2024.09.27 @ Cosmology Forum, iTHEMS

Scalar-induced gravitational wave as a cosmological phonograph

Yuichiro TADA Nagoya U. IAR

w/ Abe & Ueda 2010.06193
w/ Abe, Inui, Yokoyama 2209.13891
w/ Abe 2307.01653
w/ Escriva & Yoo 2311.17760, + Inui 2404.12591
w/ Franciolini & Veermae in prep
w/ Inui, Kuroyanagi, Makino, Yokoyama in prep

by Adobe Firefly

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'17–'18	PD, IAP	S. Renaux-Petel
'18–'21	JSPS PD, Nagoya U.	N. Sugiyama
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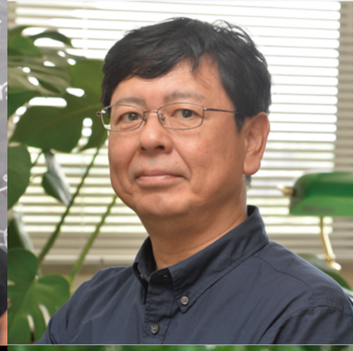
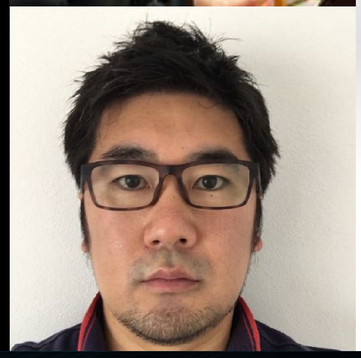


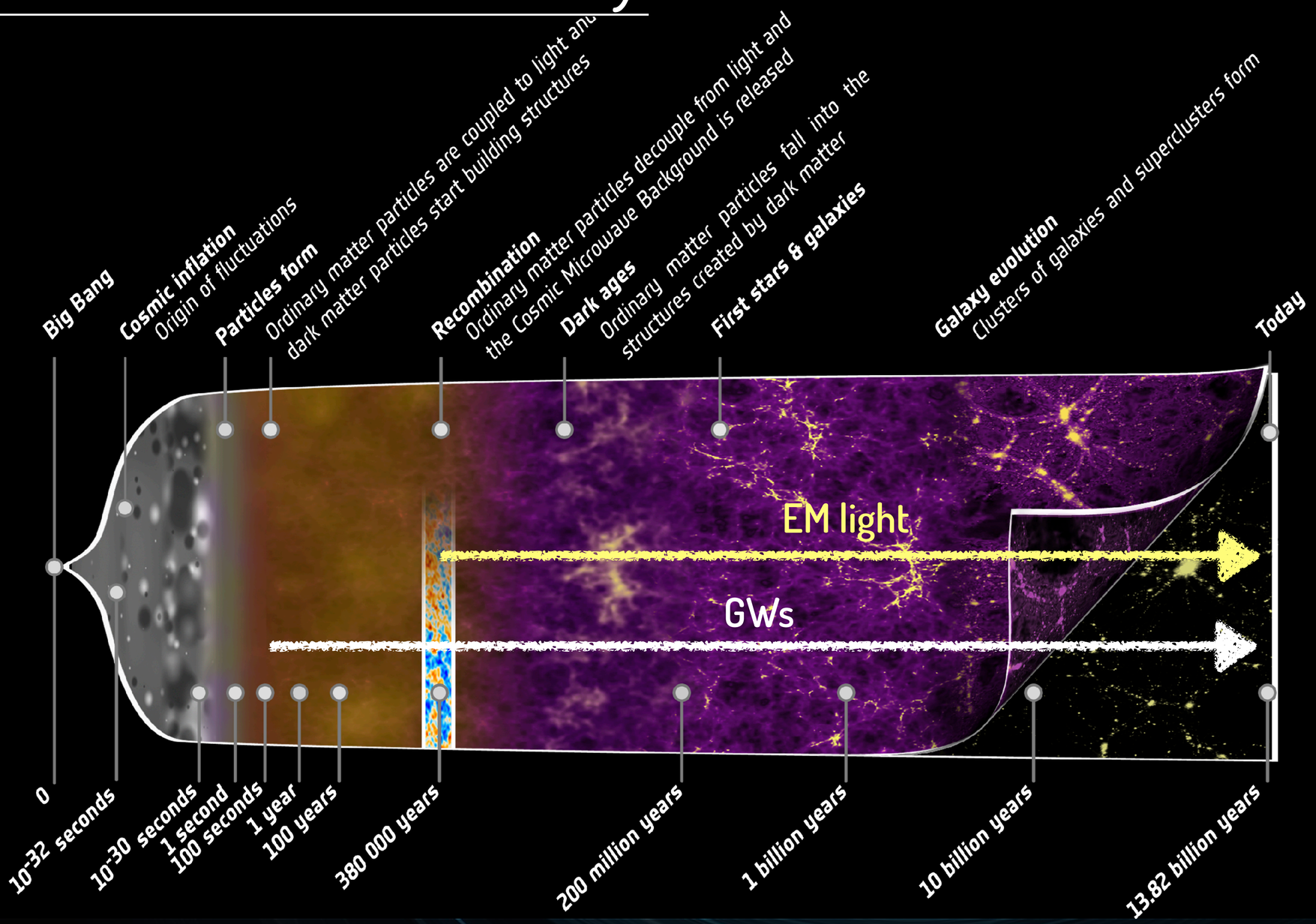




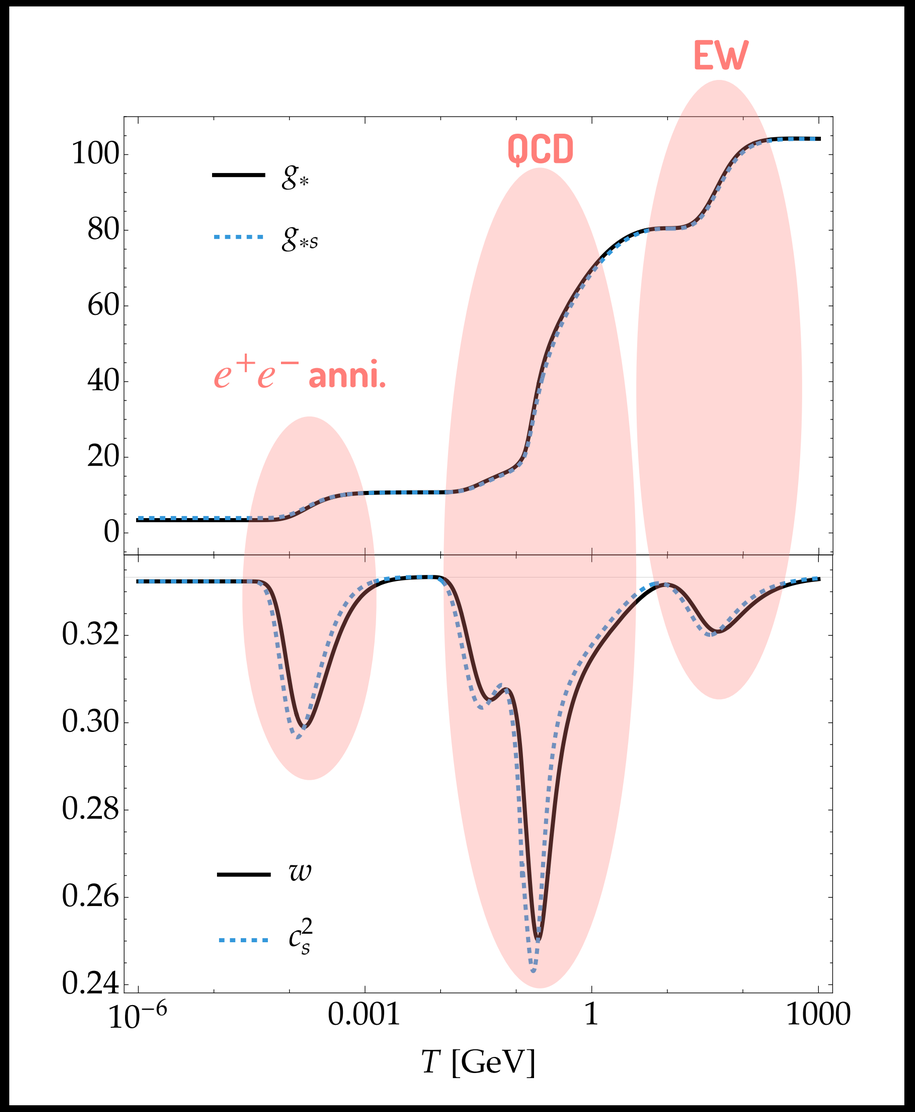

- Theoretical approach to Early Universe

  ↔ Observation = Inflation, PBH, GW, ...

Thermal History



3 crossovers



$$\rho(T) = \frac{\pi^2}{30} g_*(T) T^4, \quad s(T) = \frac{2\pi^2}{45} g_{*s}(T) T^3$$

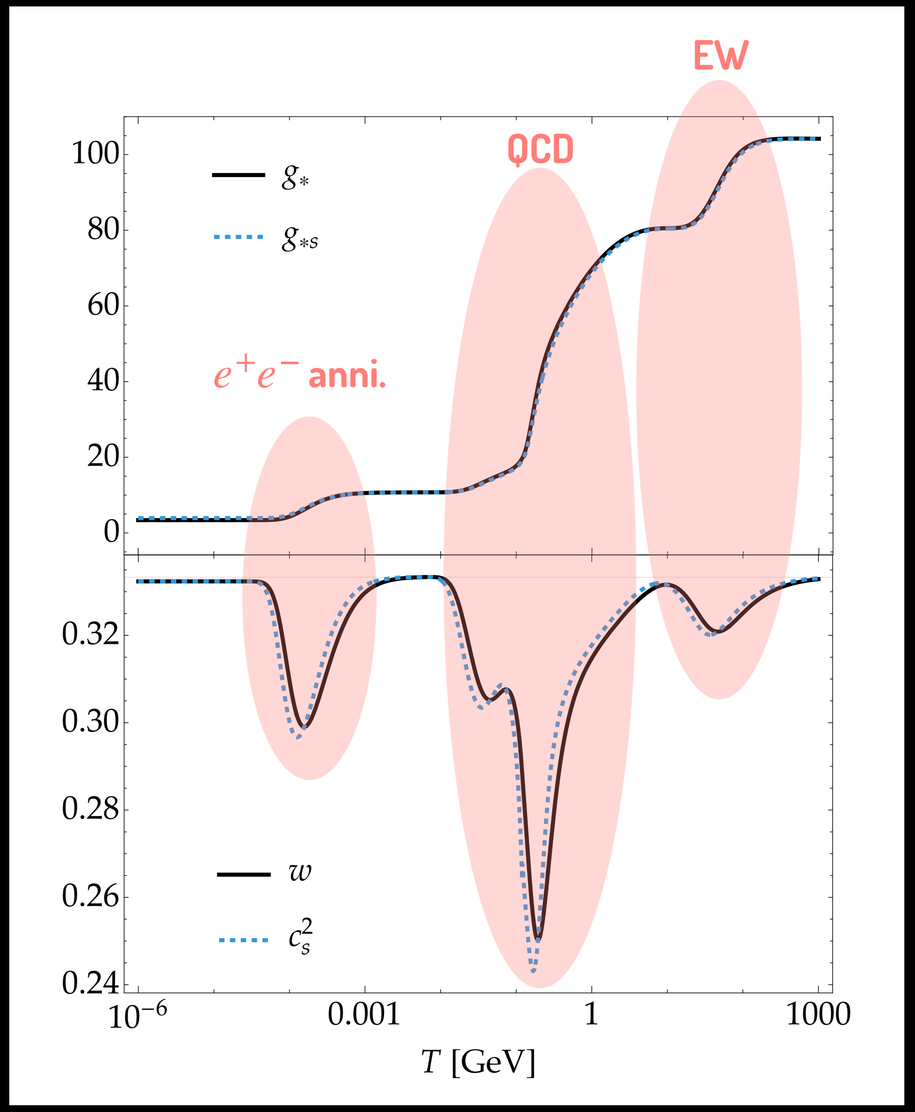
$$w(T) = \frac{p(T)}{\rho(T)}, \quad c_s^2(T) = \frac{\partial p}{\partial \rho}(T) = \frac{p'(T)}{\rho'(T)}$$

$$p(T) = Ts(T) - \rho(T)$$

- nth-order phase transition :
  $\partial_T^n p(T)$ is discontinuous @ T_c
- Crossover :
  no discontinuity

by Hatsuda-san

3 crossovers



- Electroweak crossover $\sim 100\,\mathrm{GeV}$:

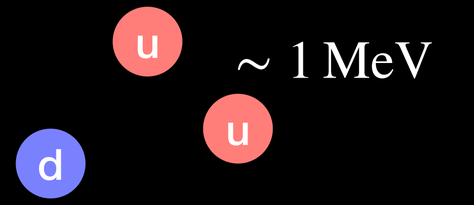
  $\langle H \rangle \sim m_W \sim m_Z \sim 100\,\mathrm{GeV}$

  Weak interaction becomes “weak”

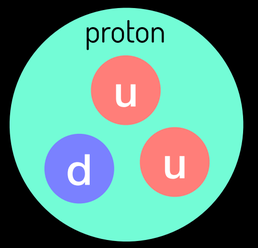
- Quantum chromodynamics crossover $\sim 100\,\mathrm{MeV}$:

  $T > 100\,\mathrm{MeV}$ $\quad g_{\mathrm{strong}} < 1$

  $T < 100\,\mathrm{MeV}$ $\quad g_{\mathrm{strong}} > 1$



$\sim 1\,\mathrm{MeV}$



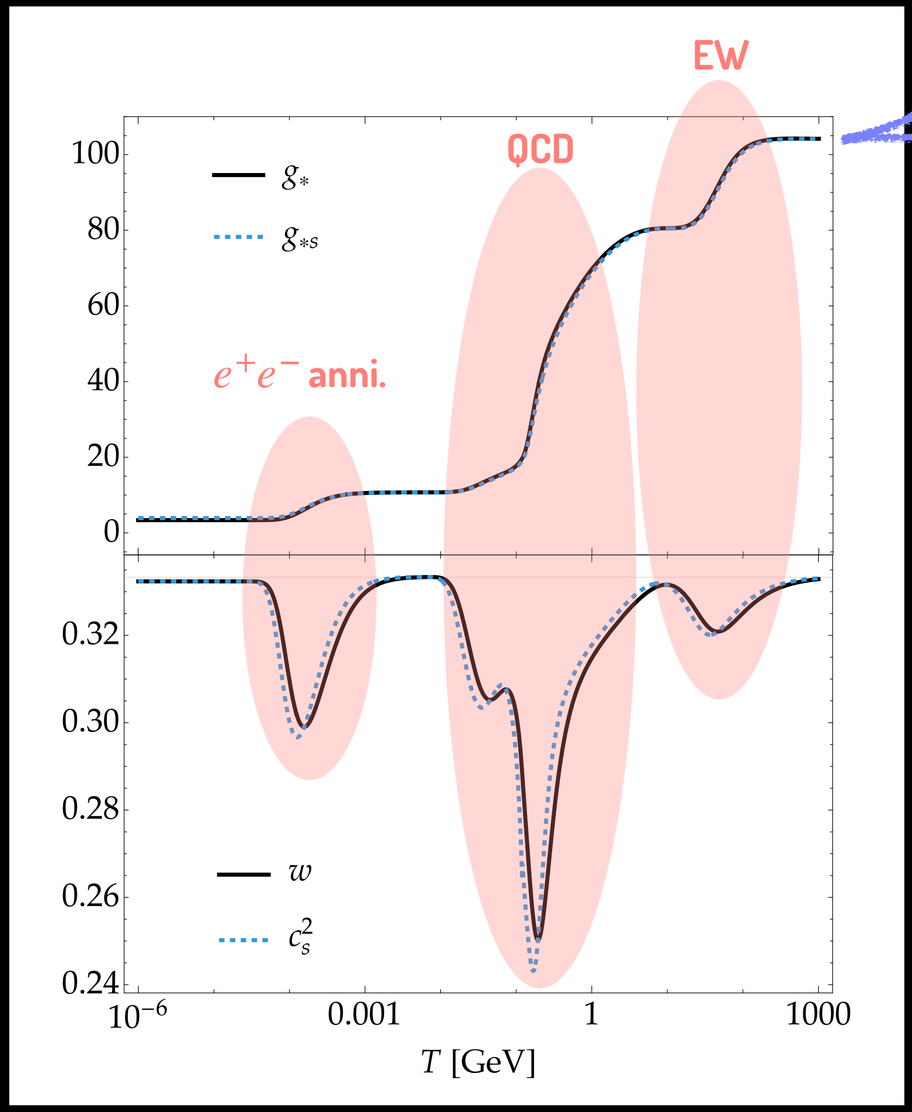
$\sim 1\,\mathrm{GeV}$

  Strong interaction becomes “strong”

- e^+e^- annihilation $\sim 0.5\,\mathrm{MeV}$:

  $m_e = 511\,\mathrm{keV}$. All baryons become non-relativistic

3 crossovers



??

cf. Kanemura-san's work : 1st-order EW

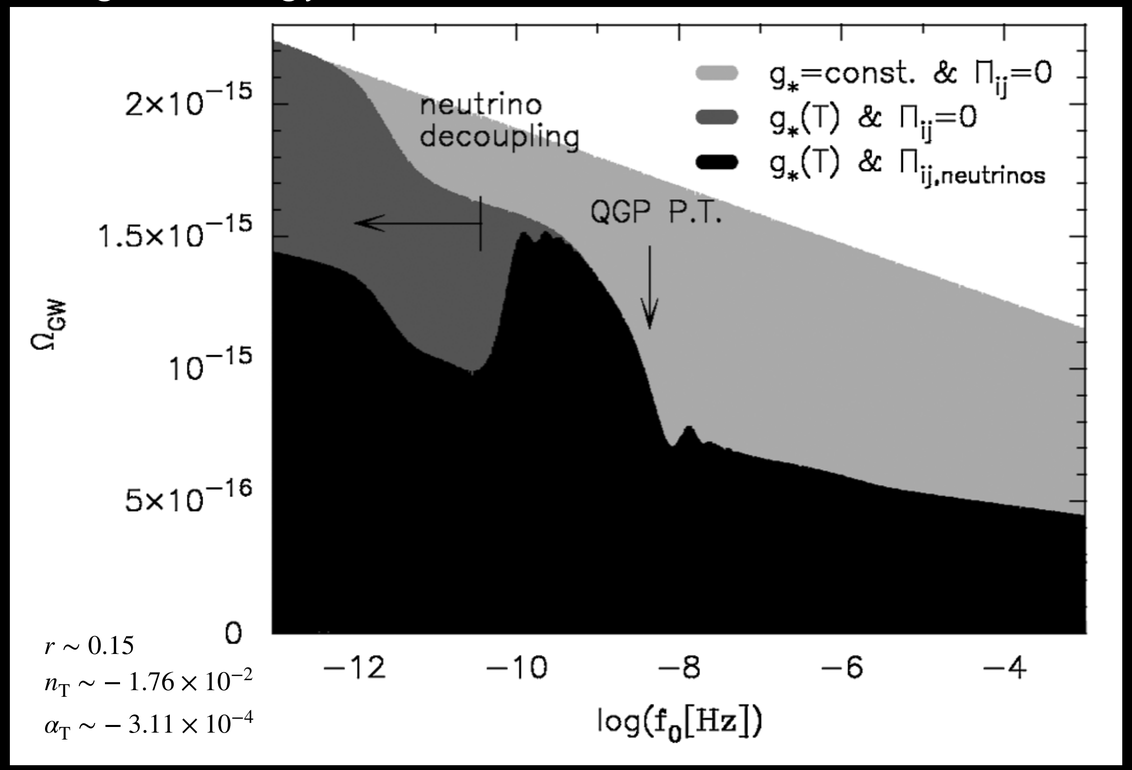
T	$\sim 0.5\,\mathrm{MeV}$	$\sim 100\,\mathrm{MeV}$	$\sim 100\,\mathrm{GeV}$	$\sim 100\,\mathrm{TeV}$
M_{PBH}	$\sim 10^7 M_\odot$	$\sim 1 M_\odot$	$\sim 1 M_\oplus$	$\sim 10^{20}\,\mathrm{g}$
	SMBH?	LVK?	OGLE?	DM?
f_{GW}	$\sim 5\,\mathrm{pHz}$	$\sim 1\,\mathrm{nHz}$	$\sim 1\,\mu\mathrm{Hz}$	$\sim 1\,\mathrm{mHz}$
		PTA?		LISA?

Linear GWs

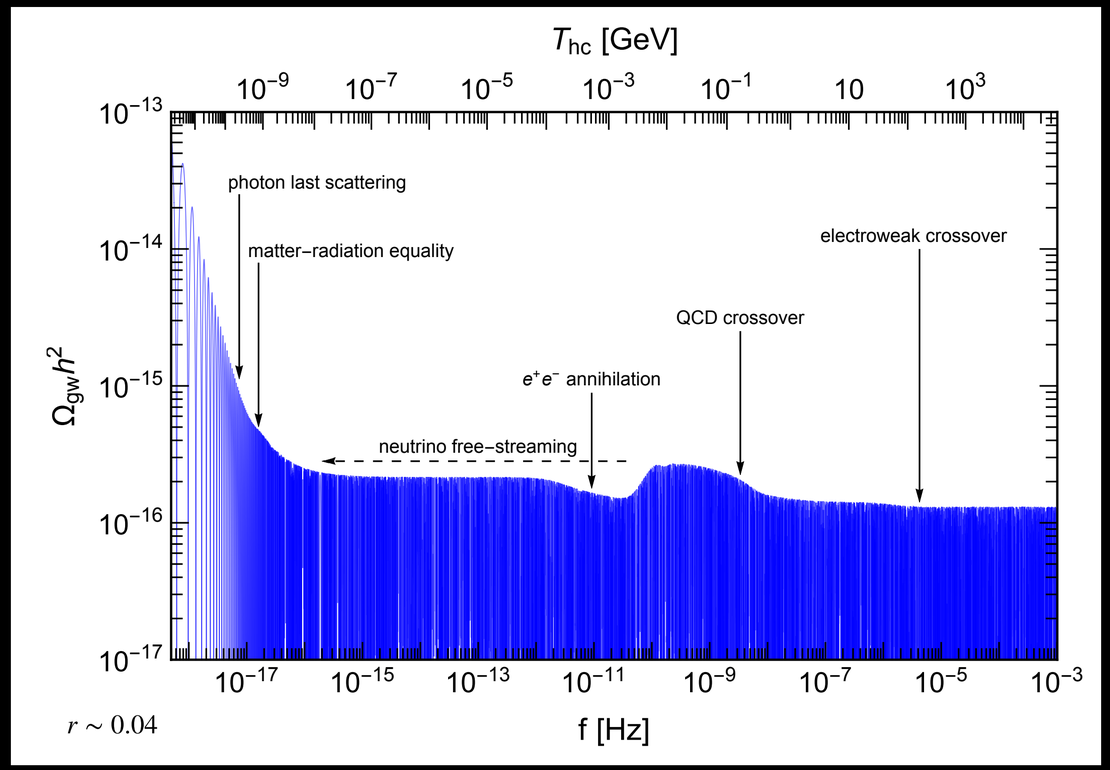
Primordial GW bg can be produced by inflation as well as density contrast

$$\rho_{\rm GW} \propto a^{-4}, \quad \rho_{\rm bg} \propto a^{-3(1+w)>-4}$$

cf. Saga, Ichiki, Sugiyama '14



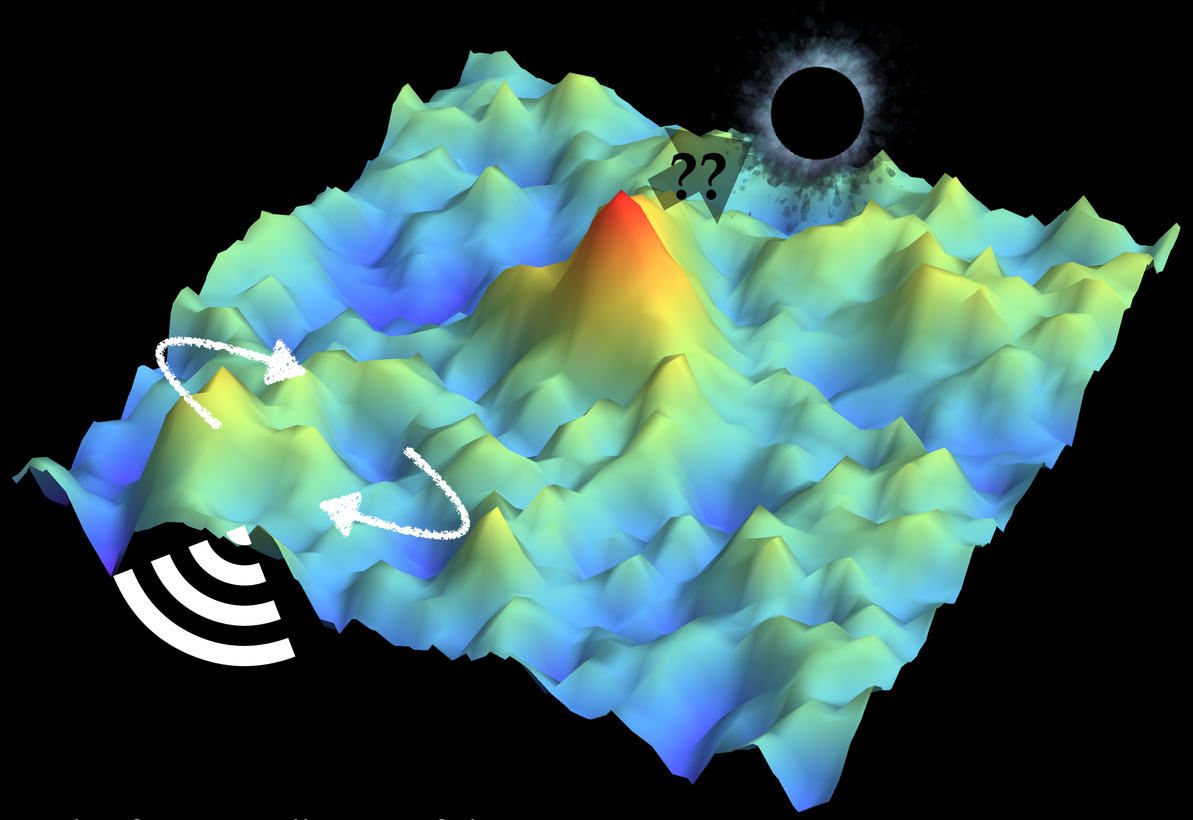
Kuroyanagi, Chiba, Sugiyama '08



Saikawa & Shirai '18

Scalar-induced GWs

Tomita '67, Baumann, Steinhardt, Takahashi, Ichiki '07, ...
Domenech '21 (review)



GW bg from oscillation of density contrast

- induced tensor

$$\left[\partial_\eta^2 + k^2 - \frac{1-3w}{2}\mathscr{H}^2\right](ah_{\mathbf{k}}) = 4aS_{\mathbf{k}}$$

$$S_{\mathbf{k}} = \int \frac{\mathrm{d}^3\mathbf{q}}{(2\pi)^3} e_{ij}(\mathbf{k}) q^i q^j \left[2\Phi_{\mathbf{q}}\Phi_{\mathbf{k}-\mathbf{q}} + \frac{4}{3(1+w)}\left(\Phi_{\mathbf{q}} + \frac{\Phi'_{\mathbf{q}}}{\mathscr{H}}\right)\left(\Phi_{\mathbf{k}-\mathbf{q}} + \frac{\Phi'_{\mathbf{k}-\mathbf{q}}}{\mathscr{H}}\right)\right]$$

- Bardeen potential (scalar)

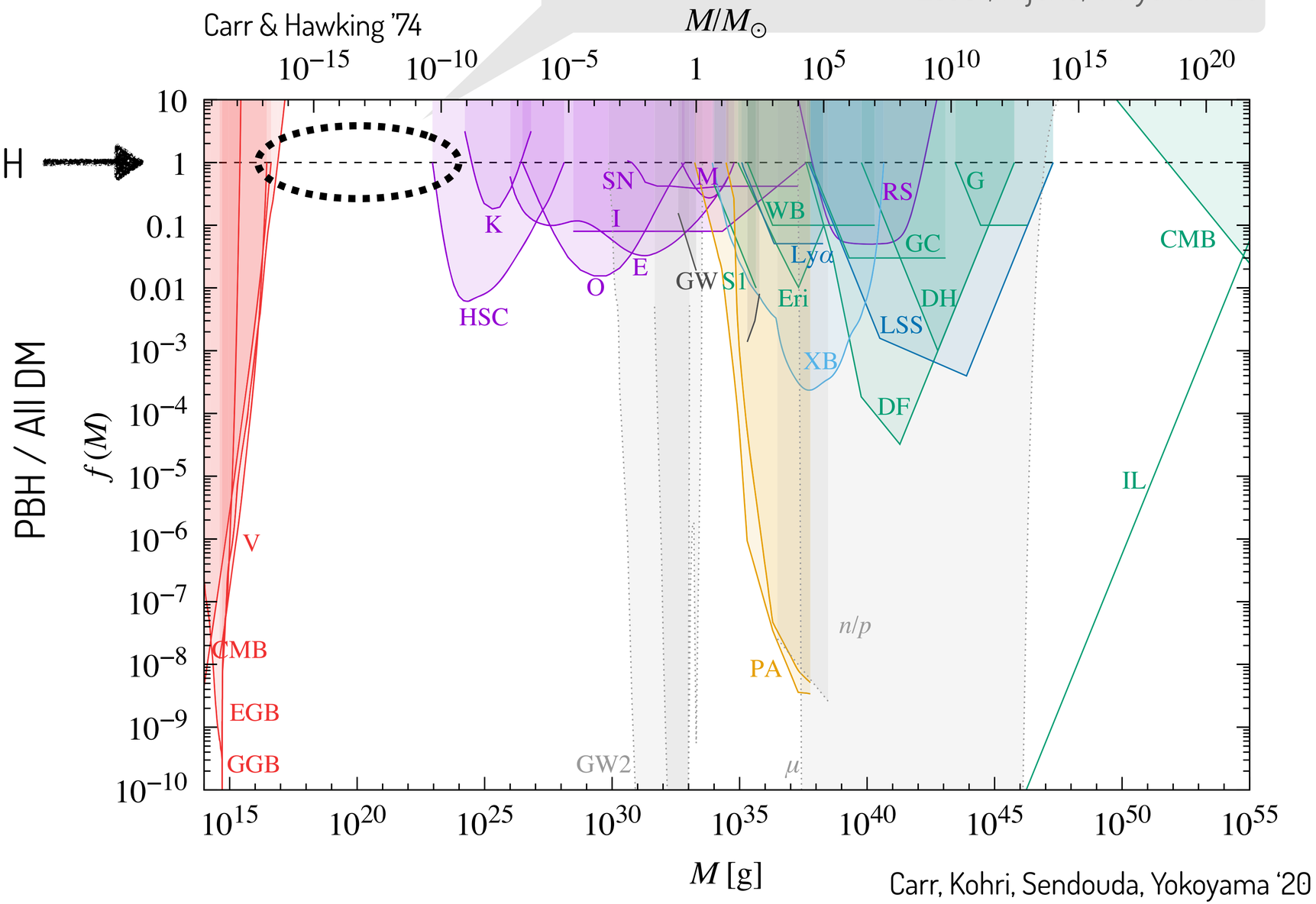
$$\Phi''_{\mathbf{k}} + 3\mathscr{H}(1+c_s^2)\Phi'_{\mathbf{k}} + \left[c_s^2 k^2 + 3\mathscr{H}^2(c_s^2 - w)\right]\Phi_{\mathbf{k}} = 0$$

Primordial BHs

Stellar Mass Function in Ultra-Faint Dwarfs...?
Esser, Rijcke, Tinyakov '23

Carr & Hawking '74

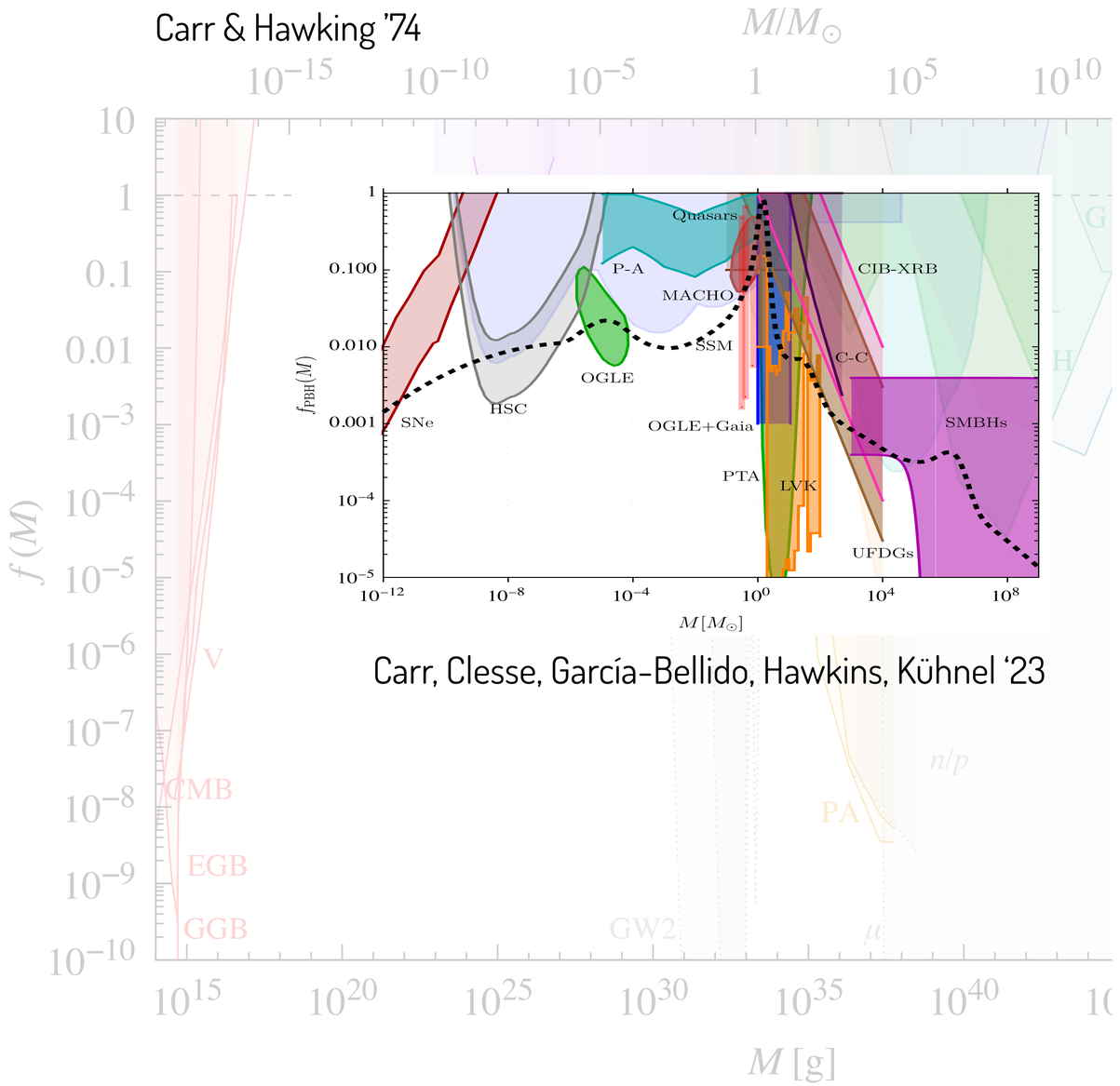
All DM = PBH



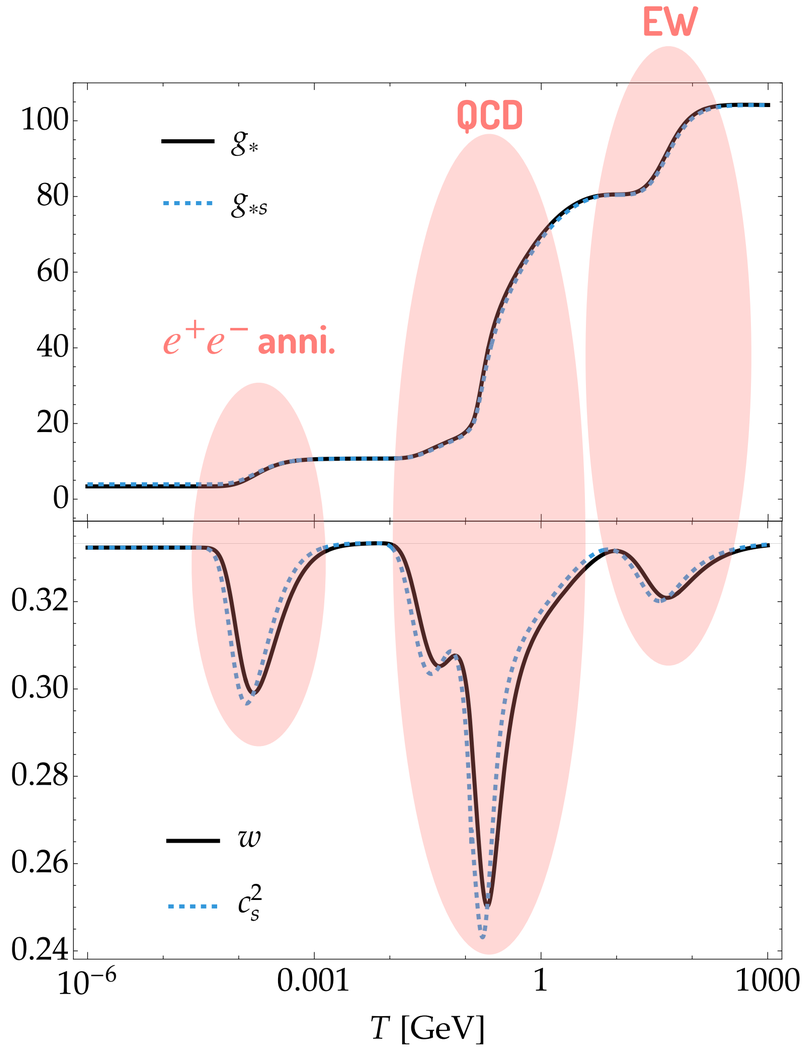
Carr, Kohri, Sendouda, Yokoyama '20

Positivist Perspective?

Carr & Hawking '74

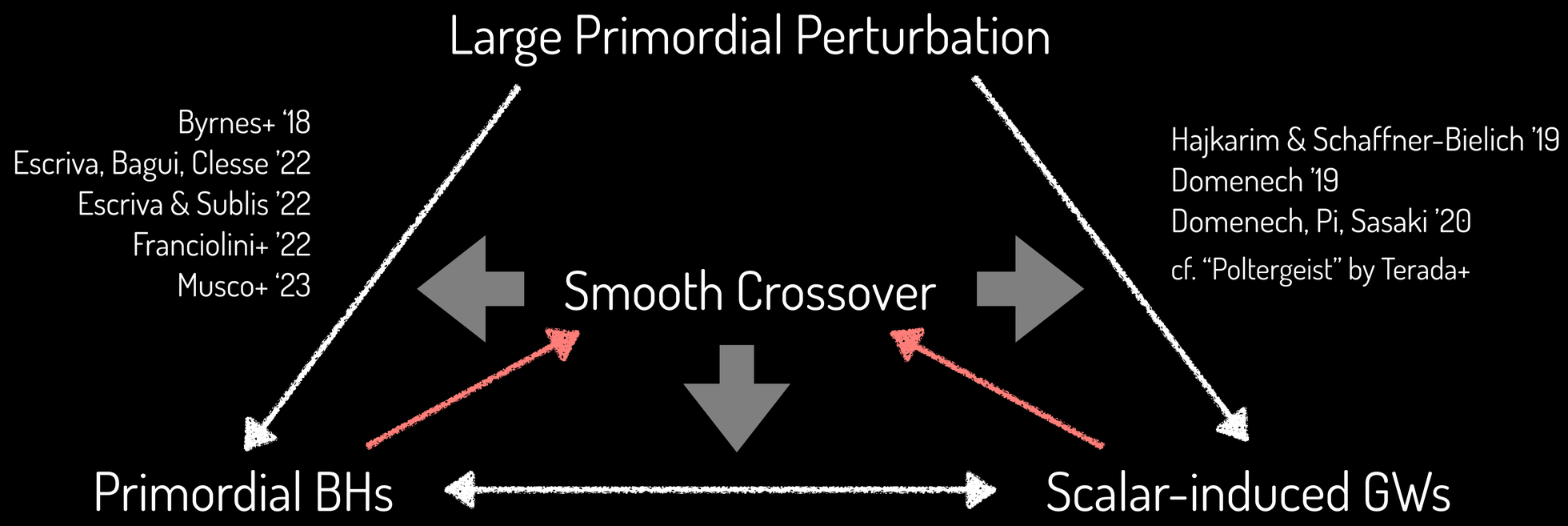


Carr, Clesse, García-Bellido, Hawkins, Kühnel '23



cf. Saikawa & Shirai '18

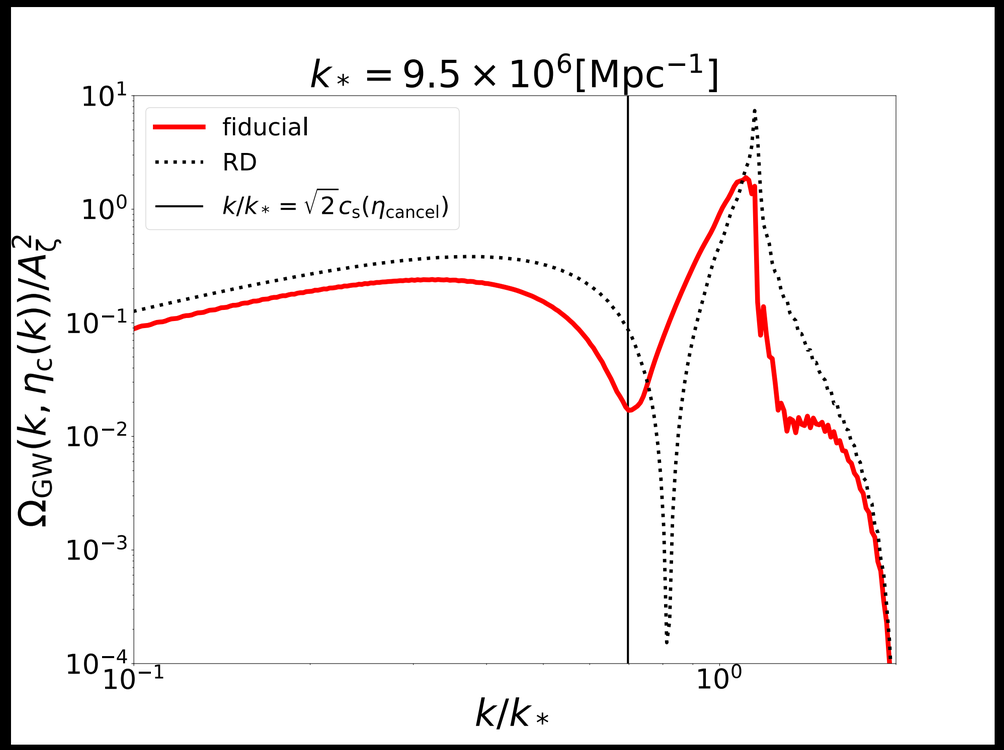
Perspectives



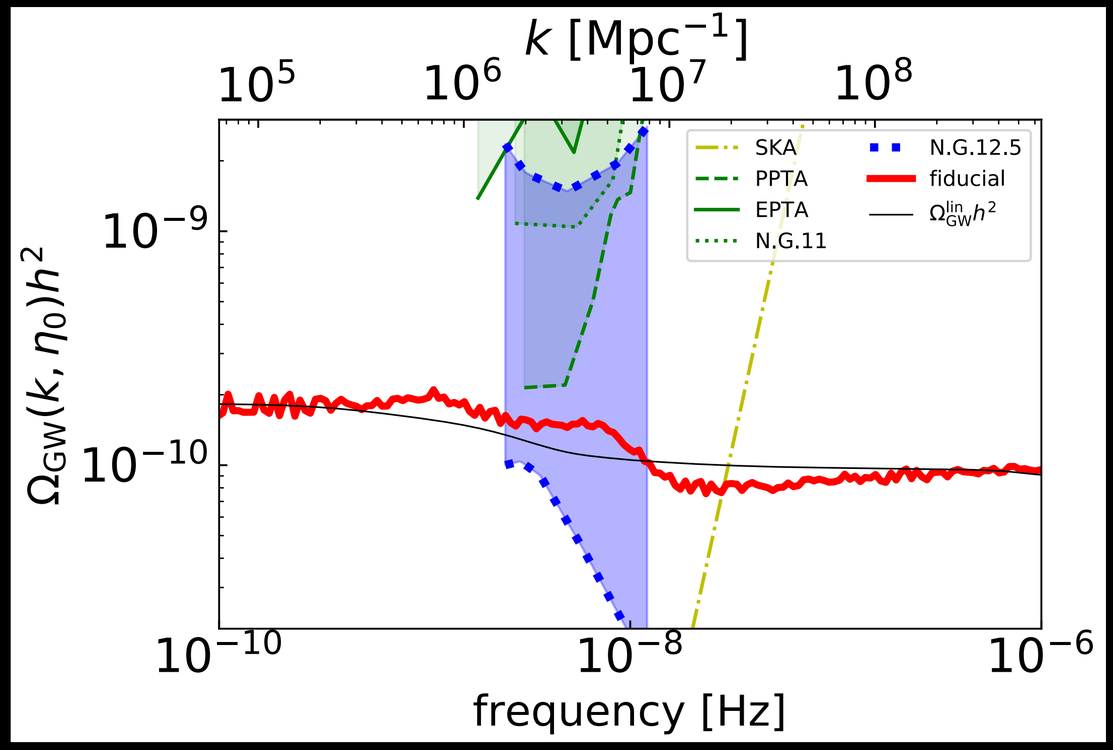
QCD on SIGWs

Abe, YT, Ueda '20

$$\mathscr{P}_\zeta(k) = A_\zeta \delta(\ln k - \ln k_*)$$



$$\mathscr{P}_\zeta(k) = A_\zeta \, (= \sqrt{7} \times 10^{-3})$$

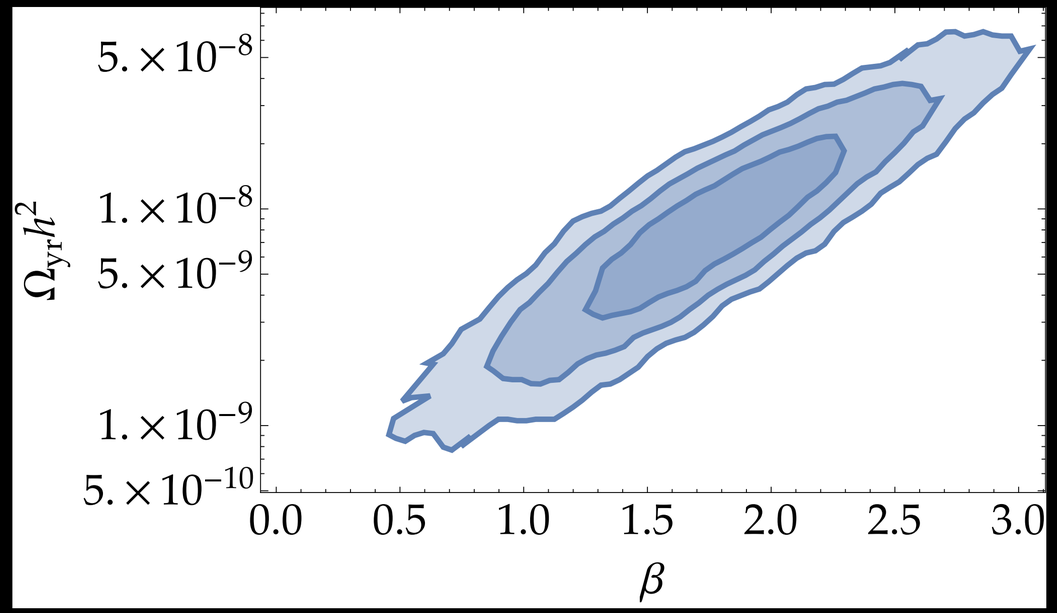


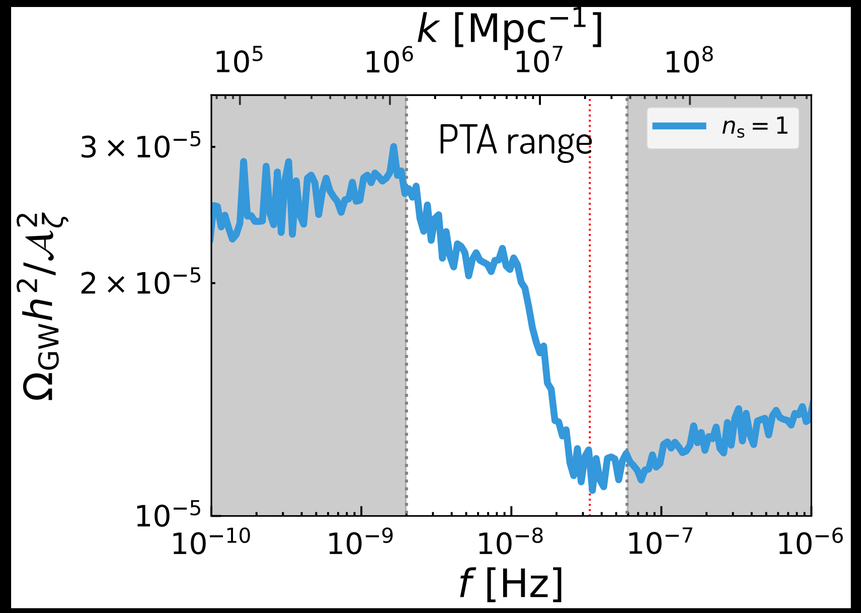
QCD on SIGWs

Abe & YT '23

NANOGrav's detection of GW bg : $\Omega_{\rm GW}h^2(f) = \Omega_{\rm yr}h^2\left(\frac{f}{1\ {\rm yr}^{-1}}\right)^{\beta}$

NANOGrav '23 (cf. EPTA, PPTA, CPTA)





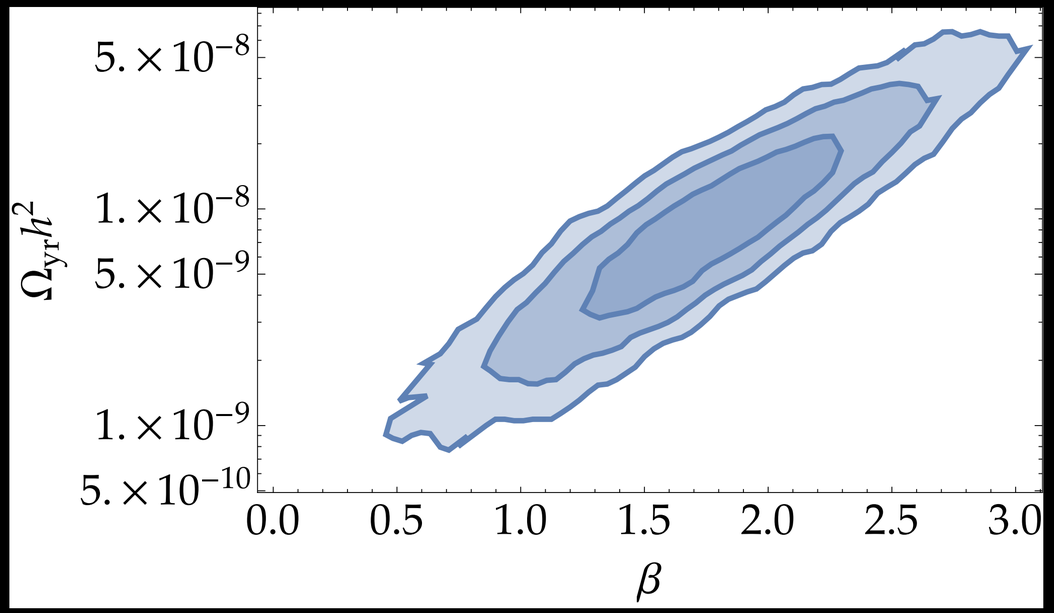
QCD on SIGWs

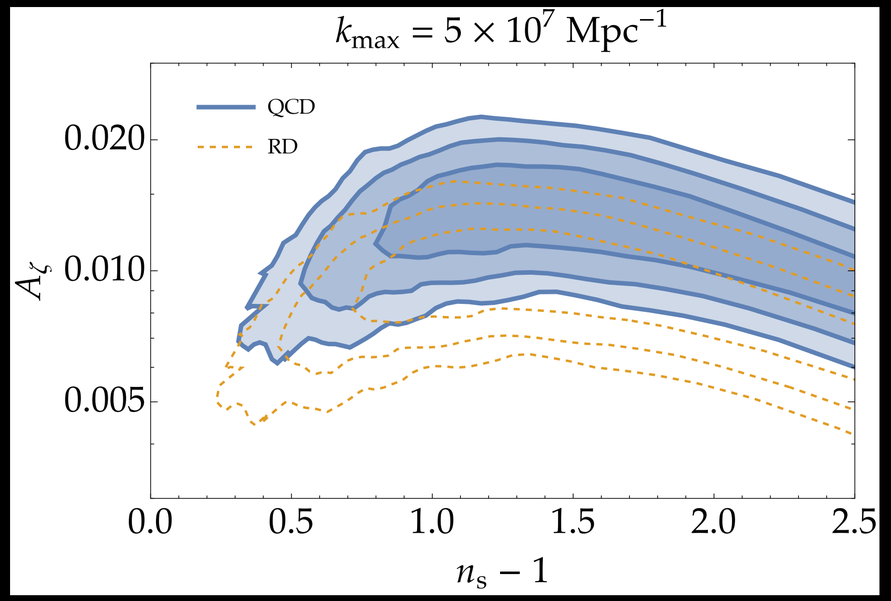
Abe & YT '23

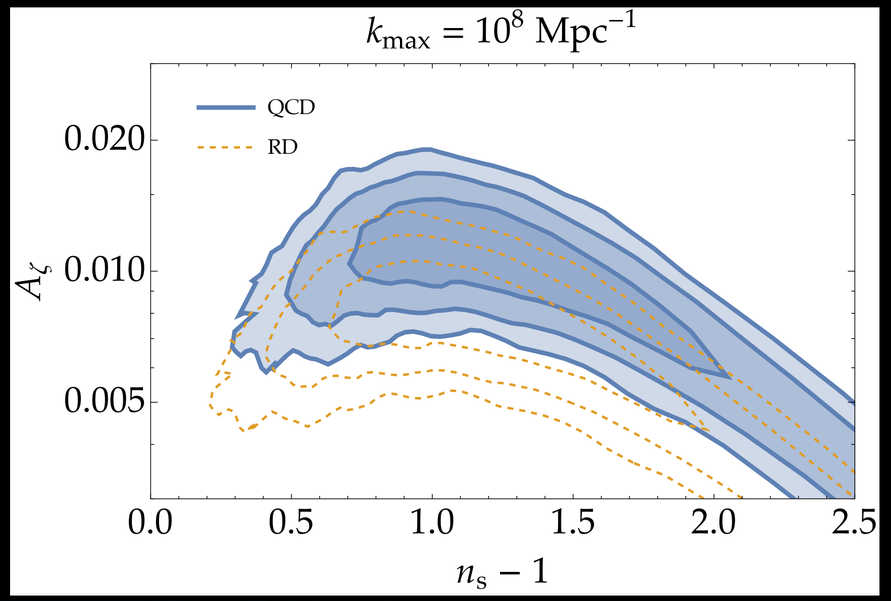
$$\mathscr{P}_\zeta(k) = A_\zeta \left(\frac{k}{1\ \mathrm{yr}^{-2}}\right)^{n_s-1} \Theta(k_{\max} - k)$$

NANOGrav's detection of GW bg : $\Omega_{\rm GW}h^2(f) = \Omega_{\rm yr}h^2 \left(\frac{f}{1\ \mathrm{yr}^{-1}}\right)^{\beta}$

NANOGrav '23 (cf. EPTA, PPTA, CPTA)



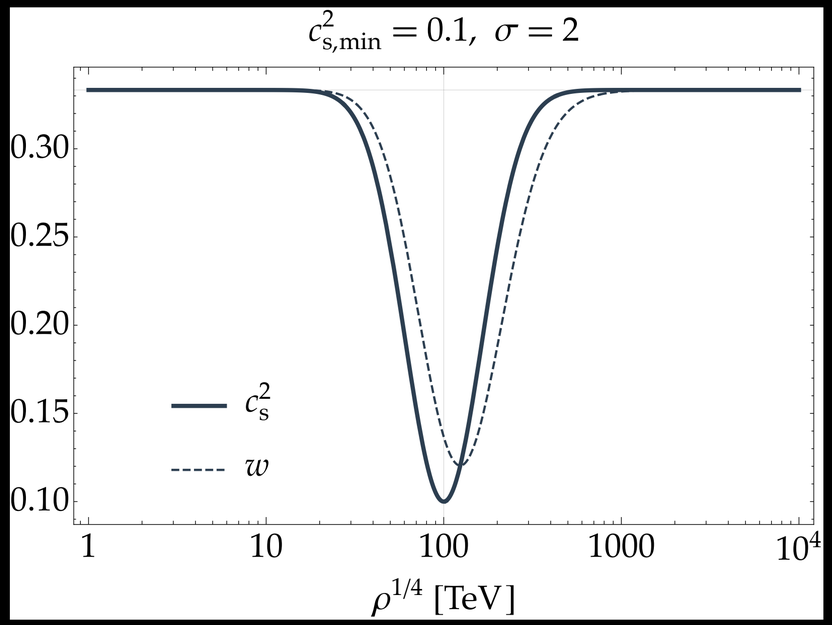


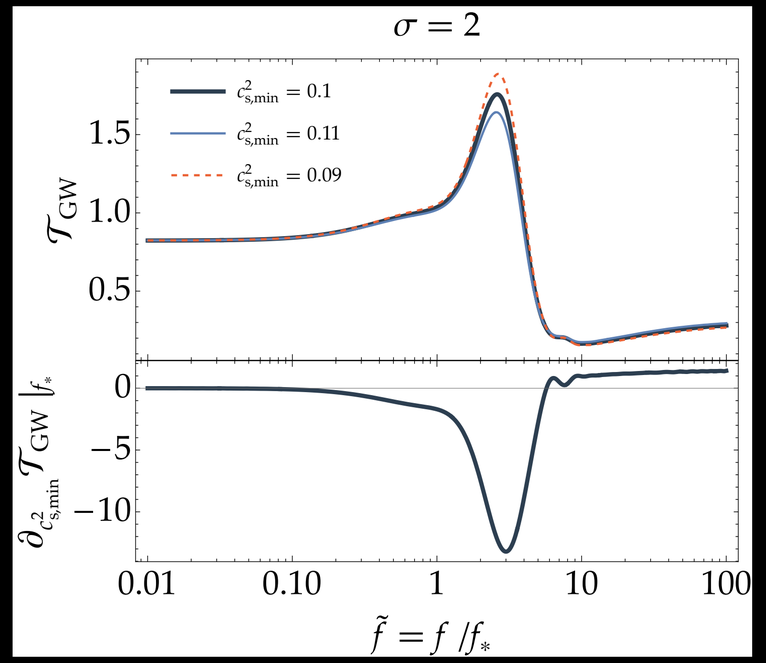


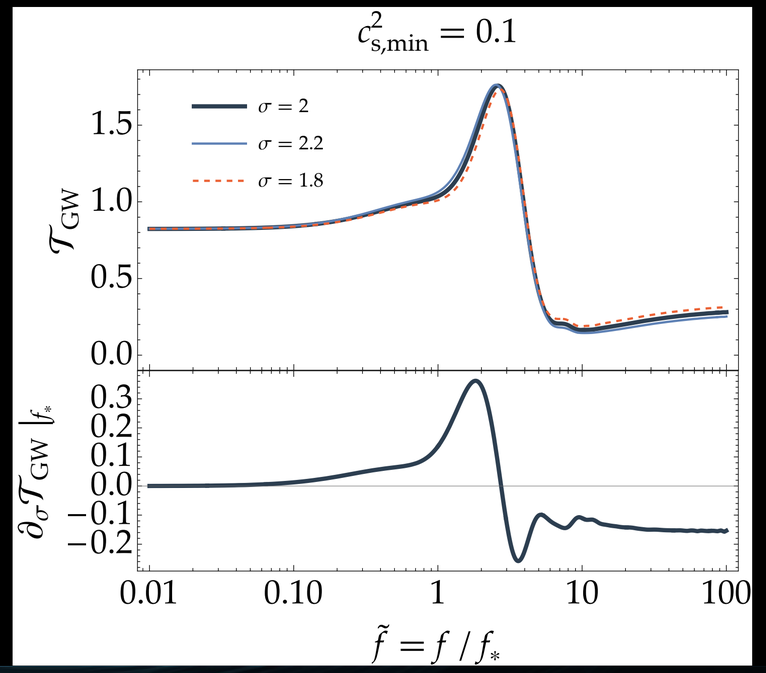
SIGWs probe Crossover

Escriva, Inui, YT, Yoo '24

$$c_s^2(\rho) = \frac{1}{3} - \left(\frac{1}{3} - c_{s,\min}^2\right) \exp\left[-\frac{\ln^2 \rho/\rho_*}{2\sigma^2}\right]$$







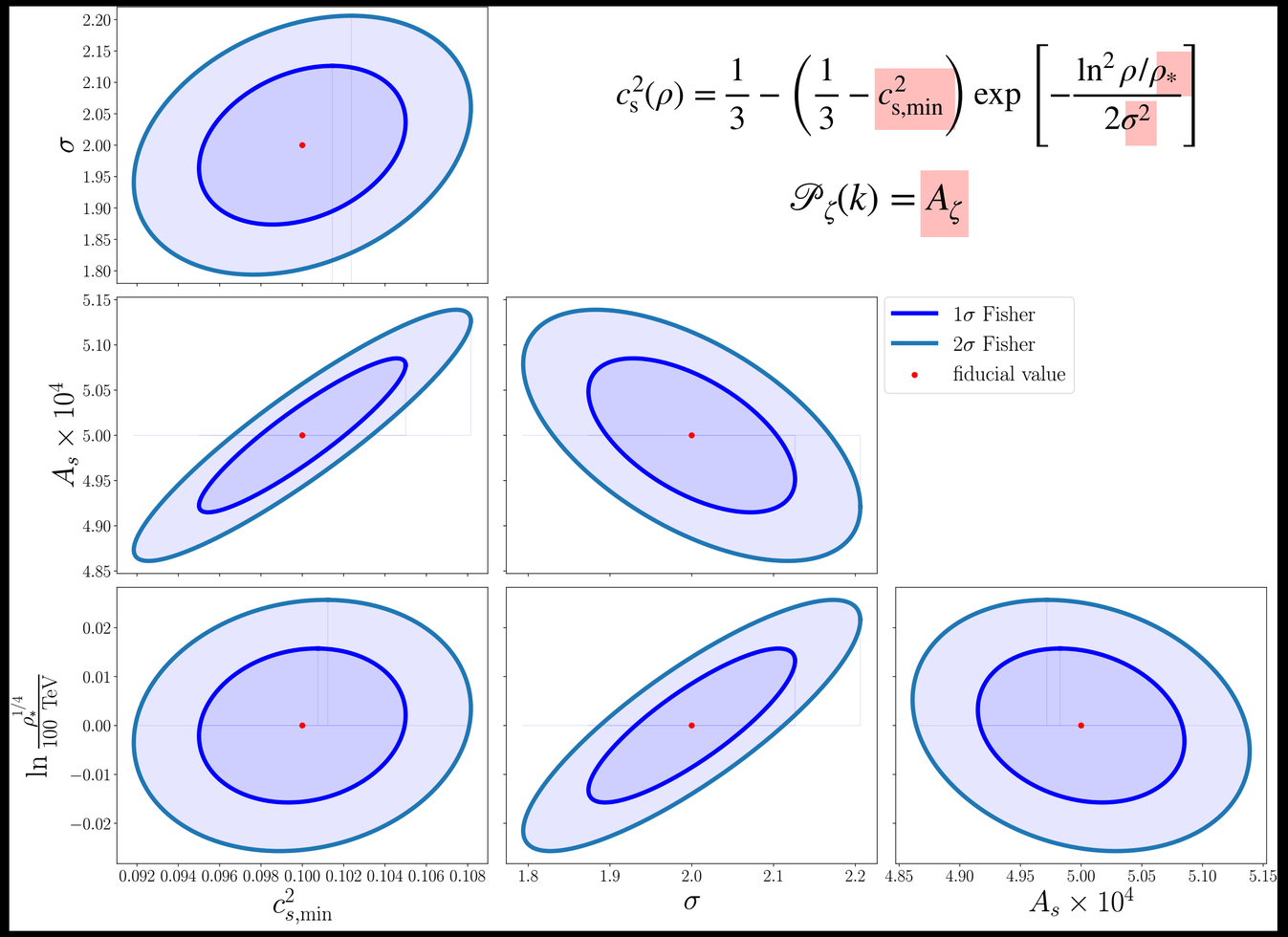
$$\mathcal{P}_\zeta(k) = A_\zeta$$

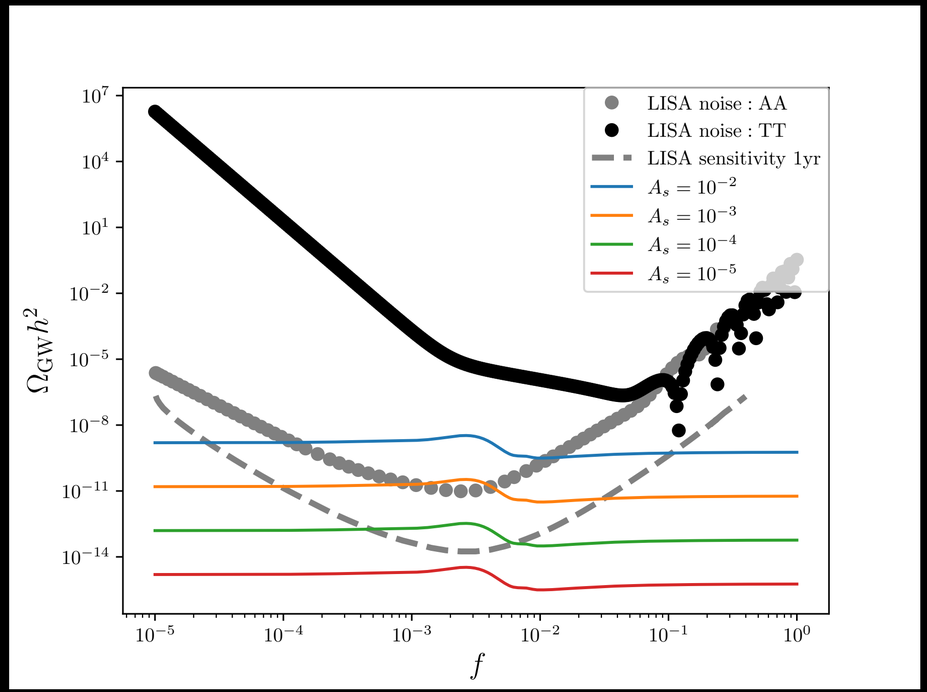
$$\Omega_{GW}(f)h^2 = \Omega_r h^2 A_s^2 \mathcal{T}_{GW}(f)$$

SIGWs probe Crossover

Escriva, Inui, YT, Yoo '24

LISA 1-yr decidability

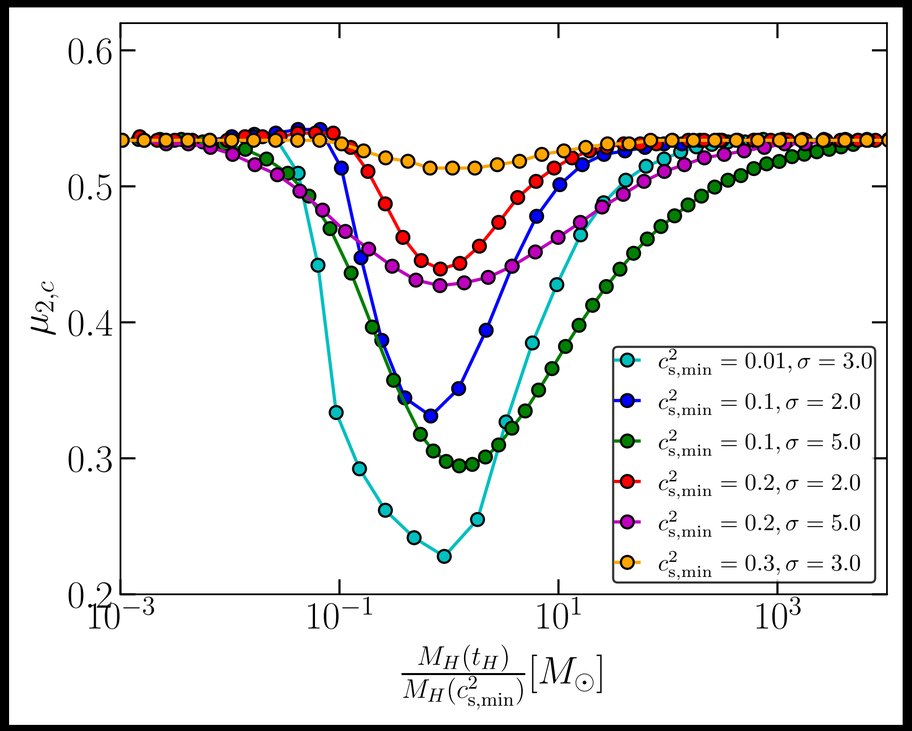




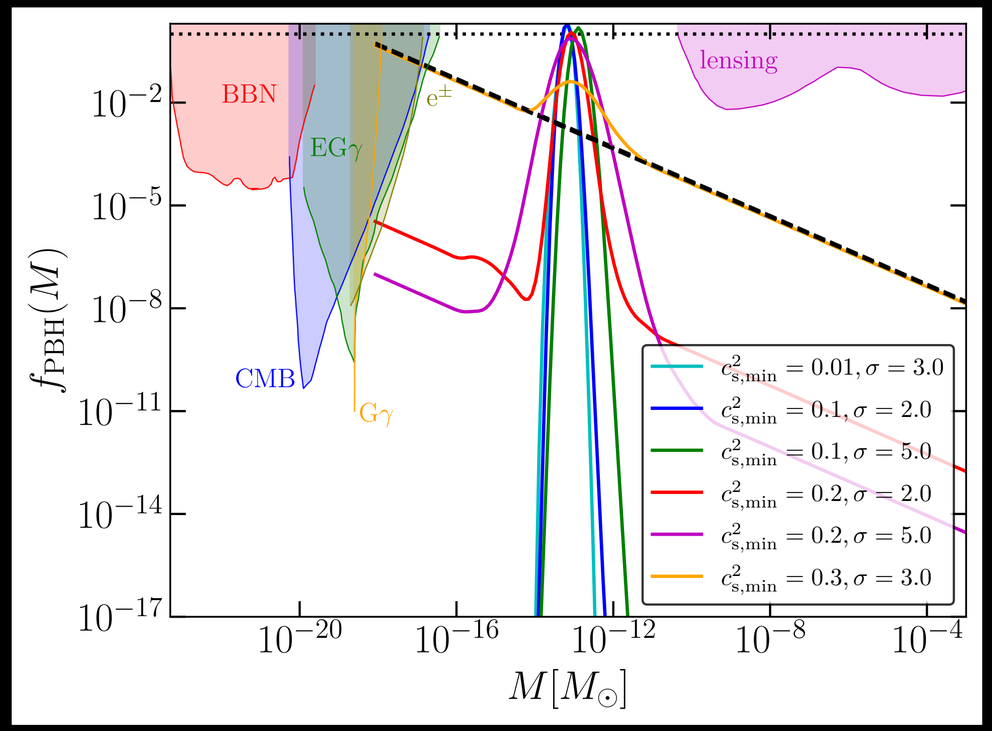
100 TeV SC for DM PBH

Escriva, YT, Yoo '23

num. rel. for threshold reduction



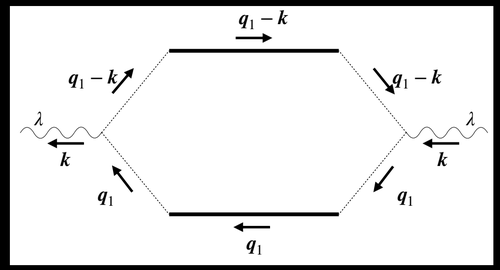
$\mathcal{P}_\zeta(k)=A_\zeta$

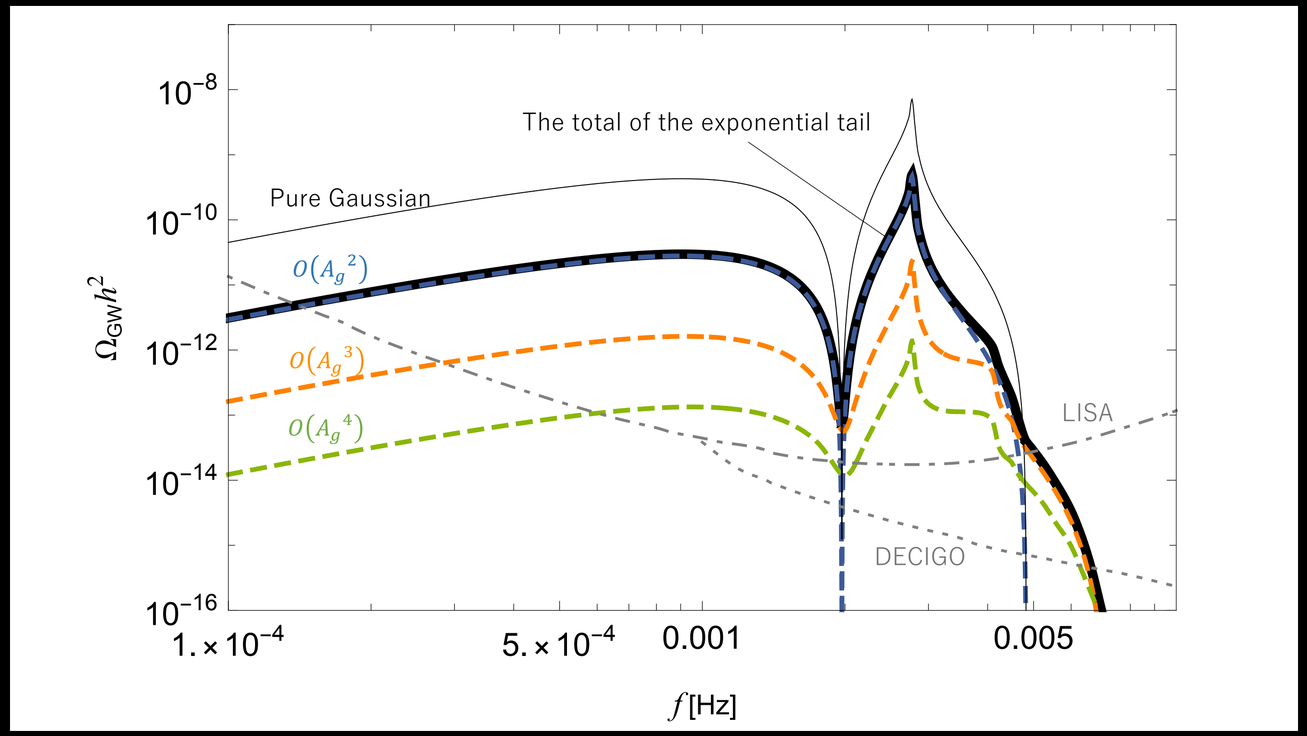


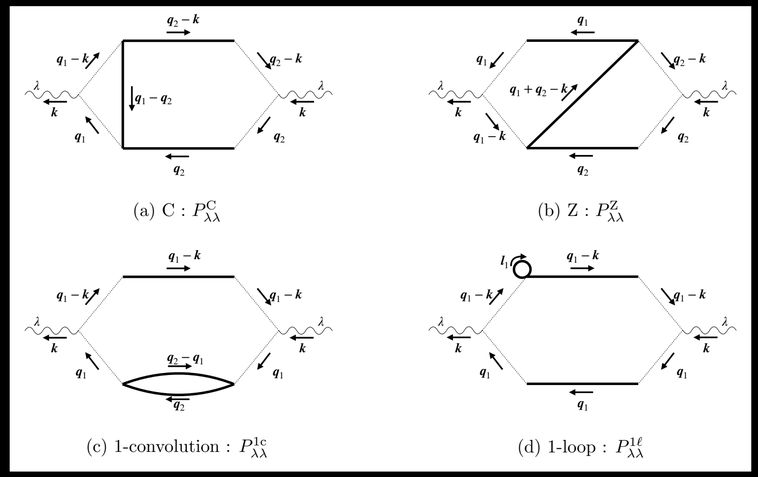
Non-Gaussianity on SIGWs

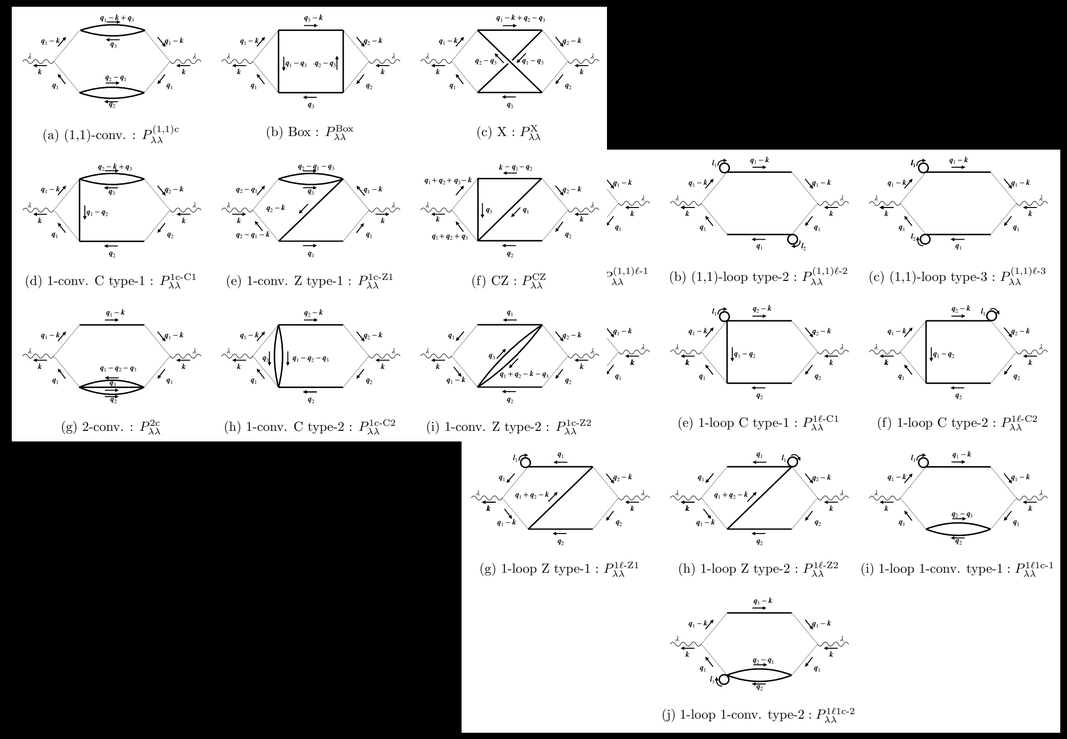
Abe, Inui, YT, Yokoyama '22

$$\zeta(\mathbf{x}) = g(\mathbf{x}) + F_{\rm NL} g^2(\mathbf{x}) + G_{\rm NL} g^3(\mathbf{x}) + \cdots$$









Kernel data? — QCD on SIGWs

Franciolini, YT, Veermae in prep

$$\mathscr{P}_h(\eta,k) = 2\int_0^\infty \mathrm{d}t \int_{-1}^1 \mathrm{d}s \left[\frac{t(2+t)(s^2-1)}{(1-s+t)(1+s+t)}\right]^2 I^2(s,t,\eta,k)\,\mathscr{P}_\zeta(uk)\,\mathscr{P}_\zeta(vk)$$

$$u = (t+s+1)/2 \qquad v = (t-s+1)/2$$

All crossover info!

$$\begin{cases} I(s,t,\eta,k) = g_{1k}(\eta)\, I_2(s,t,\eta,k) - g_{2k}(\eta)\, I_1(s,t,\eta,k) \\ I_i(s,t,\eta,k) = \dfrac{4}{9}\dfrac{k^2}{a(\eta)}\displaystyle\int_0^\eta \mathrm{d}\tilde{\eta}\, g_{ik}(\tilde{\eta})\, a(\tilde{\eta})\, S_{\mathbf{k}}(\tilde{\eta}) \end{cases}$$

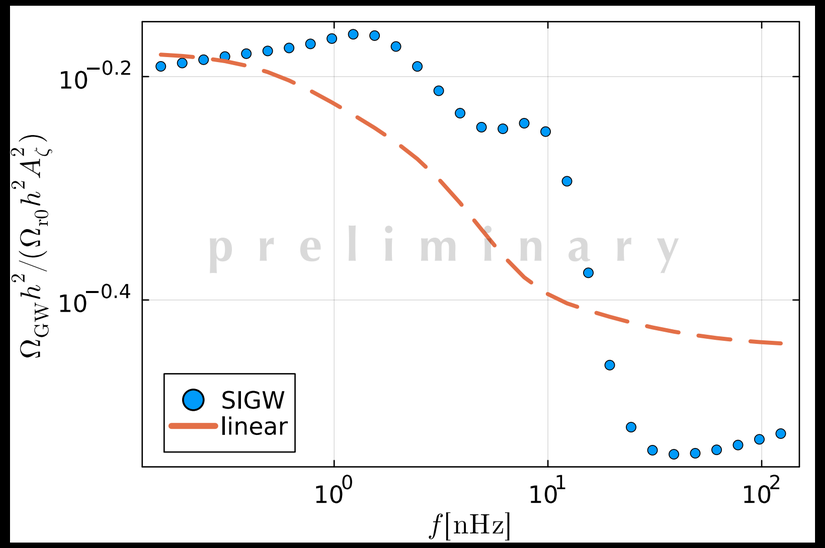
Kernel data? — QCD on SIGWs

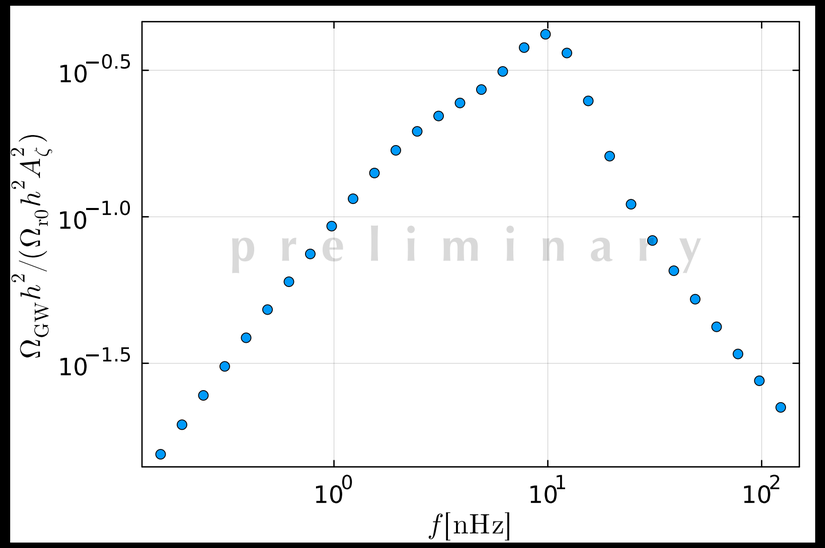
Franciolini, YT, Veermae in prep

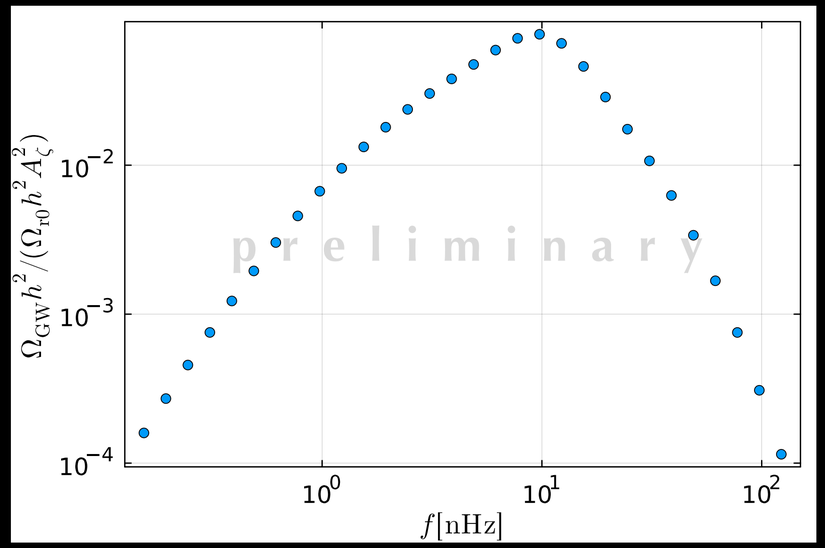
$$\mathscr{P}_\zeta(k) = A_\zeta$$

$$\mathscr{P}_\zeta(k) = A_\zeta \times \begin{cases} \left(\frac{k}{10\,\mathrm{nHz}}\right)^{0.5} & \text{for } k < 10\,\mathrm{nHz} \\ \left(\frac{k}{10\,\mathrm{nHz}}\right)^{-0.5} & \text{for } k > 10\,\mathrm{nHz} \end{cases}$$

$$\mathscr{P}_\zeta(k) = \frac{A_\zeta}{\sqrt{2\pi}} \exp\left(-\frac{\ln^2 k/(10\,\mathrm{nHz})}{2}\right)$$

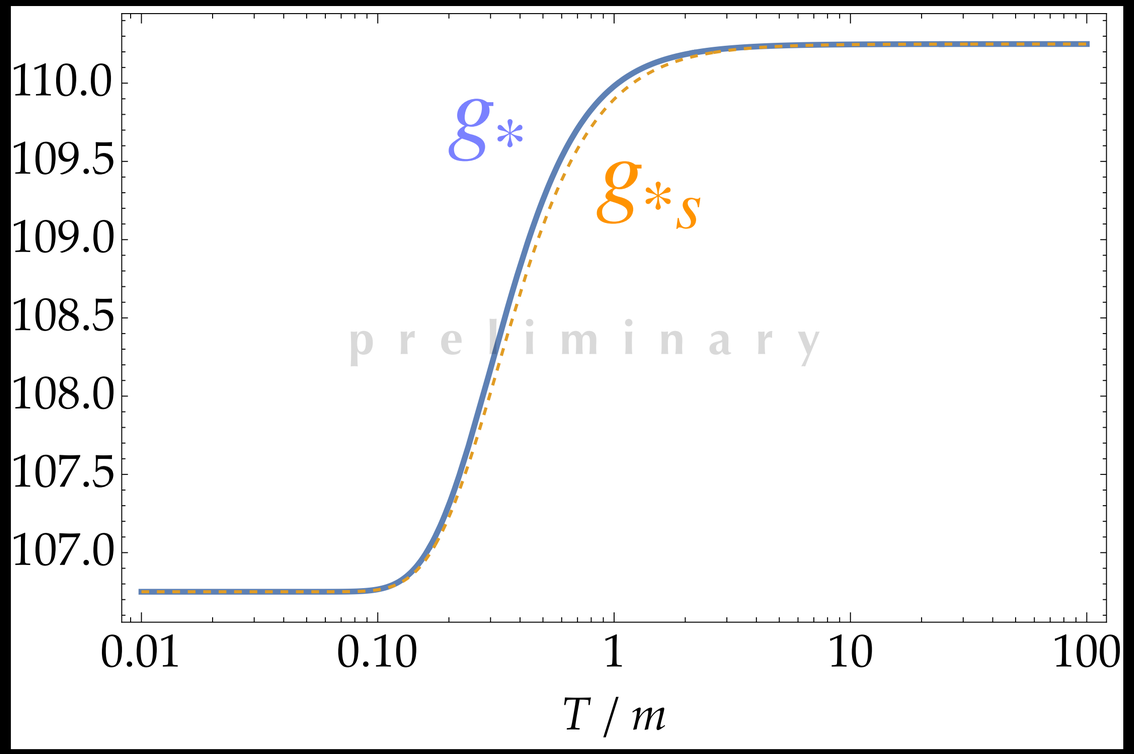


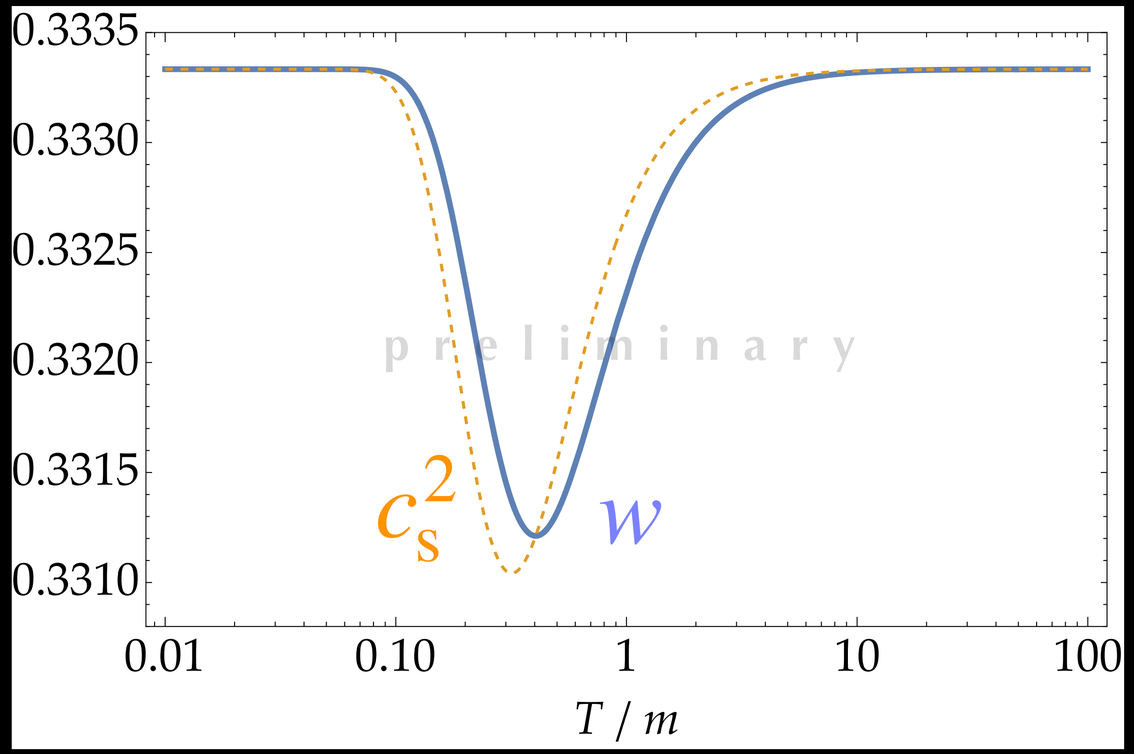




Thermal WIMP?

Inui, Kuroyanagi, Makino, YT, Yokoyama in prep





Summary

- Crossover affects SIGWs and PBHs
- SIGWs and PBHs can probe Crossover
- $100\,\mathrm{TeV}$ crossover is an interesting target of LISA & PBH-DM
- QCD effect can be included into Kernel in advance for PTA analysis