Dark matter from an astrophysical perspective

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Dipartimento di Fisica, Napoli - 28 giugno 2018

Galaxy clusters
scale

Contents

- The observational evidence for dark matter
- (some of) the solved problems of the standard cosmological model (LCDM)
- (some of) the **unsolved** problems
- (some of) possible astrophysical probes of DM **nature**
- A galaxy with no dark matter?
- Constraining dark matter properties & direct searches

A note on the history of DM

Fritz Zwicky
(Coma cluster 1933)

Vera Rubin
(Disk galaxies 1970)

Zwicky and Rubin made important contributions, but it was not the dynamics of galaxies or galaxy clusters that lead to the broad consensus that dark matter exists in large quantities

For a history of dark matter, see Bertone et al. (2016)

What Lead to the Dark Matter Consensus?

1. **Large Scale Structure.**
By the mid-80s, it was appreciated that the results of simulations matched galaxy surveys only if the universe contained large quantities of cold dark matter

2. **The**
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to CC

3. **Mic**
By the late 1990s, it was clear that most of the dark matter could not be in the form of compact objects.

4. **The Baryon Budget.**
In the 1970s, light element abundances required only $\Omega b<0.1$; high precision deuterium measurements in the 1990s improved this to $\Omega b = 0.020\pm0.002$ (h=1).

> “Galactic dynamics had little to do with the rise of particle dark matter. Cosmological considerations played a very important role”
>
> (Bertone & Hooper 2016)

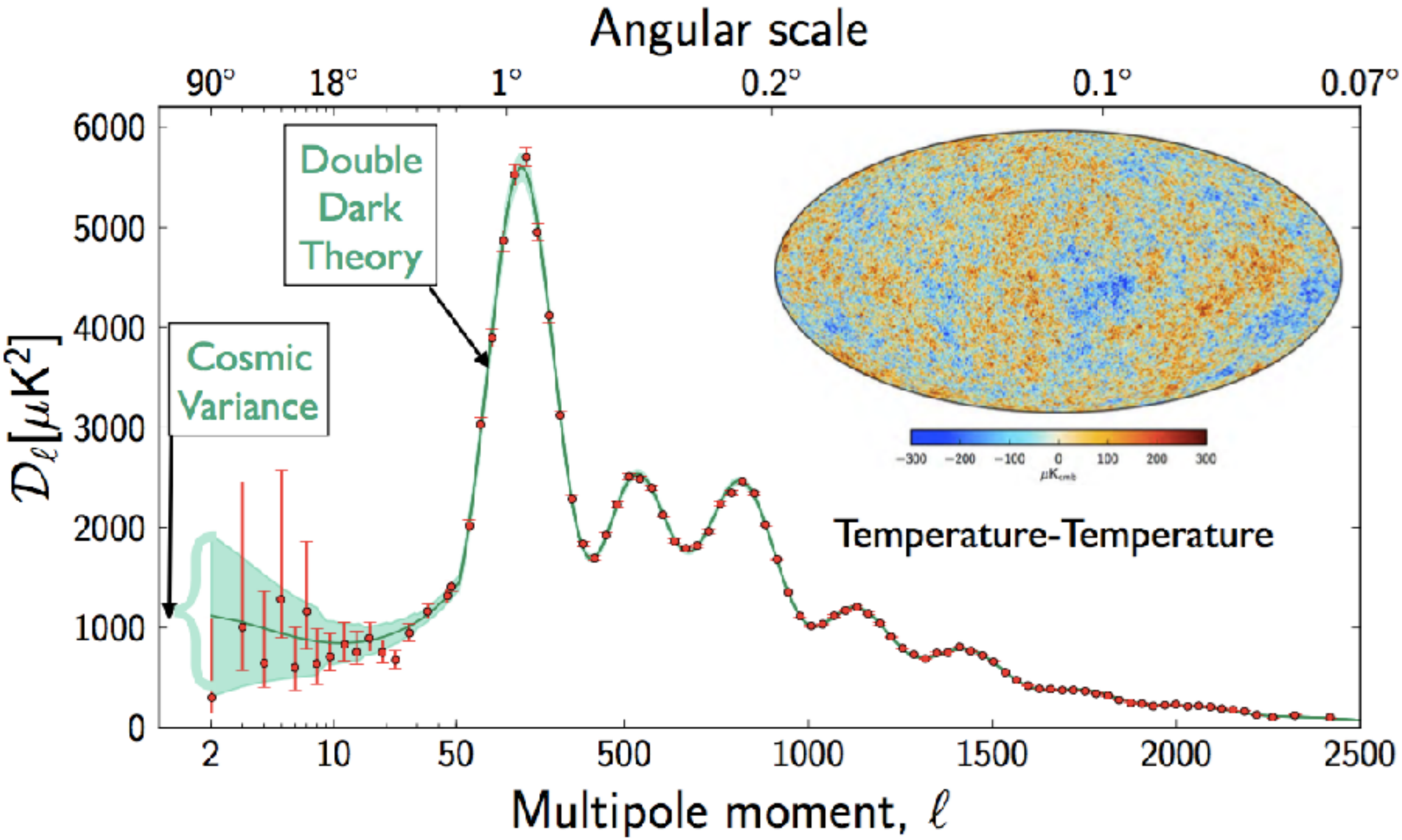
the observational evidence

Note: I will not mention here rotation curves

Observational evidence on cosmological scales

- Cosmic Microwave Background (e.g., Spergel et al. 2003)
- Large scale distribution of matter (e.g., Springel 2006)

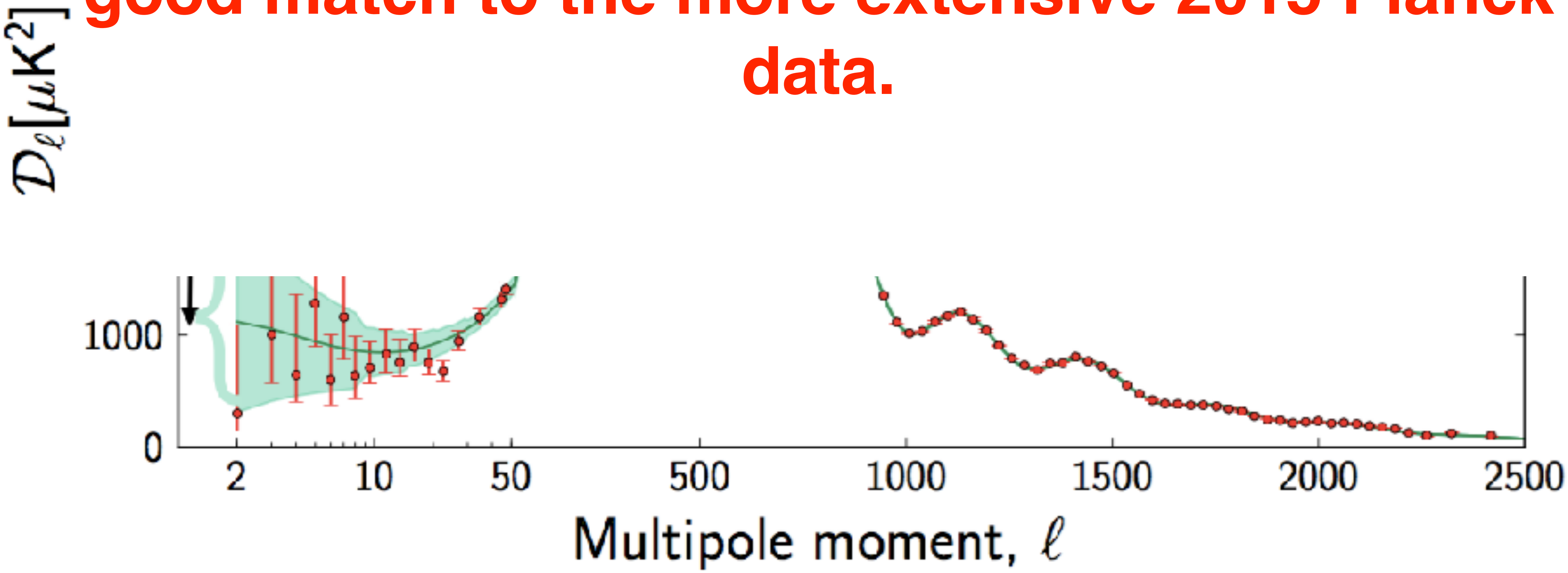
Planck Satellite Data (2015):
the temperature power spectrum



Planck Satellite Data (2015):
the temperature power spectrum

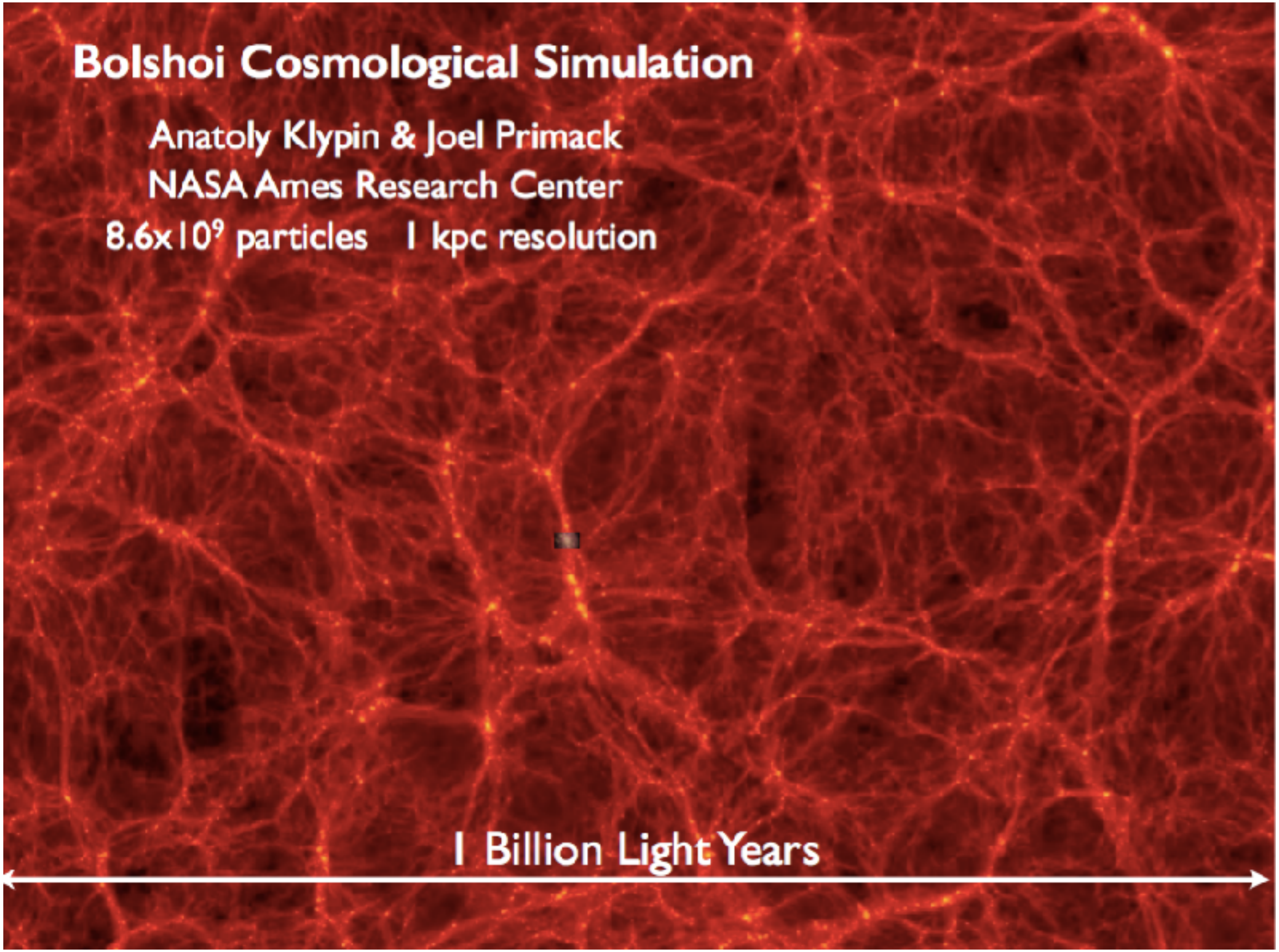
“No evidence for a departure from the base ΛCDM cosmology”

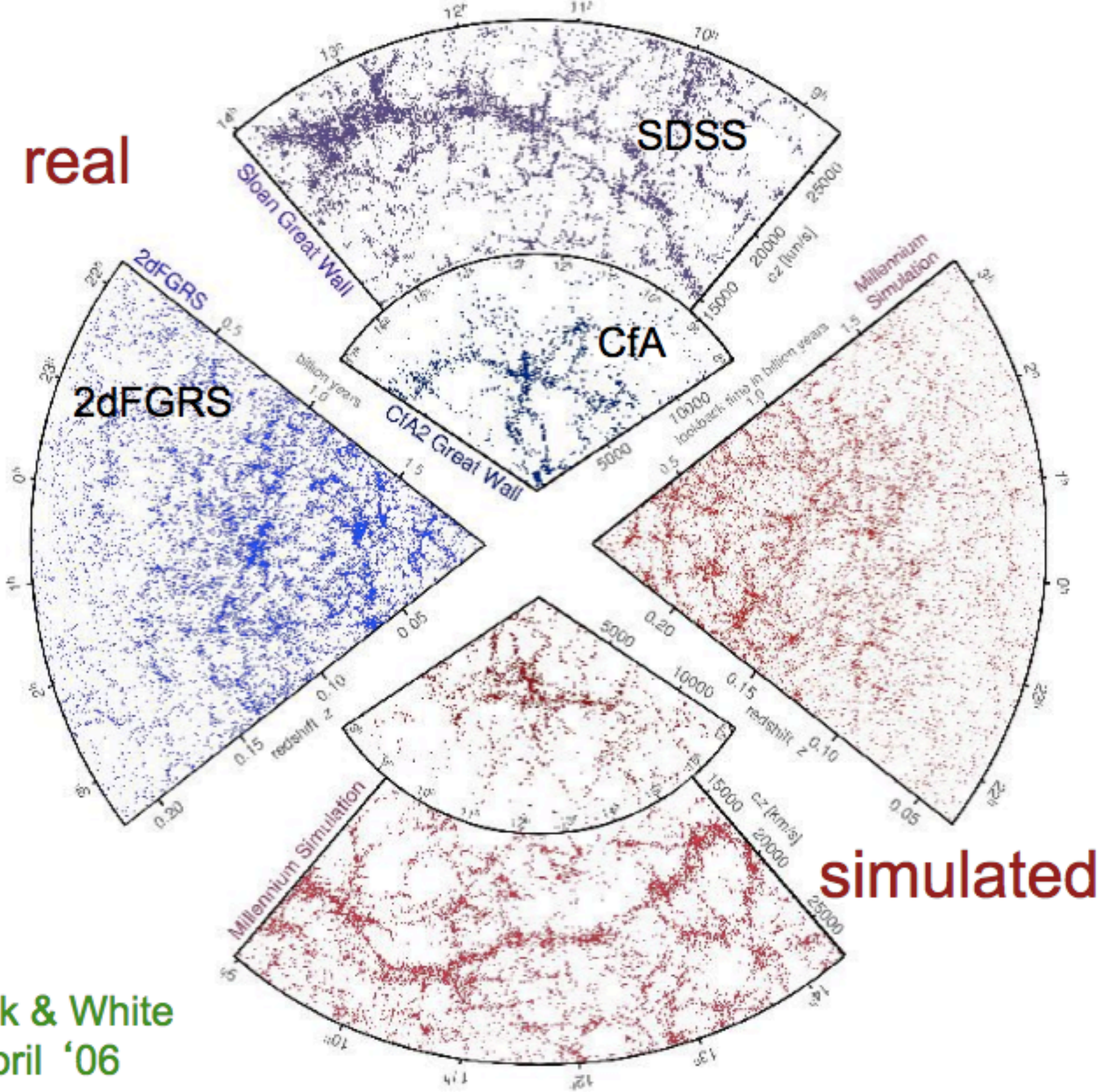
The ΛCDM model continues to provide a very good match to the more extensive 2015 Planck data.



Evidence from numerical simulations

Evidence from numerical simulations





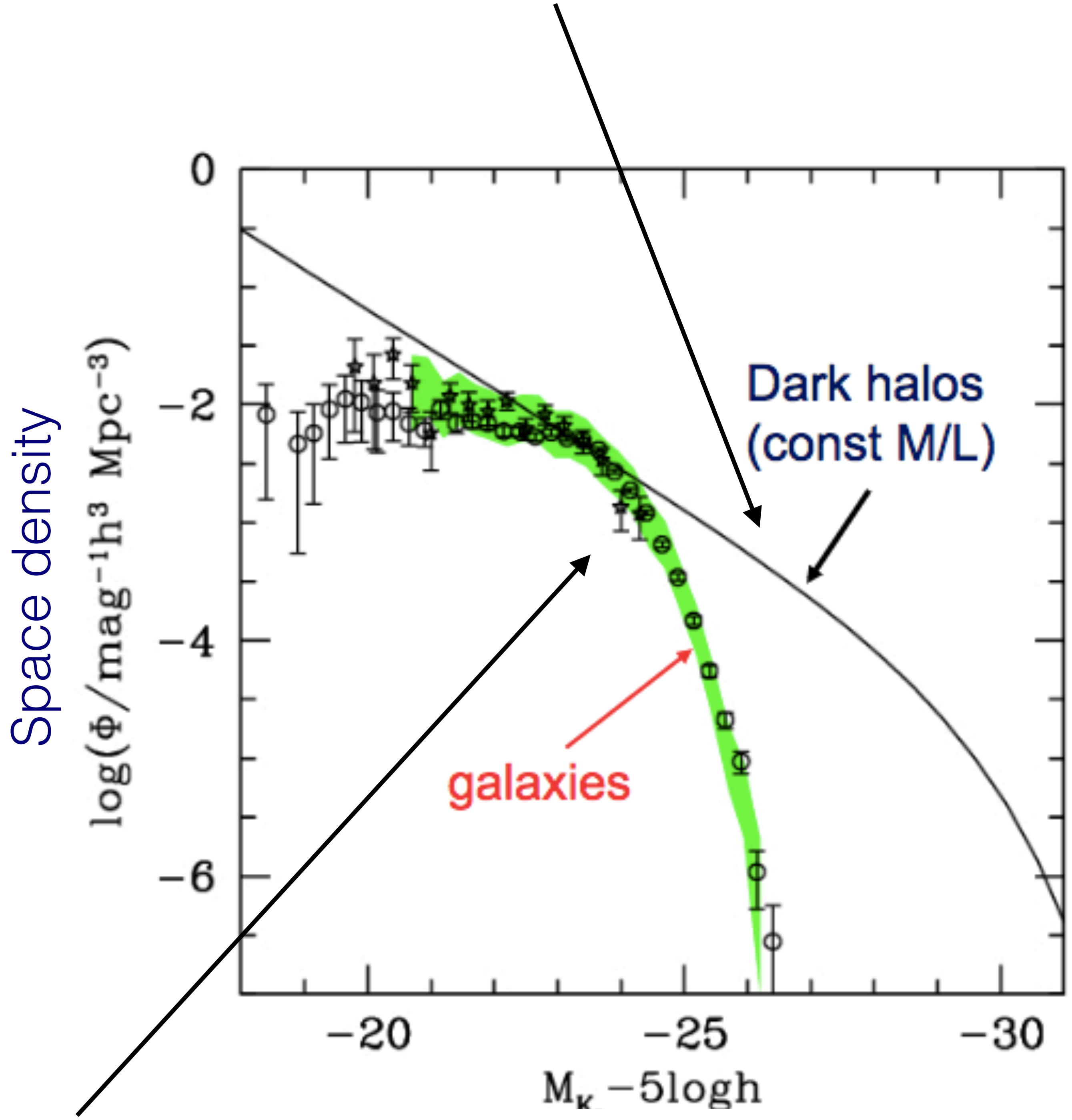
Springel, Frenk & White
Nature, April '06

DM and stellar mass functions

theory (numerical sim)

The halo mass function and the galaxy luminosity function have different shapes.

We need to allow complicated variation of M/L with halo mass.



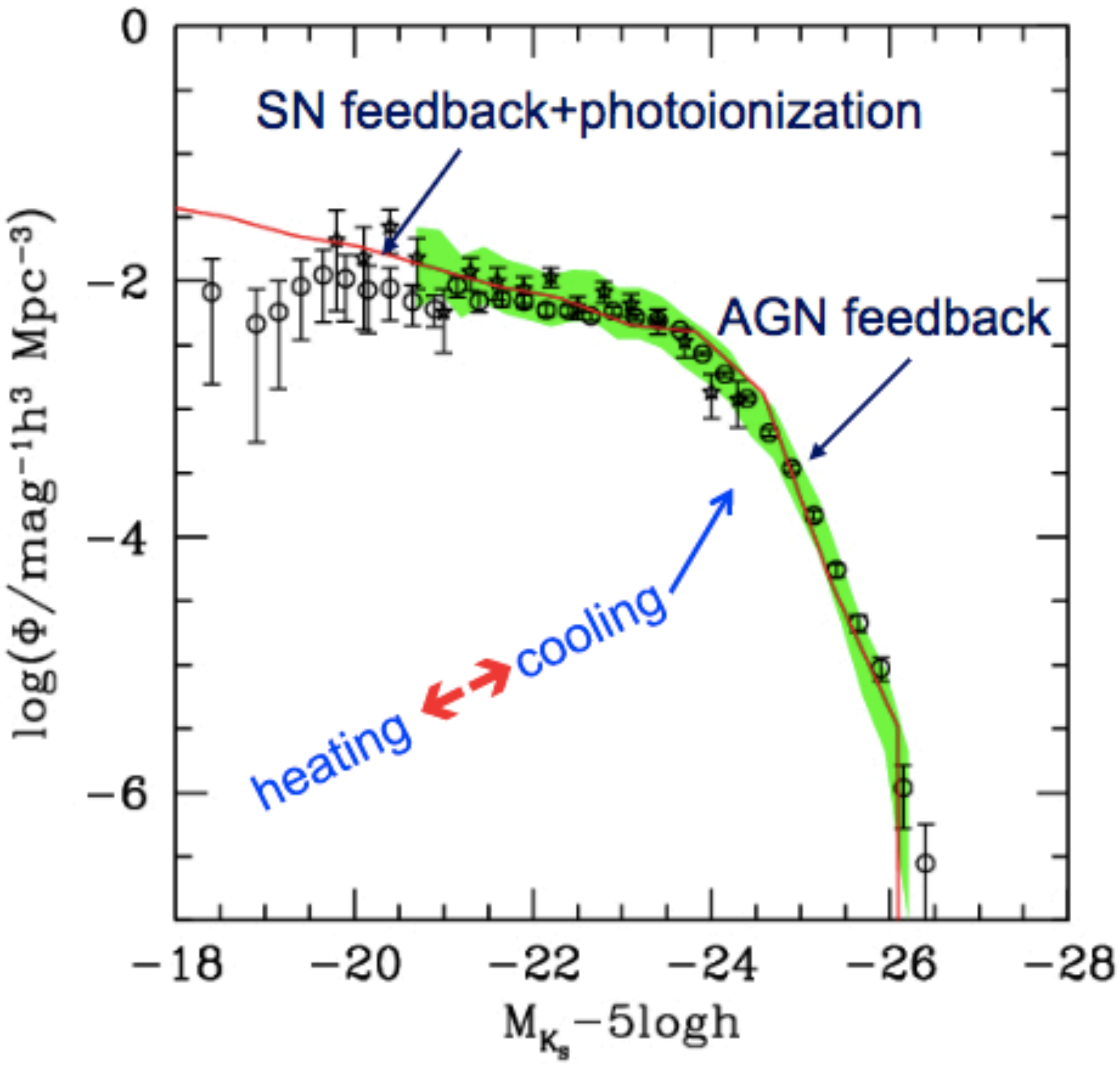
Data from astronomical surveys

magnitude

DM and stellar mass functions

Faint end:
Photoionization + reheating of cold disk gas by SN

Bright end:
AGN feedback:
energy transported by bubbles

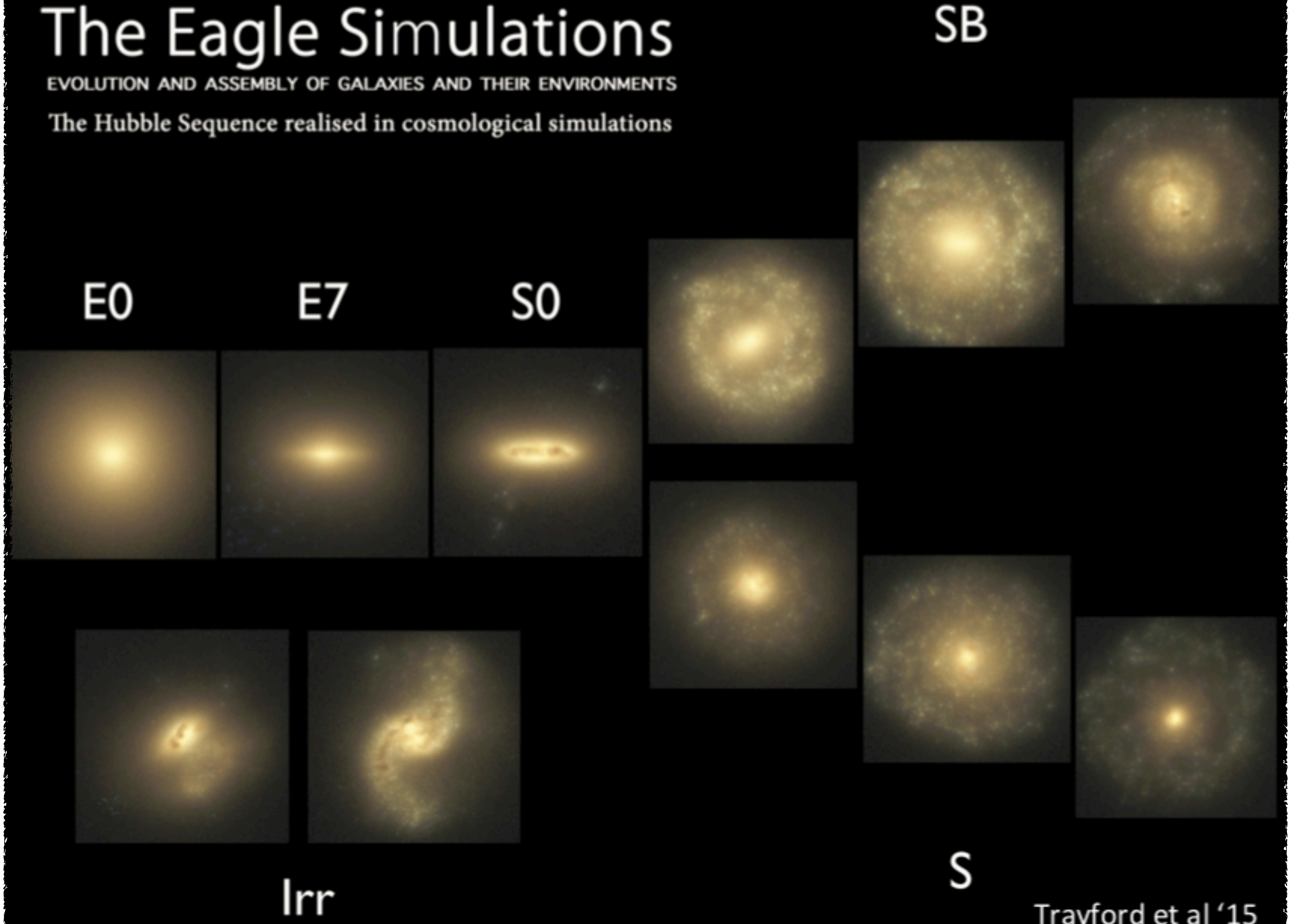


We need to understand the **complicate** baryon physics on **small scales.** *(Hic sunt leones)*

The Eagle Simulations

EVOLUTION AND ASSEMBLY OF GALAXIES AND THEIR ENVIRONMENTS

The Hubble Sequence realised in cosmological simulations



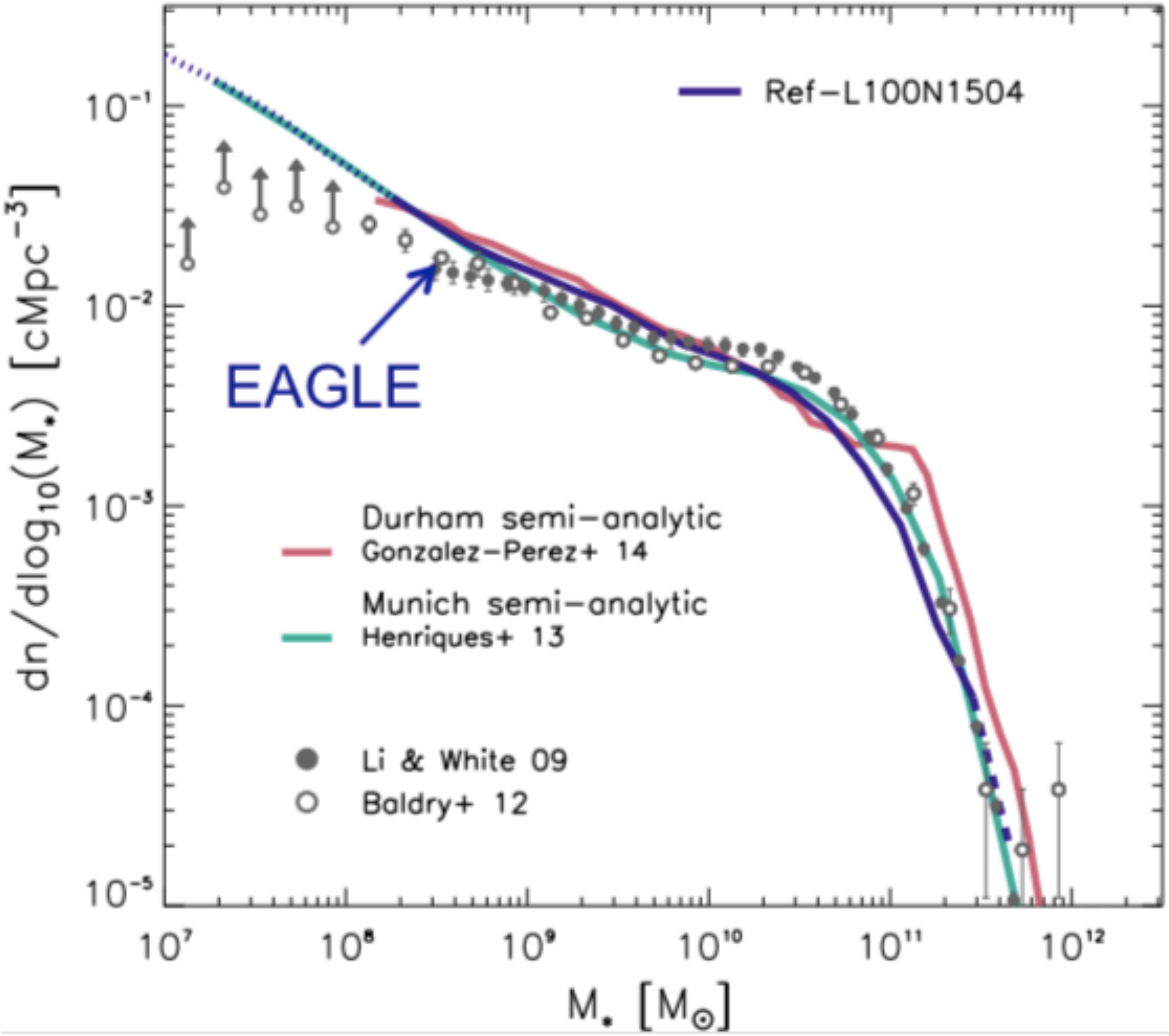
Trayford et al '15

The galaxy stellar mass function

LCDM gives an excellent match to the galaxy stellar mass function.

(Schaye et al. 2015)

Comparison to semi-analytical models and observational data



LCDM: a status

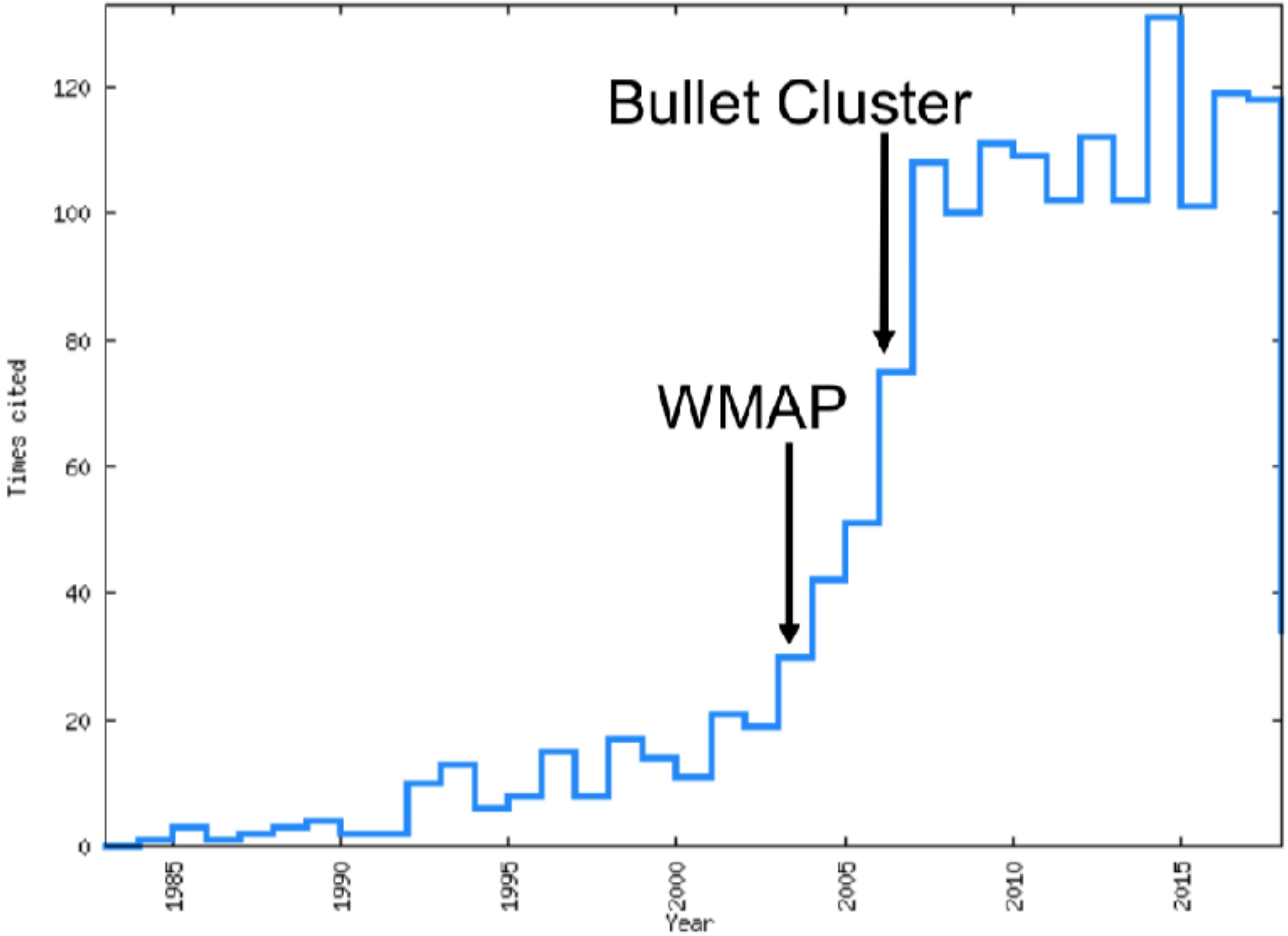
- **DM is**: cold, non-collisional, weakly (at most) interacting with baryons

- **Successes (mainly on large scales)**:
  CMB
  properties and evolution of the Large Scale Structure
  a working scenario for galaxy formation and evolution

- **Challenges (mainly on small scales)**:
  Cusp-Core
  Missing Satellite Galaxies (or, Too Big To Fail)
  The empirical laws of dynamics of disk galaxies.

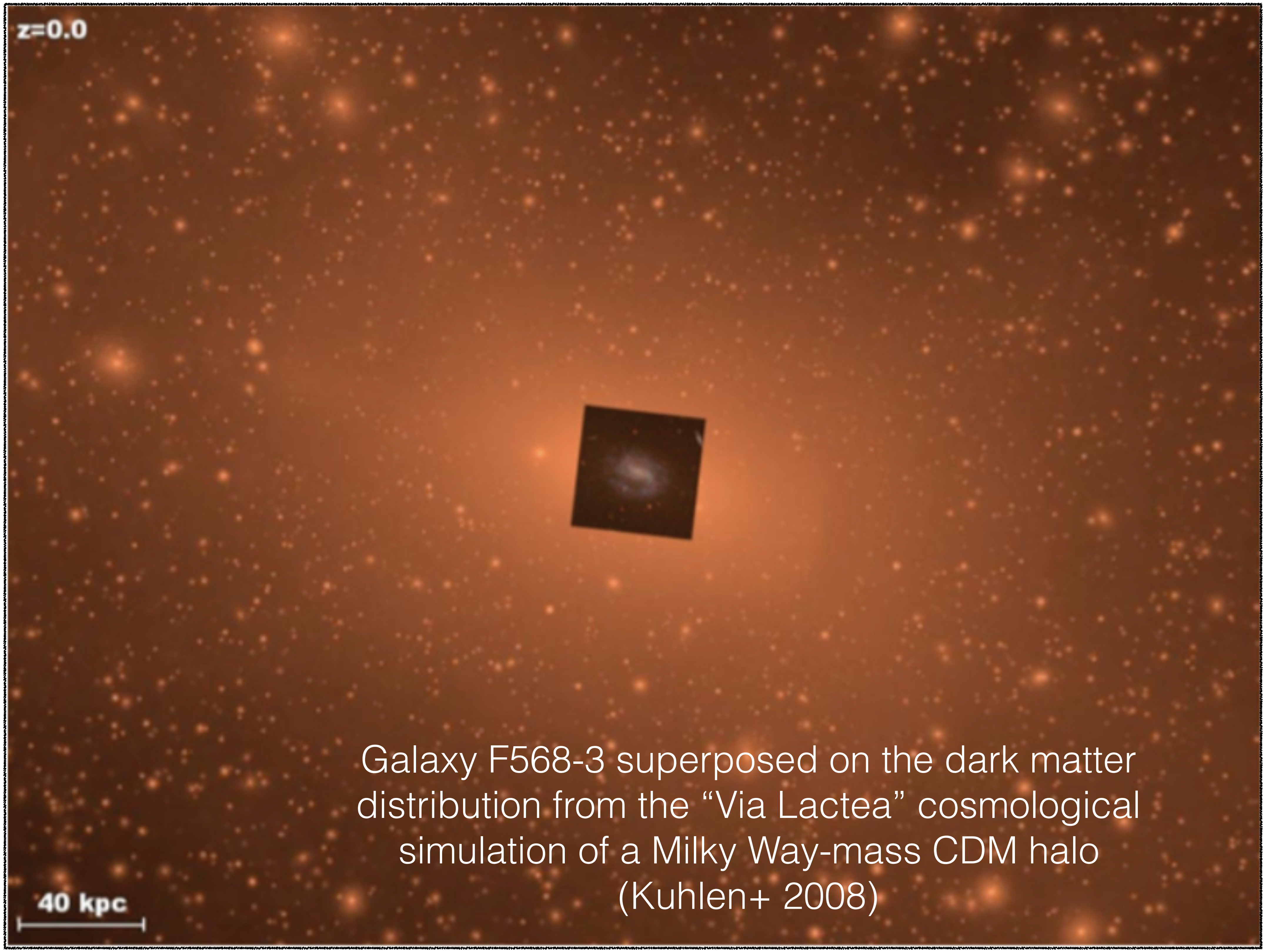
- **Opportunities for Progress Now**:
  Constraining DM-DM cross section with Gravitational Lensing

The citation rate of Milgrom's paper, "A Modification of the Newtonian dynamics as a possible alternative to the hidden mass hypothesis" (1984).

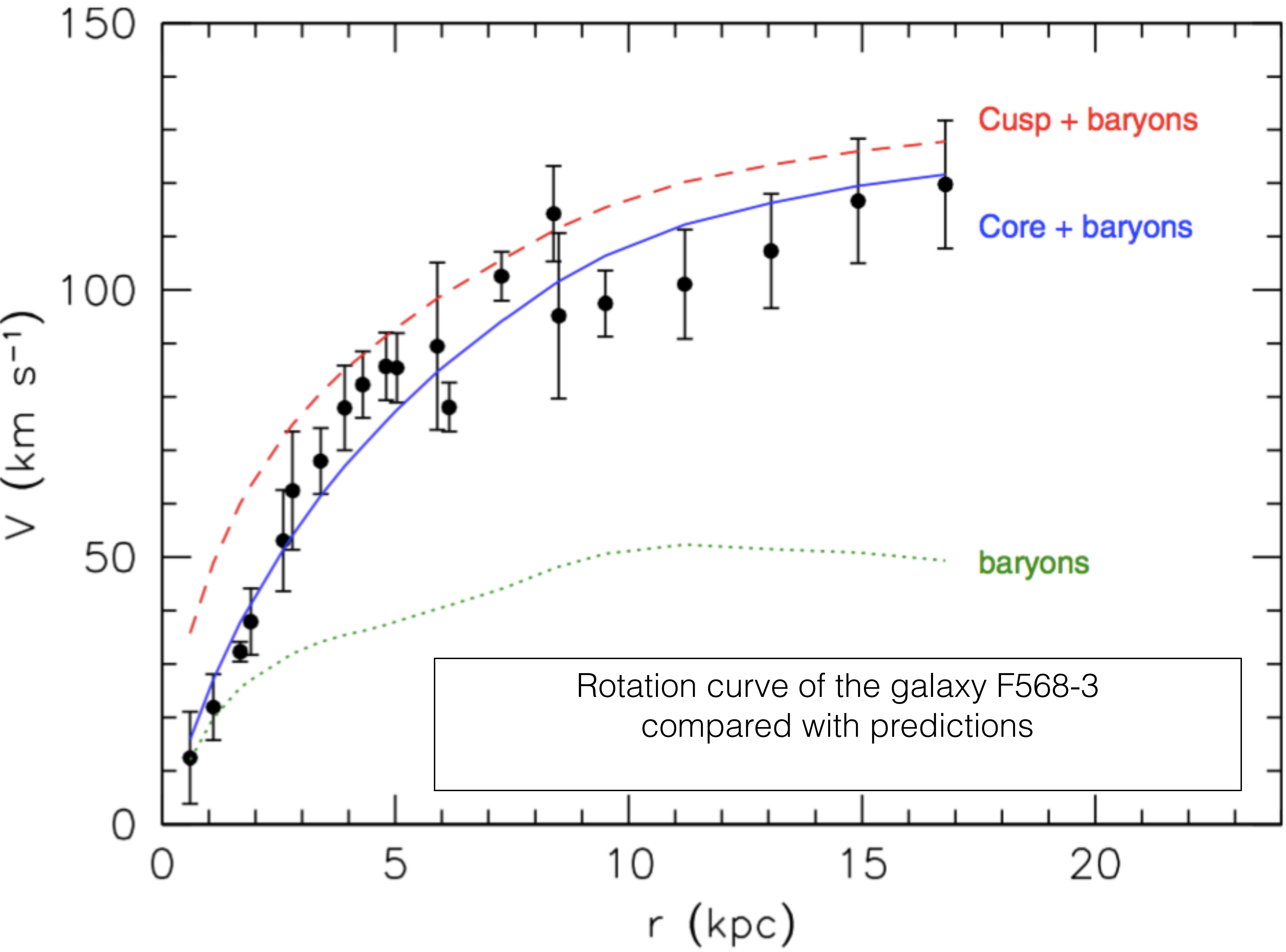


See also Bertone & Hooper (2016).

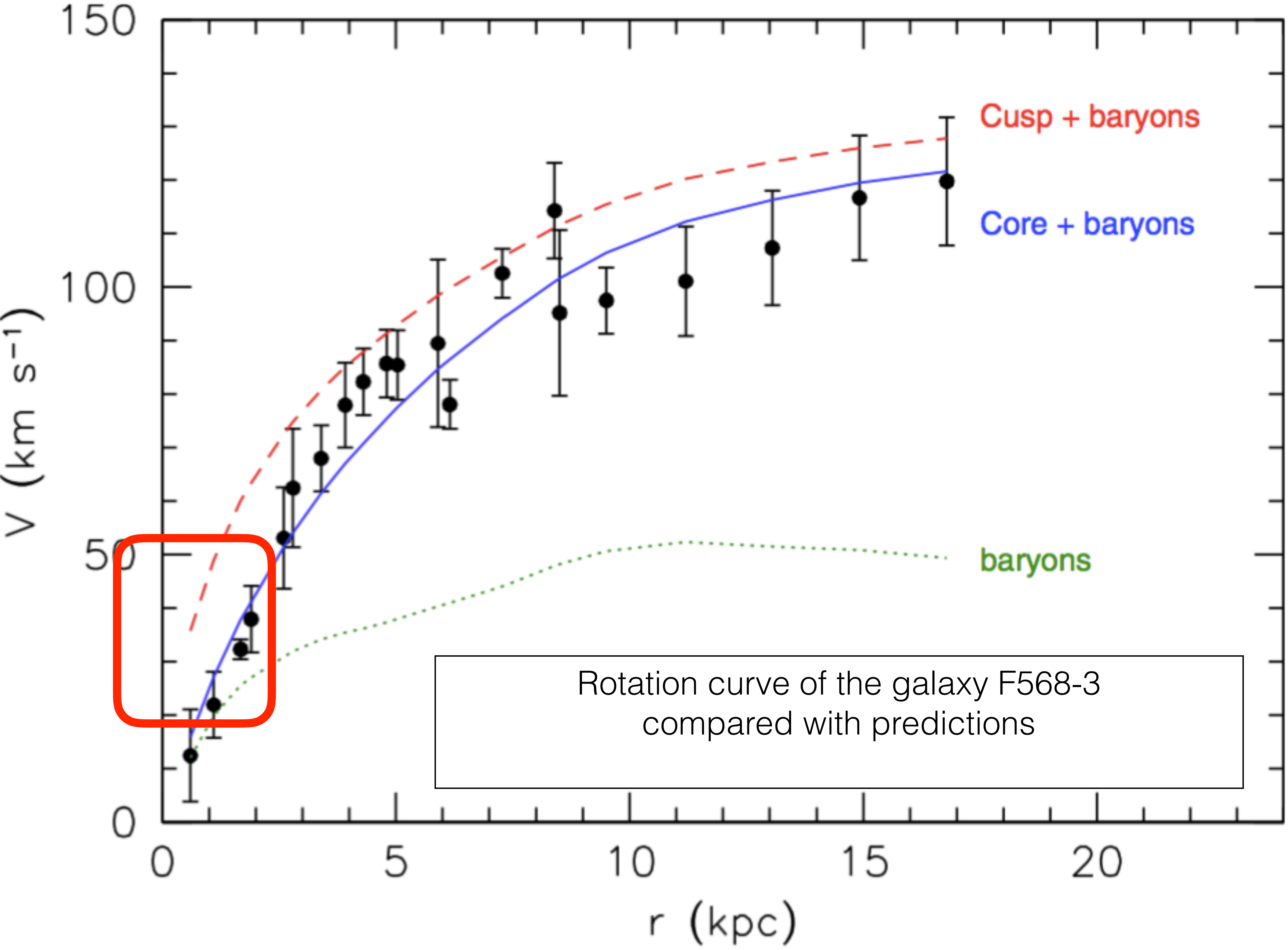
The cusp-core problem



Galaxy F568-3 superposed on the dark matter distribution from the "Via Lactea" cosmological simulation of a Milky Way-mass CDM halo (Kuhlen+ 2008)



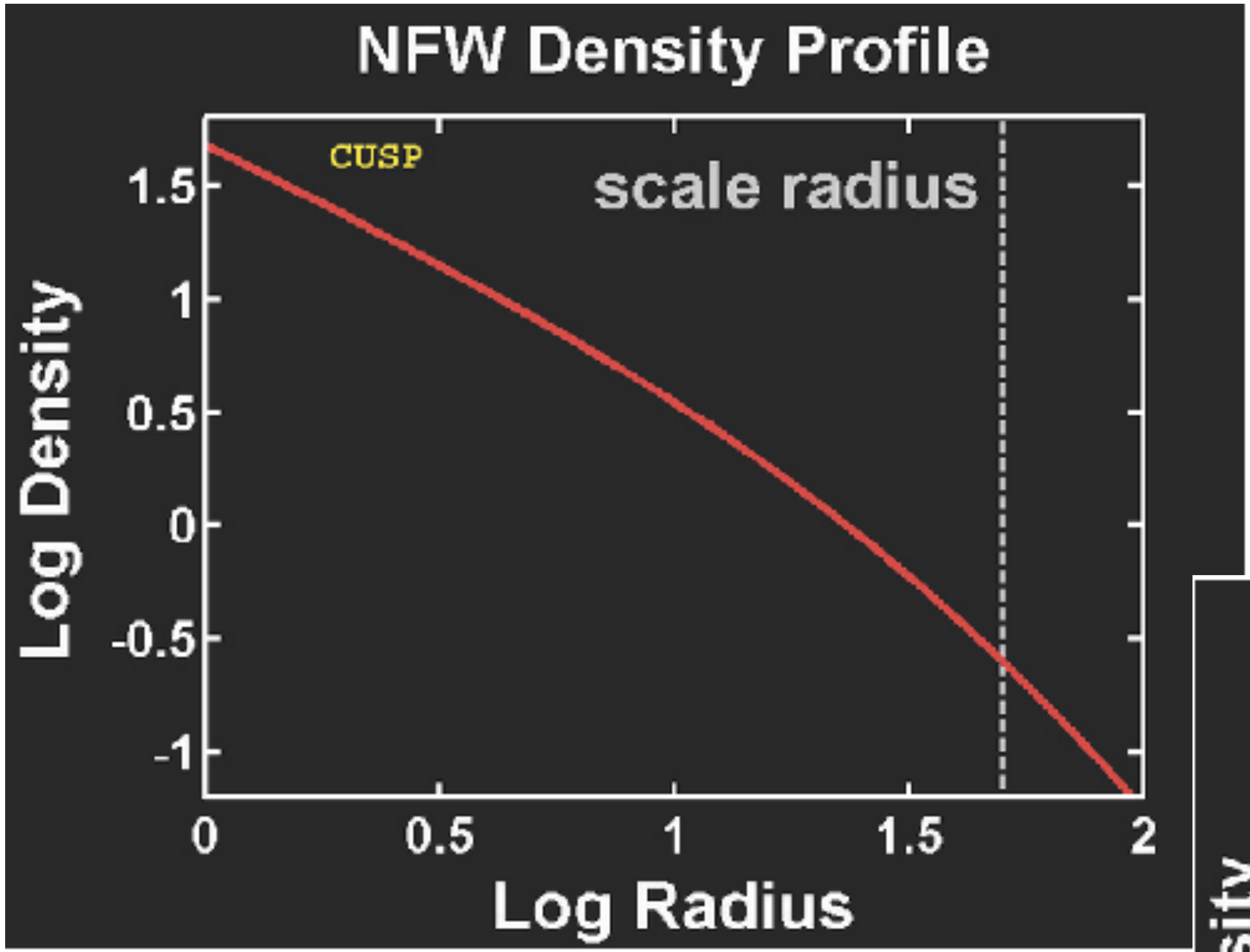
Rotation curve of the galaxy F568-3 compared with predictions



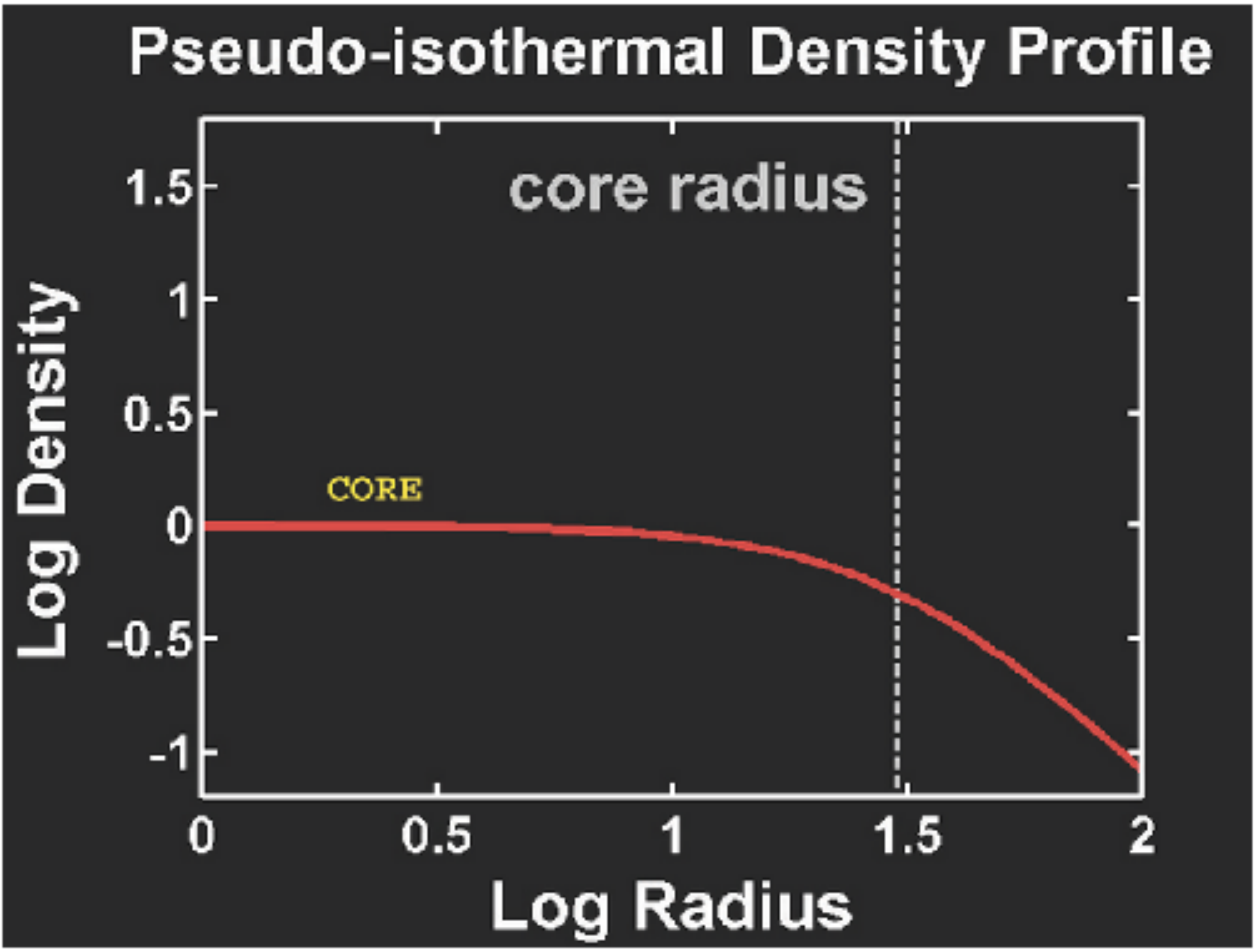
Rotation curve of the galaxy F568-3 compared with predictions

DM halos have too much matter in the inner region

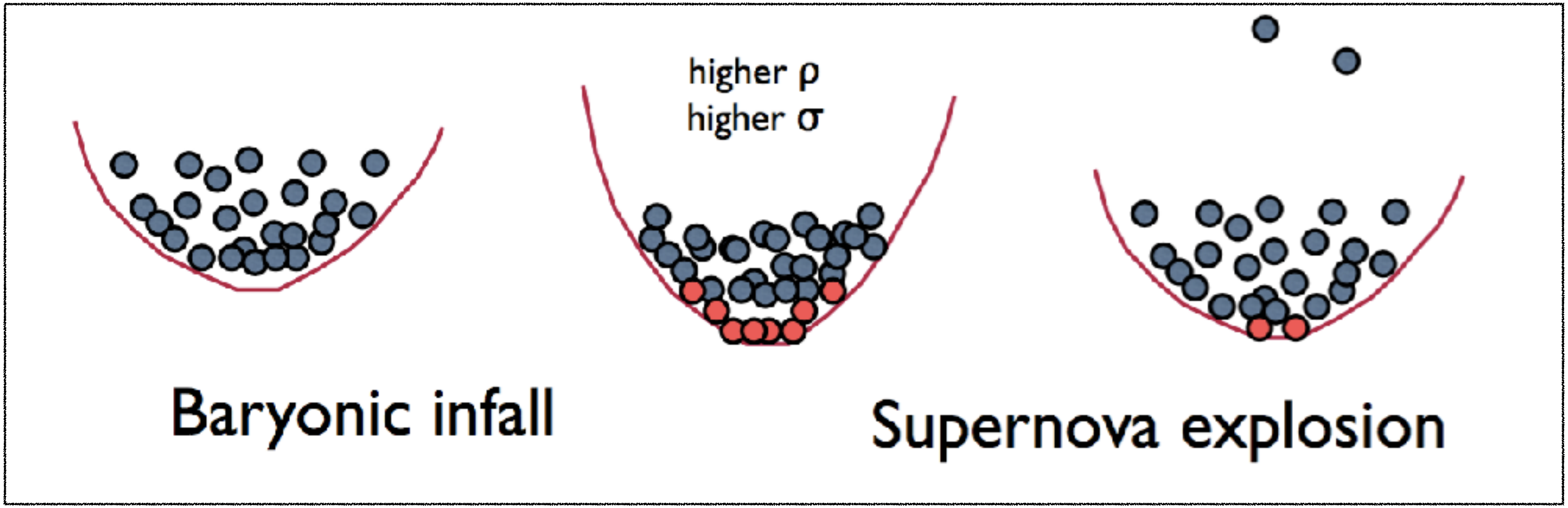
predictions from LCDM numerical simulations



observations

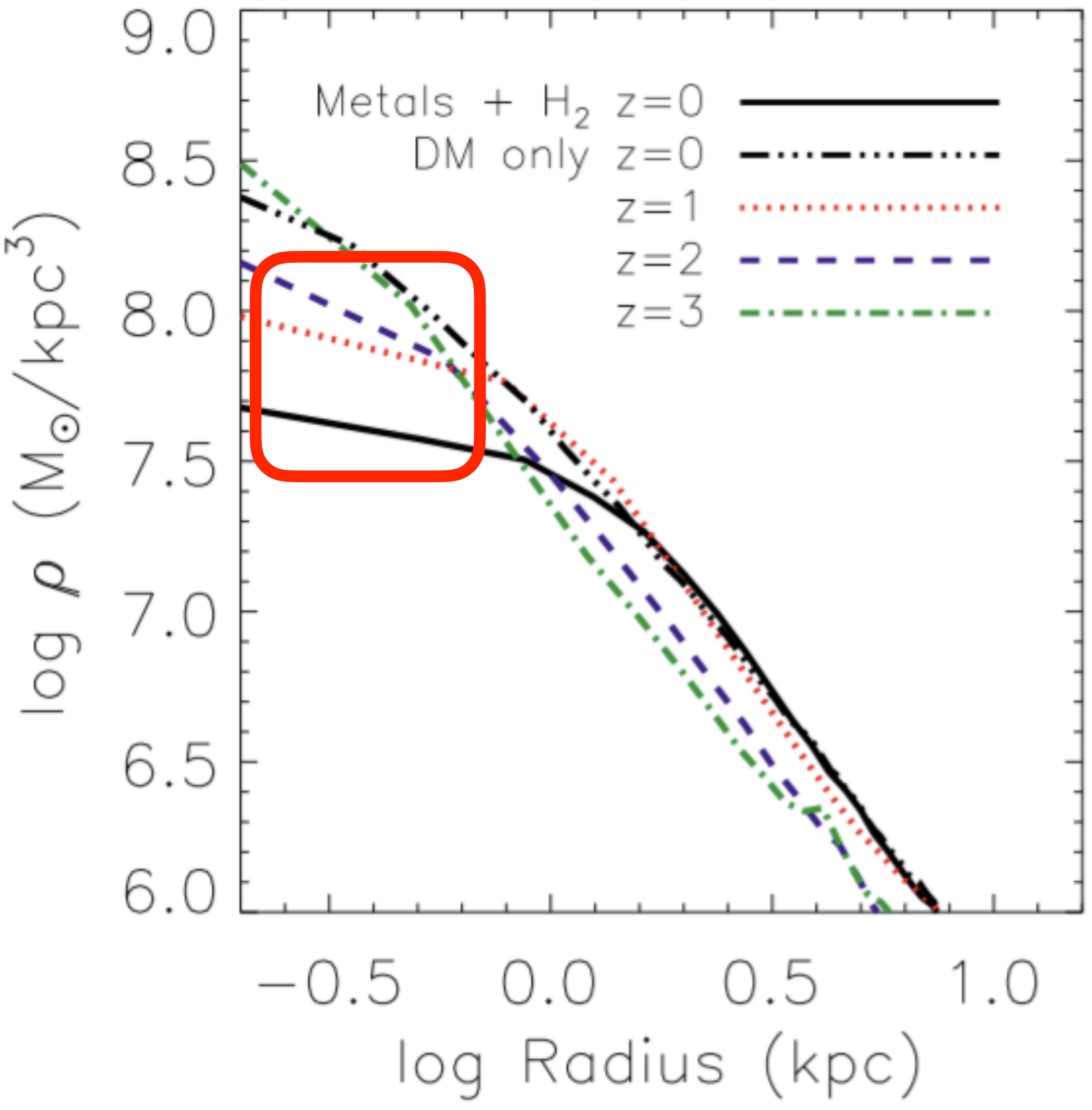


A solution from the Baryon physics?
Feedback form SN explosions

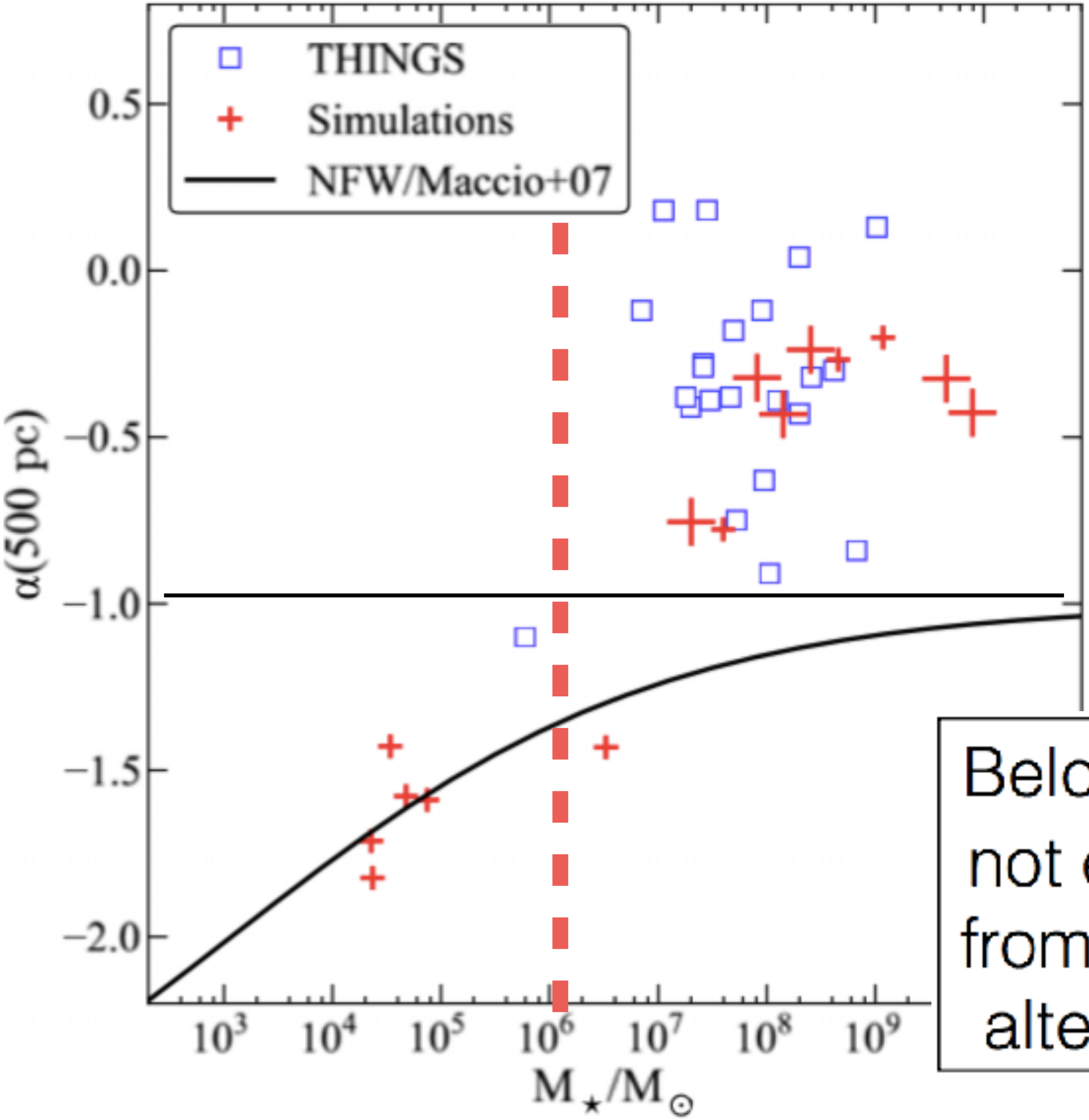


Gravitational binding energy vs. Energy injection from supernovae
Navarro, Eke, Frenk (1996)

A solution from the Baryon physics?
Feedback form SN explosions



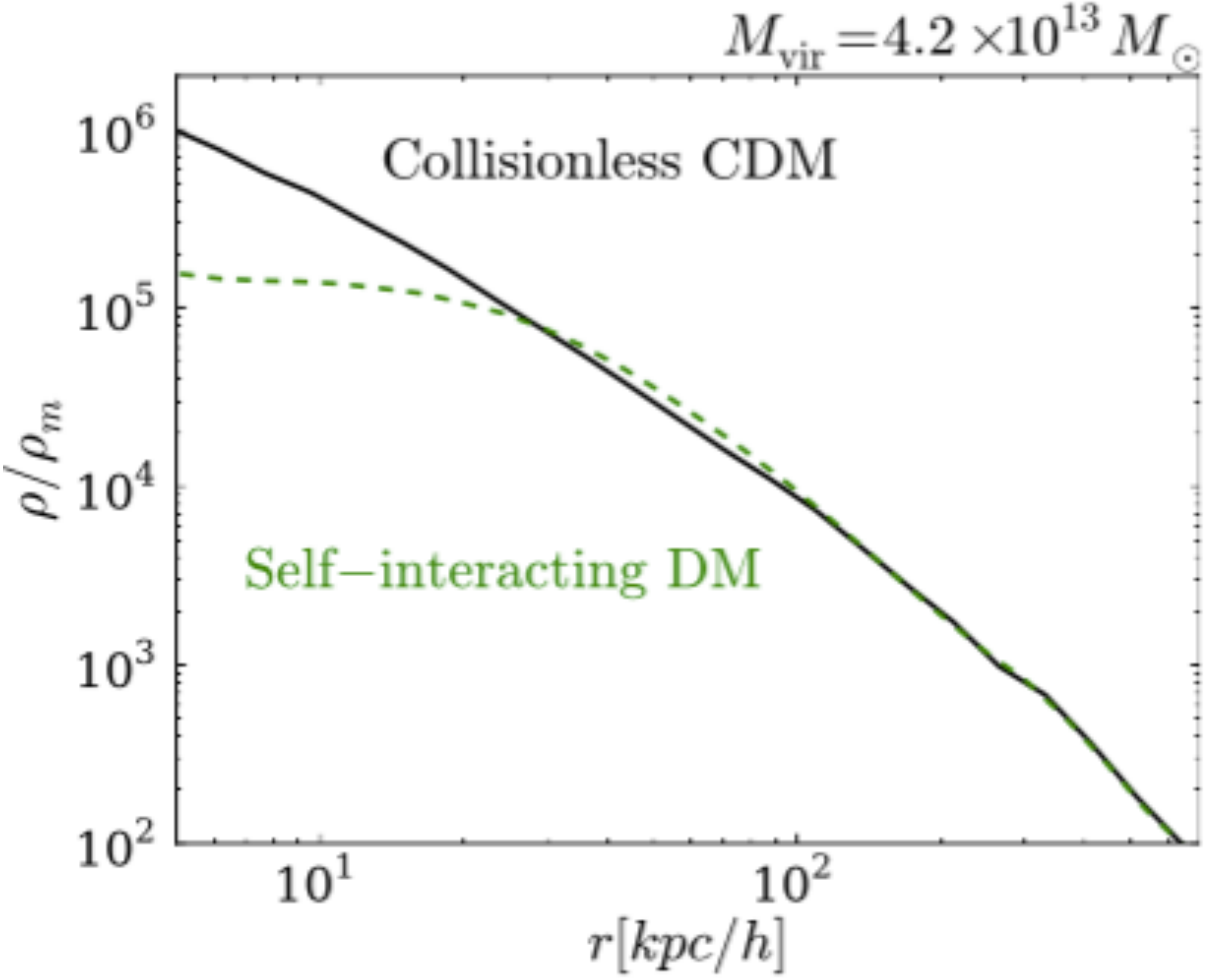
A solution from the Baryon physics?
Feedback form SN explosions



Below $M_\star \sim 10^6\ M_\odot$ not enough energy from supernovae to alter DM structure

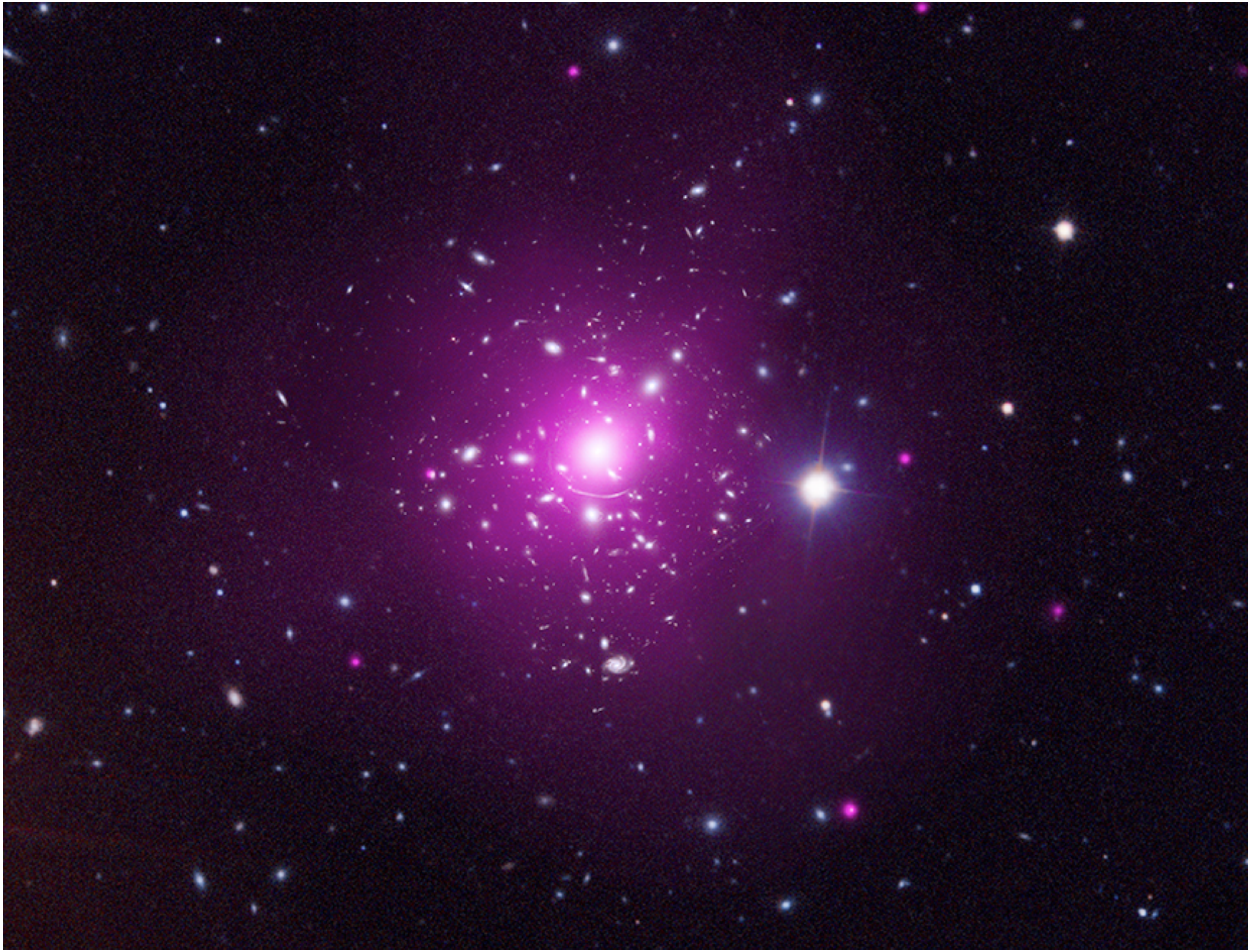
A solution on the DM side

SIDM: Cold Dark Matter with non-gravitational interactions (e.g., elastic scattering)



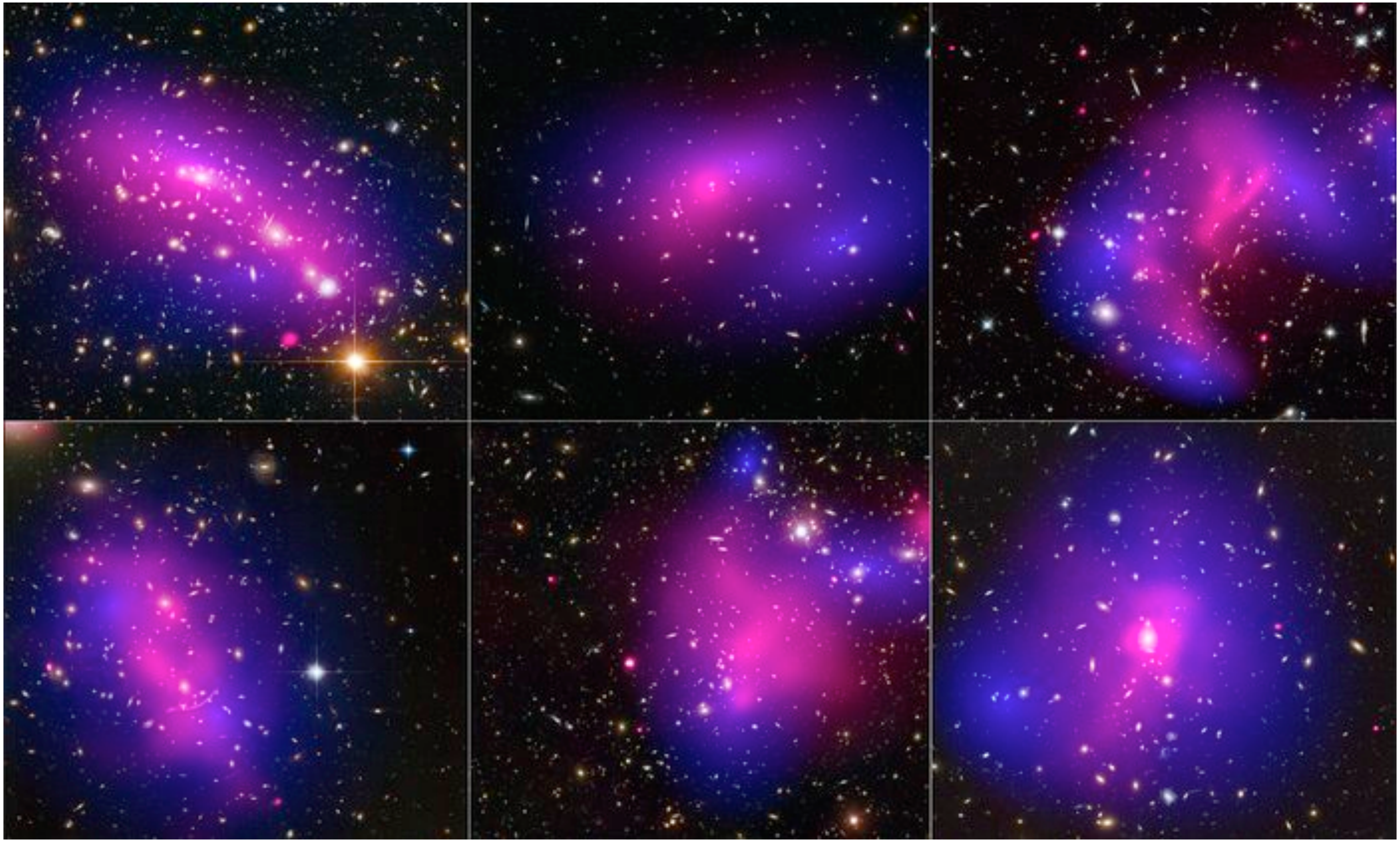
SIDM galactic halos have constant-density cores,
with significantly lower central densities than their CDM counterparts

Merging galaxy clusters:
dark matter particle (astro) colliders



Galaxy cluster A383: optical + X-ray light

A sample of merging galaxy clusters: Dark matter particle colliders



blue: DM map
purple: baryons (hot gas)
white: baryons (galaxies)

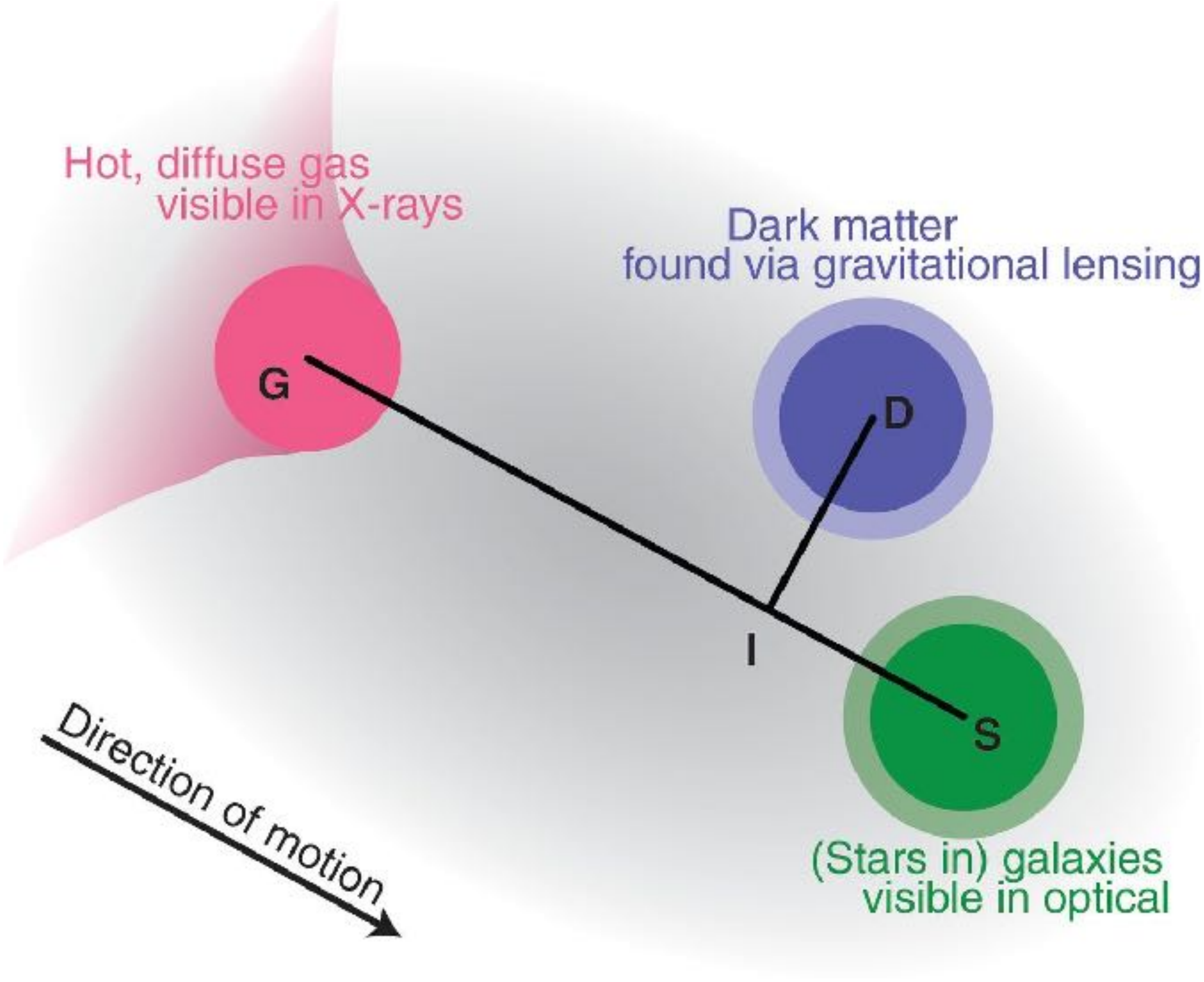
David Harvey et al., Science (2015)

Abell 576 - Bullet Cluster

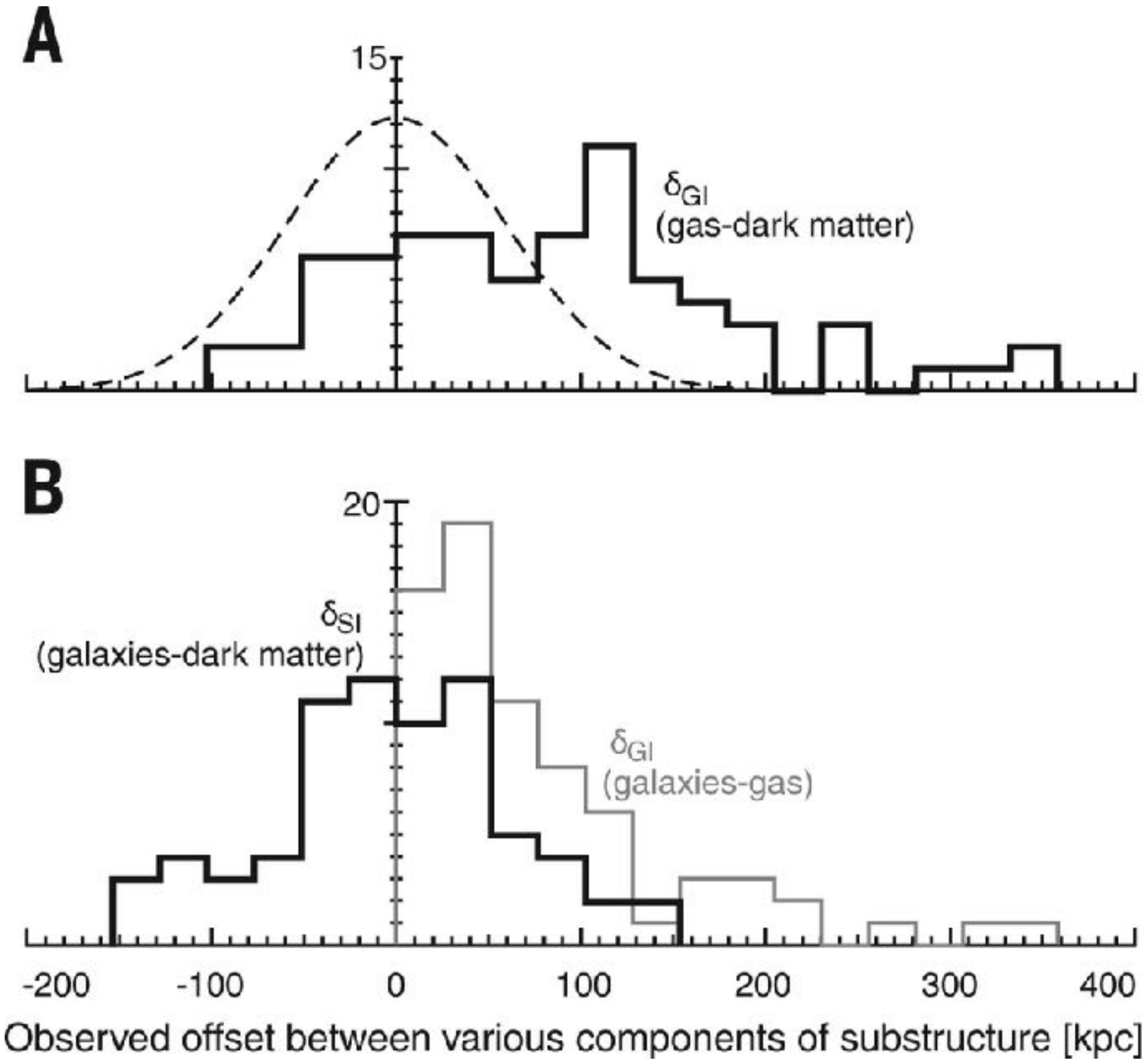
two clusters in collision

PINK: Hot Intracluster gas, contains most of the normal matter (Chandra image)
BLUE: Dark Matter, dominates the mass (from gravitational lensing, HST image)

merging galaxy clusters

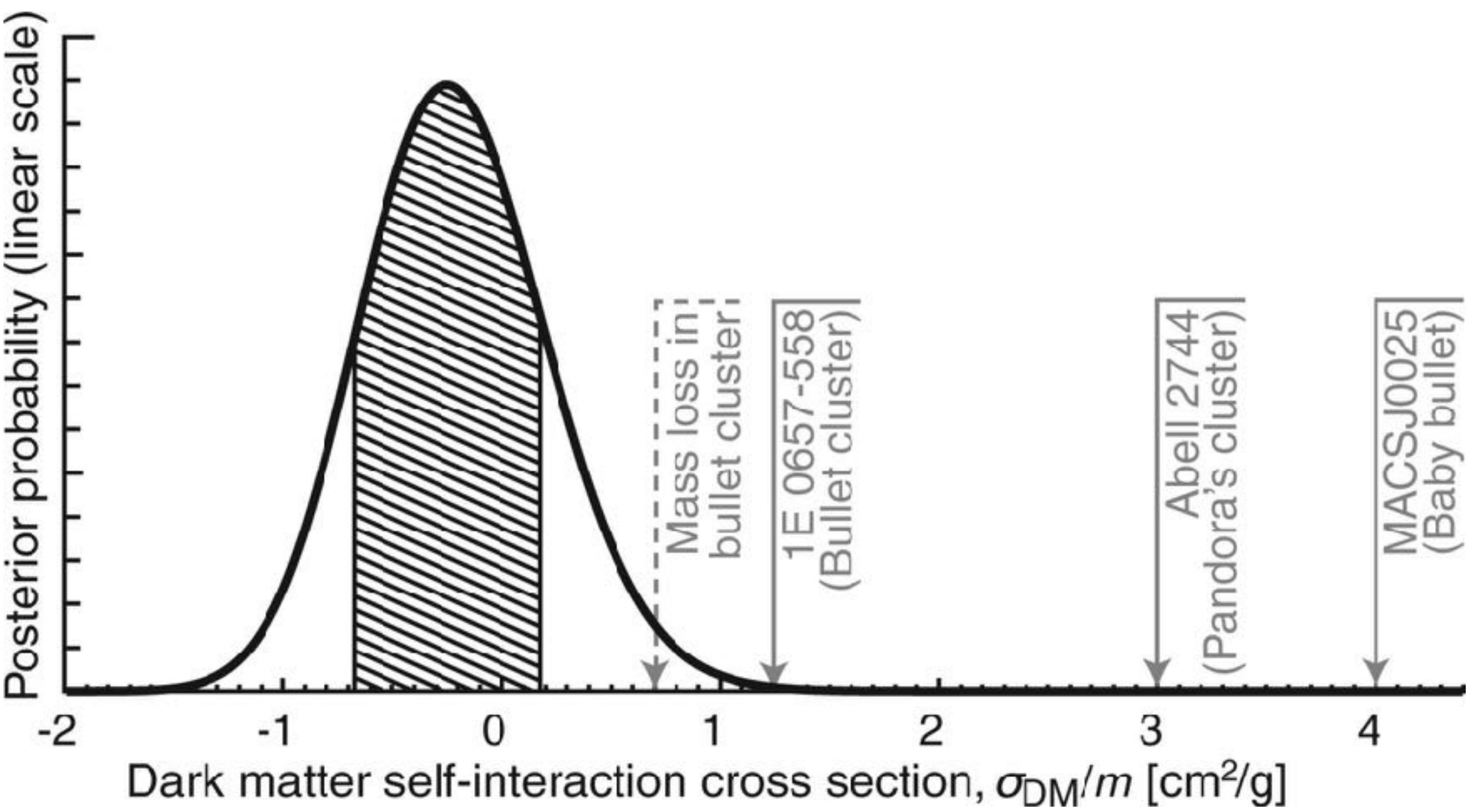


David Harvey et al., Science (2015)



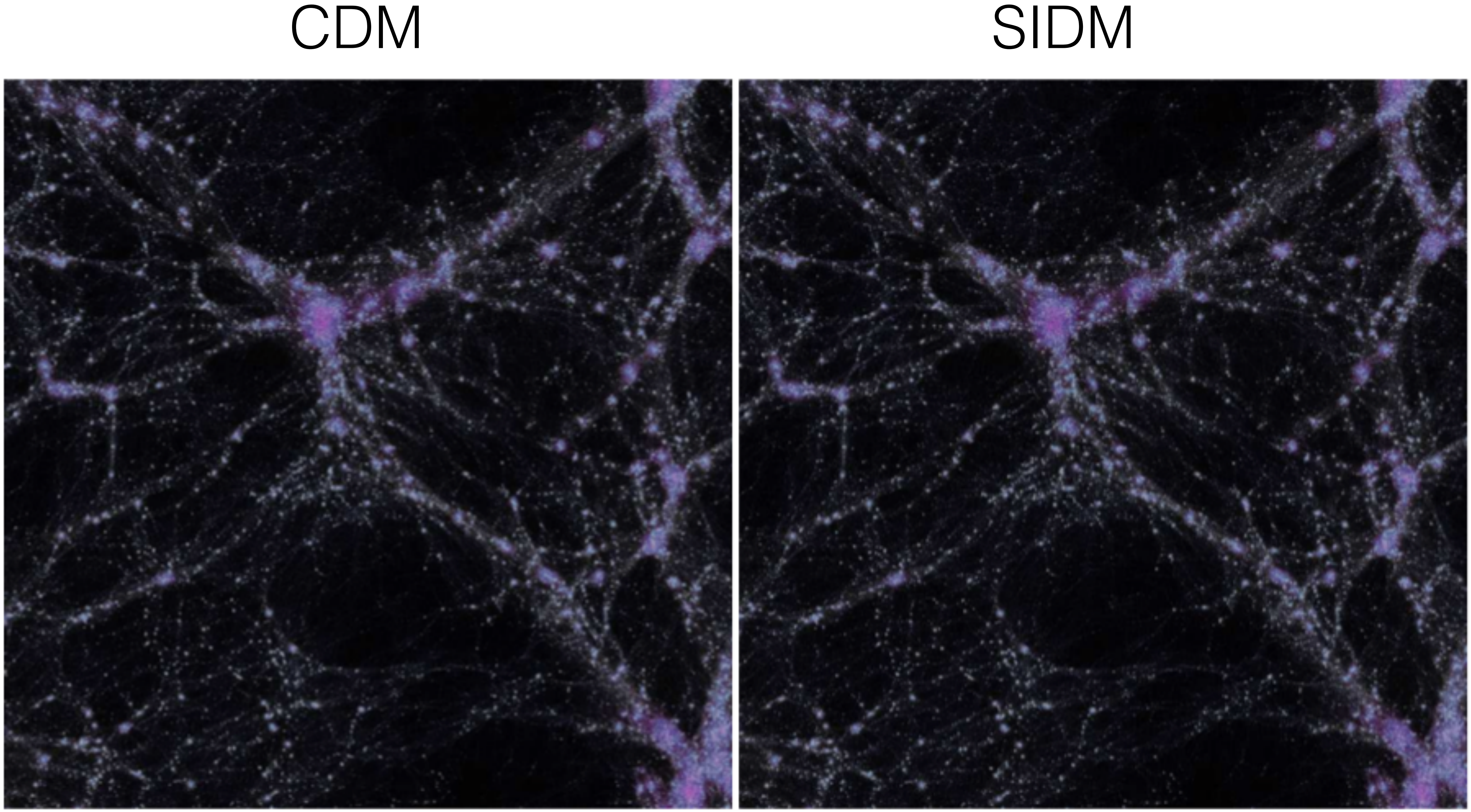
David Harvey et al., Science (2015)

Constraints on the self-interaction cross section of dark matter



David Harvey et al., Science (2015)

The large-scale successes of CDM are equally well matched by SIDM.



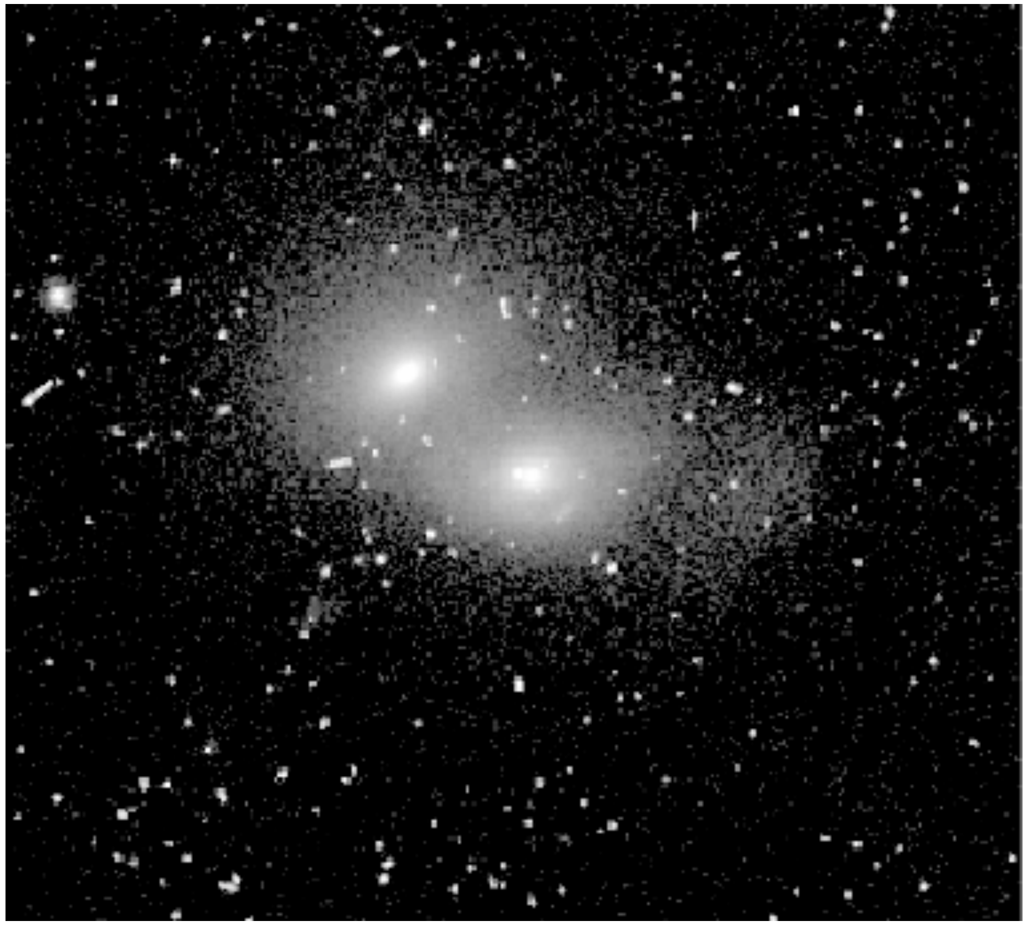
N-body simulations by Rocha et al. (2013)

Constant cross section $\sigma/m \sim 0.5 - 1\ \mathrm{cm}^2/\mathrm{g}$

Next step: explore the merging galaxies

- Different mass scale
- Different velocity collisions
- **Is the DM-DM cross section velocity dependent ?**

VLT Observational Program approved (2017)
Team: Covone, Kneib, Harvey, Fiorillo, Bastone, Milo



- Immediate aim: **use spectroscopy and lensing to measure DM offsets with respect to baryons on scale of galaxies**

- Scientific goal: **is the DM-DM cross section velocity dependent?**

Can astronomers say something about ***nature*** of DM?

A Telescope Search for Decaying Relic Axions

The team

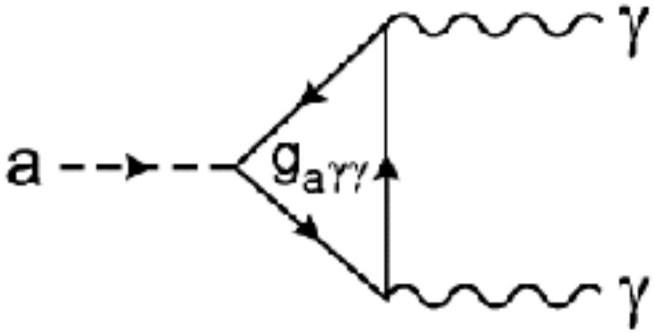
Theoretical side: Daniel Grin (Caltech, PhD student),

Marc Kamionkowski (Calthec)

Observational side: Giovanni Covone (Napoli) , Andrew Blain (Caltech), Jean-Paul Kneib (F), Eric Jullo (ESO)

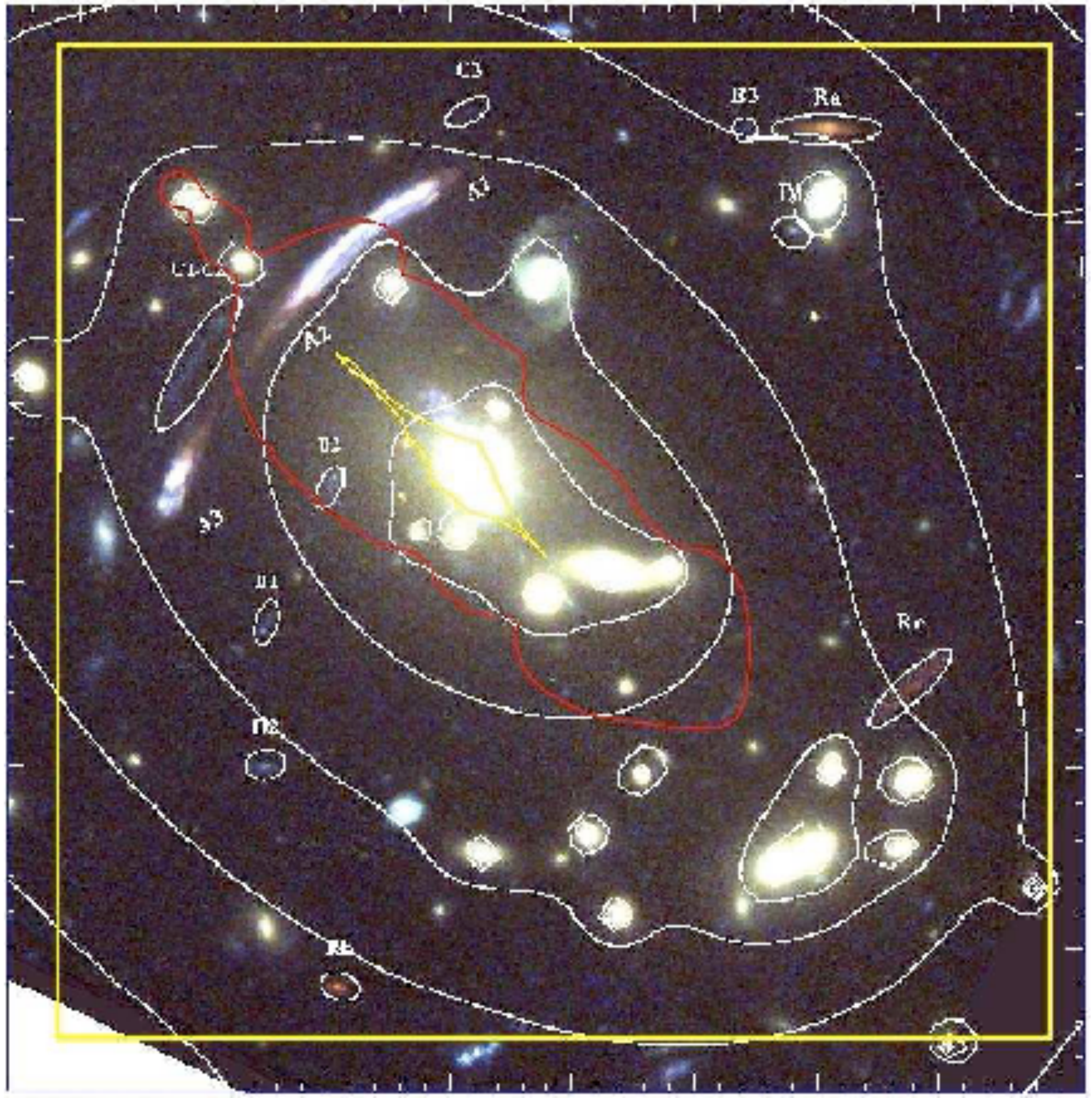
Axionic Dark Matter

- Axions are attractive because they exist even in the most conservative extensions of the standard model
- Lifetime is longer than Hubble time!
- Cold and bound today

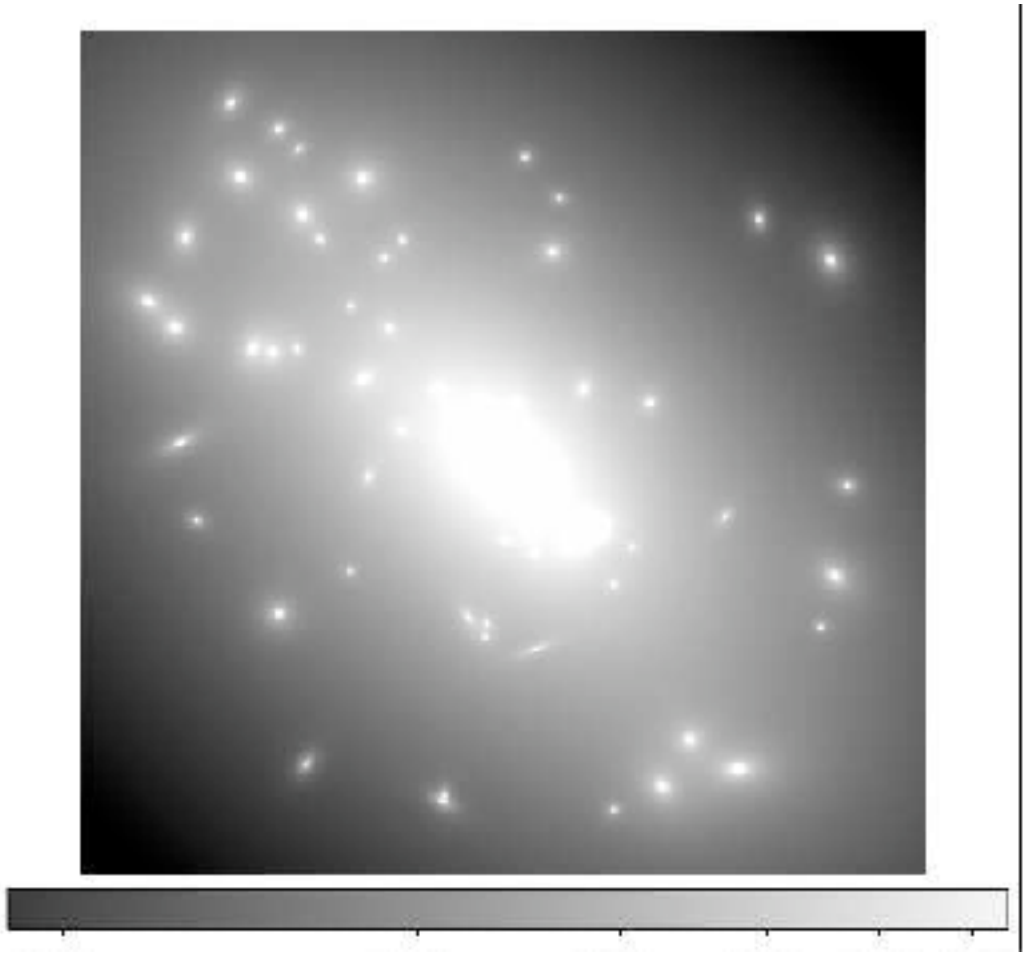


Axions are not completely "dark"!

Astronomical searches for axions: our data

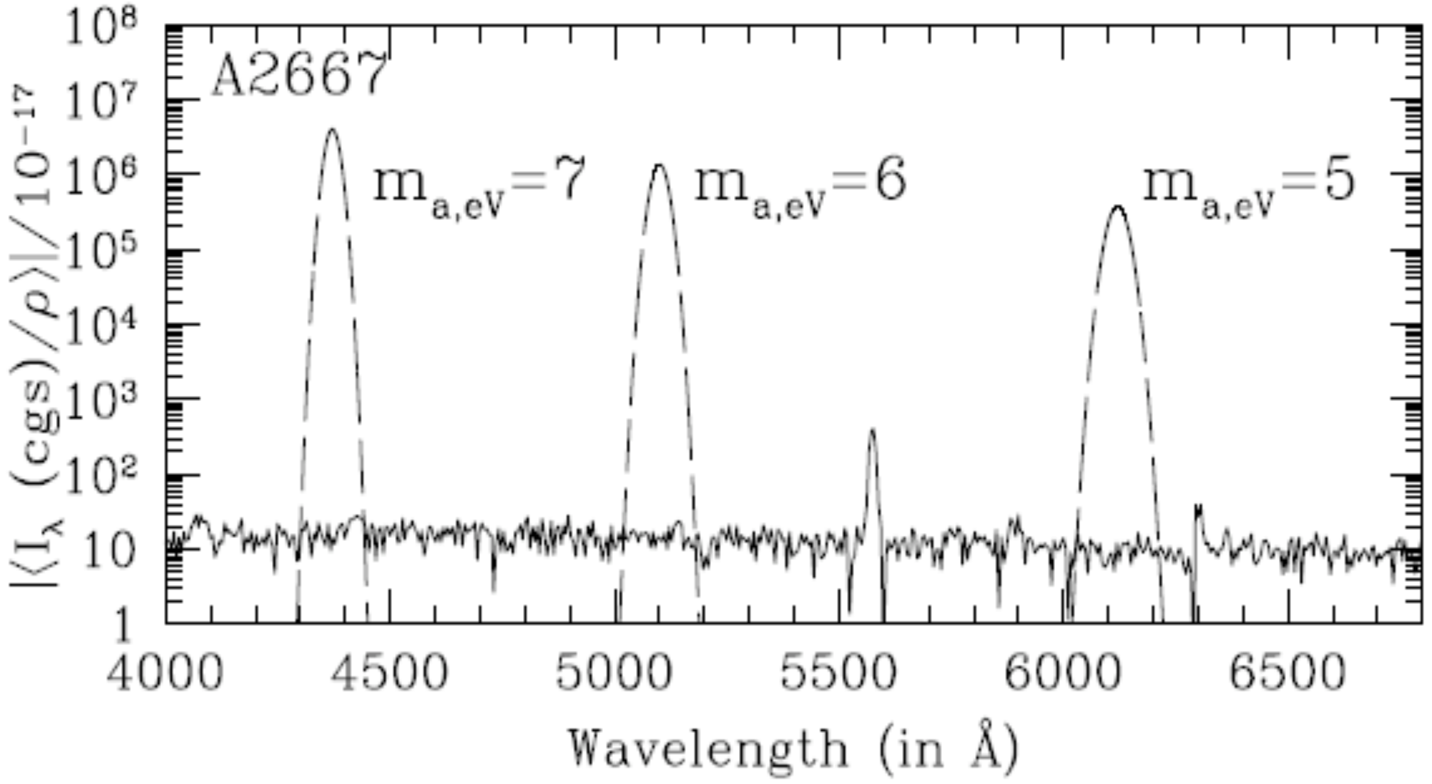


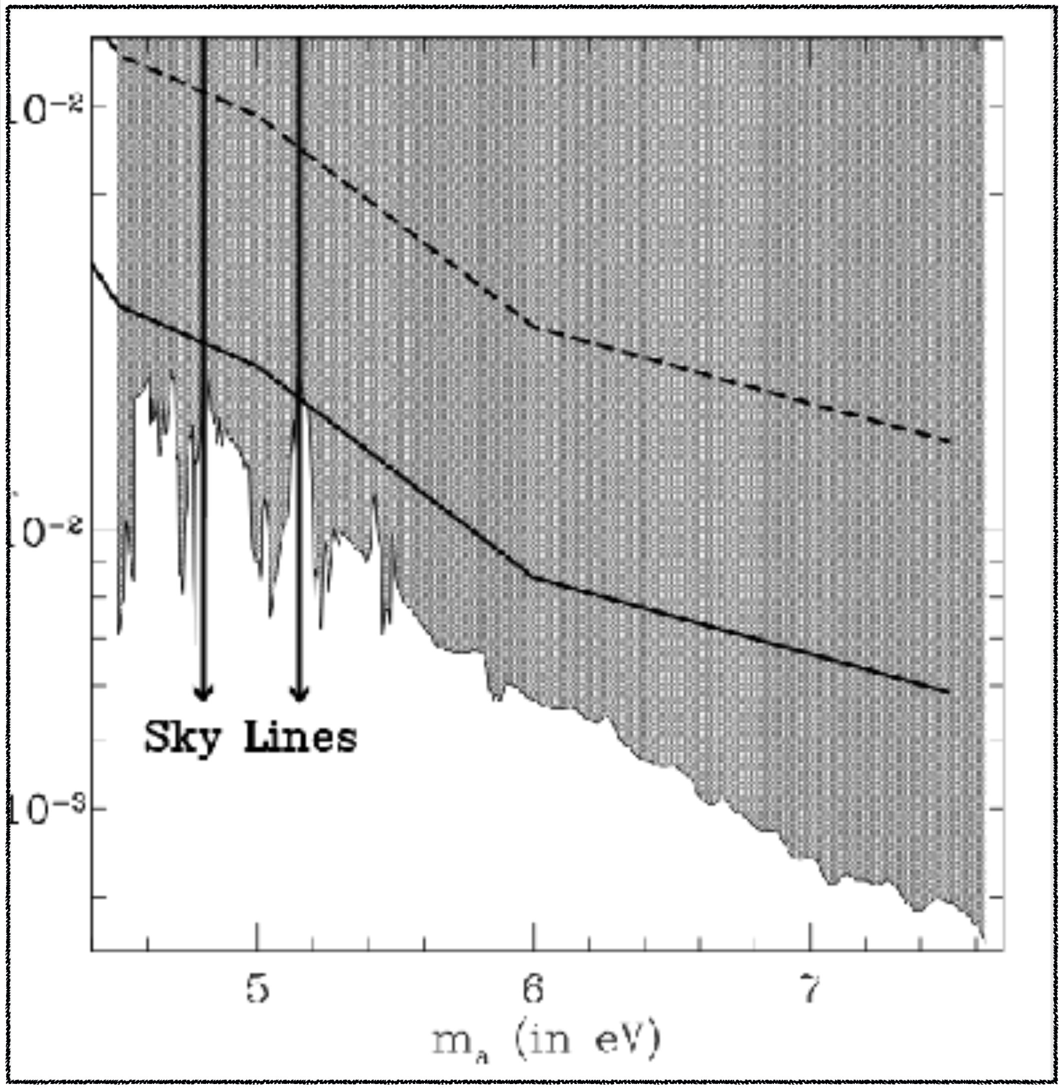
HST data of 2 clusters at z~0.23



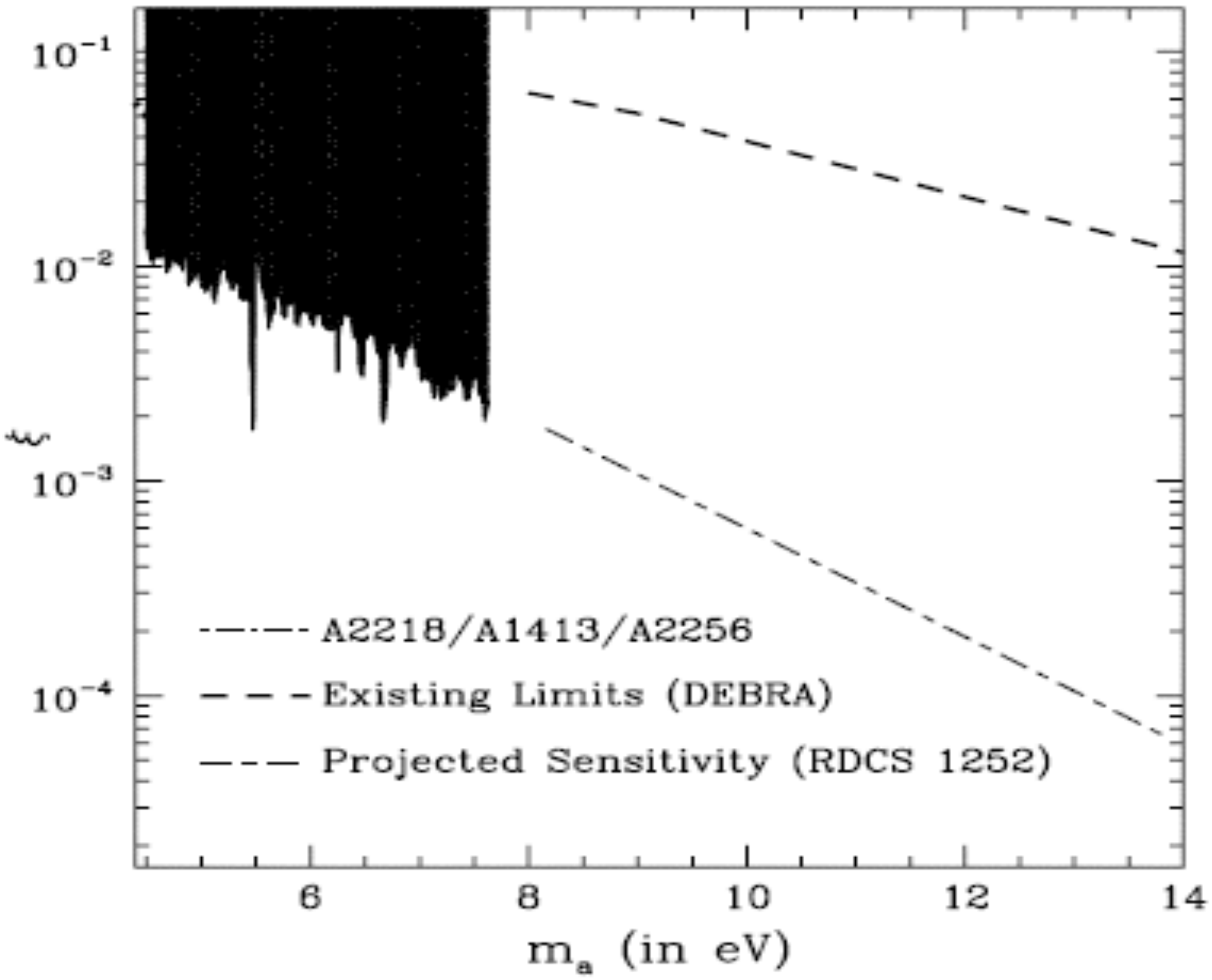
Accurate mass models from gravitational lensing

Astronomical searches for axions: results



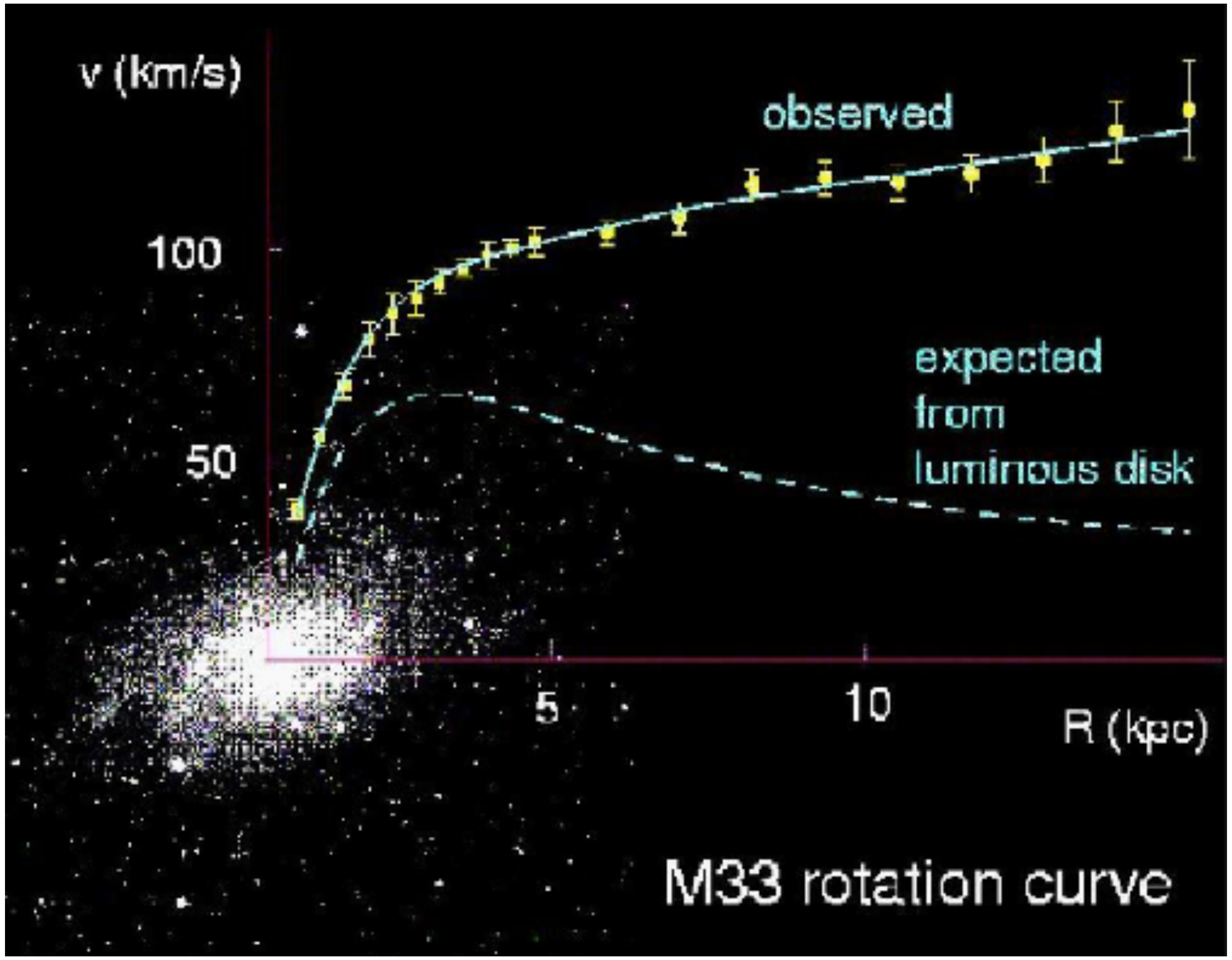


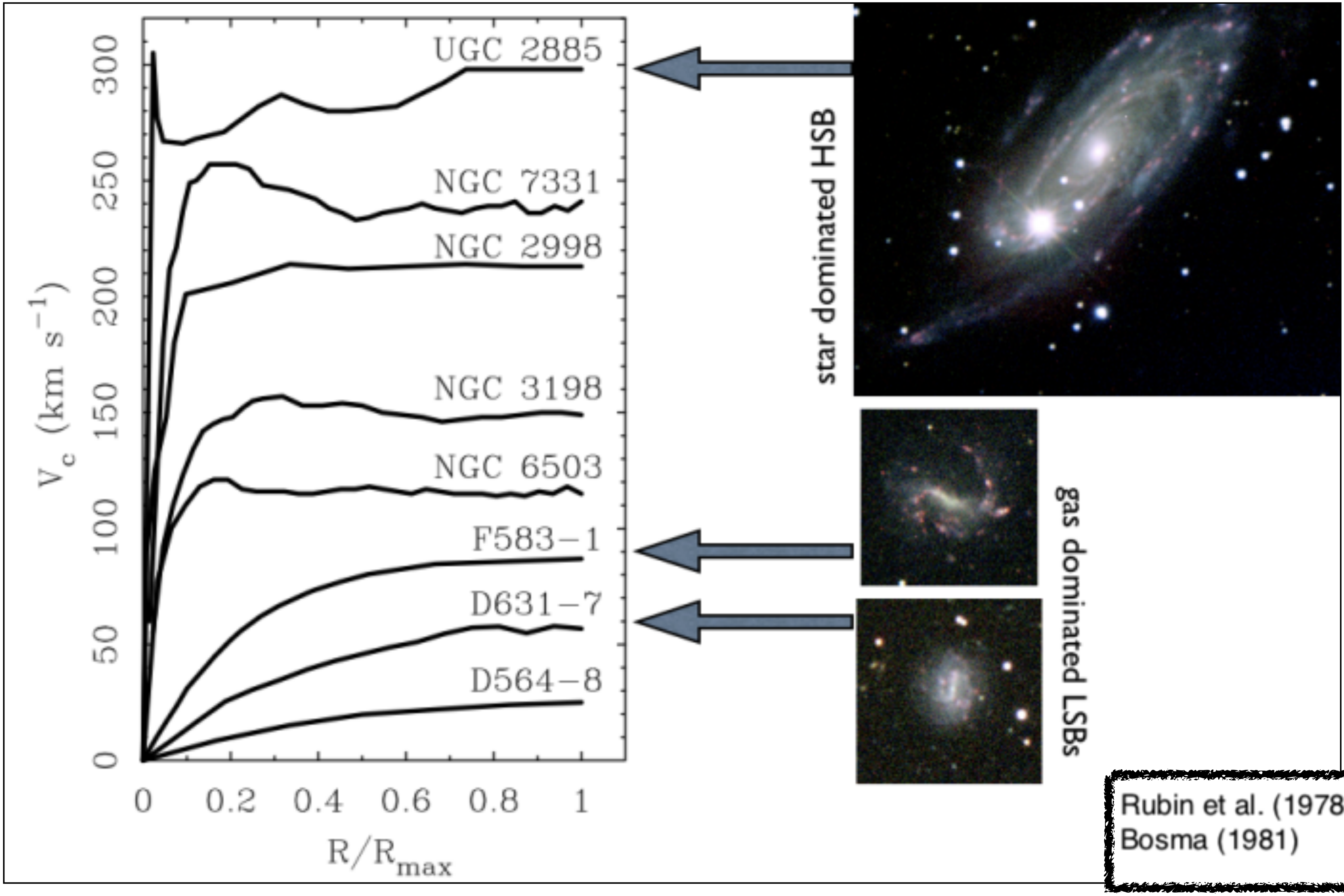
Next step: Going at z=1.2



The puzzle of rotation curves

Rotation curves of disk galaxies





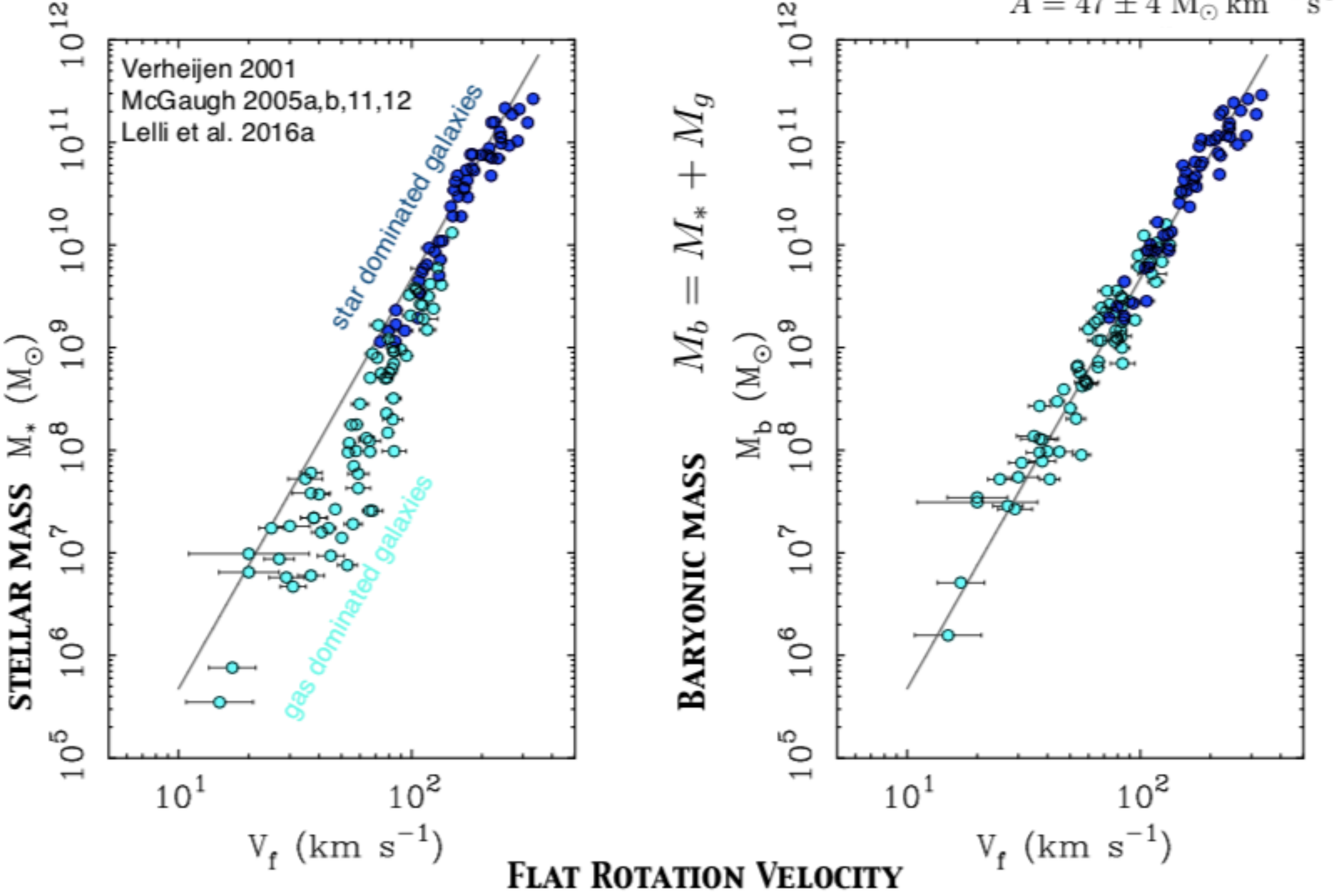
Rubin et al. (1978)
Bosma (1981)

The rotation curves of galaxies over a large dynamic range in mass, from the most massive spiral with a well measured rotation curve (UGC 2885) to tiny, low mass, low surface brightness, gas rich dwarfs.

The baryonic Tully-Fisher relation

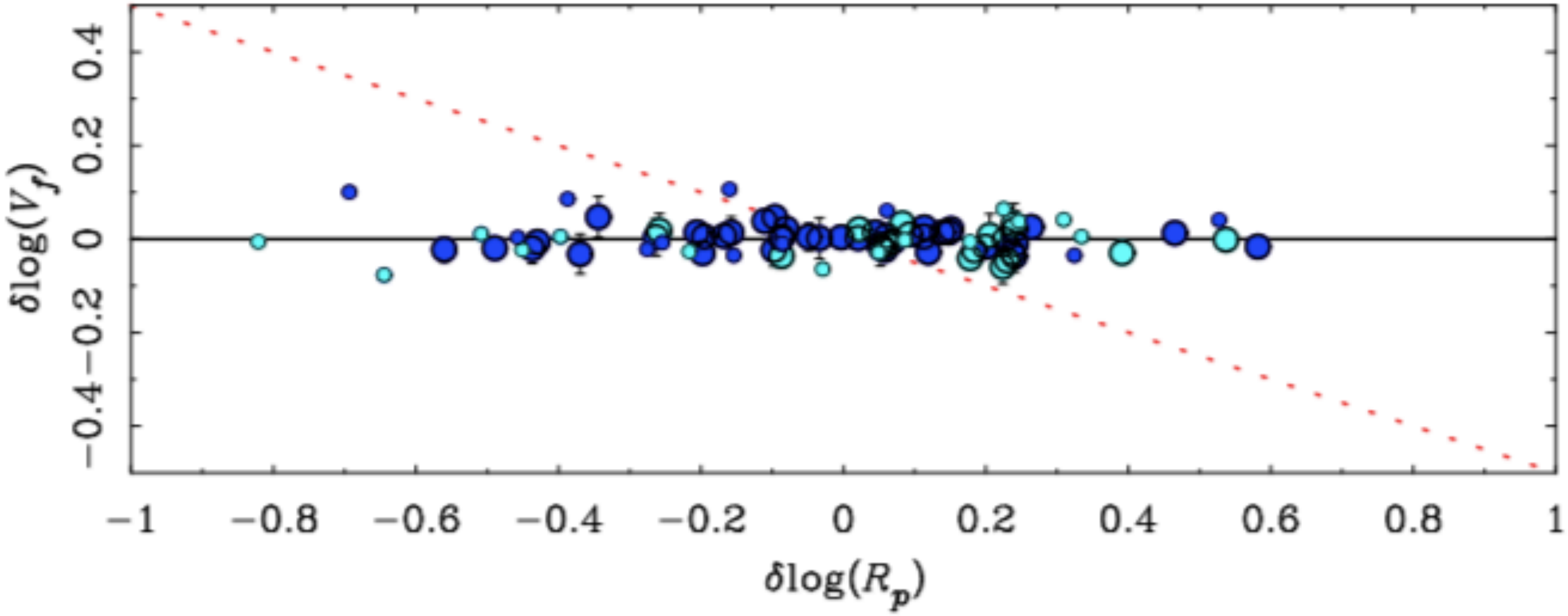
$$M_b = AV_f^4$$

$$A = 47 \pm 4\ \mathrm{M_\odot\,km^{-4}\,s^4}$$



This is not simply a correlation!

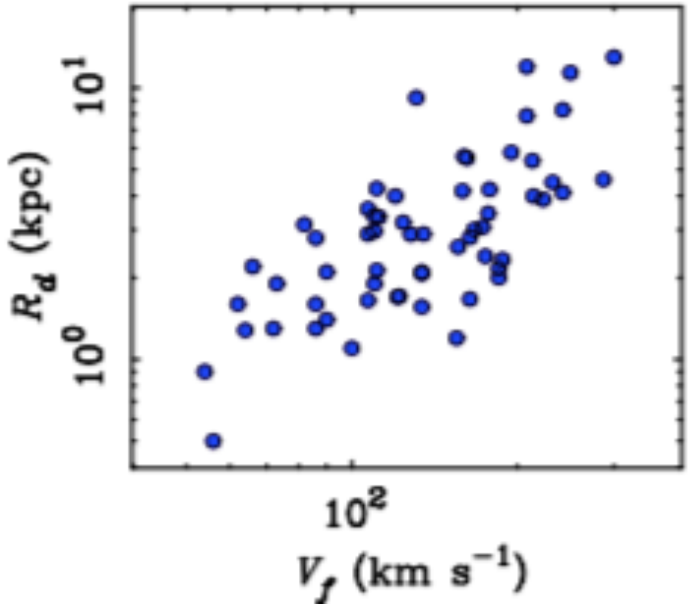
No residuals from BTFR with size or surface brightness



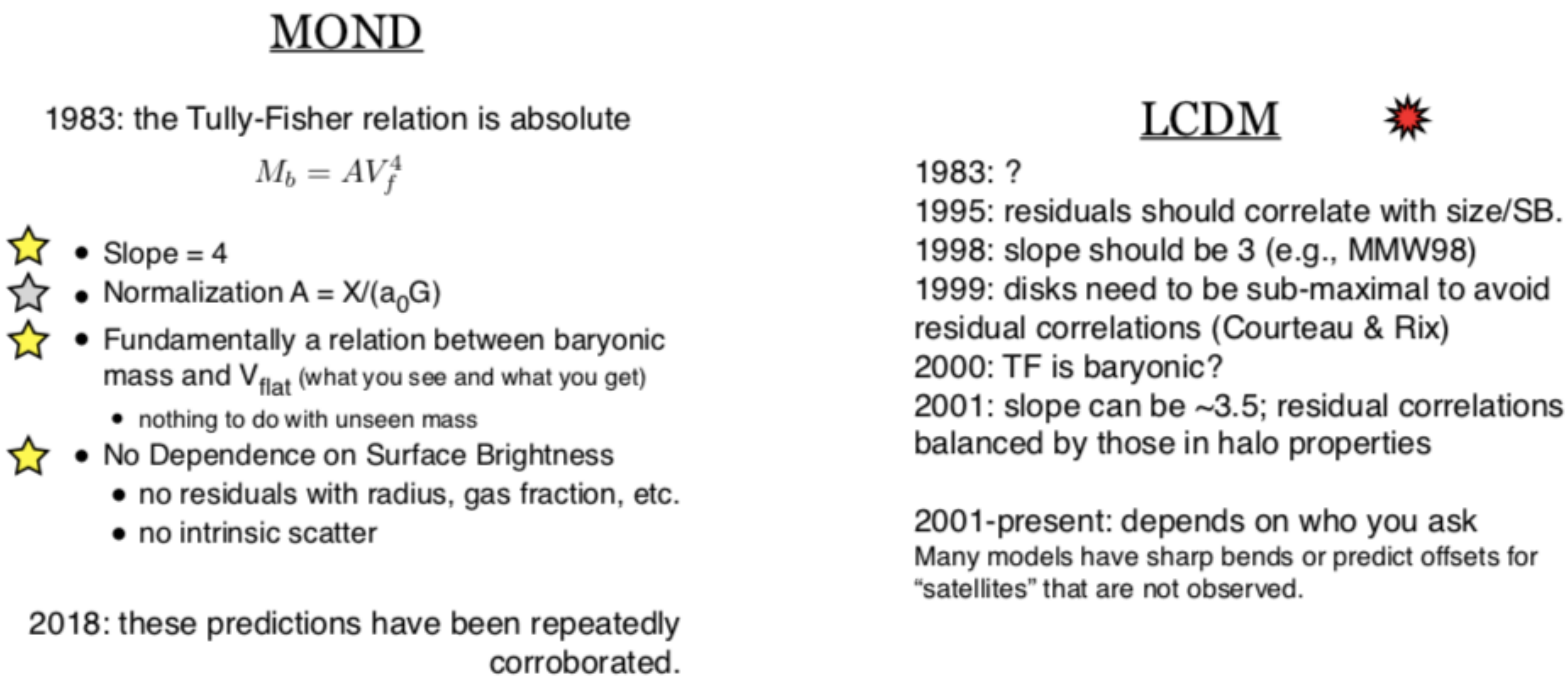
$$V^2 = G\left(\frac{M_b}{R_b} + \frac{M_{dm}}{R_{dm}}\right)$$

Fine-tuning anomaly: M/R for each component must balance to keep V constant. We'd expect the opposite effect from adiabatic compression.

Galaxies exist over a large range in M_b/R_b at fixed velocity



“Type a quote here.”



MOND

1983: the Tully-Fisher relation is absolute

$$M_b = AV_f^4$$

- ☆ Slope = 4
- ☆ Normalization A = X/(a_0G)
- ☆ Fundamentally a relation between baryonic mass and V_{flat} (what you see and what you get)
  - nothing to do with unseen mass
- ☆ No Dependence on Surface Brightness
  - no residuals with radius, gas fraction, etc.
  - no intrinsic scatter

2018: these predictions have been repeatedly corroborated.

LCDM ✸

1983: ?
1995: residuals should correlate with size/SB.
1998: slope should be 3 (e.g., MMW98)
1999: disks need to be sub-maximal to avoid residual correlations (Courteau & Rix)
2000: TF is baryonic?
2001: slope can be ~3.5; residual correlations balanced by those in halo properties

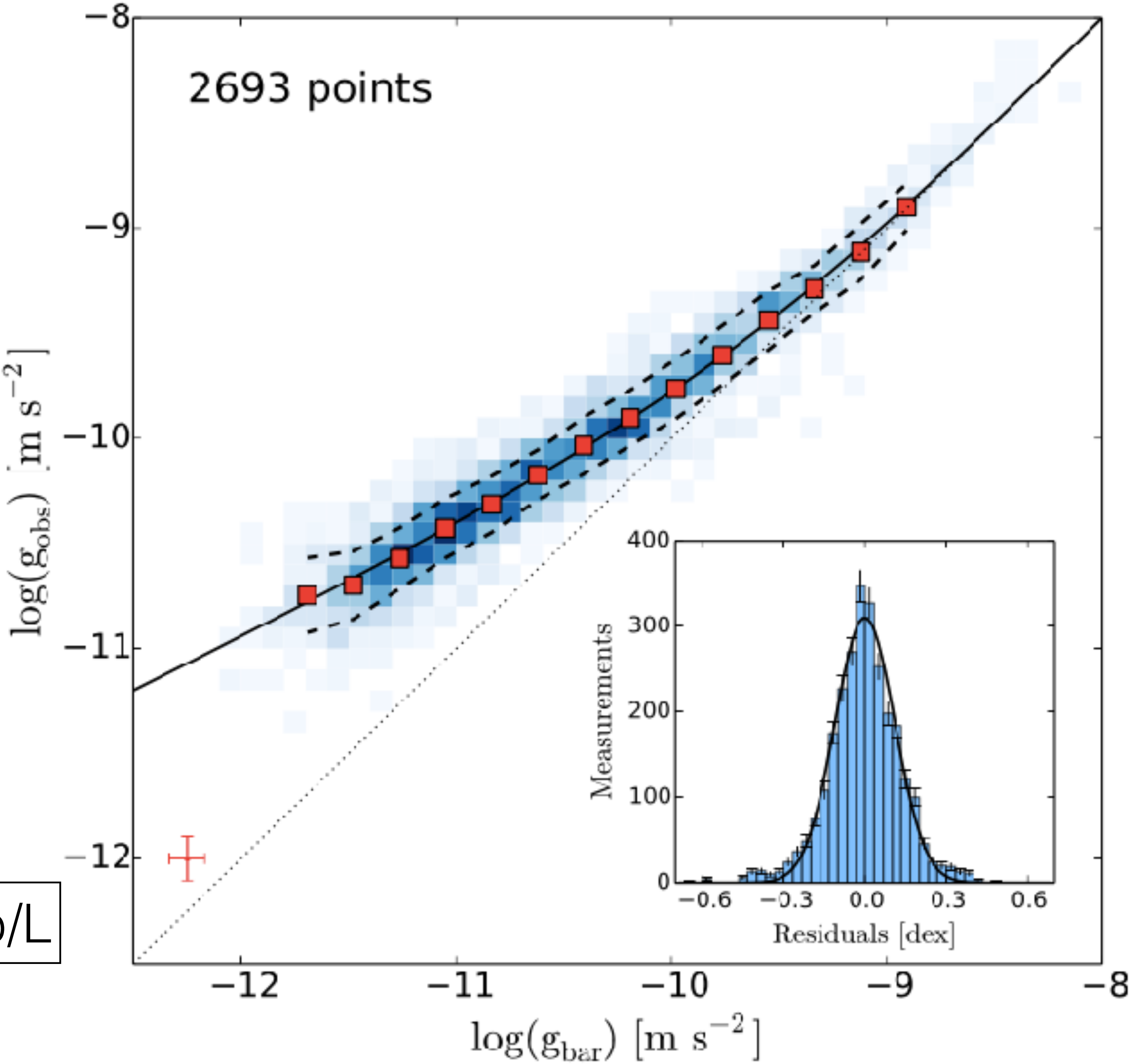
2001-present: depends on who you ask
Many models have sharp bends or predict offsets for “satellites” that are not observed.

Slide from S. McCaugh

A prediction of MOND verified:
the radial acceleration relation

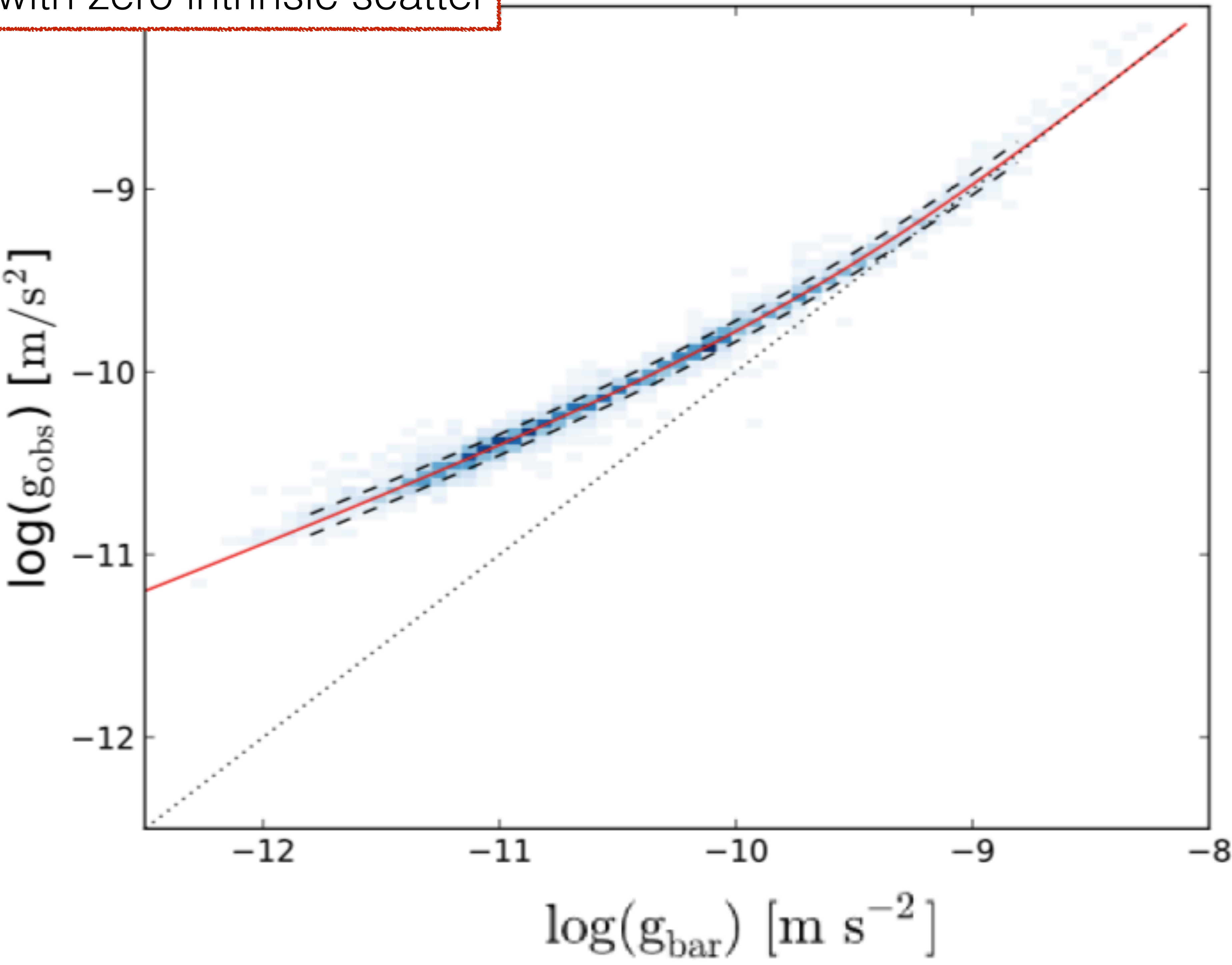
$$g_{obs} = \frac{V^2(R)}{R} = \left|\frac{\partial \Phi_{tot}}{\partial R}\right|$$

$$g_{bar} = \left|\frac{\partial \Phi_{bar}}{\partial R}\right|$$



Assuming a constante Mb/L

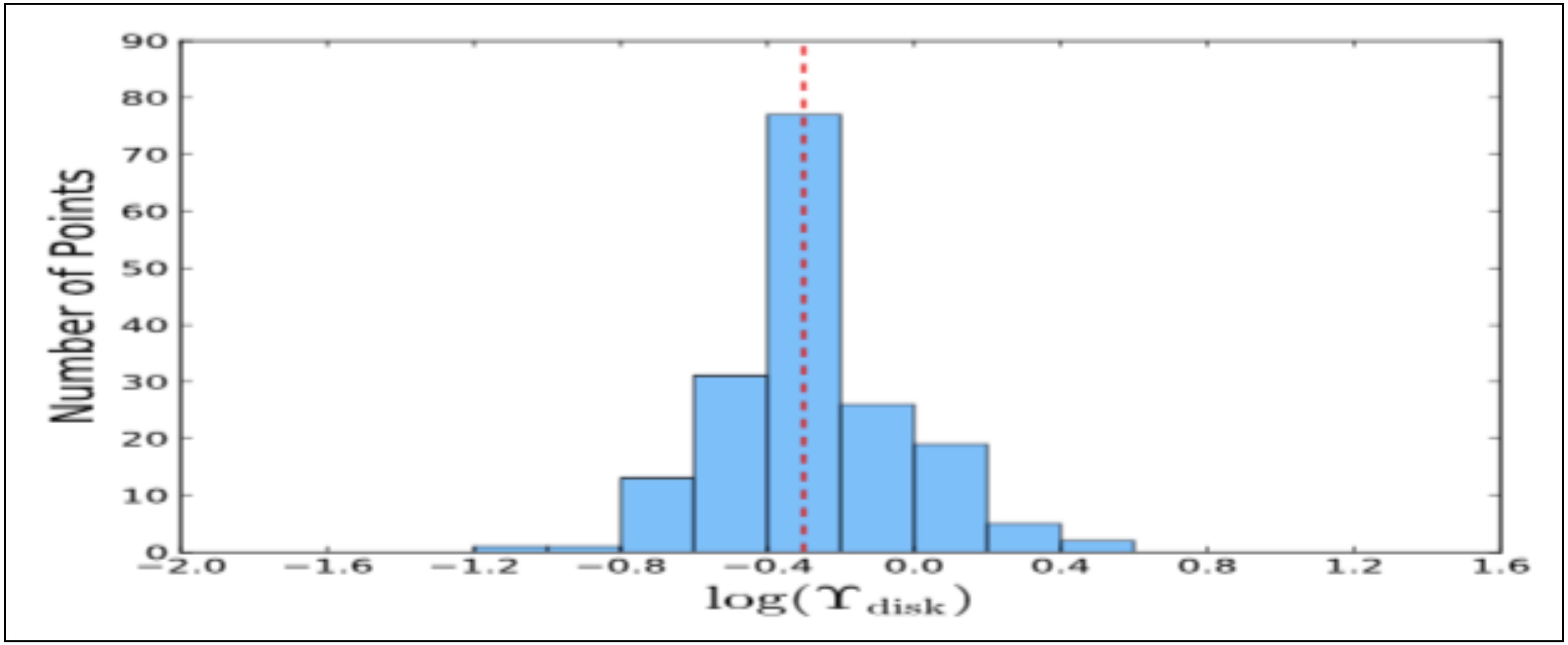
The data are consistent with zero intrinsic scatter



Scatter virtually disappears after marginalizing over the mass-to-light ratio and nuisance parameters (D, i).

The empirical RAR follows MOND.

The scatter in M*/L is consistent with that expected from stellar population models.



LETTER

doi:10.1038/nature25767

A galaxy lacking dark matter

Pieter van Dokkum[1], Shany Danieli[1], Yotam Cohen[1], Allison Merritt[1,2], Aaron J. Romanowsky[3,4], Roberto Abraham[5], Jean Brodie[4], Charlie Conroy[6], Deborah Lokhorst[5], Lamiya Mowla[1], Ewan O'Sullivan[6] & Jielai Zhang[5]

Studies of galaxy surveys in the context of the cold dark matter paradigm have shown that the mass of the dark matter ha

the total stellar mass are coupled through a function that

smoothly with mass. Their average ratio M_{halo}/M_{stars} has a min

of about 30 for galaxies with stellar masses near that of the

Way (approximately 5×10^{10} solar masses) and increase

towards lower masses and towards higher masses[1,2]. The

in this relation is not well known; it is generally thought to be less than a factor of two for massive galaxies but much larger for dwarf galaxies[3,4]. Here we report the radial velocities of ten luminous globular-cluster-like objects in the ultra-diffuse galaxy[5] NGC1052–DF2, which has a stellar mass of approximately 2×10^8 solar masses.

and Sloan Digital Sky Survey (SDSS) data: with Dragonfly it is a low-surface-brightness object with some substructure and a spatial extent of about 2′, whereas in SDSS it appears as a collection of point-like sources. Intrigued by the likelihood that these compact sources are associated with the low-surface-brightness object, we obtained follow-up spectroscopic observations of NGC1052–DF2 using the 10-m W. M. Keck Observatory. We also observed the galaxy with the Hubble Space Telescope (HST).

A colour image generated from the HST V_{606} and I_{814} data is shown in Fig. 1. The galaxy has a striking appearance. In terms of its apparent size and surface brightness, it resembles dwarf spheroidal galaxies such as those recently identified[8] in the M101 group at 7 Mpc, but the fact that it is only marginally resolved implies that it is at a much greater distance. Using the I_{814} band image, we derived a surface-brightness-fluctuation distance of $D_{SBF} = 19.0 \pm 1.7$ Mpc (see Methods). It is located only 14′ from the luminous elliptical galaxy NGC 1052, which has distance measurements ranging from 19.4 Mpc to 21.4 Mpc

in the Coma cluster[5]. The total magnitude of NGC1052–DF2 is M_{606} =

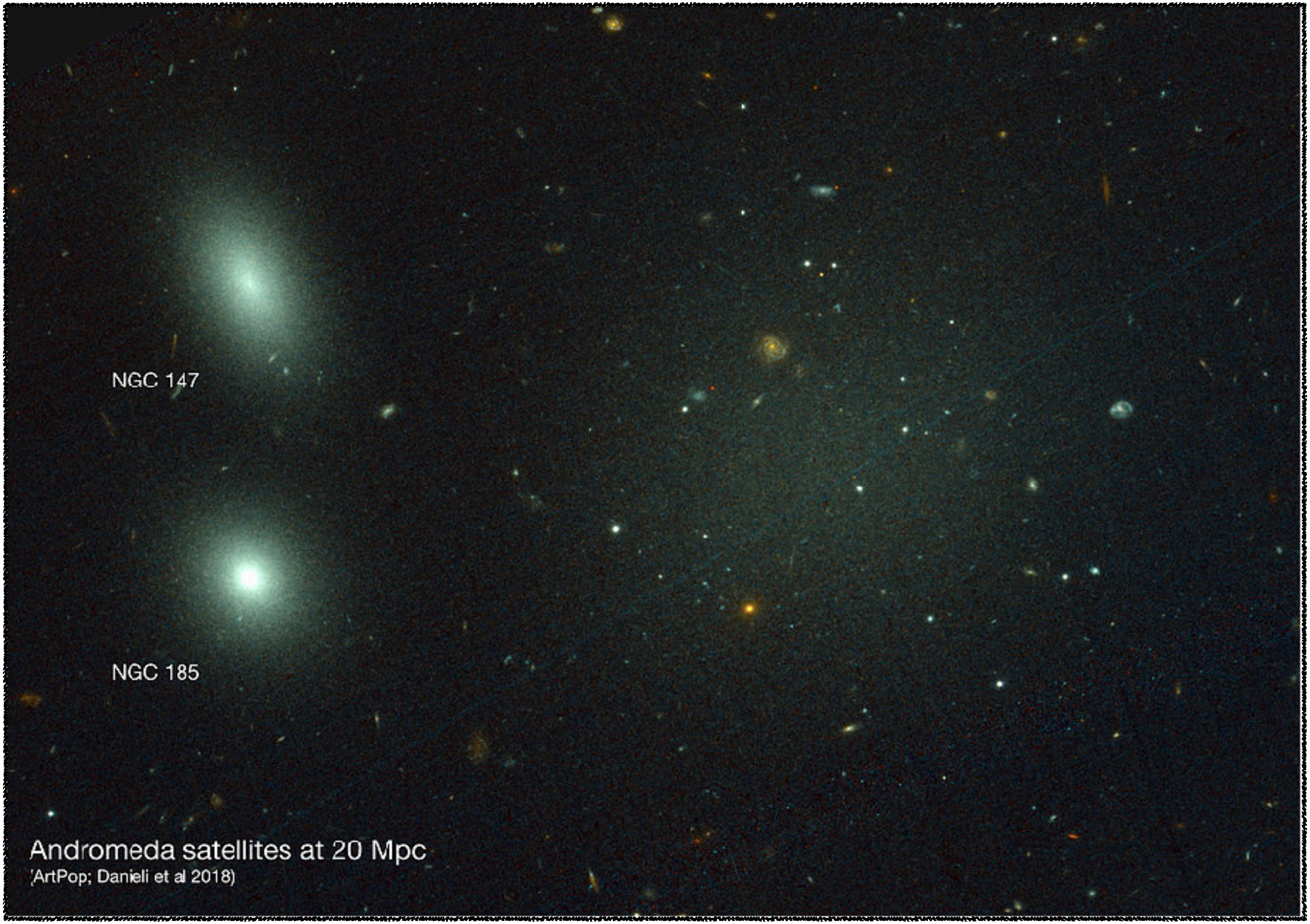
Both methods give $M_{stars} \approx 2 \times 10^8$ solar masses, $M_{\odot}$.

We obtained spectroscopy of objects in the NGC1052–DF2 field with the W. M. Keck Observatory. Details of the observations and data reduction are given in the Methods section. We found ten objects with a radial velocity close to 1,800 km s^{-1} (all other objects are Milky Way

A falsification of MOND ?

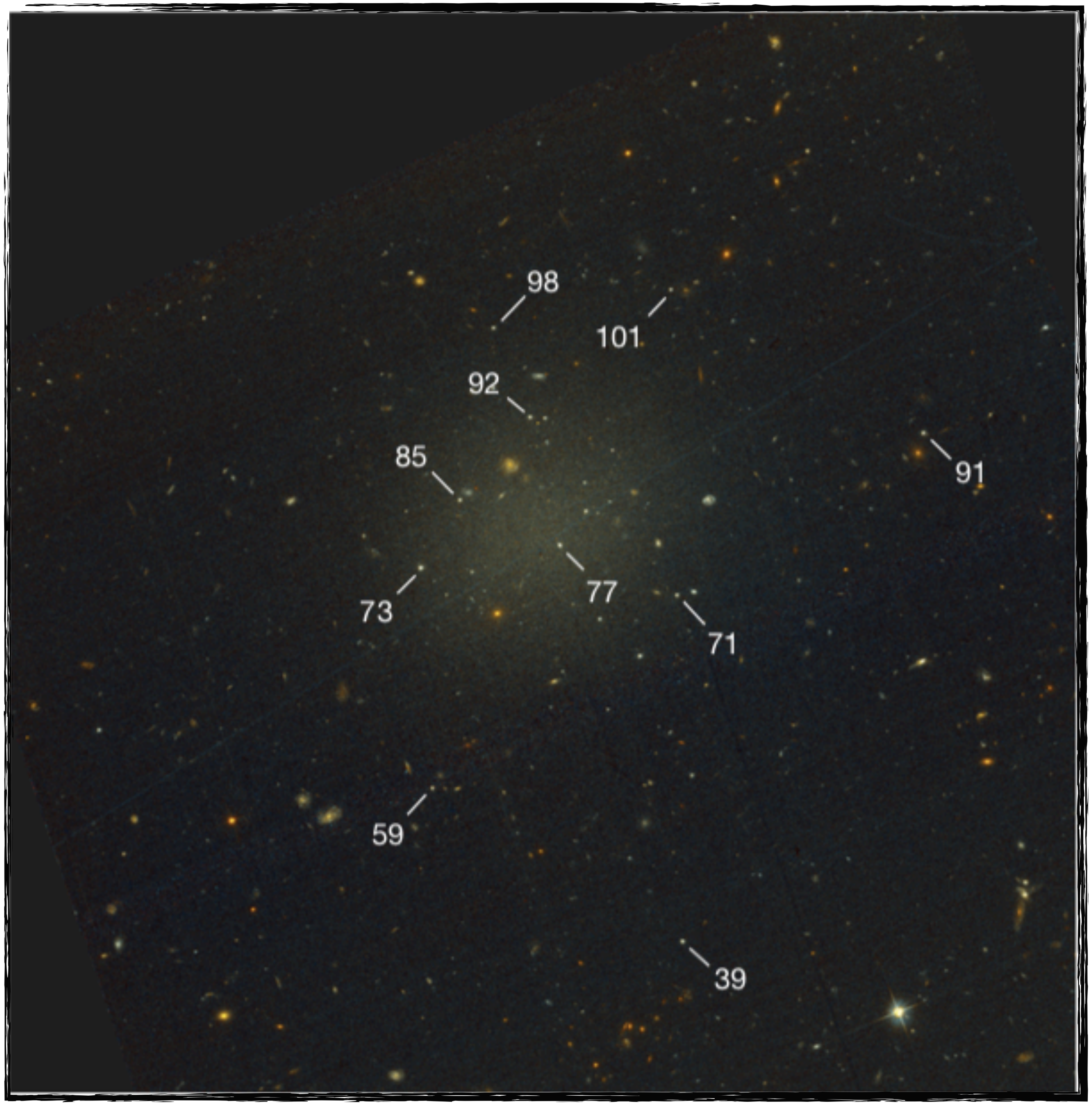
Kropua (2012):
“A galaxy with no dark matter would falsify all alternative theories of gravity”

The dwarf galaxy NGC1052-DF2

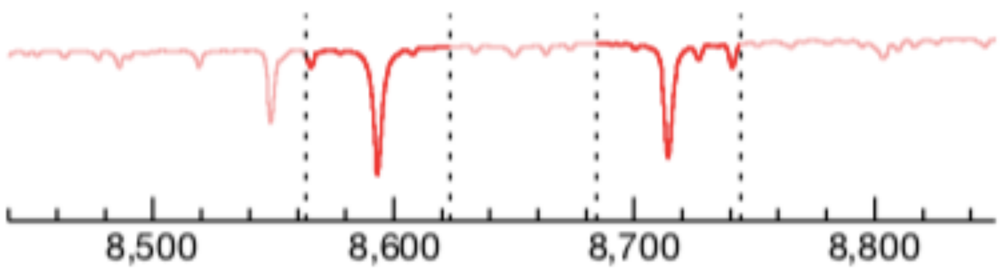


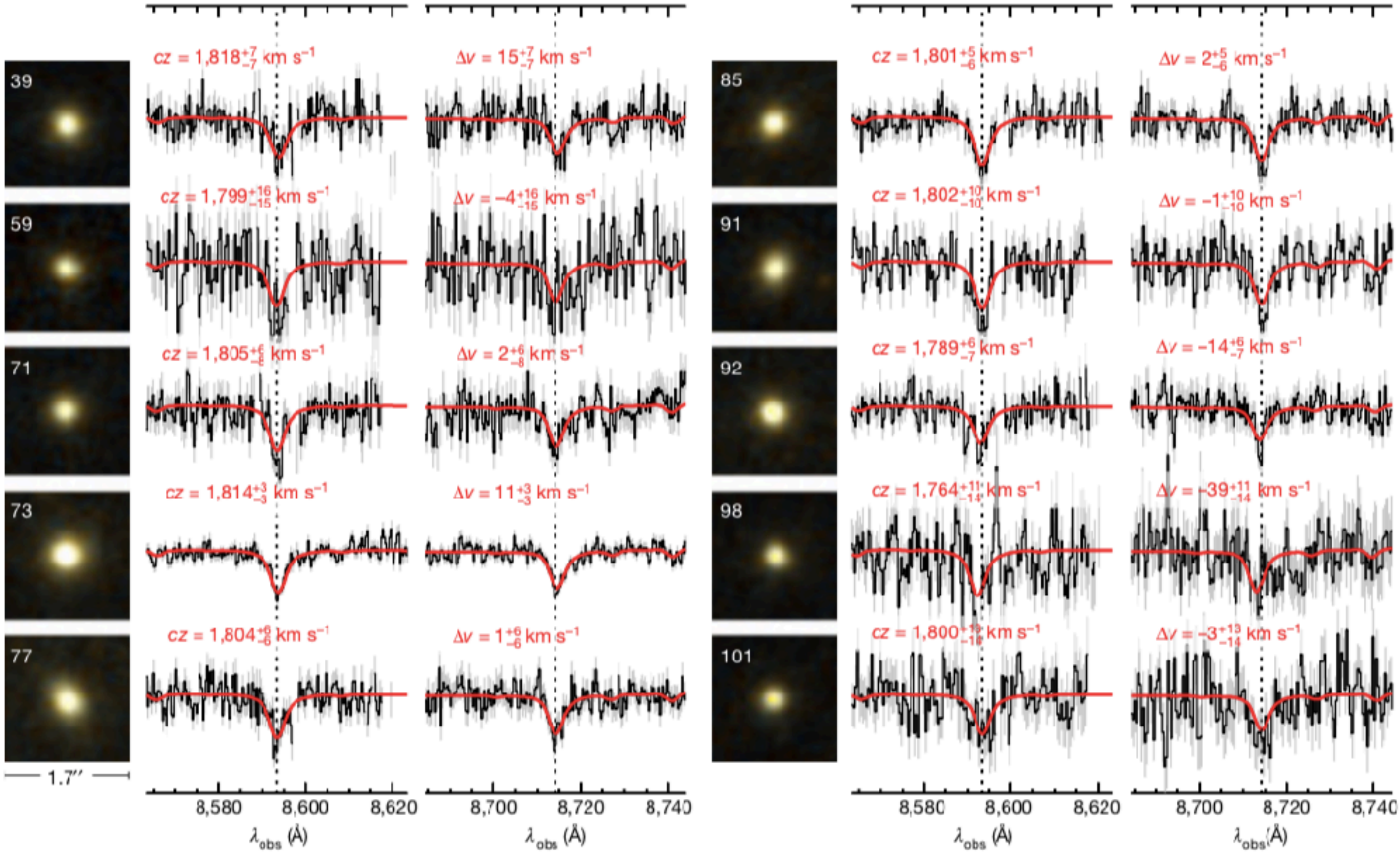
Andromeda satellites at 20 Mpc
(ArtPop; Danieli et al 2018)

The "test-particles" in the potential well



The spectra


8,500
8,600
8,700
8,800


39
$cz = 1,818^{+7}_{-7}$ km s^{-1}
$\Delta v = 15^{+7}_{-7}$ km s^{-1}
59
$cz = 1,799^{+16}_{-15}$ km s^{-1}
$\Delta v = -4^{+16}_{-15}$ km s^{-1}
71
$cz = 1,805^{+6}_{-8}$ km s^{-1}
$\Delta v = 2^{+6}_{-8}$ km s^{-1}
73
$cz = 1,814^{+3}_{-3}$ km s^{-1}
$\Delta v = 11^{+3}_{-3}$ km s^{-1}
77
$cz = 1,804^{+6}_{-6}$ km s^{-1}
$\Delta v = 1^{+6}_{-6}$ km s^{-1}
1.7″
85
$cz = 1,801^{+5}_{-6}$ km s^{-1}
$\Delta v = 2^{+5}_{-6}$ km s^{-1}
91
$cz = 1,802^{+10}_{-10}$ km s^{-1}
$\Delta v = -1^{+10}_{-10}$ km s^{-1}
92
$cz = 1,789^{+6}_{-7}$ km s^{-1}
$\Delta v = -14^{+6}_{-7}$ km s^{-1}
98
$cz = 1,764^{+11}_{-14}$ km s^{-1}
$\Delta v = -39^{+11}_{-14}$ km s^{-1}
101
$cz = 1,800^{+13}_{-14}$ km s^{-1}
$\Delta v = -3^{+13}_{-14}$ km s^{-1}
8,580
8,600
8,620
8,700
8,720
8,740
λ_{obs} (Å)

laxy velocity
on

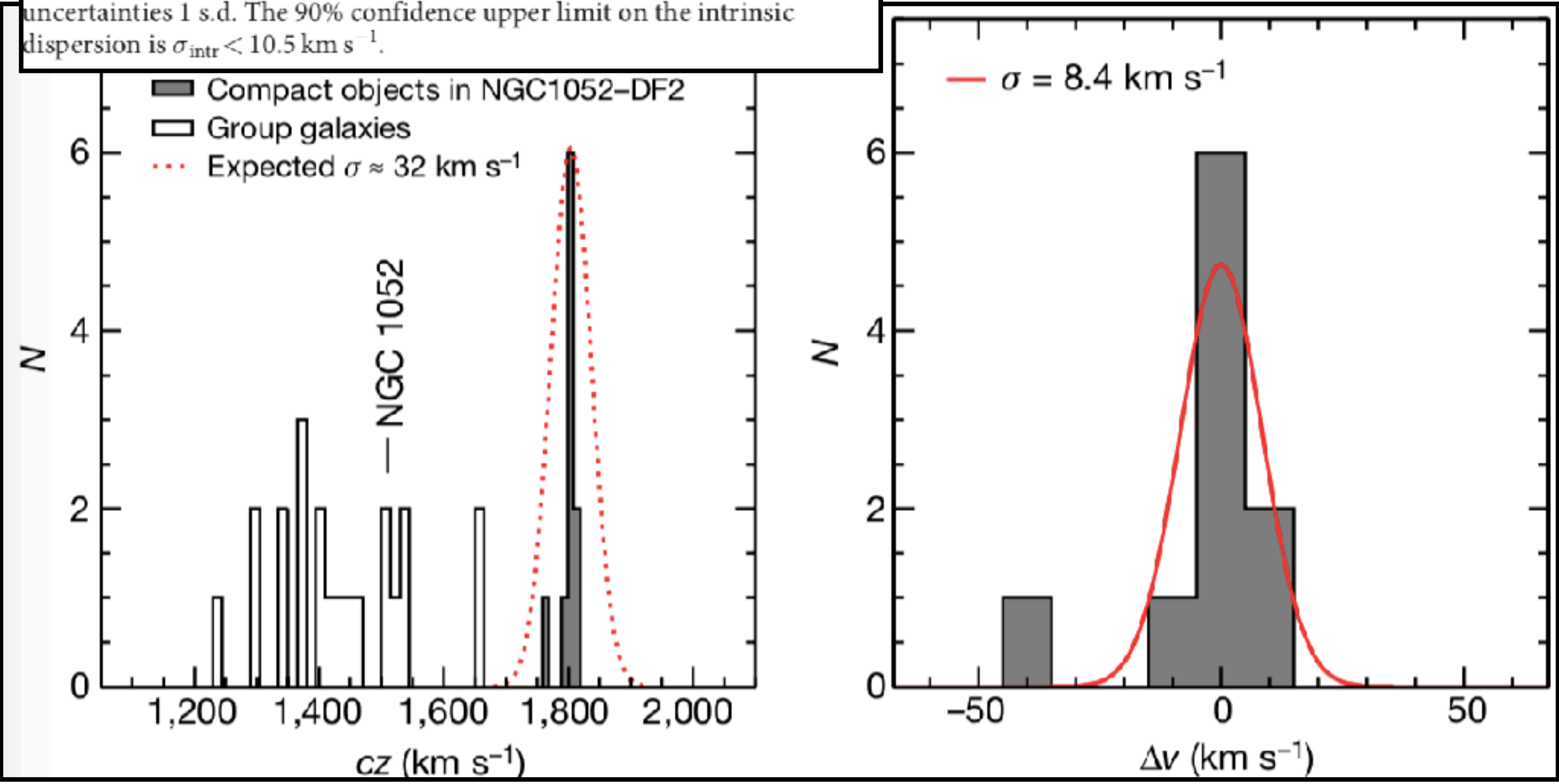
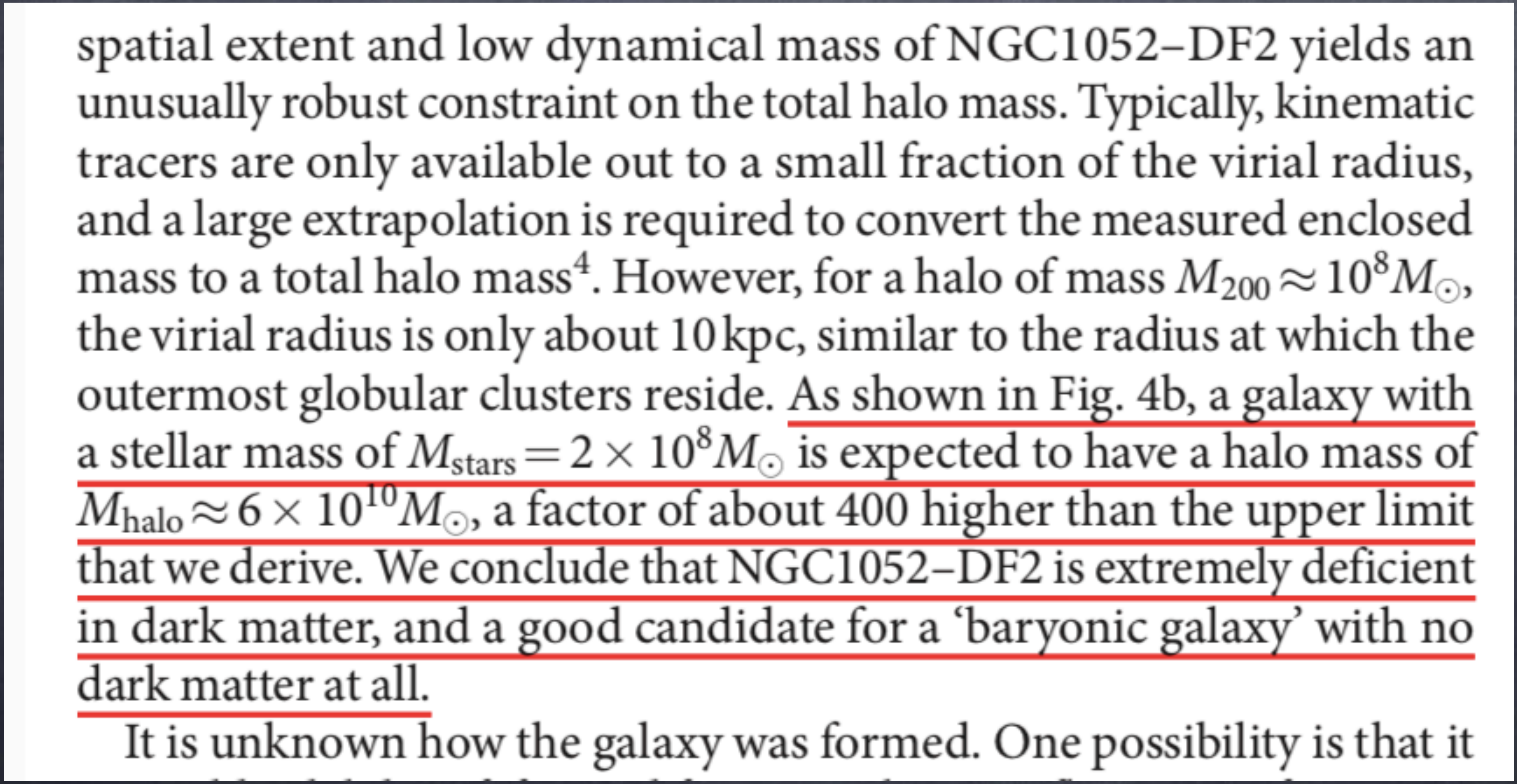


Figure 3 | Velocity dispersion. The filled grey histograms show the velocity distribution of the ten compact objects. **a**, Wide velocity range including the velocities of all 21 galaxies in the NASA/IPAC Extragalactic Database with $cz < 2{,}500\,\mathrm{km\,s^{-1}}$ that are within a projected distance of two degrees from NGC 1052. The red dotted curve shows a Gaussian with a width of $\sigma = 32\,\mathrm{km\,s^{-1}}$, the average velocity dispersion of Local Group galaxies with $8.0 \le \log(M_{\mathrm{stars}}/M_{\odot}) \le 8.6$. **b**, Narrow velocity range centred on $cz = 1{,}803\,\mathrm{km\,s^{-1}}$. The red solid curve is a Gaussian with a width that is equal to the biweight dispersion of the velocity distribution of the compact objects, $\sigma_{\mathrm{obs}} = 8.4\,\mathrm{km\,s^{-1}}$. Taking observational errors into account, we derive an intrinsic dispersion of $\sigma_{\mathrm{intr}} = 3.2^{+5.5}_{-3.2}\,\mathrm{km\,s^{-1}}$, with the uncertainties 1 s.d. The 90% confidence upper limit on the intrinsic dispersion is $\sigma_{\mathrm{intr}} < 10.5\,\mathrm{km\,s^{-1}}$.

NGC1052-DF2: the dynamical analysis in Van Dokkum et al. (2018)

- Using biweight estimator: vel. disp. = 8.4 km/s
- Intrinsic dispersion = 3.2 km/s
- 90% upper limit = 10.5 km/s
- dynamical mass < 3.4 10**8 solar units
- Best fit with M_halo = 0
- 90% upper limit M= 1.5 10 **8 solar units

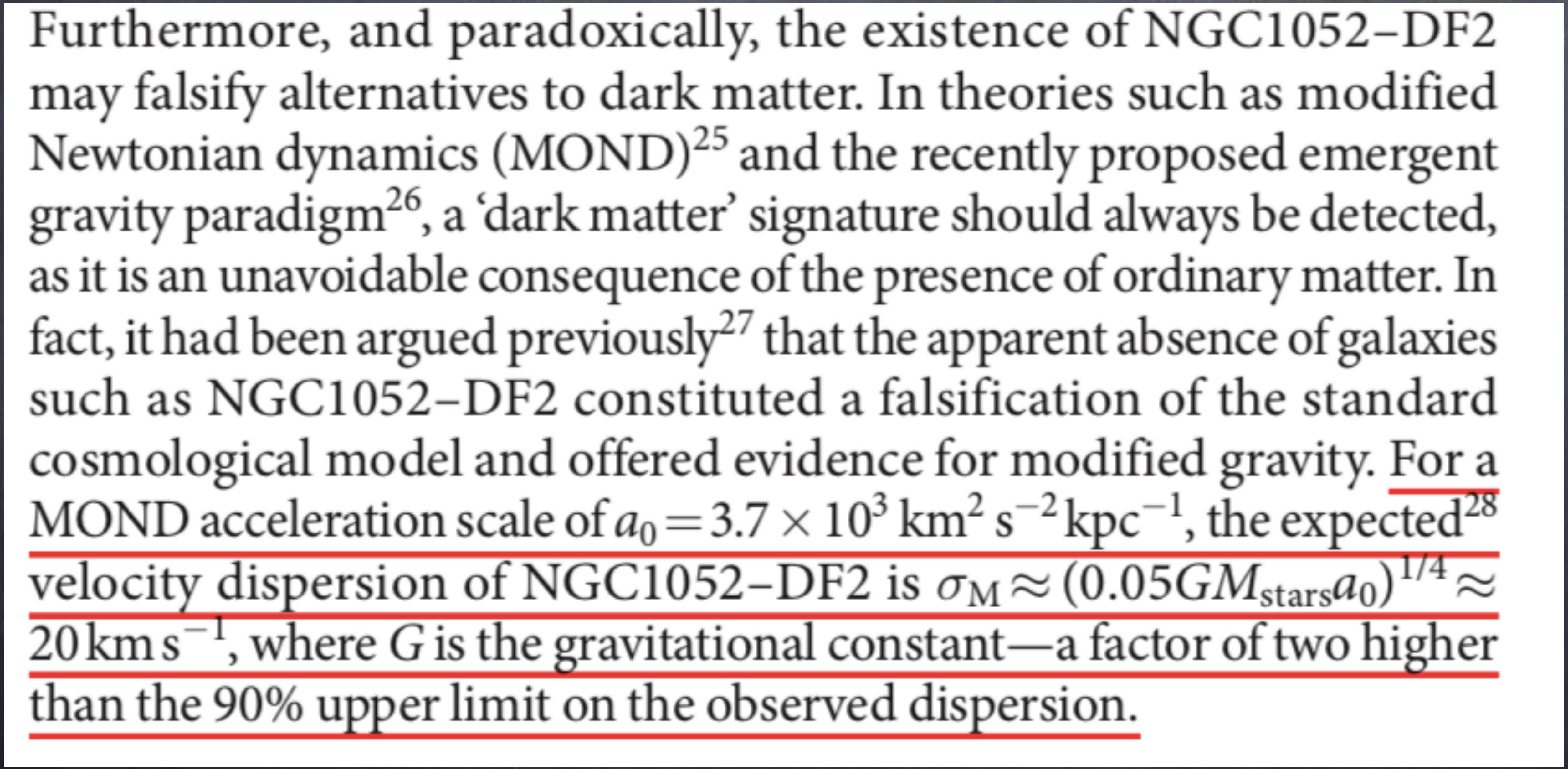
NGC1052-DF2: the dynamical analysis in Van Dokkum et al. (2018)



spatial extent and low dynamical mass of NGC1052–DF2 yields an unusually robust constraint on the total halo mass. Typically, kinematic tracers are only available out to a small fraction of the virial radius, and a large extrapolation is required to convert the measured enclosed mass to a total halo mass[4]. However, for a halo of mass $M_{200} \approx 10^8 M_\odot$, the virial radius is only about 10 kpc, similar to the radius at which the outermost globular clusters reside. As shown in Fig. 4b, a galaxy with a stellar mass of $M_{\rm stars} = 2 \times 10^8 M_\odot$ is expected to have a halo mass of $M_{\rm halo} \approx 6 \times 10^{10} M_\odot$, a factor of about 400 higher than the upper limit that we derive. We conclude that NGC1052–DF2 is extremely deficient in dark matter, and a good candidate for a 'baryonic galaxy' with no dark matter at all.

It is unknown how the galaxy was formed. One possibility is that it

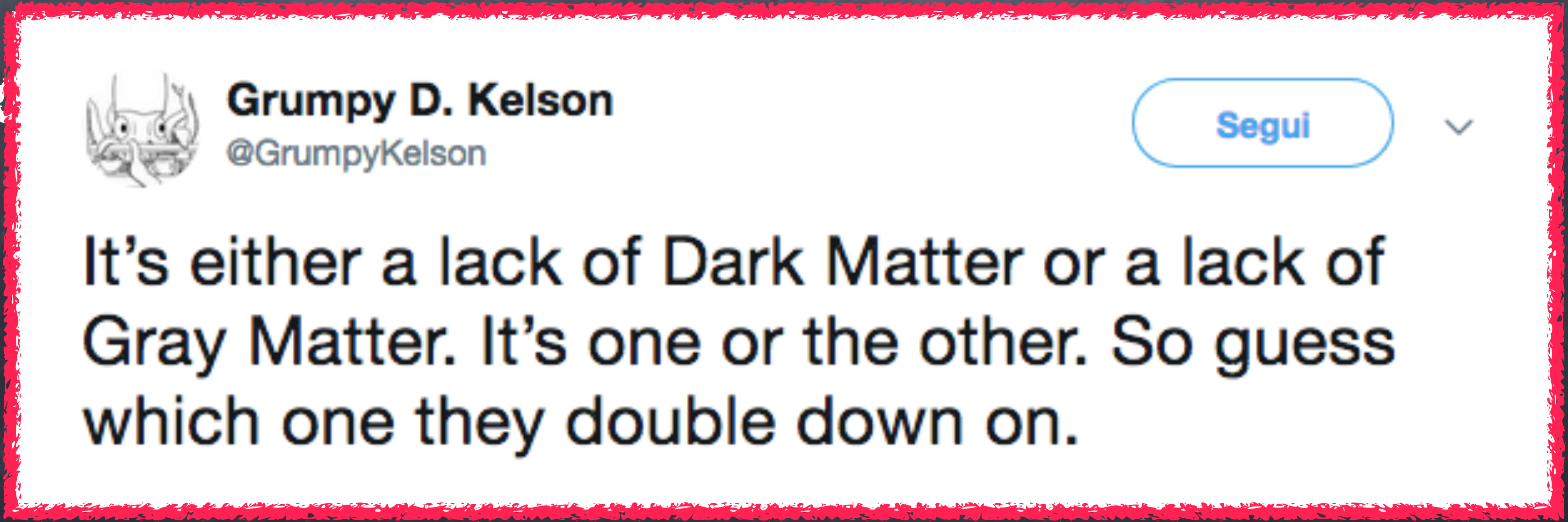
NGC1052-DF2: the dynamical analysis in Van Dokkum et al. (2018)



Furthermore, and paradoxically, the existence of NGC1052–DF2 may falsify alternatives to dark matter. In theories such as modified Newtonian dynamics (MOND)[25] and the recently proposed emergent gravity paradigm[26], a 'dark matter' signature should always be detected, as it is an unavoidable consequence of the presence of ordinary matter. In fact, it had been argued previously[27] that the apparent absence of galaxies such as NGC1052–DF2 constituted a falsification of the standard cosmological model and offered evidence for modified gravity. For a MOND acceleration scale of $a_0 = 3.7 \times 10^3\ \mathrm{km}^2\,\mathrm{s}^{-2}\,\mathrm{kpc}^{-1}$, the expected[28] velocity dispersion of NGC1052–DF2 is $\sigma_{\mathrm{M}} \approx (0.05 G M_{\mathrm{stars}} a_0)^{1/4} \approx 20\ \mathrm{km\,s}^{-1}$, where G is the gravitational constant—a factor of two higher than the 90% upper limit on the observed dispersion.

Many concerns

- If DM has been stripped.. how can the galaxy be at equilibrium?
- Is the galaxy isolated?
- Is the st
- Are GCs



Grumpy D. Kelson
@GrumpyKelson

It's either a lack of Dark Matter or a lack of Gray Matter. It's one or the other. So guess which one they double down on.

“a perverse physical situation”

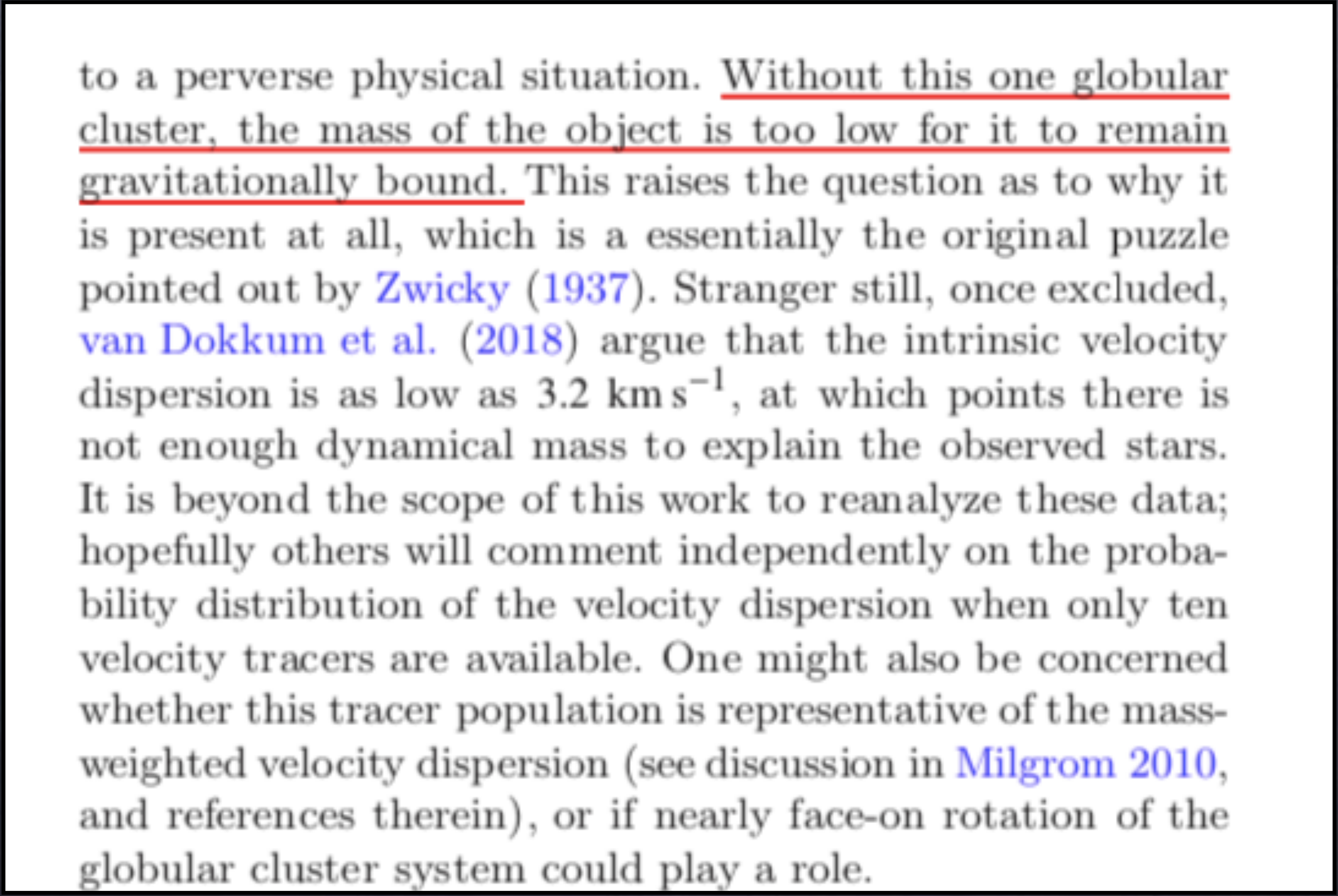
MOND and the dynamics of NGC1052-DF2

B. Famaey,[1]* S. McGaugh,[2] and M. Milgrom[3]

[1] Université de Strasbourg, CNRS UMR 7550, Observatoire astronomique de Strasbourg, 67000 Strasbourg, France

[2] Department of Astronomy, Case Western Reserve University, Cleveland, OH 44106, USA

[3] Department of Particle Physics and Astrophysics, Weizmann Institute of Science, Rehovot 76100, Israel



to a perverse physical situation. Without this one globular cluster, the mass of the object is too low for it to remain gravitationally bound. This raises the question as to why it is present at all, which is a essentially the original puzzle pointed out by Zwicky (1937). Stranger still, once excluded, van Dokkum et al. (2018) argue that the intrinsic velocity dispersion is as low as 3.2 $\mathrm{km\,s^{-1}}$, at which points there is not enough dynamical mass to explain the observed stars. It is beyond the scope of this work to reanalyze these data; hopefully others will comment independently on the probability distribution of the velocity dispersion when only ten velocity tracers are available. One might also be concerned whether this tracer population is representative of the mass-weighted velocity dispersion (see discussion in Milgrom 2010, and references therein), or if nearly face-on rotation of the globular cluster system could play a role.

Paper #1:
You need accurate MOND predictions!

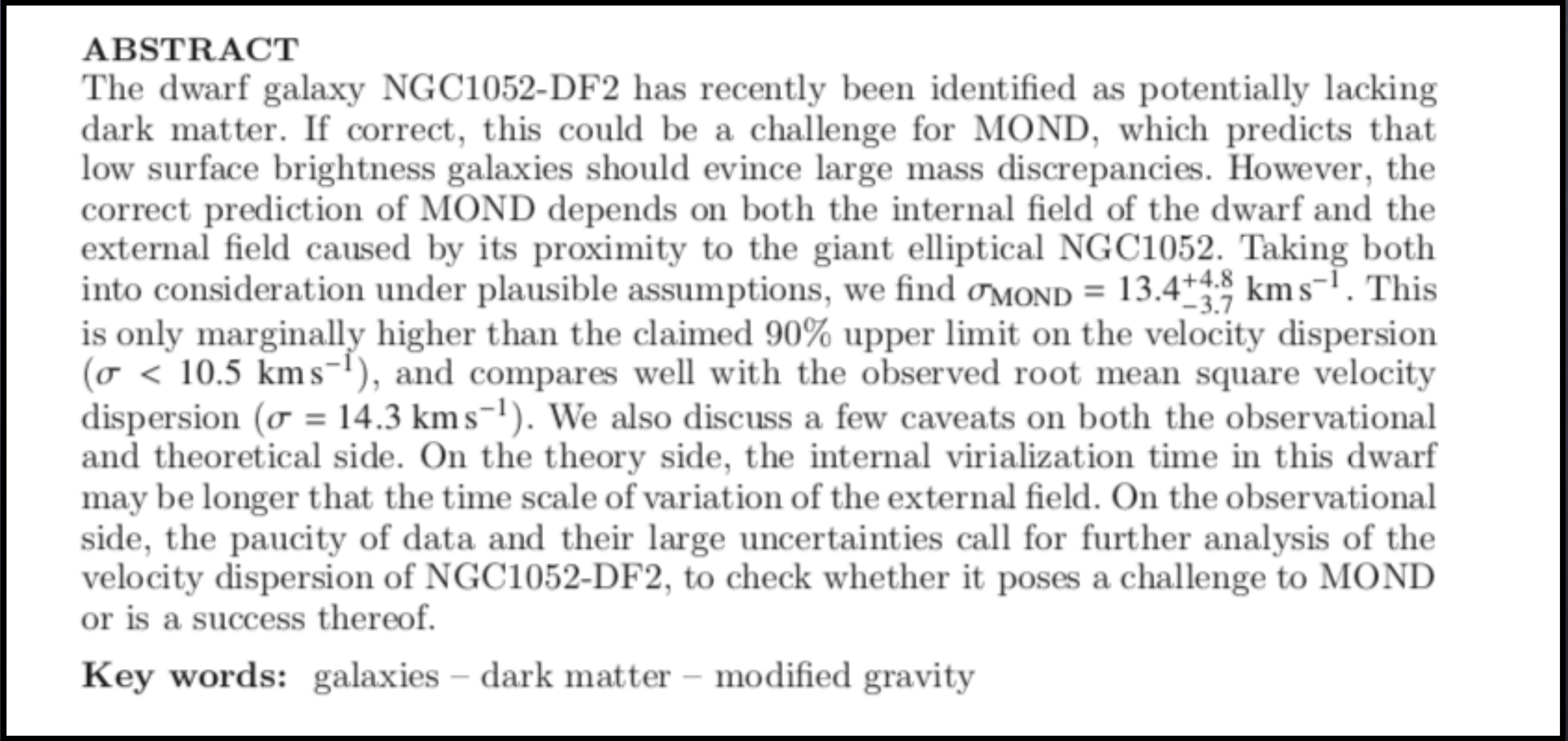
MOND and the dynamics of NGC1052-DF2

B. Famaey,[1]⋆ S. McGaugh,[2] and M. Milgrom[3]

[1] *Université de Strasbourg, CNRS UMR 7550, Observatoire astronomique de Strasbourg, 67000 Strasbourg, France*

[2] *Department of Astronomy, Case Western Reserve University, Cleveland, OH 44106, USA*

[3] *Department of Particle Physics and Astrophysics, Weizmann Institute of Science, Rehovot 76100, Israel*

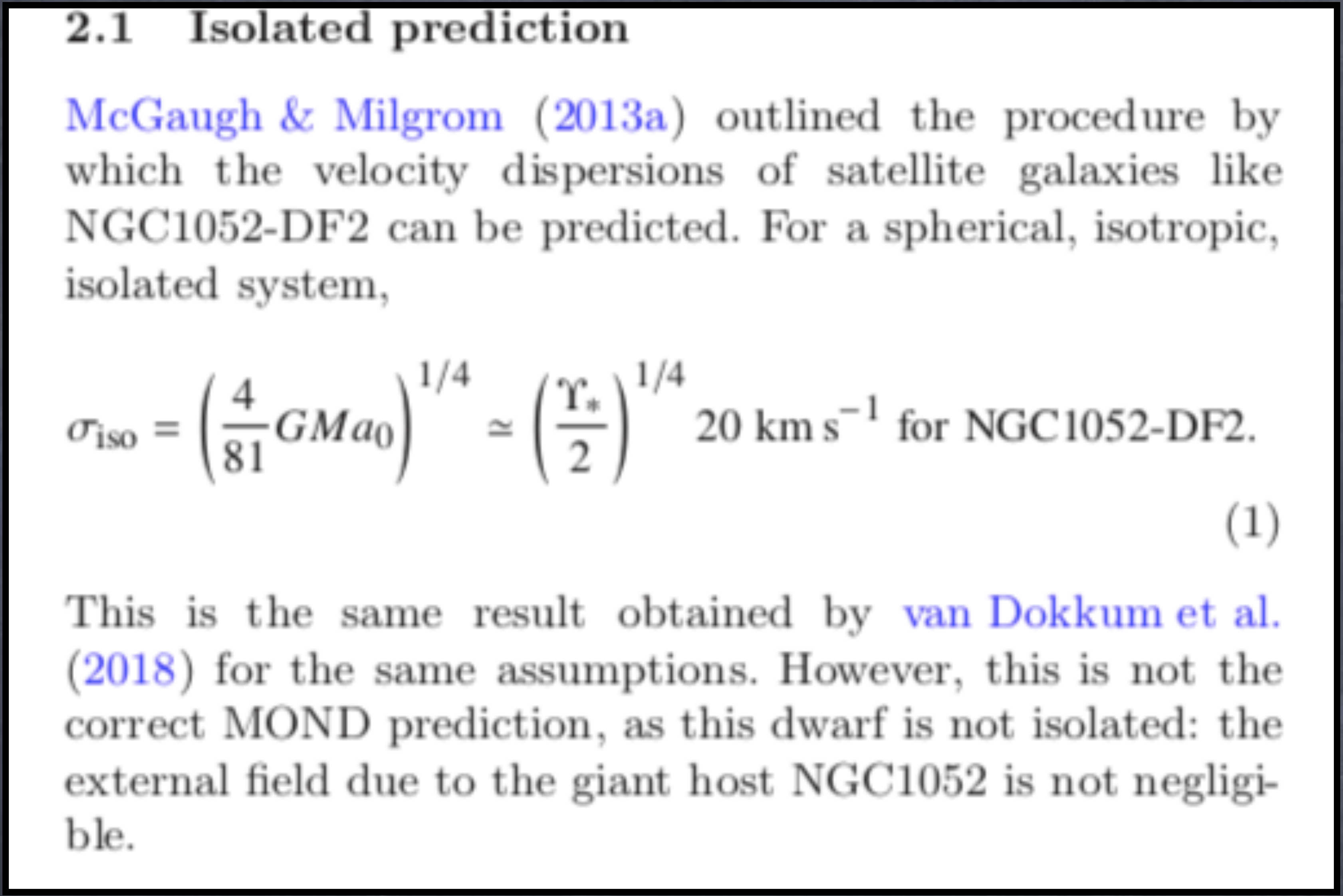


ABSTRACT

The dwarf galaxy NGC1052-DF2 has recently been identified as potentially lacking dark matter. If correct, this could be a challenge for MOND, which predicts that low surface brightness galaxies should evince large mass discrepancies. However, the correct prediction of MOND depends on both the internal field of the dwarf and the external field caused by its proximity to the giant elliptical NGC1052. Taking both into consideration under plausible assumptions, we find $\sigma_{\rm MOND} = 13.4^{+4.8}_{-3.7}$ km s^{-1}. This is only marginally higher than the claimed 90% upper limit on the velocity dispersion ($\sigma < 10.5$ km s^{-1}), and compares well with the observed root mean square velocity dispersion ($\sigma = 14.3$ km s^{-1}). We also discuss a few caveats on both the observational and theoretical side. On the theory side, the internal virialization time in this dwarf may be longer that the time scale of variation of the external field. On the observational side, the paucity of data and their large uncertainties call for further analysis of the velocity dispersion of NGC1052-DF2, to check whether it poses a challenge to MOND or is a success thereof.

Key words: galaxies – dark matter – modified gravity

Paper #2:
You need accurate MOND predictions!



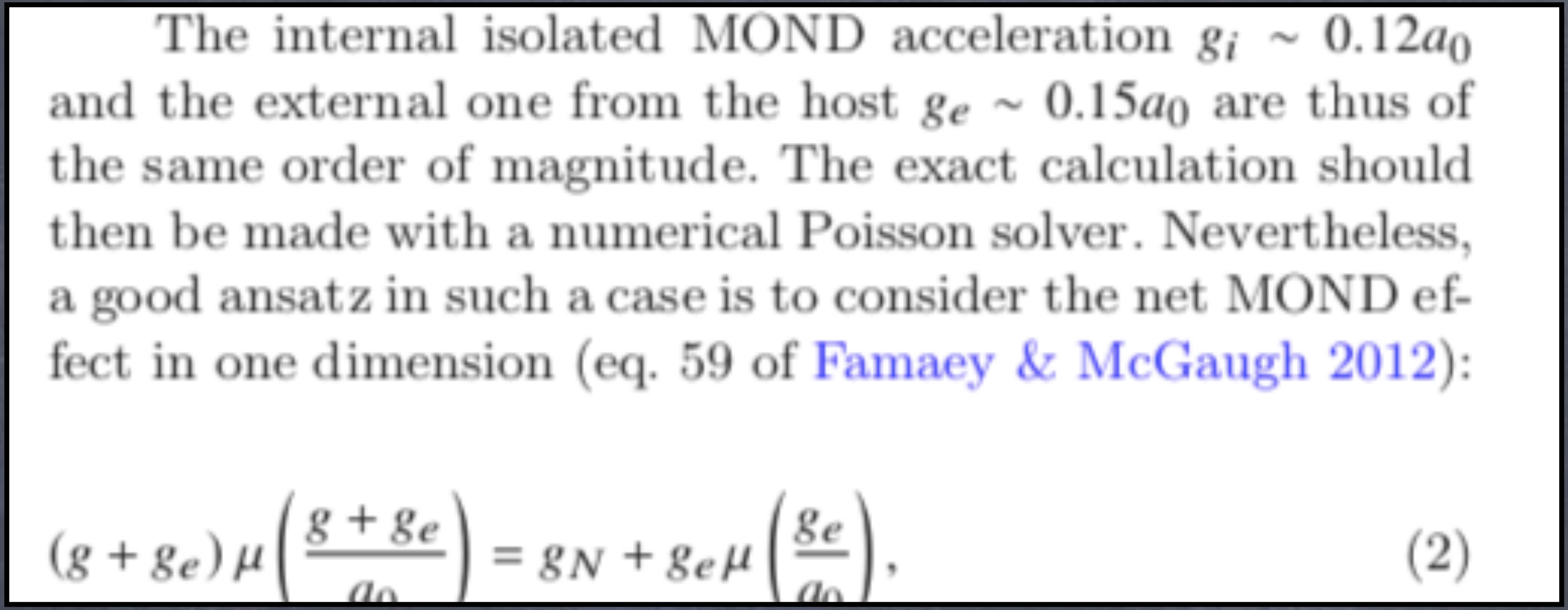
2.1 Isolated prediction

McGaugh & Milgrom (2013a) outlined the procedure by which the velocity dispersions of satellite galaxies like NGC1052-DF2 can be predicted. For a spherical, isotropic, isolated system,

$$\sigma_{\rm iso} = \left(\frac{4}{81} G M a_0\right)^{1/4} \simeq \left(\frac{\Upsilon_*}{2}\right)^{1/4} 20\ \mathrm{km\,s^{-1}}\ \text{for NGC1052-DF2.} \tag{1}$$

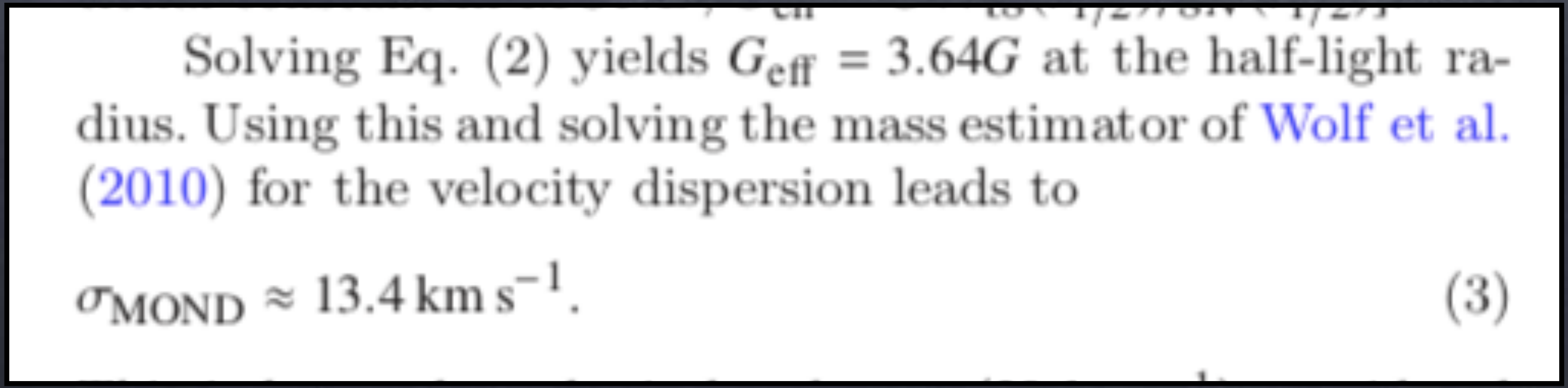
This is the same result obtained by van Dokkum et al. (2018) for the same assumptions. However, this is not the correct MOND prediction, as this dwarf is not isolated: the external field due to the giant host NGC1052 is not negligible.

Paper #2:
You need accurate MOND predictions!



The internal isolated MOND acceleration $g_i \sim 0.12 a_0$ and the external one from the host $g_e \sim 0.15 a_0$ are thus of the same order of magnitude. The exact calculation should then be made with a numerical Poisson solver. Nevertheless, a good ansatz in such a case is to consider the net MOND effect in one dimension (eq. 59 of Famaey & McGaugh 2012):

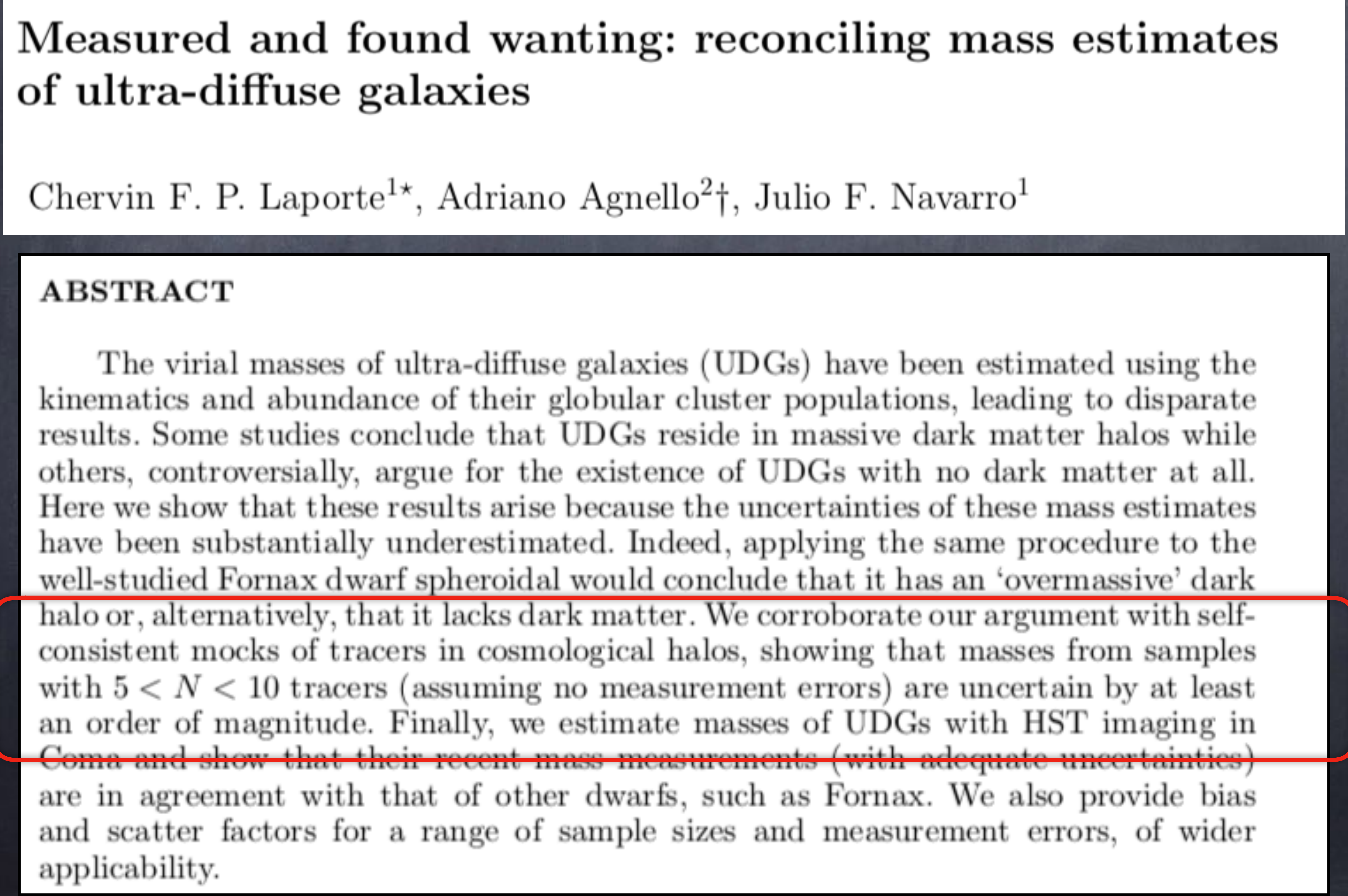
$$(g + g_e)\,\mu\left(\frac{g + g_e}{a_0}\right) = g_N + g_e\,\mu\left(\frac{g_e}{a_0}\right), \qquad (2)$$



Solving Eq. (2) yields $G_{\rm eff} = 3.64G$ at the half-light radius. Using this and solving the mass estimator of Wolf et al. (2010) for the velocity dispersion leads to

$$\sigma_{\rm MOND} \approx 13.4\,{\rm km\,s^{-1}}. \qquad (3)$$

Paper #2:
Errors undersestimated by a factor 10



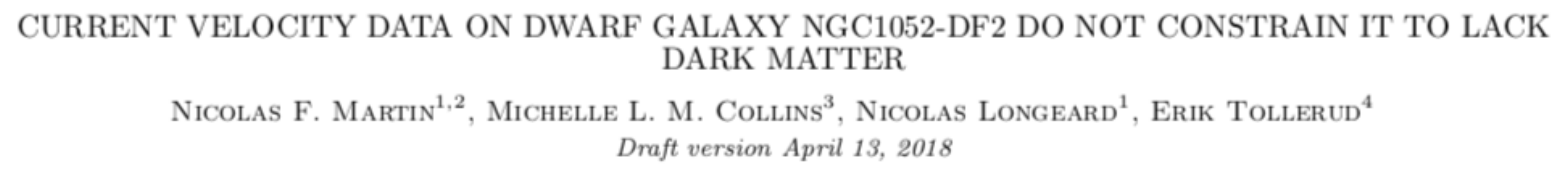
Measured and found wanting: reconciling mass estimates of ultra-diffuse galaxies

Chervin F. P. Laporte[1]*, Adriano Agnello[2]†, Julio F. Navarro[1]

ABSTRACT

The virial masses of ultra-diffuse galaxies (UDGs) have been estimated using the kinematics and abundance of their globular cluster populations, leading to disparate results. Some studies conclude that UDGs reside in massive dark matter halos while others, controversially, argue for the existence of UDGs with no dark matter at all. Here we show that these results arise because the uncertainties of these mass estimates have been substantially underestimated. Indeed, applying the same procedure to the well-studied Fornax dwarf spheroidal would conclude that it has an 'overmassive' dark halo or, alternatively, that it lacks dark matter. We corroborate our argument with self-consistent mocks of tracers in cosmological halos, showing that masses from samples with $5 < N < 10$ tracers (assuming no measurement errors) are uncertain by at least an order of magnitude. Finally, we estimate masses of UDGs with HST imaging in Coma and show that their recent mass measurements (with adequate uncertainties) are in agreement with that of other dwarfs, such as Fornax. We also provide bias and scatter factors for a range of sample sizes and measurement errors, of wider applicability.

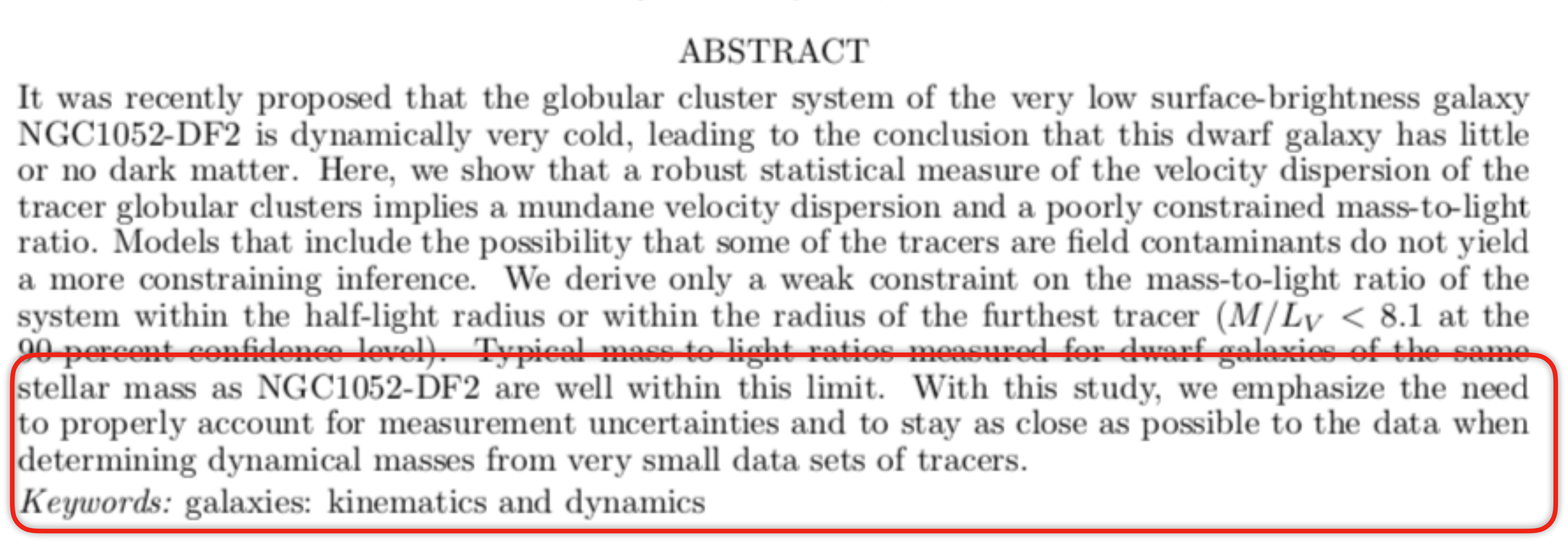
Paper #3:
Outliers should not be cut out



CURRENT VELOCITY DATA ON DWARF GALAXY NGC1052-DF2 DO NOT CONSTRAIN IT TO LACK DARK MATTER

NICOLAS F. MARTIN[1,2], MICHELLE L. M. COLLINS[3], NICOLAS LONGEARD[1], ERIK TOLLERUD[4]

Draft version April 13, 2018



ABSTRACT

It was recently proposed that the globular cluster system of the very low surface-brightness galaxy NGC1052-DF2 is dynamically very cold, leading to the conclusion that this dwarf galaxy has little or no dark matter. Here, we show that a robust statistical measure of the velocity dispersion of the tracer globular clusters implies a mundane velocity dispersion and a poorly constrained mass-to-light ratio. Models that include the possibility that some of the tracers are field contaminants do not yield a more constraining inference. We derive only a weak constraint on the mass-to-light ratio of the system within the half-light radius or within the radius of the furthest tracer ($M/L_V < 8.1$ at the 90-percent confidence level). Typical mass-to-light ratios measured for dwarf galaxies of the same stellar mass as NGC1052-DF2 are well within this limit. With this study, we emphasize the need to properly account for measurement uncertainties and to stay as close as possible to the data when determining dynamical masses from very small data sets of tracers.

Keywords: galaxies: kinematics and dynamics

Accurate MOND prediction vs data realization (Martin et al.2018)

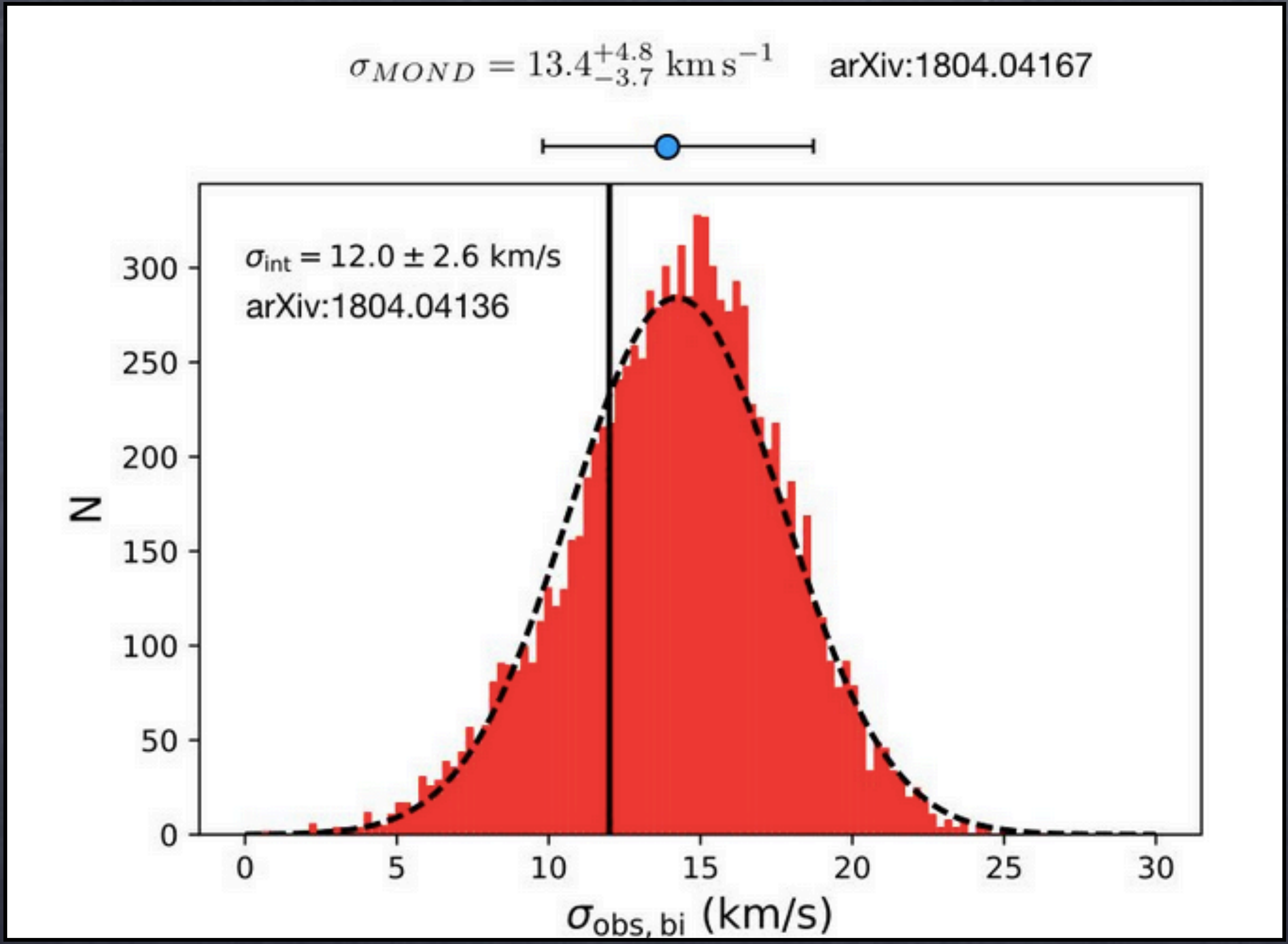
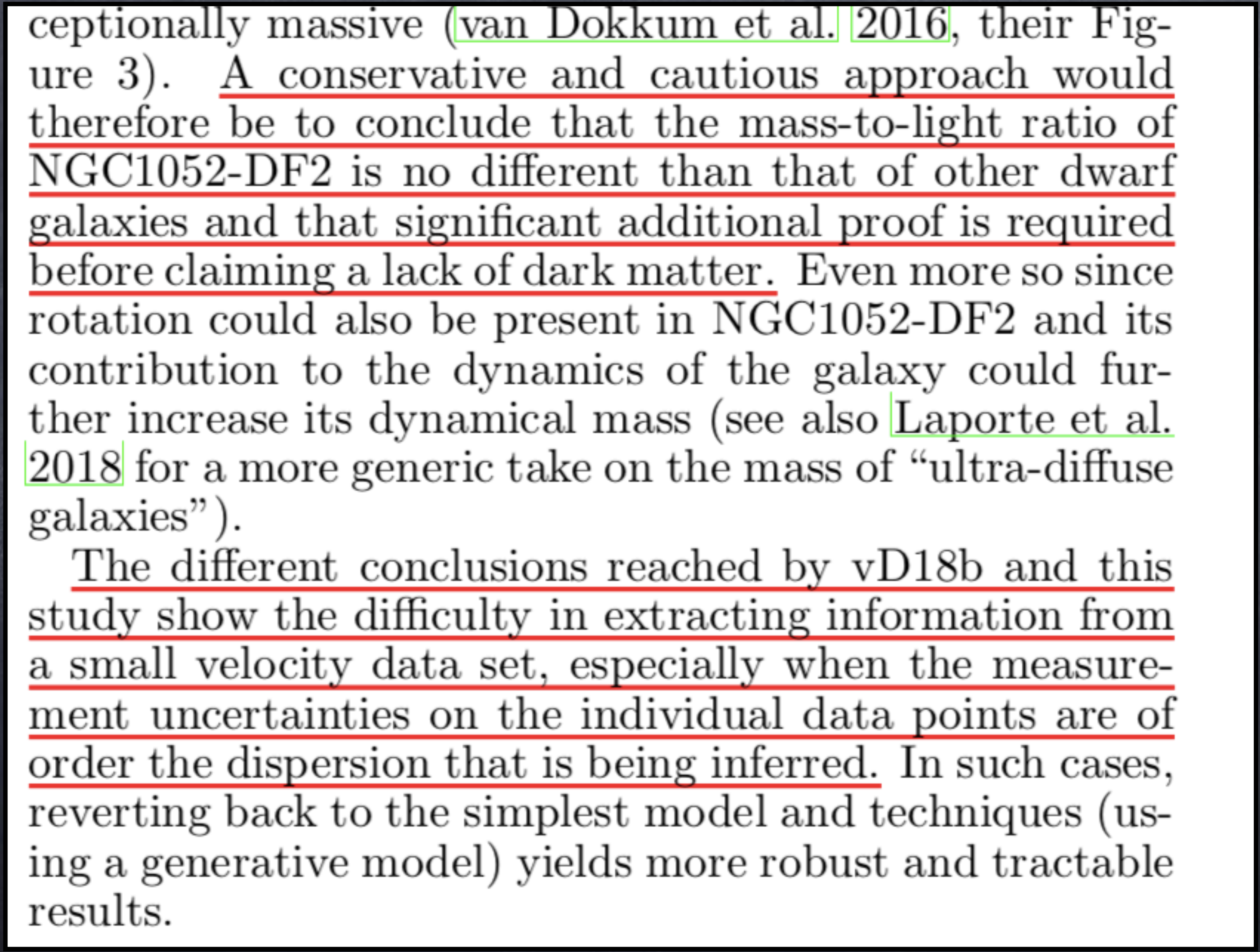


Figure 4. Results for measuring the observed biweight-midvairance dispersion from 10,000 resamples of the vD18b dataset. Here, the original velocities are perturbed within their 1σ uncertainties as described in the text. The mean observed biweight for the sample comes out as $\sigma_{\rm obs,bi} = 14.3 \pm 3.5\,\mathrm{km\,s^{-1}}$, giving $\sigma_{\rm int,bi} = 12.0 \pm 2.5\,\mathrm{km\,s^{-1}}$, higher than the 90% upper limit from vD18b, and consistent with our MCMC analysis.

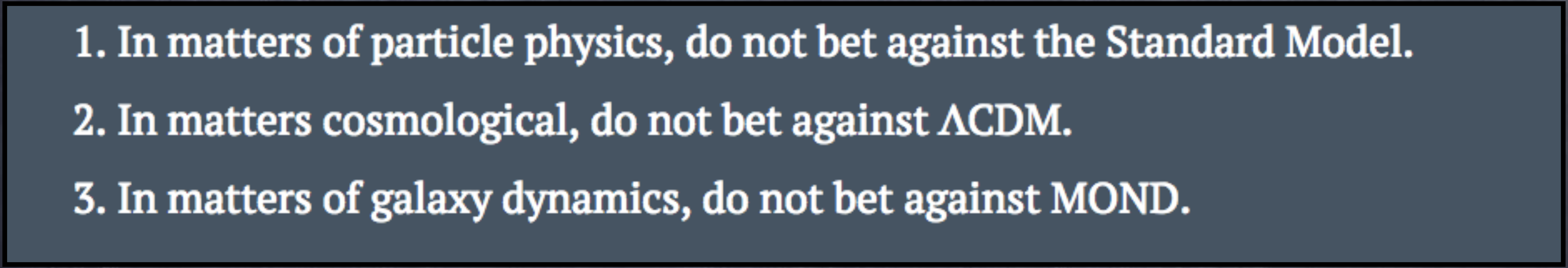
Conclusions in Martin et al. (2018)



ceptionally massive (van Dokkum et al. 2016, their Figure 3). A conservative and cautious approach would therefore be to conclude that the mass-to-light ratio of NGC1052-DF2 is no different than that of other dwarf galaxies and that significant additional proof is required before claiming a lack of dark matter. Even more so since rotation could also be present in NGC1052-DF2 and its contribution to the dynamics of the galaxy could further increase its dynamical mass (see also Laporte et al. 2018 for a more generic take on the mass of "ultra-diffuse galaxies").

The different conclusions reached by vD18b and this study show the difficulty in extracting information from a small velocity data set, especially when the measurement uncertainties on the individual data points are of order the dispersion that is being inferred. In such cases, reverting back to the simplest model and techniques (using a generative model) yields more robust and tractable results.

A conclusion form S. McGaugh



1. In matters of particle physics, do not bet against the Standard Model.
2. In matters cosmological, do not bet against ΛCDM.
3. In matters of galaxy dynamics, do not bet against MOND.

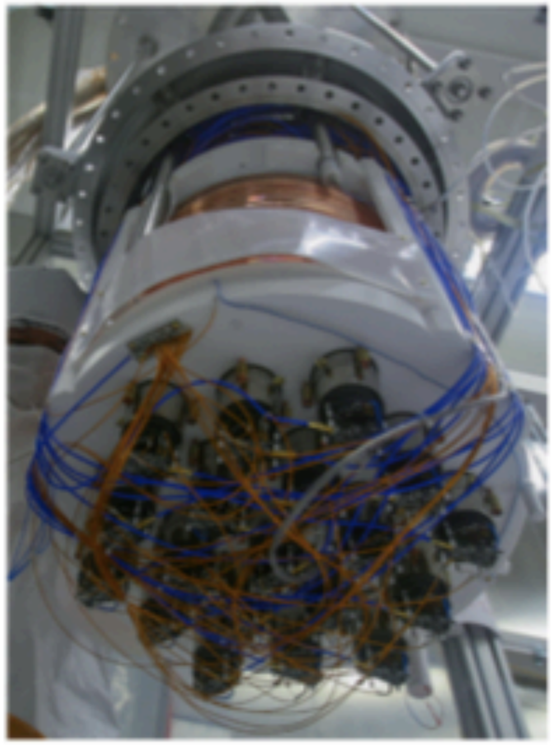
Back to asking Nature…

A direct search experiment: DarkSide

Past

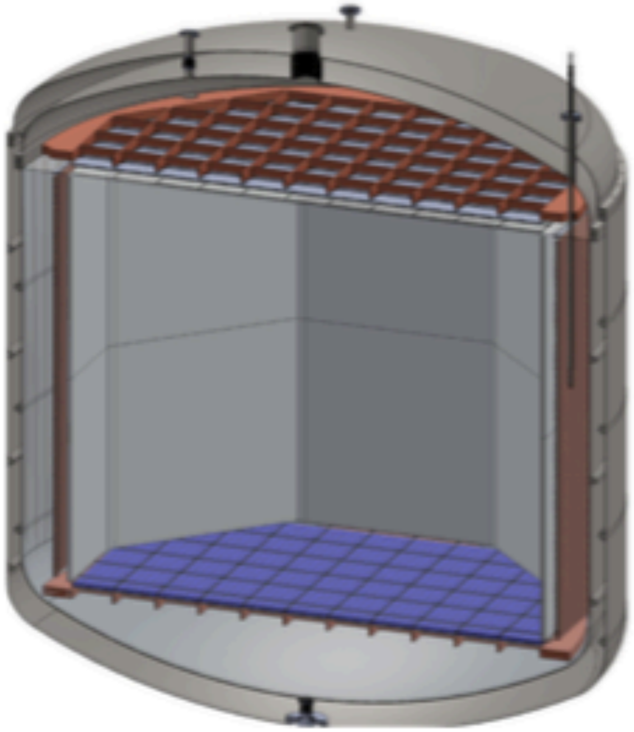
DarkSide-10

Present



DarkSide-50

Future



DarkSide-20k

- WIMP direct detection at LNGS
- Dual-phase argon TPC as the WIMP detector at center, surrounded by an active neutron veto, surrounded by a water Cherenkov detector.
- Background free operation with active background suppression

A direct search experiment: DarkSide

- An ambitious program for discovery of dark matter
- Technology developed to achieve “Zero Background” and scalability
- DarkSide-50 sensitive to 1-10 GeV WIMPs and sub- GeV DM-electron scattering
- DarkSide-20k set to start in 2021, with a projected sensitivity of 1×10-47 cm2 for a 1 TeV/c2 dark matter particle mass and an exposure of 100 tonne×yr
- **Global Argon Dark Matter Collaboration** aiming at 1,000 tonne×year search for dark matter

Liquid Argon as DM detection medium

Pro

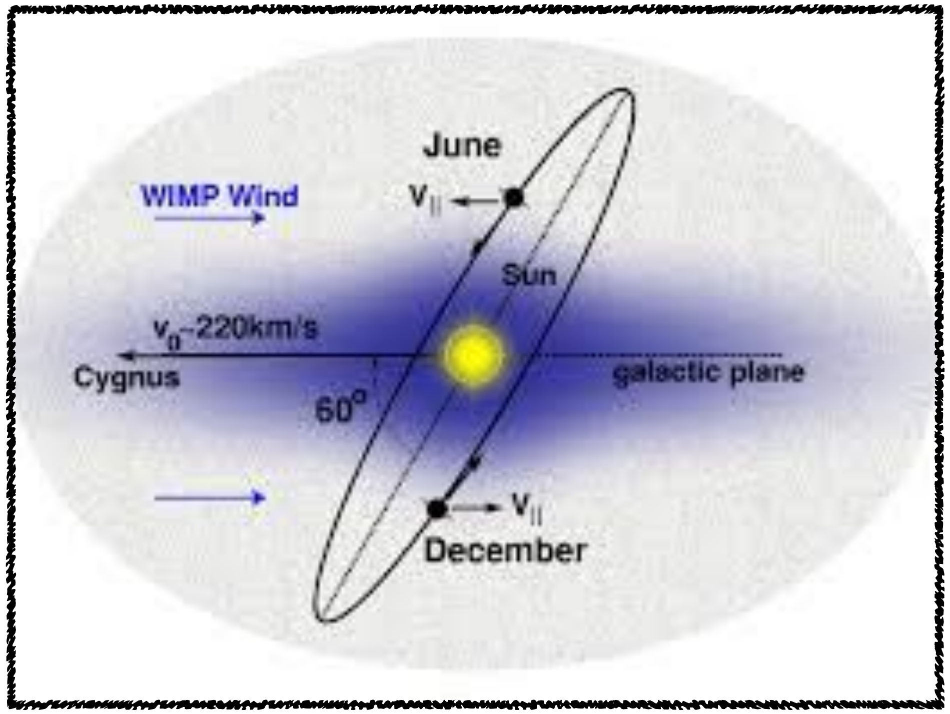
- Favoured by form factor for high recoil energy “golden events”
- Dense and easy to purify
- High scintillation yield ~ 40 γ/keV
- High ionisation yield ($W \sim 20$ eV)
- Very powerful rejection capability for electron recoil background

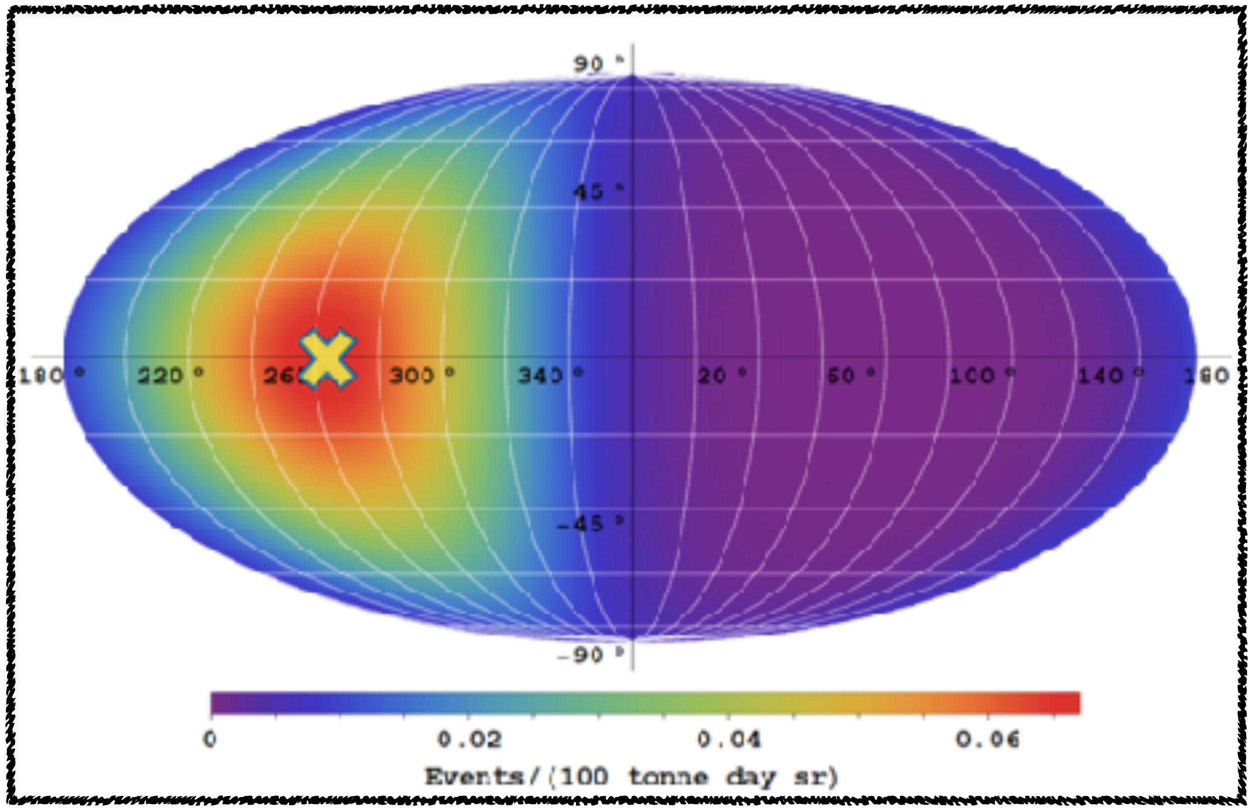
Contra

- Intrinsic ^{39}Ar radioactivity (1 Bq/kg) in atmospheric Ar (AAr) is the primary background for argon-based detectors

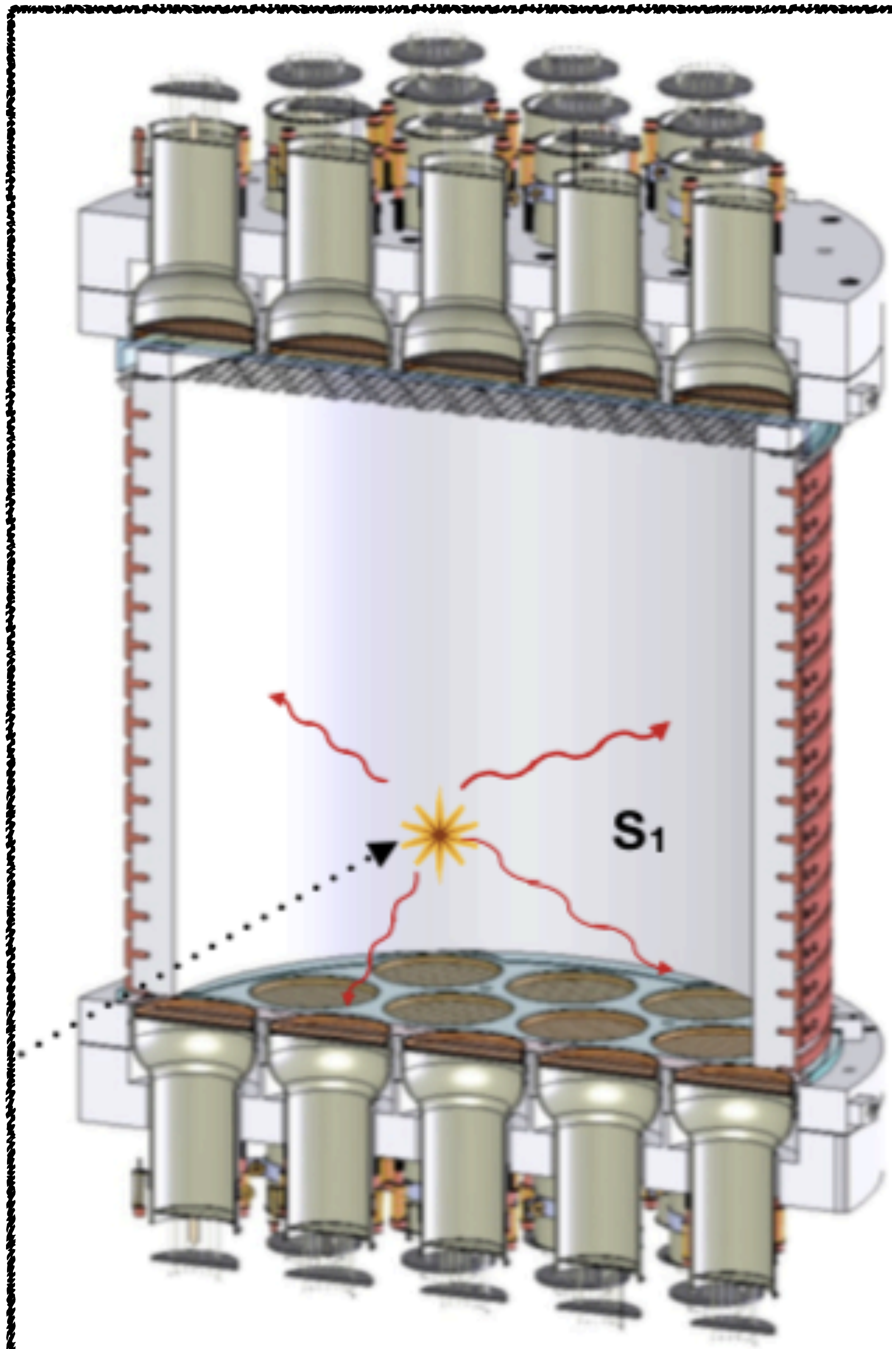
A Galactic wind of WIMPs

Observation of a few WIMP-like events might not be enough to claim discovery: directional events offer a unique signature





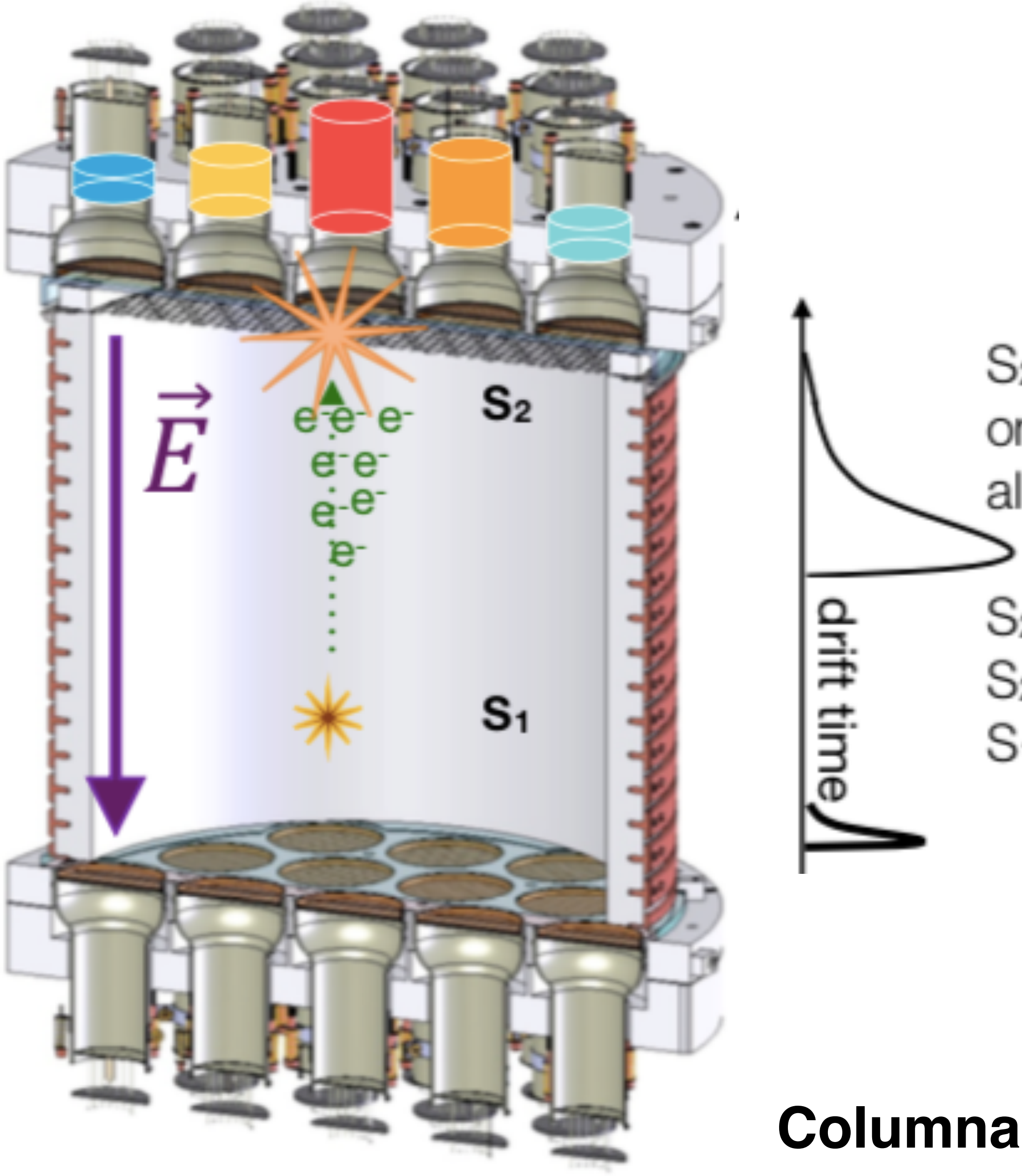
Two phase Argon TPC



S_1 primary scintillation signal collected by photosensors

Powerful **Pulse Shape Discrimination** allows to discriminate between
- nuclear recoils (WIMP, neutrons)
- electron recoils (β-γ backgrounds)

Two phase Argon TPC

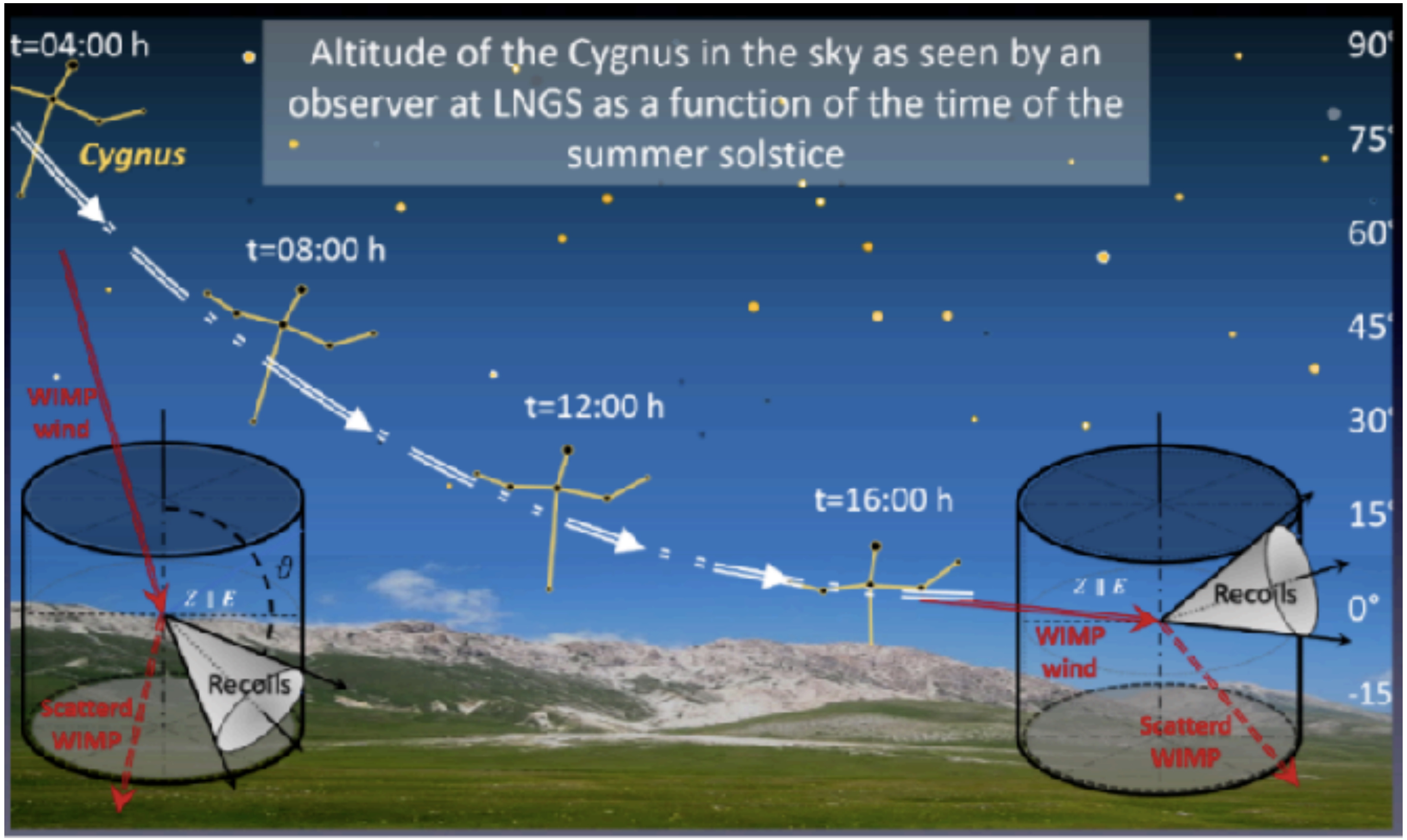


S_2 secondary electroluminescence signal
one extracted e^- → S_2~23 PE in central PMT
allows for lower threshold analysis

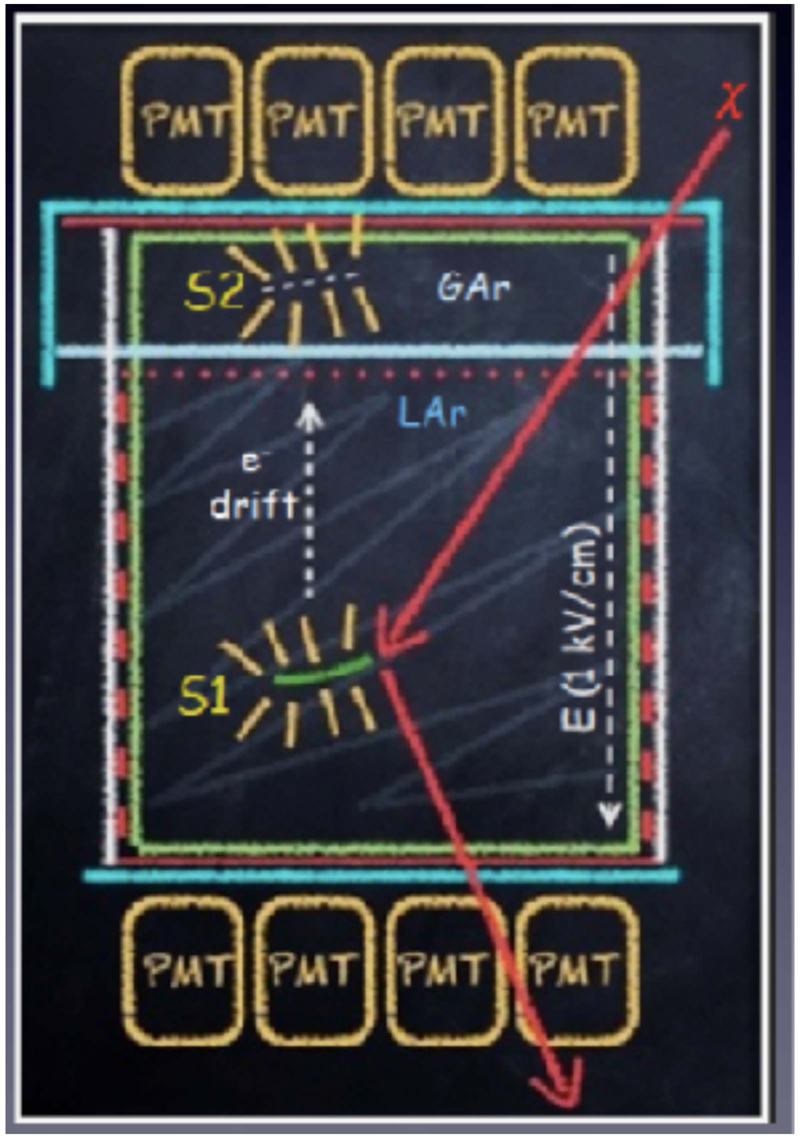
S_2-S_1 drift time → vertical position
S_2 pattern on top PMTs → horizontal position
S_1 & S_2 → 3D position reco

Columnar Recombination: when a nuclear recoil is parallel to the electric field, there will be more electron-ion recombination since the electron passes more ions as it drifts through the core of the track.

Double-phase liquid Argon TPC as a directional detector



Altitude of the Cygnus in the sky as seen by an observer at LNGS as a function of the time of the summer solstice



Some final remarks

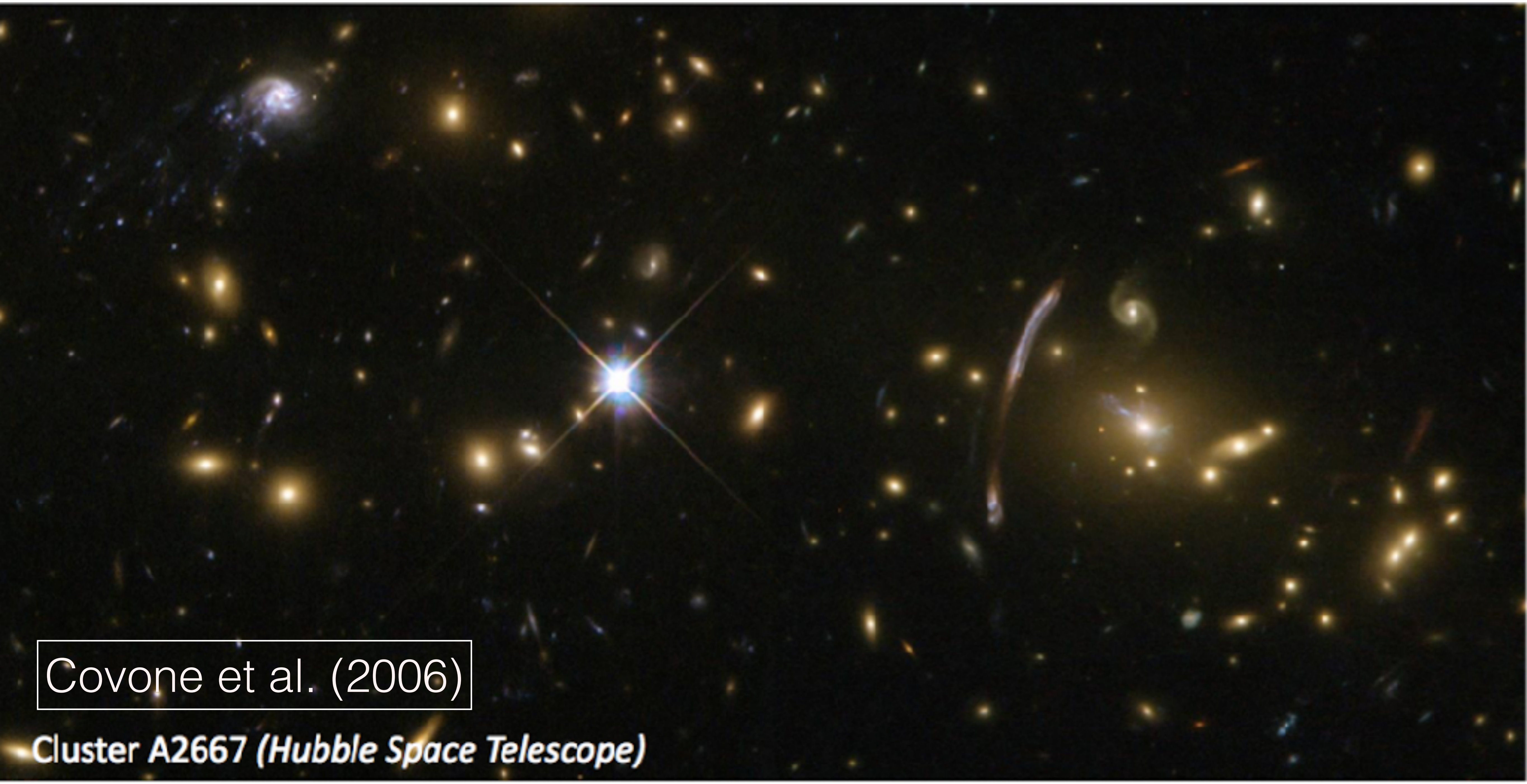
- LCDM appears to be substantially robust and still healthy. Baryon physics on small scales is not yet very well understood (*“hic sunt leones*")

- However, on small scales proposed solutions require ***some*** fine-tuning of the astrophysical parameters describing the complicate gas physics

- Competitive theories appear free from such fine-tuning, but still did not provide any large scale model (a stale-mate, or a drawn by repetition)

- SIDM is a strong candidate for the solution on small scales

- Properties of DM close to be constrained soon (but you heard this before…)



Thanks for you attention

Backup slides

Dark Matter in Galaxies
IAU Symposium, Vol. 220, 2004
S.D. Ryder, D.J. Pisano, M.A. Walker, and K.C. Freeman, eds.

The visible matter – dark matter coupling

Renzo Sancisi

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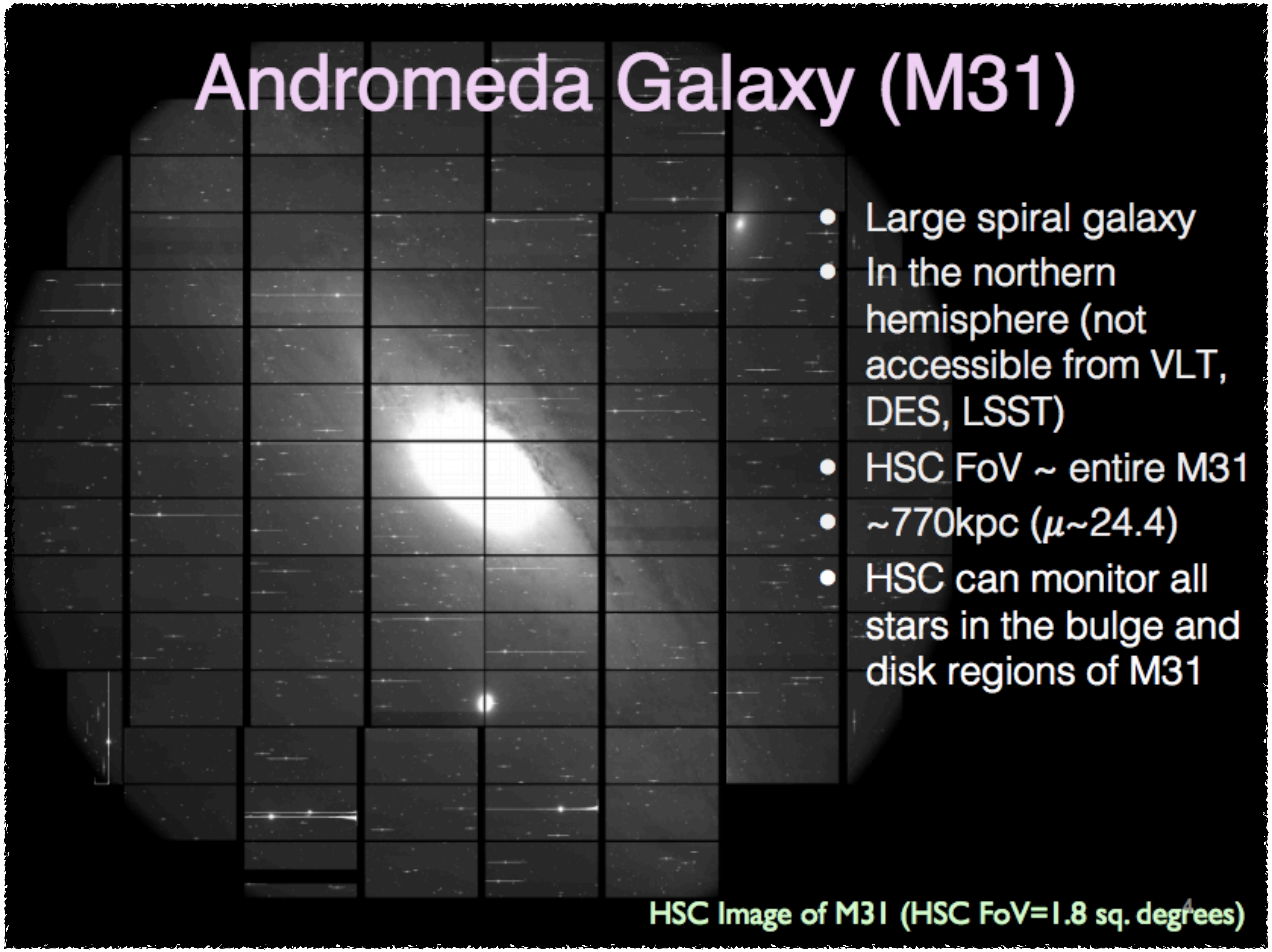
Abstract. In the inner parts of spiral galaxies, of high or low surface brightness, there is a close correlation between rotation curve shape and light distribution. For any feature in the luminosity profile there is a corresponding feature in the rotation curve and vice versa. This implies that the gravitational potential is strongly correlated with the distribution of luminosity: either the luminous mass dominates or there is a close coupling between luminous and dark matter. In a similar way, the declining rotation curves observed in the outer parts of high luminosity systems are a clear signature of the stellar disk which either dominates or traces the distribution of mass.

The notion that the baryons are dynamically important in the centres of galaxies, including LSBs, undermines the whole controversy over the cusps in CDM halos and the comparison with the observations. If the baryons dominate in the central regions of all spirals, including LSBs, how can the CDM profiles be compared with the observations? Alternatively, if the baryons do not dominate but simply trace the DM distribution, why, in systems of comparable luminosity, are some DM halos cuspy (like the light) and others (also like the light) are not?

Primordial black holes in galaxy haloes?

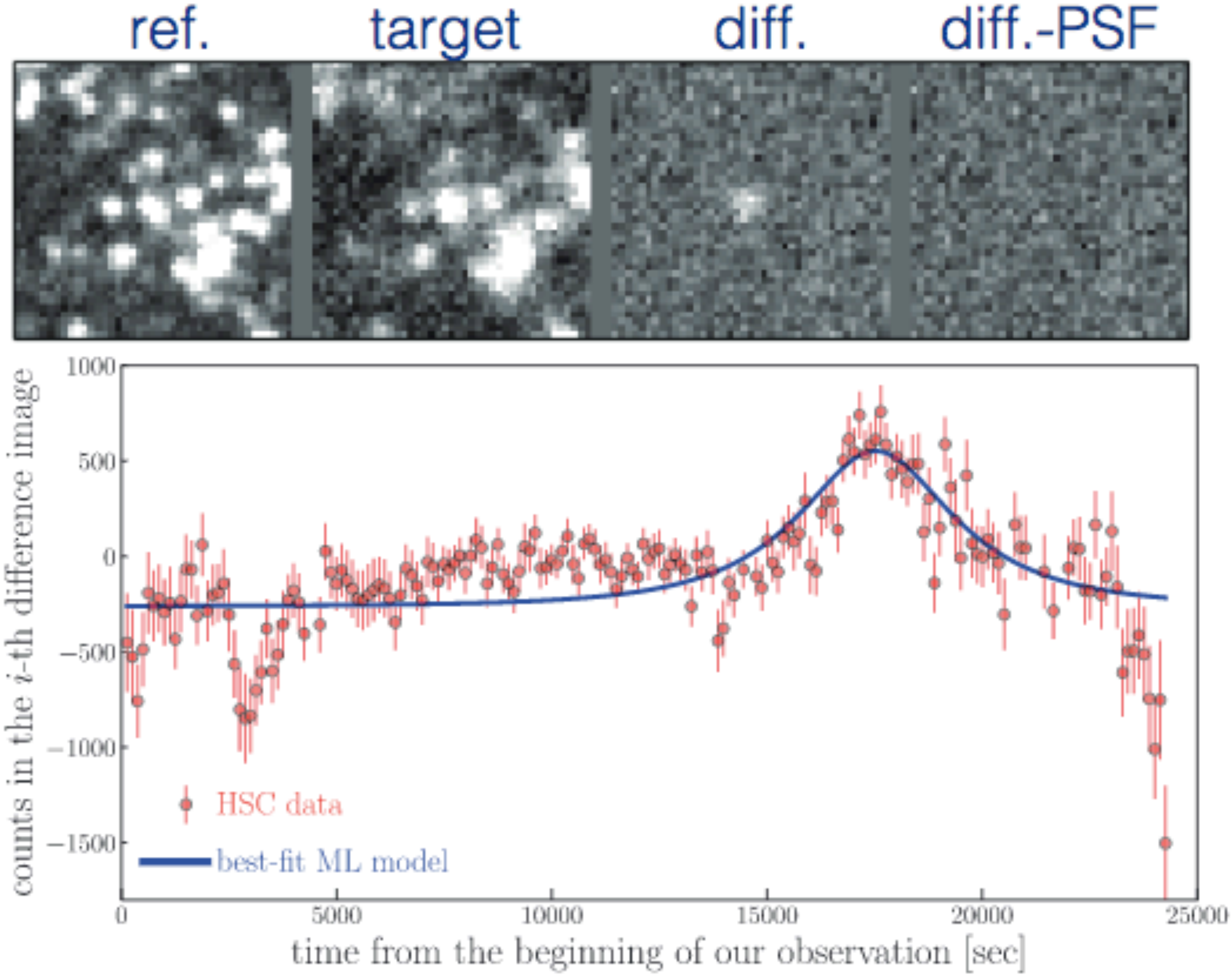


Andromeda Galaxy (M31)

- Large spiral galaxy
- In the northern hemisphere (not accessible from VLT, DES, LSST)
- HSC FoV ~ entire M31
- ~770kpc (μ~24.4)
- HSC can monitor all stars in the bulge and disk regions of M31

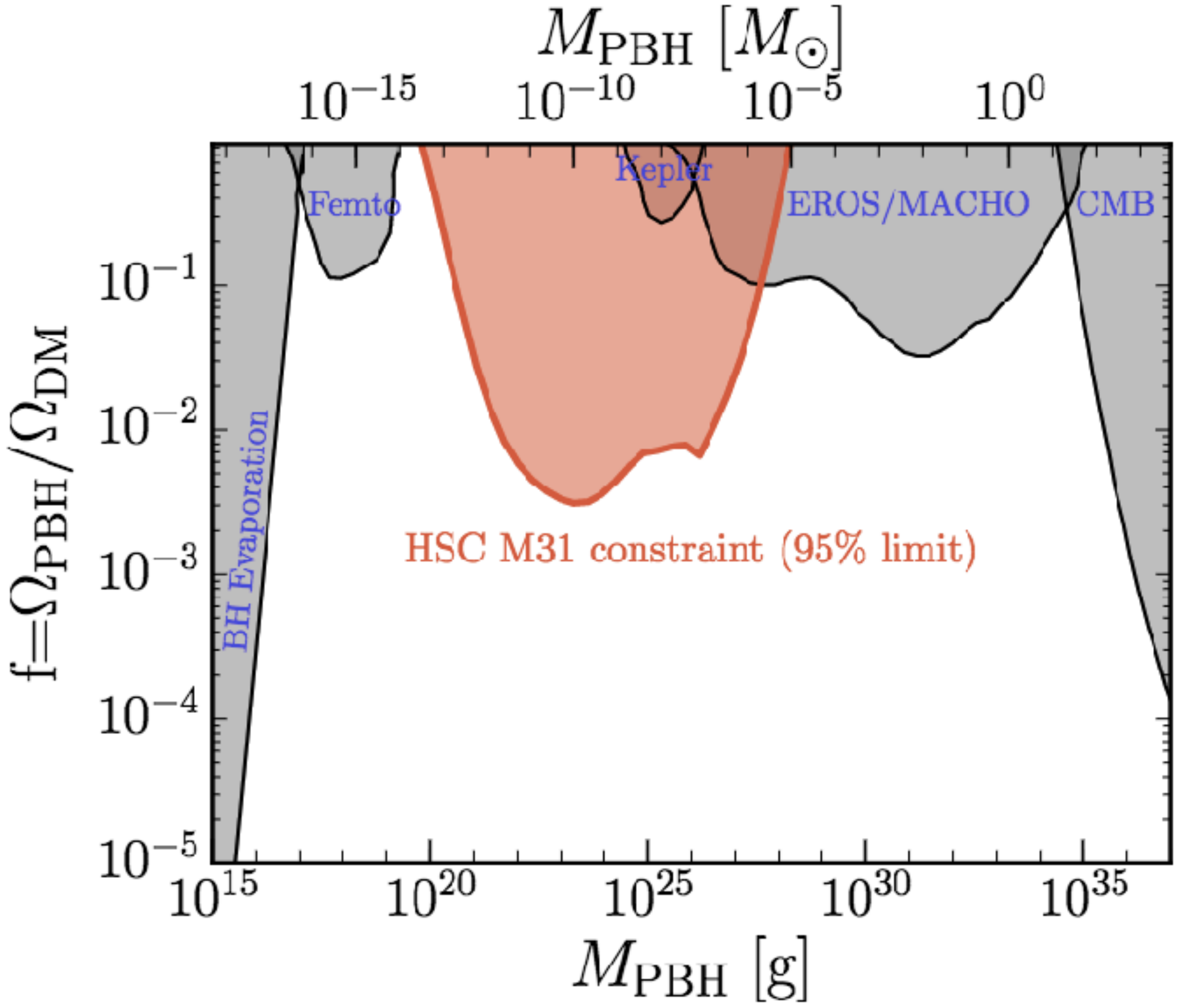
HSC Image of M31 (HSC FoV=1.8 sq. degrees)

Primordial black holes?



Microlensing search for PBH in galaxy M31
Niikura et al. (2017)

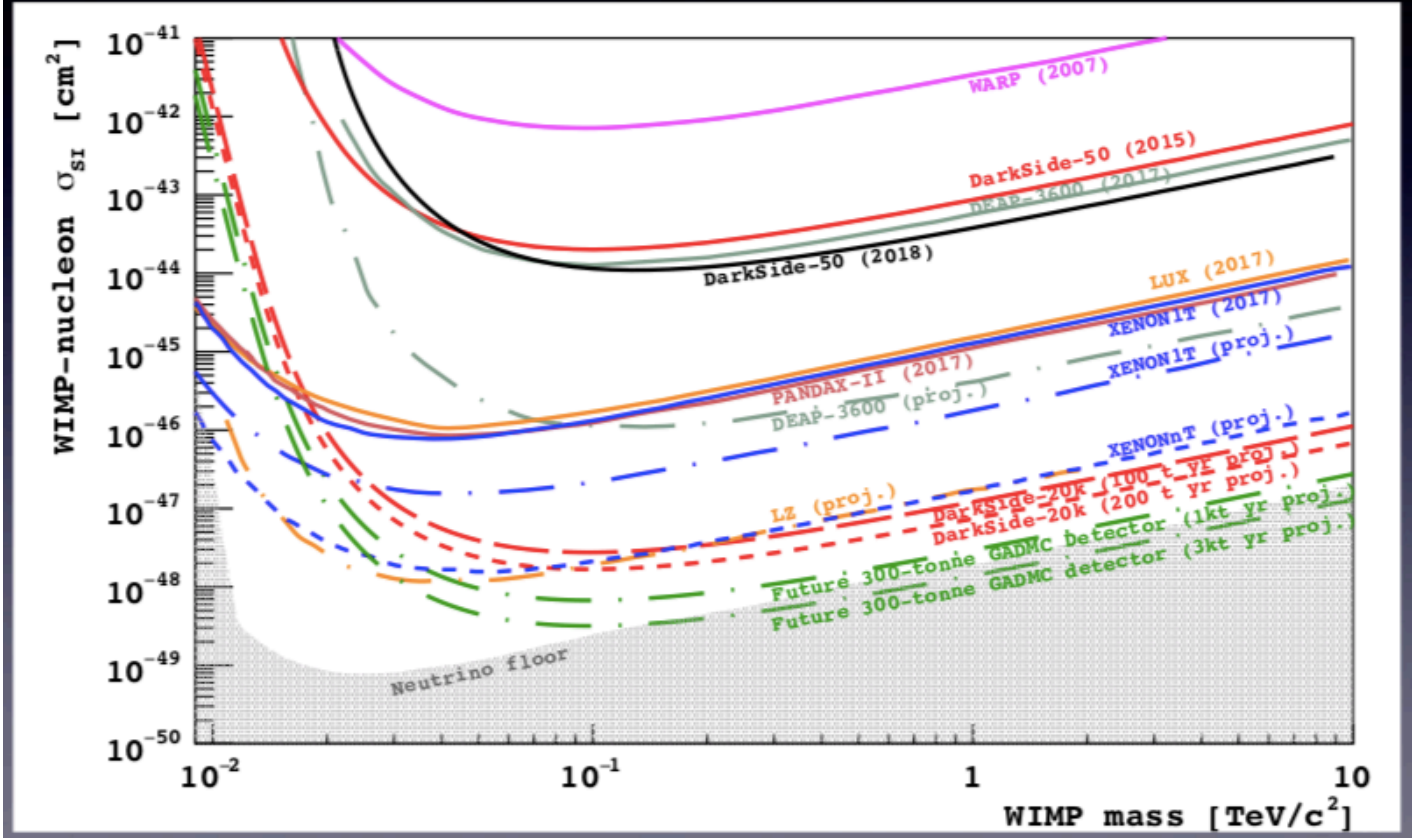
Dark halo not made of PBHs only



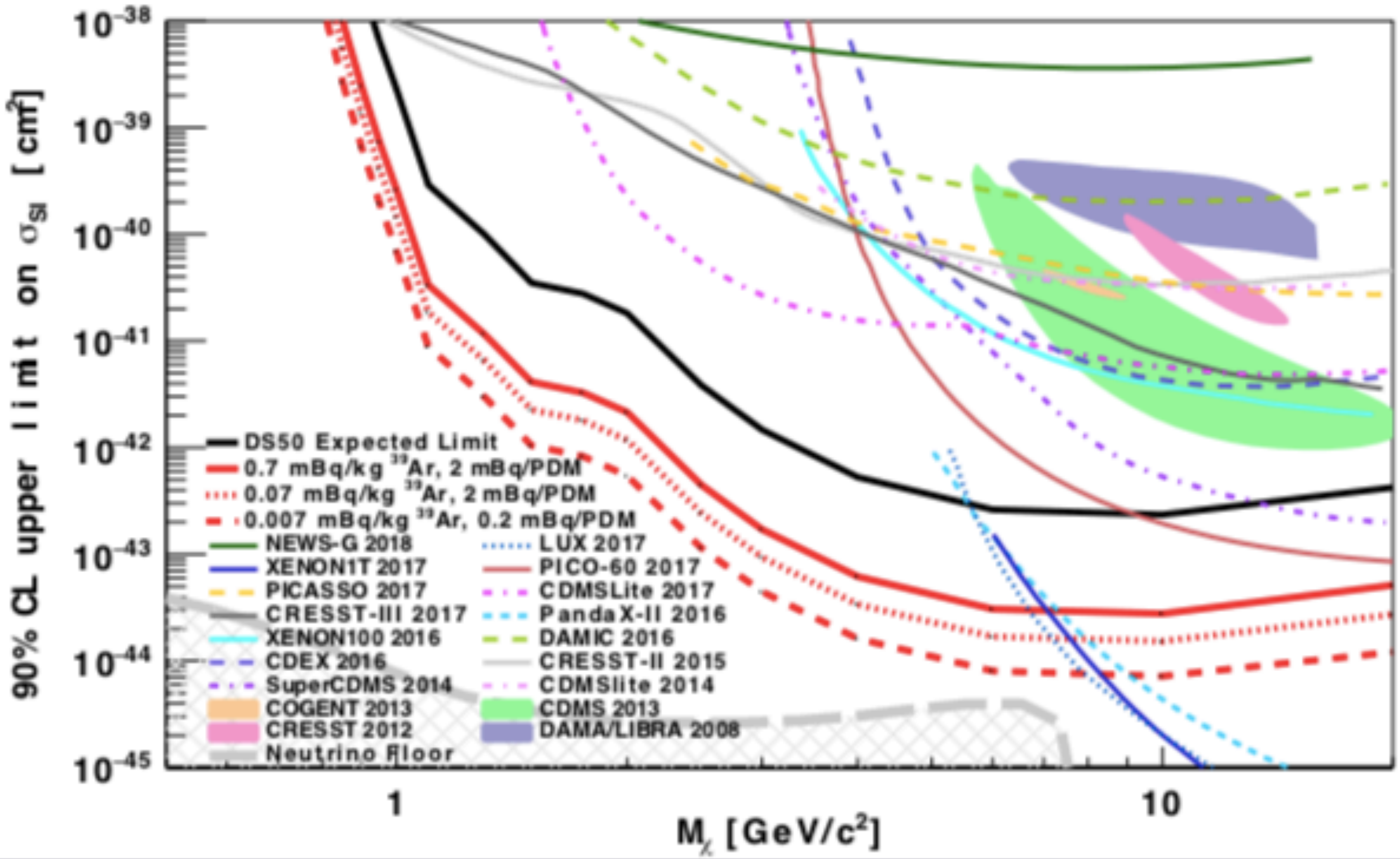
The Global Argon Dark Matter Collaboration

- A Single Global Program for Direct Dark Matter Searches
  - Currently taking data:
    - ArDM
    - DarkSide-50
    - DEAP-3600
  - Next step: **DarkSide-20k** at LNGS (2021-)
  - Last Step: 300 tonnes detector, location t.b.d (2027-)
- Also, a collaboration among Underground Labs:
  - Laboratori Nazionali del Gran Sasso
  - SNOLAB
  - Laboratorio Subterráneo de Canfranc.

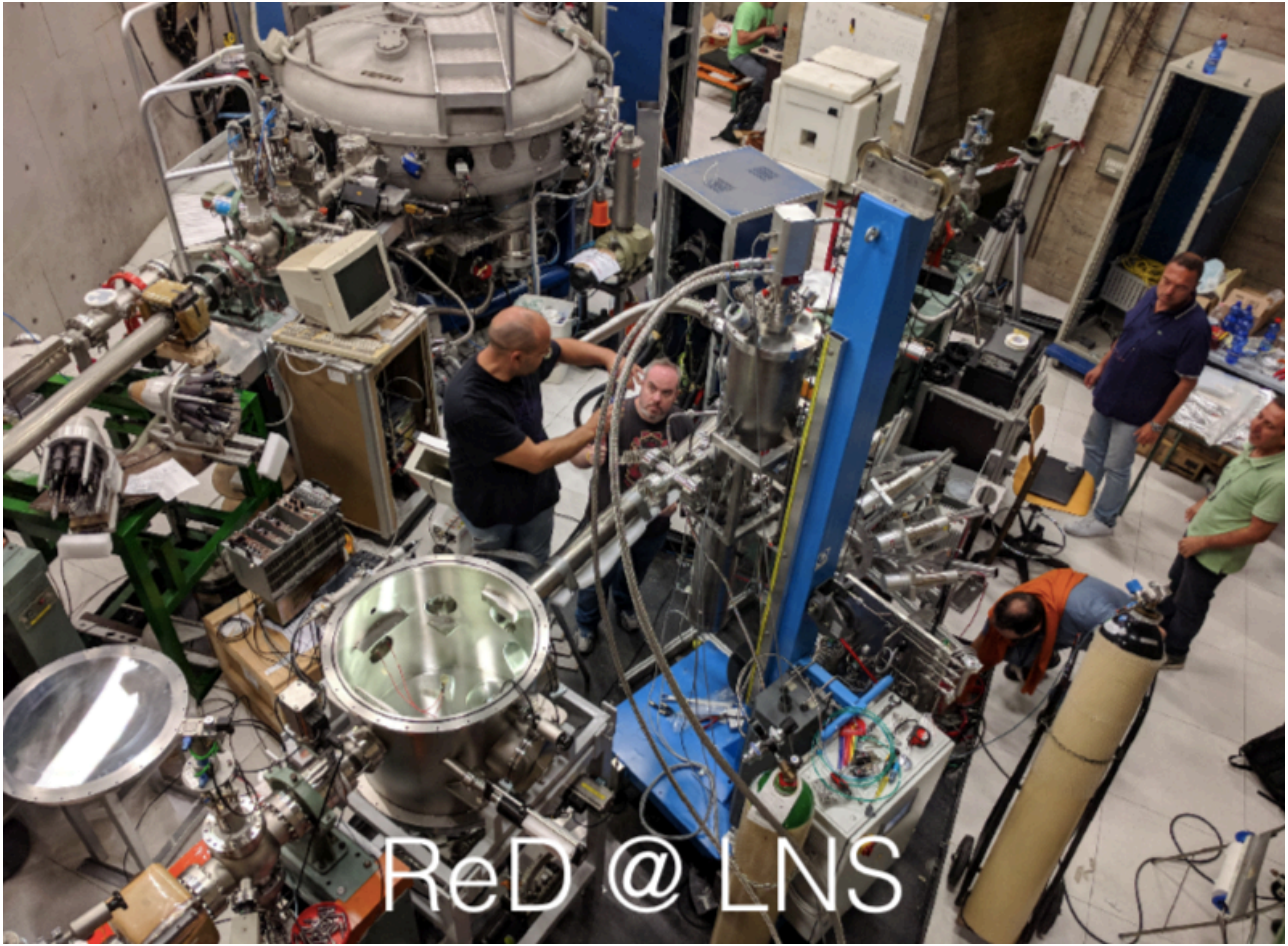
DarkSide-20k sensitivity



Future Darkside Low-Mass Searches



1 year data taking with DS-Proto



ReD @ LNS