Dark Matter Superfluidity

Justin Khoury (U. Penn)

Berezhiani & JK, 1506.07877 + 1507.01019
JK, 1602.05961
Berezhiani, Famaey & JK, 1711.05478

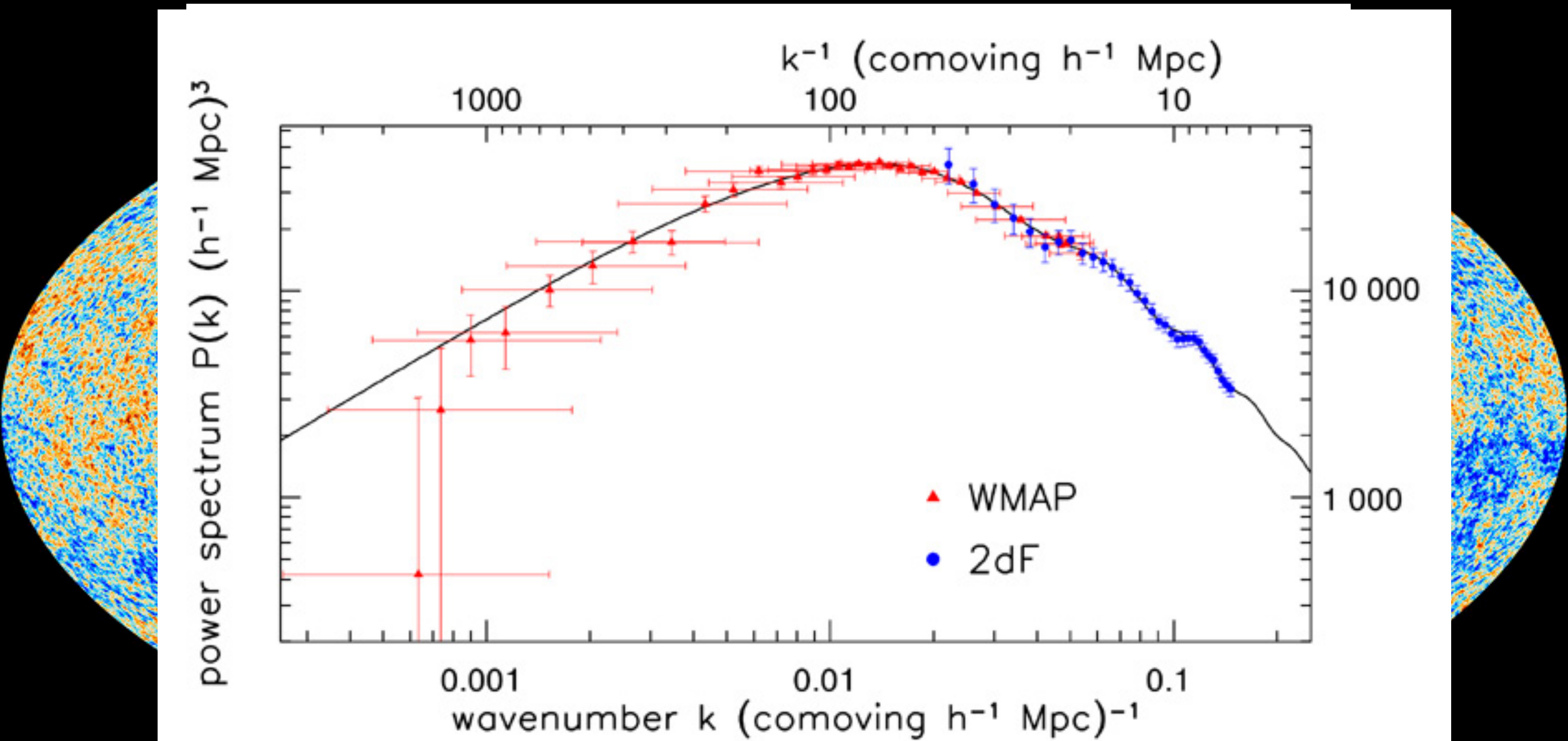
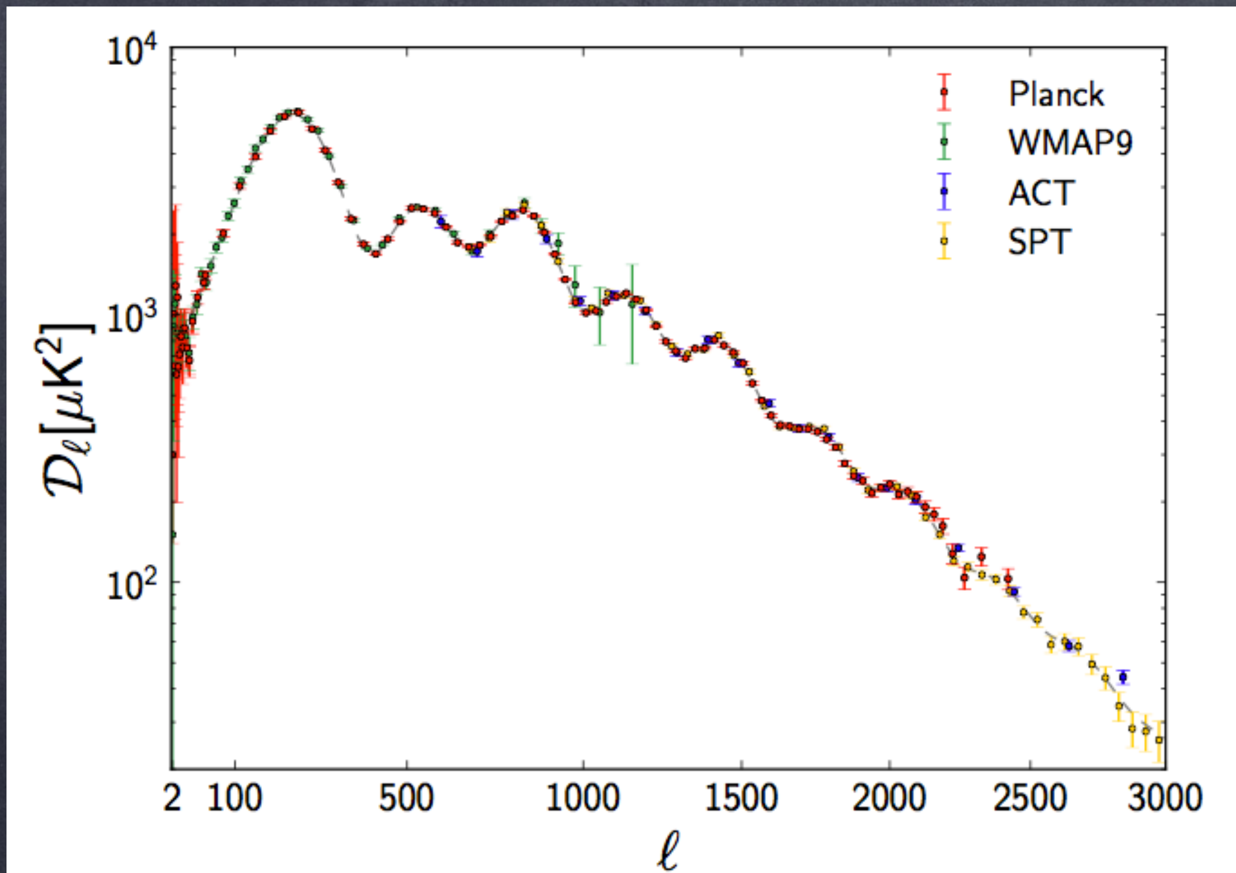


Fig 8.17 (A. Sanchez) 'Galaxies in the Universe' Sparke/Gallagher CUP 2007

NASA / WMAP Science Team
ESA / Planck Science Team

The coarse-grained success of CDM



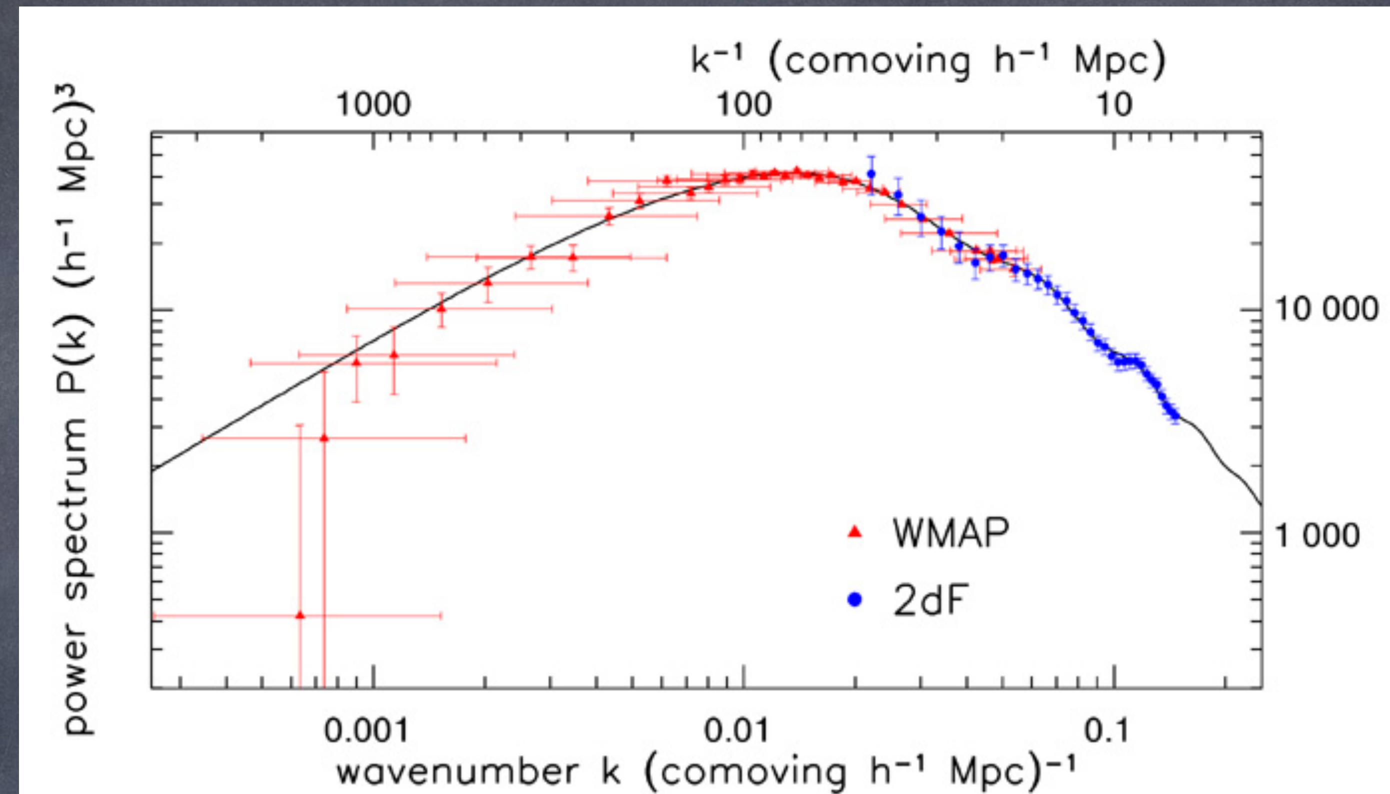


Fig 8.17 (A. Sanchez) 'Galaxies in the Universe' Sparke/Gallagher CUP 2007

- On large (linear) scales, only use the hydrodynamical limit of DM

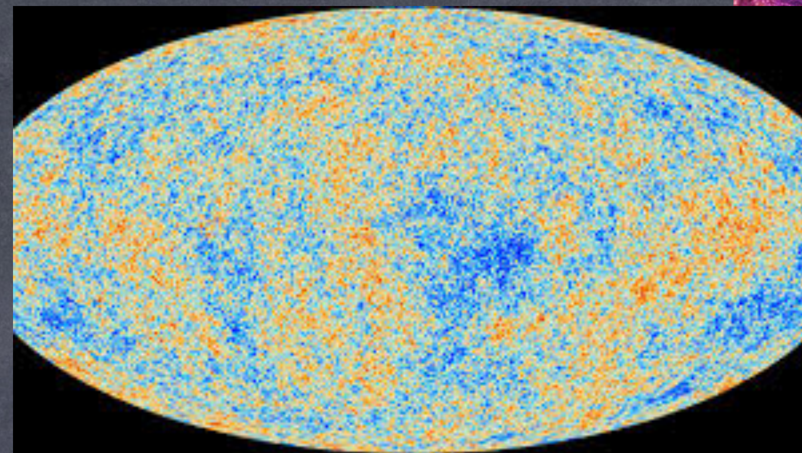
$$\boxed{T_{\mu\nu} = (\rho + P)u_\mu u_\nu + P g_{\mu\nu}}$$

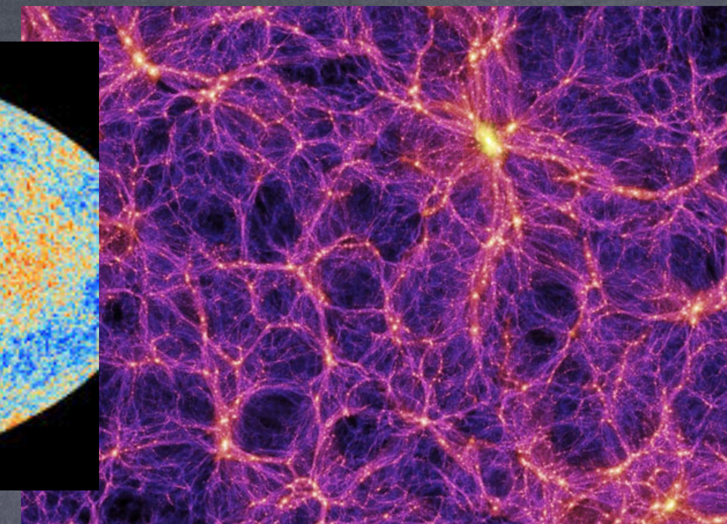
$\Longrightarrow$ Any perfect fluid with $P \simeq 0$ and $c_s \simeq 0$ does the job.

Cleanest evidence for DM, but does not offer much information about DM microphysics (SIDM, Fuzzy DM, etc.)

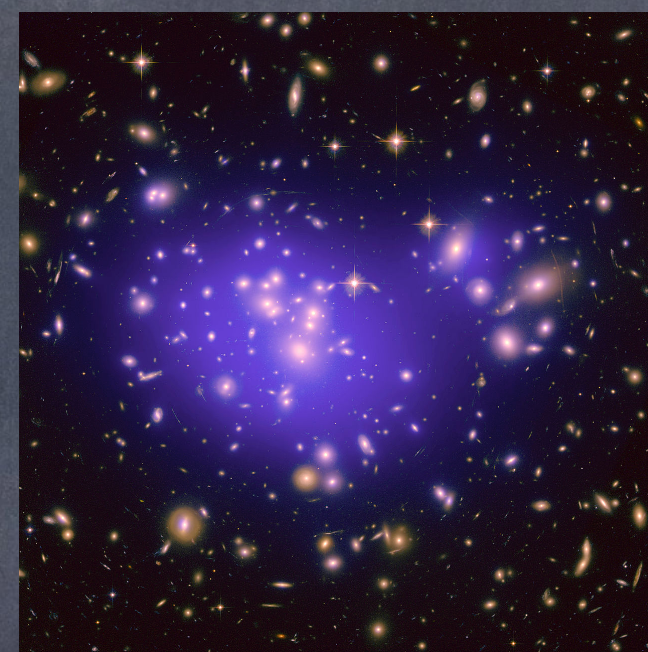
Dark matter is generally assumed of particles (WIMPs, axions, etc.), with negligible interactions among themselves and with ordinary matter (other than gravity).

Cosmic web

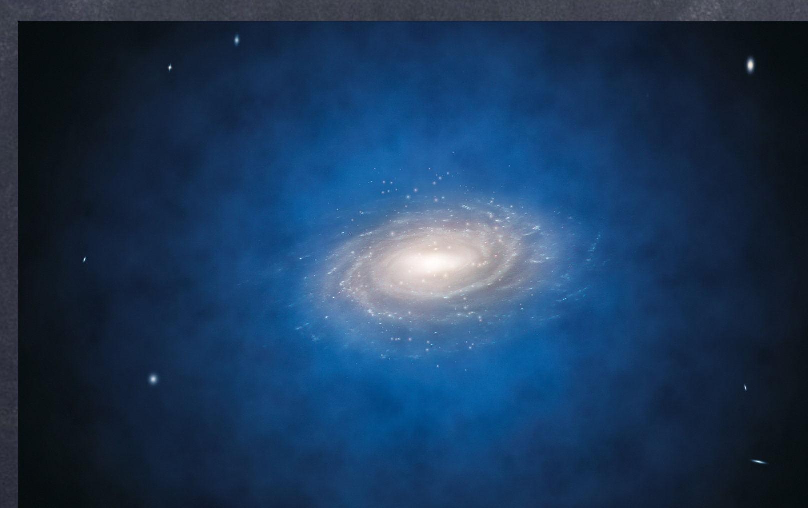




Galaxy clusters

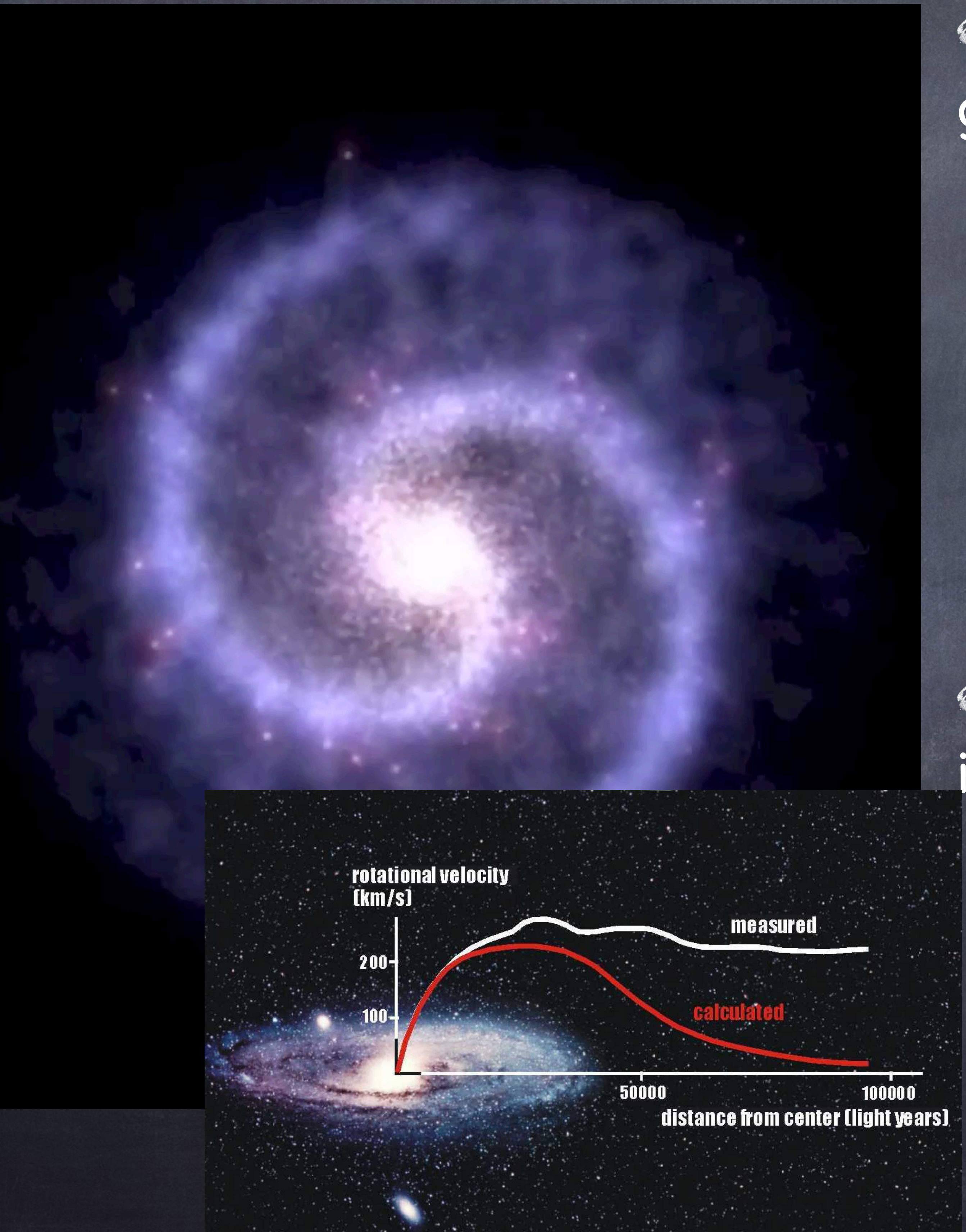


Galaxies



The Baryon Dictatorship

McGaugh, Lelli & Schombert, PRL (2017)



- Observe how baryons (stars & gas) are spatially distributed:

$$\rho_{\rm b} = \rho_* + \rho_{\rm gas}$$

Solve Poisson eq'n to infer baryonic acceleration:

$$\boxed{g_{\rm bar}}$$

- Observe how baryons rotate to infer centripetal acceleration:

$$\boxed{g_{\rm obs} = \frac{V^2}{r}}$$

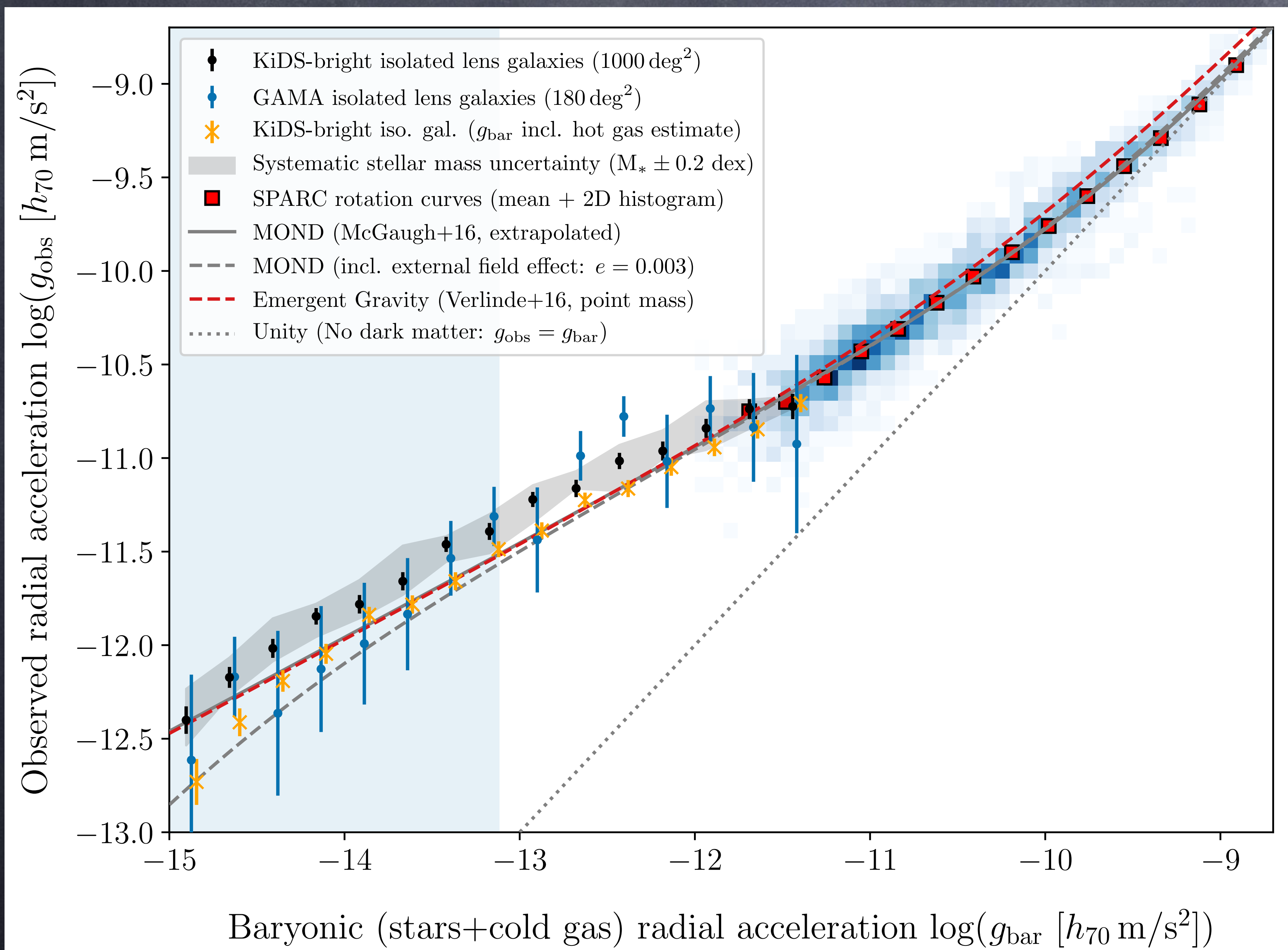
no assumption about DM or modified gravity

Radial Acceleration Relation (RAR)

McGaugh, Lelli & Schombert (2017)

Li, Lelli, McGaugh & Schombert (2018)

(Relation de l'Abominable Rugissement)



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

- Holds within 14% (0.057 dex).
- Upper bound on intrinsic scatter

Brouwer et al. (2021) [KiDS-1000 collaboration]

RAR was predicted by Milgrom nearly 40 years ago!

Milgrom (1983)

$$\boxed{a = \begin{cases} a_{\rm N} & a_{\rm N} \gg a_0 \\ \sqrt{a_{\rm N} a_0} & a_{\rm N} \ll a_0 \end{cases}}$$

$$a_{\rm N} = \frac{G_{\rm N} M_{\rm b}(r)}{r^2}$$

$$a_0 \simeq 1.2 \times 10^{-8}\ {\rm cm/s^2} \simeq \frac{1}{6} H_0$$

- Historically proposed as alternative to DM + interpreted as modification to Newtonian dynamics (MOND)

- But this is too extreme. Need DM for CMB, LSS, lensing, etc.

- Nevertheless a really powerful empirical statement about DM in galaxies

e.g. Milgrom predicted existence of low-surface brightness (LSB) galaxies!

MOND effective theory

Bekenstein & Milgrom (1984)

$$\boxed{\mathcal{L}_{\rm MOND} = -\frac{2}{3}\frac{M_{\rm Pl}^2}{a_0}(\partial\phi)^2\sqrt{|(\partial\phi)^2|} + \phi\rho_{\rm b}}$$

For static, spherically-symmetric source,

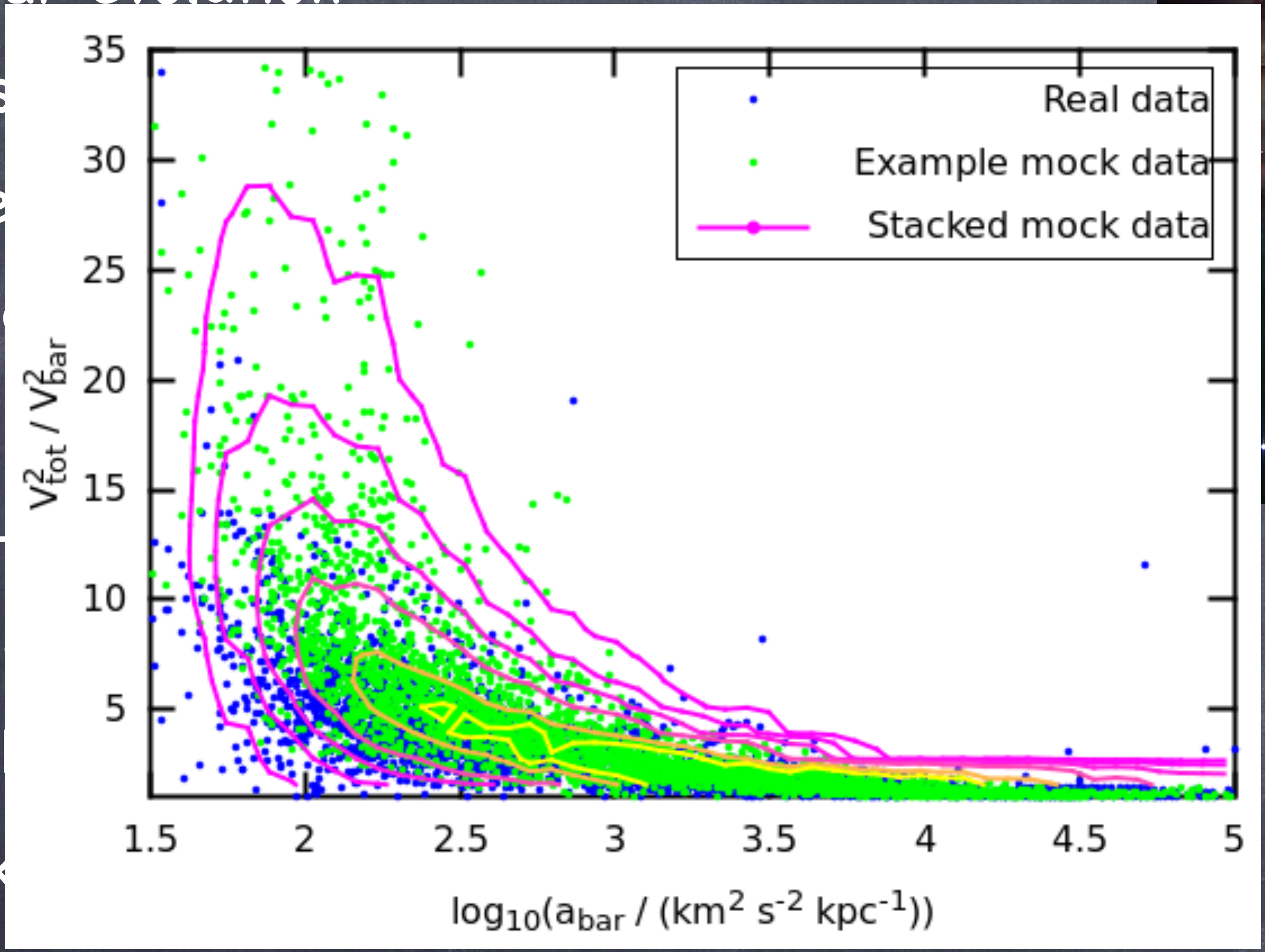
$$\vec{\nabla}\cdot\left(\frac{|\vec{\nabla}\phi|}{a_0}\vec{\nabla}\phi\right) = 4\pi G_{\rm N}\rho$$

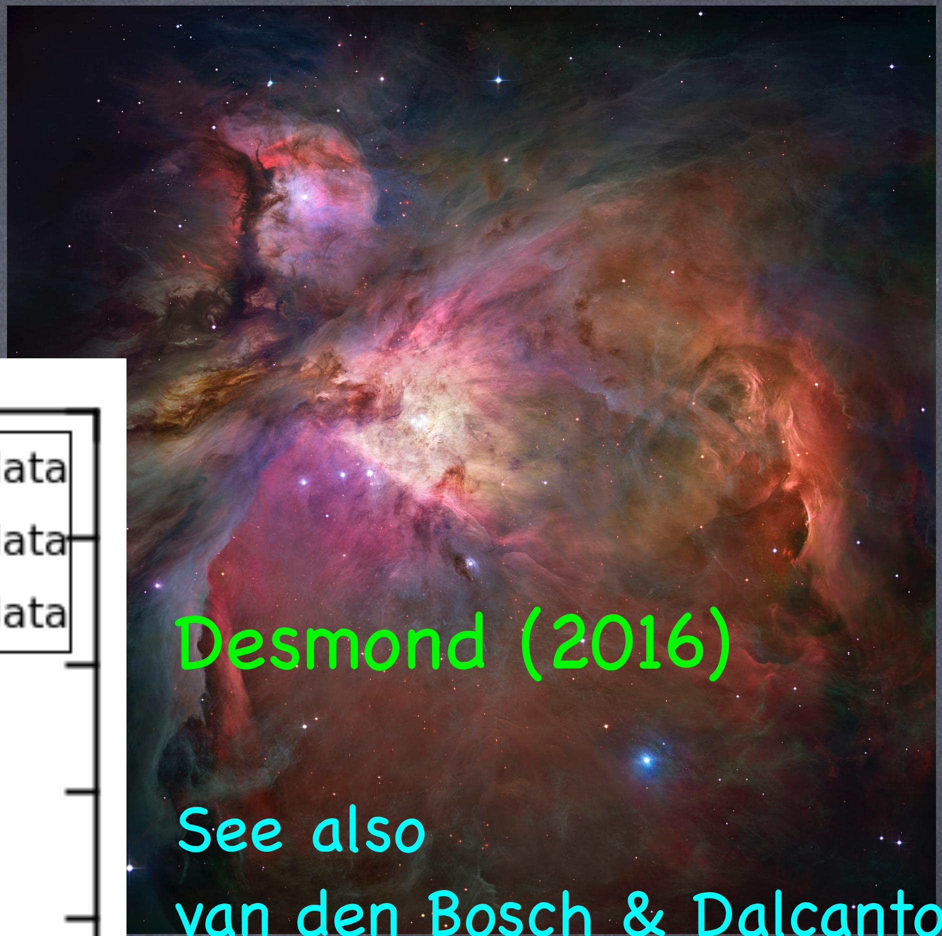
$$\Longrightarrow \qquad \phi' = \sqrt{a_0\frac{G_{\rm N}M(r)}{r^2}} = \sqrt{a_0 a_{\rm N}}$$

$$\Longrightarrow \qquad \boxed{a_{\rm tot} = a_{\rm N} + a_\phi = a_{\rm N} + \sqrt{a_0 a_{\rm N}}}$$

Orthodoxy: Feedback processes

- Star formation model
- Stellar evolution
- Mass
- Supe
- Gas (
- Cooli
- Self-
- Stell
- Local
- Black





Desmond (2016)

See also
van den Bosch & Dalcanton (2000);
Di Cintio & Lelli (2016);
Wheeler et al. (2019);
Grudic et al. (2020);
Paranjapee & Sheth (2021)

Can these feedback processes, which are inherently stochastic, result in tight correlation displayed in the MDAR?

The middle ground:

Blanchet (2006); Bruneton et al. (2008); Ho, Minic & Ng (2009); JK (2014)

- Dark matter exists and behaves like a cold, collisionless fluid on large scales.

- MOND empirical law originates in the fundamental nature of dark matter. It emerges from new interactions (beyond gravity) with ordinary matter.

e.g. New emergent long-range forces

DM superfluidity

Berezhiani & JK (2015, 2016)
Berezhiani, Famaey & JK (2017)

(Independent of MOND/MDAR motivation, the possibility of DM superfluidity is interesting and worth studying.)

e.g. New particle (contact) interactions

Famaey, JK & Penco (1712.01316)

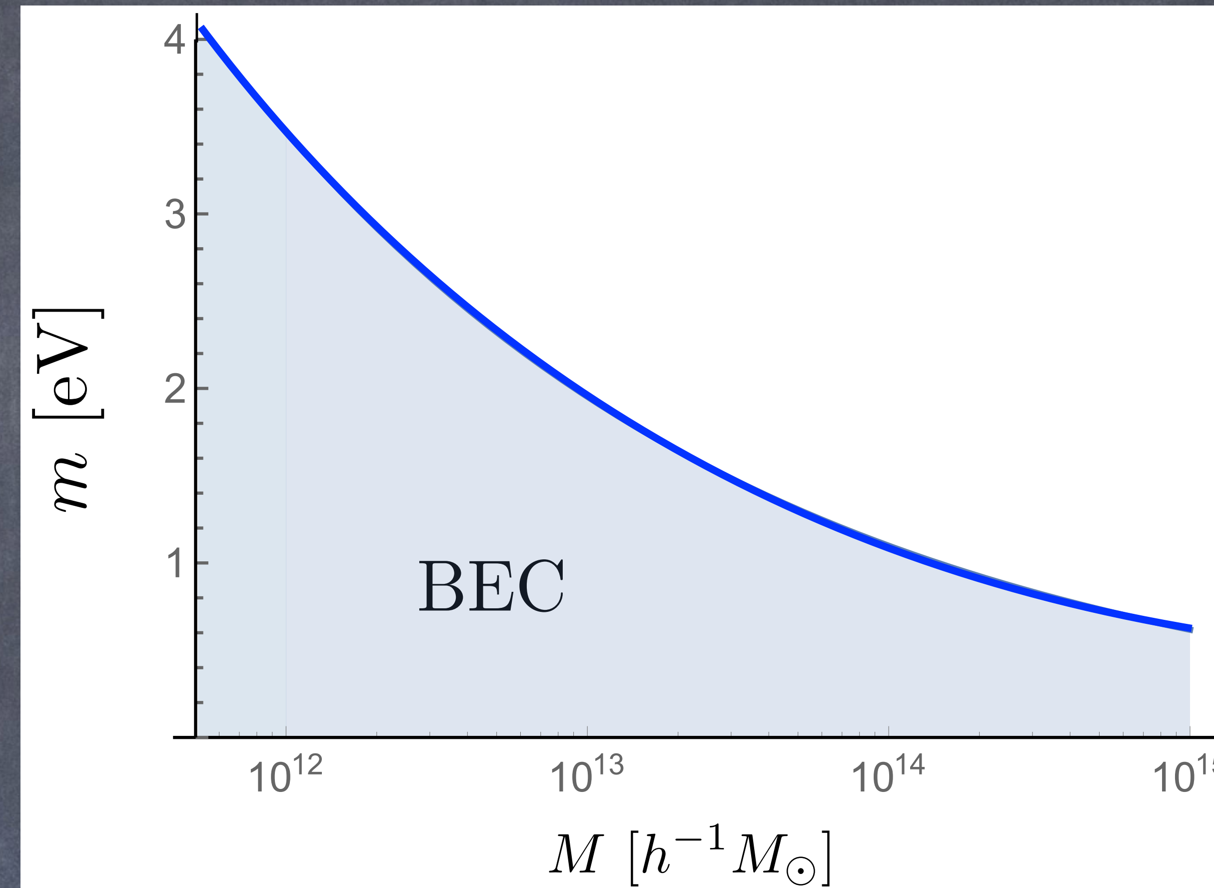

BBC FOUR

2 Conditions for DM Condensation

- Overlapping de Broglie wavelength

$$\lambda_{\rm dB} \sim \frac{1}{mv} \quad \gtrsim \quad \ell \sim \left(\frac{m}{\rho_{\rm vir}}\right)^{1/3}$$

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



- Thermal equilibrium

$$\Gamma \sim \mathcal{N} v \sigma \frac{\rho_{\rm vir}}{m} \gtrsim t_{\rm dyn}^{-1} \quad \Longrightarrow \quad \boxed{\frac{\sigma}{m} \gtrsim \left(\frac{m}{\rm eV}\right)^4 \frac{\rm cm^2}{g}}$$

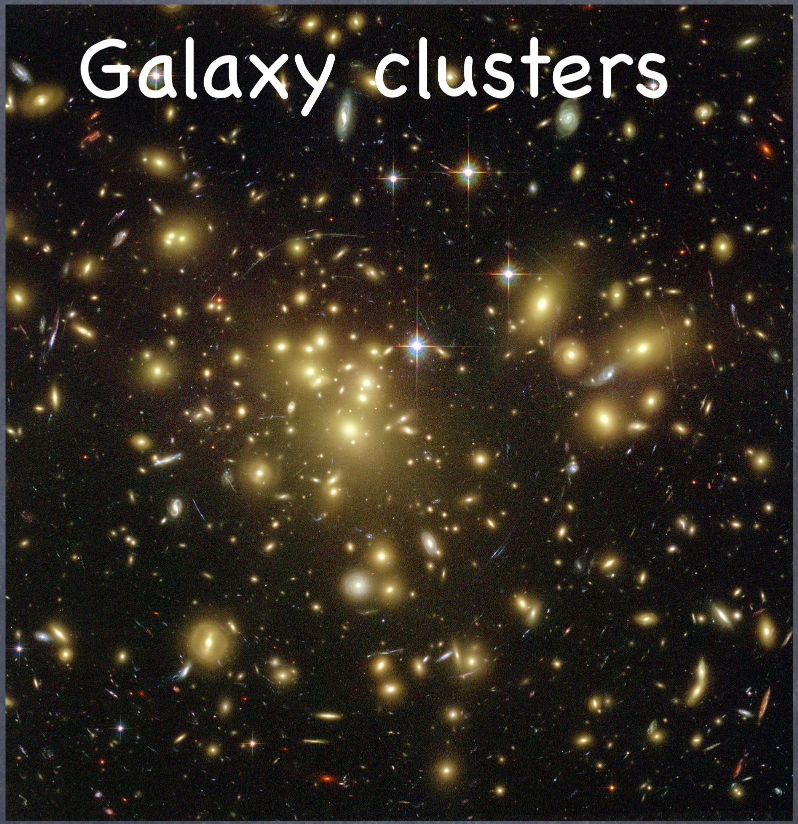
DM is quite cold:

$$T_{\rm c} = 6.5 \left(\frac{\rm eV}{m}\right)^{5/3} (1+z_{\rm vir})^2 \text{ mK}$$

(^{7}Li atoms $\Longrightarrow T_{\rm c} \sim 0.2$ mK)

Temperature set by how rapidly DM particles move

$$\boxed{T \sim m v^2}$$



$T_{\rm galaxy} \sim 0.1~{\rm mK}$

$\Longrightarrow$ Superfluid

$\Longrightarrow$ MOND

✓

$T_{\rm cluster} \sim 10~{\rm mK}$

$\Longrightarrow$ NO Superfluid

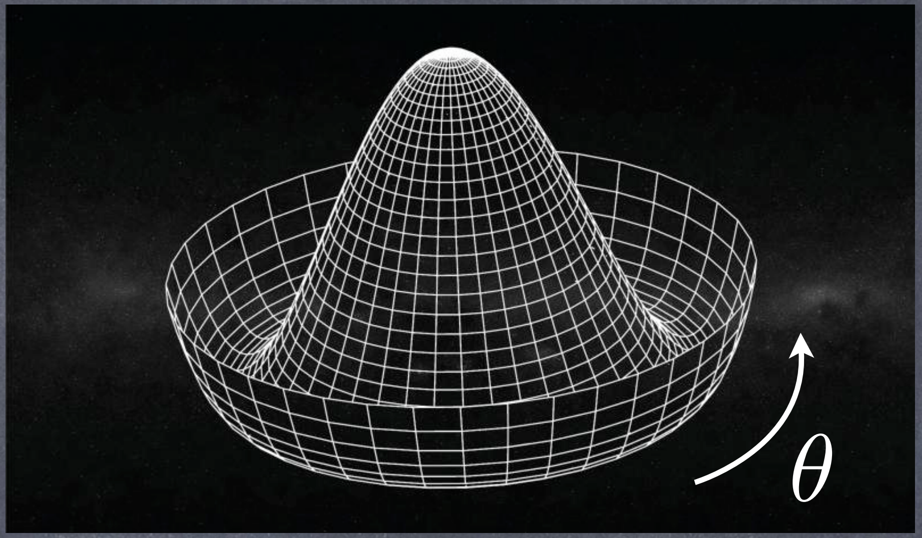
$\Longrightarrow$ NO MOND

✓

Naturally distinguishes between galaxies (where MOND works) and galaxy clusters (where MOND doesn't work).

Effective Description of Superfluids

Greiter, Wilczek & Witten (1989)



A superfluid phase is defined as:

- Global U(1) symmetry, spontaneously broken

$\Longrightarrow$ Goldstone boson $\theta \to \theta + c$

- State has finite charge density, $\langle J^0 \rangle \sim \langle \dot{\theta} \rangle \neq 0$

By redefining field, can set

$$\theta = \mu t + \phi$$

chemical potential phonons

Hence, at lowest order in derivatives the EFT of phonons is

$$\boxed{\mathcal{L} = P(X)\,; \qquad X = \mu + \dot{\phi} - \frac{(\vec{\nabla}\phi)^2}{2m}}$$

Effective Description of Superfluids

Greiter, Wilczek & Witten (1989)

$$\mathcal{L} = P(X)\,; \qquad X = \mu + \dot{\phi} - \frac{(\vec{\nabla}\phi)^2}{2m}$$

Conjecture: DM superfluid phonons are governed by MOND action

$$\boxed{P_{\rm MOND}(X) = \frac{2\Lambda(2m)^{3/2}}{3} X^{3/2}}$$

Phonons couple to baryons: $\mathcal{L}_{\rm coupling} = -\frac{\Lambda}{M_{\rm Pl}}\phi\rho_{\rm b}$

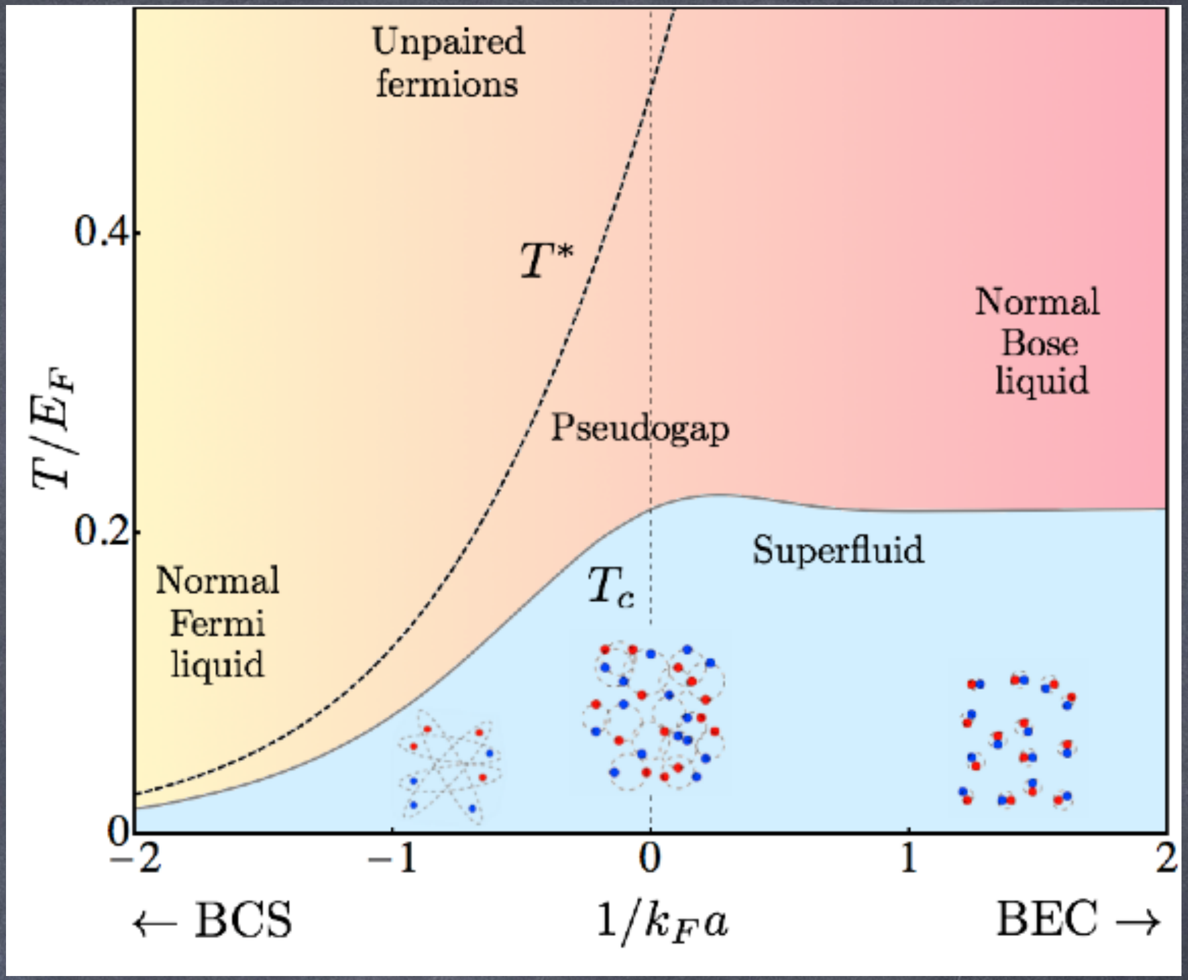
$$\Lambda = \sqrt{a_0 M_{\rm Pl}} \simeq 0.8 \text{ meV}$$

(Match to MOND scale)

- Cold Atoms Analogue?

$$\mathcal{L}_{\rm UFG} \sim m^{3/2} X^{5/2}$$

Son & Wingate (2005)



- 3-body interactions?

$$\mathcal{L} = \frac{i}{2}\left(\Psi \partial_t \Psi^* - \Psi^* \partial_t \Psi\right) - \frac{|\vec{\nabla}\Psi|^2}{2m} - \frac{\lambda}{24 m^3}|\Psi|^6$$

Split into $\Psi = \sqrt{2m\rho}\, e^{i\theta}$, and integrate out ρ ,

$$\Longrightarrow \quad \boxed{\mathcal{L} = \frac{4}{3}\frac{m^{3/2}}{\sqrt{\lambda}} X^{3/2}}$$

Equation of state

Action uniquely fixes (mean-field, zero temperature) equation of state through standard thermodynamic relations

- Pressure: $$P = \frac{2\Lambda}{3}(2m\mu)^{3/2}$$
- Number density: $$n = \frac{\partial P}{\partial \mu} = \Lambda(2m)^{3/2}\mu^{1/2}$$

$$\Longrightarrow \quad \boxed{P = \frac{1}{12\Lambda^2 m^3} n^3}$$

Generalized beyond mean-field and for $T \neq 0$

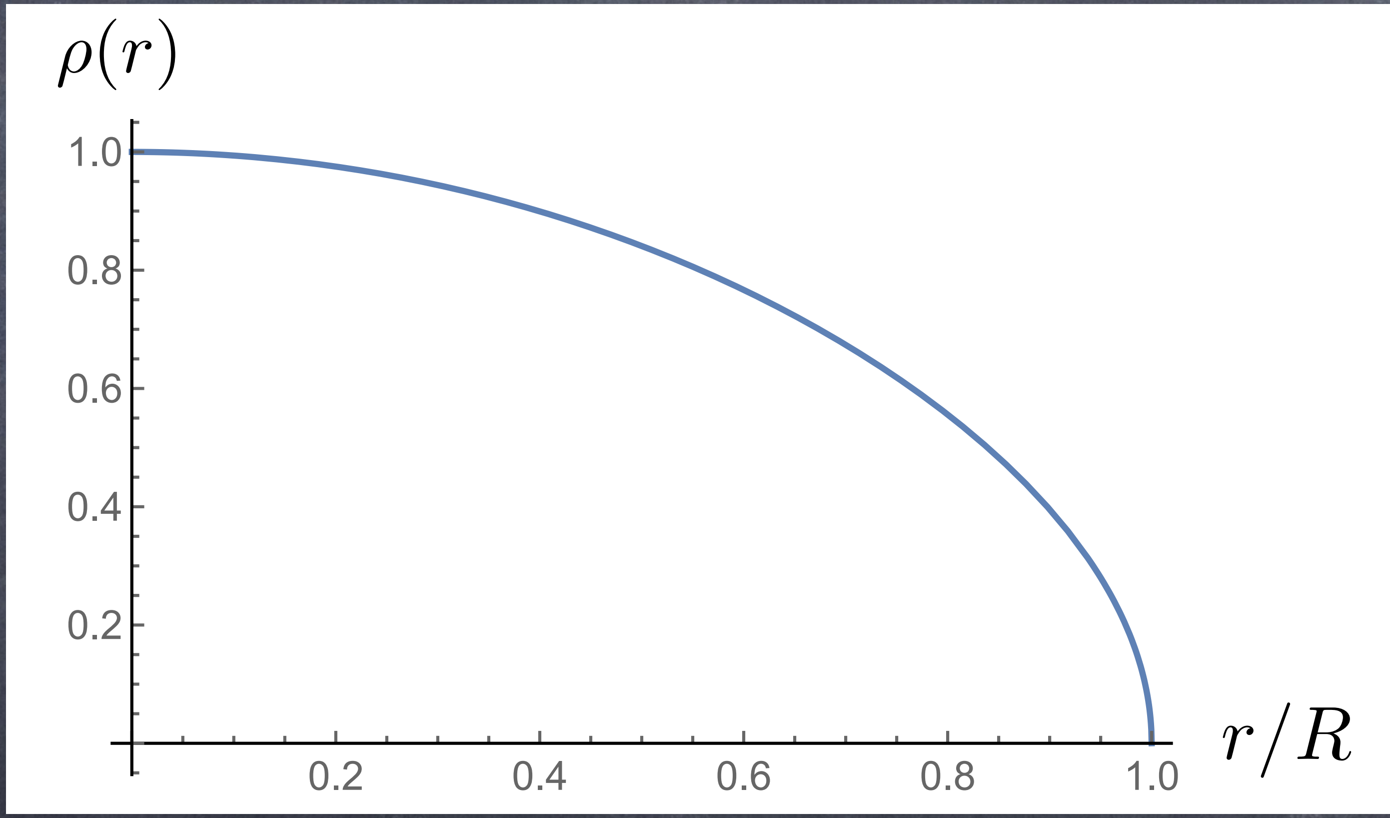
Sharma, Khoury & Lubensky, 1809.08286

Density profile (zero-temperature, DM only)

Assuming hydrostatic equilibrium,

$$\frac{1}{\rho}\frac{\mathrm{d}P}{\mathrm{d}r} = -\frac{4\pi G}{r^2}\int_0^r \mathrm{d}r'\, r'^2 \rho(r')$$

Using equation of state $P = \dfrac{\rho^3}{12\Lambda^2 m^6}$, find:



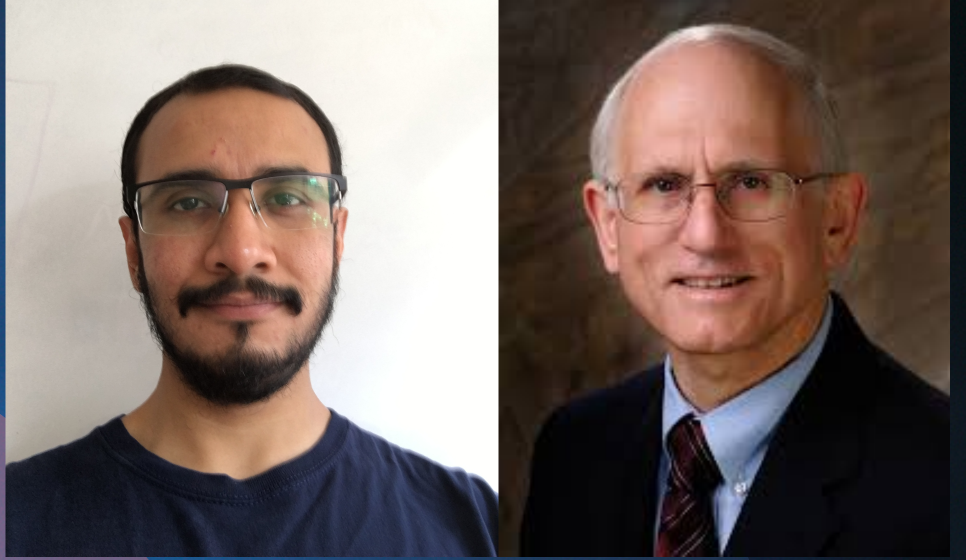
Cored density profile

$$\boxed{R = \left(\frac{M}{10^{12}\mathrm{M}_\odot}\right)^{1/5}\left(\frac{m}{\mathrm{eV}}\right)^{-6/5}\left(\frac{\Lambda}{\mathrm{meV}}\right)^{-2/5} 45\ \mathrm{kpc}}$$

Remarkably, realistic size cores with $m \sim \mathrm{eV}$ and $\Lambda \sim \mathrm{meV}$!

Finite-temperature density profile

Sharma, Khoury & Lubensky, 1809.08286



Superfluid DM

$\rho_{\rm s} \simeq \text{const.}$

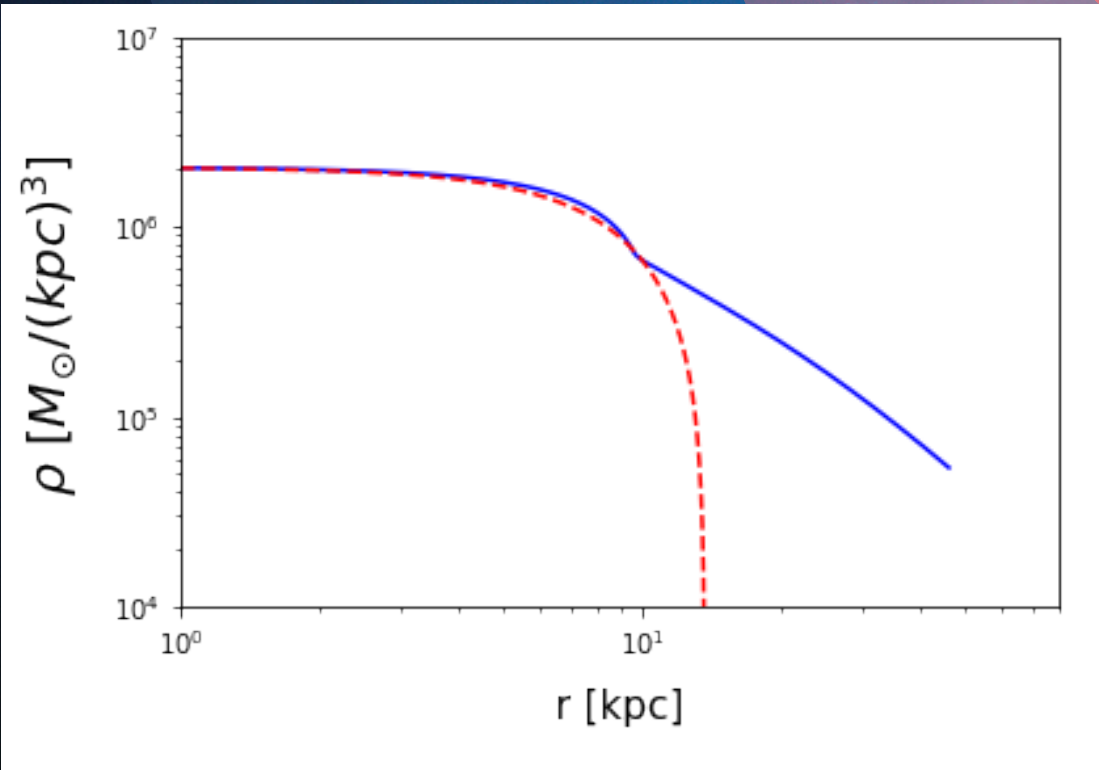
Collisionless

$\simeq$ NFW

$$\rho_{\rm NFW} = \frac{\rho_{\rm c}}{\frac{r}{r_s}\left(1+\frac{r}{r_s}\right)^2}$$

Isothermal

$$\rho_{\rm s} \sim \frac{1}{r^2}$$



Galactic rotation curves

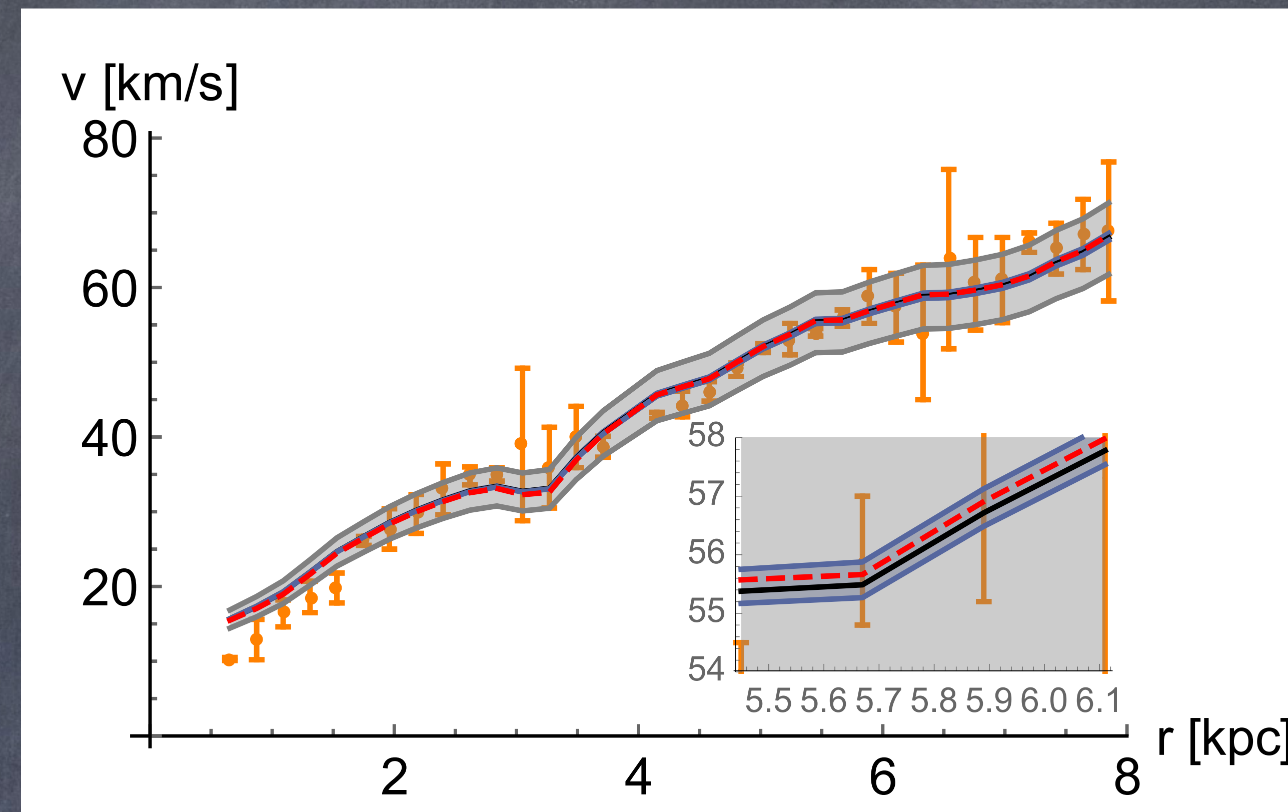
Berezhiani, Famaey & JK 1711.05748

$$\boxed{\vec{a} = \vec{a}_{\rm b} + \vec{a}_{\rm DM} + \vec{a}_{\rm phonon}}$$

$m = 1$ eV $\quad a_0 = 0.87 \times 10^{-8}$ cm/s^2

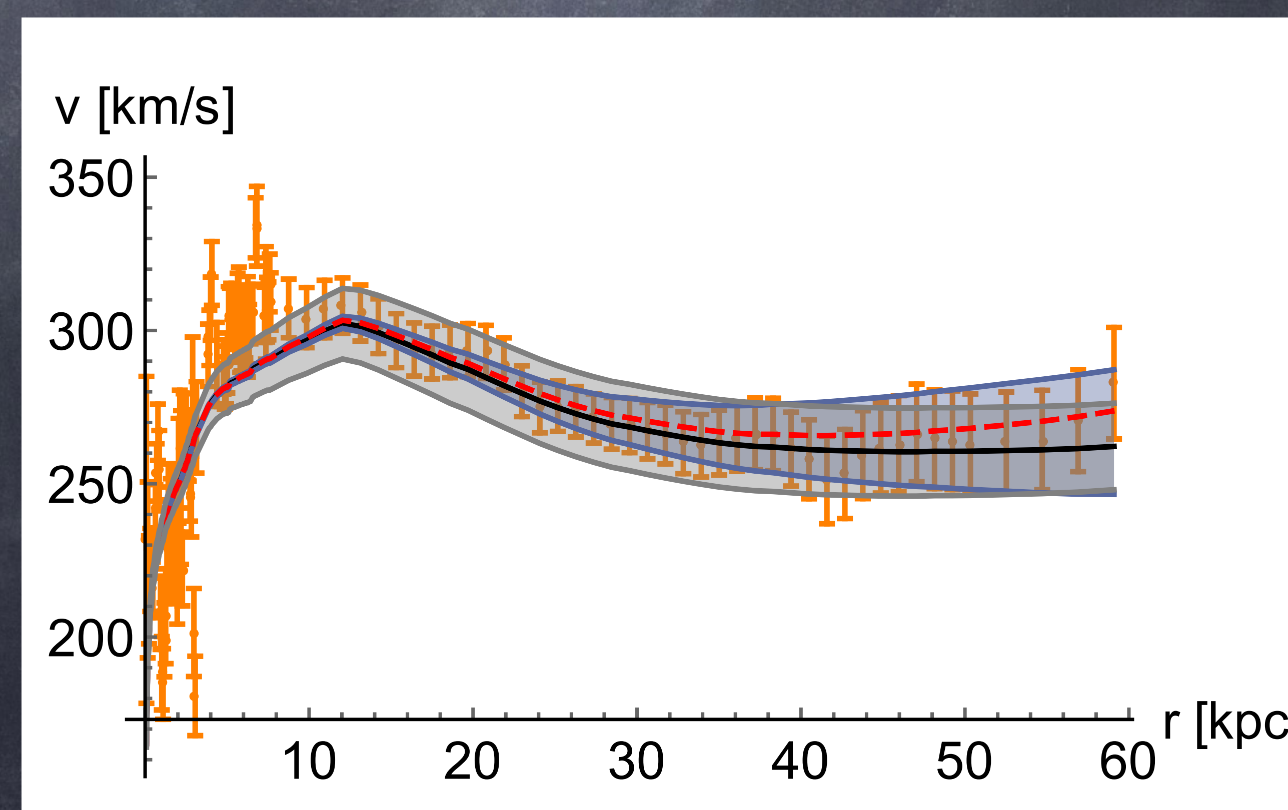
Low surface brightness (IC 2574)

$R_{\rm SF} = 40$ kpc



High surface brightness (UGC 2953)

$R_{\rm SF} = 76$ kpc



Observational Signatures

Galaxy me

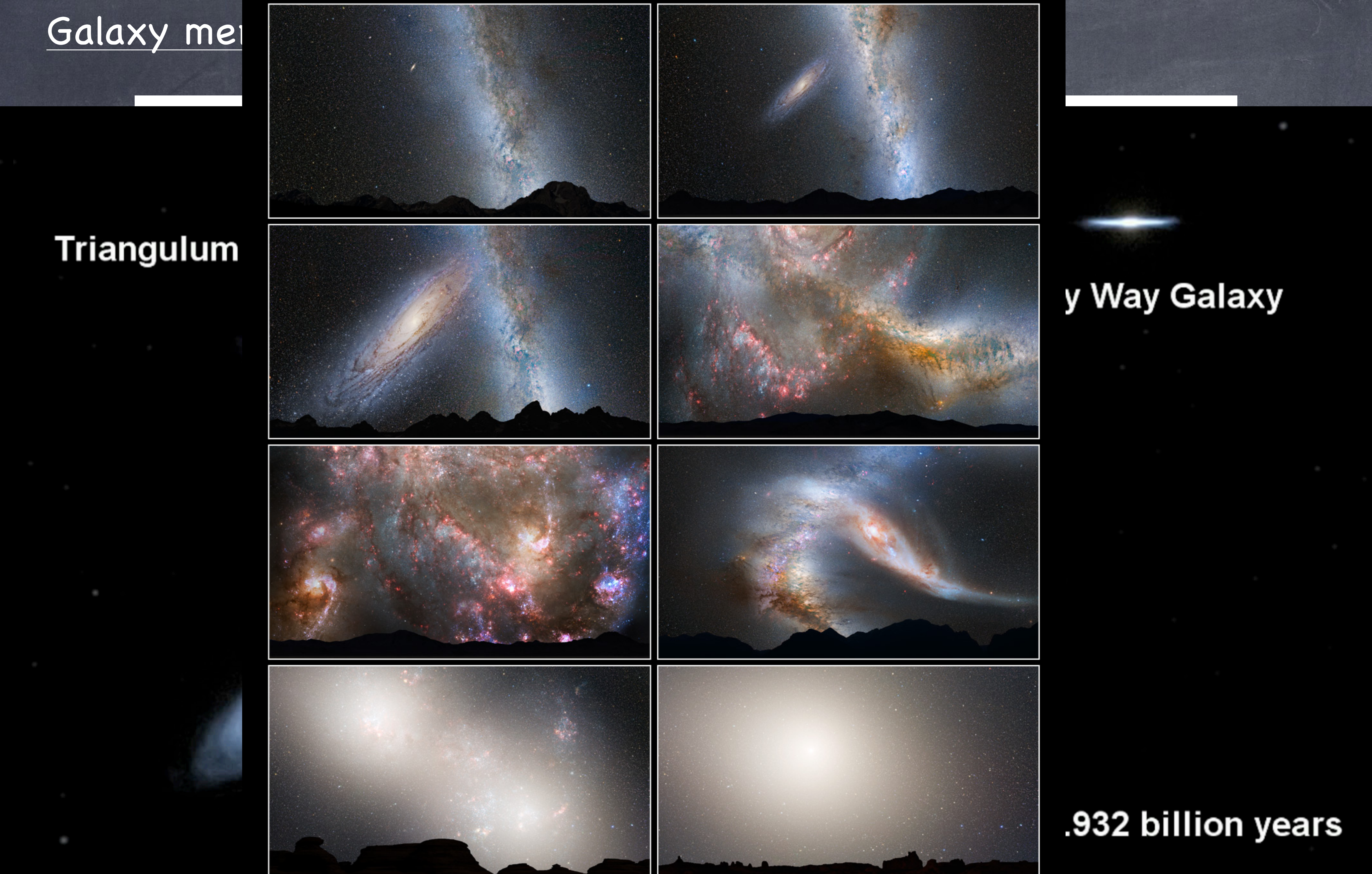
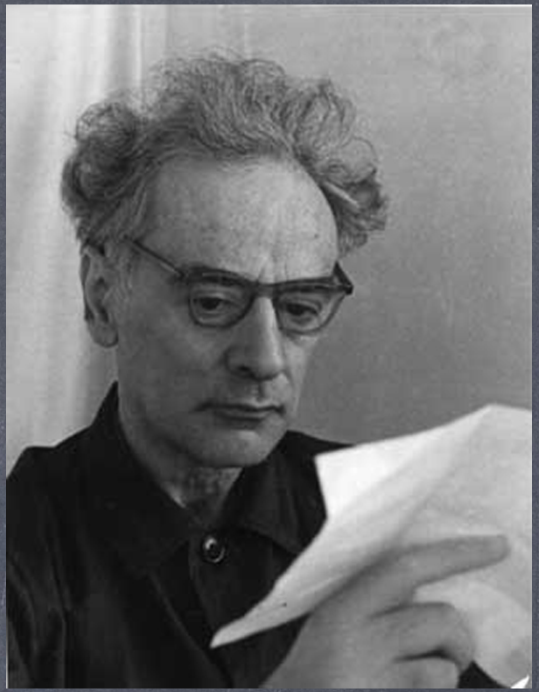


Illustration Sequence of the Milky Way
and Andromeda Galaxy Colliding

NASA, ESA, Z. Levay and R. van der Marel (STScI), T. Hallas, and A. Mellinger ▪ STScI-PRC12-20b

Dynamical friction in superfluids

Berezhiani, Elder & Khoury, 1905.09297



Superfluid cores should pass through each other with negligible dissipation if

$$v_{\rm infall} \lesssim c_s \qquad \text{(Landau's criterion)}$$

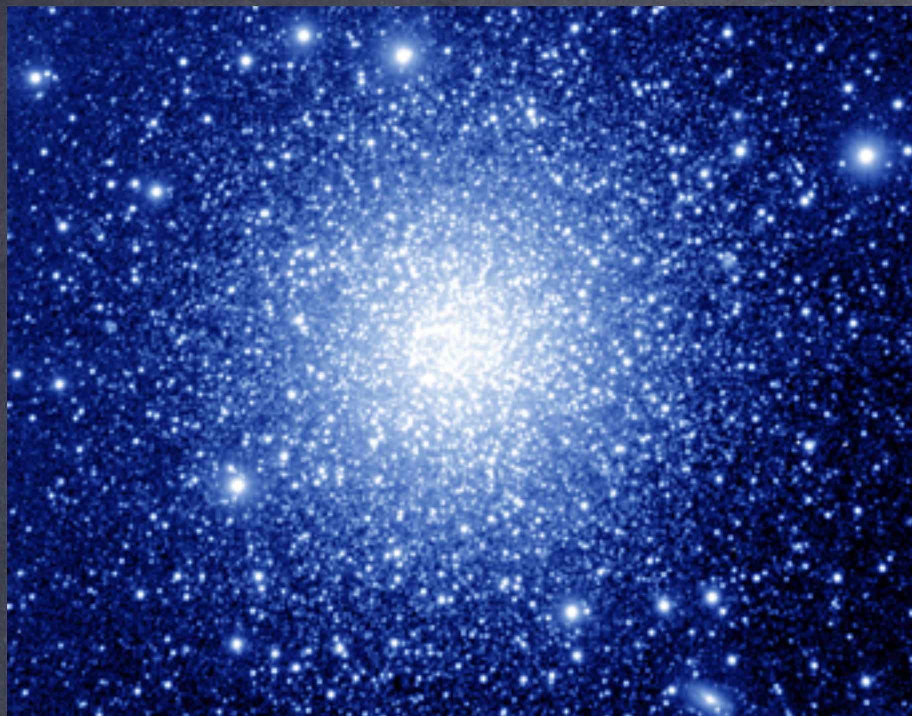
- If $v_{\rm infall} < c_s \sim 200\ {\rm km/s}$, then negligible dynamical friction between superfluids

$\Longrightarrow$ Longer merger time scale
+ multiple encounters

- If $v_{\rm infall} > c_s$, then encounter will excite DM particles out of the condensate, which will result in dynamical friction

$\Longrightarrow$ Merged halo thermalize and settle back to condensate

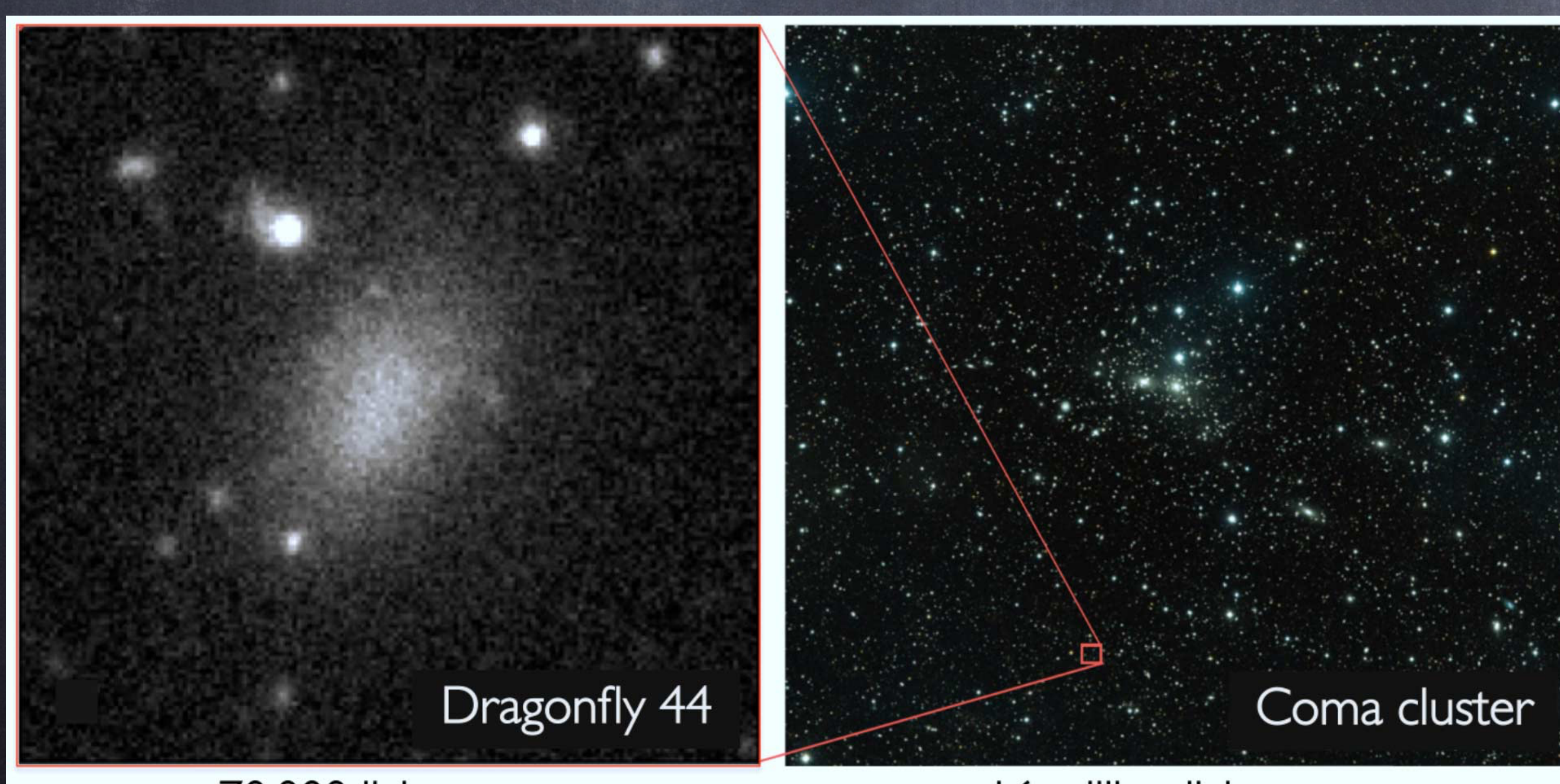
No DM $\Longrightarrow$ No MOND



Globular clusters

Ibata et al. (2011)

No superfluid $\Longrightarrow$ No external field effect



Ultra-diffuse galaxies

van Dokkum et al. (2015);
Koda et al. (2015);
Freunlich et al. (2021)

How does dark energy fit into the picture?

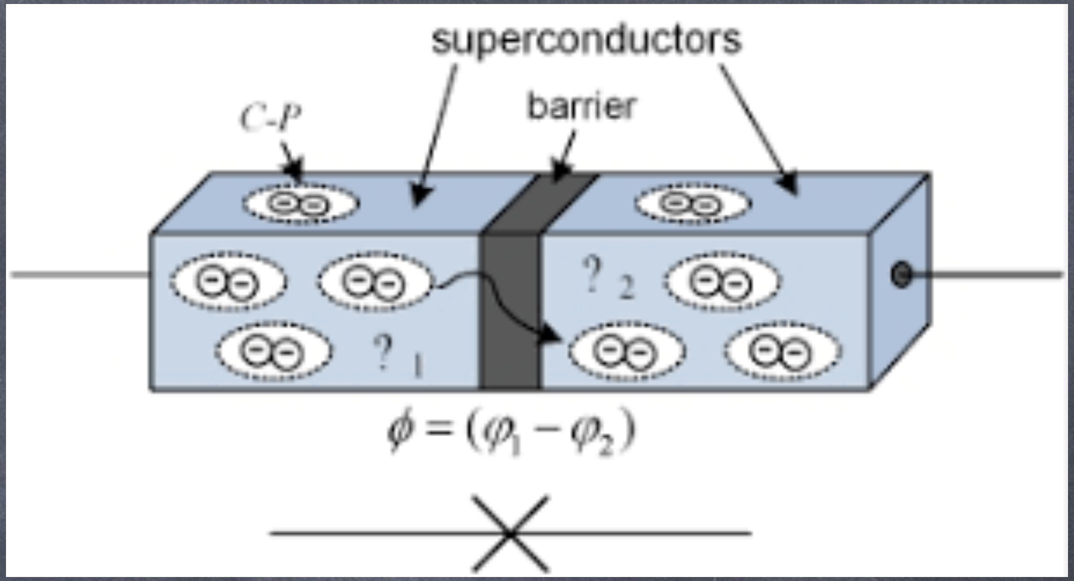
Unified Superfluid Dark Sector

Ferreira, Franzmann, Brandenberger & Khoury, 1810.09474

Mixture of 2 superfluids, e.g. DM ground state + excited state, with energy difference

$$\delta E = E_1 - E_0$$

$$\Longrightarrow \quad \mathcal{L} = P_0(X_0) + P_1(X_1)$$



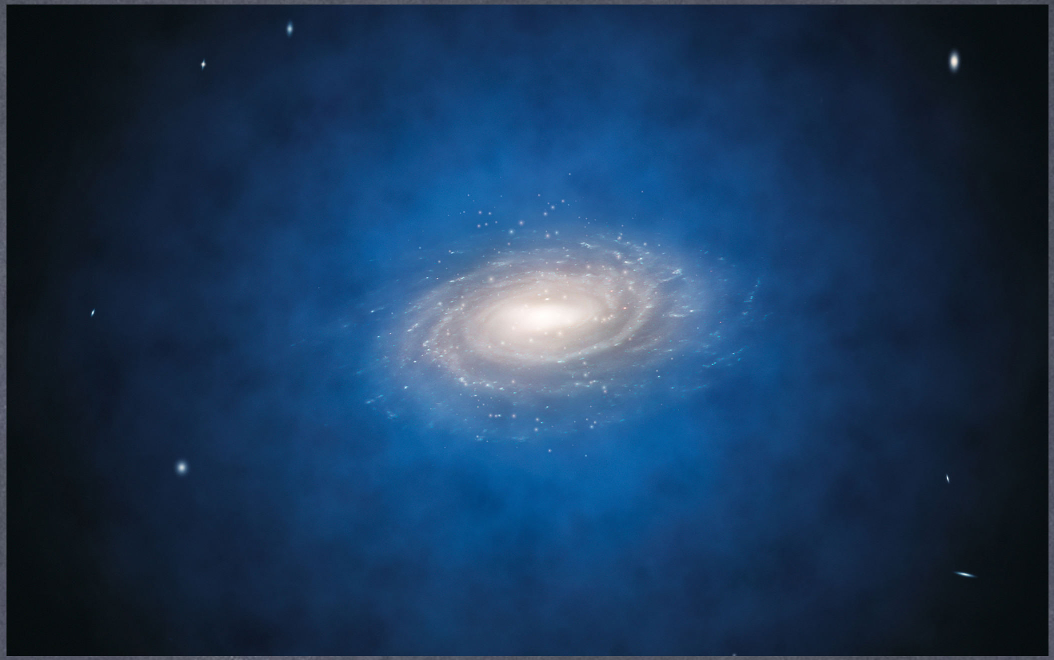
Interact through Rabi/Josephson coupling:

$$\mathcal{L}_{\rm int} \sim \Psi_0^\star \Psi_1 + \Psi_0 \Psi_1^\star$$

$$\Longrightarrow \quad \boxed{V(\theta_1, \theta_2) = \Lambda^4 \cos^2\left(\frac{\theta_1 - \theta_2 + \delta E\, t}{2f}\right) \simeq \Lambda^4 \cos^2\left(\frac{\delta E\, t}{2f}\right)}$$

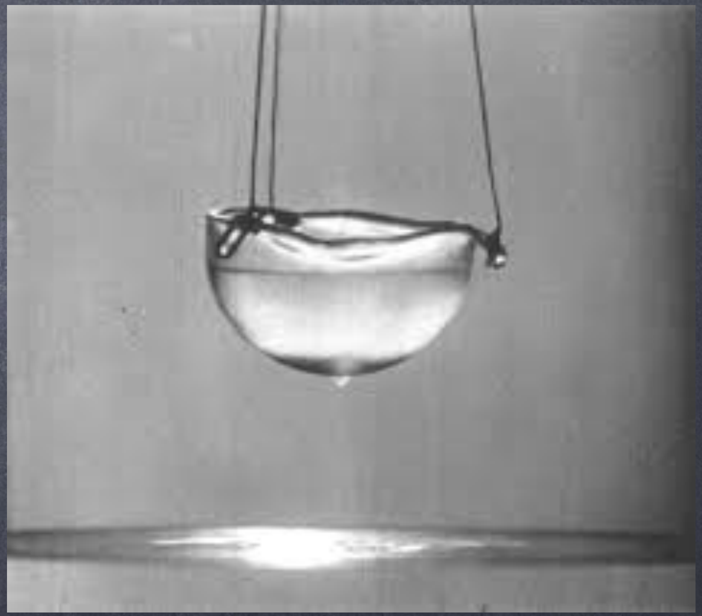
Interaction potential energy drives cosmic acceleration

Conclusions



- Cold, collisionless DM works exquisitely well on largest scales, but tight scatter of galactic scaling relations remains puzzling

- In my view, this suggests new physics: New emergent long-range interactions



- Dark Matter superfluidity:
  - Dark matter and MOND as different phases of same substance
  - Rich possible implications for galaxy mergers

- Open question:

  Can we find a precise analogue with cold atoms?