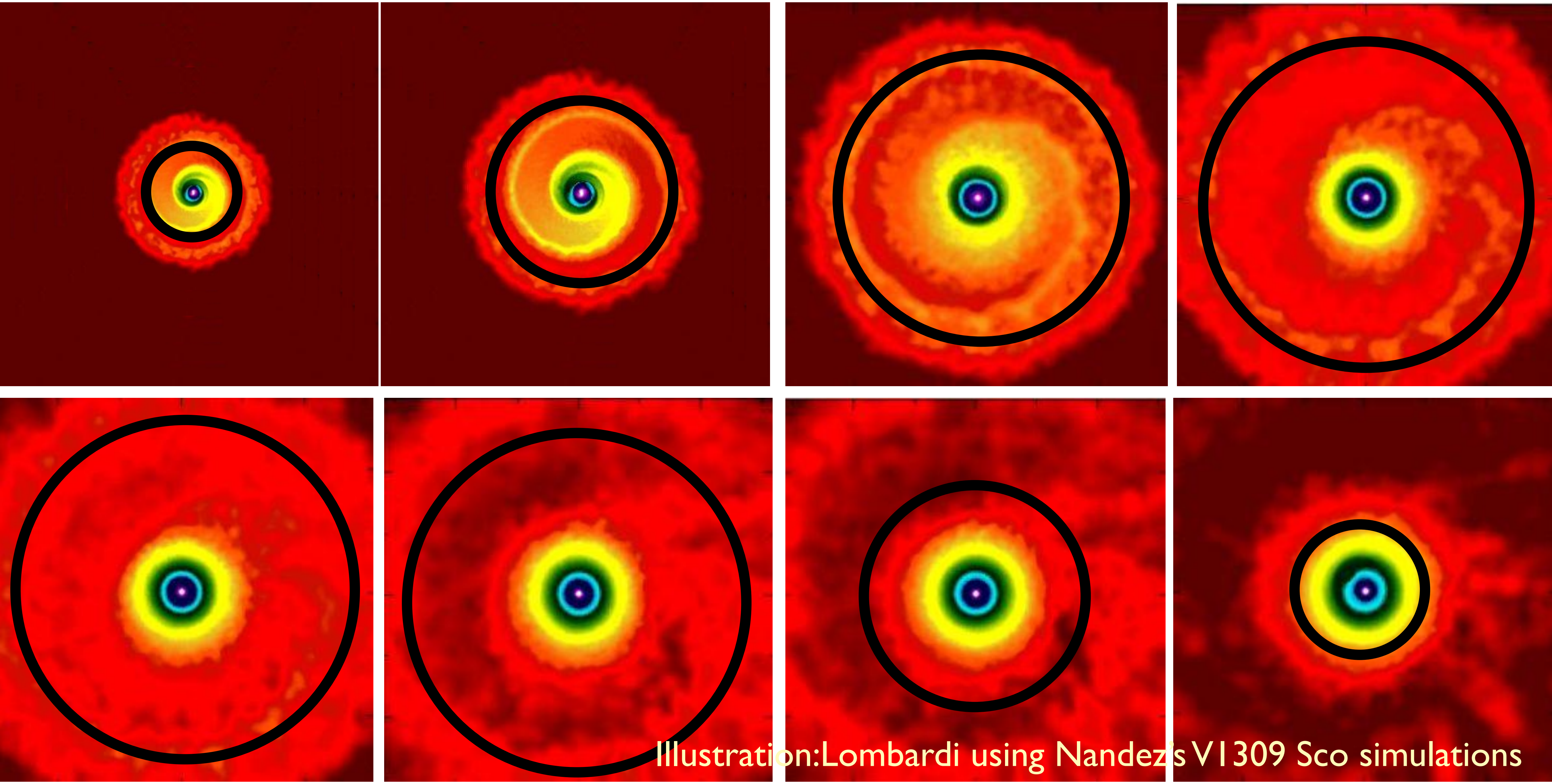


Illustration:Lombardi using Nandez's V1309 Sco simulations

How we try to model the Light Curve using SPH outcomes
(Pictures made by Roger Hatfull)

Take a snapshot of the simulation from an angle

Lay down a grid (not necessarily uniform)

Calculate flux generated from each area, by ray-tracing down to τ=10

Apply filters

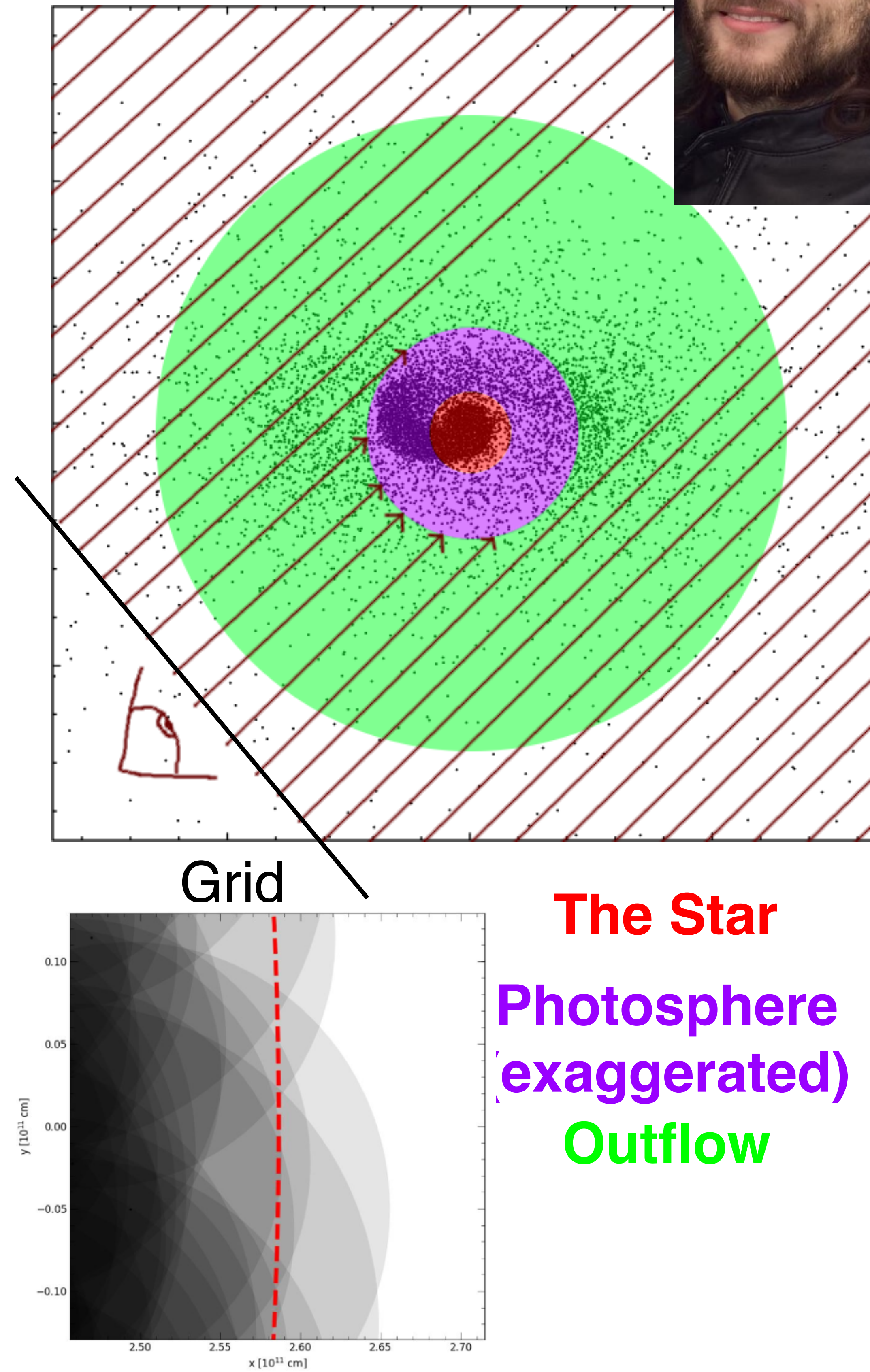
Take more snapshots over a range of time

Gives light curves in the same way an observer would record them

SPH problem: hot and opac particles.

1D star: tau=1 at ~300 km deep

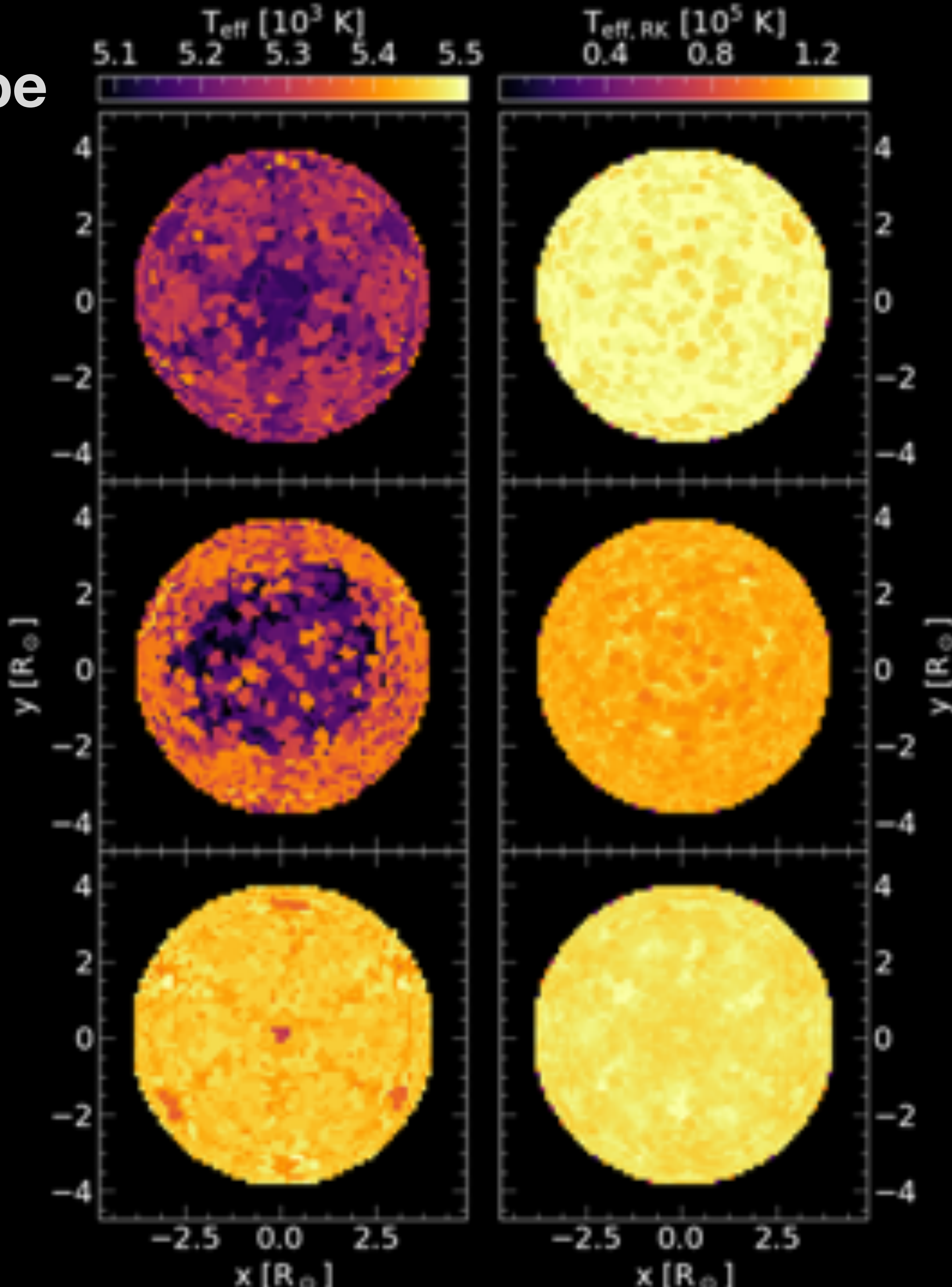
SPH particles at the surface is smoothed over >10^5 km



New: observing SPH particles

New: observing SPH particles

Envelope fitting

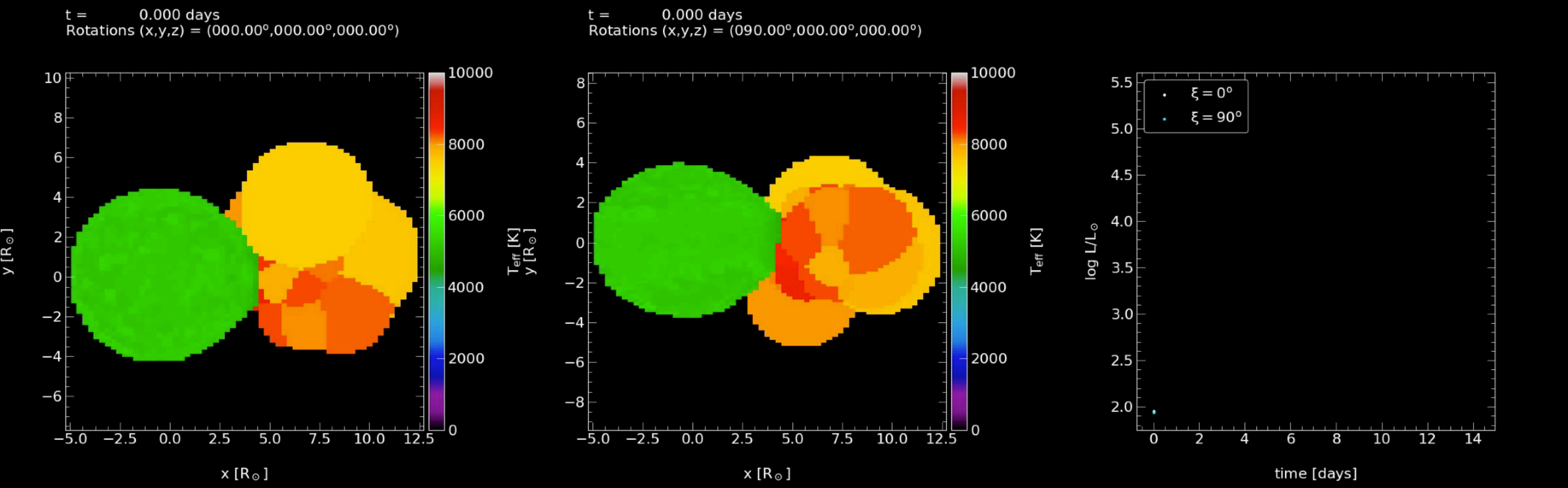


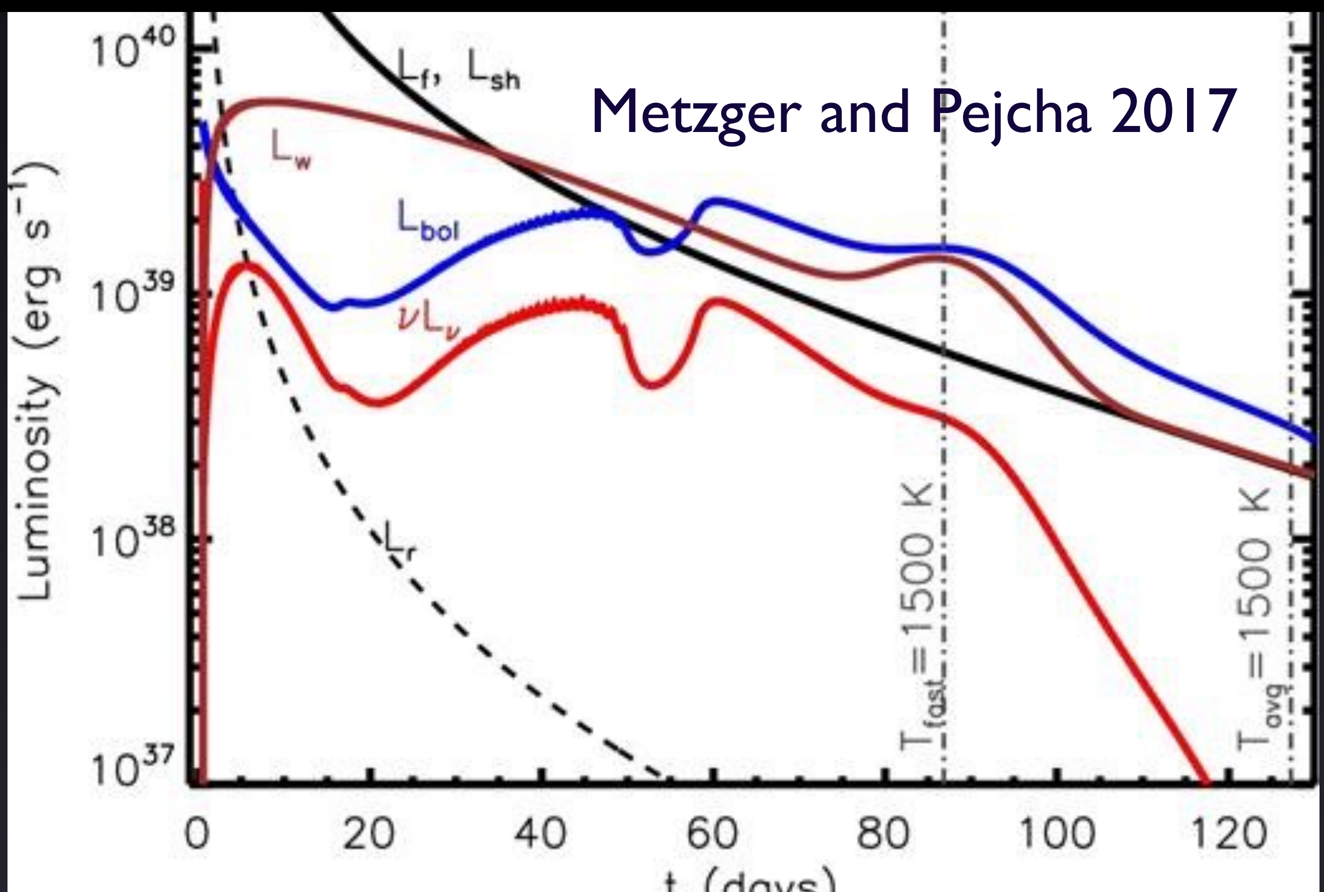
Ray tracing

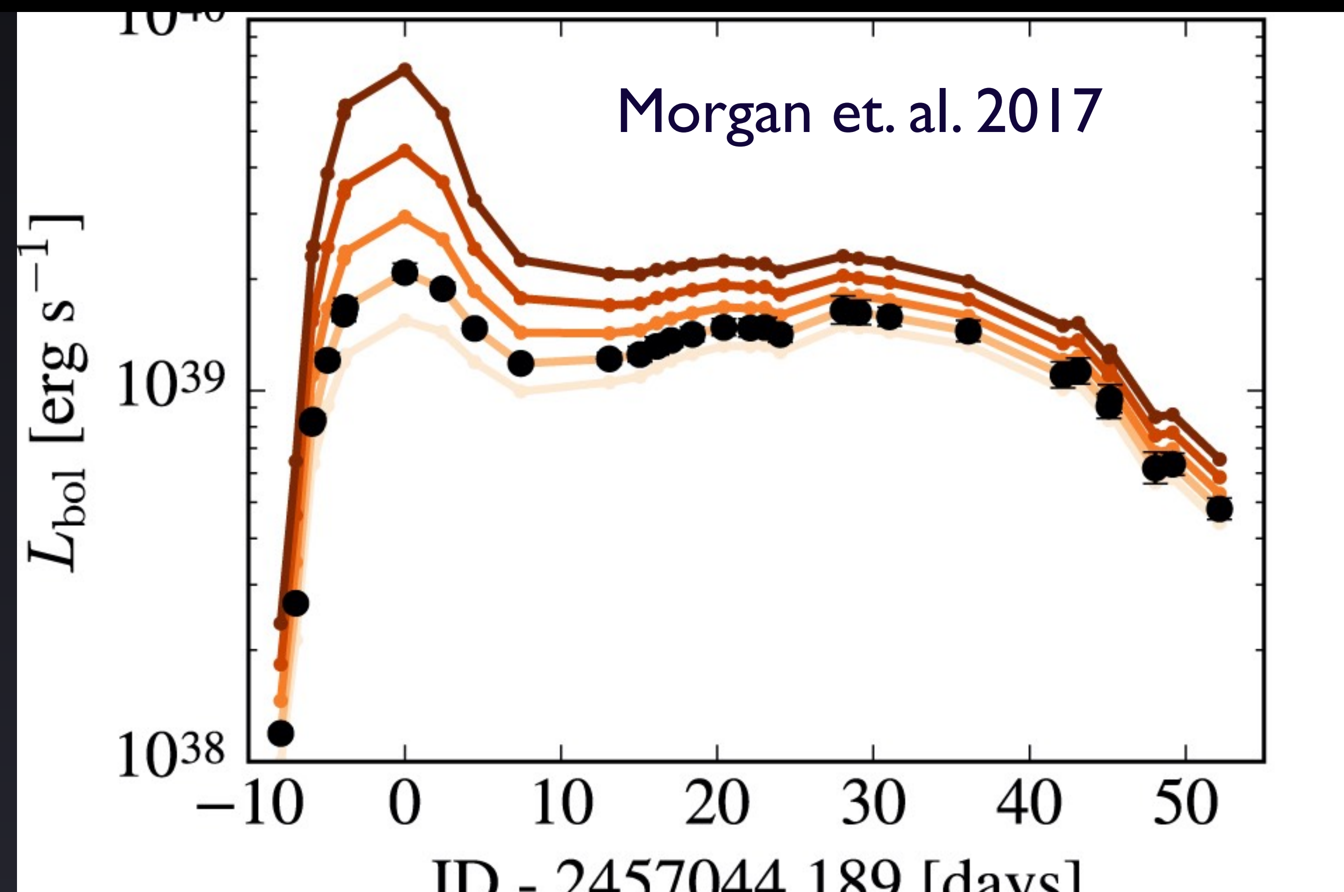
N	< T_{eff} >	< *Teff,RK* >
MESA	4,973	-
1x10^5	5,252	136,300
2x10^5	5,288	112,100
3x10^5	5,448	128,400

Roger Hatfull

Current light curve. There is still lots to do before complete light curves of CEEs.

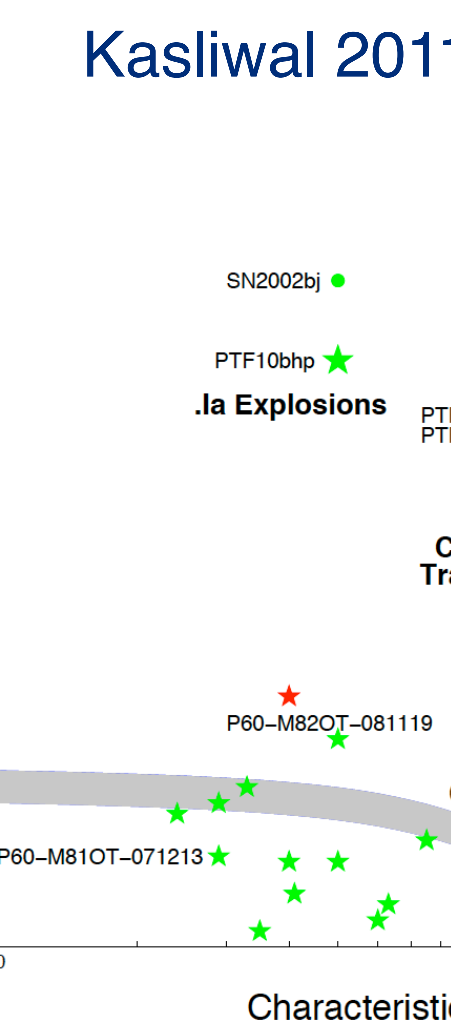


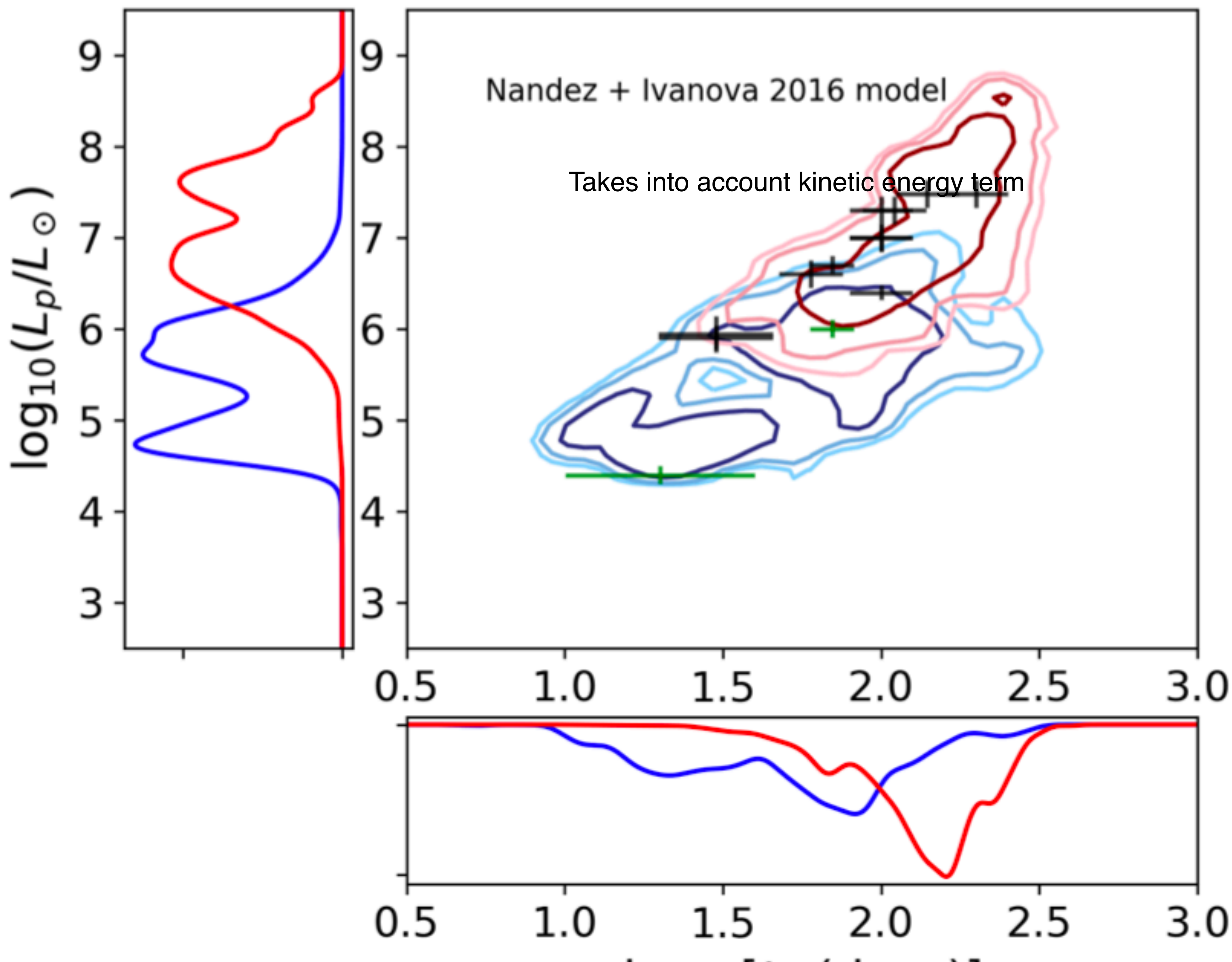




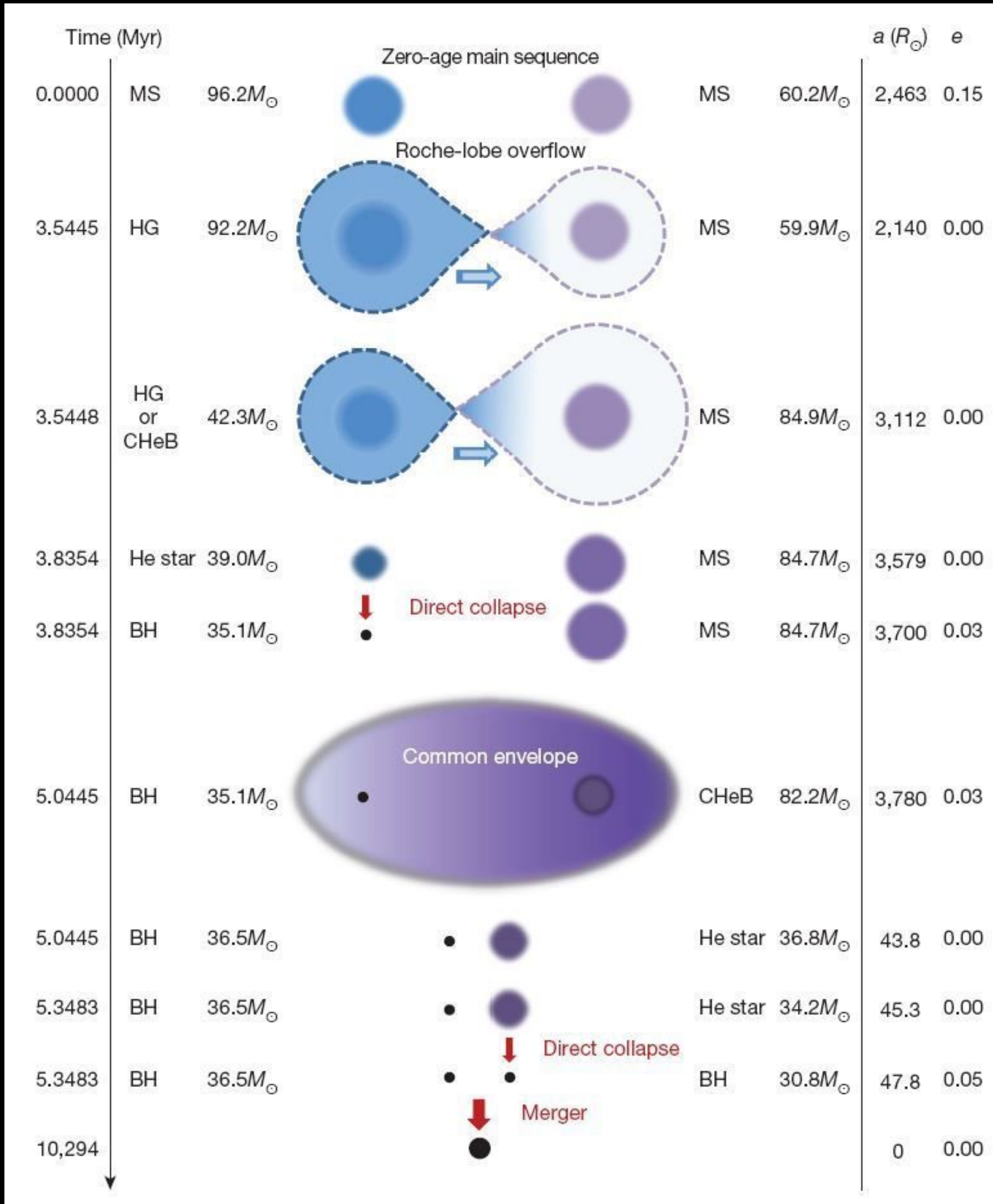
simple parameterized plane for plateau durations and luminosities (Ivanova et al 2013)

Our current … model





Howitt et al 2019



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

Belczynski *et al. 2016*

Spins are aligned

Mostly low spins

Mass ratio: range, $\Longrightarrow$ 0.8

High eccentricity is not OK

Some final notes on close binaries formation

- Styding interactions in stars is great fun
- Close binaries, observed by LIGO, can be made by three paths
- Each path still has its own problems in obtaining a proper population
- There is still lots to do for refining the physics for each of the paths, well prior compiling the entire populations. CEEs might get calibrated by observing LRNe/SPRITE events
- Eventually, we may distinguish which path is more important, by comparing the unique features of each of the theoretical populations to the observed population of LIGO events

	Spins	alighned?	q_{bin}	E
GCs	80%low/20% high	No	0.3-1	high
ChH	High	Yes	$\Rightarrow 1$	$\Rightarrow 0$
Field	Mostly low	Yes	Range $\Rightarrow 0.8$	$\Rightarrow 0$