A brief update on Nambu-Goto cosmic string models and the stochastic GW background from cosmic string loops

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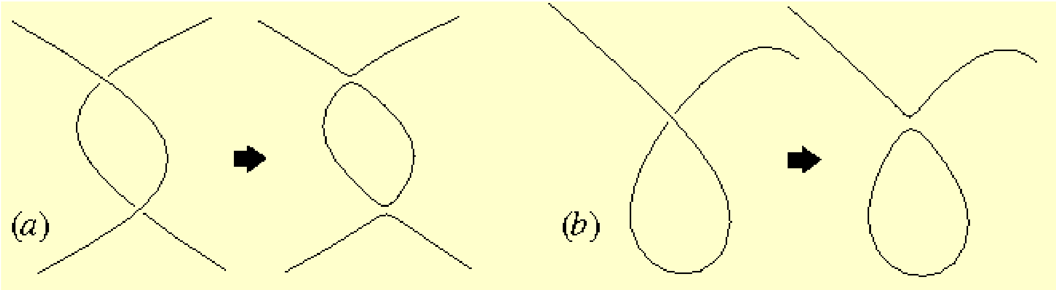
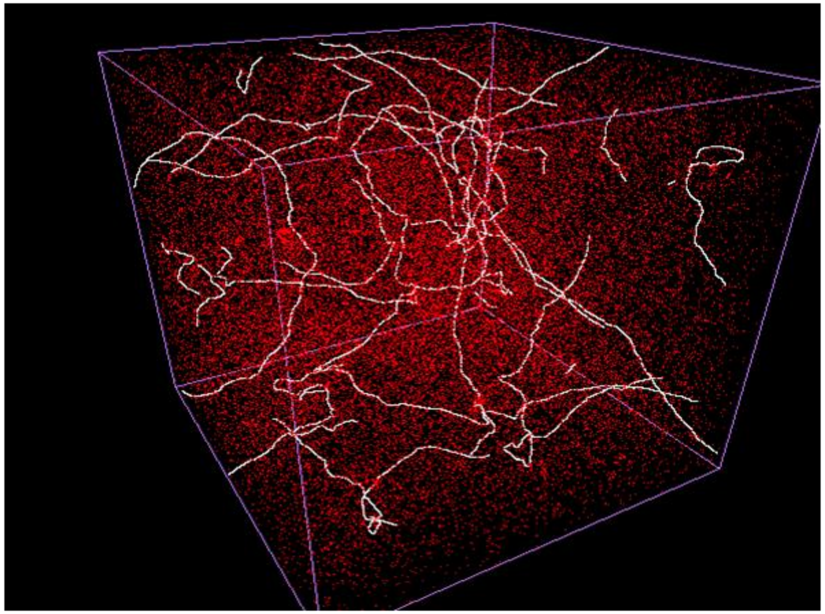
16-20 October 2017, Mainz

Nambu-Goto string network reaches a scaling regime ($G\mu$):
long strings loose energy in the form of smaller loops + GWs





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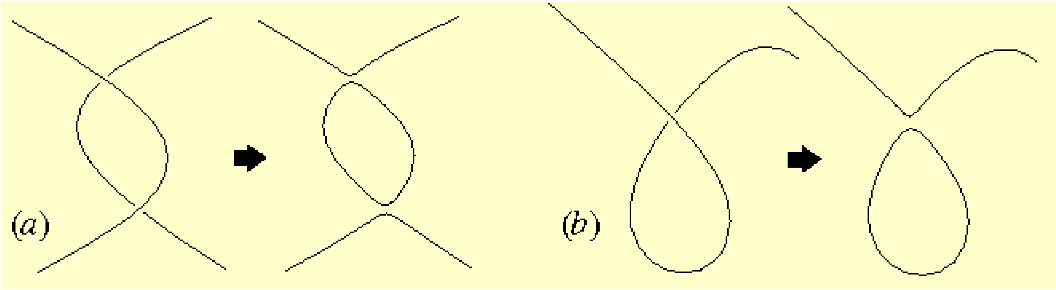
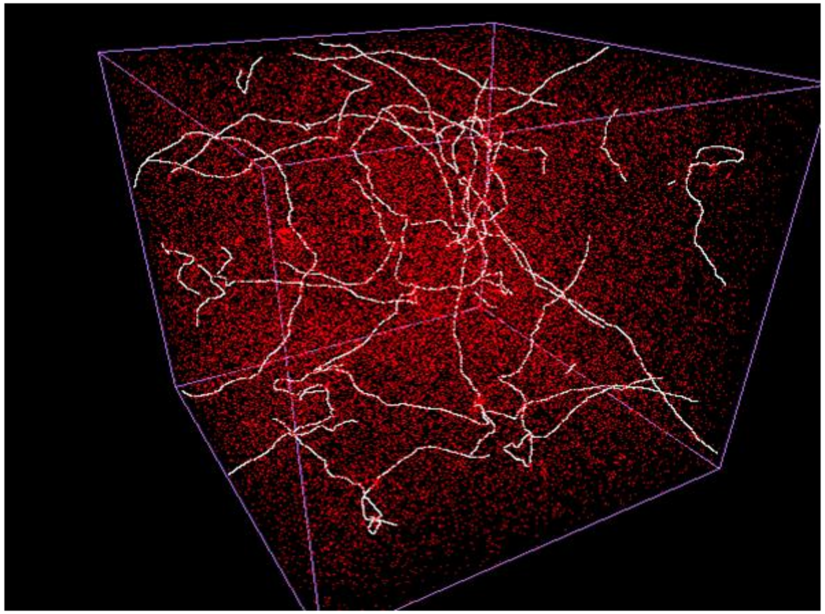
⇨ stochastic GW background: **GW frequencies are multiples of** $\omega = 4\pi/l$





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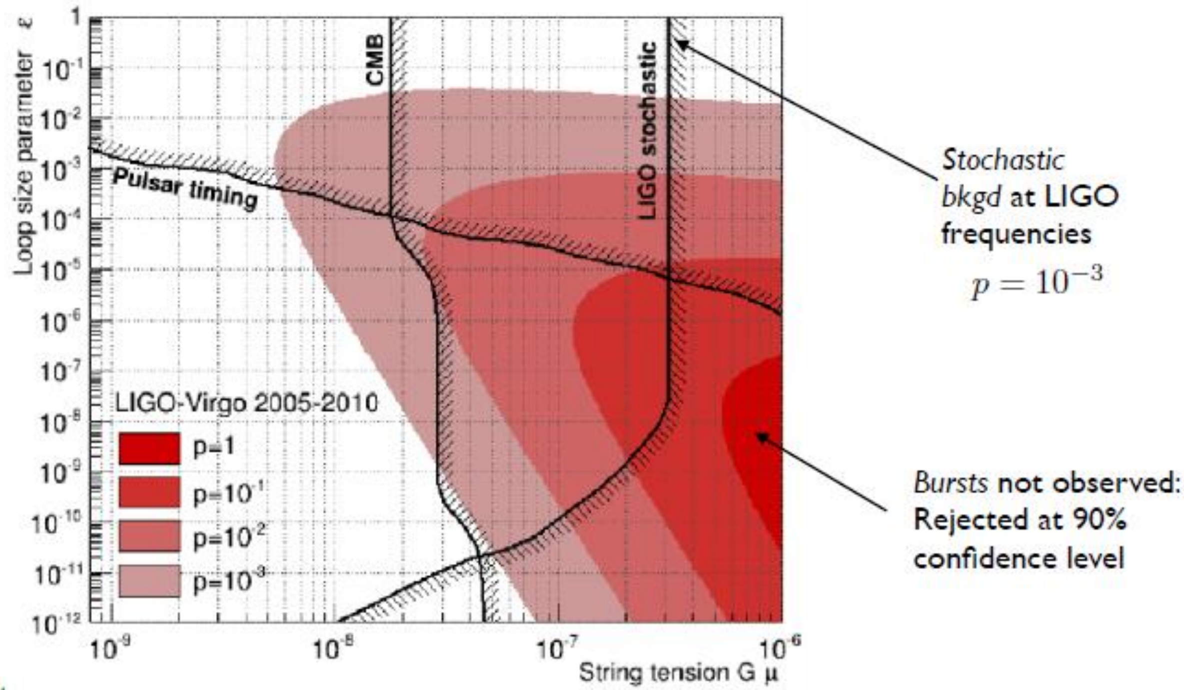
Constraints on Cosmic Strings from the LIGO-Virgo Gravitational-Wave Detectors.

PRL 112 (2014) 131101



$\ell_f = \epsilon(\Gamma G\mu)t$

– loops assumed to be formed with tiny size (fraction of horizon size), decay in a Hubble time

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- power law shape of loop distribution (through NG simulations)

Ringeval, Sakellariadou, Bouchet (2007)
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○ GW emission

$$P_{\rm GW} = \Gamma G\mu^2 \qquad \Gamma \sim \mathcal{O}(50)$$

Assumes about 1 kink/cusp per loop

⇨ *GW evaporation dominates for loops of size* $l < \Gamma G\mu t$

max scale to trust simulations

$$\gamma_{\rm d} \equiv \Gamma G\mu$$

GW emission length scale in units of t

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modified by:

- GW emission
- GW back-reaction $l_c < l_d$

GW back-reaction scale in units of t

$$\gamma_c = \Upsilon (G\mu)^{1+2\chi} \text{ where } \Upsilon \sim 10 \text{ and } \chi = 1 - P/2,$$

$$P = 1.41^{+0.08}_{-0.07}\big|_{\rm mat}, \qquad P = 1.60^{+0.21}_{-0.15}\big|_{\rm rad}$$

Polchinski, Rocha (2006)
Dubath, Polchinsk, Rocha (2018)

Ringeval, Sakellariadou, Bouchet (2007)
Lorentz, Ringeval, Sakellariadou (2010)

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modified by:

- GW emission
- GW back-reaction
- GW signal depends on number of cusps and kinks

Not known from simulations

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- GW emission
- GW back-reaction
- GW signal depends on number of **cusps** and kinks

cusps → $\omega^{-4/3}$ kinks → $\omega^{-5/3}$

Damour, Vilenkin (2001)

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Blanco-Pillado, Olum, Shlaer (2015)
Wachter, Olum (2017)
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Some recent results

Ringeval, Suyama 1709.03845

Lorentz, Ringeval, Sakellariadou (2010)
Ringeval, Sakellariadou, Bouchet (2007)

$$\frac{\rho_{\rm gw}}{\rho_{\rm crit}} \equiv \int_0^{+\infty} \frac{d\omega}{\omega} \Omega_{\rm gw}(\omega)$$

Distinction between Individually separable events (bursts) and the stochastic background is done (as usually) through the value of $|h_{\mu\nu}(\omega)|^2$

$$\hat{\Omega}_{\rm sgw}(\omega) \equiv \frac{\Omega_{\rm sgw}(\omega)}{c_\alpha^2}$$

Γ may change...

Numerical constant that contains all theoretical uncertainties associated with type of GW source (cusps, kinks, kink-kink collisions)

amplitude decays as $\boxed{\omega^{-2}}$ *but #events per loop oscillations goes as square of # kinks*

$$c_3 \equiv \frac{\eta_s^2 \sqrt{2}}{(2\pi\beta)^{2/3}}, \qquad c_{3/2} \equiv \frac{2\eta_s \sqrt{2v_\pm^2}}{(2\pi\beta)^{1/3}}, \qquad c_1 \equiv 4\sqrt{2v_+^2 v_-^2}$$

$\eta_s \simeq 4.1$. $\quad \beta = \mathcal{O}(1)$

Some recent results

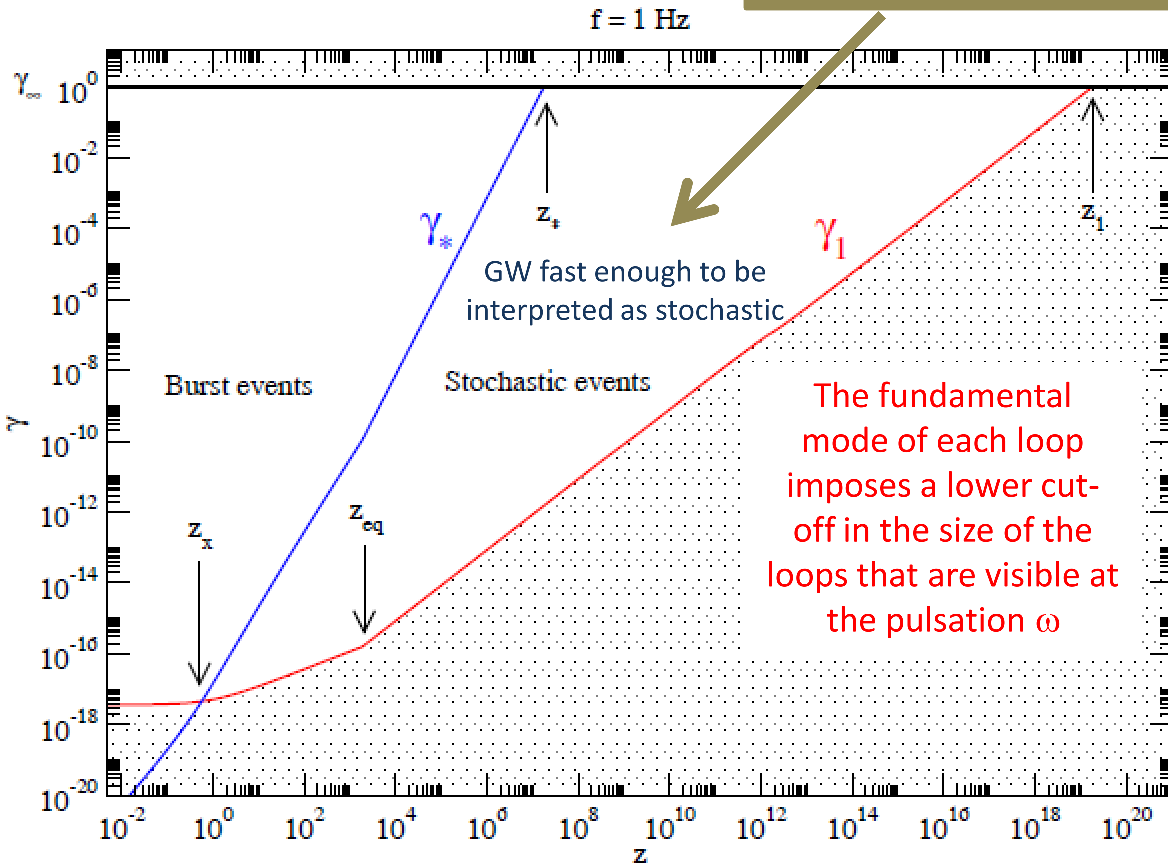
Ringeval, Suyama 1709.03845

Visibility domains

Only loops with $\gamma>\gamma_1$ oscillate slow enough to have a red-shifted fundamental mode $\omega_1<\omega$

Kink events

$$\gamma = \ell/t$$



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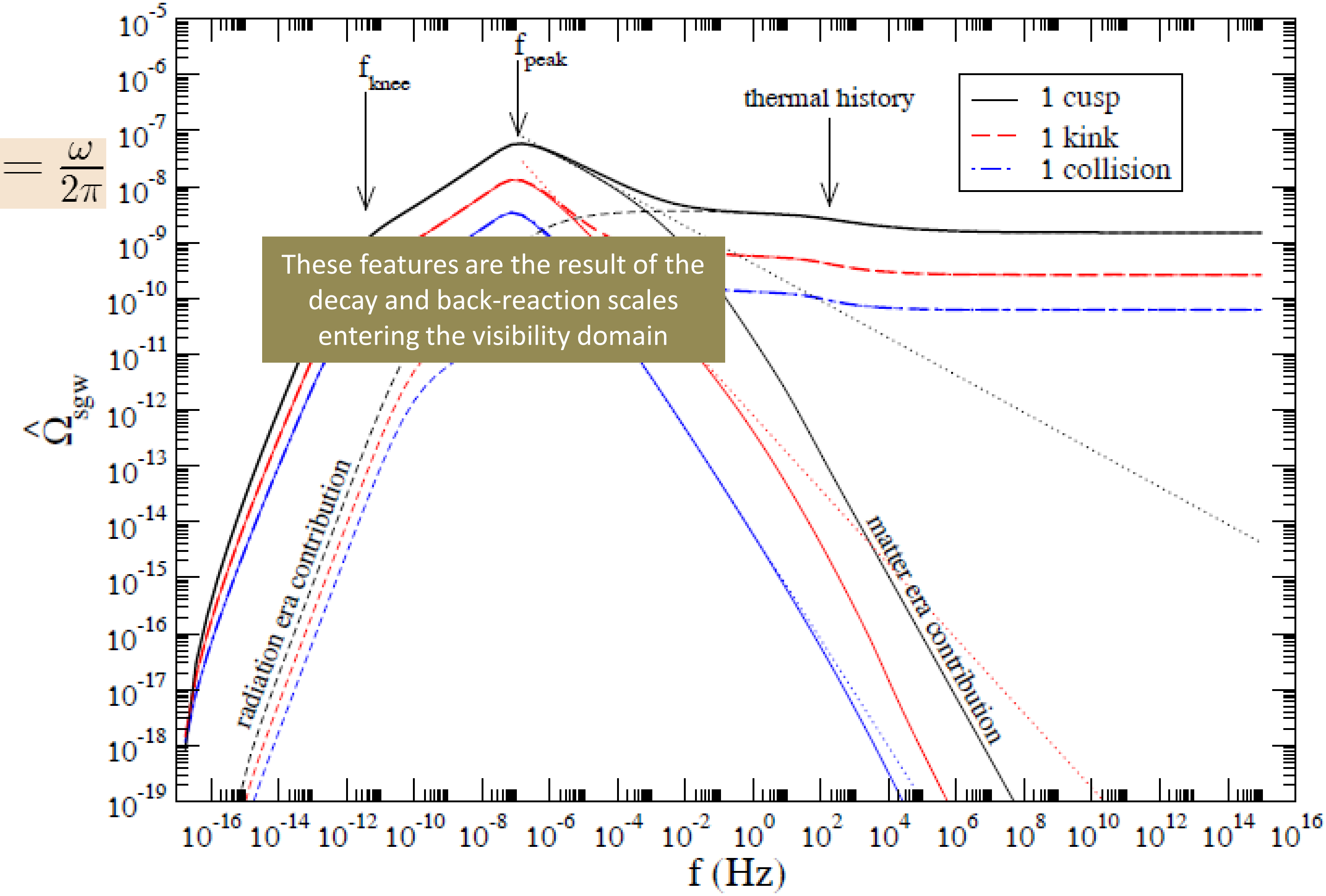
Ringeval, Suyama 1709.03845

$$G\mu = 10^{-7}$$

$$f = \frac{\omega}{2\pi}$$



These features are the result of the decay and back-reaction scales entering the visibility domain

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Ringeval, Suyama 1709.03845

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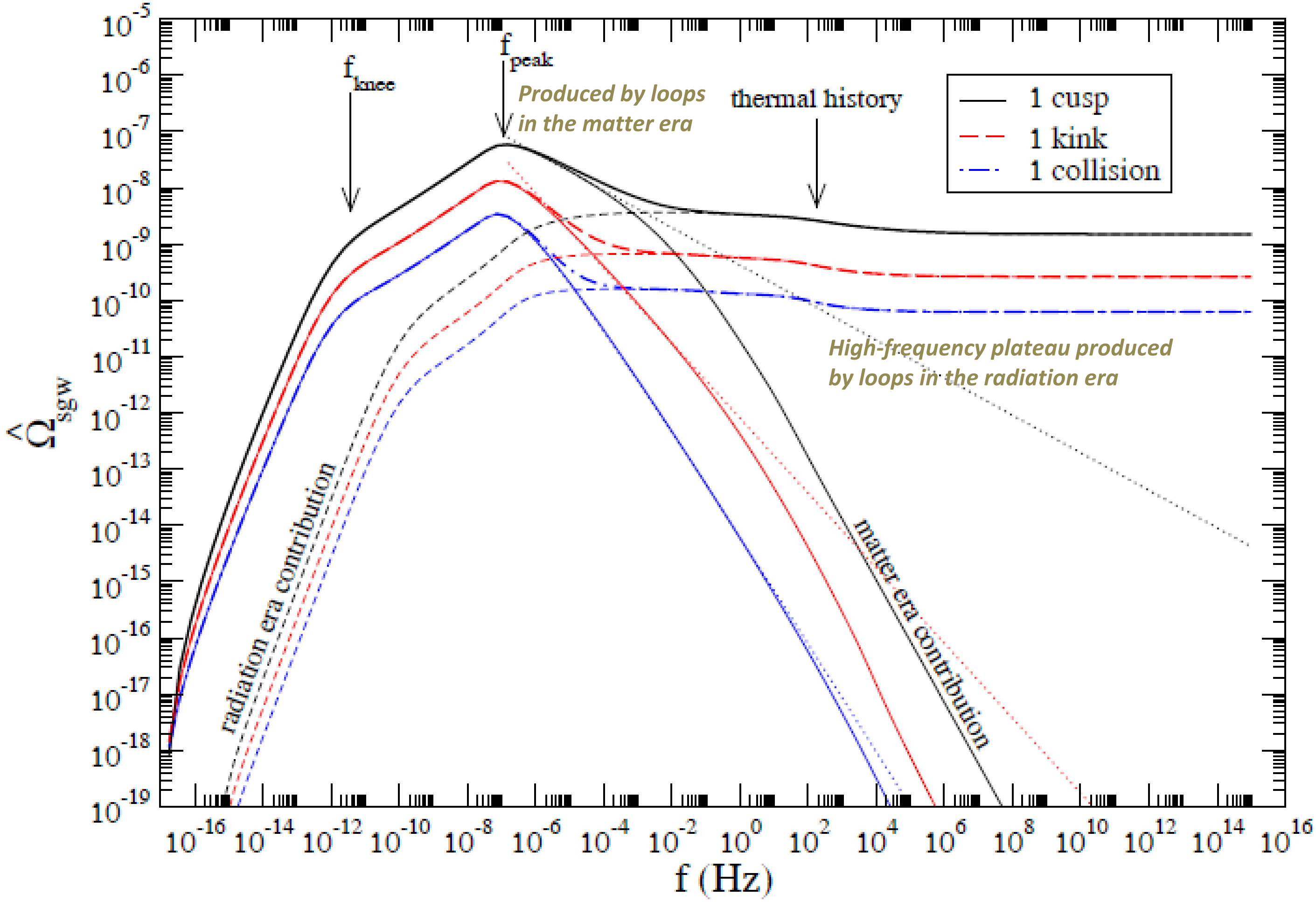

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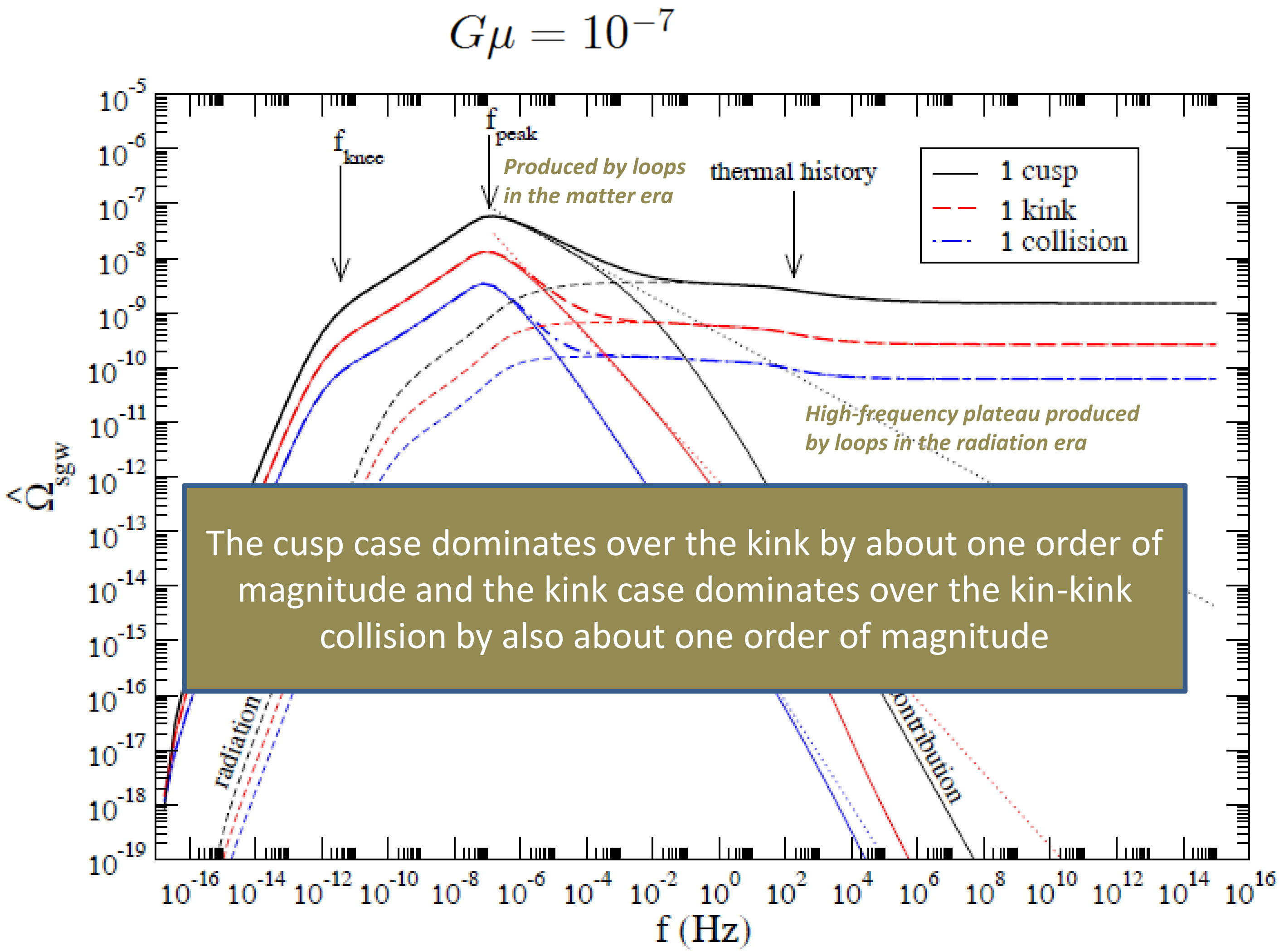

The cusp case dominates over the kink by about one order of magnitude and the kink case dominates over the kin-kink collision by also about one order of magnitude

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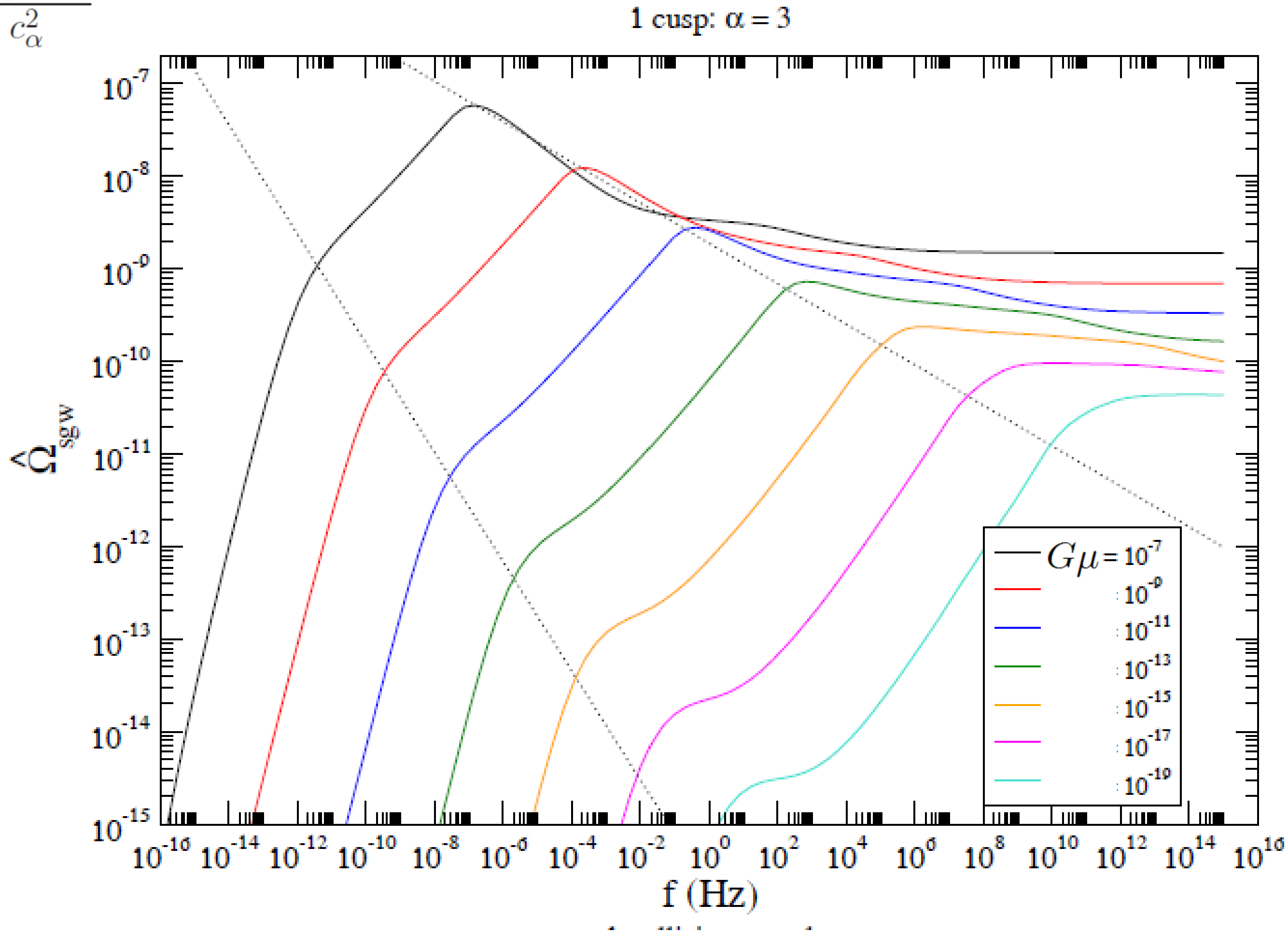
Ringeval, Suyama 1709.03845

$$\hat{\Omega}_{\rm sgw}(\omega) \equiv \frac{\Omega_{\rm sgw}(\omega)}{c_\alpha^2}$$



The overall peak is significantly higher than the knee while its amplitude decreases with Gμ much slower than the amplitude at the knee frequency.

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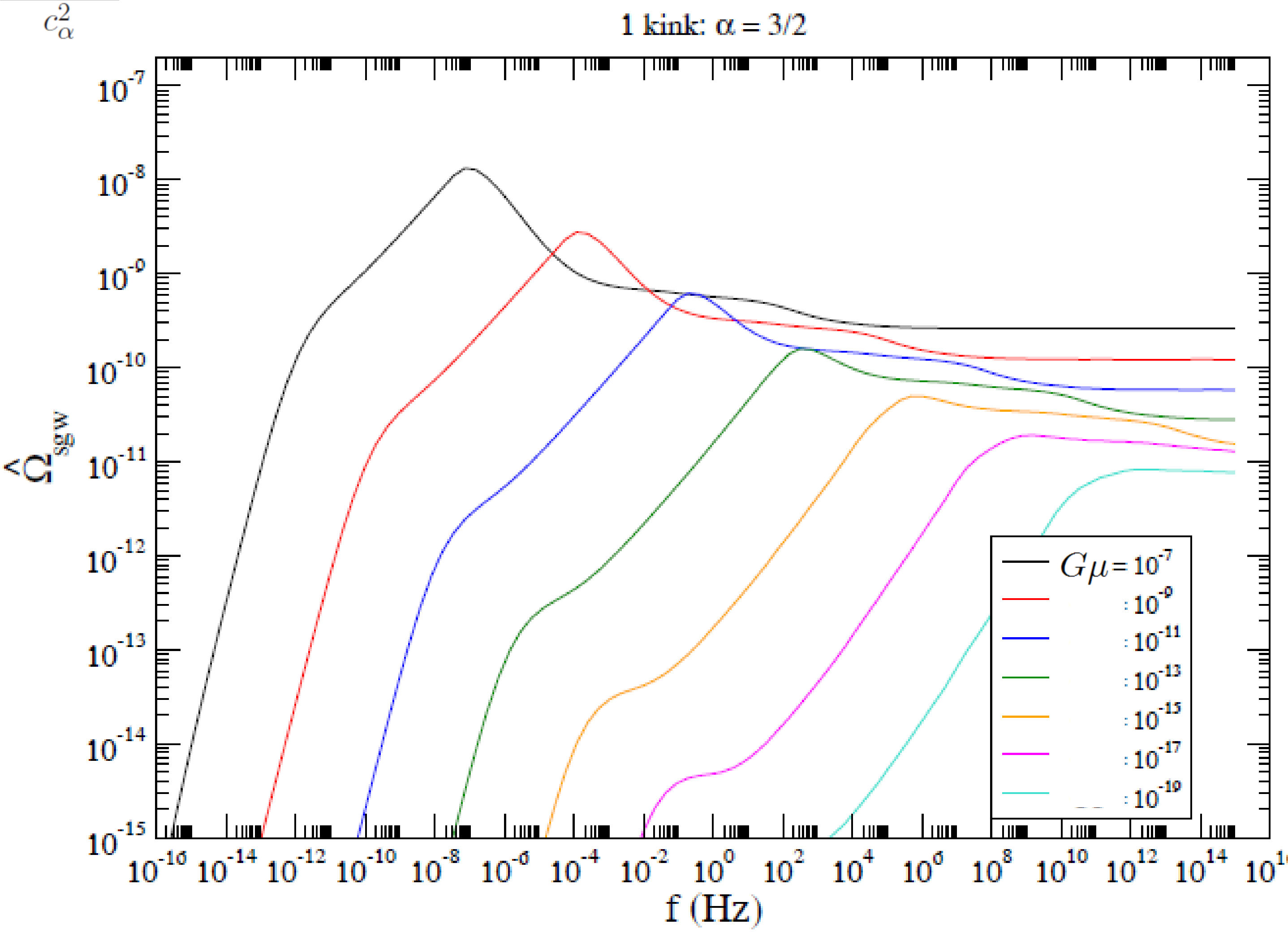

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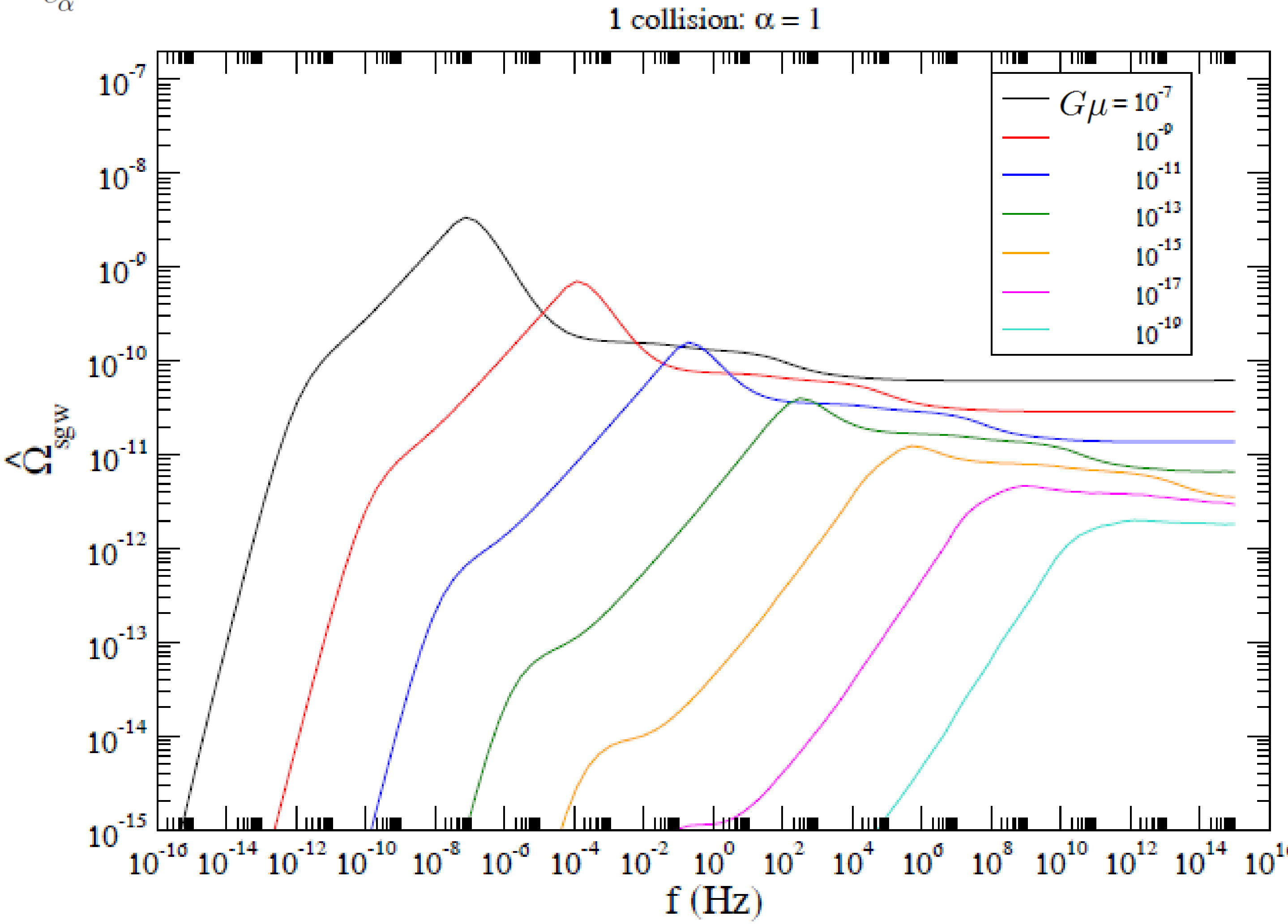

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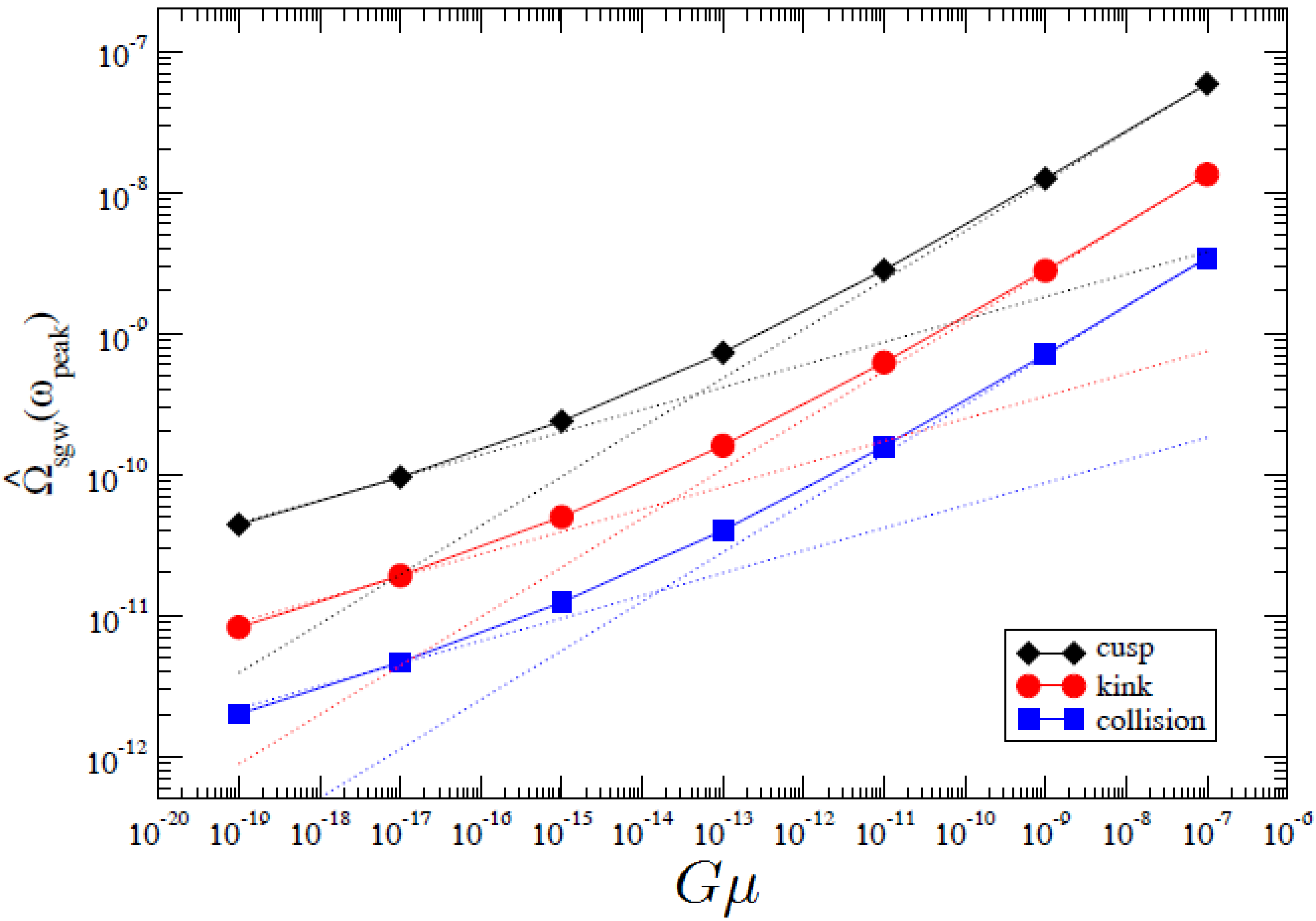

Comparison

All studies find a plateau at high frequencies, a maximum and a fast decay at low frequencies.

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Ringeval, Suyama 1709.03845	*vs.*	*Blanco-Pillado, Olum, Shlaer (2014)*
Lorentz, Ringeval, Sakellariadou (2010) *Ringeval, Sakellariadou, Bouchet (2007)*		$\gamma_{\mathrm{c}} = \gamma_{\mathrm{d}} = \Gamma G\mu$
$\gamma_{\mathrm{c}} \neq \gamma_{\mathrm{d}}$		No thermal history effects Cusp events only

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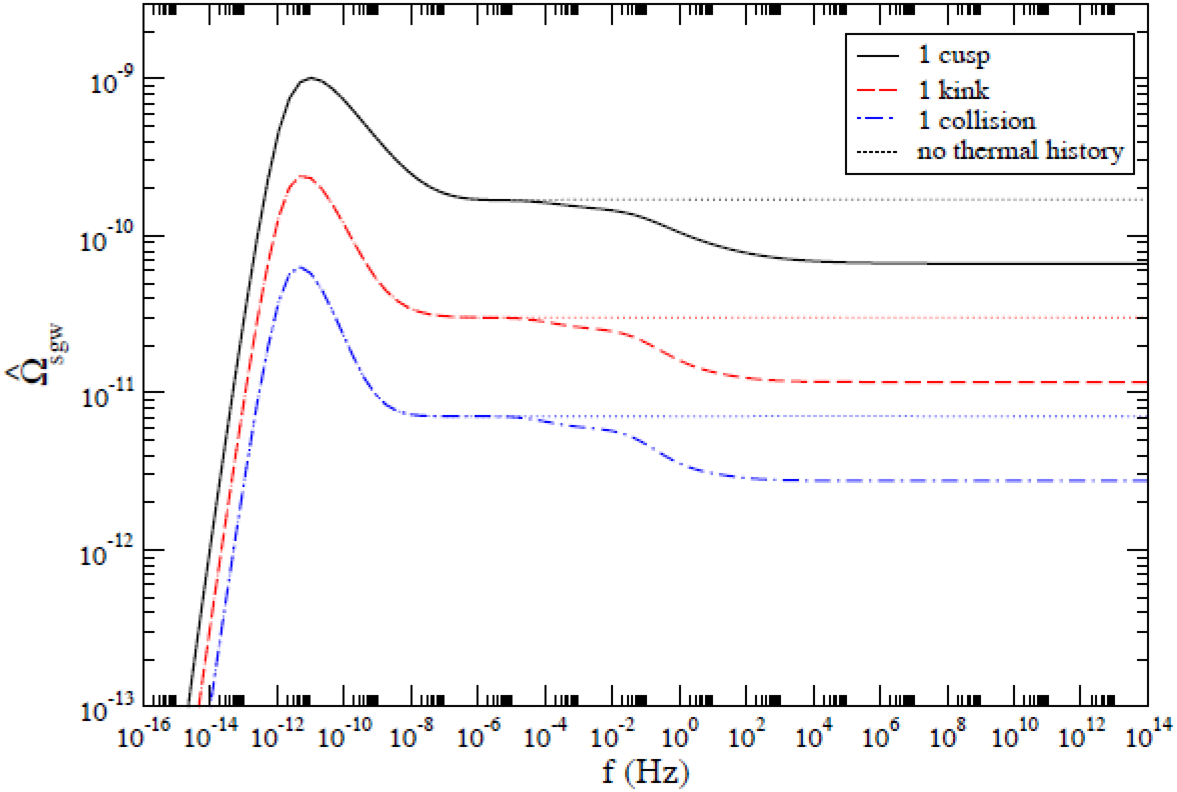

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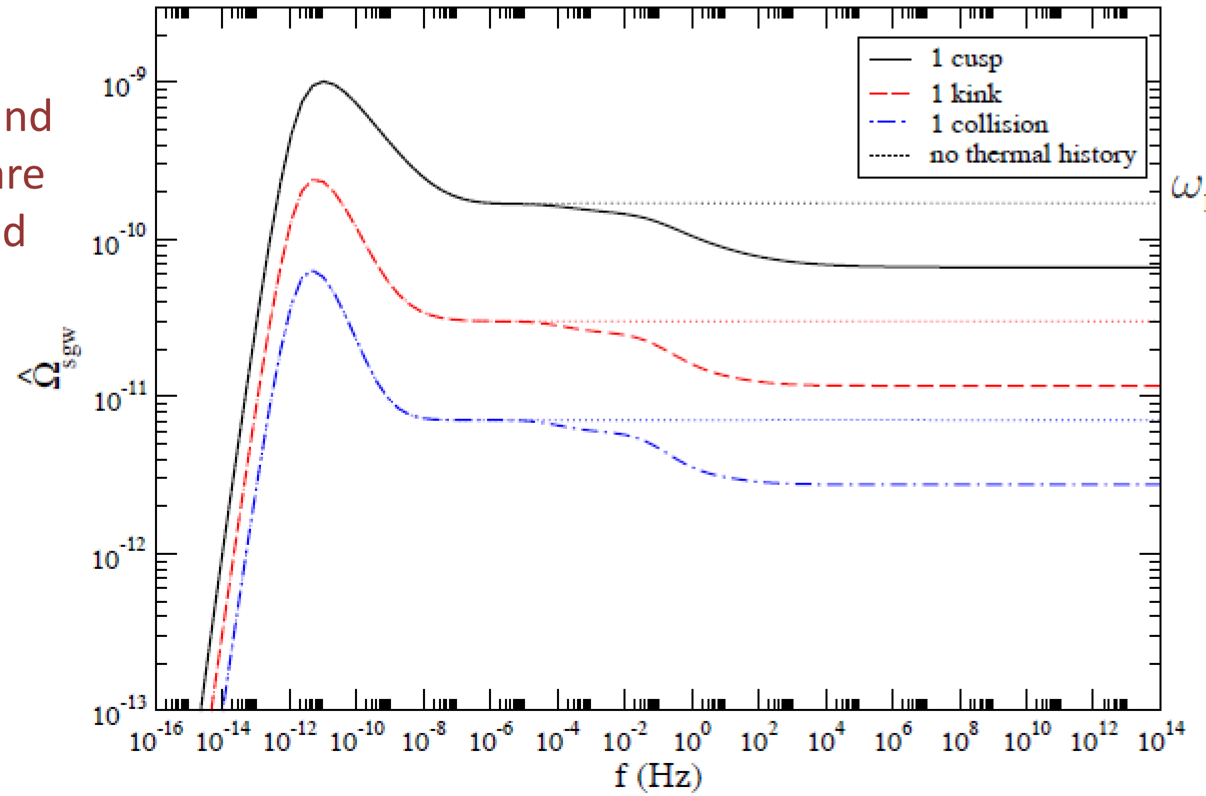
Peak and knee are merged



$$\omega_{\rm peak}/(2\pi) \simeq 1.0 \times 10^{-11}\ {\rm Hz}$$

*It matches exactly ref **

$$\Omega_{\rm sgw}(\omega_{\rm peak}) \simeq 5 \times 10^{-8}$$

10% agreement with 6×10^{-8} *of ref**

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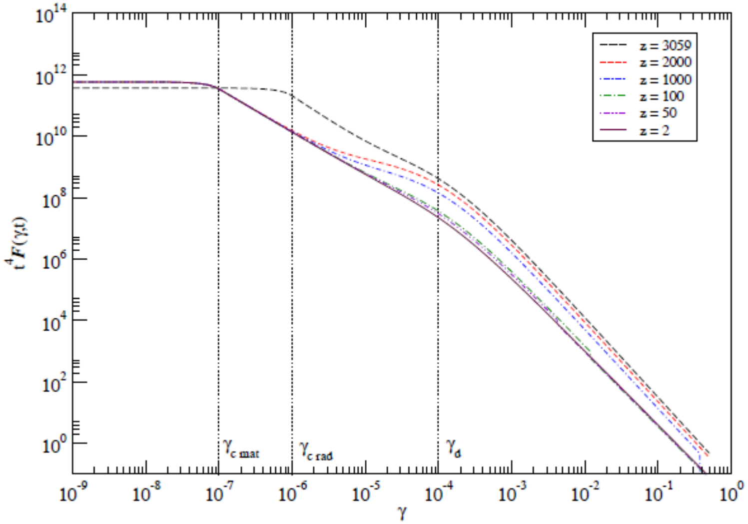
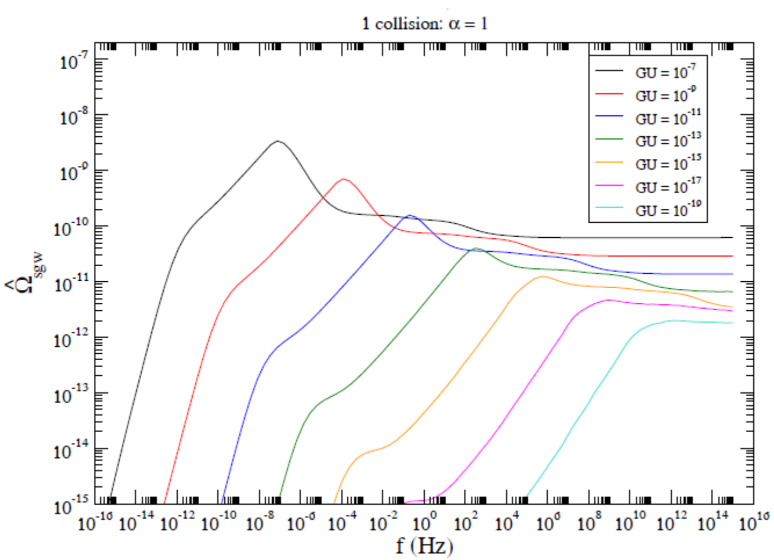




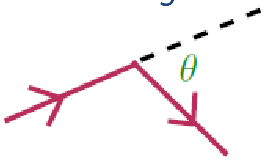
The overall peak is significantly higher than the knee while its amplitude decreases with Gμ much slower than the amplitude at the knee frequency.

Also the effect of thermal history lowers the plateau by 3 orders or magnitude around LIGO frequencies.

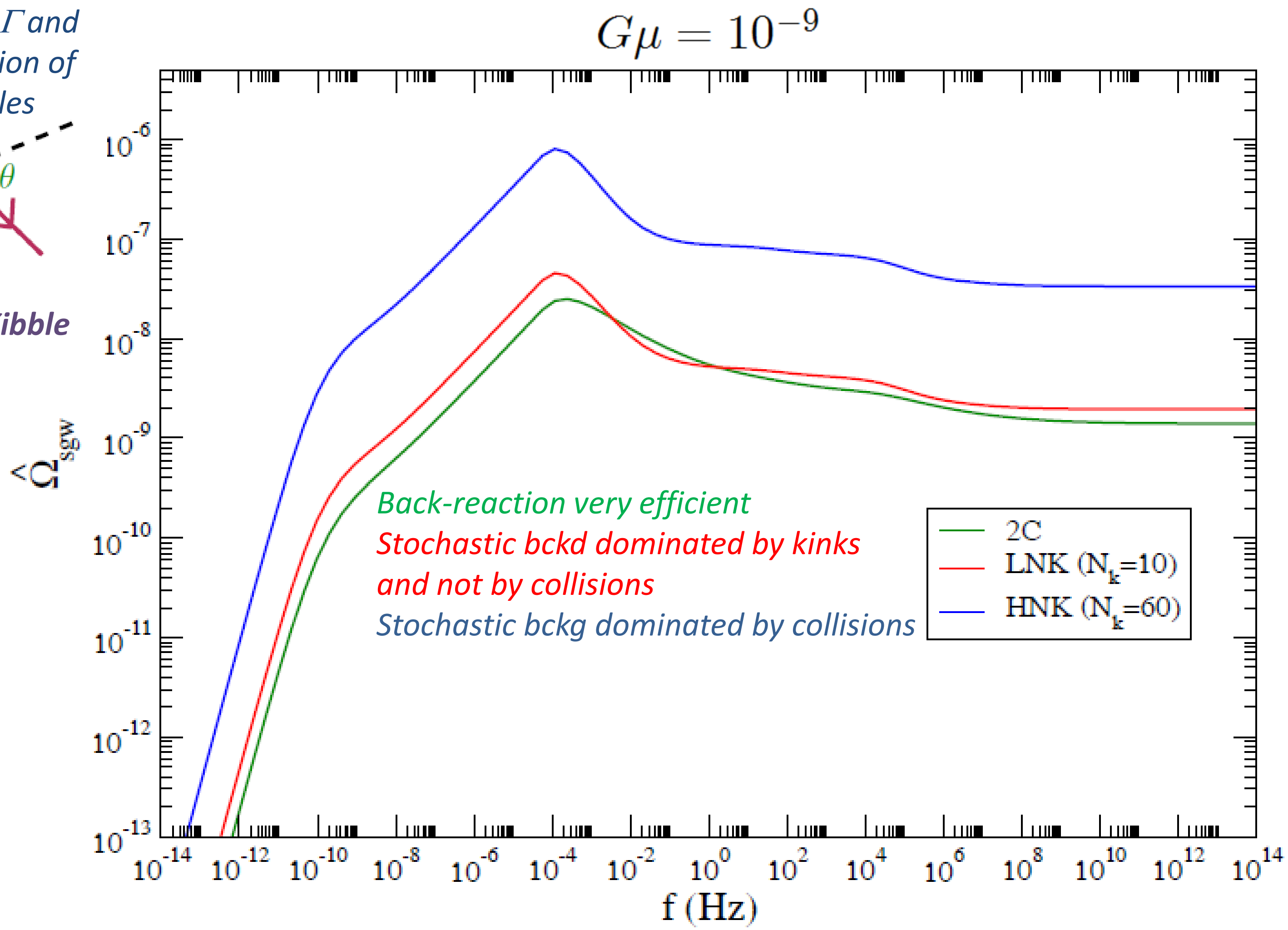
Effects of microstructure

Ringeval, Suyama 1709.03845

Worry about value of Γ and distribution of kink angles



Copeland, Kibble (2009)



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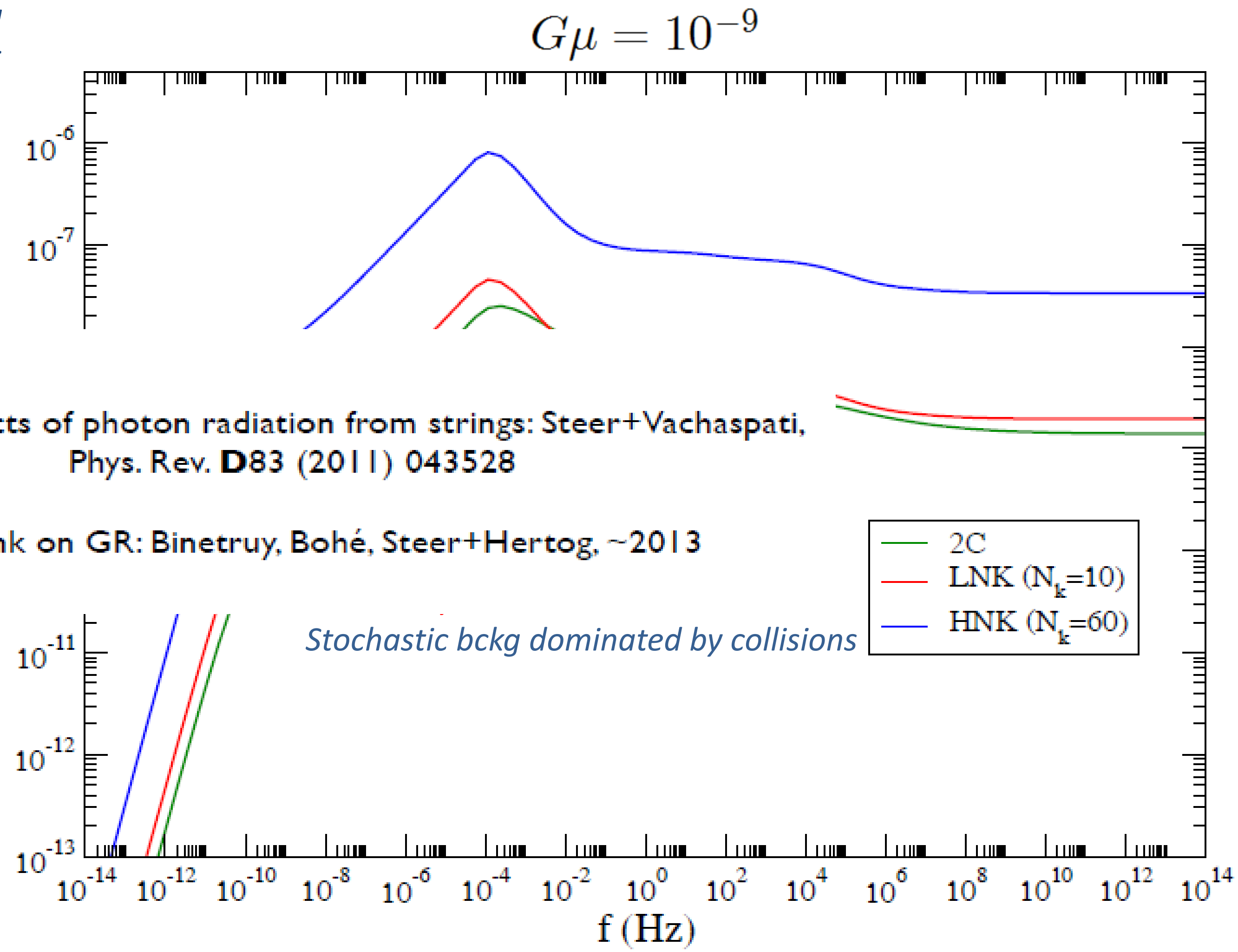

Kink-kink effects of photon radiation from strings: Steer+Vachaspati, Phys. Rev. **D83** (2011) 043528

Kink-kink on GR: Binetruy, Bohé, Steer+Hertog, ~2013

Stochastic bckg dominated by collisions

Constraints on Gμ

Ringeval, Suyama 1709.03845

Model	LIGO	EPTA	LIGO + EPTA
2C	$G\mu \leq 1.1 \times 10^{-10}$	$G\mu \leq 3.4 \times 10^{-11}$	$G\mu \leq 1.0 \times 10^{-11}$
LNK	–	$G\mu \leq 6.8 \times 10^{-11}$	$G\mu \leq 7.2 \times 10^{-11}$
HNK	$G\mu \leq 8.8 \times 10^{-14}$	$G\mu \leq 6.4 \times 10^{-12}$	$G\mu \leq 6.7 \times 10^{-14}$

Some recent results

Blanco-Pillado, Olum, Siemens 1709.02434

Blanco-Pillado, Olum (2017)

Blanco-Pillado, Olum, Shlaer (2014)

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Blanco-Pillado, Olum, Siemens 1709.02434

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Blanco-Pillado, Olum, Shlaer (2014)

- Thermal history is taken into account

$$H(z) = H_0\sqrt{\Omega_\Lambda + (1+z)^3\Omega_m + G(z)(1+z)^4\Omega_r}$$

$$G(z) = \frac{T(z)^4 g_*(z)}{T_0^4(1+z)^4 g_{*,0}}$$

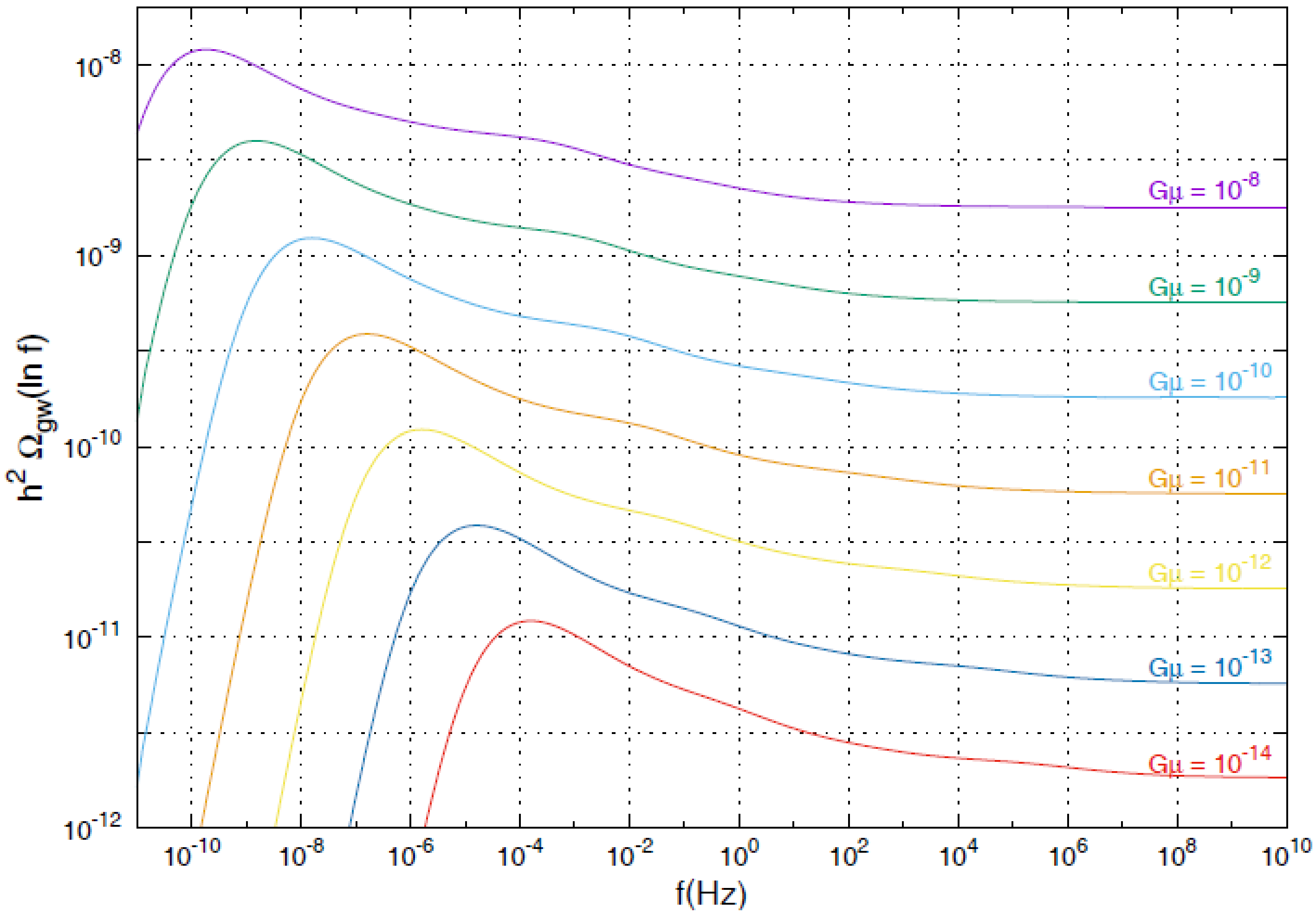
- Gravitational back-reaction is considered through a toy model of smoothing
  -- kinks are not considered (smoothed out by `convolution')

- Assumed flat background

- Find cusps and compute radiation power spectrum

Some recent results

Blanco-Pillado, Olum (2017)



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Pulsar Timing Array: $G\mu < 1.5 \times 10^{-11}$