

New ideas for detecting gravitational waves

Camilo A. Garcia Cely

Alexander von Humboldt & Ramón y Cajal Fellow



BCTP, Bonn

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Outline

- Motivation
- Gravitational Waves and the Gertsenhstein Effect
- CMB observations and 21-cm cosmology
- Experimental efforts on terrestrial experiments
- Conclusions

Motivation

Gravitational Waves

- Predicted by Poincaré (1905)
- Einstein provided a firm theoretical background for them (1916)



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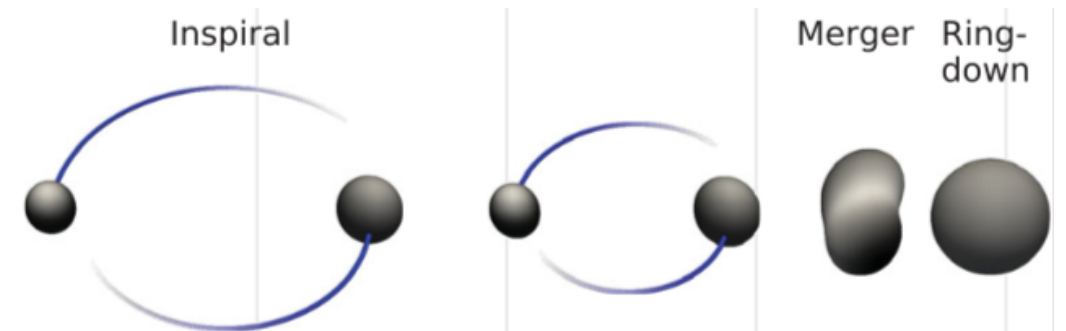
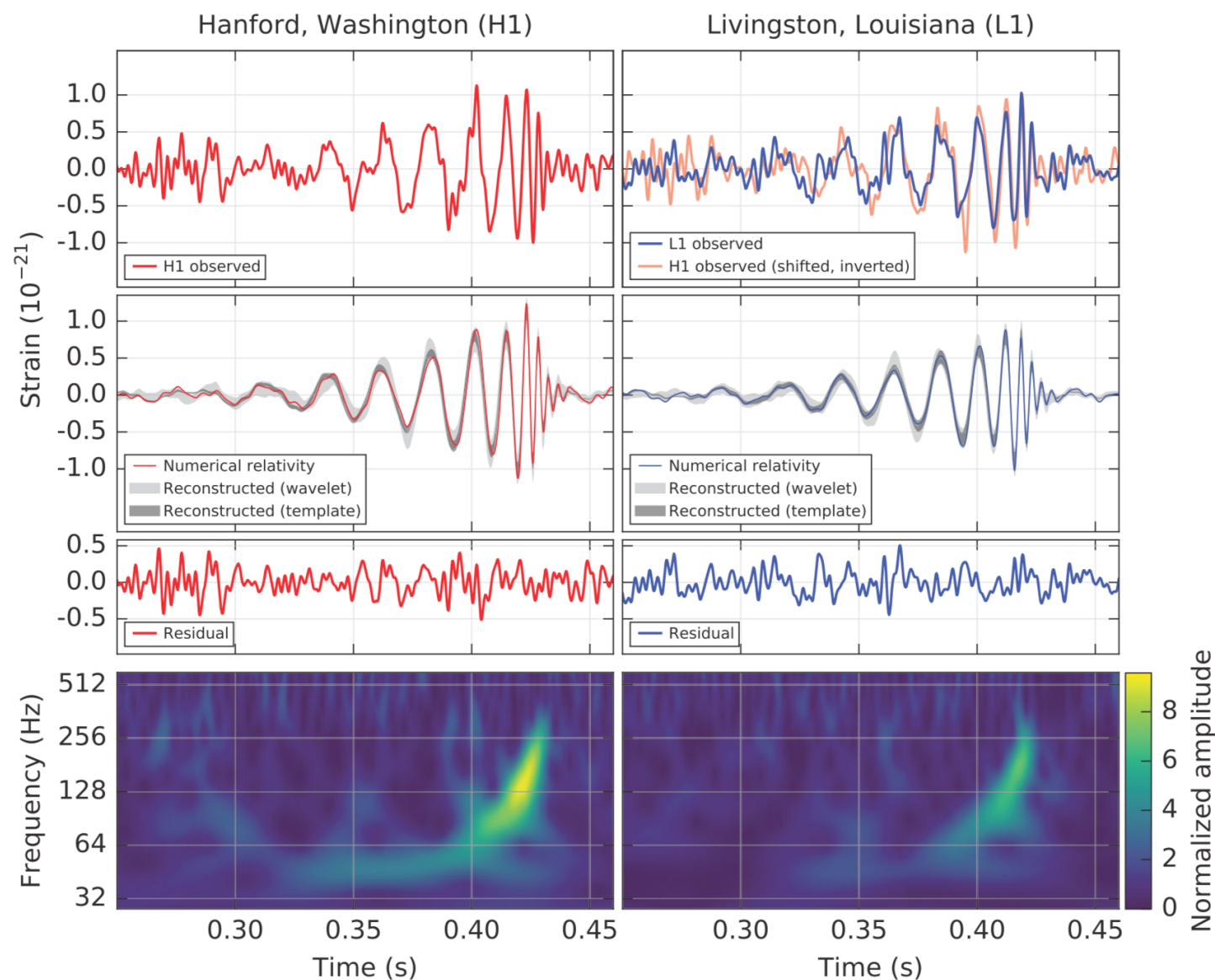


PRL **116**, 061102 (2016)

PHYSICAL REVIEW LETTERS

week ending
12 FEBRUARY 2016

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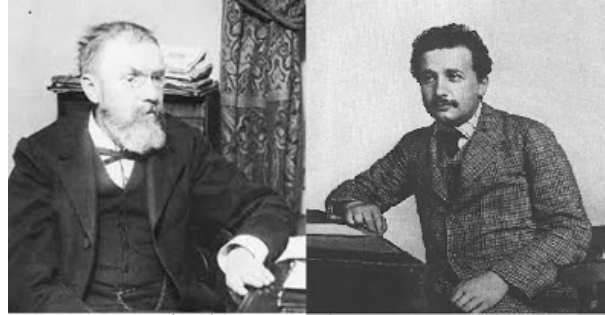
Terrestrial
interferometers



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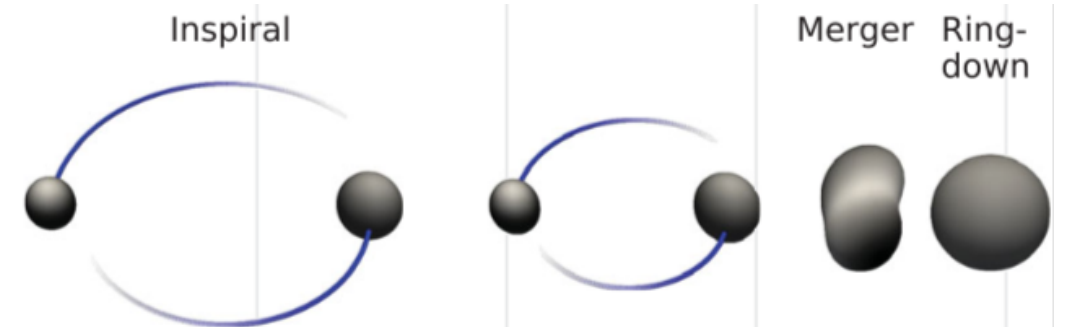
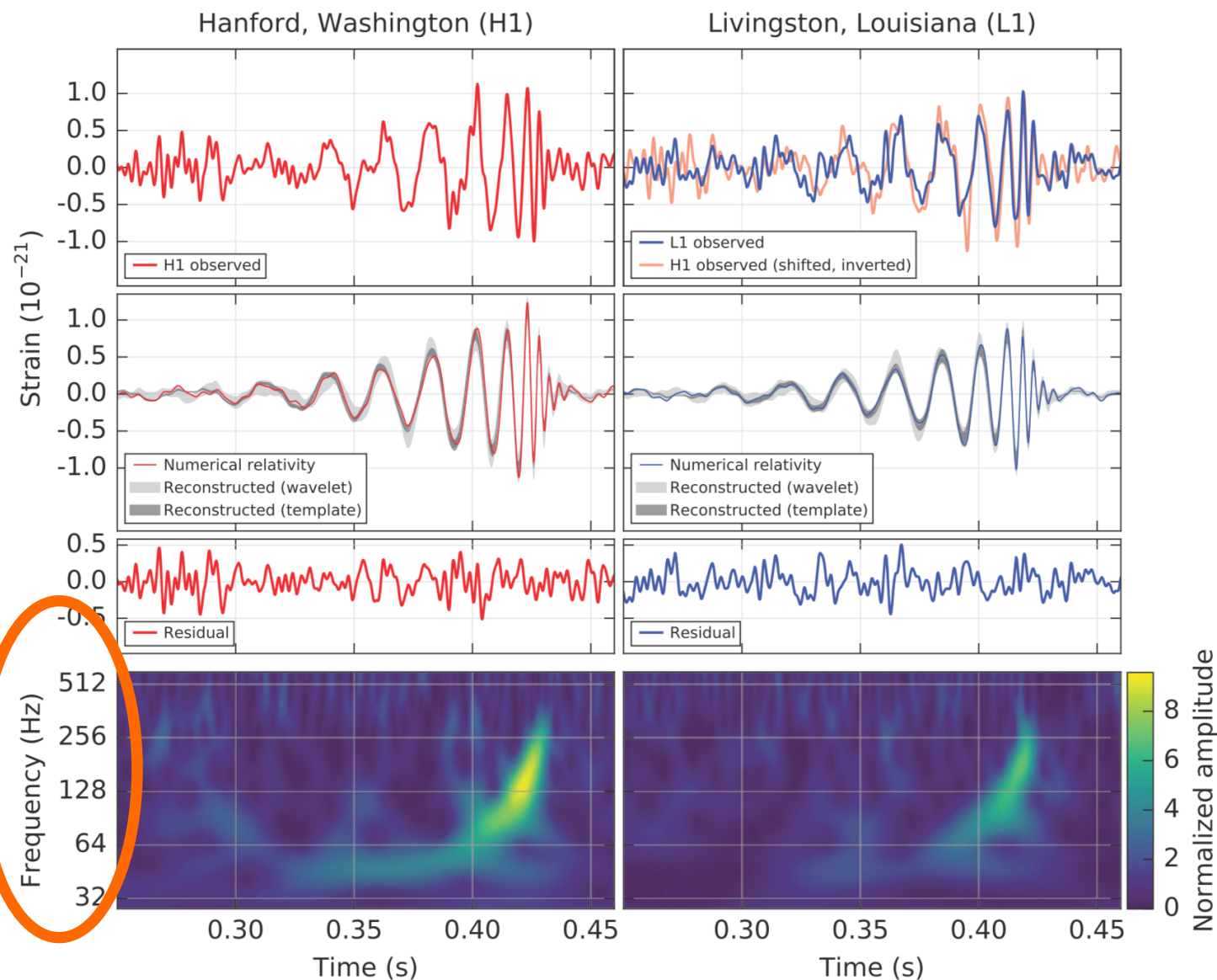


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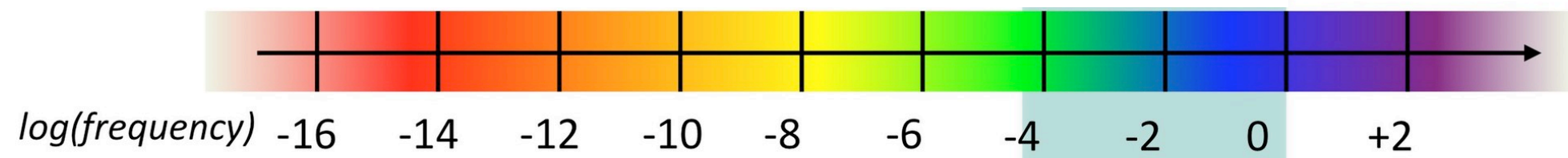


Terrestrial
interferometers



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Gravitational Wave Spectrum



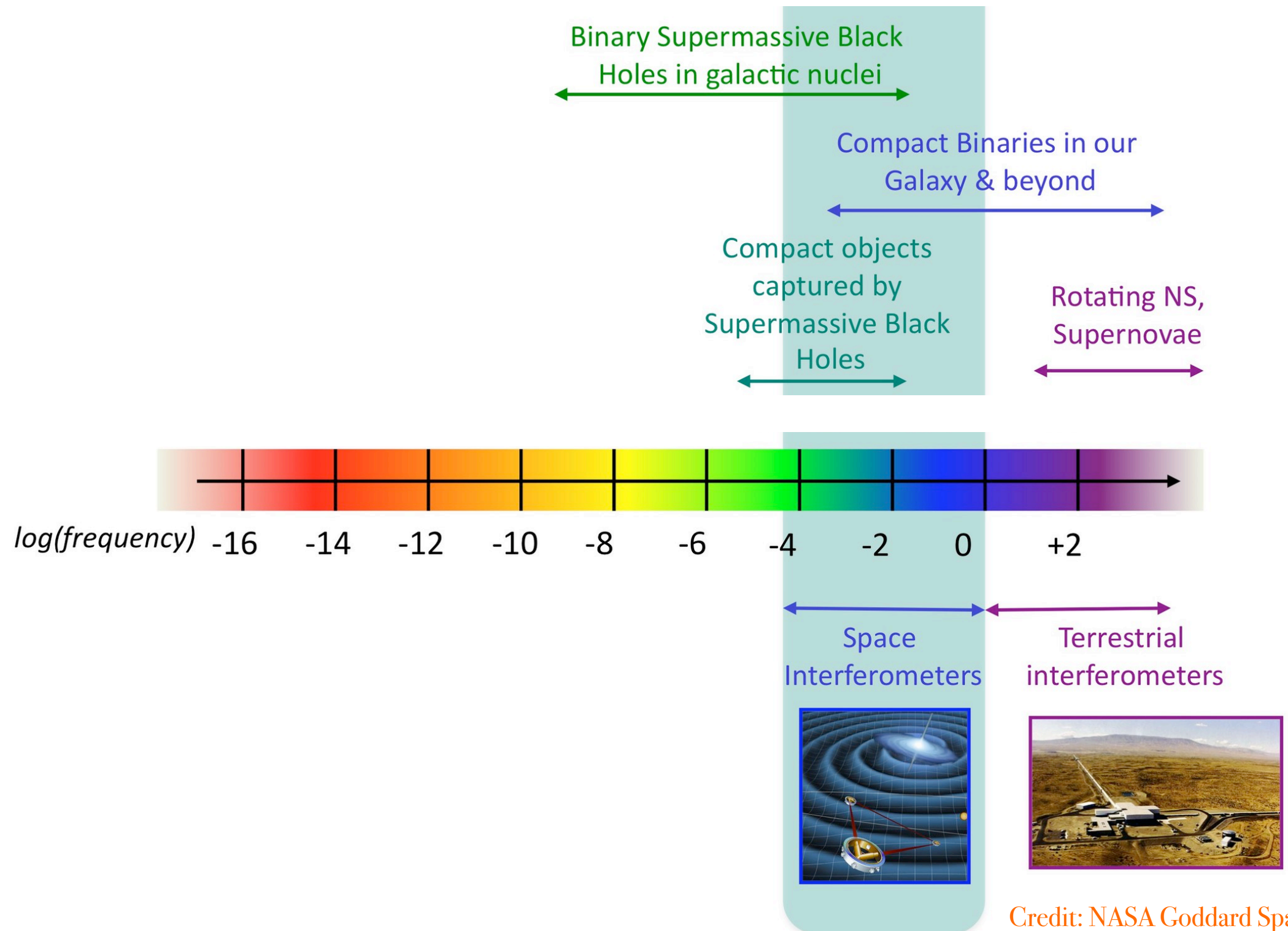
Terrestrial
interferometers



Credit: NASA Goddard Space Flight Center

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Gravitational Wave Spectrum

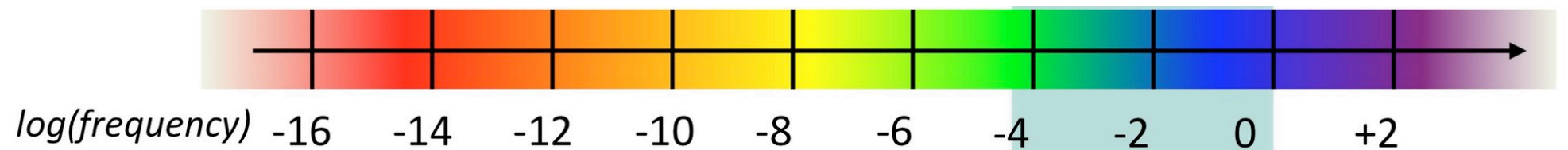
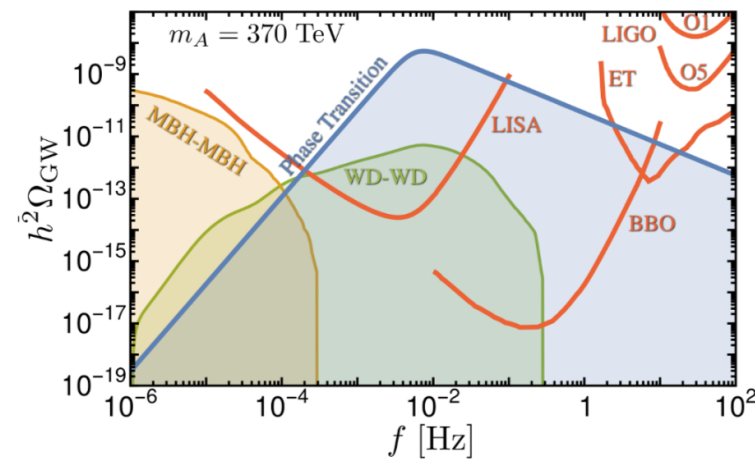


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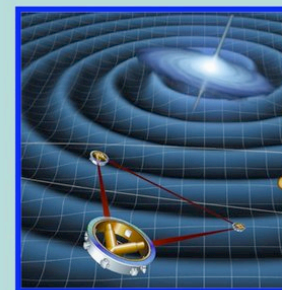
cosmological phase transitions

Baldes, CGC 2019



Space Interferometers

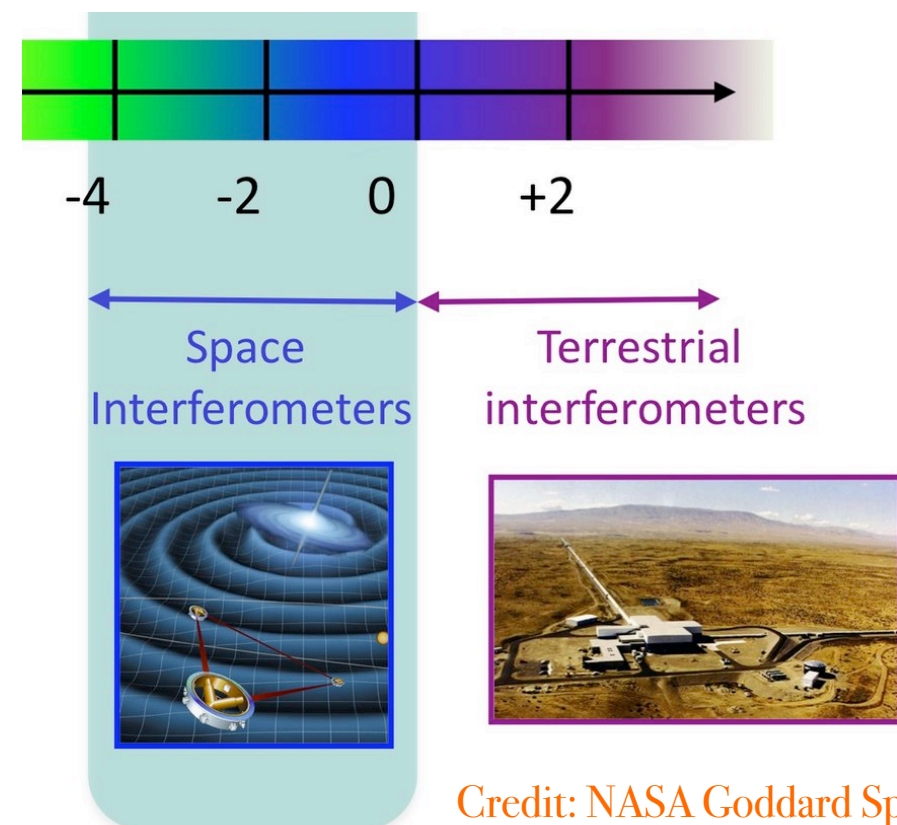
Terrestrial interferometers



Credit: NASA Goddard Space Flight Center

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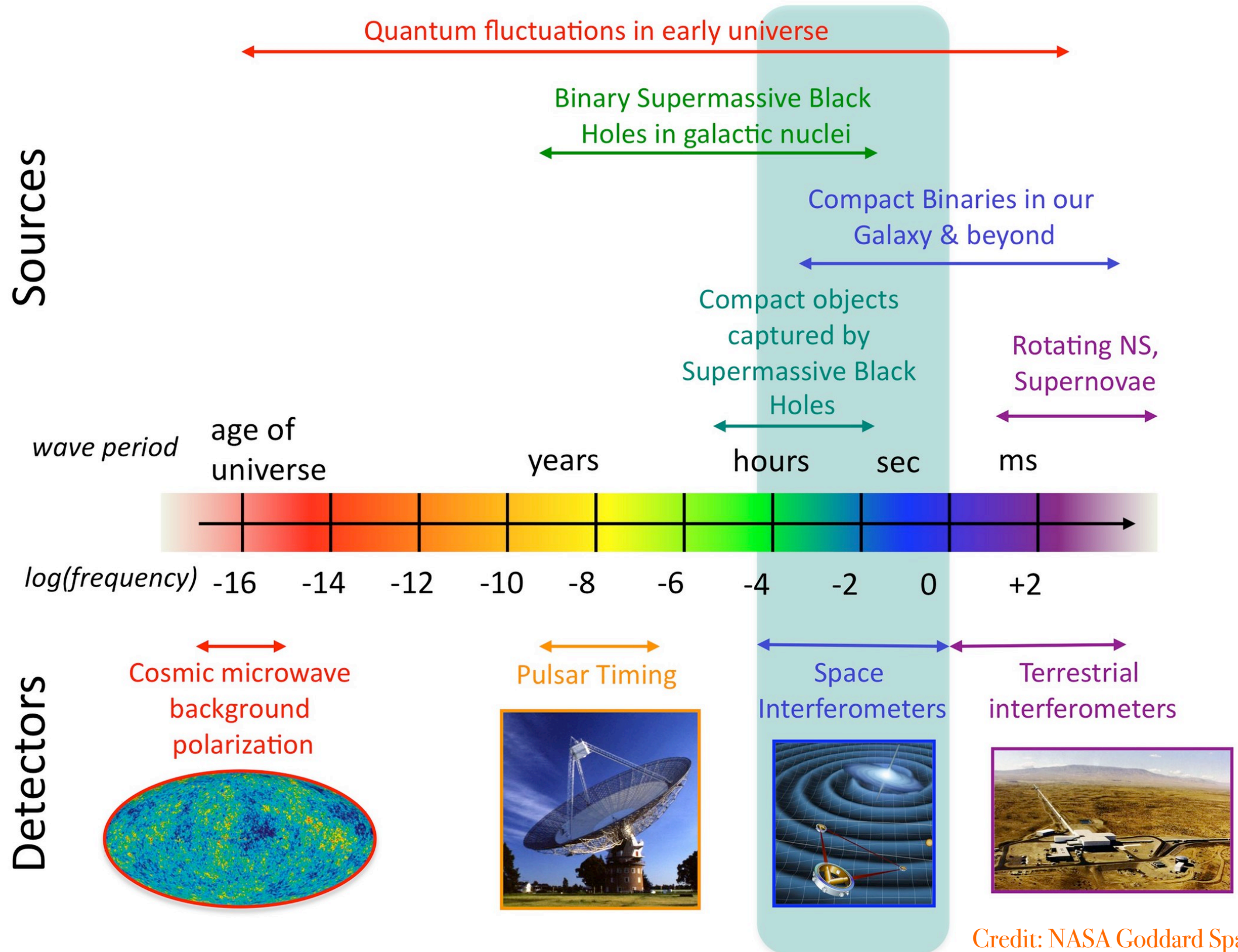
Gravitational Wave Spectrum



Credit: NASA Goddard Space Flight Center

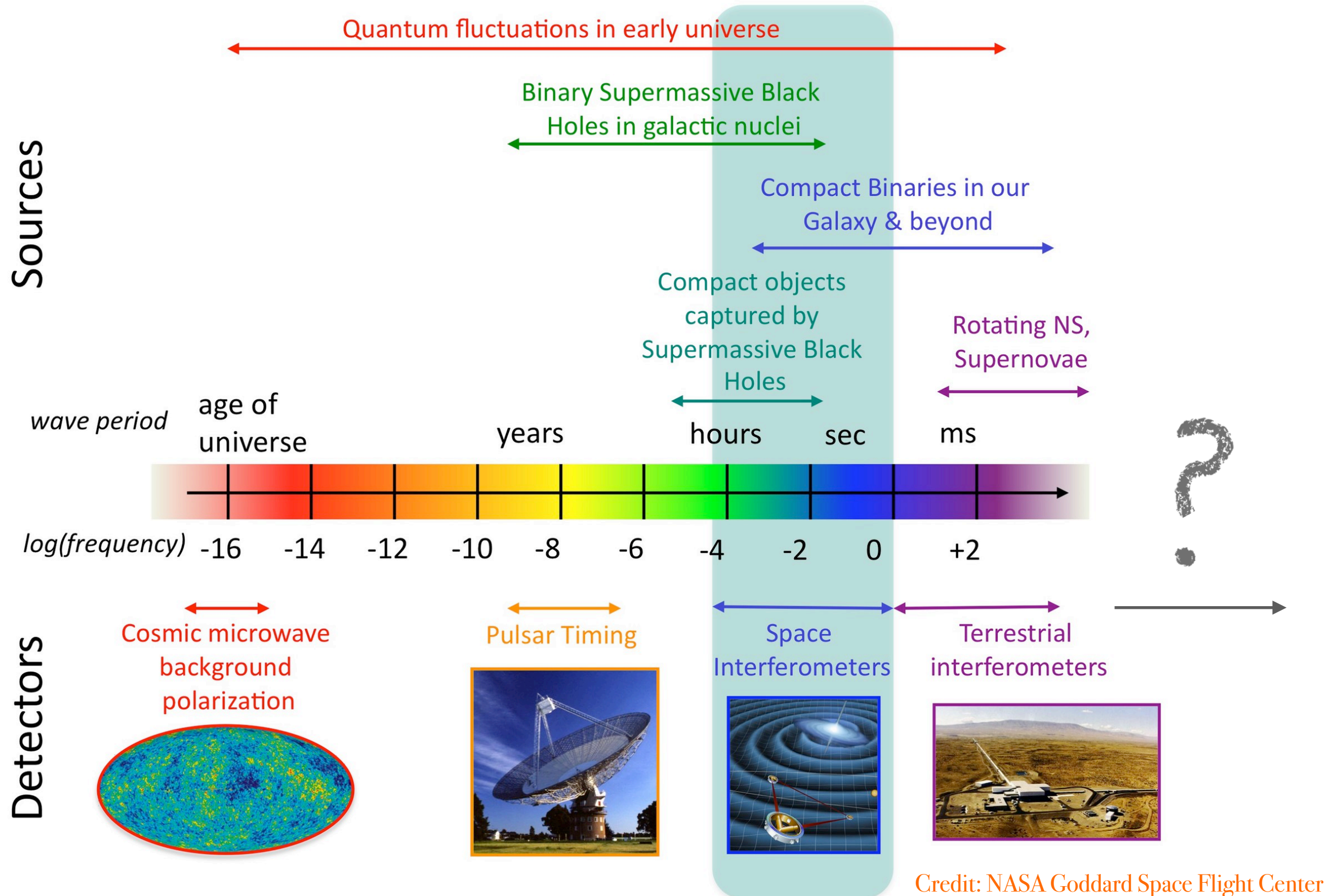
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Gravitational Wave Spectrum



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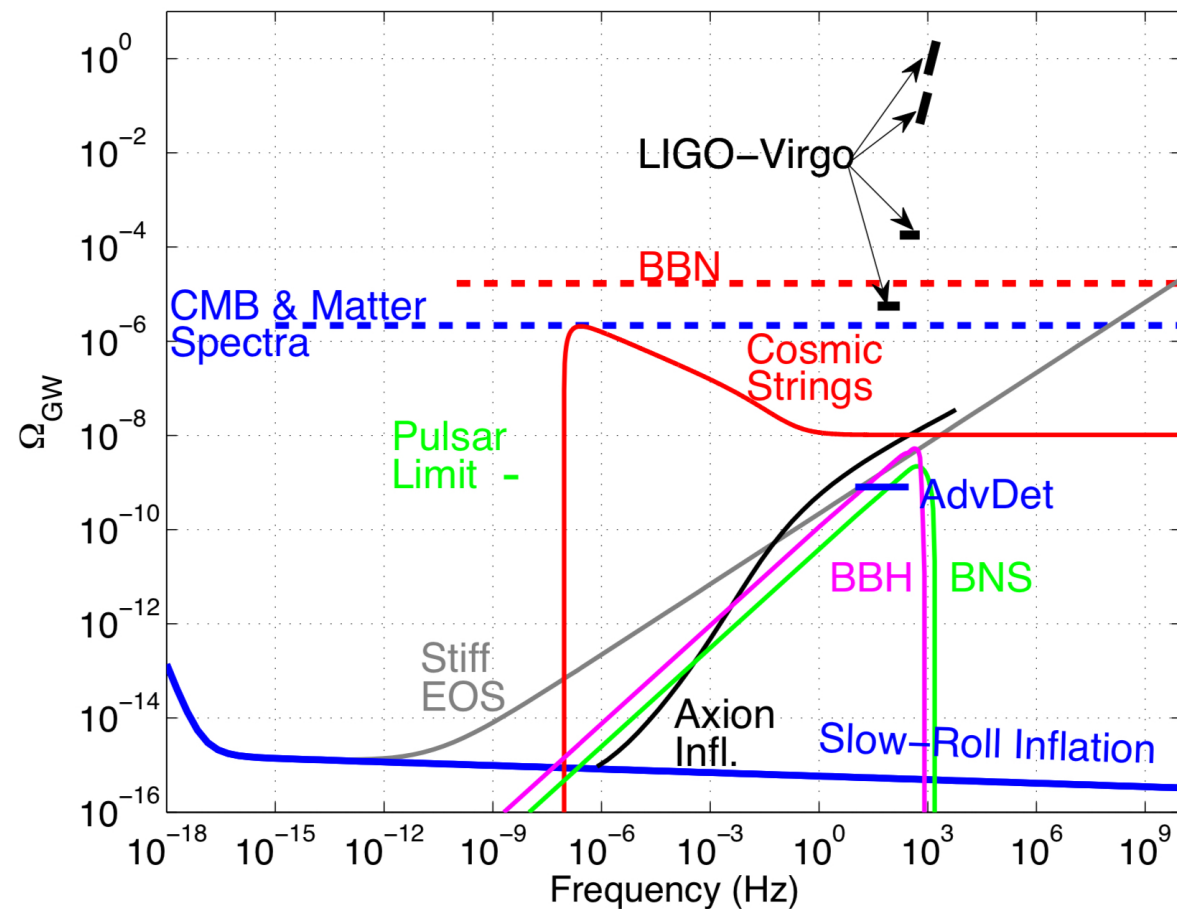


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Gravitational Wave Spectrum

what about high frequencies?

LIGO - VIRGO, 2014

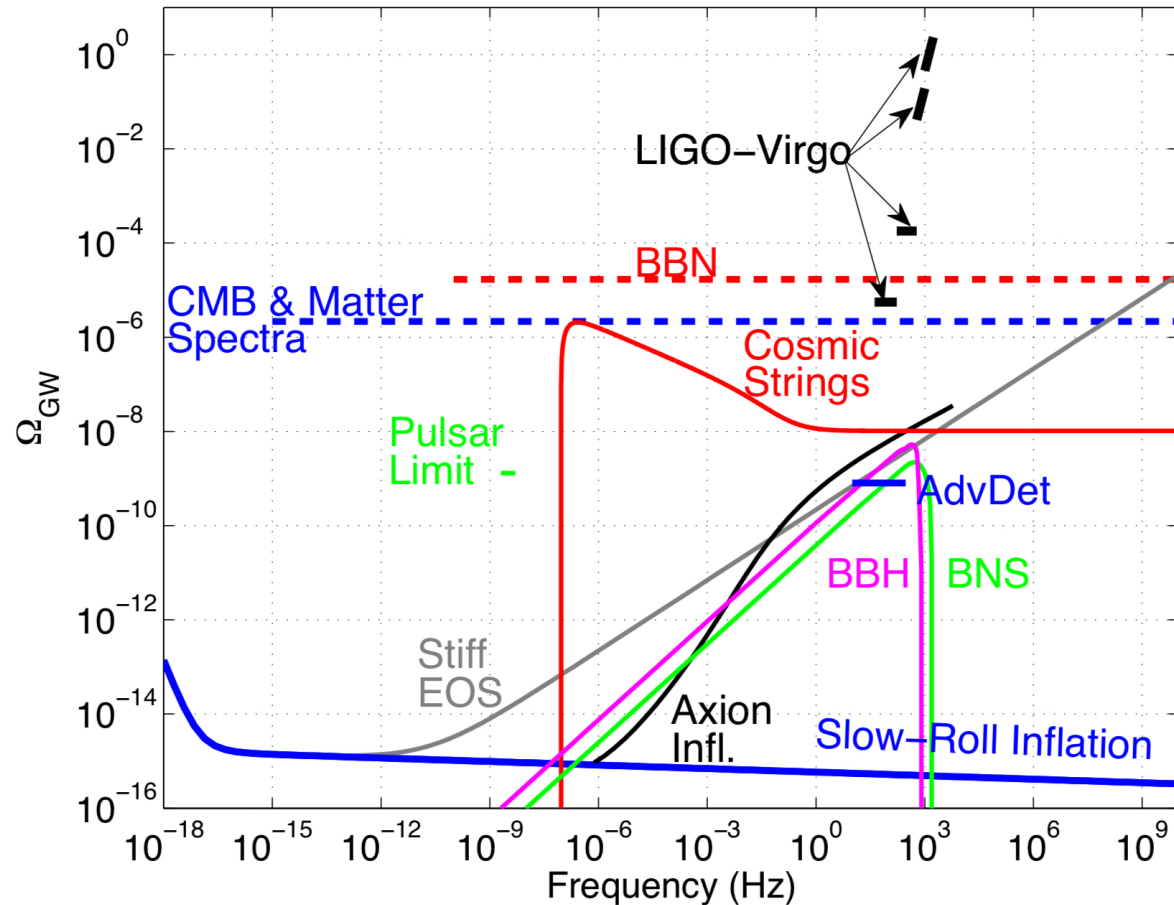


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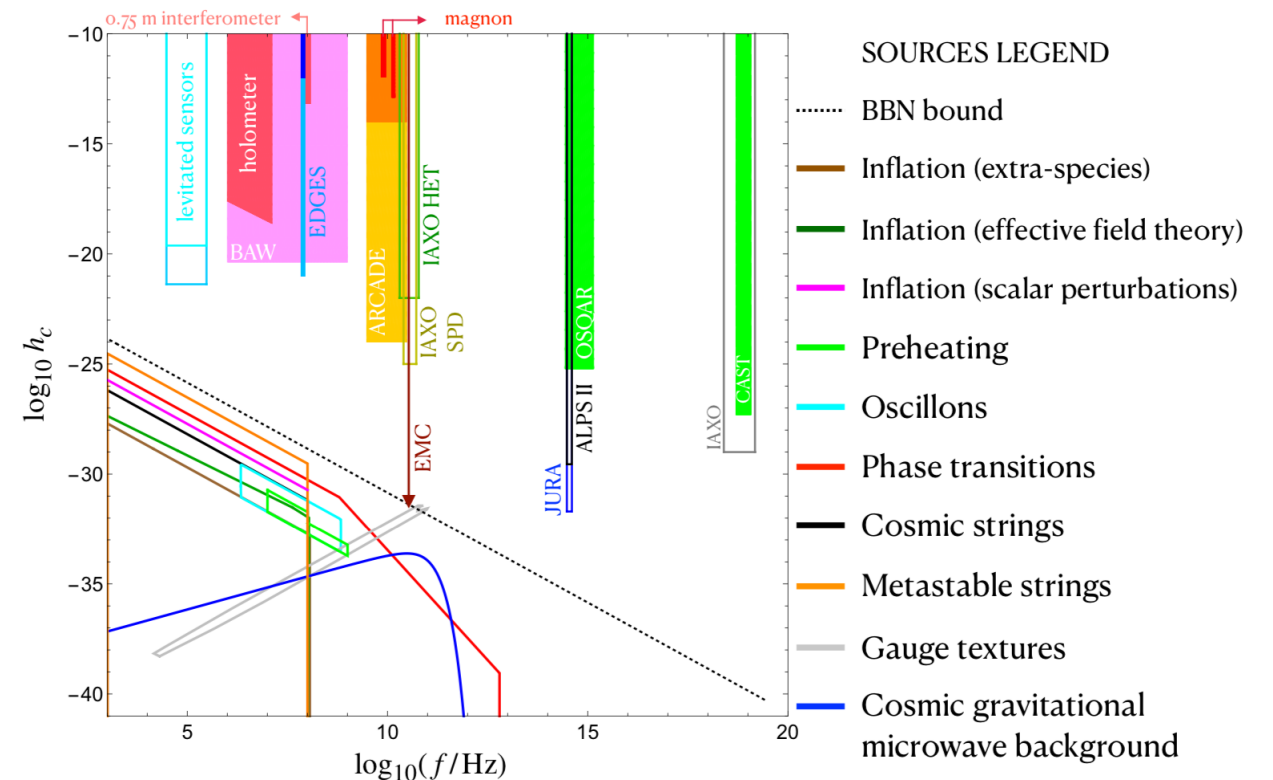
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Aggarwal et al, 2020



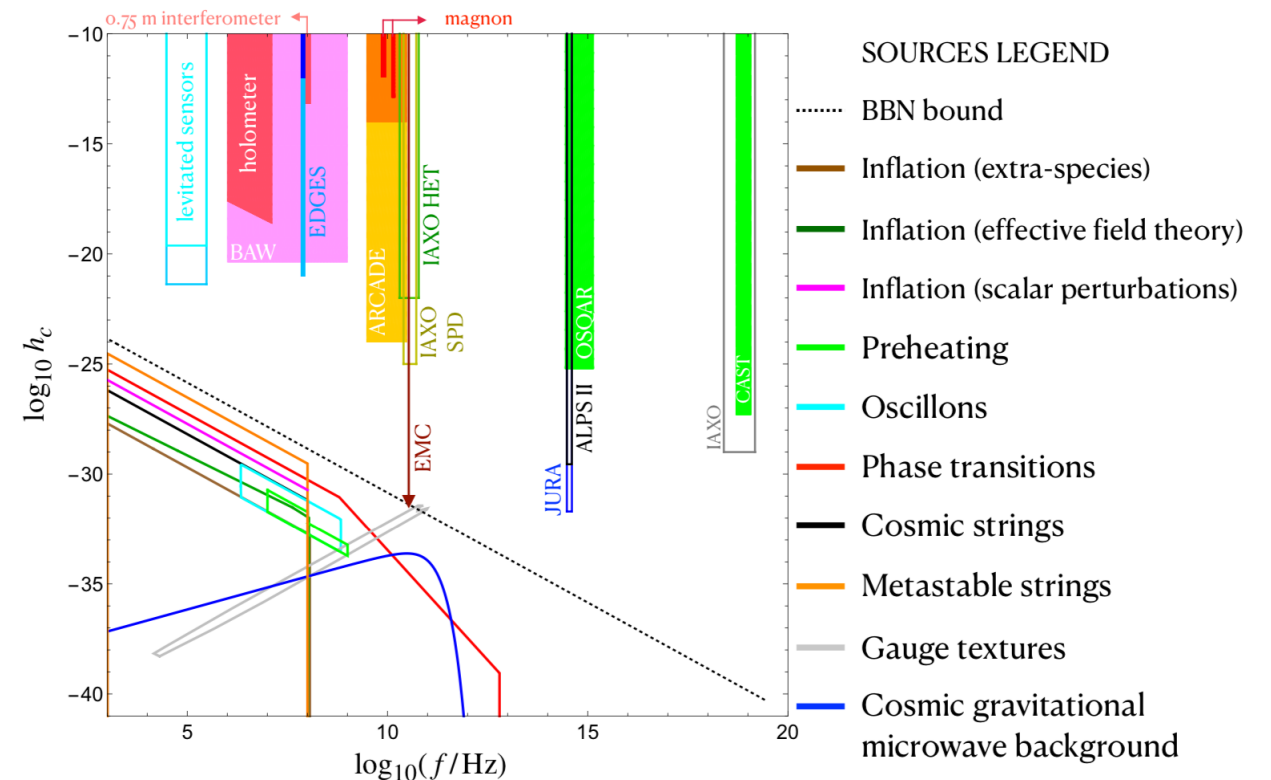
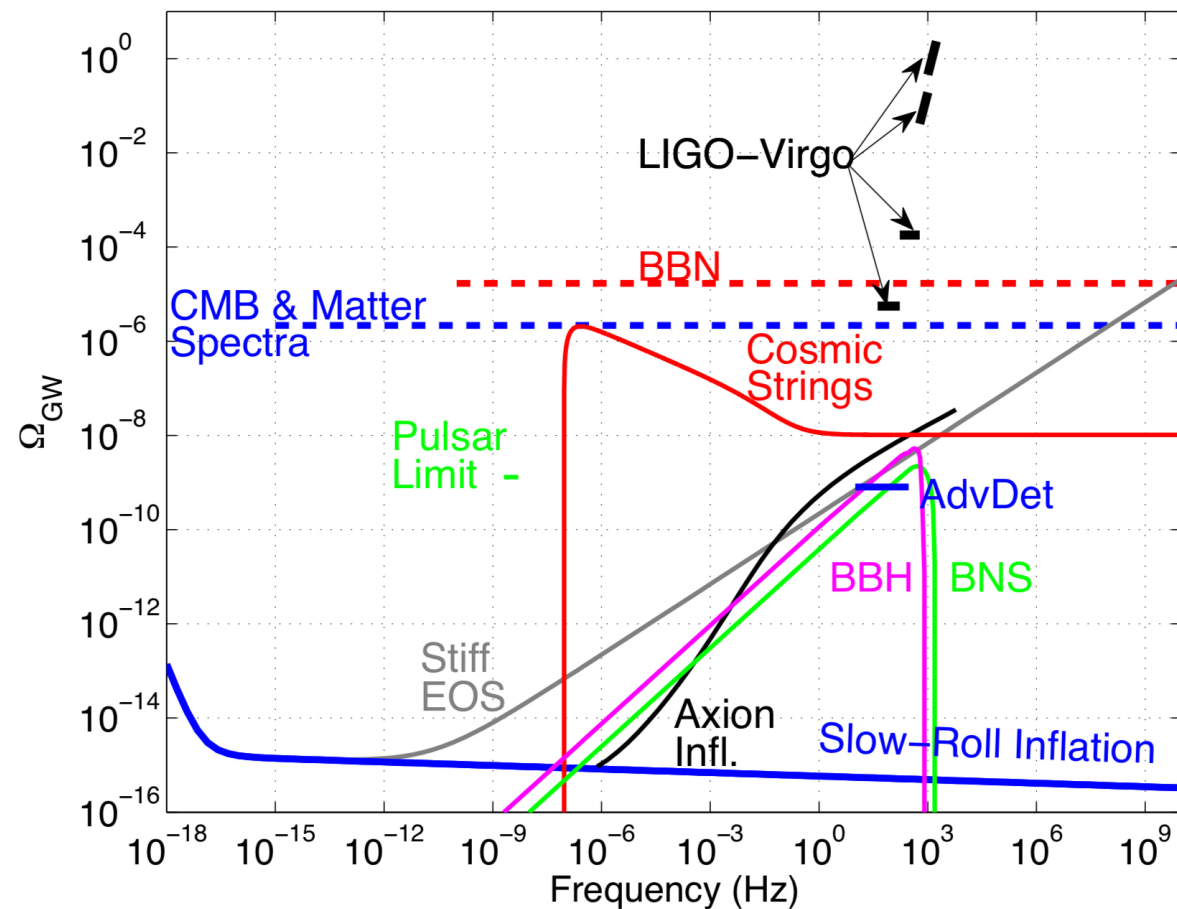
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Radio and TeV astronomy

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Revisiting Gertsenhstein's ideas

SOVIET PHYSICS JETP

VOLUME 14, NUMBER 1

JANUARY, 1962

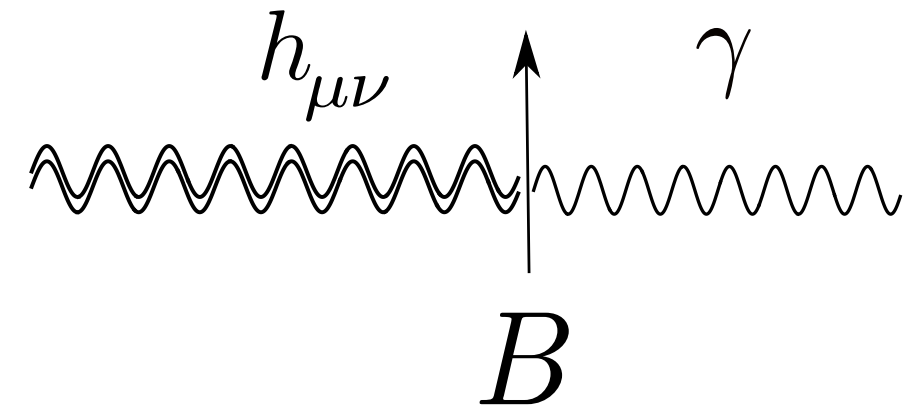
WAVE RESONANCE OF LIGHT AND GRAVITATIONAL WAVES

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.



SOVIET PHYSICS JETP

VOLUME 16, NUMBER 2

FEBRUARY, 1963

ON THE DETECTION OF LOW FREQUENCY GRAVITATIONAL WAVES

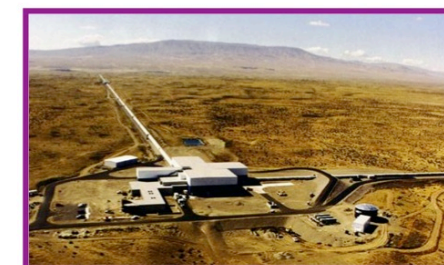
M. E. GERTSENSHTEĬN and V. I. PUSTOVOĬT

Submitted to JETP editor March 3, 1962

J. Exptl. Theoret. Phys. (U.S.S.R.) **43**, 605-607 (August, 1962)

It is shown that the sensitivity of the electromechanical experiments for detecting gravitational waves by means of piezocrystals is ten orders of magnitude worse than that estimated by Weber.^[1] In the low frequency range it should be possible to detect gravitational waves by the shift of the bands in an optical interferometer. The sensitivity of this method is investigated.

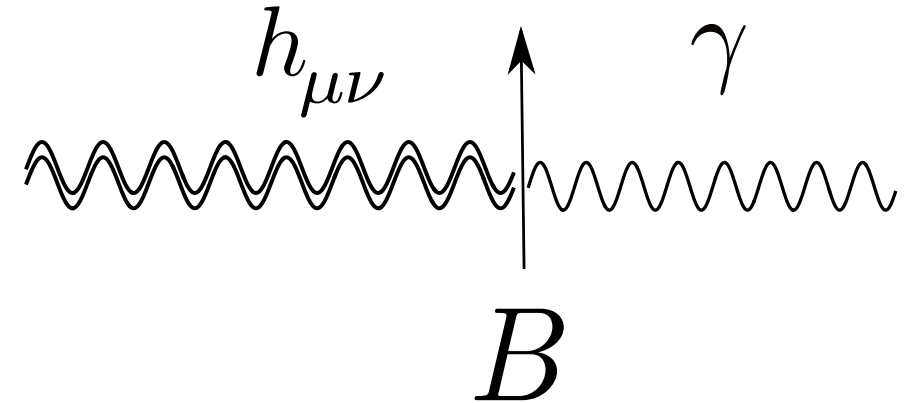
Terrestrial
interferometers



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The (inverse) Gertsenhstein Effect

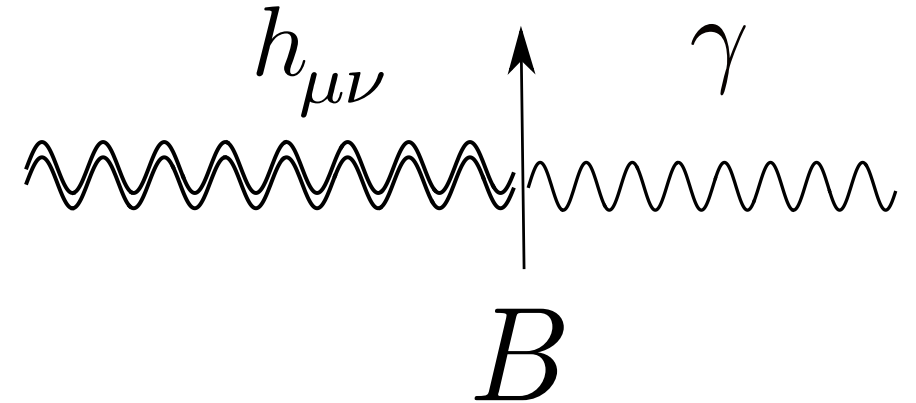
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Raffelt, Stodolski'89



Axion dark matter

- The strong CP problem: experiments put a strong upper bound on the electric dipole of the neutron

$$\mathcal{L} = \frac{g_s^2 \theta}{32\pi^2} F_{\mu\nu}^a \tilde{F}^{a\mu\nu}$$

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Peccei, Quinn 1977

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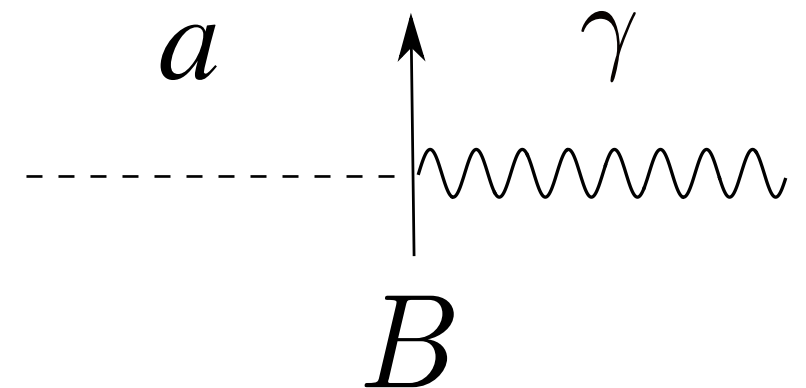
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- Excellent dark matter candidate Weinberg, Wilczek 1978

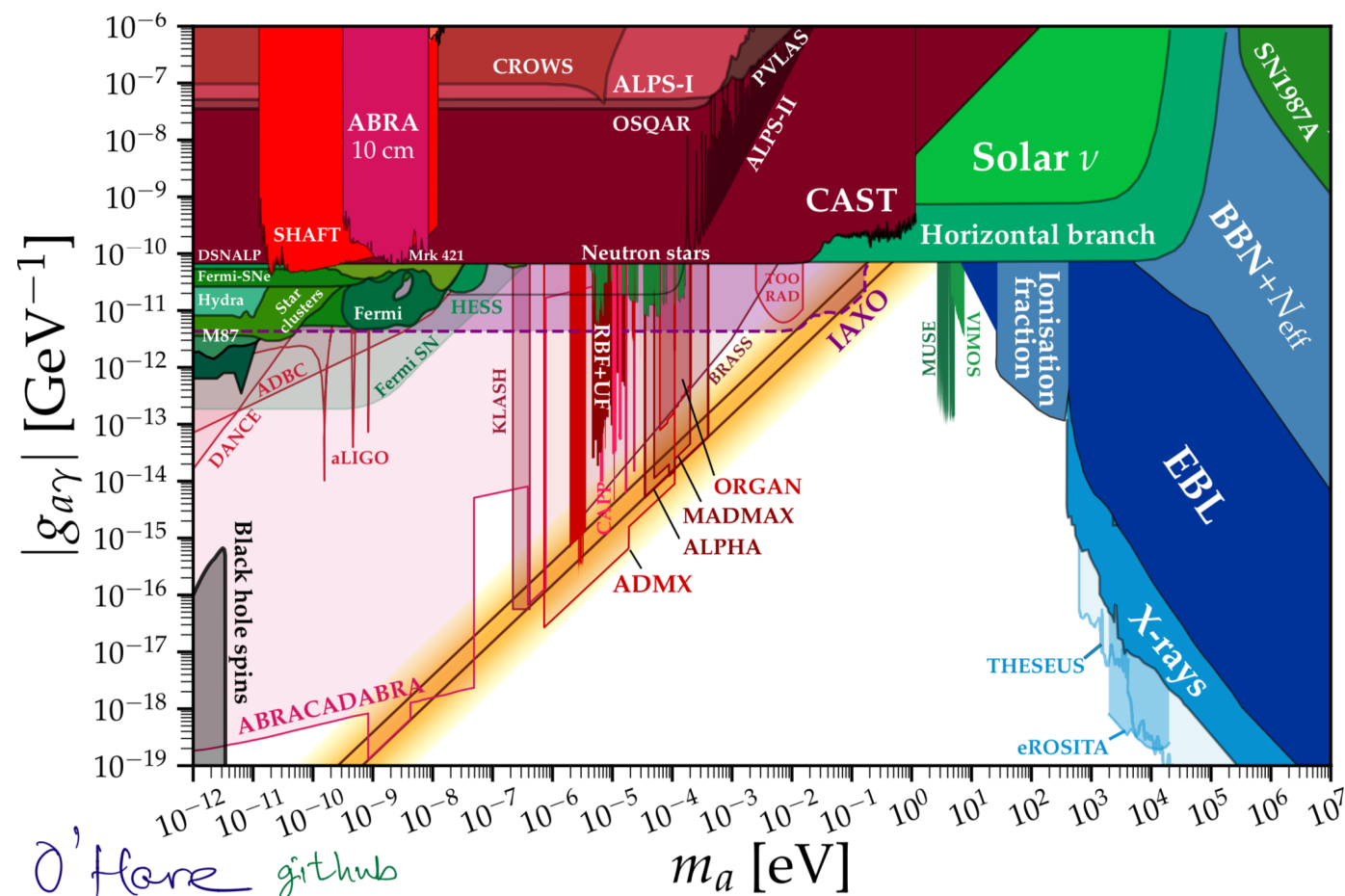
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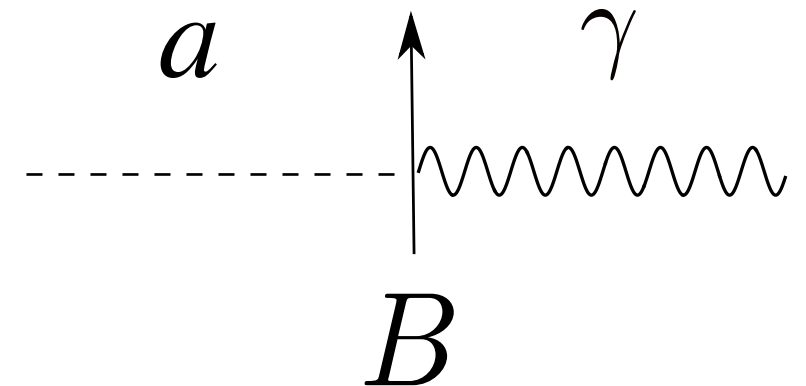


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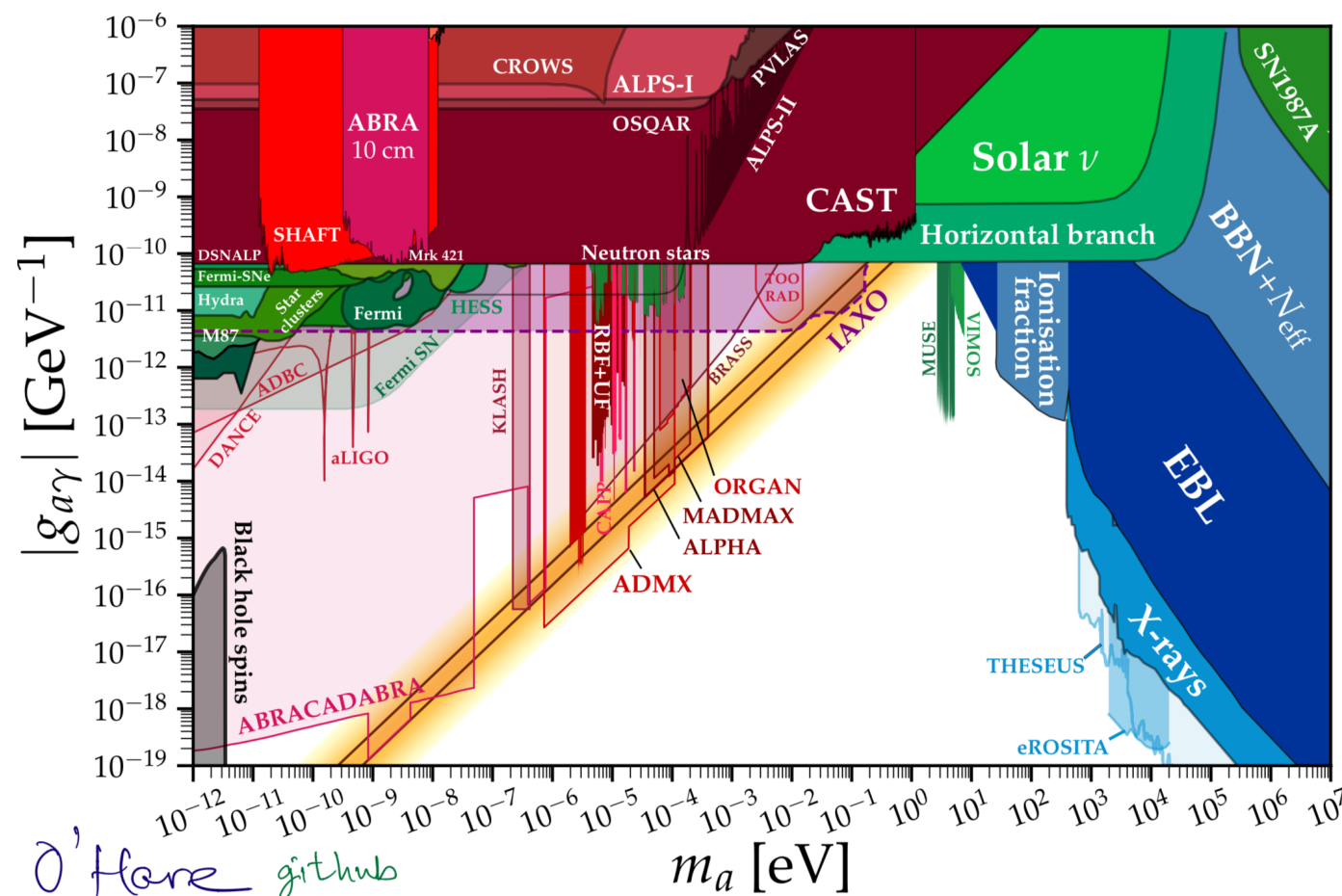
Ideas and techniques developed for axions can be adapted to gravitational waves

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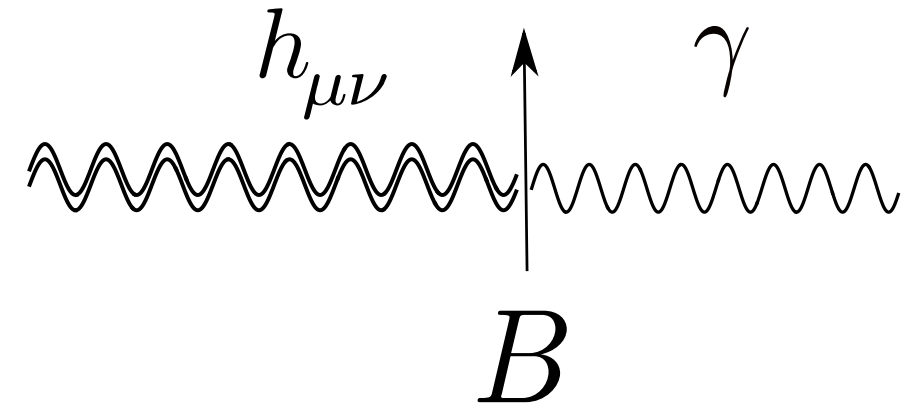
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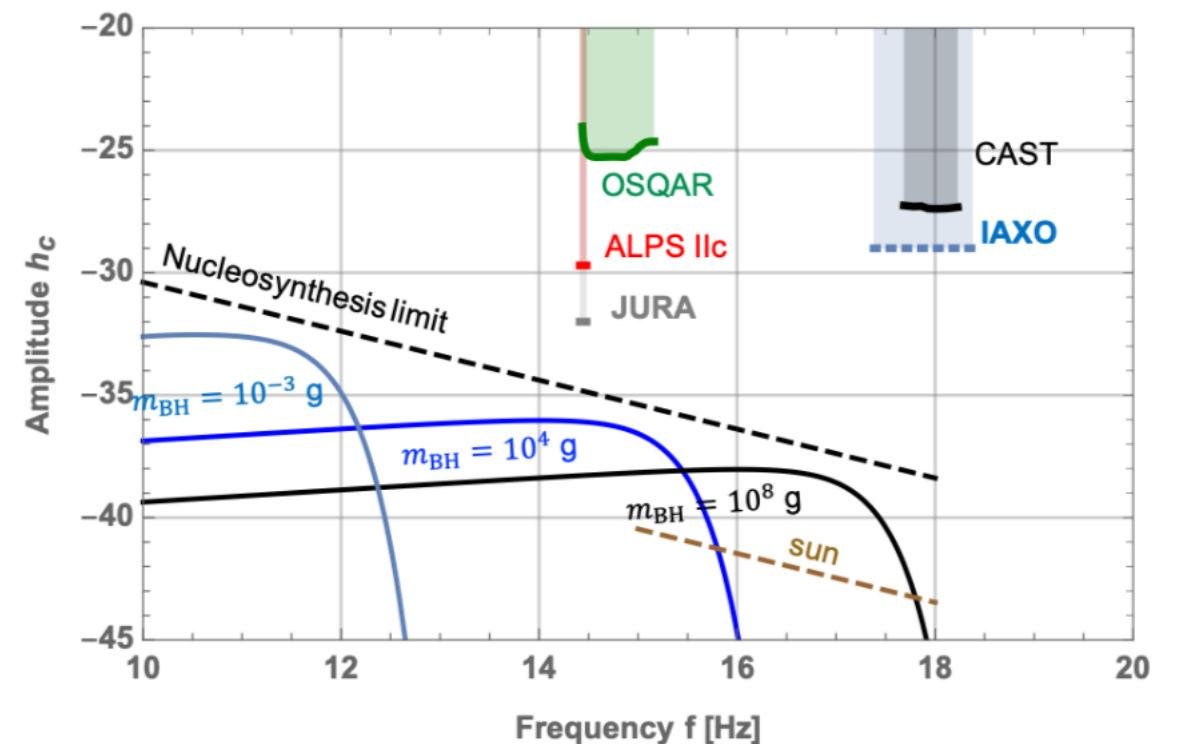
Raffelt, Stodolski'89



Upper limits on the amplitude of ultra-high-frequency gravitational waves from graviton to photon conversion

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

The European Physical Journal C **79**, Article number: 1032 (2019) | [Cite this article](#)

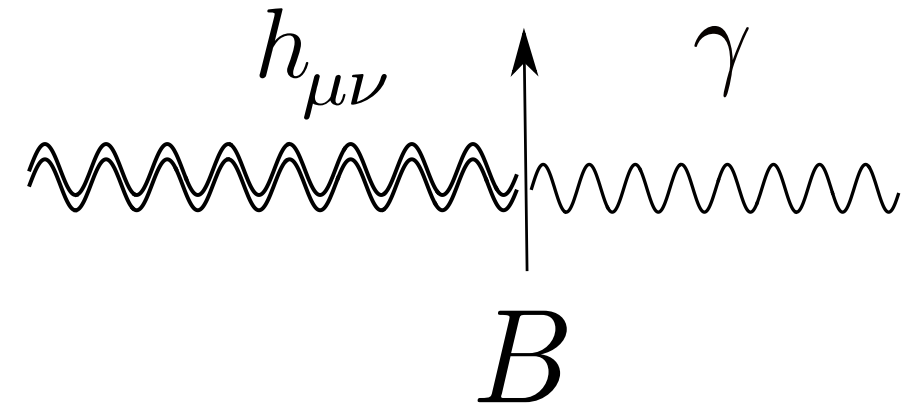


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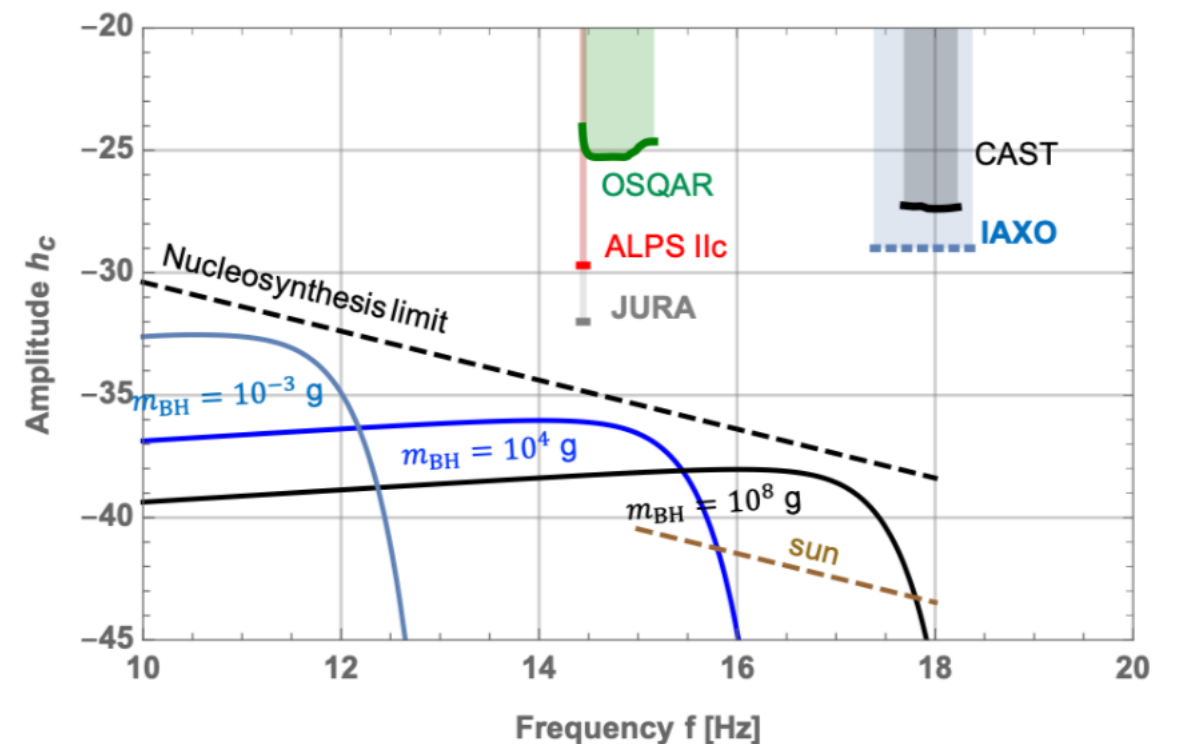
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- Distortions of the CMB



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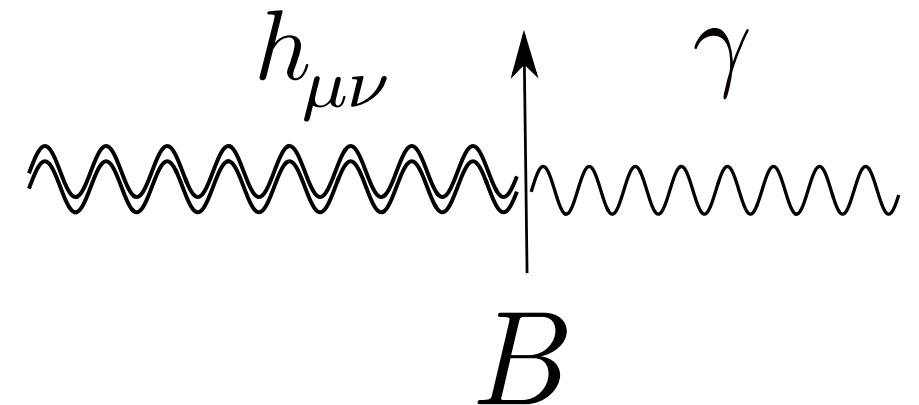
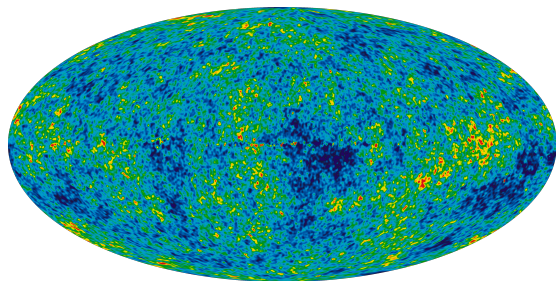
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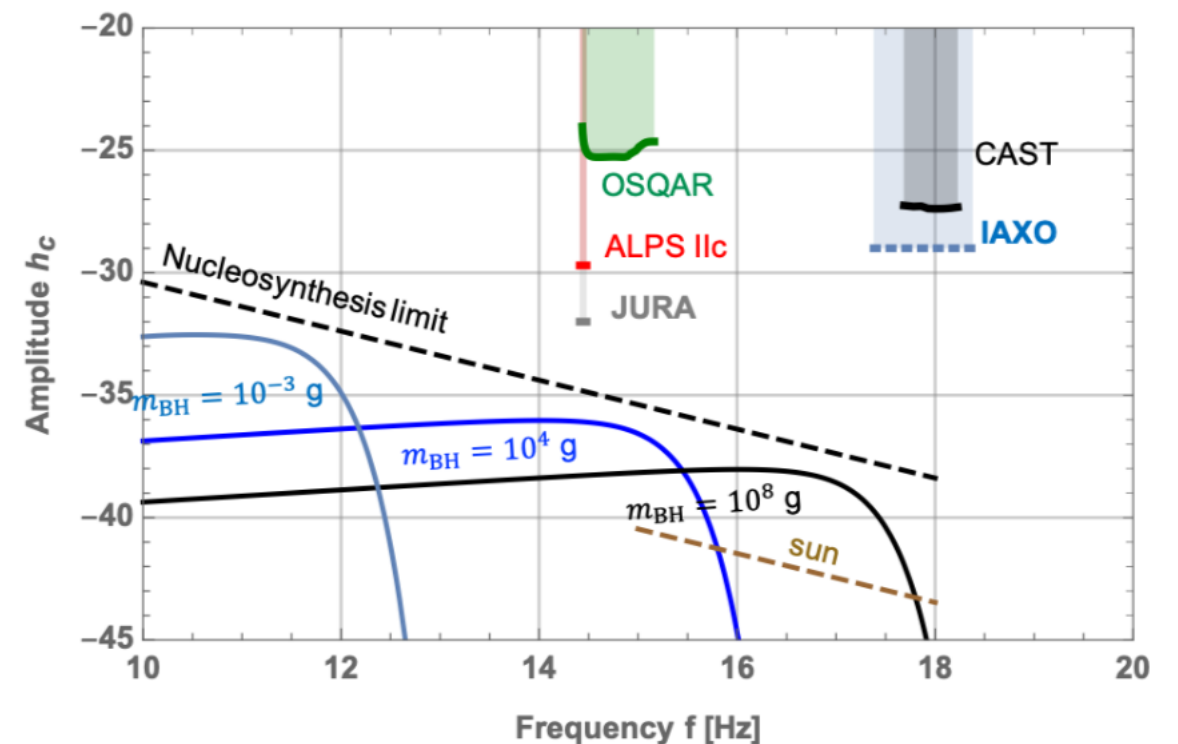
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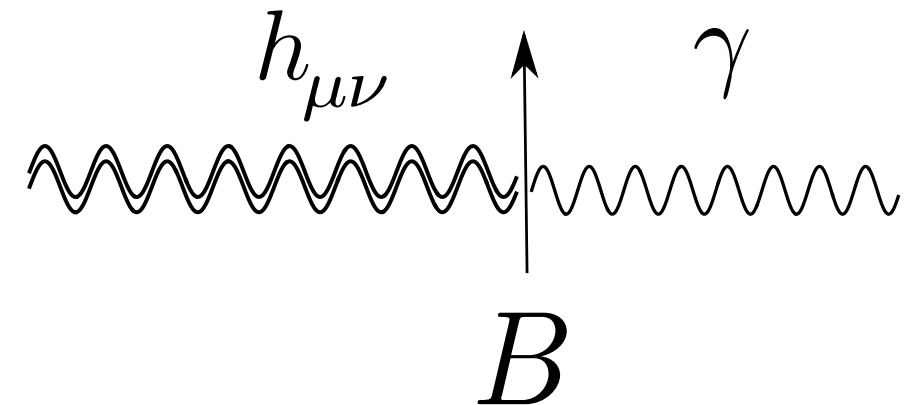
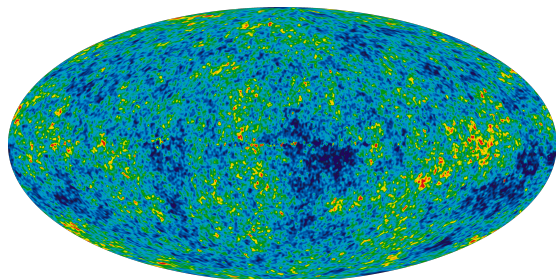
- Distortions of the CMB

Domecke, CGC 2021

Dolgov, Ejlli 2012

Pshirkov, Baskaran 2009

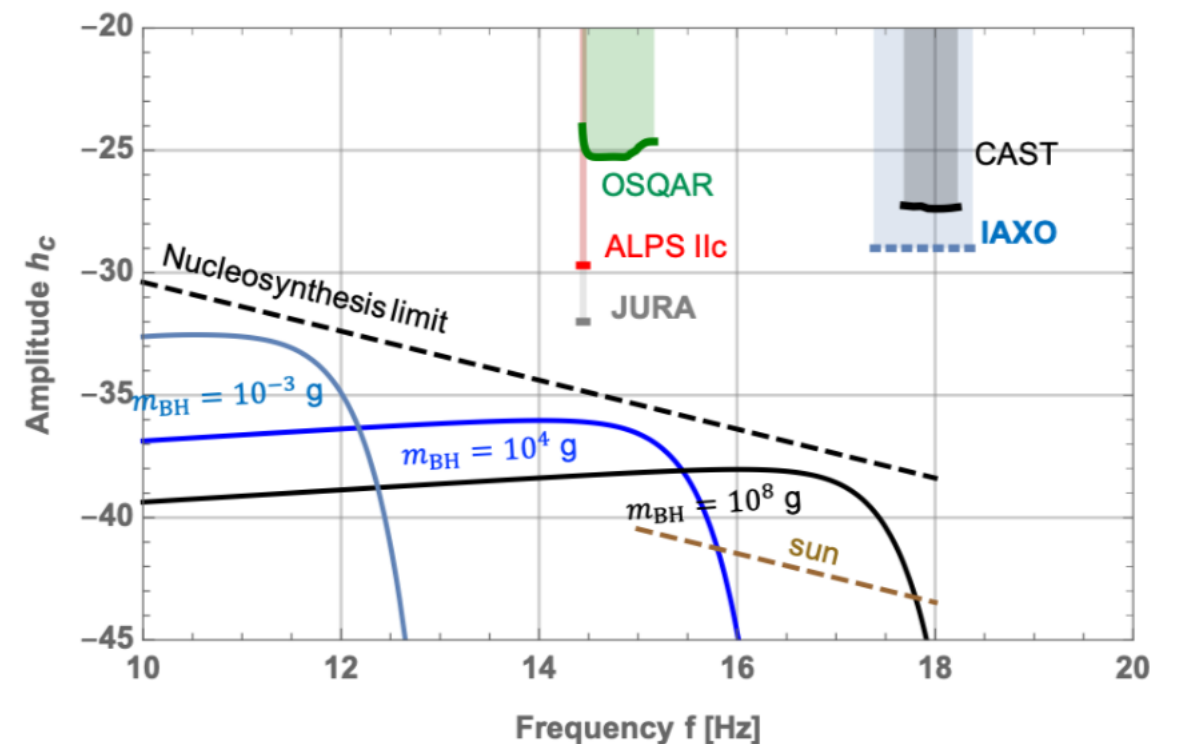
Chen 1995



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Cosmic magnetic fields and multi-messenger astronomy

Cosmic magnetic fields

Durrer, Neronov, 2013

$$\langle \mathbf{B}_i(\mathbf{x}) \mathbf{B}_j(\mathbf{x}') \rangle = \frac{1}{(2\pi)^3 a(t)^4} \int d^3k e^{i\mathbf{k} \cdot (\mathbf{x}' - \mathbf{x})} \left(\left(\delta_{ij} - \hat{k}_i \hat{k}_j \right) P_B(k) - i \epsilon_{ijk} \hat{k}_k P_{aB}(k) \right) ,$$

The adiabatic evolution of the magnetic field due to cosmic expansion is determined by the scale factor.

Cosmic magnetic fields

Durrer, Neronov, 2013

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The adiabatic evolution of the magnetic field due to cosmic expansion is determined by the scale factor.

$$\langle B^2 \rangle = \frac{1}{\pi^2 a(t)^4} \int_0^\infty dk k^2 P_B(k) = \int_{-\infty}^\infty d \log \lambda B_\lambda^2$$

average magnetic field

$$\text{where } B_\lambda^2 \equiv \frac{8\pi}{\lambda^3 a(t)^4} P_B \left(\frac{2\pi}{\lambda} \right),$$

$$\lambda_B = \int_0^\infty d\lambda \frac{B_\lambda^2}{\langle B^2 \rangle}$$

the coherence length

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Cosmic magnetic fields in 2021

PHYSICAL REVIEW LETTERS **123**, 021301 (2019)

Stringent Limit on Primordial Magnetic Fields from the Cosmic Microwave Background Radiation

Karsten Jedamzik^{1,*} and Andrey Saveliev^{2,3,†}

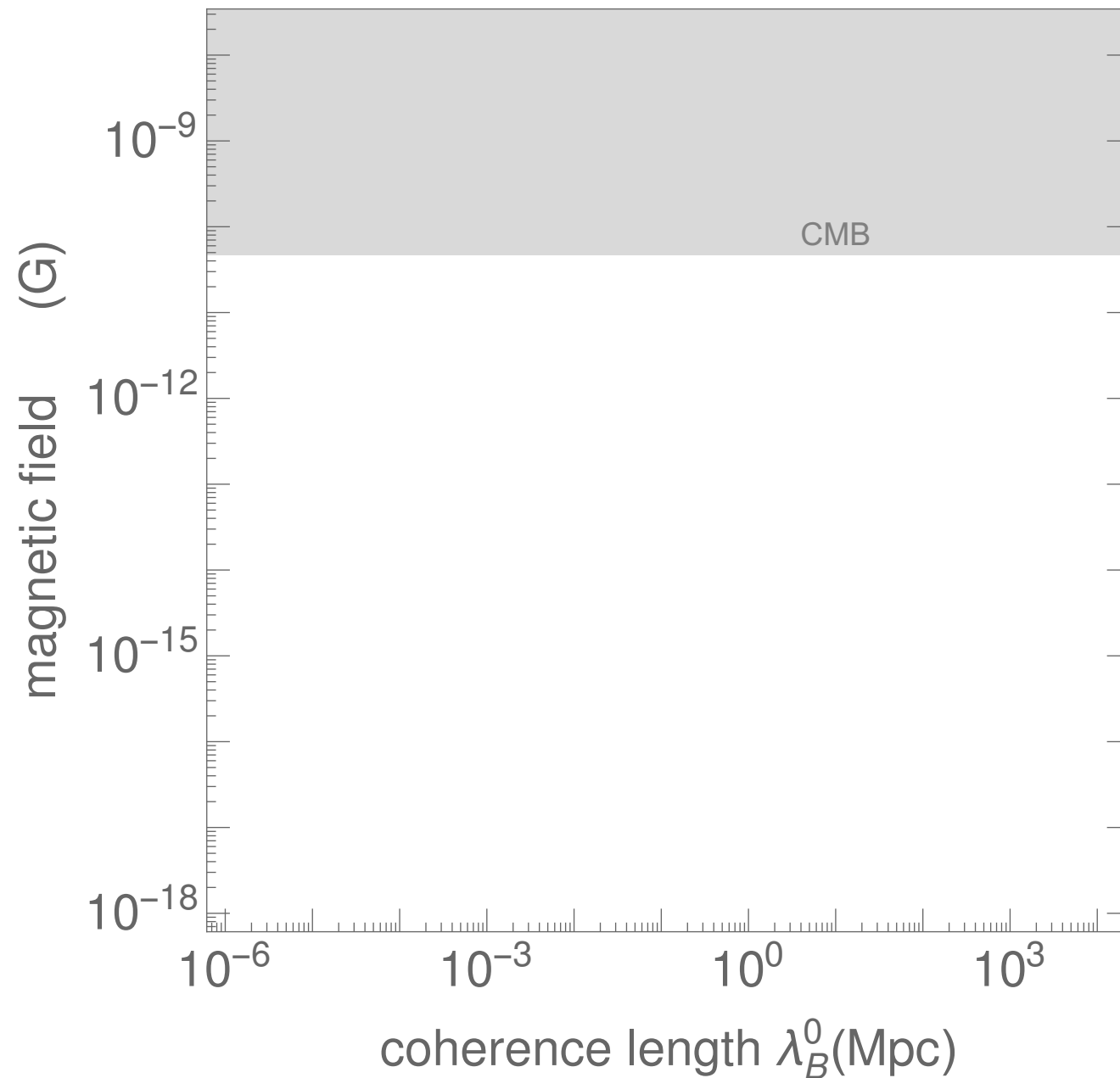
¹*Laboratoire Univers et Particules de Montpellier, UMR5299-CNRS, Université de Montpellier, 34095 Montpellier, France*

²*Institute of Physics, Mathematics and Information Technology, Immanuel Kant Baltic Federal University, 236016 Kaliningrad, Russia*

³*Faculty of Computational Mathematics and Cybernetics, Lomonosov Moscow State University, 119991 Moscow, Russia*

 (Received 8 May 2018; revised manuscript received 13 September 2018; published 10 July 2019)

Primordial magnetic fields (PMFs), being present before the epoch of cosmic recombination, induce small-scale baryonic density fluctuations. These inhomogeneities lead to an inhomogeneous recombination process that alters the peaks and heights of the large-scale anisotropies of the cosmic microwave background (CMB) radiation. Utilizing numerical compressible MHD calculations and a Monte Carlo Markov chain analysis, which compares calculated CMB anisotropies with those observed by the *WMAP* and *Planck* satellites, we derive limits on the magnitude of putative PMFs. We find that the *total remaining* present day field, integrated over all scales, cannot exceed 47 pG for scale-invariant PMFs and 8.9 pG for PMFs with a violet Batchelor spectrum at 95% confidence level. These limits are more than one order of magnitude more stringent than any prior stated limits on PMFs from the CMB, which have not accounted for this effect.



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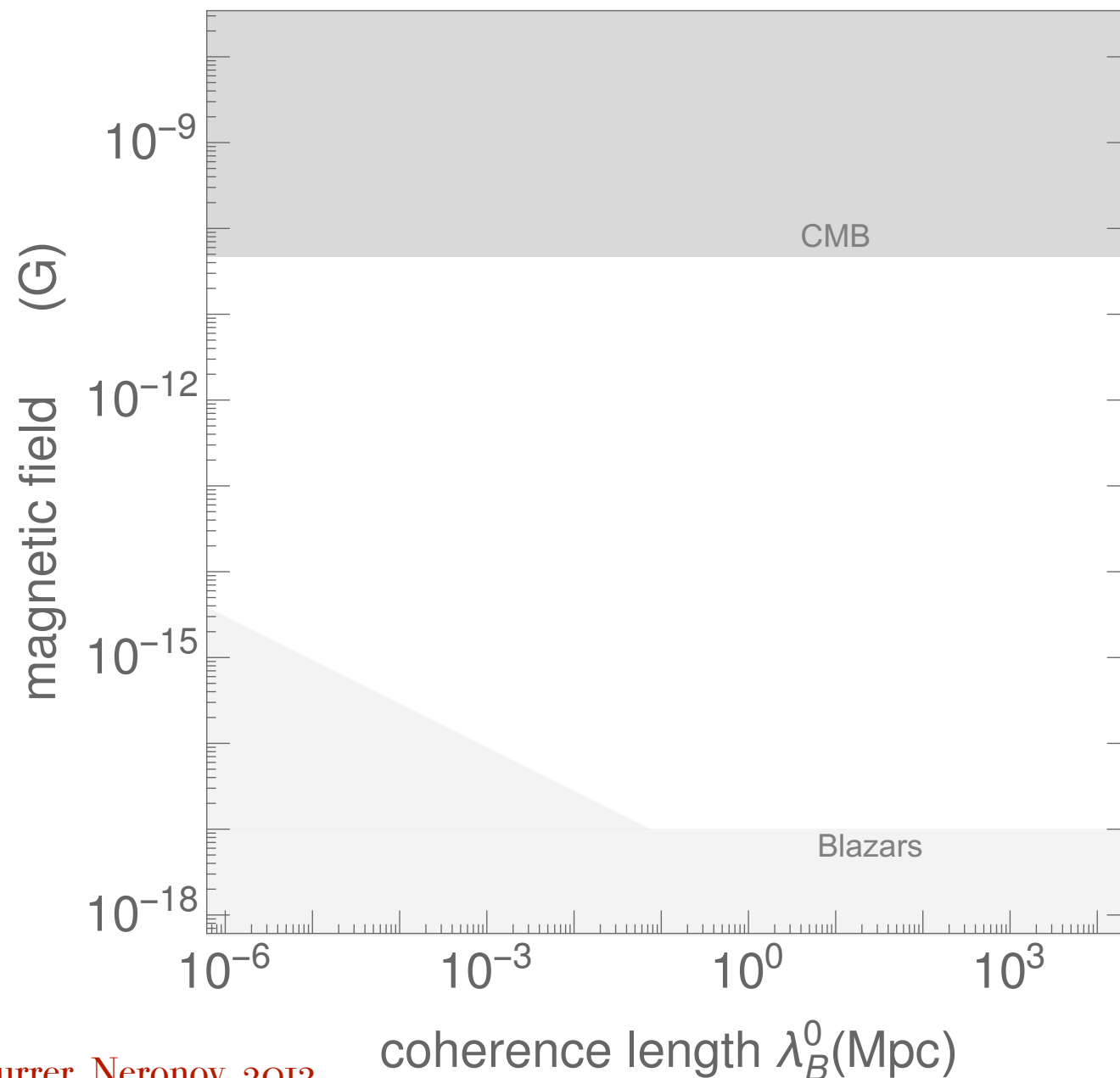
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Durrer, Neronov, 2013

Science

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Evidence for Strong Extragalactic Magnetic Fields from Fermi Observations of TeV Blazars

Andrii Neronov*, Ievgen Vovk

✚ See all authors and affiliations

Science 02 Apr 2010:
Vol. 328, Issue 5974, pp. 73-75
DOI: 10.1126/science.1184192

Article

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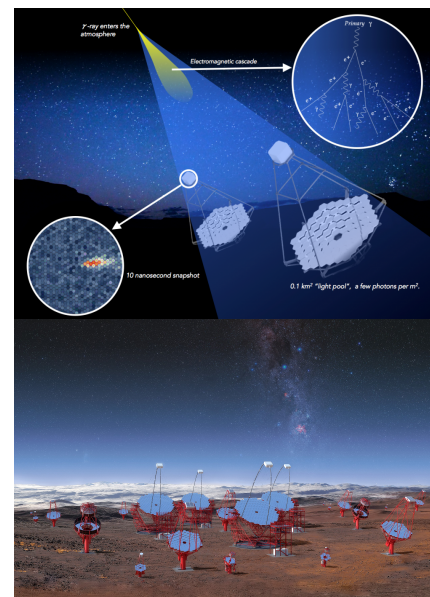
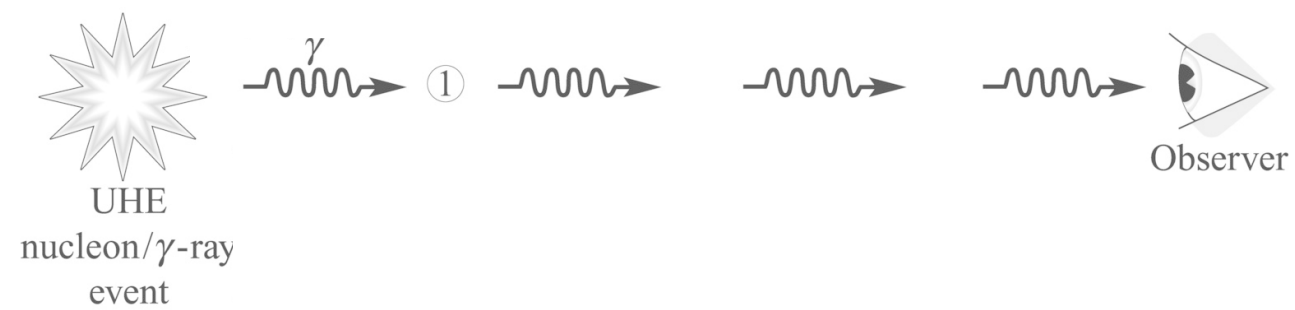
Abstract

Magnetic fields in galaxies are produced via the amplification of seed magnetic fields of unknown nature. The seed fields, which might exist in their initial form in the intergalactic medium, were never detected. We report a lower bound $B \geq 3 \times 10^{-16}$ gauss on the strength of intergalactic magnetic fields, which stems from the nonobservation of GeV gamma-ray emission from electromagnetic cascade initiated by tera-electron volt gamma rays in intergalactic medium. The bound improves as $\lambda_B^{-1/2}$ if magnetic field correlation length, λ_B , is much smaller than a megaparsec. This lower bound constrains models for the origin of cosmic magnetic fields.

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Evidence from TeV Blazars

Kronberg, 2016
Cambridge University Press

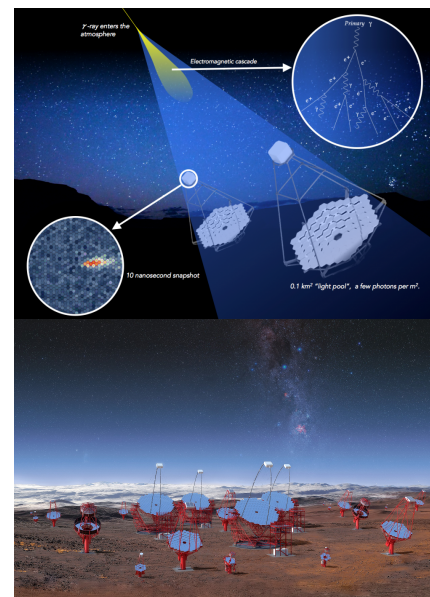
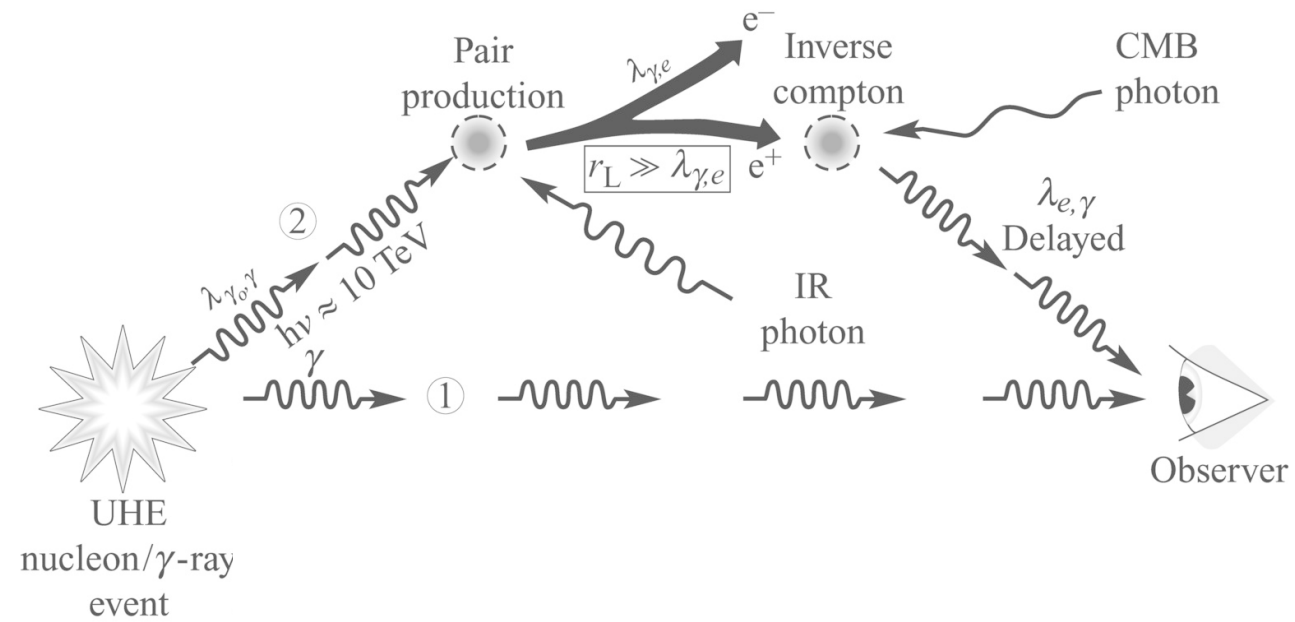


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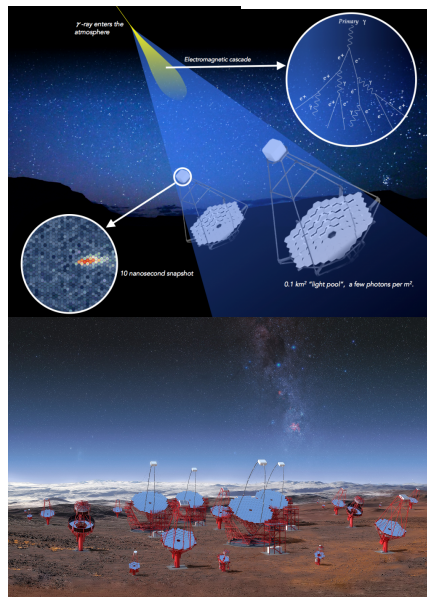
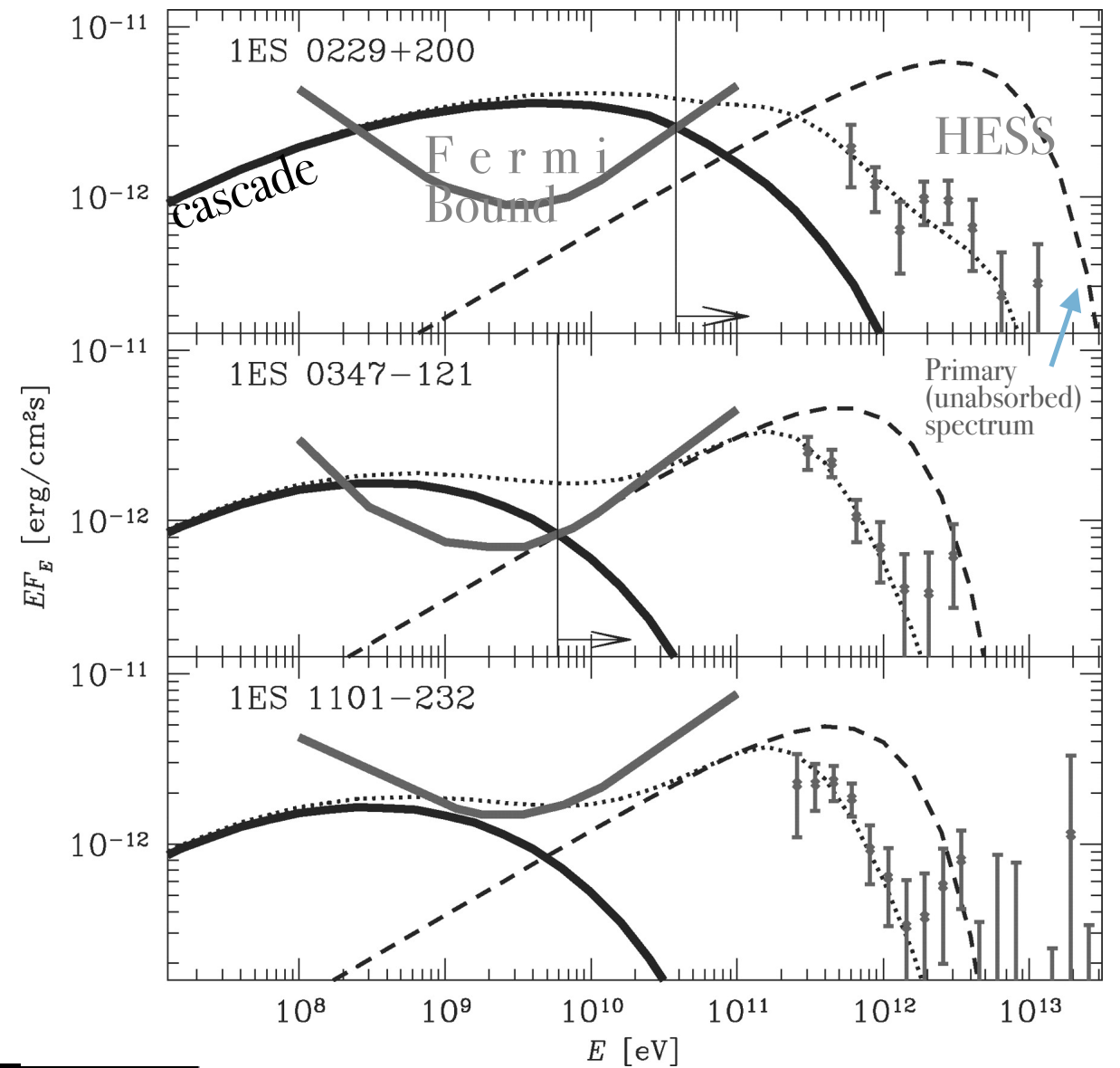
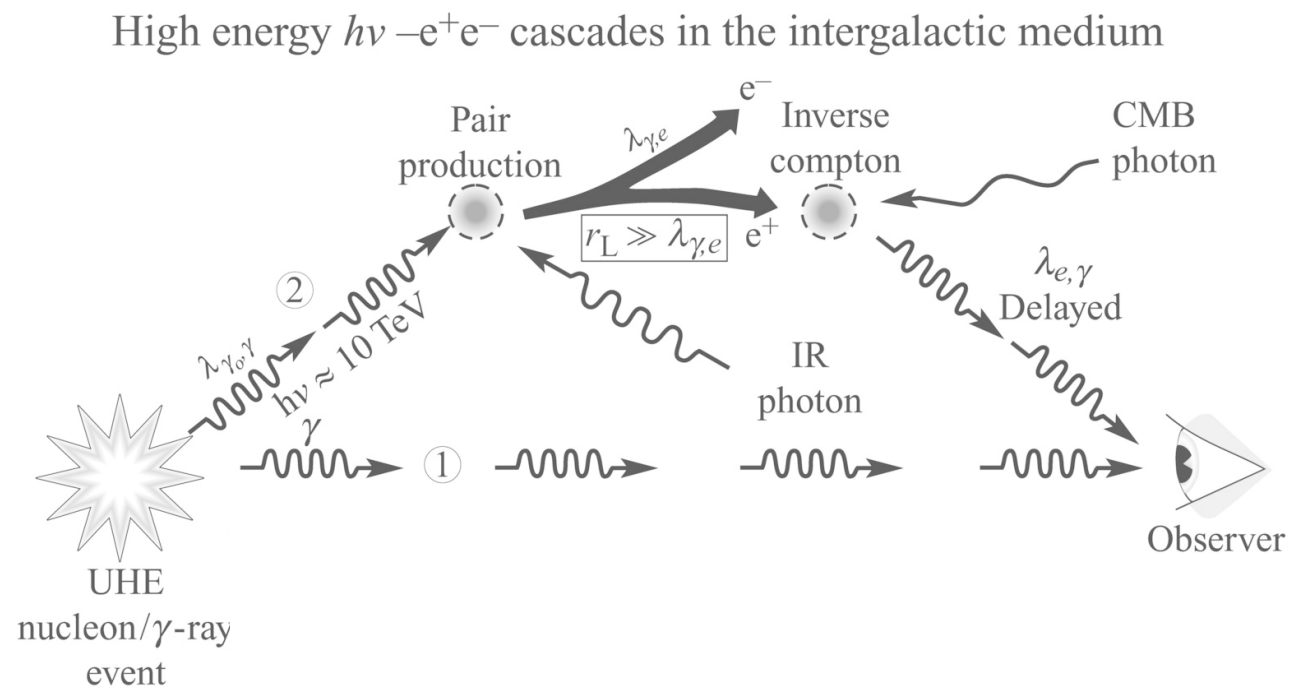
High energy $h\nu \rightarrow e^+e^-$ cascades in the intergalactic medium



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Evidence from TeV Blazars

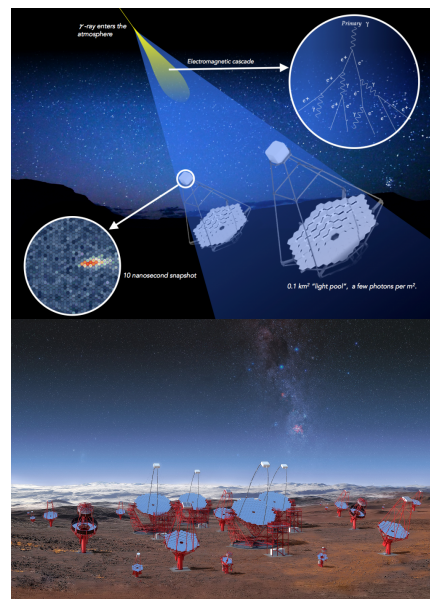
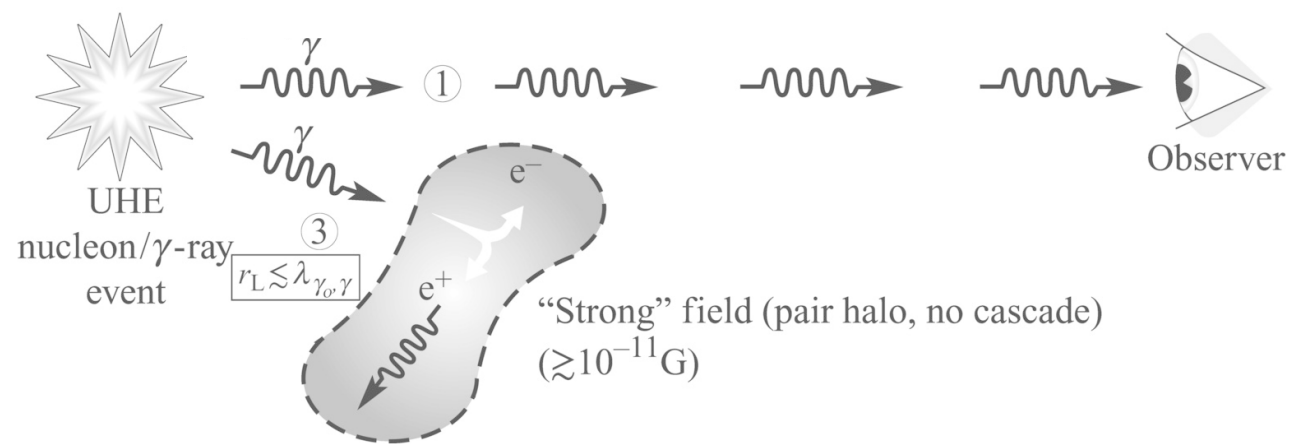
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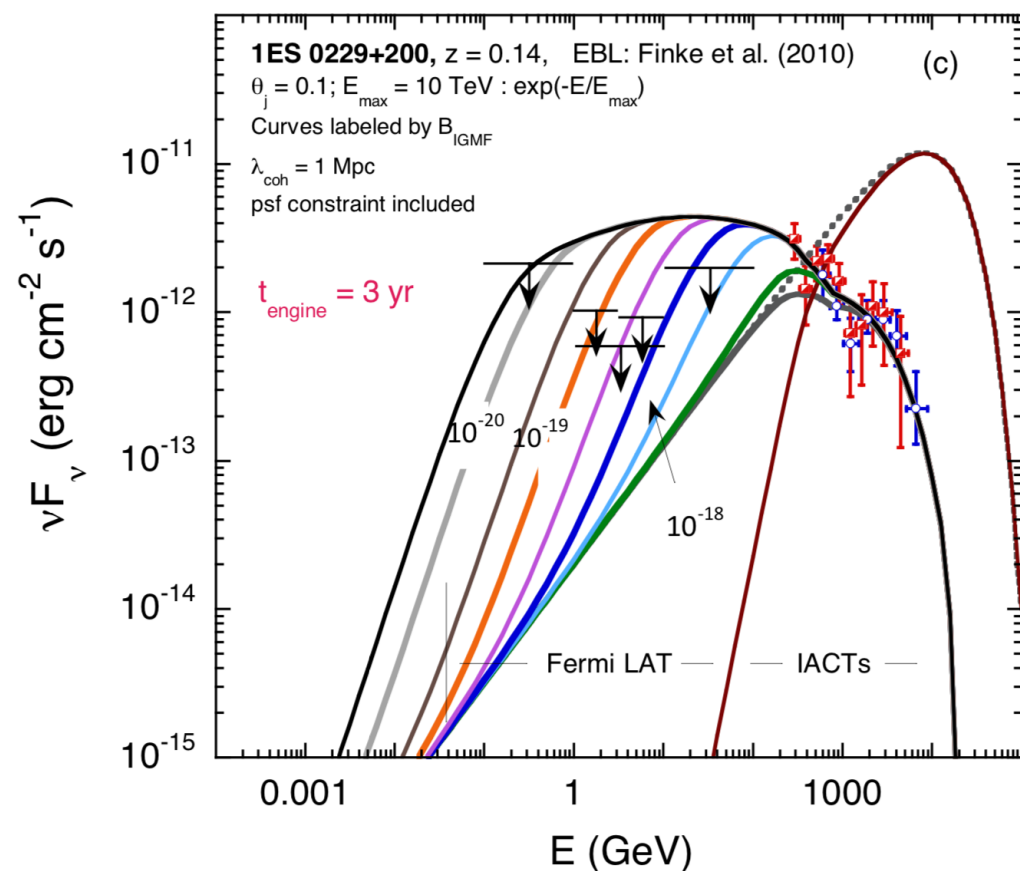
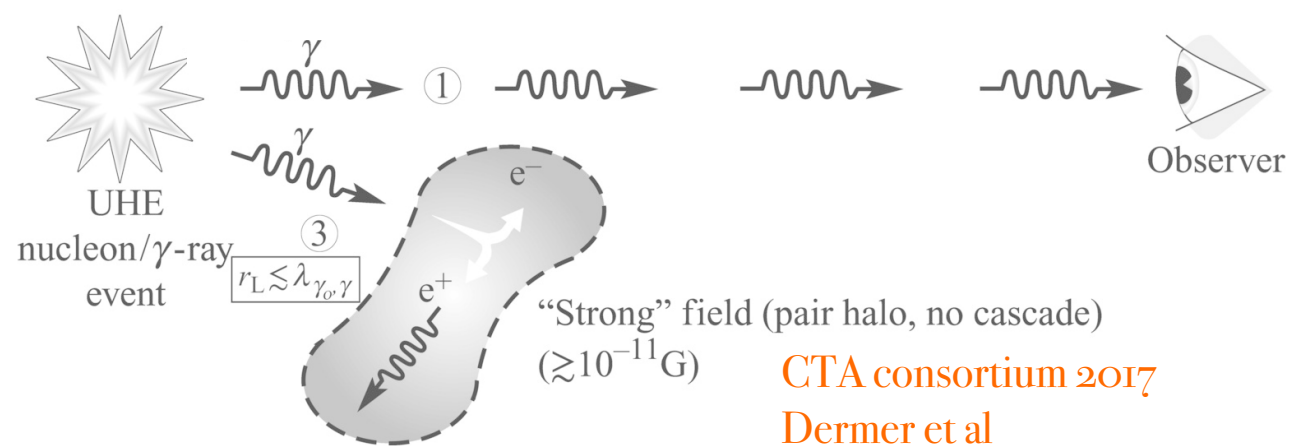
Kronberg, 2016
Cambridge University Press



Camilo A. Garcia Cely

Evidence from TeV Blazars

Kronberg, 2016
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Andrii Neronov*, Ievgen Vovk
*See all authors and affiliations

Science 02 Apr 2010:
Vol. 328, Issue 5974, pp. 73-75
DOI: 10.1126/science.1184192

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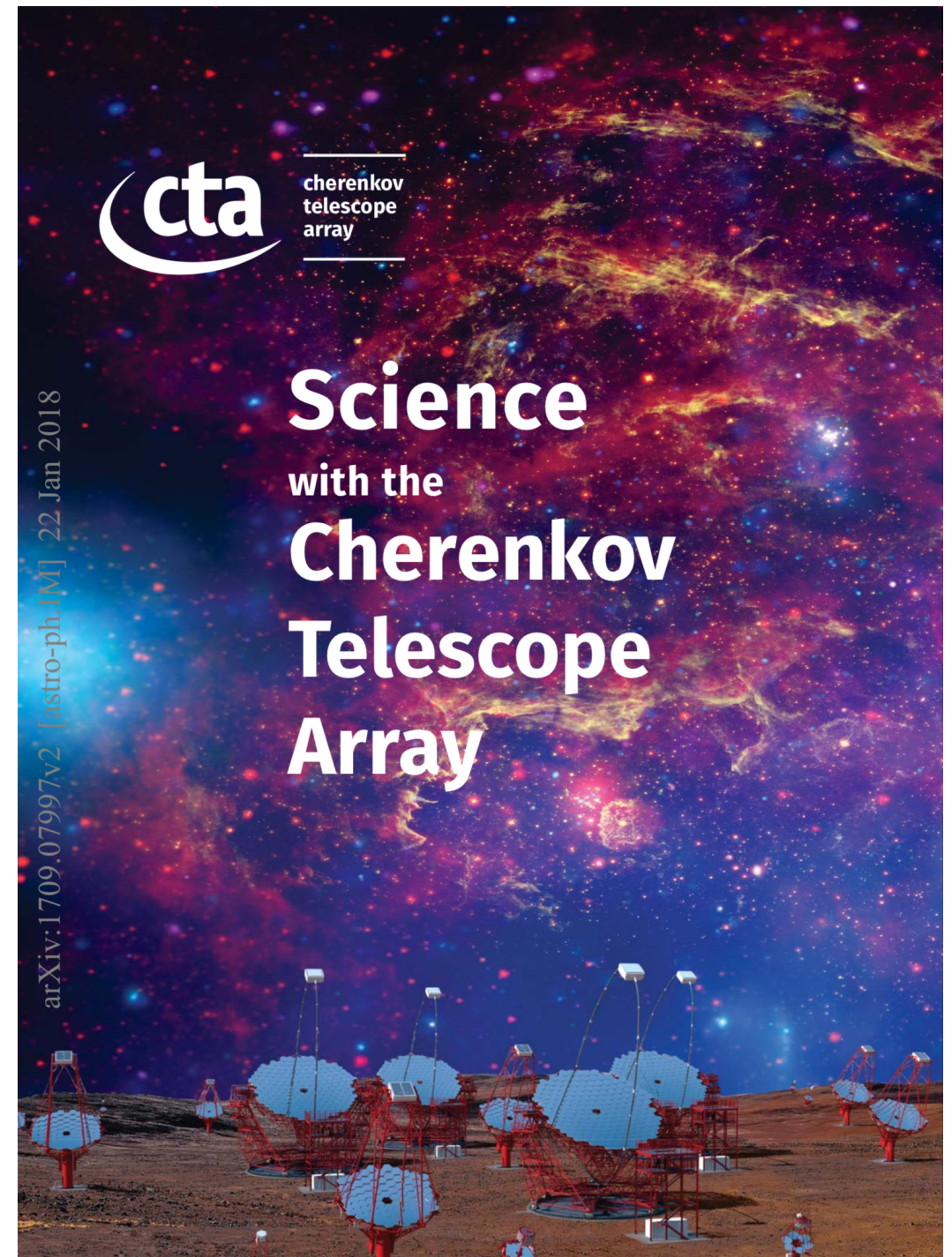
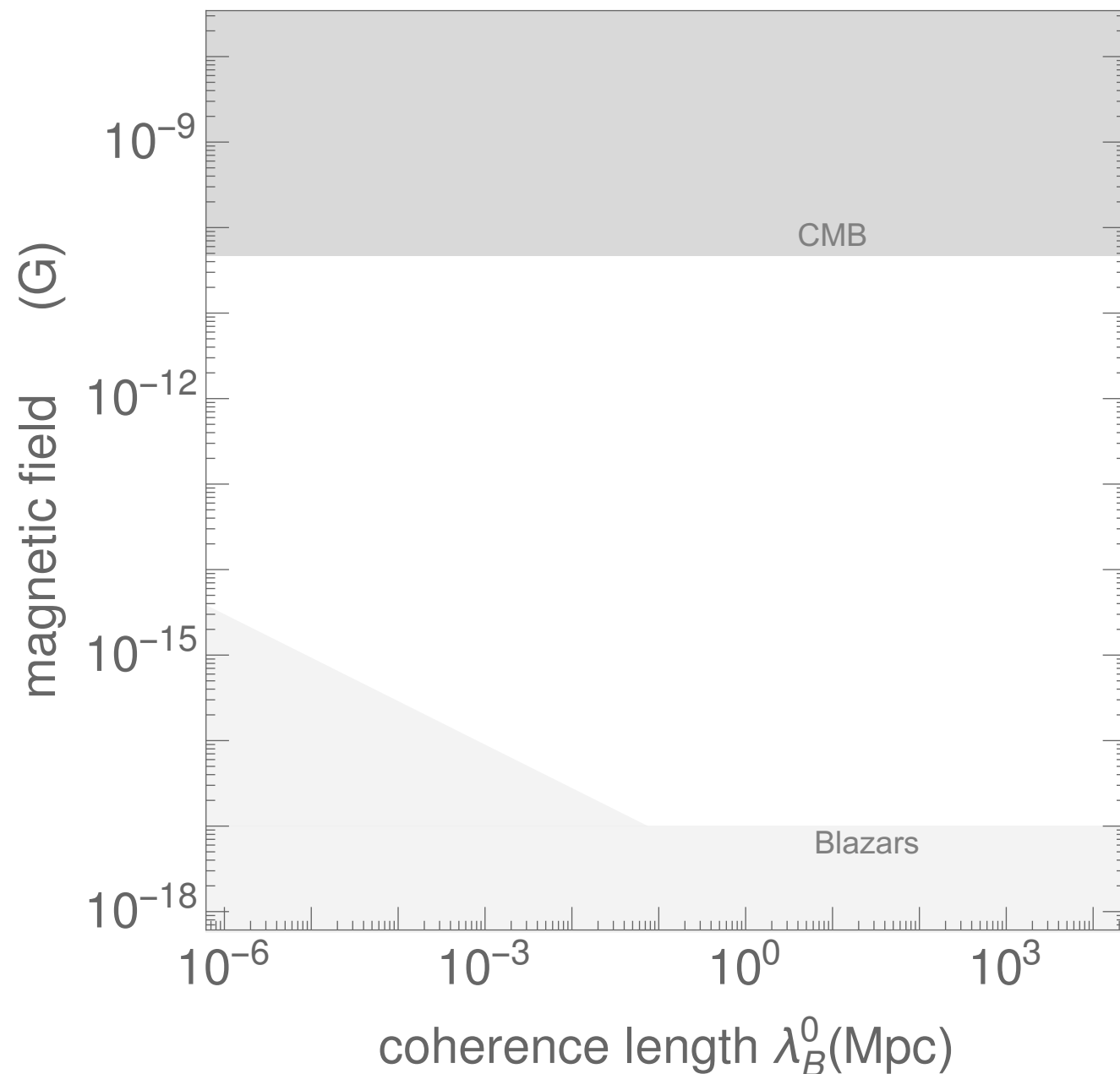
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leads to the appearance of an extended emission with an IGMF-dependent size. If the IGMF strength is in the range, $B \sim 10^{-16} - 10^{-12}$ G, the spatially-extended emission may be detectable and resolvable by CTA by virtue of its high sensitivity and angular resolution; e.g., for a source at a distance of 100 Mpc,

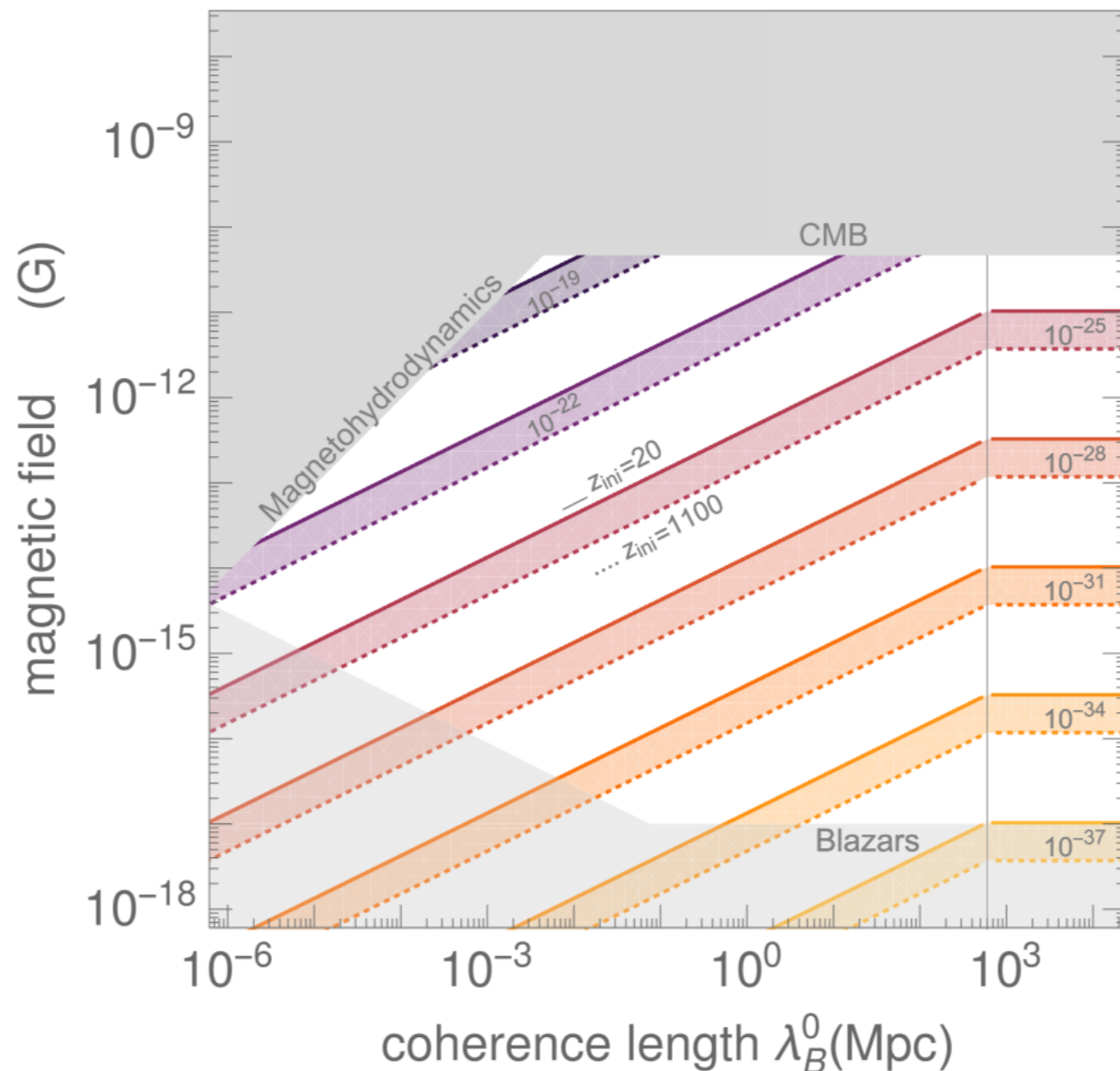
Domcke, CGC 2021



Camilo A. Garcia Cely

Cosmic magnetic fields in 2021

Domcke, CGC 2021



PHYSICAL REVIEW LETTERS **123**, 021301 (2019)

Stringent Limit on Primordial Magnetic Fields from the Cosmic Microwave Background Radiation

Karsten Jedamzik^{1,*} and Andrey Saveliev^{2,3,†}

¹Laboratoire Univers et Particules de Montpellier, UMR5299-CNRS, Université de Montpellier, 34095 Montpellier, France

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Science

Contents

News

Careers

Journals

SHARE

REPORT



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Figures & Data

Info & Metrics

eLetters

PDF

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Oscillations after the formation of the CMB

$$\left(\square + \omega_{\text{pl}}^2 \right) A_\lambda = -B \partial_\ell h_\lambda$$

$$\square h_\lambda = 16\pi G B \partial_\ell A_\lambda$$

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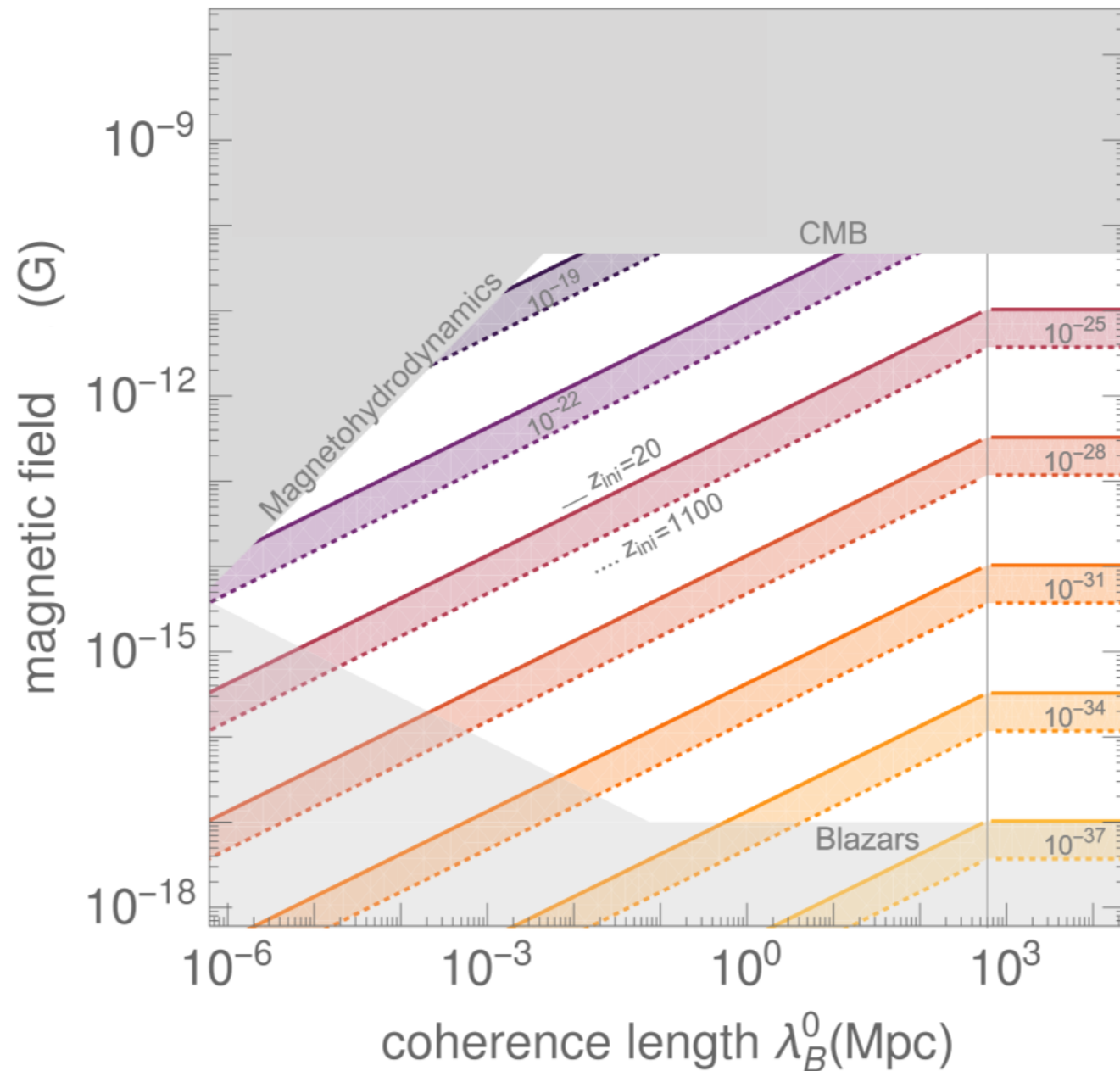
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Cosmic magnetic fields in 2021

Domcke, CGC 2021



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Science

Contents

News

Careers

Journals

SHARE

REPORT



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Info & Metrics

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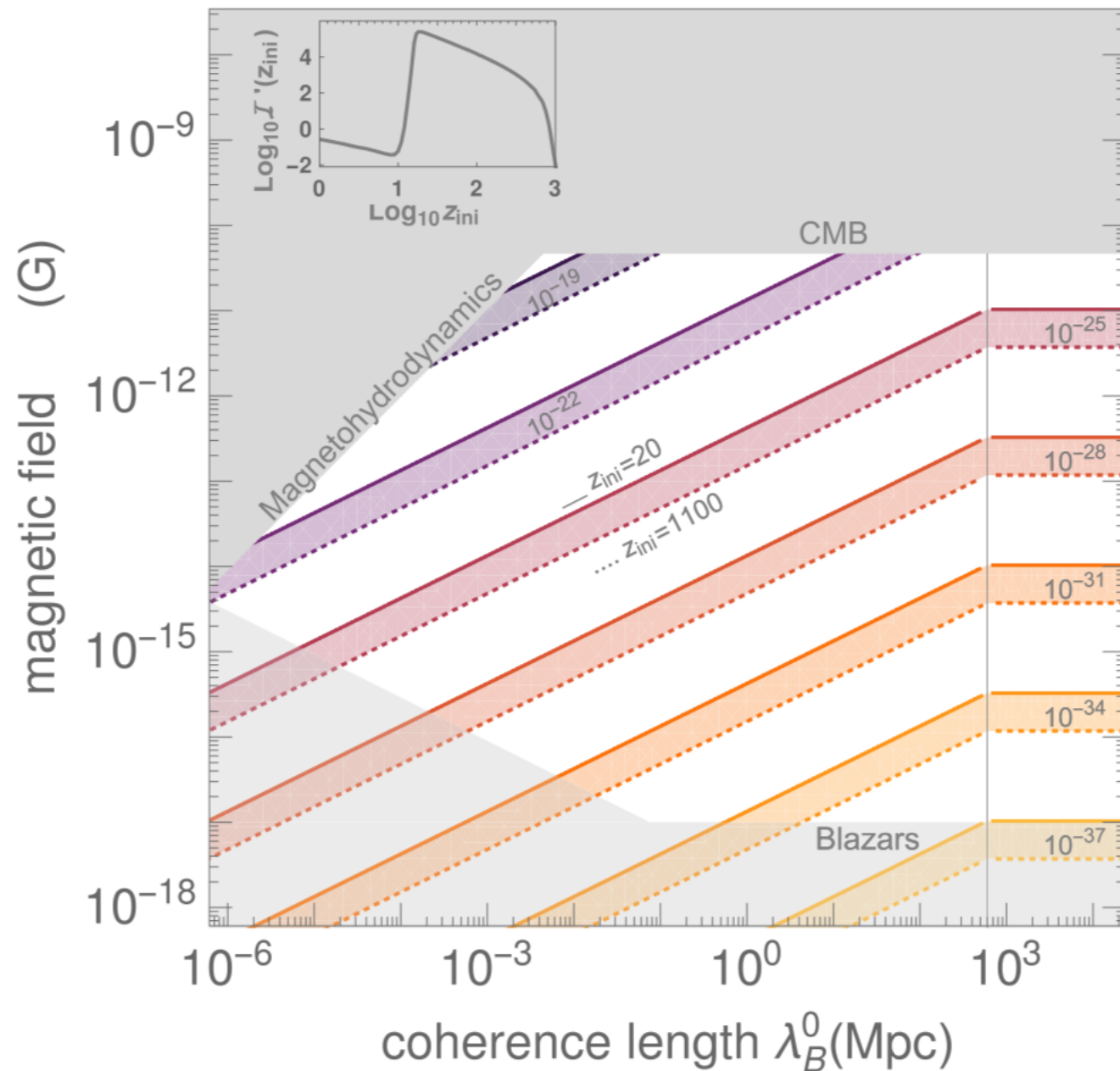
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Contents

News

Careers

Journals

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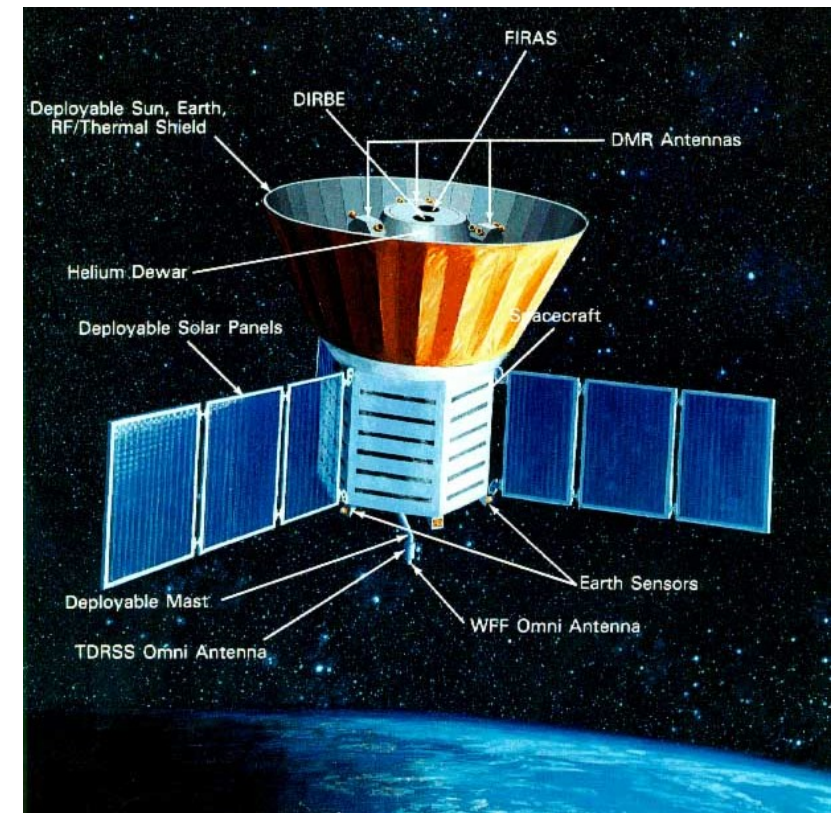
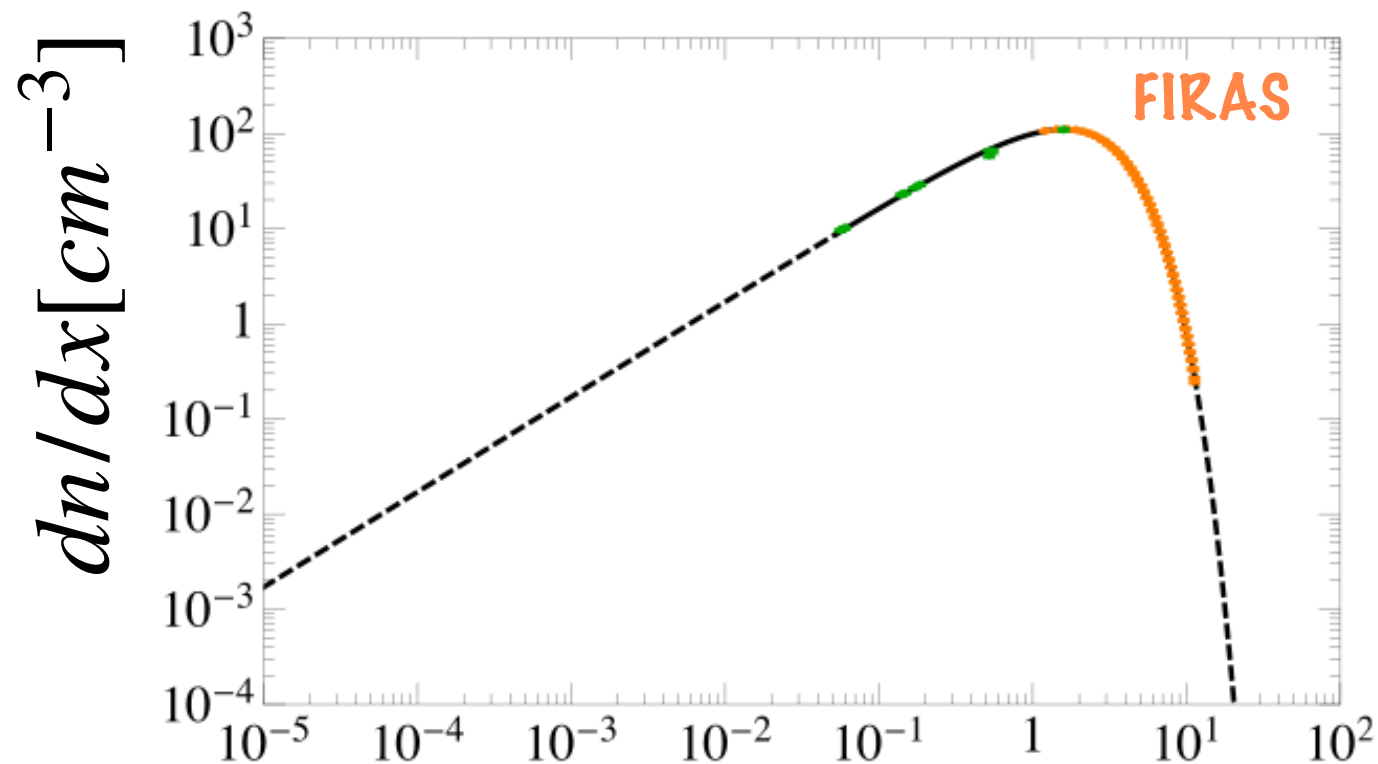
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Camilo A. Garcia Cely

CMB observations and 21-cm cosmology

CMB distortions



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THE COSMIC MICROWAVE BACKGROUND SPECTRUM FROM THE FULL *COBE*¹ FIRAS DATA SET

D. J. FIXSEN,² E. S. CHENG,³ J. M. GALES,² J. C. MATHER,³ R. A. SHAFER,³ AND E. L. WRIGHT⁴

Received 1996 January 19; accepted 1996 July 11

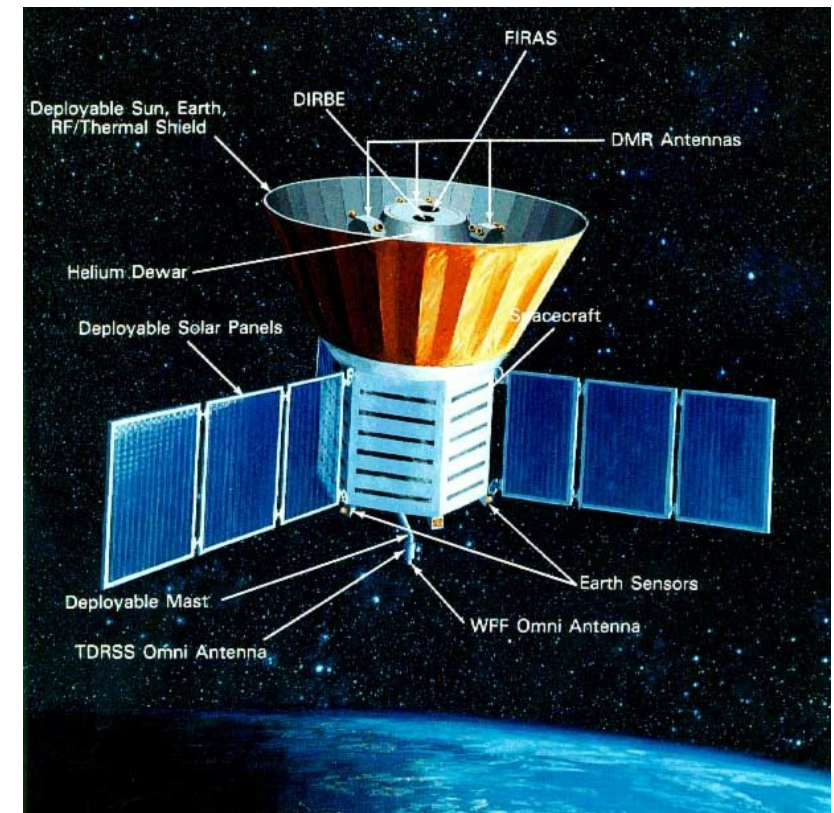
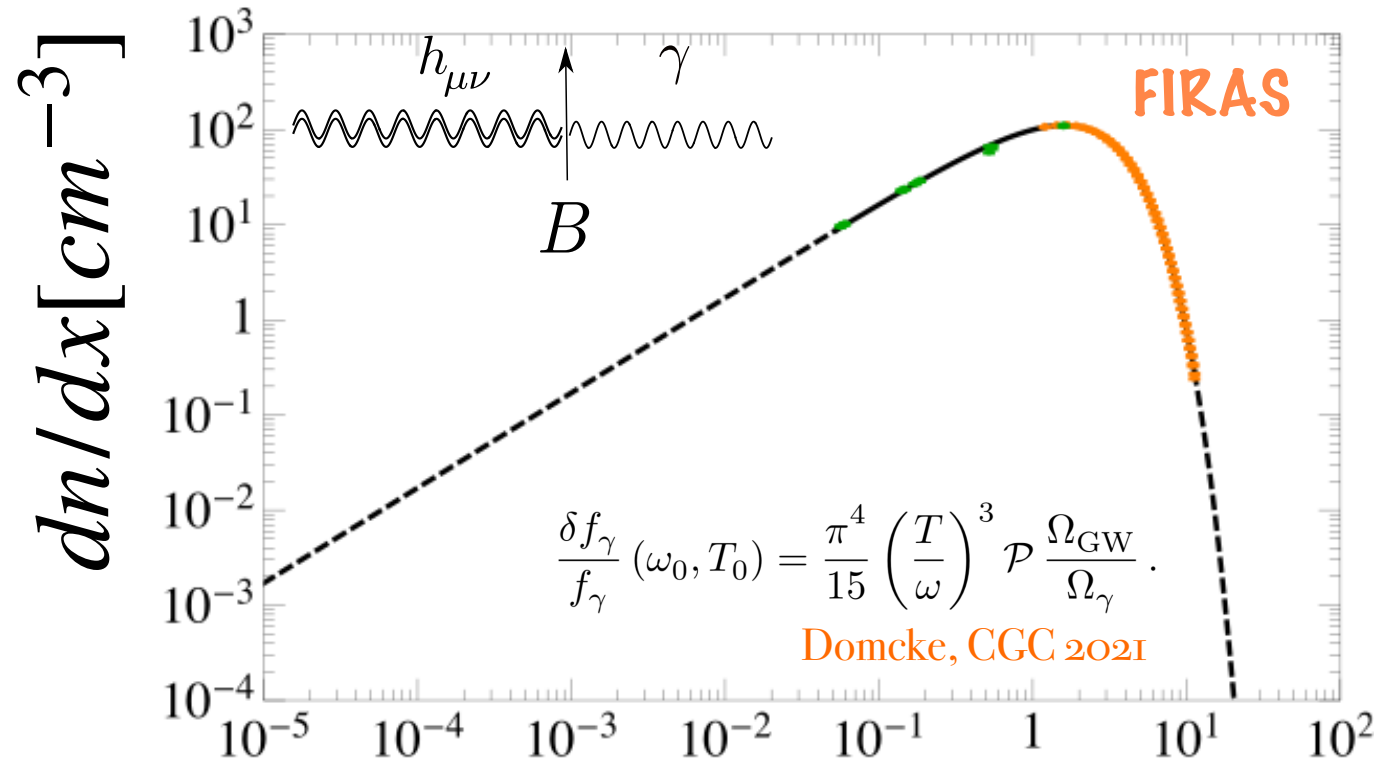
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We have refined the analysis of the data from the FIRAS (Far-Infrared Absolute Spectrophotometer) on board the *COBE* (*COSmic Background Explorer*). The FIRAS measures the difference between the cosmic microwave background and a precise blackbody spectrum. We find new, tighter upper limits on general deviations from a blackbody spectrum. The rms deviations are less than 50 parts per million of the peak of the cosmic microwave background radiation. For the Comptonization and chemical potential, we find $|y| < 15 \times 10^{-6}$ and $|\mu| < 9 \times 10^{-5}$ (95% confidence level [CL]). There are also refinements in the absolute temperature, 2.728 ± 0.004 K (95% CL), the dipole direction, $(\ell, b) = (264^\circ.14 \pm 0.30, 48^\circ.26 \pm 0.30)$ (95% CL), and the amplitude, 3.372 ± 0.014 mK (95% CL). All of these results agree with our previous publications.

Subject headings: cosmic microwave background — cosmology: observations

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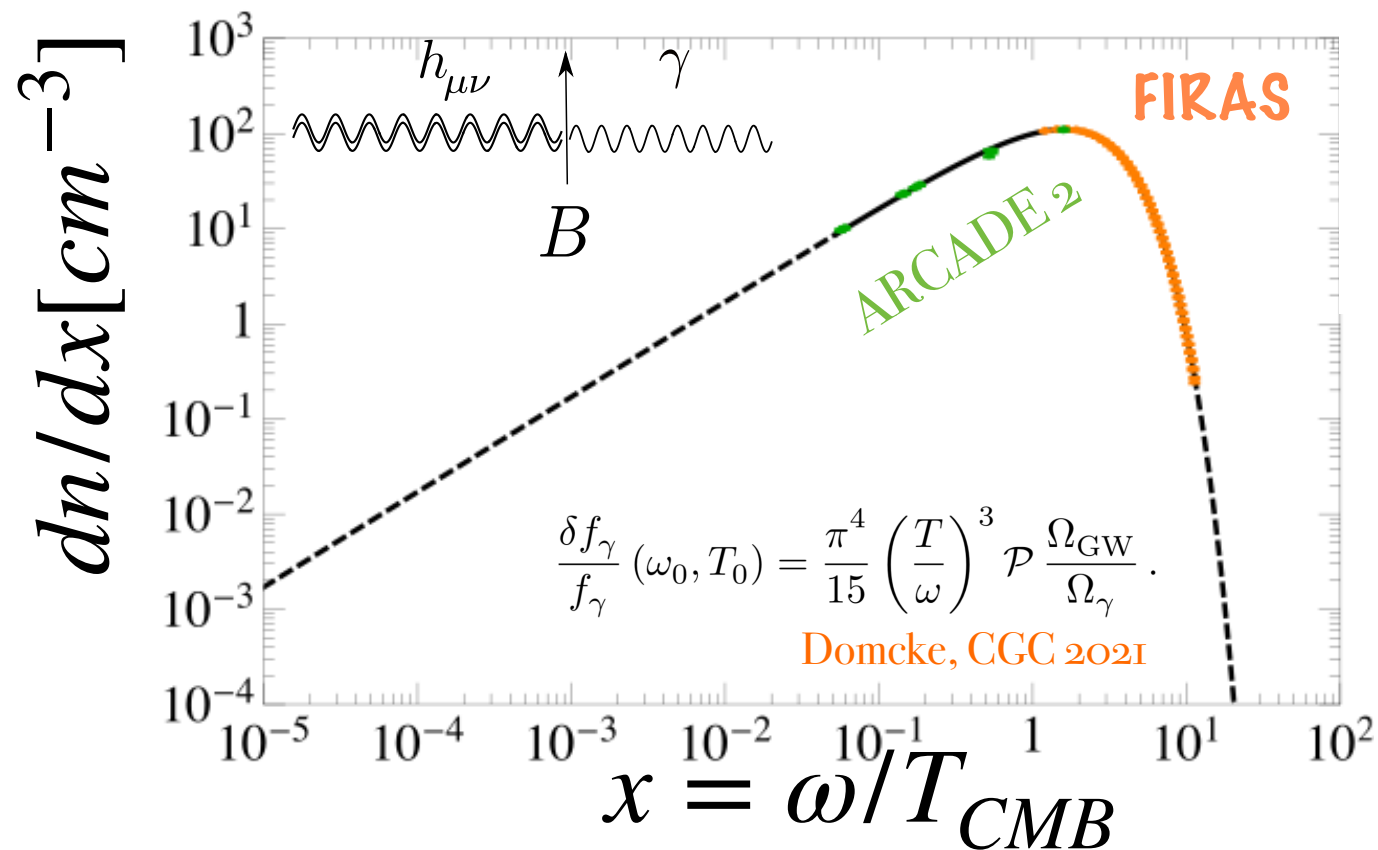
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Rayleigh-Jeans Tail

THE ASTROPHYSICAL JOURNAL



ARCADE 2 MEASUREMENT OF THE ABSOLUTE SKY BRIGHTNESS AT 3-90 GHz

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[The Astrophysical Journal, Volume 734, Number 1](#)

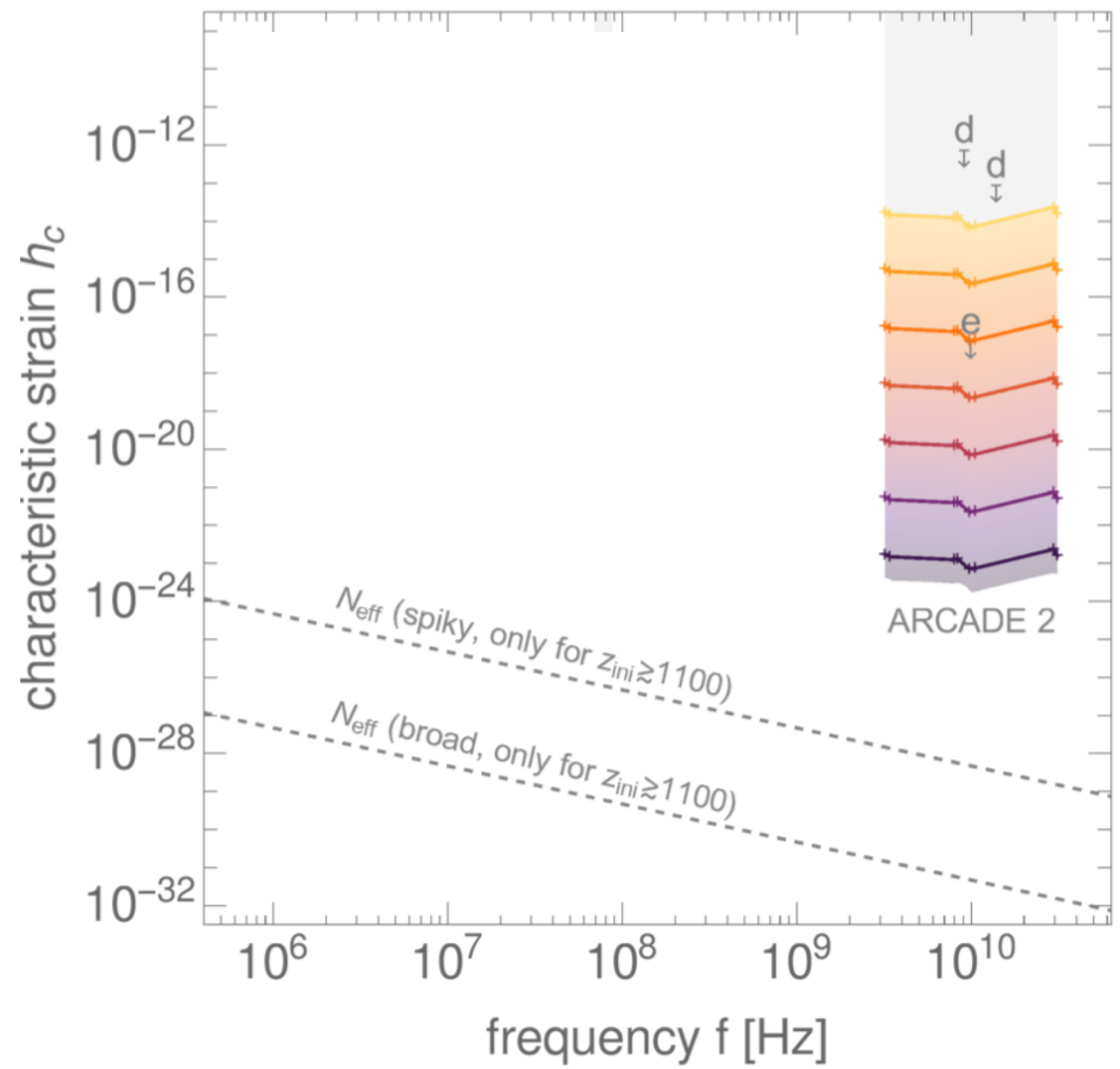
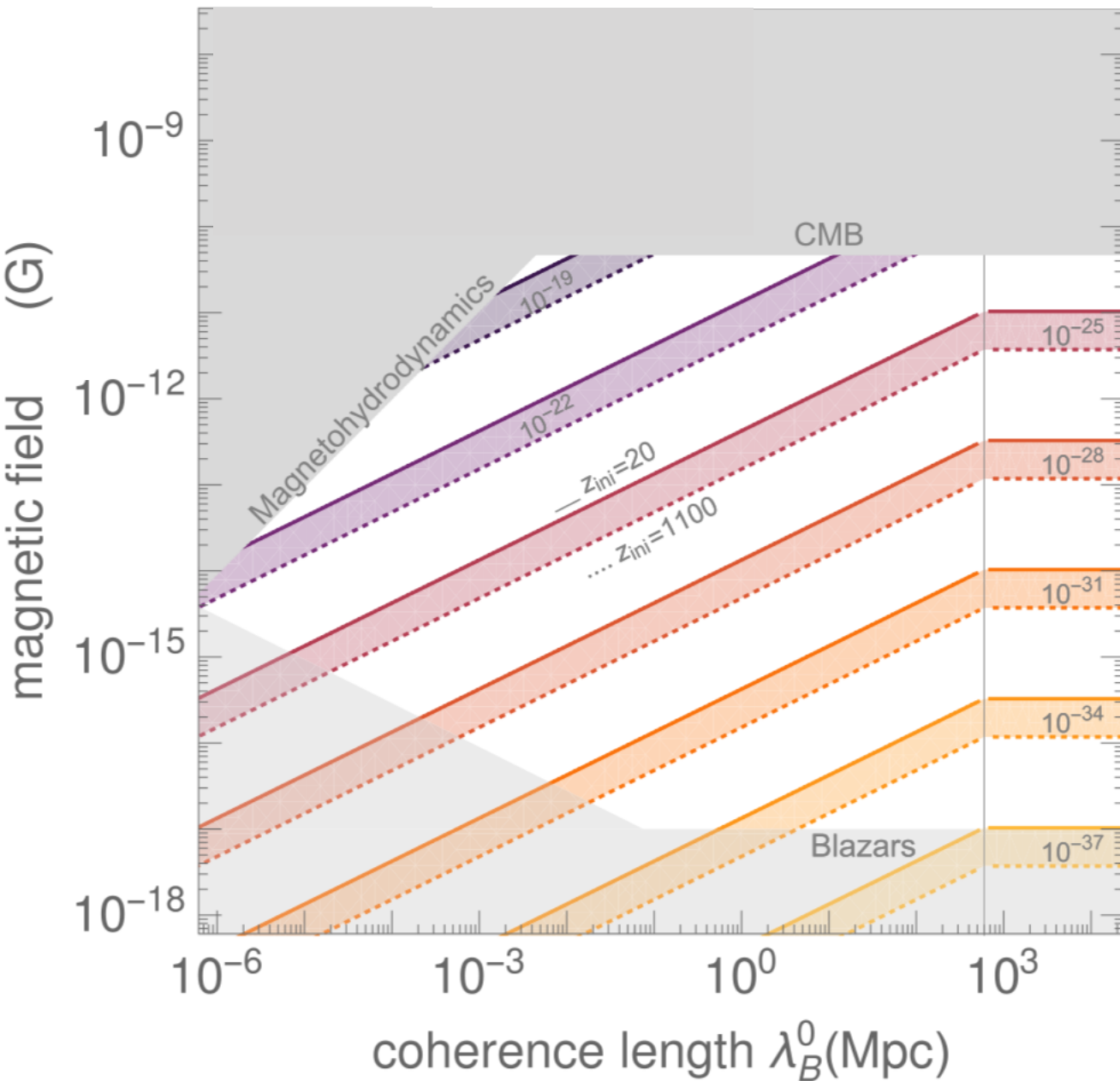
- Largely unexplored with upcoming advances in radio astronomy probing it in the near future.

Upper bounds on stochastic gravitational waves

PHYSICAL REVIEW LETTERS **126**, 021104 (2021)

Potential of Radio Telescopes as High-Frequency Gravitational Wave Detectors

Valerie Domcke^{1,2,3,*} and Camilo Garcia-Cely^{1,†}



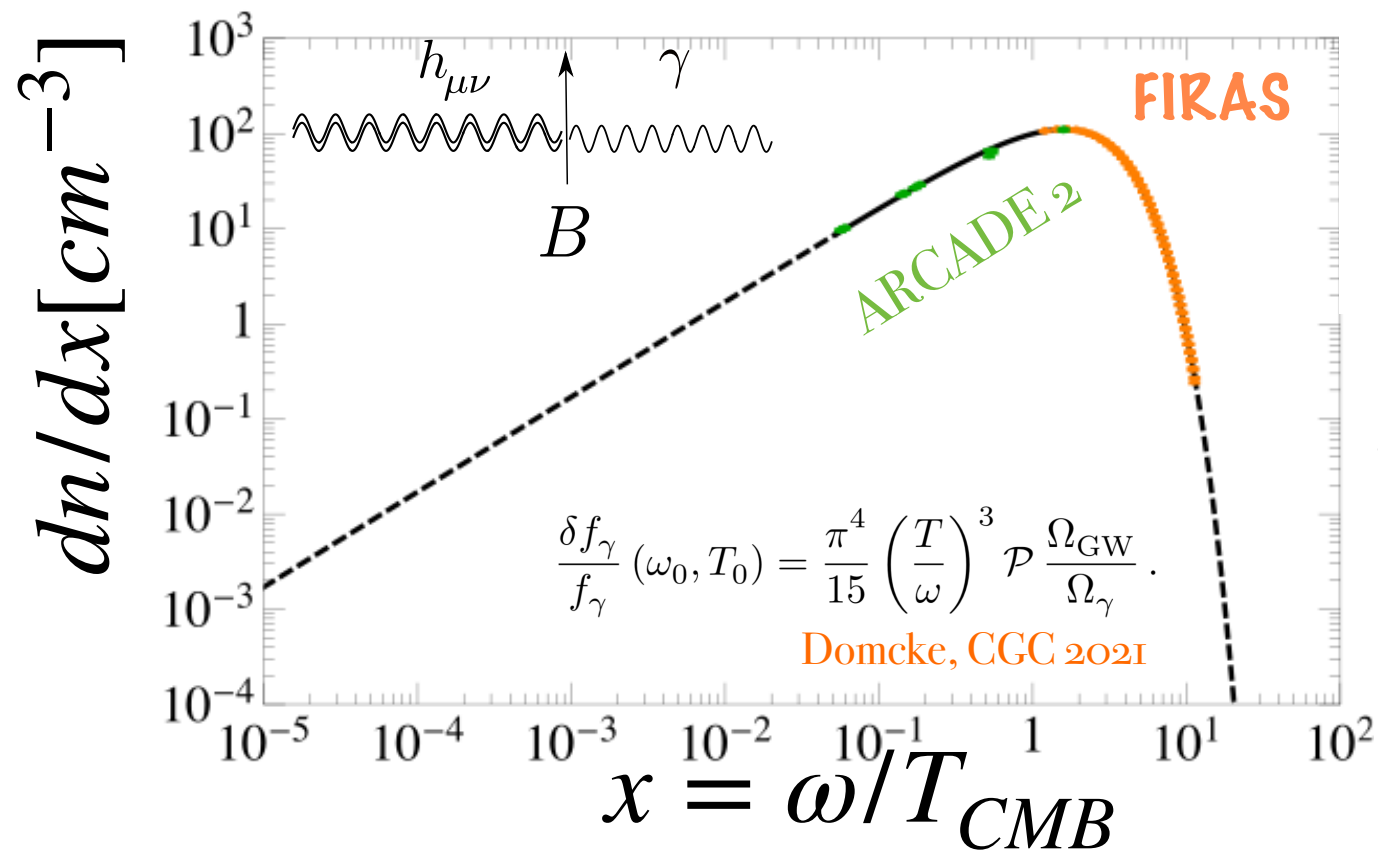
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d) magnon detector Ito, Soda '04
e) magnetic conversion detector Cruise et al '12

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nature

An absorption profile centred at 78 megahertz in the sky-averaged spectrum

Judd D. Bowman [✉](#), Alan E. E. Rogers, Raul A. Monsalve, Thomas J. Mozdzen & Nivedita Mahesh

Nature 555, 67–70(2018) | [Cite this article](#)



- Largely unexplored with upcoming advances in radio astronomy probing it in the near future.
- Puzzling signal by EDGES.
(Experiment to Detect the Global Epoch of Reionization Signature)

Camilo A. Garcia Cely

Expectations for a 21 cm signal

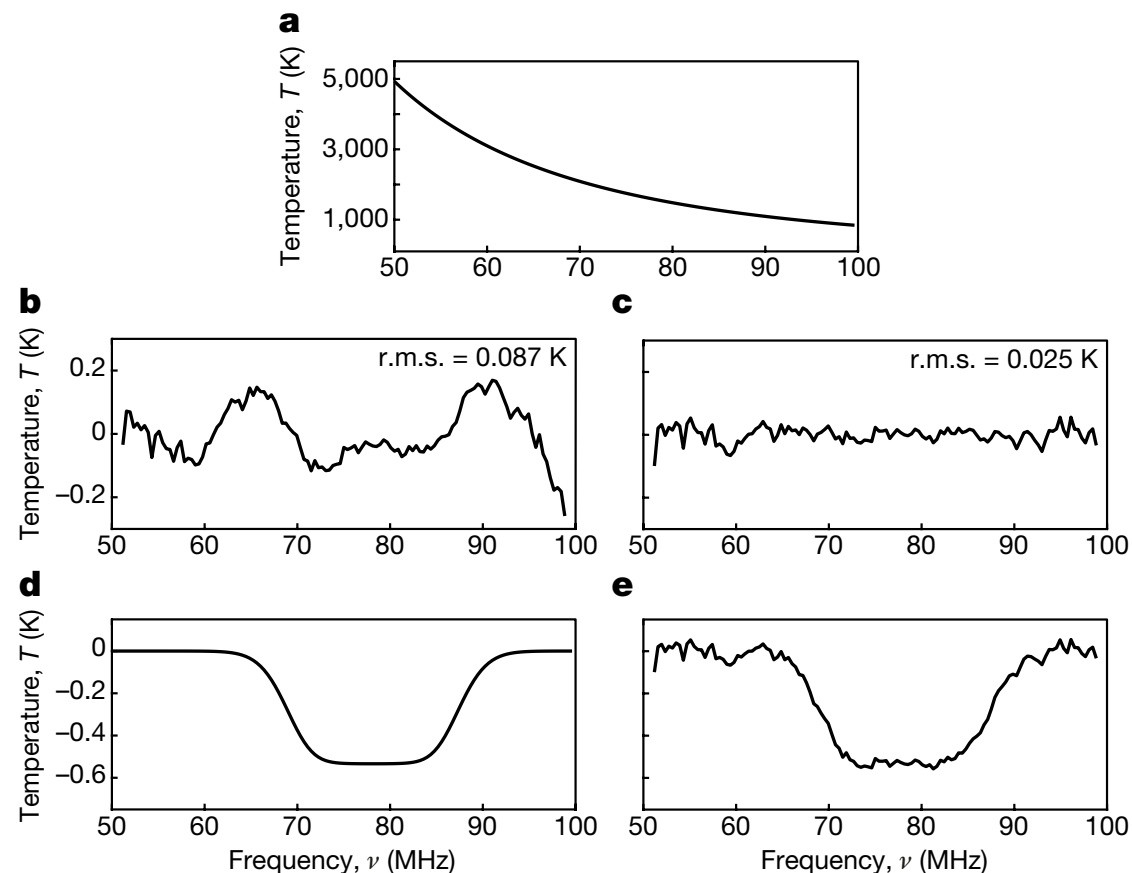
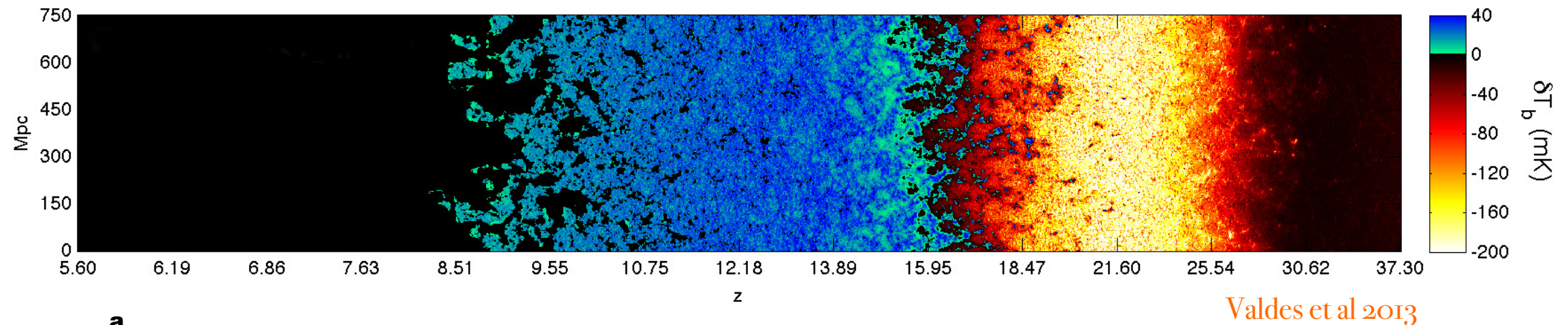



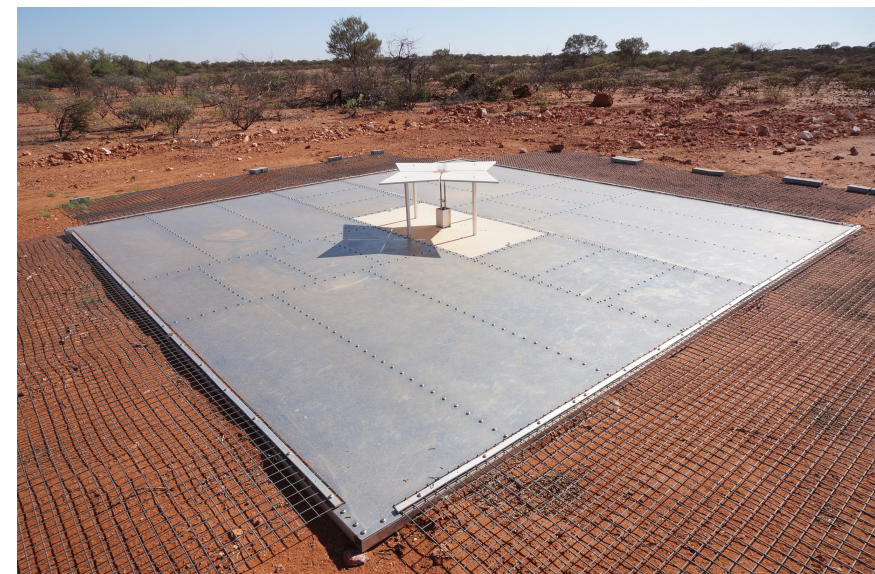
Figure 1 | Summary of detection. **a**, Measured spectrum for the reference dataset after filtering for data quality and radio-frequency interference. The spectrum is dominated by Galactic synchrotron emission. **b**, **c**, Residuals after fitting and removing only the foreground model (**b**) or the foreground and 21-cm models (**c**). **d**, Recovered model profile of the 21-cm absorption, with a signal-to-noise ratio of 37, amplitude of 0.53 K, centre frequency of 78.1 MHz and width of 18.7 MHz. **e**, Sum of the 21-cm model (**d**) and its residuals (**c**).

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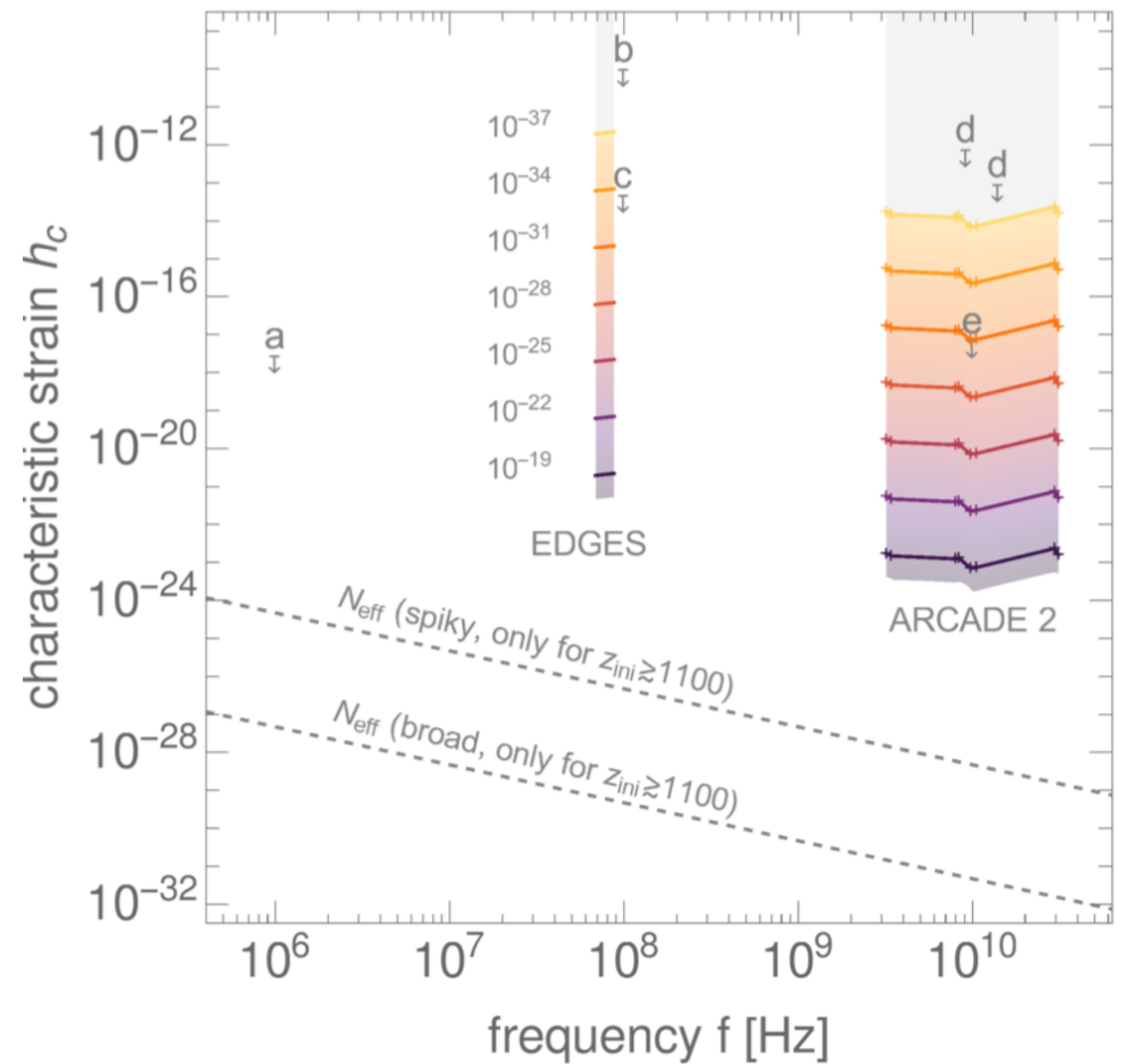
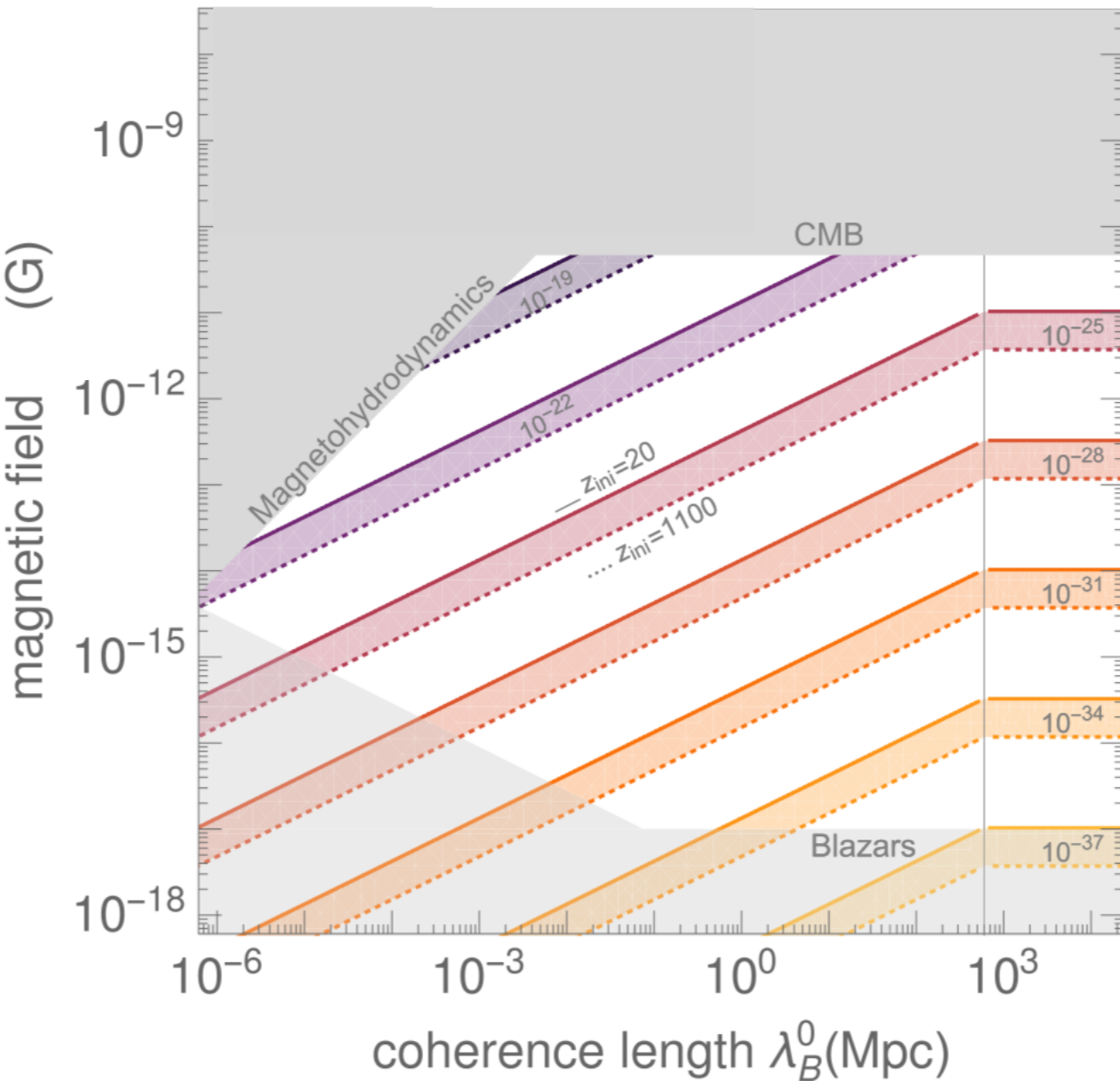
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existing laboratory bounds from

- a) superconducting parametric converter [Reece et al '84](#)
- b) waveguide [Cruise Ingleby '06](#)
- c) 0.75 m interferometer [Akutsu '08](#)
- d) magnon detector [Ito, Soda '04](#)
- e) magnetic conversion detector [Cruise et al '12](#)

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Experimental efforts on terrestrial experiments

Preliminary work

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

CERN-TH-2020-185
HIP-2020-28/TH
DESY 20-195

Challenges and Opportunities of Gravitational Wave Searches at MHz to GHz Frequencies

N. Aggarwal^{a,*}, O.D. Aguiar^b, A. Bauswein^c, G. Cella^d, S. Clesse^e, A.M. Cruise^f, V. Domcke^{g,h,i,*}, D.G. Figueroa^j, A. Geraci^k, M. Goryachev^l, H. Grote^m, M. Hindmarsh^{n,o}, F. Muia^{p,i,*}, N. Mukund^q, D. Ottaway^{r,s}, M. Peloso^{t,u}, F. Quevedo^{p,*}, A. Ricciardone^{t,u}, J. Steinlechner^{v,w,x,*}, S. Steinlechner^{v,w,*}, S. Sun^{y,z}, M.E. Tobar^l, F. Torrenti^α, C. Unal^β, G. White^γ

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, with a particular focus on *Ultra High-Frequency Gravitational Waves* (UHF-GWs), covering the MHz to GHz range. The absence of known astrophysical sources in 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 gravitational sources. We review several detector concepts which 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 the workshop *Challenges and opportunities of high-frequency gravitational wave detection* held at ICTP Trieste, Italy in October 2019, that set up the stage for the recently launched Ultra-High-Frequency Gravitational Wave (UHF-GW) initiative.

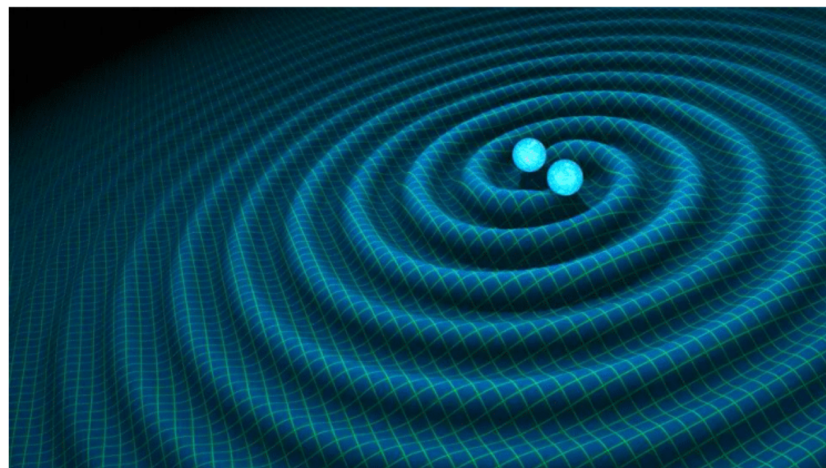
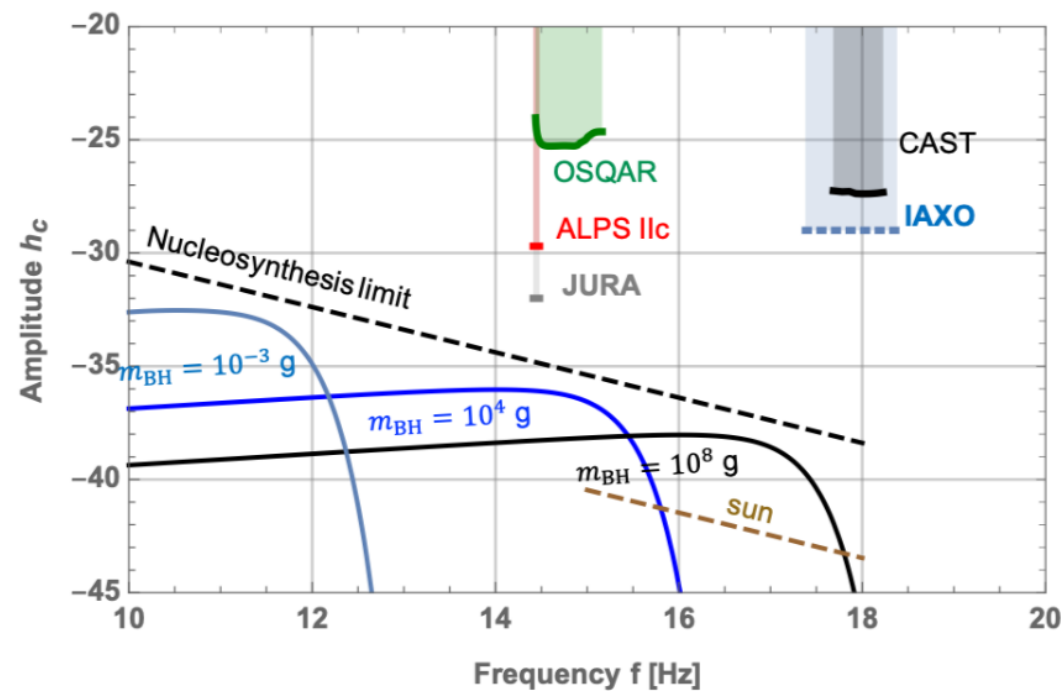
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Preliminary work with Andreas Ringwald and Guillermo Ballesteros

Upper limits on the amplitude of ultra-high-frequency gravitational waves from graviton to photon conversion

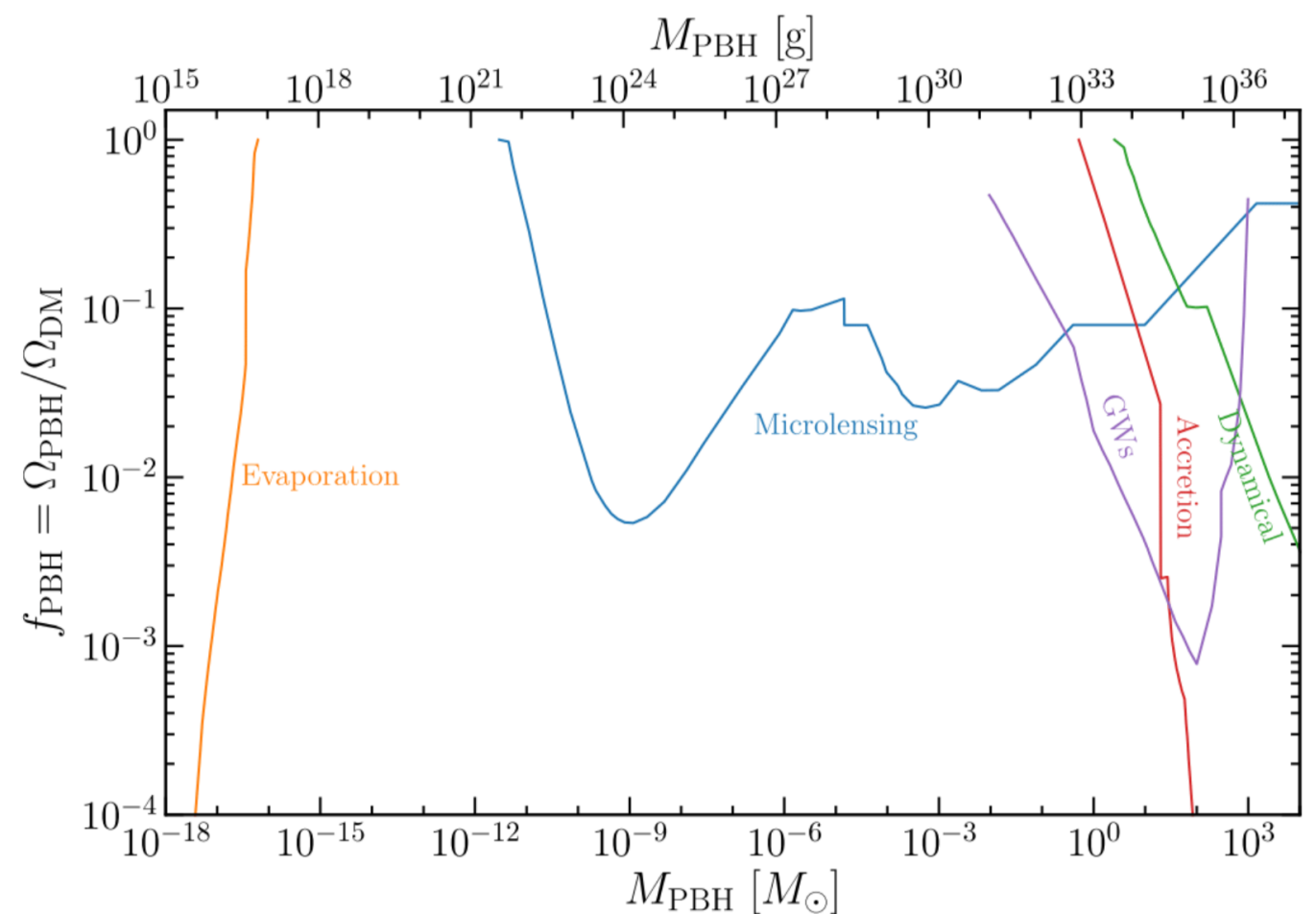
A. Ejlli , D. Ejlli, A. M. Cruise, G. Pisano & H. Grote

The European Physical Journal C **79**, Article number: 1032 (2019) | [Cite this article](#)



Hawking radiation

What about black hole mergers?



Green, Kavanagh 2020

Camilo A. Garcia Cely

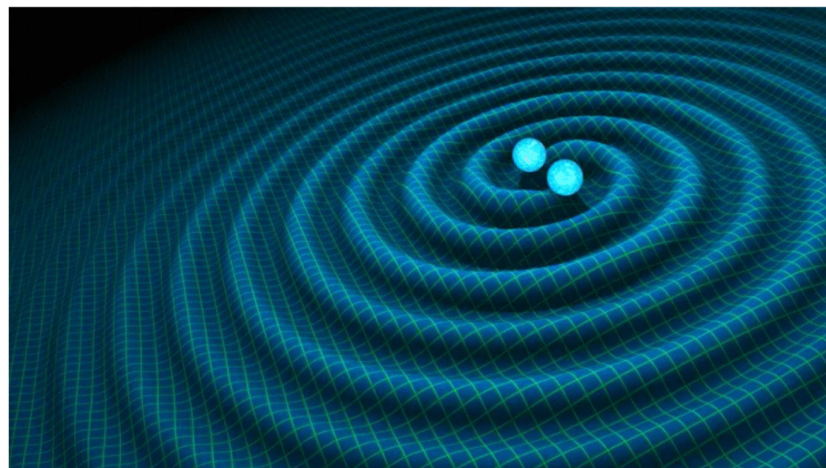
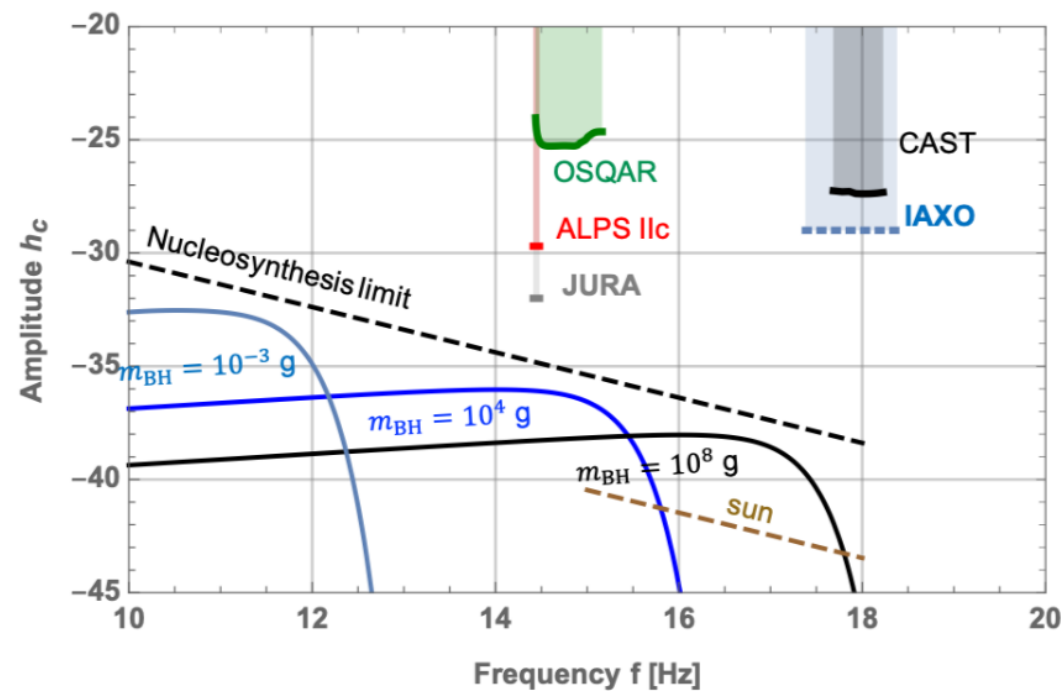
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Preliminary work with Andreas Ringwald and Guillermo Ballesteros

Upper limits on the amplitude of ultra-high-frequency gravitational waves from graviton to photon conversion

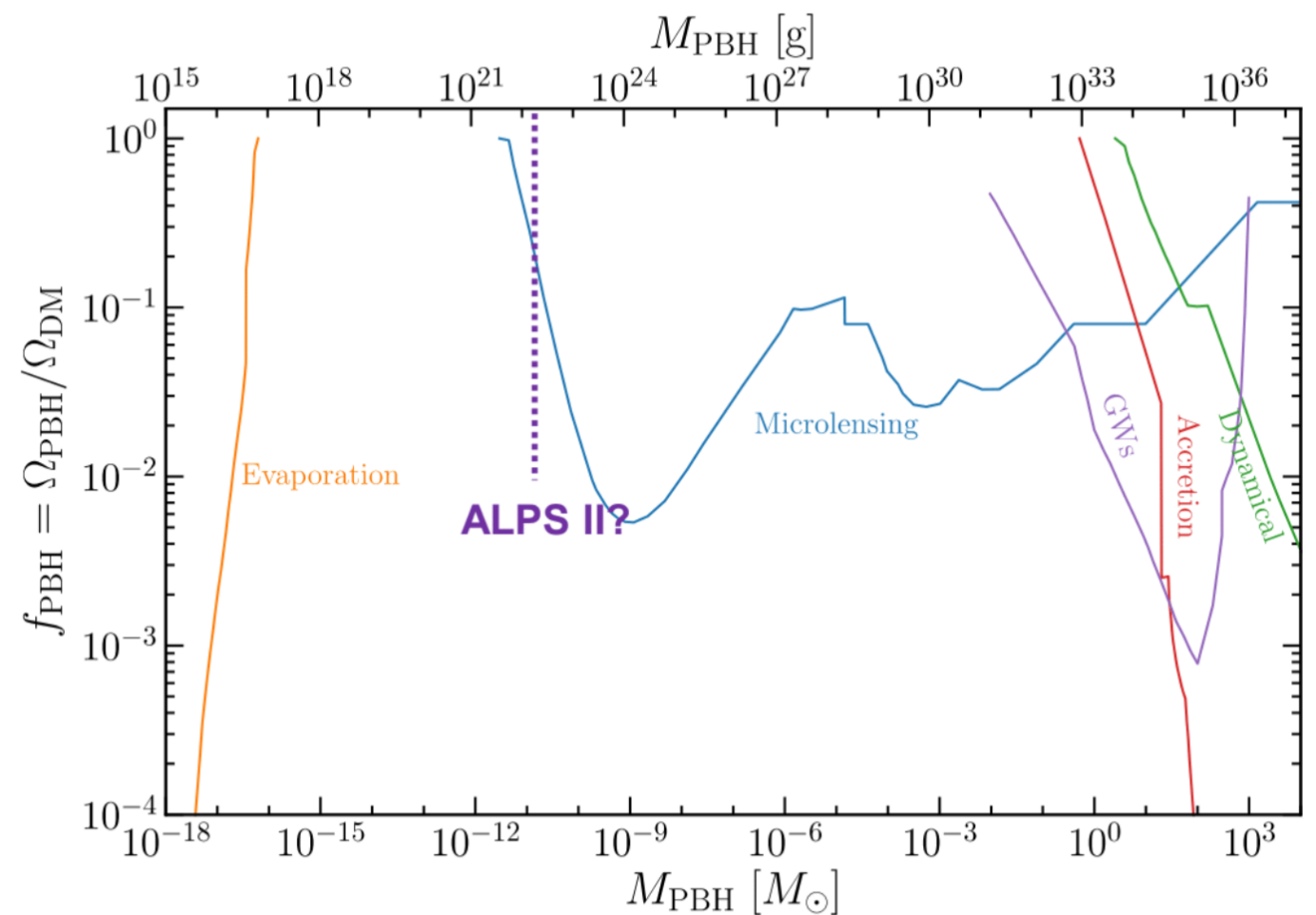
A. Ejlli , D. Ejlli, A. M. Cruise, G. Pisano & H. Grote

The European Physical Journal C **79**, Article number: 1032 (2019) | [Cite this article](#)



Hawking radiation

What about black hole mergers?



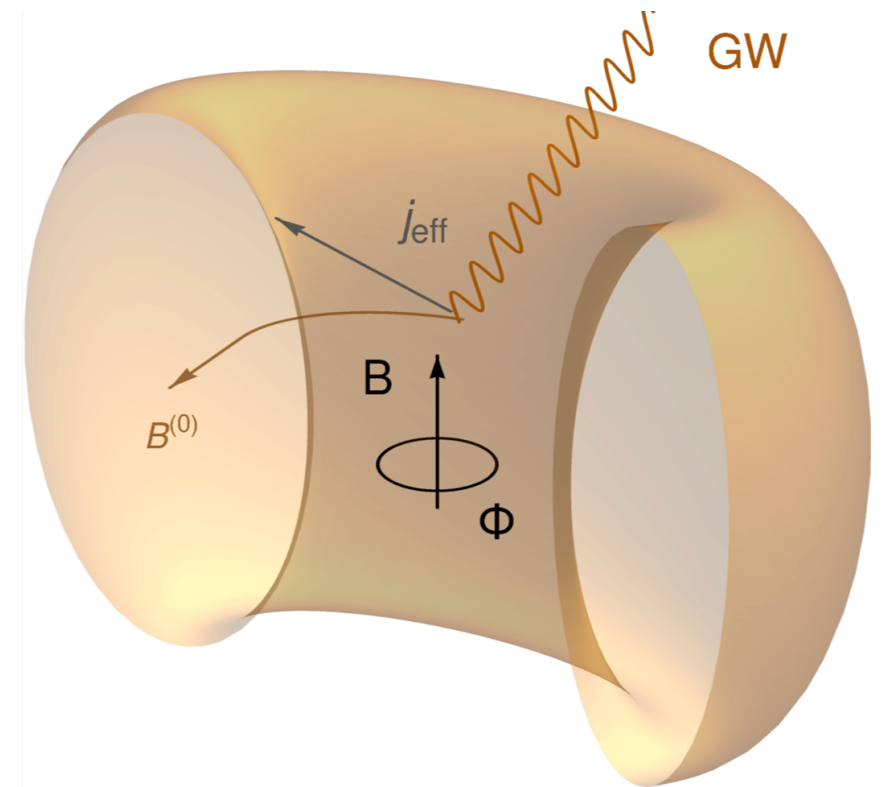
Green, Kavanagh 2020

Camilo A. Garcia Cely

Beyond the Gertsenhstein Effect

Preliminary work with Valerie Domcke and Nick Rodd

In the presence of a static electromagnetic field, a passing GW acts as a source term to Maxwell's equations, acting effectively as an additional current. This effective current in turn sources an oscillating electromagnetic field outside the boundaries of the external static field. This is different than the inverse Gertsenshtein effect which sources an electromagnetic wave in the region of space permeated by the external field.



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Conclusions

- The Gertsenshtein effect during the dark ages provides a powerful way to probe gravitational waves in the MHz-GHz range from distortions of the Rayleigh-Jeans CMB tail.
- With upcoming advances in 21cm astronomy targeting precisely this frequency range with increasing accuracy, it becomes conceivable to push the limits derived from radio telescopes below the cosmological bound constraining the total energy in gravitational wave
- Interesting prospects in the near future