The CMB as a detector of gravitational waves

Camilo A. Garcia Cely

Alexander von Humboldt Fellow

DESY.

Based on

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,†]

[1]*Deutsches Elektronen-Synchrotron DESY, Notkestrasse 85, 22607 Hamburg, Germany*

[2]*Theoretical Physics Department, CERN, 1 Esplanade des Particules, CH-1211 Geneva 23, Switzerland*

[3]*Institute of Physics, Laboratory for Particle Physics and Cosmology (LPPC), École Polytechnique Fédérale de Lausanne (EPFL), CH-1015 Lausanne, Switzerland*

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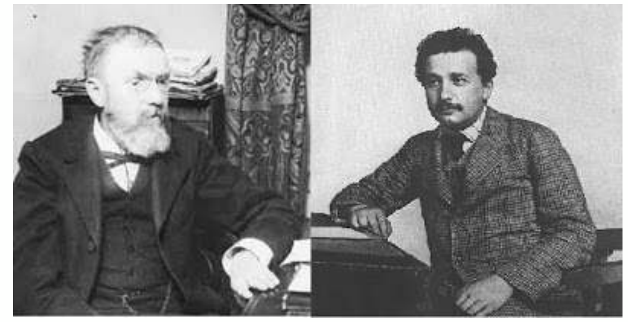
Motivation

Gravitational Waves

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

Gravitational Waves



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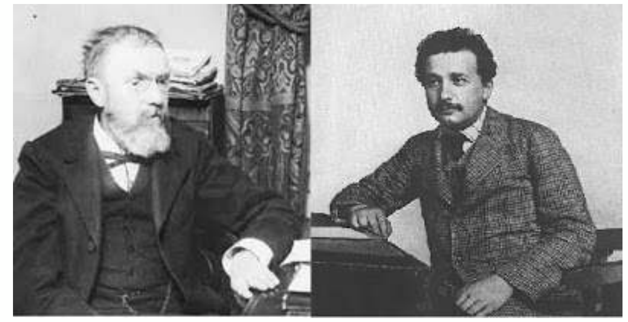
$$\Box h_{\mu\nu} = -16\pi G T_{\mu\nu}$$

Gravitational Waves



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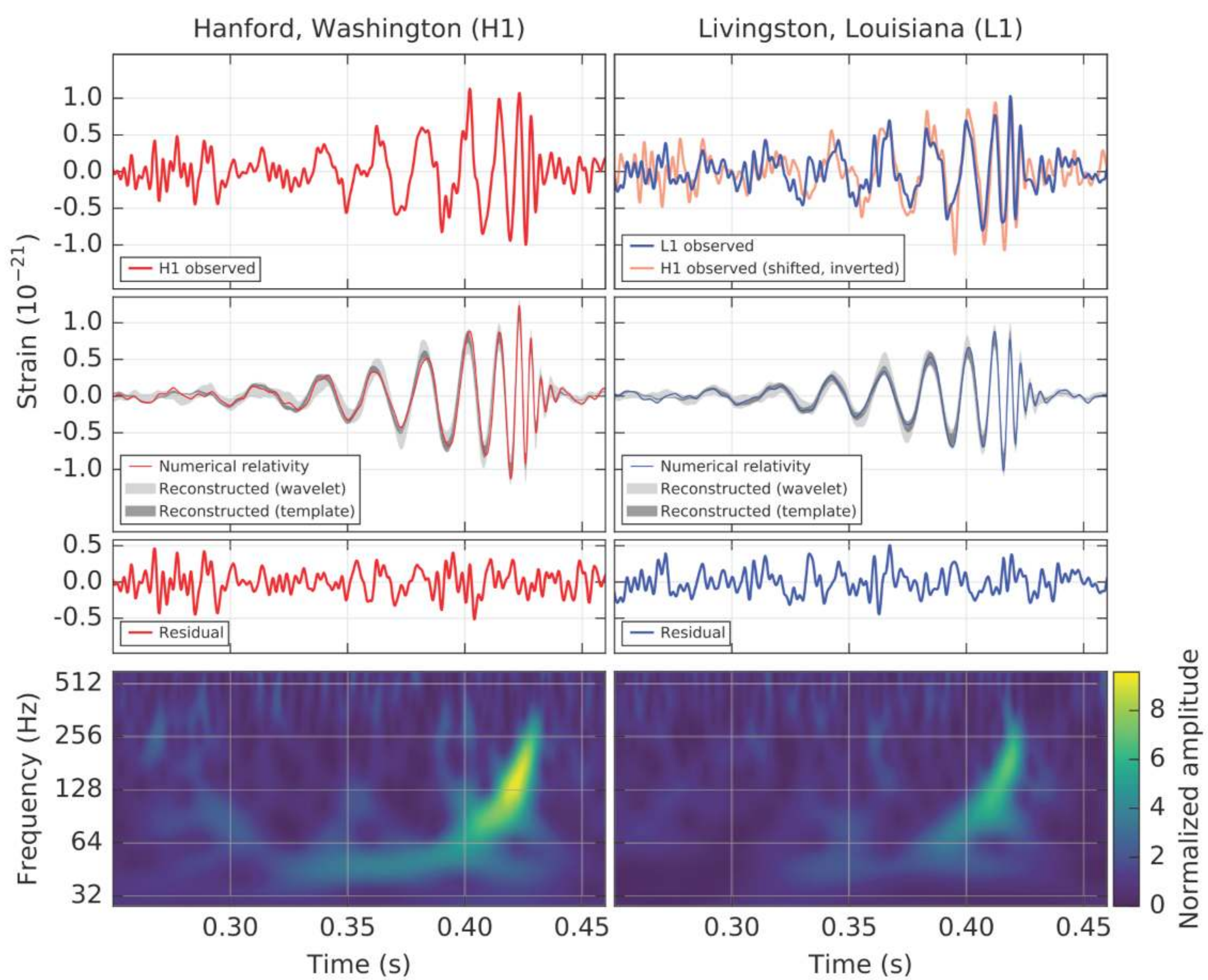
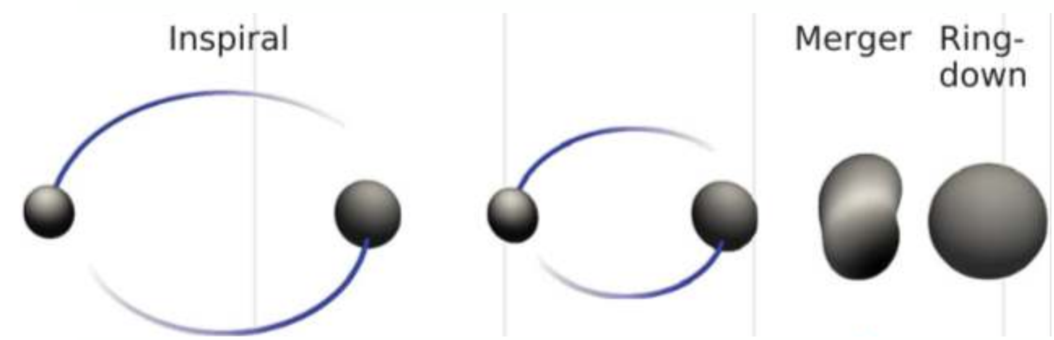
PRL 116, 061102 (2016) PHYSICAL REVIEW LETTERS week ending 12 FEBRUARY 2016





Terrestrial interferometers

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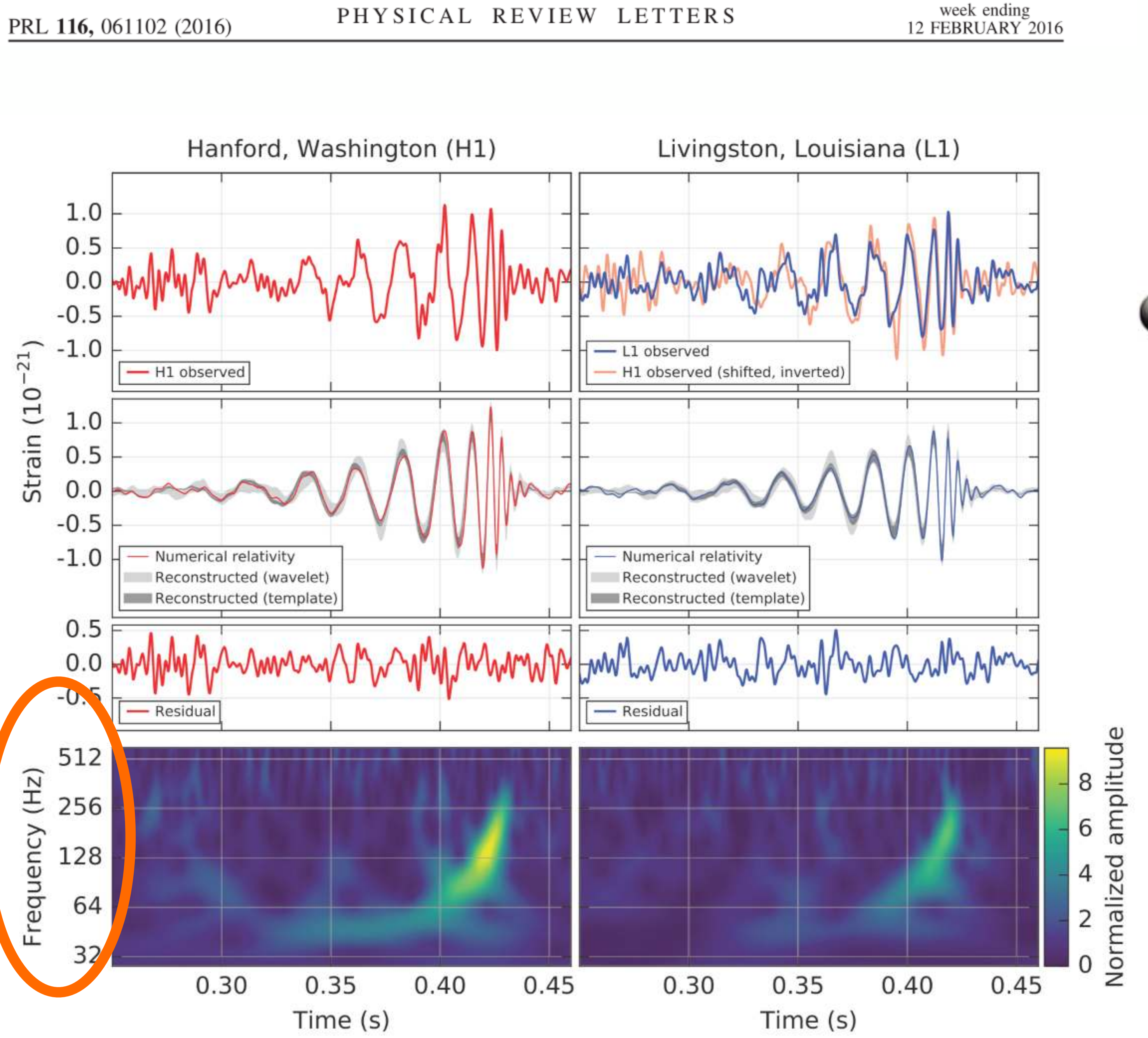

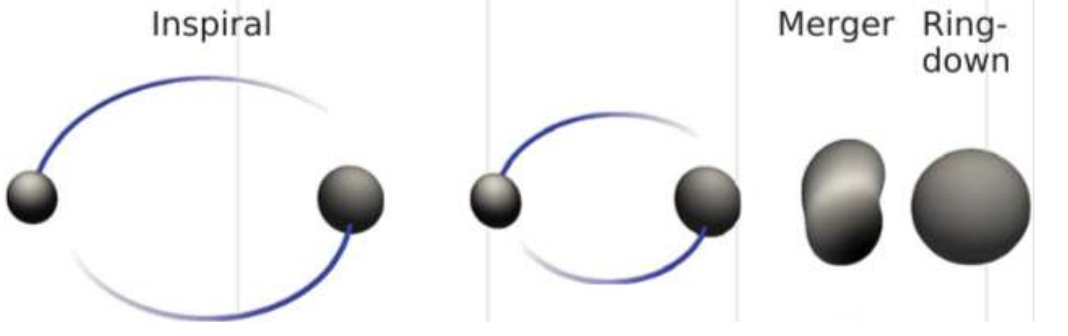

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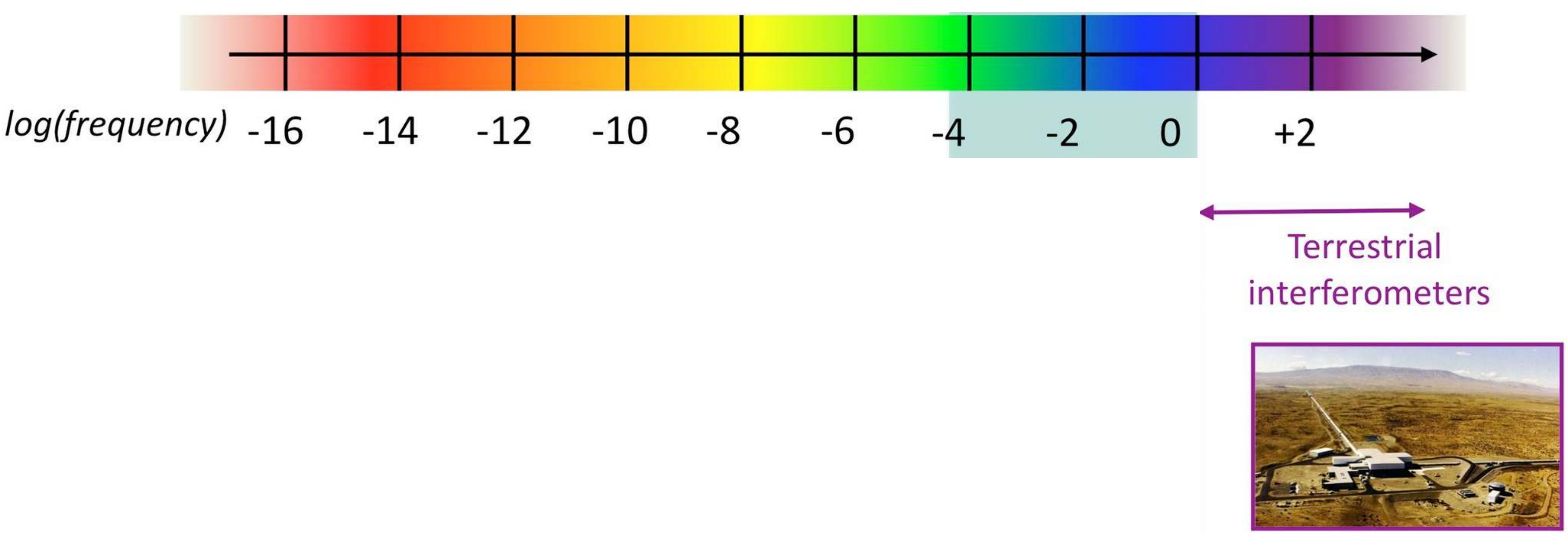
Gravitational Wave Spectrum



Credit: NASA Goddard Space Flight Center

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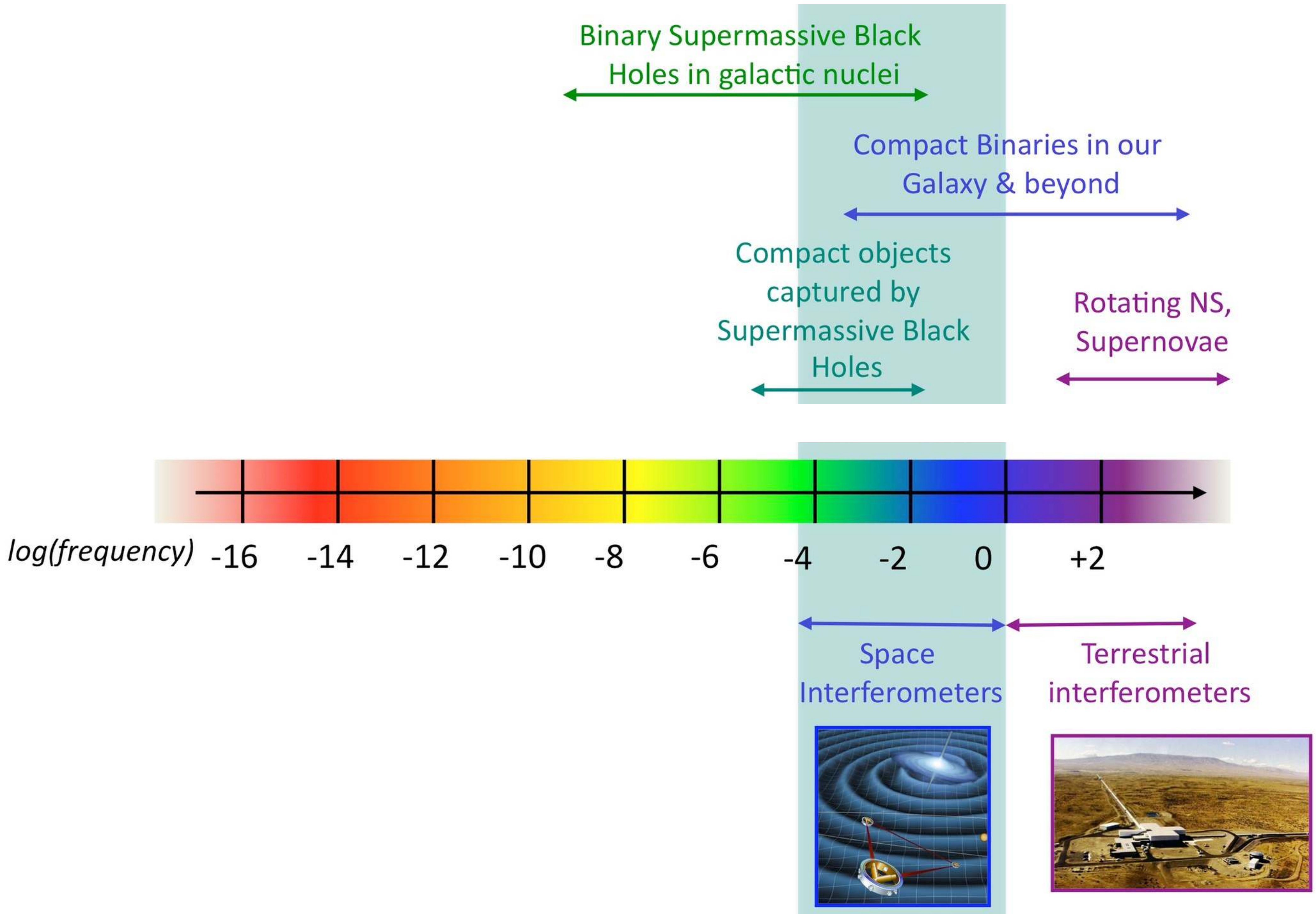

Credit: NASA Goddard Space Flight Center

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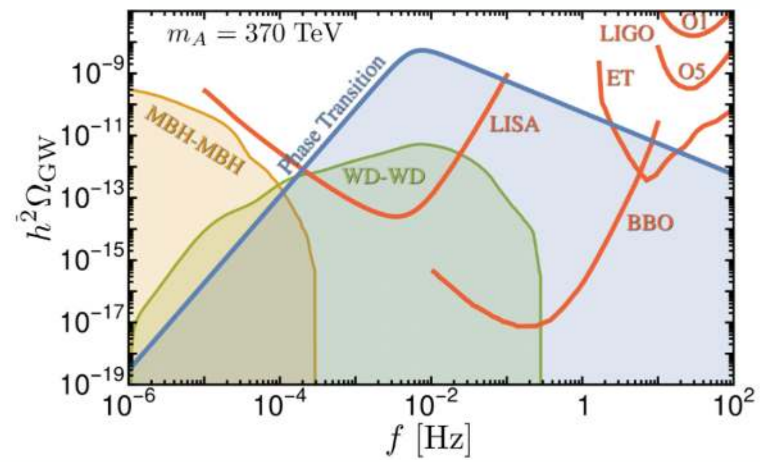
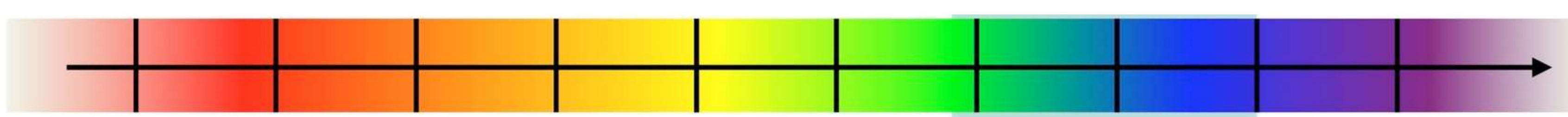
Gravitational Wave Spectrum

cosmological phase transitions

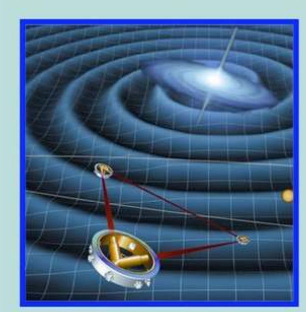
Baldes, CGC 2019





log(frequency) -16 -14 -12 -10 -8 -6 -4 -2 0 +2

Space Interferometers



Terrestrial interferometers

Credit: NASA Goddard Space Flight Center

Camilo A. Garcia Cely

cosmological phase transitions

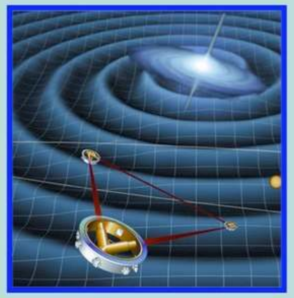
PHYSICAL REVIEW D   VOLUME 30, NUMBER 2   15 JULY 1984

Cosmic separation of phases

Edward Witten*
Institute for Advanced Study, Princeton, New Jersey 08540
(Received 9 April 1984)

A first-order QCD phase transition that occurred reversibly in the early universe would lead to a surprisingly rich cosmological scenario. Although observable consequences would not necessarily survive, it is at least conceivable that the phase transition would concentrate most of the quark excess in dense, invisible quark nuggets, providing an explanation for the dark matter in terms of QCD effects only. This possibility is viable only if quark matter has energy per baryon less than 938 MeV. Two related issues are considered in appendices: the possibility that neutron stars generate a quark-matter component of cosmic rays, and the possibility that the QCD phase transition may have produced a detectable gravitational signal.

Space Interferometers



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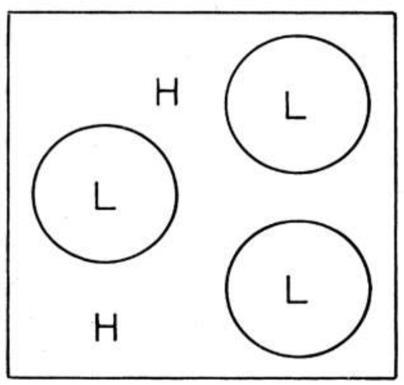
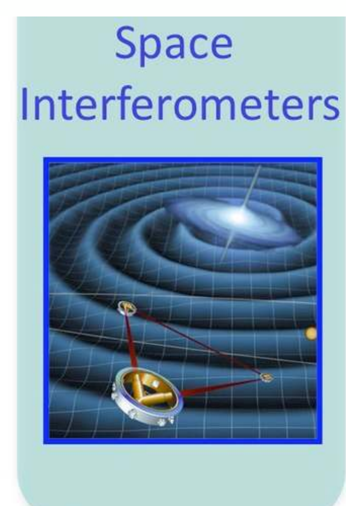


FIG. 1. Isolated expanding bubbles of low-temperature phase in the high-temperature phase.

- Symmetry is typically restored at high temperatures
- Bubbles form and their collision emits gravitational waves



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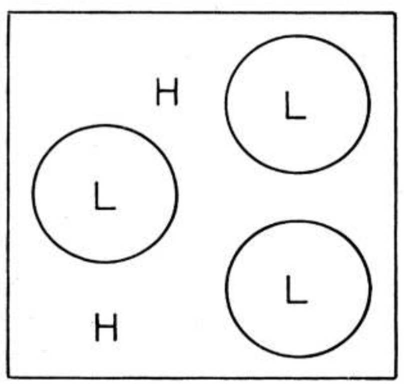

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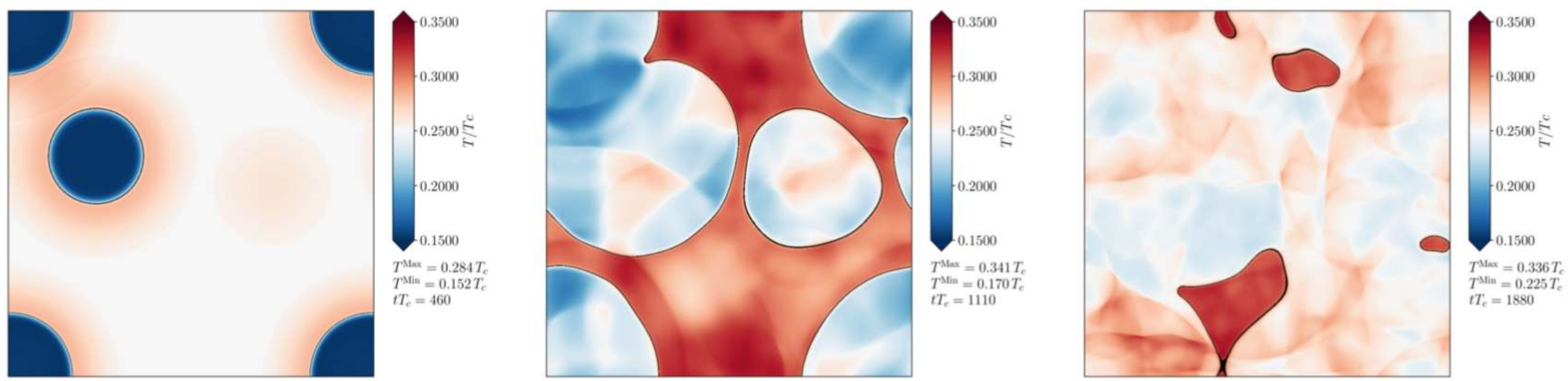
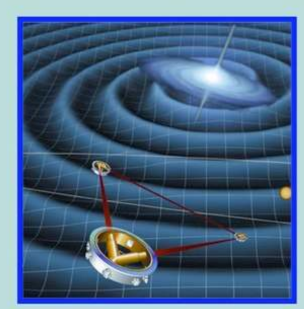
Cutting, Hindmarsch, Weir, PRL 2019



Space Interferometers



Camilo A. Garcia Cely

supercooled cosmological phase transitions

PHYSICAL REVIEW D VOLUME 30, NUMBER 2 15 JULY 1984

Cosmic separation of phases

Edward Witten*
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(Received 9 April 1984)

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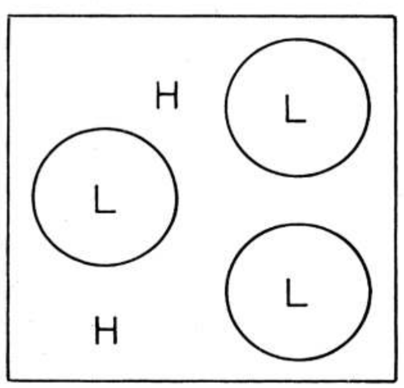
- Symmetry is typically restored at high temperatures
- Bubbles form and their collision emits gravitational waves
- Stronger emission

Cutting, Hindmarsch, Weir, PRL 2019



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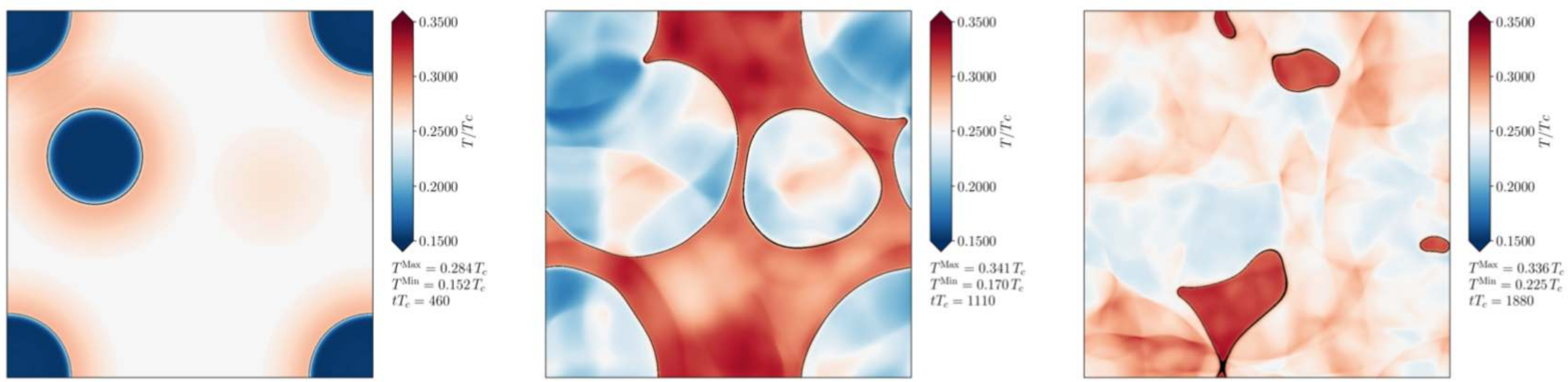

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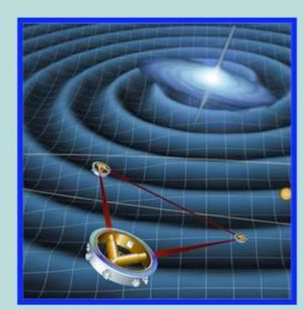

COSMOLOGICAL CONSEQUENCES OF A LIGHT HIGGS BOSON*

Edward WITTEN
Lyman Laboratory of Physics, Harvard University, Cambridge, MA 02138, USA

Received 4 July 1980

The consequences for cosmology of a Coleman-E. Weinberg light Higgs boson are considered. If SU(2) × U(1) symmetry breaking is induced by such a boson, the early universe went far out of equilibrium at the time of the SU(2) × U(1) phase transition. The universe supercooled far below the equilibrium transition temperature. The decay of the unstable vacuum, when it finally occurred, was induced by a process of "dynamical symmetry breaking" and increased the entropy to baryon ratio of the universe by a factor of 10^5 or 10^6. (Related matters have been treated in recent work by Guth and E. Weinberg.)

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A dark matter benchmark

supercooled cosmological phase transitions

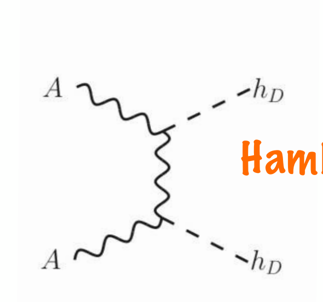
Strong gravitational radiation from a simple dark matter model

Iason Baldes & Camilo Garcia-Cely

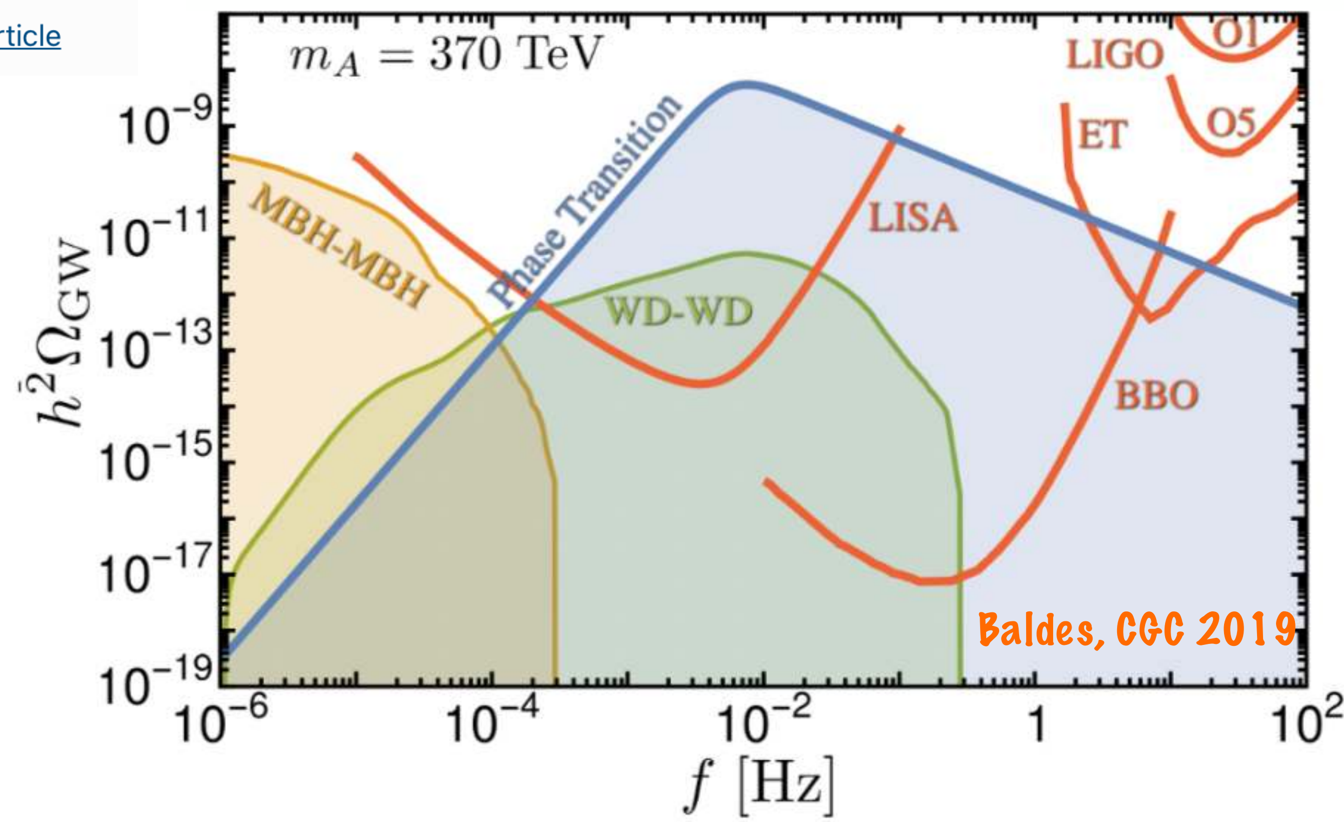
Journal of High Energy Physics **2019**, Article number: 190 (2019) | Cite this article

ABSTRACT

A rather minimal possibility is that dark matter consists of the gauge bosons of a spontaneously broken symmetry. Here we explore the possibility of detecting the gravitational waves produced by the phase transition associated with such breaking. Concretely, we focus on the scenario based on an $SU(2)_D$ group and argue that it is a case study for the sensitivity of future gravitational wave observatories to phase transitions associated with dark matter. This is because there are few parameters and those fixing the relic density also determine the effective potential establishing the strength of the phase transition. Particularly promising for LISA and even the Einstein Telescope is the super-cool dark matter regime, with DM masses above $\mathcal{O}(100)$ TeV, for which we find that the gravitational wave signal is notably strong. In our analysis, we include the effect of astrophysical foregrounds, which are often ignored in the context of phase transitions.



Hambye, Strumia, Teresi, 2018



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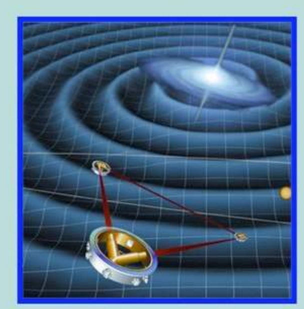

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A dark matter benchmark for multi-messenger astronomy

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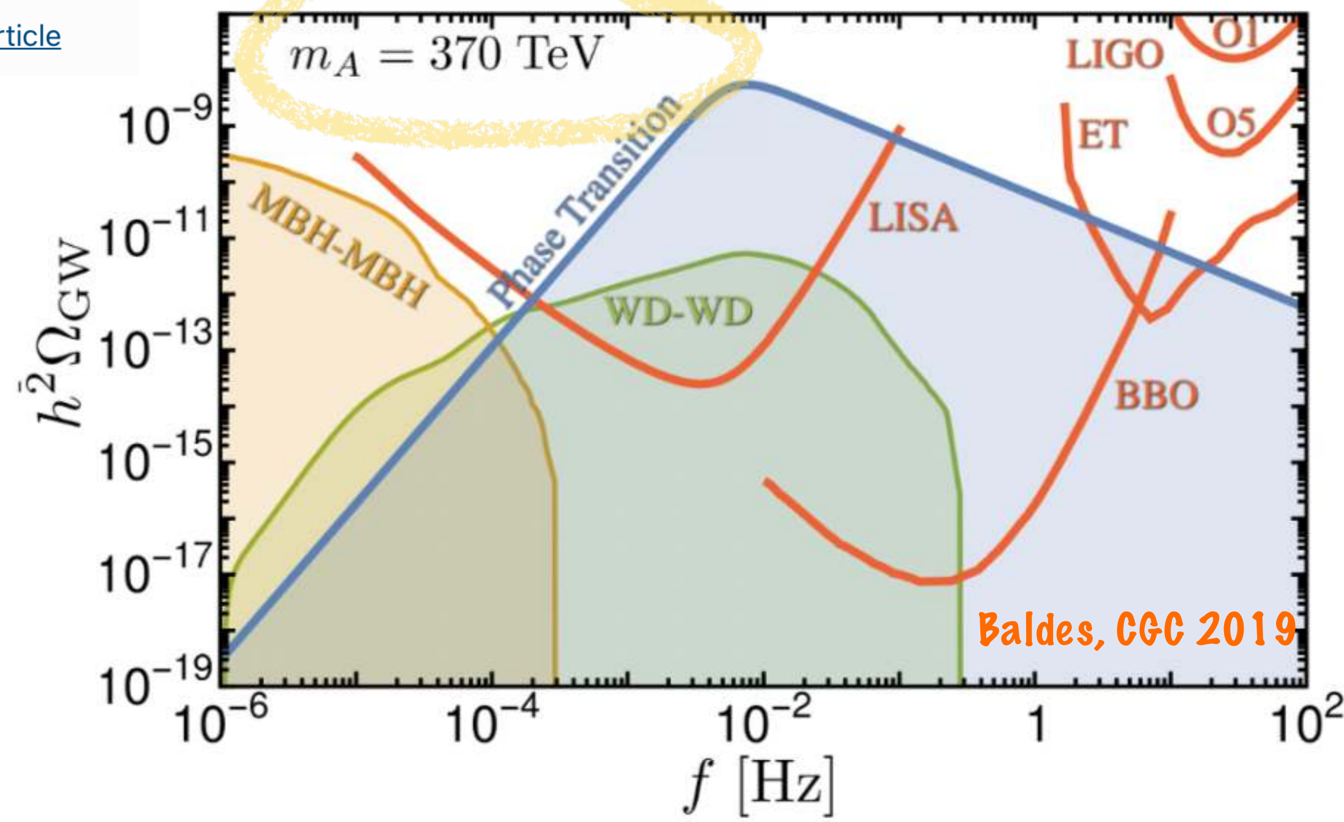
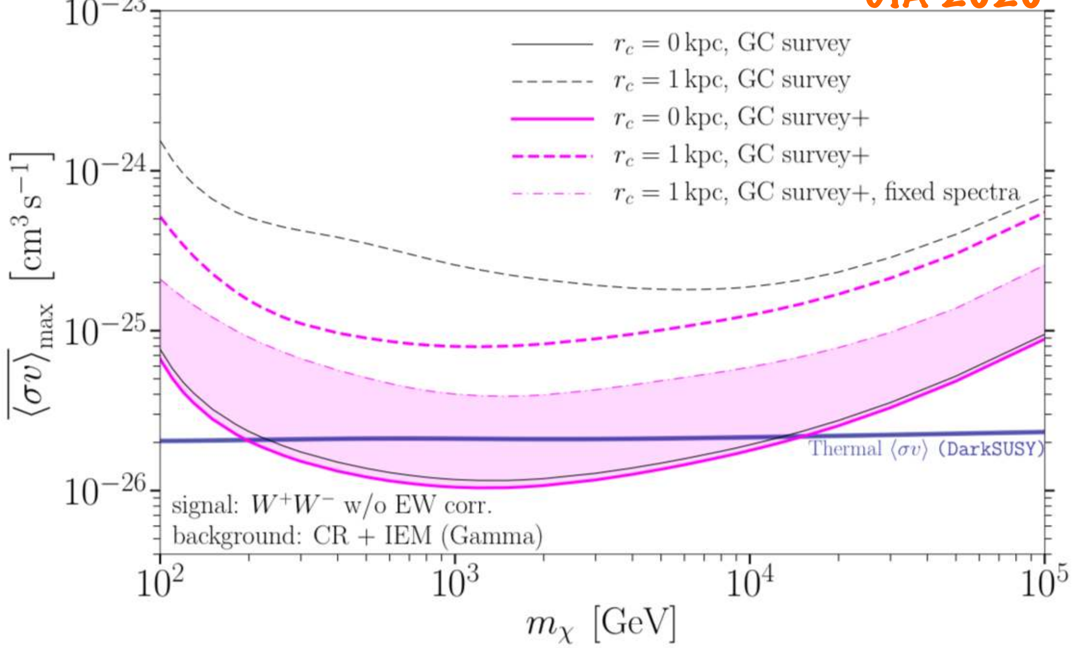
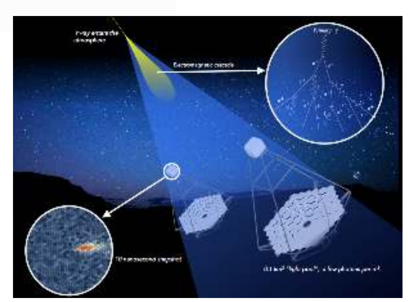
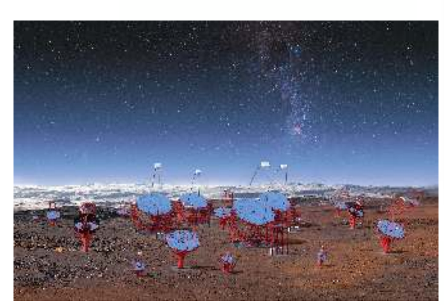


Baldes, CGC 2019

CTA 2020







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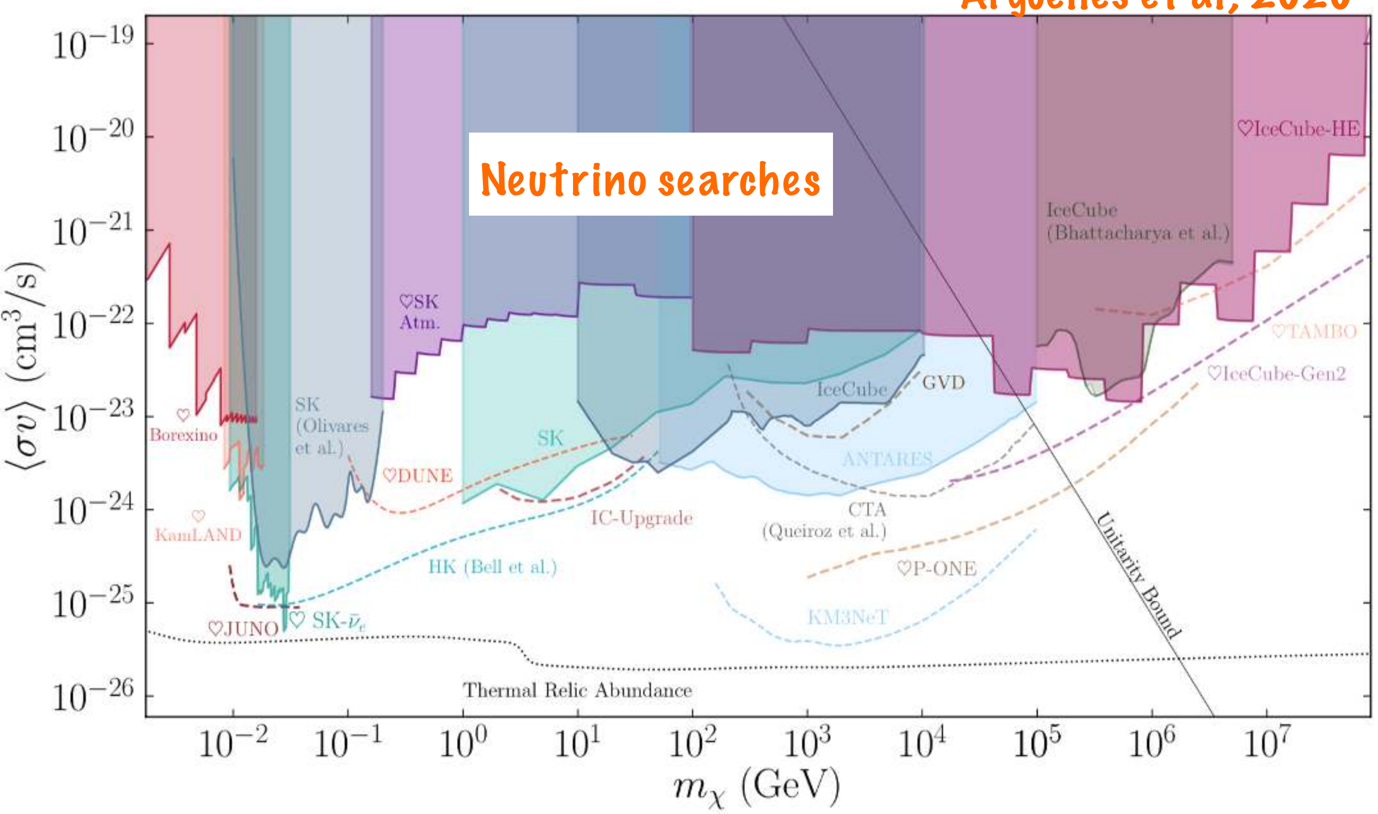
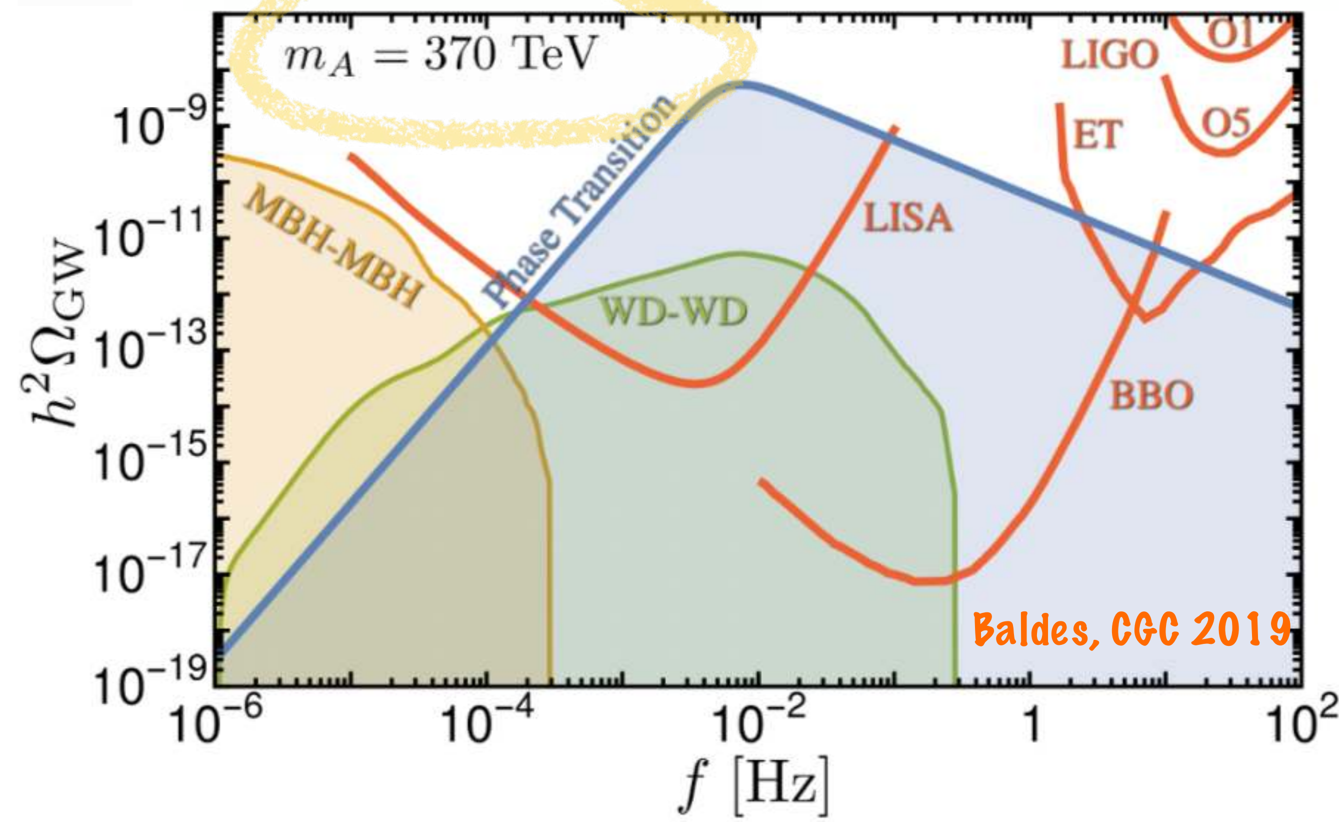
Hambye, Strumia, Teresi, 2018

Argüelles et al, 2020





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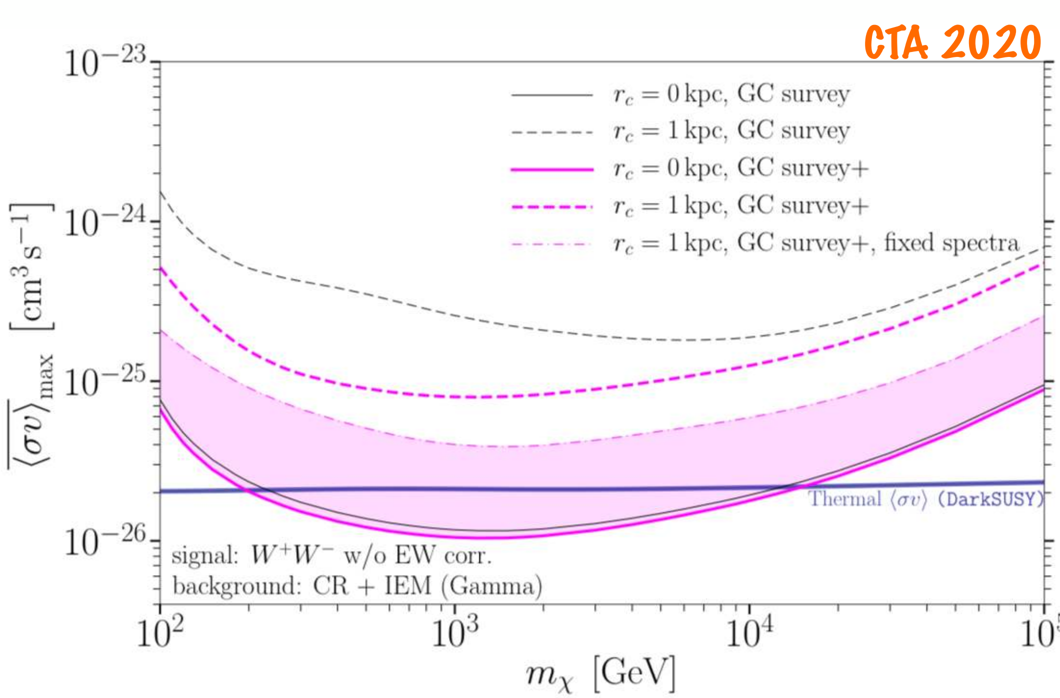
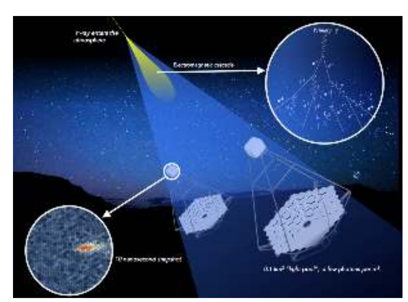
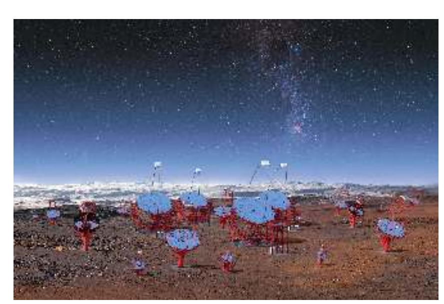
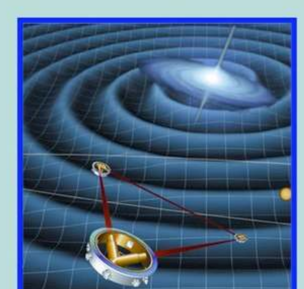
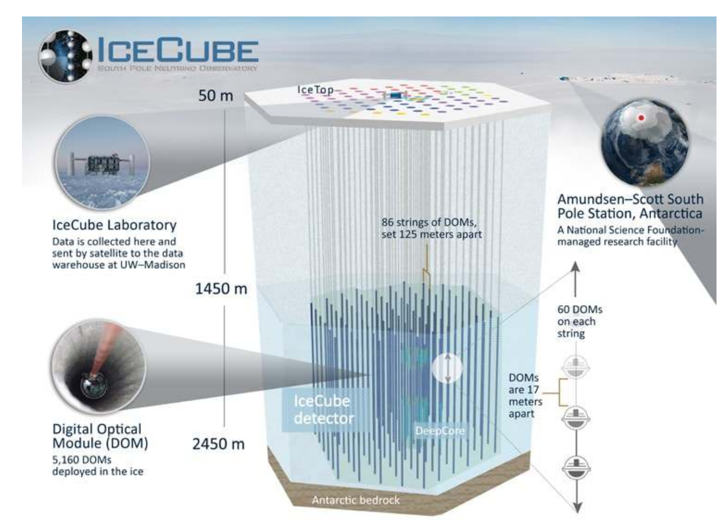






Space Interferometers





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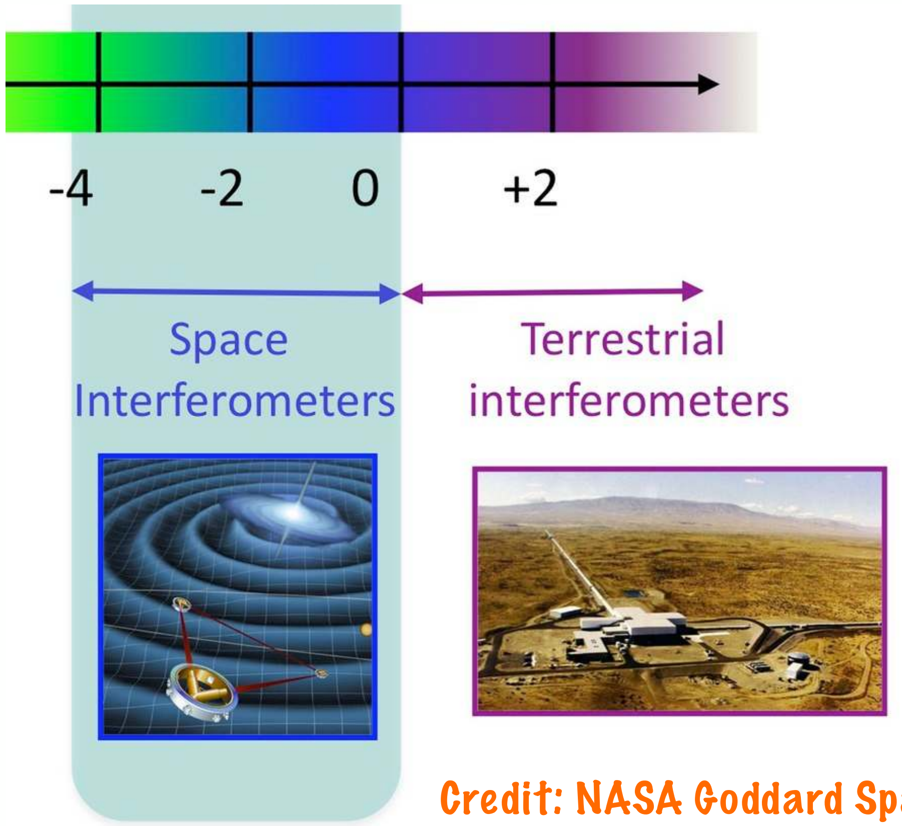
Gravitational Wave Spectrum



Credit: NASA Goddard Space Flight Center

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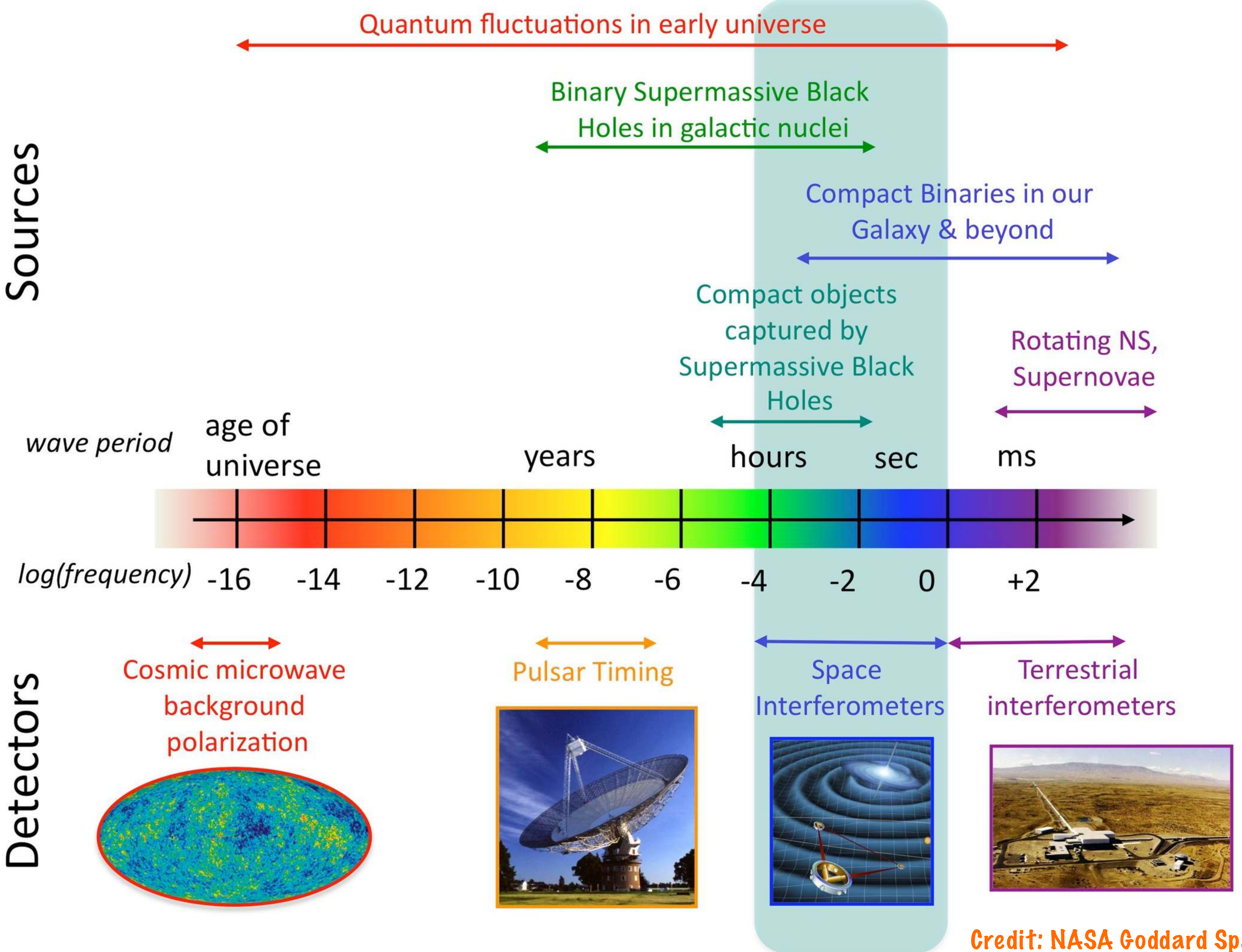

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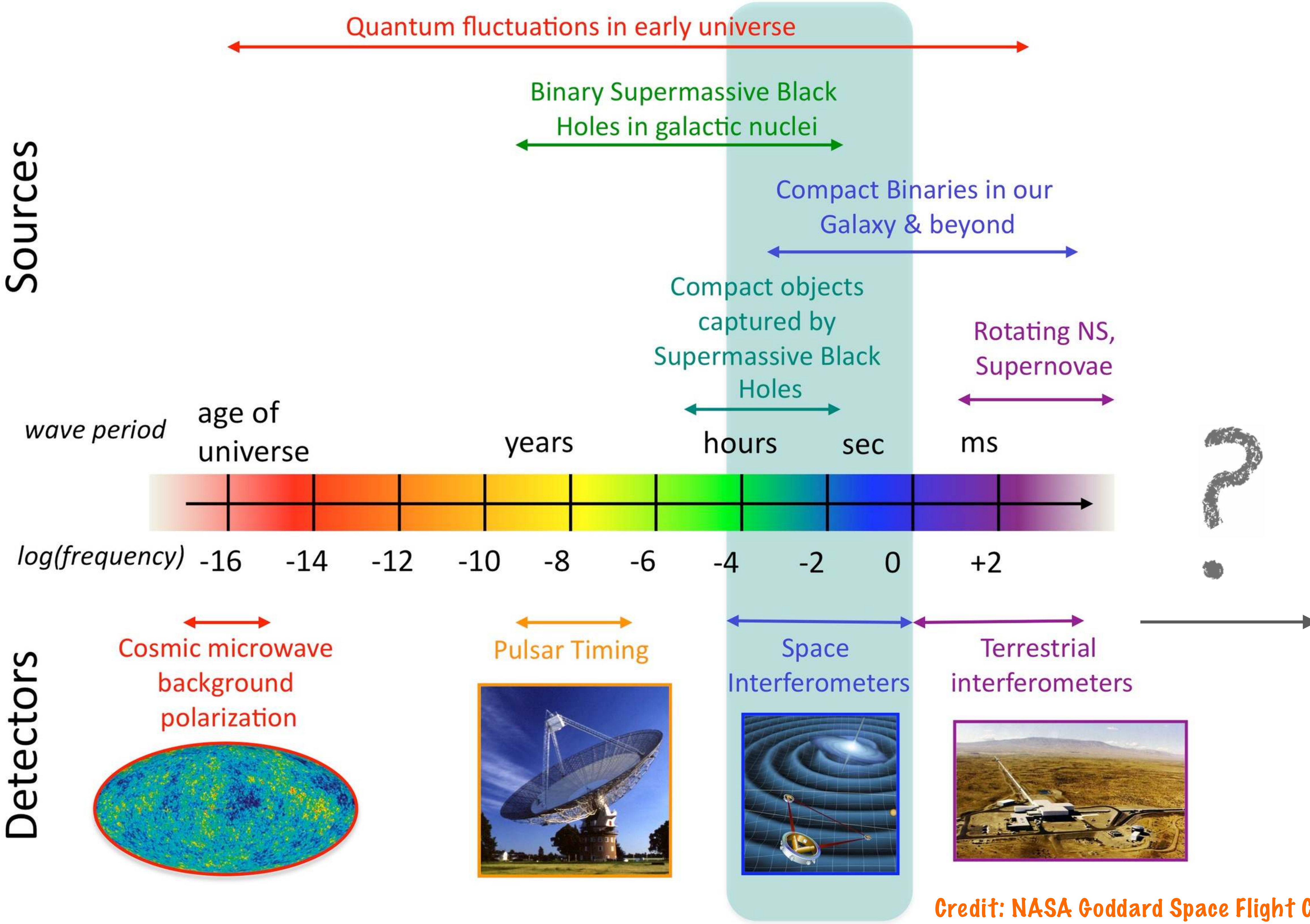

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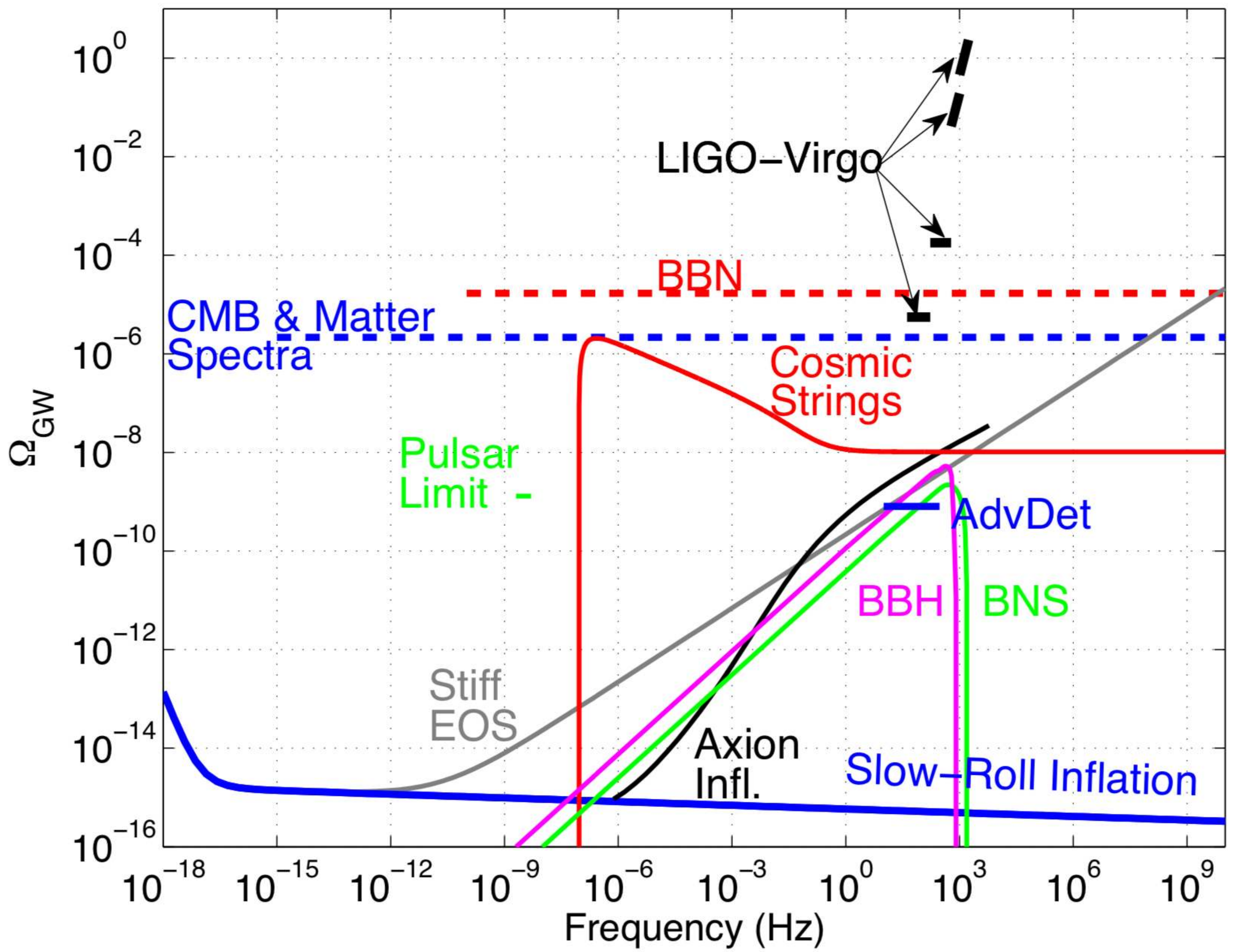
Gravitational Wave Spectrum

what about high frequencies?

LIGO - VIRGO, 2014



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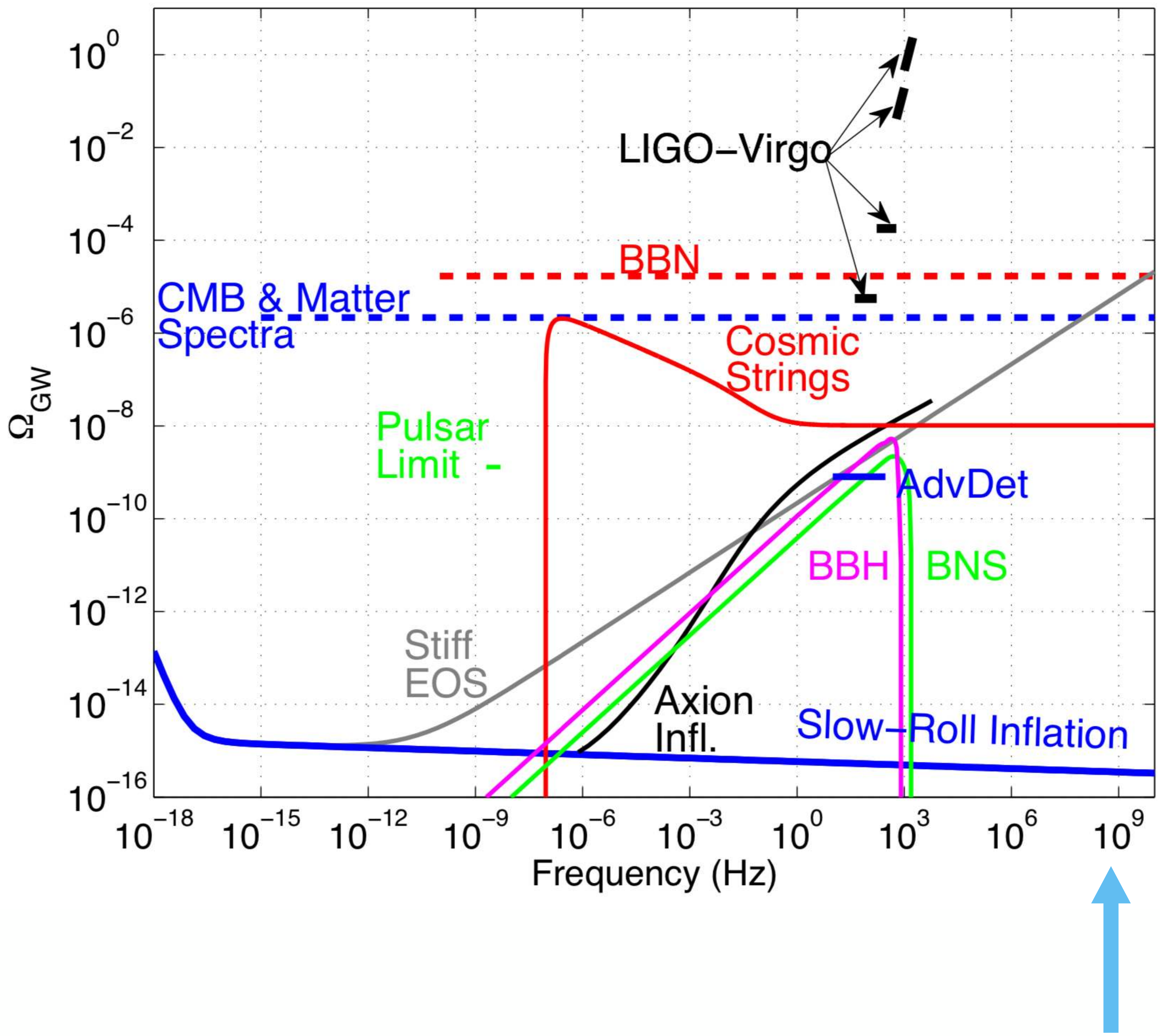

Radio and TeV astronomy

Domcke, CGC 2021

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Gravitational Wave Spectrum

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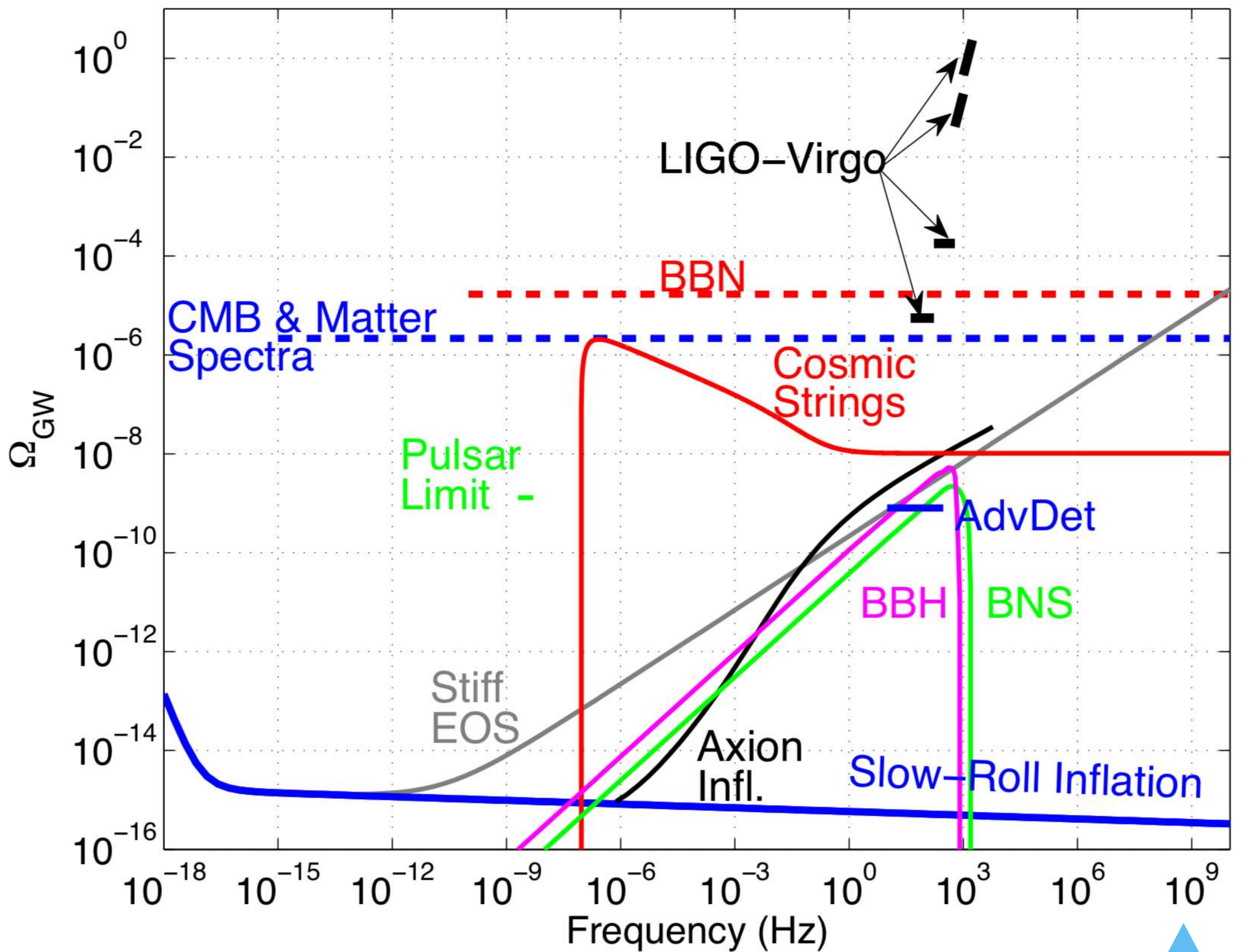

Cosmological constraints on radiation energy N_{eff}

Radio and TeV astronomy

Domcke, CGC 2021

Camilo A. Garcia Cely

Gravitational Waves and the Gertsenhstein Effect

Revisiting Gertsenhstein's ideas

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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Revisiting Gertsenhstein's ideas

SOVIET PHYSICS JETP VOLUME 14, NUMBER 1 JANUARY, 1962

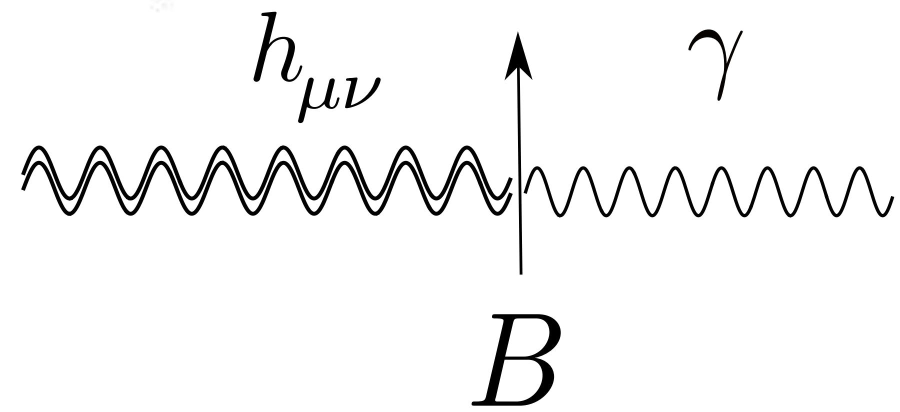
WAVE RESONANCE OF LIGHT AND GRAVITIONAL WAVES

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.



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The Gertsenhstein Effect

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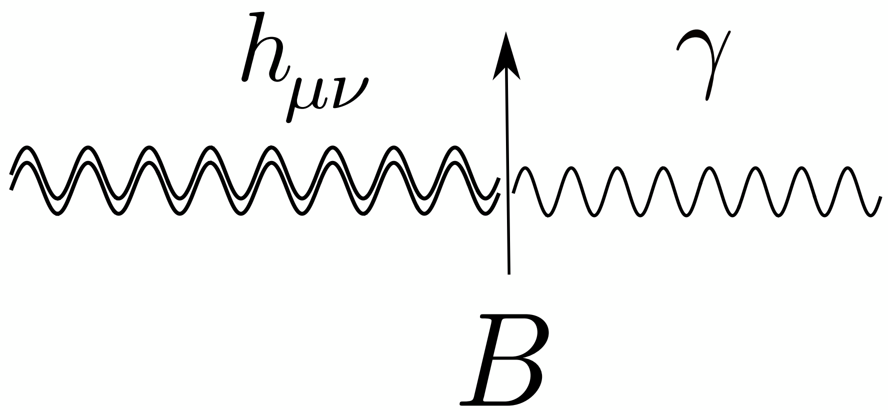

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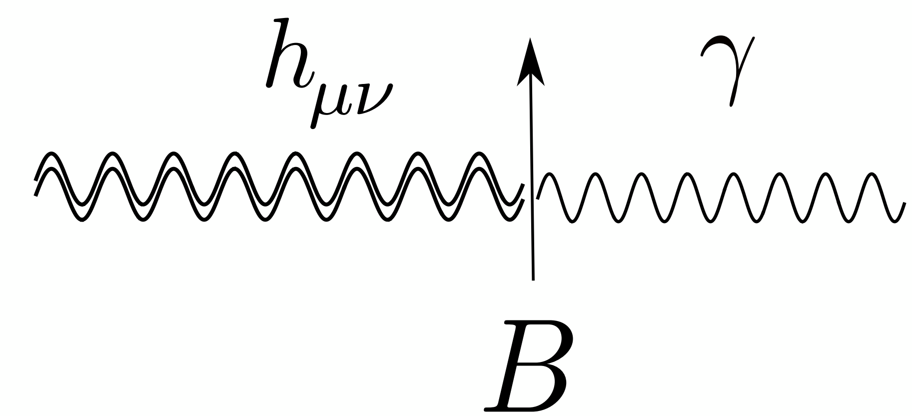

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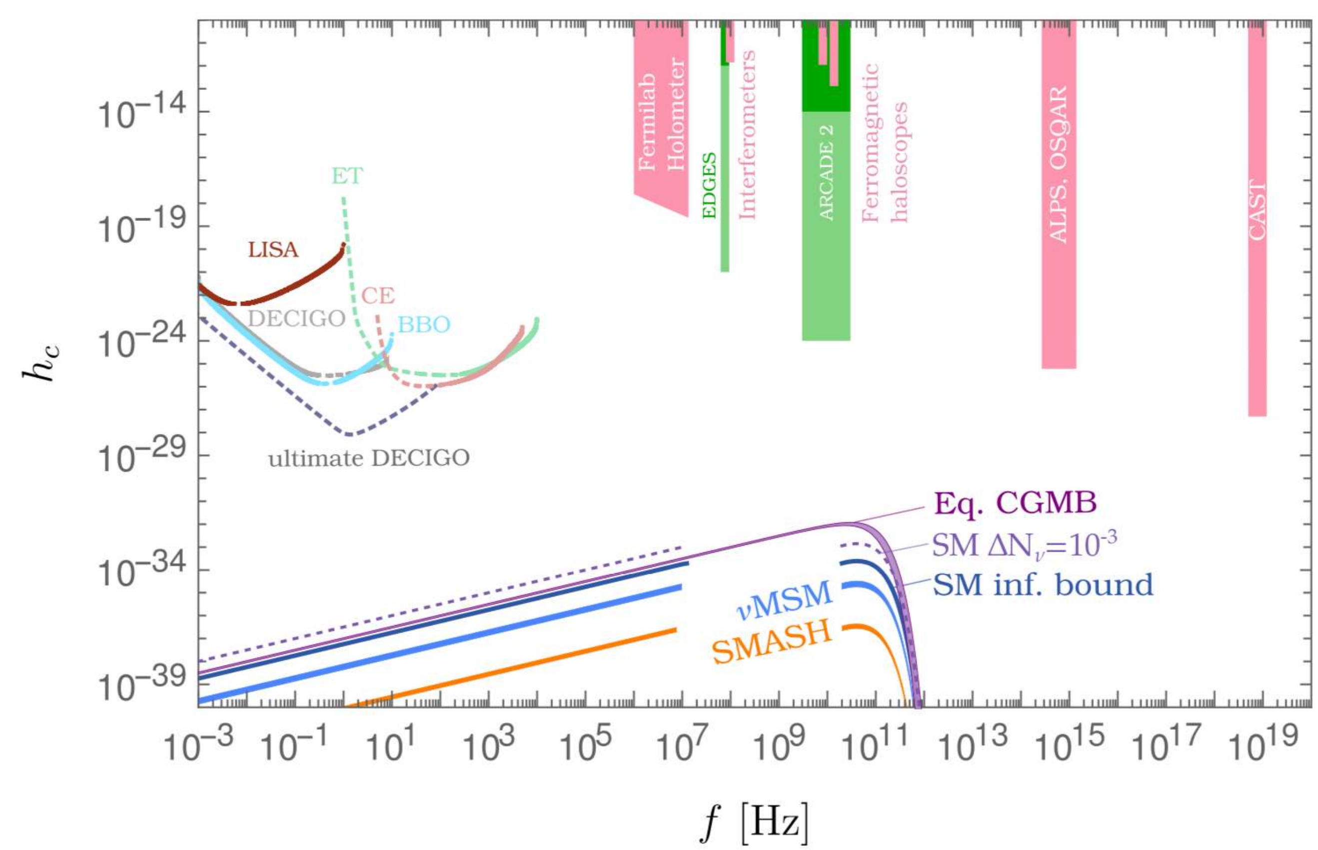

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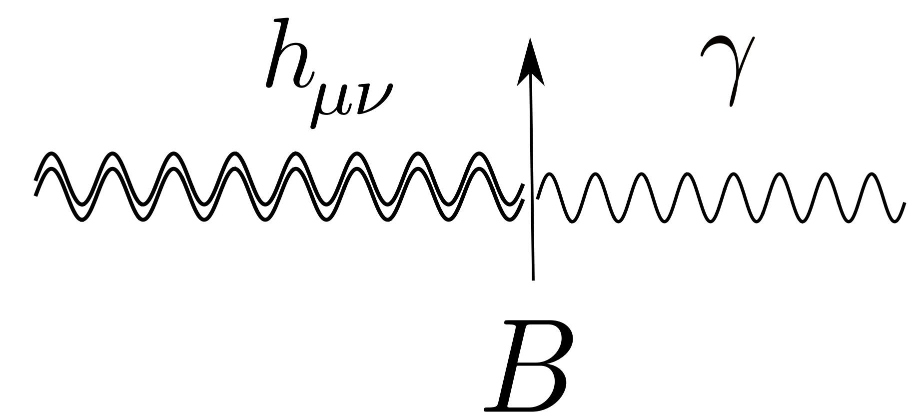
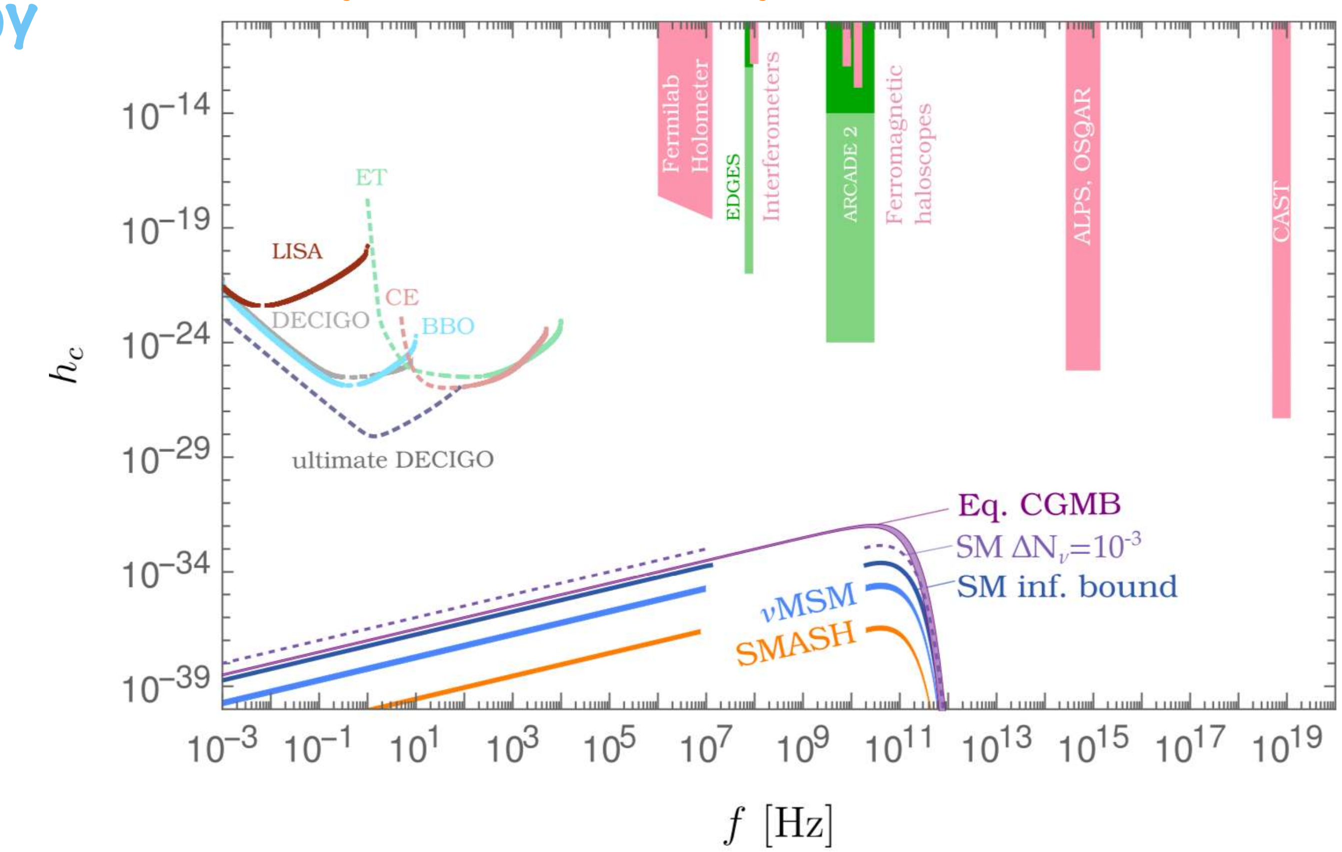
- Involving gravity the conversion probabilities are extremely small. It may be compensated by a 'detector' of cosmological size.



Ringwald, Jan Schütte-Engel, Tamarit 2011.04731



Camilo A. Garcia Cely

The Gertsenhstein Effect

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

- The process is strictly analogous to axion-photon conversion. Raffelt, Stodolski'89

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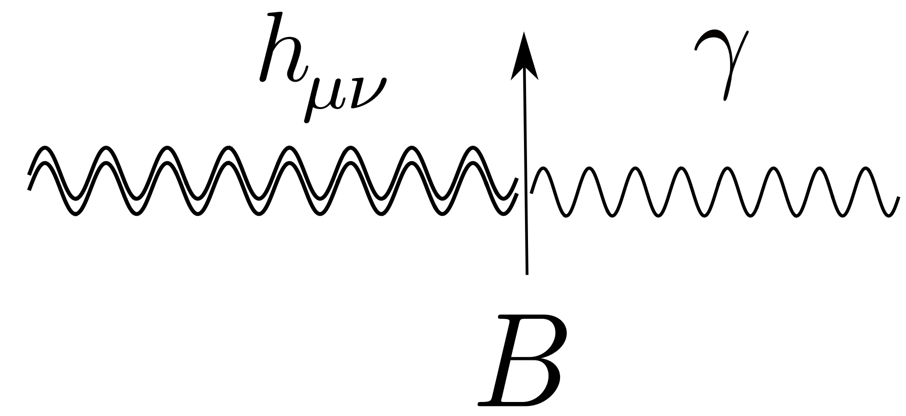
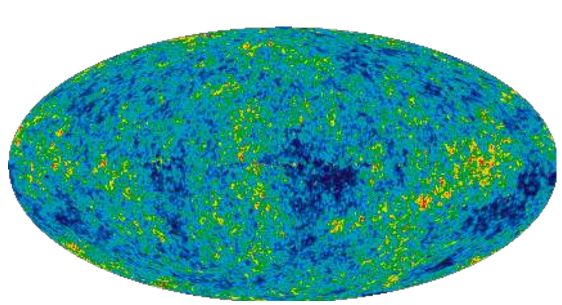
- Distortions of the CMB Domcke, CGC 2021





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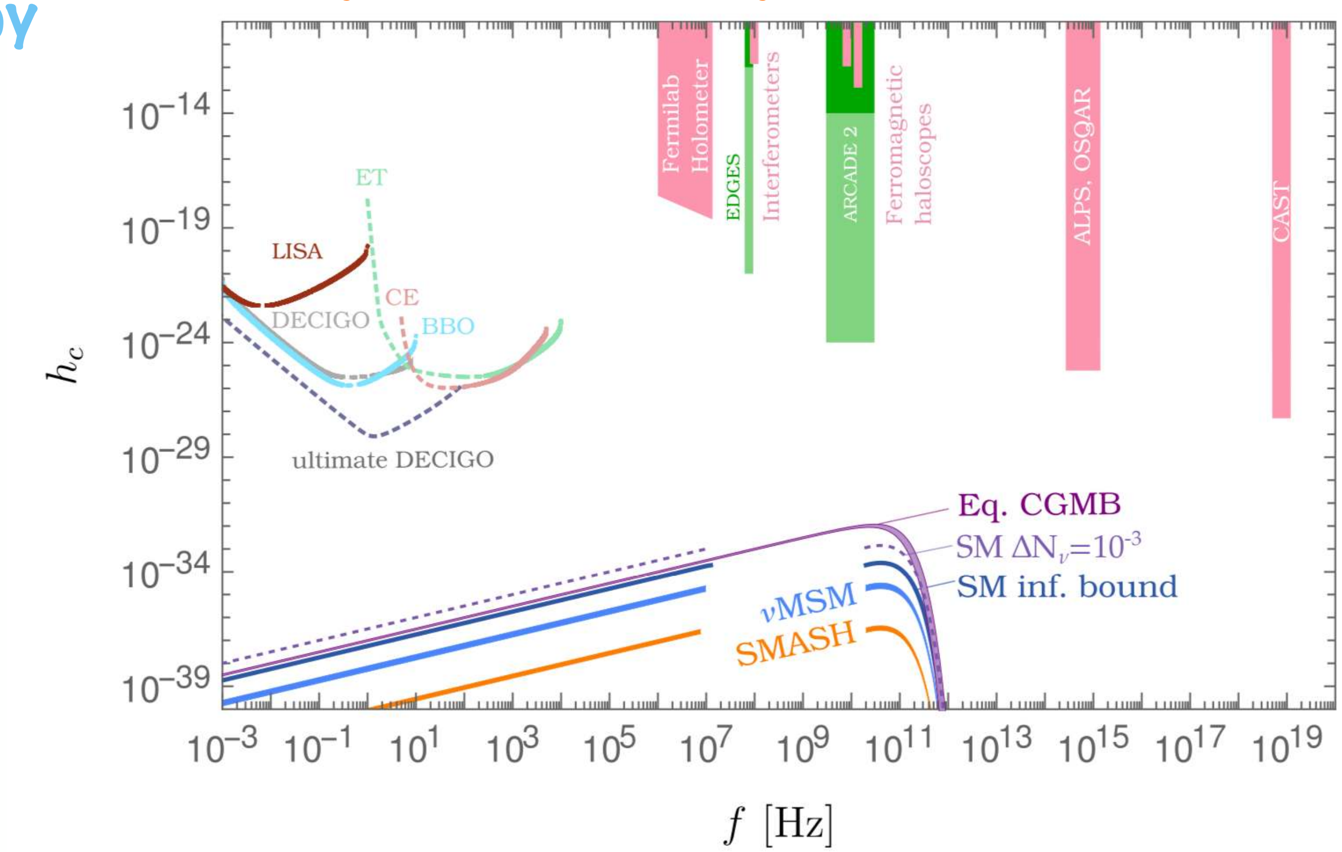

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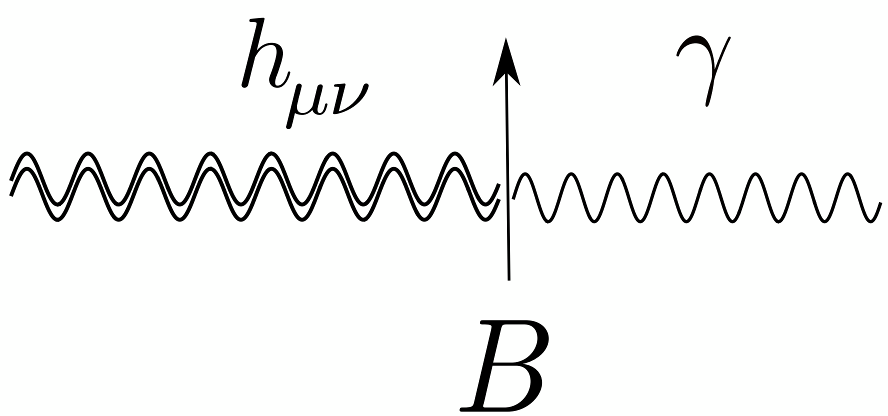

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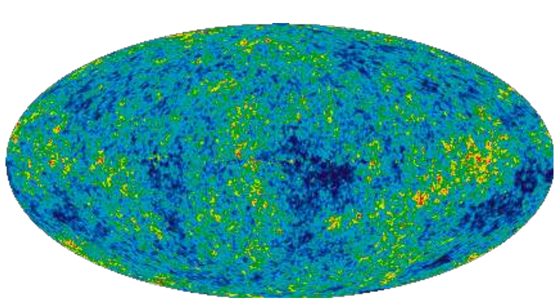
Domcke, CGC 2021

Dolgov, Ejlli 2012

Pshirkov, Baskaran 2009

Chen 1995



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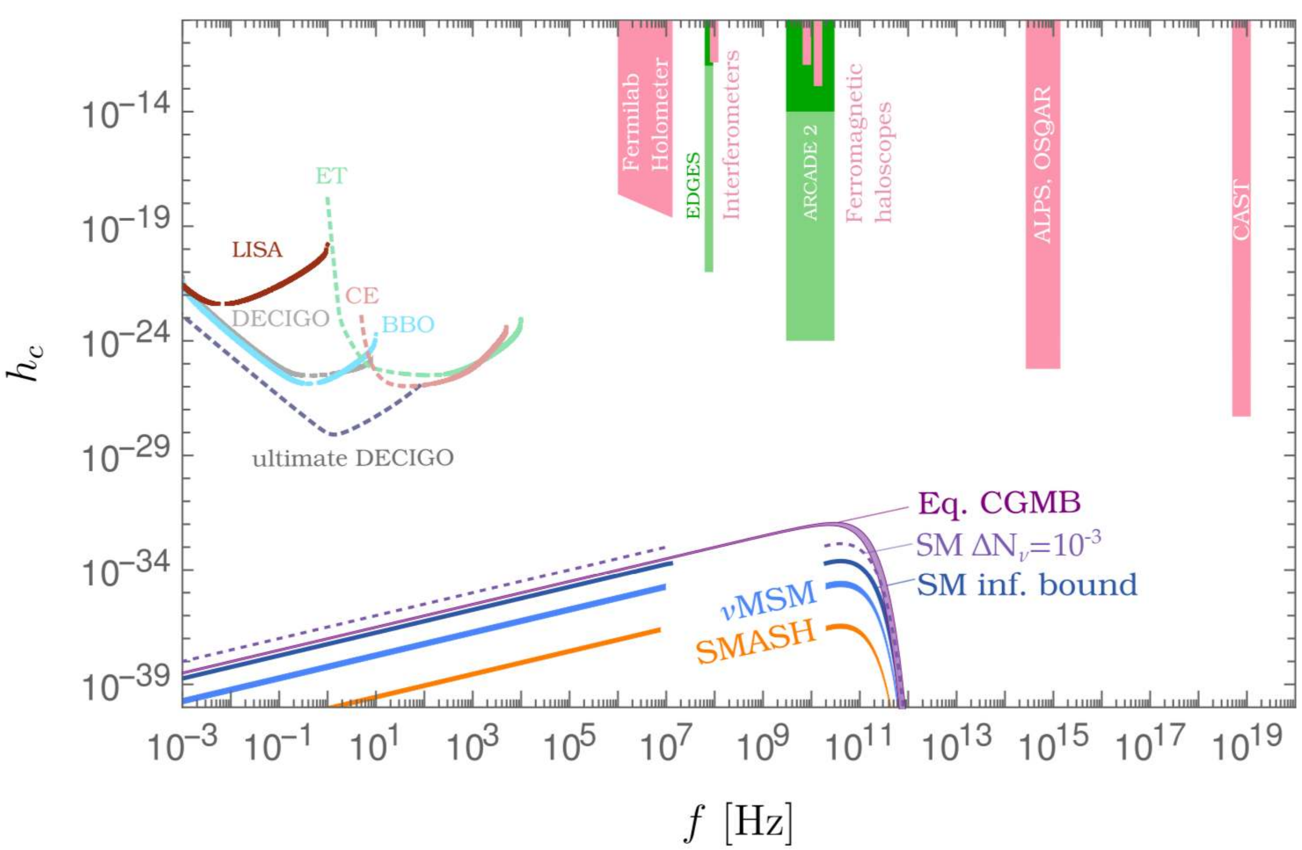
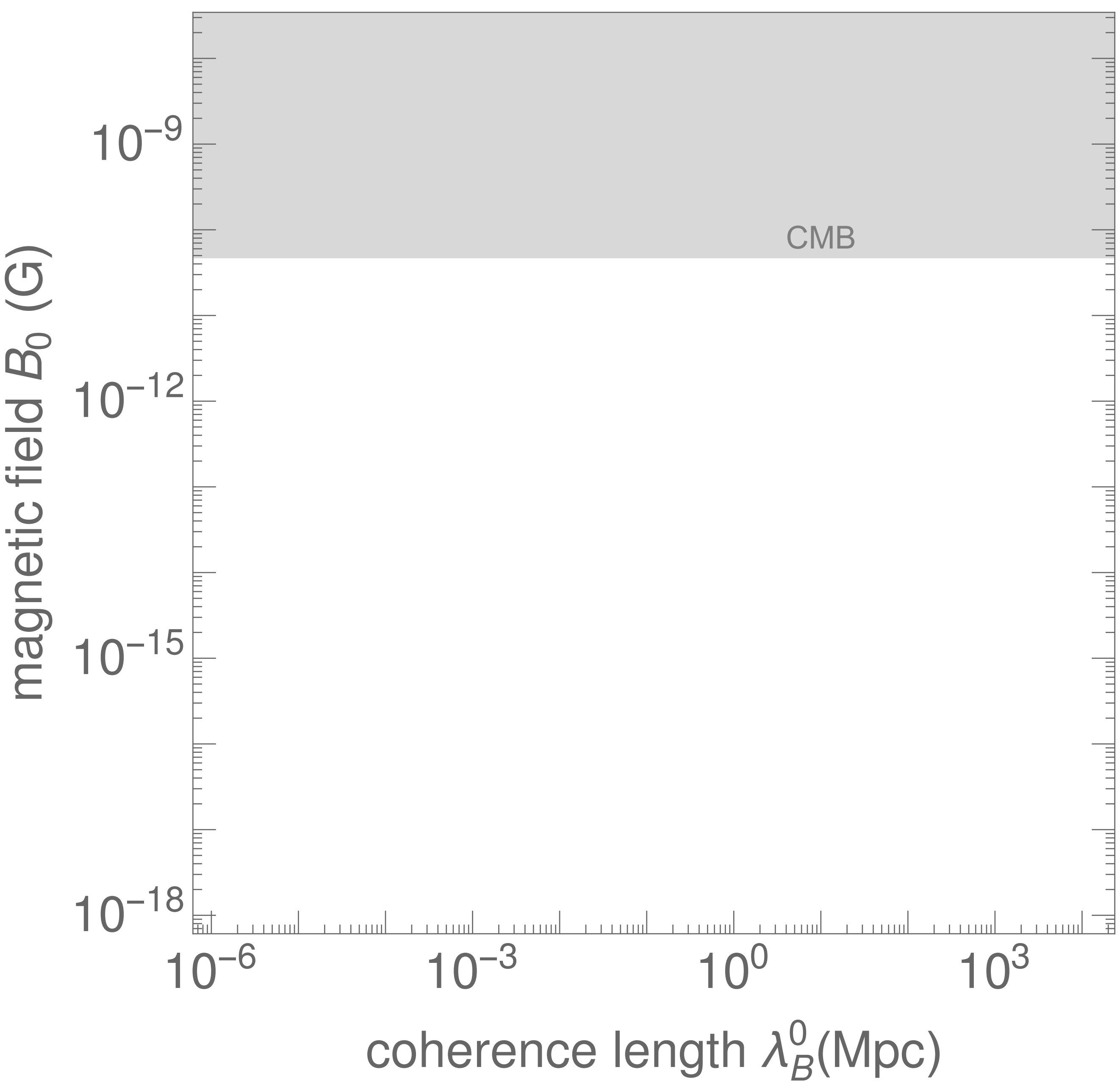


Camilo A. Garcia Cely

Cosmic magnetic fields and multi-messenger astronomy

Cosmic magnetic fields and multi-messenger astronomy

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

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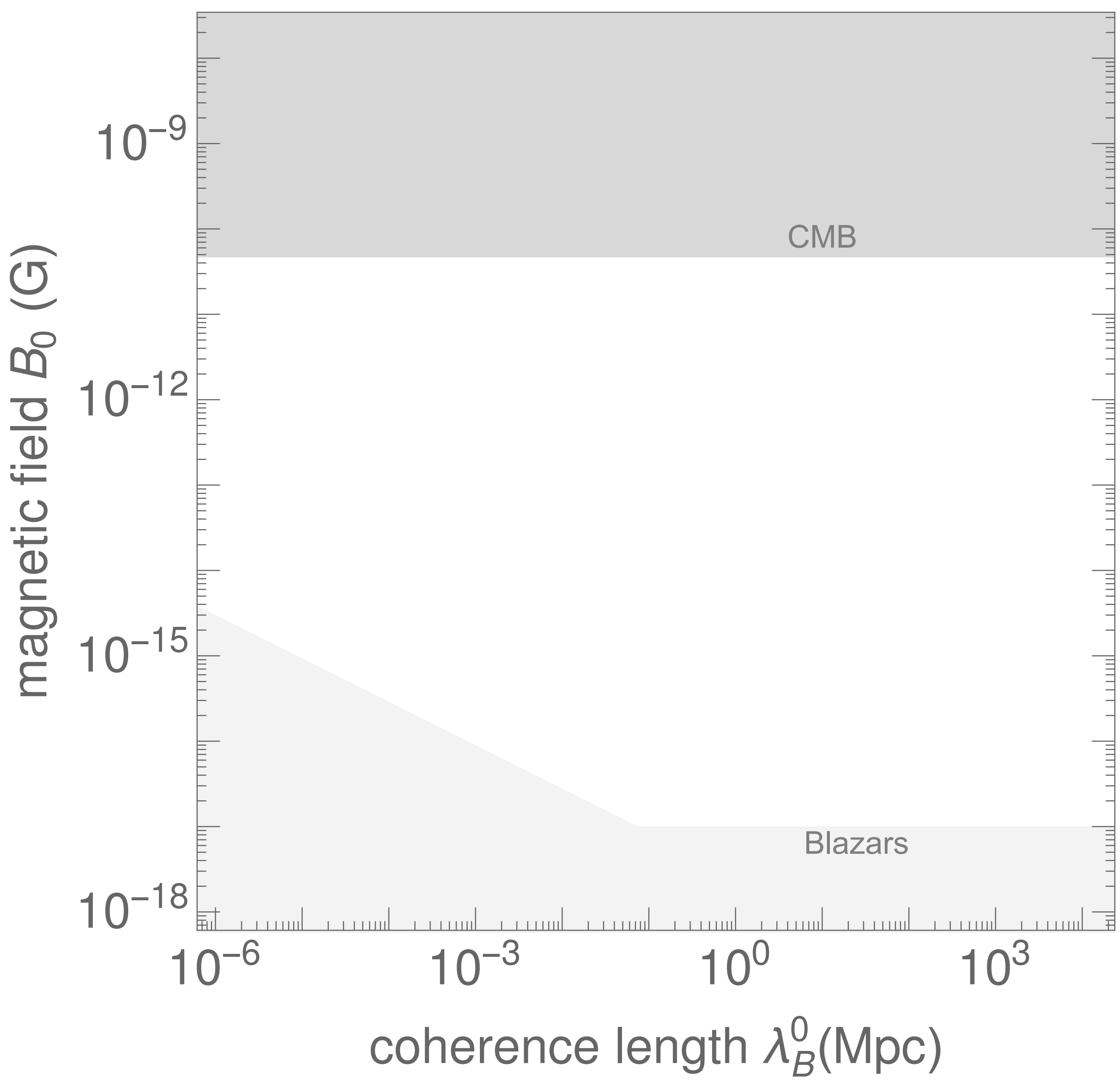

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Andrii Neronov*, Ievgen Vovk
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Science 02 Apr 2010:
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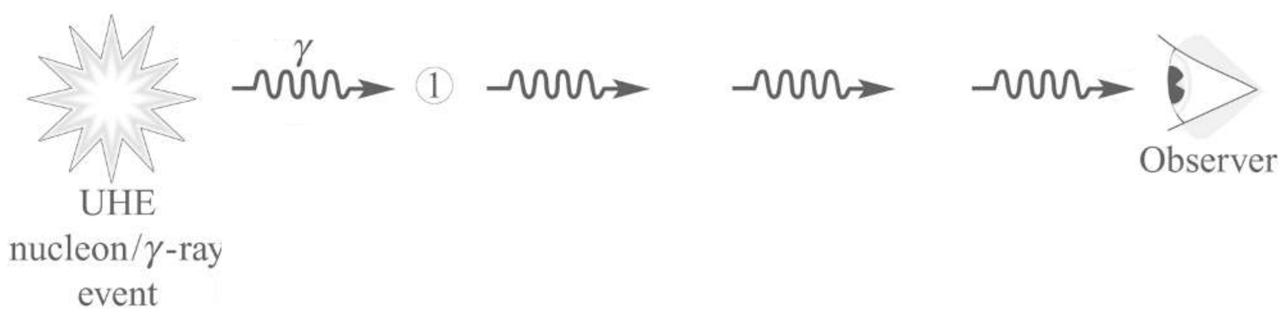
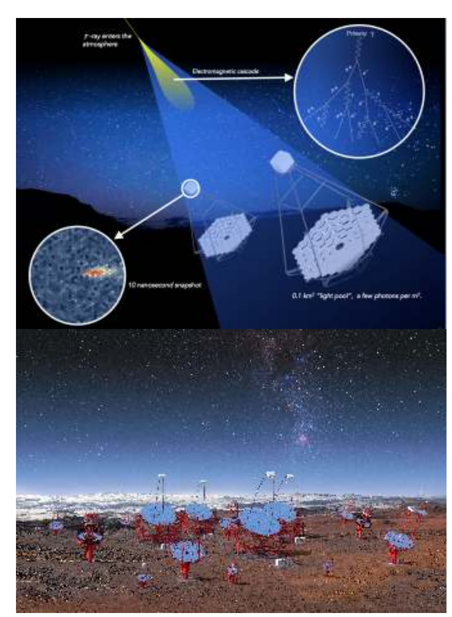
Synergy with TeV γ ray observatories

Kronberg , 2016
Cambridge University Press





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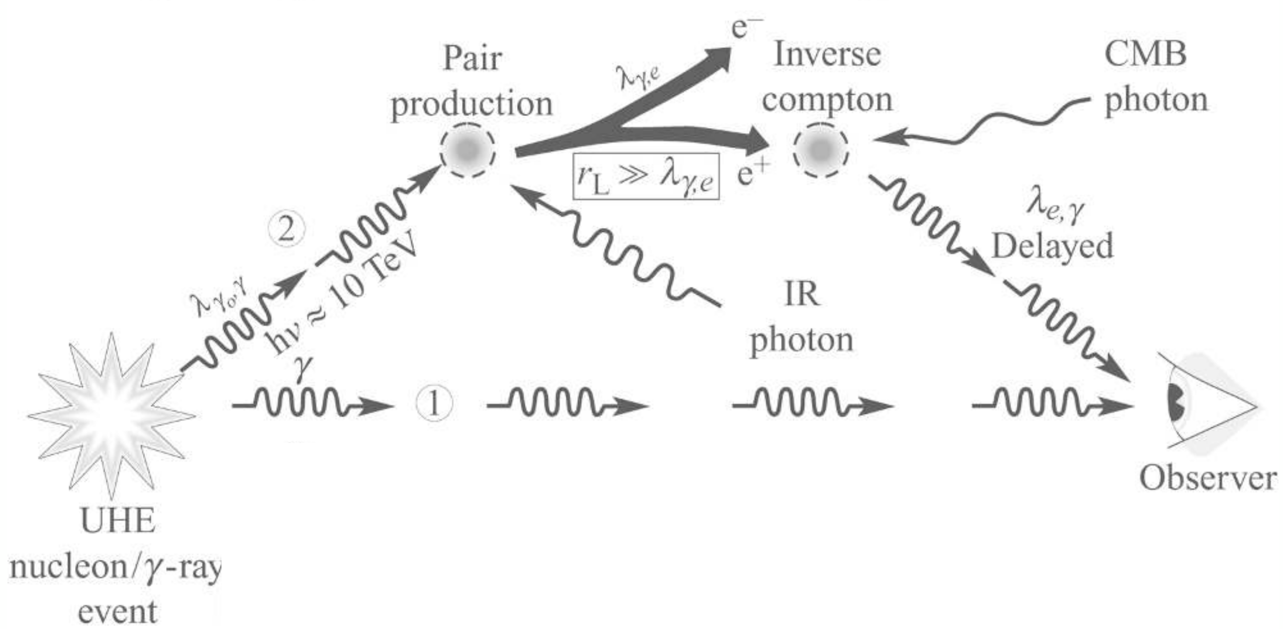
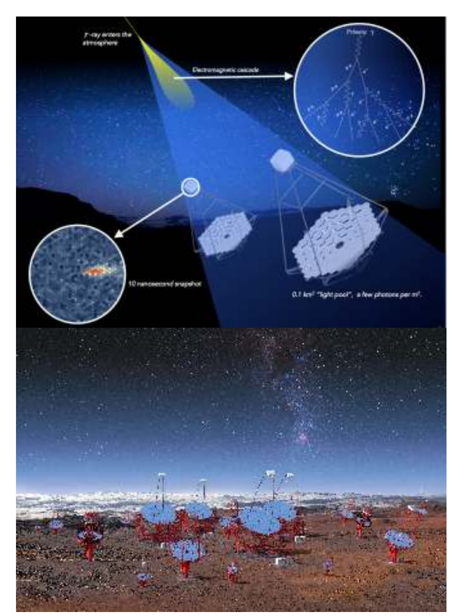
High energy $h\nu$ –e^+e^- cascades in the intergalactic medium





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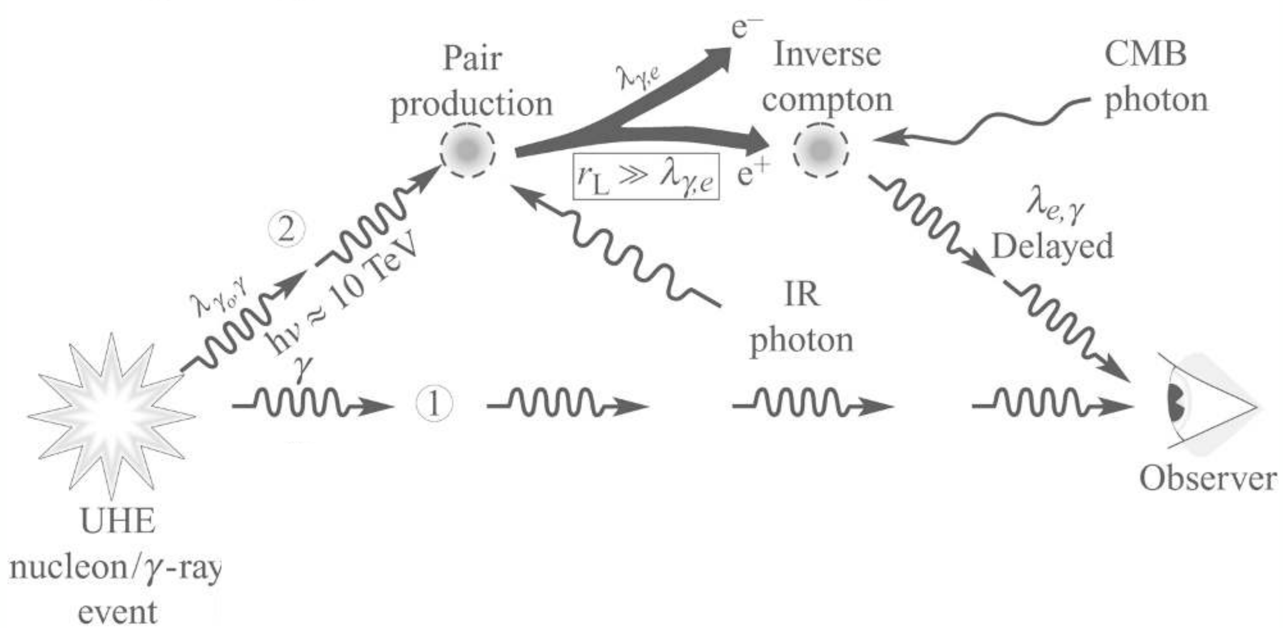

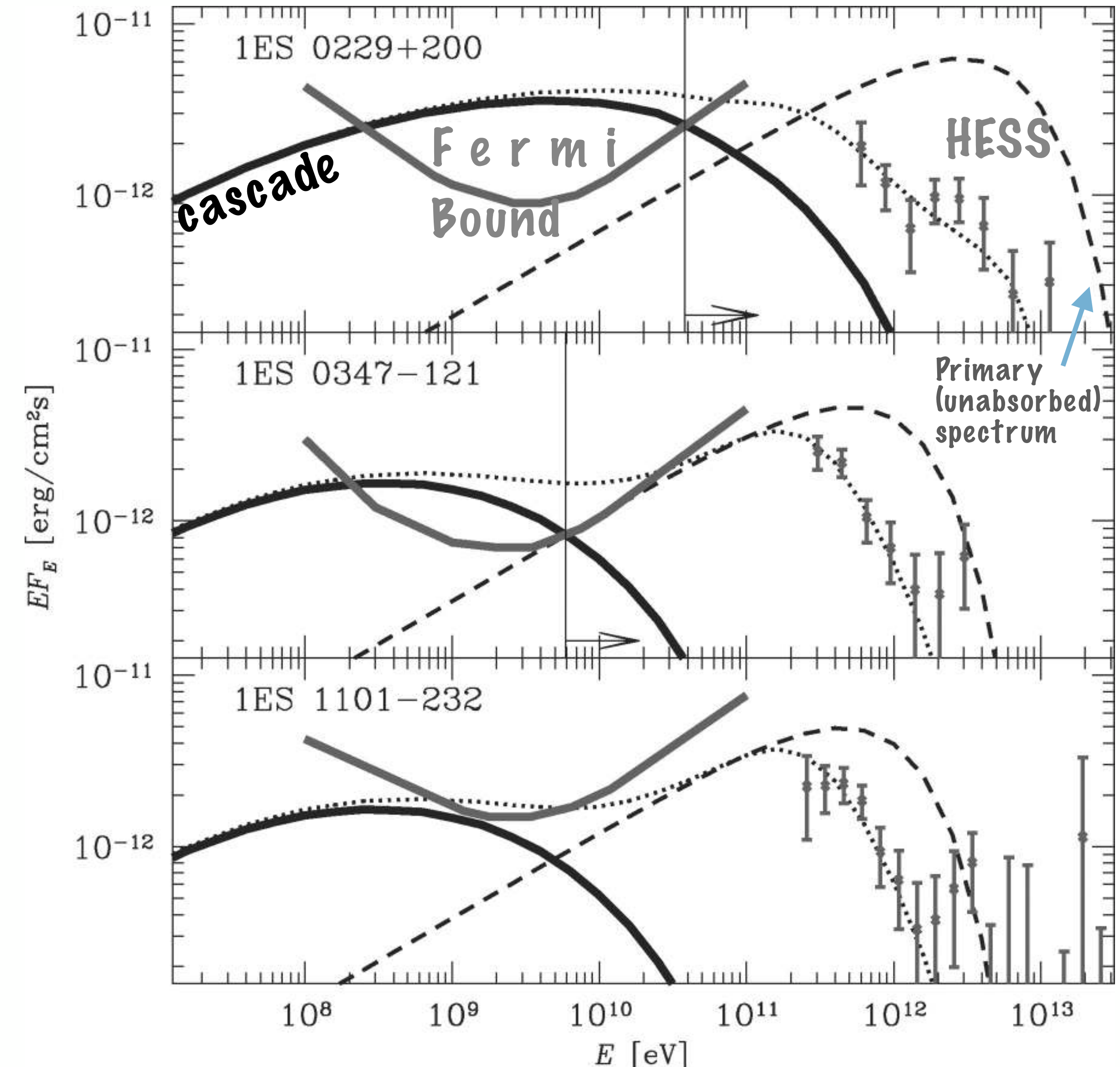

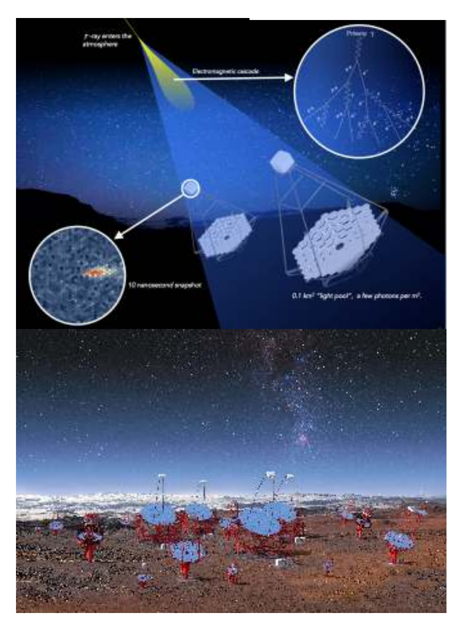

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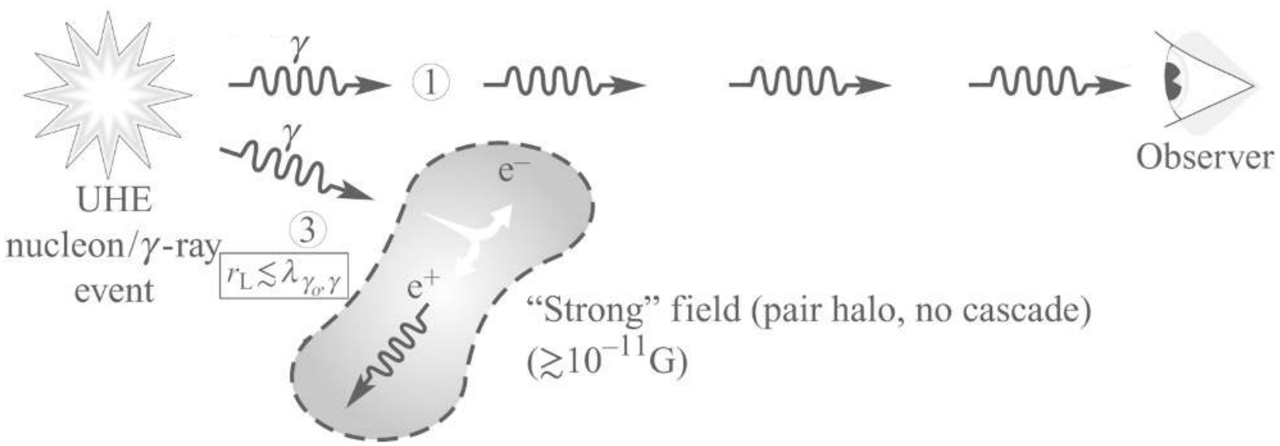

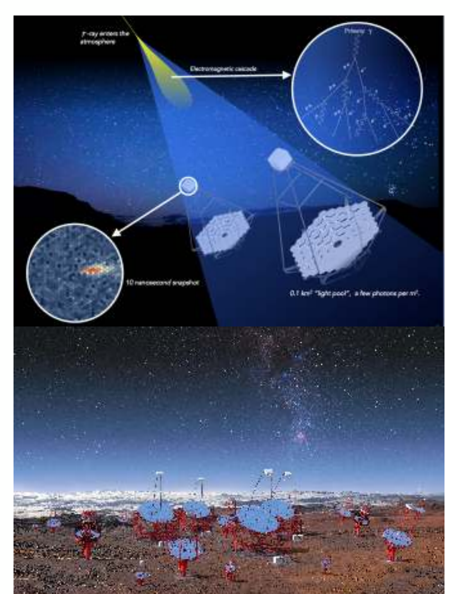

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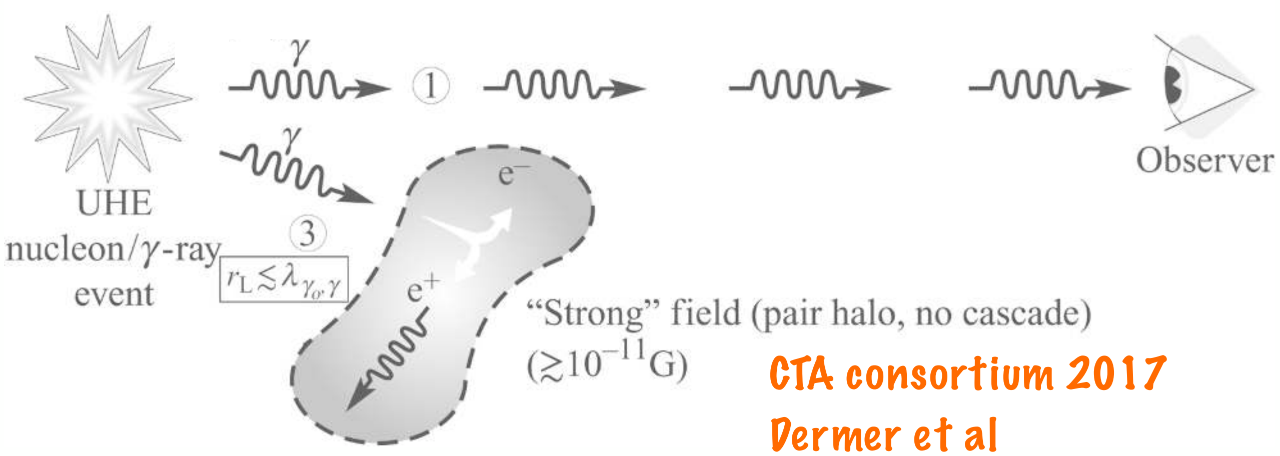
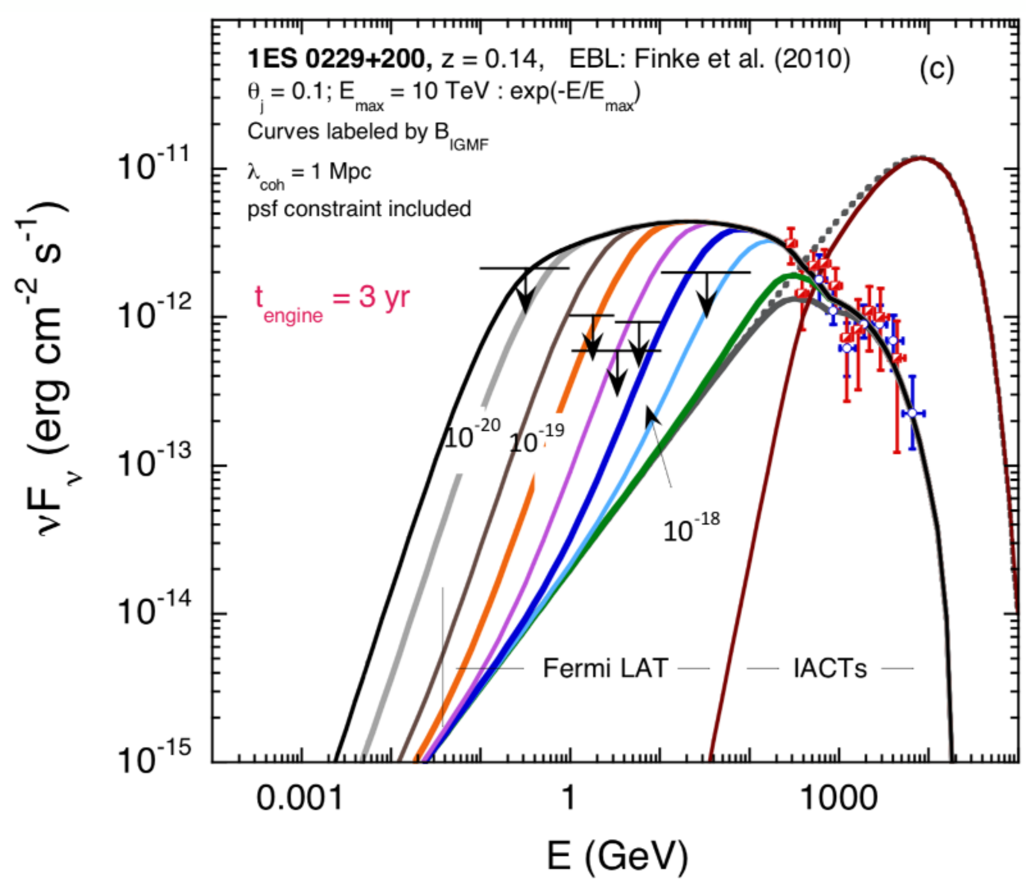
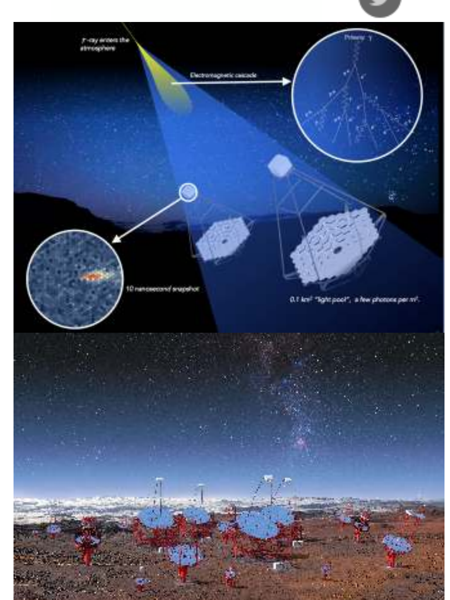
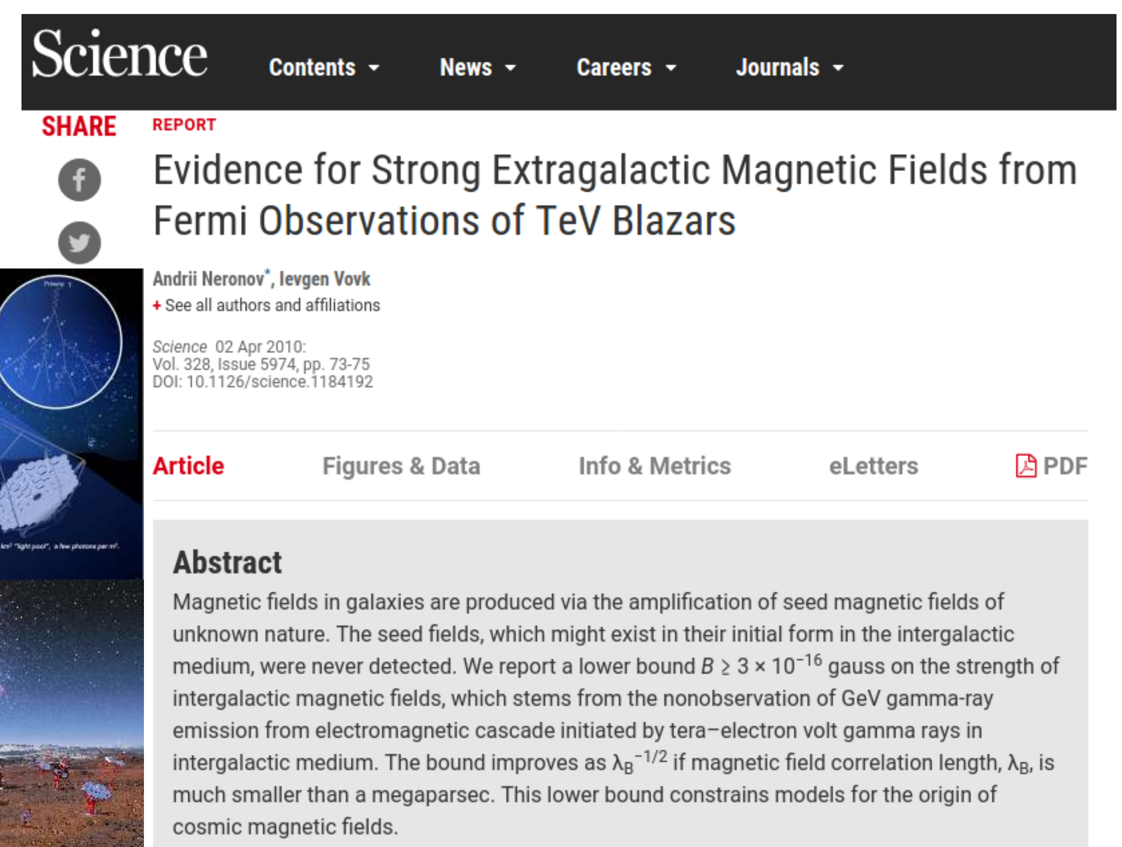


CTA consortium 2017
Dermer et al



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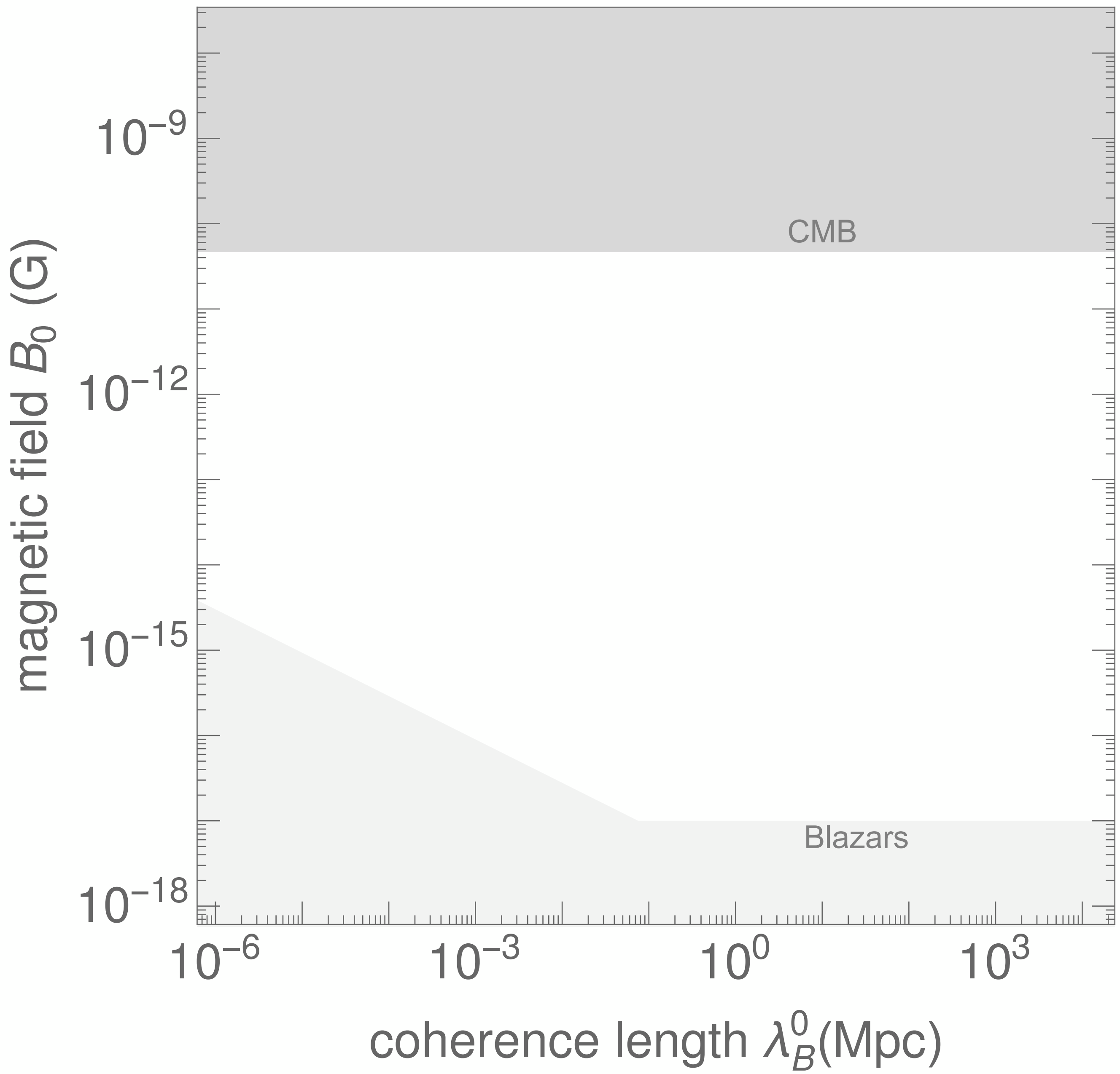
Synergy with TeV γ ray observatories

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 and multi-messenger astronomy

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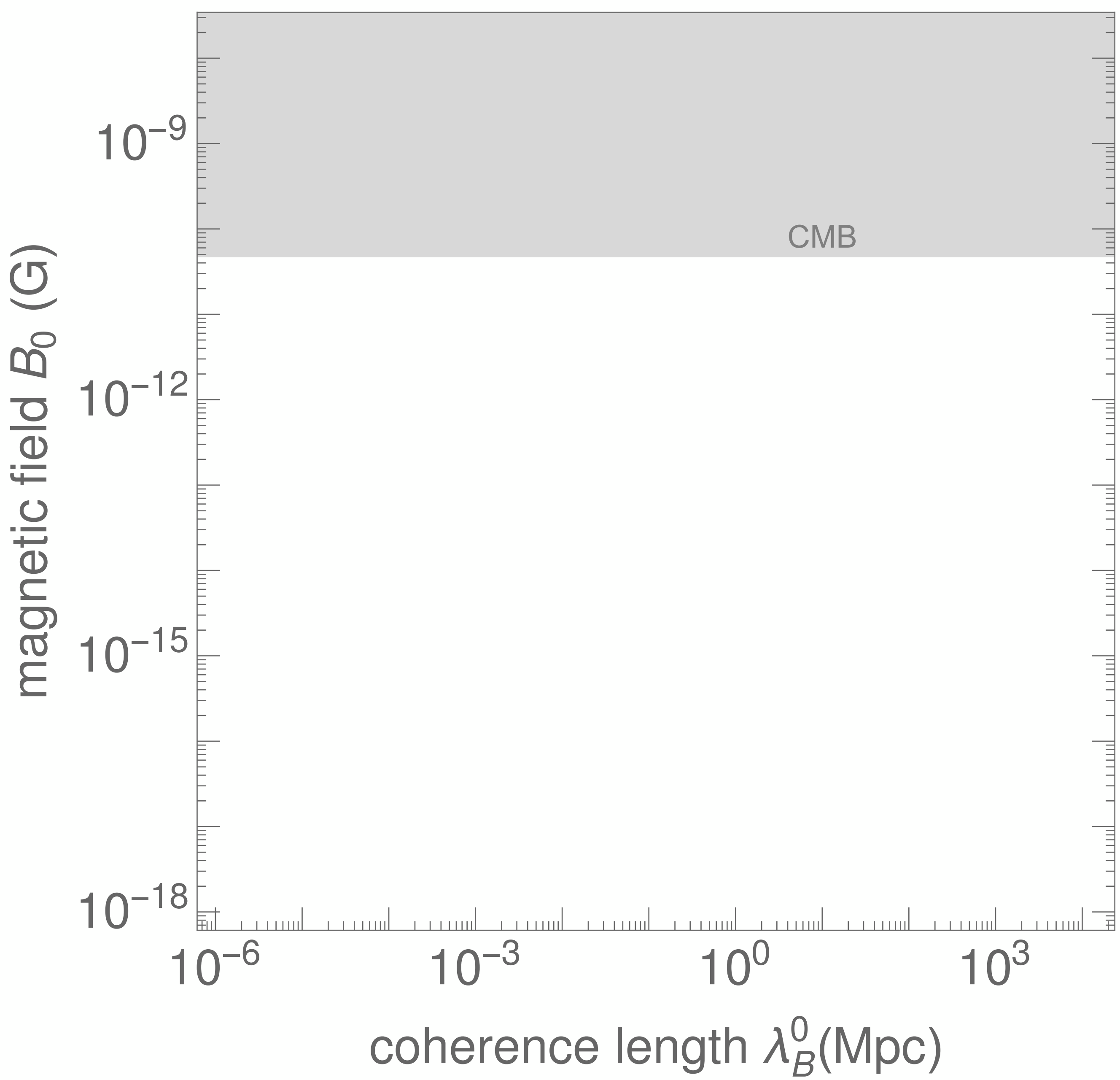

PHYSICAL REVIEW LETTERS **123,** 021301 (2019)

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

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PHYSICAL REVIEW LETTERS **125,** 181302 (2020)

Relieving the Hubble Tension with Primordial Magnetic Fields

Karsten Jedamzik[1,*] and Levon Pogosian[2,3,†]
[1]*Laboratoire de Univers et Particules de Montpellier, UMR5299-CNRS, Universite de Montpellier, 34095 Montpellier, France*
[2]*Department of Physics, Simon Fraser University, Burnaby, BC V5A 1S6, Canada*
[3]*Institute of Cosmology and Gravitation, University of Portsmouth, Portsmouth PO1 3FX, United Kingdom*

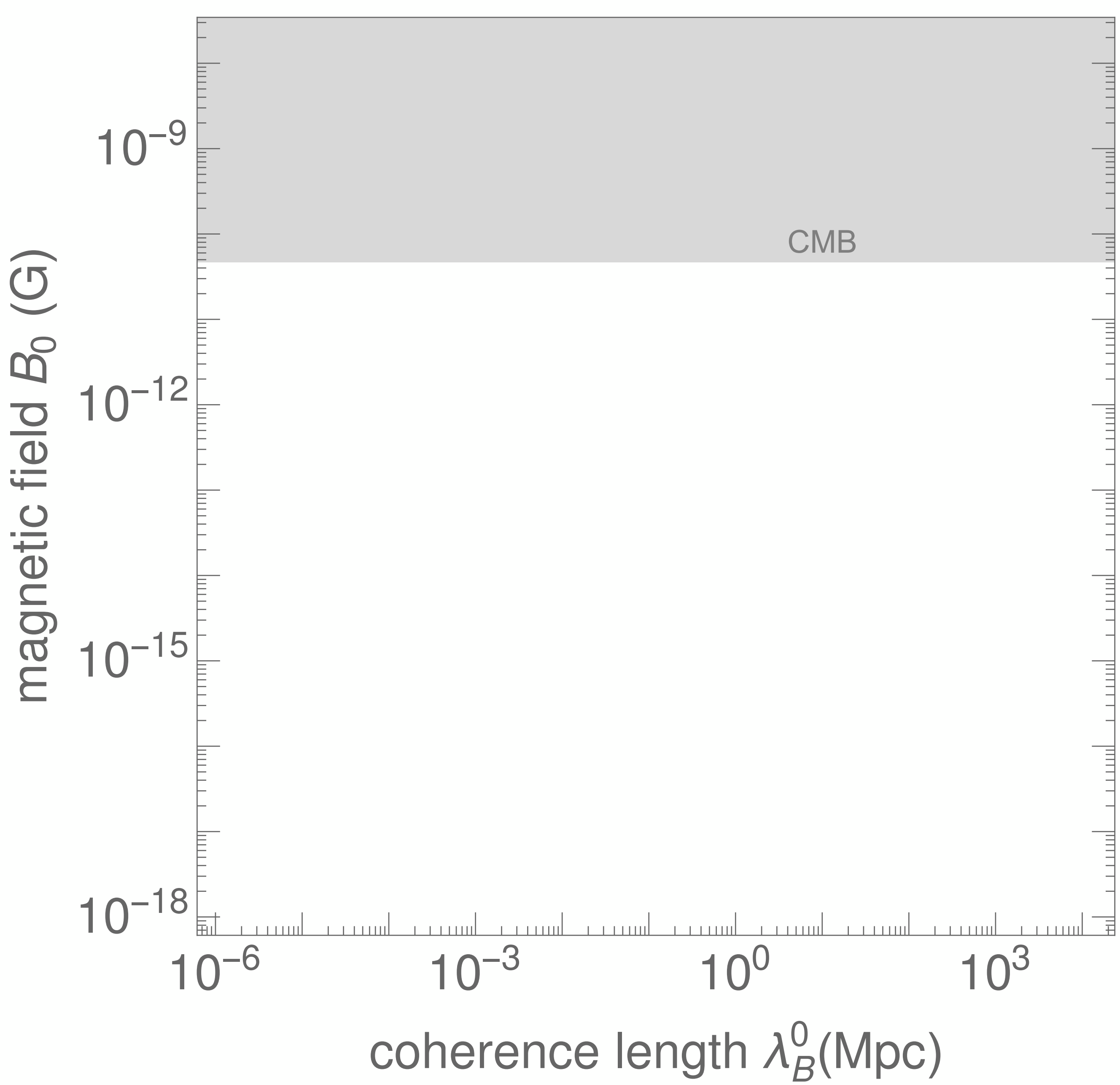
(Received 28 April 2020; revised 20 July 2020; accepted 10 September 2020; published 28 October 2020)

The standard cosmological model determined from the accurate cosmic microwave background measurements made by the Planck satellite implies a value of the Hubble constant H_0 that is 4.2 standard deviations lower than the one determined from type Ia supernovae. The Planck best fit model also predicts higher values of the matter density fraction Ω_m and clustering amplitude S_8 compared to those obtained from the Dark Energy Survey Year 1 data. Here we show that accounting for the enhanced recombination rate due to additional small-scale inhomogeneities in the baryon density may solve both the H_0 and the S_8-Ω_m tensions. The additional baryon inhomogeneities can be induced by primordial magnetic fields present in the plasma prior to recombination. The required field strength to solve the Hubble tension is just what is needed to explain the existence of galactic, cluster, and extragalactic magnetic fields without relying on dynamo amplification. Our results show clear evidence for this effect and motivate further detailed studies of primordial magnetic fields, setting several well-defined targets for future observations.

Camilo A. Garcia Cely

Cosmic magnetic fields and multi-messenger astronomy

Domcke, CGC 2021



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Potential solution to the Hubble tension

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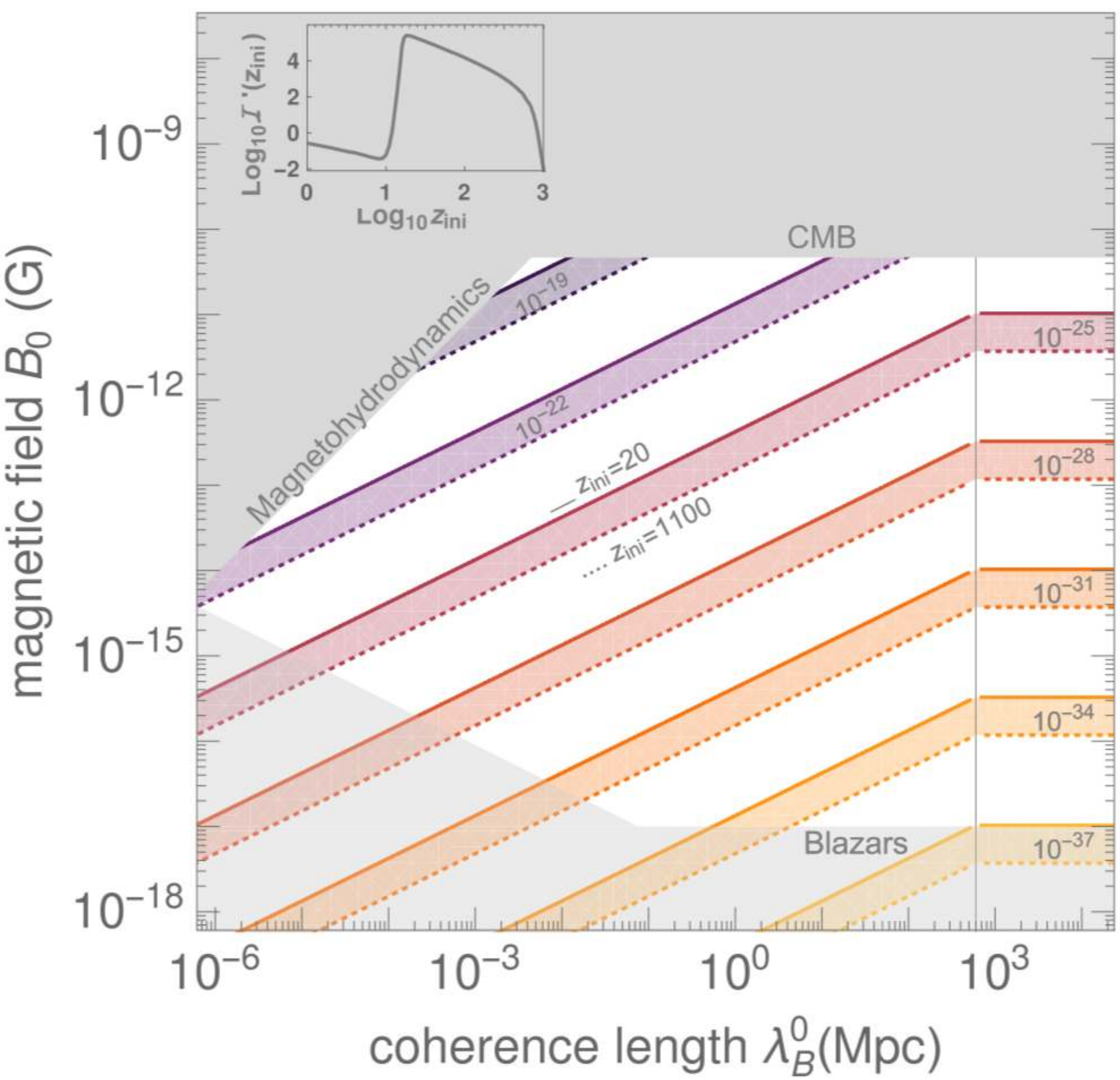
Domcke, CGC 2021



$$\mathcal{P} \equiv \int_{l.o.s.} \langle \Gamma_{g\leftrightarrow\gamma} \rangle dt$$

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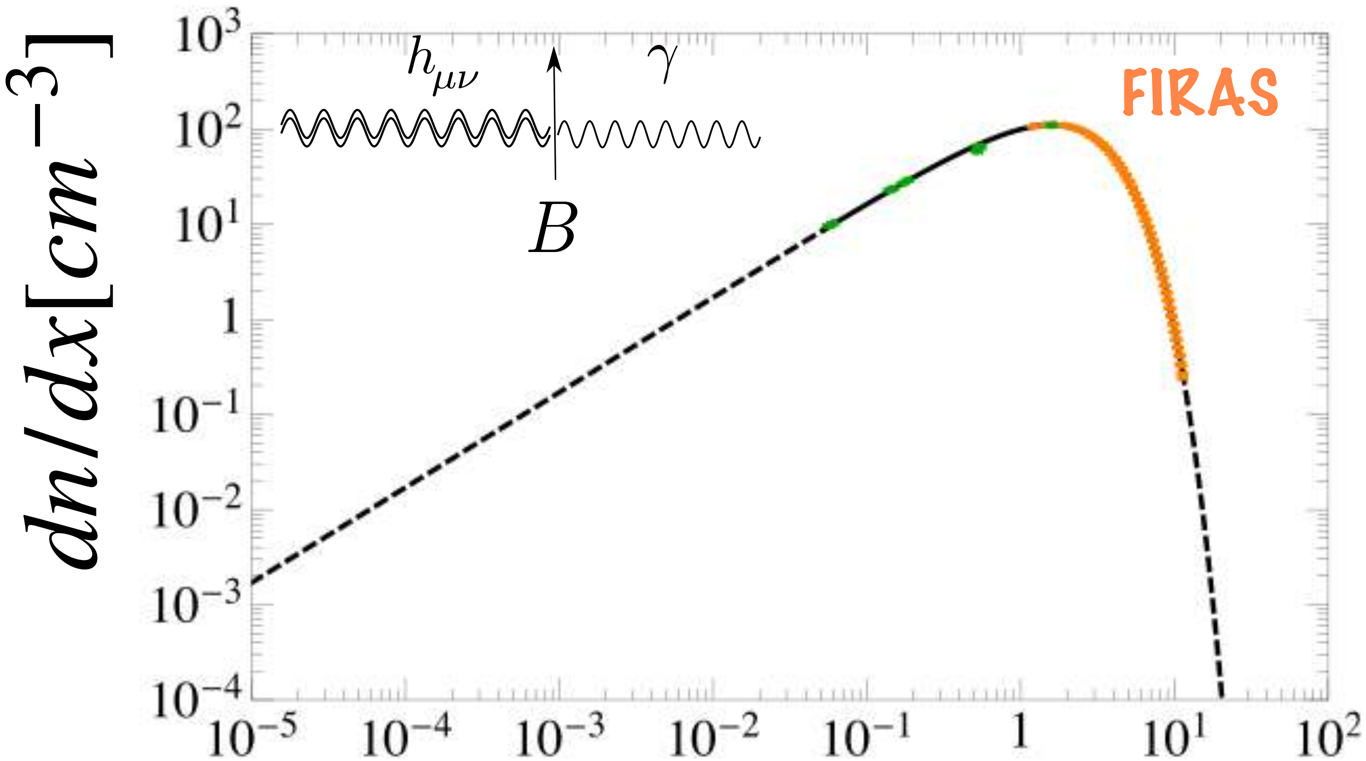
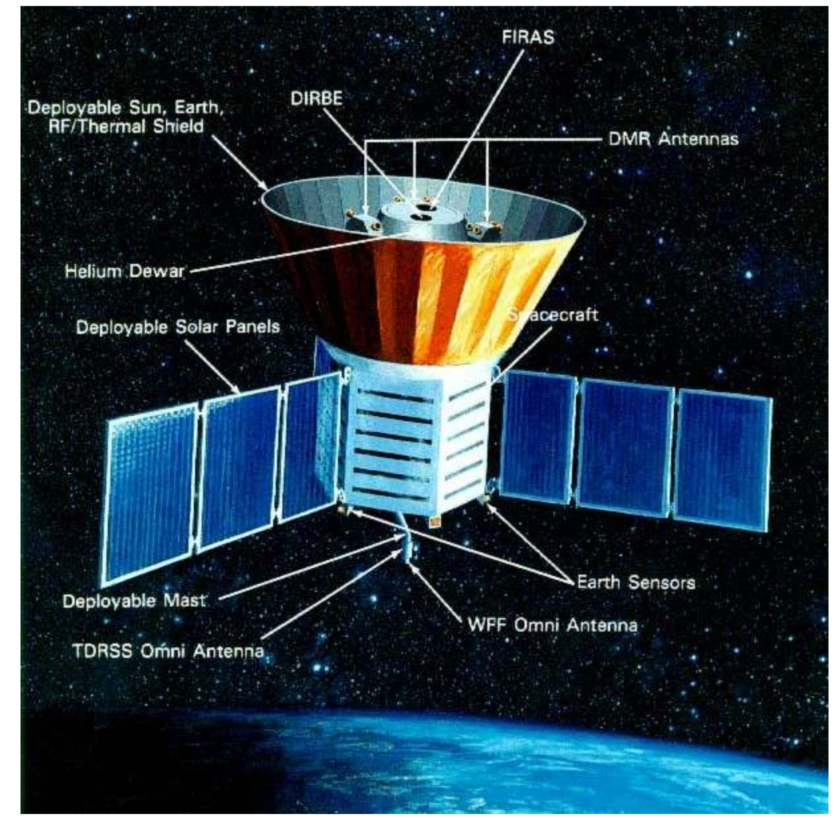
CMB observations and 21-cm cosmology

CMB distortions





Competes with the cosmological constraints on radiation energy N_{eff}

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

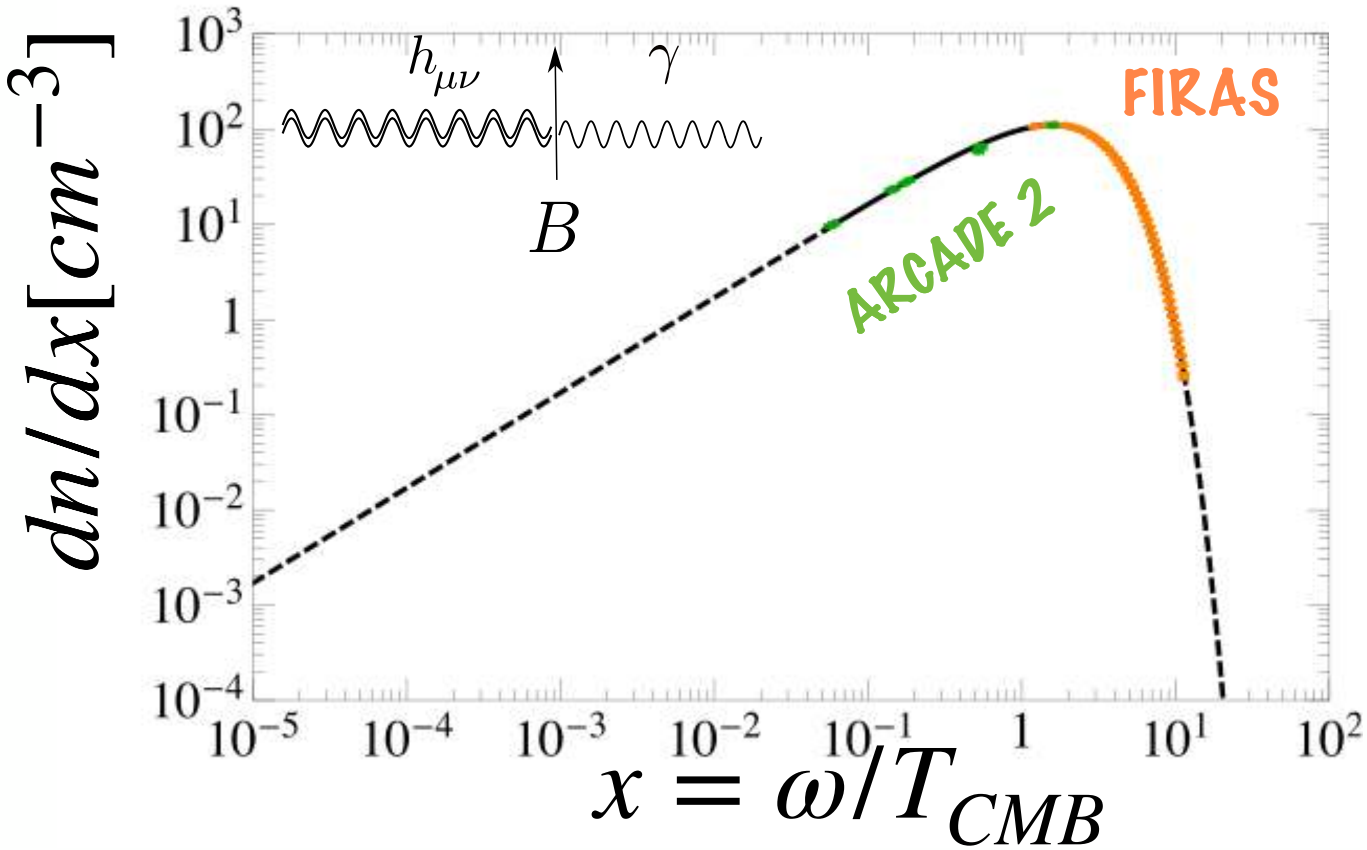
ABSTRACT

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, $(\ell, b) = (264°.14 \pm 0.30, 48°.26 \pm 0.30)$ (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

Camilo A. Garcia Cely

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.

Camilo A. Garcia Cely

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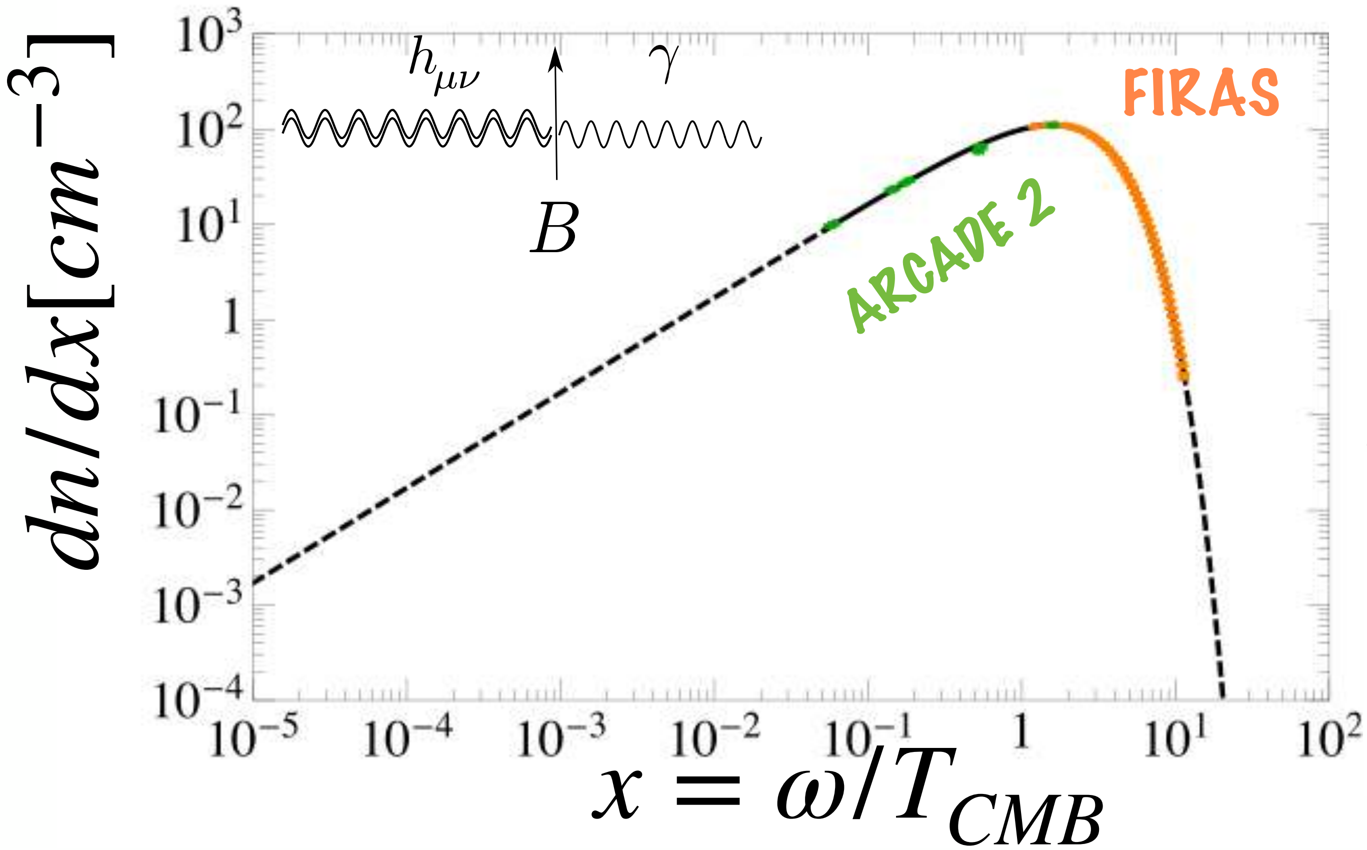

- Largely unexplored with upcoming advances in radio astronomy probing it in the near future.
- Puzzling signal by EDGES. (Experiment to Detect the Global Epoch of Reionization Signature)

THE ASTROPHYSICAL JOURNAL

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The Astrophysical Journal, Volume 734, Number 1

nature

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

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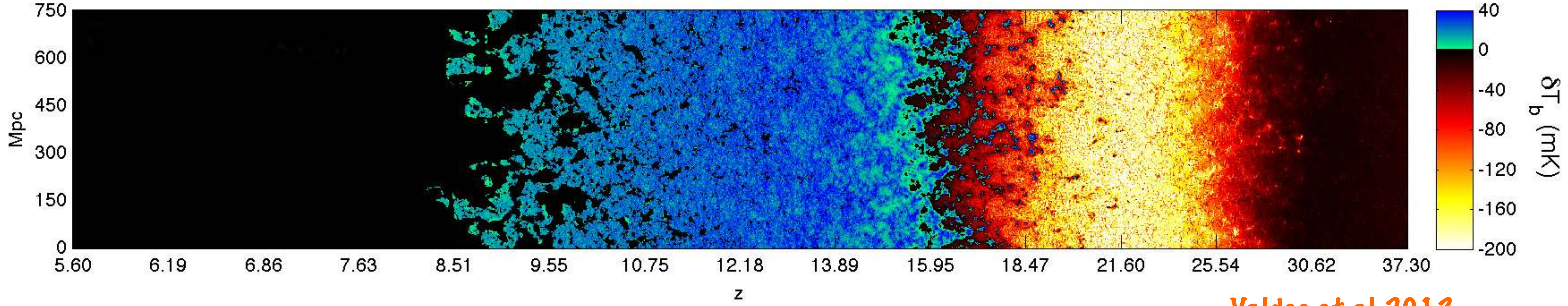
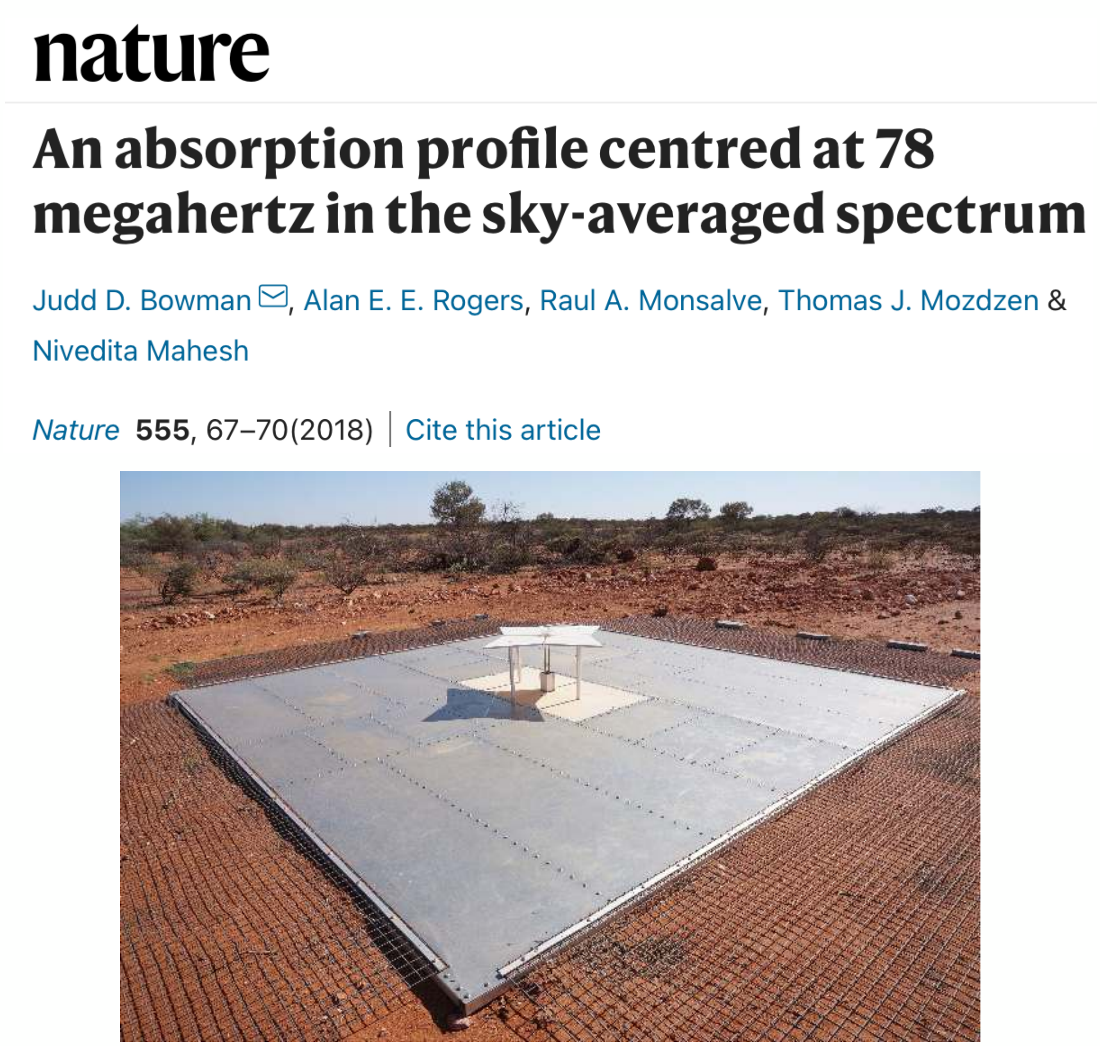
Nature **555**, 67–70(2018) | Cite this article

Expectations for a 21 cm signal



Valdes et al 2013



Camilo A. Garcia Cely

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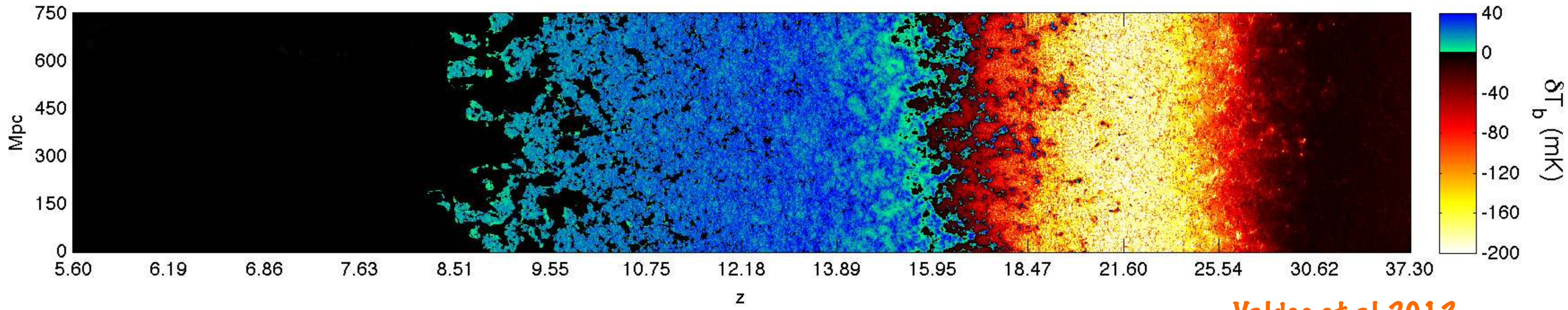

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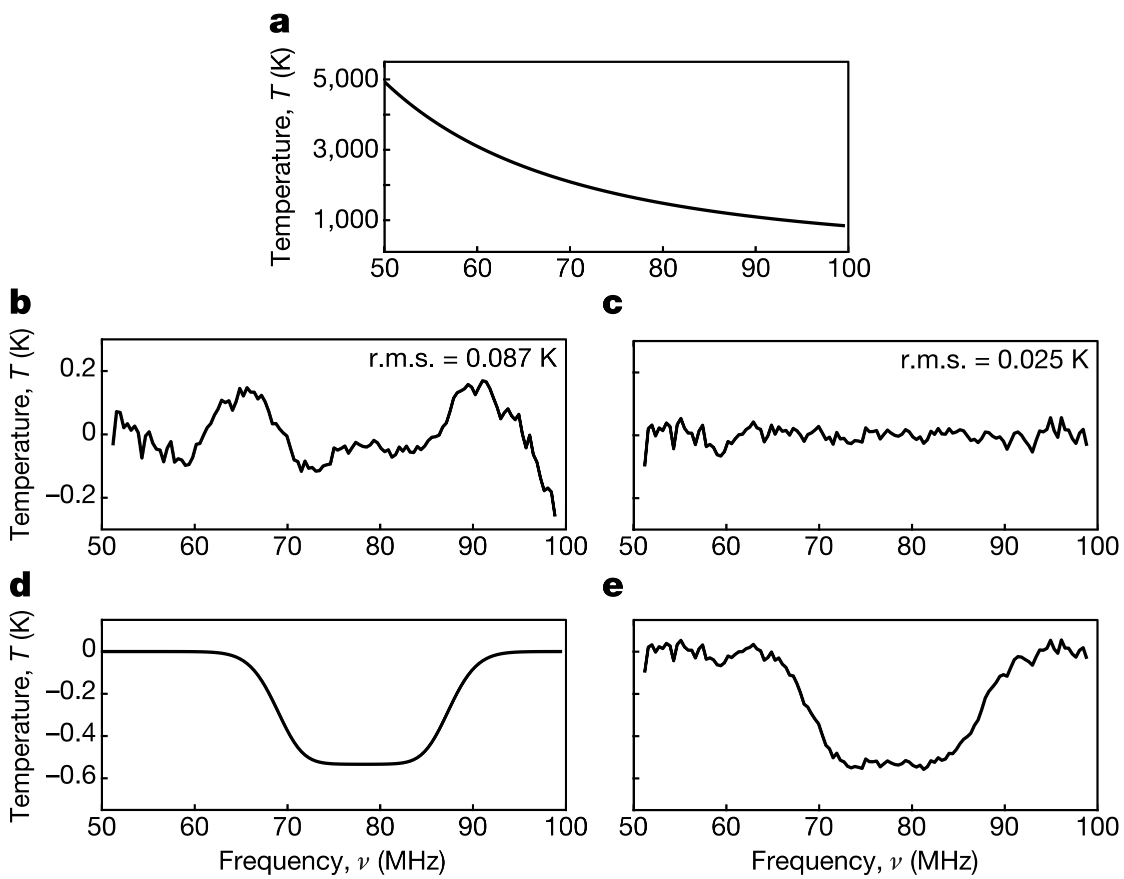

Figure 1 | Summary of detection. a, Measured spectrum for the reference dataset after filtering for data quality and radio-frequency interference. The spectrum is dominated by Galactic synchrotron emission. **b**, **c**, Residuals after fitting and removing only the foreground model (**b**) or the foreground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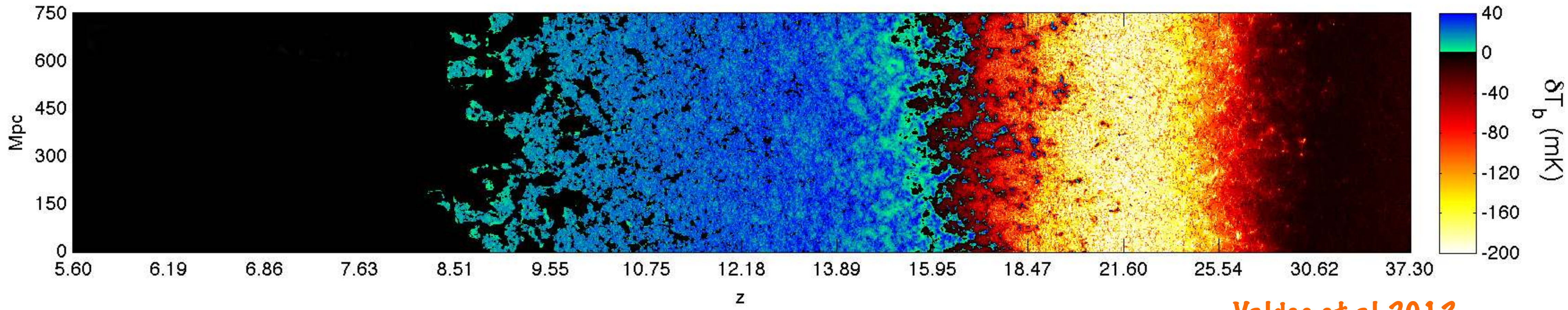

Valdes et al 2013

The absorption feature was found to be roughly twice as strong as previously expected. Conservatively, we may assume that the deviation from the expected value is due to foreground contamination, and place a bound on any stochastic GW background by using $\delta f_\gamma / f_\gamma \lesssim 1$ at 78 MHz

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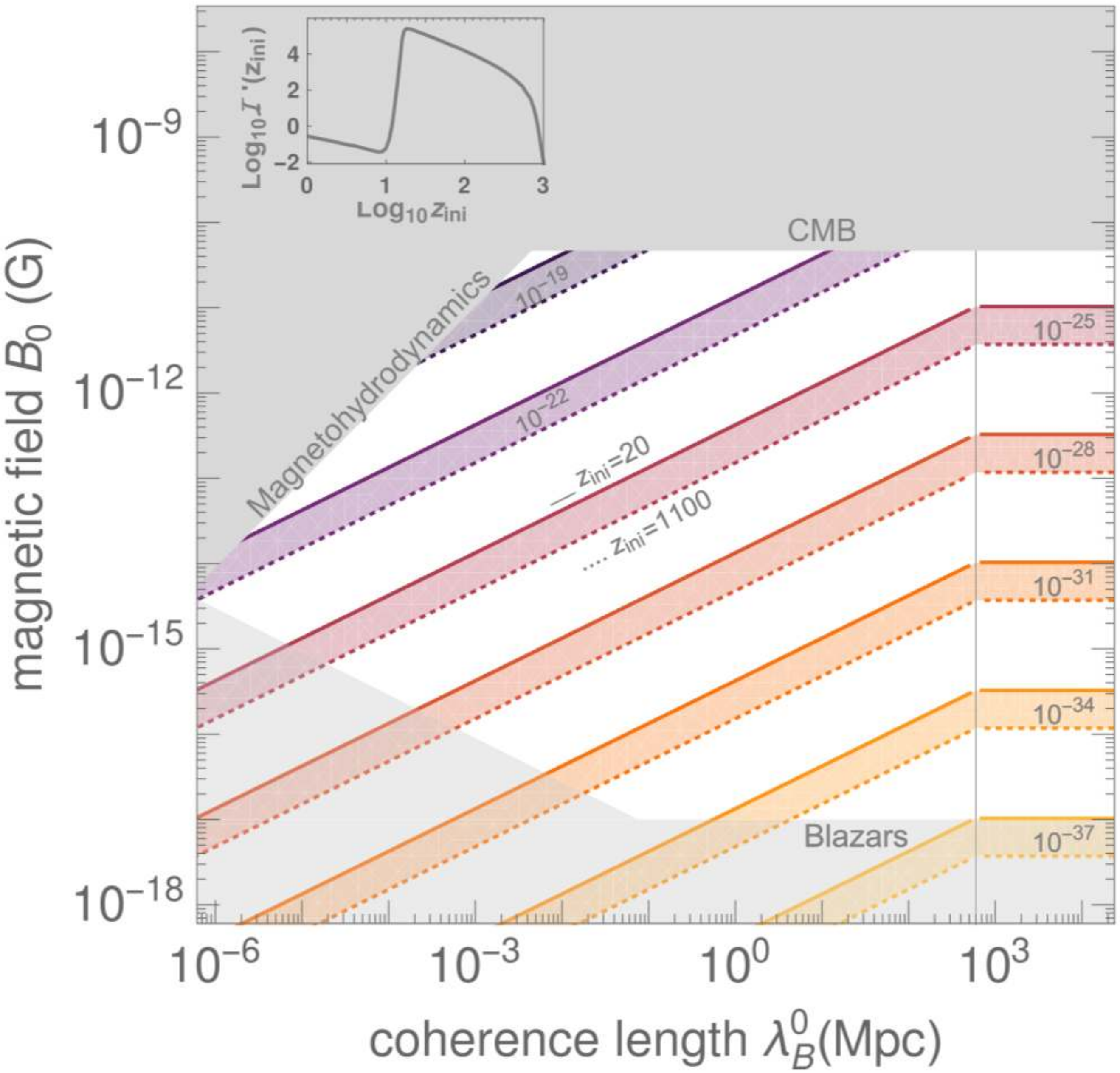
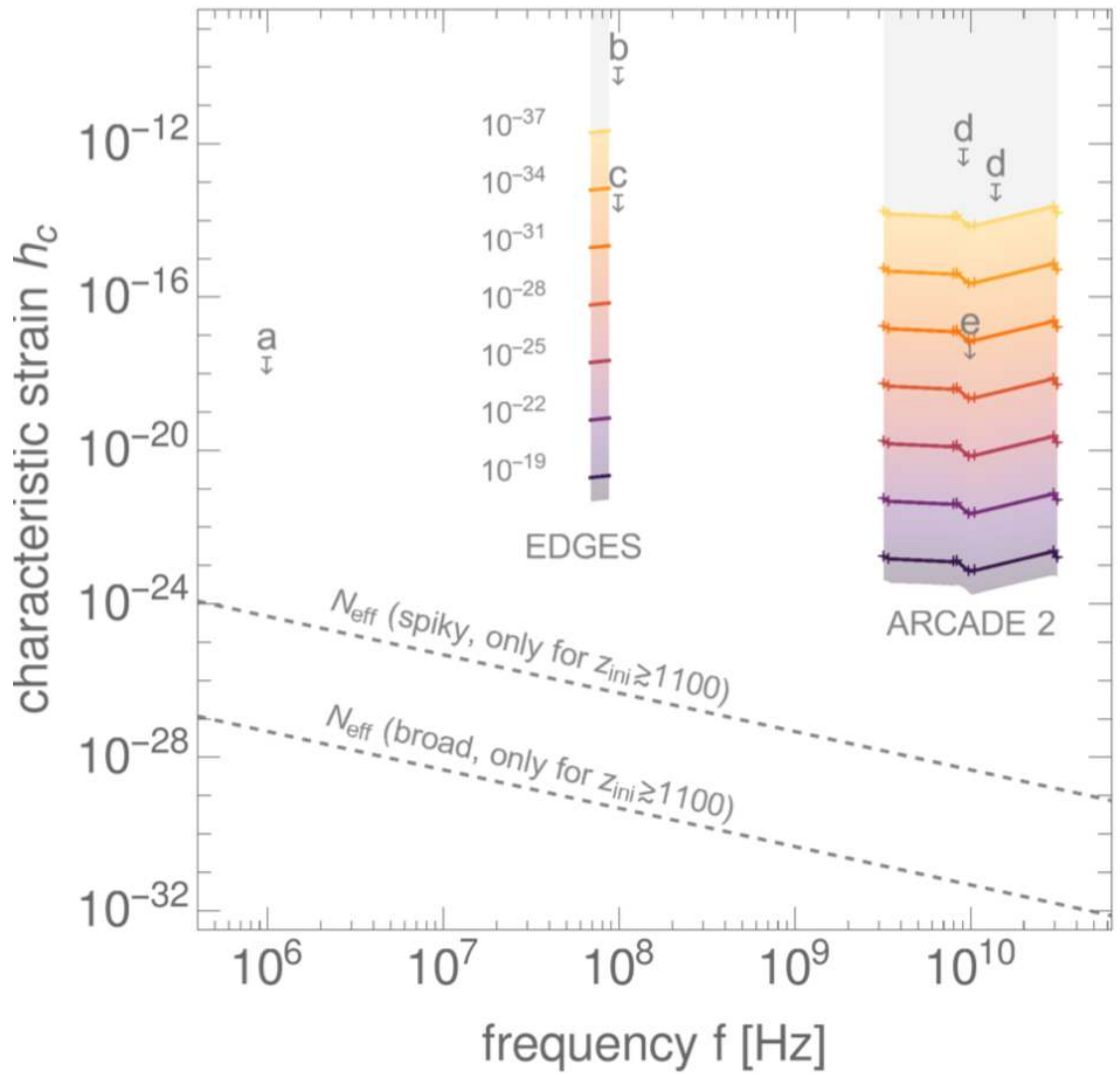
Upper bounds on stochastic gravitational waves

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,†]





$$\mathcal{P} \equiv \int_{l.o.s.} \langle \Gamma_{g\leftrightarrow\gamma} \rangle dt$$

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

Outlook and Future Prospects

arXiv.org > hep-ph > arXiv:2011.04731

High Energy Physics - Phenomenology

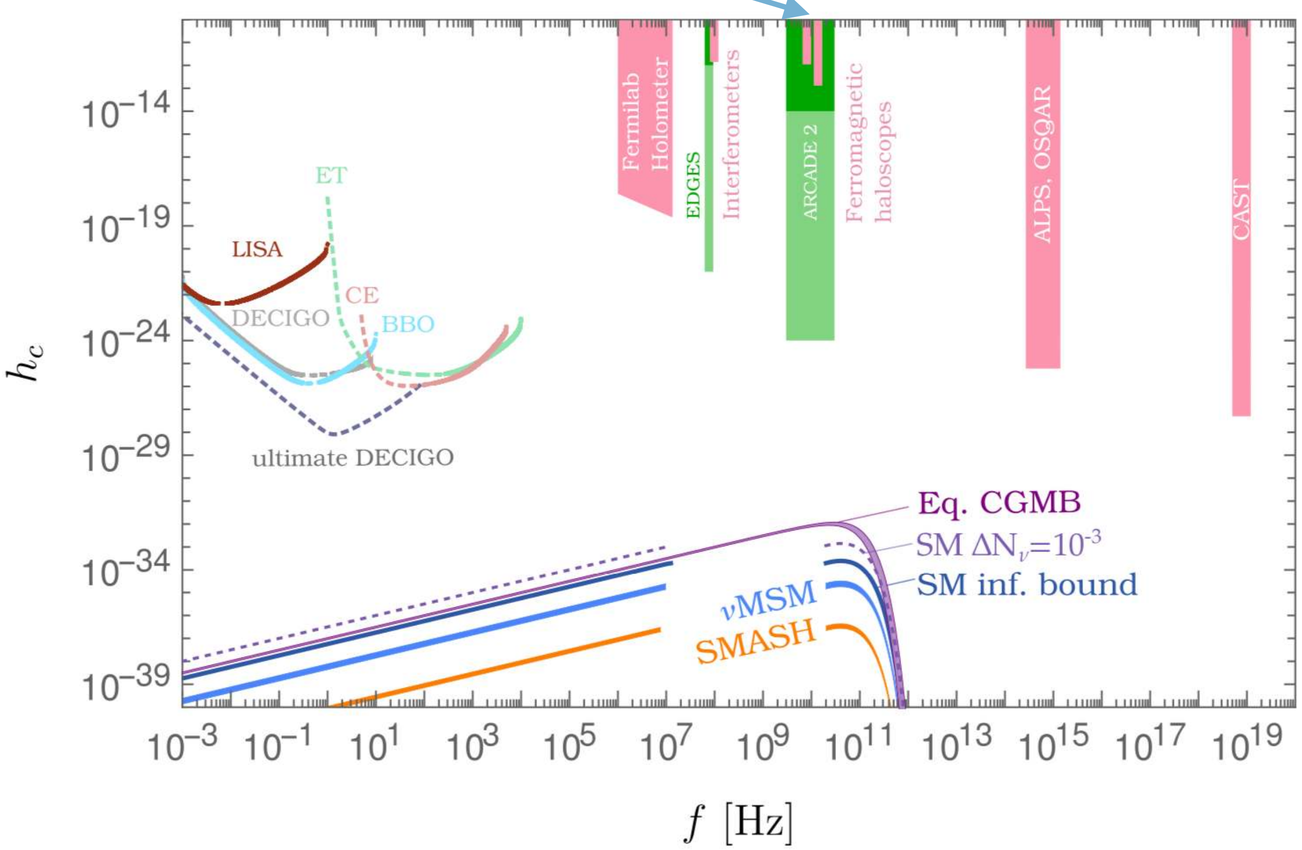
[Submitted on 9 Nov 2020]

Gravitational Waves as a Big Bang Thermometer

Andreas Ringwald, Jan Schütte-Engel, Carlos Tamarit

There is a guaranteed background of stochastic gravitational waves produced in the thermal plasma in the early universe.

this talk



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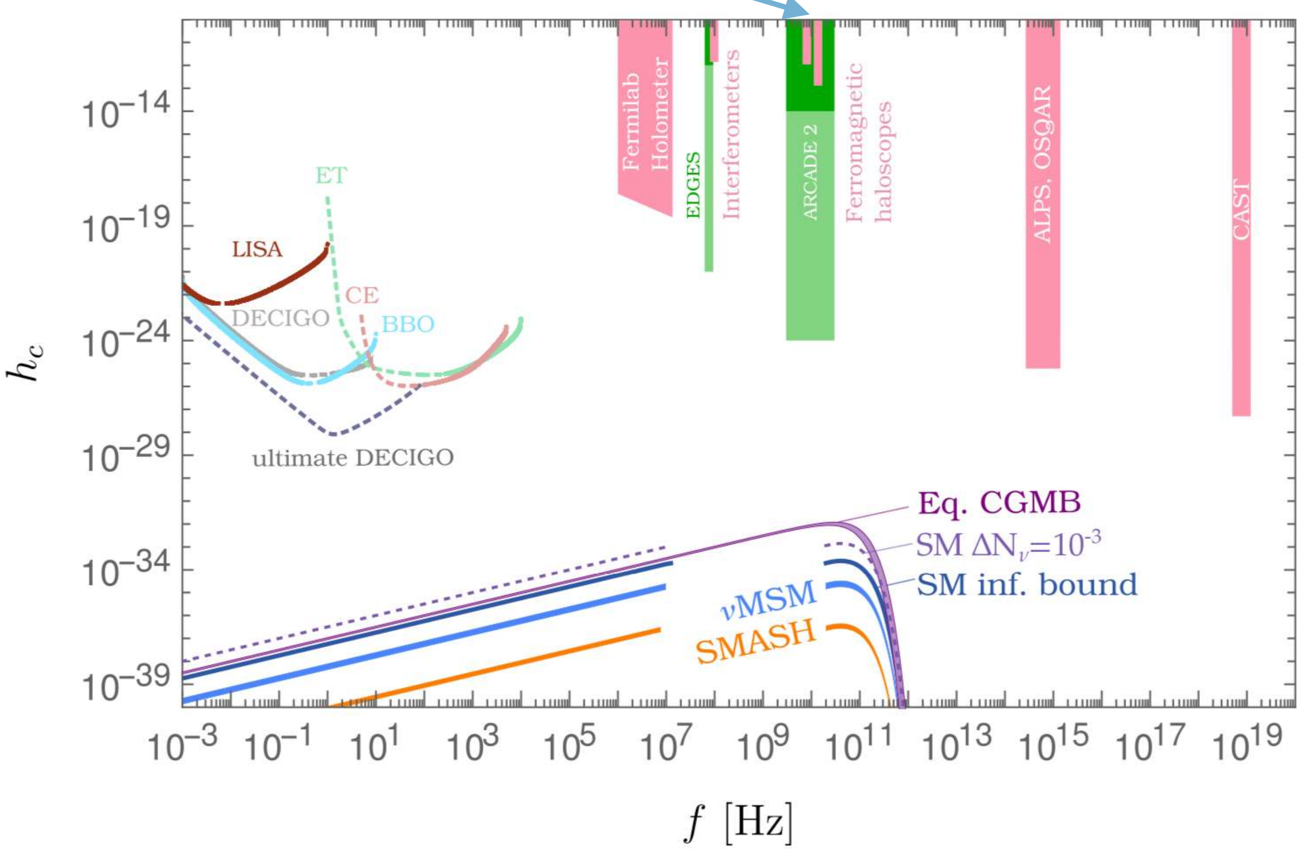
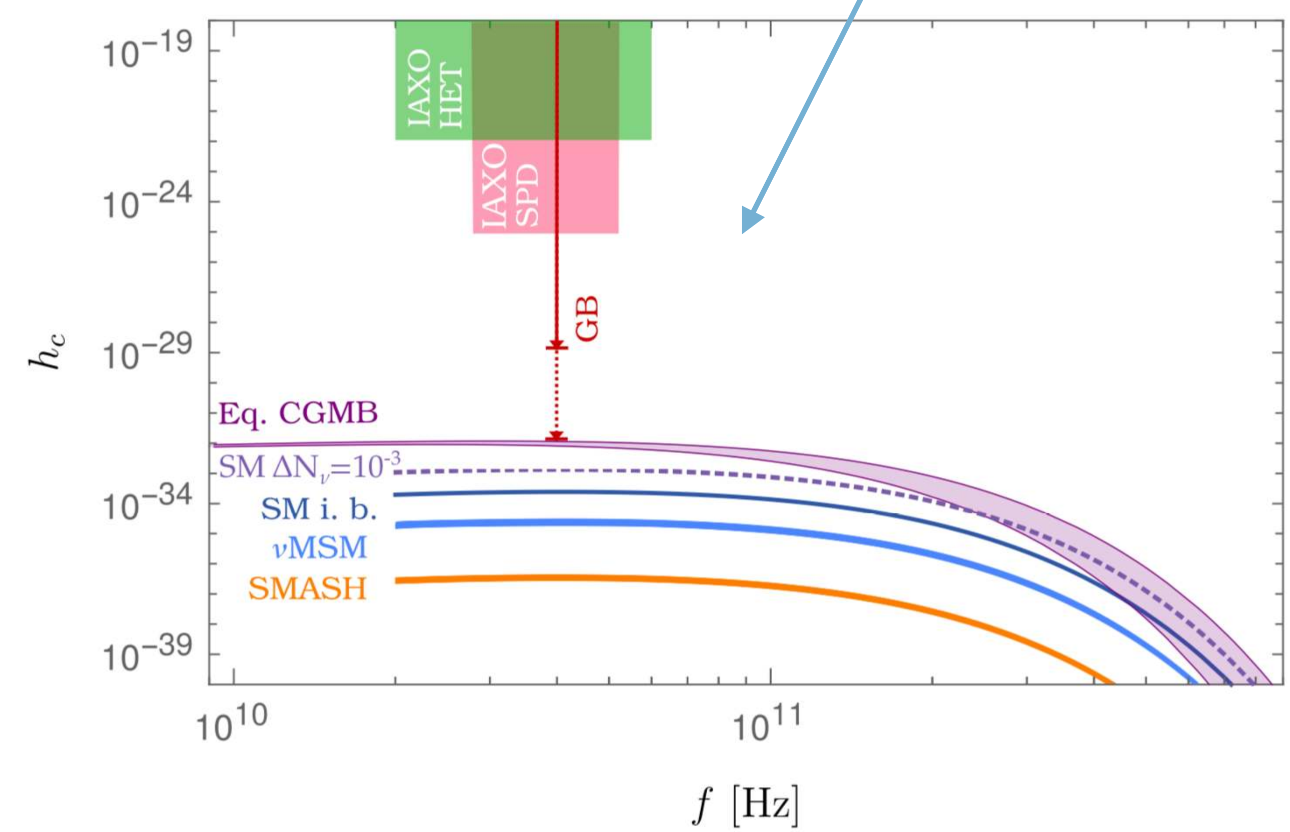


Modifications of the idea



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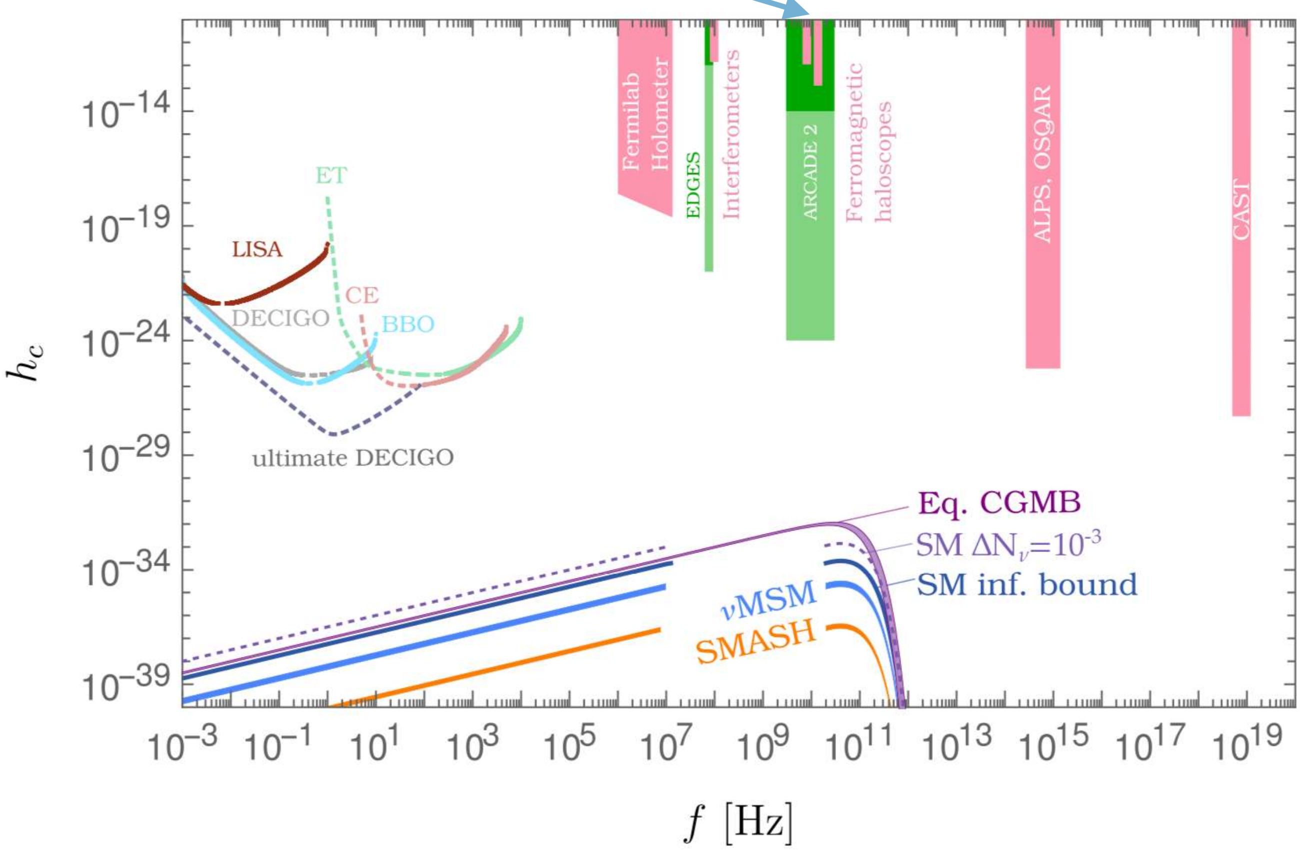
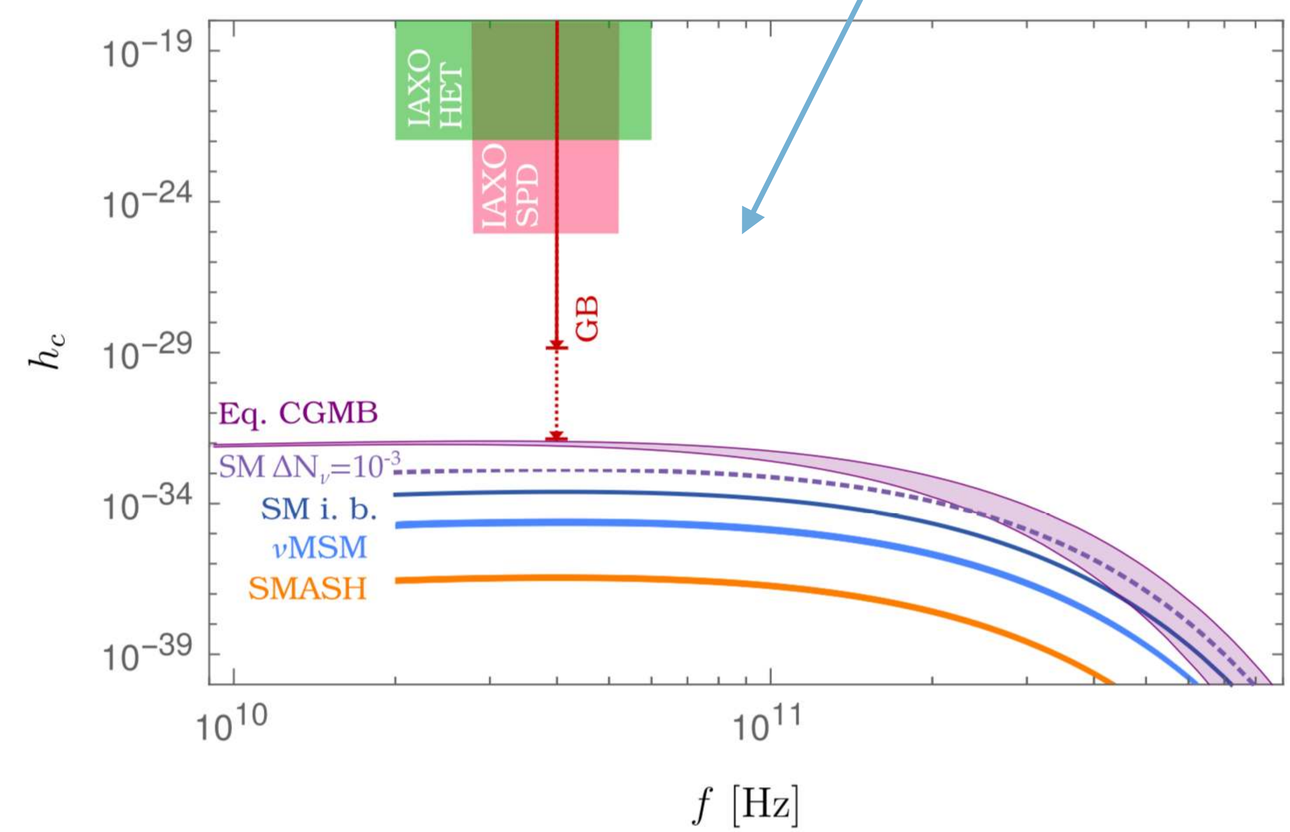




arXiv.org > gr-qc > arXiv:2011.12414

General Relativity and Quantum Cosmology

[Submitted on 24 Nov 2020]

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

N. Aggarwal, O. D. Aguiar, A. Bauswein, G. Cella, S. Clesse, A. M. Cruise, V. Domcke, D. G. Figueroa, A. Geraci, M. Goryachev, H. Grote, M. Hindmarsh, F. Muia, N. Mukund, D. Ottaway, M. Peloso, F. Quevedo, A. Ricciardone, J. Steinlechner, S. Steinlechner, S. Sun, M. E. Tobar, F. Torrenti, C. Unal, G. White

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 the MHz and 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.

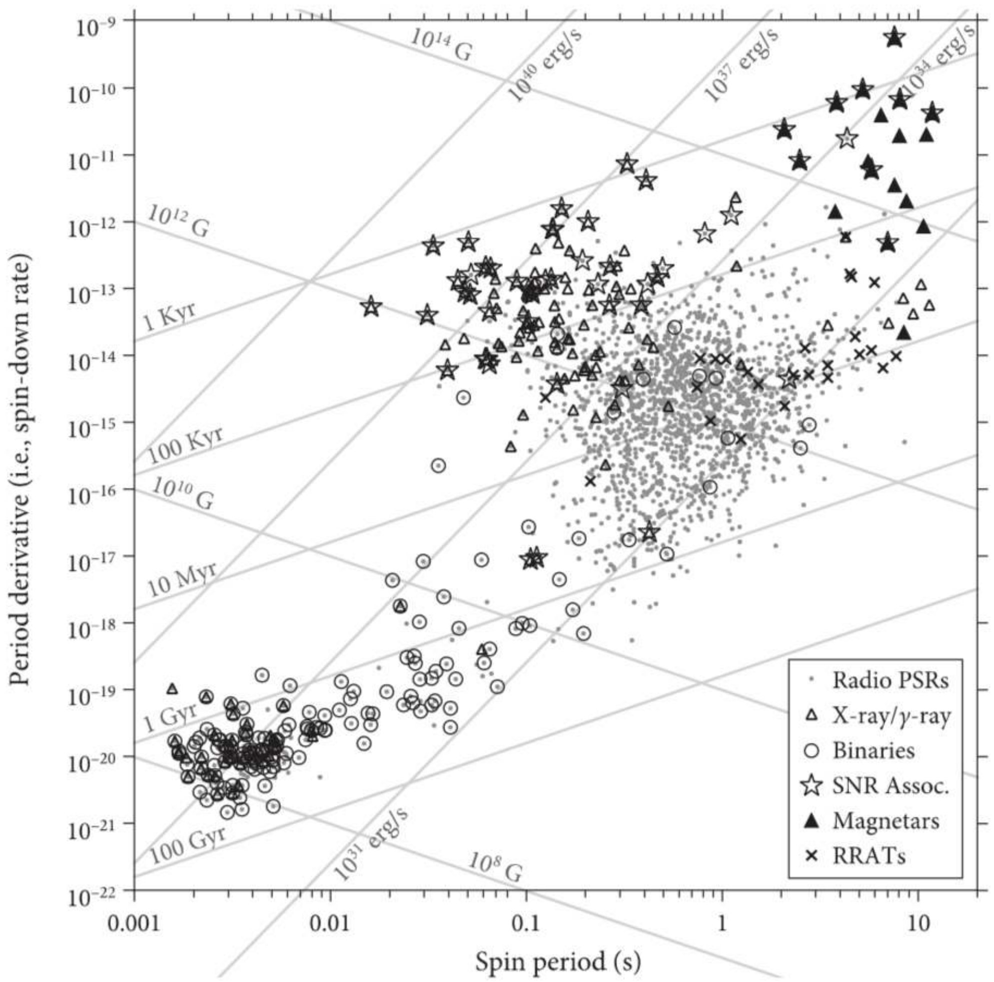
Camilo A. Garcia Cely

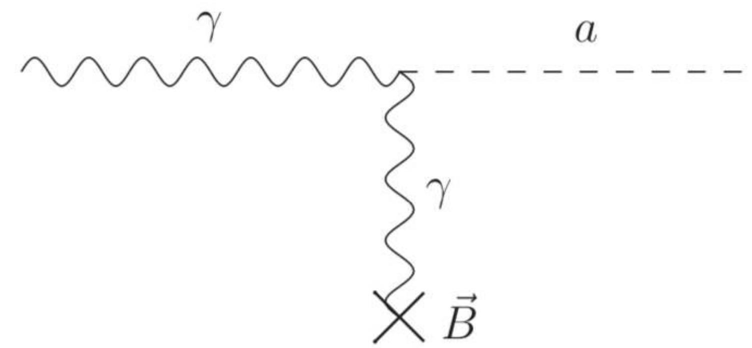
Outlook and Future Prospects

What about neutron stars?

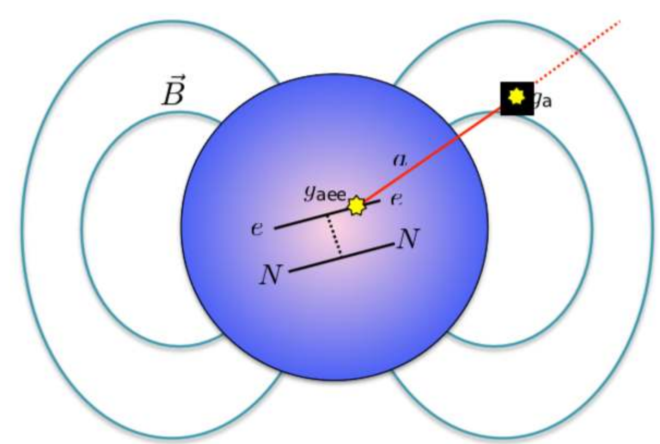
Domcke, CGC, Blas. Work in progress

James Condon, Scott Ransom





Neutron stars have the strongest known magnetic fields



Dessert et al, PRL 2019

Camilo A. Garcia Cely

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.

- This highlights the interesting prospects associated with multi-messenger astronomy.