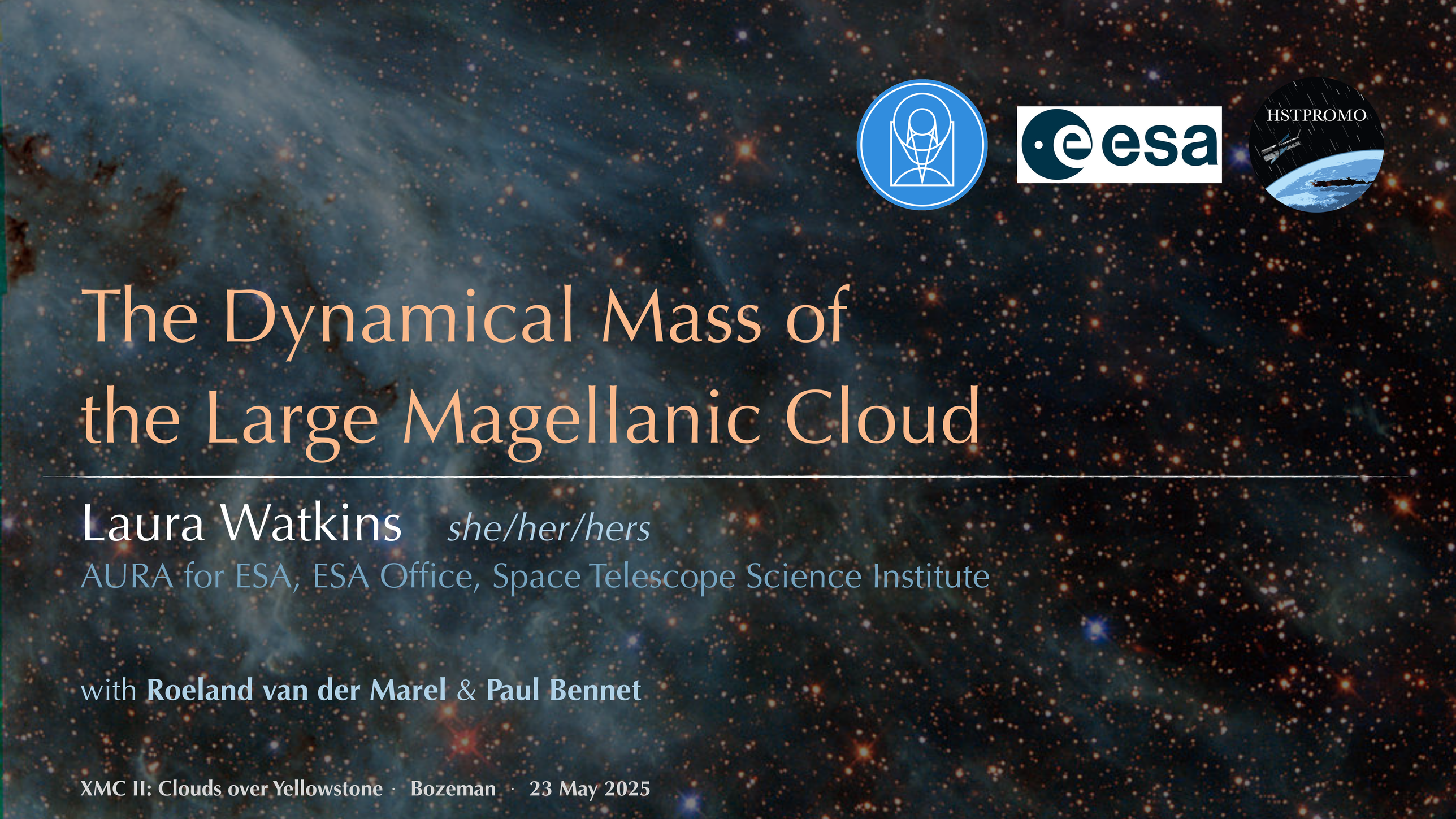


The Dynamical Mass of the Large Magellanic Cloud

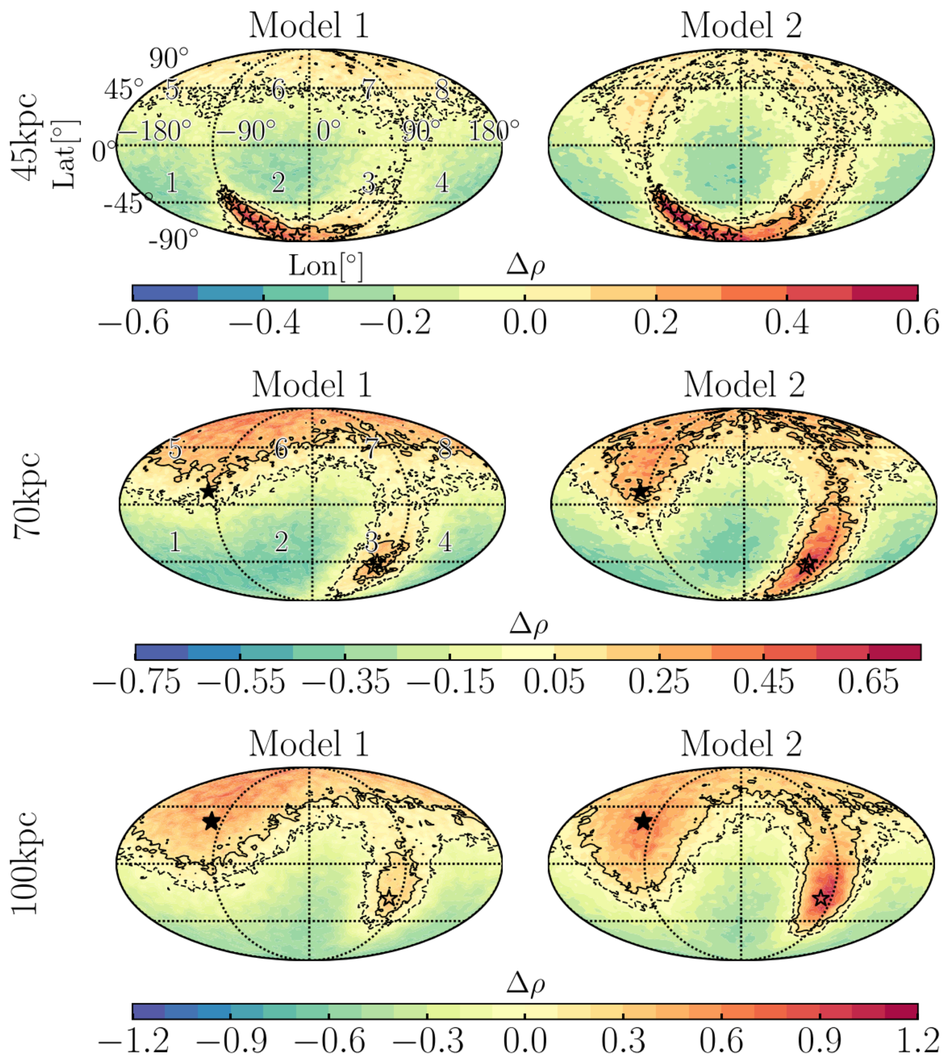
Laura Watkins *she/her/hers*

AURA for ESA, ESA Office, Space Telescope Science Institute

with **Roeland van der Marel** & **Paul Bennet**

XMC II: Clouds over Yellowstone · Bozeman · 23 May 2025

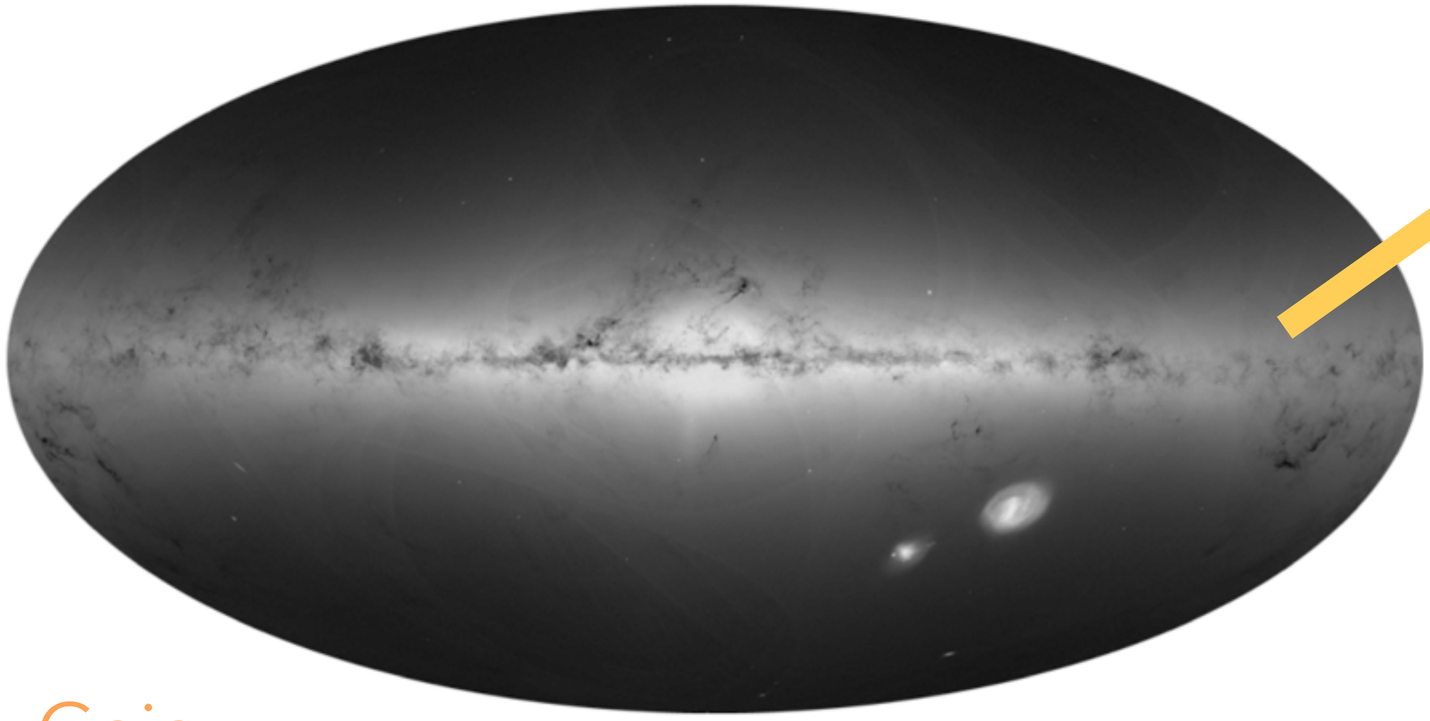
Why? Effect on the Local Group

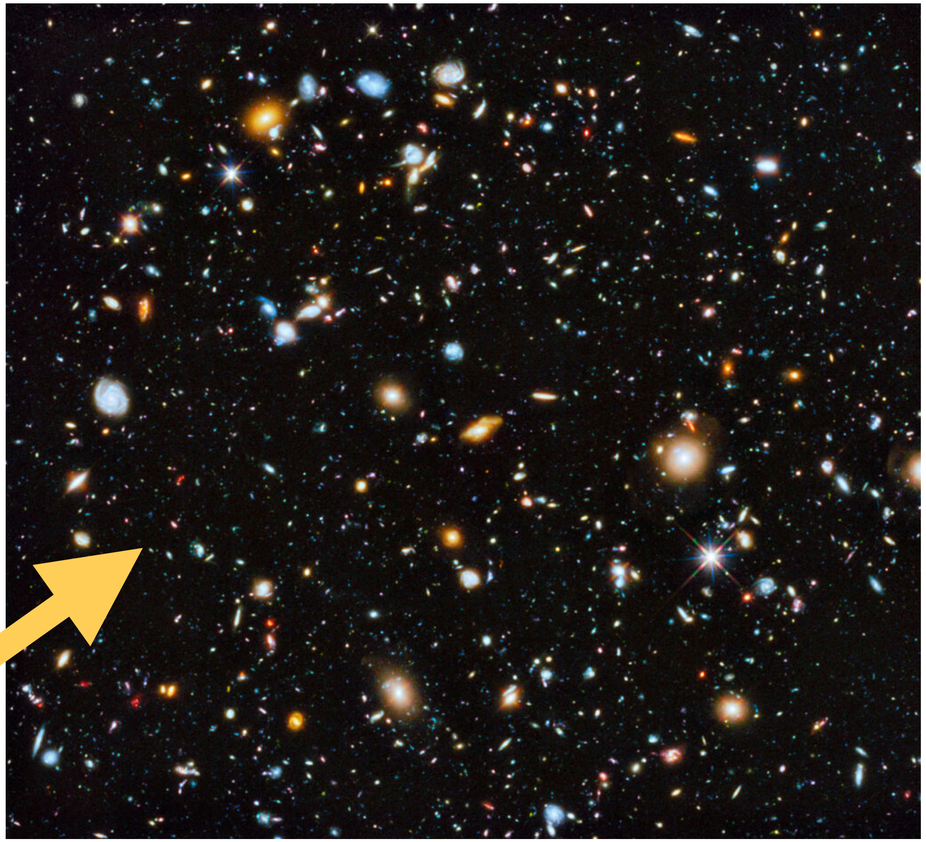


- Mass is fundamental
- Structure and evolution of the LMC
- LMC-SMC system
- LMC & SMC interactions
- Magellanic Bridge and Stream
- MW streams
- MW disk and MW halo response
- Evolution of the Local Group

Garavito-Camargo+ 2019

Why? ~Unique Benchmark





ESA, Gaia

NASA, ESA, HST

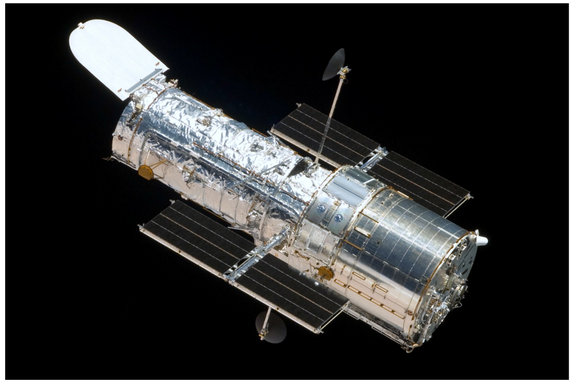
Dynamical Mass Methods

- Mass for LMC & SMC to be bound (e.g. Kallivayalil+ 2013)
- Timing Argument (e.g. Peñarrubia+ 2016)
- MW response to LMC infall (e.g. Laporte+ 2018, Erkal+ 2021)
- Effect on streams in MW halo (e.g. Erkal+ 2019, Vasiliev+ 2021, Shipp+2021)
- Abundance matching
- **TRACERS ➜ this talk!**

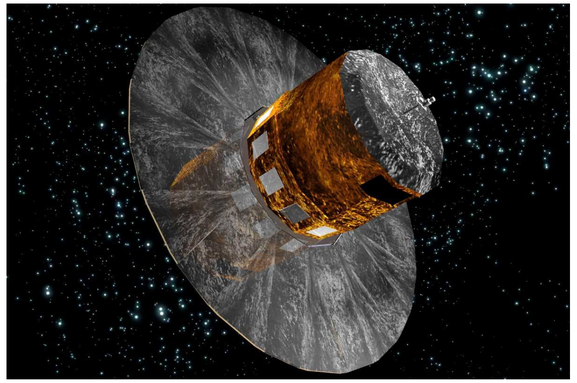
32 LMC GCs in 6D

Bennet+ 2022

- **GaiaHub** and Gaia PMs for LMC GCs



+



https://github.com/AndresdPM/GaiaHub

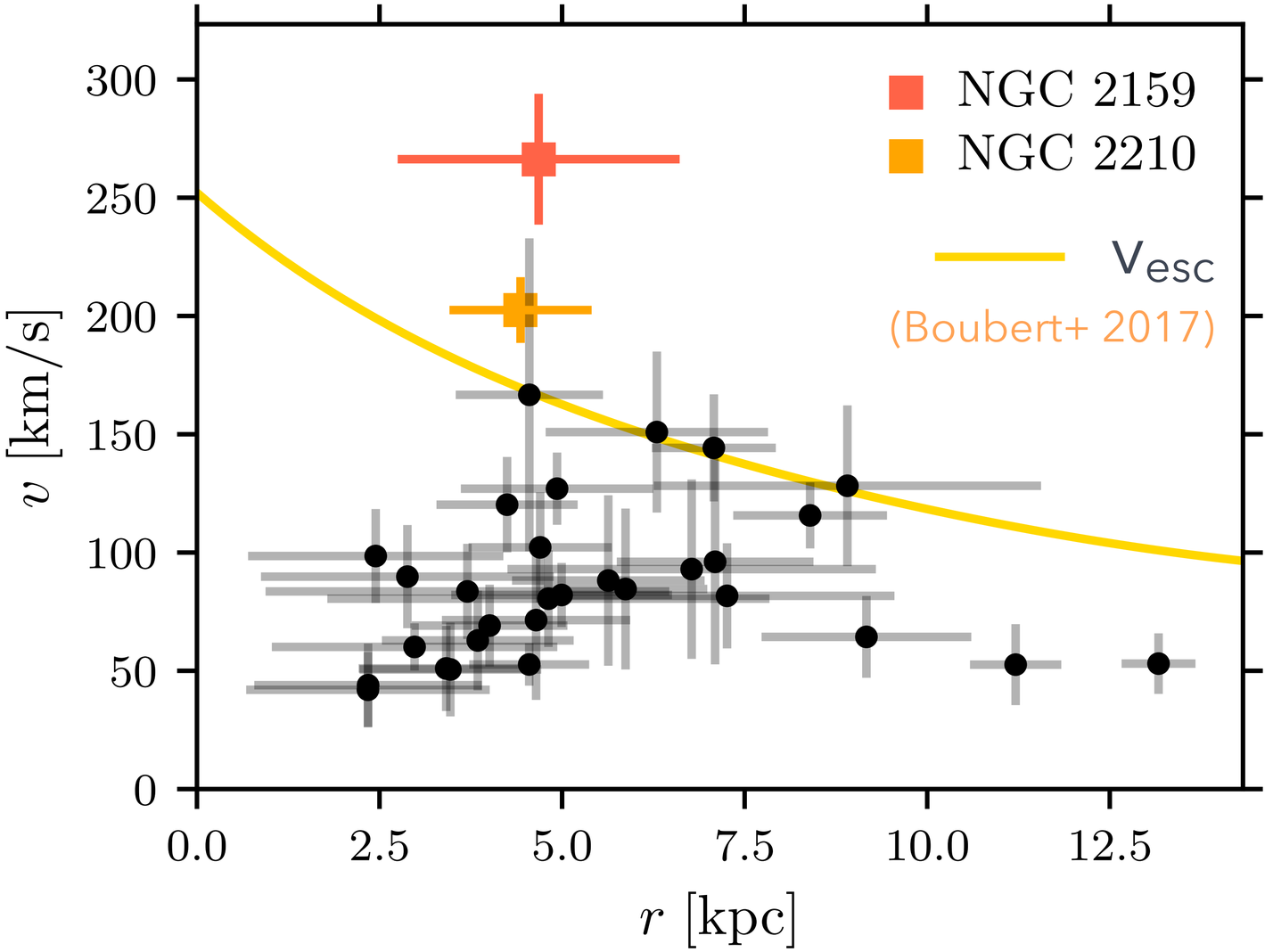
del Pino+ 2022

- + HST PMs
- Literature distances
- Literature line-of-sight velocities
- More PMs than distances and LOSVs!

32 LMC GCs in 6D

Bennet+ 2022

- **GaiaHub** and Gaia PMs for LMC GCs



- + HST PMs
- Literature distances
- Literature line-of-sight velocities
- More PMs than distances and LOSVs!

Tracer Mass Estimator

$$M\left(<r_{\max}\right)_{\mathrm{TME}} = \frac{\alpha+\gamma-2\beta}{G\left(3-2\beta\right)} r_{\max}^{1-\alpha}\left\langle v^2 r^{\alpha}\right\rangle$$

13.2 kpc

γ: tracer density power-law slope

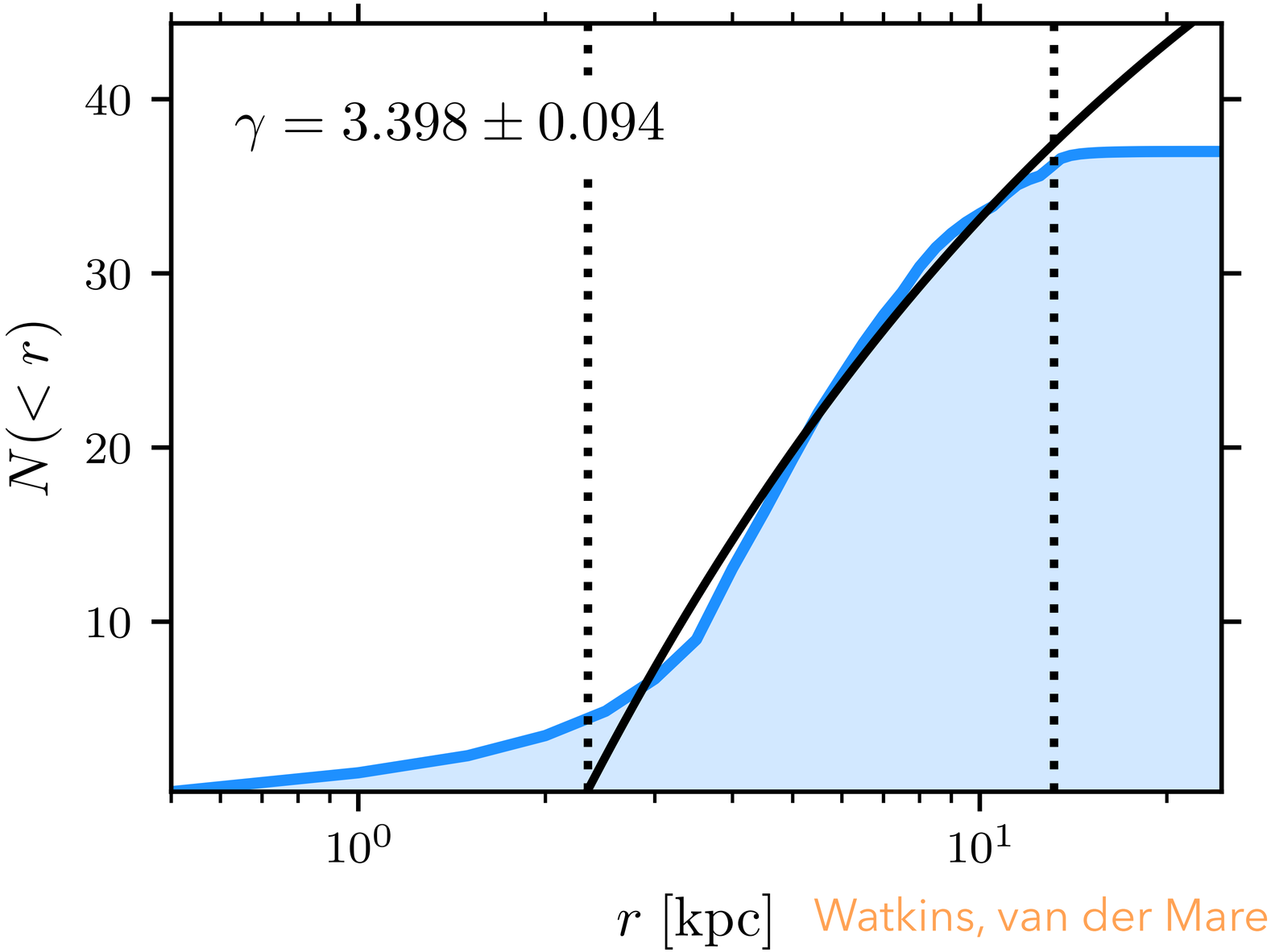
β: (constant) anisotropy

α: potential power-law slope

r_{max}: radius of most distant tracer

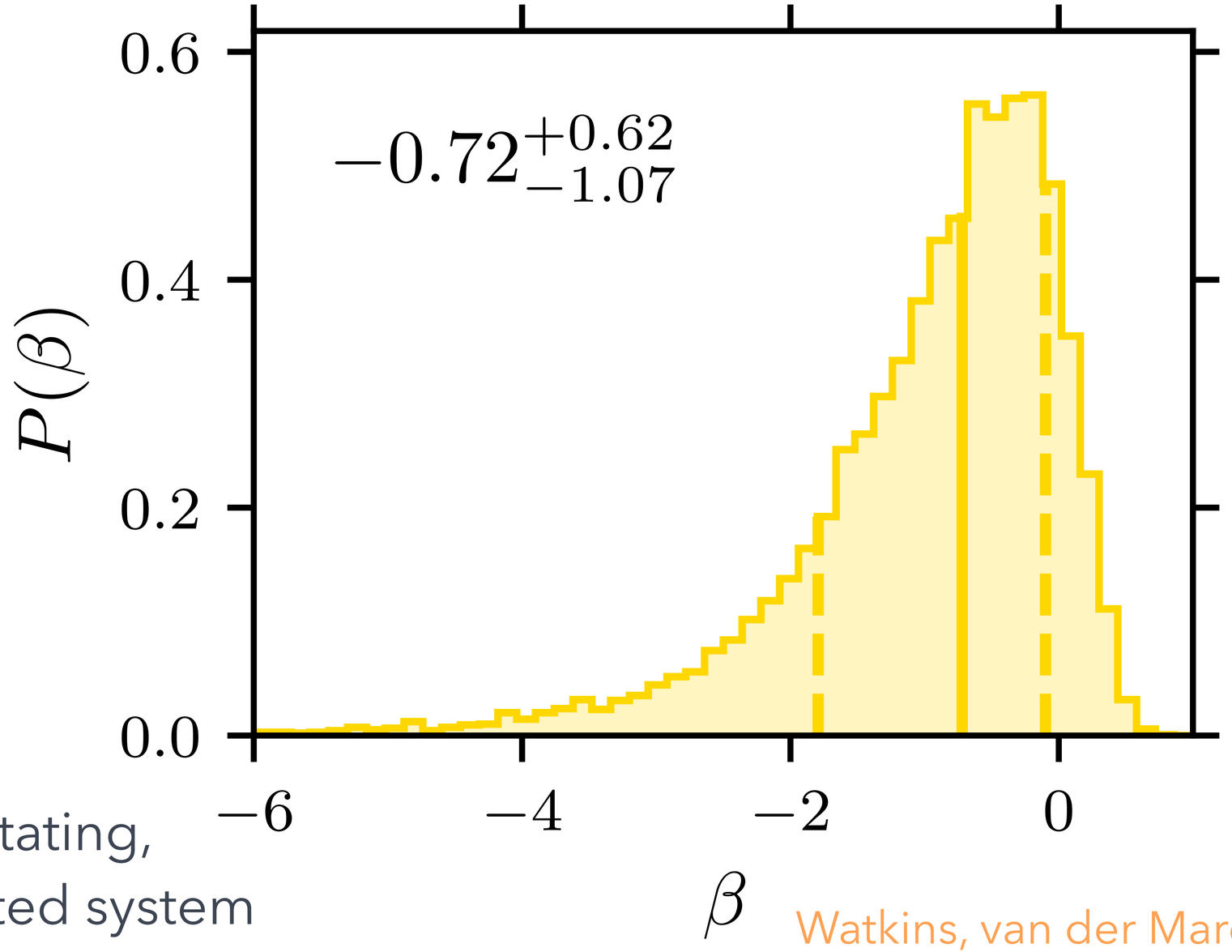
Watkins, Evans & An 2010

Tracer Density of LMC GCs



Watkins, van der Marel & Bennet (2024)

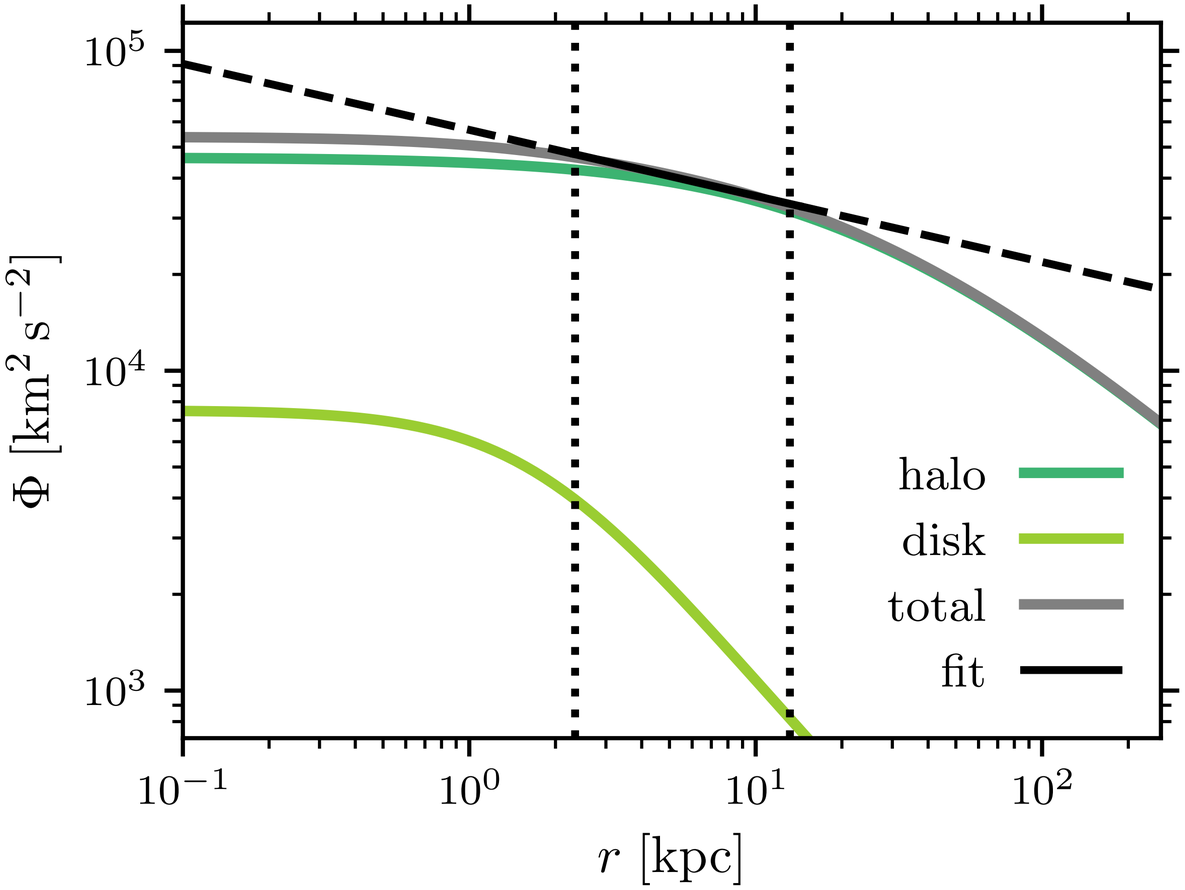
Velocity Anisotropy of LMC GCs



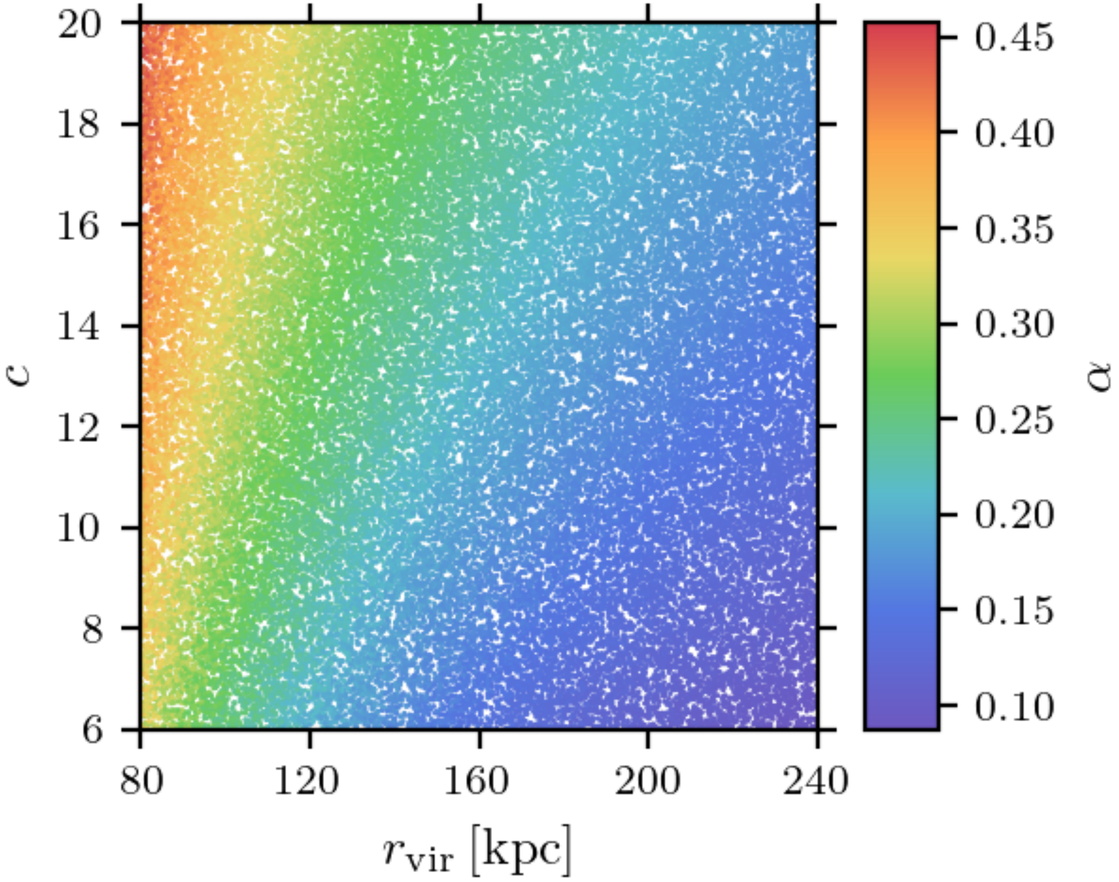
Flattened, rotating, pressure-supported system

Watkins, van der Marel & Bennet (2024)

Grid of halos ➜ Potential



disk + halo



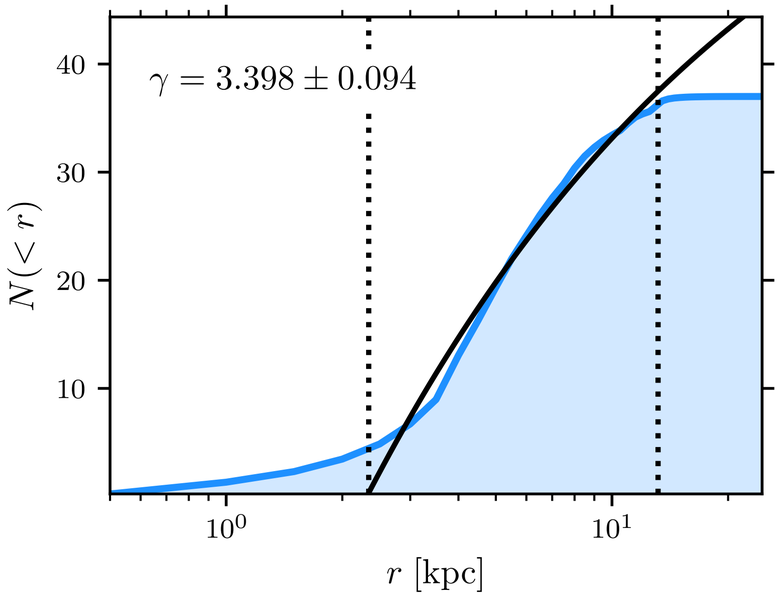
grid of halos

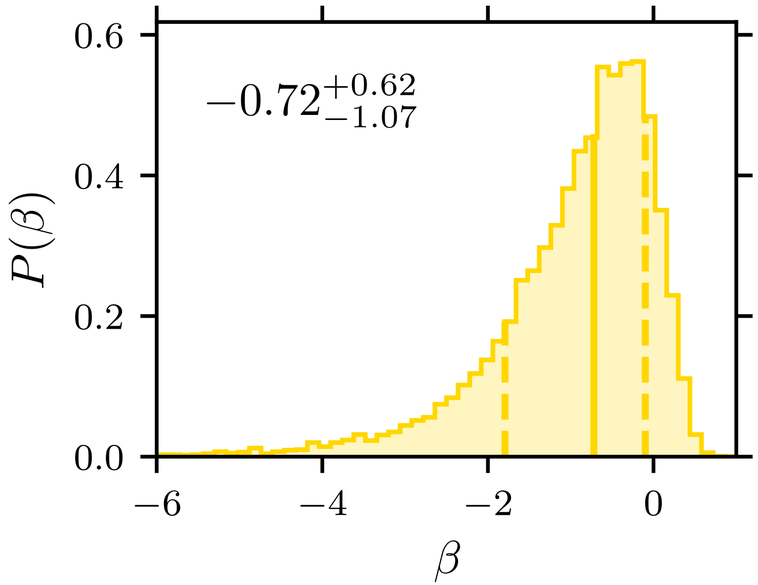
Watkins, van der Marel & Bennet (2024)

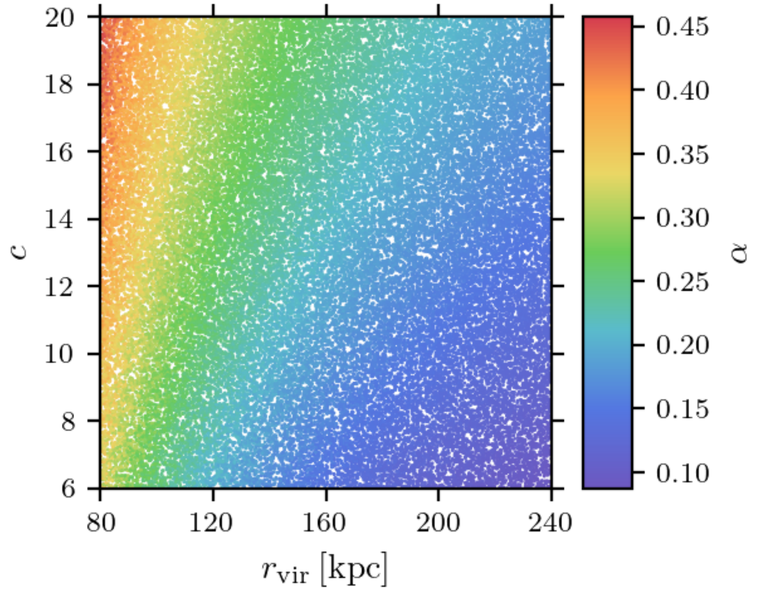
Grid of halos ➜ Potential

$$M\left(<r_{\rm max}\right)_{\rm TME} = \frac{\alpha+\gamma-2\beta}{G\left(3-2\beta\right)} r_{\rm max}^{1-\alpha}\left\langle v^2 r^{\alpha}\right\rangle$$

13.2 kpc

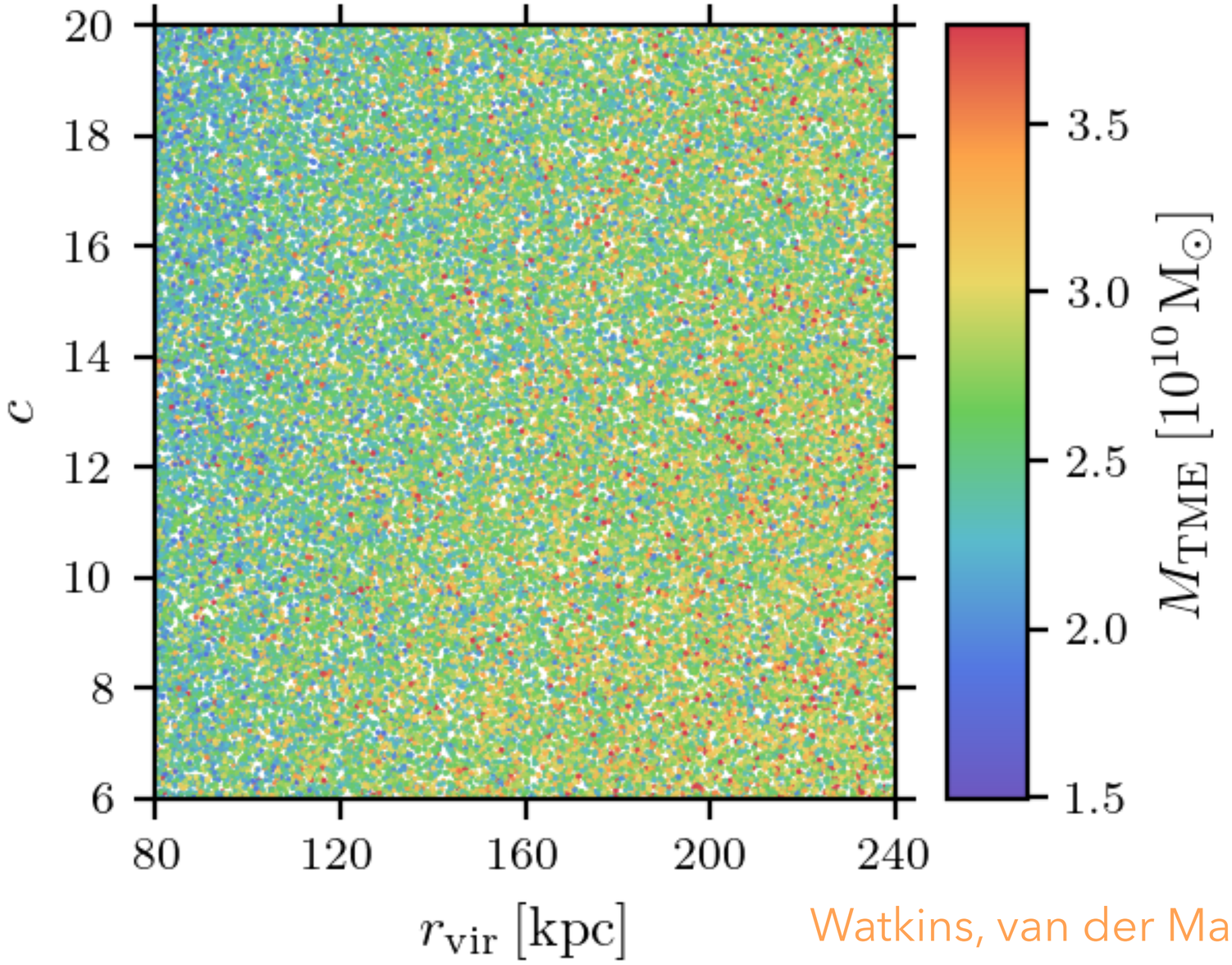






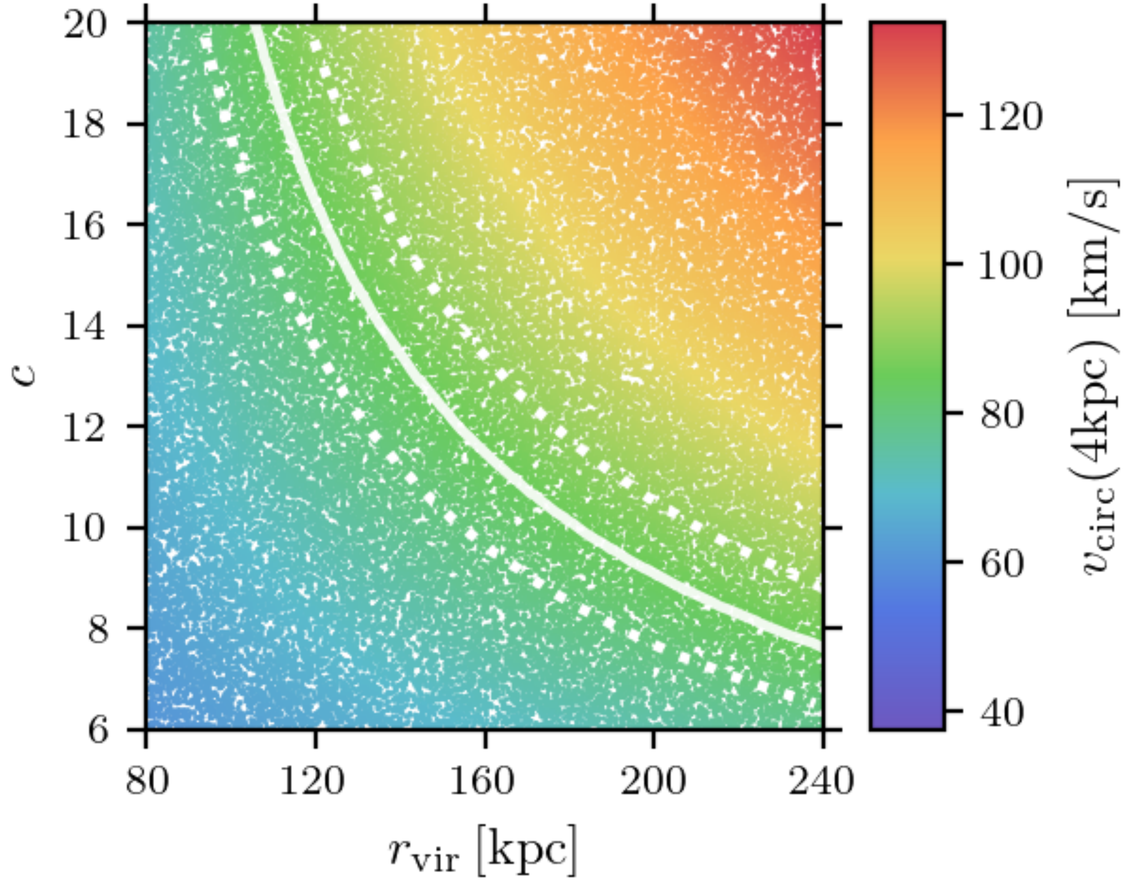
Watkins, van der Marel & Bennet (2024)

Tracer mass estimates?

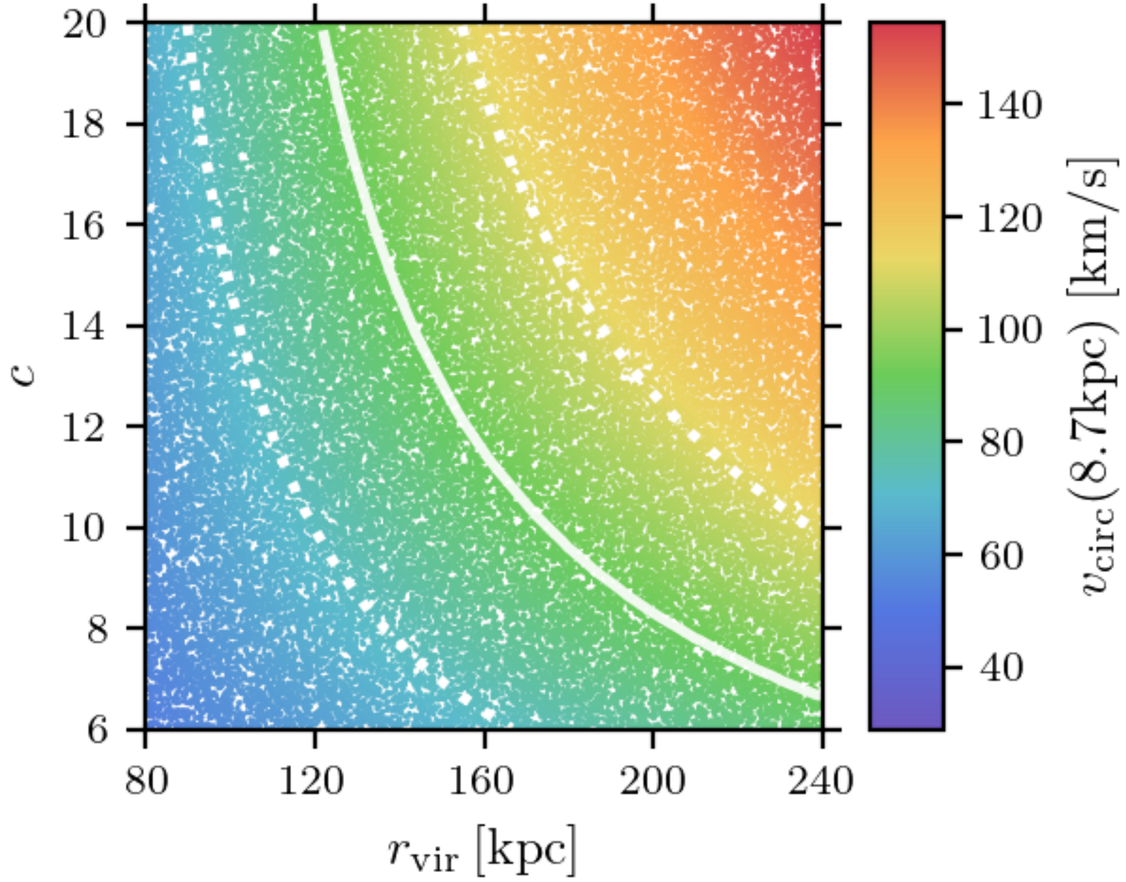


Watkins, van der Marel & Bennet (2024)

Circular Velocities



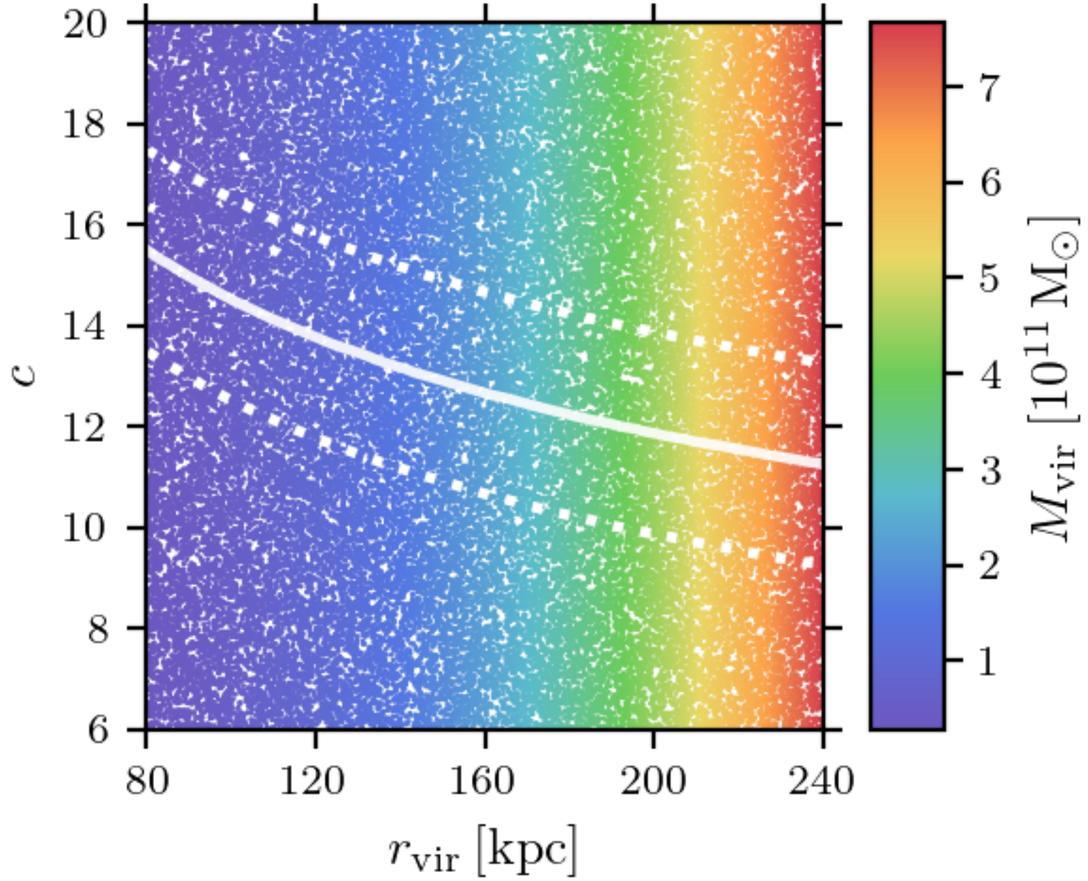
4kpc: Gaia Collaboration 2019



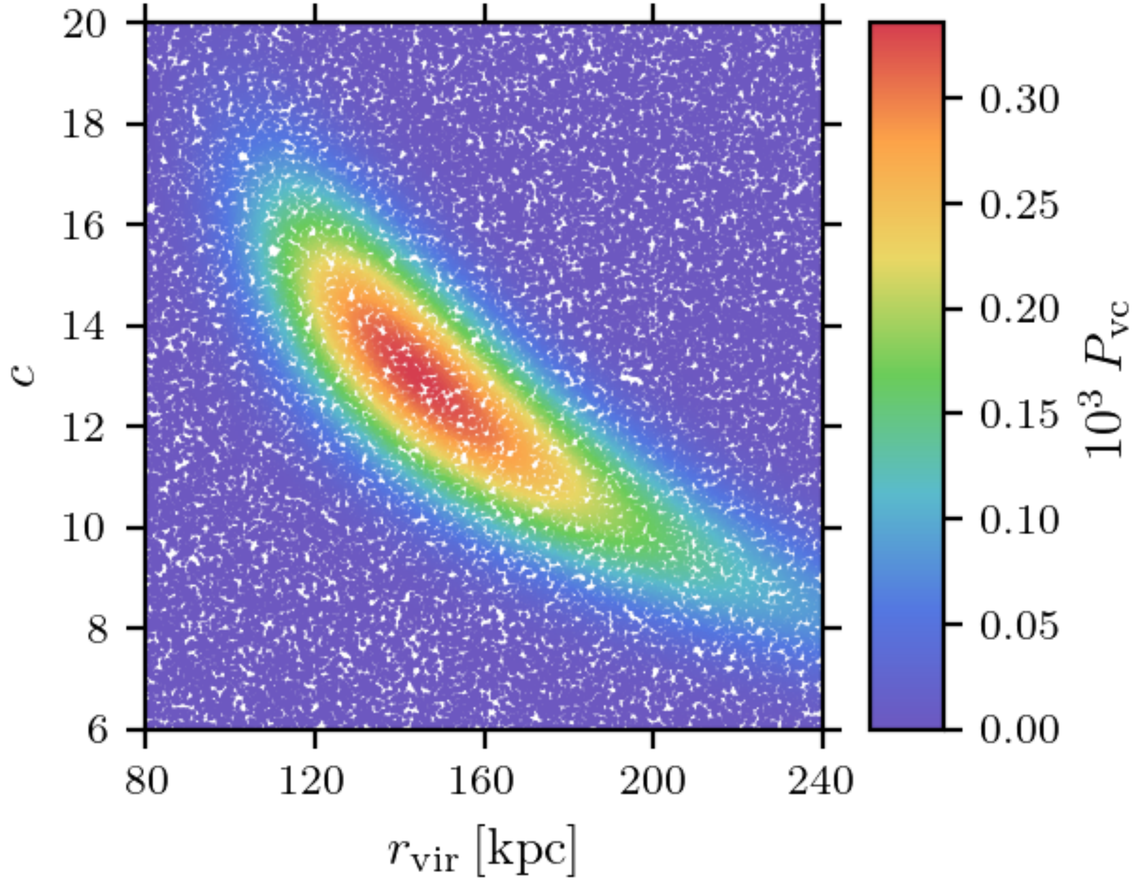
8.7kpc: van der Marel+ 2014

Watkins, van der Marel & Bennet (2024)

Virial Masses



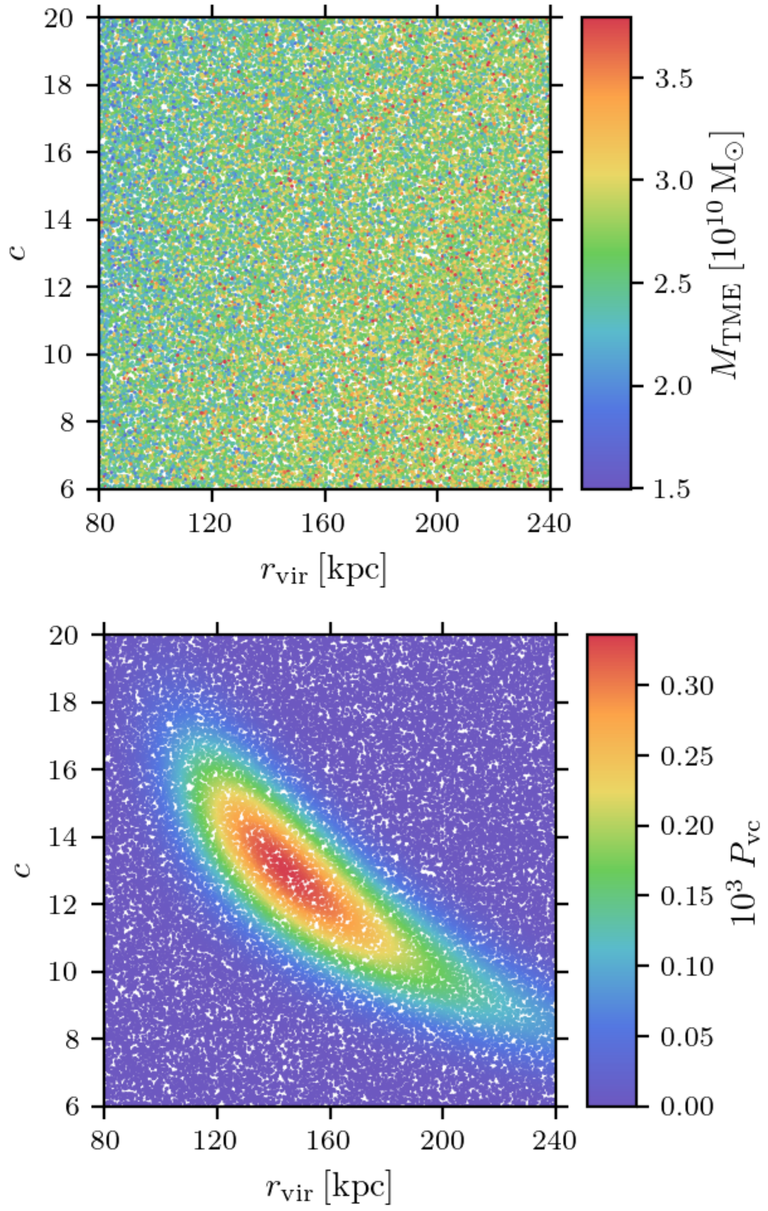
c-M_{vir}: Dutton & Macciò (2014)

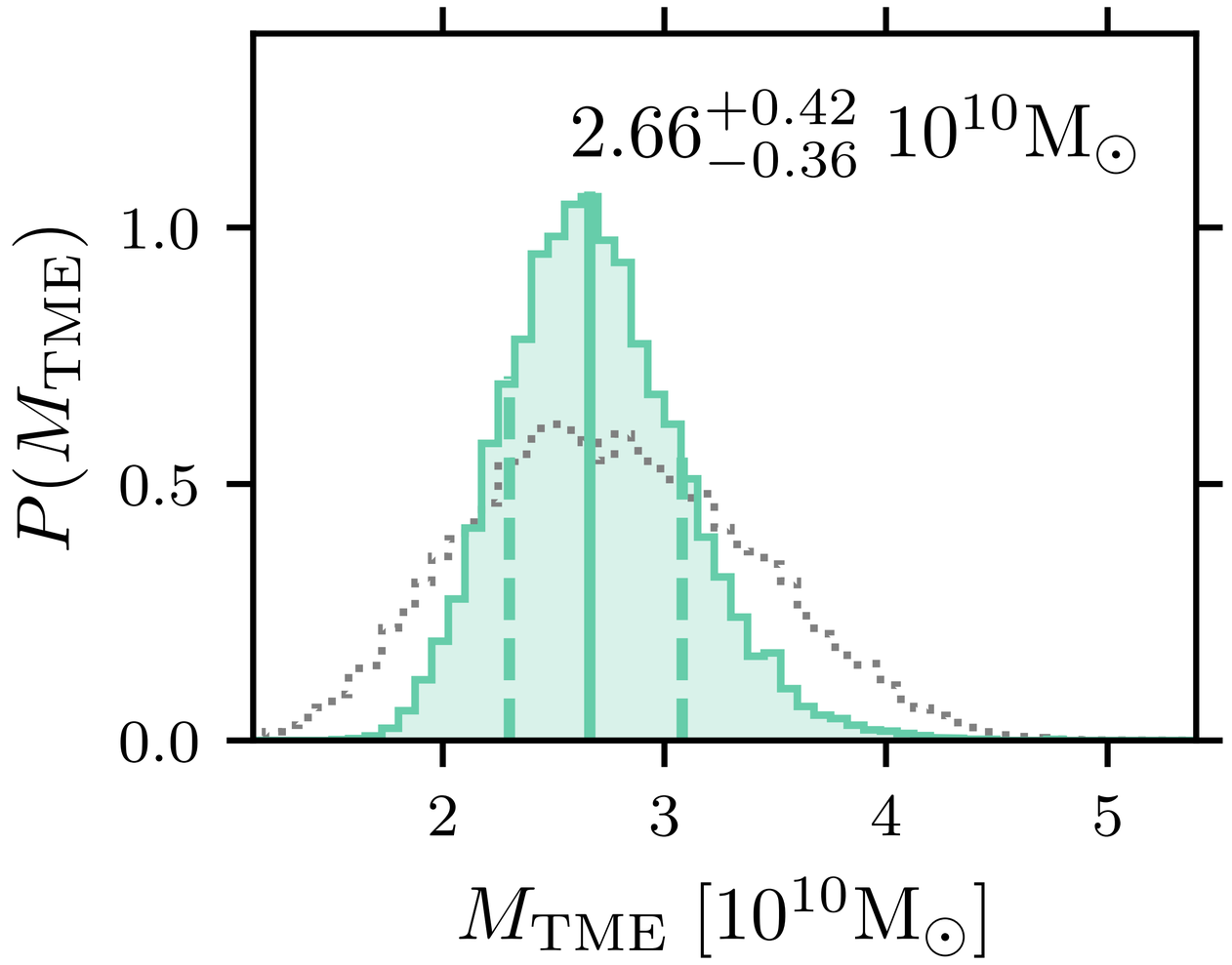


Likelihood of halo

Watkins, van der Marel & Bennet (2024)

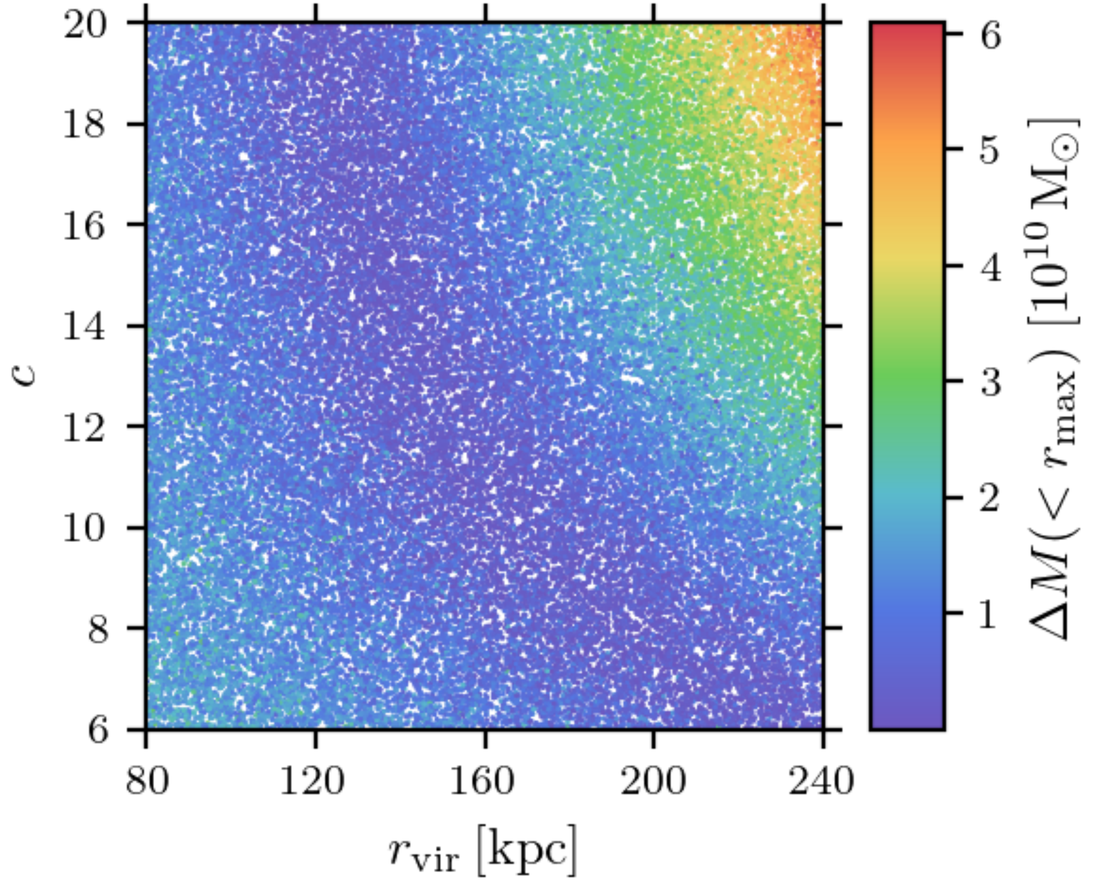
Mass within 13 kpc



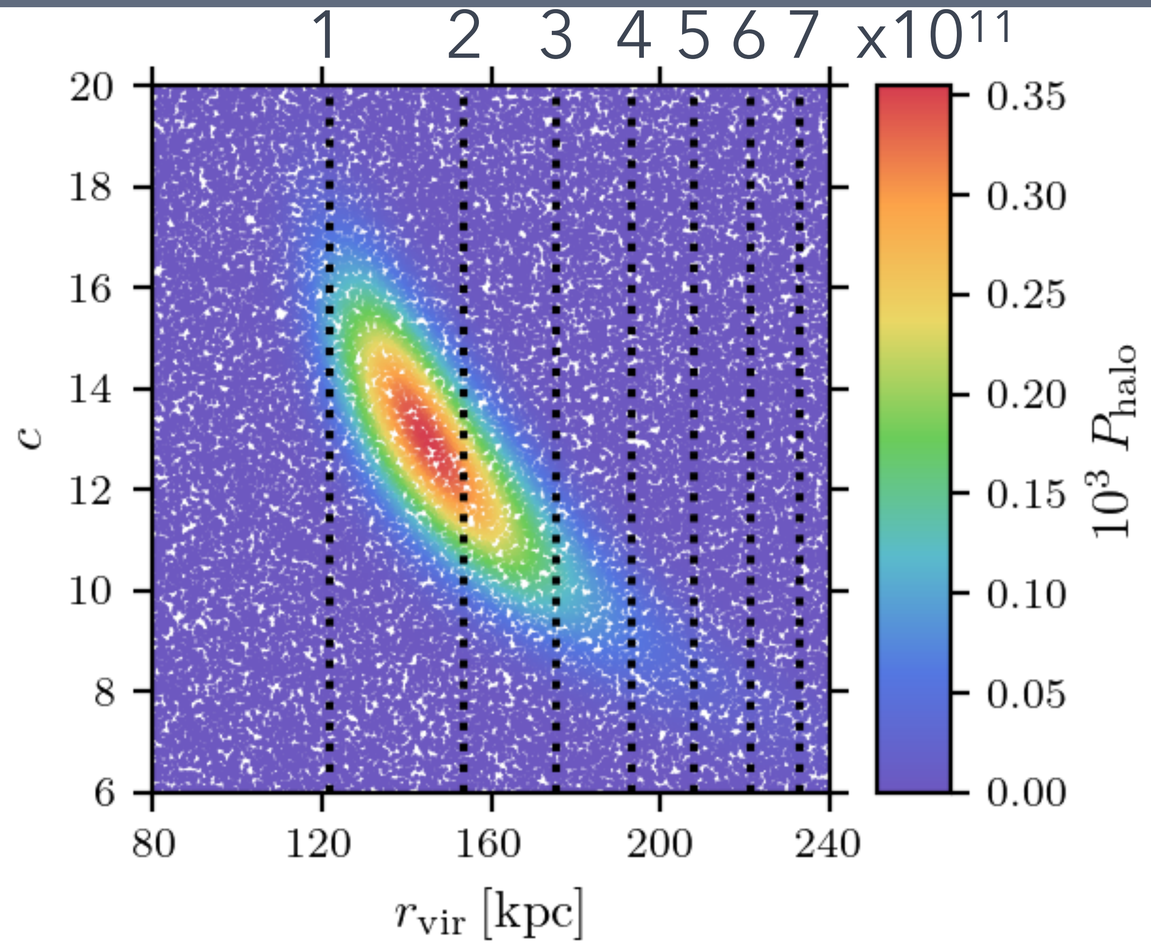


Watkins, van der Marel & Bennet (2024)

TME-Model Agreement



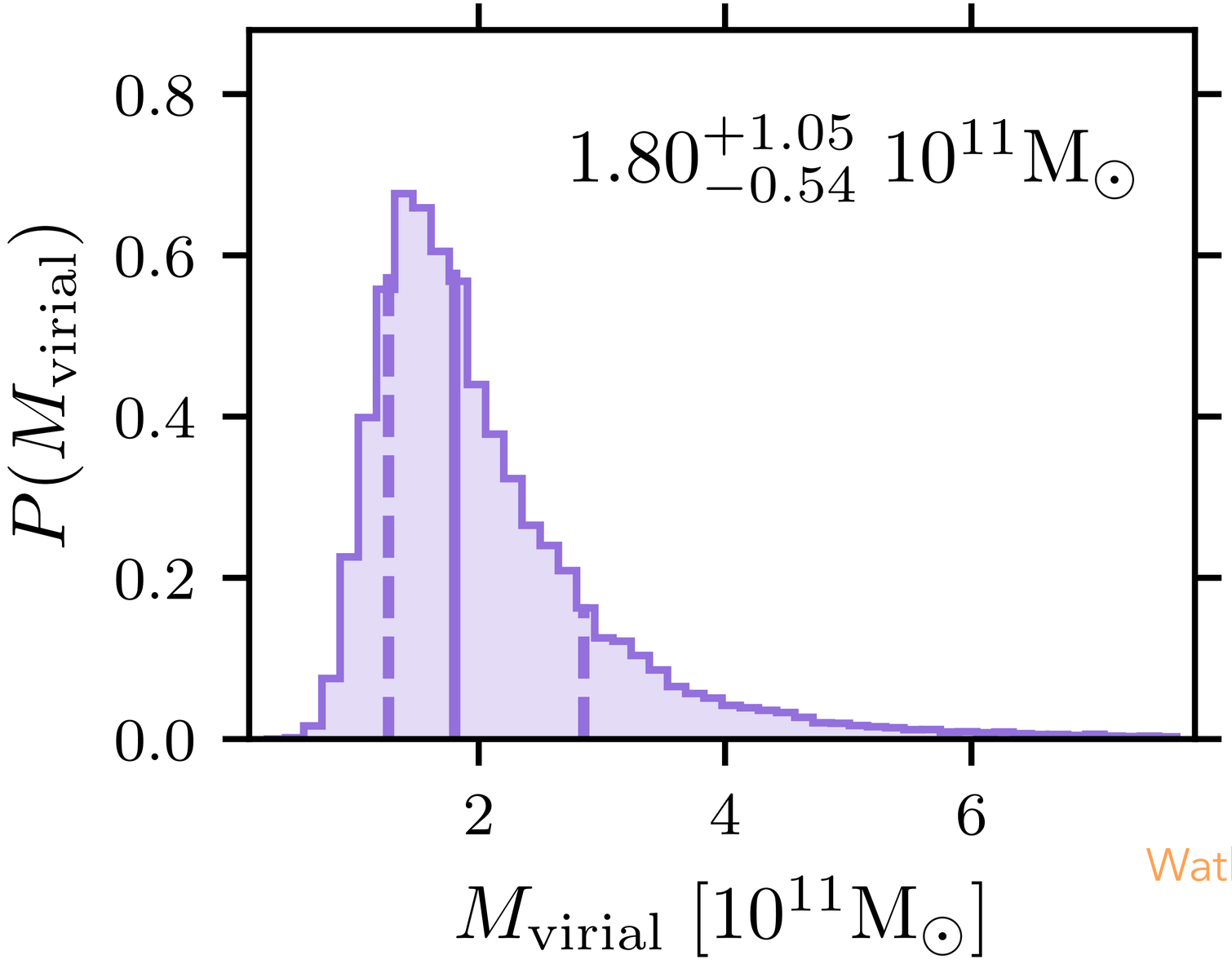
TME-model difference



Improved likelihood of halo

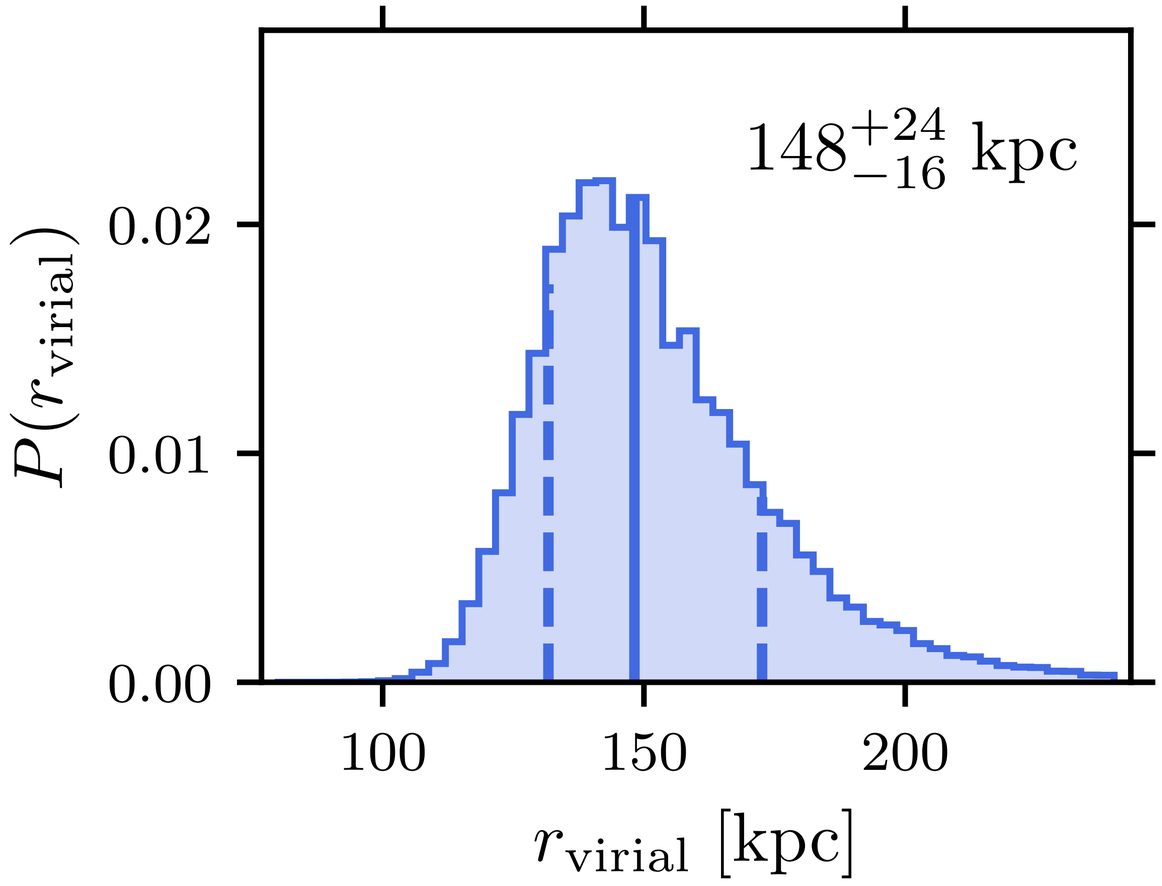
Watkins, van der Marel & Bennet (2024)

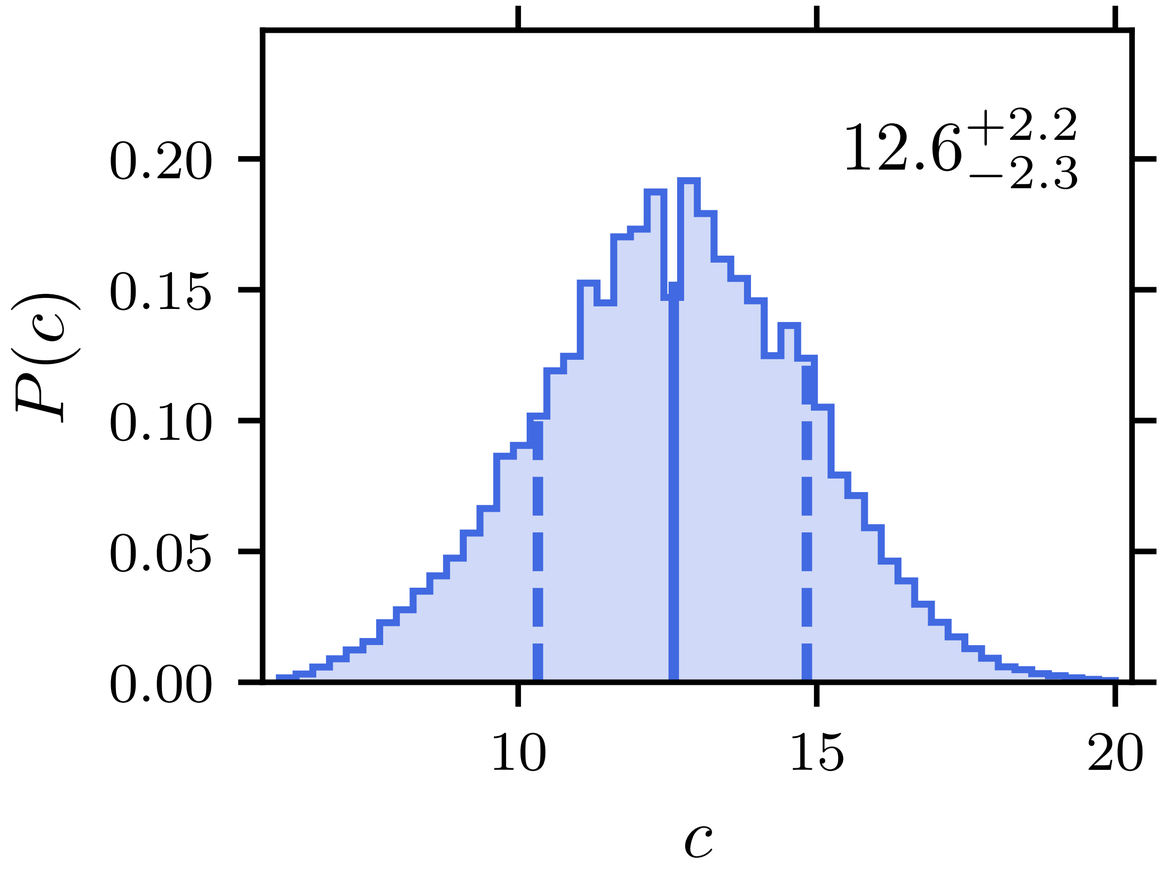
Extrapolated Virial Mass



Watkins, van der Marel & Bennet (2024)

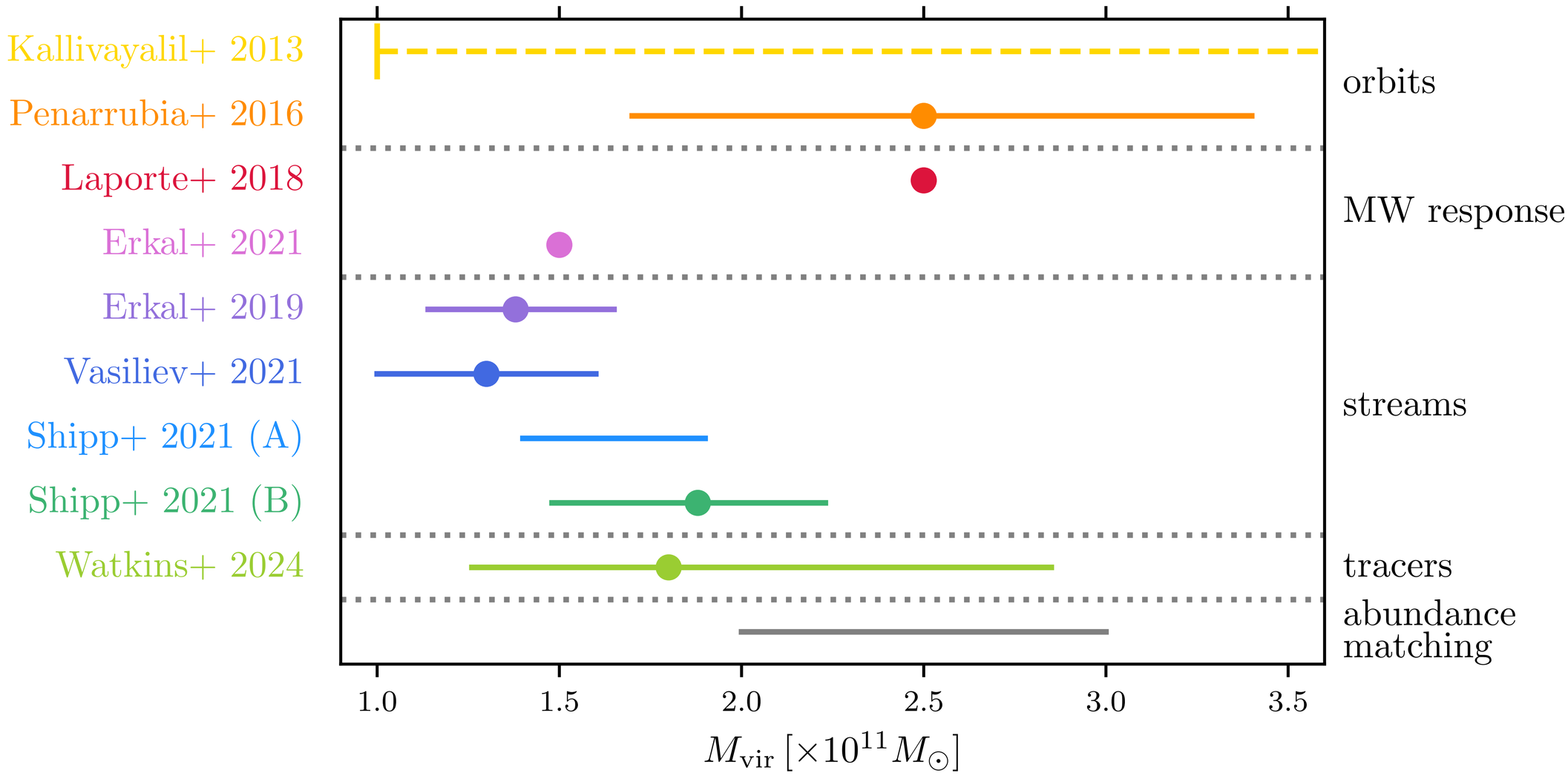
Extrapolated Virial Radius and Concentration





Watkins, van der Marel & Bennet (2024)

Comparison to Previous Studies



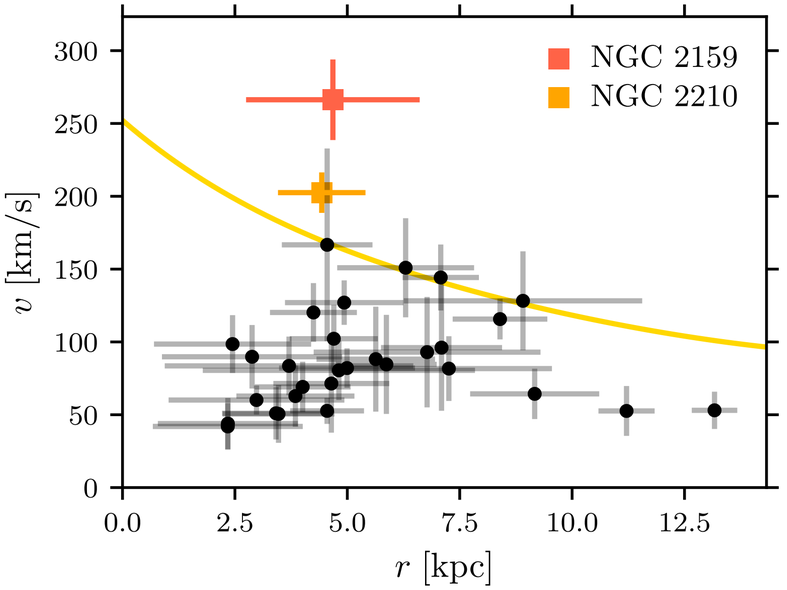
Watkins, van der Marel & Bennet (2024)

What next for tracers of the LMC & SMC?

- **LMC:**
  - New GC PM catalogue from Niederhofer+ (2024)

- **SMC:**
  - GC catalogue in prep (Bennet+)
  - Sample size too small
  - Error bars too large
  - Unlikely to make a successful mass estimate at this time

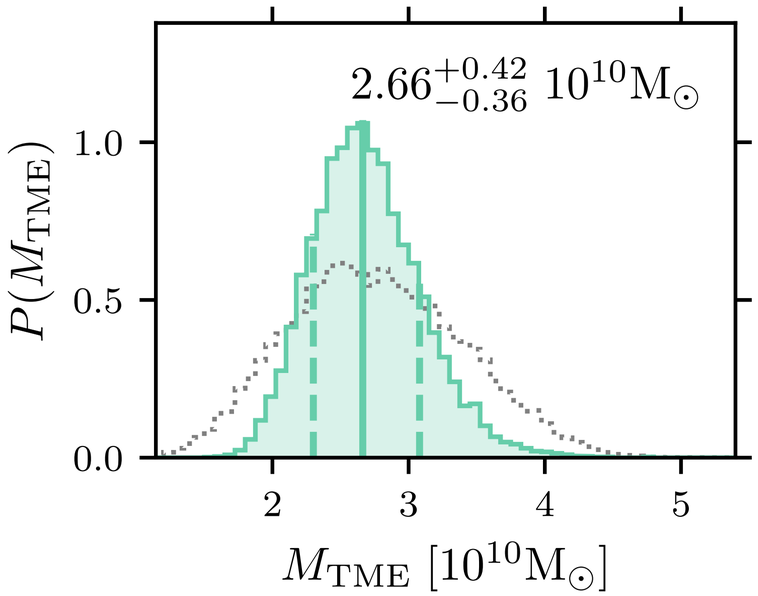
The Dynamical Mass of the LMC



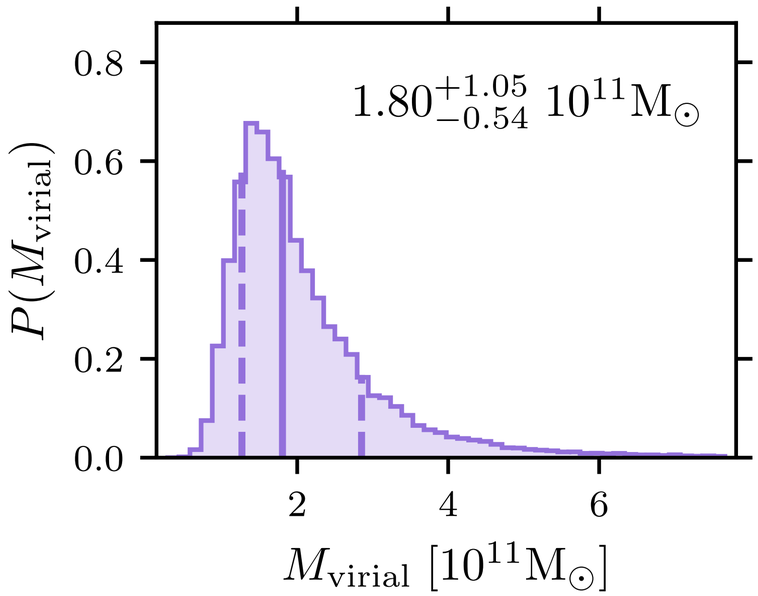
6D phase space (incl Gaia+HST PMs) for 30 LMC GCs (Bennet+ 2022)

$$M\left(<r_{\rm max}\right)_{\rm TME} = \frac{\alpha+\gamma-2\beta}{G\left(3-2\beta\right)} r_{\rm max}^{1-\alpha} \left\langle v^2 r^{\alpha} \right\rangle$$

Watkins, Evans & An 2010



Measured:
mass within 13.2 kpc



Extrapolated:
virial mass

Laura Watkins · ESA-AURA, STScI

Watkins, van der Marel & Bennet (2024)