Massive ΛCDM Subhalos and Bright Milky Way Satellites

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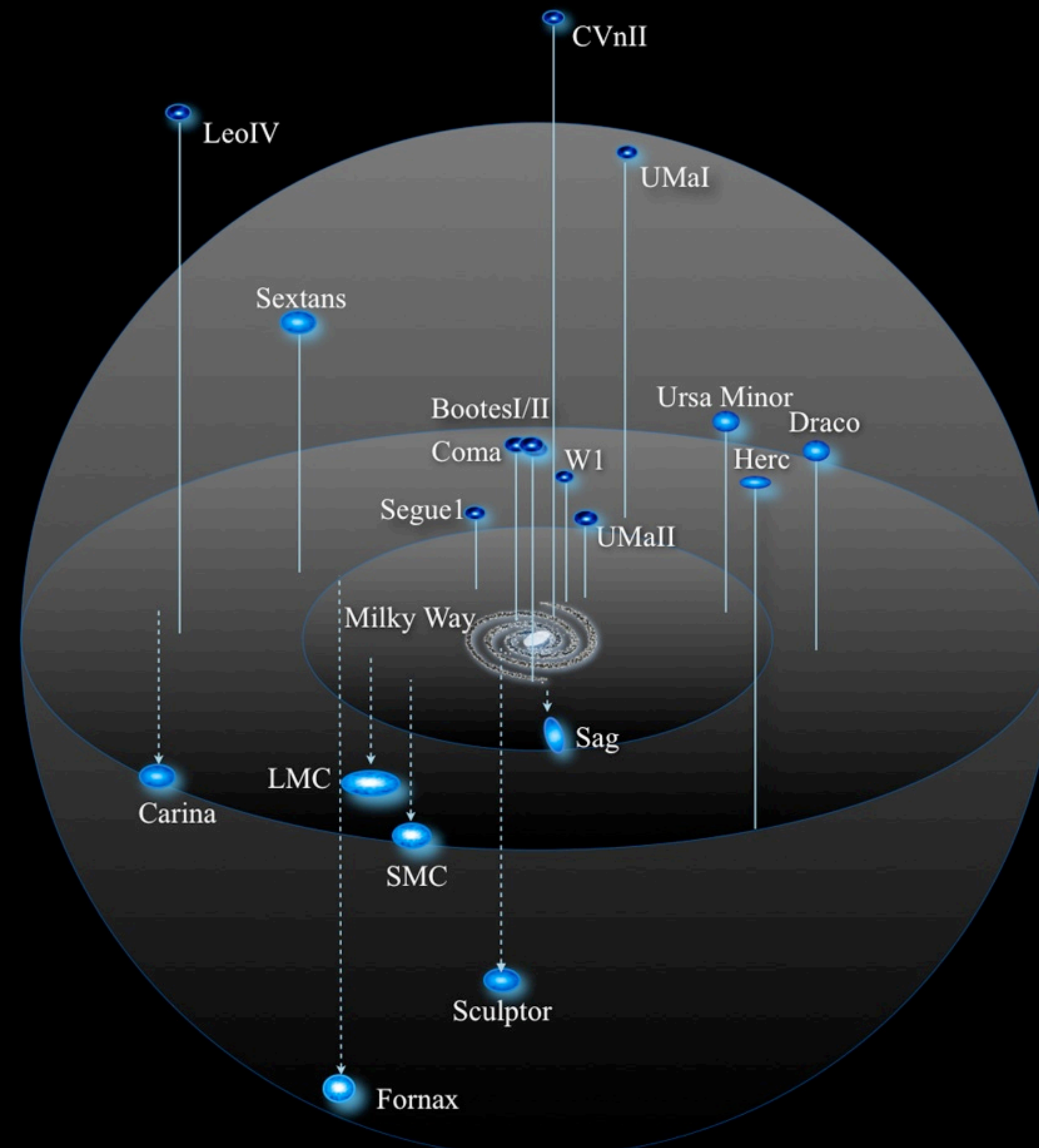
Massive ΛCDM subhalos versus bright Milky Way satellites

V. Springel / Virgo Consortium



J. Bullock

Observed Milky Way Satellites (circa 2008)

(from Tollerud et al. 2008)

Satellite	M_V	L_V ($L_\odot$)	d_{Sun} (kpc)	R_{half} (pc)
Carina	−9.4	4.92×10^5	94	210
Draco[c]	−9.4	4.92×10^5	79	180
Fornax	−13.1	1.49×10^7	138	460
LMC	−18.5	2.15×10^9	49	2591
Leo I	−11.9	4.92×10^6	270	215
Leo II[c]	−10.1	9.38×10^5	205	160
Ursa Minor	−8.9	1.49×10^5	69	200
SMC	−17.1	5.92×10^8	63	1088
Sculptor	−9.8	7.11×10^5	88	110
Sextans	−9.5	5.40×10^5	86	335
Sagittarius	−15	8.55×10^7	28	125

Pre-SDSS satellites

$L_V > 10^5 L_\odot$

Satellite	M_V	L_V ($L_\odot$)	d_{Sun} (kpc)	R_{half} (pc)
Boötes I[c]	−6.3	2.83×10^4	60	242
Boötes II[c]	−2.7	1.03×10^3	43	72
Canes Venatici I[c]	−8.6	2.36×10^5	224	565
Canes Venatici II[c]	−4.9	7.80×10^3	151	74
Coma[c]	−4.1	3.73×10^3	44	77
Hercules[c]	−6.6	3.73×10^4	138	330
Leo IV[c]	−5.0	8.55×10^3	158	116
Leo T	−8.0	5.92×10^4	417	170
Segue 1[d]	−1.5	3.40×10^2	23	29
Ursa Major I[c]	−5.5	1.36×10^4	106	318
Ursa Major II[c]	−4.2	4.09×10^3	32	140
Willman 1[c]	−2.7	1.03×10^3	38	25

SDSS-discovered satellites

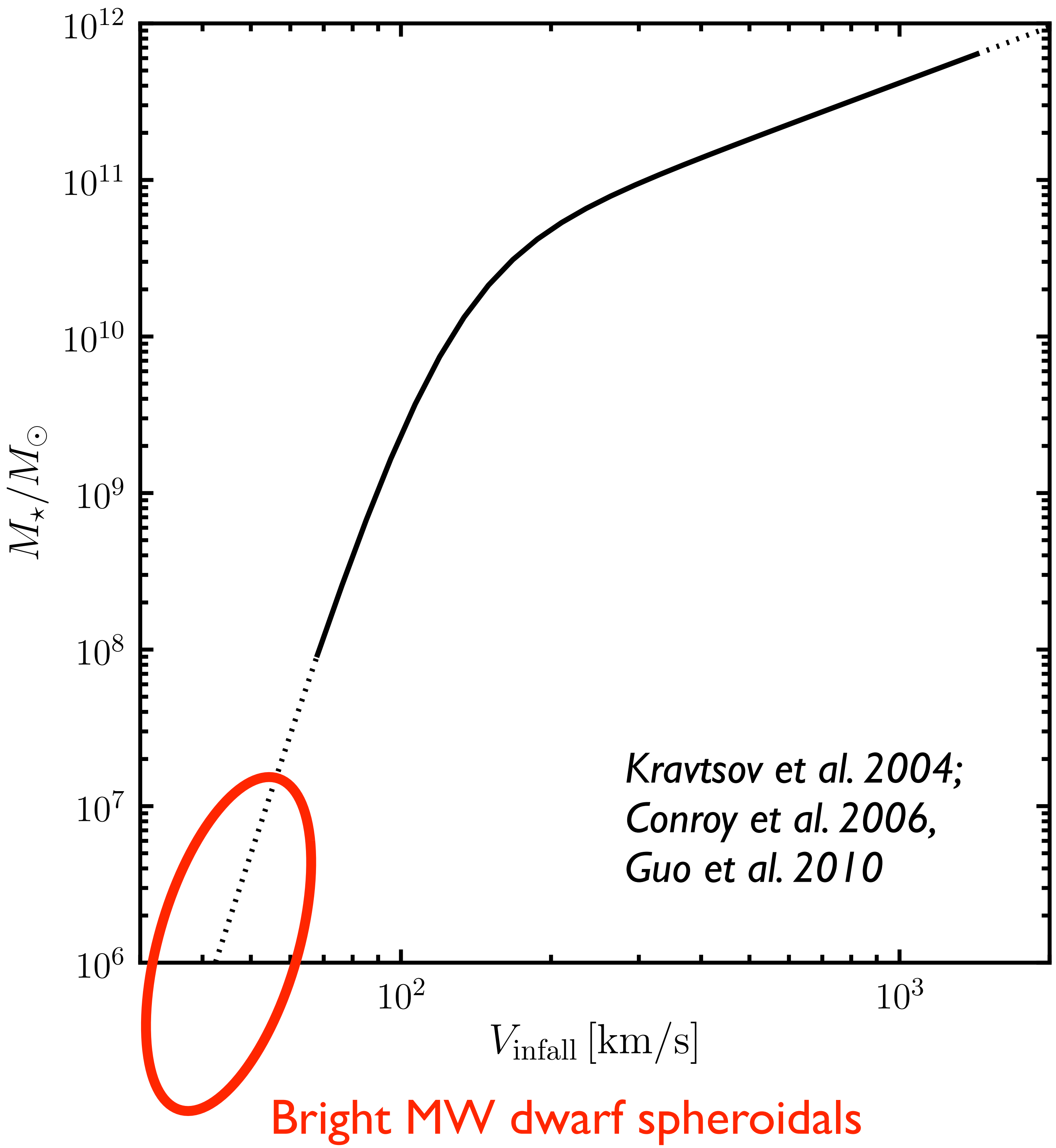
$L_V < 6 \times 10^4 L_\odot$

(except CVnI)

Associating galaxies with (sub)halos

Very simple model of galaxy - halo connection works remarkably well:

(1) every subhalo can host a galaxy, (2) more massive galaxies hosted by more massive subhalos



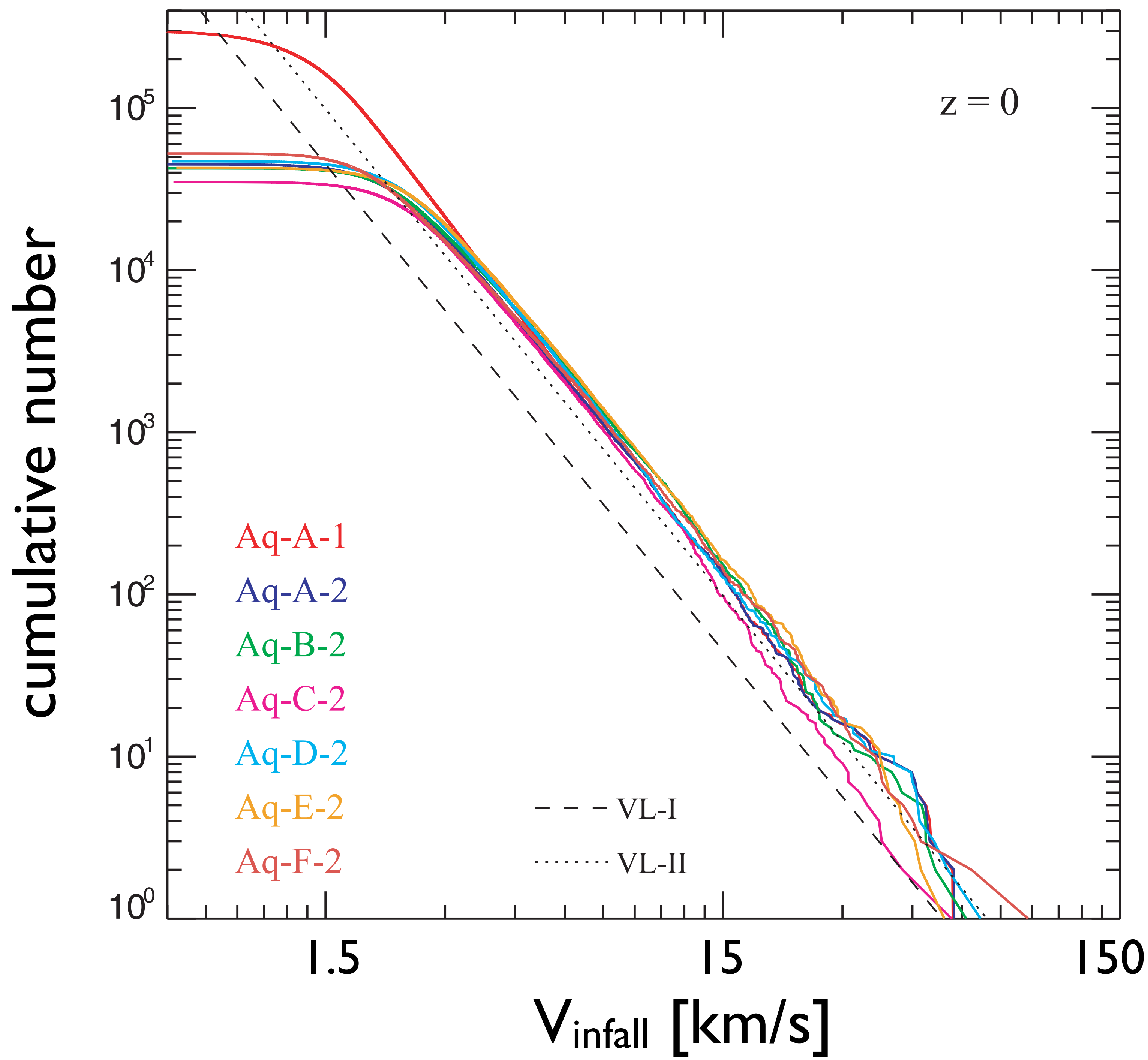
"Abundance Matching"

$$n(>M_\star) = n(>V_{\mathrm{infall}})$$

SDSS DR 7
(Abazajian et al. 2009, Li & White 2009)

Millennium, Millennium-II simulations
(Springel et al. 2005, MBK et al. 2009)

A modern look at MW substructure

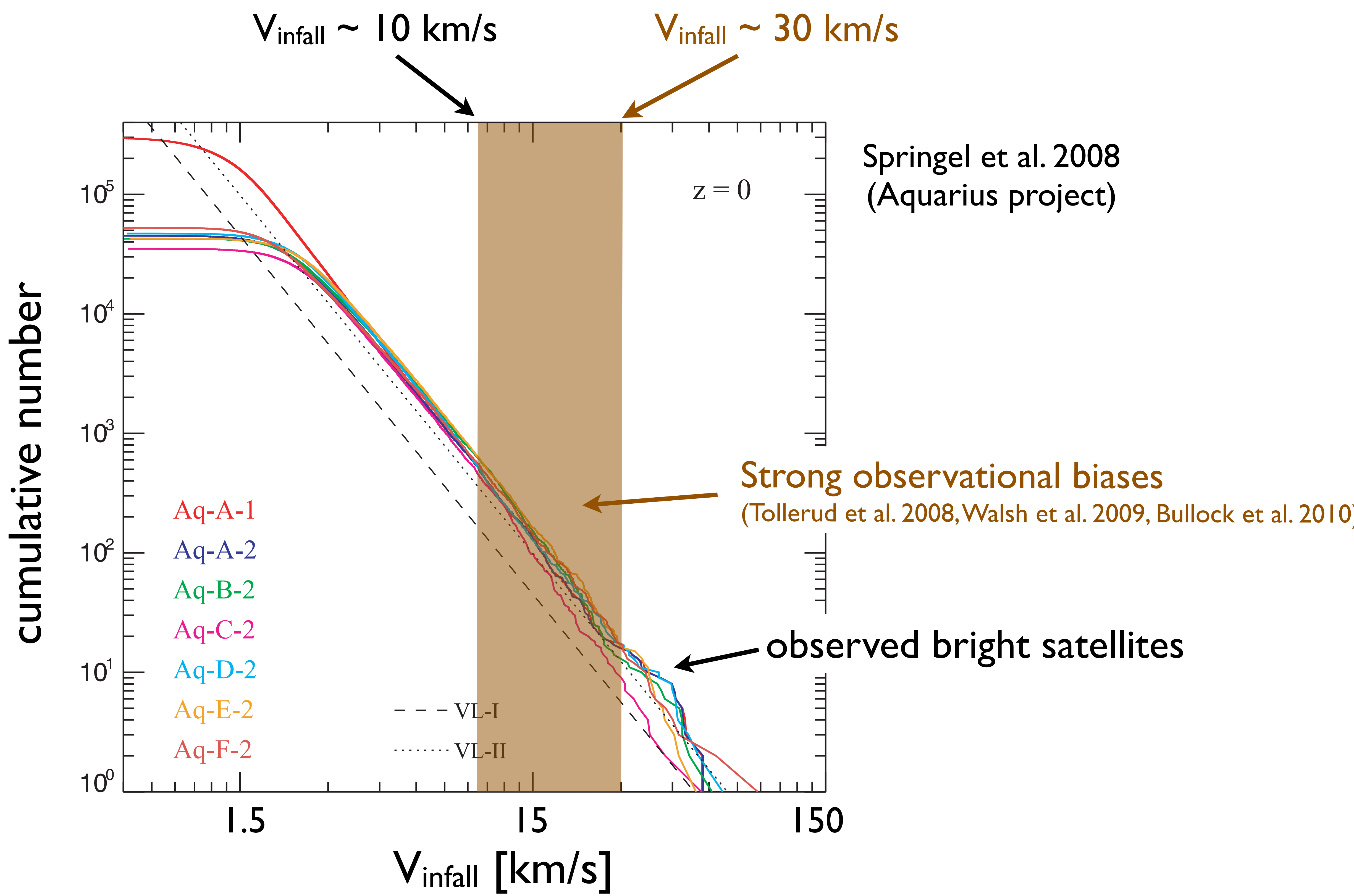


Springel et al. 2008
(Aquarius project)

Missing Satellites
(Klypin et al. 1999, Moore et al. 1999):

Mismatch between number of observed MW satellites and predicted subhalos

A modern look at MW substructure



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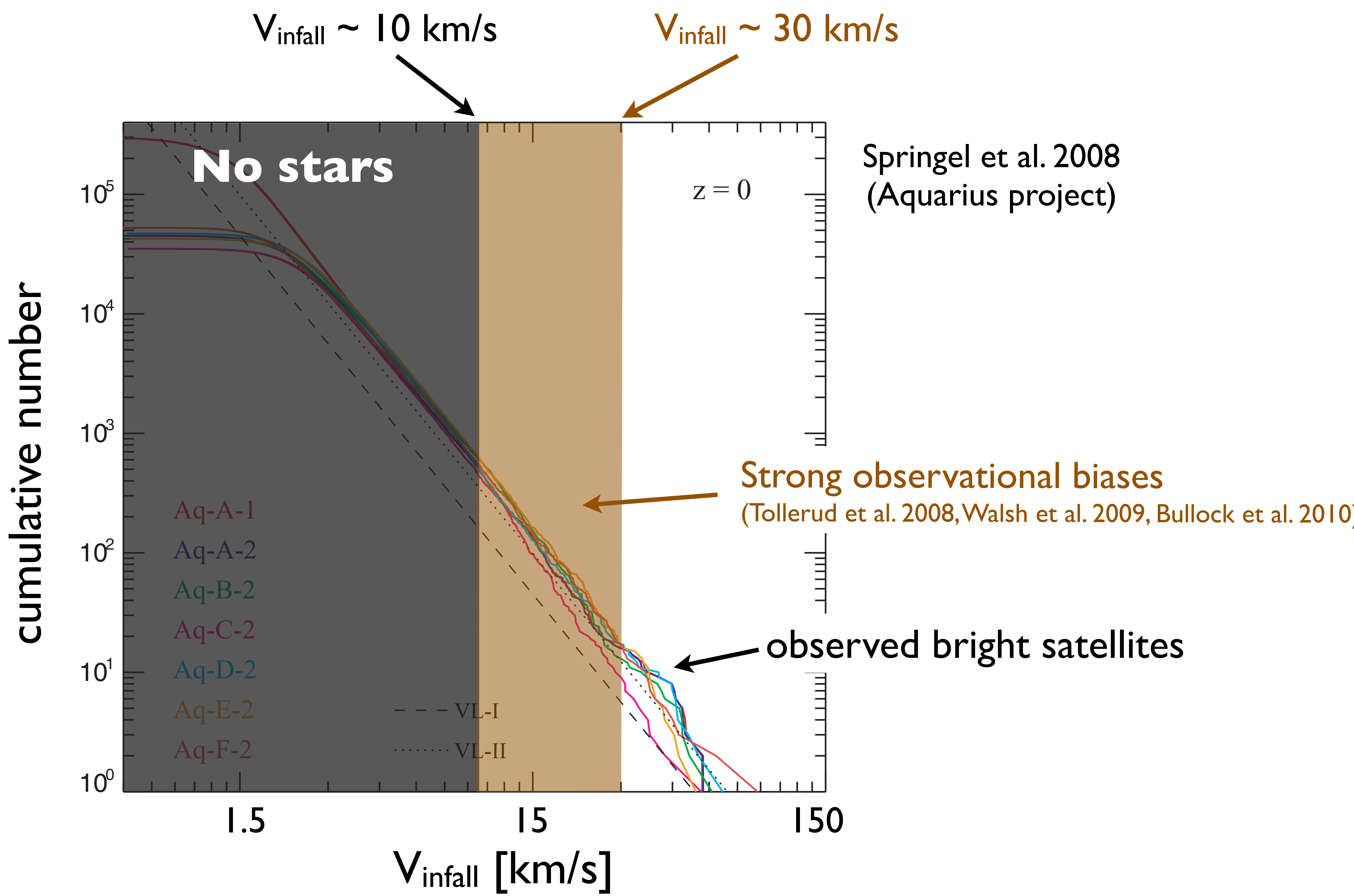
A modern look at MW substructure



Springel et al. 2008
(Aquarius project)

Does this picture work?

Comparison of **MW satellites** to **ΛCDM subhalos**:

- Dynamical mass at $R_{1/2}$ constrained to $\lesssim 10\%$ by observations (Wolf et al. 2010)
- *N*-body simulations now resolve $R_{1/2}$ (Springel et al. 2008, Diemand et al. 2008)

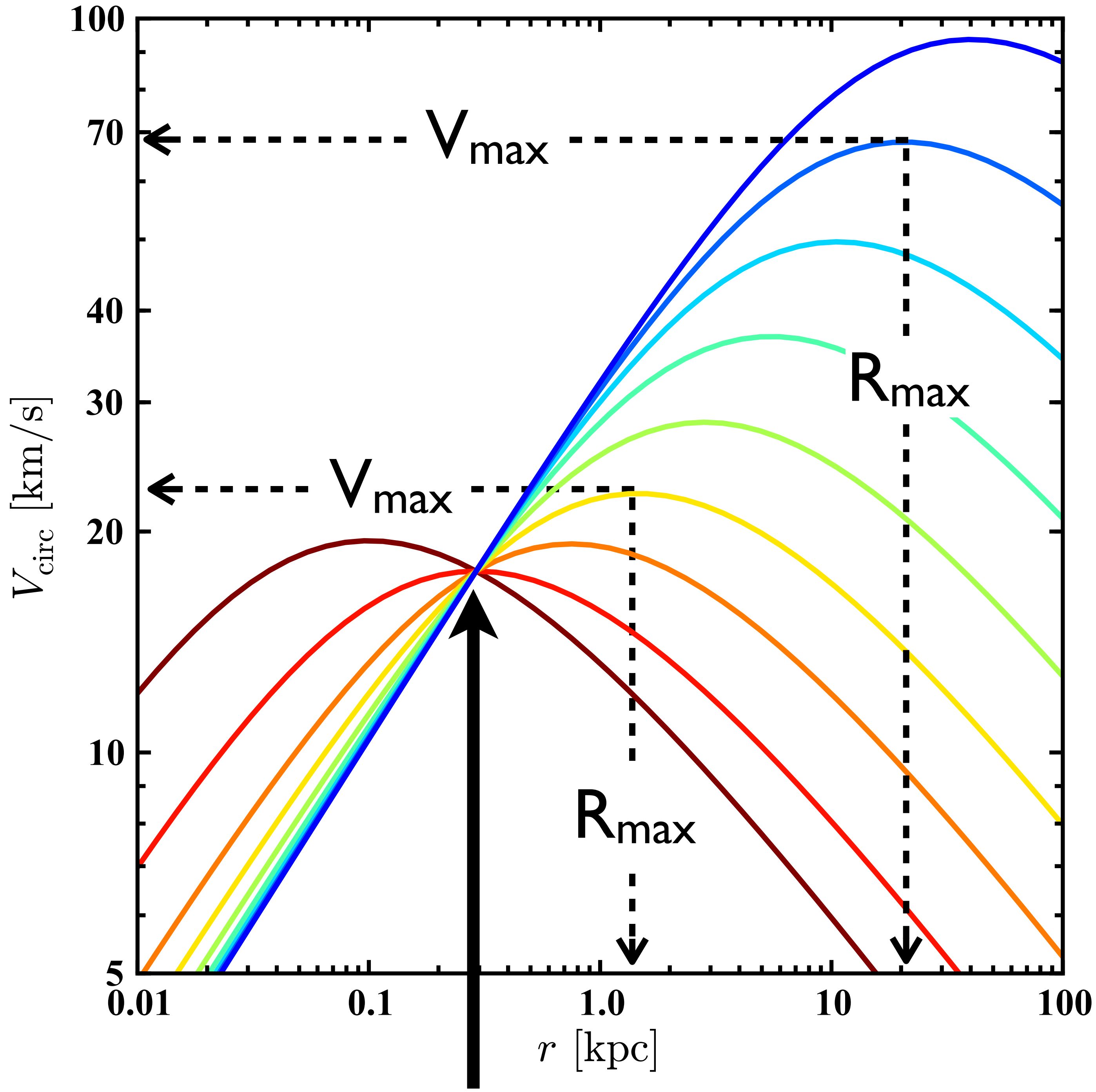
Directly compare observed satellites to simulated subhalos at $R_{1/2}$

- if mass agrees: the subhalo may be able to host the satellite;
- if mass disagrees: no way for the subhalo to host the satellite.

➡ Use $M(<R_{1/2})$ measurements to constrain subhalo structure

Example of kinematic constraint: Draco

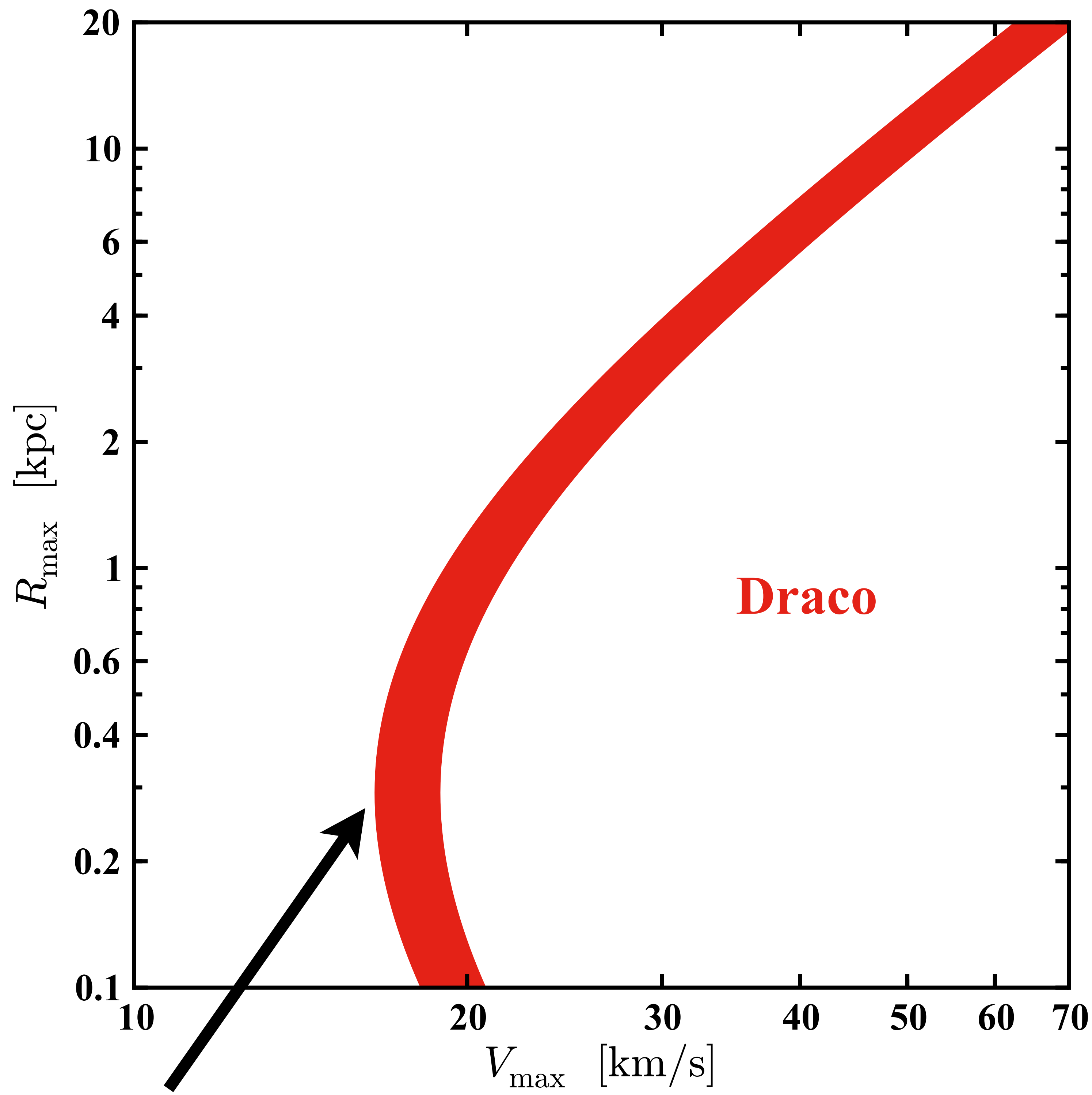
assume NFW mass profiles for subhalos (verified in simulations)



Mass well-determined at $R_{1/2}$ (291 pc)

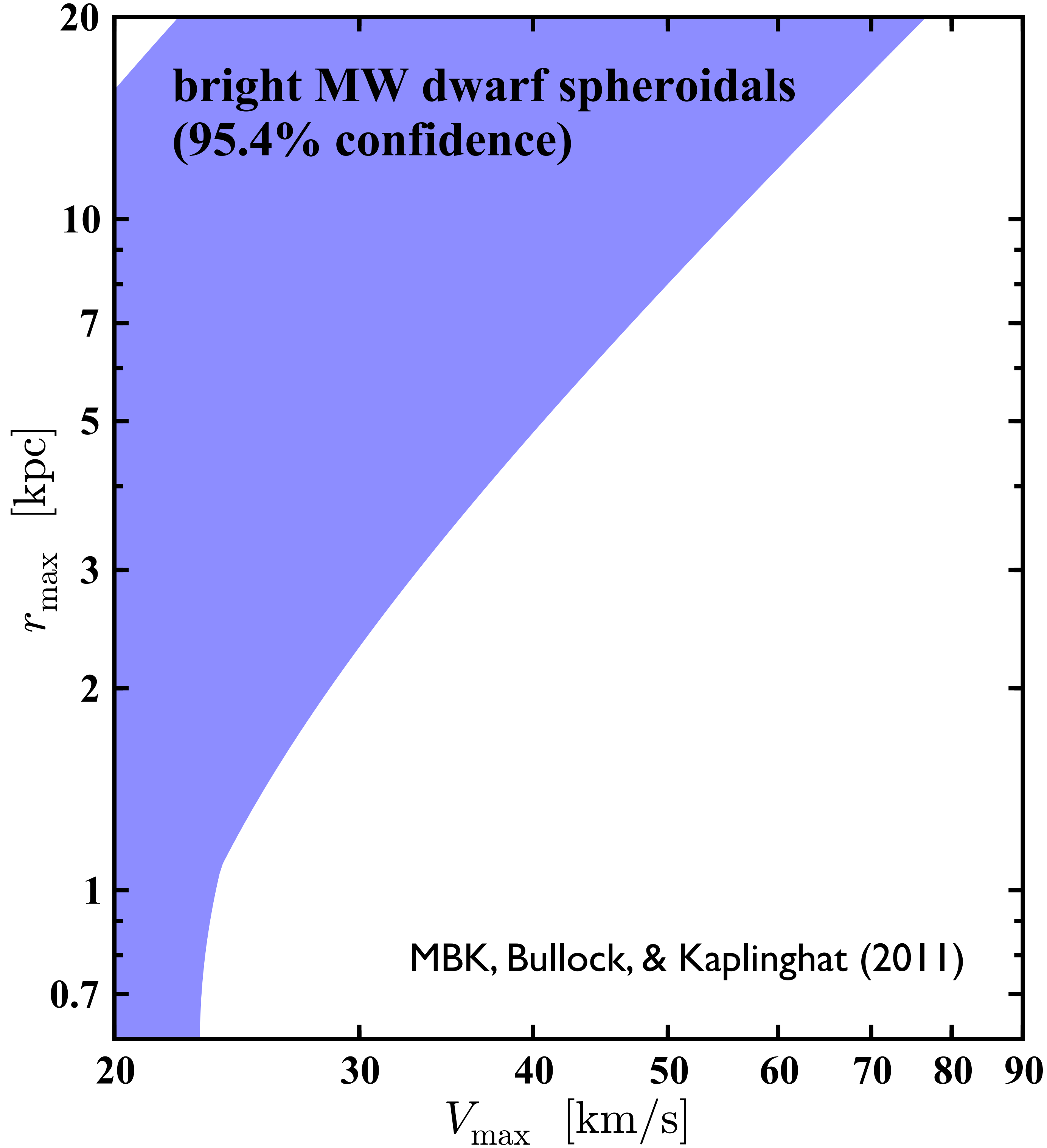
Example of kinematic constraint: Draco

assume NFW mass profiles



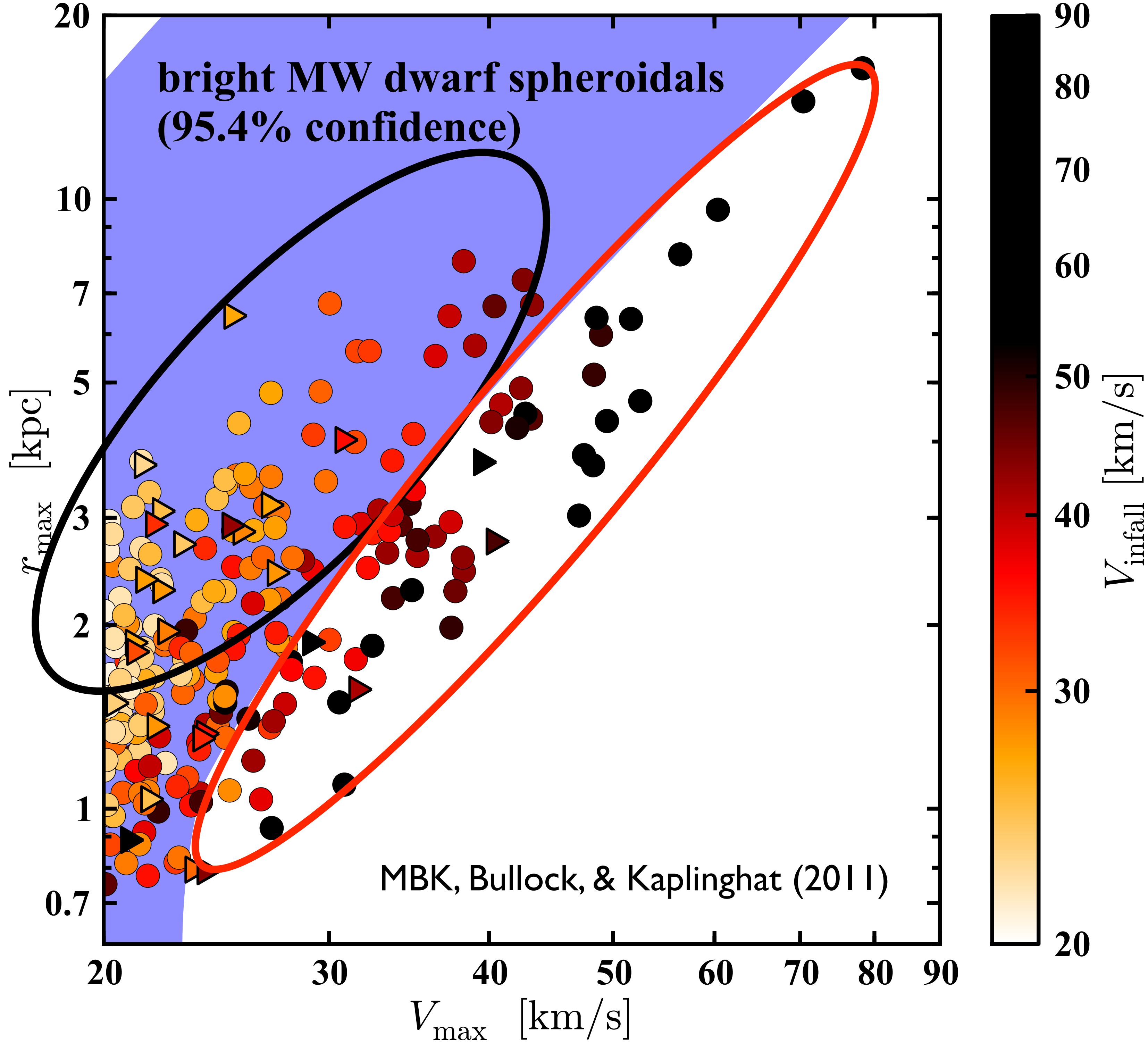
Mass well-determined at $R_{1/2}$ (291 pc)

Combined dark matter profile constraints for MW dwarfs



Adding in simulation data

seven simulations: six Aquarius + Via Lactea II

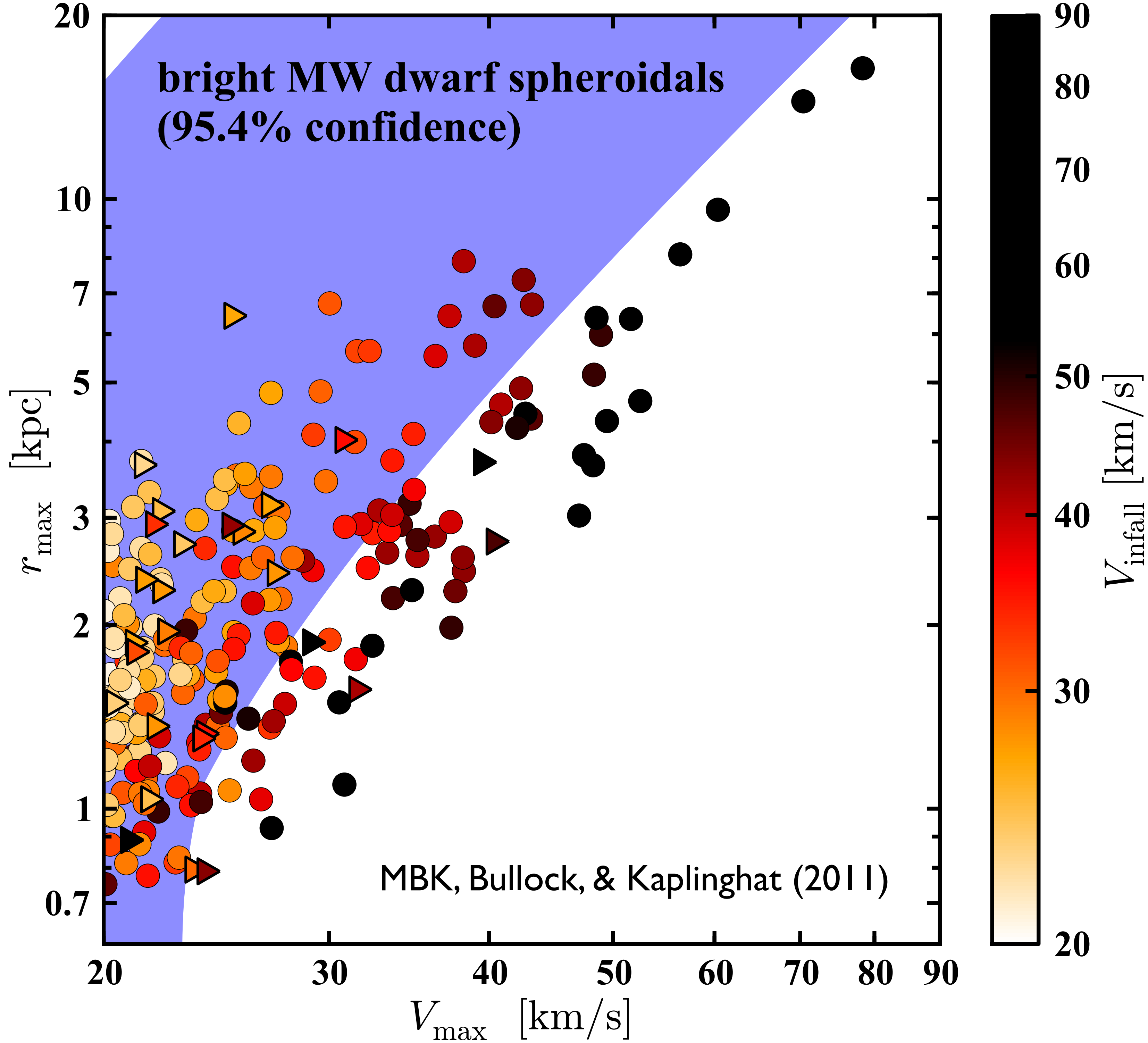


MANY subhalos consistent with dynamics of dSphs

also a population of subhalos that is ***not*** consistent with dynamics of dSphs

Adding in simulation data

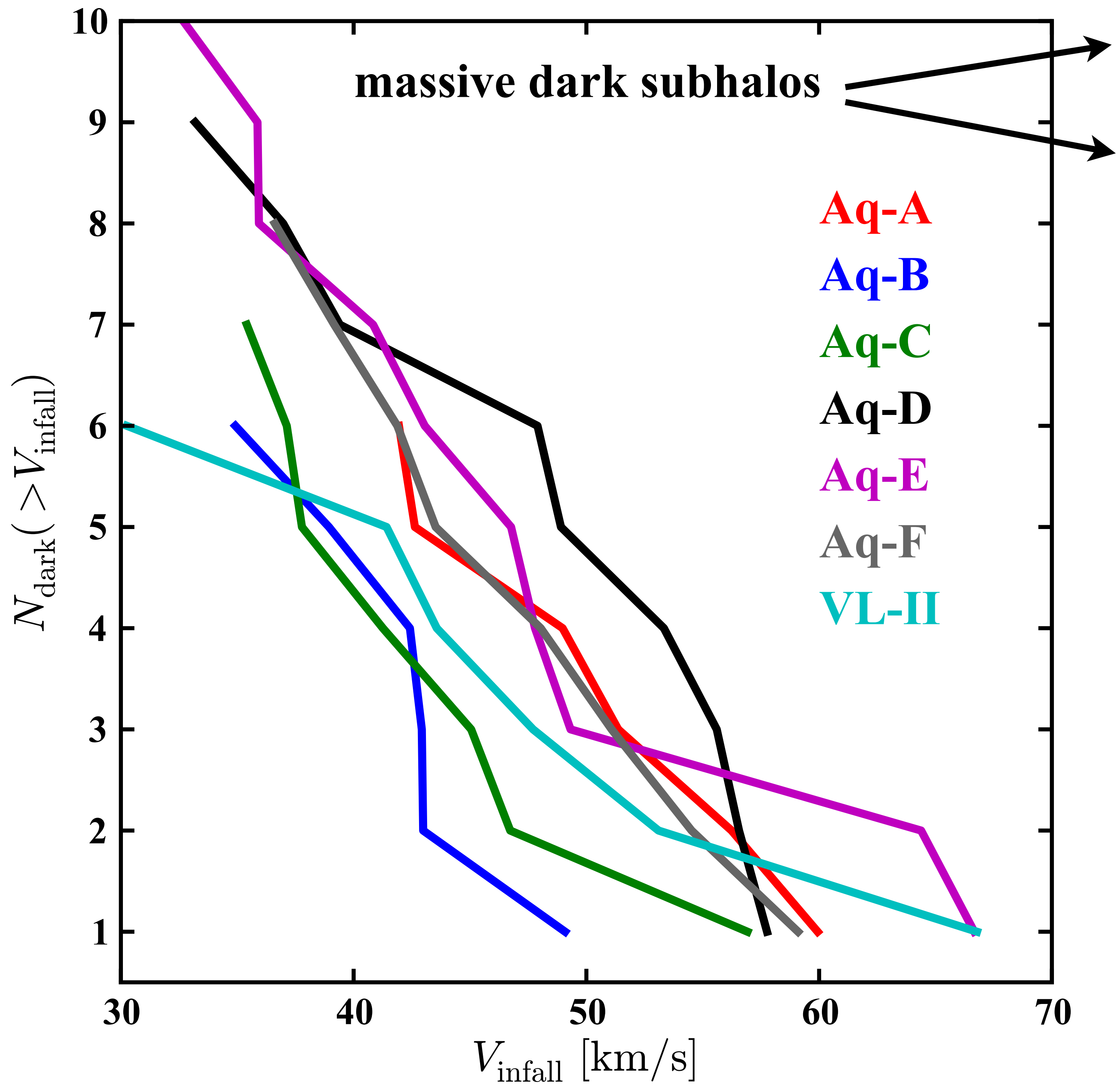
seven simulations: six Aquarius + Via Lactea II



MANY subhalos consistent with dynamics of dSphs

also a population of subhalos that is ***not*** consistent with dynamics of dSphs

We find at least 6 **massive**, **dark** subhalos in each halo



MBK, Bullock, & Kaplinghat (2011)

Massive: V_{infall} > 30 km/s

Dark: M/L > 10^4

All 7 hosts have:

at least 6 dark subhalos with V_{infall}>30 km/s

at least 4 dark subhalos with V_{infall}>40 km/s

Note: Magellanic Cloud analogs already removed from this sample

Of the ~10 biggest subhalos, ~8 cannot host *any* known bright MW satellite

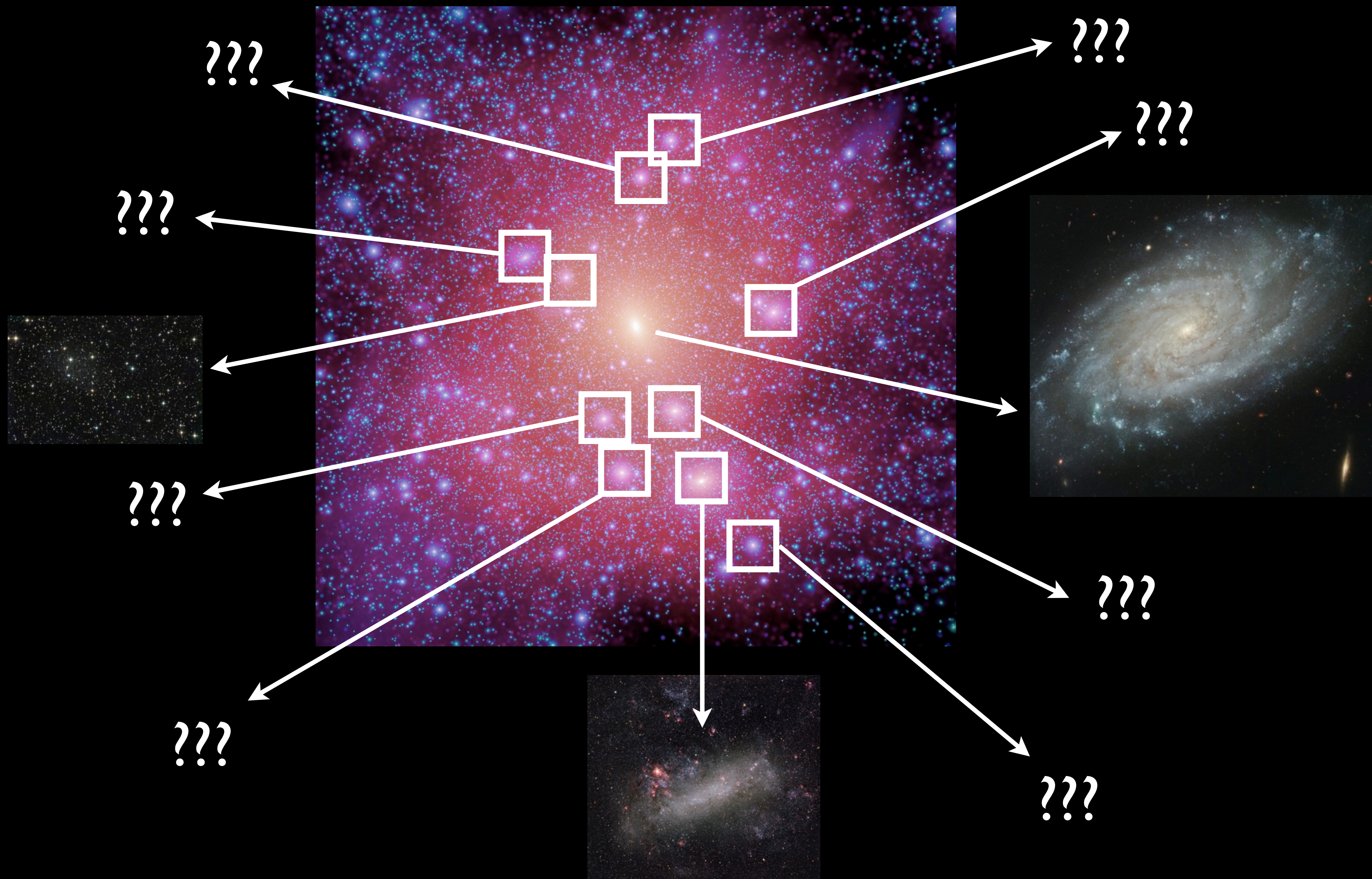
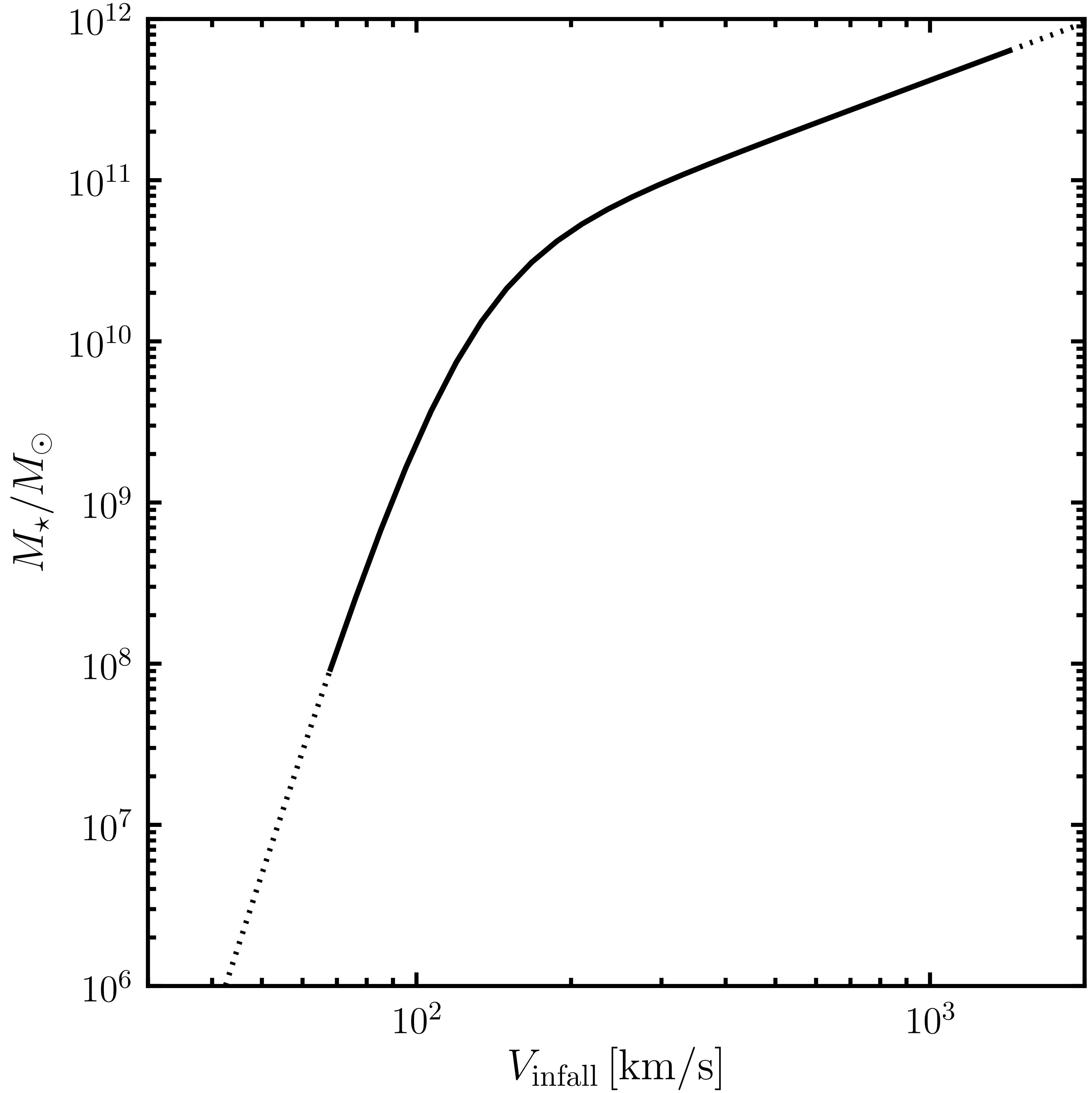


Image credits: V. Springel / Virgo Consortium; A. Riess / HST; W. Wang; AAO; M. Schirmer

Implications

- **<u>Option 1</u>**: massive dark subhalos **do** exist in the MW as predicted
  - Galaxy formation is stochastic for V < 50 km/s

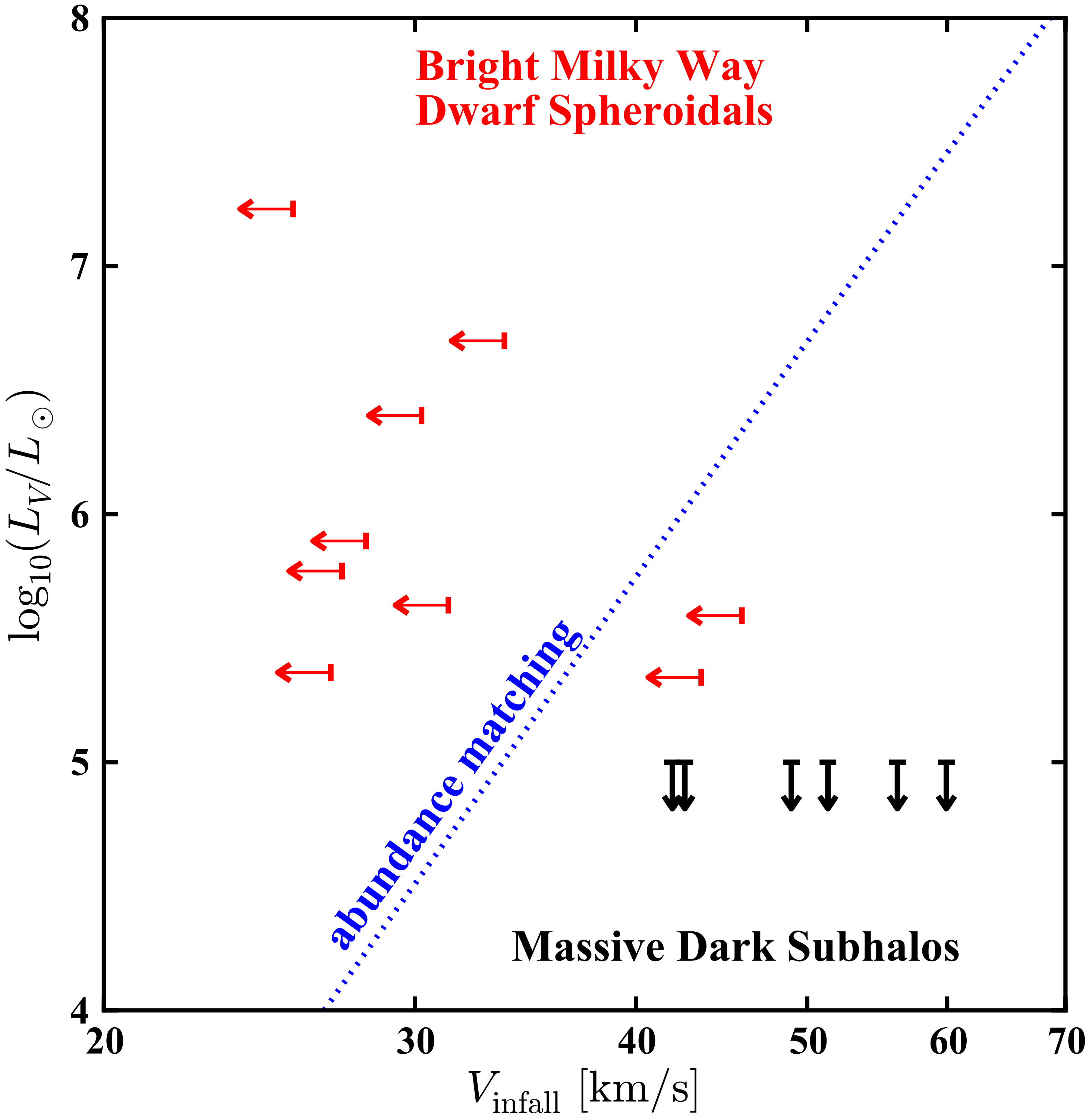
Stochastic galaxy formation



Tight relation between **L** and **V_{infall}** on scale of Magellanic Clouds and larger

MBK, Bullock, & Kaplinghat (2011)

Stochastic galaxy formation



<u>Tight</u> relation between **L** and **V$_{infall}$** on scale of Magellanic Clouds and larger

<u>No</u> relation between **L** and **V$_{infall}$** on scale of MW dwarf spheroidals

MBK, Bullock, & Kaplinghat (2011)

Implications

- **Option 1**: massive dark subhalos **do** exist in the MW as predicted
  - Galaxy formation is stochastic for V < 50 km/s
  - let's go find them! **Dark matter annihilation**? ~4 per halo with flux > Draco

Implications

- **Option 1**: massive dark subhalos **do** exist in the MW as predicted
  - Galaxy formation is stochastic for V < 50 km/s
  - let's go find them! **Dark matter annihilation**? ~4 per halo with flux > Draco
  - Already found? Some ultra-faint galaxies could lie in these subhalos
- **Option 2: No** massive dark subhalos in MW (ΛCDM interpretation)
  - the subhalo content of the Milky Way is anomalous compared to expectations
  - baryonic feedback **strongly** alters structure of subhalos on ~300-1000 pc scales
  - MW disk has important effects on subhalo populations
- **Option 3: No** massive dark subhalos in MW (modifications to ΛCDM)
  - dark matter is somewhat warm, characteristic suppression scale of ~40-50 km/s
  - dark matter has self-interactions
  - something else??

Summary

- Local Group dwarfs provide many opportunities for studying dark matter, astrophysical processes, and cosmology
- Strong constraints exist for dynamical masses of dSphs at $R_{1/2}$
- Cosmological N-body simulations now probe subhalos' mass distributions at $R_{1/2}$
- each of the 7 ultra-high-resolution simulations studied have at least 6 massive subhalos that are inconsistent with dynamics of all bright MW satellites ($L_V > 10^5$ L_{sun})
    - these subhalos are always among the most massive in the halo
    - either these subhalos are effectively dark (global $M/L > 10^4$); the MW is a statistical anomaly or baryonic physics strongly modifies abundance or structure of dark matter subhalos; or ΛCDM needs modification on scales of < 40-50 km/s
- Understanding whether these massive dark subhalos exist & what properties they have should provide insight into astrophysics, particle physics, & cosmology on small scales.

In the future

- **Observations:**
  - More complete census of Milky Way's satellites (LSST?)
  - Kinematics of M31 dwarf spheroidals (ongoing)
  - Satellites from statistical volume of low-z universe (see poster by Tollerud et al.)
- **Simulations**
  - larger number of high-resolution MW-mass halos in WMAP-7 cosmology
  - include effects of Galactic disk on subhalo properties
  - understand and accurately model star formation and feedback (easy, right?)
  - long-term goal: *ab initio* hydrodynamical simulations of MW & its satellites