

Subtopic 3: Cosmology and the dark sector of the universe

FH Division

Géraldine Servant
DESY 13-14 February 2025

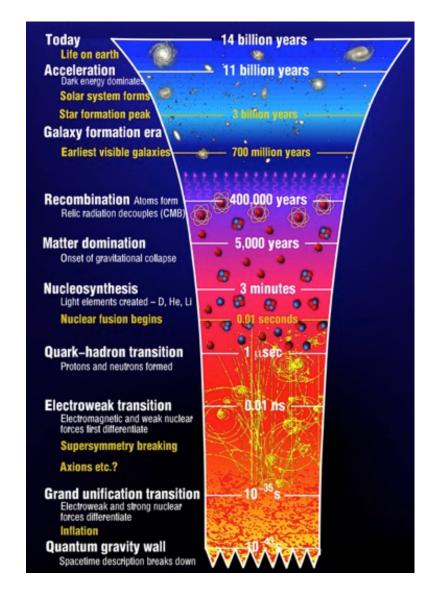


Particle cosmology research

A growing and fast-evolving field

- We are working in a global approach to comprehend the evolution of the early universe.
- Interdisciplinary problems such as Dark Matter,
 Dark Energy, Baryogenesis and Inflation require a complementarity of approaches.
- DESY has long been working in these inter-related areas and has established a strong reputation.
- Dark Matter (DM) & Gravitational-wave research intertwined, both at theoretical level & experimentally
- Gravitational waves (GW) are a new window to fundamental questions and energy scales that colliders cannot access.





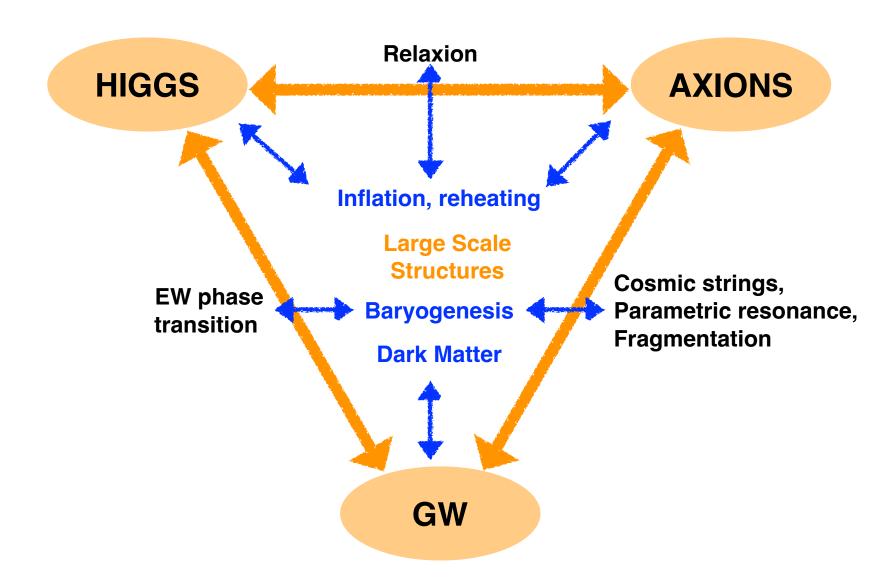
Open questions



- What drove the primordial acceleration of the expansion of the universe?
- What is the thermalising mechanism after inflation?
- What is the nature of the electroweak phase transition?
- What produces the Matter–antimatter asymmetry?
- What is Dark Matter?
- How was Dark Matter produced?
- What is the spectrum of primordial gravitational waves?
- Why is the expansion of the universe accelerating again today?

Directions of research



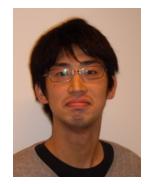


Selected success stories during the last POF period





- Kyohei Mukaida
- DESY PD →
 Faculty at KEK



- Ryosuke Sato
- DESY PD →
 Faculty at U. Osaka



- Ryusuke Jinno
- DESY PD →
 Faculty at U. Tokyo



- Valerie Domcke
- DESY junior staff → Faculty at CERN



- Filippo Sala
- DESY junior staff → Faculty at CNRS-> U. Bologna



Laura Sagunski

DESY PhD → Faculty

at U. Frankfurt

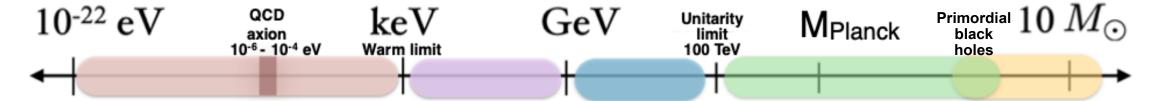


- Enrico Morgante
- DESY PhD → Faculty at U. Trieste

Dark Matter



Well-motivated over a huge mass range



Still huge uncertainty on its mass and couplings to the Standard Model, despite tremendous progress over the last decade in constraining its properties, by combining information from

- cosmological surveys
- indirect searches with telescopes
- collider searches
- non-collider direct searches
- theoretical modelling and phenomenological analysesuniverse.

Dark Matter @ DESY



Broad theoretical & experimental activities over an extensive range of masses and couplings

Theory

- → model building
- → novel Dark Matter production mechanisms, beyond the standard thermal paradigm
- → numerical simulations
- → search for novel signatures & detection strategies
- → probes in gravitational waves

Experiments

→ ATLAS & CMS

→ Belle II

→ ALPS-II

→ MADMAX

 $\rightarrow IAXO$

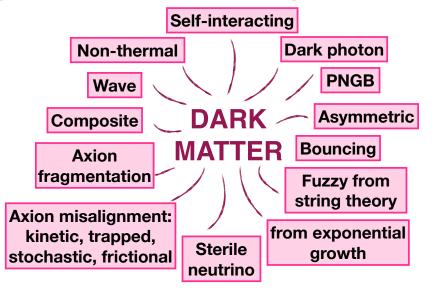
For dark sector with sizeable couplings to the SM

For axion-like-particles

-Dark sector searches with the CMS experiment, 2405.13778, Physics Reports

-ATLAS Constraints on spin-0 DM mediators with ttbar and missing transverse momentum, Eur.Phys.J.C 83 (2023) 6, 503, 2211.05426

-See talk by Axel Lindner

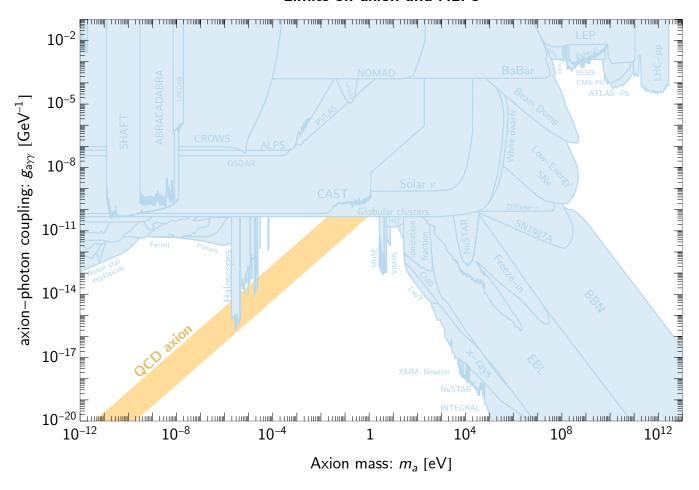


Axion-like-particles

MATTER AND M U

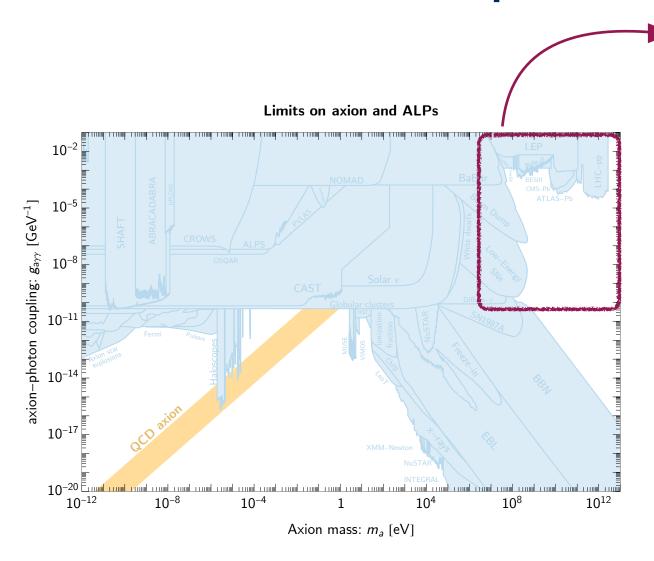
An international race

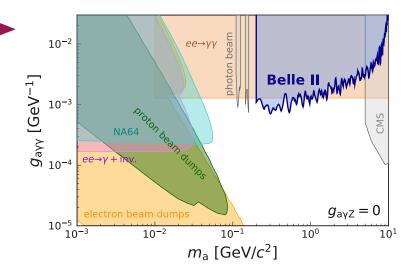
Limits on axion and ALPs



Searches for axion-like-particles at colliders



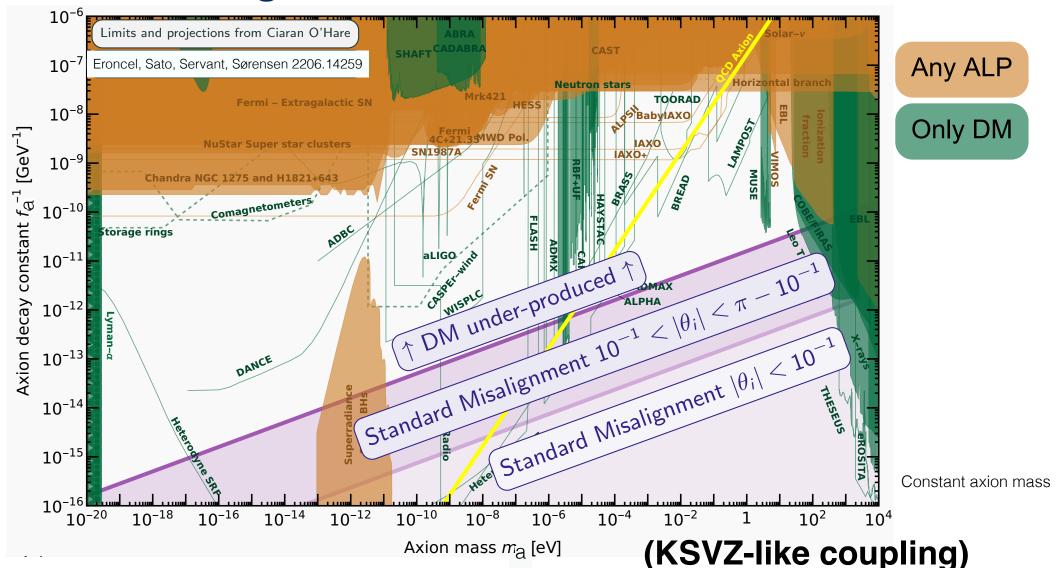




- @Belle II :Phys. Rev. Lett. 125, no. 16, 161806 (2020)
- Long-lived ALPs in Top Production at the LHC, JHEP 10 (2023) 138
- Constraining axions that couple to W-bosons and Z-bosons using diboson cross section data from ATLAS, Phys. Rev. D 104, no.9, 092005 (2021)
- Limits from rare tau lepton decays in Belle II, Phys. Rev. Lett. 130, no. 18, 181803 (2023).

Conventional misalignment makes too little DM

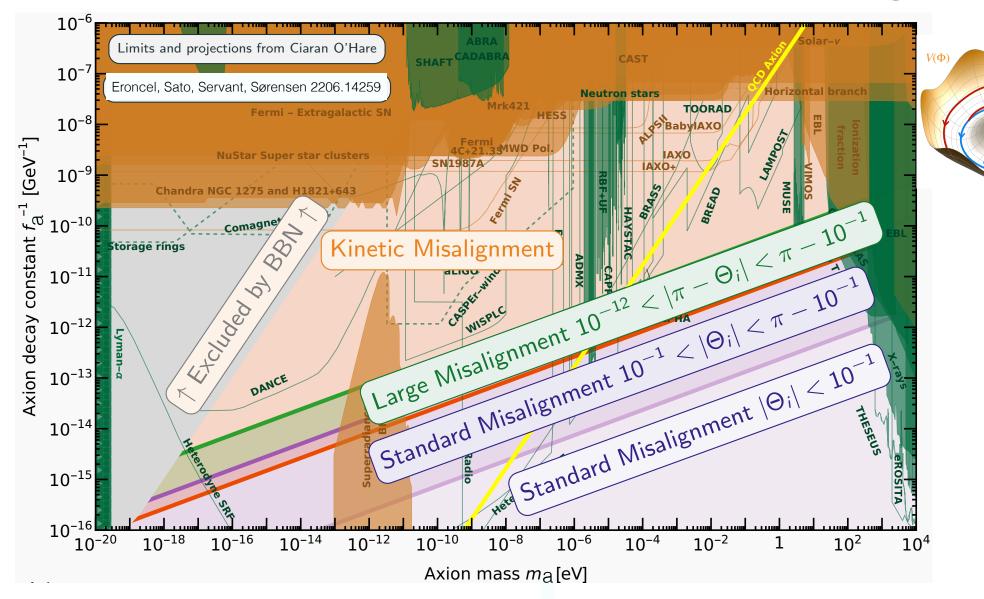




$$g_{\theta\gamma} = (\alpha_{\sf em}/2\pi)(1.92/f)$$



Opening up the parameter space with axion kinetic misalignment



Monophilic QCD axion



Another way to get the correct axion relic abundance at large axion coupling

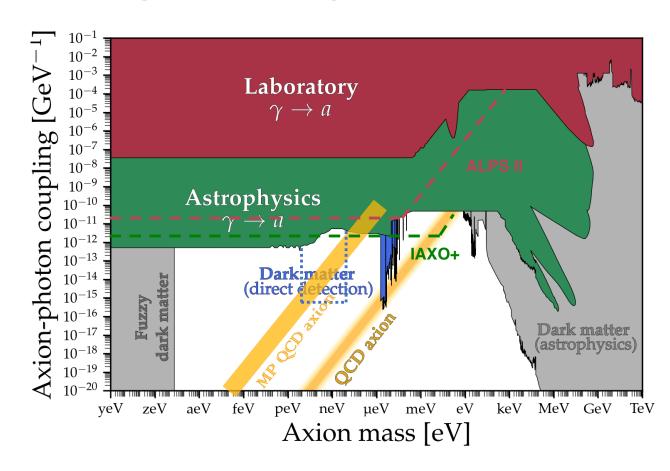
Peccei-Quinn-charged heavy quark carries magnetic charge.

Integrating out heavy magnetic monopoles results in additional electromagnetic coupling

[Sokolov, Ringwald, 2104.02574; 2205.02605; 2303.10170] [Tobar, Sokolov, Ringwald, Goryachev, 2306.13320]

Can be probed by

- ALPS II and (Baby)IAXO
- new type of low-mass haloscope axion-Maxwell equations



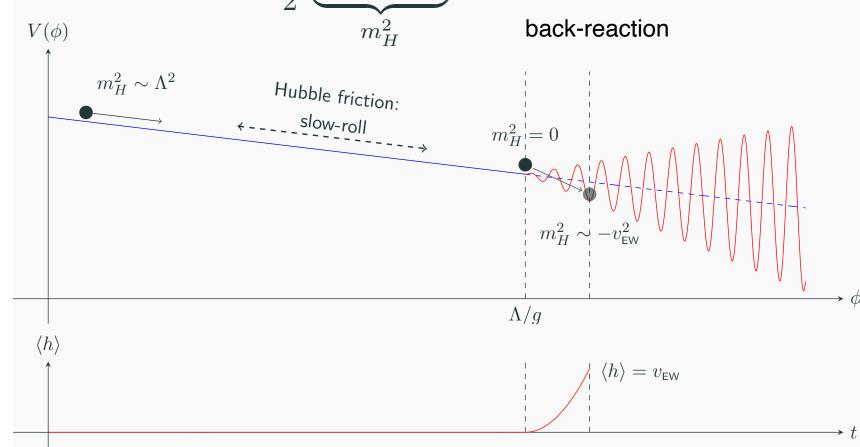


(Rel)axion: New cosmological solution to the hierarchy problem

 ϕ : relaxion, classically evolving and scanning the Higgs mass parameter

Higgs-relaxion potential to set-up the electroweak scale

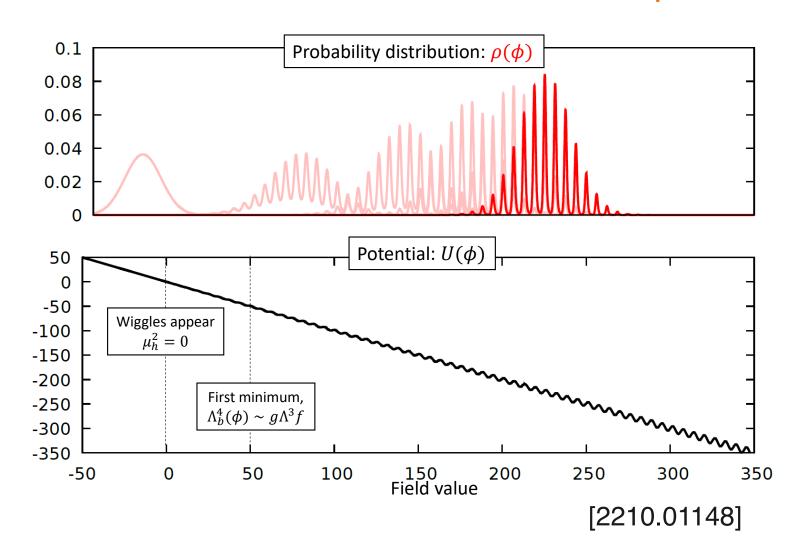
 $V(\phi,h) = -g\Lambda^3\phi + \frac{1}{2}(\underbrace{\Lambda^2 - g'\Lambda\phi})h^2 + \Lambda_b^4(h)[1-\cos(\phi/f)] + \dots$ $V(\phi) \qquad \qquad back-reaction$



Beyond the classical relaxion



Real-time numerical simulation of the Fokker-Planck equation

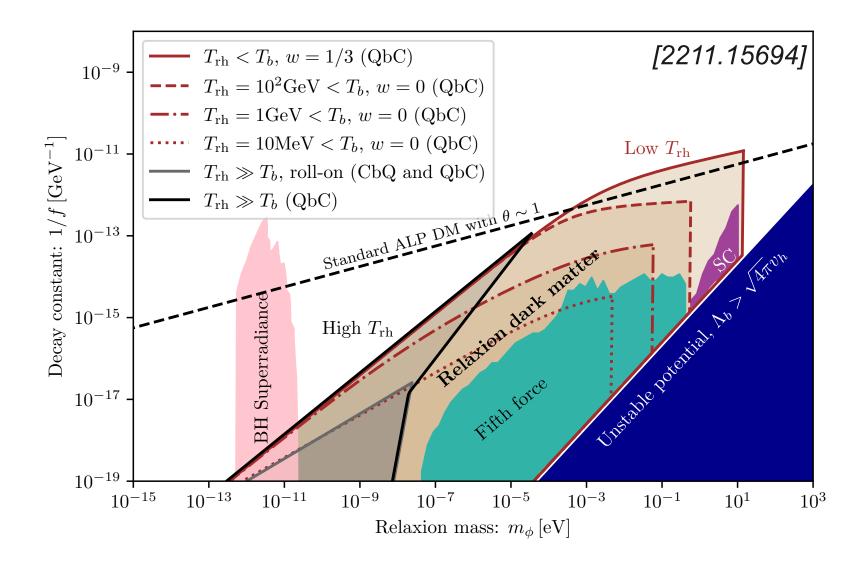


The relaxion can be dark matter



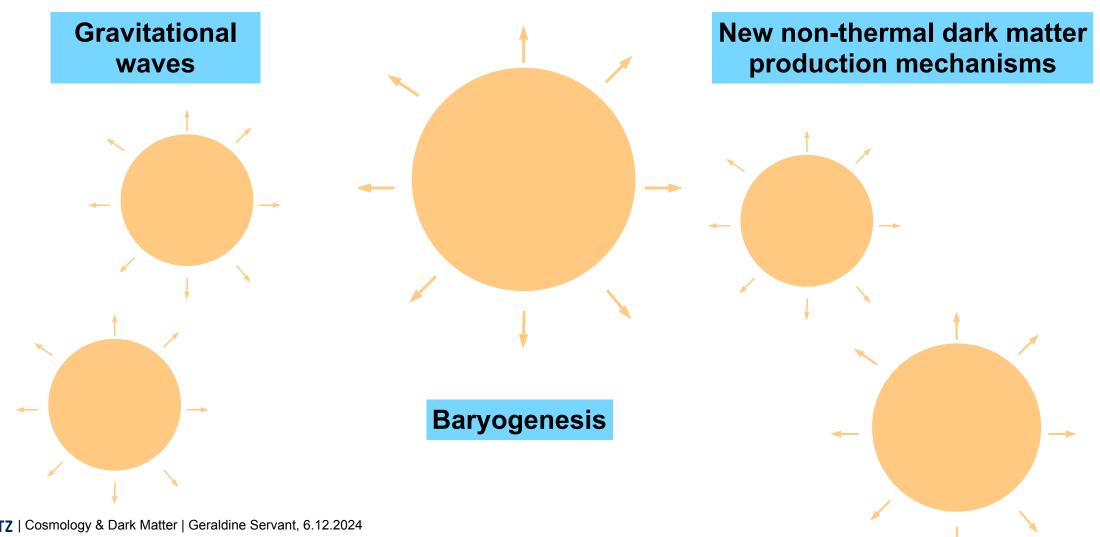
Quantum

Classical



First-order cosmological phase transitions



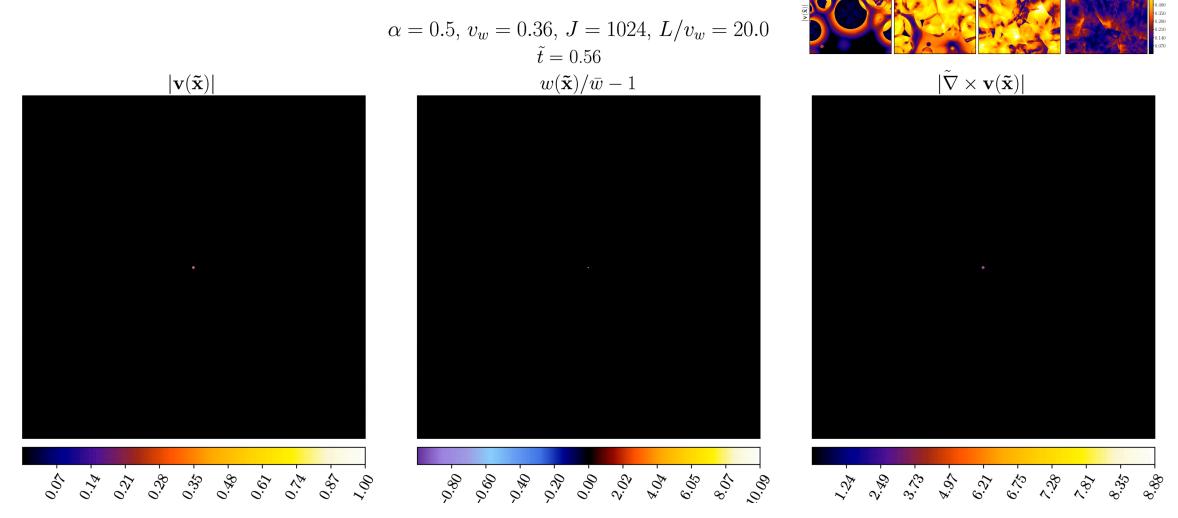


Precise predictions for phase transitions



New approach for efficient simulation of primordial fluid and the produced gravitational waves,

with turbulence and other non-linear features.



First-order cosmological phase transitions

MATTER AND THE UNIVERSE M U

Multiple pioneering studies

Defect-driven phase transitions, Blasi et al, *JCAP* 10 (2023) 051

Hydrodynamics of inverse phase transitions, Barni et al, *JCAP* 10 (2024) 042

A sonic boom in bubble wall friction, Dorsch et al, *JCAP* 04 (2022) 04, 010

Model-independent energy budget of cosmological first-order phase transitions

—A sound argument to go beyond the bag model

Giese et al, JCAP 07 (2020) 07, 057

High-Temperature Electroweak Symmetry Non-Restoration from New Fermions and Implications for Baryogenesis Matsedonskyi et al, JHEP 09 (2020) 012



First-order cosmological phase transitions



Multiple applications

Gravitational waves

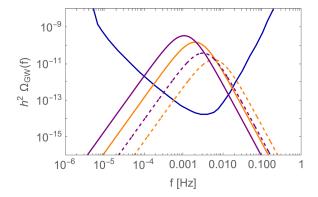
GWs from decaying sources in strong phase transitions, Caprini et al, 2409.03651

Higgsless simulations of cosmological phase transitions and GWs, Jinno et al, JCAP 02 (2023) 011

A hybrid simulation of gravitational wave production in first-order phase transitions, Jinno et al, JCAP 04 (2021) 014

Model-independent energy budget for LISA, Giese et al, JCAP 01 (2021) 072

Detecting gravitational waves from cosmological phase transitions with LISA: an update, Caprini et al, JCAP 03 (2020) 024



New non-thermal dark matter production mechanisms

Shakya 2308.16224, Mansour-Shakya 2308.13070, Giudice, Lee, Pomarol, Shakya 2403.03252

Supercool composite Dark Matter beyond 100 TeV, Baldes et al, JHEP 07 (2022) 084

Baryogenesis

On the wall velocity dependence of electroweak baryogenesis, Dorsch et al, *JCAP* 08 (2021) 020

Baryogenesis From a Dark First-Order Phase Transition, Hall et al, *JHEP* 04 (2020) 042

Bruggisser et al, Status of electroweak baryogenesis in minimal composite Higgs, *JHEP* 08 (2023) 012



Purely-gravitational probes of dark matter

Effect of DM self-interactions on the density of the subhalo of a merging system

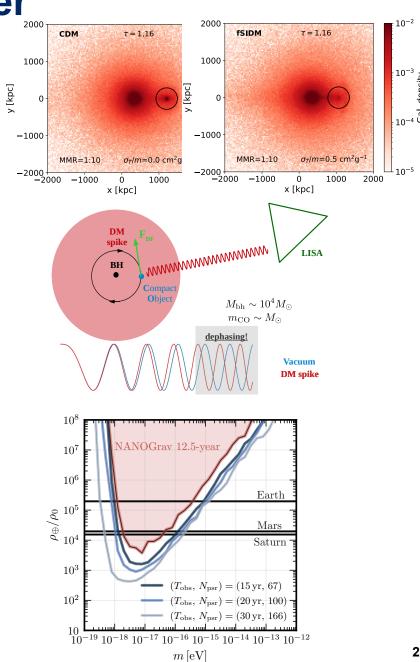
Mon. Not. Roy. Astron. Soc. 510, no. 3, 4080-4099 (2022).

GW Dephasing from denser halos associated with wave DM (light bosonic DM with a mass <~ 10 eV)

Kim et al, Phys.Rev.D 107 (2023) 8, 08300

Testing ultralight DM fluctuations

with GW interferometers , [Kim 2306.13348] with Precision astrometry [Kim 2406.03539] with Pulsar Timing Arrays [Kim and Mitridate 2312.12225]



Primordial gravitational waves



10¹⁵ GeV

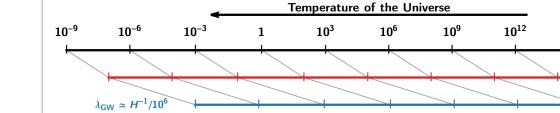
 $\lambda_{\text{GW}}^{\text{inf}} = H^{-1}$

Reading the cosmological history in the GW frequency spectrum

GW frequency

$$f_{\rm GW,0} \simeq \lambda_{\rm GW}^{-1} \left(\frac{a_{\rm prod}}{a_0} \right)$$

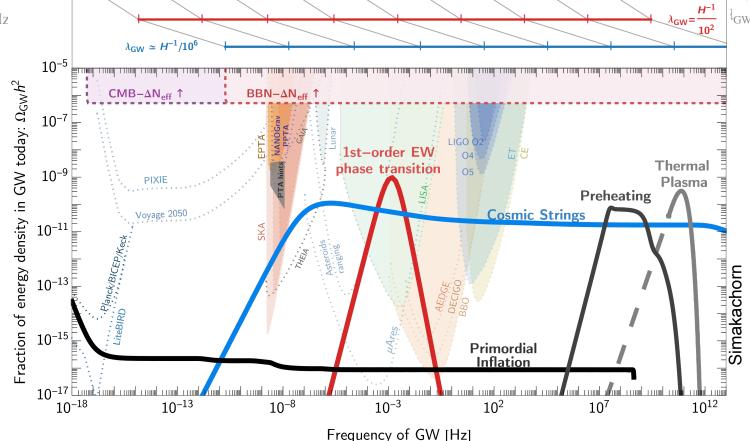




High-freq. limit $f_{\rm GW}^{\rm max} \simeq 10^{13} \; {\rm Hz}$ $R_{\rm GW} \sim H^{-1} \sim M_{\rm pl}^{-1}$

Participation to Community White Papers on future GW missions

- Cosmology With the Laser Space Antenna, 2022
- Cosmology with Einstein Telescope, Div.2 Blue Book, 2024
- Cosmology Working Group GWSpace 2050 missions
- WaveForm Coordination Unit (CU-WAV) of the LISA Distributed Data Processing Centre (DDPC)



Primordial gravitational waves

From reheating era

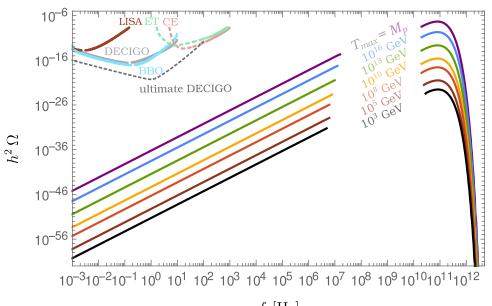
• GWs from the Standard Model thermal plasma

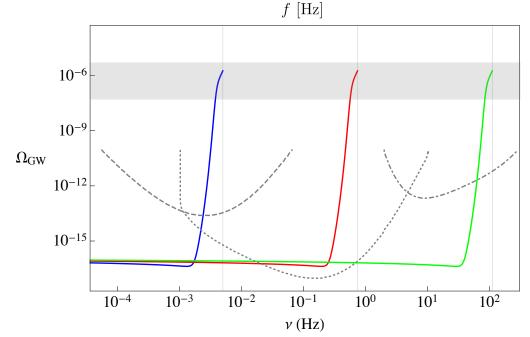
GWs as a Big Bang Thermometer, Ringwald et al, JCAP 03 (2021) 054

GWs from inflaton-hidden U(1) coupling

Westphal et al, 2112.13861







Primordial gravitational waves

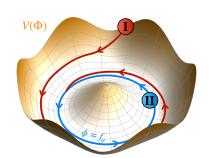
From early axion dynamics

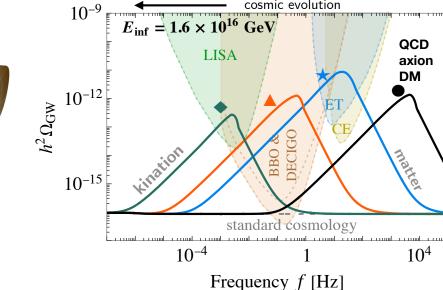
• Amplification of inflationary GW from axioninduced kination era.

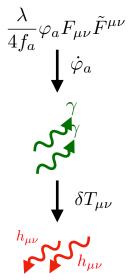
Gouttenoire et al, 2108.10328 & 2111.01150

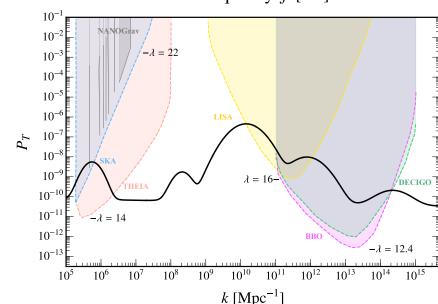


Dimastrogiovanni, Fasiello, Putti, Leedom, Westphal, 2023



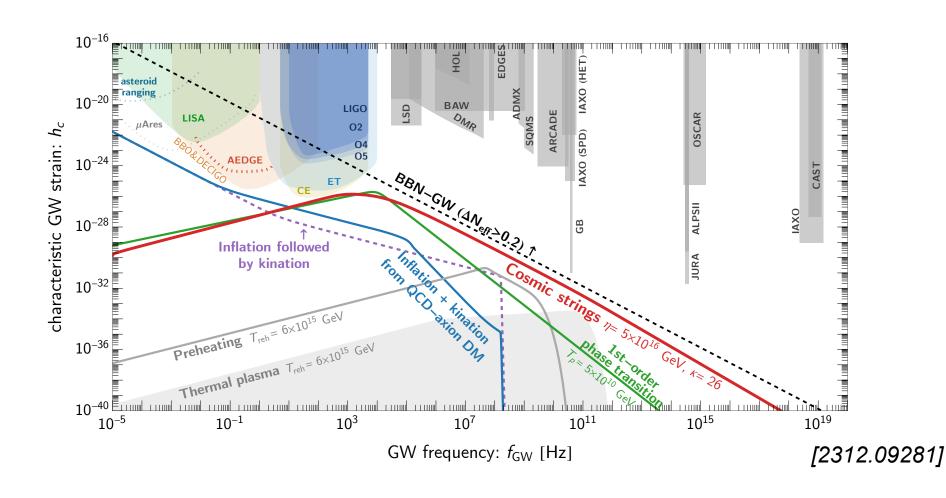






Ultra-high frequency primordial GWs





Discovery of a GW background by Pulsar Timing Arrays



The NANOGrav 15 yr Data Set: Evidence for a Gravitational-wave Background

NANOGrav Collaboration • Gabriella Agazie (Marquette U.) et al. (Jun 28, 2023)

Published in: *Astrophys. J. Lett.* 951 (2023) 1, L8 • e-Print: 2306.16213 [astro-ph.HE]

pdf

@ DOI

🗟 claim

reference search

→ 1,004 citations

#1

#2

The NANOGrav 15 yr Data Set: Search for Signals from New Physics

NANOGrav Collaboration • Adeela Afzal (Munster U. and Quaid-i-Azam U.) et al. (Jun 28, 2023)

Published in: *Astrophys. J.Lett.* 951 (2023) 1, L11, *Astrophys. J.Lett.* 971 (2024) 1, L27 (erratum) • e-Print: 2306 16219 [astro-ph HE]

2306.16219 [astro-ph.HE]

D pdf

@ links

Ø DOI

e 🖫 claim

reference search

→ 596 citations

PTArcade

v0.1.0

[2312.09281]

Main developers:

Andrea Mitridate

Deutsches Elektronen-Synchrotron DESY, Notkestr. 85, D-22607 Hamburg, Germany

David Wright

Department of Physics, University of Central Florida, Orlando, FL 32816-2385, USA

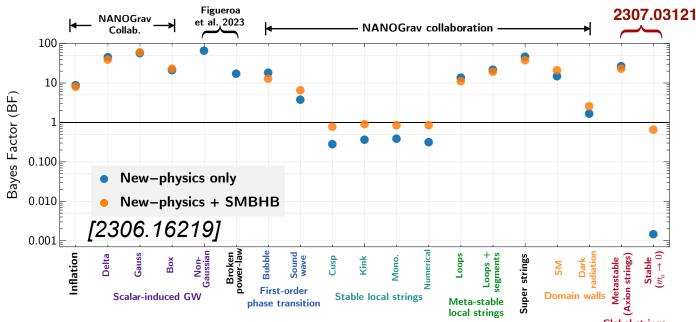




Interpretation of NANOGrav signal with cosmological GWs

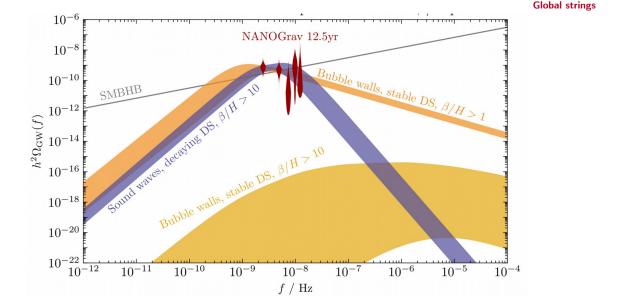
New physics or standard black holes?

New-physics vs. SMBHB interpretations of NANOGrav 15-year data



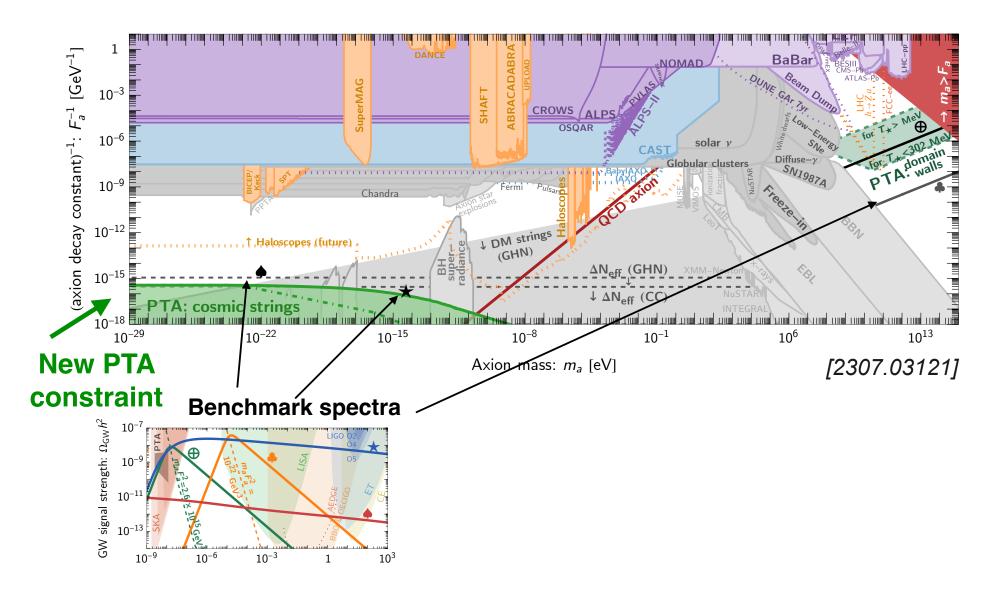
Interpretation of NANOGrav signal with a dark sector phase transition

Bringmann, Depta, Konstandin, Schmidt-Hoberg, Tasillo' 23





Constraining post-inflationary axions with PTAs



Organised local events



BRIGHT IDEAS FOR A DARK UNIVERSE.

DESY Theory Workshop 21 - 24 September 2021 **Hamburg, Germany**

Plenary Talks

V. Cardoso (U. Lisbon) M. Cicoli (U. Bologna) V. Domcke (CERN & EPFL)

D. Baumann (U. Amsterdam) D. Green (UC San Diego) M. Hindmarsh (U. Sussex)

S. Nissanke (U. Amsterdam)

P. Schwaller (U. Mainz)

M. Reece (U. Harvard)

M. Tytgat (Brussels) F. Vernizzi (IPhT. Saclav) Y. Wong (UNSW Sydney)

A. Taylor (DESY Zeuthen)

21 September 2021

DESY Heinrich Hertz Lecture on Physics

Matias Zaldarriaga (IAS Princeton)

Parallel Sessions

Contributions by young researchers are especially encouraged. Deadline for abstract submission on 25 August 2021

How fast does the bubble grow? May 15 - 17 2023 at DESY Hamburg

Plenary Talks

Oliver Gould (University of Nottingham) Thomas Konstandin (DESY) Benoit Laurent (McGill University)

Bogumiła Świeżewska (Warsaw University) Carlos Tamarit (JGU Mainz) Miguel Vanylasselaer (Brussels University)

Speakers

We especially encourage contributions by young researchers Deadline for abstract submission will be on March 15, 2023

Organizers

Andreas Ekstedt (Andreas Ekstedt@desy.de) Jorinde van de Vis (j.m.vandevis@uu.nl)

WHISPERS FROM THE DARK UNIVERSE - PARTICLES & FIELDS IN THE GRAVITATIONAL WAVE ERA

DESY Theory Workshop 24 - 27 September 2024 at DESY Hamburg, Germany

E. Lim (King's College)

M. Peloso (Padova U.)

N. Porayko (MPI Bonn)

Plenary Talks

P. Agrawal (Oxford U.) O. Buchmüller (ICL London)

M. Buschmann (GRAPPA & UvA)

A. Chou (Fermilab) S. Ellis (Geneva U.) R. Flauger (UC, San Diego)

G. Franciolini (CERN)

J. Harz (Mainz U.) R. Porto (DESY)

A. Hook (Maryland U.) C. Prescot-Weinstein (N. Hampsh. U.) M. Kamionkowski (J. Hopkins U.) E.-M. Rossi (Leiden U.)

K. Schutz (McGill U.) X. Siemens (Oregon State U.) J. van de Vis (Leiden U.)

DESY Heinrich-Hertz-Lecture

Prof. Dr. Marc Kamionkowski (Johns Hopkins University)

Parallel Sessions

Contributions by young researchers are especially encouraged. Deadline for abstract submission will be on June 30, 2024.

26 September 2024



Inspiring visitors



WOLFGANG PAULI CENTRE

25 November 2020

The Hamburg Prize for Theoretical Physics was brought into being in 2010 and recognizes outstanding achievements in the discipline

Theoretical Physics Symposium 2020



Valery Rubakov WPC Theoretical Physics Symposium 2021





DESY Lecture on Physics 2021

PHYSICAL REVIEW LETTERS

Cosmology and astrophysics into the next decade

Prof. Matias Zaldarriaga (Institute for Advanced Study, Princeton)

21 September 2021

18:00 h, talk will be live-streamed https://webcast.desy.de



HERTZ LECTURE.

DESY Lecture on Physics 2024

Consensus and confusion in cosmology

Prof. Dr. Marc Kamionkowski **Johns Hopkins University**



Thursday, September 26, 17:30 h **DESY main auditorium** https://webcast.desy.de

http://www.wpc-hh.de

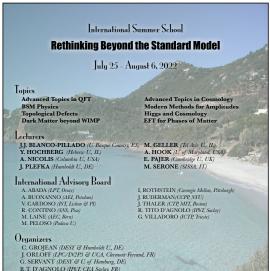
Organised events elsewhere





Institut d'Études Scientifiques de Cargèse

F-20130 Cargèse Téléphone : 04 95 26 80 40 https://iesc.universita.corsica







School on Origin of Matter Domination in the Universe

November 20 – December 1, 2023

São Paulo, Brazil

ICTP-SAIFR/IFT-UNESP









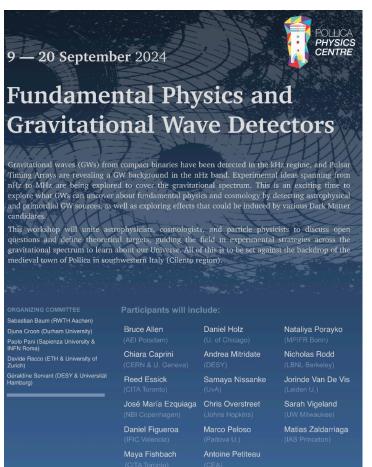
Organizers:

- Chee Sheng Fong (Centro de Ciências Naturais e Humanas, Universidade Federal do ABC, Brazil)
- Enrico Nardi (INFN, Laboratori Nazionali di Frascati, Italy & NICPB, Tallinn, Estonia)
- Rogerio Rosenfeld (ICTP-SAIFR/IFT-UNESP, Brazil)
- · Géraldine Servant (DESY, Hamburg, Germany & II. Institute of Theoretical Physics, University of Hamburg, Germany)









Networking





European ITN project



Academic Staff Exchange Programme



ET, LISA

Particle cosmology outlook



Coherent activity over the whole spectrum of studies in cosmology, fueled by intense experimental activity in the short-term and long-term future.

- -Multitude of different approaches, from model building to analytical studies, lattice calculations, numerical simulations, and analysis of constraints from cosmological observations.
- -strong links with particle theory, string theory and phenomenology activities.
- -International collaborations
- -Center of activity in Axions and in Gravitational waves of cosmological origin
- -Emergent activities related to Pulsar Timing Arrays

