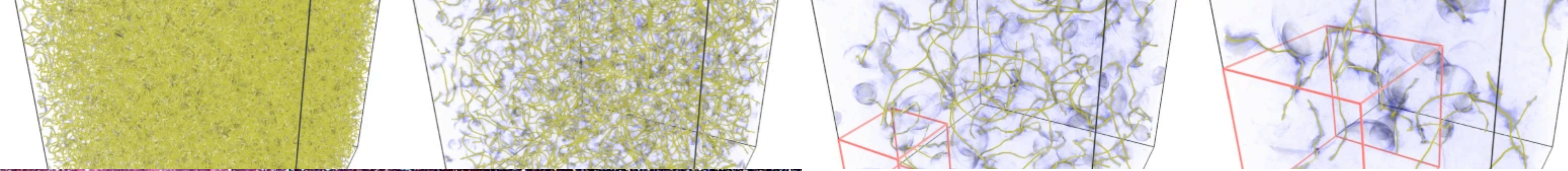


Credit: ESO (eso0708a), Buschmann et al. (2021)

WG2 Discussion

2nd General Meeting of COST Action COSMIC WISPers (CA21106),
Istanbul, Turkey
September 5, 2024

Edoardo Vitagliano
edoardo.vitagliano@unipd.it
University of Padua and INFN Padua

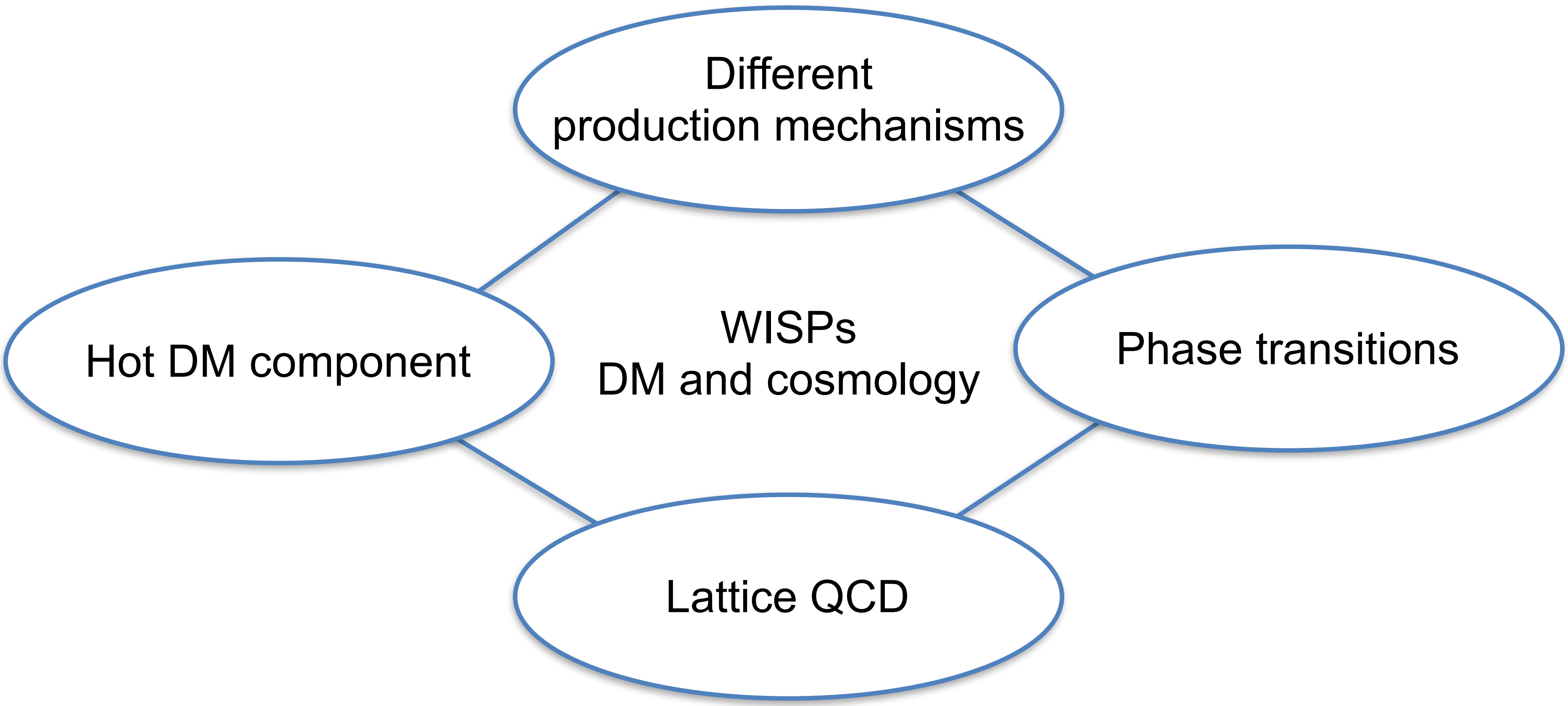
European Research Council
Established by the European Commission
EUROPEAN COOPERATION IN SCIENCE & TECHNOLOGY
COSMIC WISPERS CA21106

Working group 2 in a glance

Many questions:

- WISPs are a great DM candidate—how many ways to produce them?
- Different non-thermal processes, misalignment mechanism, phase transitions, topological defects networks
- If QCD axion is *the* DM, can we reliably predict its mass and couplings?
- What is the abundance of miniclusters? Huge consequences for WG3 and WG4

Working group 2 in a glance



A large community with many different expertises

- More than 200 people in the WG (September 2024)
- Great overlap with all the other WGs (unsurprisingly!)
- Several activities organized together with WG3 in the past years

Coordinators

Marco Gorghetto (DESY)

Edoardo Vitagliano (U. of Padua)

Important to get results

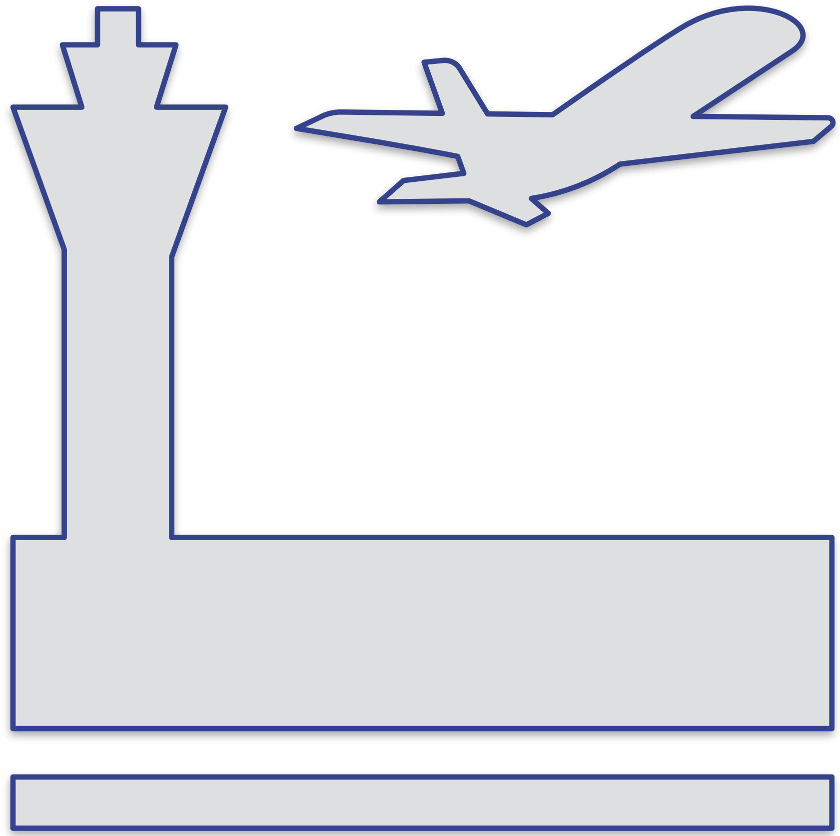
- Great experimental efforts to detect the QCD axion—extremely valuable to identify an expected mass range
- Very important consequences for large density variations
- Astrophysical signals might be very important to discover the nature of dark matter

WG2 activities during year 2

- Organization of general events:
  - Working group meeting 1-2 Feb 2024, Hamburg
  - 2nd Training School, 11-14 Jun 2024, Ljubljana
    "Axions in early universe and cosmo bounds". Lecturer: Benjamin Safdi (UC Berkley). Trainer: Toby Opferkuch (SISSA)
- 2nd General Meeting, 3-6 Sep 2024, Istanbul
  - Plenary: C. Garcia Cely, L. Visinelli, F. D’Eramo, E. Pinetti, E. Hardy, M. Boskovic, E. Todarello, A. Davis
  - Parallel: K. Muursepp, F. Giacchino, C. Smarra, S. Gasparotto, M. Kaltschmidt, G. Pierobon, T. O’Shea, M. Crnogorcevic, M. Vanvlasselaer, A. Lenoci, O. Ghosh, L. Hamolli

Many Short Term Scientific Missions

- C. Käding
- J. Eby
- M. Benito Castaño
- M. Caruana
- P. De la Torre Luque
- D. Gavilán Martín
- G. Lukasiewicz
- J. Leedom
- S. Balaji
- N. Barbieri
- A. Lella
- M. Kaltschmidt



Ongoing White Paper

Editors: A. Drew, S. Gasparotto, Marco Gorghetto, M. Kaltschmidt, E. Vitagliano

WISPs in Cosmology

(A) Axion cosmology

1 Predictions of Axion Mass from Misalignment: Status of Lattice Simulations on Topological Susceptibility and Axion Potential

Claudio Bonati, Maria Paola Lombardo

2 Comparison of String Network and Domain Wall Simulations: Range of Axion Mass

Kenichi Saikawa, Malte Buschmann, Amelia, Mathieu

3 Axion Dark Matter small-scale structure (miniclusters, axion stars)

Ciaran O'Hare, Joshua Eby, Giovanni Pierobon

4 Axions as hot/warm dark matter: Status of Calculation of Axion Thermalization rate, Bounds for Planck

Francesco D'Eramo

(B) WISP cosmology

5 Axion-like particles and ultralight dark matter

1. Jeans scale, suppression of perturbations, effect on structure formation, and cosmological bounds

   Keir Rogers, Diego Blas

2. ALPs as dark energy and as the inflaton (theory/models; observables/bounds)

   S. Gasparotto, Ippei Obata , Elisa Ferreira

3. Gravitational/gravity wave signatures

6 Dark Photons

1. Production mechanisms (from inflation, parametric resonance...)

   Wolfram Ratzinger, Lorenzo Ubaldi, Marco Gorghetto

Past activities

Together with WG3, we have organized a timely online mini workshop on NANOGrav results in 2023

Wednesday, 5th of July

- 3pm Prof. Alberto Sesana, **Nano-Hz gravitational waves: first evidence and implications**

From 4pm on the same day

- Fabrizio Rompineve (CERN), **Footprints of the QCD Crossover on Cosmological Gravitational Waves at Pulsar Timing Arrays**
- Yann Gouttenoire (Tel Aviv University), **TBC**
- Marek Lewicki (University of Warsaw), **Cosmic Superstrings Revisited in Light of NANOGrav 15-Year Data**
- Antonio Iovino (La Sapienza University of Rome), **The recent gravitational wave observation by pulsar timing arrays and primordial black holes: the importance of non-gaussianities**
- Anish Goshal (University of Warsaw), **Probing the Dark Matter density with gravitational waves from super-massive binary black holes**

Planning ahead

T2.1: Perform accurate numerical simulations to obtain precise predictions of axion and WISP DM relic abundance.

- Subtask 2.1.1: Perform additional simulations of the evolution of the string network to obtain the number density of QCD axions that contributes to DM.
- Subtask 2.1.2: Perform QCD lattice simulations at the QCD phase transition to improve the knowledge of the temperature dependence of the axion mass, which affects the relic abundance.
- Subtask 2.1.3: Perform lattice QCD simulation to determine the axion-pion thermalization rate and determine a reliable hot-dark matter axion bound.
- Subtask 2.1.4: Compile a list of WISP DM candidates and their production mechanisms, in order to identify calculations required to improve relic abundance predictions, and also to clarify whether the WISP-DM parameter space is fully explored.

T2.2: Study the formation of Large Scale Structures (LSSs) in various WISP scenarios.

- Subtask 2.2.1: Perform numerical studies of the growth of inhomogeneities in QCD axion DM, from the QCD phase transition onwards.
- Subtask 2.2.2: Study the formation of Large Scale Structures (LSSs) in various WISP scenarios and work to obtain a public code that could describe ALPs and QCD axions impact on LSS.

Planning ahead

T2.1: Perform accurate numerical simulations to obtain precise predictions of axion and WISP DM relic abundance.

- Subtask 2.1.1: Perform additional simulations of the evolution of the string network to obtain the number density of QCD axions that contributes to DM.
- Su … he QCD phase transition to improve the kn … e axion mass, which affects the relic abundance.

NEXT SLIDE STMT EXAMPLE

- Subtask 2.1.3: Perform lattice QCD simulation to determine the axion-pion thermalization rate and determine a reliable hot-dark matter axion bound.
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T2.2: Study the formation of Large Scale Structures (LSS

PART OF THE WHITE PAPER

- Subtask 2.2.1: Perform numerical studies of the growth of inhomogeneities in QCD axion DM, from the QCD phase transition onwards.
- Subtask 2.2.2: Study the formation of Large Scale Structures (LSSs) in various WISP scenarios and work to obtain a public code that could describe ALPs and QCD axions impact on LSS.

Fostering collaboration: axion mass

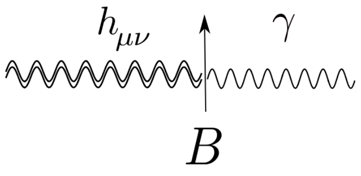
- One of the issues that could contribute to the discrepancies in the literature (interpretation of the emission spectrum and especially the associated spectral index q and its direct relation to the prediction of the axion DM mass) is that everybody is using their own code(s) to run the simulations
- Mathieu Kaltschmidt visited Amelia Drew at the DAMTP in Cambridge thanks to the COST action
- Different initial conditions can play a role
- Comparison for some benchmark between different codes (jaxions, GRChombo, axioNyx, sledgehamr)
- Ongoing work by Mathieu on it (thanks for the update!)

This workshop

See Camilo's talk

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.

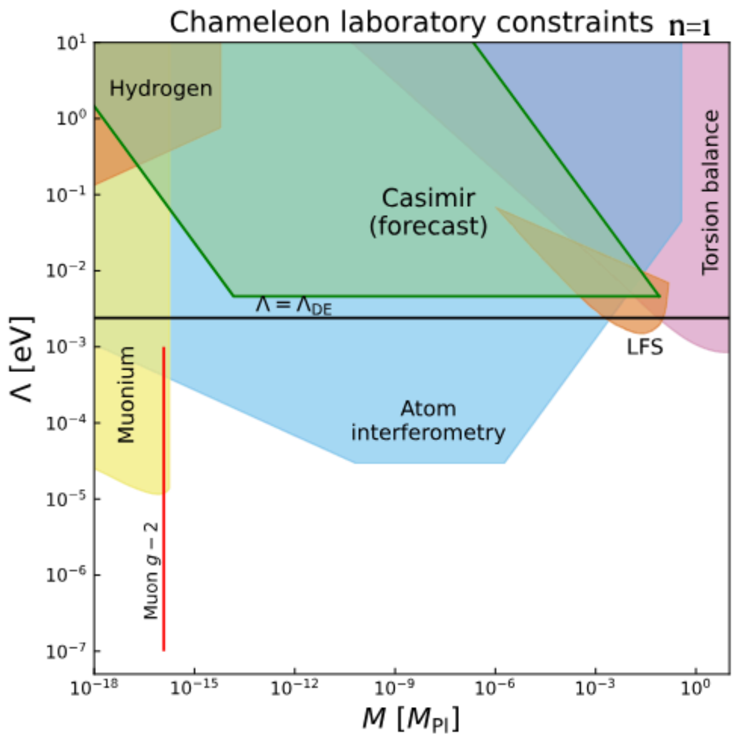
Terrestrial interferometers

6

Camilo García Cely, University of Valencia

This workshop

See Anne's talk



This workshop

See Luca's talk

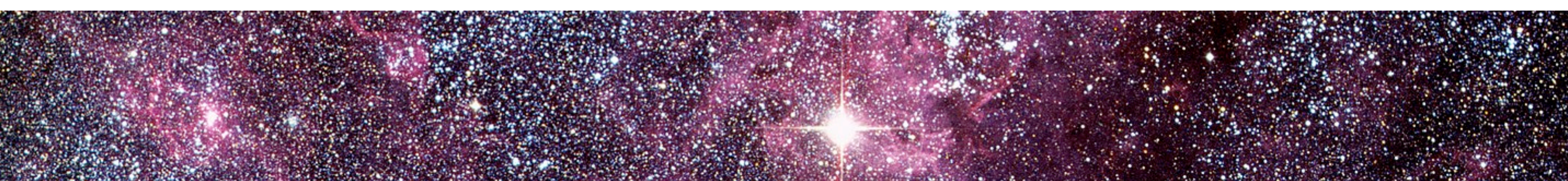
Outline

Luca Visinelli

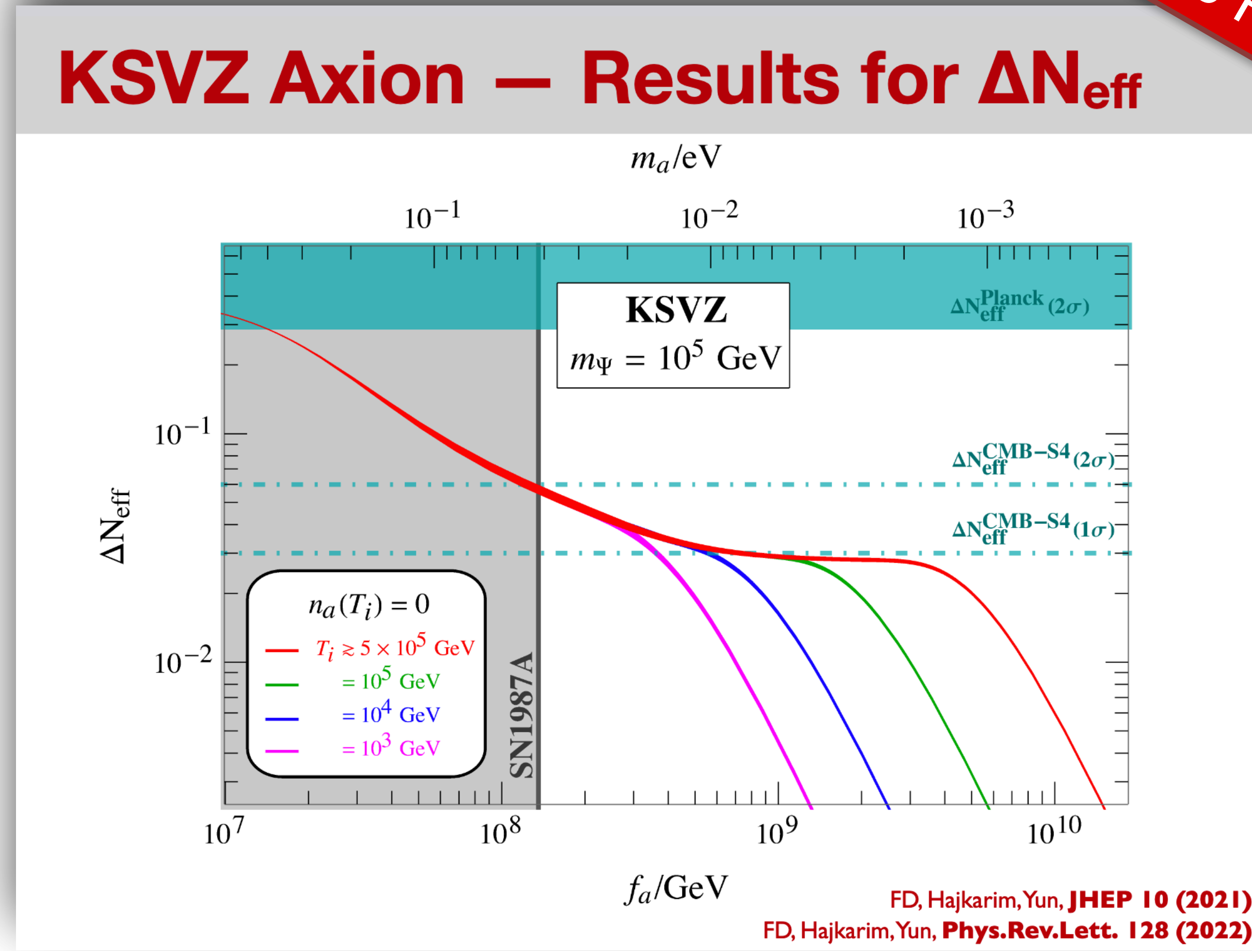
- Axion Miniclusters in the Milky Way
- Axion-photon conversion in NS magnetospheres
- Axions from the Sun
- Direct detection of the axion at INFN Frascati National Labs

See the talk by Maurizio Giannotti for the review on the QCD axion

4



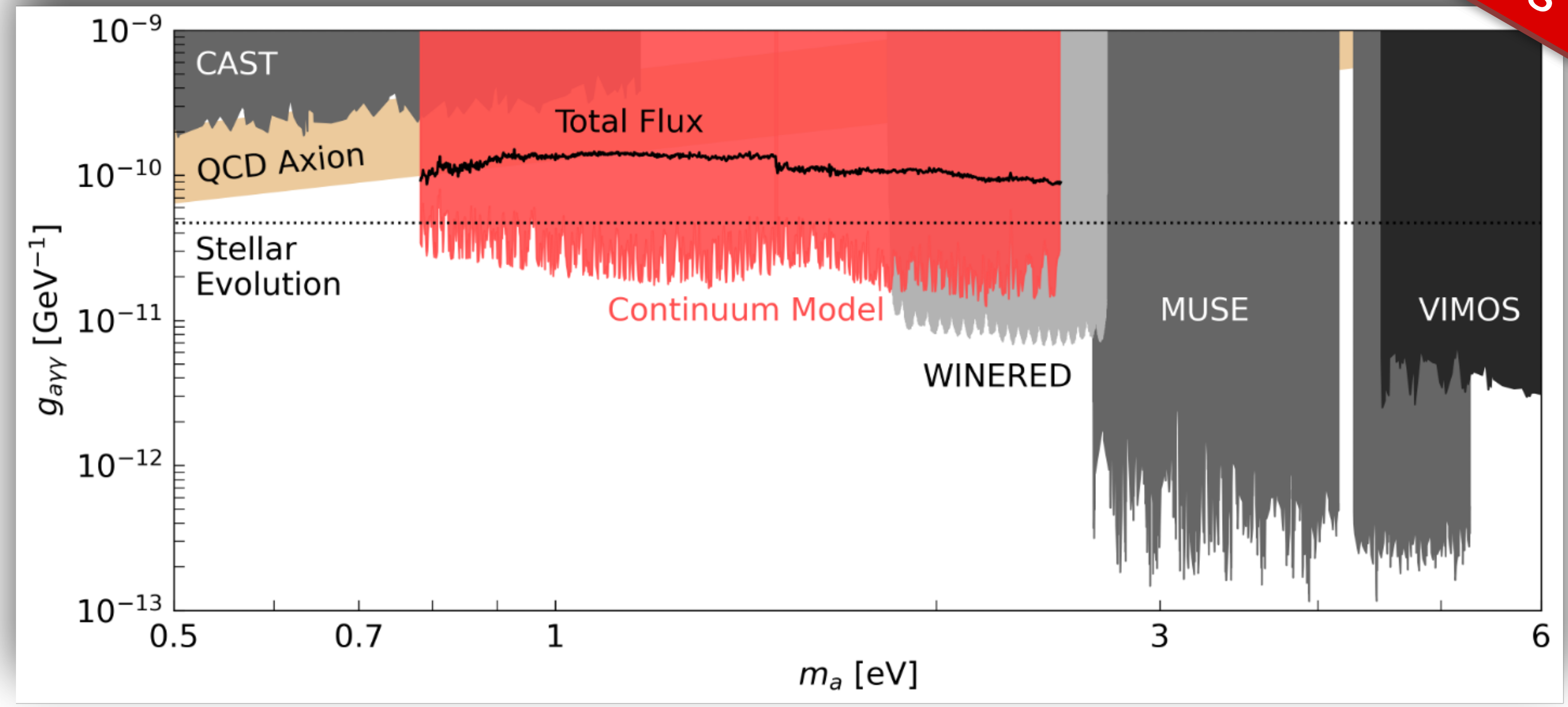
This workshop



See Francesco's talk

This workshop

See Elena's talk

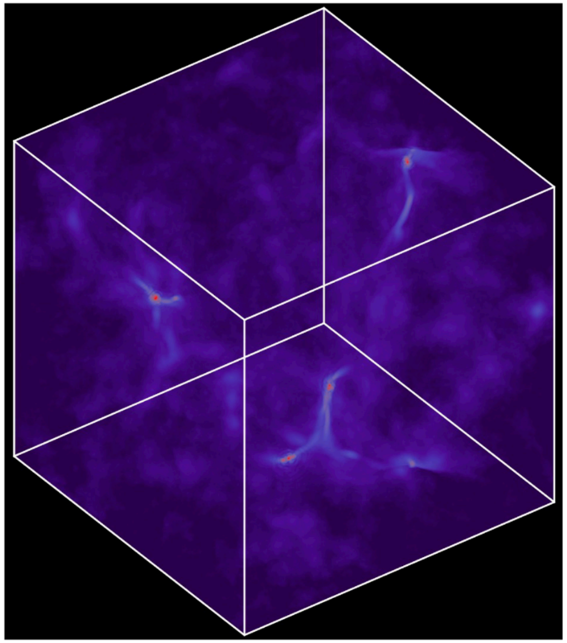


This workshop

See Ed's talk

Summary

- Previously neglected self-interactions at $T \simeq \Lambda_{\rm QCD}$ move energy to the UV
- Fluctuations on scales $k_p \simeq k_{J,\rm MRE}$
- Structures that form around MRE are solitonic “axion stars”
- 20% of DM axions bound



This workshop

WG1:
Which particle models are interesting?

WG2:
Computing the abundance, large overlaps with numerical simulation communities

WG3:
Effects on astrophysical bounds!

WG4:
Effects on laboratory searches!

WG5:
Nice plots and visualizations, good help for outreach

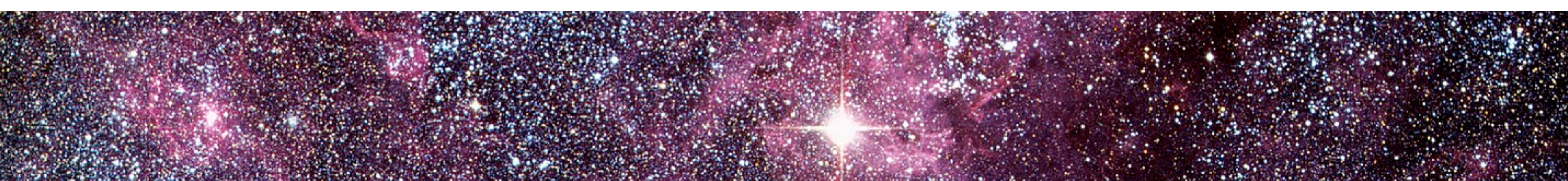
An example

- Can the QCD axion have a mass of $\sim 10^{-2}\,\mathrm{eV}$ in the post inflationary scenario?
- If so, we could be able to see both effects on the next SN cooling signal and in future CMB probes (just short of IAXO reach)
- If DM, can we detect it? @WG4, any new idea in that region of the parameter space?
- Risks and opportunities: miniclusters, other ALPs abundances in the string axiverse?

An example

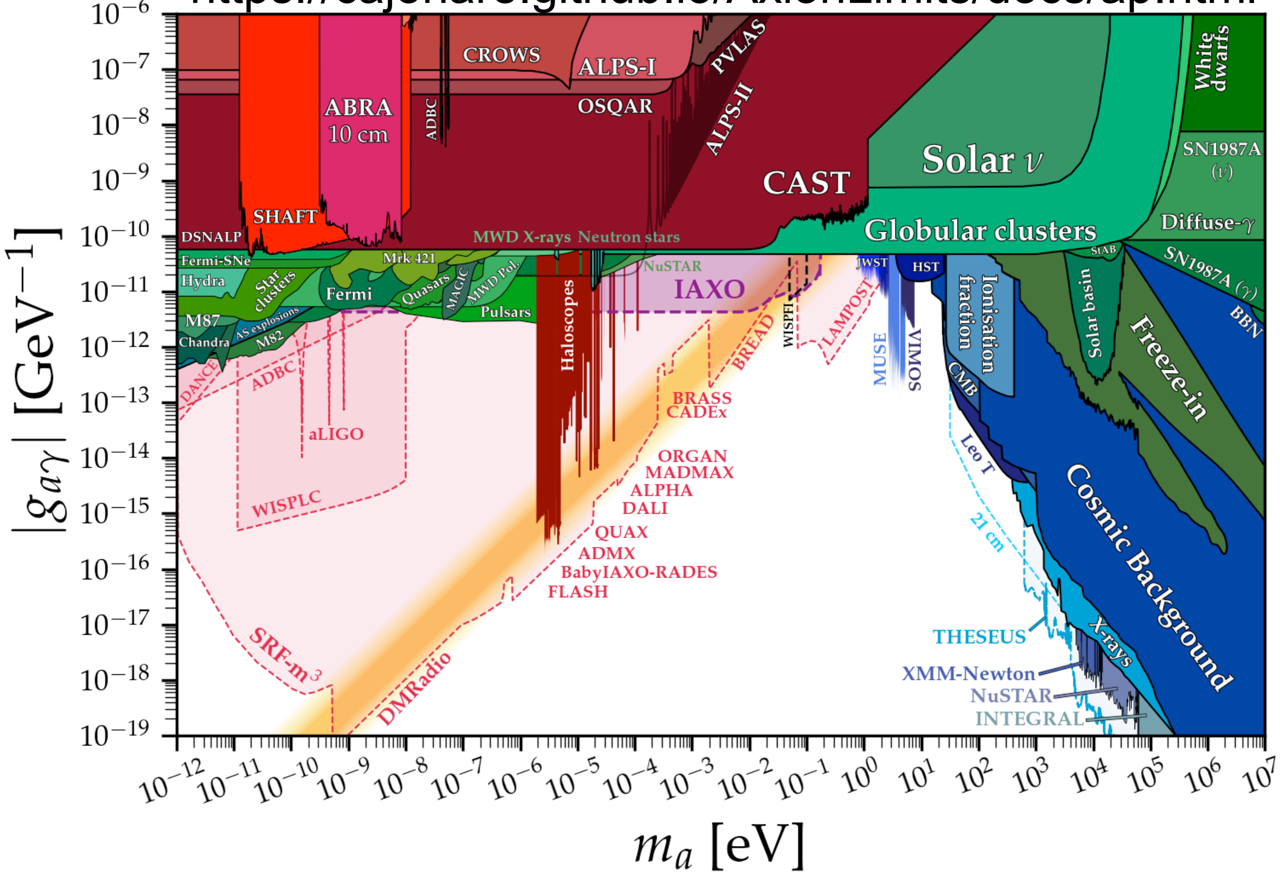
- Can the QCD axion have a mass of ~$10^{-2}\,\mathrm{eV}$ i… …ionary scenario?
- If so, we could be able t… …signal and in future CM…
- If DM, … …region of the parame…
- Risks a… …clusters, other ALPs abundances in the string axiverse?

DISCUSSION TIME!

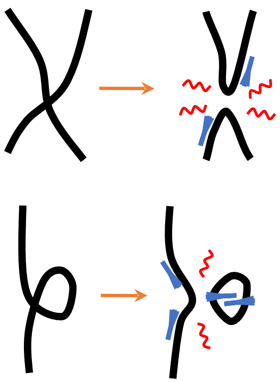


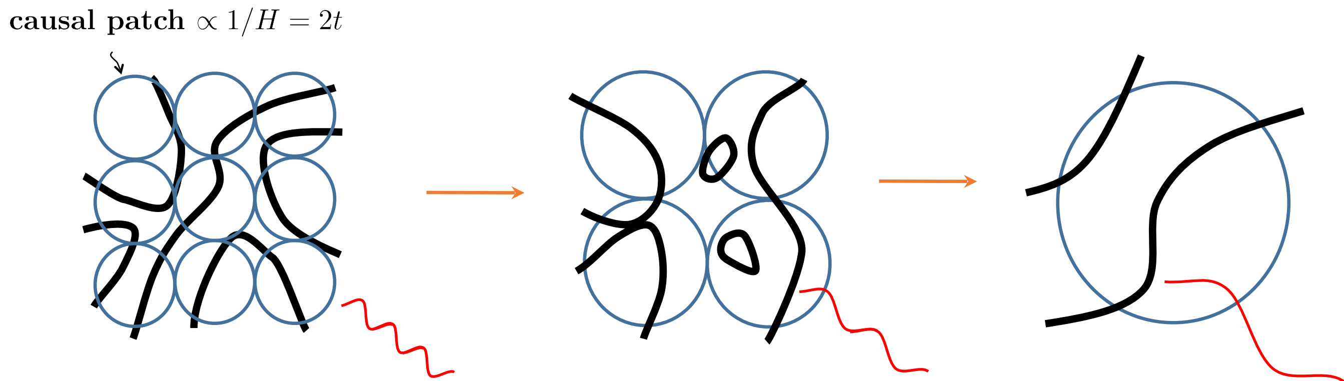
Backup slides (aka Ciaran's plot)

https://cajohare.github.io/AxionLimits/docs/ap.html



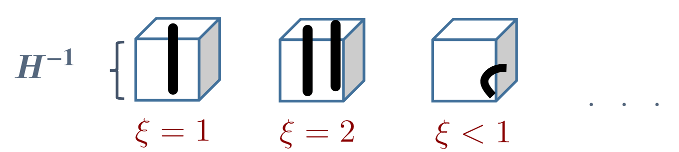
The Scaling Regime

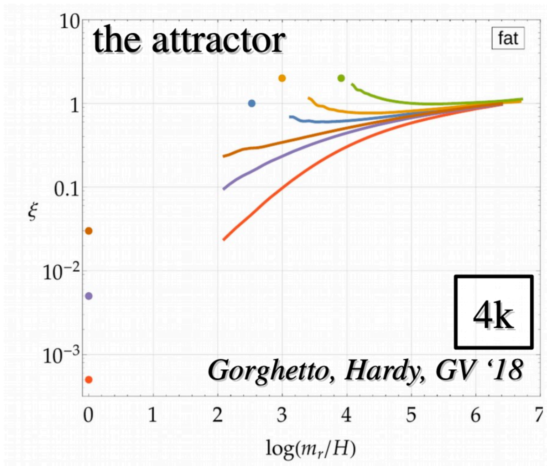


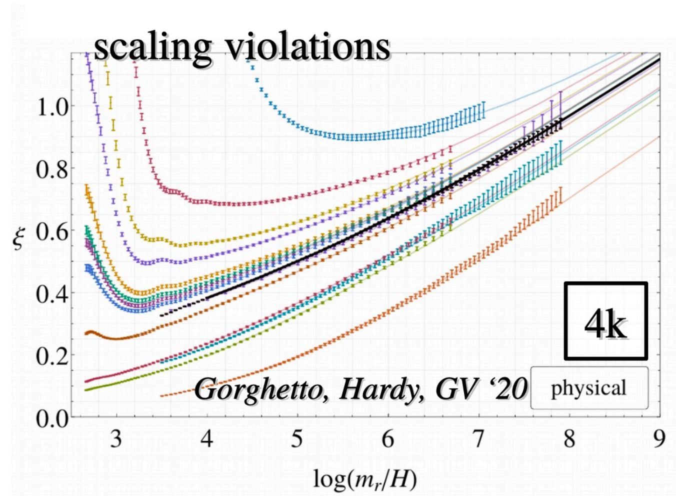


$$\rho_s = \frac{\xi\mu}{t^2}$$

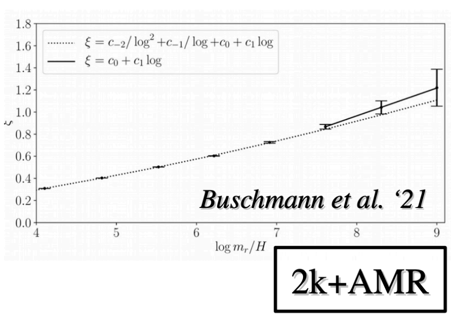
number of strings per Hubble patch

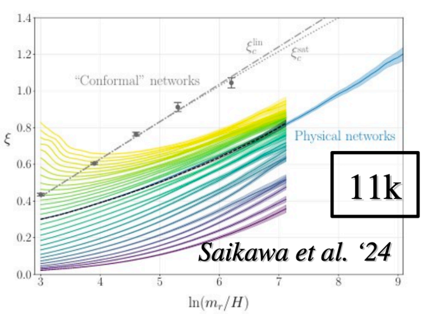


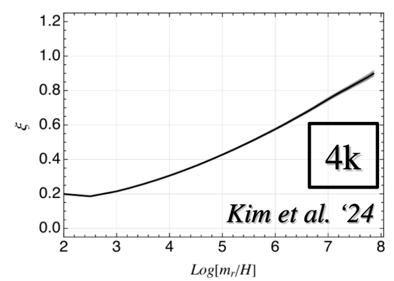




$$\xi \to \frac{\log(m_r/H)}{4 \div 5}$$



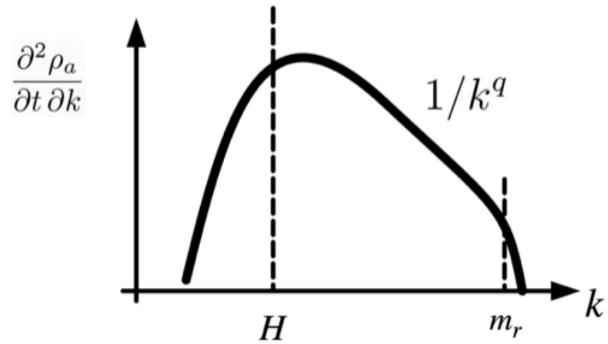




See also:

- Fleury, Moore '15
- Klaer, Moore '17, '19
- Kawasaki et al. '18
- Vaquero et al. '18
- Buschmann et al. '19

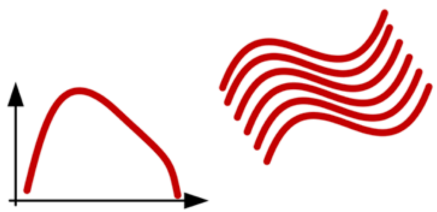
The Spectrum



$$n \sim \frac{\rho}{\langle k \rangle}$$

IR

$q > 1$

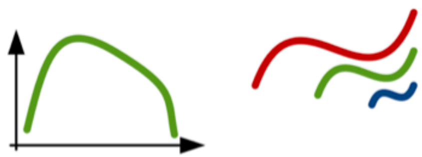


Davies, Shellard, ...

$$n \sim \frac{\rho}{H} \sim \xi \log f^2 H \sim \xi \log n^{mis}$$

$\sim 10^3$

$q = 1$

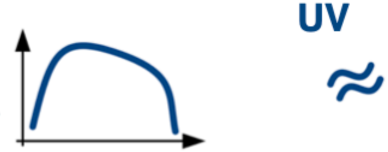


Sikivie, ...

$$n \sim \frac{\rho}{H \log} \sim \xi f^2 H \sim \xi n^{mis}$$

UV

$q < 1$



$$n \sim \frac{\rho}{H}\left(\frac{H}{m_r}\right)^{1-q} \sim n^{mis}\left(\frac{H}{m_r}\right)^{1-q}$$

$\ll 1$

Spectral index

$q > 1?$