GRAVITATIONAL WAVES FROM MORE ATTRACTIVE DARK BINARIES

NICHOLAS ORLOFSKY

2312.13378 + Work in progress with: Yang Bai, Sida Lu

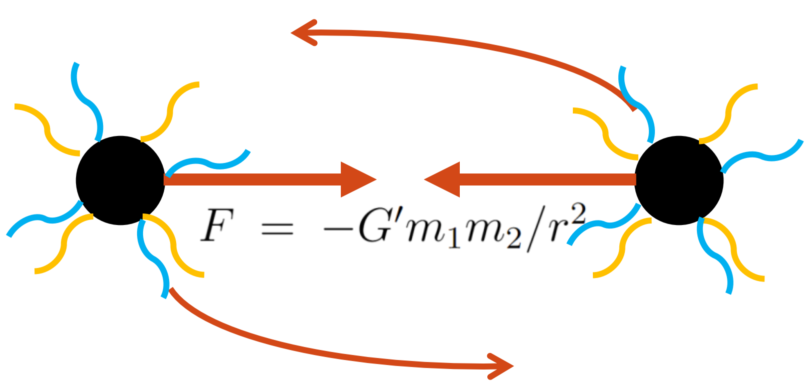
Pollica Physics Center, "Fundamental physics and gravitational wave detectors"

17 September, 2024

UNIVERSITAS VARSOVIENSIS

BASIC IDEA

- Assume a macroscopic DM in a secluded sector with a new force.
- These DM form binaries before matter-radiation equality, which continuously inspiral and merge.
- The binaries emit both GWs and the new force carrier.
- Of interest: How does the *stochastic GW* signal change when the new force carrier is introduced?



THE NEW FORCE

Total attractive force between two macroscopic DM:

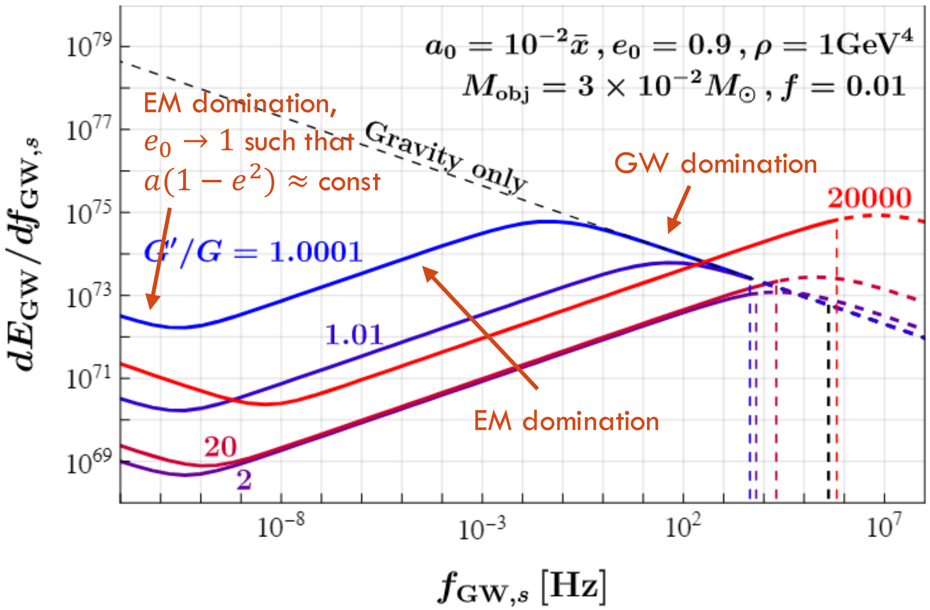
$$F = -\frac{Gm_1m_2}{r^2}\left(1 - \alpha e^{-m_{\rm med} r}(1 + m_{\rm med} r)\right)$$
$$\alpha = g^2 q_1 q_2/(4\pi G m_1 m_2)$$

In the massless mediator limit

$$m_{\rm med} \ll r^{-1}$$
$$F = -G' m_1 m_2/r^2$$
$$G' = (1-\alpha)G \equiv \beta G$$
$$\omega^2 = \frac{Gm}{a^3}\left(1 - \alpha e^{-m_{\rm med} a}(1 + m_{\rm med} a)\right) \approx \frac{G'm}{a^3}$$
$$E = -\frac{Gm^2\eta}{2a}\left(1 - \alpha e^{-m_{\rm med} a}(1 + m_{\rm med} a)\right) \approx -\frac{G'm^2\eta}{2a}$$

$$m \equiv m_1 + m_2\,,$$
$$\eta \equiv \frac{\mu}{m} \equiv \frac{m_1 m_2}{m^2}\,,$$

GW EMISSION WITH A NEW FORCE



$$\frac{dE_{\mathrm{GW}}}{df_{\mathrm{GW},s}} = \frac{\pi\sqrt{a}\,(37e^4+292e^2+96)\,G'^{3/2}M_{\mathrm{MDM}}^{5/2}}{3\sqrt{2}\,[10\,a(1-e^2)(2+e^2)(\beta-1)+(37e^4+292e^2+96)\,G'M_{\mathrm{MDM}}]}$$

Dark EM GW

$q_1 = -q_2$ and $m_1 = m_2$

BINARY MERGERS

Binaries decouple from the Hubble flow near matter-radiation equality.

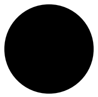
Neighboring BHs exert a tidal forces.

Calculate the probability distribution for a binary's orbital parameters.

From the orbital parameter distribution, get binary merger lifetime distribution.

[Ioka, Chiba, Tanaka, Nakamura astro-ph/9807018; Sasaki, Suyama, Tanaka, Yokoyama 1603.08338; Ali-Haïmoud, Kovetz, Kamionkowski 1709.06576; Raidal, Spethmann, Vaskonen, Veermae 1812.01930]

$$P(x,y)\,dxdy = \frac{9x^2y^2}{\bar{x}^6} e^{-(y/\bar{x})^3} dxdy$$

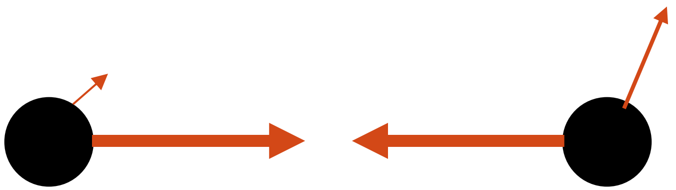


$$\bar{x} = \frac{1}{1+z_{\rm eq}} \left(\frac{8\pi G M_{\rm obj}}{3H_0^2 f \Omega_{\rm DM}} \right)^{1/3} .$$

$$a_0 = \frac{c_1}{\beta} \frac{1}{f} \frac{x^4}{\bar{x}^3} ,$$

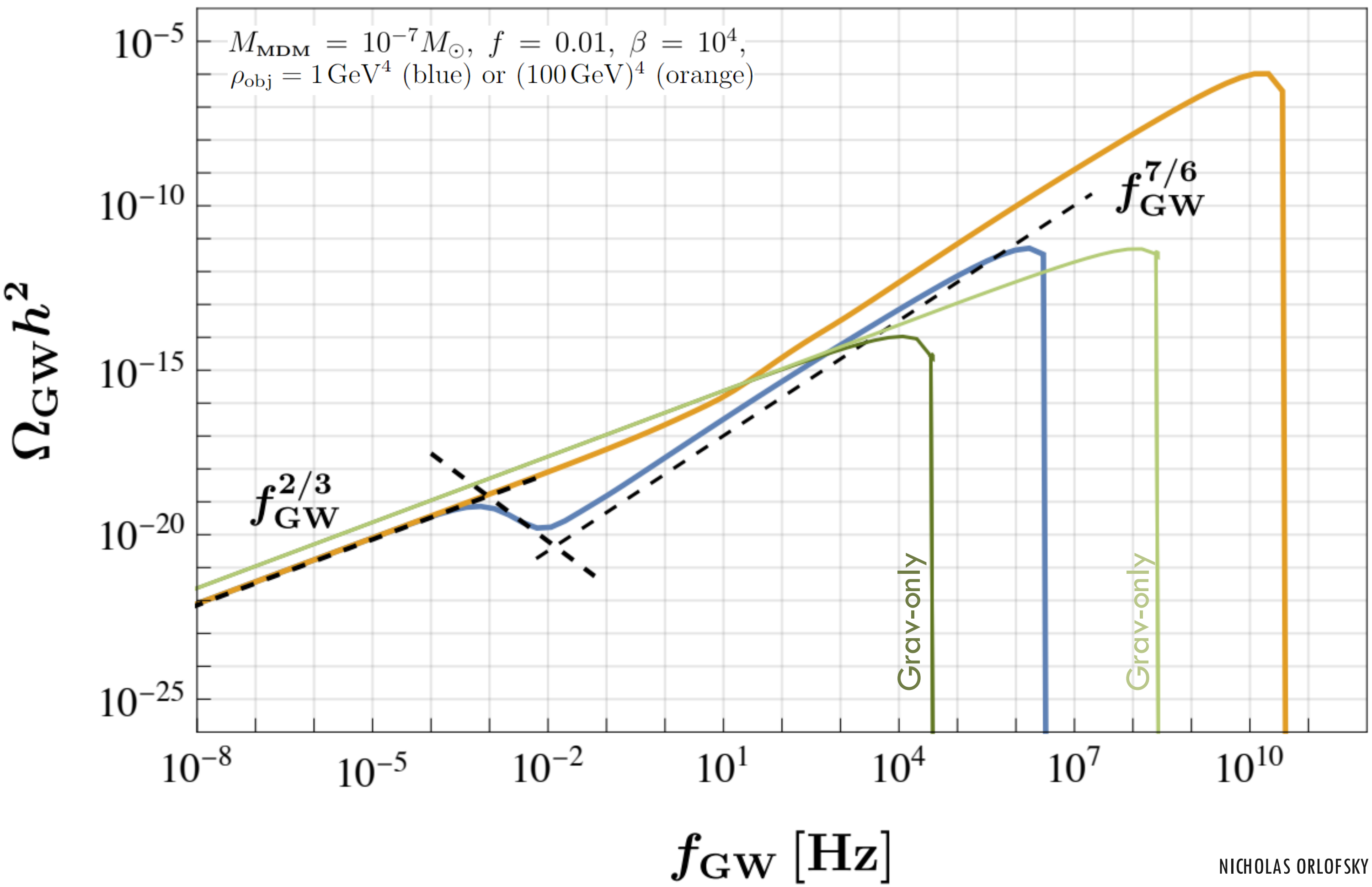
$$b_0 = c_2 \left(\frac{x}{y} \right)^3 a_0 ,$$

$$e_0 = \sqrt{1 - \left(\frac{b_0}{a_0} \right)^2}$$

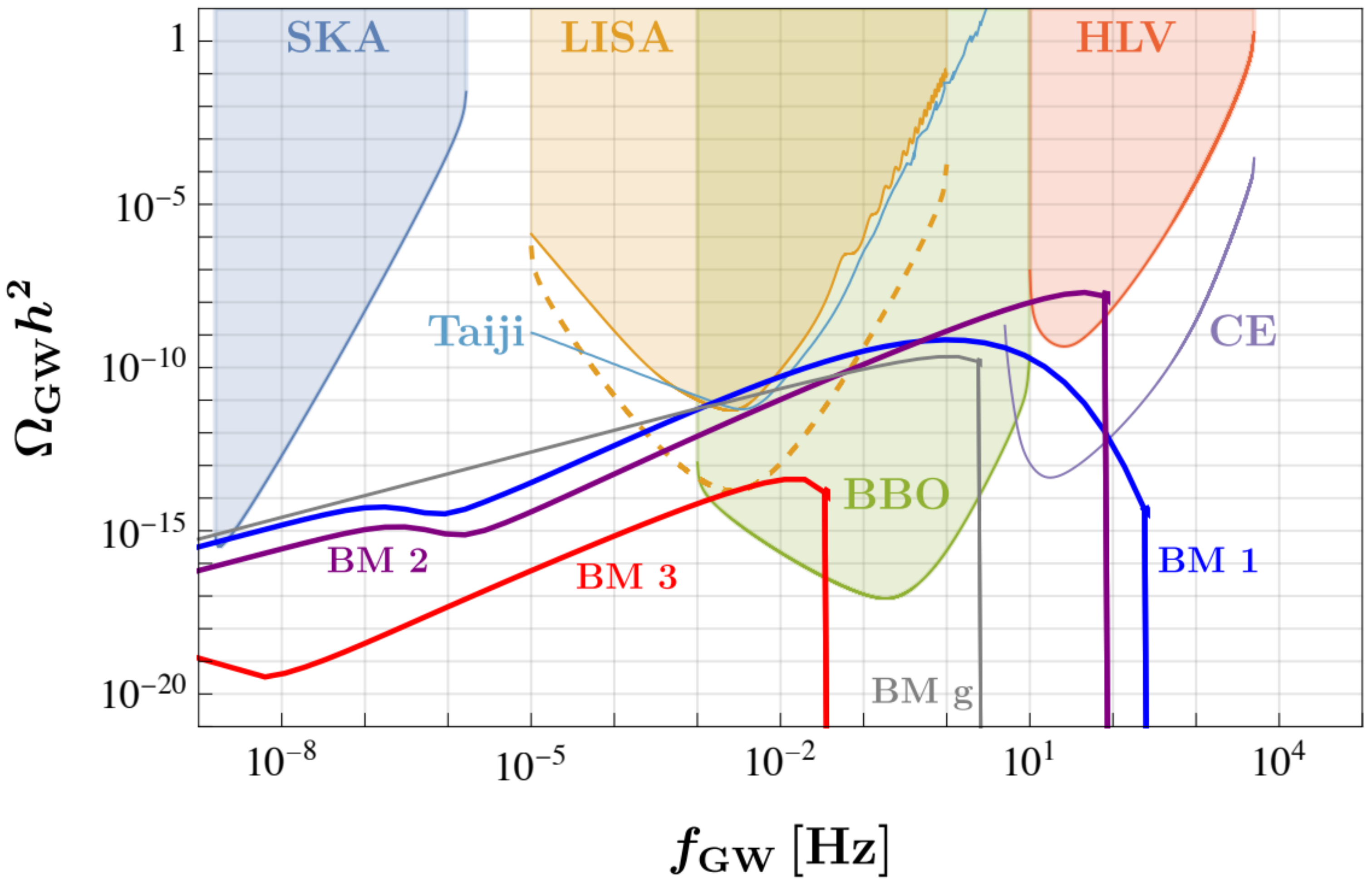


STOCHASTIC GW SIGNAL

$$\Omega_{\rm GW}(f_{\rm GW}) = \frac{f_{\rm GW}}{\rho_c}\int_{\sqrt{1-c_2^2}}^{e_{0,\rm max}} de_0 \int d\tau \frac{n_{\rm obj}}{4}\mathcal{P}(\tau, e_0)\frac{dE_{\rm GW}}{df_{{\rm GW},s}}\left[(1+z(t))f_{\rm GW}\right]$$



STOCHASATIC GW SIGNAL

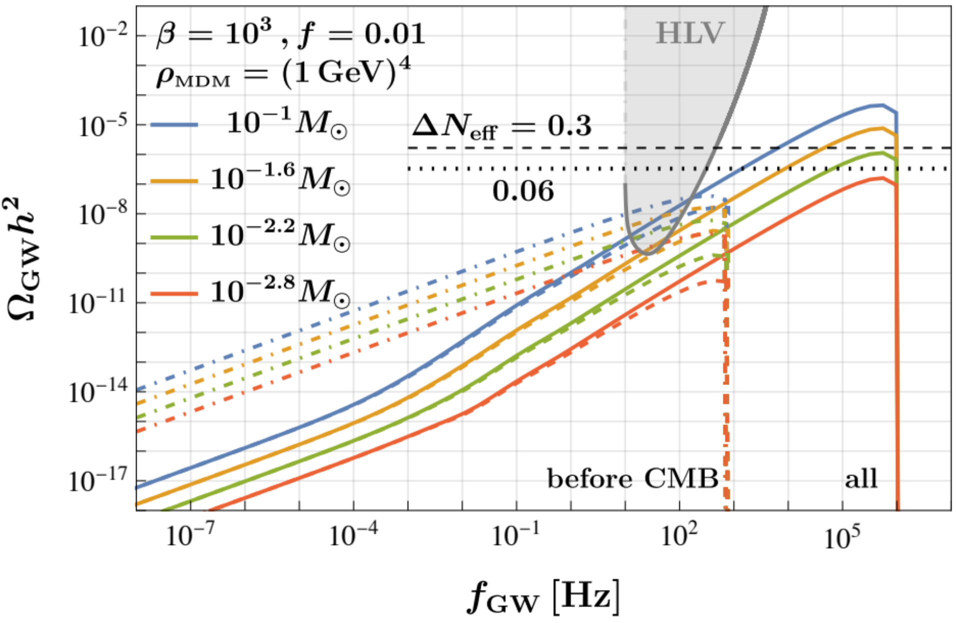


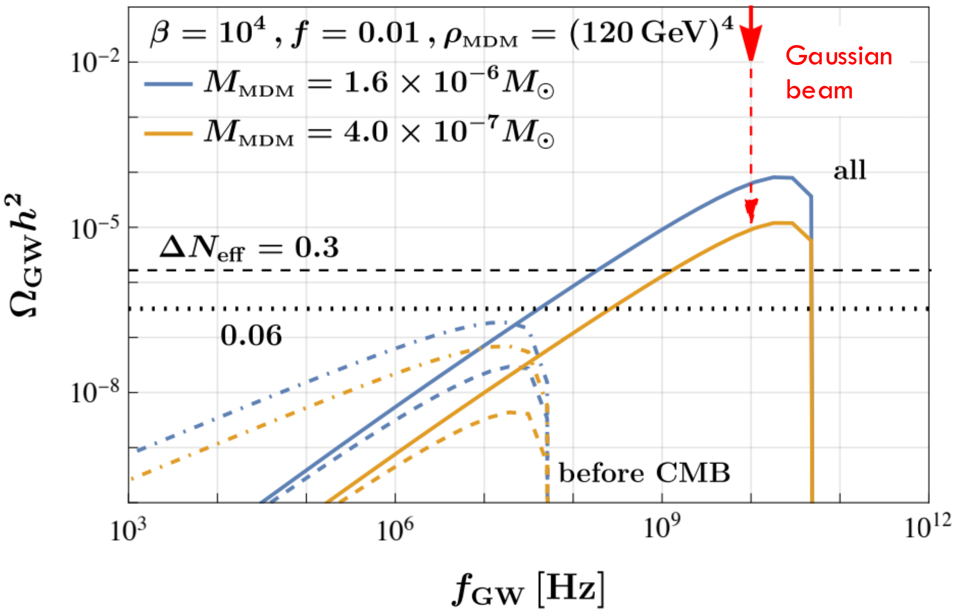
BM 1-3 are $(\beta, M_{\rm MDM}, f, \rho_{\rm MDM}^{1/4}) = (10^4, 0.1\ M_\odot, 0.25, 10\ \text{MeV})$, $(10^3, 0.1\ M_\odot, 0.25, 10\ \text{MeV})$, and $(10^4, 0.1\ M_\odot, 0.01, 100\ \text{keV})$, "BM g" has $(1, 0.1\, M_\odot, 0.25, 10\,\text{MeV})$

HIGH FREQUENCY SGW SIGNAL

CMB constraints on ΔN_{eff} are generally much stronger than proposed high-frequency GW detectors.

However, only some of the GW signal is produced before recombination:



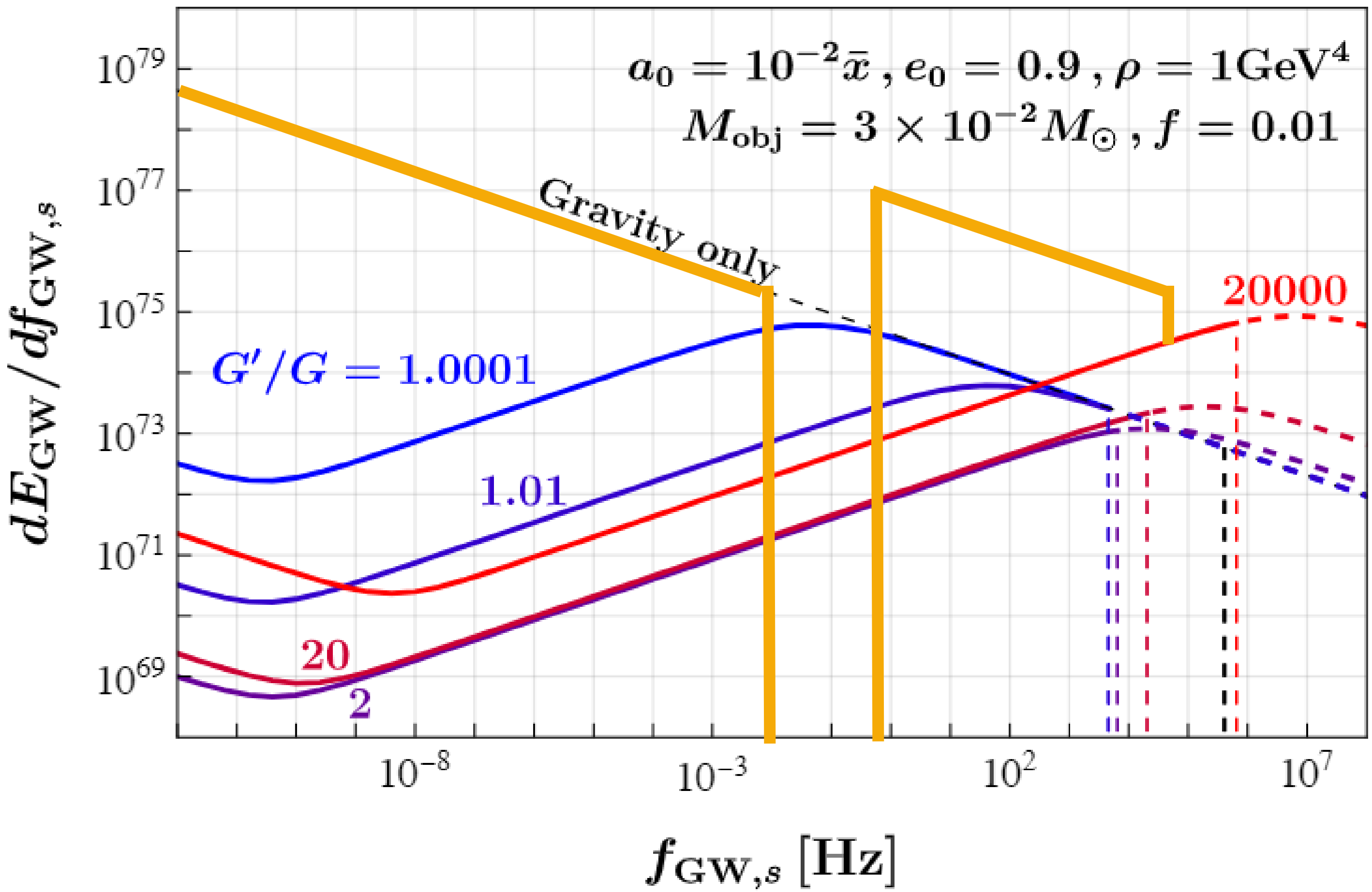


MASSIVE MEDIATOR

What changes with a massive dark force mediator (compared to massless)?

- Mediator radiation turns on later
  - More GWs at low frequency
  - Longer lifetimes
- Dark force range is shorter
  - GW spectrum modified at low frequency
  - Changes to the binary formation

GW EMISSION WITH A MASSIVE-MEDIATOR NEW FORCE



BINARY MERGERS

Binaries decouple from the Hubble flow near matter-radiation equality.

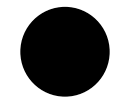
Neighboring BHs exert a tidal forces.

Calculate the probability distribution for a binary's orbital parameters.

From the orbital parameter distribution, get binary merger lifetime distribution.

[Ioka, Chiba, Tanaka, Nakamura astro-ph/9807018; Sasaki, Suyama, Tanaka, Yokoyama 1603.08338; Ali-Haïmoud, Kovetz, Kamionkowski 1709.06576; Raidal, Spethmann, Vaskonen, Veermae 1812.01930]

$$P(x,y)\,dxdy = \frac{9x^2y^2}{\bar{x}^6}e^{-(y/\bar{x})^3}dxdy$$

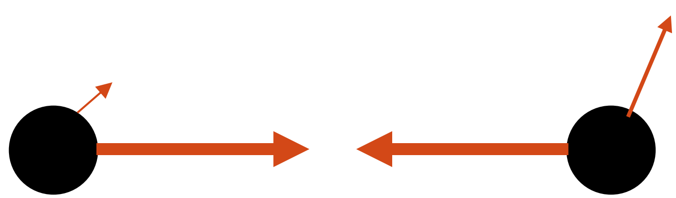


$$\bar{x} = \frac{1}{1+z_{\rm eq}}\left(\frac{8\pi G M_{\rm obj}}{3H_0^2 f\,\Omega_{\rm DM}}\right)^{1/3}.$$

$$a_0 = \frac{c_1}{\beta}\frac{1}{f}\frac{x^4}{\bar{x}^3}\,,$$

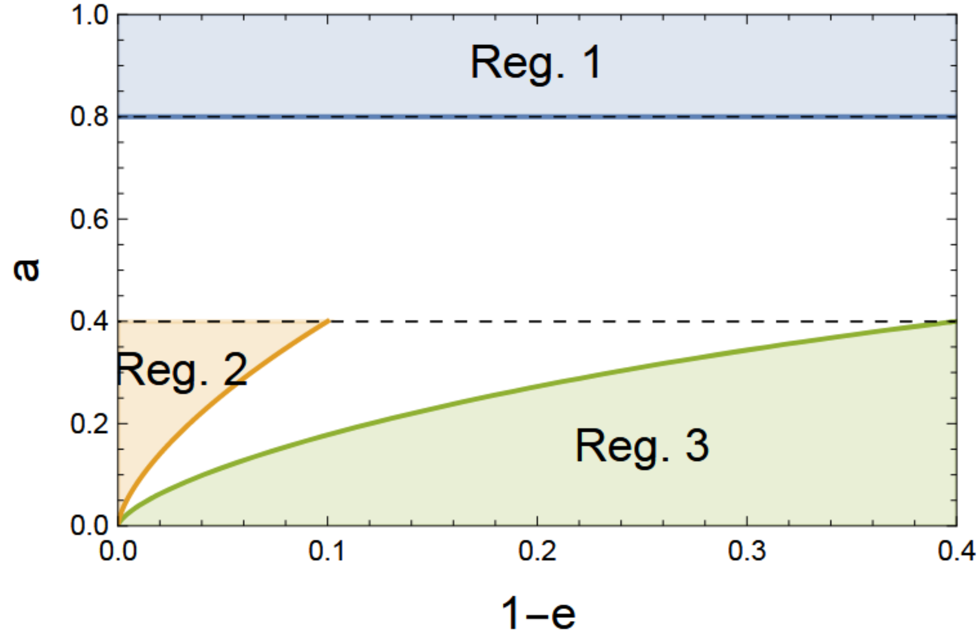
$$b_0 = c_2\left(\frac{x}{y}\right)^3 a_0\,,$$

$$e_0 = \sqrt{1-\left(\frac{b_0}{a_0}\right)^2}$$



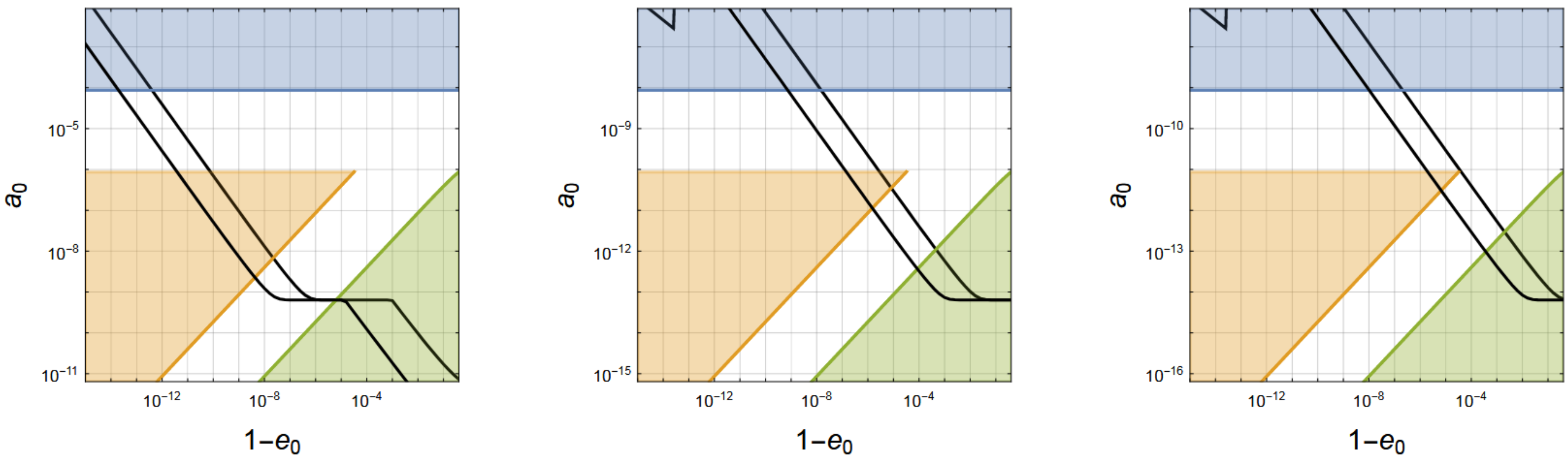
BINARY FORMATION

- Region 1: Gravity only
- Region 2: Dark force + gravity for nearest neighbors; Gravity only for tidal force
- Region 3: Dark force + gravity



BINARY MERGERS

Black lines: Mergers today (upper) or at recombination (lower)

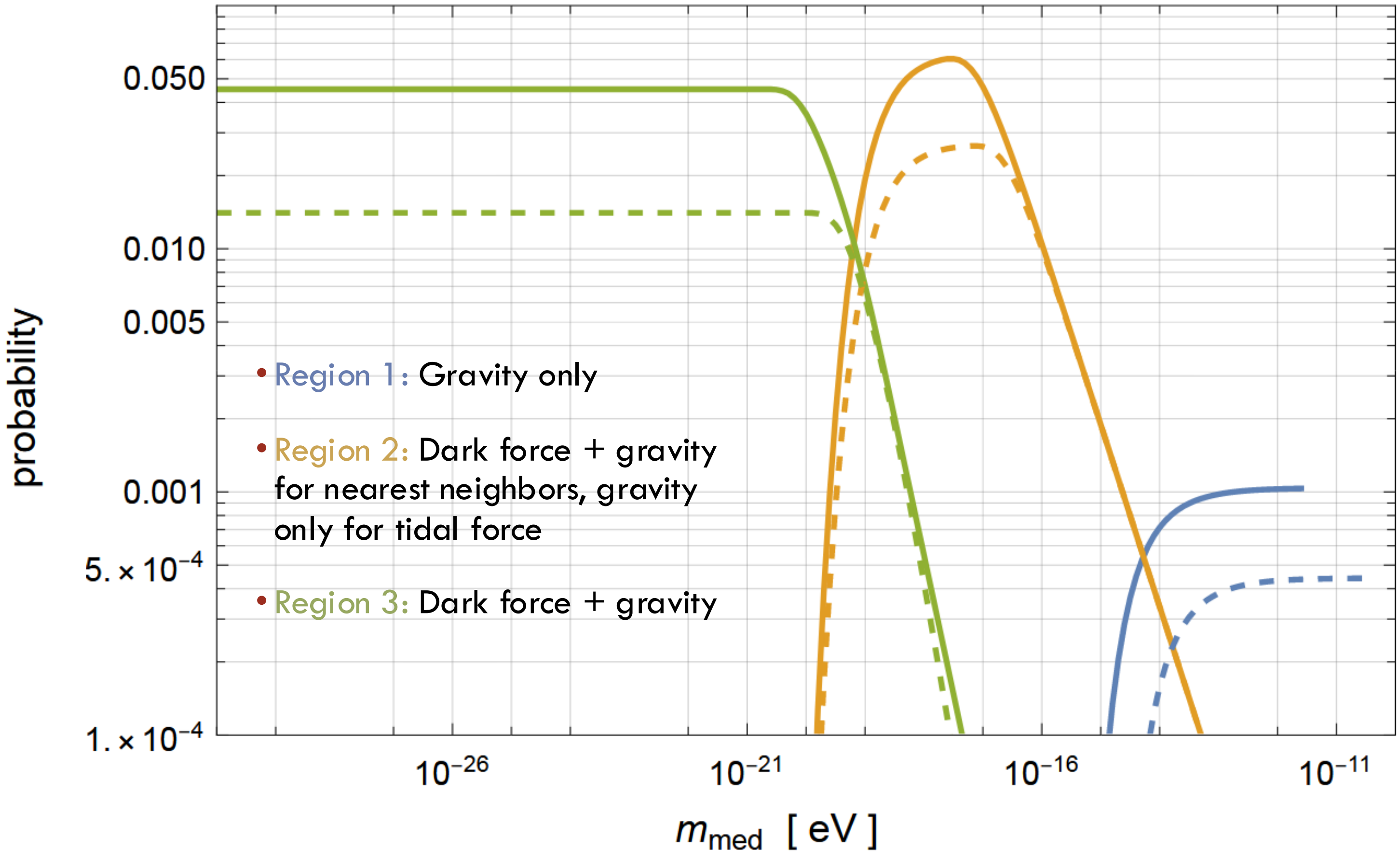


$m_{med} = 10^{-20}, 10^{-16}, 10^{-15}$ eV

- Region 1: Gravity only
- Region 2: Dark force + gravity for nearest neighbors, gravity only for tidal force
- Region 3: Dark force + gravity

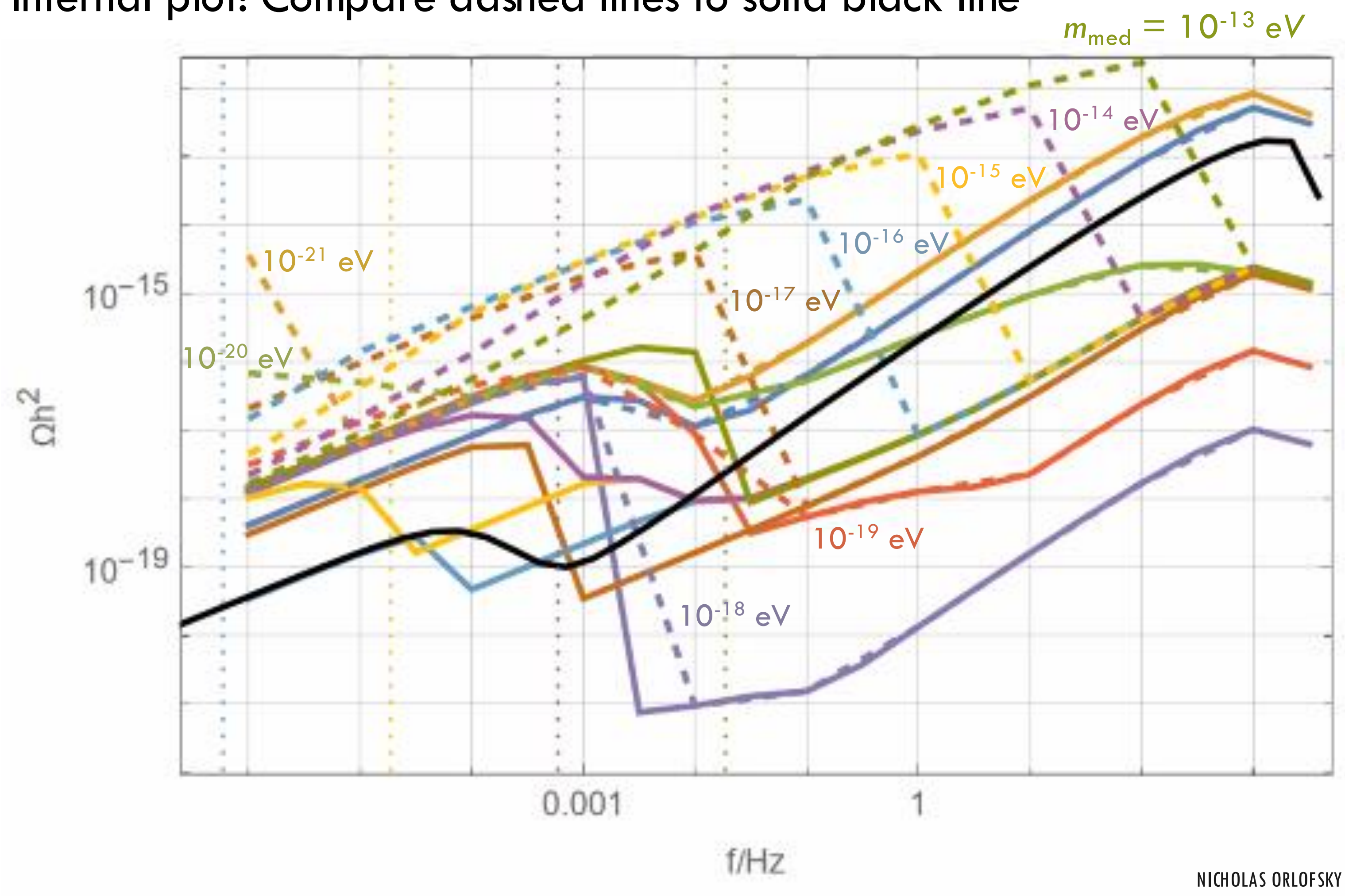
BINARY MERGERS

Mergers today (solid) or at recombination (dashed), by "region"



GW SPECTRUM

Internal plot: Compare dashed lines to solid black line



MODELS

- Mirror sector
- Charged primordial black holes
- Q-monopole-balls [Bai, Lu, NO 2111.10360] or gauged Q-balls
- Various solitonic or composite states coupled to a force carrier, including Q-balls or dark quark nuggets

Eg, for the dark quark nugget case, can have Yukawa or vector coupling to the constituent quarks:

$$\mathscr{L}_{\mathrm{dQCD}} = \sum_{i=1}^{N_f} \left[\bar{\psi}_i i \gamma^\mu D_\mu \psi_i - m_{\psi_i} \bar{\psi}_i \psi_i\right] - \frac{1}{4} G^a_{\mu\nu} G^{\mu\nu\, a}$$

$$\mathscr{L}_{\mathrm{Yukawa}} = \frac{1}{2}\partial_\mu \phi \partial^\mu \phi - \sum_i y_i \, \phi \, \bar{\psi}_i \, \psi_i - V(\phi)$$

$$\mathscr{L}_{\mathrm{vector}} \supset -\frac{1}{2} m^2_{\mathrm{med}} V_\mu V^\mu + g \sum_i \mathfrak{q}_i \, V_\mu \bar{\psi}_i \gamma^\mu \psi_i$$

SUMMARY

New forces in the dark sector can substantially alter the stochastic GW signal from dark binary mergers.

BACKUP

GW EMISSION

Assuming only GW emission:

$$\dot{E} = \dot{E}_{\mathrm{GW}}$$

$$\frac{dE_{\mathrm{GW}}}{df_{\mathrm{GW}}} = \dot{E}_{\mathrm{GW}} \dot{f}_{\mathrm{GW}}^{-1} = \pi \dot{E}_{\mathrm{GW}} \dot{\omega}^{-1}$$

$$\dot{\omega} = -\frac{3\sqrt{2}}{G' m^{5/2} \eta^{3/2}} \sqrt{-E} \dot{E}$$

$$\frac{dE_{\mathrm{GW}}}{df_{\mathrm{GW}}} = \frac{\pi^{2/3}}{3} G'^{2/3} m^{5/3} \eta f_{\mathrm{GW}}^{-1/3}$$

No dependence on initial conditions of binary (aside from lower cutoff frequency).

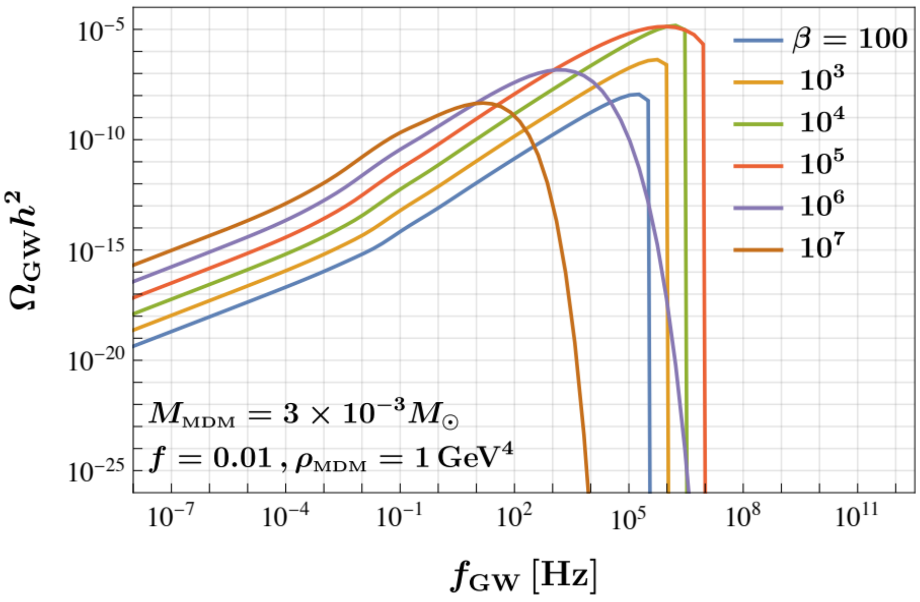
Don't need detailed knowledge of $\dot{E}$.

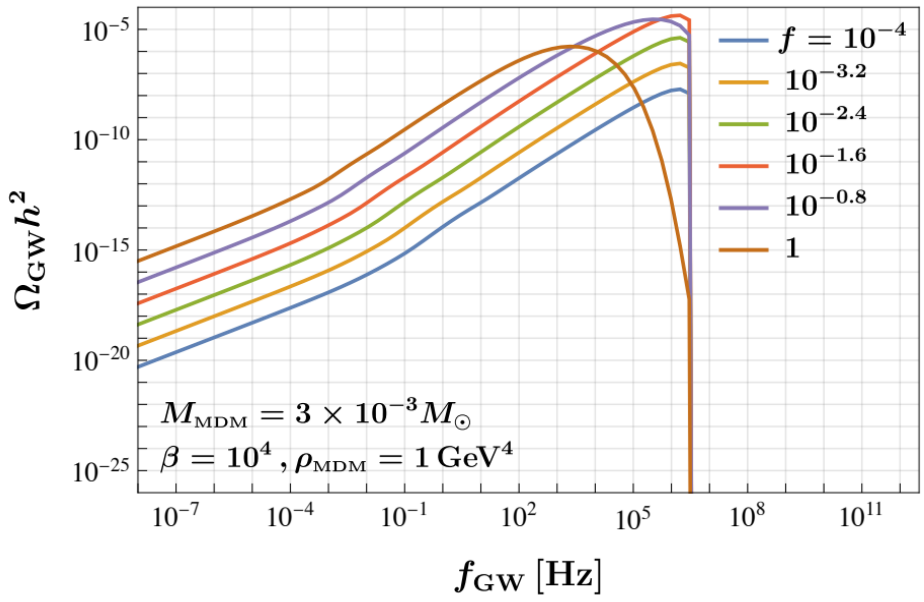
STOCHASTIC GW SIGNAL

GWs cannot be arbitrarily enhanced.

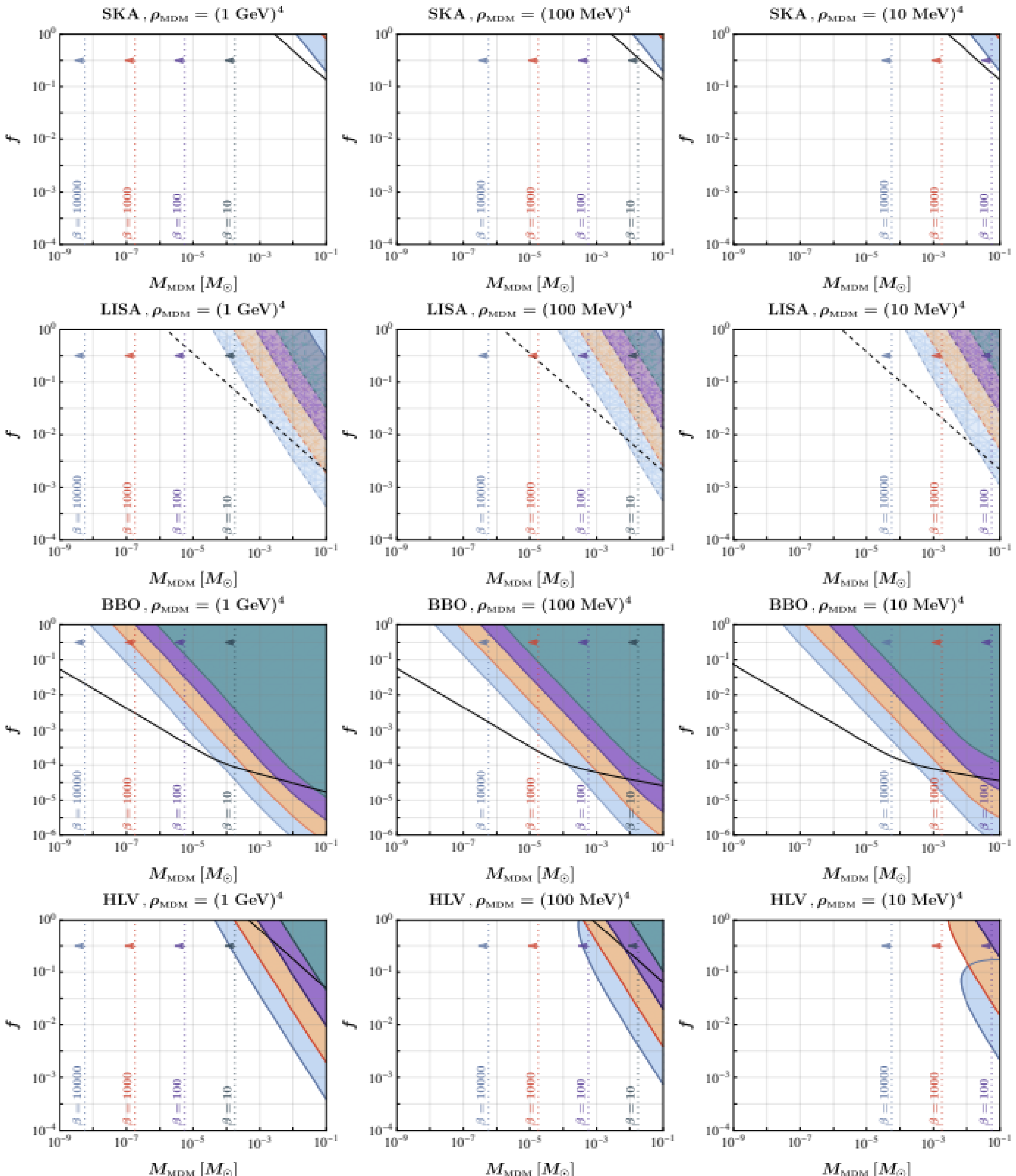
With a very strong new force, binaries form much earlier and merge much more quickly.

The GW signal is correspondingly redshifted, suppressing the peak frequency and amplitude.





STOCHASTIC GW SIGNAL



Signal-to-noise ratio:

$$\varrho^2 = \int df \frac{|h_c(f)|^2}{f^2 S_n} = \int df \frac{3H_0^2\,\Omega_{\rm GW}}{2\pi^2 f^4 S_n}$$

ASIDE ON CALCULATION OF EMISSION

Modified GW emission to including the new force:

$$\langle \dot{E}_{\rm GW} \rangle = \frac{32 G G'^3 \eta^2 m^5}{5 a^5 (1-e^2)^{7/2}} \left(1 + \frac{73}{24} e^2 + \frac{37}{96} e^4\right)$$

$$\dot{L}_{\rm GW} = \frac{32 G G'^{5/2} \eta^2 m^{9/2}}{5 a^{7/2} (1-e^2)^2} \left(1 + \frac{7}{8} e^2\right)$$

$$\dot{a} = -\frac{2a^2}{G' m^2 \eta} \dot{E}_{\rm GW} = -\frac{64 G G'^2 \eta m^3}{5 a^3 (1-e^2)^{7/2}} \left(1 + \frac{73}{24} e^2 + \frac{37}{96} e^4\right) ,$$

$$\dot{e} = -\frac{\dot{E}_{\rm GW} L_{\rm GW}^2 + 2 E_{\rm GW} L_{\rm GW} \dot{L}_{\rm GW}}{G'^2 m^5 \eta^3 e} = -\frac{304 G G'^2 \eta m^3 e}{15 a^4 (1-e^2)^{5/2}} \left(1 + \frac{121}{304} e^2\right)$$

$$a(e) = a_0 \frac{g(e)}{g(e_0)} ,$$

$$g(e) = \frac{e^{12/19}}{1-e^2} \left(1 + \frac{121}{304} e^2\right)^{870/2299}$$

$$\tau = \int_{e_0}^{0} de \left(\frac{de}{dt}\right)^{-1} = \frac{5 a_0^4 (1-e_0^2)^{7/2}}{256 G G'^2 \eta m^3} G(e_0) ,$$

$$G(e_0) = \frac{48}{19 g^4(e_0)(1-e_0^2)^{7/2}} \int_0^{e_0} de \frac{g^4(e)(1-e^2)^{5/2}}{e\left(1 + \frac{121}{304} e^2\right)}$$

ASIDE ON CALCULATION OF EMISSION

New (dark EM) force carrier emission:

$$\langle \dot{E}_{\rm EM} \rangle = \frac{GG'^2}{12\pi}\eta^2 m^4 \left(\frac{gq_1}{\sqrt{G}m_1} - \frac{gq_2}{\sqrt{G}m_2}\right)^2 \frac{1}{a^4}\frac{2+e^2}{(1-e^2)^{5/2}}$$

$$\langle \dot{L}_{\rm EM} \rangle = \frac{G'^{3/2}(gq_1 m_2 - gq_2 m_1)^2}{6\pi a^{5/2}(1-e^2)\sqrt{m}}$$

$$\dot{a} = -\frac{2a^2}{G'm^2\eta}\dot{E}_{\rm EM} = -\frac{GG'}{6\pi}\eta m^2 \left(\frac{gq_1}{\sqrt{G}m_1} - \frac{gq_2}{\sqrt{G}m_2}\right)^2 \frac{1}{a^2}\frac{2+e^2}{(1-e^2)^{5/2}},$$

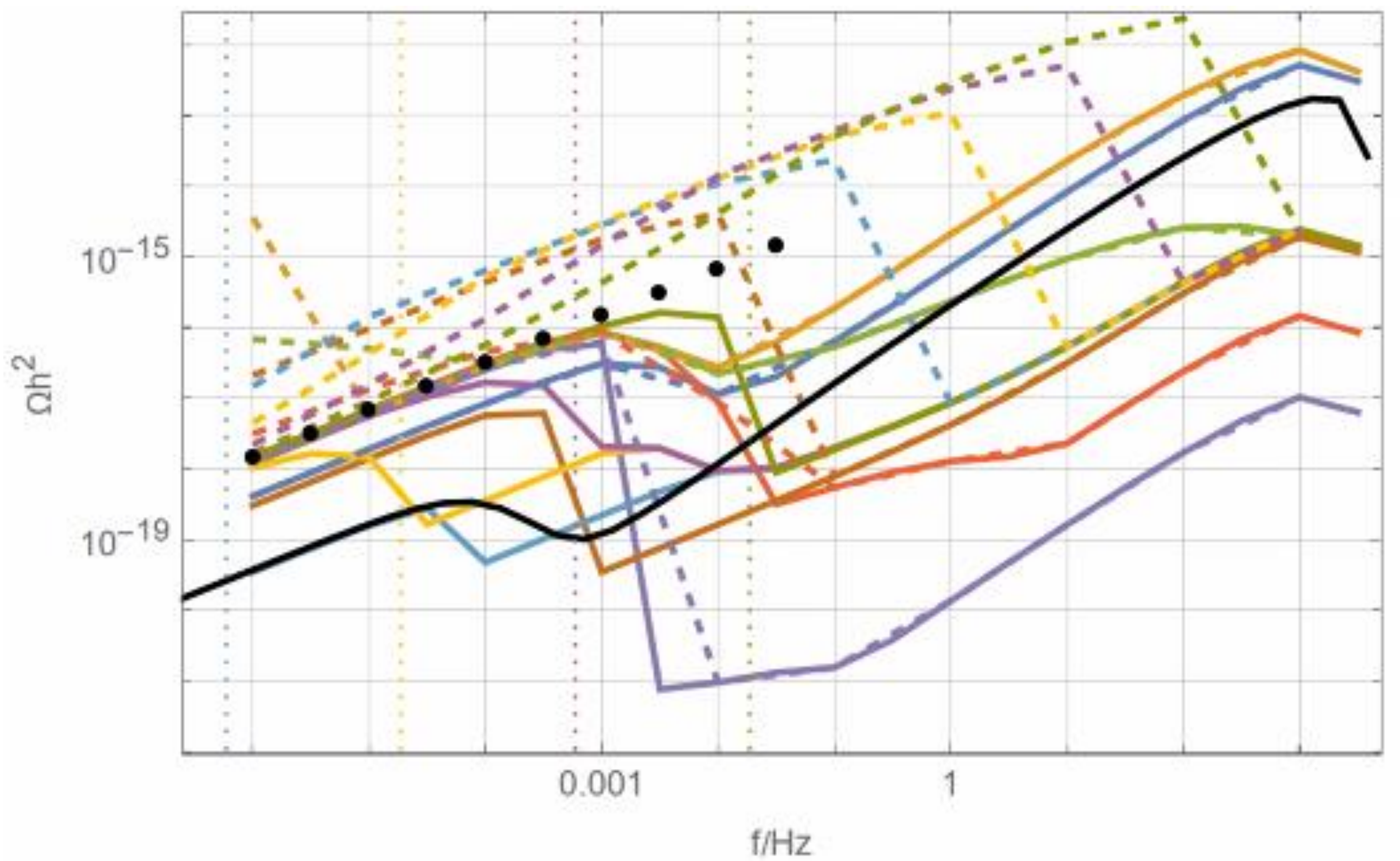
$$\dot{e} = -\frac{\dot{E}_{\rm EM}L_{\rm EM}^2 + 2E_{\rm EM}L_{\rm EM}\dot{L}_{\rm EM}}{G'^2 m^5\eta^3 e} = -\frac{GG'm^2\eta e}{4\pi a^3(1-e^2)^{3/2}}\left(\frac{gq_1}{\sqrt{G}m_1} - \frac{gq_2}{\sqrt{G}m_2}\right)^2$$

$$a(e) = a_0\frac{g(e)}{g(e_0)},$$

$$g(e) = \frac{e^{4/3}}{1-e^2}.$$

$$\tau = \frac{4\pi a_0^3}{GG'\eta m^2}\left(\frac{gq_1}{\sqrt{G}m_1} - \frac{gq_2}{\sqrt{G}m_2}\right)^{-2}\frac{(1-e_0^2)^{5/2}(1-\sqrt{1-e_0^2})^2}{e_0^4}.$$

GW SPECTRUM + GRAV-ONLY



GW EMISSION WITH A NEW FORCE

Including full $\dot{E}$, assuming same mass opposite charge w/ vector mediator:

$$q_1 = -q_2 \text{ and } m_1 = m_2$$

$$\frac{dE_{\rm GW}}{df_{{\rm GW},s}} = \frac{\pi\sqrt{a}\,(37e^4+292e^2+96)\,G'^{3/2}M_{\rm MDM}^{5/2}}{3\sqrt{2}\,[10\,a(1-e^2)(2+e^2)(\beta-1)+(37e^4+292e^2+96)\,G'M_{\rm MDM}]}$$

Dark EM GW