

GRAVITATIONAL WAVES FROM MORE ATTRACTIVE DARK BINARIES

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2312.13378 + 2412.15158 with: **Yang Bai, Sida Lu**

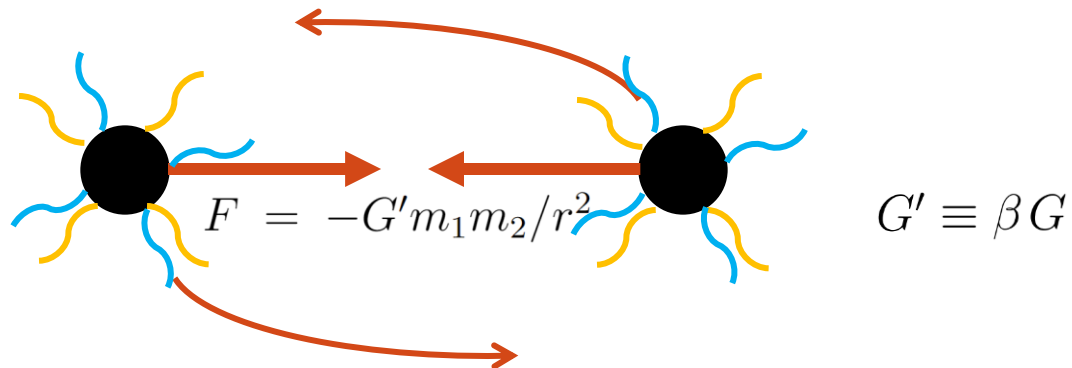
PAiP-2025 — Particle Astrophysics in Poland

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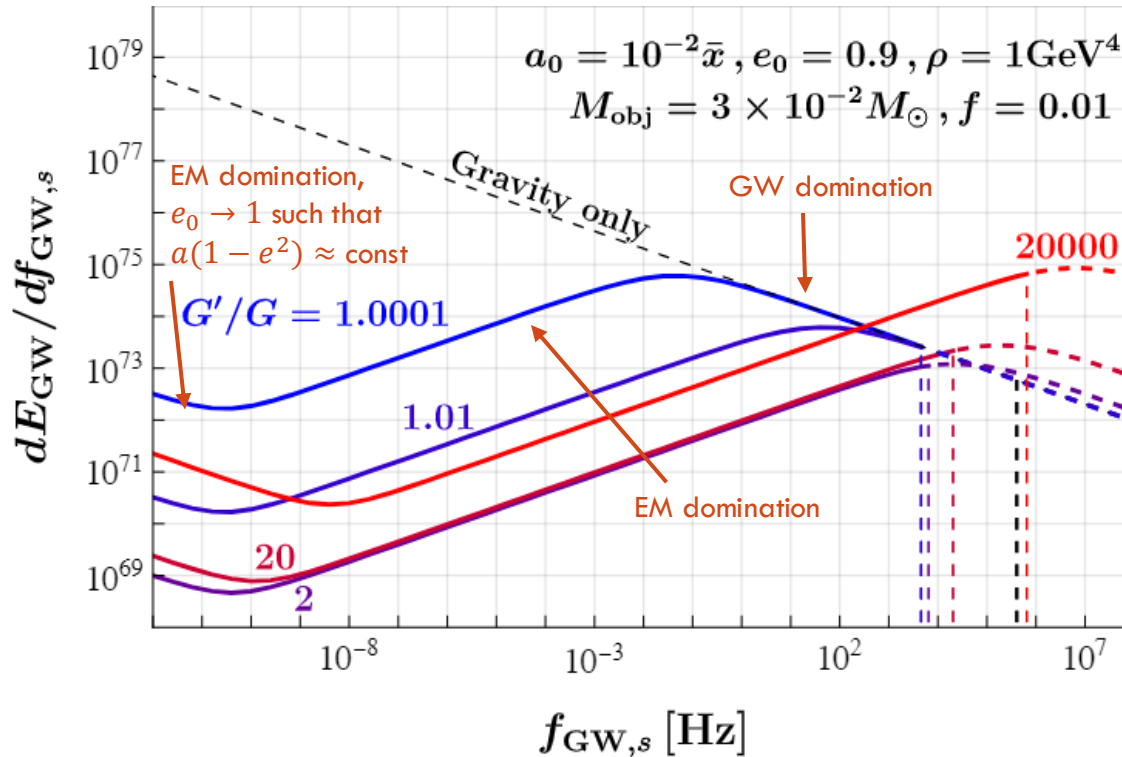


BASIC IDEA

- 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?



GW EMISSION WITH A MASSLESS-MEDIATOR DARK FORCE (INDIVIDUAL BINARY)

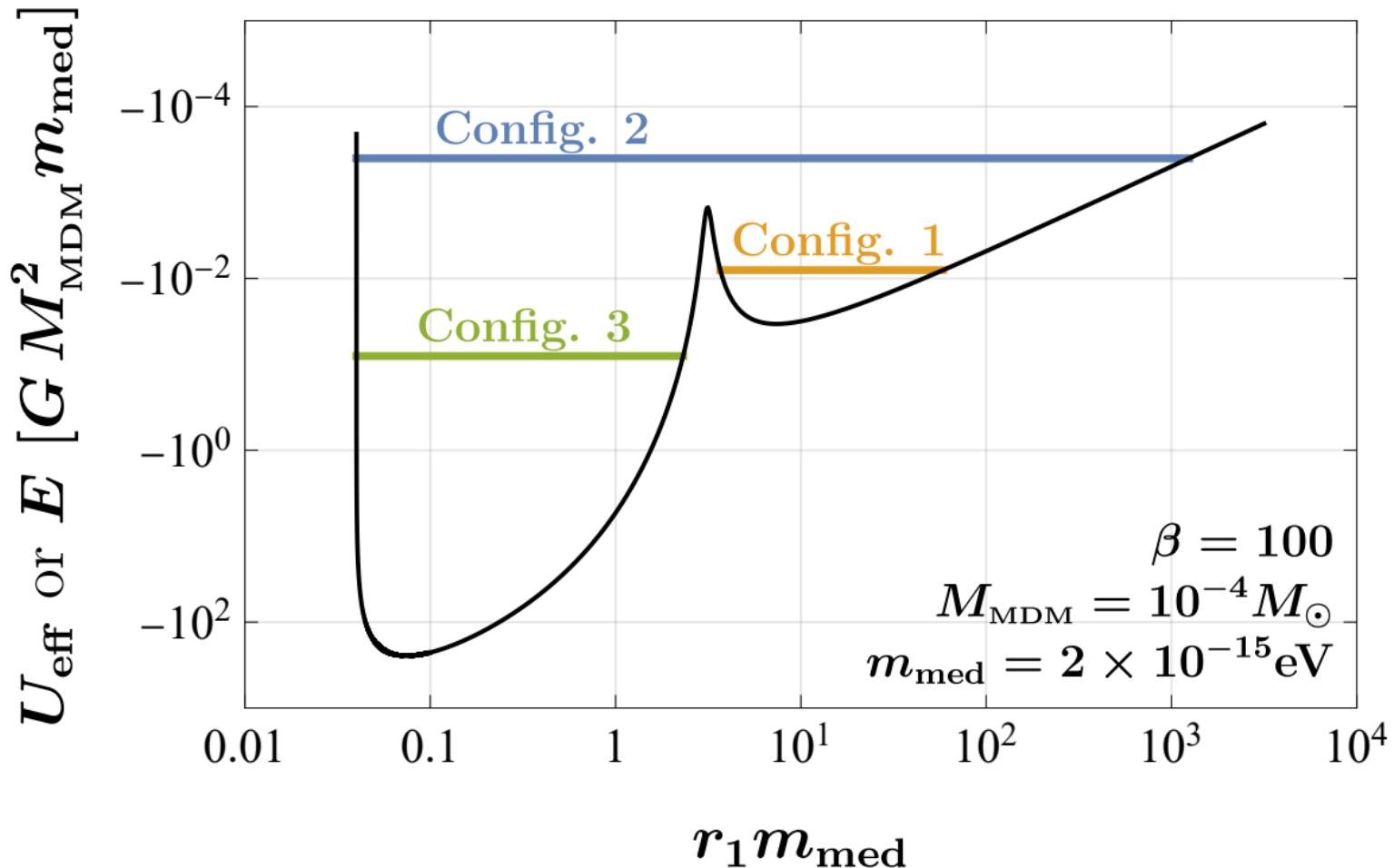


$$\frac{dE_{\text{GW}}}{df_{\text{GW},s}} = \frac{\pi \sqrt{a} (37e^4 + 292e^2 + 96) G'^{3/2} M_{\text{MDM}}^{5/2}}{3\sqrt{2} [10a(1 - e^2)(2 + e^2)(\beta - 1) + (37e^4 + 292e^2 + 96) G' M_{\text{MDM}}]}$$

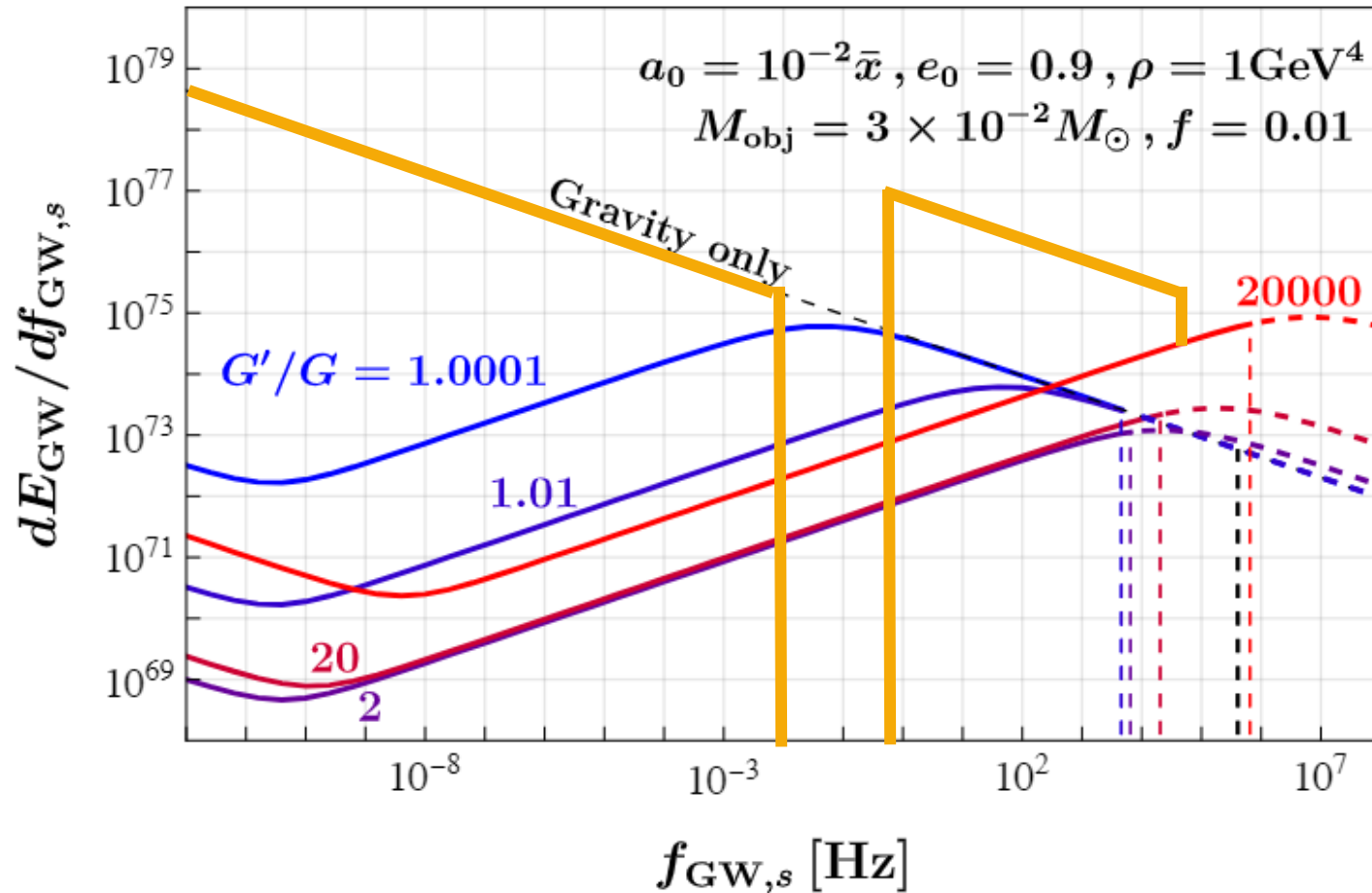
Dark EM
GW

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

GW EMISSION WITH A MASSIVE-MEDIATOR DARK FORCE (INDIVIDUAL BINARY)



GW EMISSION WITH A MASSIVE-MEDIATOR DARK FORCE (INDIVIDUAL BINARY)



BINARY FORMATION & 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;
Raïdal, Spethmann, Vaskonen, Veermae 1812.01930]

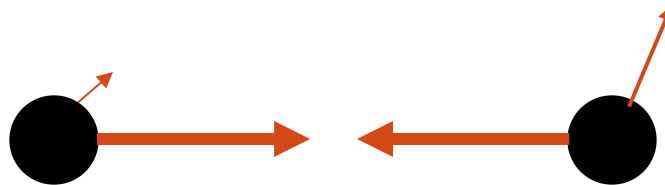
$$P(x, y) dx dy = \frac{9x^2 y^2}{\bar{x}^6} e^{-(y/\bar{x})^3} dx dy$$

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

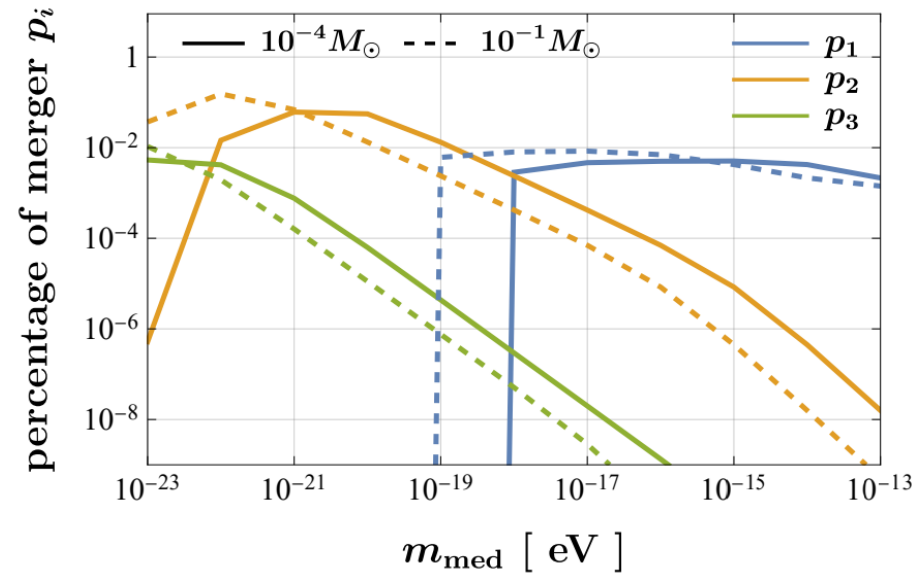
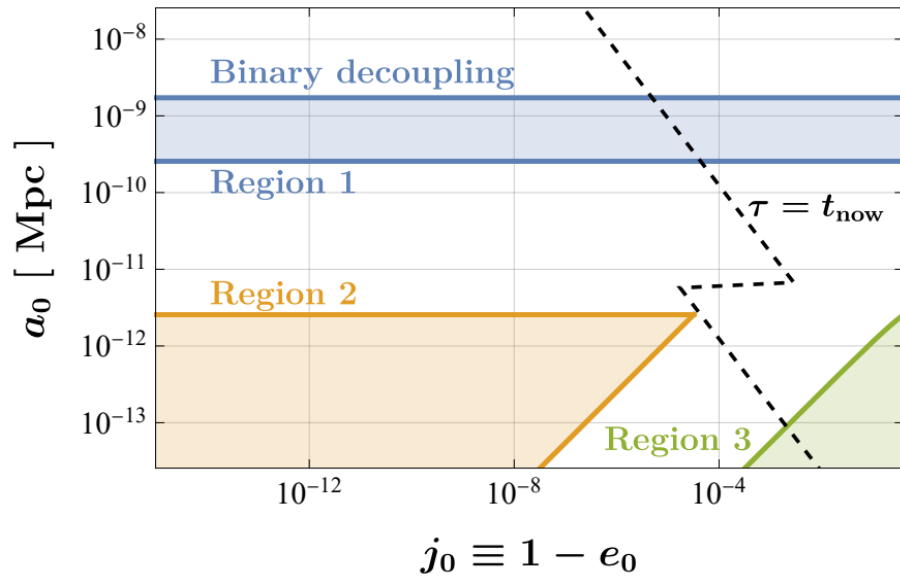
$$a_0 = \frac{c_1}{\beta} \frac{1}{f} \frac{x^4}{\bar{x}^3},$$

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

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

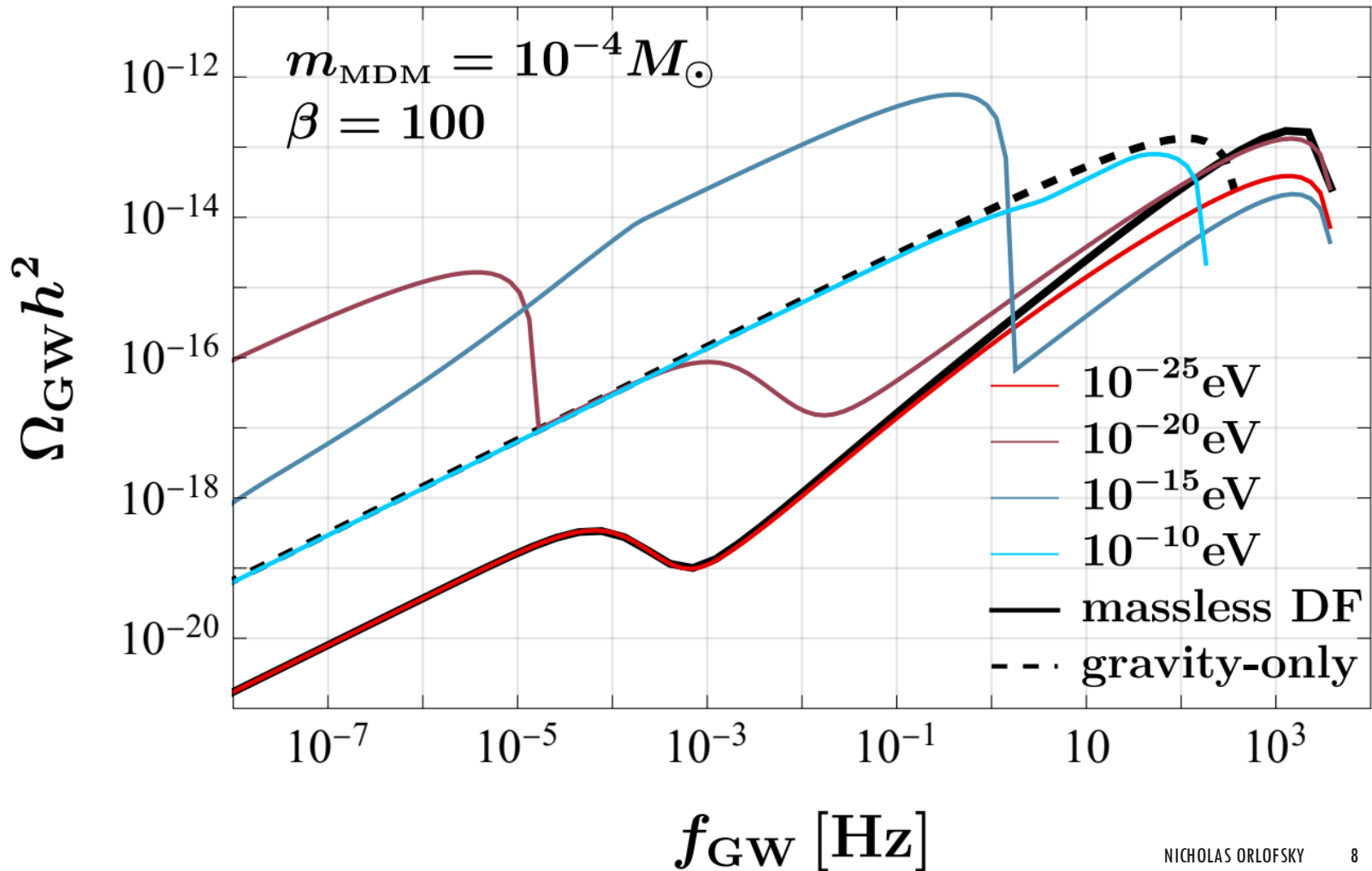


BINARY FORMATION & MERGERS

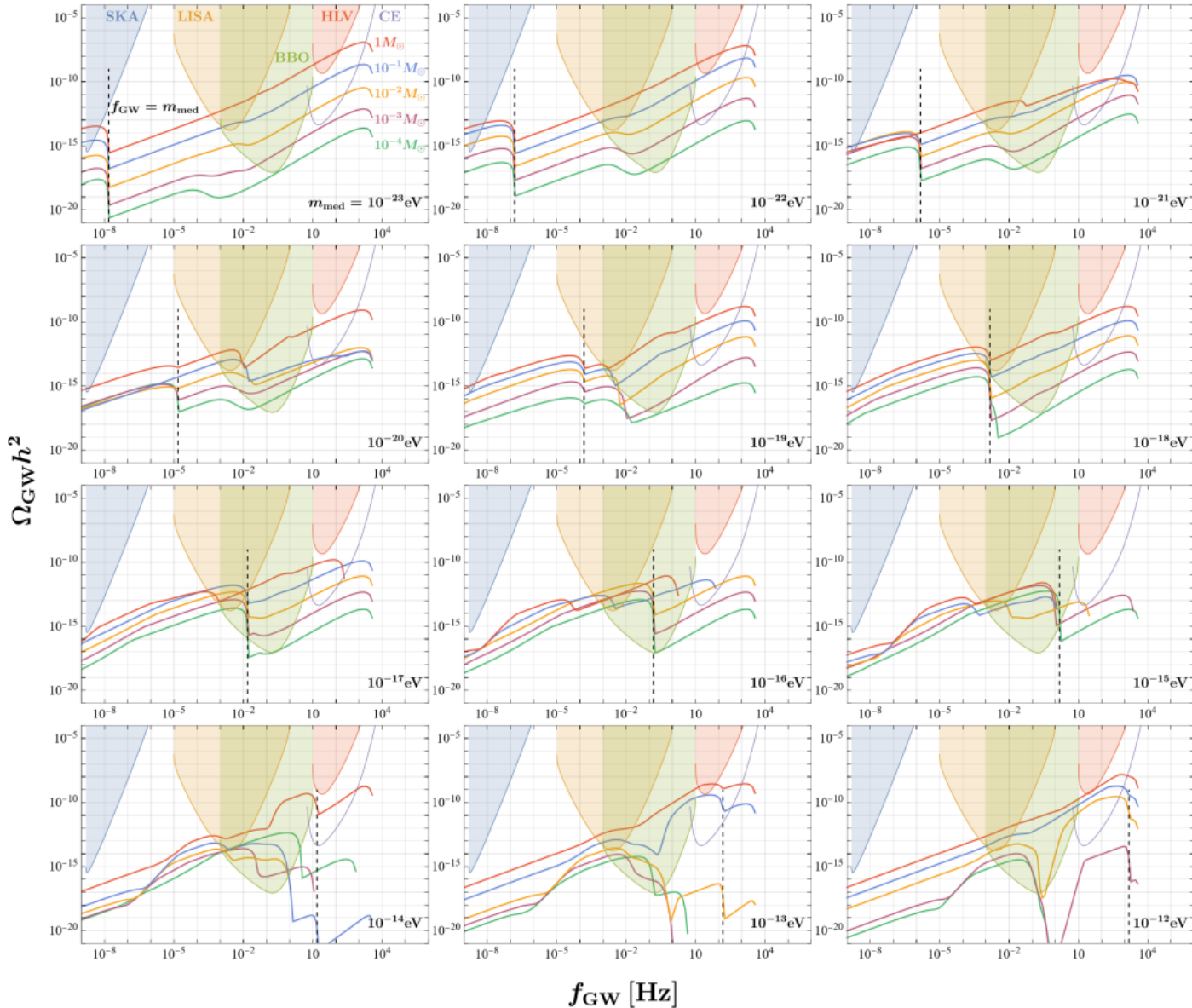


STOCHASTIC GW SIGNAL

$$\Omega_{\text{GW}}(f_{\text{GW}}) = \frac{f_{\text{GW}}}{\rho_c} \int de_0 da_0 \frac{n_{\text{MDM}}}{4} P(a_0, e_0) \frac{dE_{\text{GW}}}{df_{\text{GW},s}} [(1 + z(t(a_0, e_0))) f_{\text{GW}}]$$



STOCHASTIC GW SIGNAL



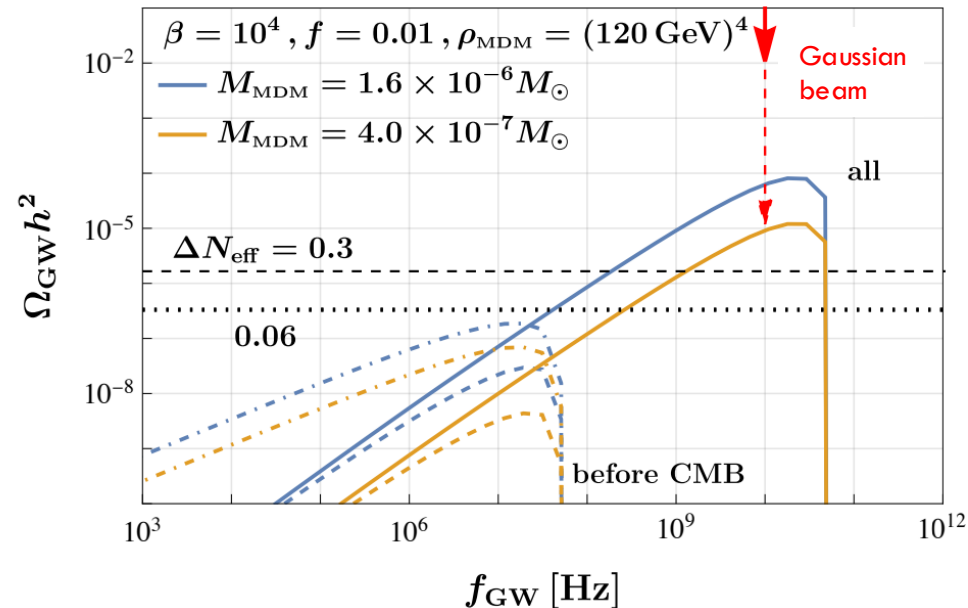
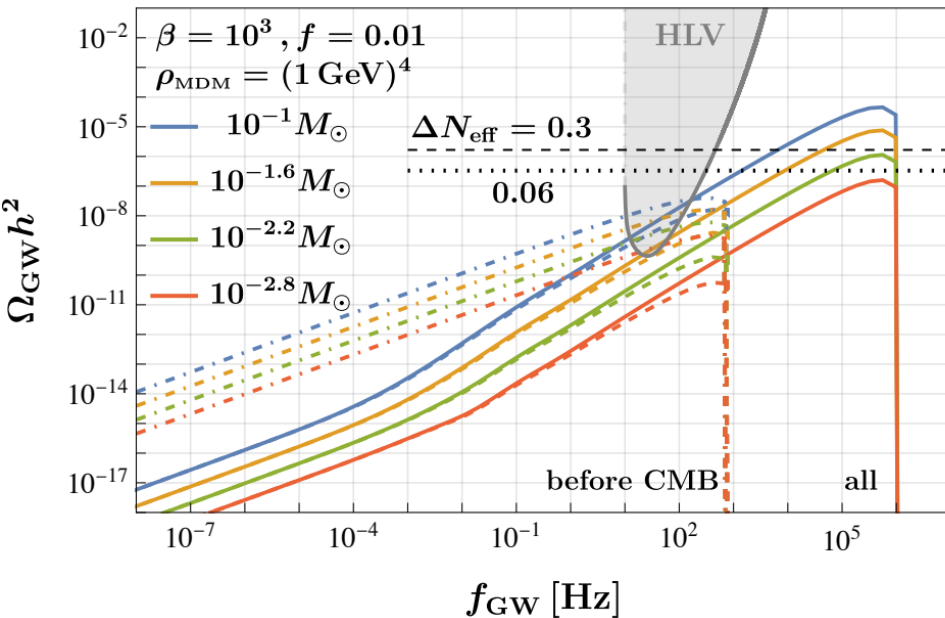
$$\rho_{\text{MDM}} = (0.1 \text{ GeV})^4,$$

$$\beta = 100, \text{ and } f_{\text{DM}} = 10^{-2}$$

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:



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:

$$\mathcal{L}_{\text{dQCD}} = \sum_{i=1}^{N_f} [\bar{\psi}_i i\gamma^\mu D_\mu \psi_i - m_{\psi_i} \bar{\psi}_i \psi_i] - \frac{1}{4} G_{\mu\nu}^a G^{\mu\nu a}$$
$$\mathcal{L}_{\text{Yukawa}} = \frac{1}{2} \partial_\mu \phi \partial^\mu \phi - \sum_i y_i \phi \bar{\psi}_i \psi_i - V(\phi)$$
$$\mathcal{L}_{\text{vector}} \supset -\frac{1}{2} m_{\text{med}}^2 V_\mu V^\mu + g \sum_i \mathbf{q}_i V_\mu \bar{\psi}_i \gamma^\mu \psi_i$$

SUMMARY

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

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

BACKUP



THE NEW FORCE

Total attractive force between two macroscopic DM:

$$F = -\frac{Gm_1m_2}{r^2} (1 - \alpha e^{-m_{\text{med}}r}(1 + m_{\text{med}}r))$$
$$\alpha = g^2q_1q_2/(4\pi Gm_1m_2)$$

In the massless mediator limit

$$m_{\text{med}} \ll r^{-1}$$
$$F = -G'm_1m_2/r^2$$
$$G' = (1 - \alpha)G \equiv \beta G$$
$$\omega^2 = \frac{Gm}{a^3} (1 - \alpha e^{-m_{\text{med}}a}(1 + m_{\text{med}}a)) \approx \frac{G'm}{a^3}$$
$$E = -\frac{Gm^2\eta}{2a} (1 - \alpha e^{-m_{\text{med}}a}(1 + m_{\text{med}}a)) \approx -\frac{G'm^2\eta}{2a}$$

$$m \equiv m_1 + m_2,$$
$$\eta \equiv \frac{\mu}{m} \equiv \frac{m_1m_2}{m^2},$$

GW EMISSION

Assuming only GW emission:

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

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

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

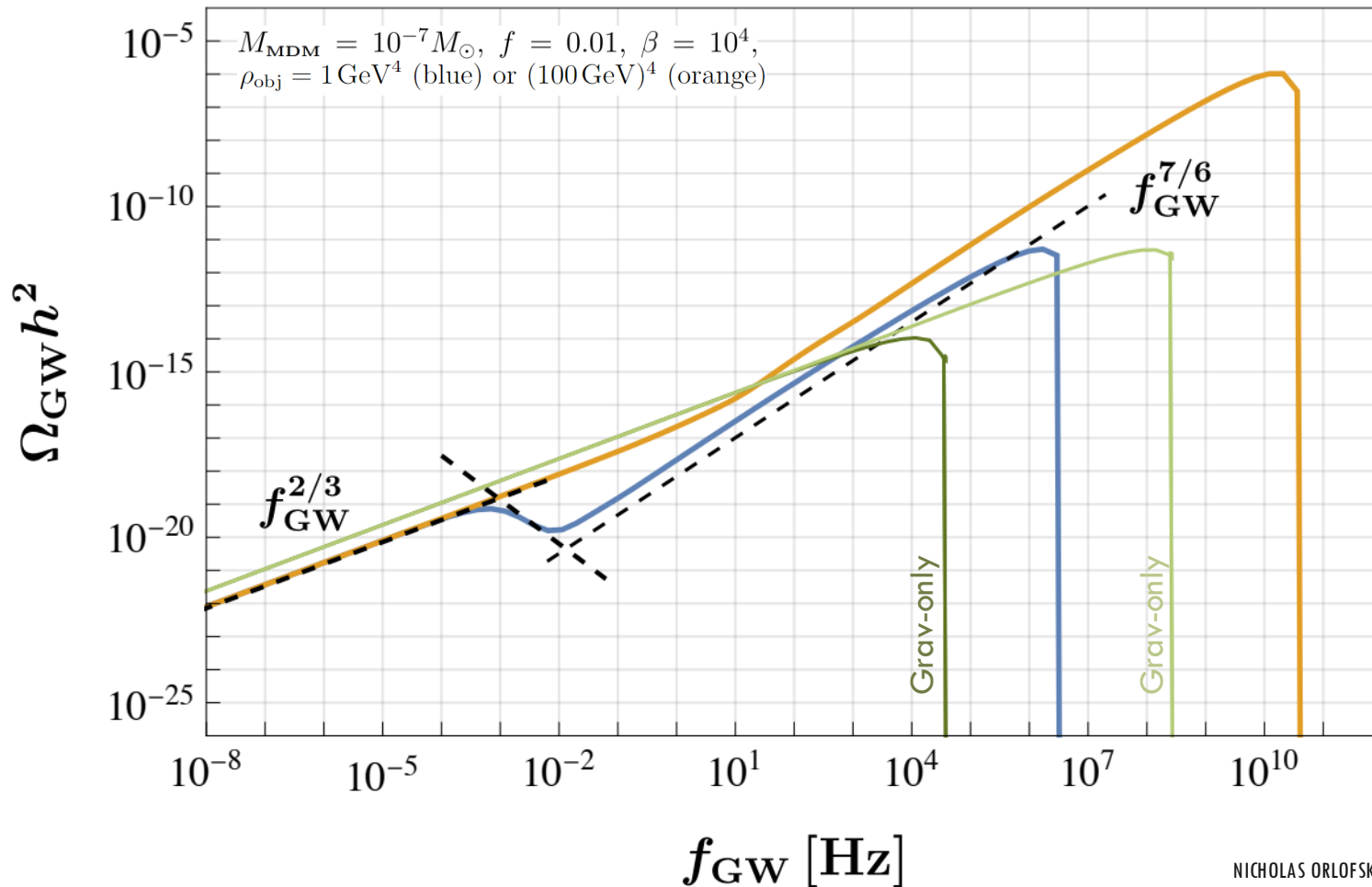
$$\frac{dE_{\text{GW}}}{df_{\text{GW}}} = \frac{\pi^{2/3}}{3} G'^{2/3} m^{5/3} \eta f_{\text{GW}}^{-1/3}$$

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

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

STOCHASTIC GW SIGNAL

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

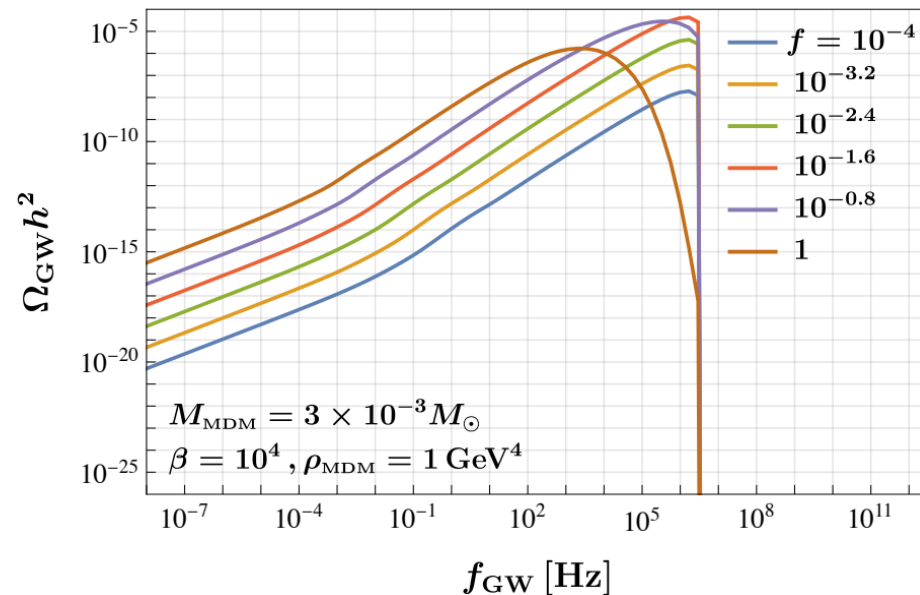
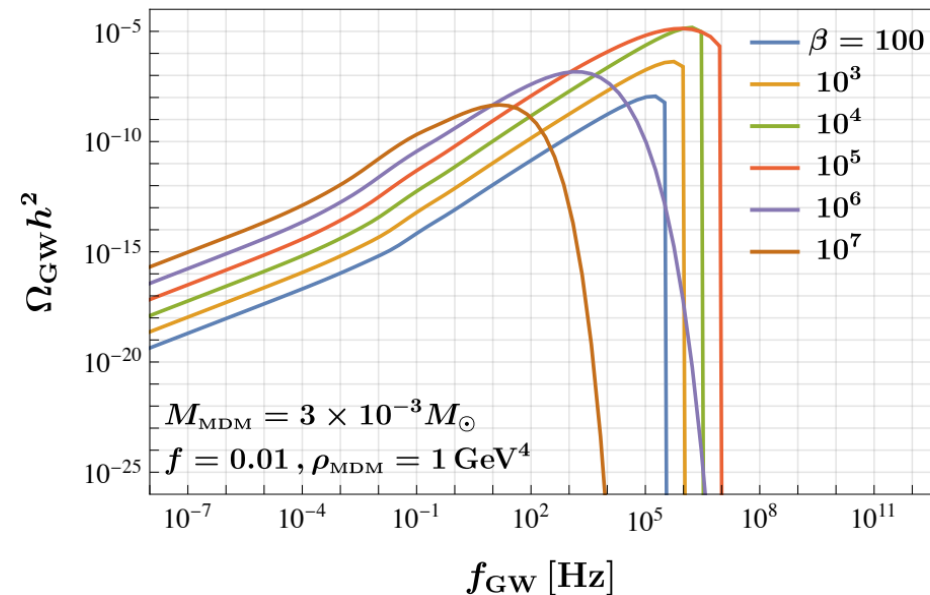


STOCHASTIC GW SIGNAL

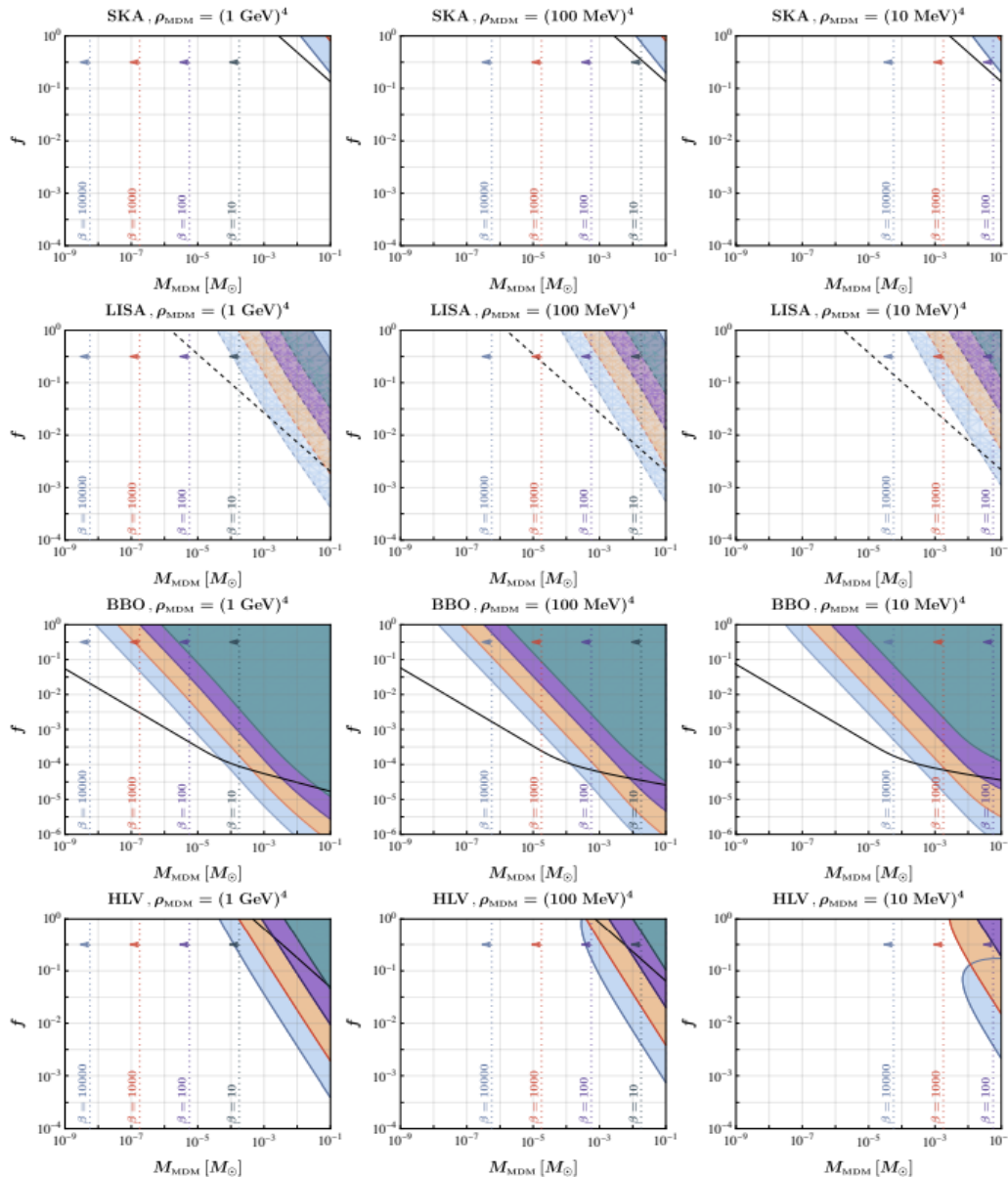
GWs cannot be arbitrarily enhanced.

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:

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

ASIDE ON CALCULATION OF EMISSION

Modified GW emission to including the new force:

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

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

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

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

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

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

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

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

ASIDE ON CALCULATION OF EMISSION

New (dark EM) force carrier emission:

$$\langle \dot{E}_{\text{EM}} \rangle = \frac{GG'^2}{12\pi} \eta^2 m^4 \left(\frac{gq_1}{\sqrt{Gm_1}} - \frac{gq_2}{\sqrt{Gm_2}} \right)^2 \frac{1}{a^4} \frac{2+e^2}{(1-e^2)^{5/2}}$$

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

$$\dot{a} = -\frac{2a^2}{G'm^2\eta} \dot{E}_{\text{EM}} = -\frac{GG'}{6\pi} \eta m^2 \left(\frac{gq_1}{\sqrt{Gm_1}} - \frac{gq_2}{\sqrt{Gm_2}} \right)^2 \frac{1}{a^2} \frac{2+e^2}{(1-e^2)^{5/2}},$$

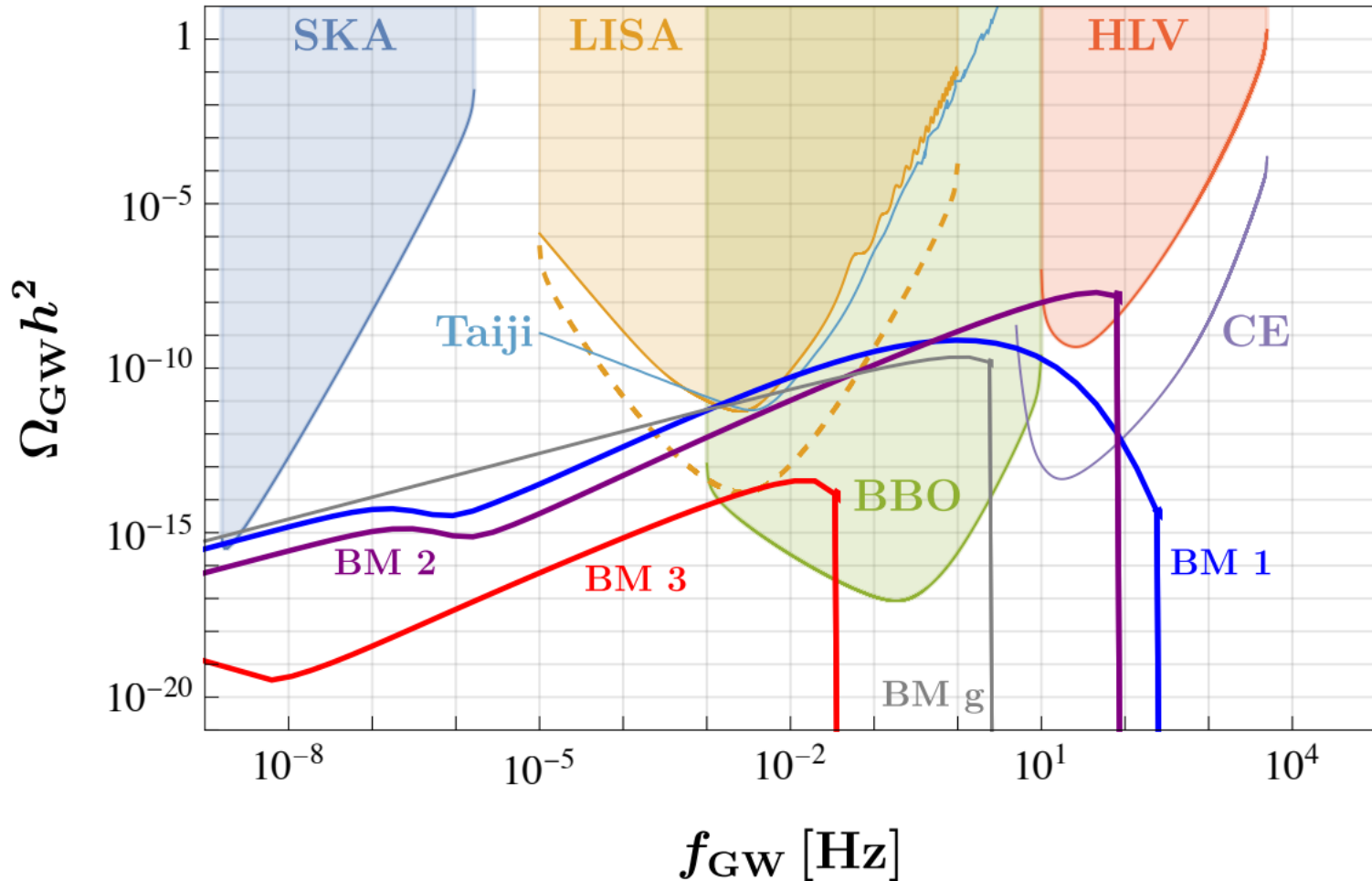
$$\dot{e} = -\frac{\dot{E}_{\text{EM}} L_{\text{EM}}^2 + 2E_{\text{EM}} L_{\text{EM}} \dot{L}_{\text{EM}}}{G'^2 m^5 \eta^3 e} = -\frac{GG'm^2 \eta e}{4\pi a^3 (1-e^2)^{3/2}} \left(\frac{gq_1}{\sqrt{Gm_1}} - \frac{gq_2}{\sqrt{Gm_2}} \right)^2$$

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

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

$$\tau = \frac{4\pi a_0^3}{GG'\eta m^2} \left(\frac{gq_1}{\sqrt{Gm_1}} - \frac{gq_2}{\sqrt{Gm_2}} \right)^{-2} \frac{(1-e_0^2)^{5/2} (1-\sqrt{1-e_0^2})^2}{e_0^4}.$$

STOCHASTATIC GW SIGNAL



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

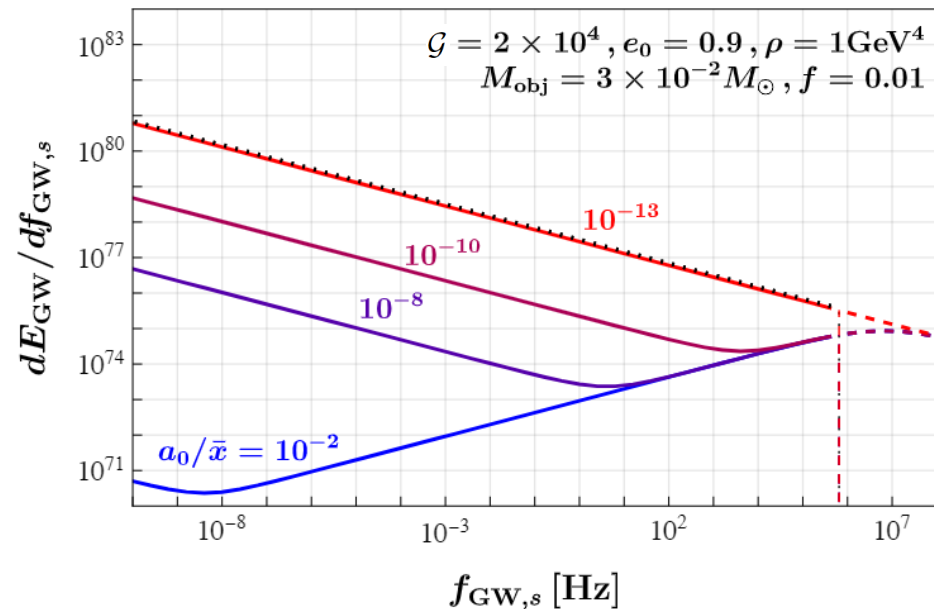
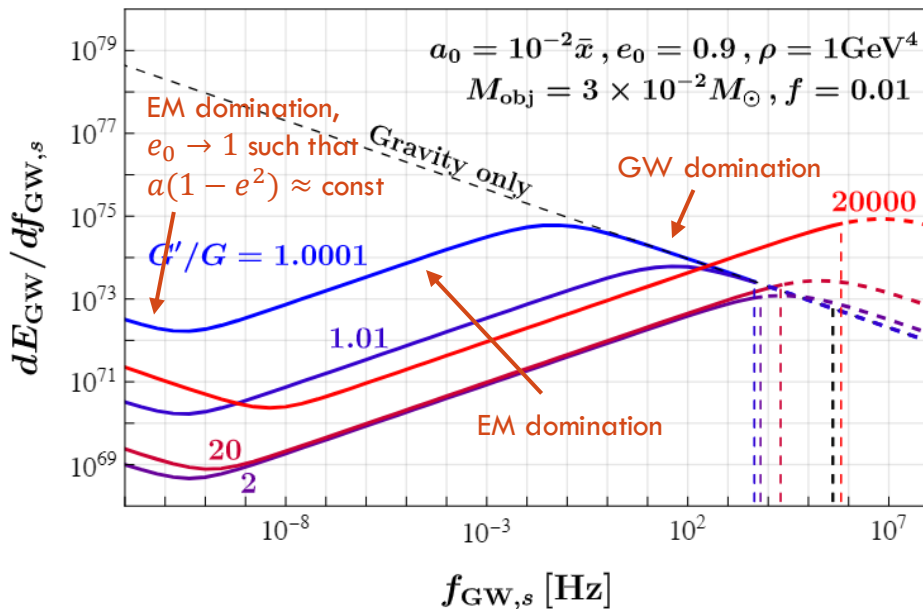
GW EMISSION WITH A NEW FORCE

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

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

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

Dark EM
GW



GW EMISSION WITH A MASSIVE NEW FORCE

