Formation of Double Compact Stars

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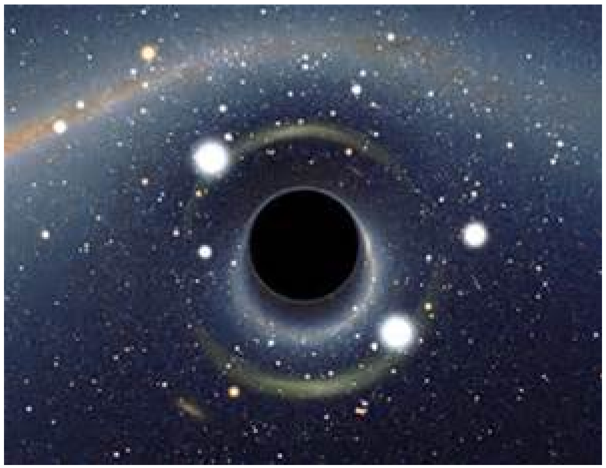
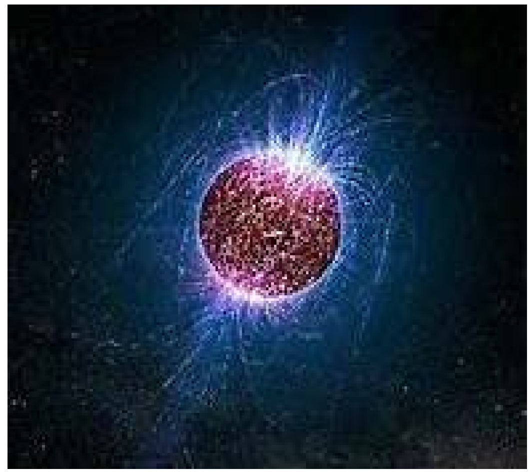
Compact Stars



Black holes
(BHs)



Neutron Stars
(NSs)

White Dwarfs
(WDs)

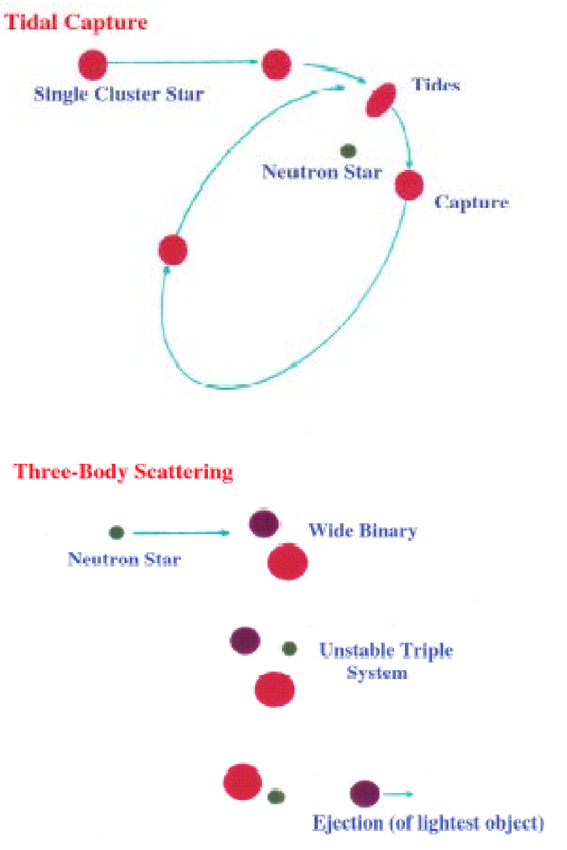
Double Compact Star binaries

Objects	Observational appearance
NS+NS	Binary radio pulsars, GW/short GRBs/kilo-novae
NS+WD	(Millisecond) radio pulsars, Ultra-compact X-ray binaries
WD+WD	CVn, Supernovae Ia (?)
BH+BH	GW
BH+WD	47 Tuc X9 (?)
BH+NS	Binary radio pulsars (?), GW (?)

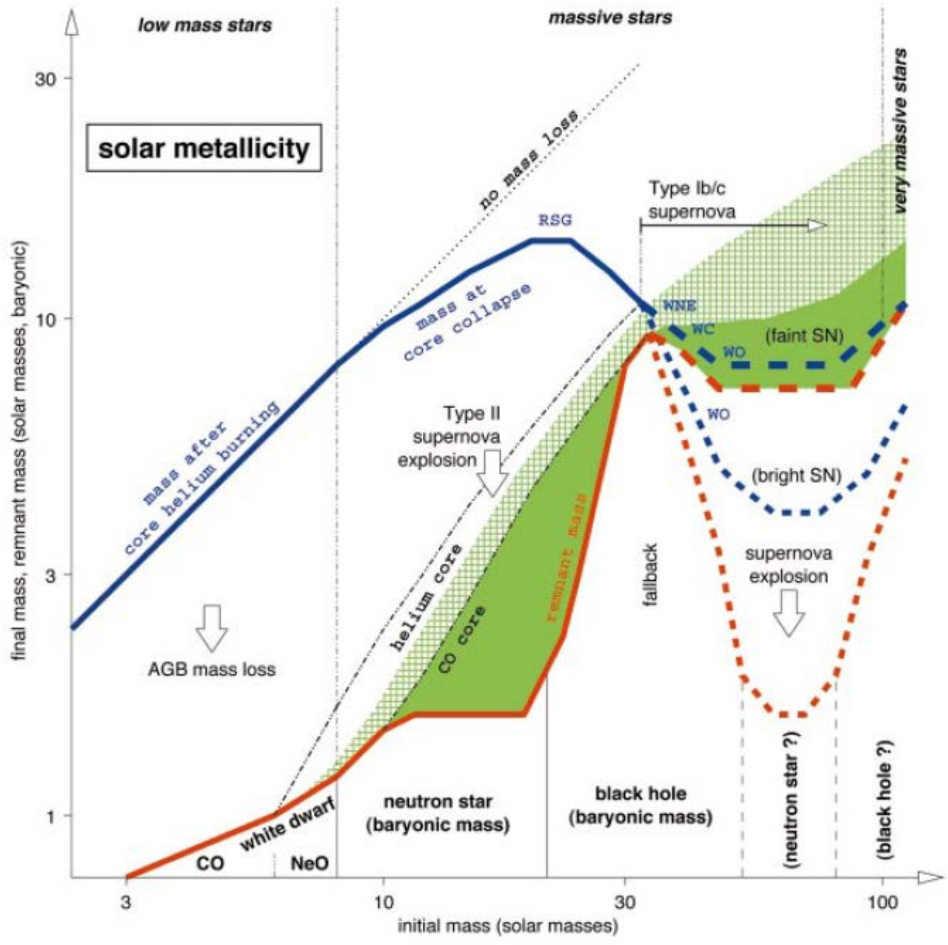
Formation of Double Compact Stars

- Dynamical interaction
  - tidal capture and exchange encounter in galactic center and globular clusters
- Isolated evolution
  - binary evolution in the galactic disk

See Belczynski, Bulik, Tauris & Nelemans 2018 for a recent review

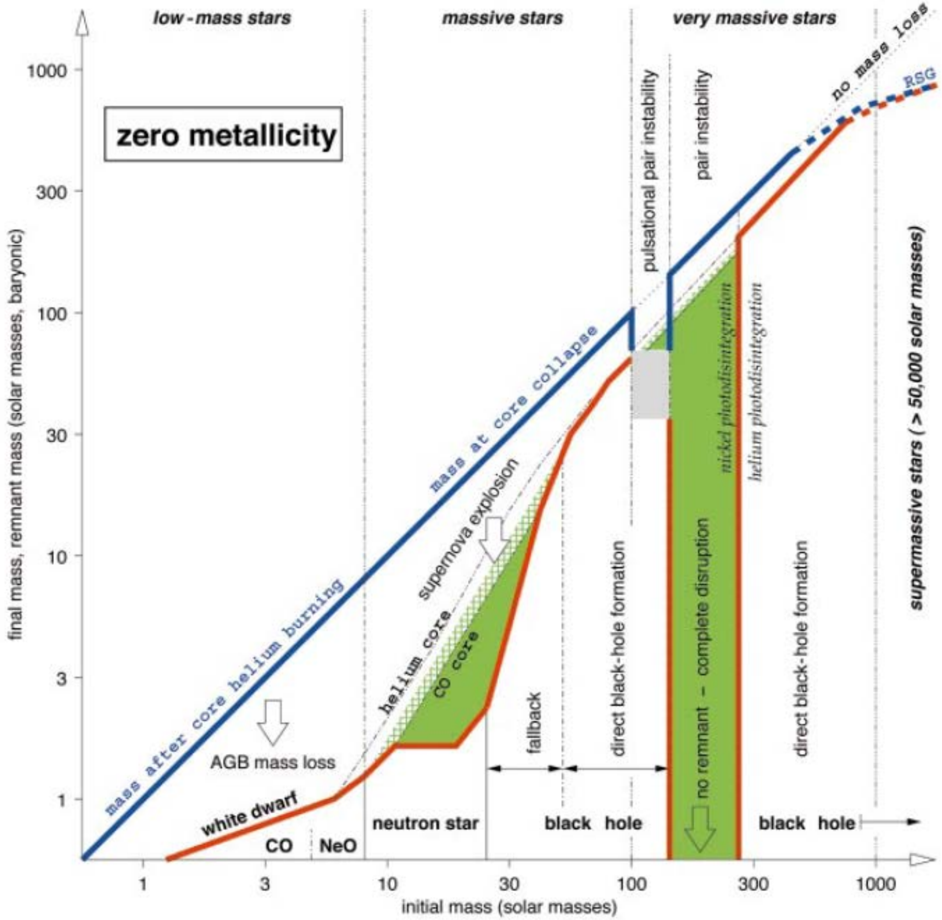


Initial-Final Mass Function of Non-rotating Stars of Solar Composition



Woosley & Heger 2002

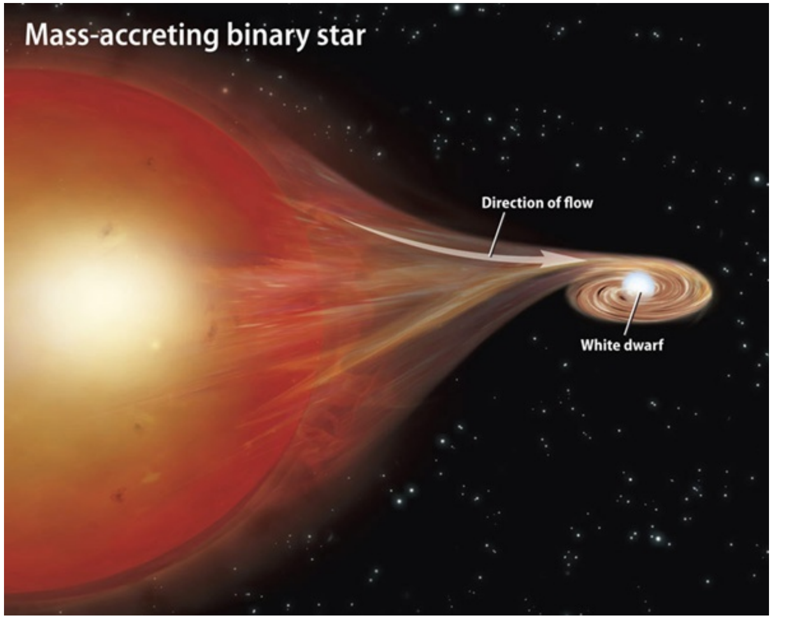
Initial-Final Mass Function of Non-rotating Primordial Stars (Z=0)



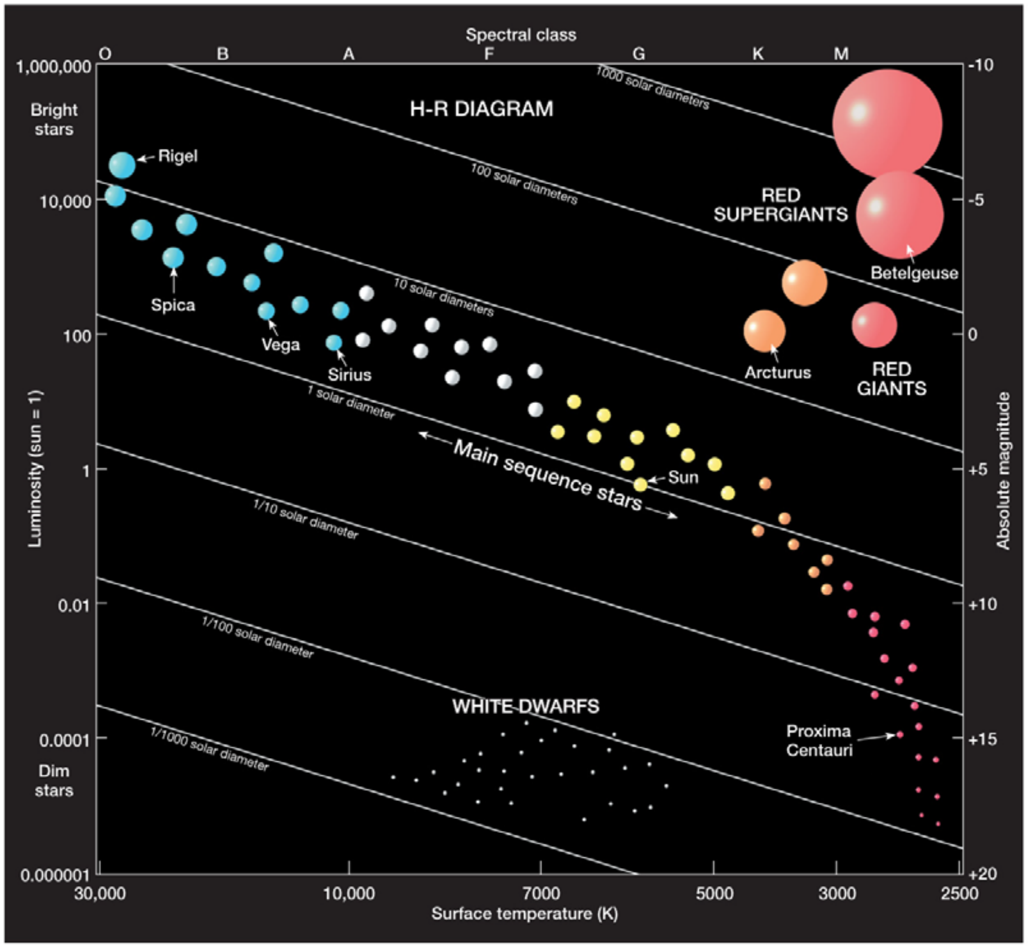
Woosley & Heger 2002

Mass-transferring Binary Stars

- Most massive stars are born in binary systems
- Mass transfer influences
  - Stellar evolution
  - Orbital evolution
  - High-energy radiation



Progenitor Binaries vs. Double Compact Stars



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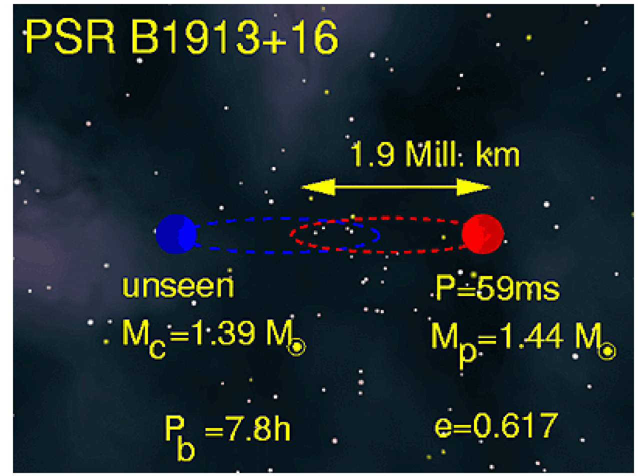
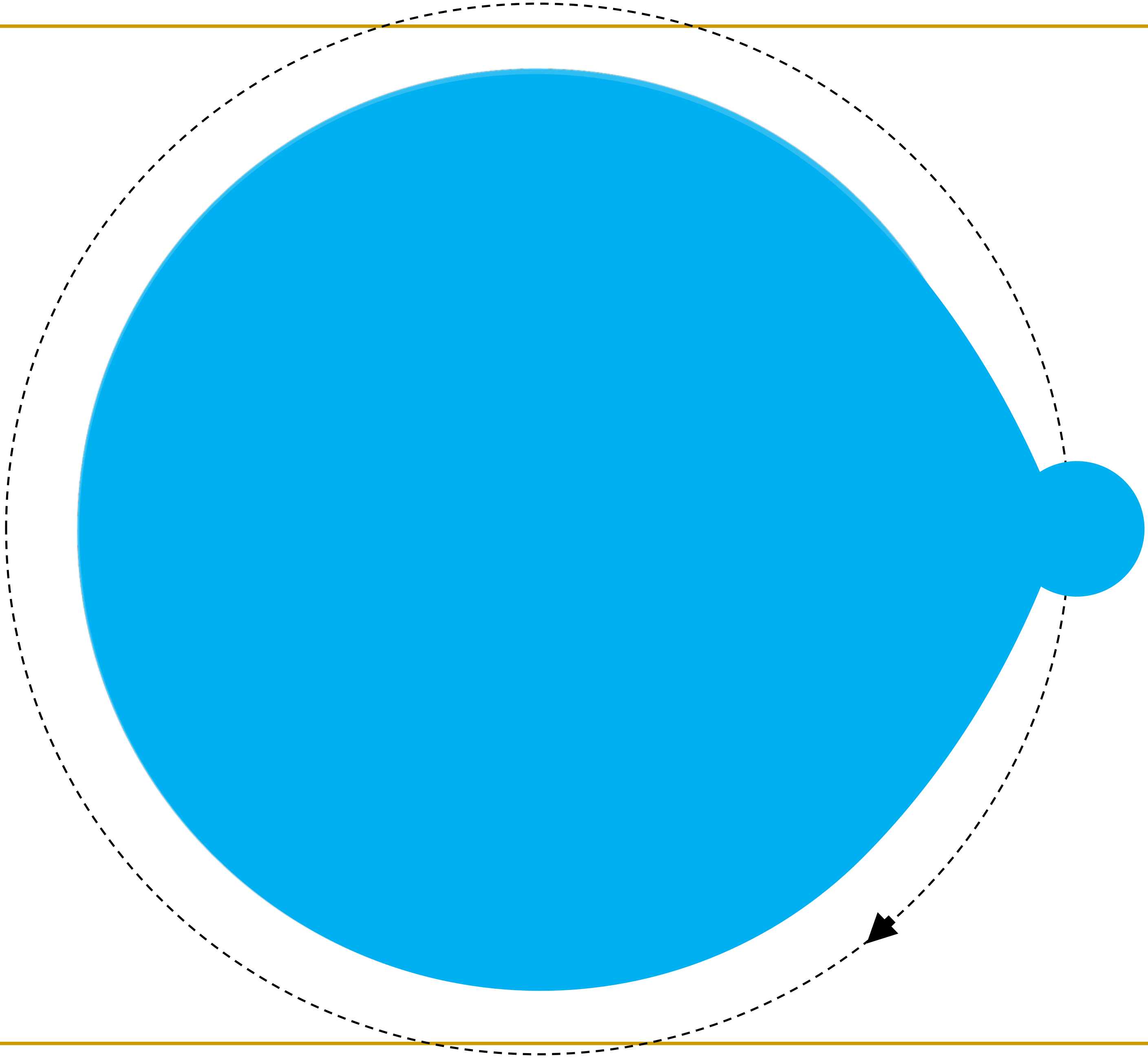
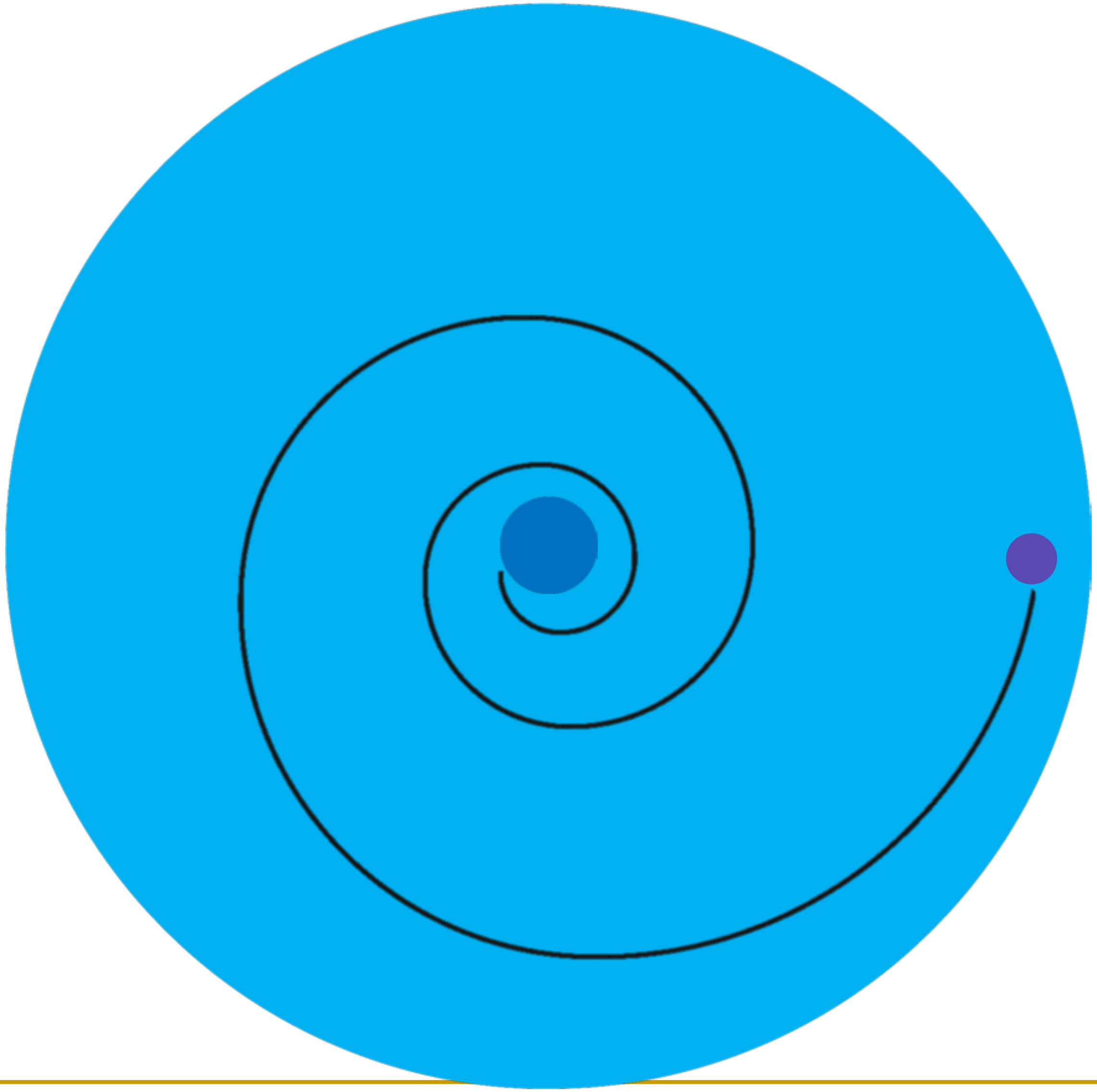


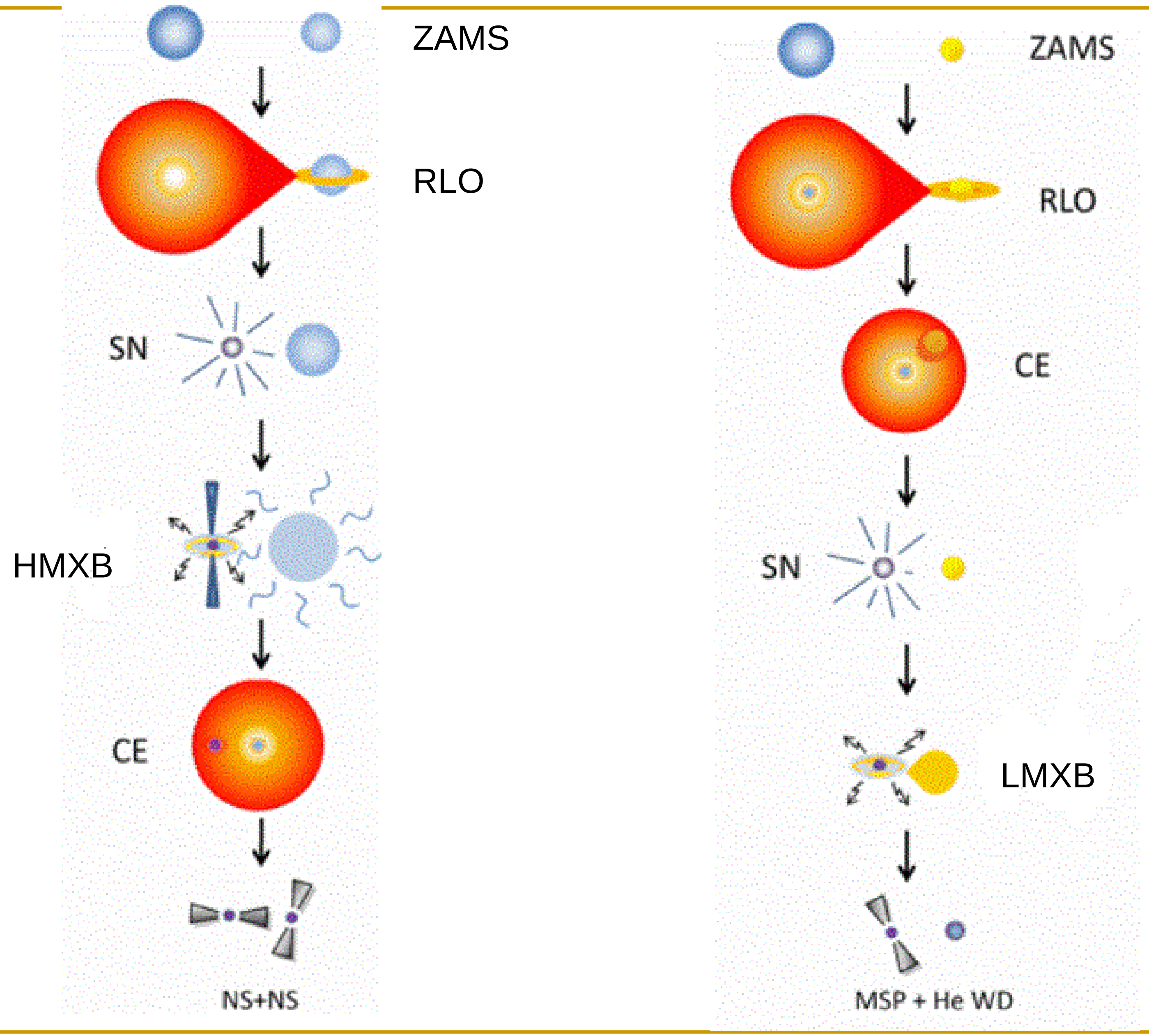
significant mass and orbital angular momentum loss



Dynamically unstable mass transfer

Common Envelope (CE) Evolution





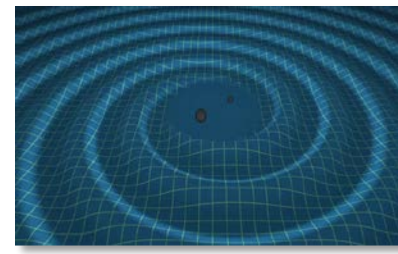
Ivanova et al. 2013

Population Synthesis of Binary Stars and Formation of Double Compact Stars

star formation history
binary fraction
initial mass function
mass ratio
orbital separation
orbital eccentricity
metallicity
spatial distribution

→ PS →

stellar evolution
mass transfer
CE evolution
tidal interaction
mass loss
…



Double compact stars

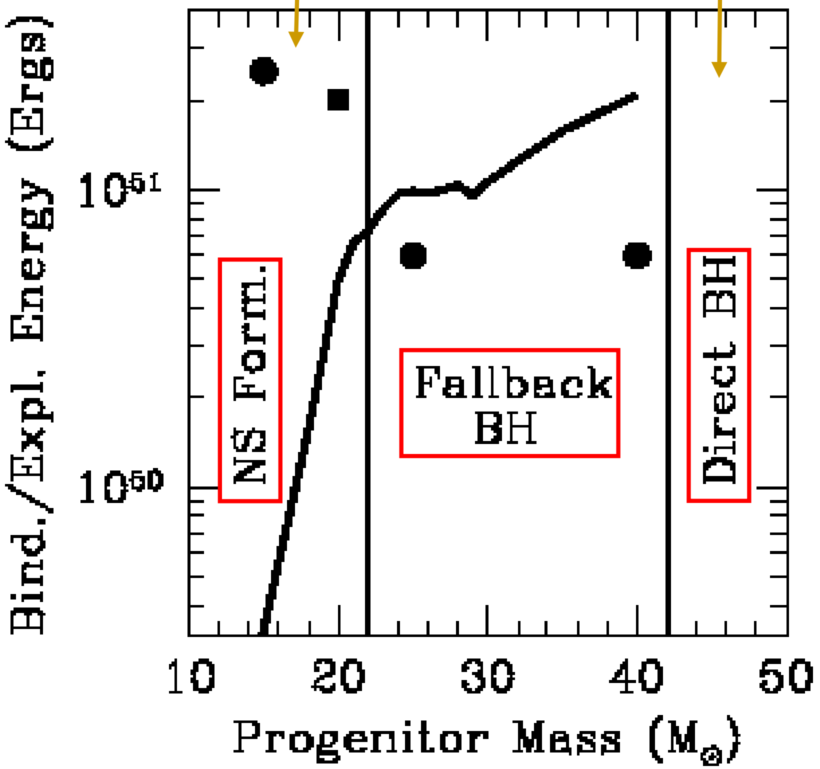
Uncertainties in the Formation Theory

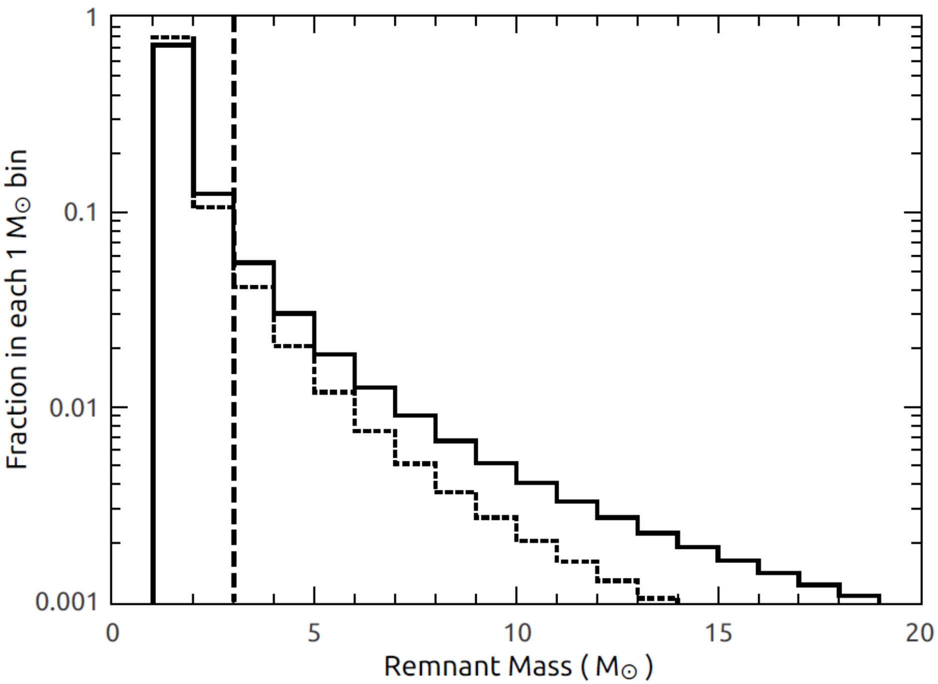
- The initial-remnant mass relation
- The common envelope evolution
- Kicks to newborn BHs and NSs
- …

1. Which Stars Make BHs and NSs?

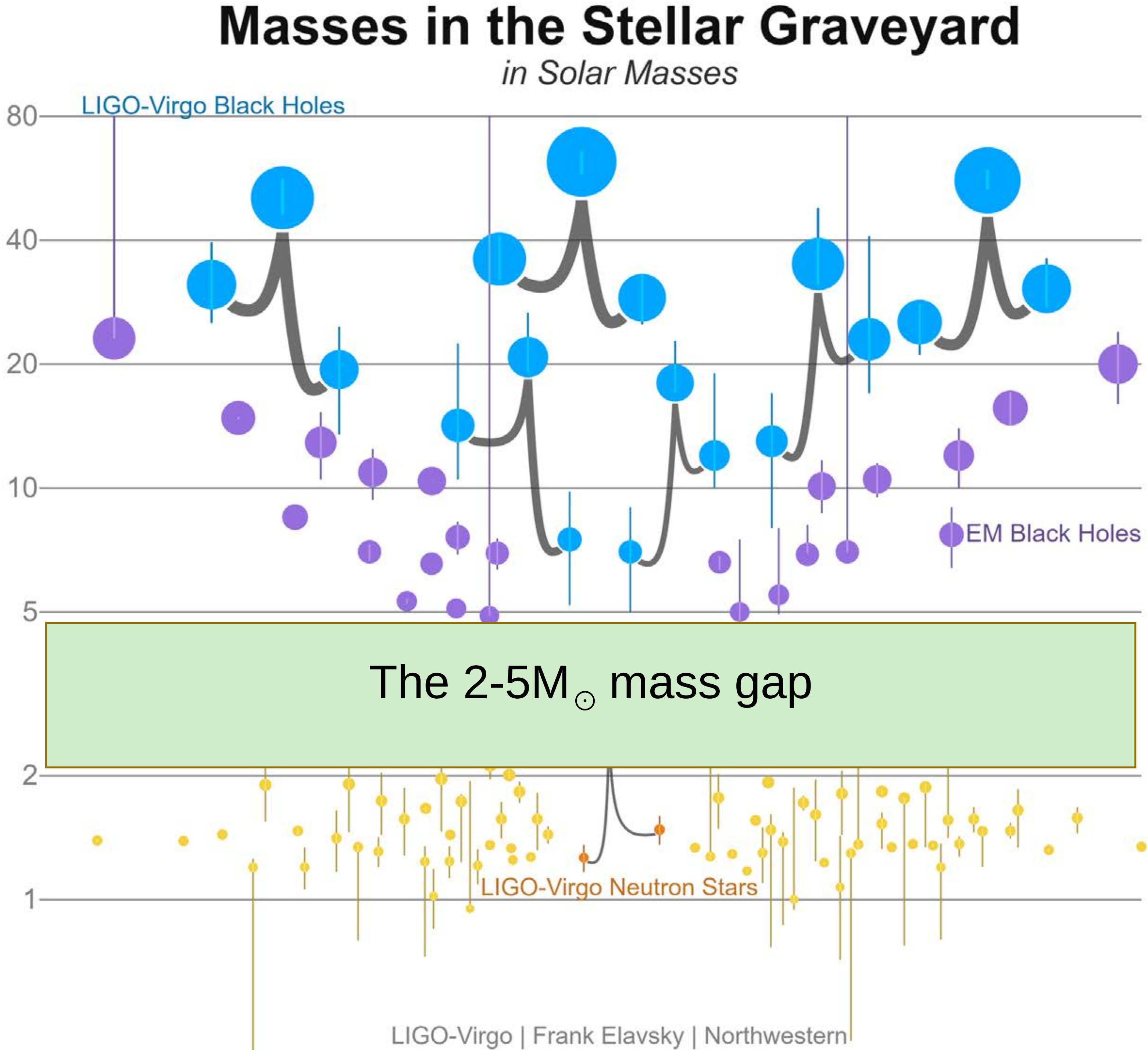
Successful supernovae

Failed supernova





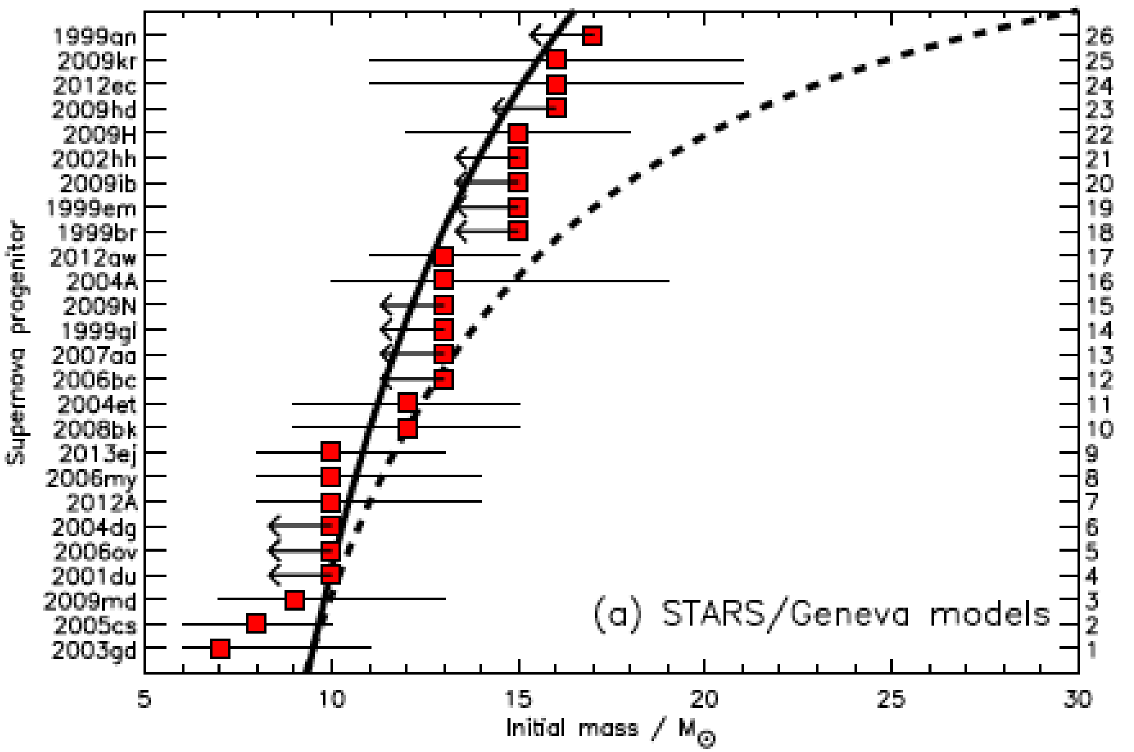
Fryer (1999)



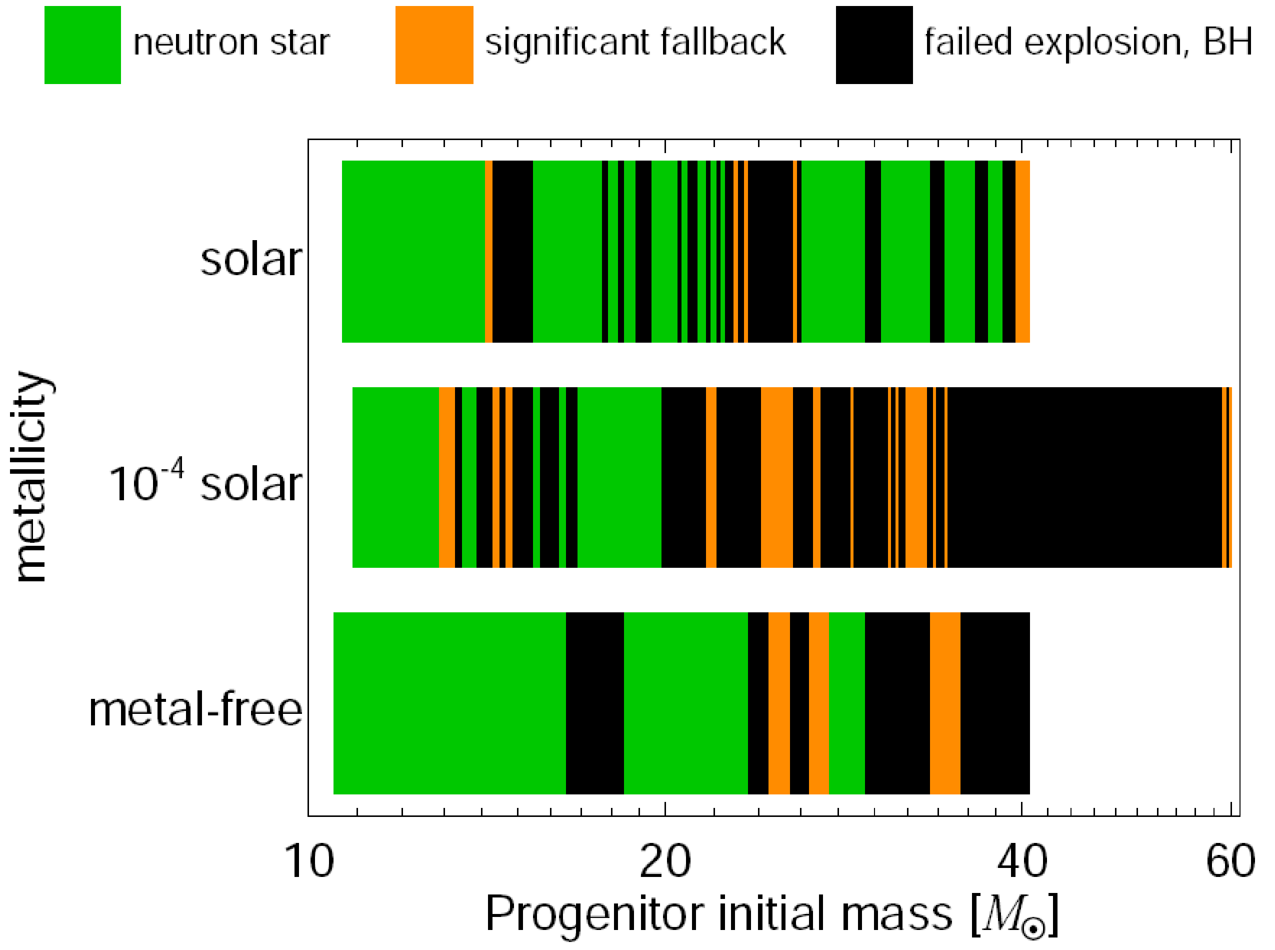
The 2-5$M_\odot$ mass gap

The Red Supergiant Problem

- Absence of type IIp supernova progenitors with mass ~17-25 $M_\odot$ (Smartt et al. 2009)

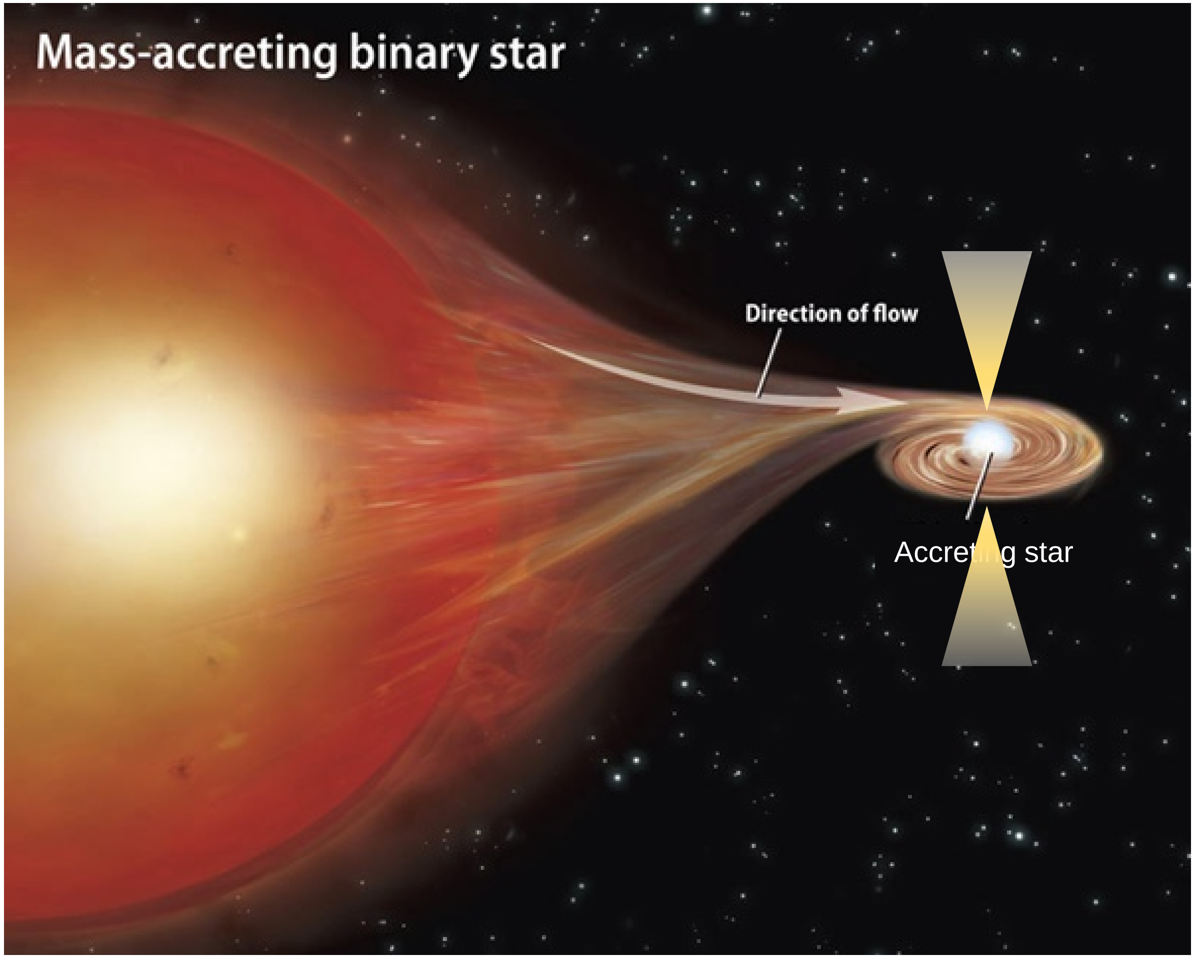


The Initial - Remnant Mass Relation

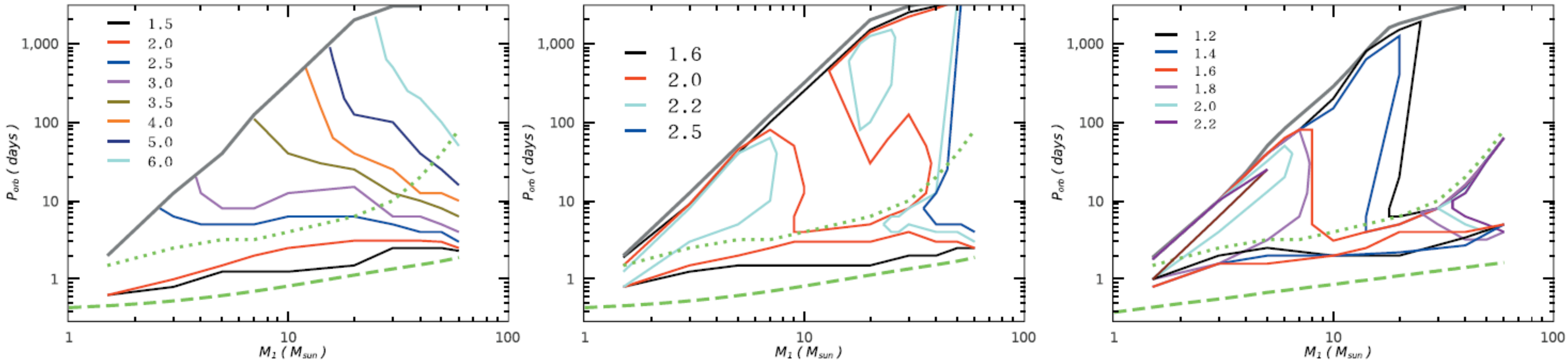


Sukhbold et al. (2016, 2018)

2. What is the Condition for Stable Mass Transfer?



The Allowed Parameter Space for Stable Mass Transfer



Mode I

rotation-dependent mass accretion

Almost no mass accreted

Mode II

half mass accreted and half mass lost

Mode III

thermal equilibrium limited mass accretion

Conservative mass transfer

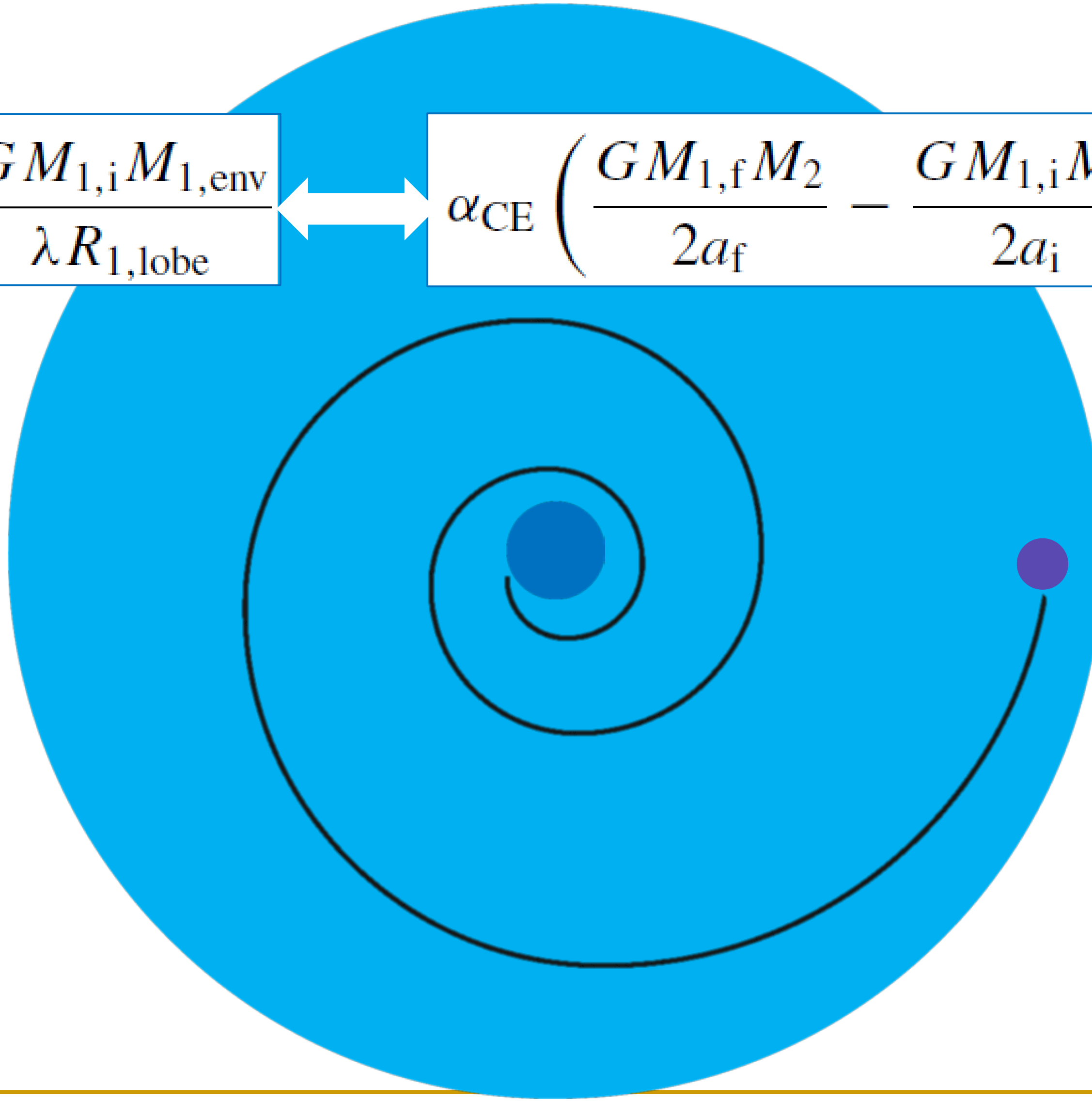
Shao & Li 2014

Common Envelope (CE) Evolution

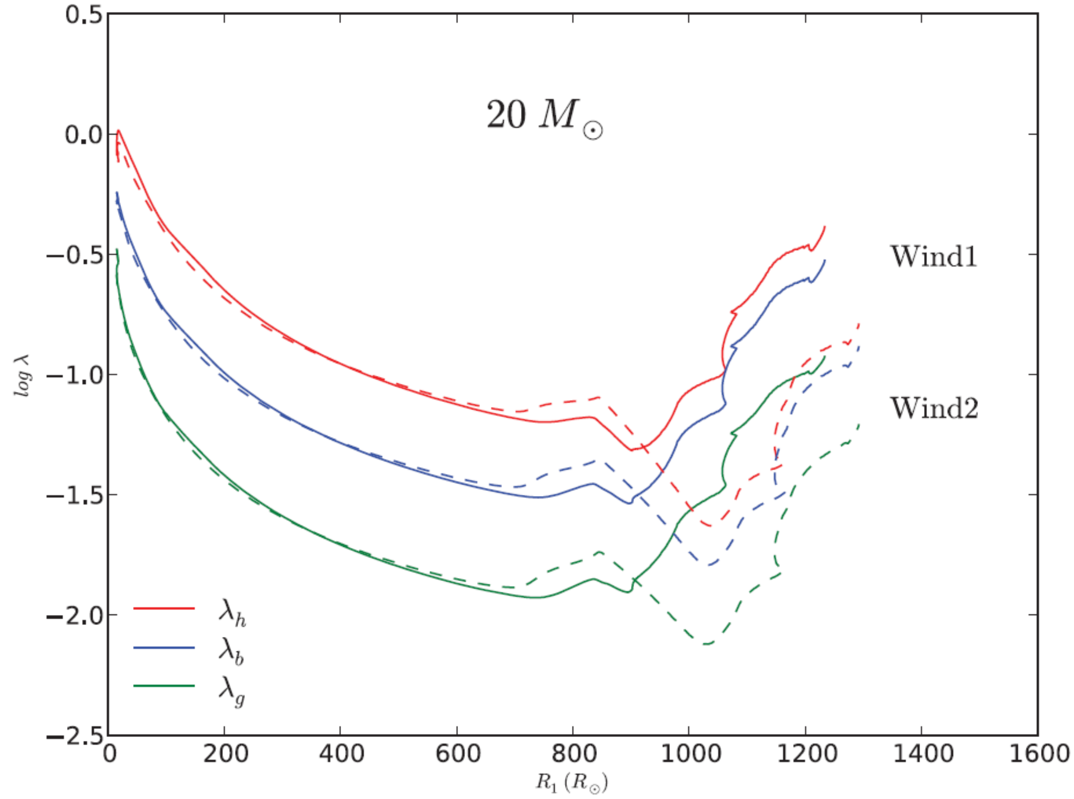
Binding energy of donor's envelope

$$\frac{GM_{1,\mathrm{i}}M_{1,\mathrm{env}}}{\lambda R_{1,\mathrm{lobe}}} \Leftrightarrow \alpha_{\mathrm{CE}}\left(\frac{GM_{1,\mathrm{f}}M_2}{2a_\mathrm{f}} - \frac{GM_{1,\mathrm{i}}M_2}{2a_\mathrm{i}}\right)$$

Orbital energy of accreting star



3. How to Correctly Estimate the Binding Energy of the Stellar Envelope



Wang, Jia, & Li 2016

4. What are the Kick Velocity Distributions of Newborn NSs & BHs

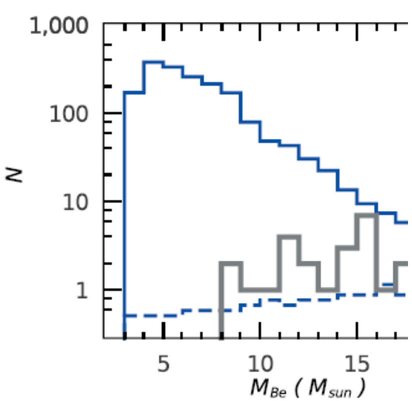
- Core collapse supernovae
  - Inert iron core (> M_{Ch}) collapse
  - Relatively high kick velocity
- Electron capture supernovae
  - Electron captures onto ^{24}Mg removes electrons (pressure support)
  - Relatively low kick velocity
- BH kick velocities - high or low?

Constraints from Galactic Populations of Compact Star Binaries

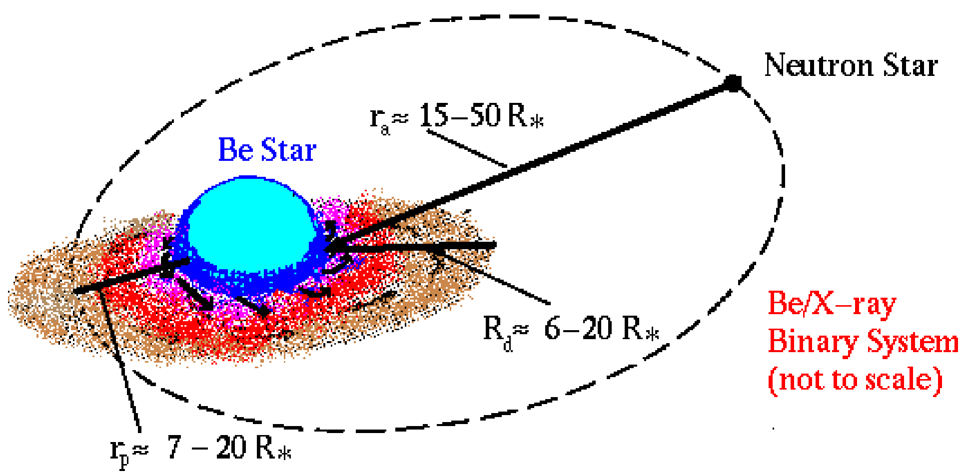
- Accreting WD binaries (Cataclysmic variables)
- Accreting NS/BH binaries (X-ray binaries)
- Non-accreting NS binaries (Binary pulsars)
- Non-accreting BH binaries (LB-1-like objects?)

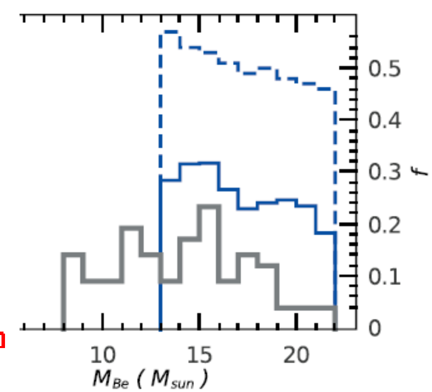
Clues from Be/X-ray binaries

- Why Be stars in X-ray binaries have spectral types earlier than B2 (Negueruela 1998), while isolated Be stars have a spectral distribution of A0−O9 (Slettebak 1982)?



Mode I

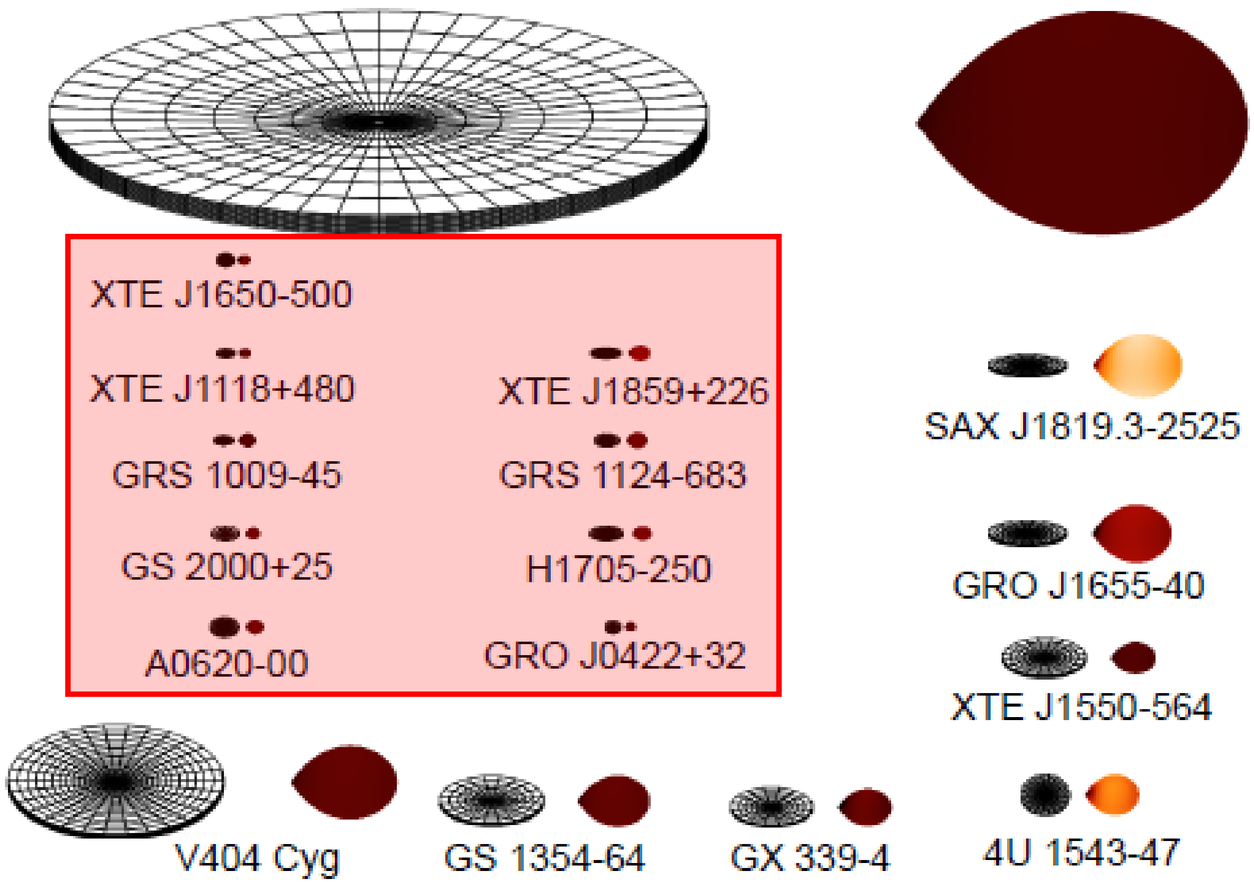




Mode III

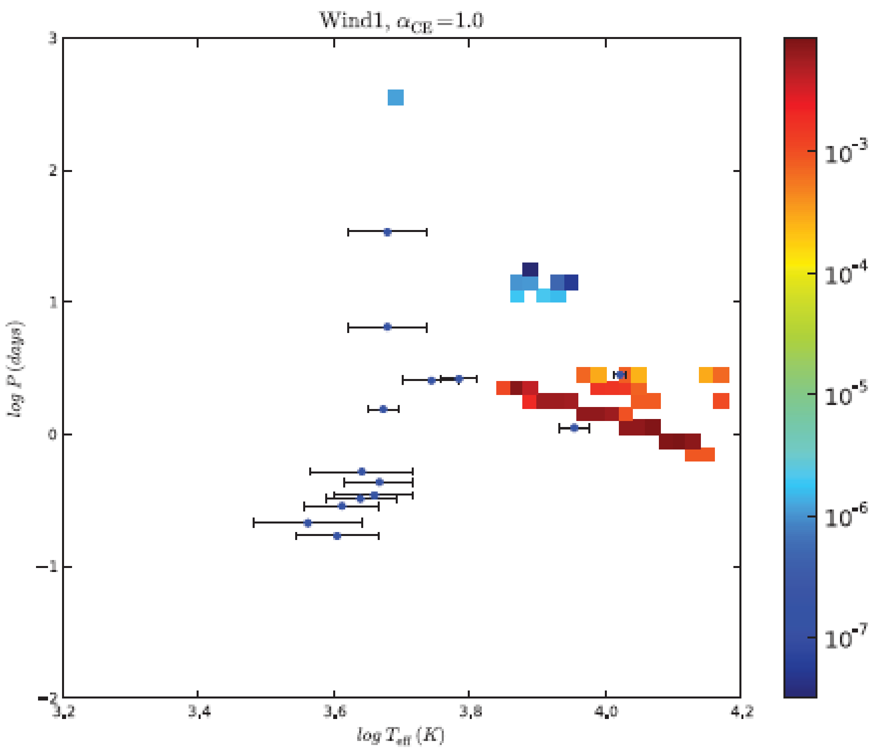
Shao & Li 2014

Clues from BH LMXBs

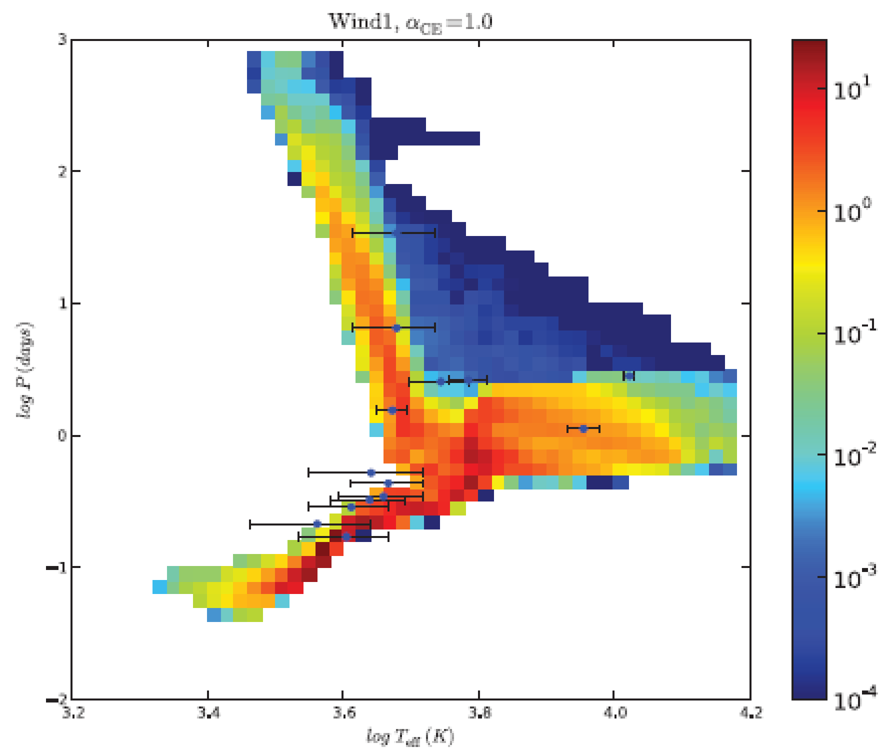


Wang, Jia, & Li 2016

Clues from BH LMXBs



Standard supernova model

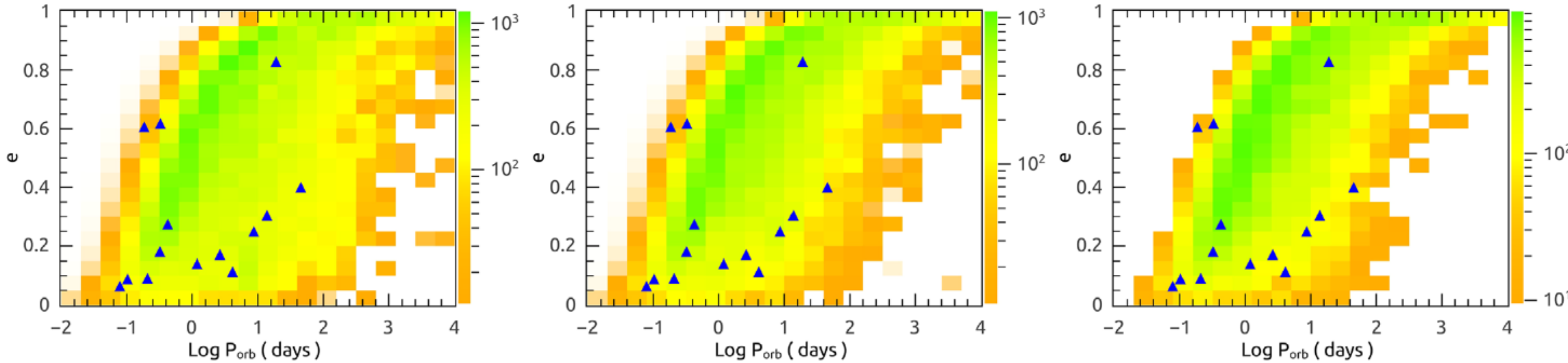


Failed supernova model

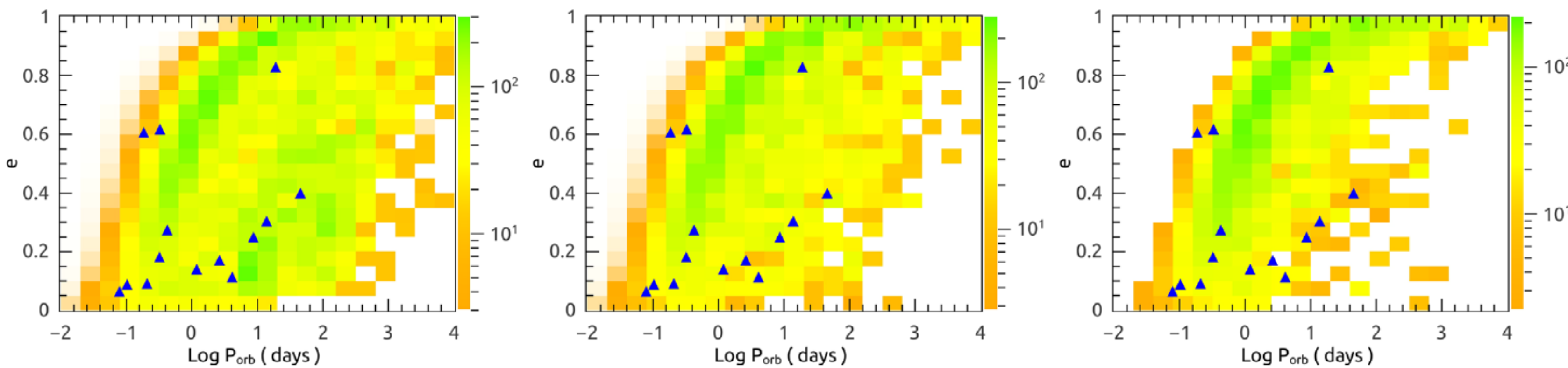
Wang, Jia, & Li 2016

Clues from Double NSs

σ_{ecs}=20 kms^{-1} σ_{ecs}=40 kms^{-1} σ_{ecs}=80 kms^{-1}



σ_{ccs}=150 kms^{-1}



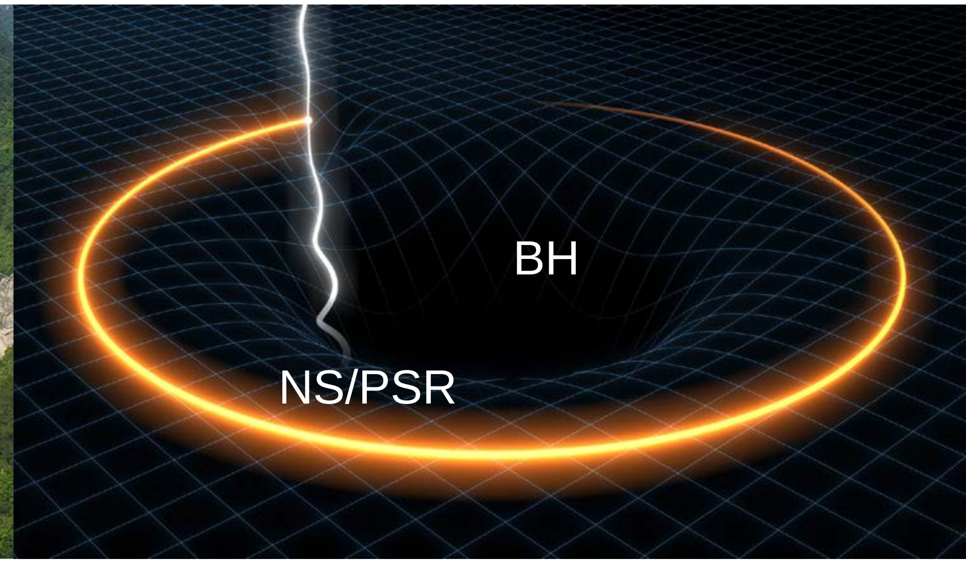
σ_{ccs}=300 kms^{-1}

Shao & Li 2018a

Merger rate and GW Detection Rate

	Merger rate in the Galaxy (Myr^{-1})	Detection rate by aLIGO (Myr^{-1})
BH/BH	~1-10	~10-70
NS/NS	~10-30	~0.1-1
BH/NS	~0.3-2	~0.1-1

Can BH/PSRs be detected by FAST?



Expected number of detectable BH/PSR binaries

S ($M_\odot\,\mathrm{yr}^{-1}$)	σ_k ($\mathrm{km\,s^{-1}}$)	R_birth ($\mathrm{Myr^{-1}}$)	N_T	N_{PM} *	N_{FAST} *
1	50	2.7	16	0.2	1.5
	150	1.3	8	0.1	0.9
	300	0.6	3	0.04	0.3
3	50	8.0	48	0.5	4.5
	150	4.0	24	0.3	2.7
	300	1.8	10	0.1	0.9
5	50	13.3	80	0.8	7.5
	150	6.7	40	0.5	4.5
	300	3.0	17	0.2	1.5

Shao & Li 2018b

Conclusions

- Observation: to understand the formation of double compact stars requires multi-messenger information
- Theory: it is important to reproduce both the merger rate of double compact stars and the characteristics of the Galactic populations of CVs, XRBs, double NSs, etc.