"Workshop Summary"

Thoughts inspired by the talks at the CERN-Korea Theory Institute on Axions in the Laboratory and in the Cosmos
This workshop had the distinguished presence of astrophysicists

Scott Tremaine
Lam Hui
Astrophysics

dark matter

Particle Physics

The Sociology
Scott Tremaine

- Fuzzy dark matter assumed to evolve classically (Schroedinger-Poisson equations)
- Uehling-Uhlenbeck equation (1933)
- Relaxation time of halos $\propto \sigma^6$
- FDM halos and constraints thereon (4 questions)
- GAIA reveals spiral structures in $(z, v_z)$ phase space
- Formation of solitons at galactic centers in FDM numerical simulations
Relaxation rate of the axion dark matter fluid due to gravitational self-interactions

\[ t_{\text{relax}} \sim \ldots \sigma^6 \]

\[ \sigma \equiv \text{velocity dispersion} \]

\[ \Gamma \sim n \, v \, \sigma_g \, \mathcal{N} \]

\[ n \equiv \text{density} \quad \quad v \equiv \text{velocity dispersion} \]

\[ \sigma_g \equiv \text{cross section for large angle gravitational scattering} \]

\[ \mathcal{N} \equiv \text{quantum degeneracy} \]
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\[ \sigma_g \equiv \text{cross section for large angle gravitational scattering} \]

\[ \mathcal{N} \equiv \text{quantum degeneracy} \]
\[ \sigma_g \sim \frac{4 \ G^2 \ m^2}{v^4} \]

\[ \mathcal{N} \sim \frac{(2\pi)^3 n}{(mv)^3} \]

\[ \Gamma \sim n \ \frac{4G^2 m^2}{v^4} \ v \ \frac{(2\pi)^3 n}{(mv)^3} \propto \frac{1}{v^6} \]

For dark matter axions today, in intergalactic space ...
\[ m \, n \sim 10^{-29} \, \text{gr/cm}^3 \]

\[ m \sim 10^{-5} \, \text{eV} \]

\[ v \sim \frac{1}{m \, t_{QCD}} \frac{a_{QCD}}{a_0} \sim 10^{-17} c \]

If axions are decoupled

\[ N \sim 10^{61} \]
Cold dark matter axions thermalize by gravitational self-interactions!

\[ t_{\text{relax}} \sim 0.3 \text{ sec} \]

(Qiaoli Yang + PS, 2009)

What happens when they do so thermalize?
Quantum Bose field thermalization

\[
\frac{dN}{dE}
\]

\[
E
\]

\[
\frac{dN}{dE}
\]

\[
E
\]

\[
\frac{dN}{dE}
\]

\[
T
\]

\[
E
\]
Classical field thermalization

\[ \frac{dN}{dE} \]

\[ T = 0 \]

UV catastrophe
What implications does axion Bose-Einstein condensation have?
Axion cosmology was thoroughly discussed

Asimina Arvanitaki
Giovanni Villadoro
Malte Buschmann
David Marsh
Jihn E. Kim
Kwang Sik Jeong
Fuminoku Takahashi
Important topics

- Axion cosmological energy density $\Omega_a(m_a)$
- Constraints on ULALPs
- Axion string evolution & radiation spectrum
- Fate of domain walls and oscillons
- Evolution of axion mini-clusters
- Axion field evolution during QCD phase transition
Effective potential $V(T, \Phi)$

$T > f_a$

$T > 1\text{GeV} > f_a$

$1\text{GeV} > T$

- axion strings
- axion domain walls
Giovanni Villadoro

- $m_a = \sqrt{\xi_{top} / f_a} \approx 5.8 \mu eV \ (10^{12}/GeV)$
  $\xi_{top} \approx 75.5 \text{ MeV}$

- $\Omega = 0.1 \ k \ \theta_0^2 (f_a/10^{12} \text{ GeV})^{1+\epsilon}$
  dilute gas approx. $k = 1$ and $\epsilon = 1/6$ (DIGA)
  numerical work by Bonati et al. (2015, 2018) and
  Borsanyi et al. (2016), not far from DIGA.

- contribution from string decay, approximately one string per horizon,
  but increases with log of ratio of scales $e^{70}$, fat string trick

- $10\%$ of strings in small loops

- $d \rho / dk \propto k^{-q}$ $q \approx 0.75$ for log $\approx 3$ to 8
  but $q$ increases over that range
• scaling violation = dependence on log(m/H)
• \#strings/horizon increases with log
• oscillons appear in the simulations, ultimately dissipate
• qualitative agreement with G. Villadoro et al.
• fewer dense miniclusters than Kolb and Tkachev found

• \( m_a = 25.2 \pm 11.0 \) micro eV
Axion string evolution and radiation spectrum is a beautiful (difficult) problem in classical field theory

\[ \partial_\mu \partial^\mu \Phi - \mu^2 \Phi + \lambda \Phi^\dagger \Phi \Phi = 0 \]

\[ \log(\mu \, t_{\text{QCD}}) \sim 70 \]

Critical issues:

- Number of strings per horizon $\xi$
- Spectrum of radiated axions $\frac{d\rho}{dk} \propto \frac{1}{k^q}$
Stellar evolution constrains on axions/ALPs were reviewed and discussed

Alessandro Mirizzi
Kfir Blum
Koichi Hamaguchi
Important topics

How robust is the constraint on axions from SN1987a? (K. Blum et al., 2109)

Are stellar cooling anomalies in white dwarfs explained by ALP emission?

What’s happening with the neutron star in Cassiopeia A?
Axion model building was creatively explored

Kwang Sik Jeong
Jihn E. Kim
Keisuke Harigaya
Important topics

- Axions in SUSY extensions of the Standard Model
- Axions in string theory
- Baryogenesis in ALP driven 1\textsuperscript{st} order phase transition
- ALPs and the Hierarchy Problem (relaxion)
- Properties of ALP dark matter
- Possibility of axion-ALP level crossing
New axion detection methods were presented and old methods reviewed

Andreas Ringwald
David Marsh (topological insulators)
Maria Baryakhtar (LIGO)
PS (echo method)
Masha Baryakhtar

- Black hole superradiance $30 \text{ M}_\text{sun} \sim 10^{-12} \text{ eV}$
- Massive particles are effectively reflected, produce a "black hole bomb." $\alpha \equiv G M_{\text{bh}} m_a$
- Energy levels $m_a (1 - \alpha^2/2 n^2 + i \Gamma)$
- ~10 year lifetime to spin down to ~0.6
- BH spin (e.g. in x-ray binaries) determines the innermost stable orbit of the accretion disk (depends on disk inclination)
- $2 \times 10^{-11}$ to $6 \times 10^{-13}$ eV (stellar mass BH)
- $2.5 \times 10^{-19}$ to $2.1 \times 10^{-17}$ eV (super massive BH)
- Ruled out for axions (spin zero)
• monochromatic gravitational waves emitted in axion transitions between two levels, may be seen by LIGO

• the attractive $\lambda \phi^4$ interactions may cause the axion cloud around a BH to collapse (bosenova), relaxes spin constraints, axion waves emanating from BH may be detected in axion haloscopes
• Light Shining through a Wall: ..., ALPs @ DESY (2010), OSQAR@CERN (2015), ALPs II promises 3082 improvement in the e.m. coupling for 2021-22, JURA (100mm, 13T magnets for FCC, 426 m, 2.5 MW)

• Solar axion search using a -> x-ray conversion in a magnetic field: ... CAST@CERN, (baby)IAXO@DESY

• Dark matter axion searches using the cavity method: --- ADMX@UW, HAYSTAC@Yale, ORGAN in Australia, CAST-CAPP (4 detectors) in Korea, RADES@CAST, KLASH @ FRASCATI)
• Axion dark matter search using Dish Antennas are broad-band: BRASS-6 @ DESY

• Dielectric plate Haloscope: MADMAX (80 discs, 10T dipole, 2m long) reaches DFSZ axion dark matter

• LC circuit axion haloscope: ABRACADABRA(MIT) 10 cm version has obtained limits, plan to go to the QCD axion dark matter, DM-Radio(Stanford)

• Magnetic Resonance: CASPER-Electric (Boston), CASPER-Wind (Mainz), QUAX (Legnaro)
• Searches for Axion Mediated Forces: ..., ARIADNE rotating mass (at Larmor freq.) and polarized target at NorthWestern with SQUIDs from CAPP

• Minimal flavored MASH has axion induced FCNC: NA62
Axion physics (cosmology, astrophysics, detection methods, ...) is providing new tools to investigate our universe.
Our heartfelt thanks to the organizers of the CERN-Korea TH Institute on Axions!

Kfir Blum
Babette Dobrich
Deog Ki Hong
Seung J. Lee
Matthew McCullough
Hyun Min Lee
Benjamin Safdi

Michelle Connor
Asimina Arvanitaki
Kwang Sik Jeong

• Extension of Standard Model with an ALP, a quasi-Nambu-Goldstone boson, $\phi^2 |H|^2$ interaction with Higgs

• Motivated by cosmological relaxation of the Higgs mass (relaxion), and dark matter.

• Electroweak Baryogenesis enabled through ALP driven 1st order phase transition.

• ALP is a candidate for ‘Freeze-in’ dark matter, i.e. dark matter that was never in thermal equilibrium.
Jihn E. Kim
• Eridanus 2 heating constraint: $m > 3 \times 10^{-20}$ eV except for special $m$ bands

• Black hole superradiance excludes
  $10^{-16}$ eV > $m$ > $10^{-19}$ eV (supermassive BH)
  and $10^{-11}$ eV > $m$ > $10^{-13}$ eV

• LISA will address intermediate mass BH
• ALP is a pNG boson that has a discrete shift symmetry
  \[ a \rightarrow a + 2\pi f_a \]

• possibility of inflation with \( H << 1 \) GeV, in which case the axion field moves slowly towards its CP conserving value before reheating

• ALP may be related to dark matter, dark energy (\( m < 10^{-33} \) eV), dark radiation, inflation ...

• ALP dark matter produced by the misalignment mechanism tends to be more weakly coupled than the QCD axion for \( m_a > 10^{-8} \) eV. Counter-example with ALP-axion level crossing.
Keisuke Harigaya
ULALP (m $\sim 1\times 10^{-21}$ eV) with $f_a \sim$ GUT scale has $\Omega_a \sim 0.1$

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Black hole superradiance excludes

\begin{align*}
10^{-16} \text{ eV} &> m > 10^{-19} \text{ eV} \quad \text{(supermassive BH)} \\
and \quad 10^{-11} \text{ eV} &> m > 10^{-13} \text{ eV}
\end{align*}

LISA will address intermediate mass BH

Discussion of axion cosmological energy density, axion miniclusters

high mass axion detection with topological insulators
\[ \Omega_{\text{ULALP}} \sim 0.1 \left( \frac{f}{10^{17} \text{ GeV}} \right)^2 \left( \frac{m}{10^{-22} \text{ eV}} \right)^{1/2} \]

- description of a vortex, \( \Psi = 0 \) in the middle, the velocity has circulation along a loop enclosing the vortex
- vortex loops appear in simulations solving the Schrodinger-Poisson equations
- vortices may be observed by gravitational lensing
- Black hole hair from oscillating scalar field
- Interesting questions concerning vortices
stellar density increases when approaching the center of a galaxy – galactic nuclei

quasars are AGN with $L \sim 10^{13} L_{\text{sun}}$, at least $10^8 M_{\text{sun}}$ in mass (from Eddington luminosity)
quasars require black holes ($< 10^{12}$ m from gravitational lensing, energy conversion efficiency)
quasars peak at $z \sim 3$ “cosmic noon”
Sun is $8.18 \pm 0.01$ kpc from MW center
MW BH has ass $4.15 \pm 0.01 \times 10^6 M_{\text{sun}}$
Event horizon telescope too picture of M87 BH
gravitational relaxation near BH
• LISA should be able to see supermassive BH mergers (galaxies merge, followed by the merger of their BHs brought in by dynamical friction)
• however there is a bottleneck (final parsec problem) as the stars near the BH binary become depleted
• M31 has BH with mass \( \sim 10^8 \) M\(_{\text{sun}}\)
• tidal disruption events when a star comes near a BH, Roche criterion applies, many candidate events have been observed
Masha Baryakhtar

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• globular cluster (all stars have the same age and same initial composition), lifetime of horizontal branch stars $g_{em} < 0.66 \times 10^{-10}$/GeV
• several stellar systems (white dwarfs, ..) appear to cool faster than expected, hint of ALPs
• SN1987a neutrino events imply $f_a > 10^9$ GeV, recently being relaxed to $f_a > 3 \times 10^8$ GeV, may be removed if collapsed star has accretion disk
Koichi Hamaguchi

• Cooling of neutron star in Cassiopeia A, 3 to 4% in 10 years, explosion was 380 years ago
• modified URCA process neutrino emission implies $T \propto t^{-1/6}$, too small (0.3 %)
• Cooper pair breaking process (occurring just now) may explain the increased cooling
• axion bremsstrahlung is relevant for $f_a > 5 \times 10^8$ GeV so as not too mess up