GWDAW-14
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Stochastic backgrounds of GWs from extragalactic sources

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Why stochastic backgrounds from extragalactic sources?

Foreground noise for GW signals emitted in the primordial Universe

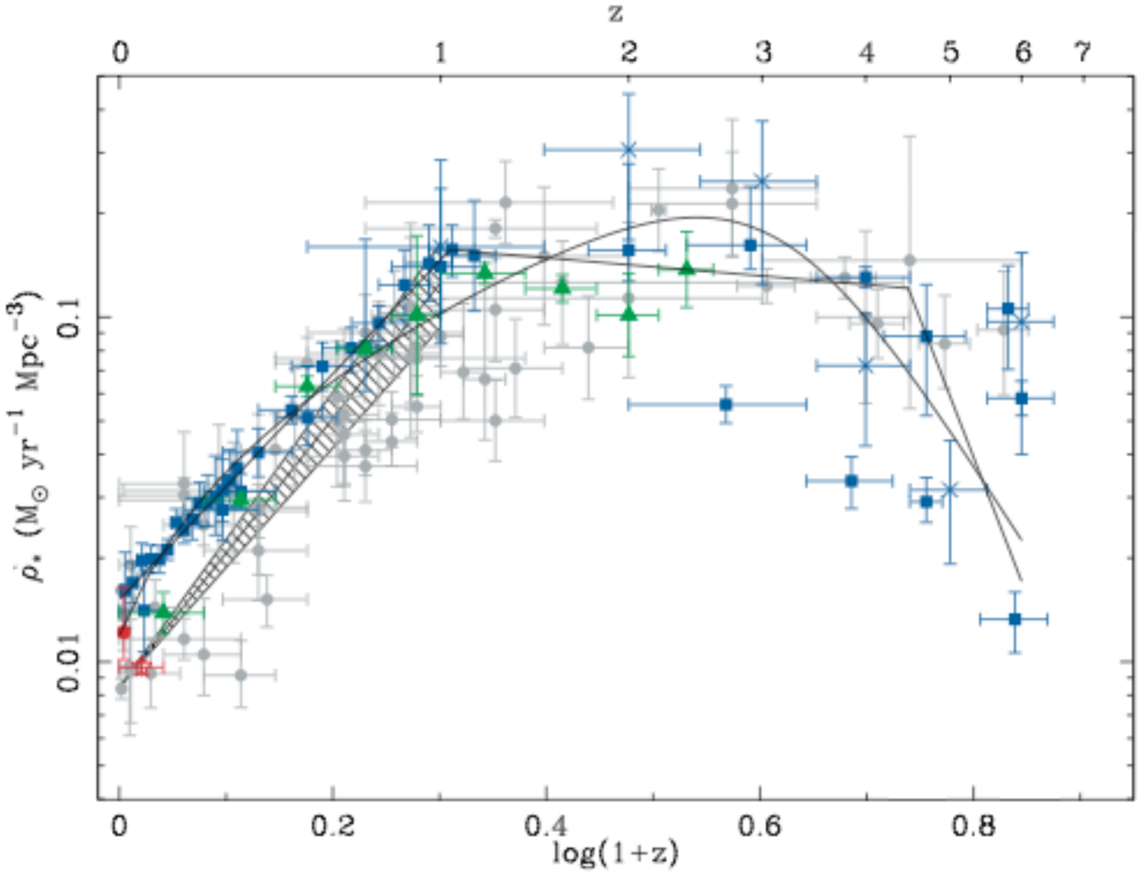
Cumulative emission of different sources at early cosmic times

→ Insights on GW sources

→ Constraints on distant stellar populations

Cosmic star formation history: the observational view

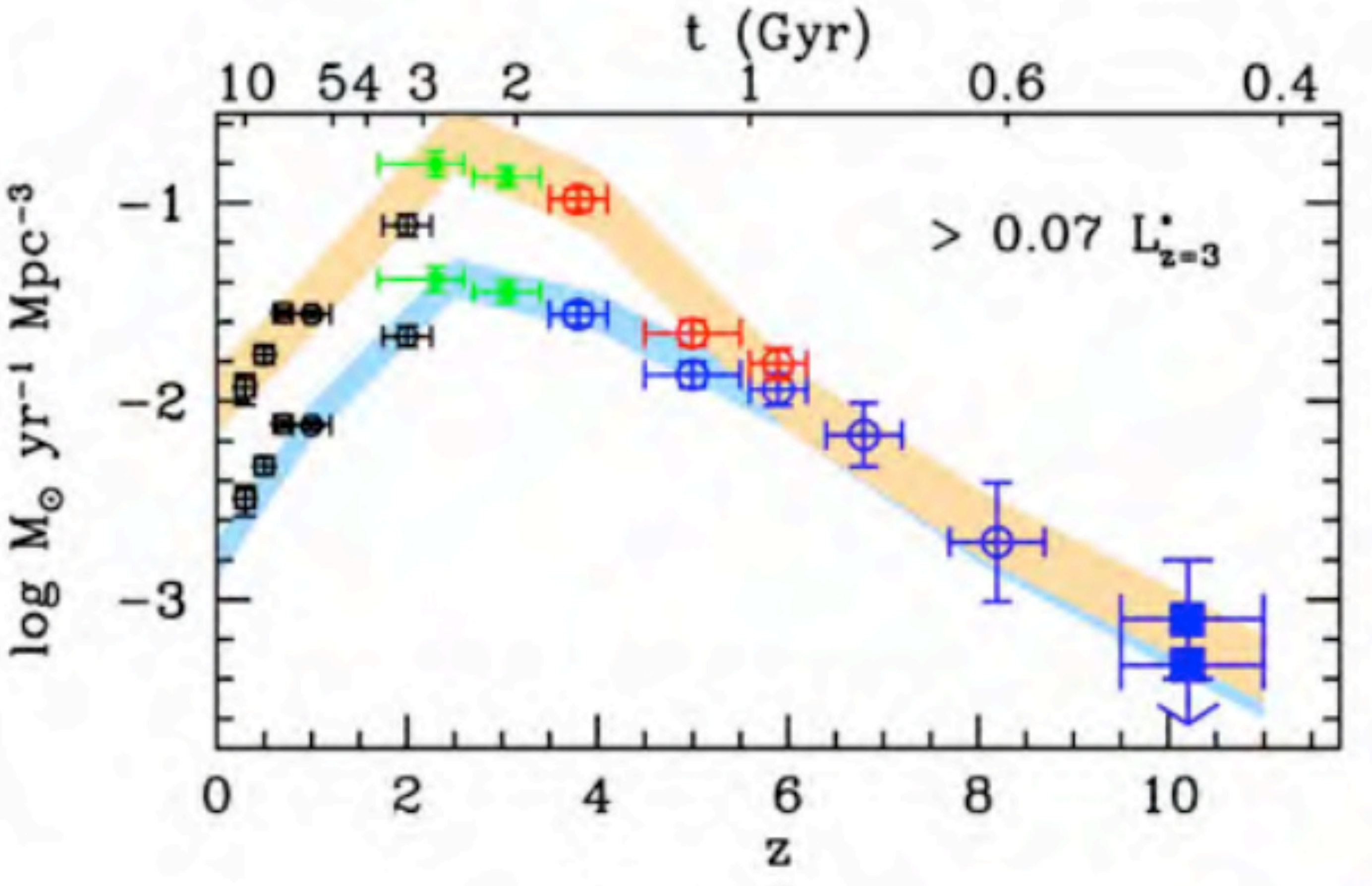
Recent collection of observations by Hopkins & Beacom (2006)



Cosmic star formation history: the observational view

Hubble Ultra-Deep WFC3 observations: star formation density out to z = 10!

Bouwens et al. (2010)



GWs from stellar remnants

- core collapse supernovae

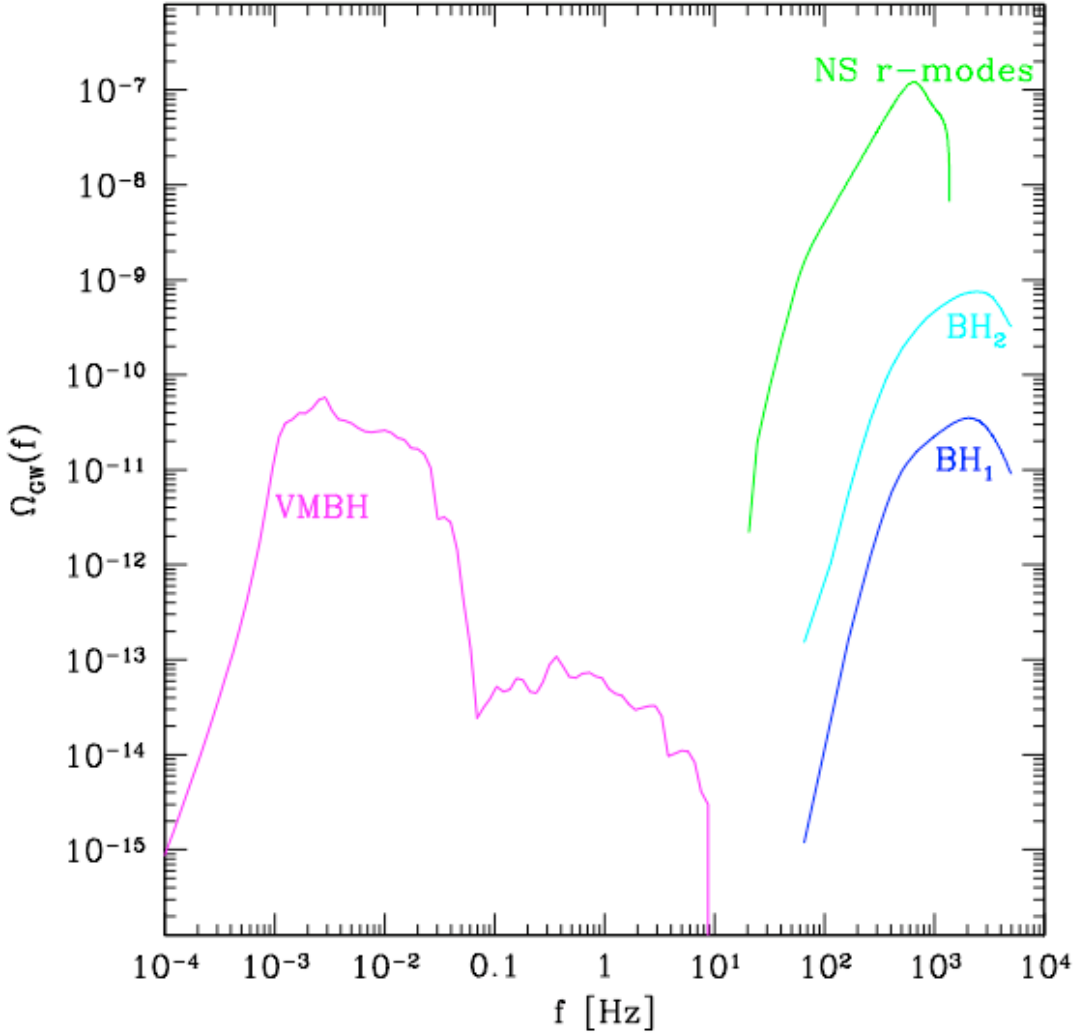
  $m_{star} > 20\ M_{sun}$ → collapse to BH (Stark & Piran 1985-1986)

  $8\ M_{sun} < m_{star} < 20\ M_{sun}$ → NS r-modes instability (Andersson 1998; Owen et al. 1998)

- collapse to VMBHs of very massive stars

- GWs from inspiraling compact binaries

Stochastic backgrounds: early predictions



Ferrari, Matarrese, RS (1999a)

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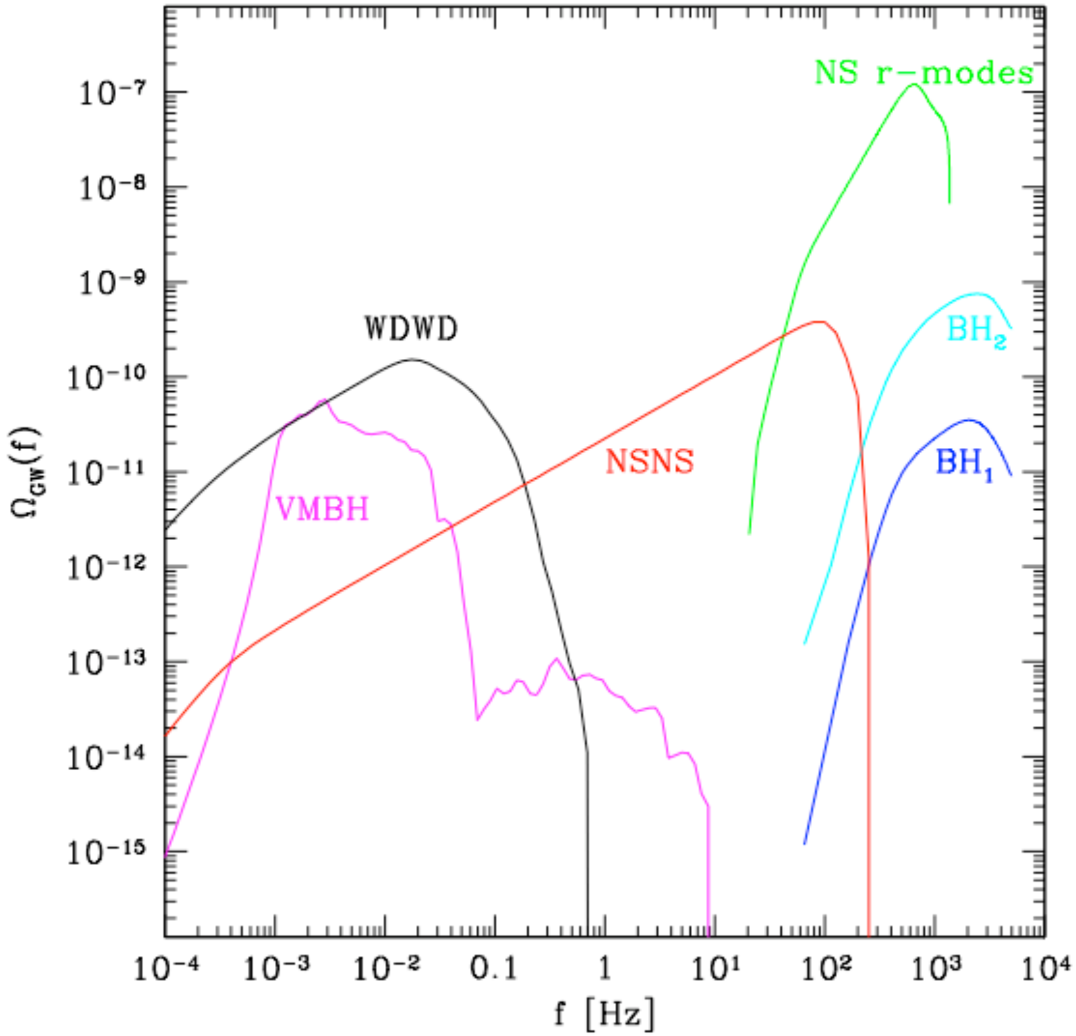
RS, Ferrara, Ciardi, Ferrari, Matarrese (2000)

Stochastic backgrounds: early predictions



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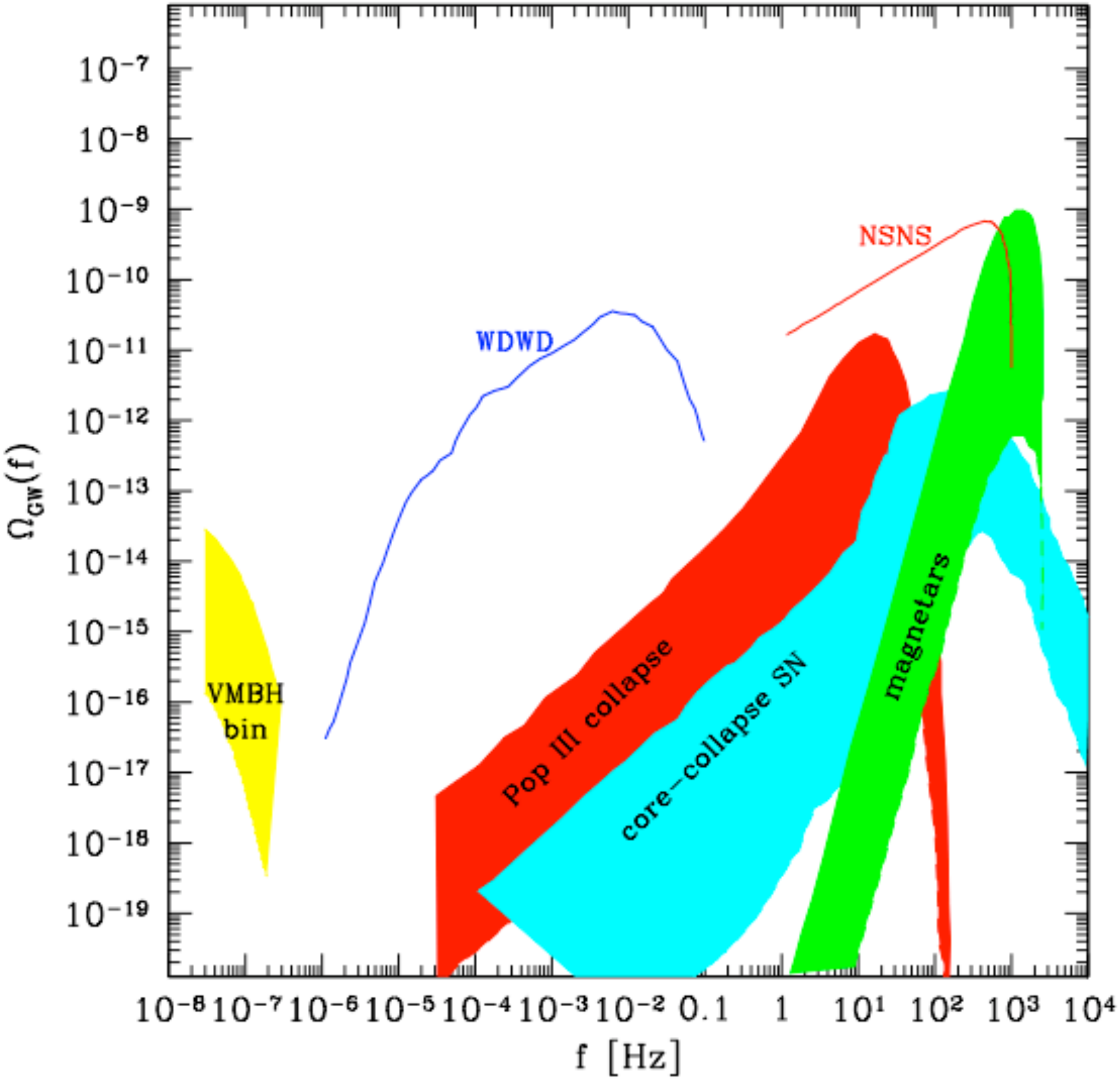
RS, Ferrara, Ciardi, Ferrari, Matarrese (2000)

RS, Ferrari, Matarrese, Portegies Zwart (2001)

Stochastic backgrounds: additional studies



Buonanno et al. (2005)

Farmer & Phinney (2003)

Regimbau & de Freitas Pacheco (2006)

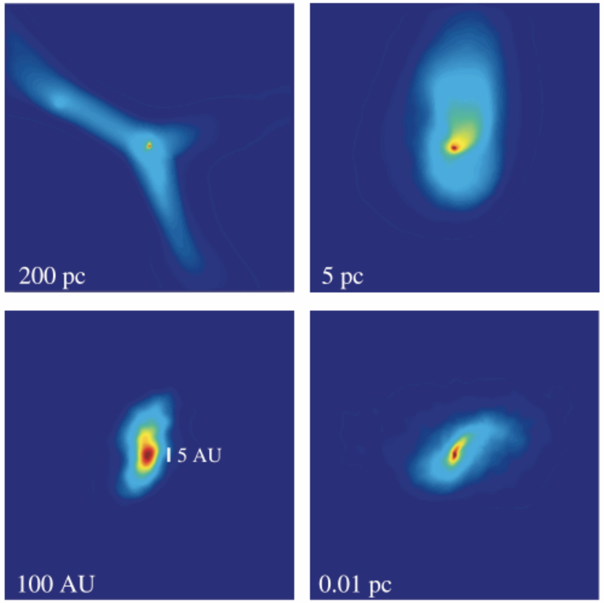
Regimbau & Chauvineau (2007)

Sandick et al. (2006)

Sesana, Vecchio & Colacino (2008)

Formation of Pop III/Pop II stars

Population III stars: form at $z = 20 - 30$ in the dark matter mini-halos ($10^6 M_{sun}$)



Yoshida et al. 2006

$30\ M_{sun} < M_{ch,star} < 100\text{-}300\ M_{sun}$

Abel et al. (2000-2002); Bromm et al. (2001); Yoshida et al. (2006); O'Shea & Norman (2007); Gao et al. (2007); Turk et al. (2008); Tan & McKee (2003-2005)

Population II/I stars:

$M_{ch,star} \approx 1\ M_{sun}$ Salpeter initial mass function $0.1\ M_{sun} < M_{star} < 100\ M_{sun}$

Pop III/Pop II transition is controlled by metal/dust enrichment

$10^{-6}\ Z_{sun} < Z_{cr} < 10^{-4}\ Z_{sun}$

Bromm et al. (2001); RS et al. (2002, 2003, 2006); Bromm & Loeb (2003); Santoro & Shull (2006); Omukai et al. (2005); Tsuribe & Omukai (2006); Clark et al. (2008); RS & Omukai (2009)

numerical simulations

Tornatore, Ferrara & RS (2007)

GADGET-2 (Springel et al 2005)

Improved treatment of chemical enrichment (Tornatore et al 2007)

Metallicity-dependent stellar IMF

- $Z > Z_{cr}$ Salpeter IMF $0.1 < M/M_{sun} < 100$
  $y = y(Z)$ $\varepsilon = 3.4\ 10^{15}$ erg/gr
  Woosley & Weaver 1995
- $Z < Z_{cr}$ Salpeter IMF $100 < M/M_{sun} < 500$
  $y = 0.183$ $\varepsilon = 3.5\ 10^{16}$ erg/gr
  Heger & Woosley 2002

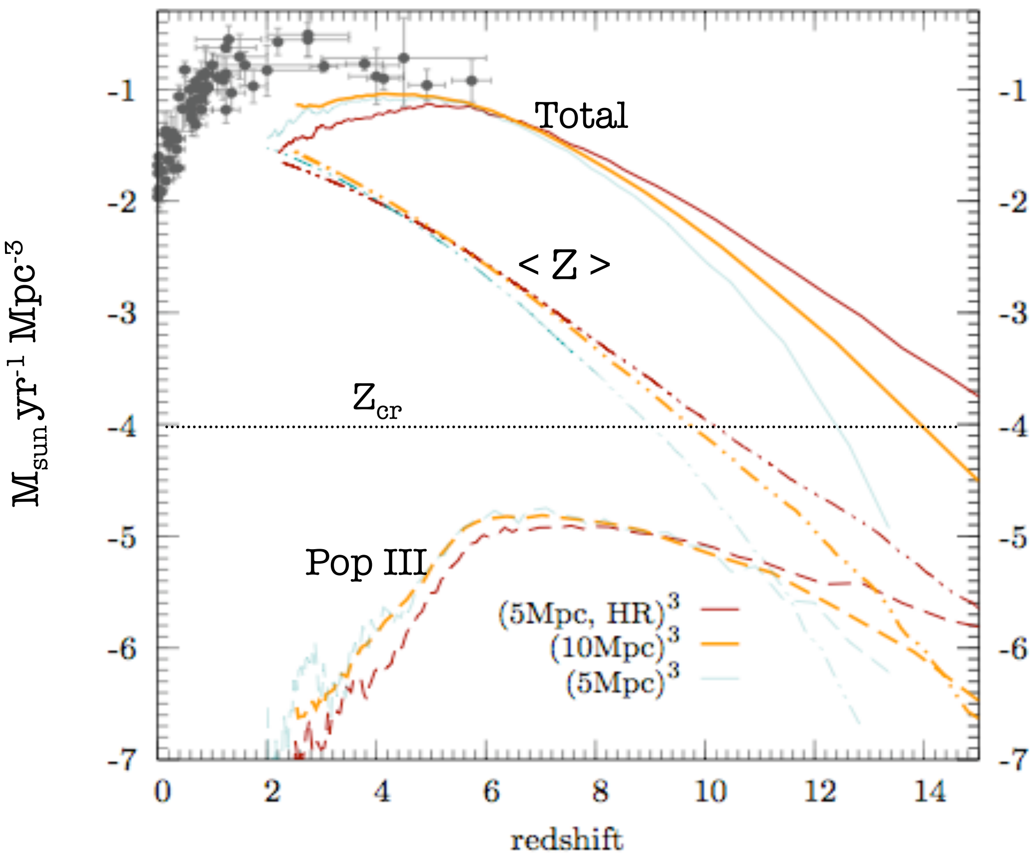
$Z_{cr} = 10^{-4}\ Z_{sun}$

$L_{box} = 10h^{-1}$ Mpc $N_p = 2 \times 256^3$ $M_p = 3.6\ 10^6\ h^{-1}\ M_{sun}$

ΛCDM model $\Omega_m = 0.24$ $\Omega_\Lambda = 0.76$ $\Omega_b = 0.041$ $h = 0.73$ $n = 1$ $\sigma_8 = 0.8$

2 additional runs: $L_{box} = 5\ h^{-1}$ Mpc $N_p = 2\mathrm{x}256^3$ $M_p = 4.5\ 10^5\ h^{-1}\ M_{sun}$
$5\ h^{-1}$ Mpc $N_p = 2\mathrm{x}128^3$ $M_p = 3.6\ 10^6\ h^{-1}\ M_{sun}$

star formation history



$F_{b,III}$ = 2 10^{-6}

- Pop III stars continue to form well beyond the epoch at which <Z> > Z_{cr}
- Pop II stars are always the dominant SF mode: 1% of the stars at z=14 are Pop III
- Additional suppression of Pop III stars is caused by the IGM photo-heating due to reionization $z_{rei} \approx 7$

Single source GW emission

- ✔ Pop II stars $8\ M_{sun} < m_{star} < 20\ M_{sun}$

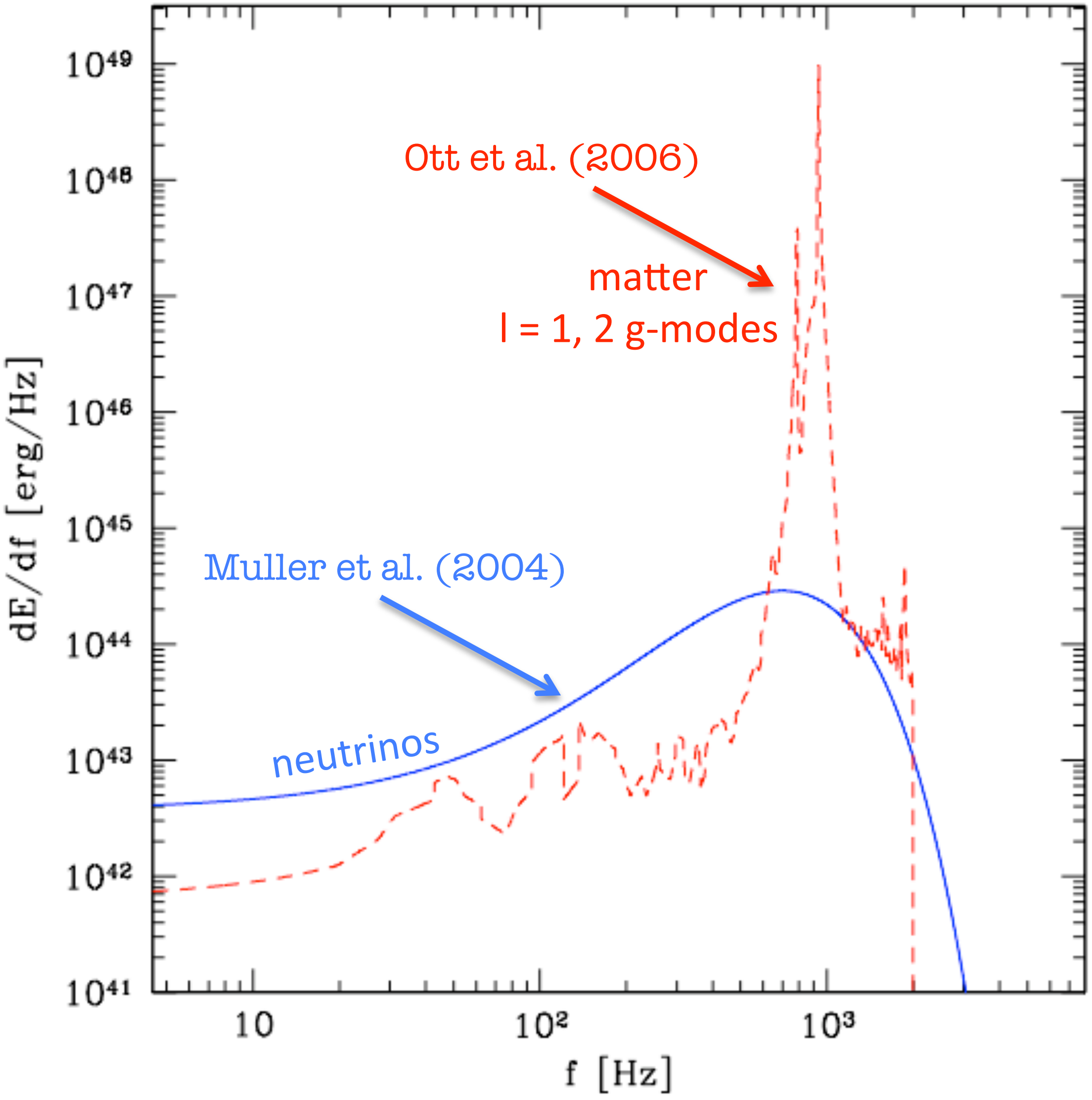
Core collapse SN leading to NS remnant $E_{GW} \approx 1.8 \times 10^{-8}\ M_{sun}\ c^2$ (Muller et al. 2004)

Oscillations of proto-neutron star: g-modes emission

$$E_{GW} \approx \begin{cases} 1.4 \times 10^{-8}\ M_{sun}\ c^2 \ \text{for a } 15\ M_{sun} \text{ progenitor} \\ 8.2 \times 10^{-5}\ M_{sun}\ c^2 \ \text{for a } 25\ M_{sun} \text{ progenitor} \end{cases}$$

(Ott et al. 2006)

NS collapse of Pop II stars



Ott et al. (2006)

matter
l = 1, 2 g-modes

Muller et al. (2004)

neutrinos

Single source GW emission

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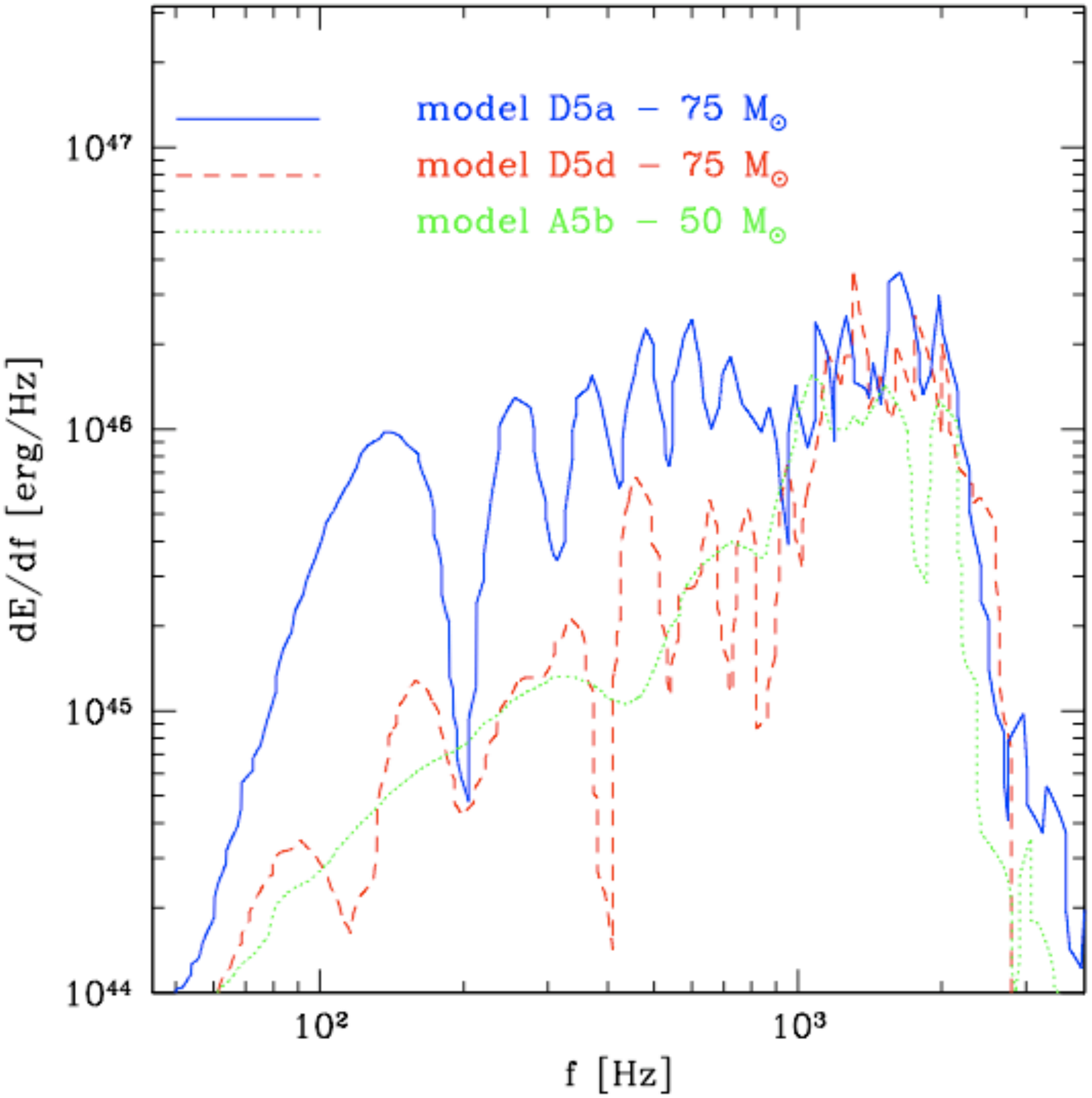
- ✓ Pop II stars $20\ M_{sun} < m_{star} < 100\ M_{sun}$

  Prompt/delayed BH formation of rotating massive cores

  $E_{GW} \approx 2 - 3 \times 10^{-7} M_{sun} c^2$ for 50 – 75 M_{sun} progenitors (Sekiguchi & Shibata 2005)

BH collapse of Pop II stars



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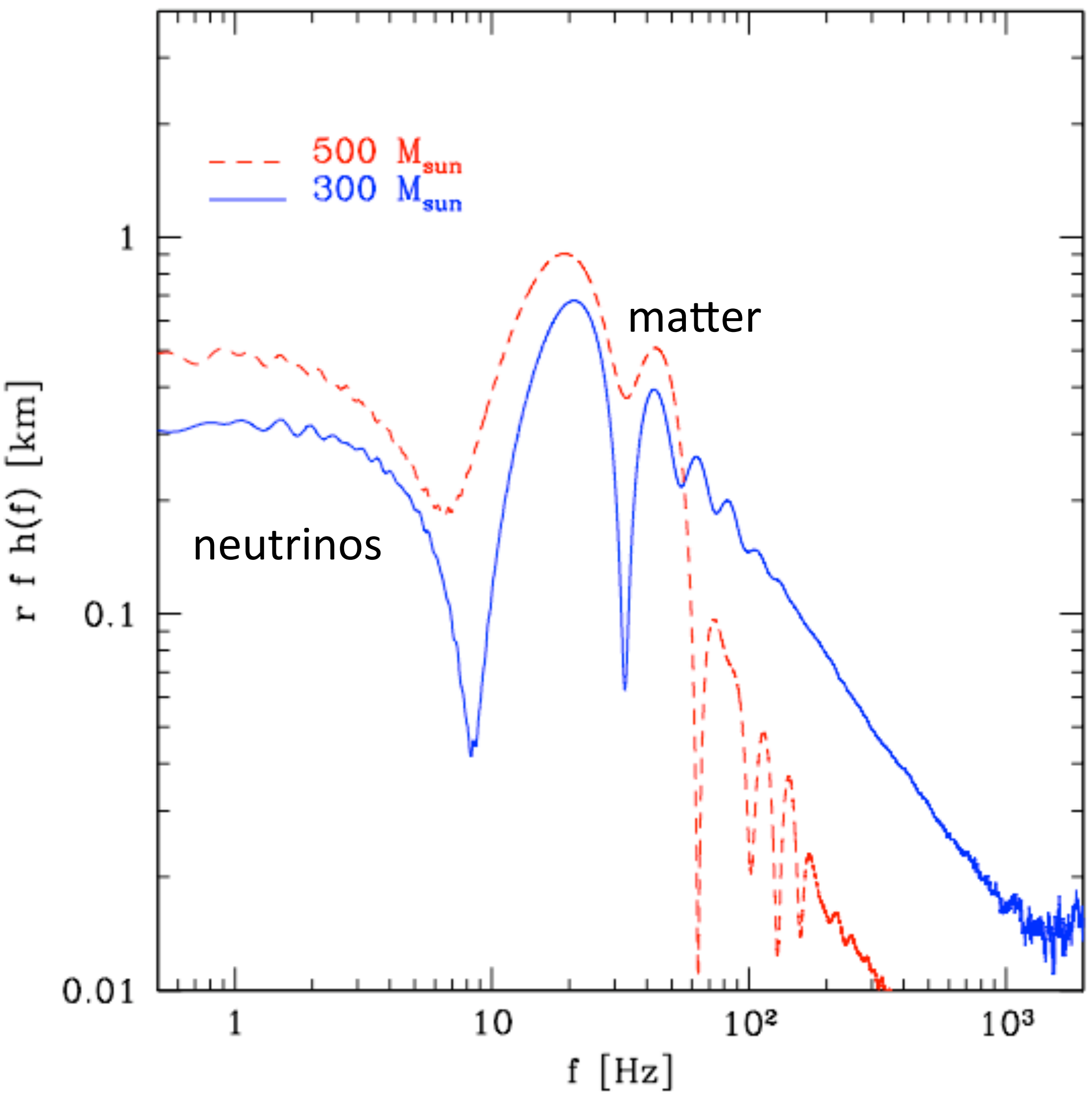
✓ Pop III stars $100\ M_{sun} < m_{star} < 140\ M_{sun}$ and $260\ M_{sun} < m_{star} < 500\ M_{sun}$

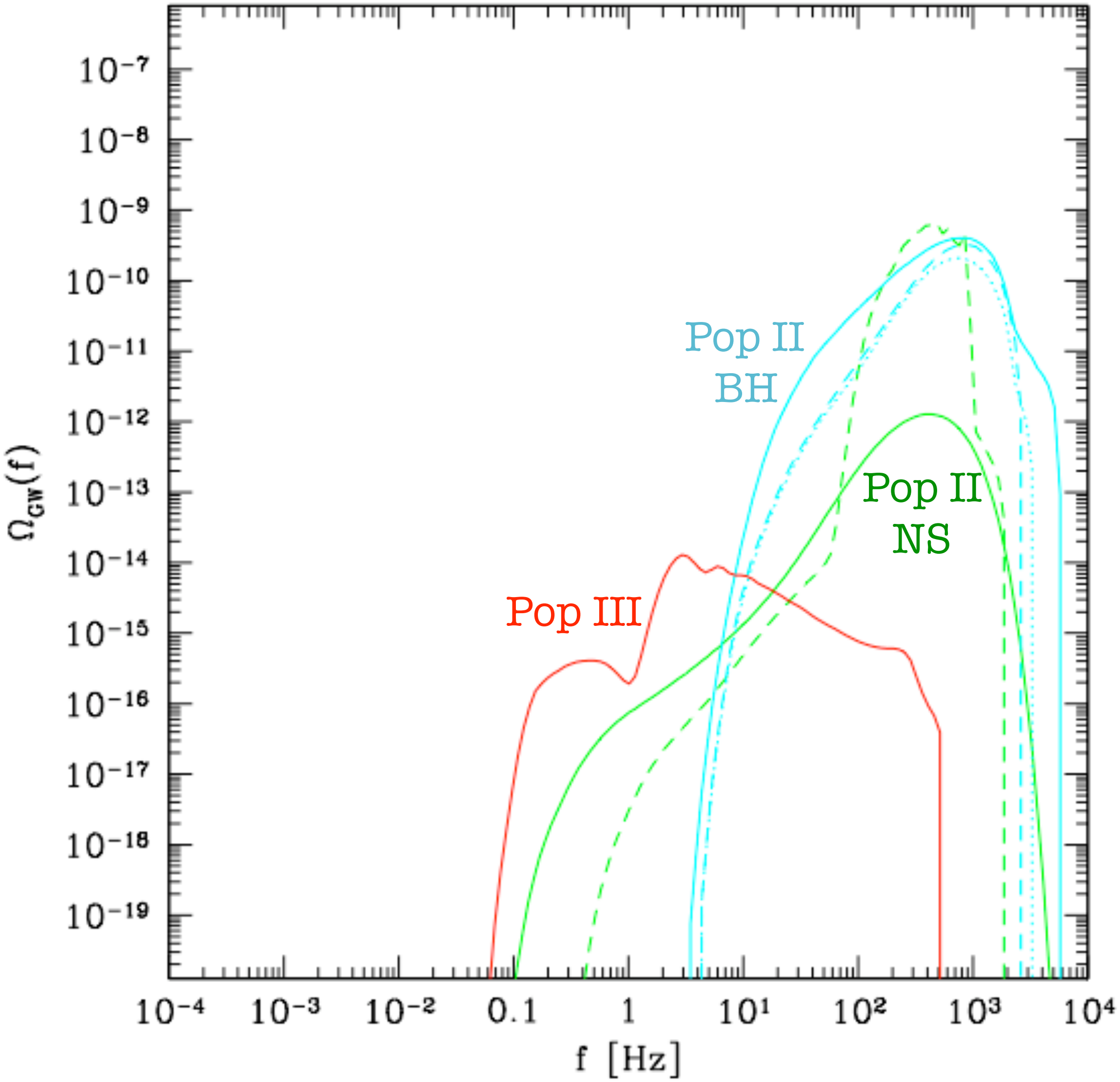
Collapse to BHs of comparable mass (no mass loss at $Z = 0$):

$$E_{GW} \approx \begin{cases} 2 \times 10^{-3}\ M_{sun}\ c^2 & \text{Fryer et al. (2001)} \\ 2 \times 10^{-4}\ M_{sun}\ c^2 & \text{Suwa et al. (2007)} \end{cases}$$

BH collapse of Pop III stars – Suwa et al. (2007)



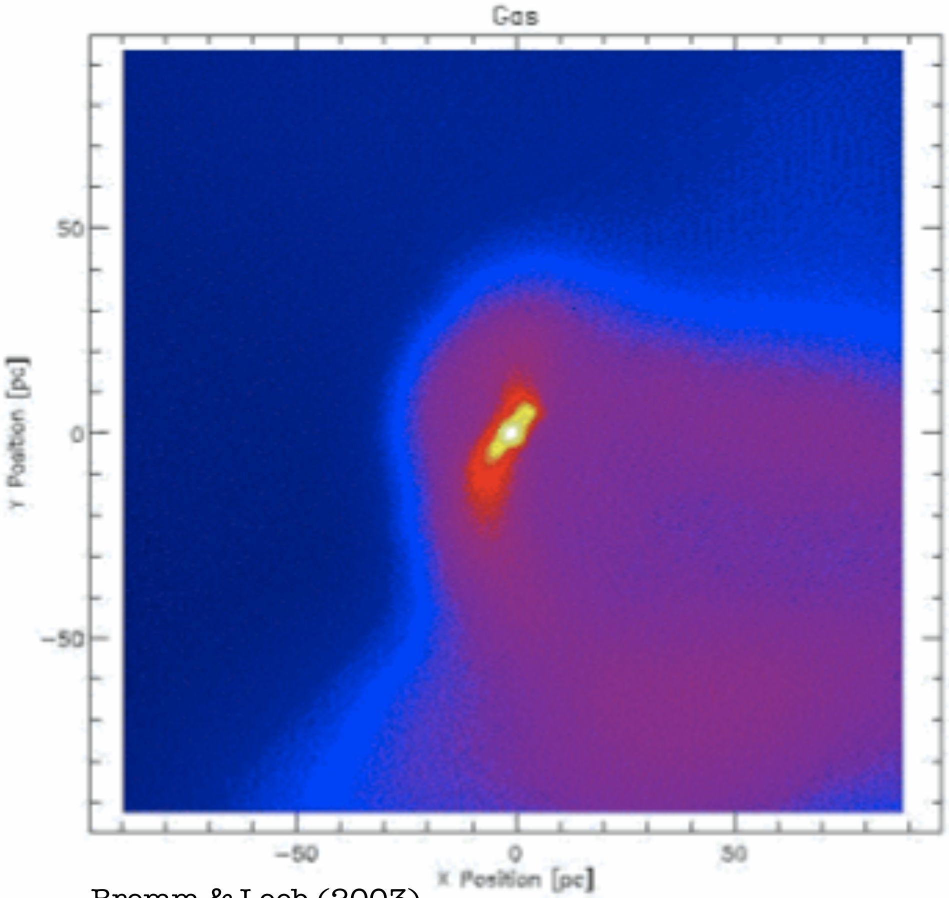
Stochastic backgrounds from PopIII/PopII stars



Marassi, RS, Ferrari (2009)

Formation of SMBHs from direct collapse of a SMS

formation of a ≈ 10^6 M_{sun} black hole in a proto-galaxy at z ≈10



Bromm & Loeb (2003)

- $T_{vir} > 10^4$K → cooling by atomic H
- metal-free gas
- strong UV background which photo-dissociate H_2

The galaxy metallicity must be < Z_{cr} where

Omukai, RS, Haiman (2008)

$Z_{cr} = 5\ 10^{-6}\ Z_{sun}$ with dust

$Z_{cr} = 10^{-4}\ Z_{sun}$ with gas metals only

GW emission from SMS collapsing to SMBHs

Upper limit on the SMBH formation rate: the present-day observed SMBHs density

$$f_{\mathrm{smbh}} \int_{M_{\min}(z=10)}^{\infty} \frac{\mathrm{d}n(M, 10)}{\mathrm{d}M} M_{\mathrm{smbh}}(M)\, \mathrm{d}M \leq 4.3 \times 10^{5} (h/0.7)^{2}\, \mathrm{M}_{\odot} \mathrm{Mpc}^{-3}$$

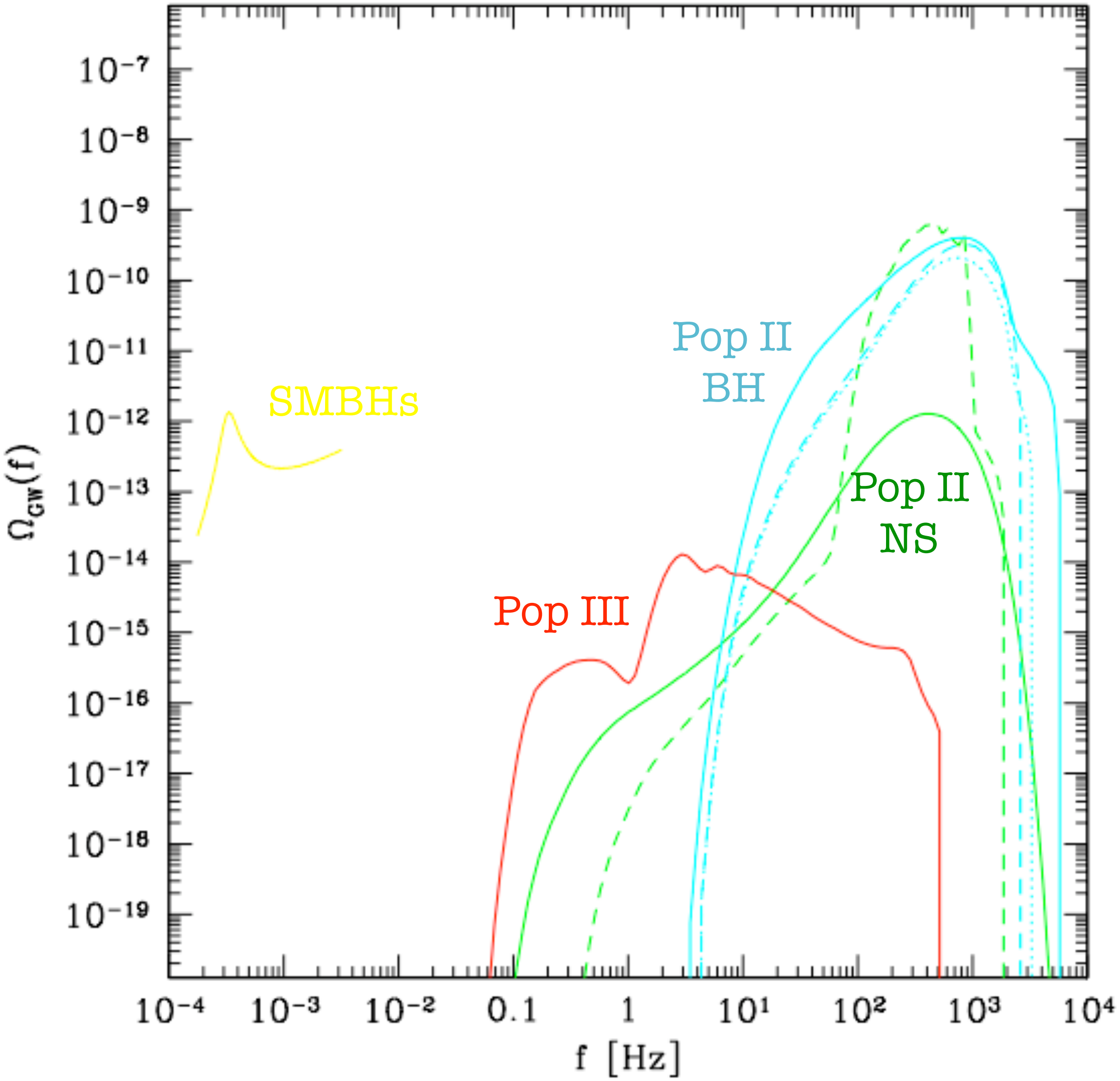
Merloni & Heinz (2008)

SMBHs collapse GW emission: (Saijo et al. 2002; Shibata & Shapiro 2002; Liu et al. 2007)

Single burst modeled as a Lorentzian centered on $f = c/10R_g$ (RS et al. 2000)

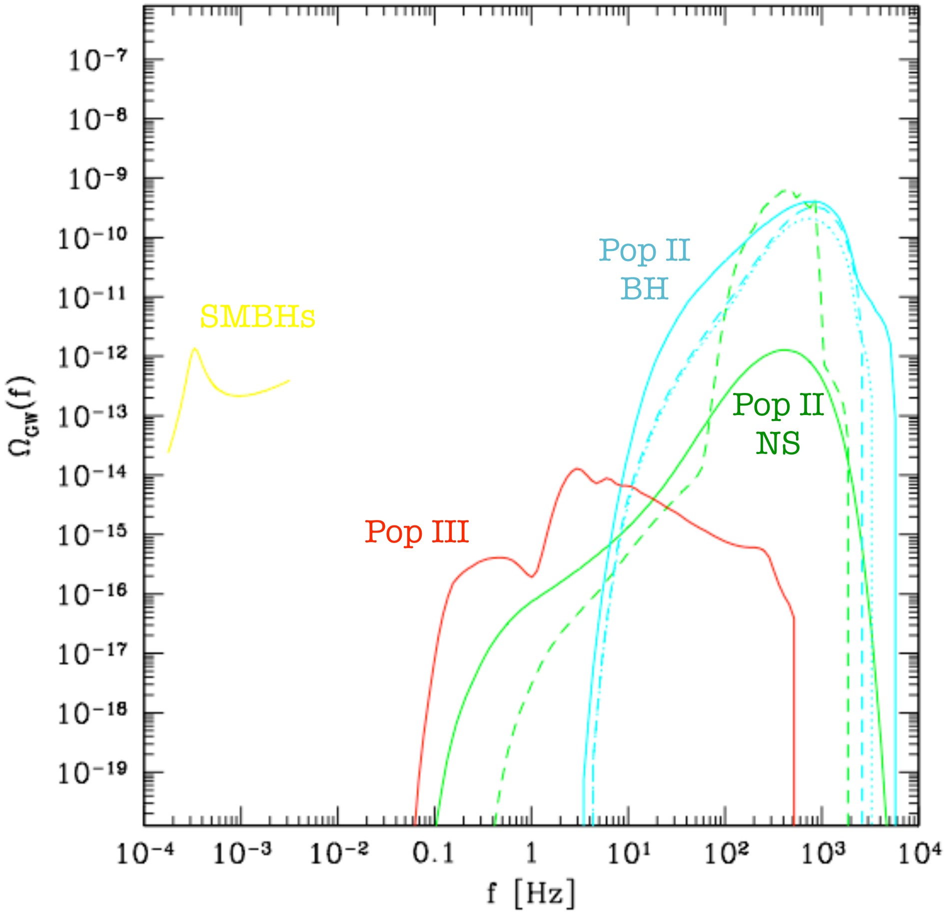
$E_{GW} \approx 2 \times 10^{-5} M_{smbh} c^2$ (Fryer et al. 2001)

Stochastic backgrounds: new predictions



Marassi, RS, Ferrari (2009)

comparison with previous work



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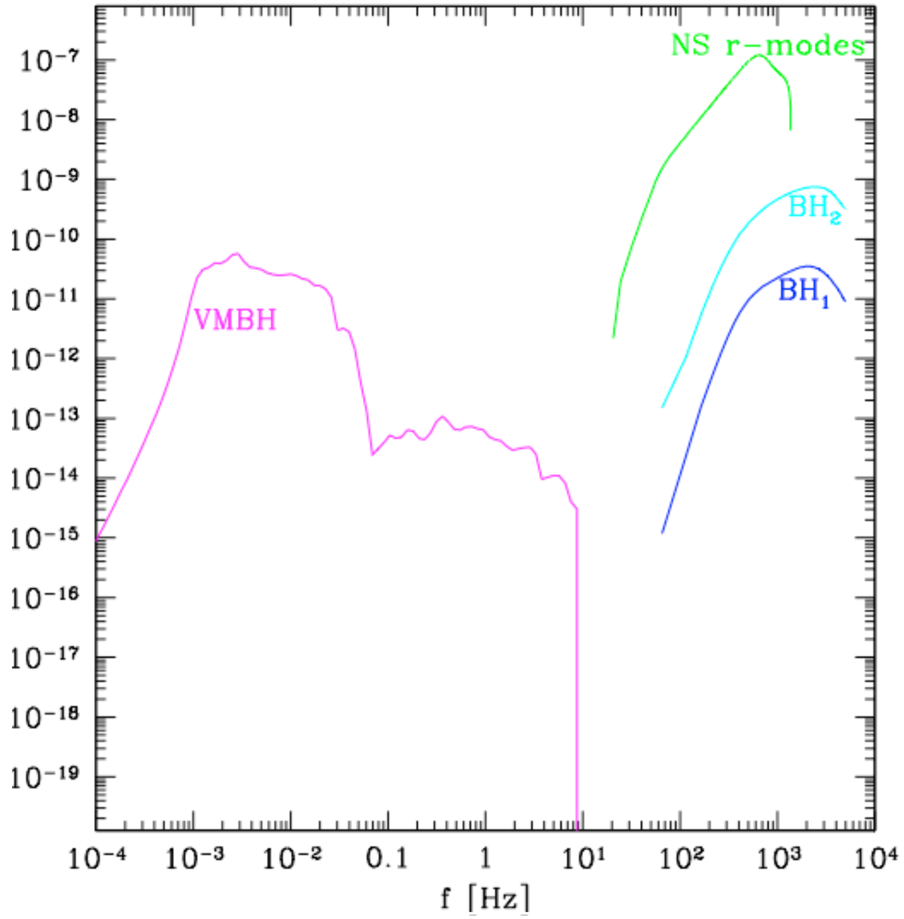

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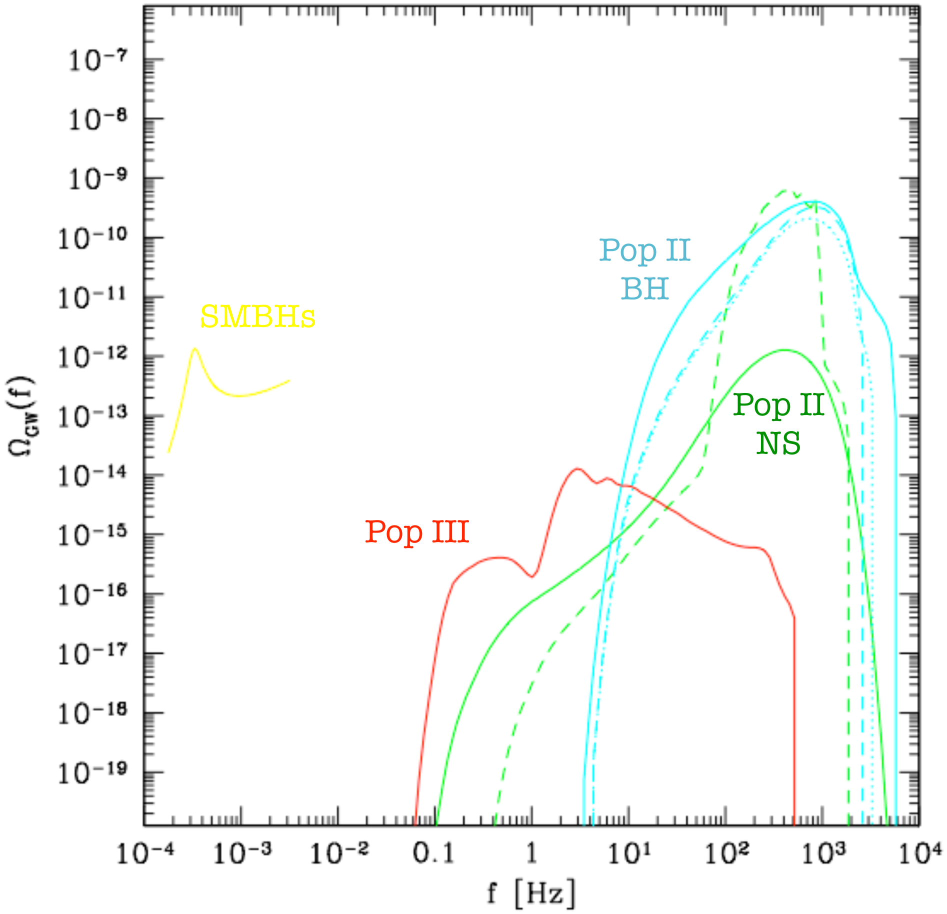

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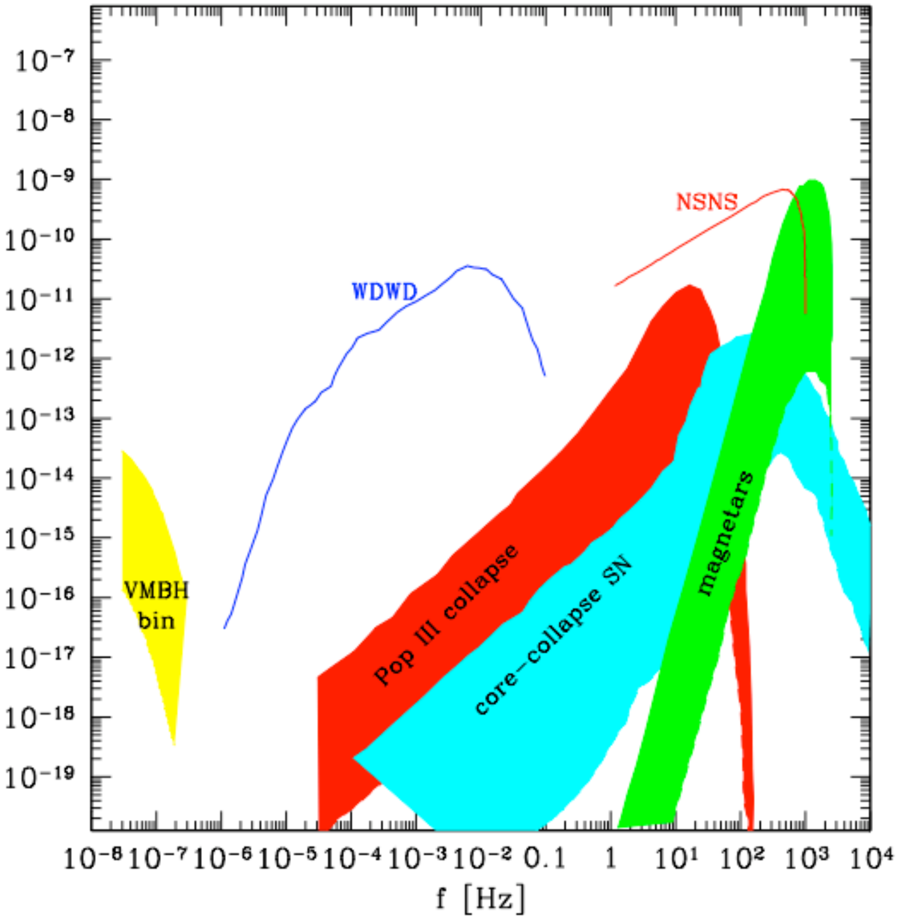

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Sandick et al. (2006)

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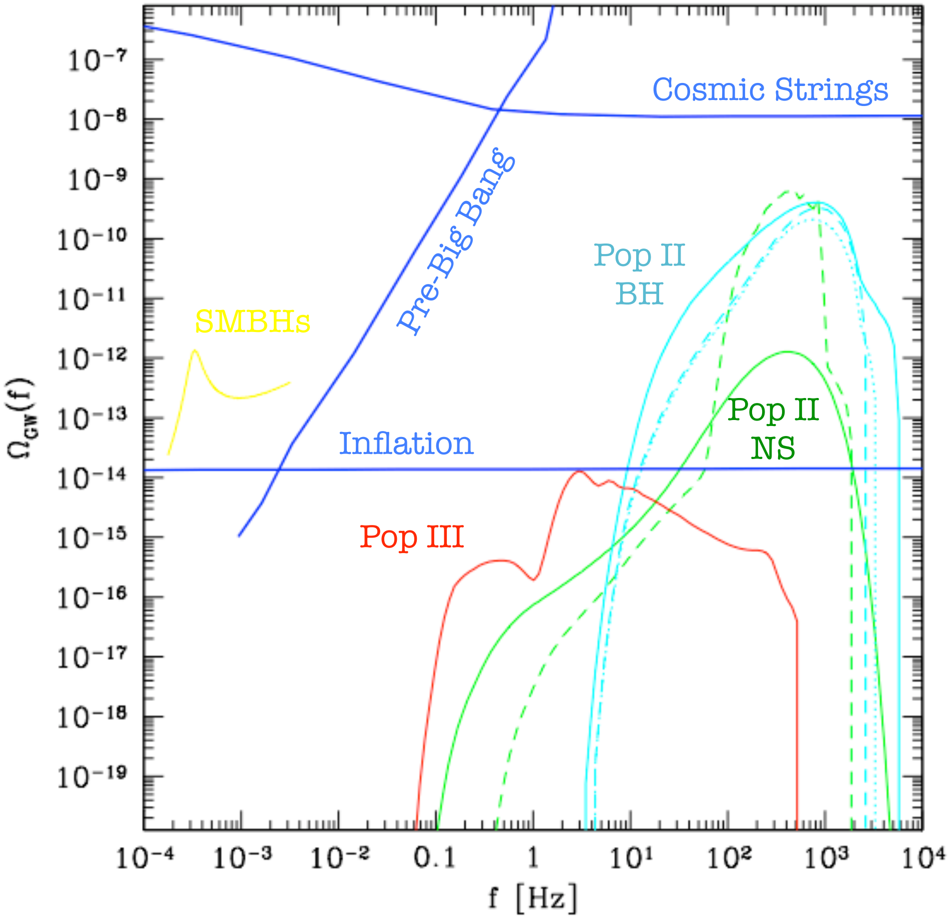
astrophysical vs primordial backgrounds



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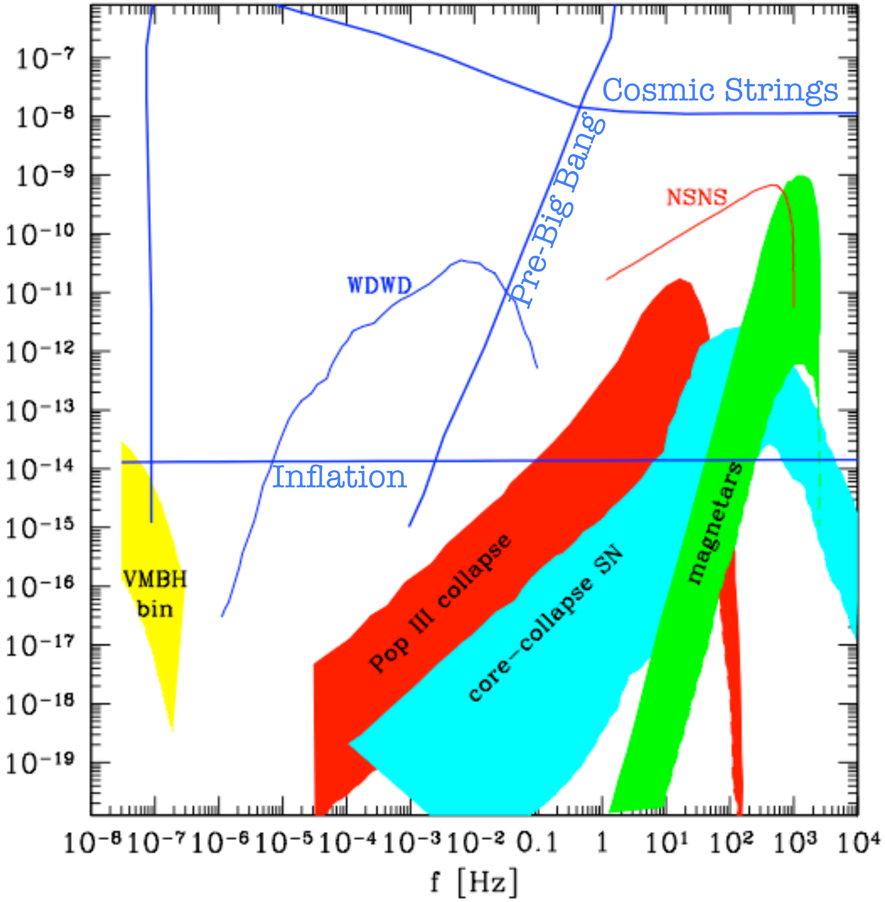


Primordial background data
from Abbott et al. (2009)

Buonanno et al. (2005)

Farmer & Phinney (2003)

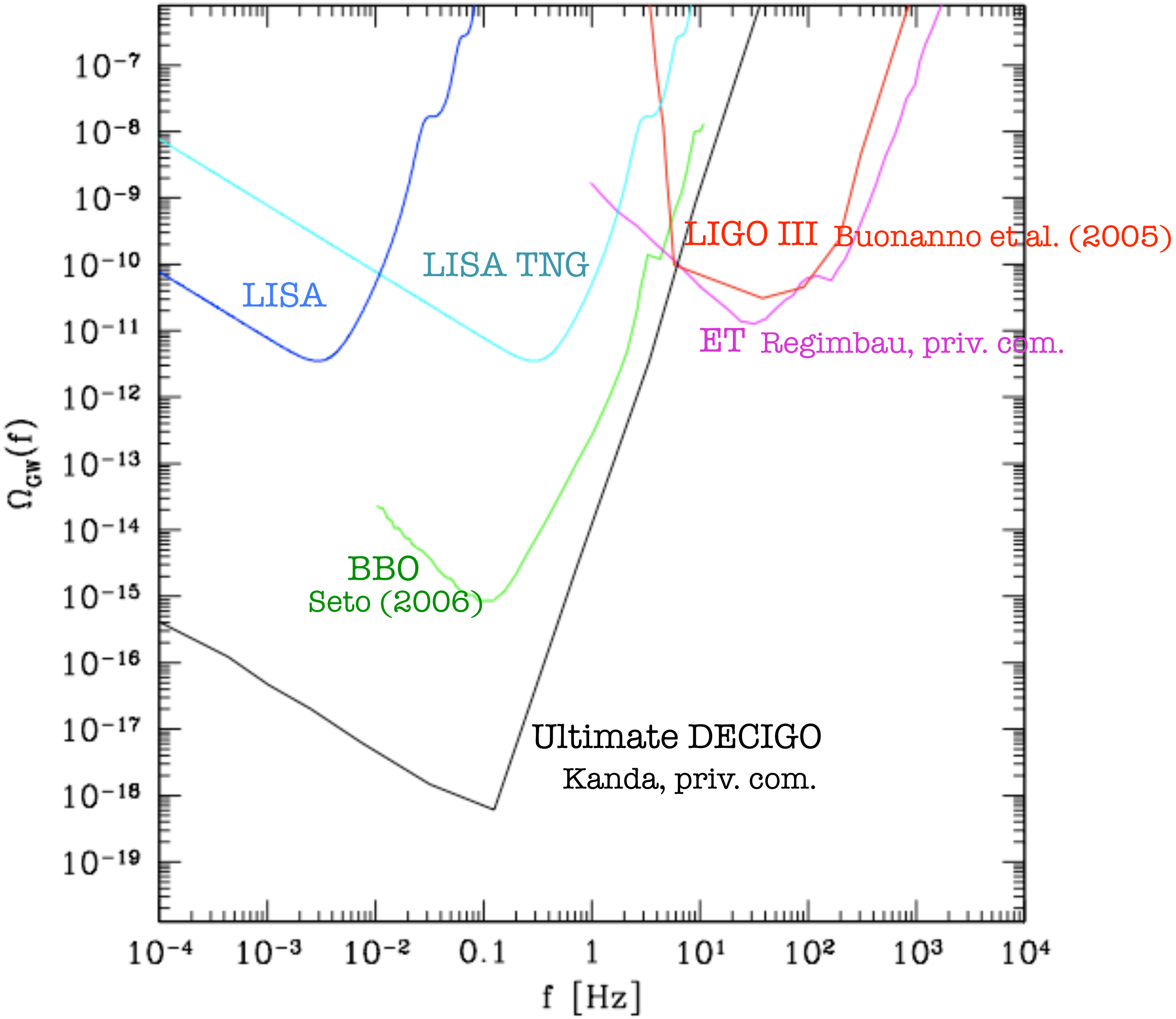
Regimbau & de Freitas Pacheco (2006)

Regimbau & Chauvineau (2007)

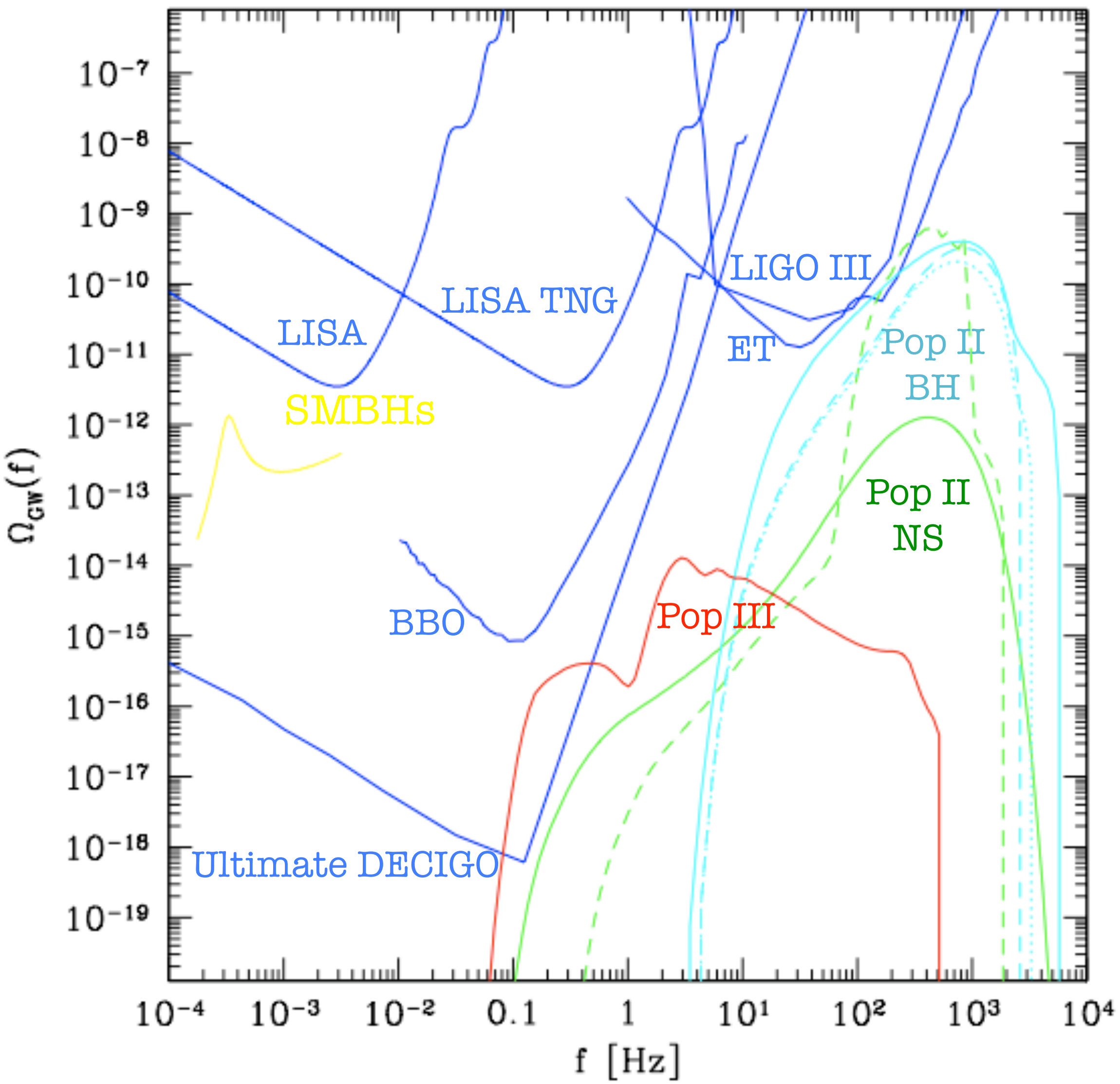
Sandick et al. (2006)

Sesana, Vecchio & Colacino (2008)

observability



observability



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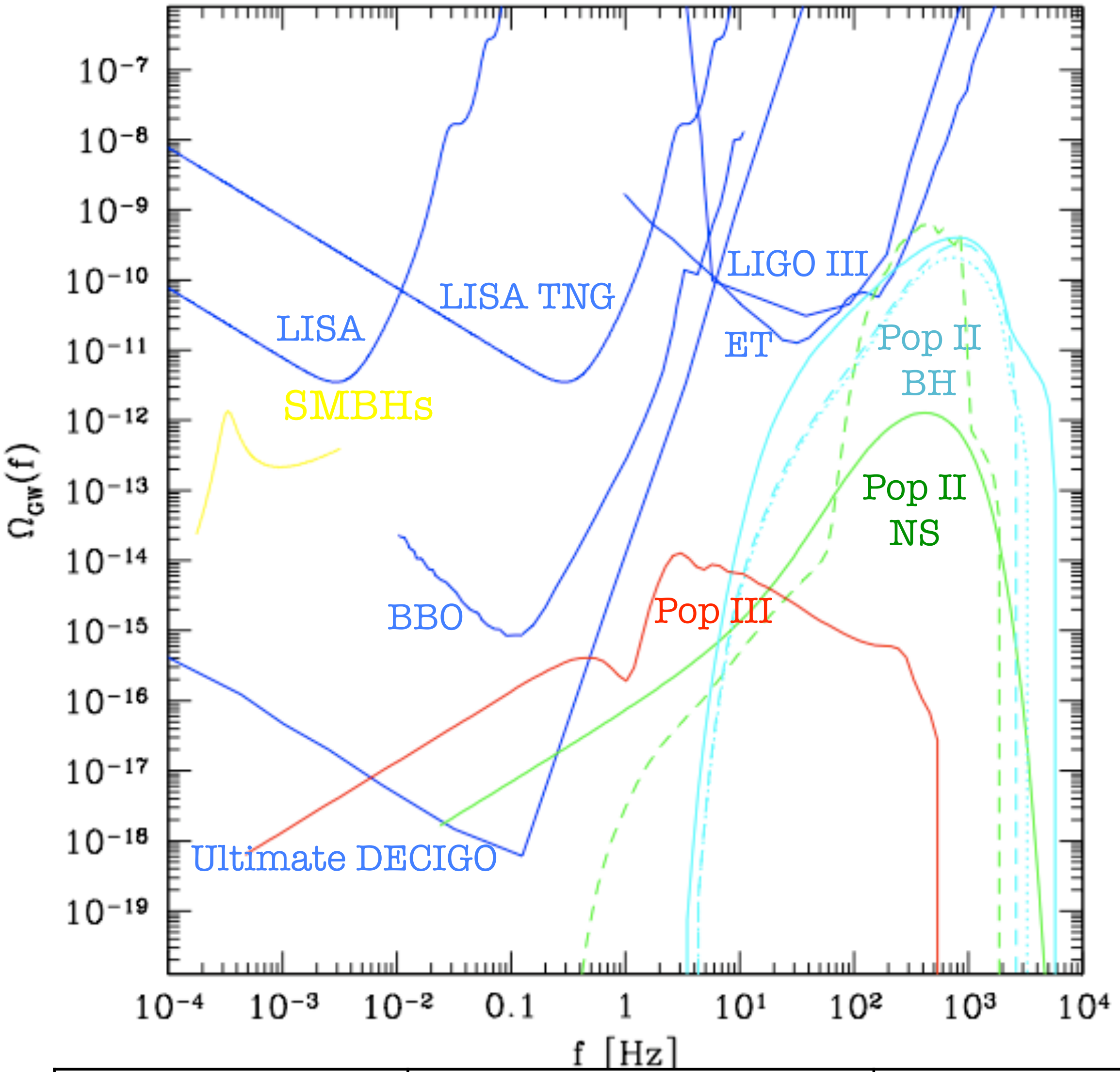

Duty Cycle	Pop II NS: Δτ = 1 ms	Pop II BH Δτ = 1 (100) ms	Pop III Δτ = 100 ms
	8.6×10^{-2}	3.1×10^{-2} (3.1)	3.1×10^{-4}