Upper Bound on Thermal Gravitational Wave Backgrounds from Hidden Sectors

Yannis Georis
based on work in collaboration with M. Drewes, J. Klarić and P. Klose
[arXiv:2312.13855]

CERN TH Institute *Particle Production in the Early Universe*
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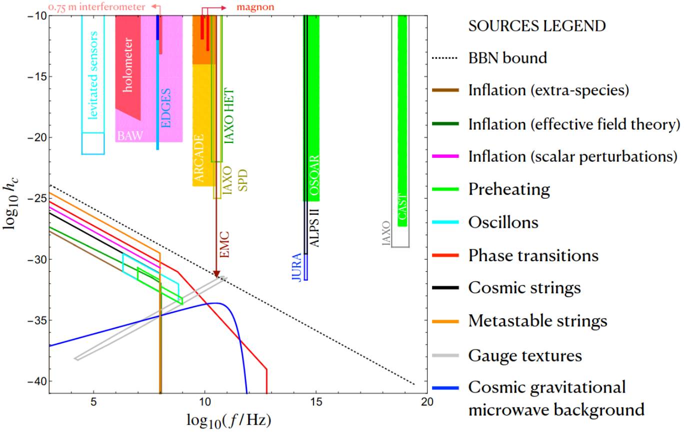
Ultra-High-Frequency Gravitational Waves



[arXiv:2011.12414]

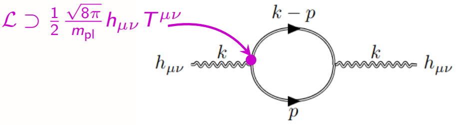
- No known astrophysical background at frequencies above 10^4 Hz
  $\longrightarrow$ Powerful probe of cosmological backgrounds
- Many different sources: inflation, preheating, topological defects, ...

Gravitational Waves from thermal fluctuations

- Even in equilibrium, thermal plasma emit gravitational waves from microscopic processes

$$\frac{d\dot{e}_{\rm gw}}{d\ln k} + 4H\frac{de_{\rm gw}}{d\ln k} = 16\pi^2 \left(\frac{k}{2\pi a}\right)^3 \frac{\Pi(k/a)}{m_{\rm pl}^2} \quad \sim \langle T^{\mu\nu} T^{\rho\sigma} \rangle$$

- GW production rate governed by the self-energy



- Assuming standard cosmic history

$$h^2\Omega_{\rm gw}(f) \approx 2.02\cdot 10^{-38} \times \left(\frac{f}{\rm Hz}\right)^3 \times \int_{T_{\rm min}}^{T_{\rm max}} \frac{dT'}{m_{\rm Pl}} \frac{\Pi\,(2\pi f a_0/a')}{8T'^4} \,.$$

- Contribution is small but unavoidable ! Act as cosmic GW floor.

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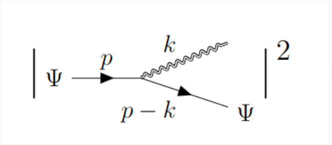
$\mathcal{L} \supset \frac{1}{2}\frac{\sqrt{8\pi}}{m_{pl}} h$



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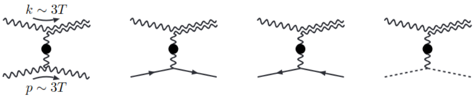
Boltzmann vs hydrodynamic regime

- For hard graviton momentum/frequency $k \sim \pi T$, Π dominated by particle scatterings (Boltzmann regime) *e.g.*

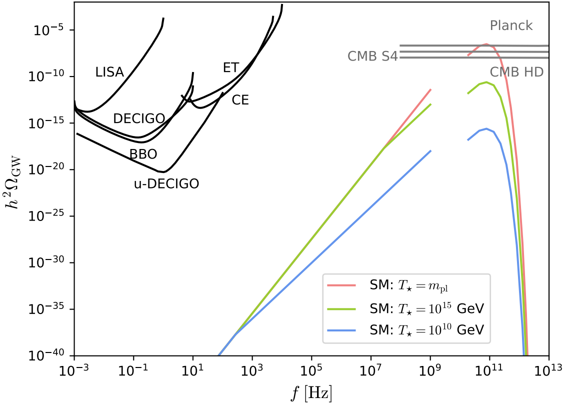


$\longrightarrow$ Computed at LO for the SM by [Ghiglieri/Jackson/Laine/Zhu, 2004.11392]

- For soft momentum $k \ll T$, long-range hydrodynamic fluctuations dominate (hydrodynamic regime)

$\longrightarrow$ Estimated for the SM by [Ghiglieri/Laine, 1504.02569]

Standard Model GW background



[See Ghiglieri/Jackson/Laine/Zhu '15,'20, Ringwald/Schütte-Engel/Tamarit '20]

- GW spectrum peaks for $f \sim 10^{11}$ Hz (Model independent: $k \sim \pi T$)

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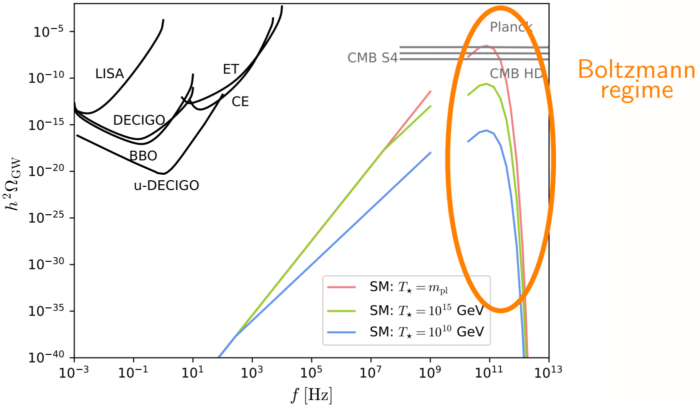

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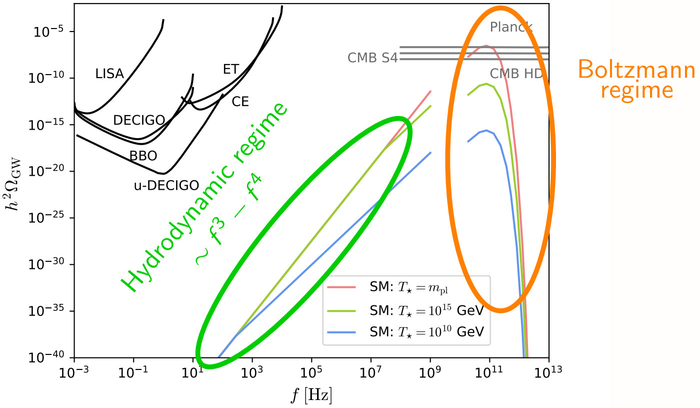

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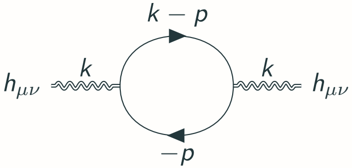
Gravitational Waves from hidden sectors

- Stress-energy tensor given at leading order by

$$T_{ij}(x) \supset \frac{c_X}{4}\overline{\psi}_x iD_{ij}\psi_x,\ \ iD_{ij} = \gamma_i i\partial_j + \gamma_j i\partial_i$$



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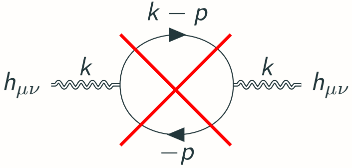

- Tree level contributions vanishes for kinematical reasons: Need to resum (in the hydrodynamic regime) !

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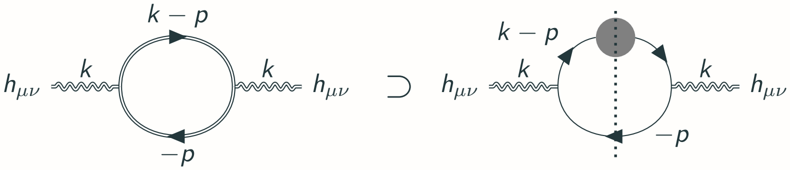

- In hydrodynamic regime, enhanced for feebly interacting particles

Plasma shear viscosity

$$\Pi(k) \sim 8T\eta \sim \frac{T^4}{\Upsilon}$$

Particles' width

$\longrightarrow$ Can dominate SM contribution !

Is it a good way to probe hidden sectors ?

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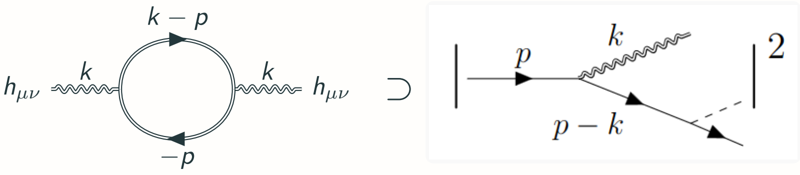

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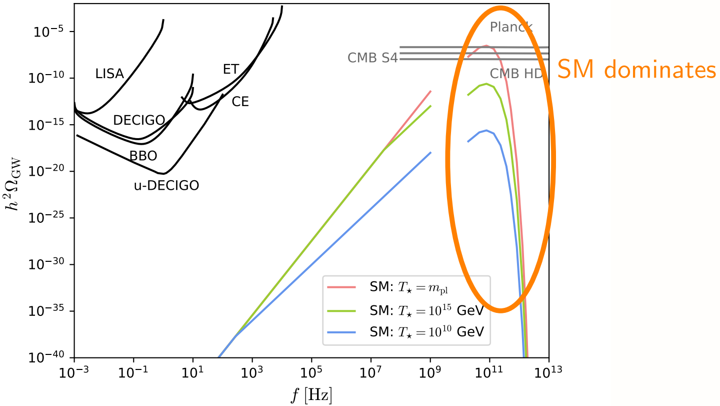

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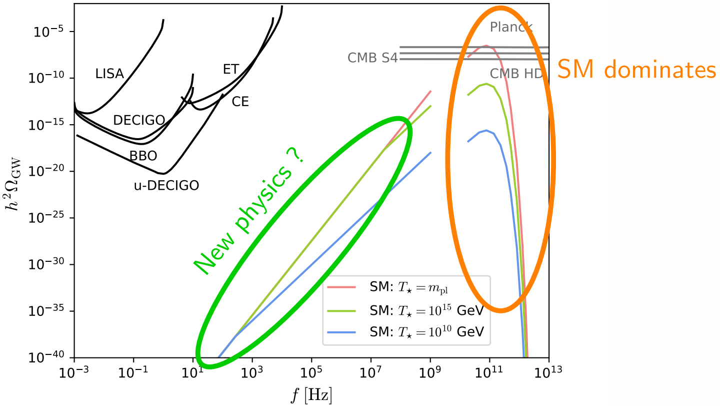

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GW production rate

- Fermionic production rate in real time (in-in) formalism

$$\Pi(k) = -\frac{c_X^2}{8}\int \frac{d^3\boldsymbol{p}}{(2\pi)^3}\int \frac{dp_0}{2\pi}\, \mathbb{L}^{ij;kl}\, p_i p_k \,\mathrm{Tr}[\gamma_j\, iS^>_p\, \gamma_l\, iS^<_{p-k} + \gamma_j\, iS^<_p\, \gamma_l\, iS^>_{p-k}]$$

Traceless-transverse projector

Derivative coupling

$\sim (\not p + m)\,\frac{\Gamma_p}{\Omega_p^2+\Gamma_p^2}(1-f)$

- After some algebra,

$$\Pi(k) \overset{m \ll T}{\simeq} g_X \frac{16\pi^2}{225} T^5 \frac{5\Upsilon_{\rm av}}{k^2 + 10\Upsilon_{\rm av}^2}\,, \qquad g_X = \begin{cases} 1 & \text{Spin } 0 \\ 2\cdot c_X & \text{Spin } \frac{1}{2} \end{cases}$$

- Hydrodynamic regime:

$$k < \sqrt{10}\Upsilon_{\rm av}, \Pi(k) \sim \frac{1}{\Upsilon_{\rm av}},$$

Boltzmann regime:

$$k > \sqrt{10}\Upsilon_{\rm av}, \Pi(k) \sim \Upsilon_{\rm av}$$

- For renormalisable interactions $\Upsilon_{\rm av} = yT$

$$k < \sqrt{10}\Upsilon_{\rm av} \longleftrightarrow f < f_c = y\cdot 6\cdot 10^{10}\mathrm{Hz}$$

Hubble suppression

- GW evolution equation

$$\ddot{h}_{ij} + 3H\dot{h}_{ij} - \frac{\nabla^2 h_{ij}}{a^2} = \frac{16\pi\, T_{ij}}{a^2 m_{\rm Pl}^2}$$

- 2 regimes
  1. Super-Horizon ($k < H$) modes are static
  2. Sub-Horizon ($k > H$) modes

- GW production is delayed until $k = \frac{2\pi f a_0}{a} > H = T^2/M_0$

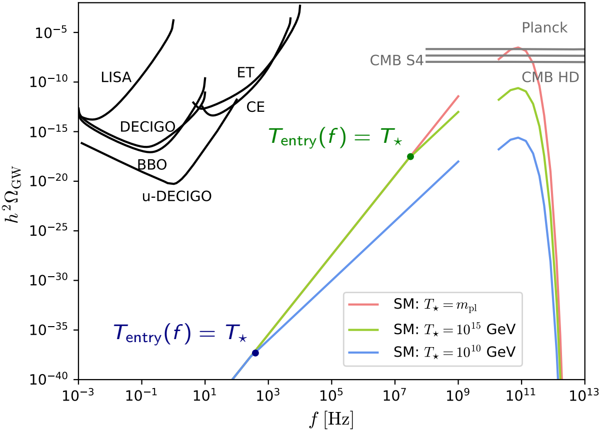
- In terms of temperature, production is delayed until

frequency dependent !

$$T < T_{\rm entry}(f) \approx 4 \cdot 10^7 \mathrm{GeV} \frac{f}{\mathrm{Hz}}$$

→ SM contribution behaves as f^4 at low frequencies, not f^3 !

Standard Model GW background



[See Ghiglieri/Jackson/Laine/Zhu '15,'20, Ringwald/Schütte-Engel/Tamarit '20]

Upper bound on GW emission

- Production rate in the relativistic regime

$$\Pi(k) \overset{m \ll T}{\simeq} g_X \frac{16\pi^2}{225} T^5 \frac{5\Upsilon_{\rm av}}{k^2 + 10\Upsilon_{\rm av}^2}$$

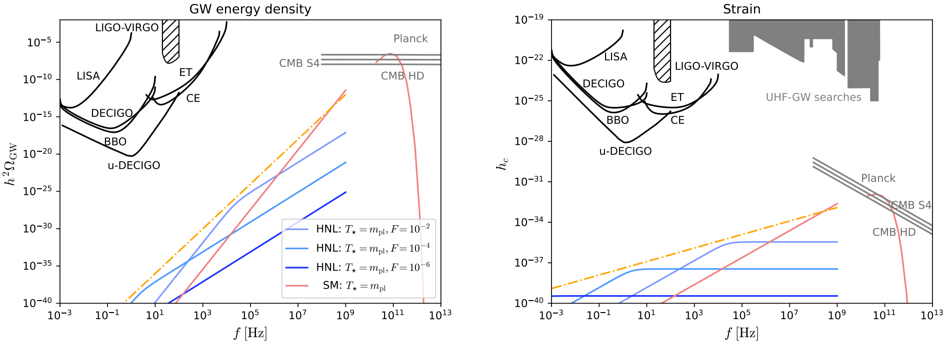
$\longrightarrow$ Maximised for a width $\Upsilon_{\rm av} = k/\sqrt{10}$ ($\Upsilon_{\rm av} = k/2$ in the non-relativistic case)

- Leads to the model-independent upper bound

$$h^2\Omega_{\rm gw}(f) < 4.9 \cdot 10^{-40} \times g_X \left(\frac{f}{\rm Hz}\right)^3$$

- Tradeoff: Larger enhancement for smaller Υ but arises for smaller frequencies
- Does not apply in case of
  1. Out-of-equilibrium dynamics
  2. Hidden sector hotter than SM
  3. Beyond radiation domination

Illustration: Right-handed neutrinos



[Drewes/YG/Klarić/Klose, 2312.13855]

- Coupled to SM through Yukawa coupling

$$\mathcal{L} \supset F\psi(\tilde{\phi}^\dagger \ell) + \text{h.c.}$$

- Right-handed neutrino width

$$\Upsilon_{\rm av} \simeq 0.2\frac{F^2 T}{16\pi} \, ,$$

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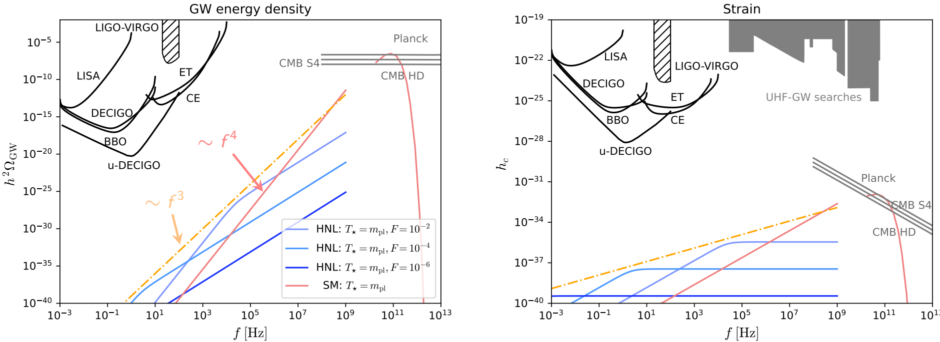

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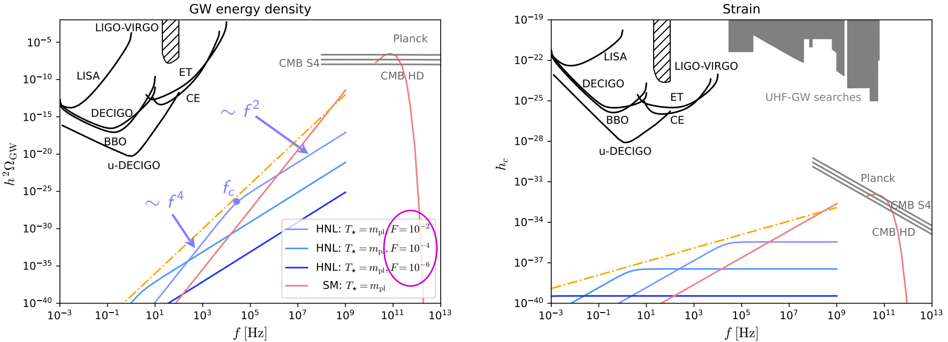

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Summary and outlook

- Ultra-High-Frequency GWs are powerful probes of new physics because of lack of astrophysical background
- Can be produced by plasma in thermal equilibrium
  $\rightarrow$ Constitutes an irreducible background for every theories
- Background can be enhanced for feebly interacting particles
- Upper bound on such background is very restrictive
- Inclusion of hydrodynamic and Hubble suppression crucial for accurate estimate of GW emission
- Formalism can also be applied to non-equilibrium situations

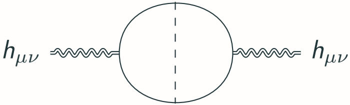
Thanks for your attention!

Backup slides

Circumventing our upper bound

- Non-Standard Cosmic History, *e.g.*
  1. Entropy transfer between SM and hidden sector
  2. Large number of degrees of freedom in the hidden sector

- Contributions from vertex-type diagrams *e.g.*



$\longrightarrow$ Only plays a role at high frequencies $f \gg f_c$!

- Out-of-equilibrium dynamics, *e.g.*
  1. Freeze-in
  2. Peaked distribution function (not only dominated by on-shell region)
  3. Scales other than T, m *e.g.* condensate oscillation during reheating

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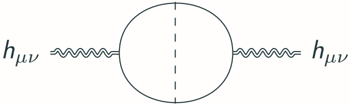

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  1. Freeze-in   Underabundant if thermal production !
  2. Peaked distribution function (not only dominated by on-shell region)
  3. Scales other than T, m *e.g.* condensate oscillation during reheating

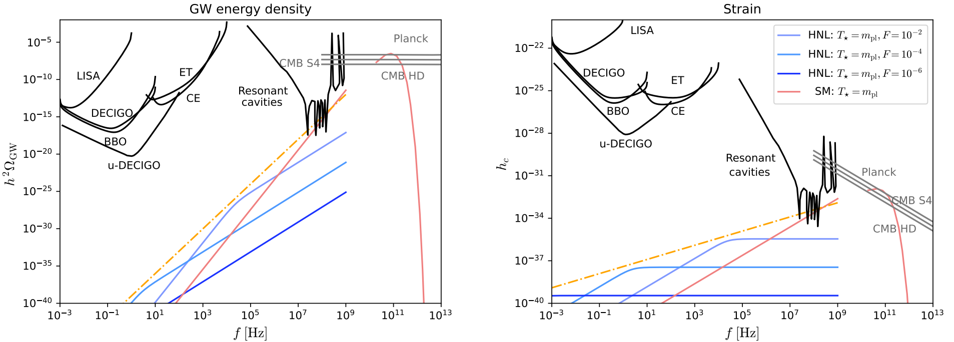
N_{eff} as Big Bang thermometer

	SM	νMSM	SMASH	MSSM
T_{max} [GeV] $<$	$(1.2\text{-}5.1) \times 10^{19}$	$(1.3\text{-}5.4) \times 10^{19}$	$(1.4\text{-}6.0(1)) \times 10^{19}$	$(2.3\text{-}9.4) \times 10^{19}$
$T_{\mathrm{max}}^{\Delta N_{\mathrm{eff}}=0.001}$ [GeV] $<$	2.3×10^{17}	2.4×10^{17}	2.7×10^{17}	4.39×10^{17}

[Ringwald/Schütte-Engel/Tamarit '20]

- Can (in theory) probe the maximal temperature of the SM plasma by measuring N_{eff}

Resonant cavity searches

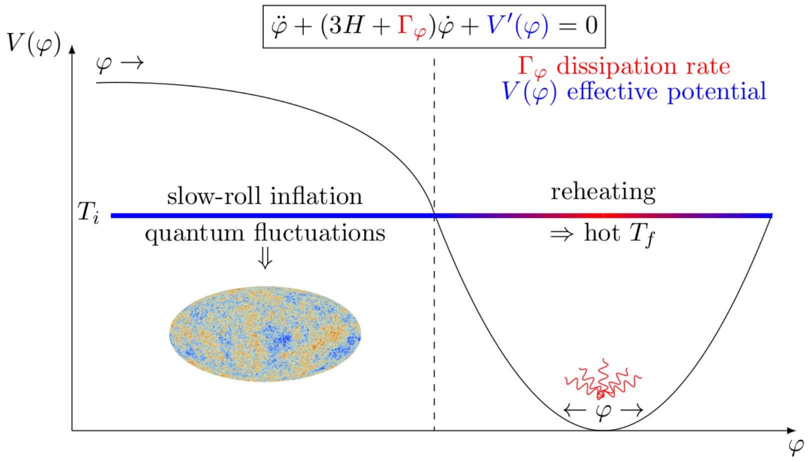


[Drewes/YG/Klarić/Klose, 2312.13855]

Resonant cavity searches [Herman/Lehoucq/Füzfa, '22] can potentially test these models but rely on unknown technology !

Beyond SM radiation domination: Inflation and reheating

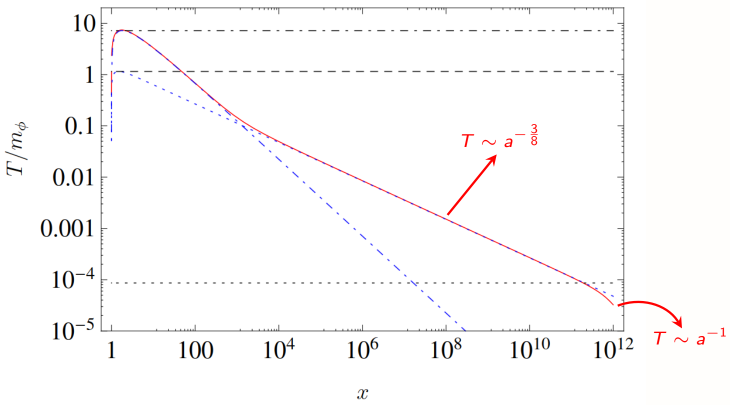
- Many processes predict deviations from SM radiation domination



[credit: Gilles Buldgen]

Beyond SM radiation domination: Reheating

- Many processes predict deviations from SM radiation domination
- *E.g.* inflaton decay during reheating slows down redshifting



[M. Drewes, 1406.6243]

GWs beyond SM radiation domination

- Can we adapt our formula to GW production if
    1. SM do not dominate energy budget ?
    2. entropy exchange between SM and hidden sector ?

- If production is still thermal:

$$h^2\Omega_{\rm gw}(f) \approx 2.02\cdot 10^{-38}\times\left(\frac{f}{\rm Hz}\right)^3 \int_{T_{\rm min}}^{T_{\rm max}} \frac{{\rm d}T'}{m_{\rm Pl}}\,\frac{\Pi\left(\frac{2\pi f a_0}{a}\right)}{8\,T'^4}\left|\frac{{\rm d}\ln a}{{\rm d}\ln T'}\right|\left(\frac{T'}{\overline{T}'}\right)\left(\frac{\rho_{\rm SM}}{\rho_{\rm tot}}\right)^{\frac{1}{2}}$$

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Radiation domination

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Radiation domination — Non-standard cosmic history

- Many works on graviton bremstrahlung during reheating: expect hydrodynamic and Hubble suppression effect to be relevant at low frequencies !
- During inflation, $\Gamma \ll H < k$

  $\longrightarrow$ No hydrodynamic suppression expected

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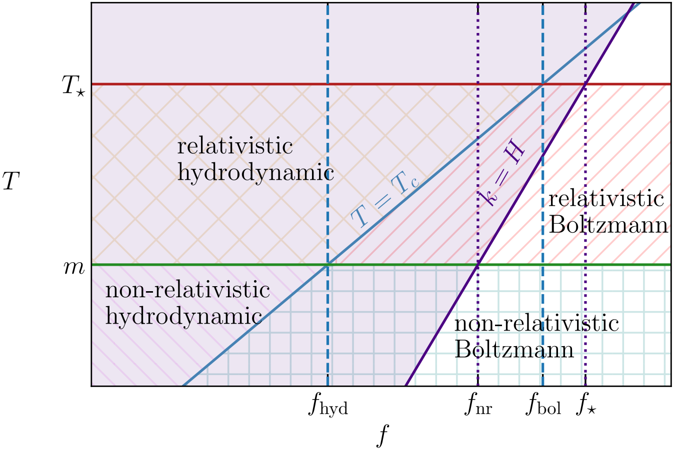
Production regimes



[Drewes/YG/Klarić/Klose, 2312.13855]

- Different possible scenarios depending on Hubble vs hydrodynamics scale

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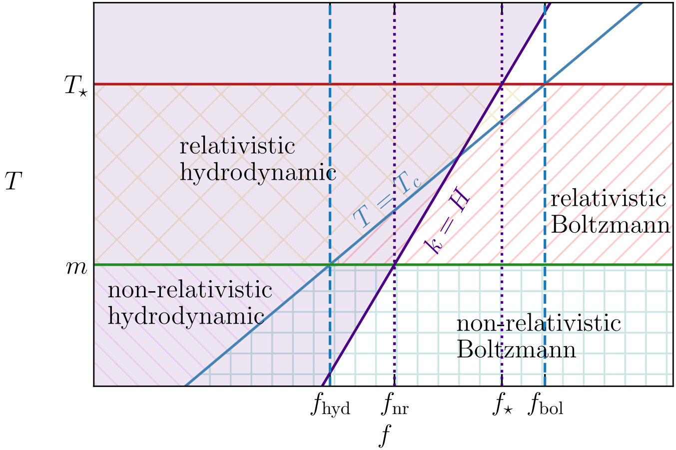

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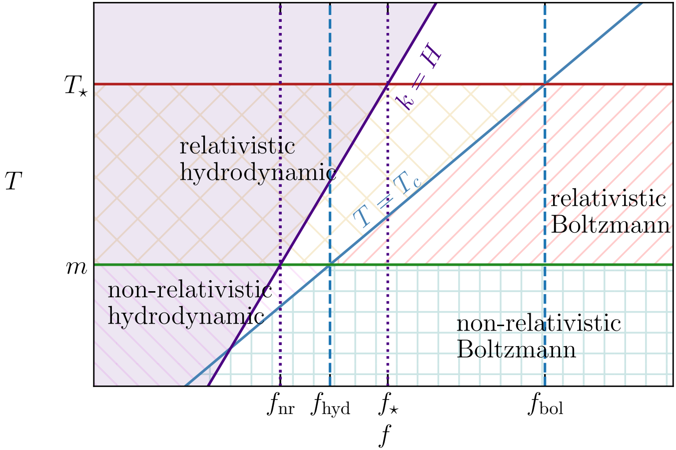

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- Different possible scenarios depending on Hubble vs hydrodynamics scale

Case 1

$$h^2\Omega_{\rm gw}^{T>m}(f) \overset{f_X > f_{\rm bol}}{\simeq} g_X \frac{1.6\cdot 10^{-40}}{2(d-4)+1}\left(\frac{f}{\rm Hz}\right)^2 \frac{f_{\rm bol}}{\rm Hz}\begin{cases} 0 & \text{for} \quad f < f_{\rm nr}\,, \\ \left(\frac{f}{f_\star}\right)^{2(d-4)} & \text{for} \quad f_{\rm nr} < f < f_\star\,, \\ \frac{f_\star}{f} & \text{for} \quad f_\star < f\,. \end{cases}$$

Case 2

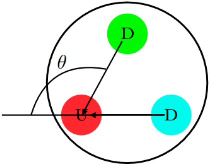
$$h^2\Omega_{\rm gw}^{T>m}(f) \overset{f_\star \gg f_{\rm bol}}{\simeq} g_X \frac{1.6\cdot 10^{-40}}{2(d-4)+1}\left(\frac{f}{\rm Hz}\right)^2 \frac{f_{\rm bol}}{\rm Hz}\begin{cases} 0 & \text{for} \quad f < f_{\rm nr}\,, \\ \left(\frac{f}{f_\star}\right)^{2(d-4)} & \text{for} \quad f_{\rm nr} < f < f_x\,, \\ \beta\,\frac{f_x}{f_{\rm bol}}\left(\frac{f}{f_x}\right)^{\frac{1}{2(d-4)}} & \text{for} \quad f_x < f < f_{\rm bol}\,, \\ \frac{f_\star}{f} & \text{for} \quad f_{\rm bol} < f\,. \end{cases}$$

Case 3

$$h^2\Omega_{\rm gw}^{T>m}(f) \underset{f_{\rm hyd}\gg f_{\rm nr}}{\overset{f_{\rm bol}\gg f_\star}{\simeq}} g x \frac{1.6\cdot 10^{-40}}{2(d-4)+1}\left(\frac{f}{\rm Hz}\right)^2 \frac{f_{\rm bol}}{\rm Hz}\begin{cases} 0 & \text{for} \quad f < f_{\rm hyd}\,, \\ \beta\frac{f_x}{f_{\rm bol}}\left(\frac{f}{f_x}\right)^{\frac{1}{2(d-4)}} & \text{for} \quad f_{\rm hyd} < f < f_{\rm bol}\,, \\ \frac{f_\star}{f} & \text{for} \quad f_{\rm bol} < f\,. \end{cases}$$

Example 2: Axion-like particles

- Neutron EDM $|d_n| \lesssim 10^{-26} e \cdot \text{cm}$

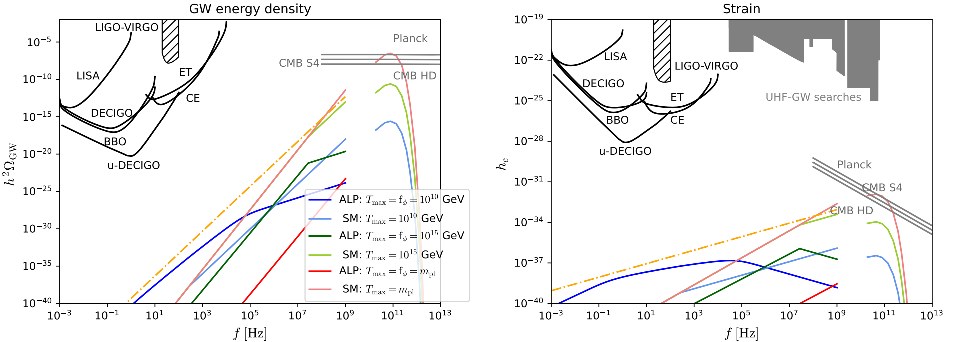


- QCD axion initially introduced as solution to the strong CP-problem

$$\mathcal{L} \supset \frac{1}{2}\left(\partial_\mu \phi \partial^\mu \phi - m^2 \phi^2\right) - \frac{\alpha}{16\pi \mathrm{f}_\phi} \phi \, \widetilde{G}_{\mu\nu} G^{\mu\nu}$$

- In general, axion-like particles are good candidates to
    1. form Dark Matter
    2. drive inflation

Example 2: Axion-like particles



[Drewes/YG/Klarić/Klose, 2312.13855]

- Thermal width

$$\Upsilon_{\rm av} \overset{m \ll T}{\leq} \kappa\, n_c^3 (n_c^2 - 1) \frac{\alpha^5 T^3}{{\rm f}_\phi^2} \,, \quad \kappa \approx 1.5 \,, \quad \frac{1}{\alpha} \approx \frac{22 n_c}{12\pi} \ln\left(\frac{2\pi T}{\Lambda_{\rm IR}}\right)$$

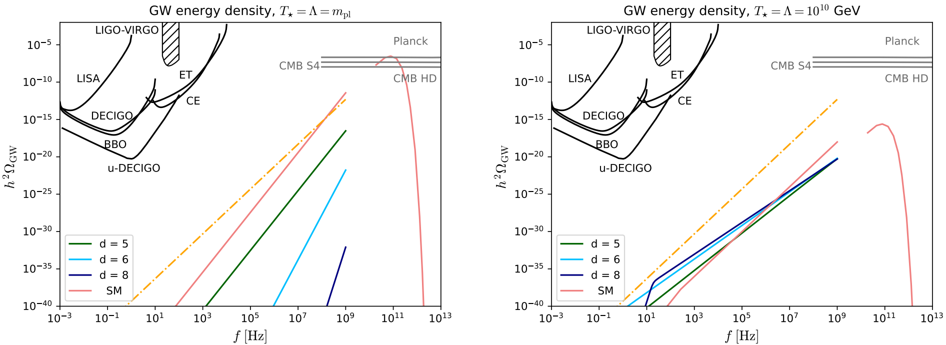
Frequency dependence of the GW spectrum $T^\star = m_{\rm pl}$

$$h^2\Omega_{\rm gw}^{T>m}(f) \overset{f_x > f_{\rm bol}}{\simeq} g_X \frac{1.6\cdot 10^{-40}}{2(d-4)+1}\left(\frac{f}{\rm Hz}\right)^2 \frac{f_{\rm bol}}{\rm Hz}\begin{cases} 0 & \text{for} \quad f < f_{\rm nr}\,, \\ \left(\frac{f}{f_\star}\right)^{2(d-4)} & \text{for} \quad f_{\rm nr} < f < f_\star\,, \\ \frac{f_\star}{f} & \text{for} \quad f_\star < f\,. \end{cases}$$

- Such frequency scaling depends on the ratios between $T_\star, \Lambda, m, \ldots$

  $\longrightarrow$ Can extract information on the particle's properties from the scaling !

Example 3: Higher dimensional operators



[Drewes/YG/Klarić/Klose, 2312.13855]

- Assuming generically that the width scales as

$$\Upsilon_{\rm av} \simeq y\, T \left(\frac{T}{\Lambda}\right)^{2(d-4)} \begin{cases} 1 & T \gg m \\ \left(\frac{m}{T}\right)^n & T \lesssim m \end{cases}, \qquad n \leq 1 + 2(d-4)$$

- Unavoidable contribution to the width (at least) at $d = 8$ from graviton exchanges

Frequency dependence of the GW spectrum $T^\star = 10^{10}$ GeV

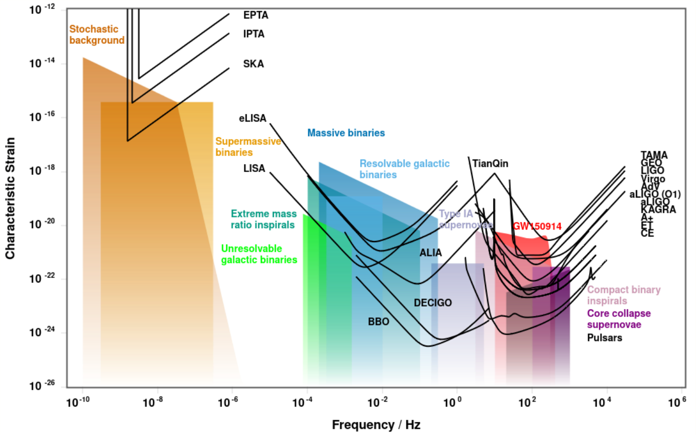
$$h^2\Omega_{\rm gw}^{T>m}(f) \overset{f_\star \gg f_{\rm bol}}{\simeq} g_X \frac{1.6\cdot 10^{-40}}{2(d-4)+1}\left(\frac{f}{\rm Hz}\right)^2 \frac{f_{\rm bol}}{\rm Hz} \begin{cases} 0 & \text{for} \quad f < f_{\rm nr}\,, \\ \left(\frac{f}{f_\star}\right)^{2(d-4)} & \text{for} \quad f_{\rm nr} < f < f_x\,, \\ \beta\,\frac{f_x}{f_{\rm bol}}\left(\frac{f}{f_x}\right)^{\frac{1}{2(d-4)}} & \text{for} \quad f_x < f < f_{\rm bol}\,, \\ \frac{f_\star}{f} & \text{for} \quad f_{\rm bol} < f\,. \end{cases}$$

- Such frequency scaling depends on the ratios between $T_\star, \Lambda, m, \ldots$

  $\longrightarrow$ Can extract information on the particle's properties from the scaling !

Gravitational Waves landscape

CMB B-modes



Ultra-high-frequency GW detectors

[Moore/Cole/Berry, 1408.0740]

- Combination of ground- and space-based interferometers + PTAs will $\approx$ cover the frequency band $[10^{-9}, 10^{4}]$ Hz