Kavli Institute
for Cosmological Physics
at The University of Chicago

Modeling High-Mass X-ray Binary Formation in the Chandra Era

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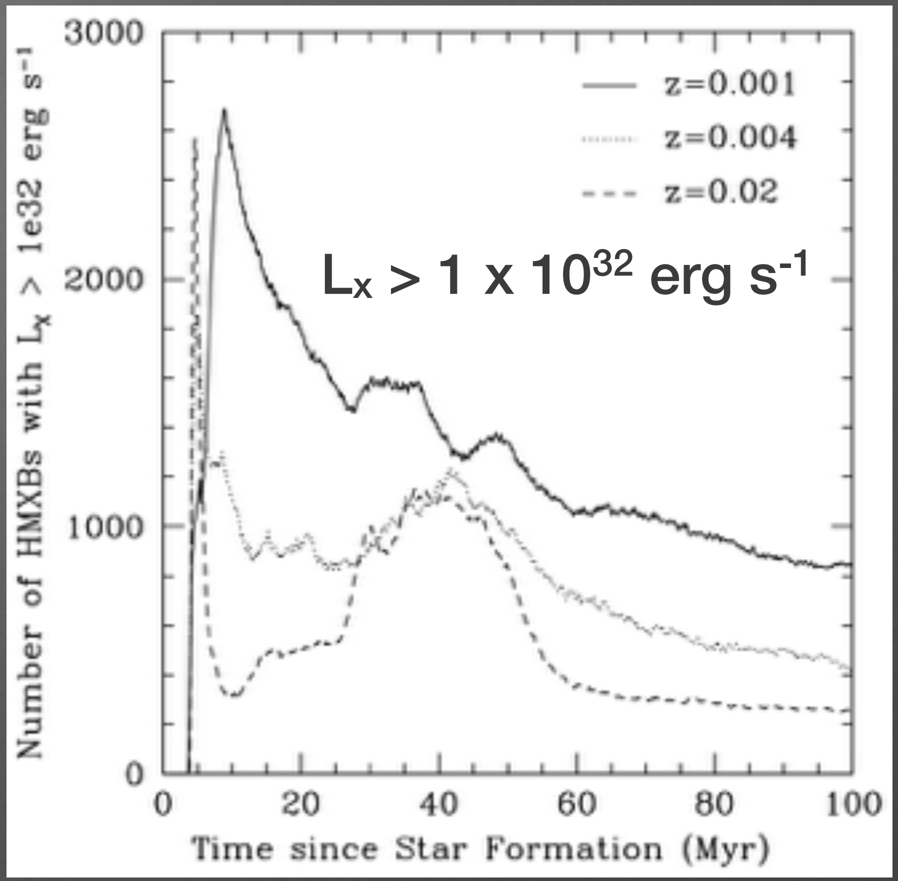
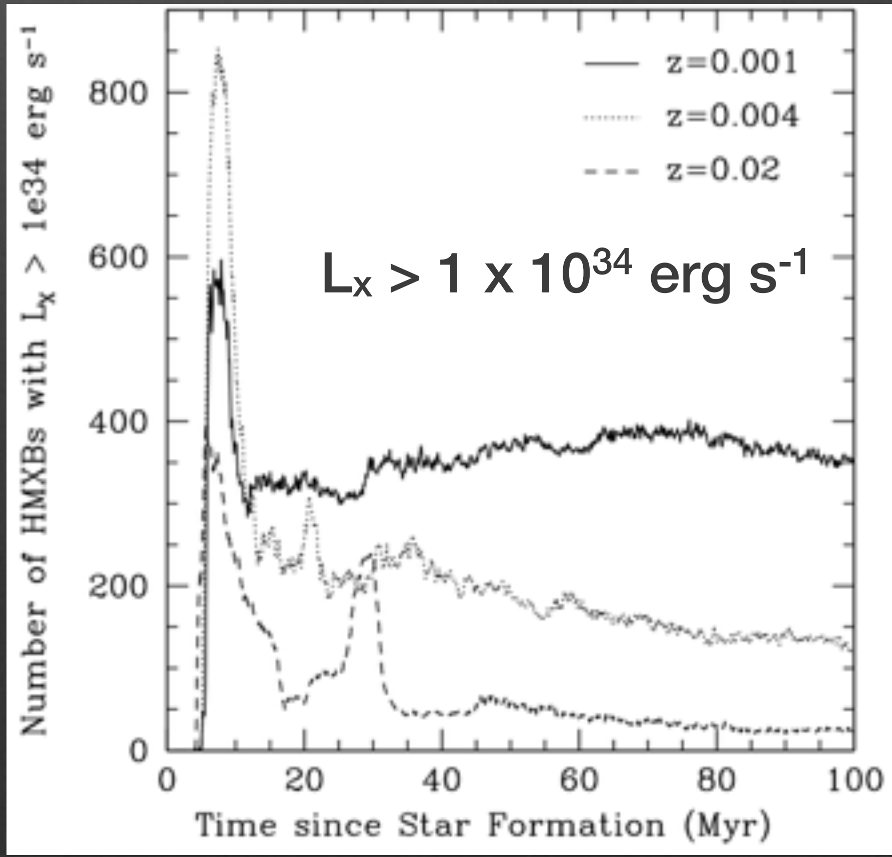
Numerical Modeling of HMXBs

- Have Evolutionary Models for the evolution of single stars (use Single Star Evolution)
- At each step in stellar evolution, calculate if there are important binary interactions, these generally happen on a faster timescale than stellar evolution
- Make adjustments to the stellar properties (assume the star is in equilibrium) based on the outcome of the binary interaction, and continue single star evolution

HMXBs Formed by Starbursts

- Largest population of HMXBs is formed in the first 4-10 Myr after star formation
- The number of HMXBs is highly luminosity dependent
    - Different types of HMXBs!
- Also depends strongly on metallicity

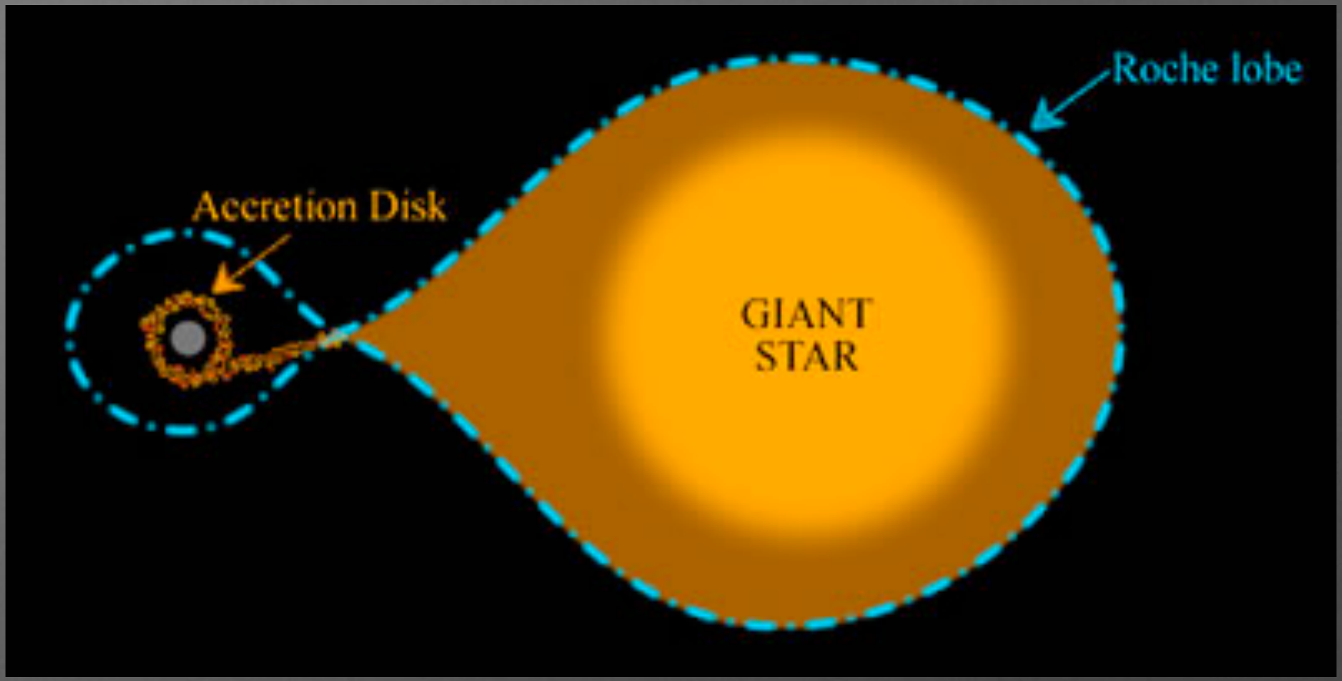


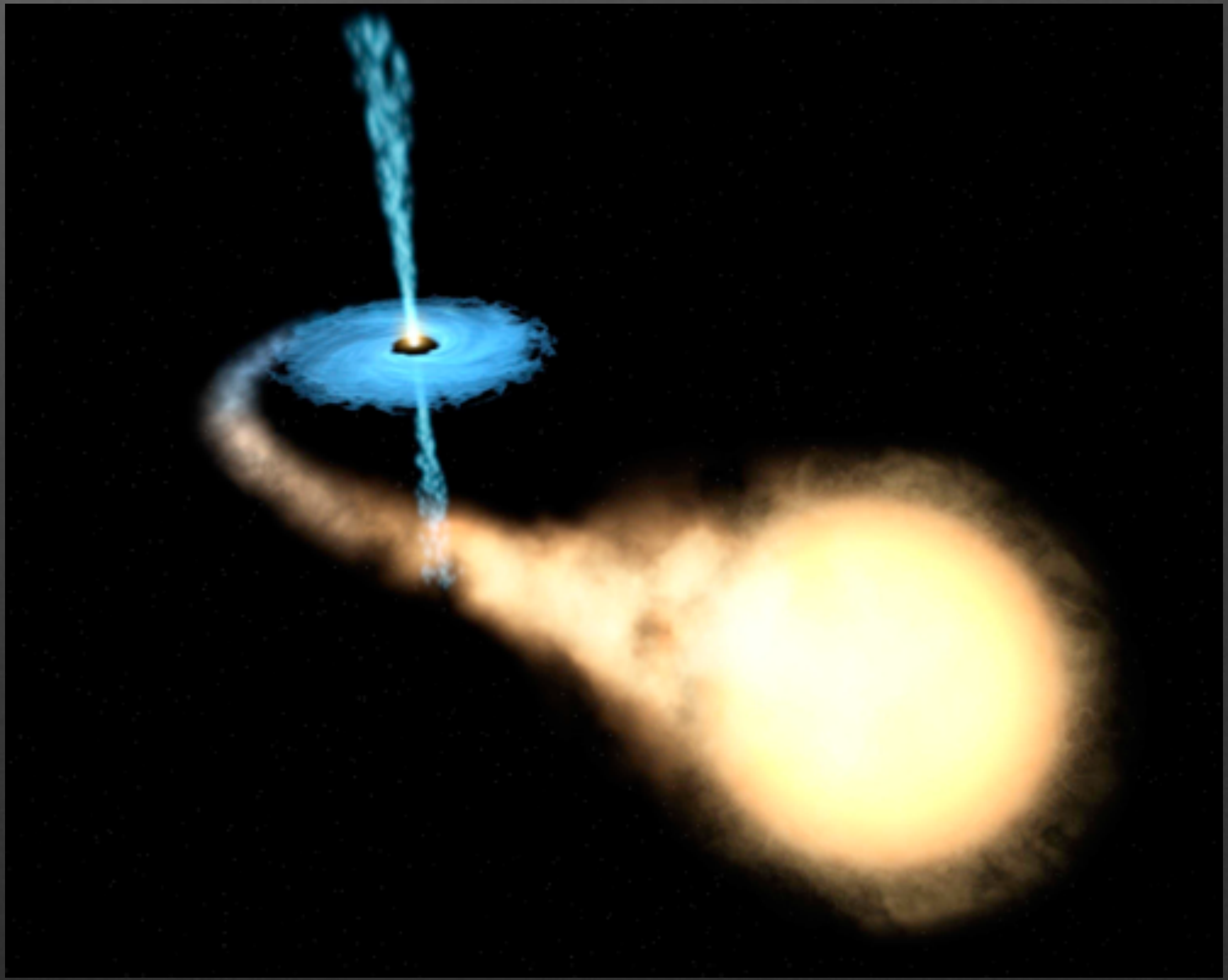


Roche Lobe Overflow vs. Wind Accretion

- Two Methods for producing bright X-Ray emission from accretion onto a compact object

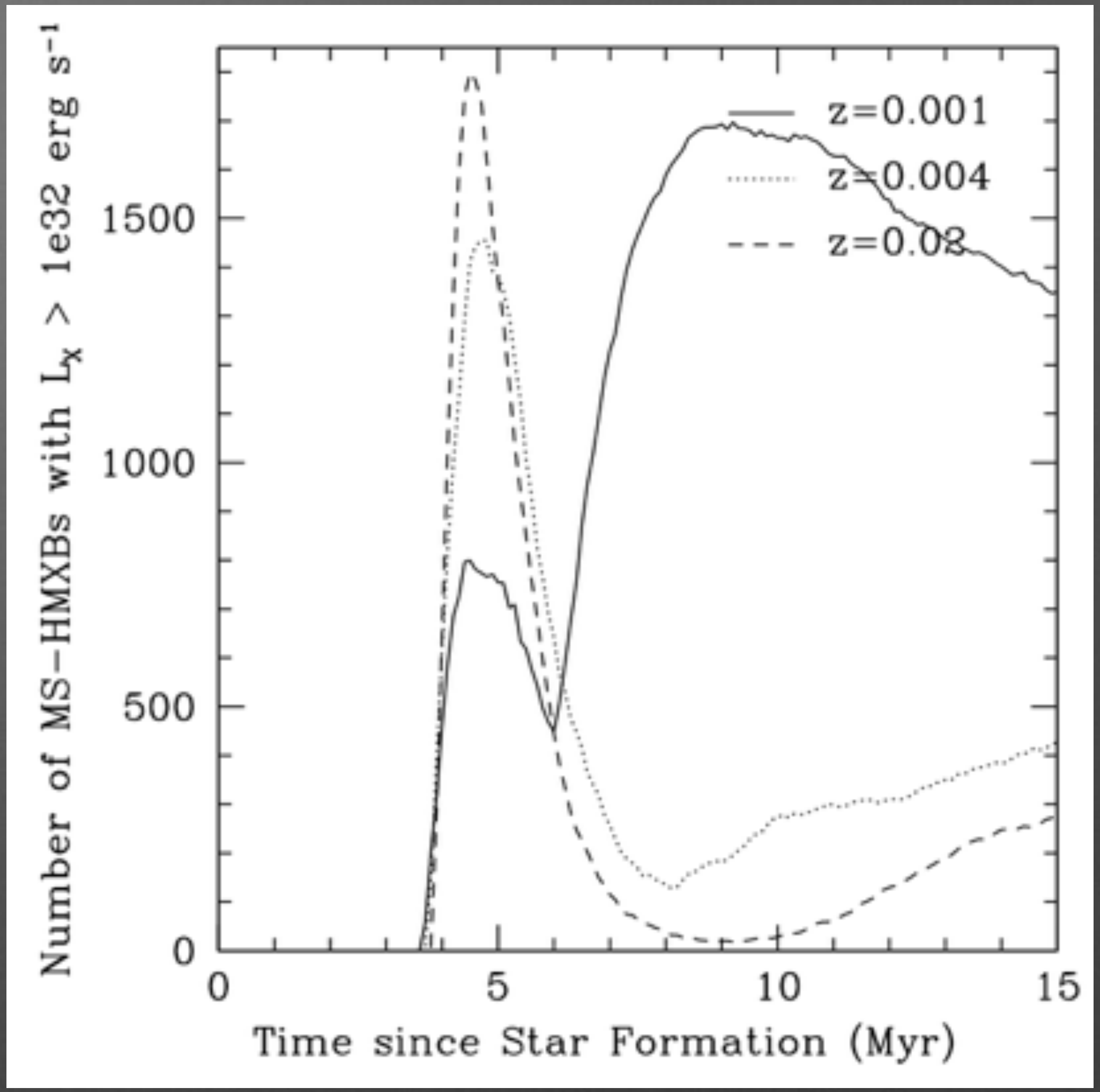
- <u>These methods require different evolution pathways:</u>
  - Different orbital separations
  - Different evolution states for the donor star
  - Different epochs of mass transfer





Wind Accretion HMXBs

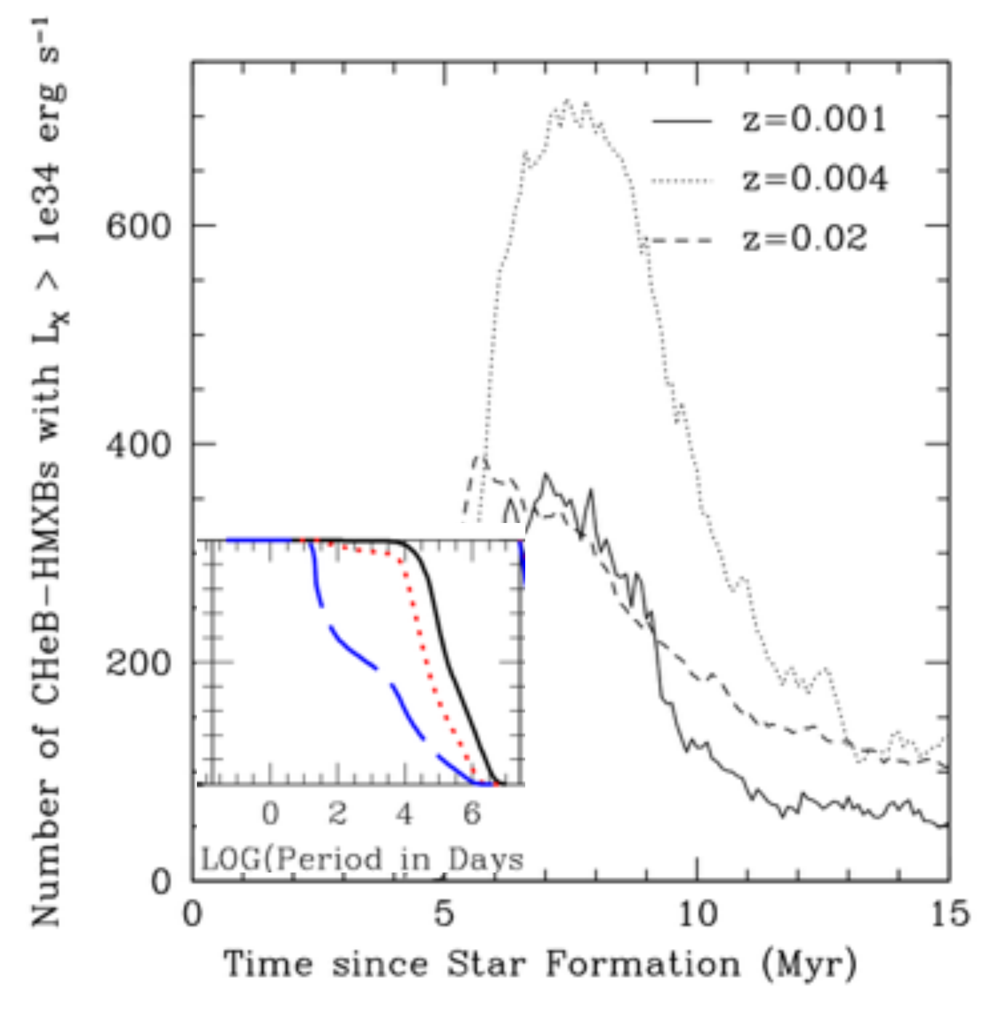
- Luminosity depends on:
  - Wind strength of the donor star (evolution state, metallicity)
  - Orbital Separation
- These systems have ***low*** X-Ray luminosities
  - All systems with a main sequence donor have a luminosity below 10^{34} erg s^{-1}.
- Metallicity greatly influences system formation (see slides below)

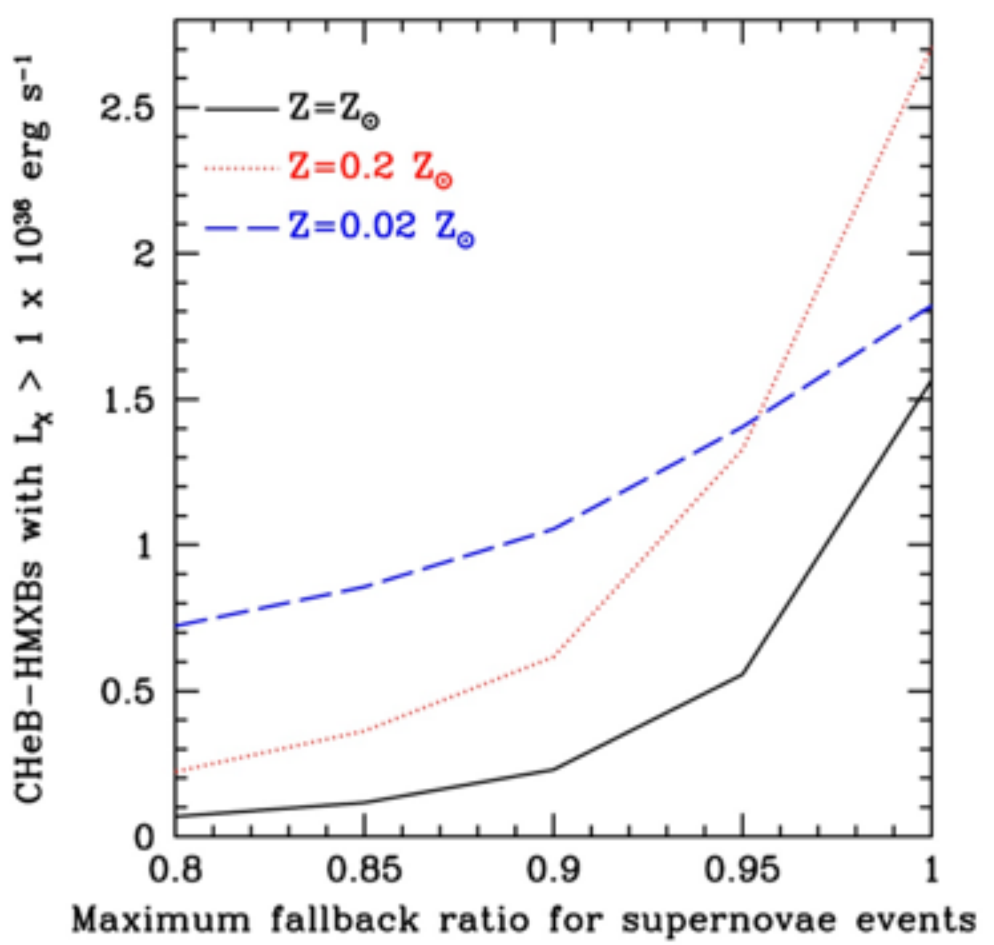


wind-accretion HMXBs with a main sequence donor

Wind Accretion HMXBs

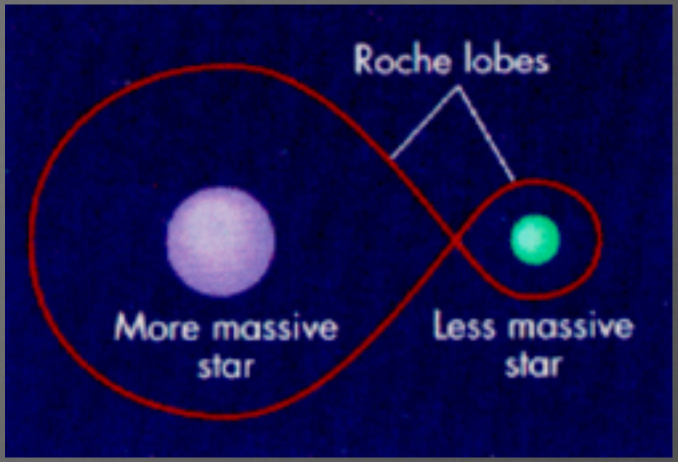
- One method to form very bright HMXBs, systems with very strong winds
  - e.g. (super)giant donor stars
- Can maintain X-Ray luminosities above 10^{36} erg s^{-1}, even for orbital periods larger than 10,000 days
- However, these systems are not observed
- Even small natal kicks (to direct collapse black holes) can disrupt these systems
- More closely bound systems can still survive

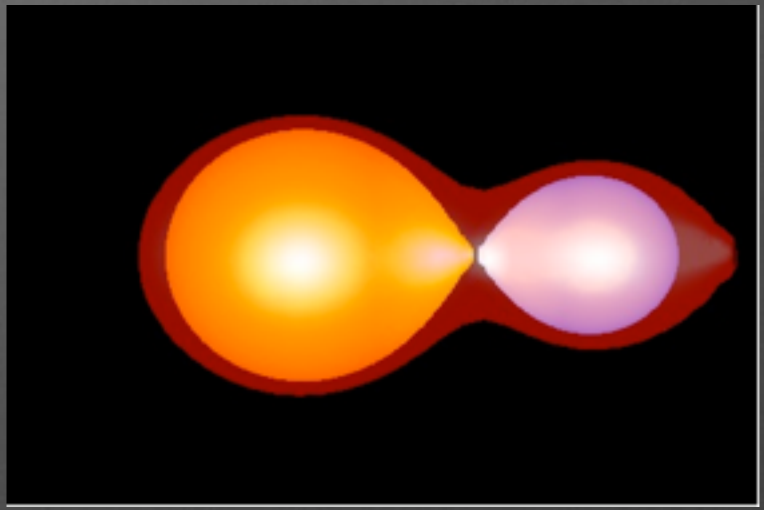


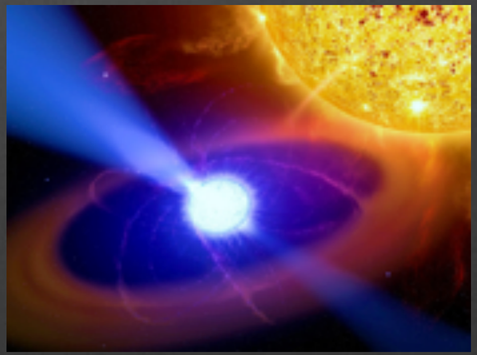


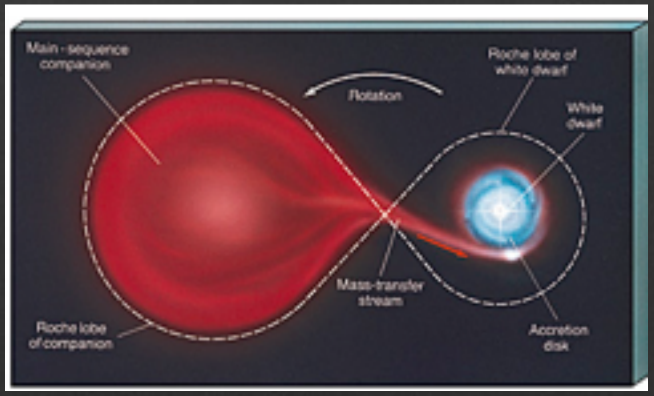
Roche-Lobe Overflow HMXBs

- Complex Evolutionary Mechanism:
  - Binary system begins in relatively tight orbit
  - Common Envelope of primary star draws systems closer together
  - Systems survive natal kick
  - Roche Lobe overflow of the secondary system onto the primary compact object



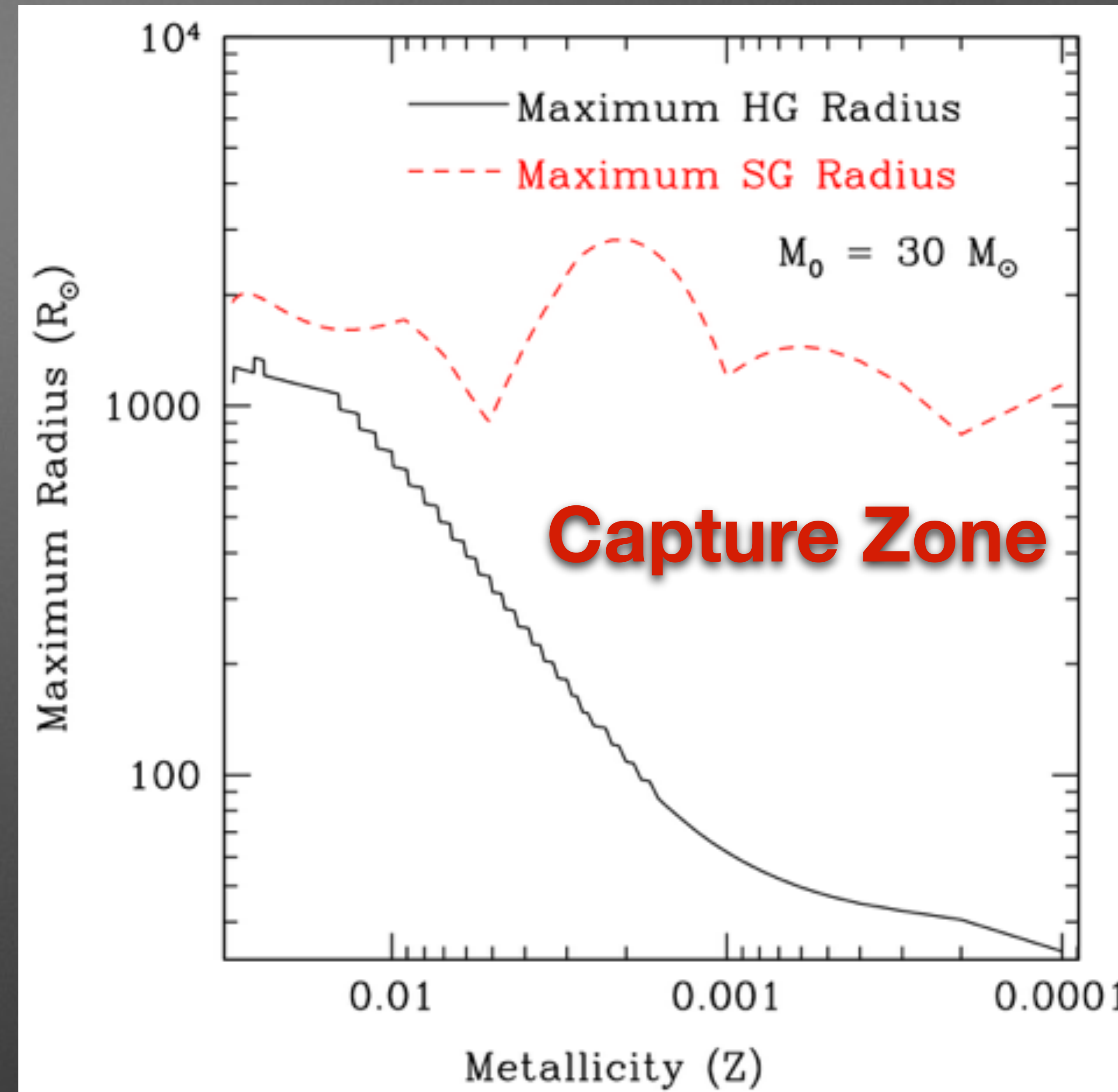






Roche-Lobe Overflow HMXBs

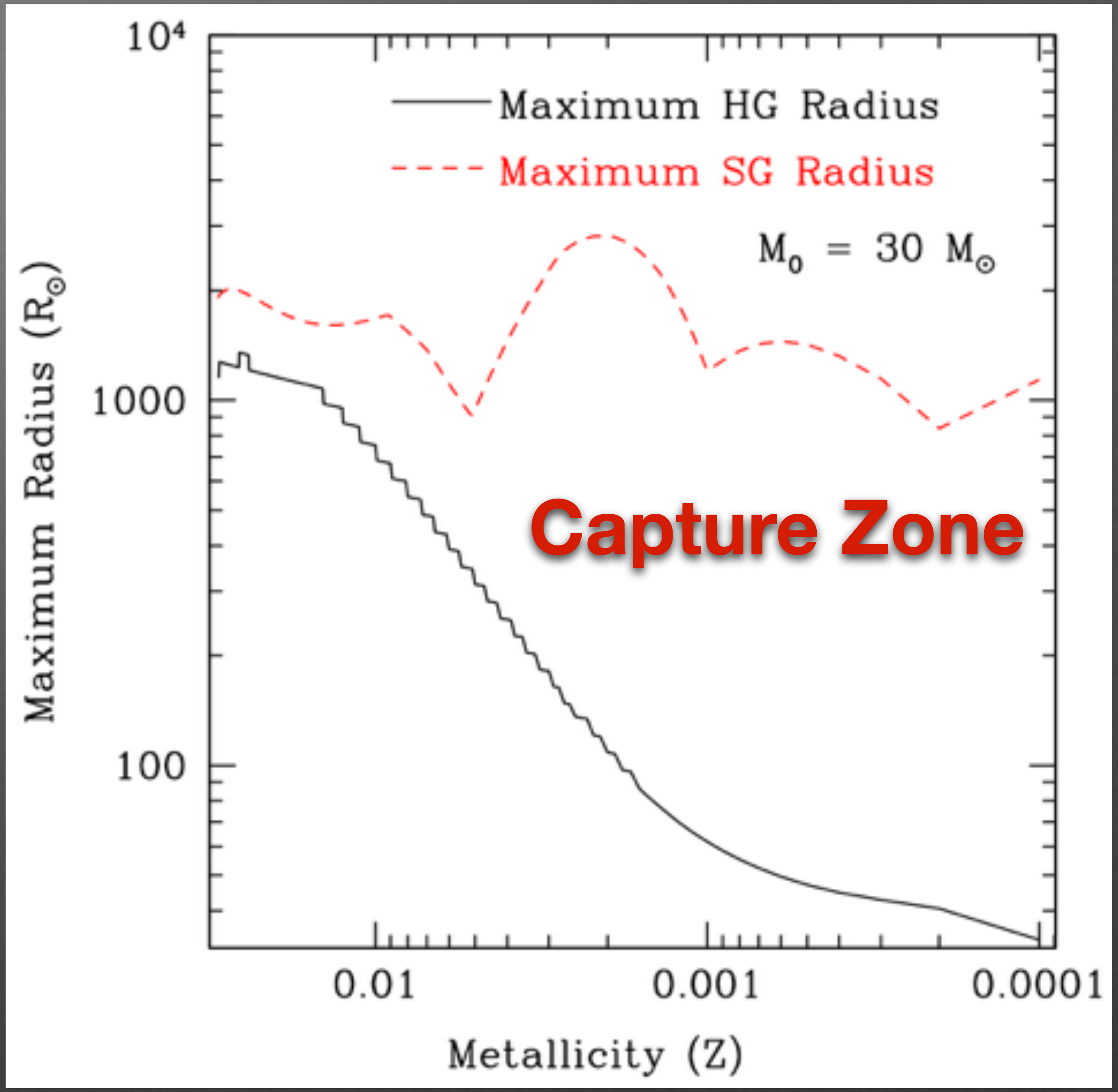
- Ingredients:
  - Need a large initial mass ratio between the primary and secondary
  -
  -



calculated by Single Star Evolution (SSE) code
Hurley et al. (2000)

Roche-Lobe Overflow HMXBs

- Ingredients:
  - Need a large initial mass ratio between the primary and secondary
  - Initial orbital separation must be large enough to avoid a common envelope when the primary star evolves through the Hertzsprung Gap (Taam & Sandquist 2000)
  -



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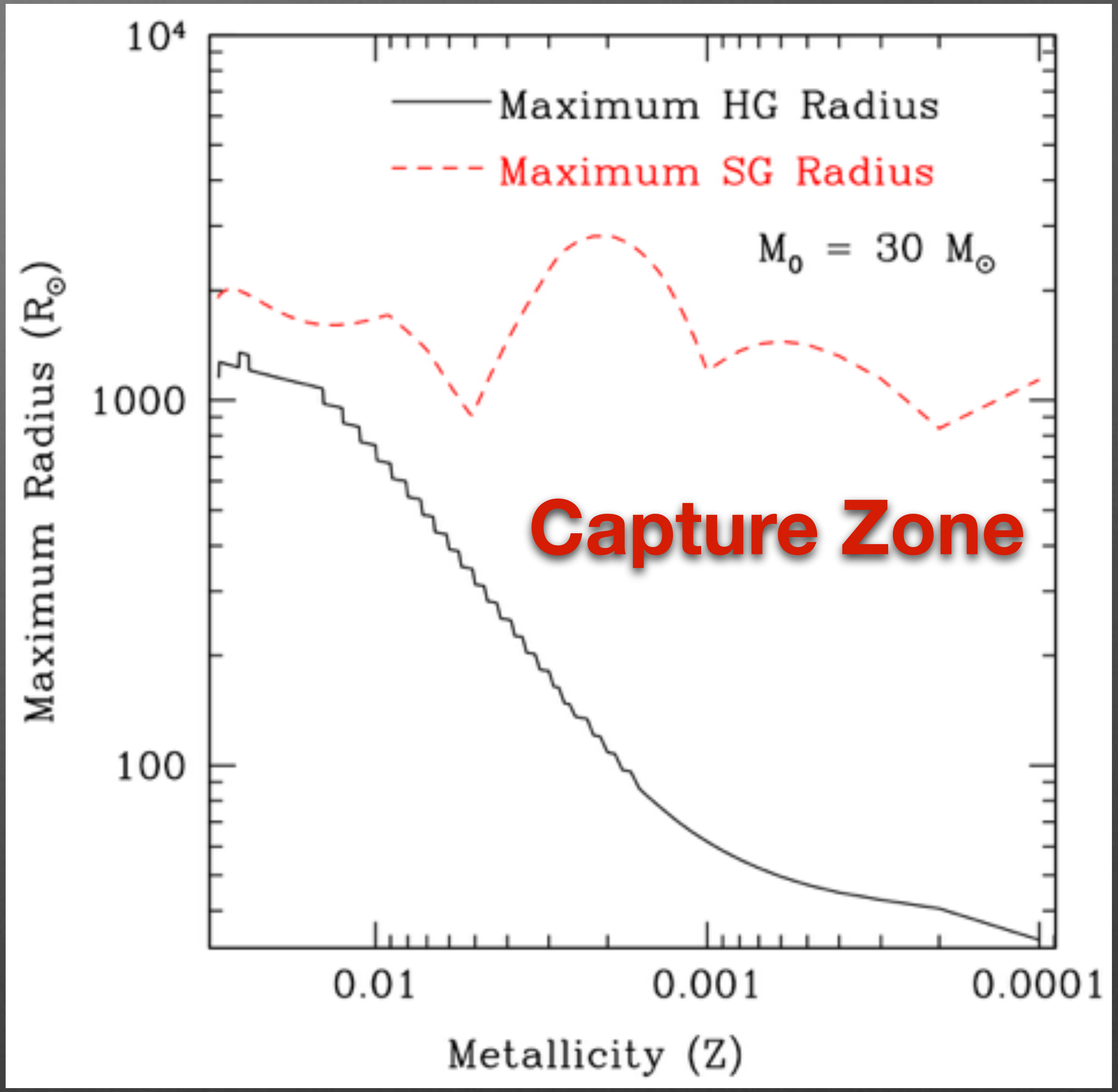
Roche-Lobe Overflow HMXBs

- Ingredients:
  - Need a large initial mass ratio between the primary and secondary
  - Initial orbital separation must be large enough to avoid a common envelope when the primary star evolves through the Hertzsprung Gap (Taam & Sandquist 2000)
  - Initial orbital separation must be small enough to produce a common envelope during the supergiant stage of the primary star.



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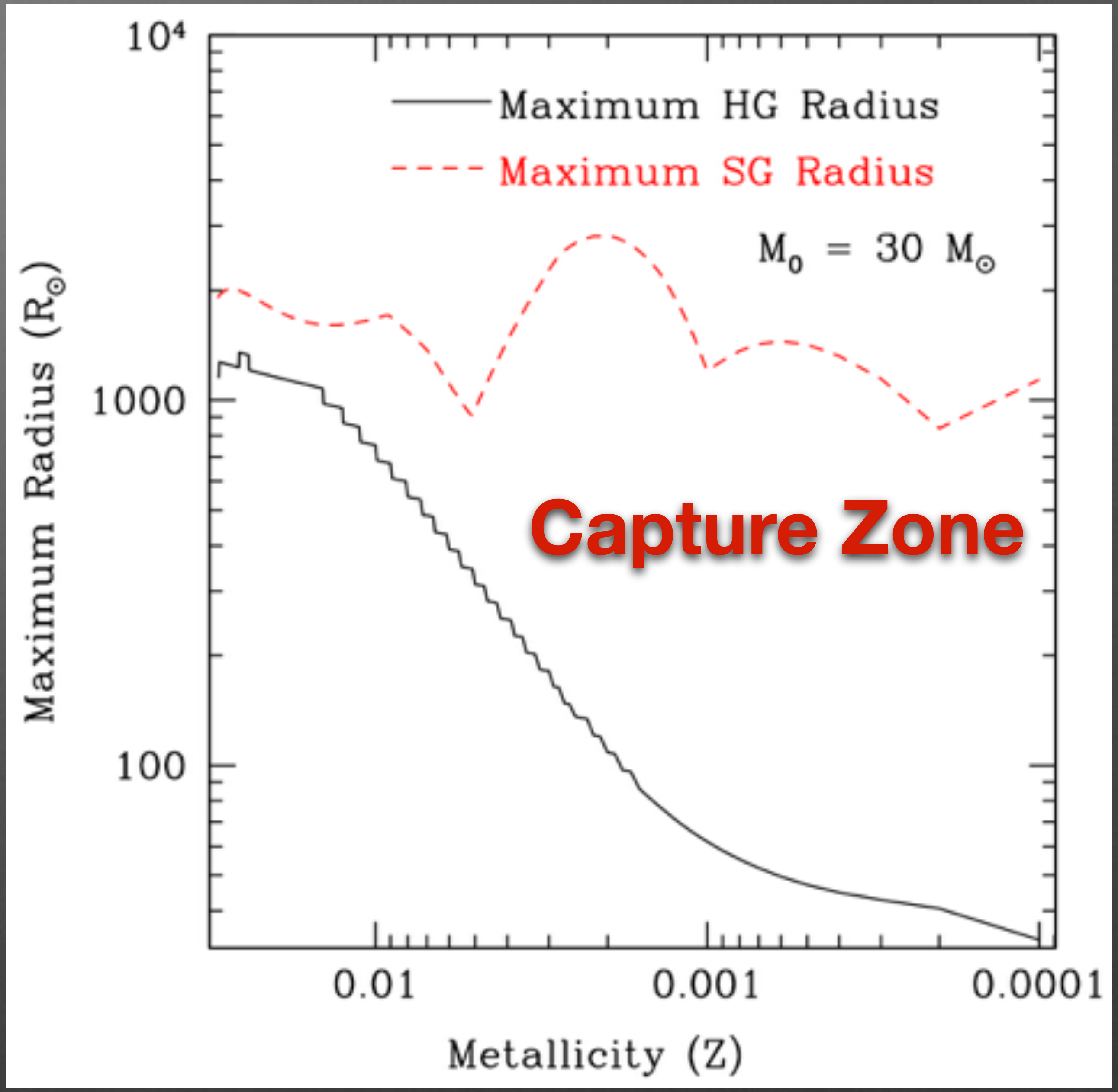
Hurley et al. (2000)

Roche-Lobe Overflow HMXBs

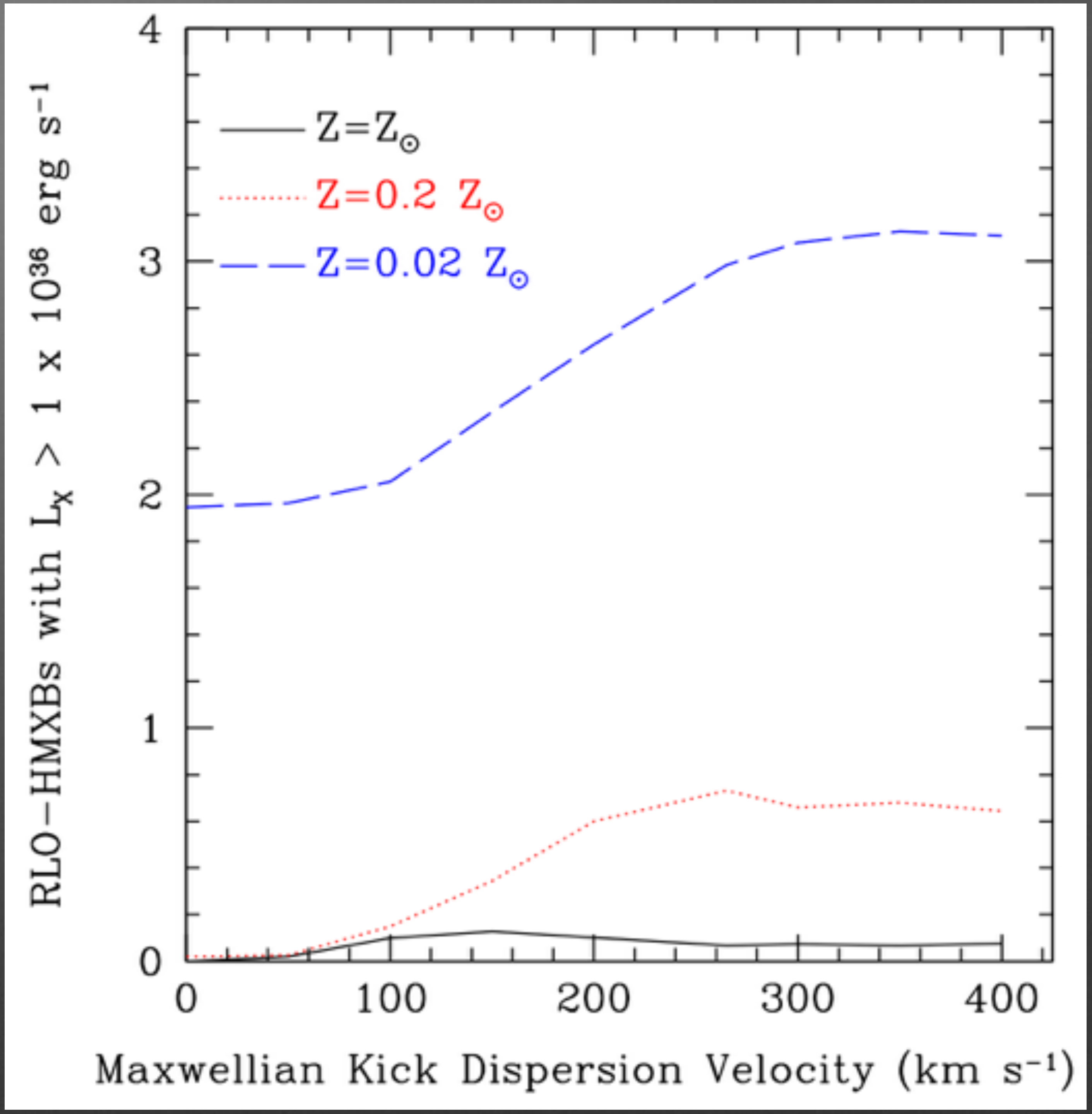
- To Survive the CE, the potential energy in the binary orbit must exceed the envelope binding energy (Webbink 1984)
- Note: Strong metallicity dependence in the parameter space for survivable CEs.
    - Produces a population of HMXBs which is strongly metallicity dependent



calculated by Single Star Evolution (SSE) code
Hurley et al. (2000)

Effect of Natal Kicks on RLO-HMXBs

- Interestingly, this is not enough:
  - At the termination of the CE, the systems must not be in Roche-Lobe Overflow
  - However, the binary must re-enter Roche-Lobe Overflow.
  - Two possibilities:
    - Evolution of donor star (expanding radius)
    - Supernova Natal Kicks!



Linden et al. (2010)

*also observed in LMXBs (Kalogera & Webbink 1998)

Apply these Models to Three Current Problems

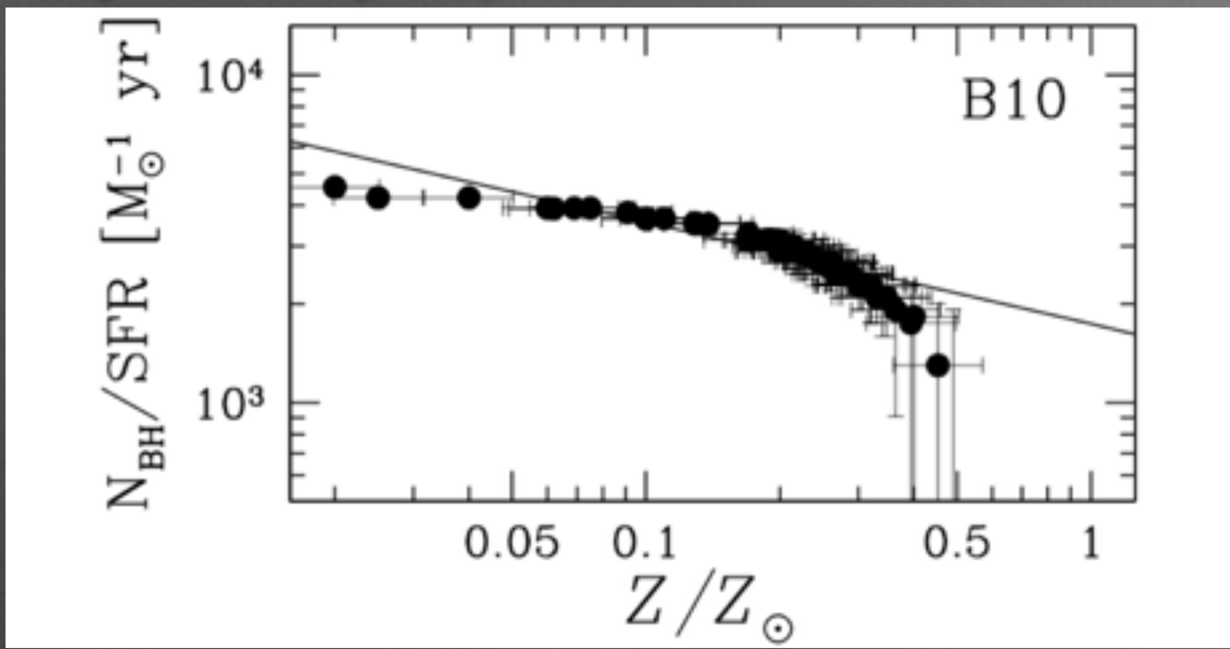
- The Population of Ultra-luminous X-Ray Sources (ULX)

- The population of HMXBs with a B[e] type donor (Be-HMXBs)

- The paucity of HMXBs with a Wolf-Rayet donor

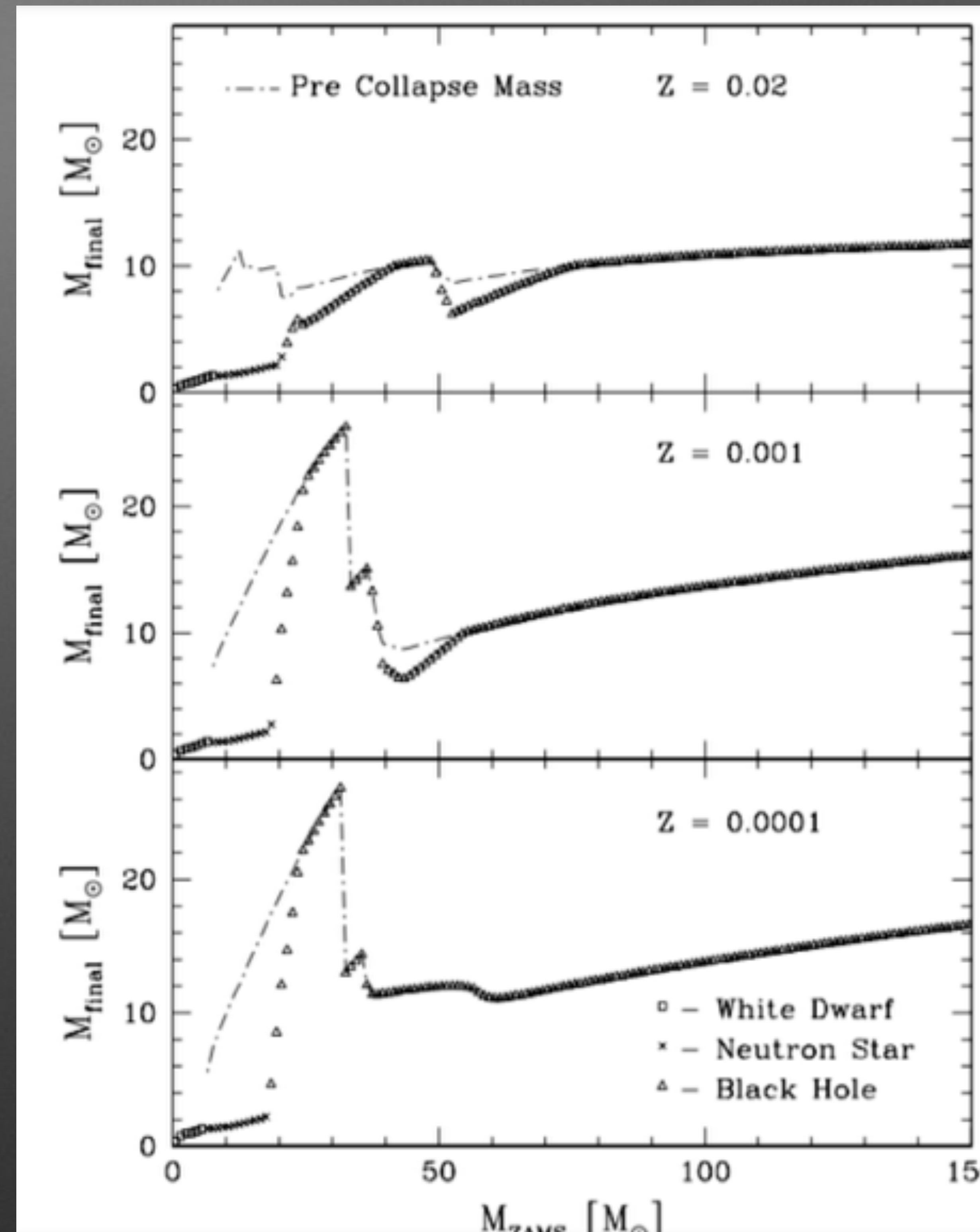
ULX as a Function of Metallicity

Mapelli et al. (2010)



- Observations indicate that ULX formation rate increases with decreasing metallicity

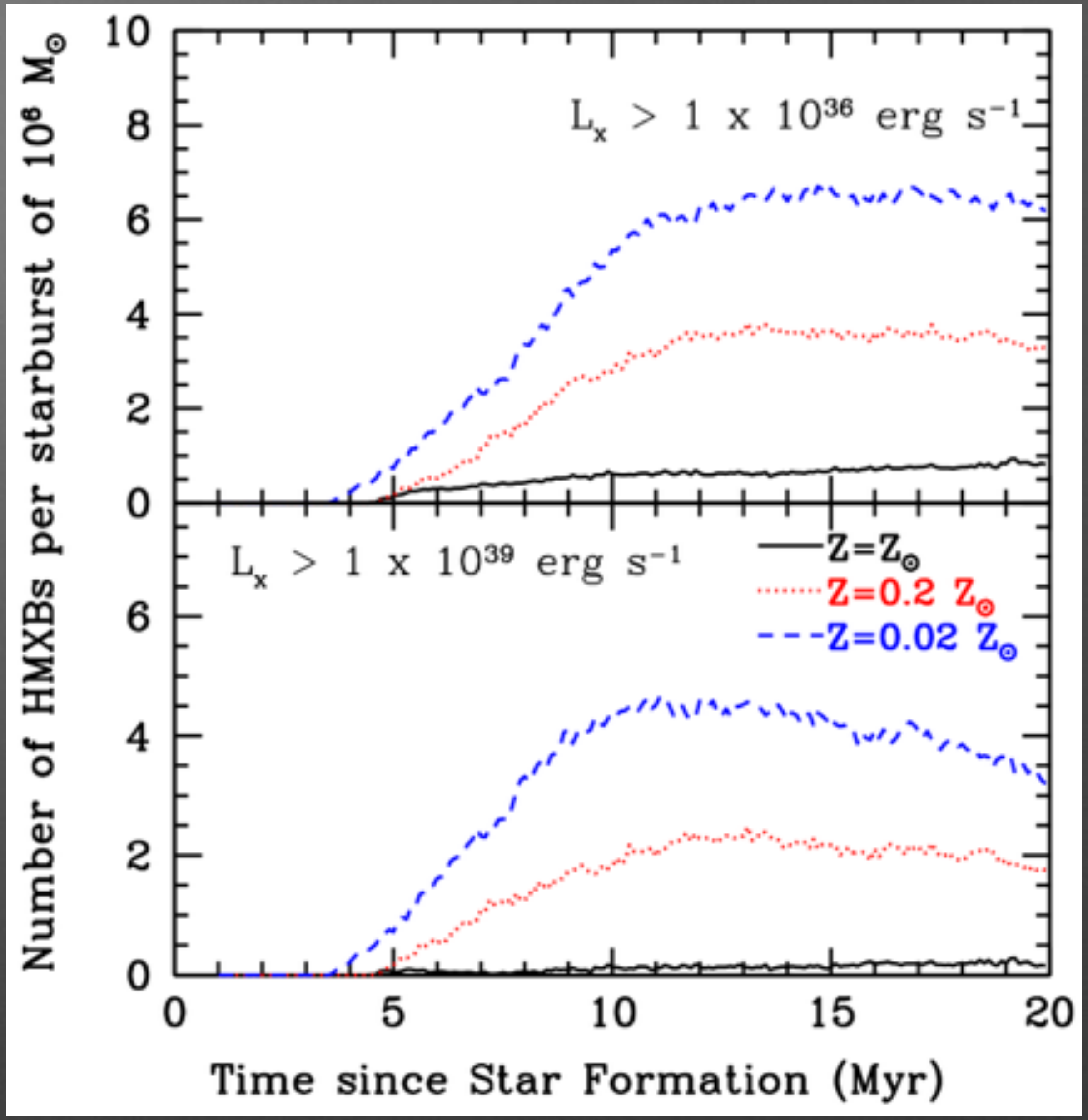
- Previous Theory: Low metallicity means heavier black holes and brighter HMXBs



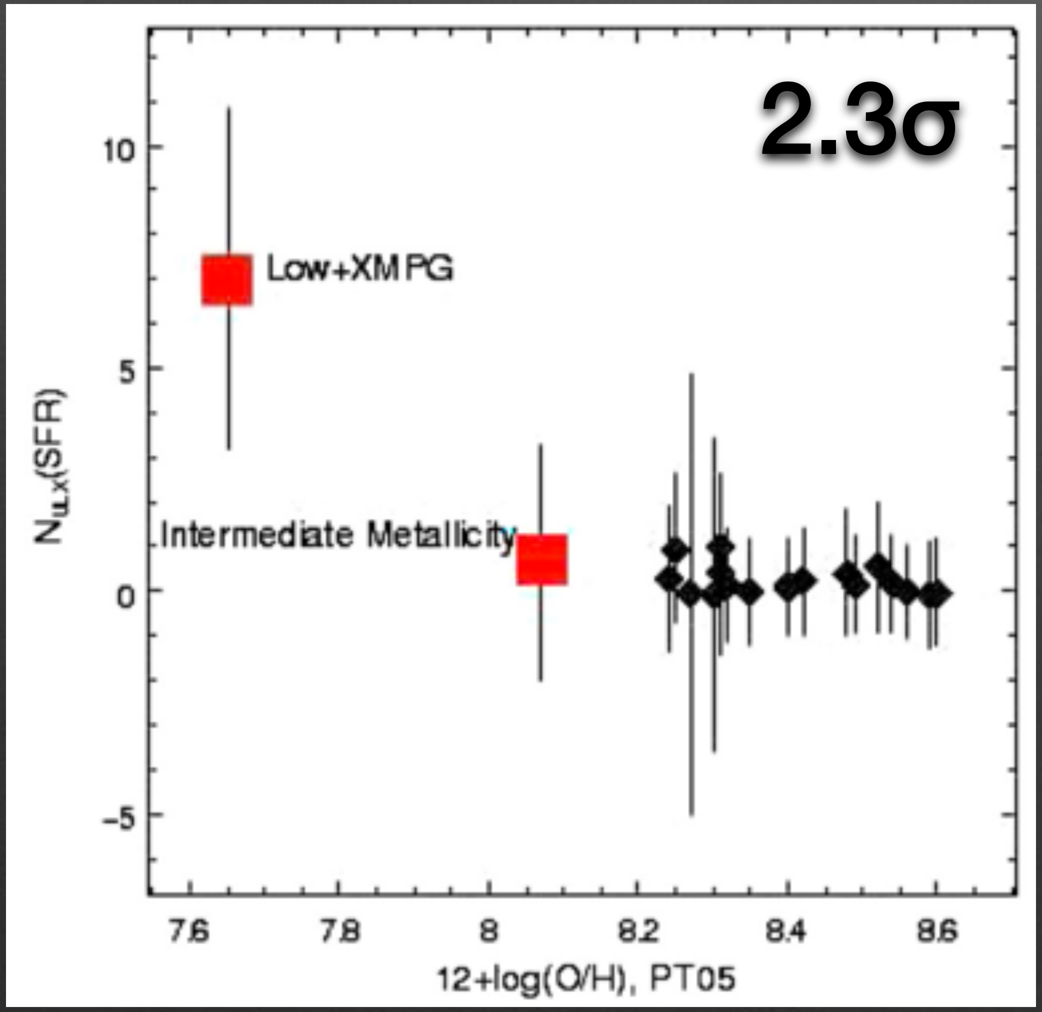
Belczynski et al. (2004)

Ultra-Luminous X-Ray Sources

- The majority of ULX are powered by Roche Lobe Overflow
- Binary evolution provides you with a mechanism to explain the observed overabundance of ULX in low-metallicity environments

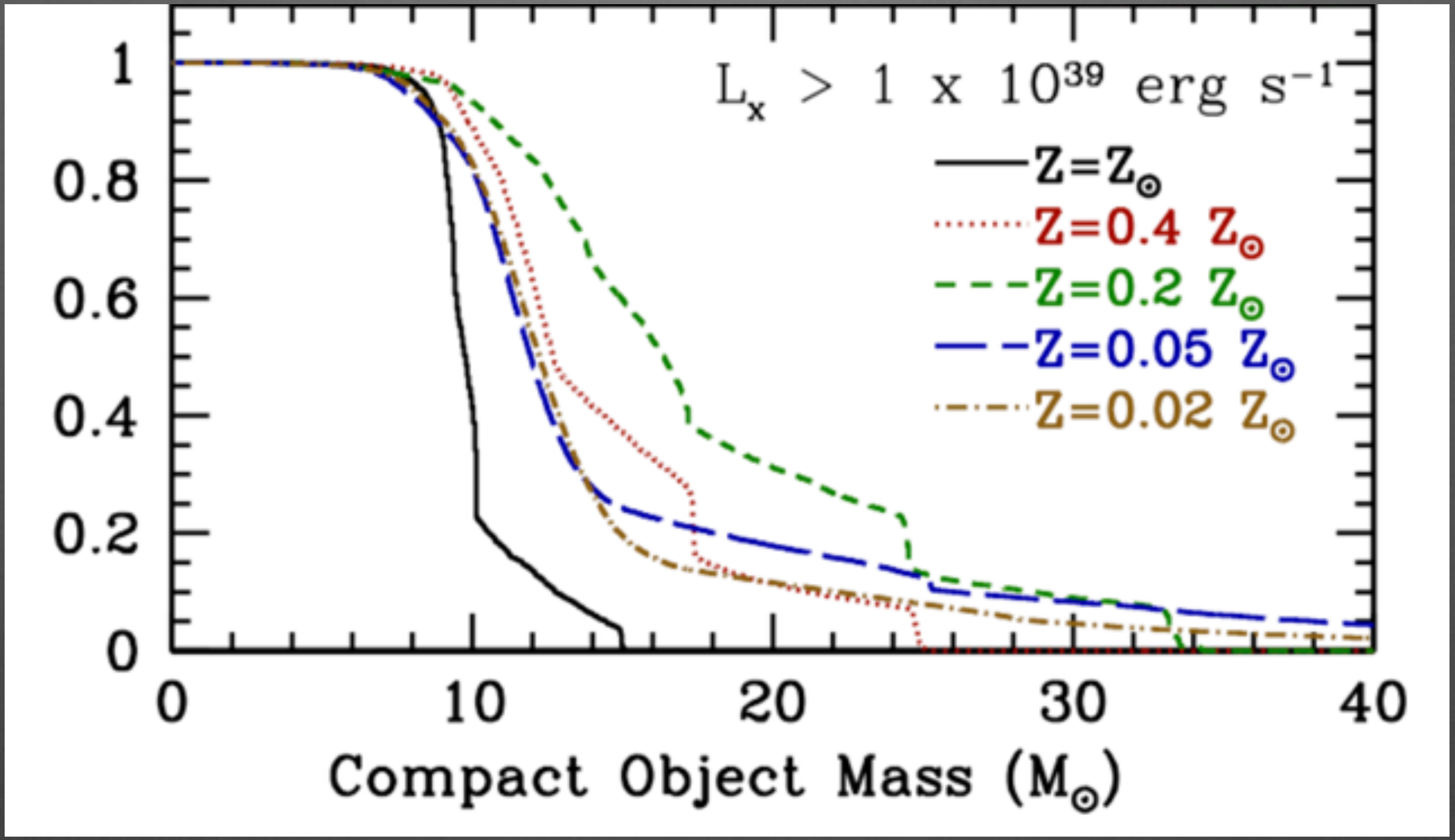


Linden et al. (2010)



Prestwich et al. (2013)

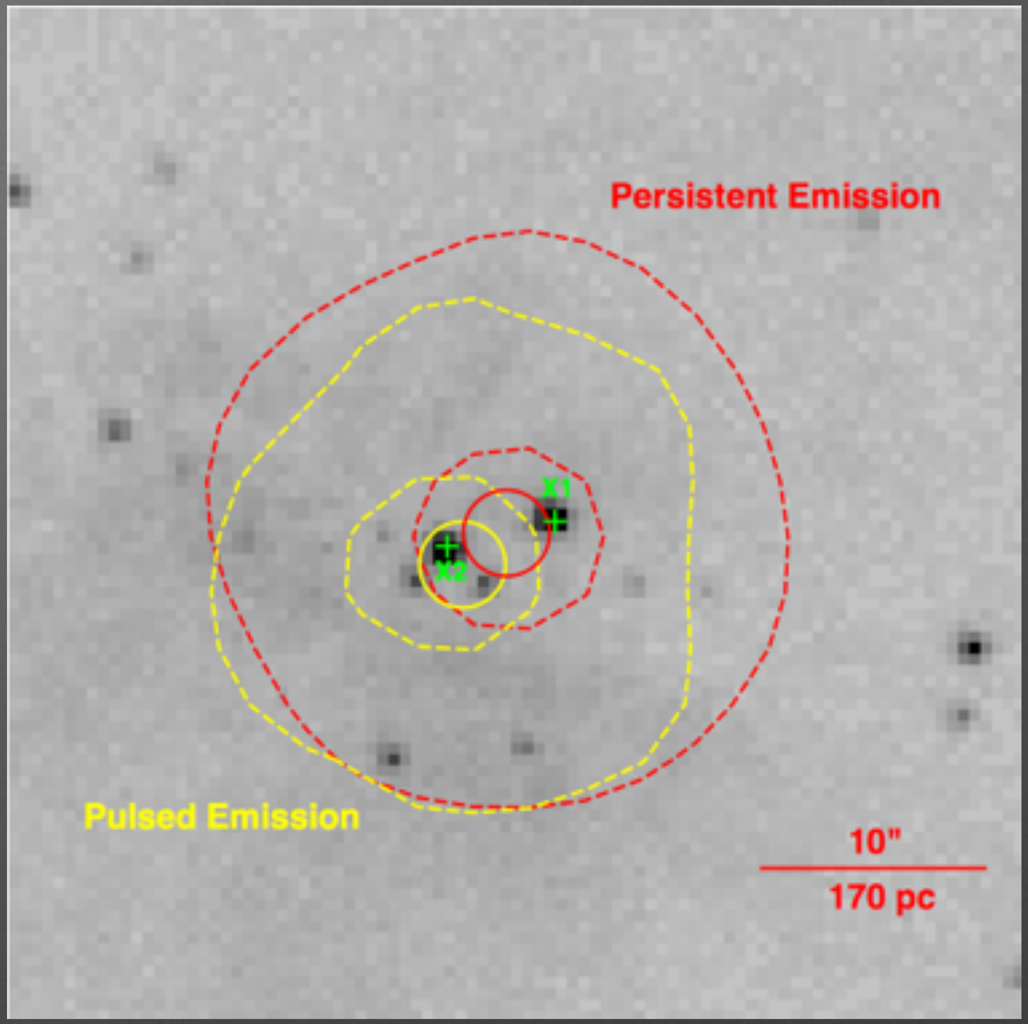
These Models are Testable!



- In the single star evolution mechanism there is a clear negative correlation between the metallicity and the compact object mass
- In the binary evolution mechanism, there is a positive correlation between the metallicity and the black hole mass

A Neutron Star ULX in M82 !?

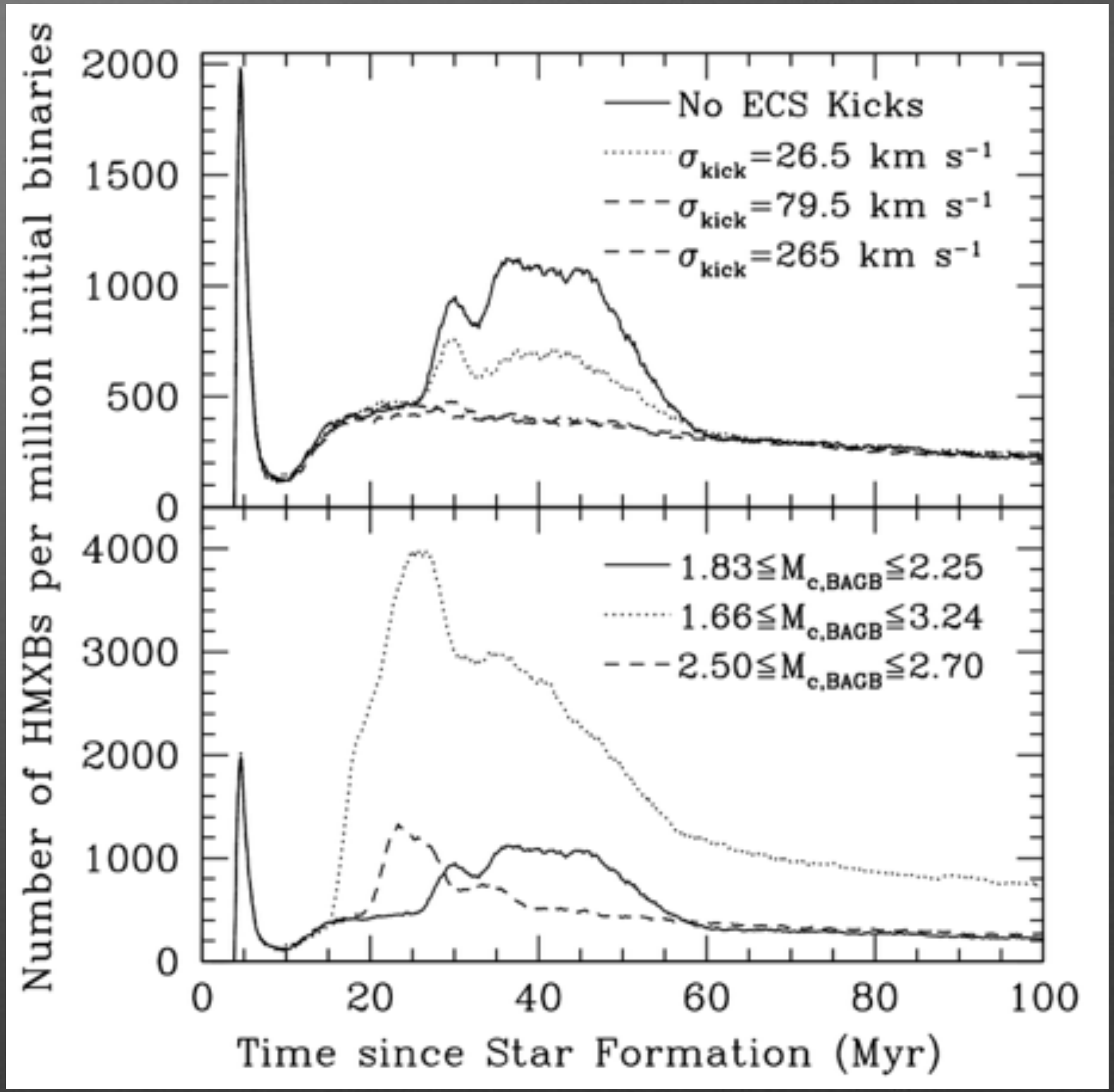
- Observation of an ULX with a neutron star compact object
- Obviously, is not formed due to single star evolution properties
- A strong indication that binary evolution plays a critical role in ULX formation



Bachetti et al. (2014)

Be-HMXBs

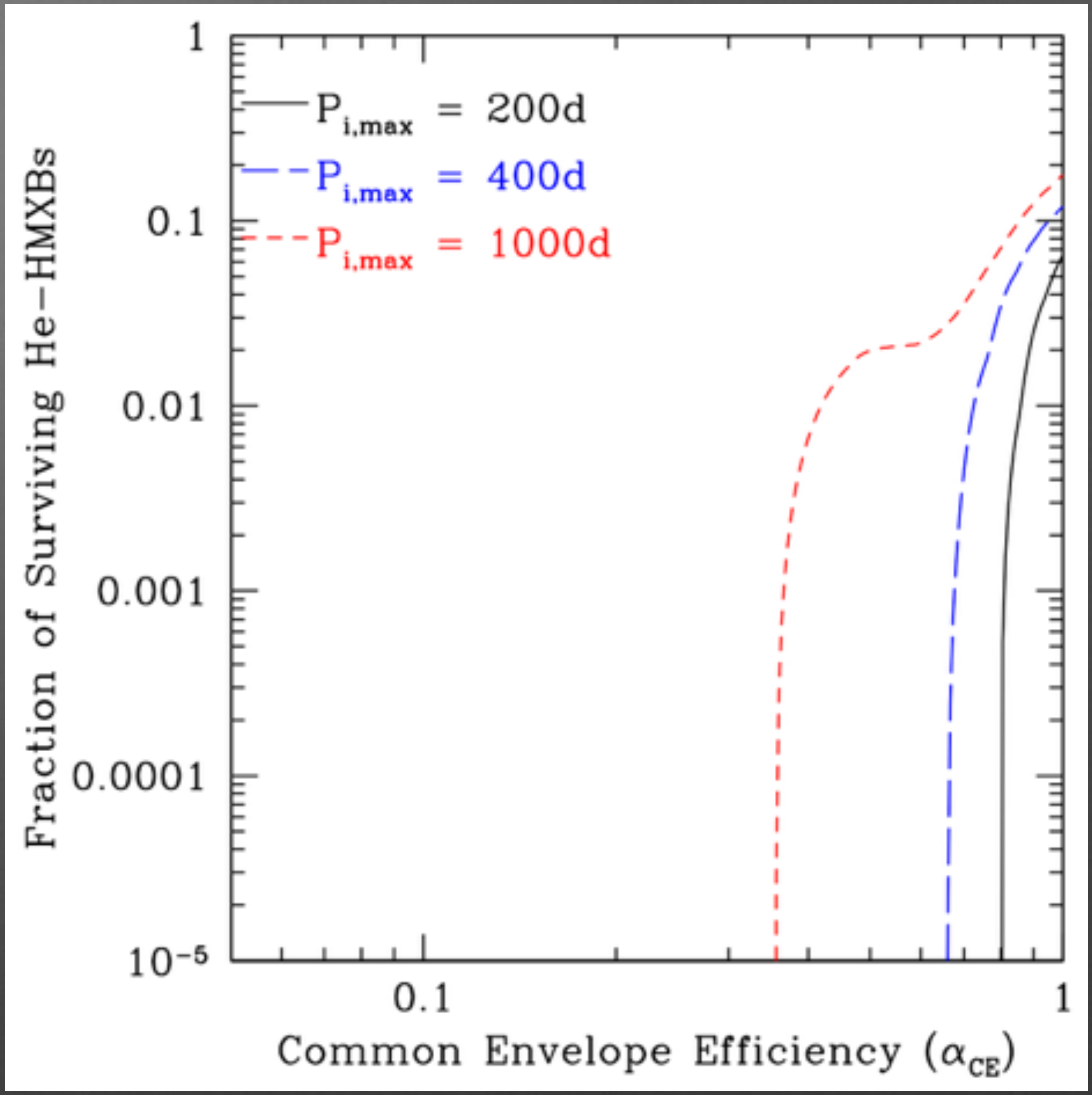
- At lower luminosities, Be-HMXBs form a substantial fraction of the total HMXB number
- Be-HMXBs require a negligible natal kick in the primary NS
- Electron Capture Supernovae provide a natural explanation
  - Age (form in stars with ZAMS mass 8-12 $M_{\odot}$, lifetime ~ 30 Myr)
  - Natal Kick Velocities
  - Spin-up (stable, long term mass transfer prior to SN pushes angular momentum onto the donor)
- This forms a powerful probe of neutron star formation at relatively low masses (8-12 $M_{\odot}$)



TL, Sepinsky, Kalogera, Belczynski (2009)

WR-HMXBs

- A primary theoretical question is the lack of observed HMXBs with a Wolf-Rayet donor
- These systems should be extremely bright, and detectable.
- They should be the formed as a final evolution state of the observed B[e]-HMXB population
- This constrains modeling uncertainties to the CE phase between the B[e]-HXMB and WR-HMXB periods
- Find that this constraints the common envelope efficiency to be smaller than 1 (α_{CE} < 0.88)



TL, Valsecchi, Kalogera (2012)

Conclusions

- Multiple evolutionary pathways can produce a bright HMXB — different pathways lead to different characteristics of the system
- Metallicity plays an important role in determining the HMXB population
  - Not in determining the parameters of a system moving through an evolutionary pathway
  - Primarily in determining the efficiency of each evolutionary pathway