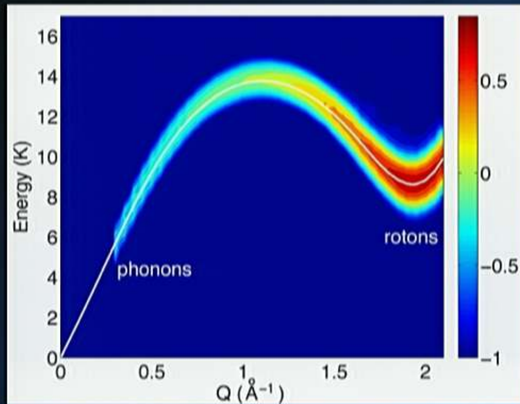
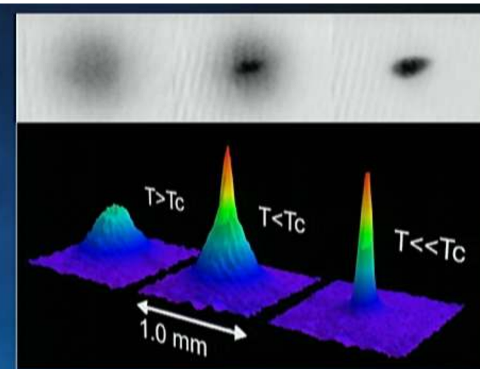
Title: A Dark Matter of Superfluid

Date: Jun 14, 2016 02:30 PM

URL: http://pirsa.org/16060008

Abstract:





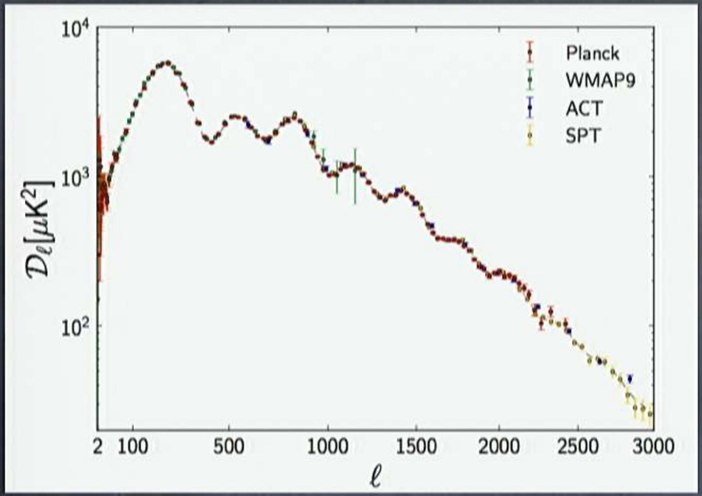
A Dark Matter Superfluid

Justin Khoury (U. Penn)

JK, 1409.0012, 1602.05691
L. Berezhiani & JK, 1506.07877 + 1507.01019

Ongoing work with
B. Elder, B. Famaey, T. Lubensky, V. Miranda, D. Mota, A. Sharma,
J. Wang, H. Winther, H. Zhao

The coarse-grained success



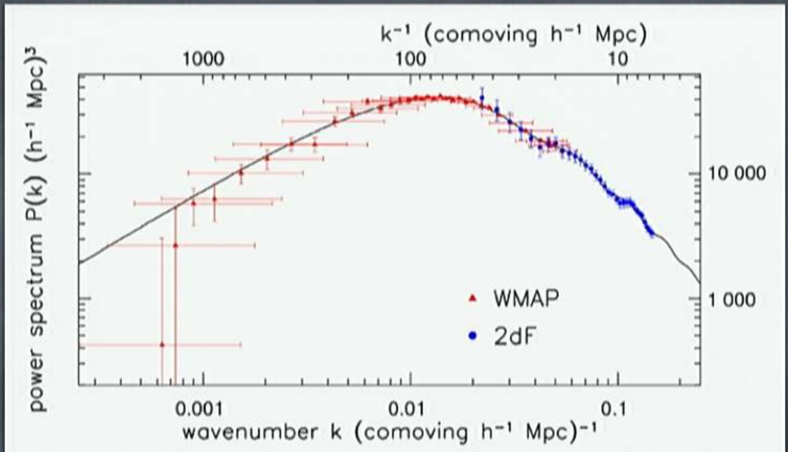


Fig 8.17 (A. Sanchez) 'Galaxies in the Universe' Sparke/Gallagher CUP 2007

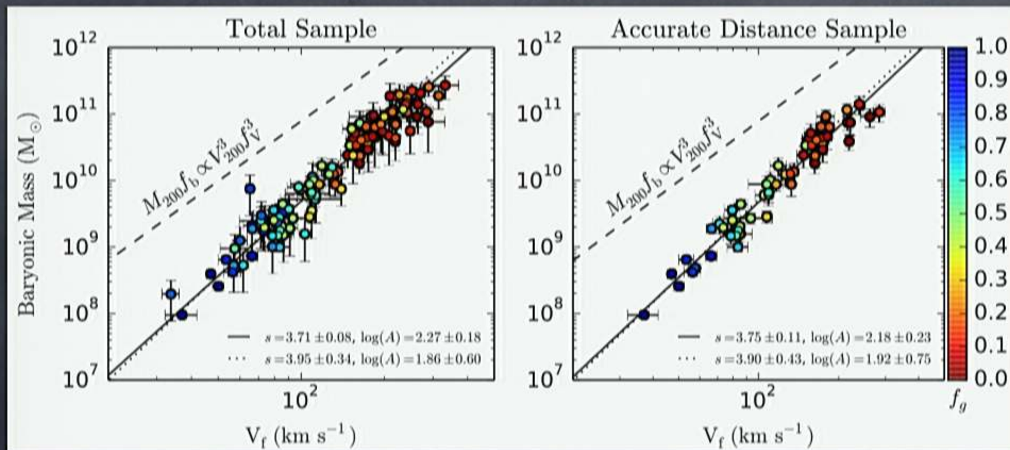
- On large (linear) scales, only use the hydrodynamical limit of DM

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

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

Plenty of room for new physics on galactic scales

- Baryonic Tully-Fisher relation McGaugh (2015)

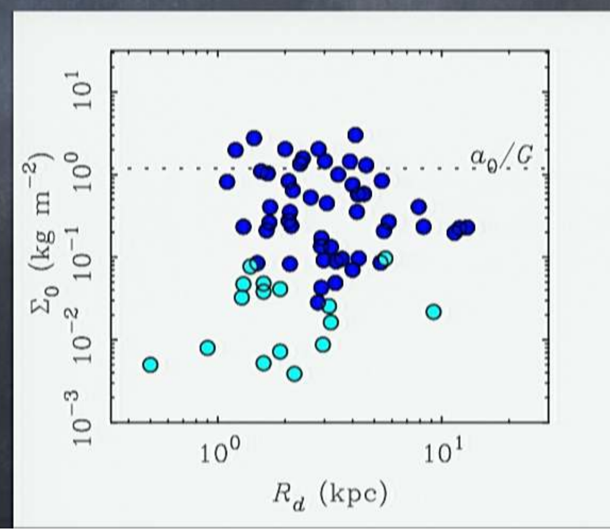


$$v_{\rm flat}^4 = a_0 G_{\rm N} M_{\rm b}$$

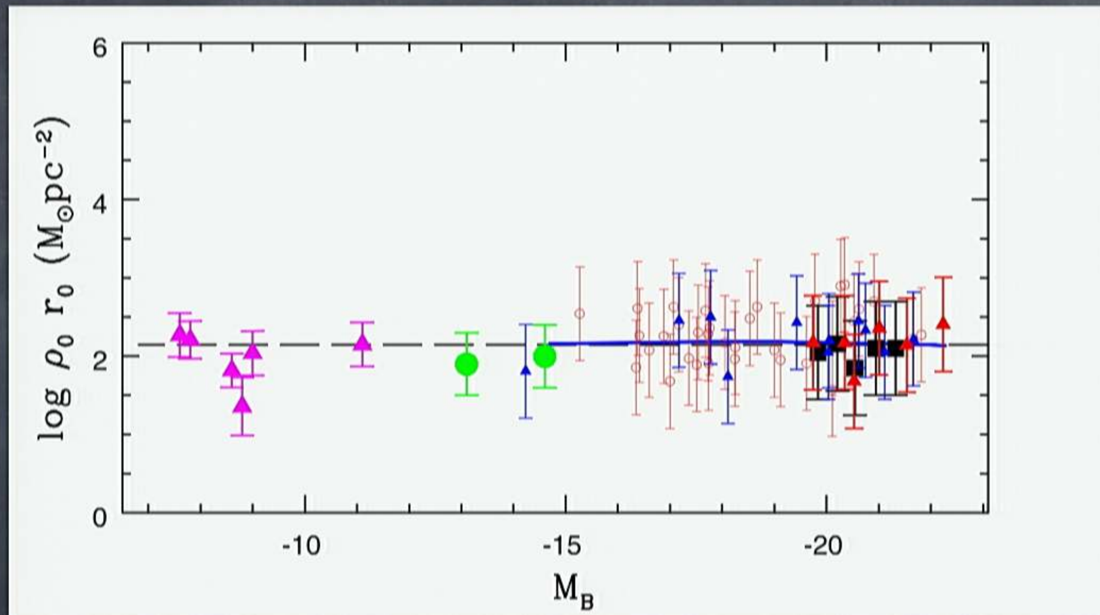
$$a_0 = 1.2 \times 10^{-8}\ {\rm cm/s^2}$$

- Freeman limit

$$\Sigma \lesssim \frac{a_0}{G_{\rm N}}$$



- Universal DM central "surface brightness" Donato et al. (2009)

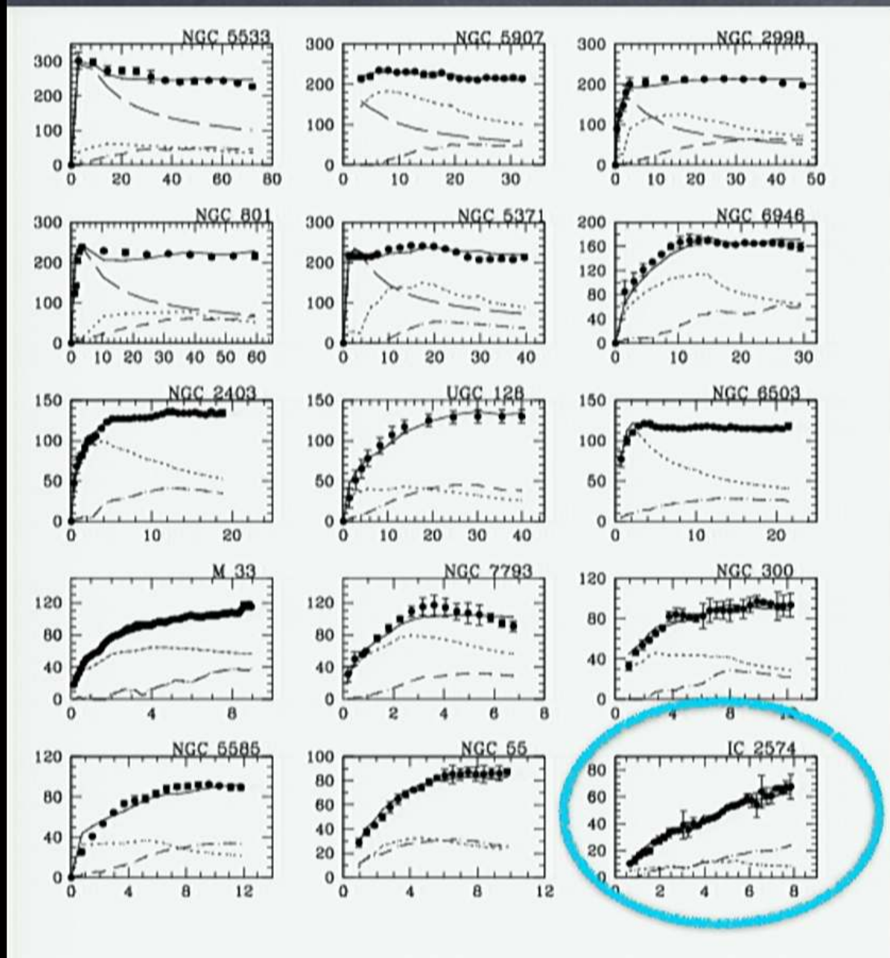


$$\rho_0 r_0 = 140^{+80}_{-30}\ M_\odot/\mathrm{pc}^2$$

Note: $$\frac{a_0}{2\pi G_\mathrm{N}} = 138\ M_\odot/\mathrm{pc}^2$$

Milgrom's empirical law (NOT theory)

Milgrom (1983)



$$a = \begin{cases} a_N & a_N \gg a_0 \\ \sqrt{a_N a_0} & a_N \ll a_0 \end{cases}$$

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

BTFR and Freeman's law both follow.

Those are facts.

The acceleration scale a_0 is in the data.

Can take one of 3 attitudes...

One extreme: It's all feedback!

- Star formation model
- Stellar evolution
- Mass and metal return
- Supernovae rates
- Gas enrichment
- Cooling and heating rates
- Self-shielding
- Stellar feedback
- Local and non-local SNII feedback
- Black hole and AGN feedback

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

One extreme: It's all feedback!

- Star formation model
- Stellar evo
- Mass and
- Supernova
- Gas enrich
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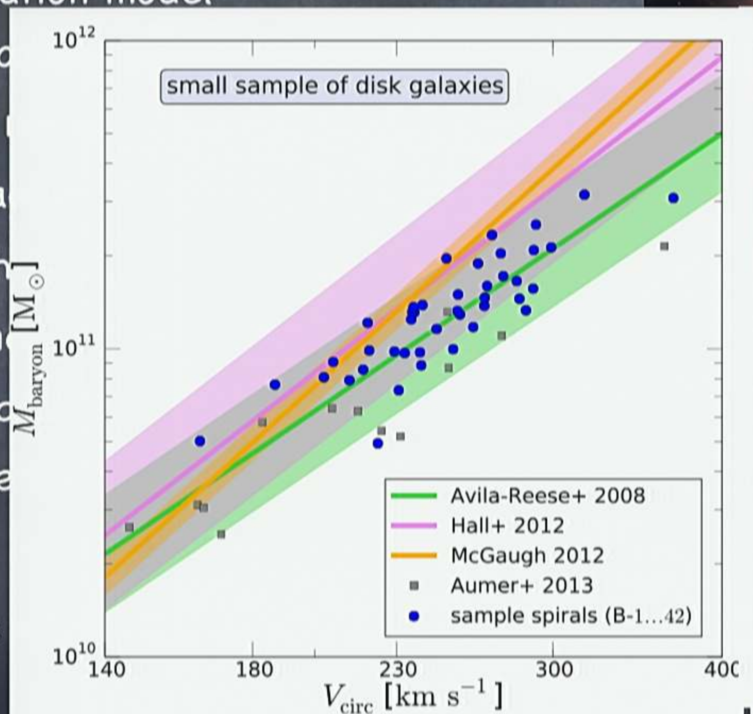
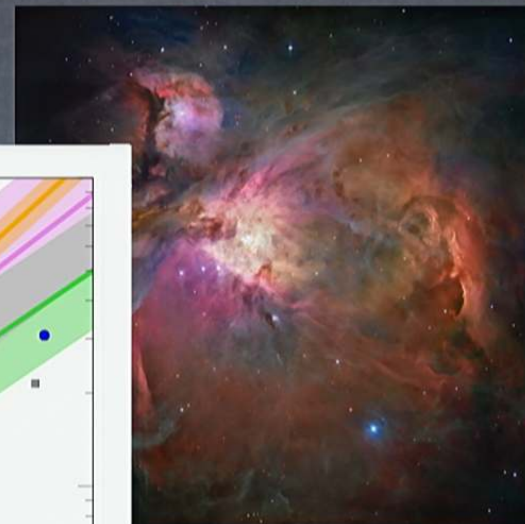
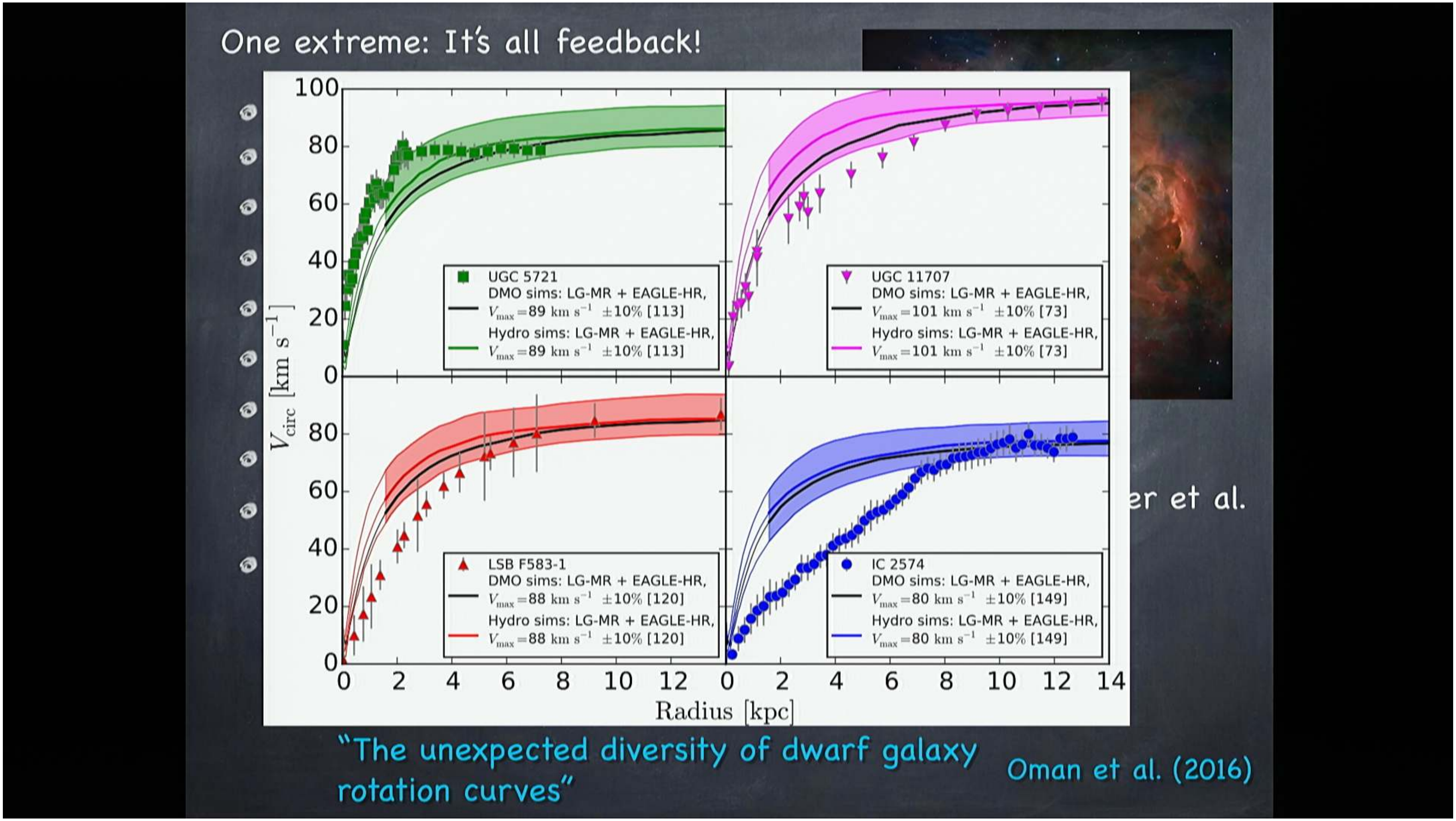




Vogelsberger et al. (2014)

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


One extreme: It's all feedback!
UGC 5721
DMO sims: LG-MR + EAGLE-HR, Vmax = 89 km s−1 ±10% [113]
Hydro sims: LG-MR + EAGLE-HR, Vmax = 89 km s−1 ±10% [113]
UGC 11707
DMO sims: LG-MR + EAGLE-HR, Vmax = 101 km s−1 ±10% [73]
Hydro sims: LG-MR + EAGLE-HR, Vmax = 101 km s−1 ±10% [73]
LSB F583-1
DMO sims: LG-MR + EAGLE-HR, Vmax = 88 km s−1 ±10% [120]
Hydro sims: LG-MR + EAGLE-HR, Vmax = 88 km s−1 ±10% [120]
IC 2574
DMO sims: LG-MR + EAGLE-HR, Vmax = 80 km s−1 ±10% [149]
Hydro sims: LG-MR + EAGLE-HR, Vmax = 80 km s−1 ±10% [149]
Vcirc [km s−1]
Radius [kpc]
er et al.
"The unexpected diversity of dwarf galaxy rotation curves"
Oman et al. (2016)

The other extreme: it's all modified gravity!

MOND is described by the effective theory:

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

Bekenstein & Milgrom (1984)

MOND? For static, spherically-symmetric source,

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

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

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

The middle ground:

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

The middle ground:

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

- MOND empirical law originates in the fundamental nature of dark matter

e.g. in this talk: DM superfluidity


BBC FOUR


BBC FOUR

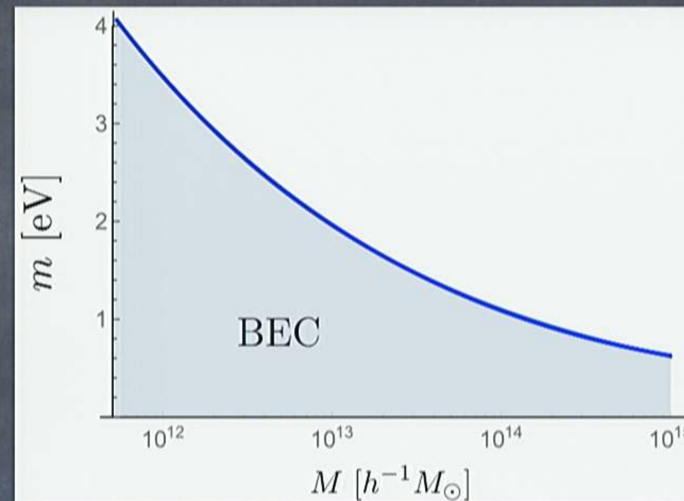

BBC FOUR

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

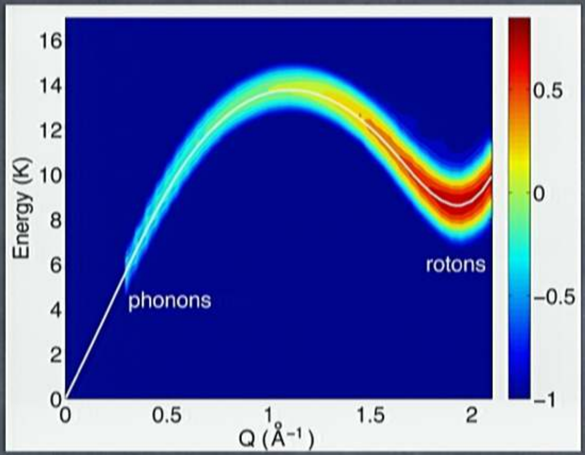
$$\Gamma \sim \mathcal{N} v \sigma \frac{\rho_{\rm vir}}{m} \gtrsim t_{\rm dyn}^{-1} \quad \Longrightarrow \quad \boxed{\frac{\sigma}{m} \gtrsim \left(\frac{m}{\rm eV}\right)^4 \frac{\rm cm^2}{g}}$$

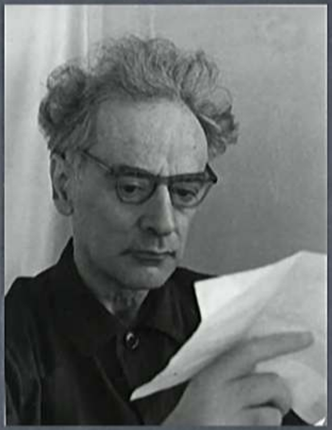
Current bound: $\frac{\sigma}{m} \lesssim 0.5 \frac{\rm cm^2}{g}$ Harvey et al. (2015)

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)

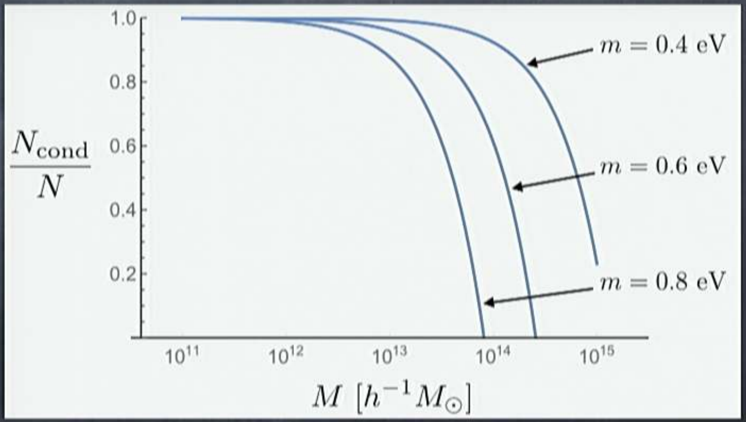
Two-fluid model





Free bose gas:

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



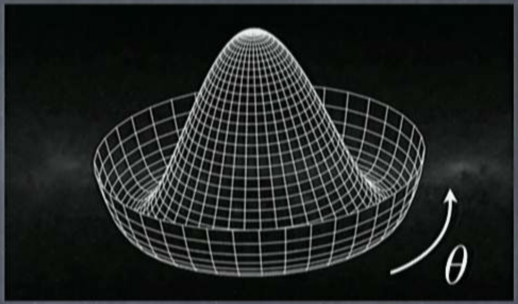
- Galaxies are mostly condensed
- Galaxy clusters are in mixed or normal phase

Can generalize to include interactions.

Khoury, Lubensky, Miranda & Sharma (to appear)

Effective Description of Superfluids

Greiter, Wilczek & Witten (1989)



A superfluid phase is defined as:

- Global U(1) symmetry, spontaneously broken

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

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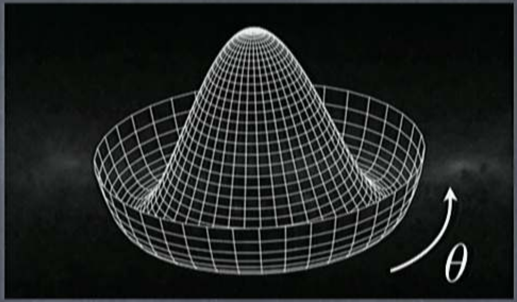
Greiter, Wilczek & Witten (1989)



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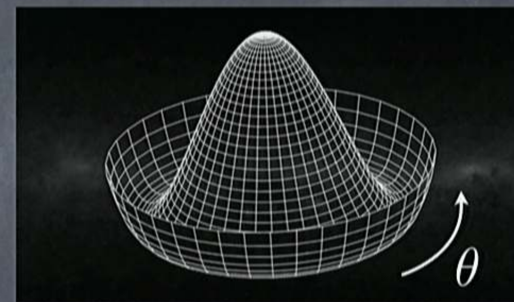

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- Global U(1) symmetry, spontaneously broken

  $\Longrightarrow$ 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 (μt) — phonons (ϕ)

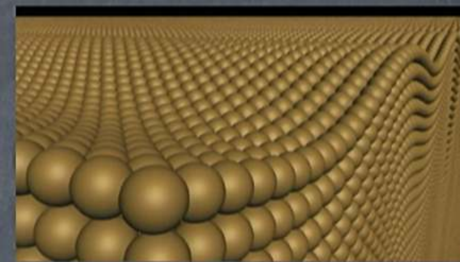
Hence, at lowest order in derivatives the EFT of phonons is

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

Superfluid phonons

At lowest order in derivatives, the zero temperature effective action is

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



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

Conjecture: DM superfluid phonons are governed by MOND action

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

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

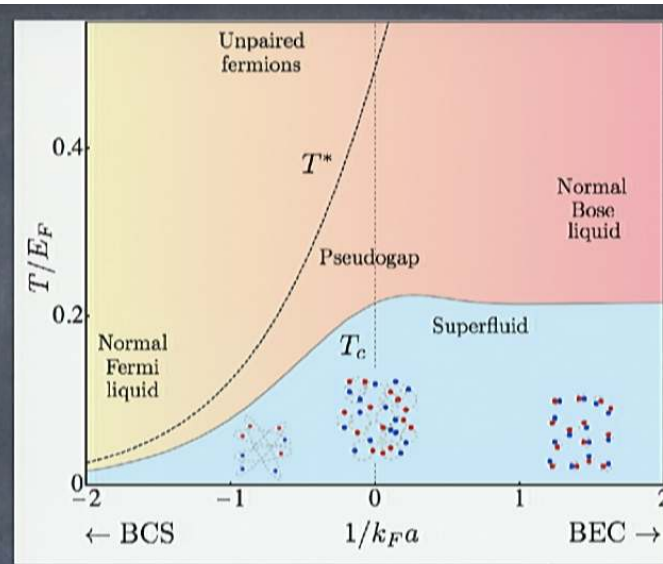
$$\Lambda = \sqrt{a_0 M_{\rm Pl}} \simeq 0.8 \text{ meV}$$

(Match to MOND scale)

- Cold Atoms Analogue?

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

Son & Wingate (2005)



- 3-body interactions?

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

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

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

Condensate properties

Action uniquely fixes properties of the condensate through standard thermodynamics

- Pressure: $$P_{\rm cond} = \frac{2\Lambda}{3}(2m\mu)^{3/2}$$
- Number density: $$n_{\rm cond} = \frac{\partial P_{\rm cond}}{\partial \mu} = \Lambda(2m)^{3/2}\mu^{1/2}$$

In the non-relativistic approx'n, $\rho_{\rm cond} = m n_{\rm cond}$, therefore:

$$\boxed{P_{\rm cond} = \frac{\rho^3_{\rm cond}}{12\Lambda^2 m^6}}$$

- Polytropic equation of state, with index $n = 1/2$
- Different than BEC DM, where $P_{\rm cond} \sim \rho^2_{\rm cond}$

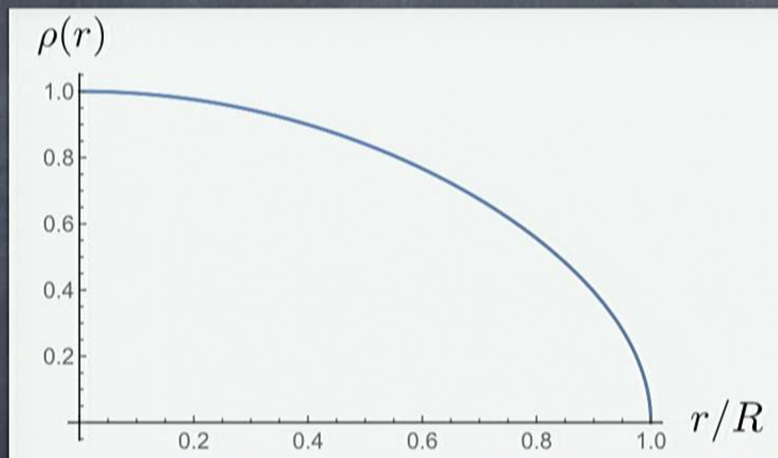
Sin (1994), Goodman (2000), Peebles (2000), Boehmer & Harko (2007)

Density profile

Assuming hydrostatic equilibrium,

$$\frac{1}{\rho_{\rm cond}(r)}\frac{{\rm d}P_{\rm cond}(r)}{{\rm d}r} = -\frac{4\pi G_{\rm N}}{r^2}\int_0^r {\rm d}r' r'^2 \rho(r')$$

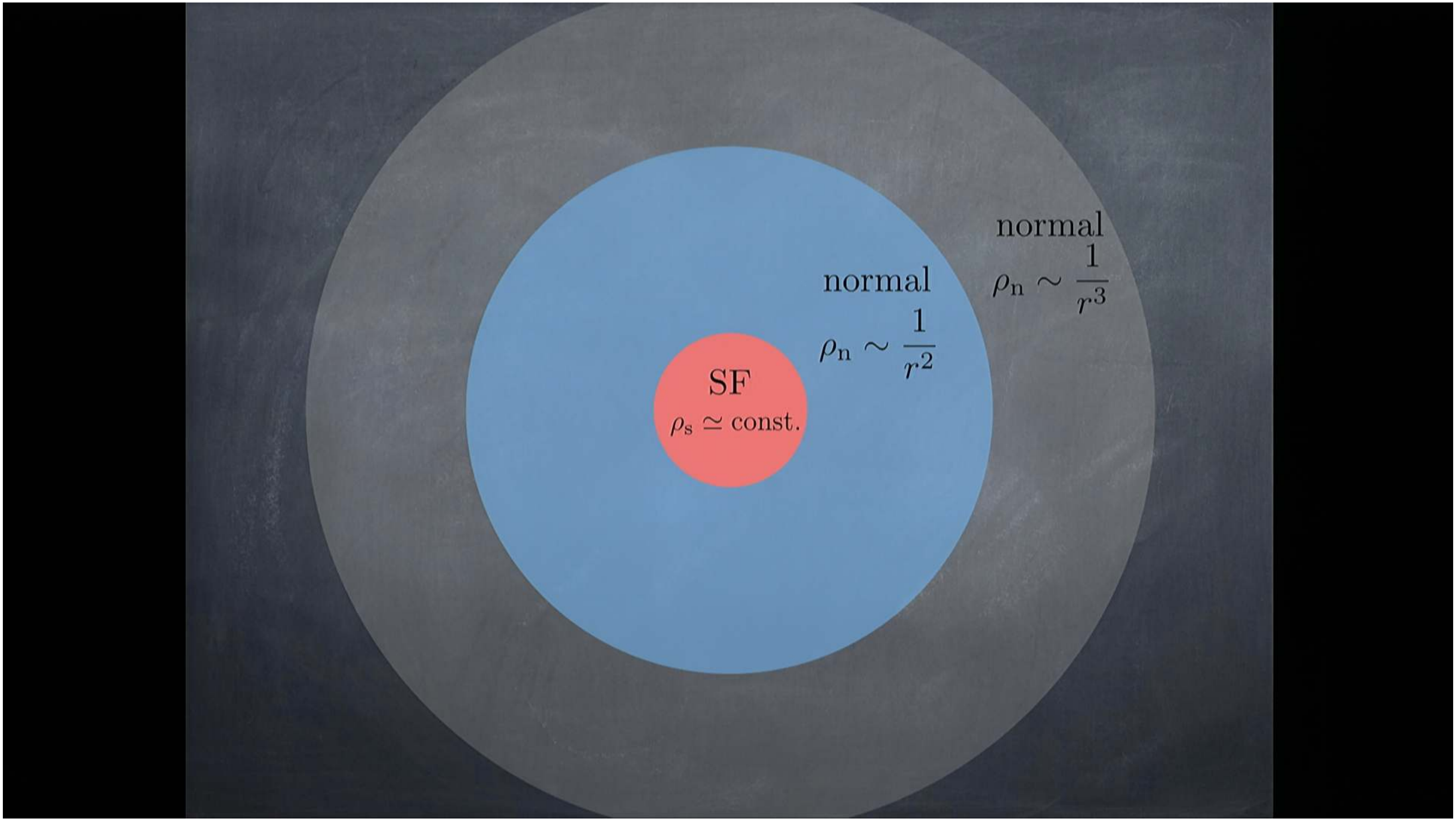
Using equation of state $P_{\rm cond} \sim \rho^3_{\rm cond}$, find:



Cored density profile

$$R_{\rm core} = \left(\frac{M}{10^{12}M_\odot}\right)^{1/6}(1+z_{\rm vir})^{1/4}\left(\frac{m}{\rm eV}\right)^{-9/5}\left(\frac{\Lambda}{\rm meV}\right)^{-3/5} 21\ {\rm kpc}$$

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


normal
$\rho_{\rm n} \sim \frac{1}{r^3}$
normal
$\rho_{\rm n} \sim \frac{1}{r^2}$
SF
$\rho_{\rm s} \simeq \text{const.}$

Density profile

Assuming hydrostatic equilibrium,

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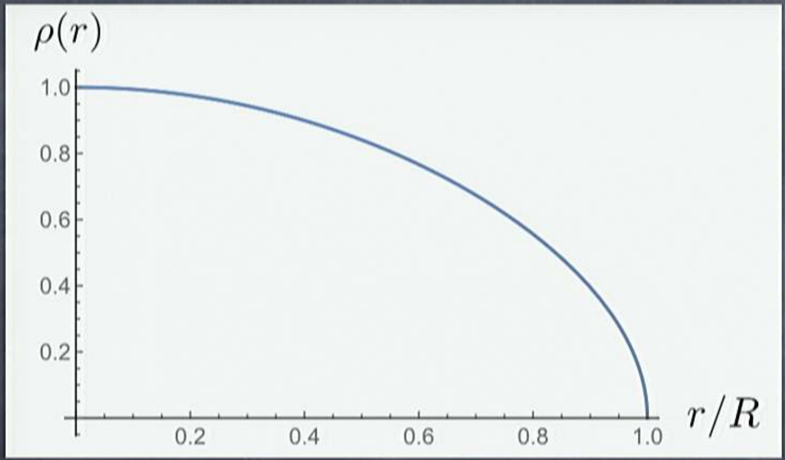

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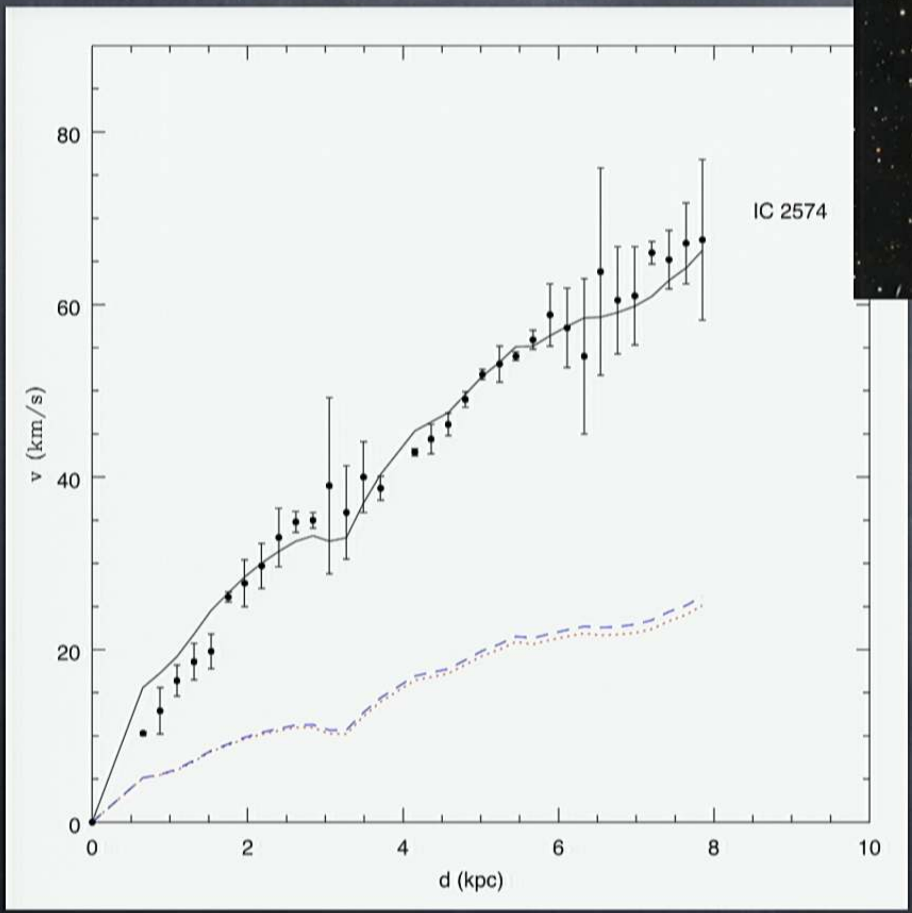
Remarkably, realistic size cores with $m \sim {\rm eV}$ and $\Lambda \sim {\rm meV}$!

e.g. LSB galaxy

w. Benoit Famaey (to appear)



$$m = 0.6 \text{ eV}$$

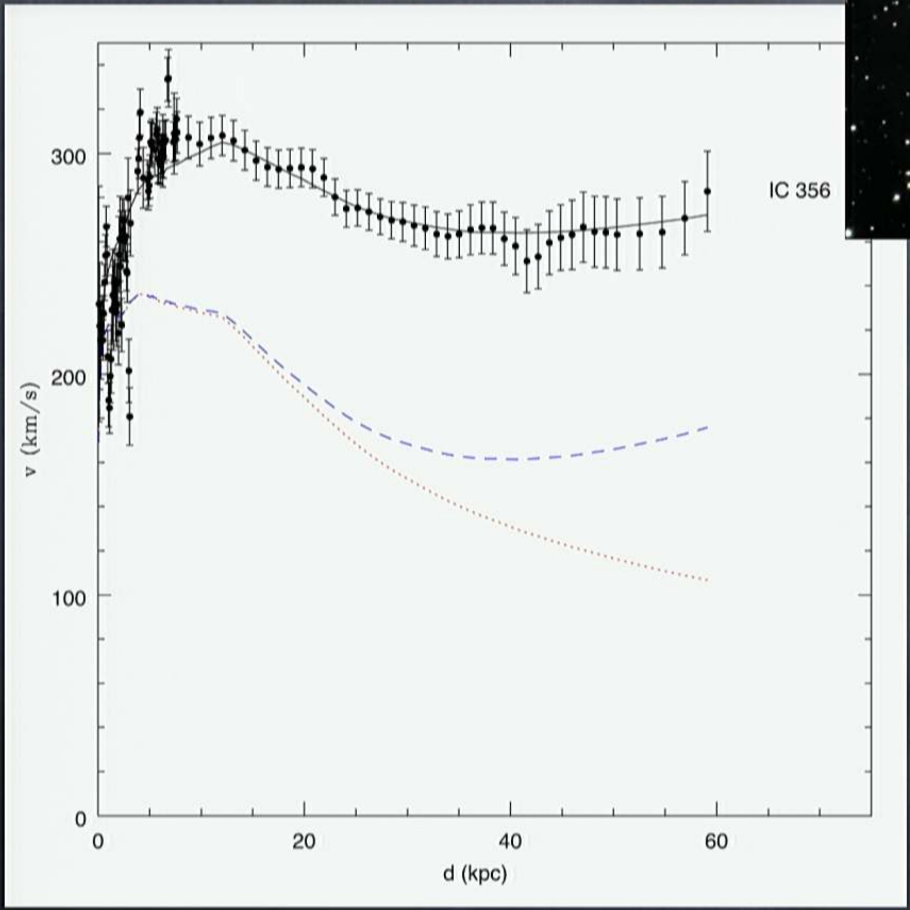
$$\Lambda = 1 \text{ meV}$$

$$a_0 = 0.9 \times 10^{-8} \text{cm/s}^2$$

$$\Longrightarrow \quad R_{\text{core}} = 29 \text{ kpc}$$

e.g. HSB galaxy

w. Benoit Famaey (to appear)



$$m = 0.6 \text{ eV}$$

$$\Lambda = 1 \text{ meV}$$

$$a_0 = 0.9 \times 10^{-8} \text{cm/s}^2$$

$$\Longrightarrow \quad R_{\text{core}} = 76 \text{ kpc}$$

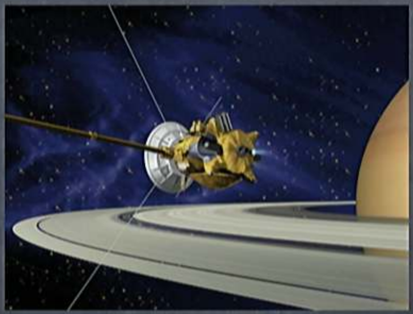
Validity of effective theory

$$v_{\rm s} = \frac{|\nabla\phi|}{m} < v_{\rm c} \sim \left(\frac{\rho}{m^4}\right)^{1/3}$$

Satisfied for $r \gtrsim \rm kpc$

$\Longrightarrow$ Quasi-particle production (DM-like behavior) in inner regions of galaxies

Solar system



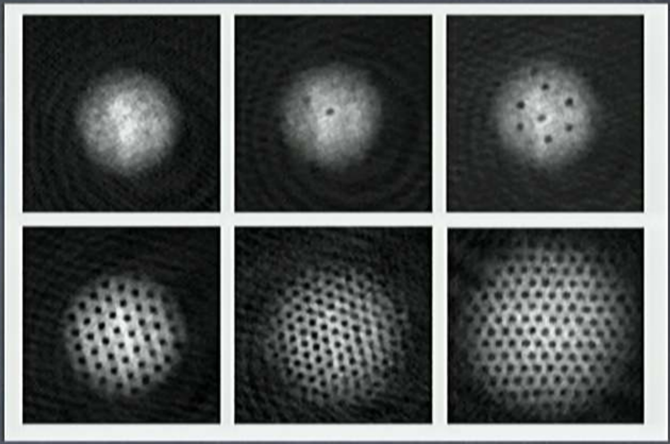
A MOND scalar acc'n, $\frac{\Delta a}{a_{\rm N}} = \sqrt{\frac{a_0}{a_{\rm N}}}$,
albeit small in the solar system, is ruled out.

$\Longrightarrow$ must we complicate the theory?

Observational Signatures

Vortices

When spun faster than critical velocity, superfluid develops vortices.



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

For a halo of density ρ ,

$$\omega \sim \lambda\sqrt{G_{\rm N}\rho} \sim 10^{-18}\lambda\,{\rm s}^{-1}\,; \qquad 0.01 < \lambda < 0.1$$

$\Longrightarrow$ Vortex formation is unavoidable

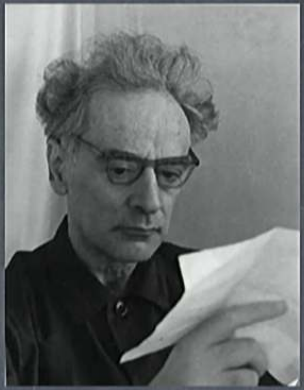
Line density: $\sigma_{\rm v} \sim m\omega \sim 10^2\lambda\ {\rm AU}^{-2}$

cf. Silverman & Mallett (2002); Rindler-Daller & Shapiro (2012)

Observational consequences?

Galaxy mergers

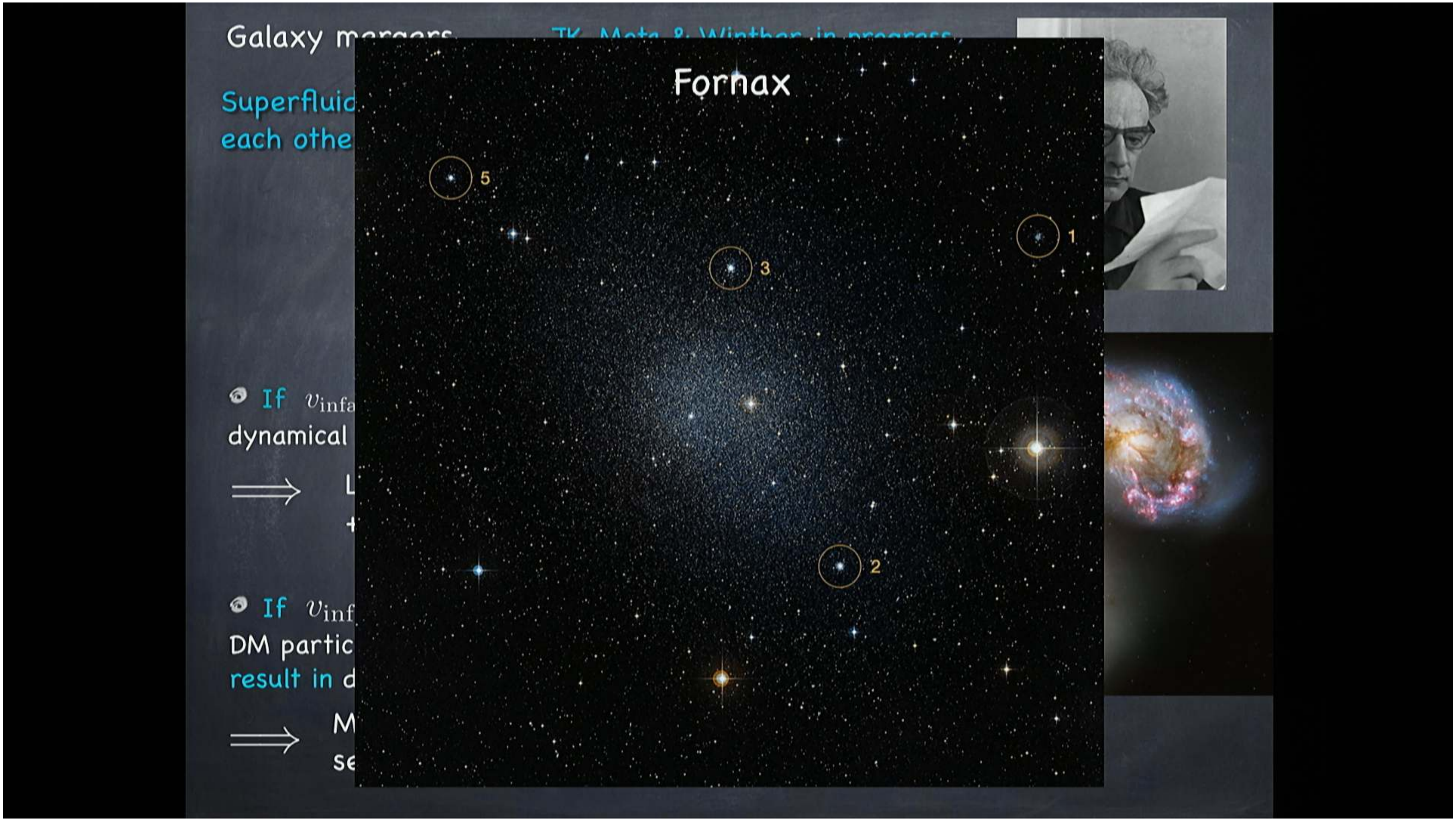
JK, Mota & Winther, in progress



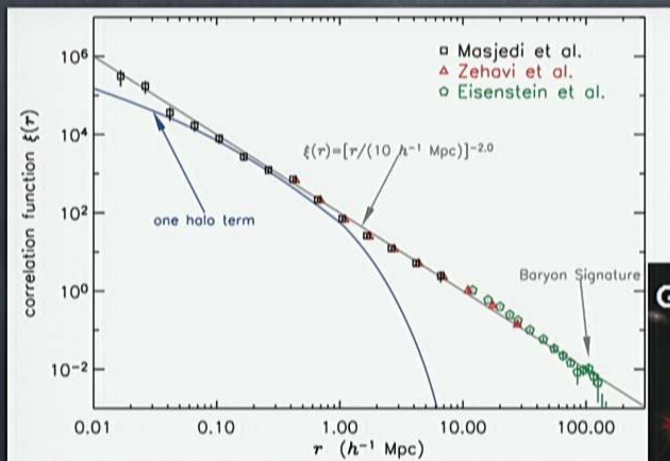
Superfluid cores should pass through each other with negligible dissipation if

$$v_{\mathrm{infall}} \lesssim c_s$$

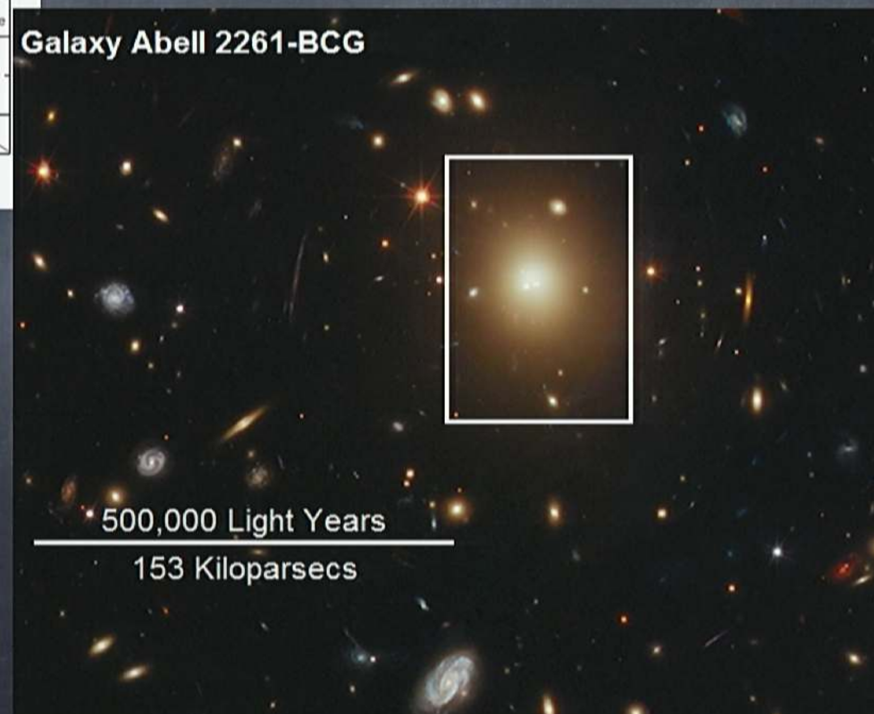
(Landau's criterion)


Galaxy m
Superfluid
each othe
If $v_{\rm infa}$
dynamical
If $v_{\rm inf}$
DM partic
result in d
Fornax
5
1
3
2

Reduced dynamical fraction?

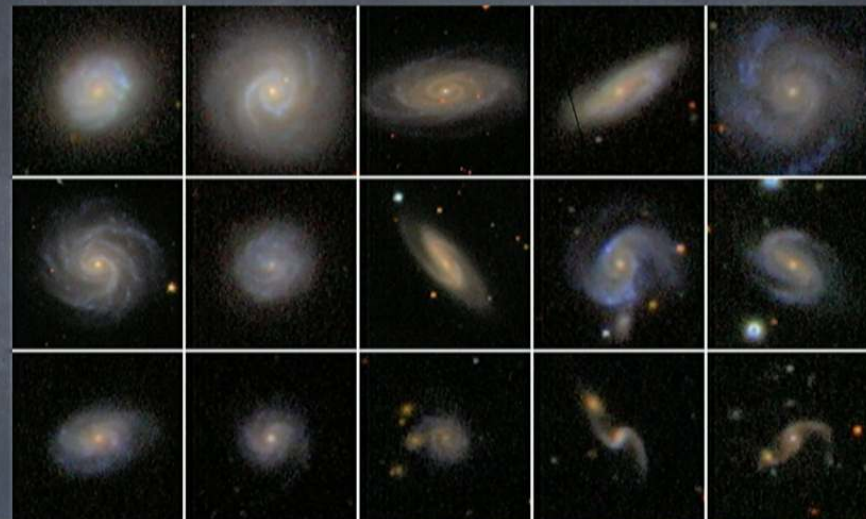


Masjedi et al. (2006)

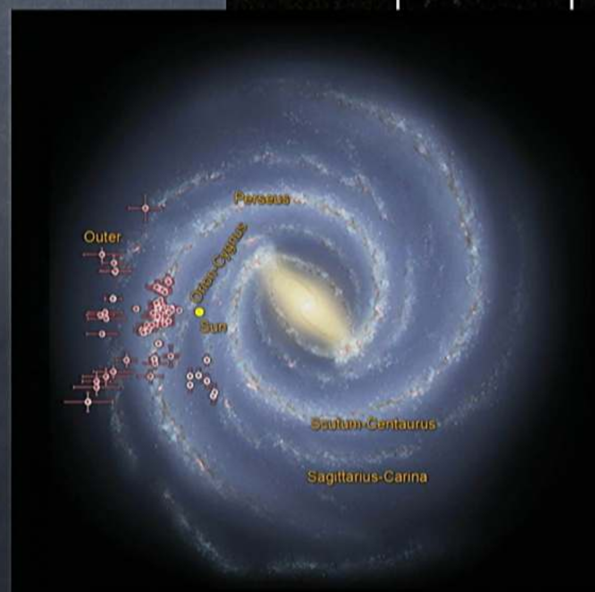


"This is surprising, as one might expect the direct interactions between galaxies (e.g., dynamical friction, galaxy merger, tidal impulses, etc.) to create features in the correlation function."

Reduced dynamical fraction?

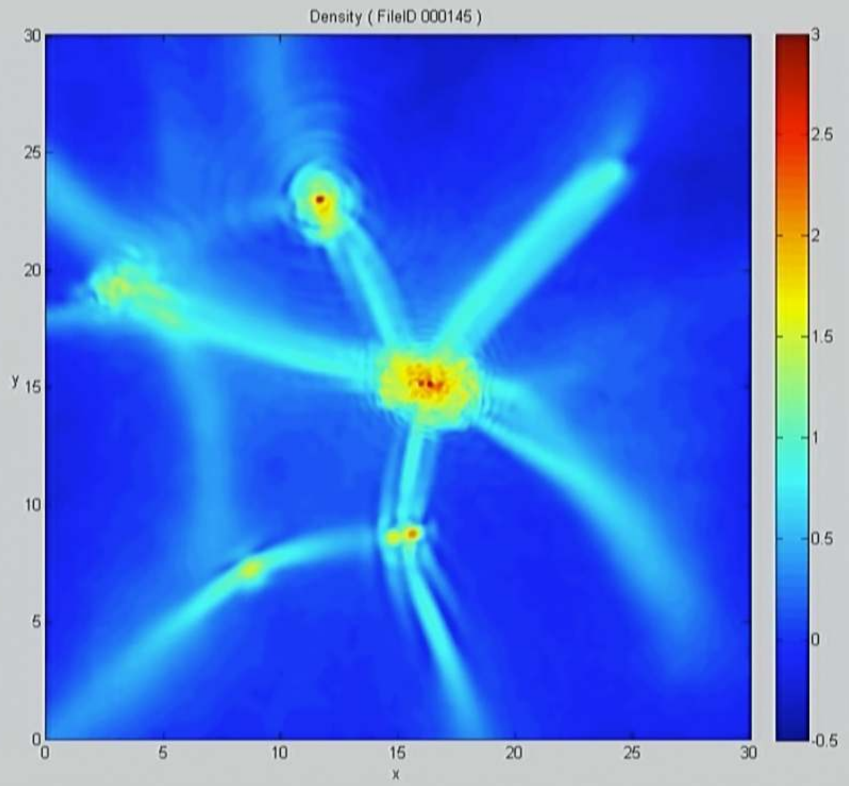


- Bulgeless galaxies



- Galactic bars

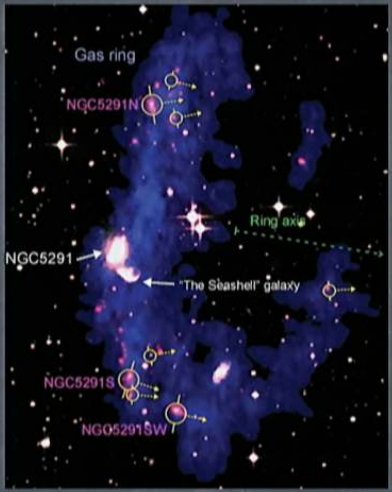
When superfluids collide



No DM $\Longrightarrow$ No MOND

Globular clusters

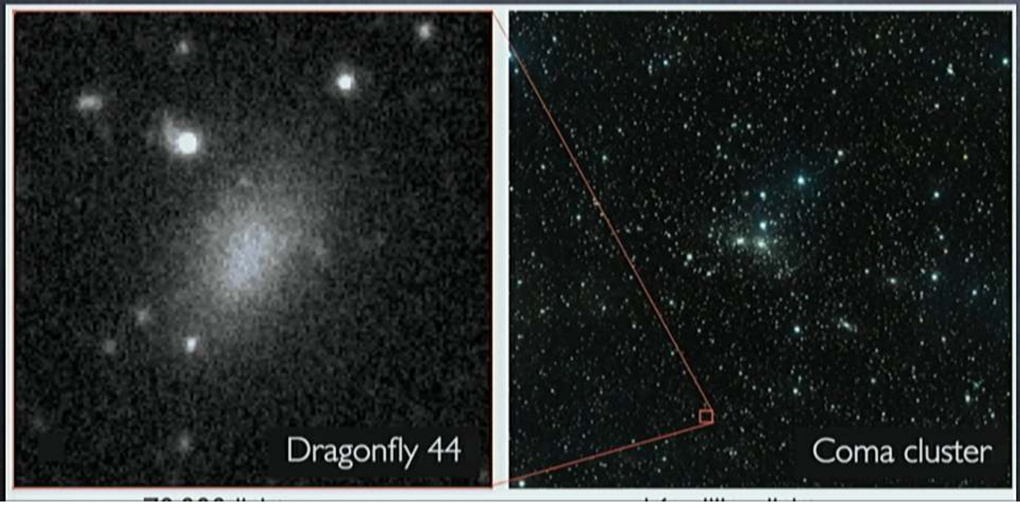
Ibata et al. (2011)



Tidal dwarfs

Lelli et al. (2015)

No superfluid $\Longrightarrow$ No external field effect



Ultra-diffuse galaxies

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