Scatter Carefully:
Constraining the faint end of the halo-galaxy connection with the Local Group

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Abundance matching

Assume monotonic

log $M_{\text{star}}$

log $M_{\text{halo}}$

Halo number density

e.g. Tinker+2008

Halo mass

from simulations

Galaxy number density

e.g. Baldry+2012

Galaxy stellar mass

from observations
Abundance matching

Use counts in the Local Group to explore faint-end extrapolations

Stellar Mass $[M_\odot]$
Abundance matching in the LG

$M_{\text{star}} \propto M_{\text{halo}}^\alpha$

$\alpha = 1.412$

Behroozi+2013 AM predicts too many faint galaxies in the LG when applied to LG-like simulations.

Behroozi+2013

ELVIS Satellites

MW

M31

LG incompleteness

GK+2014a
Modified Behroozi+2013 using a steeper low-mass slope (Baldry+2012) agrees well with...
But we know scatter exists at higher masses…

What is the scatter at the low mass end? Can we constrain it with the LG?

What are the implications of large scatter? e.g., on extant problems in $\Lambda$CDM?

Can the scatter suggested by simulations be correct? Will it correctly predict the LG?
The impact of scatter on mass functions

\[ \log_{10}(M_{\text{star}}) \] [M\text{sun}]

\[ \log_{10}(M_{\text{halo}}) \] [M\text{sun}]

\[ M_{\text{star}} = f_{b} M_{\text{halo}} \]

Behroozi + 2013

\[ M_{\text{star}} \propto M^{2.6}_{\text{peak}} \]

\[ M_{\text{star}} \propto M^{1.8}_{\text{peak}} \]

GK+ in prep

2 dex
The impact of scatter on mass functions

Different slope and scatter

Same slope, different scatter

MW + M31 combined

$M_{\text{star}} \propto M_{\text{halo}}^{1.8}$, $\sigma = 0$

$M_{\text{star}} \propto M_{\text{halo}}^{2.6}$, $\sigma = 2$ dex

GK+ in prep
More realistic AM: adding scatter

Low mass ($M_{\text{halo}} \lesssim 10^{11} M_{\odot}$) log-slope $\alpha$ allowed to vary freely

Assume symmetric, log-normal scatter, which also varies freely (quoted $\sigma$ is one standard deviation)

Tested many models for assigning stellar mass to halos (one-sided or variable scatter, $M_{\text{star}} < f_\text{b} M_{\text{halo}}$, cut-offs in star formation, etc.)

All yield qualitatively similar results!
Scatter and slope are degenerate

Averaged over 24 systems, each with 500 realizations

⇒ 12,000 realizations per combination of $\sigma$ and $\alpha$
Scatter and slope are degenerate

Qualitatively identical results using the Local Field

GK+ in prep

Better fit
Effects of large $\sigma$: too-big-to-fail
What is too-big-to-fail?

Theory: $N_{\text{subhalos}} \gg 1000$

Klypin et al. 1999; Moore et al. 1999; Kauffmann et al. 1993
What is too-big-to-fail?

Theory: \( N_{\text{subhalos}} \gg 1000 \)

Observations: \( N_{\text{galaxies}} \sim 10 \)

Klypin et al. 1999; Moore et al. 1999; Kauffmann et al. 1993
What is too-big-to-fail?

Obvious solution: only the largest clumps form stars and host galaxies

Klypin et al. 1999; Moore et al. 1999; Kauffmann et al. 1993
What is too-big-to-fail?

Does this actually work?

Klypin et al. 1999; Moore et al. 1999; Kauffmann et al. 1993
What is too-big-to-fail?

Massive subhalos are too dense to match the data.

\[ V_{\text{circ}}(r) = \sqrt{\frac{GM(<r)}{r}} \]

Aquarius simulations (Springel+2008)

Does this actually work?
Too big to fail

Subhalos selected by **largest mass**

Lots of subhalos that *should* have formed stars, but without any observational counterparts.
Many large halos scatter below $M_{\text{star}}$ cut!

Reminder: $N_{\text{halos}} \approx N_{\text{galaxies}}$ by design
TBTF with large scatter

One realization of the MW:

Lots of TBTF systems when $\sigma = 0$

Large $\sigma \Rightarrow$ realizations with classical dSphs living in small halos...

...and massive (problematic) subhalos hosting ultra-faint dwarfs
TBTF with large (constant) scatter

Reminder: $N_{\text{halos}} \approx N_{\text{galaxies}}$ by design

MW satellites

Local Field

average number of massive failures

fraction with no failures

best-fit faint-end log-slope

scatter [dex]

GK+ in prep
Observational evidence for large scatter?

Direct measurements of $M_{\text{halo}}$ impossible; indirect hints?

Unquenched, faint galaxies?

Galaxies hosted by low-mass ($\lesssim 10^9 \, M_{\text{sun}}$) halos; all quenched by $z \sim 2$

With large scatter, some faint galaxies live in massive halos, which are resistant to reionization quenching.
Theoretical evidence for large scatter?

$\log_{10}(M_{\text{star}}) [M_\text{sun}]$

$\log_{10}(M_{\text{halo}}) [M_\text{sun}]$

Ultra-high resolution simulations fail to reproduce the downward scatter necessary to avoid overproducing counts in the LG

**CAVEAT:**

Need a large sample of simulations, run with identical physics.
Conclusions

Scatter in $M_{\text{star}} - M_{\text{halo}}$ boosts galaxy counts at fixed $M_{\text{star}}$

Require a rapid fall-off to avoid overproducing LG dwarfs: *simulations should not trace Behroozi+13 if they exhibit scatter*

Large scatter eliminates TBTF from ~25% of realizations by assigning the massive, problematic subhalos ultra-faints

Very difficult to directly test hypothesis that $\sigma \sim 2$ dex, but *clues may exist in star formation histories or internal dynamics*

No theoretical evidence yet (but need more sims!)