Stochastic gravitational wave background from binary black holes

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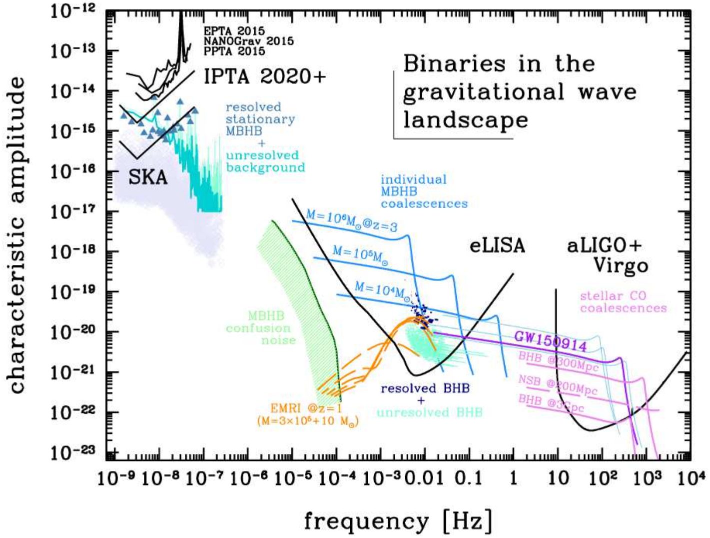
Keith Olive (U Minnesota)

MNRAS 461, 3877 [arXiv:1604.04288]
Phys. Rev. D 94, 103011 [arXiv:1607.06818]

IAP, 27 January 2017

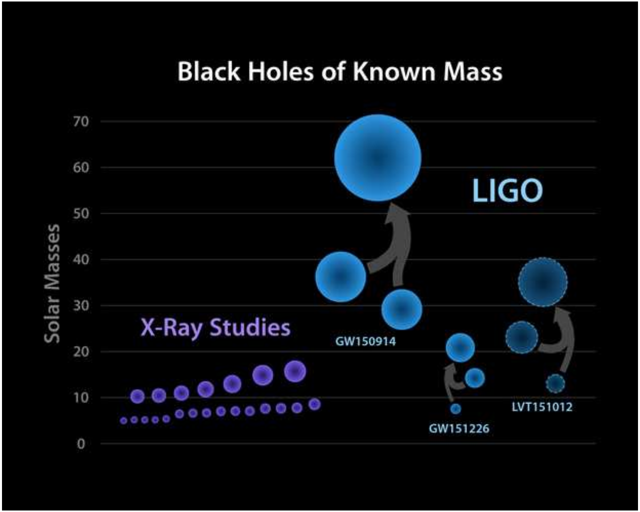
Institut d'astrophysique de Paris



Colpi & Sesana (2016)

Astrophysics with gravitational waves

S
Starting to measure the BH mass distribution (LIGO/VIRGO Collaborations [1606.04856])



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- Core collapse SN/direct collapse to a BH
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Core collapse: islands of 'explodability'?

The goal: $M_{BH} = f(M_{initial}, Z, ?)$

Ugliano et al. (2012)

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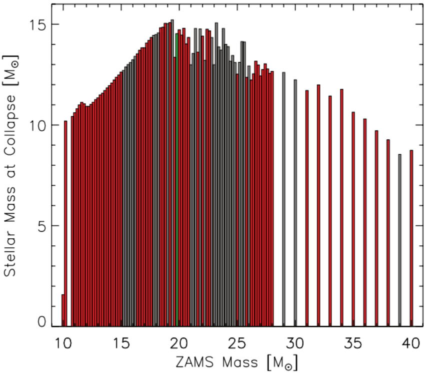
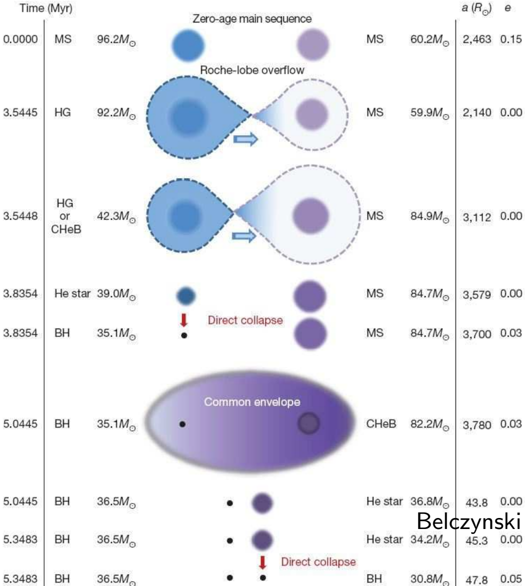


Ugliano et al. (2012)

Common envelope evolution

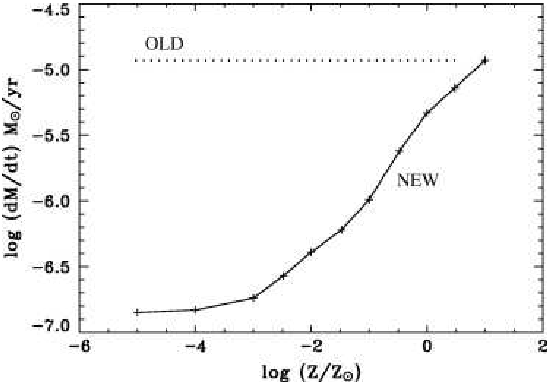


Belczynski et al. (2016)

Isolated evolution of massive stars, $M_{BH} = f(M_{initial}, Z)$

From massive stars to black holes

Mass prior to core collapse is determined by stellar winds



Vink (2008)

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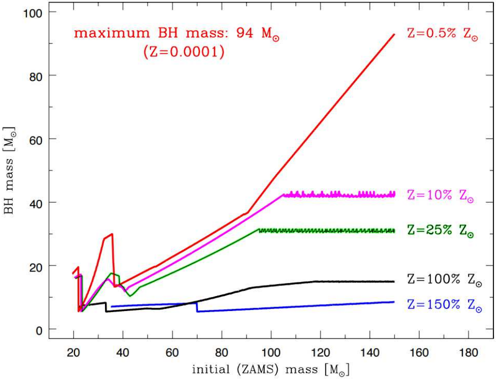
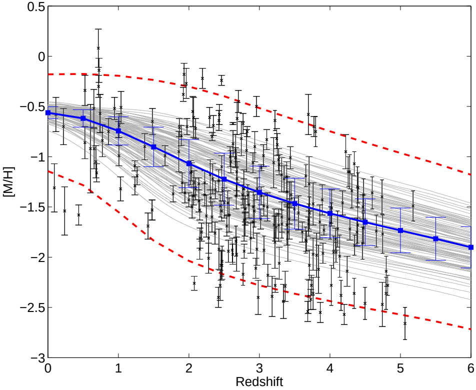


Belczynski et al. (2016)

Cosmic metallicity evolution

Damped Ly-α systems data from Rafelski et al. (2012)



Dvorkin et al. (2015)

Self-consistent model of BBH birth rate: overview

Daigne et al. (2004, 2006), Vangioni et al. (2015), Dvorkin et al. (2015)

Input

- Galaxy growth (inflow and outflow) prescriptions
- Cosmic star formation rate
- Stellar initial mass function
- Stellar yields
- Black hole mass as a function of initial stellar mass and metallicity

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Note: to get merger rate we need to assume time delay distribution

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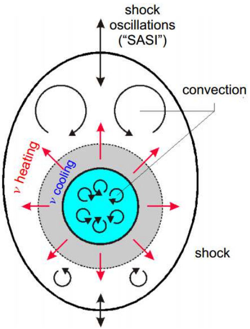
	Model name	Ref.	Parameters	Parameter values
BH masses	*WWp*	Woosley & Weaver (1995)	A, β, γ	$0.3, 0.8, 0.2$
	Fryer	Fryer et al. (2012)	-	-
	WWp+K	Kinugawa et al. (2014)	$Z_{\rm limit}/Z_{\odot}$	0.001 or 0.01
	Fryer+K			
SFR	*Fiducial*	Vangioni et al. (2015)	ν, z_m, a, b	$0.178, 2.00, 2.37, 1.8$
	PopIII			$0.002, 11.87, 13.8, 13.36$
	GRB-based			$0.146, 1.72, 2.8, 2.46$
IMF	*Fiducial*	Salpeter (1955)	x	2.35
	Steep IMF	Chabrier, Hennebelle & Charlot (2014)		2.7

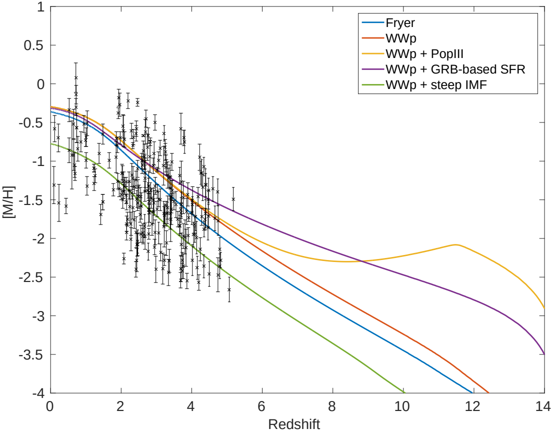
Dvorkin et al. [1604.04288]

Black hole mass as a function of stellar mass and metallicity

- Woosley & Weaver (1995): piston-driven explosion, assuming an explosion energy
- Fryer et al. (2012) : analytic model, assume time delay, calculate the explosion energy and fallback mass
- Kinugawa et al. (2014) : $M_{BH} = f(M_{core})$ from Herant et al. (1994); Belczynski et al. (2002)

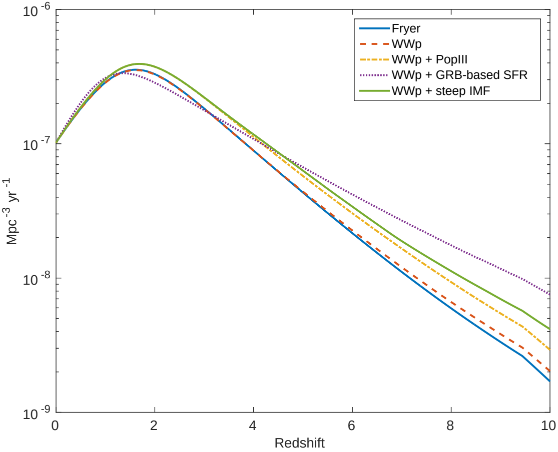


Metallicity



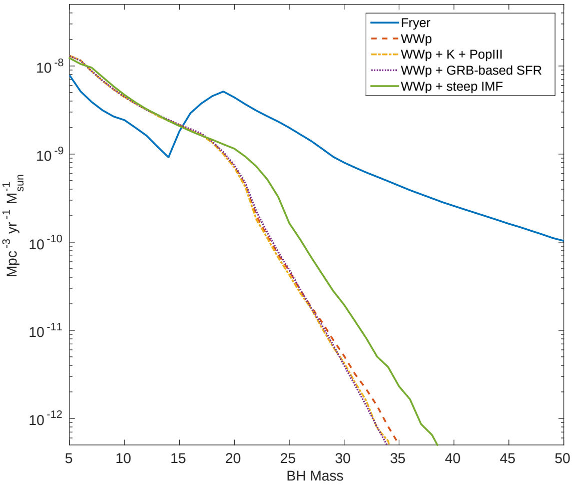
Total merger rates

Normalized to the observed merger rate: $R = 10^{-7}$ Mpc^{-3} yr^{-1}



Merger rates vs. mass

Normalized to the observed merger rate: $R = 10^{-7}$ Mpc^{-3} yr^{-1}



Stochastic gravitational wave background

- The background due to unresolved mergers of binary BHs

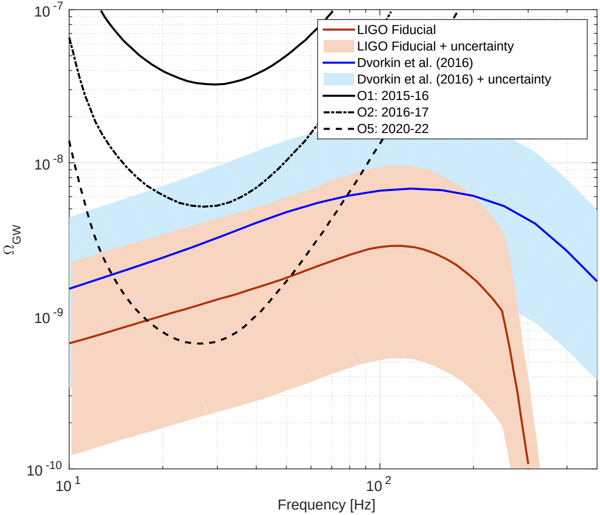
Stochastic gravitational wave background

- The background due to unresolved mergers of binary BHs
- Dimensionless density parameter (energy density in units of ρ_c per unit logarithmic frequency)

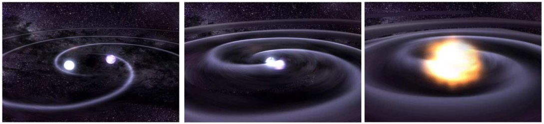
$$\Omega_{\rm gw}(f_o) = \frac{8\pi G}{3c^2 H_0^3} f_o \int dm_{bh} \int dz \frac{R_{\rm source}(z, m_{bh})}{(1+z)E_V(z)} \frac{dE_{\rm gw}(m_{bh})}{df}$$

$R_{\rm source}(z, m_{bh})$ is the merger rate, dE_{gw}/df is the emitted spectrum

Stochastic gravitational wave background



BH binaries number density (simple case)



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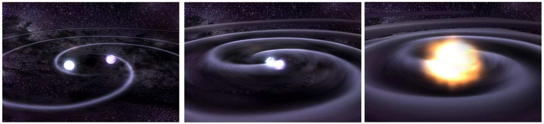

If all BH are in binaries, and all merger products remain single, the number density n_X of binaries in a certain mass M and orbital parameters bin is set by: [where $\mathbf{w} = (a, e)$]

- The formation rate of BH (determined from stellar physics) $R_X(M, t)$
- The initial distribution of orbital parameters $\mathcal{P}_X(\boldsymbol{w})$
- The evolution in time of the orbital parameters of the binary $\mathrm{d}\boldsymbol{w}/\mathrm{d}t$

Evolution of the orbital parameters

General case ($\mathbf{w} = (a, e)$):

$$\frac{\mathrm{d}\boldsymbol{w}}{\mathrm{d}t} = \boldsymbol{f}(\boldsymbol{w}, M)$$

A merger occurs when $\boldsymbol{w} = \boldsymbol{w}_{\mathrm{merger}}$

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Example: evolution due to emission of GW [Peters & Mathews (1963)]

$$\frac{\mathrm{d}a}{\mathrm{d}t} = -\frac{64}{5}\frac{G^3\mu m^2}{c^5 a^3}\frac{\left(1 + \frac{73}{24}e^2 + \frac{37}{96}e^4\right)}{(1-e^2)^{7/2}}$$

$$\frac{\mathrm{d}e}{\mathrm{d}t} = -\frac{304}{15}\frac{G^3\mu m^2}{c^5 a^4}\frac{e\left(1 + \frac{121}{304}e^2\right)}{(1-e^2)^{5/2}}$$

Continuity equation

Hydrodynamics (matter density ρ, coordinate x, velocity $u = \mathrm{d}x/\mathrm{d}t$):

$$\frac{\mathrm{d}\rho}{\mathrm{d}t} + \frac{\mathrm{d}}{\mathrm{d}\boldsymbol{x}}.[\rho \boldsymbol{u}] = 0$$

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Binaries (number density n_X, coordinate $\boldsymbol{w}$, velocity $\boldsymbol{f} = \mathrm{d}\boldsymbol{w}/\mathrm{d}t$):

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Assuming $\partial/\partial t = 0$ (stationary distribution of binaries in the galaxy) $\longrightarrow$ stochastic GW emission from coalescing binary NS

Buitrago, Moreno-Garrido & Mediavilla (1994); Moreno-Garrido, Mediavilla & Buitrago (1995); Ignatiev et al. (2001)

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$$\frac{\mathrm{d}n_X}{\mathrm{d}t} + \frac{\mathrm{d}}{\mathrm{d}\boldsymbol{w}}.[n_X \boldsymbol{f}] = R_X$$

No stationarity

Source function R_X is given by astrophysics

Continuity equation (single population)

$$\frac{\mathrm{d}\boldsymbol{w}}{\mathrm{d}t} = \boldsymbol{f}(\boldsymbol{w}, M)$$

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$$\frac{\mathrm{d}\boldsymbol{w}}{\mathrm{d}t} = \boldsymbol{f}(\boldsymbol{w}, M)$$

$$\frac{\mathrm{d}n_X^{(1)}(M, t)}{\mathrm{d}t} = S\left(M', M', t\right)$$

Continuity equation (single population)

$$
\begin{aligned}
\frac{\mathrm{d}\boldsymbol{w}}{\mathrm{d}t} &= \boldsymbol{f}(\boldsymbol{w}, M) \\
\frac{\mathrm{d}n_X^{(1)}(M,t)}{\mathrm{d}t} &= S\left(M', M', t\right) \\
\frac{\mathrm{d}n_X^{(2)}(M,M,\boldsymbol{w},t)}{\mathrm{d}t} &= \frac{1}{2} R_X(M,t)\mathcal{P}_X(\boldsymbol{w}) \\
&- \frac{\partial}{\partial \boldsymbol{w}}.\left[\boldsymbol{f}\left(\boldsymbol{w}, M\right) n_X^{(2)}\left(M, M, \boldsymbol{w}, t\right)\right]
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\end{aligned}
$$

S is source term due to mergers

All the merger products remain single, all objects are born in binaries

Initial distribution of orbital parameters

Sana et al. (2012); de Mink & Belczynski (2015)

Joint distribution: $\mathcal{P}_X(\boldsymbol{w}) = P(e)P(a)$

- $P(e) \propto e^{-0.42}$
- $P(\log T) \propto (\log T)^{-0.5}$ in $T \in (T_{min}, T_{max})$

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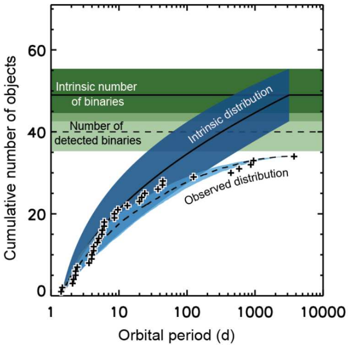
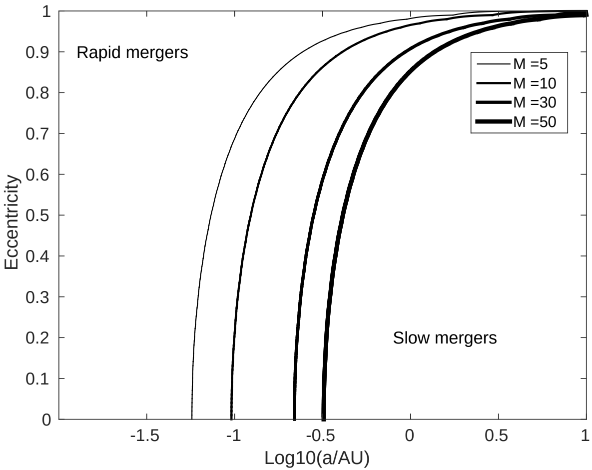


Time to coalescence

a_{min} chosen so as to fit the observed merger rate ($\tau_{merger} \propto a^4$)



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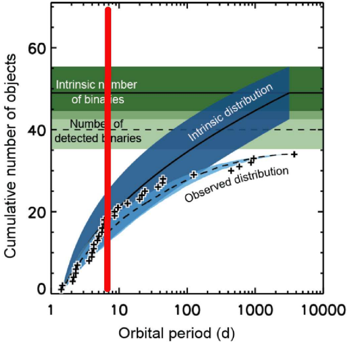
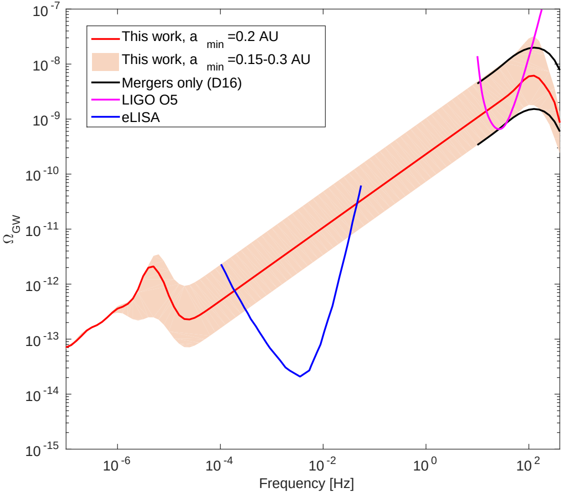


GW background from BH binaries

Dvorkin et al. [1607.06818]



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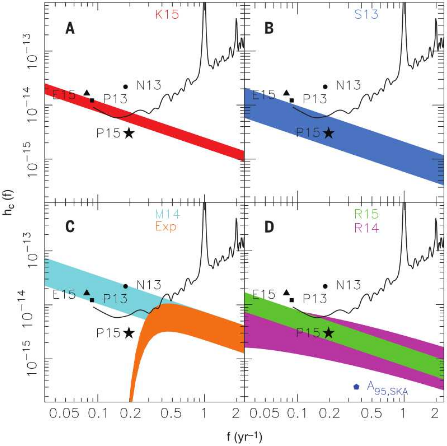
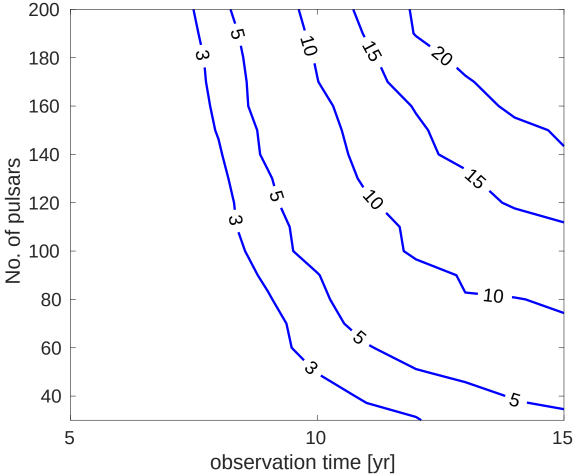
Shannon et al. 2016



Estimated SNR with SKA

Assuming timing accuracy of 30 ns [PRELIMINARY RESULTS!!!]



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  - Properties of compact binary systems
- ... and galaxy-MBH co-evolution:
  - Formation of MBH binaries
  - Binary evolution, merger rates
- More detections to come soon: need tools to analyze them and extract astrophysical information