Gravitational Waves from Compact Object Binaries

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Institute for Physics and Mathematics of the Universe Seminar
Kashiwa, Japan • Feb. 25, 2009

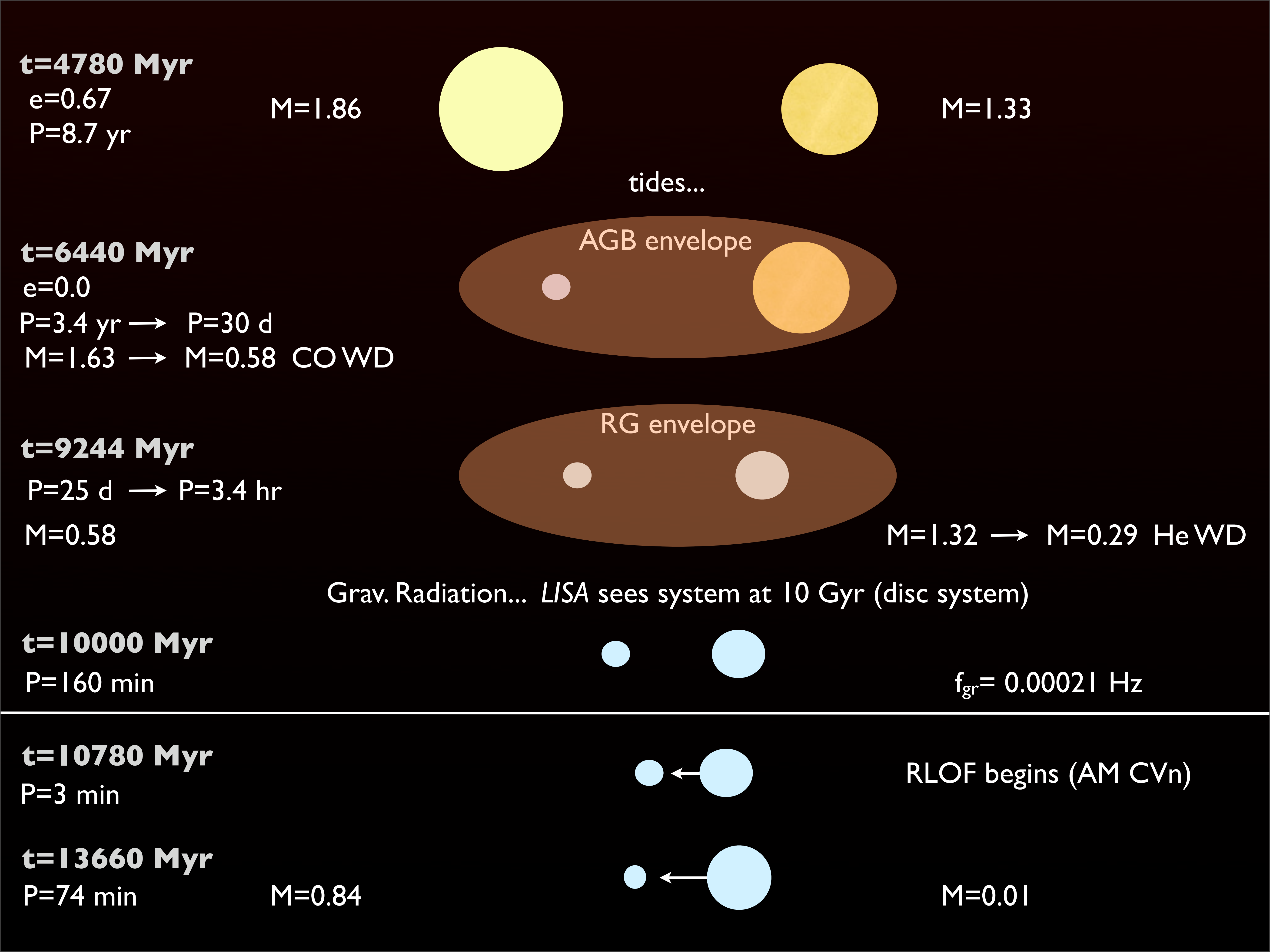
Outline

- binary evolution very brief overview
- StarTrack population synthesis code
- wd + wd binaries (LISA)
- ns + ns, ns + bh, bh + bh (e.g., LIGO)

Binary Star Evolution

importance of close binaries

- ~ 2/3 of stars are in binary systems (50% binary fraction)
- Observations: initial orbital parameters (separations, eccentricities, initial binary star mass ratios) somewhat constrained (observations very difficult)!
- Close binaries give rise to interesting and higly energetic astrophysical phenomena (SNIa explosions, novae bursts, Super Soft X-ray Sources, accretion-induced collapse, Gravitational Radiation (GR), Gamma Ray Bursts)
- Most uncertain phase of binary evolution which “brings stars close together”: Common Envelope (CE)


t=4780 Myr
e=0.67
P=8.7 yr
M=1.86
M=1.33
tides...
t=6440 Myr
e=0.0
P=3.4 yr ⟶ P=30 d
M=1.63 ⟶ M=0.58 CO WD
AGB envelope
RG envelope
t=9244 Myr
P=25 d ⟶ P=3.4 hr
M=0.58
M=1.32 ⟶ M=0.29 He WD
Grav. Radiation... *LISA* sees system at 10 Gyr (disc system)
t=10000 Myr
P=160 min
f_{gr}= 0.00021 Hz
t=10780 Myr
P=3 min
RLOF begins (AM CVn)
t=13660 Myr
P=74 min
M=0.84
M=0.01

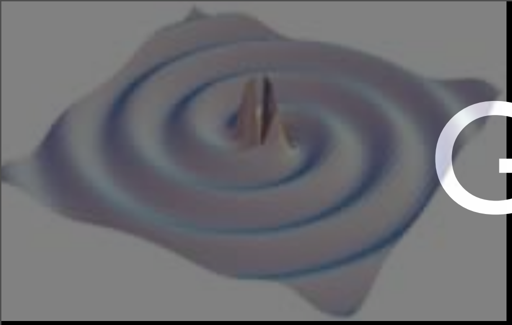
Modeling the Stellar Population(s)

- Population Synthesis - *Monte Carlo method* of evolving a stellar population from the ZAMS to uncover and assess the efficiency of particular formation channels of various stellar/binary types

- Use the *StarTrack* population synthesis code (Belczynski et al. 2002; 2008) to evolve the (Galactic) population of field single and binary stars incorporating modified analytical formulae for stellar evolution (Hurley et al. 2000)

- Binary evolution: Consider common envelope (CE) evolution, metallicity, IMF, binary fraction, mass accretion efficiencies, supernova kicks, gravitational radiation, magnetic braking, SFR

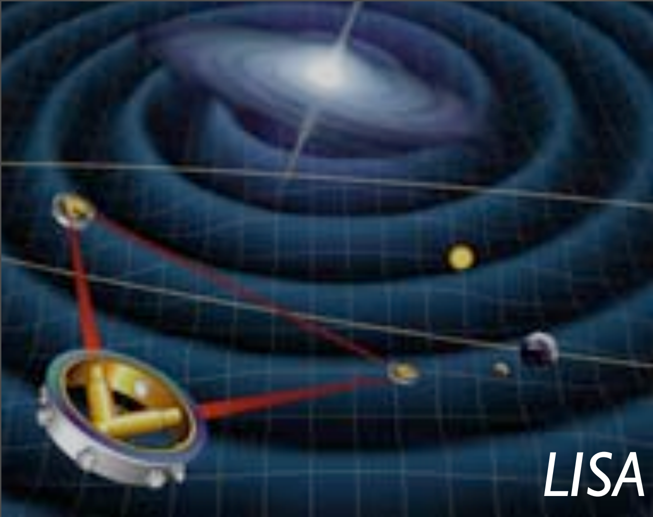
- Identify the formation channels and physical characteristics, (e.g. calculate *LISA* **gravitational wave frequencies**, CV X-ray luminosity function(s) or SN Ia delay times and rates)



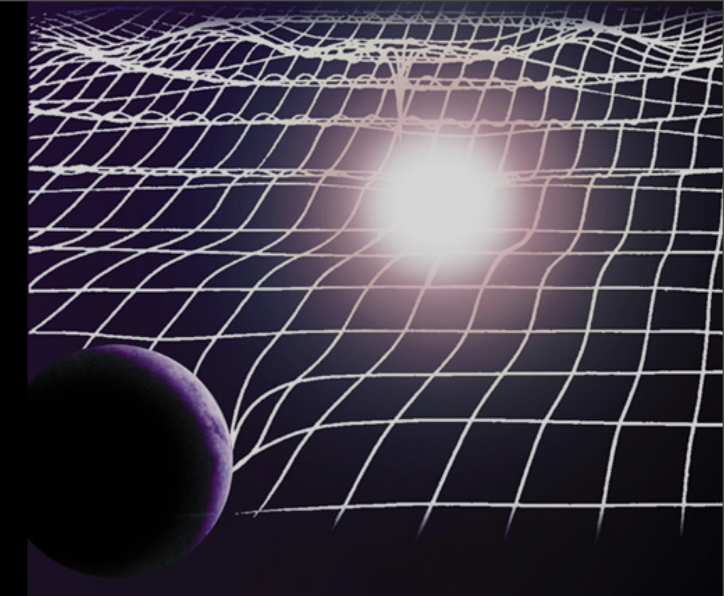
Gravitational Radiation (GR)

- Predicted by General Relativity: massive objects undergoing acceleration will warp space-time in a detectable* way
- Many astrophysical objects are not observable in the electromagnetic spectrum, but can be bright in gravitational waves
- Close binary stars will lose orbital angular momentum due to emission of GWs: circular binaries $f_{GR} = 2/P_{orb}$ [Hz]; the space-time distortion propagates outward manifested as GWs
- Ground-based GW detectors are currently operational (f_{GR} > 10 Hz) - no detections yet...

*GWs have not yet been directly observed, but have been inferred from observations (pulsar 1913+16, Hulse & Taylor)



LISA: Laser Interferometer Space Antenna

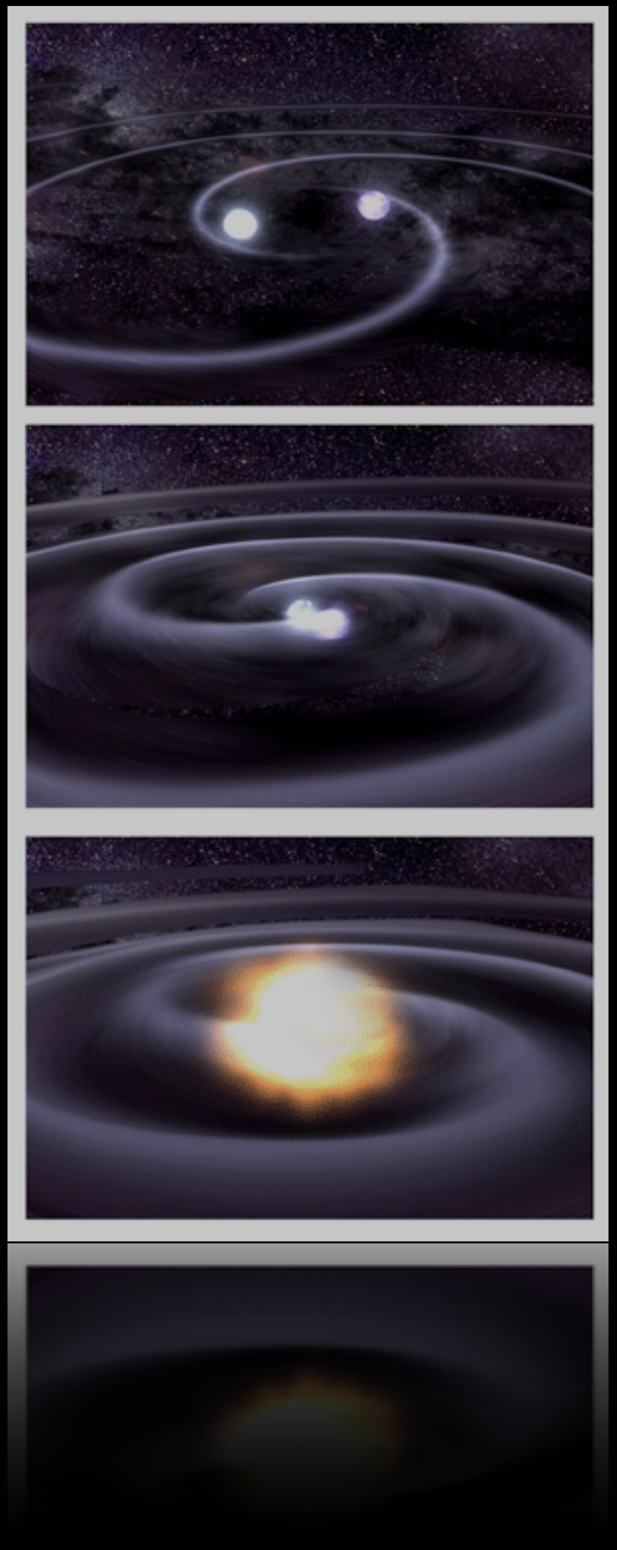


- Future *space-based* *Gravitational Wave detector* and will be sensitive to astrophysical sources such as merging supermassive BHs, Extreme Mass Ratio Inspirals (EMRIs), & stellar-mass binaries in MW (also: *DECIGO*)
- At low frequencies, there will be 100s of MW white dwarf binaries per ***resolvable frequency bin***, and so signal will be "confusion-limited" and binaries unresolvable (confusion foreground)

Δf_{bin} = 30 nHz

- Not ONLY "noise"! Some 1000s of WD binaries will be **resolved** offering an unprecedented opportunity to study post-Common Envelope binaries and learn more about binary evolution, WD structure

Galactic Double WDs - important confusion noise for *LISA*

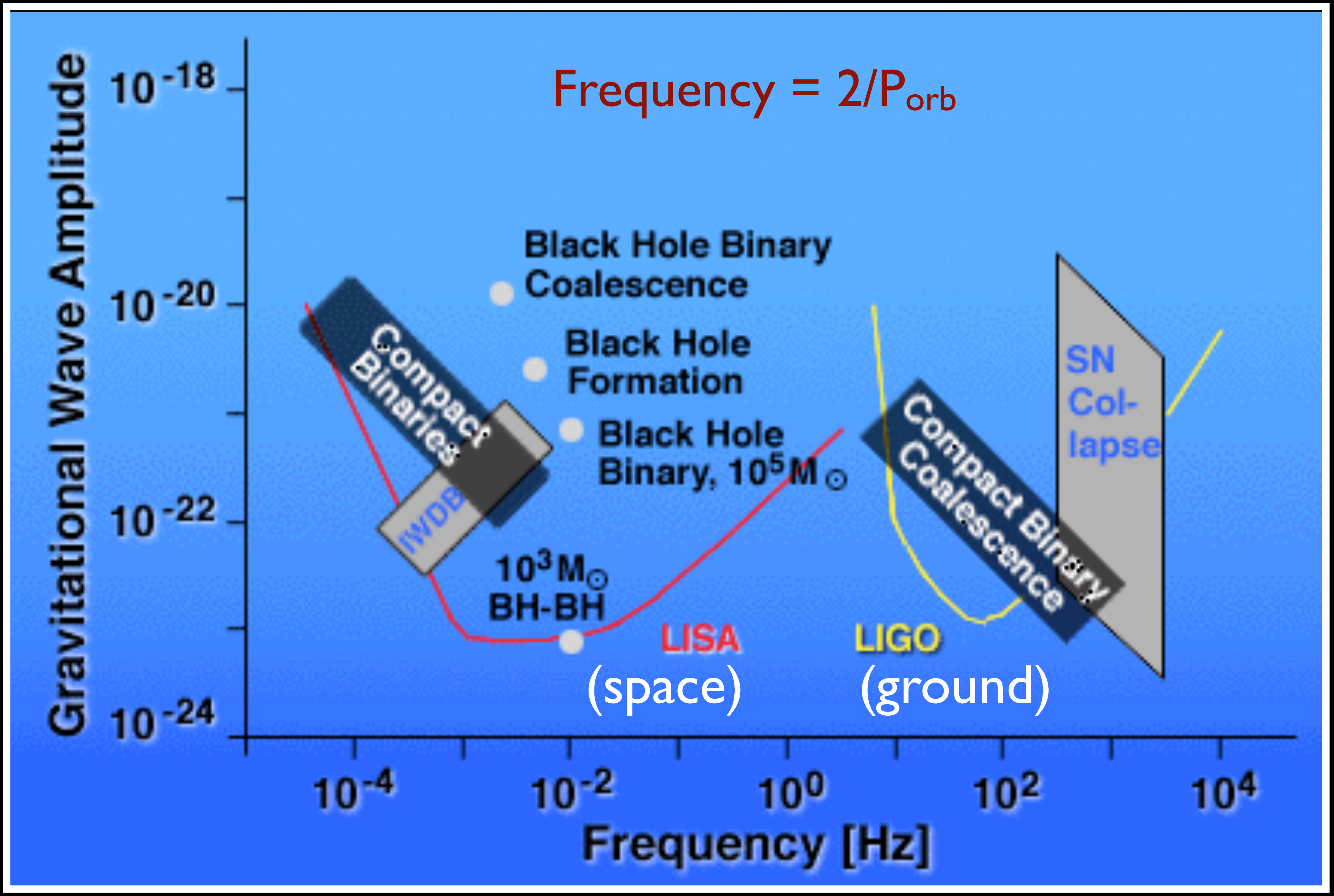


- Double WD confusion foreground will hinder detection of other GW sources below a few mHz (i.e., extreme mass ratio inspirals - probe of strong gravity regime)
- Understanding of physical characteristics of Galactic double WDs allows to correctly remove them from *LISA* data stream

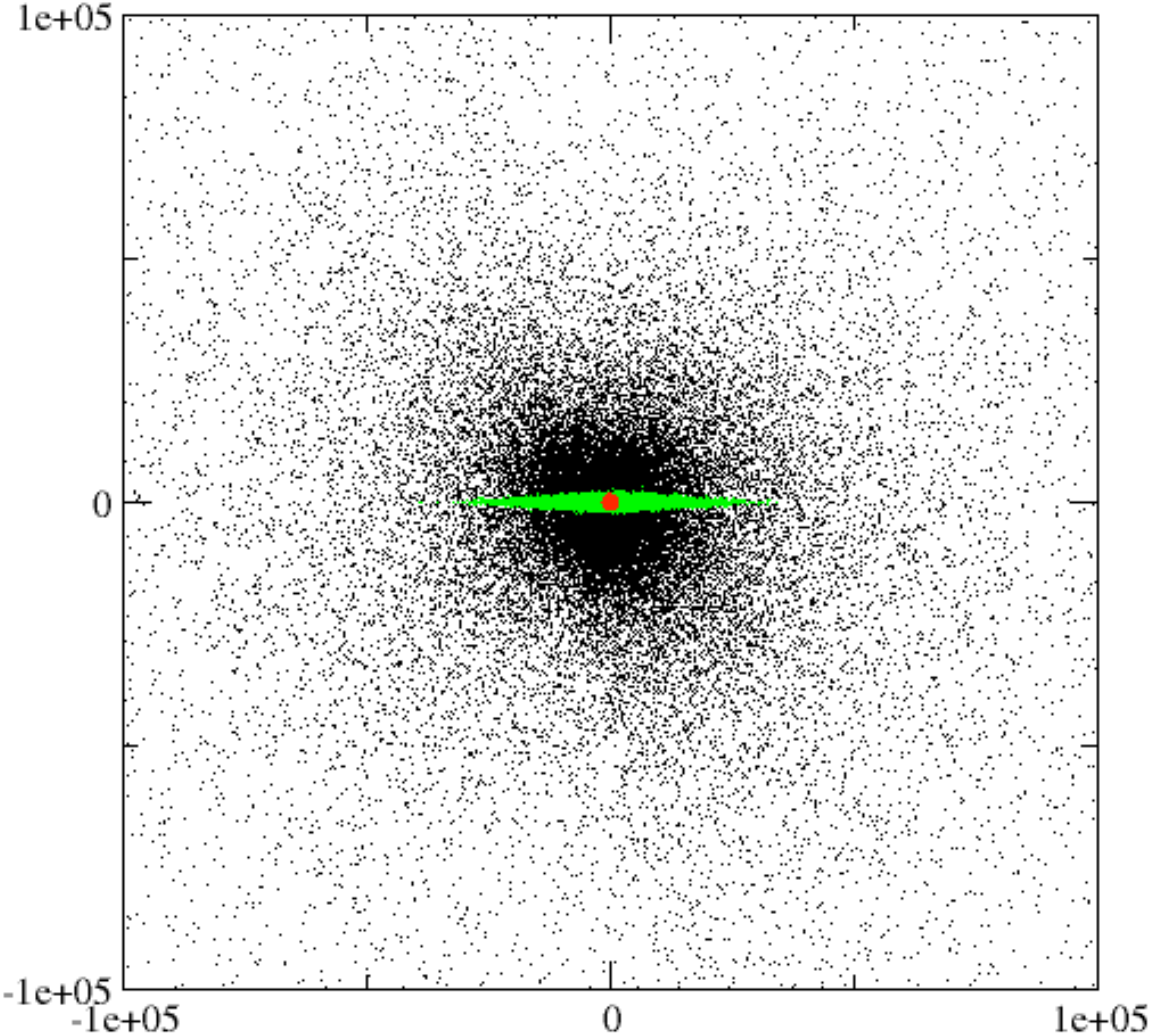
Setting limits on double WD physical properties will aid in the development of improved data analysis techniques (Mock *LISA* Data Challenges); optimize GR source detection

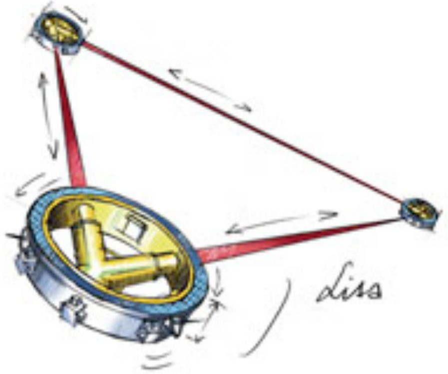
LISA sensitivity to Galactic double WDs: Confusion Noise

Several studies (i.e., Hils et al. 1990; Nelemans et al. 2001, etc.) have calculated the LISA GR signal from Galactic WD binaries



StarTrack spatial distribution of sources (bulge, disc, halo)





Galactic and Halo DWD *LISA* signals

(*LISA* signal simulator; Benacquista et al. 2004)

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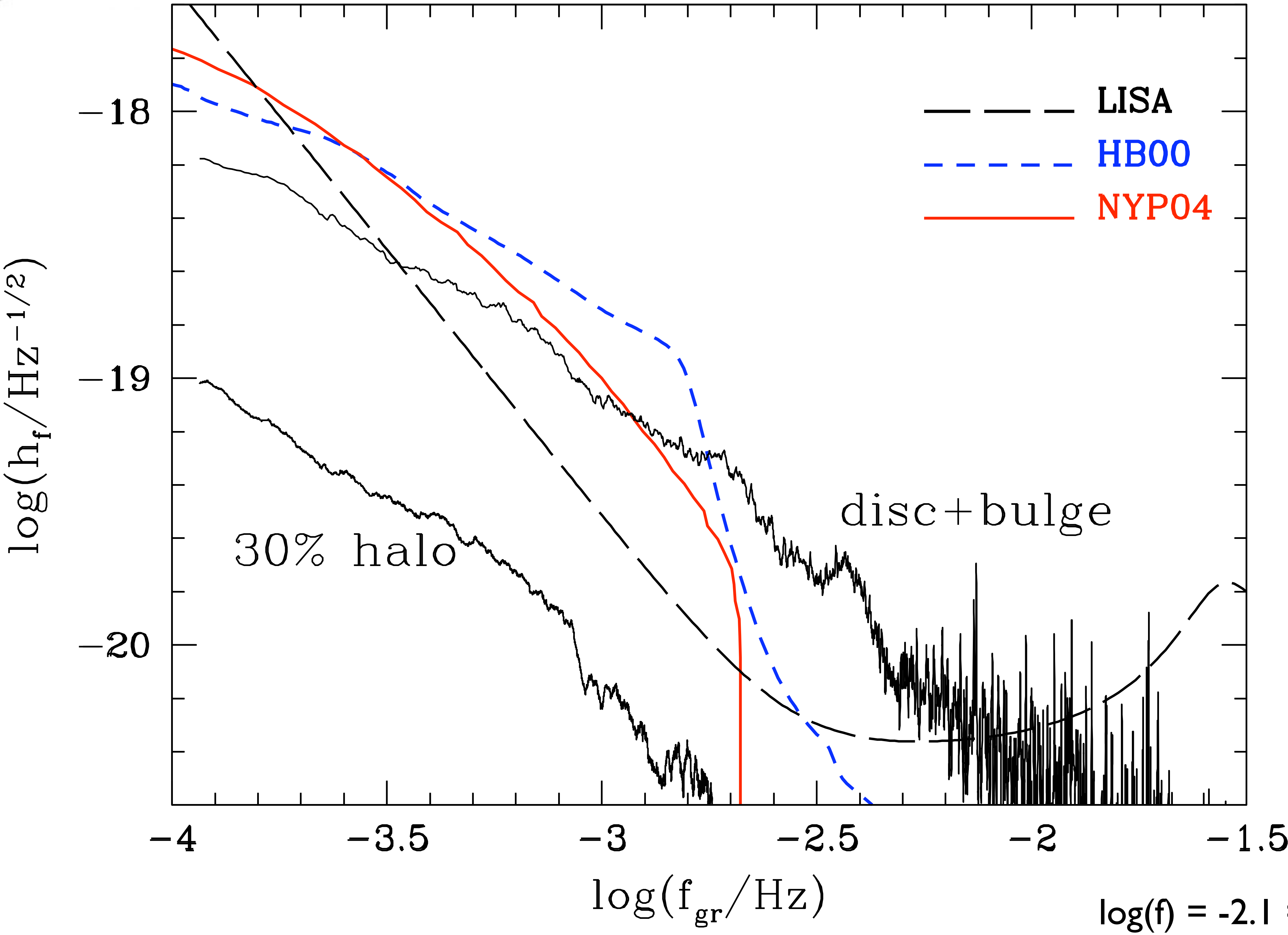

log(f) = -2.1 = 0.008 Hz

Double Compact Objects: A Brief Overview

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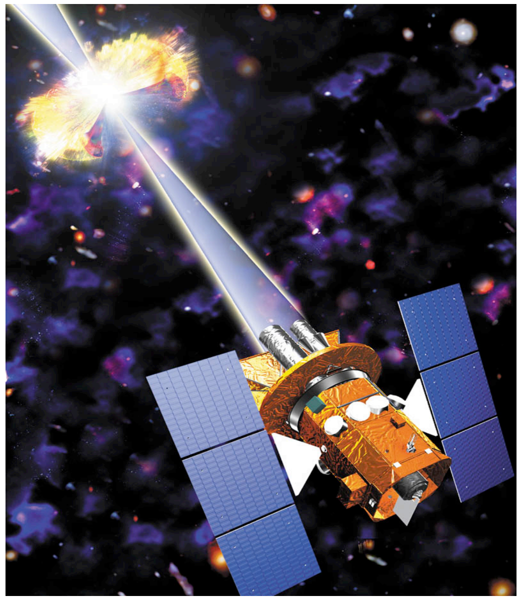
[3]*EXIST* Team



Ashley Ruiter on Behalf of Chris Belczynski, Japan, Feb 2009

Observations: known double compact objects

- BH-BH, BH-NS: no observations
- NS-NS: 9 Galactic systems. 6 are close:

Phone #	$M_{ns,1}/M_\odot$	$M_{ns,1}/M_\odot$	t_{mrg}/Gyr	Comment
1) B1913+16	1.44	1.39	0.33	field
2) B1534+12	1.33	1.35	2.7	filed
3) J0737-3039	1.34	1.25	0.09	field
4) J1756-2251	1.39	1.18	1.7	field
5) J1906+0746	1.25	1.37	0.30	field
6) B2127+11C	1.36	1.38	0.22	cluster

– short lived systems: $\sim$ 0.3 Gyr (pulsar age) + $\sim$ 0.1-3 Gyr (merger time)

– empirical Galactic merger rate: 3-190 Myr^{-1} (Kim et al. 06)

Predictions for LIGO: field populations

Galactic merger rates:

- high for NS-NS inspiral
- small for BH-NS and BH-BH (model dependent: CE phase)

LIGO detection rates:

- no chance for LIGO I
- many detections for LIGO II

Detection rates dominated by:

- NS-NS: $\mathcal{M}_{\rm chirp} = 1.2 M_\odot$ (Mod1)
- if BH-BH (Mod2): field population: $\mathcal{M}_{\rm chirp} \sim 7 M_\odot$ (survival through CE: how?)

Table: Galactic Merger Rates [Myr^{-1}]

Model	NS-NS	BH-NS	BH-BH
Mod1	15	0.1	0.02
Mod2	80	4	10

Table: LIGO II Detection Rates [yr^{-1}]

Model	NS-NS	BH-NS	BH-BH
Mod1	20	1	2
Mod2	100	30	500

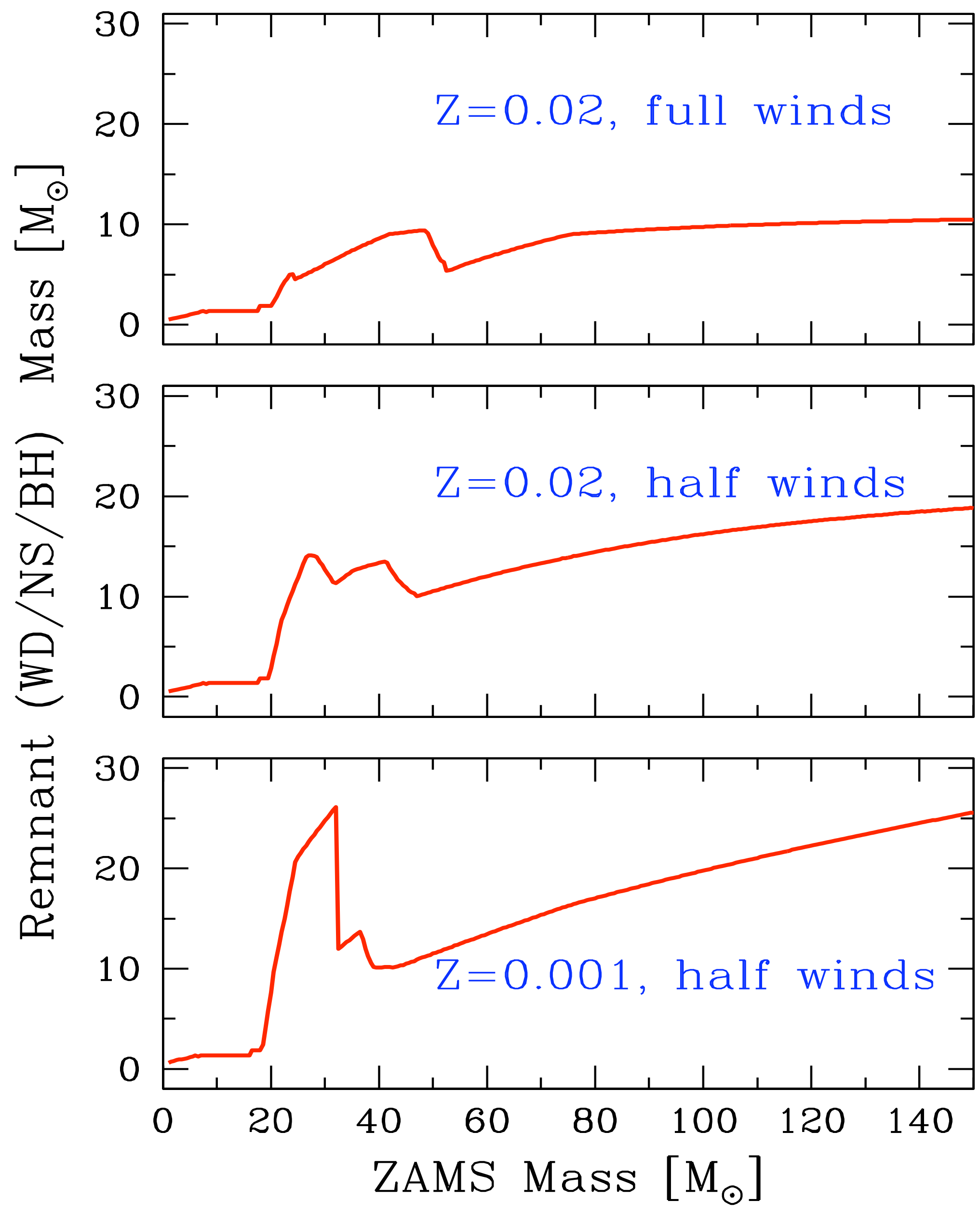
Mod1 (mergers) -> Mod2 (avoided):
Mergers in Common Envelope with Hertzsprung Gap donors

Observations: known BH masses

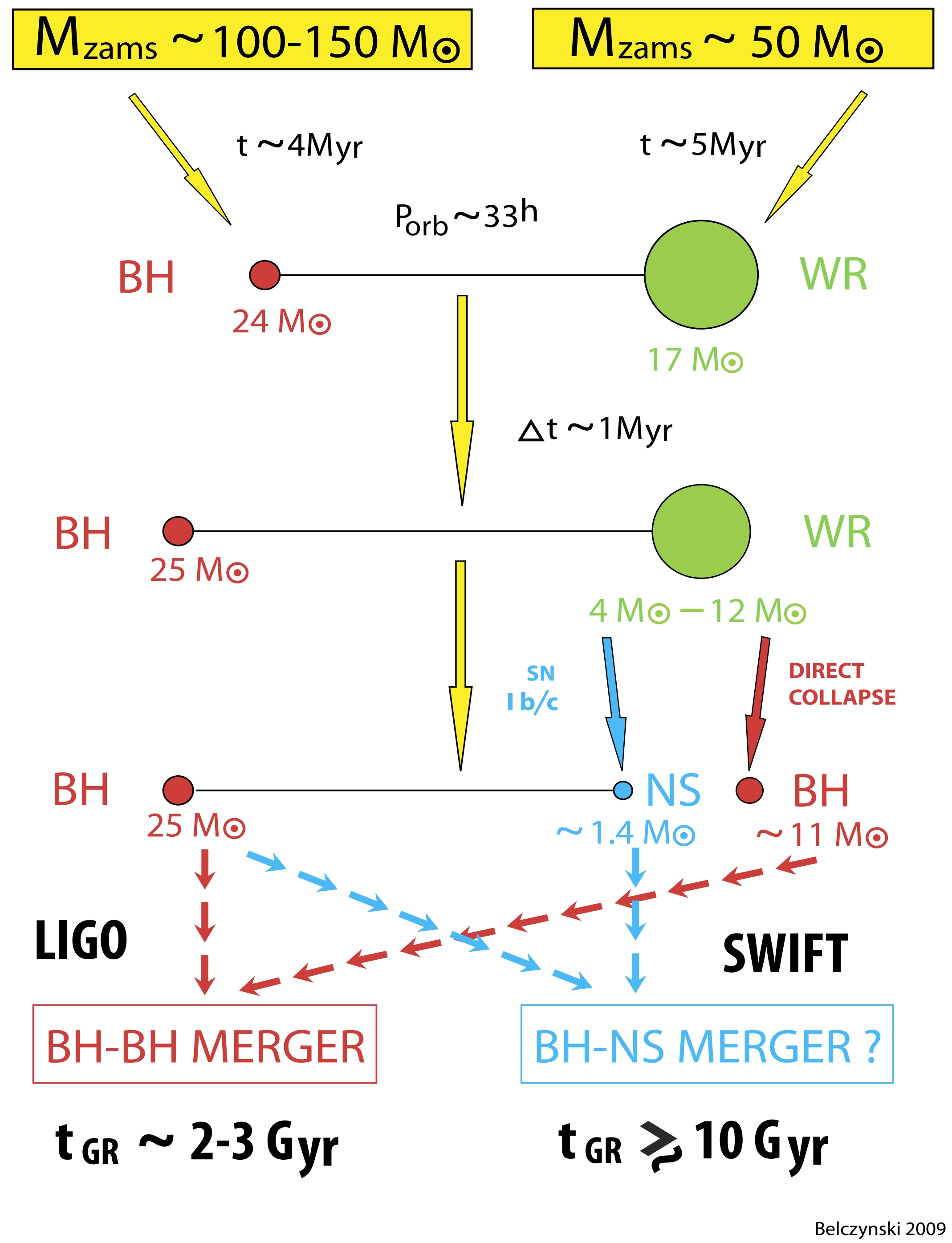
- $4-14M_{\odot}$: Galactic BHs (20 known)
  – 17 transients: low mass companion
  – 3 persistent: massive companion
  BH-NS? most probably SN disruption
- $16M_{\odot}$: M33 X-7 (Orosz et al. 07)
  – massive $70M_{\odot}$ close companion
  BH-BH? most probably MT merger
- $24M_{\odot}$: IC10 X-1 (Prestwich et al. 07)
  – massive $17M_{\odot}$ close WR companion
  BH-BH? most probably YES

Despite recent claims:
Stellar models can explain BHs to $\sim 30M_{\odot}$

StarTrack models:
(Belczynski 2002, 2004, 2006, 2008)



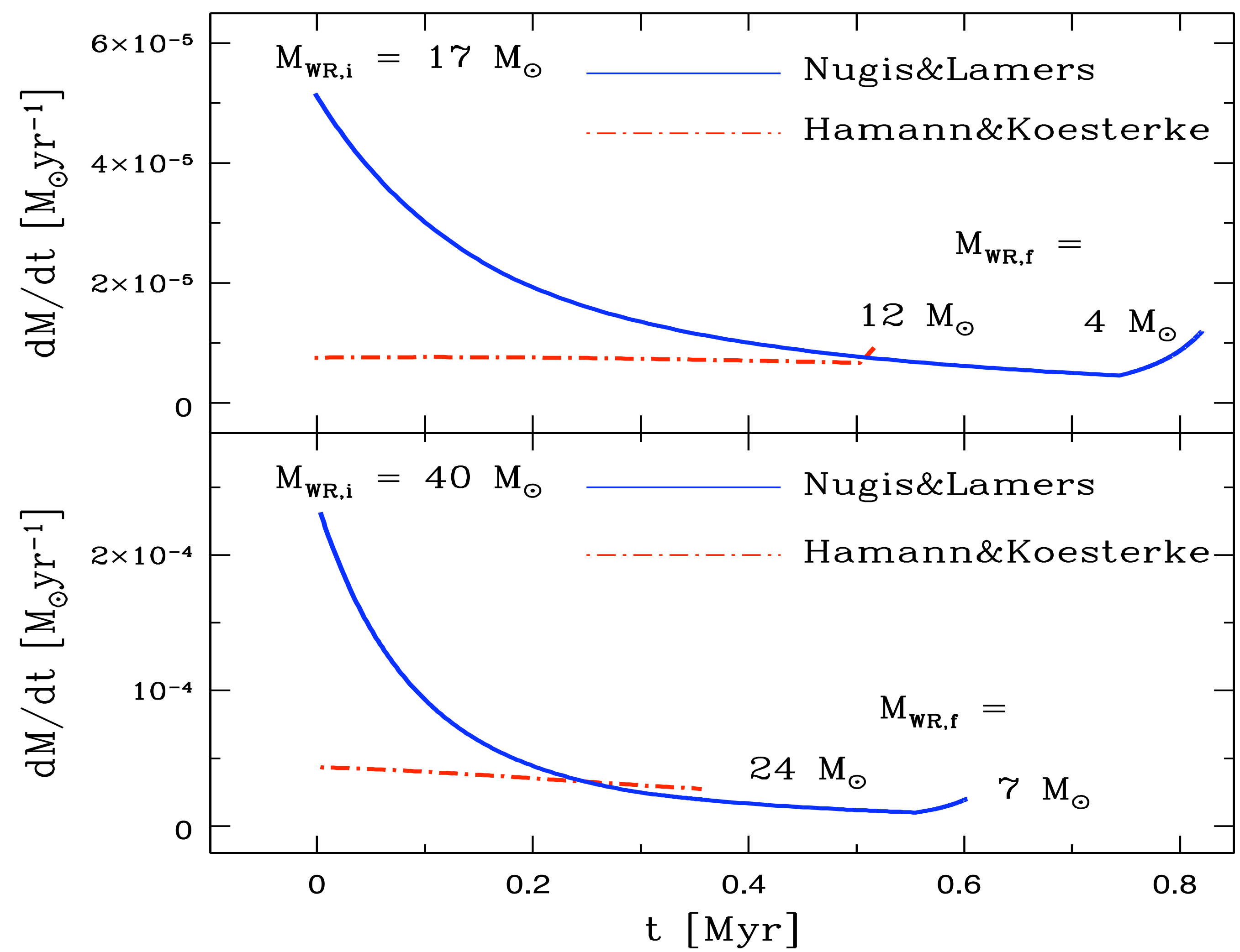
IC10 X-1: evolution and fate



Depending on the adopted WR winds:

- BH-NS is formed (Nugis&Lamers)
- BH-BH is formed (Hamann&Koesterke)

StarTrack models (Belczynski 2008):



Gravitational radiation: LIGO/VIRGO

Galactic NS-NS merger rates:

- empirical NS-NS: 3-190 Myr^{-1} (Kim, Kalogera & Lorimer 06)
- recent population synthesis: 10-100 Myr^{-1} (Belczynski et al. 07)

LIGO/VIRGO detection rates: $\mathcal{R}_{gr} \ll 1 yr^{-1}$ ($\sim$ 1 per 100 yr)

IC10 BH-BH-like merger rates:

- $\mathcal{M}_{\rm chirp} \sim 20 M_\odot$: detectable to $d_{bhbh} \sim 200$ Mpc
- $\mathcal{R}_{gr} = 0.63 \left(\frac{4\pi}{\Omega_s}\right) \left(\frac{\mathcal{M}_{chirp}}{18 M_\odot}\right)^{5/2} \left(\frac{d_{nsns}}{18\rm Mpc}\right)^3 \left(\frac{2\rm Mpc}{d_{chandra}}\right)^3 \left(\frac{10^6 \rm\ yr}{t_{xray}}\right) \rm yr^{-1}$

LIGO/VIRGO: $\mathcal{R}_{gr} \sim 1 yr^{-1}$ (Bulik, Belczynski & Prestwich 08)

Summary

- Gravitational wave detectors can uncover the formation history (evolution) of close binary stars
- Modeling: parameter space is quite large; need to test different model assumptions a priori (initial orbital parameters, prescriptions for CE efficiency, stellar winds, etc.)
- Important for understanding Gamma Ray Burst progenitors, potential progenitors of Type Ia supernovae, accretion-induced collapse neutron stars, R Cr B stars, X-ray binary star evolution, etc.