Testing SIDM with galaxy warps

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Overview

- Effects of SIDM on galaxy morphology
- Modelling disk warping
- Measuring disk warping
- Constraining the cross-section
- Caveats and future prospects

Drag force affects galaxy shapes

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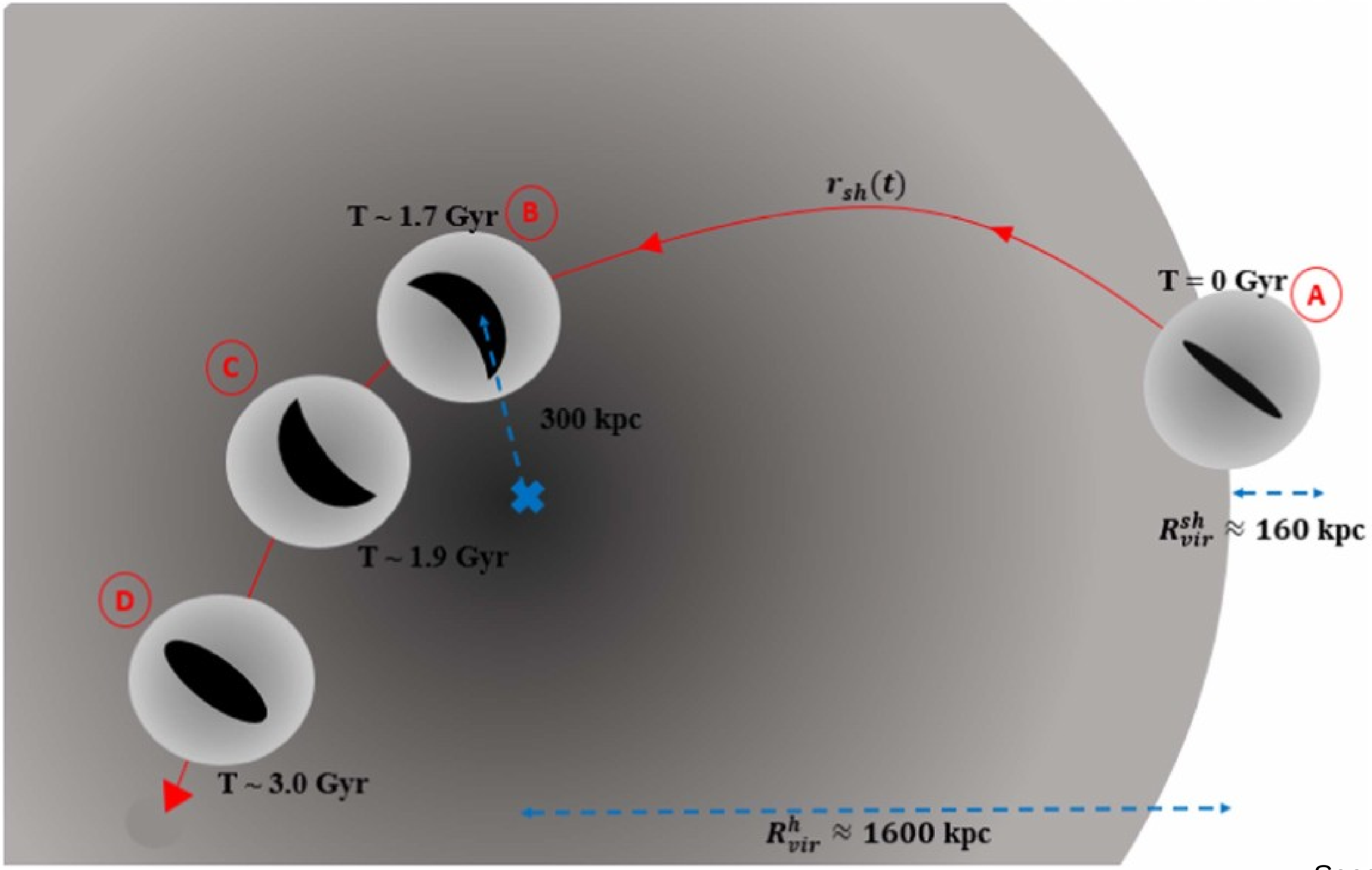
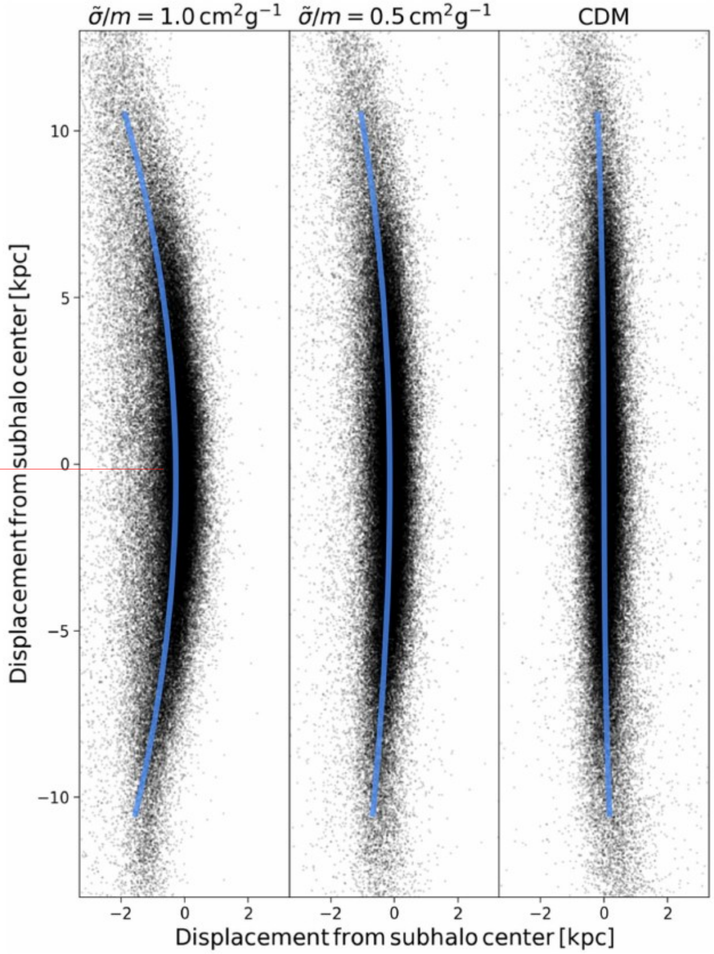
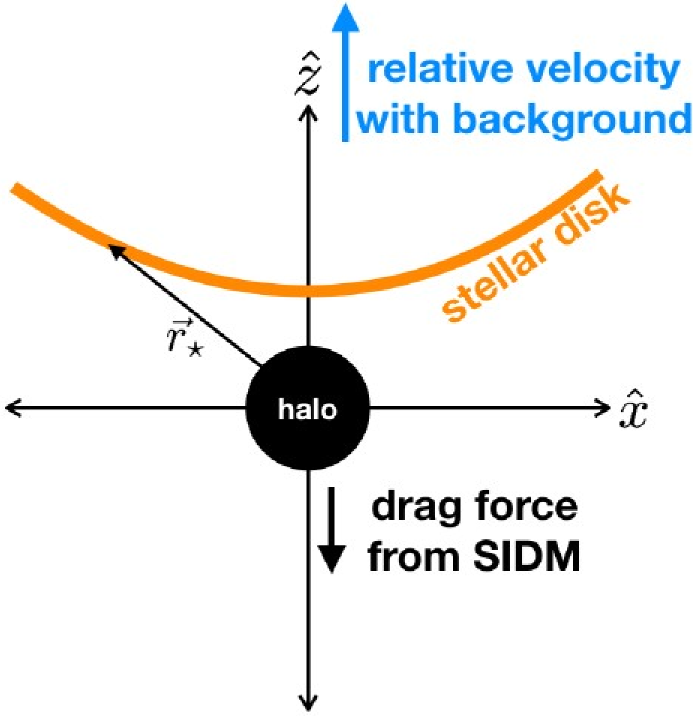


Secco+ 2018

Warping of stellar disks

Direction of motion





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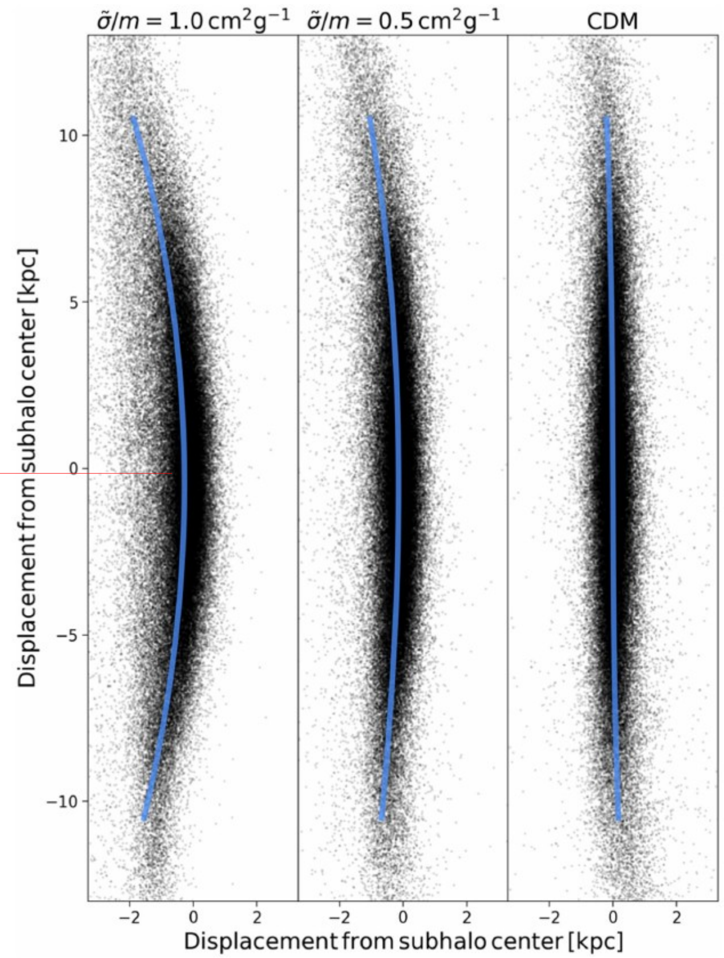

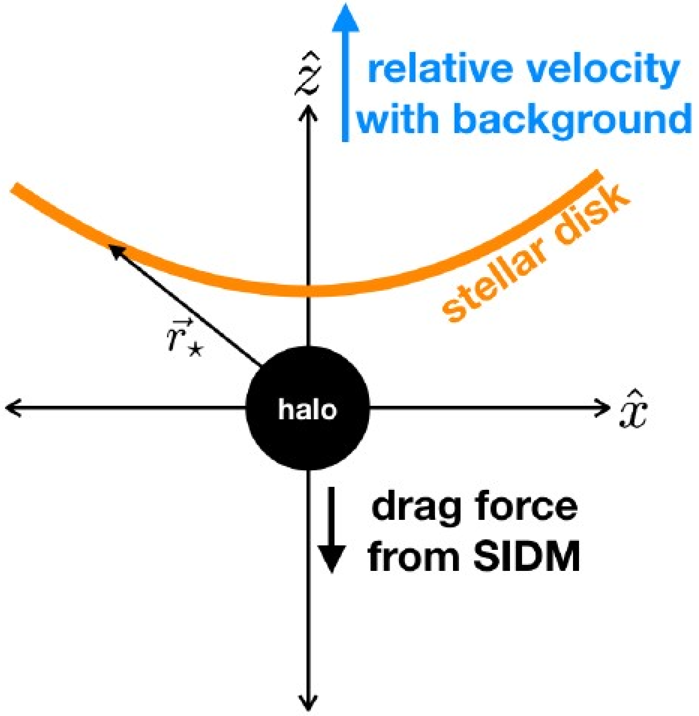

In clusters: SIDM generically causes drag
In the field: long-range interactions only

Drag formalism

- Particle of mass m_{DM} moves through medium of density ρ_{bg} under a long-range self-interaction

$$dN = \frac{\rho_{\mathrm{bg}}}{m_{\mathrm{DM}}} \frac{d\sigma}{d\Omega} v \; dt \; d\Omega$$

$$\vec{a}_{\mathrm{drag}} = \frac{\vec{F}_{\mathrm{drag}}}{m_{\mathrm{DM}}} = \frac{\rho_{\mathrm{bg}}}{m_{\mathrm{DM}}} v^2 \int \frac{d\sigma}{d\Omega} (\cos\theta - 1) \; d\Omega \; \hat{v}$$

$$\frac{d\sigma}{d\Omega} = \frac{\alpha_{\mathrm{DM}}^2}{m_{\mathrm{DM}}^2 v^4 \sin^4\theta}$$

Dispersion correction

$$\tilde{\sigma} \equiv -16\pi \, \alpha_{\mathrm{DM}}^2 / m_{\mathrm{DM}}^2$$

$$\vec{a}_{\mathrm{drag}} = -\frac{1}{4} \chi_p \left(\frac{\tilde{\sigma}}{m_{\mathrm{DM}}} \right) \rho_{\mathrm{bg}} \frac{c^4}{v^2} \; \hat{v}$$

$$\chi_{\mathrm{p}} = \frac{v^3}{v^3 + v_{\mathrm{disp}}^3}$$

Kummer+ 2018

Drag formalism

- Particle of mass $m_{\rm DM}$ moves through medium of density $\rho_{\rm bg}$ under a long-range self-interaction

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Kummer+ 2018

- Under instead a finite-range interaction

Evaporation correction

Contact

$$\vec{a}_{\rm drag}^{\rm \, contact} = -\frac{1}{4} \chi_{\rm d} \chi_{\rm p} \left(\frac{\tilde{\sigma}_{\rm DM}}{m_{\rm DM}} \right) \rho_{\rm bg} v^2 \; \hat{v} \qquad \chi_{\rm d} = 1 - 4 \int_{\sqrt{x^2/(1+x^2)}}^{1} dy \; y^2 \sqrt{y^2 - x^2(1-y^2)} \qquad x \equiv v_{\rm esc}/v$$

Markevitch+ 2004

Intermediate

$$\vec{a}_{\rm drag}^{\rm \, inter} = -\frac{1}{4} \chi_d^{\rm inter} \chi_p \left(\frac{\tilde{\sigma}}{m_{\rm DM}} \right) \rho_{\rm bg} v^2 \left(\frac{c}{v} \right)^m \qquad \chi_d^{\rm inter} = 1 - (1 - \chi_d) \exp[-2m]$$

m=0: Contact
m=4: Long-range

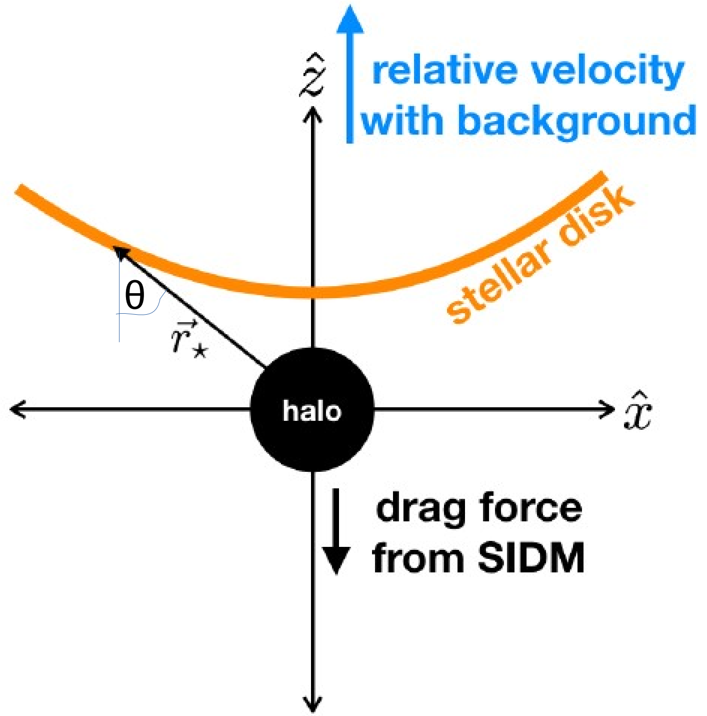
Calculating the warp

- Warp curve as a function of drag force

$$\vec{a}_{\mathrm{h}} = \vec{a}_{\mathrm{bg}} - \vec{a}_{\mathrm{drag}} \qquad \vec{a}_\star = \vec{a}_{\mathrm{bg}} - \frac{GM_{\mathrm{h}}}{r_\star^2}\hat{r}$$

$$\vec{a}_{\mathrm{drag}} = \frac{GM_{\mathrm{h}}}{r_\star^2}\hat{z}\cos\theta = \frac{GM_{\mathrm{h}}}{r_\star^2}\hat{z}\left(\frac{z}{x}\right) \qquad r_* \approx x$$

$$\rho(r) = \rho_s\left(\frac{r_s}{r}\right)^n \qquad \boxed{z = a_{\mathrm{drag}}\frac{3-n}{4\pi\rho_s}|x|^n}$$



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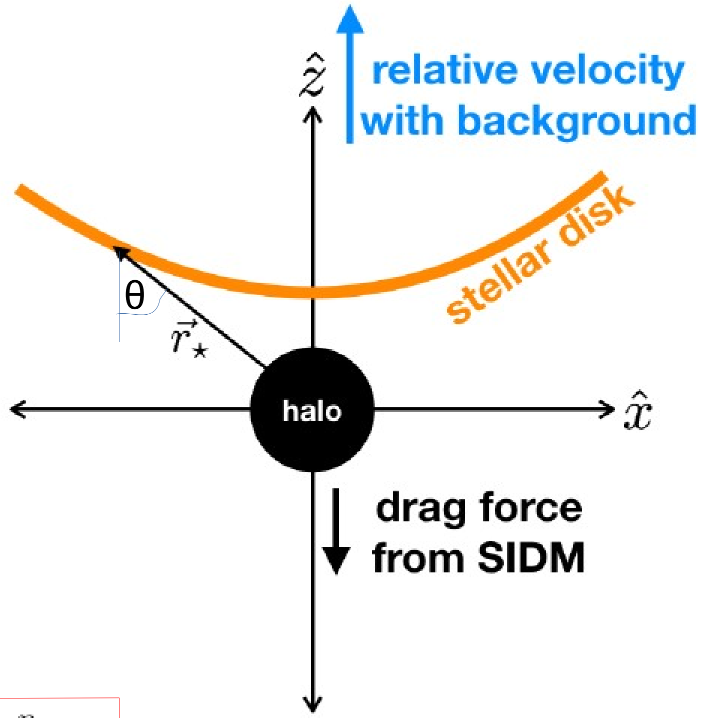


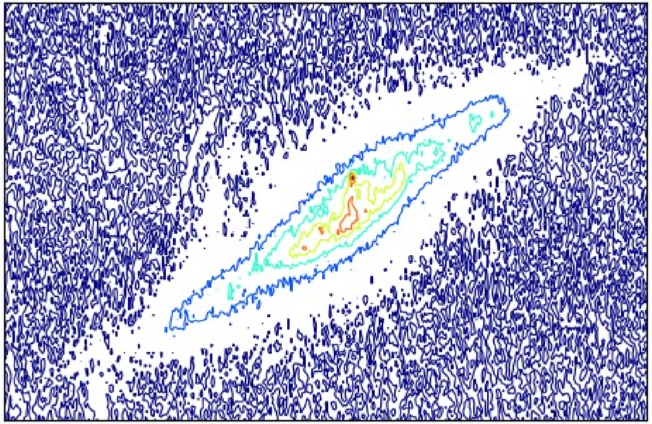
- Summarising the warp strength

$$w_1 = \frac{1}{L^3}\int_{-L}^{L}(z - \langle z\rangle)\,|x|\,dx \qquad \boxed{w_1 = \frac{n(3-n)}{(n+1)(n+2)}\frac{a_\mathrm{drag}}{4\pi G\rho_s}\left(\frac{L}{r_s}\right)^n\frac{1}{L}}$$

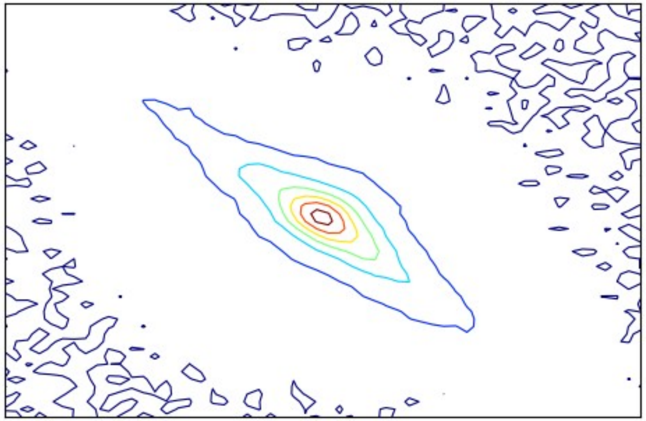
$$L = 3R_\mathrm{eff}$$

Observational sample

3,213 galaxies from SDSS with $b/a<0.15$, $M_{*}>10^{9}$ M_{sun} and $D<250$ Mpc



J115012.10+065956.9

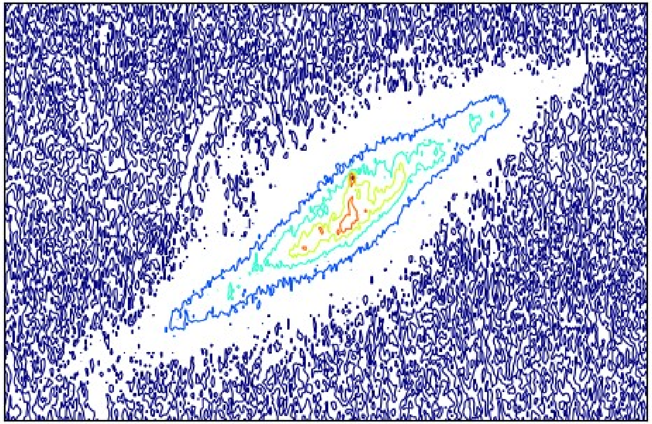


J003938.31+143951.2

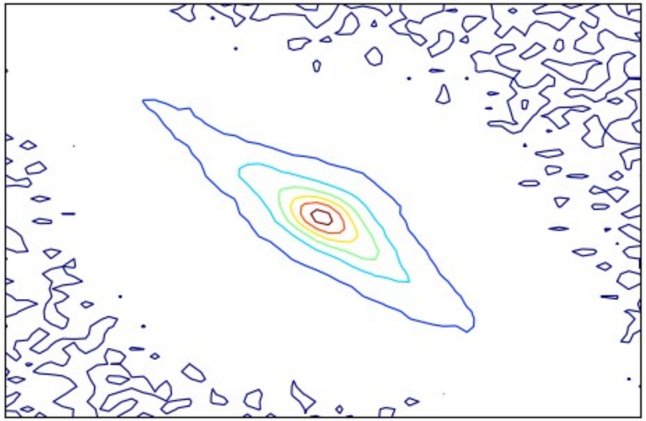
Observational sample

3,213 galaxies from SDSS with $b/a<0.15$, $M_*>10^9$ M_{sun} and $D<250$ Mpc

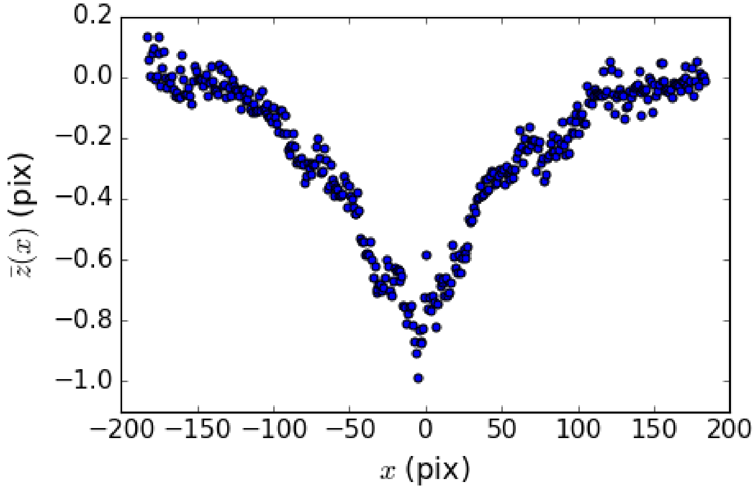
$$w_1 = \frac{1}{(3R_{\rm eff})^3} \sum_{x=-3R_{\rm eff}}^{x=3R_{\rm eff}} |x|\, \bar{z}'(x)$$

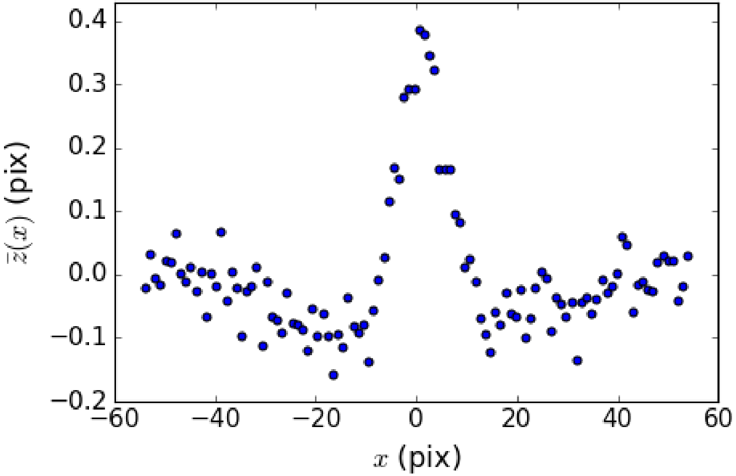


J115012.10+065956.9 – $w_1 = 1.7\text{x}10^{-3}$



J003938.31+143951.2 – $w_1 = -1.1\text{x}10^{-4}$





Estimating the relevant parameters

$$\vec{a}_{\rm drag}^{\,\rm inter} = -\frac{1}{4}\chi_d^{\rm inter}\chi_p\left(\frac{\tilde{\sigma}}{m_{\rm DM}}\right)\rho_{\rm bg}v^2\left(\frac{c}{v}\right)^m$$

$$w_1 = \frac{n(3-n)}{(n+1)(n+2)}\frac{a_{\rm drag}}{4\pi G\rho_s}\left(\frac{3R_{\rm eff}}{r_s}\right)^n\frac{1}{3R_{\rm eff}}$$

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- Estimate halo parameters (r_s, ρ_s, v_{disp}) using inverse sub-halo abundance matching
- *n* given uniform prior between 0.5 and 2

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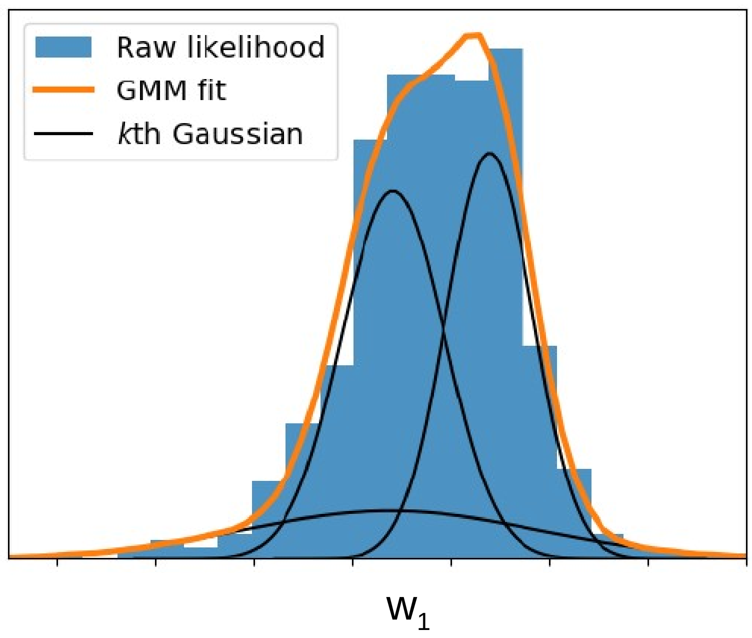
- *n* given uniform prior between 0.5 and 2
- ρ_{bg} estimated using Bayesian Origin Reconstruction from Galaxies (BORG) algorithm
- Velocity of ambient DM medium from linear perturbation theory applied to ρ_{bg}
- Galaxy peculiar velocities either a constant or that of the nearest galaxy in the CosmicFlows-3 catalogue
- Project onto plane of sky and disk normal assuming infall towards nearest 2M++ galaxy

Likelihood model

- Generate w1 likelihood by Monte Carlo-sampling the parameters from their priors (*simulation based / implicit likelihood inference*)

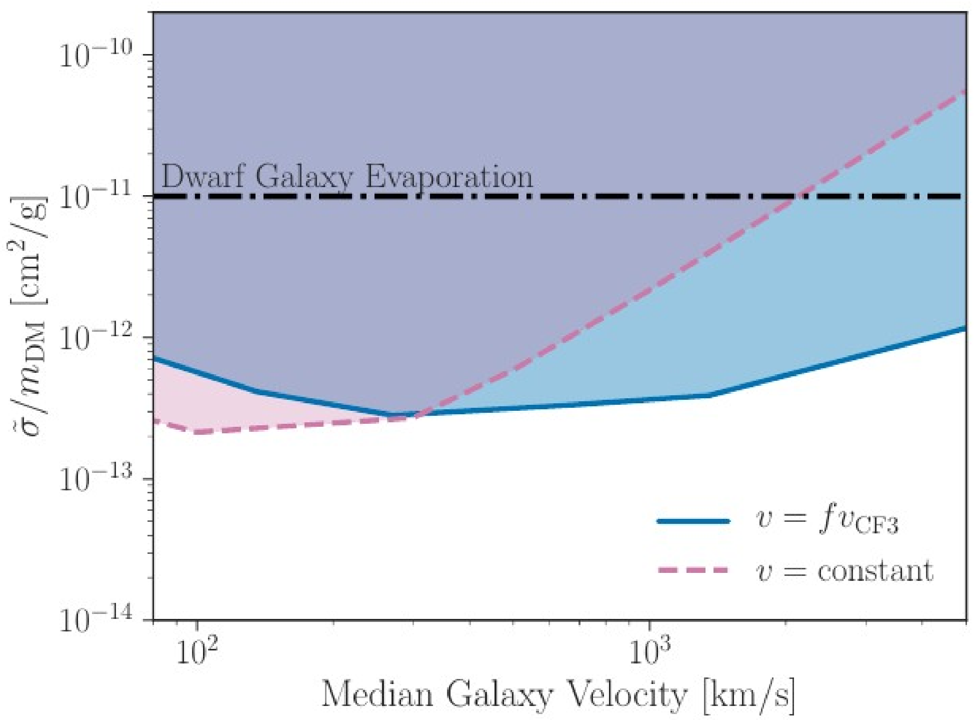
- Create continuous likelihood function by fitting a Gaussian mixture model

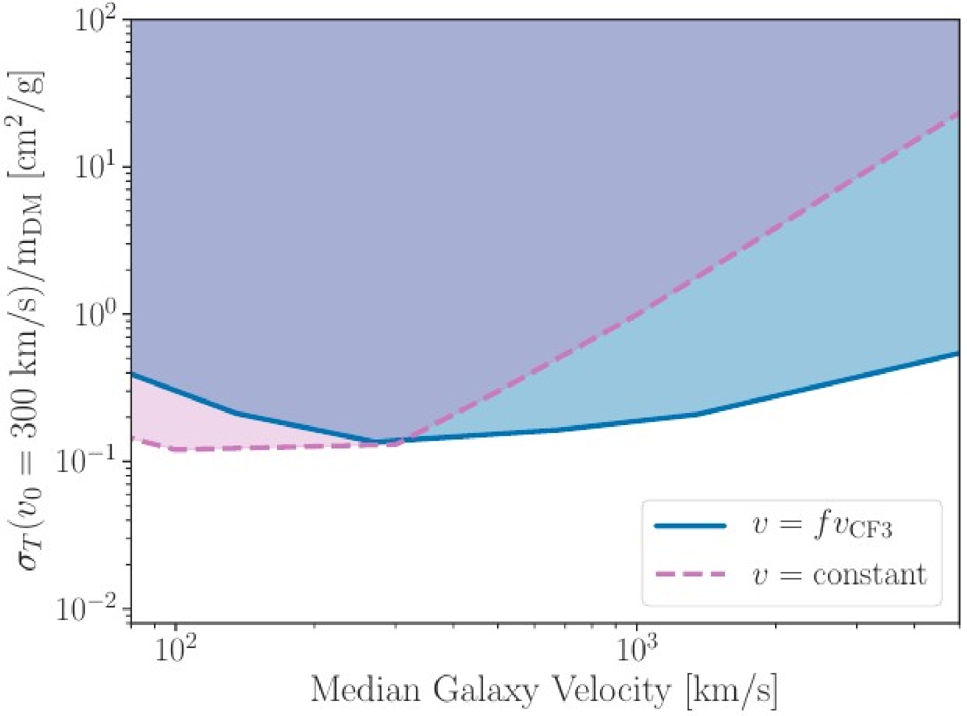
- Introduce extra astrophysical noise term σ_{w1} to capture non-SIDM contributions to warp, and marginalise over it



Results

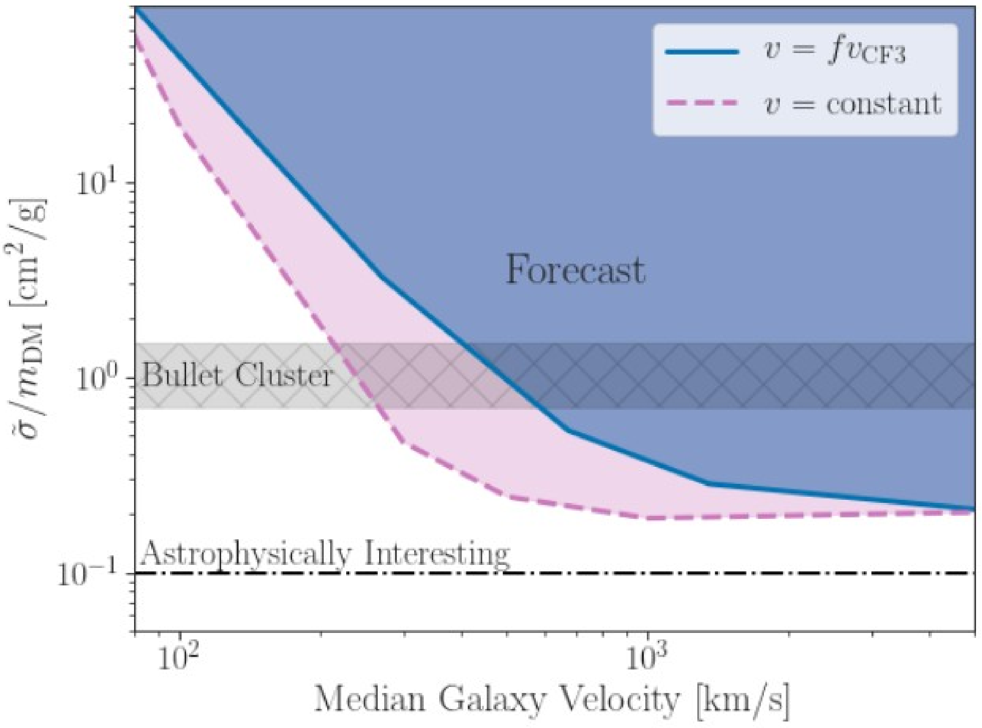
I. Long-range interactions

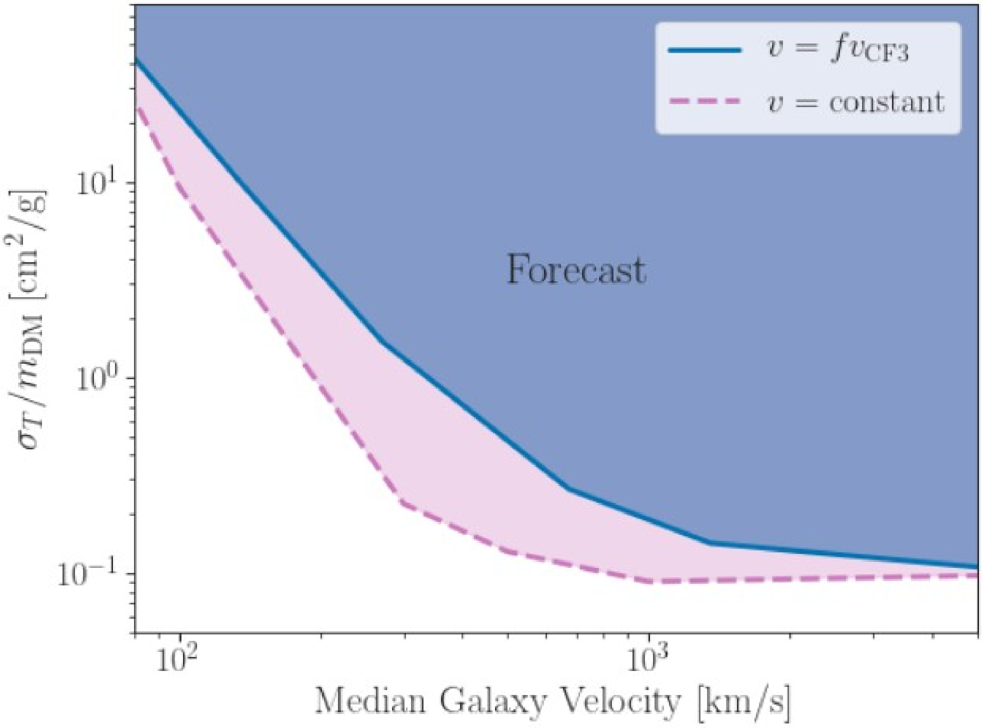




Results

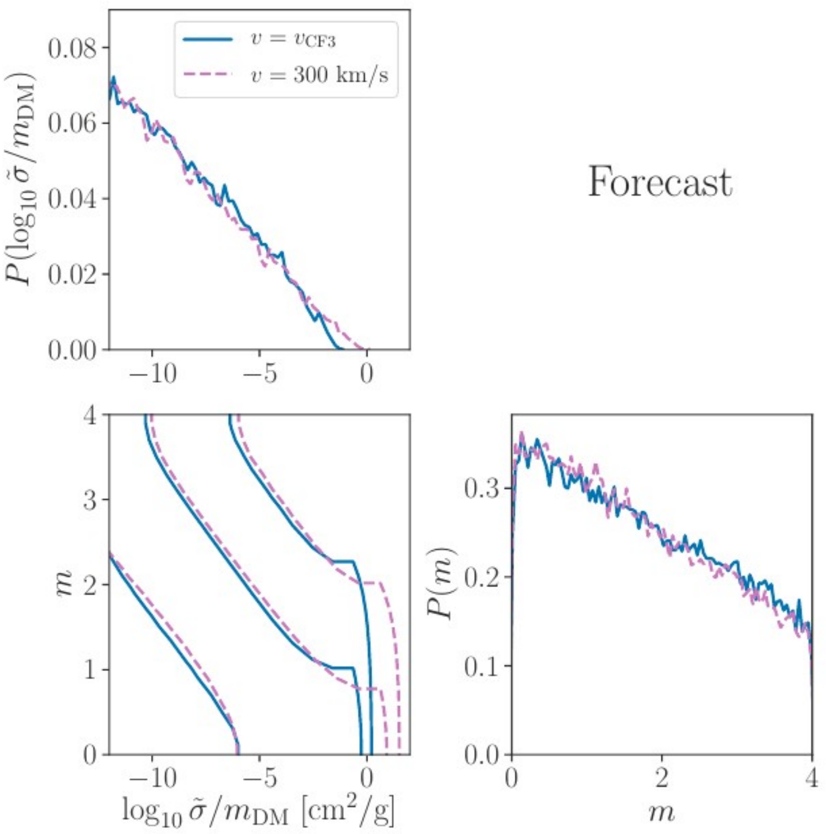
II. Forecast for contact interactions

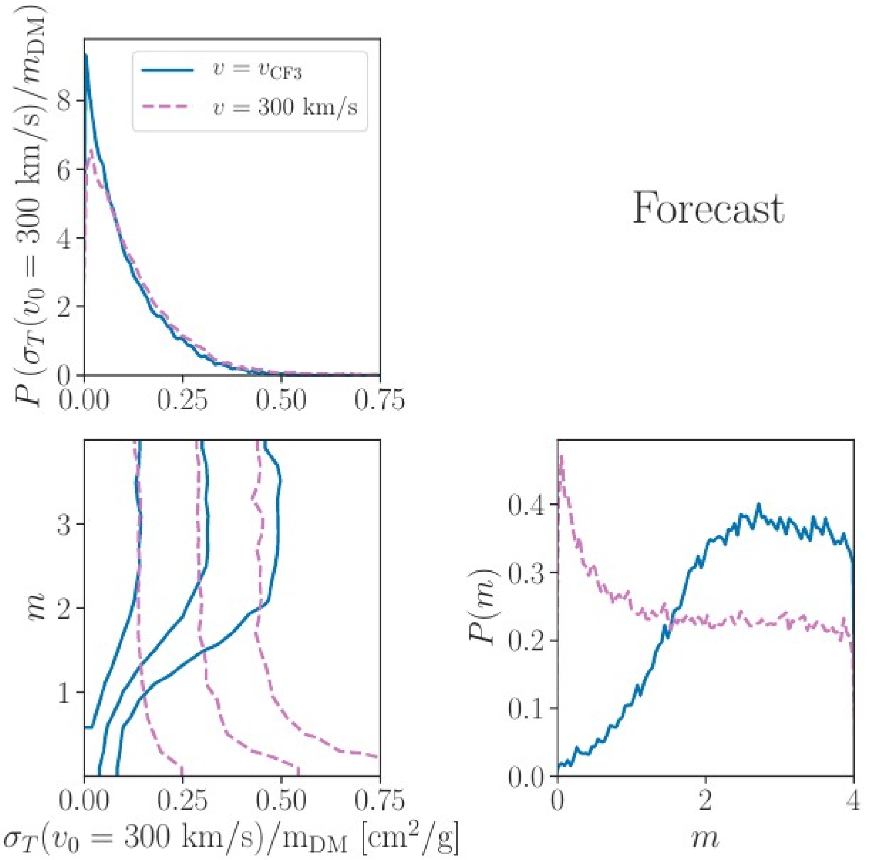




Results

III. Forecast for intermediate-range interactions





Assumptions, systematics & future prospects

- Assume warps of fixed magnitude in equilibrium, but may not be stable
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- Assume warps of fixed magnitude in equilibrium, but may not be stable
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  - Need simulations of warps in field galaxies
- Fluid approximation restricts us to long-range interactions
  - Sample disks in clusters with short interaction timescales and multi-streaming
- Noise assumed Gaussian and uncorrelated with anything else
- Baryonic and tidal effects neglected
  - Ram pressure goes in same direction as SIDM $\rightarrow$ results conservative

Assumptions, systematics & future prospects

- Highly uncertain peculiar velocities, especially their directions
  - Expanding scope and precision of vpec modelling, e.g. CosmicFlows-4

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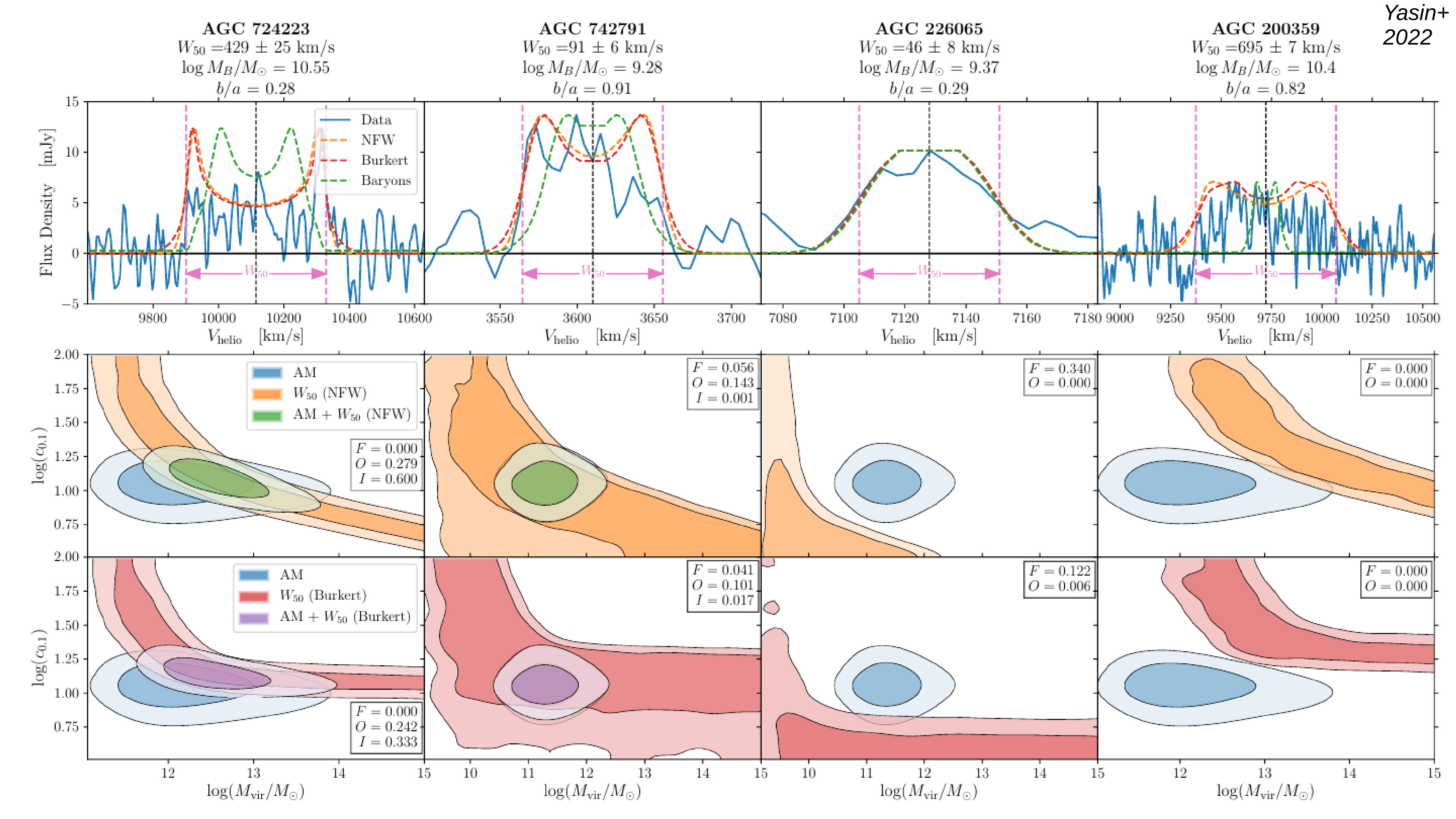
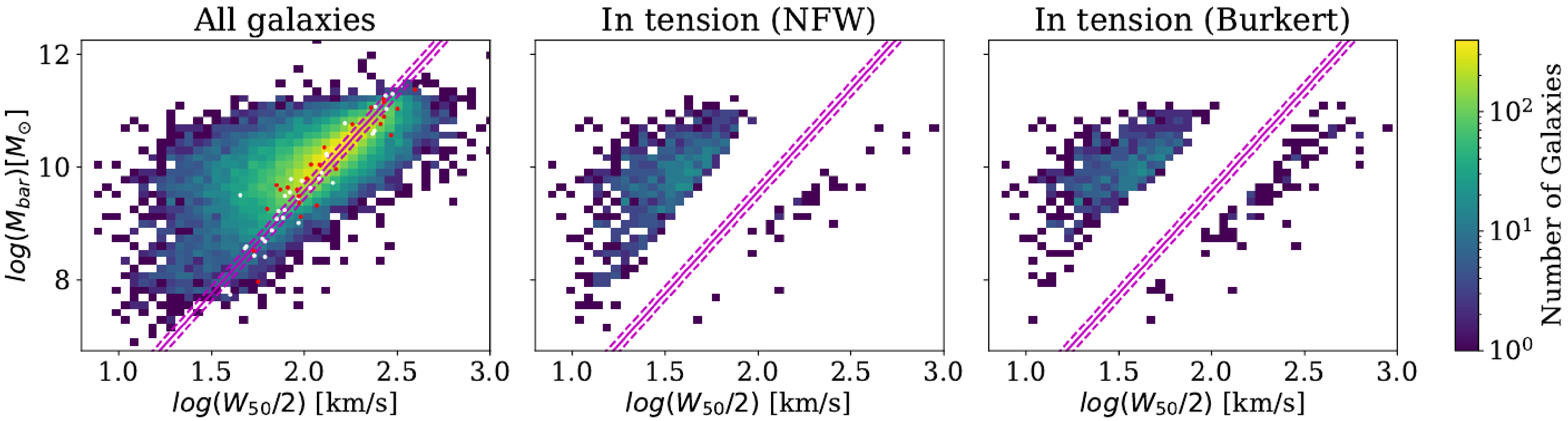
- Assumptions on density profile of halos, and galaxy-halo connection
- ΛCDM built into calculation of ρ_{bg}, r_s, ρ_s, v_{disp}
  - Need SIDM sims

Conclusion

- Classic SIDM drag effect potentially best detected through galaxy morphology
- Warping is readily measurable in galaxy images, yielding potentially strong constraints on long-range self-interactions
- Can pick out small signals statistically from large samples with very low S/N per object using Bayesian forward modelling
- A method with promise for the future...


Yasin+ 2022
AGC 724223
W_{50} =429 ± 25 km/s
$\log M_B/M_\odot$ = 10.55
b/a = 0.28
AGC 742791
W_{50} =91 ± 6 km/s
$\log M_B/M_\odot$ = 9.28
b/a = 0.91
AGC 226065
W_{50} =46 ± 8 km/s
$\log M_B/M_\odot$ = 9.37
b/a = 0.29
AGC 200359
W_{50} =695 ± 7 km/s
$\log M_B/M_\odot$ = 10.4
b/a = 0.82
Data
NFW
Burkert
Baryons
Flux Density [mJy]
$V_{\rm helio}$ [km/s]
W_{50}
AM
W_{50} (NFW)
AM + W_{50} (NFW)
F = 0.000
O = 0.279
I = 0.600
F = 0.056
O = 0.143
I = 0.001
F = 0.340
O = 0.000
F = 0.000
O = 0.000
AM
W_{50} (Burkert)
AM + W_{50} (Burkert)
F = 0.000
O = 0.242
I = 0.333
F = 0.041
O = 0.101
I = 0.017
F = 0.122
O = 0.006
F = 0.000
O = 0.000
$\log(c_{0.1})$
$\log(M_{\rm vir}/M_\odot)$



All galaxies
In tension (NFW)
In tension (Burkert)
$log(M_{bar})[M_\odot]$
12
10
8
1.0
1.5
2.0
2.5
3.0
$log(W_{50}/2)$ [km/s]
Number of Galaxies
10^0
10^1
10^2

Extra Slides

Momentum transfer cross-section

$$\sigma_T = 4\pi \int_0^1 \frac{d\sigma}{d\Omega}(1-\cos\theta)\ d(\cos\theta) \qquad \frac{d\sigma}{d\Omega} = \frac{\alpha_{\rm DM}^2}{m_{\rm DM}^2 v^4 \sin^4\theta} \qquad \theta_{\rm min} = \frac{4\alpha_{\rm DM}}{\lambda_{\rm De} m_{\rm DM} v^2}$$

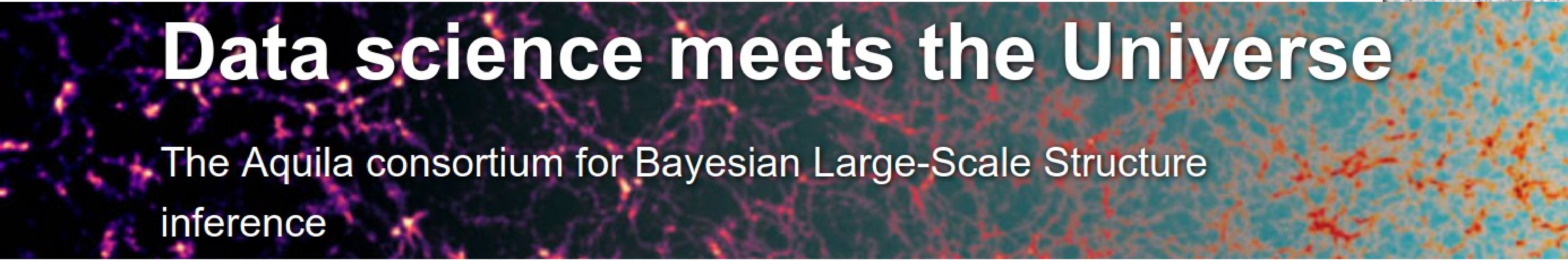
$$\vec{a}_{\rm drag} = -\frac{\sigma_T(v)}{2m_{\rm DM}}\rho_{\rm bg} v^2\ \hat{v} \qquad \sigma_T(v) = \frac{16\pi\alpha_{\rm DM}^2}{m_{\rm DM}^2}\frac{1}{v^4}\left[1 - 2\log\left(\frac{8\sqrt{\pi\alpha^3\rho}}{m_{\rm DM}^2 v^3}\right)\right]$$

$$\sigma_T(v) = \sigma_T(v_0)\left(\frac{v_0}{v}\right)^4 \frac{1-2\log\Lambda(v)}{1-2\log\Lambda(v_0)} \qquad \vec{a}_{\rm drag} = -\frac{\sigma_T(v_0)}{2m_{\rm DM}}\rho_{\rm bg} v^2 \left(\frac{v_0}{v}\right)^4 \frac{1-2\log\Lambda(v)}{1-2\log\Lambda(v_0)}\ \hat{v}$$

$$\vec{a}_{\rm drag} = -\frac{\sigma_T}{2m_{\rm DM}}\rho_{\rm bg} v^2\ \hat{v} \qquad \vec{a}_{\rm drag} = -\frac{\sigma_T(v_0)}{2m_{\rm DM}}\rho_{\rm bg} v^2 \left(\frac{v_0}{v}\right)^m\ \hat{v}$$

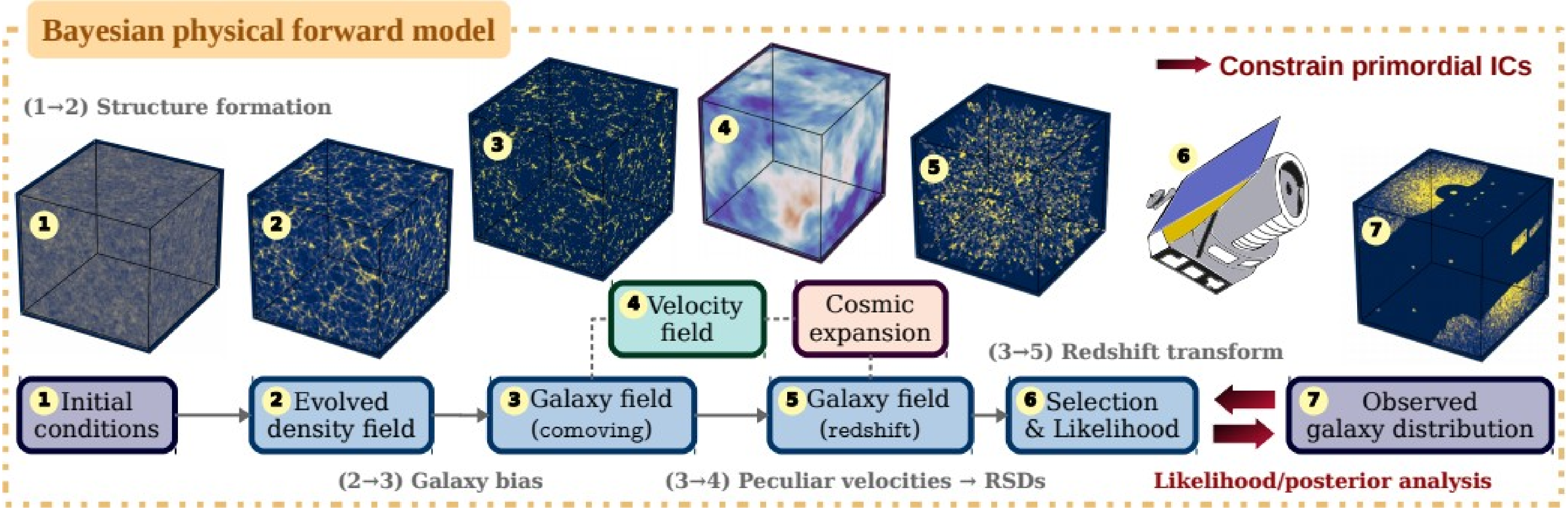
Inferring the initial phases

www.aquila-consortium.org



The BORG algorithm

(**B**ayesian **O**rigin **R**econstruction from **G**alaxies)

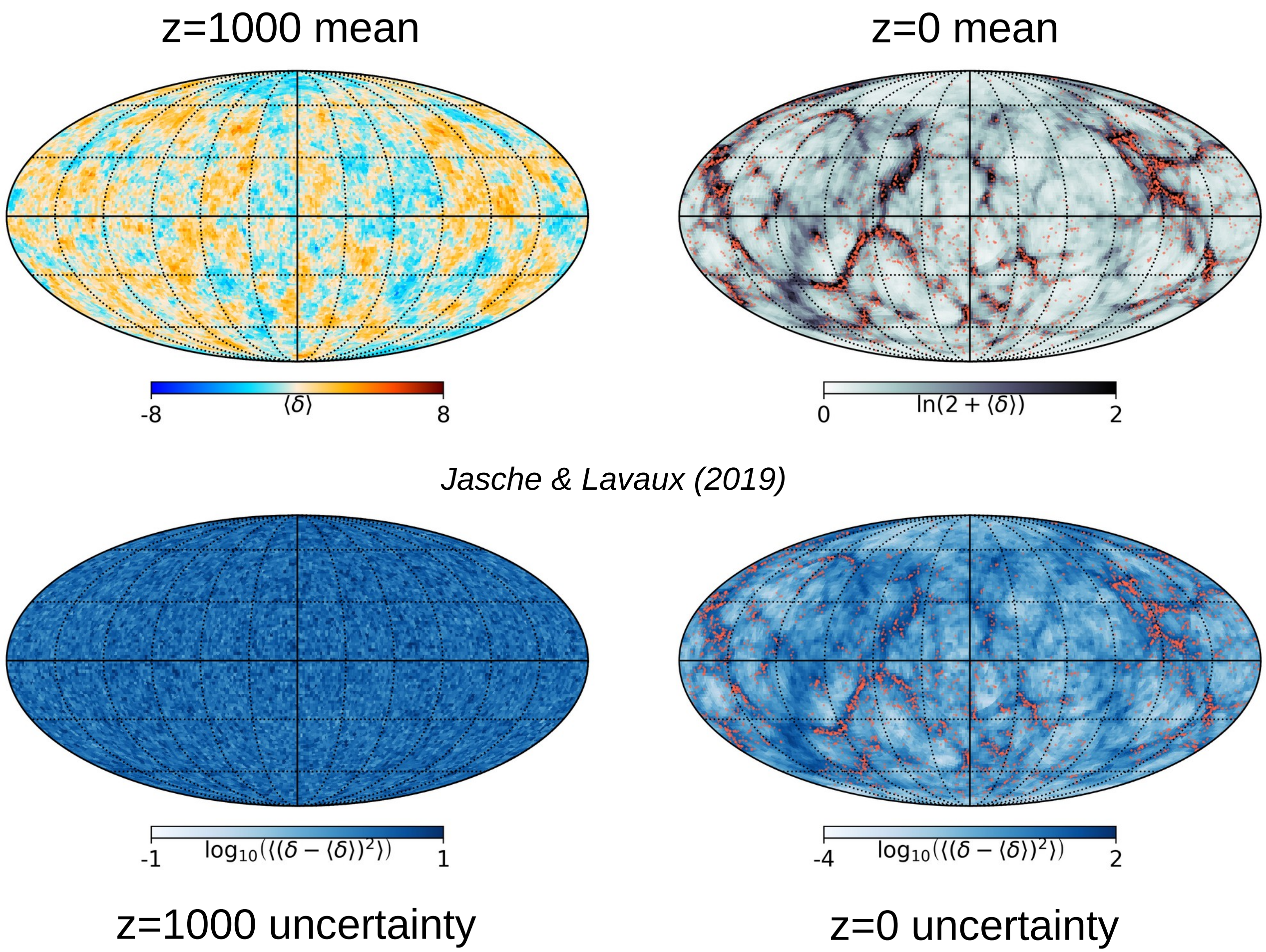


Kostic et al (2021)

The 2M++ BORG reconstruction

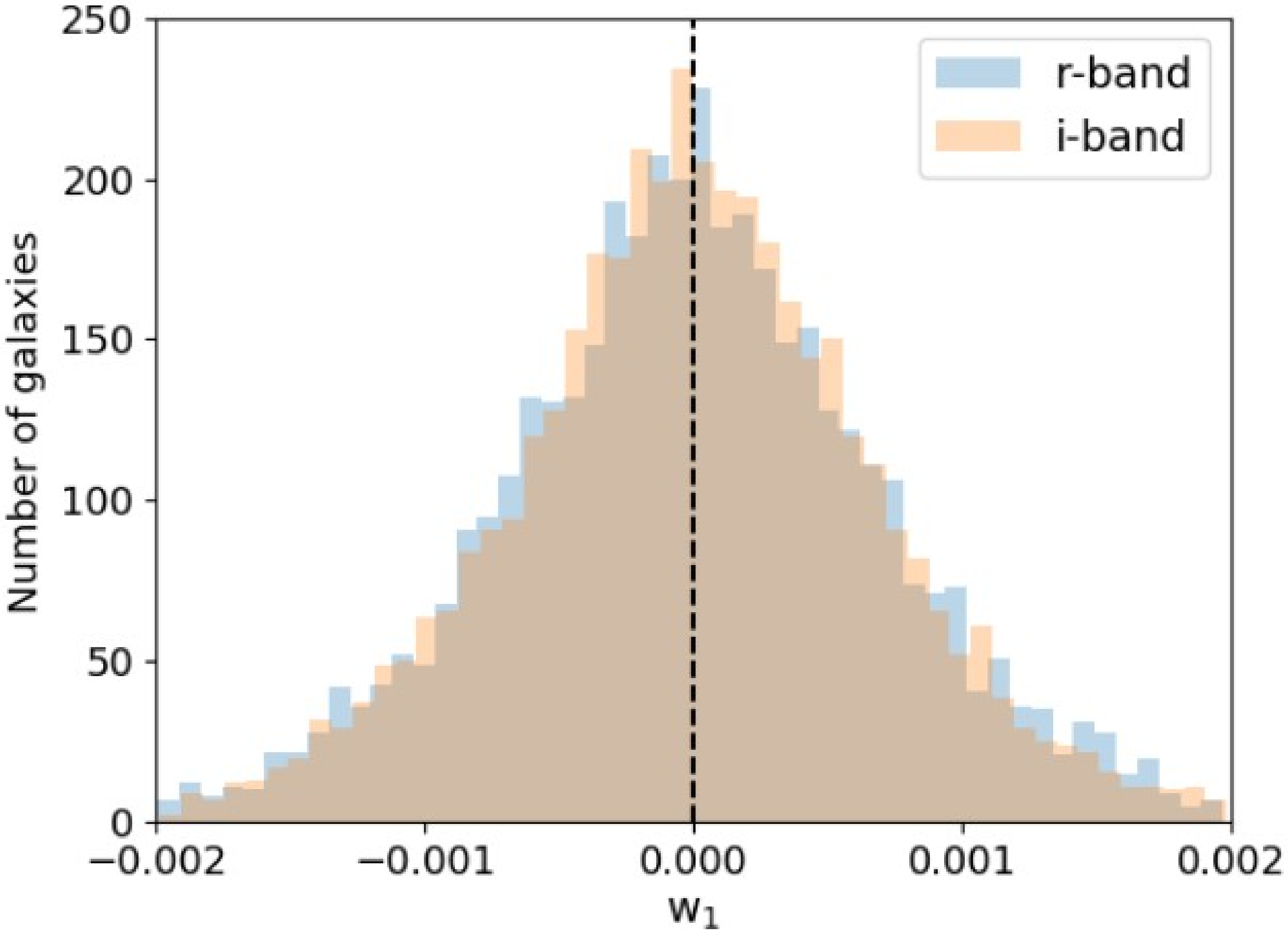
- Data from the 2M++ galaxy compilation (~70k galaxies, full sky, r$\lesssim$200 Mpc, K<12.5)

- Inference done with 256^3 voxels in (677.7 Mpc/h)^3 volume → ~10^7 constraints at 2.65 Mpc/h resolution



Jasche & Lavaux (2019)

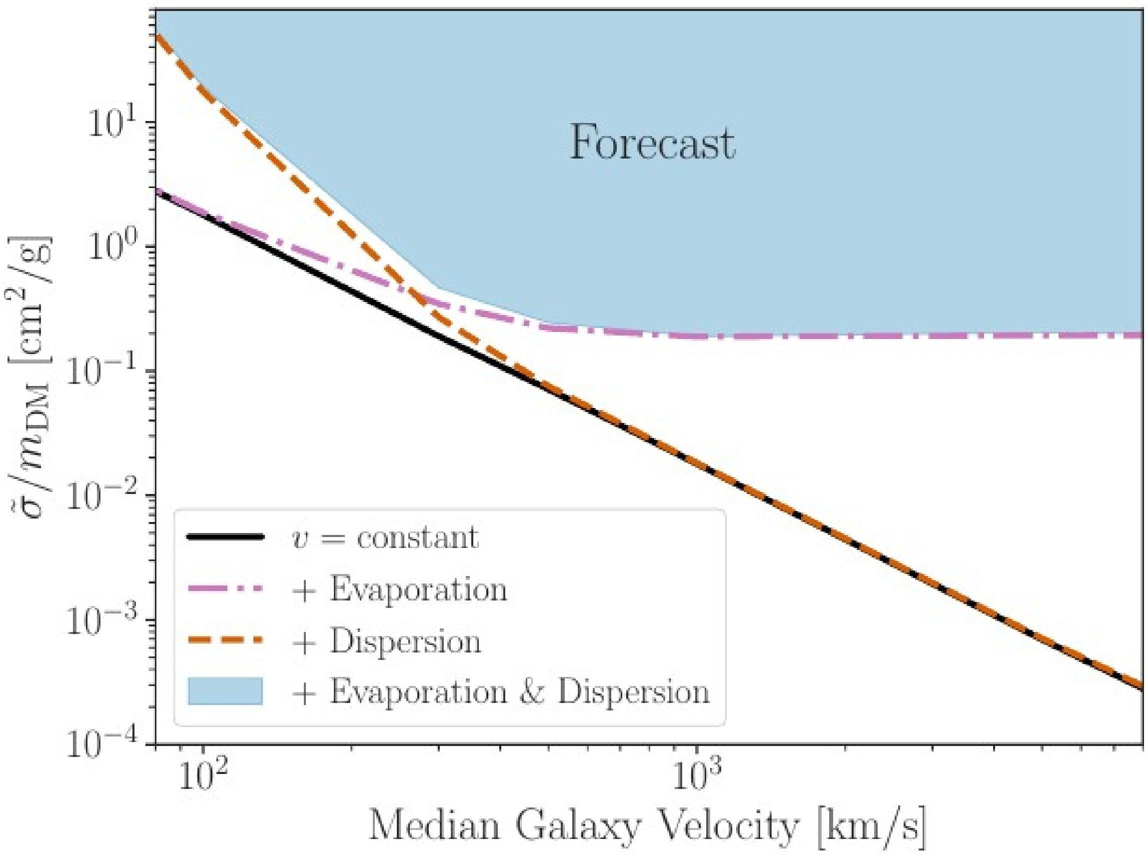
Parameter	Source of Uncertainty	Model Used
$P(n)$	Inner DM halo density slope	Uniform prior $n \in [0.5, 1.5]$
$P(\rho_s, r_s \mid M_r; \alpha, \sigma_{\rm AM})$	Stochasticity in galaxy–halo connection	200 mock AM catalogs at fixed α and $\sigma_{\rm AM}$
$P(\rho_{\rm bg}\|\vec{x})$	Background DM density	10 draws from BORG posterior
$P(v)$	Galaxy relative velocity	Delta function at set velocity (see Sec. III B)
$P(\theta)$	Unknown relative velocity direction	Delta function at set angle (see Sec. III B)



r-band
i-band
Number of galaxies
250
200
150
100
50
0
−0.002
−0.001
0.000
0.001
0.002
w_1

Assumed Velocity	Evaporation?	Dispersion?	68% Upper Limit $\mathrm{cm^2/g}$	95% Upper Limit $\mathrm{cm^2/g}$
$v = 300\,\mathrm{km/s}$	N/A	-	2.0×10^{-13}	4.4×10^{-13}
	N/A	✓	2.7×10^{-13}	6.1×10^{-13}
$v = v_{\mathrm{CF3}}$	N/A	-	4.7×10^{-14}	1.2×10^{-13}
	N/A	✓	3.9×10^{-13}	9.4×10^{-13}

Assumed Velocity	Evaporation?	Dispersion?	68% Upper Limit $\mathrm{cm^2/g}$	95% Upper Limit $\mathrm{cm^2/g}$
$v = 300\,\mathrm{km/s}$	N/A	-	0.10	0.21
	N/A	✓	0.13	0.29
$v = v_{\mathrm{CF3}}$	N/A	-	0.03	0.07
	N/A	✓	0.21	0.51



Forecast
$\tilde{\sigma}/m_{\rm DM}$ [cm^2/g]
10^{1}
10^{0}
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{2}
10^{3}
Median Galaxy Velocity [km/s]
v = constant
+ Evaporation
+ Dispersion
+ Evaporation & Dispersion