The binary companion to the progenitor of iPTF13bvn

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Waseda University

Workshop on "The Progenitor-Supernova-Remnant Connection"
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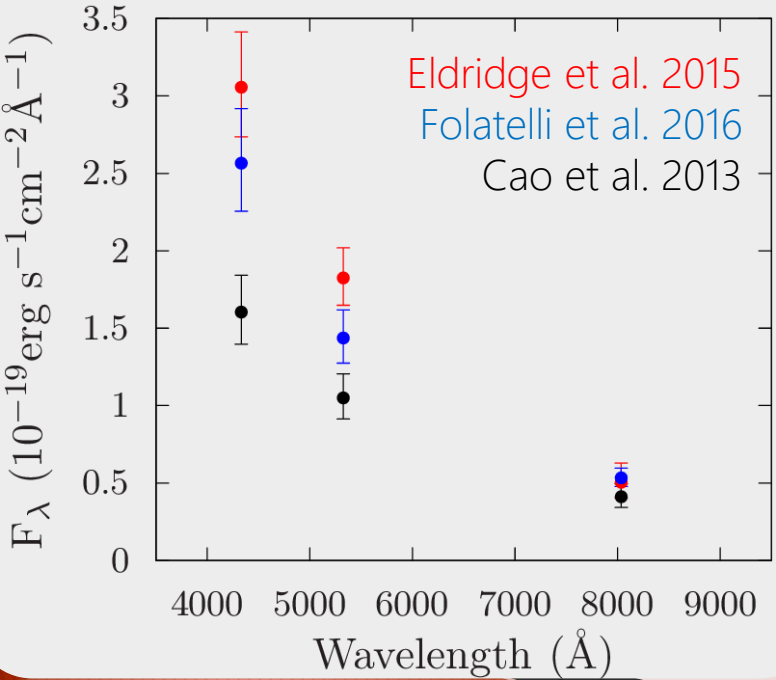
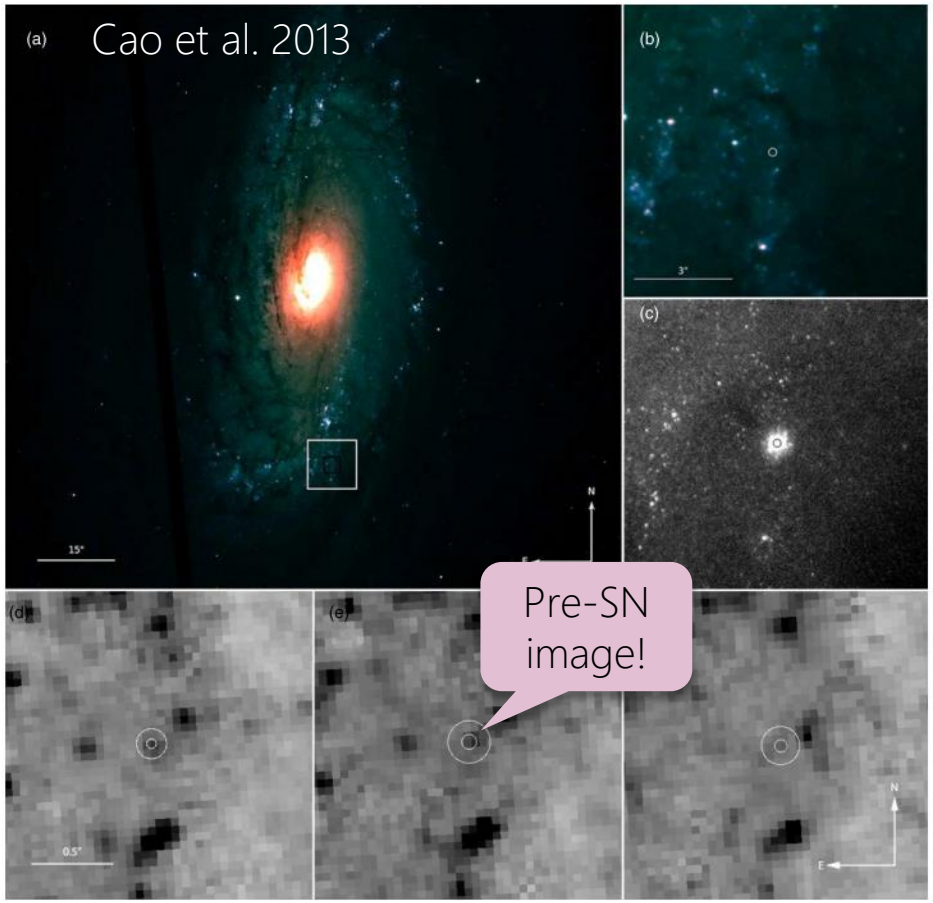
About iPTF13bvn

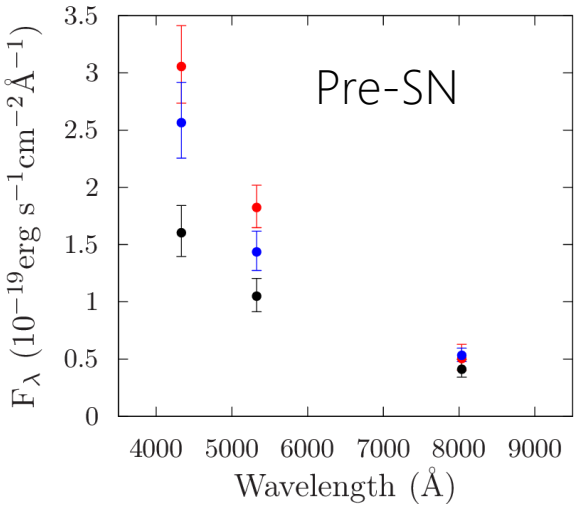
- Discovered by the Intermediate Palomar Transient Factory
- The ONLY SNIb with Pre-SN image taken by HST

Discovery	16/6/2013
Galaxy	NGC 5806
SN type	Ib

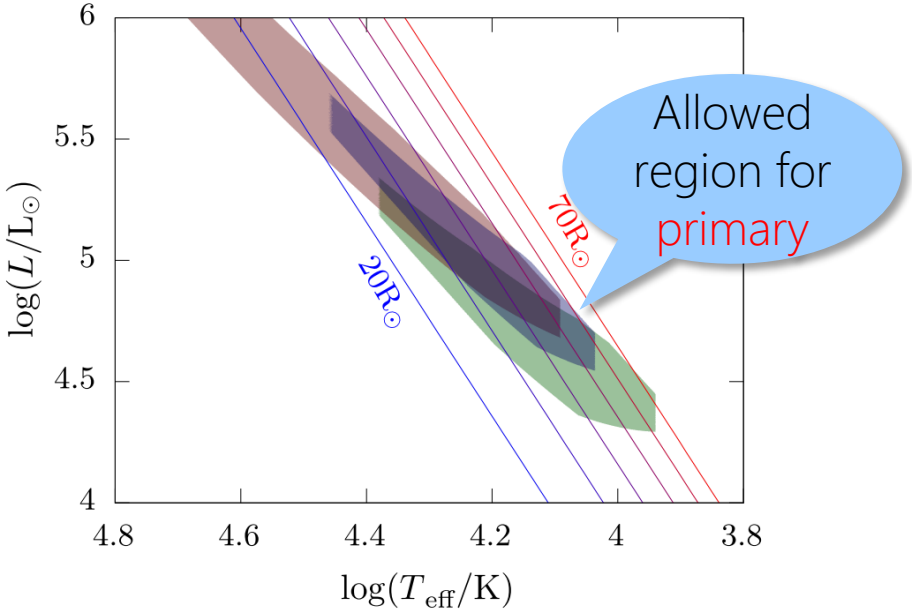


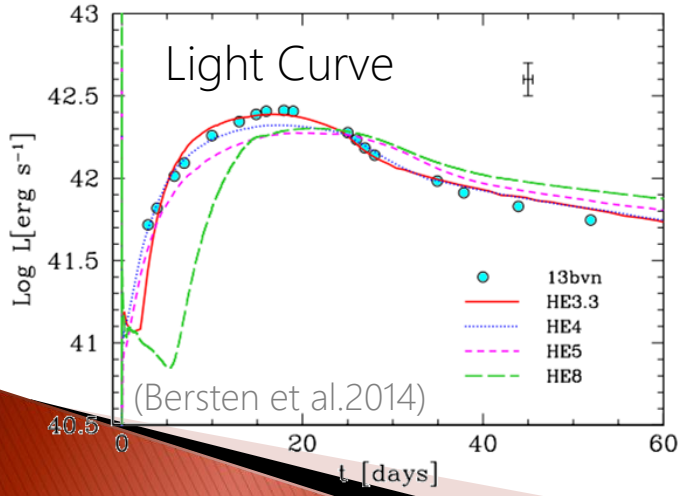


Constraints on the Progenitor



+extinction, distance uncertainty





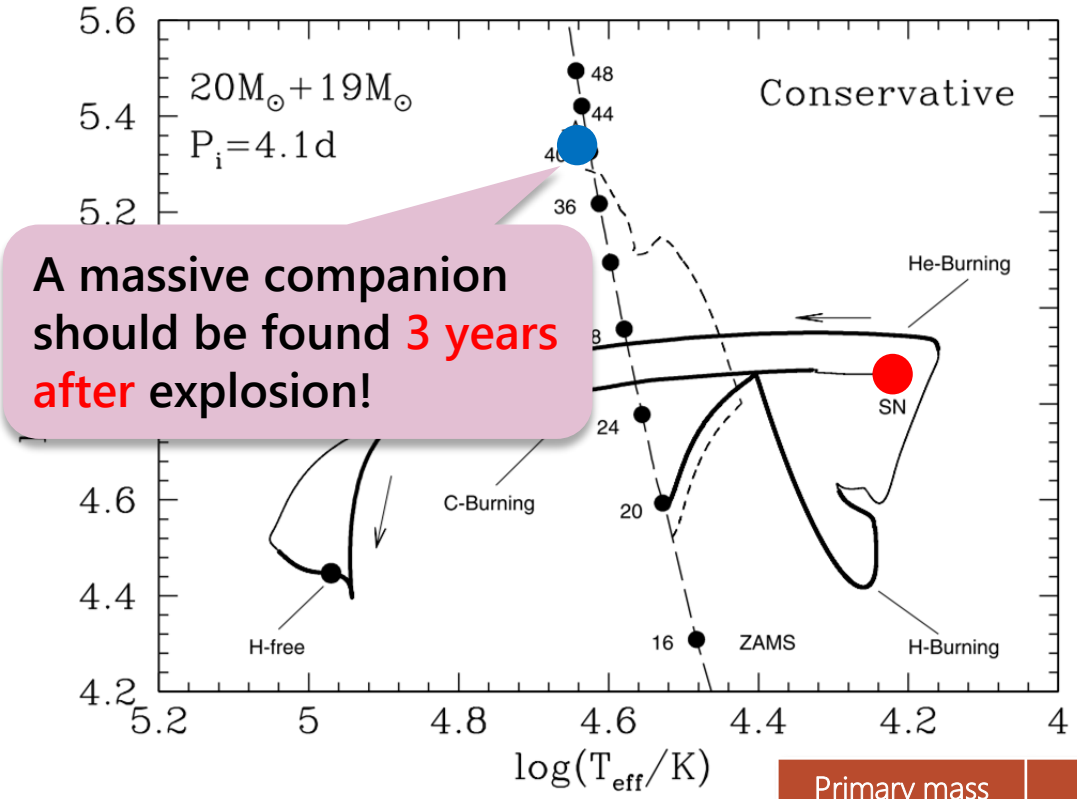
$$M_{ej} \sim 1.9 M_\odot$$
$$\Rightarrow M_{prog} \sim 3.5 M_\odot$$

Progenitor should have been ≃3.5M$_\odot$ He star !

How was the progenitor formed?

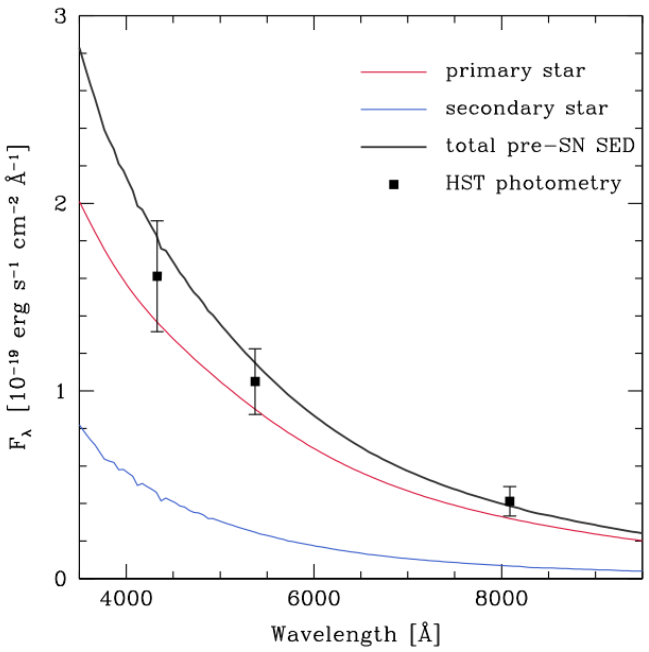
Previous Works

Binary interaction necessary to produce a $\simeq 3.5M_{\odot}$ He star (Wolf Rayet models $\gtrsim 8M_{\odot}$)



A massive companion should be found 3 years after explosion!

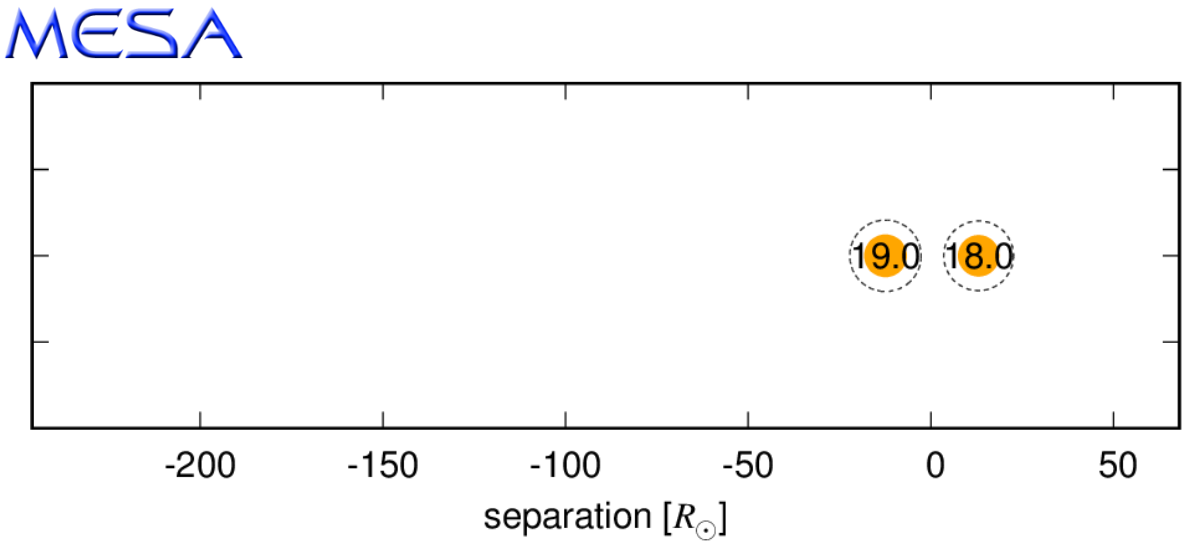
Bersten et al.2014



Primary mass [$M_{\odot}$]	Mass ratio	Final companion mass [$M_{\odot}$]
$15 \lesssim M_1^i \lesssim 25$	$0.8 \lesssim M_2^i/M_1^i \lesssim 0.95$	$23 \lesssim M_2^f \lesssim 45\ (\beta = 1)$ $18 \lesssim M_2^f \lesssim 45\ (\beta = 0.5)$

Ejecta-Companion interaction

- How does the companion look if it is heated by the ejecta? (Hirai et al. 2015)



	initial	Final
M_1	19 $M_\odot$ ⇒	3.5 $M_\odot$
M_2	18 $M_\odot$ ⇒	33.5 $M_\odot$
Period	2.45 d ⇒	61.7 d

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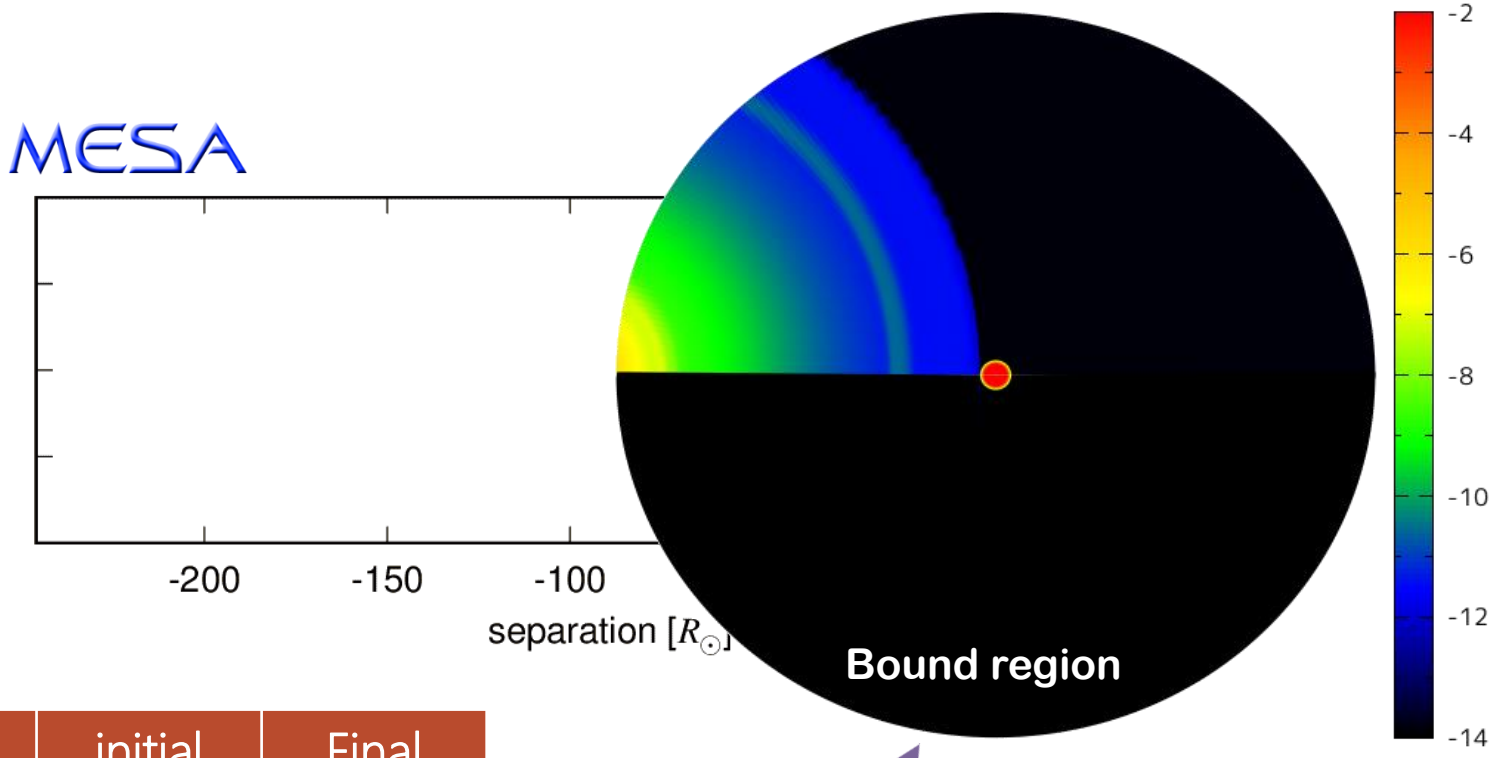

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Input the progenitor into a hydrodynamic simulation code

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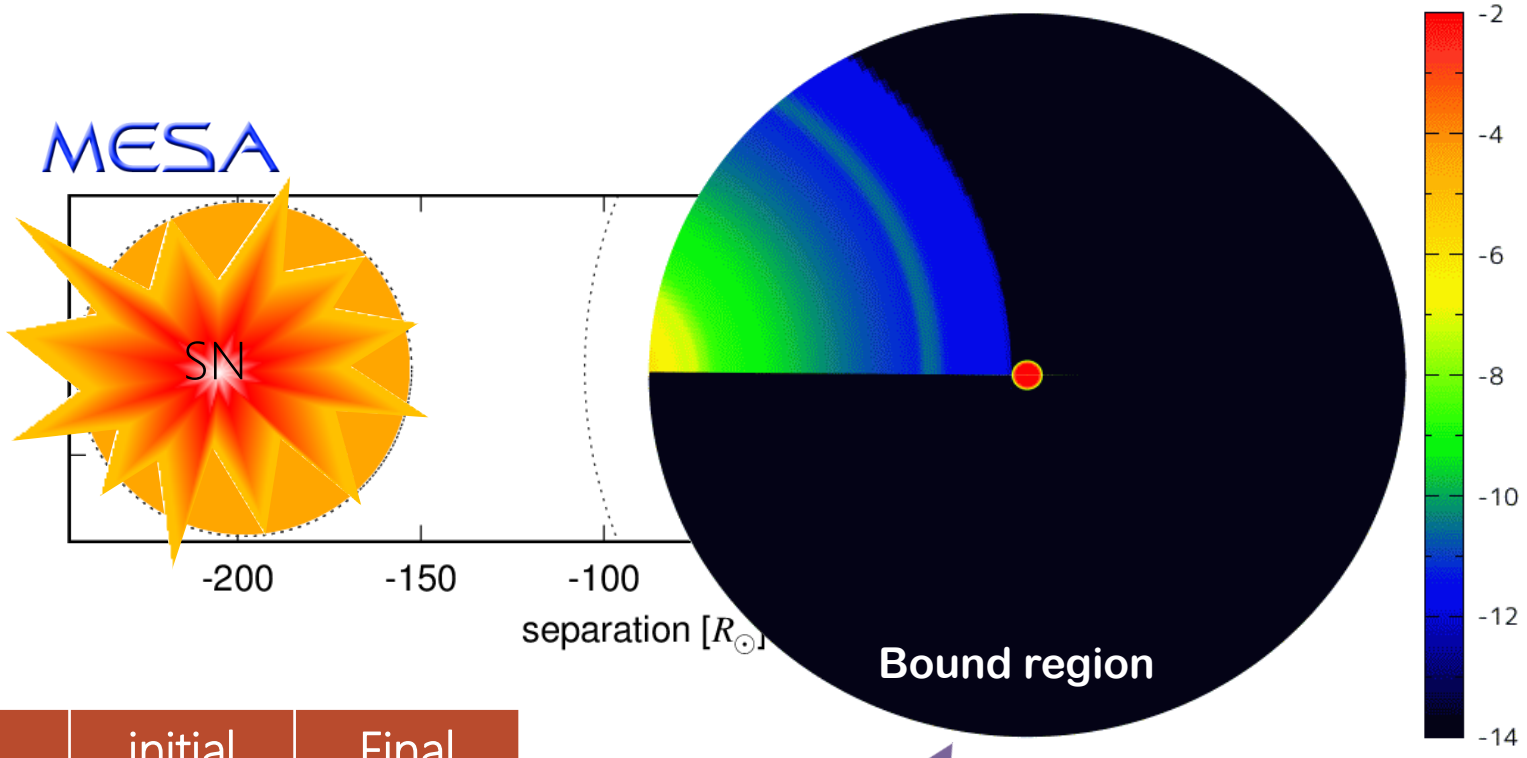

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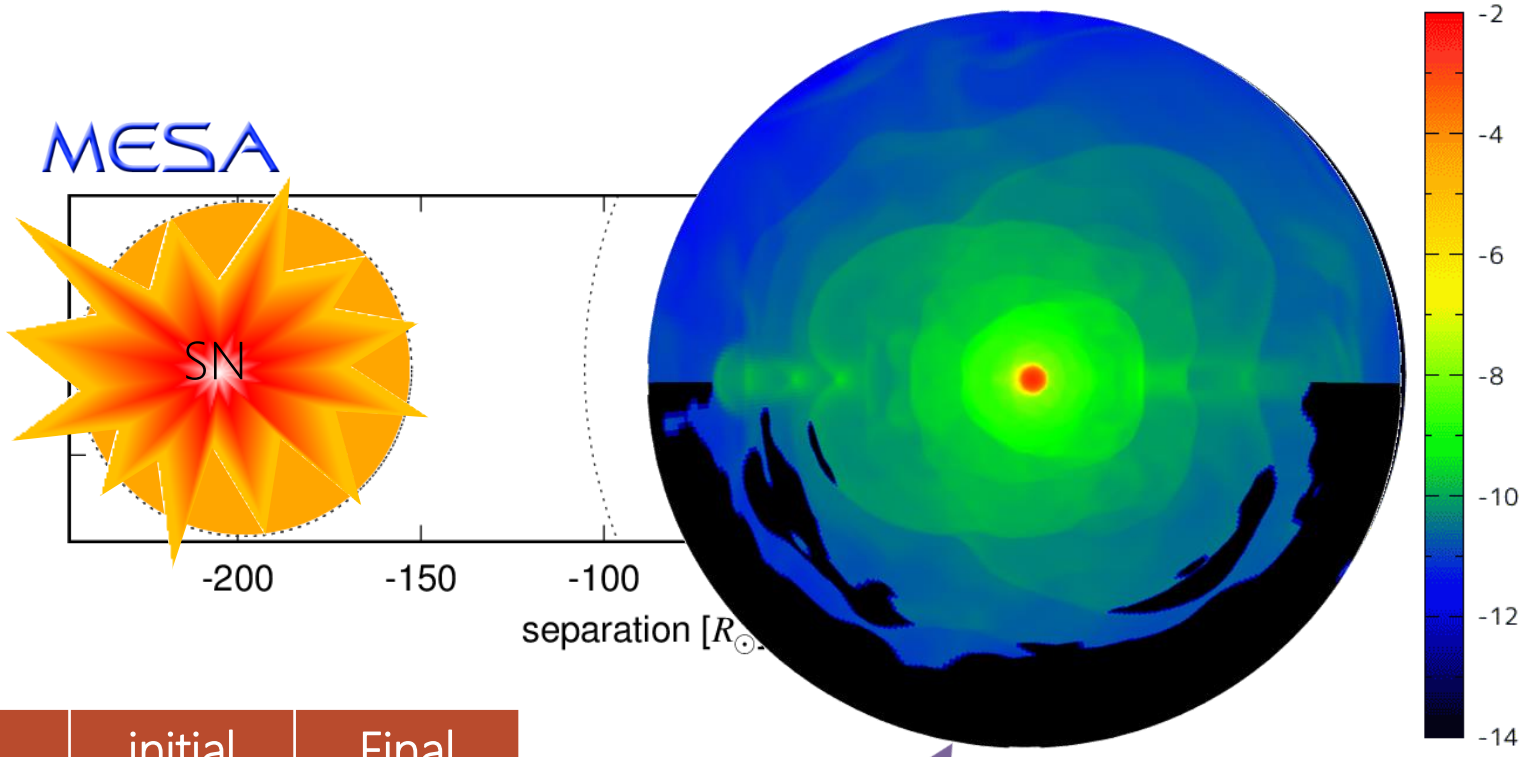

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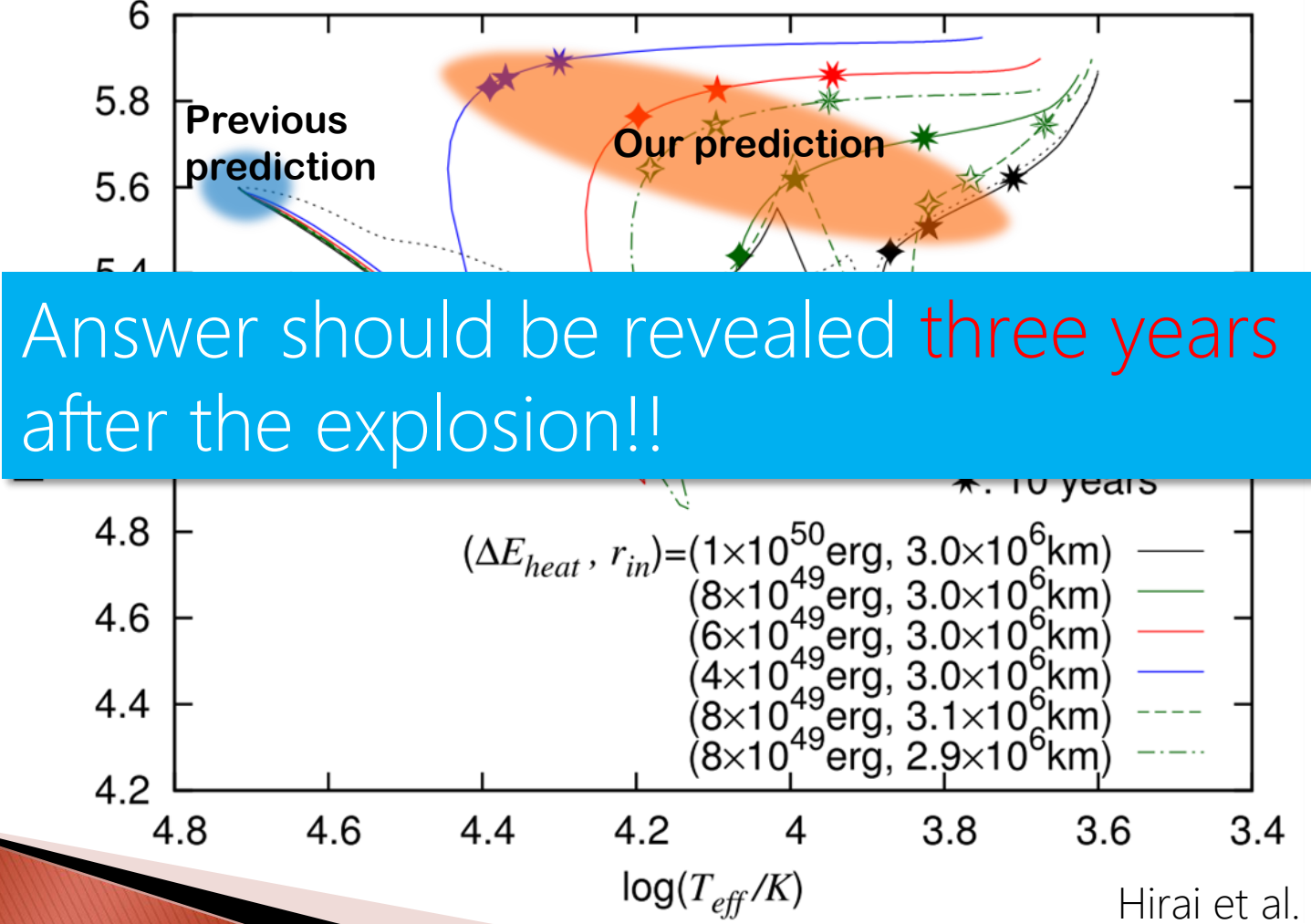
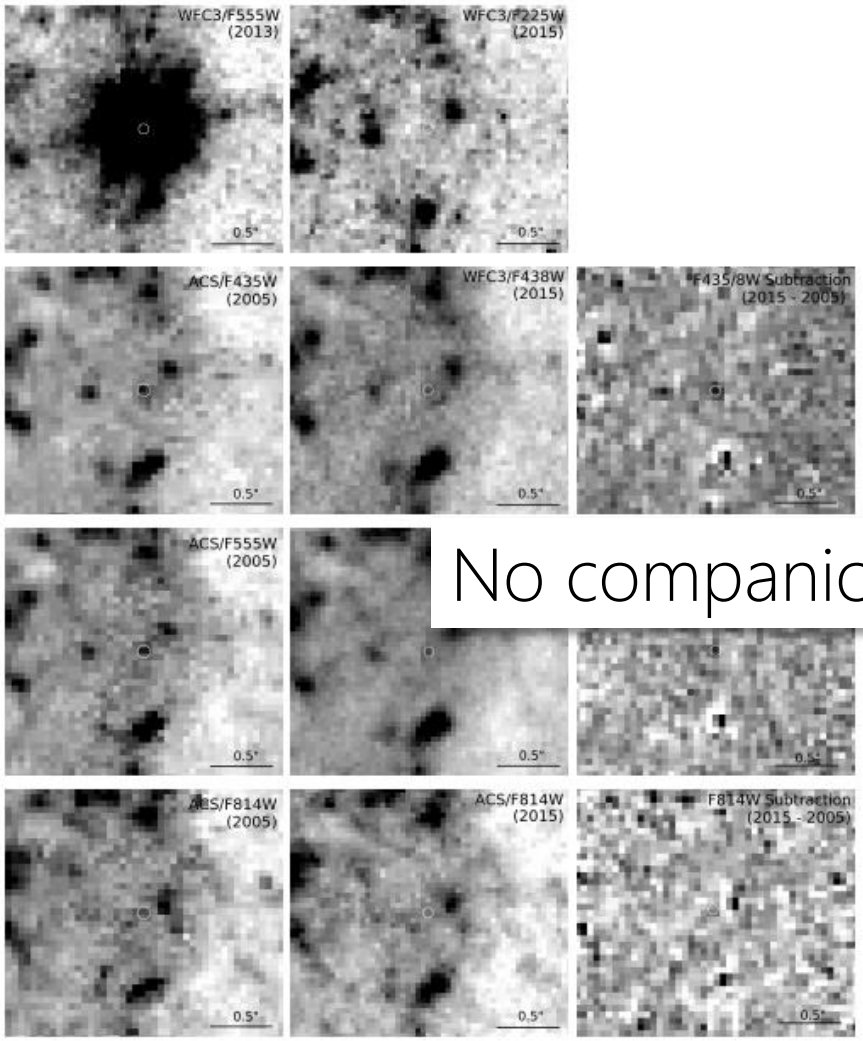
Ejecta-Companion interaction

- The companion expands by the heat, and may change its appearance (temperature, luminosity)

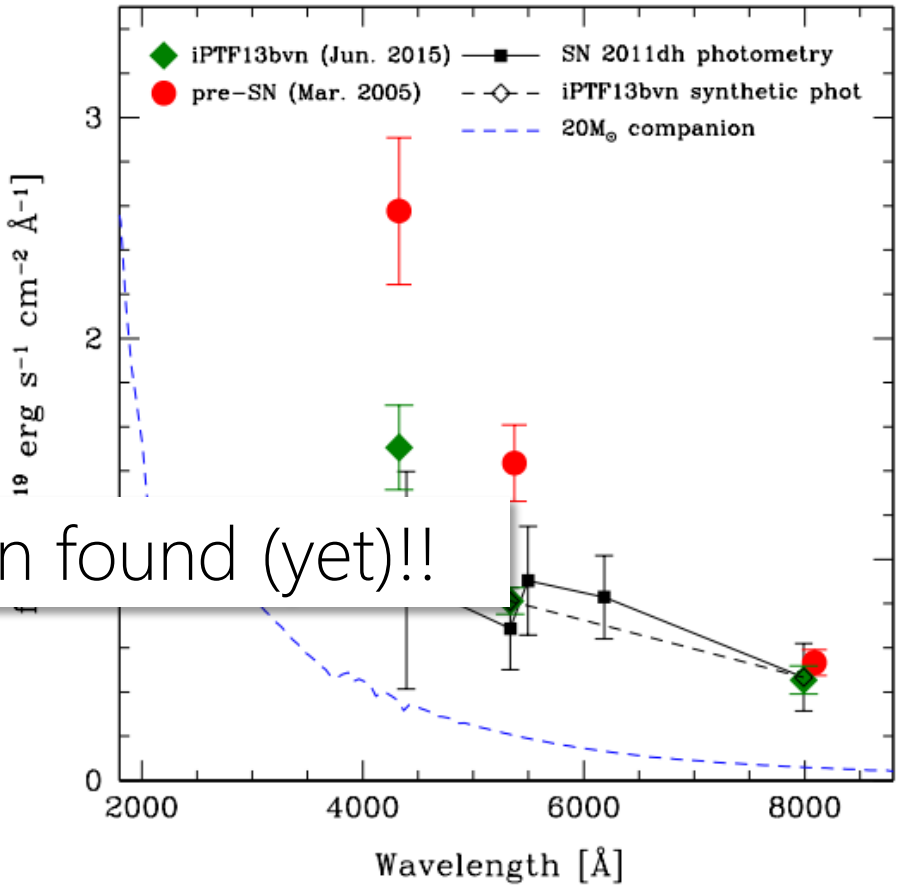


Answer should be revealed three years after the explosion!!

Hirai et al. 2015



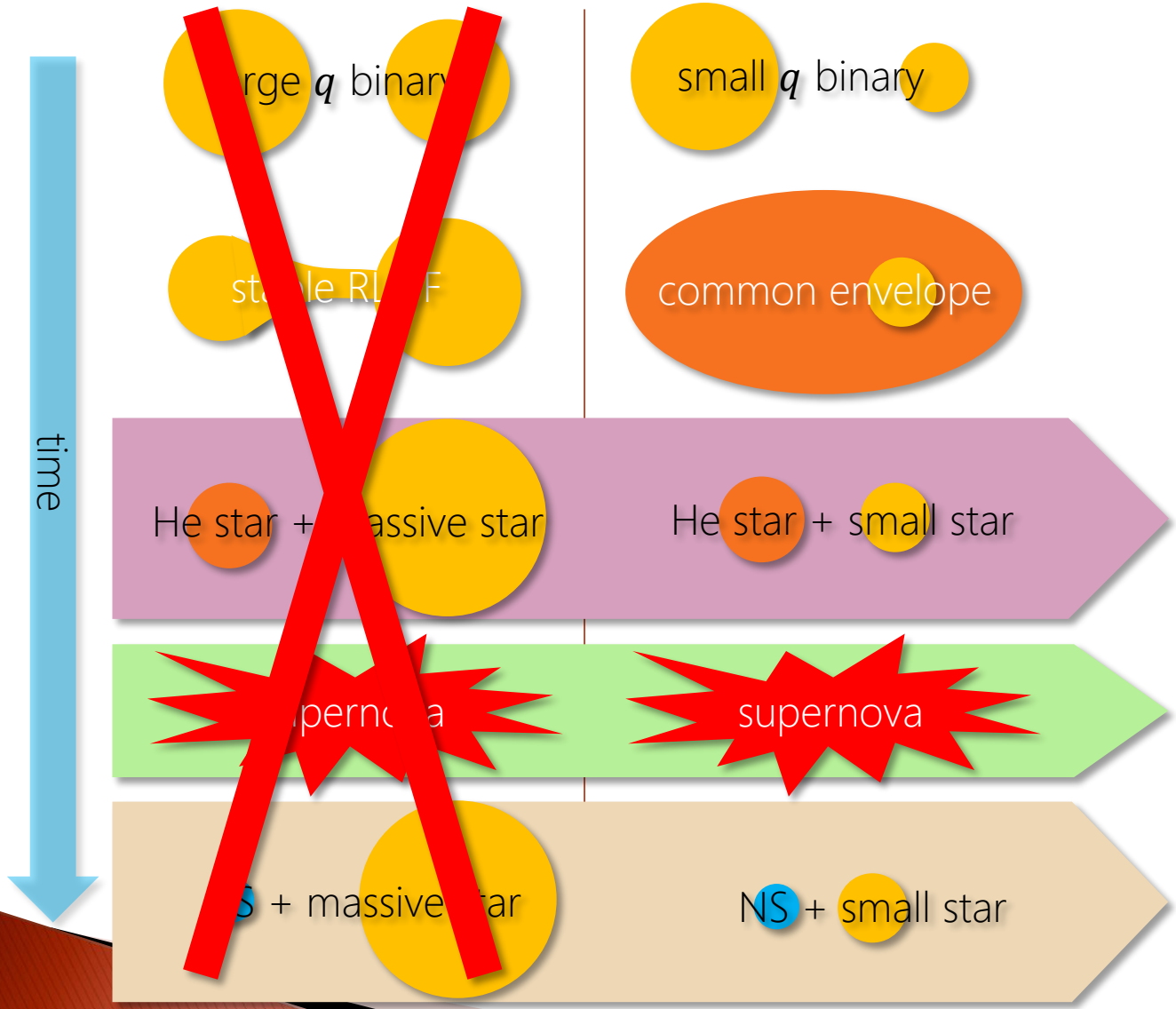
No companion found (yet)!!

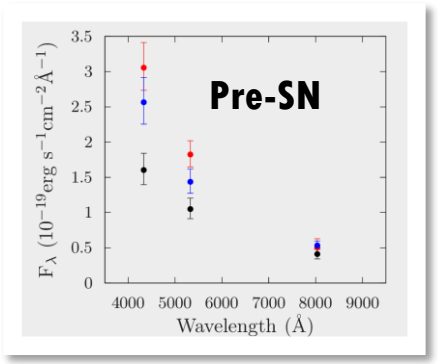


Folatelli et al. 2016

At least the companion is not an O-star

Suggested Evolutionary Paths





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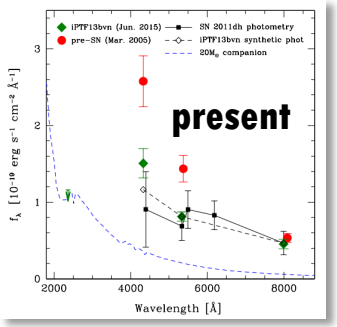
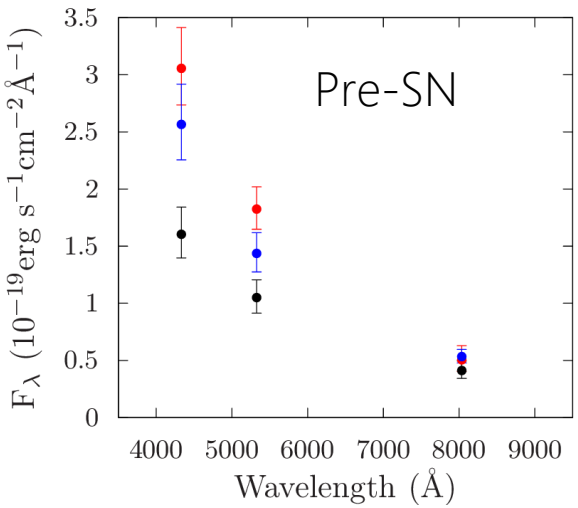


Stellar constraints from observation



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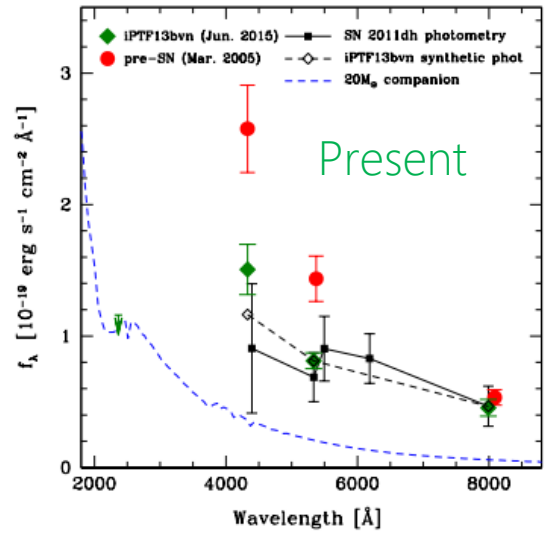

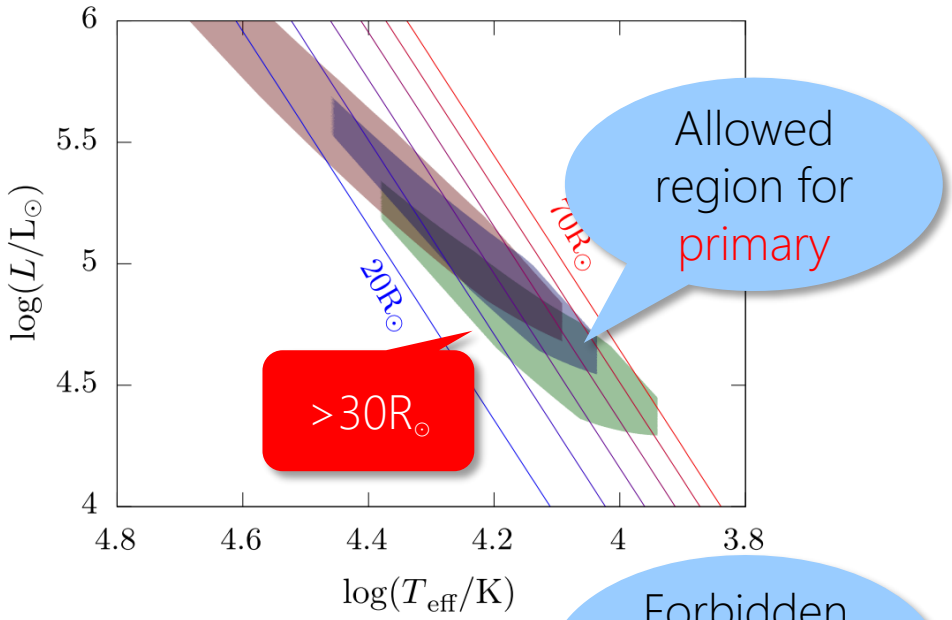

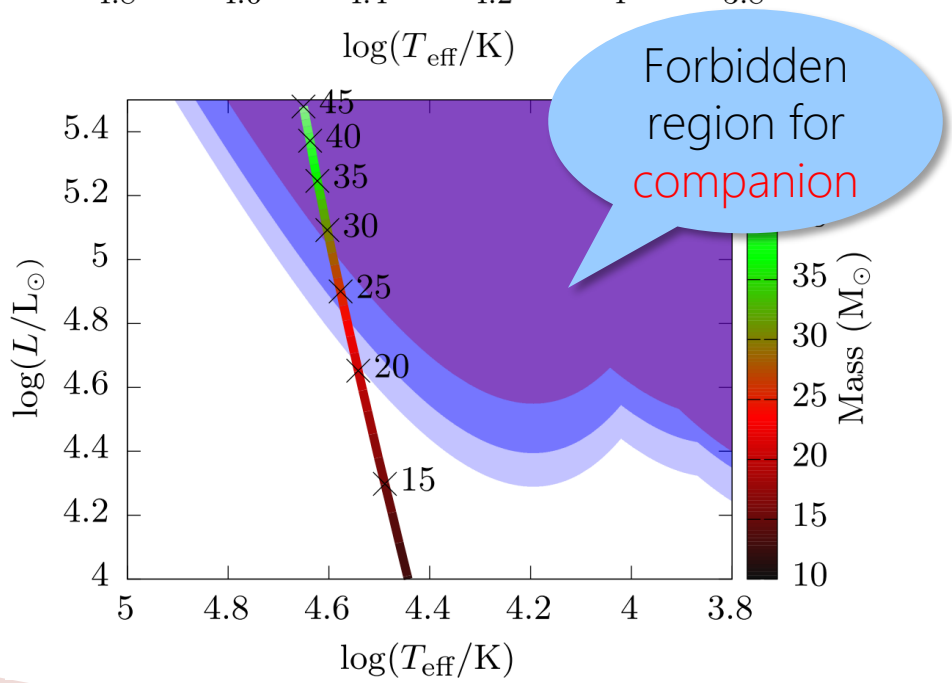

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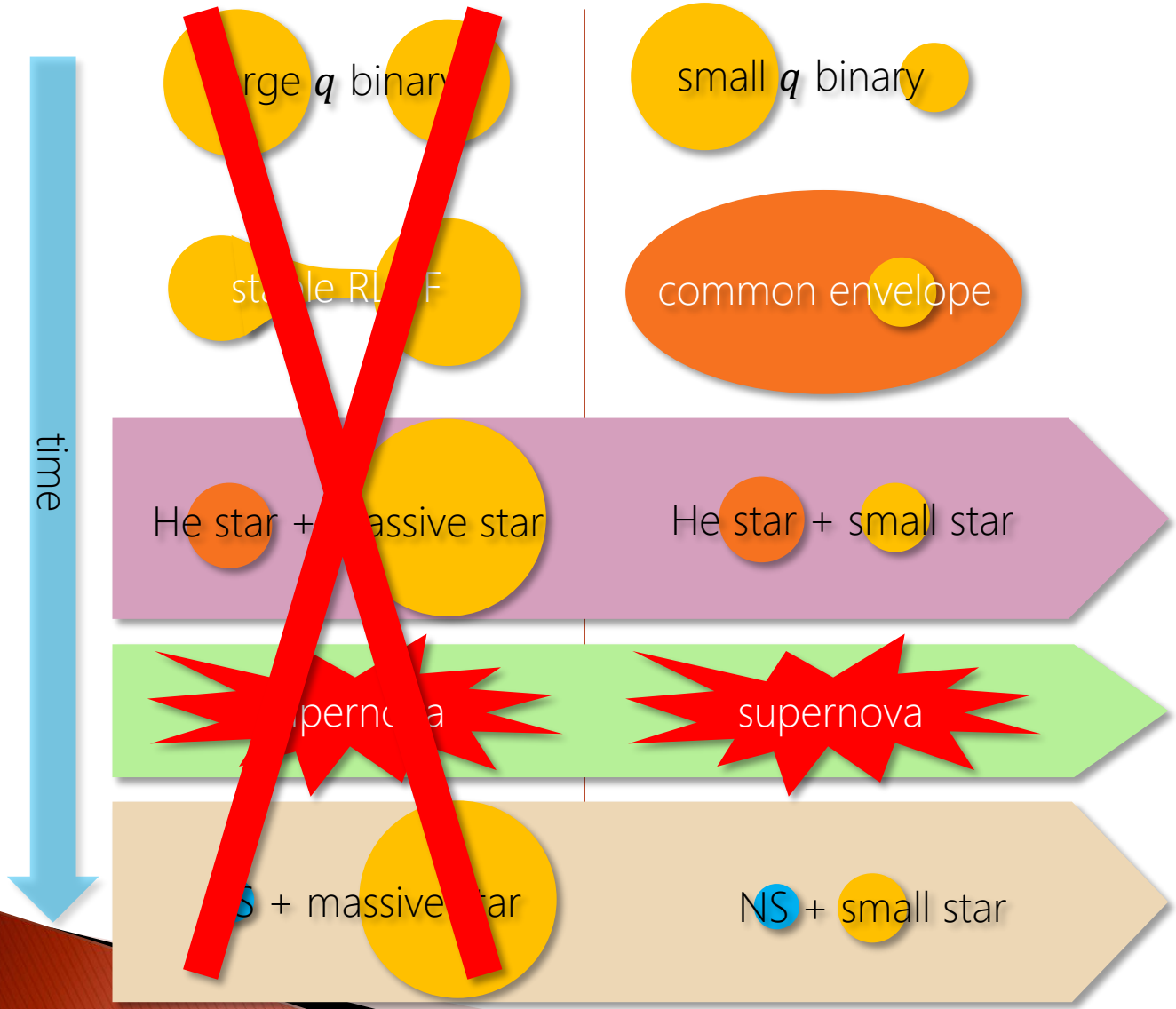

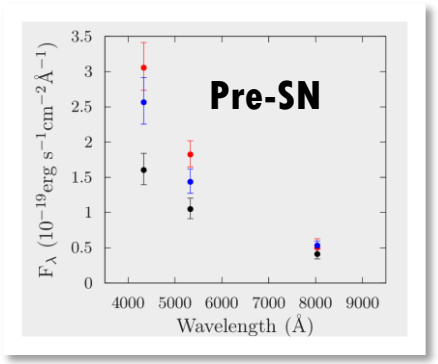

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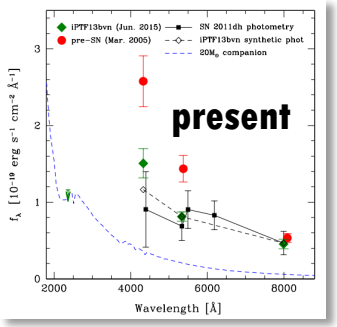
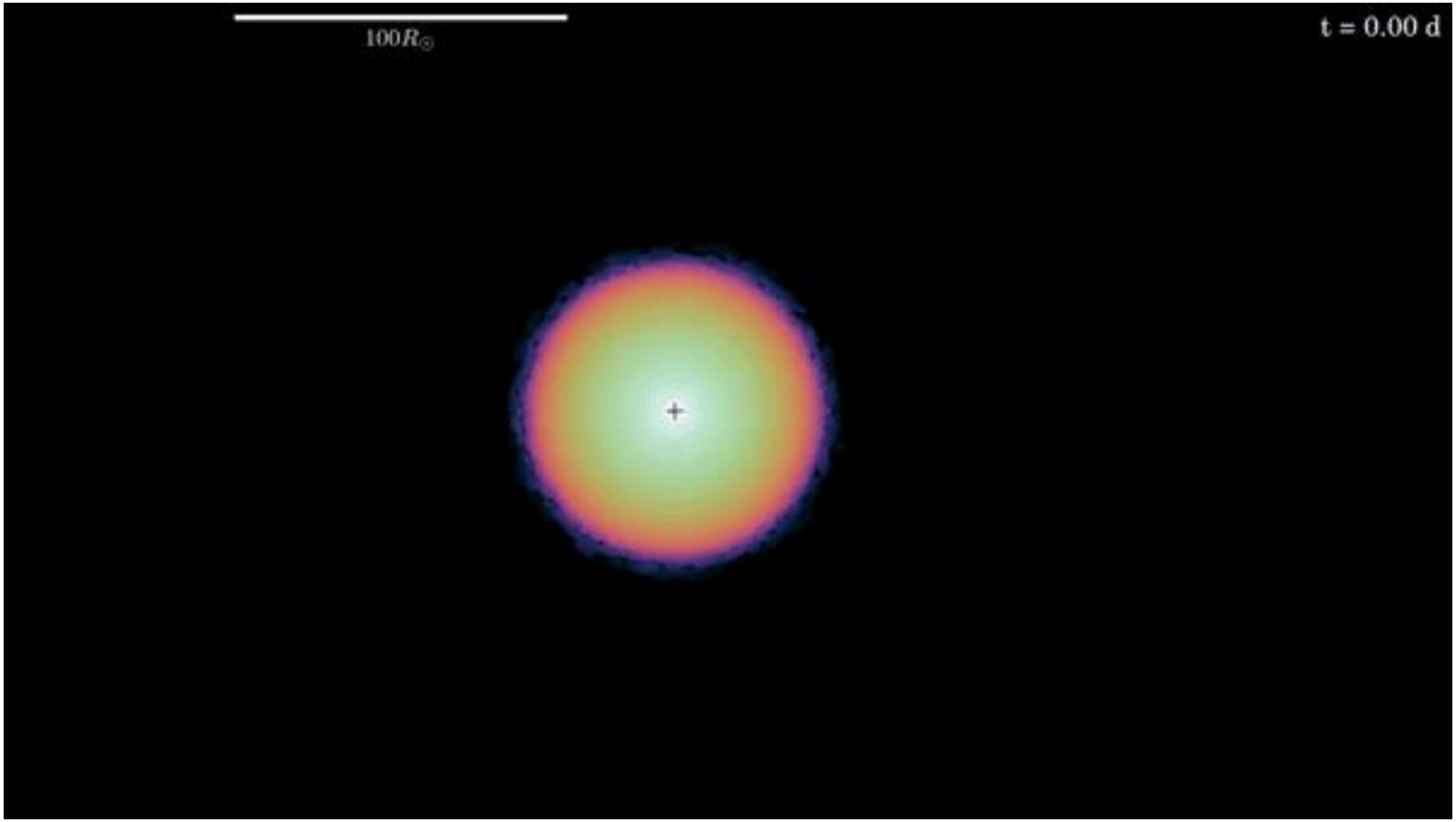


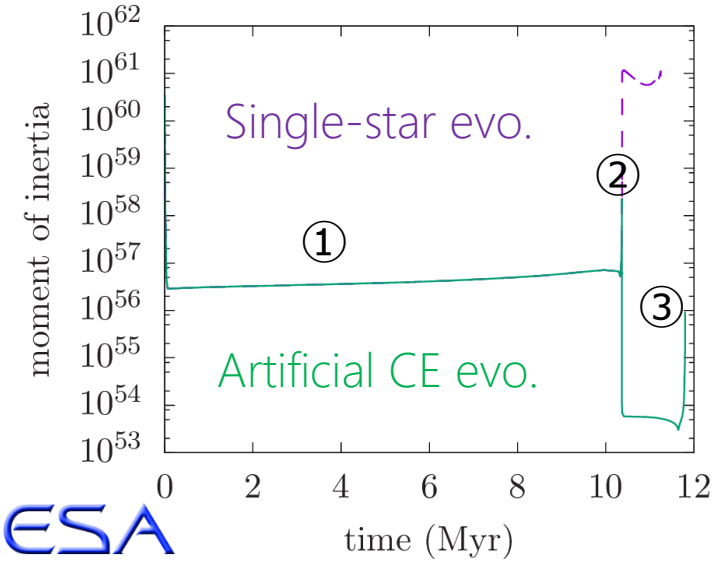
What are Common Envelopes?

Ohlmann et al. 2016



Highly efficient
- orbital shrinkage
- envelope stripping

Common envelope calculations



MESA

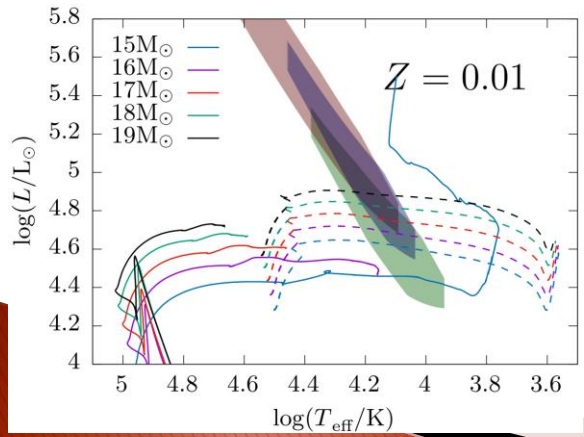
Numerical Procedure

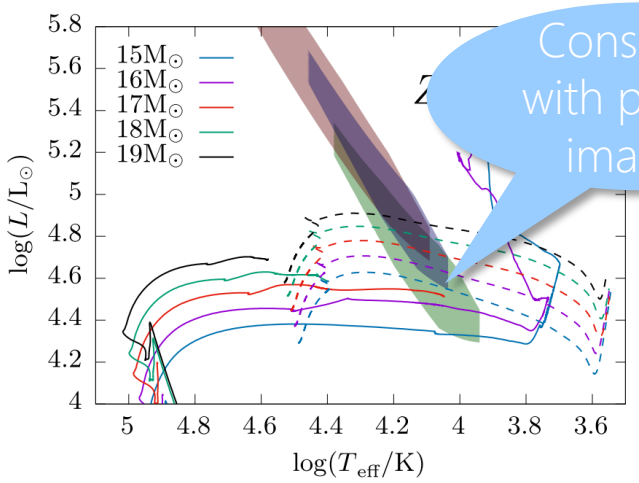
① Evolve a star up to the RG phase.

② Remove the envelope artificially.

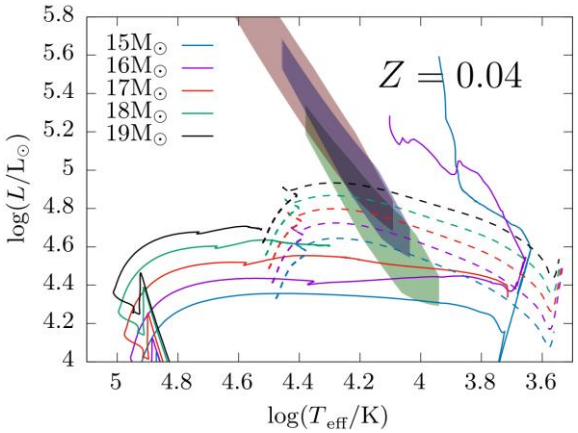
③ Evolve up to core-collapse.

Results





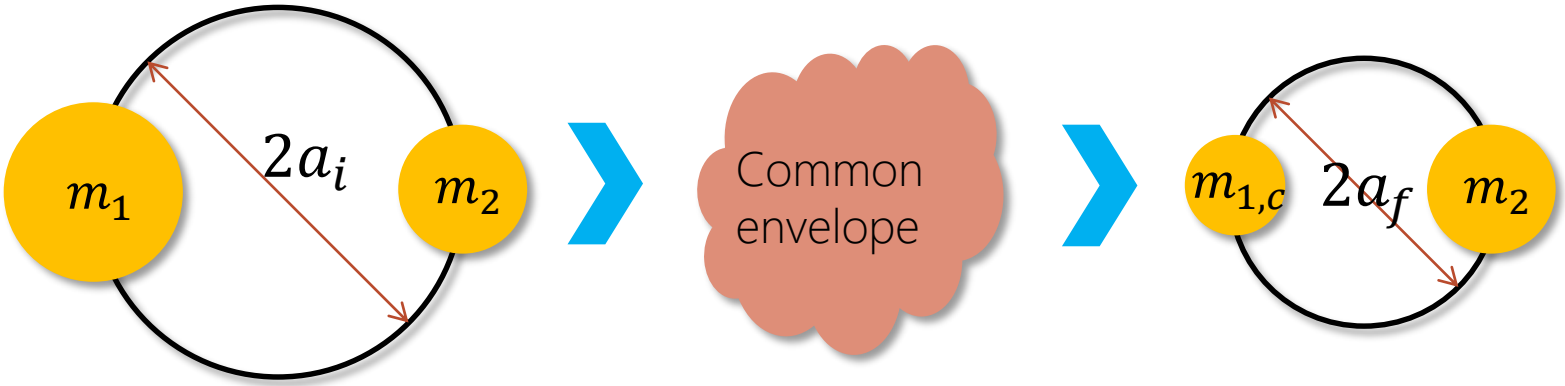
Consistent with pre-SN image!!



Energy formalism

- "α-formalism" (Webbink 1984)

$$E_{env} = \alpha_{CE}\left(-\frac{Gm_1m_2}{2a_i} + \frac{Gm_{1,c}m_2}{2a_f}\right)$$



α_{CE}: efficiency of envelope ejection
(typically taken as ~1)

E_{env}: binding energy of the ejected envelope

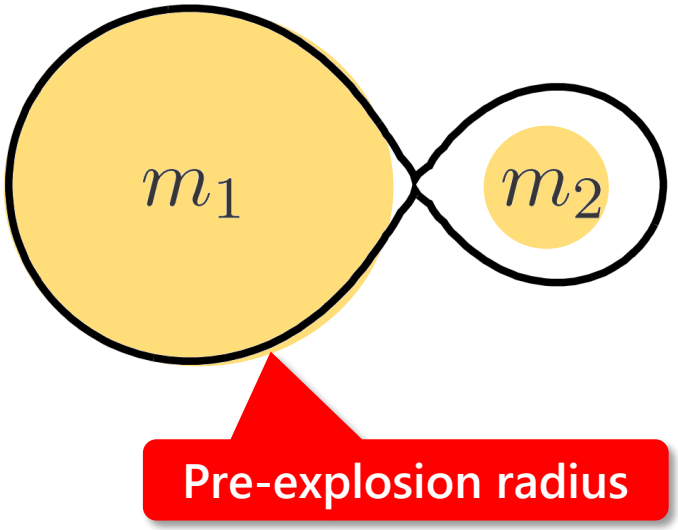
α_{CE} represents the energy reservoir for envelope ejection

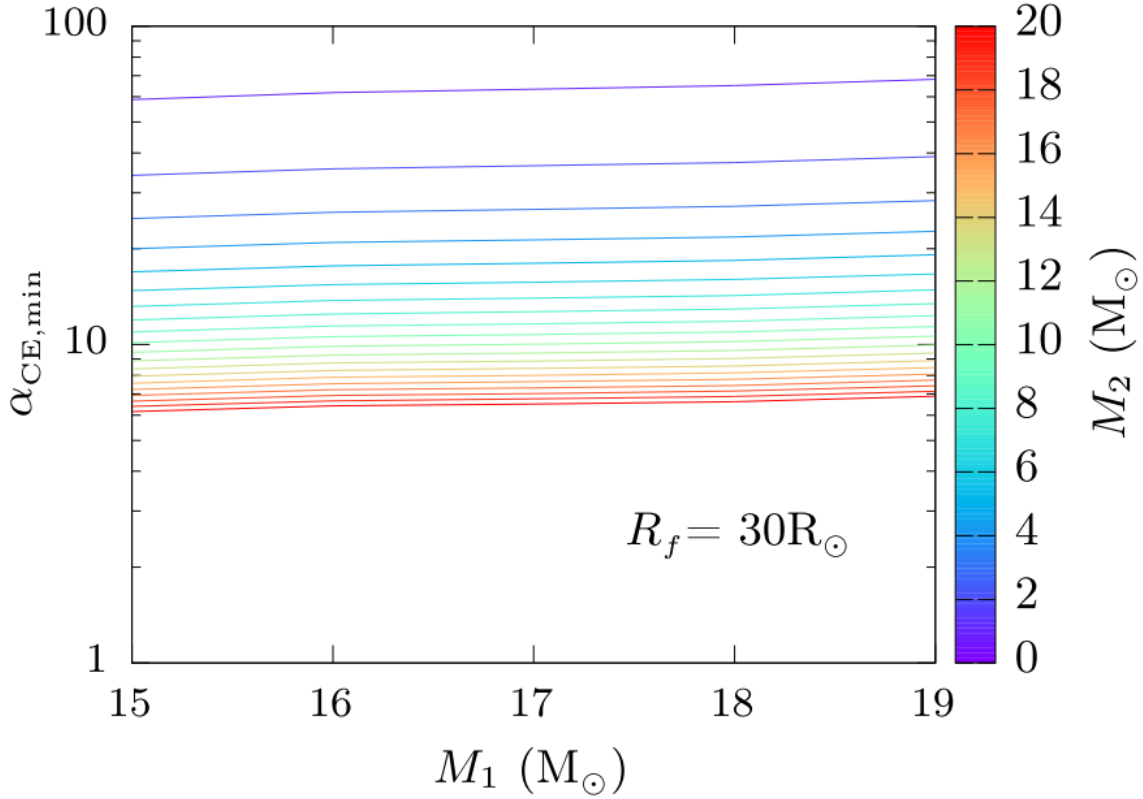
Conditions for CE success

$$\alpha_{\rm CE} = E_{\rm env}\left(-\frac{Gm_1m_2}{2a_{\rm i}} + \frac{Gm_{1,\rm c}m_2}{2a_{\rm f}}\right)^{-1} \geq \frac{2E_{\rm env}a_{\rm f}}{Gm_2m_{1,\rm c}}$$

$$a_{f,\min} = \max\left(\frac{R_f}{f(q)}, \frac{R_2}{f(q^{-1})}\right)$$

$$f(q) \equiv \frac{0.49q^{2/3}}{0.6q^{2/3} + \log(1+q^{1/3})}$$





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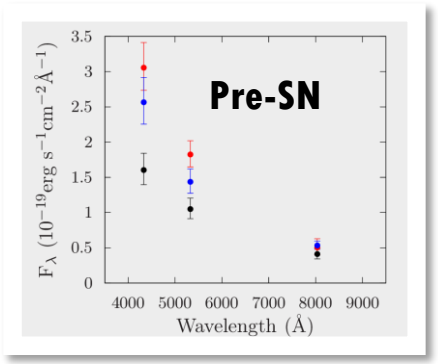

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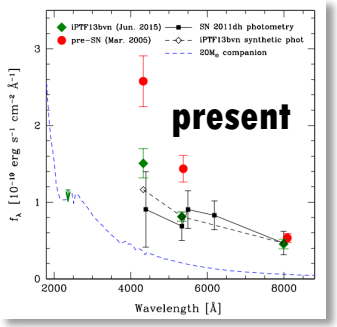

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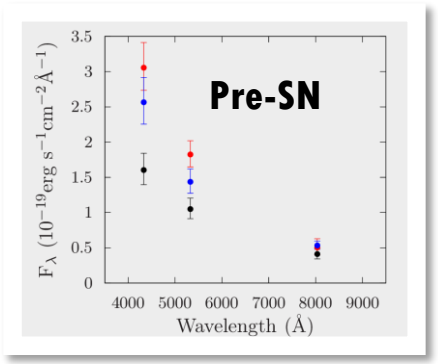

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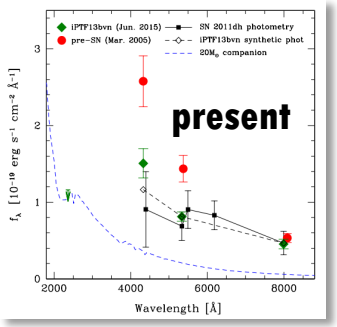
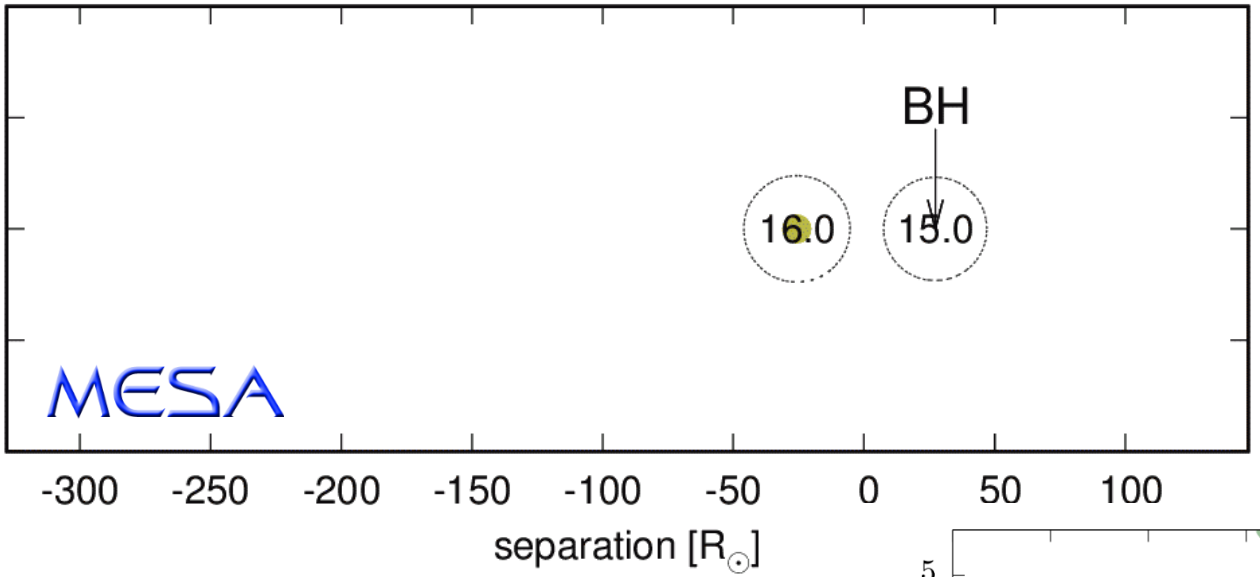


X-ray binary evolution

Simulate binary evolution with a black hole

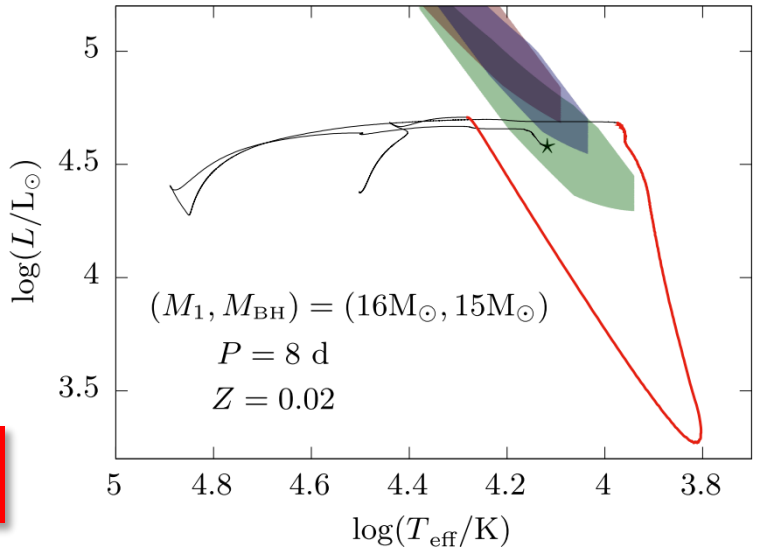


Parameter region

$m_1 = 15 - 17\mathrm{M}_\odot$

$m_2/m_1 > 0.8$

$P \sim 4 - 20\mathrm{d}$



Leaves a wide BH-NS binary

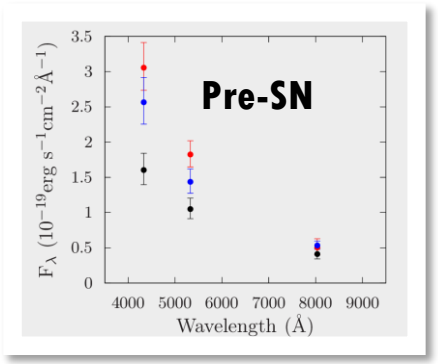
(Hirai 2017)

How was the progenitor formed?

black hole

How was the ~~progenitor~~ formed?

Summary of Binary Evolution Models



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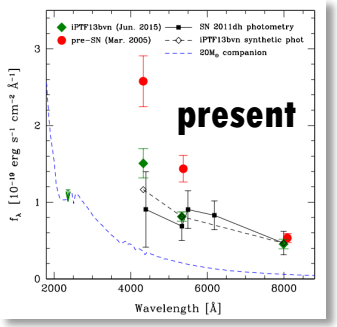
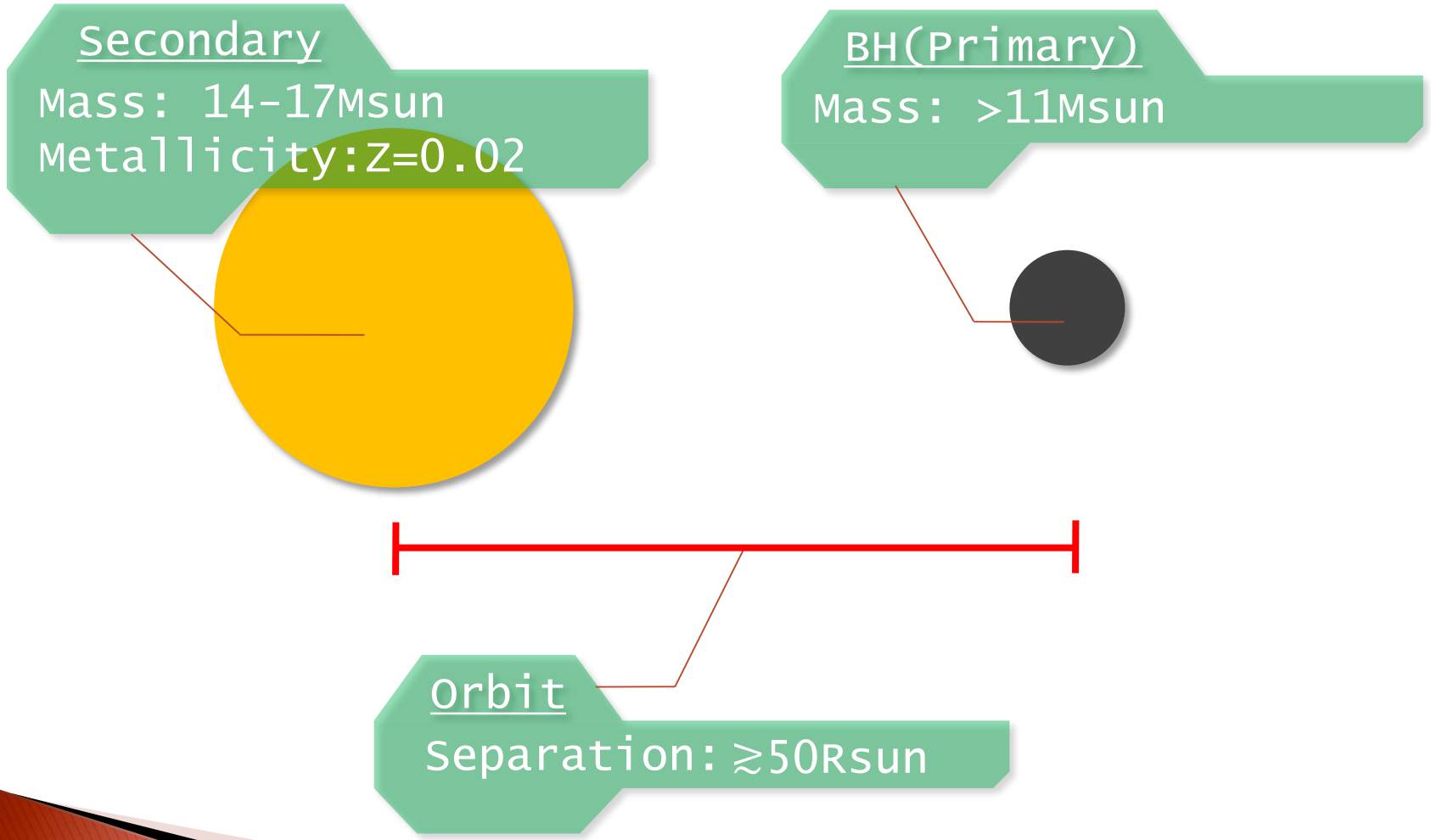


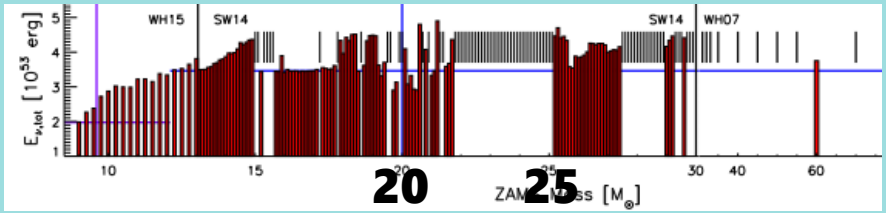
What is our goal?

Let us clarify the properties of the binary we want to produce



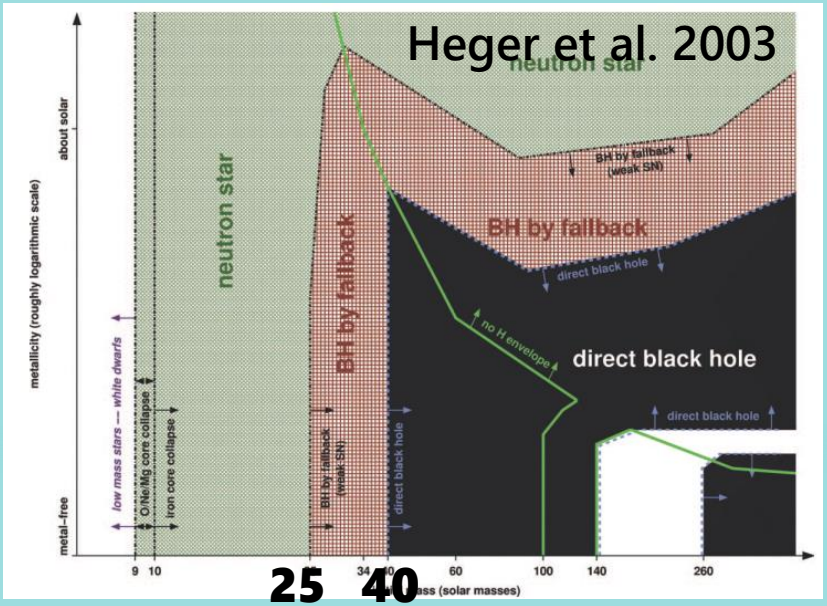
Black Hole Formation in General

Stellar evolution theory



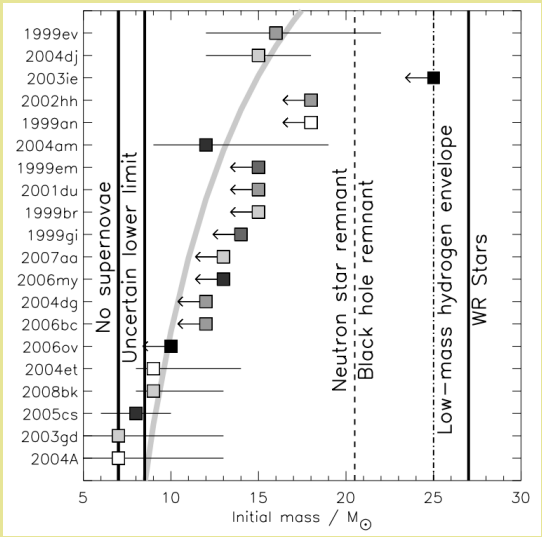
ZAMS mass ($M_\odot$)

Sukhbold et al. 2016



ZAMS mass ($M_\odot$)

Supernova observations

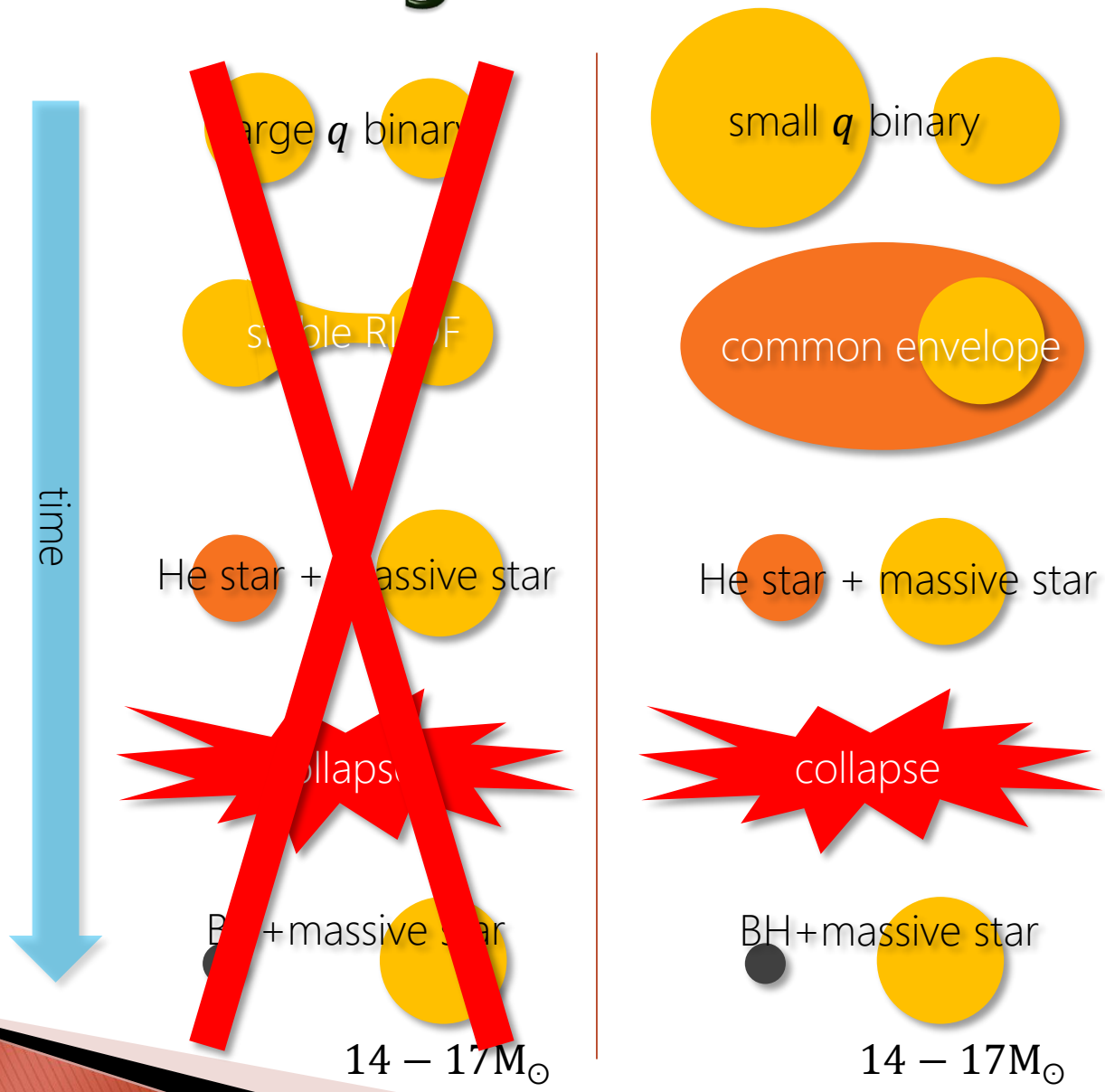


Smartt et al. 2009

Observed progenitor masses suggest that stars with $18\ M_\odot \lesssim M_{ZAMS} \lesssim 25\ M_\odot$ do not explode (?)

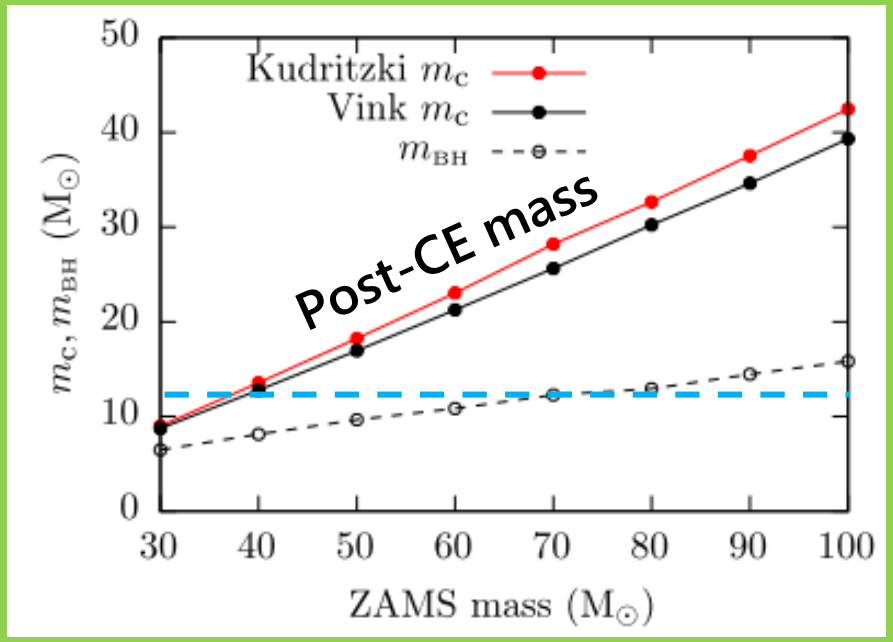
Stars with mass >18$M_\odot$ all collapse to BHs

The First Stage of Evolution

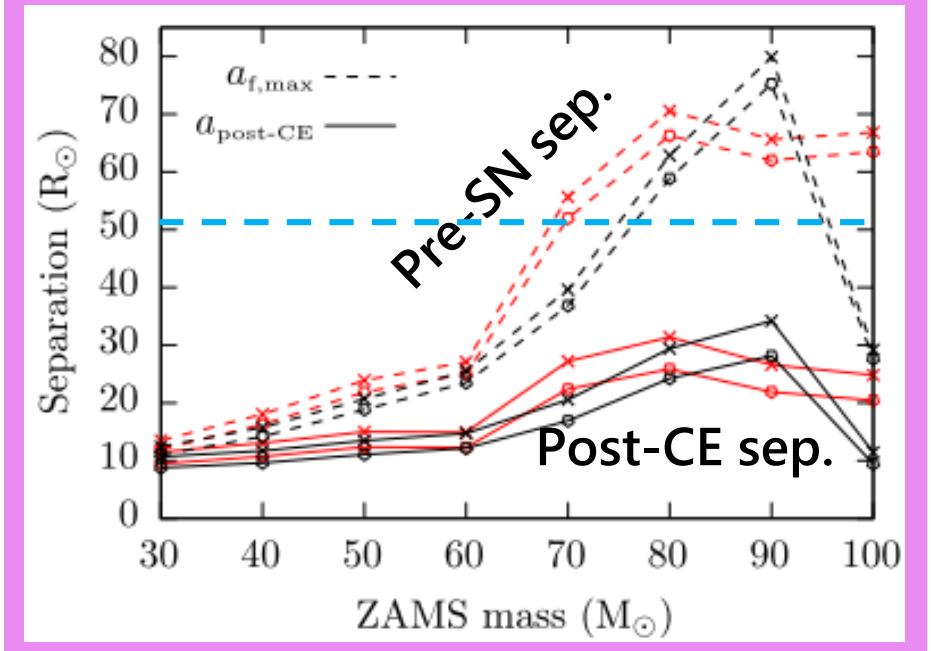


The Common Envelope Scenario

time



He core mass



Post-CE and Pre-SN separation

Summary

① How was the progenitor of iPTF13bvn formed?

- Common envelope scenarios are unlikely.
- The progenitor was a 14-17$M_\odot$ star and likely had a large black hole companion (ULX-like binary).

② How was the black hole of iPTF13bvn formed?

- The binary separation at the onset of the XRB phase should be >50$R_\odot$
- The binary started with a >70$M_\odot$ primary and experienced a common envelope phase.
- Such binaries only consist <0.1% of the whole stellar population so iPTF13bvn may have been a rare event.