“Workshop Summary”

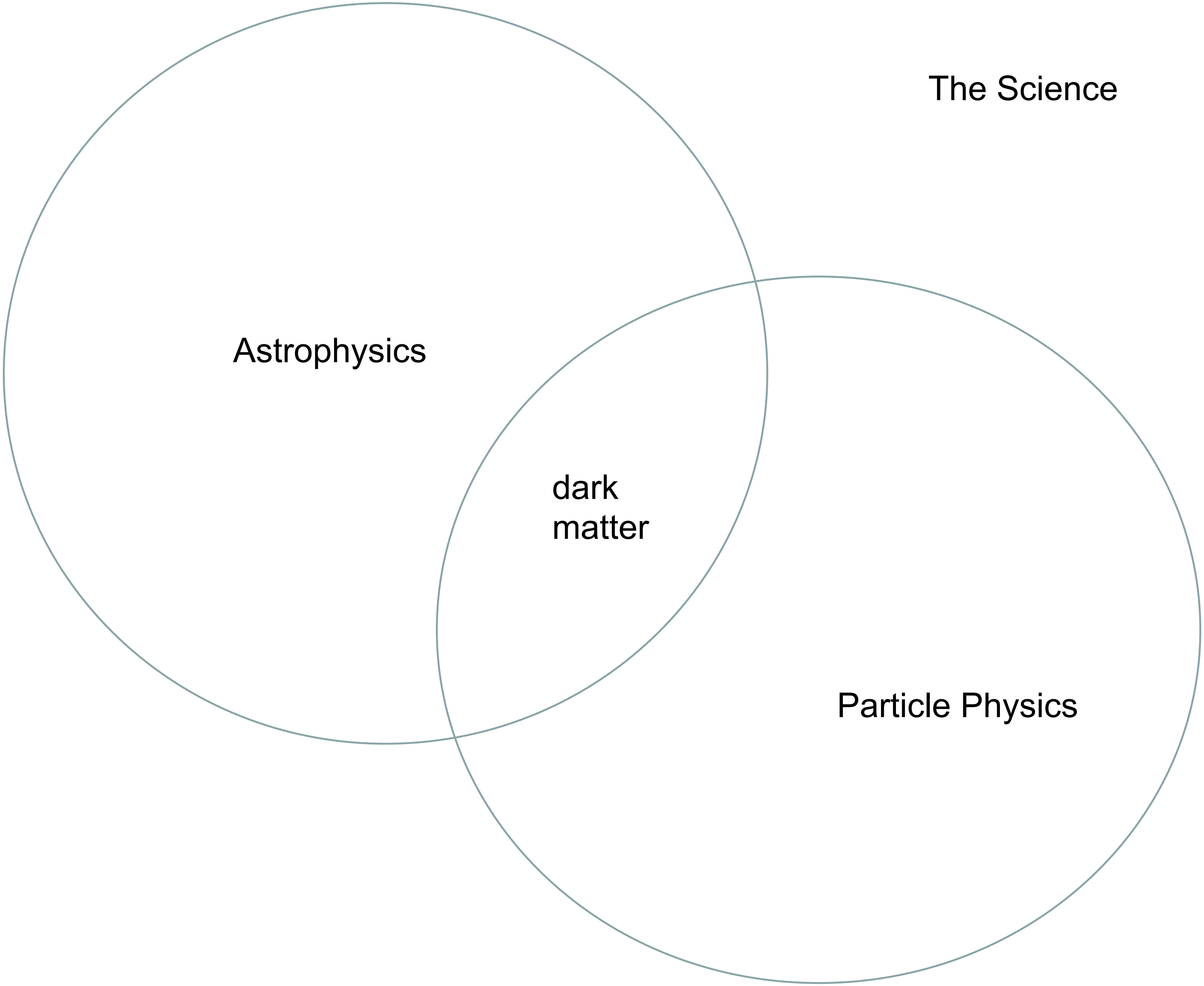
Thoughts inspired by the talks at the
CERN-Korea Theory Institute on
Axions in the Laboratory and in the Cosmos
CERN, July 15-19, 2019.

This workshop had the distinguished presence of astrophysicists

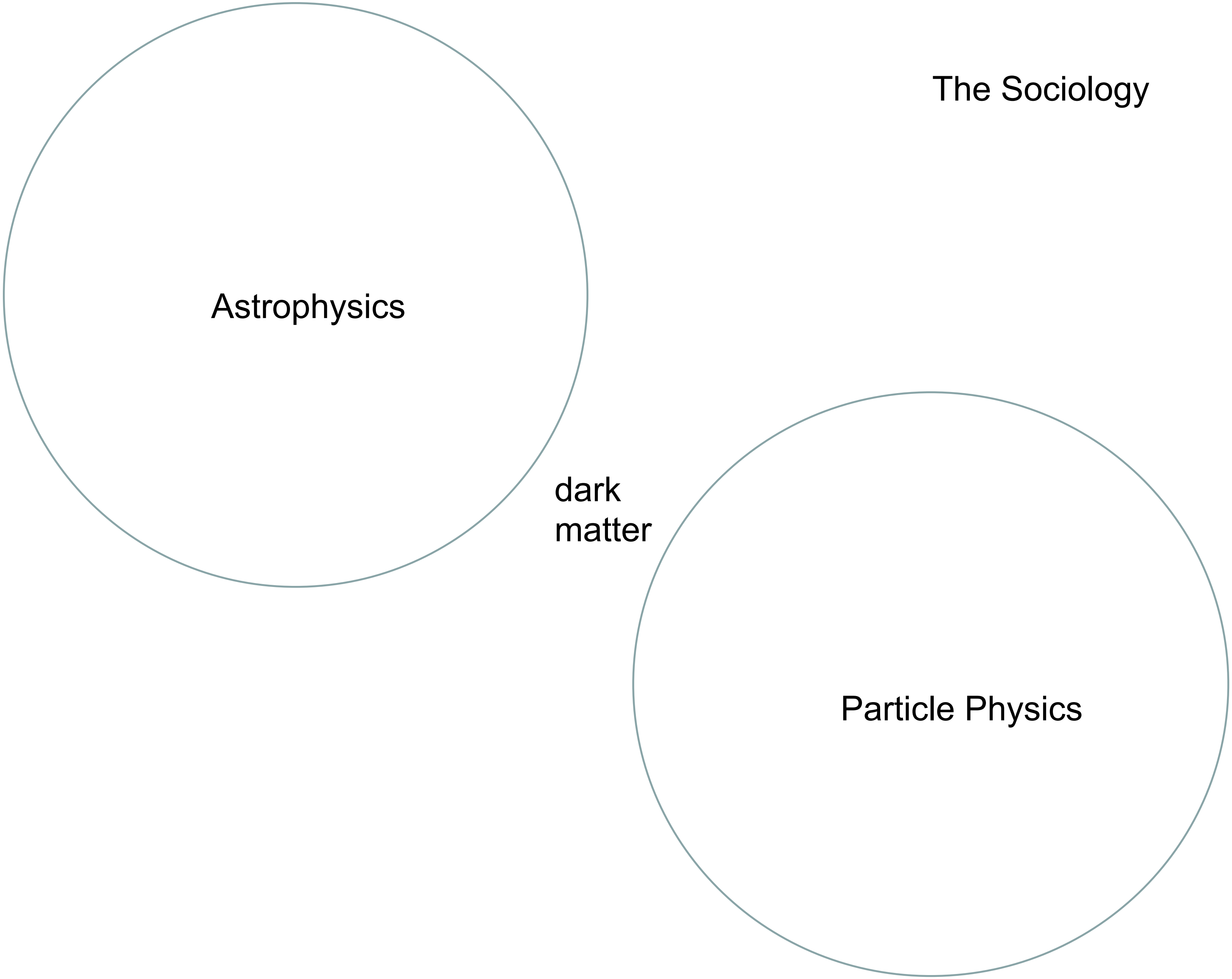
Scott Tremaine

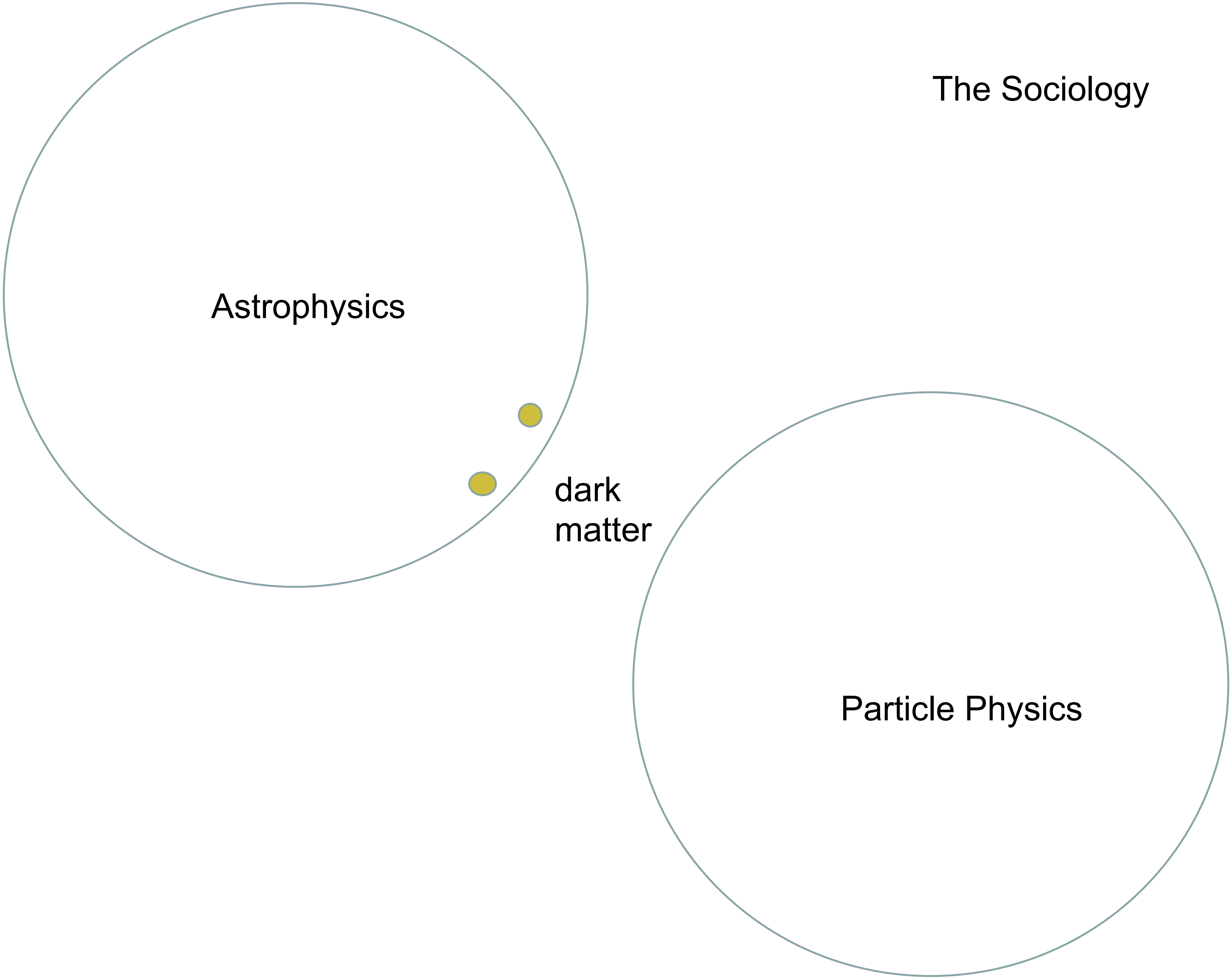
Lam Hui

The Science



The Sociology




The Sociology
Astrophysics
dark
matter
Particle Physics

Scott Tremaine

- Fuzzy dark matter assumed to evolve classically (Schrodinger-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

$$t_{\text{relax}} \sim \; \dots \; \sigma^6$$

$$\sigma \;\equiv\; \text{velocity dispersion}$$

$$\Gamma \sim n \, v \, \sigma_g \, \mathcal{N}$$

$n \;\equiv\;$ density

$v \;\equiv\;$ velocity dispersion

$\sigma_g \;\equiv\;$ cross section for large angle gravitational scattering

$\mathcal{N} \;\equiv\;$ quantum degeneracy

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$$\sigma_g \sim \frac{4\ G^2\ m^2}{v^4}$$

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

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

For dark matter axions today, in intergalactic space ...

$$m\,n \sim 10^{-29}\ \mathrm{gr/cm^3}$$

$$m \sim 10^{-5}\ \mathrm{eV}$$

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

if axions are decoupled

$$\mathcal{N} \sim 10^{61}$$

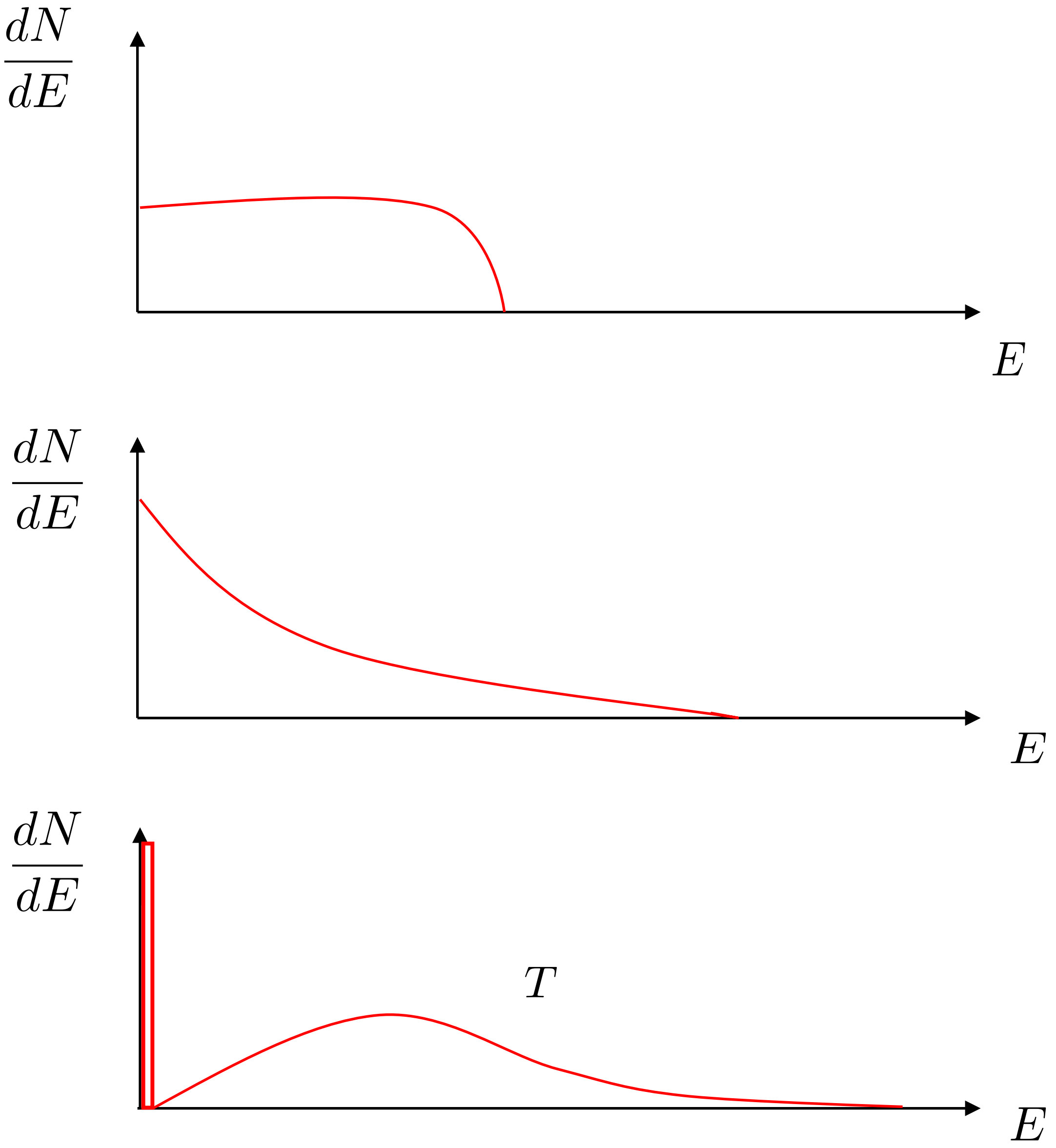
$$t_{\rm relax} \sim 0.3 \text{ sec}$$

Cold dark matter axions thermalize by gravitational self-interactions !

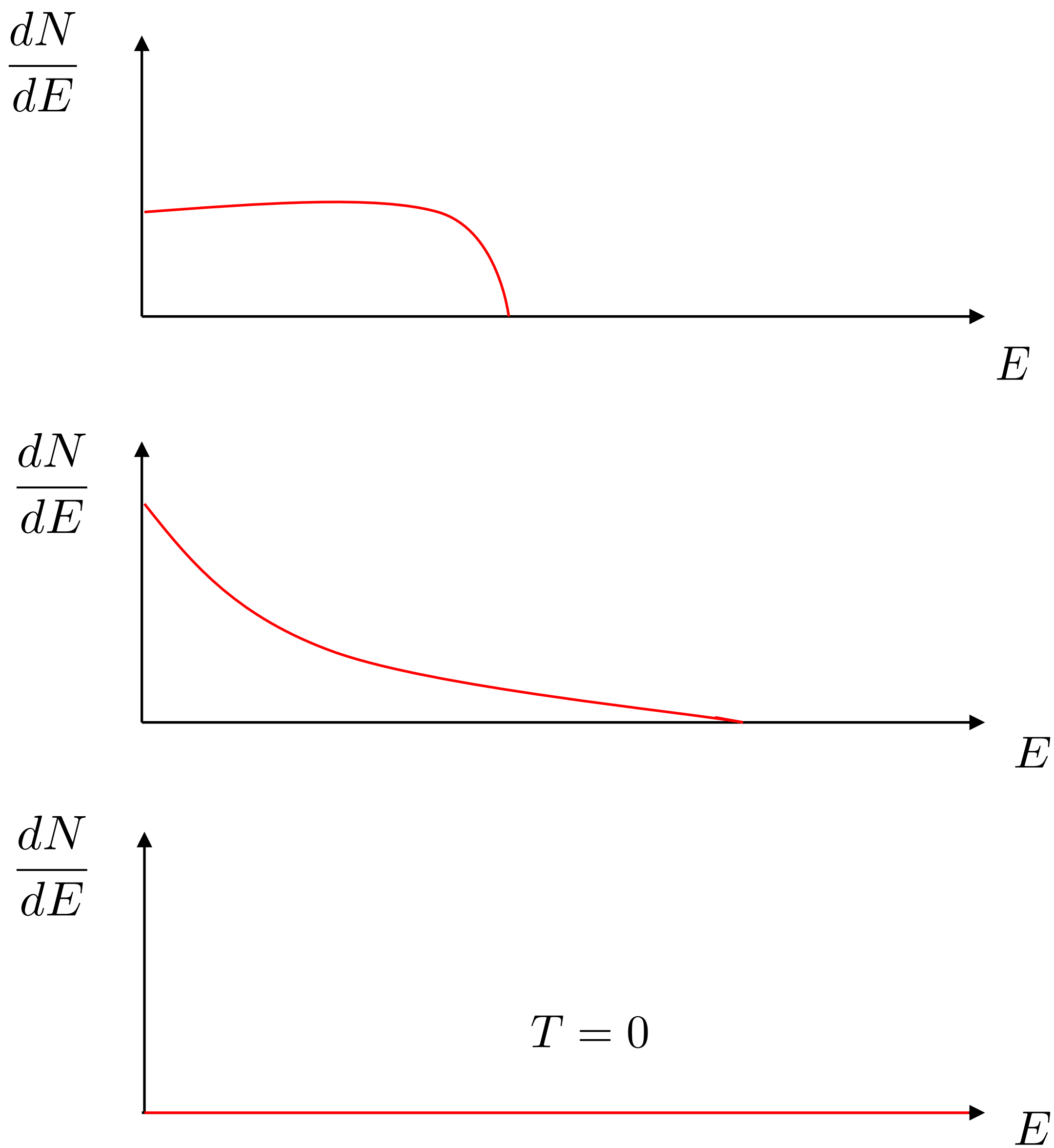
(Qiaoli Yang + PS, 2009)

What happens when they do so thermalize ?

Quantum Bose field thermalization



Classical field thermalization



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

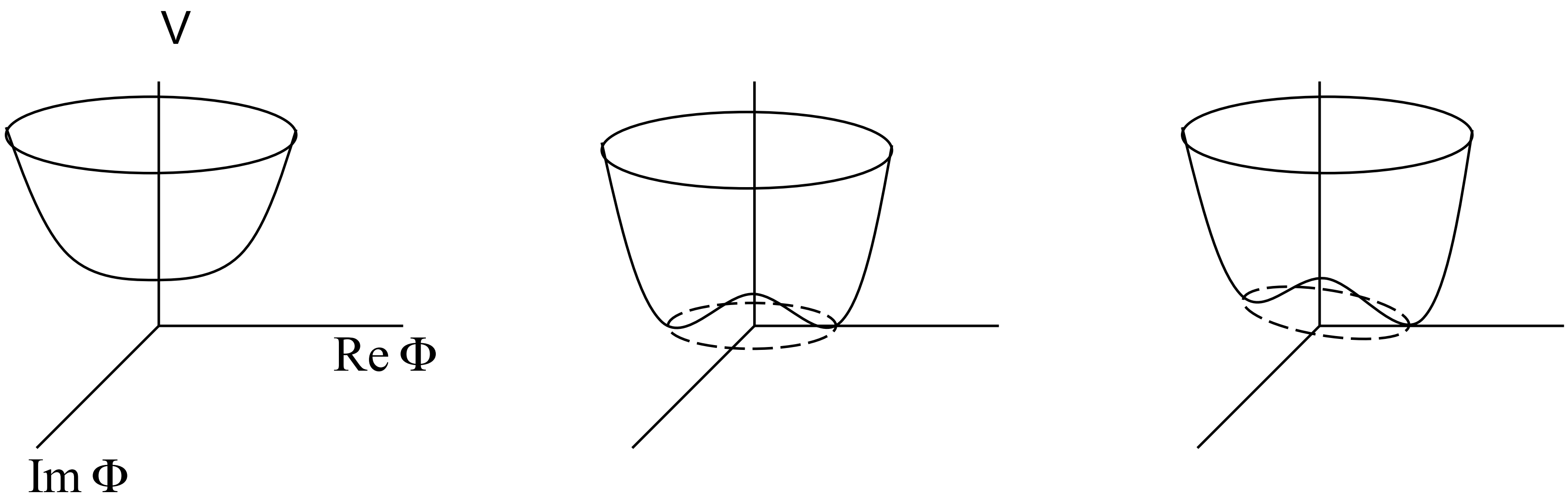
Axion string evolution & radiation spectrum

Fate of domain walls and oscillons

Evolution of axion mini-clusters

Axion field evolution during QCD phase transition

Effective potential V(T, Φ)



$T > f_a$

$f_a > T > 1\,\mathrm{GeV}$ → axion strings

$1\,\mathrm{GeV} > T$ → axion domain walls

Giovanni Villadoro

- m_a = \sqrt{\xi}_top / f_a \simeq 5.8 \mu eV (10^{12}/GeV)
  \xi_top \simeq 75.5 MeV

- \Omega = 0.1 k \theta_0^2 (f_a/10^{12} 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 \propro k^{-q}   q \simeq 0.75   for log \sim 3 to 8
  but   q   increases over that range

Malte Buschmann

- 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

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

$$\log(\mu \; t_{\rm QCD}) \sim 70$$

Critical issues:

Number of strings per horizon $\qquad \xi$

Spectrum of radiated axions $\qquad \frac{d\rho}{dk} \propto \frac{1}{k^q}$

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 1st 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 M_sun -- 10^{-12} eV
- massive particles are effectively reflected, produce a 'black hole bomb. \alpha \equiv G M_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 10^{-11} to 6 10^{-13} eV (stellar mass BH)
  2.5 10^{-19} to 2.1 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

Andreas Ringwald

- 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

David J.E. Marsh

- Eridanus 2 heating constraint: $m > 3\ 10^{-20}$ 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

Fumi Takahashi

- ALP is a pNG boson that has a discrete shift symmetry
  $a \to a + 2\pi f_a$

- possibility of inflation with $H \ll 1$ 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

David J.E. Marsh

- ULALP ($m \sim 10^{-21}$ eV) with $f_a \sim$ GUT scale has $\Omega_a \sim 0.1$
- Eridanus 2 heating constraint $m > 3 \; 10^{-20}$ 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
- Discussion of axion cosmological energy density, axion miniclusters
- high mass axion detection with topological insulators

Lam Hui

- $\Omega_{ULALP} \sim 0.1 (f/10^{17} \text{ GeV})^2 (m/10^{-22} \text{ eV})^{1/2}$
- 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

Scott Tremaine Colloquium:
“Dynamics of galactic nuclei”

- stellar density increases when approaching the center of a galaxy – galactic nuclei
- quasars are AGN with L ~ 10^{13} L_sun, at least 10^8 M_sun in mass (from Eddington luminosity)
- quasars require black holes (< 10^{12} m from gravitational lensing, energy conversion efficiency)
- quasars peak at z~3   “cosmic noon”
- Sun is 8.18 \pm 0.01 kpc from MW center
- MW BH has ass 4.15 \pm 0.01 10^6 M_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 ~ 10^8 M_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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- massive particles are effectively reflected, produce a 'black hole bomb. \alpha \equiv G M_bh m_a
  energy levels m_a (1 - \alpha^2/2 n^2 + i \Gamma)
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Alessandro Mirizzi

- globular cluster (all stars have the same age and same initial composition), lifetime of horizontal branch stars $g_{em} < 0.66\ 10^{-10}$/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 $f_a > 3\ 10^8$ 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 bremstrahlung is relevant for $f_a > 5\ 10^8$ GeV so as not too mess up