UNIVERSITY OF
CAMBRIDGE

Gravitational waves from the Hagedorn phase

Gonzalo Villa de la Viña
Based on 2310.11494 [hep-th] and WIP
With A. R. Frey, R. Mahanta, A. Maharana, F. Muia and F. Quevedo
26/06/2024, String Pheno’24, Padova, Italy

The early Universe as a GW factory

High-energy processes in the early Universe source high-frequency GWs

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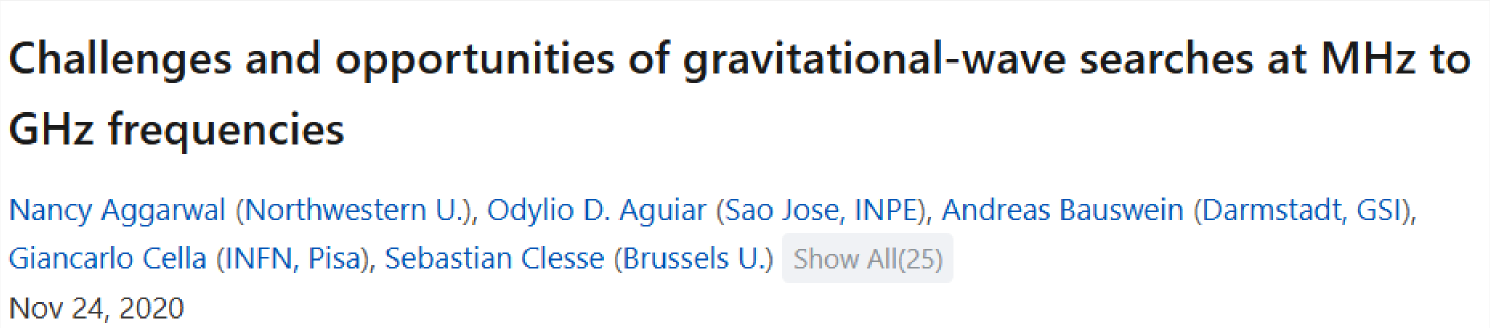

Challenges and opportunities of gravitational-wave searches at MHz to GHz frequencies

Nancy Aggarwal (Northwestern U.), Odylio D. Aguiar (Sao Jose, INPE), Andreas Bauswein (Darmstadt, GSI), Giancarlo Cella (INFN, Pisa), Sebastian Clesse (Brussels U.) Show All(25)

Nov 24, 2020

238 citations

(take-home: not a crazy theorist idea)
See also: Roshan - White ‘24

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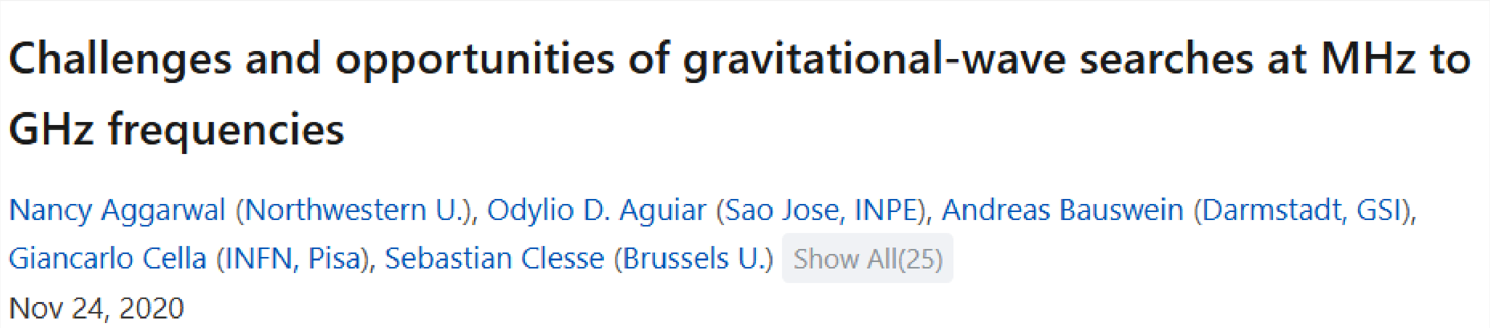

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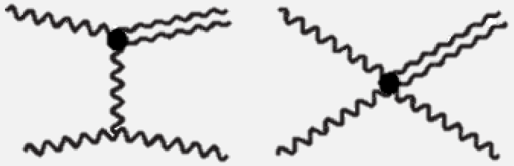

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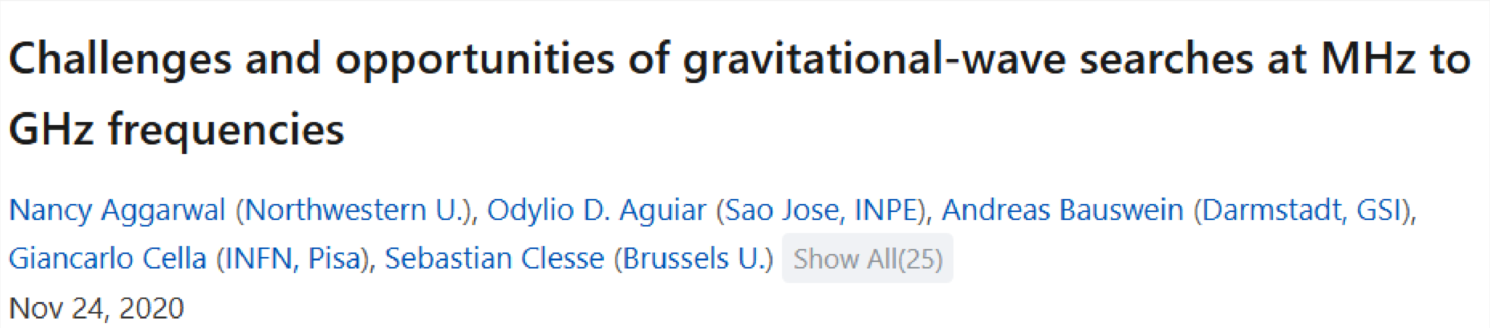

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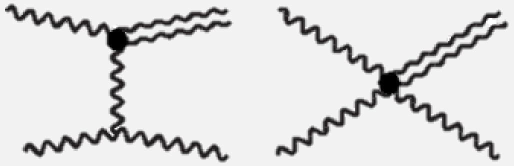

$$\longrightarrow \frac{d}{d\log a}\left(\frac{d\rho_{\mathrm{GW}}}{d\log f}\right) = \frac{T}{M_p}\,\rho_{\mathrm{bath}}\,a(t)^4 F(\omega/T)$$

Ghiglieri-Laine’15
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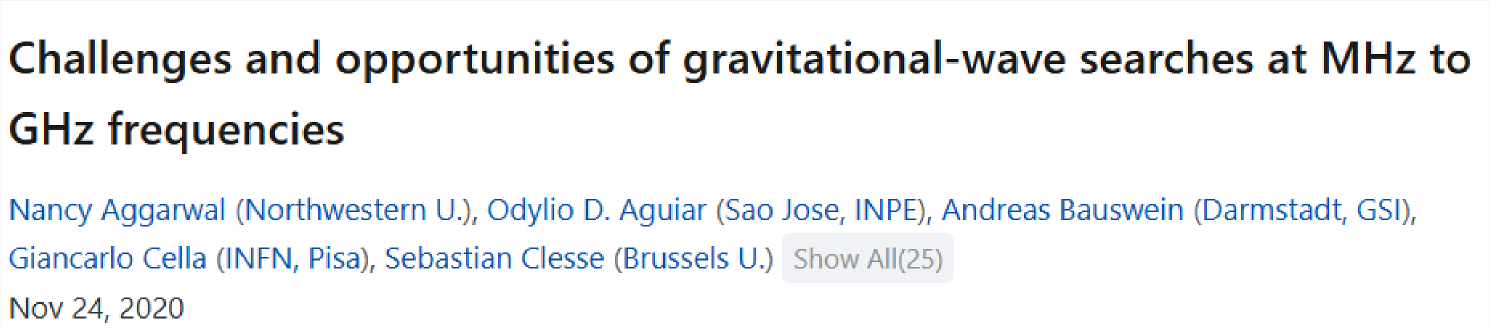

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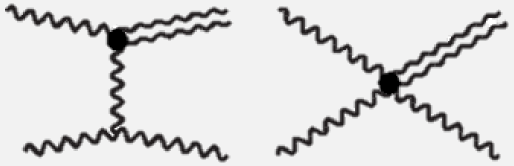

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UV sensitive!

An opportunity for strings?

At energies of order of the (local) string scale, systems enter a *Hagedorn phase.*

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- At sufficiently high energy, the density of states in any compact background allowing for a worldsheet CFT description reads:

$$d(E) = \frac{e^{\beta_H E}}{\mathrm{E}}, \qquad \beta_H \sim \sqrt{\alpha'}$$

Brandenberger - Vafa’89

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Brandenberger – Vafa'89

- The thermodynamics is well understood.

Abel-Barbón-Kogan-Rabinovici '99
Deo-Jain-Tan '88, '89, '91

- Equilibrium distributions in 3D noncompact directions with branes:

$$n_o(l) \simeq V_{3D} n_d^2 e^{-l/L}\,, \qquad n_c(l) \simeq V_{3D}\,\frac{e^{-l/L}}{l^{5/2}}\,, \qquad 1/L = \beta - \beta_H$$

A Hagedorn phase in cosmology

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An explicit analysis with Boltzmann equations for typical strings reveals that:

- They source the expansion of the Universe.
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- They source out of equilibrium gravitons.
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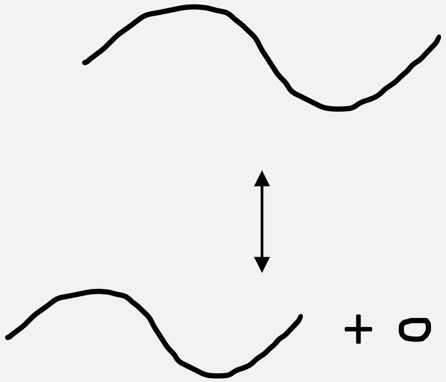
This talk

Note: *do not need (but compatible with)* inflation.

Graviton production rate: what to compute?

In a thermodynamic setup we are interested in *typical* behaviour.



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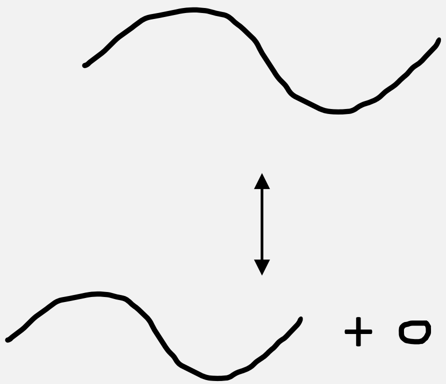

Consider the averaged semi-inclusive decay rate:

$$\frac{F(N,N')}{\mathcal{G}(N)} = \frac{1}{\mathcal{G}(N)} \sum_{\Phi_N} \sum_{\Phi_{N'}} |\langle \Phi_N | V_g(k) | \Phi_{N'} \rangle|^2$$

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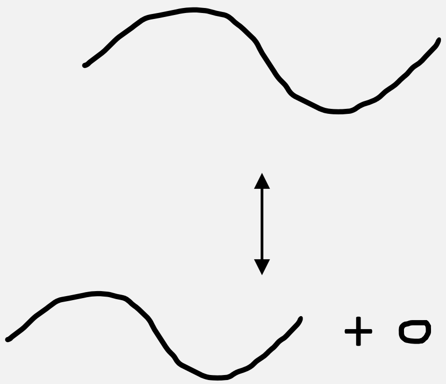

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These sums can be replaced by a trace by inserting projectors:

$$F(N,N') = \oint \frac{dz}{2\pi i z^{1+N}} \oint \frac{dz'}{2\pi i z'^{1+N'}} \mathbf{Tr}\left[z^{\hat{N}} V_g(k,1)^\dagger z'^{\hat{N}} V_g(k,1) \right]$$

Amati-Russo'99
Mañes'03
Kawamoto-Matsuo'13

Graviton production from a highly excited string

After the dust settles, we find a greybody spectrum at the Hagedorn temperature:

$$\frac{d\Gamma_{l\to g}}{d\omega\, dl} \simeq l \left(\frac{M_s}{M_p} \right)^2 \omega^2 \, \frac{e^{-\omega/T_H}}{\left(1 - e^{-\omega/2T_H}\right)^2}$$

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The contribution to the GW spectrum per e-fold thus reads:

$$\frac{d\rho_g}{dt} + 4H\rho_g = \int_{l_c}^{\infty} \omega\, \frac{d\Gamma_{l\to g}}{d\omega\, dl}\, \frac{n_o(l)}{V_{3D}}\, dl = \left(\frac{M_s}{M_p}\right)^2 I\left(\frac{\omega}{T_H}\right) \rho_o\, M_s$$

Gravitational waves from the Hagedorn phase

In terms of the fractional energy density and fidutial values, we find:

$$h^2\Omega_{\mathrm{GW}} \simeq 10^{-6}\left(\frac{X}{1}\right)^4\left(\frac{M_s}{10^{15}\ \mathrm{GeV}}\right)\left(\frac{\omega_0}{100\mathrm{GHz}\cdot X}\right)^{5/2} I\left(\frac{\omega_0}{100\mathrm{GHz}\cdot X}\right)$$

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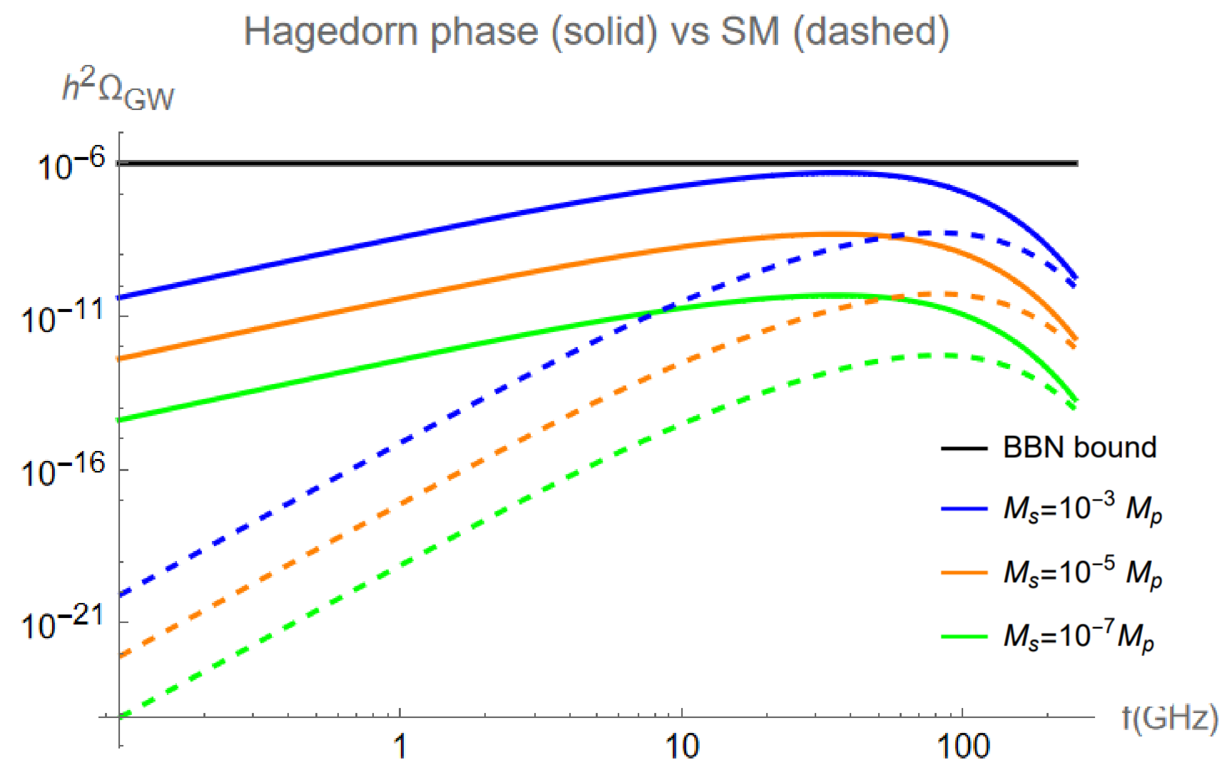


<u>Assuming standard cosmology</u>

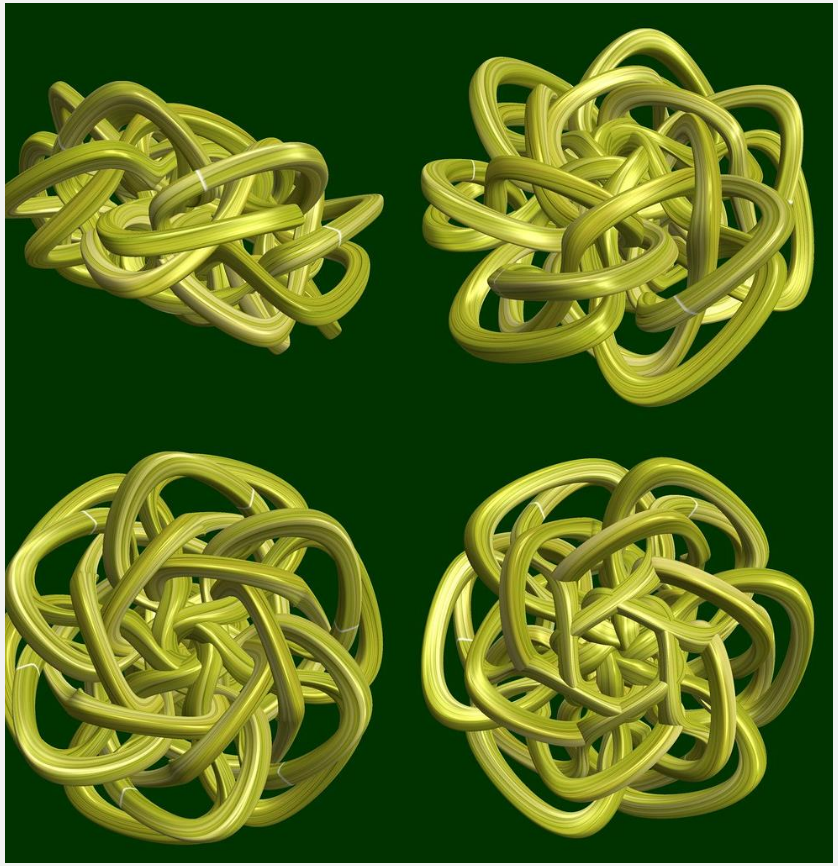
1) *Large* amplitude

2) Similar peak frequency as SM.

3) Amplitude larger than the SM prediction for a given reheating (Hagedorn) temperature.

Conclusions and future directions

- *GWs at large frequencies provide an incomparable opportunity to test (very) High Energy Physics.*
- Our setup predicts more model-dependent remnants, including closed string moduli and axions. It would be interesting to study further implications of this scenario for DM, etc.
- We have, at the moment, ignored the important issue of moduli stabilization. This is an obvious future direction.



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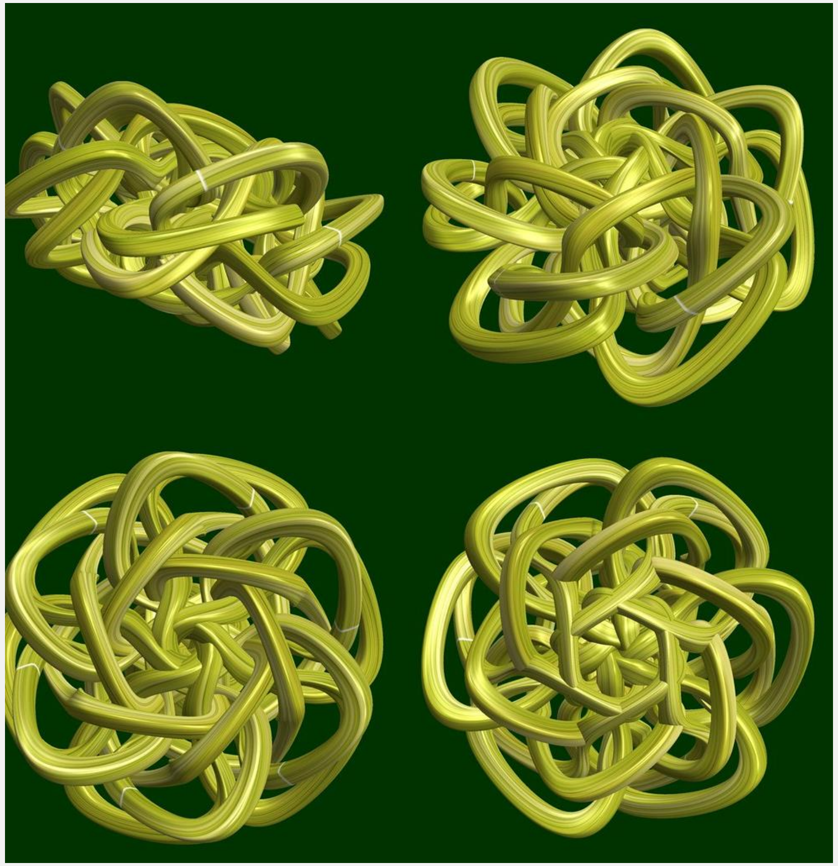
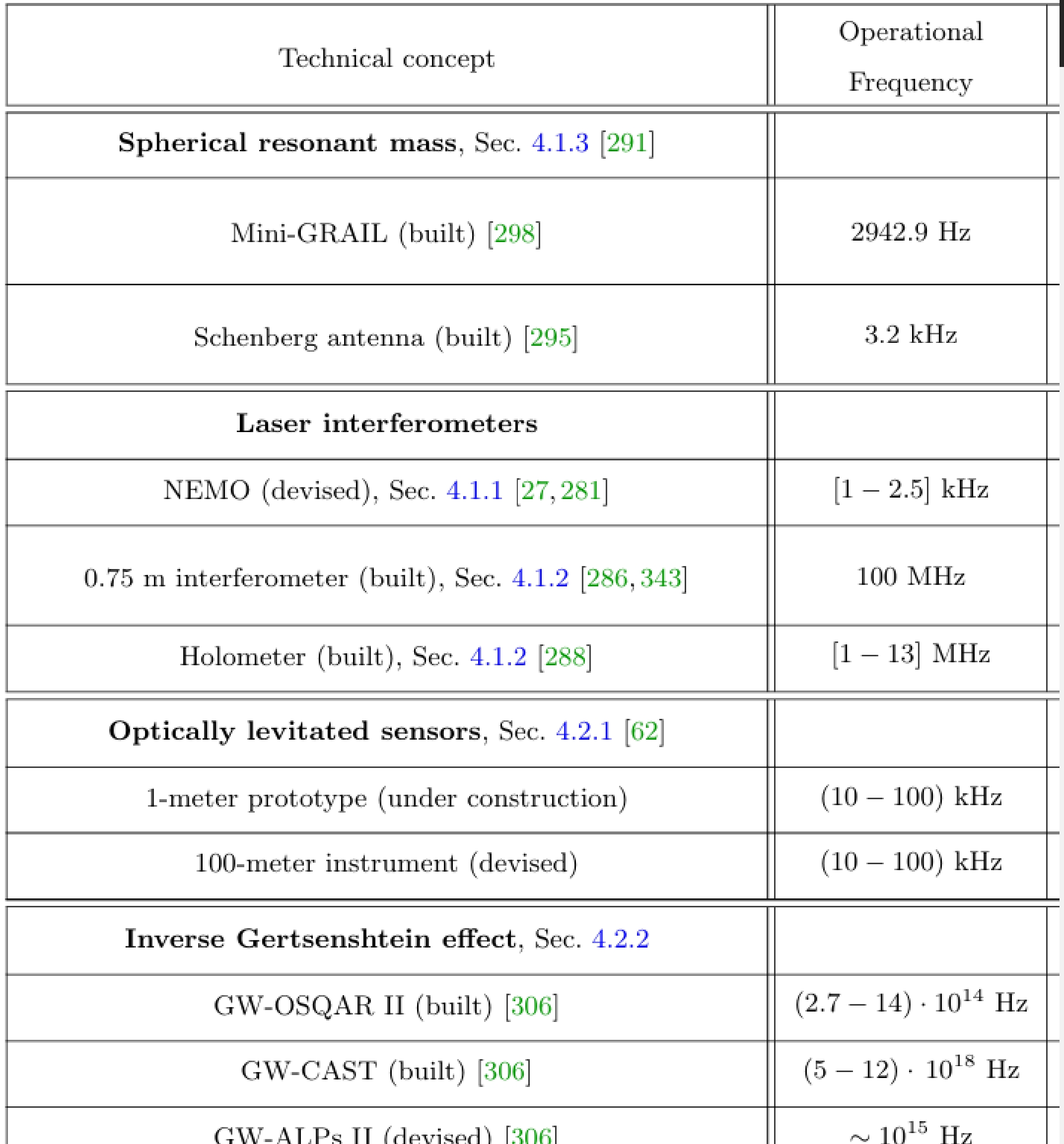
THANK YOU!

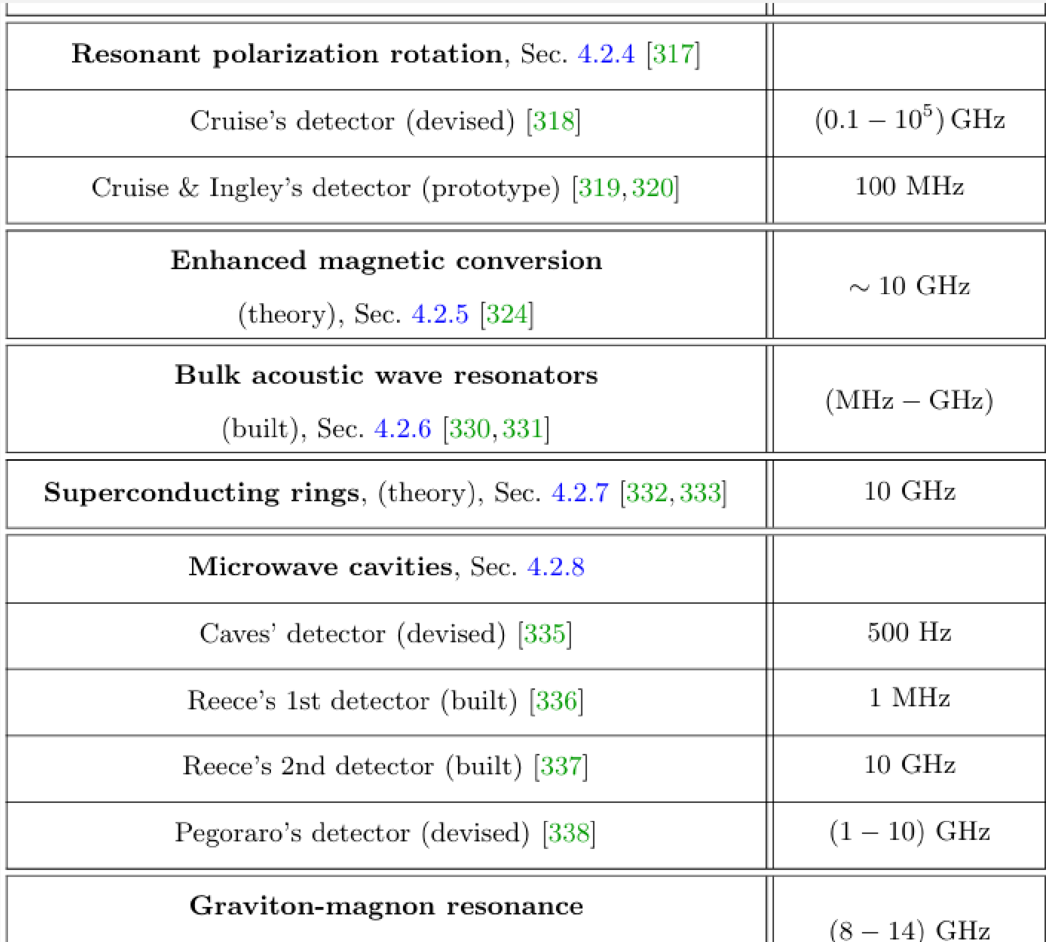


Bonus: Proposed detectors (Dec. 2020)



Technical concept	Operational Frequency
Spherical resonant mass, Sec. 4.1.3 [291]	
Mini-GRAIL (built) [298]	2942.9 Hz
Schenberg antenna (built) [295]	3.2 kHz
Laser interferometers	
NEMO (devised), Sec. 4.1.1 [27, 281]	[1 – 2.5] kHz
0.75 m interferometer (built), Sec. 4.1.2 [286, 343]	100 MHz
Holometer (built), Sec. 4.1.2 [288]	[1 – 13] MHz
Optically levitated sensors, Sec. 4.2.1 [62]	
1-meter prototype (under construction)	(10 – 100) kHz
100-meter instrument (devised)	(10 – 100) kHz
Inverse Gertsenshtein effect, Sec. 4.2.2	
GW-OSQAR II (built) [306]	$(2.7 - 14) \cdot 10^{14}$ Hz
GW-CAST (built) [306]	$(5 - 12) \cdot 10^{18}$ Hz
GW-ALPs II (devised) [306]	$\sim 10^{15}$ Hz

Adapted from Aggarwal et al'20
Sensitivities *not shown* (but challenging!)



Resonant polarization rotation, Sec. 4.2.4 [317]	
Cruise's detector (devised) [318]	$(0.1 - 10^{5})$ GHz
Cruise & Ingley's detector (prototype) [319, 320]	100 MHz
Enhanced magnetic conversion (theory), Sec. 4.2.5 [324]	~ 10 GHz
Bulk acoustic wave resonators (built), Sec. 4.2.6 [330, 331]	(MHz – GHz)
Superconducting rings, (theory), Sec. 4.2.7 [332, 333]	10 GHz
Microwave cavities, Sec. 4.2.8	
Caves' detector (devised) [335]	500 Hz
Reece's 1st detector (built) [336]	1 MHz
Reece's 2nd detector (built) [337]	10 GHz
Pegoraro's detector (devised) [338]	(1 – 10) GHz
Graviton-magnon resonance	(8 – 14) GHz

The early Universe as a GW producer