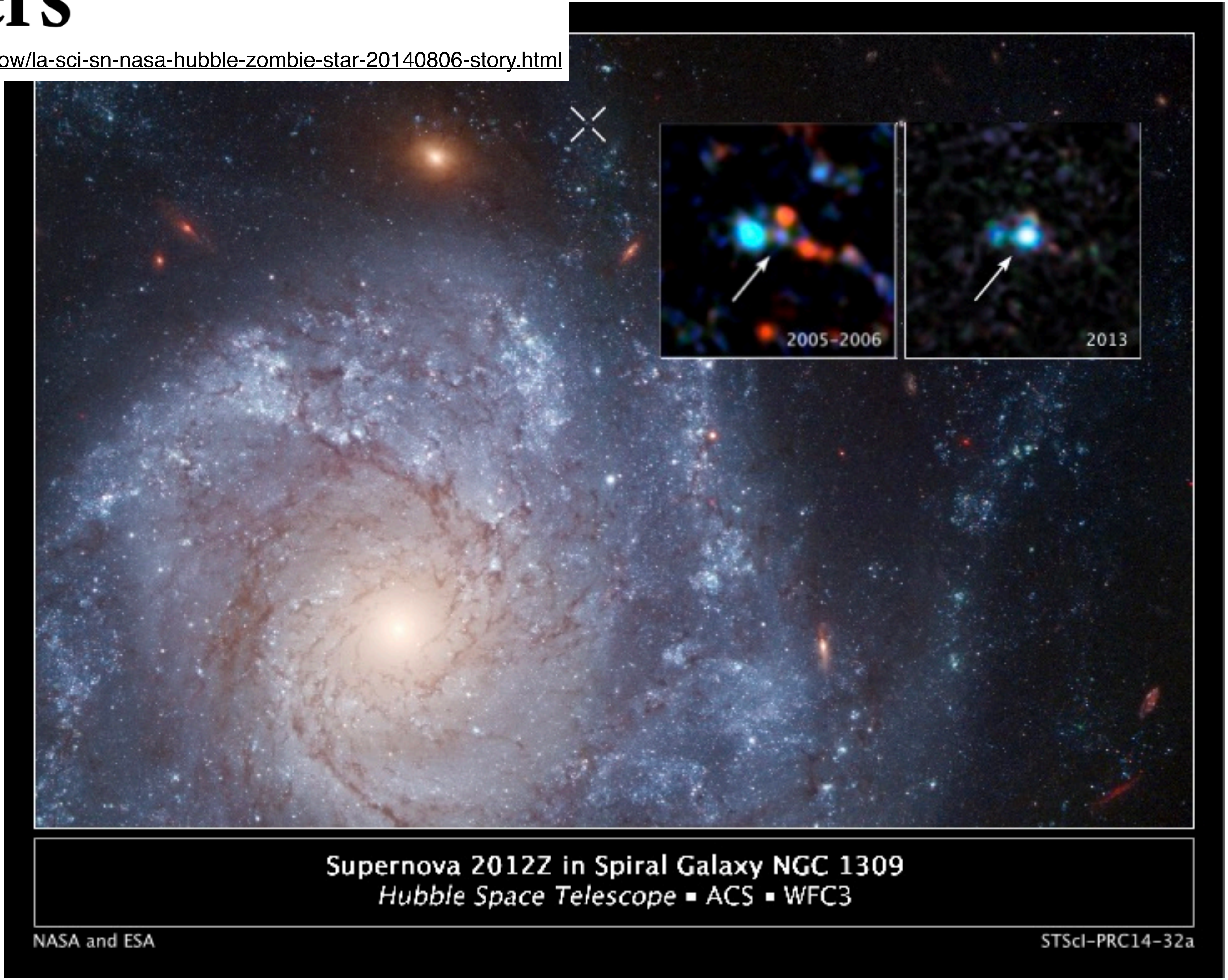
Hubble sees 'zombie star' lurking in space: What it is, why it matters

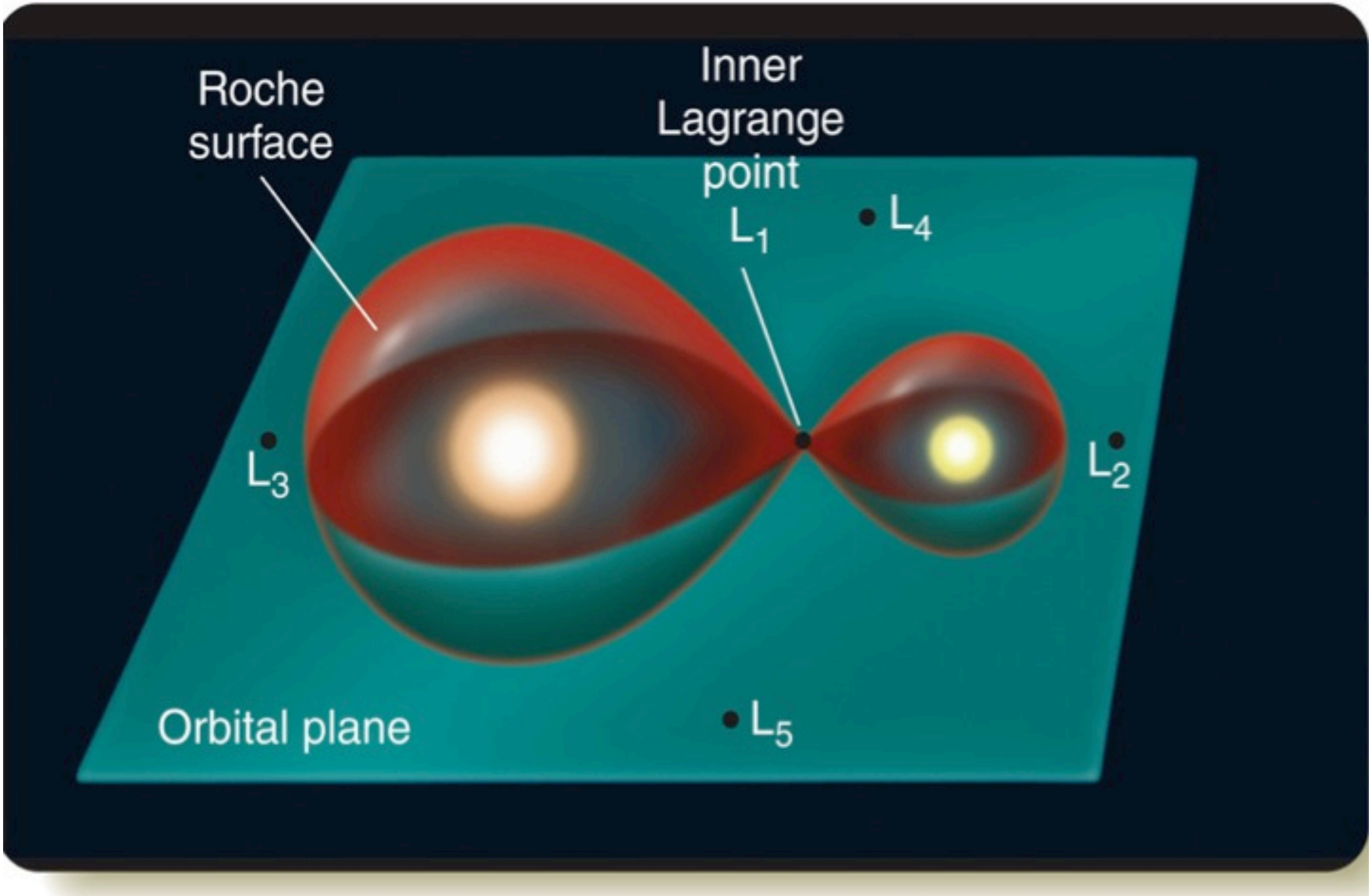
http://www.latimes.com/science/sciencenow/la-sci-sn-nasa-hubble-zombie-star-20140806-story.html



Lecture 19: Novae & Supernovae

Rutgers Physics 441/541: Stars & Star Formation   April 5, 2022

Stars in Binaries: Roche lobe



from http://crab0.astr.nthu.edu.tw/~hchang/ga1/ch10-05.htm (see also L&L eqn. 28.8)

Stars in Binaries: Principles

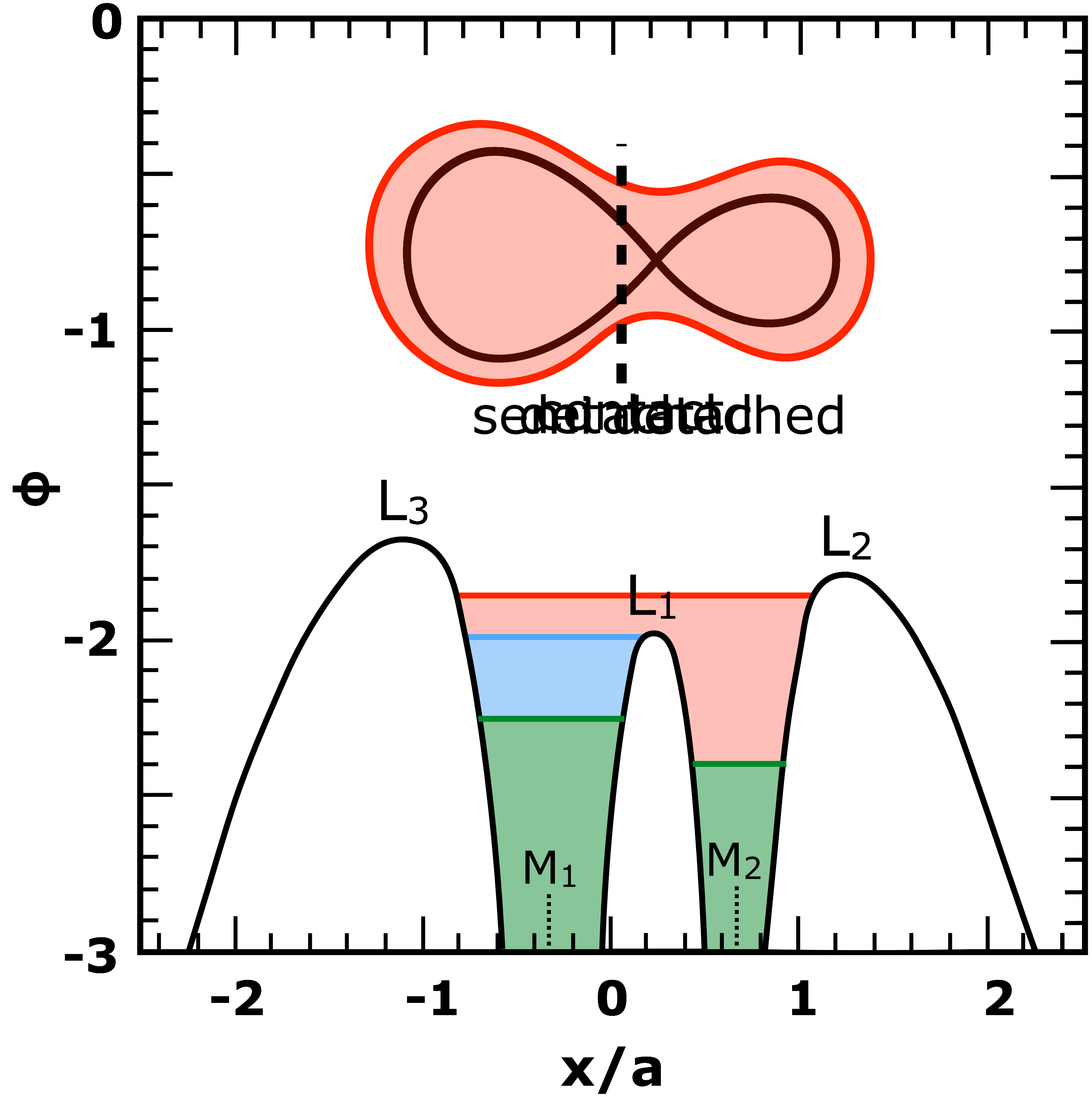
Contact phases

Binaries interact when the size of one of the two components reaches or overflows its Roche lobe.

Detached system: both stars safely fit inside their Roche lobes; matter cannot flow between them

Semi-detached system: M_1 (the more massive component) fills its Roche lobe; gas can flow freely from M_1 to M_2.

Contact system: both stars have filled their Roche lobes and are in contact with one another.



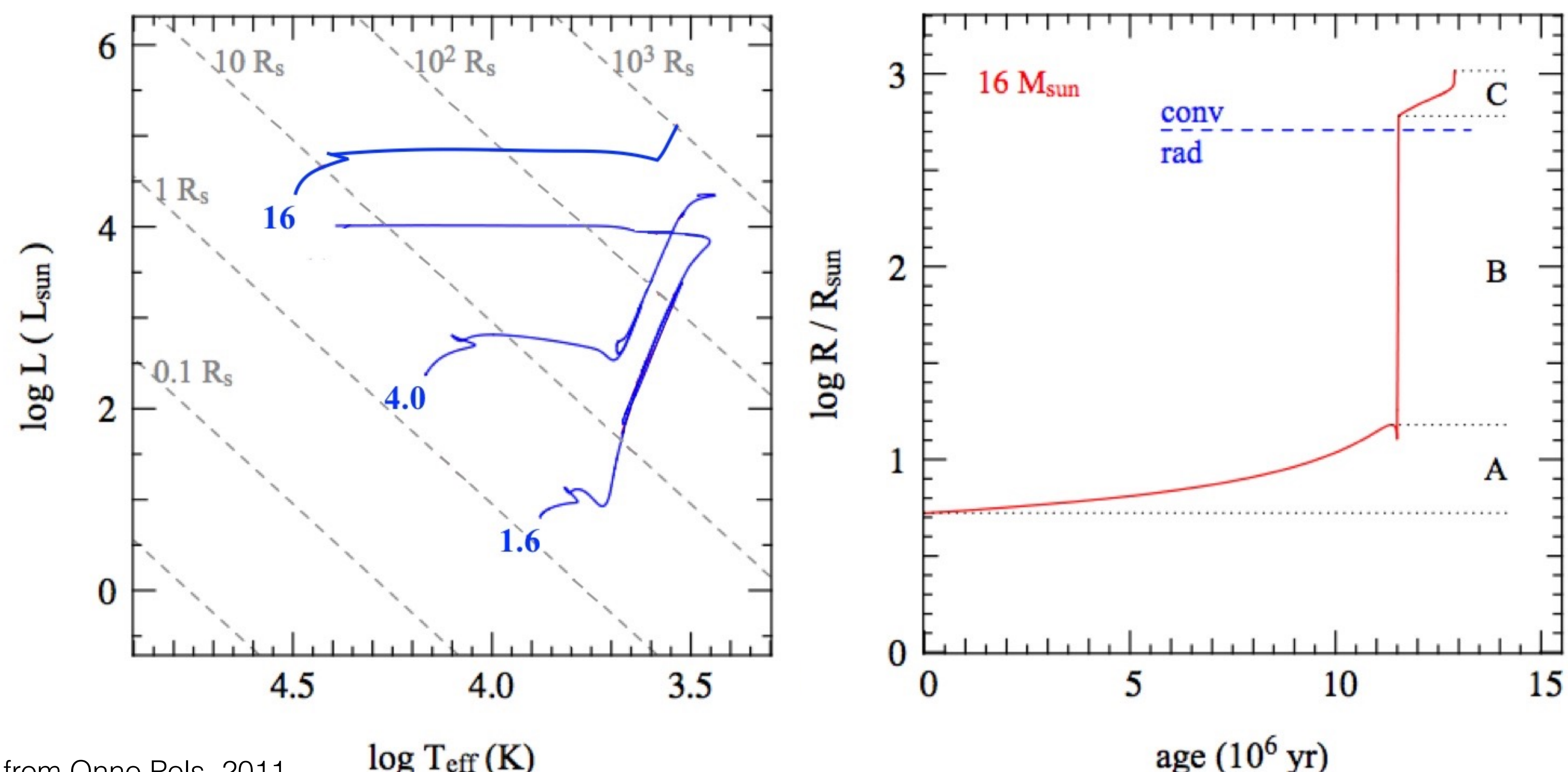
Adapted from Onno Pols, 2011.

Stars in Binaries: Principles

Contact phases

Binaries interact when the size of one of the two components reaches or overflows its Roche lobe.

Case A: first contact during main sequence phase
Case B: first contact during H shell fusion
Case C: first contact while the star is on the Hayashi track (nearly fully convective; e.g., AGB star)



Adapted from Onno Pols, 2011.

Stars in Binaries: Principles

Changes during mass transfer

Mass transfer changes the period and separation of a binary. If we consider the time derivatives of the stellar masses $\dot{M}_1$ and $\dot{M}_2$, in the case of conservative mass transfer:

$$-\dot{M}_1 = \dot{M}_2 \quad \text{and} \quad \dot{J} = 0$$

Stars in Binaries: Principles

Changes during mass transfer

If M_1 is the mass of the donor (so $\dot{M}_1 < 0$), the orbit will shrink if $M_1 > M_2$ and expand if $M_1 < M_2$. The minimum orbit is reached when the stars have an equal mass.

The change in a can be derived directly from the conditions that J and $M_1 + M_2$ are both constant. From this:

$$M_1^2 \; M_2^2 \; a \; = \; J^2 \, (M_1 + M_2)/G = \text{constant}$$

This implies that after mass transfer we can express the ratio between the final separation and period (a and P) and their initial values (a_i and P_i) as:

$$\frac{a}{a_i} = \left(\frac{M_{1i}}{M_1} \cdot \frac{M_{2i}}{M_2}\right)^2 \quad \text{and} \quad \frac{P}{P_i} = \left(\frac{M_{1i}}{M_1} \cdot \frac{M_{2i}}{M_2}\right)^3$$

(the last equation follows from Kepler's 3rd law…)

Stars in Binaries: Principles

Three time scales associated with single stars are important for the study of binary evolution. In order of increasing length these are:

the dynamical time scale This is the time scale on which a star counteracts a perturbation of its hydrostatic equilibrium. It is given by the ratio of the radius of the star R and the average sound velocity of the stellar matter c_s:

$$\tau_{\rm dyn} = \frac{R}{c_{\rm s}} \approx 0.04 \left(\frac{M_\odot}{M}\right)^{1/2} \left(\frac{R}{R_\odot}\right)^{3/2} \text{ day} \tag{6.3}$$

the thermal or Kelvin-Helmholtz time scale This is the time scale on which a star reacts when energy loss and energy production are no longer in equilibrium. It is given by the ratio of the thermal energy content of the star $E_{\rm th}$ and the luminosity L:

$$\tau_{\rm KH} = \frac{E_{\rm th}}{L} \approx \frac{GM^2}{2RL} \approx 1.5 \times 10^7 \left(\frac{M}{M_\odot}\right)^2 \frac{R_\odot}{R} \frac{L_\odot}{L} \text{ yr} \tag{6.4}$$

the nuclear time scale This is the time scale on which a star uses its nuclear fuel. It is given by the product of the available fusable matter $M_{\rm core}$ and the fusion energy per unit mass Q, divided by the stellar luminosity. For hydrogen fusion with $Q = 0.007c^2$, this is:

$$\tau_{\rm nuc} = 0.007 \frac{M_{\rm core} c^2}{L} \approx 10^{10} \frac{M}{M_\odot} \frac{L_\odot}{L} \text{ yr} \tag{6.5}$$

from Onno Pols, http://www.astro.ru.nl/~onnop/education/binaries_utrecht_notes/

Stars in Binaries: Principles

Stable and runaway mass transfer

1) <u>Stable mass transfer on the evolution timescale of the donor</u>

   Occurs when the donor star radius decreases, due to mass transfer, faster than the size of the Roche lobe. Mass transfer will shrink the donor star; it then expands again due to its evolution and mass transfer begins again. Happens in Case A mass transfer when the donor is still on the MS with a radiative envelope

Stars in Binaries: Principles

Stable and runaway mass transfer

2) Runaway mass transfer: dynamically unstable mass transfer

Occurs when mass transfer shrinks the Roche lobe, while the donor radius does not shrink (or even keeps expanding). In this case the donor is out of hydrostatic equilibrium. Happens in Case C mass transfer in stars with deep convection zones (i.e., on the Hayashi track)

This happens because these stars' L is set by M_c and their T_{eff} is almost constant, making the radius independent of the mass of the envelope and causing a runaway mass transfer process from the star's envelope. Ends when the donor contracts to become a WD (low mass) or WR star (massive).

3) Unstable mass transfer on thermal timescale of donor

A middle ground between the two extremes above. The donor star is out of thermal equilibrium but mass transfer is slow enough to maintain hydrostatic equilibrium; the timescale for mass transfer is shorter than the dynamical timescale. Readjusting to thermal equilibrium occurs on a K-H timescale. This happens in Case B mass transfer, when stars have radiative envelopes that are expanding post-MS but have not reached the Hayashi track yet.

Stars in Binaries: Evolution

Table 6.1. End products of stellar evolution as a function of stellar mass, for single stars and for components of close binary stars (roughly, those undergoing case B mass transfer). The columns 'He-core mass' give the maximum mass of the helium core reached by a star of the given initial mass range, for single and close binary stars. The values given are only indicative, and depend on the metallicity (assumed to be solar) and uncertainties in mass loss rates and convective overshooting (mild overshooting was assumed). For binary stars, they also depend on the orbital period and mass ratio.

	single star		close binary star	
initial mass	He-core mass	final remnant	He-core mass	final remnant
$\lesssim 2.0\ M_\odot$	$\approx 0.6\ M_\odot$	CO white dwarf	$< 0.47\ M_\odot$	He white dwarf
$2.0 - 6\ M_\odot$	$0.6 - 1.7\ M_\odot$	CO white dwarf	$0.4 - 1.3\ M_\odot$	CO white dwarf
$6 - 8\ M_\odot$	$1.7 - 2.2\ M_\odot$	ONe white dwarf	$1.3 - 1.7\ M_\odot$	CO white dwarf
$8 - 10\ M_\odot$	$2.2 - 3.0\ M_\odot$	neutron star	$1.7 - 2.2\ M_\odot$	ONe white dwarf
$10 - 25\ M_\odot$	$3.0 - 10\ M_\odot$	neutron star	$2.2 - 8\ M_\odot$	neutron star
$\gtrsim 25\ M_\odot$	$> 10\ M_\odot$	black hole	$> 8\ M_\odot$	neutron star/black hole

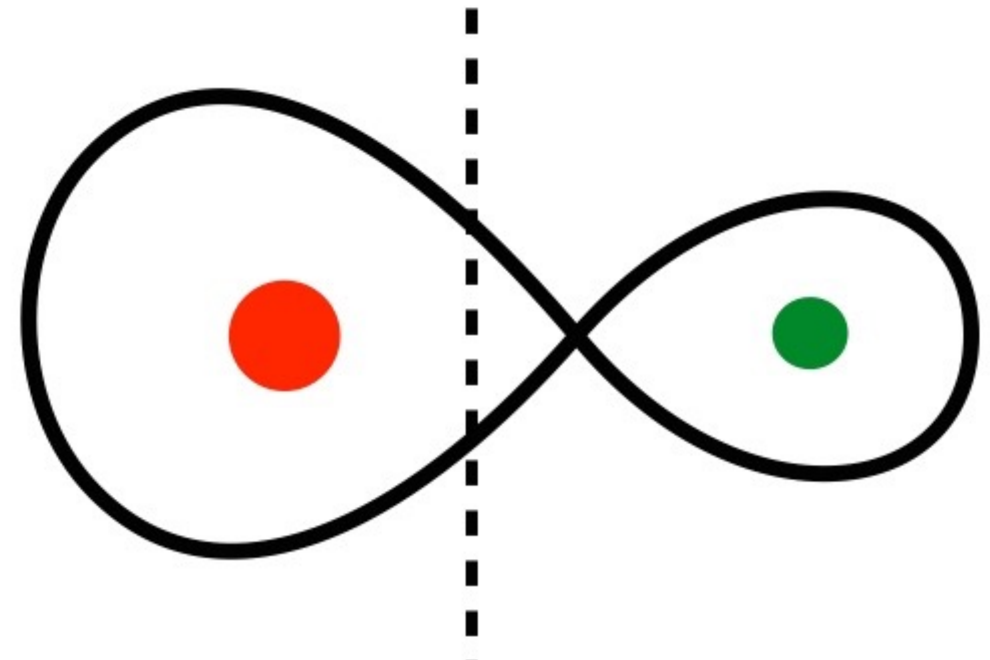
from Onno Pols, http://www.astro.ru.nl/~onnop/education/binaries_utrecht_notes/

Stars in Binaries: Evolution

Example: Case C

A: initial configuration of star 1 (red) and star 2 (green)

A



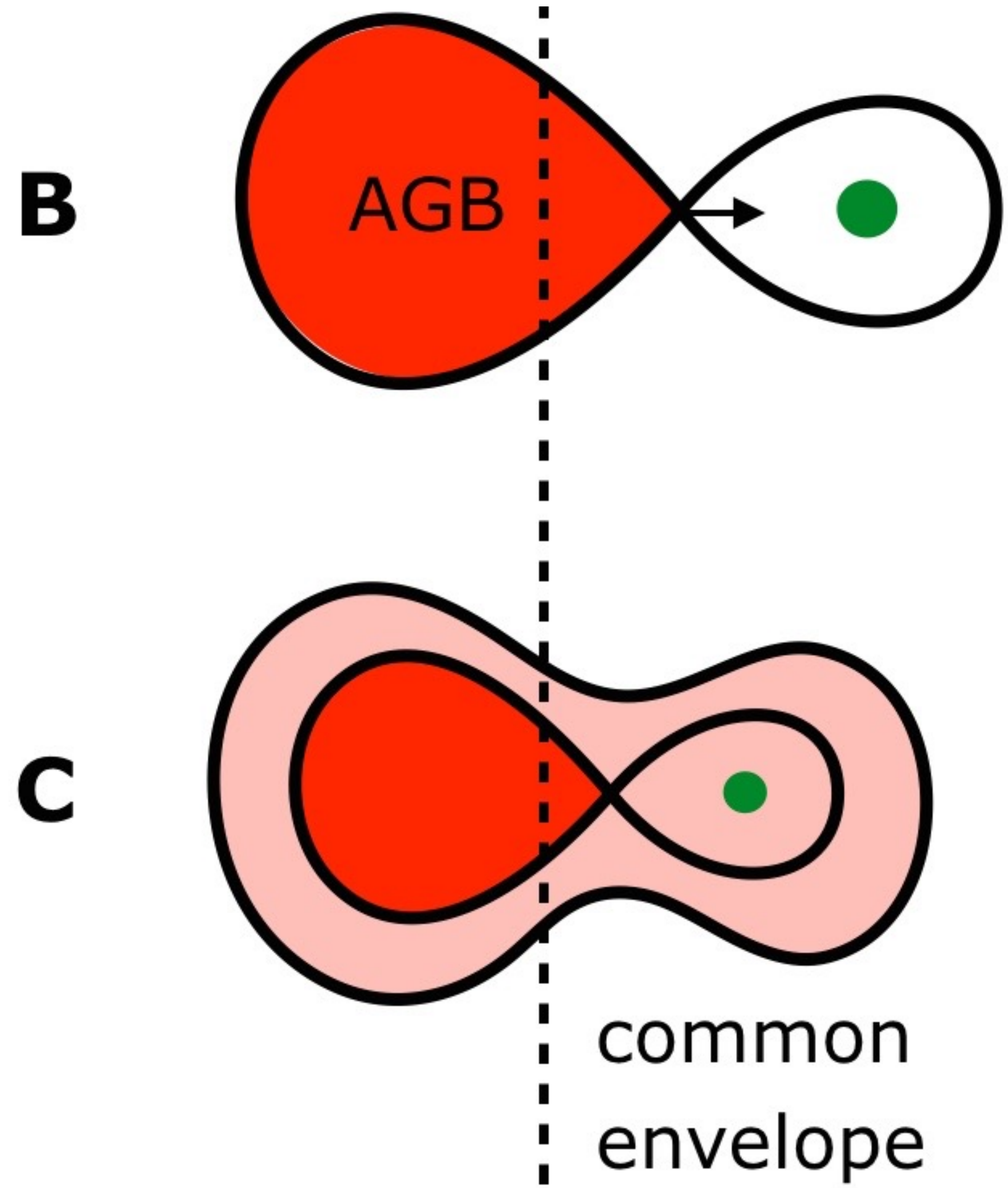
Stars in Binaries: Evolution

Example: Case C

A: initial configuration of star 1 (red) and star 2 (green)

B: unstable mass transfer when star 1 is on Hayashi line. Orbital separation & Roche lobe size decrease.

C: mass loss rate so high that star 2 can’t adjust, overfills its Roche lobe. Both stars now overflow lobes and occupy a common envelope.



Stars in Binaries: Evolution

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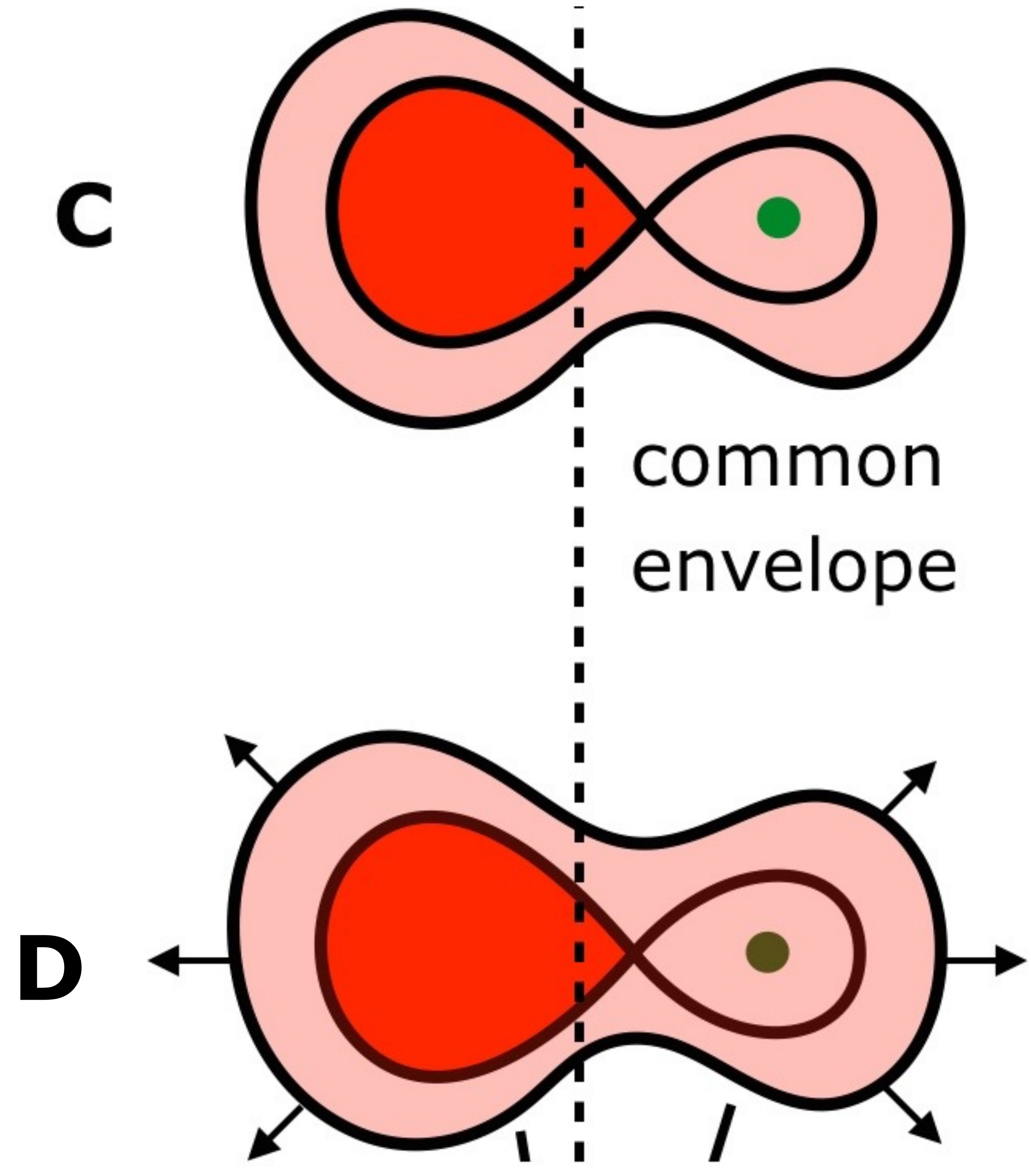
D: friction heats envelope, matter lost from system



Stars in Binaries: Evolution

Example: Case C

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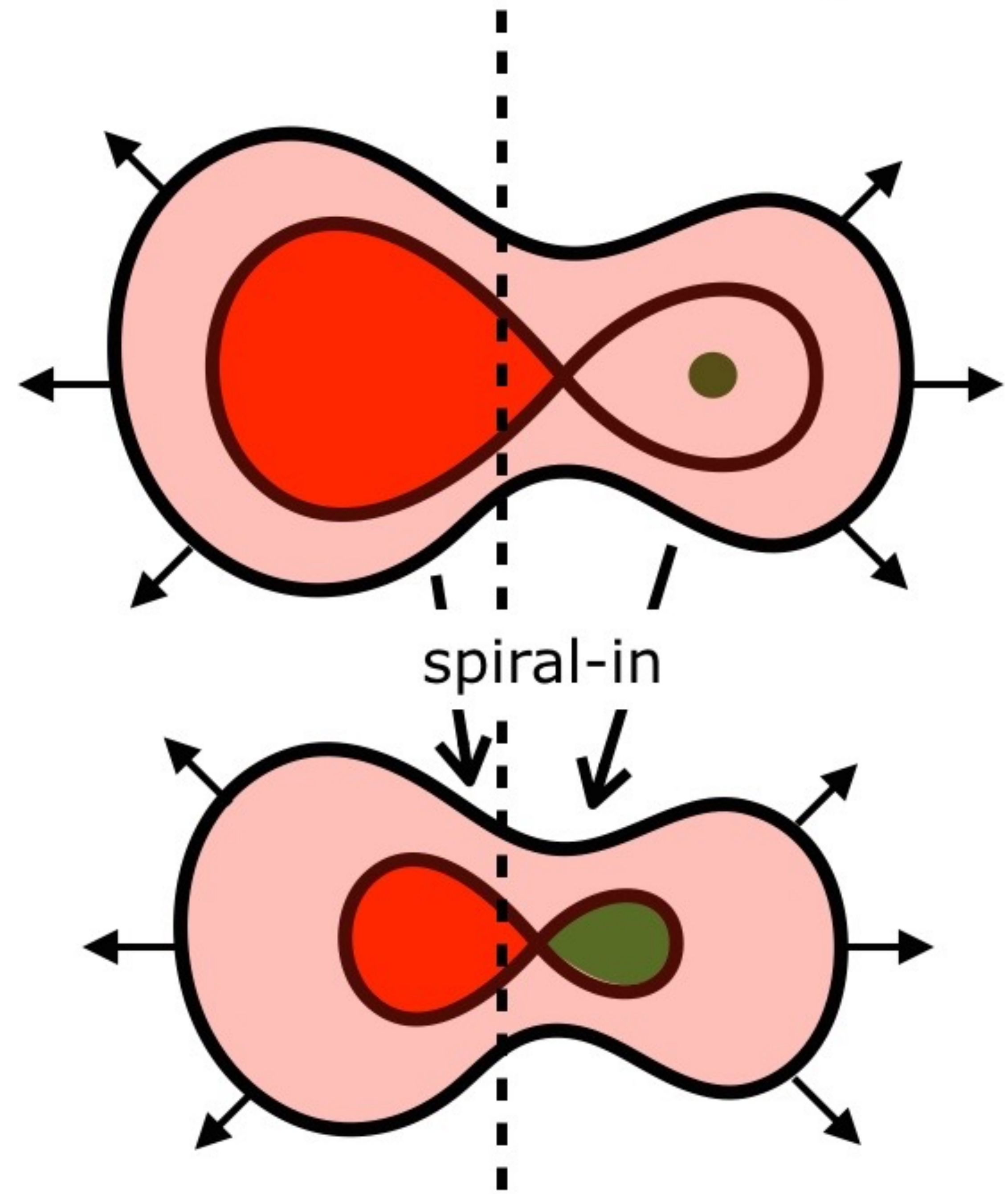
D: friction heats envelope, matter lost from system

E: friction leads to spiral-in of the two stars

D



E

Stars in Binaries: Evolution

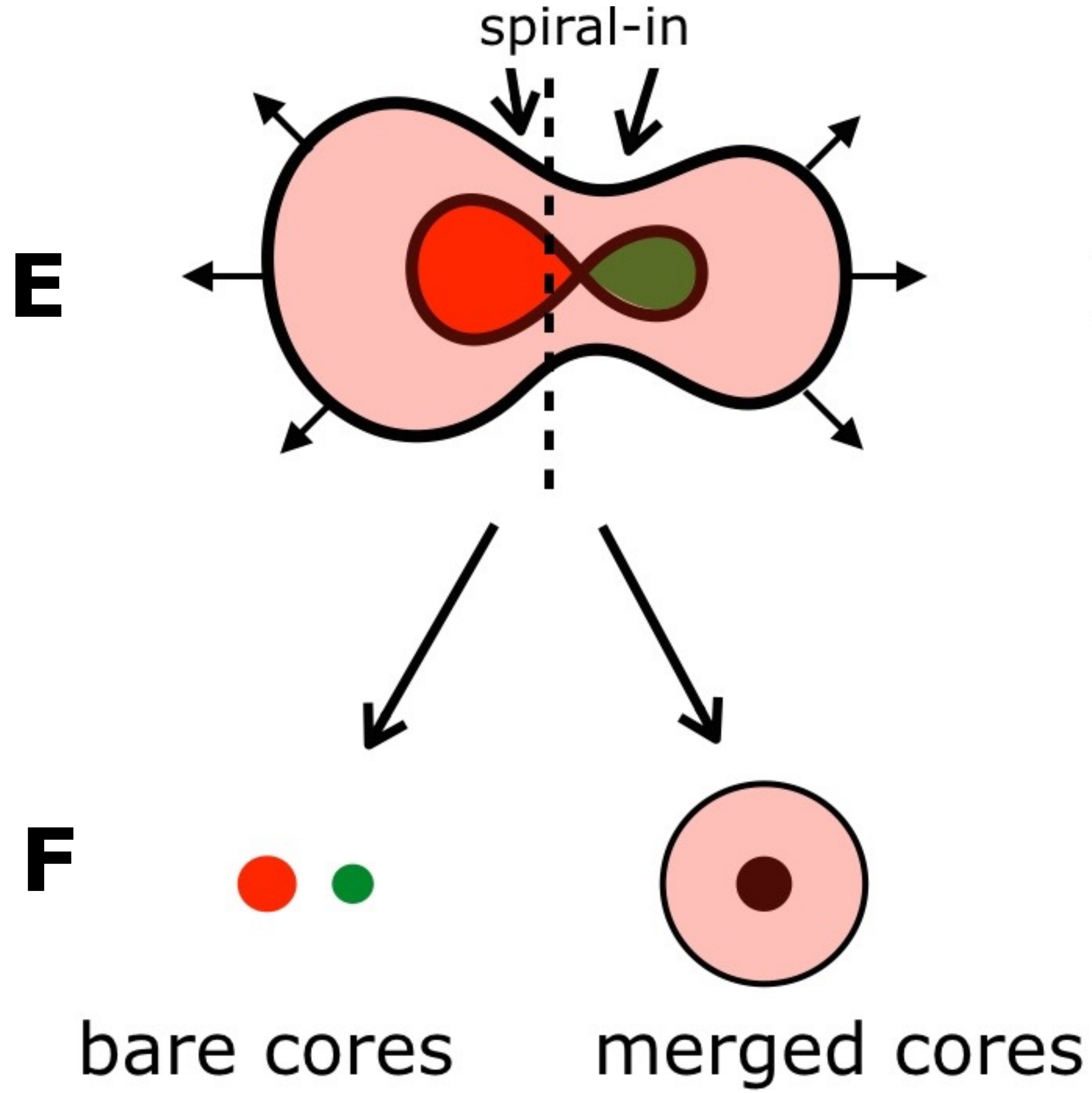
Example: Case C

E: friction leads to spiral-in of the two stars

F: system has two possible outcomes…

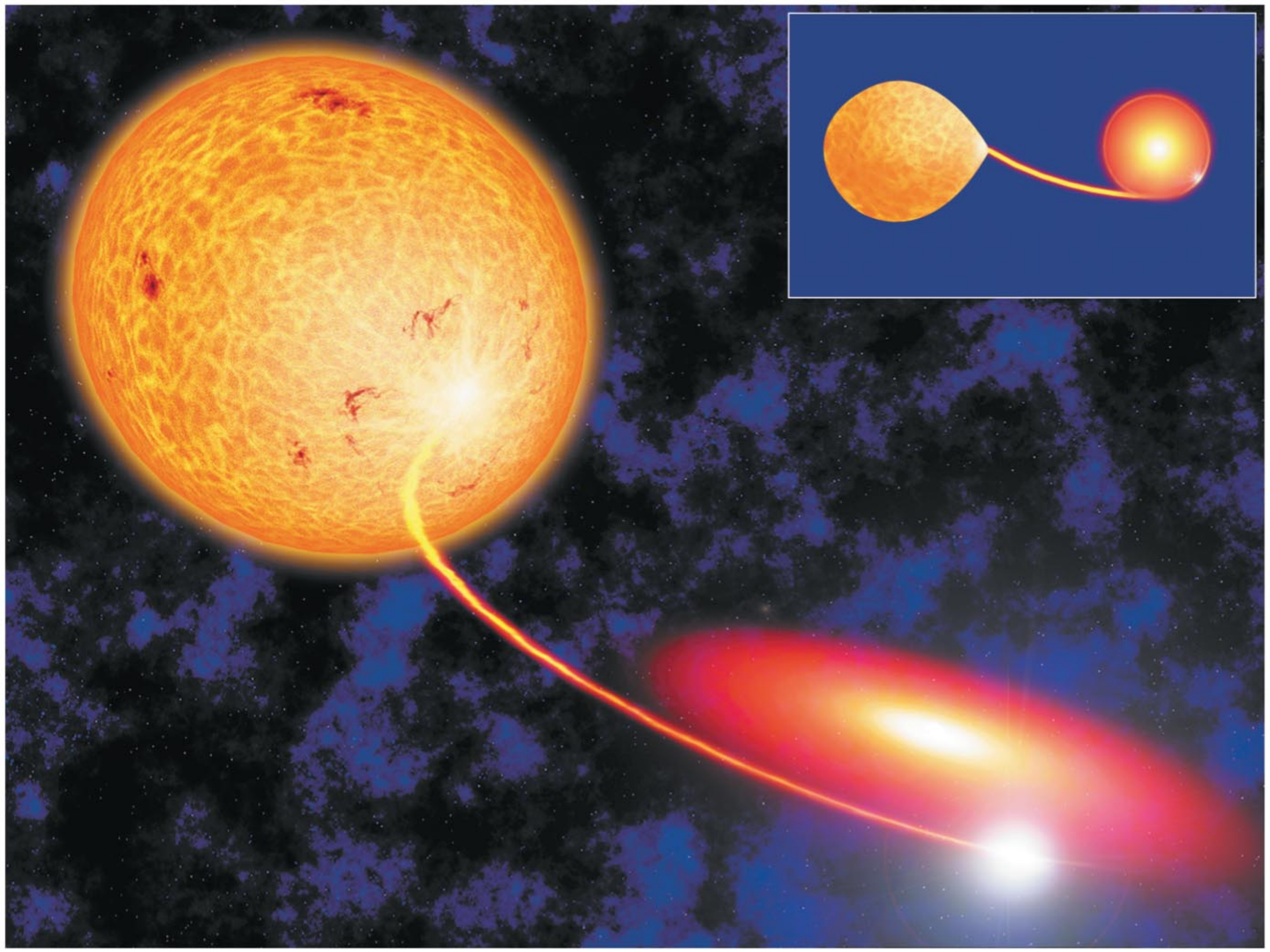
Left: energy released by friction and shrinking leads to very high T; envelope escapes, leaving two bare cores in a close orbit

Right: slow-down of orbital motion by friction leads to a spiral-in, merger of two cores surrounded by an envelope (a new single star!)



Depends on net energy; $E_{net}=E_{fric}-E_{rad}$

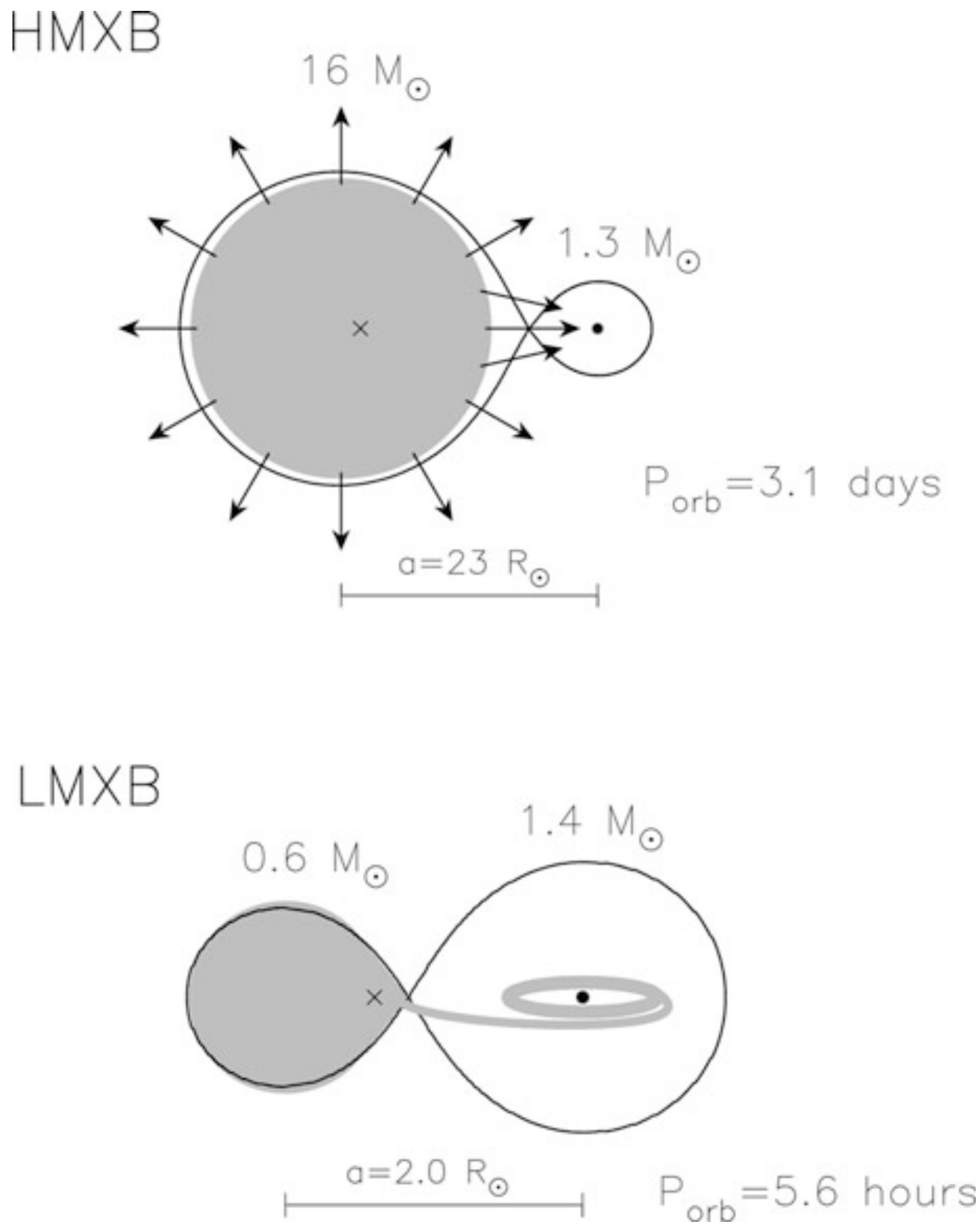
Accretion in Close Binary Systems



- Mass falling toward a white dwarf, neutron star, or black hole from its close binary companion has some angular momentum.
- The matter therefore orbits the compact object in an *accretion disk*.
- Friction between orbiting rings of matter in the disk transfers angular momentum outward and causes the disk to heat up and glow.

Stars in Binaries: X-ray Binaries

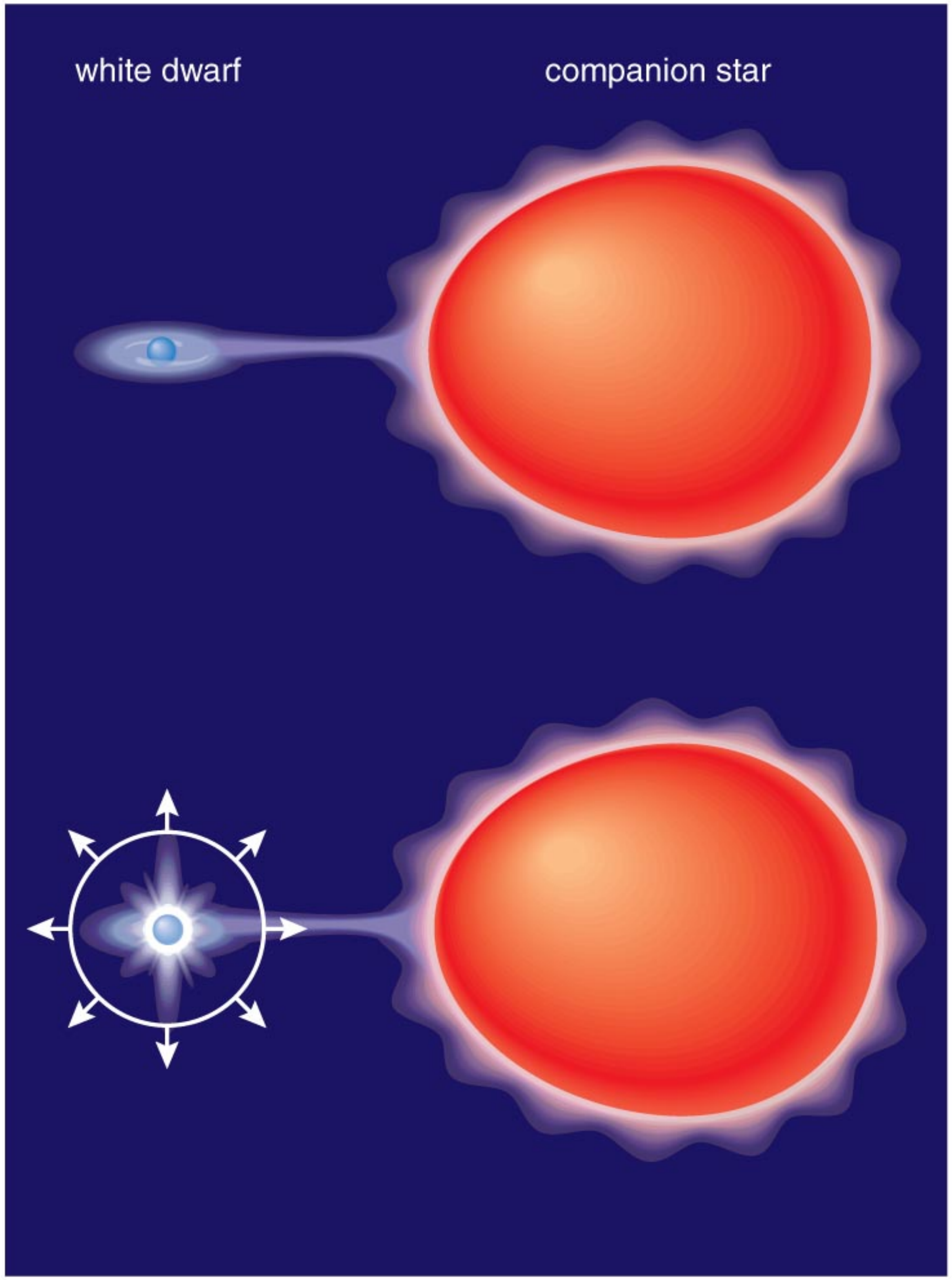
Fig. 1 Examples of a typical HMXB (*top*) and LMXB (*bottom*). The neutron star in the HMXB is fed by a strong high-velocity wind. The neutron star in the LMXB is surrounded by an accretion disk which is fed by Roche-lobe overflow. Also HMXBs and LMXBs are known in which the accreting compact object is a *black hole* (Credit: Tauris and van den Heuvel 2006, Cambridge University Press)



accretion onto a neutron star (or a black hole)

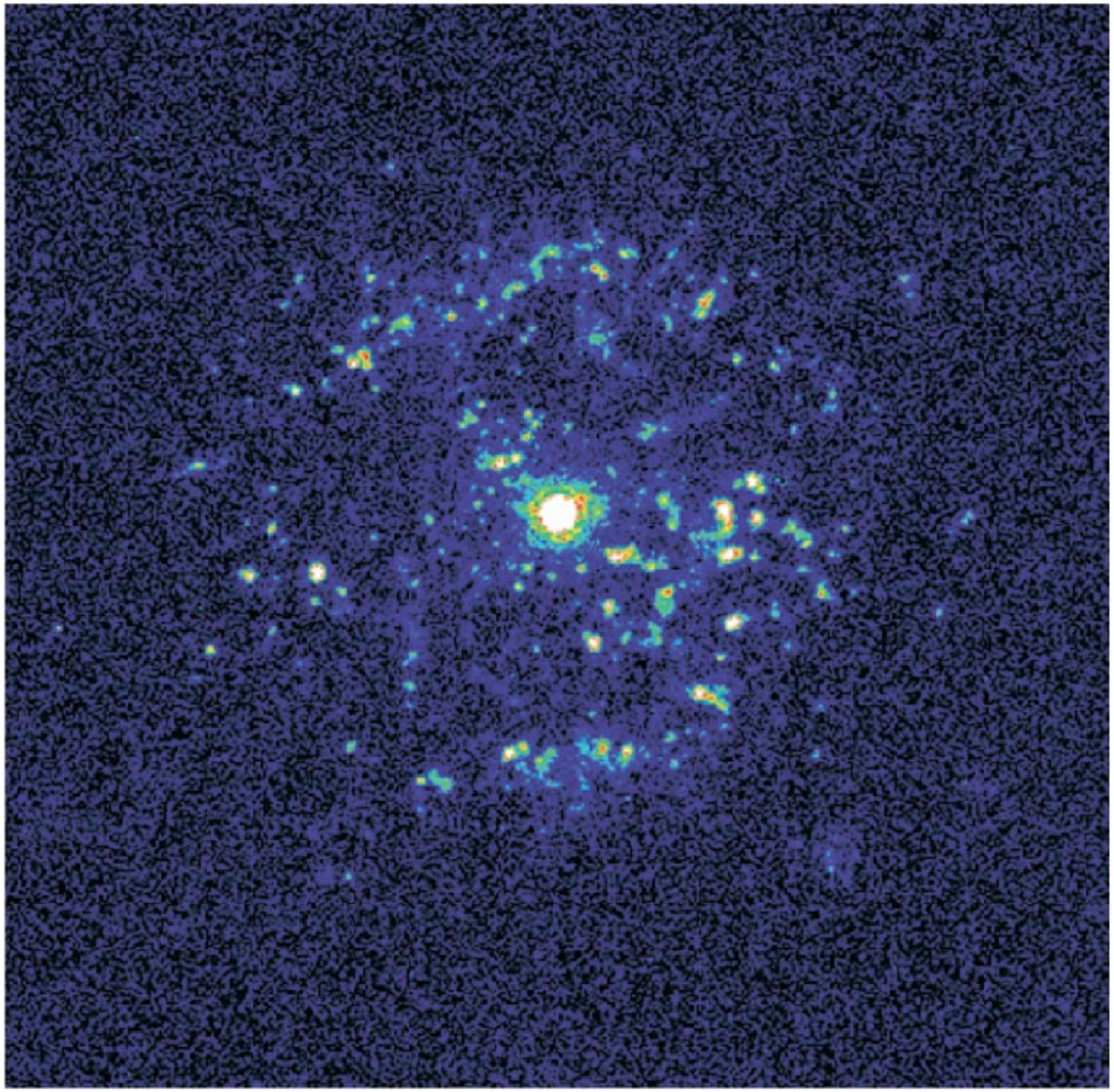
from https://link-springer-com.proxy.libraries.rutgers.edu/referenceworkentry/10.1007/978-3-319-20794-0_75-1

Accretion onto a white dwarf: Nova



- The temperature of accreted matter eventually becomes hot enough for hydrogen fusion.
- Fusion begins suddenly and explosively, causing a *nova.*

Nova



- The nova star system temporarily appears much brighter.
- The explosion drives accreted matter out into space.

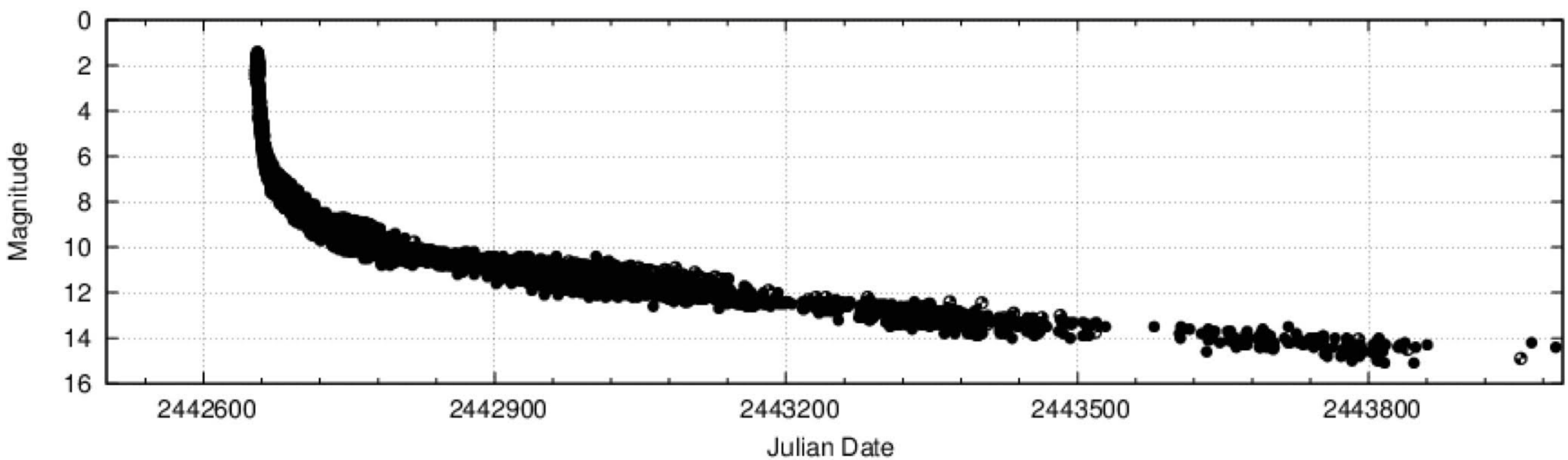
Stars in Binaries: Novae

Novae: accretion onto a WD in semi-detached systems

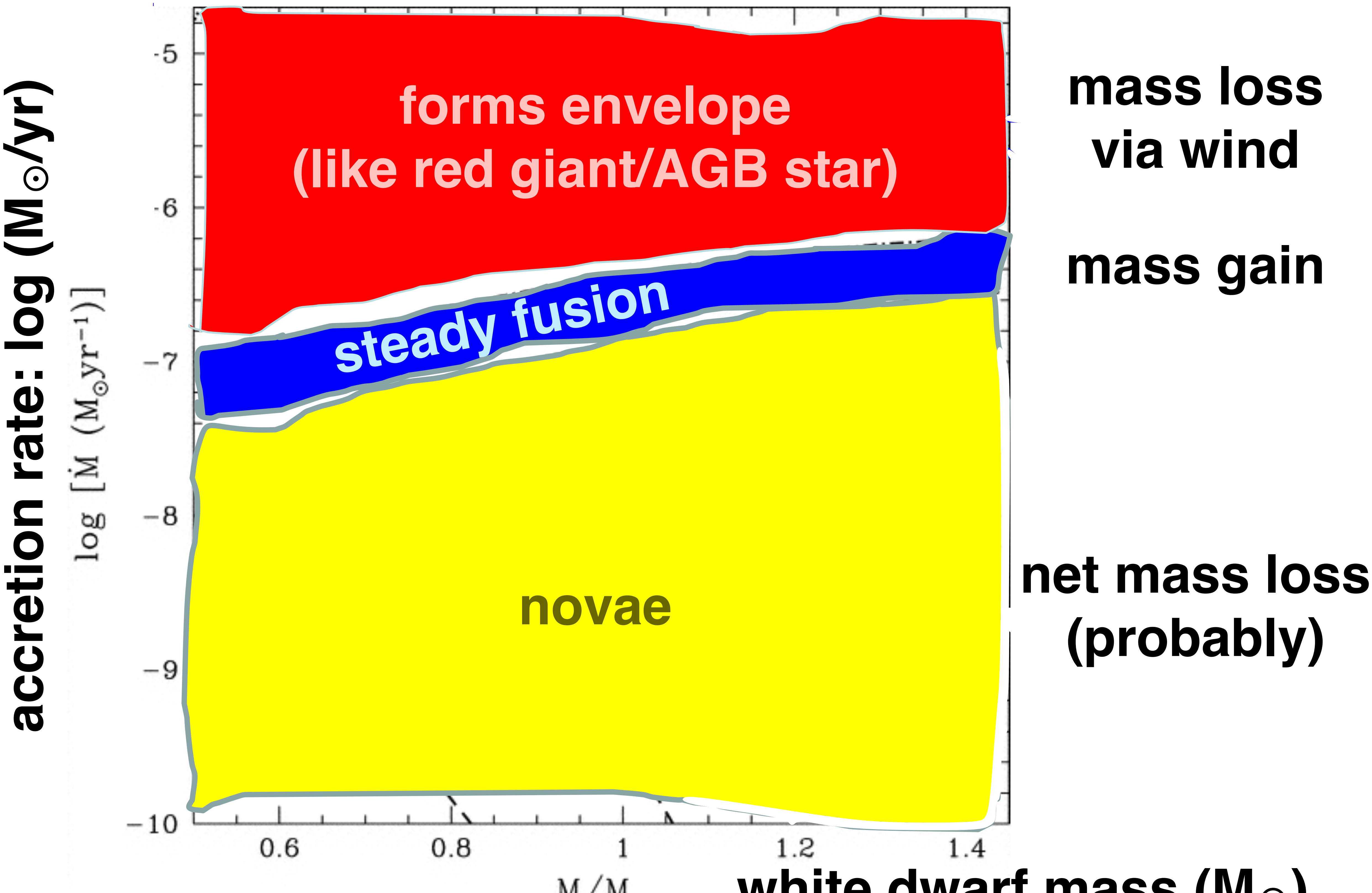
Novae are close binary systems that show recurrent outbursts. They have orbital periods of ~1-10 hours and consist of a WD and a star of type G or later with an initial mass of $\sim 1 M_\odot$.

Classical nova: brightness increases (within a few hours) from a typical WD ($M_V \sim 5$, $L \sim L_\odot$) to as high as $M_V = -6$ to -9, $L \sim 2\times10^4 - 3\times10^5 L_\odot$. Maximum lasts a few days; then brightness decreases over ~10-100 days to its normal level.

V1500 Cyg



Stars in Binaries: Evolution



Nomoto+ 2007

from Zhanwen Han (talk at Rapa Nui 2016)

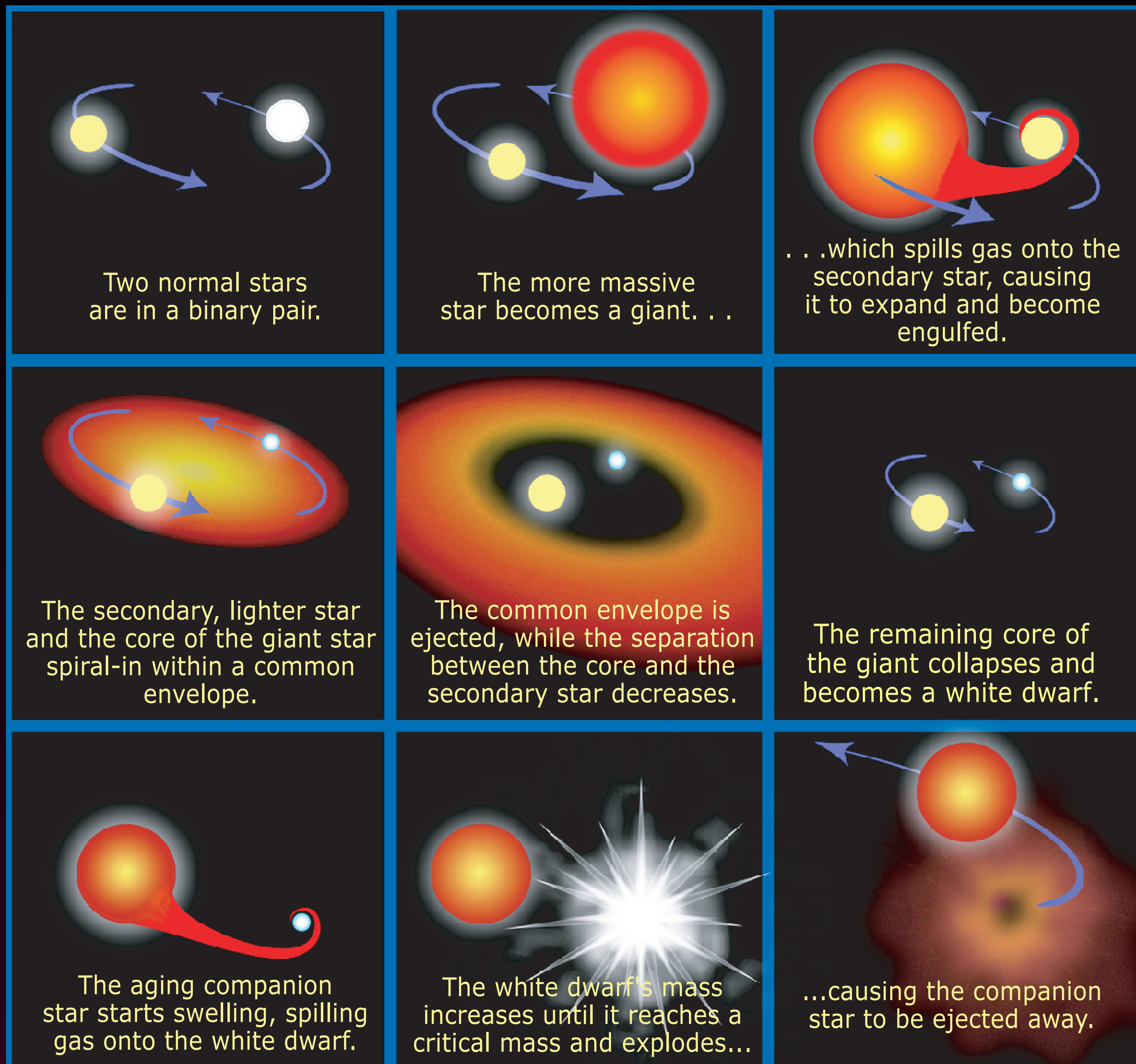
Nova or Supernova?

- Supernovae are MUCH MUCH more luminous (about 10 thousand times)!!!
- Nova: H to He fusion of a layer of accreted matter, white dwarf left intact
- Supernova: complete explosion of white dwarf, nothing left behind

The Sun will end up as a white dwarf...
will it ever become a nova or a supernova?

No! because it is not in a binary star system

Thermonuclear (Type Ia) Supernovae



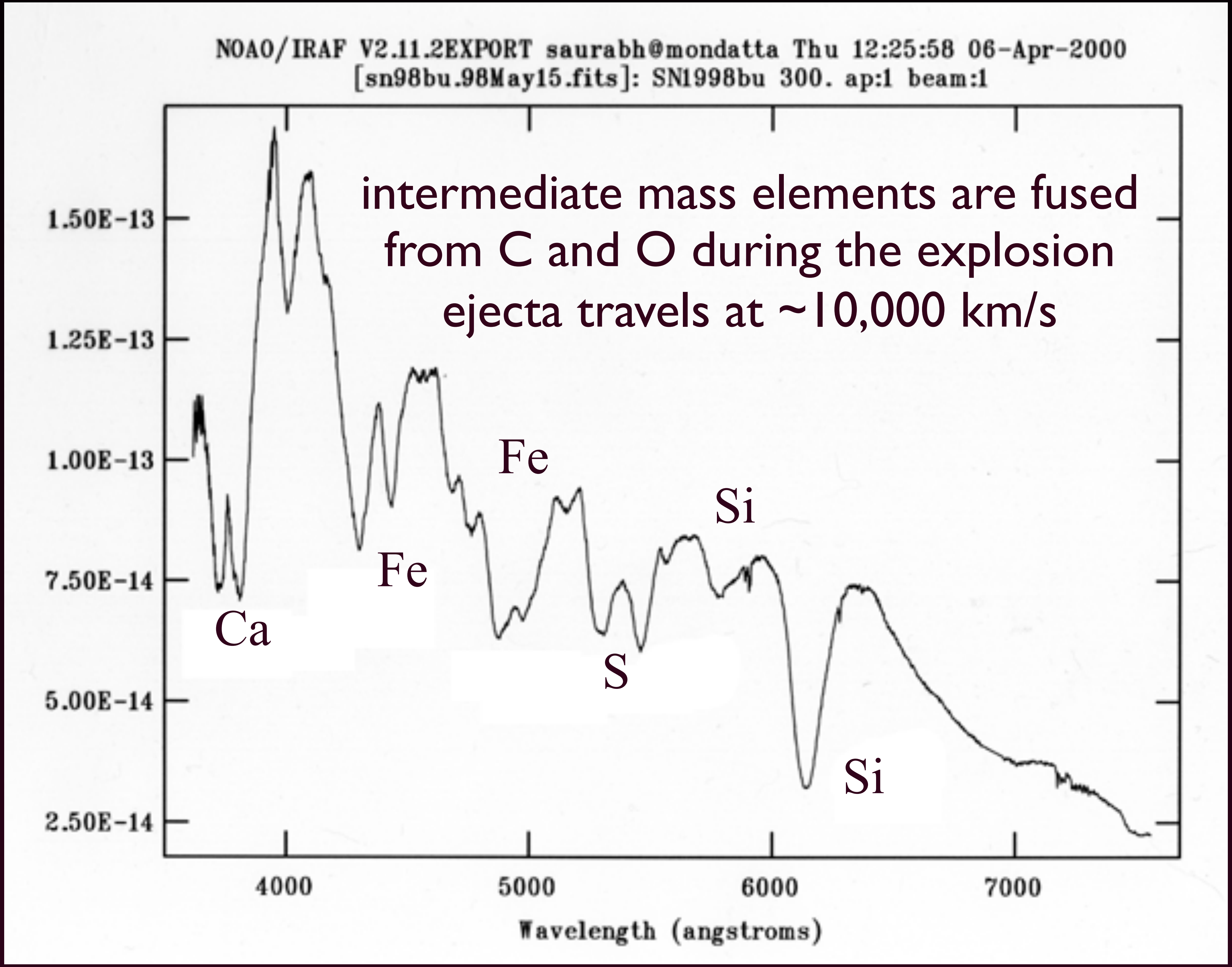
a complicated and uncertain story,
but we observe them to be very homogeneous

Type Ia SN 1998bu in M96

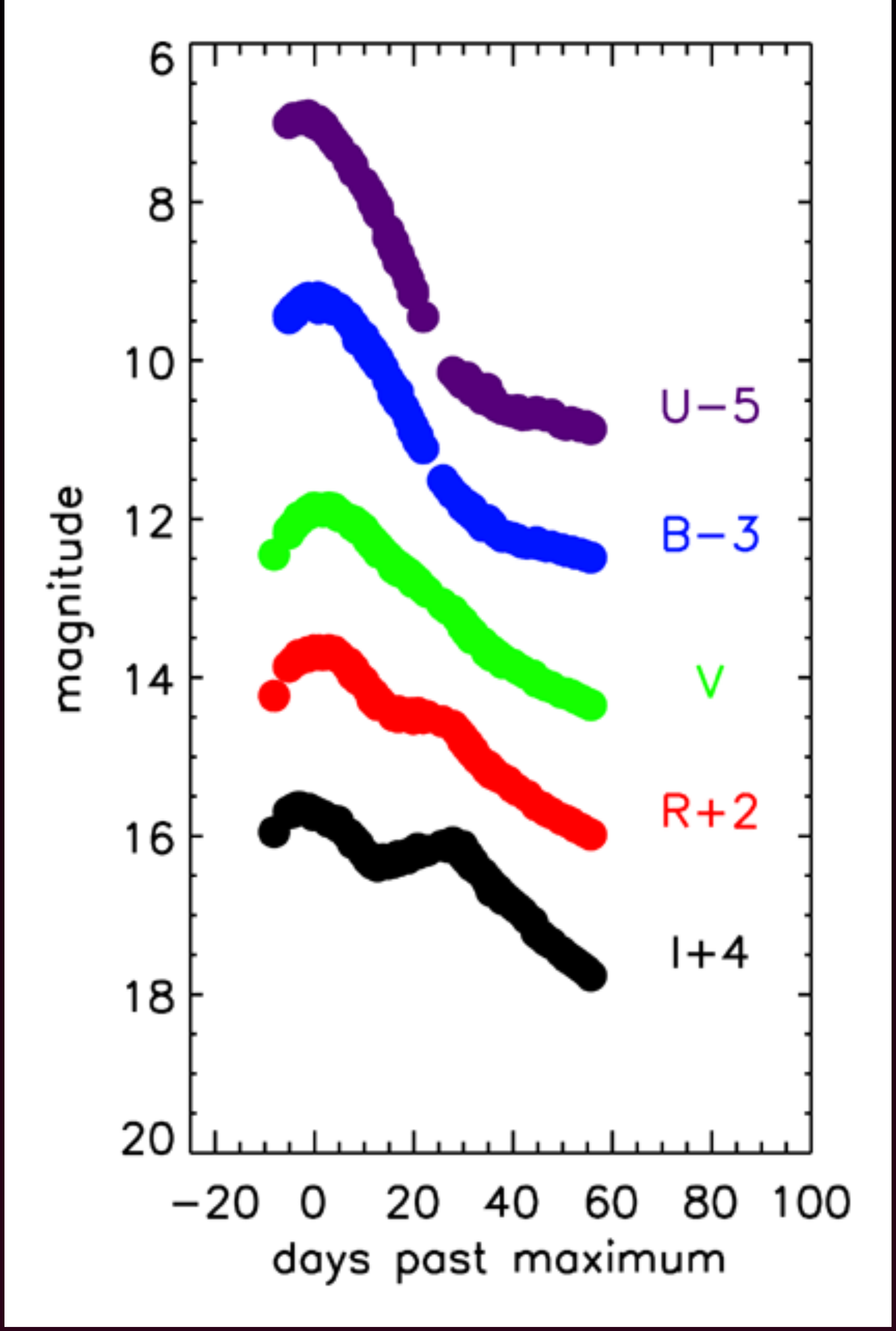
March 14, 1997

May 18, 1998

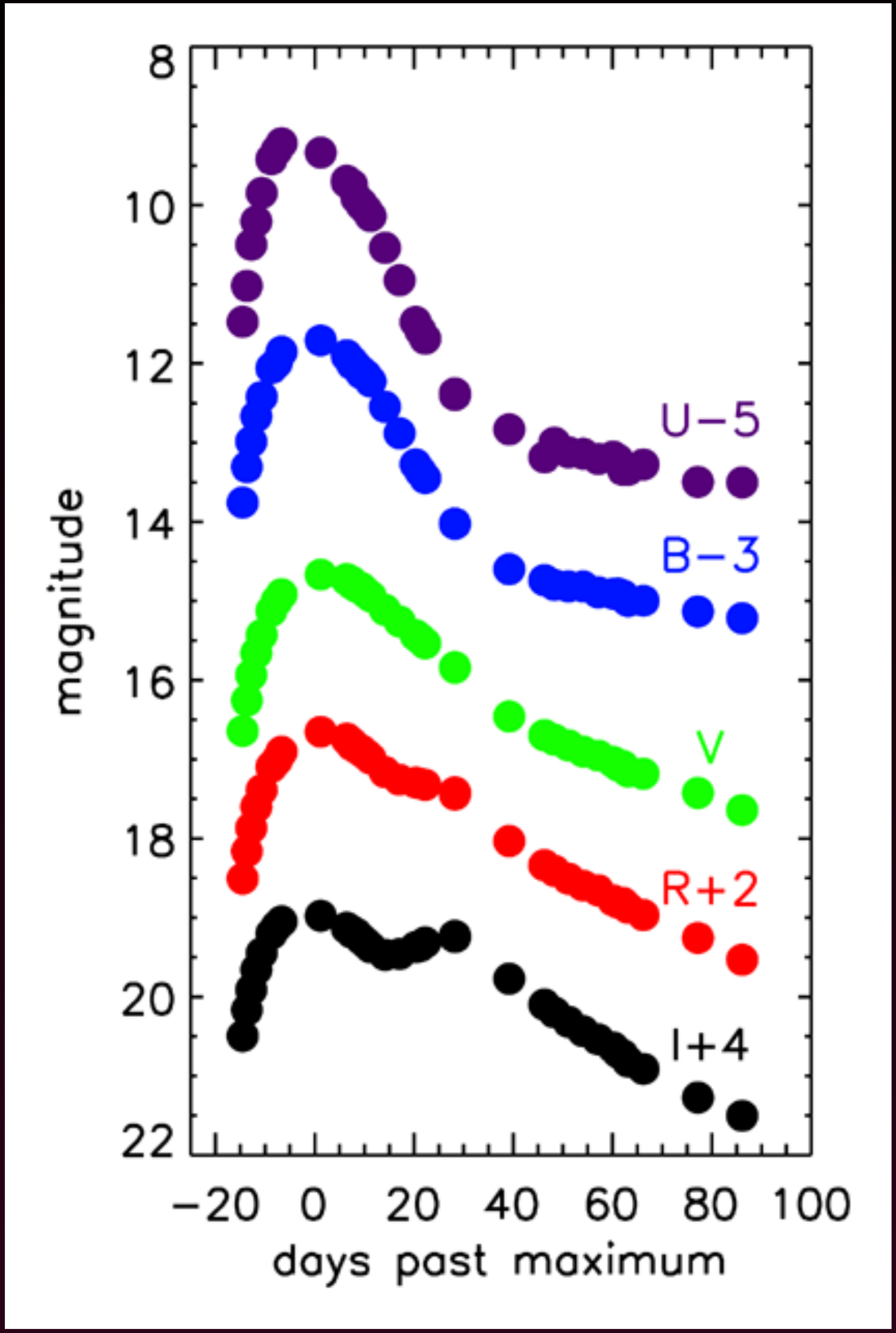
SN 1998bu maximum light spectrum



Some "Nearby" SN Ia Light Curves

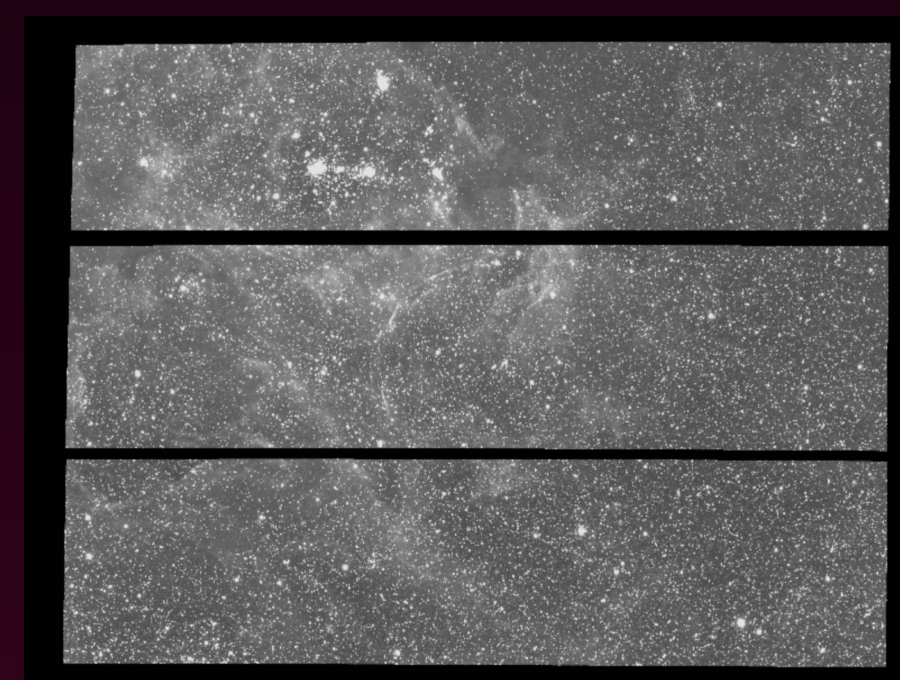


SN 1998bu in M 96



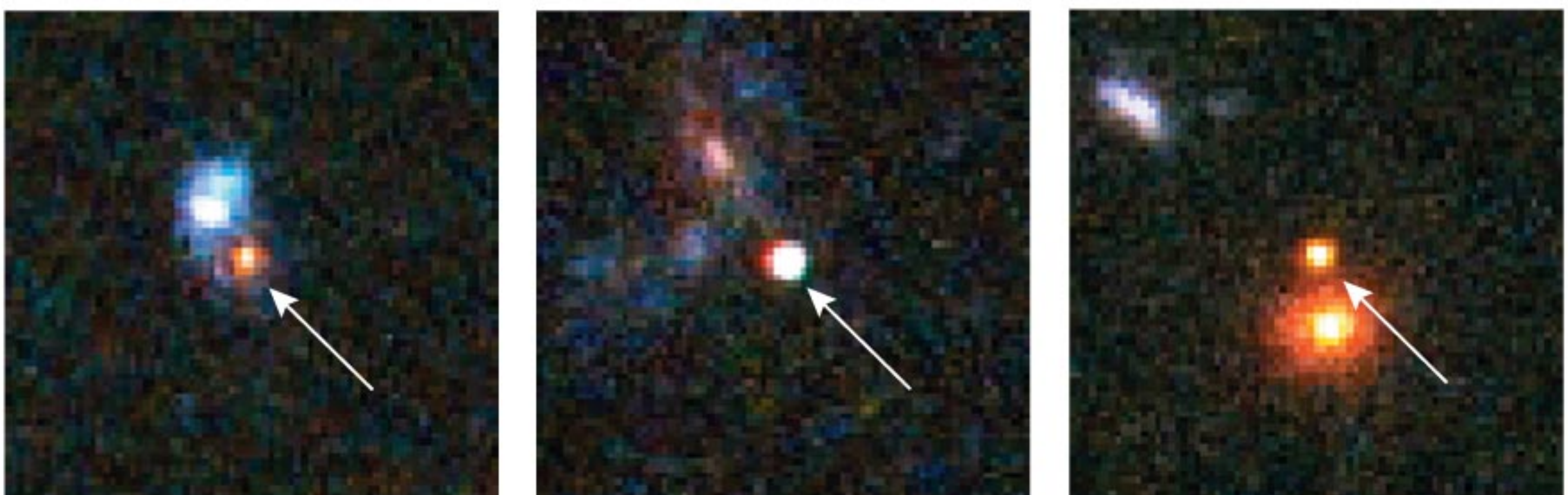
SN 2001V in NGC 3987

Finding Distant Supernovae

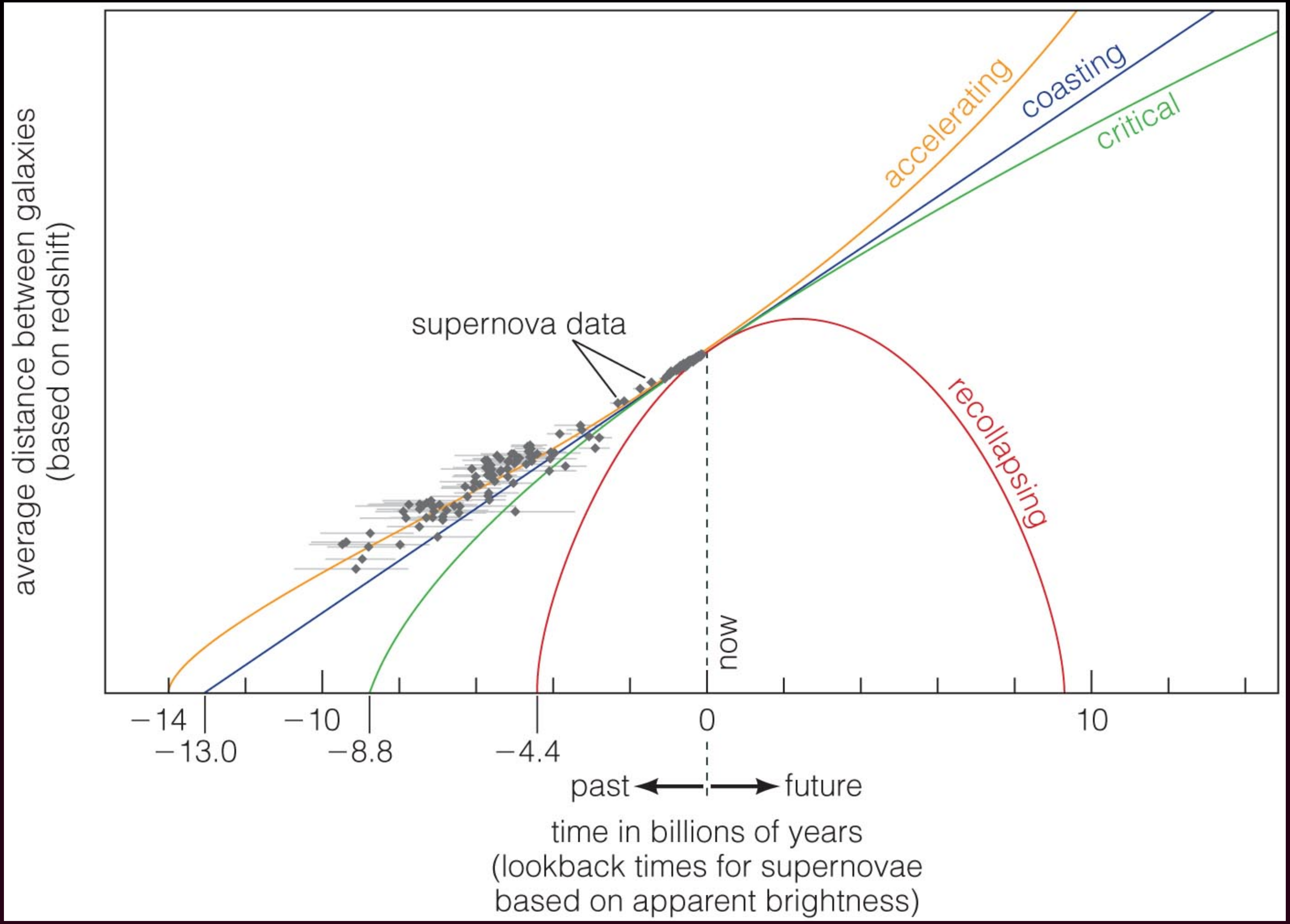


Distant galaxies before supernova explosions

The same galaxies after supernova explosions



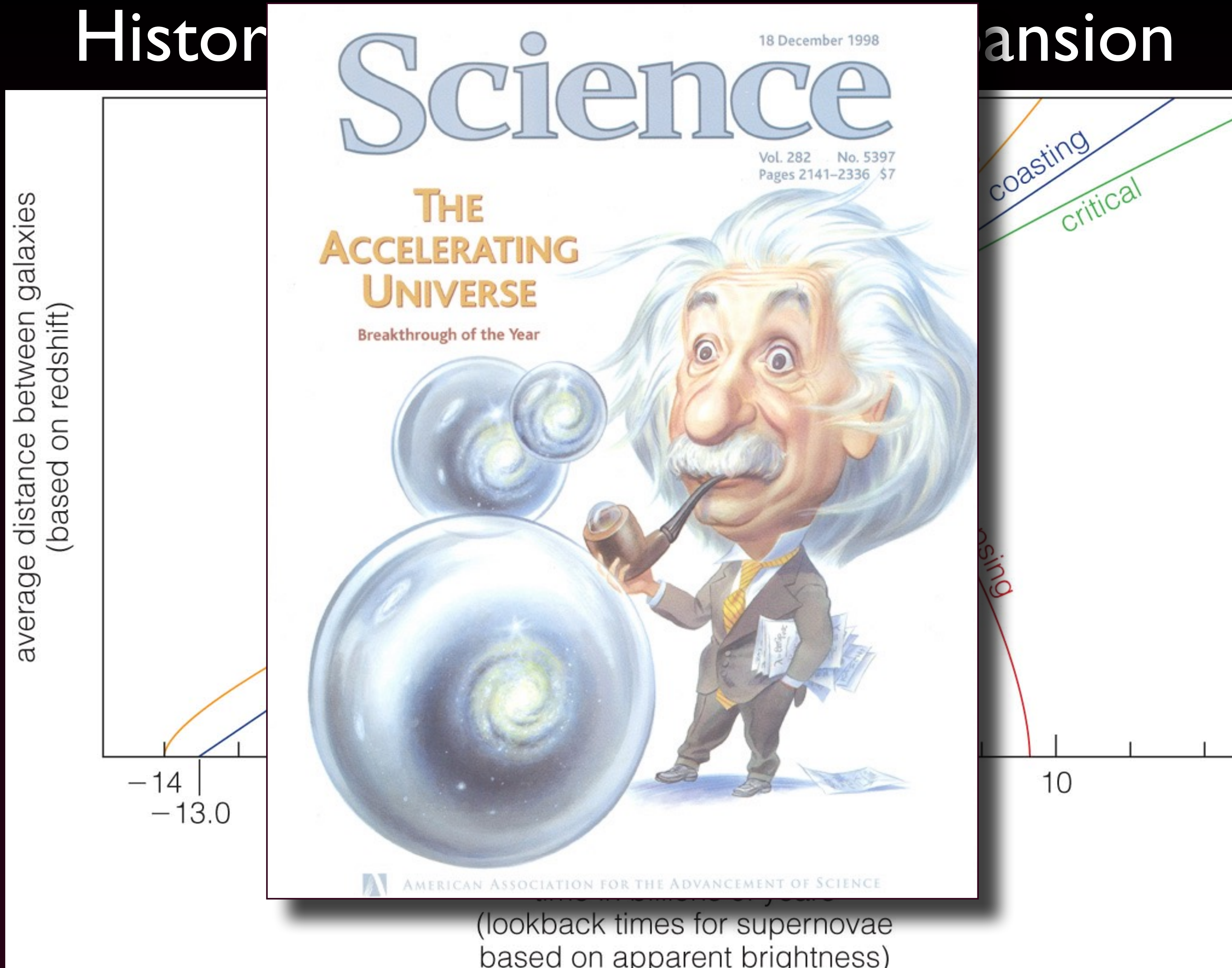
History and Future of the Expansion



High-Z SN Search Team
Riess et al. (1998)

Supernova Cosmology Project
Perlmutter et al. (1999)

Histor ansion



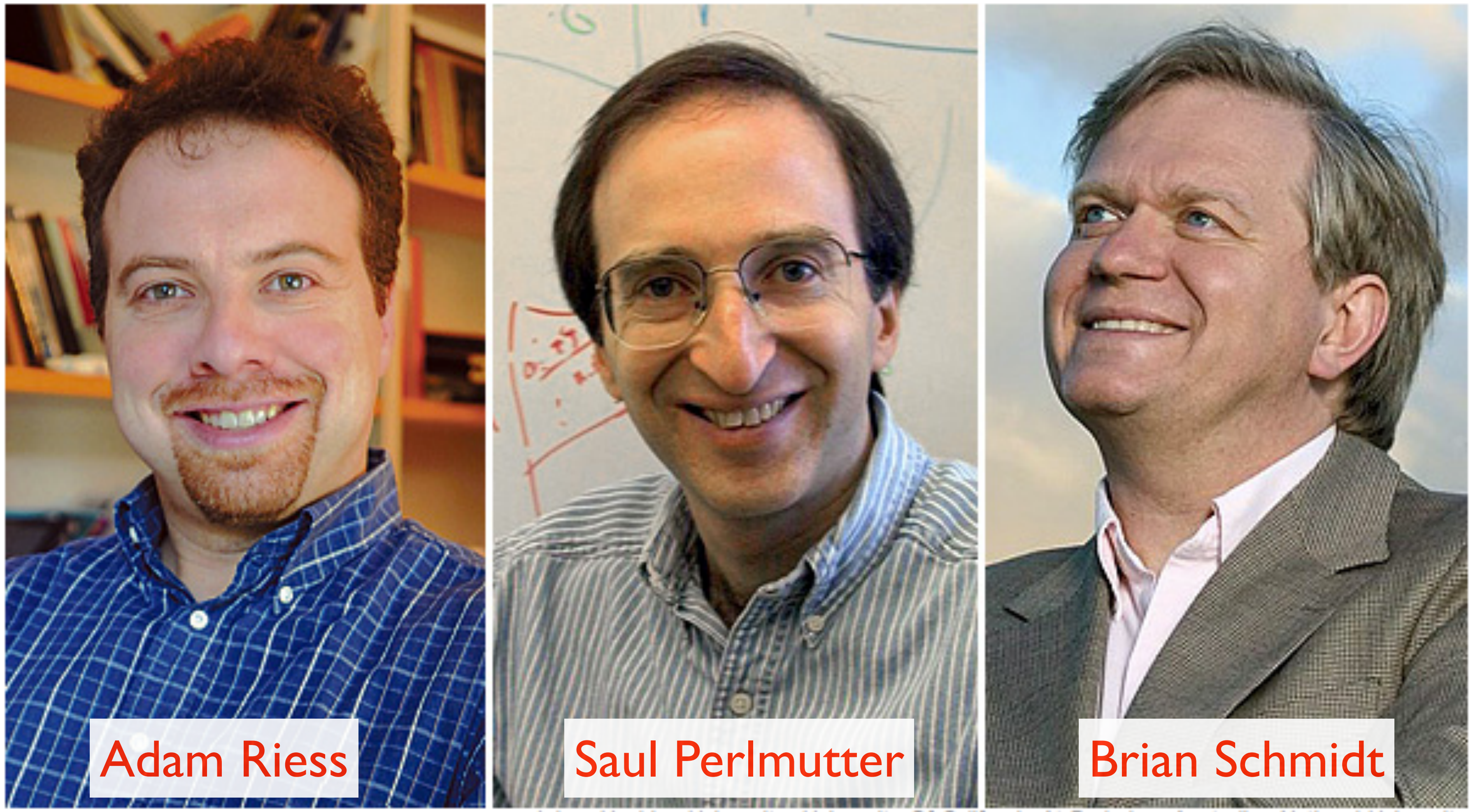
High-Z SN Search Team
Riess et al. (1998)

Supernova Cosmology Project
Perlmutter et al. (1999)

2011 Nobel Prize in Physics

from the New York Times

Studies of Universe's Expansion Win Physics Nobel



Johns Hopkins University; University Of California At Berkeley; Australian National University

From left, Adam Riess, Saul Perlmutter and Brian Schmidt shared the Nobel Prize in physics awarded Tuesday.

"for the discovery of the accelerating expansion of the Universe through observations of distant supernovae"

OBSERVATIONAL EVIDENCE FROM SUPERNOVAE FOR AN ACCELERATING UNIVERSE AND A COSMOLOGICAL CONSTANT

THE ASTRONOMICAL JOURNAL, 116:1009–1038, 1998 September

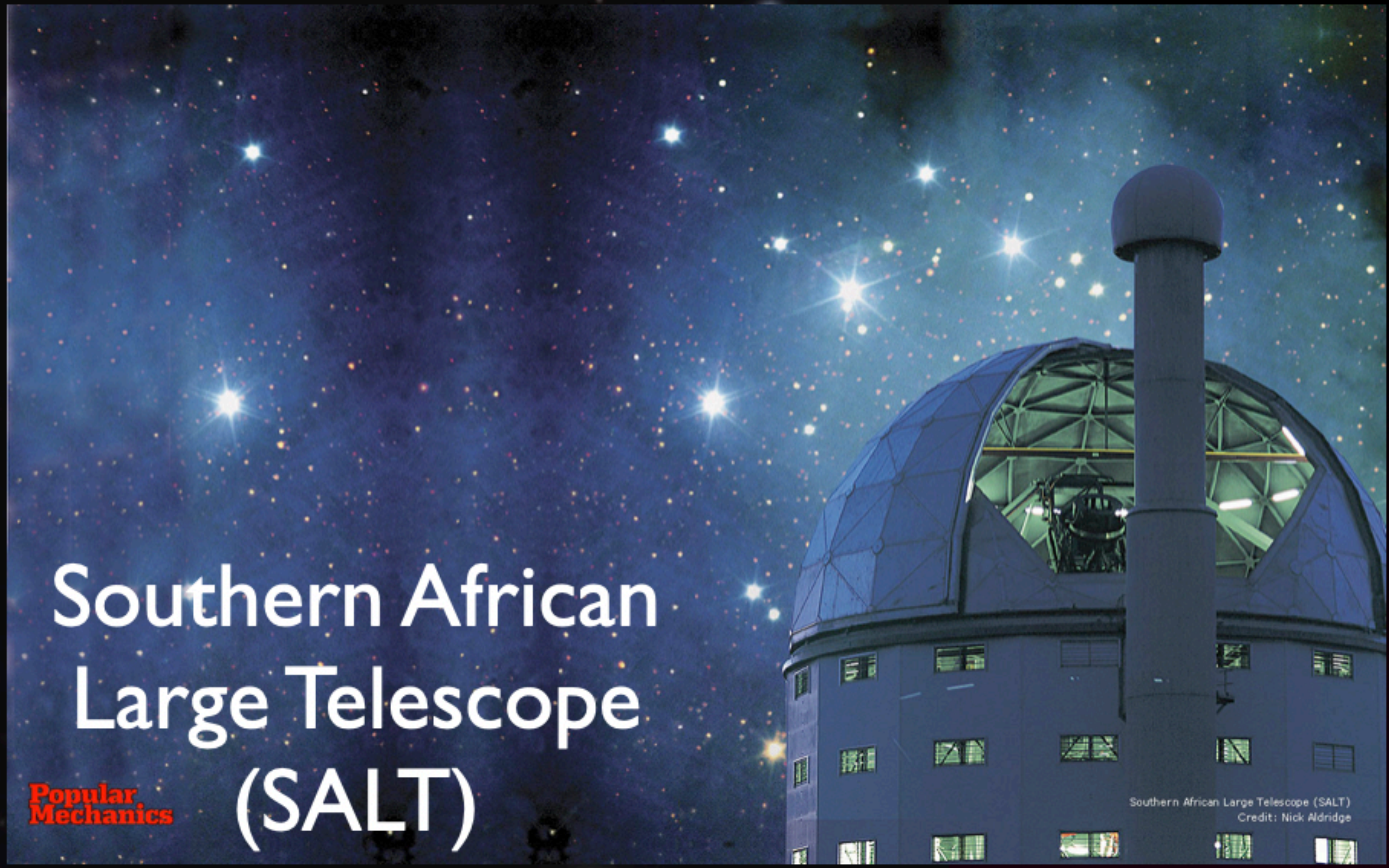
ADAM G. RIESS,[1] ALEXEI V. FILIPPENKO,[1] PETER CHALLIS,[2] ALEJANDRO CLOCCHIATTI,[3] ALAN DIERCKS,[4] PETER M. GARNAVICH,[2] RON L. GILLILAND,[5] CRAIG J. HOGAN,[4] SAURABH JHA,[2] ROBERT P. KIRSHNER,[2] B. LEIBUNDGUT,[6] M. M. PHILLIPS,[7] DAVID REISS,[4] BRIAN P. SCHMIDT,[8,9] ROBERT A. SCHOMMER,[7] R. CHRIS SMITH,[7,10] J. SPYROMILIO,[6] CHRISTOPHER STUBBS,[4] NICHOLAS B. SUNTZEFF,[7] AND JOHN TONRY[11]

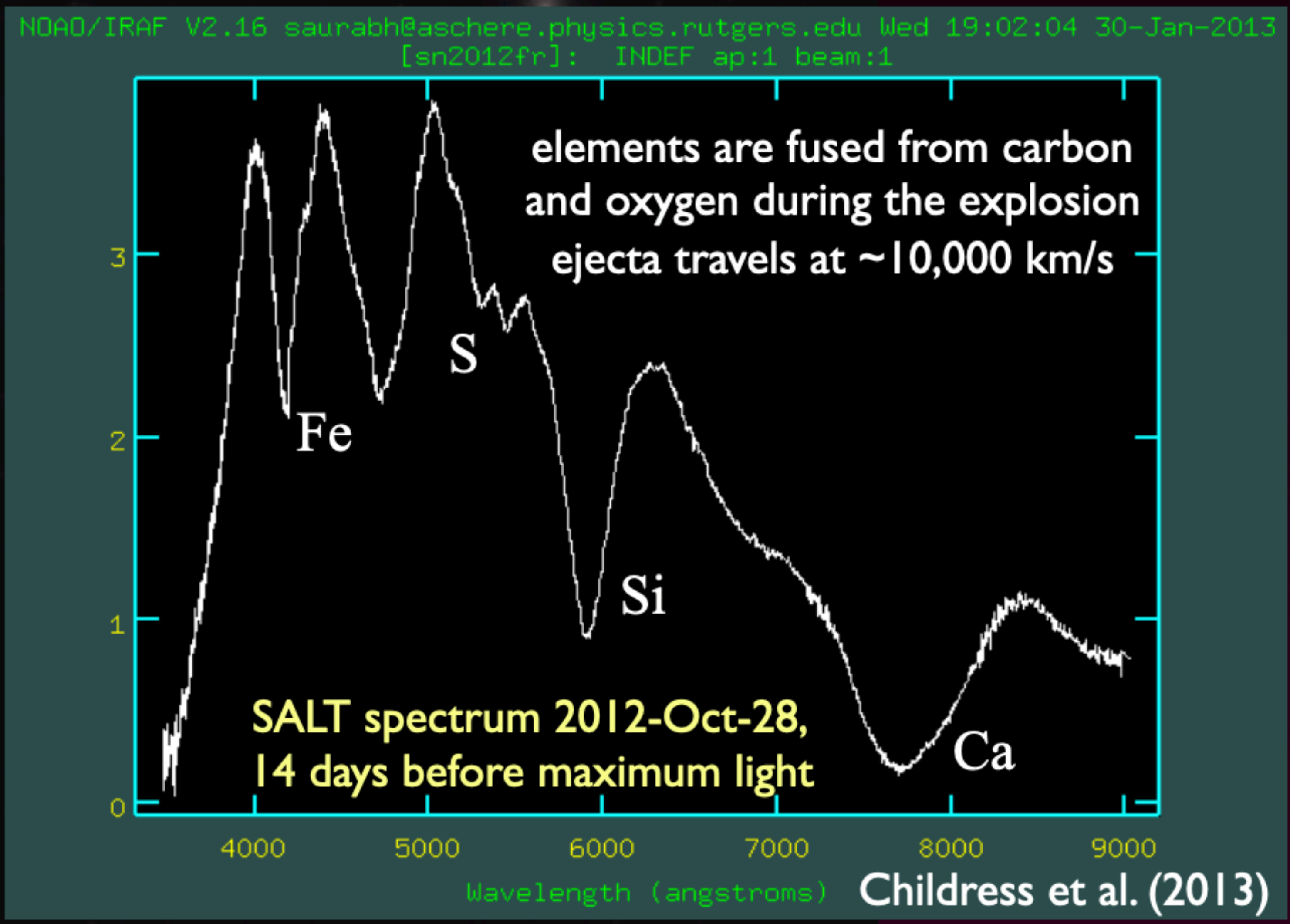
Received 1998 March 13; revised 1998 May 6


NOBELPRISE
The Nobel Prize
THE NOBEL BANQUET
THE CITY HALL
10 DECEMBER 2011

SALT observes Supernova 2012fr

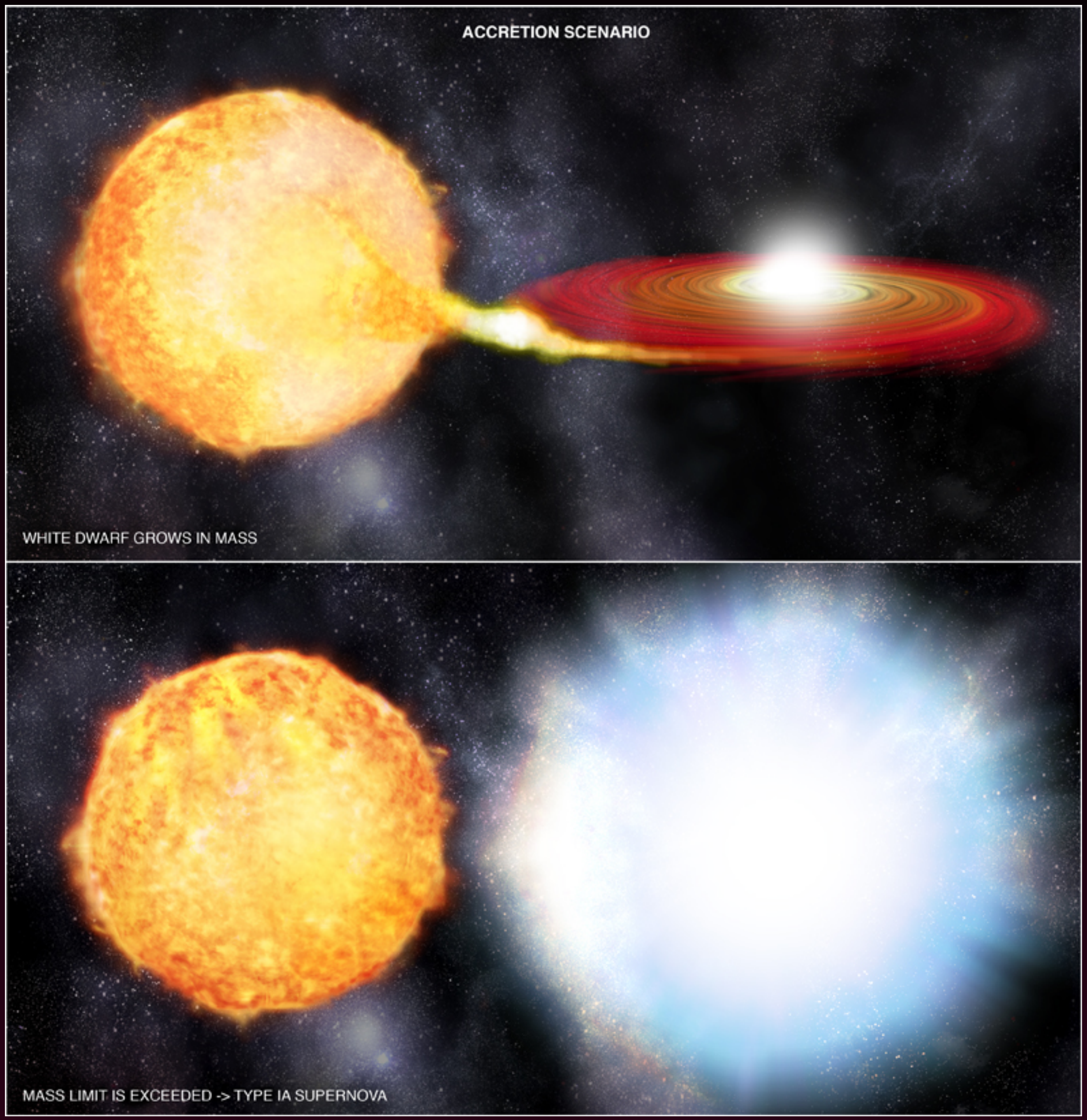
http://apod.nasa.gov/apod/ap121124.html

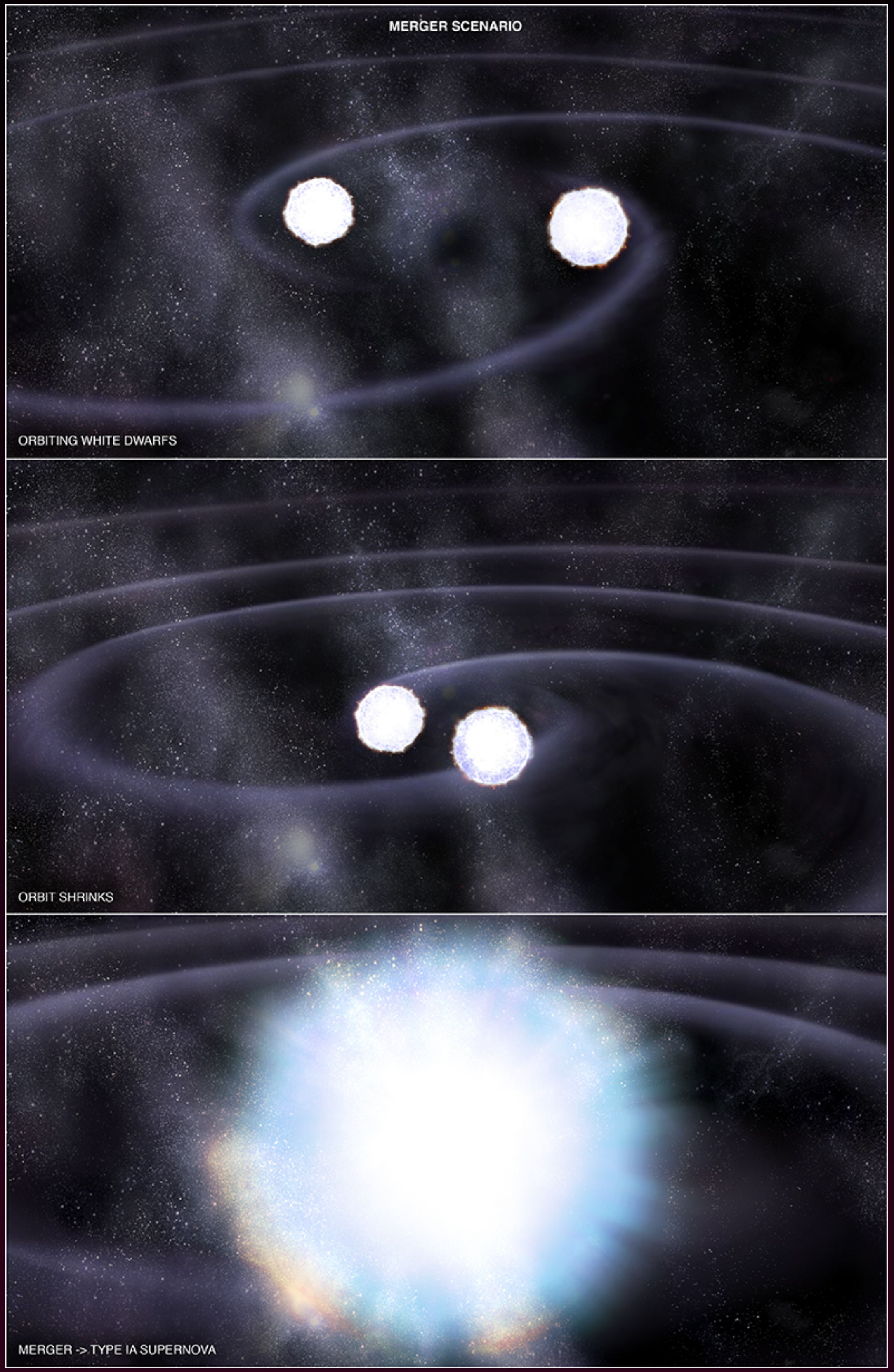




progenitors: single or double degenerate?

one white dwarf...   or two?

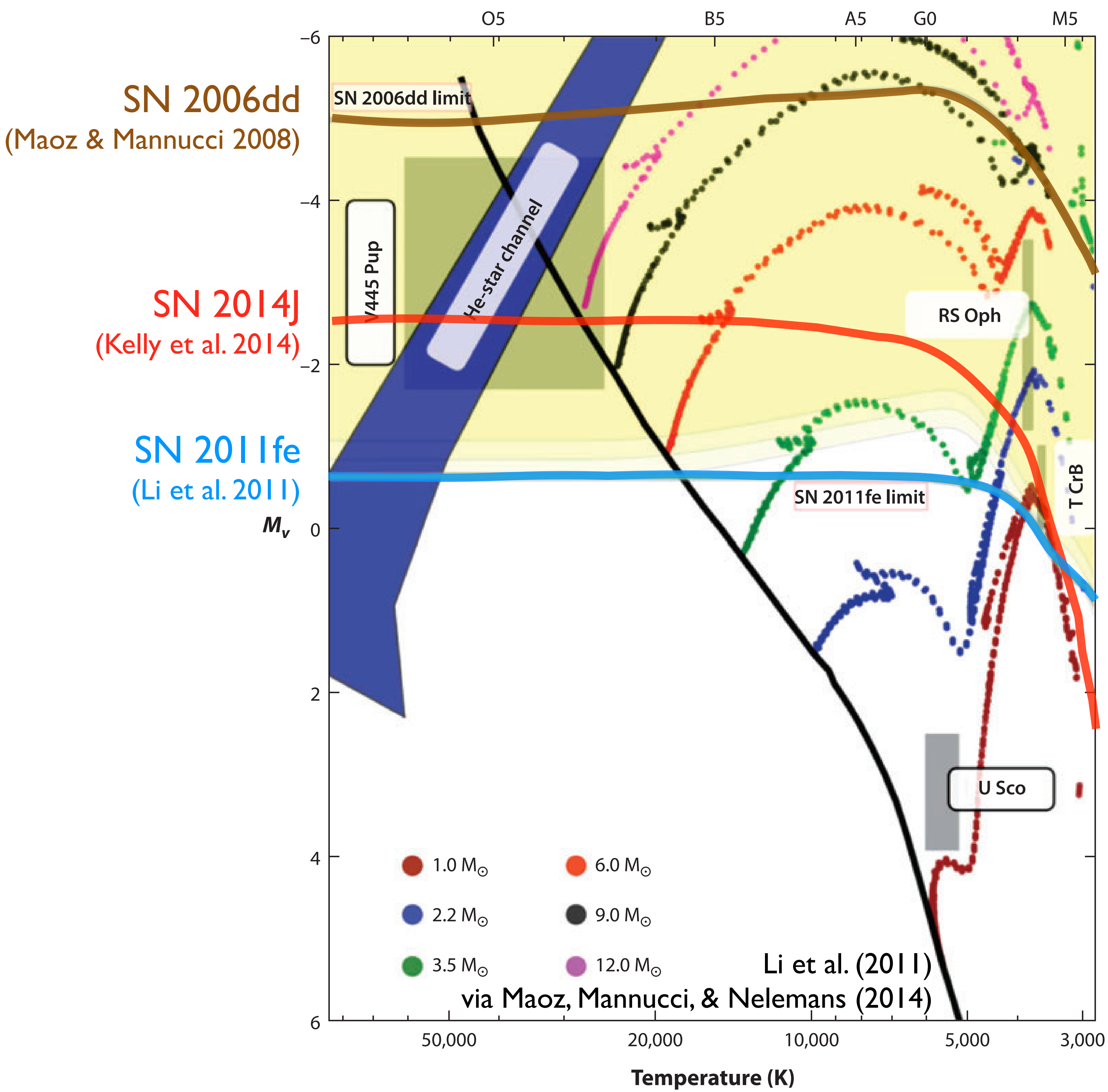


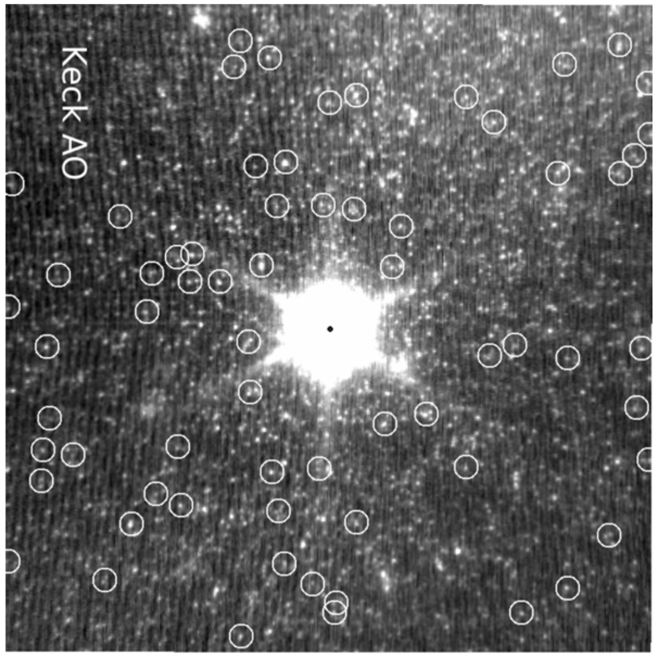


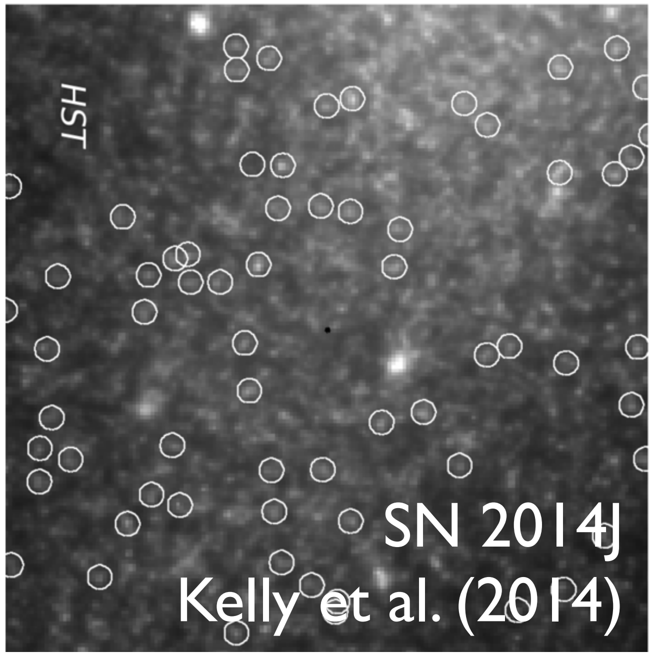
NASA/CXC/M.Weiss http://chandra.harvard.edu/photo/2010/typeIa/more.html

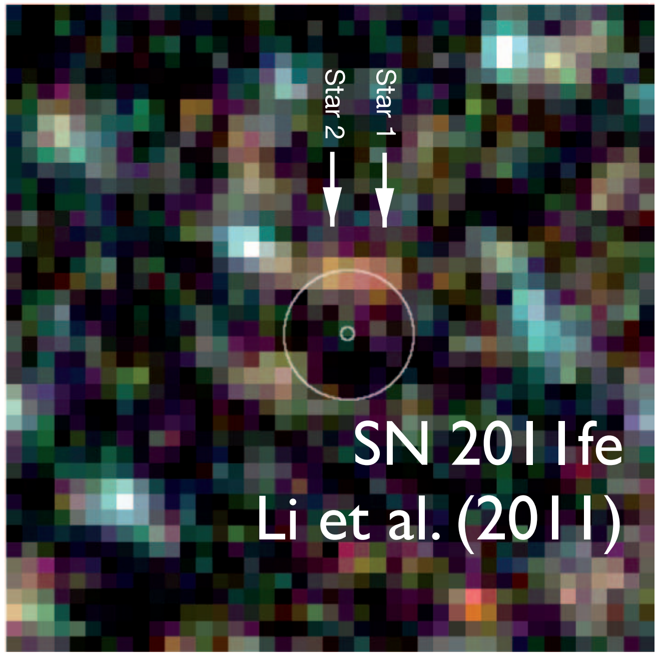
so far, no direct evidence found for companion star in SD scenario for normal SN Ia

pre-explosion limits for normal SN Ia







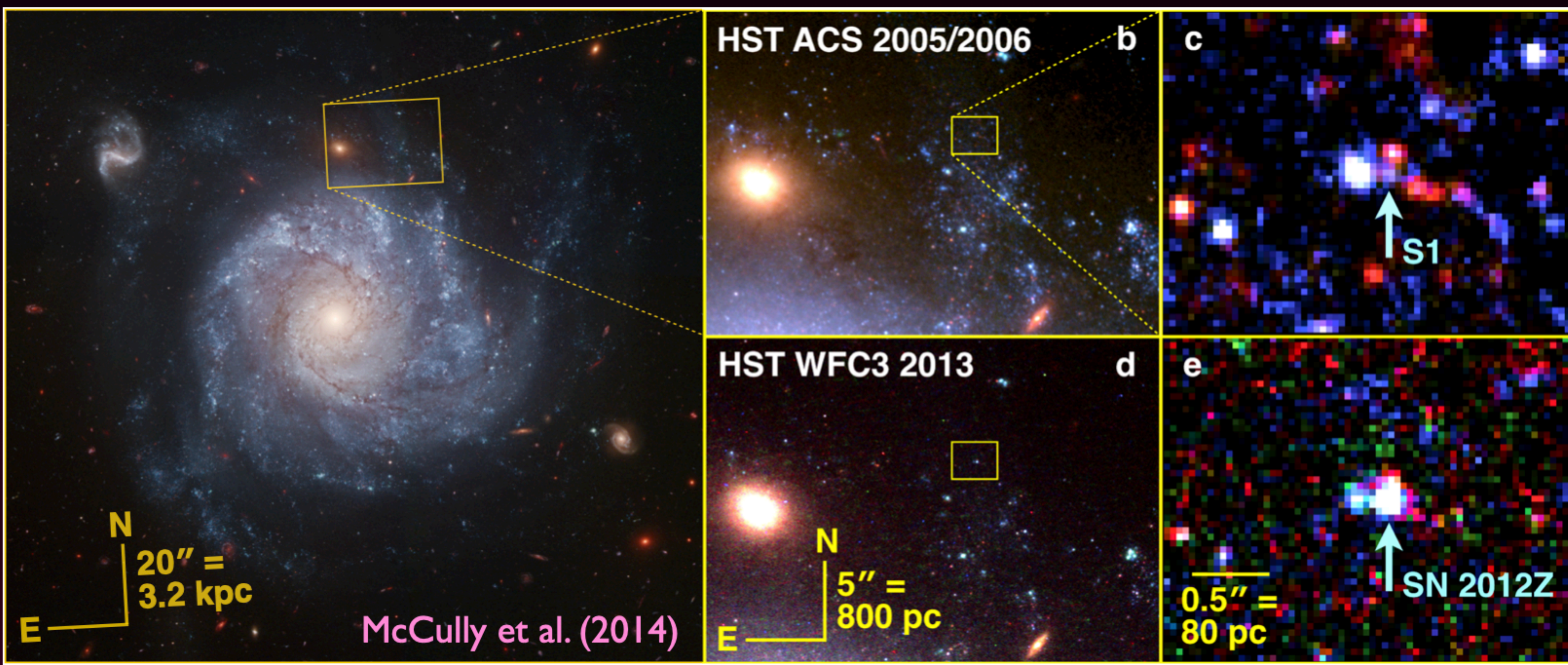


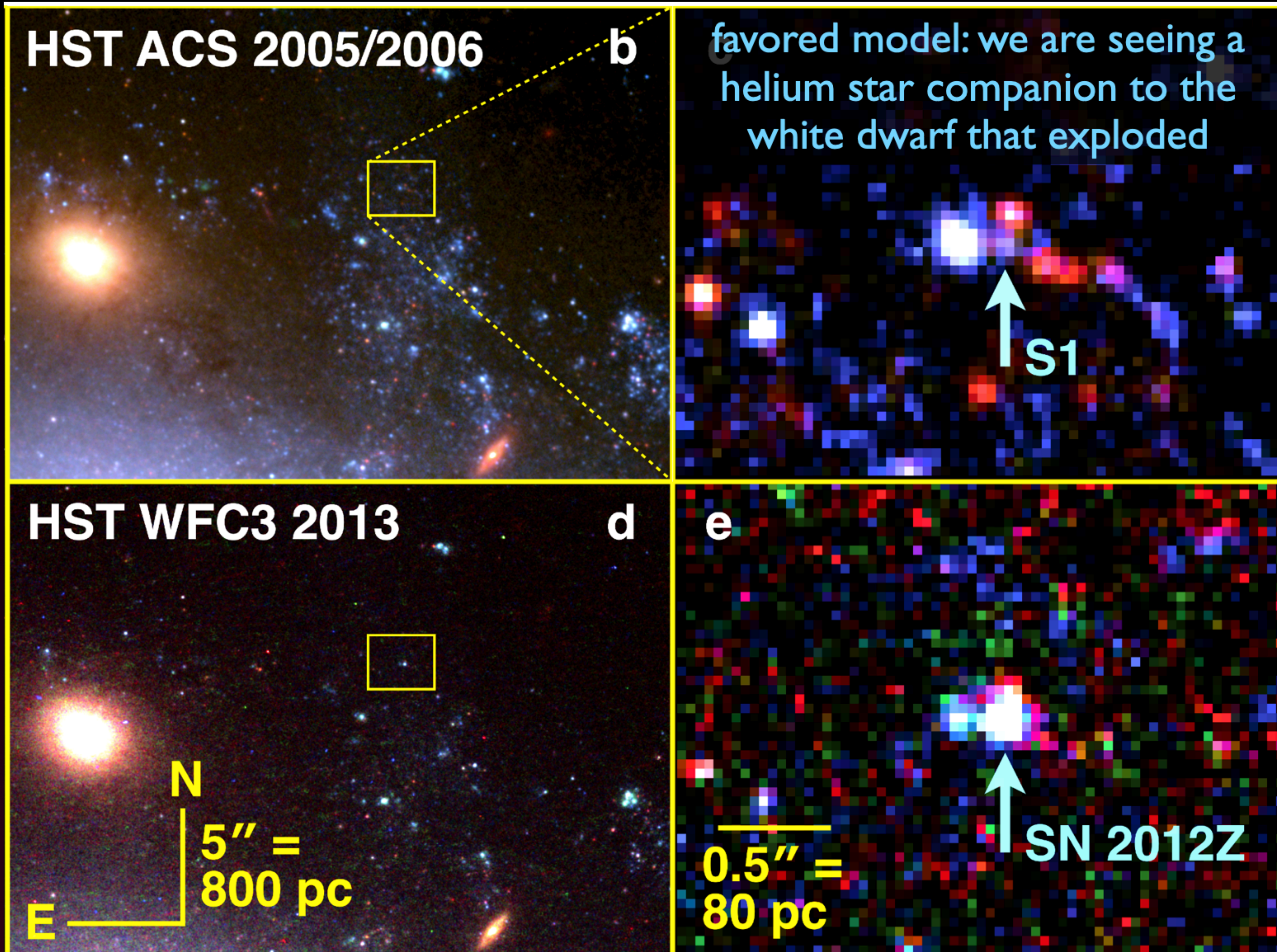
LETTER

doi:10.1038/nature13615

A luminous, blue progenitor system for the type Iax supernova 2012Z

Curtis McCully[1], Saurabh W. Jha[1], Ryan J. Foley[2,3], Lars Bildsten[4,5], Wen-fai Fong[6], Robert P. Kirshner[6], G. H. Marion[6,7], Adam G. Riess[8,9] & Maximilian D. Stritzinger[10]

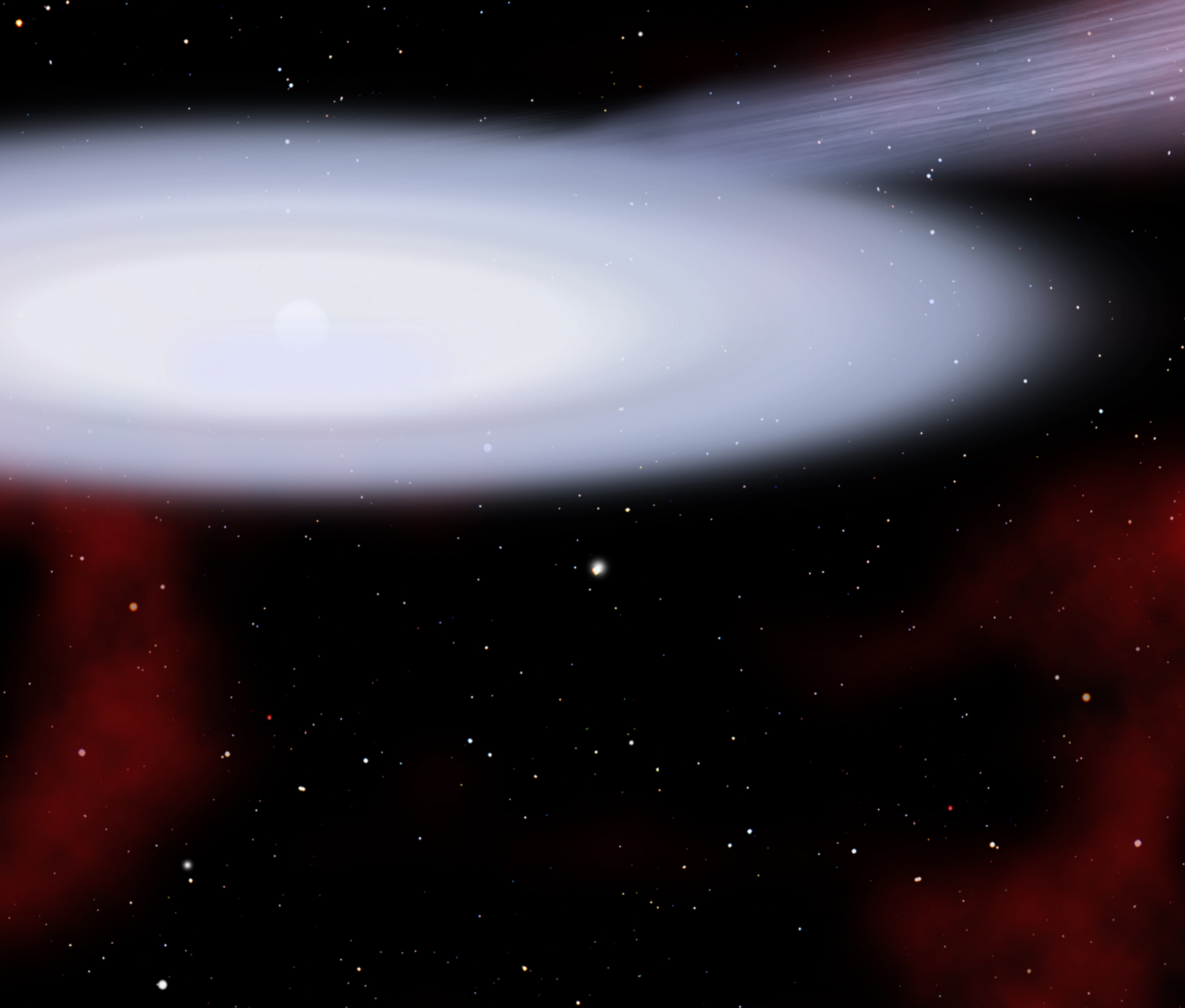




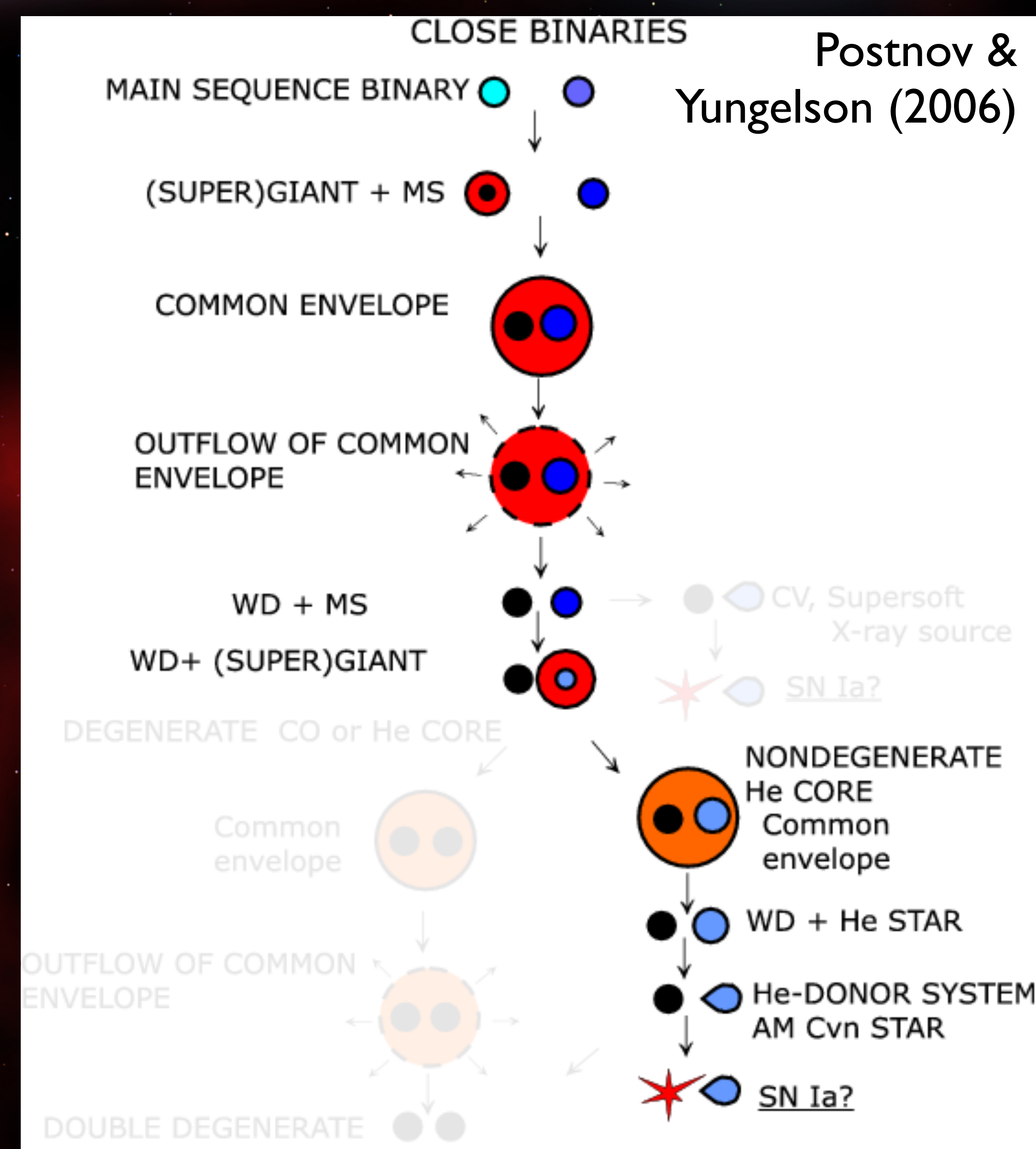
McCully et al. (2014)

C/O white dwarf + helium star model

- e.g., binary evolution model of Liu et al. (2010)
  7 M_{Sun} + 4 M_{Sun} close binary →
  1 M_{Sun} C/O WD + 2 M_{Sun} He star



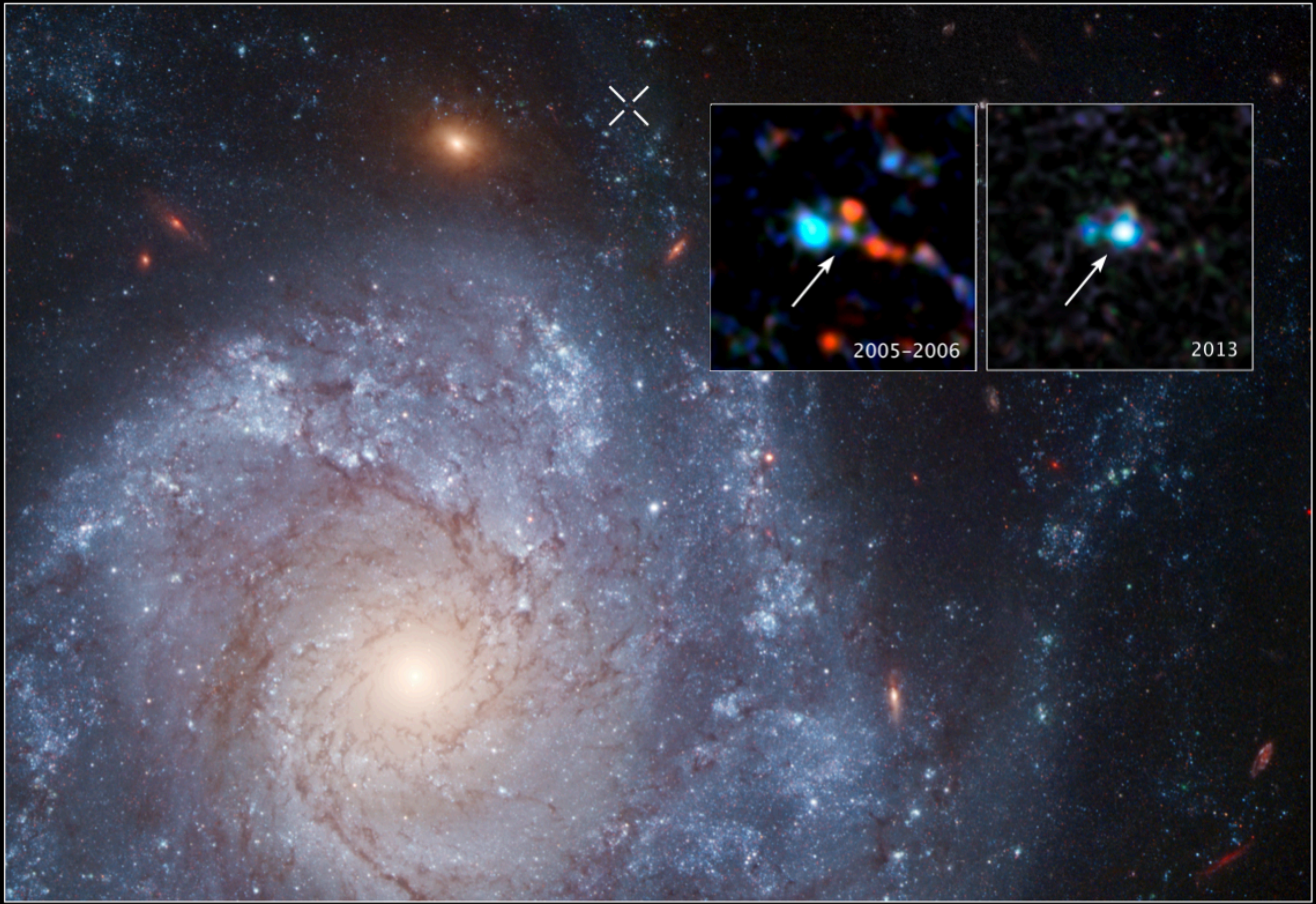
artist's conception by Christine Pulliam (CfA)



Postnov & Yungelson (2006)

Hubble sees 'zombie star' lurking in space: What it is, why it matters

http://www.latimes.com/science/sciencenow/la-sci-sn-nasa-hubble-zombie-star-20140806-story.html



Supernova 2012Z in Spiral Galaxy NGC 1309
Hubble Space Telescope ▪ ACS ▪ WFC3

NASA and ESA

STScI-PRC14-32a