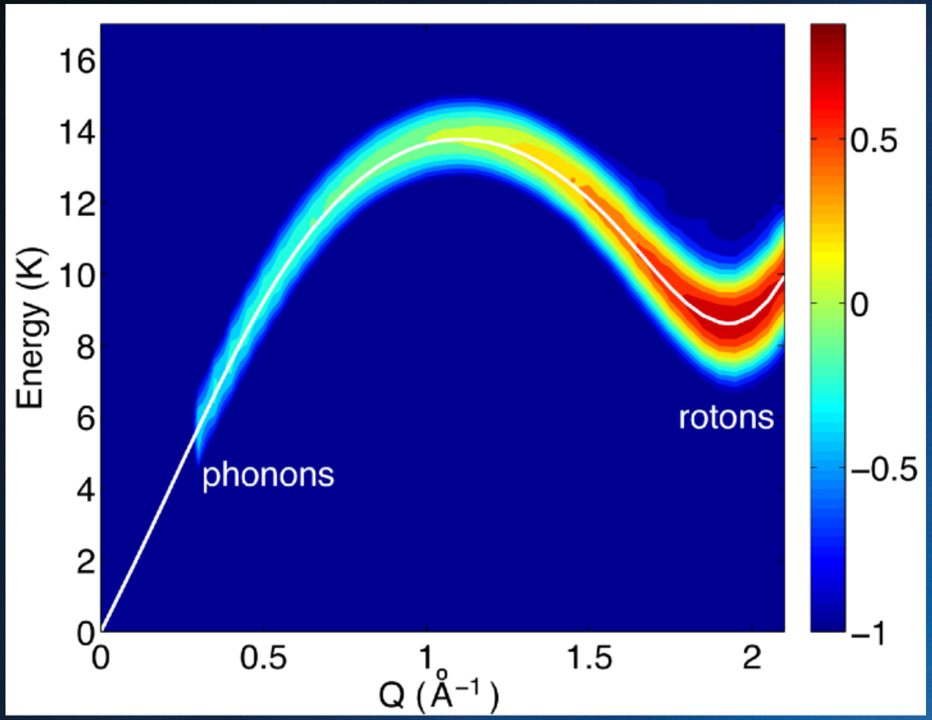
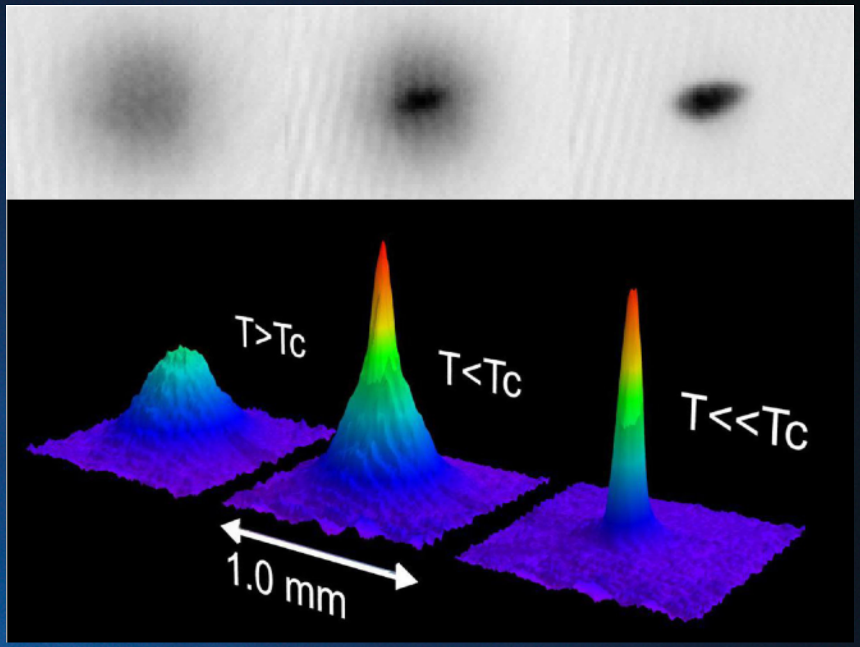




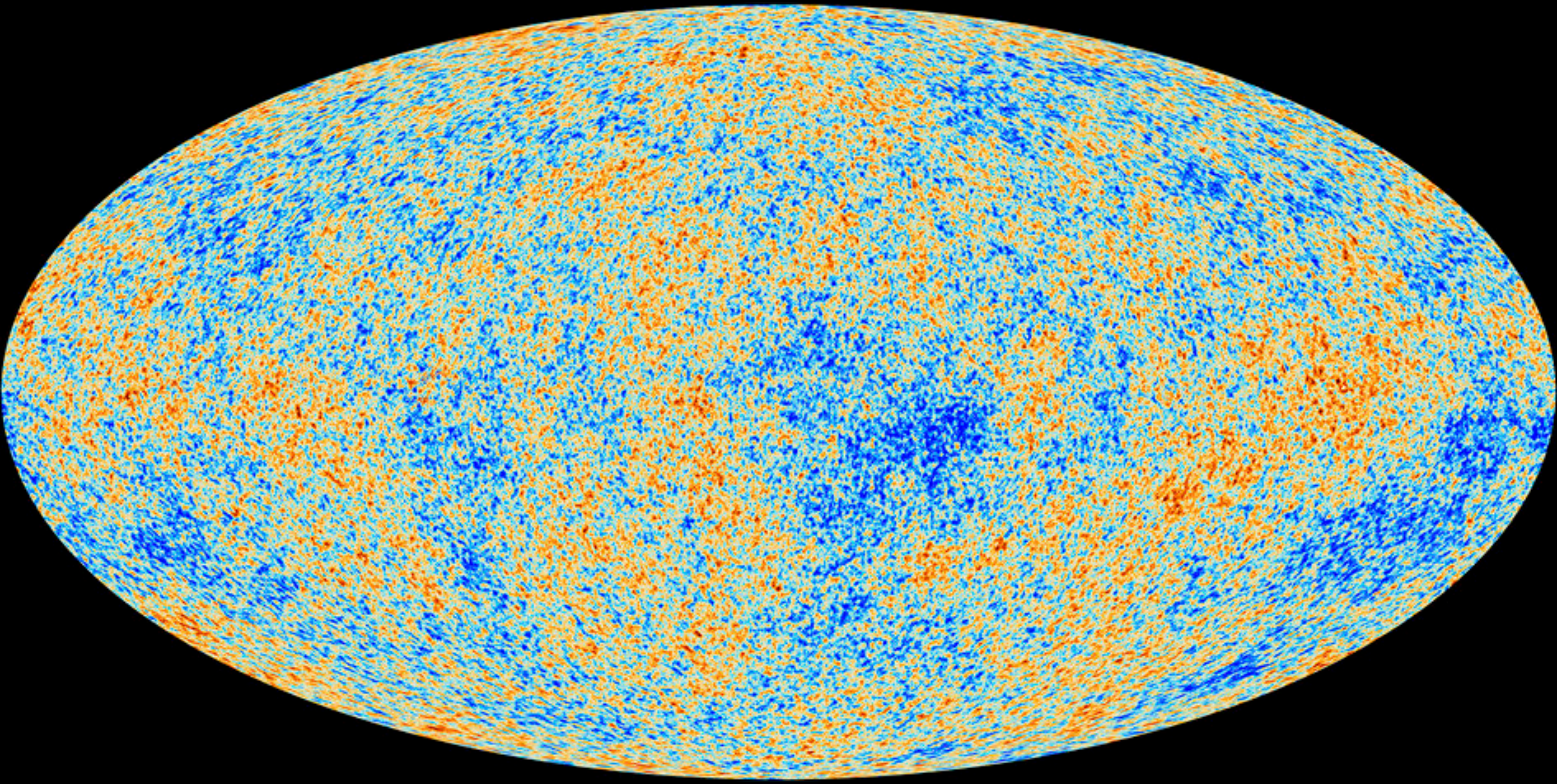
New Approaches to Dark Matter

Justin Khoury (U. Penn)

L. Berezhiani & JK, 1506.07877 + 1507.01019
JK 1602.05691

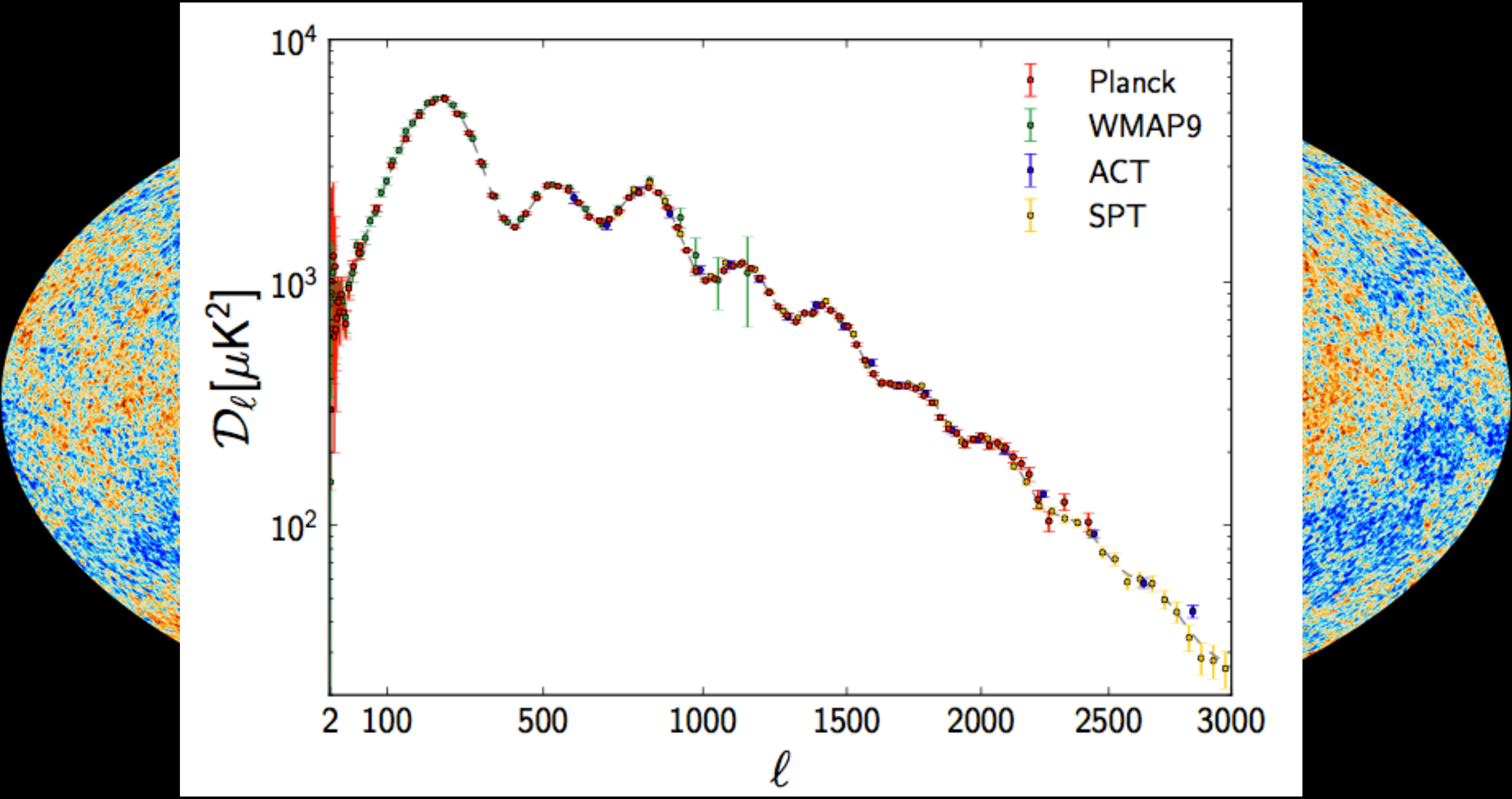
Ongoing work with
L. Berezhiani, B. Elder, B. Famaey, G. Kartvelishvili, T. Lubensky,
V. Miranda, A. Sharma, A. Solomon

Large-scale evidence

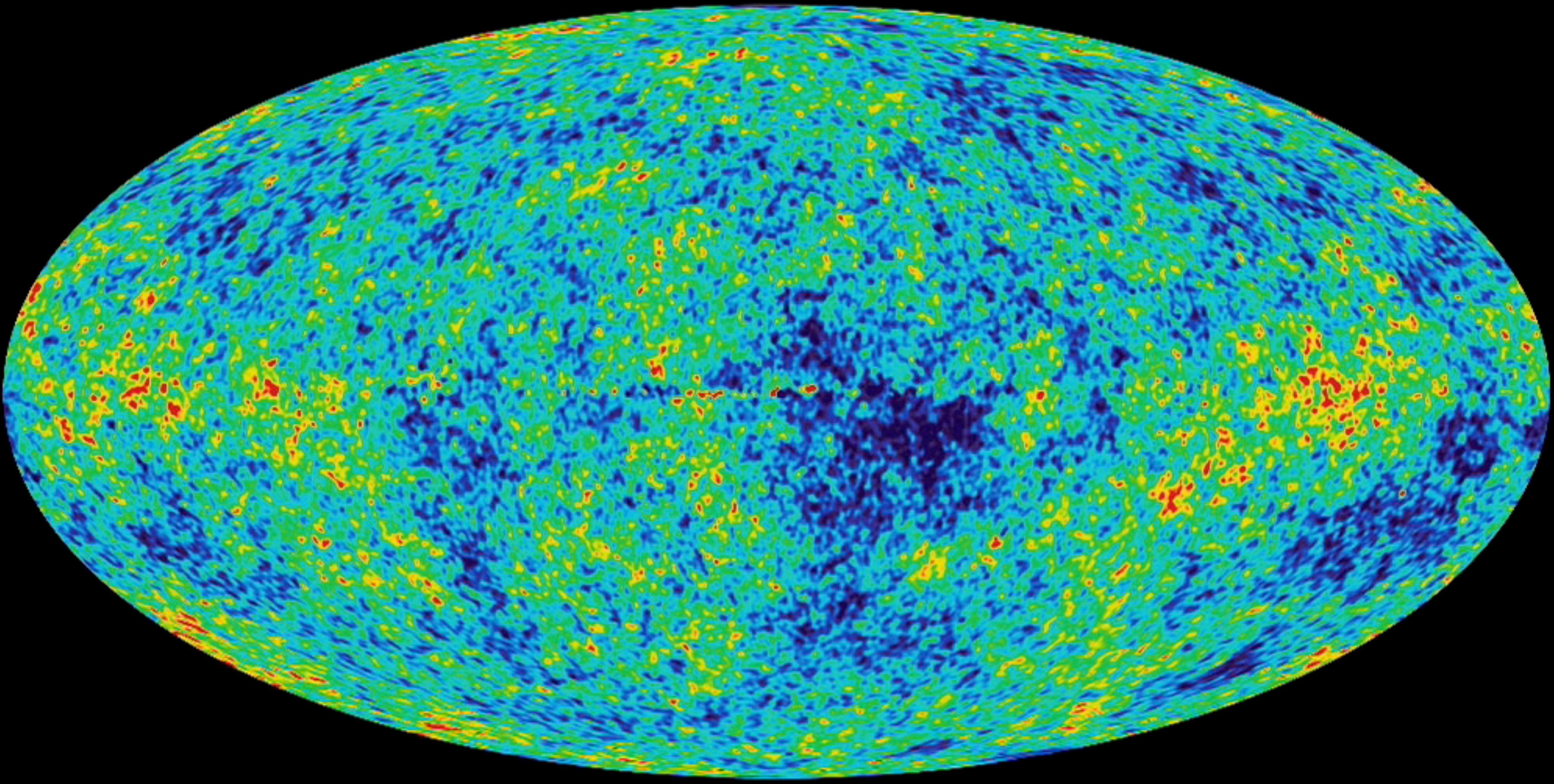


ESA Planck Science Team

Large-scale evidence



ESA Planck Science Team



NASA/WMAP Science Team

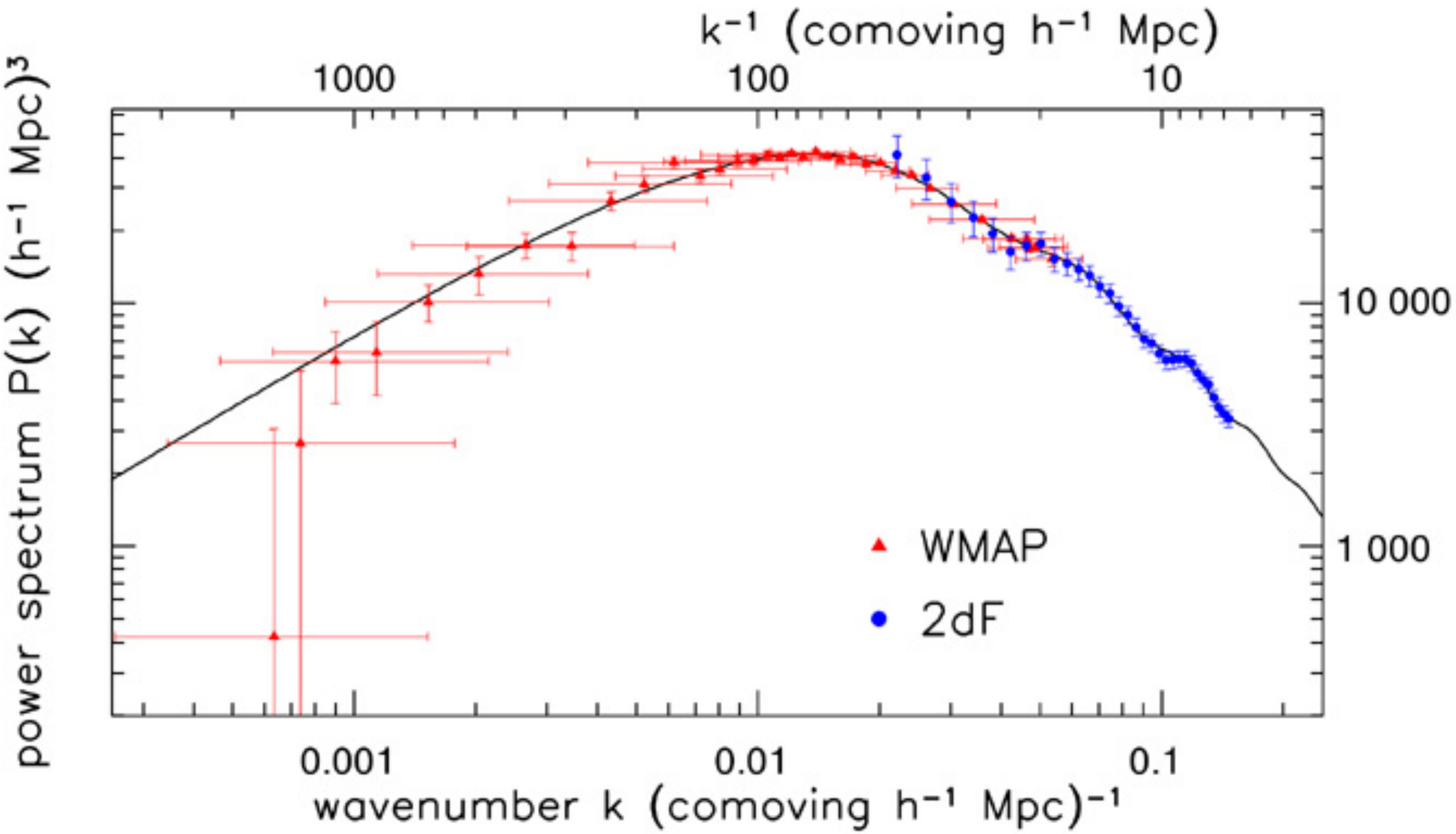
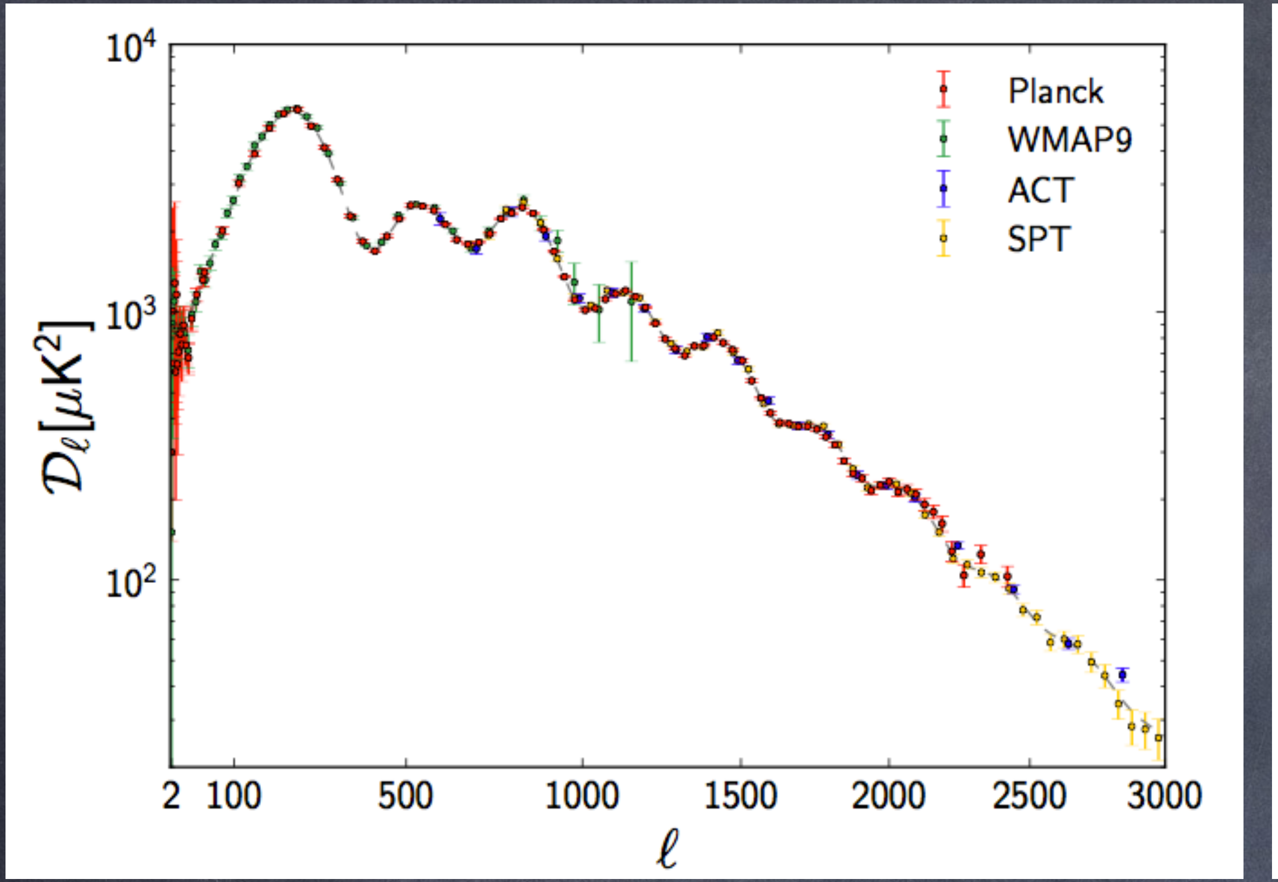


Fig 8.17 (A. Sanchez) 'Galaxies in the Universe' Sparke/Gallagher CUP 2007

The coarse-grained success



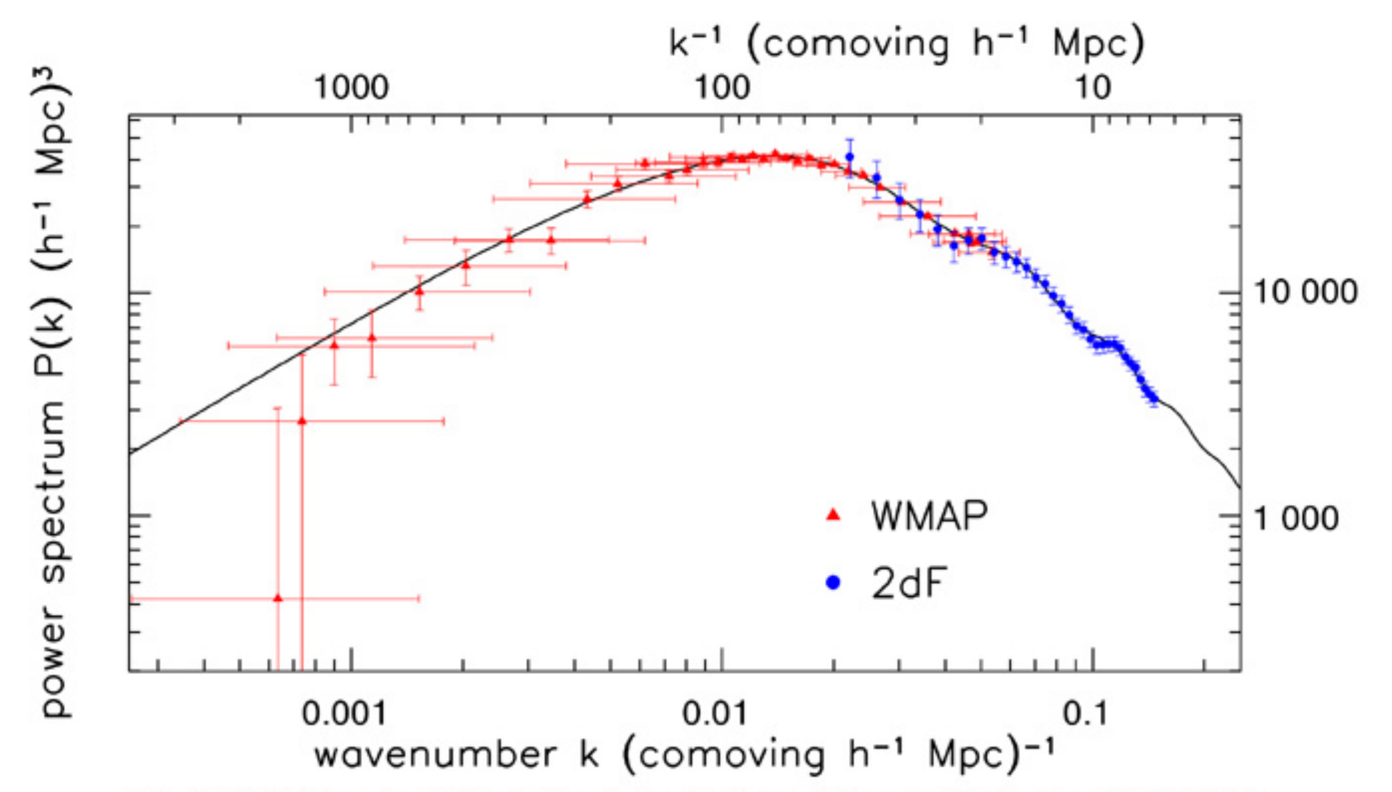
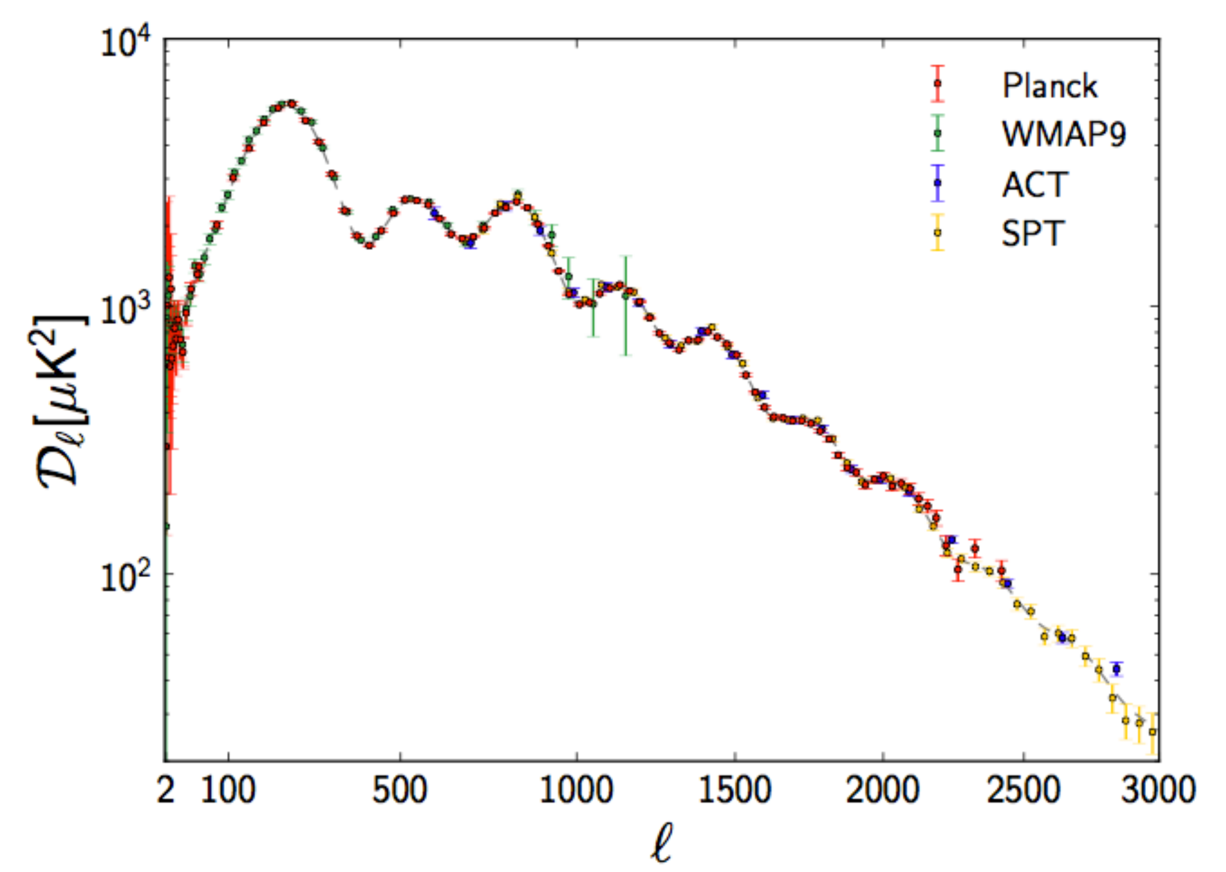


Fig 8.17 (A. Sanchez) 'Galaxies in the Universe' Sparke/Gallagher CUP 2007

The coarse-grained success



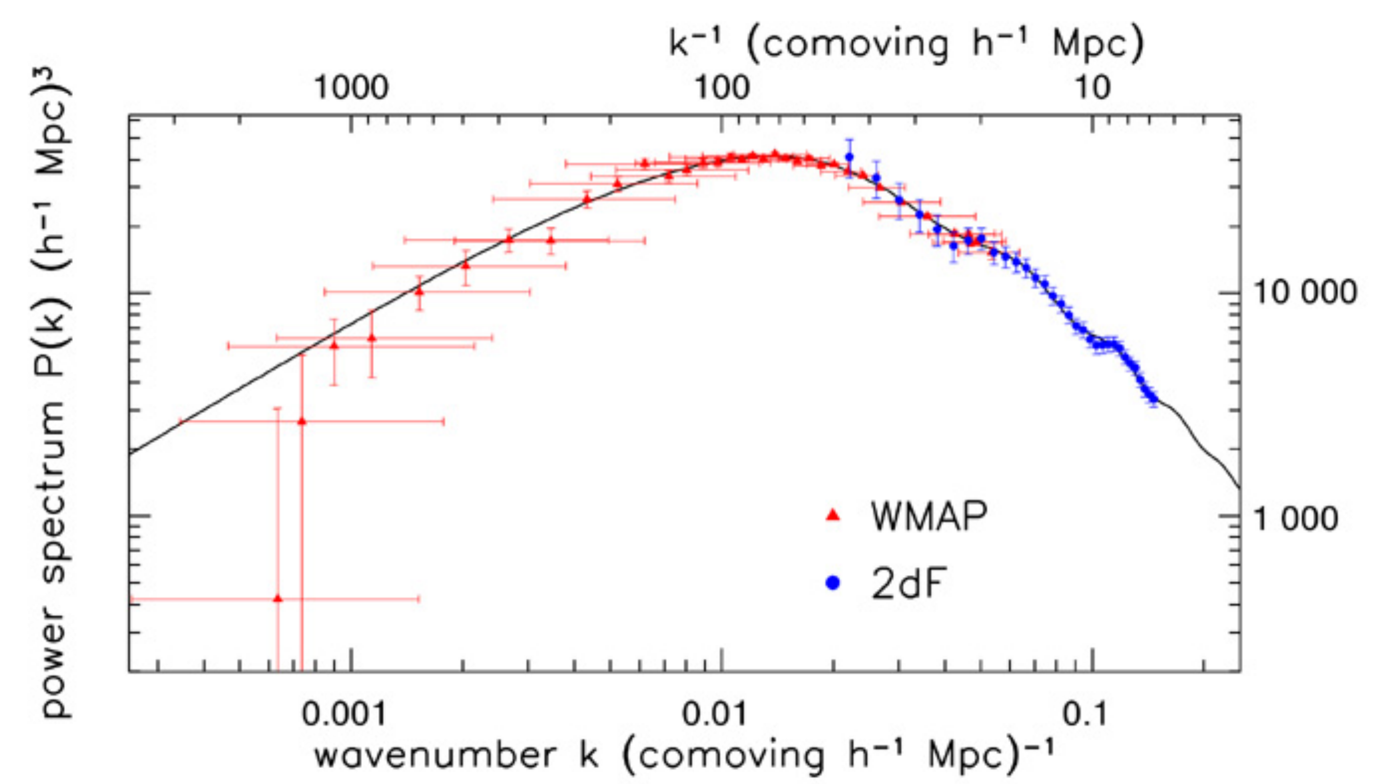


Fig 8.17 (A. Sanchez) 'Galaxies in the Universe' Sparke/Gallagher CUP 2007

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

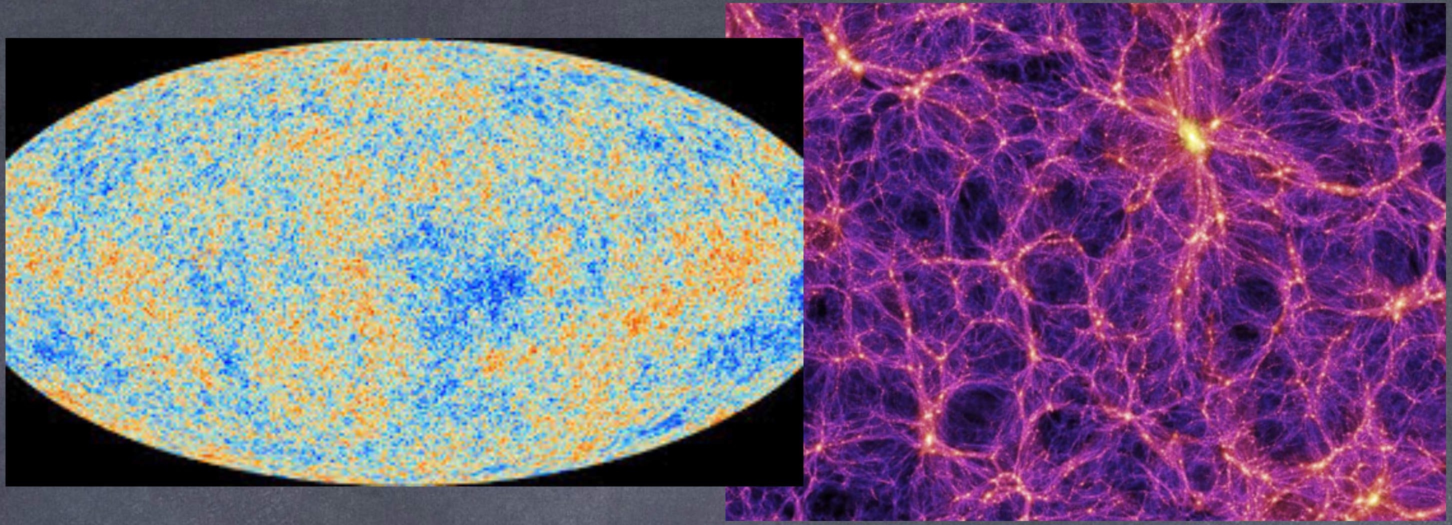
$$\boxed{T_{\mu\nu} = (\rho + P)u_\mu u_\nu + P g_{\mu\nu}}$$

$\Longrightarrow$ 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

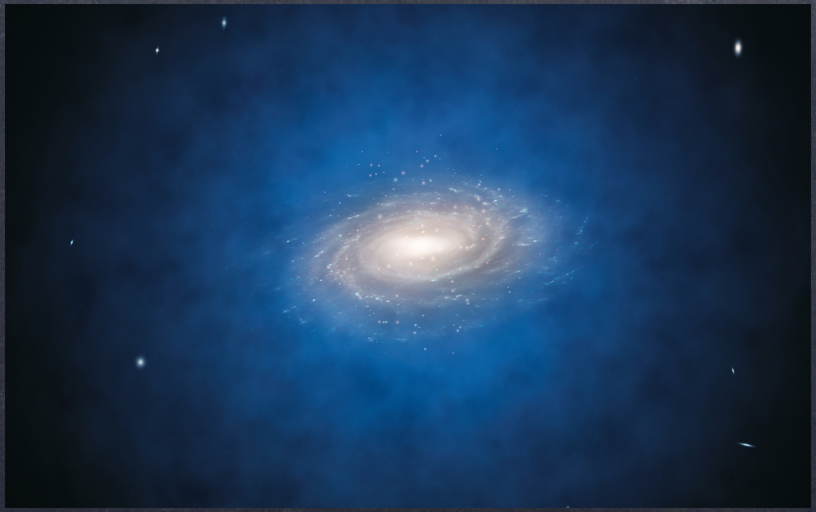
Dark matter is generally assumed to consist of subatomic particles (WIMPs, axions, etc.), with negligible interactions among themselves and with ordinary matter (other than gravity).

Cosmic web

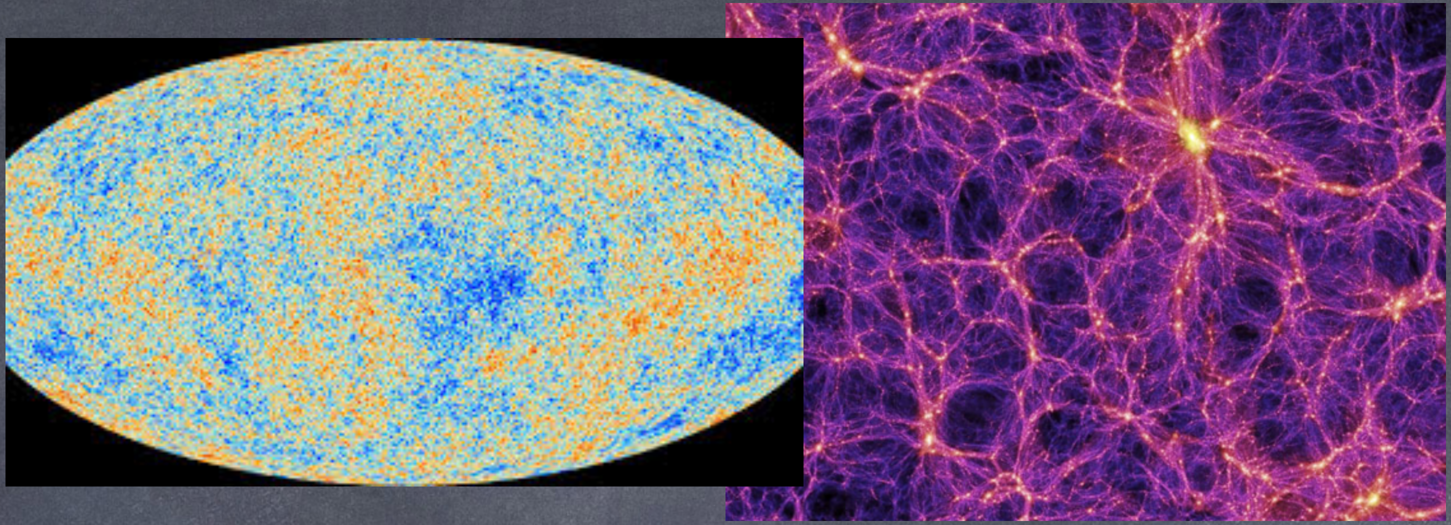


Galaxy clusters

Galaxies

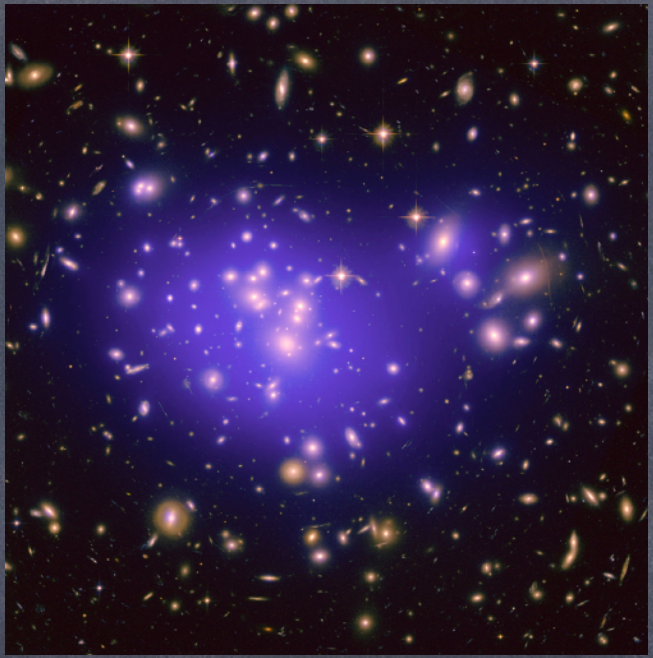


Cosmic web

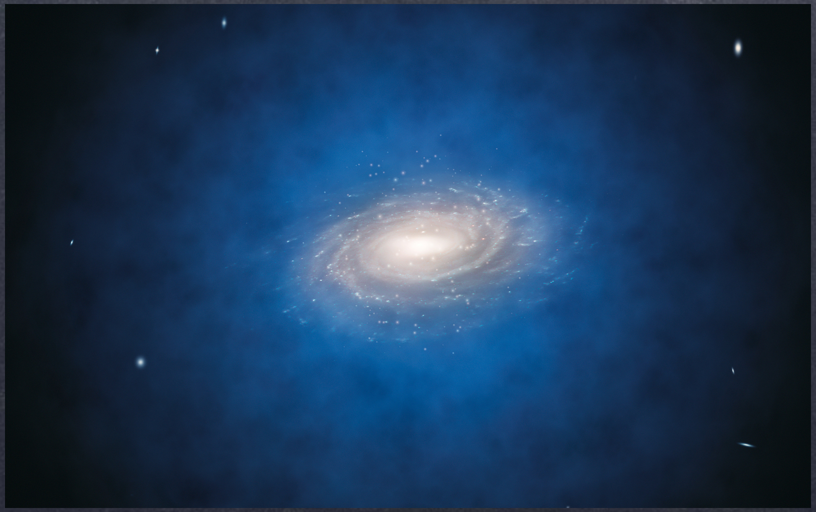


✓

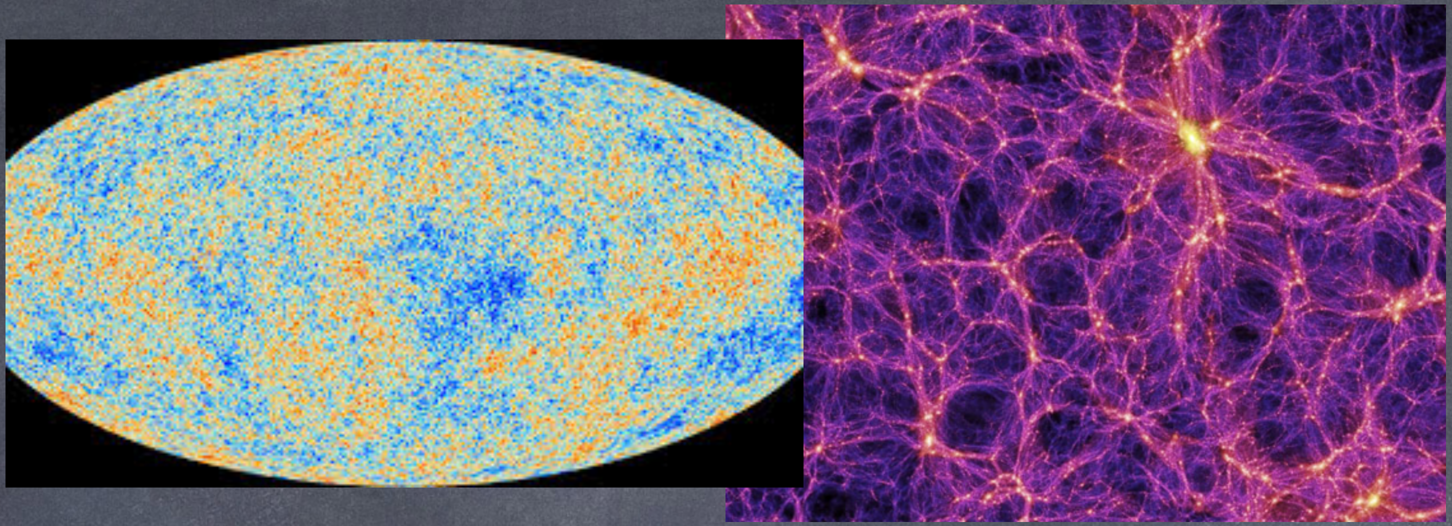
Galaxy clusters



Galaxies

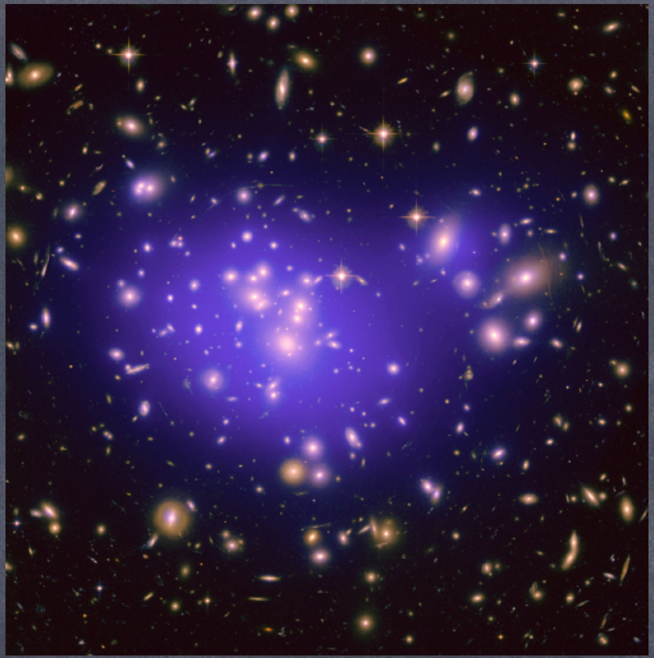


Cosmic web



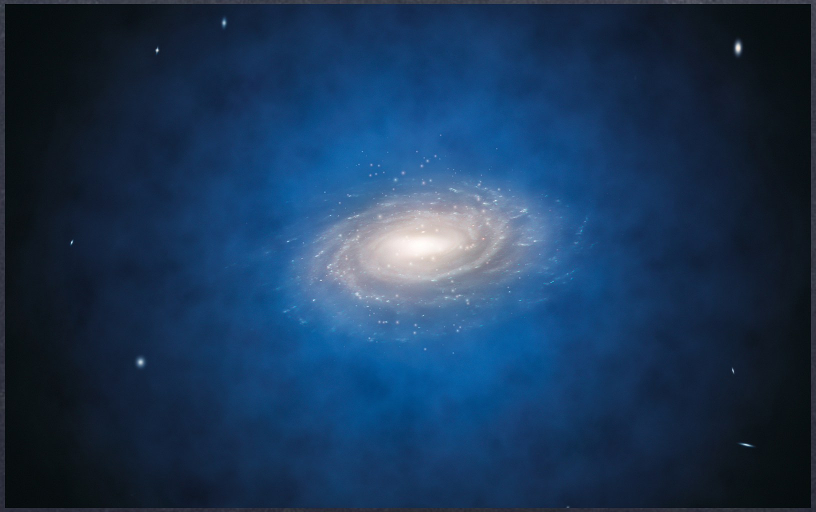
✓

Galaxy clusters

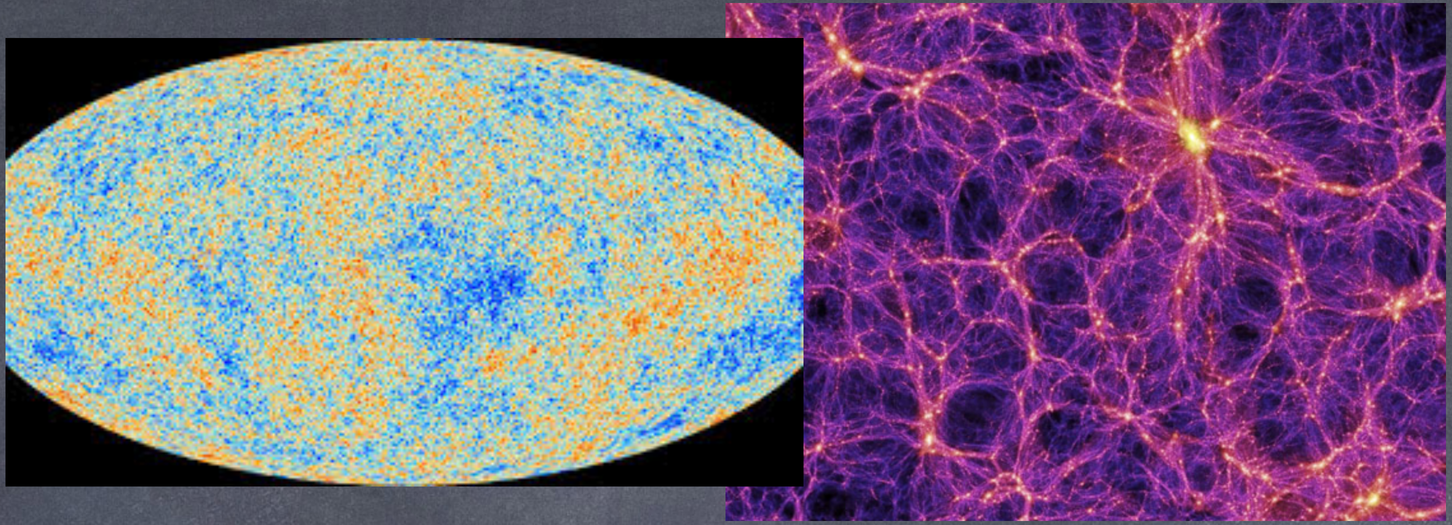


✓

Galaxies



Cosmic web



✓

Galaxy clusters

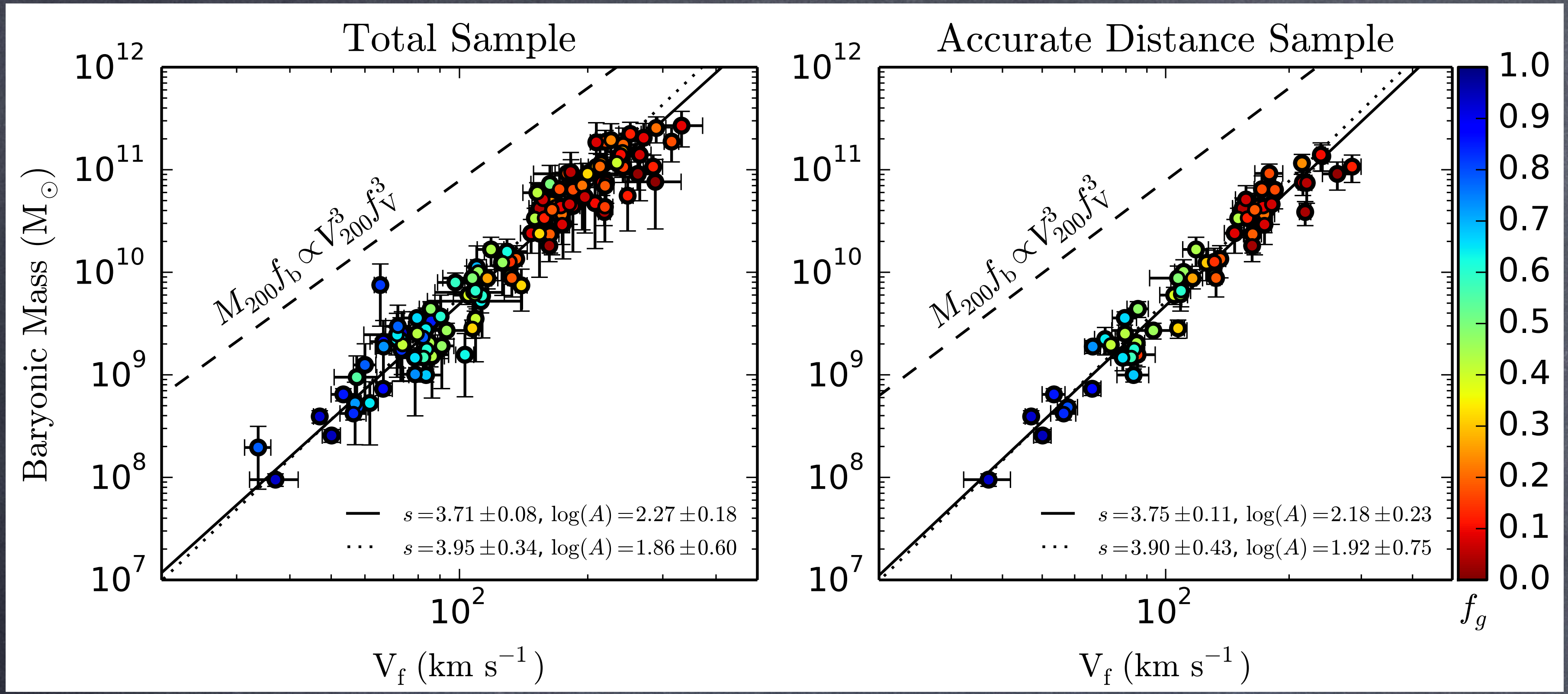
✓

Galaxies

The Conspiracy in Galaxies

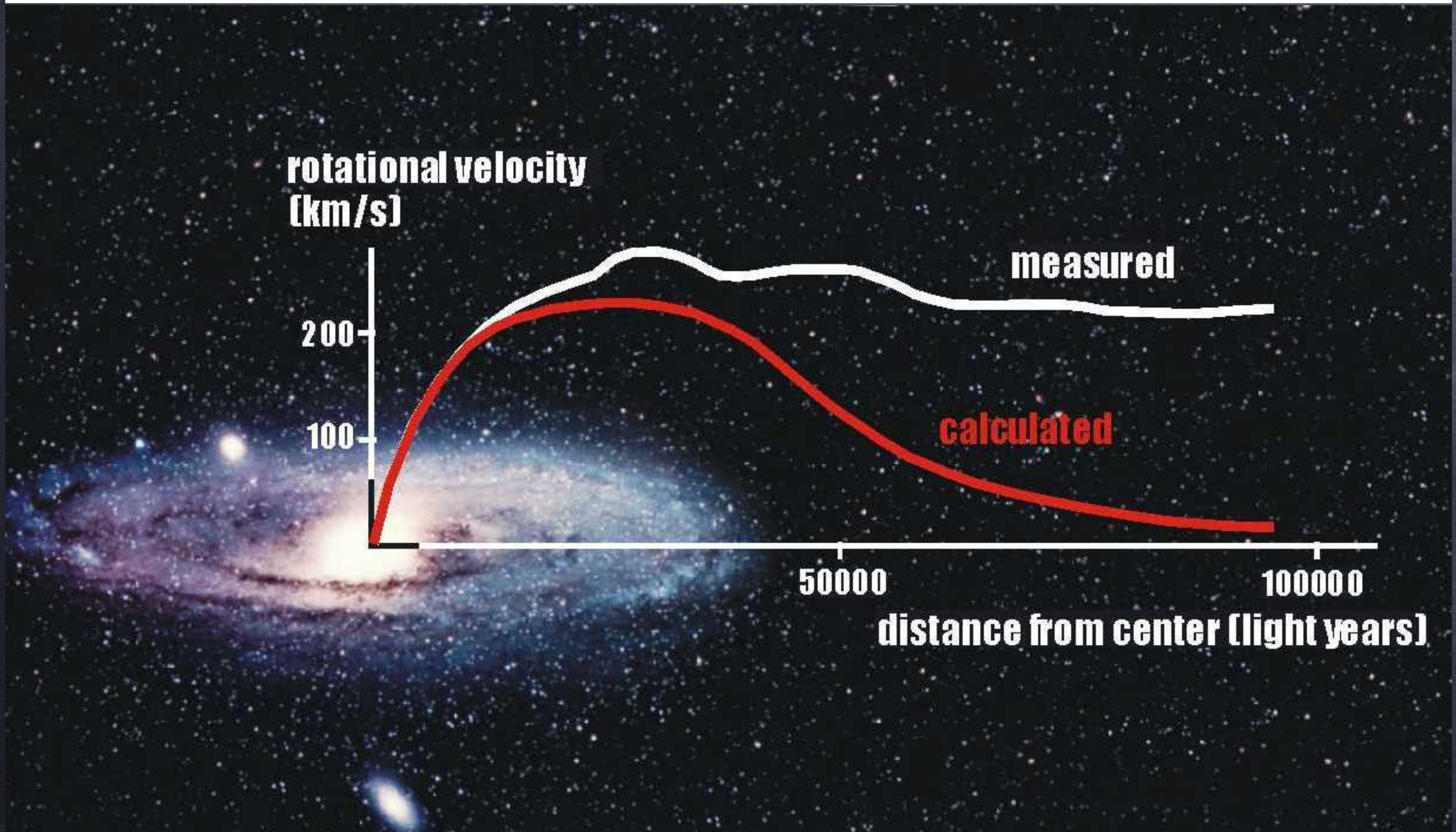
Baryonic Tully-Fisher relation

McGaugh (2015)



Total Sample

Accurate Distance Sample

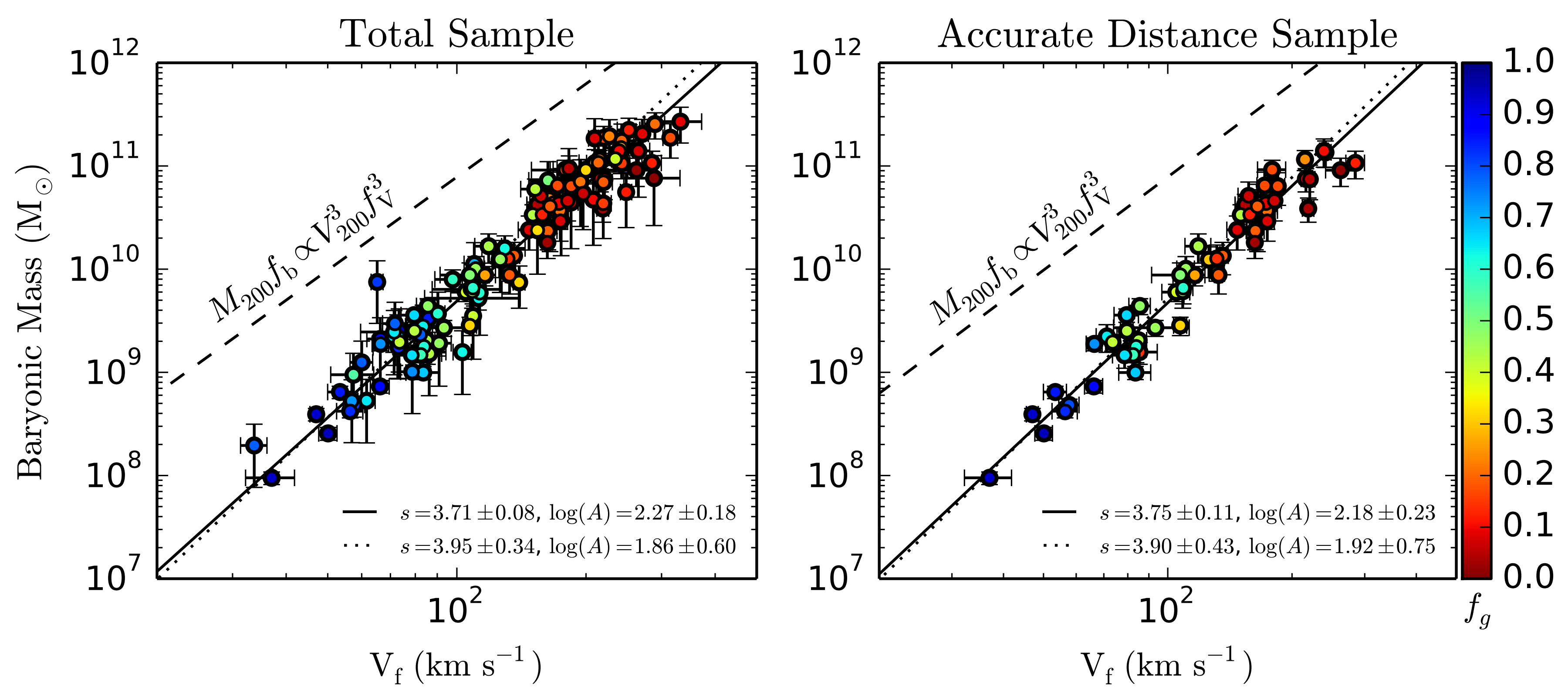


$$\boxed{v_{\rm flat}^4 = a_0 G_{\rm N} M_{\rm b}}$$

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

- Baryonic Tully-Fisher relation

McGaugh (2015)



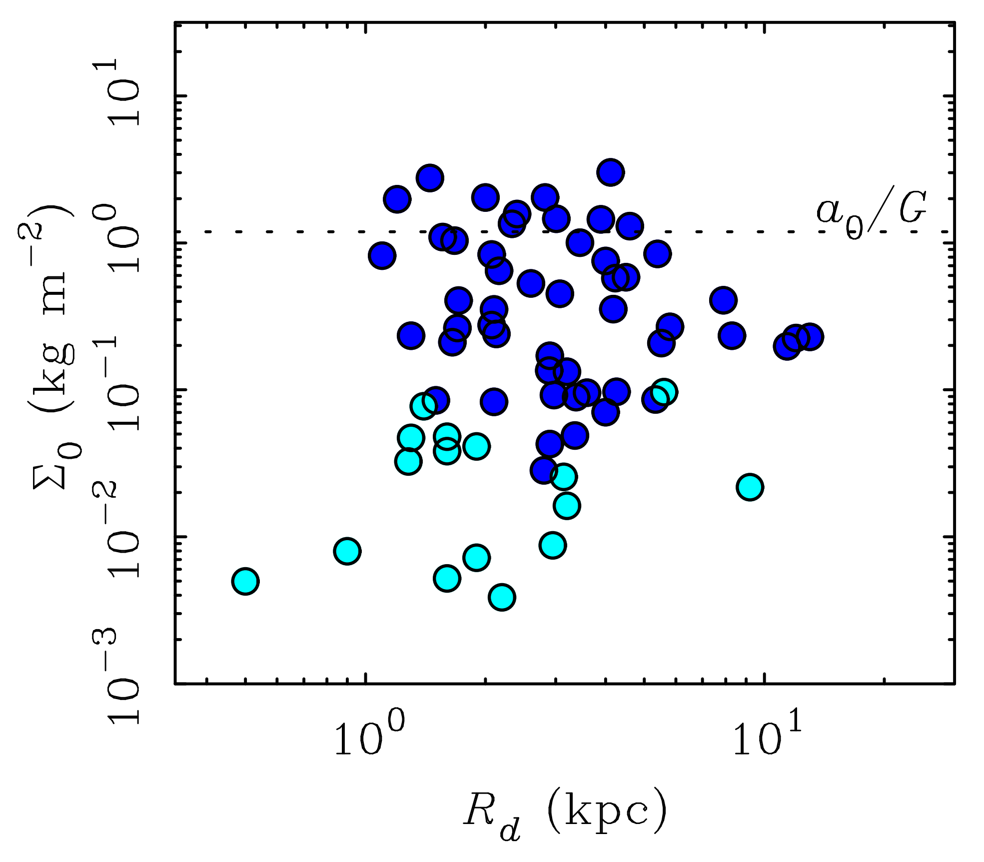
$$\boxed{v_{\rm flat}^4 = a_0 G_{\rm N} M_{\rm b}}$$

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

- Freeman limit

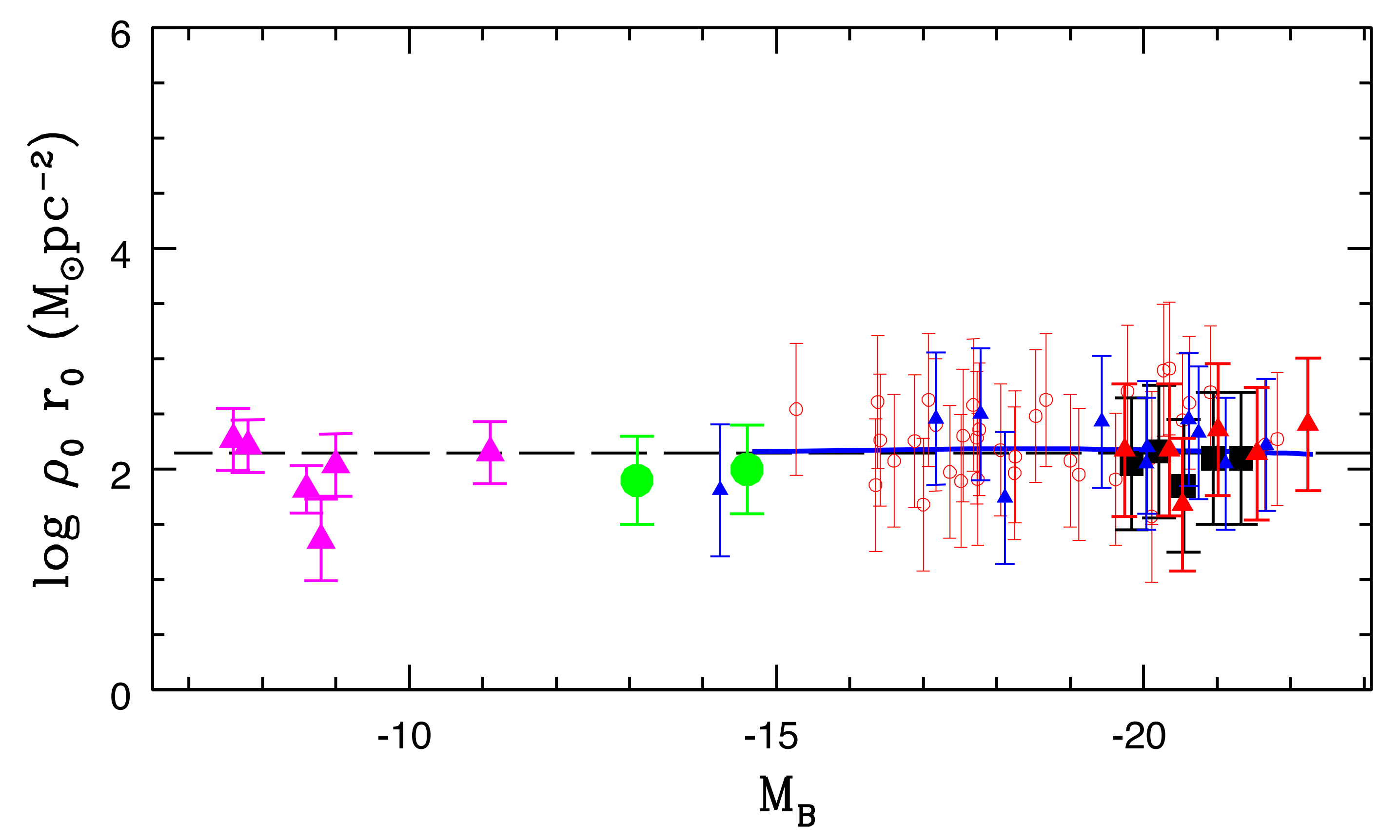
$\Sigma \equiv$ surface brightness

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



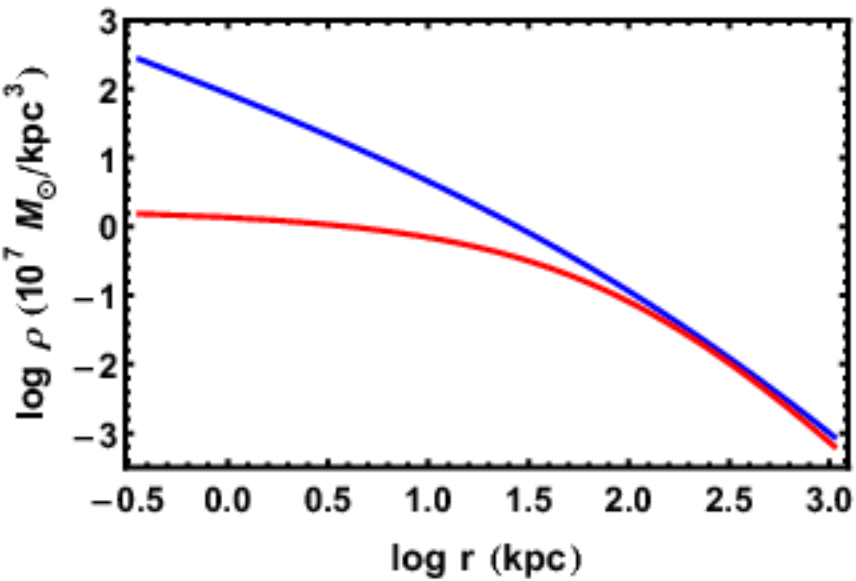
- Universal DM central "surface brightness"

Donato et al. (2009)



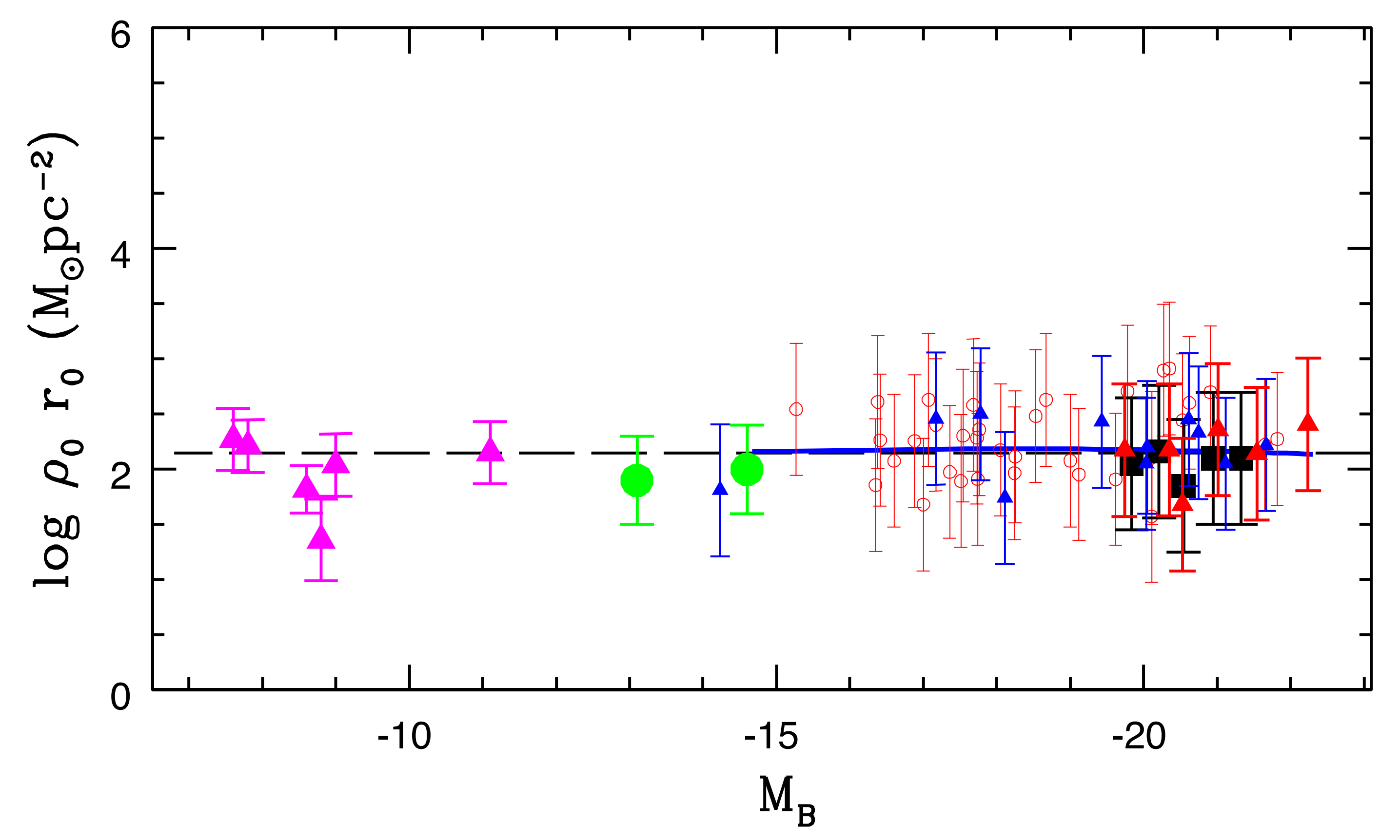
Fit to Burkert profile:

$$\rho(r) = \frac{\rho_0 r_0^3}{(r+r_0)(r^2+r_0^2)}$$



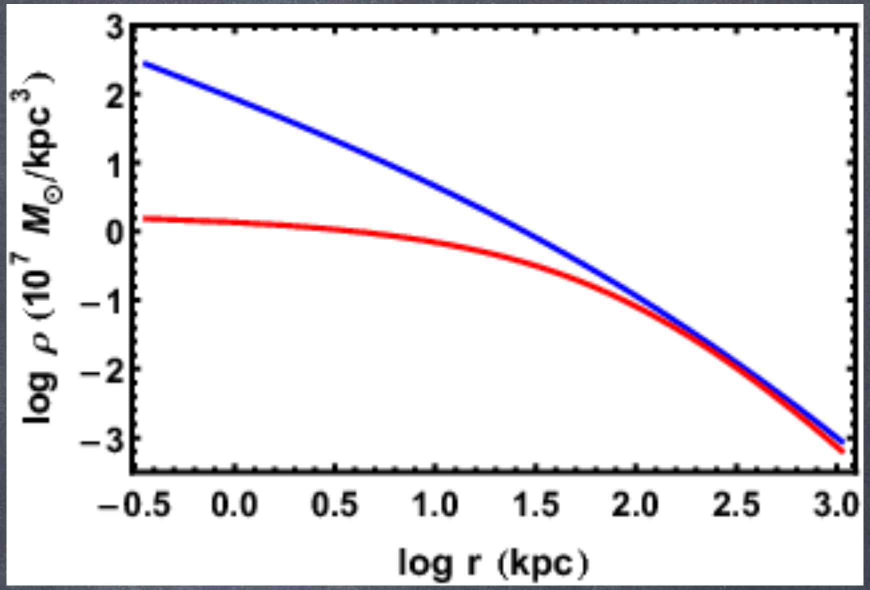
Universal DM central "surface brightness"

Donato et al. (2009)



Fit to Burkert profile:

$$\boxed{\rho(r) = \frac{\rho_0 r_0^3}{(r+r_0)(r^2+r_0^2)}}$$

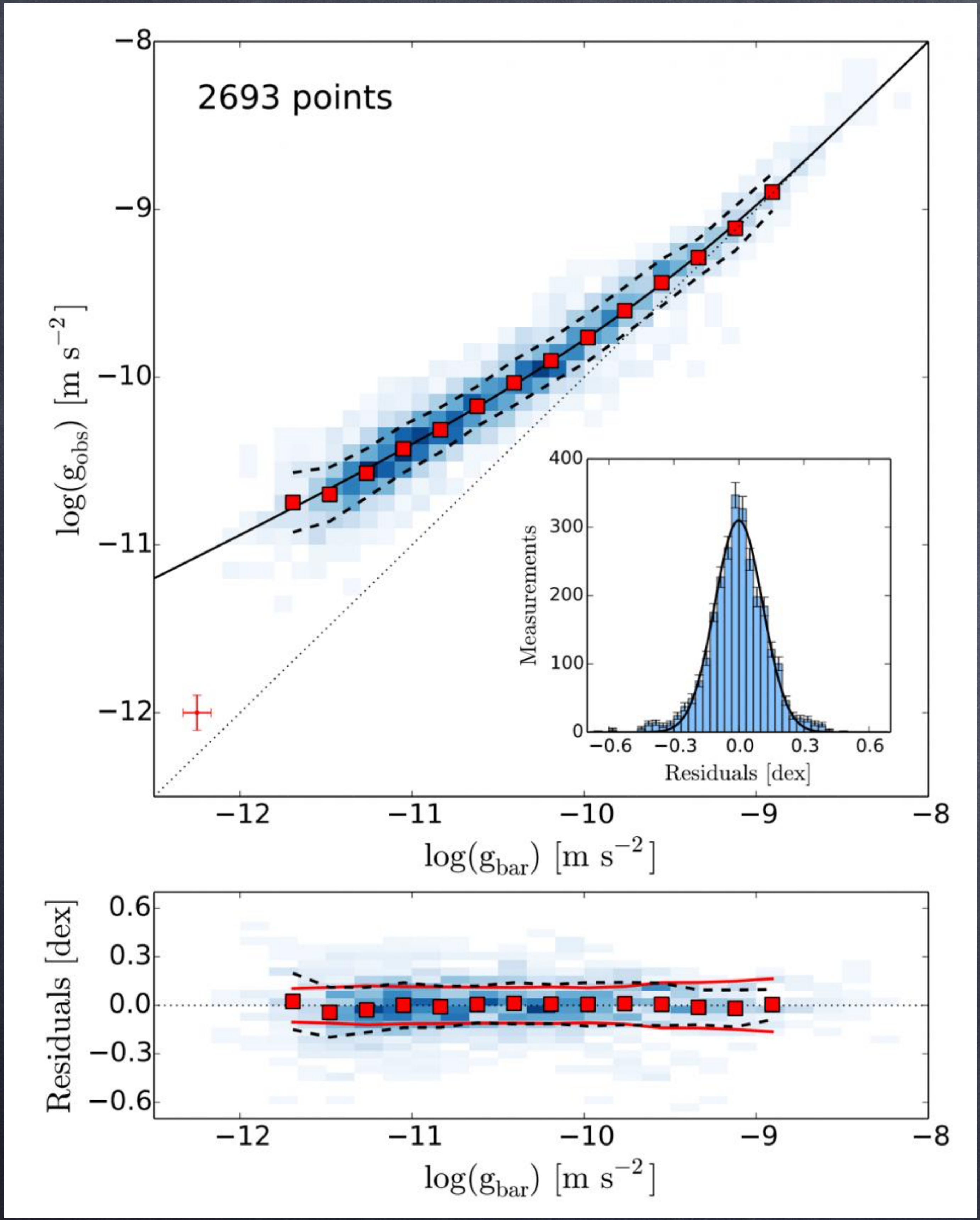


$$\boxed{\rho_0 r_0 = 140^{+80}_{-30}\ M_\odot/\mathrm{pc}^2}$$

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

Baryons dictate everything!

McGaugh, Lelli & Schombert, 1609.05917



- 153 galaxies analyzed

- Fitting form:

$$\boxed{g_{\rm obs} = \frac{g_{\rm bar}}{1 - e^{-\sqrt{g_{\rm bar}/g_*}}}}$$

$$g_* = \Big(1 \pm 0.2\ ({\rm syst.})\Big) \times a_0$$

Those are facts.

Those are facts.

The acceleration scale a_0 is in the data.

Those are facts.

The acceleration scale a_0 is in the data.

Can take one of 3 attitudes...

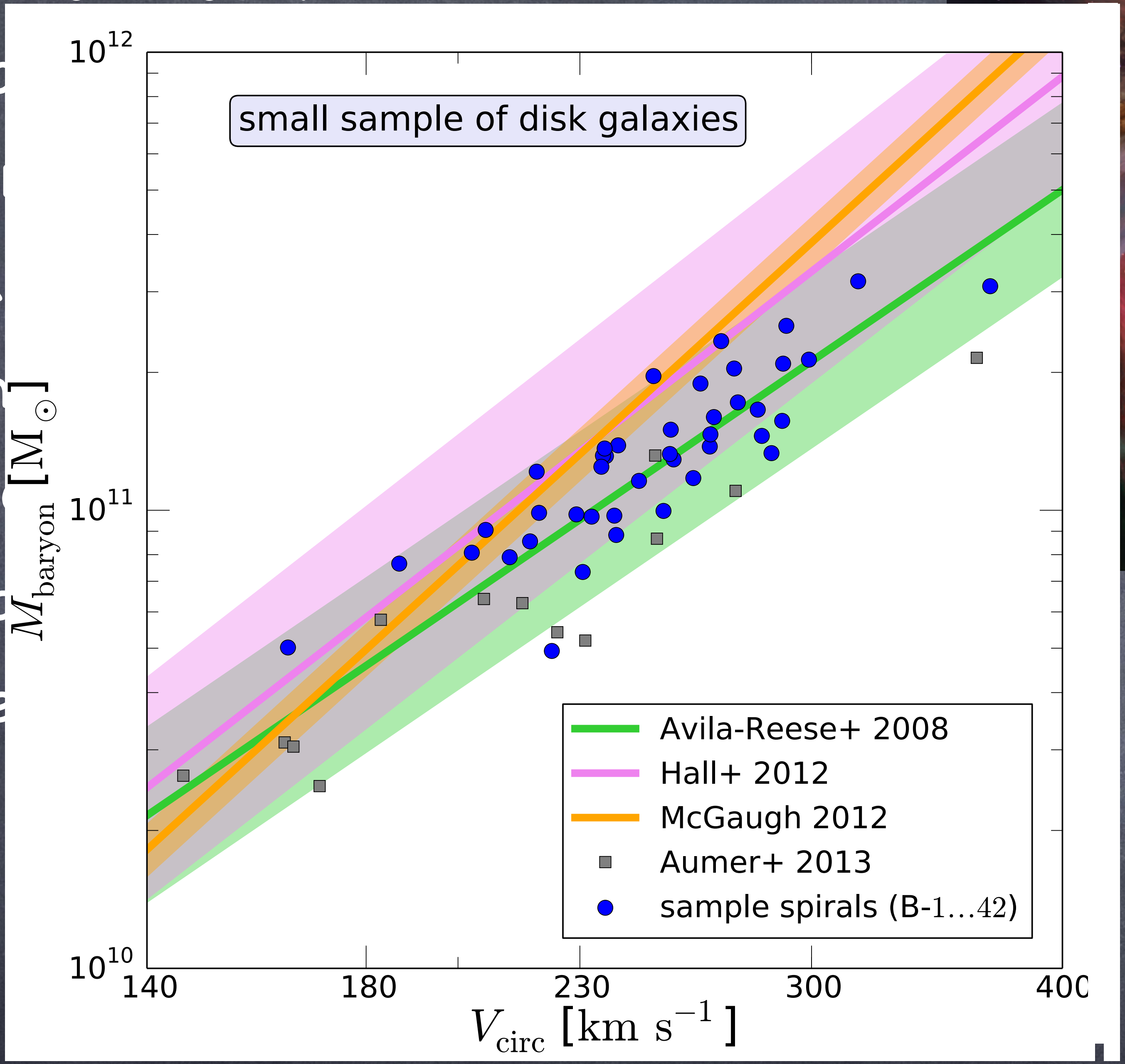
One extreme: It's all feedback!

- 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 Tully-Fisher relation?

One extreme: It's all feedback!

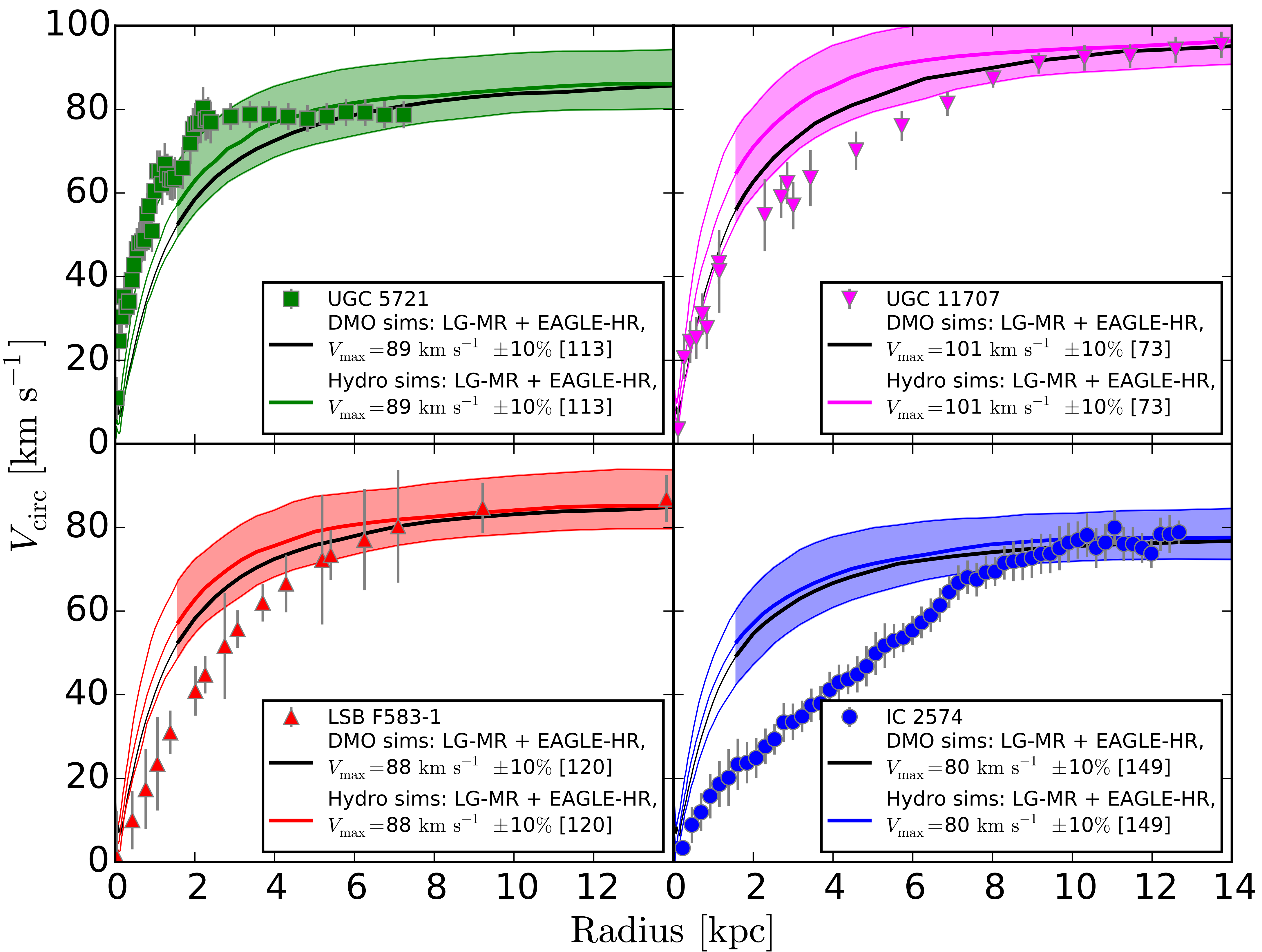
- Star formation model
- Stellar evo
- Mass and
- Supernova
- Gas enrich
- Cooling an
- Self-shiel
- Stellar fee
- Local and
- Black hole



Vogelsberger et al. (2014)

Can these feedback processes, which are inherently stochastic, result in tight correlation displayed in Tully-Fisher relation?

One extreme: It's all feedback!



er et al.

astic,

n?

"The unexpected diversity of dwarf galaxy rotation curves"

Oman et al. (2016)

The other extreme: it's all modified gravity!

Modified Newtonian Dynamics (MOND)

Milgrom (1983)

- No dark matter
- Newtonian gravity fails at low acceleration

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

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

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

MOND effective theory:

Bekenstein & Milgrom (1984)

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

MOND effective theory:

Bekenstein & Milgrom (1984)

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

MOND? For static, spherically-symmetric source,

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

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

MOND effective theory:

Bekenstein & Milgrom (1984)

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

MOND? For static, spherically-symmetric source,

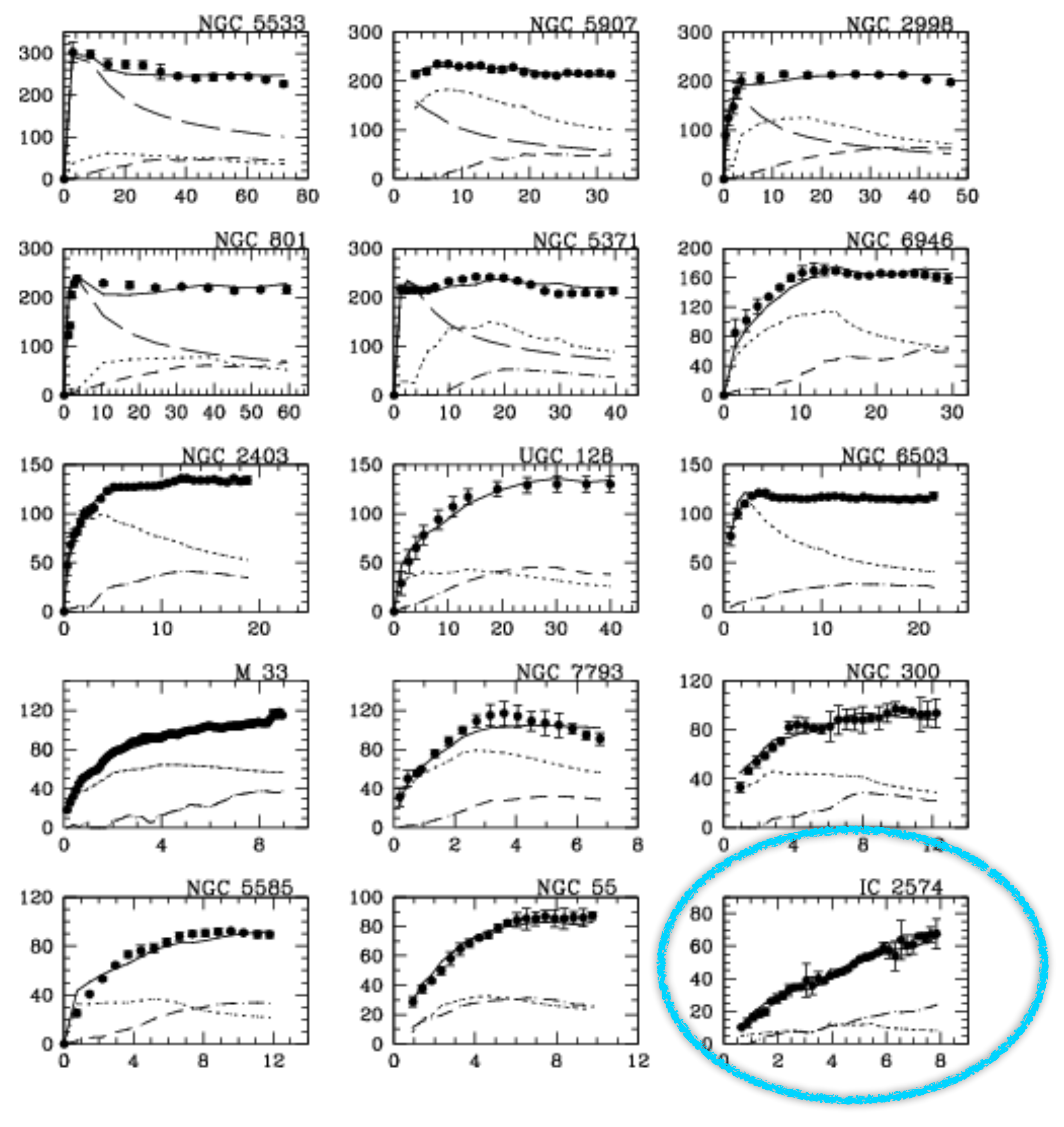
$$\vec{\nabla}\cdot\left(\frac{|\vec{\nabla}\phi|}{a_0}\vec{\nabla}\phi\right) = 4\pi G_{\rm N}\rho$$

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

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

Milgrom's MOND empirical law

Milgrom (1983)

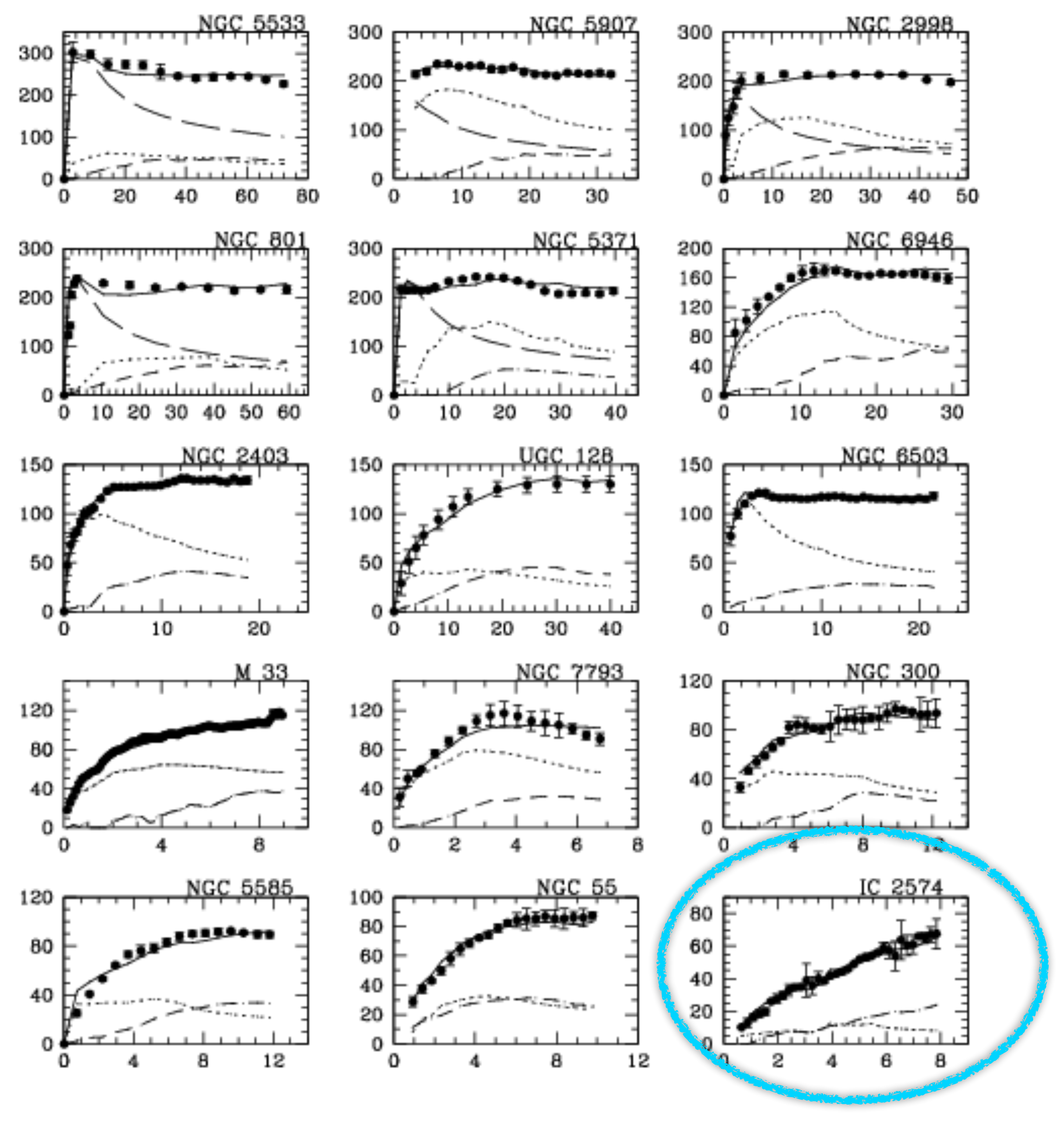


$$a = \begin{cases} a_{\rm N} & a_{\rm N} \gg a_0 \\ \sqrt{a_{\rm N} a_0} & a_{\rm N} \ll a_0 \end{cases}$$

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

Milgrom's MOND empirical law

Milgrom (1983)



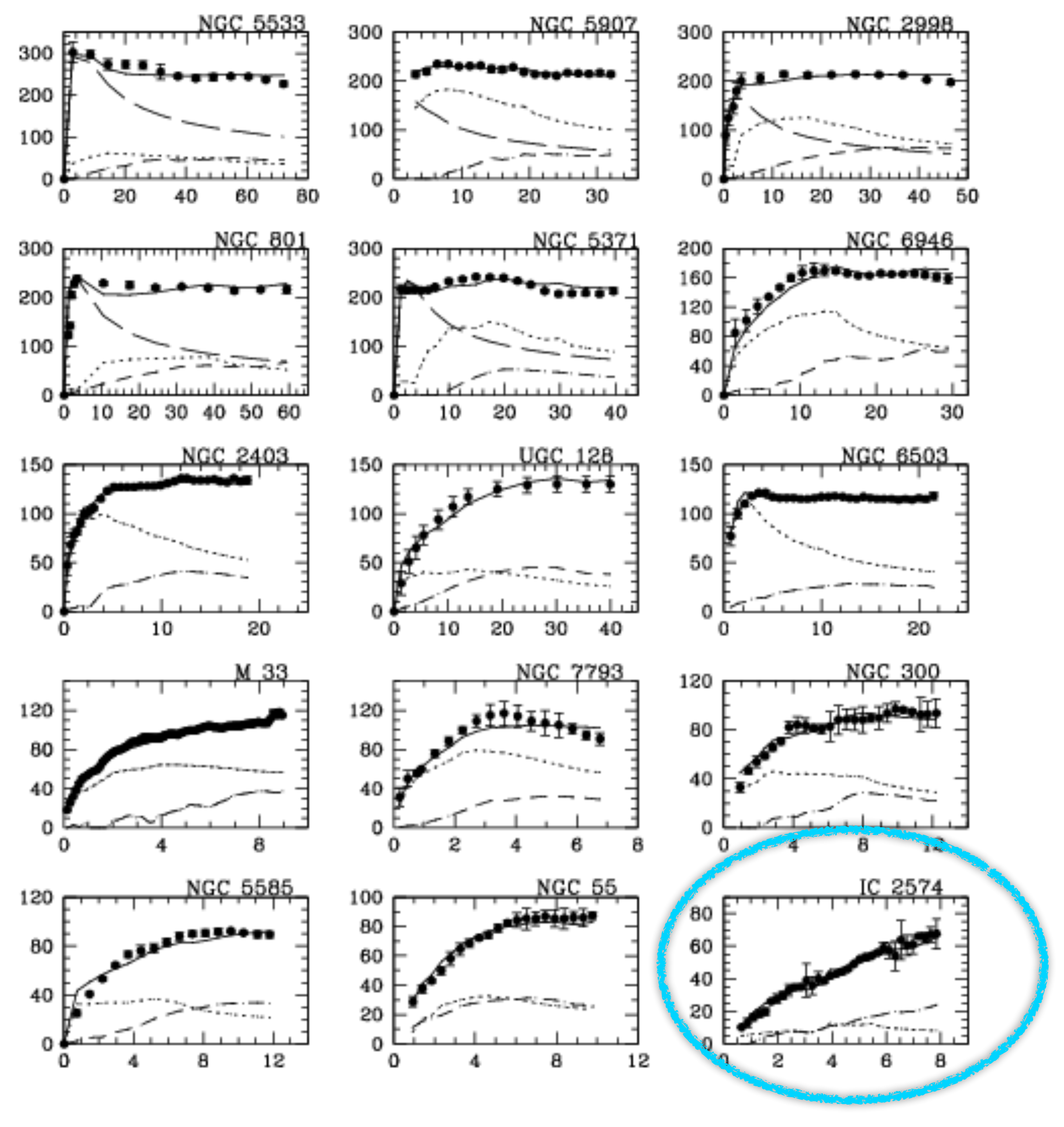
$$a = \begin{cases} a_{\rm N} & a_{\rm N} \gg a_0 \\ \sqrt{a_{\rm N} a_0} & a_{\rm N} \ll a_0 \end{cases}$$

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

Tully-Fisher relation and Freeman's law both follow. ✓

Milgrom's MOND empirical law

Milgrom (1983)



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

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

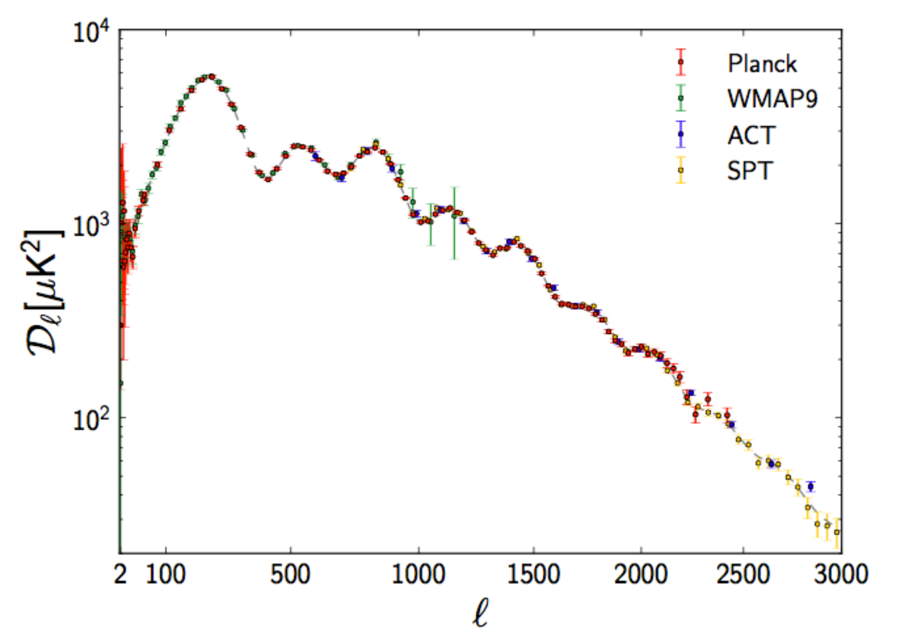
Tully-Fisher relation and Freeman's law both follow. ✓

Effective surface brightness (in HSB galaxies):

$$\rho_0 r_0 = \frac{a_0}{2\pi G_{\mathrm{N}}}$$ ✓

Obvious problems

What about large scales?



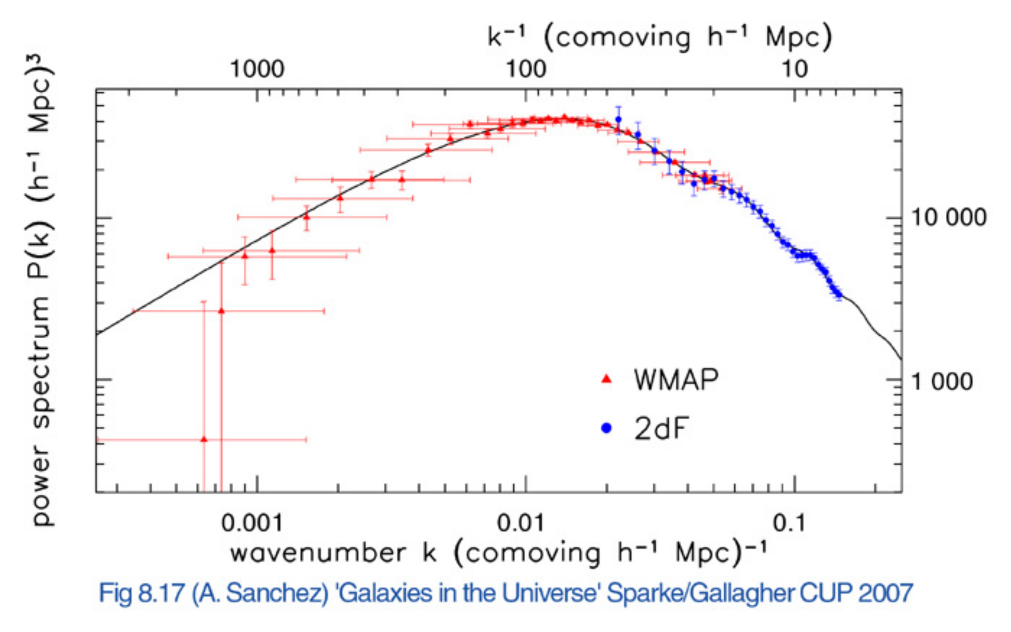
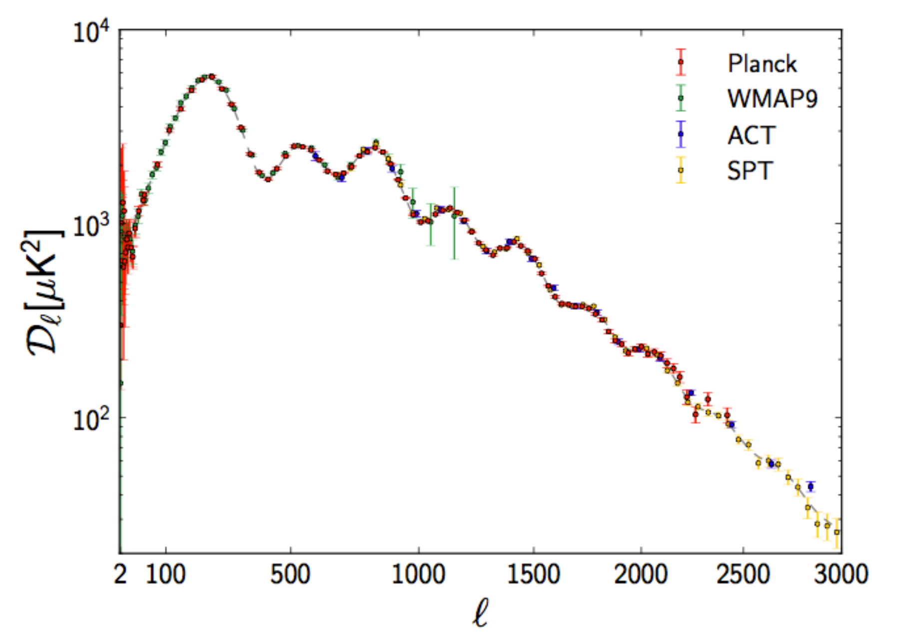


Fig 8.17 (A. Sanchez) 'Galaxies in the Universe' Sparke/Gallagher CUP 2007

Obvious problems

What about large scales?



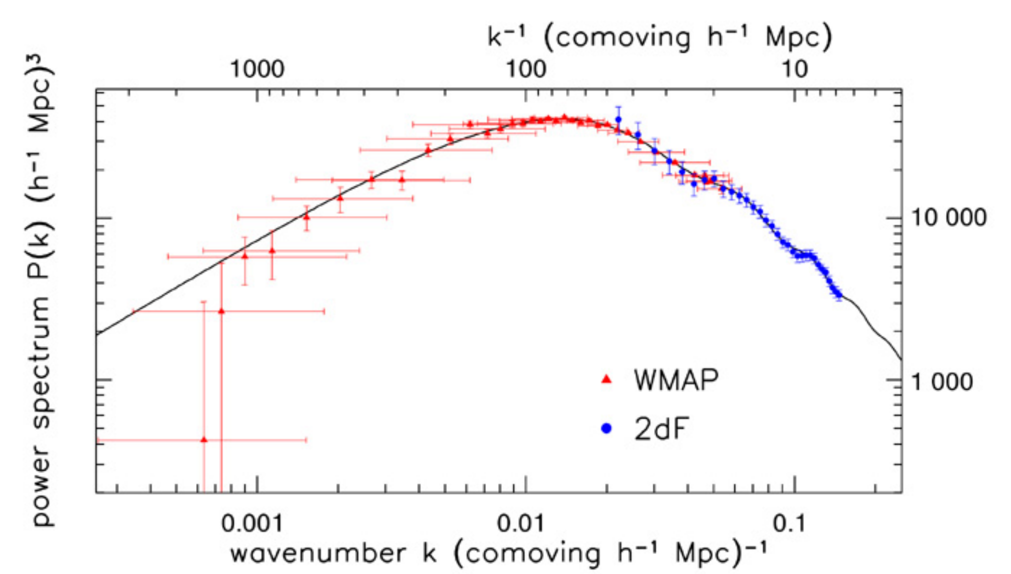
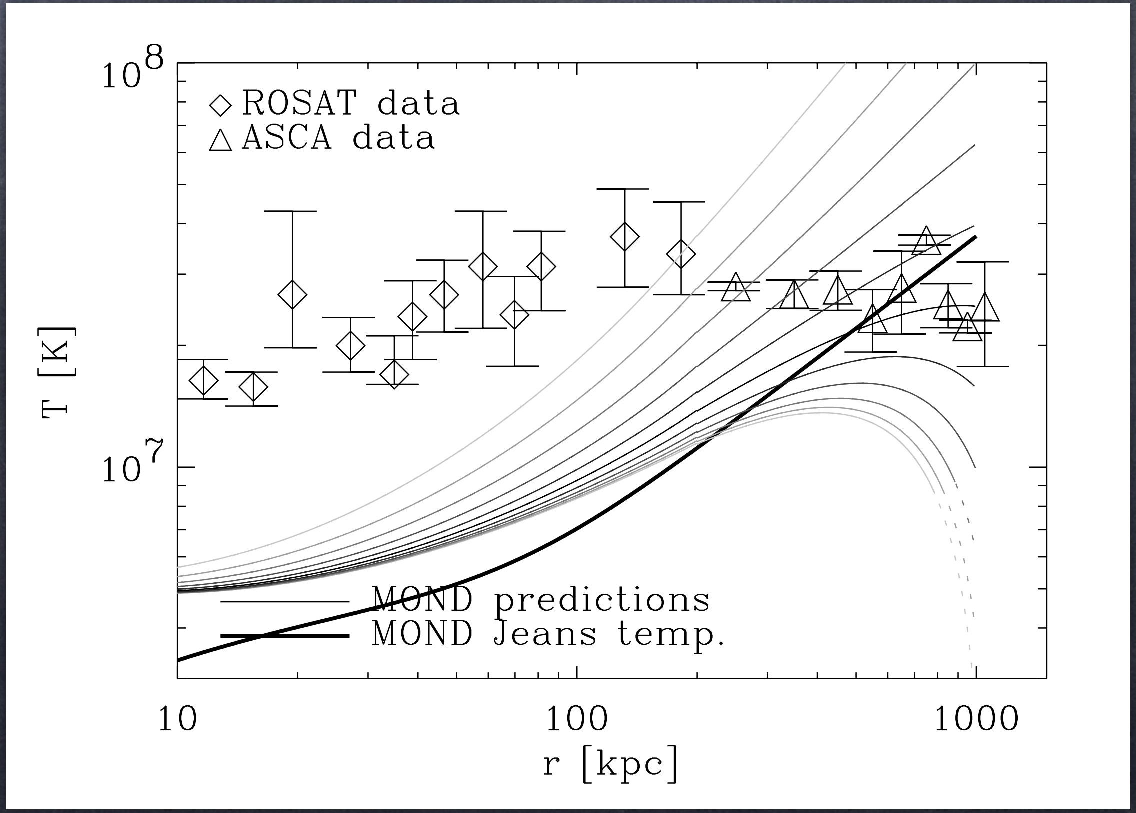


Fig 8.17 (A. Sanchez) 'Galaxies in the Universe' Sparke/Gallagher CUP 2007

Poor fit to galaxy clusters:

Aguirre (2001)



The middle ground:

Blanchet (2006); Bruneton et al. (2008);
Ho, Minic & Ng (2009); JK (2014); Verlinde (2016)

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

The middle ground:

Blanchet (2006); Bruneton et al. (2008);
Ho, Minic & Ng (2009); JK (2014); Verlinde (2016)

- 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.

The middle ground:

Blanchet (2006); Bruneton et al. (2008);
Ho, Minic & Ng (2009); JK (2014); Verlinde (2016)

- 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. in this talk: DM superfluidity

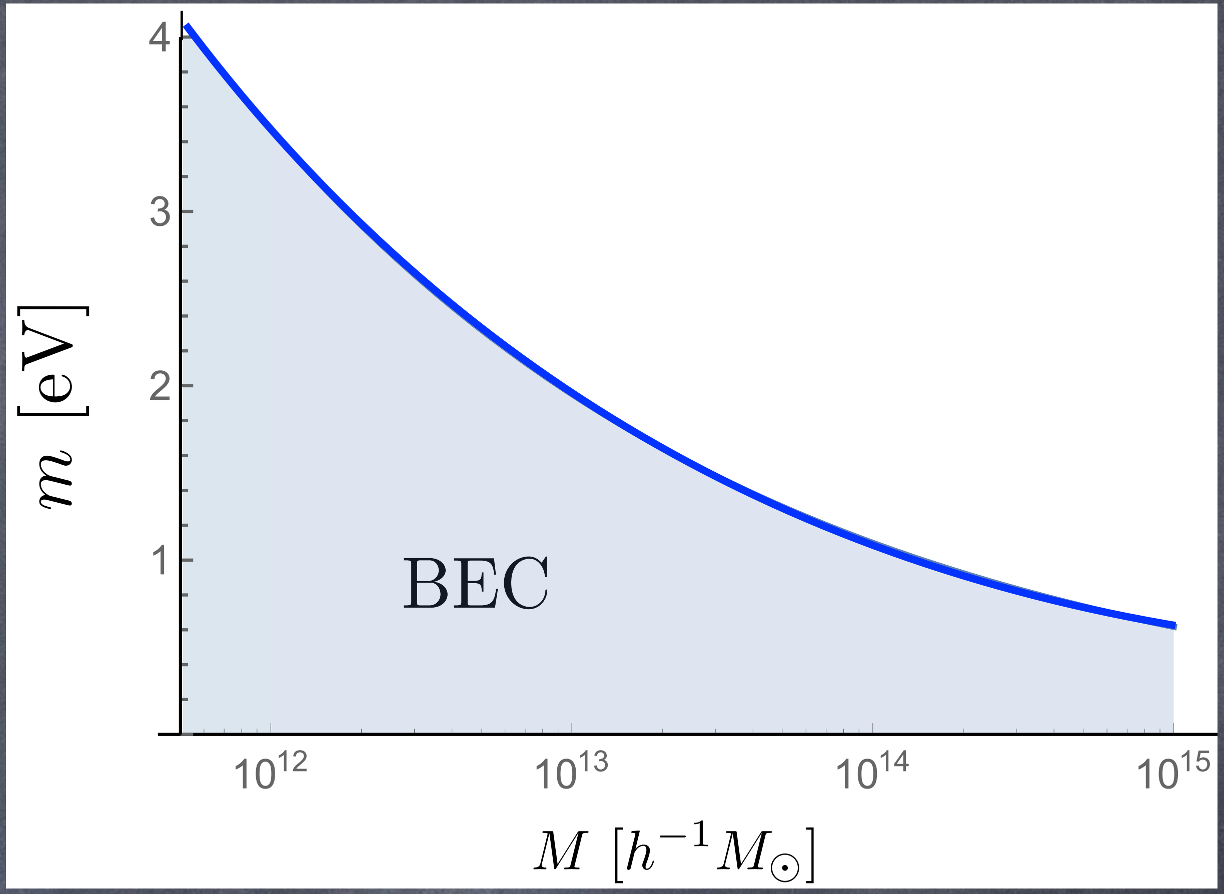
2 Conditions for DM Condensation

2 Conditions for DM Condensation

- Overlapping de Broglie wavelength

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

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

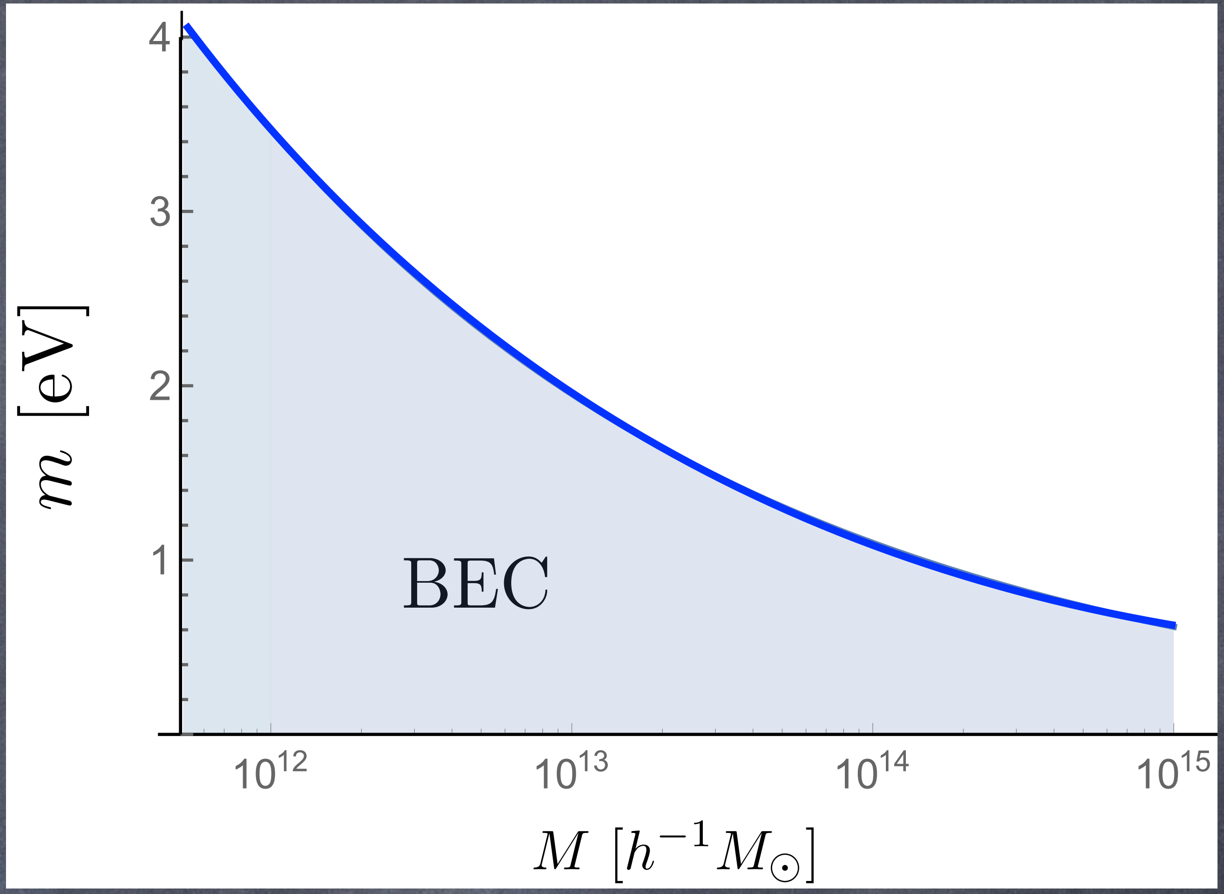


2 Conditions for DM Condensation

- Overlapping de Broglie wavelength

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

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



- Thermal equilibrium

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

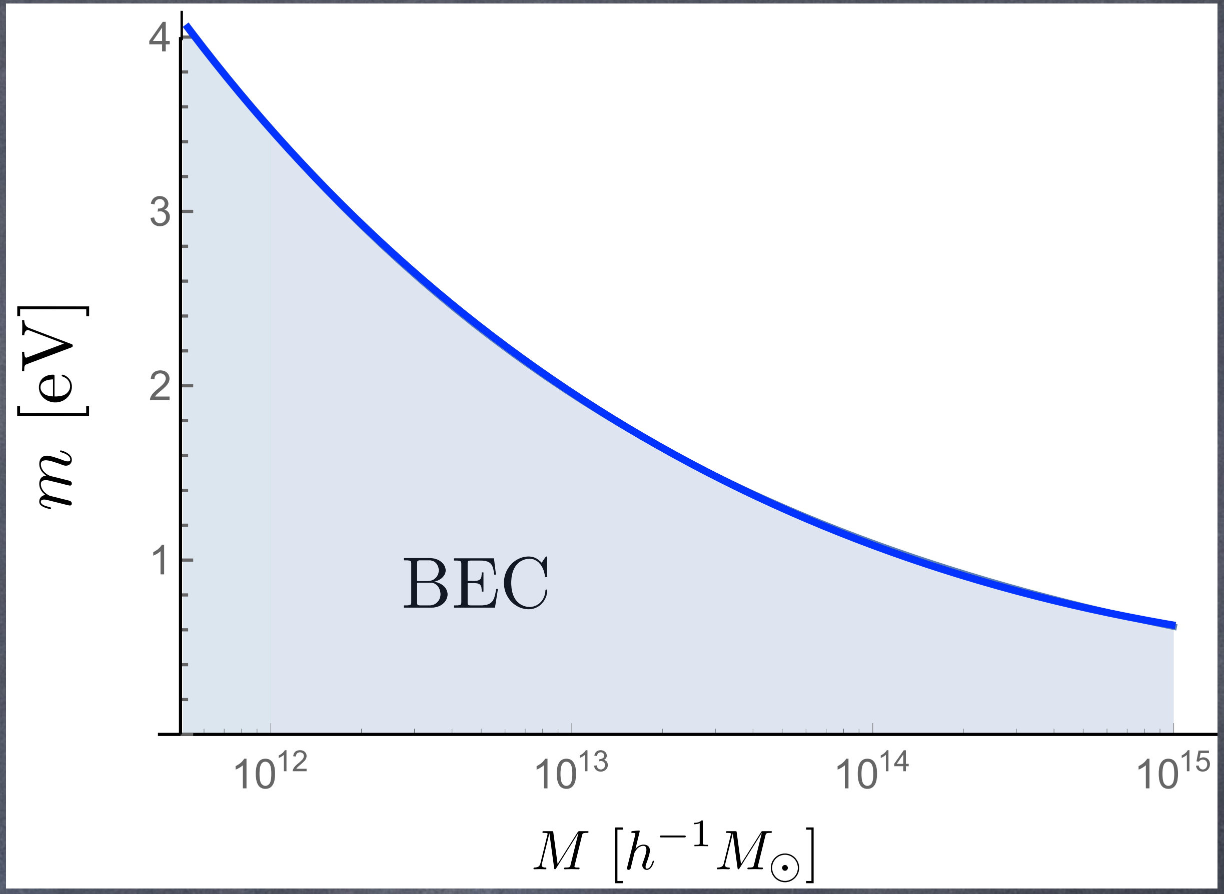
Current bound: $\frac{\sigma}{m} \lesssim 0.5\,\frac{{\rm cm}^2}{g}$ Harvey et al. (2015)

2 Conditions for DM Condensation

- Overlapping de Broglie wavelength

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

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



- Thermal equilibrium

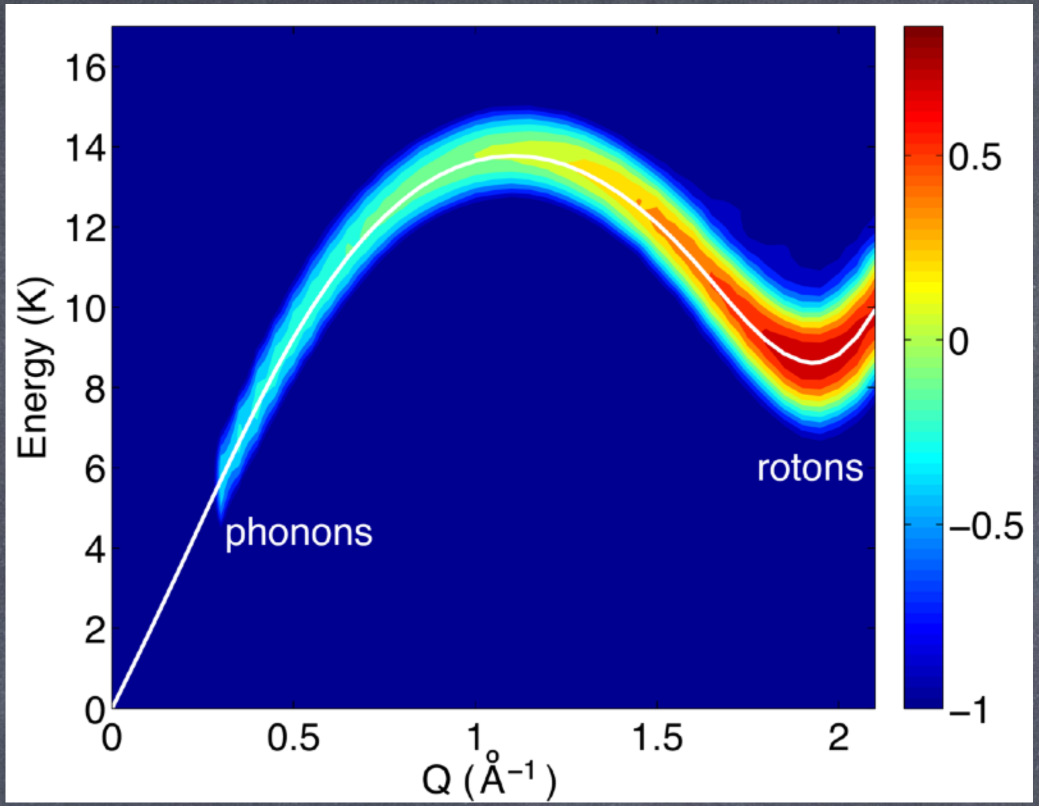
$$\Gamma \sim \mathcal{N} v \sigma \frac{\rho_{\mathrm{vir}}}{m} \gtrsim t_{\mathrm{dyn}}^{-1} \quad \Longrightarrow \quad \boxed{\frac{\sigma}{m} \gtrsim \left(\frac{m}{\mathrm{eV}}\right)^{4} \frac{\mathrm{cm}^2}{g}}$$

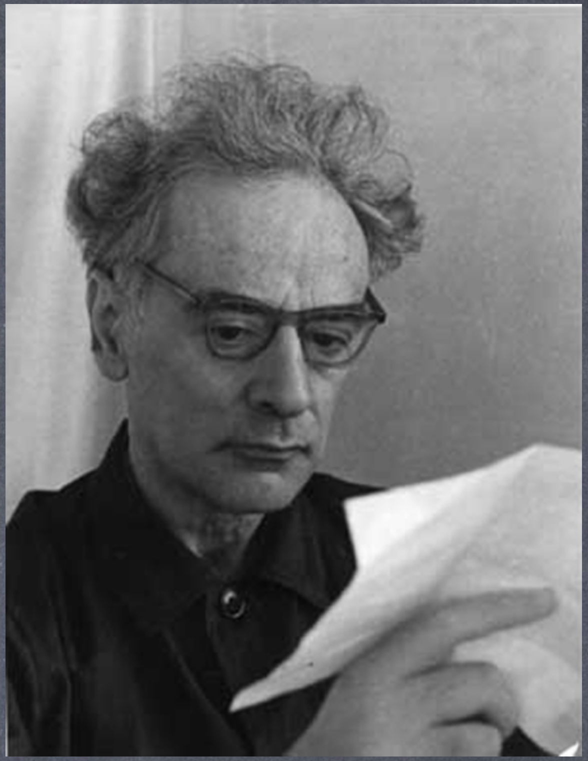
Current bound: $\frac{\sigma}{m} \lesssim 0.5 \frac{\mathrm{cm}^2}{g}$ Harvey et al. (2015)

DM is quite cold: $T_{\mathrm{c}} = 6.5 \left(\frac{\mathrm{eV}}{m}\right)^{5/3} (1+z_{\mathrm{vir}})^2\ \mathrm{mK}$

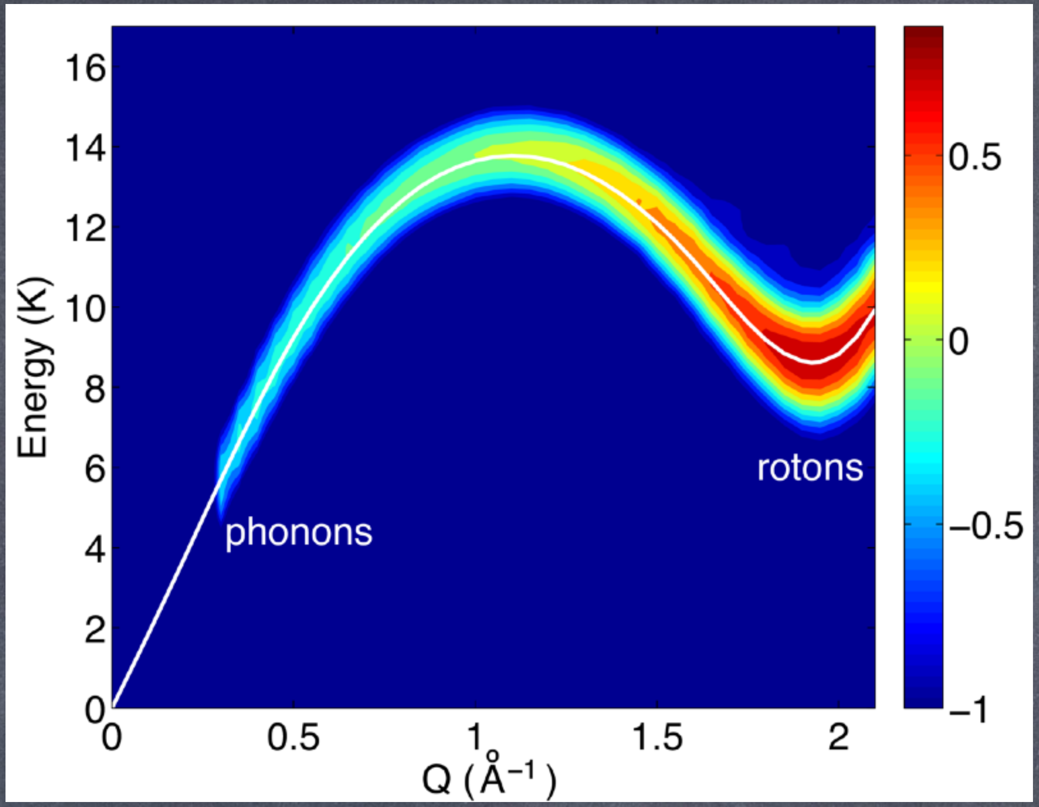
($^7\mathrm{Li}$ atoms $\Longrightarrow T_{\mathrm{c}} \sim 0.2\ \mathrm{mK}$)

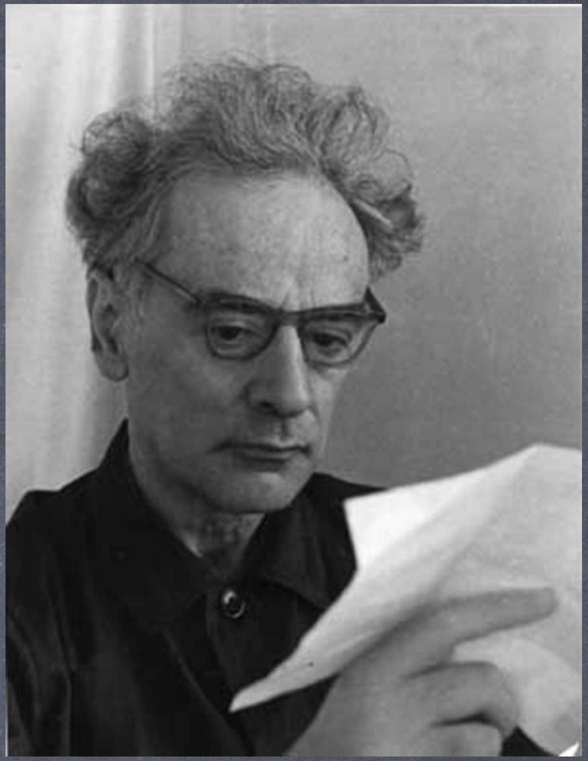
Two-fluid model





Two-fluid model

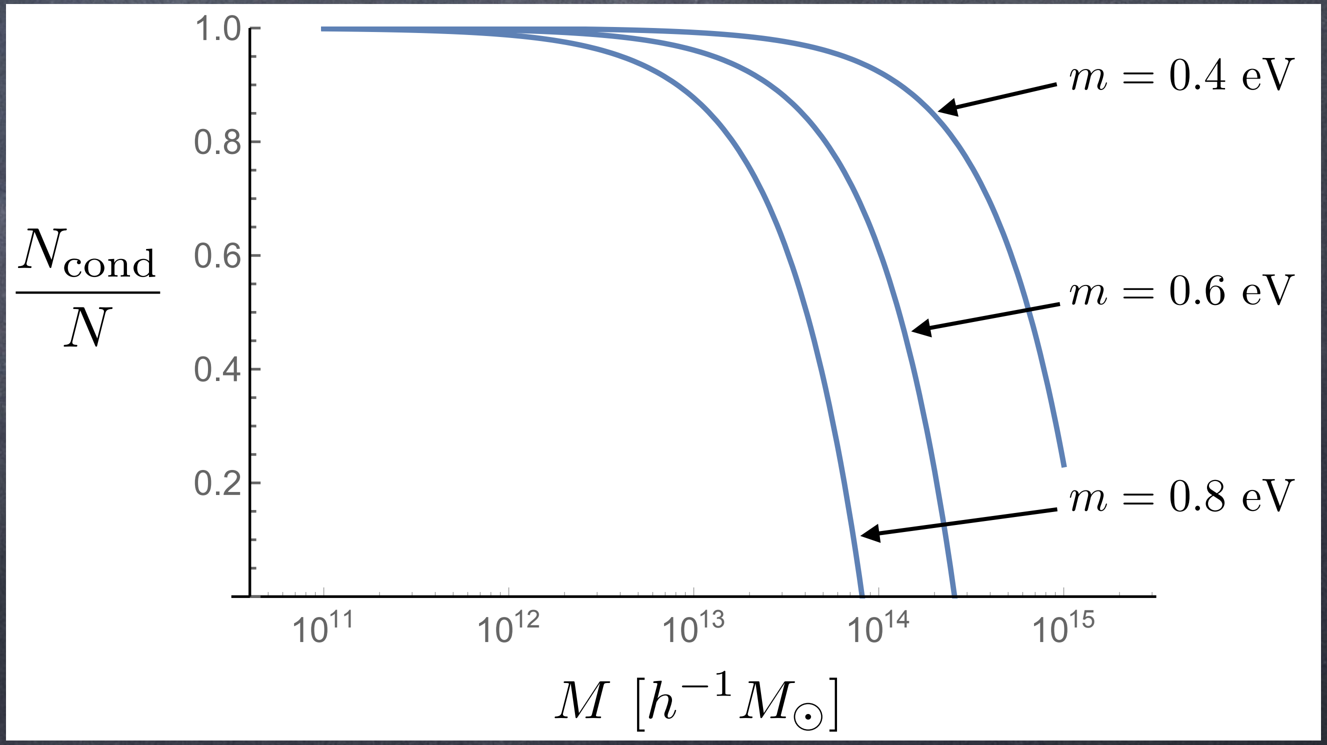




Free bose gas:

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

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

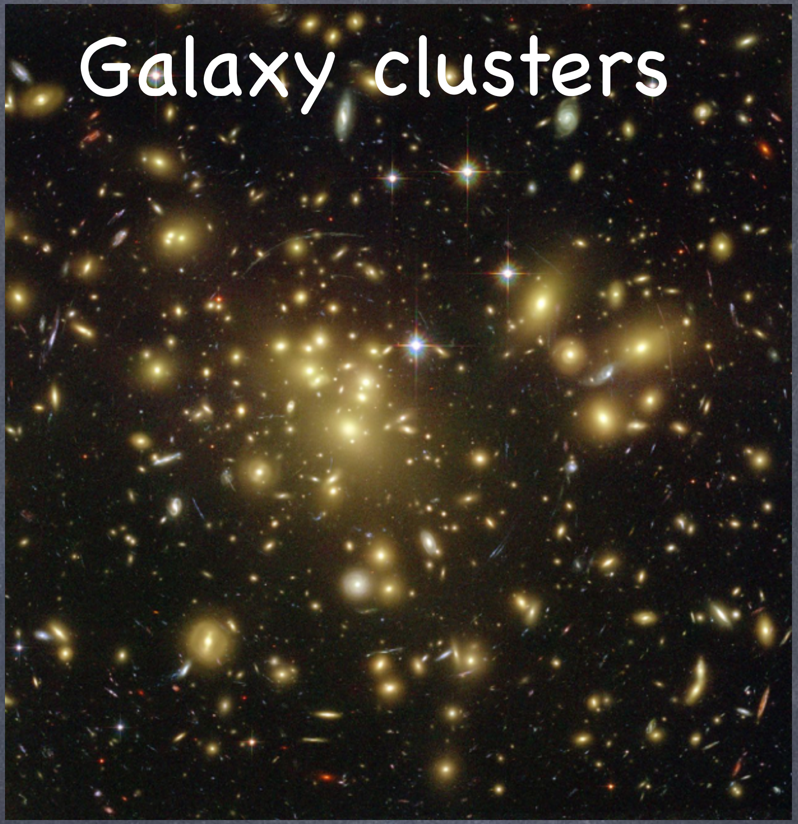


Can generalize to include interactions.

Khoury, Lubensky, Miranda & Sharma (to appear)

Temperature set by how rapidly DM particles move

$$\boxed{T \sim mv^2}$$



$$T_{\text{galaxy}} \sim 0.1 \text{ mK}$$

$$T_{\text{cluster}} \sim 10 \text{ mK}$$

$\Longrightarrow$ Superfluid ✓

$\Longrightarrow$ MOND

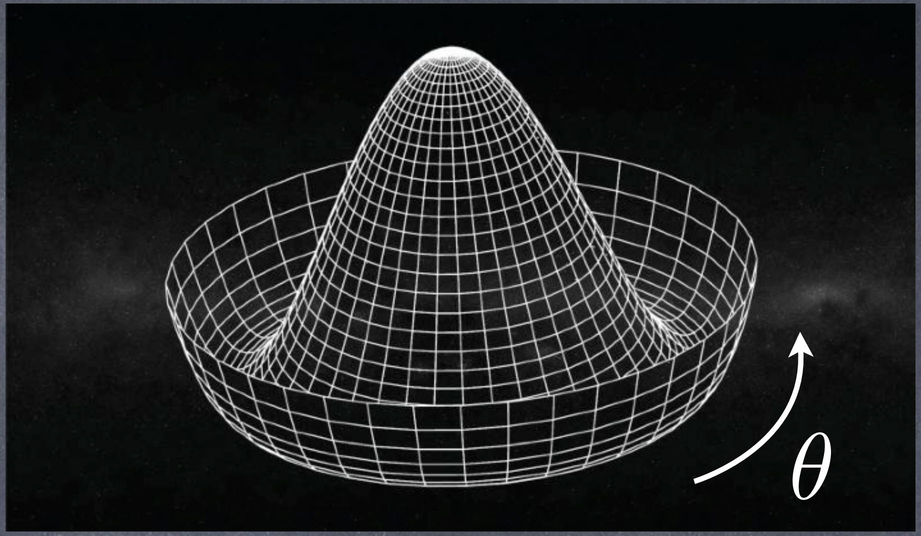
$\Longrightarrow$ NO Superfluid ✓

$\Longrightarrow$ 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)



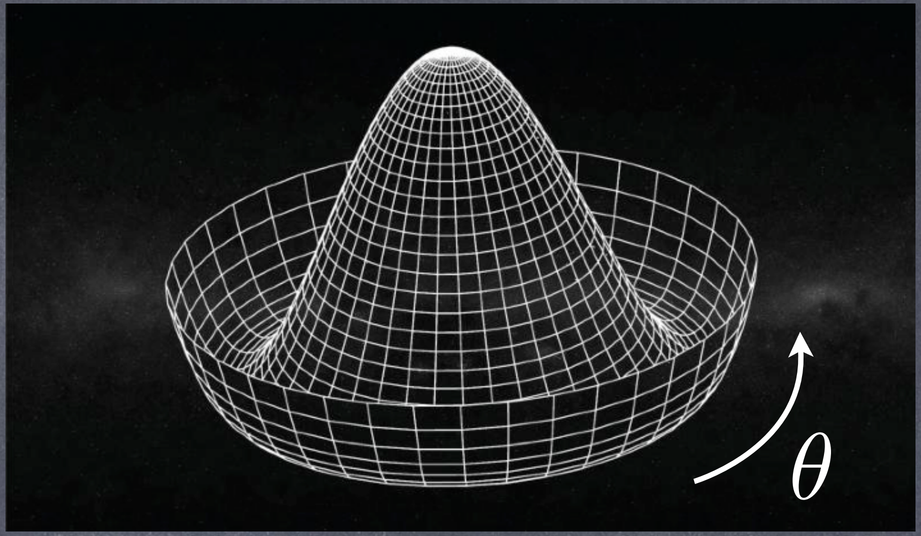
A superfluid phase is defined as:

- Global U(1) symmetry, spontaneously broken

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

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

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

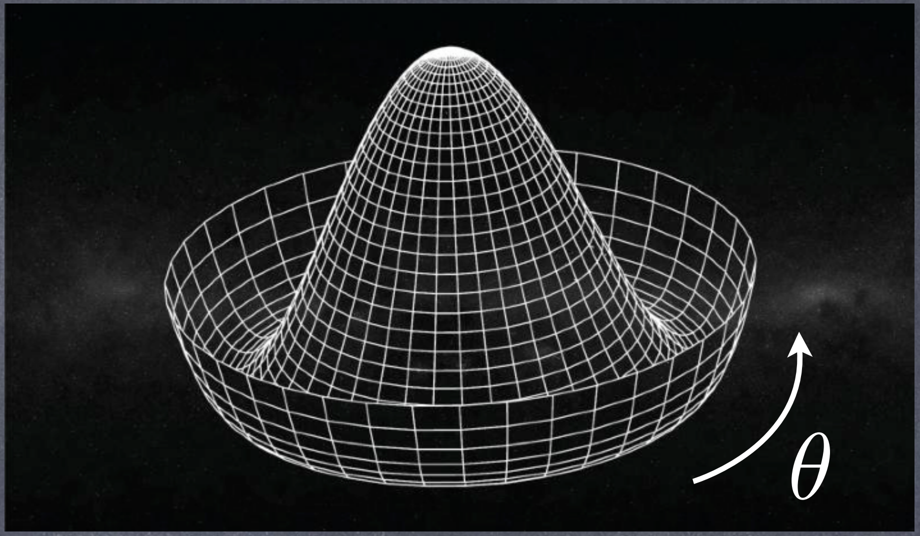
chemical potential

phonons

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

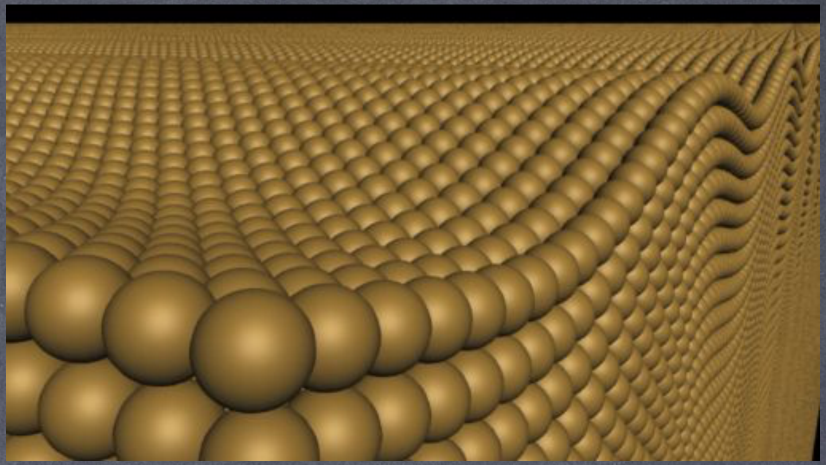
phonons

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

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

Superfluid phonons

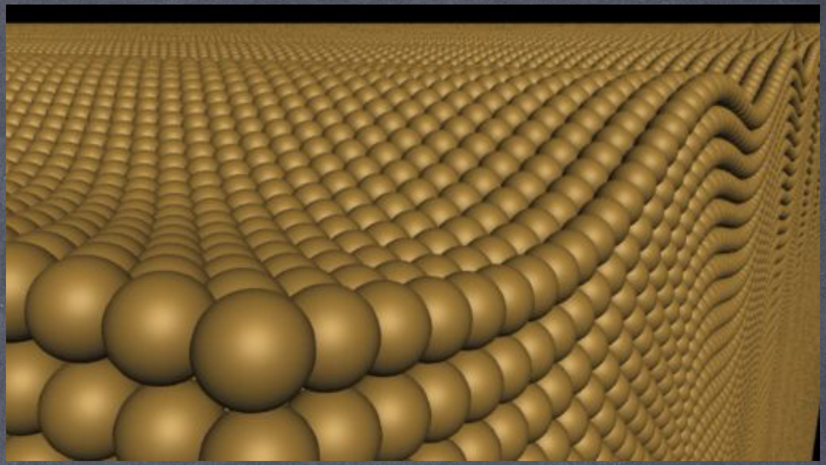
At lowest order in derivatives, the zero temperature effective action is



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

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

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

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

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

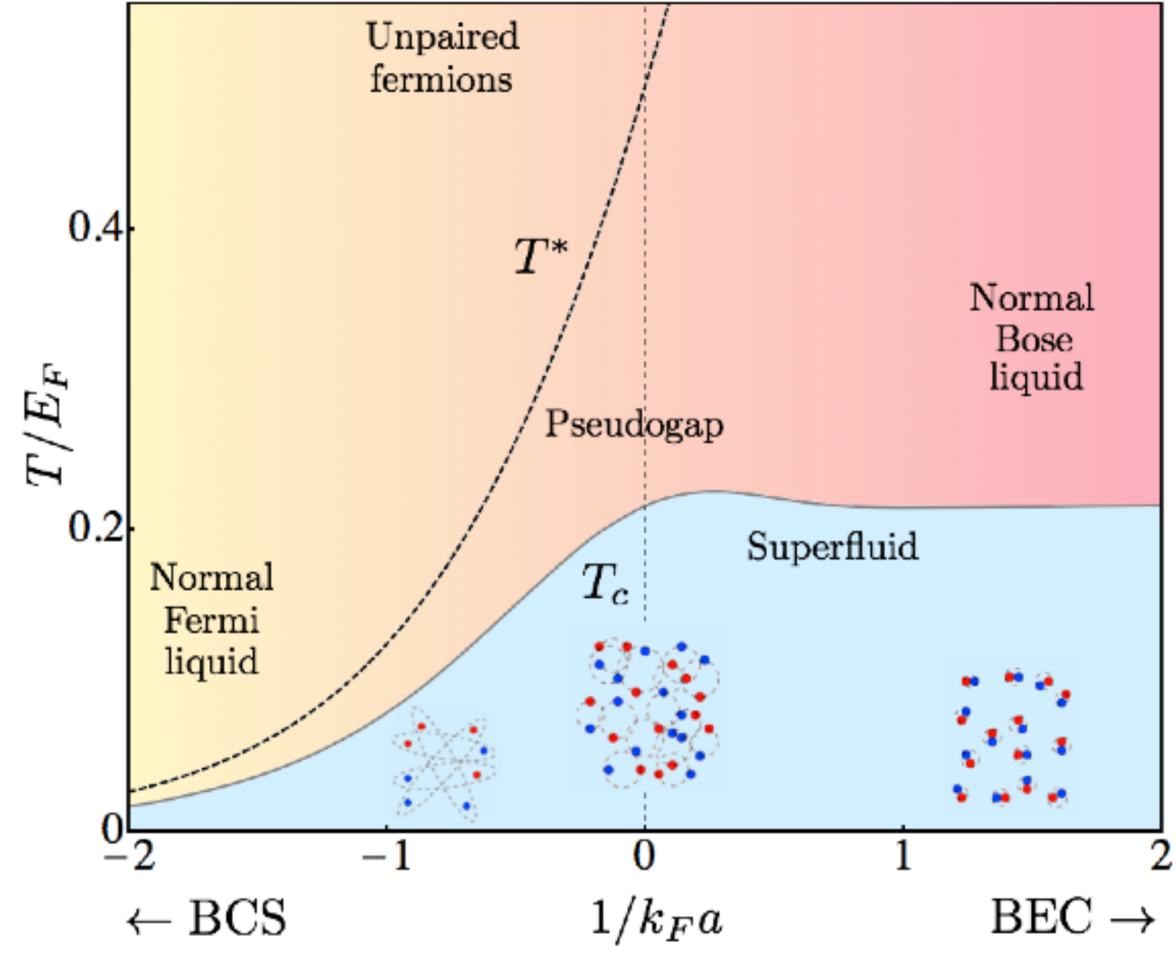
$$\Lambda = \sqrt{a_0 M_{\rm Pl}} \simeq 0.8 \text{ meV}$$

(Match to MOND scale)

- Cold Atoms Analogue?

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

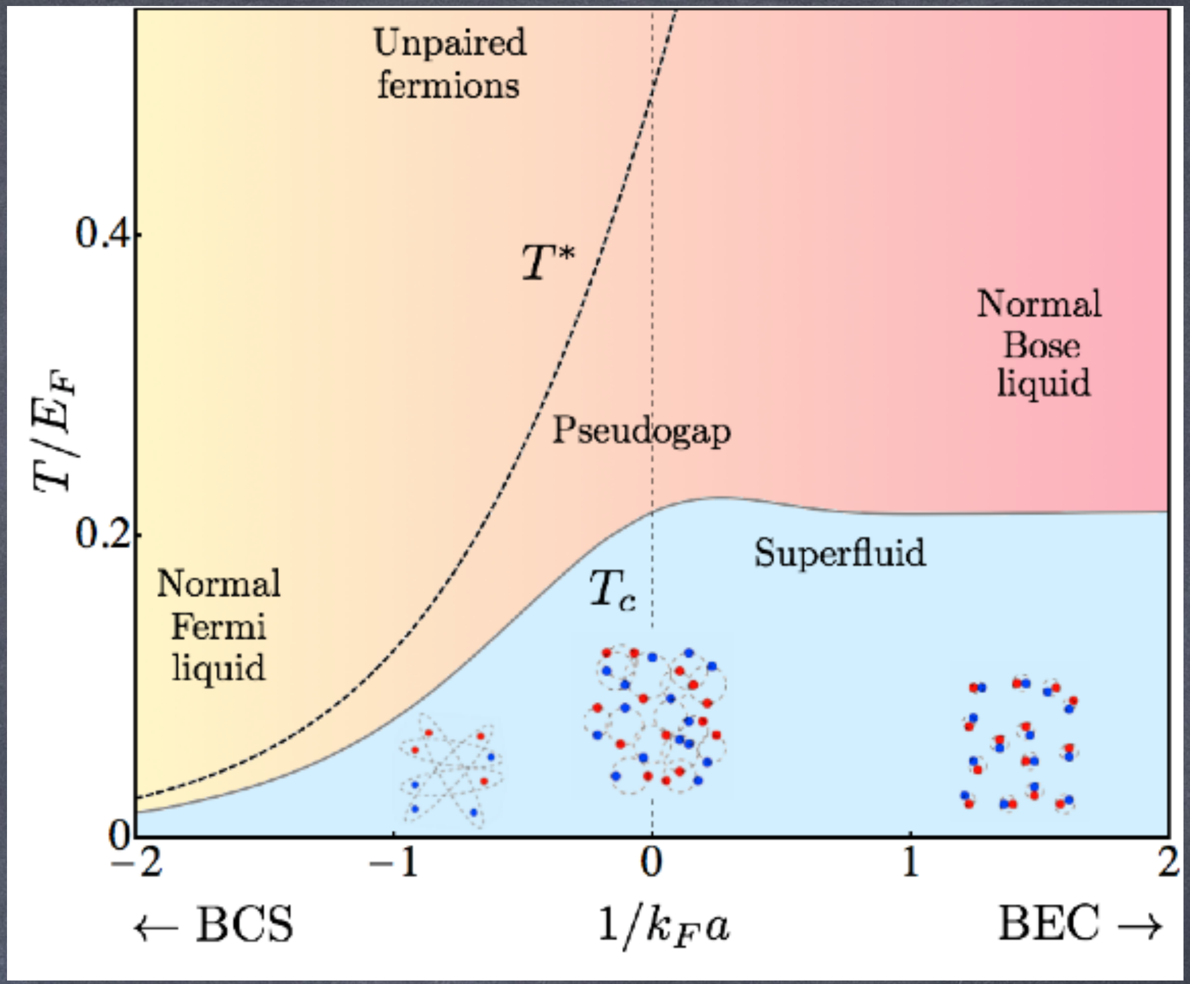
Son & Wingate (2005)



- 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 $P_{\rm cond} \sim \rho^2_{\rm cond}$

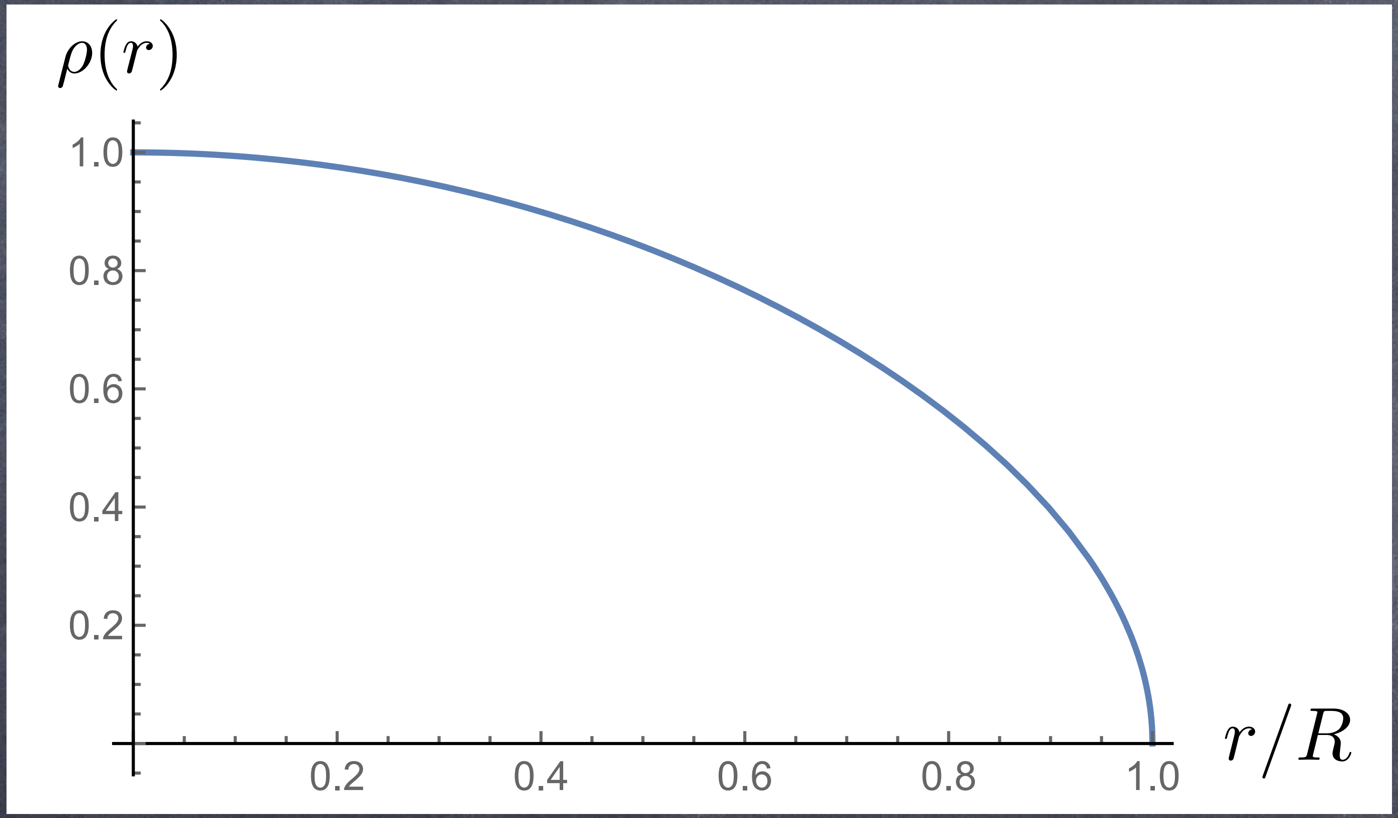
Sin (1994), Goodman (2000), Peebles (2000), Boehmer & Harko (2007)

Density profile

Assuming hydrostatic equilibrium,

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

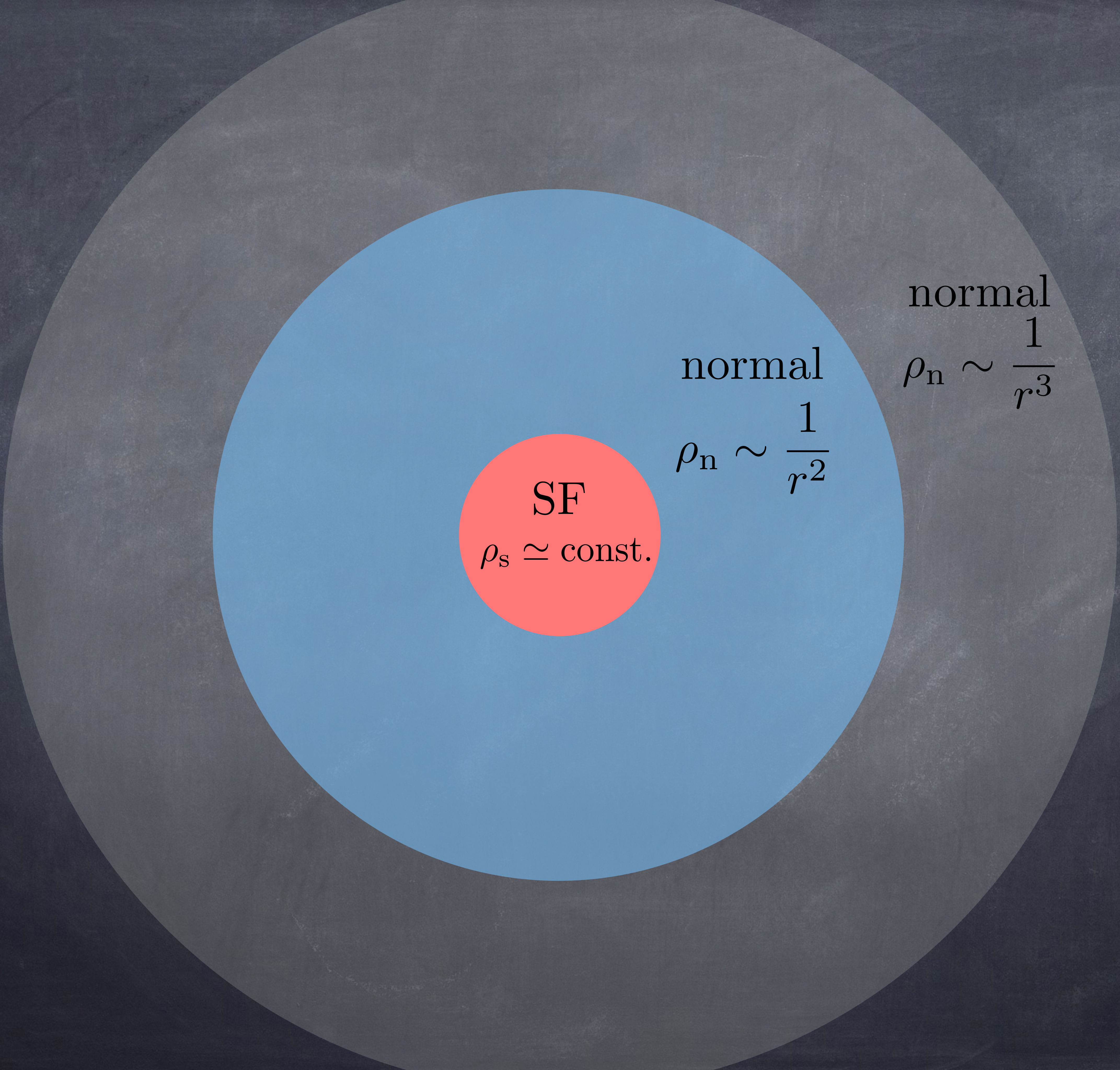
Using equation of state $P_{\rm cond} \sim \rho_{\rm cond}^3$, find:



Cored density profile

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

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



normal

$\rho_{\mathrm{n}} \sim \frac{1}{r^3}$

normal

$\rho_{\mathrm{n}} \sim \frac{1}{r^2}$

SF

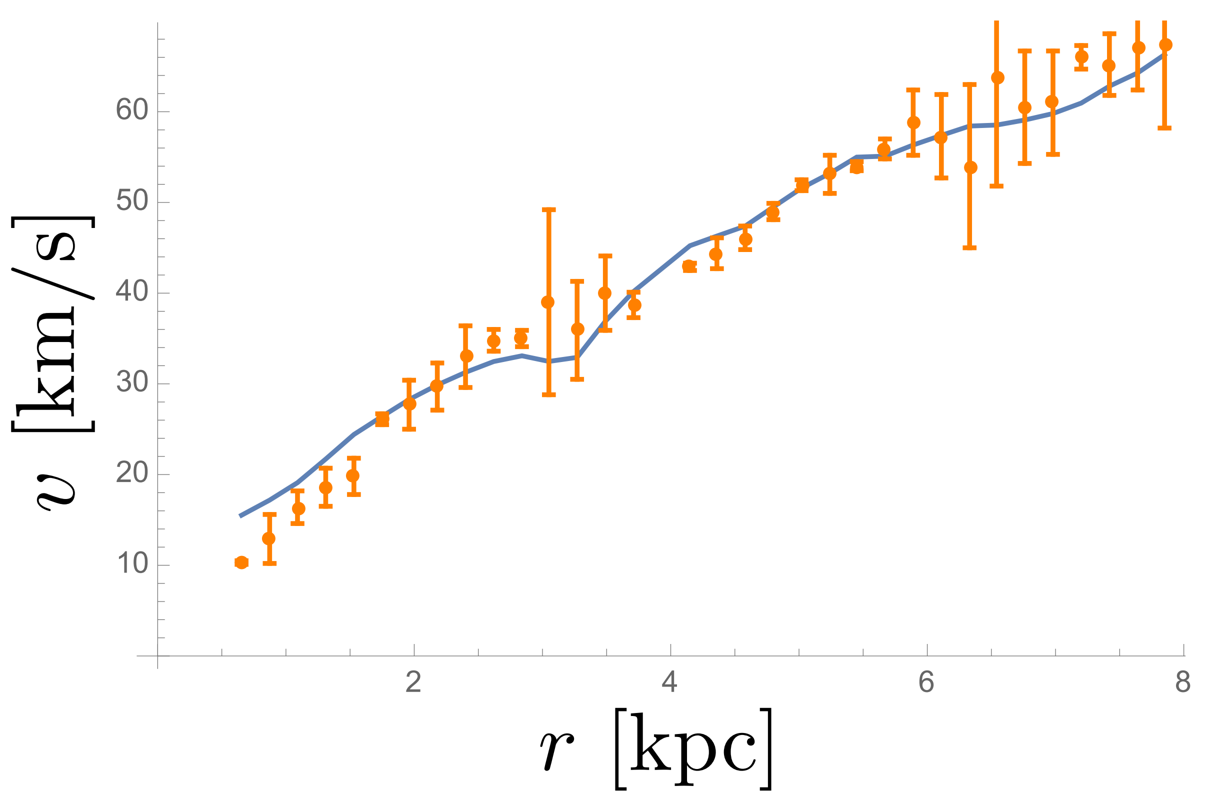
$\rho_{\mathrm{s}} \simeq \mathrm{const.}$

Rotation curves

w. L. Berezhiani & B. Famaey (to appear)

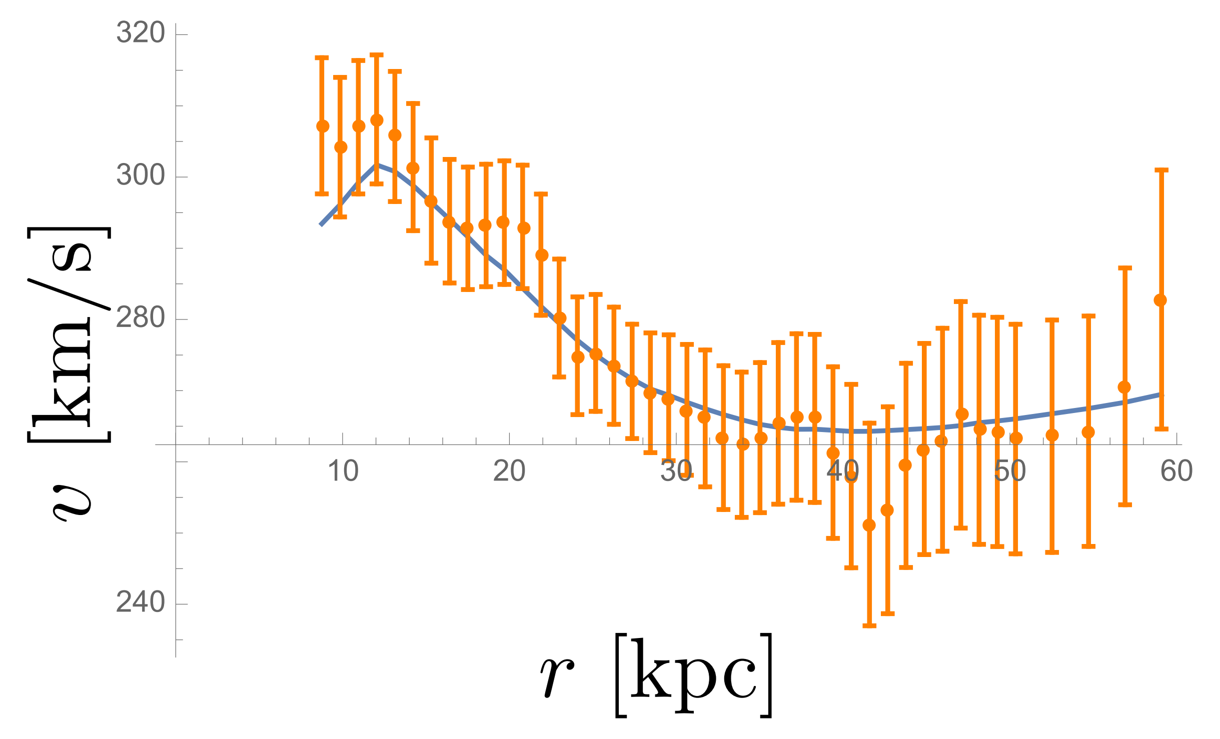
$m = 0.6 \text{ eV} \qquad \Lambda = 0.3 \text{ meV} \qquad a_0 = 0.87 \times 10^{-8} \text{ cm/s}^2$

LSB galaxy
(IC 2574)



$R_{\text{core}} = 37.5 \text{ kpc}$

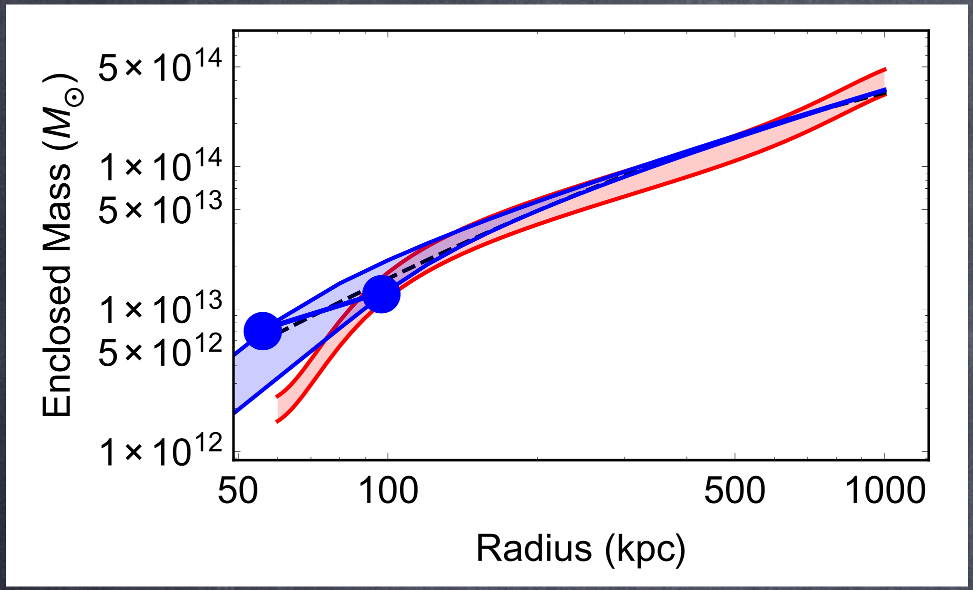
HSB galaxy
(UGC 2953)



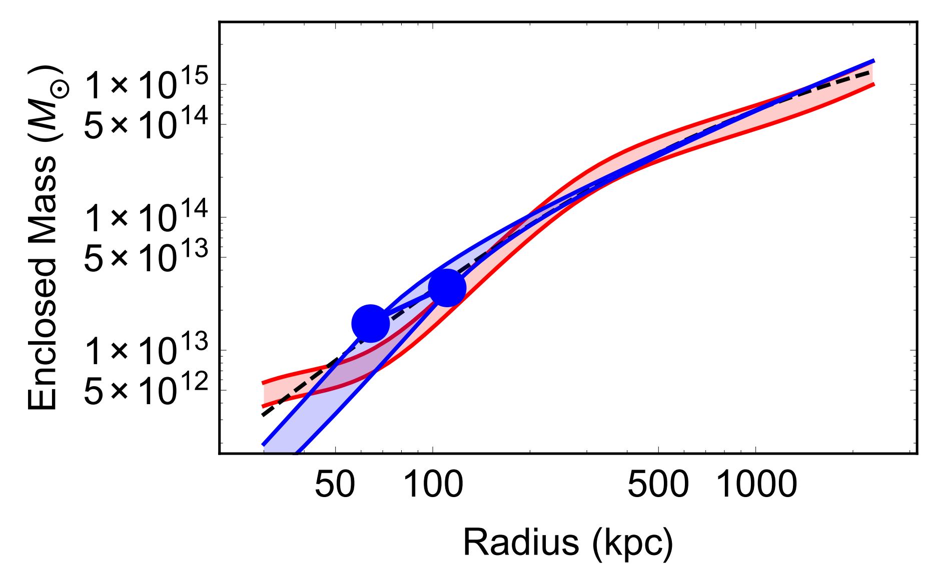
$R_{\text{core}} = 73.2 \text{ kpc}$

Galaxy clusters

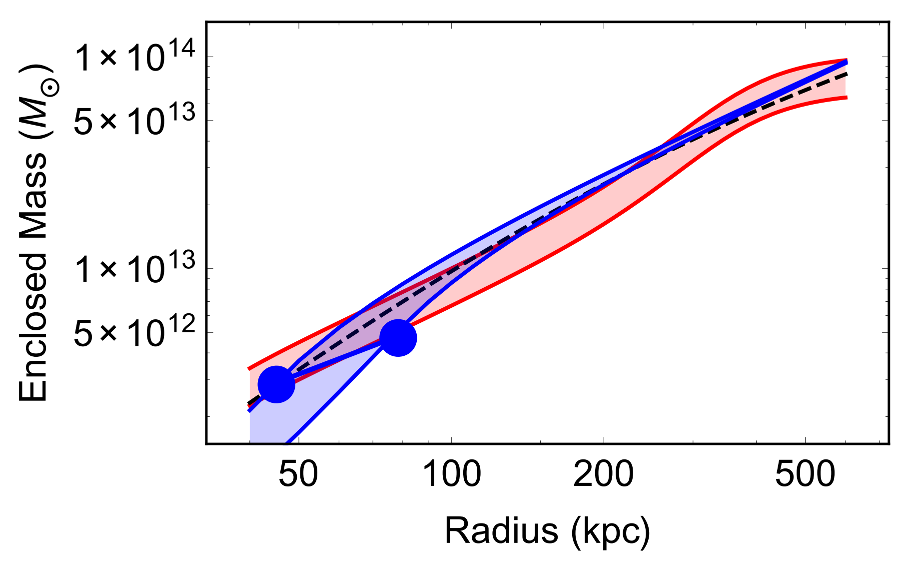
Hodson, Zhao, Khoury & Famaey, 1611.05876



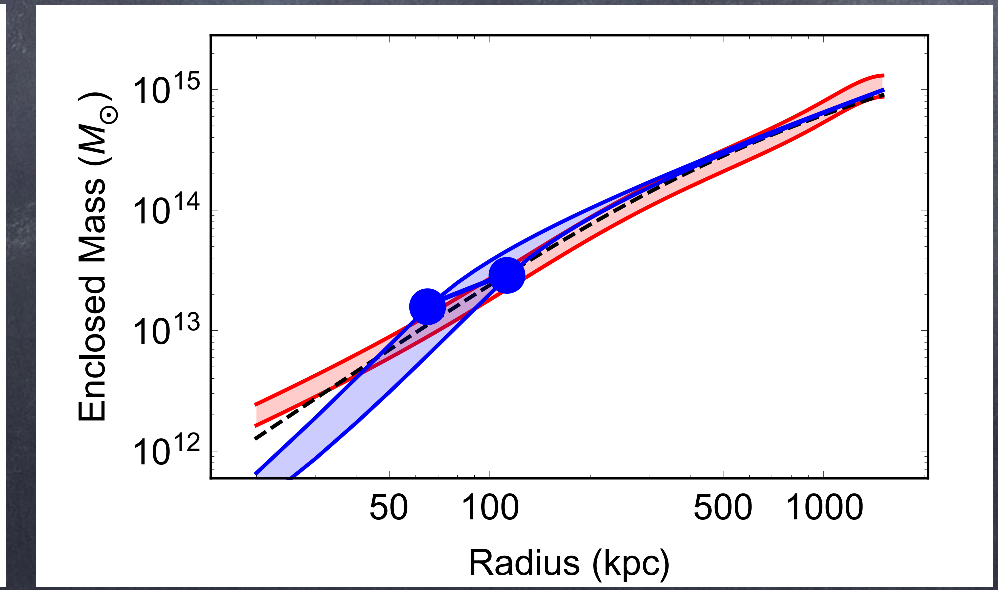
A133



A478



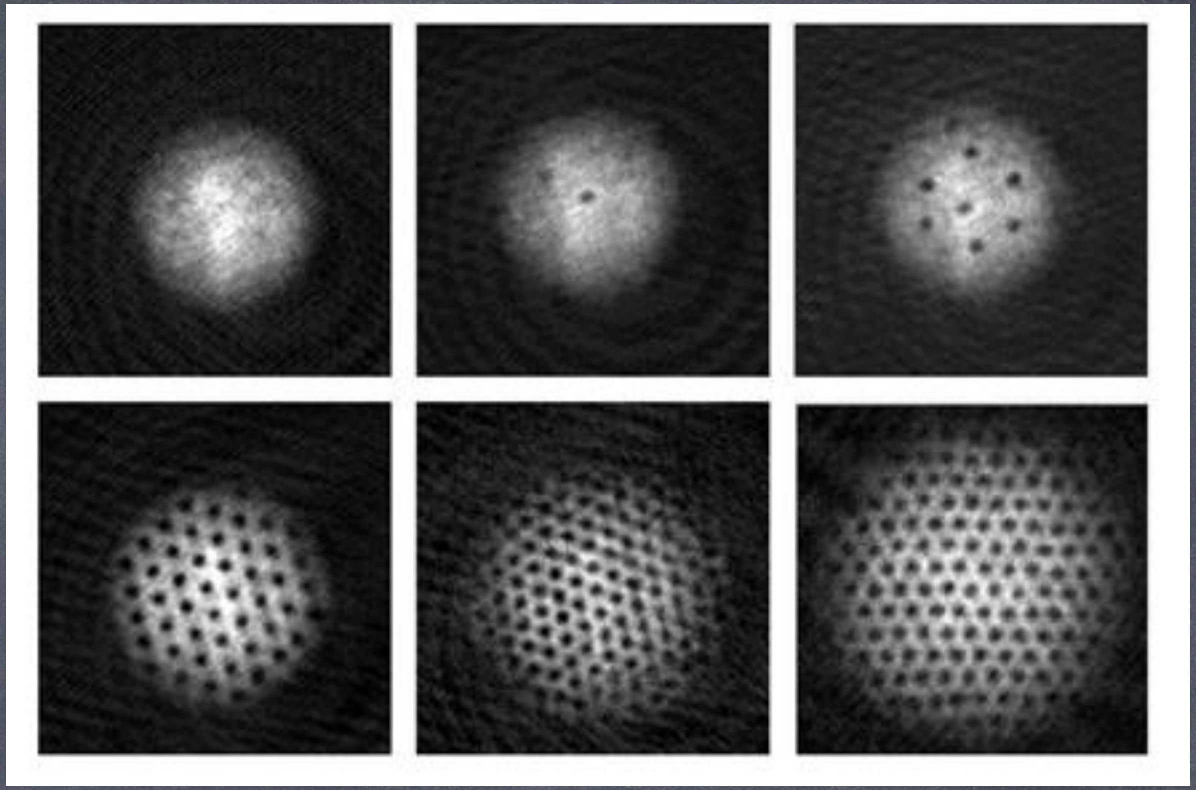
A262



A413

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

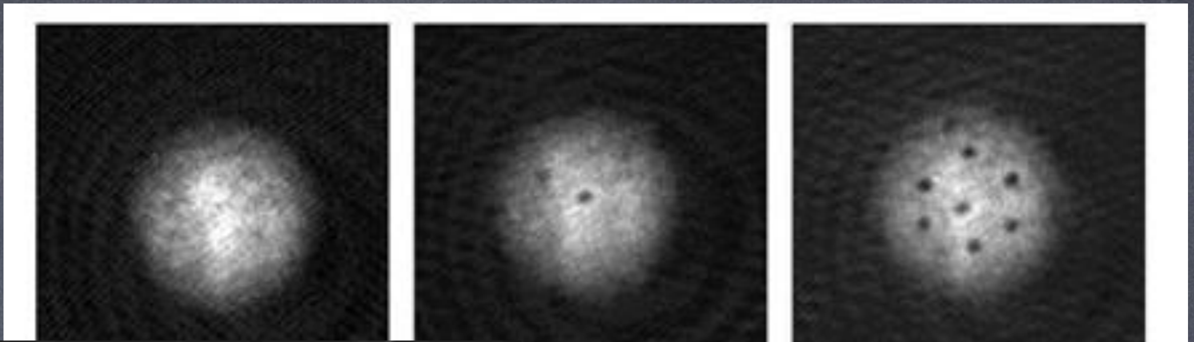
Line density: $\boxed{\sigma_{\rm v} \sim m\omega \sim 10^2\lambda\ {\rm AU}^{-2}}$

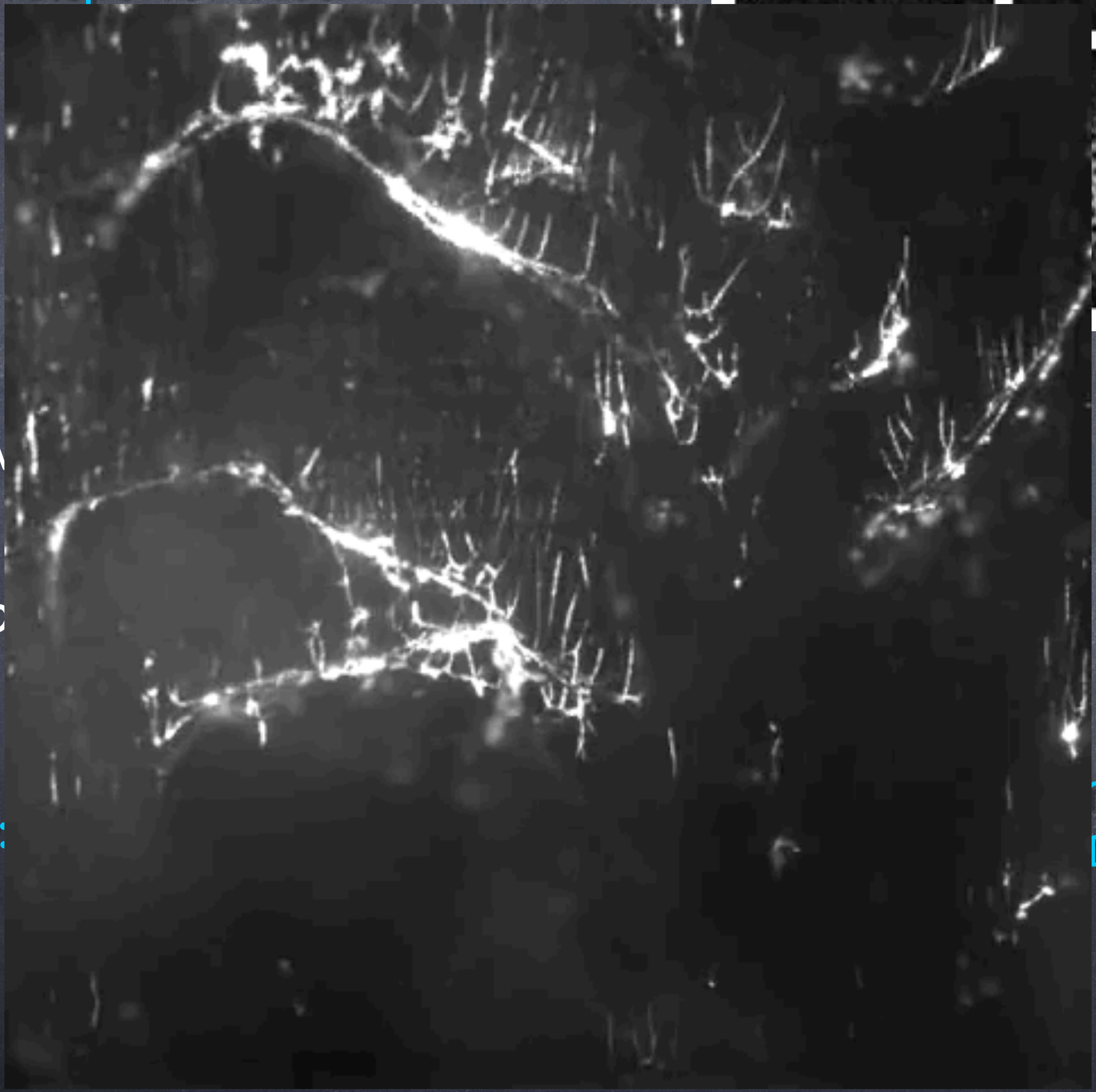
cf. Silverman & Mallett (2002);
Rindler-Daller & Shapiro (2012)

Observational consequences?

Vortices

When spun faster than critical velocity, superfluid develops vortices.





$\omega_{\rm cr} \sim$

For a halo of

$\omega \sim \lambda$

$\Longrightarrow$ Vo

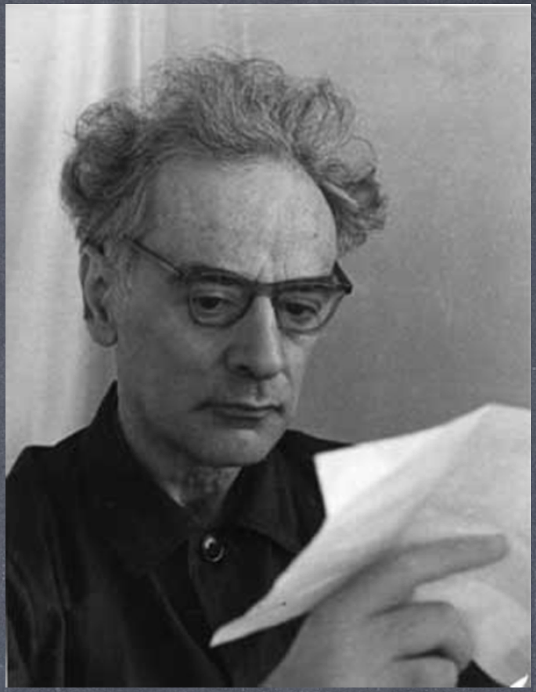
Line density:

rman & Mallett (2002);
Daller & Shapiro (2012)

Sreenivasan's group at U. Maryland

Galaxy mergers

Elder, JK, Mota & Winther, in progress



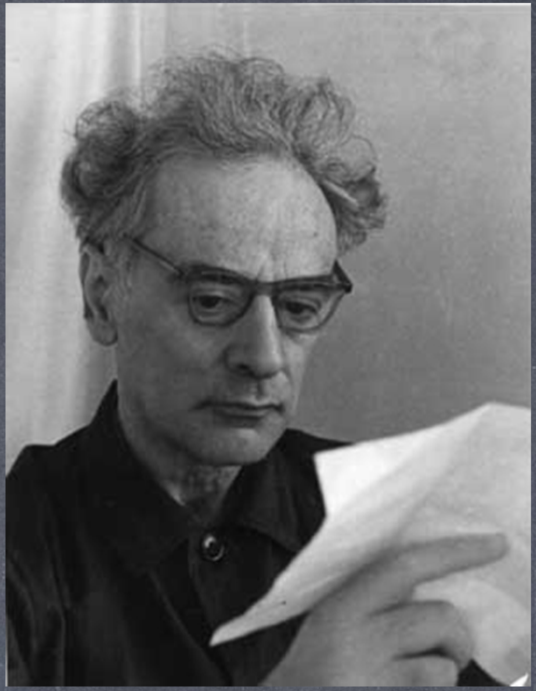
Superfluid cores should pass through each other with negligible dissipation if

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

(Landau's criterion)

Galaxy mergers

Elder, JK, Mota & Winther, in progress



Superfluid cores should pass through each other with negligible dissipation if

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

(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

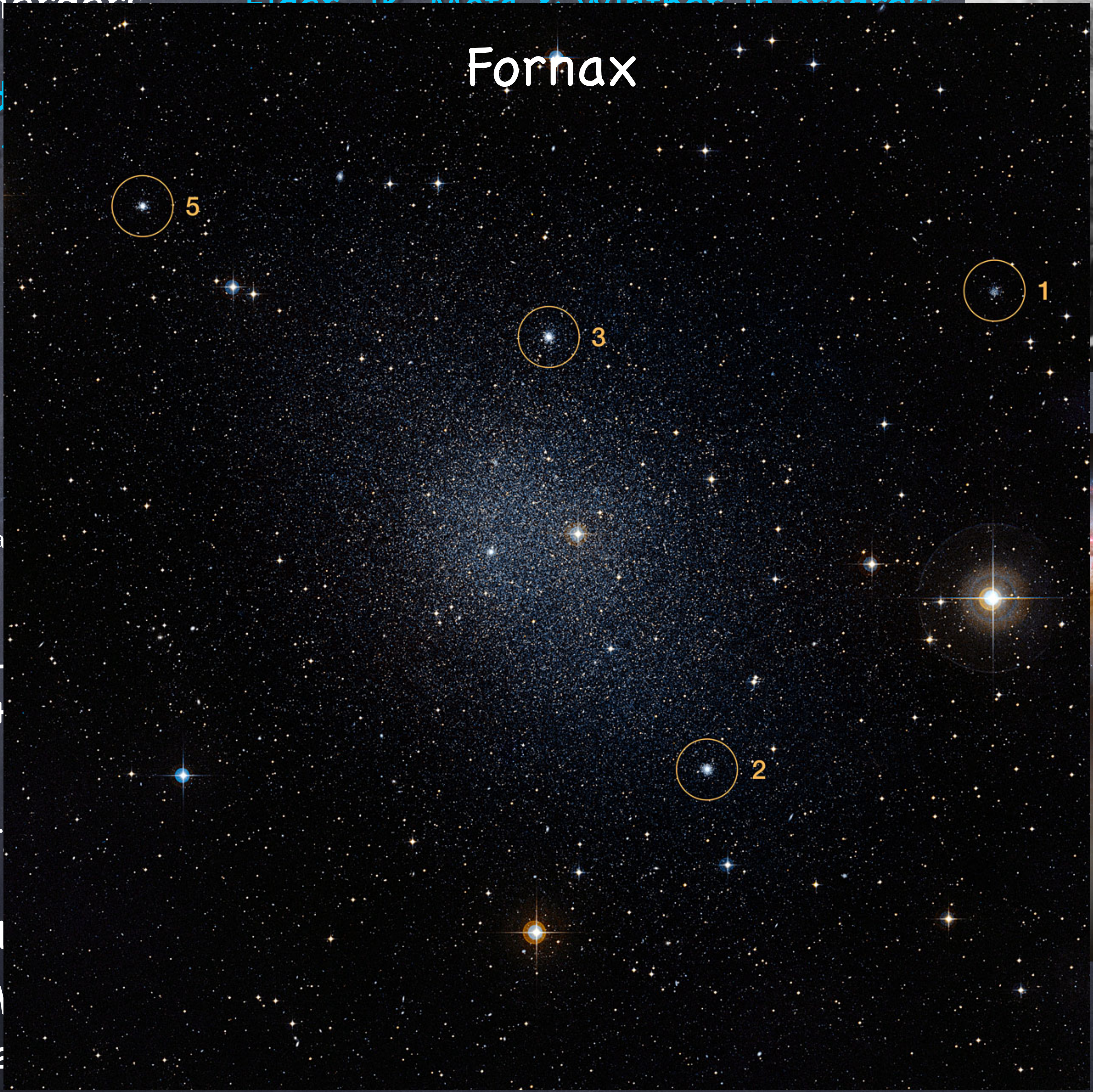
$\Longrightarrow$ Merged halo thermalize and
settle back to condensate

Galaxy mergers

Elder, JK, Motta & Winther, in progress

Superfluid

each othe



- If v_{infa}

dynamical

$\Longrightarrow$ L

+

- If v_{inf}

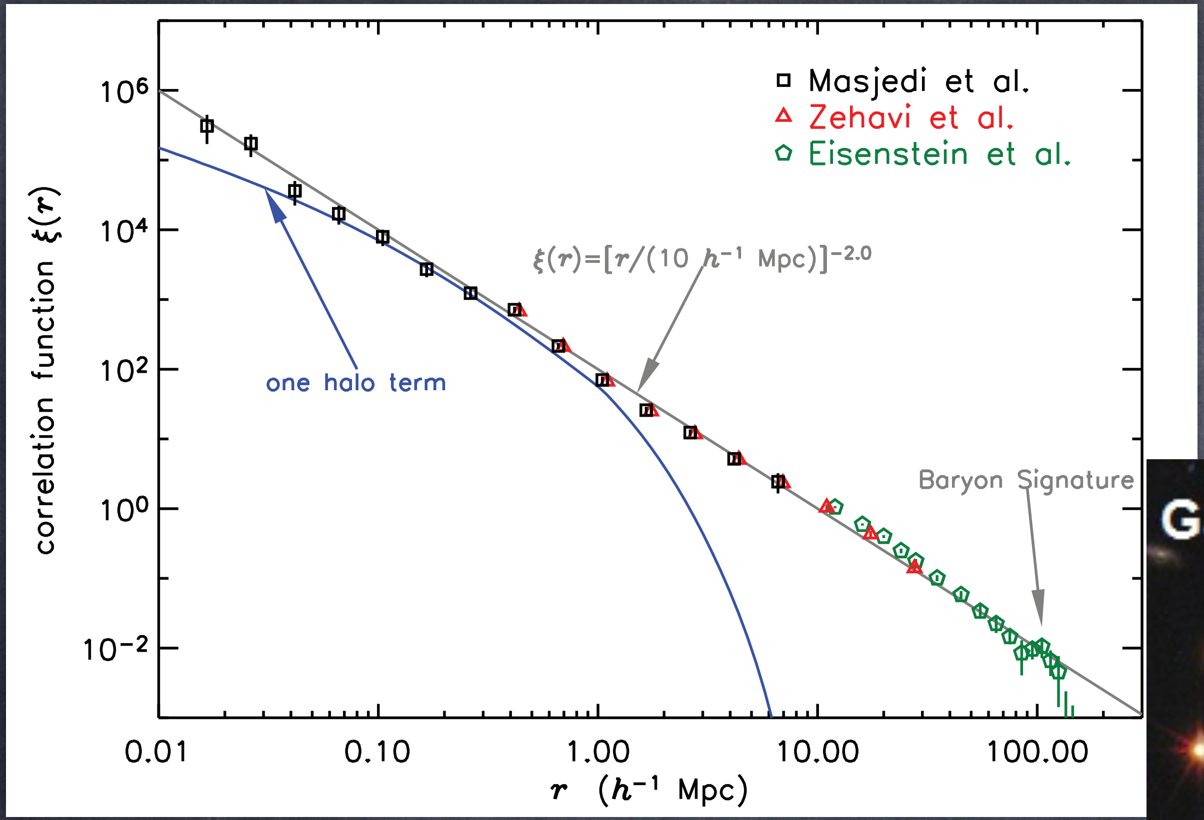
DM partic

result in d

$\Longrightarrow$ M

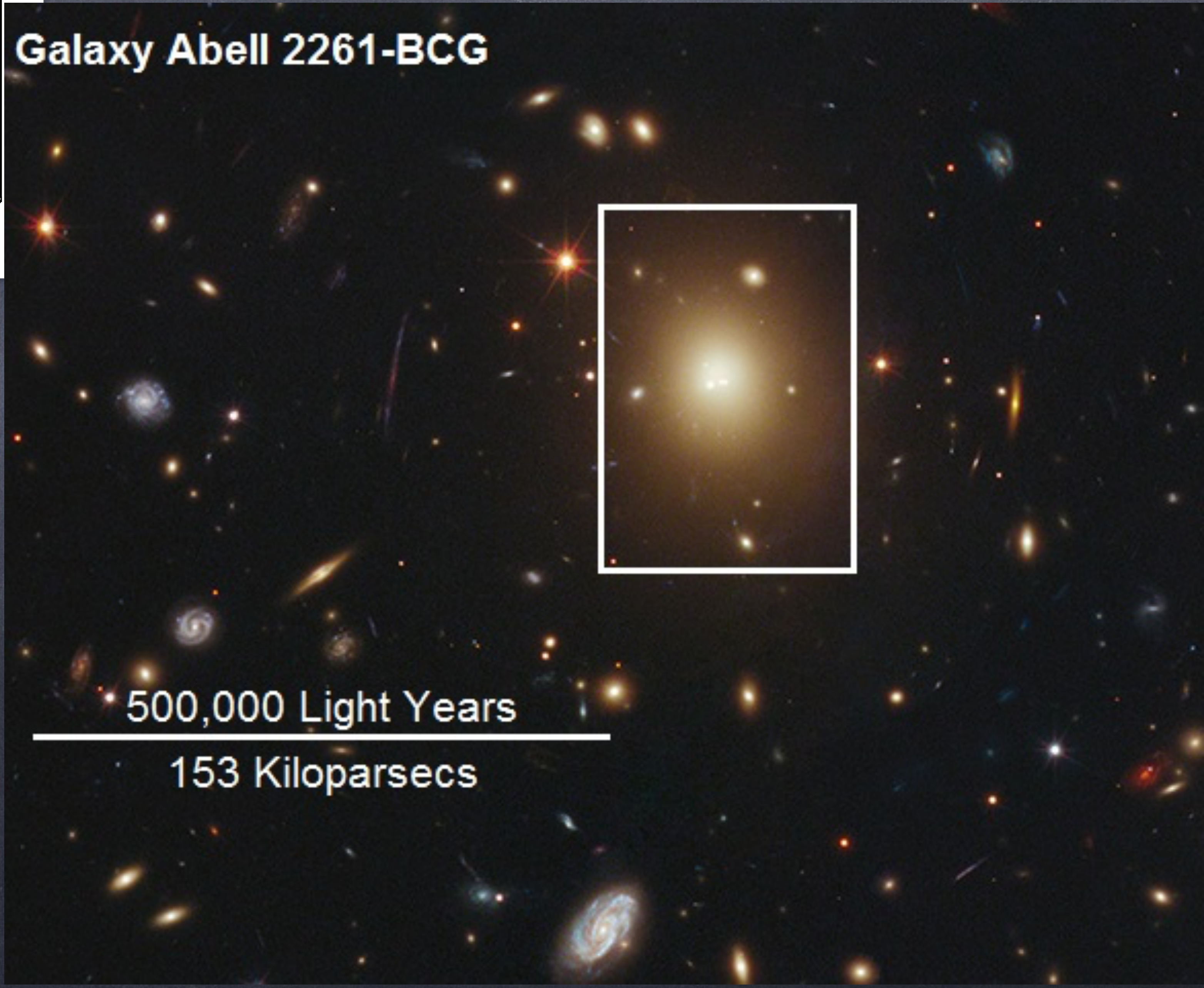
se

Reduced dynamical fraction?



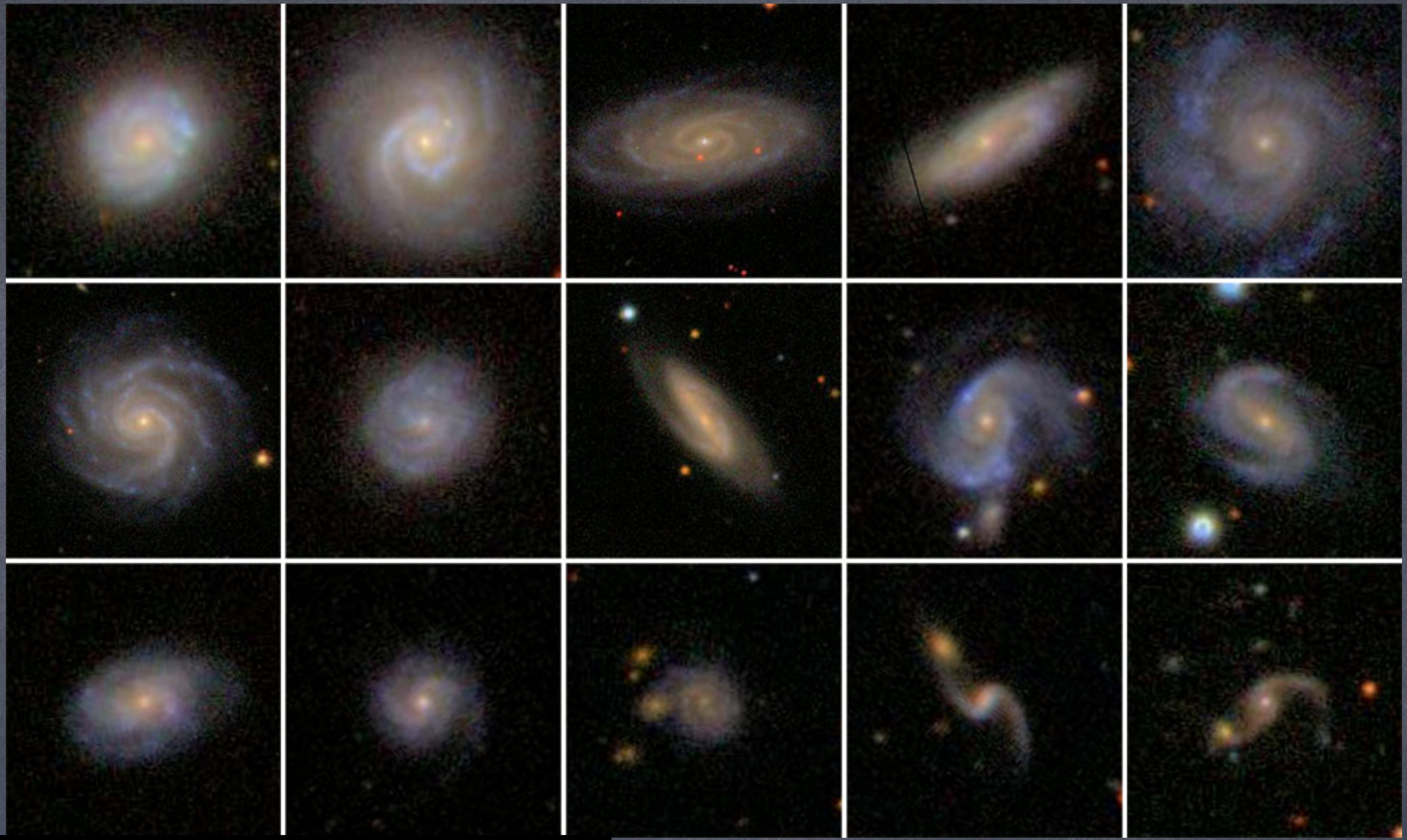
Masjedi et al. (2006)

“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.”

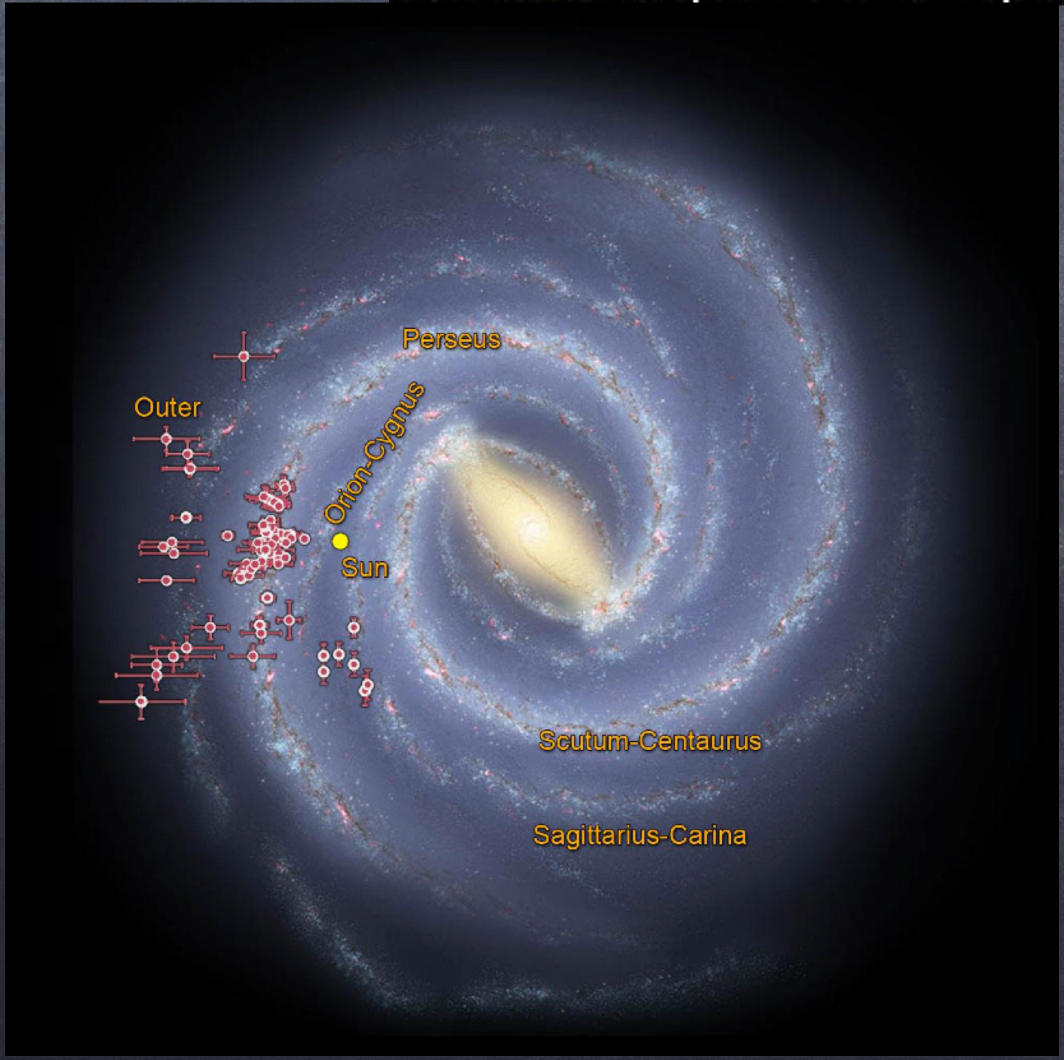


Reduced dynamical fraction?

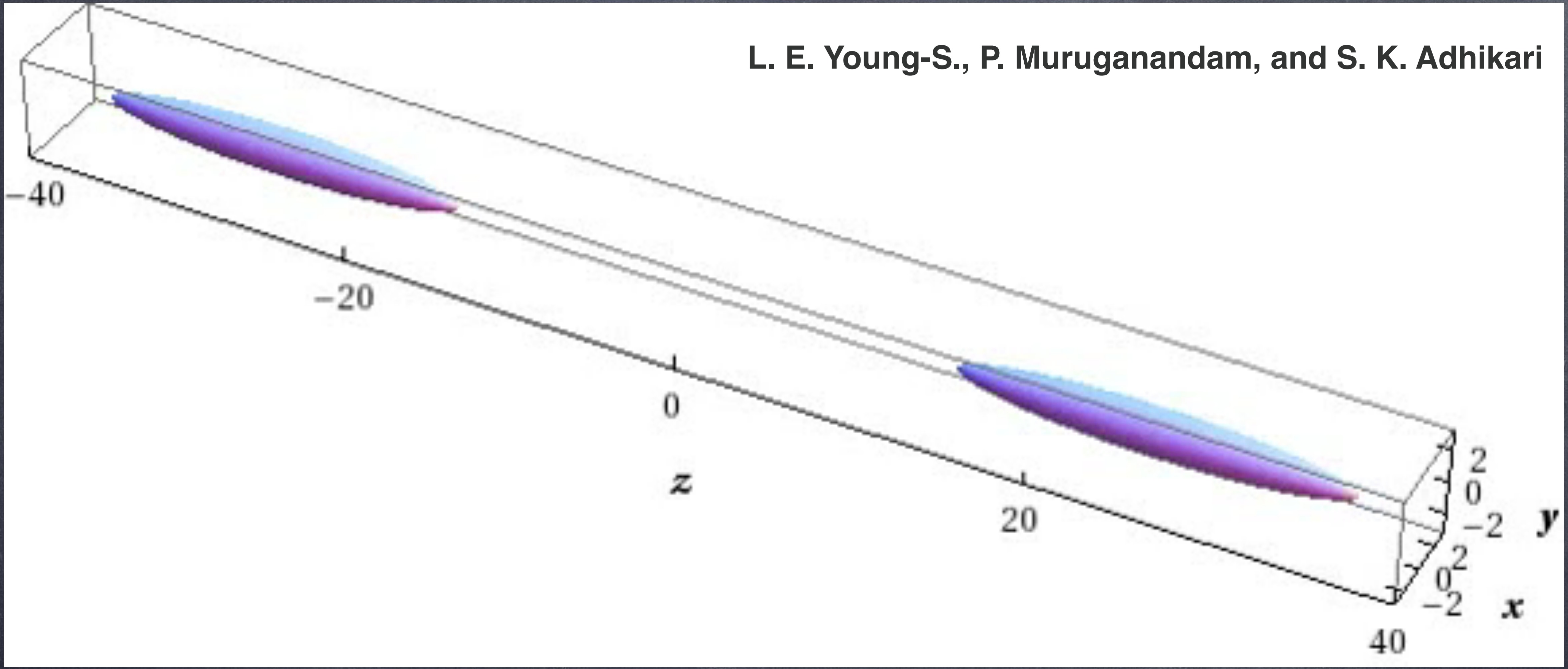
- Bulgeless galaxies



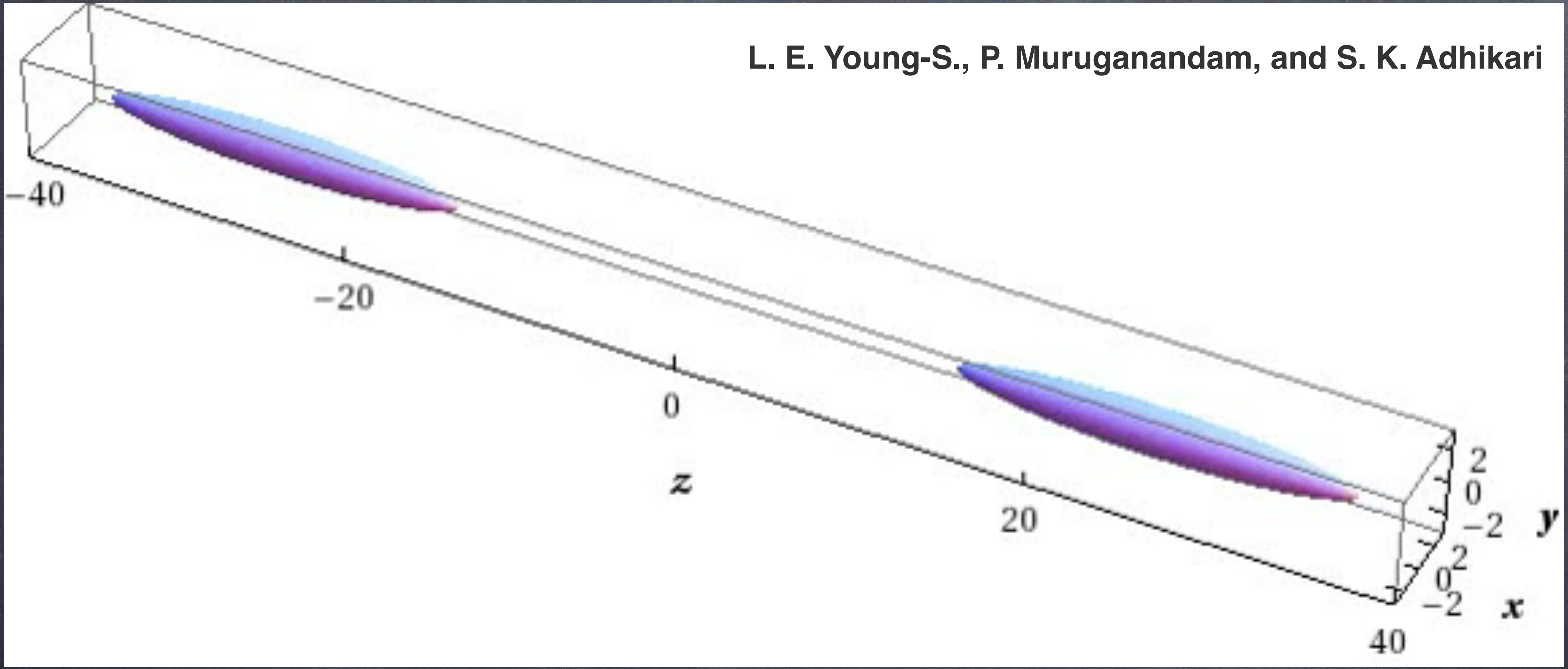
- Galactic bars



When superfluids collide



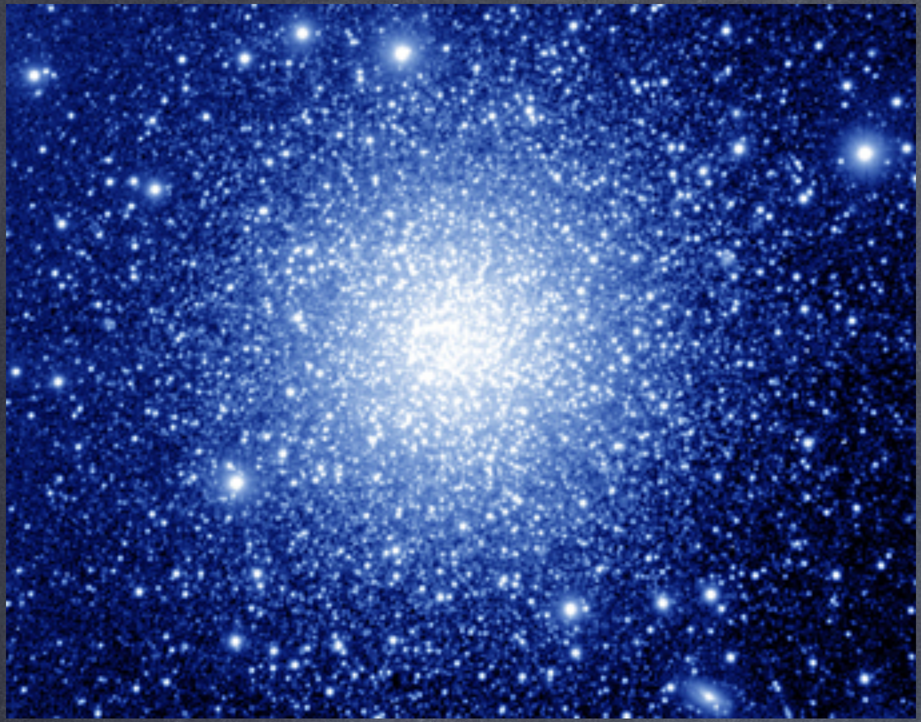
When superfluids collide



L. E. Young-S., P. Muruganandam, and S. K. Adhikari

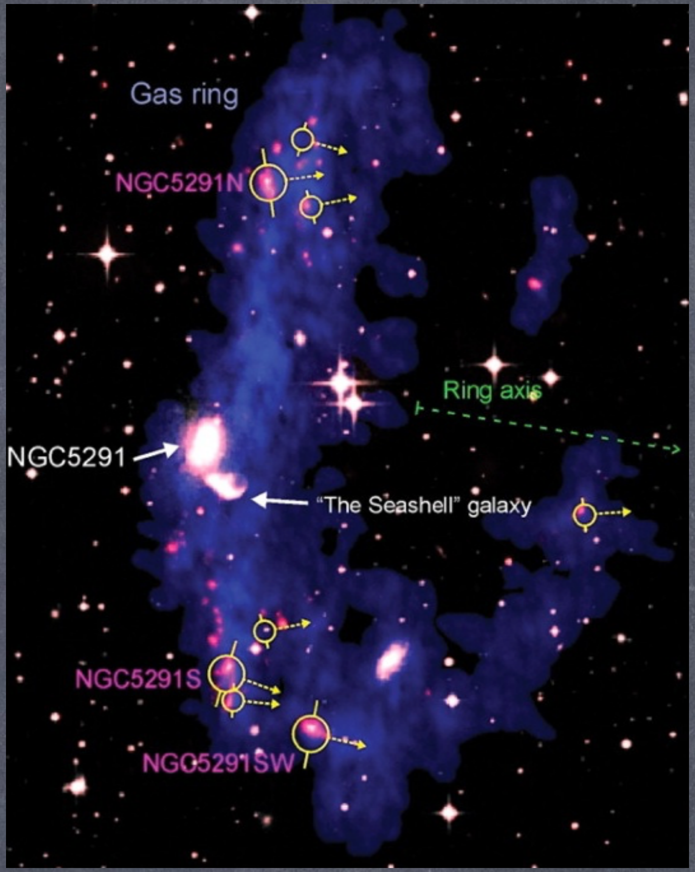
When superfluids collide

No DM $\Longrightarrow$ No MOND



Globular clusters

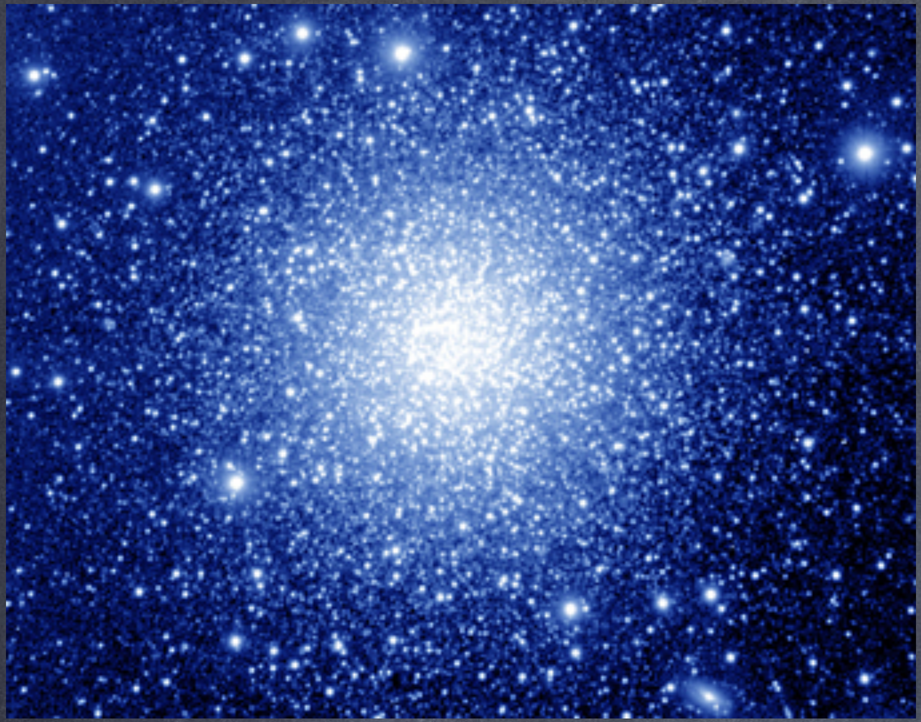
Ibata et al. (2011)



Tidal dwarfs

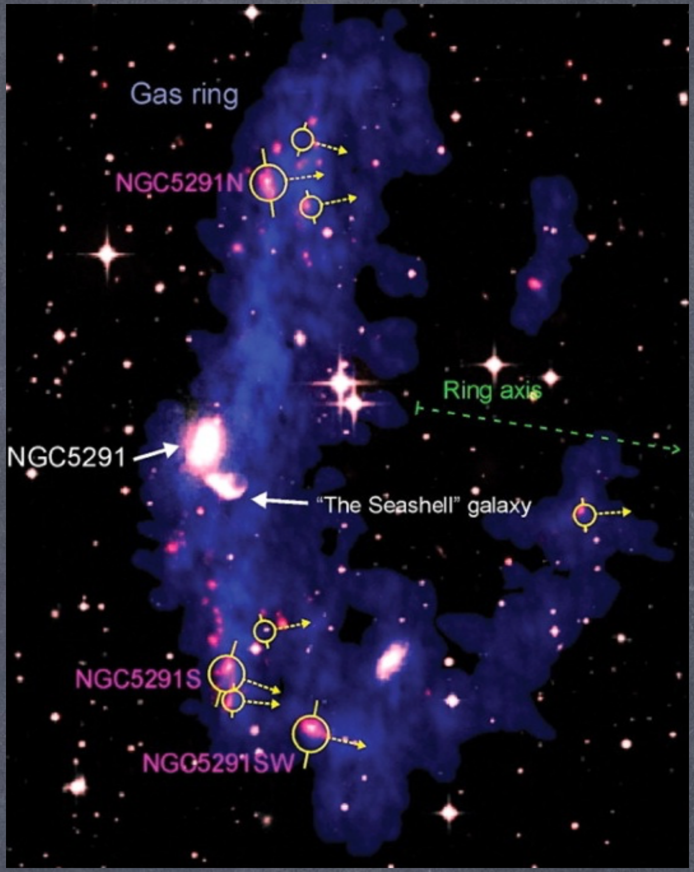
Lelli et al. (2015)

No DM ⟹ No MOND



Globular clusters

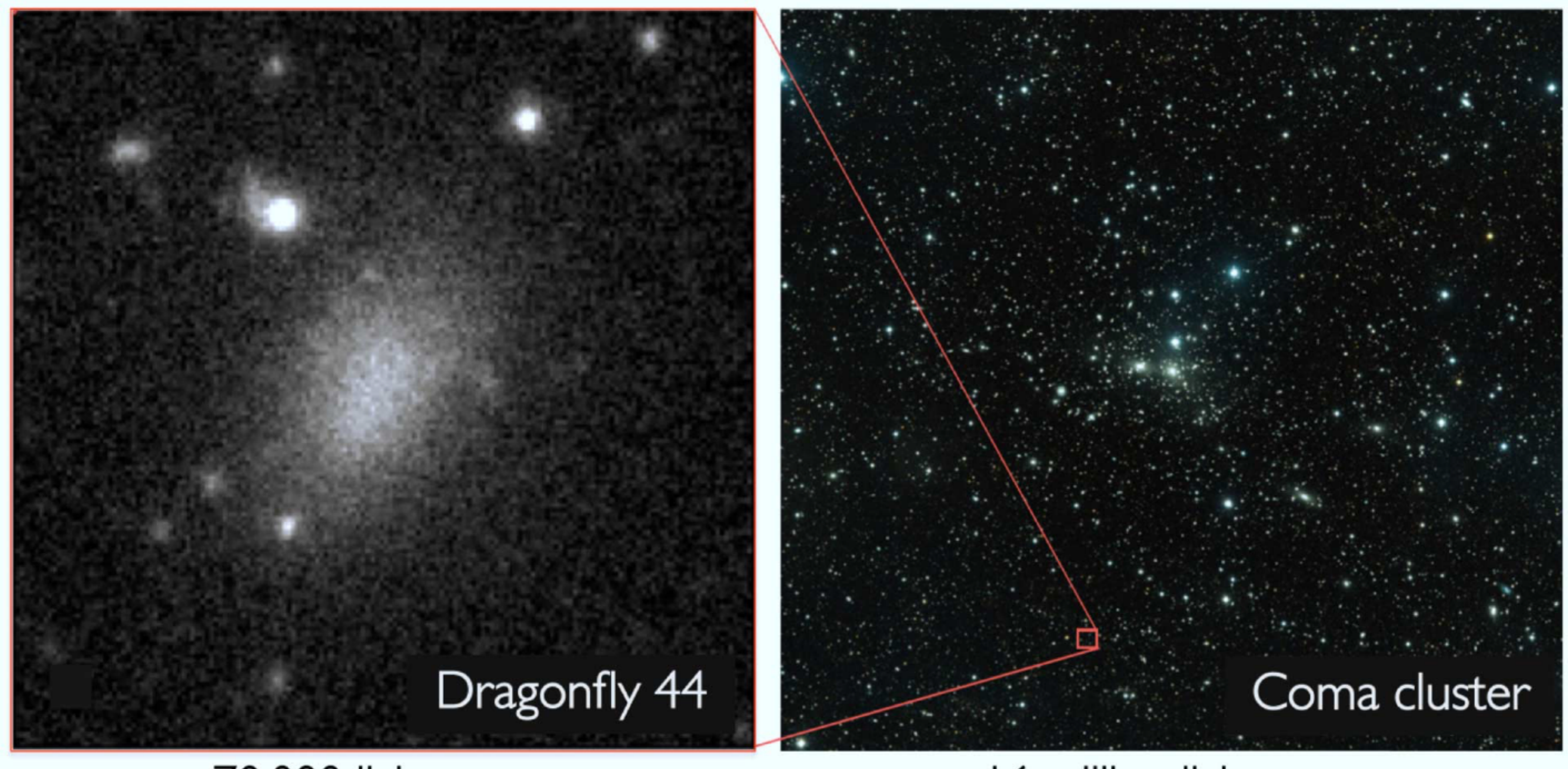
Ibata et al. (2011)



Tidal dwarfs

Lelli et al. (2015)

No superfluid ⟹ No external field effect



Ultra-diffuse galaxies

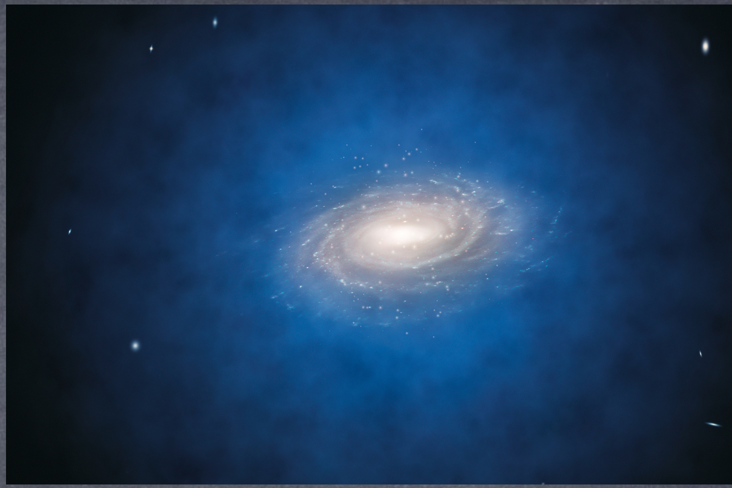
van Dokkum et al. (2015); Koda et al. (2015)

Take-home messages

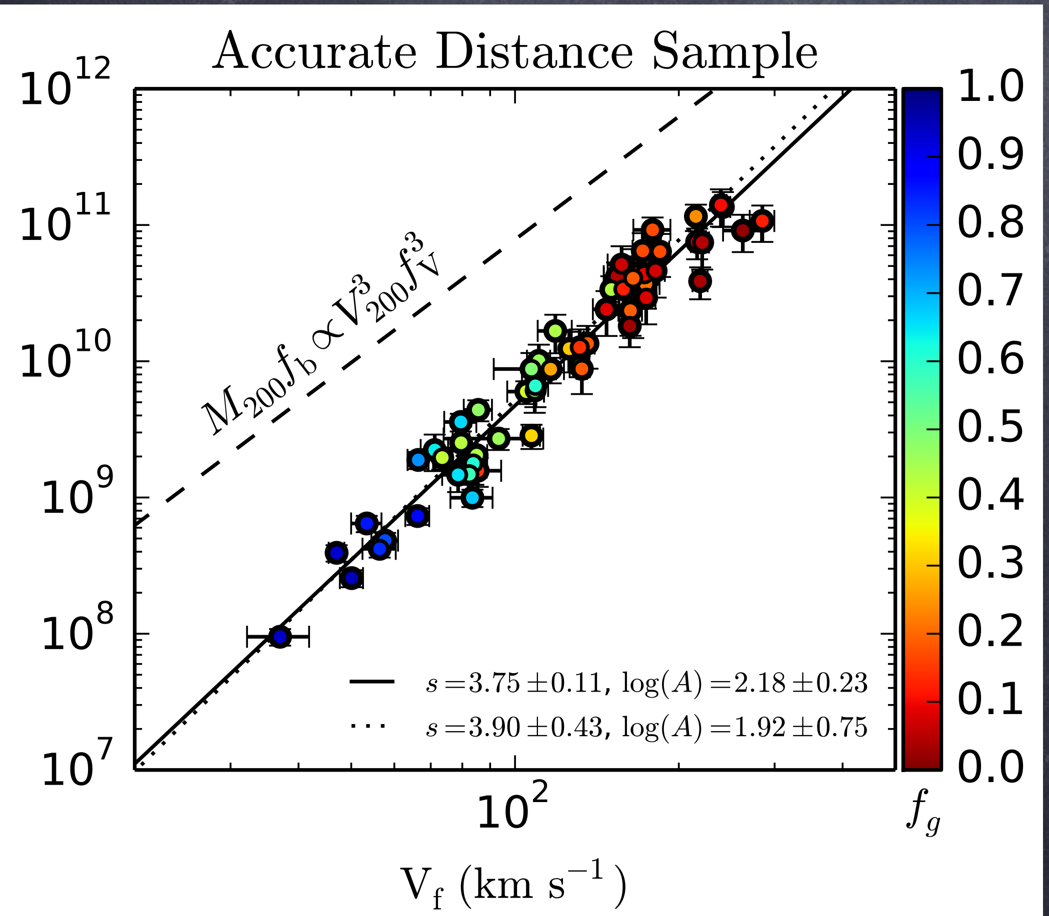
Take-home messages

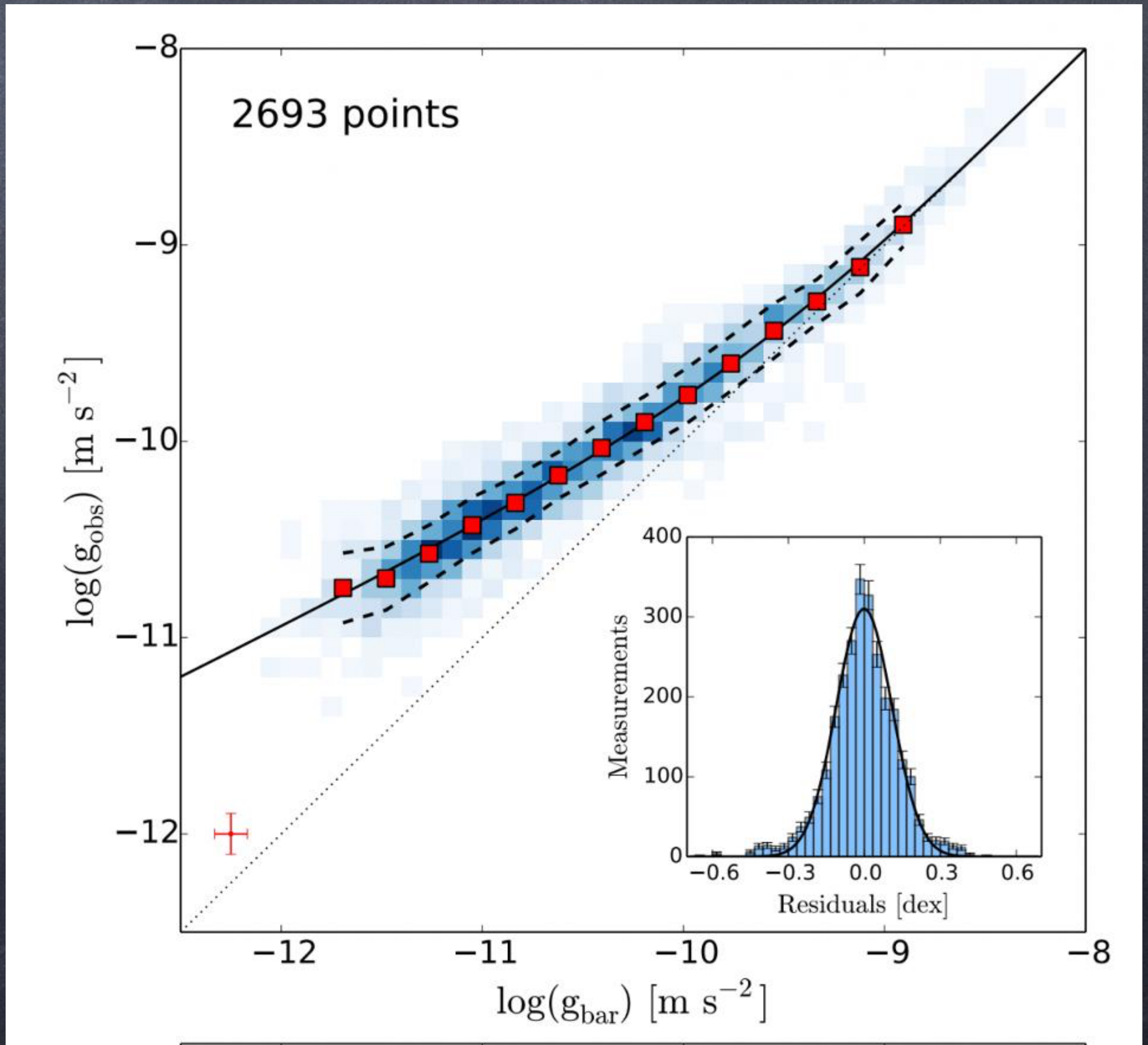
Believe in conspiracies!

Take-home messages

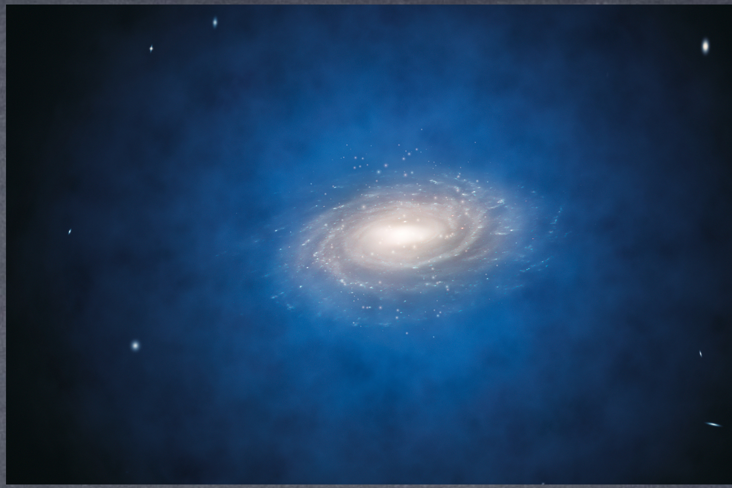


- Cold, collisionless DM works exquisitely well on largest scales, but something is going on with galaxies





Take-home messages

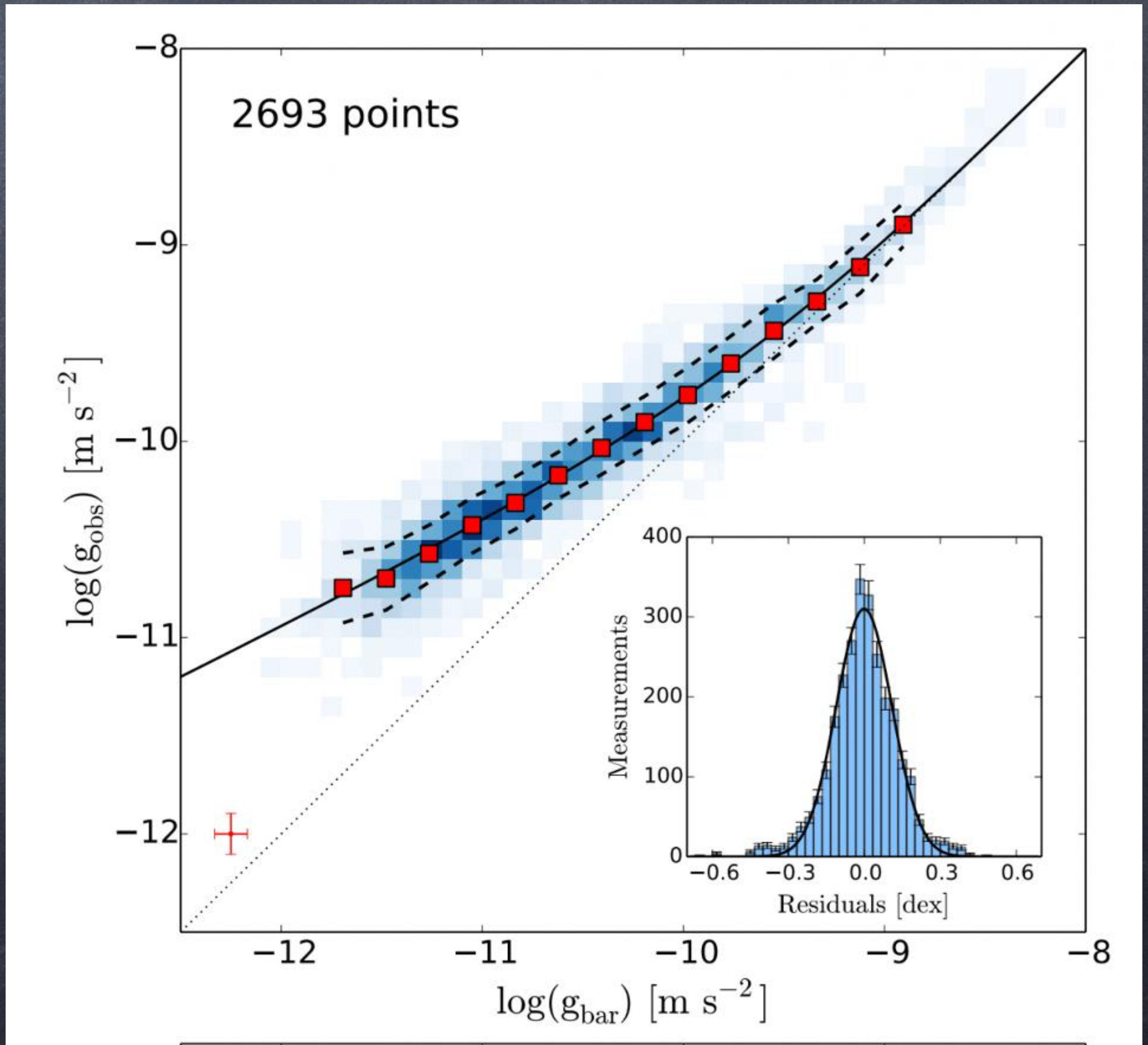


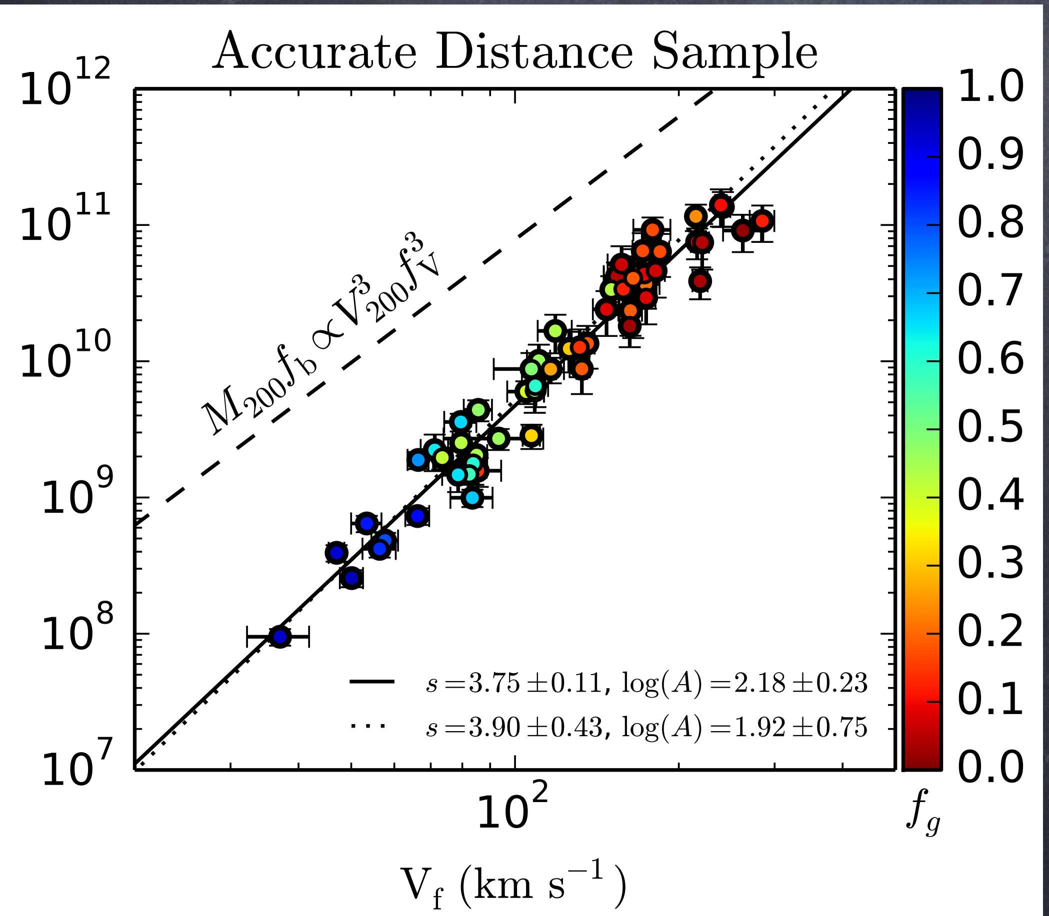
- Cold, collisionless DM works exquisitely well on largest scales, but something is going on with galaxies

The left-wing hippies
"Modified gravity!"

The middle-ground
"It's non-standard DM."

The right-wing evangelicals
"It's all feedback!"





Galaxies are giving us strong hints about the fundamental nature of dark matter…

Galaxies are giving us strong hints about the fundamental nature of dark matter...

Nature is singing loud and clear!

Mother Nature

Cosmologist

How does dark energy fit into the picture?