Gravitational waves and cosmological magnetic fields

Swiss CTA Observatory Day (Dec. 14, 2023)
International Space Science Institute (ISSI), University of Bern

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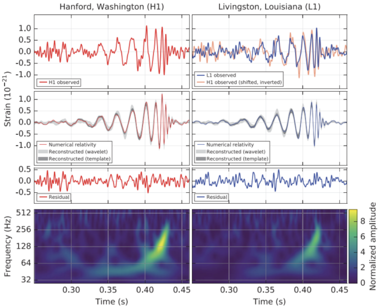
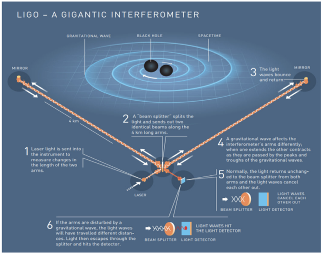
SNSF Ambizione fellow
University of Geneva

Introduction and Motivation

- Gravitational waves are opening a new window into our understanding of the Universe
    - First event GW150914 detected by LIGO-Virgo collaboration[1]




LIGO – A GIGANTIC INTERFEROMETER

1 Laser light is sent into the instrument to measure changes in the length of the two arms.

2 A "beam splitter" splits the light and sends out two identical beams along the 4 km long arms.

3 The light waves bounce and return.

4 A gravitational wave affects the interferometer's arms differently; when one extends the other contracts as they are passed by the peaks and troughs of the gravitational waves.

5 Normally, the light returns unchanged to the beam splitter from both arms and the light waves cancel each other out.

6 If the arms are disturbed by a gravitational wave, the light waves will have travelled different distances. Light then escapes through the splitter and hits the detector.

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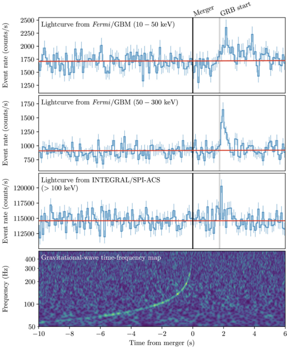
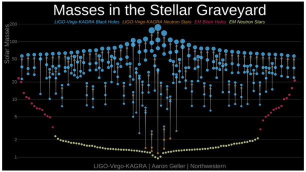
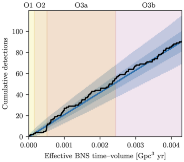
[1] [LIGO-Virgo Collaboration], *Phys. Rev. Lett.* **116**, 061102 (2016)

Introduction and Motivation

- GW170817 NS binary merger[2] first detection of GW and EM counterpart (constraint on the GW speed, measure of the Hubble rate, neutron star equation of state, ...)
- Several following events: LIGO-Virgo-KAGRA started the fourth observing run (O4) in May 2023 → 90 events up to O3b[3]







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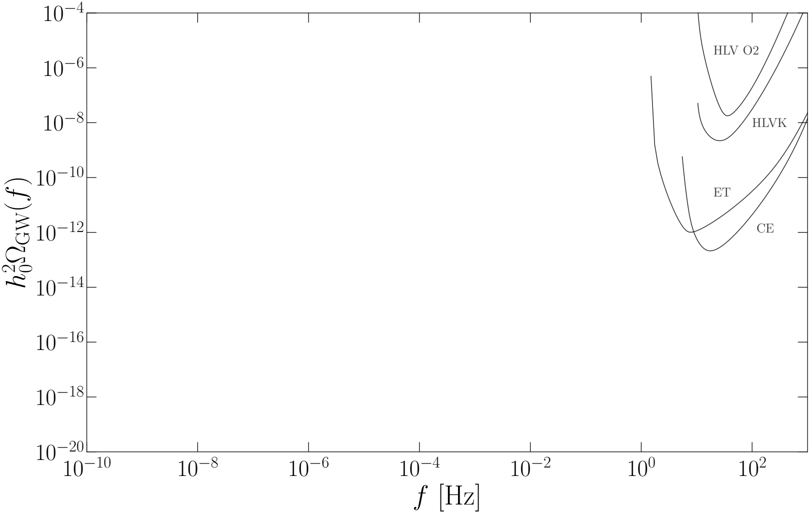
[2] [LIGO-Virgo-Fermi GBM-Integral collaborations], Astrophys.J.Lett. 848 (2017) 2, L13

[3] [LIGO-Virgo Collaboration], GWTC-3, arXiv:2111.03606 (2021).

Gravitational spectrum (ground-based detectors)



LISA

- Laser Interferometer Space Antenna (LISA) is a space–based interferometer
- Approved in 2017 as one of the main research missions of ESA (L3) with NASA collaboration
- Launch planned for 2034
- Composed by three spacecrafts in a distance of 2.5M km

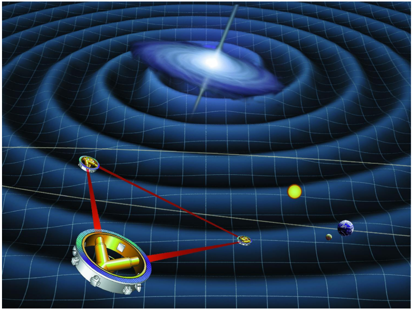
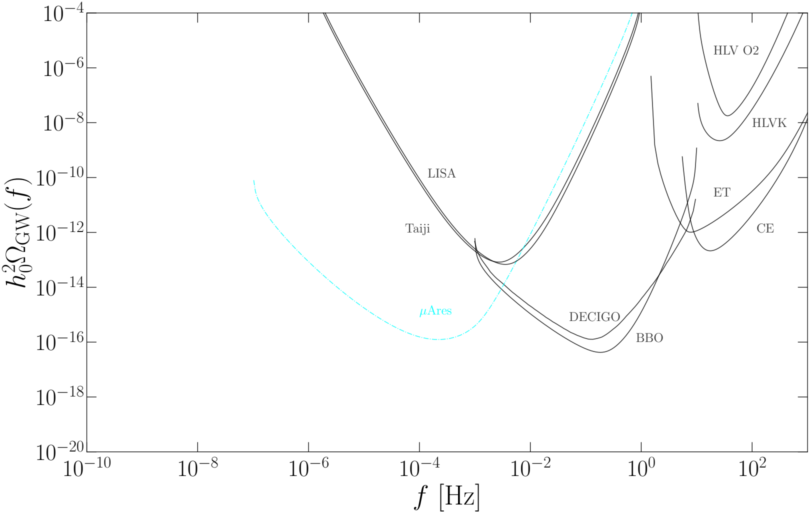


Figure: Artist's impression of LISA from Wikipedia

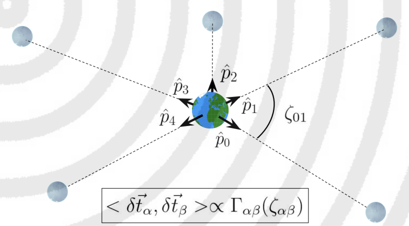
Gravitational spectrum (space-based detectors)



Pulsar Timing Array (PTA)

- An array of millisecond pulsars (MSP) is observed in the radio band to compute the delays on the time of arrival due to the presence of GWs.
- Collected data is the time series of residuals for each pulsar:

$$\delta t^i = t^i_{\mathrm{obs}} - t^i_{\mathrm{TM}}$$



Credit: Mikel Falxa

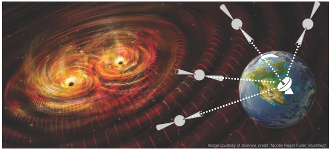
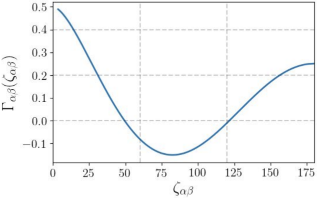


Figure: Image courtesy of Science, credit: Nicolle Rager Fuller

The correlation $\Gamma_{\alpha\beta}$ follows in GR the Hellings-Downs curve[4]



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[4] R. W. Hellings and G. S. Downs, *Astrophys. J. Lett.* **265** (1983) L39-L42.

Pulsar Timing Array (PTA) collaborations

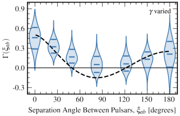
- International PTA collaborations combine their data in the IPTA collaboration.
- European Pulsar Timing Array (EPTA): *Effelsberg, Lovell, Nancay Radio Telescope, Sardinia Radio Telescope, Westerbork Synthesis Radio Telescope.*
- North American Nano-Hertz Observatory for Gravitational Waves (NANOGrav): *Green Bank Telescope (GBT), Arecibo (until 2020), Very Large Array (VLA), Canadian Hydrogen Intensity Mapping Experiment (CHIME).*
- Parkes PTA (PPTA): *Murriyang radio telescope.*
- Indian PTA (InPTA): *GMRT.*
- Chinese Pulsar Timing Array (CPTA): *Five-hundred-meter Aperture Spherical Telescope (FAST).*
- MeerKAT PTA (MPTA).

PTA detection

- The PTA collaborations reported for the first-time evidence of a stochastic gravitational wave background on a press release on June 28, 2023 (plus a series of papers by each collaboration).

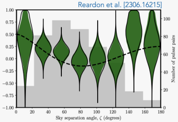
NANOGrav:
68 pulsars, 16yr of data
~3-4σ significance

Agazie et al. [2306.16213]



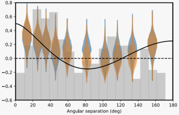
PPTA:
32 pulsars, 18yr of data
~2σ significance

Reardon et al. [2306.16215]



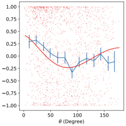
EPTA + InPTA:
25 pulsars, 24yr of data
~3σ significance

Antoniadis et al. [2306.16214]



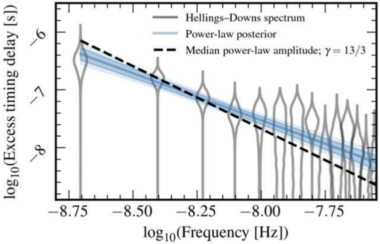
CPTA:
57 pulsars, 3yr of data
~4.6σ significance

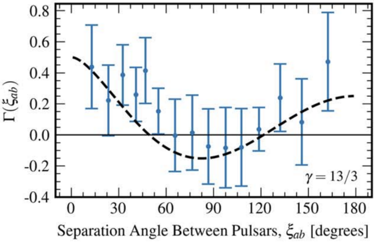
Xu et al. [2306.16216]



Credit: Andrea Mitridate

NANOGrav 15 yr data observation[5]





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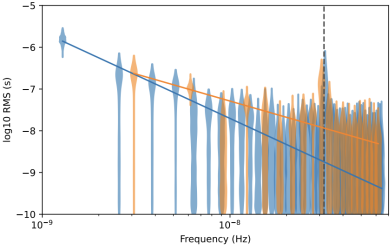
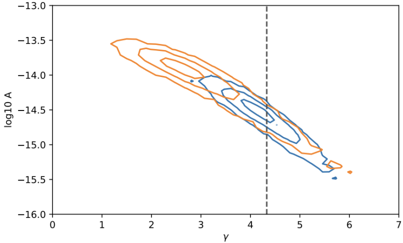
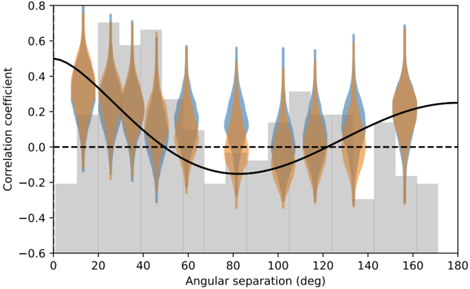
[5] [NANOGrav collaboration], *ApJ Lett.* **951**, 8 & 11 (2023).

EPTA 10.3 yr data observation (DR 2 new)[6]







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[6] [EPTA Collaboration], arXiv:2306.16224.

Cosmological GWs

Main considered source of the signal is from the superposition of supermassive black hole binaries (SMBHB), but other sources are also possible: individual sources[7] or early universe sources[8] (cosmological GW background).

Cosmological GWs have the potential to provide us with *direct information on early universe physics* that is *not directly accessible via electromagnetic observations, possibly complementary to collider experiments*:
nature of first-order phase transitions (baryogenesis, BSM physics, high-energy physics),
primordial origin of intergalactic magnetic fields.

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[7] [EPTA Collaboration], *The second data release from the European Pulsar Timing Array IV. Search for continuous gravitational wave signals*, arXiv:2306.16226

[8] [EPTA Collaboration] (incl. ARP), *The second data release from the European Pulsar Timing Array: V. Implications for massive black holes, dark matter and the early Universe*, arXiv:2306.16227.
[NANOGrav Collaboration], *The NANOGrav 15 yr Data Set: Search for Signals from New Physics*, arXiv:2306.16219.

Probing the early Universe with GWs

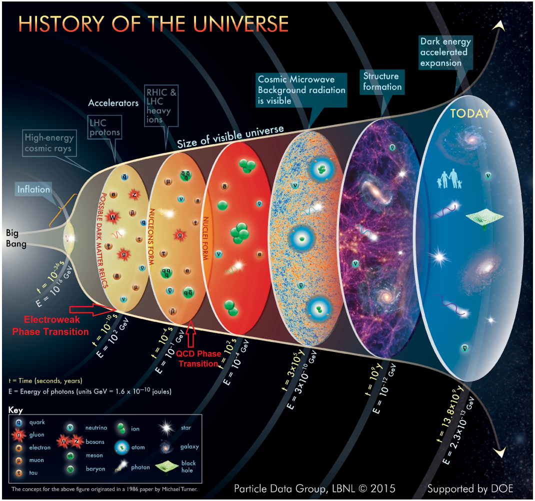
Cosmological (pre-recombination) GW background

- Why background? Individual sources are not resoluble, superposition of single events occurring in the whole Universe.

$$f_* \simeq 1.64 \times 10^{-3} \frac{100}{R_* \mathcal{H}_*} \frac{T_*}{100\,\mathrm{GeV}}\,\mathrm{Hz}$$

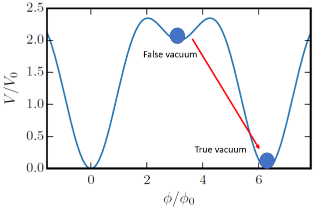
- Phase transitions
  - Ground-based detectors (LVK, ET, CE) frequencies are 10–1000 Hz
    Peccei-Quinn, B-L, left-right symmetries $\sim 10^7, 10^8$ GeV.
  - Space-based detectors **(LISA)** frequencies are 10^{-5}–10^{-2} Hz
    Electroweak phase transition $\sim$ 100 GeV
  - Pulsar Timing Array (PTA) frequencies are 10^{-9}–10^{-7} Hz
    Quark confinement (QCD) phase transition $\sim$ 100 MeV

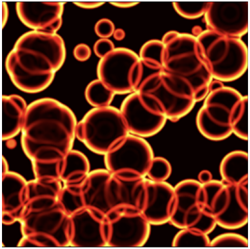
- From inflation
  - B-modes of CMB anisotropies ($f_c \sim 10^{-18}$ Hz).
  - Can cover all f spectrum, depending on end-of-reheating T, and blue-tilted (beyond slow-roll inflation).

HISTORY OF THE UNIVERSE
Big Bang
Inflation
High-energy cosmic rays
Accelerators
LHC protons
RHIC & LHC heavy ions
Size of visible universe
Cosmic Microwave Background radiation is visible
Structure formation
Dark energy accelerated expansion
TODAY
POSSIBLE DARK MATTER RELICS
NUCLEONS FORM
NUCLEI FORM
$t = 10^{-36}$ s
$E = 10^{16}$ GeV
Electroweak Phase Transition
$t = 10^{-10}$ s
$E = 10^{2}$ GeV
$t = 10^{-4}$ s
$E = 10^{-1}$ GeV
QCD Phase Transition
$t = 10^{2}$ s
$E = 10^{-4}$ GeV
$t = 3x10^{5}$ y
$E = 3x10^{-10}$ GeV
$t = 10^{9}$ y
$E = 10^{-12}$ GeV
$t = 13.8x10^{9}$ y
$E = 2.3x10^{-13}$ GeV
t = Time (seconds, years)
E = Energy of photons (units GeV = 1.6 x 10^{-10} joules)
Key
quark
gluon
electron
muon
tau
neutrino
bosons
meson
baryon
ion
atom
photon
star
galaxy
black hole
The concept for the above figure originated in a 1986 paper by Michael Turner.
Particle Data Group, LBNL © 2015
Supported by DOE

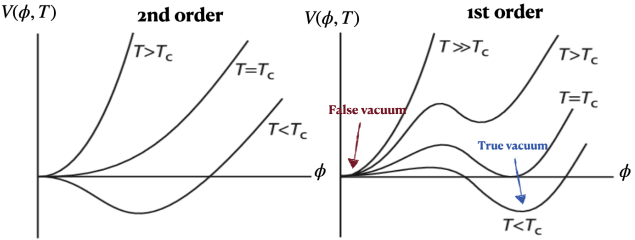
First–order phase transition

$$V(\phi, T) = \frac{1}{2}M^2(T)\phi^2 - \frac{1}{3}\delta(T)\phi^3 + \frac{1}{4}\lambda\phi^4$$





Credits: I. Stomberg



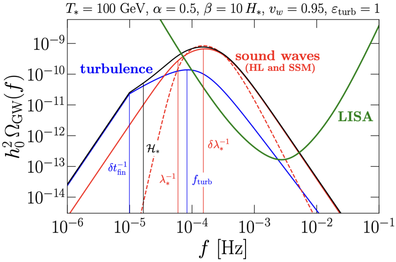
GW sources in the early universe

- Magnetohydrodynamic (MHD) sources of GWs:
  - Sound waves generated from first-order phase transitions.
  - (M)HD turbulence from first-order phase transitions.
  - Primordial magnetic fields.

- High-conductivity of the early universe leads to a high-coupling between magnetic and velocity fields.

- Other sources of GWs include
  - Bubble collisions.
  - Cosmic strings.
  - Primordial black holes.
  - Inflation.

ARP *et al.*, 2307.10744, 2308.12943



Primordial magnetic fields

- Magnetic fields can either be produced at or present during cosmological phase transitions.
- The magnetic fields are strongly coupled to the primordial plasma and inevitably lead to MHD turbulence.[9]
- Present magnetic fields can be amplified by primordial turbulence via dynamo.[10]

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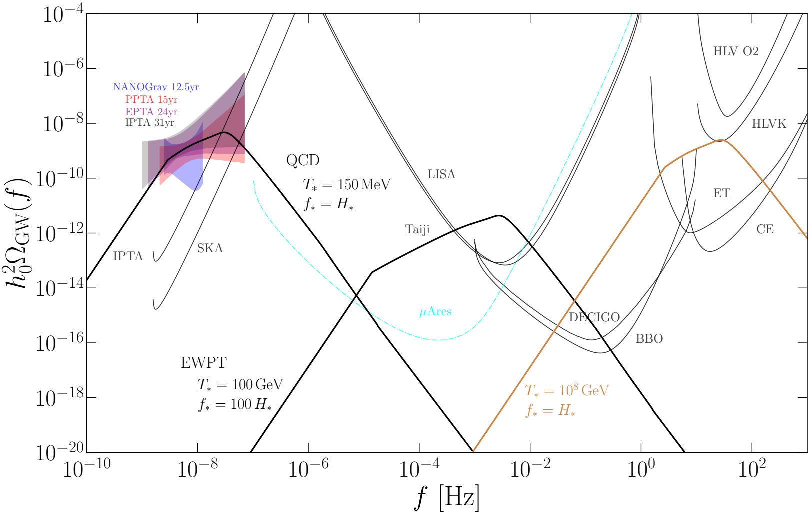
[9] J. Ahonen and K. Enqvist, *Phys. Lett. B* **382**, 40 (1996).

[10] A. Brandenburg *et al.* (incl. ARP), *Phys. Rev. Fluids* **4**, 024608 (2019).

Gravitational spectrum (turbulence from PTs)[11]



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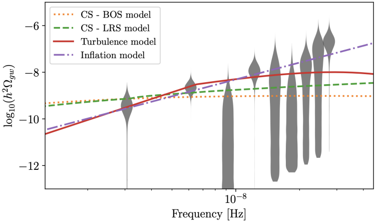
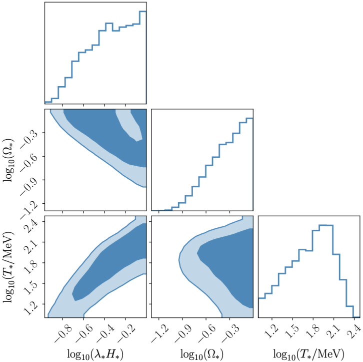
[11] ARP, C. Caprini, A. Neronov, D. Semikoz, *PRD* **105**, 123502 (2022)
A. Neronov, ARP, C. Caprini, D. Semikoz, *PRD* **103**, L041302 (2021)
ARP *et al.*, arXiv:2307.10744 (2023).

Primordial magnetic field constraints with PTA[12]





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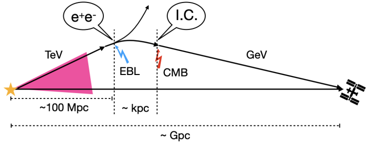
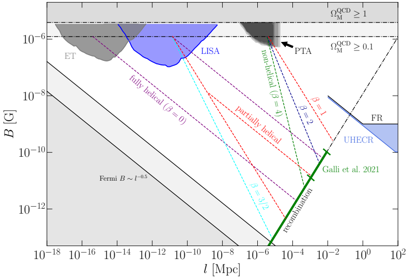
[12] [EPTA collab.] (incl. ARP), arXiv:2306.16227 (2023).

Multi-messenger constraints on primordial magnetic fields[3]

- Primordial magnetic fields would evolve through the history of the universe up to the present time and could explain the lower bounds in cosmic voids found by the Fermi collaboration.[4]



- Maximum amplitude of primordial magnetic fields is constrained by the big bang nucleosynthesis.[5]
- Additional constraints from CMB, Faraday Rotation, ultra-high energy cosmic rays (UHECR).



- CTA telescopes will allow to explore a broader range of parameters of the intergalactic magnetic field with strengths 1–10 pG, estimated[13]using deep exposure of the nearest hard spectrum blazar Mrk 501

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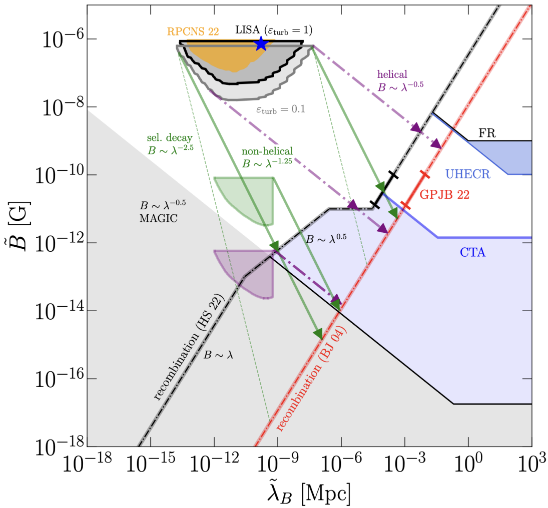
[3] ARP *et al.*, arXiv:2307.10744 (2023).

[4] A. Neronov and I. Vovk, *Science* **328**, 73 (2010).

[5] V. F. Shvartsman, *Pisma Zh. Eksp. Teor. Fiz.* **9**, 315 (1969).

[6] Korochkin, Kalashev, Neronov, Semikoz, *PoS ICRC2021* (2021) 919

Multi-messenger constraints with LISA and CTA [14]



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[14] ARP *et al.*, arXiv:2307.10744 (2023).

Conclusions

- Primordial magnetic fields in the early universe can significantly contribute to the stochastic GW background (SGWB) and lead to the production of MHD turbulence.
- The SGWB produced by MHD turbulence requires, in general, performing high-resolution numerical simulations, which can be done using the PENCIL CODE.
- LISA, PTA, and next-generation ground-based detectors can potentially be used to probe the origin of magnetic fields in the largest scales of our Universe, which is still an open question in cosmology.
- γ-ray observations can constrain intergalactic magnetic fields.
- Primordial magnetic fields can be studied in a multi-messenger approach, combining GW (interferometers and radio telescopes), CMB, and γ-ray observations.

Thank You!

alberto.roperpol@unige.ch

github.com/AlbertoRoper/cosmoGW
cosmology.unige.ch/users/alberto-roper-pol

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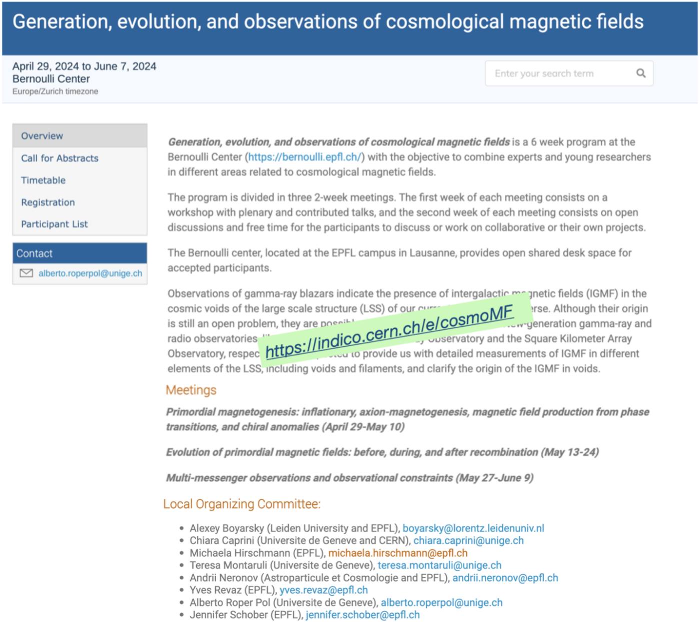
SHOTA RUSTAVELI NATIONAL SCIENCE FOUNDATION

APC, CNRS, FRANCE

LASP
Laboratory for Atmospheric and Space Physics
University of Colorado **Boulder**

NORDITA
The Nordic Institute for Theoretical Physics



Generation, evolution, and observations of cosmological magnetic fields

April 29, 2024 to June 7, 2024
Bernoulli Center
Europe/Zurich timezone

alberto.roperpol@unige.ch

Generation, evolution, and observations of cosmological magnetic fields is a 6 week program at the Bernoulli Center (https://bernoulli.epfl.ch/) with the objective to combine experts and young researchers in different areas related to cosmological magnetic fields.

The program is divided in three 2-week meetings. The first week of each meeting consists on a workshop with plenary and contributed talks, and the second week of each meeting consists on open discussions and free time for the participants to discuss or work on collaborative or their own projects.

The Bernoulli center, located at the EPFL campus in Lausanne, provides open shared desk space for accepted participants.

Observations of gamma-ray blazars indicate the presence of intergalactic magnetic fields (IGMF) in the cosmic voids of the large scale structure (LSS) of our curr erse. Although their origin is still an open problem, they are possib ew-generation gamma-ray and radio observatories Observatory and the Square Kilometer Array Observatory, respec to provide us with detailed measurements of IGMF in different elements of the LSS, including voids and filaments, and clarify the origin of the IGMF in voids.

https://indico.cern.ch/e/cosmoMF

Meetings

Primordial magnetogenesis: inflationary, axion-magnetogenesis, magnetic field production from phase transitions, and chiral anomalies (April 29-May 10)

Evolution of primordial magnetic fields: before, during, and after recombination (May 13-24)

Multi-messenger observations and observational constraints (May 27-June 9)

Local Organizing Committee:

- Alexey Boyarsky (Leiden University and EPFL), boyarsky@lorentz.leidenuniv.nl
- Chiara Caprini (Universite de Geneve and CERN), chiara.caprini@unige.ch
- Michaela Hirschmann (EPFL), michaela.hirschmann@epfl.ch
- Teresa Montaruli (Universite de Geneve), teresa.montaruli@unige.ch
- Andrii Neronov (Astroparticule et Cosmologie and EPFL), andrii.neronov@epfl.ch
- Yves Revaz (EPFL), yves.revaz@epfl.ch
- Alberto Roper Pol (Universite de Geneve), alberto.roperpol@unige.ch
- Jennifer Schober (EPFL), jennifer.schober@epfl.ch