Interacademic course
GW astrophysics

Gijs Nelemans

Practicalities

- Lectures streamed via https://www.youtube.com/watch?v=i7-tqr47-Ek
- Skype connection to UvA, UL, RUG via gijs_nelemans
- Let's see if this works...
- Grading: 50% on exercises 50% on exam
- TA: Dr. Shaon Ghosh S.Gosh@astro.ru.nl

Programme

Feb 12 GW signals from different types of sources, Gijs Nelemans

Feb 19 Recap General Relativity and Gravitational Waves, Samaya Nissanke

Feb 26 GW data analysis, Samaya Nissanke

Mar 4 eLISA mission overview, Gijs Nelemans

Mar 11 eLISA mission: SMBHs now and in GW 1, Elena Rossi

Mar 18 eLISA mission: SMBHs now and in GW 2, Elena Rossi

April 15 eLISA mission: WD binaries now and in GW 1, Gijs Nelemans/Paul Groot

April 22 eLISA mission: WD binaries now and in GW 2, Paul Groot

April 29 LIGO/Virgo detectors, TBD

May 13 LIGO/Virgo sources, Gijs Nelemans

May 20 Double NS/BH formation, Gijs Nelemans

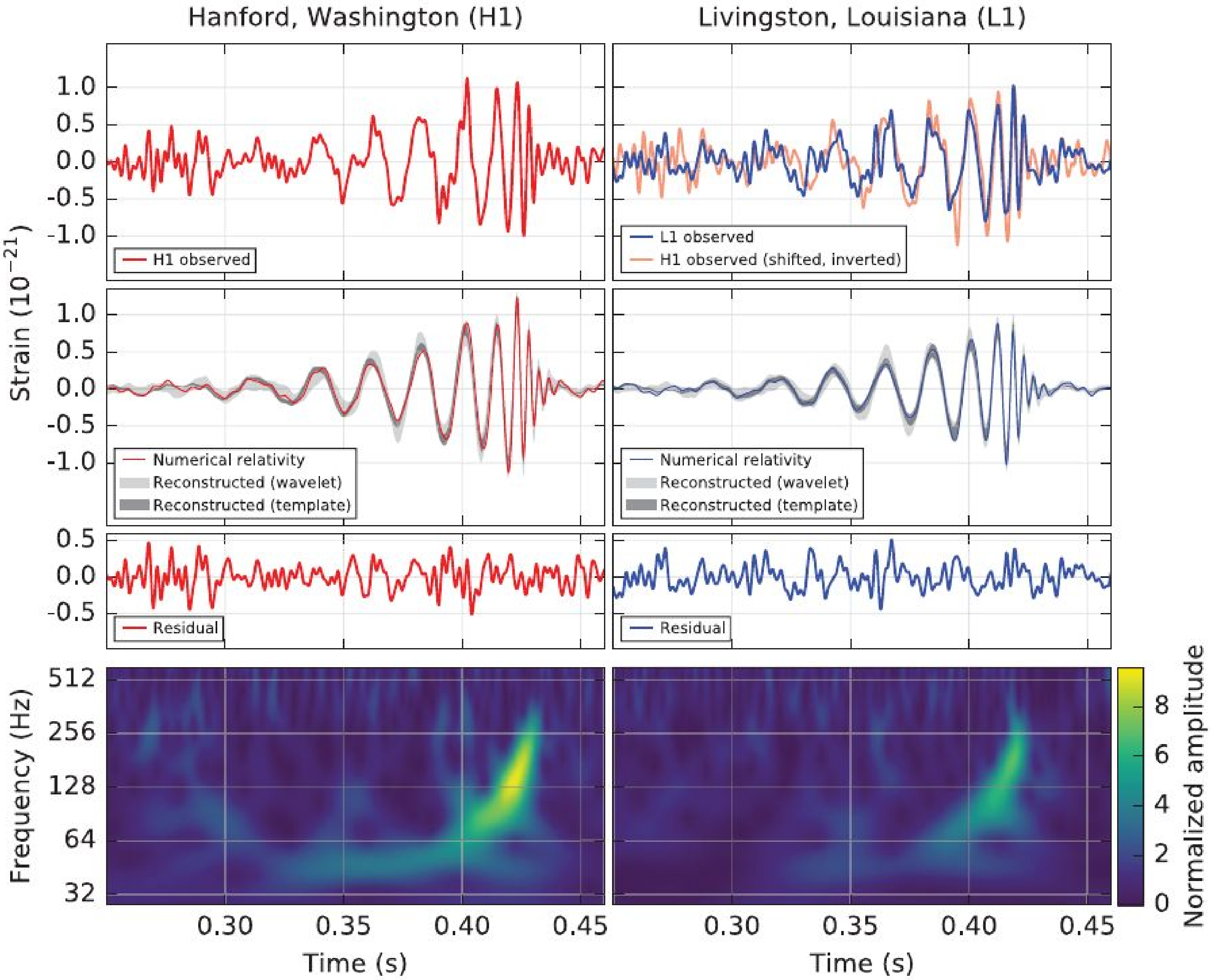
May 27 EM counterparts, Peter Jonker

June 3 Future ground-based detectors and their science, Paul Groot

June 10 Pulsar Timing method, Jason Hessels/Gemma Janssen

June 17 Pulsar Timing results, Jason Hessls/Gemma Janssen

GW150914


Hanford, Washington (H1)
Livingston, Louisiana (L1)
Strain (10^{-21})
1.0
0.5
0.0
-0.5
-1.0
H1 observed
L1 observed
H1 observed (shifted, inverted)
Numerical relativity
Reconstructed (wavelet)
Reconstructed (template)
Residual
Frequency (Hz)
512
256
128
64
32
0.30
0.35
0.40
0.45
Time (s)
Normalized amplitude
0
2
4
6
8

General Relativity

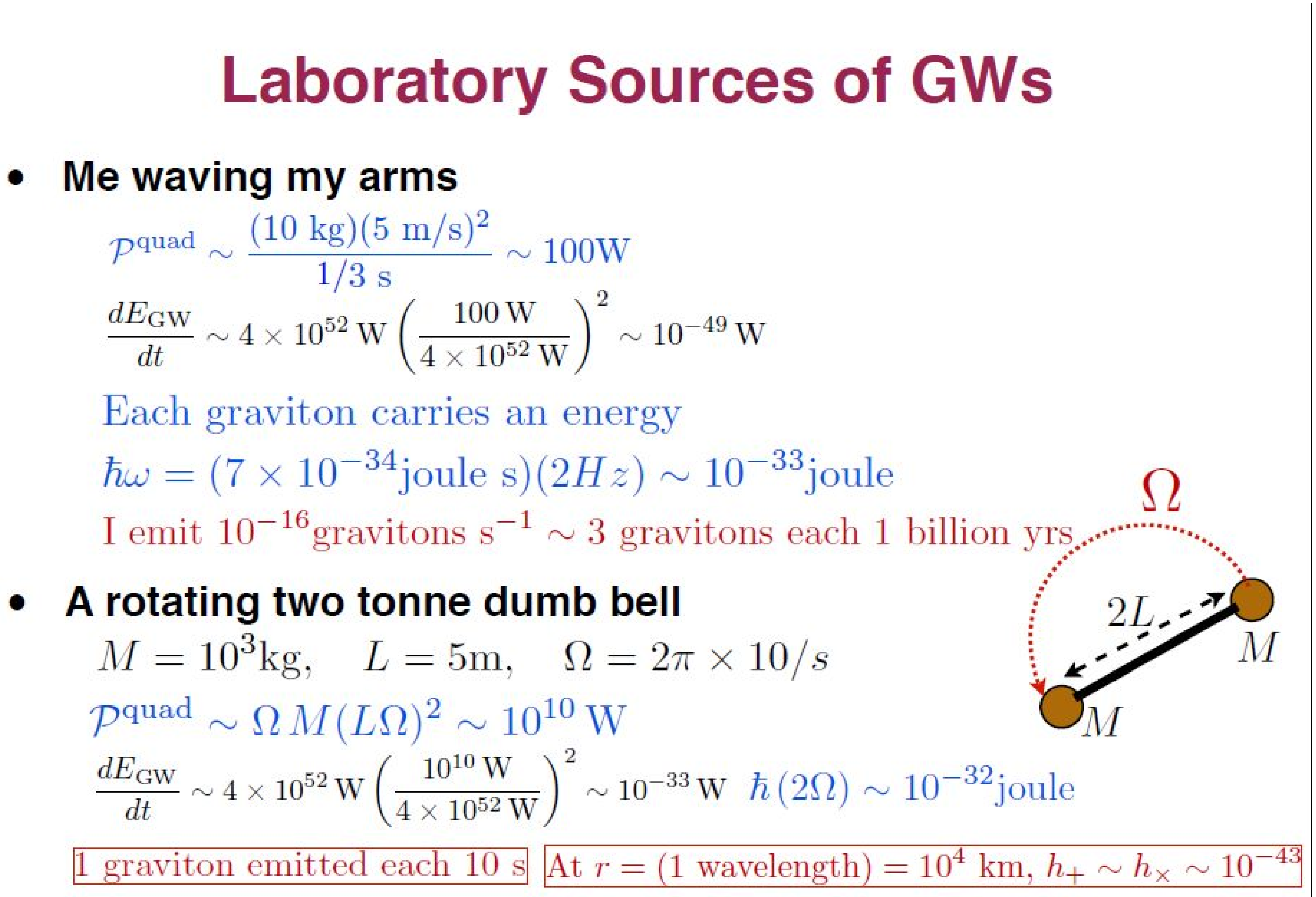
- Extension of Special relativity to accelerated observers
- Acceleration equivalent to gravity… Need to include gravity
- Gravity = deformation space (time)
- Combined description of space(time) and energy: Einstein Field equations

Estimates of GW

- Rotating rod of length L:

$$\dot{E}_{GW} = \frac{2G}{45c^5} M^2 L^4 \omega^6 \simeq 1.2 \times 10^{-54} W M_{kg}^2 L_m^4 \omega_{s^{-1}}^6$$

Kip Thorne (Lorentz professor 2009)



Laboratory Sources of GWs

- **Me waving my arms**

$$\mathcal{P}^{\rm quad} \sim \frac{(10\ {\rm kg})(5\ {\rm m/s})^2}{1/3\ {\rm s}} \sim 100{\rm W}$$

$$\frac{dE_{\rm GW}}{dt} \sim 4\times 10^{52}\ {\rm W}\left(\frac{100\ {\rm W}}{4\times 10^{52}\ {\rm W}}\right)^2 \sim 10^{-49}\ {\rm W}$$

Each graviton carries an energy

$$\hbar\omega = (7\times 10^{-34}{\rm joule\ s})(2Hz) \sim 10^{-33}{\rm joule}$$

I emit 10^{-16}gravitons s^{-1} ~ 3 gravitons each 1 billion yrs

- **A rotating two tonne dumb bell**

$$M = 10^3{\rm kg}, \quad L = 5{\rm m}, \quad \Omega = 2\pi\times 10/s$$

$$\mathcal{P}^{\rm quad} \sim \Omega\, M(L\Omega)^2 \sim 10^{10}\ {\rm W}$$

$$\frac{dE_{\rm GW}}{dt} \sim 4\times 10^{52}\ {\rm W}\left(\frac{10^{10}\ {\rm W}}{4\times 10^{52}\ {\rm W}}\right)^2 \sim 10^{-33}\ {\rm W} \quad \hbar\,(2\Omega) \sim 10^{-32}{\rm joule}$$

1 graviton emitted each 10 s

At $r = $ (1 wavelength) $= 10^4$ km, $h_+ \sim h_\times \sim 10^{-43}$

Generation and detection of GWs in lab is hopeless

Stellar binaries (also problems)

$$\omega^2 \approx GM/L^3:$$

$$\dot{E}_{GW} \approx \frac{c^5}{G}\left(\frac{GM}{c^2 L}\right)^5 < \frac{c^5}{G} = 10^{52.6}\,W$$

Characteristic wave frequency:

$$\omega \approx \left(\frac{GM}{R_s^3}\right)^{1/2} \approx \frac{c^3}{GM} \approx \frac{c}{R_s} = \left(\frac{M}{10^{5.3} M_\Theta}\right)^{-1} \mathrm{Hz}$$

Types of detectors and sources

- High frequency detectors (LIGO, Virgo)
  - kHz regime → low masses
  - merging neutron stars/black holes
  - Wavelength ~300 km

- Low-frequency regime (LISA)
  - mHz regime → high masses
  - merging supermassive black holes
  - compact stellar mass binaries
  - Wavelength ~ 300 million km

Types of detectors and sources

- Very low frequency detectors
  - Pulsar timing array
  - Measure collective changes of arrival times of ensemble of pulsars → movement of Earth due to GWR
  - Wide supermassive black hole binaries
  - GW backgrounds (from inflation?)
- CMB → sensitive to ultra-low f GW, signs of inflation

Astrophysical Sources

Binaries

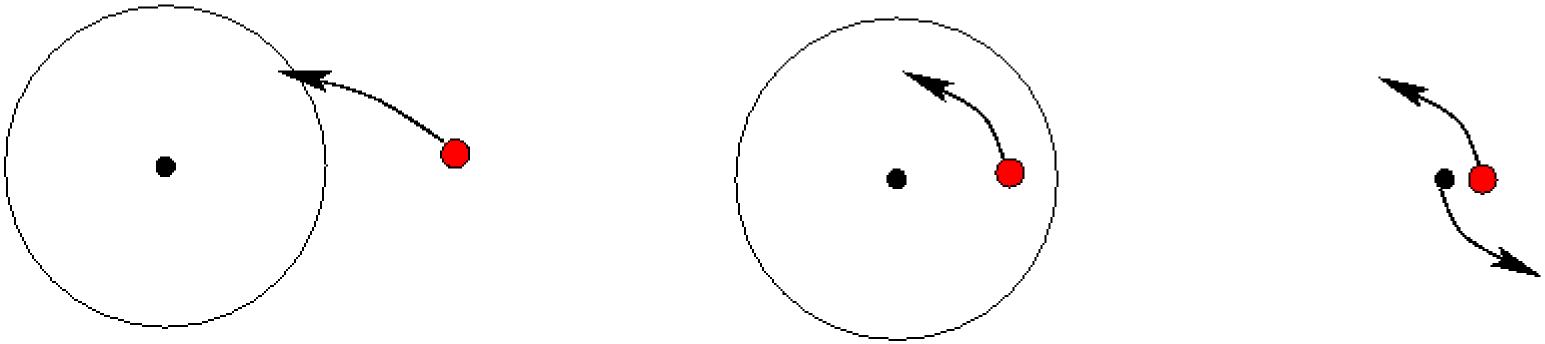
Spinning neutron stars

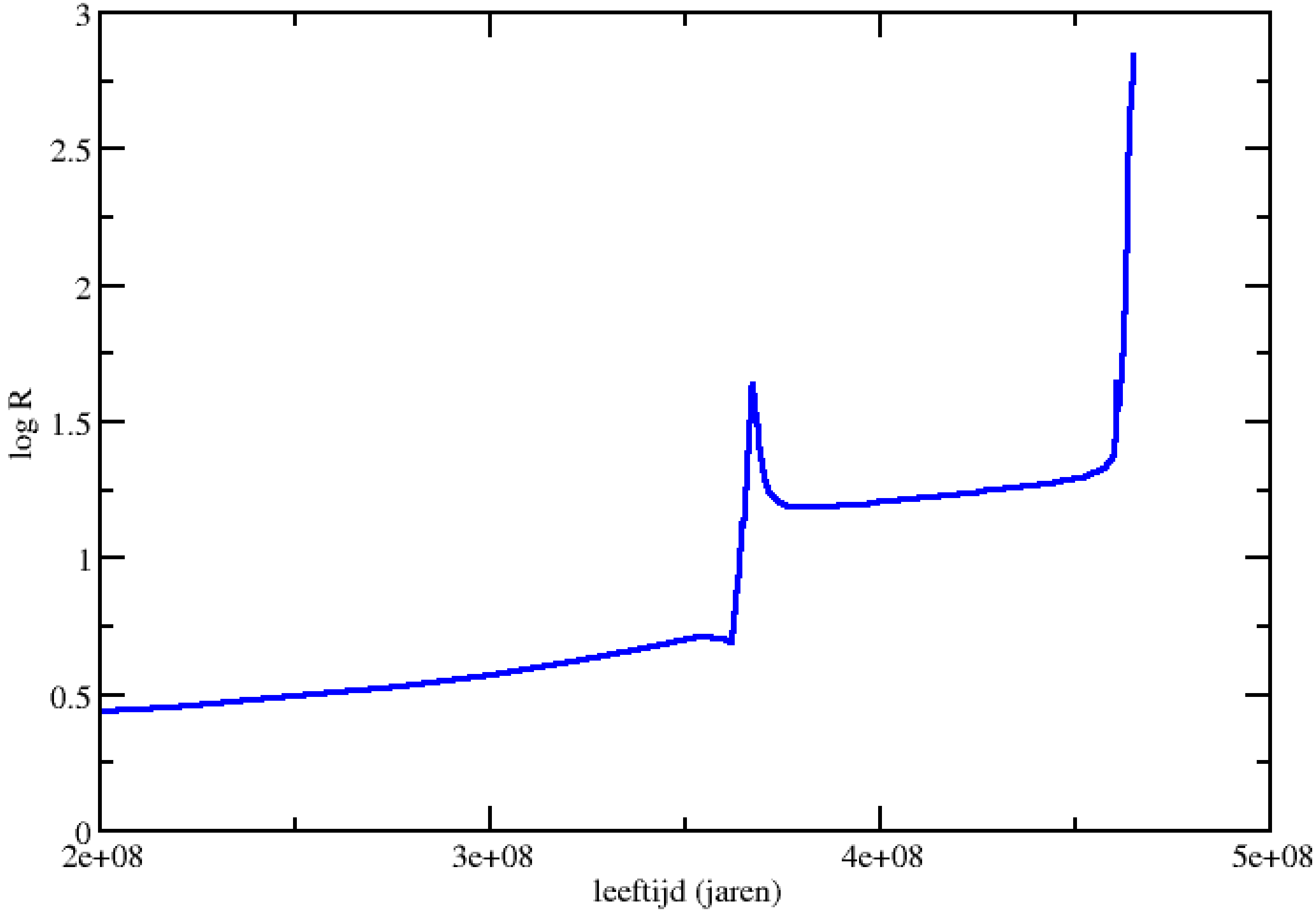
Super-massive black holes

Extreme mass-ratio inspirals

Binary evolution

- Most massive star evolves first
- If orbit close enough → mass transfer
- Often this is unstable:
  - Runaway mass transfer
  - We don’t really know what happens
  - Common-envelope




log R
0
0.5
1
1.5
2
2.5
3
2e+08
3e+08
4e+08
5e+08
leeftijd (jaren)

Kicks

- Neutron star get “kick” on birth
- Is important for formation of double neutron stars (kick might unbind the binary!)
- What about black holes?
  - ❑ We don’t really know
  - ❑ First I thought NO (based on velocities binaries)
  - ❑ Now I think YES (based on scale height bins)
  - ❑ …..

Observations and population synthesis

- Our knowledge of binary evolution is not good enough to determine numbers
- Need to observe binaries
- But we cannot see all binaries
- Population synthesis can help

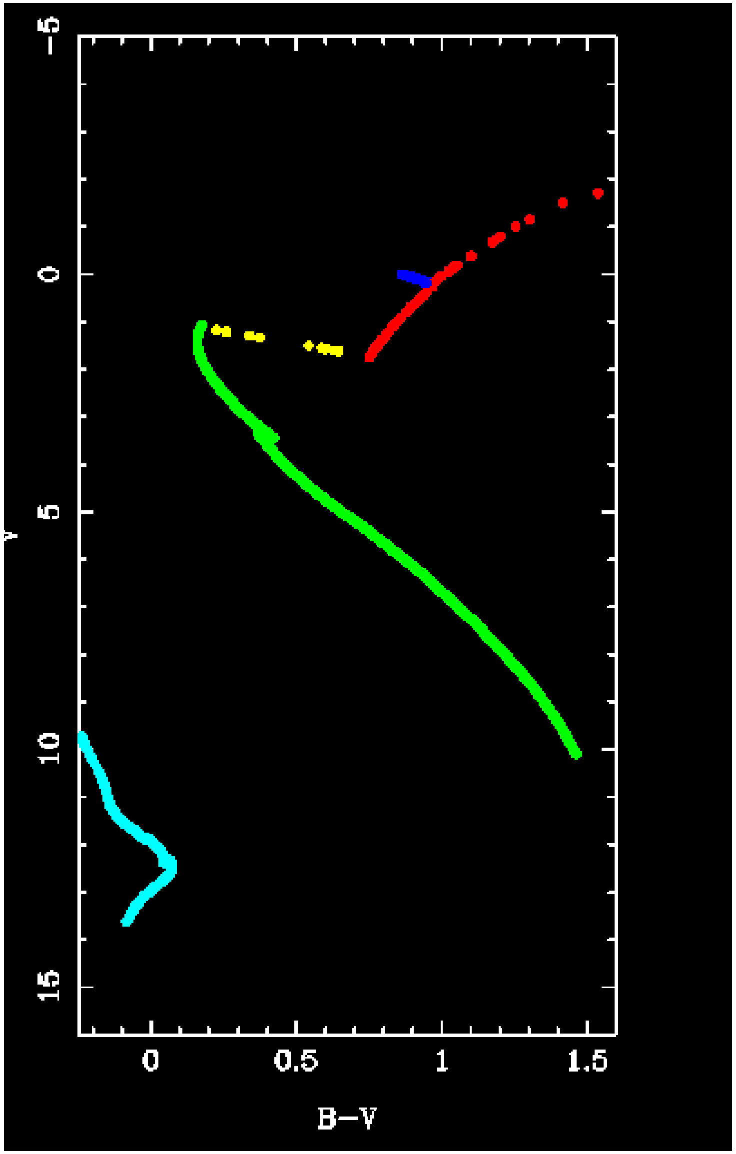
Population synthesis

- Model large population of binaries
- Need to do fast
  - ❑ Simple approximations to stellar evolution
  - ❑ Simple recipes for mass transfer etc.
  - ❑ Need to include kicks, SN etc
- Also need initial conditions
- Star formation history

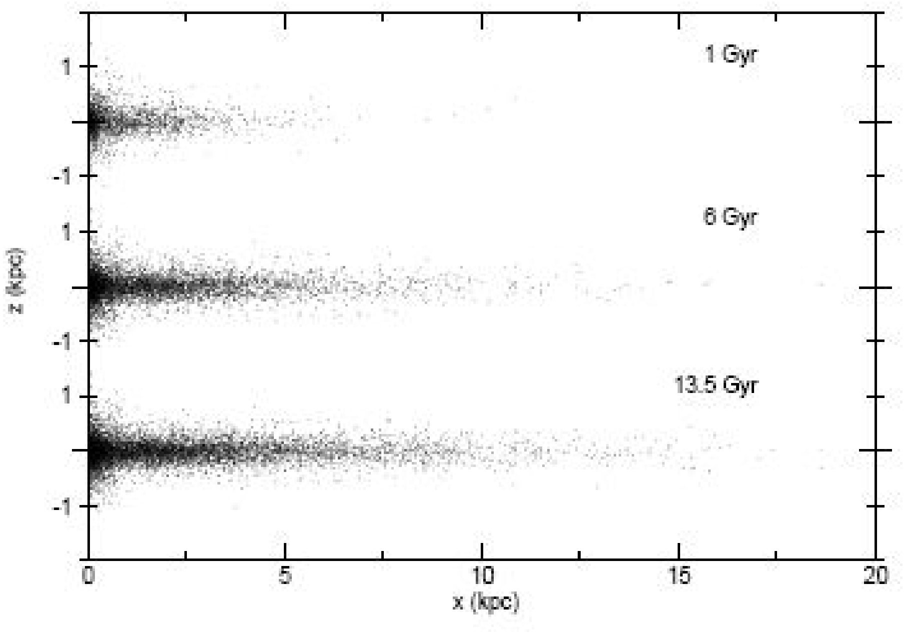
Simple fits to stellar evolution

- Based on detailed models
- Very fast

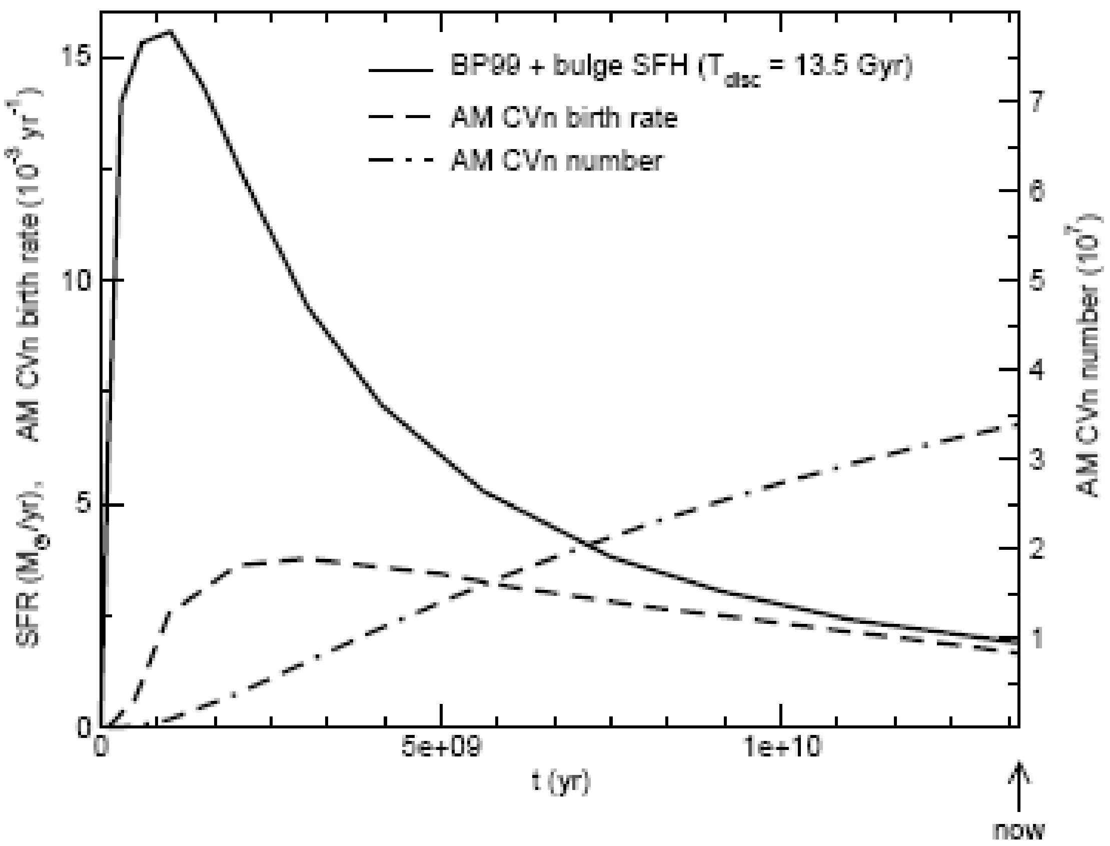
  (1000 full binary evolutions per second)
- Initial distributions
  - IMF
  - Mass ratio
  - Period/separation
  - Eccentricity



Galactic model



Star formation



High frequency sources for LIGO/VIRGO/GEO

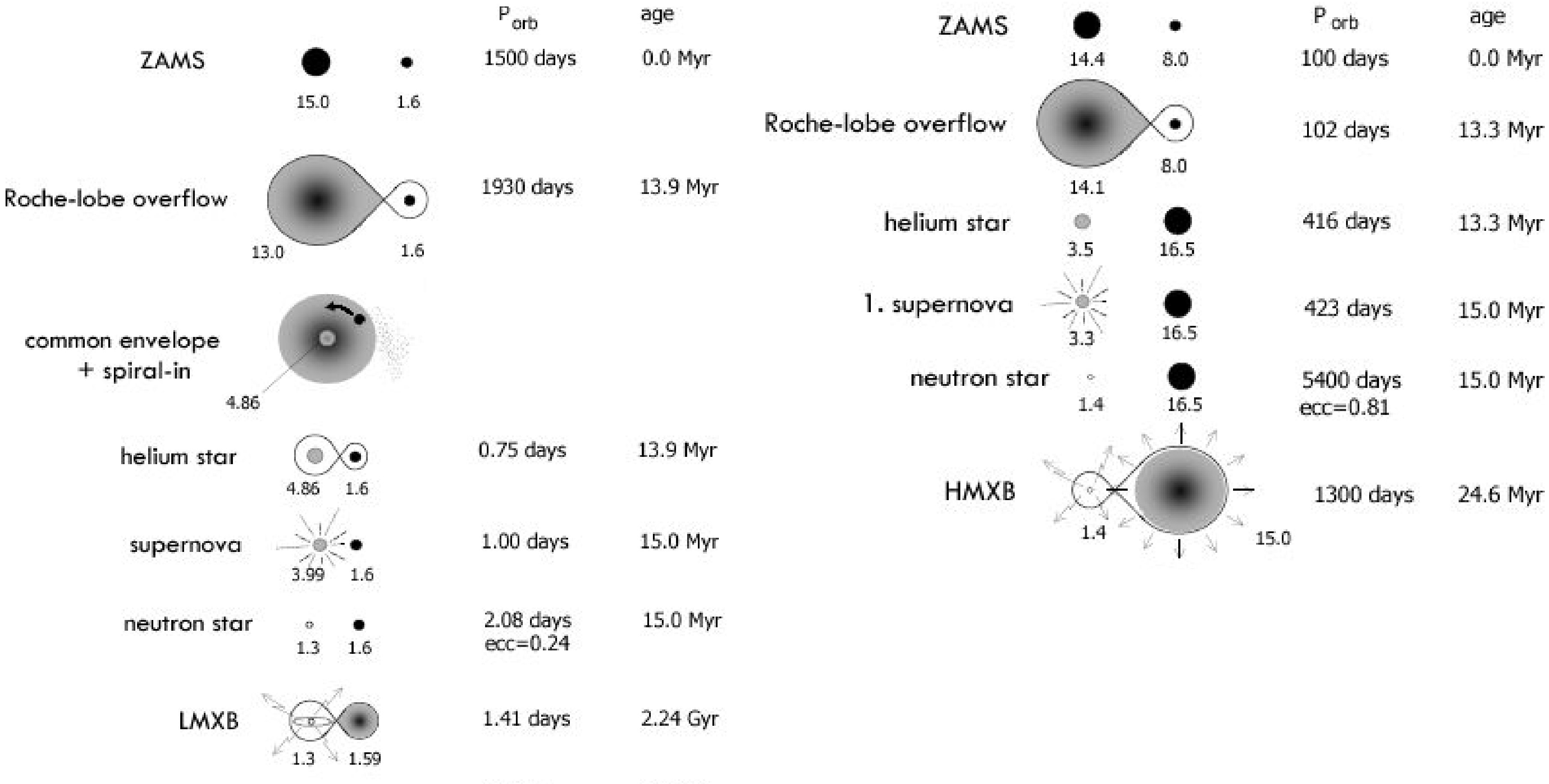
Spinning neutron stars

Double neutron stars

Rapidly spinning neutron stars

- Formed in accreting systems (low-mass X-ray binaries)
- Many found to have several 100 Hz speeds
- Are they detectable?

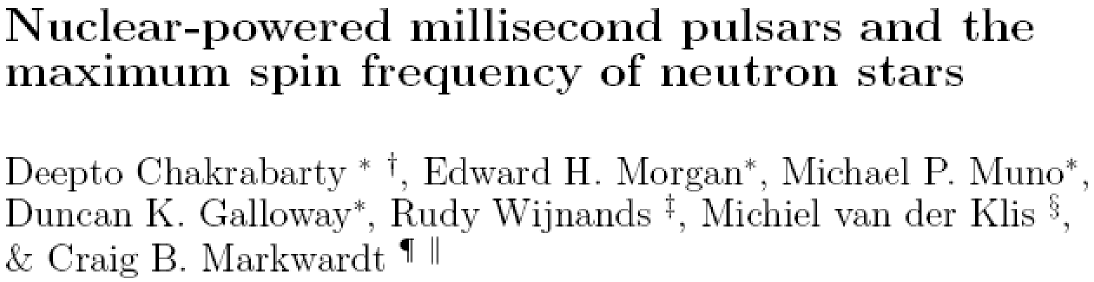
Formation X-ray binaries



Spinning neutron stars

- Neutron stars in LMXBs accrete → spin up
- Can calculate equilibrium spin: spin-up balanced by spin-down due to B field
- Observed distribution of spins:

  all below equilibrium spin!



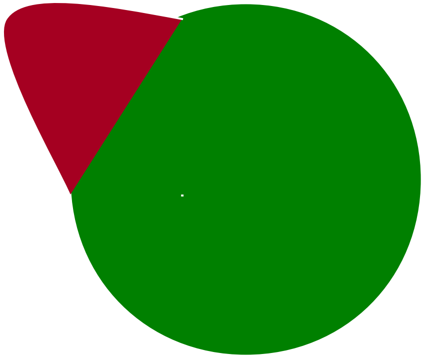
Nuclear-powered millisecond pulsars and the maximum spin frequency of neutron stars

Deepto Chakrabarty [*] [†], Edward H. Morgan[*], Michael P. Muno[*],
Duncan K. Galloway[*], Rudy Wijnands [‡], Michiel van der Klis [§],
& Craig B. Markwardt [¶] [‖]

Gravitational waves!

Bildsten 98

Way 1: build a mountain (magnetic or elastic stresses)

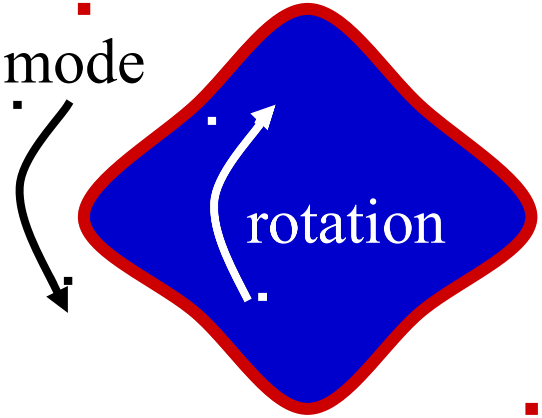


Frequency 2×spin or spin

LIGO would see a few in the Galaxy

Hard to build a mountain on neutron star!

Way 2: unstable mode



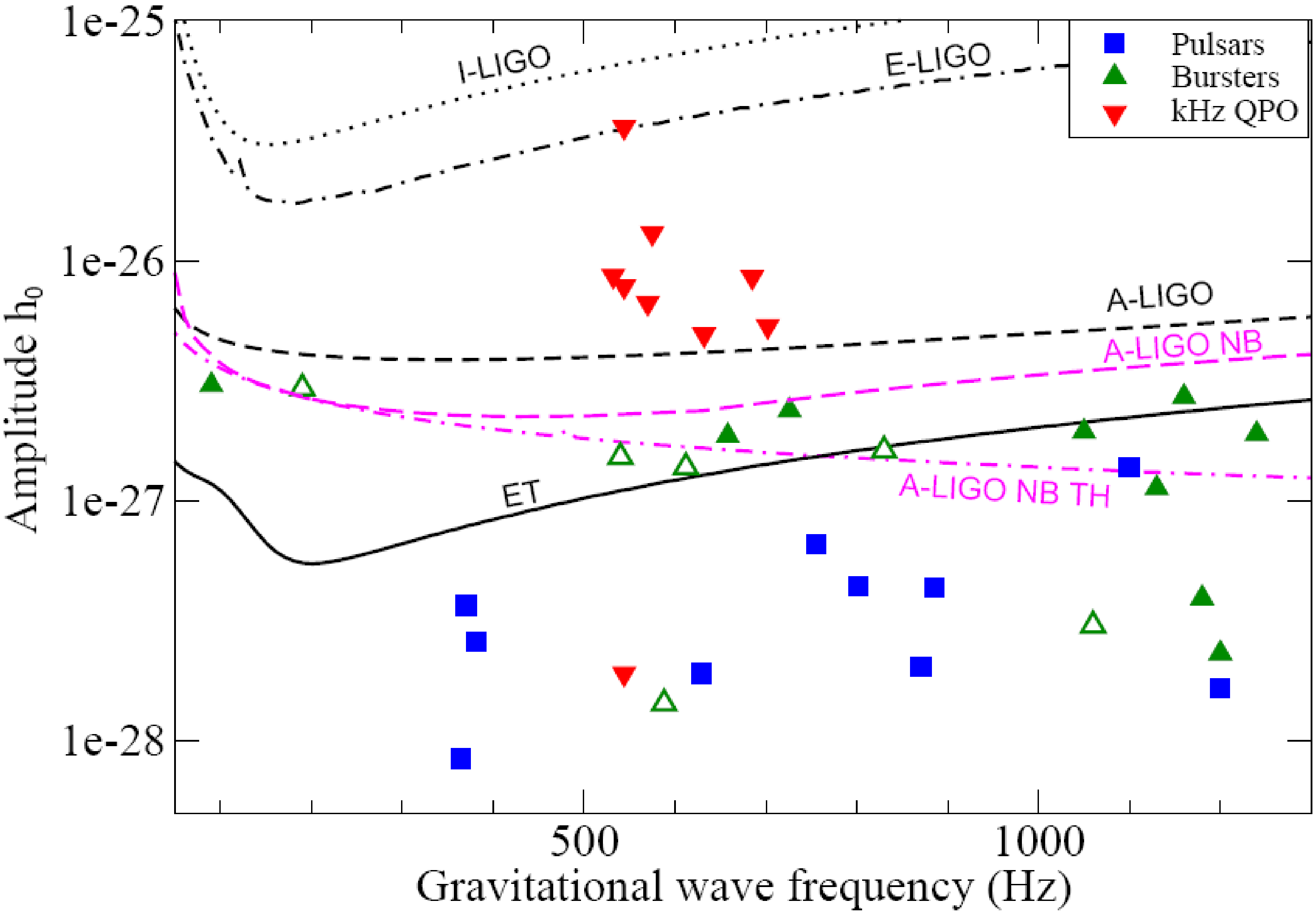
if $V_{mode} < V_{rotation}$

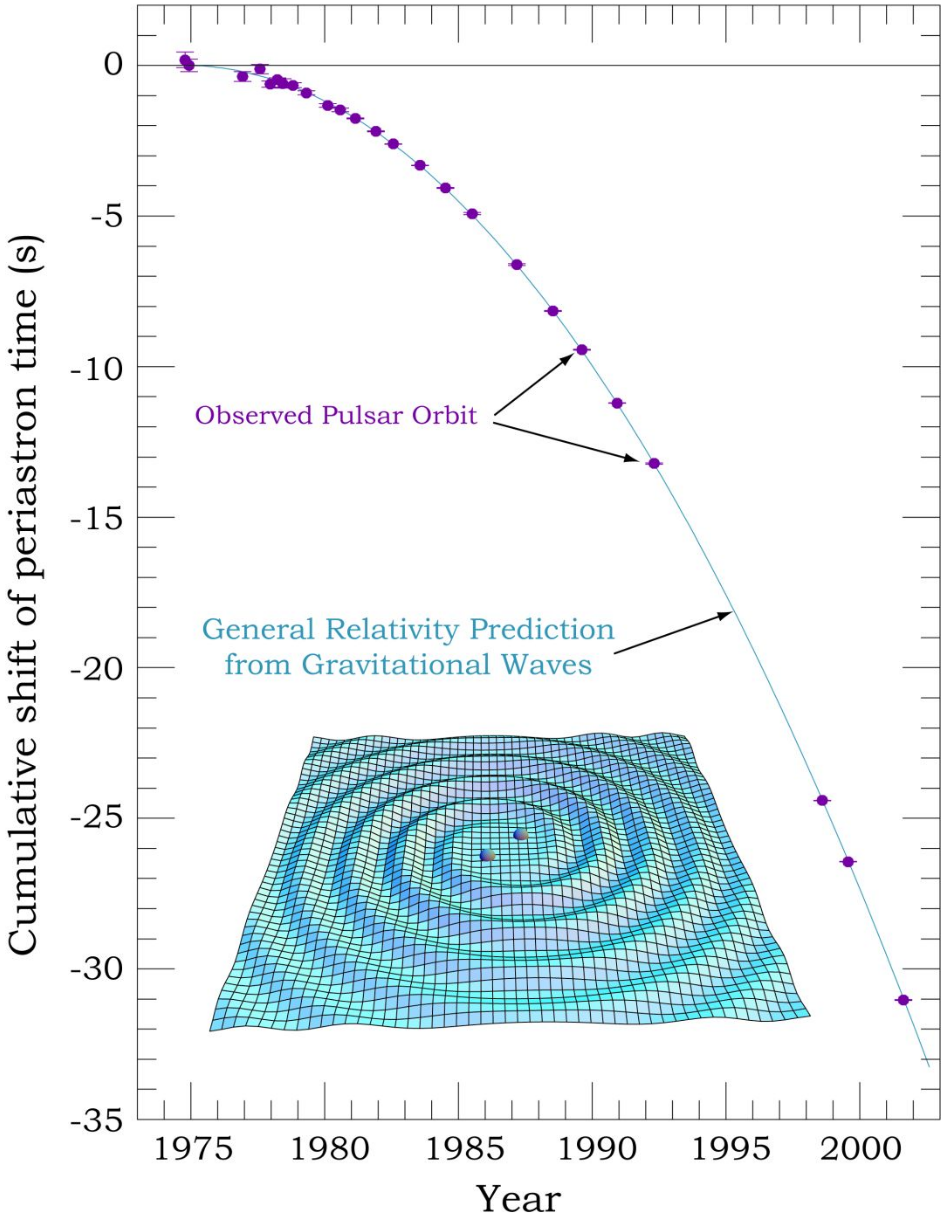
then mode unstable!

Chandrasekhar 70, Friedman & Schutz 78

Expected signals

Watts et al.



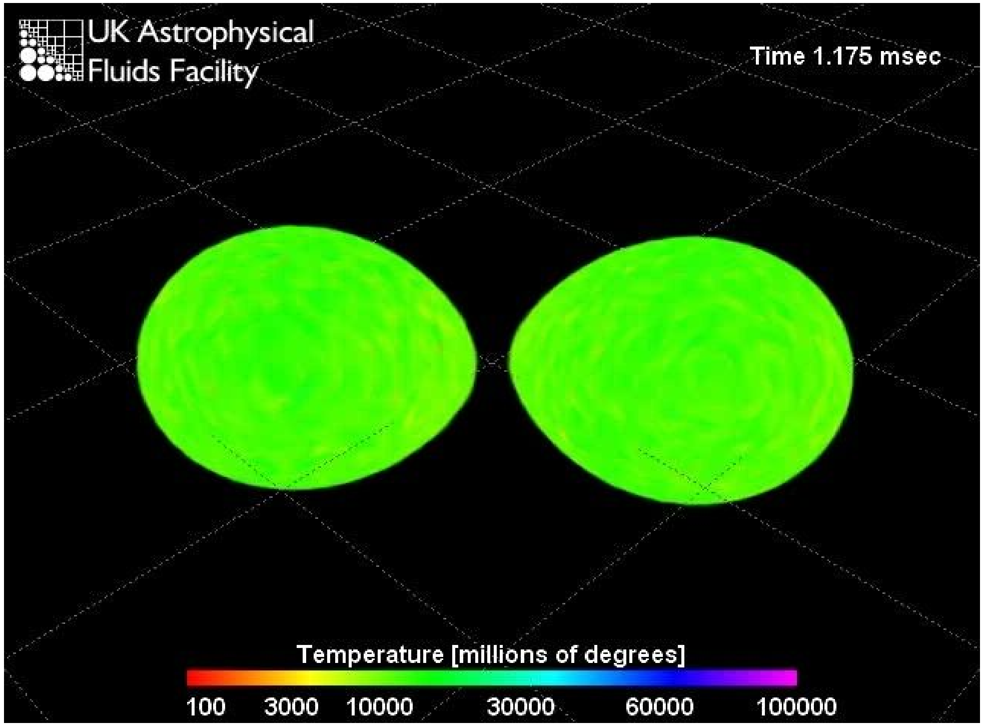


- Binary neutron star PSR 1913+16 follows predictions GR
- 1993: Nobel price Hulse & Taylor
- There are 10 of these binaries known
- Eventually they will merge

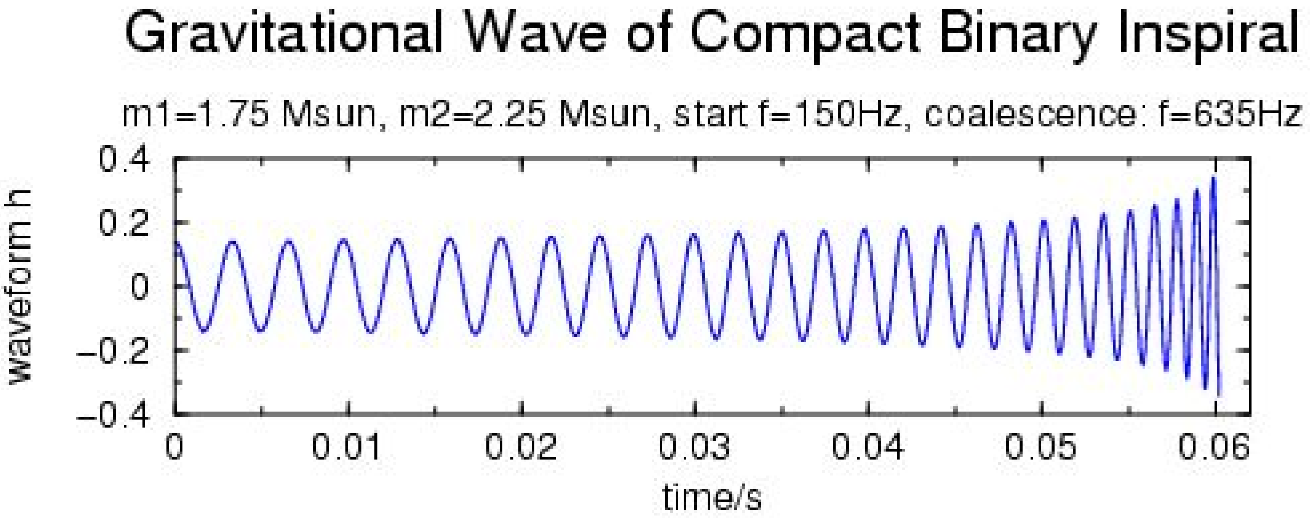
Double pulsar PSR J0737-3039A

- Double neutron star in which both stars are radio pulsars
- Orbital period is only 2.4 hr
- Merger time only 85 million years
- Has changed estimates of merger rates, i.e. event rates for LIGO

Binary neutron star merger simulation

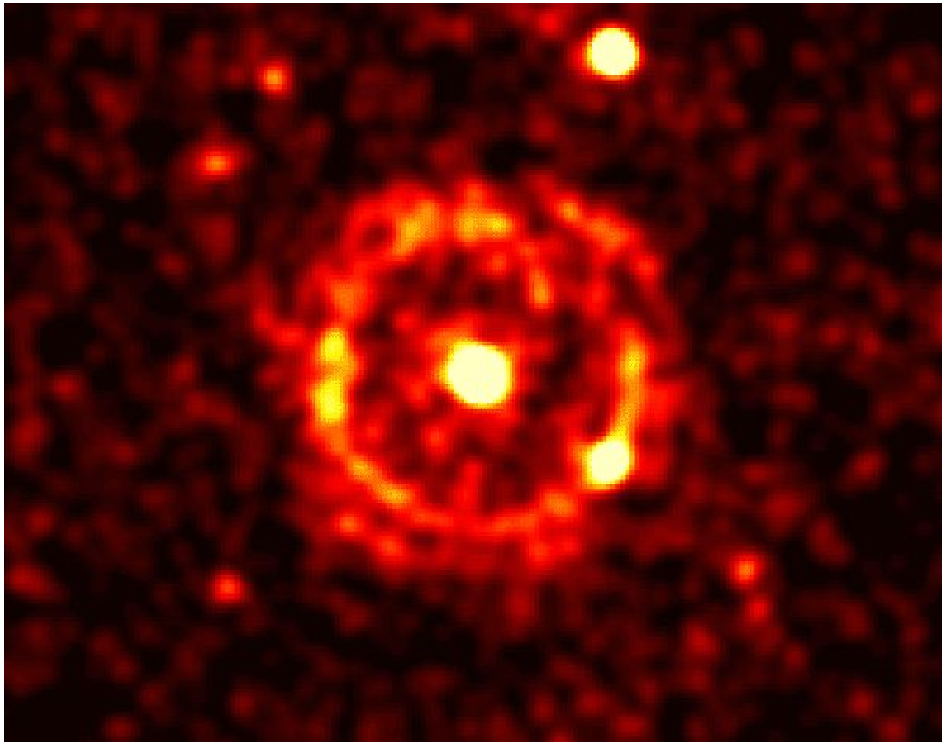


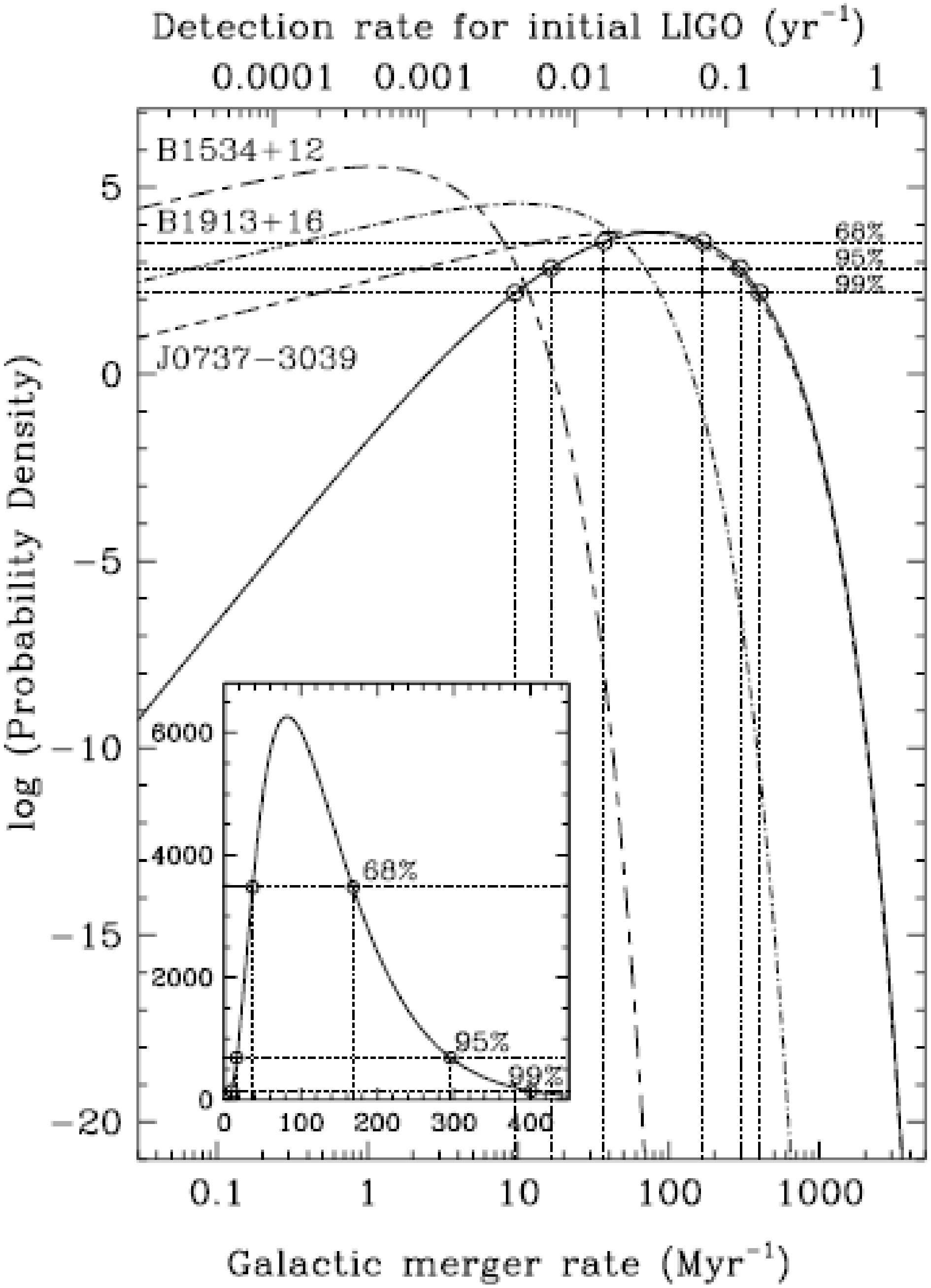
GR signal of merging double NS



Merging double NS as GRBs?

- GRBs are extremely energetic explosions
- One of the models is merging double neutron star
- Unfortunately we are not sure and rates are uncertain (due to beaming)



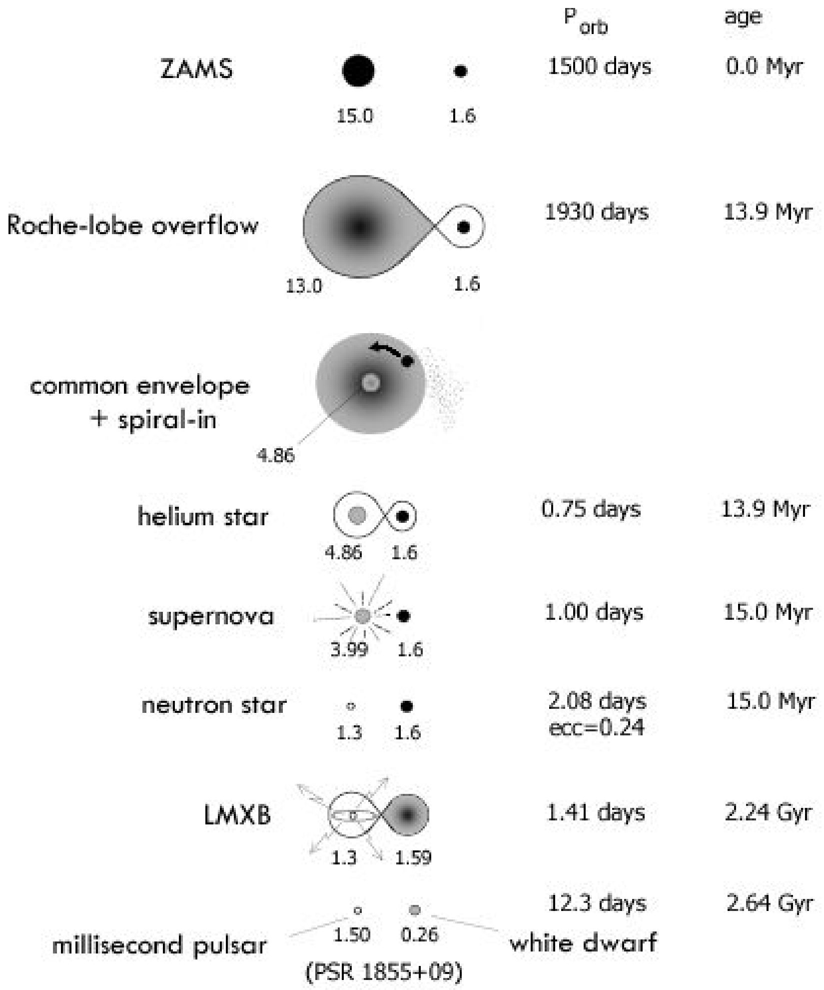


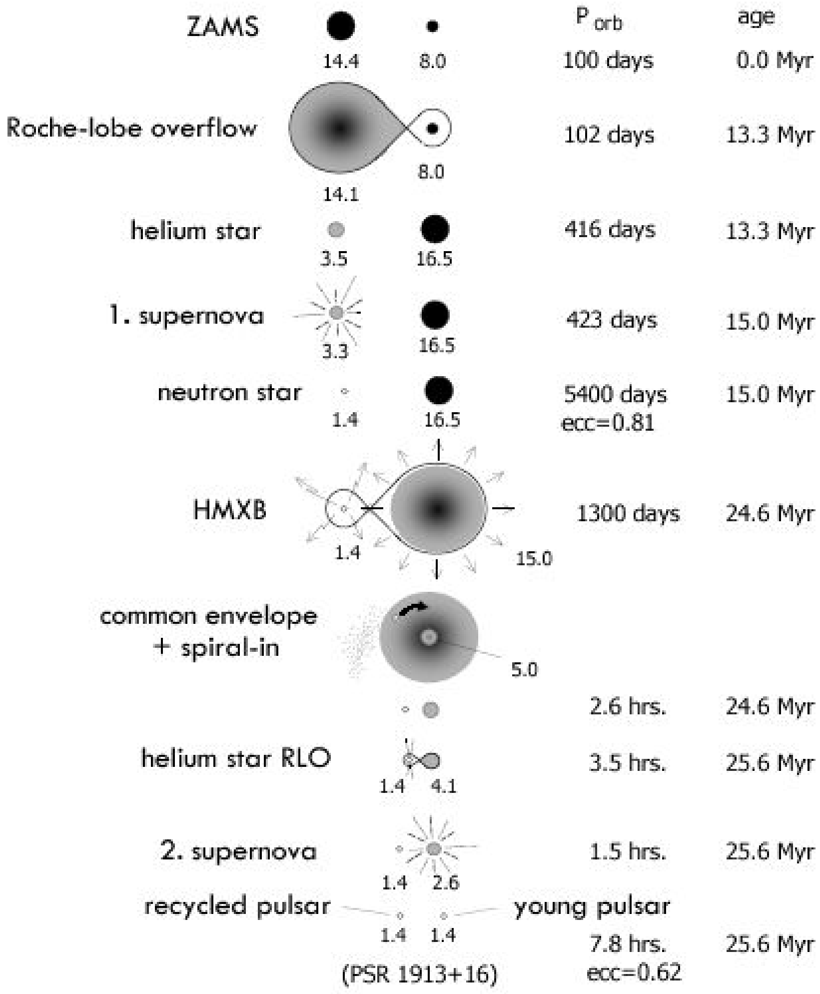
Merger rates estimated based on observed pulsars

Complex probability calculations

Agrees with population synthesis calculations

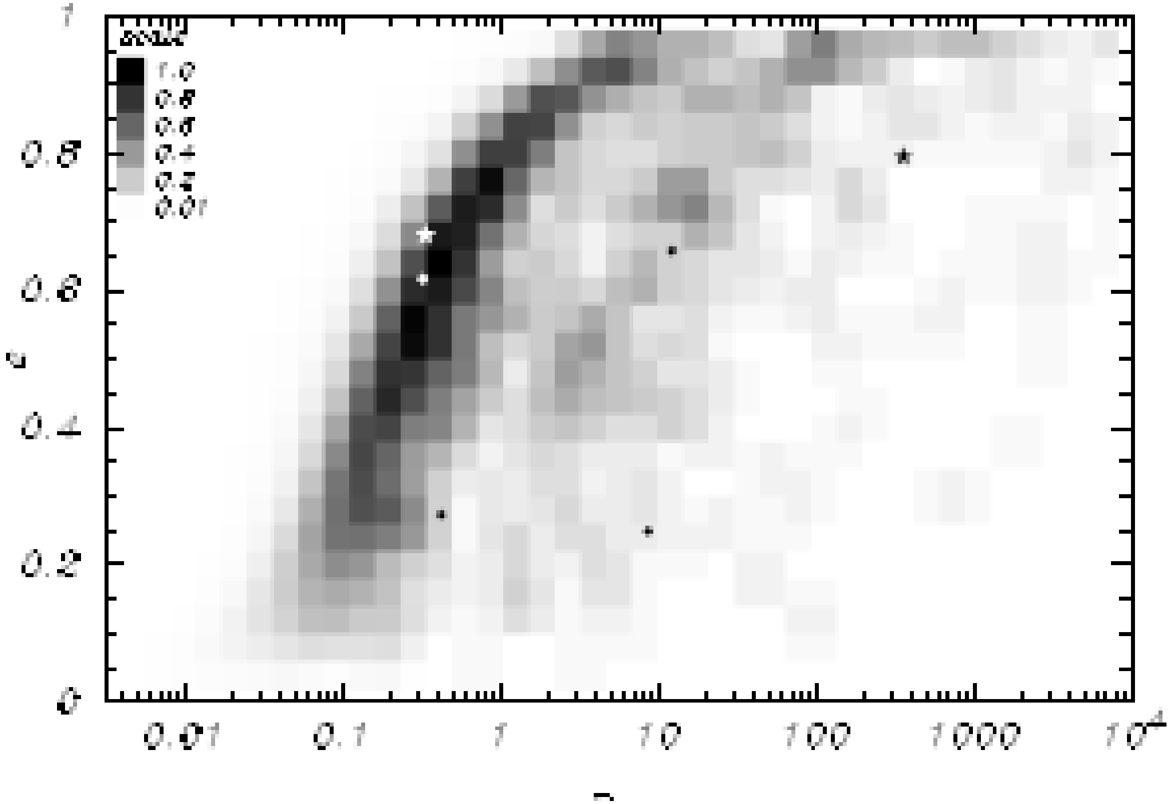
Formation double neutron stars and NS-WD, NS-BH binaries

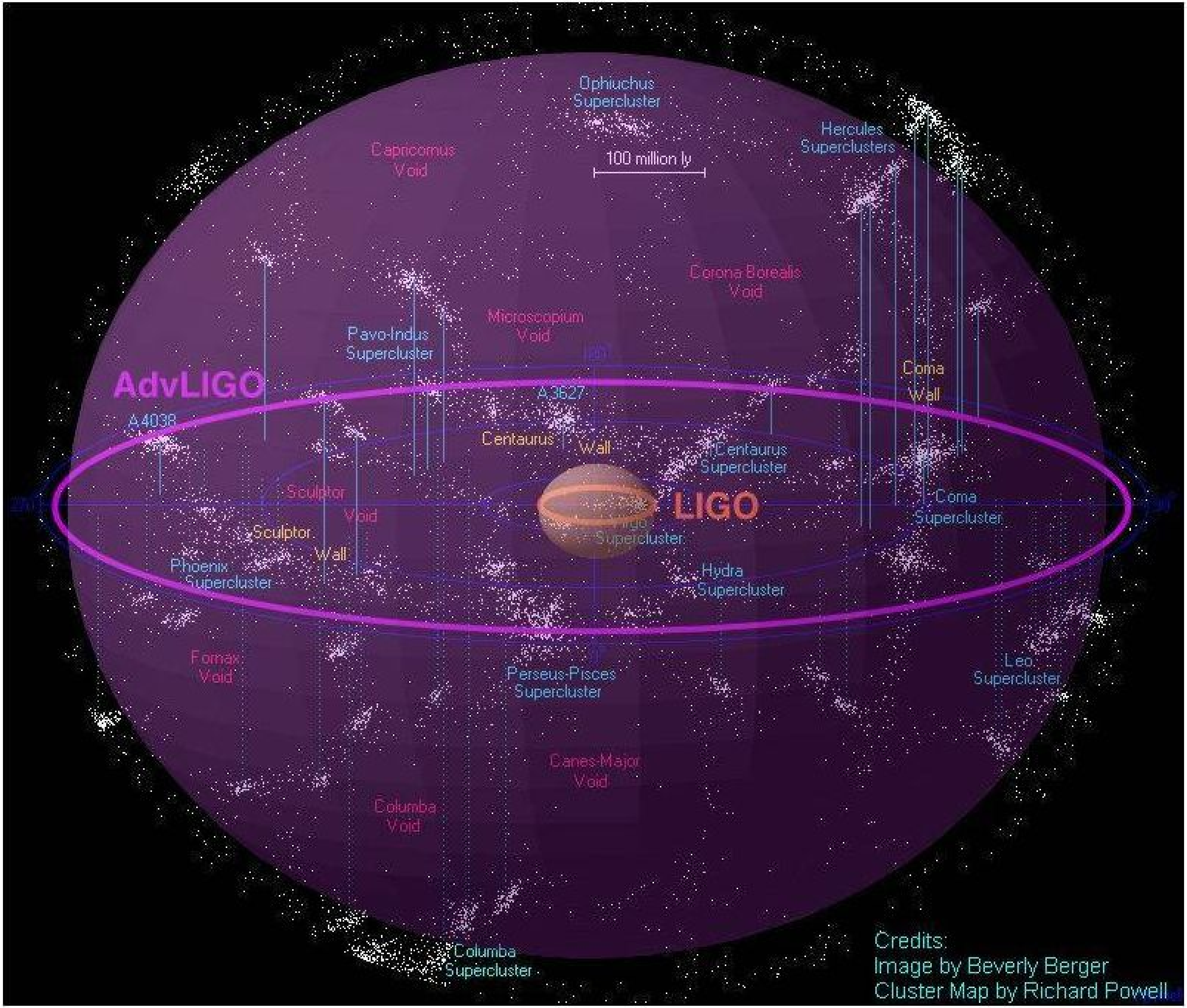




Population synthesis double NS

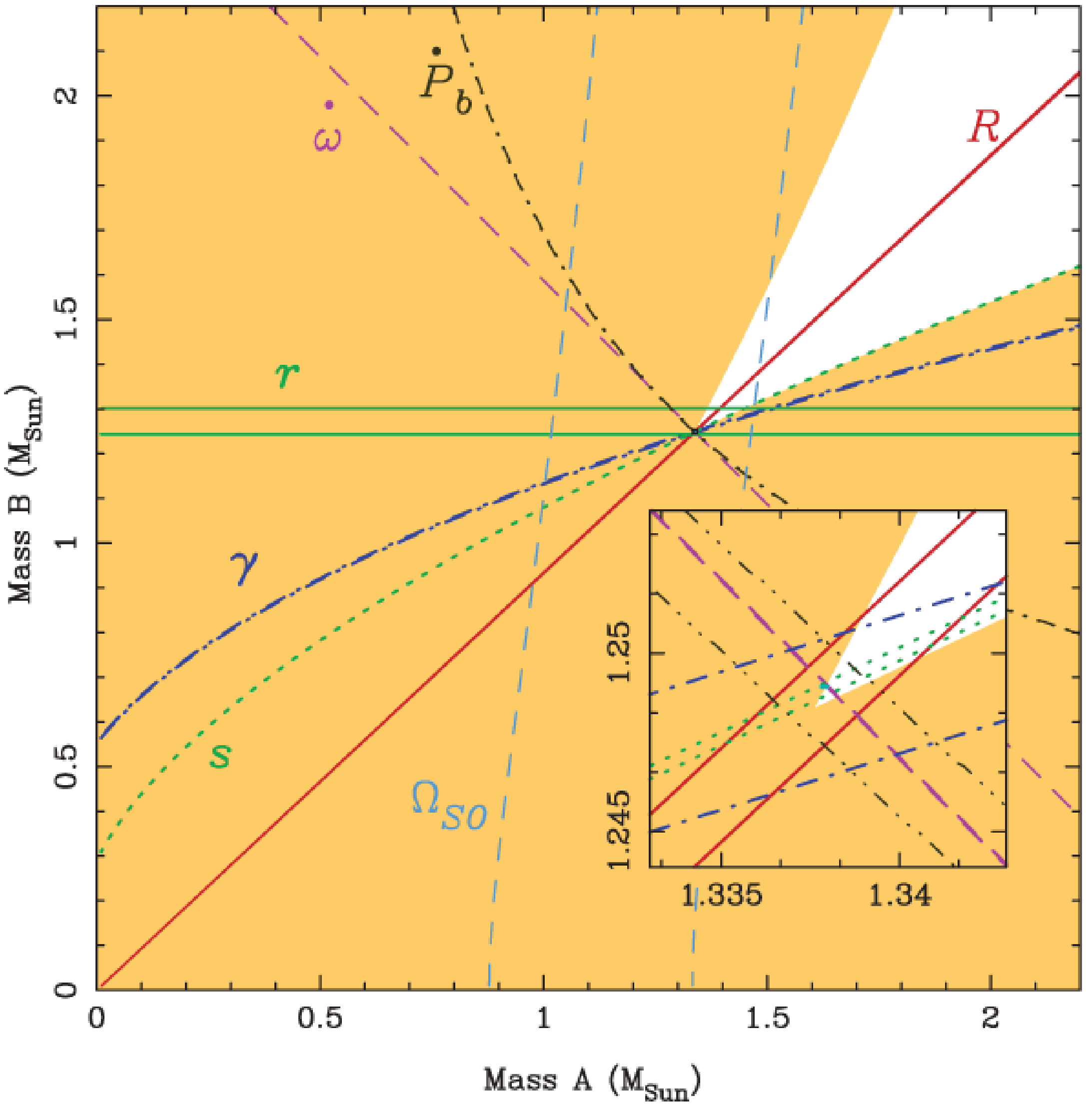
Portegies Zwart & Yungelson 1998

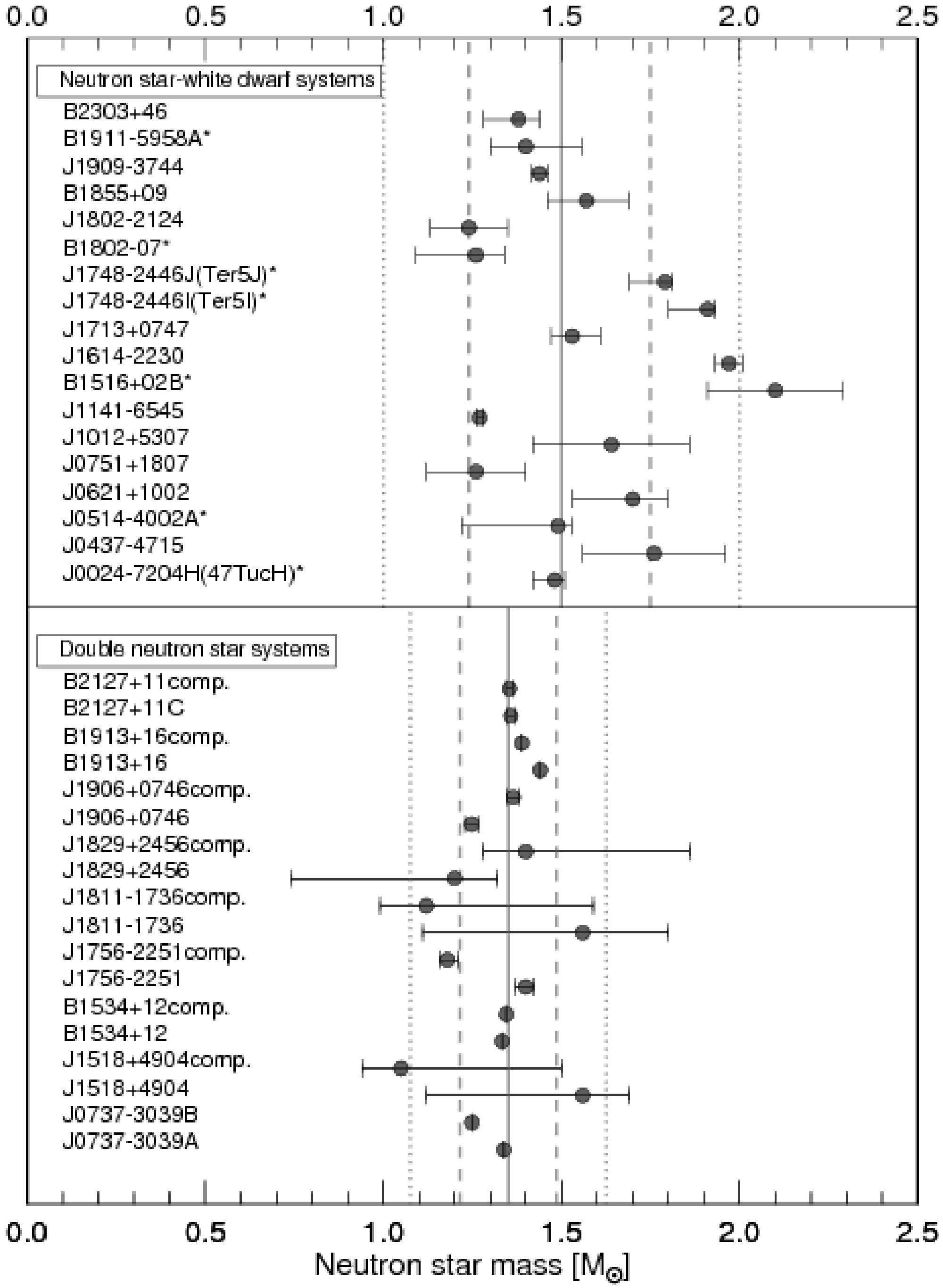




Credits:
Image by Beverly Berger
Cluster Map by Richard Powell

Precision test of GR and mass determination

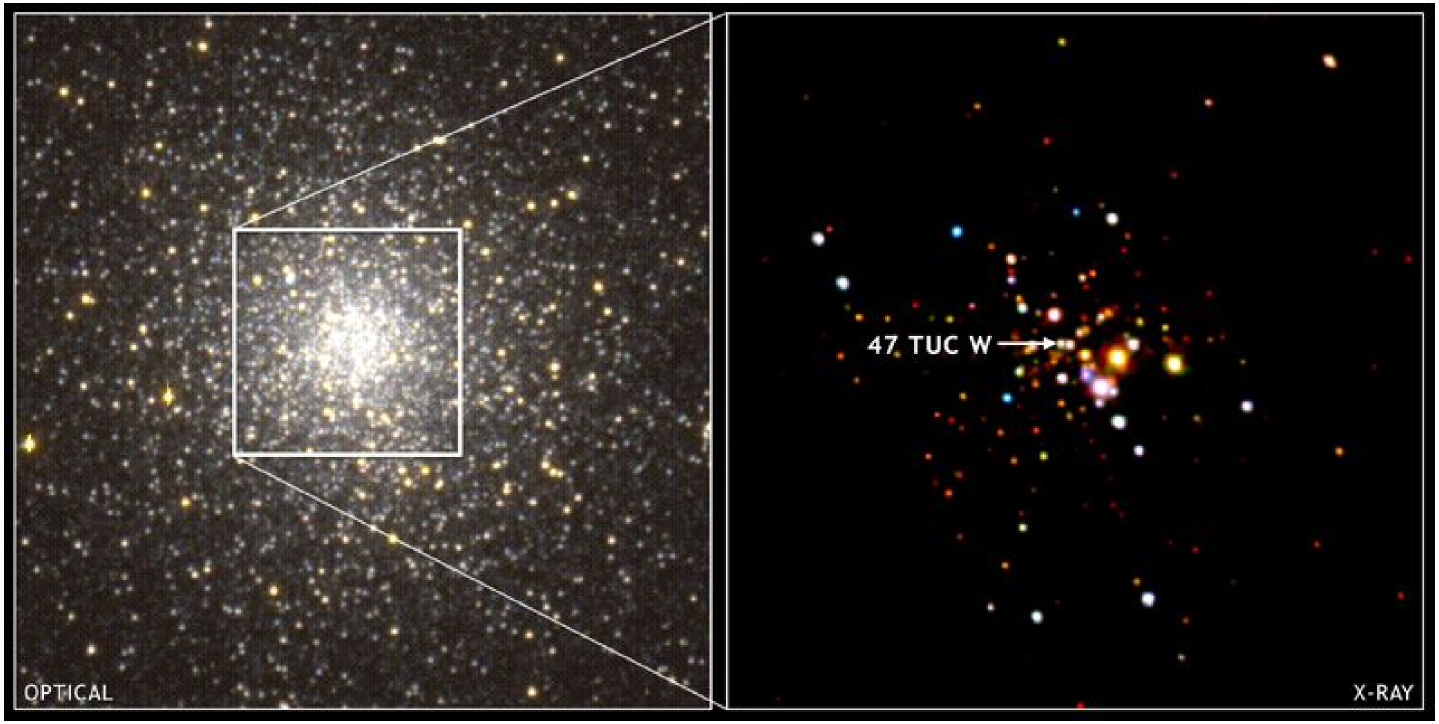



0.0
0.5
1.0
1.5
2.0
2.5
Neutron star-white dwarf systems
B2303+46
B1911-5958A*
J1909-3744
B1855+09
J1802-2124
B1802-07*
J1748-2446J(Ter5J)*
J1748-2446I(Ter5I)*
J1713+0747
J1614-2230
B1516+02B*
J1141-6545
J1012+5307
J0751+1807
J0621+1002
J0514-4002A*
J0437-4715
J0024-7204H(47TucH)*
Double neutron star systems
B2127+11comp.
B2127+11C
B1913+16comp.
B1913+16
J1906+0746comp.
J1906+0746
J1829+2456comp.
J1829+2456
J1811-1736comp.
J1811-1736
J1756-2251comp.
J1756-2251
B1534+12comp.
B1534+12
J1518+4904comp.
J1518+4904
J0737-3039B
J0737-3039A
0.0
0.5
1.0
1.5
2.0
2.5
Neutron star mass [$M_\odot$]

Double black holes from clusters?

- In globular clusters black holes are ejected (are the most massive objects)
- Most likely as binary, but with long periods
- BUT: eccentric orbits→merge quickly!

Portegies Zwart
McMillan
1999

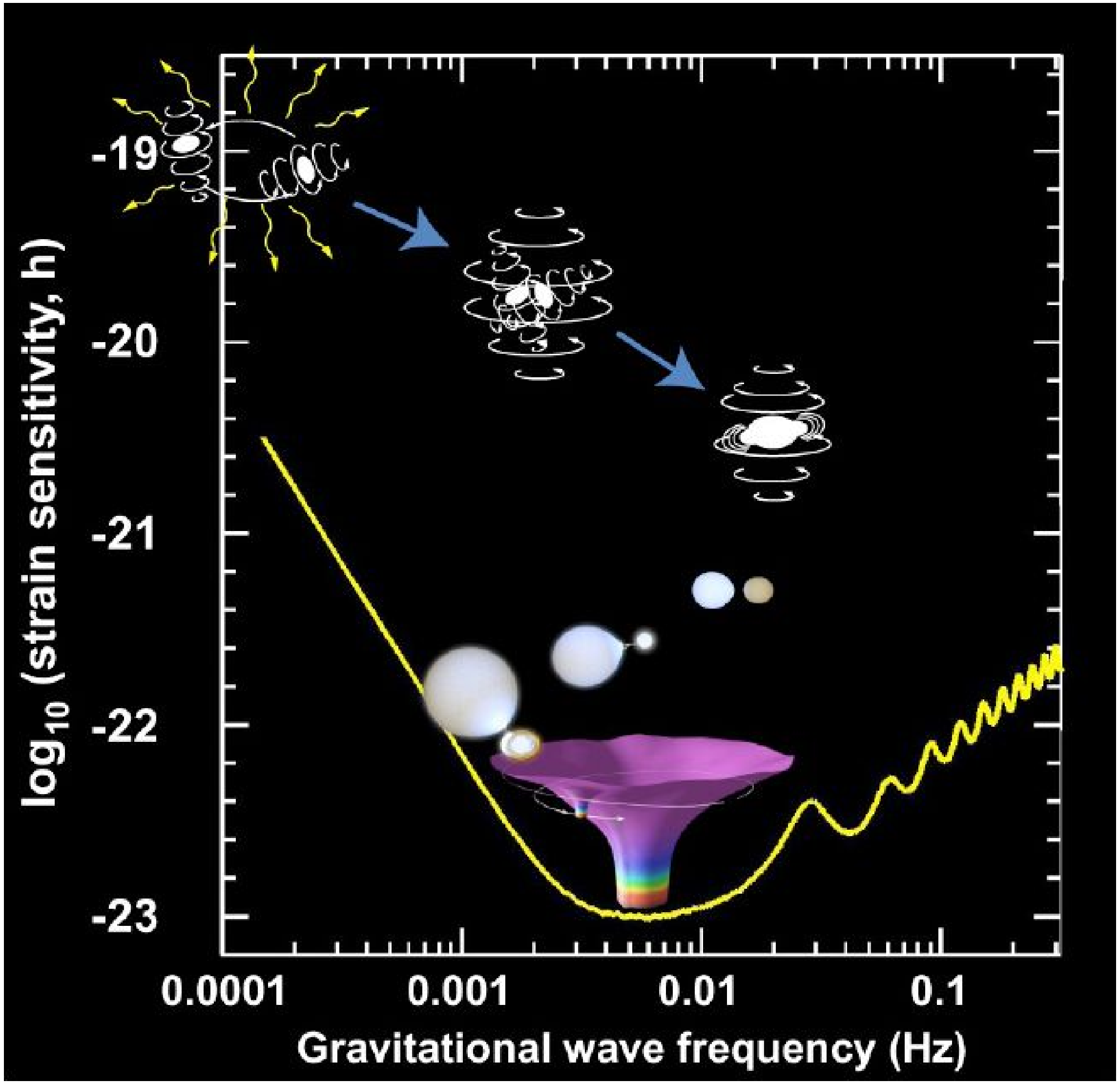


Low-frequency sources for LISA

Compact binaries

Super-massive black hole mergers

Extreme mass-ratio inspirals



-19
-20
-21
-22
-23
log10 (strain sensitivity, h)
0.0001
0.001
0.01
0.1
Gravitational wave frequency (Hz)

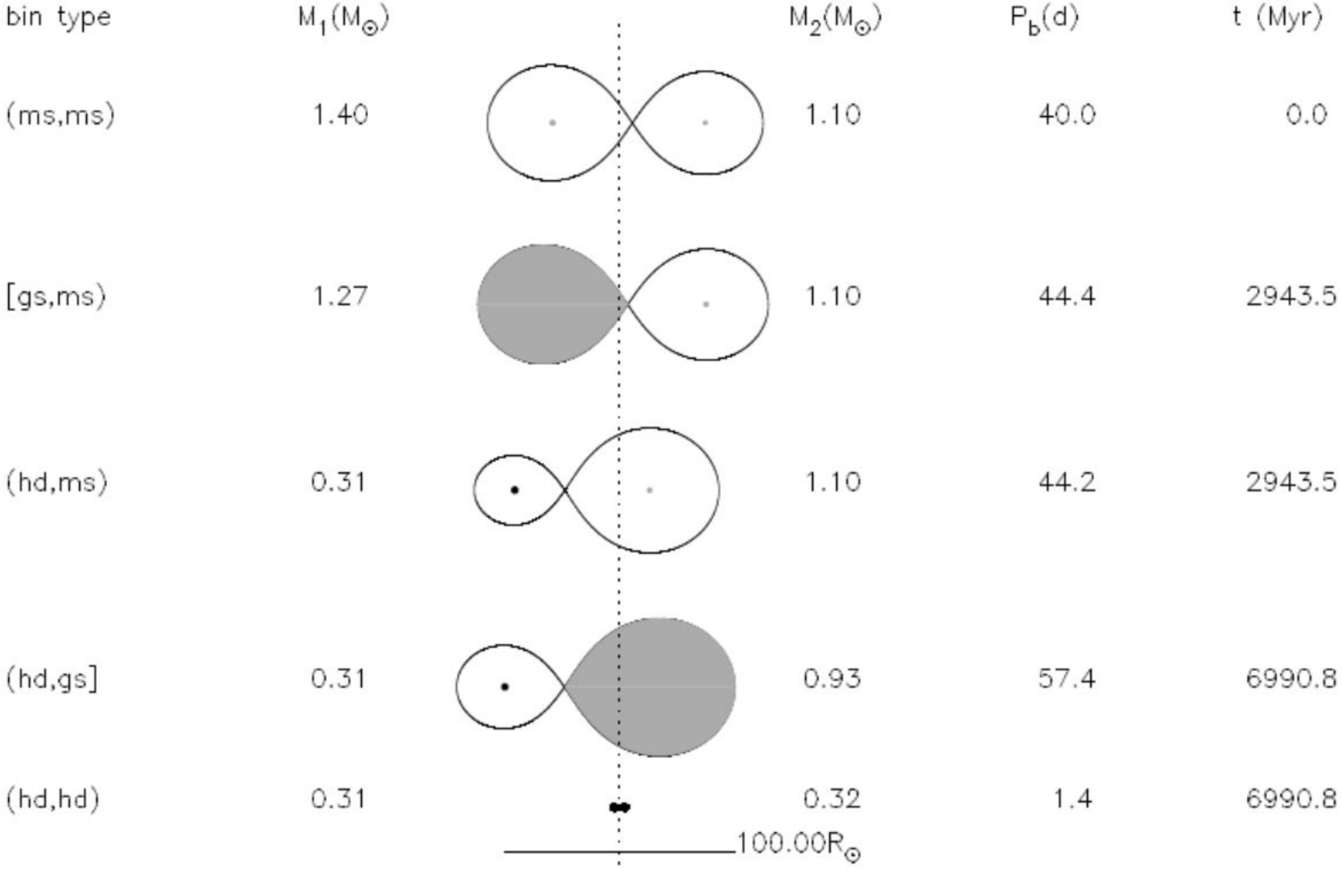
(Ultra-)compact binaries

- Double white dwarfs: millions in our Galaxy
- Through gravitational wave radiation they get closer and closer
- Merge or survive as mass-transferring binaries:

  AM CVn stars or

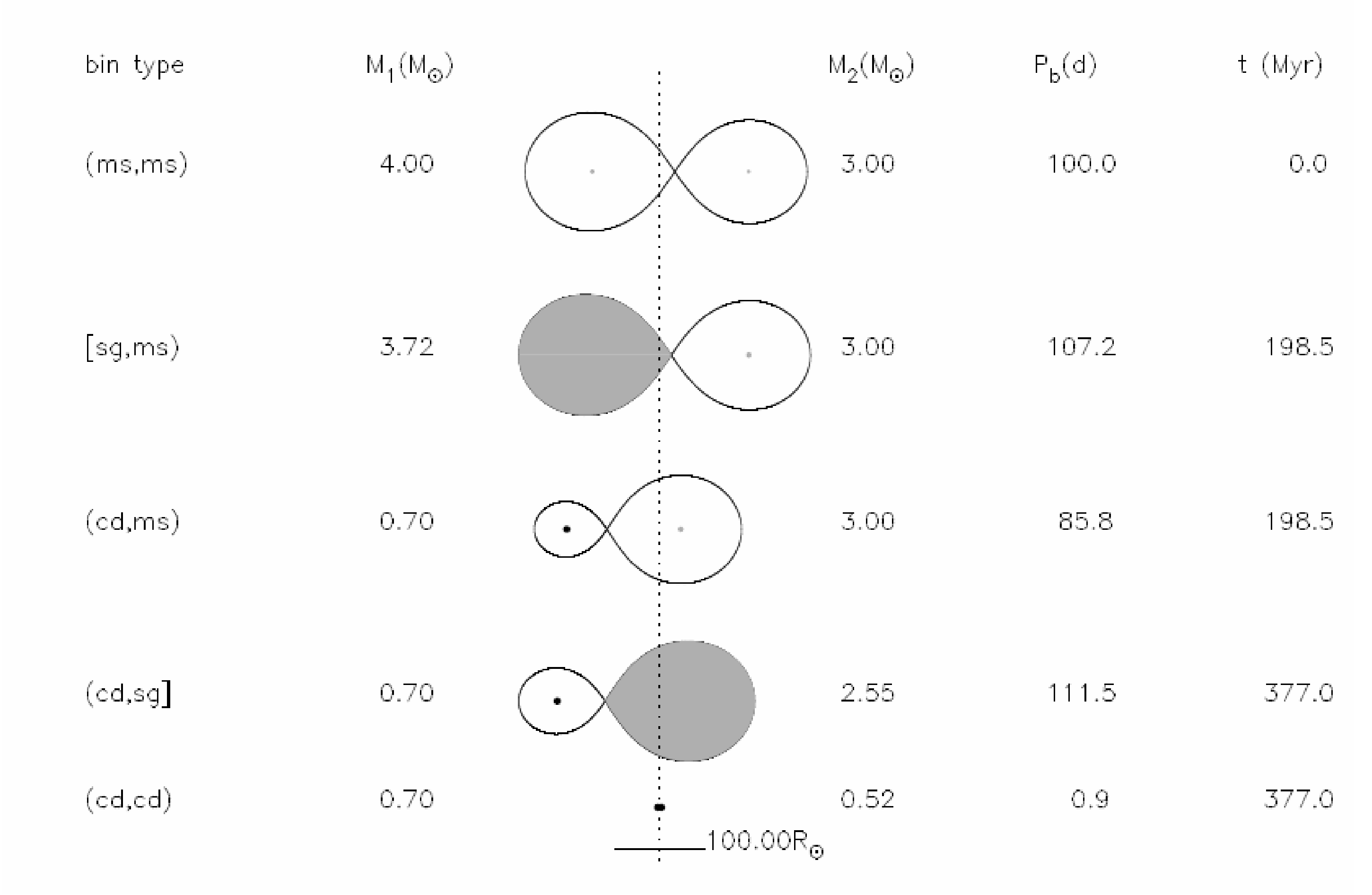
  Ultra-compact X-ray binaries

Formation of double white dwarfs



bin type	$M_1(M_\odot)$	$M_2(M_\odot)$	P_b(d)	t (Myr)
(ms,ms)	1.40	1.10	40.0	0.0
[gs,ms)	1.27	1.10	44.4	2943.5
(hd,ms)	0.31	1.10	44.2	2943.5
(hd,gs]	0.31	0.93	57.4	6990.8
(hd,hd)	0.31	0.32	1.4	6990.8

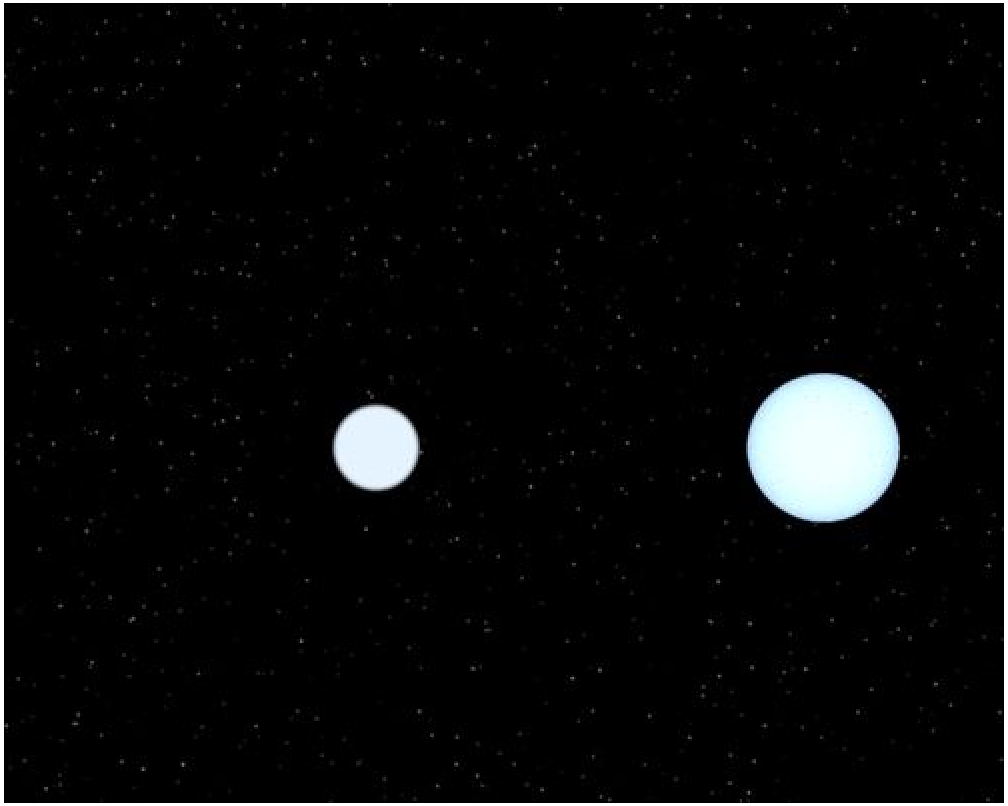
Formation of double white dwarfs



bin type	$M_1(M_\odot)$	$M_2(M_\odot)$	$P_b(d)$	t (Myr)
(ms,ms)	4.00	3.00	100.0	0.0
[sg,ms)	3.72	3.00	107.2	198.5
(cd,ms)	0.70	3.00	85.8	198.5
(cd,sg]	0.70	2.55	111.5	377.0
(cd,cd)	0.70	0.52	0.9	377.0

Merging double white dwarf

Mass-transferring ultra-compact binaries



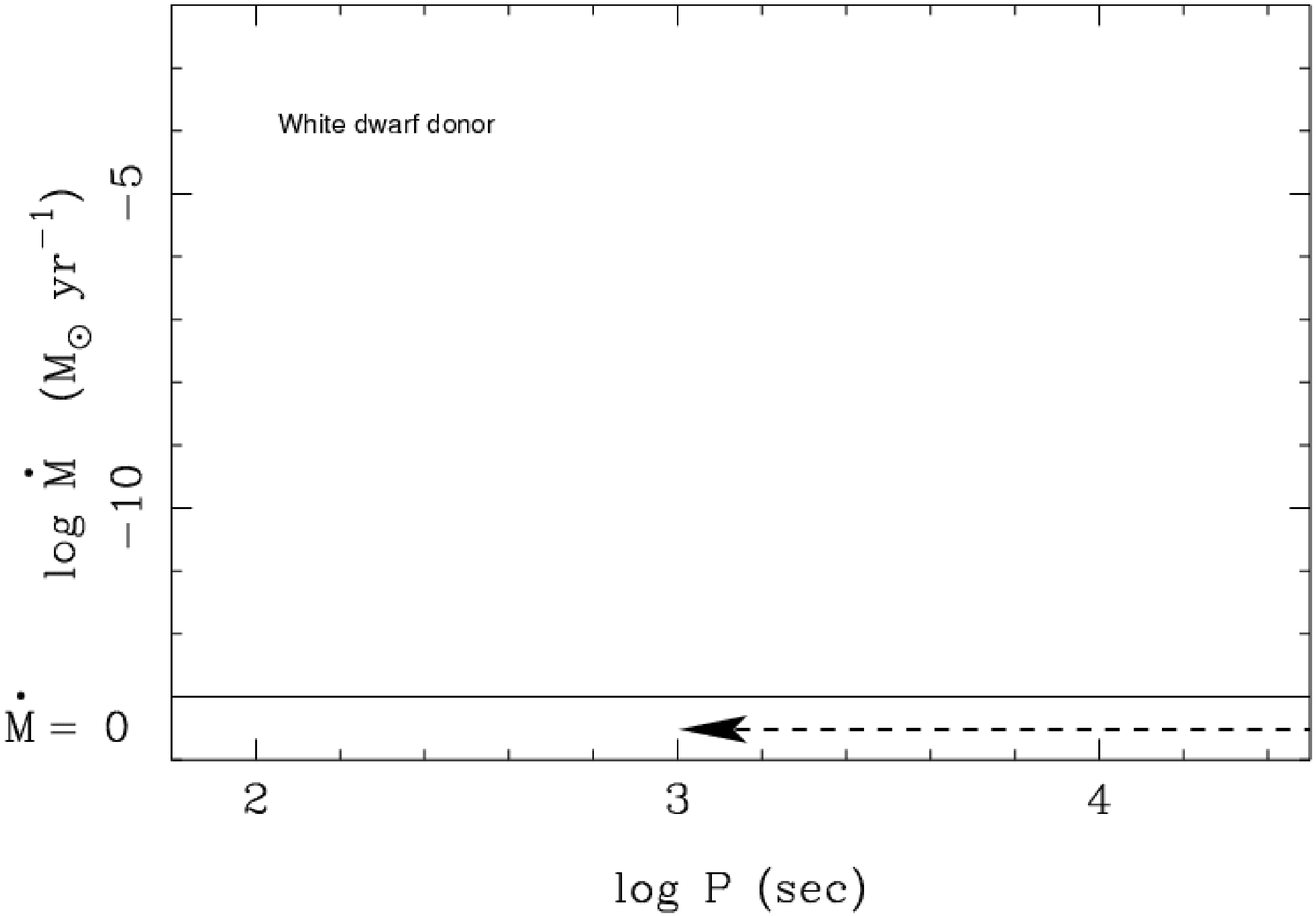
Formation of ultra-compact binaries

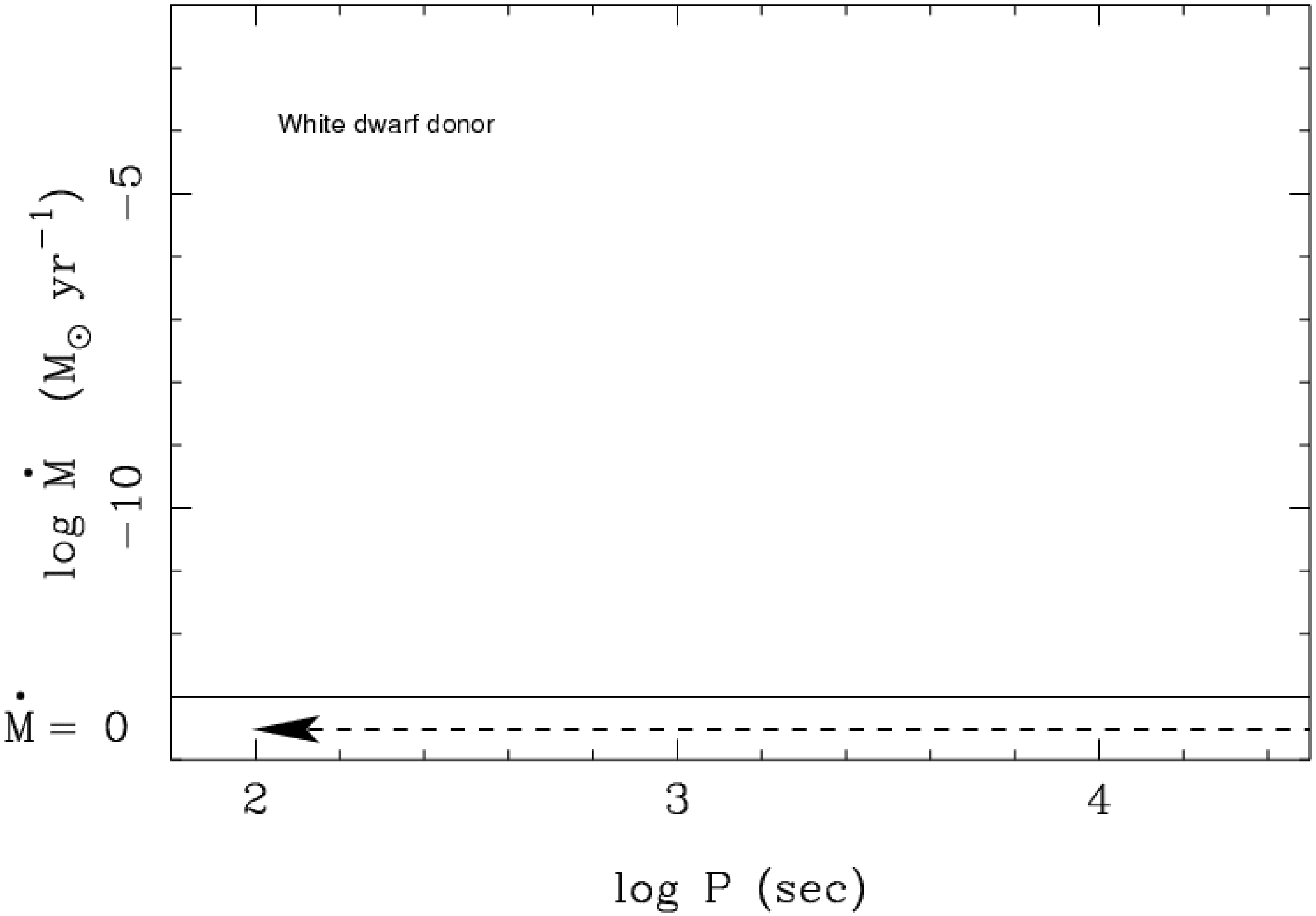
- 3 Channels have been proposed
  - ❑ Donor stars is a white dwarf

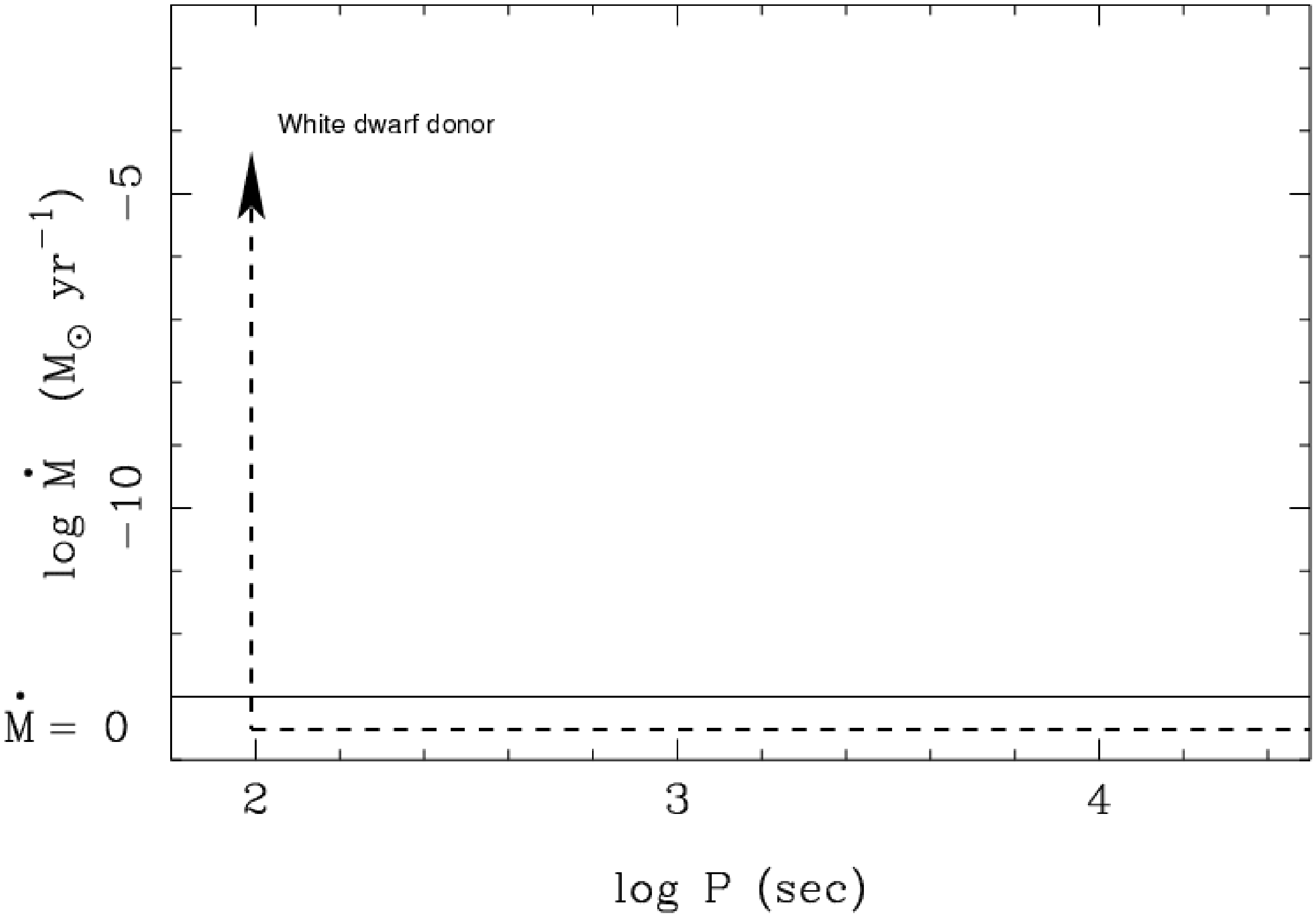
    Webbink & Pringle 1975; Tutukov & Yungelson 1979, Nather et al. 1981
  - ❑ Donor was a helium burning star

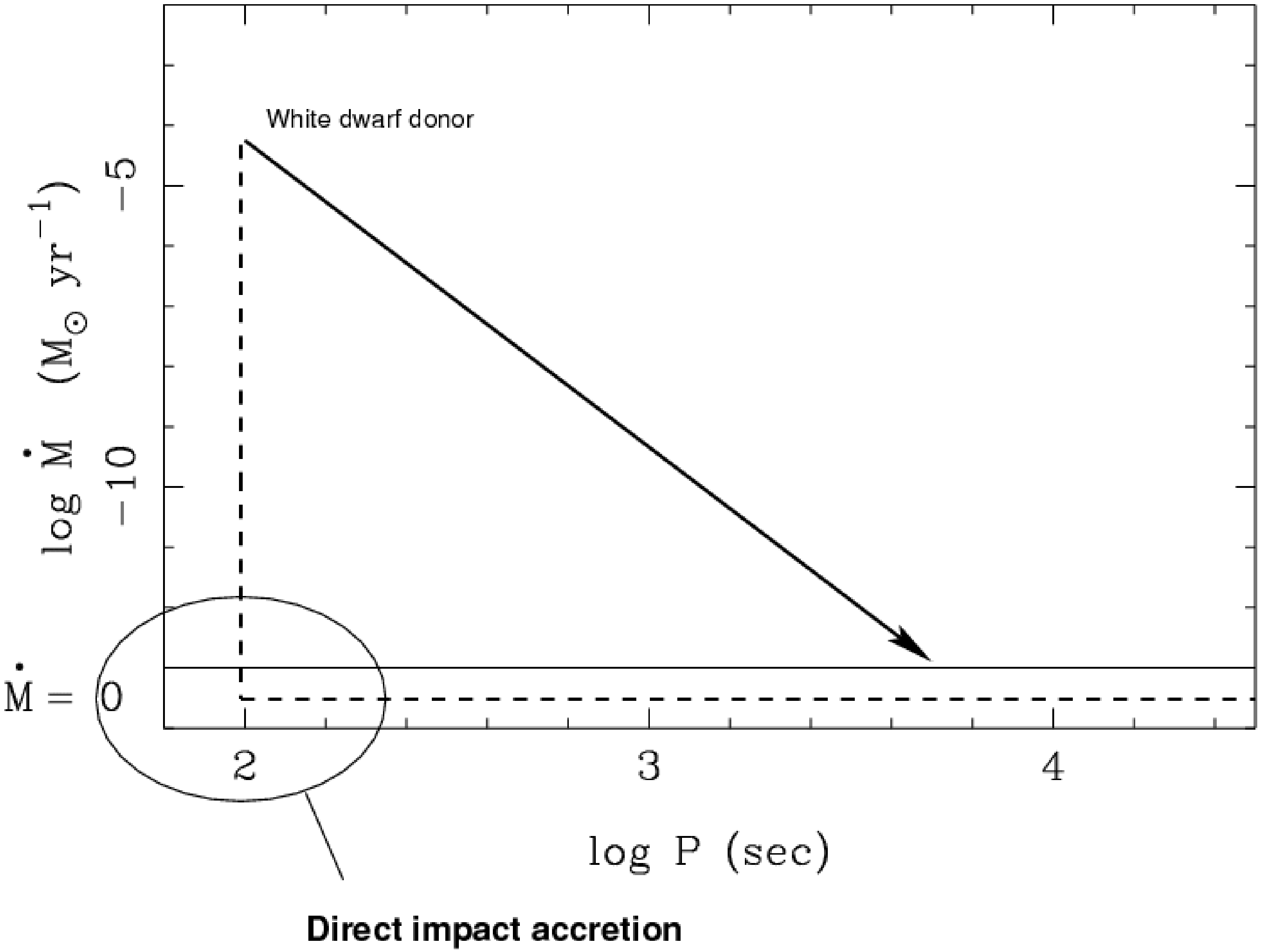
    Savonije et al. 1986, Iben & Tutukov 1991
  - ❑ Donor was a hydrogen burning star

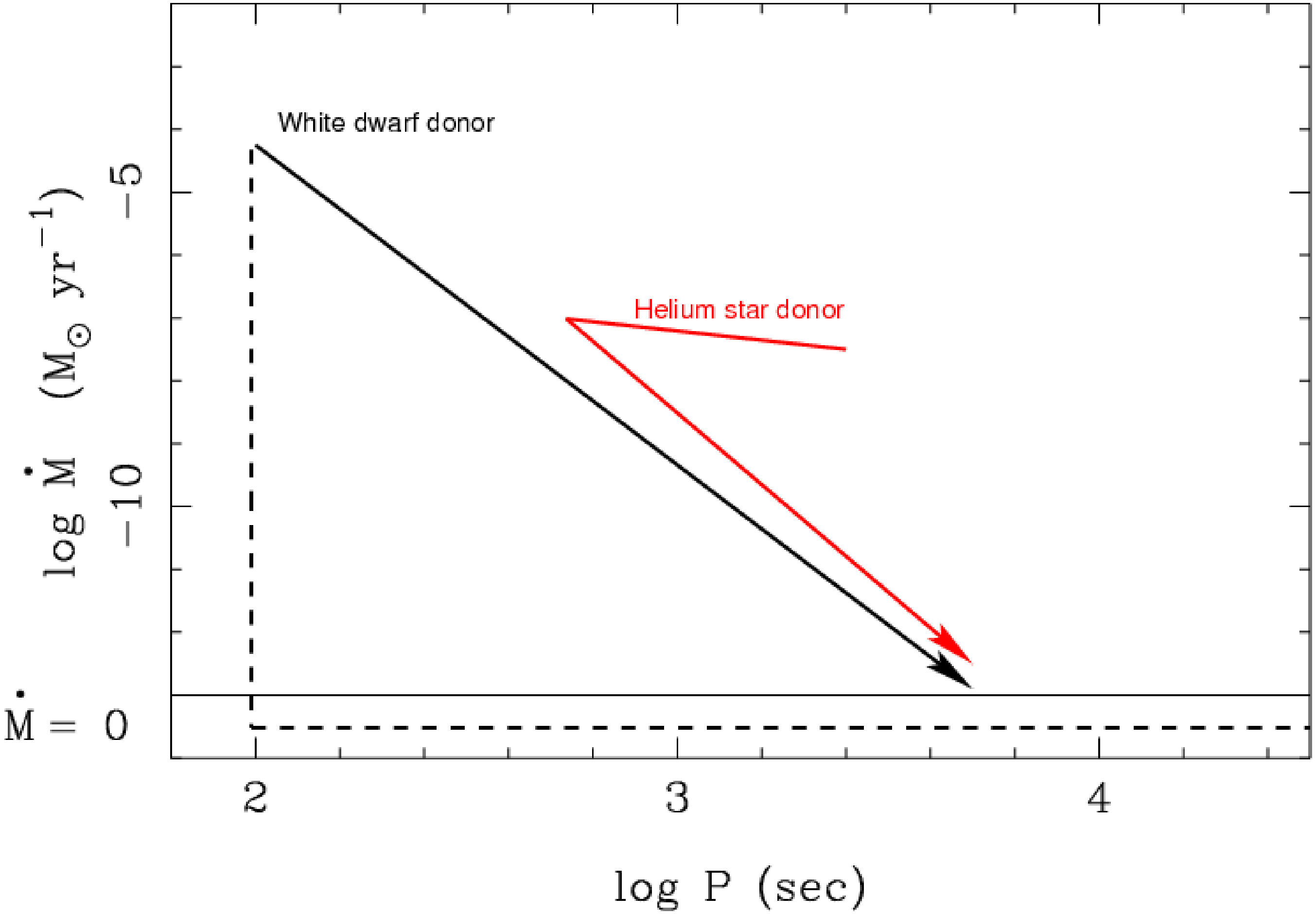
    Tutukov et al. 1987, Podsiadlowski et al. 2002

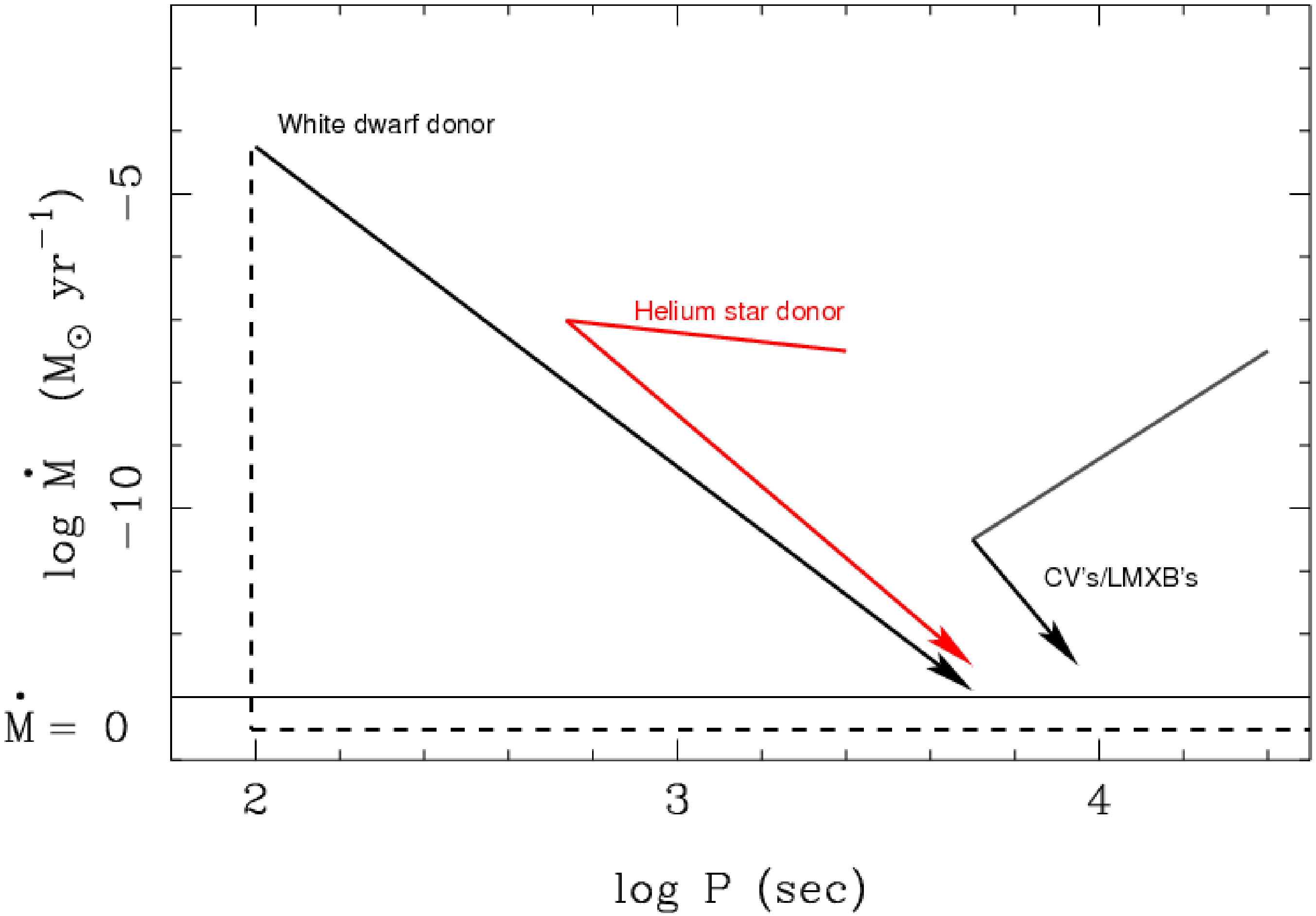

White dwarf donor
log Ṁ (M$_\odot$ yr^{-1})
−5
−10
Ṁ = 0
2
3
4
log P (sec)

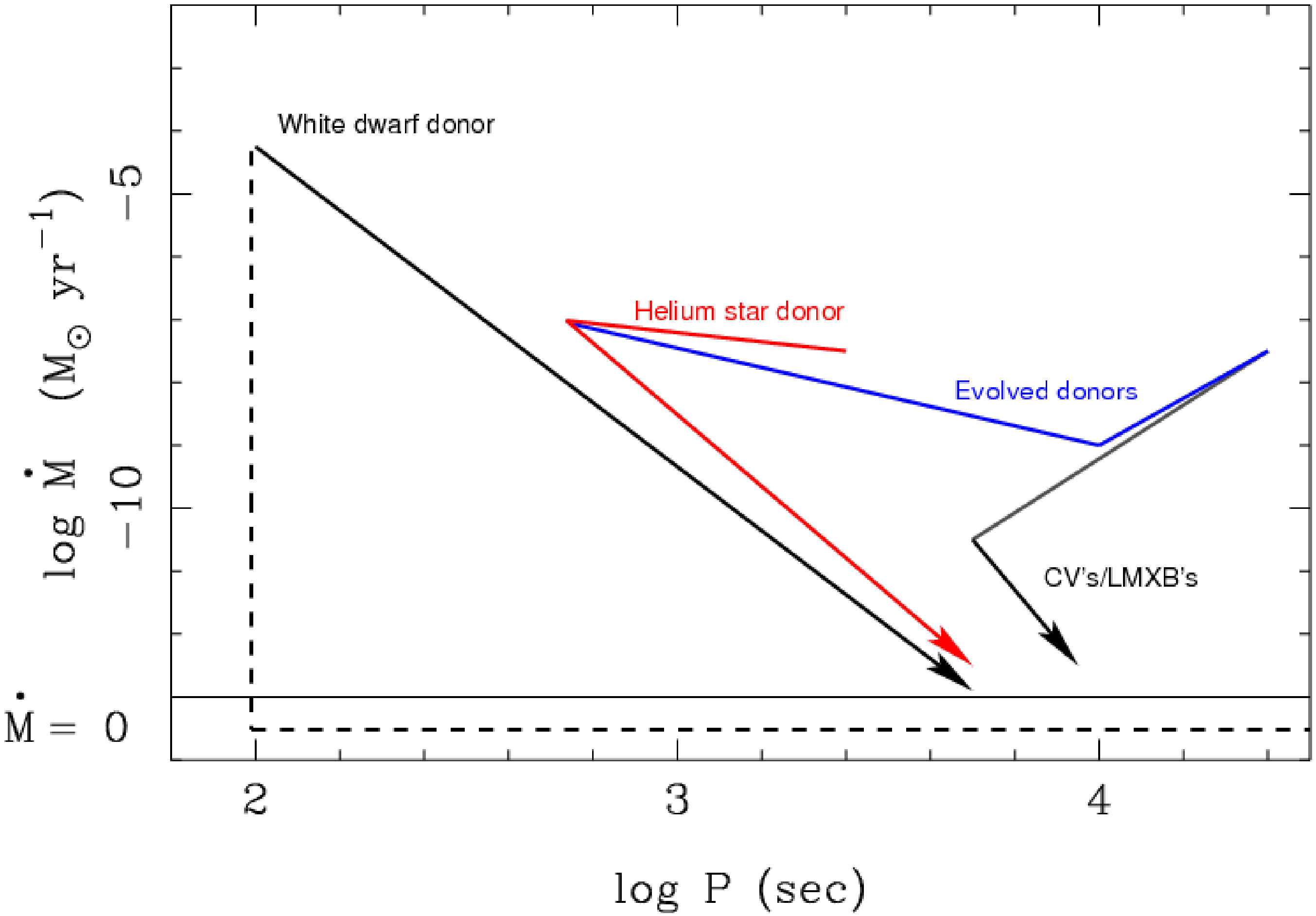

White dwarf donor
log $\dot{M}$ ($M_\odot$ yr^{-1})
−5
−10
$\dot{M}$ = 0
2
3
4
log P (sec)

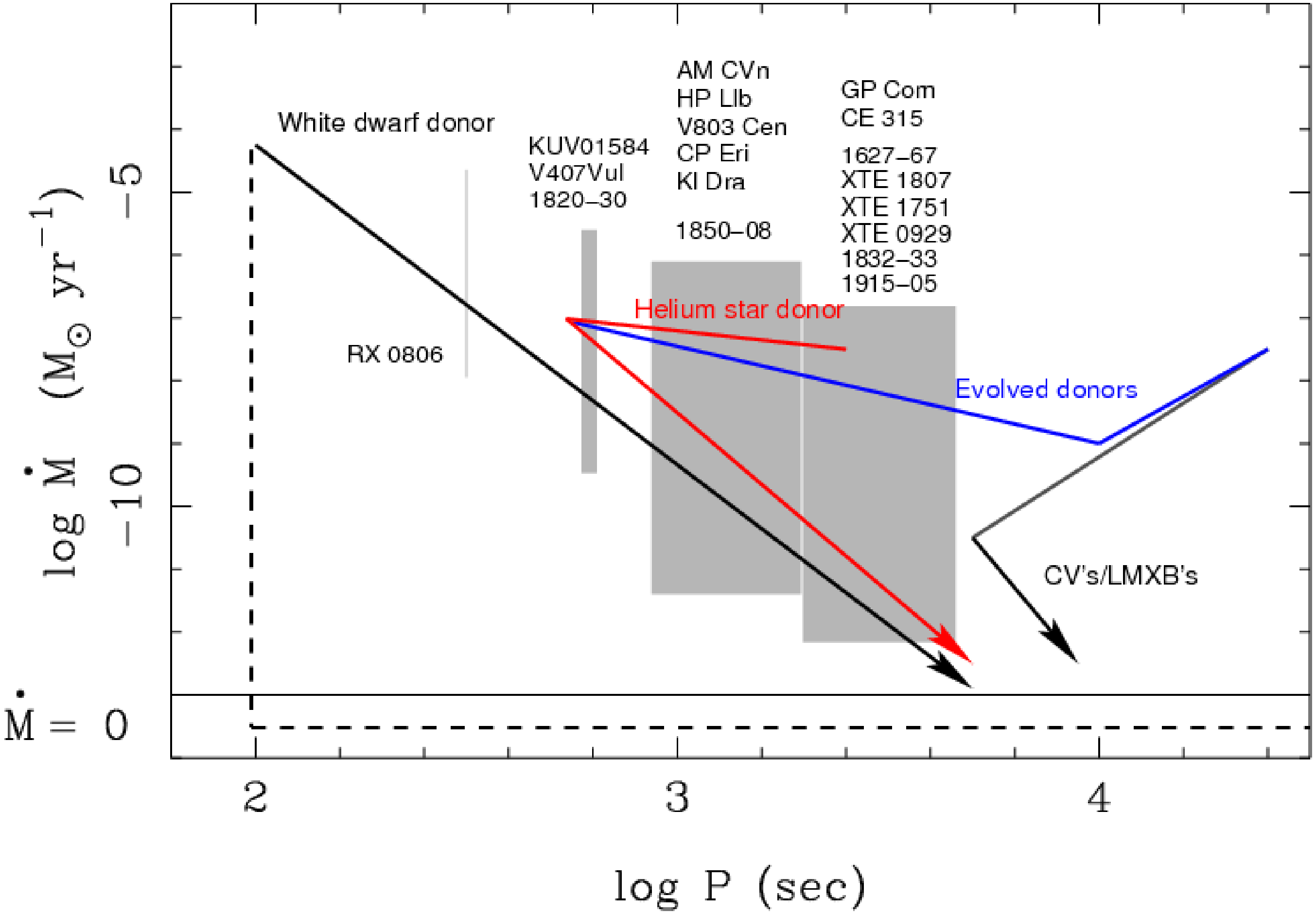

White dwarf donor
log Ṁ (M⊙ yr⁻¹)
−5
−10
Ṁ = 0
2
3
4
log P (sec)


White dwarf donor
log $\dot{M}$ ($M_\odot$ yr^{-1})
−5
−10
$\dot{M}$ = 0
2
3
4
log P (sec)
Direct impact accretion

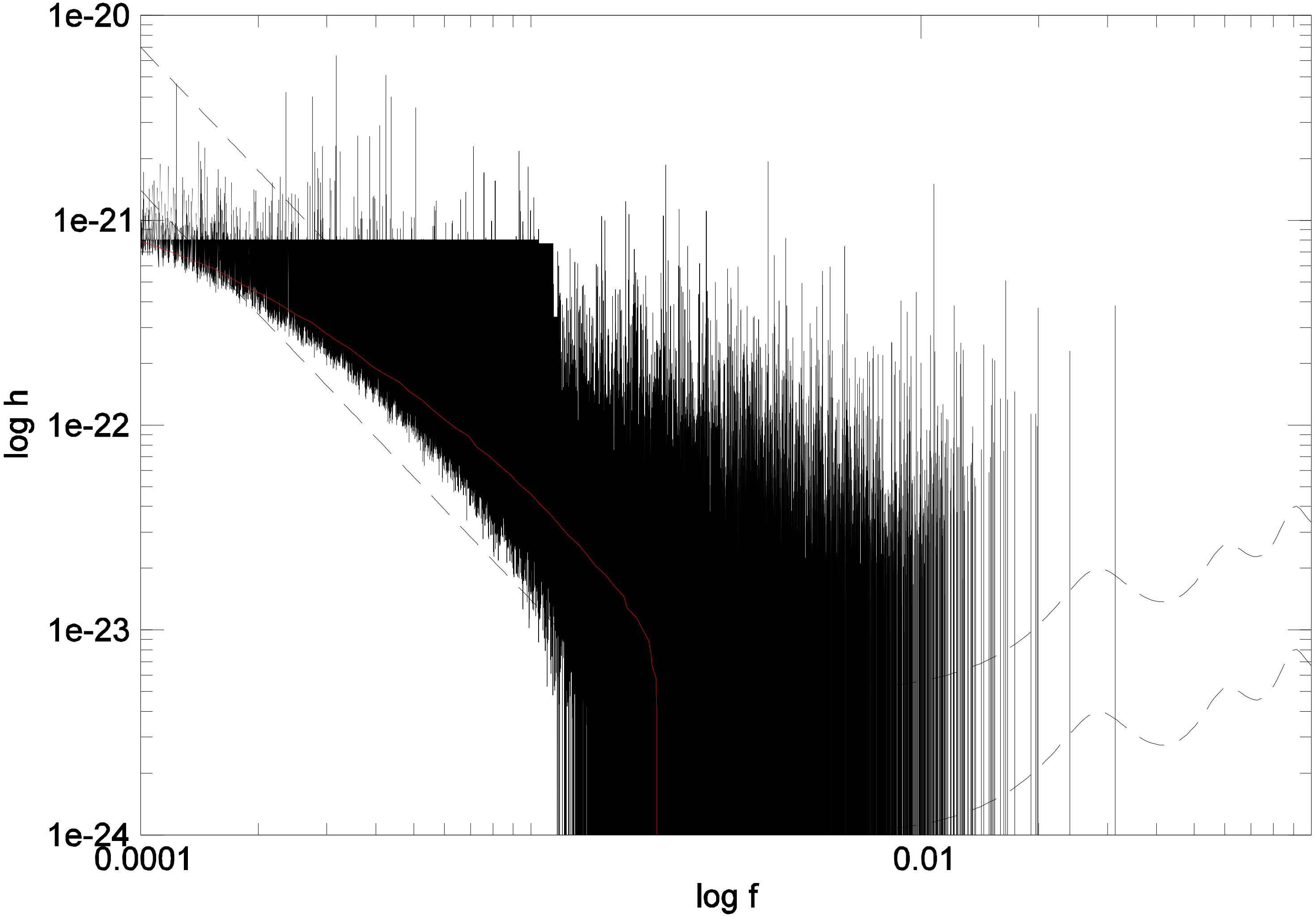

White dwarf donor
Helium star donor
$\log \dot{M} \quad (M_\odot\ \mathrm{yr}^{-1})$
−5
−10
$\dot{M} = 0$
2
3
4
log P (sec)


White dwarf donor
Helium star donor
CV's/LMXB's
log $\dot{M}$ ($M_\odot$ yr^{-1})
−5
−10
$\dot{M}$ = 0
2
3
4
log P (sec)


White dwarf donor
Helium star donor
Evolved donors
CV's/LMXB's
log $\dot{M}$ ($M_\odot$ yr^{-1})
−5
−10
$\dot{M}$ = 0
2
3
4
log P (sec)


White dwarf donor
KUV01584
V407Vul
1820–30
AM CVn
HP Llb
V803 Cen
CP Eri
KI Dra
1850–08
GP Com
CE 315
1627–67
XTE 1807
XTE 1751
XTE 0929
1832–33
1915–05
Helium star donor
RX 0806
Evolved donors
CV's/LMXB's
log Ṁ (M⊙ yr⁻¹)
−5
−10
Ṁ = 0
2
3
4
log P (sec)

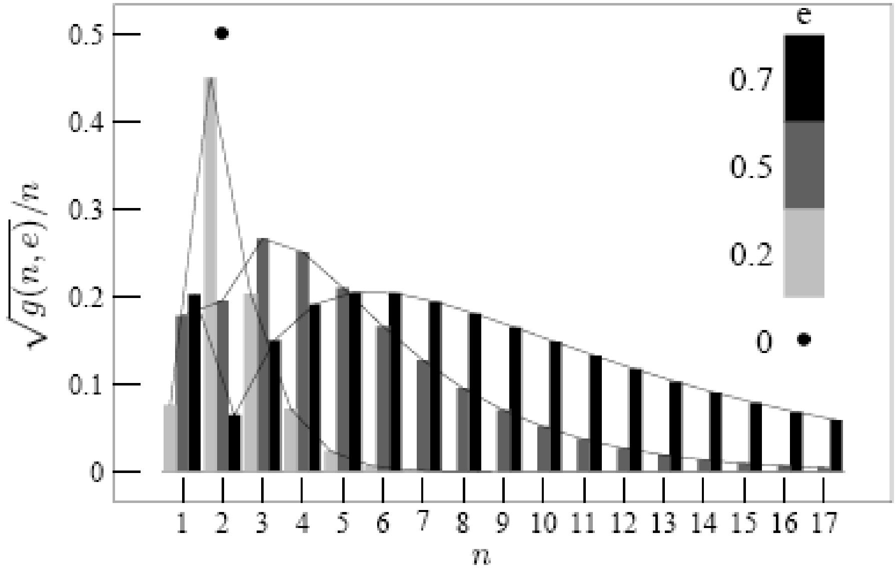
LISA signal of Galactic double white dwarfs



Galactic compact binaries

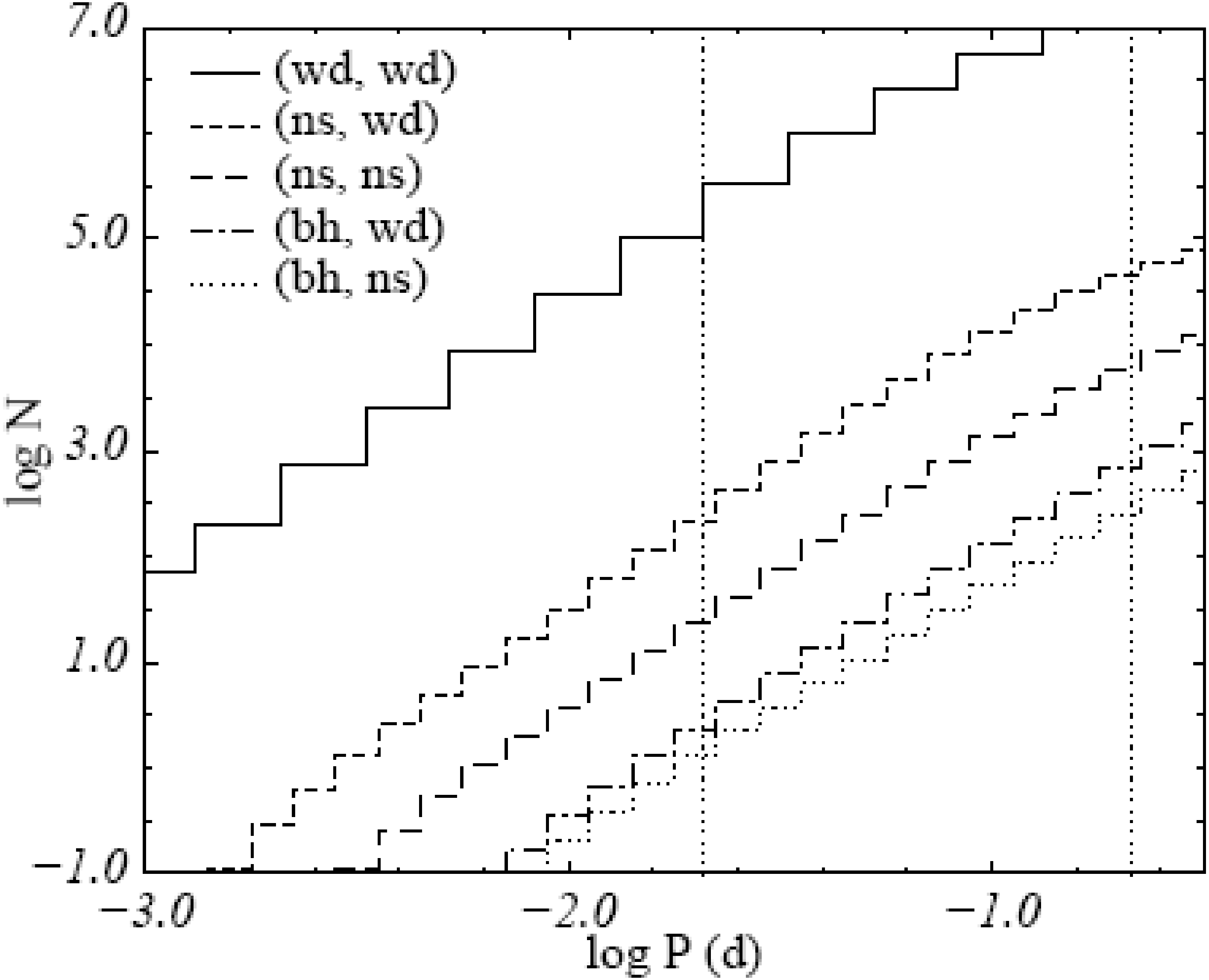
(Nelemans et al. 2001/2004)

- Population synthesis all compact binaries
- Including eccentricity

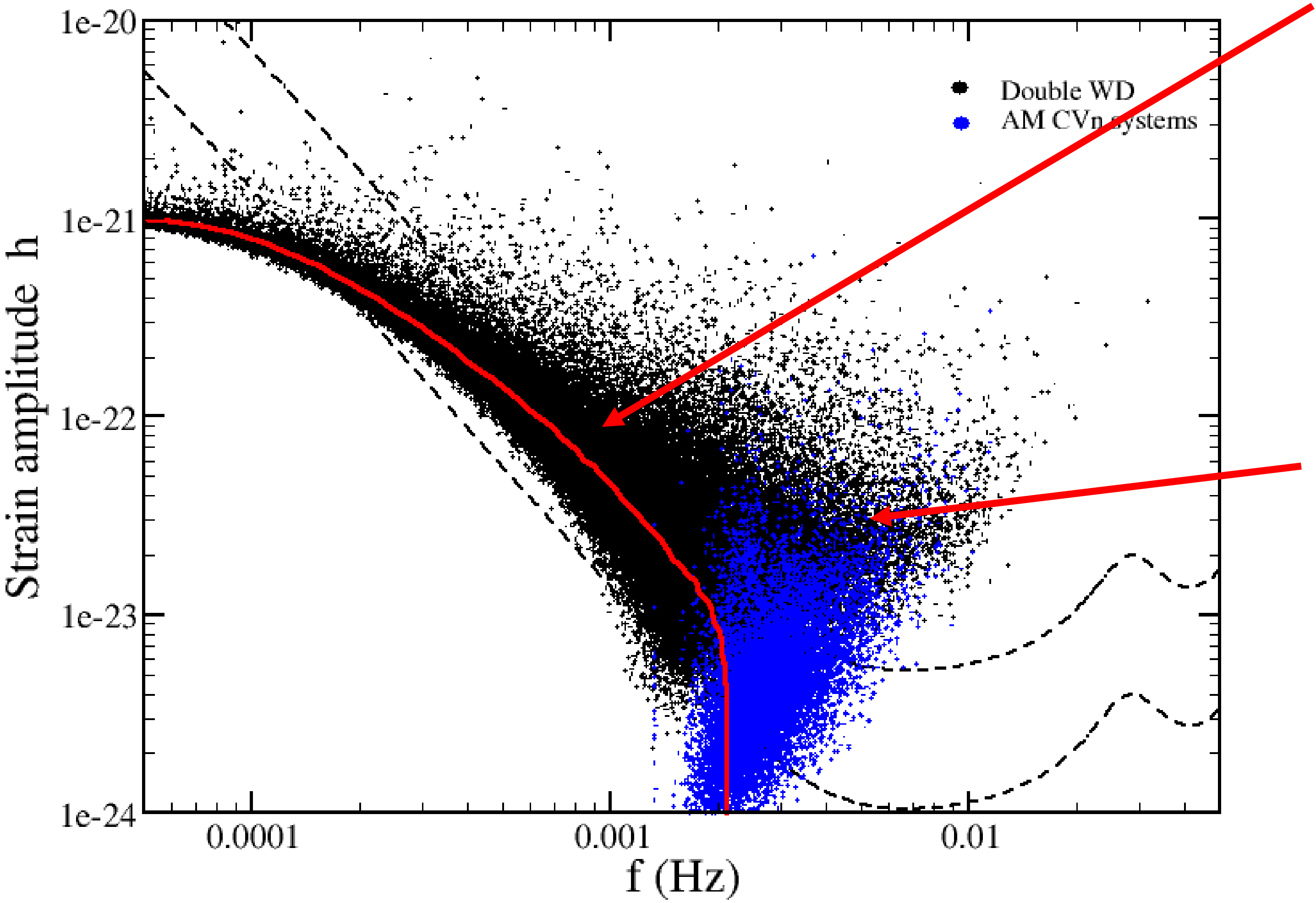


$$h(n,e) = \left[\frac{16\pi\, G}{c^3\, \omega_{\rm g}^2}\,\frac{L(n,e)}{4\pi\, d^2}\right]^{1/2} \qquad (3)$$

$$= 1.0\, 10^{-21}\, \frac{\sqrt{g(n,e)}}{n} \left(\frac{\mathcal{M}}{\rm M_\odot}\right)^{5/3} \left(\frac{P_{\rm orb}}{1\,\rm hr}\right)^{-2/3} \left(\frac{d}{1\rm kpc}\right)^{-1},$$


(wd, wd)
(ns, wd)
(ns, ns)
(bh, wd)
(bh, ns)
7.0
5.0
3.0
1.0
−1.0
log N
−3.0
−2.0
−1.0
log P (d)

Galactic population of gravitational wave sources



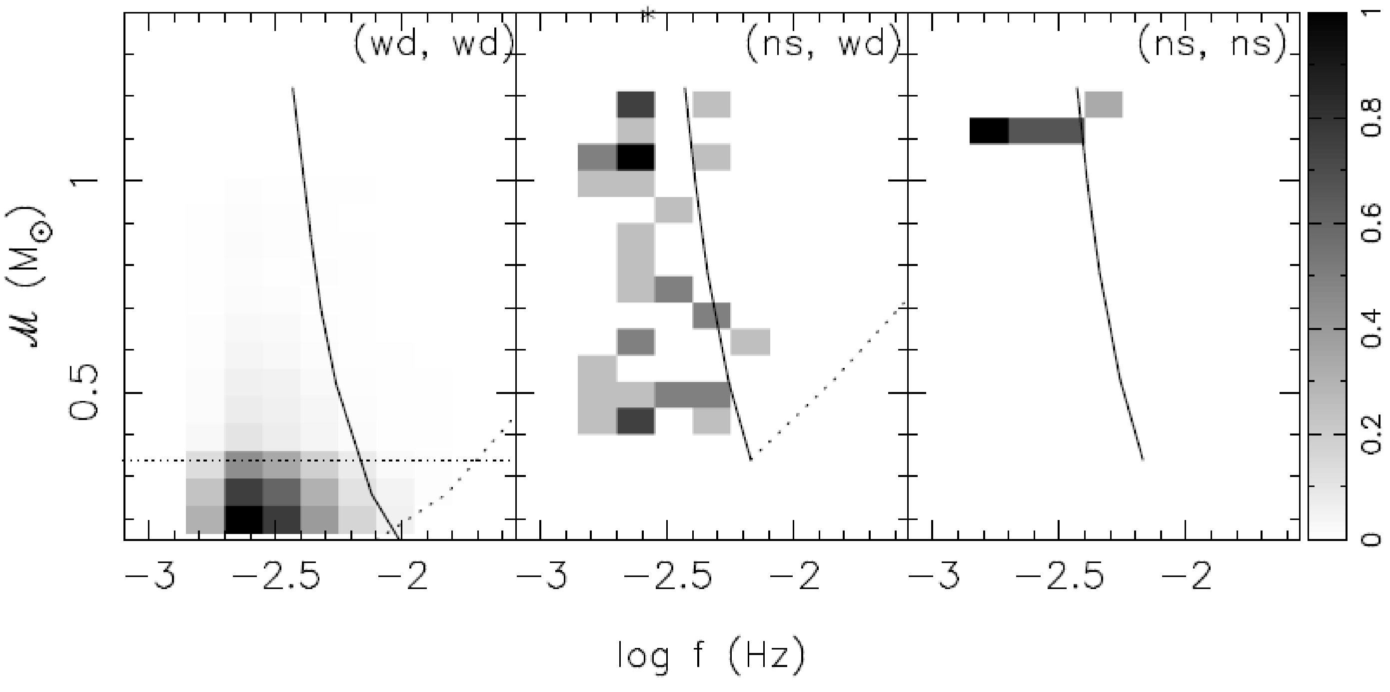
Unresolved
double WD
background

Above and at
high f systems
resolved: ~10,00
of both double
WD and
AM CVns

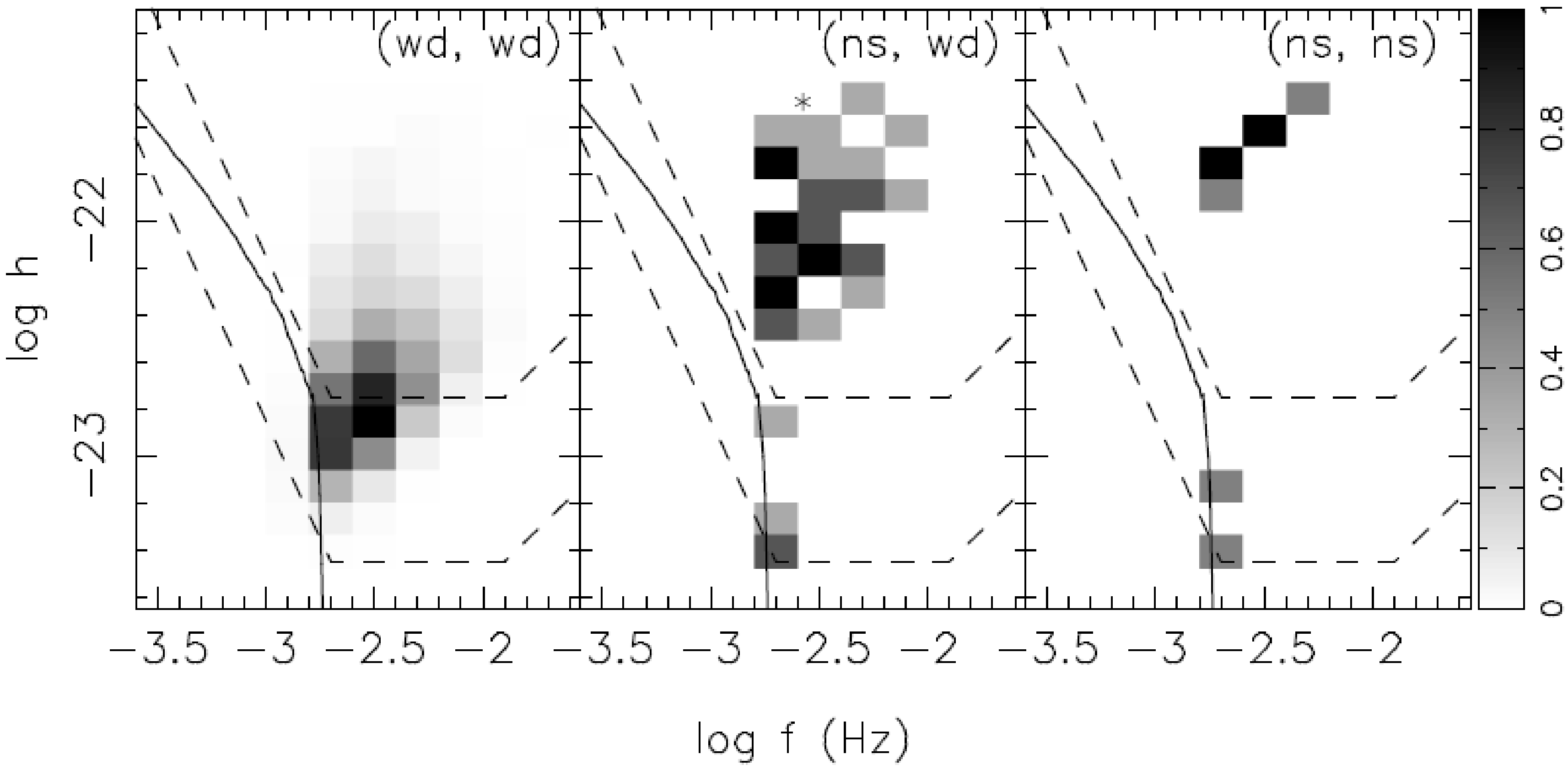
(but with too
optimistic model

Chirp masses

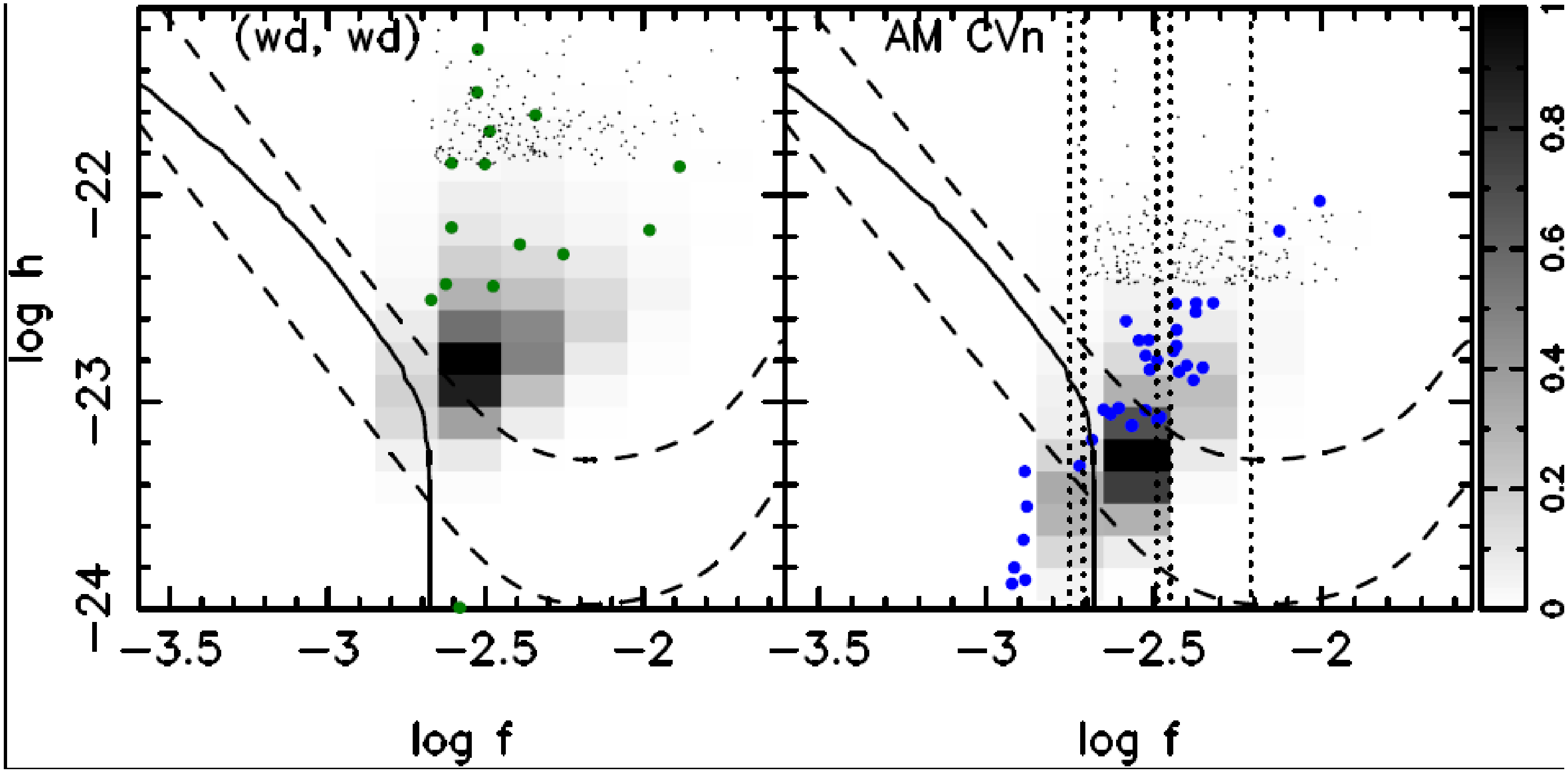
$$M_{chirp} = \frac{(Mm)^{3/5}}{(M+m)^{1/5}}$$

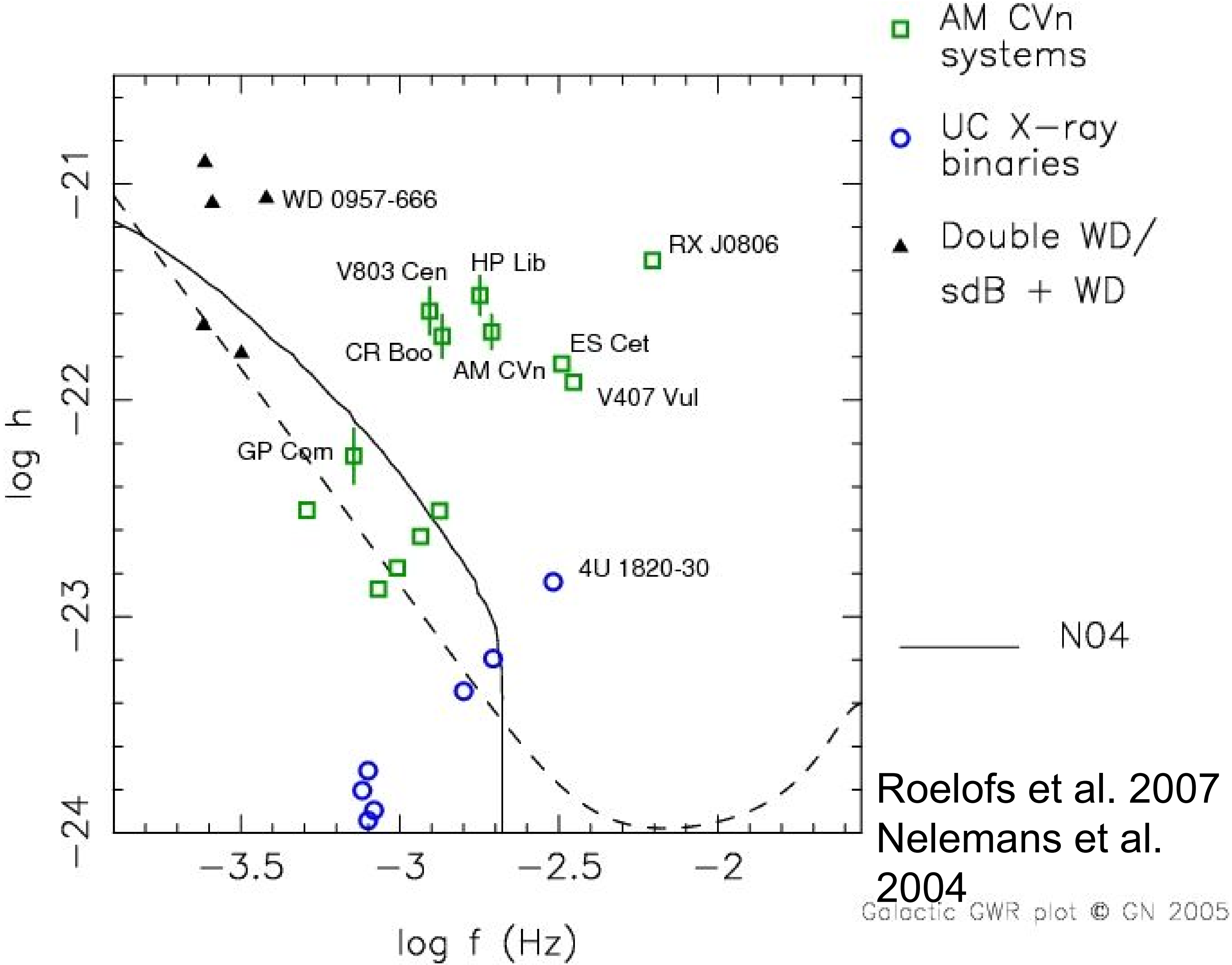


LISA signals



Also for interacting binarie

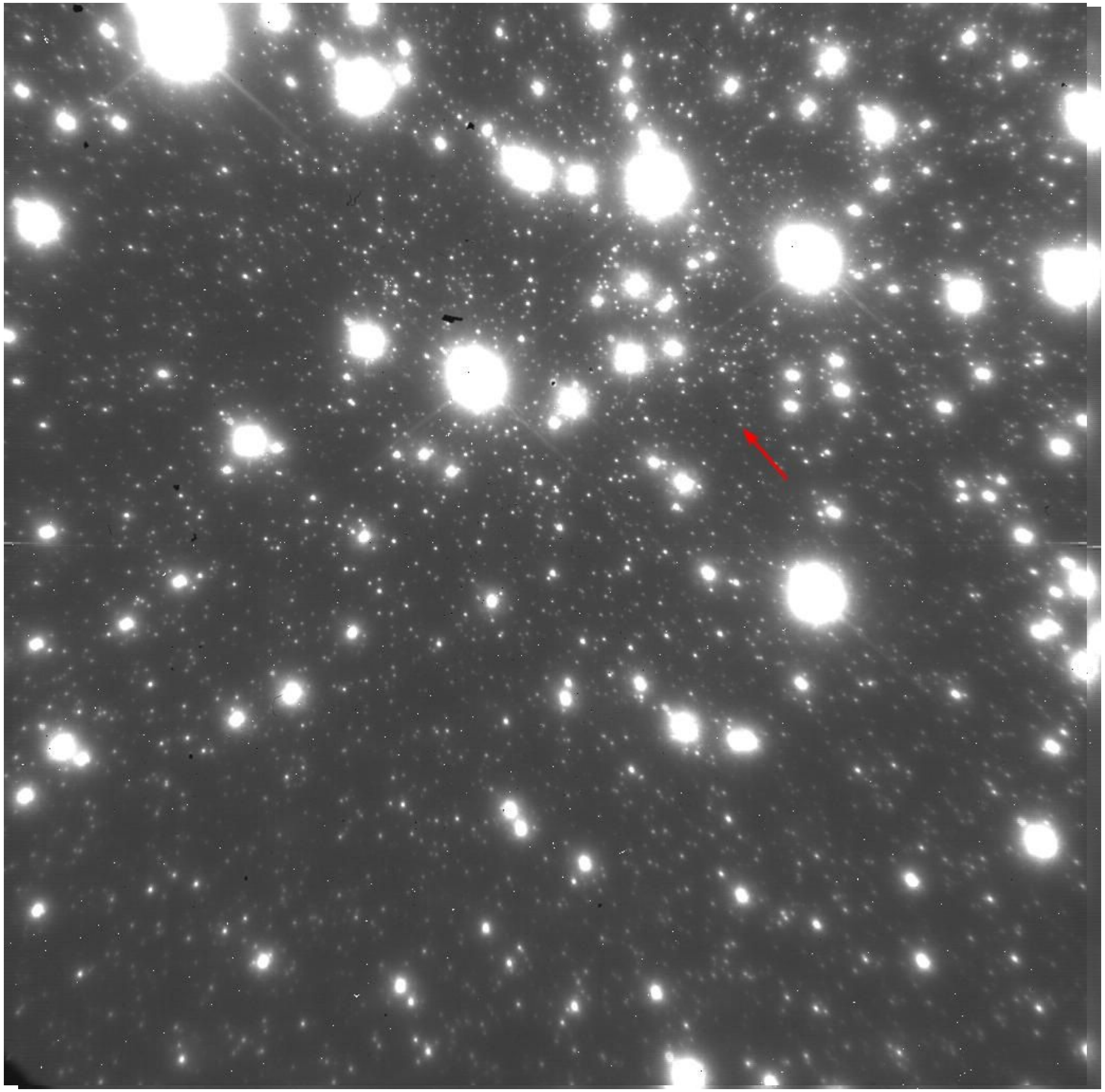


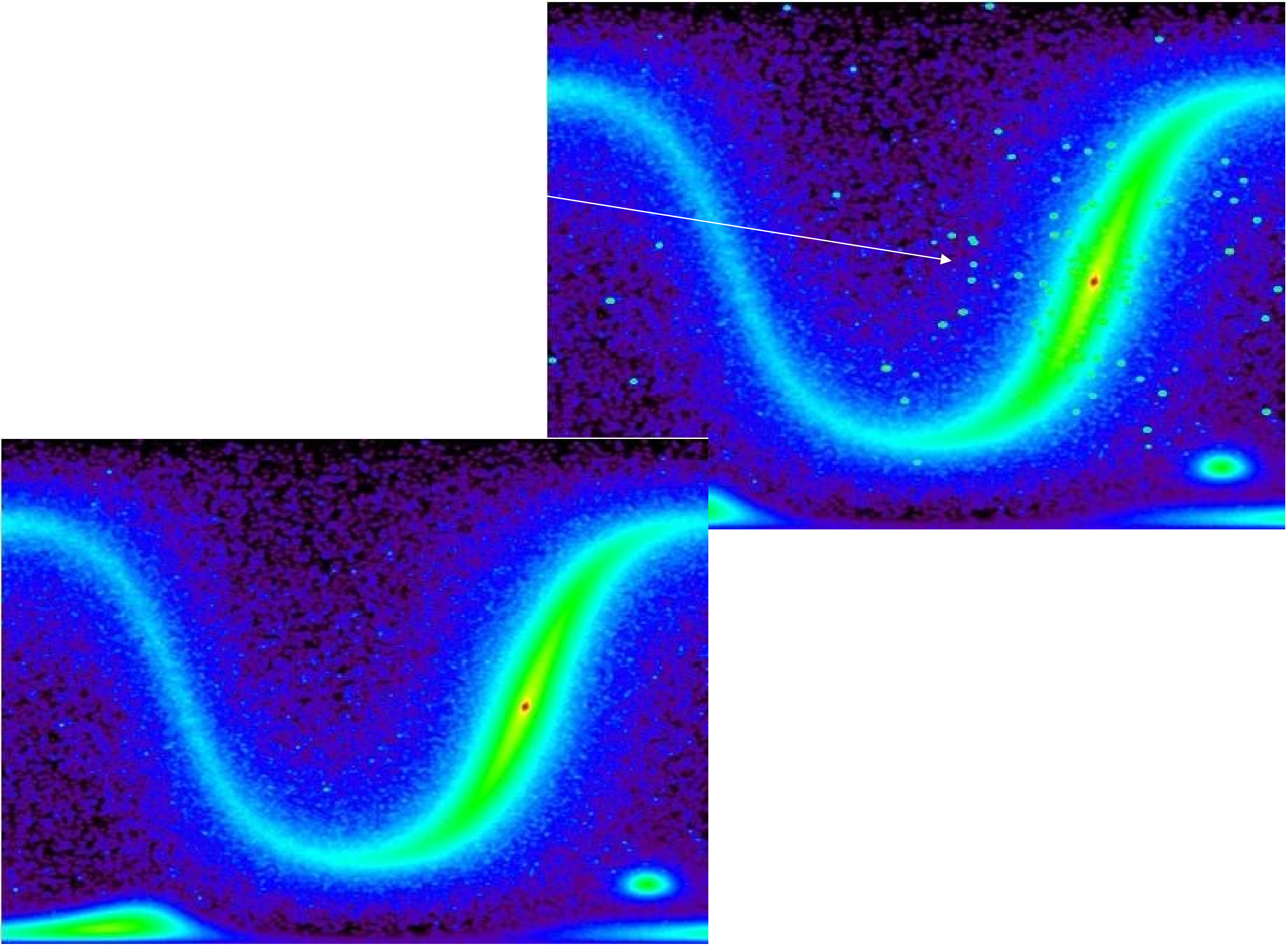


Roelofs et al. 2007
Nelemans et al. 2004

4U 1820-30
In globular
cluster

VLT + NAOS/Conica

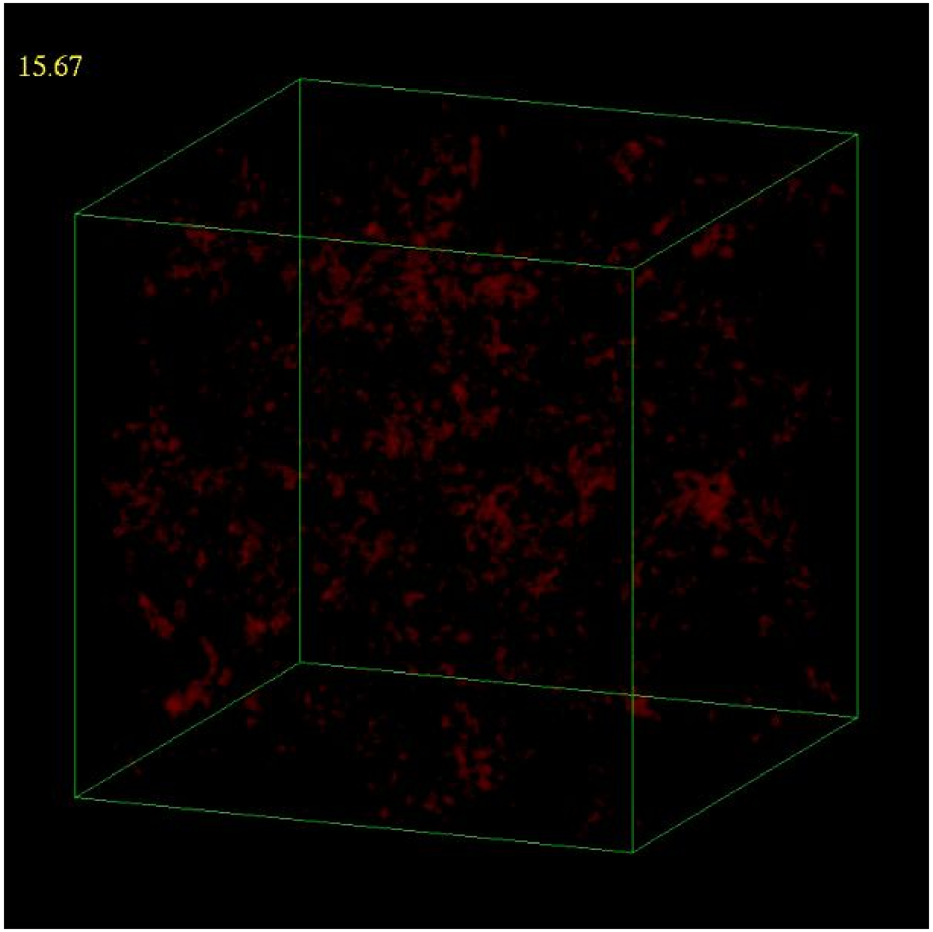




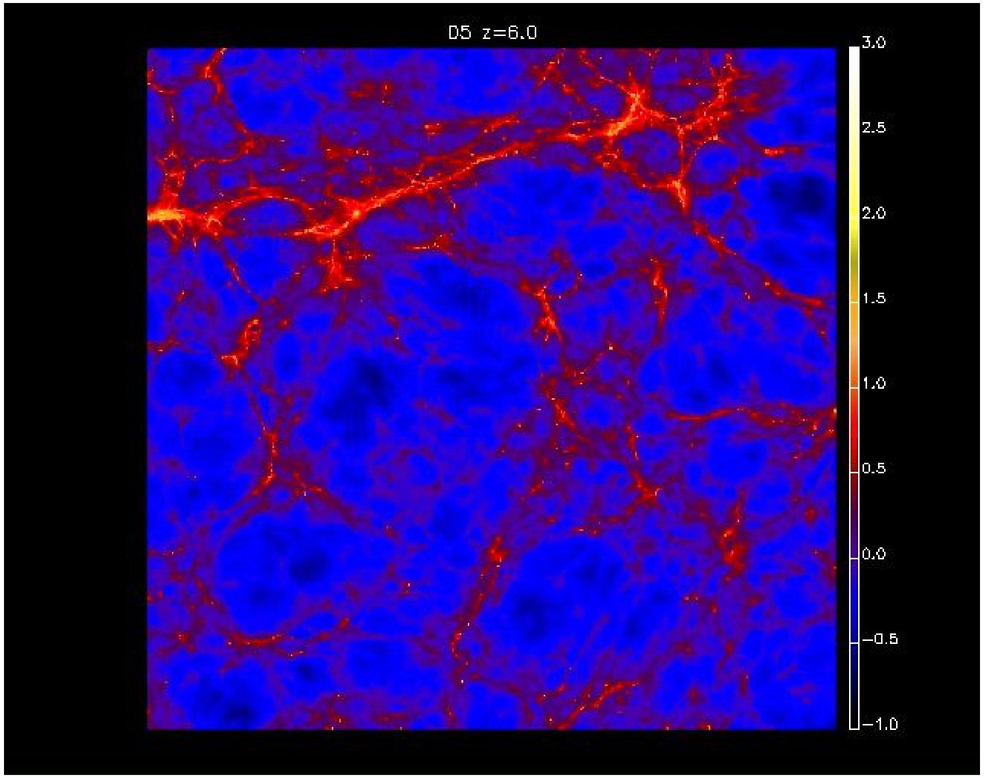
Supermassive black hole mergers

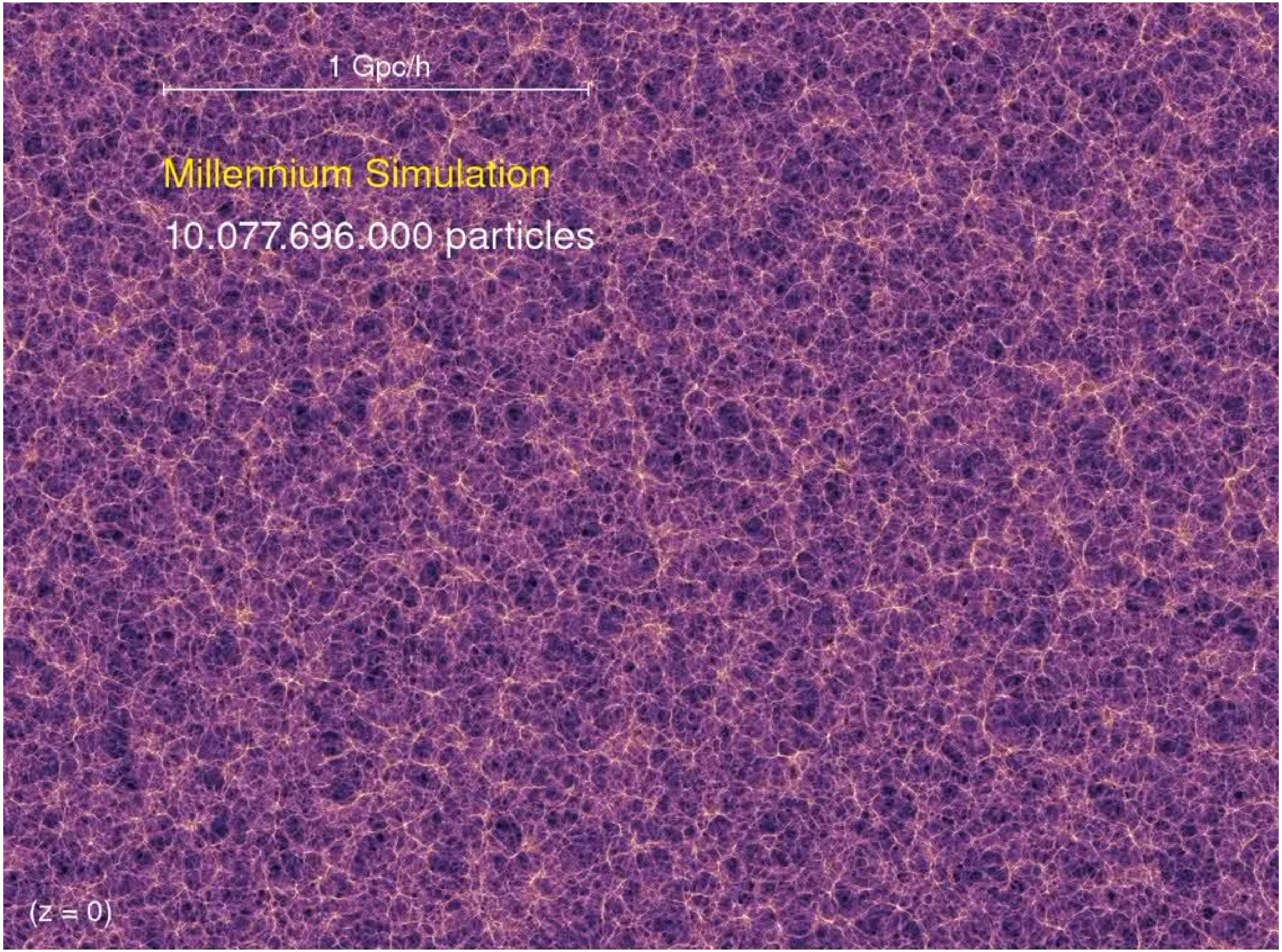
The formation of galaxies

Structure formation

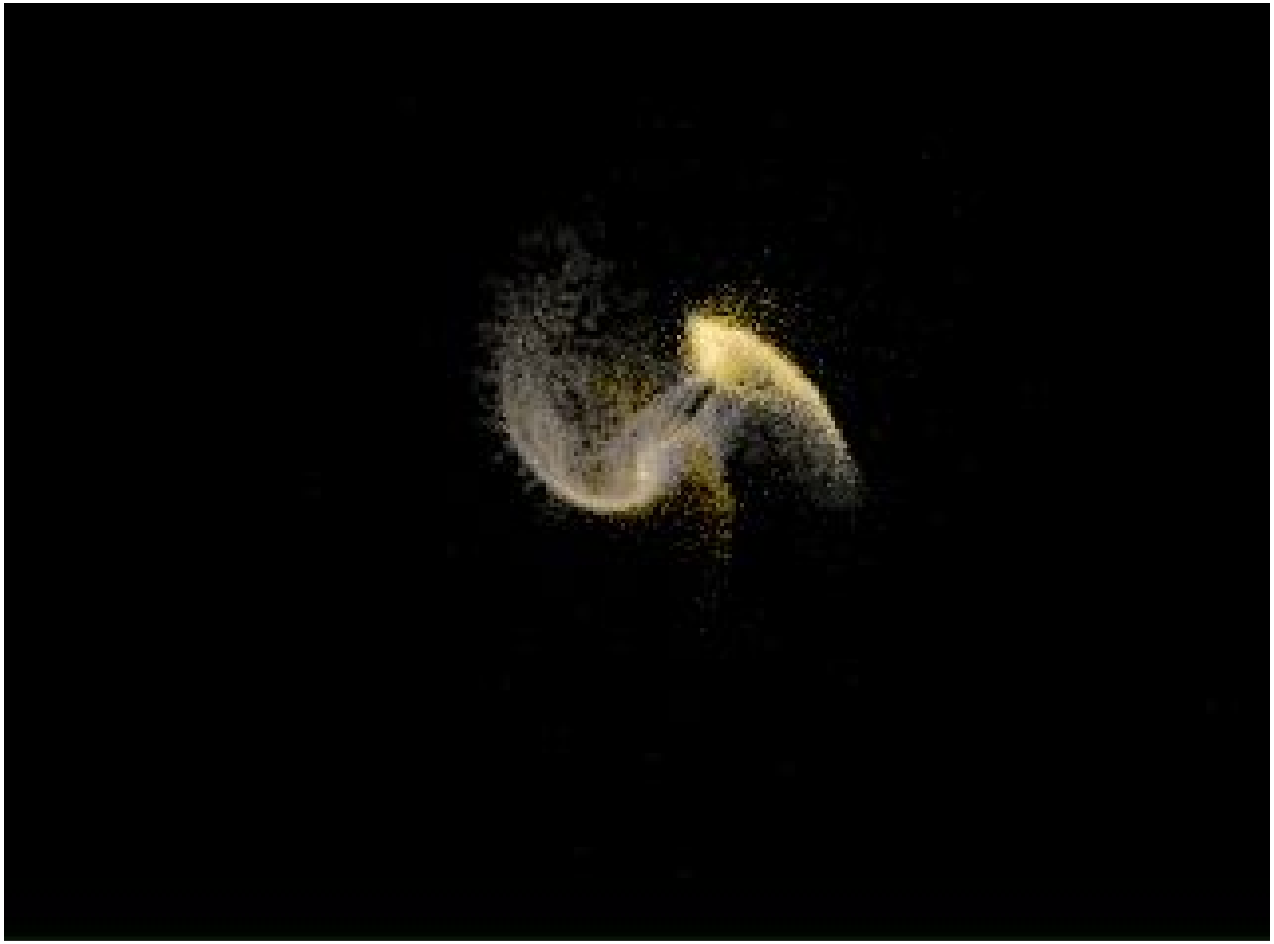


Structure formation

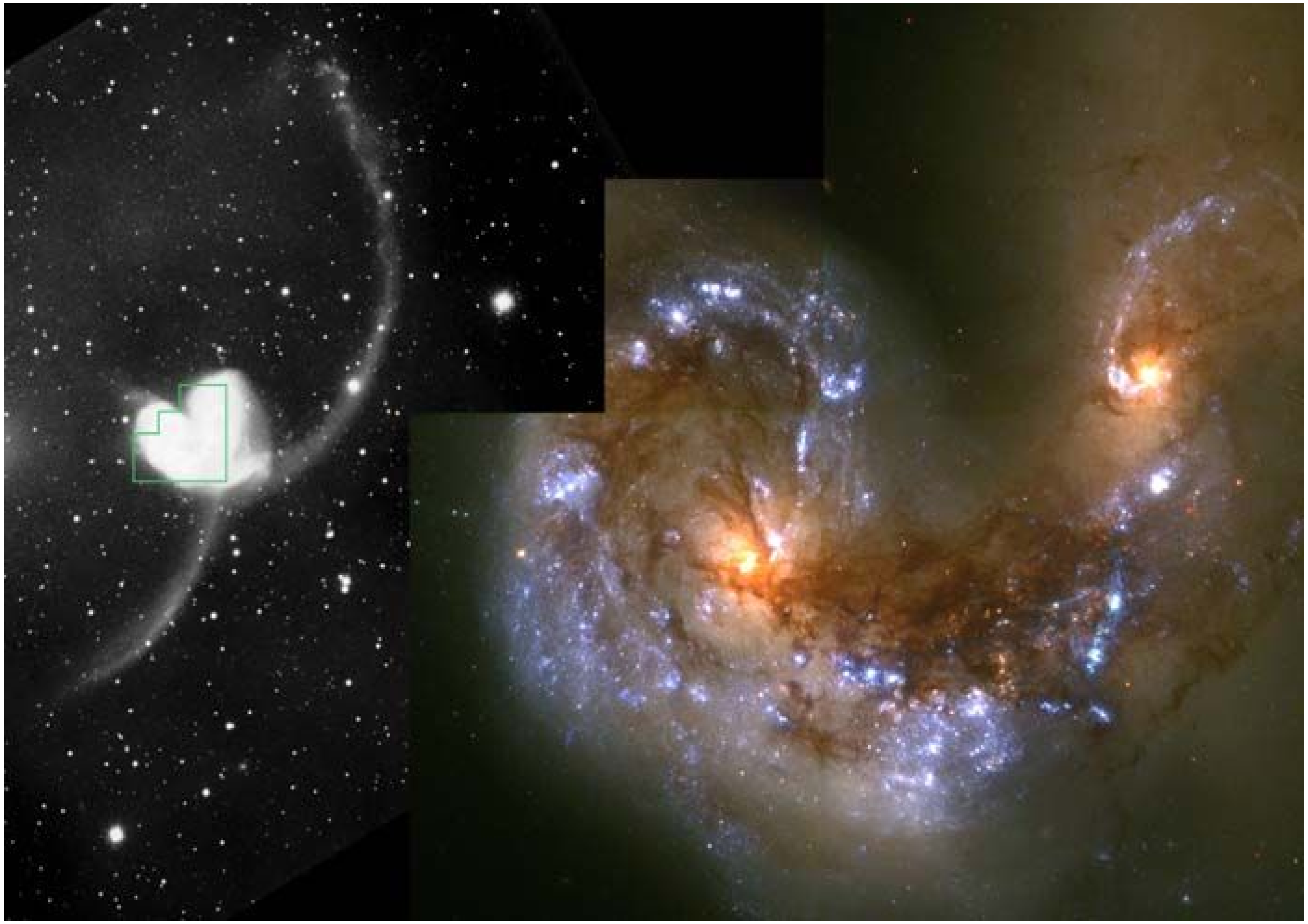



1 Gpc/h
Millennium Simulation
10.077.696.000 particles
(z = 0)

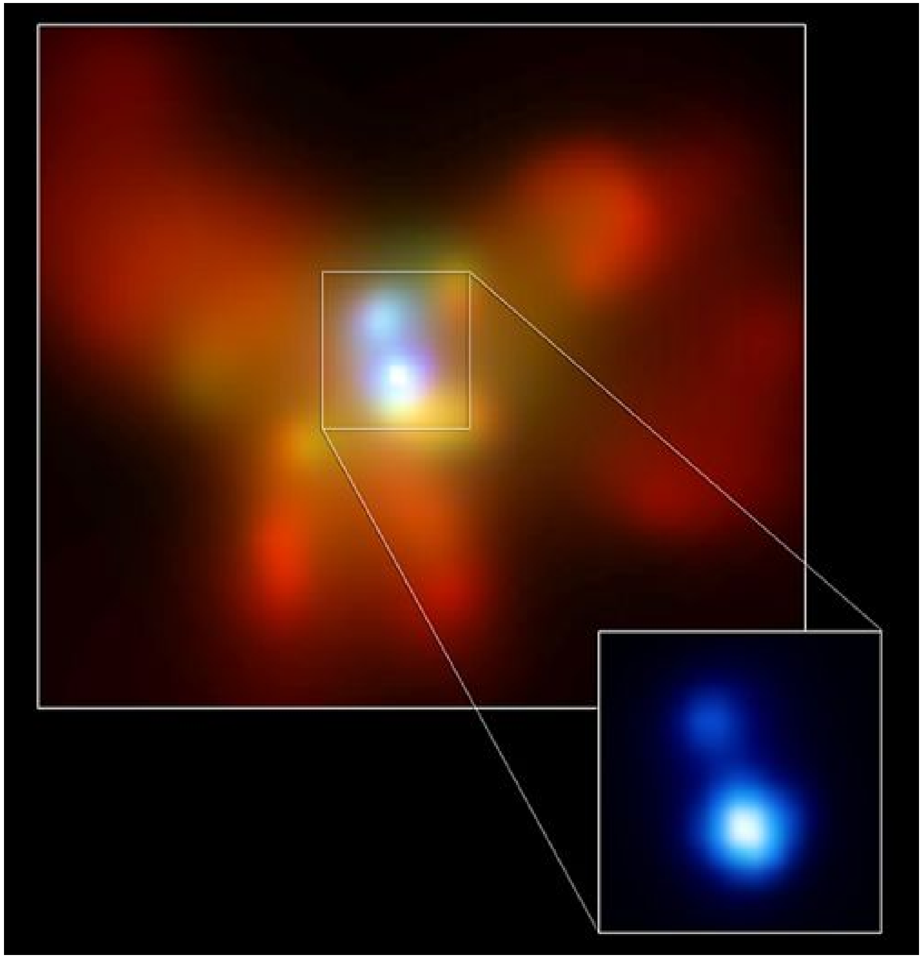
Colliding galaxies



Antennae galaxies



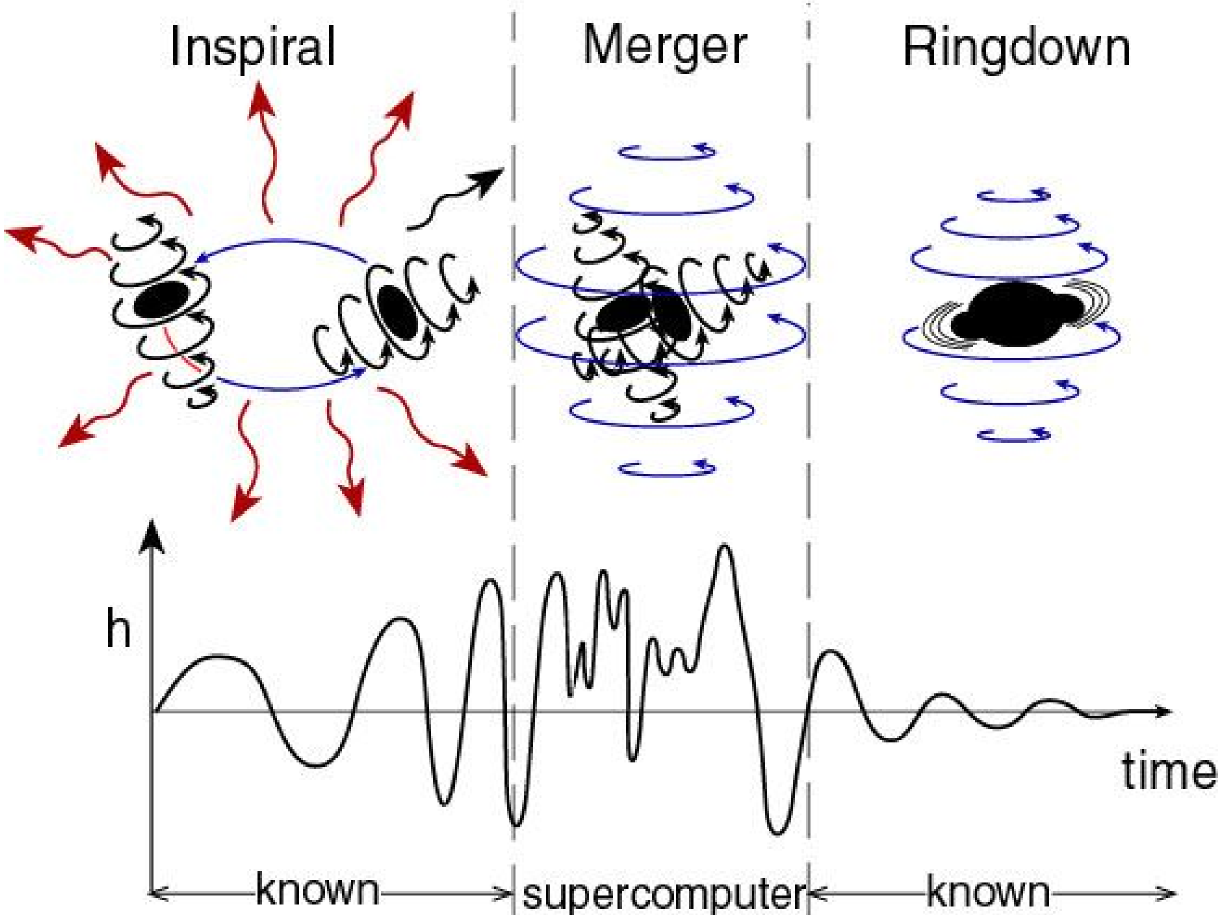
After the merger possibly a binary black hole in the core



Merger

BBH Coalescence

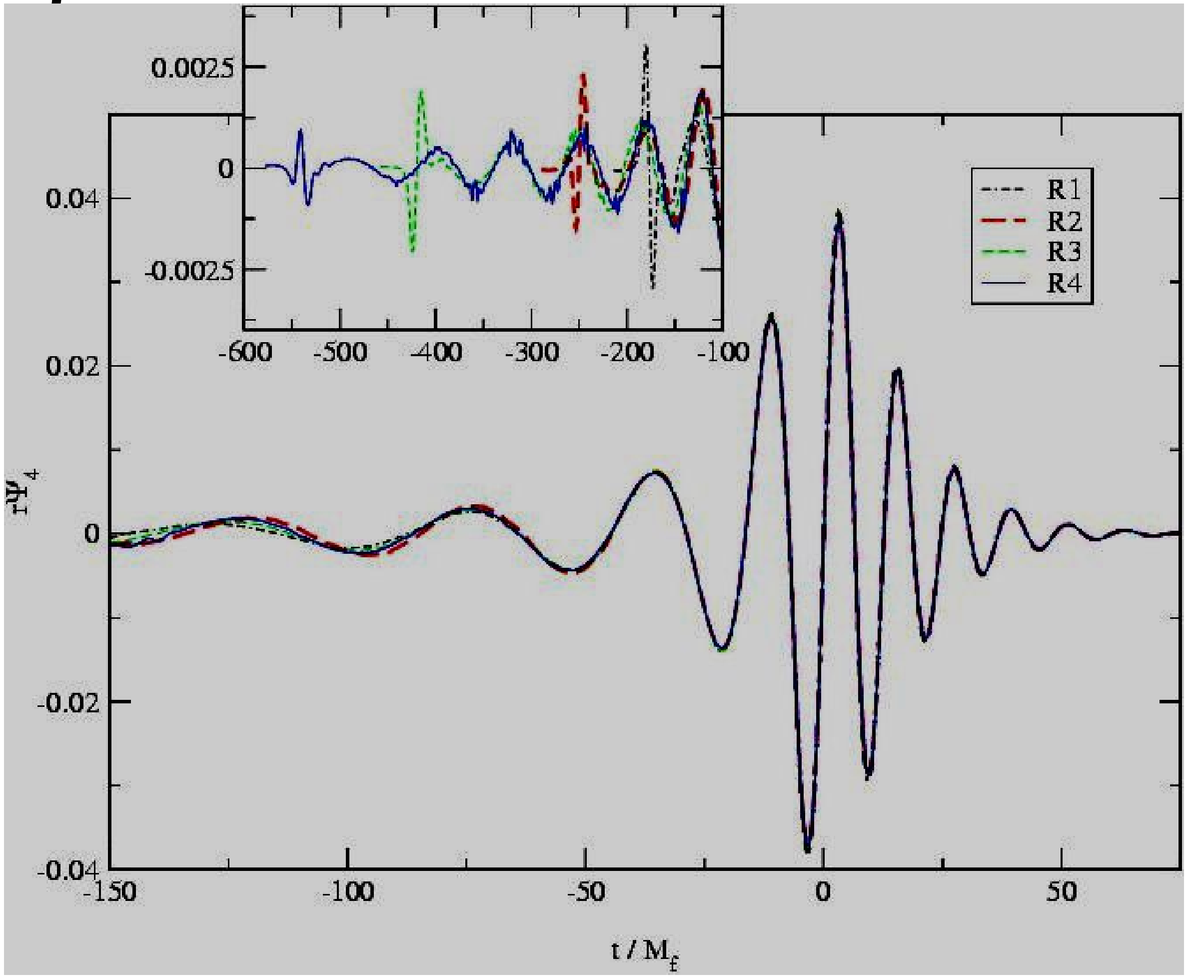
- Coalescence driven by GW emission can be roughly divided into 3 phases.
  - Adiabatic Inspiral (orbits quickly circularize)
  - Plunge/Merger (2bh → 1bh)
  - Ring-down (Merged BH)



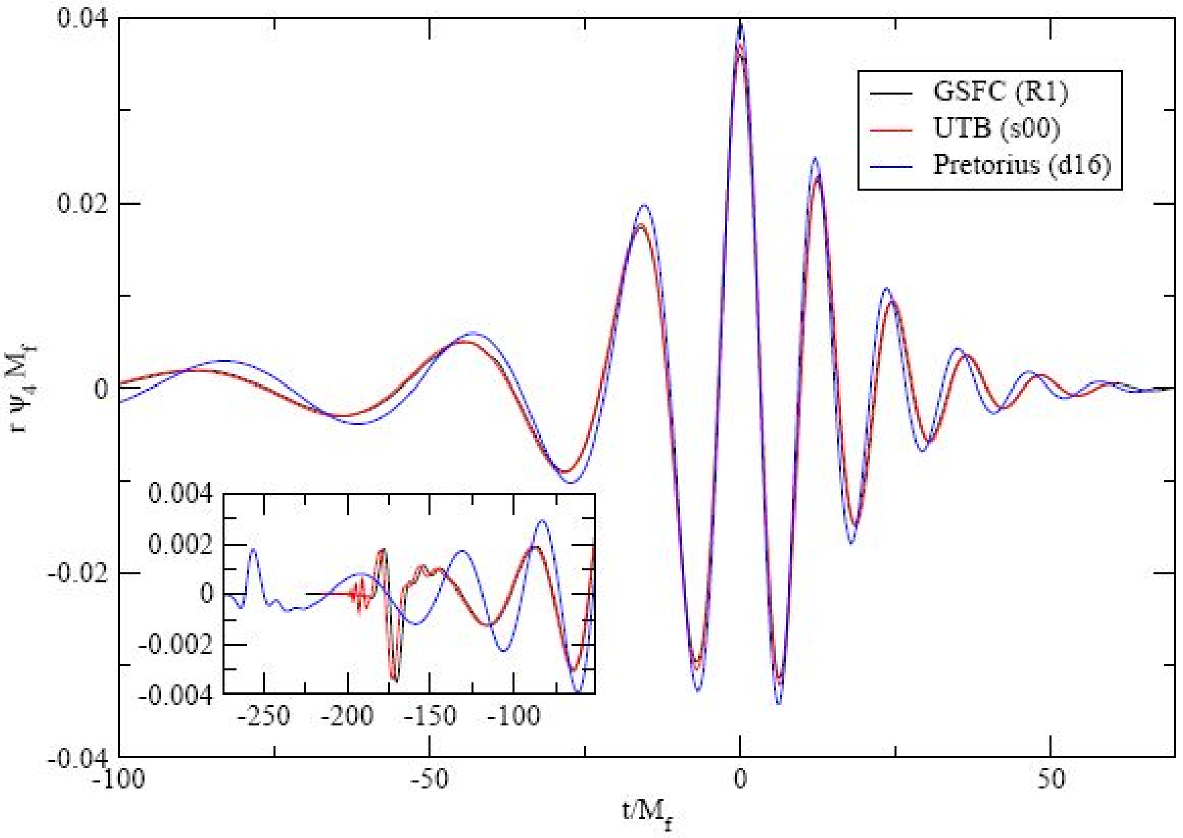
Numerical Relativity: recent breakthrough

- Can now do many orbits (they use geometrical units:

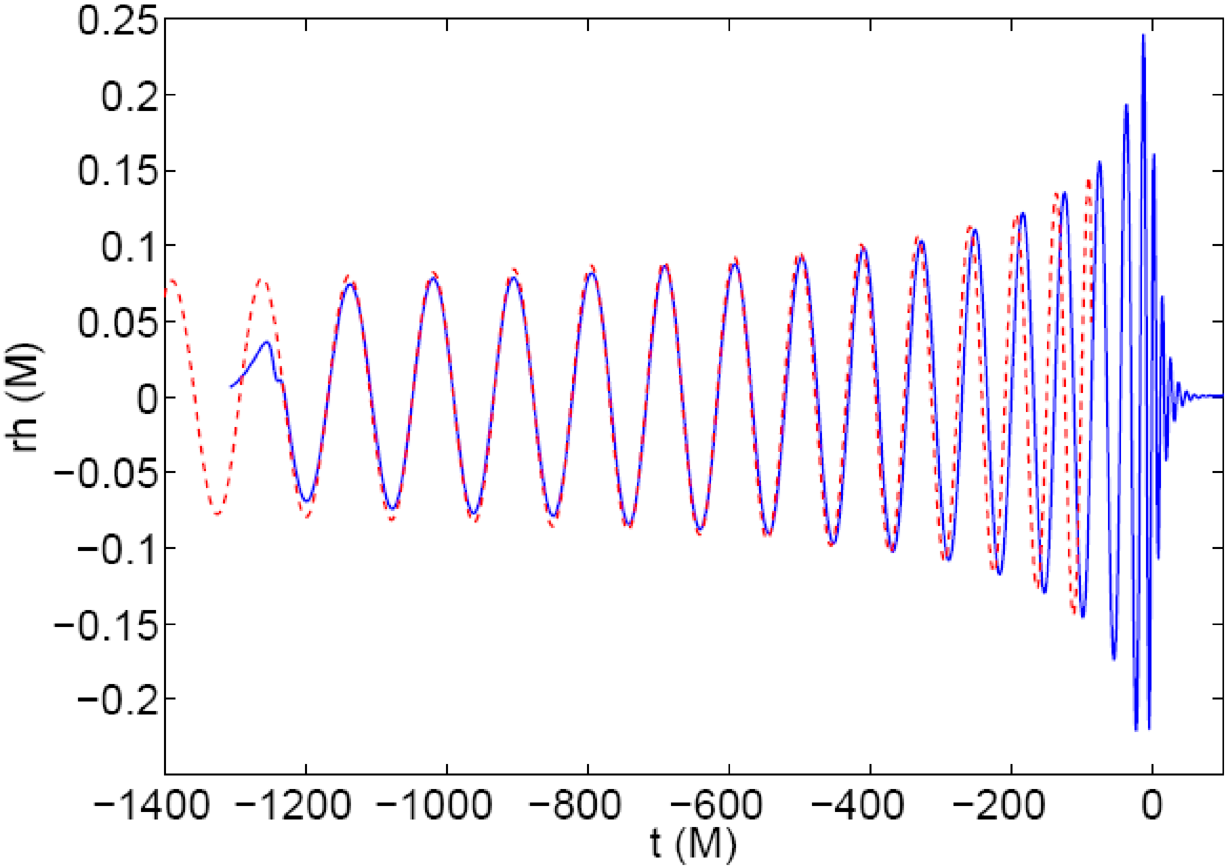
  G = c = 1, everything in M)



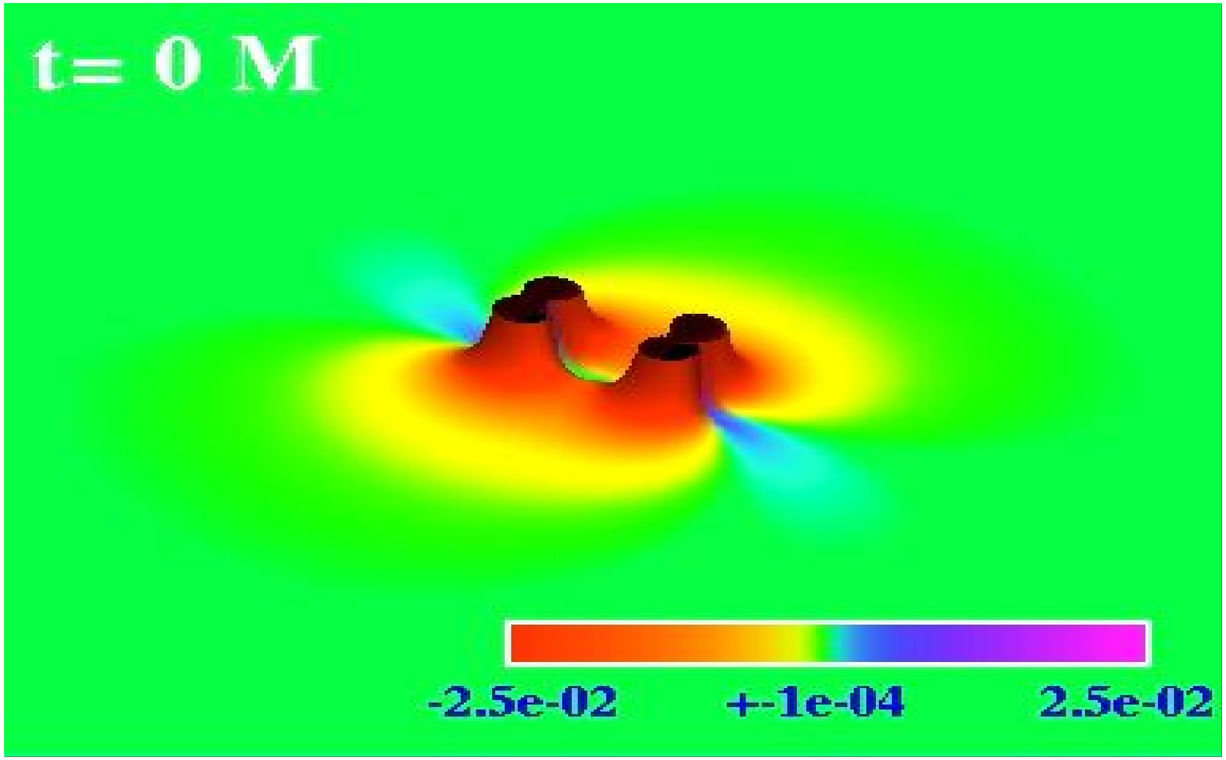
Comparison of groups



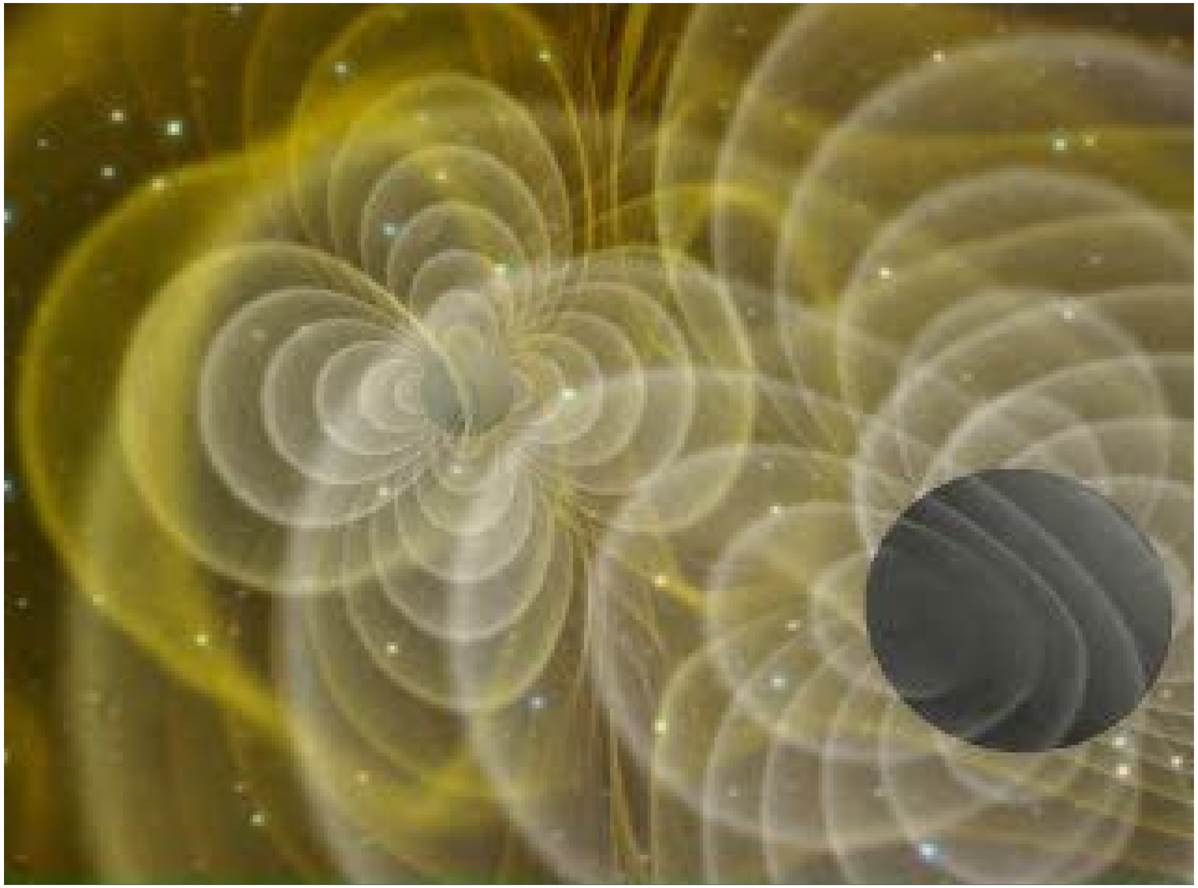
Comparison with Post-Newtonian calculations

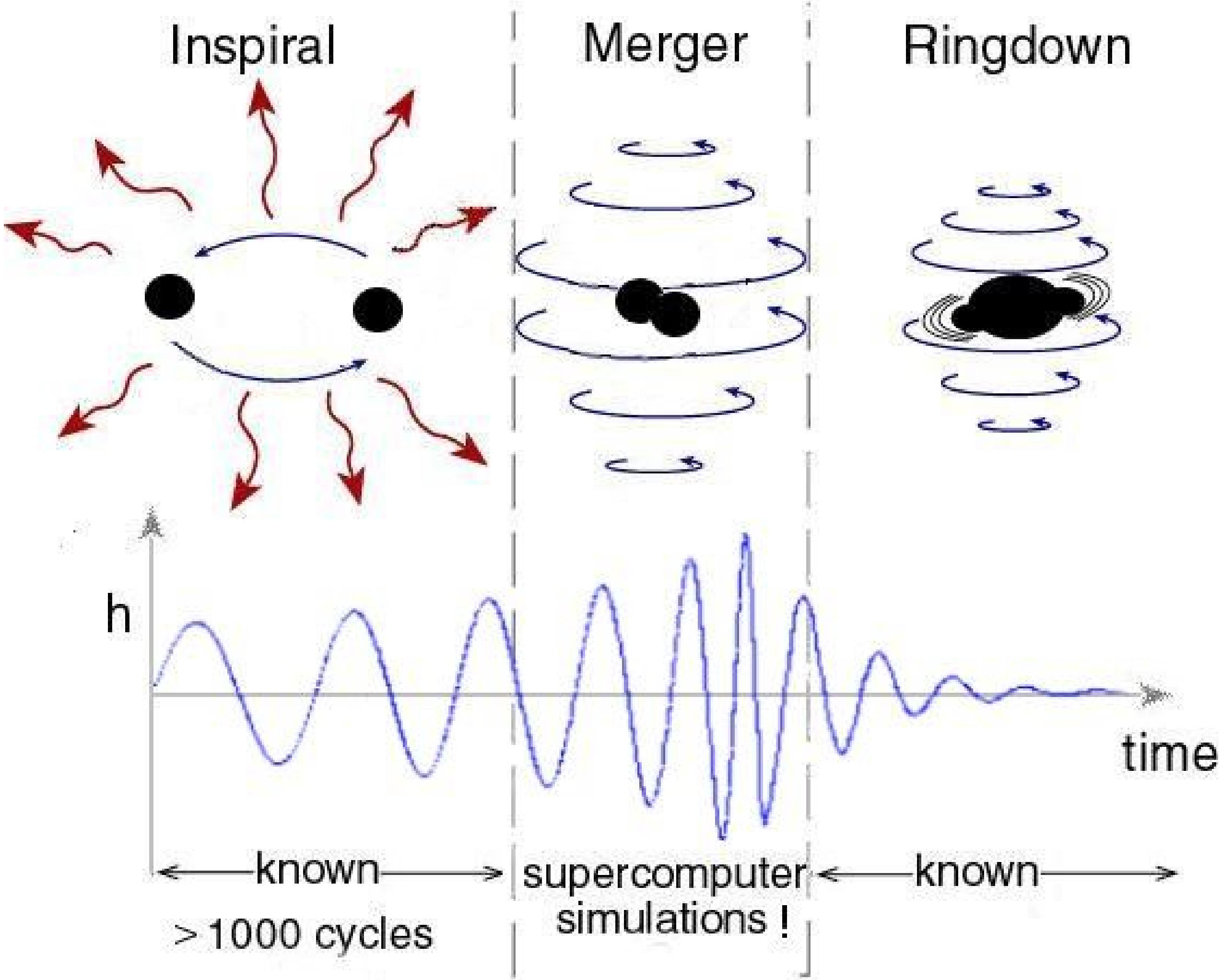


Frans Pretorius

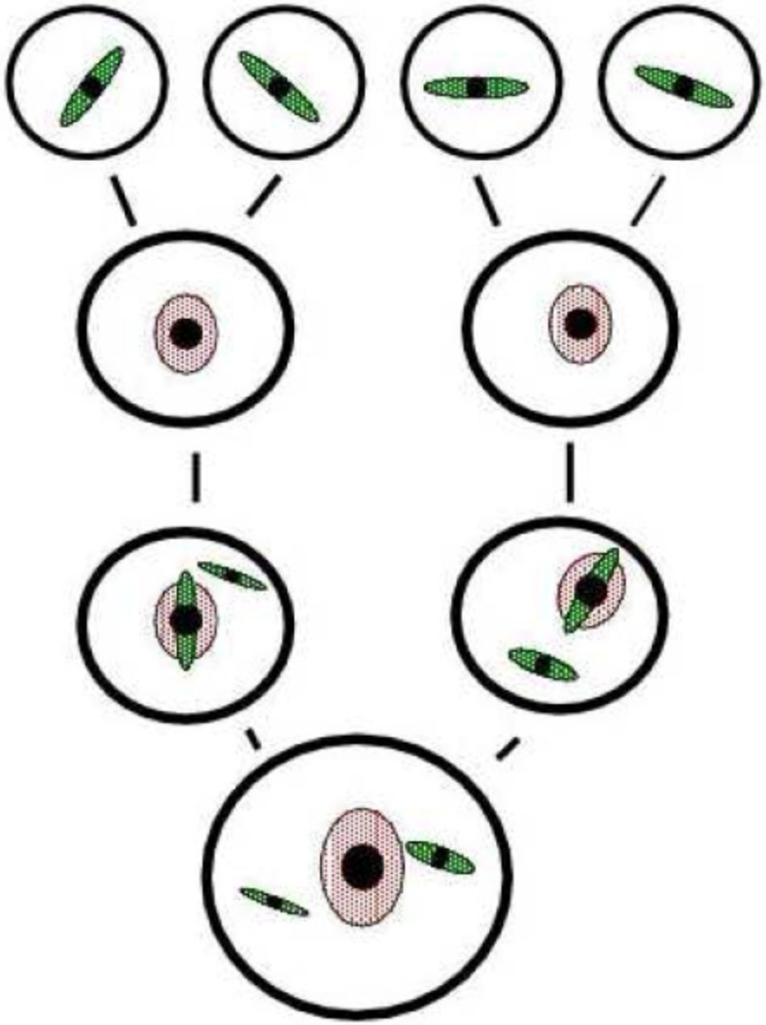


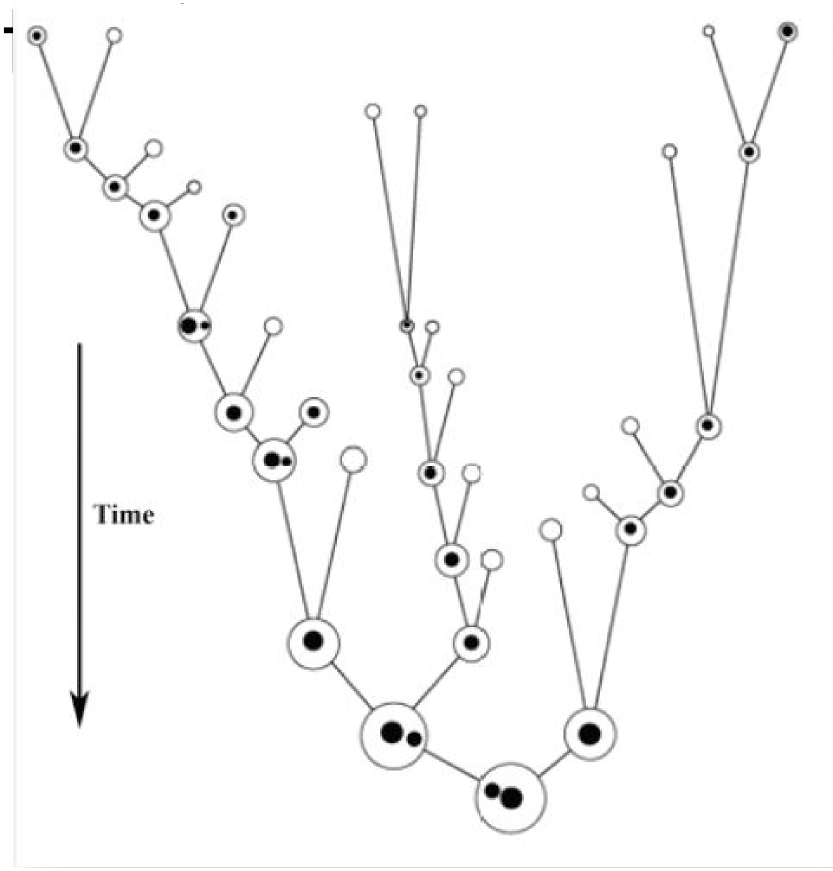
Goddard group (Baker, Centrella)




Inspiral
Merger
Ringdown
h
time
known
>1000 cycles
supercomputer
simulations !
known

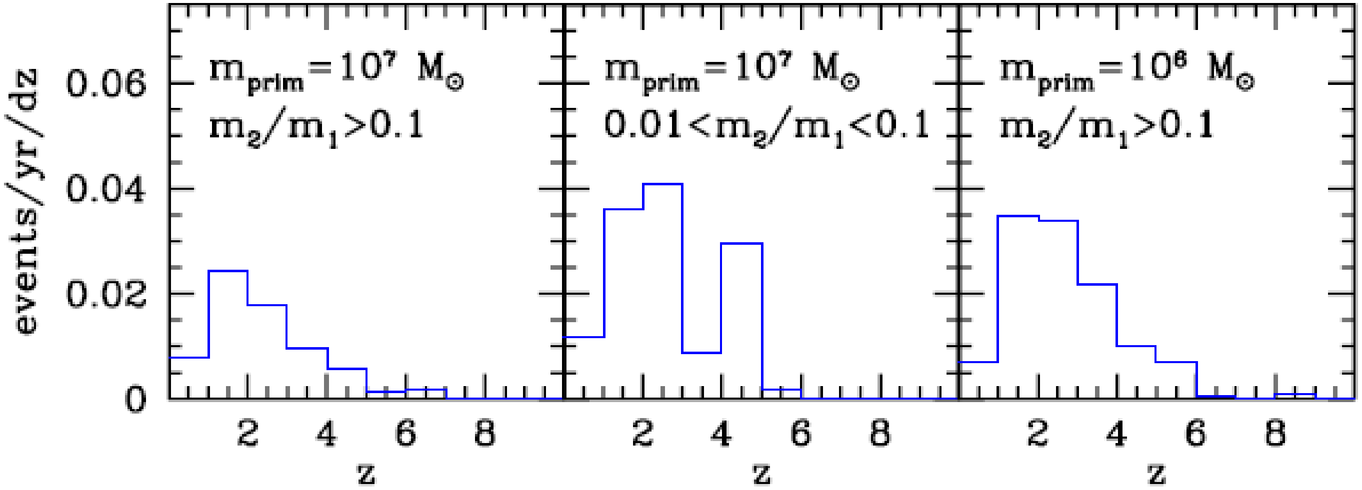
Hierarchical clus

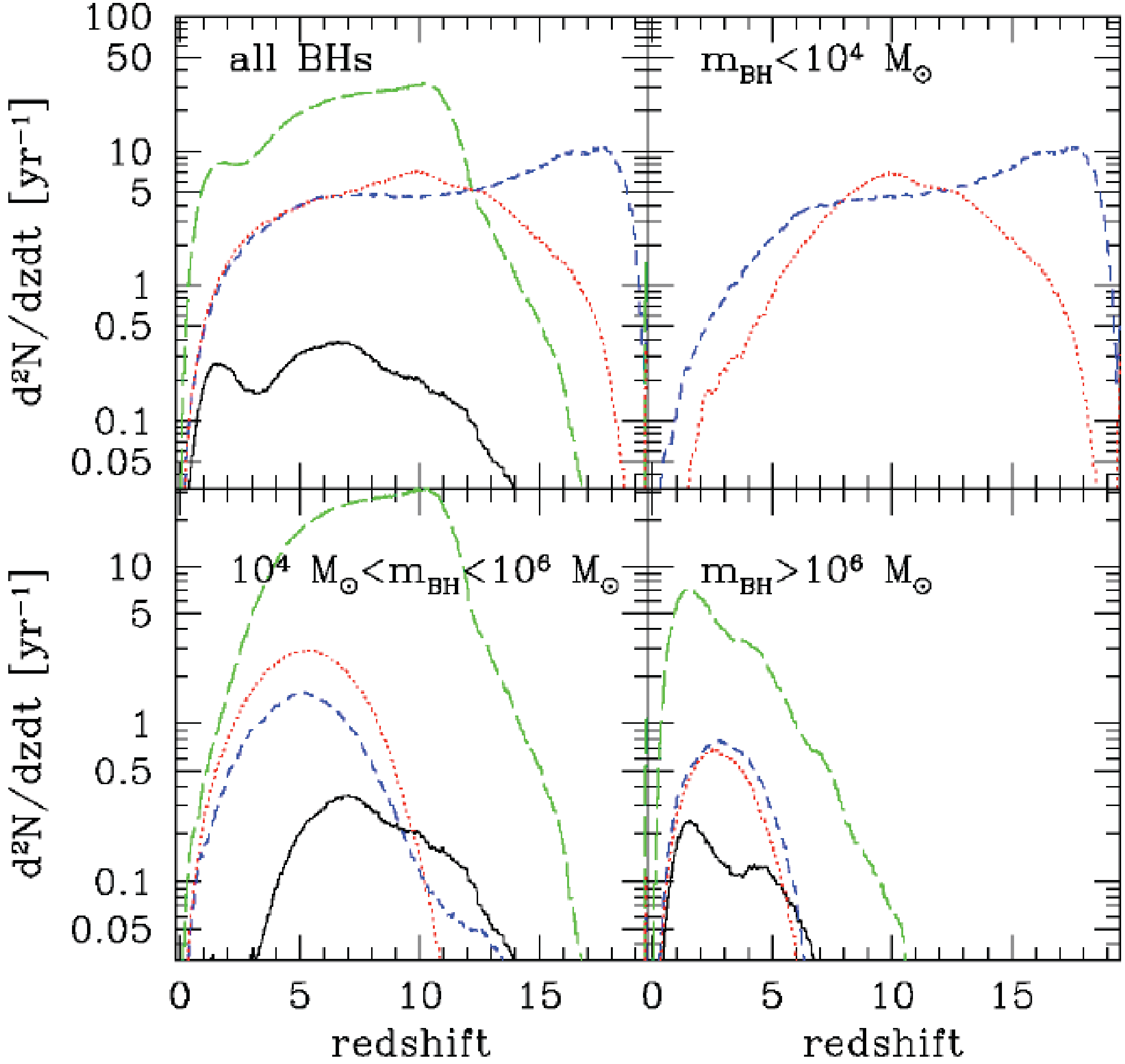




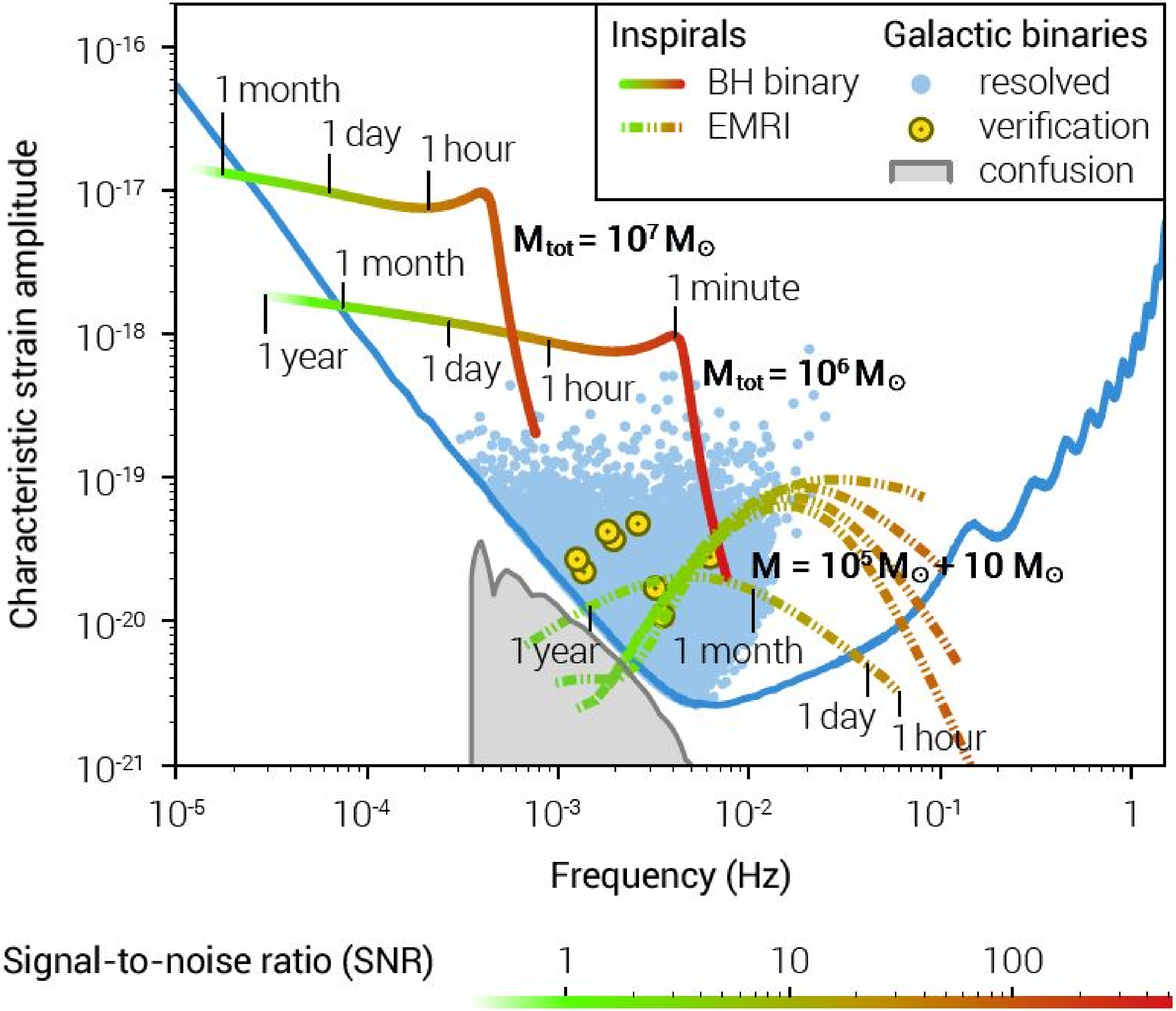
Event rates

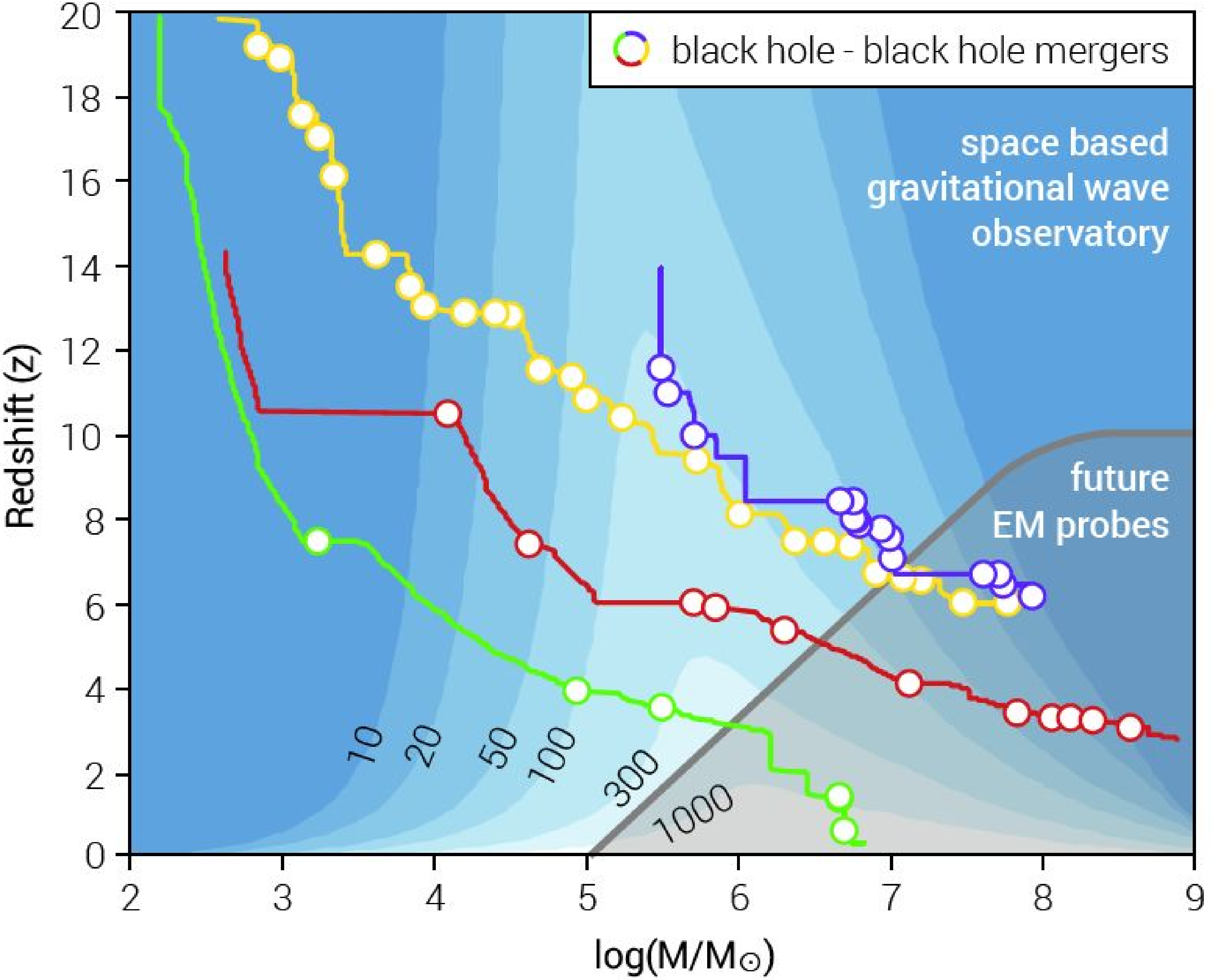
- Very uncertain, because we don't know much about early mergers



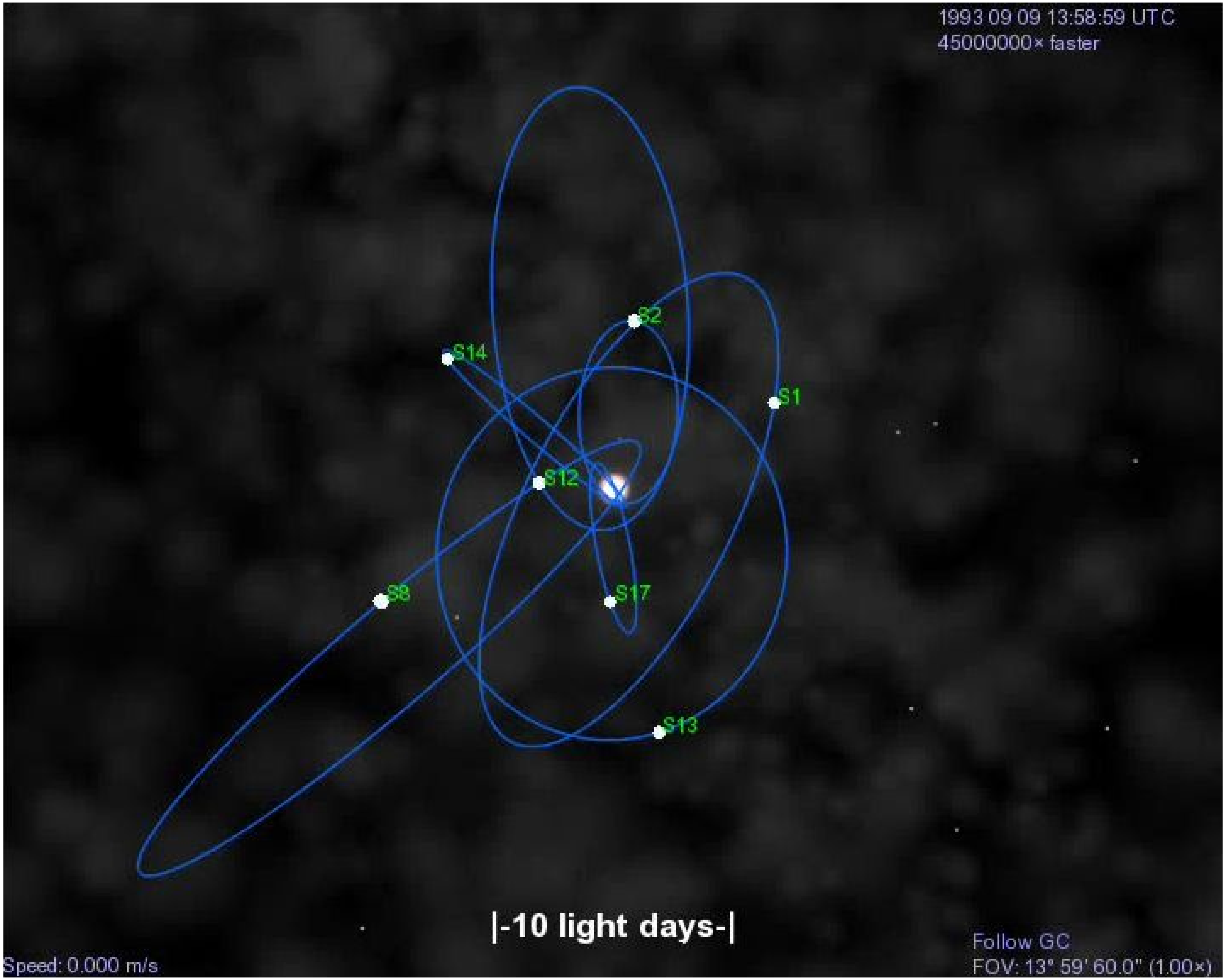

all BHs
$m_{BH}<10^4$ $M_\odot$
10^4 $M_\odot<m_{BH}<10^6$ $M_\odot$
$m_{BH}>10^6$ $M_\odot$
$d^2N/dzdt$ [yr^{-1}]
100
50
10
5
1
0.5
0.1
0.05
0
5
10
15
redshift

LISA signals

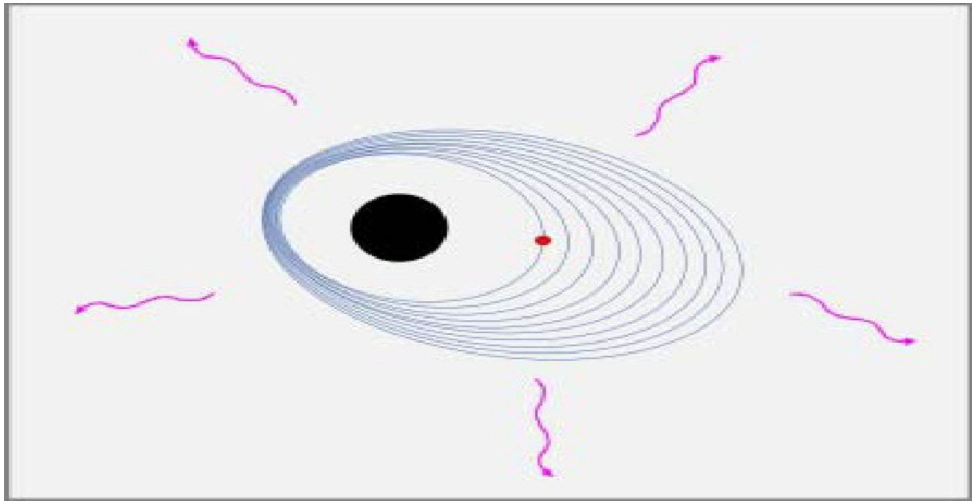



black hole - black hole mergers
space based
gravitational wave
observatory
future
EM probes
10
20
50
100
300
1000
Redshift (z)
0
2
4
6
8
10
12
14
16
18
20
log(M/M⊙)
2
3
4
5
6
7
8
9

Extreme mass-ratio inspirals

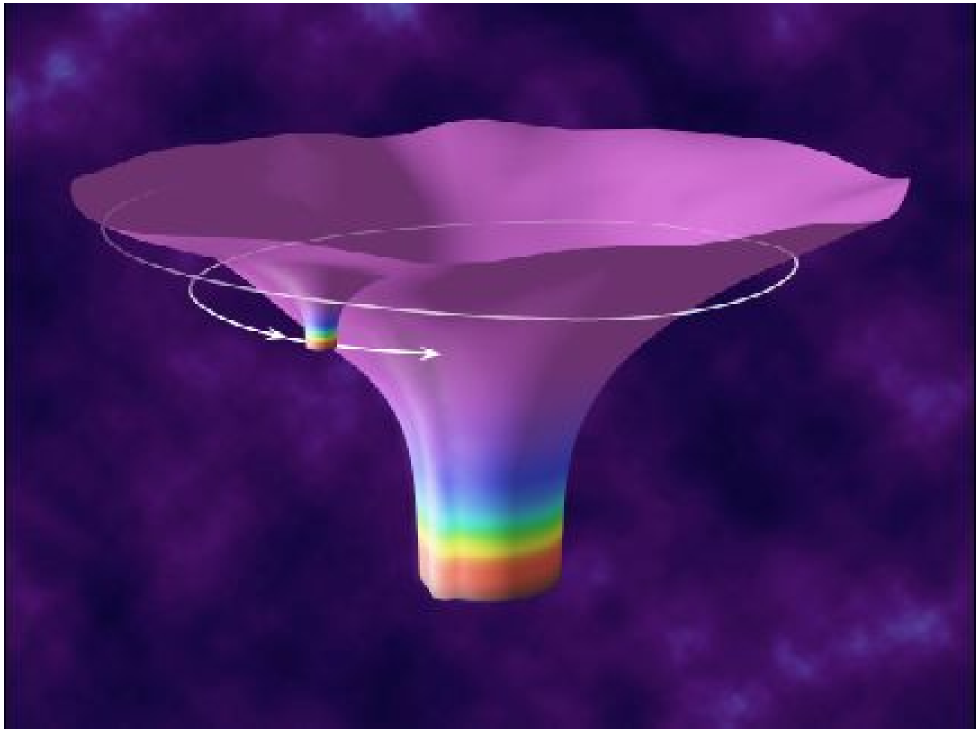

1993 09 09 13:58:59 UTC
45000000× faster
S2
S14
S1
S12
S8
S17
S13
|-10 light days-|
Speed: 0.000 m/s
Follow GC
FOV: 13° 59' 60.0" (1.00×)

Compact object in tight orbit: GWR

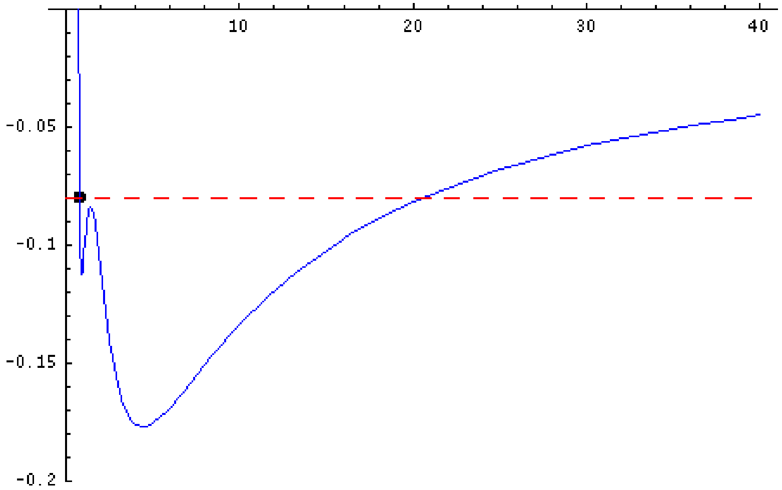


“Extreme mass-ratio inspiral”

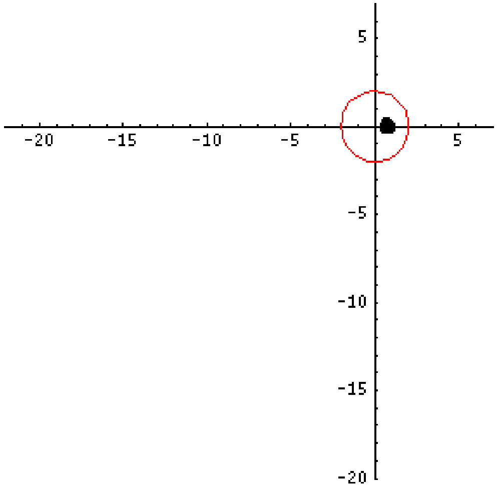
EMRI



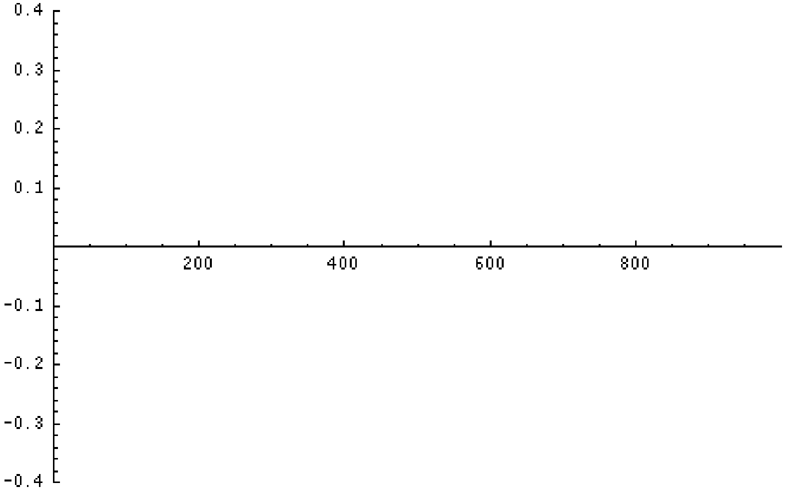
Potential



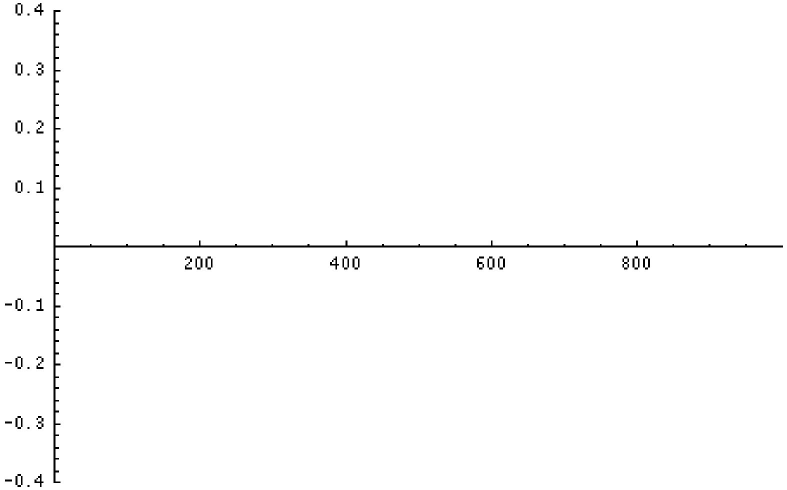
Orbit



h+ Waveform



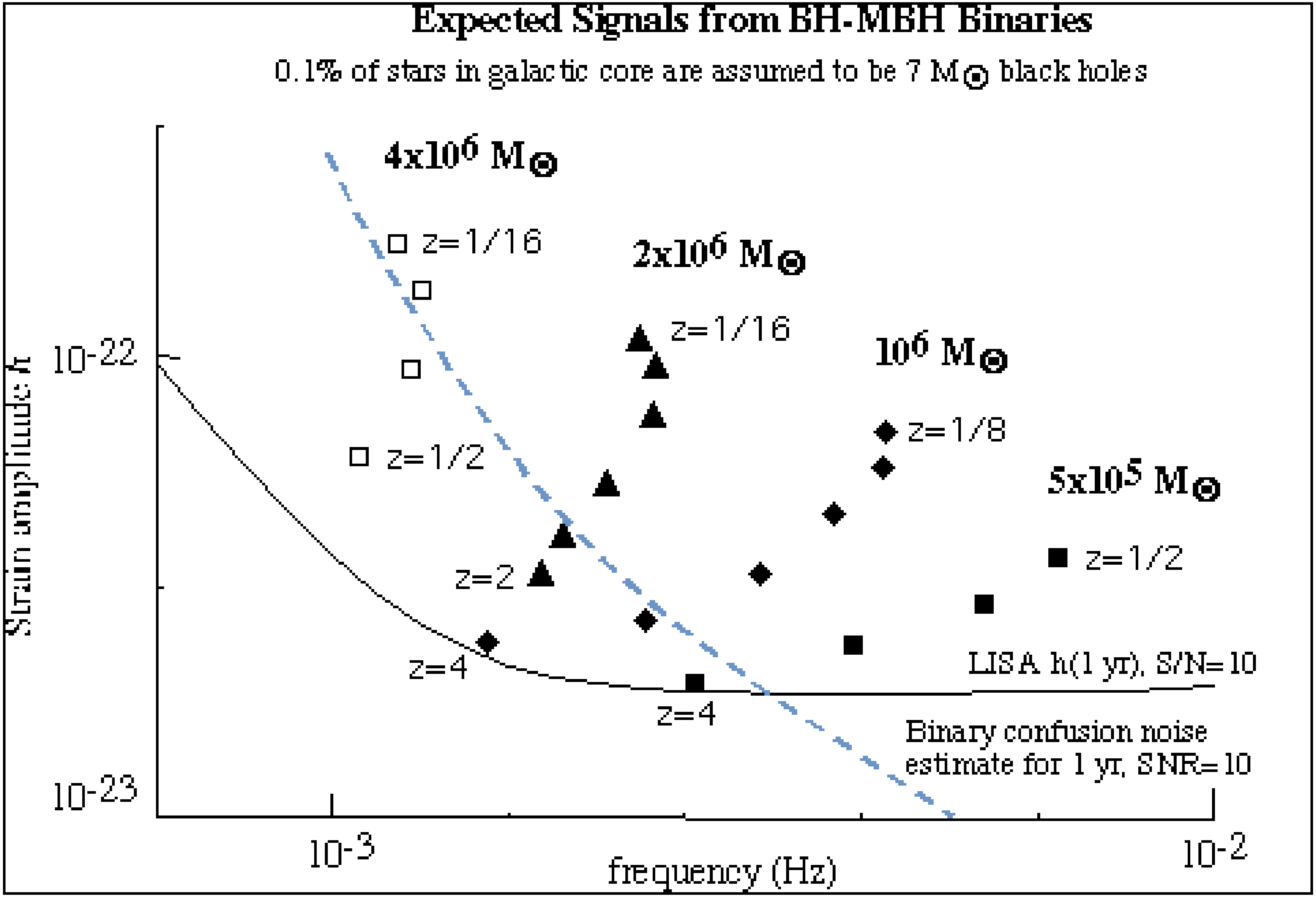
hx Waveform



Extreme mass-ratio inspirals

Sound of a circular inspiral (Kerr BH)

Sound of an eccentric orbit

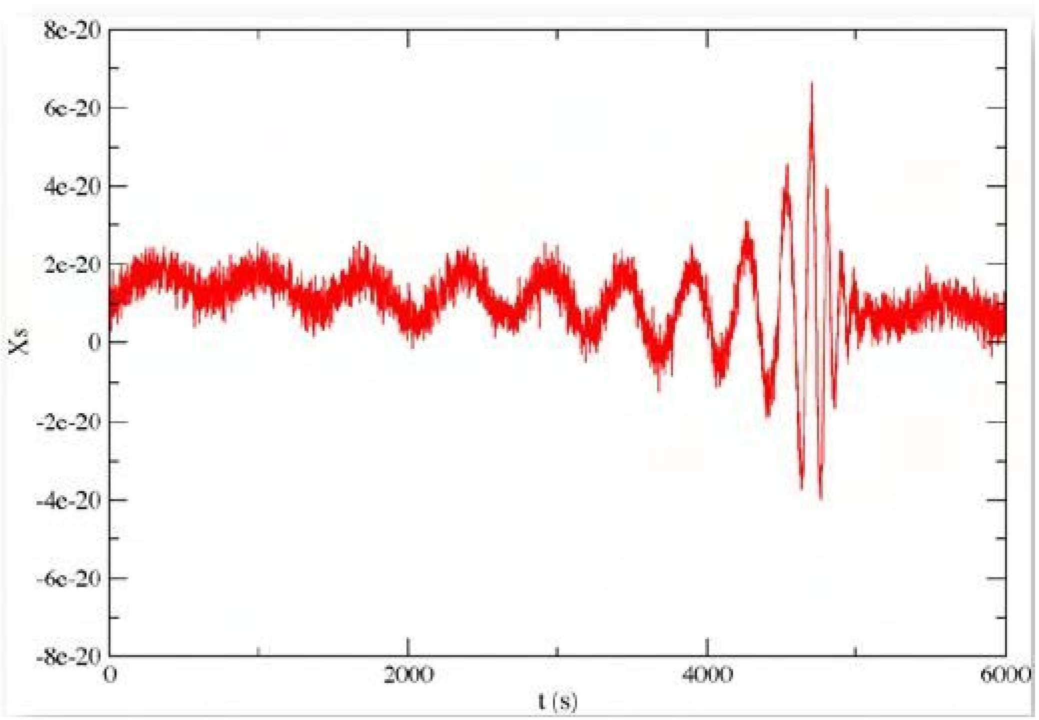


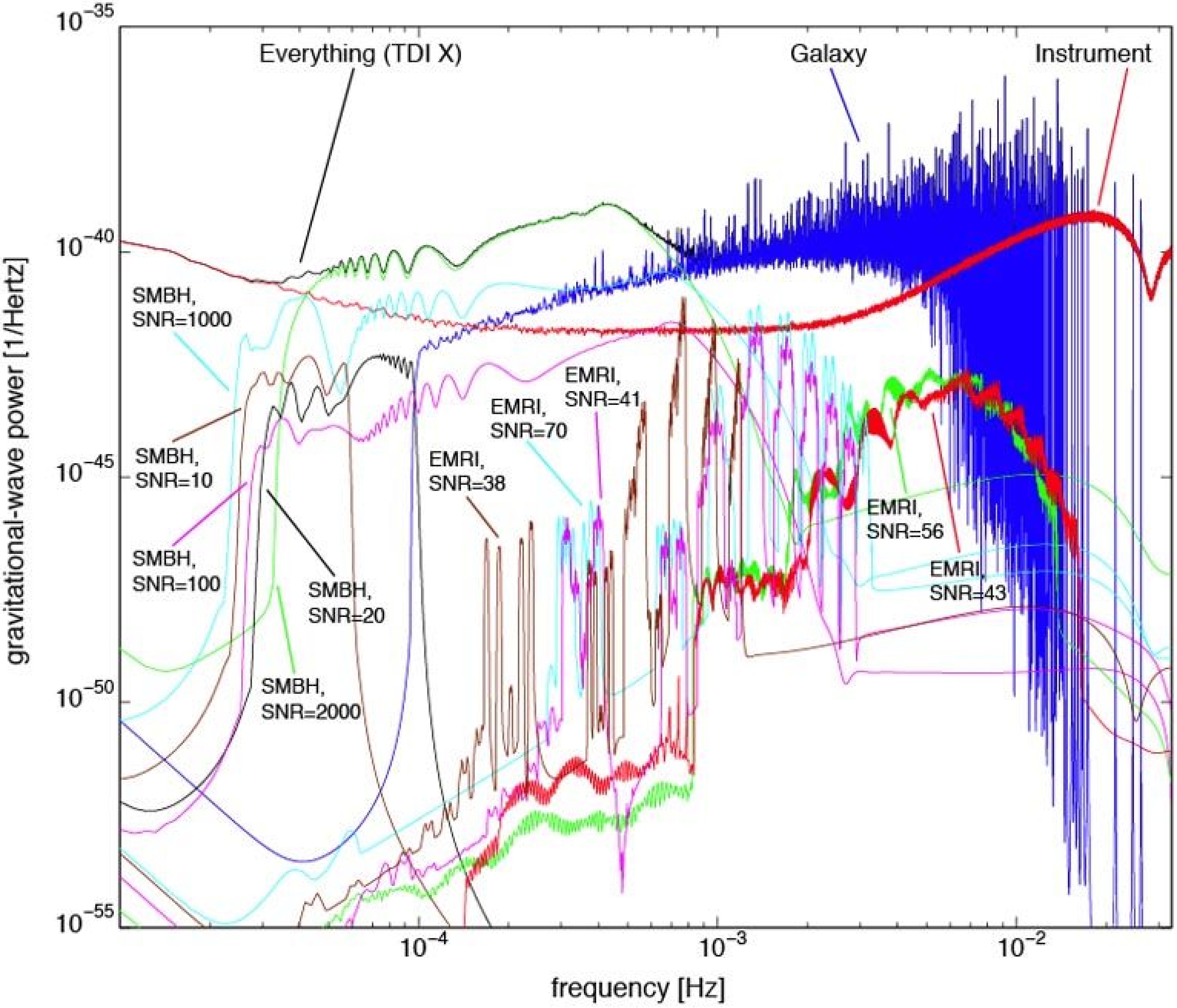
Expected Signals from BH-MBH Binaries

0.1% of stars in galactic core are assumed to be 7 M☉ black holes

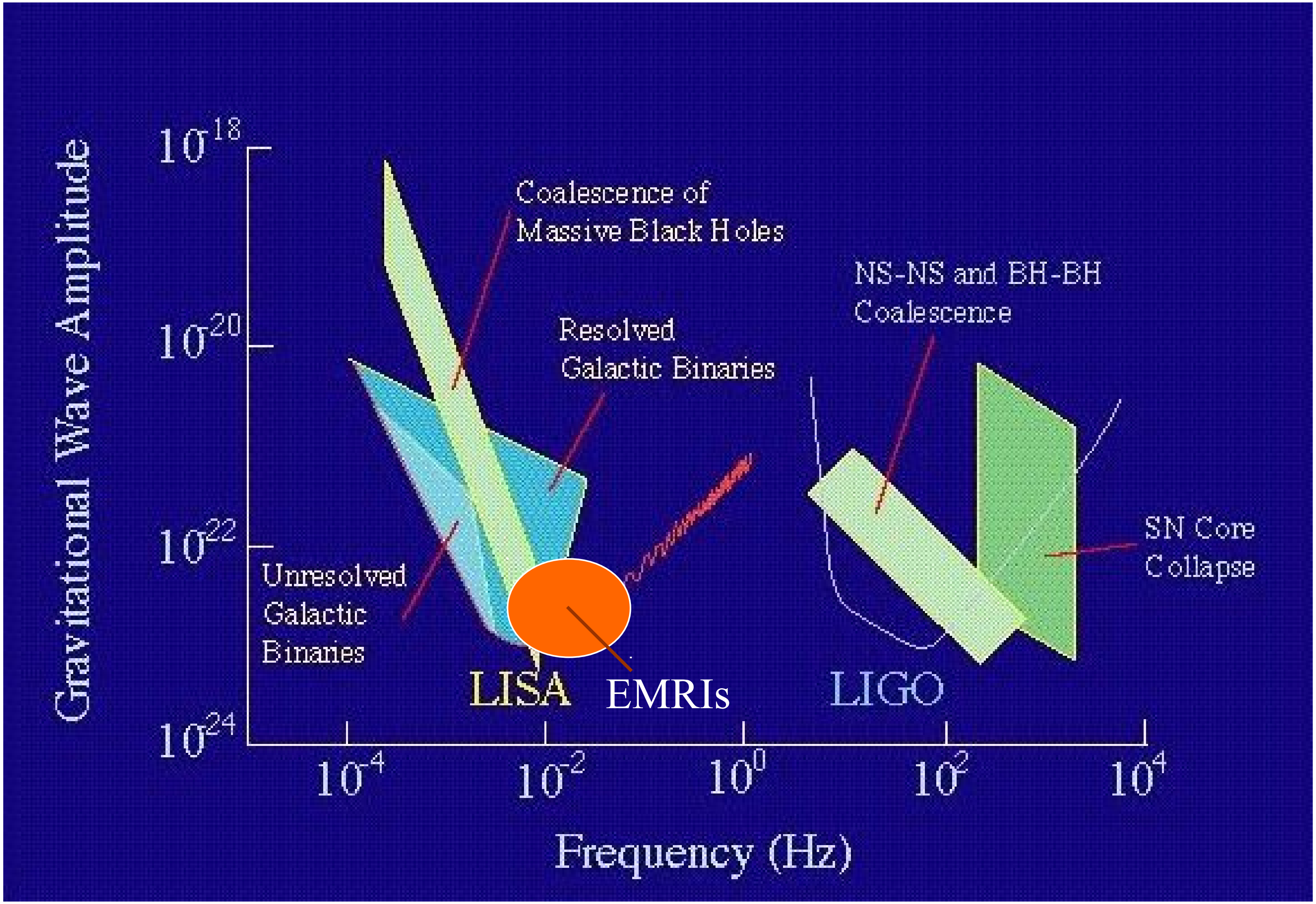
Data analysis

- Ligo/Virgo: low S/N sources
  - ❑ Matched filtering
  - ❑ Computer intensive
- LISA: many high S/N sources




Everything (TDI X)
Galaxy
Instrument
SMBH, SNR=1000
SMBH, SNR=10
SMBH, SNR=100
SMBH, SNR=20
SMBH, SNR=2000
EMRI, SNR=38
EMRI, SNR=70
EMRI, SNR=41
EMRI, SNR=56
EMRI, SNR=43
10^{-35}
10^{-40}
10^{-45}
10^{-50}
10^{-55}
10^{-4}
10^{-3}
10^{-2}
gravitational-wave power [1/Hertz]
frequency [Hz]

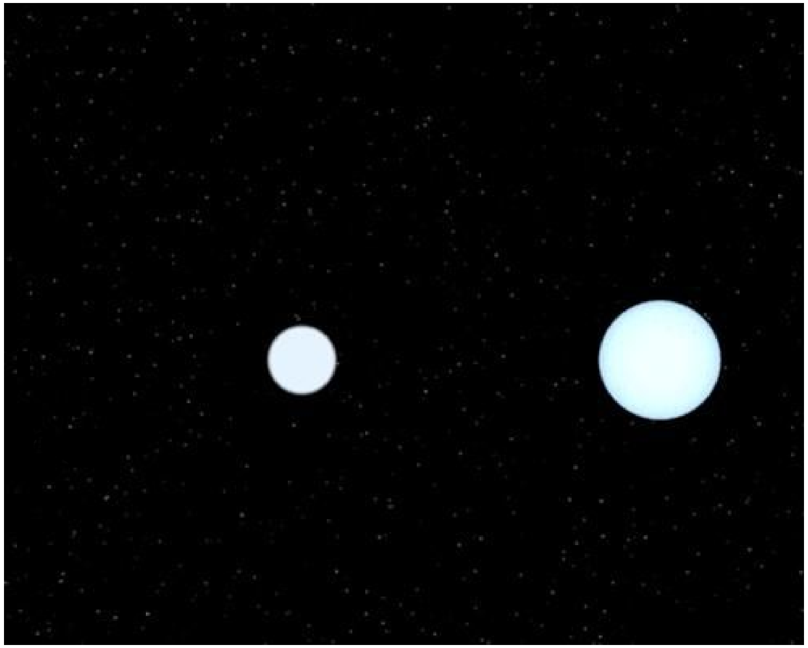
Sources: overview



What can we learn from this?

Compact binaries:

- Details (binary)stellar evolution
- Test predictions GR
- Distribution compact binaries in Galaxy
- Details (tidal) interaction



Supermassive black holes & EMRIs

- Existence of black holes
- Test *details* GR
- Formation black holes and galaxies
- Formation and future universe