The CMB as a detector of gravitational waves

Camilo A. Garcia Cely

Alexander von Humboldt Fellow

Central European Institute of Cosmology

November 4, 2021

New ideas for detecting gravitational waves

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Outline

- Motivation
- Gravitational Waves and the Gertsenhstein Effect
- CMB observations and 21–cm cosmology
- Conclusions

Motivation

Gravitational Waves

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

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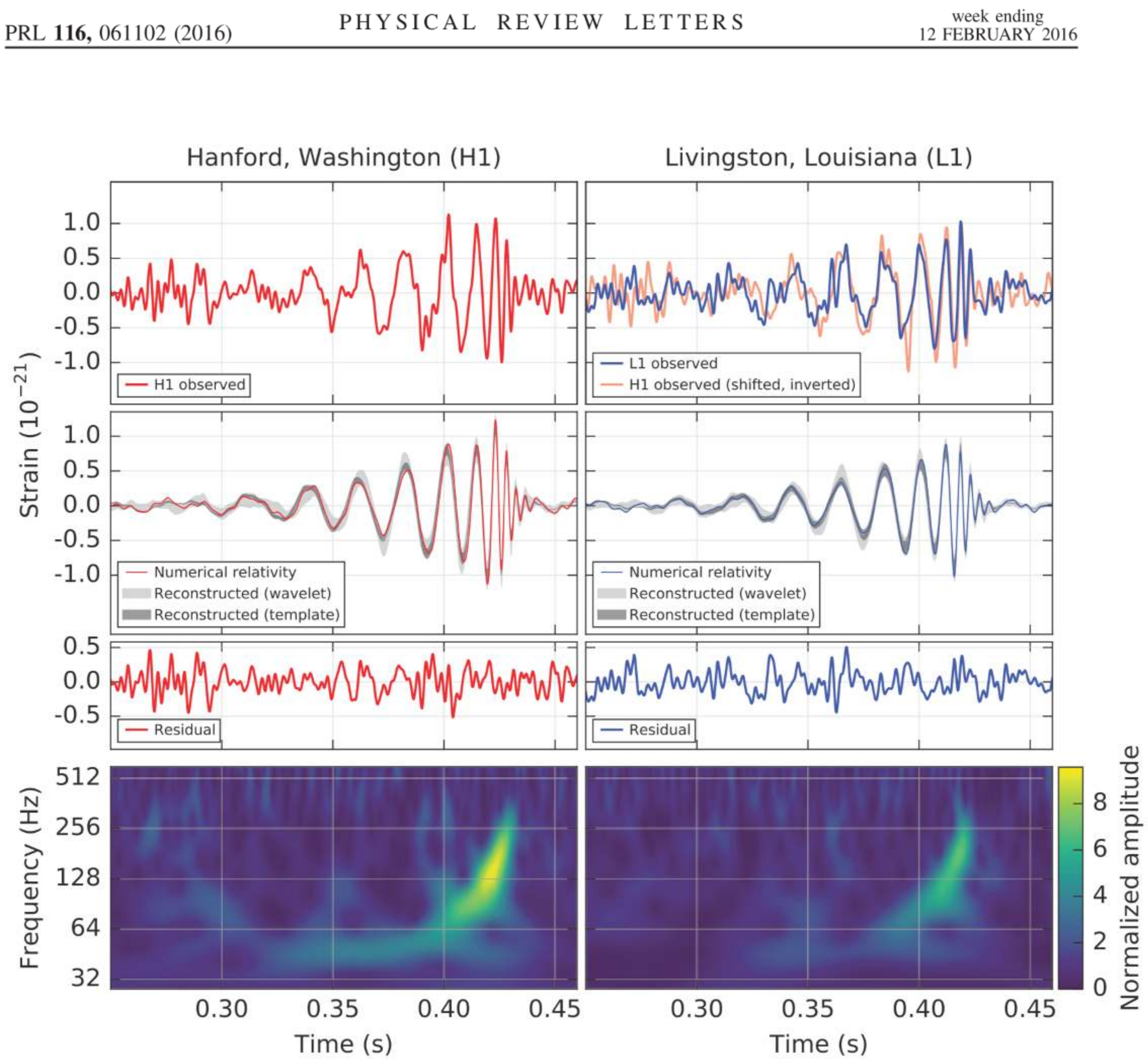

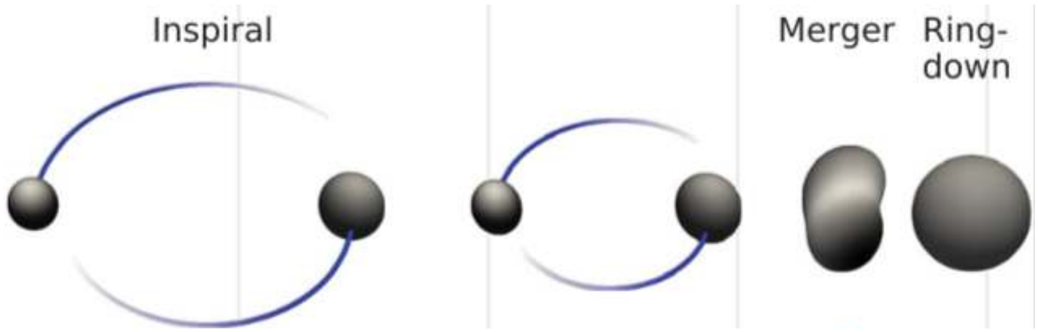

Terrestrial interferometers

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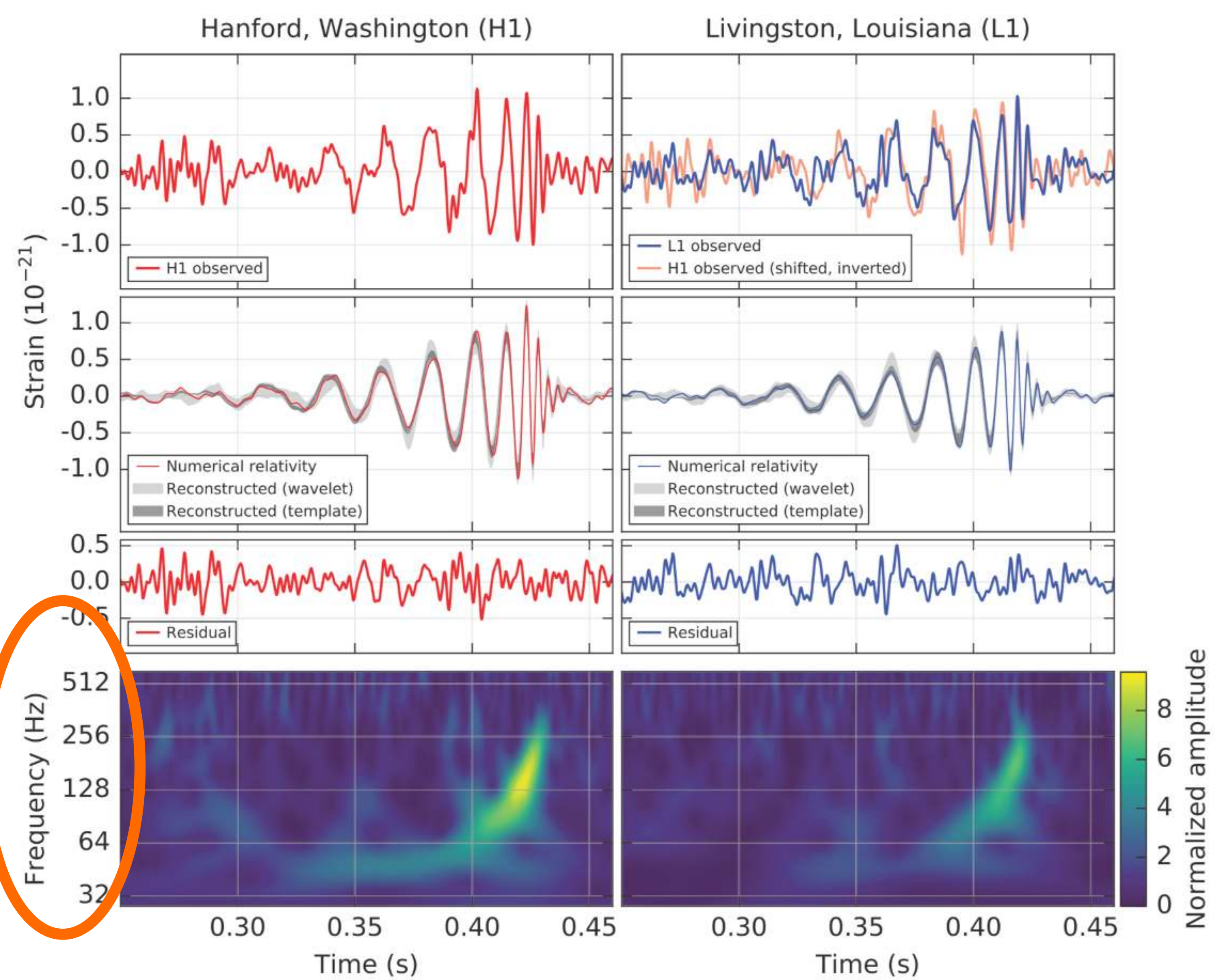
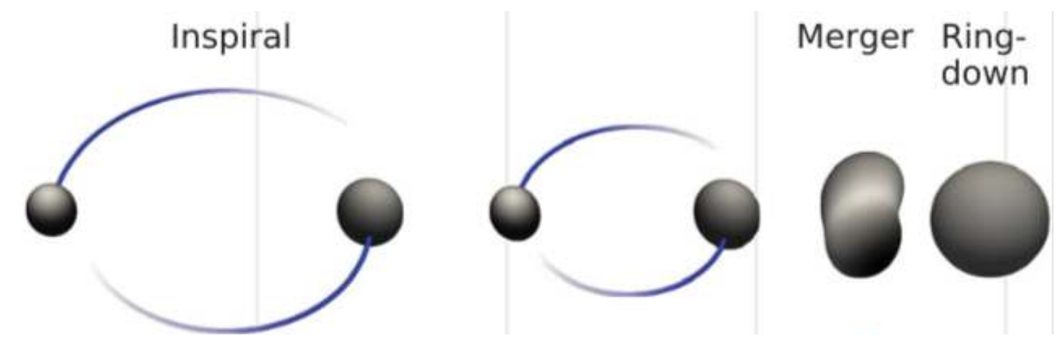
PRL **116,** 061102 (2016) PHYSICAL REVIEW LETTERS week ending 12 FEBRUARY 2016





Terrestrial interferometers

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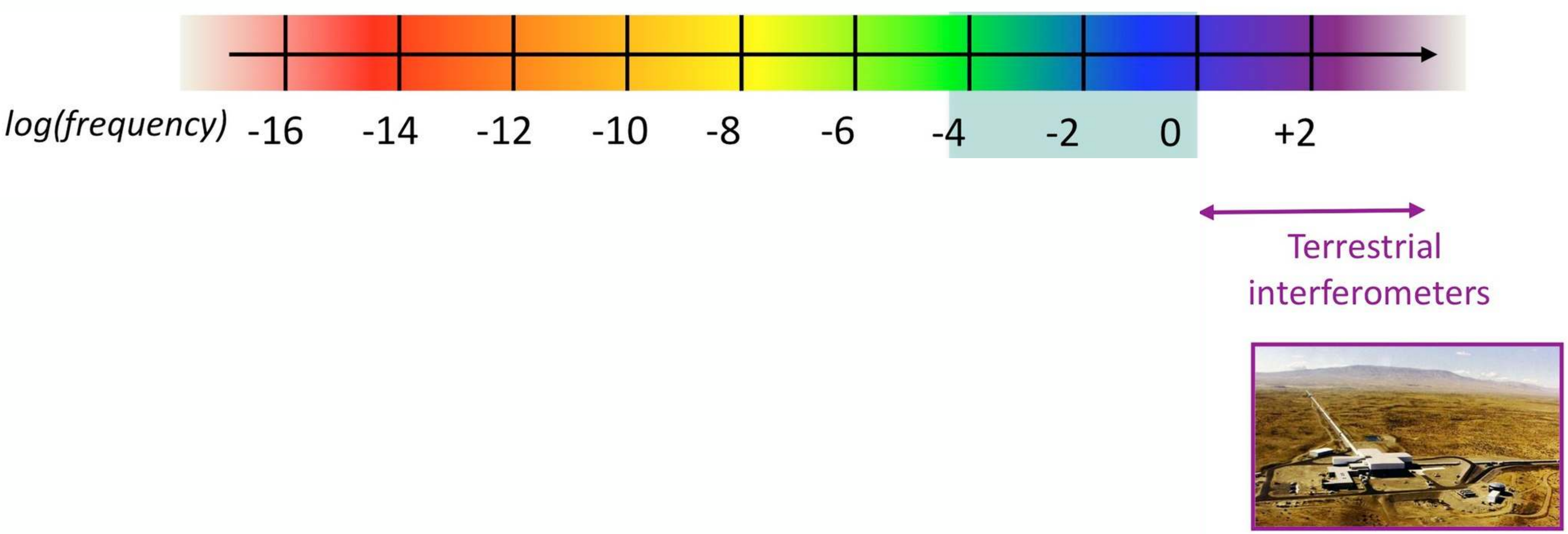
Gravitational Wave Spectrum



Credit: NASA Goddard Space Flight Center

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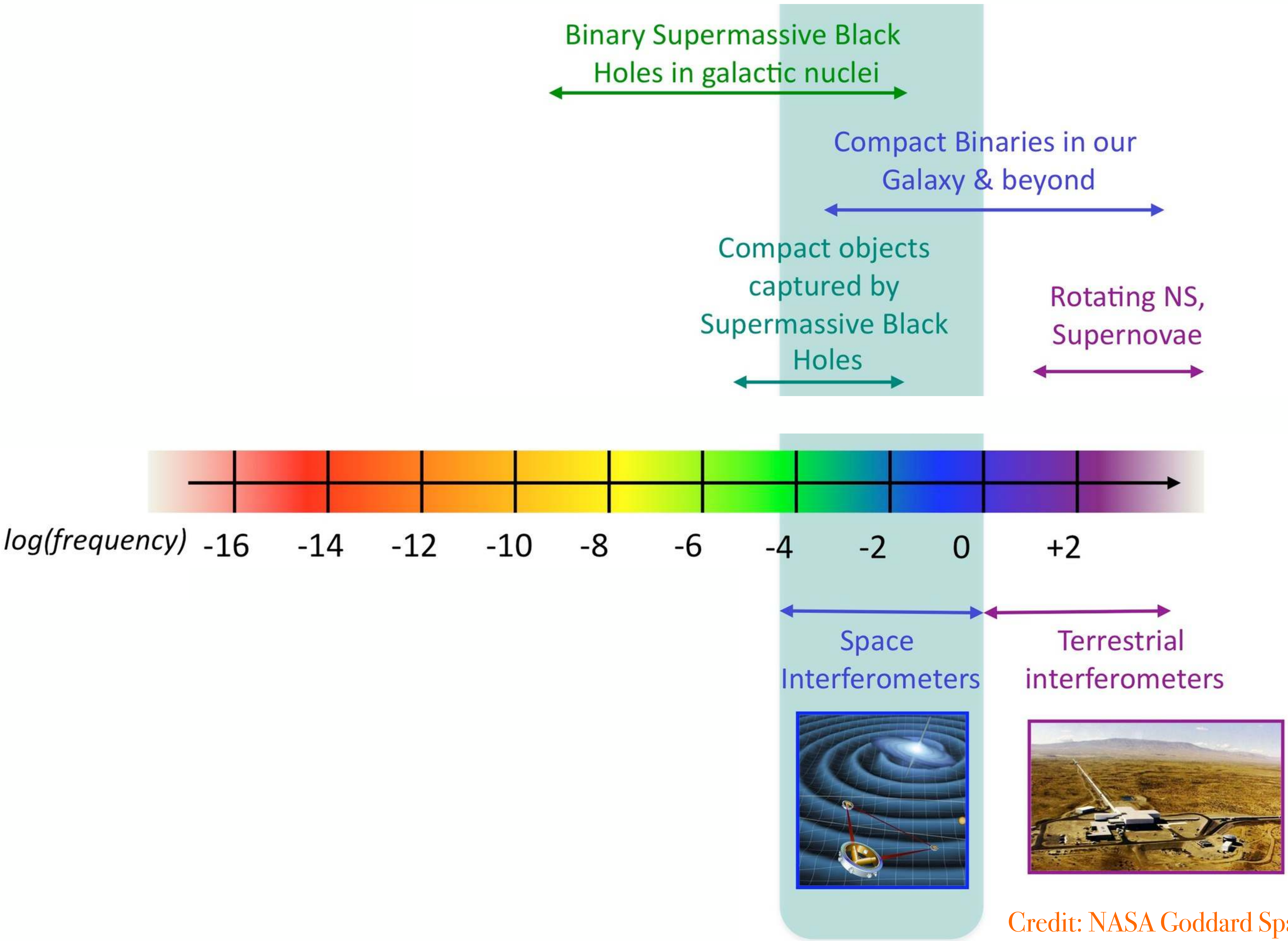

Credit: NASA Goddard Space Flight Center

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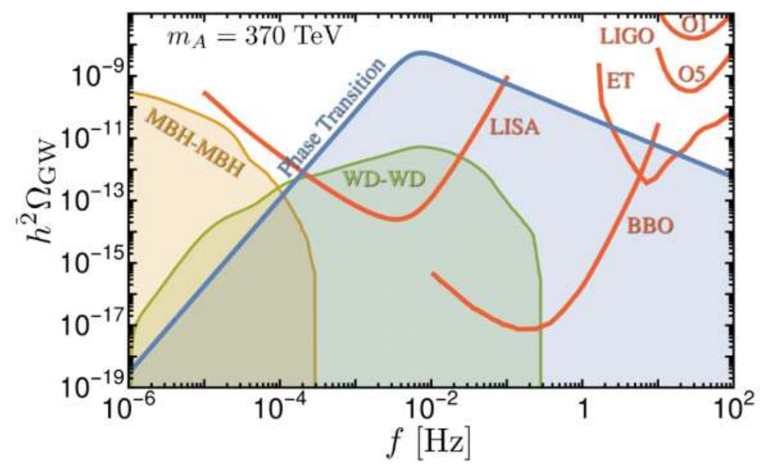
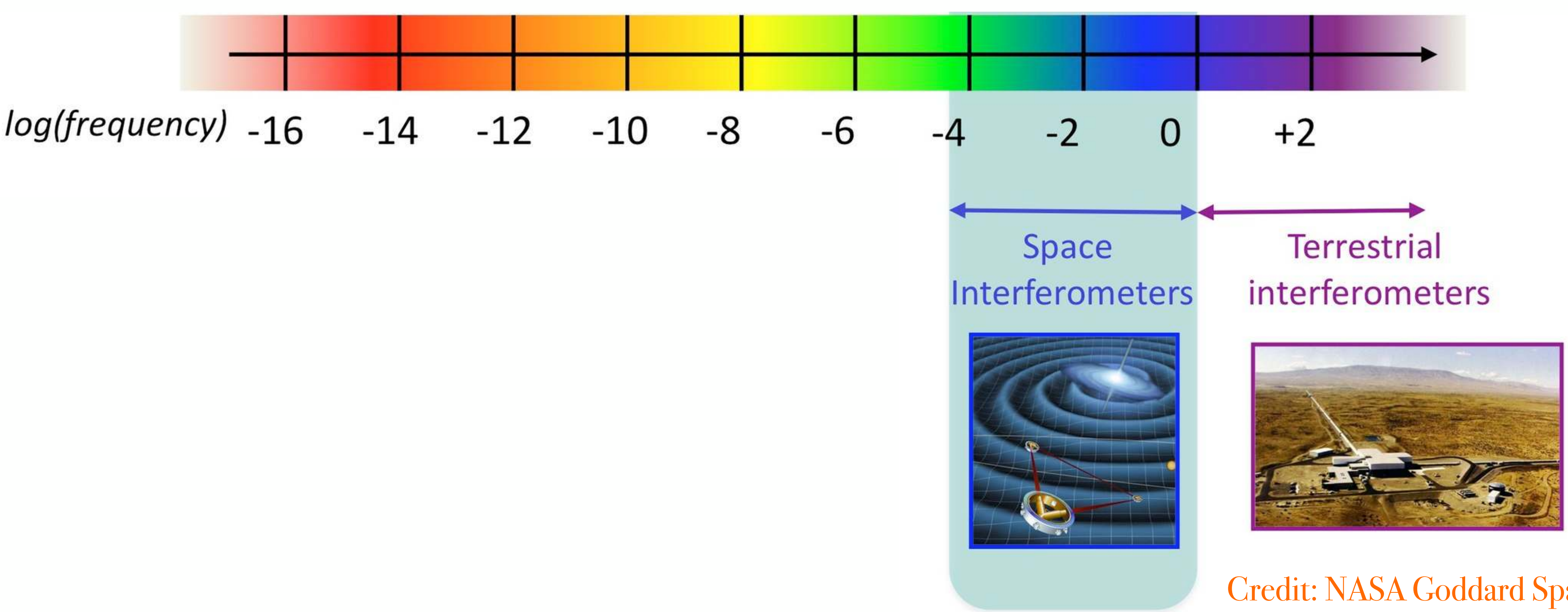
Gravitational Wave Spectrum

cosmological phase transitions

Baldes, CGC 2019





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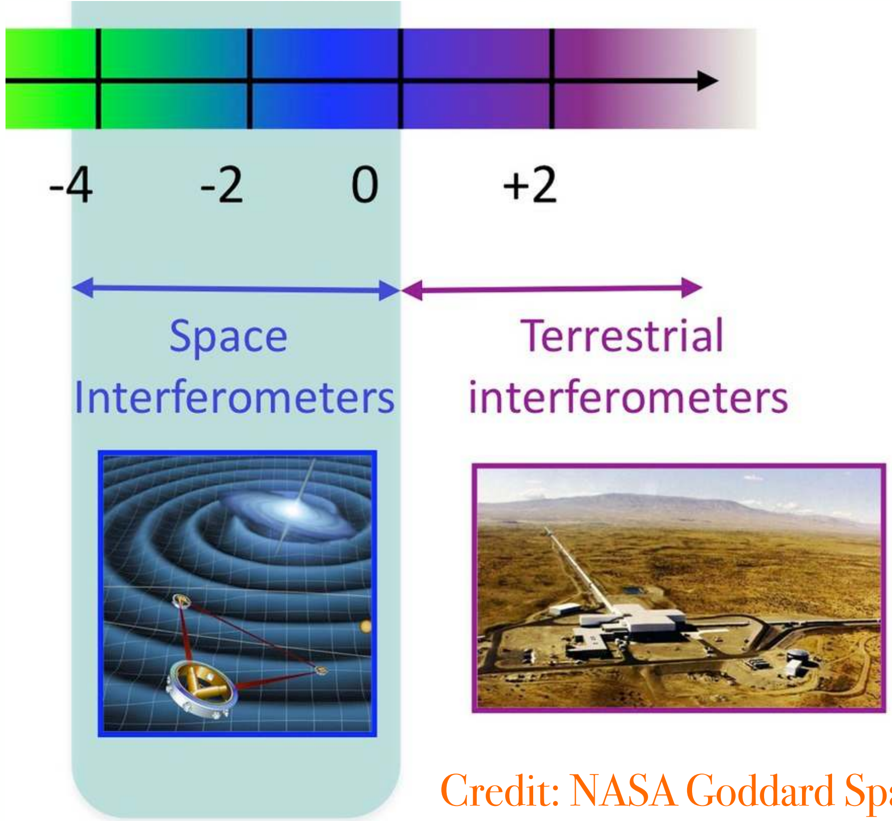

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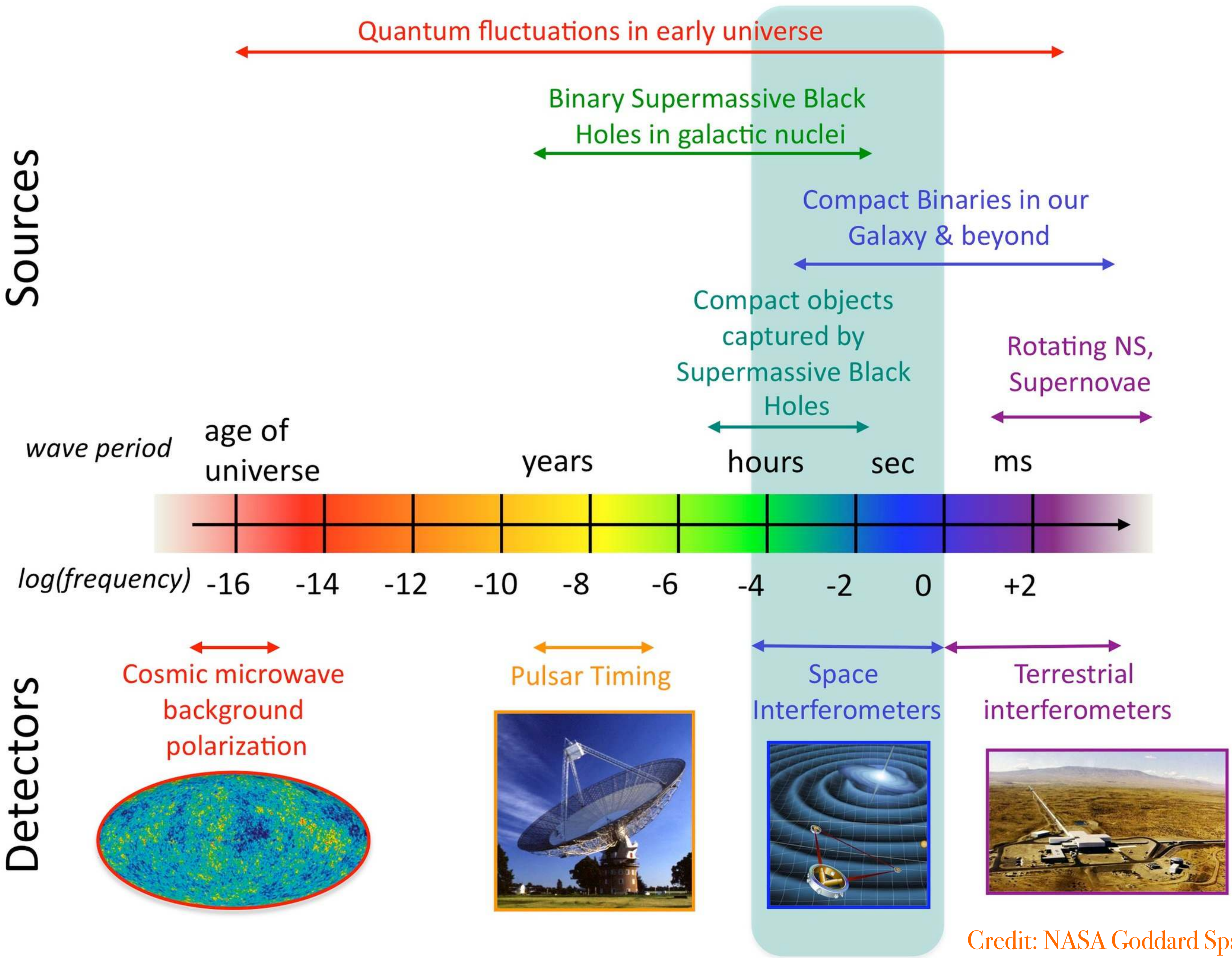

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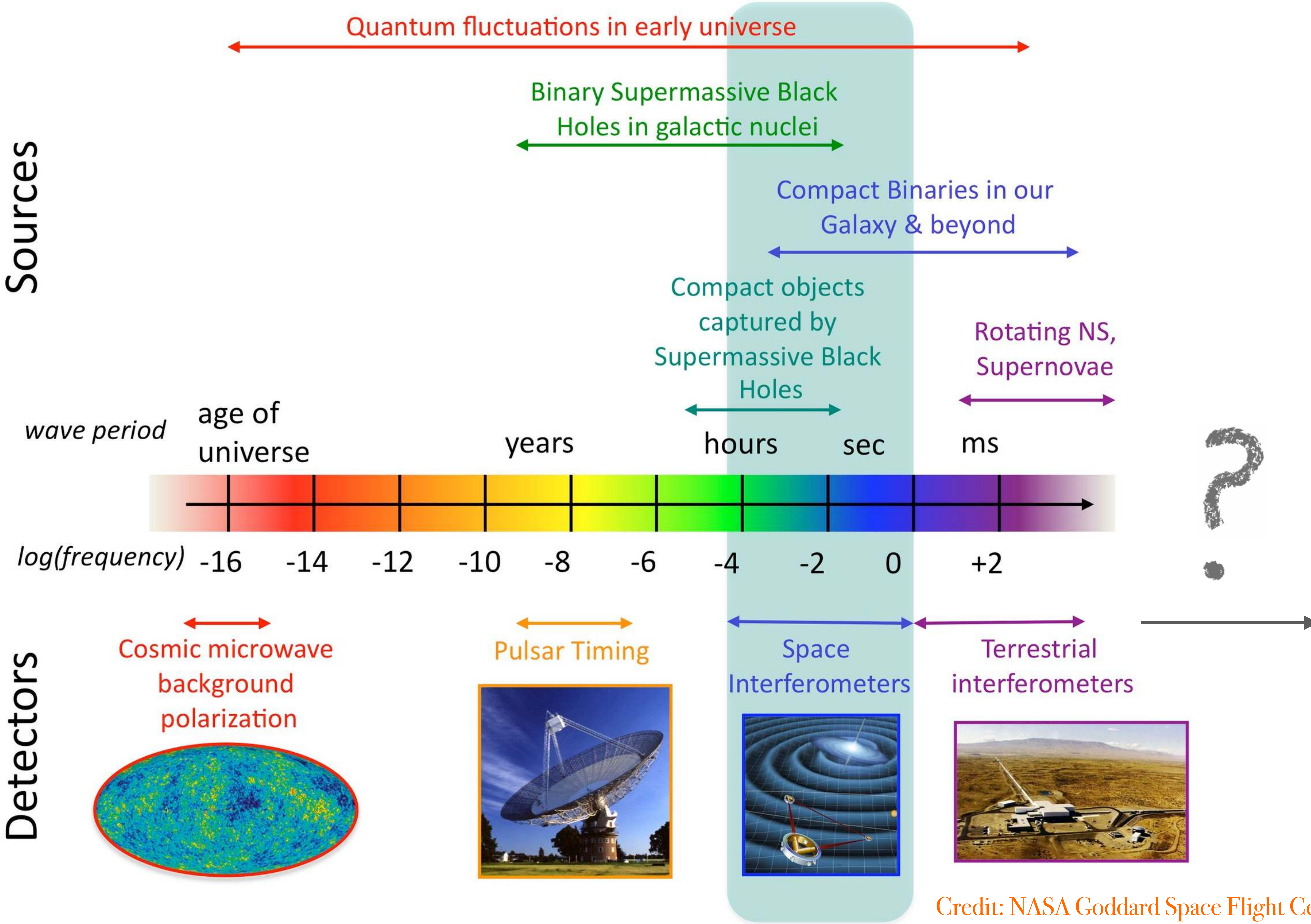

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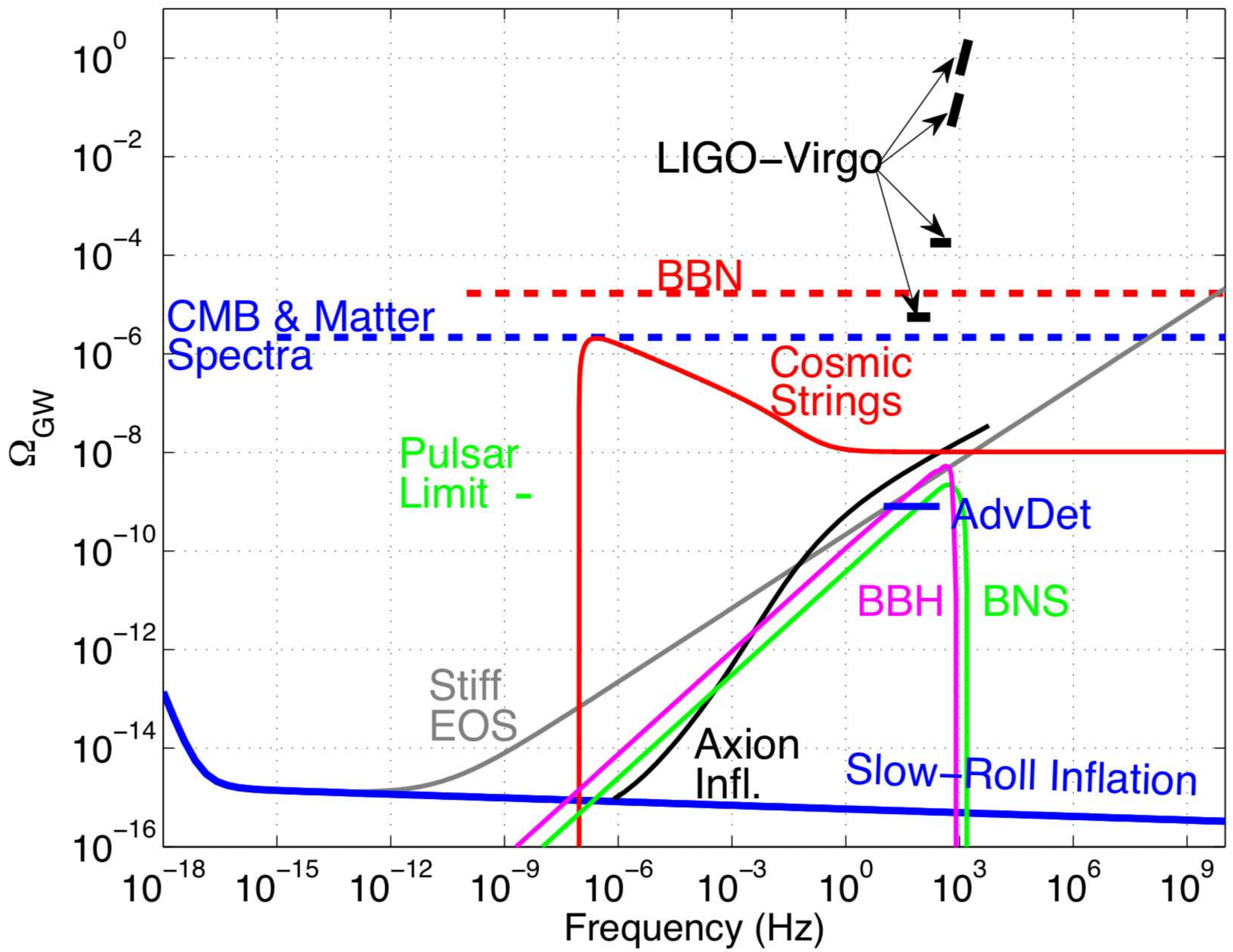
Gravitational Wave Spectrum

what about high frequencies?

LIGO - VIRGO, 2014



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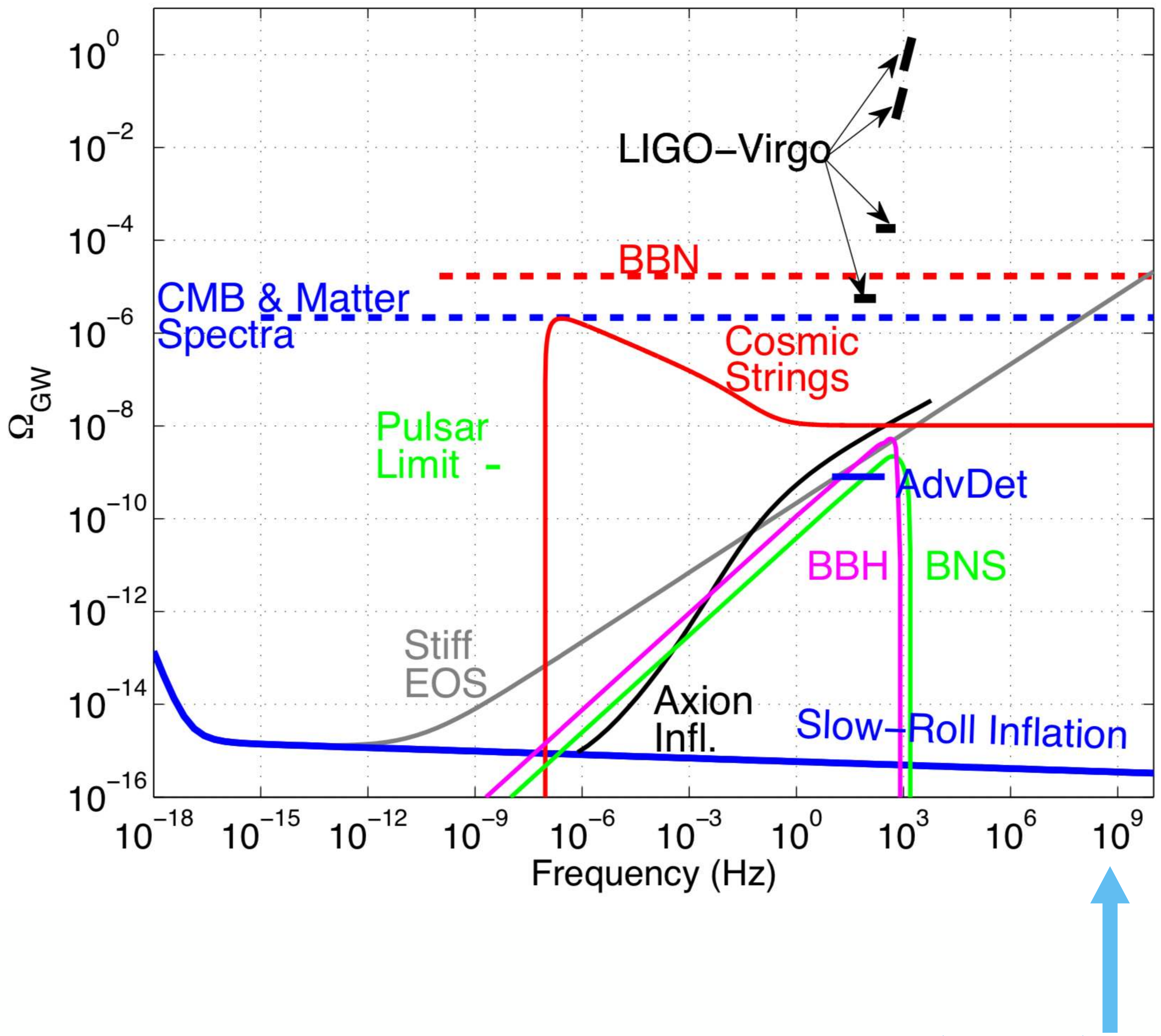

Radio and TeV astronomy

Domcke, CGC 2021

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Gravitational Wave Spectrum

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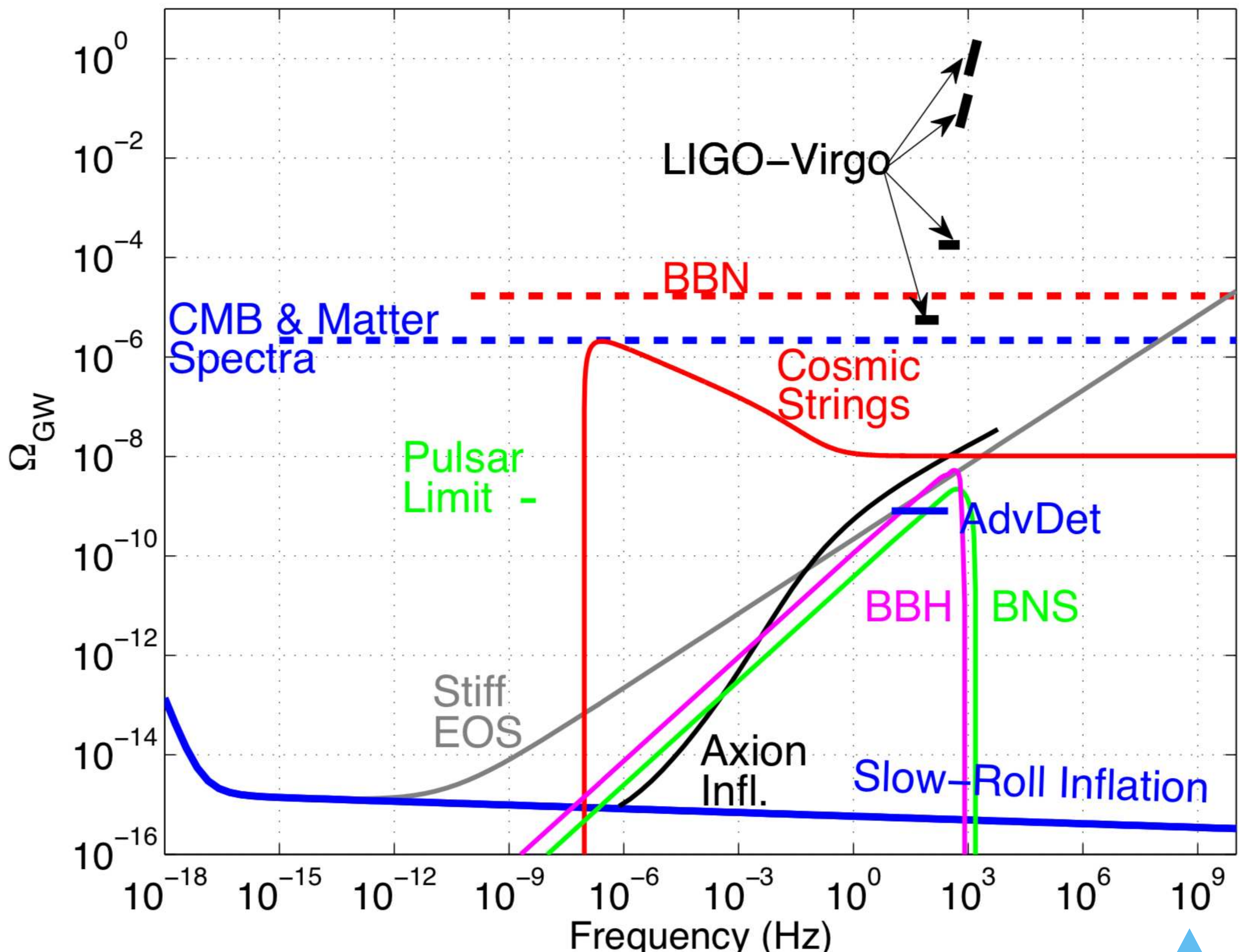

Cosmological constraints on radiation energy N_{eff}

Radio and TeV astronomy

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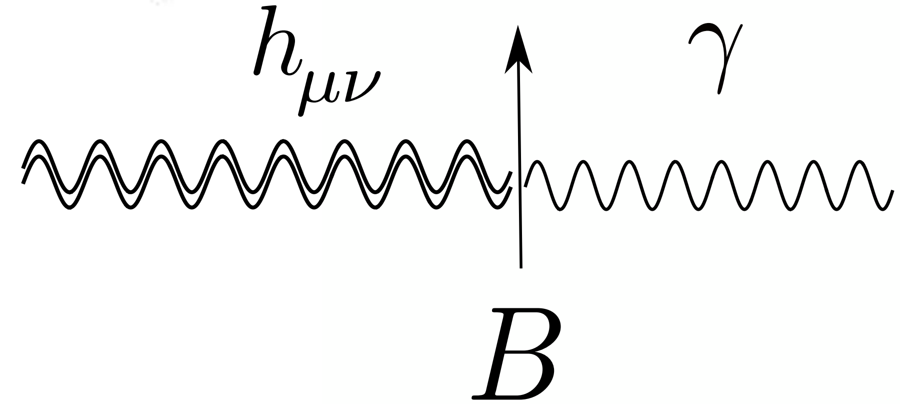
Gravitational Waves and the Gertsenhstein Effect

Revisiting Gertsenhstein's ideas

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.

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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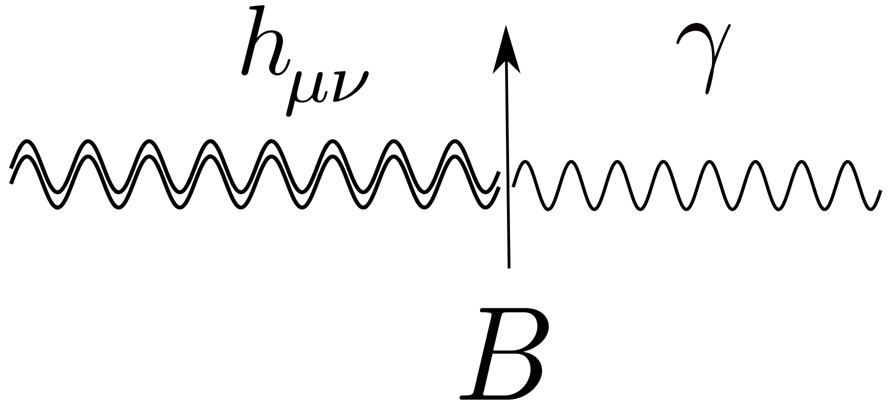
The (inverse) Gertsenhstein Effect

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



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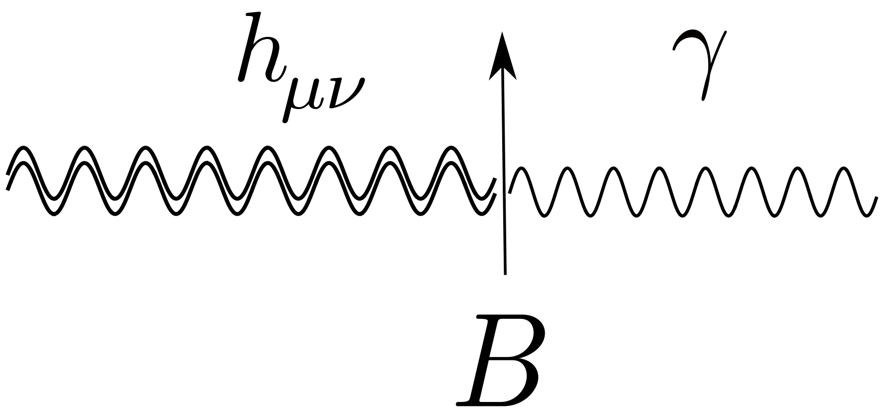

Axion dark matter

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

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

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Peccei, Quinn 1977

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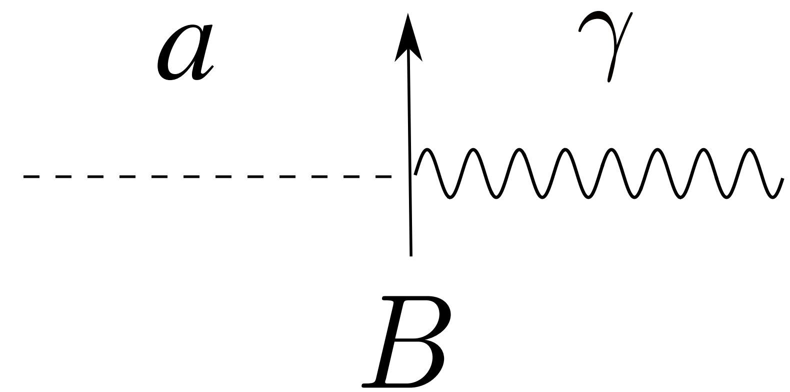

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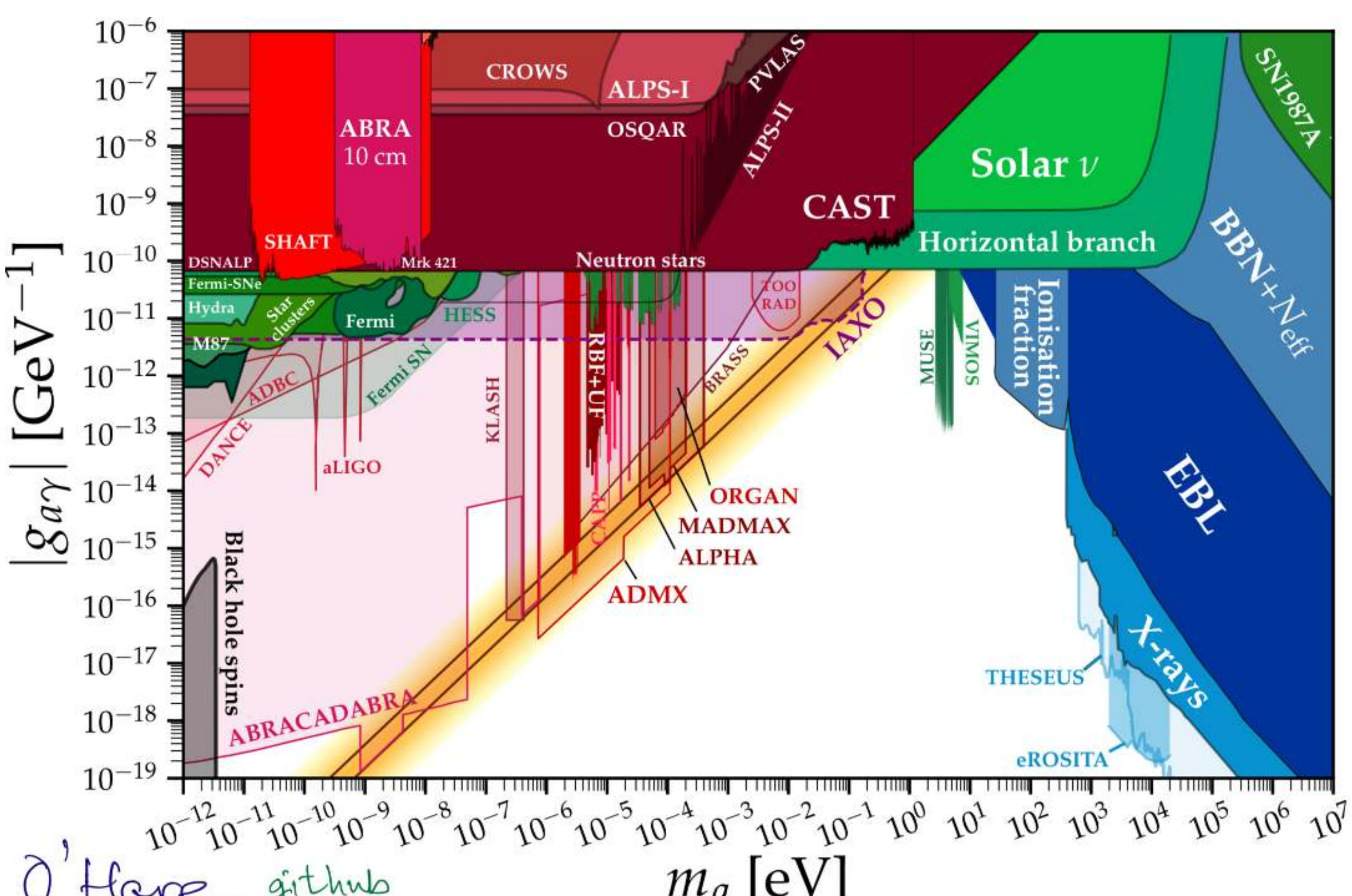

O'Hare github

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Axion dark matter

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

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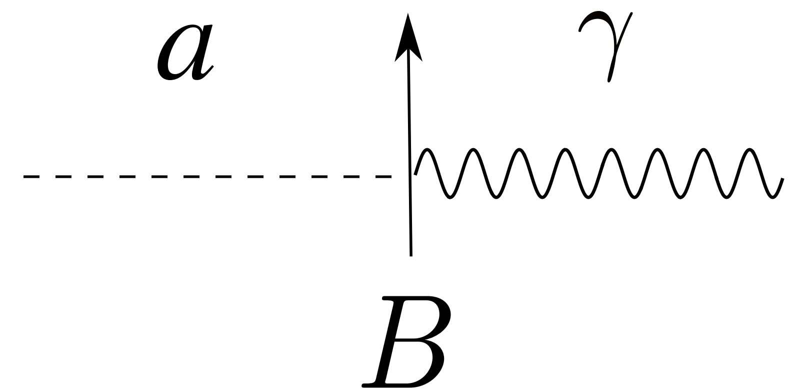

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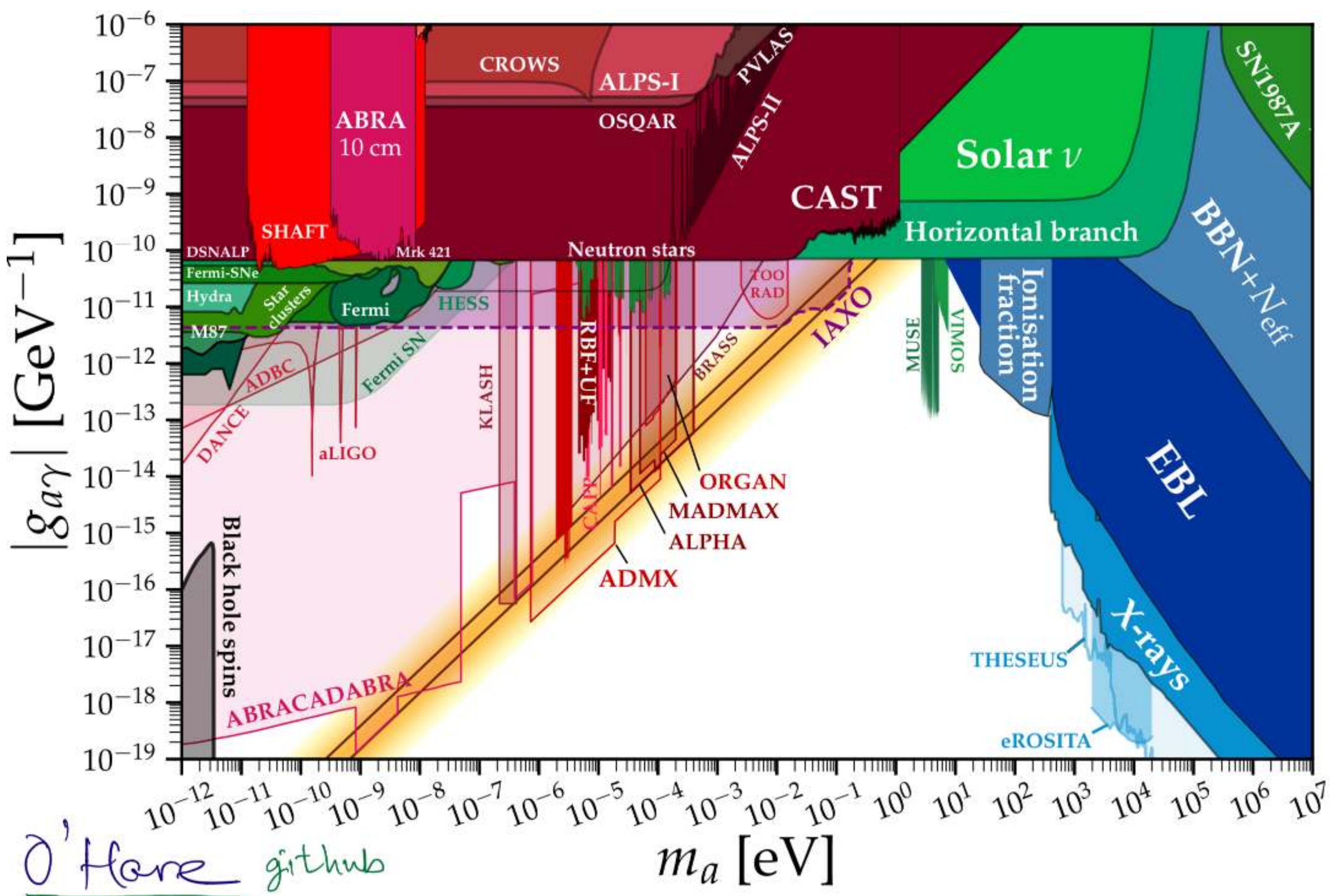

Camilo A. Garcia Cely

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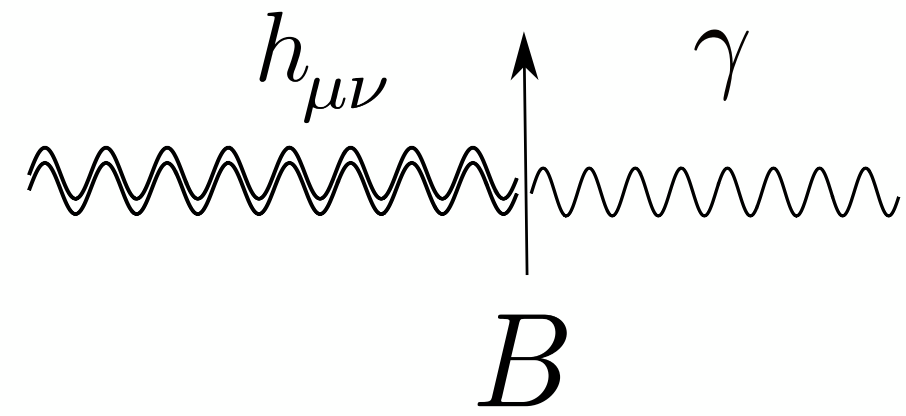
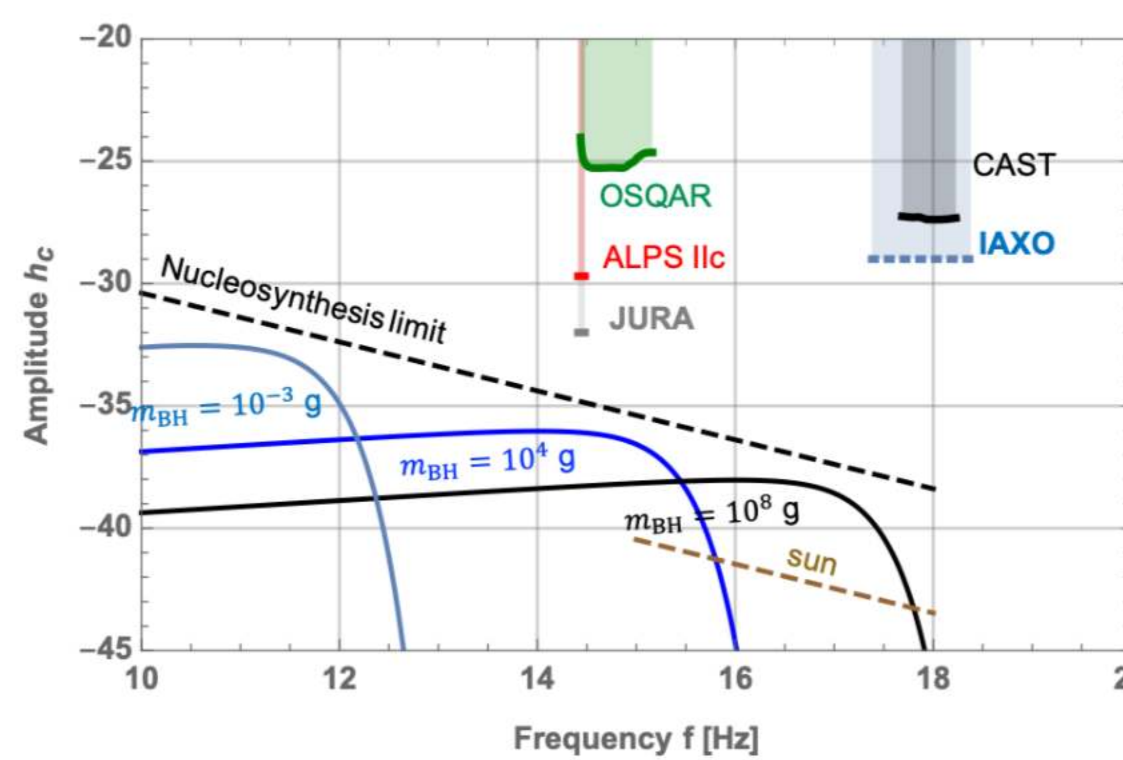


Upper limits on the amplitude of ultra-high-frequency gravitational waves from graviton to photon conversion

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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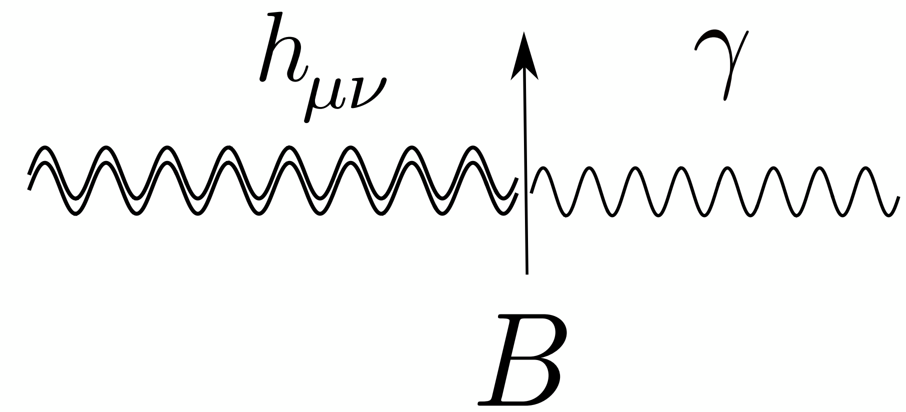

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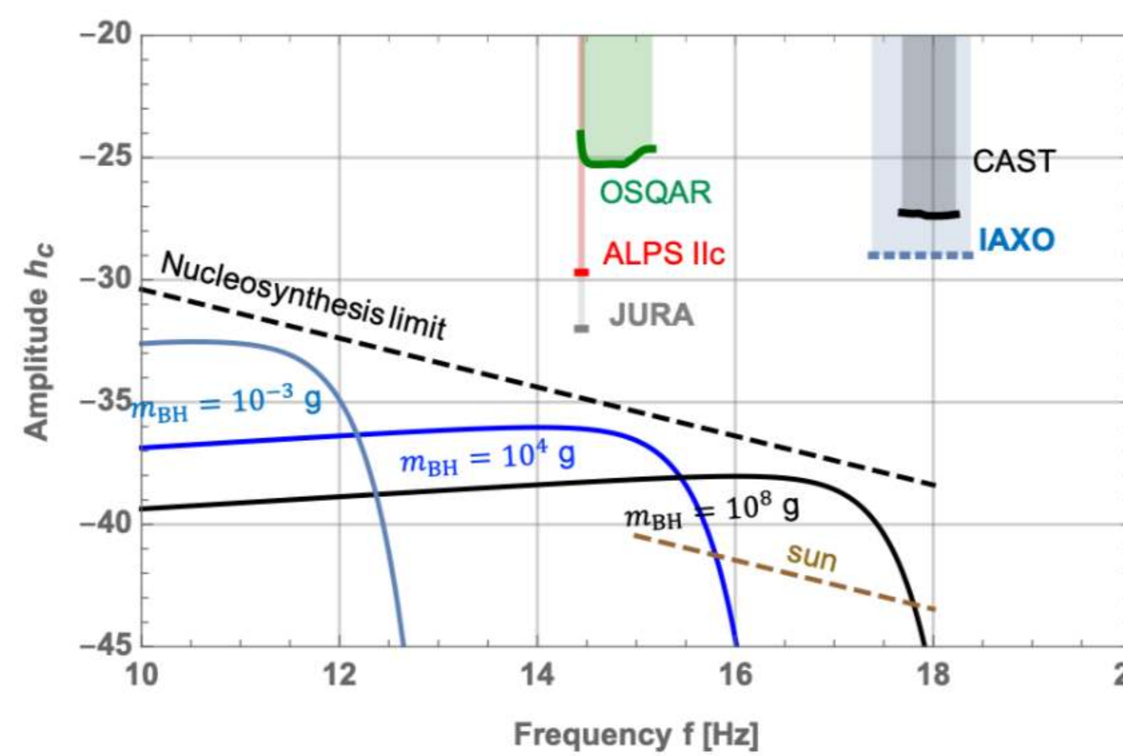

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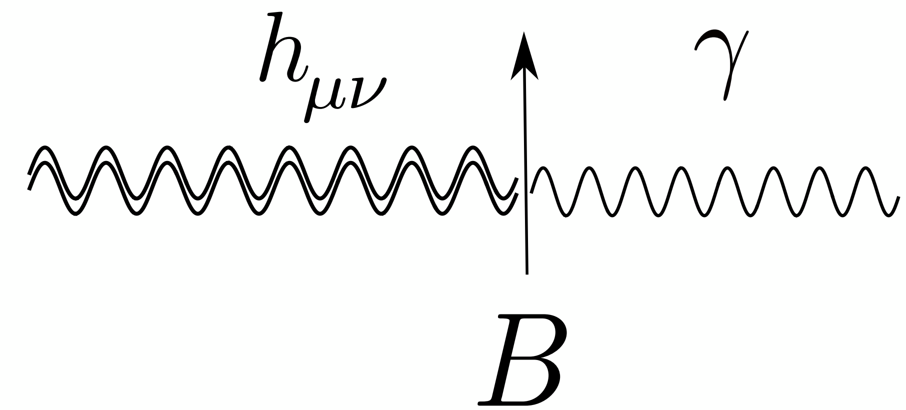

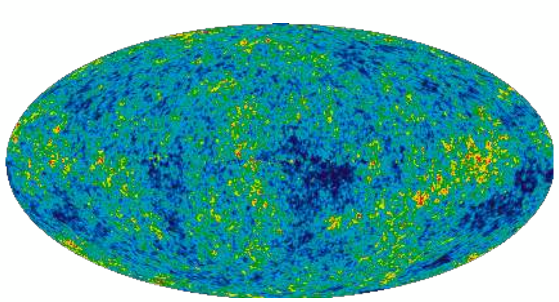

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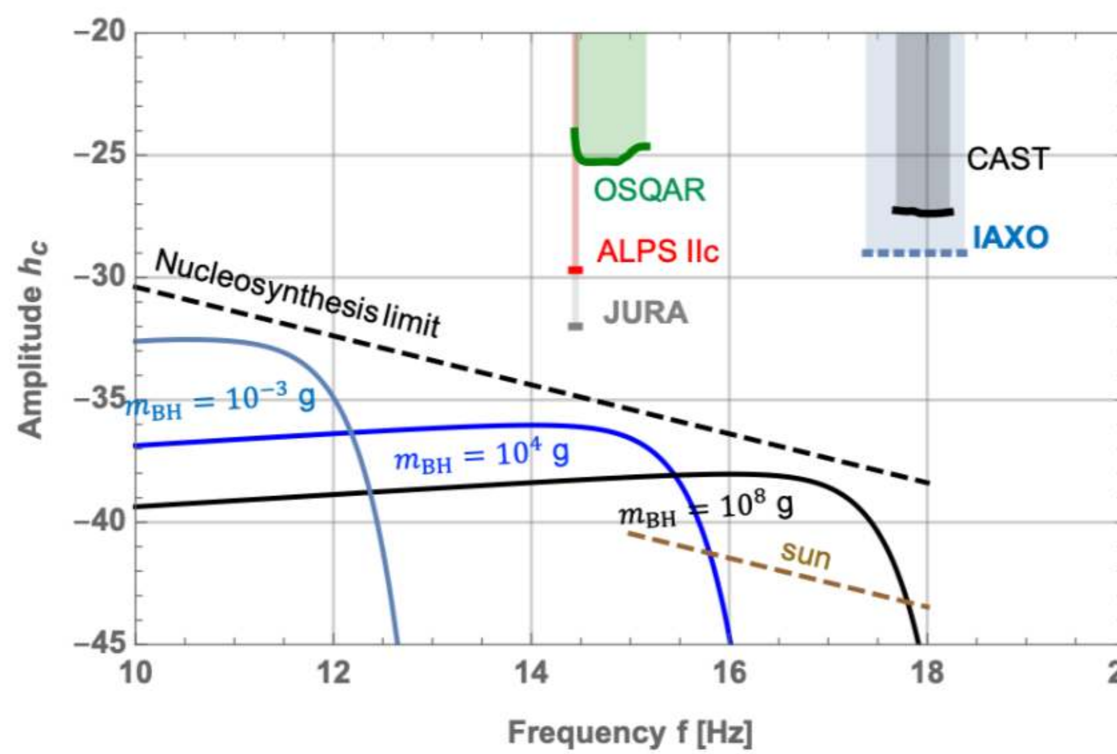

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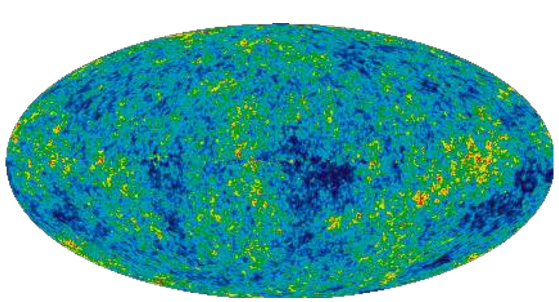
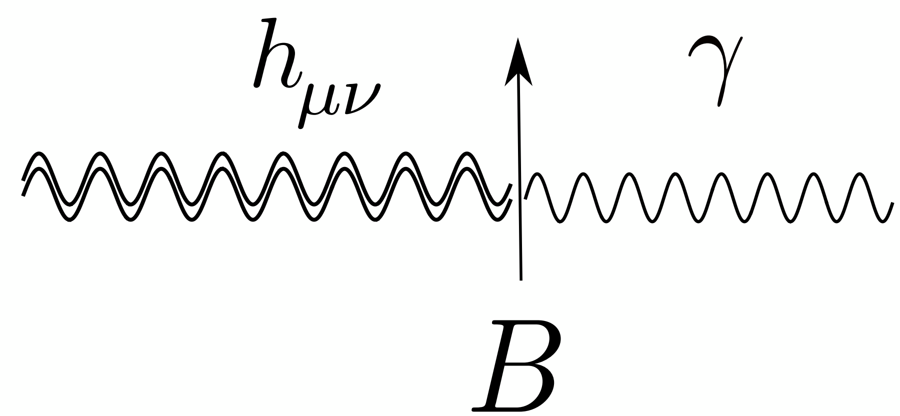
Domcke, CGC 2021

Dolgov, Ejlli 2012
Pshirkov, Baskaran 2009
Chen 1995





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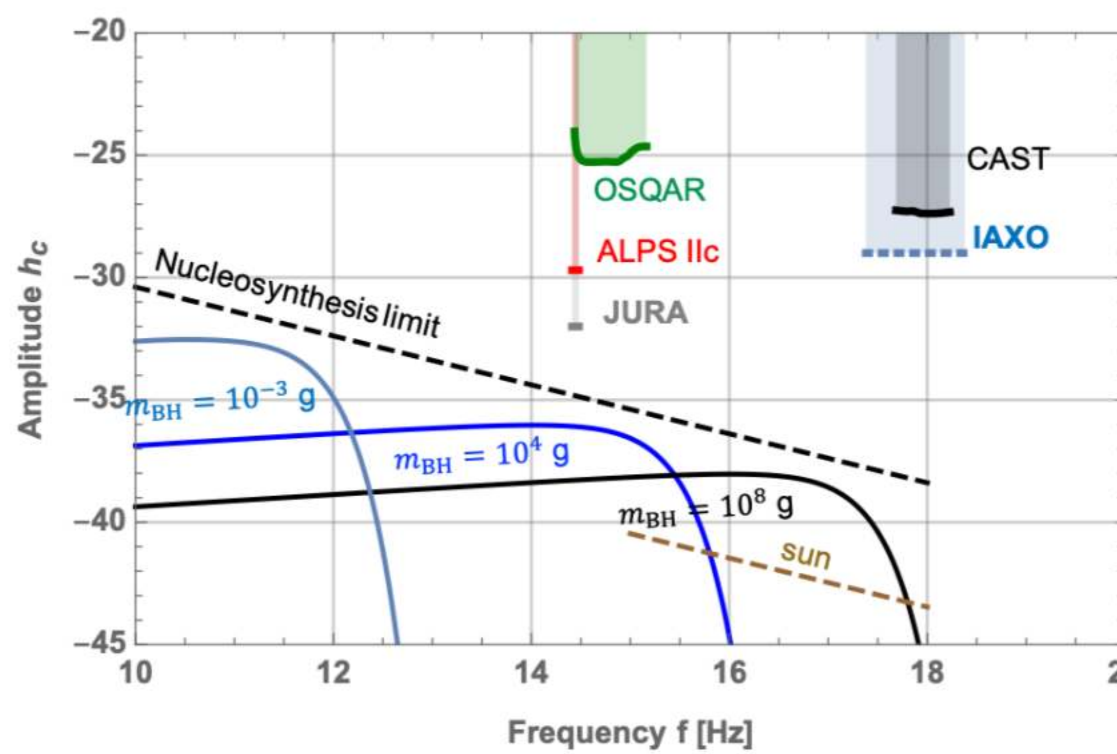

Camilo A. Garcia Cely

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.

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

average magnetic field

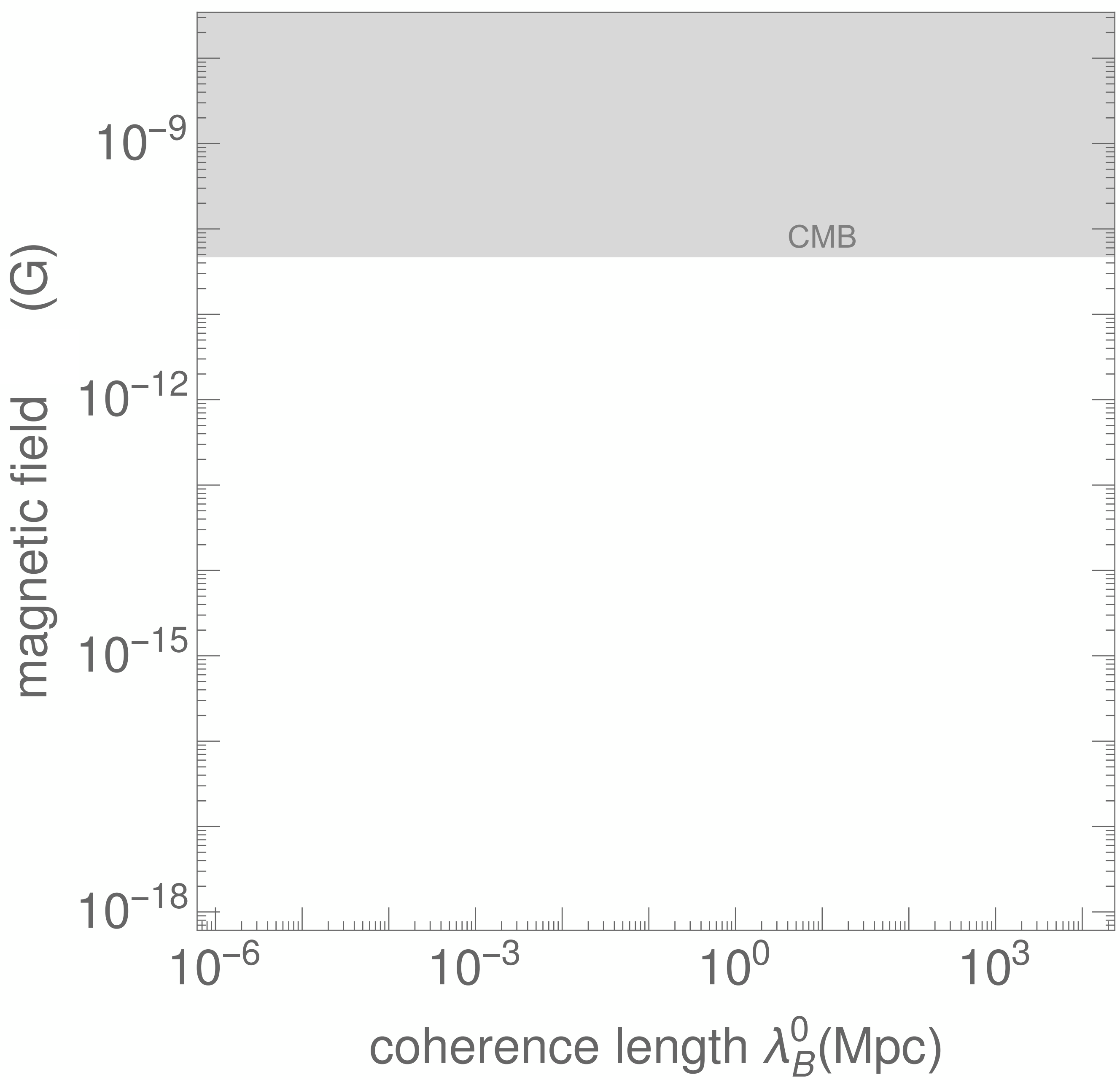
where $B_\lambda^2 \equiv \frac{8\pi}{\lambda^3 a(t)^4} P_B\left(\frac{2\pi}{\lambda}\right)$,

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

the coherence length

Camilo A. Garcia Cely

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,†]

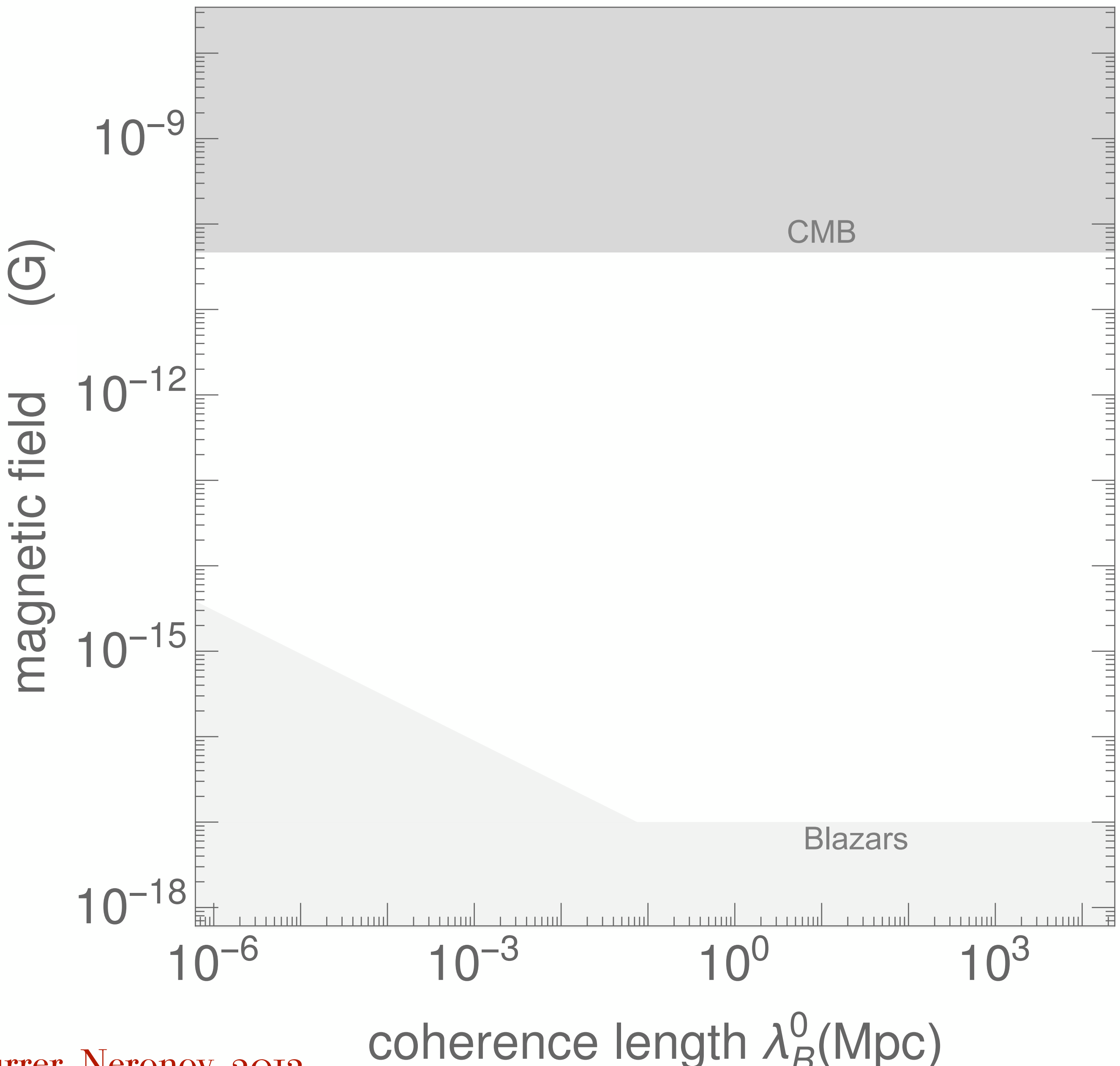
[1]*Laboratoire Univers et Particules de Montpellier, UMR5299-CNRS, Université de Montpellier, 34095 Montpellier, France*
[2]*Institute of Physics, Mathematics and Information Technology, Immanuel Kant Baltic Federal University, 236016 Kaliningrad, Russia*
[3]*Faculty of Computational Mathematics and 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.

Camilo A. Garcia Cely

Cosmic magnetic fields in 2021



Durrer, Neronov, 2013

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REPORT

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 Figures & Data Info & Metrics eLetters PDF

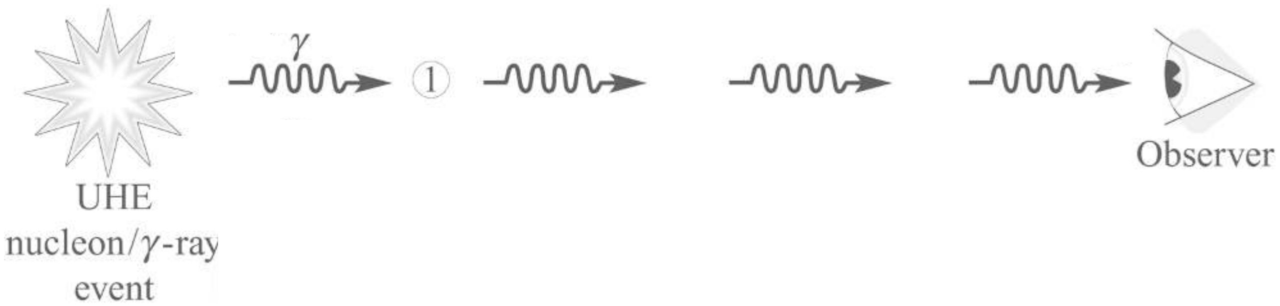
Abstract

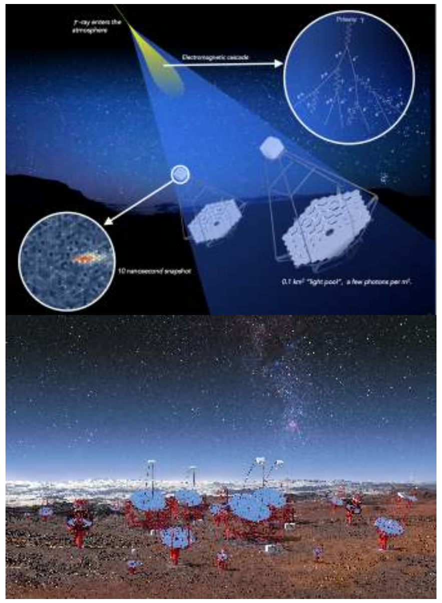
Magnetic fields in galaxies are produced via the amplification of seed magnetic fields of unknown nature. The seed fields, which might exist in their initial form in the intergalactic medium, were never detected. We report a lower bound $B \geq 3 \times 10^{-16}$ gauss on the strength of intergalactic 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.

Camilo A. Garcia Cely

Evidence from TeV Blazars

Kronberg , 2016
Cambridge University Press





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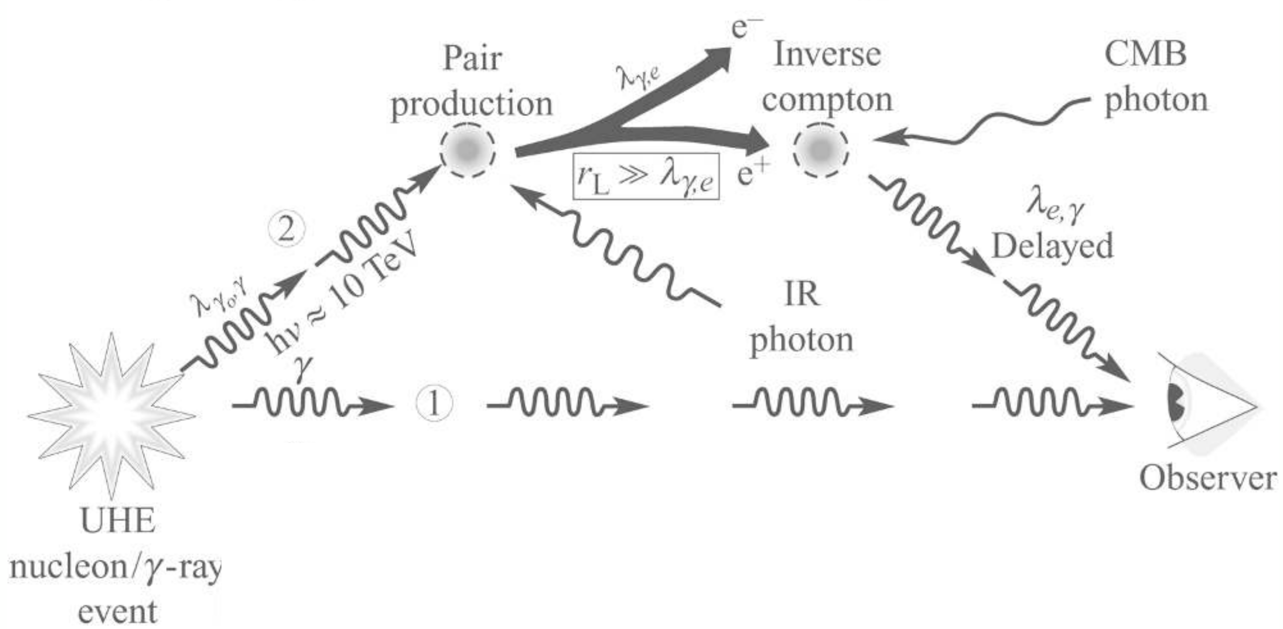
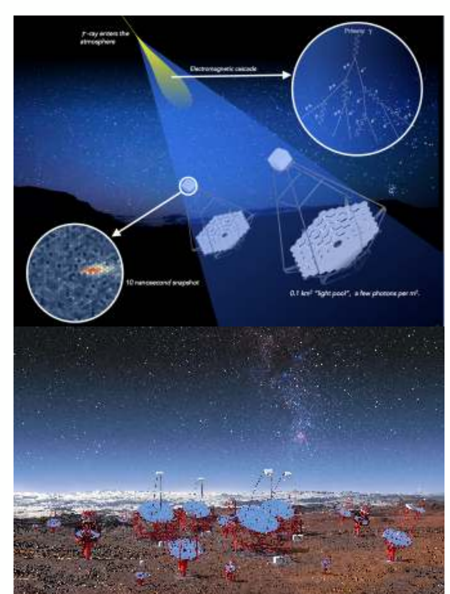
High energy $h\nu$ –e^+e^- cascades in the intergalactic medium





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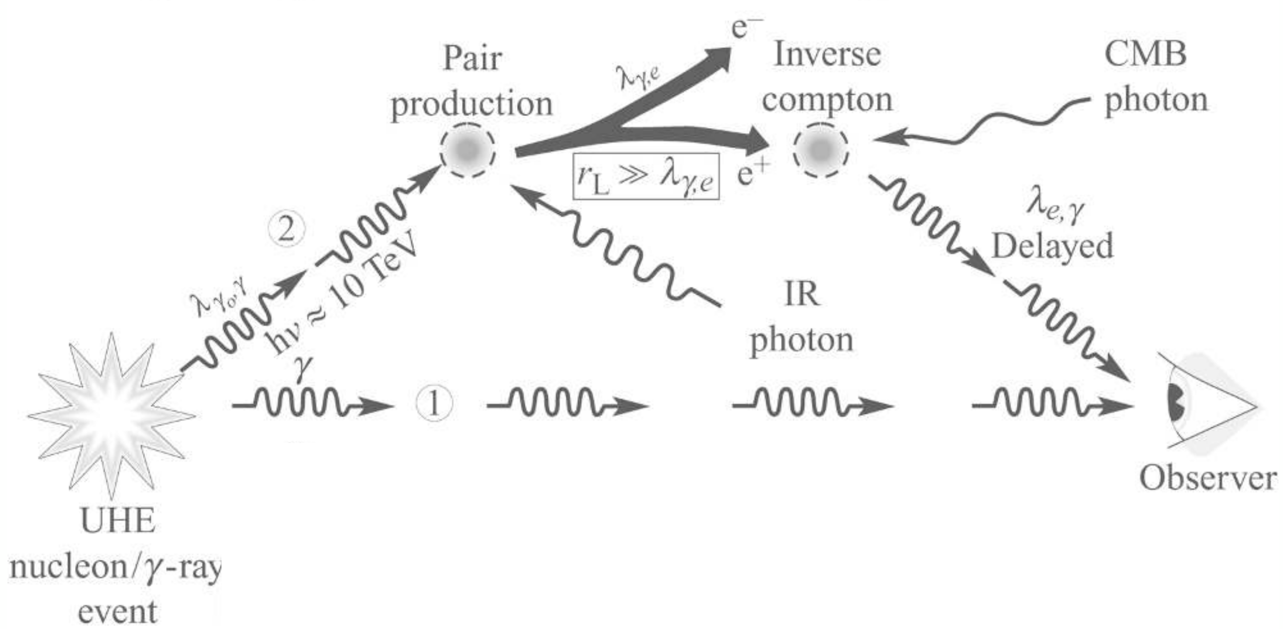

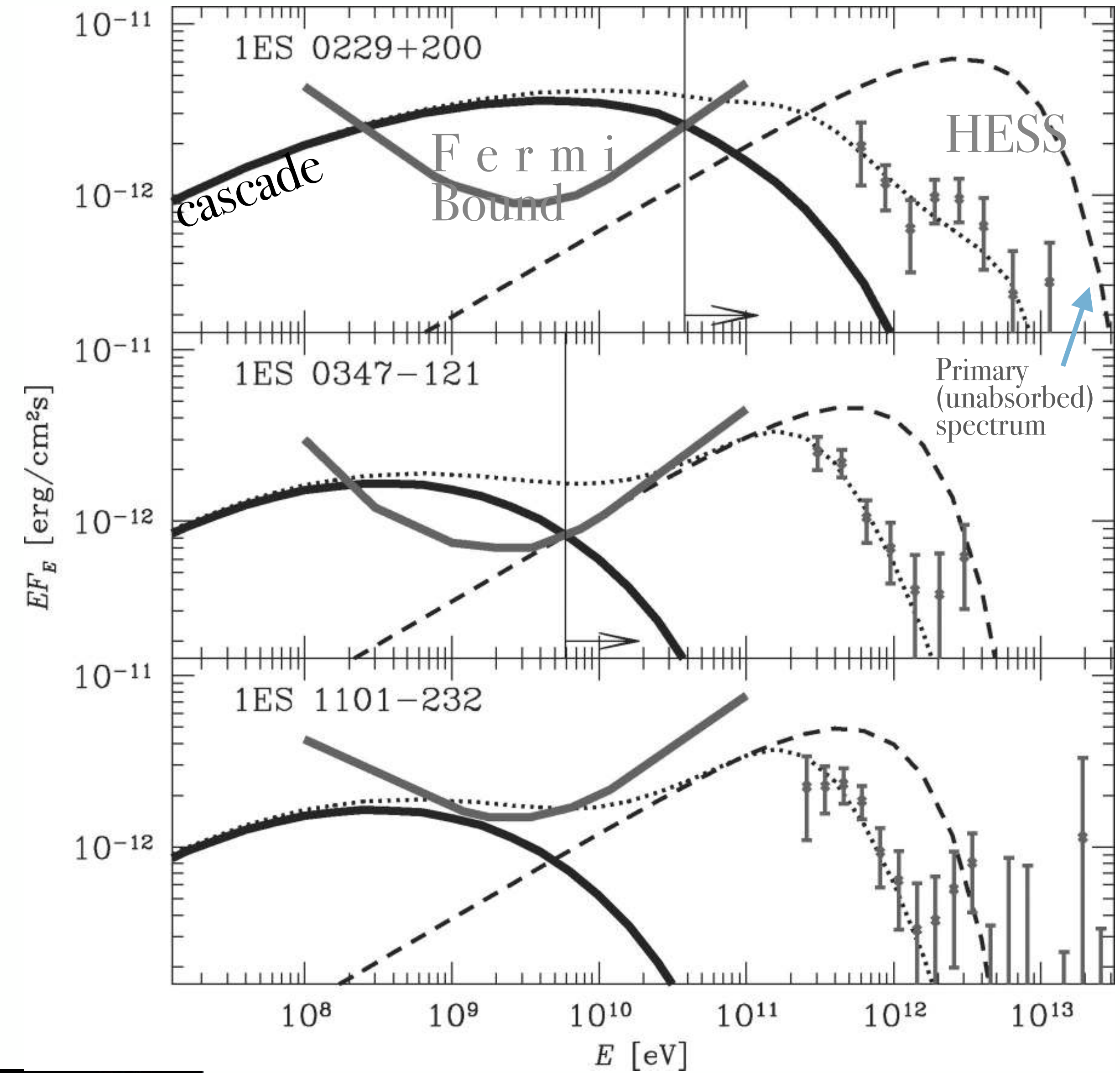

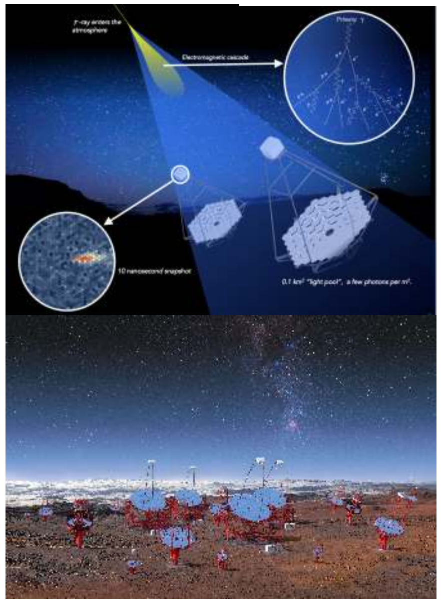

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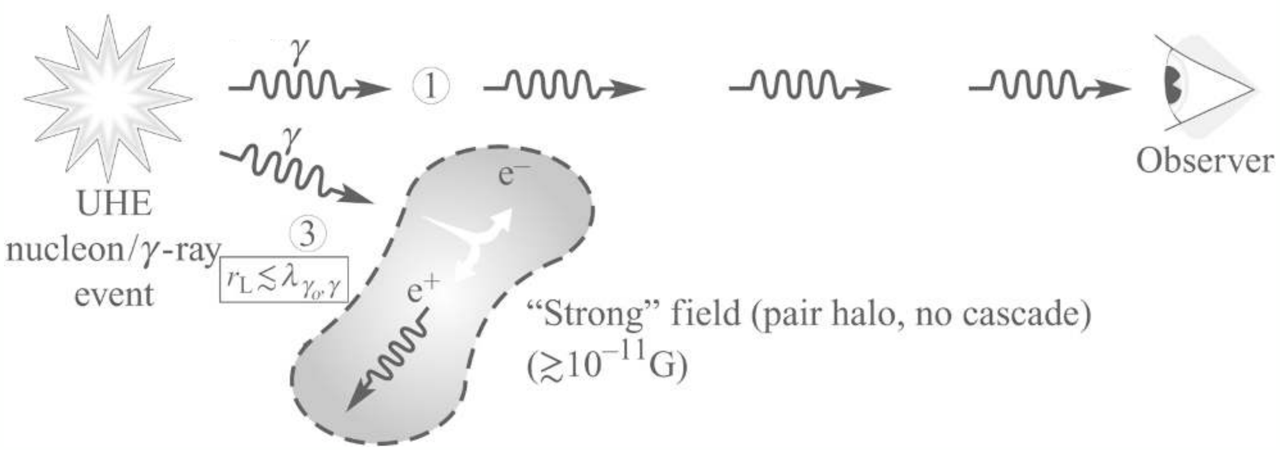
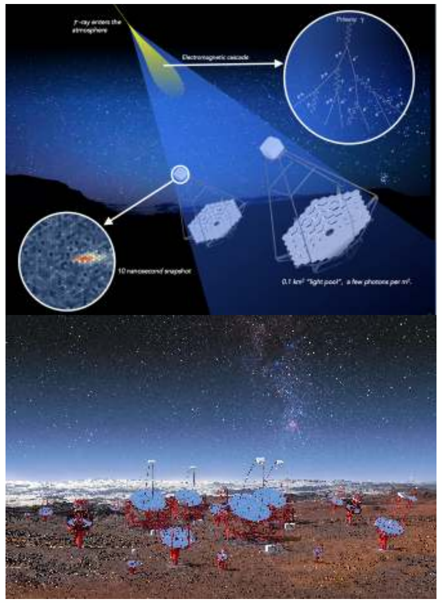
Evidence from TeV Blazars

Kronberg , 2016
Cambridge University Press





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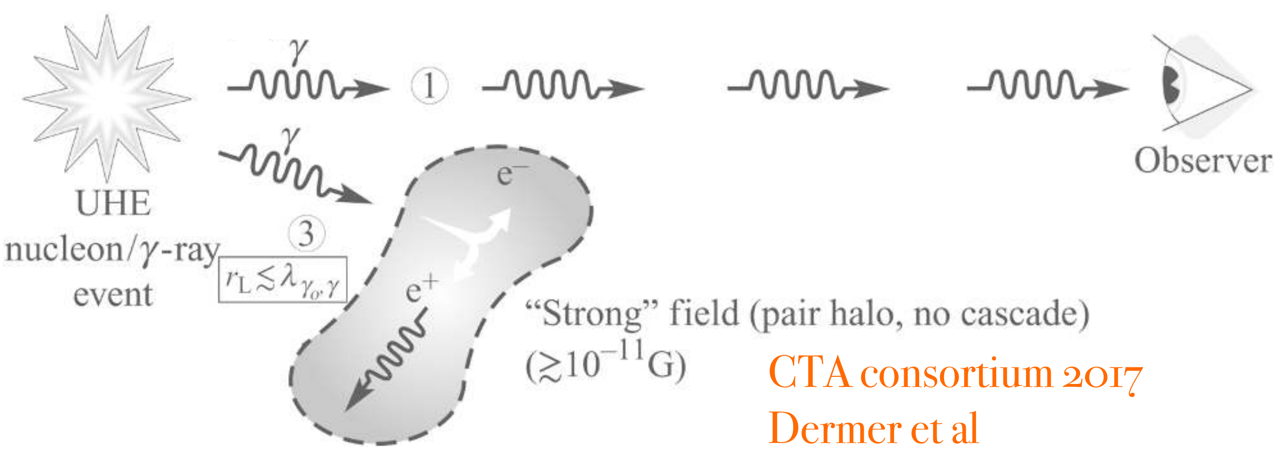
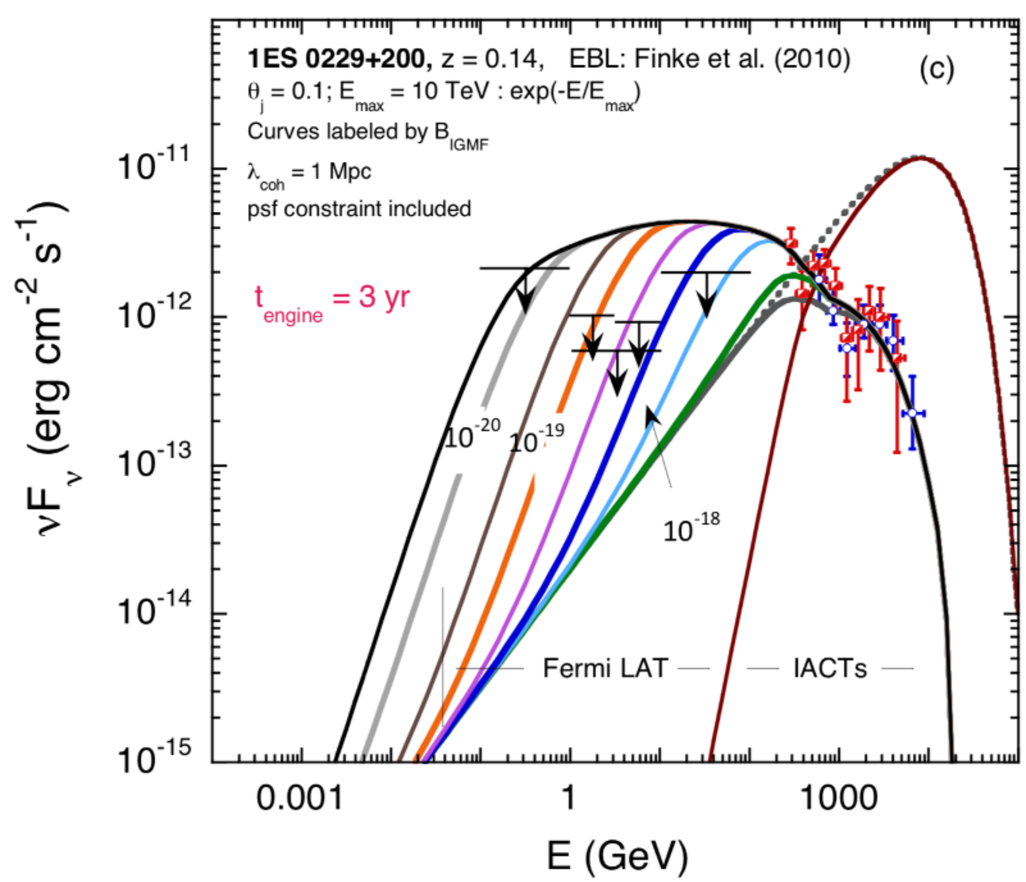
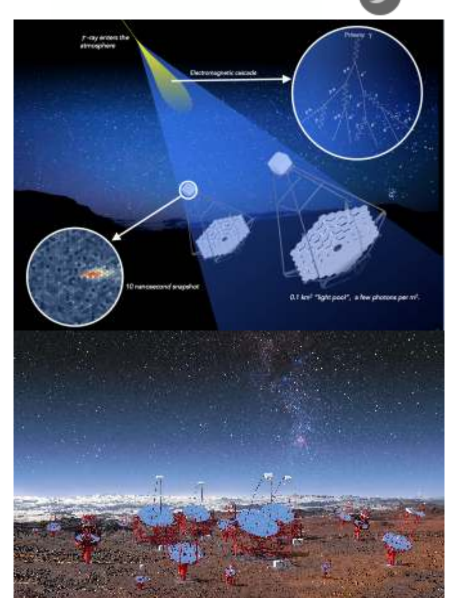
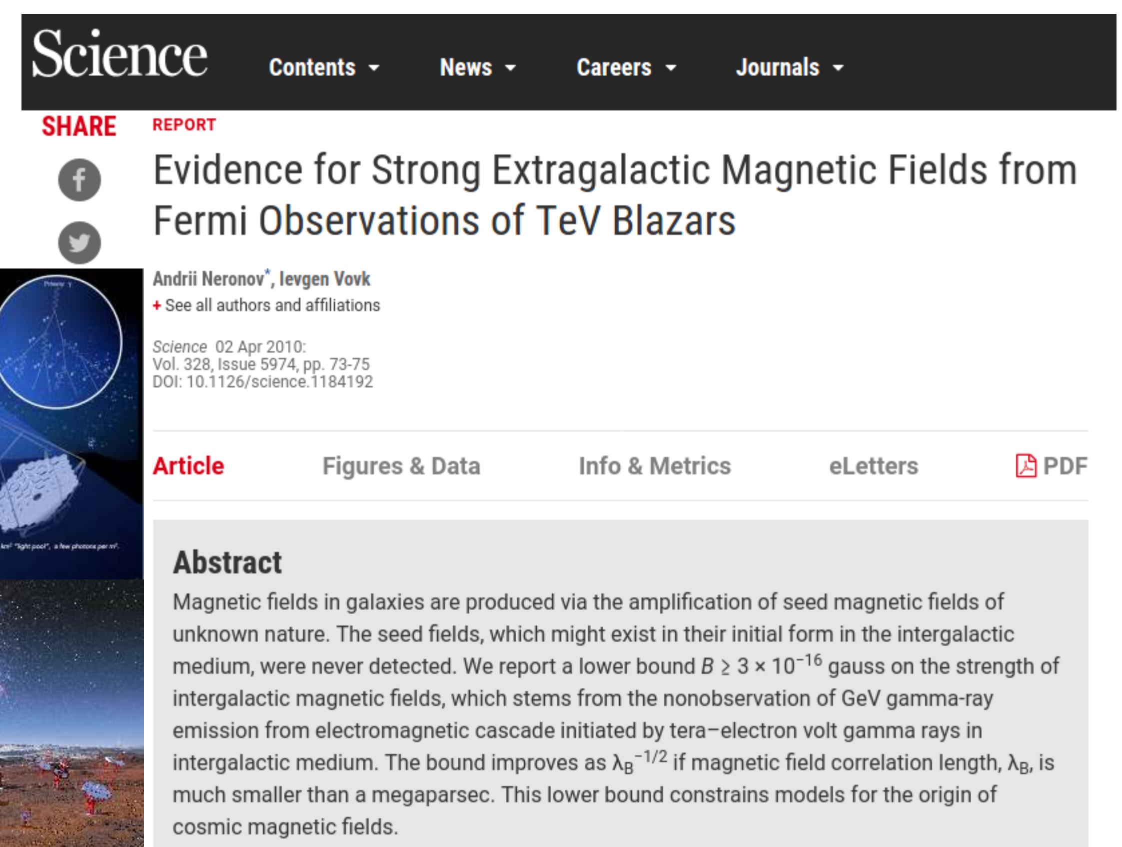


CTA consortium 2017
Dermer et al



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Andrii Neronov*, Ievgen Vovk
+ See all authors and affiliations

Science 02 Apr 2010:
Vol. 328, Issue 5974, pp. 73-75
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Article Figures & Data Info & Metrics eLetters PDF

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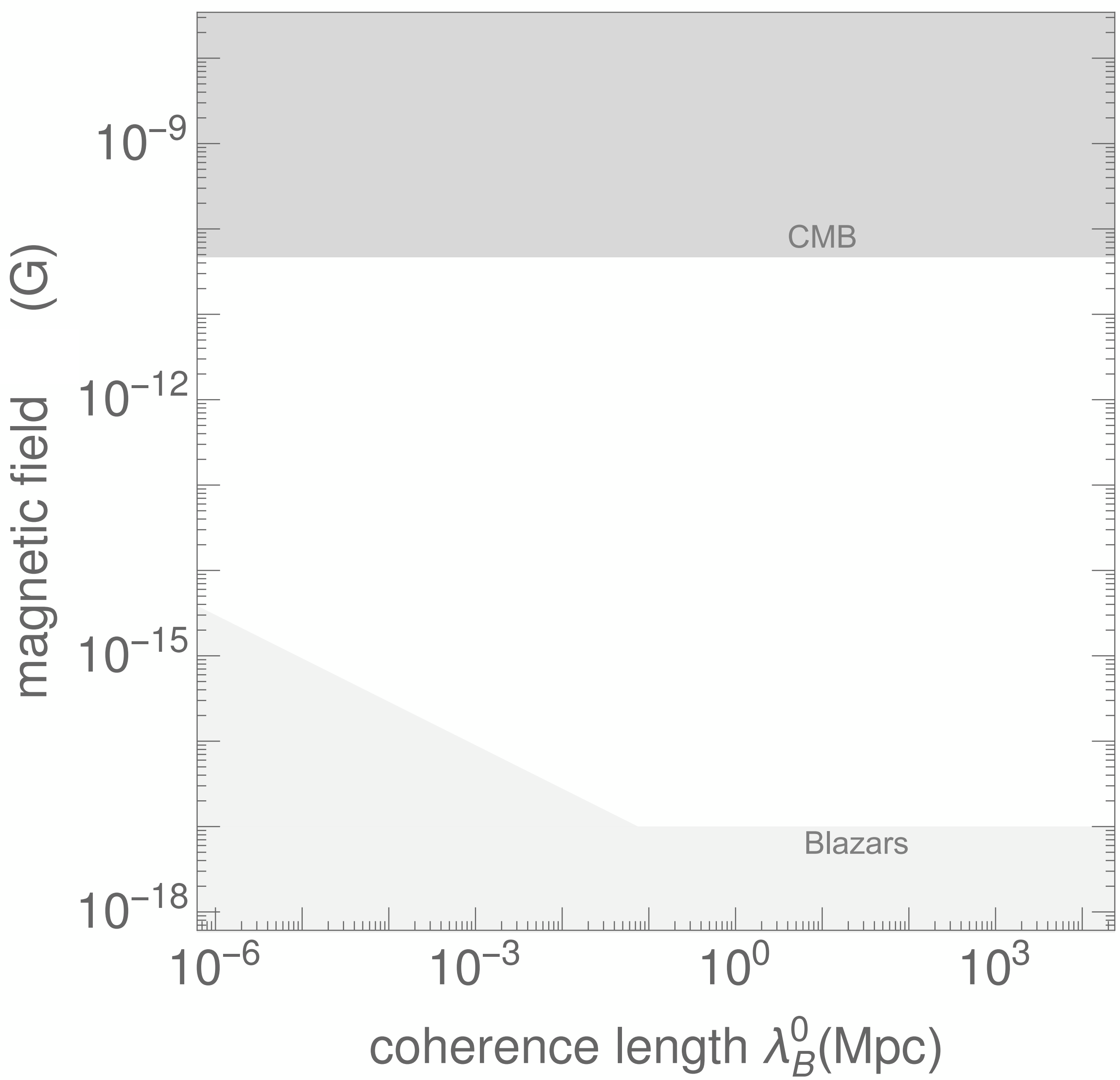
Camilo A. Garcia Cely

Evidence from TeV Blazars

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



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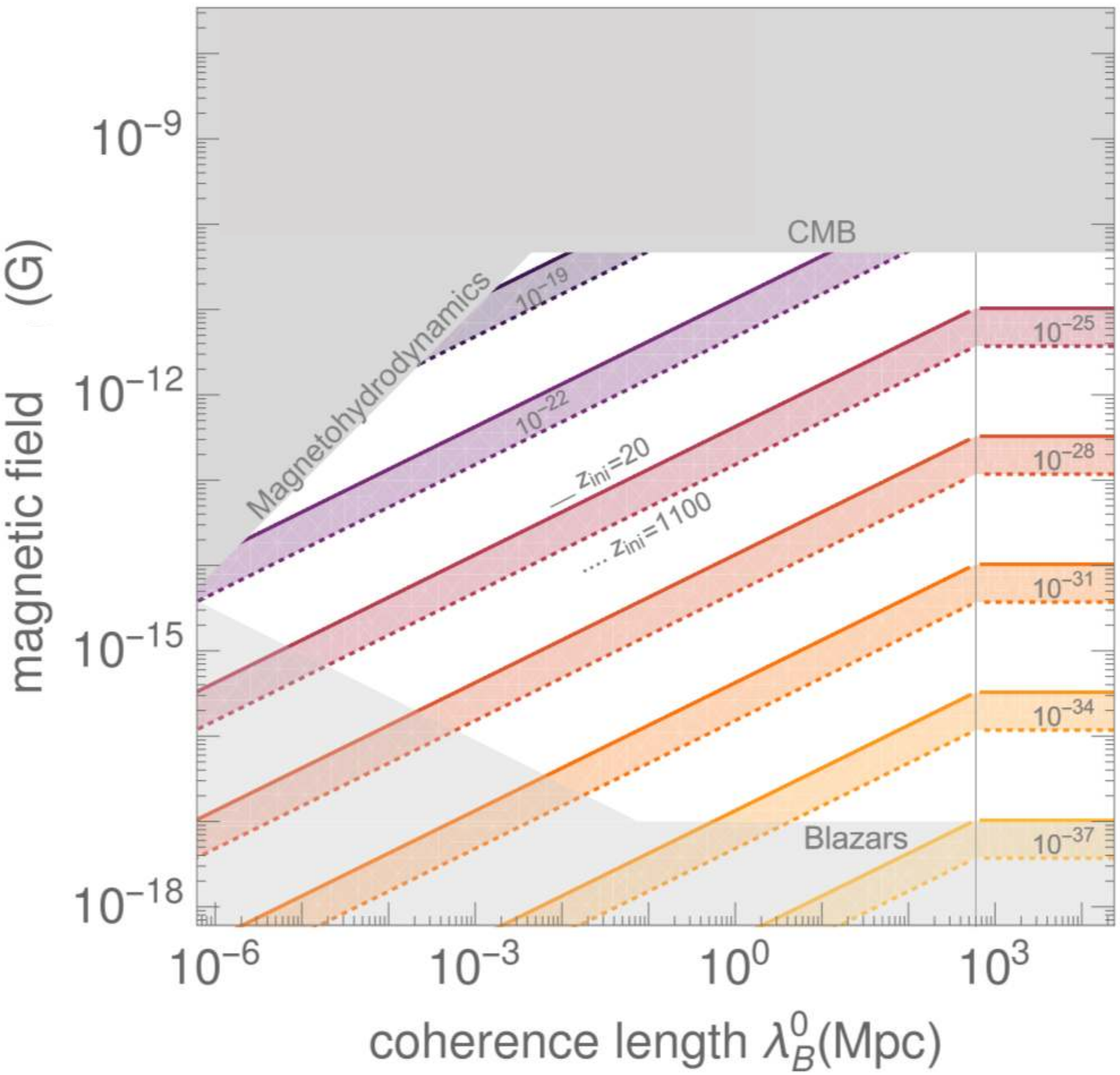
Cosmic magnetic fields in 2021

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,†]

[1]*Laboratoire Univers et Particules de Montpellier, UMR5299-CNRS, Université de Montpellier, 34095 Montpellier, France*
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Oscillations after the formation of the CMB

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

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

$$\omega_{\rm pl} = \sqrt{e^2 n_e / m_e}$$

The plasma frequency acts as an effective mass term

Domcke, CGC 2021

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Domcke, CGC 2021

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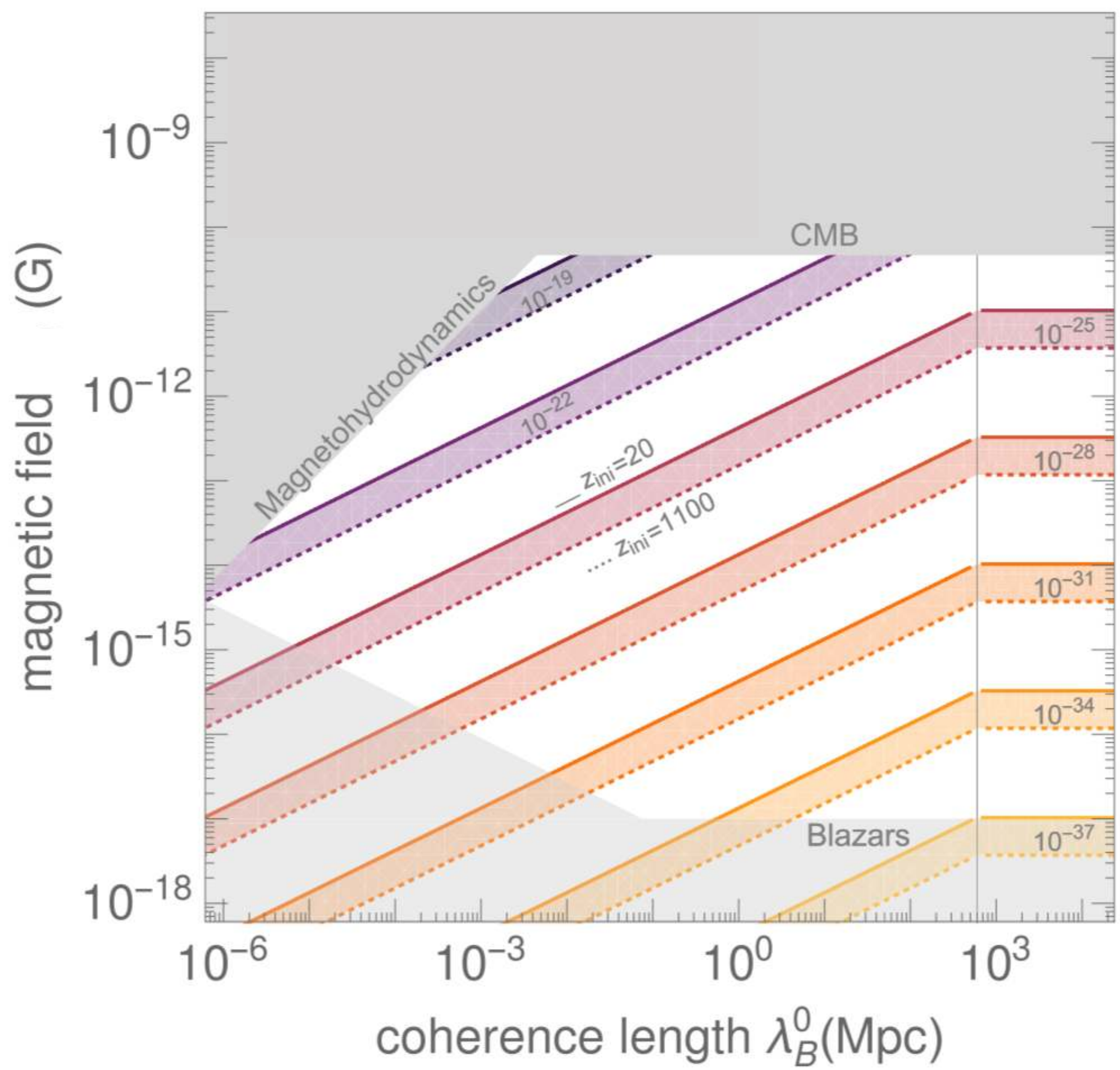
Domcke, CGC 2021



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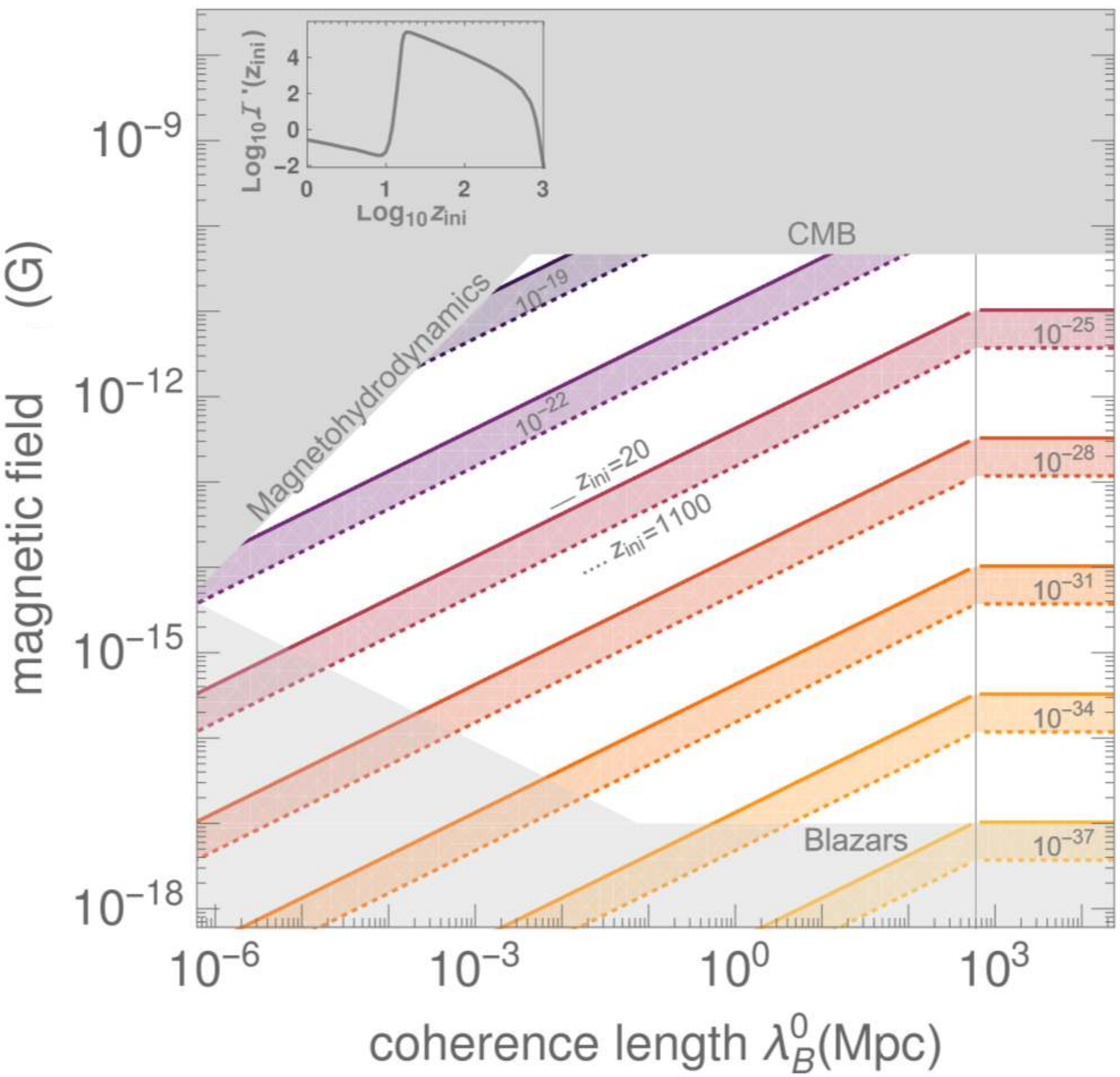
Domcke, CGC 2021



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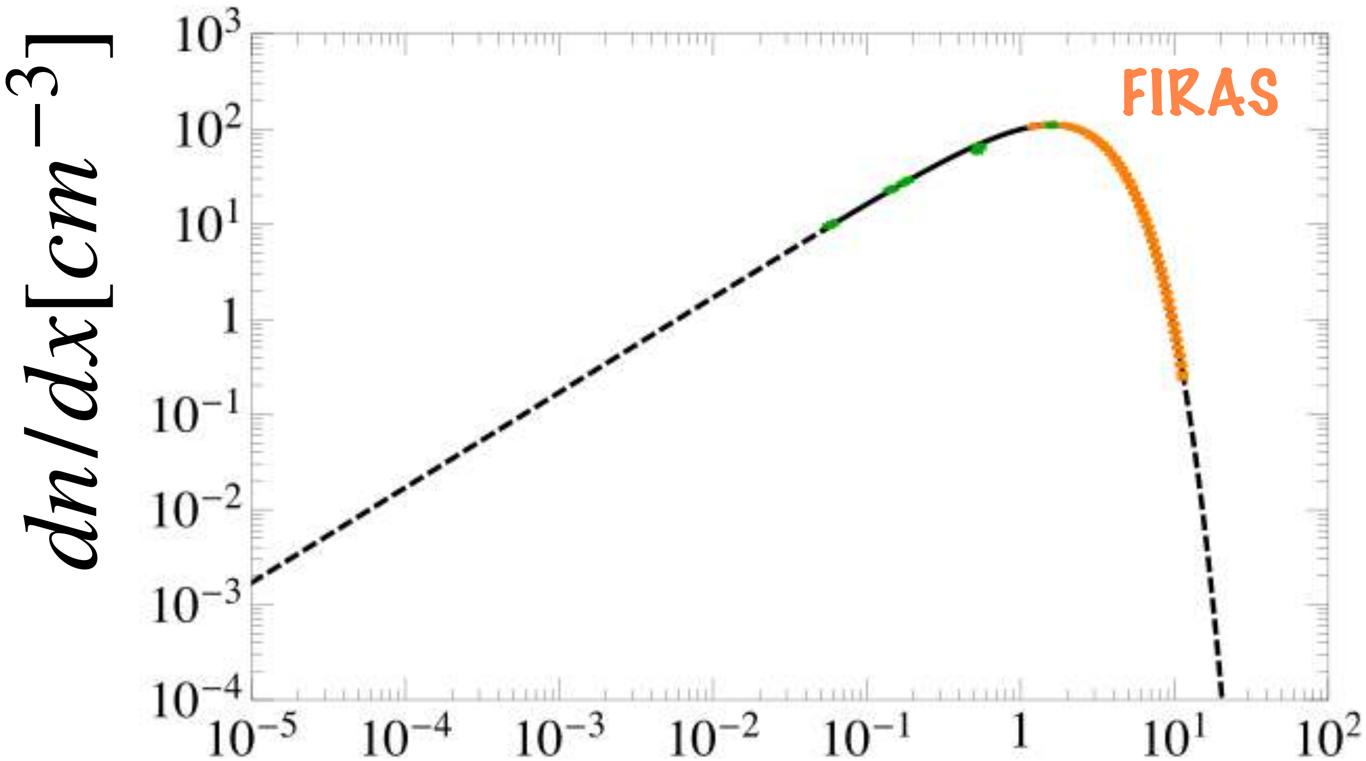
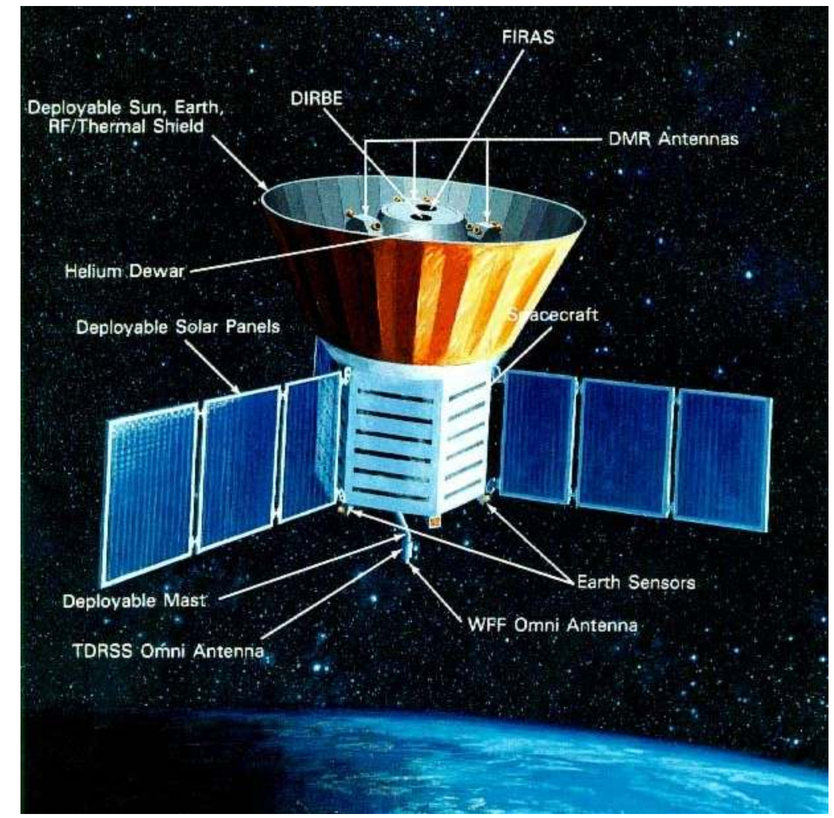
CMB observations and 21-cm cosmology

CMB distortions





THE ASTROPHYSICAL JOURNAL, 473:576–587, 1996 December 20

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. WRIGHT[4]
Received 1996 January 19; accepted 1996 July 11

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Subject headings: cosmic microwave background — cosmology: observations

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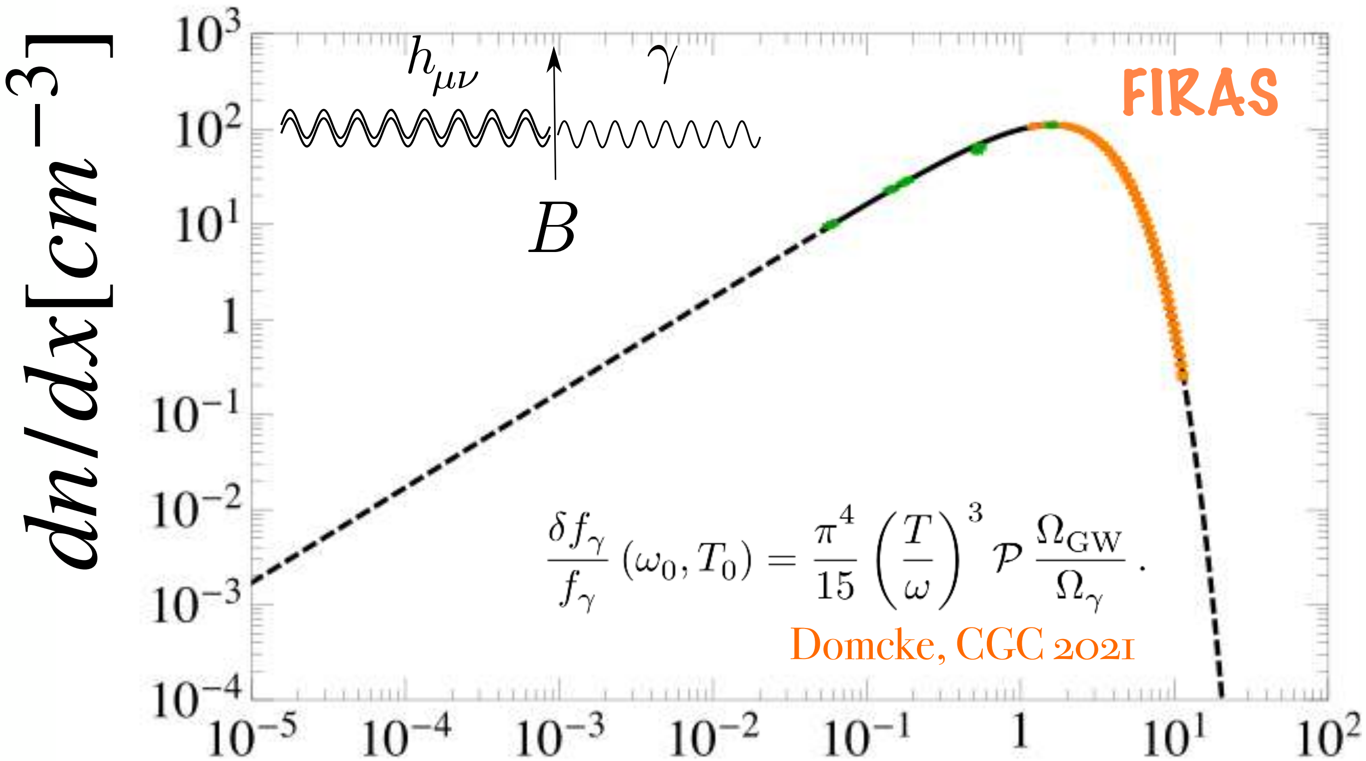

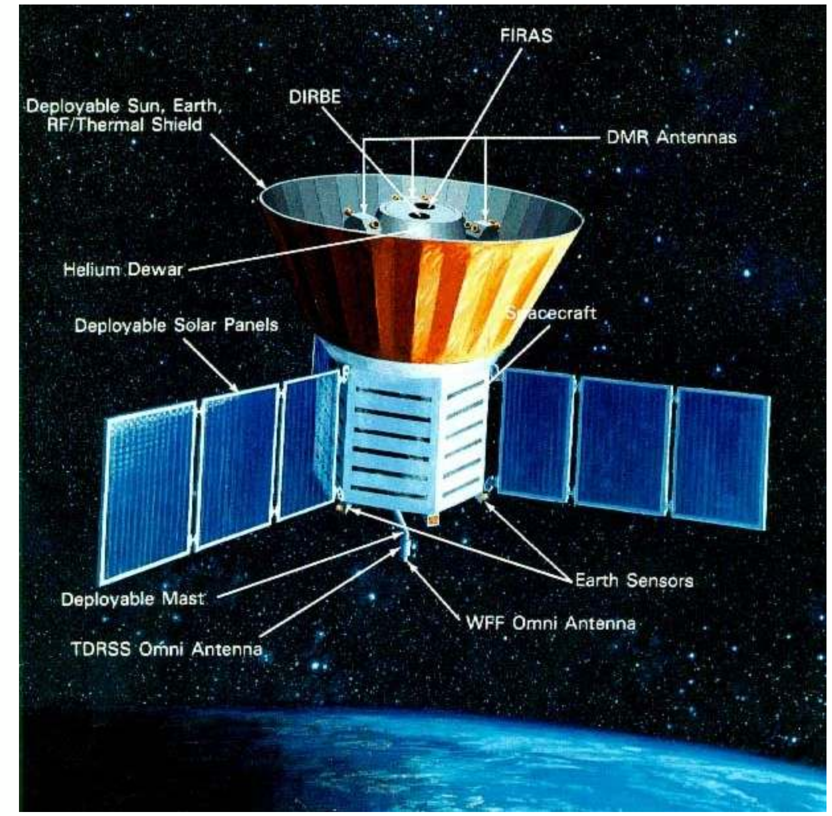

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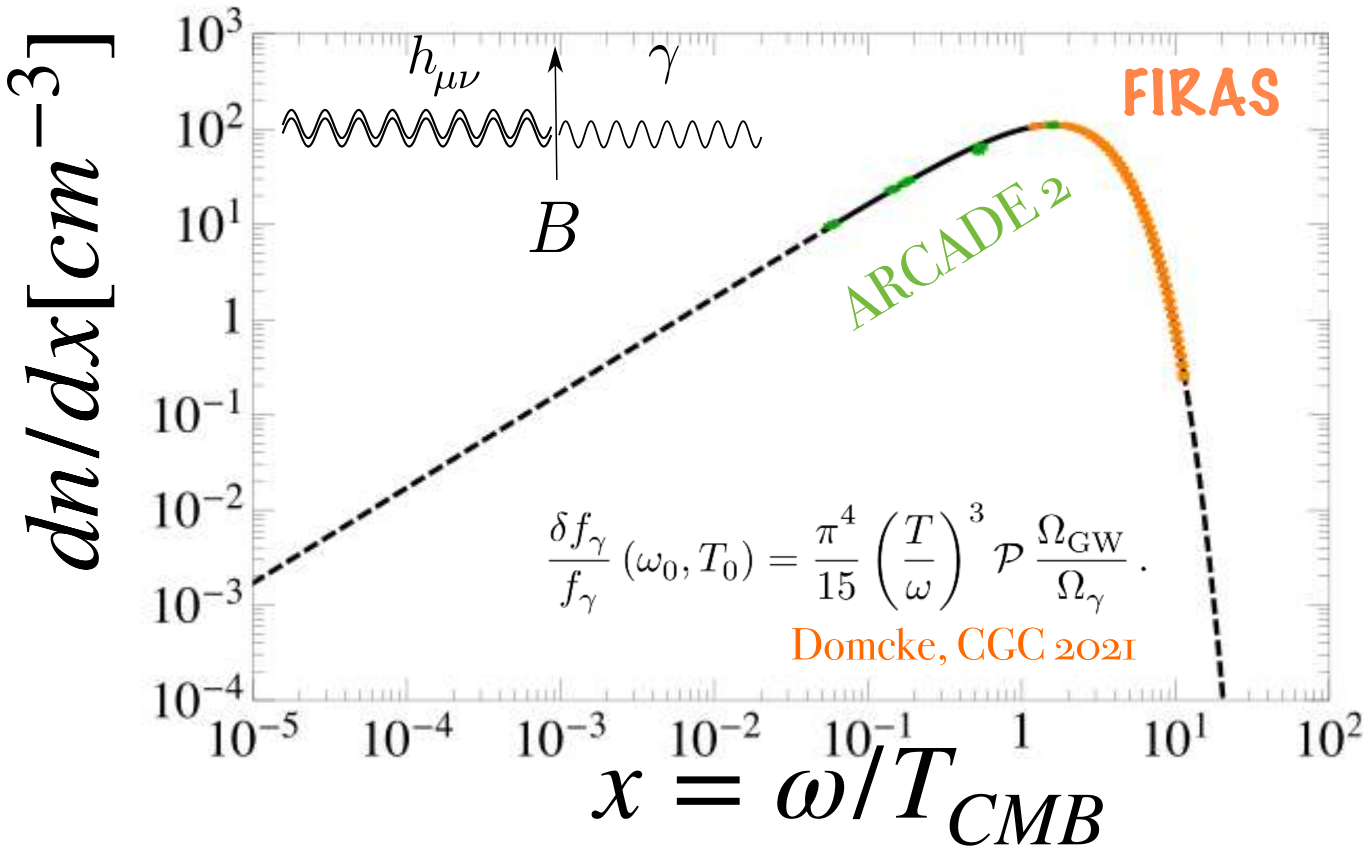
Rayleigh-Jeans Tail



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

THE ASTROPHYSICAL JOURNAL

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

D. J. Fixsen[1], A. Kogut[2], S. Levin[3], M. Limon[4], P. Lubin[5], P. Mirel[6], M. Seiffert[3], J. Singal[7], E. Wollack[2], T. Villela[8] +Show full author list

Published 2011 May 17 •

The Astrophysical Journal, Volume 734, Number 1

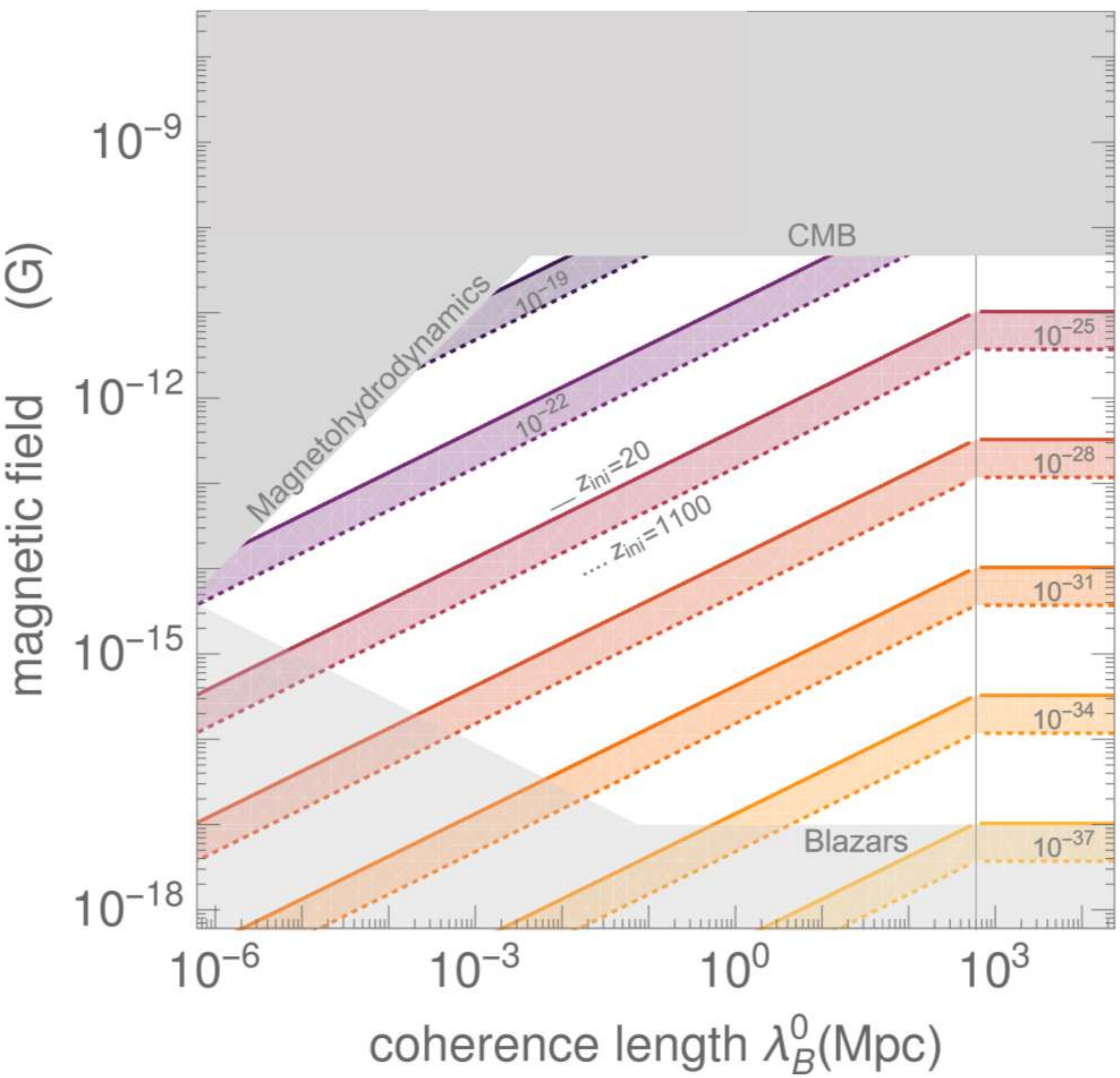
Camilo A. Garcia Cely

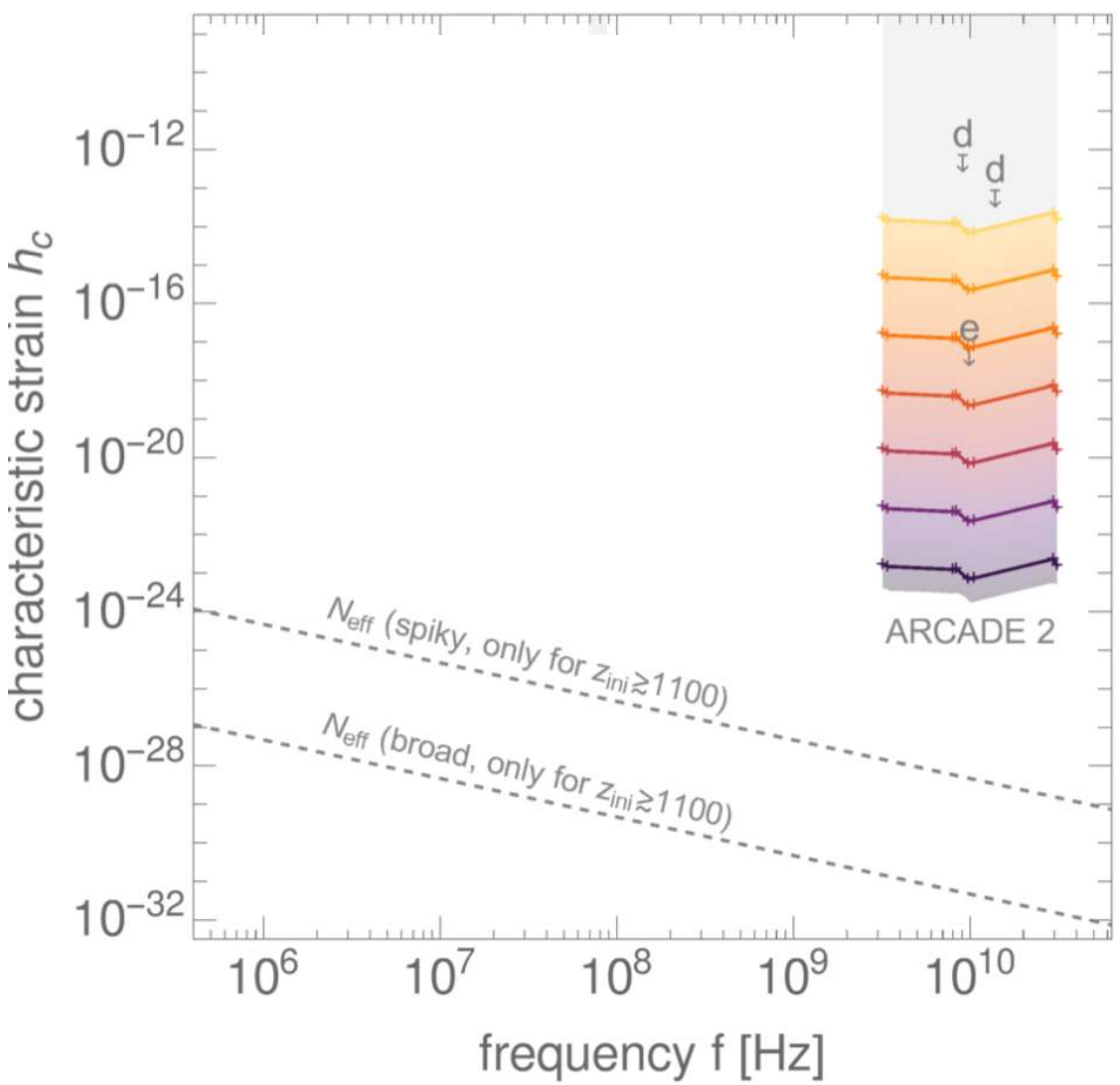
Upper bounds on stochastic gravitational waves

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,†]





existing laboratory bounds from

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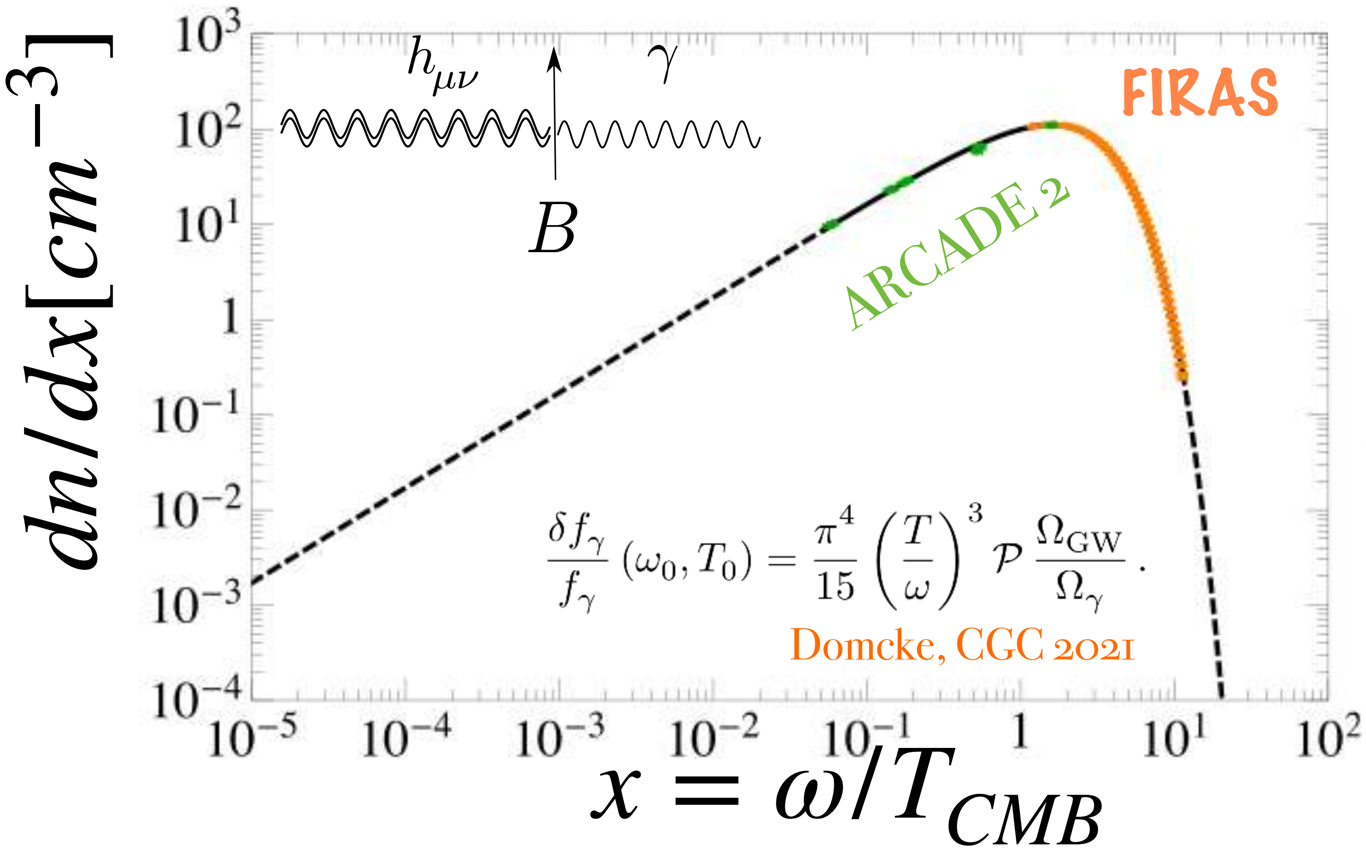
d) magnon detector Ito, Soda '04
e) magnetic conversion detector Cruise et al '12

Rayleigh-Jeans Tail



- 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)

THE ASTROPHYSICAL JOURNAL

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nature

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Nature **555**, 67–70(2018) | Cite this article

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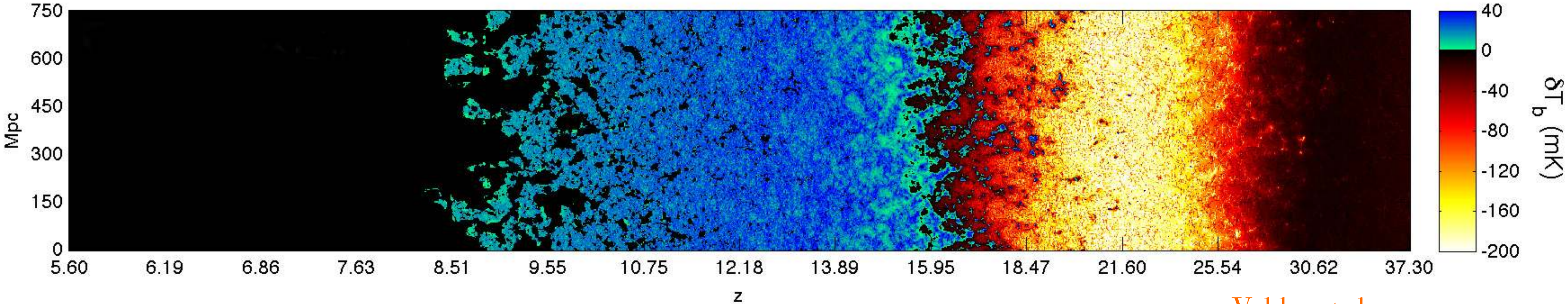
Expectations for a 21 cm signal



Valdes et al 2013

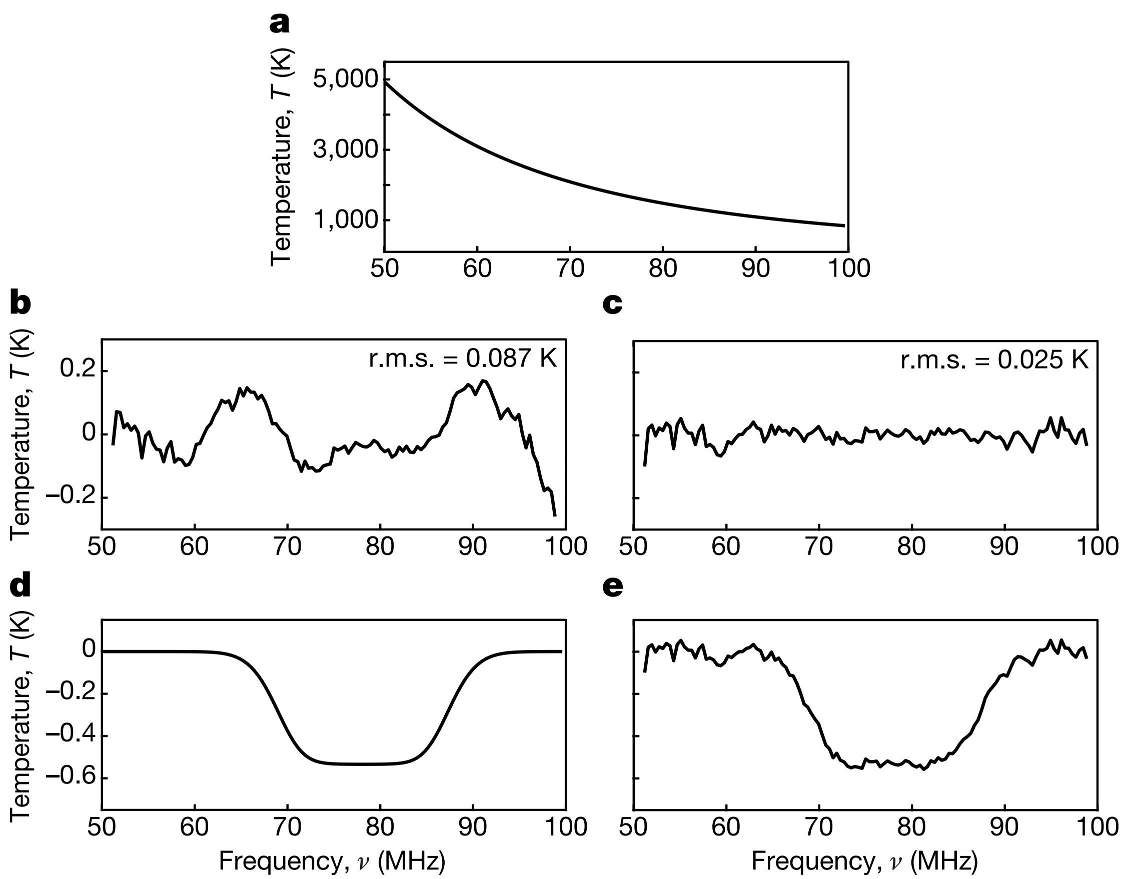


Figure 1 | Summary of detection. a, Measured spectrum for the reference dataset after filtering for data quality and radio-frequency interference. The spectrum is dominated by Galactic synchrotron emission. **b**, **c**, Residuals after fitting and removing only the foreground model (**b**) or the foreground 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**).

nature

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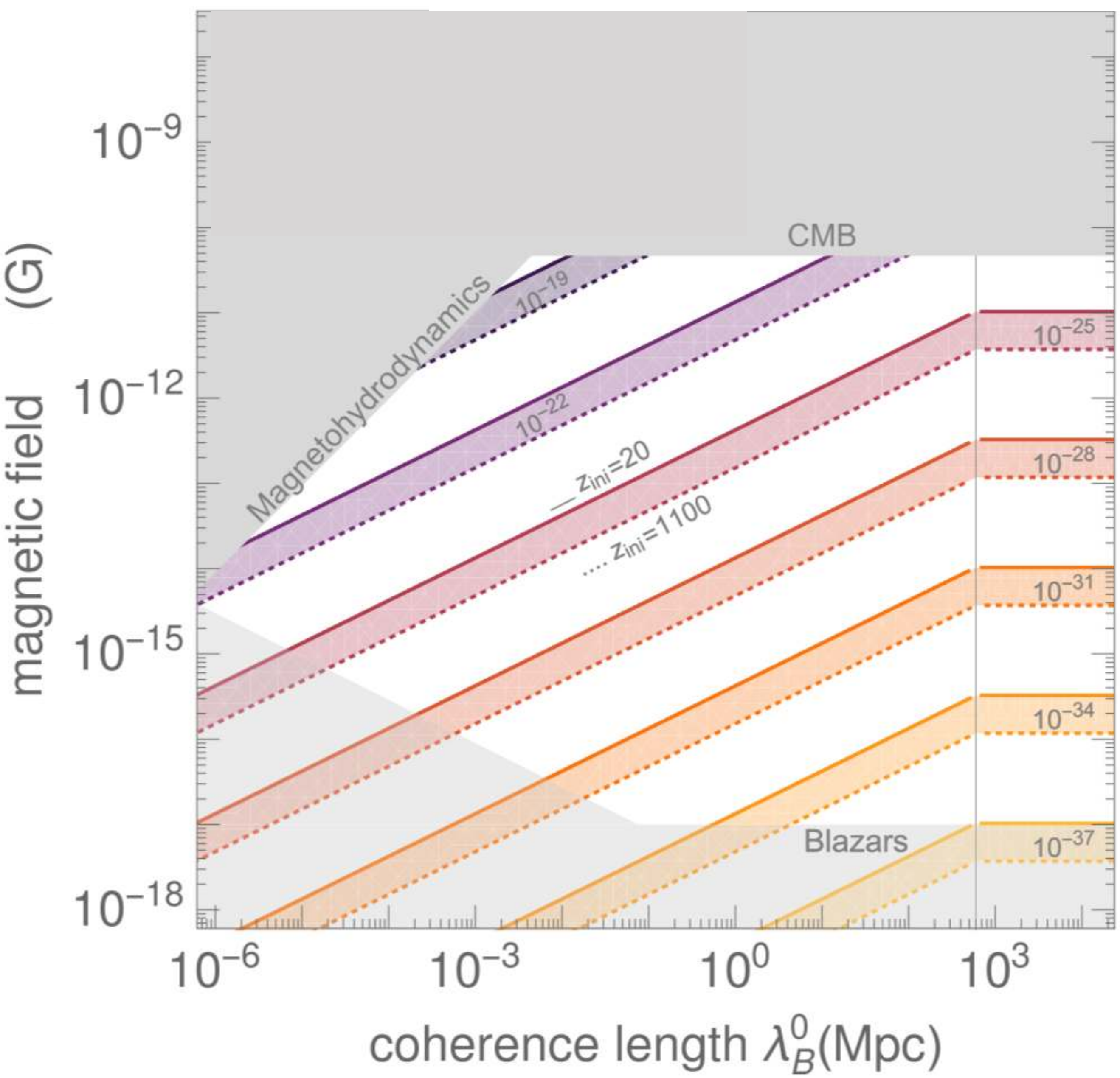

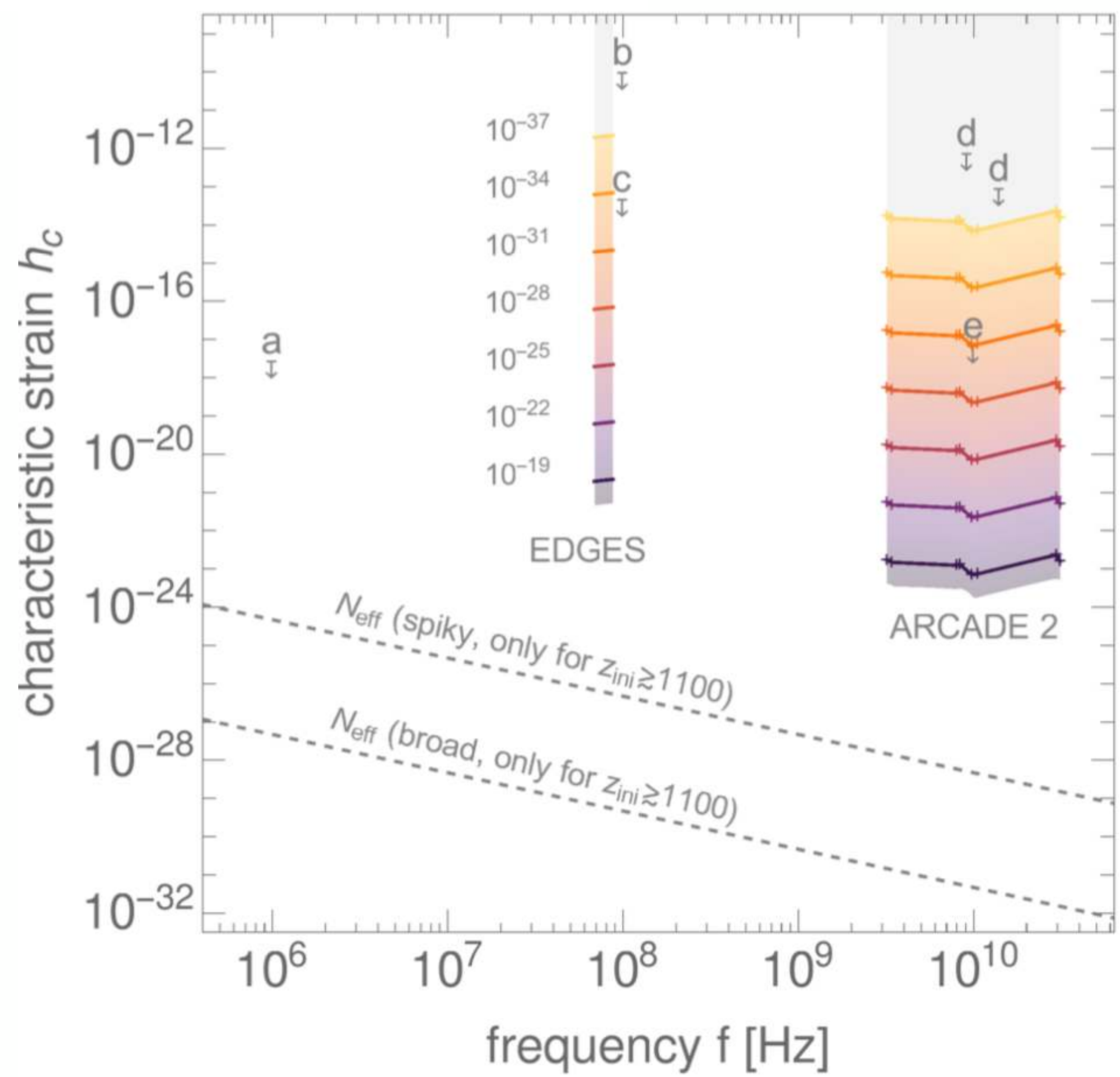

existing laboratory bounds from

a) superconducting parametric converter Reece et al '84
b) waveguide Cruise Ingley '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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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 waves.