Complete Gravitational-Wave Spectrum of the Sun

TeV Particle Astrophysics
TeVPA
Valencia 2025

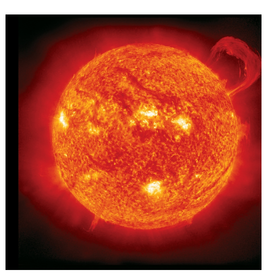
November 3, 2025

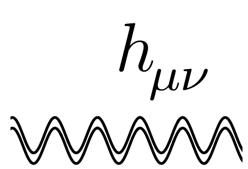
Camilo García Cely

CSIC Consejo Superior de Investigaciones Científicas
Vniversitat de València
IFIC Institut de Física Corpuscular
Excelencia Severo Ochoa
Agencia Estatal de Investigación

Outline

- Motivation
- Solar gravitational waves
- Conclusions





PHYSICAL REVIEW LETTERS **135,** 061001 (2025)

Complete Gravitational-Wave Spectrum of the Sun

Camilo García-Cely[1] and Andreas Ringwald[2]

Motivation

High-frequency gravitational waves

A growing community is seriously considering the search of high frequency gravitational waves

arXiv > gr-qc > arXiv:2501.11723

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General Relativity and Quantum Cosmology

[Submitted on 20 Jan 2025]

Challenges and Opportunities of Gravitational Wave Searches above 10 kHz

Nancy Aggarwal, Odylio D. Aguiar, Diego Blas, Andreas Bauswein, Giancarlo Cella, Sebastian Clesse, Adrian Michael Cruise, Valerie Domcke, Sebastian Ellis, Daniel G. Figueroa, Gabriele Franciolini, Camilo Garcia-Cely, Andrew Geraci, Maxim Goryachev, Hartmut Grote, Mark Hindmarsh, Asuka Ito, Joachim Kopp, Sung Mook Lee, Killian Martineau, Jamie McDonald, Francesco Muia, Nikhil Mukund, David Ottaway, Marco Peloso, Krisztian Peters, Fernando Quevedo, Angelo Ricciardone, Andreas Ringwald, Jessica Steinlechner, Sebastian Steinlechner, Sichun Sun, Carlos Tamarit, Michael E. Tobar, Francisco Torrenti, Caner Ünal, Graham White

SOVIET PHYSICS JETP VOLUME 14, NUMBER 1 JANUARY, 1962

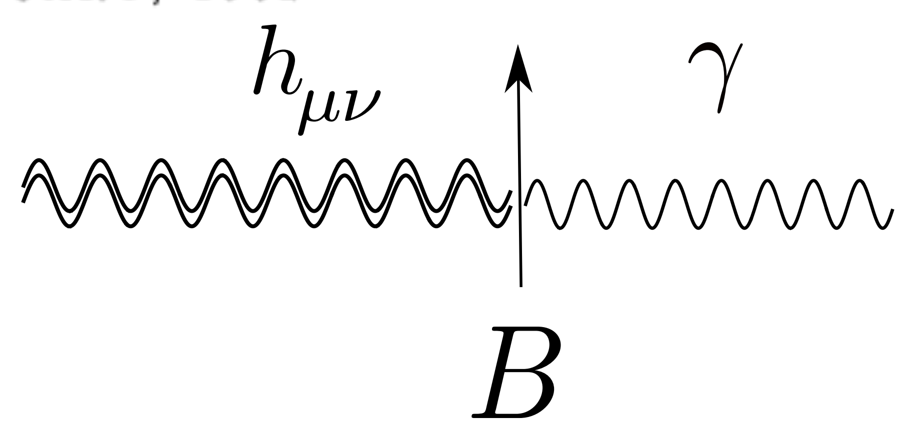
WAVE RESONANCE OF LIGHT AND GRAVITIONAL WAVES

M. E. GERTSENSHTEĬN

Submitted to JETP editor July 29, 1960

J. Exptl. Theoret. Phys. (U.S.S.R.) **41**, 113-114 (July, 1961)

The energy of gravitational waves excited during the propagation of light in a constant magnetic or electric field is estimated.



The (inverse) Gertsenhstein Effect

- The conversion of gravitational waves into electromagnetic waves is a classical process. Its rate does not involve $\hbar$

$$P \sim G B^2 L^2$$

- Cosmological conversion

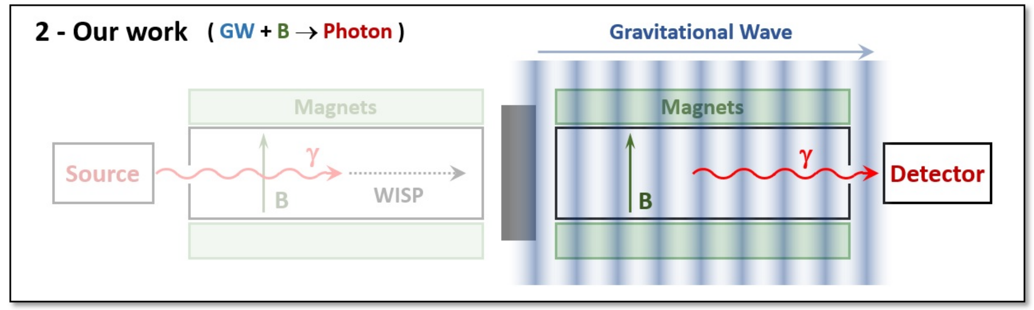
Potential of Radio Telescopes as High-Frequency Gravitational Wave Detectors

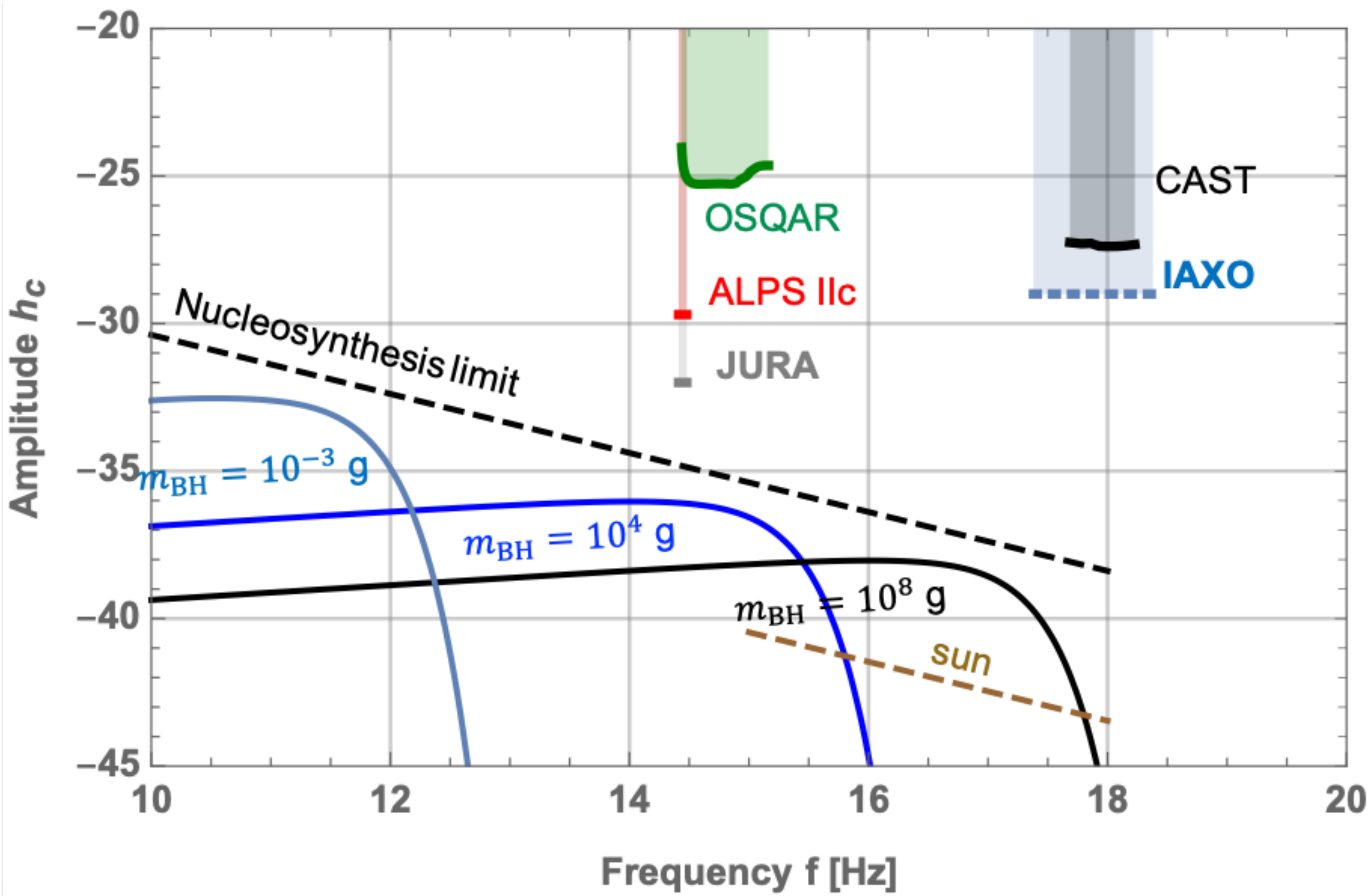
Valerie Domcke and Camilo Garcia-Cely
Phys. Rev. Lett. **126**, 021104 – Published 14 January 2021

- The process is strictly analogous to axion conversion.

Raffelt, Stodolski'89

The (inverse) Gertsenhstein Effect





A. Ejlli, D. Ejlli, A. M. Cruise, G. Pisano & H. Grote

The European Physical Journal C **79**, Article number: 1032 (2019)

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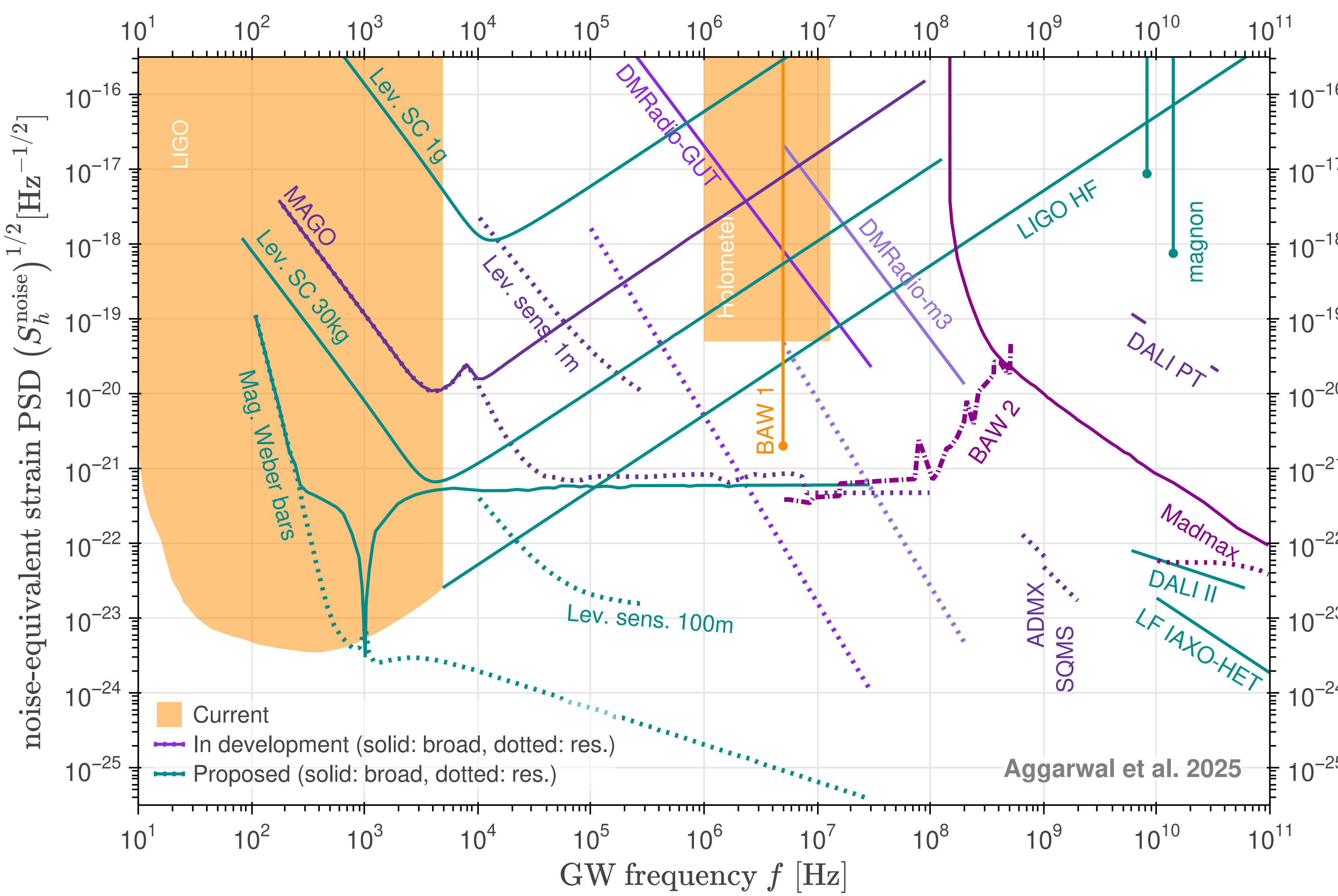
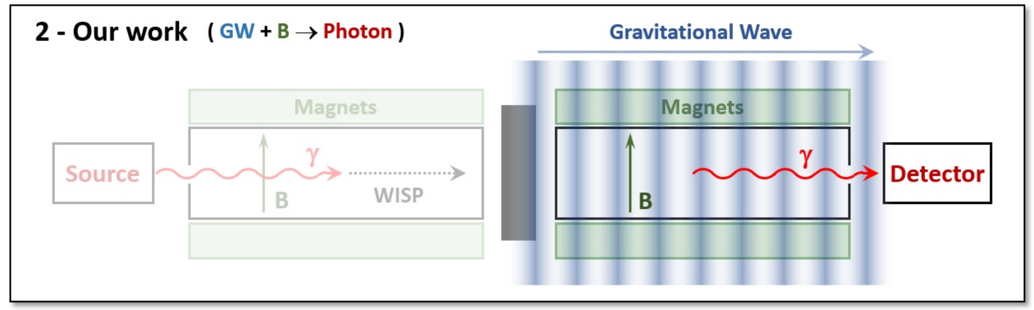
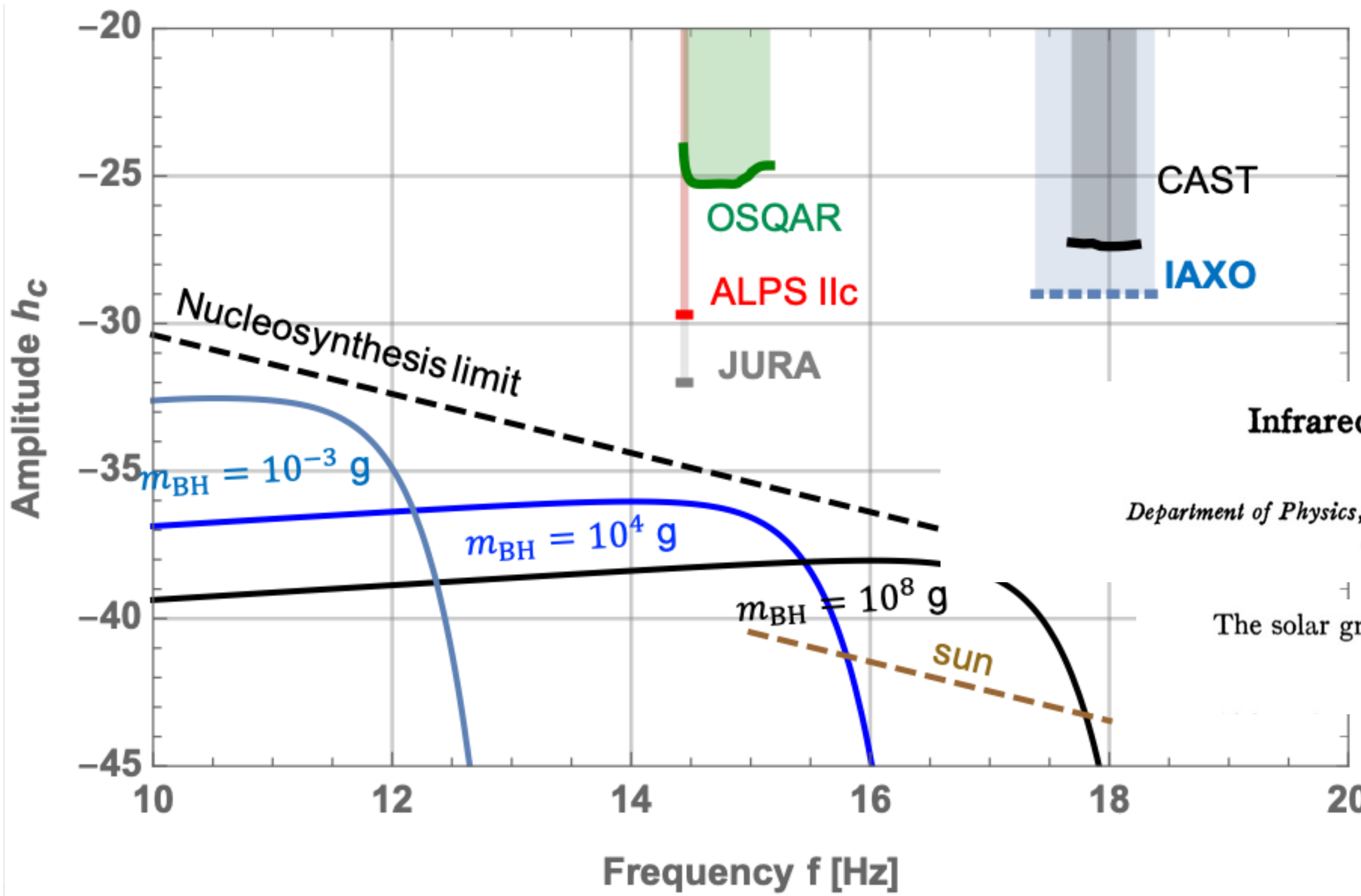


The (inverse) Gertsenhstein Effect





Infrared Photons and Gravitons*

STEVEN WEINBERG†
Department of Physics, University of California, Berkeley, California

(Received 1 June 1965)

The solar gravitational radiation power is then

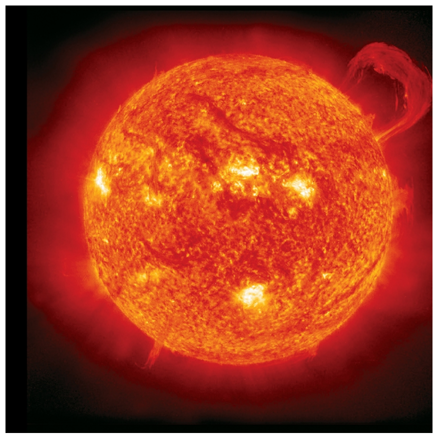
$$P_{\odot} \simeq 6 \times 10^{14}\ \text{erg/sec}. \quad (4.24)$$

A. Ejlli, D. Ejlli, A. M. Cruise, G. Pisano & H. Grote
The European Physical Journal C **79**, Article number: 1032 (2019)

ANOTHER MOTIVATION: SPIN-2 PARTICLES

$$\mathcal{L} = \frac{1}{2}\partial_\rho h_{\mu\nu}\partial^\rho h^{\mu\nu} - \frac{1}{2}\partial_\rho h \partial^\rho h + \partial_\rho h \partial_\nu h^{\rho\nu} - \partial_\rho h_{\mu\nu}\partial^\nu h^{\mu\rho}$$
$$-m^2(h_{\mu\nu}h^{\mu\nu} - h^2)/2 + (8\pi G')^{\frac{1}{2}} h_{\mu\nu}T^{\mu\nu}\,,$$

Fierz-Pauli, 1939



- Mediators of dark Yukawa forces
- Spin -2 Dark Matter
- Bimetric theories

Naturally related to solar gravitational waves!

Solar gravitational waves

Camilo García-Cely

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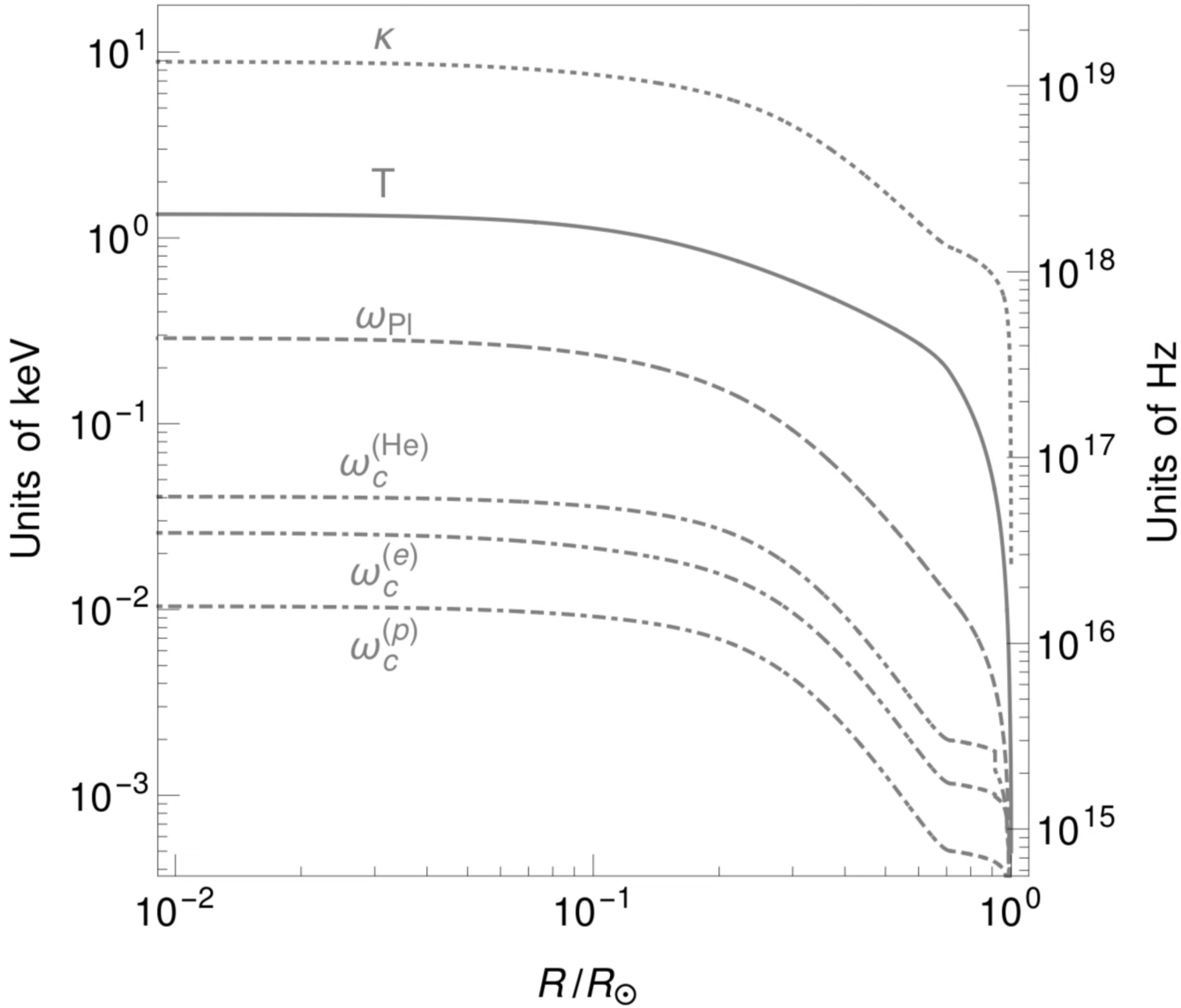
Solar gravitational waves

Microscopic vs macroscopic



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Solar gravitational waves

Macroscopic contribution: Hydrodynamical fluctuations

Gravitational wave background from Standard Model physics: qualitative features

J. Ghiglieri[1] and M. Laine[1]

Published 16 July 2015 • Journal of Cosmology and Astroparticle Physics, Volume 2015, July 2015

Citation J. Ghiglieri and M. Laine JCAP07(2015)022

DOI 10.1088/1475-7516/2015/07/022

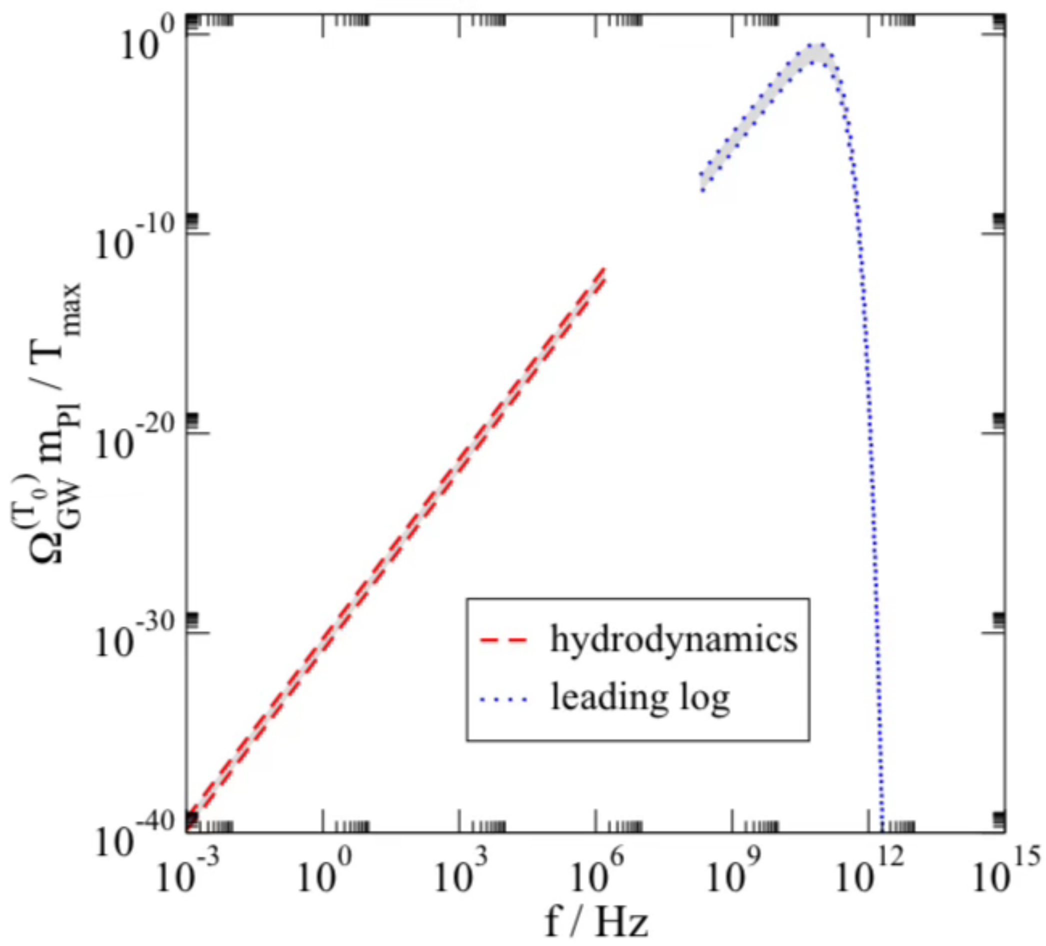
Article PDF

References

+ Article and author information

Abstract

Because of physical processes ranging from microscopic particle collisions to macroscopic hydrodynamic fluctuations, any plasma in thermal equilibrium emits gravitational waves. For the largest wavelengths the emission rate is proportional to the shear viscosity of the plasma. In the Standard Model at



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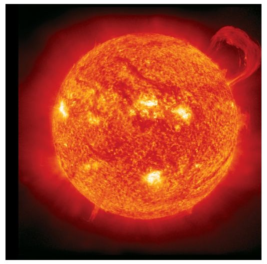
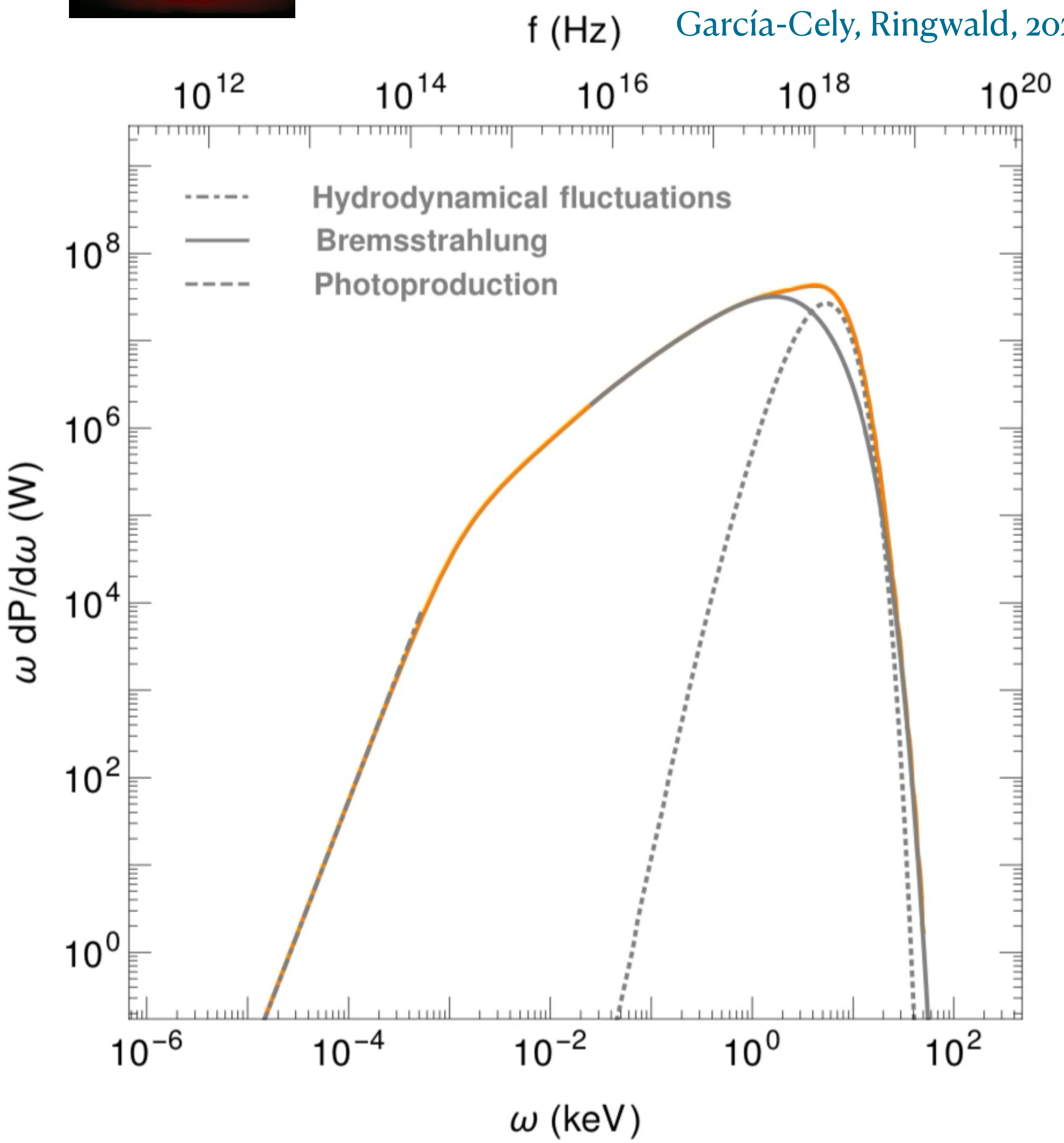
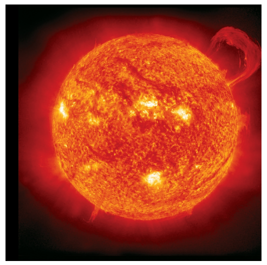
Solar gravitational waves



García-Cely, Ringwald, 2025

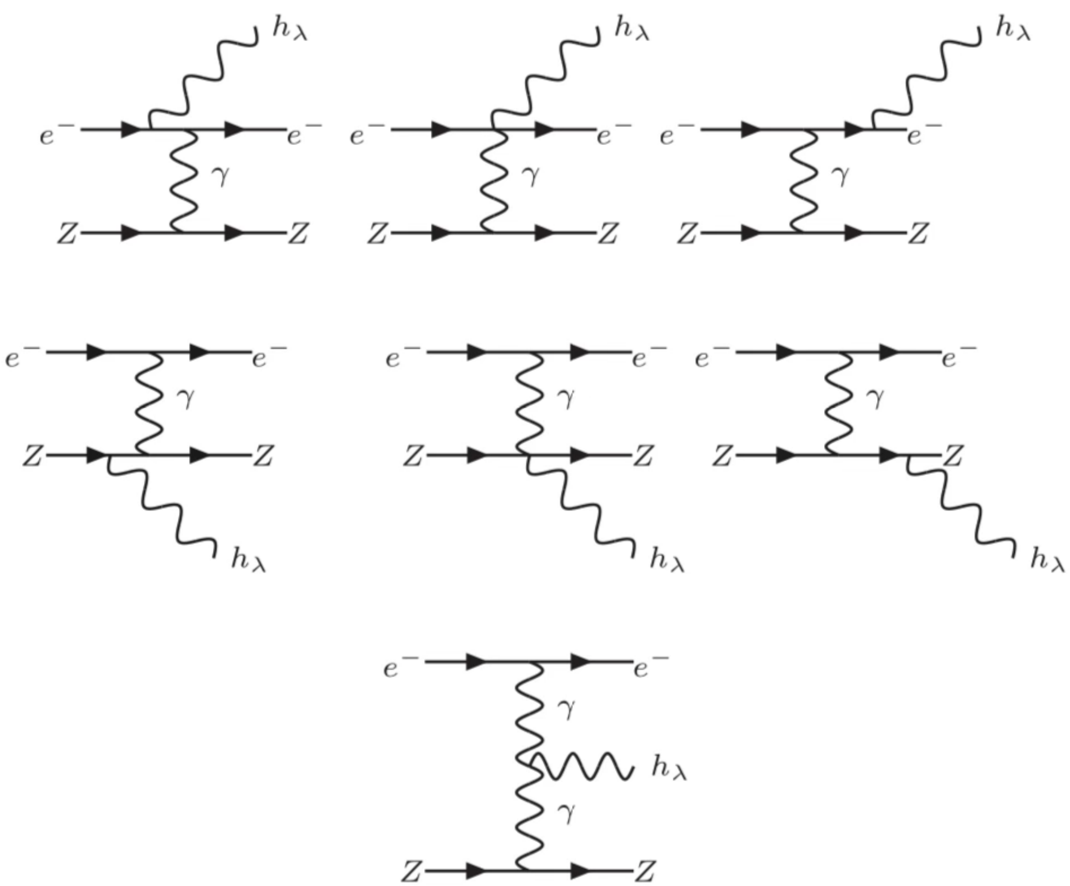


Solar gravitational waves

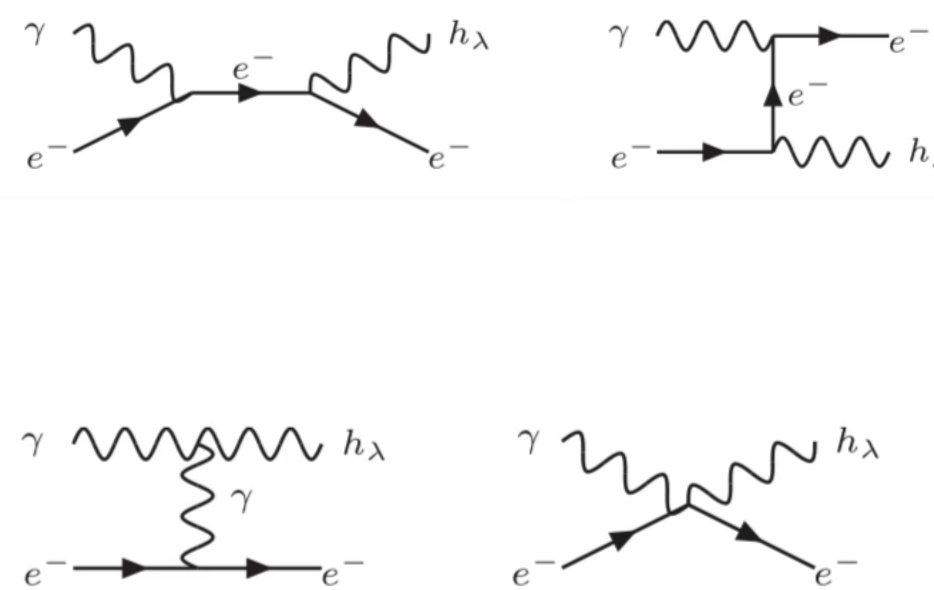


Microscopic contribution: graviton emission

Bremsstrahlung

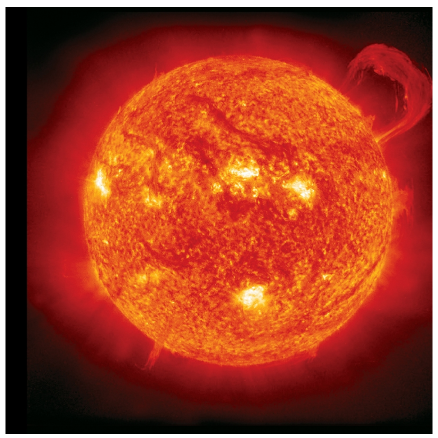


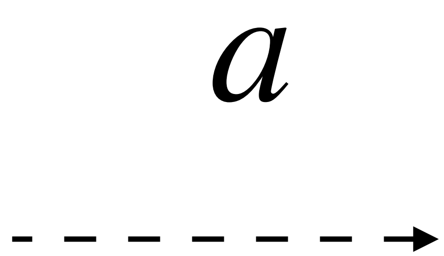
Photoproduction

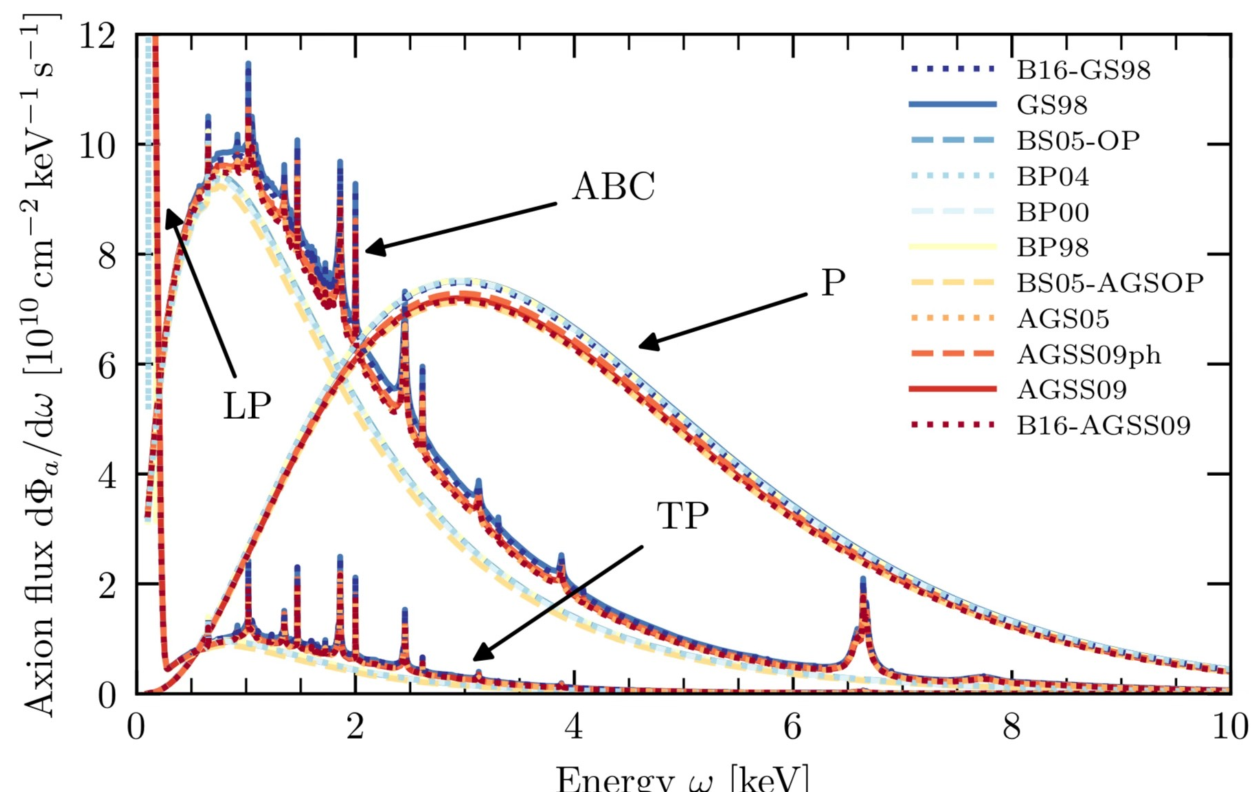


García-Cely, Ringwald, 2024

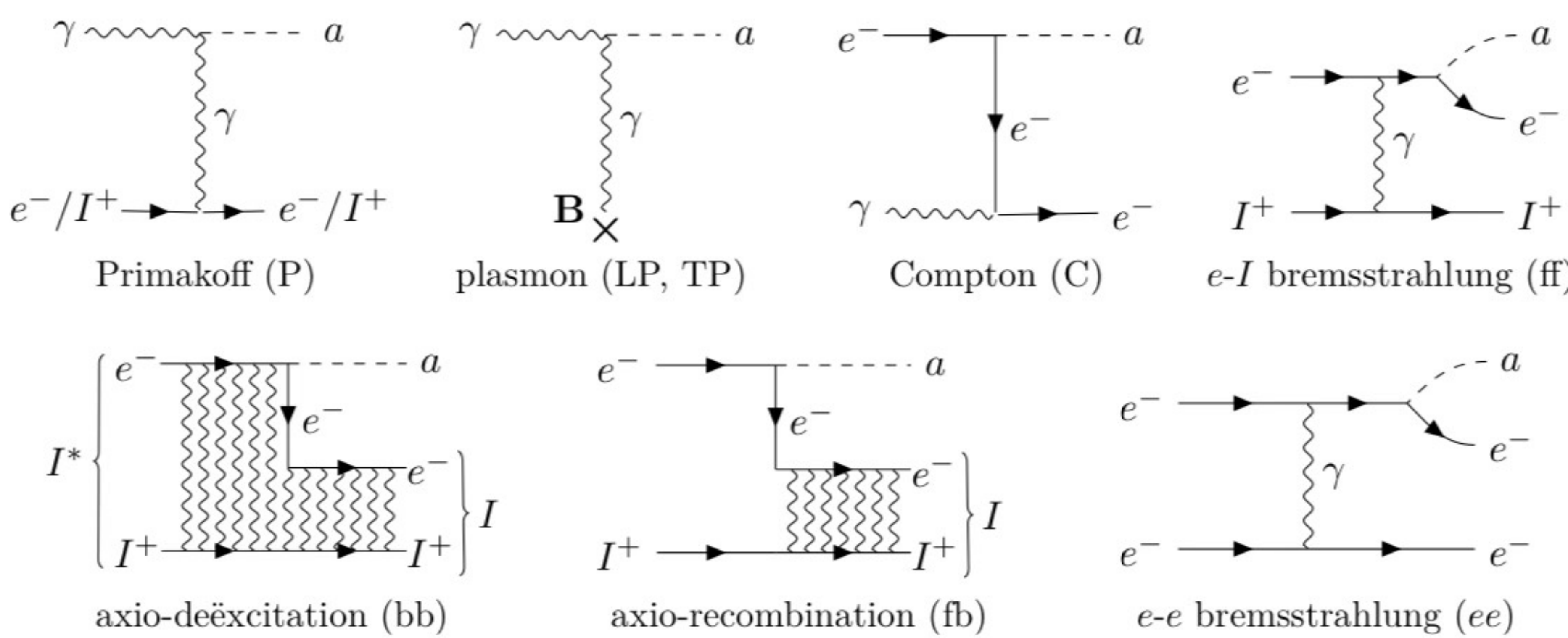
Solar axions







Hoof et al, 2021



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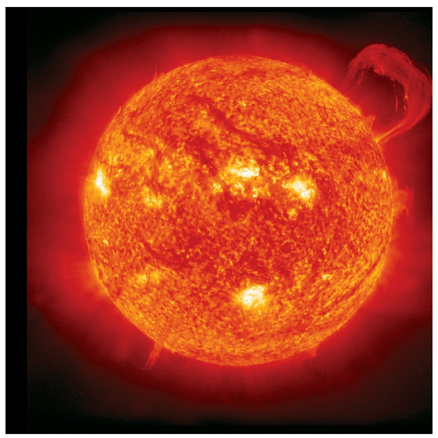
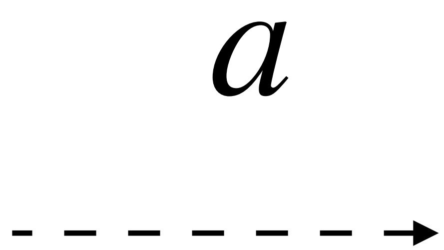
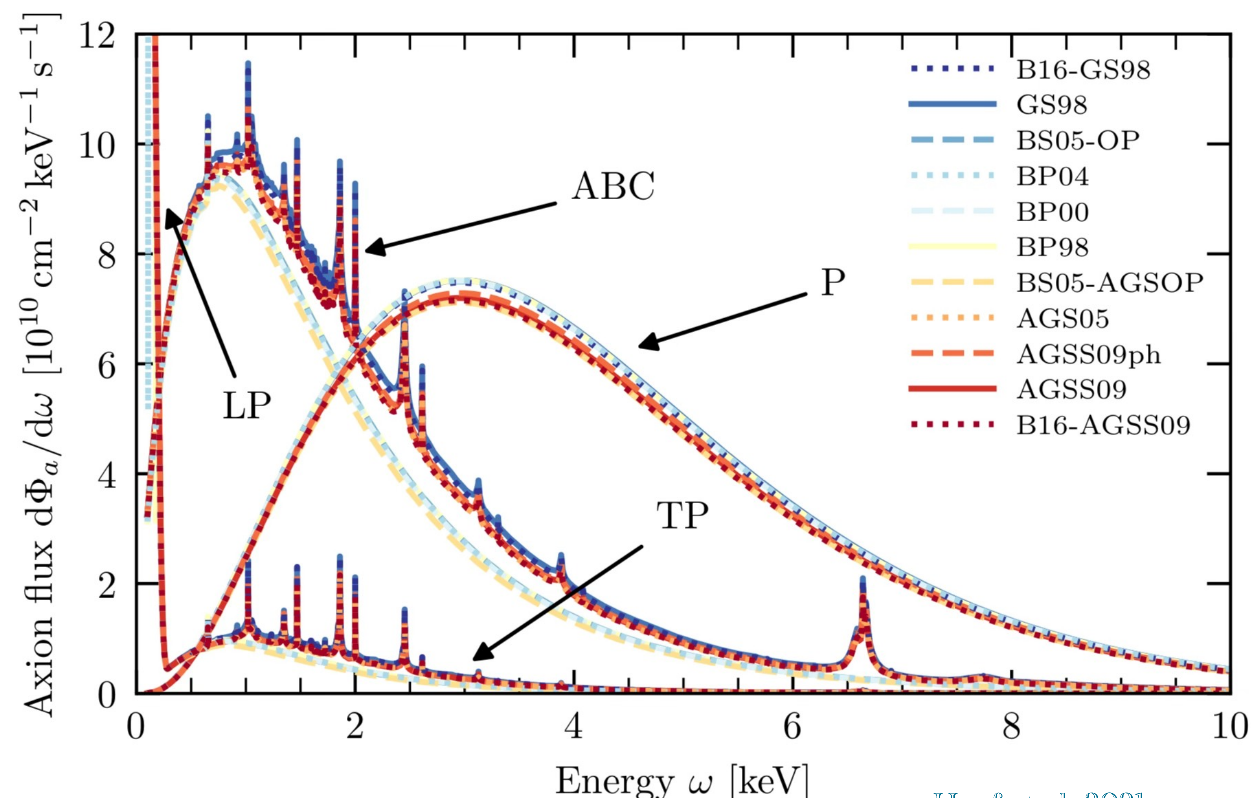
Solar axions







Hoof et al, 2021

PHYSICAL REVIEW D VOLUME 33, NUMBER 4 15 FEBRUARY 1986

Astrophysical axion bounds diminished by screening effects

Georg G. Raffelt

PHYSICAL REVIEW D VOLUME 37, NUMBER 6 15 MARCH 1988

Plasmon decay into low-mass bosons in stars

Georg G. Raffelt

PHYSICAL REVIEW D **102,** 043019 (2020)

Axion helioscopes as solar magnetometers

Ciaran A. J. O'Hare,[1,*] Andrea Caputo,[2,†] Alexander J. Millar,[3,4,‡] and Edoardo Vitagliano[5,§]

PHYSICAL REVIEW D **101,** 123004 (2020)

Revisiting longitudinal plasmon-axion conversion in external magnetic fields

Andrea Caputo,[1,*] Alexander J. Millar,[2,3,†] and Edoardo Vitagliano[4,‡]

PHYSICAL REVIEW D **102,** 123024 (2020)

Production of axionlike particles from photon conversions in large-scale solar magnetic fields

Ersilia Guarini,[1] Pierluca Carenza,[1,2] Javier Galán,[3] Maurizio Giannotti,[4] and Alessandro Mirizzi[1,2]

Axion emission by magnetic-field induced conversion of longitudinal plasmons

N. V. Mikheev
Department of Theoretical Physics, Yaroslavl State University, Sovietskaya 14, Yaroslavl 150000, Russia

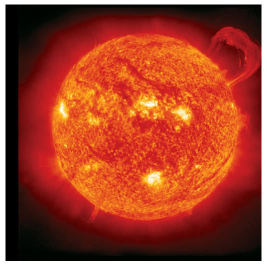
G. Raffelt
Max-Planck-Institut für Physik (Werner-Heisenberg-Institut), Föhringer Ring 6, 80805 München, Germany

L. A. Vassilevskaya

Solar axion flux from the axion-electron coupling

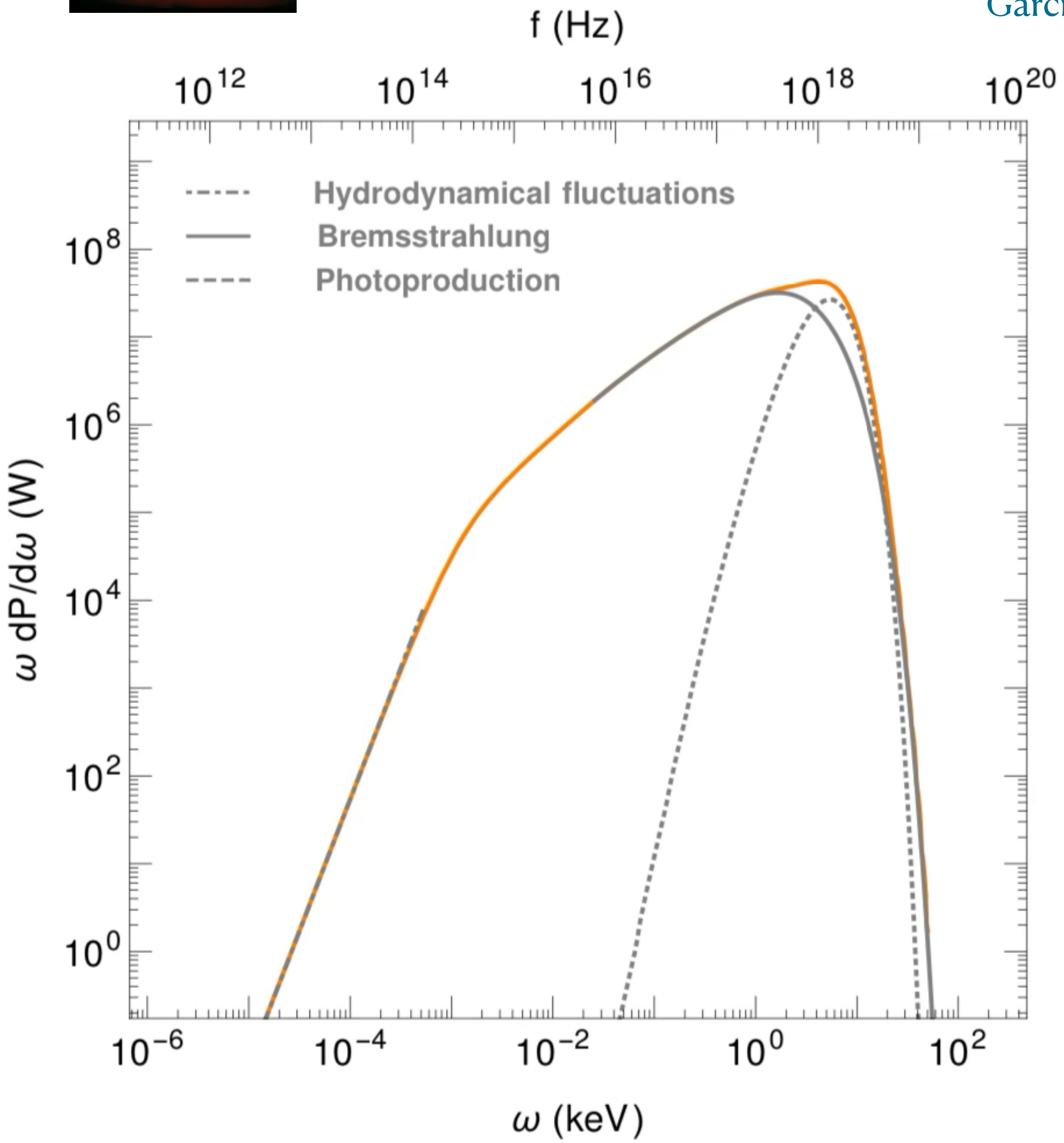
Javier Redondo (Munich U., ASC and Munich, Max Planck Inst.)
Oct 2, 2013

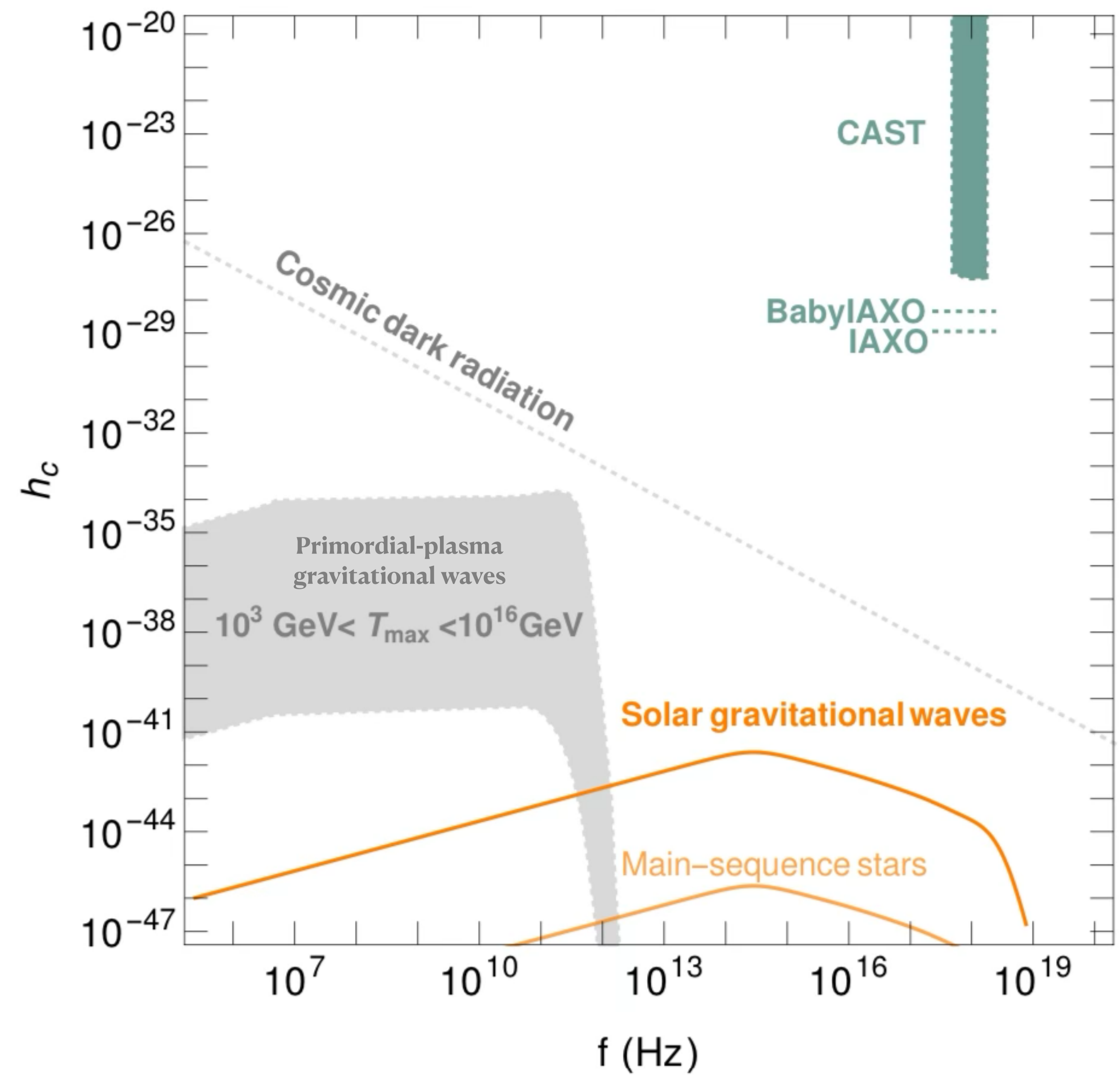
Solar gravitational waves



$h_{\mu\nu}$

García-Cely, Ringwald, 2025



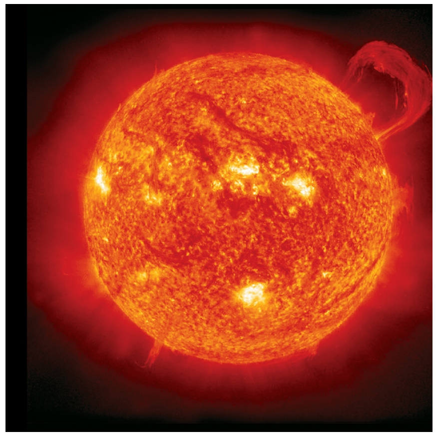


CONCLUSIONS

- High-frequency gravitational waves provide a new observational frontier, extending well beyond the astrophysical sources targeted by LIGO–Virgo.
- The Sun and other macroscopic media can generate high-frequency backgrounds through microscopic and hydrodynamic processes in this frequency range.
- Current sensitivities remain far from the strongest predicted signals, but the field is young and rich with opportunities for innovation.

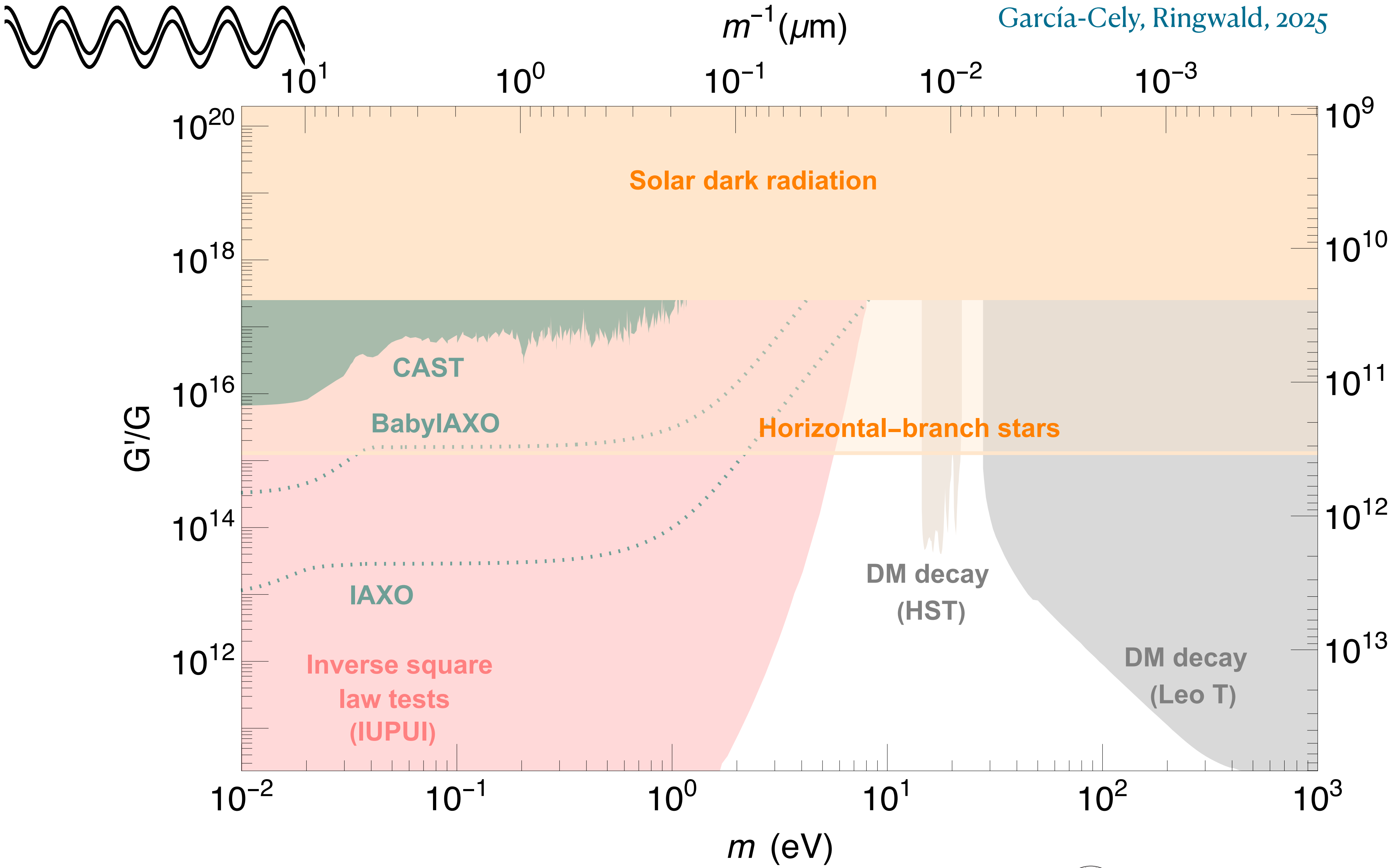
SPIN-2 PARTICLES

$$\mathcal{L} = \frac{1}{2}\partial_\rho h_{\mu\nu}\partial^\rho h^{\mu\nu} - \frac{1}{2}\partial_\rho h \partial^\rho h + \partial_\rho h \partial_\nu h^{\rho\nu} - \partial_\rho h_{\mu\nu}\partial^\nu h^{\mu\rho}$$
$$-m^2(h_{\mu\nu}h^{\mu\nu} - h^2)/2 + (8\pi G')^{\frac{1}{2}} h_{\mu\nu}T^{\mu\nu} ,$$

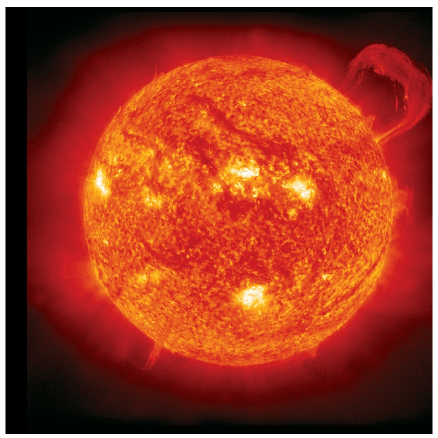


$h_{\mu\nu}$

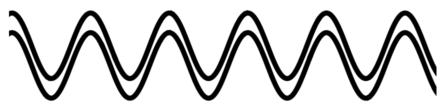
García-Cely, Ringwald, 2025



SOLAR EMISSION OF SPIN-2 PARTICLES



$h_{\mu\nu}$



Collision	λ	$\frac{\mathrm{d}\Gamma}{\mathrm{d}\omega \mathrm{d}V}$	
Photo-production	± 2	$n_\gamma n_Z G' Z^2 \alpha\pi\, \delta(\omega - p_i) \int \mathrm{d}\cos\theta \cot^2\frac{\theta}{2} [1+\cos^2\theta] F(\theta)$	$F(\theta) = \frac{\left(2\omega \sin\frac{\theta}{2}\right)^2}{\kappa^2 + \left(2\omega\sin\frac{\theta}{2}\right)^2}$
$\gamma Z \to Z\, h_\lambda$	± 1	0	
	0	$\frac{4}{3} n_\gamma n_Z G' Z^2 \alpha\pi\, \delta(\omega - p_i) \int \mathrm{d}\cos\theta \cot^2\frac{\theta}{2} \sin^4\frac{\theta}{2} F(\theta)$	
Bremsstrahlung	± 2	$\frac{32 n_e n_Z G' Z^2 \alpha^2 p_i}{15\omega} \left(\frac{1}{m_e} + \frac{1}{m_Z}\right) \left(3(1+\xi^2)L + 10\xi + \mathcal{O}(\xi_s^2)\right)$	$\xi = \frac{p_f}{p_i}, \quad \xi_s = \frac{\kappa}{p_i}$
$eZ \to eZ\, h_\lambda$	± 1	0	
	0	$\frac{16 n_e n_Z G' Z^2 \alpha^2 p_i}{45\omega} \left(\frac{1}{m_e} + \frac{1}{m_Z}\right) \left((1+\xi^2)L + 30\xi + \mathcal{O}(\xi_s^2)\right)$	$\omega = E_i(1-\xi^2)$
Bremsstrahlung	± 2	$\frac{16 n_e^2 G' \alpha^2 p_i}{15\omega m_e} \left(\left(6(1+\xi^2) - \frac{3(1-\xi^2)^4 + 7(1-\xi^4)^2}{2(1+\xi^2)^3}\right) L + 20\xi - \frac{6\xi(1+\xi^4)}{(1+\xi^2)^2} + \mathcal{O}(\xi_s^2)\right)$	$L = \log\sqrt{\frac{(1+\xi)^2 + \xi_s^2}{(1-\xi)^2 + \xi_s^2}}$
$ee \to ee\, h_\lambda$	± 1	0	
	0	$\frac{16 n_e^2 G' \alpha^2 p_i}{15\omega m_e} \left(\left(\frac{1}{3}(1+\xi^2) - \frac{(1-\xi^2)^4 + 29(1-\xi^4)^2}{12(1+\xi^2)^3}\right) L + \frac{29\xi}{3} + \frac{2\xi^3}{3(1+\xi^2)^2} + \mathcal{O}(\xi_s^2)\right) <$	

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