Towards the Determination of the Ultra-High Frequency Gravitational Wave Floor

Andreas Ringwald
”Quantum Sensing meets Ultra-high Frequency Gravitational Waves"
MITP – Mainz Institute for Theoretical Physics
Johannes Gutenberg University Mainz
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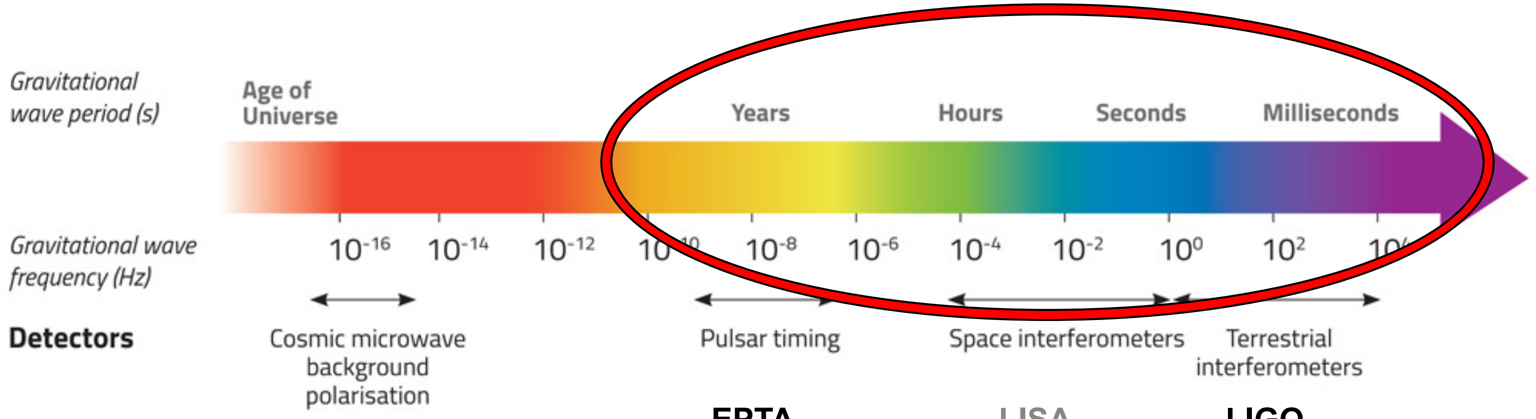
HELMHOLTZ RESEARCH FOR GRAND CHALLENGES
CLUSTER OF EXCELLENCE QUANTUM UNIVERSE
cost EUROPEAN COOPERATION IN SCIENCE & TECHNOLOGY
COSMIC WISPERS CA21106
DESY.

Motivation

A new window to explore the universe

Current and planned projects to detect GWs designed and optimised to search for GWs in the nHz to 10 kHz frequency range



EPTA
NANOGrav
PPTA
SKA

LISA
BBO
DECIGO

LIGO
VIRGO
KAGRA
ET

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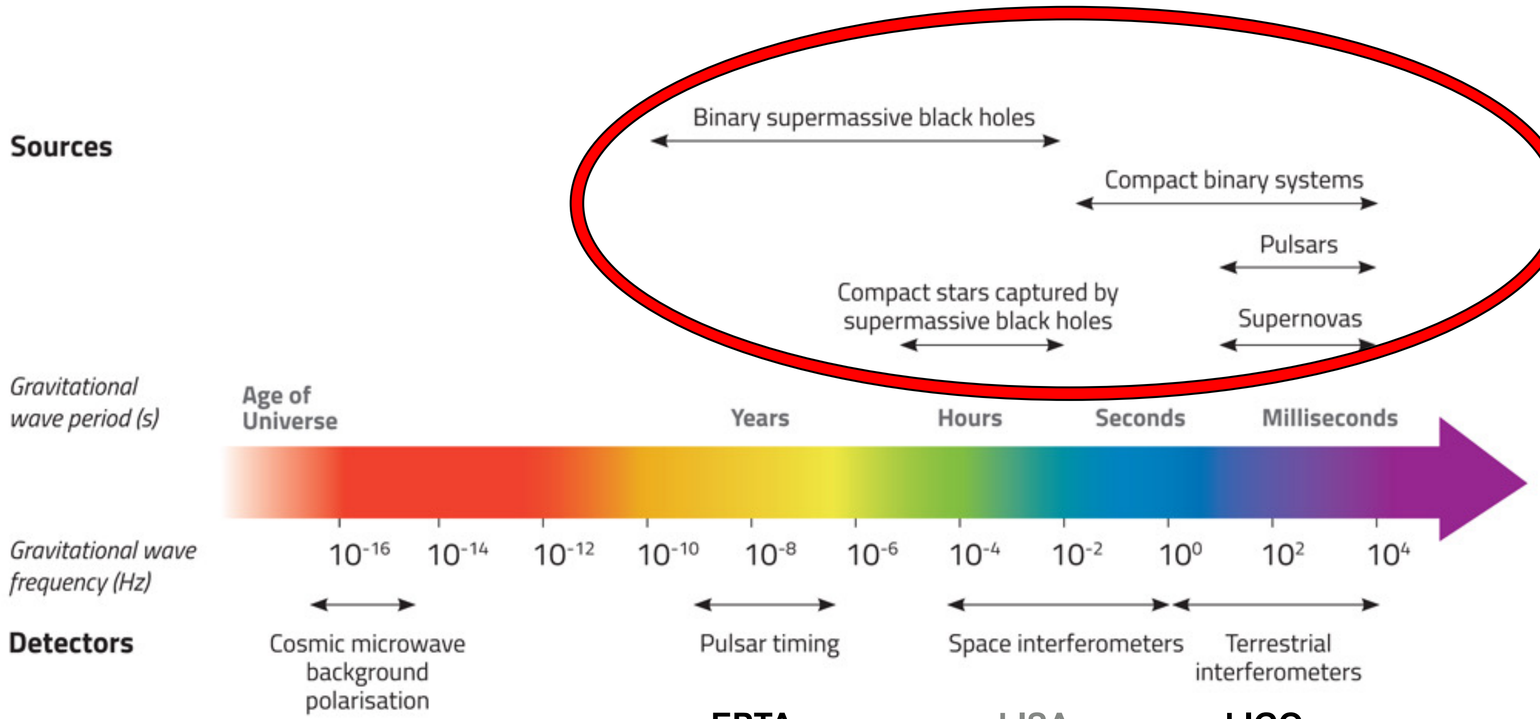
Current and planned projects to detect GWs designed and optimised to search for GWs in the nHz to 10 kHz frequency range which is particularly well-motivated by known astrophysical sources



[https://www.scienceinschool.org/article/2017/gravitational-waves-taxonomy/]

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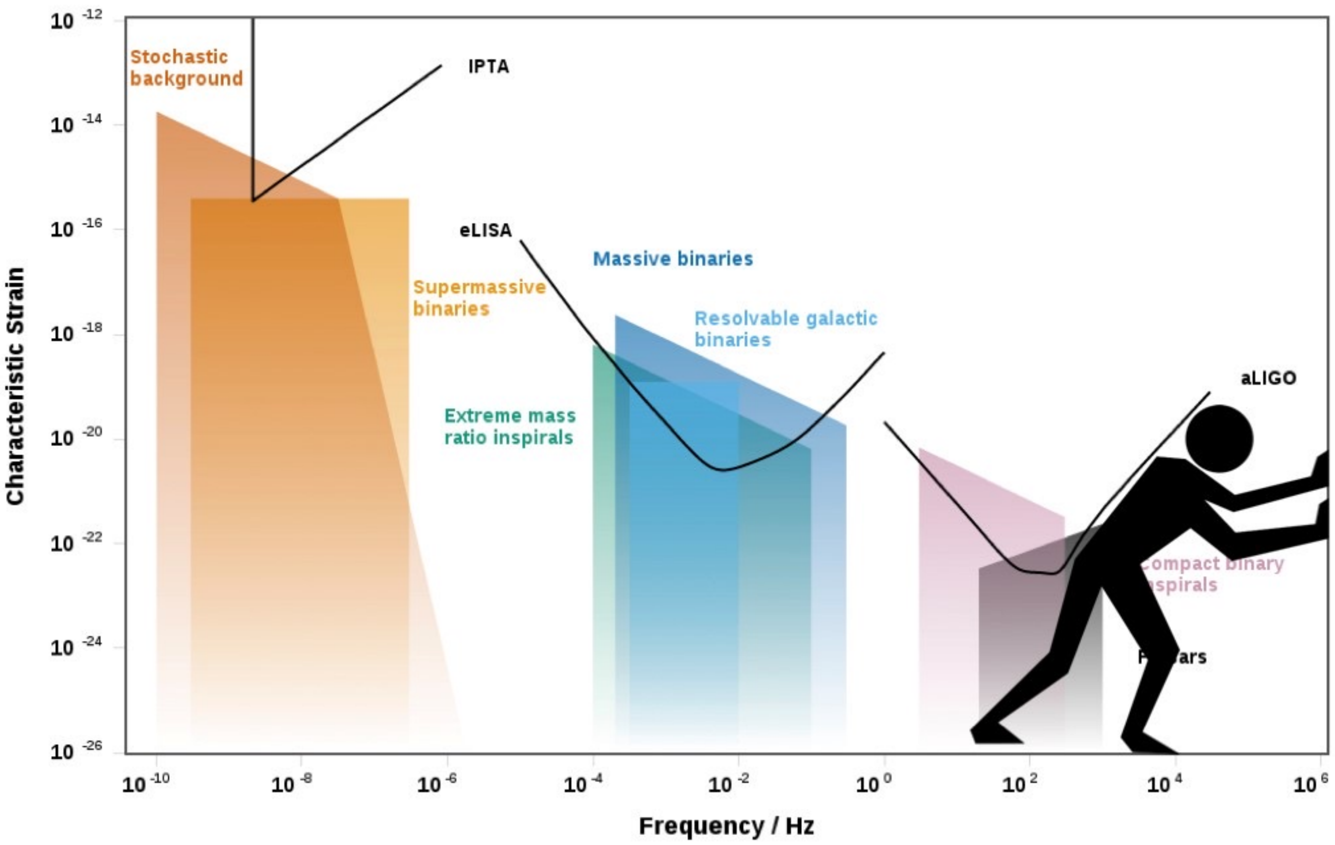
It is highly motivated to consider also GWs at higher frequencies



[https://www.ctc.cam.ac.uk/activities/UHF-GW.php]

Living Reviews in Relativity manuscript No.
(will be inserted by the editor)

Challenges and Opportunities
of Gravitational Wave Searches above 10 kHz

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Abstract The first direct measurement of gravitational waves by the LIGO and Virgo collaborations has opened up new avenues to explore our Universe. This white paper outlines the challenges and gains expected in gravitational-wave searches at frequencies above the LIGO/Virgo band. The scarcity of possible astrophysical sources in most of this frequency range provides a unique opportunity to discover physics beyond the Standard Model operating both in the early and late Universe, and we highlight some of the most promising of these sources. We review several detector concepts that have been proposed to take up this challenge, and compare their expected sensitivity with the signal strength predicted in various models. This report is the summary of a series of workshops on the topic of high-frequency gravitational wave detection, held in 2019 (ICTP, Trieste, Italy), 2021 (online) and 2023 (CERN, Geneva, Switzerland).

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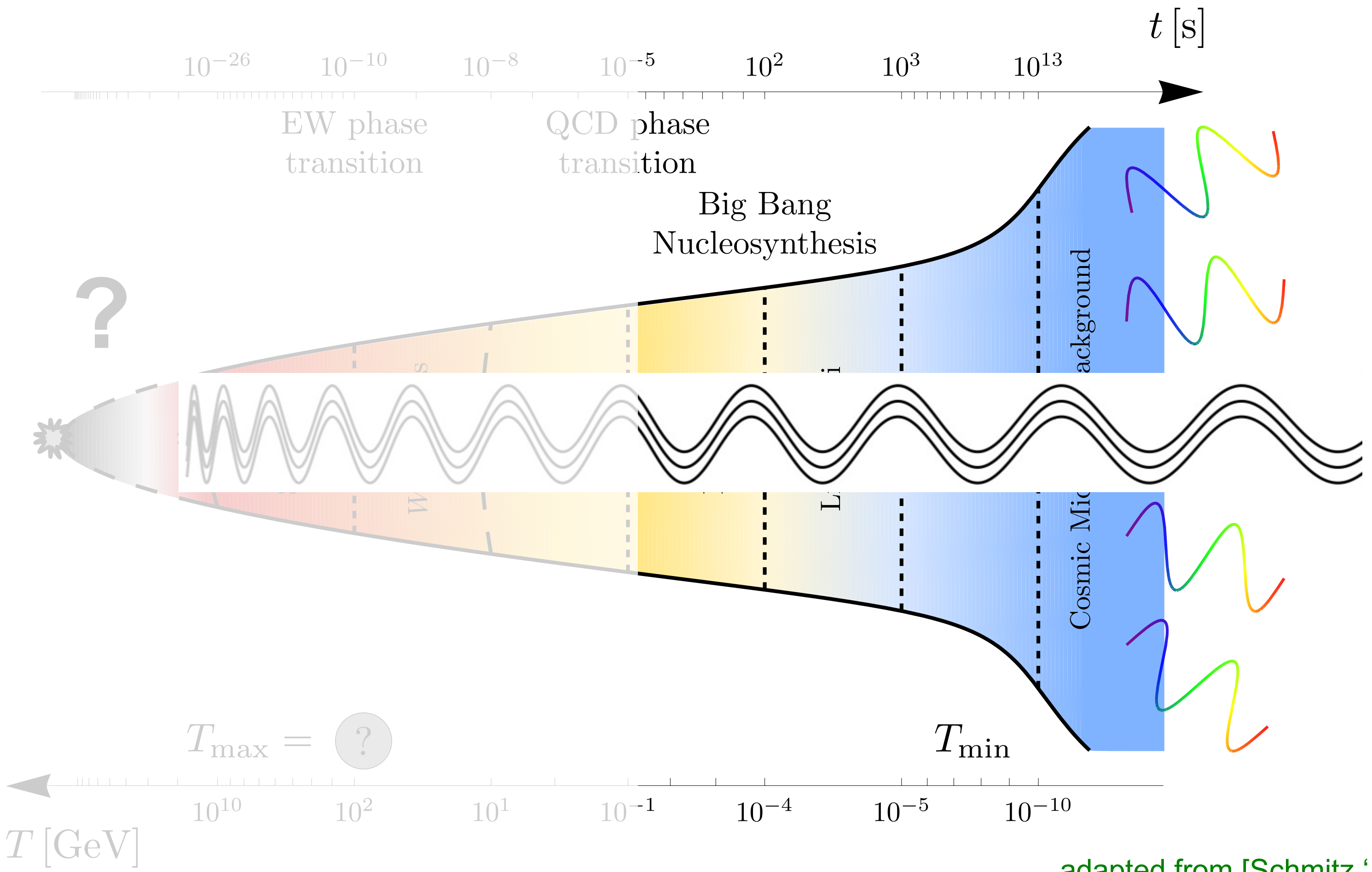
Motivation

A new window to explore the universe

In cosmology, GWs may be the only way to observe certain epochs before Big Bang Nucleosynthesis

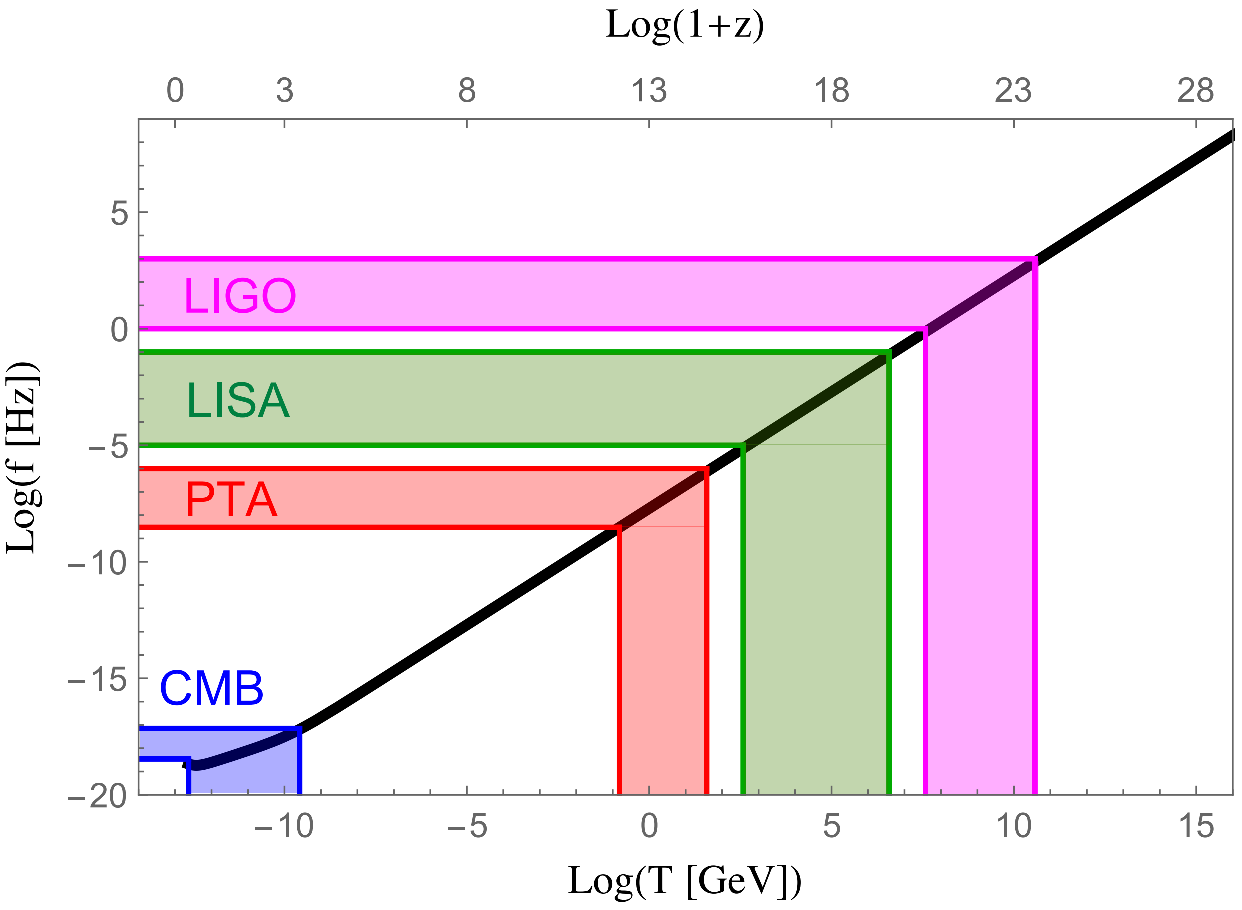


adapted from [Schmitz '12]

Motivation

A new window to explore the universe

- Signals at frequencies above the range of the existing laser interferometers correspond to gravitational waves produced at temperatures $\gtrsim 10^{10}$ GeV



[Figueroa, Caprini 1801.04268]

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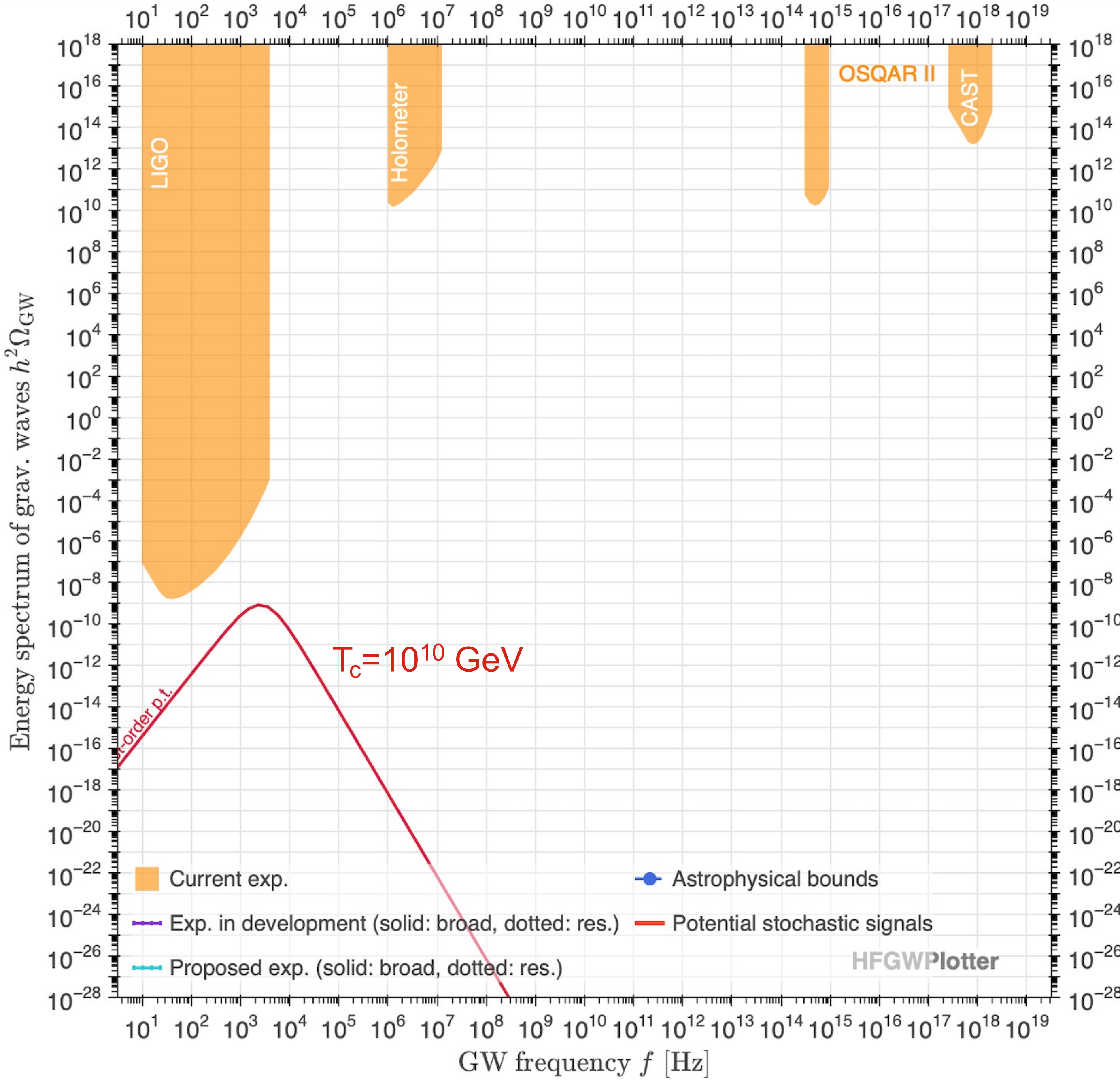
- Phenomena like phase transitions and preheating after inflation would naturally produce gravitational waves with frequencies in the range from around 10 kHz to GHz



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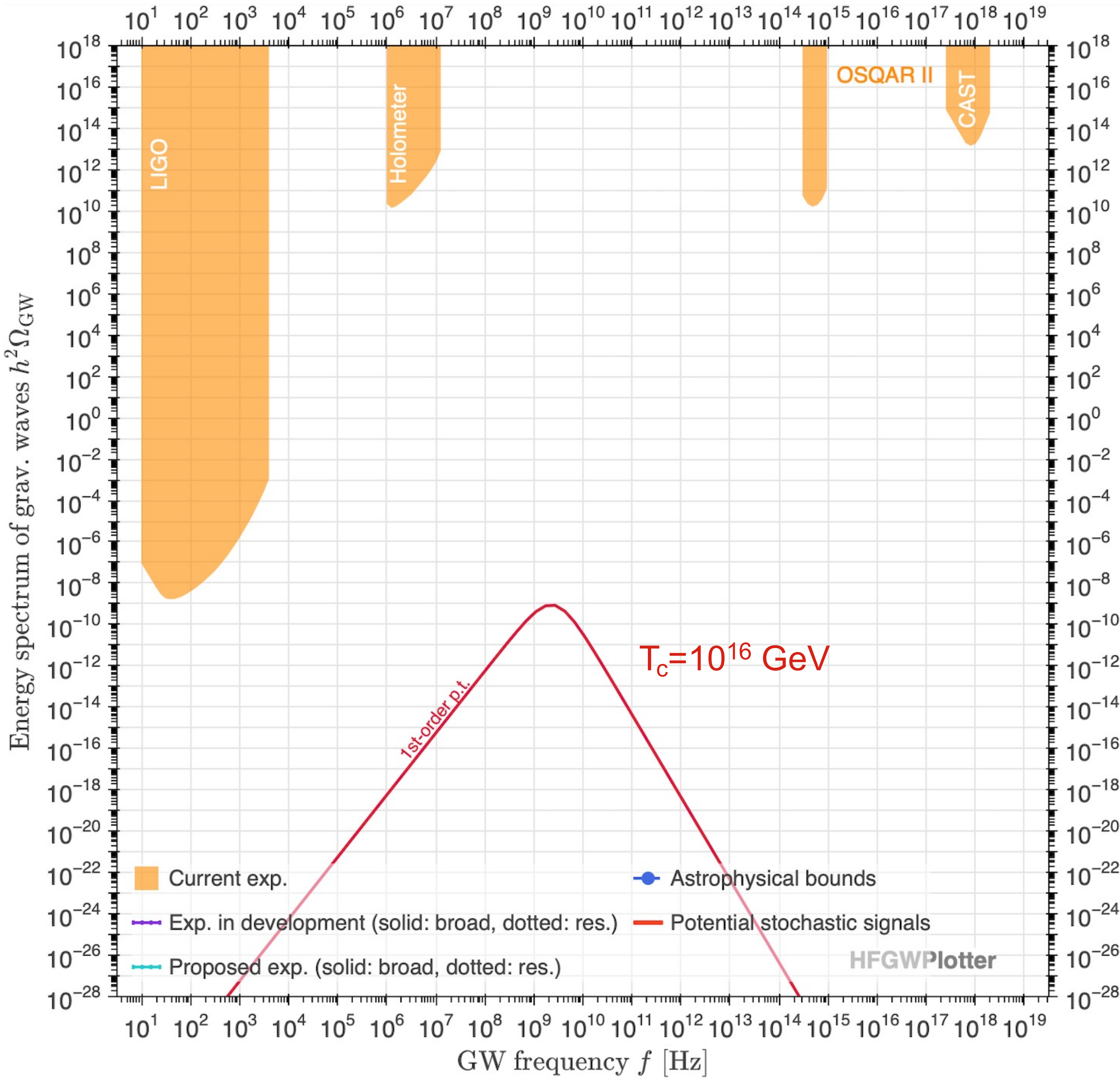

Motivation

Discovery potential of UHF GW detection depends on UHF GW floor

- "There are hardly any known astrophysical objects small and dense enough to potentially emit at frequencies beyond 10 kHz with a sizeable amplitude. Any discovery of gravitational waves at higher frequencies would thus indicate new physics beyond the Standard Model of particle physics, linked for instance to exotic astrophysical objects (such as primordial black holes or boson stars) or to cosmological events in the early Universe such as phase transitions, preheating after inflation, oscillons, cosmic strings, ..., etc., ..."

[Aggarwal et al., "Challenges and Opportunities of Gravitational Wave Searches above 10 kHz", 2501.11723]

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- In order to assess the discovery potential of UHF GW detection for new physics beyond the Standard Model, one has to determine the

UHF GW floor - the inevitable UHF GW background from known sources and physics

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UHF GW floor - the inevitable UHF GW background from known sources and physics

- **Will consider here the UHF GW background from the high-temperature plasma in the**
  - **Sun and other main-sequence stars**
  - **Early Universe**

GWs from a Thermal Plasma

Mechanisms for GW production in a thermal plasma

In a thermal plasma, GWs are produced through

1. microscopic and
2. macroscopic

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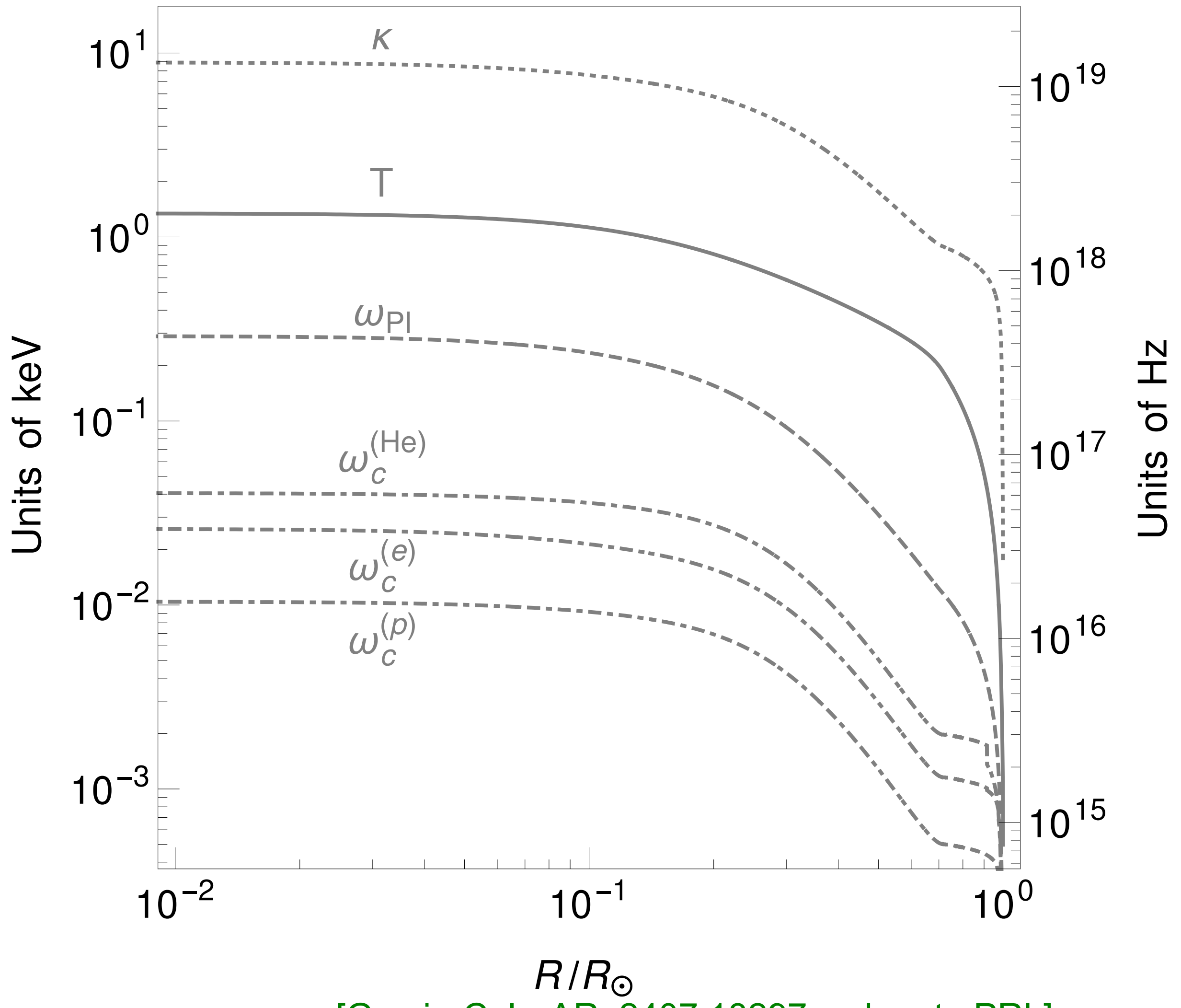

[Garcia-Cely, AR, 2407.18297, subm. to PRL]

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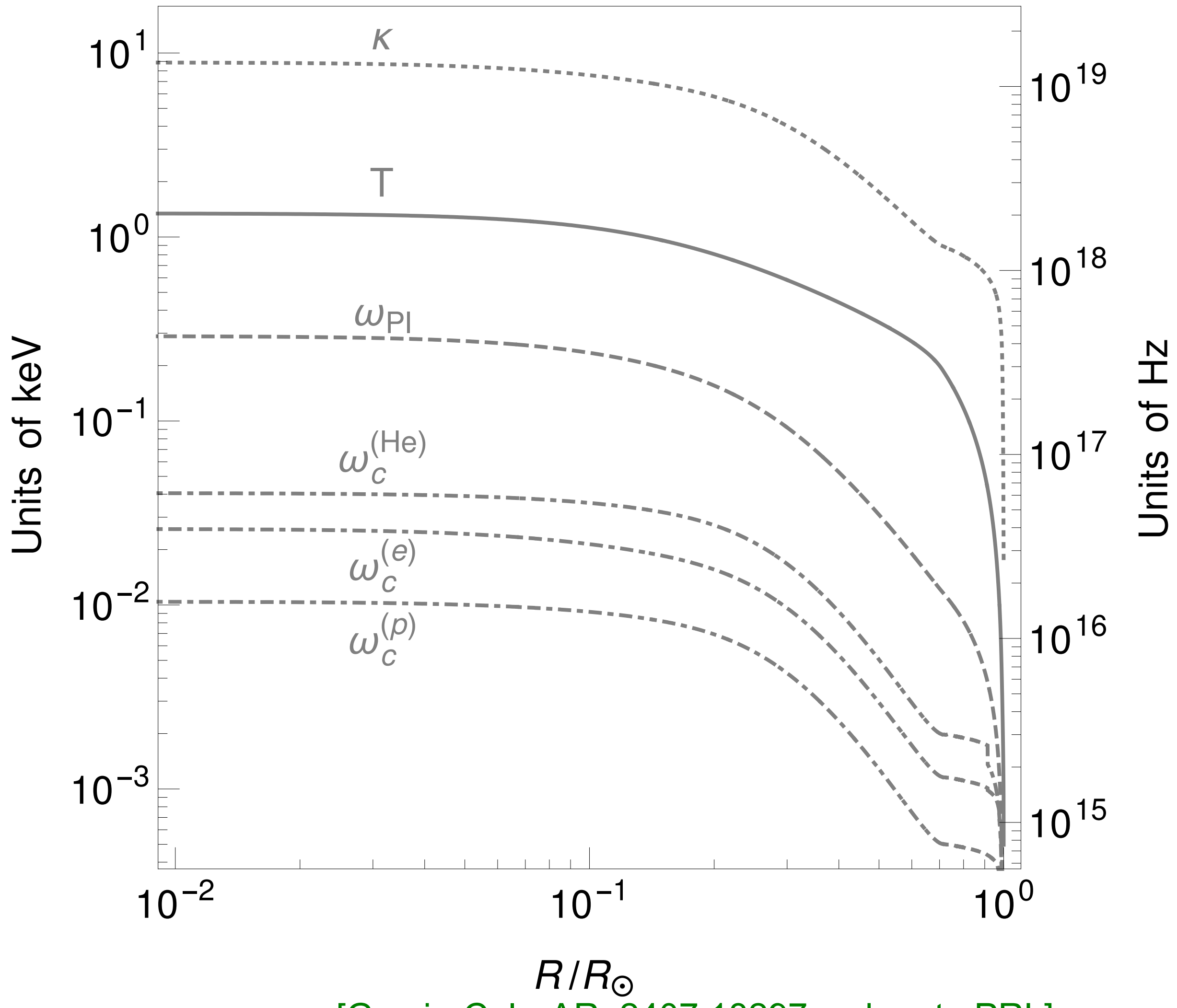
The latter applies to frequencies below all collision frequencies of the plasma (for the Sun, << 10^{16} Hz)



[Garcia-Cely, AR, 2407.18297, subm. to PRL]

GWs from the Thermal Plasma in the Sun and Other MS Stars

Solar GWs from particle collisions

[S. Weinberg, Physical Review 140 (1965) B516]

GWs from the Thermal Plasma in the Sun and Other MS Stars

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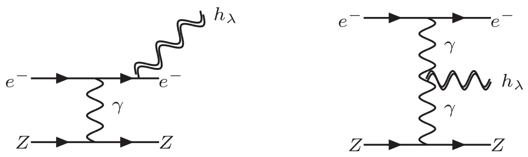
Obtained by thermally averaging individual graviton emission rates,

$$\left.\frac{\mathrm{d}P}{\mathrm{d}\omega}\right|_{\mathrm{Collisions}} = \int_{\mathrm{Sun}} \mathrm{d}^3\mathbf{r} \sum_i \omega \left\langle \frac{\mathrm{d}\Gamma^{(i)}(\mathbf{r})}{\mathrm{d}\omega \mathrm{d}V} \right\rangle$$

Here i runs over the different processes:

Bremsstrahlung



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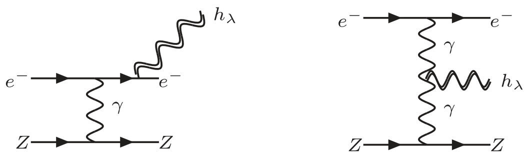
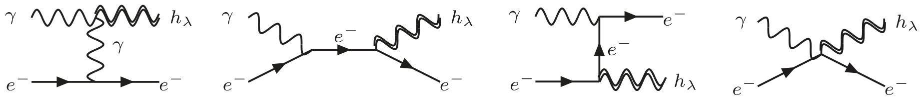


Photoproduction



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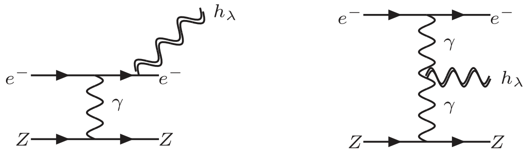

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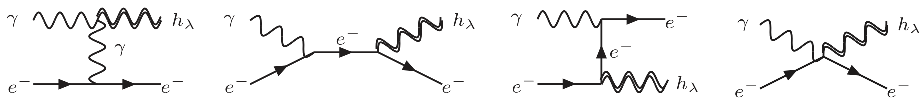
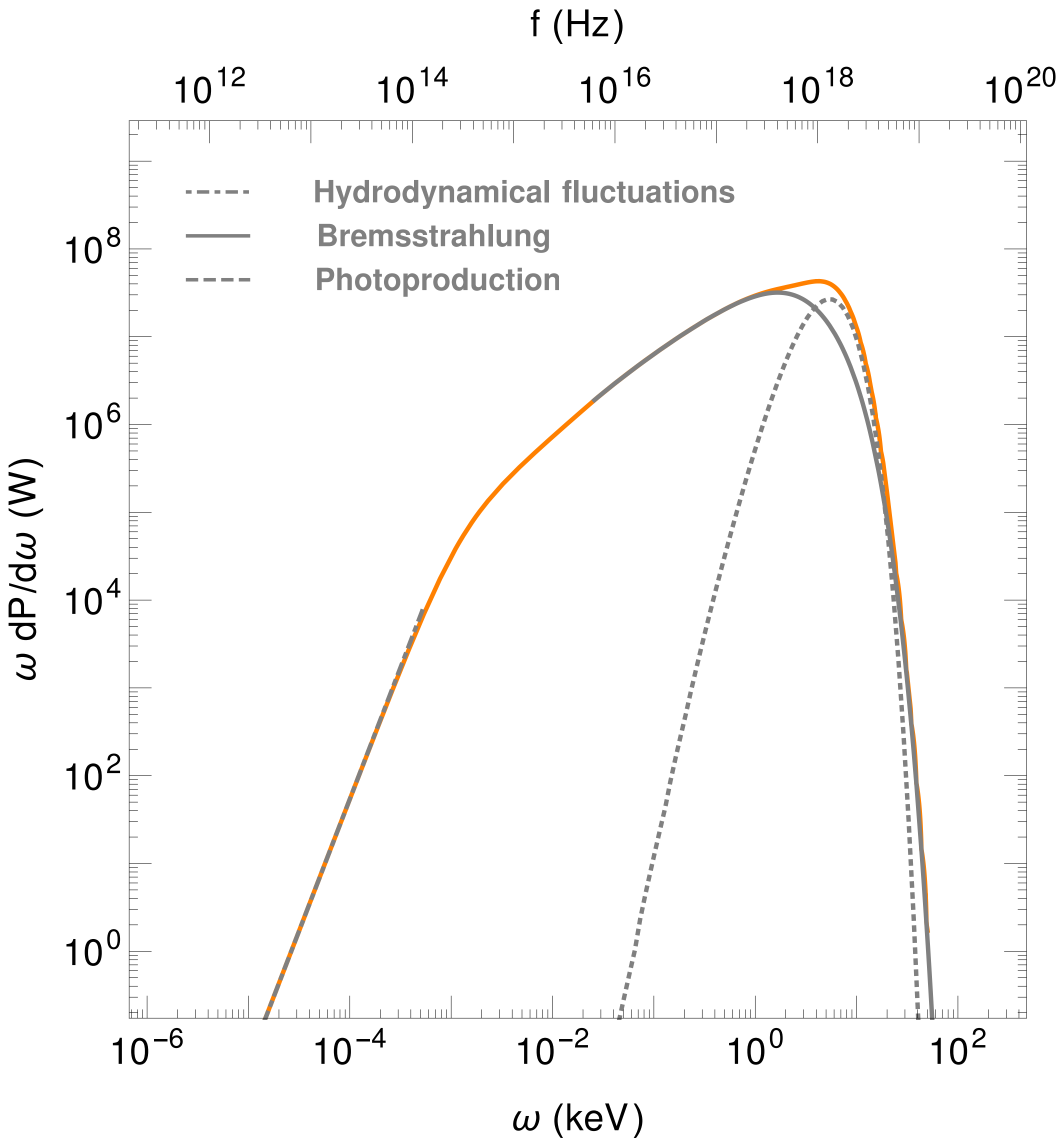


Collision	$\frac{\mathrm{d}\Gamma}{\mathrm{d}\omega\mathrm{d}V}$	
Photoproduction $\gamma\, Z/e \to Z/e\, h$	$n_\gamma n_Z G Z^2 \alpha\pi\, \delta(\omega - E_i) \frac{p_i}{\omega} \int \mathrm{d}\cos\theta \left(\cot^2\frac{\theta}{2}[1+\cos^2\theta]\lvert F(\theta)\rvert^2 + \mathcal{O}(\omega_{\text{Pl}}^2/\omega^2)\right)$	$\lvert F(\theta)\rvert^2 = \frac{\left(2\omega\sin\frac{\theta}{2}\right)^2}{\kappa^2+\left(2\omega\sin\frac{\theta}{2}\right)^2}$
Bremsstrahlung $eZ \to eZ\, h$	$\frac{32 n_e n_Z G Z^2 \alpha^2 p_i}{15\omega}\left(\frac{1}{m_e}+\frac{1}{m_Z}\right)\left(3(1+\xi^2)L + 10\xi + \mathcal{O}(\xi_s^2)\right)$	$\xi = p_f/p_i, \quad \xi_s = \kappa/p_i$ $\omega = E_i(1-\xi^2)$
Bremsstrahlung $ee \to ee\ h$	$\frac{16 n_e^2 G\alpha^2 p_i}{15\omega m_e}\left(\left(6(1+\xi^2) - \frac{3(1-\xi^2)^4+7(1-\xi^4)^2}{2(1+\xi^2)^3}\right)L + 20\xi - \frac{6\xi(1+\xi^4)}{(1+\xi^2)^2} + \mathcal{O}(\xi_s^2)\right)$	$L = \log\sqrt{\frac{(1+\xi)^2+\xi_s^2}{(1-\xi)^2+\xi_s^2}}$

TABLE S1. Emission rates of gravitons, h, from the indicated process in the non-relativistic limit. p_i (p_f) denotes the initial (final) momentum of the colliding particles in the center-of-mass frame, and E_i is total kinetic energy.



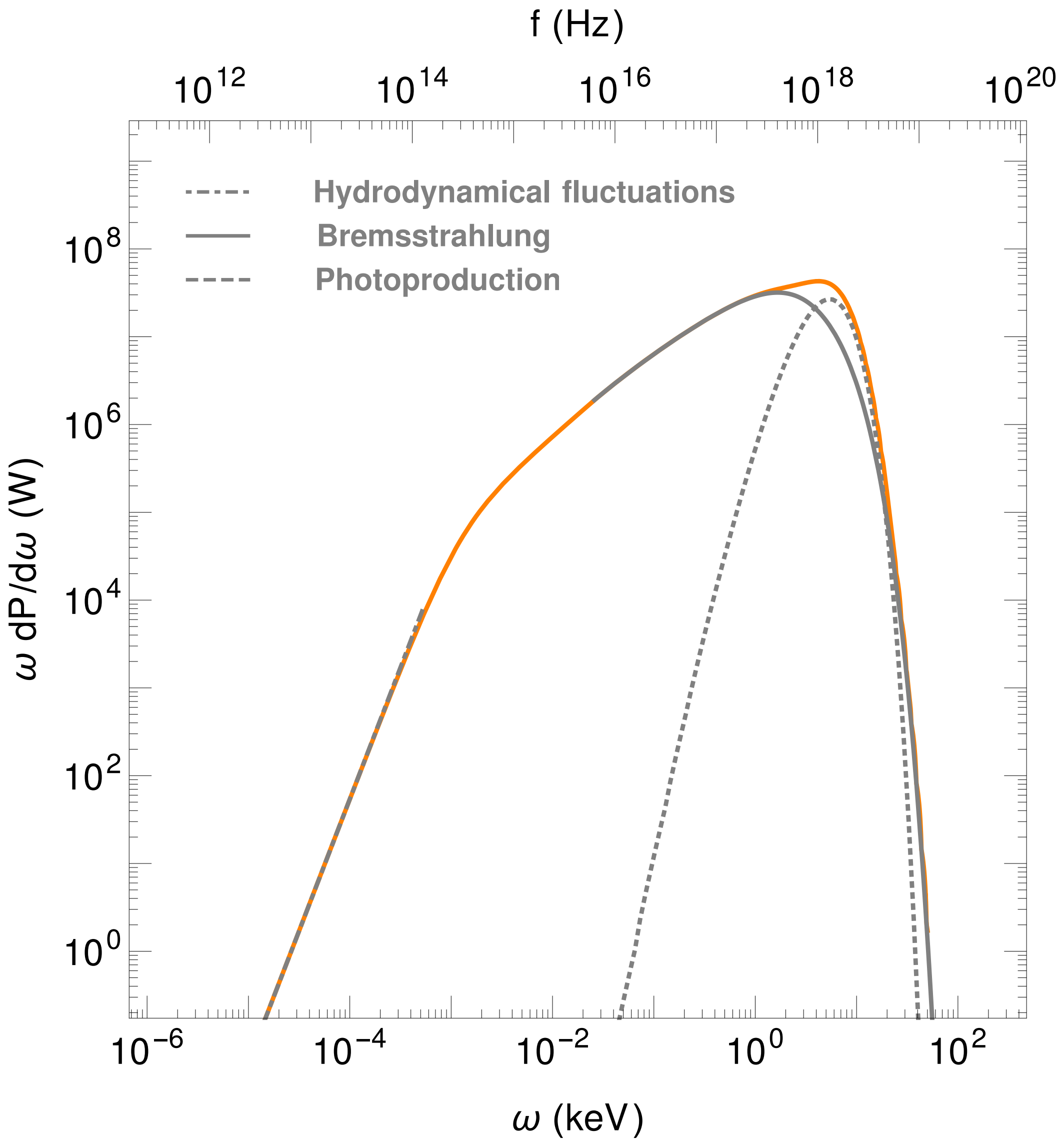
GWs from the Thermal Plasma in the Sun and Other MS Stars

Solar GWs from hydrodynamic fluctuations

[Garcia-Cely, AR, 2407.18297, subm. to PRL]

At frequencies below all collision frequencies, GWs sourced by the shear viscosity, η, of the plasma,

$$\left.\frac{\mathrm{d}P}{\mathrm{d}\omega}\right|_{\mathrm{Hydrodynamics}} = \frac{16G\omega^2}{\pi}\int_{\mathrm{Sun}} \mathrm{d}^3\mathbf{r}\,\eta T$$



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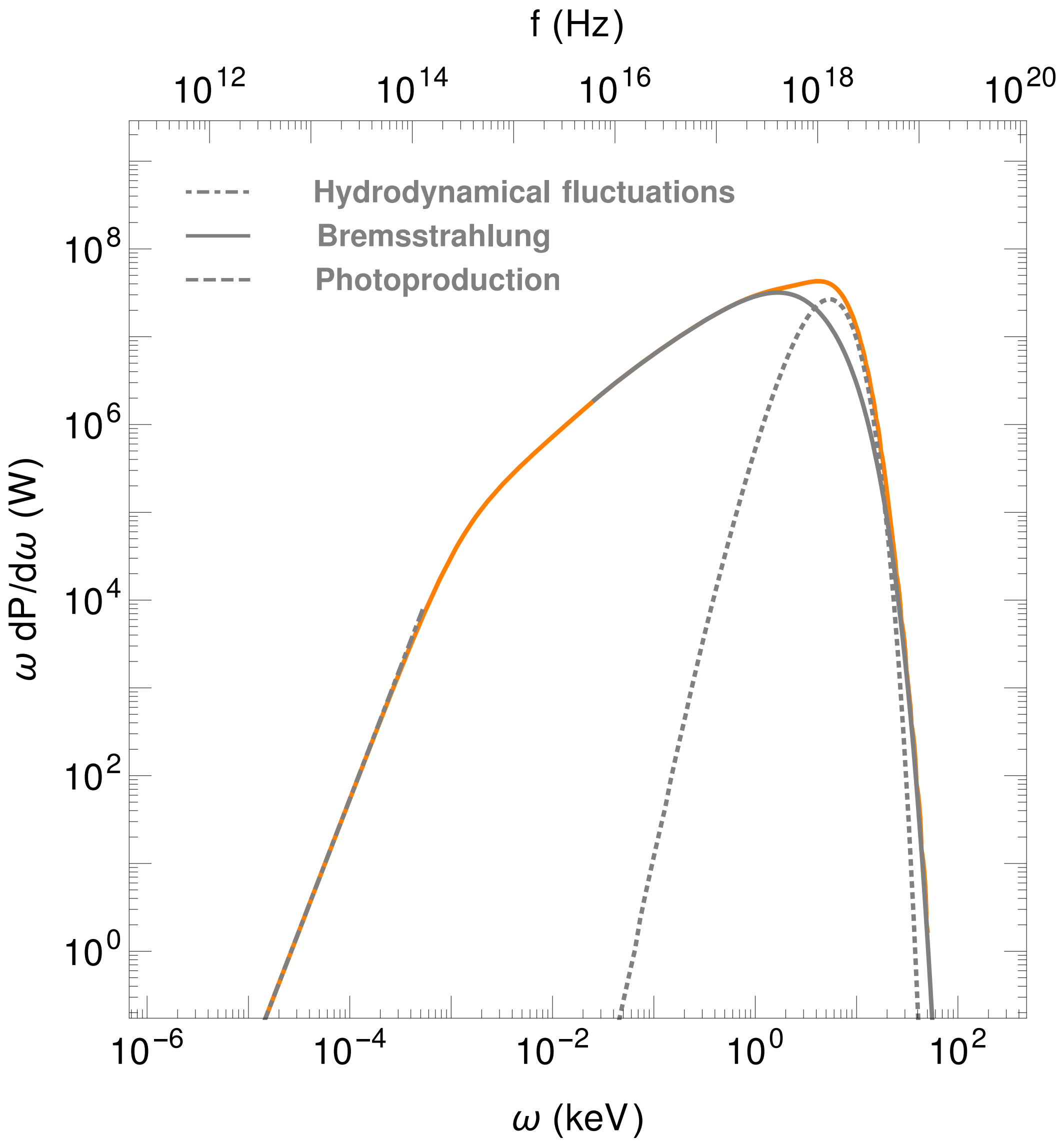
$$\eta \sim m_p v_p / \sigma_V^{(pp)}$$



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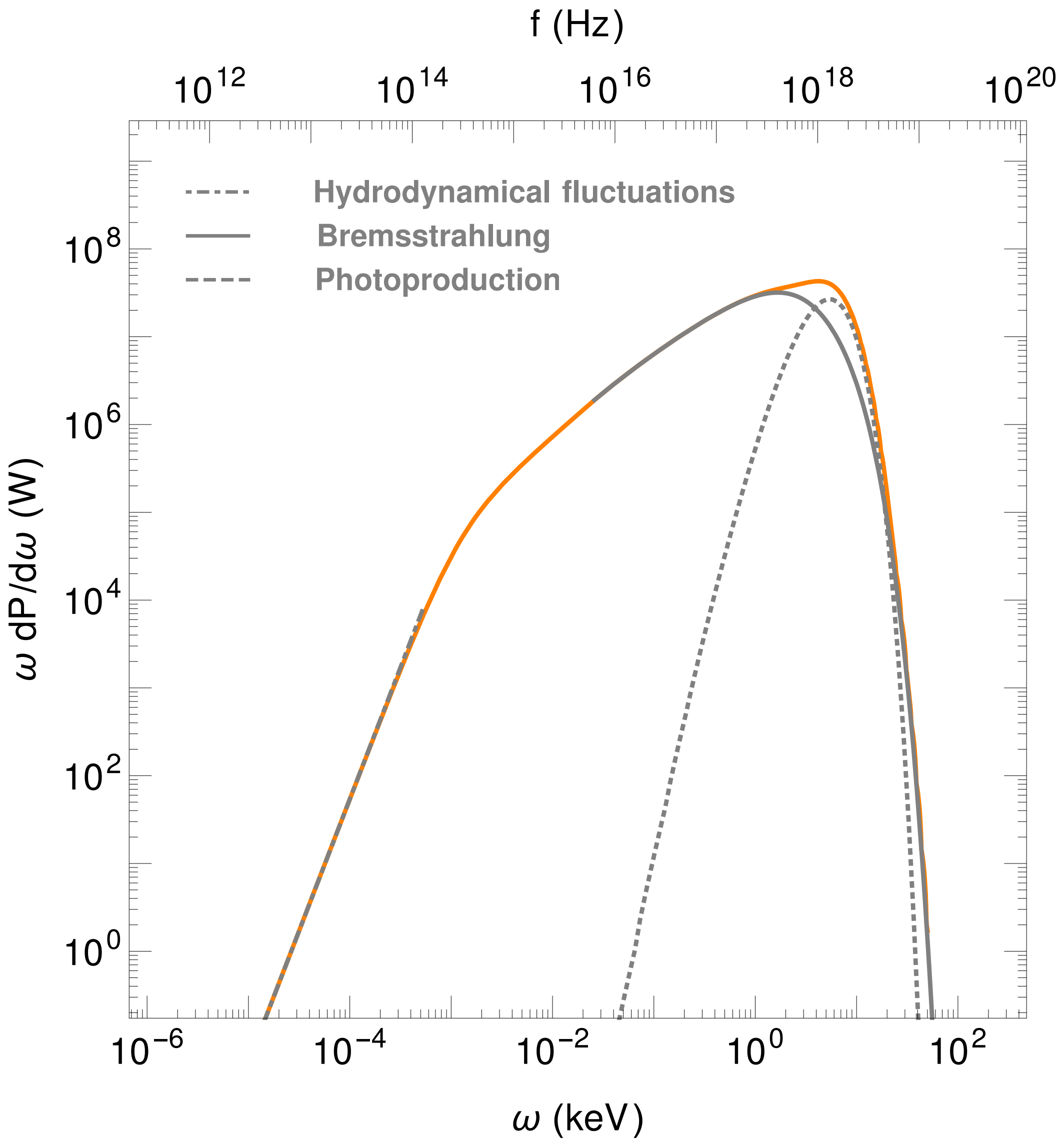
For better accuracy, used the parametrisation of the viscosity of a one-component non-relativistic plasma obtained via state-of-the-art simulations

[Daligault et al., Phys. Rev. E 90 (2014) 033105]

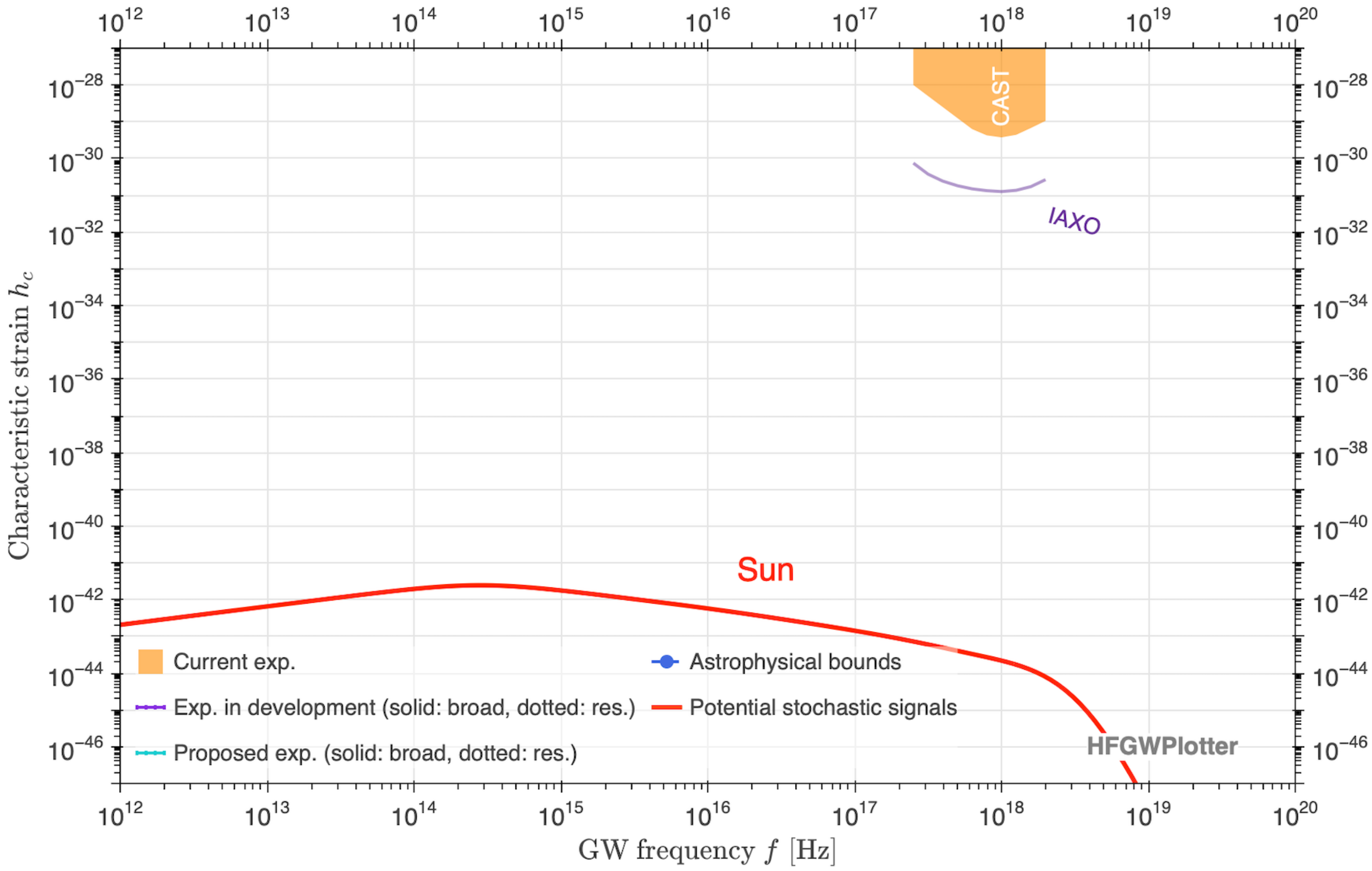


GWs from the Thermal Plasma in the Sun and Other MS Stars

Complete solar GW spectrum confronted with experiments

[Garcia-Cely, AR, 2407.18297, subm. to PRL]

Many orders of magnitude below characteristic strain sensitivity of current and planned helioscopes:



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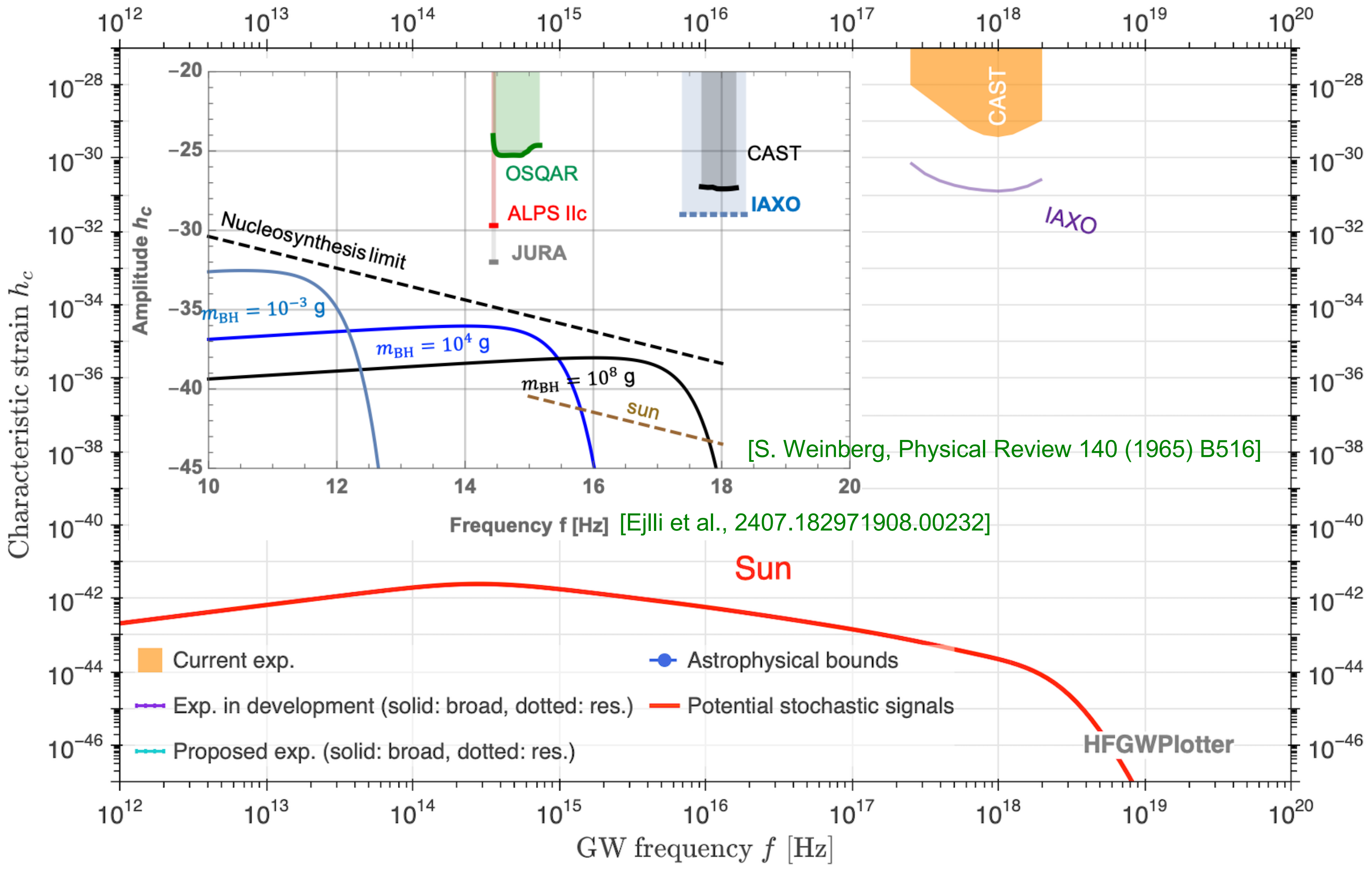

GWs from the Thermal Plasma in the Sun and Other MS Stars

Stochastic GW spectrum from all main-sequence stars confronted with experiments

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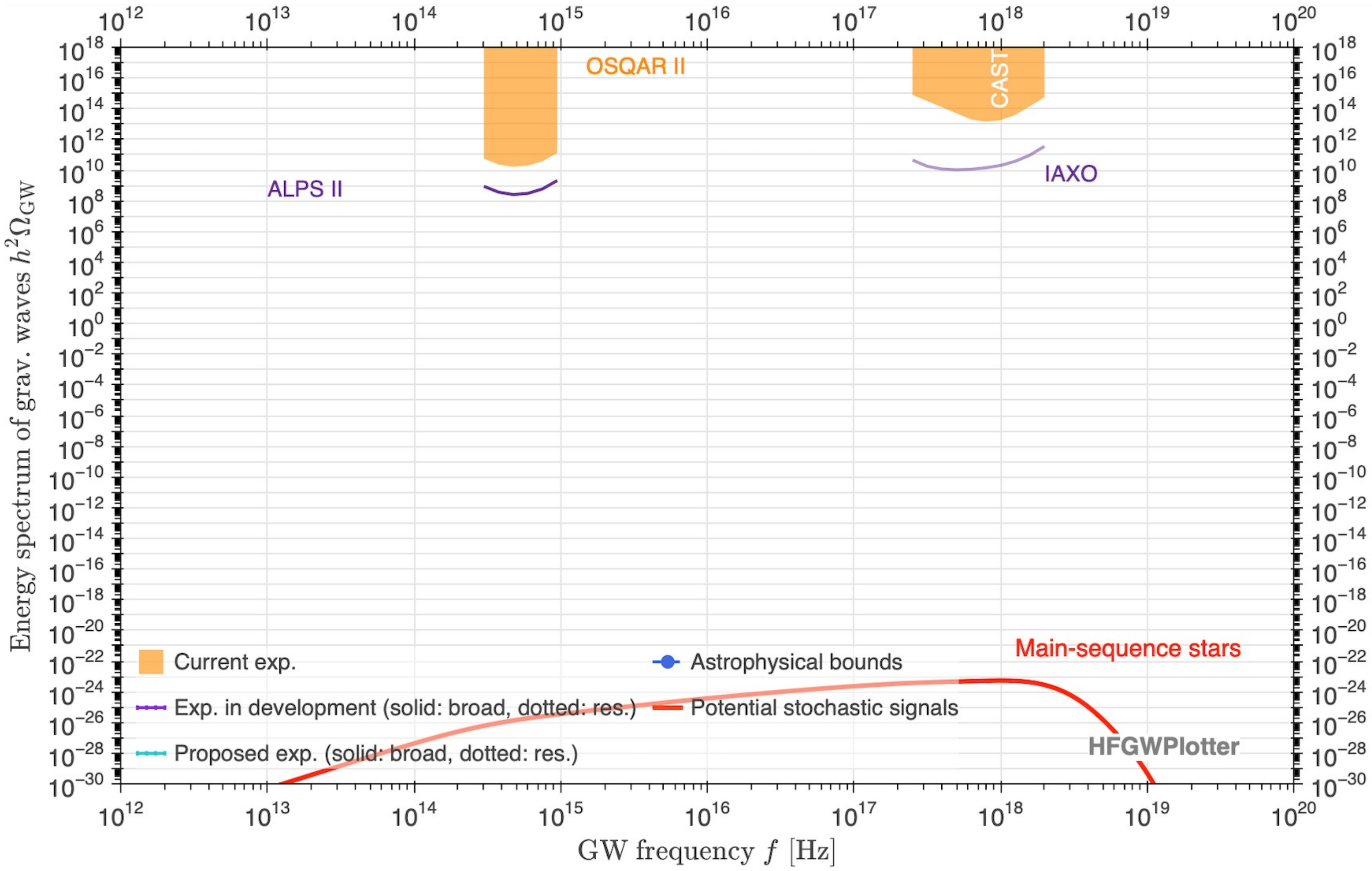

GWs from the Thermal Plasma in the Early Universe

GWs from particle collisions

[Ghilieri,Laine `15; Ghiglieri,Jackson,Laine,Zhu ’20; AR,Schütte-Engel,Tamarit `20]

At small wavelength, corresponding to large wave numbers, $k \gg T$, sourced by particle collisions

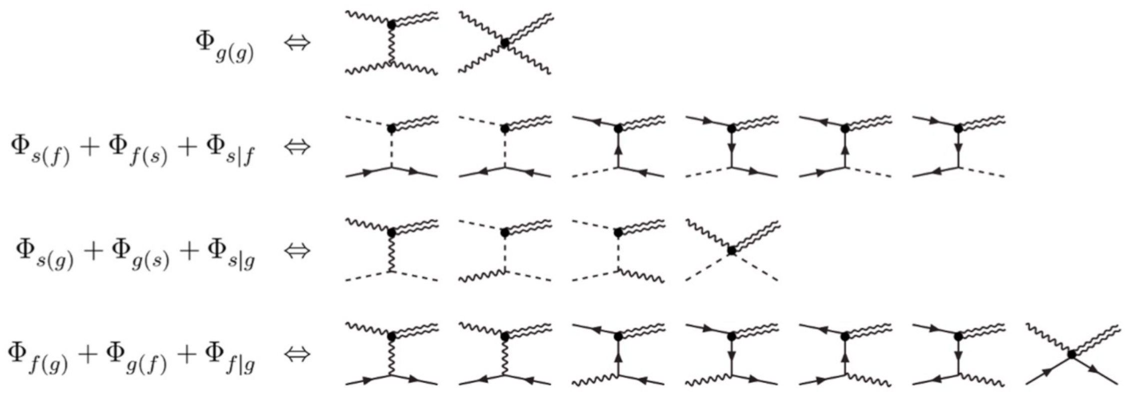

Figure 2. t-channel $2 \leftrightarrow 2$ scatterings contributing to gravitational wave production (further processes are obtained with u and s-channel reflections). The notation is as in figure 1, with the double line indicating a graviton. Up to numerical prefactors, the amplitudes squared originating from these processes, after summing over the physical polarization states of the gravitons and Standard Model particles, correspond to the cuts shown in eqs. (2.36)–(2.38) (cf. section 2.4).

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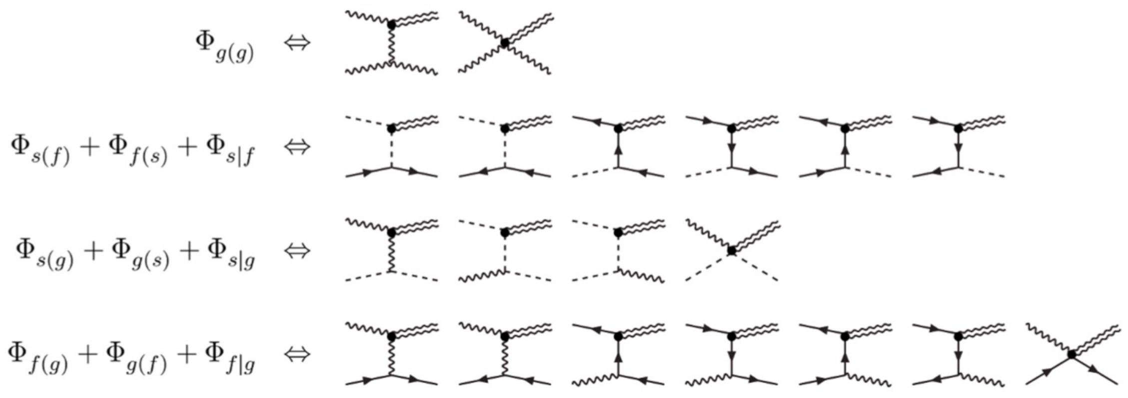
$$[\partial_t + 4H(t)]\,\rho_{\mathrm{CGMB}}(t) = 4\,G_N\,T^4 \int \frac{\mathrm{d}^3\mathbf{k}}{(2\pi)^3}\,\hat{\eta}\left(T, \frac{k}{T}\right)$$



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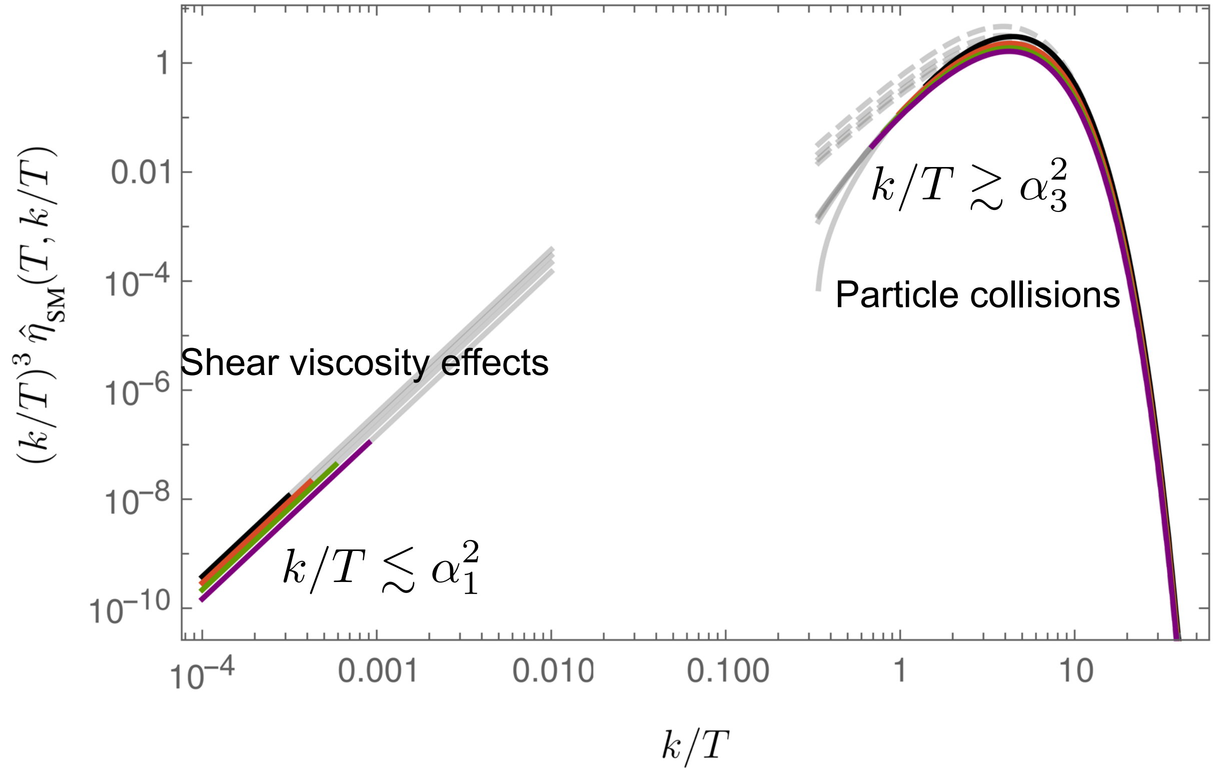


[AR,Schütte-Engel,Tamarit ‘20]

For $T \gg T_{\mathrm{ewco}} \simeq 160\,\mathrm{GeV}$, complete leading order approximation for has been obtained for the SM [Ghiglieri,Jackson,Laine,Zhu ‘20] and then extended to generic weakly interacting BSM extension (gauge fields, fermions, scalars) [AR,Schütte-Engel,Tamarit ‘20]

GWs from the Thermal Plasma in the Early Universe

Sourced by hydrodynamics

[Ghilieri,Laine `15; Ghiglieri,Jackson,Laine,Zhu '20; AR,Schütte-Engel,Tamarit `20]

At large wavelengths, corresponding to small wave numbers, $k \ll T$, they are sourced by macroscopic hydrodynamic fluctuations, described by the shear viscosity of the plasma

Shear viscosity inversely proportional to a scattering cross section and therefore large for a relativistic plasma in which there are some weakly interacting particles

In the Standard Model (SM), for temperatures well above the electroweak crossover, $T \gg T_{\rm ewco} \simeq 160\,{\rm GeV}$, and in leading-log (LL) approximation:

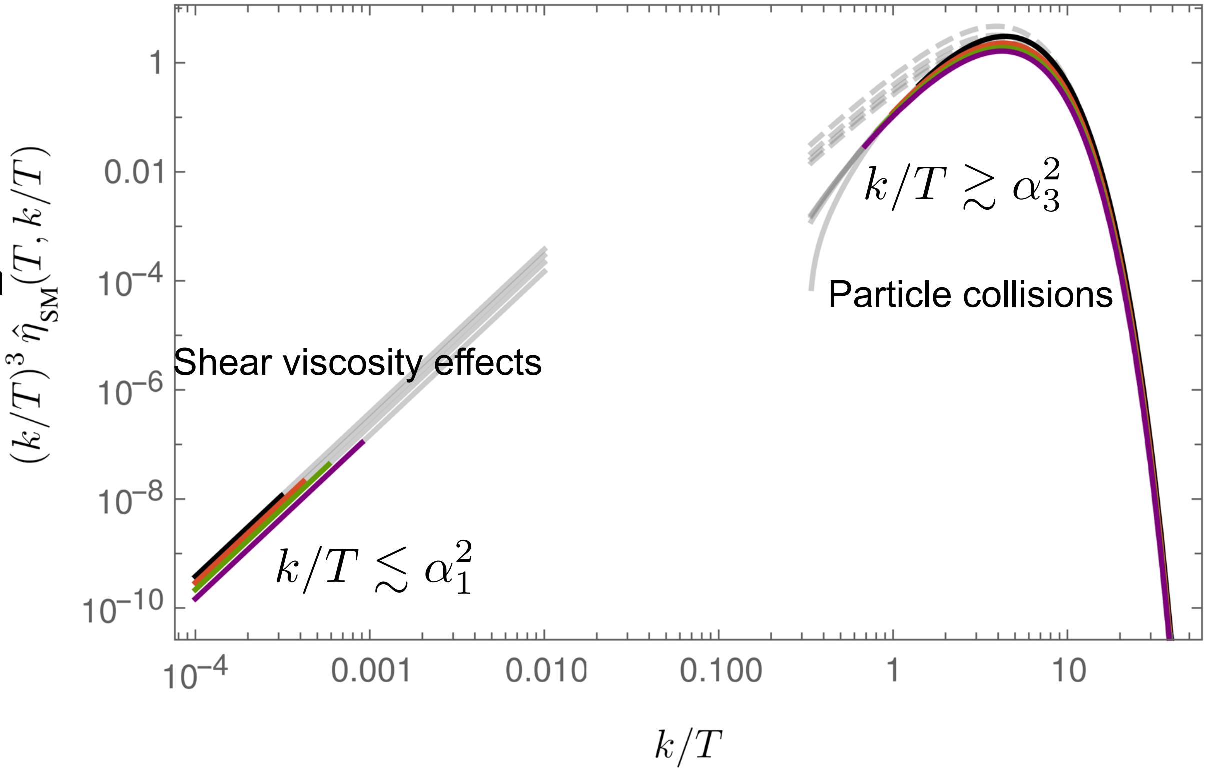
$$\eta^{\rm shear}_{\rm LL,SM}(T) = \frac{15.51\,T^3}{g_1(T)^4 \ln(5/\hat{m}_{1,\rm SM}(T))}$$

[Arnold,Moore,Yaffe '00]

$$\hat{m}^2_{1,\rm SM}(T) = \frac{m^2_{1,\rm SM}(T)}{T^2} = \frac{11}{6} g_1(T)^2$$

Debye thermal mass of hypercharge gauge boson

$$[\partial_t + 4H(t)]\,\rho_{\rm CGMB}(t) = 4\,G_N\,T^4 \int \frac{{\rm d}^3\mathbf{k}}{(2\pi)^3}\,\hat{\eta}\left(T, \frac{k}{T}\right)$$

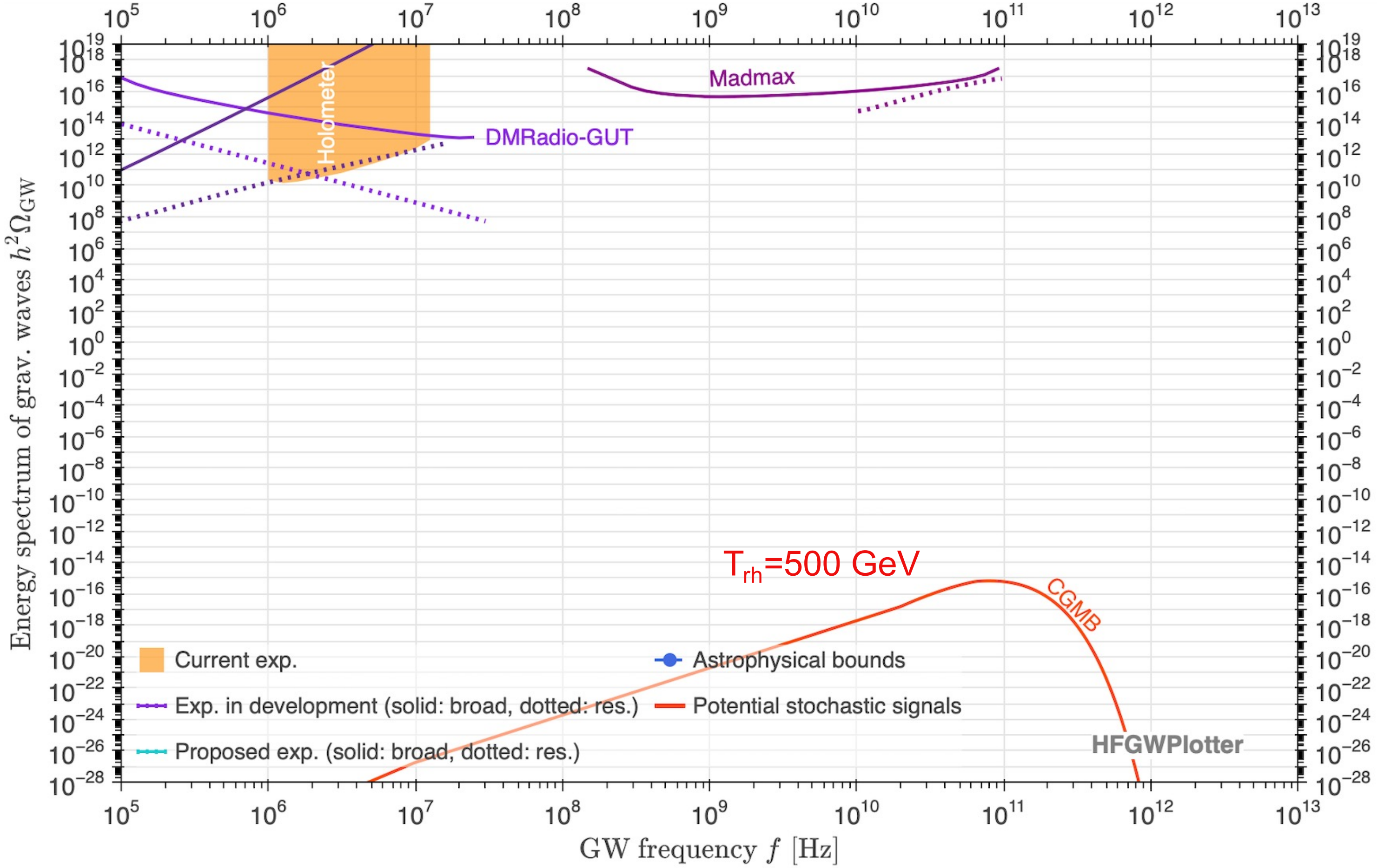


[AR,Schütte-Engel,Tamarit '20]

GWs from the Thermal Plasma in the Early Universe

Robust prediction of Cosmic Gravitational Microwave Background (CGMB)

Assuming radiation domination all the way to matter–radiation equality, resulting “CGMB” power spectrum depends mainly on the maximal temperature of the primordial plasma after reheating, T_{rh}:



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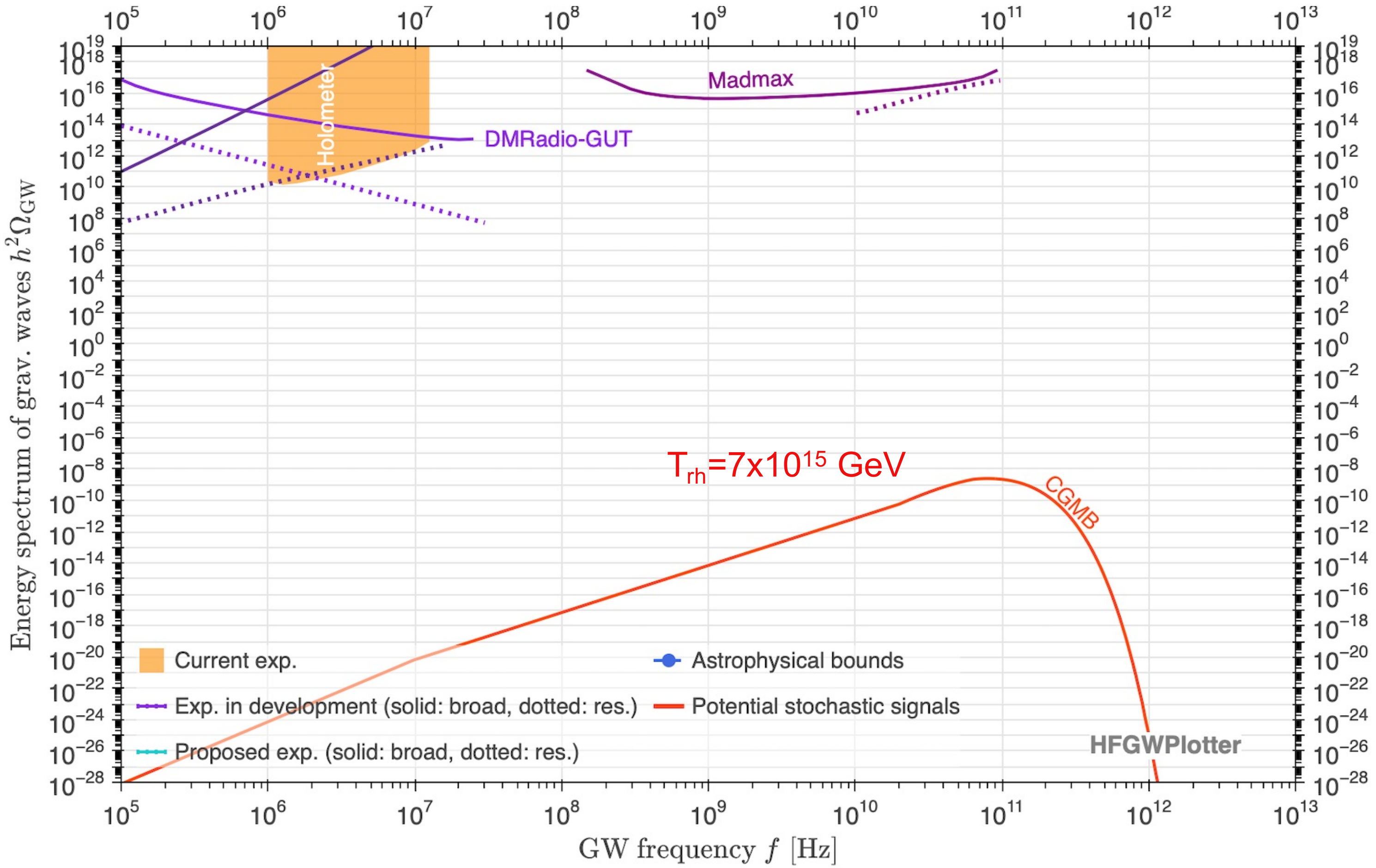
Robust prediction of Cosmic Gravitational Microwave Background (CGMB)

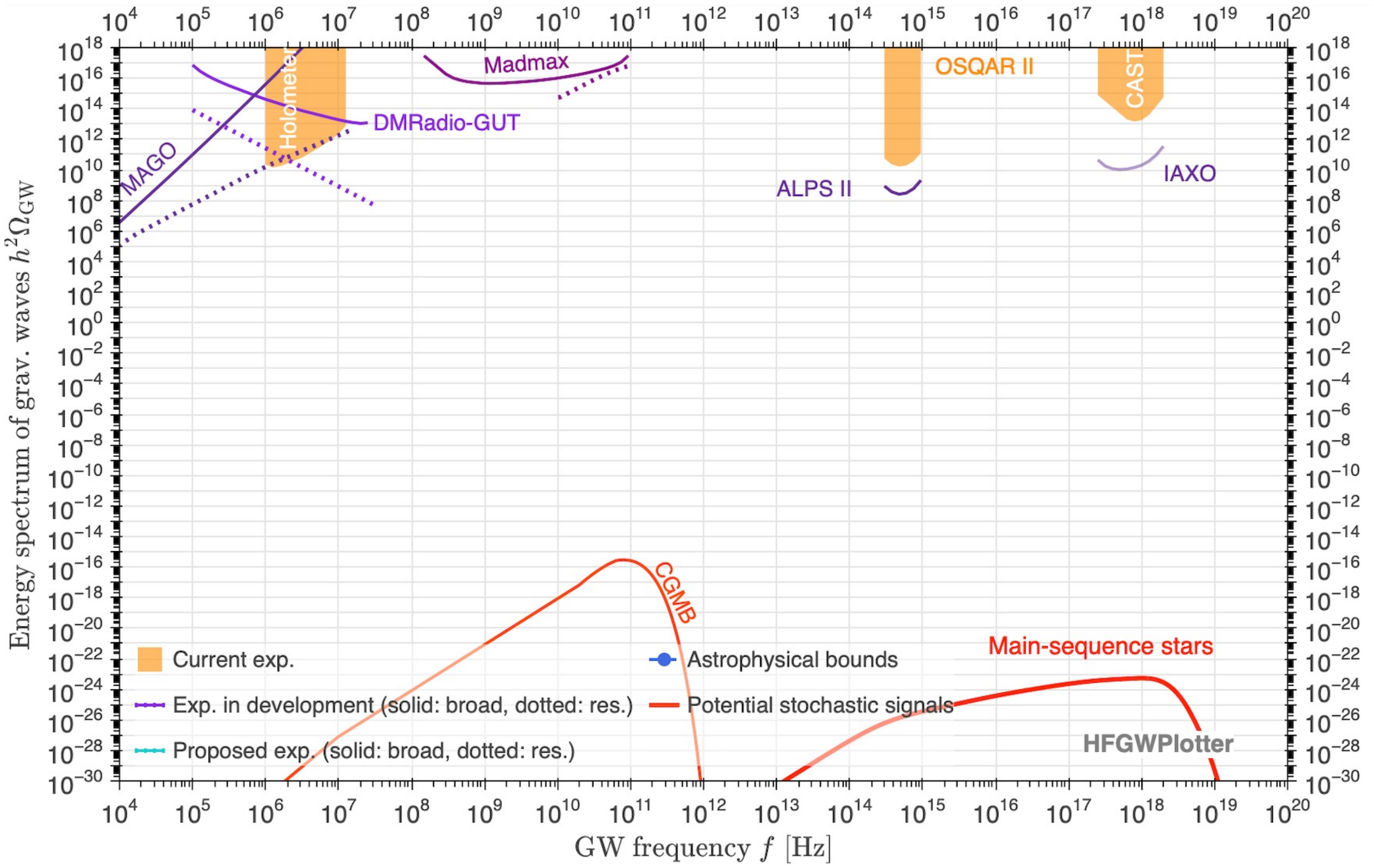
Assuming radiation domination all the way to matter–radiation equality, resulting "CGMB" power spectrum depends mainly on the maximal temperature of the primordial plasma after reheating, T_{rh}:



Summary: UHF GW Floor from Thermal Plasma

Lots of unexplored discovery space for new physics and exotic sources

CGMB for low reheating temperature around electroweak cross-over and GW background from MS stars:



High Frequency Gravitational Wave Plotter

Interactive web applications for visualizing and analysing sensitivity curves for GW experiments

Francesco Muia, Andreas Ringwald, Carlos Tamarit,

"High frequency gravitational wave plotter: Noise-equivalent strain", https://doi.org/10.5281/zenodo.15720342

"High frequency gravitational wave plotter: Stochastic signals", https://doi.org/10.5281/zenodo.15720443