THE DETECTION RATE OF MERGING NEUTRON STARS / BLACK HOLES

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Realtime Astroparticle Physics – Bonn 2013

Thomas Tauris (Bonn Uni / MPIfR)

Content

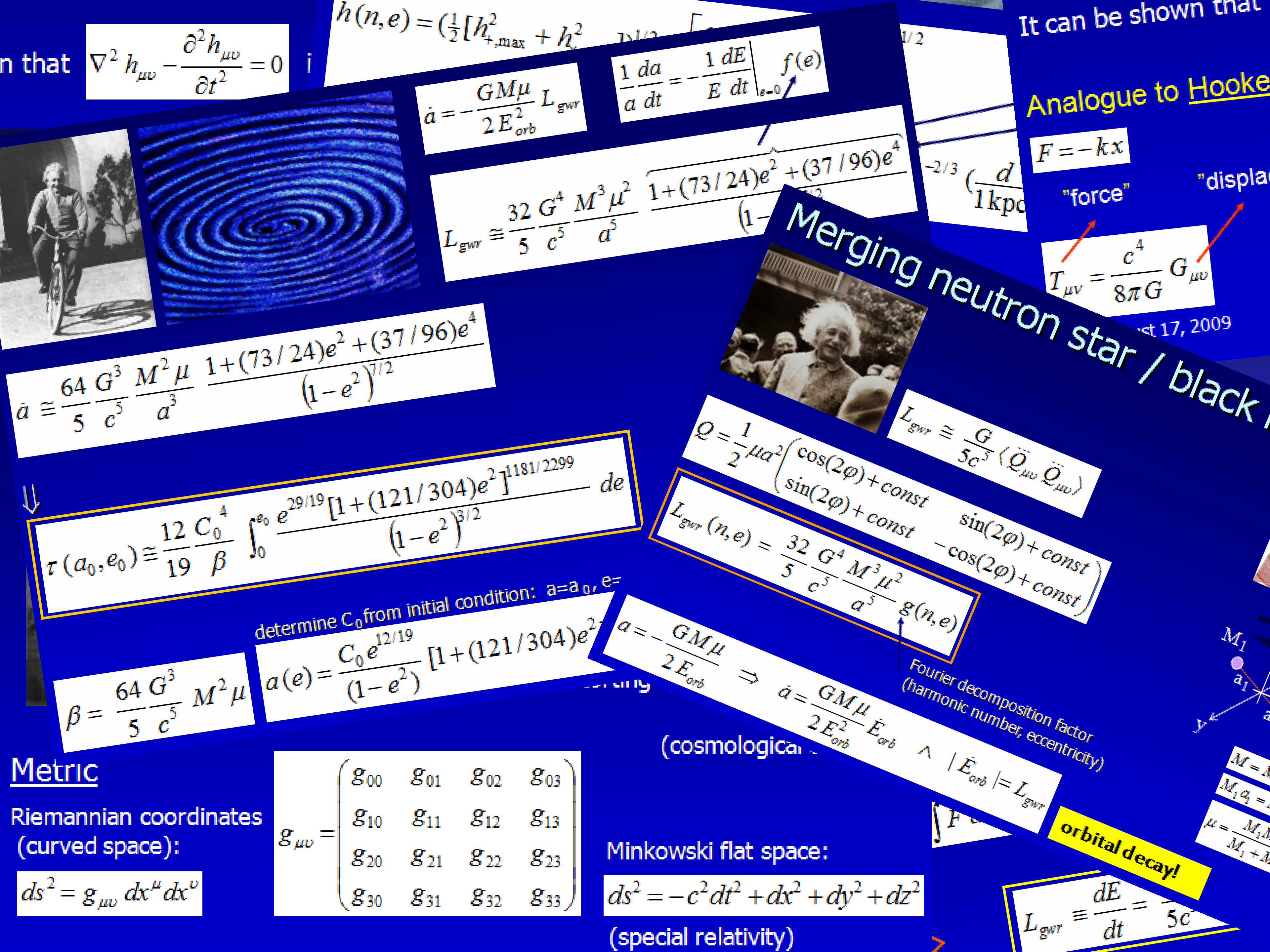
aLIGO vs. LIGO

Detection rates

Formation of a NS-BH binary

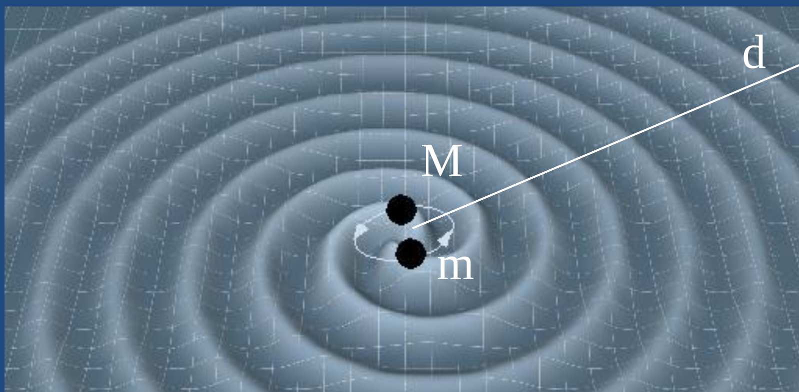
Merger rates in the local Universe

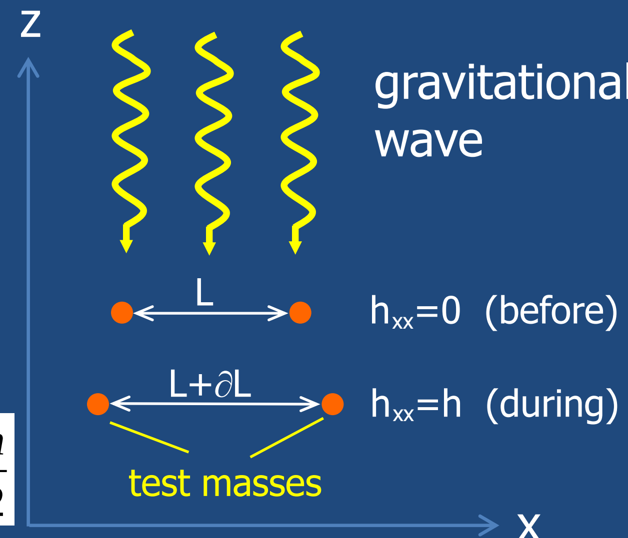
The Bonn initiative


n that $\nabla^2 h_{\mu\upsilon} - \frac{\partial^2 h_{\mu\upsilon}}{\partial t^2} = 0$
$h(n,e) = (\frac{1}{2}[h_{+,\max}^2 + h^2$
$\dot{a} = -\frac{GM\mu}{2E_{orb}^2} L_{gwr}$
$\frac{1}{a}\frac{da}{dt} = -\frac{1}{E}\frac{dE}{dt}\Big|_{e=0} f(e)$
$L_{gwr} \cong \frac{32}{5}\frac{G^4}{c^5}\frac{M^3\mu^2}{a^5} \frac{1+(73/24)e^2+(37/96)e^4}{(1-$
It can be shown that
Analogue to Hooke
$F = -kx$
"force"
"displac
$T_{\mu\upsilon} = \frac{c^4}{8\pi G} G_{\mu\upsilon}$
st 17, 2009
Merging neutron star / black
$\dot{a} \cong \frac{64}{5}\frac{G^3}{c^5}\frac{M^2\mu}{a^3}\frac{1+(73/24)e^2+(37/96)e^4}{(1-e^2)^{7/2}}$
$L_{gwr} \cong \frac{G}{5c^5}\langle \dddot{Q}_{\mu\upsilon}\dddot{Q}_{\mu\upsilon}\rangle$
$Q = \frac{1}{2}\mu a^2 \begin{pmatrix} \cos(2\varphi)+const & \sin(2\varphi)+const \\ \sin(2\varphi)+const & -\cos(2\varphi)+const \end{pmatrix}$
$\tau(a_0,e_0) \cong \frac{12}{19}\frac{C_0^4}{\beta}\int_0^{e_0} \frac{e^{29/19}[1+(121/304)e^2]^{1181/2299}}{(1-e^2)^{3/2}} de$
$L_{gwr}(n,e) = \frac{32}{5}\frac{G^4}{c^5}\frac{M^3\mu^2}{a^5} g(n,e)$
determine C_0 from initial condition: $a = a_0$, e=
$a = -\frac{GM\mu}{2E_{orb}} \Rightarrow \dot{a} = \frac{GM\mu}{2E_{orb}^2}\dot{E}_{orb} \wedge |\dot{E}_{orb}| = L_{gwr}$
Fourier decomposition factor
(harmonic number, eccentricity)
$\beta = \frac{64}{5}\frac{G^3}{c^5}M^2\mu$
$a(e) = \frac{C_0 e^{12/19}}{(1-e^2)}[1+(121/304)e^2$
(cosmological
orbital decay!
Metric
Riemannian coordinates
(curved space):
$ds^2 = g_{\mu\upsilon}dx^\mu dx^\upsilon$
$g_{\mu\upsilon} = \begin{pmatrix} g_{00} & g_{01} & g_{02} & g_{03} \\ g_{10} & g_{11} & g_{12} & g_{13} \\ g_{20} & g_{21} & g_{22} & g_{23} \\ g_{30} & g_{31} & g_{32} & g_{33} \end{pmatrix}$
Minkowski flat space:
$ds^2 = -c^2dt^2 + dx^2 + dy^2 + dz^2$
(special relativity)
$L_{gwr} \equiv \frac{dE}{dt} = \frac{}{5c}$
M_1
a_1

Gravitational wave detection

$f_{\rm gwr} = 2\, f_{\rm orb}$ (ecc.=0)





$$\frac{\delta L}{L} \approx \frac{h}{2}$$

the wave amplitude is twice the relative length change

strain (amplitude):

$$h(n,e) = \left(\tfrac{1}{2}\left[h^2_{+,\max} + h^2_{\times,\max}\right]\right)^{1/2} = \left[\frac{16\pi G}{c^3\omega^2_{\rm gwr}}\,\frac{L_{\rm gwr}(n,e)}{4\pi d^2}\right]^{1/2}$$

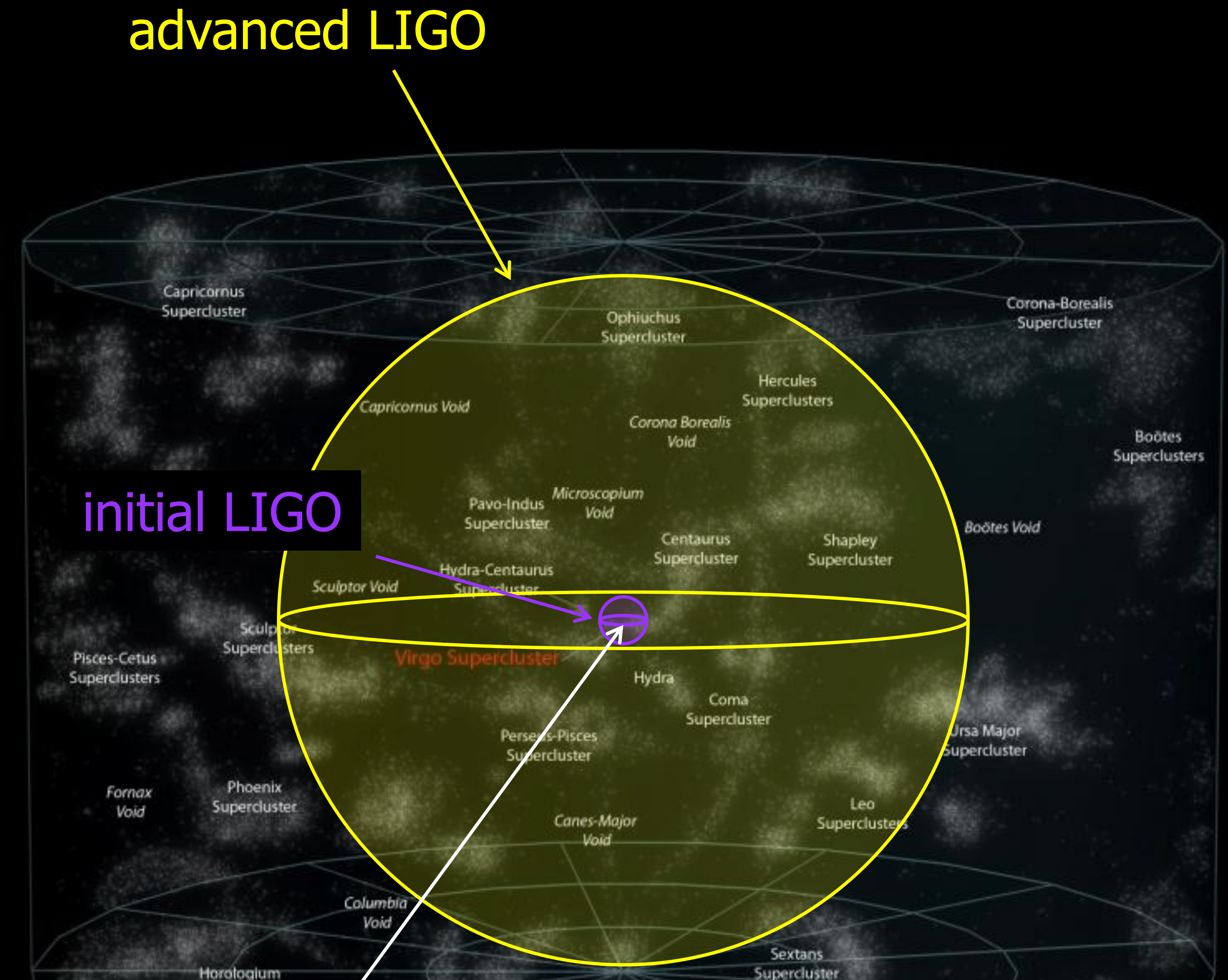
$$= 1.0\times 10^{-21}\,\frac{\sqrt{g(n,e)}}{n}\,\left(\frac{Mm\,(M+m)^{-1/3}}{{\rm M}_\odot^{5/3}}\right)\left(\frac{P_{\rm orb}}{1\,{\rm hr}}\right)^{-2/3}\left(\frac{d}{1\,{\rm kpc}}\right)^{-1}$$

massive

tight

nearby

scale factor



aLIGO vs LIGO

Sensitivity: 10-15x
(a few hours aLIGO
= 1 year LIGO obs.)

Range: 15x
(NSNS merger 300 Mpc)
(NSBH merger 650 Mpc)
(BHBH merger 1 Gpc)
Z=0.4

Event rate: 3000x

Angular resolution:
~100 sqr. deg. on sky
3 detectors LIGO/VIRGO

Predicted merger rates:

LIGO Scientific Collaboration, Virgo Collaboration
"Predictions for the rates of compact binary coalescences observable by ground-based gravitational-wave detectors", Abadie at al. (2011)

Galactic merger rates:

TABLE II: Compact binary coalescence rates per Milky Way Equivalent Galaxy per Myr.

Source	$R_{\rm low}$	$R_{\rm re}$	$R_{\rm high}$	$R_{\rm max}$
NS-NS ($\rm MWEG^{-1}\ Myr^{-1}$)	1 [1][a]	100 [1][b]	1000 [1][c]	4000 [16][d]
NS-BH ($\rm MWEG^{-1}\ Myr^{-1}$)	0.05 [18][e]	3 [18][f]	100 [18][g]	
BH-BH ($\rm MWEG^{-1}\ Myr^{-1}$)	0.01 [14][h]	0.4 [14][i]	30 [14][j]	
IMRI into IMBH ($\rm GC^{-1}\ Gyr^{-1}$)			3 [19][k]	20 [19][l]
IMBH-IMBH ($\rm GC^{-1}\ Gyr^{-1}$)			0.007 [20][m]	0.07 [20][n]

LIGO detection rates:

TABLE V: Detection rates for compact binary coalescence sources.

IFO	Source[a]	$N_{\rm low}$ $\rm yr^{-1}$	$N_{\rm re}$ $\rm yr^{-1}$	$N_{\rm high}$ $\rm yr^{-1}$	$N_{\rm max}$ $\rm yr^{-1}$
	NS-NS	2×10^{-4}	0.02	0.2	0.6
	NS-BH	7×10^{-5}	0.004	0.1	
Initial	BH-BH	2×10^{-4}	0.007	0.5	
	IMRI into IMBH			<0.001[b]	0.01[c]
	IMBH-IMBH			10^{-4}[d]	10^{-3}[e]
	NS-NS	0.4	40	400	1000
	NS-BH	0.2	10	300	
Advanced	BH-BH	0.4	20	1000	
	IMRI into IMBH			10[b]	300[c]
	IMBH-IMBH			0.1[d]	1[e]

Predicted merger rates:

LIGO Scientific Collaboration, Virgo Collaboration
"Predictions for the rates of compact binary coalescences observable by ground-based gravitational-wave detectors", Abadie at al. (2011)

Galactic NSBH merger rates:

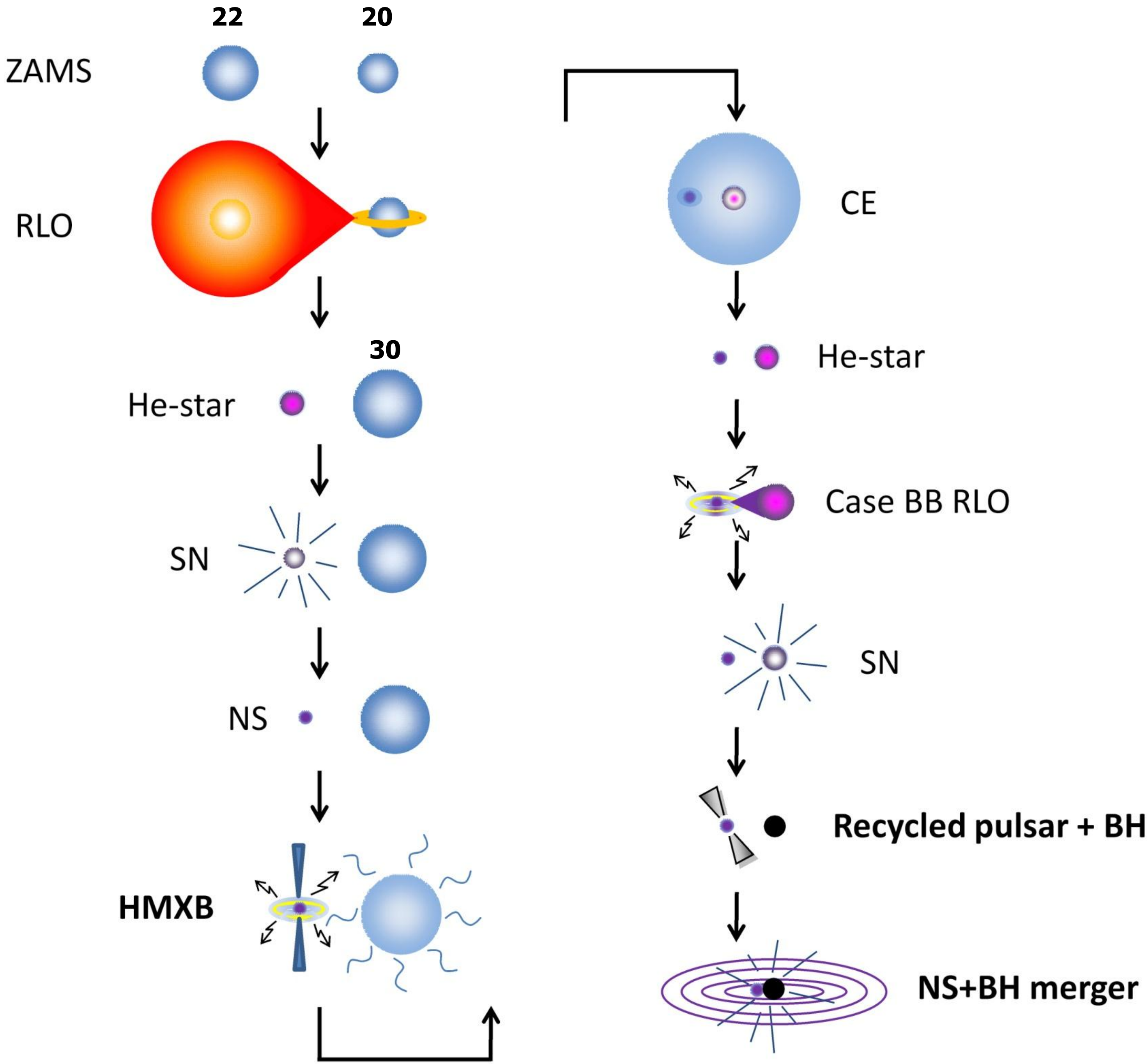
B. NS-BH rates

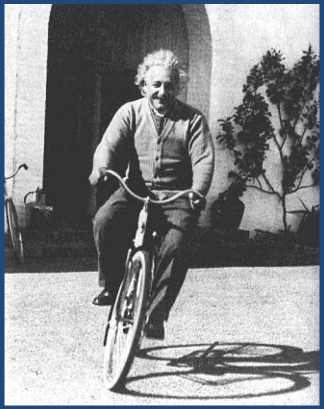
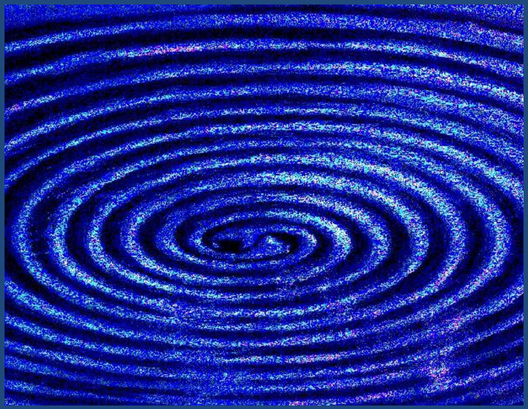
TABLE VII: Estimates of NS-BH inspiral rates.

Rate model	$R_{\rm low}$ MWEG^{-1} Myr^{-1}	$R_{\rm re}$ MWEG^{-1} Myr^{-1}	$R_{\rm high}$ MWEG^{-1} Myr^{-1}	$R_{\rm max}$ MWEG^{-1} Myr^{-1}
O'Shaughnessy et al. pop. synth. [18][a]	0.05	3	100	
Voss & Tauris pop. synth. [34][b]	0.2	0.58	5	
Belczynski et al. pop. synth.: model A of [35][c]		0.07		
Belczynski et al. pop. synth.: model B of [35][c]		0.09		
Belczynski et al. pop. synth.: model C of [35][c]		3.2		
Nelemans pop. synth. [36][d]	0.2	10	500	
"Double-core" scenario: Dewi et al. [37][e]	0.14	6.32		

[a]Predictions from constrained population-synthesis models [18]. A visual estimate of the center of the NS-BH probability distribution peak of Figure 6 is used as the value of $R_{\rm re}$; a visual estimate of the left / right edge of this peak is used as the values of $R_{\rm low}$ / $R_{\rm high}$.
[b]Predictions from the population-synthesis study of Voss & Tauris [34]. The realistic estimate is taken from model A and the plausible pessimistic / optimistic rates are based on the lowest (model D) and highest (model B) predictions from Table 7 of [34]. The values for BHNS and NSBH rates are summed. The range may significantly underestimate the true uncertainty.
[c]Predictions from the population-synthesis studies of Belczynski et al. [35], which analyze the impact of assumptions about common-envelope evolution. See section IV C for details regarding models A, B, and C. Values are taken from Table 2 of [35].
[d]Predictions from population-synthesis models of Nelemans [36]. The realistic estimate is taken from the merger rate quoted in Table 1 of [36]. The plausible pessimistic and optimistic estimates are obtained, respectively, by dividing and multiplying that realistic estimate by the uncertainty factor of 50 quoted in that table.
[e]Predictions for NS-BH binaries that form through the "double-core" scenario. The plausible pessimistic and realistic rates are taken to be the lowest and highest merger rates in Table 2 of Dewi et al. [37].

Formation of a NSBH binary


22
20
ZAMS
RLO
30
He-star
SN
NS
HMXB
CE
He-star
Case BB RLO
SN
Recycled pulsar + BH
NS+BH merger

Merger time of a given binary (M, m, a, e)

$$\tau(a_0, e_0) \cong \frac{12}{19}\frac{C_0^4}{\beta}\int_0^{e_0}\frac{e^{29/19}[1+(121/304)e^2]^{1181/2299}}{\left(1-e^2\right)^{3/2}}\,de$$

Peters (1964)

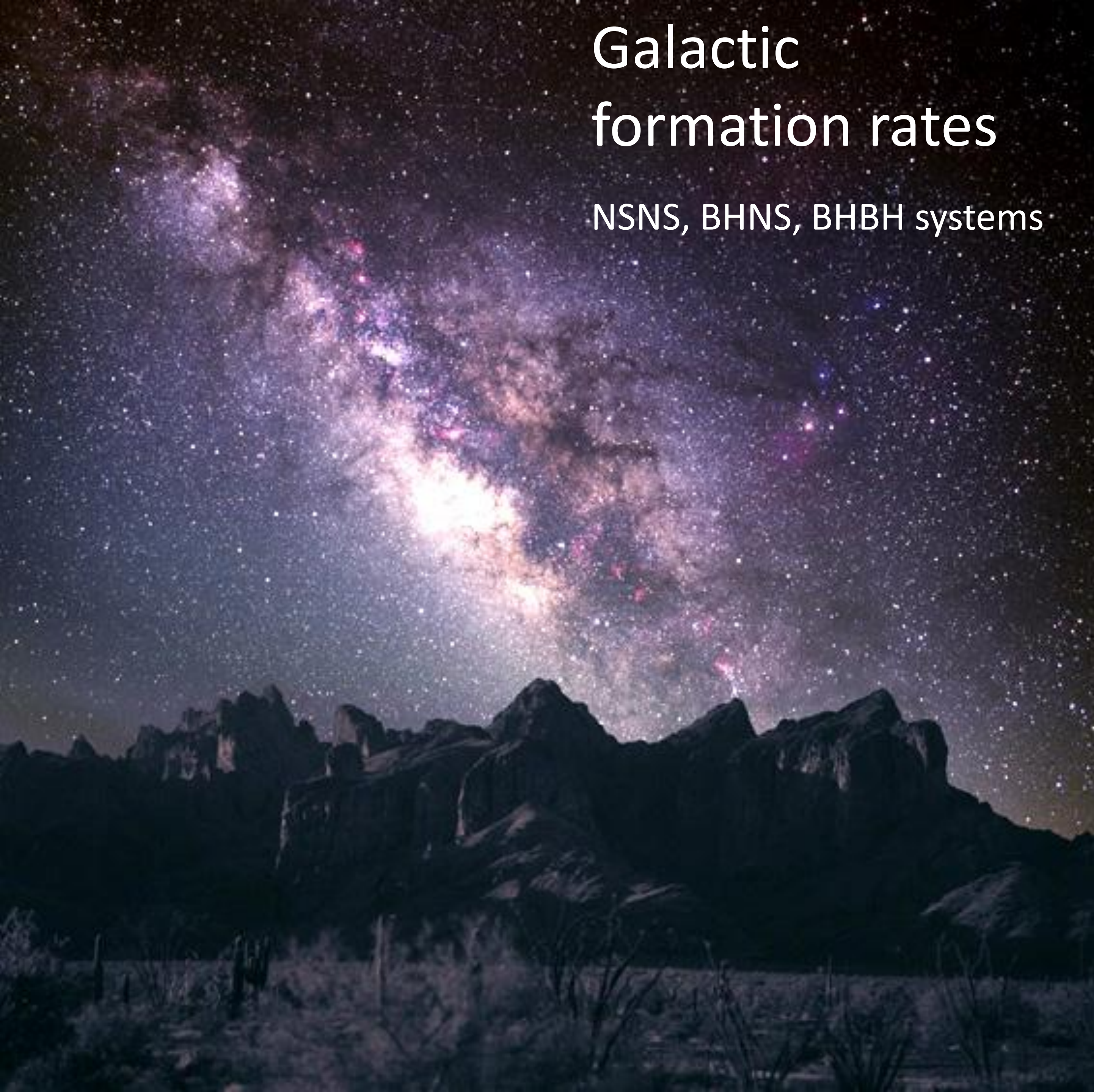
$$\beta = \frac{64}{5}\frac{G^3}{c^5}M^2\mu$$

determine C_0 from initial condition: $a=a_0$, $e=e_0$

$$a(e) = \frac{C_0 e^{12/19}}{(1-e^2)}[1+(121/304)e^2]^{870/2299}$$

Galactic formation rates

NSNS, BHNS, BHBH systems



Population synthesis (Monte Carlo simulation)

- ZAMS binary

(M_1, q, a, e)

- thermal eccentricity distribution
- separation (flat in log a)
- mass-ratio function determines secondary mass $f(q) = \frac{2}{(1+q)^2}$
- primary mass from Salpeter-like IMF $N(m) \propto m^{-\alpha}$

- Stellar evolution models (MS stars, helium stars)
  metallicities, rotation, wind-mass loss

- Asymmetric SN explosions (Maxwellian momentum kicks)

\+ a large number of input physics parameters

Galactic star formation rate

- Contineous star formation in Galactic disk over 12 Gyr **(Gilmore 2001)**
- Central star formation in a burst < 1Gyr **(Kennicut 1998)**
- Assume formation of one binary $M_1 > 0.8 M_\odot \ yr^{-1}$
- $\rightarrow \Theta_{BSFR} = f \cdot 0.01 \ yr^{-1}$ of a massive binary $M_1 > 10 M_\odot \ \wedge \ M_2 > 4 M_\odot$

Galactic potentials (*location* of merger)

- Dark matter halo + central component + disk
  (Flynn, Sommer-Larsen & Christensen 1996), (Miyamoto & Nagai 1975)
- Constant surface brightness $\leftrightarrow$ $\Phi \propto \sqrt{M_{galaxy}}$ **(Binney & Tremain 1994)**
- Birth place follows density distribution; at rest in local frame $v = v_{rot}$

NSBH merger-rate history of the Milky Way

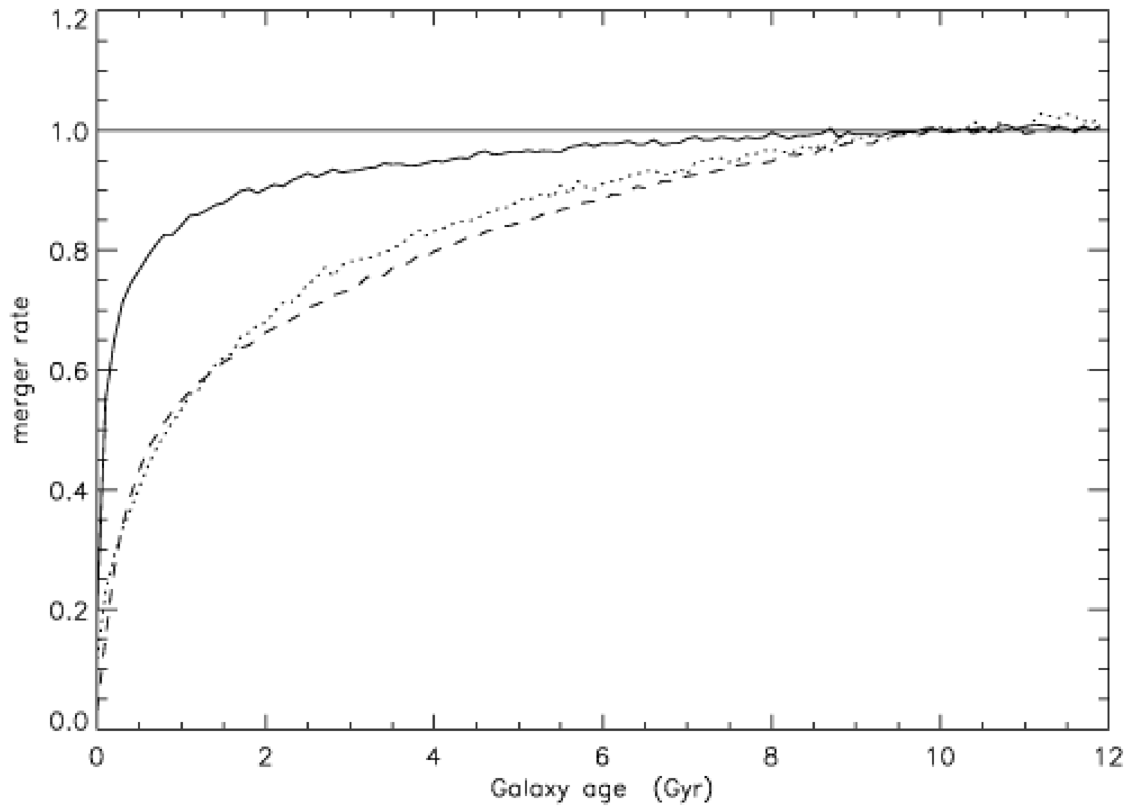


Figure 14. Merger rates (relative to present merger rates) as a function of the age of our Galaxy for NSNS systems (solid line), BHNS+NSBH systems (dashed line) and BHBH systems (dotted line) for a constant Galactic star formation rate. The curves show the emergence of a 'steady state'.

Voss & Tauris (2003)

Merger rates in the local Universe

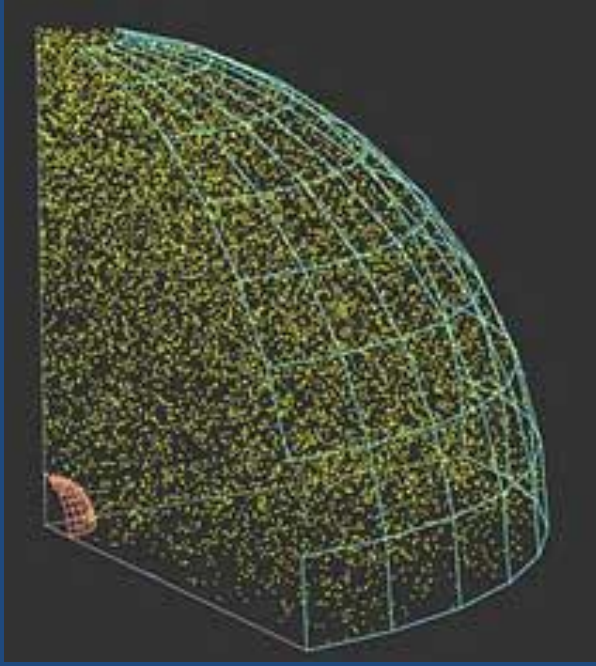
Extrapolation to local Universe

$$\text{aLIGO } MR \approx \text{Milky Way } MR \times factor$$

Scaling based on galaxy number density
or B-band luminosity of galaxies:

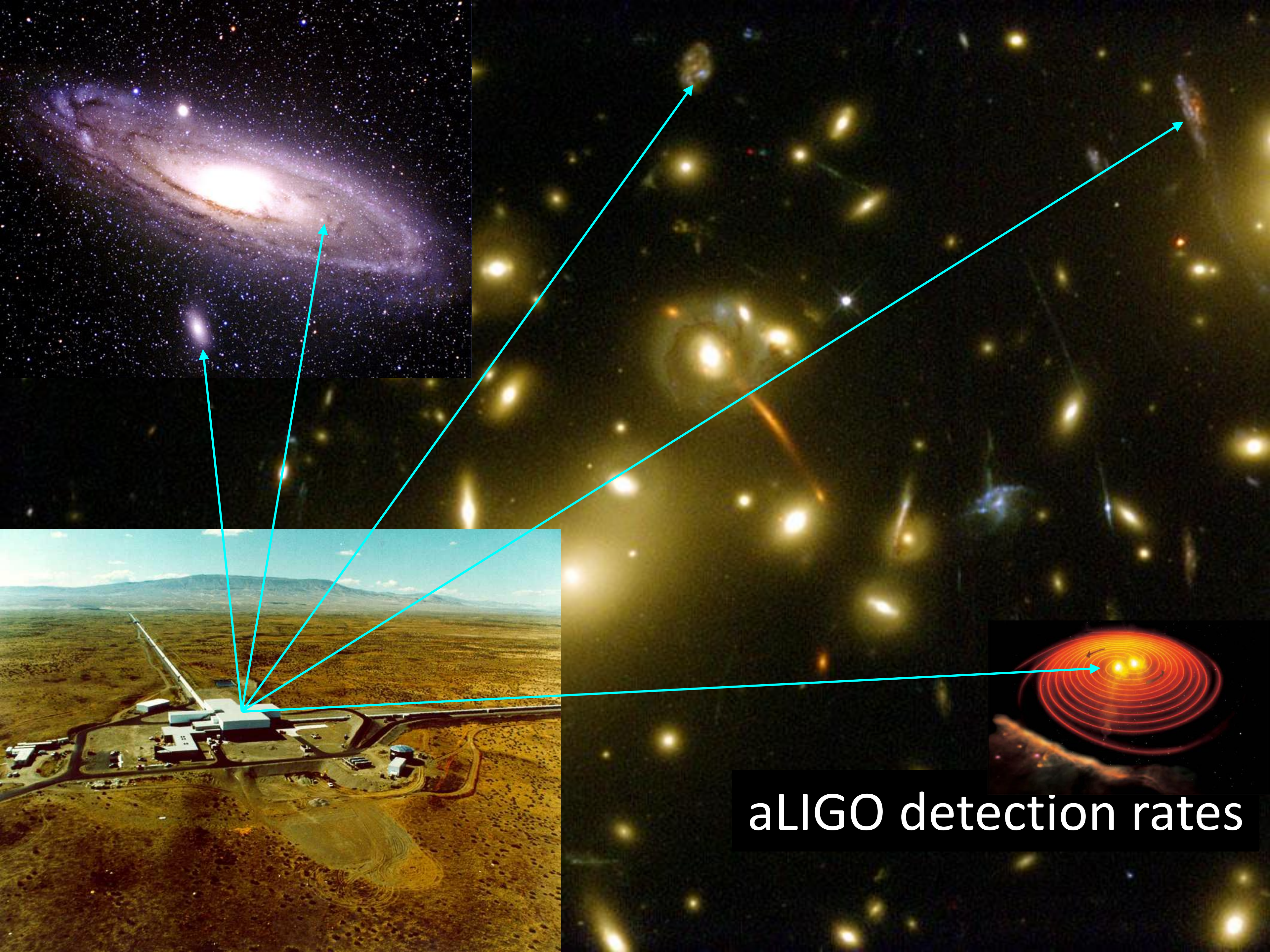
$$(1.0 - 1.5) \times 10^{-2}\ Mpc^{-3}$$

Kalogera et al. (2001)

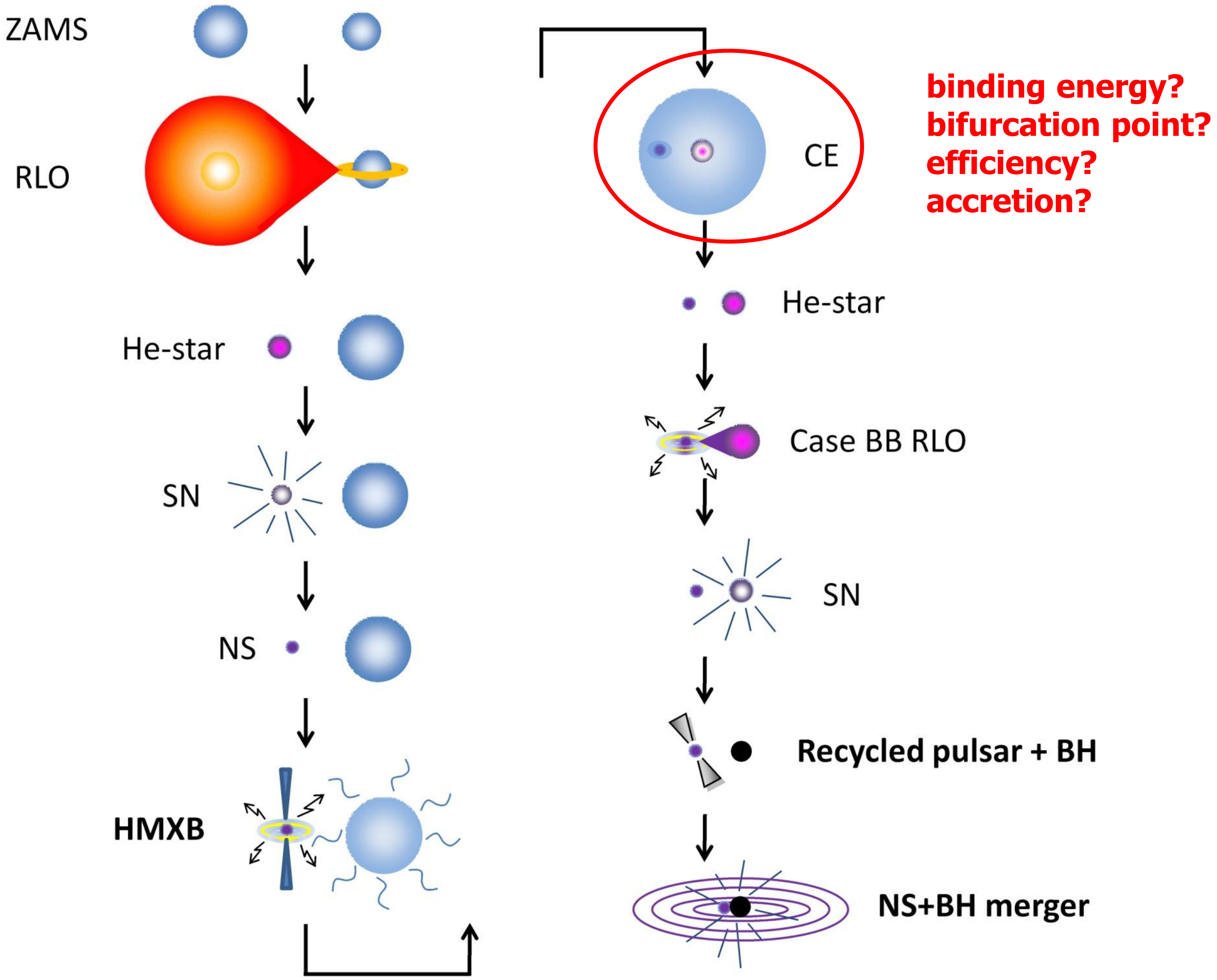


$$\text{aLIGO: } d \sim 300\, Mpc \quad NSNS - merger \quad \rightarrow \quad factor = 1.3 \times 10^{6}$$

$$\text{aLIGO: } d \sim 1200\, Mpc \quad BHBH - merger \quad \rightarrow \quad factor = 8.4 \times 10^{7}$$

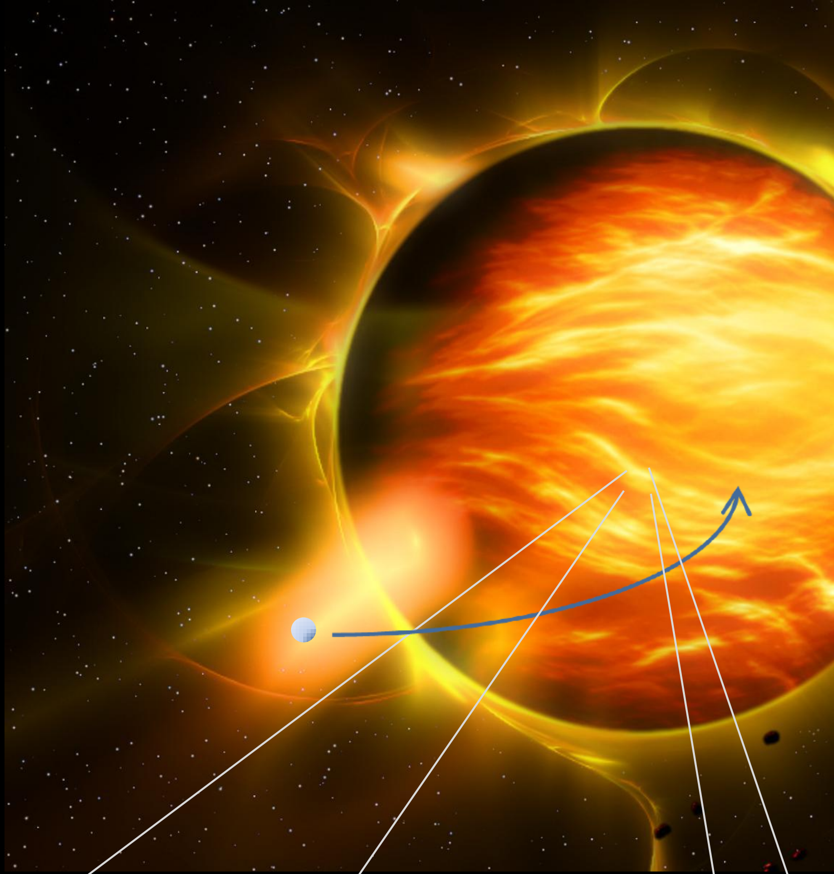

aLIGO detection rates

The NSBH formation rate
is extremely sensitive to
a few key parameters


ZAMS
RLO
He-star
SN
NS
HMXB
CE
binding energy?
bifurcation point?
efficiency?
accretion?
He-star
Case BB RLO
SN
Recycled pulsar + BH
NS+BH merger

$$\dot{E}_{orb} = -\frac{GM_{donor}M_{NS}}{2a^2}\frac{da}{dt} = \xi(\mu)\pi R_{acc}^2 \rho_{donor} v^3$$

Dissipation of E_{orb} by drag force (Bondi & Hoyle 1944)



$$E_{env} \equiv \eta \, \Delta E_{orb}$$

(Dewi & Tauris 2000, 2001)

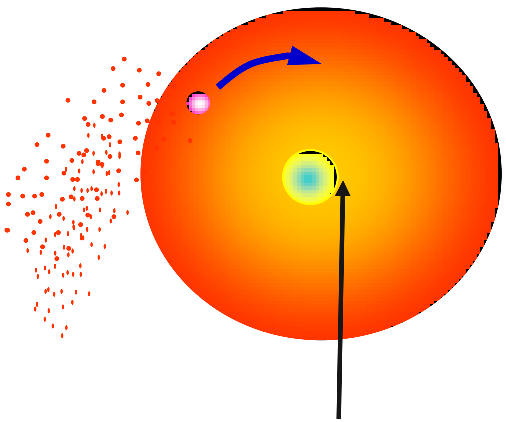
$$E_{env} = -\int_{M_{core}}^{M_{donor}} \frac{GM(r)}{r} dm \quad + \quad \alpha_{th}\int_{M_{core}}^{M_{donor}} U \, dm$$

gravitational binding energy

internal thermodynamic energy

- thermal energy
- energy of radiation
- ionization energy
- Fermi energy of e^--gas

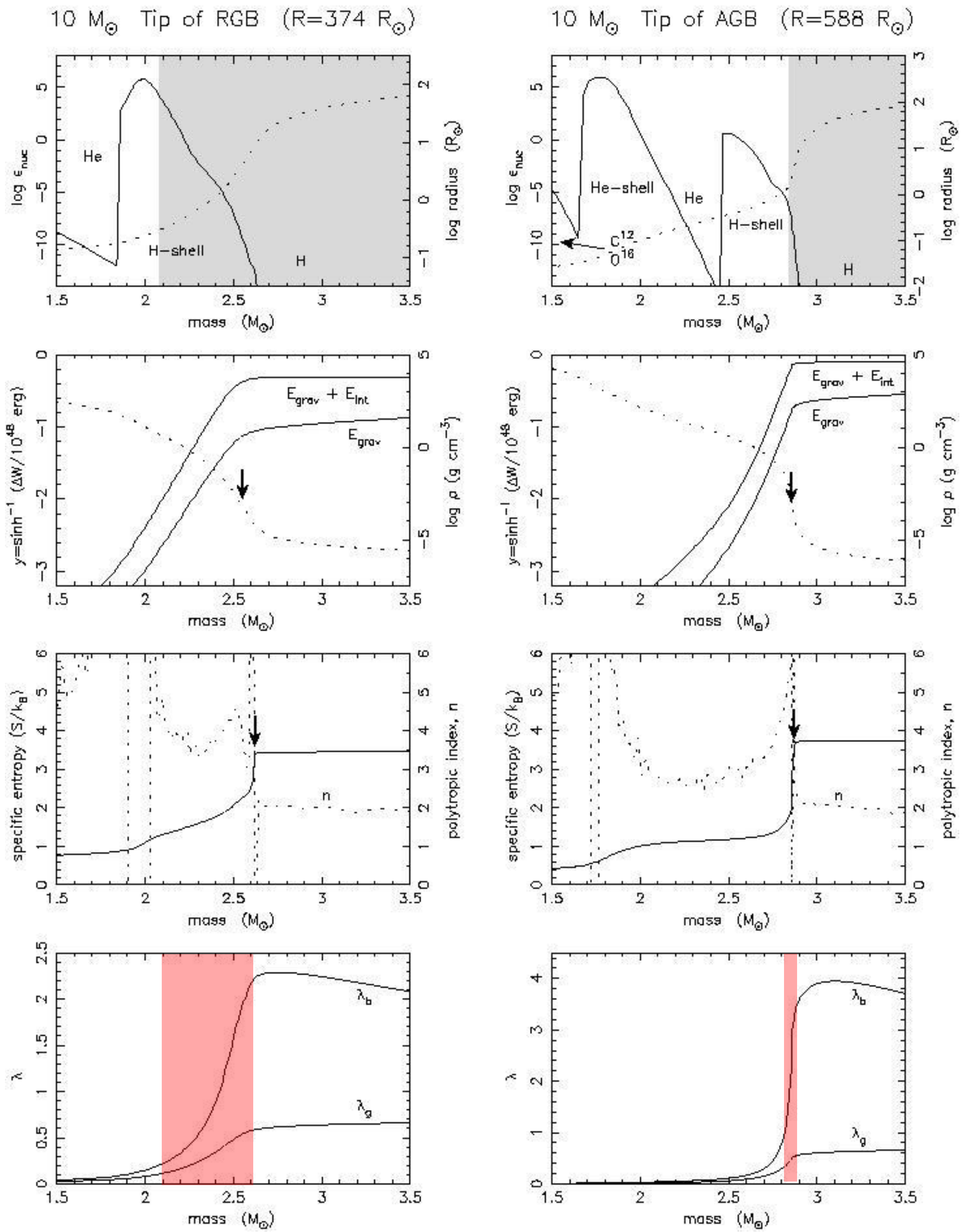
Common envelope evolution



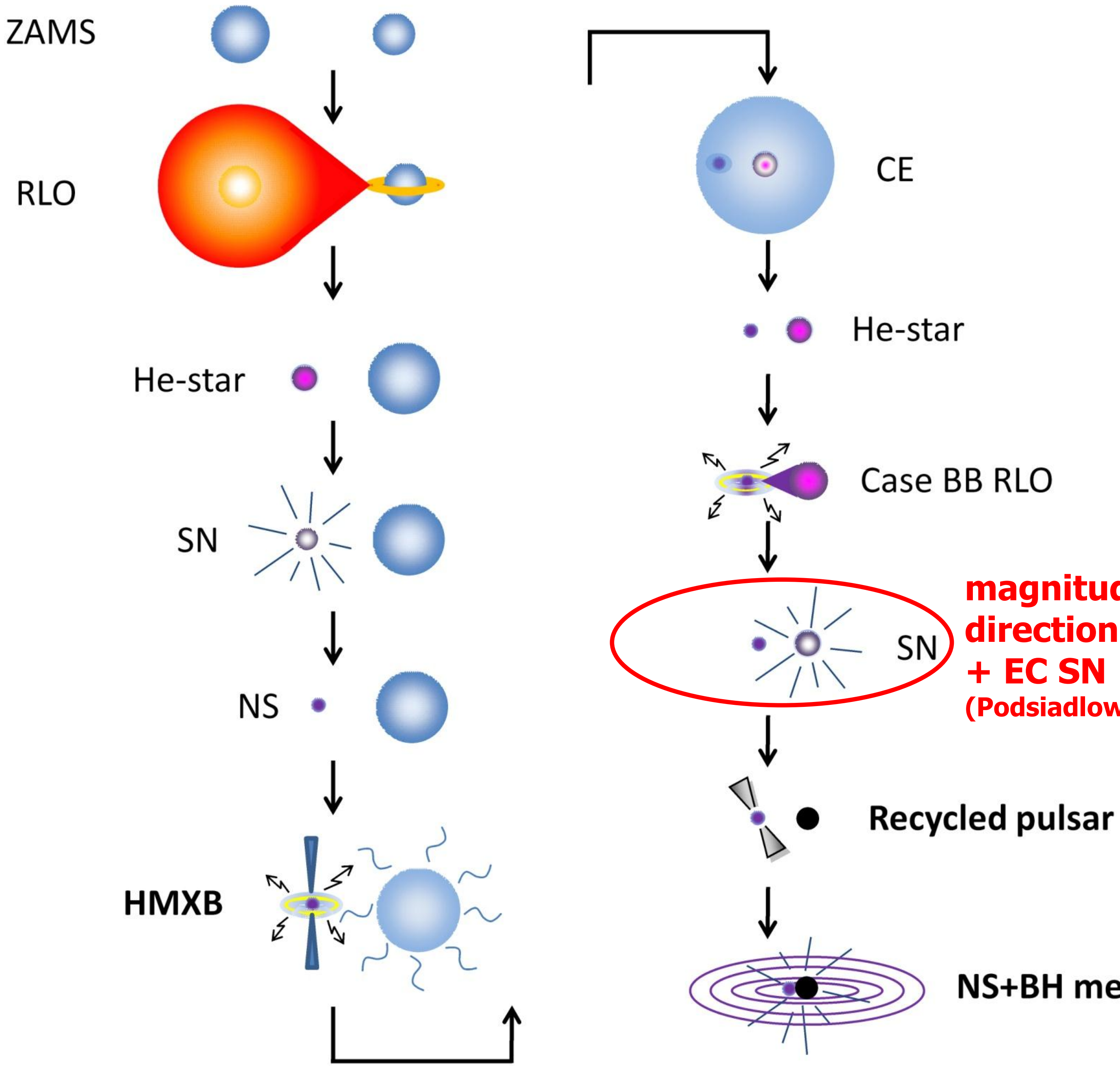
bifurcation point

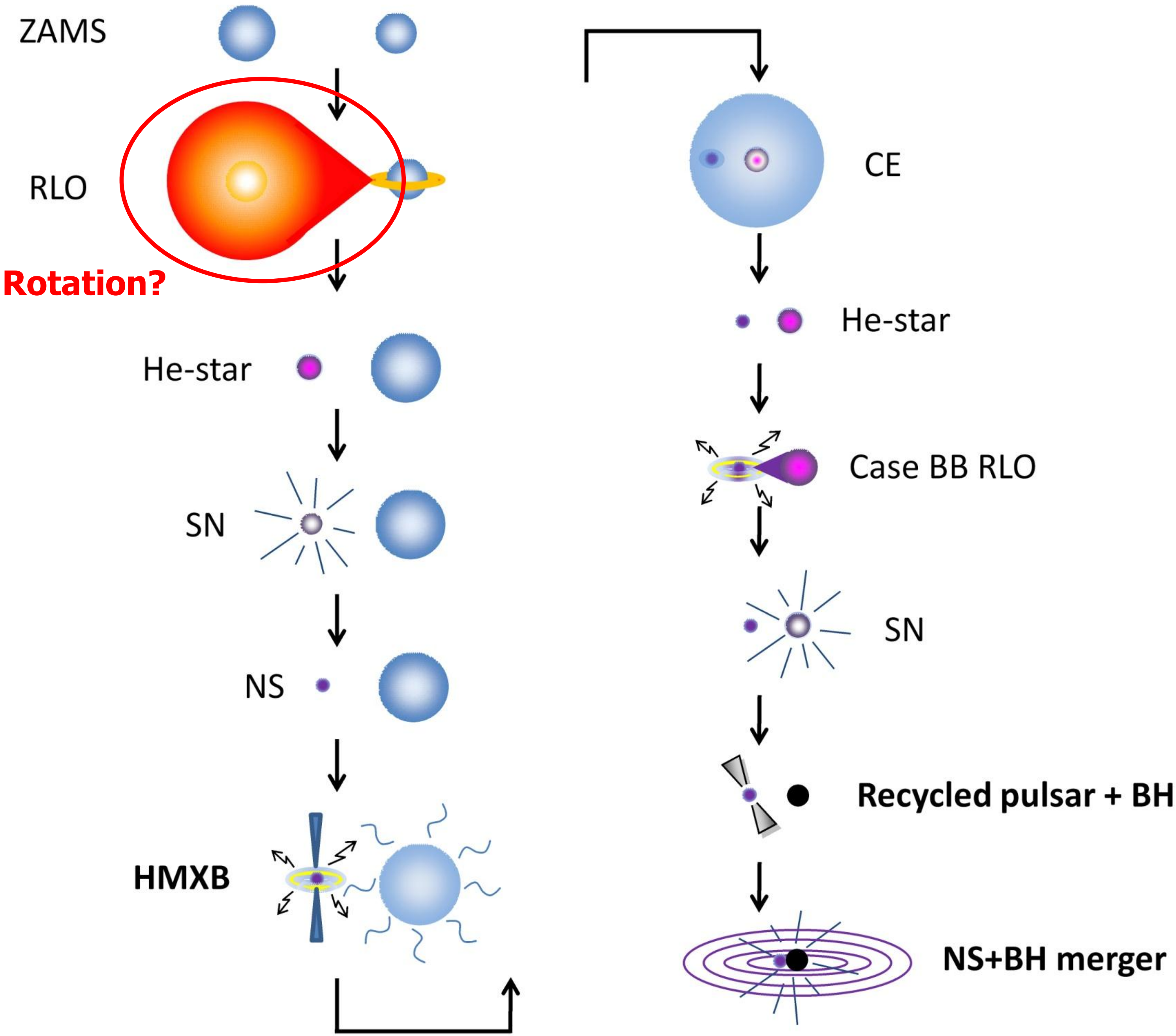
Tauris & Dewi (2001)

Ivanova (2011)



Tauris & Dewi (2001)

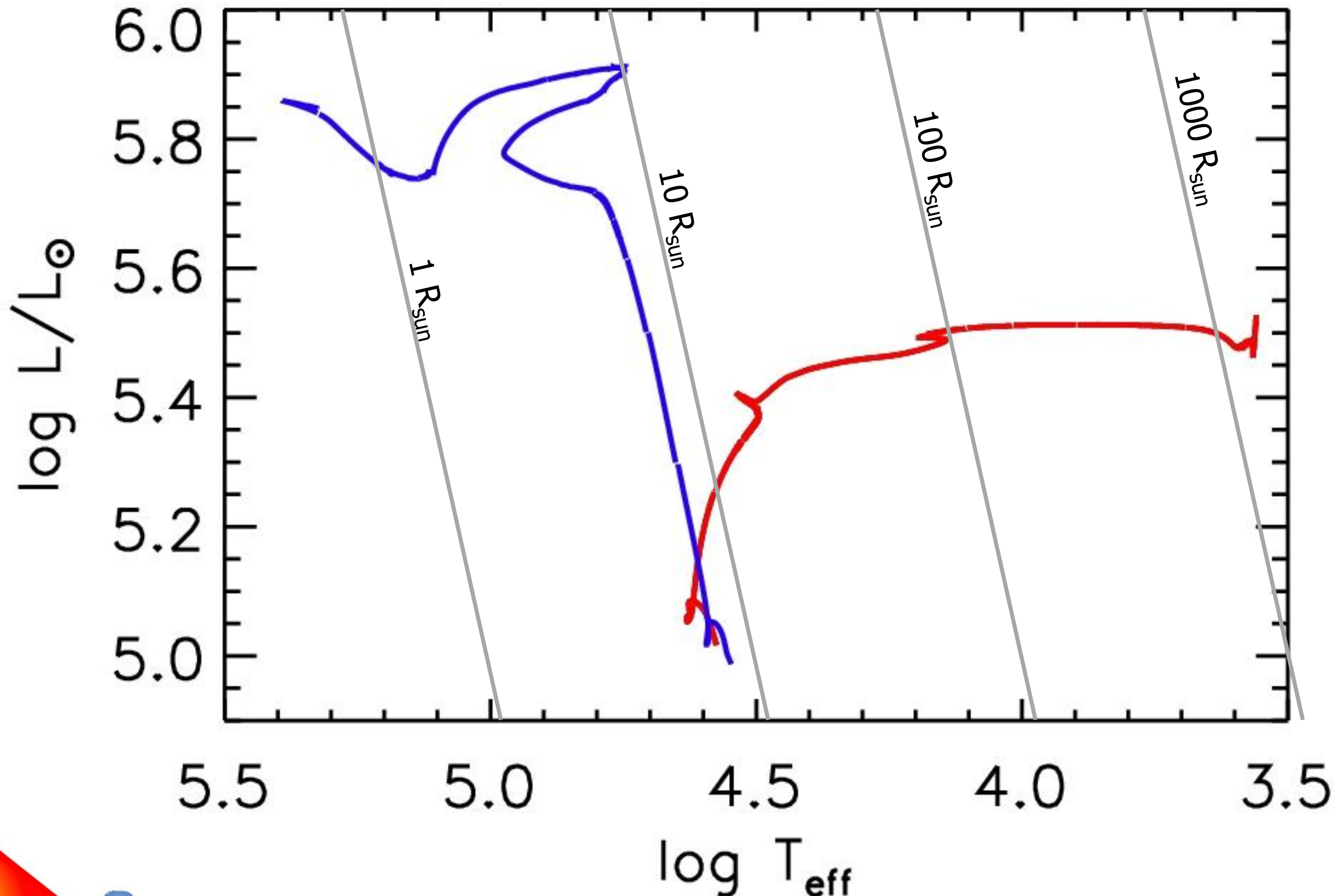

ZAMS
RLO
He-star
SN
NS
HMXB
CE
He-star
Case BB RLO
SN
magnitude? (Janka 2012)
direction?
+ EC SN
(Podsiadlowski et al. 2004)
Recycled pulsar + BH
NS+BH merger

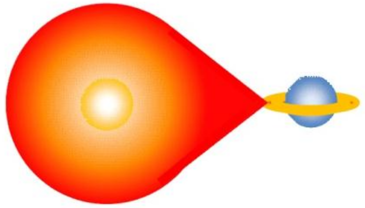


ZAMS
RLO
Rotation?
He-star
SN
NS
HMXB
CE
He-star
Case BB RLO
SN
Recycled pulsar + BH
NS+BH merger

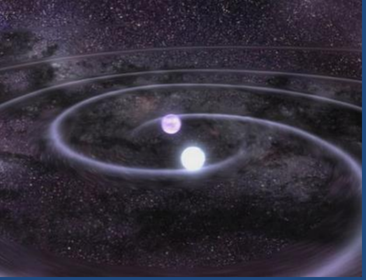
Chemically Homogeneous Evolution of a 30 M_{sun} star with Z=0.002

These **rotating stars** remain blue and compact, and avoid RLO and mergers in close-orbit binaries





Yoon, Langer & Normann (2006)



The Bonn initiative

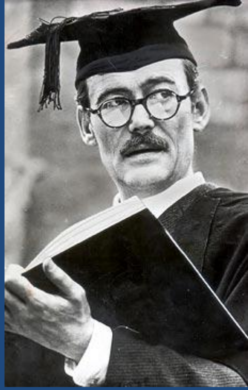
(Tauris, Langer, Kramer, Izzard)

- A state-of-the-art population synthesis – including:
  - Rotationally induced mixing of chemical elements
  - Better constrains on CE evolution (core boundary, E_{bind} , L_{acc})
  - Electron capture SNe
  - Latest VLT-FLAMES Tarantula Survey results (binary frequency, P_{orb} distribution, mass-ratio,…)
  - Most recent wind-mass loss models (massive + WR stars)
  - Updated threshold masses for BH production in close binaries
  - Using two *independent* population synthesis codes

DFG proposal

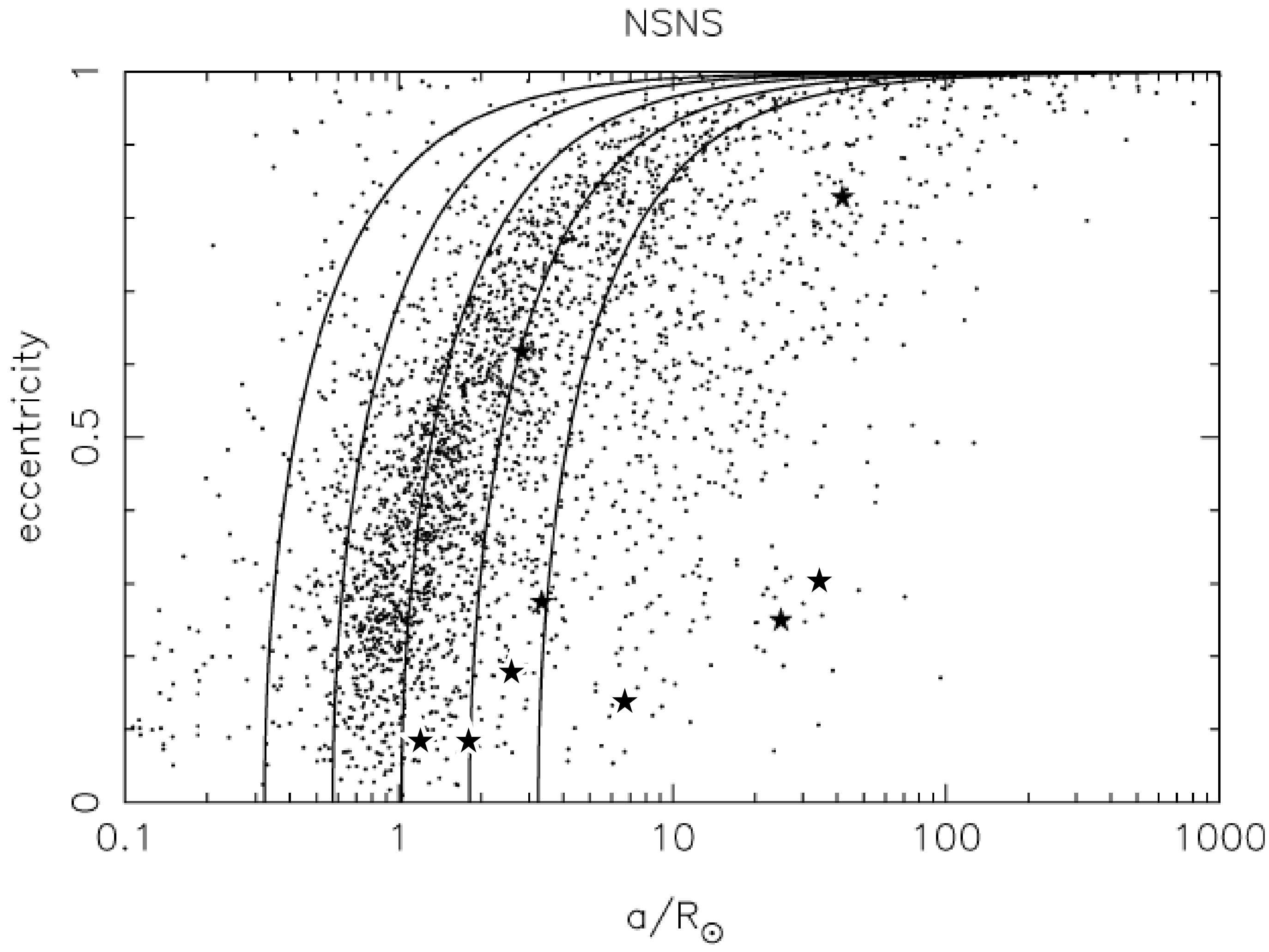
- Predict updated detection rates of merging NSNS, NSBH and BHBH
- Expected properties of mildly recycled pulsars orbiting a BH
- Optimize radio surveys using the Effelsberg 100-m telescope
- HMXB binaries (numbers, properties, lifetimes) e-ROSITA

The Bonn initiative - cont.



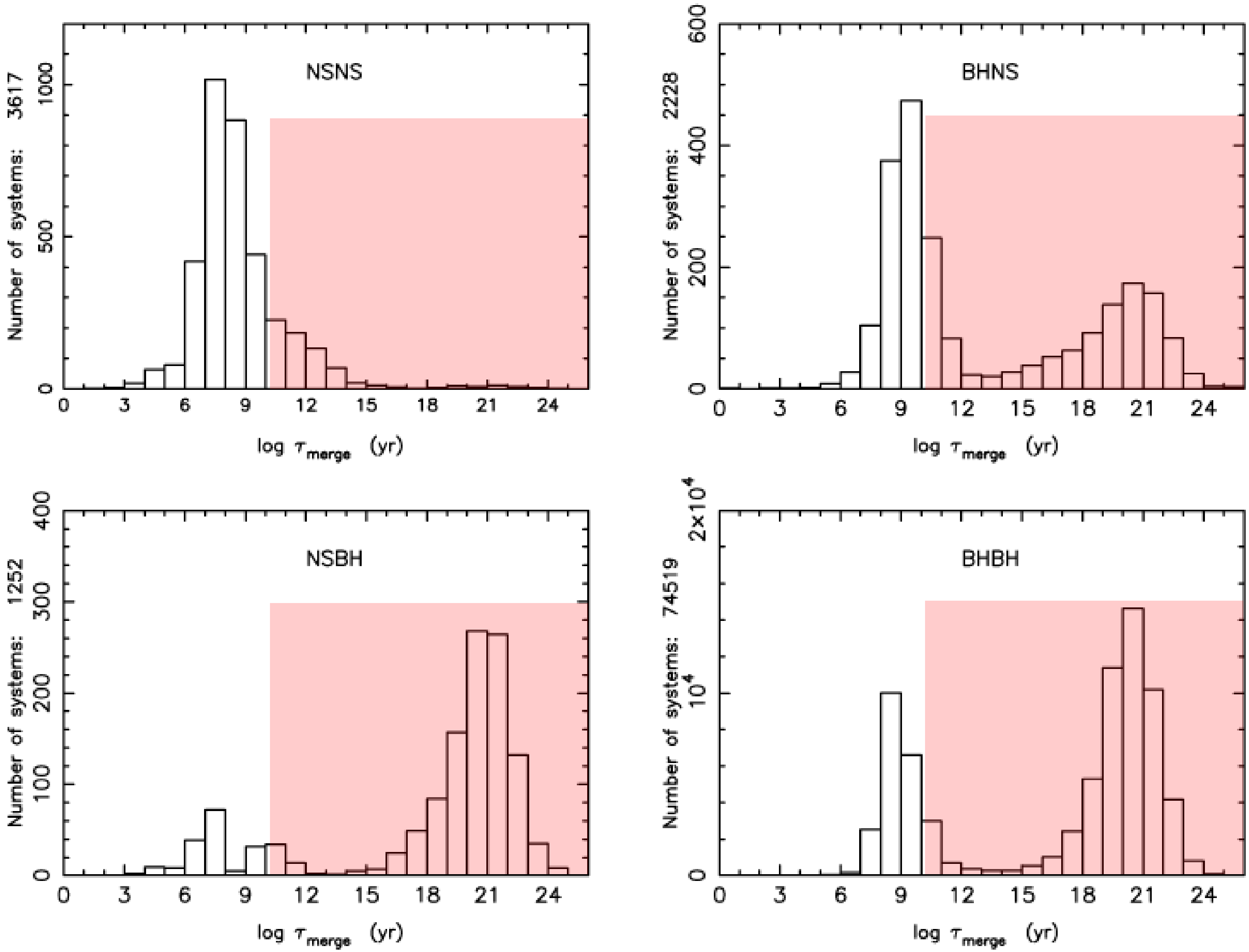
Once we know the aLIGO deterction rates we can constrain our binary stellar evolution models

Examples of simulations



Voss & Tauris (2003)

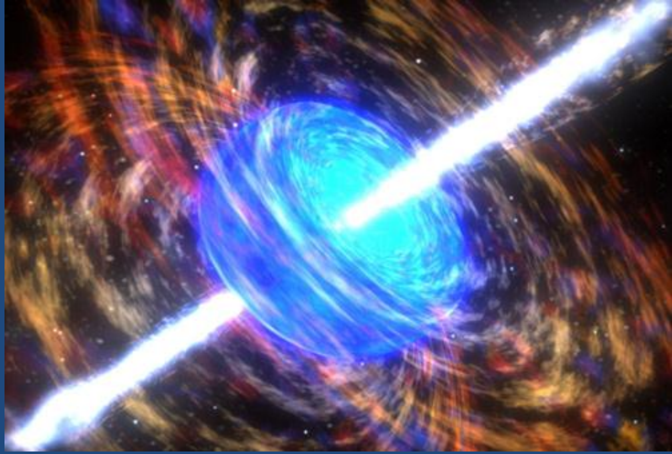
Tauris & van den Heuvel (2006)

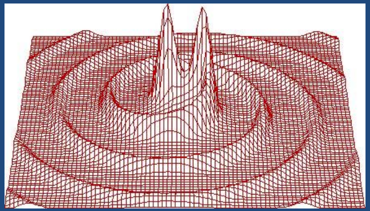


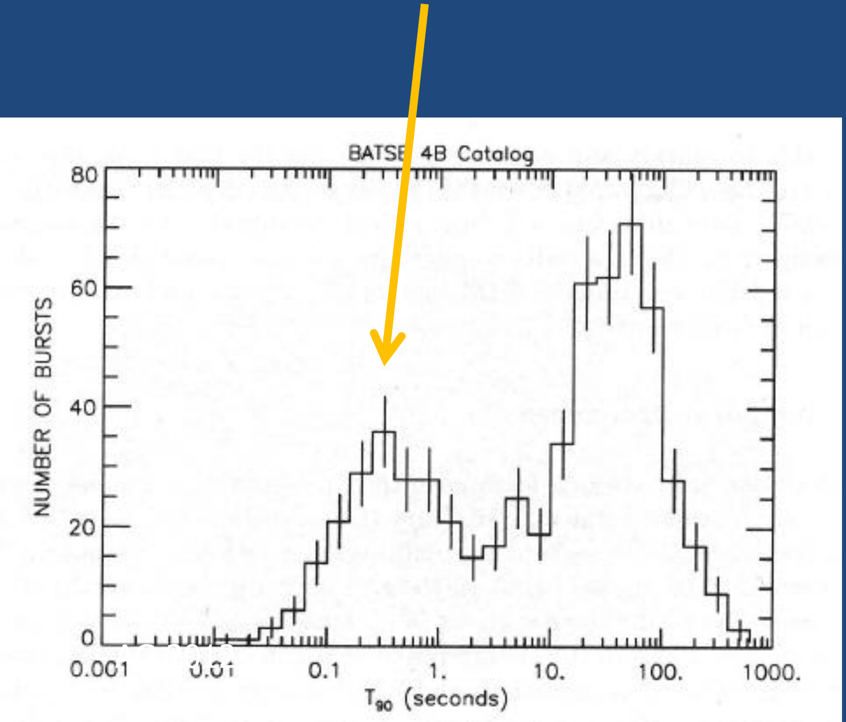
Voss & Tauris (2003)

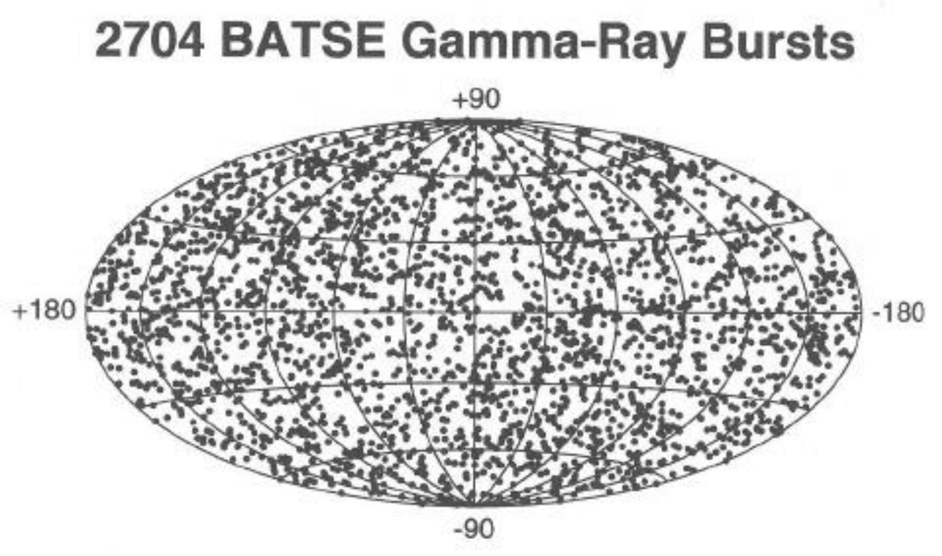
Collision of NSNS or NSBH

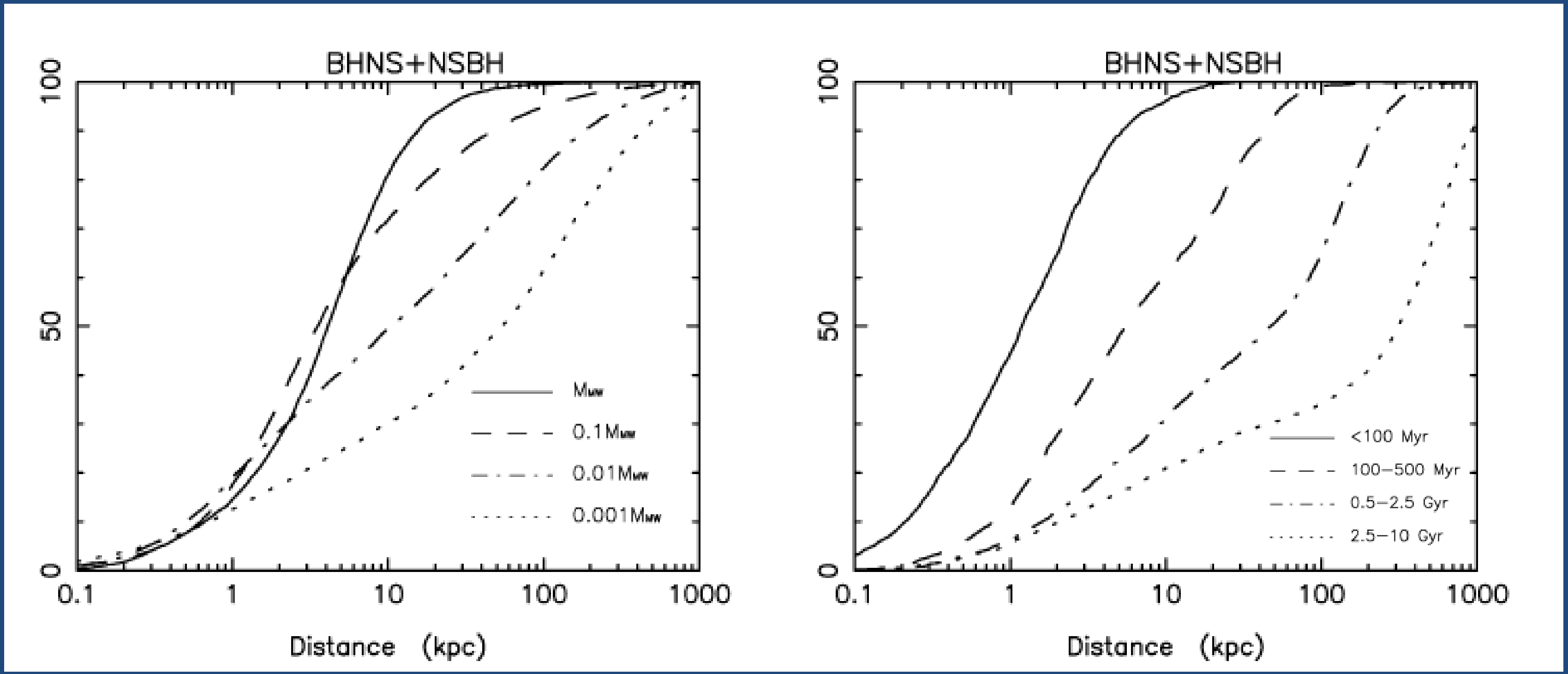
- origin of short GRBs? **(e.g. Nakar 2007)**



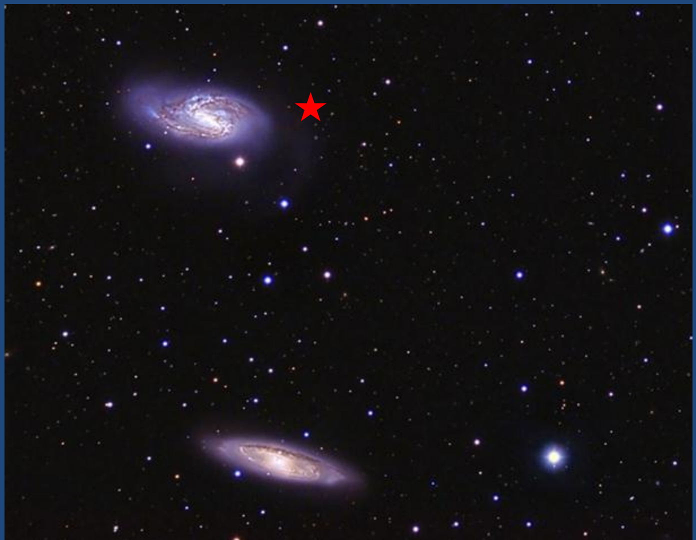








Voss & Tauris (2003)

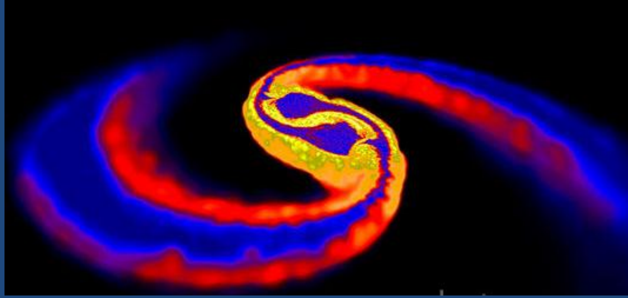


Hope for the next decade

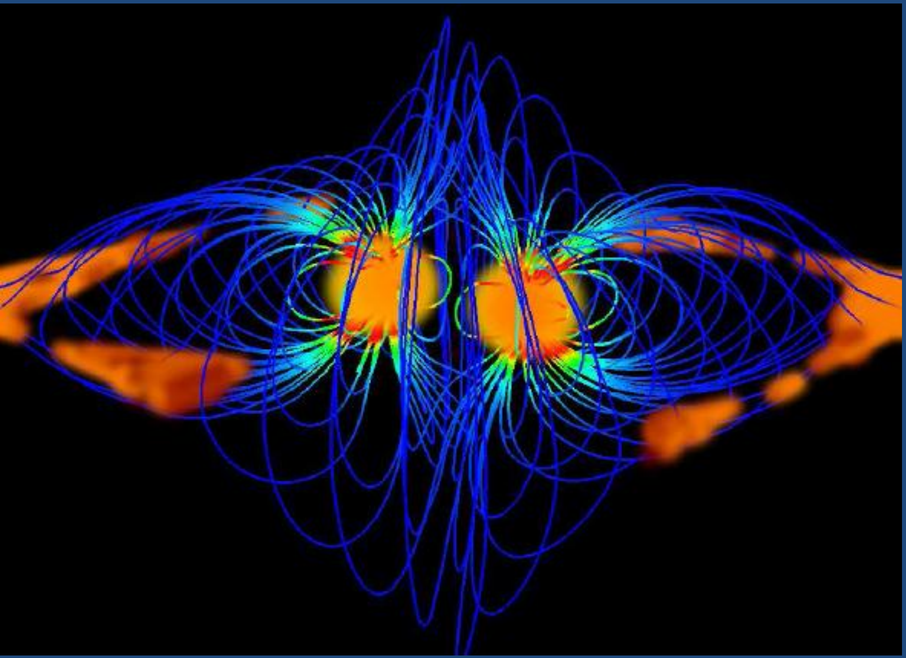
gravitational waves

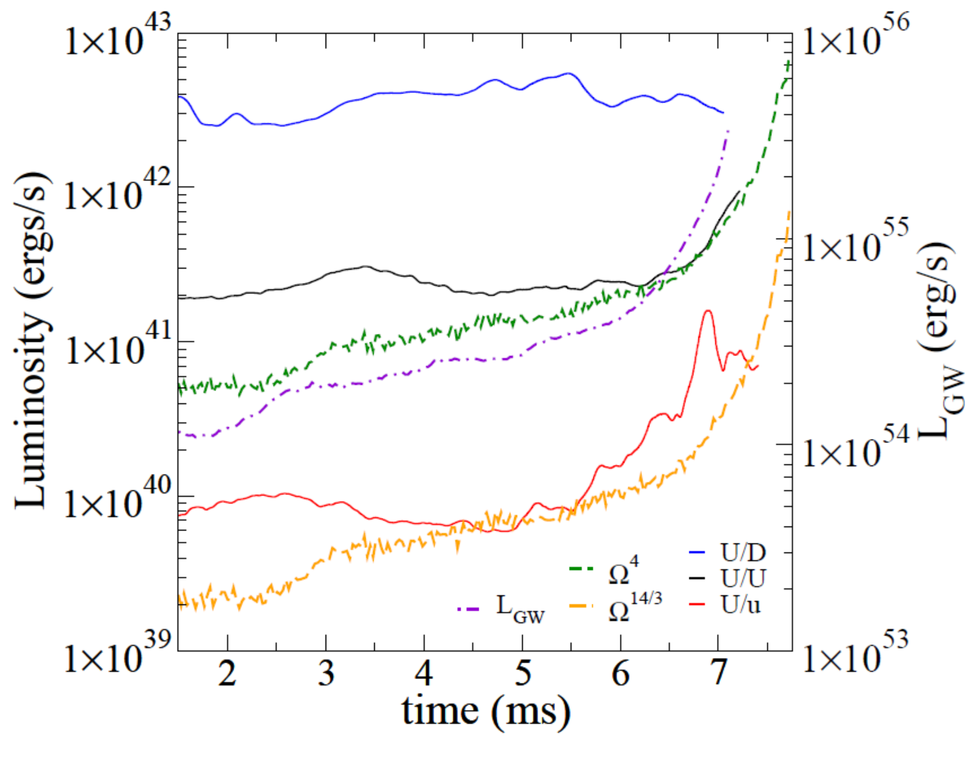
neutrinos

electromagnetic radiation



Detection of various signals from the same source!





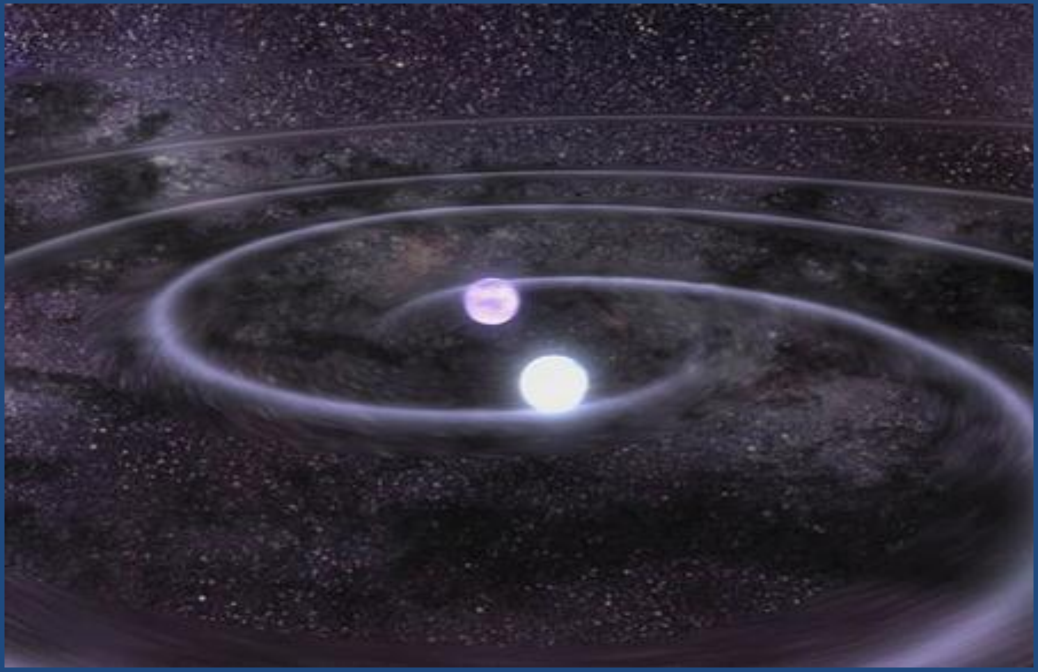
Palenzuele et al. (2013) gr-qc: 1301.7074

Conclusions

- Merger rates are sensitive to a number of key parameters
- Galactic merger rate of NSNS systems is ~10 Myr^{-1} (within a factor 10)
- aLIGO detection rate ~1 $week^{-1}$ (within a factor 10)

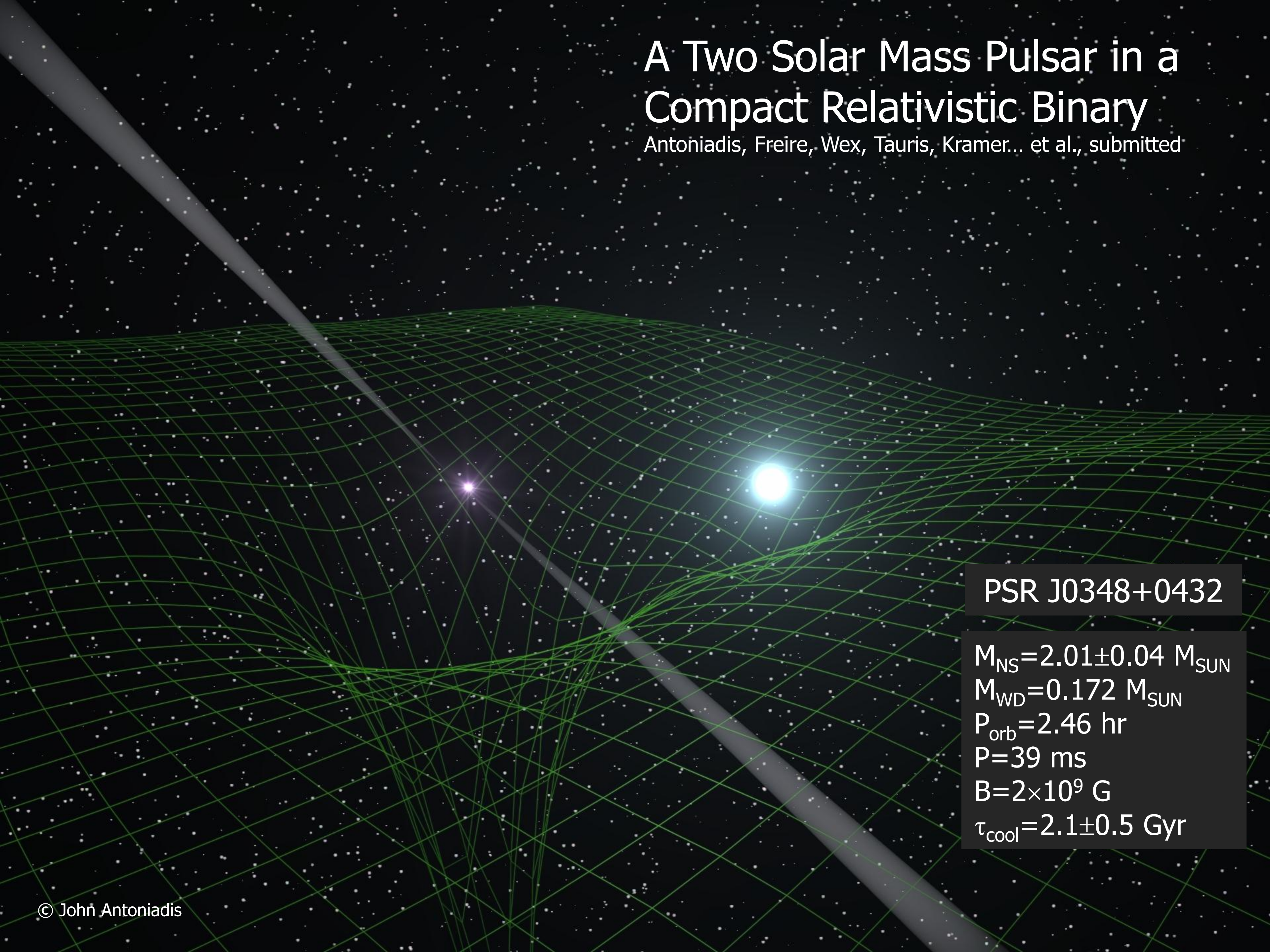
- Bonn initiative: a new population synthesis code with updated physics

- 2016: aLIGO detection rates $\rightarrow$ better understanding of binary evolution



A Two Solar Mass Pulsar in a Compact Relativistic Binary

Antoniadis, Freire, Wex, Tauris, Kramer… et al., submitted



PSR J0348+0432

M_{NS}=2.01±0.04 M_{SUN}
M_{WD}=0.172 M_{SUN}
P_{orb}=2.46 hr
P=39 ms
B=2×10^9 G
τ_{cool}=2.1±0.5 Gyr