Alternatives to Dark Matter: Ultra-Light Fields

Elisa Ferreira

Max Planck Institute for Astrophysics

EF, *"Alternatives to Dark Matter: Ultra-Light Fields",* The Astronomy and Astrophysics Review, to appear.

Preview: *elisagmferreira.com/dmreview*

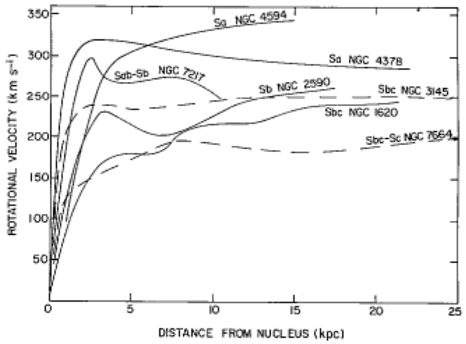
Cosmic Acceleration
IPMU, February 2020

Image: Markos Kay for Quanta Magazine

Dark Matter

Dark matter from all scales

Galaxies

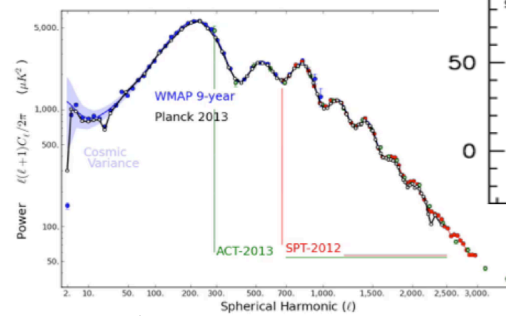


Rubin, Ford, Thornnard (1978)

Clusters

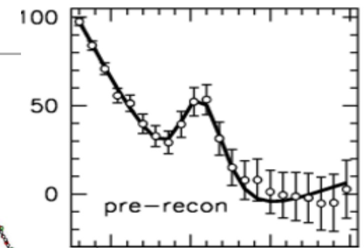
NASA, ESA, CXC, M. Bradac and S. Allen

Large scales



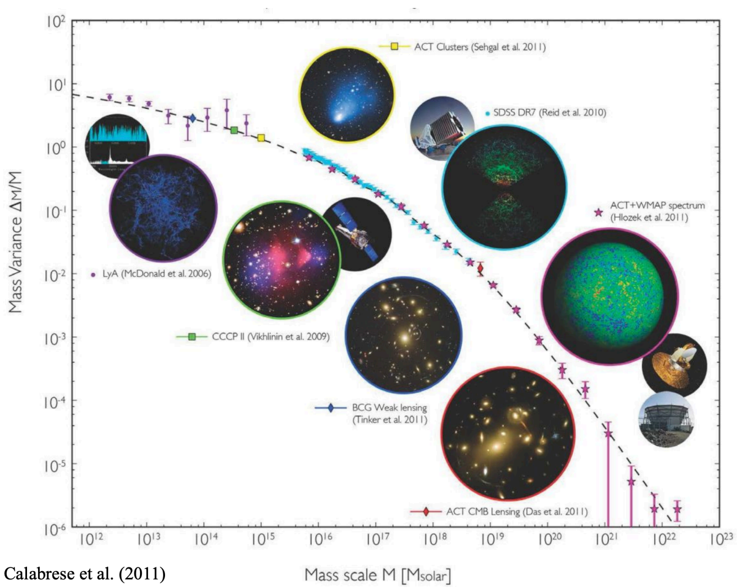
Spergel

Anderson et al (2013b)



+ Gravitational lensing
+ Ly-α ; + heating clusters
+ …

Large scales: ΛCDM, a remarkable success



Calabrese et al. (2011)

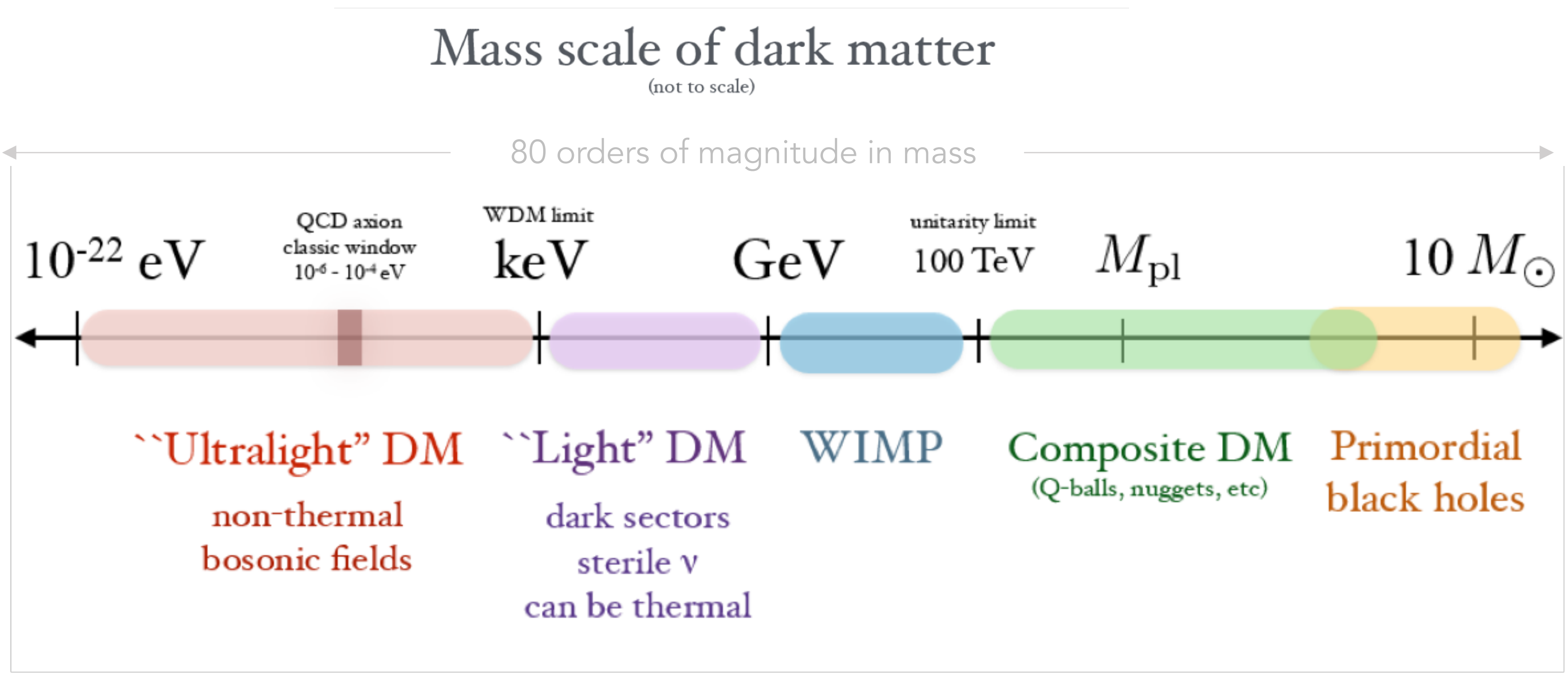
- DM: Cold Dark Matter (CDM)

CDM is described as a fluid which is

- Cold
- Pressure-less
- Massive
- Collision-less
- Dark

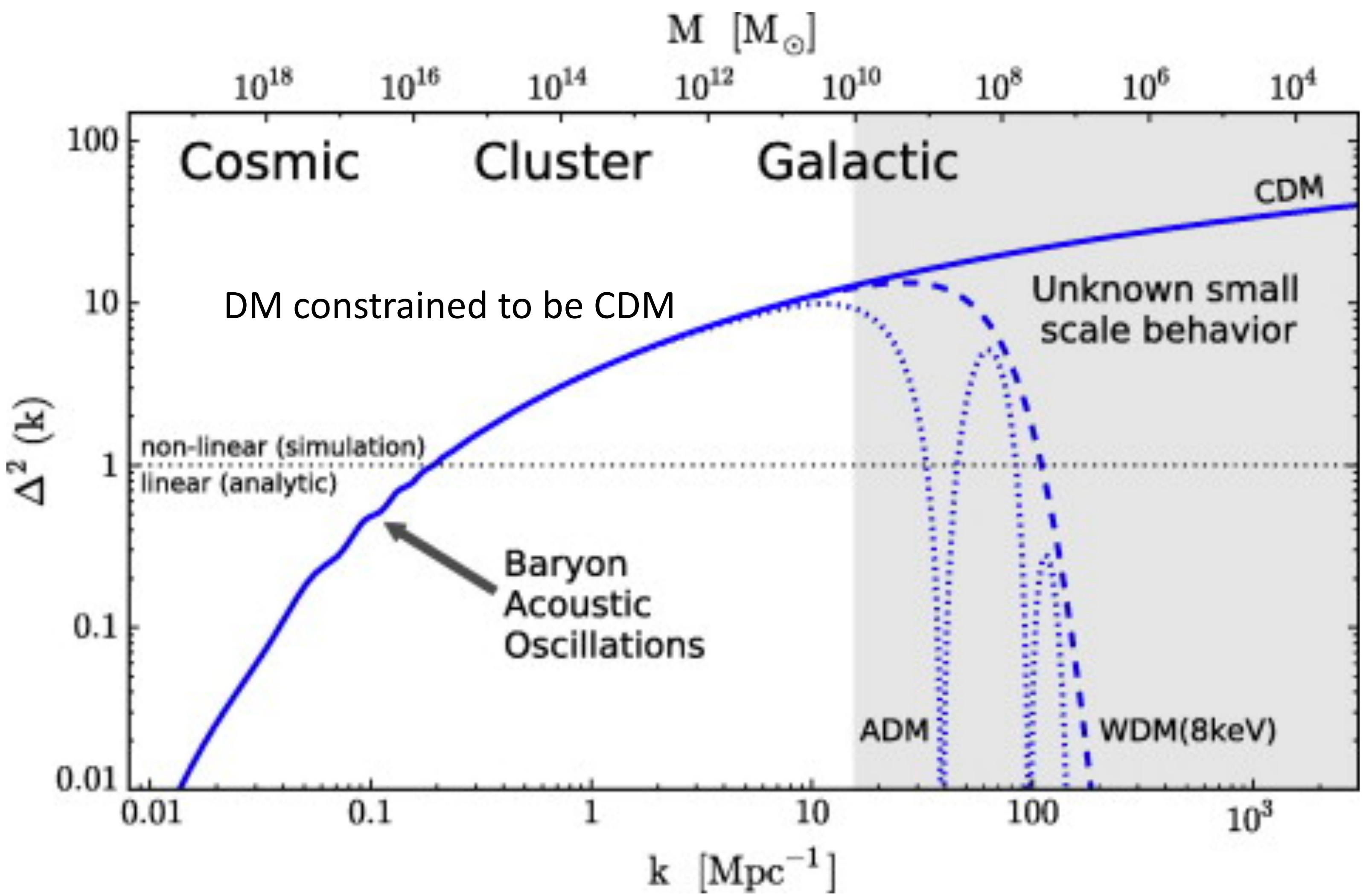
Cold dark matter: what we don't know

- What is the microphysics of DM?



- Self-interacting?
- Warm?
- Interacts with baryons?

Small Scales might offer some hints of the nature of DM



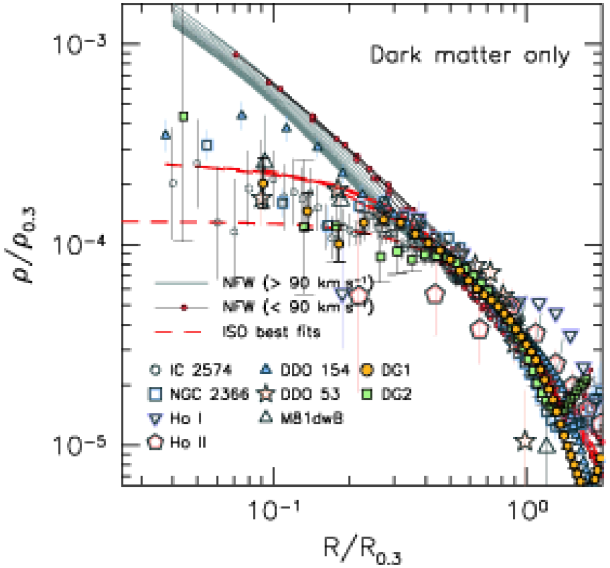
M. Kuhlen, M. Vogelsberger, R. Angulo, Phys.Dark Univ. 1 (2012) 50

Small Scale ~~Challenges~~ Curiosities
Galaxies

- **Galactic scales**
  - Cusp-core problem
  - Missing satellites problem
  - Too big to fail
  - …
- Regularity/diversity of rotation curves
  - ✓ *BTFR*
  - ✓ *Radial acceleration relation (RAR)*
  - ✓ *…*

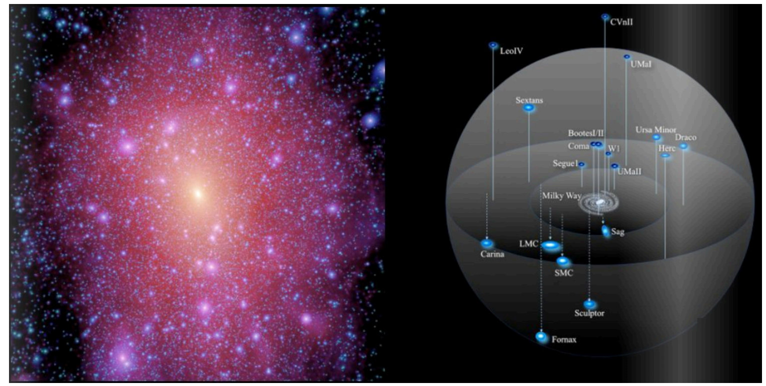
Small Scale ~~Challenges~~ Curiosities

Cusp core problem



THINGS (HI Near Galaxy Survey)/LITTLE THINGS

Missing satellites

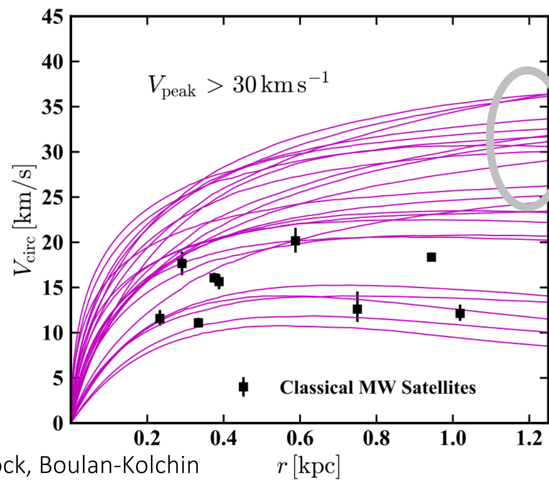


Bullock, Baylon-Kolchin

Mismatch between the # of predicted satellites by LCDM simulations and the # of observed satellites.

Solutions: (1) additional ultra-faint dwarfs; (2) Galaxy formation suppression; (3) Suppression of structure formation

Too big to fail



Bullock, Boulan-Kolchin

"too big to fail"

Mismatch between central masses of simulated DM systems and observed galaxies

Solutions might be: (1) Feedback; (2) Suppression of structure.

Small Scale ~~Challenges~~ Curiosities

Galaxies

- **Galactic scales**
  - Cusp-core problem
  - Missing satellites problem
  - Too big to fail
  - …
- Regularity/diversity of rotation curves

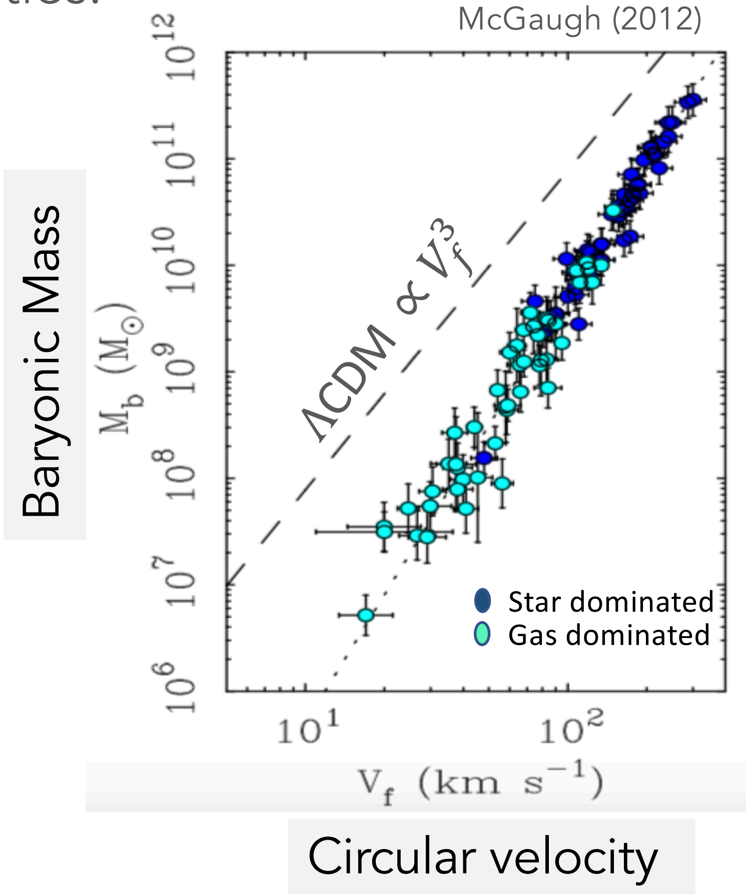
✓ *BTFR*
✓ *Radial acceleration relation (RAR)*
✓ …

Small Scale Challenges
Galaxies

- Baryonic Tully Fisher Relation (BTFR)

Remarkably tight scaling relations between dynamical and baryonic properties.

McGaugh (2012)



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

Dark Matter: Large Scales: standard cold DM particle

Small scales:

- Feedback
  - Star formation
  - Stellar evolution
  - Sn rates
  - BH and AGN feedback
  - Stellar feedback
  - …

Still under debate:
- ≠ simulations, ≠ parametrization of those effects
- Feedback enough?
- Can they yield such tight correl.?

- MOND

~~MOND without DM~~

Empirical force law

$$a = \begin{cases} a_N^b, & a_N^b \gg a_0. \\ \sqrt{a_N^b a_0}, & a_N^b \ll a_0. \end{cases}$$

Curious: Baryons drive the dynamics!

Works extremely well in: (1) Fitting rotation curves; (2) Scaling relations

- Modification of DM

Modify DM to a component that behaves different than CDM on small scales.

To address the small scales challenges:
- ✓ Suppress formation of small scales structures and/or
- ✓ ≠ profile in the core and/or
- ✓ Emergent dynamics on galactic scales

→ Small scales can offer hints of the nature of DM!

Dark Matter: Large Scales: standard cold DM particle

Small scales:

- Changes in the analysis
- Feedback
  - Star formation
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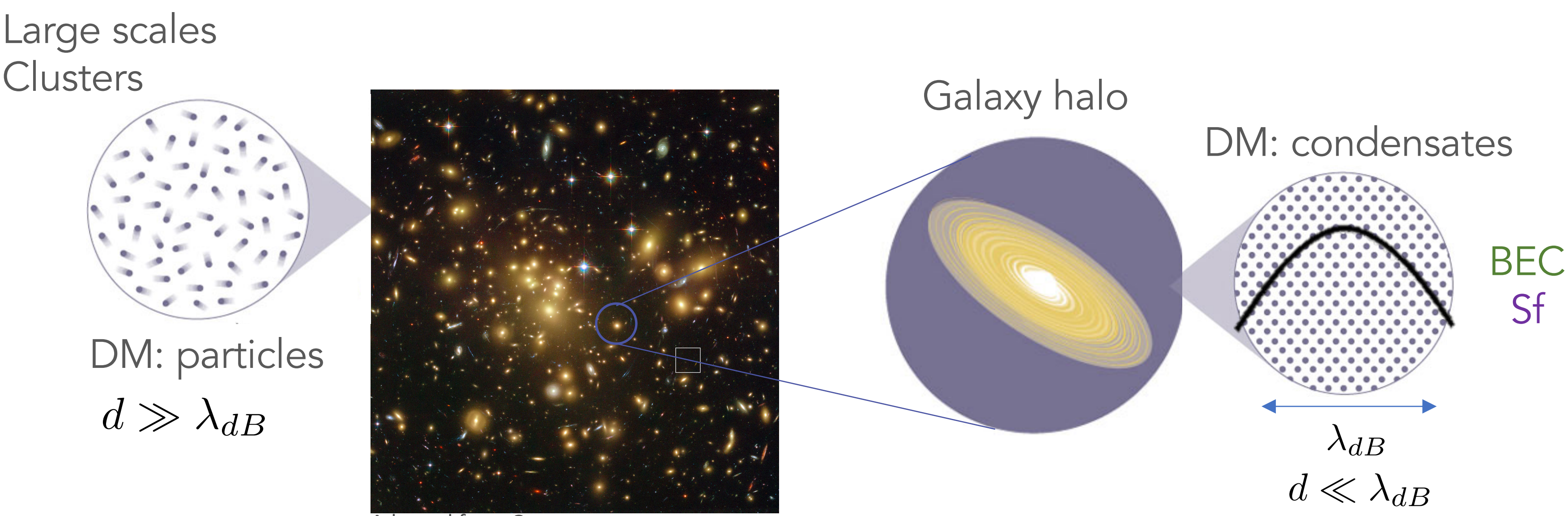
Ultra-Light Dark Matter

Idea:

- Large scales: DM behaves like standard particle DM (CDM).

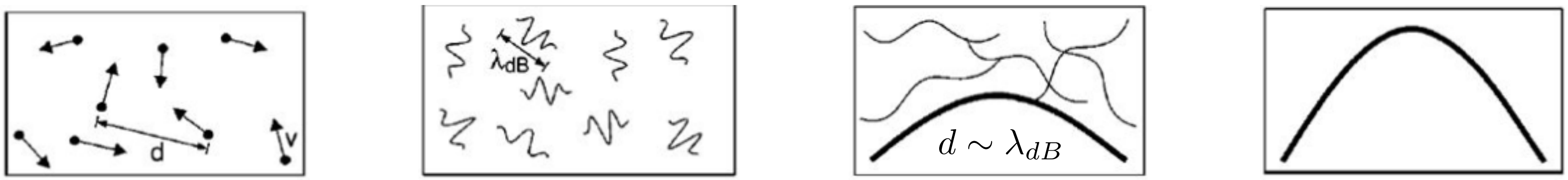
- Galactic scales: Given their small mass, their $\lambda_{dB} \sim 1/mv$ is large. On those scales DM behaves differently: it condenses forming a Bose-Einstein condensate (BEC) and maybe a superfluid. DM behaves in a collective macroscopic behavior → ≠ effective dynamics



Adapted from Quanta

BEC and Superfluid

- BEC: macroscopic occupancy of the lowest energy state.



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 wave"

- At low temperatures, fluid condensates into a BEC.
- De Broglie wavelength (λ_B) of each particle is large enough that their quantum wave function overlaps, and a single wave function describes the entire liquid.

Idea Bose gas

$$\frac{N_0}{N} = 1 - \left(\frac{T}{T_c}\right)^{3/2}$$

Small T → $n\lambda_{dB}^3 \gg 1$

- Quantum phenomenon that appears at low T and macroscopic scales.

Superfluidity:

- Another macroscopic quantum phenomena that appears at low T after the superfluid condenses into a BEC.
- **Effective dynamics of superfluid**: fluid flows without friction.

Description of the condensate and superfluid

- (pure) BEC → non-interacting many-body system of bosons
- Superfluid → interacting many-body system of bosons $(\hat{\Psi} - \text{Bose field operator})$
- Dynamics given by the many-body Hamiltonian of N (non-)interacting bosons.

Mean field approximation:

$$\hat{\Psi}(\mathbf{r},t) = \psi(\mathbf{r},t) + \delta\hat{\Psi}(\mathbf{r},t)$$

with $\psi(\mathbf{r},t) = \langle\hat{\Psi}(\mathbf{r},t)\rangle$

Fixed $n_0 = |\psi(\mathbf{r},t)|^2$

$\psi(\mathbf{r},t)$: classical field "wavefunction of the condensate"

$\delta\hat{\Psi}(\mathbf{r},t)$: small perturbation: describes depletion of the condensate

For a 2-body interacting system, in a trapping potential:

$$i\partial_t\psi(\mathbf{r},t) = \left(-\frac{\nabla^2}{2m} + V_{trap}(\mathbf{r}) + U_0|\psi(\mathbf{r},t)|^2\right)\psi(\mathbf{r},t)$$

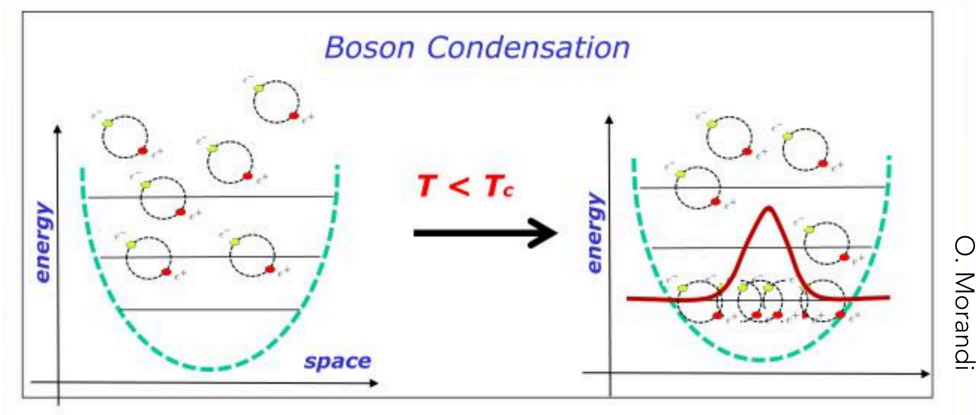
Gross-Pitaevskii equation: non-linear Schrödinger equation for the condensate wavefunction

$$\psi(\mathbf{r},t) = \phi(\mathbf{r})e^{-i\mu t}$$

μ: Chemical potential

Description of the condensate and superfluid

BEC can be seen as a *phase transition* where a macroscopic number of bosons occupy the lowest energy state



O. Morandi

Weakly interacting Bose system can be seen as a particle conserving system with spontaneous breaking of a U(1) symmetry (symmetry of the many body Hamiltonian)

Credit: Peking University

Methods from field theory are very appropriate to describe this system.

Description of the condensate and Sf

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

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

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

$$\Psi = \Psi_0 + \delta\Psi$$

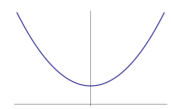
→ 2-body interaction

- *Condensate*: $\Psi_0 = ve^{\pi(x,t)}$

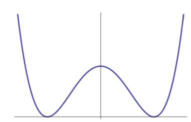
Current: $\dot{j}_0 = v^2\dot{\pi} = \text{const.} \Rightarrow \dot{\pi} = \mu$ ⇒ $\Psi_0 = v\, e^{i\mu t}$

Symmetry spont. broken by the ground state

- $\mu^2 < m^2$ Symmetry restoring phase



- $\mu^2 > m^2$ Bose Einstein condensation

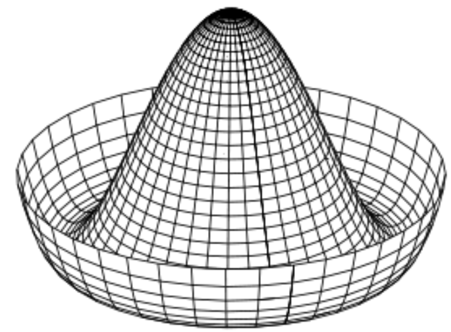


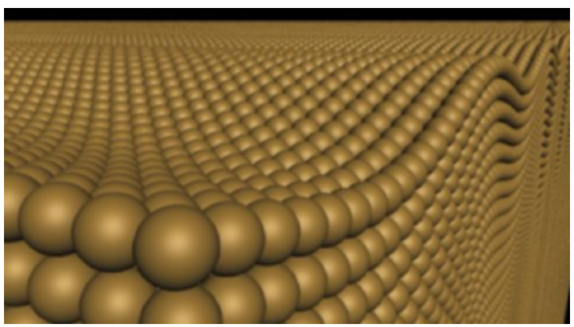
Description of the superfluid

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

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

$$\Psi = \Psi_0 + \delta\Psi \quad \begin{cases} \textit{Condensate:} & \Psi_0 = v\, e^{i\mu t} \\ \textit{Excitations:} & \Psi = (v+\rho)e^{i\overbrace{(\mu t+\theta)}^{\Theta}} \end{cases}$$





Crystal Lens

Collective excitations: massless Goldstone and massive quasi-particles.

Low energy: only θ excited - phonon

$$w_k \sim c_s k$$ Propagates as wave

(Mediates long range force $\sim 1/r^2$)

In the limit $\lambda \to 0$: BEC **stops** exhibiting superfluidity. Phonon → gapless particle

$$w_k = k^2/2m$$

Description of the BEC and Sf

We can recover the previous approaches:

Adding a trapping potential

Gross-Pitaevskii equation

Taking the non-relativistic limit and rewriting the field as: $\Psi = \frac{1}{2m}\psi \, e^{-imt}$

$$i\dot{\psi} = \left(-\frac{1}{2m}\nabla^2 + V_{trap} + \frac{\lambda}{8m^2}|\psi|^2 \right) \psi$$

Mandelung equations

Writing: $\psi \equiv \sqrt{\frac{\rho}{m}}\, e^{i\theta}$ $\quad \mathbf{v} \equiv \frac{1}{m}\nabla\theta$

$$\dot{\rho} + \nabla \cdot (\rho \mathbf{v}) = 0$$

$$\dot{\mathbf{v}} + (\mathbf{v} \cdot \nabla)\mathbf{v} = -\frac{1}{m}\nabla \left(V_{trap} - \frac{1}{2m}\frac{\nabla^2\sqrt{\rho}}{\sqrt{\rho}} \right)$$

Quantum pressure

Effective Field Theory of Superfluids

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 $\theta \to \theta + c$

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

$$\mathcal{L} = P(X)$$

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

Gravitational potential

Different phenomena $P(X) \propto \left(\dot{\theta}/m\right)^n$

$n = 2:$	$P \sim \rho^2$	BEC
$n = 3/2:$	$P \sim \rho^3$	"MOND"
$n = 5/2:$	$P \sim \rho^{5/3}$	Unitary Fermi gas

Equivalence (low energies)

2-body $\mathcal{L} = -|\partial\Psi| - m^2|\Psi|^2 - \frac{\lambda}{2}|\Psi|^4 \Longleftrightarrow \mathcal{L} = P(X) \propto X^2 \longrightarrow p \propto \rho^2$

3-body $\mathcal{L} = -|\partial\Psi| - m^2|\Psi|^2 - \frac{g_3}{3}|\Psi|^6 \Longleftrightarrow \mathcal{L} = P(X) \propto X^{3/2} \longrightarrow p \propto \rho^3$

Ultra-Light Dark Matter

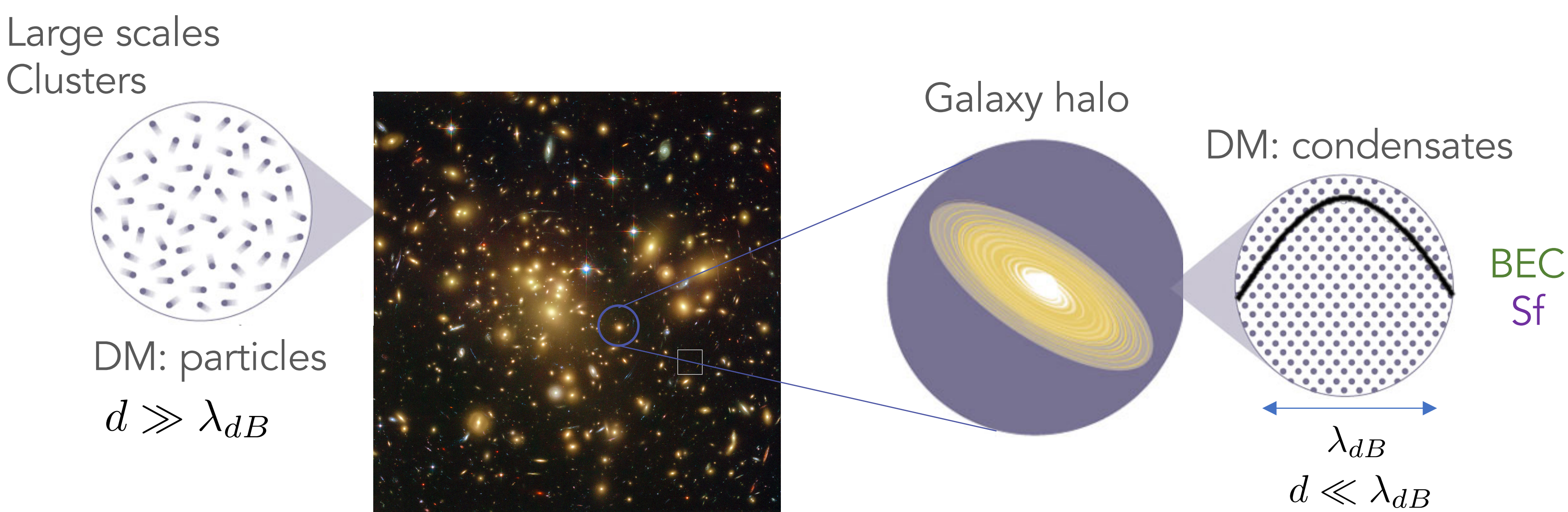
Ultra-Light Dark Matter

Class of models where DM forms a Bose-Einstein condensate (BEC) or a superfluid on galactic scales.

Idea: wave nature of DM on astrophysical scales

- Suppresses structure on those scales
- Homogeneous core
- Modifies the dynamics on small scales,

while maintaining the successes of CDM on large scales.

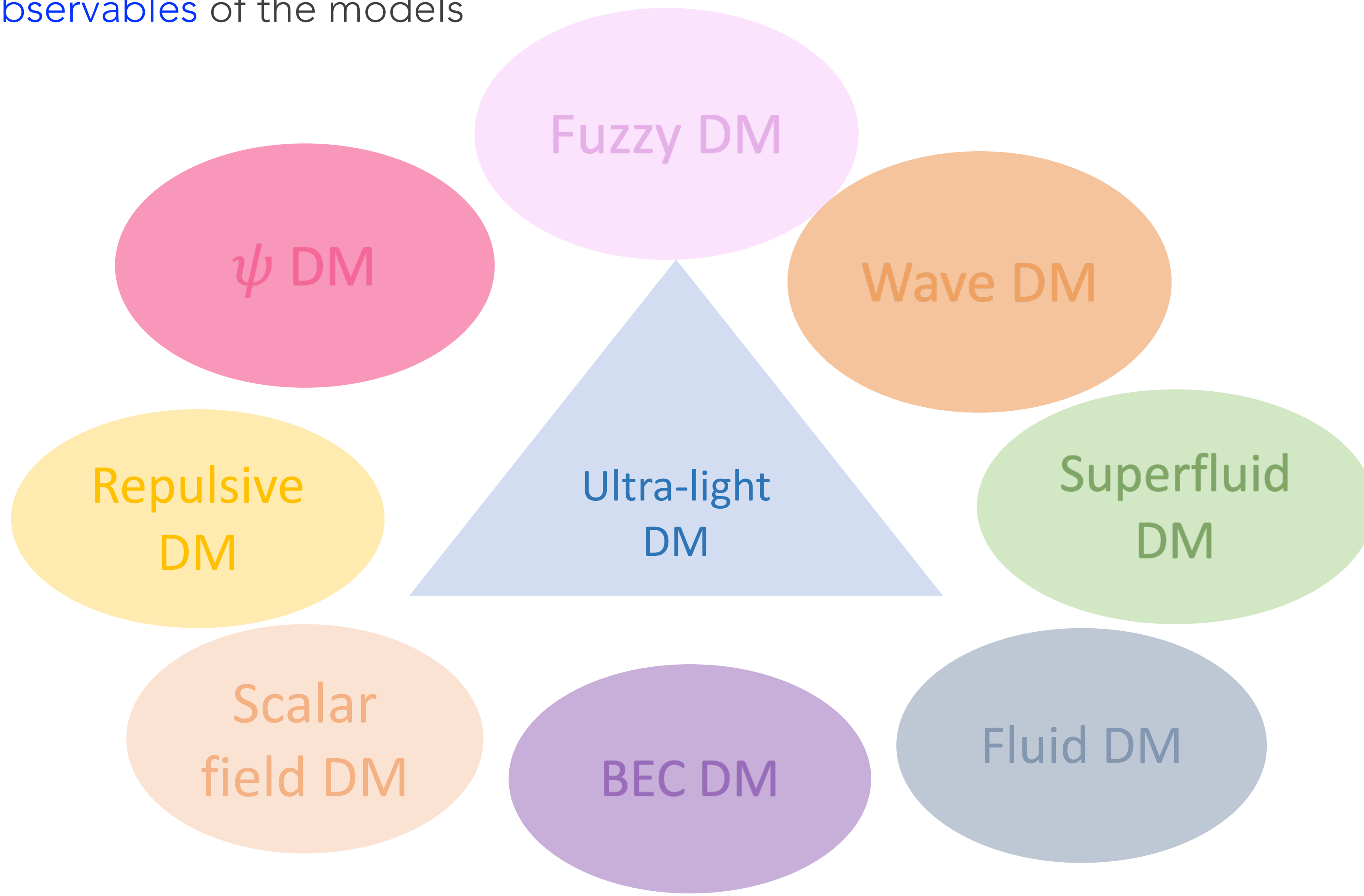


Adapted from Quanta

Ultra-Light Dark Matter

Many models in the literature.

Invoke condensation in similar but distinct ways that have important implications for the observables of the models

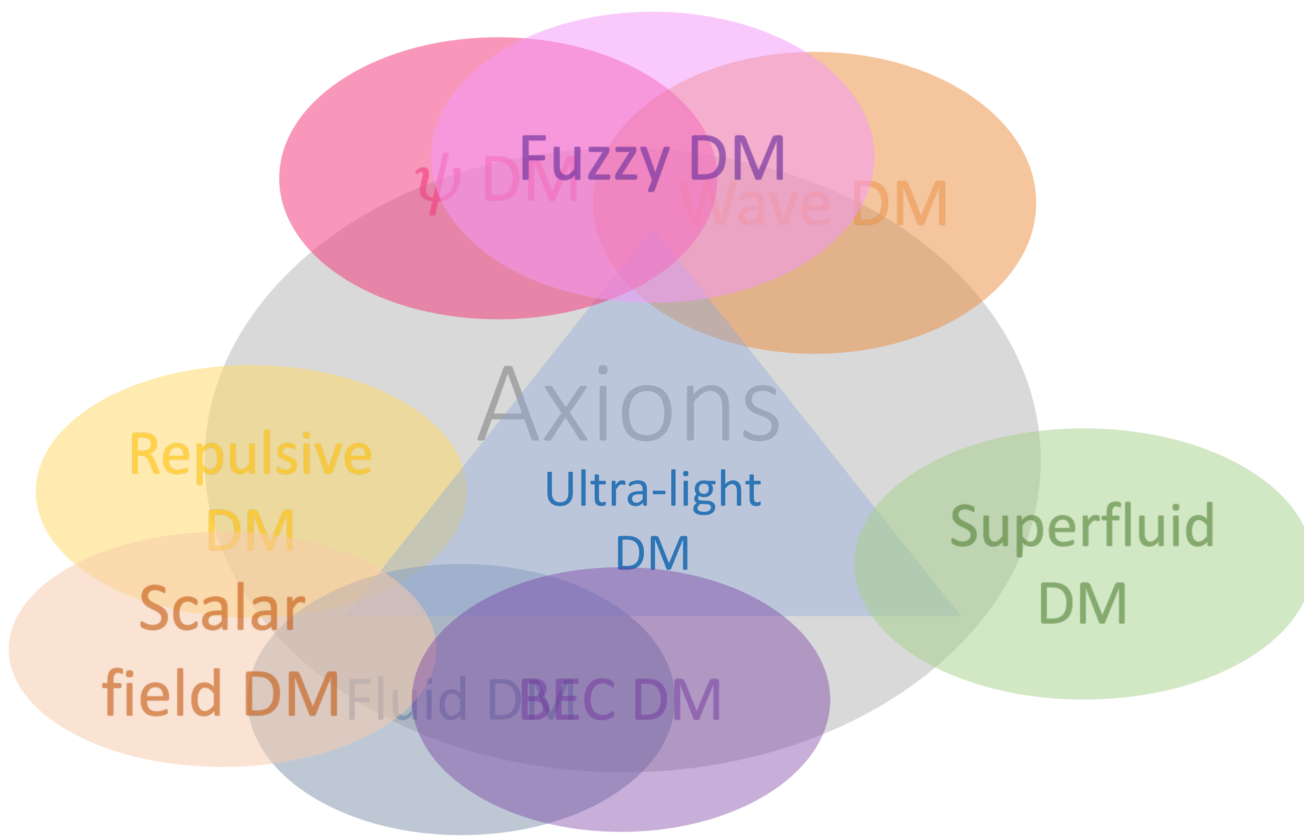


Ultra-Light Dark Matter

Many models in the literature.

Invoke condensation in similar but distinct ways that have important implications for the observables of the models

BUT, can be basically divided into 3 categories



Ultra-Light Dark Matter

3 categories

Classification is based on the different

Scalar Filed Dark Matter (SFDM): described by a self-interacting scalar field with 2-body interaction (or higher order interaction).

→ Equivalent: Weakly coupled BEC. Exhibits superfluidity after condensation.

Also called: repulsive DM, scalar field DM, fluid dark matter, among others

Fuzzy DM: described by a ultra-light scalar field under the influence of gravitational potential

→ Equivalent: BEC (NO superfluid)

Also called: wave DM or ψDM.

Superfluid DM: described by a superfluid with specific EoS to reproduce MOND (long range interactions) on galactic scales.

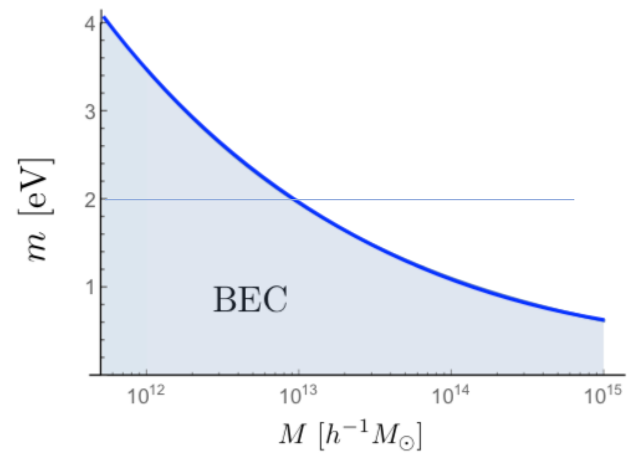
→ Equivalent: Superfluid described by the EFT of Sf with $P \propto \rho^3$

Condition for Condensation

DM has to condensate in galaxies:

- de Broglie wavelength of the particles must overlap ($n_{gal}\lambda_{dB} \gg 1$).

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



$$\Longrightarrow \quad \boxed{m \leq 2\text{eV}}$$

- Thermalization

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

Cold atoms in the lab

SFDM and Fuzzy DM

Lets consider a self-interacting scalar field in a FRW universe:

$$S = \int d^4x\sqrt{-g}\left[\frac{1}{2}|\partial\Psi| - m^2|\Psi|^2 - \frac{\lambda}{4}|\Psi|^4\right]$$

NR regime and $\Psi = \frac{1}{2m}\psi\, e^{-imt}$. In an FRW universe $ds^2 = (1+2\Phi)dt^2 - a^2(t)(1-2\Phi)d\mathbf{r}^2$

$$\Rightarrow \quad i\left(\dot{\psi} + \frac{3}{2}H\psi\right) = \left(-\frac{1}{2ma^2}\nabla^2 + \frac{\lambda}{8m^2a^2}|\psi|^2 - m\Phi\right)\psi$$

Consider time scales smaller than the expansion, we can ignore expansion:

$$i\dot{\psi} = \left(-\frac{1}{2m}\nabla^2 + \frac{\lambda}{8m^2}|\psi|^2 - m\Phi\right)\psi$$ Gross-Pitaevskii equation

$$\nabla^2\Phi = 4\pi G(m|\psi|^2 - \bar{\rho})$$ Poisson equation

SFDM and Fuzzy DM

Both models can be described by:

$$\begin{cases} i\dot{\psi} = \left(-\frac{1}{2m}\nabla^2 + \frac{\lambda}{8m^2}|\psi|^2 - m\Phi\right)\psi \\ \nabla^2\Phi = 4\pi G(m|\psi|^2 - \bar{\rho}) \end{cases}$$

where

$\lambda = 0$	→	Fuzzy DM
$\lambda \neq 0$	→	Scalar Field DM

Sf

Self-interacting scalar field in a FRW universe is analogous to the theory for the weakly interacting BEC

SFDM and Fuzzy DM
Condensate and Stability

Scalar Field DM

$$i\dot{\psi} = \left(-\frac{1}{2m}\nabla^2 + \frac{\lambda}{8m^2}|\psi|^2 \right)\psi$$

$$\psi(\mathbf{x},t) = \psi_c(t) + \delta\psi(\mathbf{x},t)$$

Perturbations:

$\tilde{\omega}_k^2 = 0$;

$\lambda > 0$ Oscillates, stable

$$k_* = -\frac{|\lambda| n_0}{2m}$$

$\lambda < 0$
- $l > l_*$ Structures grow, no condensate
- $l < l_*$ Oscillates, stable, forming a condensate, the soliton

For attractive interactions can only form localized clumps (solitons) of size $l < l_*$

Fuzzy DM

$$i\dot{\psi} = -\frac{1}{2m}\nabla^2\delta\psi + m\Phi\psi$$

$$\nabla^2\Phi = 4\pi G(m|\psi|^2 - \bar{\rho})$$

Like an attractive interaction

Perturbations:

$\tilde{\omega}_k^2 = 0$;

$$k_J = (16\pi G m^3 n_0)^{1/4}$$

- $\lambda > \lambda_J$ Gravity dominates, collapse happens CDM
- $\lambda < \lambda_J$ Quantum pressure dominates. Solution is stable and oscillates – NO structure formation!

$$\lambda_J = 55 \left(\frac{m}{10^{-22}\,\mathrm{eV}}\right)^{-1/2} \left(\frac{\rho}{\bar{\rho}}\right)^{-1/4} (\Omega_m h)^{-1/4}\,\mathrm{kpc}$$

SFDM and Fuzzy DM
Condensate and Stability

Summarizing:

SFDM

- $\lambda > 0$ Long range coherence → when it exhibits superfluidity
- $\lambda < 0$ Only localized clumps (solitons)

Fuzzy DM

- Finite size coherent core
- Small mass to have a size relevant to galactic scales $m \sim 10^{-22}\,\mathrm{eV}$

Fuzzy DM

W. Hu; R. Barkana; A. Gruzinov (2000)

Ultra-light scalar field under the influence of grav. potential → Forms a BEC at galactic scales

$$m \leq 10^{-20}\mathrm{eV} \;\Rightarrow\; \lambda_{dB} > \mathcal{O}(\mathrm{kpc})$$

<u>Picture</u>

- $\lambda > \lambda_J$ — CDM
- $\lambda < \lambda_J$ — Condensed regime, oscillates NO structure formation!

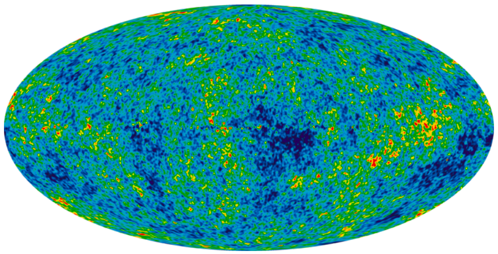
$$\lambda_J = 55 \left(\frac{m}{10^{-22}\,\mathrm{eV}}\right)^{-1/2} \left(\frac{\rho}{\bar{\rho}}\right)^{-1/4} (\Omega_m h)^{-1/4}\,\mathrm{kpc}$$

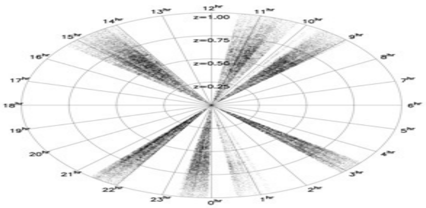
Fuzzy DM

Gravitational Signatures and bounds

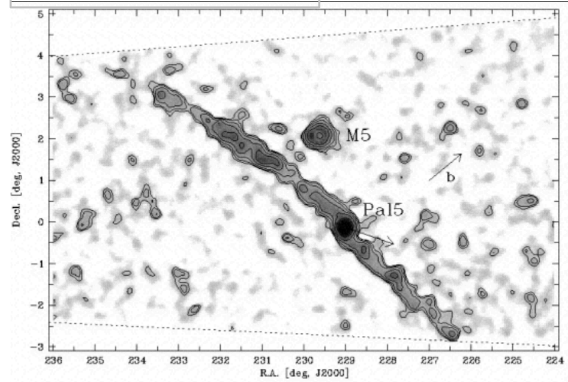
Bounds on the mass

CMB/LSS

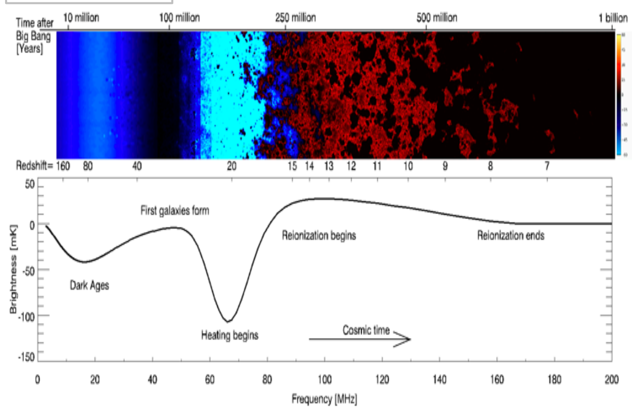




Lyman alpha



21 cm



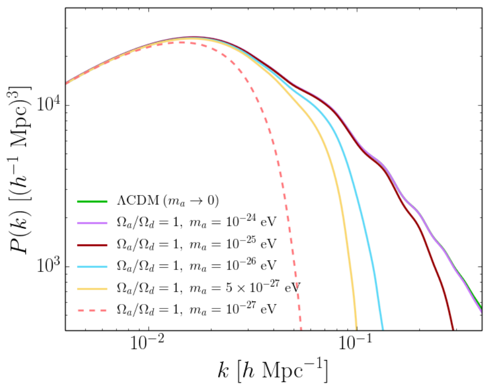
Fuzzy DM

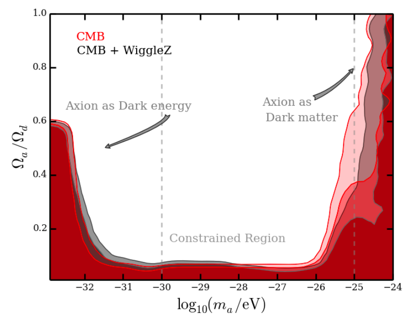
Gravitational Signatures and bounds

Bounds on the mass

CMB/LSS

Hlozek et al, (2015)

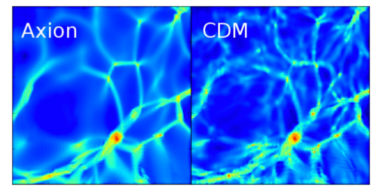


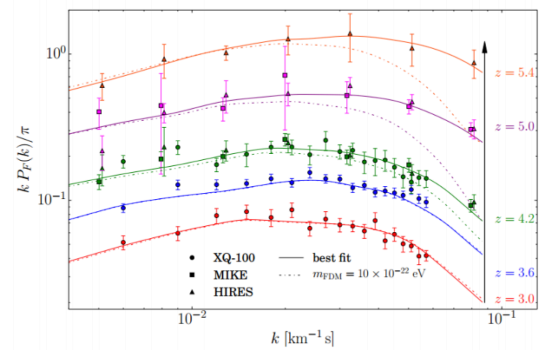


$$m \gtrsim 10^{-24}\mathrm{eV}$$

Lyman alpha

Armengaud et al. (2017); Iršič et al. (2017)





$$m \gtrsim 10^{-21}\mathrm{eV}$$

so enough Mpc-scale power in Ly-α forest at z = 5

21 cm

EDGES global 21 cm signal

Olof Nebrin et al.(2019)

Suspressed small scale structure

⬇

Postpone Ly-α coupling, heating, reionization H

⬇

Smaller 21-cm global signal

$$m \gtrsim 6 \times 10^{-22}\mathrm{eV}$$

At 2 σ signal full width

Fuzzy DM

Gravitational Signatures and bounds

Maximum density

Dwarf Galaxies

$$\lambda_{dB} < R_{Virial}$$

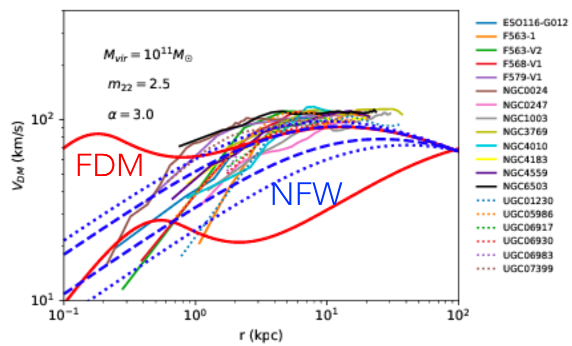
$$\rho_c \leq 7.05 M_\odot \mathrm{pm}^{-3} \left(\frac{10^9}{M_\odot}\right)^{-4} \left(\frac{10^{-22}}{m}\right)^{-6}$$

dSph
- $m = 8^{+5}_{-3} \times 10^{-23} \mathrm{eV}$ Draco
- $m = 6^{+7}_{-2} \times 10^{-22} \mathrm{eV}$ Sextans

Cored! ~~Cusp-core~~

Disputed:

Emily Kendall, Richard Easther (2019)



Lower bound on halo masses

Jeans mass: smallest structured formed

$$M_J = \frac{4\pi}{3}\rho\left(\frac{1}{2}\lambda_J\right)^3$$

No halos w/ $M_{halo} < 10^{18} M_\odot$

Missing satellites solved
No too big to fail

Other interesting consequences:
- Dynamical friction
- Soliton bounds EHT
- Subhalo Mass Function for FDM

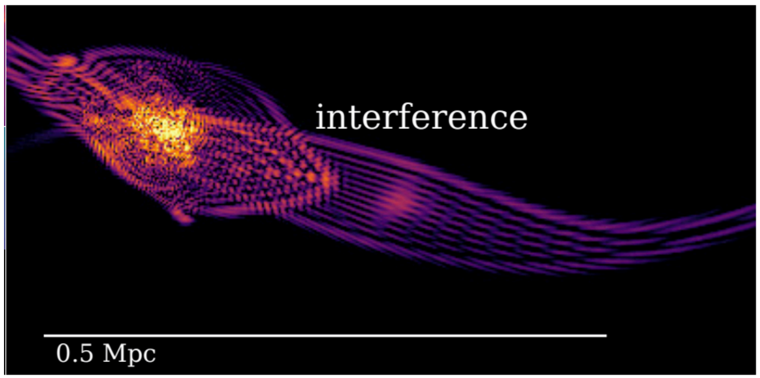
Fuzzy DM

Gravitational Signatures and bounds

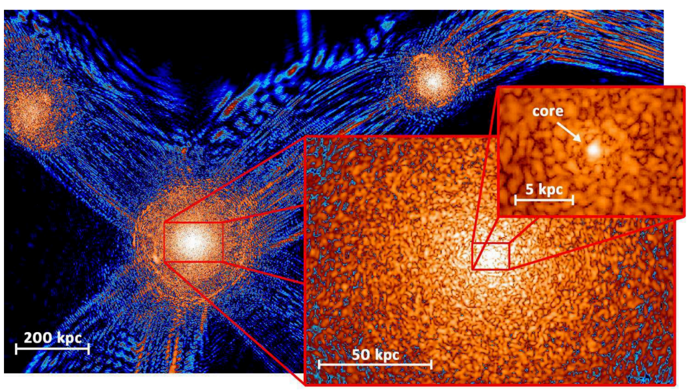
Interesting prediction

Interference

P. Mocz et al (2019)



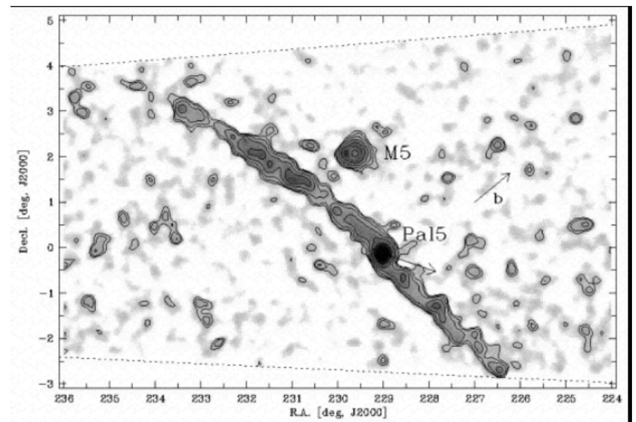
Schive, Chiueh, Broadhurst



Probing the quantum mechanical nature of FDM

Interesting probe

Stellar streams



- DM properties encoded in variations density in stellar streams
- Opportunity to probe the nature of DM
- *Ibata et al. (2020):* at this stage, hard to disentangle DM signal. No evidence.

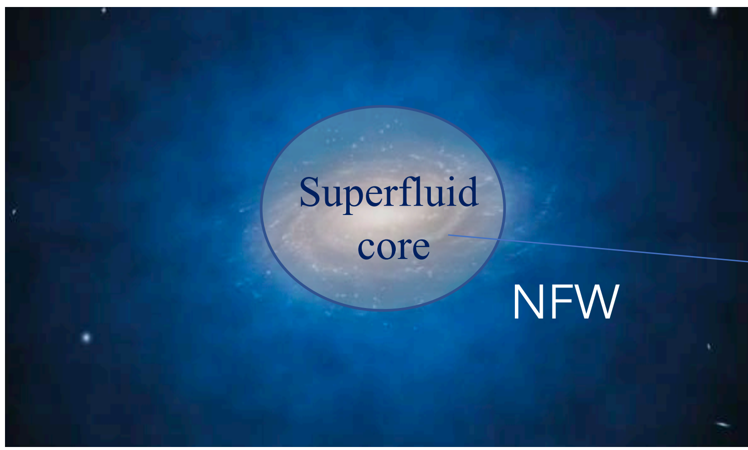
Future: **PFS**

Superfluid DM

Lasha Berezhiani and Justin Khoury (2016)

Goal:

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



Explain the scaling relations + rotation curves

MOND dynamics emerges on galactic scales

On top of addressing the other challenges like fuzzy given the presence of a superfluid core.

MOND from phonons

L. Berezhiani and J. Khoury (2016)

EFT of superfluids $\mathcal{L} = P(X)$ $X = \dot{\theta} - m\Phi - \frac{(\vec{\nabla}\theta)^2}{2m}$

To describe non-relativistic MOND, it is imposed that:

$$P(X) = \frac{2\Lambda\,(2m)^{3/2}}{3} X\sqrt{|X|}$$

→ Leads to an equation of state $P \sim \rho^3$.

To mediate the MONDian force, couple phonons to baryons:

$$\mathcal{L}_{int} \sim \frac{\Lambda}{M_{pl}}\,\theta\rho_b$$

Softly breaks shift symmetry

$$\Lambda = \sqrt{a_0 M_{pl}} \sim 0.8\,\mathrm{meV}$$

MOND regime

- Newtonian limit: $|\vec{\nabla}\Phi| > 3\,a_0$

$$\Longrightarrow \quad \boxed{\vec{\nabla}^2\Phi = \frac{\rho_s + \rho_b}{2M_{pl}^2}}$$

- MOND limit: $|\vec{\nabla}\Phi| < 3\,a_0$

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

Only DM

Mostly DM

"MOND"

No MOND

→ Landau criteria

$$v_s^{\odot} \ll v_c^{MW} \sim \left(\frac{\rho}{m^4}\right)^{\frac{1}{3}}$$

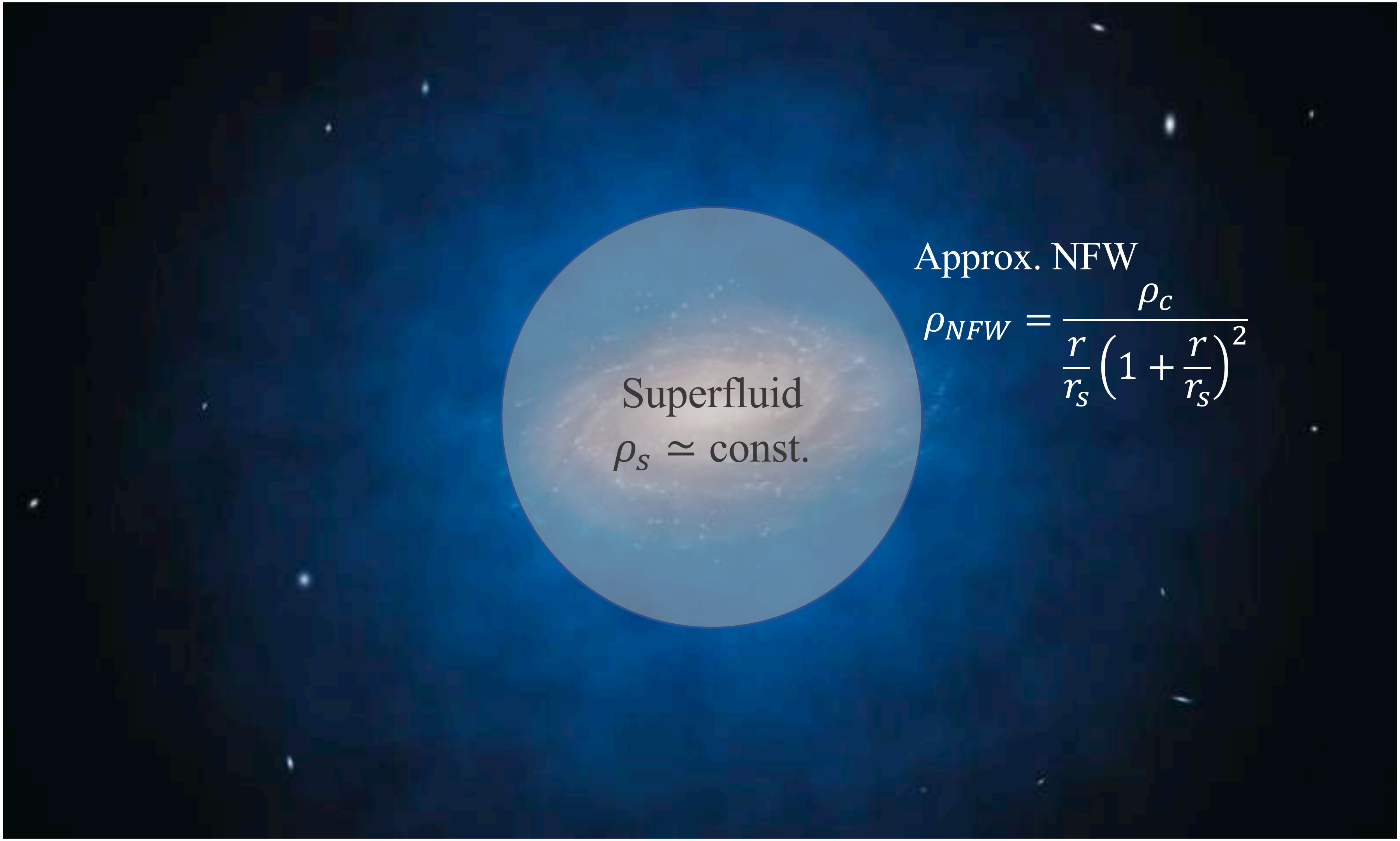
$$r \gg 250\left(\frac{m}{\mathrm{eV}}\right)^{-1/3}\left(\frac{\Lambda}{\mathrm{meV}}\right)^{-5/9}\mathrm{AU}$$

Sf velocity:

$$v_s = \partial_r\phi/m \sim \sqrt{m(\mu - m\Phi)/m}$$

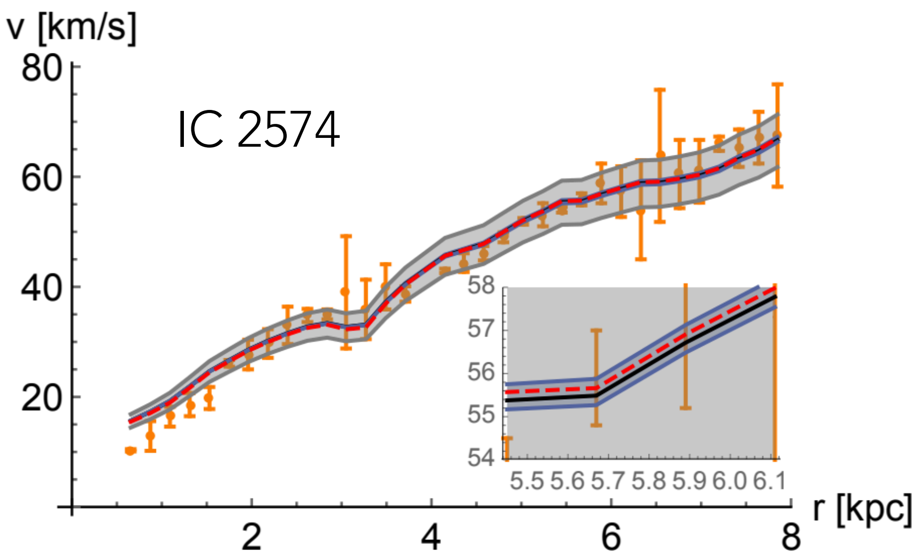
Density profile

L. Berezhiani, B. Famaey, J. Khoury, 2017

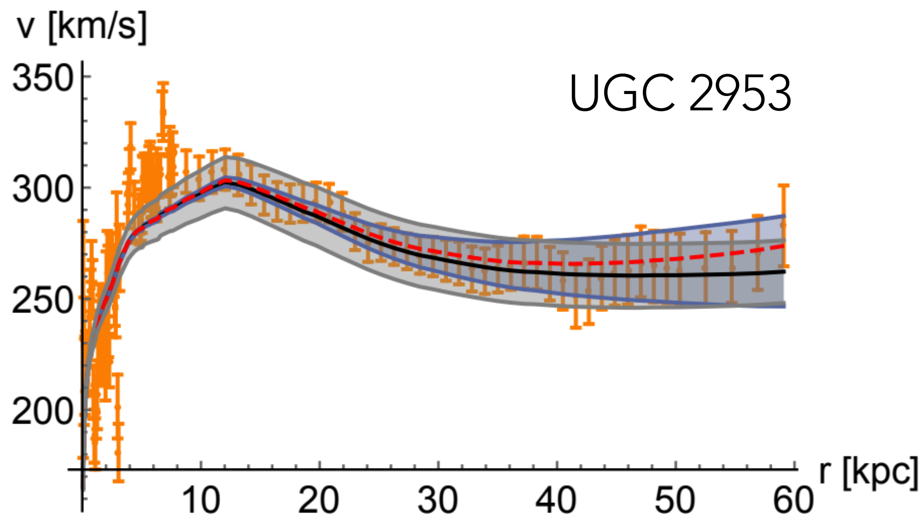


Rotation curves

Low surface brightness



High surface brightness



Superfluid core:

$$R_{halo} = 57\,\mathrm{kpc}$$

$$R_{Sf} = 40\,\mathrm{kpc}$$

58% of total mass of the halo

$$R_{halo} = 445\,\mathrm{kpc}$$

$$R_{Sf} = 79\,\mathrm{kpc}$$

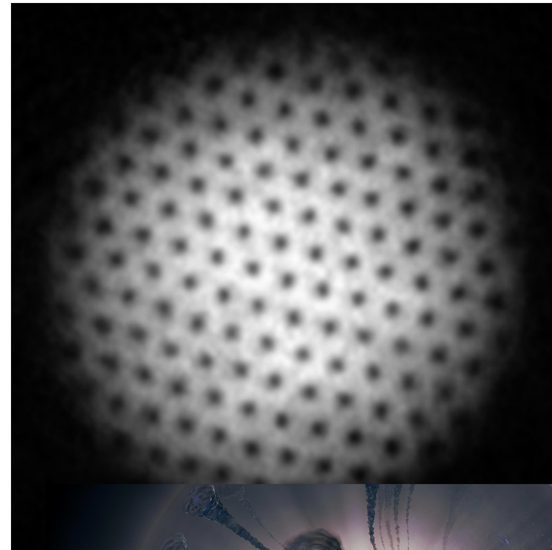
25% of total mass of the halo

Observational consequences of Sf DM

System	Behavior
Rotating Systems	
Solar system	Newtonian
Galaxy rotation curve shapes	MOND (+ small DM component making HSB curves rise)
Baryonic Tully–Fisher Relation	MOND for rotation curves (but particle DM for lensing)
Bars and spiral structure in galaxies	MOND
Interacting Galaxies	
Dynamical friction	Absent in superfluid core
Tidal dwarf galaxies	Newtonian when outside of superfluid core
Spheroidal Systems	
Star clusters	MOND with EFE inside galaxy host core — Newton outside of core
Dwarf Spheroidals	MOND with EFE inside galaxy host core — MOND+DM outside of core
Clusters of Galaxies	Mostly particle DM (for both dynamics and lensing)
Ultra-diffuse galaxies	MOND without EFE outside of cluster core
Galaxy-galaxy lensing	Driven by DM enveloppe $\Longrightarrow$ not MOND
Gravitational wave observations	As in General Relativity

See JCAP 1910 (2019) no.10, 074

Vortices



Observational signature of superfluidity

Reveals quantum mechanical nature of superfluid

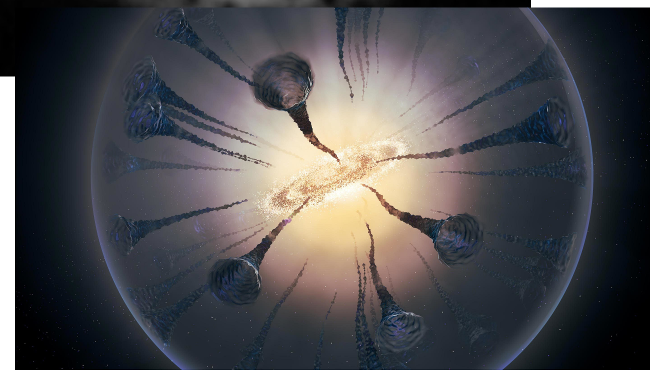
Superfluid cannot rotate uniformly.
If the superfluid rotates faster than the critical vel.:

$$\omega_{cr} \sim \frac{1}{mR^2} \sim 10^{-41}\mathrm{s}^{-1}$$

$$>$$

$$\omega \sim \lambda\sqrt{G_N \rho_{halo}} \sim 10^{-18}\lambda \mathrm{s}^{-1}$$

Formation of vortices!



Markos Kay for Quanta Magazine

For a halo $R \sim 100$ kpc

↓

$N_v \sim 10^{23}$ vortices with r_v~mm

Observable?
Need to solve the Gross-Pitaesvskii/Poisson equation system!

Superfluid DM
Challenges for this model

Local Milky Way observations

High Energy Physics – Phenomenology

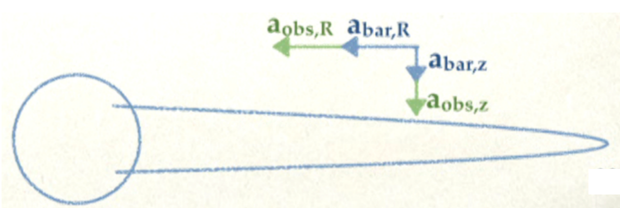
The Inconsistency of Superfluid Dark Matter with Milky Way Dynamics

Mariangela Lisanti, Matthew Moschella, Nadav Joseph Outmezguine, Oren Slone

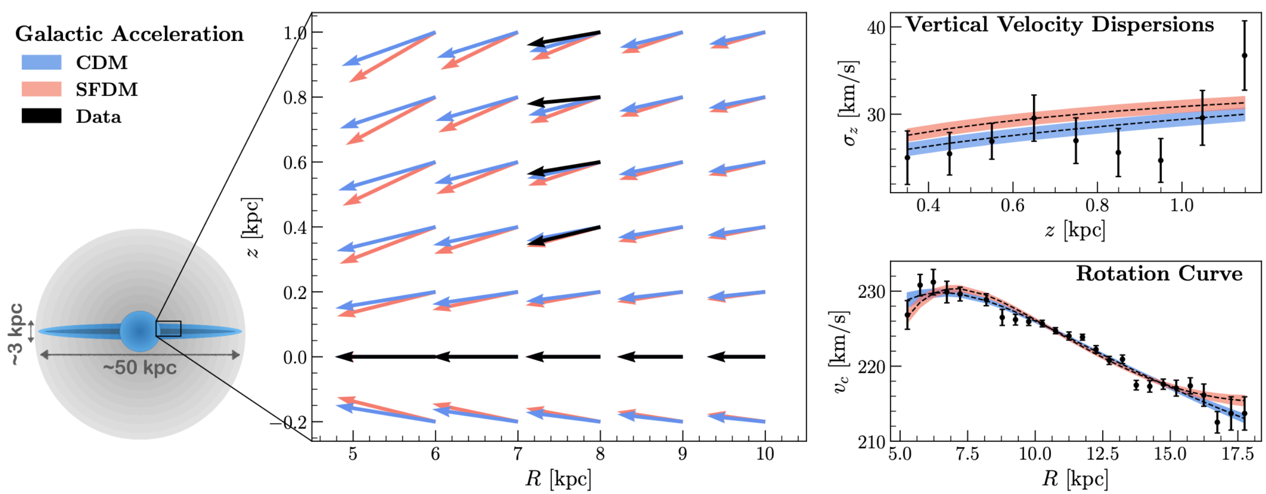
(Submitted on 27 Nov 2019)

There are many well-known correlations between dark matter and baryons that exist on galactic scales. These correlations can essentially be encompassed by a simple scaling relation between observed and baryonic accelerations, historically known as the Mass Discrepancy Acceleration Relation (MDAR). The existence of such a relation has prompted many theories that attempt to explain the correlations by invoking additional fundamental forces on baryons. The standard lore has been that a theory that reduces to the MDAR on galaxy scales but behaves like cold dark matter (CDM) on larger scales provides an excellent fit to data, since CDM is desirable on scales of clusters and above. However, this statement should be revised in light of recent results showing that a fundamental force that reproduces the MDAR is challenged by Milky Way dynamics. In this study, we test this claim on the example of Superfluid Dark Matter. We find that a standard CDM model is strongly preferred over a static superfluid profile. This is due to the fact that the superfluid model over-predicts vertical accelerations, even while reproducing galactic rotation curves. Our results establish an important criterion that any dark matter model must satisfy within the Milky Way.

Comments: 6+5 pages, 2+4 figures
Subjects: **High Energy Physics – Phenomenology (hep-ph)**; Cosmology and Nongalactic Astrophysics (astro-ph.CO); Astrophysics of Galaxies (astro-ph.GA)
Cite as: arXiv:1911.12365 [hep-ph]
(or arXiv:1911.12365v1 [hep-ph] for this version)



Oren Slone



MOND-like force amplifies:

a_R not enough

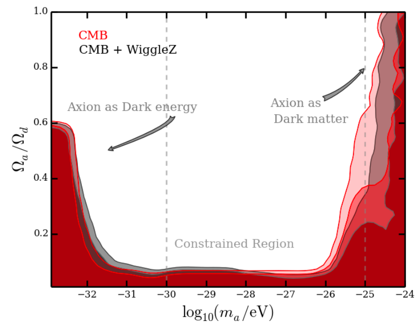
a_z too much

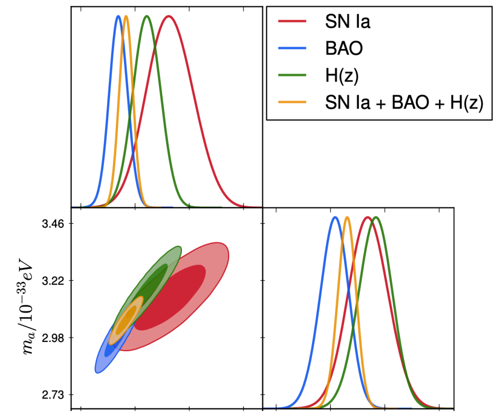
Ultra-Light Fields: Dark Energy

Fuzzy: Hlozek et al, 2015; Jiangang Kang et al. (2019)

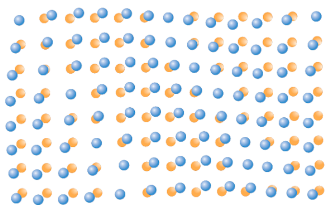
Behaves like dark energy with $w \sim -1$ for

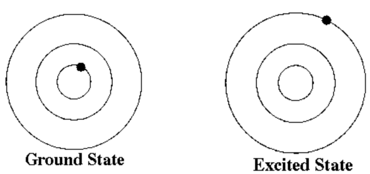
$$m_a < 10^{-32}\mathrm{eV}$$





Superfluid DM: Unified Dark superfluid EF, G. Franzmann, J. Khoury, R. Brandenberger, 2018



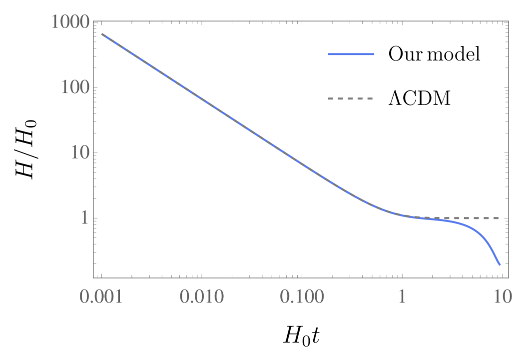


Atoms in these states interact!

Superfluid with two distinguishable states.

Phonons that propagate with different phases for each species

$$\mathcal{L} = P(X_1) + P(X_2) - \frac{M^4}{2}\left[1 + \cos\left(\frac{\theta_2 - \theta_1 + \Delta E\, t}{f}\right)\right]$$



Unified framework DM alone!

Summary

Model	Interaction	EoS	Superfluidity
SFDM	2-body	$P \sim n^2$	Yes
Superfluid DM	"3-body" $\to P(X)_{MOND}$	$P \sim n^3$	Yes
Fuzzy DM	$\lambda = 0$ (Grav. interaction)	"Quantum pressure"	No

- Class of DM models of ultra-light particles that condenses into a BEC or forms a superfluid on galactic scales
- Wave property of condensate core can suppress structures and modify the dynamics at small scales.
- Analogous to condensed matter system: motivation.
- Distinct observational signatures on small scales
    - Exciting place to probe DM! Just starting… PFS
- Ultra-light fields can also give behave like DE.
- Still much to do on the theory side as well.

Thank you