Small-scale problems of cosmology and how modified dynamics might address them

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CASE WESTERN RESERVE
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think beyond the possible™

with support from the John Templeton Foundation

Small-scale problems

Assumption:

Standard Λ cold dark matter (DM) cosmology

- DM dominating matter component
- Hierarchical structure formation
- Galaxies form in centers of DM haloes

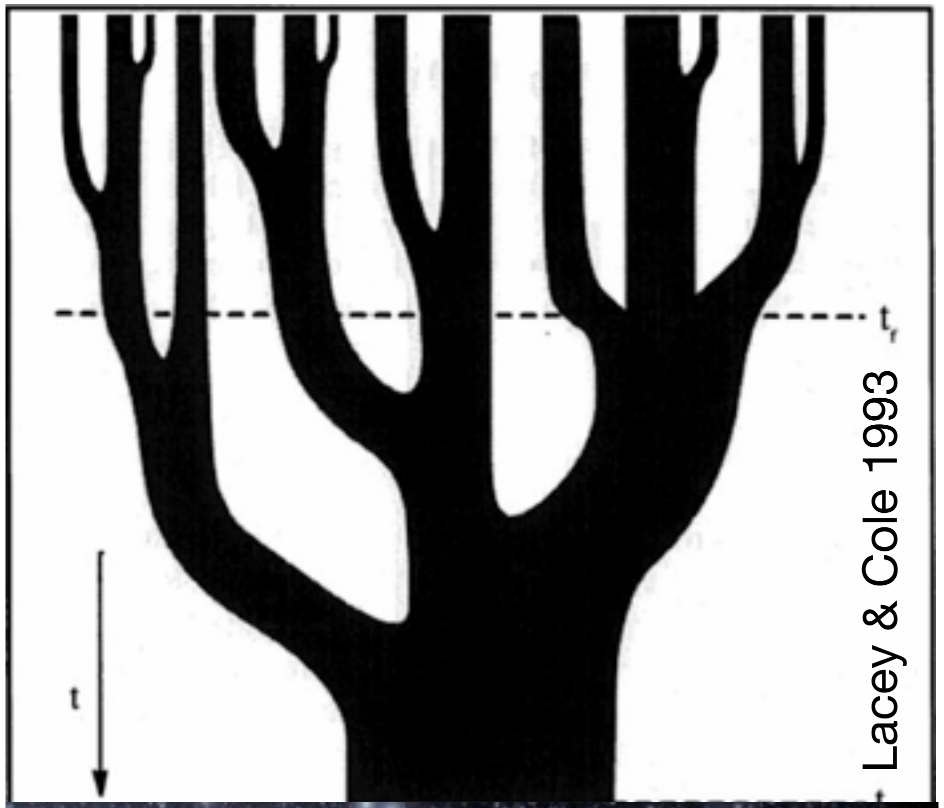
Test:

Compare ΛCDM *simulations* with observations

- Concentrate on ~galaxy scales here
  (in local Universe, i.e. near-field cosmology)

➡ Small-scale problems

Simulations or model can be wrong



Lacey & Cole 1993

Diemand et al. (2008)

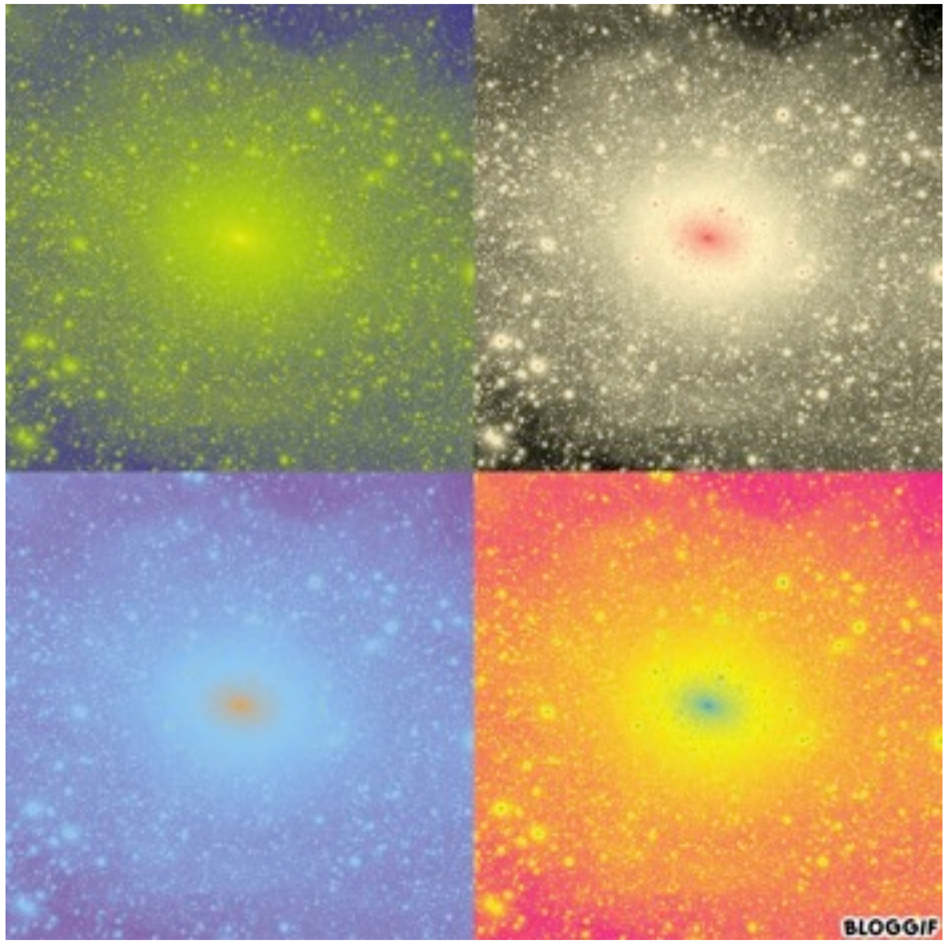
(Some) Small-Scale Problems: An Overview

“Popular”/acknowledged problems

- Missing Satellites
- Core/cusp
- Too-big-to-fail
- Satellite planes

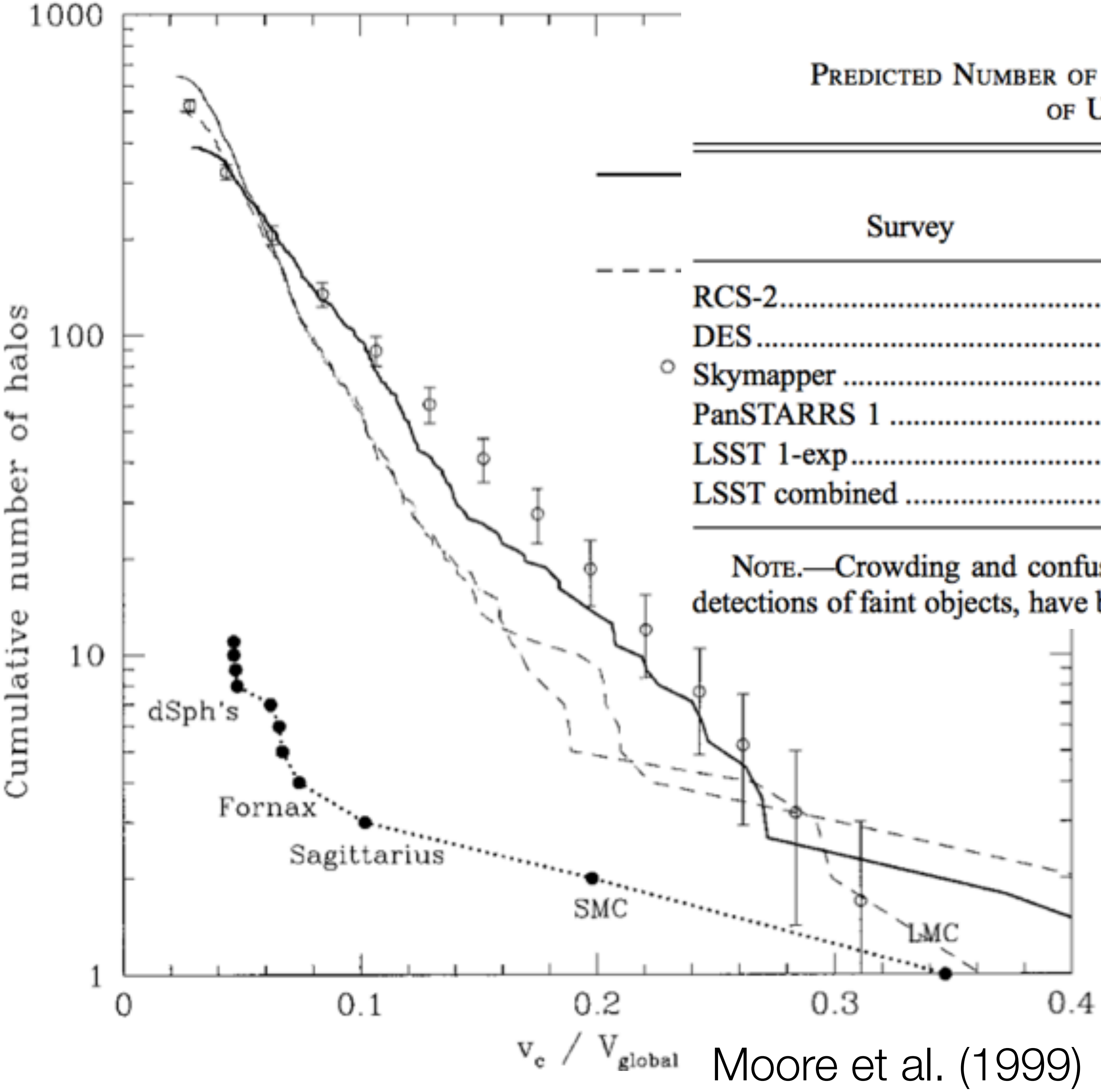
Less popular or “forgotten” problems

- *Baryonic* Tully Fisher relation (BTFR)
- Mass-discrepancy–acceleration relation (MD
- (In-)Stability of LSB galaxy disks
- Abundance of bulge-less galaxies
- Dynamical Friction (e.g. Sagittarius)
- Length of tidal tails
- What are Ultra Diffuse Galaxies?



> “In the future, every LCDM problem will be world-famous for 15 minutes.” - Andy Warhol

Missing Satellites Problem



Moore et al. (1999)

TABLE 4

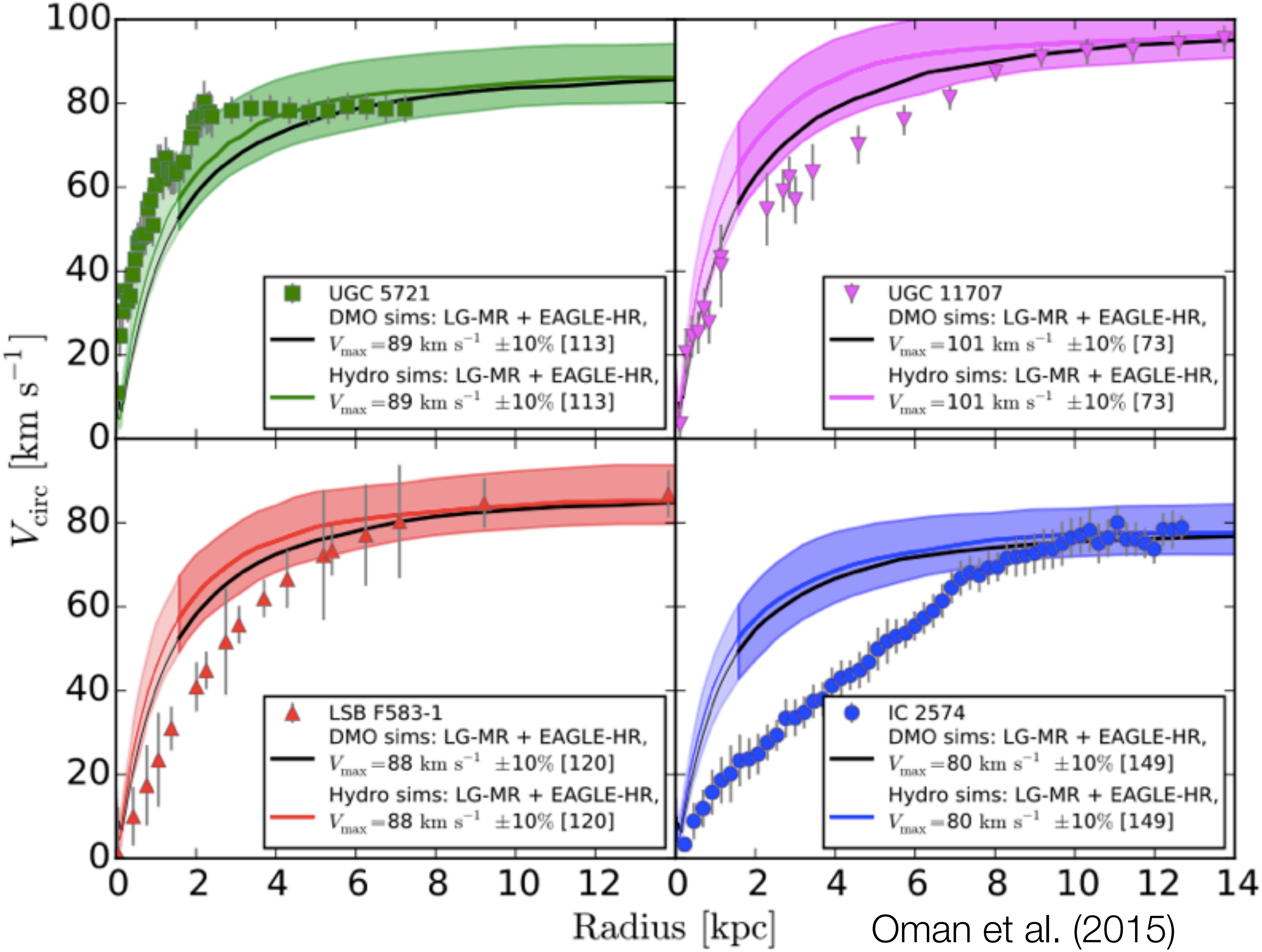
Predicted Number of Detectable Satellites in a Series of Upcoming Surveys

Survey	Area (deg^2)	Limiting r (mag)	N_{sats}
RCS-2	1000	24.8	3–6
DES	5000	24	19–37
Skymapper	20000	22.6	42–79
PanSTARRS 1	30000	22.7	61–118
LSST 1-exp	20000	24.5	93–179
LSST combined	20000	27.5	145–283

Note.—Crowding and confusion effects, which will reduce the number of detections of faint objects, have been ignored.

Tollerud et al. (2008)

Core/Cusp Problem



Oman et al. (2015)

Too-big-to-fail problem

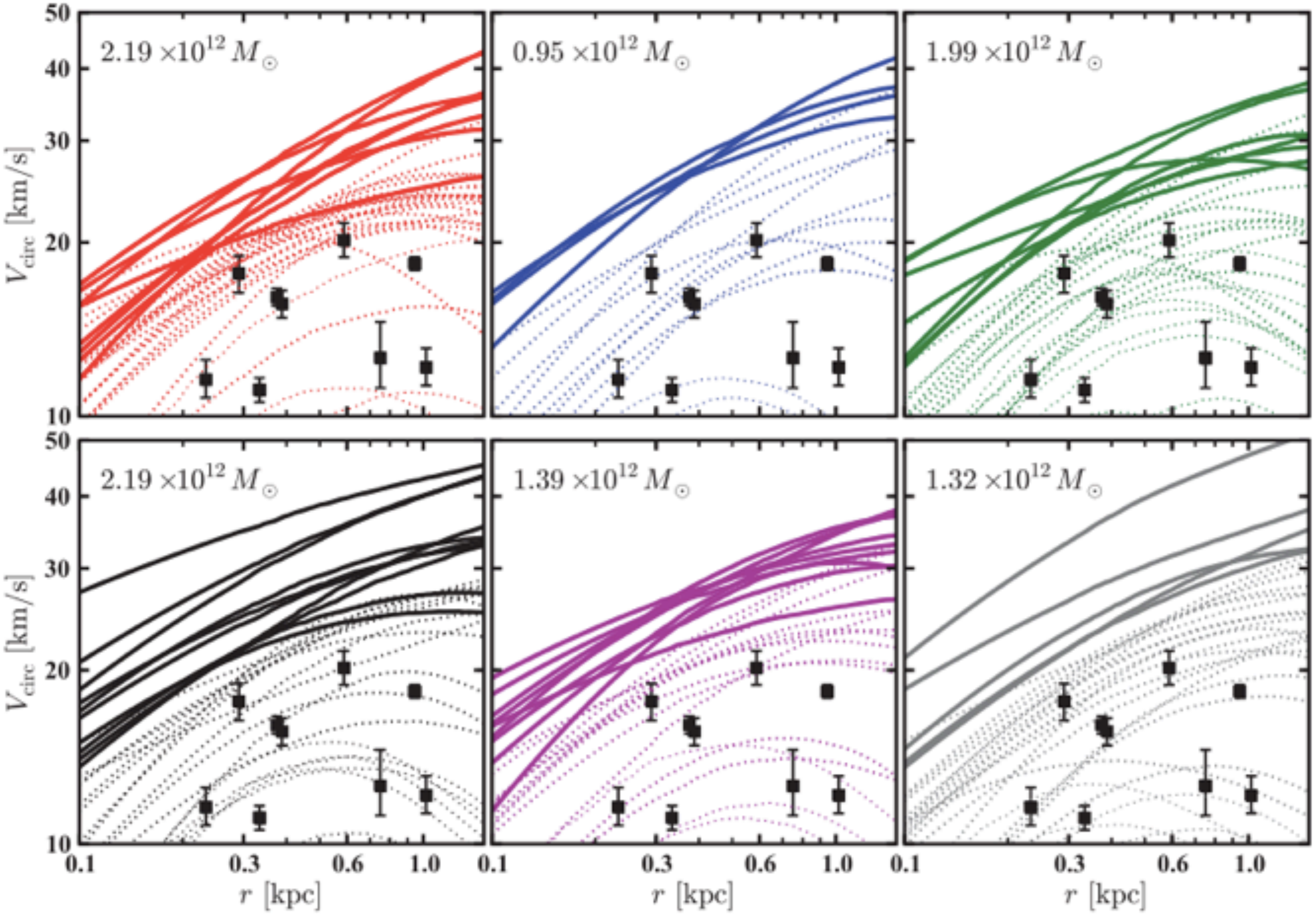
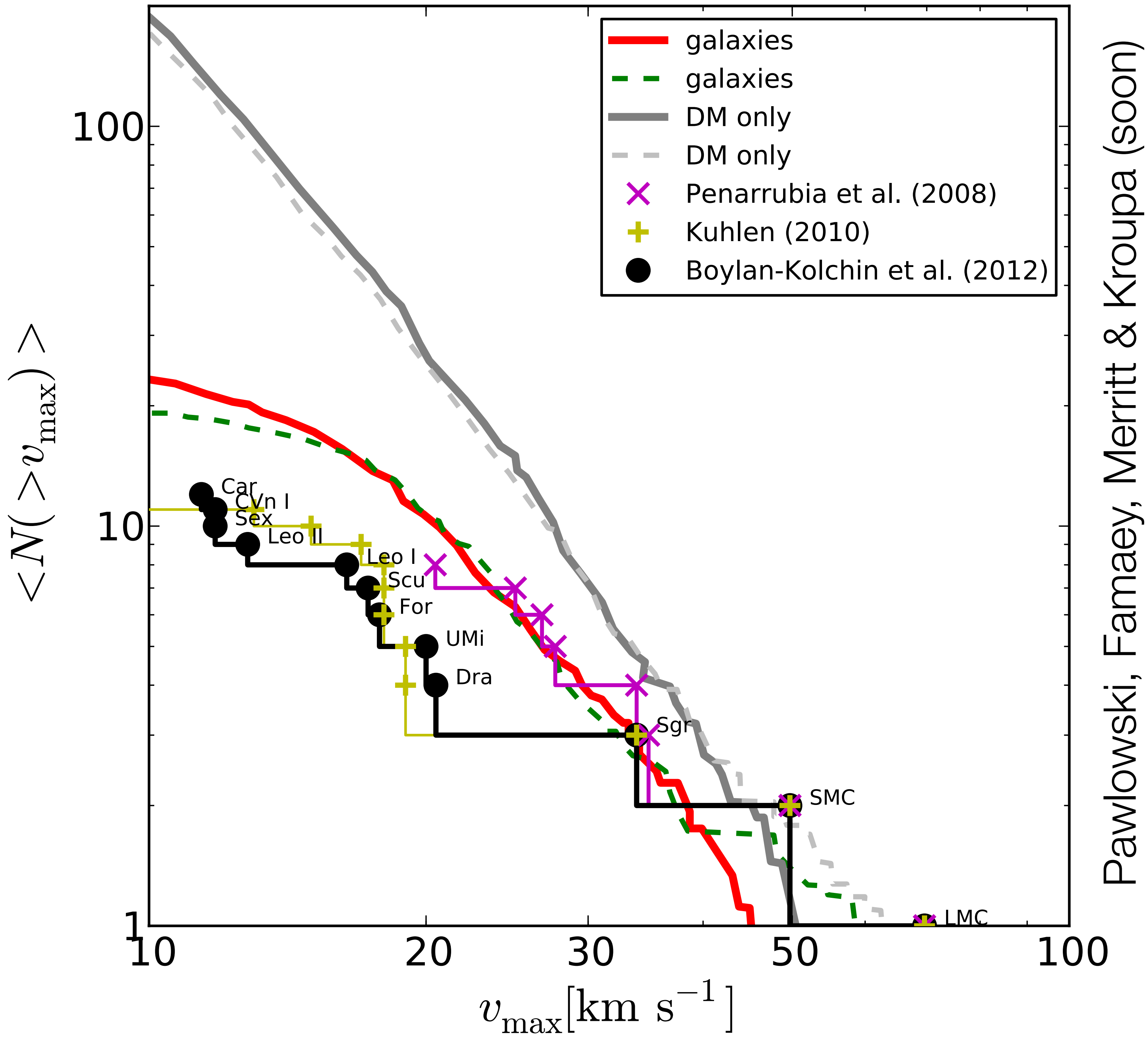


Figure 3. Rotation curves for all subhaloes with $V_{\rm infall} > 30\,{\rm km\,s^{-1}}$ and $V_{\rm max} > 10\,{\rm km\,s^{-1}}$, after excluding MC analogues, in each of the six Aquarius simulations (top row, from the left-hand to right-hand side: A, B, C; bottom row, from the left-hand to right-hand side: D, E, F). Subhaloes that are at least 2σ denser than every bright MW dSph are plotted with the solid curves, while the remaining subhaloes are plotted as the dotted curves. Data points with errors show measured $V_{\rm circ}$ values for the bright MW dSphs. Not only does each halo have several subhaloes that are too dense to host any of the dSphs, each halo also has several massive subhaloes (nominally capable of forming stars) with $V_{\rm circ}$ comparable to the MW dSphs that have no bright counterpart in the MW. In total, 7–22 of these massive subhaloes are unaccounted for in each halo.

Boylan-Kolchin, Bullock & Kaplinghat (2012)

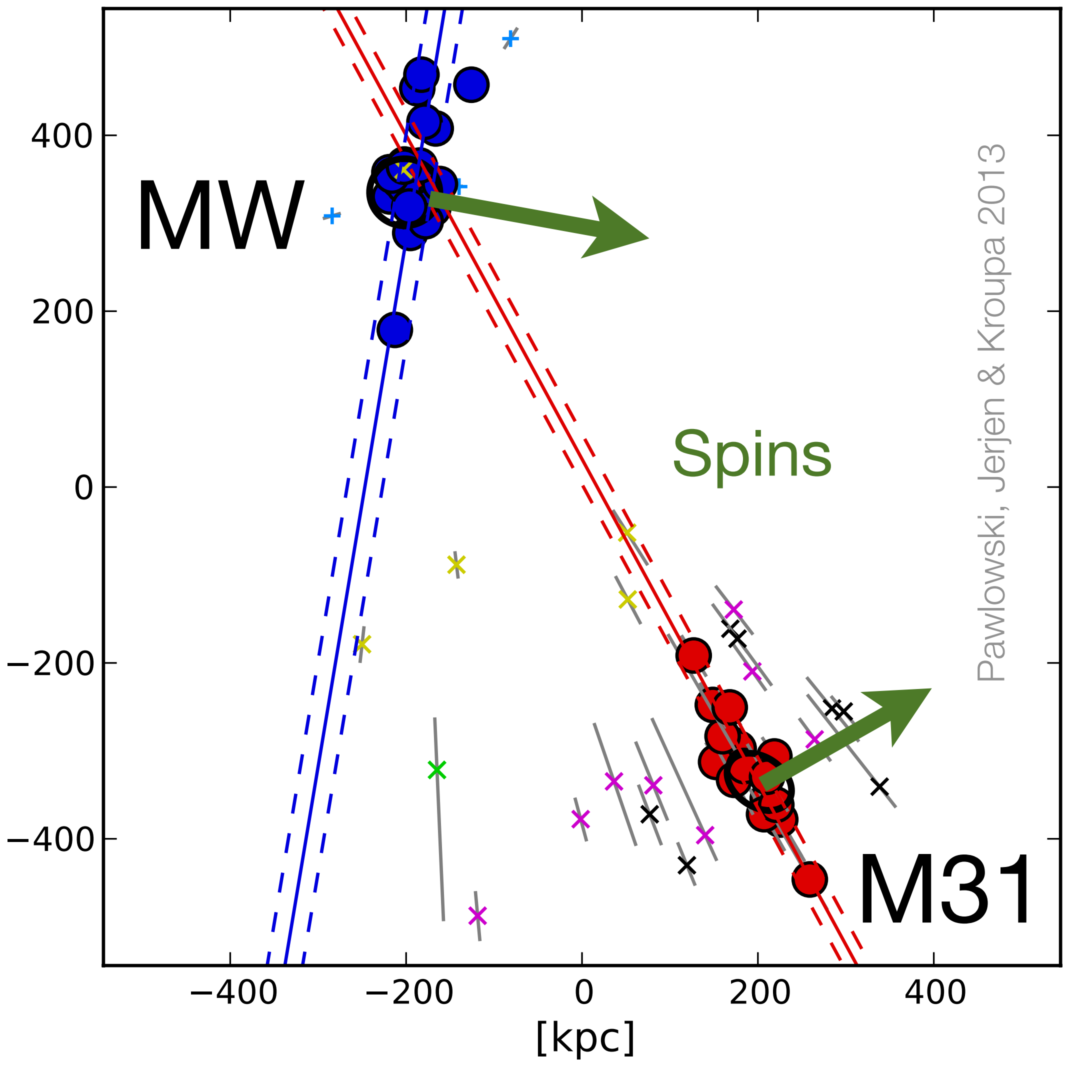
Too-big-to-fail problem
… about Sawala et al. (2014)'s "solution"



Pawlowski, Famaey, Merritt & Kroupa (soon)

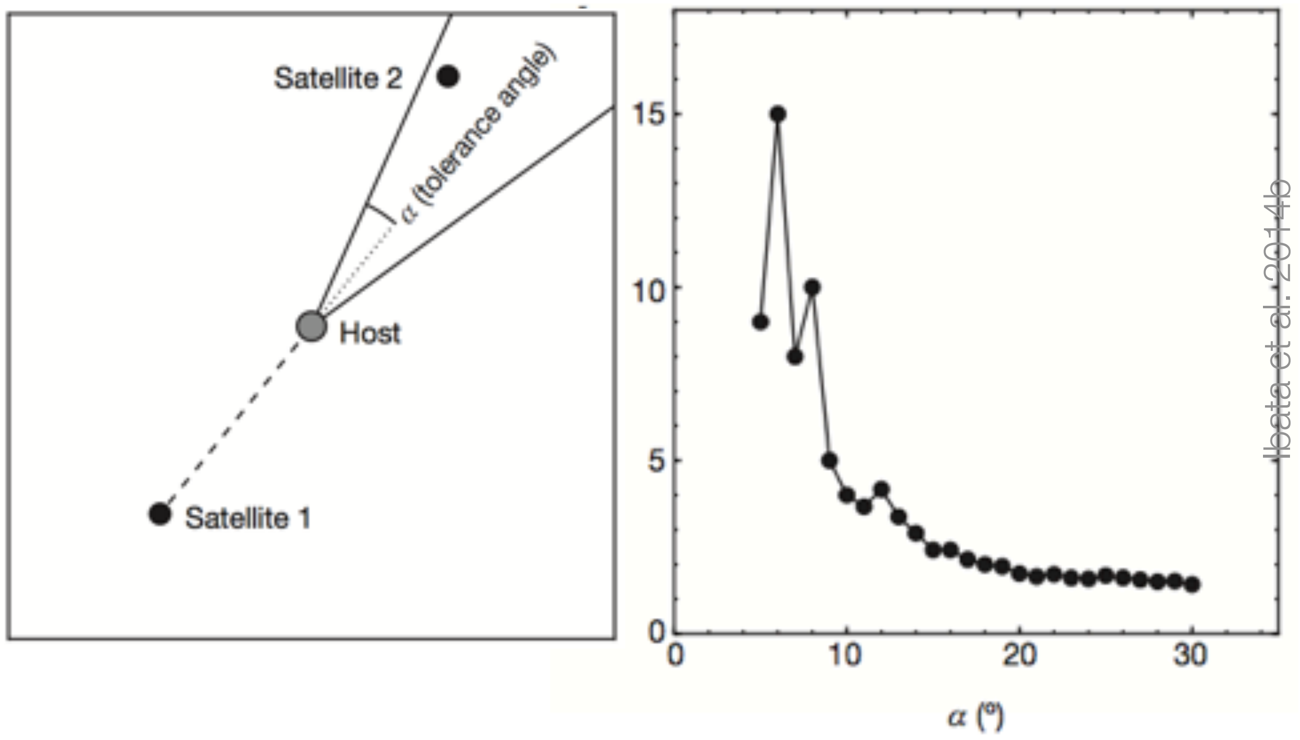
Co-orbiting planes of satellites

Local Group



Pawlowski, Jerjen & Kroupa 2013

SDSS



Ibata et al. 2014b

Elsewhere

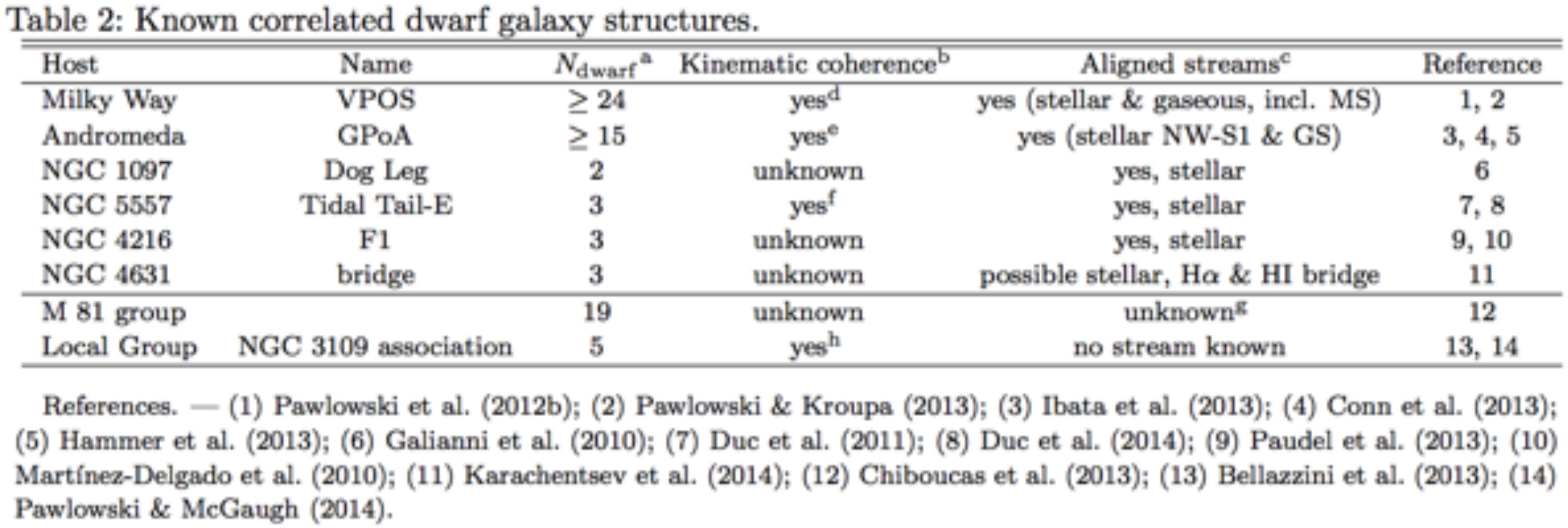


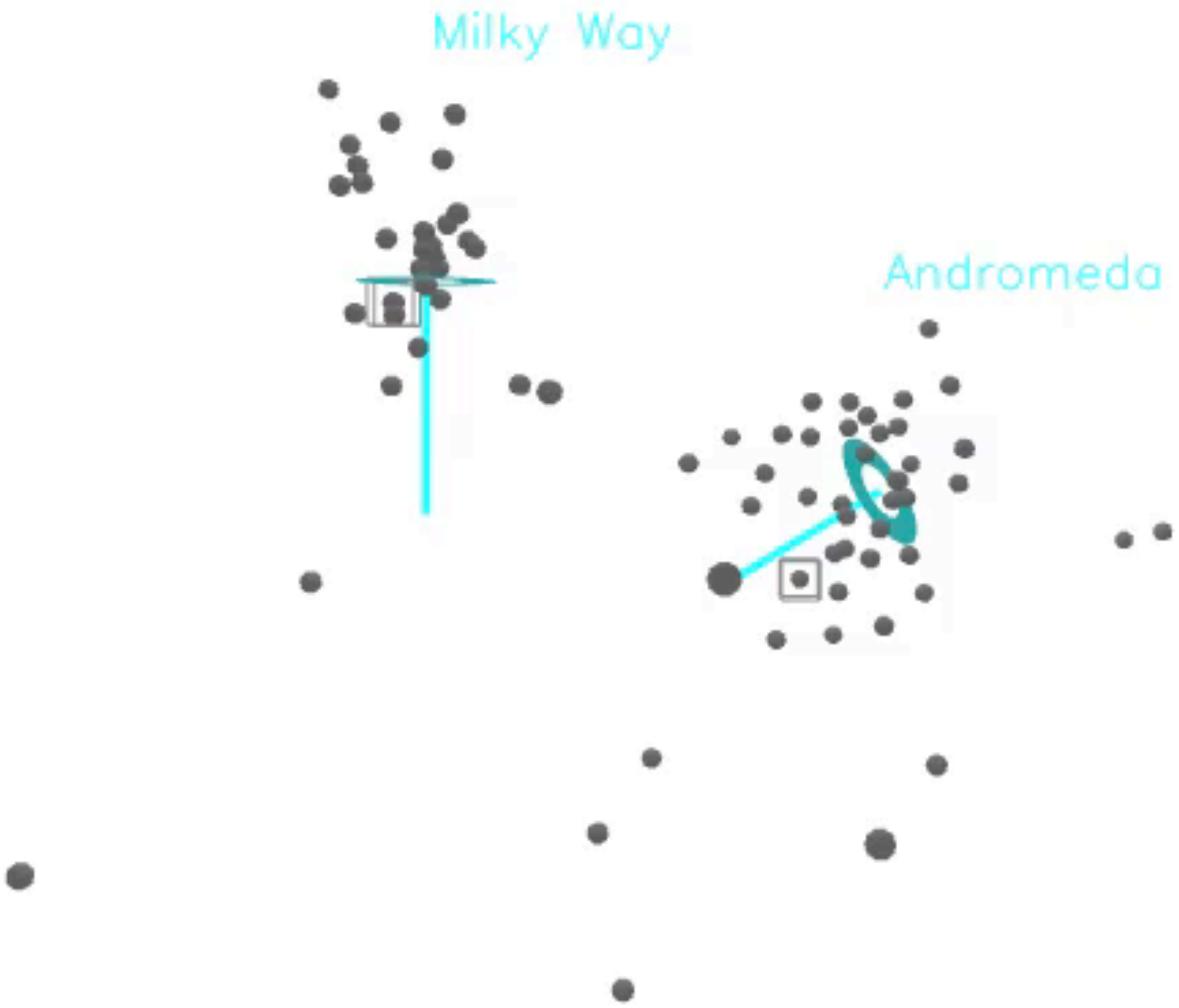
Table 2: Known correlated dwarf galaxy structures.

Host	Name	N_{dwarf}[a]	Kinematic coherence[b]	Aligned streams[c]	Reference
Milky Way	VPOS	≥ 24	yes[d]	yes (stellar & gaseous, incl. MS)	1, 2
Andromeda	GPoA	≥ 15	yes[e]	yes (stellar NW-S1 & GS)	3, 4, 5
NGC 1097	Dog Leg	2	unknown	yes, stellar	6
NGC 5557	Tidal Tail-E	3	yes[f]	yes, stellar	7, 8
NGC 4216	F1	3	unknown	yes, stellar	9, 10
NGC 4631	bridge	3	unknown	possible stellar, Hα & HI bridge	11
M 81 group		19	unknown	unknown[g]	12
Local Group	NGC 3109 association	5	yes[h]	no stream known	13, 14

References. — (1) Pawlowski et al. (2012b); (2) Pawlowski & Kroupa (2013); (3) Ibata et al. (2013); (4) Conn et al. (2013); (5) Hammer et al. (2013); (6) Galianni et al. (2010); (7) Duc et al. (2011); (8) Duc et al. (2014); (9) Paudel et al. (2013); (10) Martínez-Delgado et al. (2010); (11) Karachentsev et al. (2014); (12) Chiboucas et al. (2013); (13) Bellazzini et al. (2013); (14) Pawlowski & McGaugh (2014).

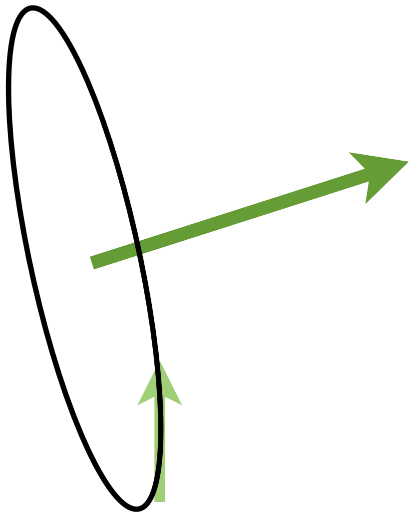
Pawlowski & Kroupa 2014

For movies see: http://marcelpawlowski.com/research/movies-astronomy/

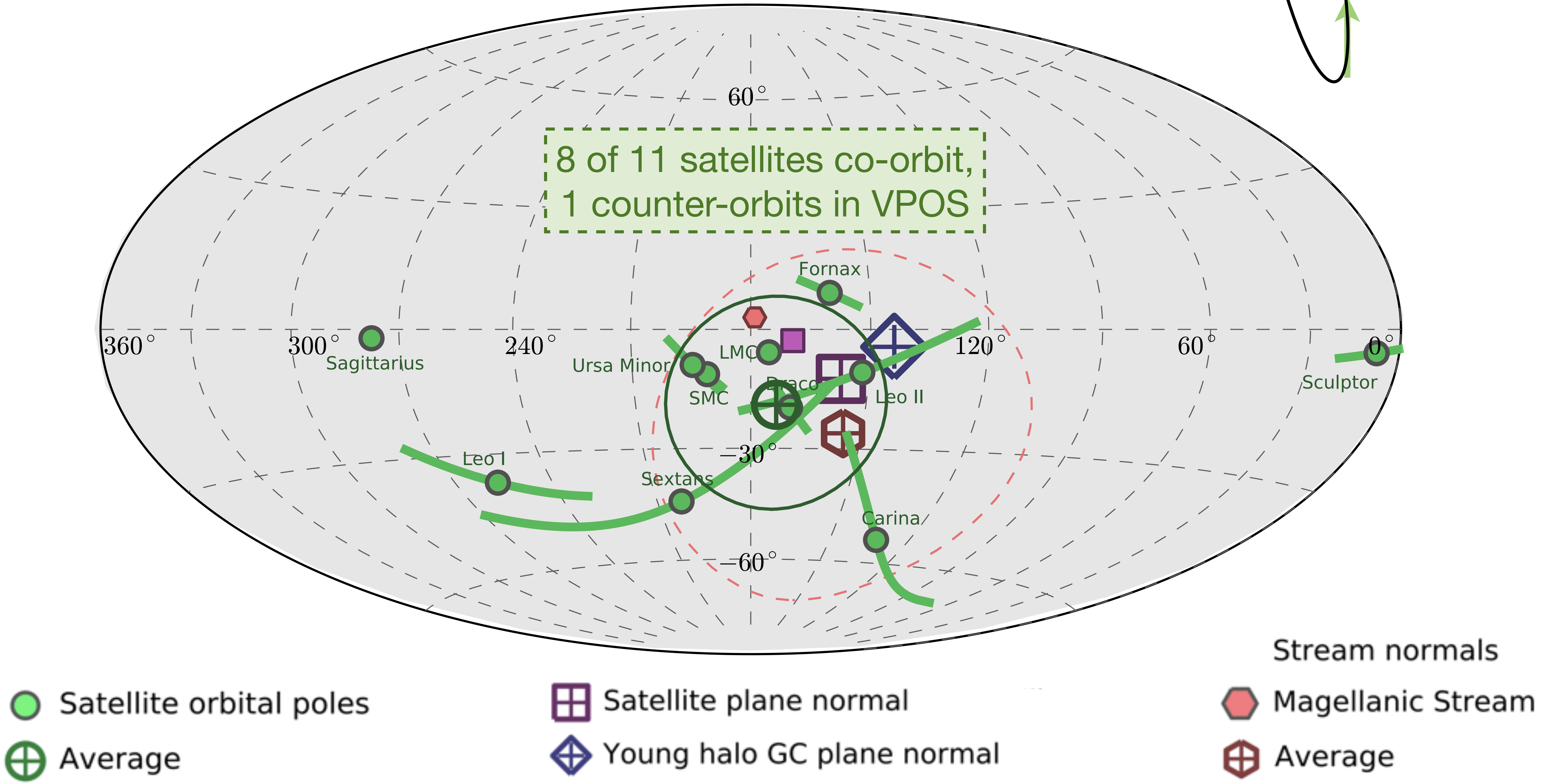


Coherent velocities: the VPOS is rotating

Pawlowski & Kroupa (2013, MNRAS, 435, 2116)



- Orbital poles of the MW satellites
  - ➡ directions of angular momenta = normals to orbital planes


8 of 11 satellites co-orbit, 1 counter-orbits in VPOS

Significance of the VPOS

Pawlowski in prep.

Probability to find at least as extreme structure in isotropic distribution?

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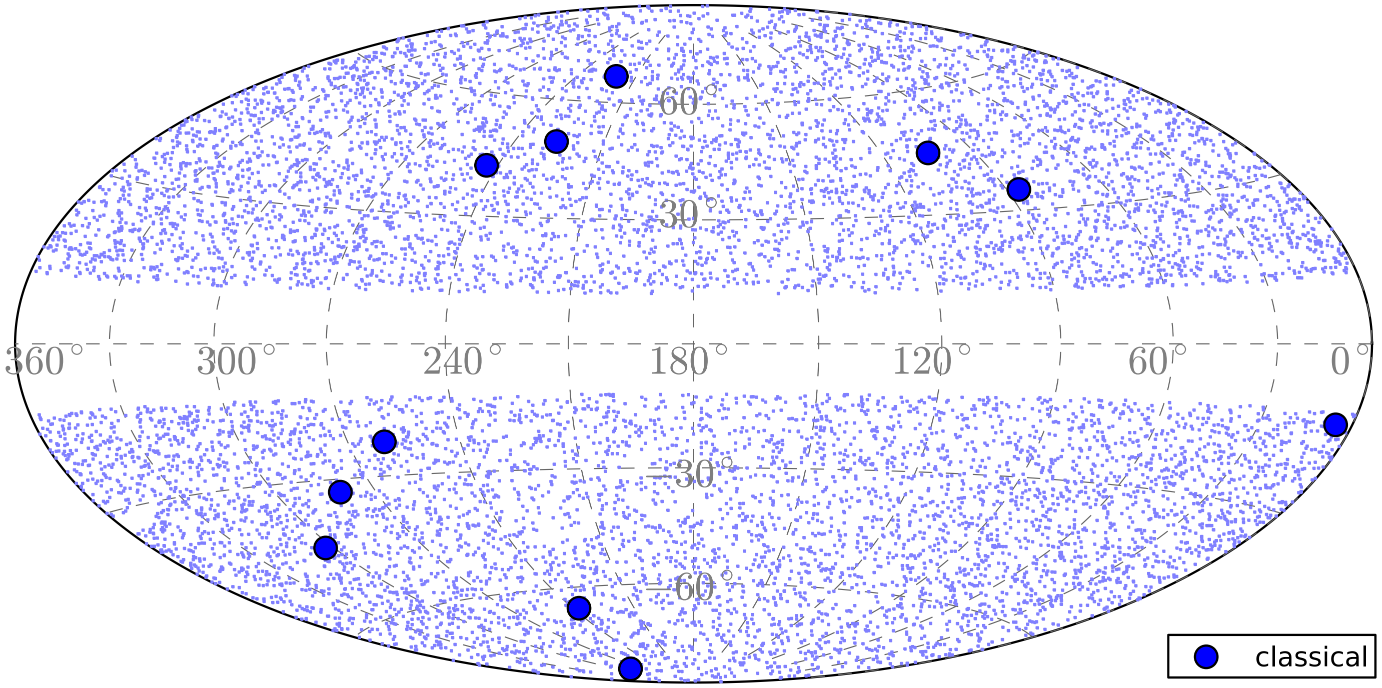
Pawlowski in prep.

Probability to find at least as extreme structure in isotropic distribution?

11 classical satellites in narrow plane (Δ_{rms} = 19.6 kpc height)
(consider 12° obscuration by Milky Way)

P = 1.3 x 10^{-2}
(~ 2.5 σ)



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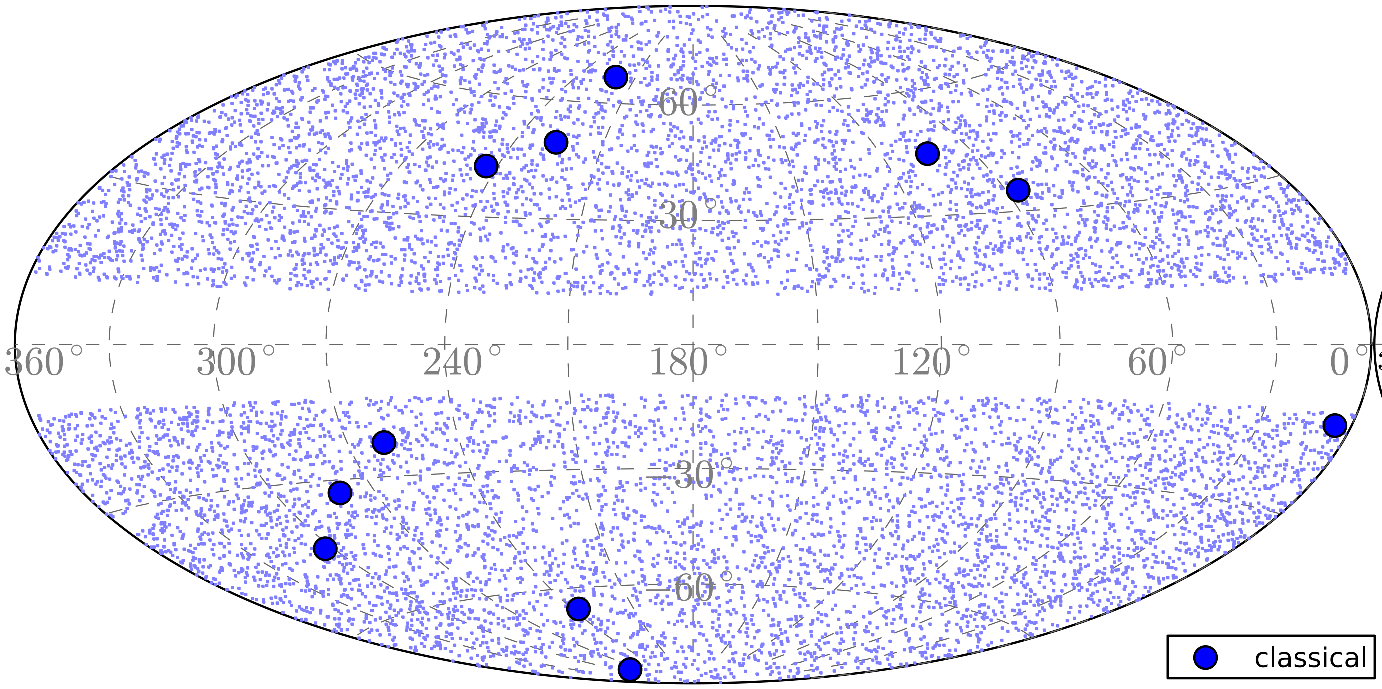
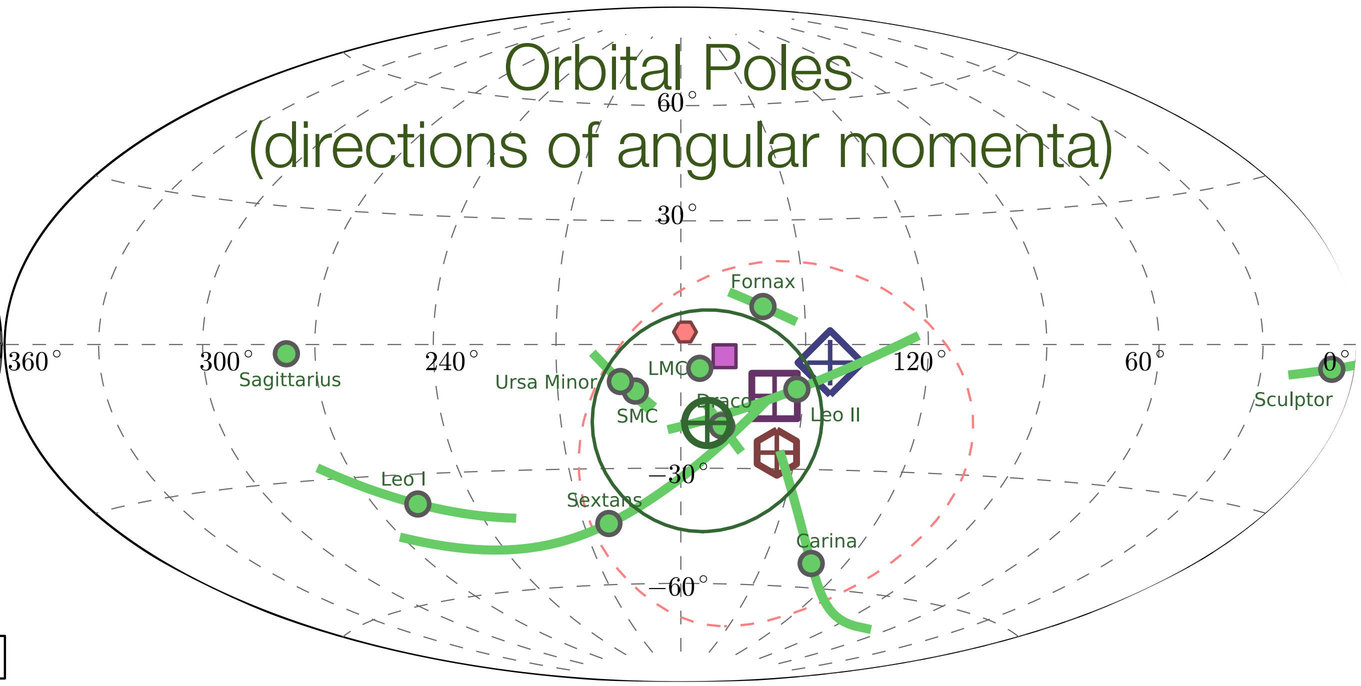
(~ 4.0 σ)





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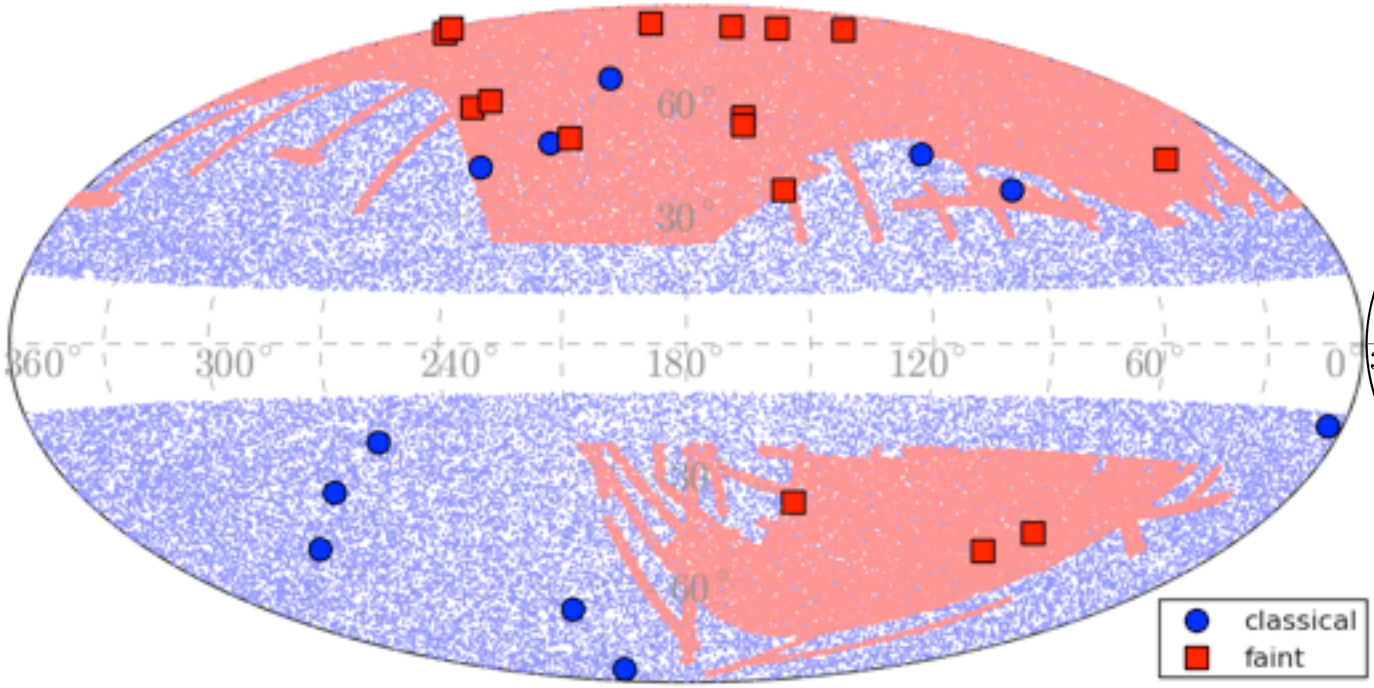
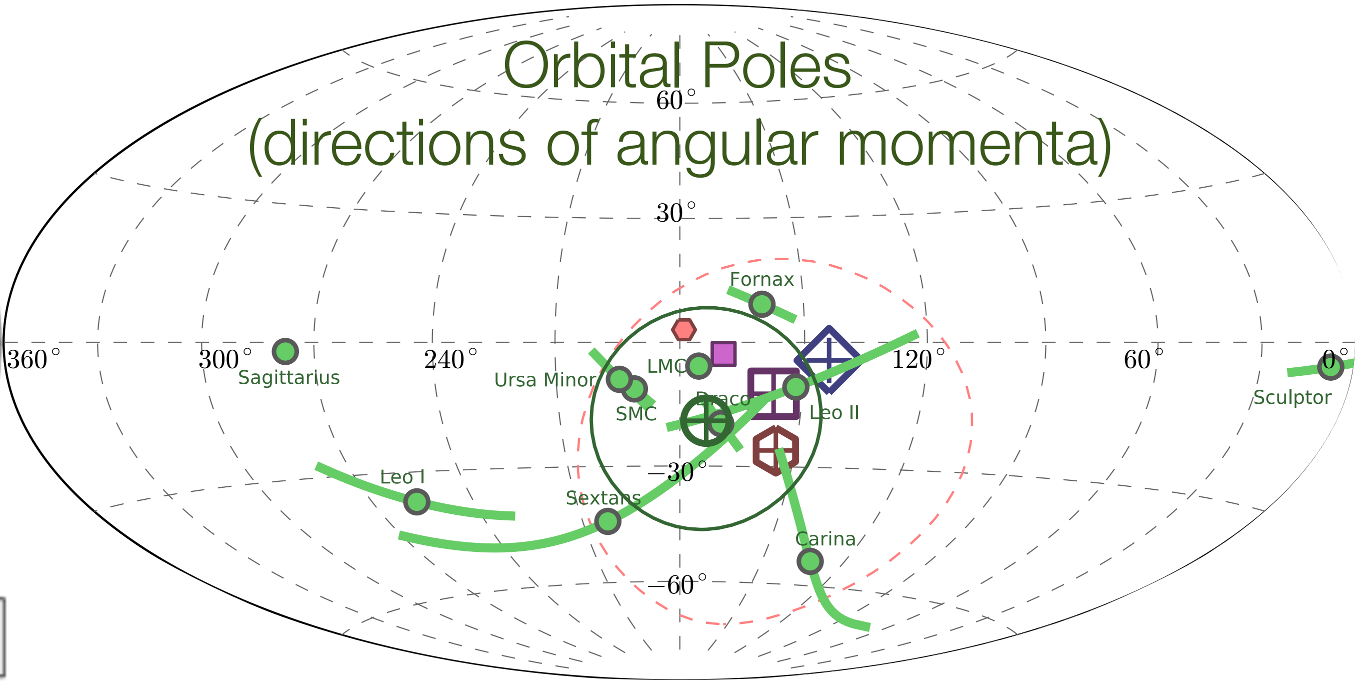
(~ 4.0 σ)

+ **16 SDSS satellites** define narrow plane (Δ_{rms} = 25.9 kpc)
aligned with classical satellites (22°)
(consider exact SDSS DR10 footprint and 2x MW obscuration)

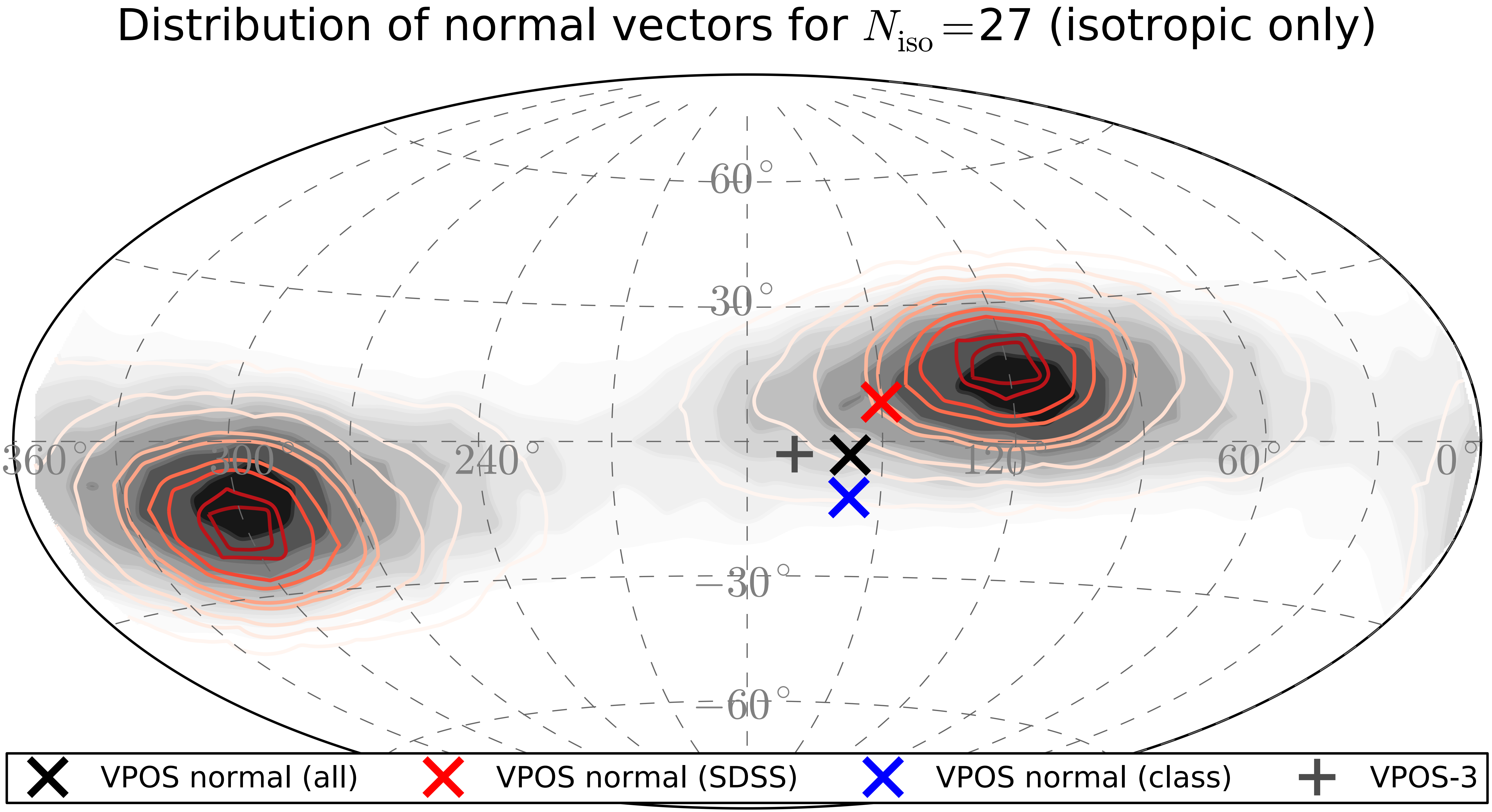
$P = 3.7 \times 10^{-7}$
(~ 5.1 σ)




Orbital Poles
(directions of angular momenta)

Significance of the VPOS

Pawlowski in prep.

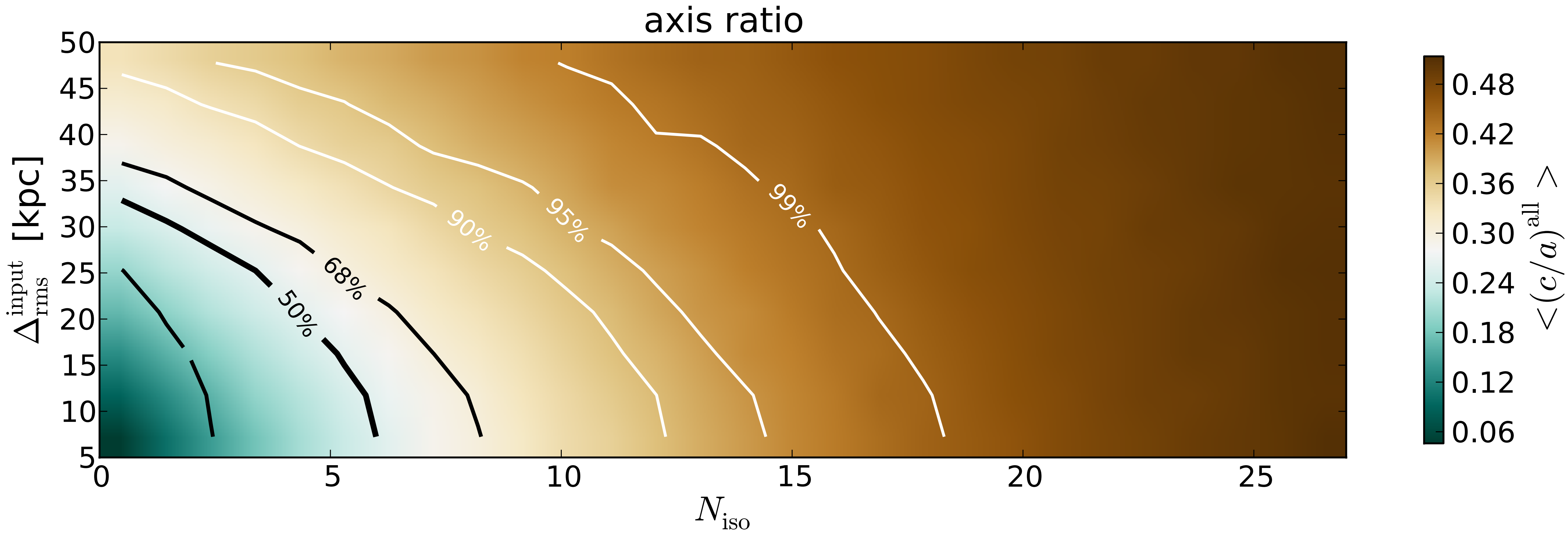


Distribution of normal vectors for $N_{\mathrm{iso}} = 27$ (isotropic only)

How many MW satellites can be part of isotropic distribution? Pawlowski in prep.

Set up artificial MW satellite distributions following SDSS survey footprint:

- Preserve Galactocentric distances
- $N_{\rm iso}$: 0 to 27 satellites in isotropic distribution
- The others in planar, polar distribution with input rms height of 5 to 50 kpc



➡ Expect 1 to 6 of the considered satellites to not be part of satellite plane

➡ > 50% in isotropic distribution excluded at ≥95%

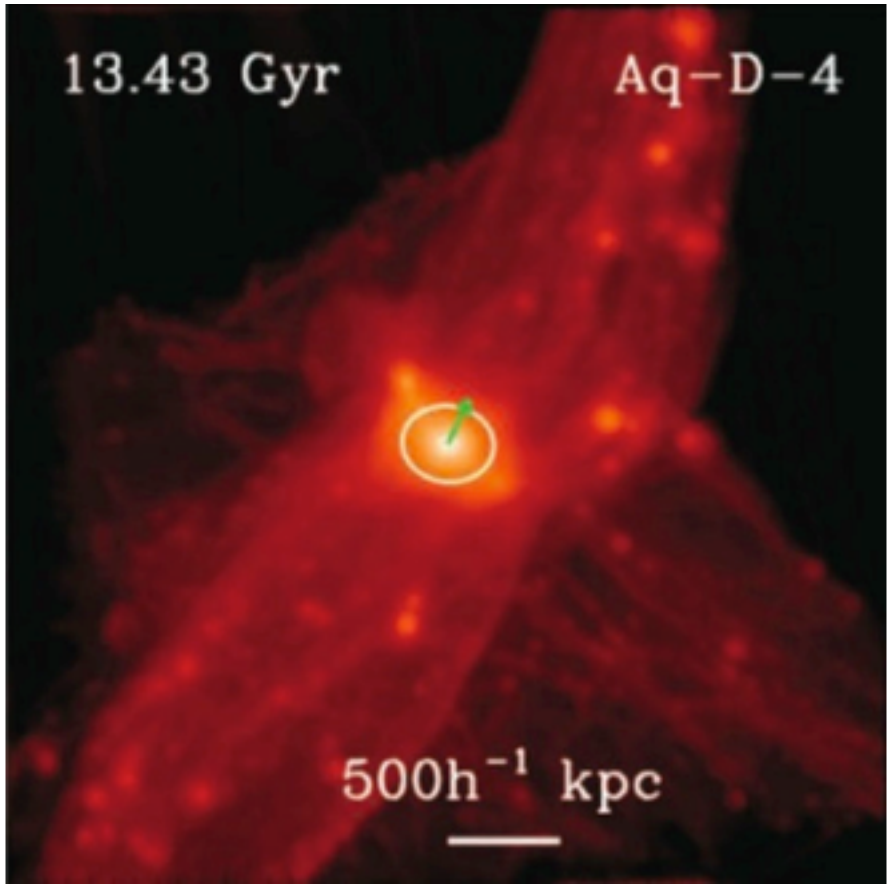
Suggested origins

Satellite planes too significant to be coincidence, require explanation.
Several formation scenarios have been suggested:

Suggested origins

Satellite planes too significant to be coincidence, require explanation. Several formation scenarios have been suggested:

- Filamentary accretion

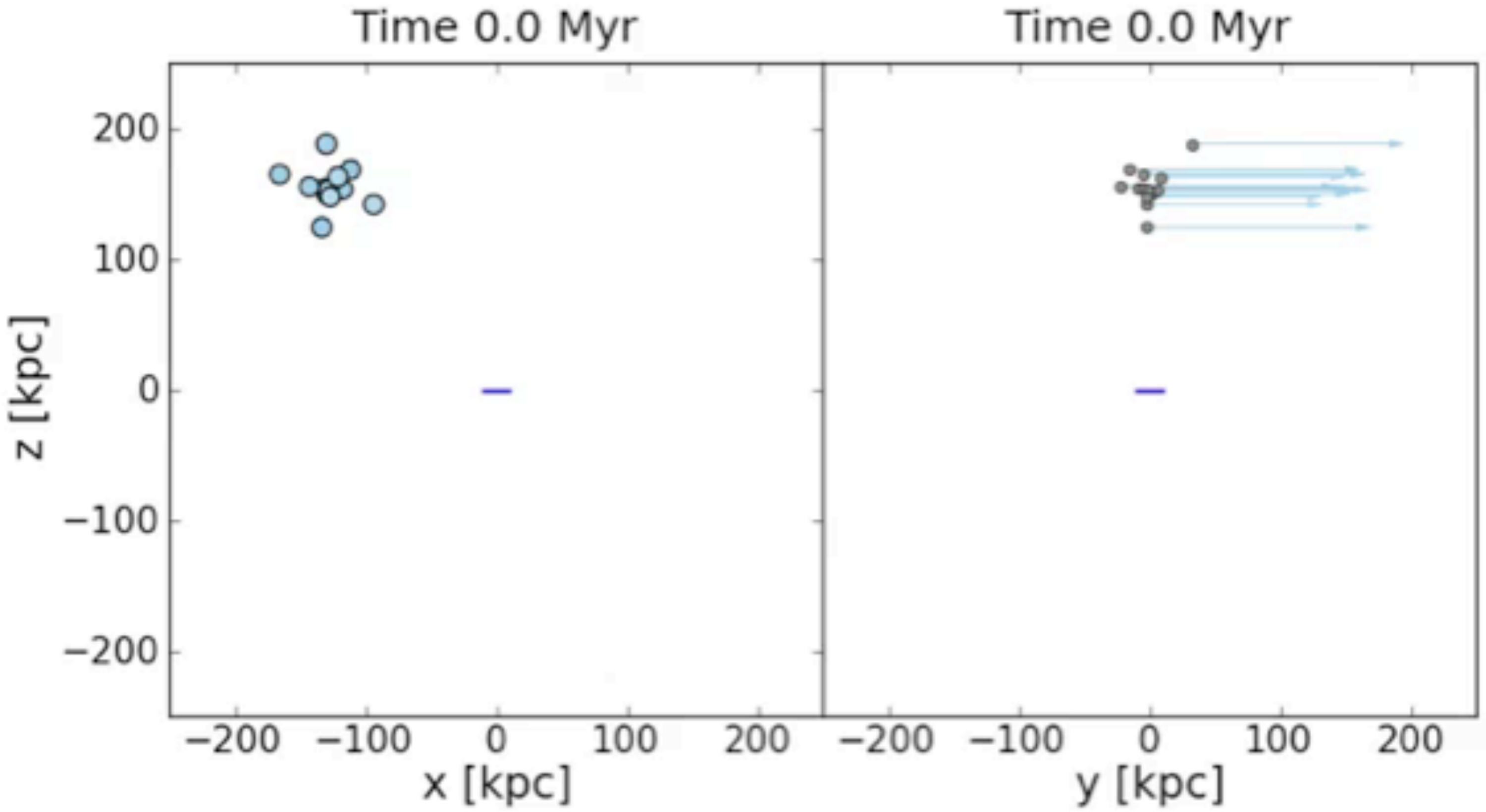


Vera-Ciro et al. (2011)

Suggested origins

Satellite planes too significant to be coincidence, require explanation. Several formation scenarios have been suggested:

- Filamentary accretion
- Group infall

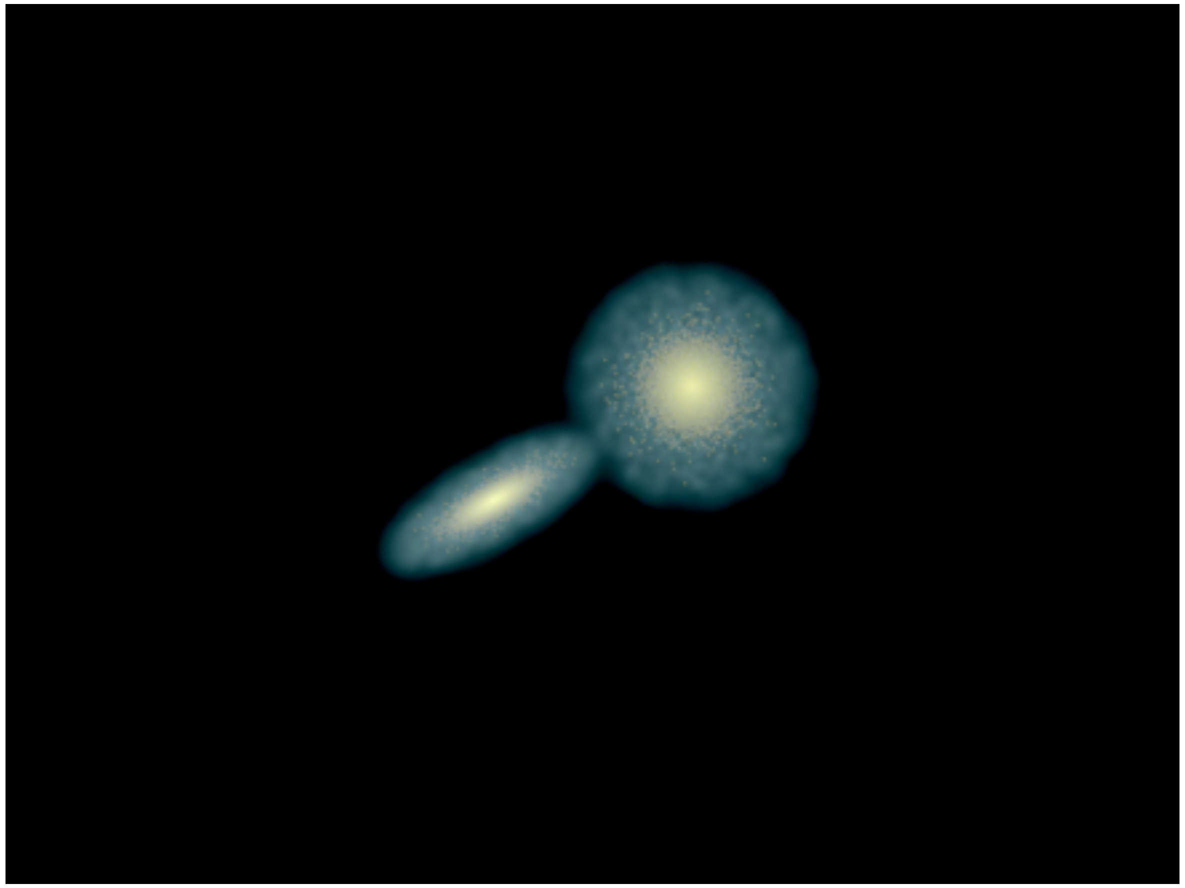


Pawlowski in prep.

Suggested origins

Satellite planes too significant to be coincidence, require explanation.
Several formation scenarios have been suggested:

- Filamentary accretion
- Group infall
- Tidal Dwarf Galaxies (TDGs)



Wetzstein et al. (2007)

Suggested origins

Satellite planes too significant to be coincidence, require explanation.
Several formation scenarios have been suggested:

- Filamentary accretion
- Group infall
- Tidal Dwarf Galaxies (TDGs)

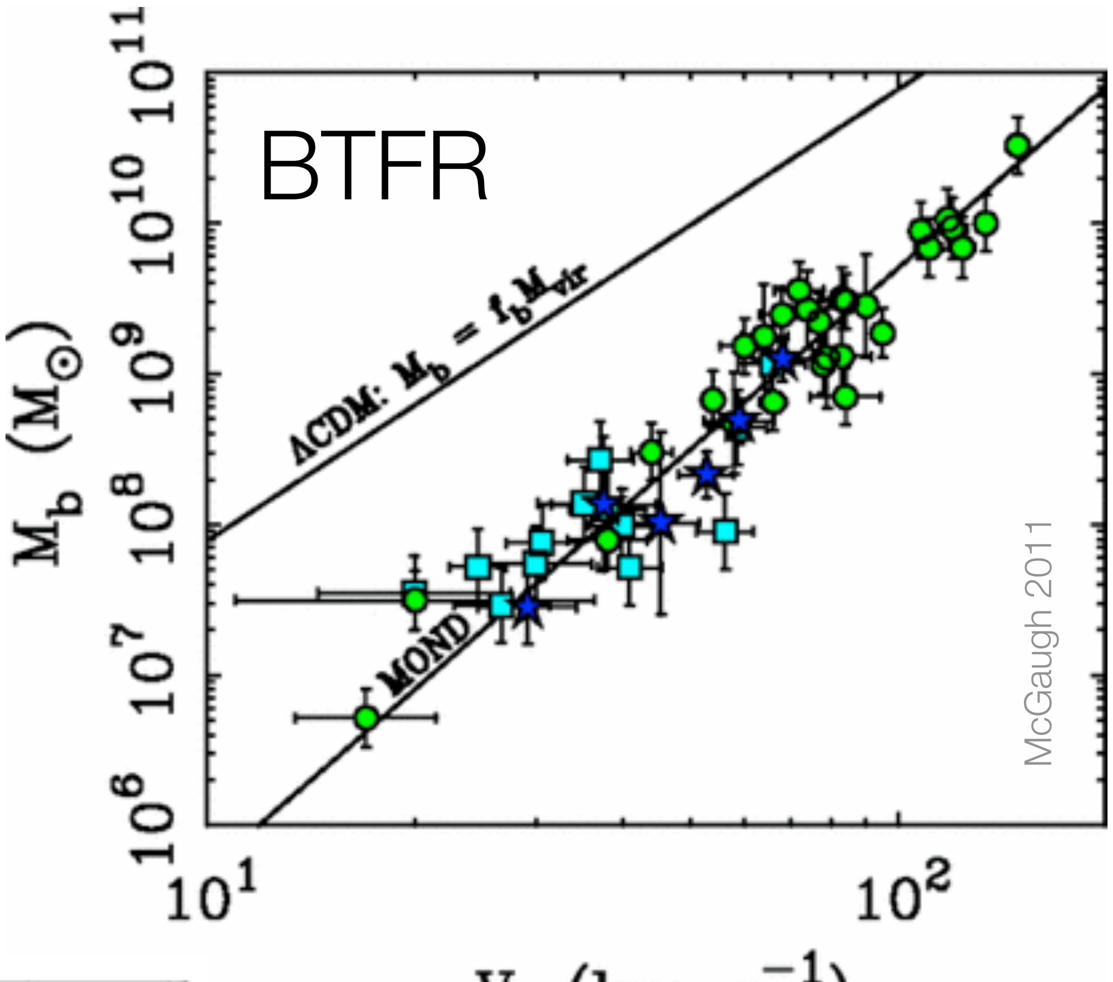
} Must already be part of cosmological simulations

Significant anisotropy ≠ sufficiently strong planar alignment

Predictive success of baryons

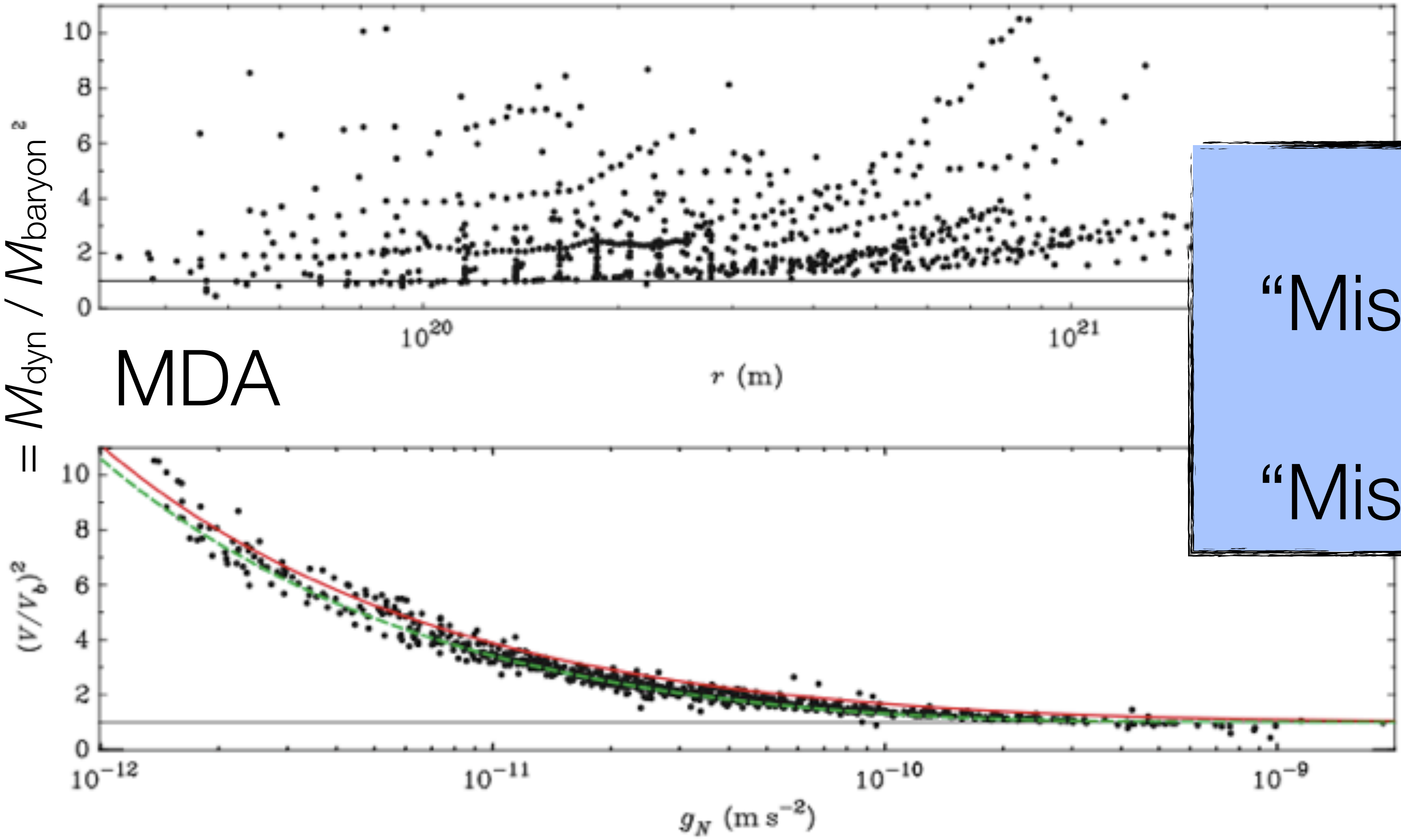
Galaxy formation in ΛCDM highly stochastic, but baryons very successfully predict dynamics

- Baryonic Tully-Fisher relation
- Mass discrepancy – acceleration relation
- Dwarf galaxy velocity dispersions



BTFR

McGaugh 2011

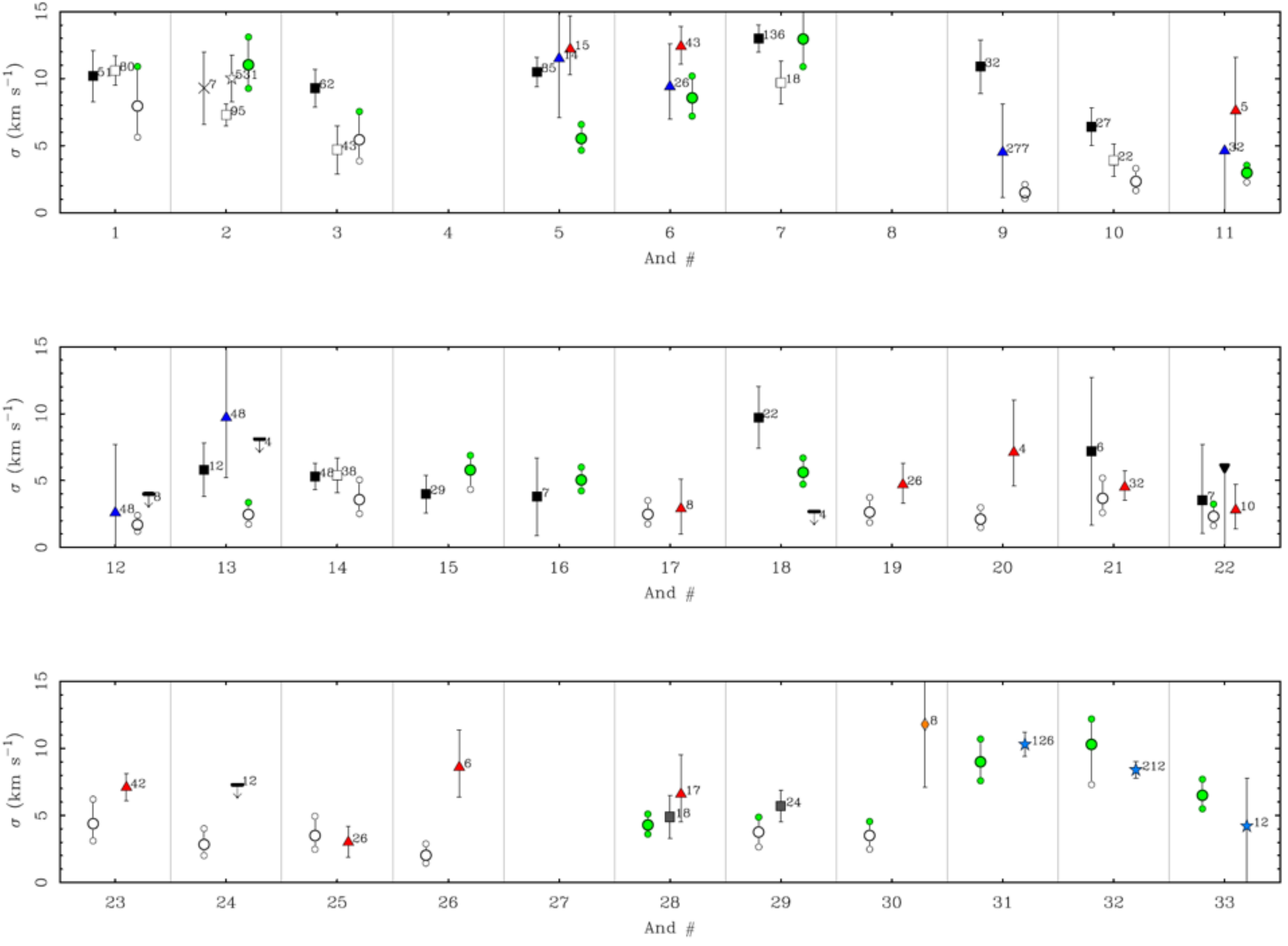


$= M_{dyn} / M_{baryon}$ ^{2}

MDA

Famaey & McGau

Not only a
"Missing Mass Problem"
but also a
"Missing Mess Problem"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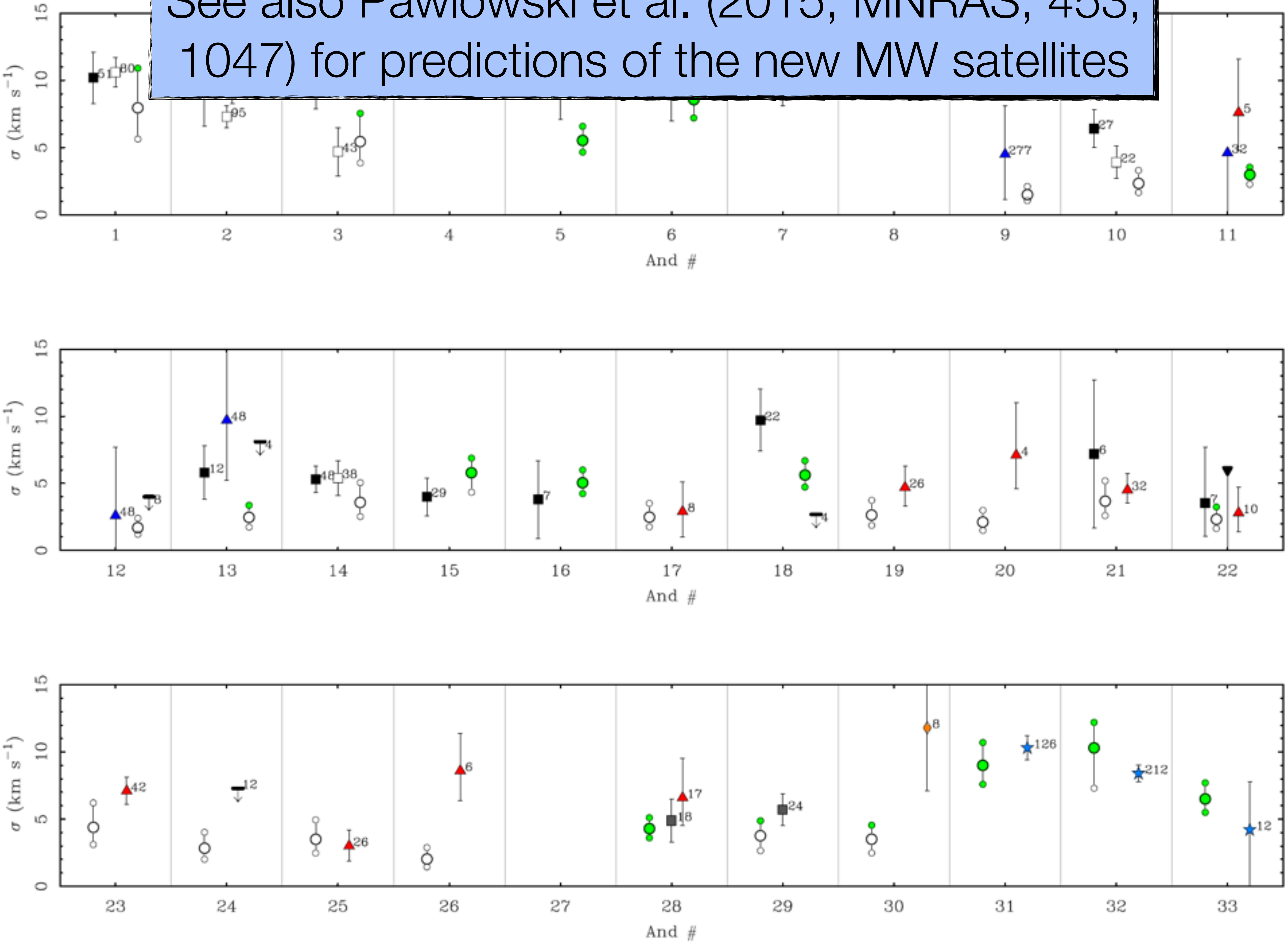
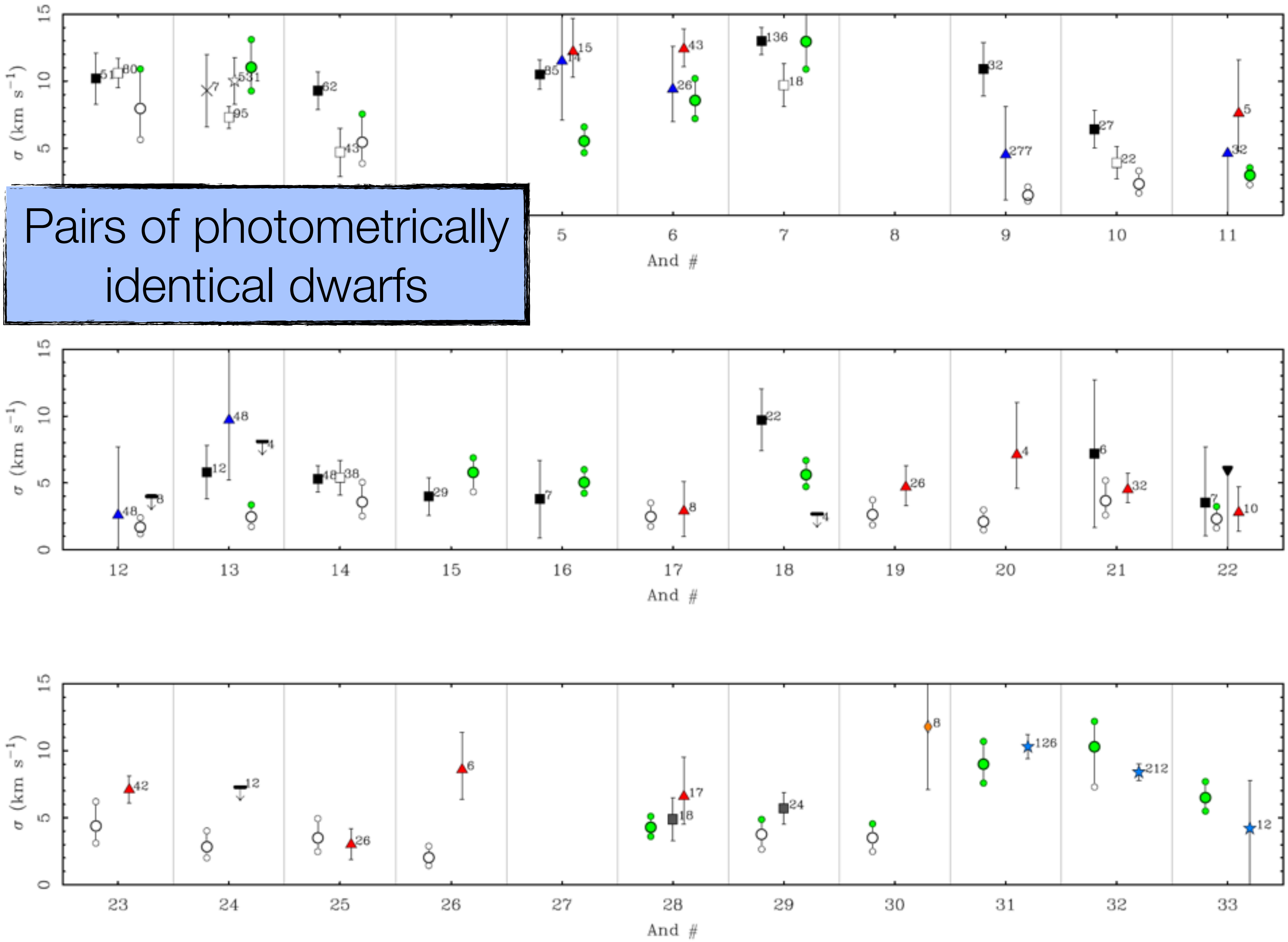
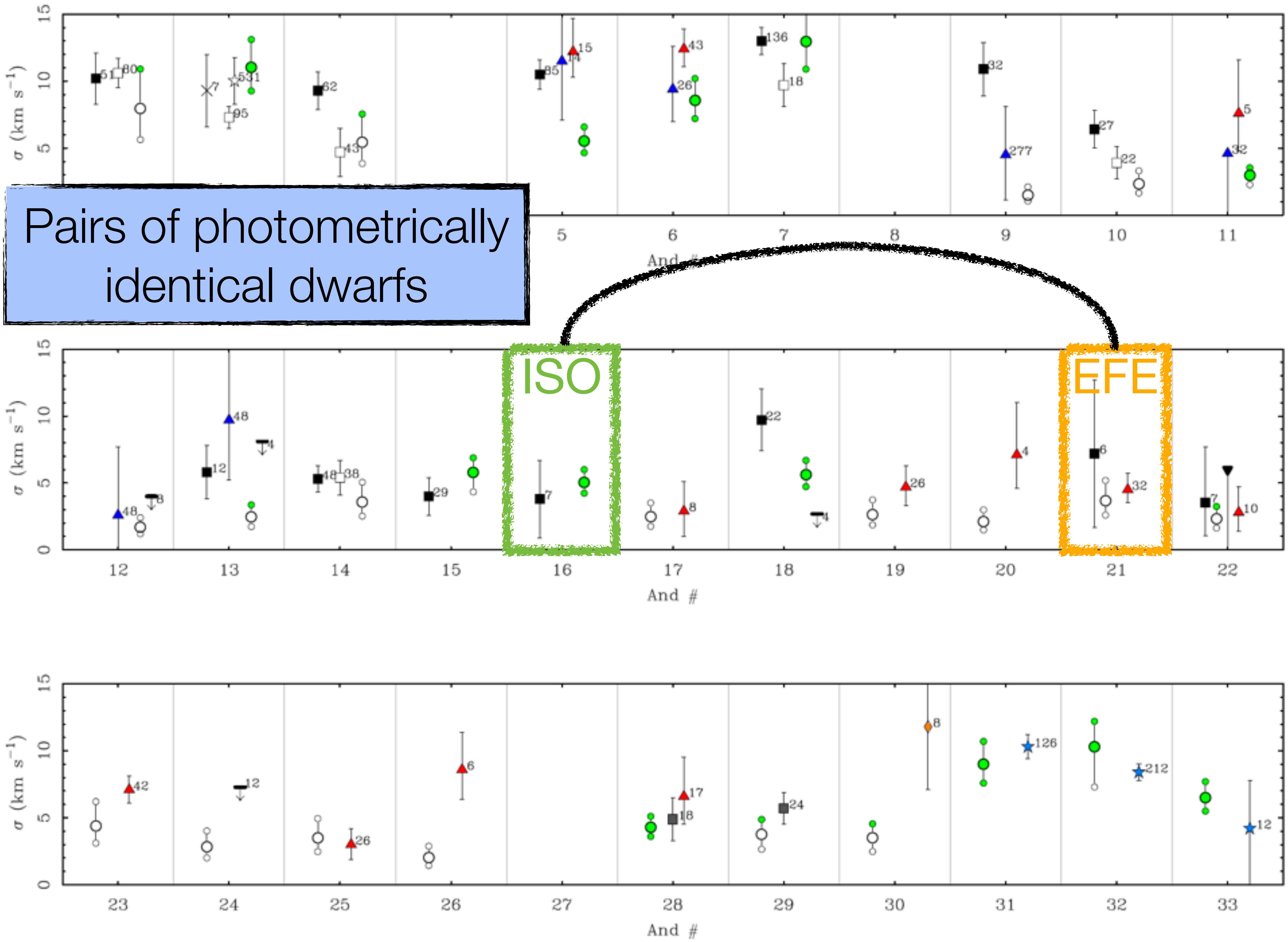
See also Pawlowski et al. (2015, MNRAS, 453, 1047) for predictions of the new MW satellites





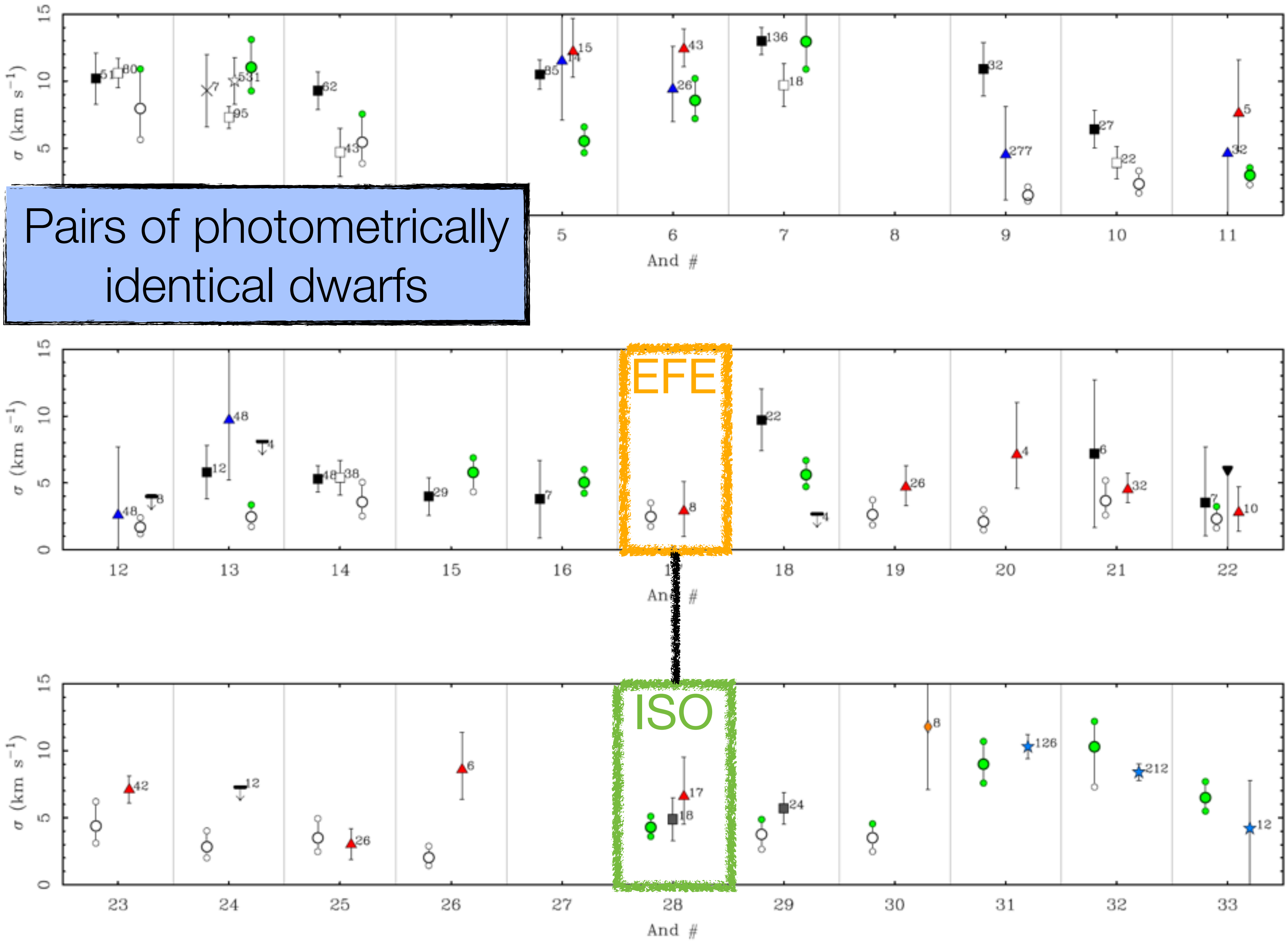
Pairs of photometrically identical dwarfs



Pairs of photometrically identical dwarfs

ISO

EFE



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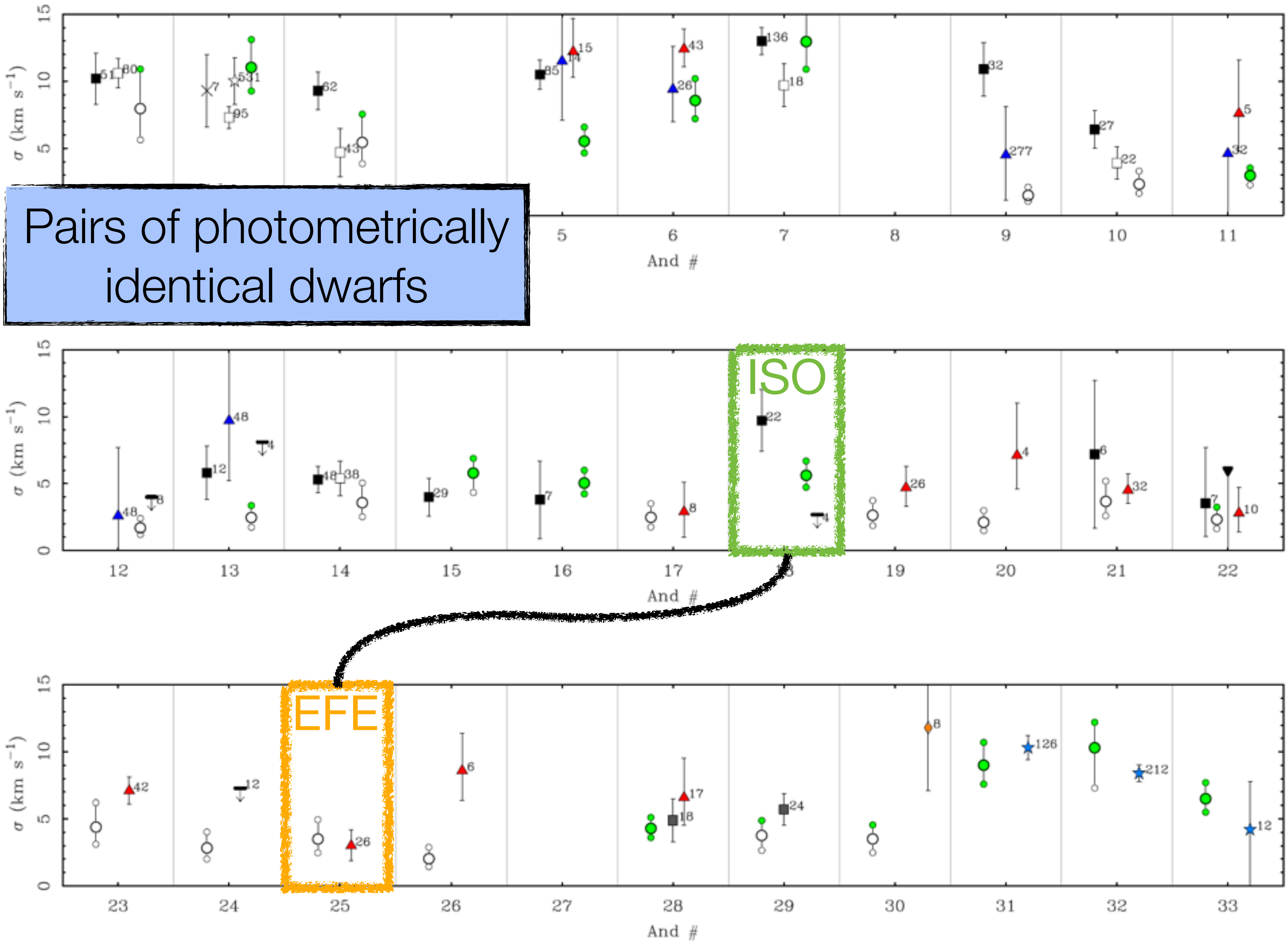

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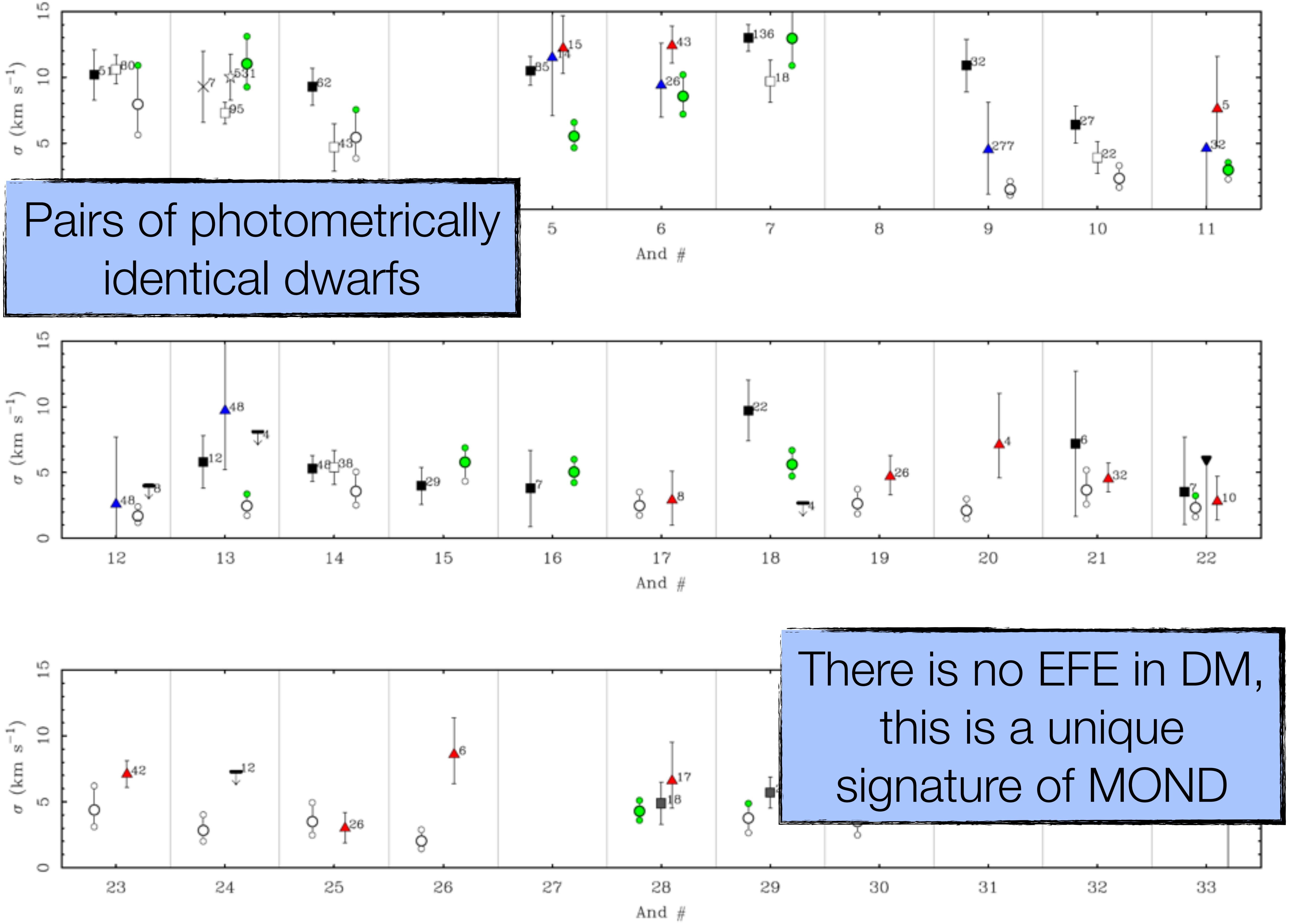
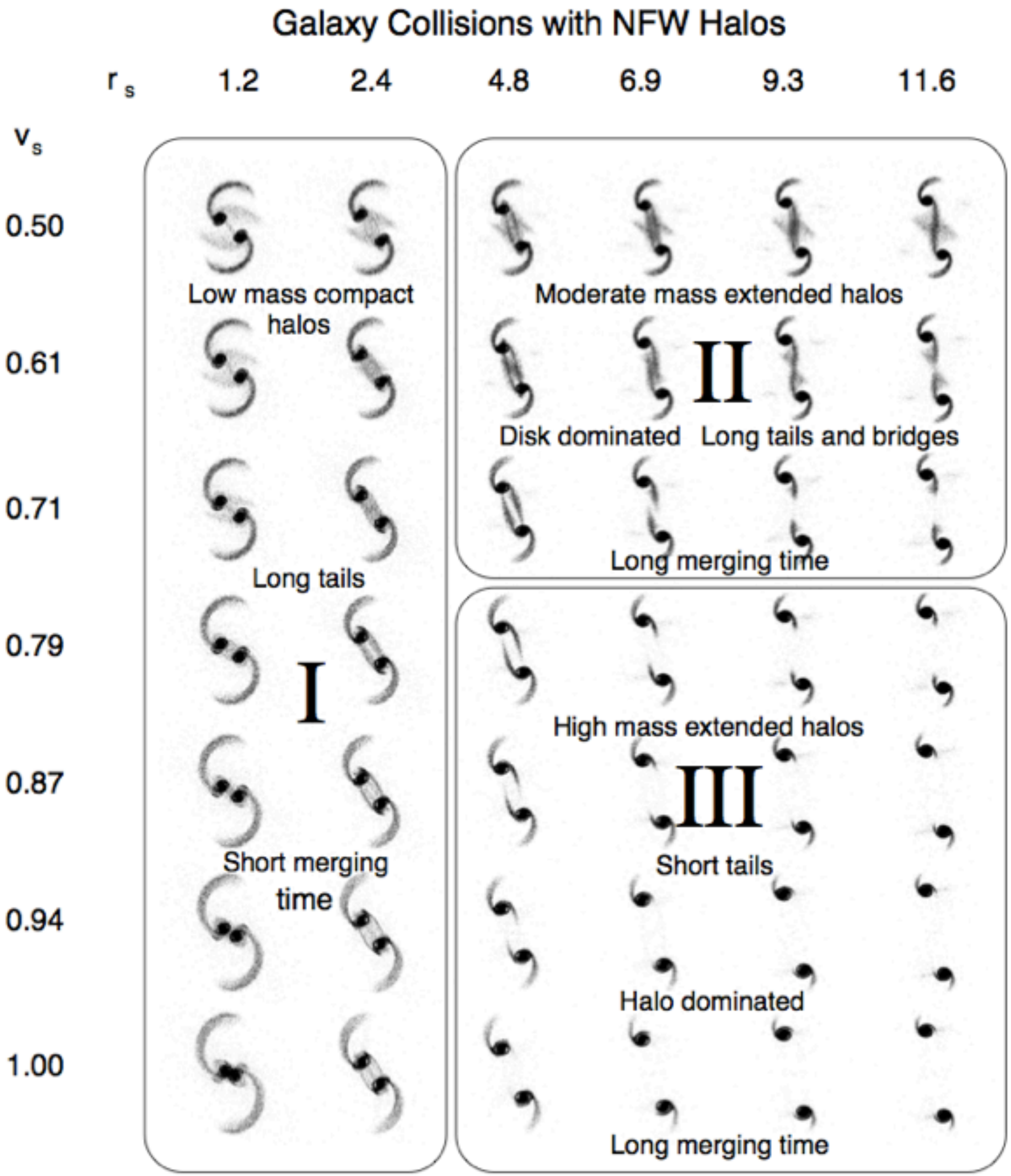


Pairs of photometrically identical dwarfs

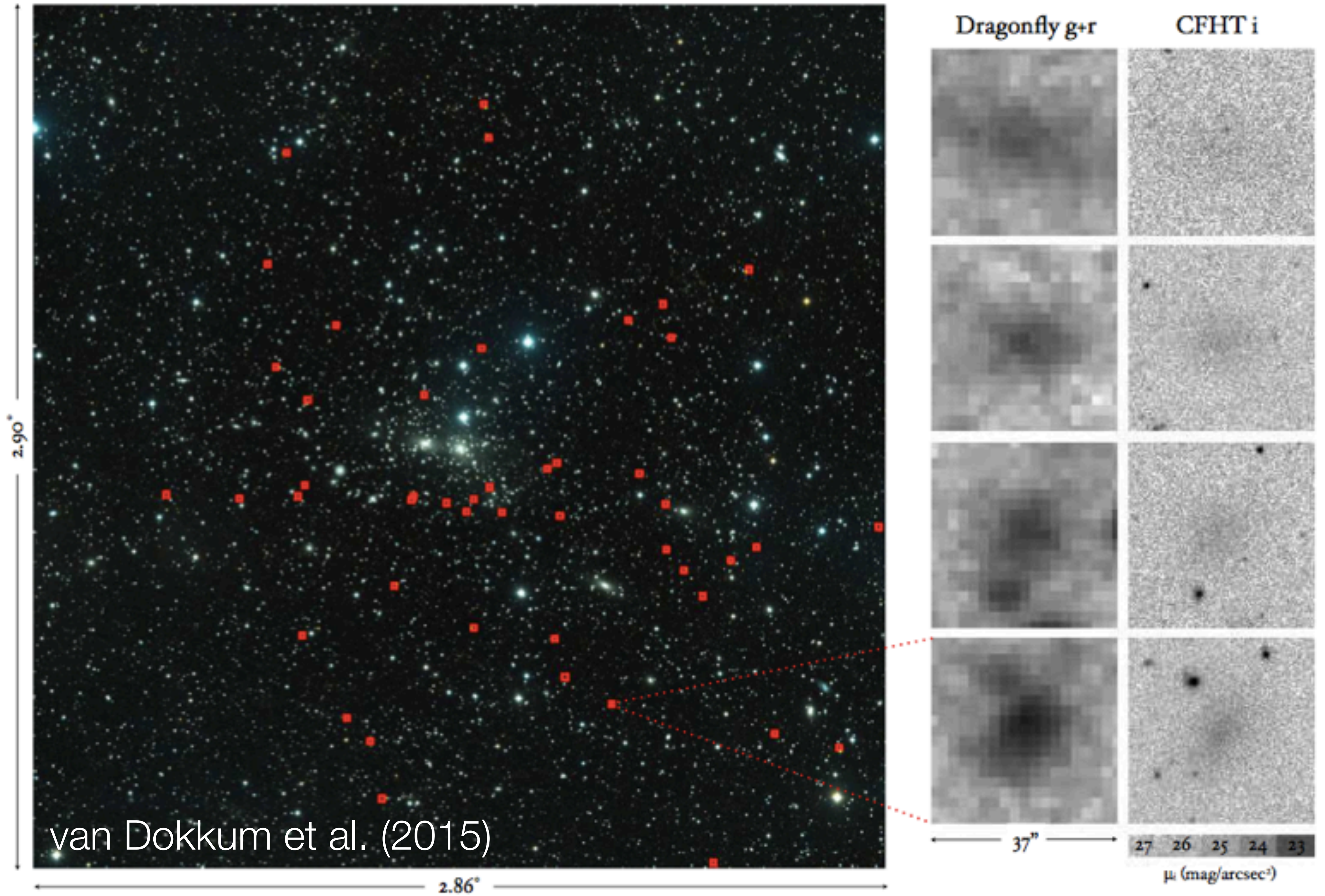
There is no EFE in DM, this is a unique signature of MOND

Tidal tail length



Dubinski, Mihos & Hernquist (1999)

Ultra Diffuse Galaxies



van Dokkum et al. (2015)

Figure 1. Main panel: spatial distribution of the newly discovered galaxies, projected on a color image of the Coma cluster created from the Dragonfly *g* and *r* images. Only the 2.°86 × 2.°90 area that is covered by CFHT imaging is shown, as we cannot confirm candidate galaxies that have no CFHT coverage. Panels at right: typical examples of the galaxies, spanning a range in brightness. They are easily detected but barely resolved in the Dragonfly data, and barely detected but easily resolved in the CFHT images.

Ultra Diffuse Galaxies

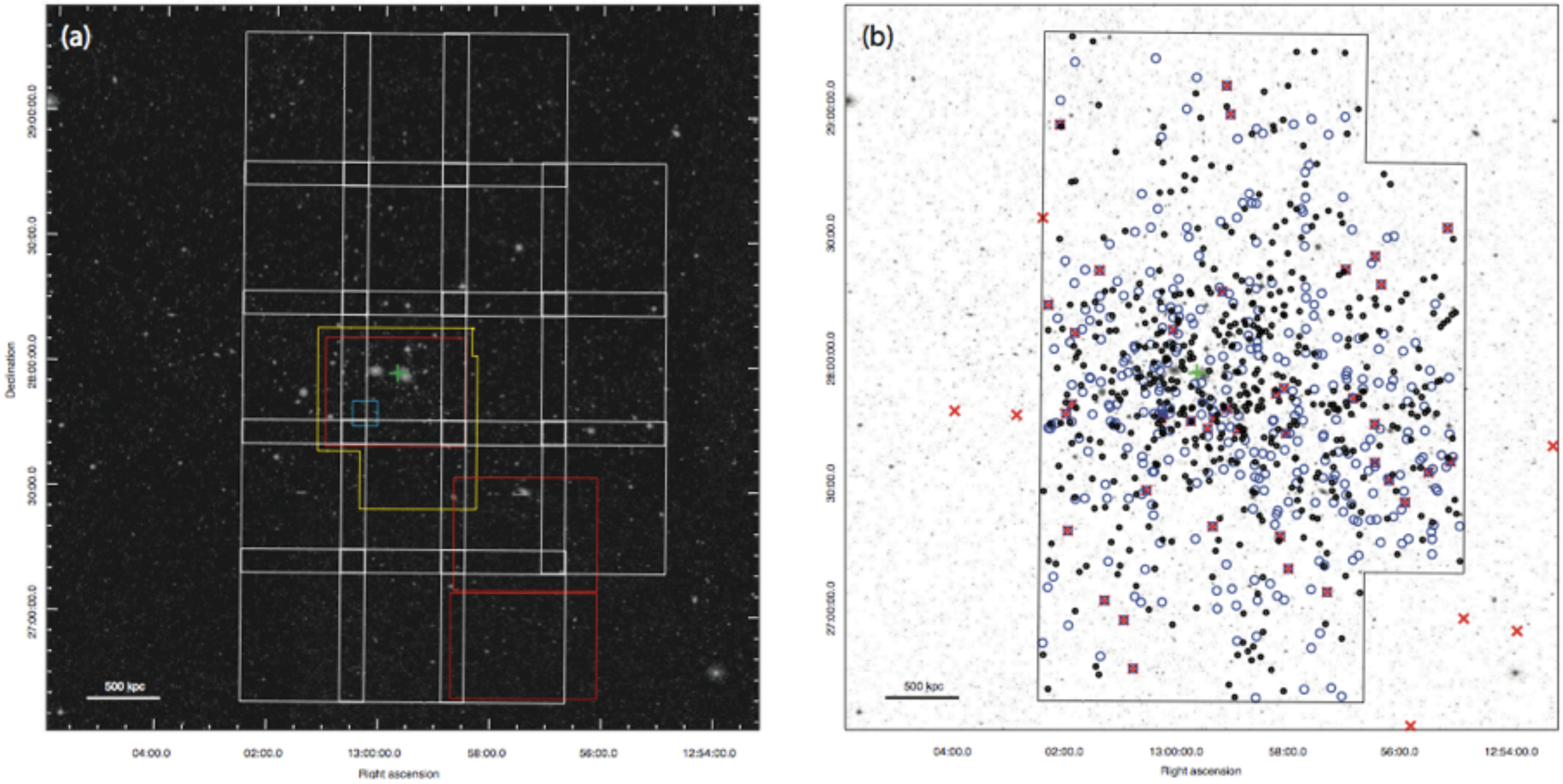


Fig. 1.— The 2.86 deg ×2.90 deg (~ 4.87 × 4.94 Mpc^2) area centered on the Coma cluster, the same area as in Figure 1 of van Dokkum et al. (2015a). (a) Image from the Digitized Sky Survey. The white borders show the 18 fields covered in the Subaru R band (Okabe et al. 2014), which have the total area of 4.1 degree^2, about 1/2 of the Dragonfly coverage. Red indicates the area analyzed by Yamanoi et al. (2012). Yellow outlines the area analyzed by Yagi et al. (2010) using the Subaru B, R, Hα, i bands. Cyan indicates the area in Figure 2. The center of the cluster (α_{J2000},δ_{J2000})=(12:59:42.8,+27:58:14) is marked with a green cross (White et al. 1993). (b) The same area as in (a), showing the distribution of the 854 Subaru UDGs (circles). The MW-sized UDGs, with large effective radii (> 1.5 kpc), are shown in blue. The Subaru field coverage in R is enclosed with the solid line. The 47 Dragonfly UDGs are indicated with red crosses.

Koda et al. (2015)

Suggested solutions in ΛCDM

Problems affected by baryons:

- Missing Satellites
- TBTF
- Core-Cusp

Showing that a baryonic effect can solve one problem does not mean it simultaneously solves all others! Solutions might be mutually exclusive (e.g. Penarrubia et al., 2012).

Problems not strongly affected by baryons

- Satellite galaxy planes (assuming the satellites are sub-halos!)
- Length of tidal tails

Modifications to DM:

- WDM
- IDM
- SIDM
- mixed DM
- …

The problems in MOND

Problems solved automatically

… or observations predicted by MOND:

- Baryonic Tully-Fisher relation
- Mass-discrepancy–acceleration relation
- …

Problems that do not even apply

- Missing Satellites
- Too-big-to-fail
- Core-cusp

While those problems do not apply to MOND because they are based on comparison with ΛCDM sub-halos, the first two might well have an equivalent in MOND!

➡ Need structure formation in MOND -> hard!

Problems that might be solved

Possible, but nor guaranteed a priori -> need simulations

- Stability of LSB disks (requires tool to precisely set up disks)
- Abundance of bulge-less galaxies (needs structure formation in MOND, but more simple tests of bulge formation in interacting galaxies possible first)
- Dynamical Friction (e.g. Guillaume’s work on Sagittarius)
- Length of tidal tails (first result by Florent)
- Ultra Diffuse Galaxies (Milgrom suggests simple simulations)
- Satellite planes: via TDGs?

How can MOND help to solve the Satellite Plane Problem

---

1) Tidal Dwarf Galaxies

- Naturally explain phase-space correlation (incl. counter-rotation)
- Shouldn’t contain DM, so MOND would explain hight M/L of satellites

2) Structure formation different?

- Maybe primordial galaxies are accreted differently in MOND?

➡ Needs large-scale simulations!

Why solving the Satellite Plane Problem in MOND is not trivial

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What do we need to show?

Do enough TDGs (of sufficient mass) form to make up ≥50% of MW/M31 satellites?

Can the TDGs have lost all their gas by now, but still be stable?

Can the TDGs have star formation histories consistent with observed dSphs?

Is there a consistent galaxy collision scenario forming TDGs?

Do these end up in the right places (orientation, spin, extend of satellite planes)

How can we do this?

Divide and conquer: approach the problems separately first.

Major project, difficult for one person alone. Work together!

Be aware that this solution might not work out!

Small-scale problems for MOND

Some systems do not follow MOND predictions:

- But can we always be sure about the data/assumptions?
- Difficult to judge relative to LCDM: at least MOND makes predictions

Ultra-faint dwarf galaxies have too-high velocity dispersions in MOND:

- But are they even expected to be in equilibrium in MOND?

➡ Can be tested with PoR simulations.

Tidal Dwarf Galaxy rotation curves (see Lelli et al. 2015, arXiv 1509.05404):

- First thought to be success for MOND, now new analysis says opposite.

➡ Need additional (and better) observations to see if this is really a problem.

➡ Simulate TDGs formation in PoR to determine more accurate MOND prediction.

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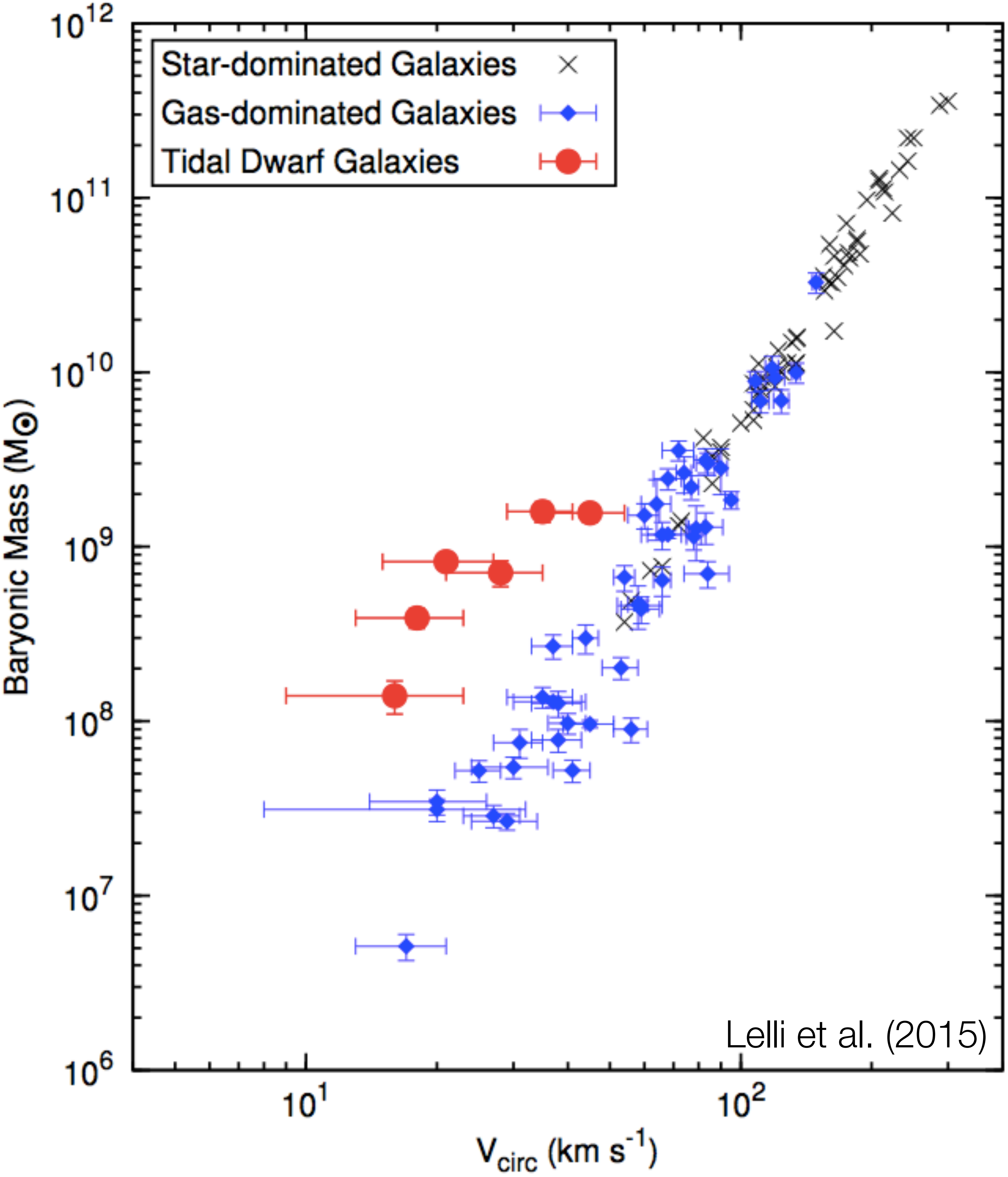

Lelli et al. (2015)

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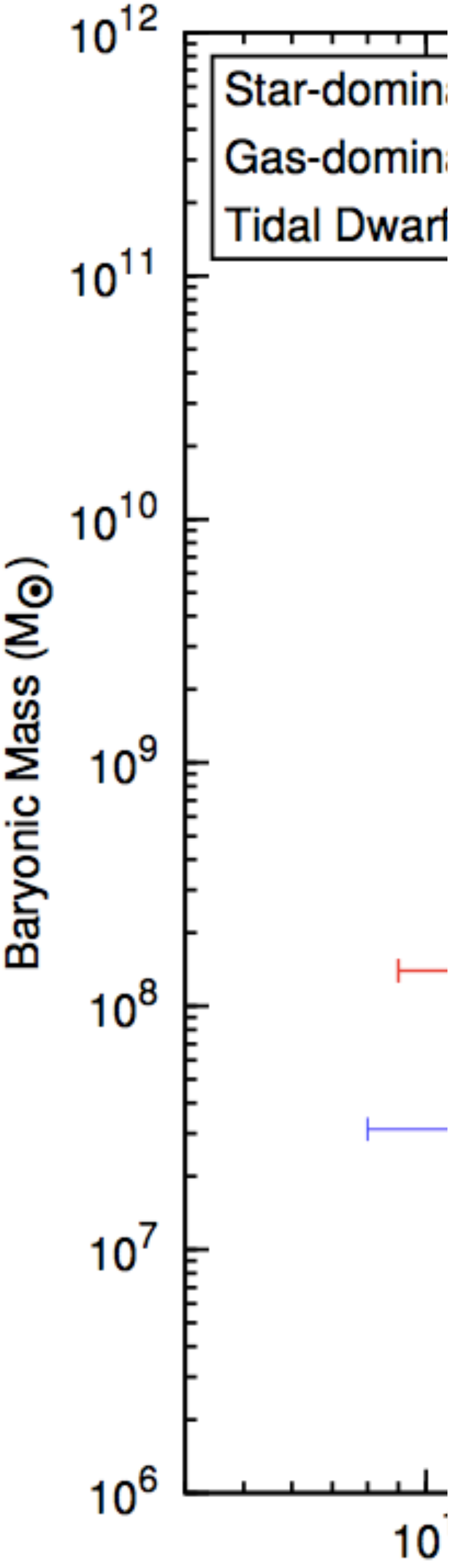
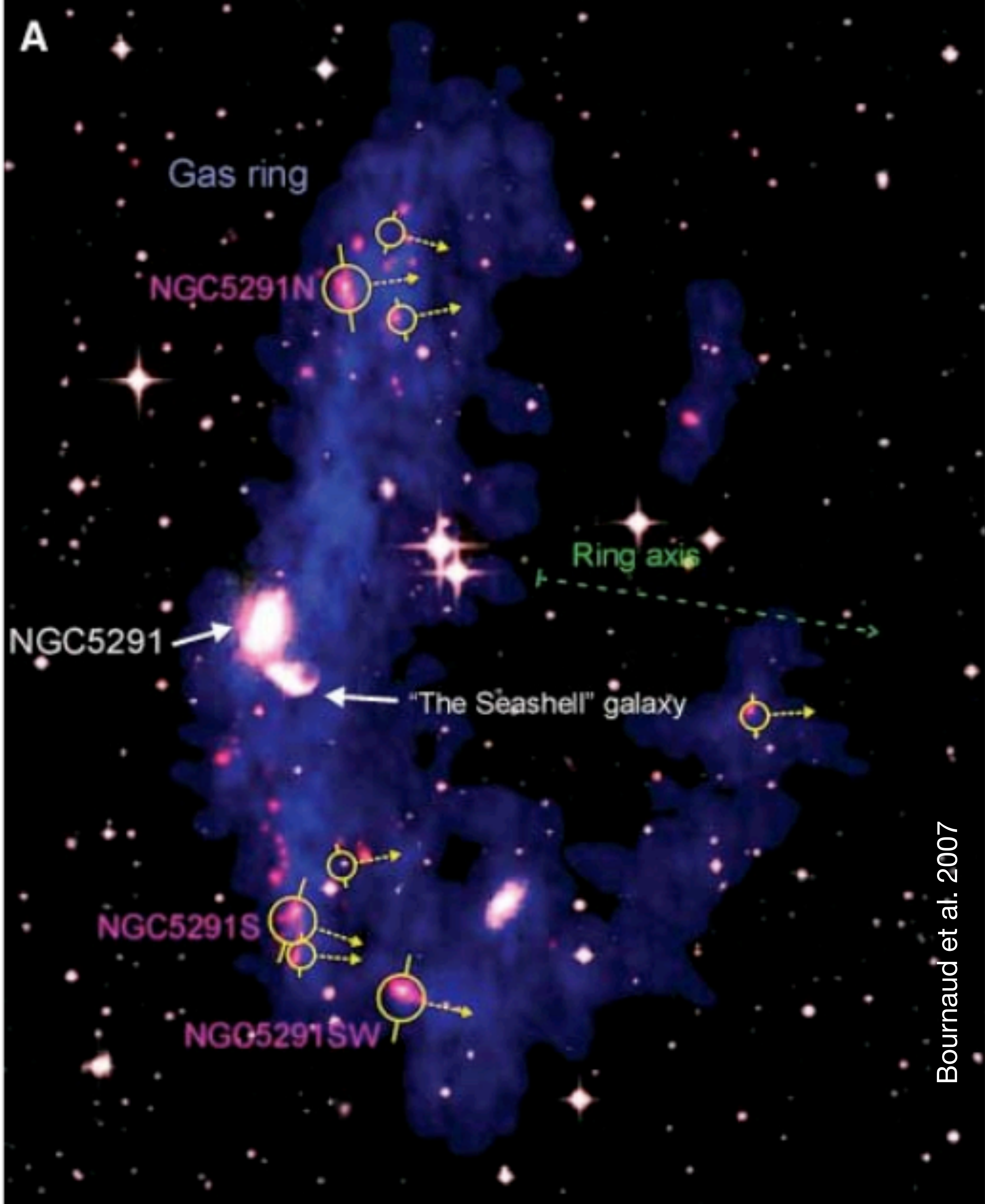
➡ Simu
pred





Bournaud et al. 2007

Conclusion

MOND …

… avoids many of the well-known small-scale problems of LCDM altogether.

… naturally gives rise to the observed scaling relations.

… has the potential to address many other open issues, especially via simulations.

The satellite plane issue, while addressed more easily in MOND via TDGs, still requires a lot of work to be solved satisfactorily!