Unified Superfluid Dark Sector

Elisa Ferreira

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EF, Justin Khoury, Robert Brandenberger and G. Franzmann. 1810.09474, JCAP.

FAPESP & JSPS Workshop,
University of São Paulo, February 2019

The model

Different approach to the problem!

New model that **unifies** into a **single** framework:

- ✓ Dark energy
- ✓ Cold dark matter
- ✓ Small scale behavior of dark matter

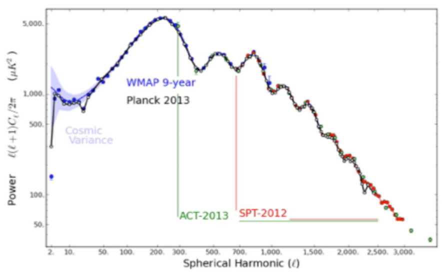
↳ Minimal: DM only model

This can be done using the physics of superfluidity!

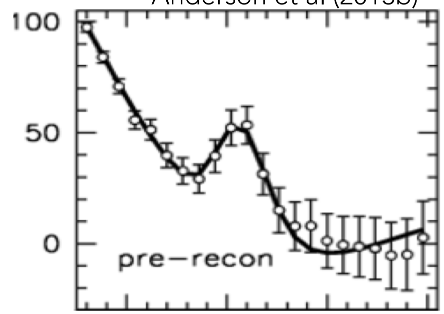
Predictions that can be tested.

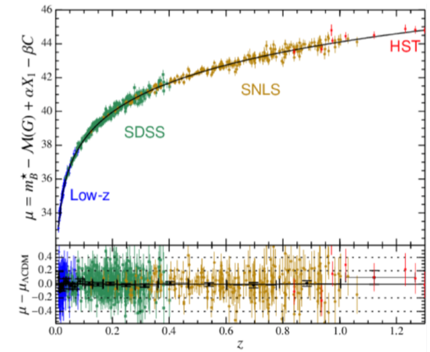
Dark Matter and Dark Energy

Spergel



Anderson et al (2013b)



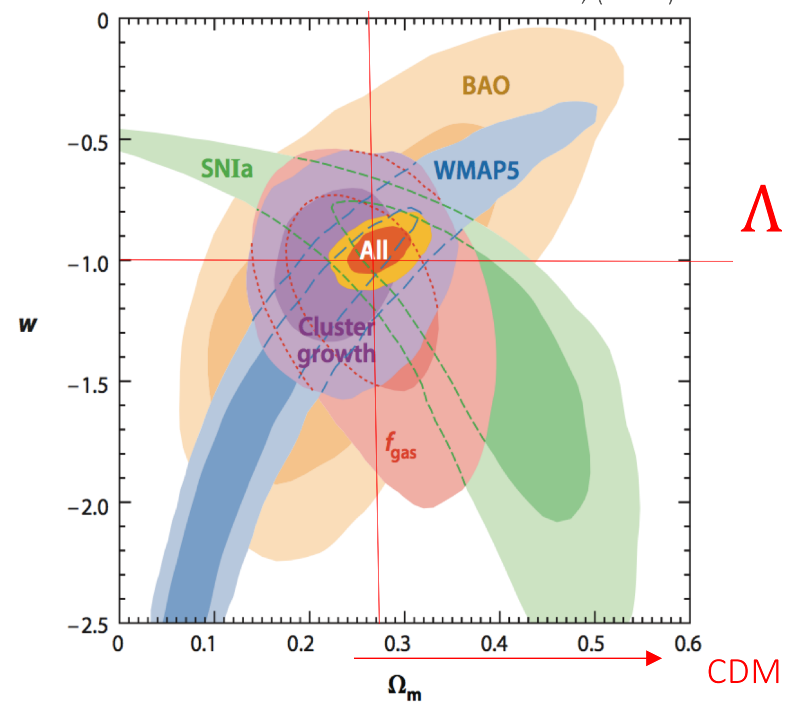


ΛCDM: Simple, yet exotic…

- **Dark matter**: collisionless, cold, presureless particle

- **Dark energy** : cosmological constant Λ drives cosmic acceleration.

Allen et al, (2013)



Challenges

Dark Energy: Λ

THEORY

- Fine tuning:

$$\rho_\Lambda^{th} = \begin{cases} 10^{76} GeV^4 \ (Planck) \\ 10^{64} GeV^4 \ (GUT) \end{cases} \quad \text{vs.} \quad \rho_\Lambda^{obs} \sim \rho_{c,0} \sim 10^{-47} GeV^4$$

- **Radiative instability**: at each order in perturbation theory, repeatedly fine tune required.

Dark Matter: Small scales

OBSERVATIONS

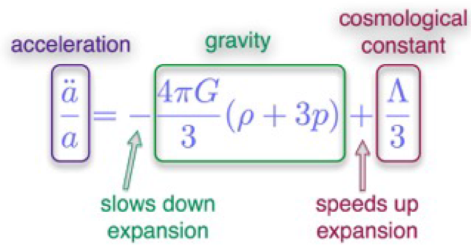
- **Galactic scales**
- Regularity/diversity of rotation curves

✓ BTFR $\quad V_f^4 = \boldsymbol{a_0} G_N M_b$

✓ Radial acceleration relation (RAR)

✓ …

Dark Energy:



- Dark Energy: new fluid with *p<0.*
- Modified Gravity

Dark Matter: Large Scales: standard cold DM particle

Small scales

$$a = \begin{cases} a_{\mathrm{N}} & a_{\mathrm{N}} \gg a_0 \\ \sqrt{a_{\mathrm{N}} a_0} & a_{\mathrm{N}} \ll a_0 \,. \end{cases}$$

Empirical force law

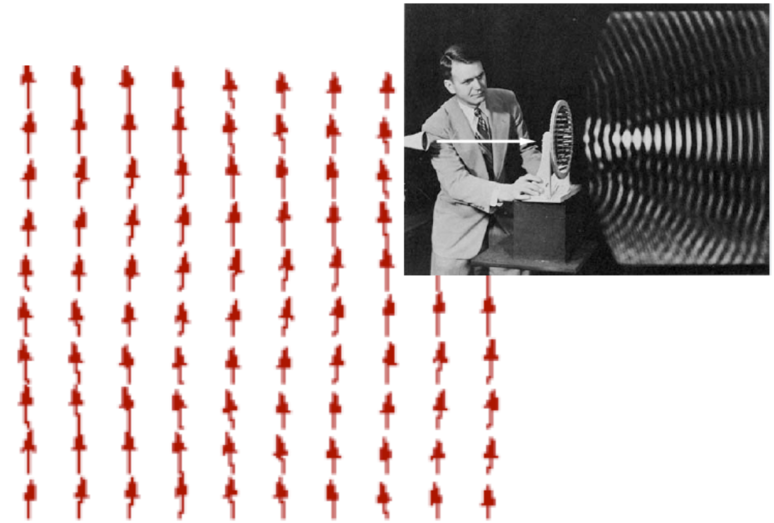
- Feedback
- MOND
- Modification of DM

Challenging to write a unified theory that describes those 3 phases.

Collective modes

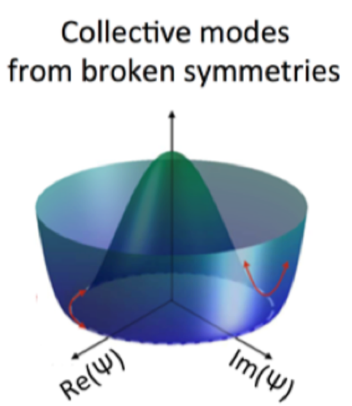
- Described by the collective behaviour of the particles.

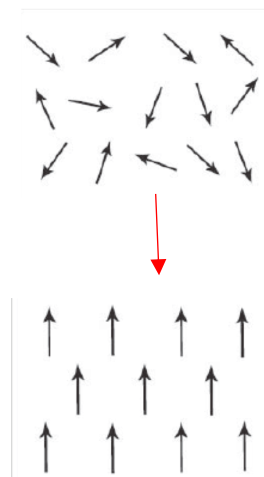
- No need for microphysics: symmetry alone describes the system.



Tom‡š Brauner

- Collective modes related to symmetry = Nambu–Goldstone bosons





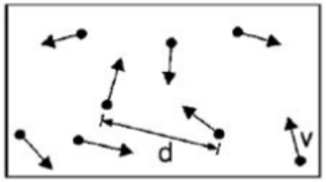
Order parameter

Effective degree of freedom

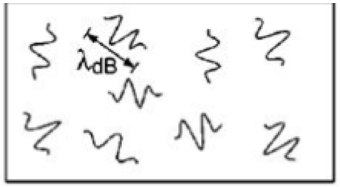
Effective dynamics

Superfluid

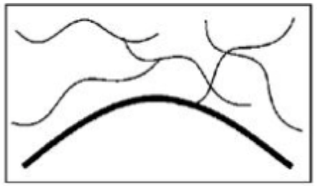
- At low temperatures, it is a superfluid when it condensates into a Bose-Einstein condensate (BEC).
- De Broglie wavelength (λ_B) of each particle is large enough that their quantum wave function overlap, and a single wave function describes the entire liquid.
- Quantum phenomenon that appears at low temperatures and macroscopic scales.
- **Effective dynamics**: fluid that can flow without friction.



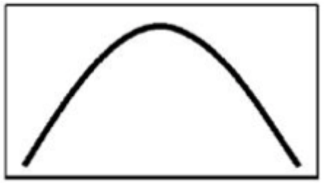
High temperature
Thermal velocities



Low temperature
$\lambda_B \sim T^{-1/2}$
"wave packets"



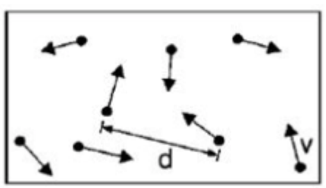
$T = T_c$
BEC
"matter wave overlap"



$T = 0$
Pure BEC
"giant matter w7ve"

Goal:

Use this property of the collective behaviour to explain the modified dynamics at certain scales/times in the evolution of the universe.



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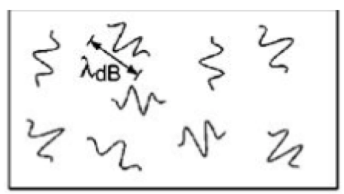

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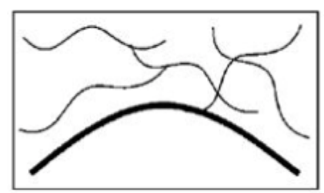

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BEC
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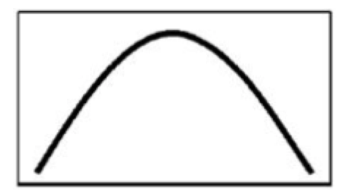


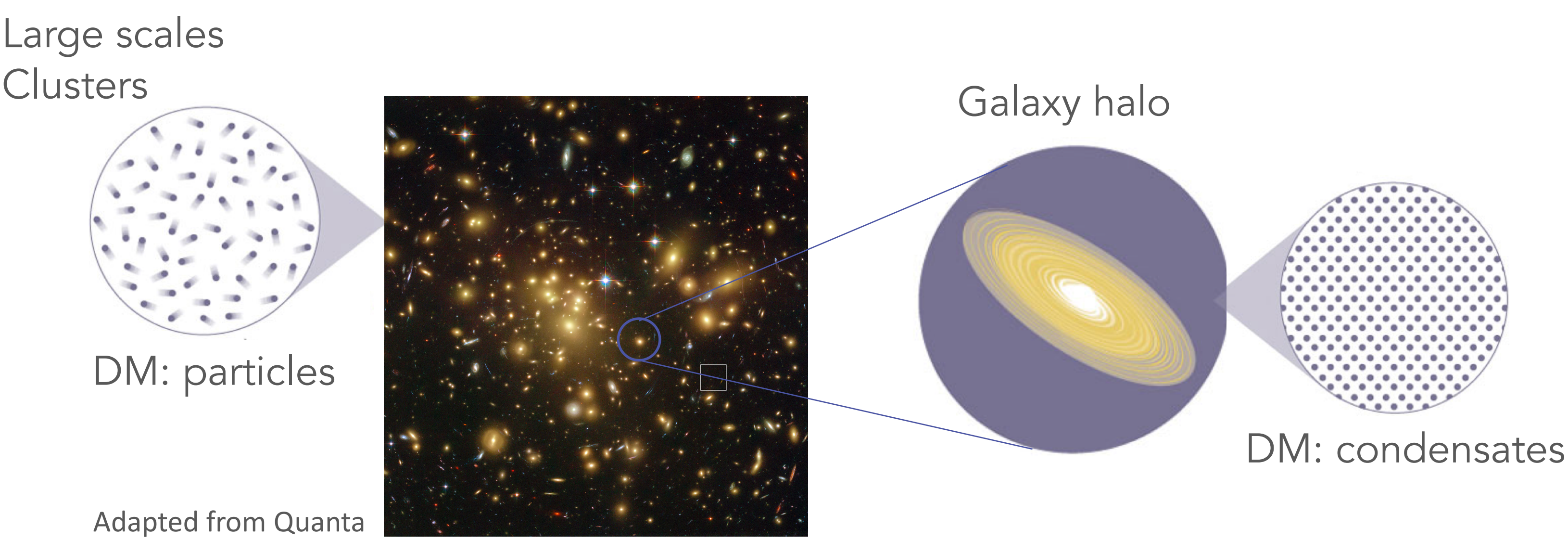
$T = 0$
Pure BEC
"giant matter wave"

Dark Matter Superfluid

Lasha, J. Khoury

DM and MOND two phases of the same substance:

- Large scales: DM behaves like standard particle dark matter.
- Galactic scales: DM forms a condensate where collective macroscopic behavior leads to the modification of the dynamics at low accelerations.



Adapted from Quanta

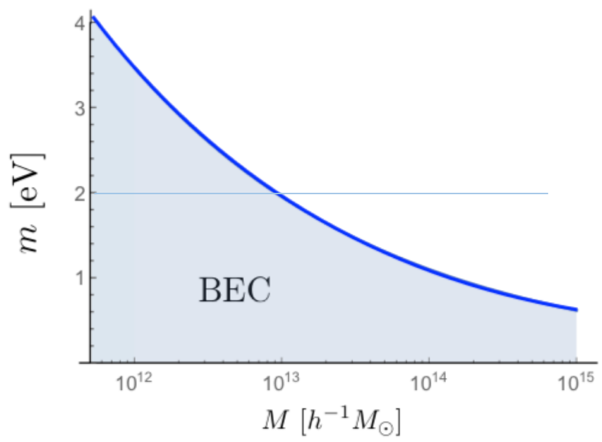
Condition for Superfluidity

- DM has to condensate in galaxies:

the de Broglie wavelength of the particles has to overlap.

$$\lambda_b \sim \frac{1}{mv} \gtrsim d \sim \left(\frac{m}{\rho_{vir}}\right)^{\frac{1}{3}}$$

$$\Longrightarrow \boxed{m \lesssim 2\ \mathrm{eV}}$$



Strongly interacting axion-like particle.
DM is cold: $T_c \sim \mathrm{mK}$

Cold atoms in the lab

$$\frac{\sigma}{m} \gtrsim 0.1\ \frac{\mathrm{cm}^2}{g}$$

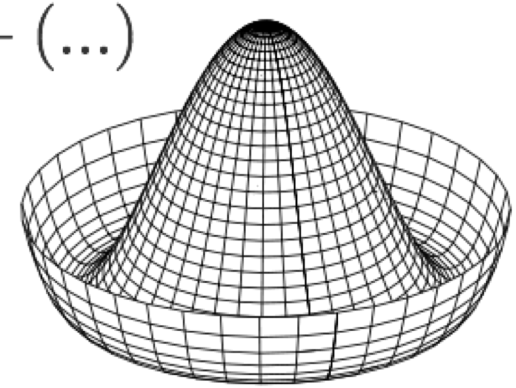
Description of the superfluid

The present context of a bosonic superfluid is a Bose Einstein condensate, in the presence of self interactions.

Effective field theory that describes a superfluid is represented by a:

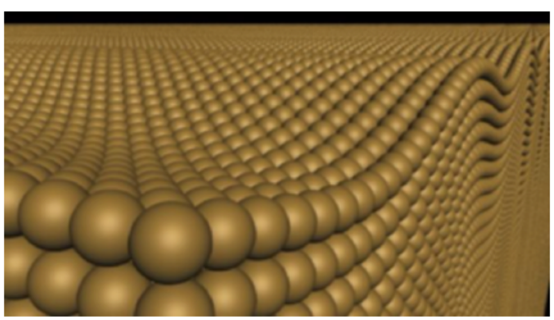
- System with a U(1) global symmetry that is spontaneously broken.

$$\mathcal{L}_0 = -|\partial\Psi|^2 - m_\Psi^2|\Psi|^2 - \frac{\lambda}{2}\Psi^4 + (\ldots)$$



Ansatz: $\Psi_{bg} = \bar{v}e^{i\bar{\mu}t}$

Excitations: $\Psi = (v+\rho)\, e^{i\overbrace{(\mu t+\pi)}^{\theta}}$



Collective excitations: massless Goldstone and massive quasi-particles.

Low energy: only θ excited - phonon

Description of the superfluid

Low energies $(\dot{\theta}/m \ll 1)$

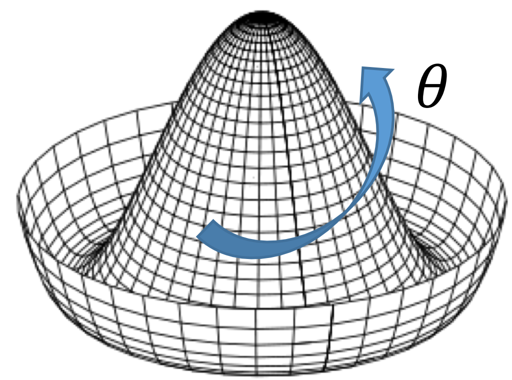
Greiter, Wilczek & Witten (1989); Son and Wingate (2005)

- Low energy DOF: Only massless Goldstone bosons excited θ

Shift symmetry $\theta \to \theta + c$

$$\theta = \mu t + \pi$$

Chemical potential ← μt; π → Phonon excitations



$c = \mu t$

In the non-relativistic regime and at lowest order in derivatives:

$$\mathcal{L} = P(X)\,, \qquad X = \dot{\theta} - m\Phi - \frac{\left(\vec{\nabla}\right)^2}{2m}\,, \qquad \dot{\theta}/m \ll 1$$

$m\Phi$: Gravitational potential

MOND from higher-derivative corrections

To describe non-relativistic DM and MOND-like:

$$\mathcal{L} = \mathcal{L}_{\rm LO} + \mathcal{L}_{\rm NLO/grav}\,.$$

Leading order:

$$\mathcal{L}_{\rm LO} = \frac{\Lambda^4}{n}\left(\frac{X}{m}\right)^n\,.$$

- n=2: $P \sim \rho^2$ - standard BEC.
- n=3/2: $P \sim \rho^3$
- n=5/2 (Unitary Fermi Gas): $P \sim \rho^{5/3}$

Next–to-leading order: Correction involving $(\vec{\nabla}X)^2 \to m^2(\vec{\nabla}\Phi)^2$ modify the kinetic term for gravity.

Symmetry breaking potential: $\mathcal{L}_{NLO/grav} = \mathcal{L}_{NLO/grav}(\vec{\nabla}\Phi)$

$$X = \dot{\theta} - m\Phi - (\vec{\nabla}\theta)^2/2m$$

OR by adding a coupling to baryons: $\mathscr{L}_{\rm int} \sim \frac{\Lambda}{M_{\rm Pl}}\theta\rho_{\rm b}$

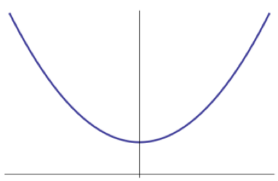
MOND from higher-derivative corrections

- Symmetry restoring: $|\vec{\nabla}\Phi| > 3a_0$

$$\mathcal{L}_{\text{NLO/grav}} \simeq -M_{\text{Pl}}^2 (\vec{\nabla}\Phi)^2$$

$$\implies \quad \boxed{\vec{\nabla}^2\Phi = \frac{\rho_s + \rho_b}{2M_{\text{Pl}}^2}}$$

Newtonian limit



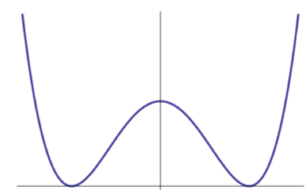
$\chi = 0$

- Symmetry breaking: $|\vec{\nabla}\Phi| < 3a_0$

$$\mathcal{L}_{\text{NLO/grav}} \simeq -\frac{2M_{\text{Pl}}^2}{3a_0}\left((\vec{\nabla}\Phi)^2\right)^{3/2} + \frac{M_{\text{Pl}}^2}{9}\frac{(\vec{\nabla}\Phi)^4}{a_0^2}$$

$$\implies \quad \boxed{\vec{\nabla}\cdot\left(\frac{|\vec{\nabla}\Phi|}{a_0}\vec{\nabla}\Phi\right) = \frac{\rho_s + \rho_b}{2M_{\text{Pl}}^2}}$$

MOND limit



$\chi = \pm\sqrt{\frac{3a_0}{|\vec{\nabla}\Phi|} - 1}$

Only DM

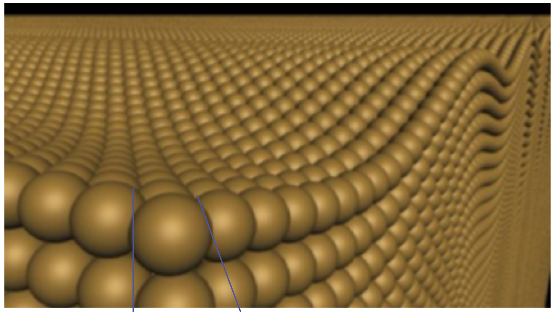
Mostly DM

"MOND"

No MOND

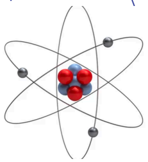
Description of the superfluid

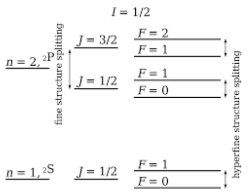
Phonon



Low energy: phonon, vibration quanta- can be understood as sound waves.

But, not the entire story…

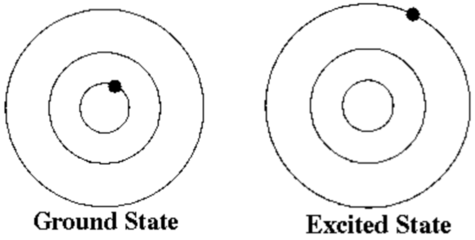




Taking a closer look into the superfluid: atoms.

Full richness of the internal DOF needs to be takes into consideration. (Out of lab!)

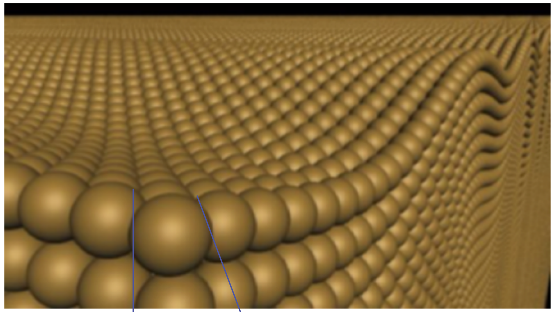
Components of the (same) superfluid can be in two distinguishable states. (Refinement)



Atoms in these states are in contact, interact!

Description of the superfluid

Phonon



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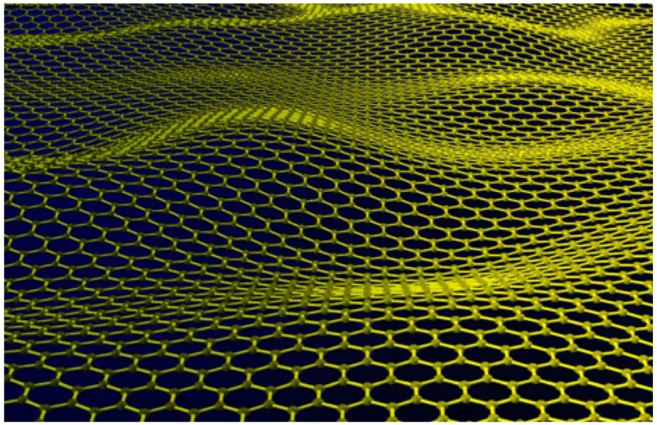

Seol Seung-kwon (2014)

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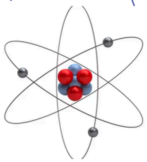
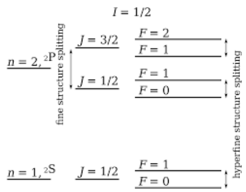


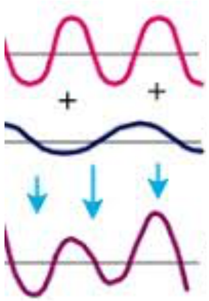


Superfluid with two distinguishable states.

Phonons that propagate with different phases for each species

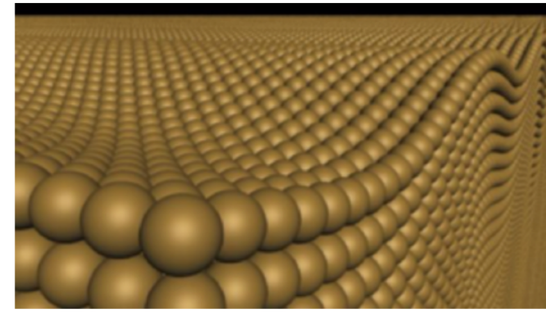
Phonons interact!
The complex field interacts!

Analogous to interference of waves



Description of the superfluid

Phonon



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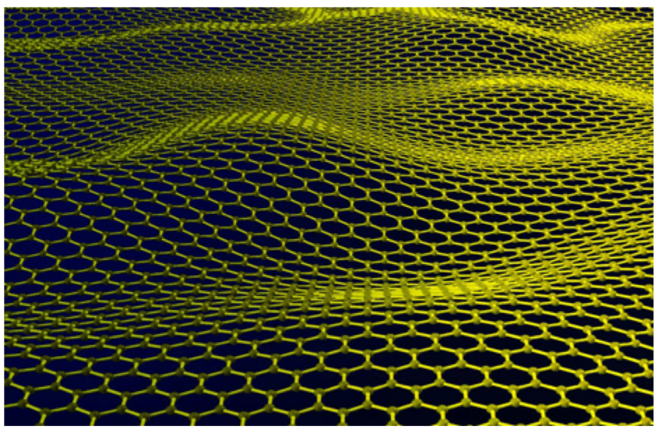


Seol Seung-kwon (2014)

Excitations in different parts of the superfluid come from different configurations or states

Phonons that propagate with different phases at different locations

E.g.: Superfluid described by the Copper pairs

Different phases of the copper pairs in different parts of the superfluid describe distinct excitations.

Description of the Superfluid

The present context of a bosonic superfluid is a Bose Einstein condensate, in the presence of self interactions.

$$\Phi = (v+\rho)e^{i(\mu_1 t+\pi)}$$
$$\Psi = (v+\bar{\rho})e^{i(\mu_2 t+\bar{\pi})}$$

Model by two superfluids: $U(1) \times U(1)$ global symmetry

$$\mathcal{L}_0 = -|\partial\Phi|^2 - m_\Phi^2|\Phi|^2 - \frac{\lambda}{2}|\Phi|^4 - |\partial\Psi|^2 - m_\Psi^2|\Psi|^2 - \frac{\sigma}{2}|\Psi|^4$$

Interaction: breaks $U(1)\times U(1) \longrightarrow U_r(1)$

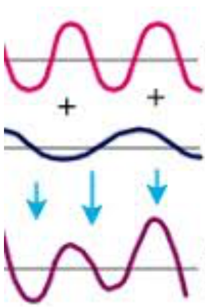
$$\mathcal{L}_{int} = -\alpha\frac{\Phi^*\Psi + \Psi^*\Phi}{|\Phi|\,|\Psi|}$$

Josephson or Rabi coupling:
- Contact interaction;
- Long-range phase coherence b/ components;
- Conversion of species.

Low-energies: $\Theta_2 - \Theta_1$

$$\mathcal{L} = P(X_1) + P(X_2) + 2\alpha\cos(\Theta_2 - \Theta_1)$$

Analogous to interference of waves $\Longrightarrow$ depends only on angle difference



Ref: P. Tommasini, E. J. V. de Passos, A. F. R. de Toledo Piza, and M. S. Hussein, PRA 67

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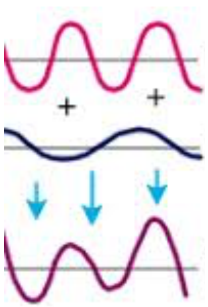

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- From condensed matter:
  - Josephson tunneling
  - Iron-based superconductors
  - MgB2
  - High Tc cuprate superconductor
  - XY model

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1: Ground state
2: Excited state

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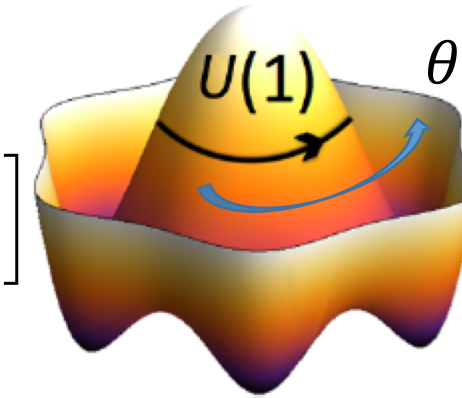
Well motivated to have a potential term!
Can this potential drive accelerated expansion?

Unified Dark Energy/Dark Matter Superfluid
Low energy effective description

- Massless Goldstone bosons θ_i, non-relativistic regime $\Rightarrow \quad \dot{\theta}/m \ll 1$

$$\mathcal{L} = \sum P(X_i) - V(\theta_2 - \theta_1 + \Delta E t)$$
$$= \sum \frac{\Lambda^4}{n}\left(\frac{X_i}{m_i}\right)^n - \frac{M^4}{2}\left[1 + \cos\left(\frac{\theta_2 - \theta_1 + \Delta E t}{f}\right)\right]$$



- Oscillatory potential is well motivated from the fundamental description and phenomenologically: $X = \dot{\theta} - m\Phi - (\vec{\nabla}\theta)^2/2m$

$\Rightarrow$ Breaks shift symmetry weakly into a discrete symmetry.

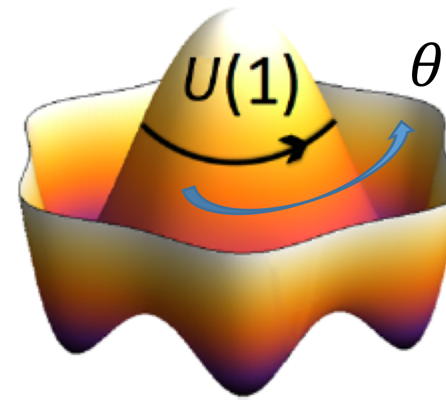
- Still protects the potential from quantum corrections.
- Suppresses fifth forces: naturally screened DE (and DM).

Analogous to a pNGB potential in θ. Frieman et al 1995

Unified Dark Energy/Dark Matter Superfluid
Low energy effective description

- Massless Goldstone bosons θ_i, non-relativistic regime $\Rightarrow \dot{\theta}/m \ll 1$

$$\mathcal{L} = \sum P(X_i) - V(\theta_2 - \theta_1 + \Delta E t)$$
$$= \sum \frac{\Lambda^4}{n}\left(\frac{X_i}{m_i}\right)^n - \frac{M^4}{2}\left[1 + \cos\left(\frac{\Delta E t}{f}\right)\right]$$



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$\Rightarrow$ Breaks shift symmetry weakly into a discrete symmetry.

- Still protects the potential from quantum corrections.
- Suppresses fifth forces: naturally screened DE (and DM).

Analogous to a pNGB potential in θ.

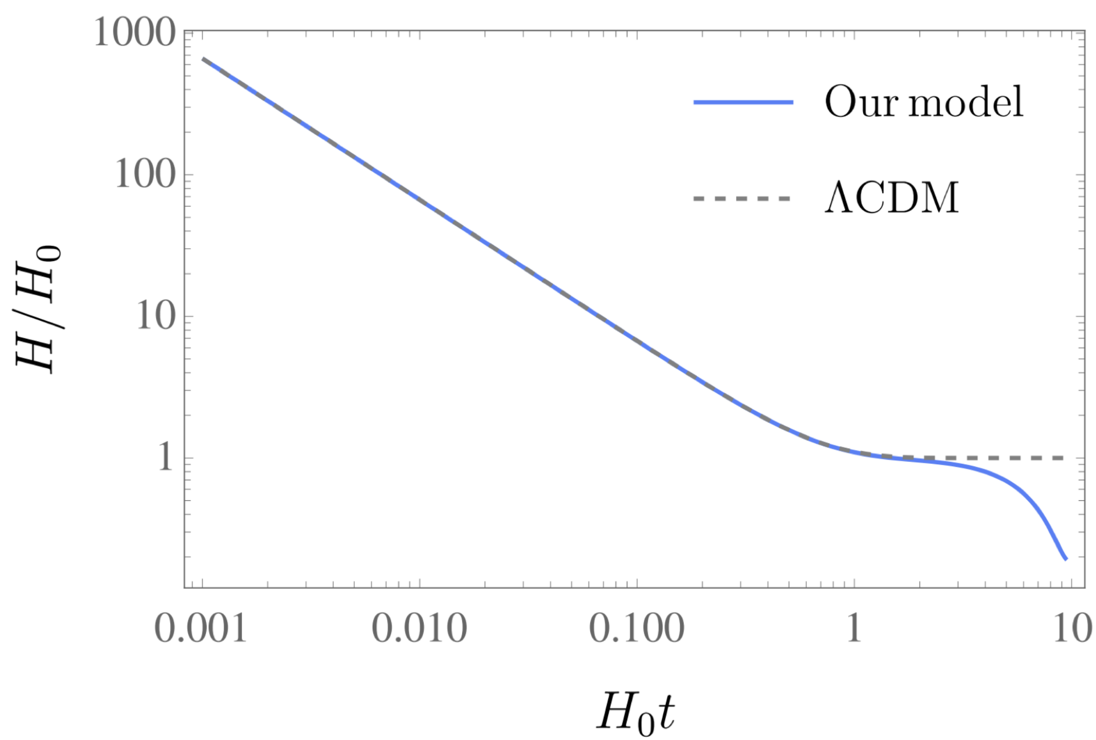
Valid for any *P(X)*!

$$H_{init} \ll \Delta E \ll m_i$$

Background Evolution

In a FRW universe, for any *P(X)* superfluid in the NR limit:

$$2\dot{H} + 3H^2 = \frac{V(\Delta E\, t)}{M_{\rm Pl}^2}$$



Equation of state

$$w = \frac{p}{\rho} = \frac{\sum \frac{\Lambda^4}{n} \left(\frac{\dot{\theta}_i}{m_i}\right)^n - V(\Delta E\, t)}{\sum \frac{\Lambda^4}{n} \left(\frac{\dot{\theta}_i}{m_i}\right)^{n-1} + V(\Delta E\, t)}$$

For $1 < n \leq 2$:

- As $\dot{\theta}$ decays $\longrightarrow$ Past: kinetic term dominates;
  Late times: potential term dominates.

Equation of state

$$w = \frac{p}{\rho} = \frac{\frac{\Lambda^4}{n}\left(\frac{\dot{\theta}}{m}\right)^n}{\Lambda^4\left(\frac{\dot{\theta}}{m}\right)^{n-1}}$$

Past

For $1 < n \leq 2$:

- As $\dot{\theta}$ decays $\longrightarrow$ Past: kinetic term dominates;
  Late times: potential term dominates.
- Pressure has a higher power of $\dot{\theta}/m$ than the energy density. So, in the regimes where the kinetic term dominates (past):

$$w \to \frac{\dot{\theta}}{m} \ll 1$$

$\Rightarrow$ Dark matter!

Equation of state

$$w = \frac{p}{\rho} = \frac{\sum \frac{\Lambda^4}{n}\left(\frac{\dot{\theta}_i}{m_i}\right)^n}{\sum \frac{\Lambda^4}{n}\left(\frac{\dot{\theta}_i}{m_i}\right)^{n-1}}$$ Past

For $1 < n \leq 2$:

- As $\dot{\theta}$ decays $\longrightarrow$ Past: kinetic term dominates;
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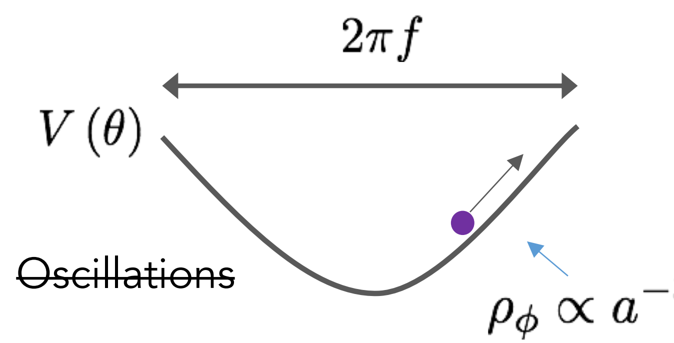
- Pressure has a higher power of $\dot{\theta}/m$ than the energy density.

$$w \to \frac{\dot{\theta}}{m} \ll 1$$

Dark matter!

* Naturally provides an EoS of matter- "Overdamped"
* No damped oscillations around the minimum of the potential, e.g., spintessence, pNGB, …



* It will always have small EoS and decaying, until potential term makes it negative.

Equation of state

$$w = \frac{p}{\rho} = \frac{\sum \frac{\Lambda^4}{n}\left(\frac{\dot{\theta}_i}{m_i}\right)^n}{\sum \frac{\Lambda^4}{n}\left(\frac{\dot{\theta}_i}{m_i}\right)^{n-1}}$$ Past

For $1 < n \leq 2$:

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  Late times: potential term dominates.
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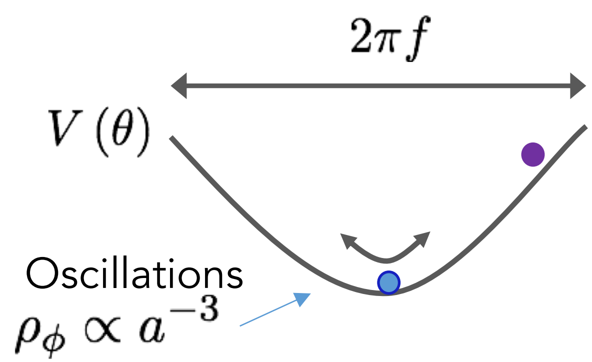

Equation of state

$$w = \frac{p}{\rho} = \frac{\sum \frac{\Lambda^4}{n}\left(\frac{\dot{\theta}_i}{m_i}\right)^n - V(\Delta E\, t)}{\sum \frac{\Lambda^4}{n}\left(\frac{\dot{\theta}_i}{m_i}\right)^{n-1} + V(\Delta E\, t)}$$

For $1 < n \leq 2$:

- As $\dot{\theta}$ decays, the kinetic term will be important in the past and the potential term at late times.
- Pressure has a higher power of $\dot{\theta}/m$ than the energy density. So, in the regimes where the kinetic term dominates (past):

$$w \to \frac{\dot{\theta}}{m} \ll 1$$

Dark matter!

- As $\dot{\theta}$ decays, when the potential term dominates we can have an EoS of acceleration, denoting the dark energy.

Parameter Constraint

Free parameters: m, Λ, M and f.

Initial condition:
matter-radiation equality

$$\rho_{eq} \simeq 0.4\,\mathrm{eV}^4$$

$$c_{s,i} \ll 10^{-6}$$

n=2: $$\Lambda_i = 500\,eV$$

Slow-roll: possible solution where V >> K, for n=2 :

$$f_\chi \sim 10^{-2} M_{pl}$$

Constraint

Final condition: H_0 constraints M

$$M \sim meV$$

Superfluid condition

$$m \sim eV$$

$$\Delta E \sim 10^{-11}\,eV$$

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constraints M

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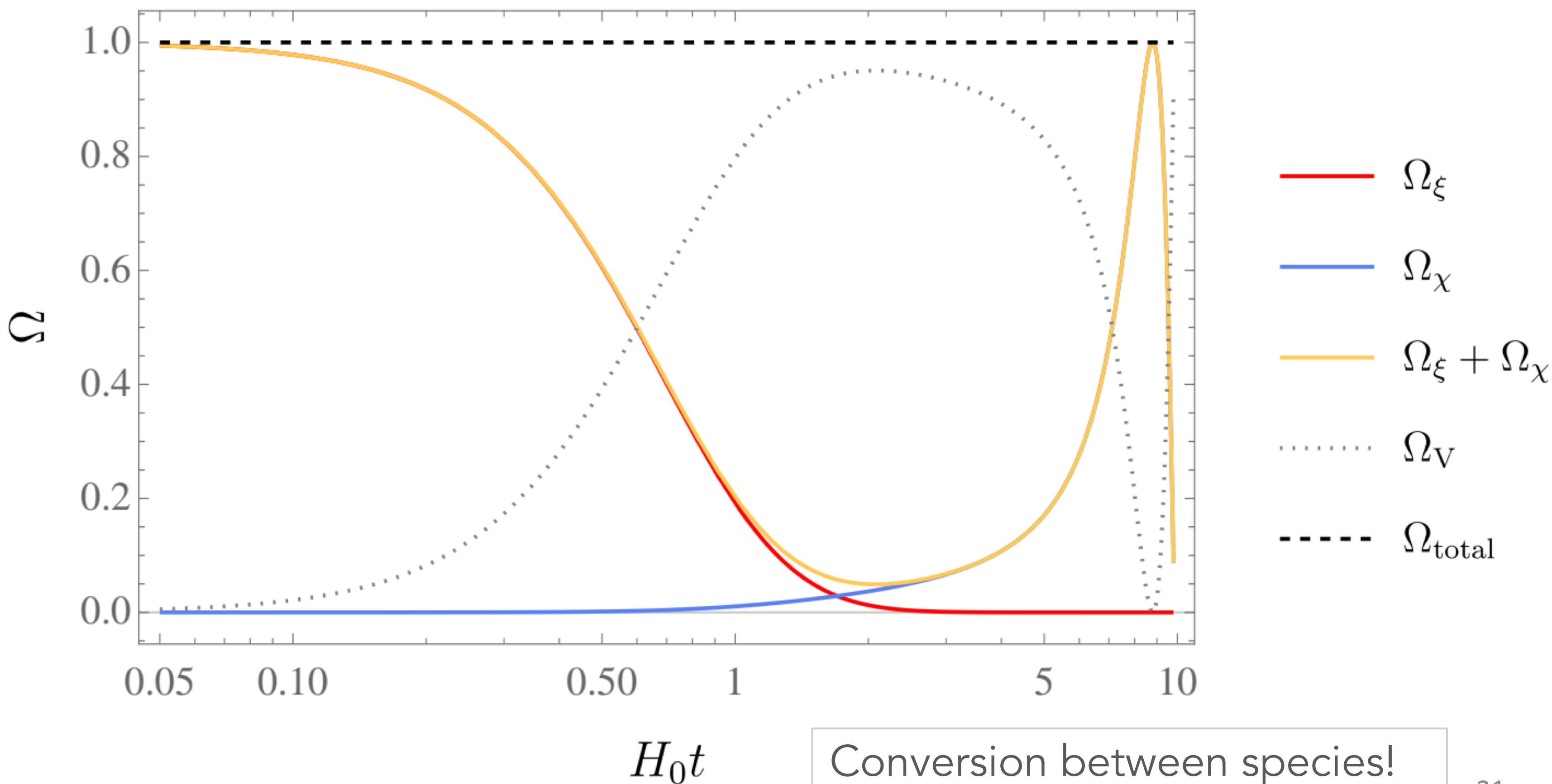
Densities Evolution

Initial condition (eq): All DM in the ground state (θ_1) at eq.

Production mechanism: for sub-eV DM out of equilibrium

$$H \sim m = eV,\ z_{prod} \sim 10^{16} \Rightarrow T_{prod} \sim eV$$

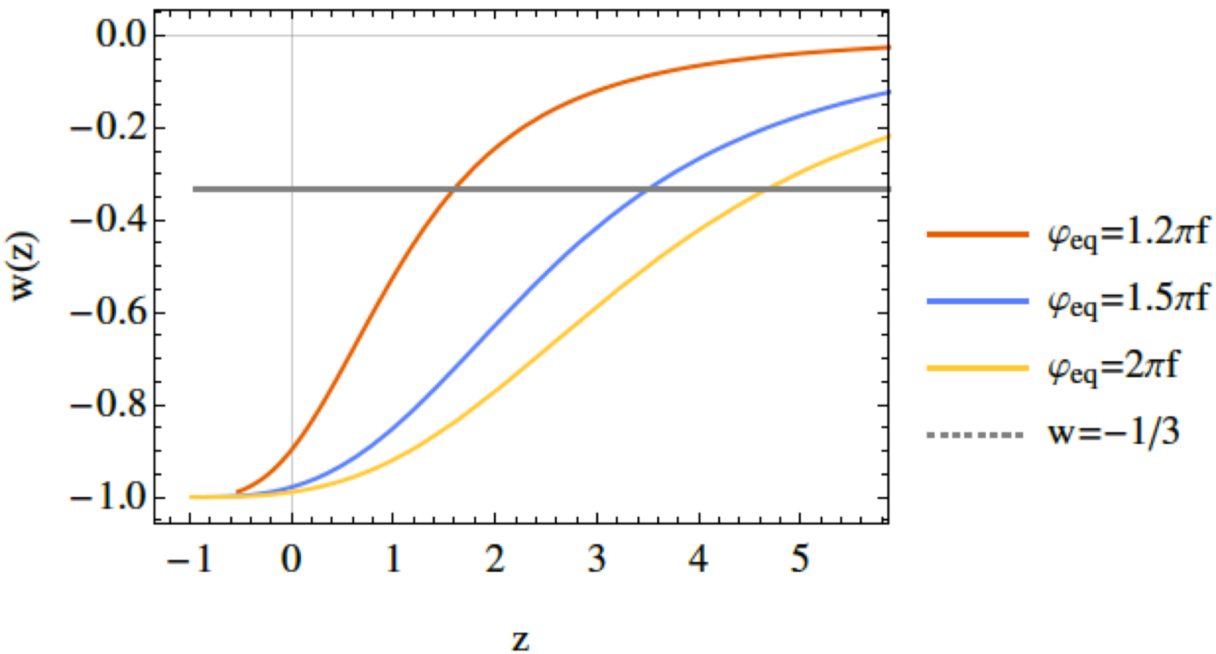
At eq.: $T_{eq}^{dm} \sim 10^{-26}\,\mathrm{eV} \Rightarrow$ $T_{eq}^{dm} \ll \Delta E$



Conversion between species!

Equation of state

$$w = \frac{p}{\rho} = \frac{\sum \frac{\Lambda^4}{n}\left(\frac{\dot{\theta}_i}{m_i}\right)^n - V(\Delta E\, t)}{\sum \frac{\Lambda^4}{n}\left(\frac{\dot{\theta}_i}{m_i}\right)^{n-1} + V(\Delta E\, t)}$$

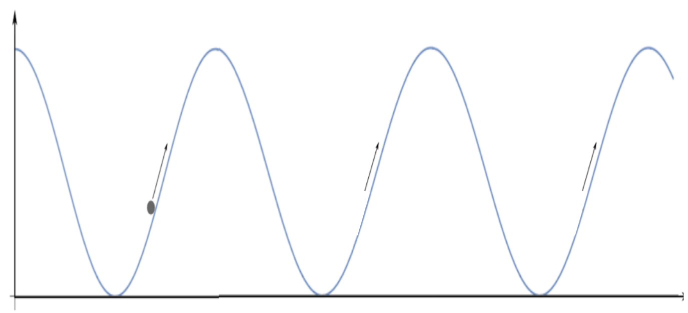


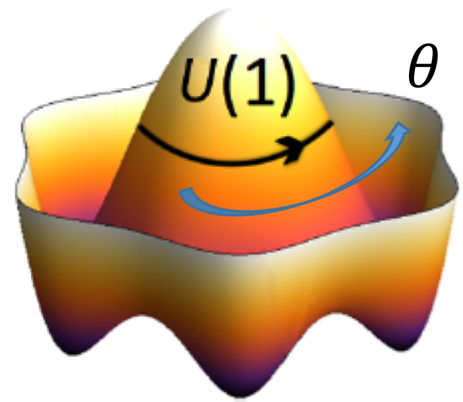
- Apparently it does not depend too much on the initial conditions: gets acceleration today – different instance to the coincidence problem. (Ongoing analysis)
- Exception: bottom of the potential $(2n+1)\pi f$ - takes too long to accelerate

Cosmological Evolution

- Radiation: $\dot{\theta}/m \sim 1$ (not described by the NR theory)

Field rotates fast for many cycles and does not feel the potential.





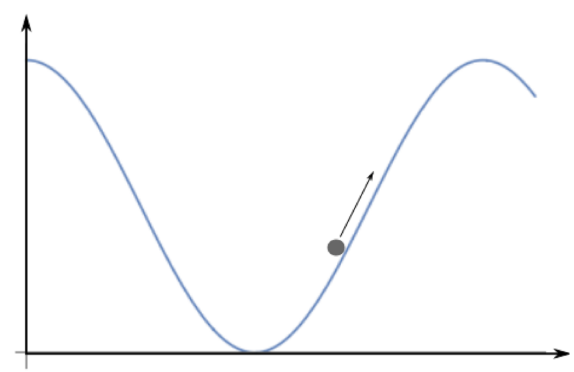
Cosmological Evolution

- Radiation: $\dot{\theta}/m \sim 1$ (not described by the NR theory)

Field rotates fast for many cycles and does not feel the potential.

- Matter: $\dot{\theta}/m \ll 1$.

Kinetic term dominates with $w \to \frac{\dot{\theta}}{m} \ll 1$



Cosmological Evolution

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Field rotates fast for many cycles and does not feel the potential.

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Kinetic term dominates with $w \to \frac{\dot{\theta}}{m} \ll 1$

- Dark Energy: $V(\theta)$ dominates.

Cosmological Evolution

Radiation

t_{eq}

Matter

$t_{dm/de}$

Dark Energy

- Radiation: $\dot{\theta}/m \sim 1$ (not described by the NR theory)

Field rotates fast for many cycles and does not feel the potential.

- Matter: $\dot{\theta}/m \ll 1$

Kinetic term dominates with $w \to \frac{\dot{\theta}}{m} \ll 1$

- Dark Energy: $V(\theta)$ dominates.

Small scales: gradients important
DM behaviour on galactic scales

Cosmological Evolution

FUTURE

Acceleration

- Dark Energy: $V(\theta)$ dominates.

Matter

- Matter: $\dot{\theta}/m \ll 1$

Kinetic term dominates with $w \to \dfrac{\dot{\theta}}{m} \ll 1$

$t_{dm/de}$

Dark Energy

- Dark Energy: $V(\theta)$ dominates.

Perturbations

Viable alternative to the ΛCDM :should be able to describe the growth of density perturbations that leads to the structures we observe.

Linear Newtonian perturbation theory

Neglecting gradients

$$\boxed{\ddot{\delta} + \left(2H - \frac{\Delta E\, V'}{\bar{\rho}}\right)\dot{\delta} = \frac{1}{2M_{\rm Pl}^2}\bar{\rho}\,\delta + \frac{\Delta E\, V'}{\bar{\rho}}\left(5H + \frac{\Delta E\, V'}{\bar{\rho}}\right)\delta\,.}$$

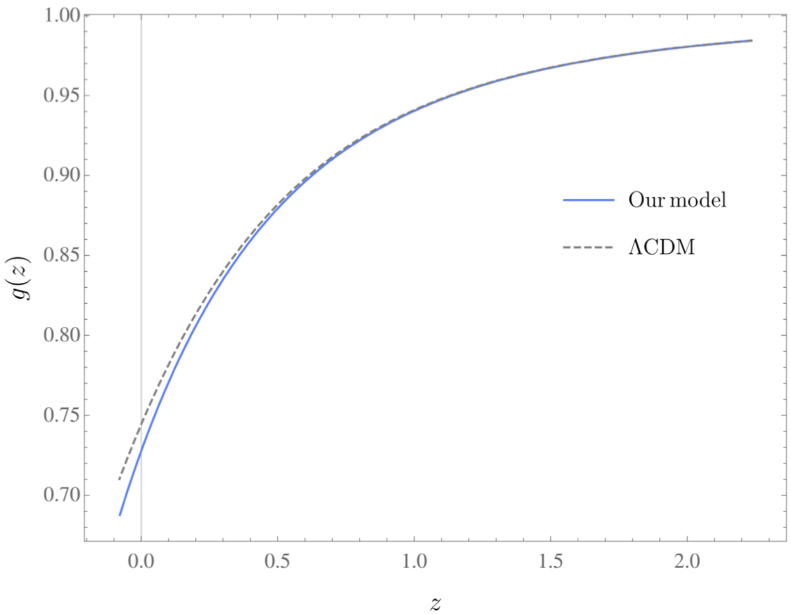
n=2: $$c_{s,i}^2 = \frac{\theta_i}{m} \ll 1$$

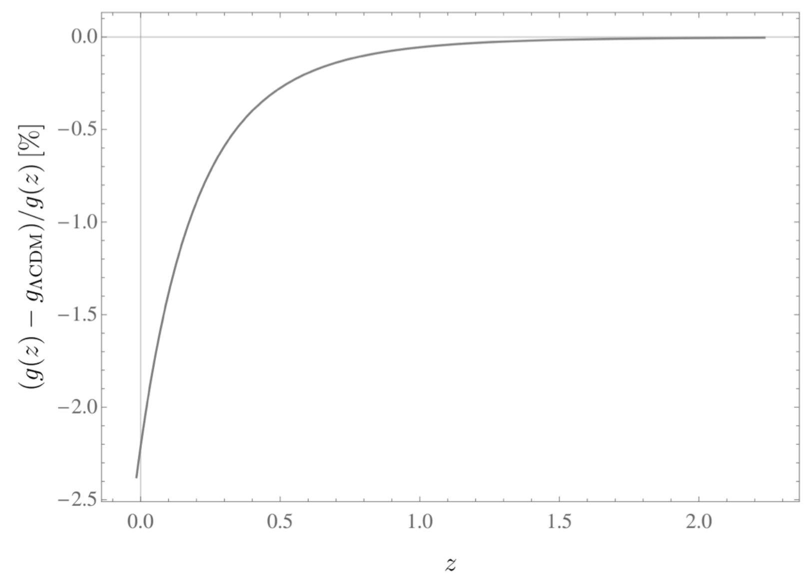
Observational Signatures

- **Clustering: growth factor**

Clustering in a model where the varying sound speed, dynamical evolution.

Growth function $$g(z) = \frac{1+z}{1+z_{\rm eq}} \frac{\delta(z)}{\delta_{\rm eq}}$$





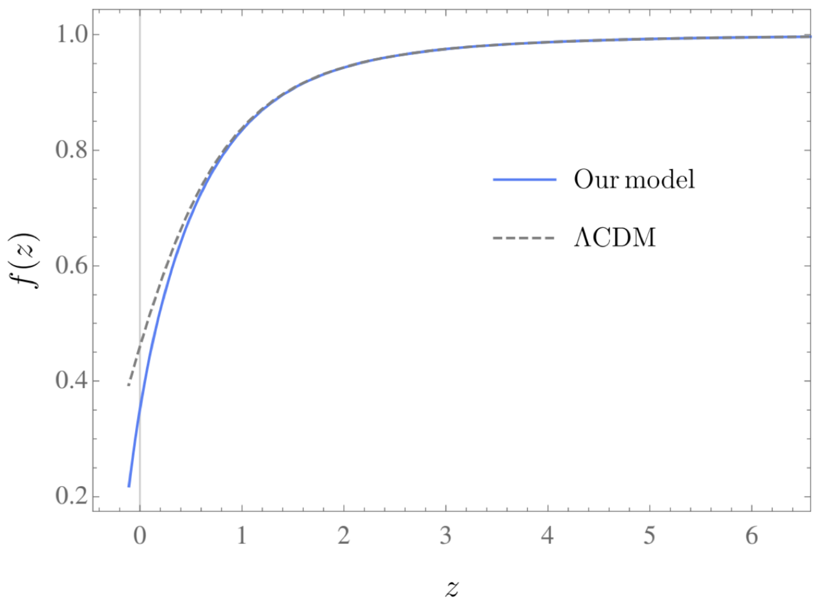
- Small suppression of density perturbation growth.
- > 2.0% difference

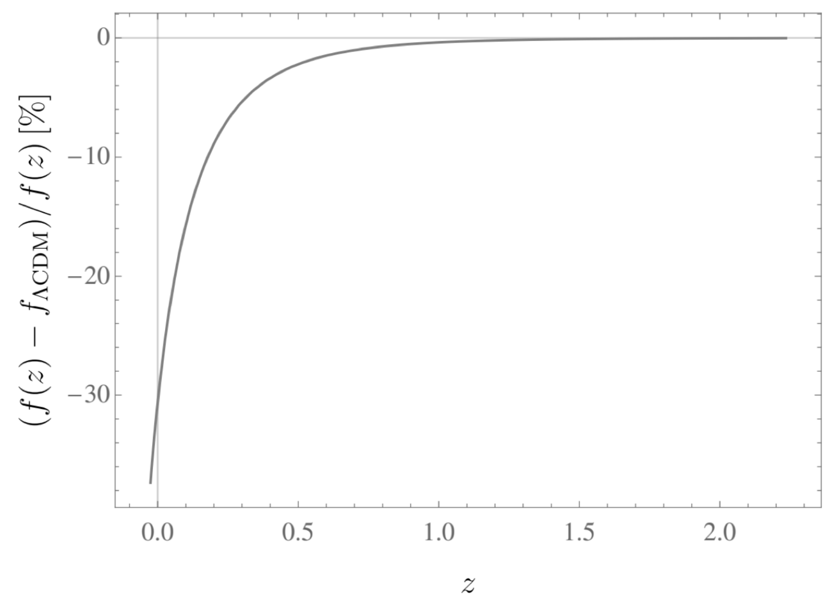
Observational Signatures

- **Clustering: growth factor**

Clustering in a model where the varying sound speed, dynamical evolution.

Growth rate $$f(z) \equiv -\frac{d\ln\delta(z)}{d\ln(1+z)} = 1 - \frac{d\ln g(z)}{d\ln(1+z)}$$





- Steeper suppression of density perturbation growth.
- > 30.0% difference from ΛCDM

Summary

- New model that unifies the large scale CDM, MOND and dark energy in a single framework using the physics of superfluidity.
- Only needs the presence of DM in the form of a superfluid.
- The theory is found in analogue condensed matter system that motivates the origin and the choice of potential.
- Observational signatures:
  Predicts: 30% deviation in the growth rate from ΛCDM.

Future

- Local DE contribution

  Soon after production, DM becomes superfluid

$$\left(\frac{T}{T_c}\right)_{\rm cosmo} \simeq 10^{-28} \qquad vs \qquad \left(\frac{T}{T_c}\right)_{\rm MW} \simeq 10^{-2}$$

→ Difference abundance of ground and excited states

→ Different local acceleration in galaxies?

- Hydrodynamical simulations (Illustris – Prof. Volker Springel) – solve Gross-Pitaevskii equation.

- Observational signatures
  - Clustering, halo abundance and cluster counts
  - Non-linear regime
  - Effects from the new description of DM: vortices; …

- Dynamical M;

Thank you!

Phenomenological consequences of SfDM

Sf phonon coupled to baryonic matter

Lasha Berezhiani, Benoit Famaey, Justin Khoury, 1711.05748

- Rotation curves of both high and low surface brightness galaxies can be reproduced
  - Slightly rising rotation curve at large radii in massive high surface brightness galaxies -> subtly different from Milgrom's law
- Expected differences with Milgrom's law
  - Dwarf spheroidal satellite galaxies, tidal dwarf galaxies, and globular clusters -> Milgromian or Newtonian behavior depends on the position with respect to the

superfluid core of the host galaxy.

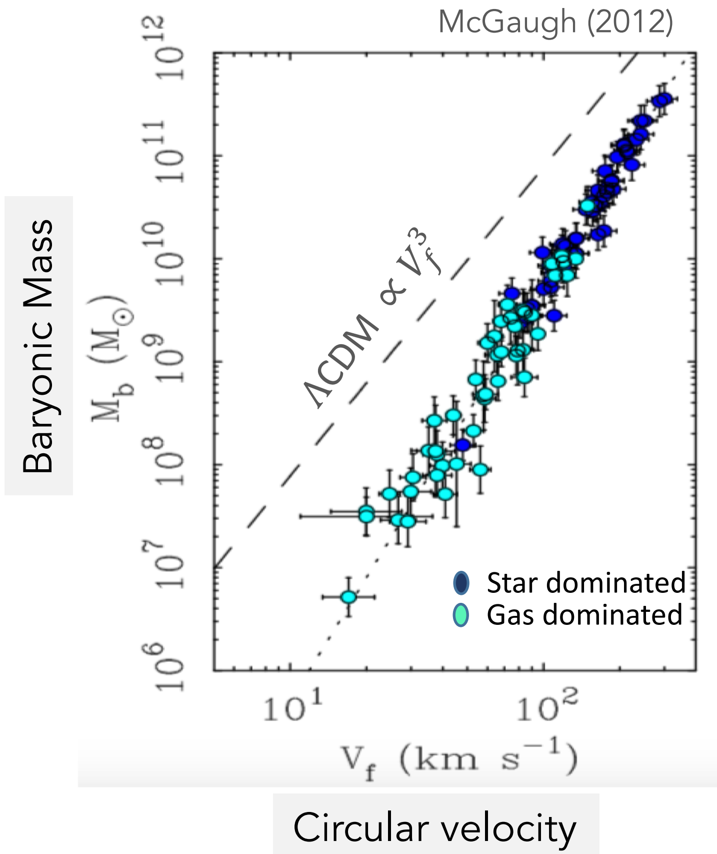
  - Ultra-diffuse galaxies within galaxy clusters to have velocities slightly above the BTFR.
- Photons and gravitons follow the same geodesics, and that galaxy-galaxy lensing, probing larger distances within galaxy halos than rotation curves, should follow predictions closer to the standard cosmological model than those of Milgrom's law.

Small Scale Challenges
Galaxies

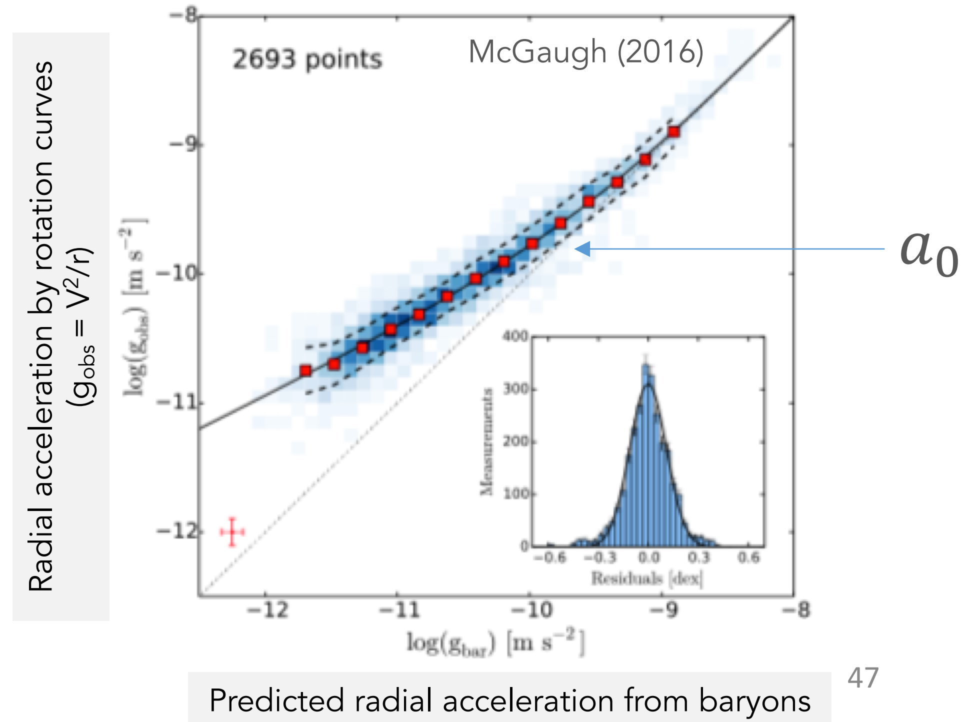
- Baryonic Tully Fisher Relation (BTFR)

Remarkably tight scaling relations between dynamical and baryonic properties.

$$a_0 \simeq \frac{1}{6} H_0 \simeq 1.2 \times 10^{-8}\ \mathrm{cm/s^2} = 2.7 \times 10^{-34}\ \mathrm{eV}\,.$$



- Radial acceleration relation (RAR)



MOND from higher-derivative corrections

To describe non-relativistic DM and MOND-like:

$$\mathcal{L} = \mathcal{L}_{\rm LO} + \mathcal{L}_{\rm NLO/grav}\,.$$

Leading order:

$$\mathcal{L}_{\rm LO} = \frac{\Lambda^4}{n}\left(\frac{X}{m}\right)^n\,.$$

- n=2: $P \sim \rho^2$ - standard BEC.
- n=3/2: $P \sim \rho^3$
- n=5/2 (Unitary Fermi Gas): $P \sim \rho^{5/3}$

Next–to-leading order: Correction involving $(\vec{\nabla}X)^2 \to m^2(\vec{\nabla}\Phi)^2$ modify the kinetic term for gravity.

$$\mathcal{L}_{\rm NLO/grav} = -\frac{1}{2}Z^2(\partial\chi)^2 - M_{\rm Pl}^2(\vec{\nabla}\Phi)^2\left(\frac{1}{1+\chi^2} + \frac{(\vec{\nabla}X)^2}{9m^2a_0^2}\chi^2\right)\,.$$

Symmetry is broken or not depending on the sign of the mass at $\chi = 0$

$$m_\chi^2 = \left.\frac{{\rm d}^2V}{{\rm d}\chi^2}\right|_{\chi=0} = 2M_{\rm Pl}^2(\vec{\nabla}\Phi)^2\left(-1 + \frac{(\vec{\nabla}\Phi)^2}{9a_0^2}\right)$$

Dark Matter Superfluid: Cosmology

Axion-like $m \sim \text{eV}$ →

- Must be produced out of equilibrium.
- Decoupled from ordinary matter throughout the cosmological history.
- Self-interactions: reaches thermal equilibrium at $T \ll T_{\gamma b} \implies$ superfluid!
- Cosmologically it remains superfluid forever after.

<u>Relativist Completion</u>

$$V(\chi) = -M_{\rm Pl}^2 \left\{ \frac{R}{2} - \left(\frac{2}{3}\Box n + \frac{\Box \mathcal{Y}}{m^2} \right) \right\} F$$

$$\begin{cases} \Theta = mt + \theta \\ \mathcal{Y} = -\frac{1}{2}(\partial\Theta)^2 \simeq \frac{m^2}{2} + mX \end{cases}$$

⇒

$$m_\chi^2 = 3H^2 M_{\rm Pl}^2 \left(1 + \frac{\dot{\mathcal{Y}}^2}{9m^4 a_0^2} \right)$$

Always positive!

Cosmologically: always in the Einstein-gravity, symmetry-restoring phase

⇓

Background expansion history and linear growth of perturbations indistinguishable from ΛCDM.

Long Range Forces

Dangerous terms like

$$\mathcal{L} \propto M\,\bar{\psi}\psi$$

are forbidden by the (discrete) shift symmetry.

Allowed terms

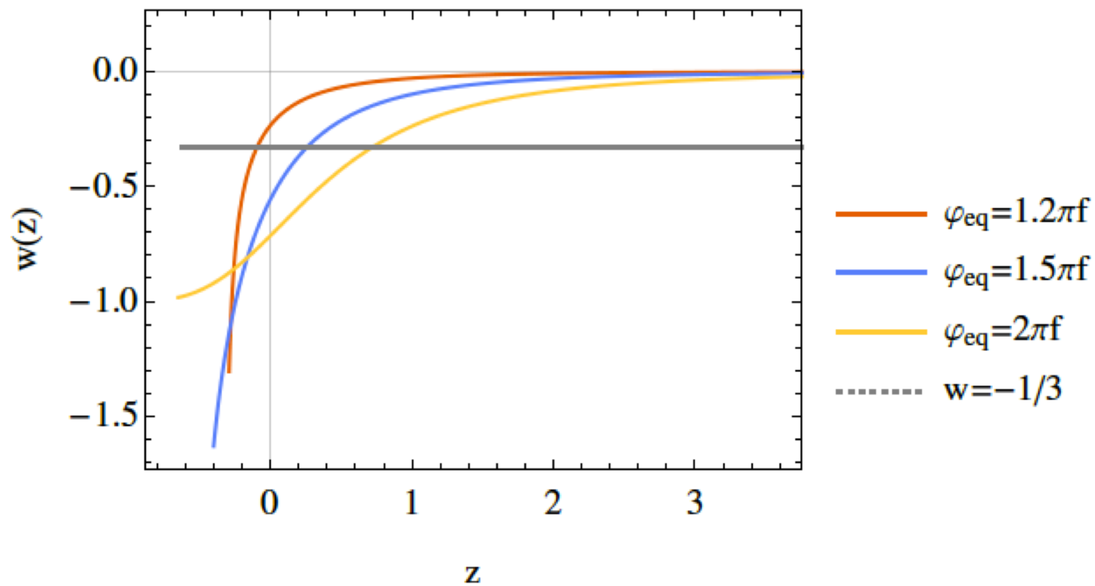
$$\delta\mathcal{L} \sim \beta' \frac{\partial_\mu \phi}{M_P} \bar{\psi}\gamma^\mu \gamma^5 \psi$$

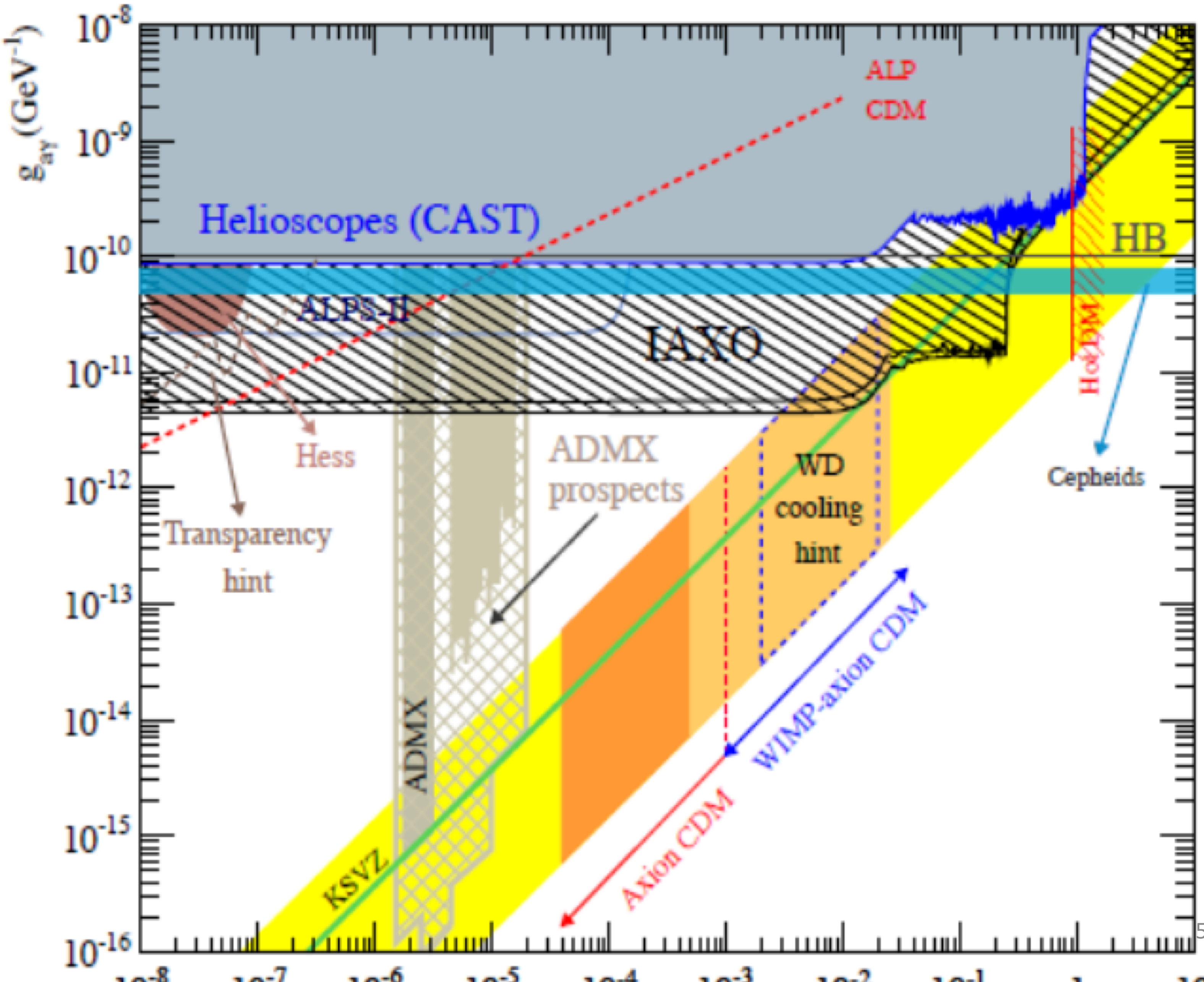
$$\mathcal{L} \supset \sum_{i=1}^{N} \alpha \frac{\phi_i}{4\,M_P} F_{\mu\nu}\tilde{F}^{\mu\nu}$$

Numerical Analysis

- Phantom Dark Energy $f = 10^{33}\,,\qquad \Lambda \sim 5\text{eV}$

Equation of state




$g_{a\gamma}$ (GeV^{-1})
Helioscopes (CAST)
ALP
CDM
HB
ALPS-II
IAXO
Hot DM
Hess
Transparency
hint
ADMX
prospects
WD
cooling
hint
Cepheids
ADMX
KSVZ
Axion CDM
WIMP-axion CDM