Weighing the Milky Way

Mike Boylan-Kolchin
Center for Galaxy Evolution / UC Irvine

Santa Cruz galaxy formation workshop, August 2012

In Collaboration With:

James Bullock (UCI)

S. Tony Sohn, Roeland van der Marel (STScI)

Gurtina Besla (Columbia)

Steve Majewski (UVA)

AND WITH THANKS TO:

The Aquarius, Via Lactea, and GHALO collaborations

Why should you care about M_{MW}?

And why is "~10^{12} M_{sun}" not good enough?

Note: virial mass defined with respect to 95 $\rho_{\rm crit}$ throughout

Why should you care about M_{MW}?

And why is "~10^{12} M_{sun}" not good enough?

- Virial mass estimates range from ~(0.5-3)x10^{12} M_{sun} -- <u>result in very different expectations for galaxy formation models</u>

Note: virial mass defined with respect to 95 $\rho_{\rm crit}$ throughout

Why should you care about M_{MW}?

And why is "~10^{12} M_{sun}" not good enough?

- Virial mass estimates range from ~(0.5-3)x10^{12} M_{sun} -- <u>result in very different expectations for galaxy formation models</u>
- Example: baryonic content of the MW
  - if M_{vir} ~ 7e11, most or all of MW's baryons are accounted for by observations
  - if M_{vir} ~ 2e12, most of the MW's baryons are "missing"
- Example: satellite galaxy abundance
  - satellite galaxy abundance scales ~linearly with M_{vir}, so interpretation of potential small scale issues depends on M_{MW}

Note: virial mass defined with respect to 95 $\rho_{\rm crit}$ throughout

Tracers of the MW's potential

Is Leo I bound? See: Zaritsky et al. 1989, Fich & Tremaine 1991, Kochanek 1996, Sales et al. 2007, Sohn et al. 2007, Mateo et al. 2008, Watkins et al. 2010

Tracers of the MW's potential

- stars (BHB, RR Lyrae): large numbers out to ~50 kpc, density falls off quickly at larger radii (Xue et al. 2008, Gnedin et al. 2010, Deason et al. 2012)

Is Leo I bound? See: Zaritsky et al. 1989, Fich & Tremaine 1991, Kochanek 1996, Sales et al. 2007, Sohn et al. 2007, Mateo et al. 2008, Watkins et al. 2010

Tracers of the MW's potential

- stars (BHB, RR Lyrae): large numbers out to ~50 kpc, density falls off quickly at larger radii (Xue et al. 2008, Gnedin et al. 2010, Deason et al. 2012)
- gas: forget about it

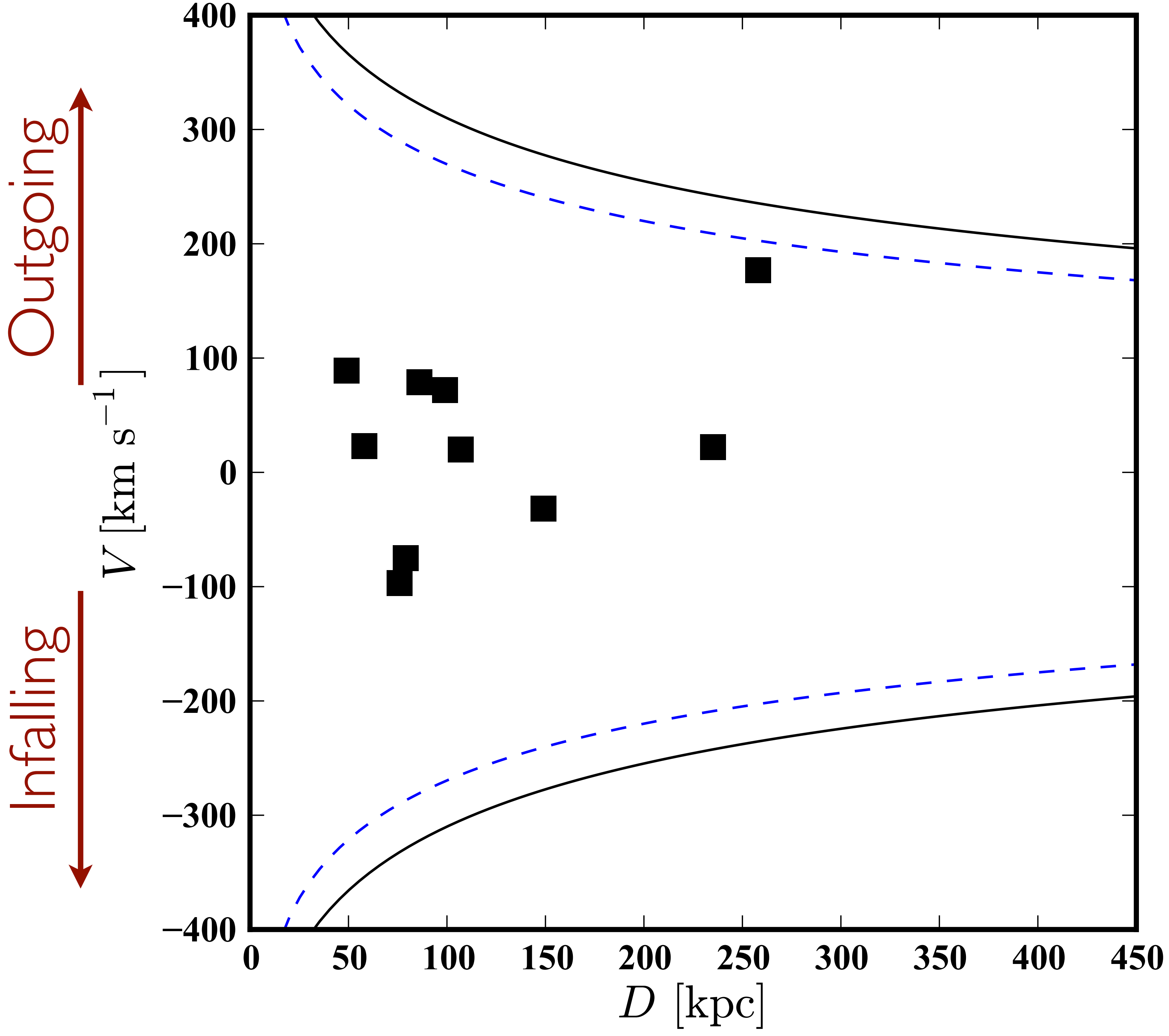
Is Leo I bound? See: Zaritsky et al. 1989, Fich & Tremaine 1991, Kochanek 1996, Sales et al. 2007, Sohn et al. 2007, Mateo et al. 2008, Watkins et al. 2010

Tracers of the MW's potential

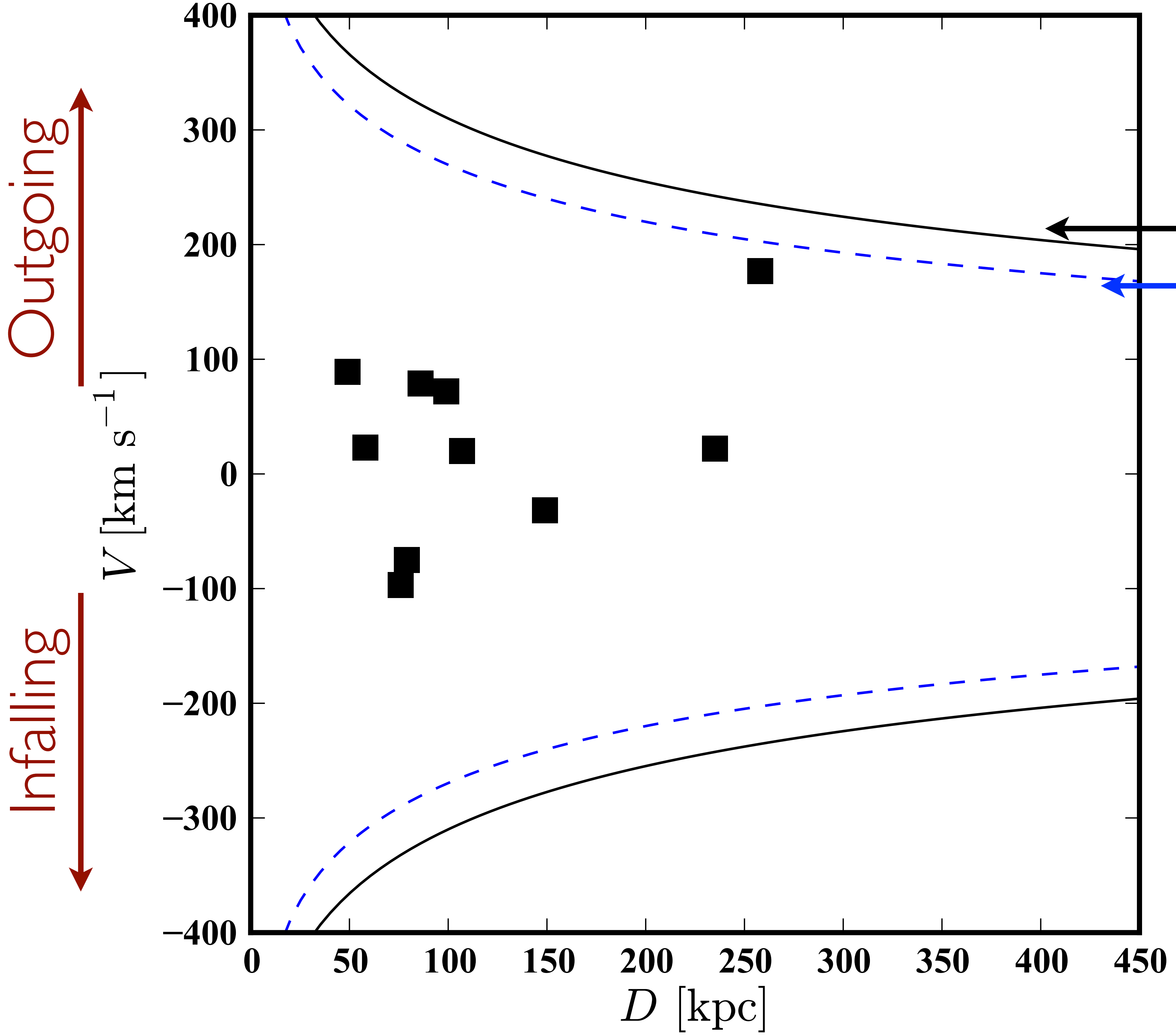
- stars (BHB, RR Lyrae): large numbers out to ~50 kpc, density falls off quickly at larger radii (Xue et al. 2008, Gnedin et al. 2010, Deason et al. 2012)
- gas: forget about it
- satellite galaxies: small number, but can be studied in detail
    - *Magellanic Clouds*: D=50-60 kpc, likely on first infall. Models reproducing the Clouds' orbit and production of the Magellanic Stream can constrain MW mass
    - *Leo I*: distant (D=260 kpc) and fast-moving (V_r ~ 175 km/s) classical dSph satellite (stellar mass ~ 5×10^6 M_{sun}, half-light radius of ~400 pc). Plays the largest role of all satellites in constraining the MW mass, but is it bound?

Is Leo I bound? See: Zaritsky et al. 1989, Fich & Tremaine 1991, Kochanek 1996, Sales et al. 2007, Sohn et al. 2007, Mateo et al. 2008, Watkins et al. 2010

Radial velocities of the classical MW satellites



Radial velocities of the classical MW satellites



V_{escape} for

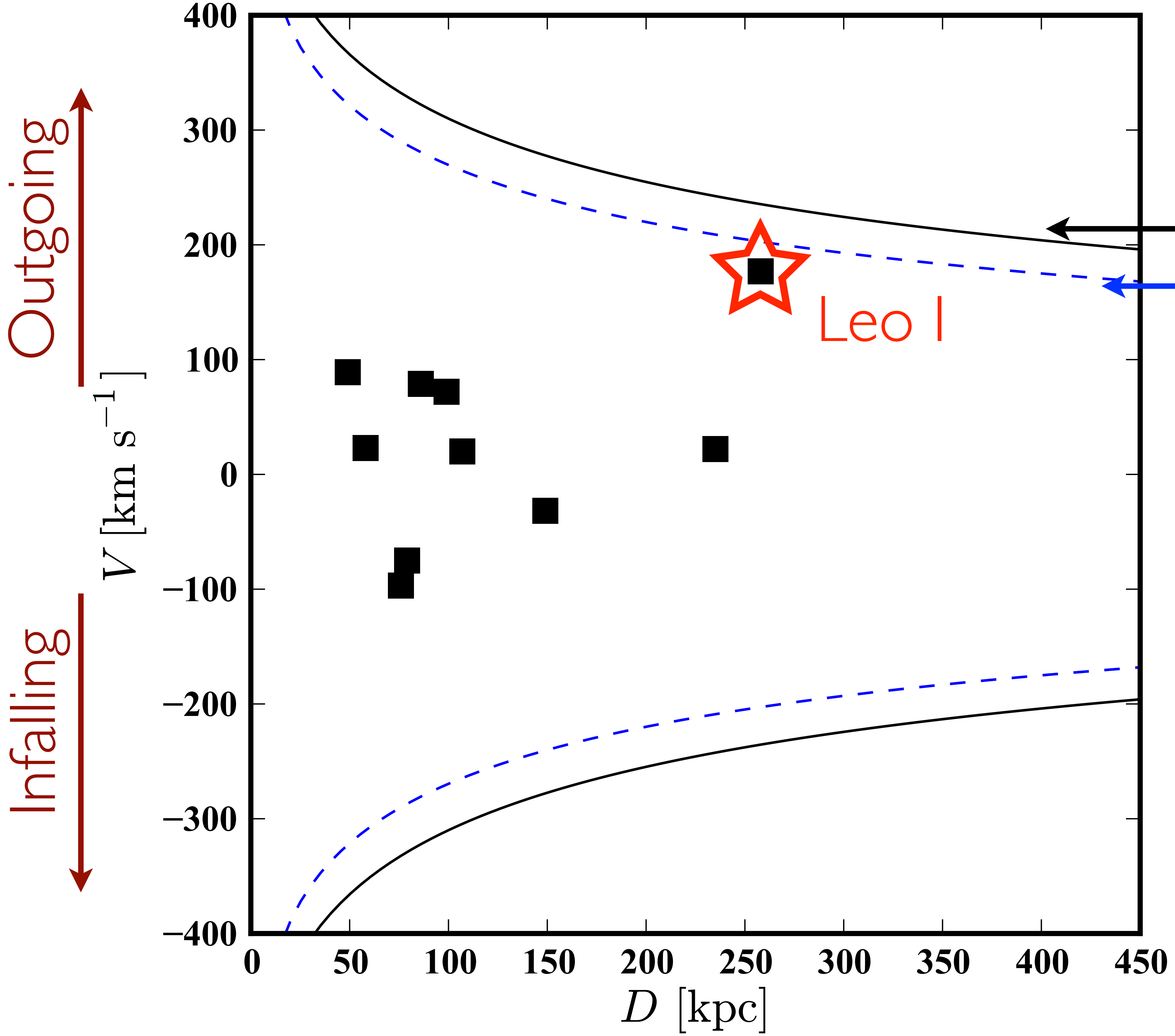
$M_{\rm vir,MW} = 10^{12}\ M_\odot$

$M_{\rm vir,MW} = 7 \times 10^{11}\ M_\odot$

also includes

$M_{\star,\rm MW} = 6 \times 10^{10}\ M_\odot$

Radial velocities of the classical MW satellites



V$_{\text{escape}}$ for

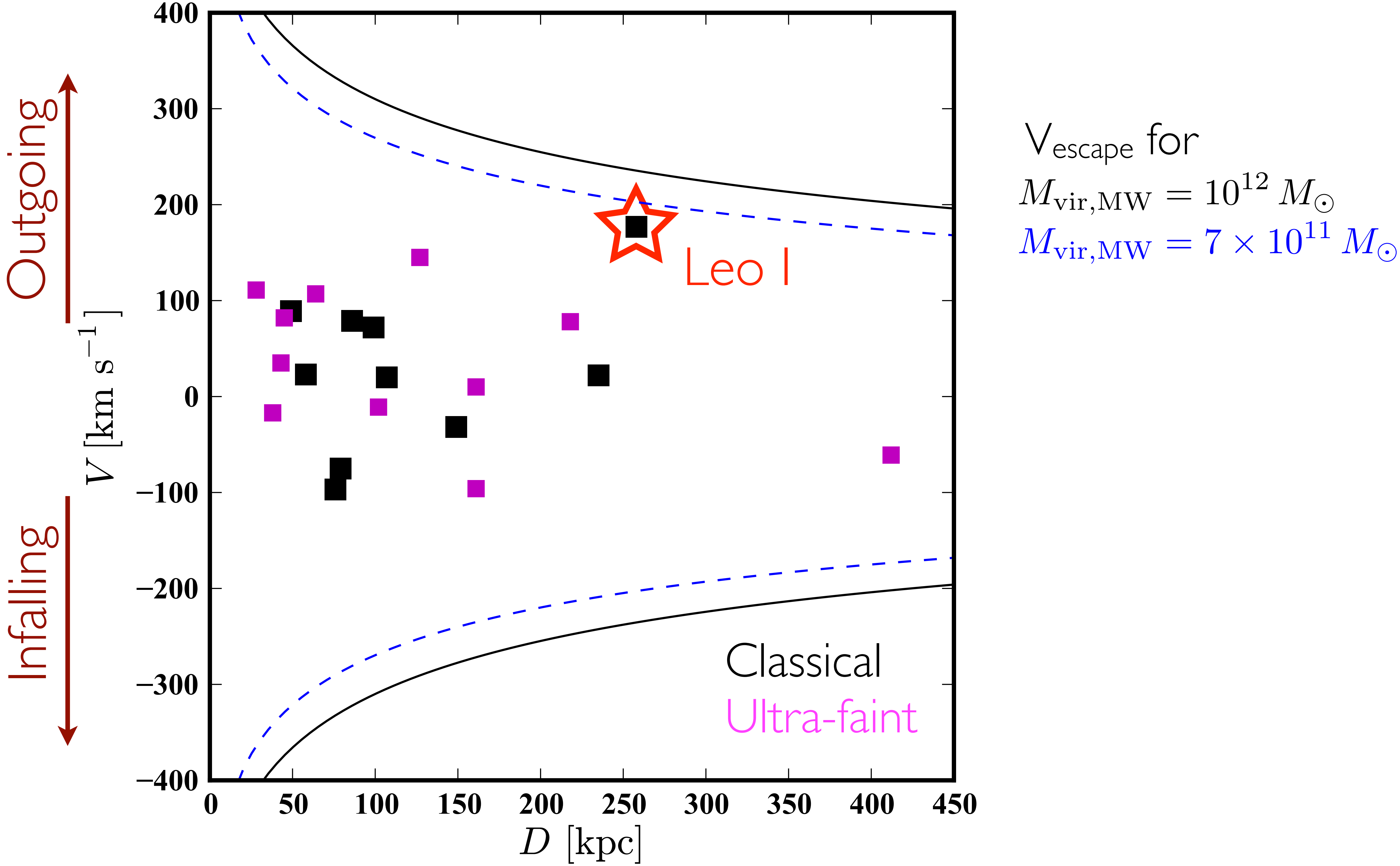
$M_{\mathrm{vir,MW}} = 10^{12}\ M_\odot$

$M_{\mathrm{vir,MW}} = 7 \times 10^{11}\ M_\odot$

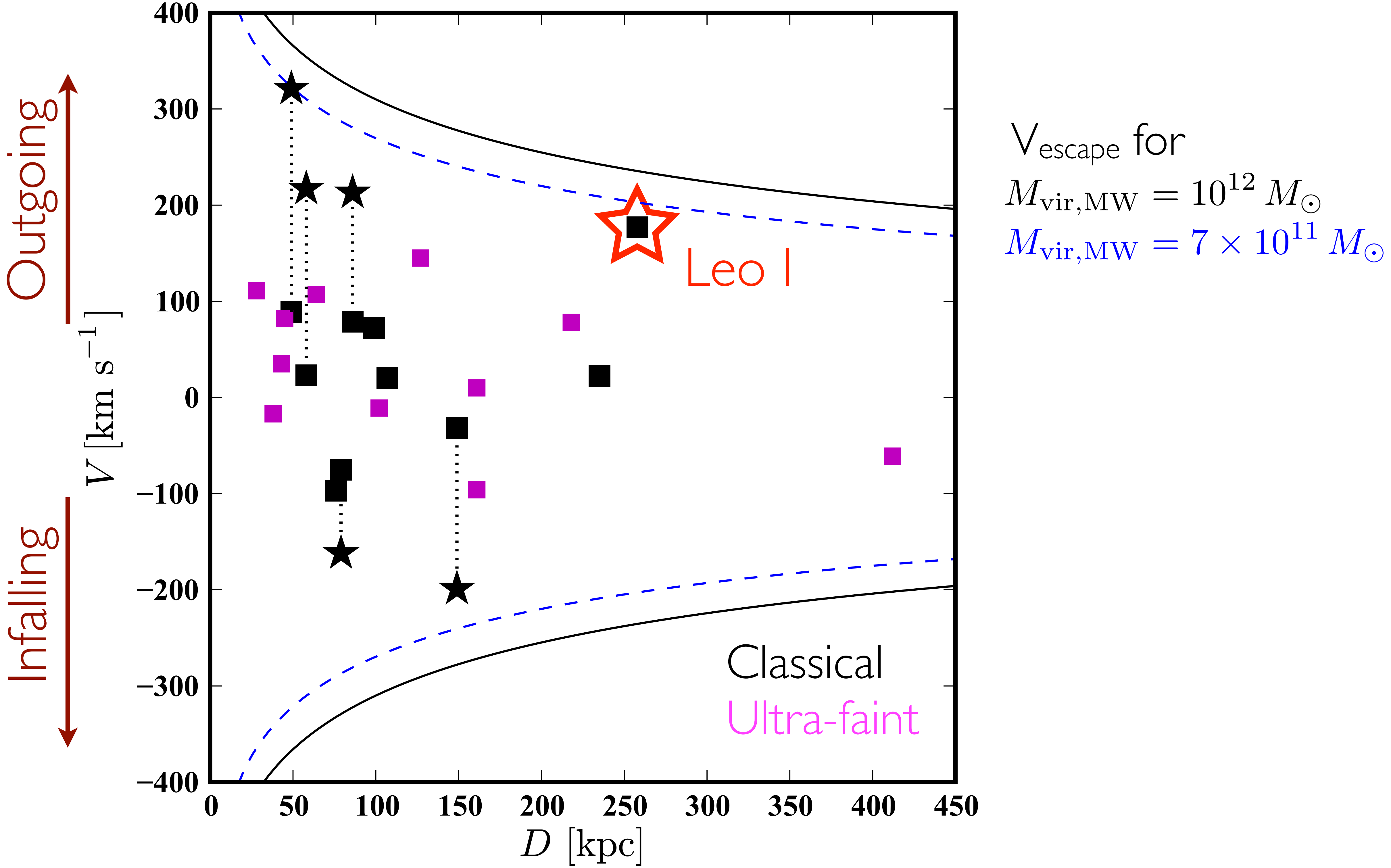
also includes

$M_{\star,\mathrm{MW}} = 6 \times 10^{10}\ M_\odot$

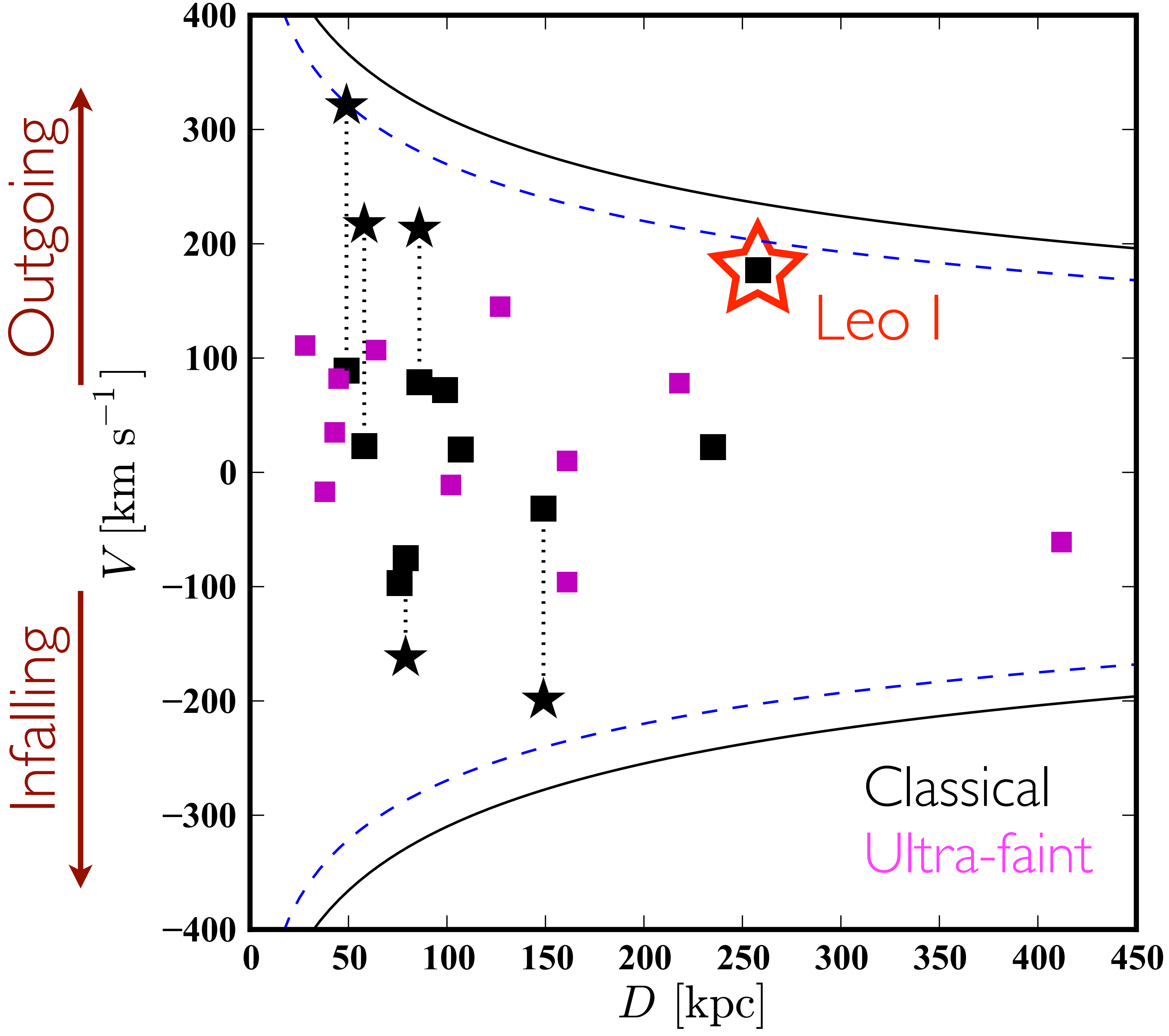
Radial velocities of the MW satellites



In terms of *3D* velocity



In terms of *3D* velocity



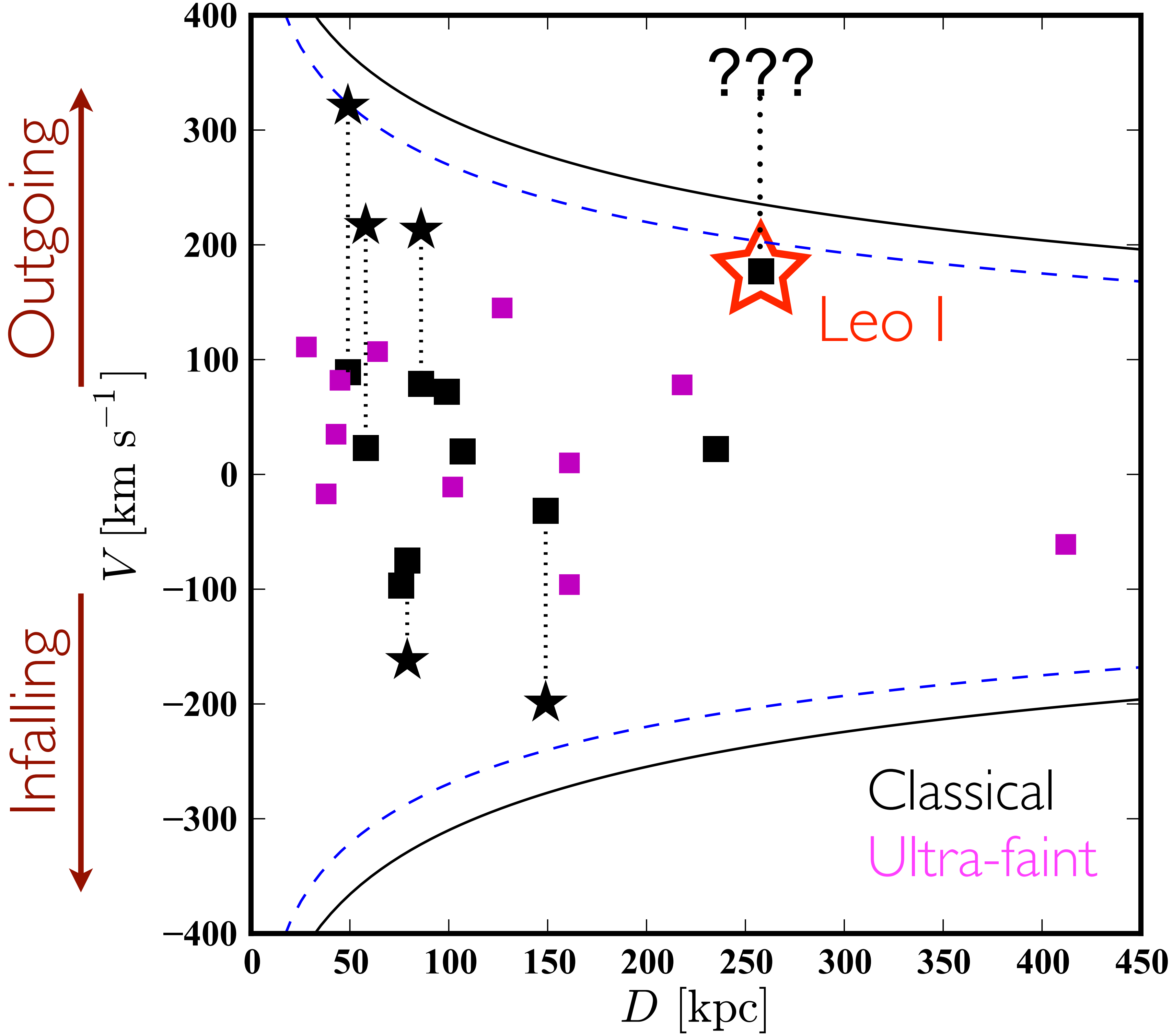
V$_{\text{escape}}$ for

$M_{\text{vir,MW}} = 10^{12}\ M_{\odot}$

$M_{\text{vir,MW}} = 7 \times 10^{11}\ M_{\odot}$

All satellites with well-measured proper motions have V$_{\text{tan}}$ > V$_{\text{r}}$ (!!)

In terms of <u>*3D*</u> velocity



V_{escape} for

$M_{\mathrm{vir,MW}} = 10^{12}\ M_\odot$

$M_{\mathrm{vir,MW}} = 7 \times 10^{11}\ M_\odot$

<u>All</u> satellites with well-measured proper motions have $V_{\mathrm{tan}} > V_{\mathrm{r}}$ (!!)

Measuring Leo I's proper motion

- Proper motion measurements usually use background quasars; Anderson, Mahmud van der Marel, & Sohn developed a technique to use background *galaxies* instead (recently used for M31 proper motion).

- requires accurate astrometry for both stars in Leo I, background galaxies

- measurement using HST/ACS with 5 yea[redacted] baseline:

$$(\mu_W, \mu_N) = (114.0 \pm 29.5 \text{[redacted]} 6 \pm 29.3)\,\mu\text{as}\,\text{yr}^{-1}$$

- In "more useful" units:

$$V_\text{rad} = 16\text{[redacted]}\,\text{km}\,\text{s}^{-1}$$

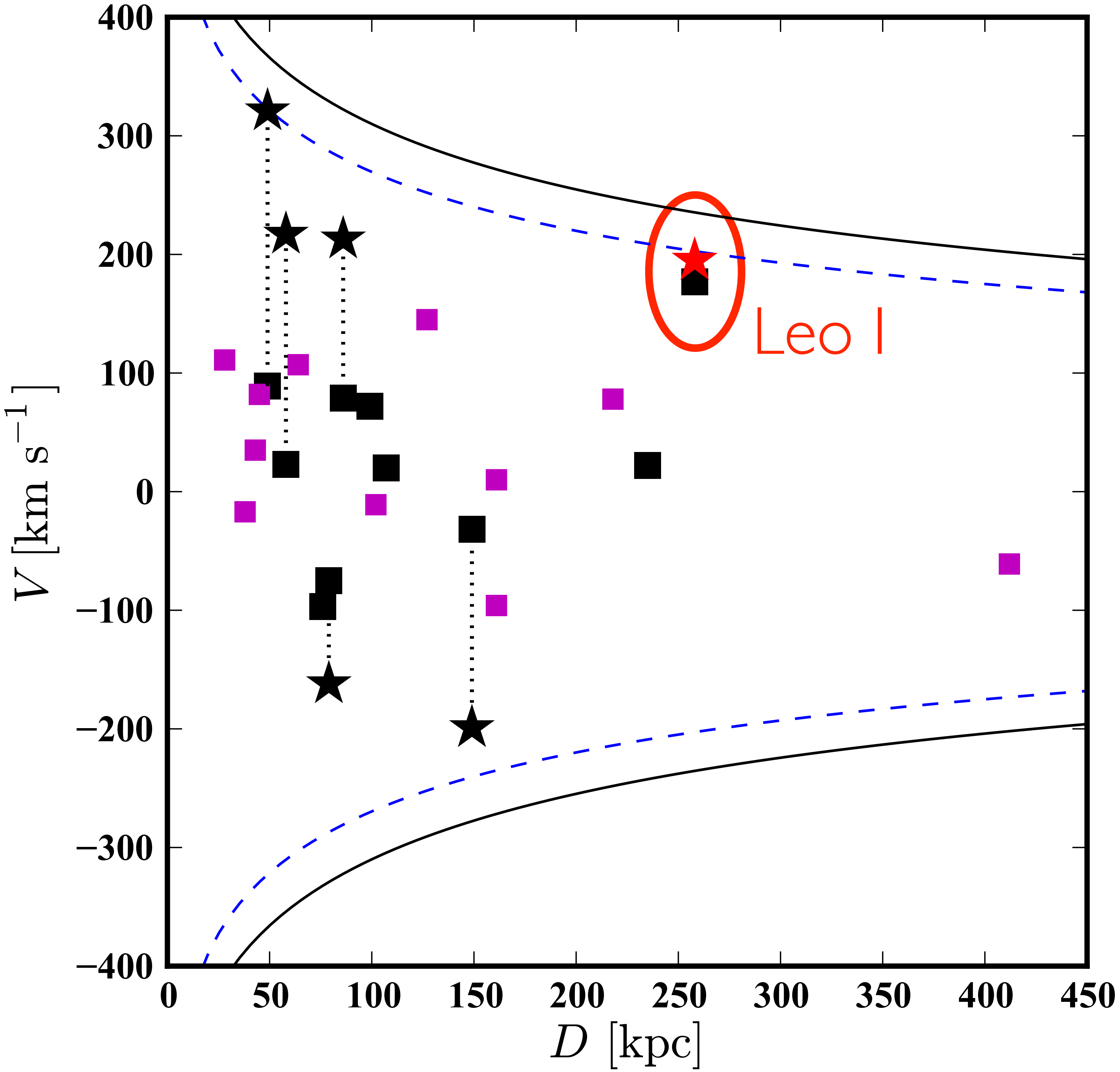
$$V_\text{tan} = \text{[redacted]}\,34.4\,\text{km}\,\text{s}^{-1}$$

$$\boxed{V_\text{tot} = \text{[redacted]}^{+21.7\ (+45.8)}_{-17.1\ (-21.7)}\,\text{km}\,\text{s}^{-1}}$$

PRELIMINARY

Sohn et al. (2012, in preparation)

In terms of *3D* velocity



V$_{\text{escape}}$ for

$M_{\mathrm{vir,MW}} = 10^{12}\ M_\odot$

$M_{\mathrm{vir,MW}} = 7 \times 10^{11}\ M_\odot$

Leo I:

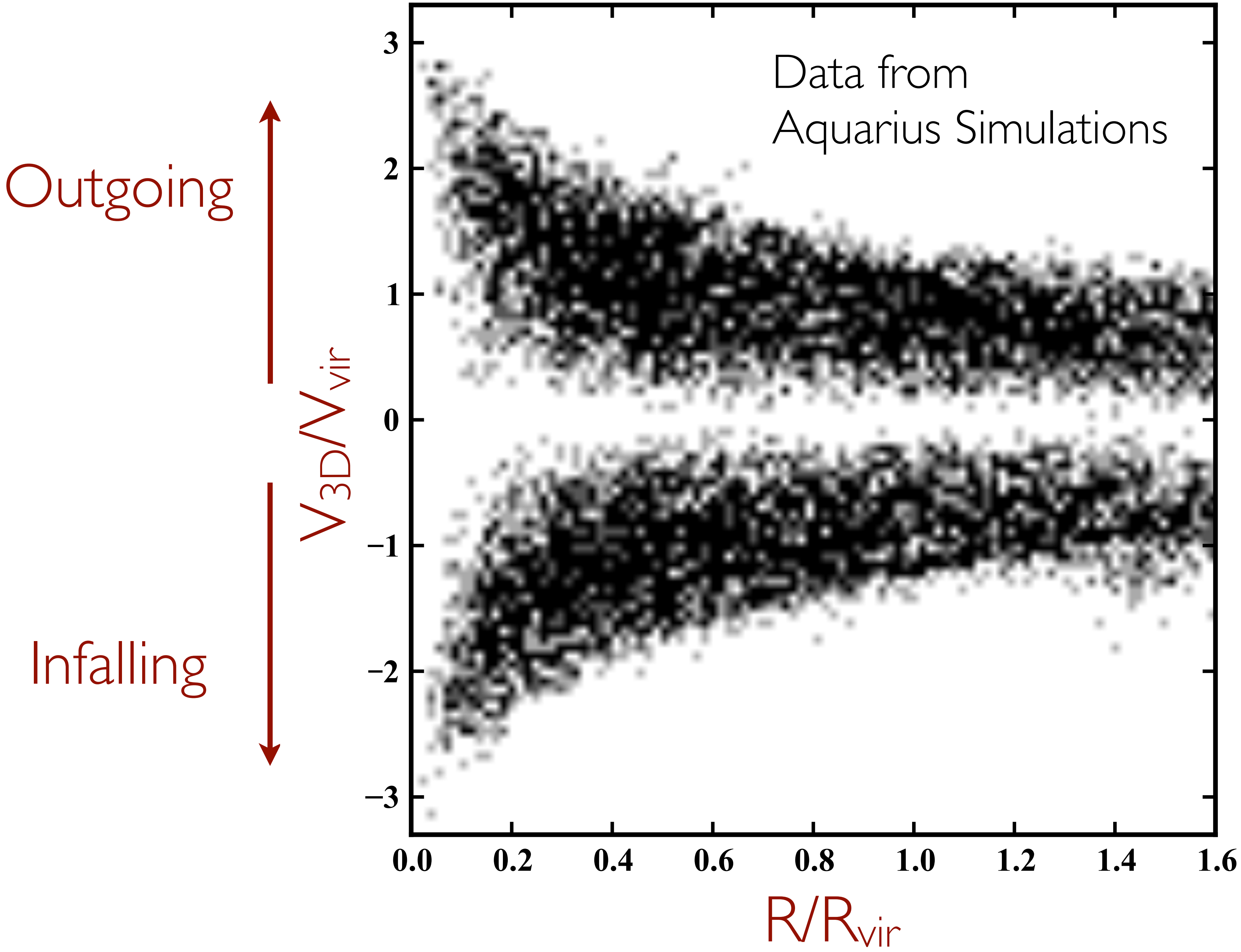
V$_{\text{rad}}$=170 km/s

V$_{\text{tan}}$=101 km/s

V$_{\text{3D}}$=196 km/s

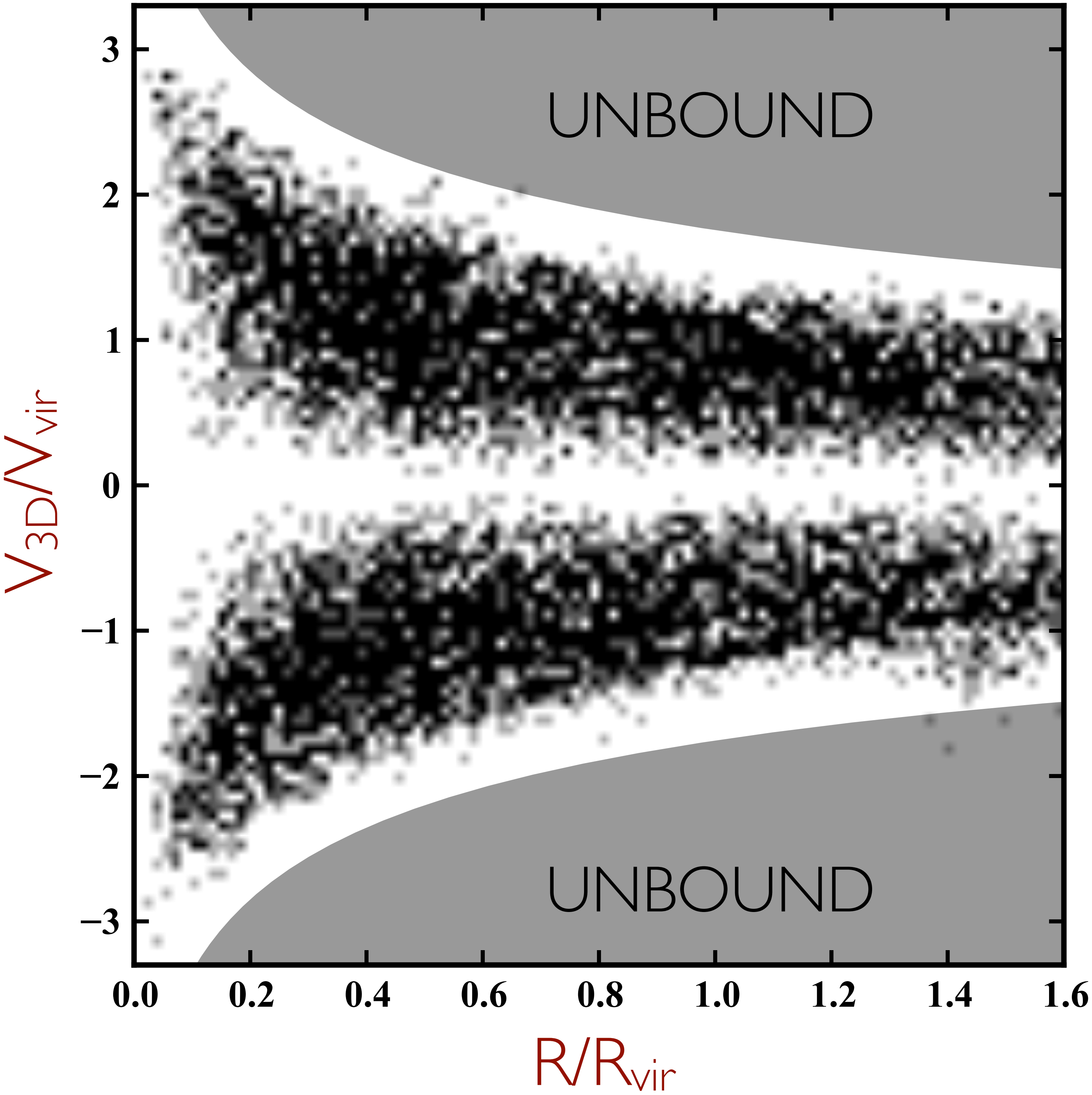
What does this mean for the MW virial mass?

Phase space in terms of total velocity

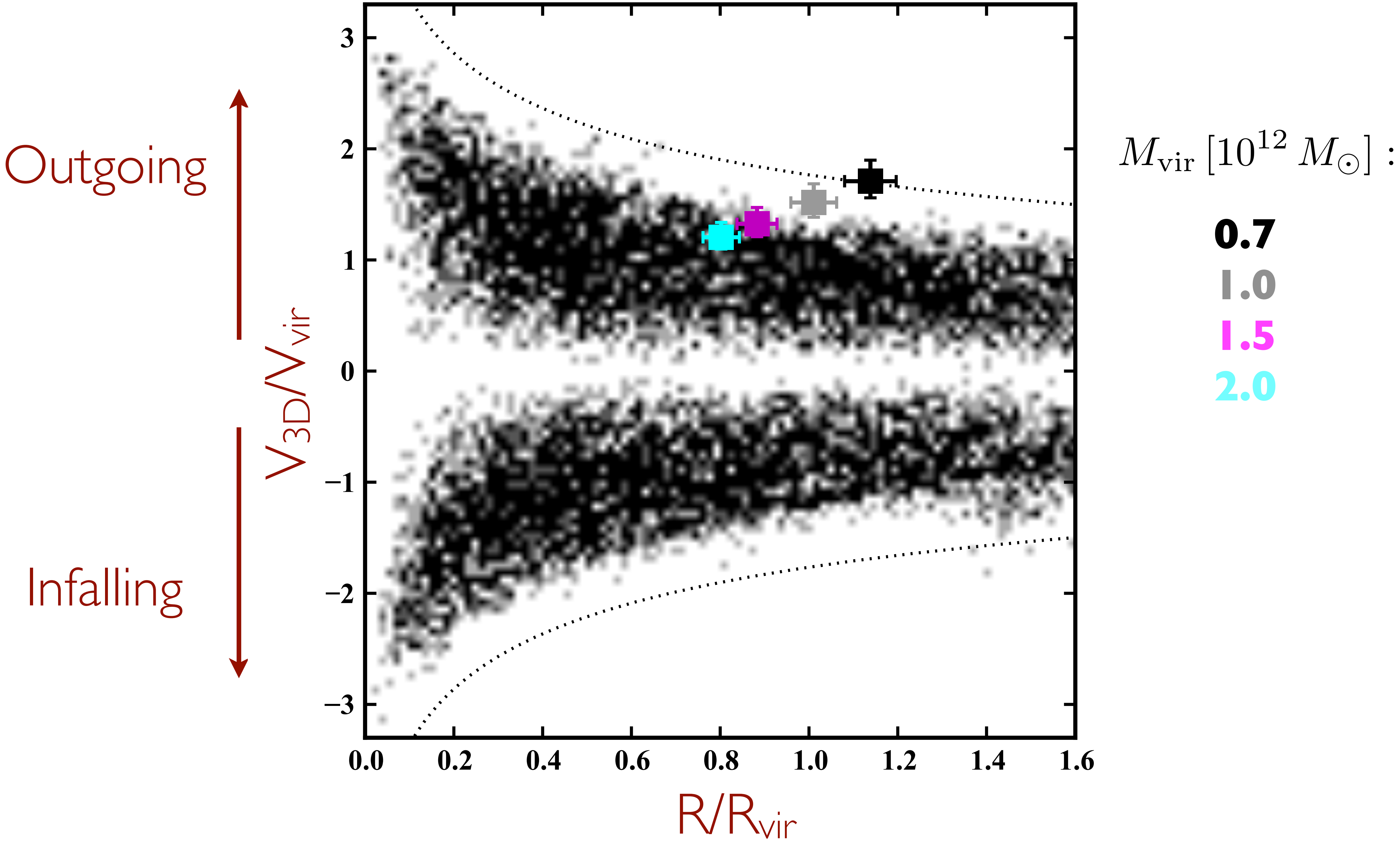


MBK et al. 2012 (in preparation)

Unbound subhalos: very rare

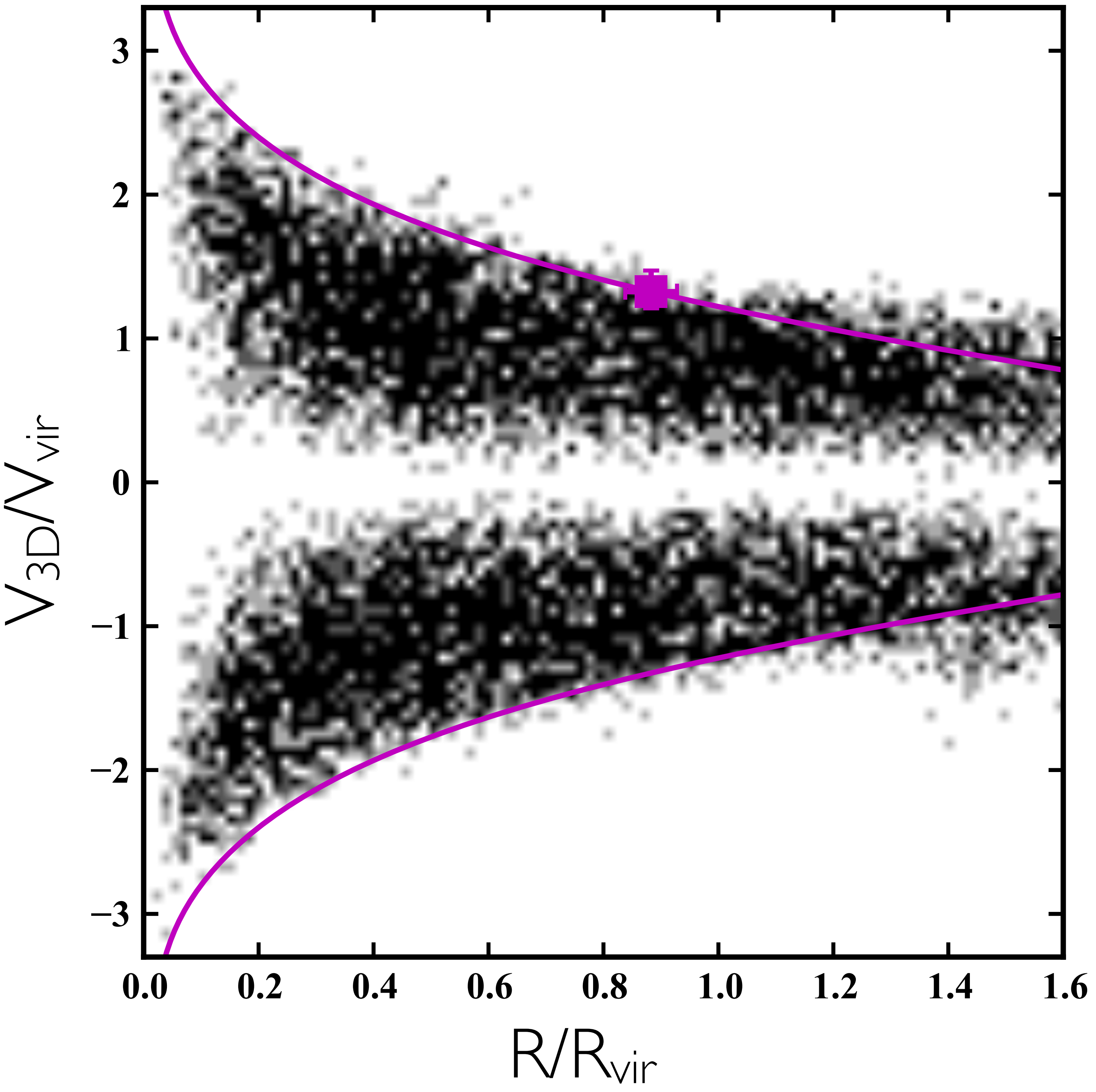


Where is Leo I in this phase space?



MBK et al. 2012 (in preparation)

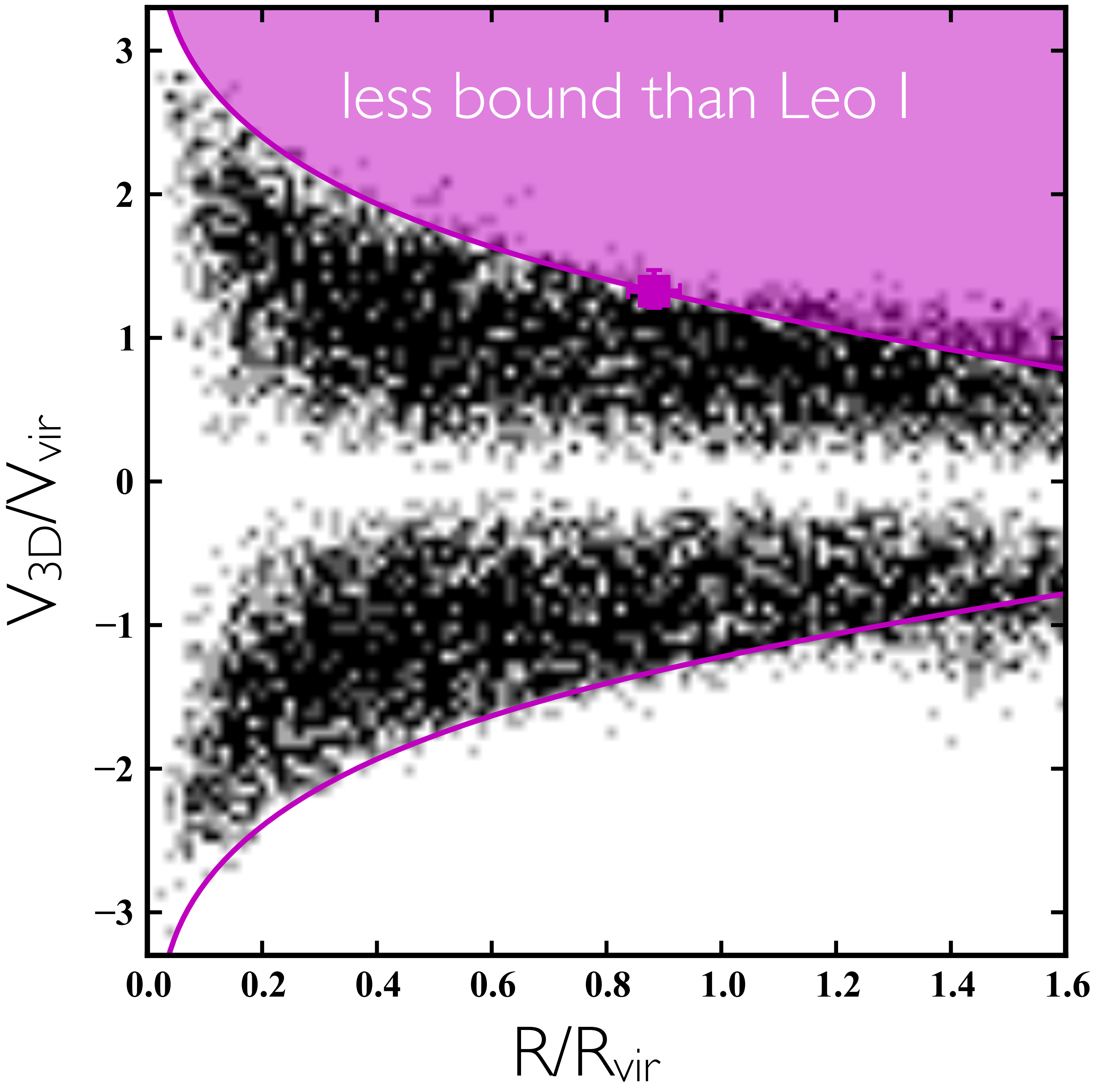
Deriving a constraint on M_{MW}



constant energy contour at Leo I's V_{3D} for M_{vir}=1.5e12

MBK et al. 2012 (in preparation)

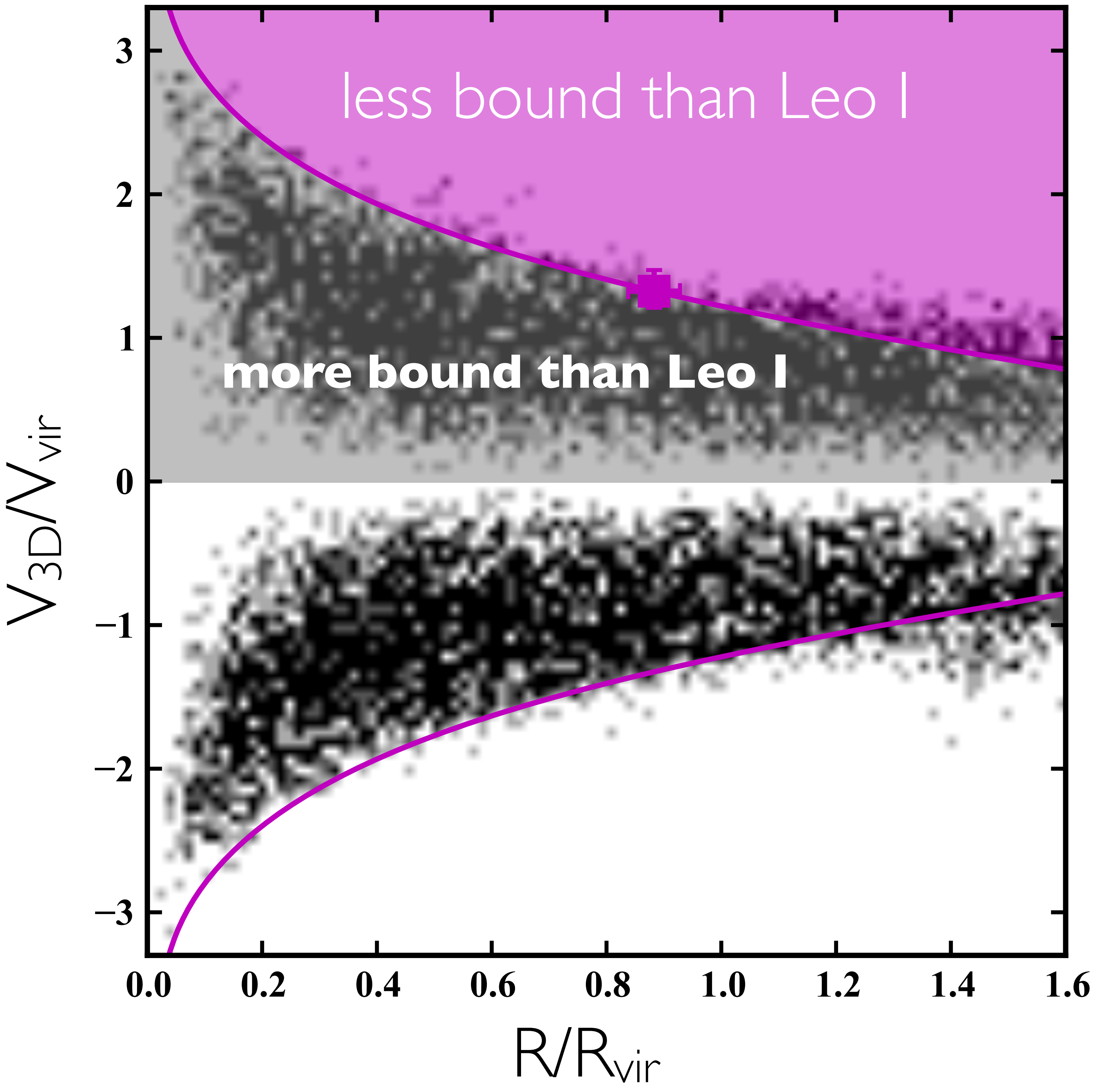
Deriving a constraint on M_{MW}



constant energy contour at Leo I's V_{3D} for M_{vir}=1.5e12

MBK et al. 2012 (in preparation)

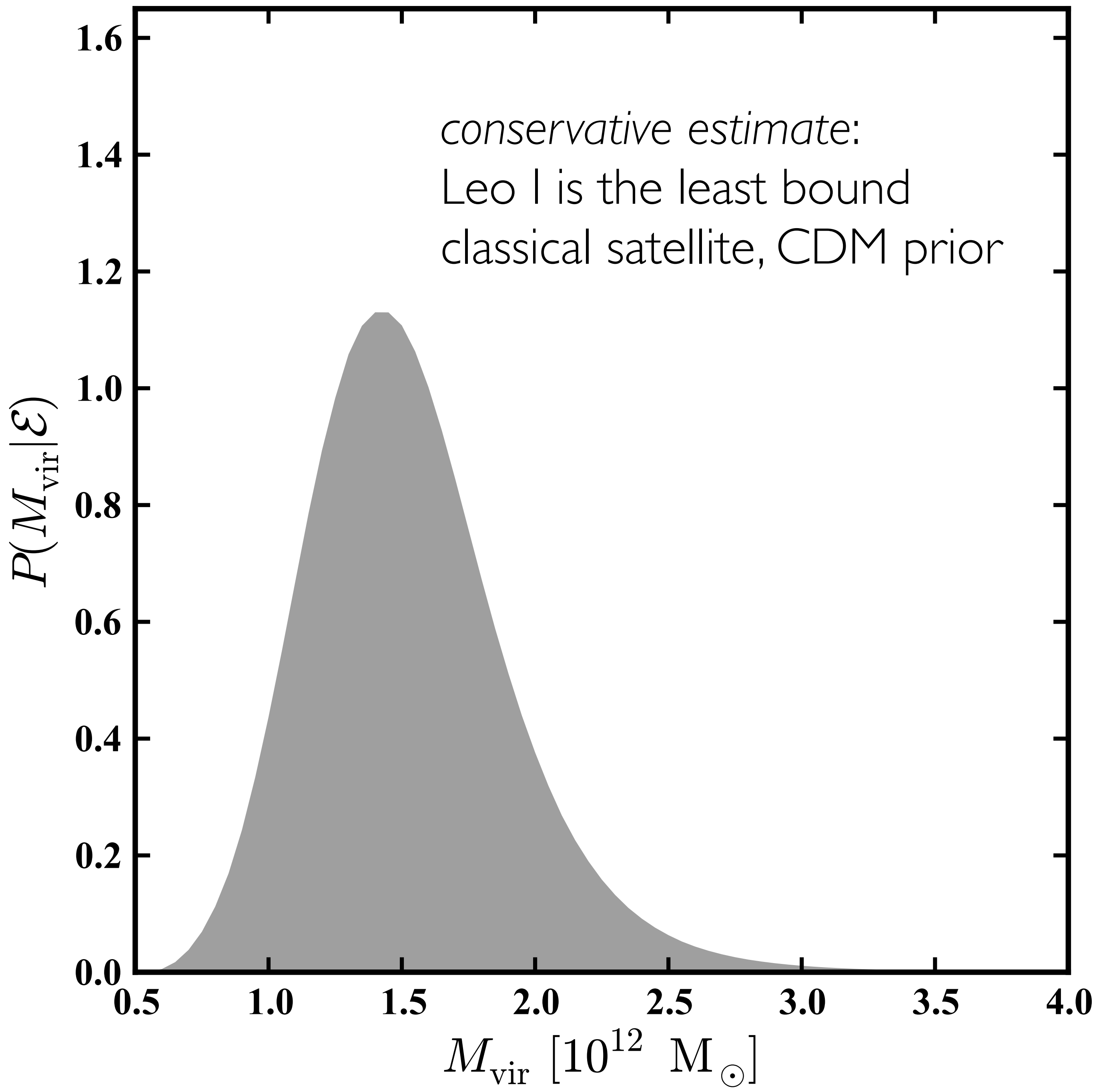
Deriving a constraint on M_{MW}



constant energy contour at Leo I's V_{3D} for M_{vir}=1.5e12

MBK et al. 2012 (in preparation)

The Virial Mass of the Milky Way



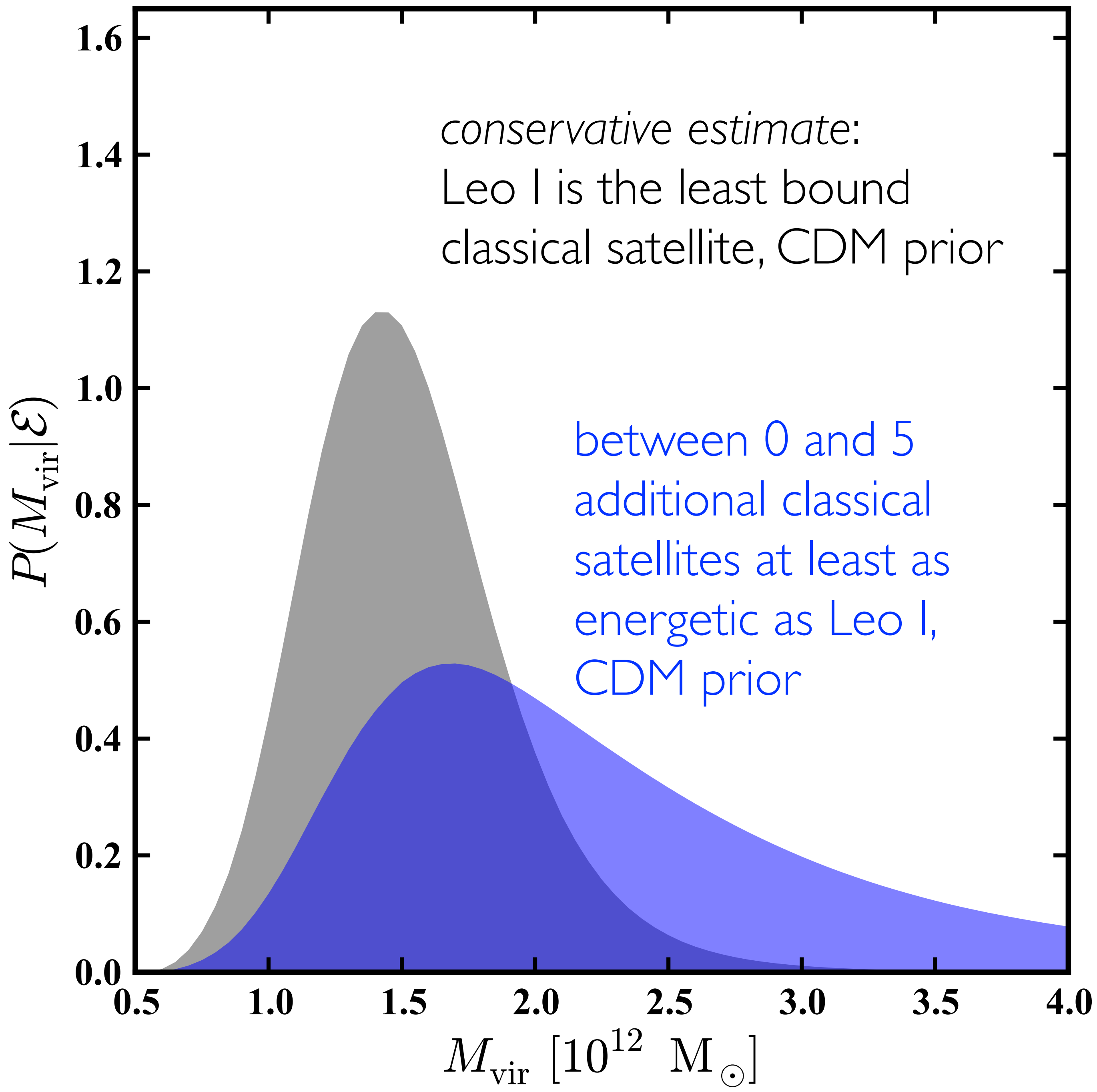
$$M_{\rm vir,MW} = 1.46 \times 10^{12}\,M_\odot$$

$$\text{90\% confidence interval}:$$

$$[0.95 - 2.19] \times 10^{12}\,M_\odot$$

MBK et al. 2012 (in preparation)

The Virial Mass of the Milky Way



conservative estimate:
Leo I is the least bound
classical satellite, CDM prior

between 0 and 5
additional classical
satellites at least as
energetic as Leo I,
CDM prior

$$M_{\rm vir,MW} = 1.46 \times 10^{12}\, M_\odot$$

$$90\% \text{ confidence interval :}$$

$$[0.95 - 2.19] \times 10^{12}\, M_\odot$$

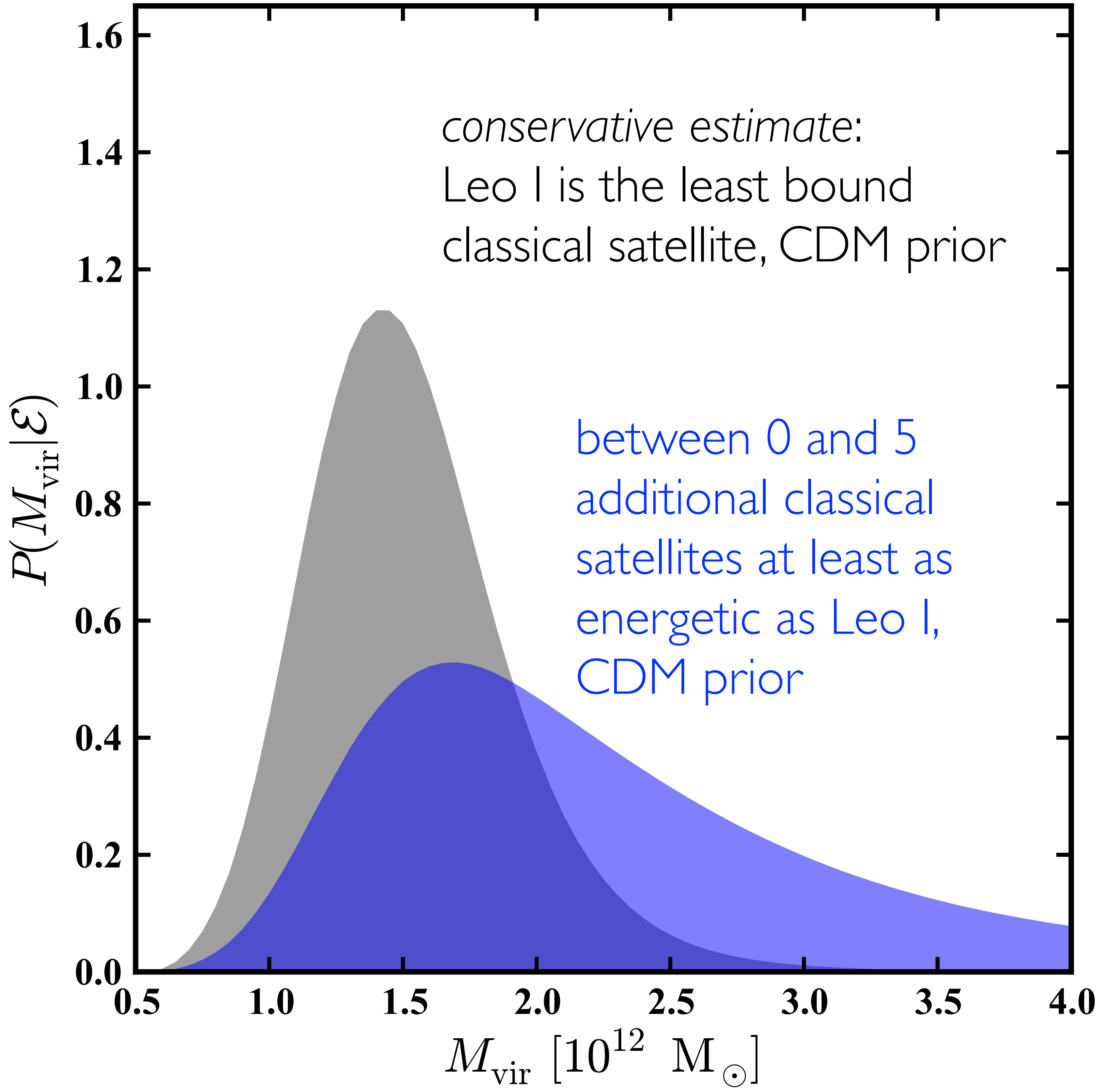
$$M_{\rm vir,MW} = 2.11 \times 10^{12}\, M_\odot$$

$$90\% \text{ confidence interval :}$$

$$[1.14 - 5.18] \times 10^{12}\, M_\odot$$

MBK et al. 2012 (in preparation)

The Virial Mass of the Milky Way



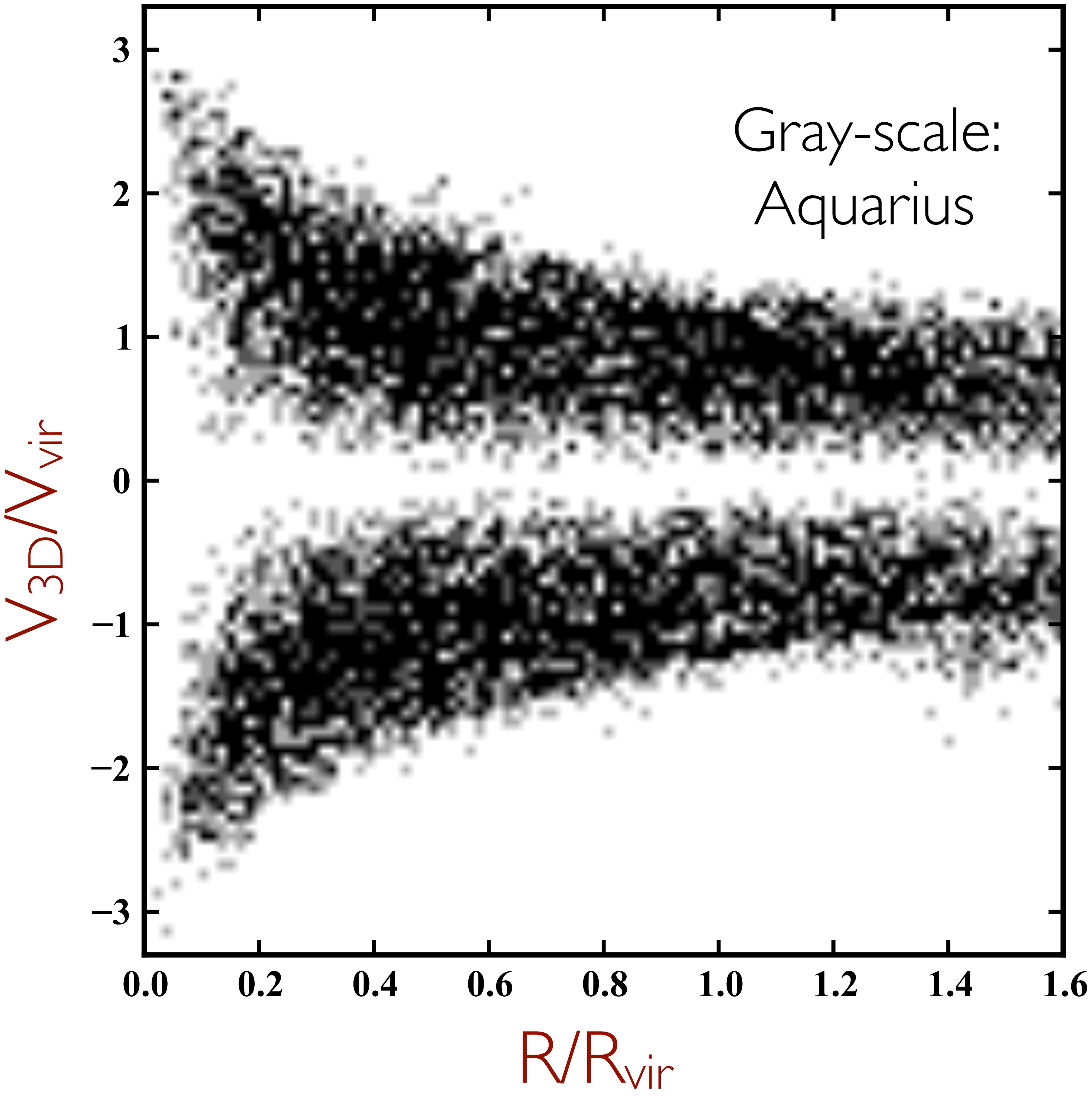
Best constraint for MW:

$M_{\rm vir} > 0.95 \times 10^{12}\, M_\odot$

at 95% confidence; nearly independent of assumptions about number of fast-moving satellites

MBK et al. 2012 (in preparation)

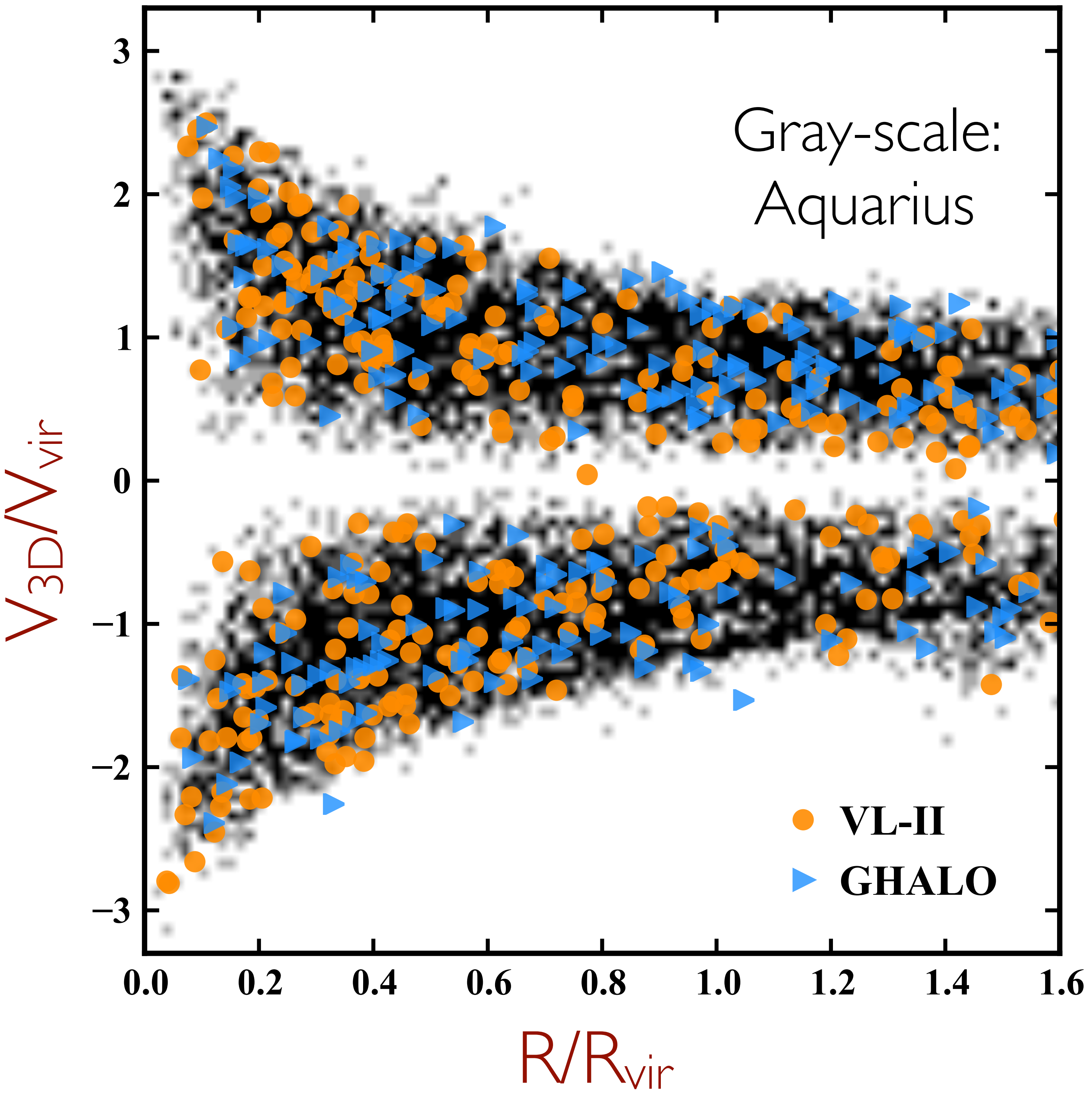
Cosmology dependence?



WMAP 1

MBK et al. 2012 (in preparation)

Cosmology Independence

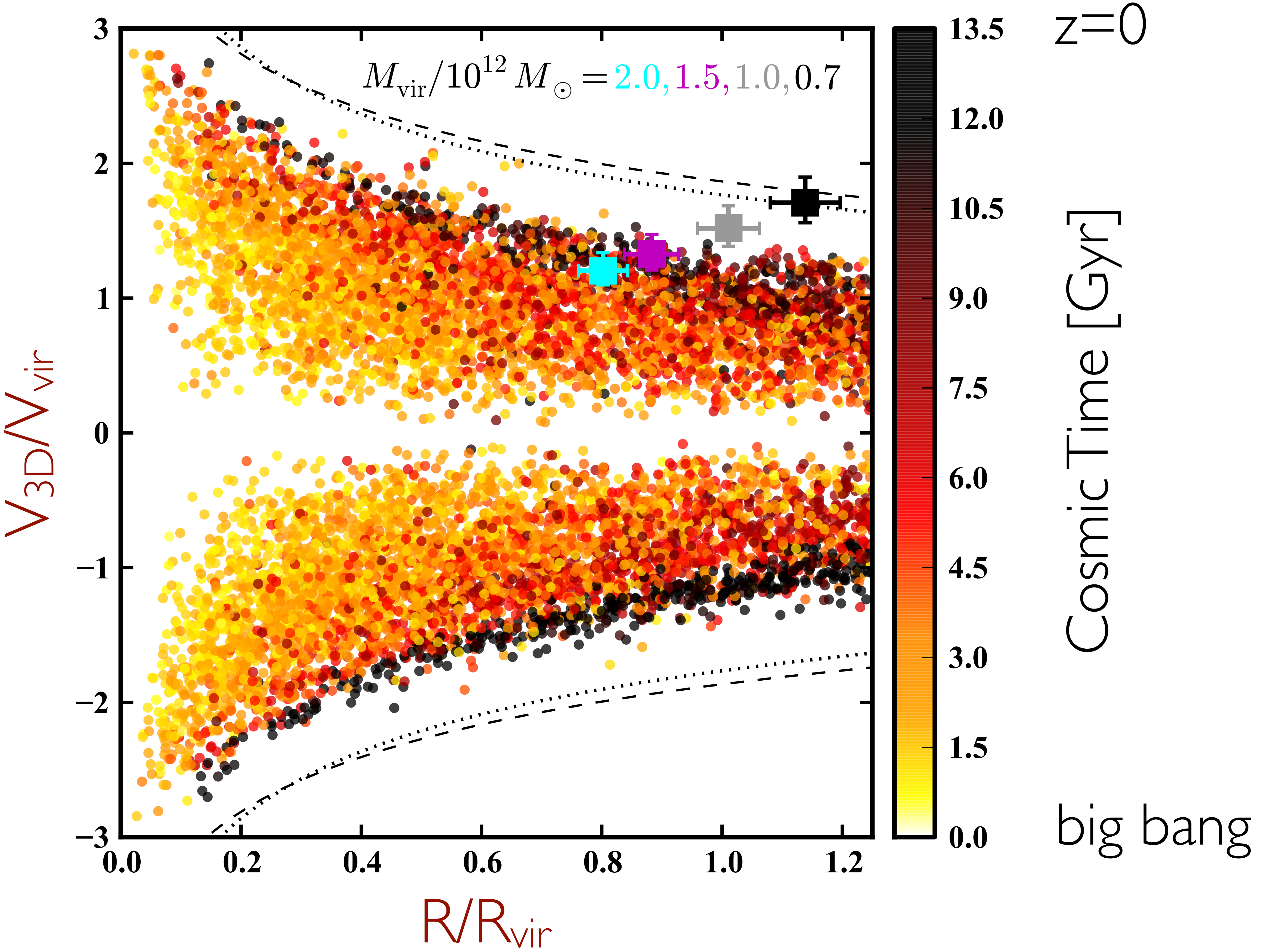


WMAP 1

WMAP 3

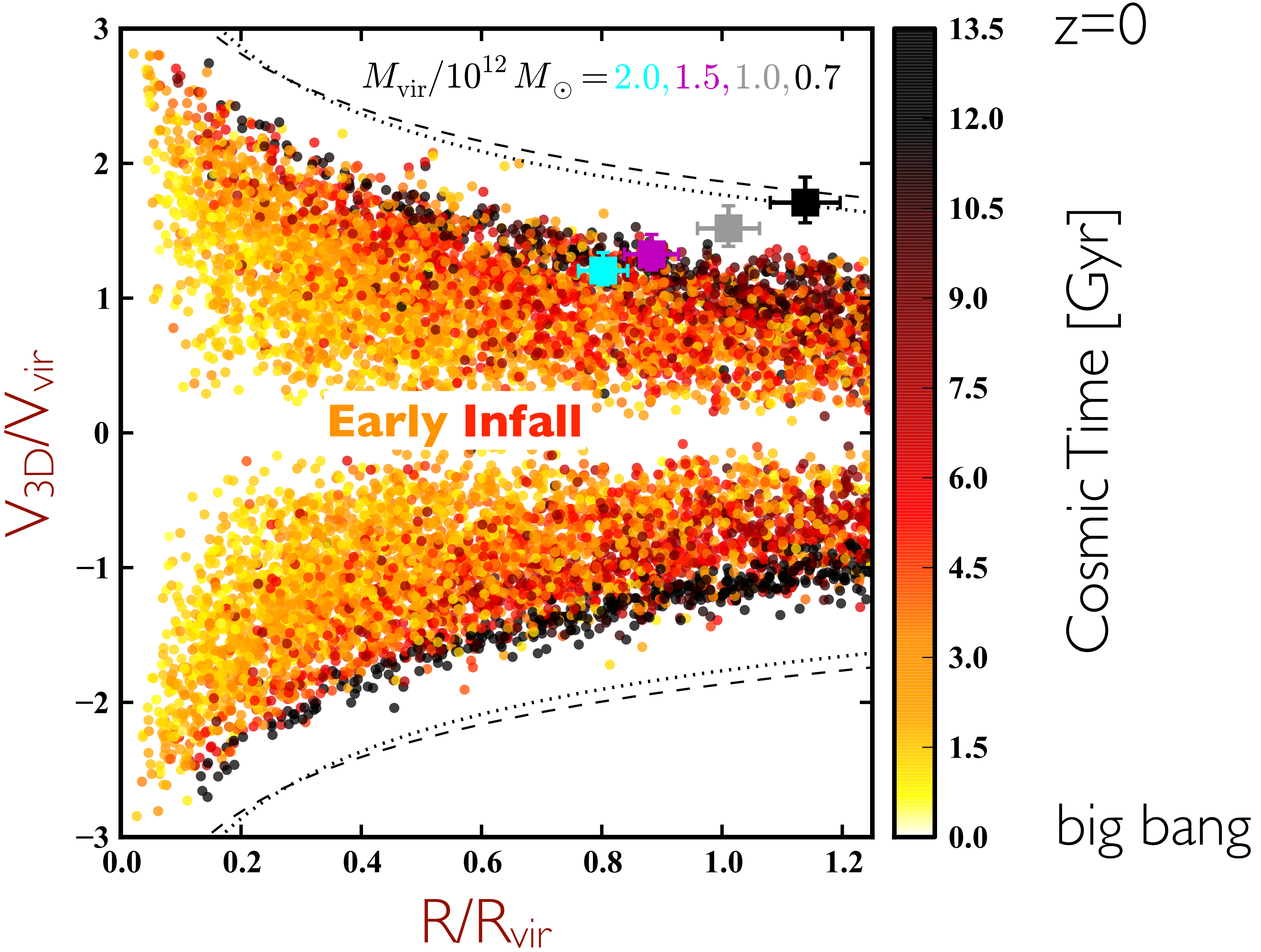
MBK et al. 2012 (in preparation)

Phase space is stratified based on infall time



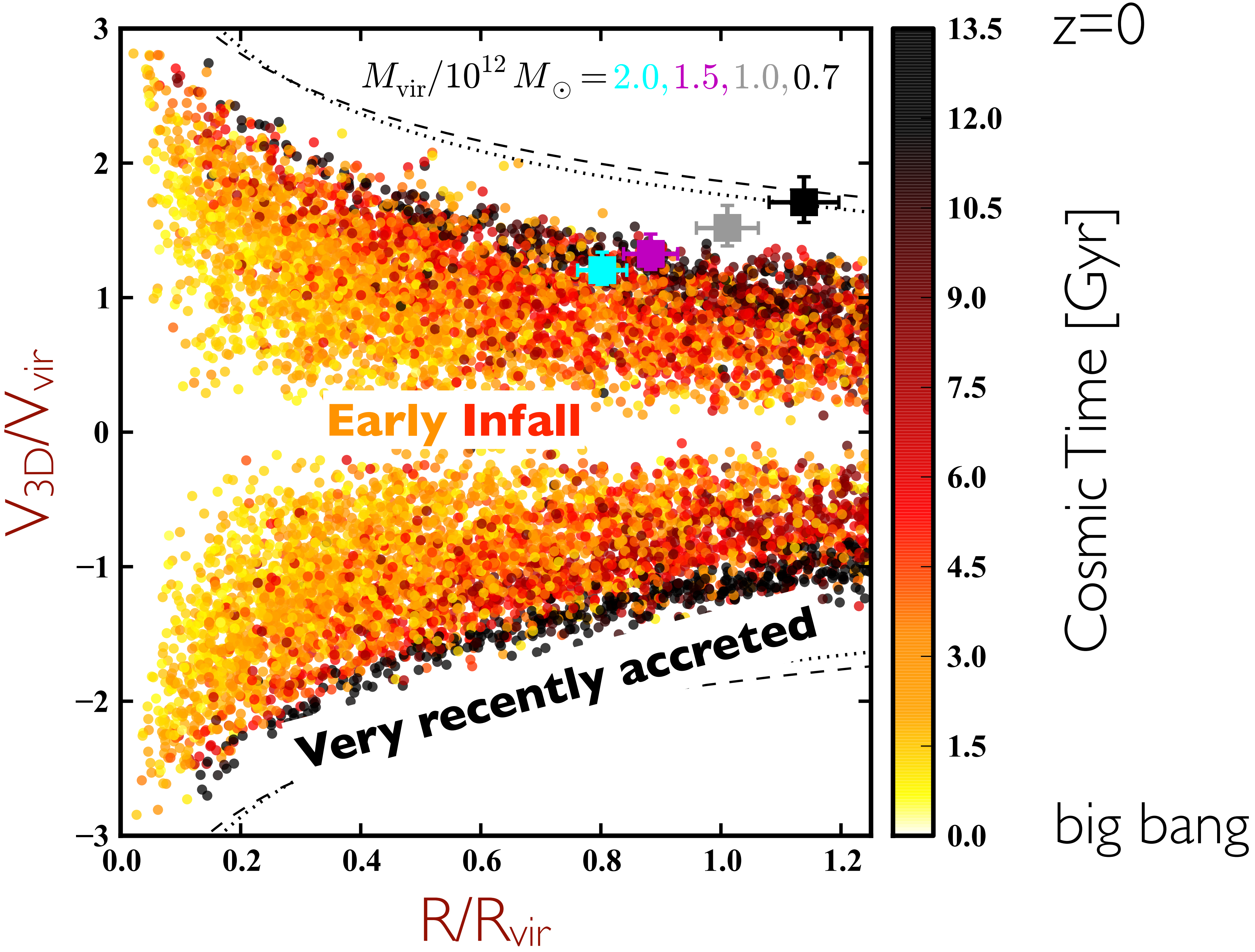
MBK et al. 2012 (in preparation); also see Rocha et al. 2012

Phase space is stratified based on infall time



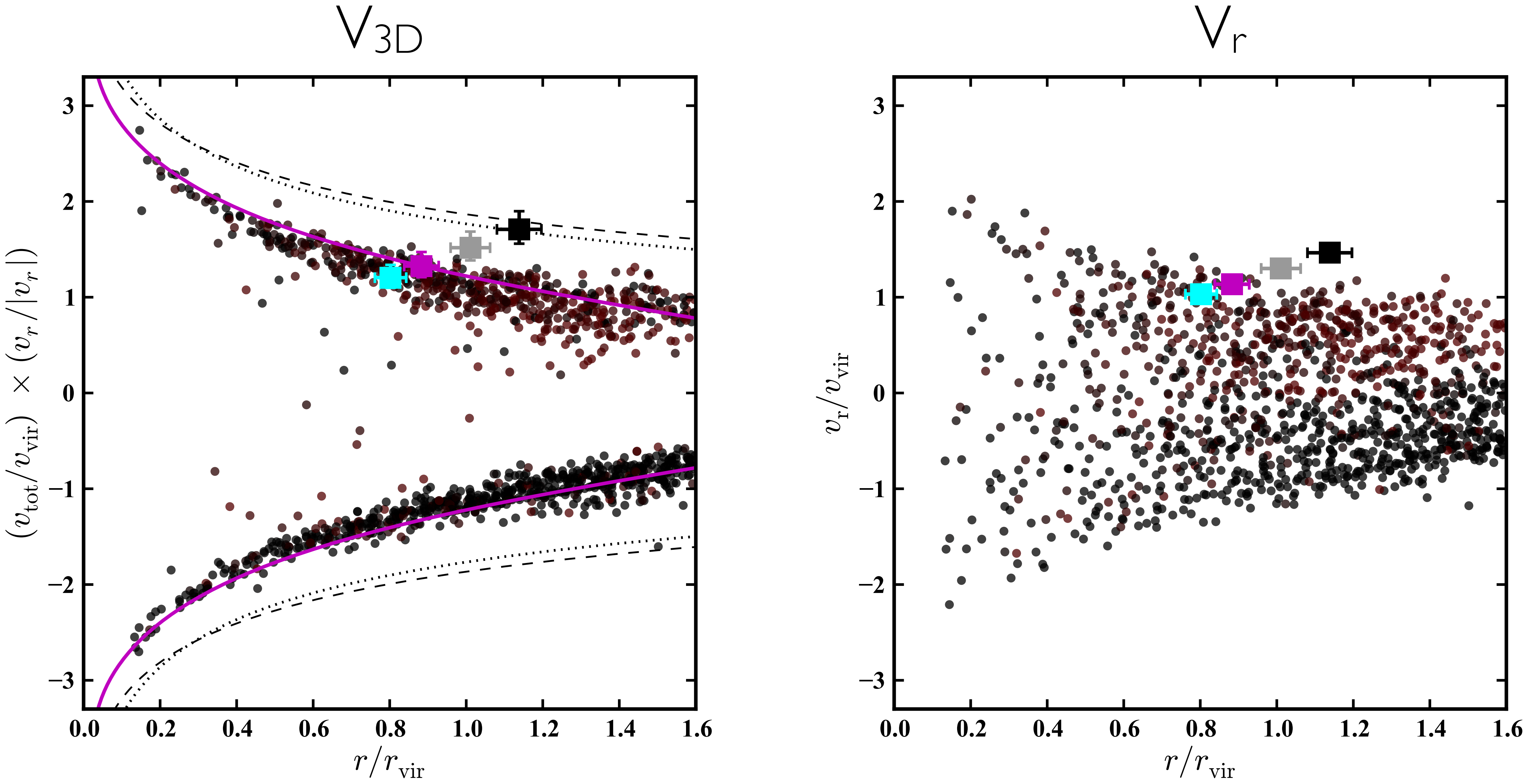
MBK et al. 2012 (in preparation); also see Rocha et al. 2012

Phase space is stratified based on infall time



MBK et al. 2012 (in preparation); also see Rocha et al. 2012

Only 3D velocity is stratified based on T_{infall}



Subhalos with z_{peak} in last 4 Gyr

MBK et al. 2012 (in preparation)

One implication of a $1.5\text{x}10^{12}$ Milky Way

- baryonic allotment of the MW is ~$2.5\text{x}10^{11}$ $M_{sun.}$ Observed baryonic content is ~$7\text{x}10^{10}$ M_{sun}. *Missing ~$1.8\text{x}10^{11}$ M_{sun} of baryons.*
    - Maybe these baryons never made it into the halo?
    - Maybe these baryons were ejected from the halo?
    - Maybe these baryons be hidden in an extended hot gas corona?

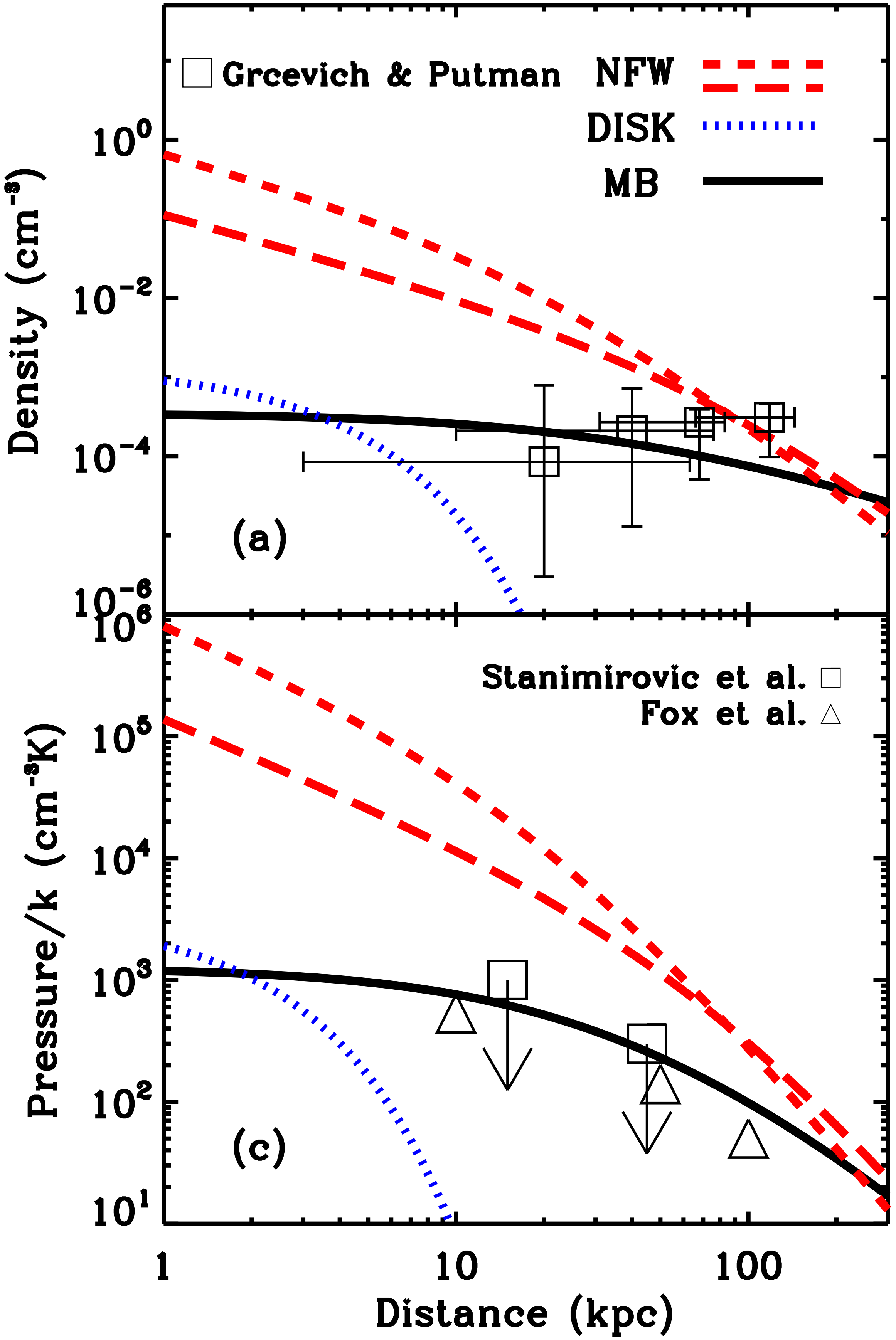
- These 3 possibilities have very different implications for our understanding of galaxy formation

MW hot gas constraints

Fang, Bullock, MBK 2012: constraints on hot (~10^6 K) gas in the MW halo depend strongly on adopted gas profile.

- Hot gas disk (from MW ISM): negligible contribution to MW baryon budget
- NFW distribution for gas (c=3 or 12): hot halo can only hold a small fraction of missing baryons (cf. Anderson & Bregman 2010)
- extended, cored distribution: *most* or *all* of the missing baryons could be within the virial radius, even for $M_{vir} \sim 1.5\times10^{12}$
    - profile motivated by Maller & Bullock 2004: adiabatic gas in hydrostatic equilibrium with NFW dark matter halo

ram pressure
stripping of dwarfs



NFW

Extended corona

Local Hot Disk

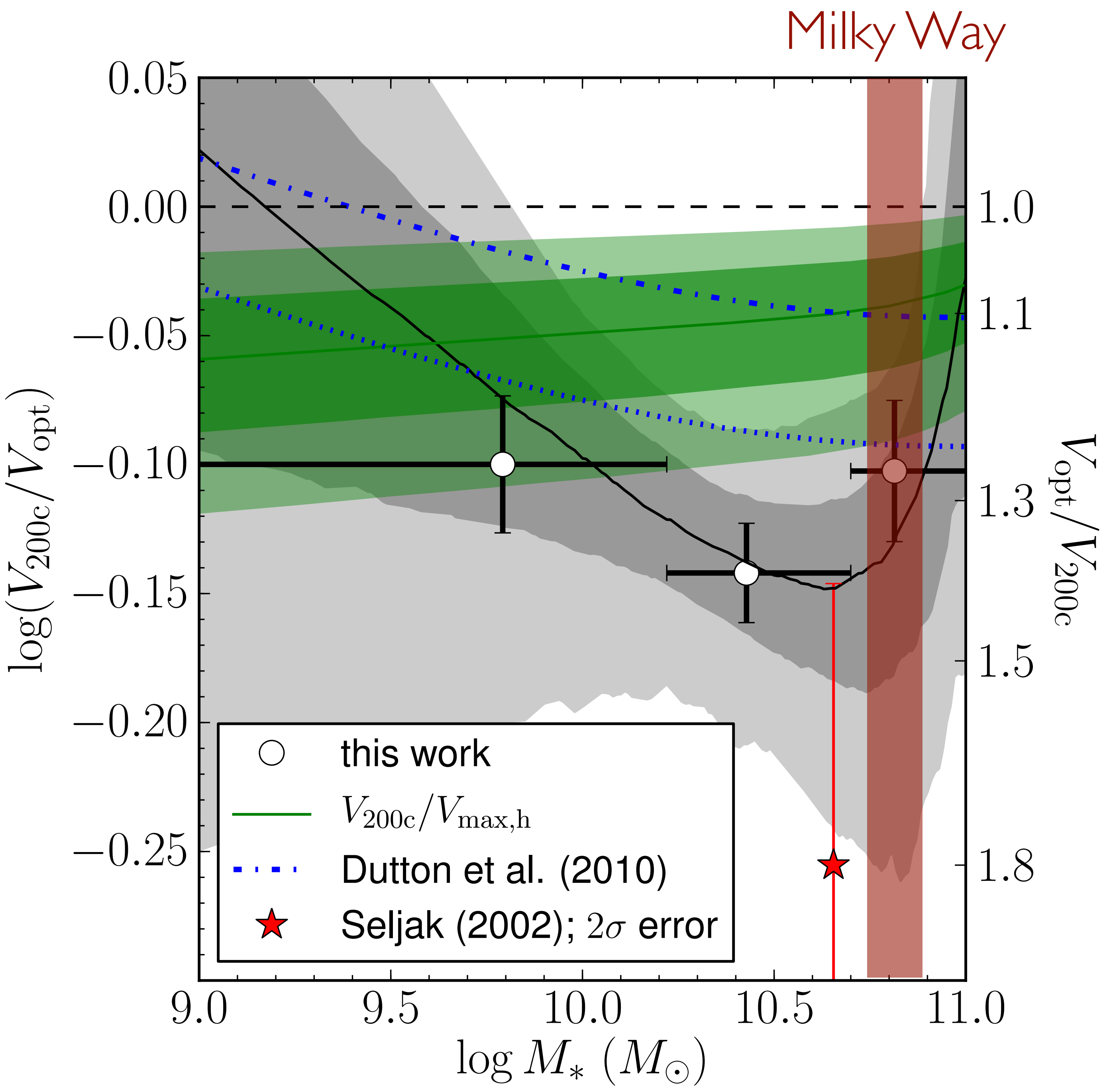
HVC pressure
confinement in the
Magellanic Stream

Fang, Bullock, MBK (2012, to be submitted)

Conclusions

- The virial mass of the Milky Way is *important*. Reducing the uncertainty in $M_{vir,MW}$ is crucial for making progress in several areas of galaxy formation.
- Leo I plays an outsized role in driving satellite-based estimates of M_{MW}, but interpreting its motion has been contentious
- Sohn et al. 2012 have measured Leo I's proper motion: Leo I has significant tangential velocity (~100 km/s).
- LCDM simulations: relaxed hosts have virtually no unbound subhalos
- comparing to LCDM simulations, find $M_{vir,MW}=(1.5\text{-}2.1)\times10^{12}\ M_{sun}$ and $M_{vir,MW} > 10^{12}\ M_{sun}$ at 95% confidence
- strong correlation between orbital energy and infall time; in general, not present only with radial velocities, need proper motions

Galaxy-galaxy lensing + Tully-Fisher



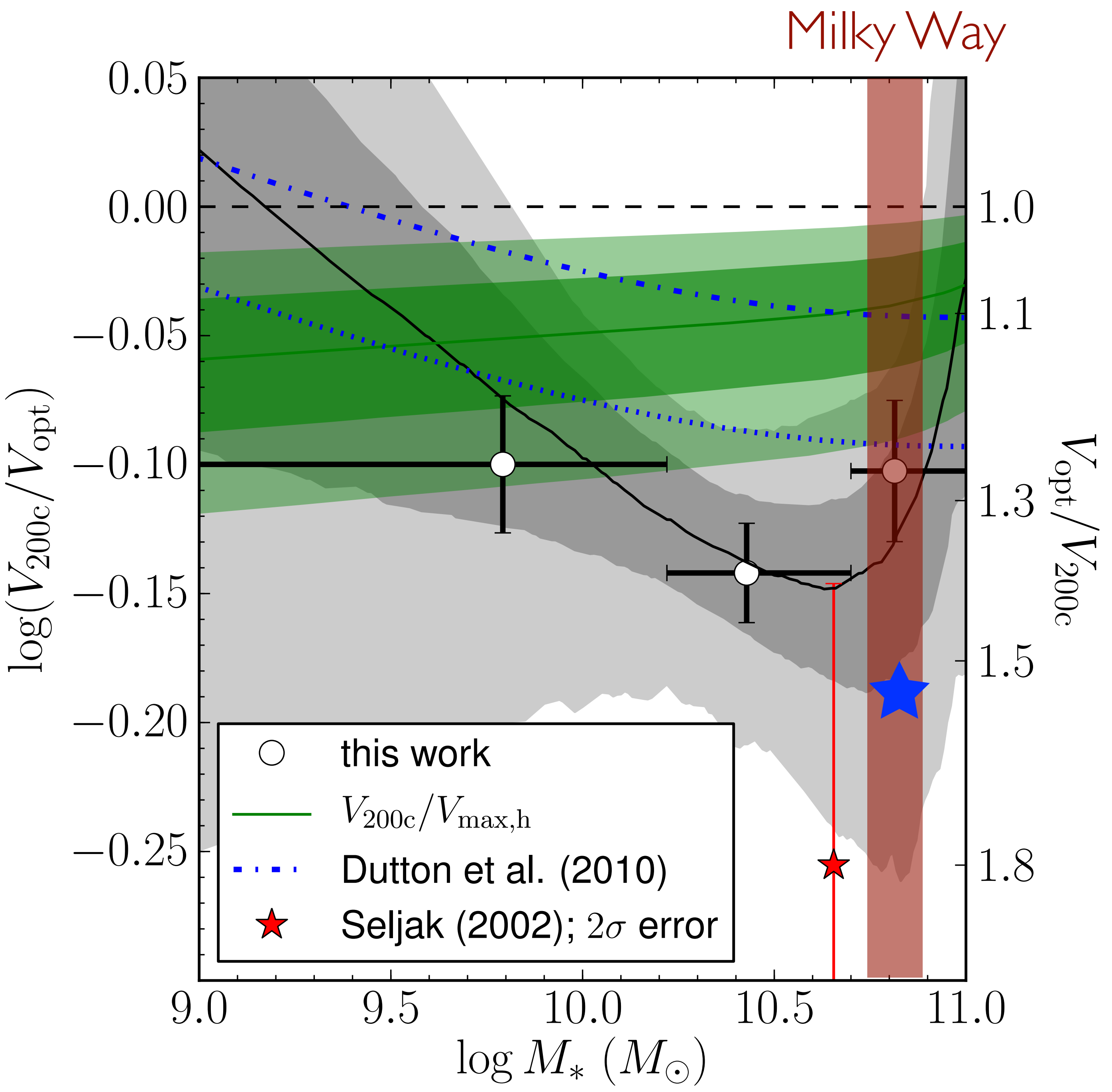
$$V_{\rm opt,MW} = 240 \pm 10\,{\rm km\,s^{-1}}$$

median V_{200c}=190 km/s for Milky Way's stellar mass. This gives M_{vir}~$2.5\text{x}10^{12}$

Reyes et al. 2012

Galaxy-galaxy lensing + Tully-Fisher

Milky Way



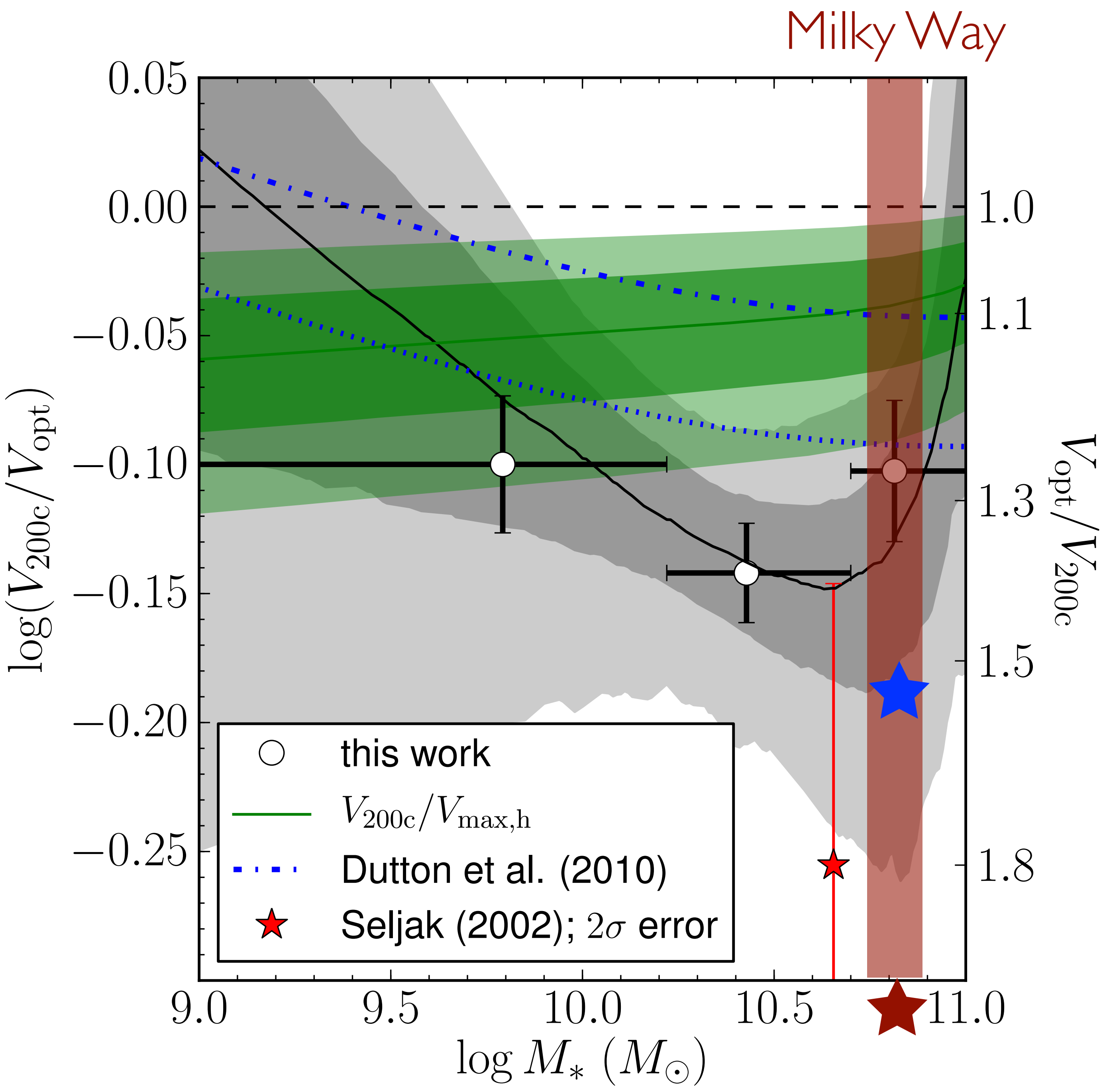
$$V_{opt,MW} = 240 \pm 10\,\mathrm{km\,s^{-1}}$$

median V_{200c}=190 km/s for Milky Way's stellar mass. This gives M_{vir}~2.5×10^{12}

for $M_{vir}=1.5\times10^{12}$, get V_{200c} =157 km/s

Reyes et al. 2012

Galaxy-galaxy lensing + Tully-Fisher



$$V_{\rm opt,MW} = 240 \pm 10\,{\rm km\,s^{-1}}$$

median V_{200c}=190 km/s for Milky Way's stellar mass. This gives M_{vir}~2.5×10^{12}

for $M_{vir}=1.5\times10^{12}$, get V_{200c} =157 km/s

for $M_{vir}=7\times10^{11}$, get V_{200c} =122 km/s

Reyes et al. 2012