Gravitational Wave form Phase Transition in Holographic QCD

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Outline

- Review of the gravitational wave
- Gravitational wave from 1st-order phase transition
- Holographic QCD models
- Gravitational wave spectrum
- Conclusion

Meng-Wei Li, YY and Pei-Hung Yuan, arXiv:1812.09676

GW Spectrum and Detection

- Ground interferometers

  $10^{0} \sim 10^{5}$ Hz

- Space interferometers

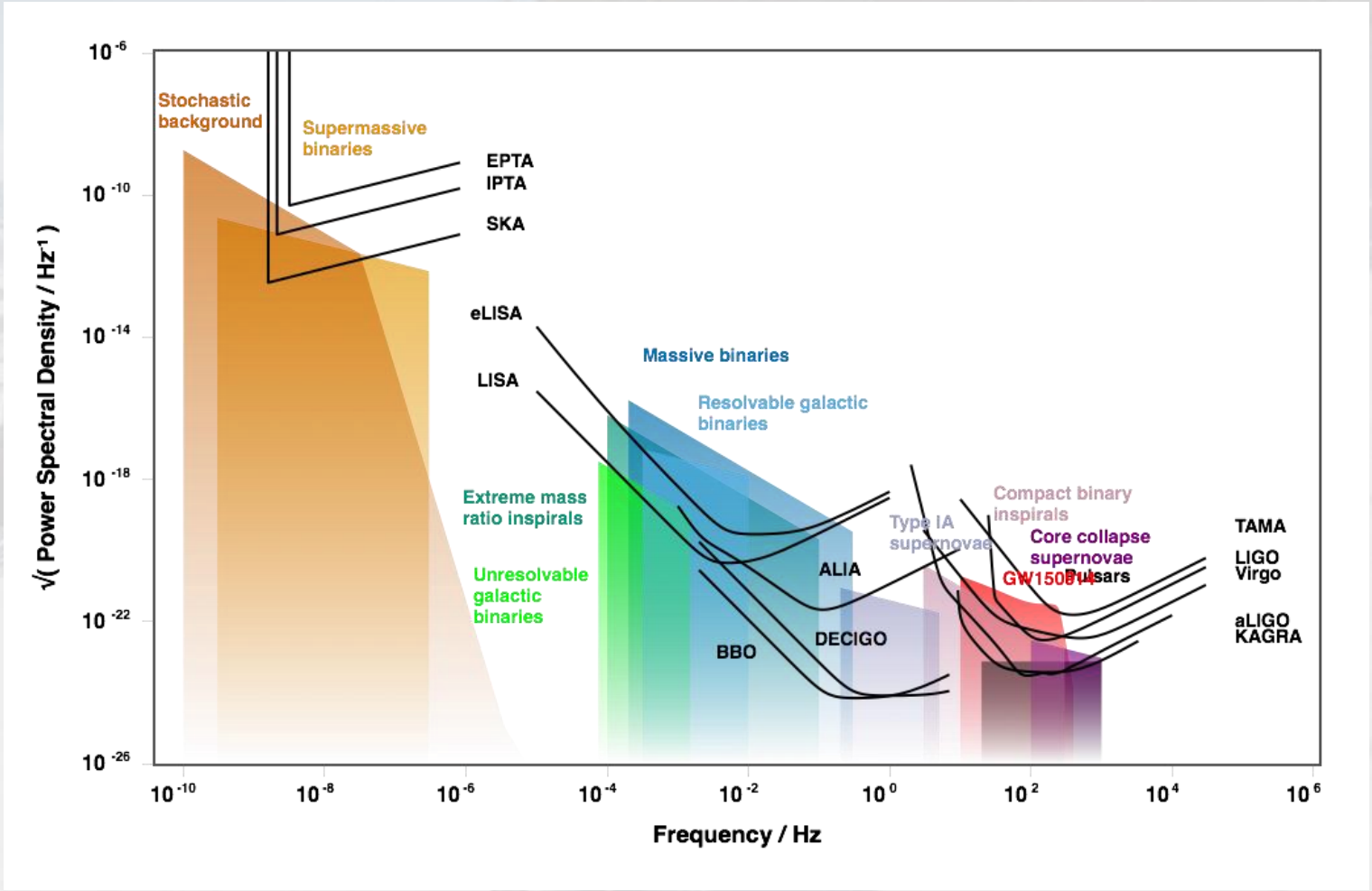
  $10^{-1} \sim 10^{-5}$ Hz

- Pulsar timing array

  $10^{-6} \sim 10^{-9}$ Hz

- CMB polarization

  $10^{-16} \sim 10^{-18}$ Hz

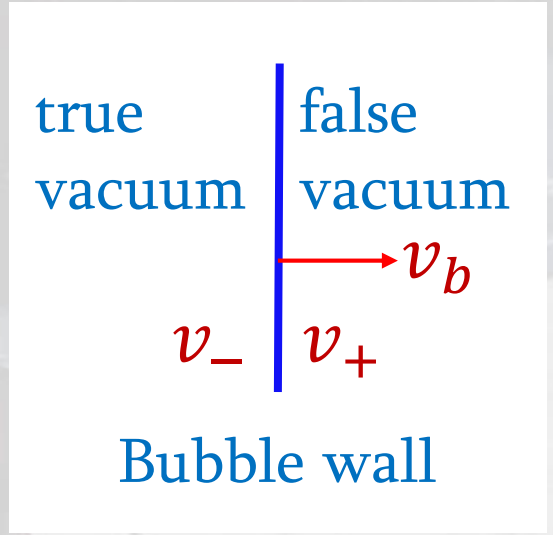


GW Sources

- Binary systems:
  - BH merges
- Phase transitions:
  - cosmic string, domain wall…
- Primordial universe: B-mode in CMB
  - Inflation, reheating…

Bubble Nucleation

- False vacuum → true vacuum: bubble wall
- Speed of bubble wall $v_b \leq c$
- Detonation: $v_+ > v_-$
- Deflagration: $v_+ < v_-$

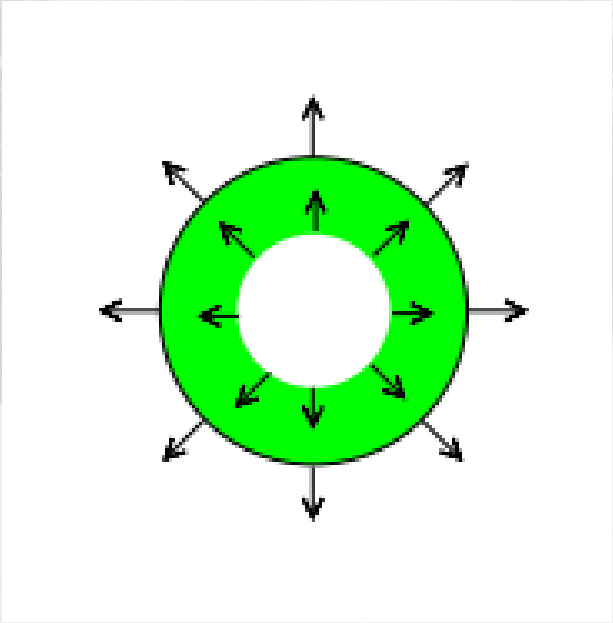


$$v_+ = \frac{1}{1+\alpha}\left[\left(\frac{v_-}{2}+\frac{1}{6v_-}\right) \pm \sqrt{\left(\frac{v_-}{2}+\frac{1}{6v_-}\right)^2 - \frac{1}{3} + \alpha^2 + \frac{2}{3}\alpha}\right]$$

Bubble Expansion

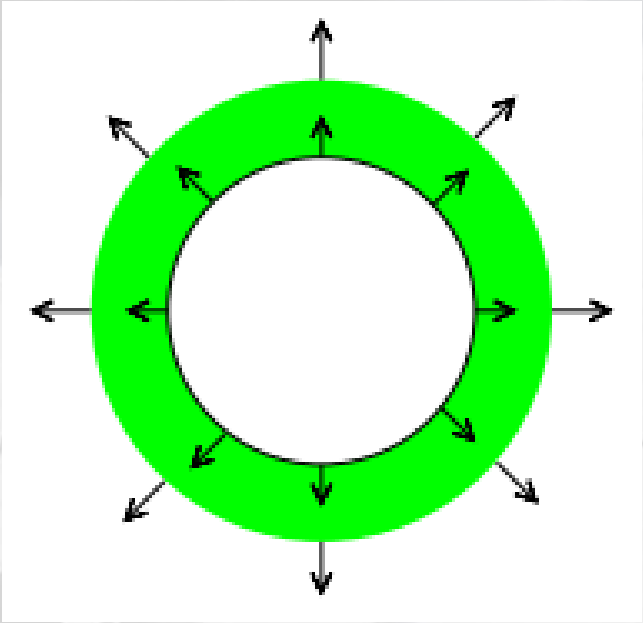
detonation

$v_b > c_s \Rightarrow v_+ > v_-$



deflagration

$v_b < c_s \Rightarrow v_+ < v_-$



GW Contributions

- Bubble collision Ω_{en}
  - thin shell & envelope approximation
- Magnetohydrodynamics (MHD) turbulent Ω_{tu}
  - inflation, reheating…
- Sound waves Ω_{sw}

GW Spectrum

- Runaway bubbles: $v_b \sim c$

  $\Omega_{tot} = \Omega_{en} + \Omega_{sw} + \Omega_{tu}$

- Non-runaway bubbles: $\Omega_{tot} = \Omega_{sw} + \Omega_{tu}$

  - Detonations: $v_b > c_s$
  - Defragrations: $v_b < c_s$

GW from Bubble Collision

$$h^2\Omega_{en} = 3.5\times10^{-5}\left(\frac{0.11v_b^3}{0.42+v_b^2}\right)\left(\frac{H_*}{\tau}\right)^2\left(\frac{\kappa\alpha}{1+\alpha}\right)^2\left(\frac{10}{g_*}\right)^{1/3} S_{en}(f)$$

$$S_{en}(f) = \frac{3.8(f/f_{en})^{2.8}}{1+2.8(f/f_{en})^{3.8}}$$

$$f_{en} = 1.13\times10^{-8}[Hz]\left(\frac{f_*}{\tau}\right)\left(\frac{\tau}{H_*}\right)\left(\frac{T_*}{100MeV}\right)\left(\frac{g_*}{10}\right)^{1/6}$$

$$\frac{f_*}{\tau} = \frac{0.62}{1.8-0.1v_b+v_b^2}, \qquad \kappa = 1-\frac{\alpha_\infty}{\alpha}$$

GW from Sound Waves

$$h^2\Omega_{sw} = 5.7 \times 10^{-6} v_b \left(\frac{H_*}{\tau}\right)^2 \left(\frac{\kappa_v \alpha}{1+\alpha}\right)^2 \left(\frac{10}{g_*}\right)^{1/3} S_{sw}(f)$$

$$S_{sw}(f) = \left(\frac{f}{f_{sw}}\right)^3 \left(\frac{7}{4 + 3(f/f_{sw})^2}\right)^{7/2}$$

$$f_{sw} = 1.3 \times 10^{-8}[Hz] \left(\frac{1}{v_b}\right)\left(\frac{\tau}{H_*}\right)\left(\frac{T_*}{100MeV}\right)\left(\frac{g_*}{10}\right)^{1/6}$$

$$\kappa_v = \frac{v_b^{6/5} 6.9\alpha}{1.36 - 0.037\sqrt{\alpha} + \alpha} = \frac{\sqrt{\alpha}}{0.135 - \sqrt{0.98 + \alpha}}$$

GW from MHD Turbulent

$$h^2\Omega_{tu} = 7.2\times10^{-4} v_b \left(\frac{H_*}{\tau}\right)^2 \left(\frac{\kappa_{tu}\alpha}{1+\alpha}\right)^2 \left(\frac{10}{g_*}\right)^{1/3} S_{tu}(f)$$

$$S_{tu}(f) = \frac{(f/f_{tu})^3}{(1+f/f_{tu})^{11/3}(1+8\pi f/h_*)^3}$$

$$f_{tu} = 1.3\times10^{-8}[Hz]\left(\frac{1}{v_b}\right)\left(\frac{\tau}{H_*}\right)\left(\frac{T_*}{100MeV}\right)\left(\frac{g_*}{10}\right)^{1/6}$$

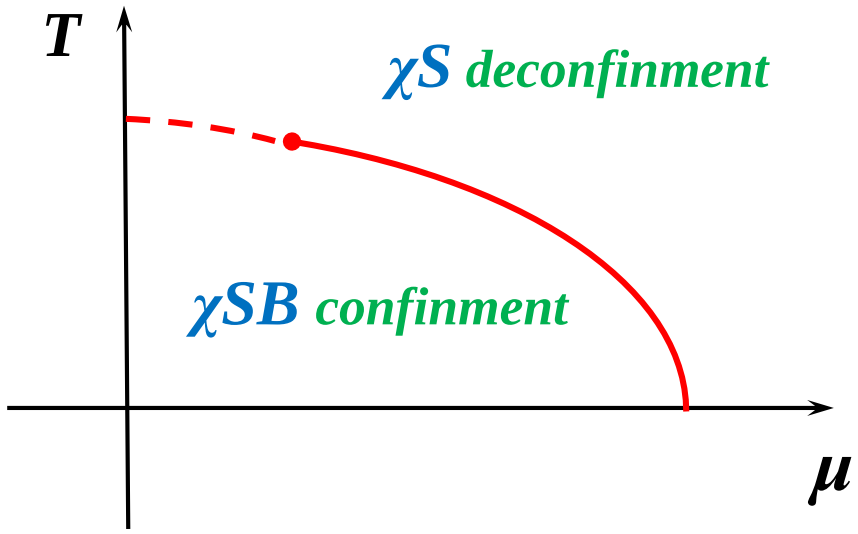
$$\kappa_{tu} = \epsilon\kappa_v, \qquad h_* = 1.1\times10^{-8}[Hz]\left(\frac{T_*}{100MeV}\right)\left(\frac{g_*}{10}\right)^{1/6}$$

Thermal Energy Density

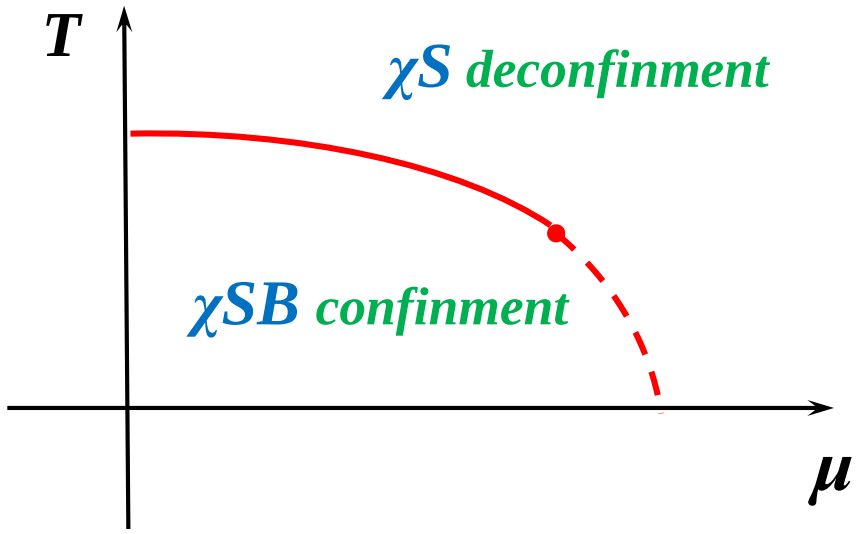
$$\alpha = \frac{\epsilon_*}{\frac{\pi^2}{30} g_* T_*^4}$$

$$\epsilon_* = \left[-\Delta F(T) + T \frac{d}{dT} \Delta F(T) \right]_{T=T_*}$$

Phase Diagram of QCD



Light quarks



Heavy quarks

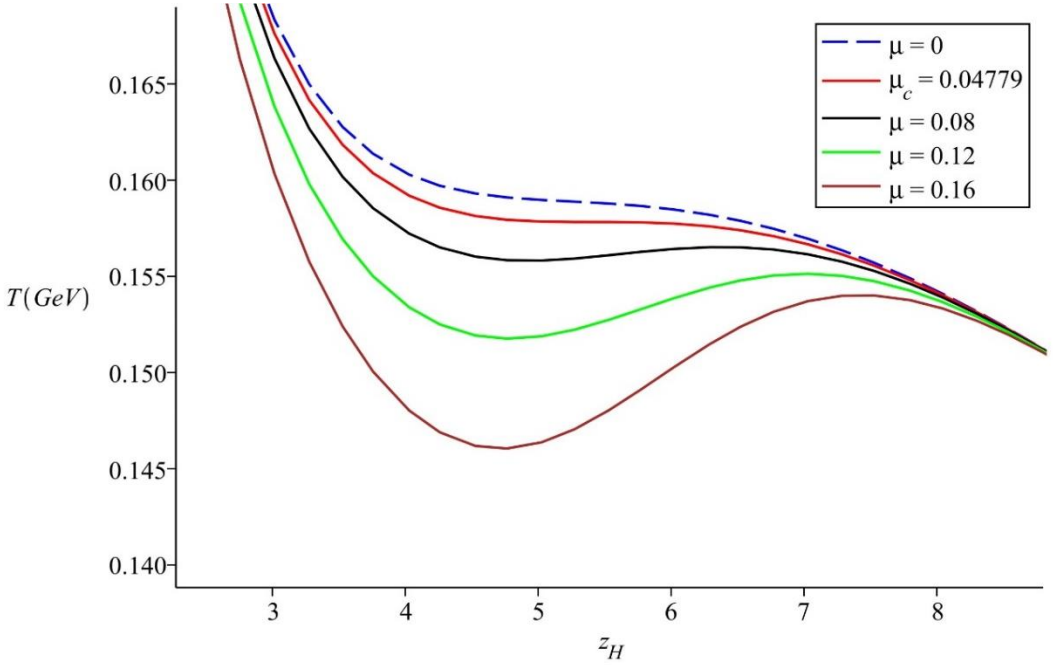
Holographic QCD Model

- Einstein-Maxwell-Scalar system

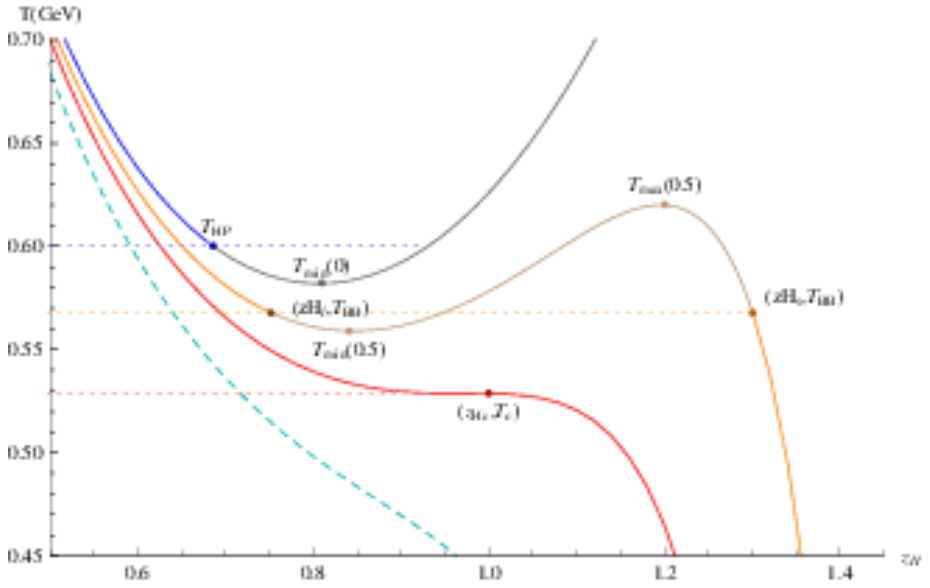
$$S_b = \int d^5x \sqrt{-g} \left[R - \frac{f(\phi)}{4} F^2 - \frac{1}{2} \partial\phi\partial\phi - V(\phi) \right]$$

- A family of analytic black hole solutions
- Chemical potential
- Regge meson spectrum
- Confinement-deconfinement phase transition

Temperature

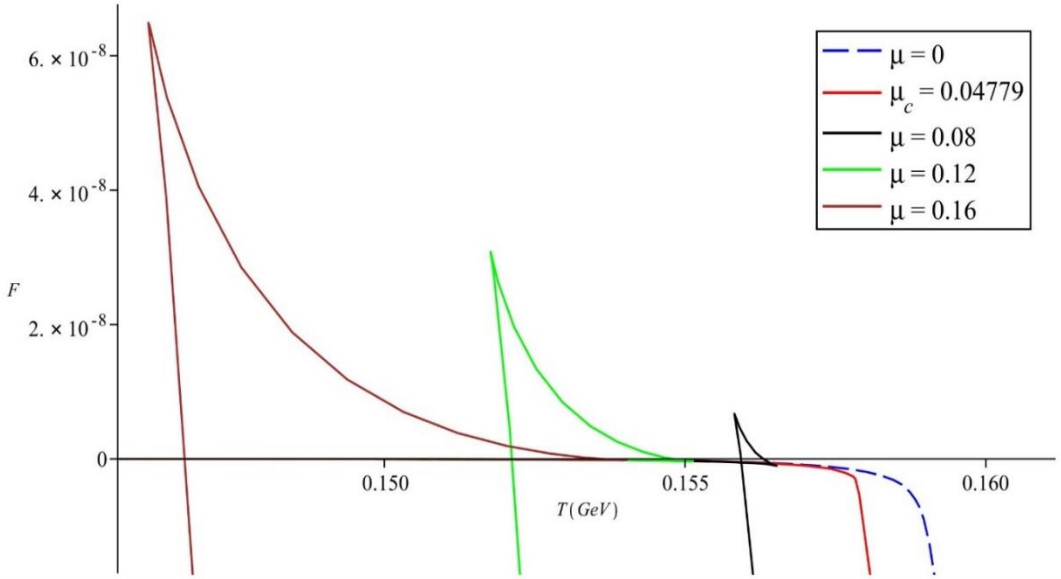


Light quarks

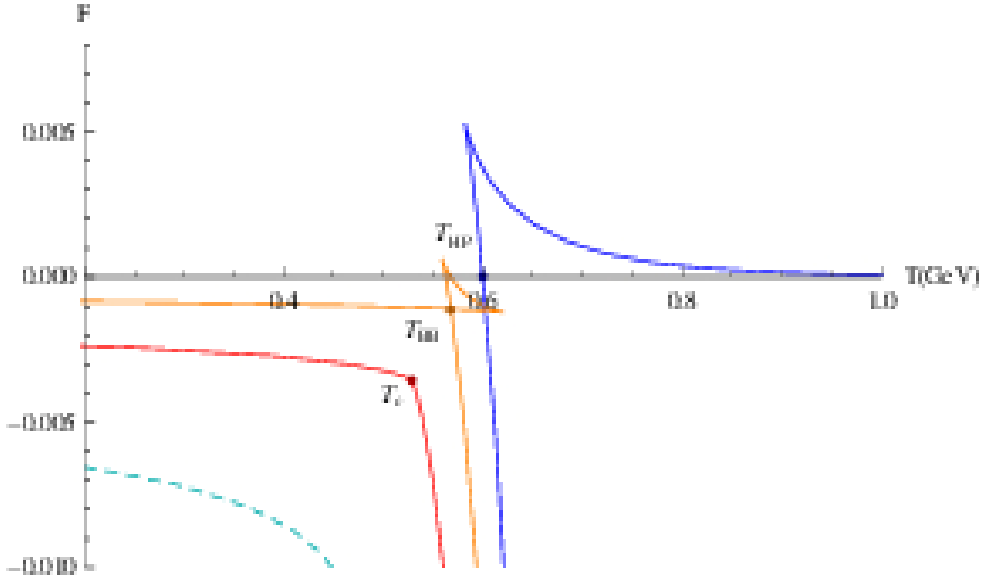


Heavy quarks

Free Energy

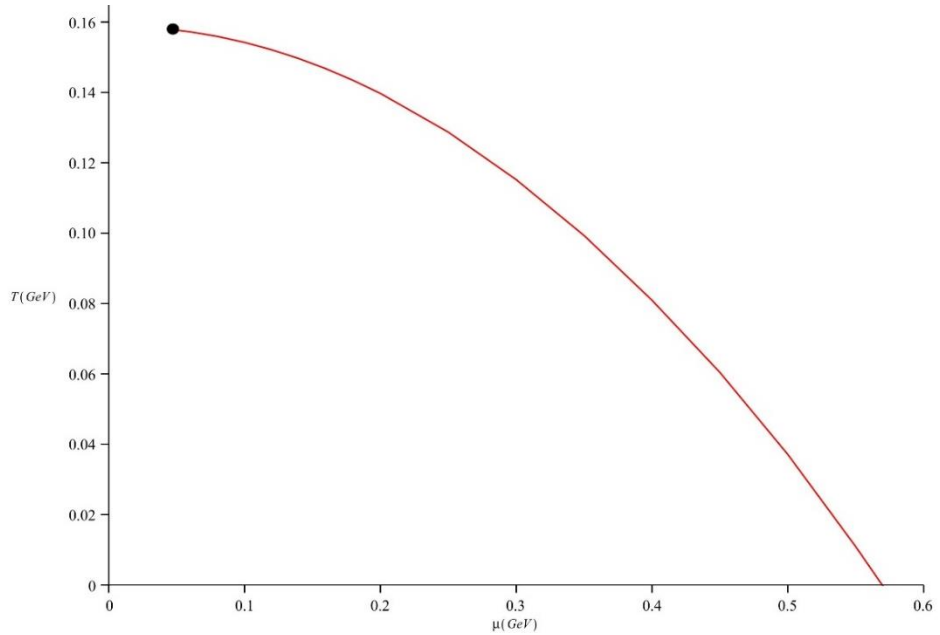


Light quarks

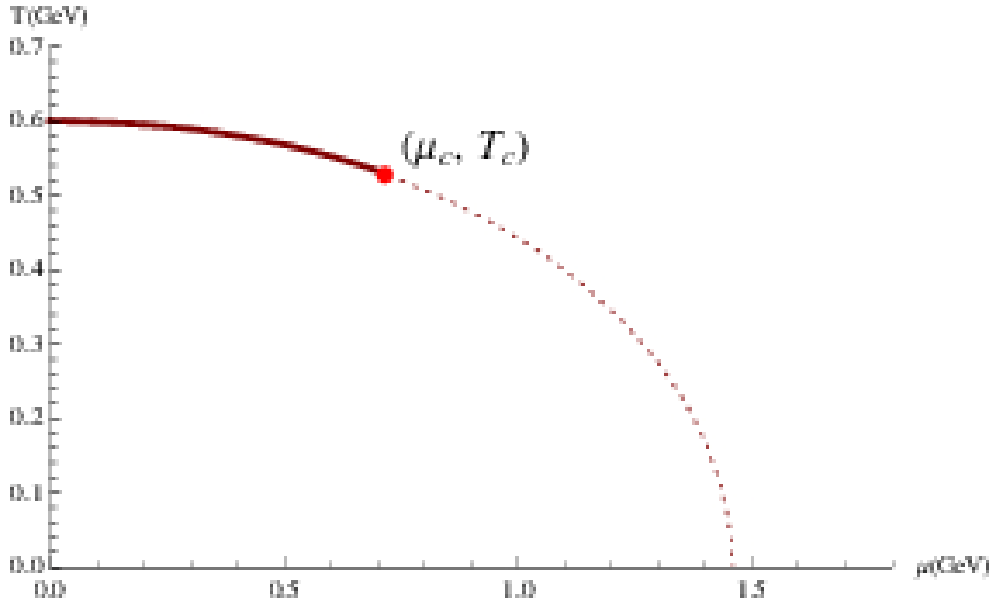


Heavy quarks

Phase Diagram

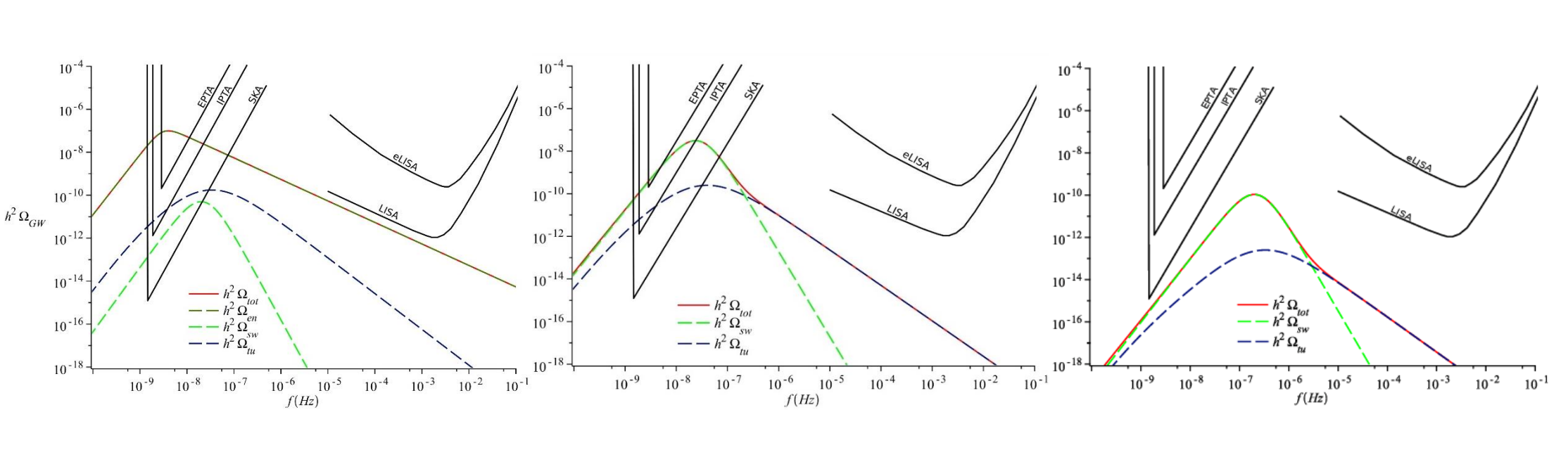


Light quarks



Heavy quarks

GW Spectrum for Light Quarks



Runaway

$v_b \sim c$

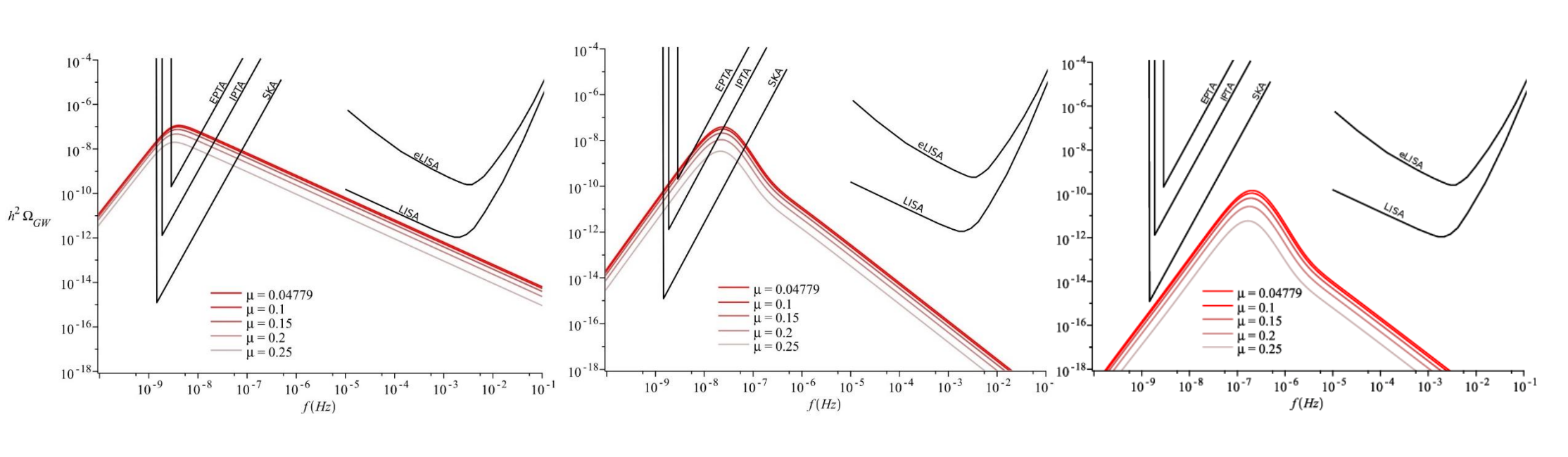
Detonation

$v_b > c_s$

Deflagration

$v_b < c_s$

GW Spectrum for Light Quarks



Runaway

$v_b \sim c$

Detonation

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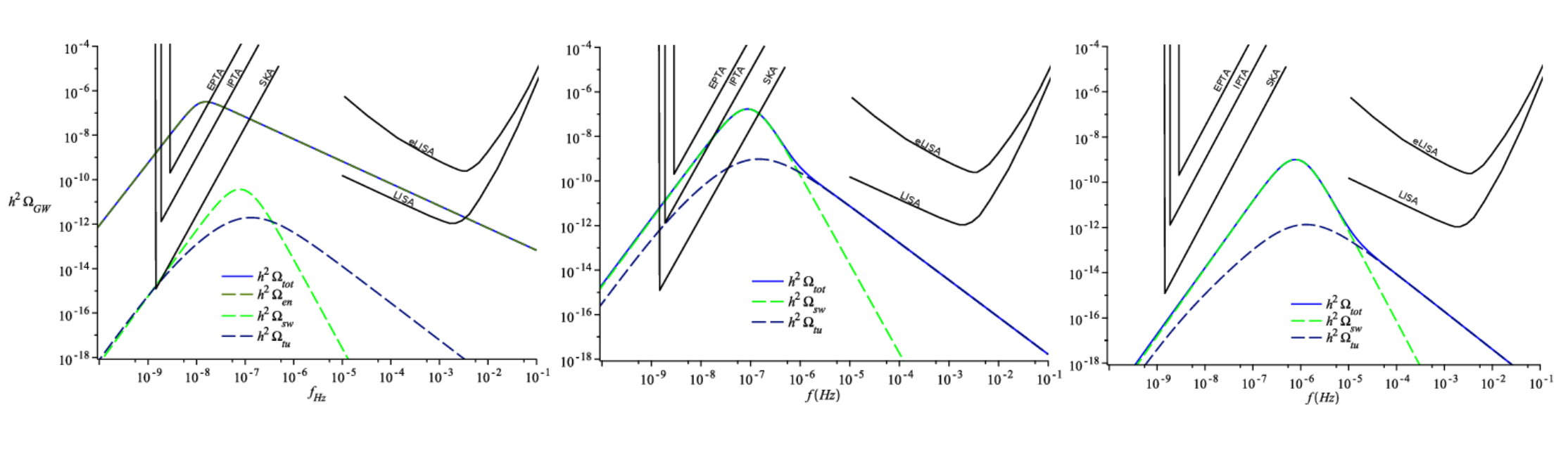
Deflagration

$v_b < c_s$

GW Spectrum for Heavy Quarks



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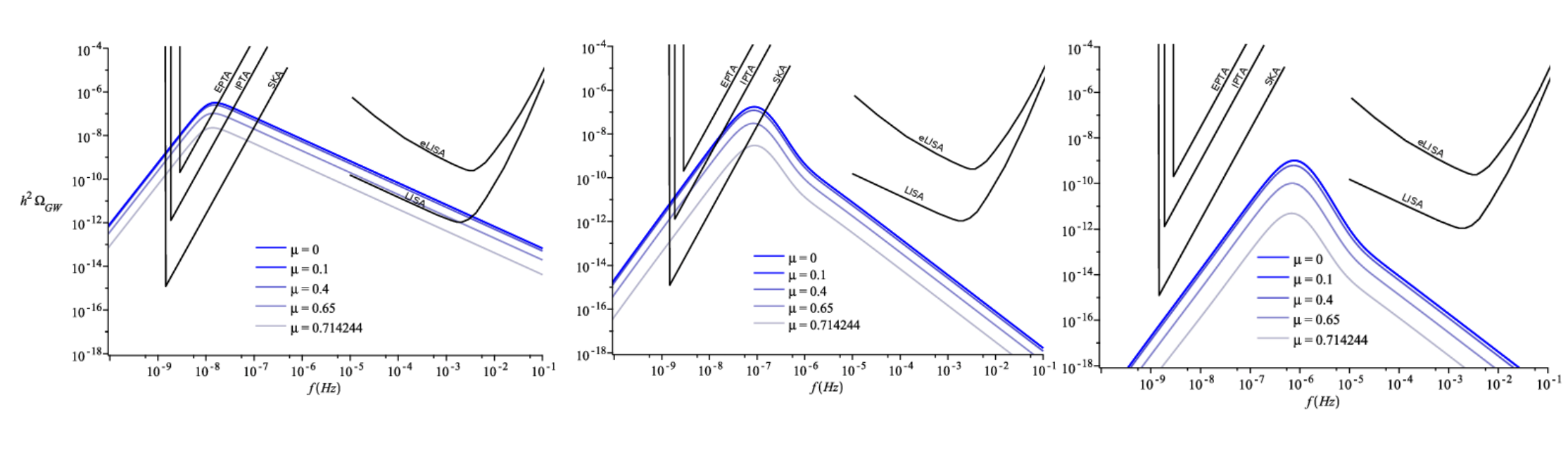
GW Spectrum for Heavy Quarks



Runaway

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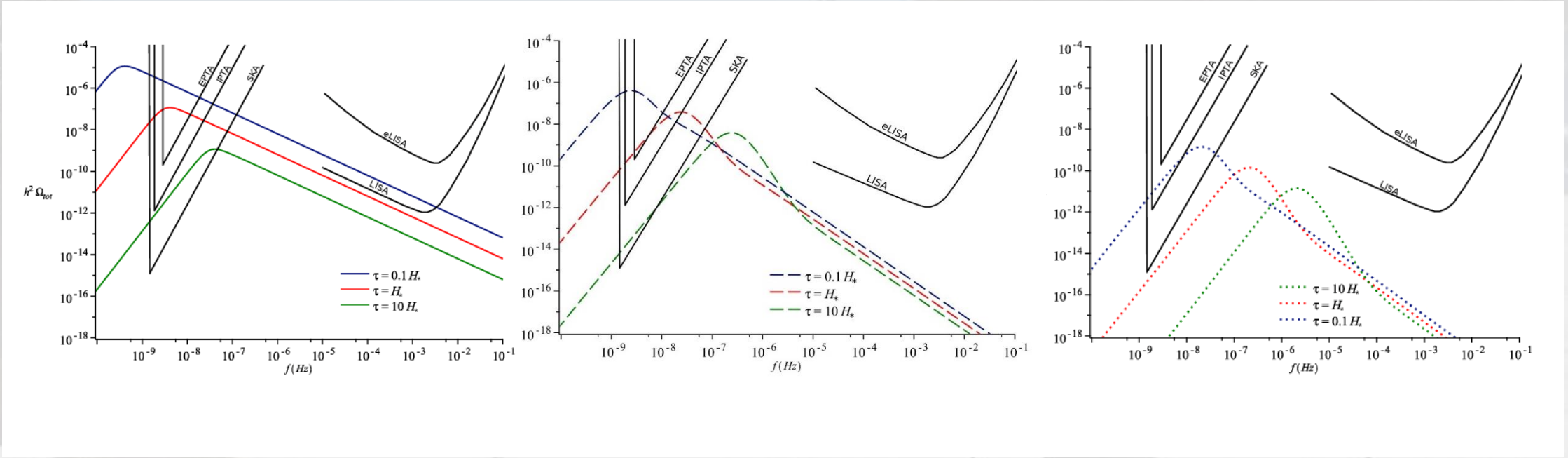
Duration of Phase Transition



Runaway

$v_b \sim c$

Detonation

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Deflagration

$v_b < c_s$

Summary

- AdS/QCD
- Phase transition
- GW sources:

  runaway

  detonation

  deflagration