Fifth Force Searches in Galaxies

Harry Desmond

8 Dec 2020

PONT Avignon

Galaxy morphology rules out astrophysically relevant Hu-Sawicki $f(R)$ gravity

Harry Desmond[1,*] and Pedro G. Ferreira[1]

arXiv:
2009.08743

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Fifth Forces

- Generic extensions to the standard model couple new dynamical fields to matter
- → New (*fifth*) forces, described by strength and range

$$\Phi_{\rm tot} = -\frac{G_N M}{r}\left(1+\frac{\Delta G}{G_N}e^{-mr}\right) = \Phi_N - \frac{\Delta G M}{r}e^{-mr}$$

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- Strongly constrained by local tests
  - Lab: torsion balance, atom interferometry...
  - Solar system: Lunar Laser Ranging, planetary orbits, Cassini...

Screening Mechanisms

Fifth force goes away in dense environments

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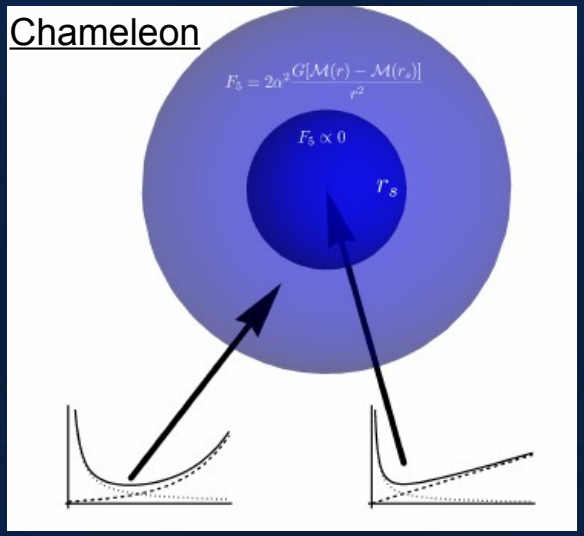
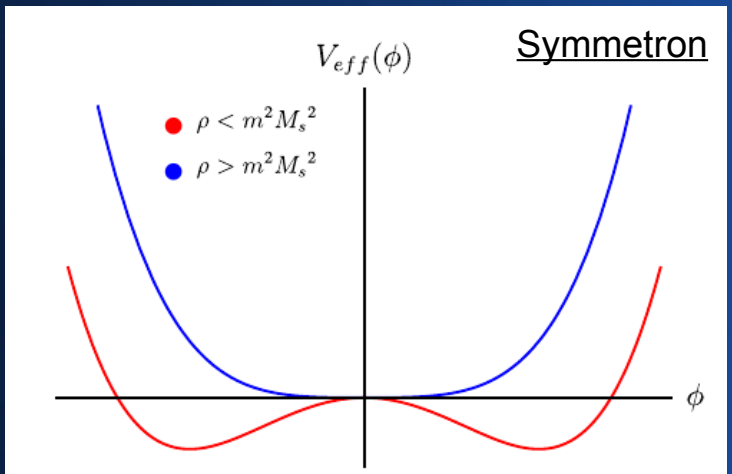
- *Chameleon*: $m_{eff} \rightarrow \infty$ (e.g. f(R))
- *Kinetic*: $\partial\varphi \rightarrow \infty$ (e.g. K-mouflage)
- *Symmetron* & *Vainshtein*: $\Delta G \rightarrow 0$ (e.g. Galileons, DGP)

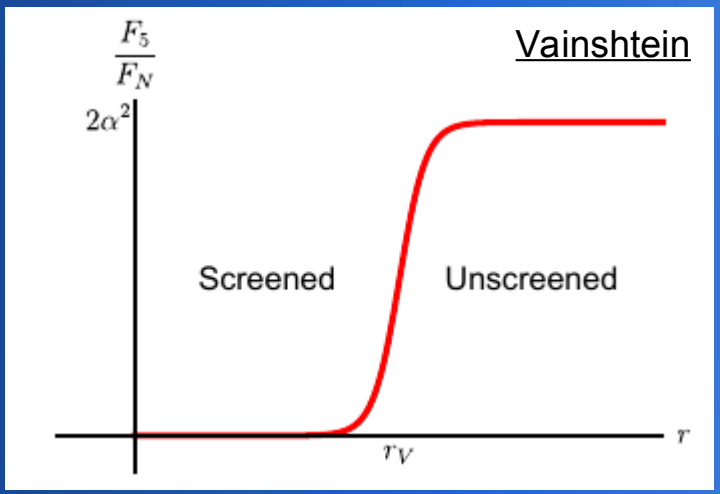
Chameleon



Symmetron



Vainshtein



Searching for Screening

Mechanism	Dominant term at high ρ	Observational proxy
Chameleon	Mass	Newtonian potential Φ
Kinetic/K-mouflage	Kinetic	Acceleration a
Vainshtein	Higher-order	Curvature K

Khoury 2013

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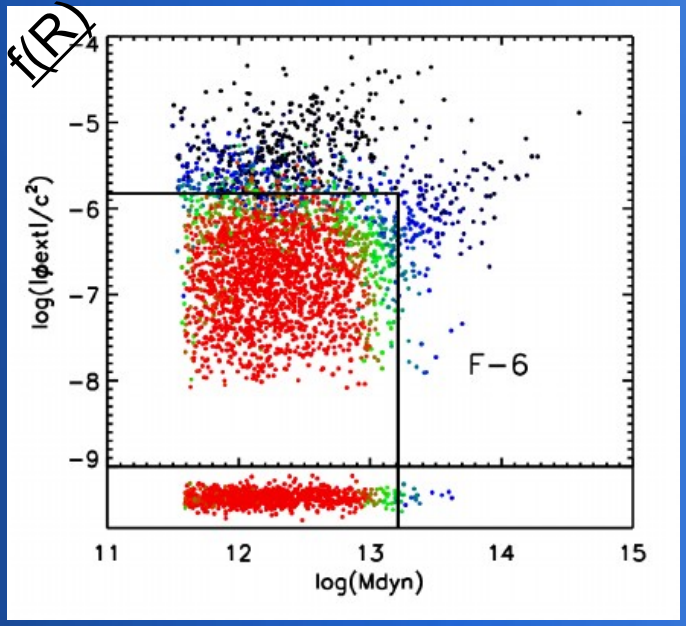

Cabre+ 2012

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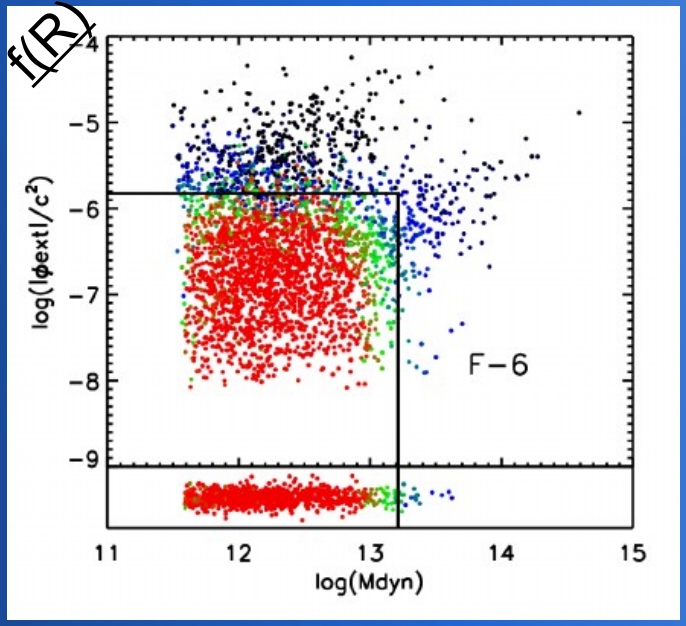
Khoury 2013

1) Map Φ, *a*, *K* over local universe
2) Forward-model signals
3) Constrain fifth-force strength & range by Bayesian inference

Cabre+ 2012



Gravitational Mapmaking

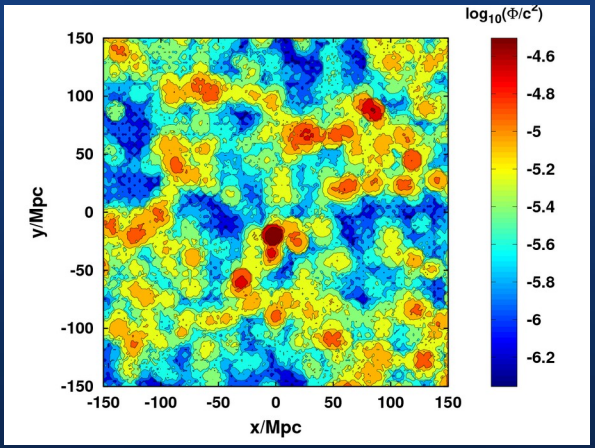
$\Phi_j \sim \sum_i GM_i/r_{ij}$	$\vec{a}_j \sim \sum_i GM_i \hat{\vec{r}}_{ij}/r_{ij}^2$	$K_j \sim \sum_i GM_i/r_{ij}^3$

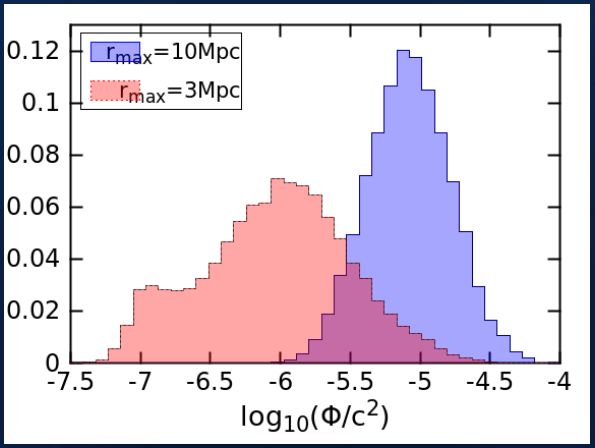
Three contributions to each:

1) Halo mass associated with 2M++ or SDSS galaxies
2) Halos hosting faint galaxies from N-body simulation
3) Mass in long-wavelength modes (BORG)

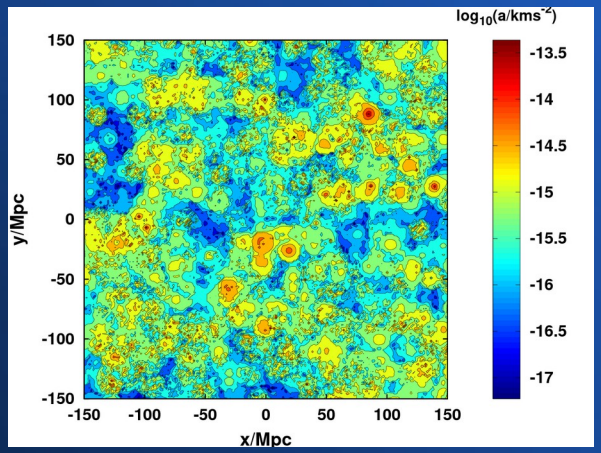
Results: maps and distributions

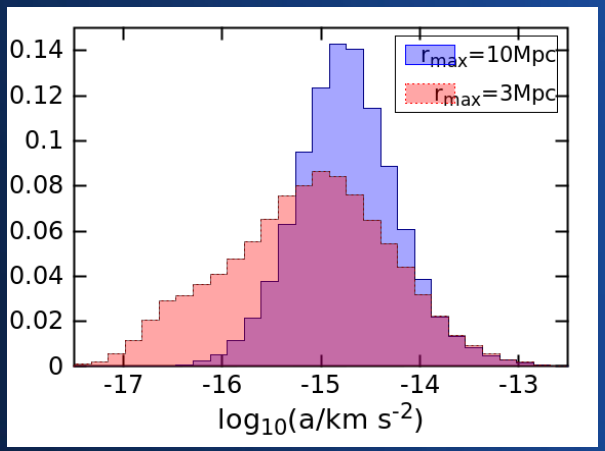
potential



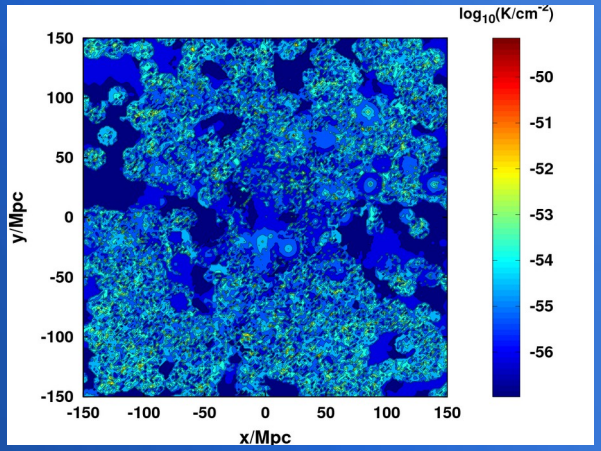


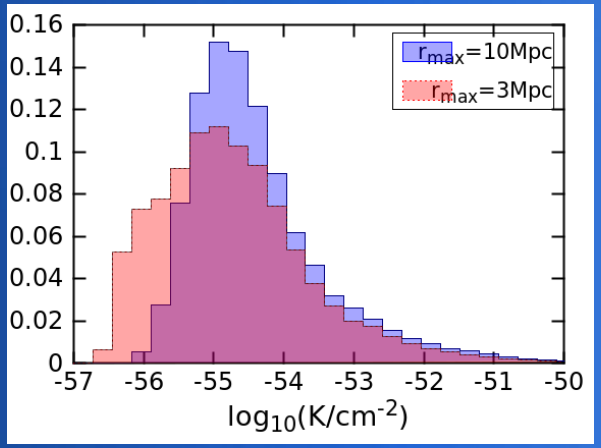
acceleration



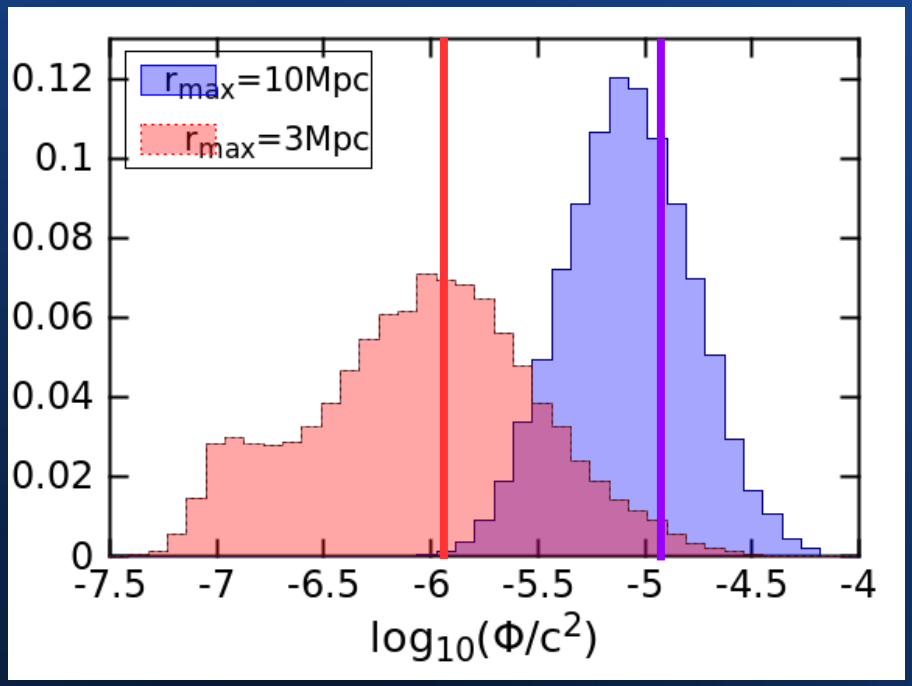


curvature





Application to Hu-Sawicki f(R)



$$\lambda_C = 32\sqrt{f_{R0}/10^{-4}}\,Mpc \quad (n=1)$$

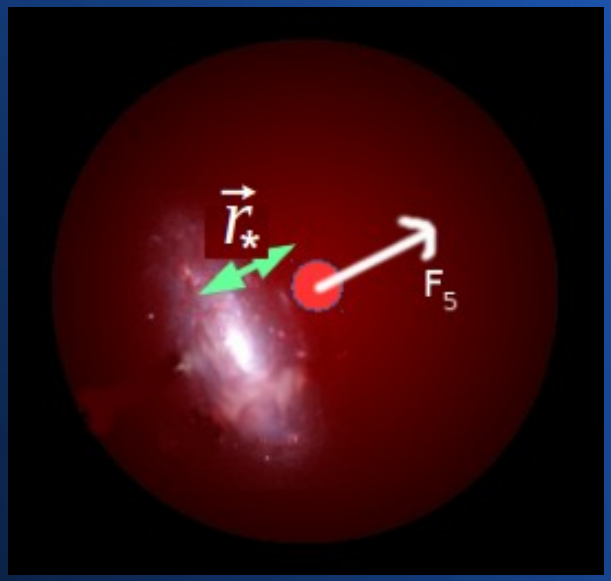
$$\chi \equiv \frac{\Phi_c}{c^2} = \frac{3}{2} f_{R0}$$

E.g. $f_{R0} = 10^{-6} \Rightarrow \lambda_C = r_{max} \simeq 3\,Mpc$

$f_{R0} = 10^{-5} \Rightarrow \lambda_C = r_{max} \simeq 10\,Mpc$

Signal #1: Separation of stars and gas

- In unscreened galaxies, stars self-screen and lag behind gas & dark matter (Hui+ 2009, Jain & VanderPlas 2011)



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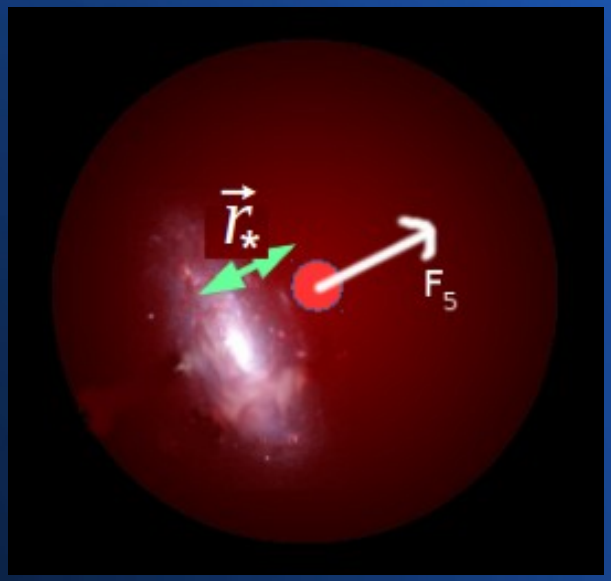


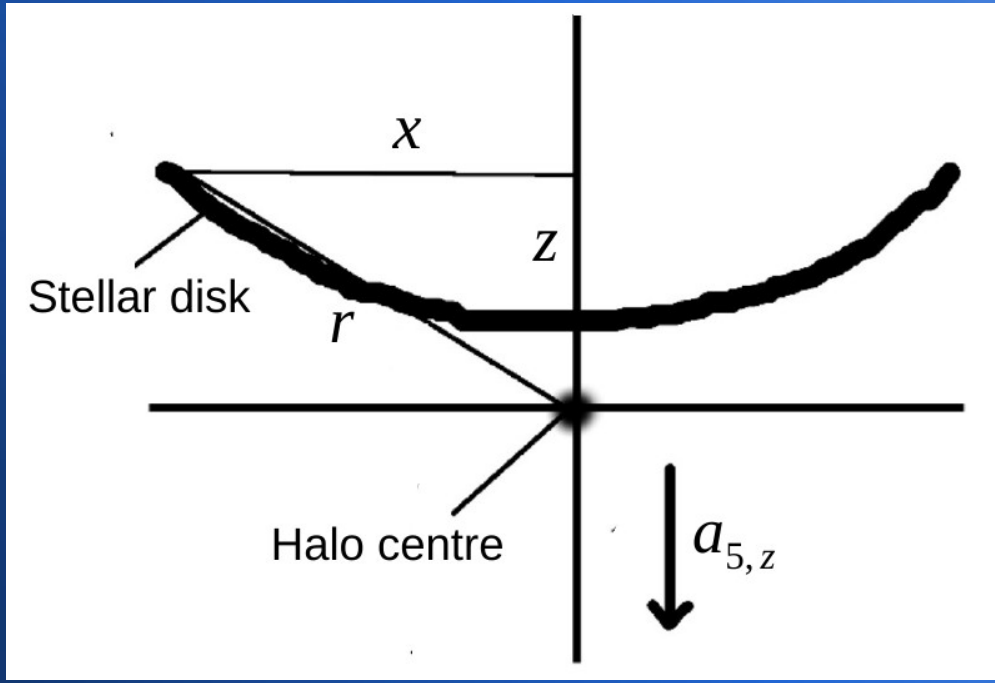
- Equilibrium offset $\vec{r}_*$ satisfies

$$\frac{G_{\rm N} M(r_*)}{r_*^2}\,\hat{r}_* = \vec{a}_5\,\frac{\Delta G}{G_{\rm N}}$$

Signal #2: Warps in galactic disks

- Potential gradient across disk bends it into U-shape
- Calculate shape by requiring each point on disk to have same z-acceleration

$$z(x) \simeq -a_{5,z} \frac{\Delta G}{G_{\rm N}^2} \frac{|x|^3}{M(x)}$$



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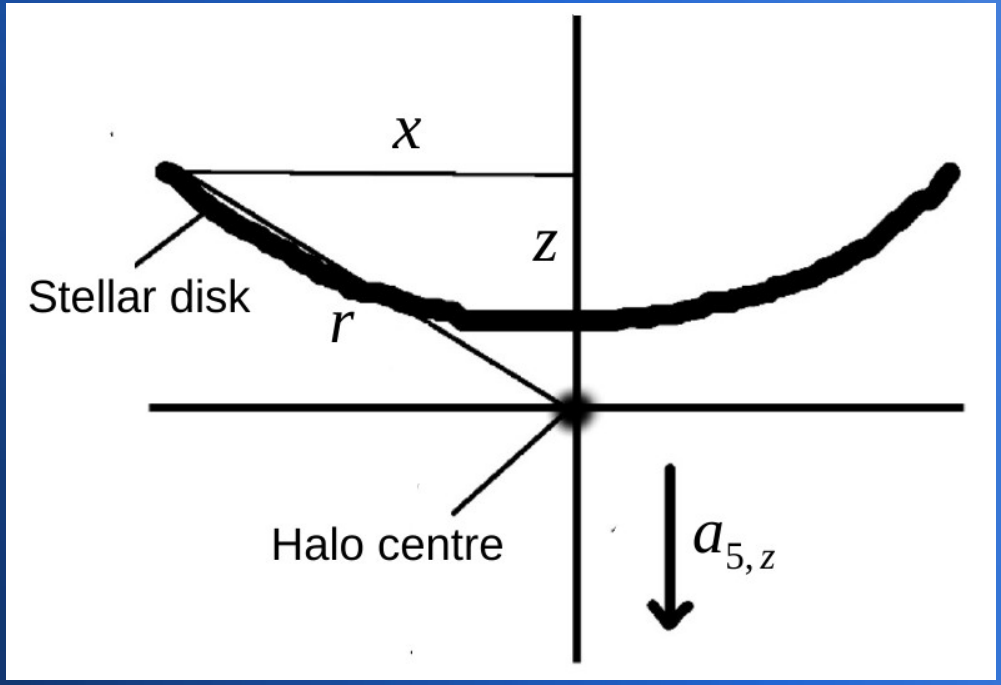
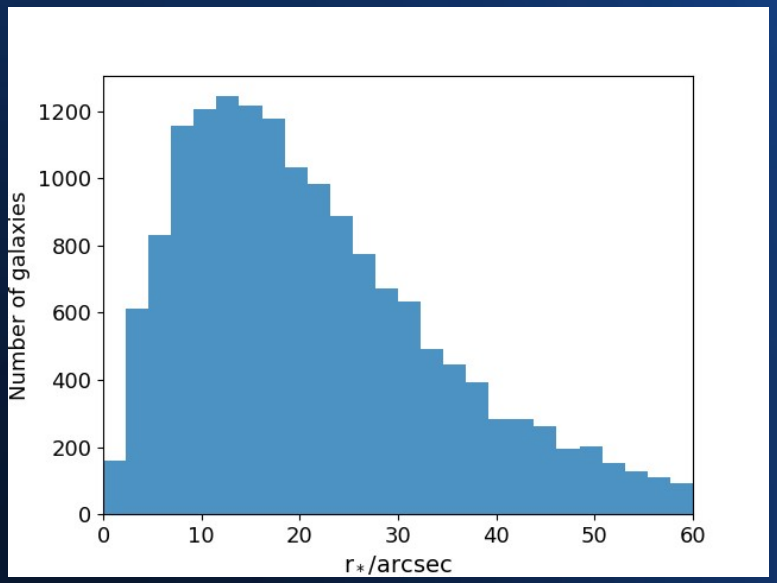


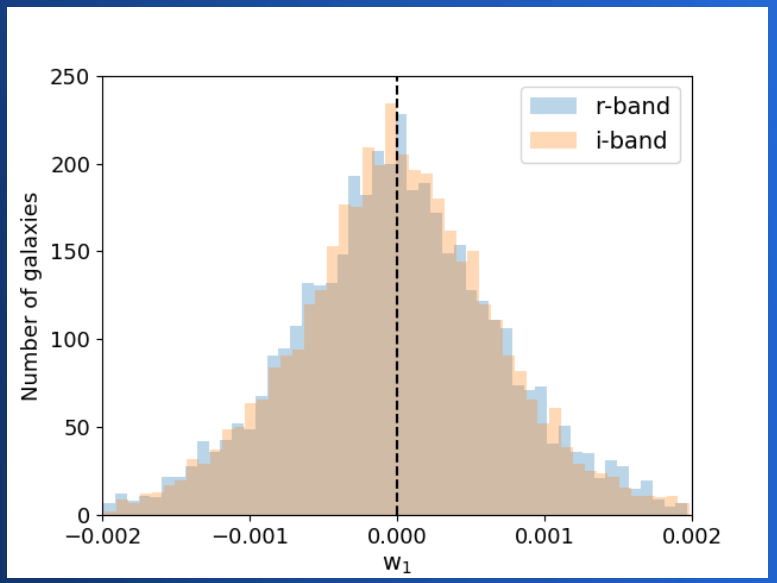
- Summarise by weighted average *z*:

$$w_1 \equiv \frac{1}{L_x^3} \int_{-L_x}^{L_x} |x|\, z(x)\, dx$$

Observational Data

- Gas–star offsets: ~16,000 galaxies cross-matched between ALFALFA and the Nasa Sloan Atlas (NSA)
- Warps: ~4,000 edge-on disk galaxies from the NSA





Likelihood Model
I. Fifth-force expectation

- Forward-model $\vec{r}_*$ and w_1 for each galaxy as a function of 1) fifth-force parameters, 2) gravitational environment, and 3) internal galaxy/halo properties

- Assume power-law halo density across galaxy, with normalisation calibrated by abundance matching: $\rho(r) = \rho_{rs}\,(r/r_s)^{-\beta}$

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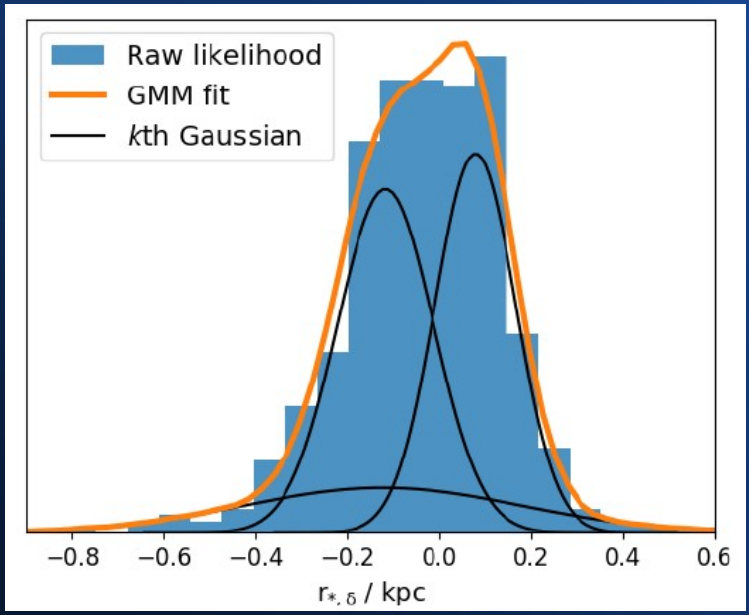
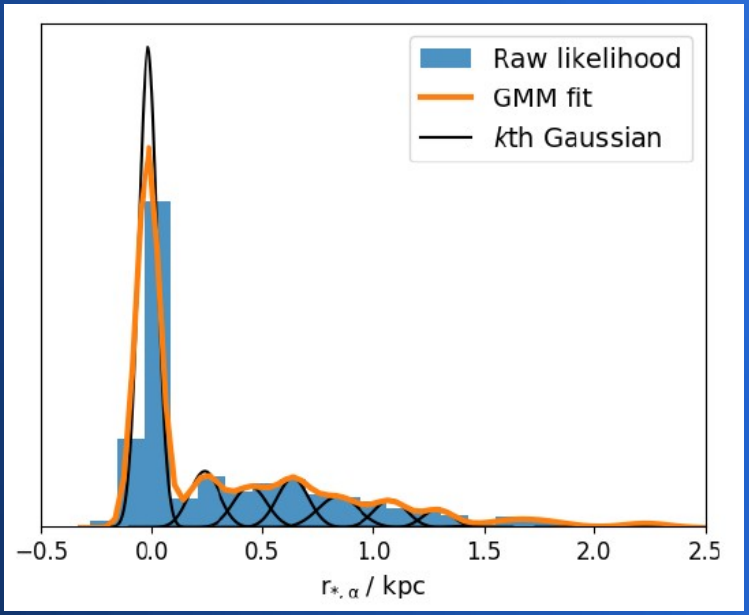
$$\vec{r}_* = \left(a_5 \frac{\Delta G}{G_{\rm N}^2} \frac{3-\beta}{4\pi\rho_{rs}} r_s^{-\beta} \right)^{\frac{1}{1-\beta}} \hat{a}_5$$

$$w_1 = -\frac{\beta\,(3-\beta)}{(\beta+1)(\beta+2)}\, a_{5,z} \frac{\Delta G}{G_{\rm N}^2} \frac{1}{4\pi\rho_{rs}} \frac{(3R_{\rm eff}/r_s)^\beta}{3R_{\rm eff}}$$

Likelihood Model
II. Constructing the likelihood

- Probabilistic inputs → build likelihood empirically by Monte Carlo sampling, then fit with Gaussian Mixture Model





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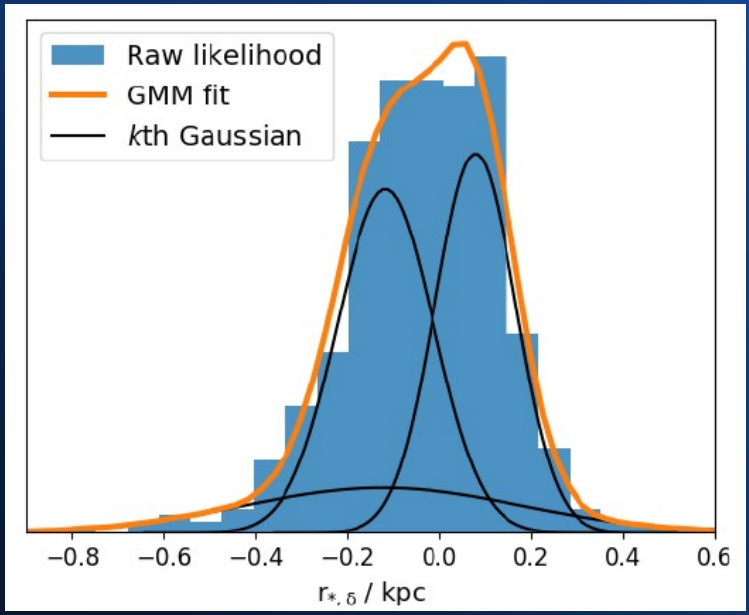
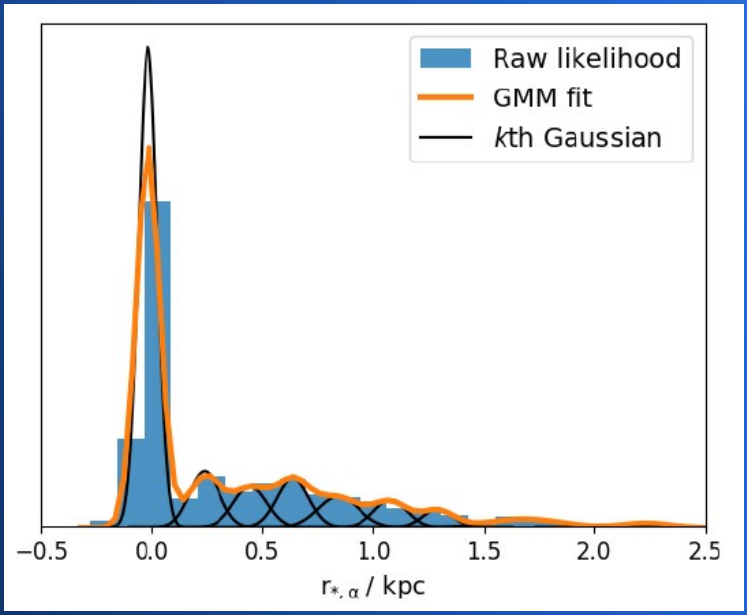




$$\mathcal{L}_{5,i}(y_i|\Delta G/G_\mathrm{N}, \lambda_C) = (1 - f_i)\,\delta(y_i) + f_i \sum_{k=1}^{N_\mathrm{G}} \frac{W_{ik}}{\sqrt{2\pi}\,F[\Delta G/G_\mathrm{N}]\,s_{ik}} \exp\left\{-\frac{(F[\Delta G/G_\mathrm{N}]\,\bar{y}_{ik} - y_i)^2}{2F[\Delta G/G_\mathrm{N}]^2\,s_{ik}^2}\right\}$$

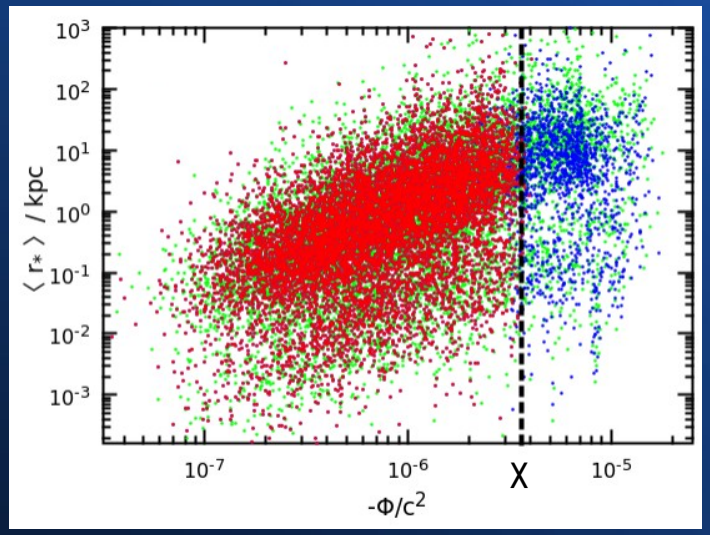
$$y \in \{r_{*,\alpha}, r_{*,\delta}, w_1\}$$

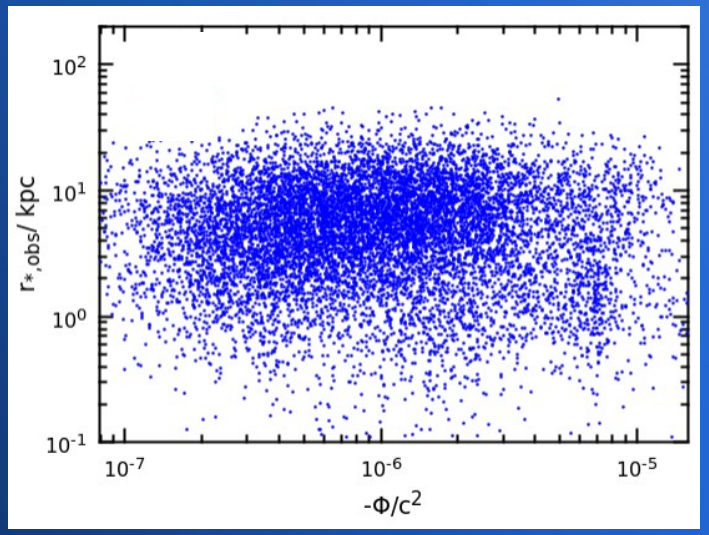
Predicted vs measured signals

Predicted ($\Delta G=G_N$, λ_C=5 Mpc)

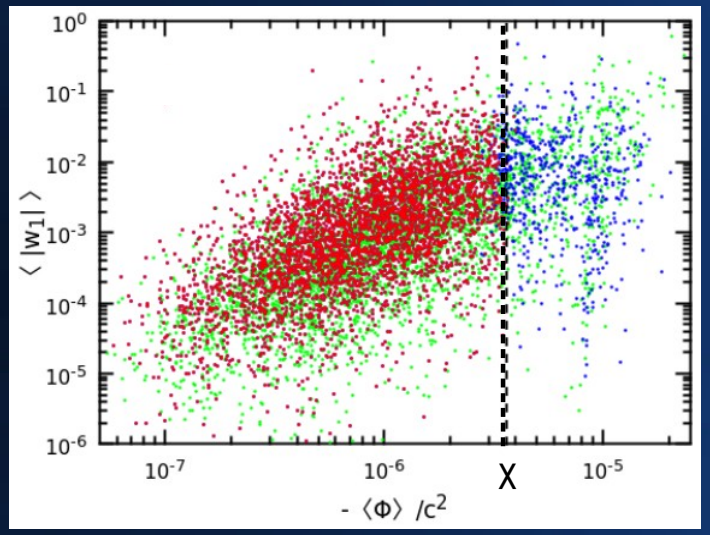
Observed

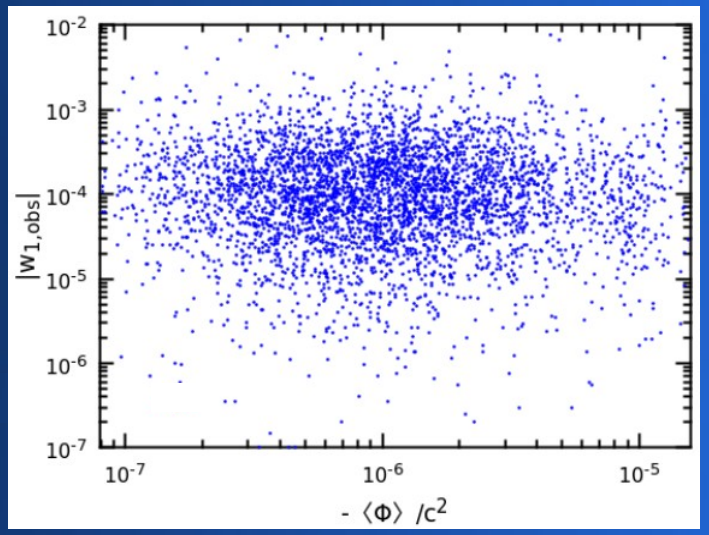
Gas–star offset





Warp





Likelihood Model
III. Noise component

- Convolve F5 likelihood with Gaussian of width σ describing measurement noise and astrophysical contributions to signals

$$\mathcal{L}_i(y_i|\Delta G/G_{\rm N}, \lambda_C, \sigma_i) = (1-f_i)\,\frac{\exp\{-y_i^2/2\sigma_i^2\}}{\sqrt{2\pi}\,\sigma_i} + f_i \sum_{k=1}^{N_{\rm G}} \frac{W_{ik}}{\sqrt{2\pi(F[\Delta G/G_{\rm N}]^2\, s_{ik}^2 + \sigma_i^2)}} \exp\left\{-\frac{(F[\Delta G/G_{\rm N}]\,\bar{y}_{ik} - y_i)^2}{2(F[\Delta G/G_{\rm N}]^2\, s_{ik}^2 + \sigma_i^2)}\right\}$$

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- Parametrise σ_i and constrain along with ΔG and λ_C:
  - $\sigma_i = \sigma_{\rm const}$ is the same for all galaxies
  - $\sigma_i = \sigma_D D_i$, i.e. fixed angular resolution
  - σ_i a general function of galaxy parameters

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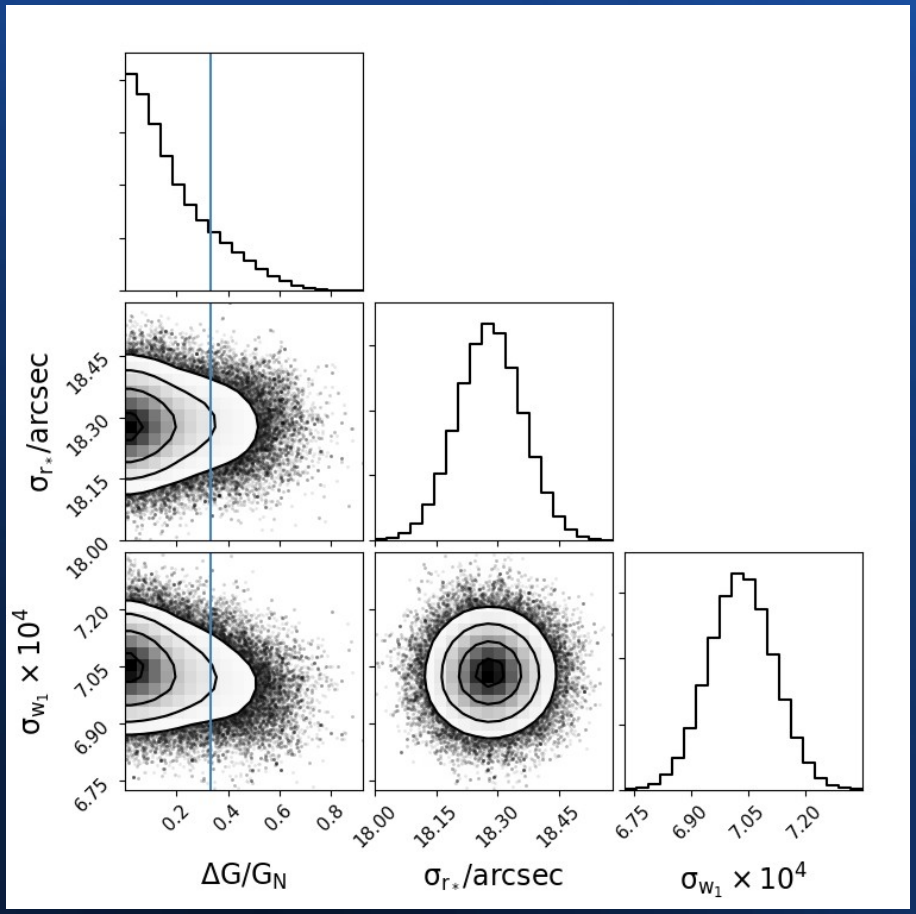
$$y \in \{r_{*,\alpha}, r_{*,\delta}, w_1\}$$

- Parametrise σ_i and constrain along with ΔG and λ_C:
  - $\sigma_i = \sigma_{\rm const}$ is the same for all galaxies — Warps σ_{w1}
  - $\sigma_i = \sigma_D D_i$, i.e. fixed angular resolution — Offsets σ_{r*}
  - σ_i a general function of galaxy parameters

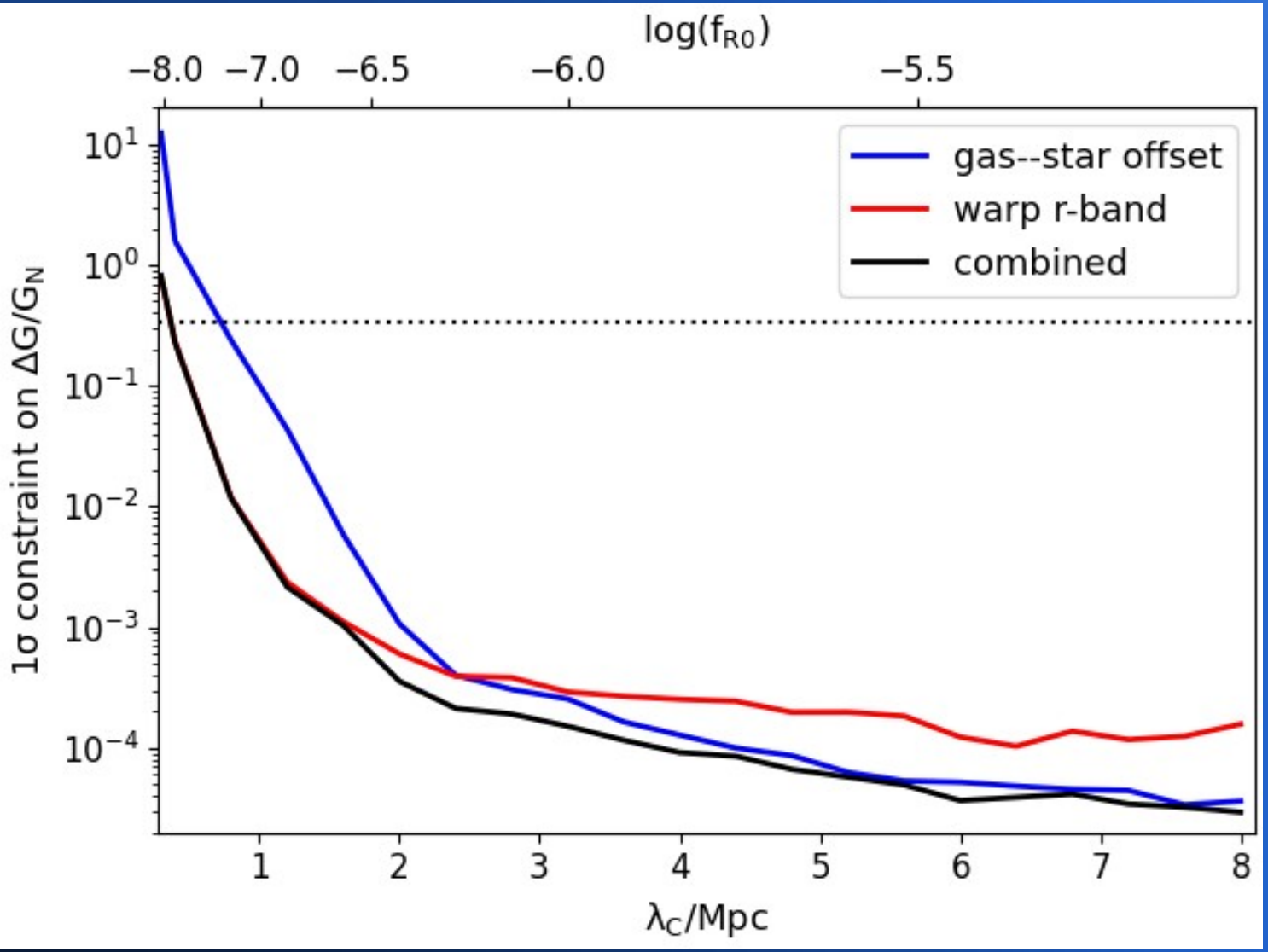
Results
I. Degeneracy with noise terms



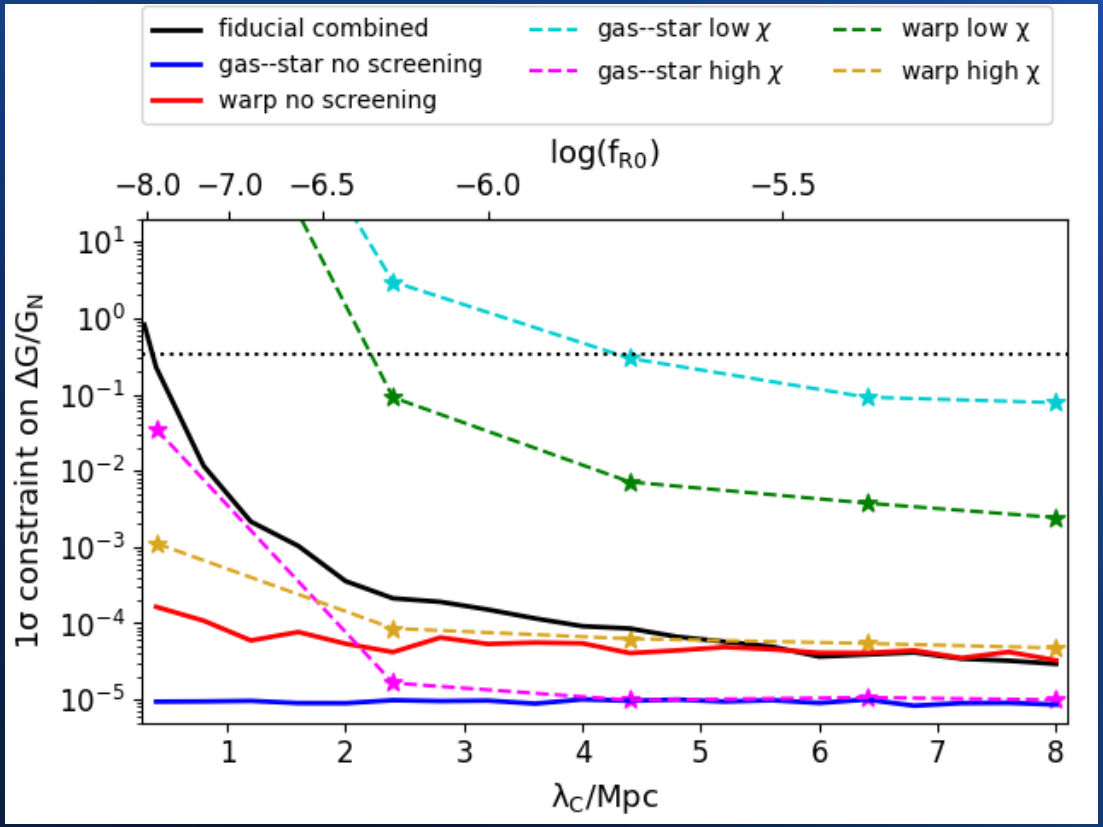
λ_C = 0.4 Mpc (f_{R0} = 1.6e-8)

- Noise parameters constrained by widths of measured r_* and w_1 distributions
- Fifth-force constraints set by galaxy-by-galaxy correlation of measured and predicted signals

Results
II. Constraints



Results
III. Constraints on additional models



- 'warp no screening' constraint applies to F5 acting only in the dark sector: $\Delta G/G_N < 1e\text{-}4$
- Varying χ at fixed λ_C corresponds to $n \neq 1$ in Hu-Sawicki f(R), or freeing up 3rd chameleon parameter

Systematics

1. “Galaxy formation”/baryonic physics affects stars, gas & DM differently, so may be degenerate with F5

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2. Assumed ΛCDM for calculating density profiles and screening/fifth-force fields
3. Uncertain DM distribution across galaxies

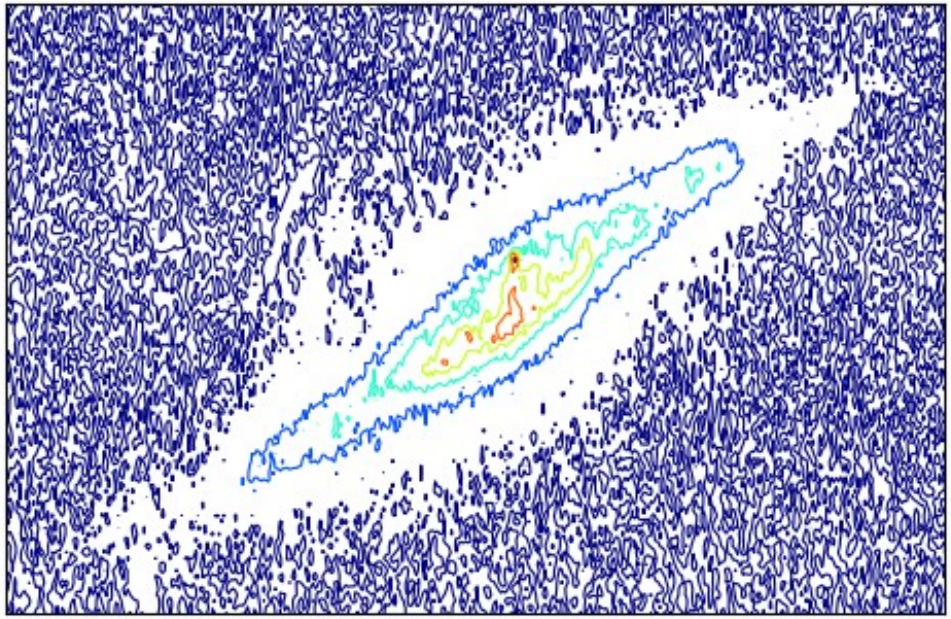
Conclusions

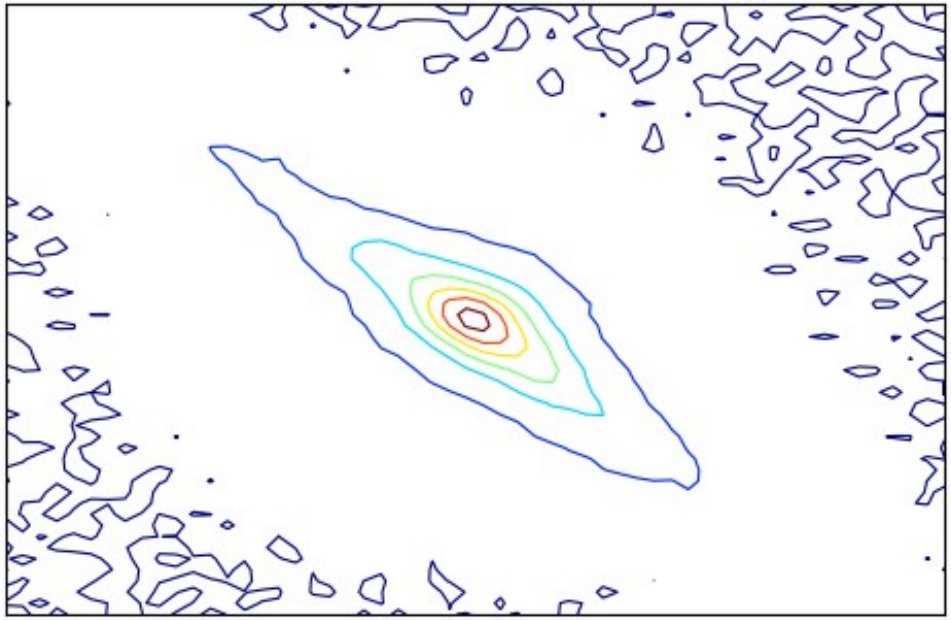
- Galaxy structure probes gravity in new regions of parameter space with potentially great sensitivity
- Environment dependence → require *gravitational maps* of the local universe
- Two tests of chameleon & symmetron screening:
  - Separation of stars and gas
  - Warping of stellar disks

$f_{R0} < 1.4e\text{-}8 : \ \Delta G/G_N < 1e\text{-}4$ for F5 only in dark sector

- Much promise for the future:
  - Several signals still to explore (Jain & Vanderplas 2011)
  - ++ quantity and quality of data with upcoming surveys

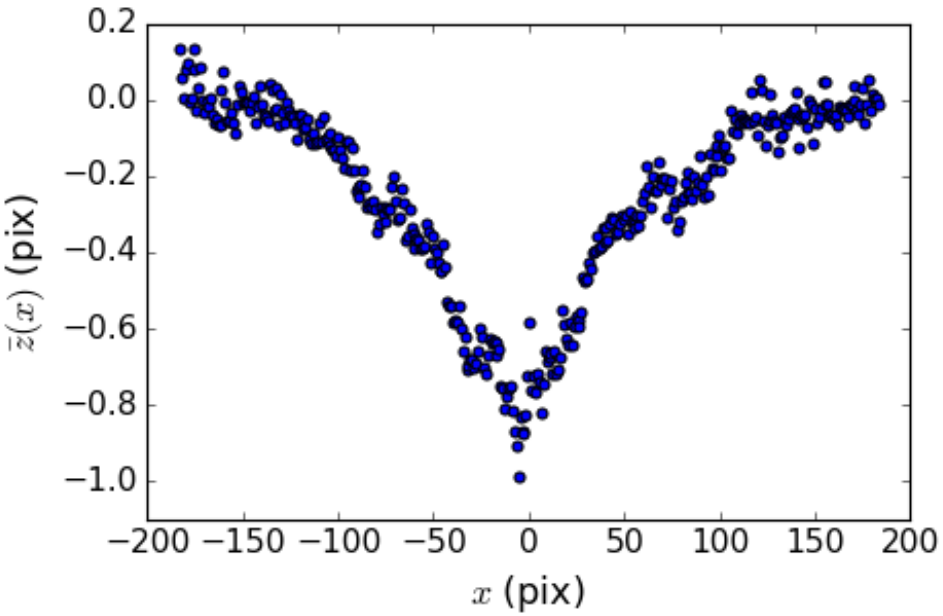
Extra slides

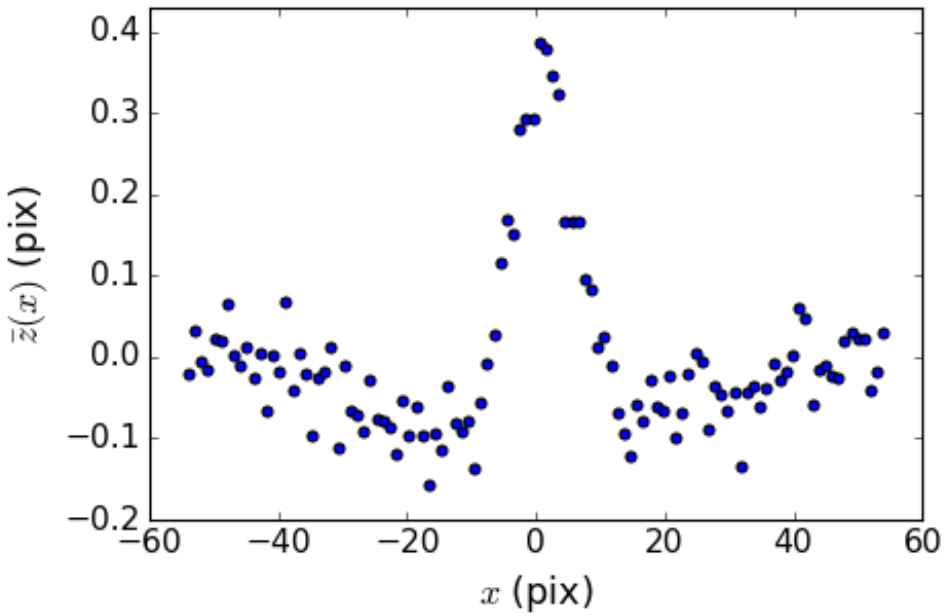




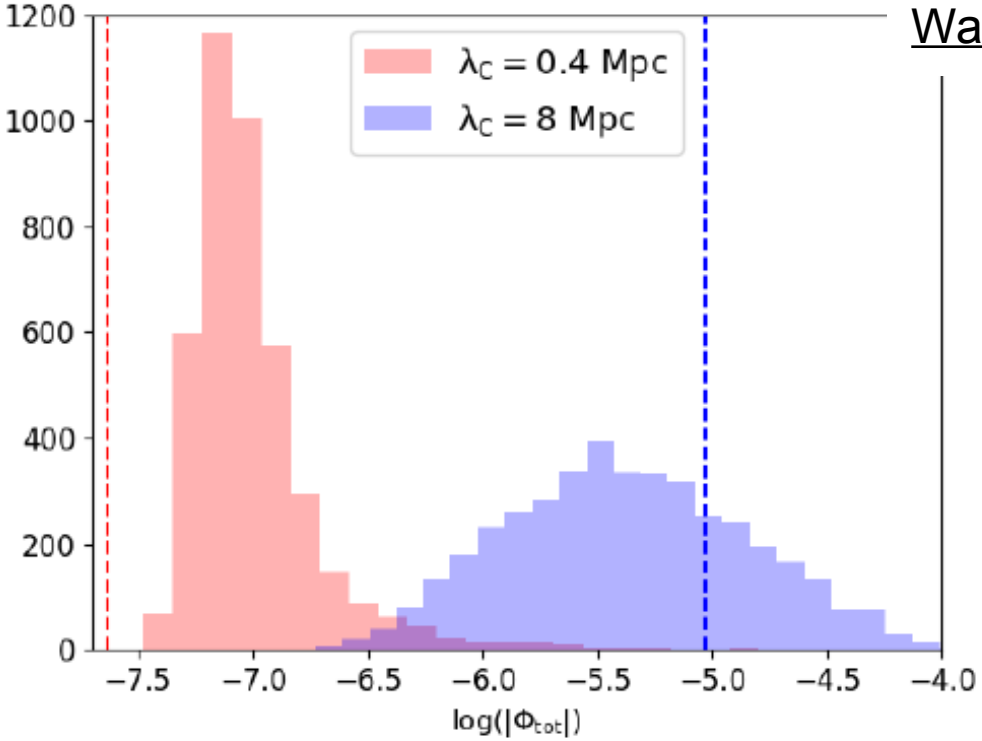
J115012.10+065956.9 – $w_1 = 1.7 \times 10^{-3}$

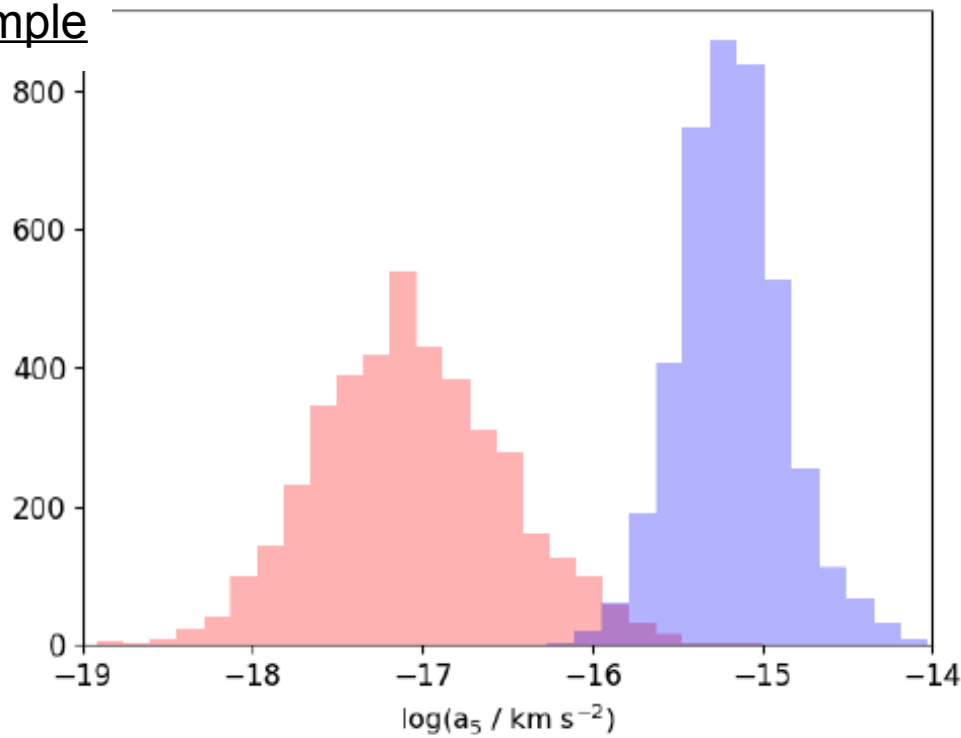
J003938.31+143951.2 – $w_1 = -1.1 \times 10^{-4}$

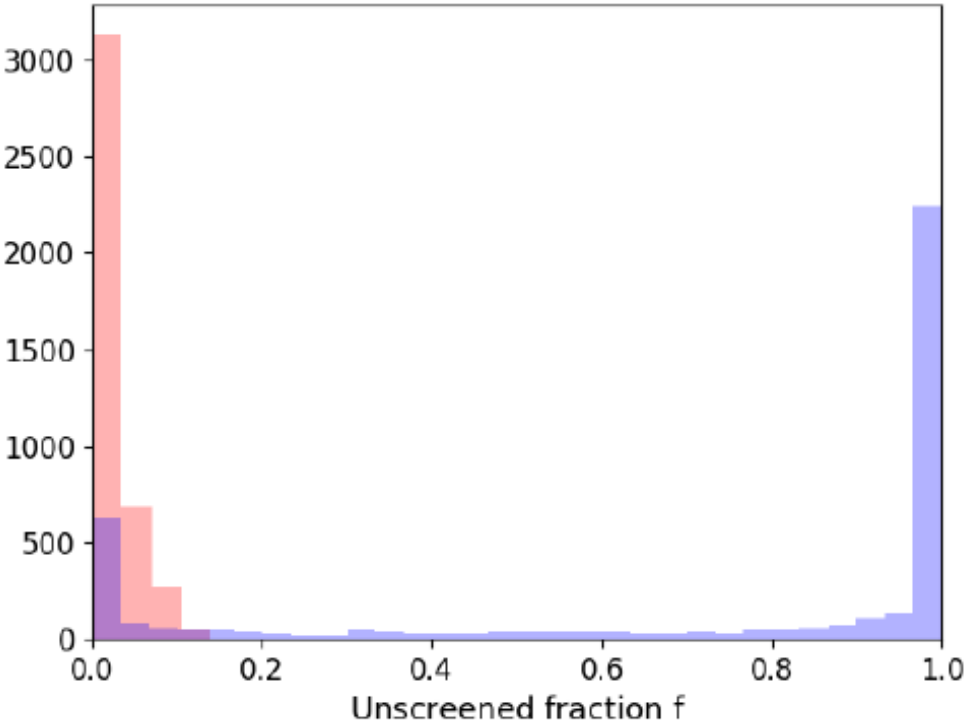


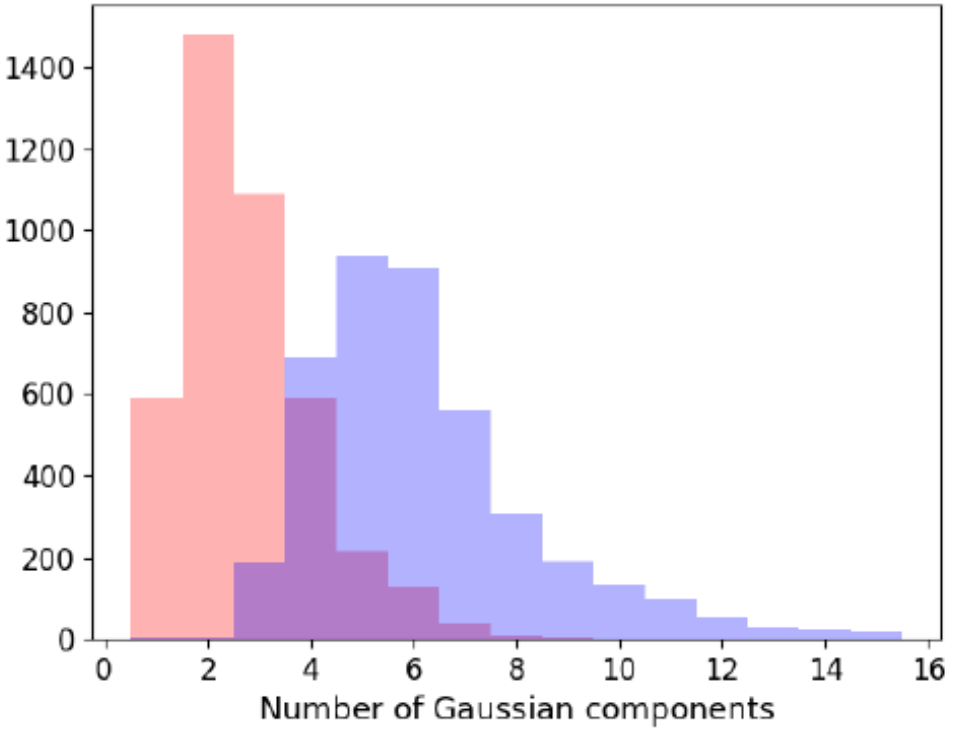


Warp Sample

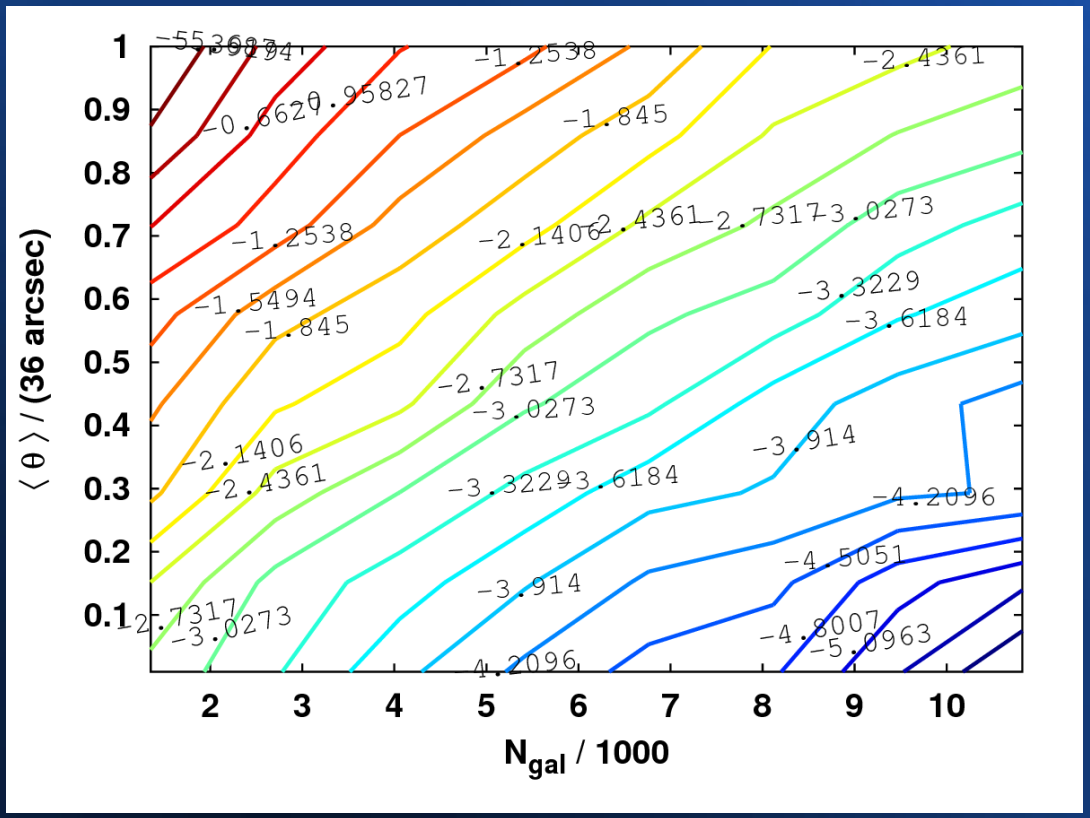

$\lambda_C = 0.4$ Mpc
$\lambda_C = 8$ Mpc
log(|Φtot|)

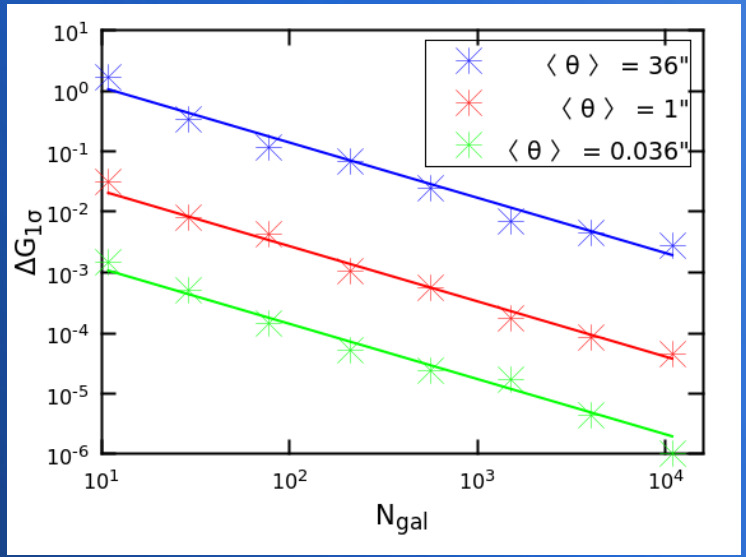

log(a5 / km s−2)

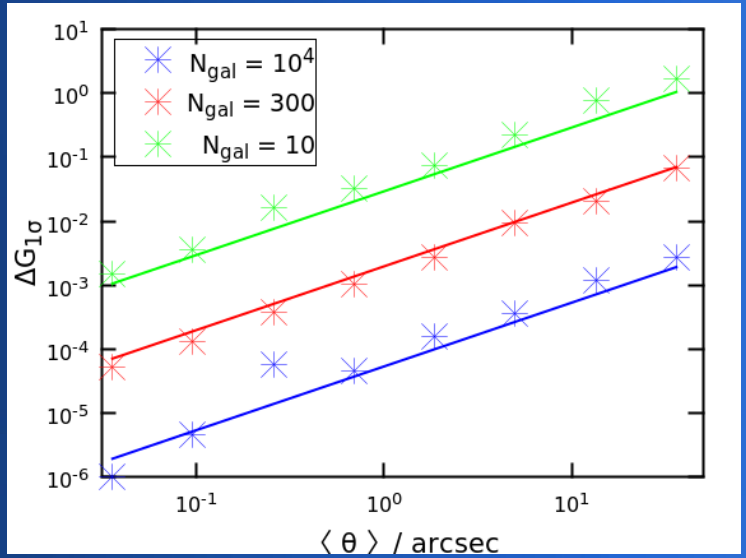

Unscreened fraction f


Number of Gaussian components

Forecasting for future surveys





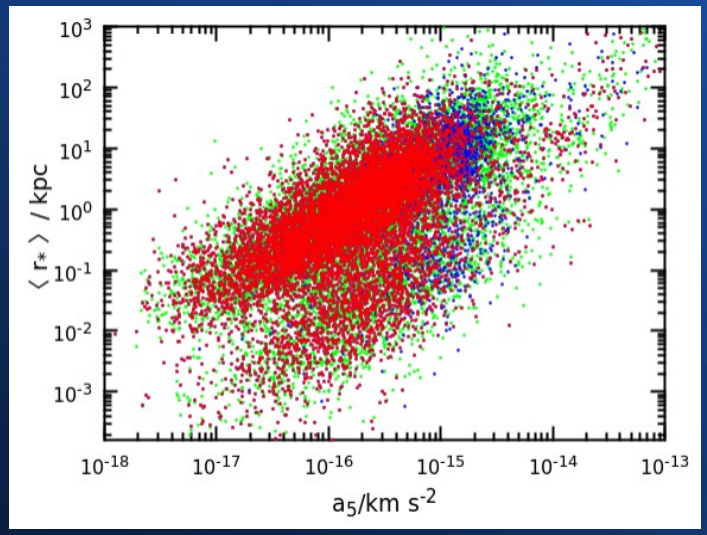


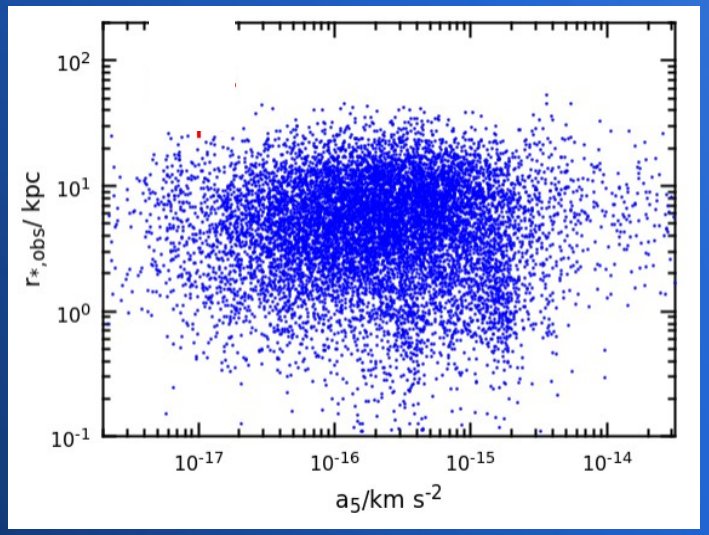
Predicted vs measured signals

Predicted ($\Delta G=G_N$, λ_C=5 Mpc)

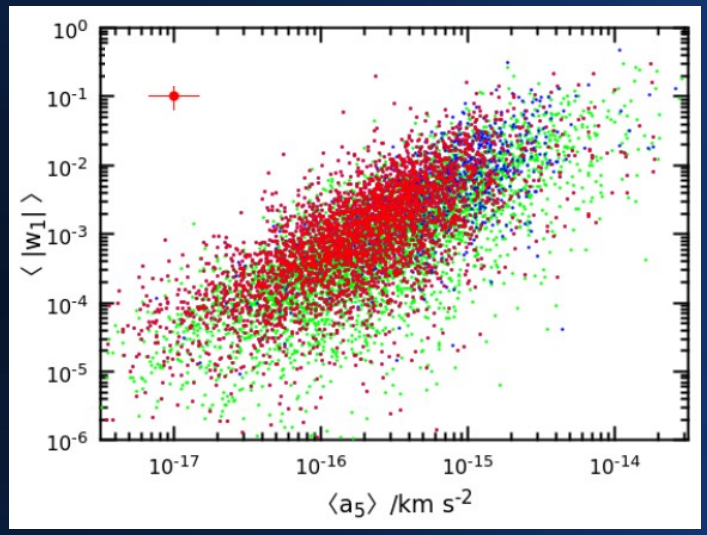
Observed

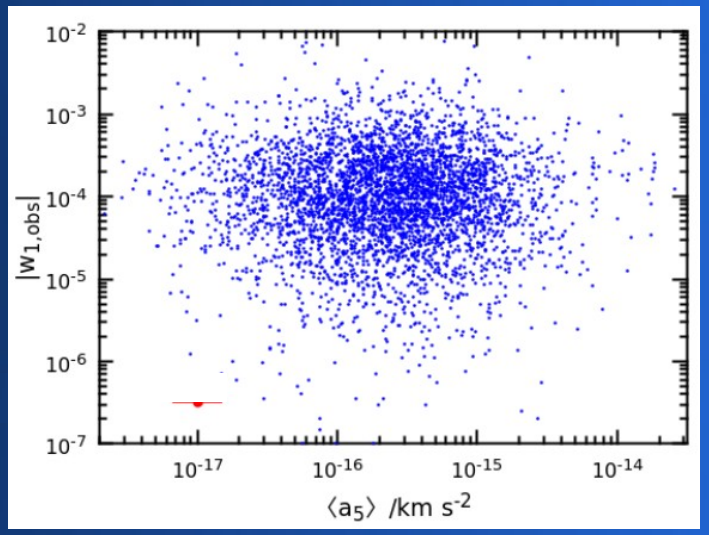
Gas–star offset





Warp





Previous constraints

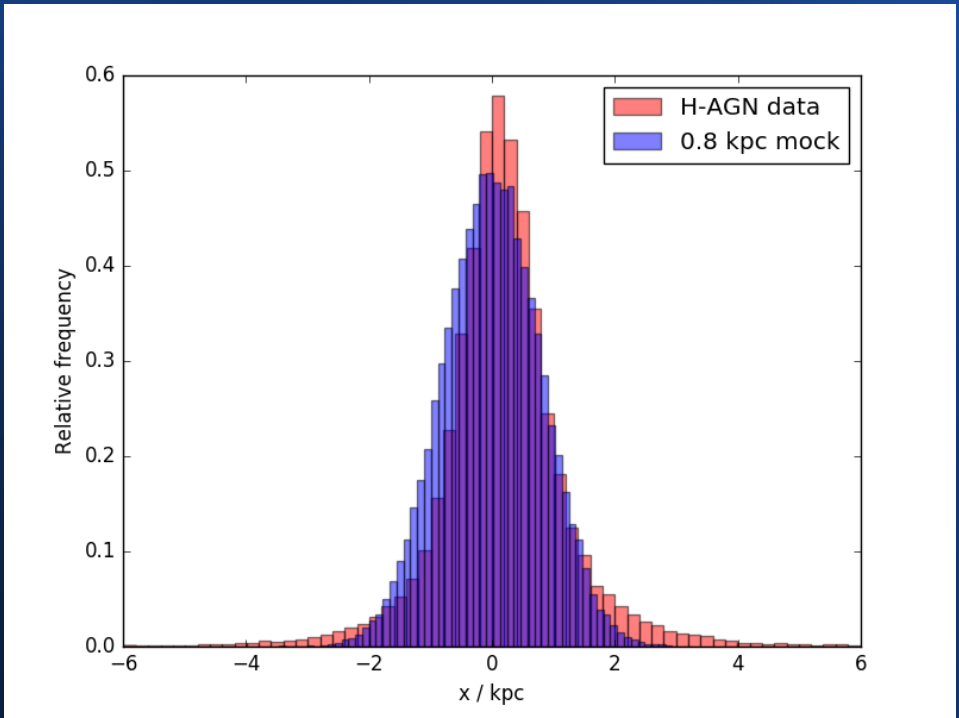
Measurement	redshift	scale	$\lvert f_{R0}\rvert$ constraint
Integrated Sachs-Wolfe (ISW) effect	$\lesssim 10$	$\gtrsim 25h^{-1}$ Mpc	$< 3.5 \times 10^{-1}$
Galaxy-ISW cross correlations	$\lesssim 5$	$\gtrsim 40h^{-1}$ Mpc	$< 6.9 \times 10^{-2}$
Galaxy power spectrum (WiggleZ)	$0.2 - 1$	$\gtrsim 60h^{-1}$ Mpc	$10^{-4} \lesssim \lvert f_{R0}\rvert \lesssim 2 \times 10^{-1}$
Galaxy power spectrum (WiggleZ)	$0.2 - 1$	$\gtrsim 30h^{-1}$ Mpc	$\lesssim 1.4 \times 10^{-5}$
Redshift-space distortions (LRG)	$0.16 - 0.47$	$(15 - 300)h^{-1}$ Mpc	$\lesssim 10^{-4}$
E_G probe	0.32	$(10 - 50)h^{-1}$ Mpc	$\lesssim 10$
CMB lensing (ACT)	$\lesssim 6$	$(1 - 60)h^{-1}$ Mpc	$\lesssim 10^{-1}$
CMB lensing (SPT)	$\lesssim 6$	$(1 - 50)h^{-1}$ Mpc	$\lesssim 2 \times 10^{-2}$
CMB lensing (Planck)	$\lesssim 6$	$\gtrsim 1h^{-1}$ Mpc	$\lesssim 10^{-2}$
Cluster abundance (Chandra)	< 0.15	$(1 - 10)h^{-1}$ Mpc	$< 1.3 \times 10^{-4}$
Cluster abundance (MaxBCG)	0.18, 0.25	$(1 - 10)h^{-1}$ Mpc	$< 1.9 \times 10^{-4}$
Gravitational redshift of galaxies in clusters	$0.1 - 0.55$	$(0.5 - 10)h^{-1}$ Mpc	...
Cluster density profiles (maxBCG)	0.23	$(0.2 - 20)h^{-1}$ Mpc	$< 3.6 \times 10^{-3}$
Coma gas measurements	0.02	$(0.1 - 1)h^{-1}$ Mpc	$< 6 \times 10^{-5}$
Strong gravitational lenses (SLACS)	$0.06 - 0.36$	$(1 - 10)$ kpc	$< 2.5 \times 10^{-6}$
Solar System	0	$\lesssim 20$ au / 8 kpc	$< 8 \times 10^{-7}$
Supernova monopole radiation	~ 0	$\sim 200R_\odot$	$\lesssim 10^{-2}$
Distance indicators in dwarf galaxies	$\lesssim 0.002$	$\lesssim 100R_\odot$	$< 5 \times 10^{-7}$
Relativistic effects in galaxy-clustering	$\lesssim 1$	$\gtrsim 200h^{-1}$ Mpc	$\lesssim 10^{-1}$
21 cm intensity mapping + CMB	$0.7 - 2.5$	$\gtrsim 50h^{-1}$ Mpc	$\lesssim 10^{-5}$
CMB ISW-lensing bispectrum	$\lesssim 5$	$\gtrsim 40h^{-1}$ Mpc	$\lesssim 10^{-2}$
Matter bispectrum	~ 0	$\lesssim 30h^{-1}$ Mpc	$10^{-6} \lesssim \lvert f_{R0}\rvert \lesssim 10^{-4}$
Stacked phase-space distribution	$0.2 - 0.4$	$(1 - 20)h^{-1}$ Mpc	$\lesssim (10^{-6} - 10^{-5})$
Galaxy infall kinematics	0.25	$(0.5 - 30)h^{-1}$ Mpc	$\lesssim (10^{-5} - 10^{-4})$
Dwarf galaxies	~ 0	~ 1 kpc	$\lesssim 10^{-7}$

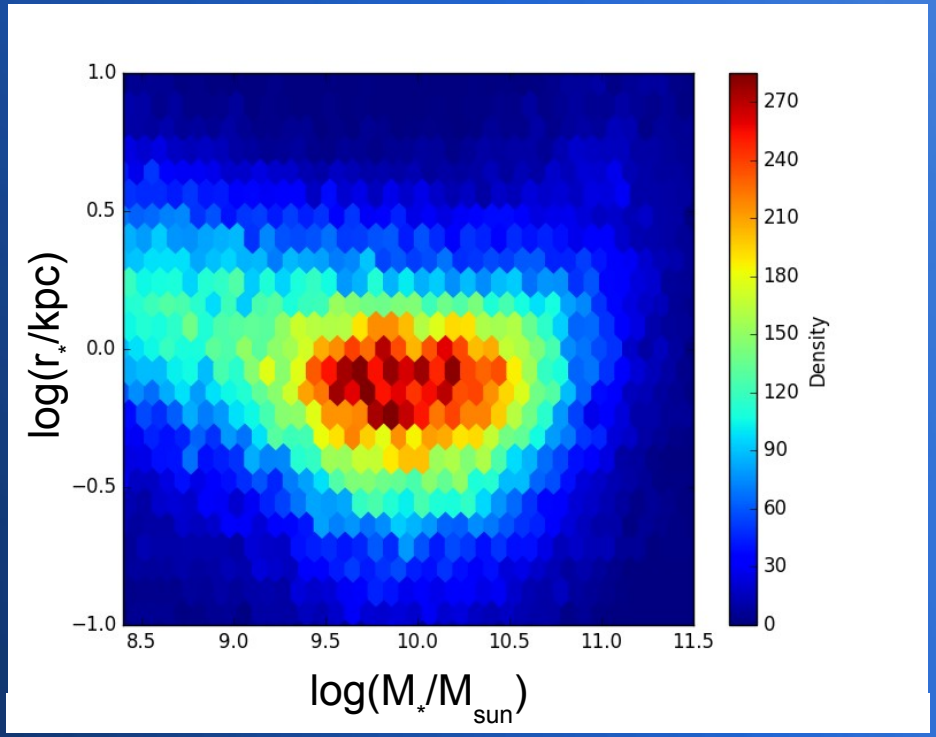
Lombriser 2015

Systematics

1. "Galaxy formation"/baryonic physics affects stars & gas differently, so may be degenerate with F5
   - Unlikely to correlate $\vec{r}_*$ with gravitational environment and halo density in same way as screened fifth force (?)
   - Check with cosmological hydro sims
2. Assumed ΛCDM for calculating density profiles and screening/fifth-force fields
   - Difference should be small for $\{\Delta G, \lambda_c\}$ as low as here
   - Repeat self-consistently in mod. grav. sims
3. Calculation of DM density within ~100pc of halo centre
   - Affects inference of ΔG but not $\Delta\log(L)$–λ_c
   - Repeat for galaxies with kinematics at small r

1. Gas–star offsets in the Horizon-AGN simulation





Simulated $\vec{r}_*$ consistent with Gaussian random noise

Uncertainty introduced by Monte Carlo sampling