The Radial Acceleration Relation in Rotationally Supported Galaxies

Stacy S. McGaugh and Federico Lelli
Department of Astronomy, Case Western Reserve University,
10900 Euclid Avenue, Cleveland, OH 44106, USA

James M. Schombert
Department of Physics, University of Oregon, Eugene, OR 97403, USA
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LA FIN DU MOND? ΛCDM IS FULLY CONSISTENT WITH SPARC ACCELERATION LAW

B.W. Keller[1] and J. W. Wadsley
Department of Physics and Astronomy, McMaster University, Hamilton, Ontario, L8S 4M1, Canada

Sheridan B. Green

Spitzer Photometry and Accurate Rotation Curves (SPARC) (McGaugh et al. 2016)

- 175 **rotationally-supported** galaxies (spirals and irregulars)
  - Low redshift
- Near-infrared (3.6μm) observations from *Spitzer*
  - Stellar Mass from light
- 21 cm observations
  - Atomic Gas Mass
  - Velocity fields & rotation curves
- Spatially resolved data for gas, stars and rotation curves

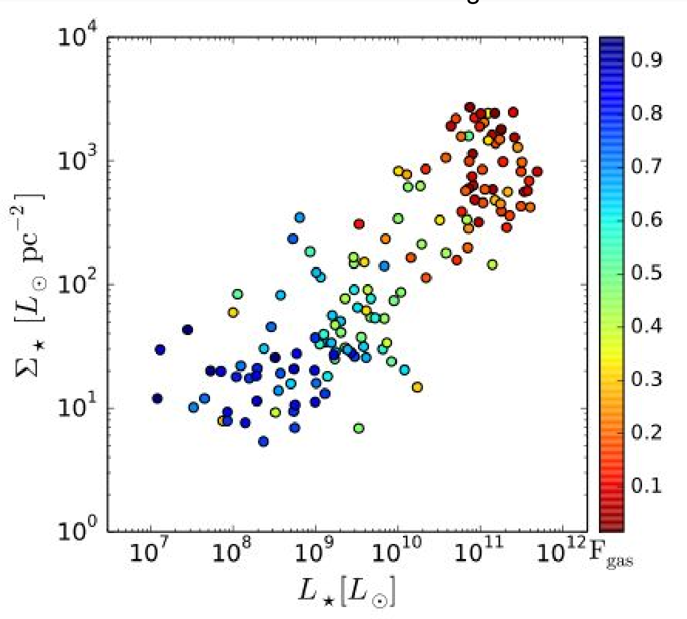
Data Quality Control:

- Cut 10 face-on galaxies with i<30°
- Cut 12 galaxies with asymmetric rotation curves
- Total remaining 153 galaxies

SPARC samples:

- Low to high mass
- Low to high surface brightness
- Negligible to dominant gas content

McGaugh et al. 2016



Gravitational Potential of Baryons

- Define baryonic mass as: $M_{bar}=M_*+M_{gas}$
- Thus surface density: $\rho_{bar}=\rho_*+\rho_{gas}$
- Near-IR data converted to stellar density ρ_*
  - Assumes constant mass-to-light ratio $\Upsilon_* \cong 0.5\ M_\odot/L_\odot$ for all rotationally supported galaxies
  - Υ_* explored in companion paper; result not sensitive to Υ_*
  - By using only one disc value of Υ_*, minimize assumptions included in data analysis
  - For excessively bulged galaxies, modeled separate bulge $\Upsilon_* \cong 0.7\ M_\odot/L_\odot$ from outer disc
- 21cm data converted to gas density ρ_{HI}
  - Uses hydrogen spin-flip physics, and $\rho_{gas}= 1.33*\rho_{HI}$ because of Helium
- Solve Poisson:

$$\nabla^2\Phi_{\rm bar} = 4\pi G\rho_{\rm bar}$$

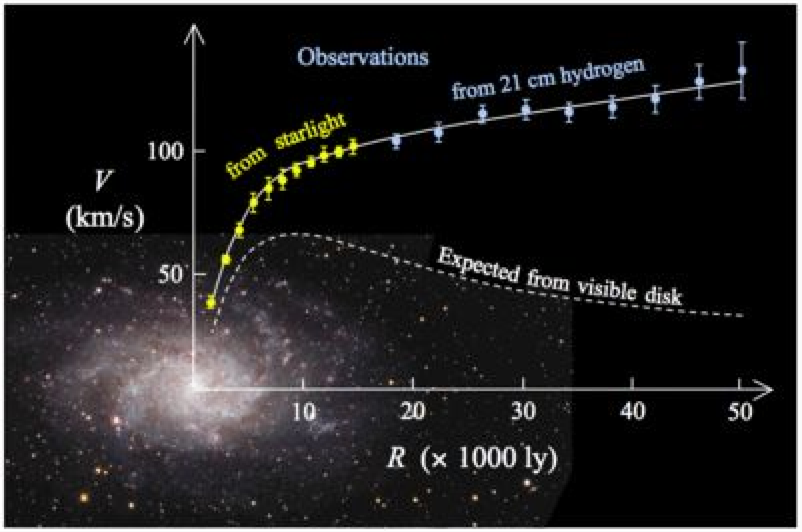
- Baryonic acceleration derived only from observed baryons:

$$g_{\rm bar} = \left|\frac{\partial\Phi_{\rm bar}}{\partial R}\right|$$

- Presumably, $g_{obs}=g_{bar}+g_{DM}$ if ΛCDM

ΛCDM

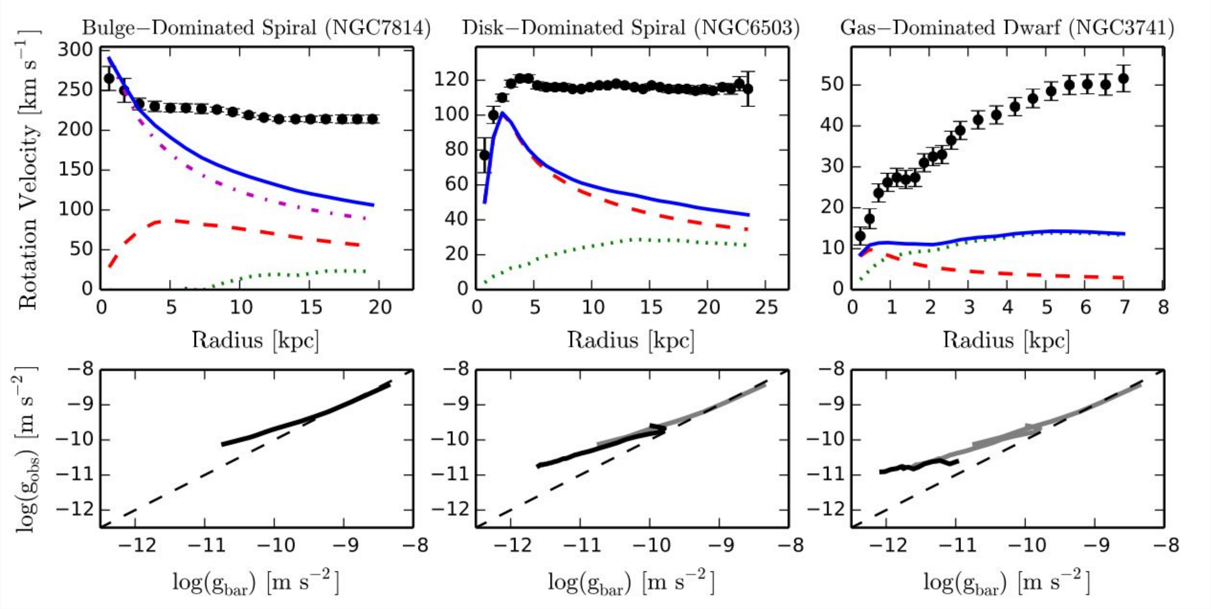
- Rotation Curve Discrepancies
  - Fritz Zwicky 1930s
- Potential Explanations:
  - Dark Matter (DM)
  - Modified Gravity (MOND)
- $g_{obs}=g_{bar}+g_{DM}$



Wikipedia

Results

- Baryonic Mass Model velocity curve: $v_{bar}=v_{*,disc}+v_{*,bulge}+v_{gas}$
- Observed velocity curves from velocity field data
- Compare derived g_{bar} from stellar + gas mass to observed g_{obs} from rotation curves
- This radial acceleration relation persists for all galaxies of all types in SPARC
- g_{bar}-g_{obs} plotted with all galaxies stacked
- Outer regions of high surface brightness galaxies map smoothly to the inner regions of low surface brightness galaxies
- Morphologically agnostic! Same mass discrepancies at same accelerations!



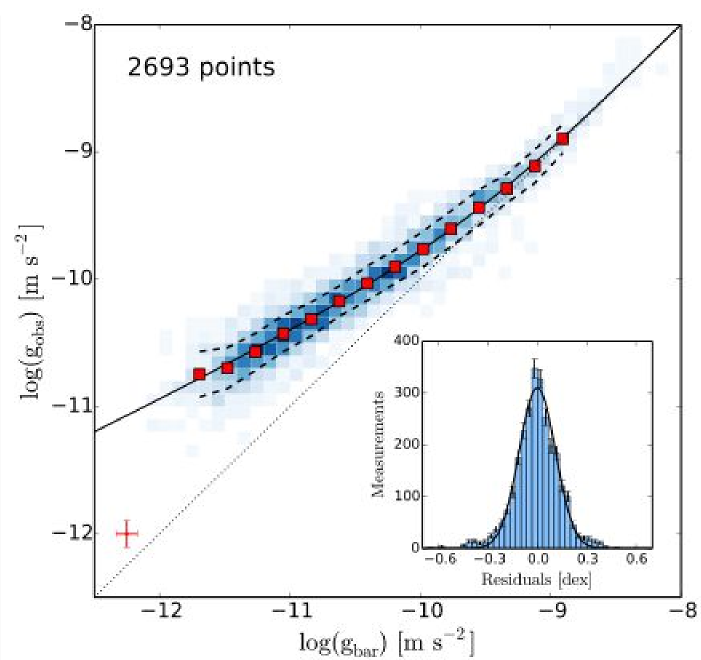
McGaugh et al. 2016

Results

- $g_{obs}=V^2/R$ plotted against g_{bar} as defined earlier
- ~2700 data points for the 153 galaxies
- Residuals in dex (decimal exponents), just error in $\log_{10}$units
- Mean of binned data
- Dotted = line of unity
- Solid line =

$$g_{\rm obs} = \mathcal{F}(g_{\rm bar}) = \frac{g_{\rm bar}}{1 - e^{-\sqrt{g_{\rm bar}/g_{\dagger}}}}$$

- Fit param: $g_{\dagger}$ = $(1.20 \pm 0.26)\times10^{-10}$ m/s^2
- Uncertainties total at 0.12 dex
  - Υ_* scatter at 0.06 dex
  - Measurement error & calibration are the rest
- **Tight relation, little room for intrinsic scatter**



Discussion

- Observational data leads the theory in this one
- Low intrinsic scatter with all measurement errors
- **SPARC radial acceleration acceleration** empirical with minimal assumptions
- Possible reasons:

1. The end product of galaxy formation.
   a. Baryonic feedback, **can be included in DM simulations for comparison**
2. New dark sector physics that leads to the observed coupling
   a. DM fluid?
3. The result of new dynamical laws rather than dark matter (MOND)
   a. One-to-one relation could mean baryons somehow source the g_{obs}

$$g_{\rm obs} = \mathcal{F}(g_{\rm bar}) = \frac{g_{\rm bar}}{1 - e^{-\sqrt{g_{\rm bar}/g_{\dagger}}}}$$

~MOND interpolation function, modified gravitational acceleration in **LOW, LOW acceleration regimes**: only reached by galaxies, not seen in solar system/Earth

Since the radial acceleration relation holds across all rotationally-supported morphologies, it is ostensibly a law of nature, a "Kepler's law for rotating galaxies"

La Fin Du MOND? (Keller & Wadsley 2016)

- Response paper to McGaugh et al. 2016
- Variety of issues currently in ΛCDM:
  - Core/Cusp problem
  - Missing Satellites problem
  - Too Big To Fail problem
- These problems all arise in comparison between DM-only N-body simulations (ΛCDM) and observations
- Issues fixed when baryonic physics included
  - Semi-analytic sub-grid models
- Chief baryonic processes:
  - Black hole feedback
  - Supernovae
- These affect star formation history, thus light/density profile of galaxies

Methodology

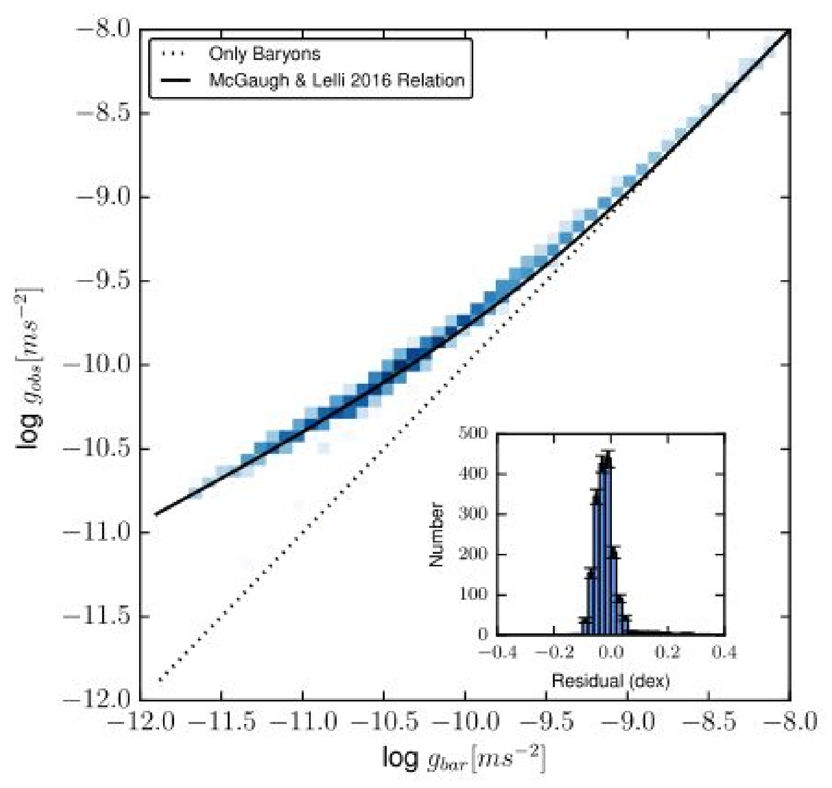
- Conduct same analysis as McGaugh et al. but with ΛCDM+baryonic physics zoomed in DM halos from cosmological simulations
- McMaster Unbiased Galaxy Simulations 2 (MUGS2)
  - WMAP3 ΛCDM cosmology
  - GASOLINE N-body simulator
  - AMIGA halo finder
  - “Physically motivated, first principles model for treating feedback from supernovae”
- Measured rotation curves of simulated galaxies
  - Used DM particle velocities to calculate total angular momentum vector
  - Oriented galaxy such that angular momentum vector perpendicular to x-y plane
- For spatial resolution, divided into 100 annuli each 300 pc thick
- g_{obs}: sum up acceleration contributions from DM, gas, and star particles
- g_{bar}: sum up only contributions from gas and star particles
- Direct summation process identical to numerical solution of Poisson from McGaugh et al.

Results

- z=0 simulation datapoints in Hess diagram
- Solid line is the original relation from McGaugh et al.
- Dotted line is line of unity

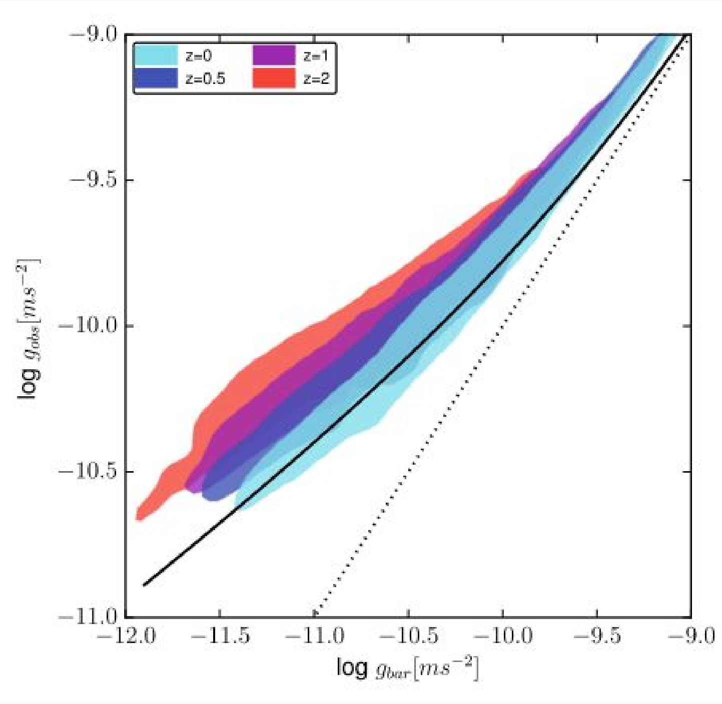
Surprising results:

- Simulations match the empirical relation **better** than the observational data!
- Uncertainty at 0.05 dex
  - Originally estimated at 0.06 dex, agrees!
- Sample of 1800 datapoints
  - ~⅔ sample size of McGaugh's ~2700 points
- Reduced χ^2=1.25



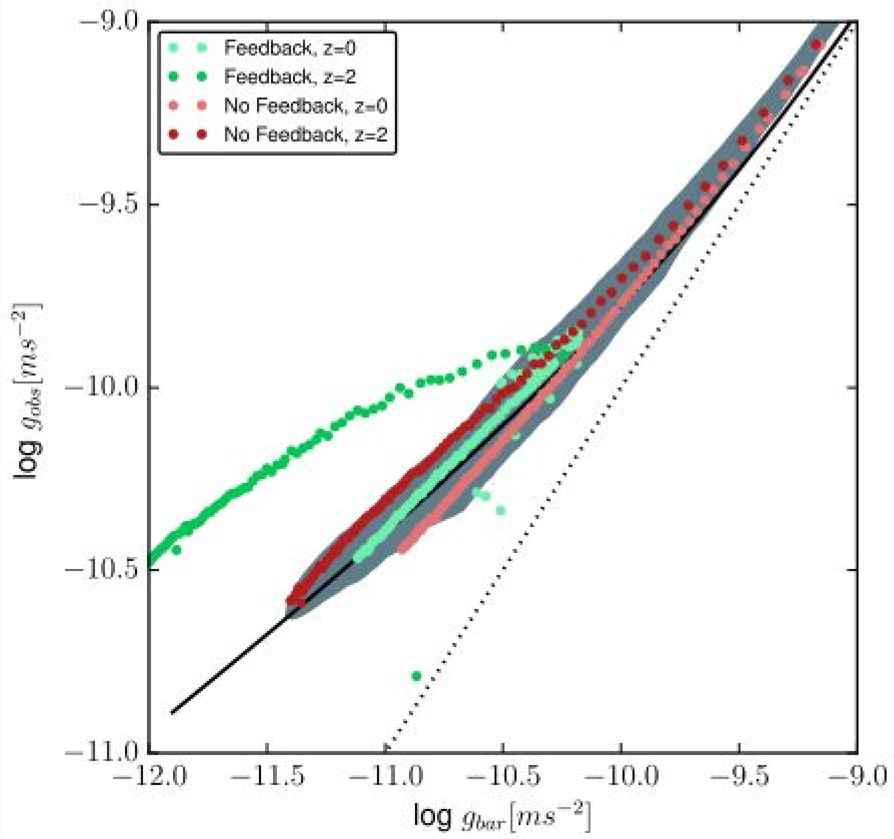
Discussion: No New Physics, Just ΛCDM Hard at Work

- If this relation was due to new, dark sector physics, should show no redshift dependence, because the physics would remain present through universe history
- Would expect redshift dependence if a result of galaxy evolution
- DM simulation snapshots of the same galaxy at different redshifts
  - Sizes scaled by scale factor to remain consistent
- Stellar feedback plays big role in galaxies at z~2
  - Supernovae: hot gas outflows
- z~2 galaxies depleted of baryons
  - Exactly demonstrated by results!



Discussion: Feedback?

- Simulate same galaxy with and without SNe feedback
- No feedback: no redshift dependence
  - Both z=0 and z=2 simulation fall within SPARC relation scatter
- Source of redshift dependence must clearly be SNe feedback
- No feedback, only simple dissipative collapse of gas is enough to reproduce SPARC relation



Conclusion

- MOND/SPARC radial acceleration relation can be explained through basic ΛCDM and dissipative gas collapse
- Relation does not hold for all redshifts, since simulations MUST include stellar feedback to accurately represent real galaxies
  - Vigorous feedback in high redshift galaxies flattens g_{obs}-g_{bar} relation
- For a universal radial acceleration relation:
  - Would need a fitting parameter $g_\dagger = g_\dagger(z)$
- **No need for dark sector physics or MOND, just DM!**

Needed:

- High z observational data to look at empirical g_{obs}-g_{bar} redshift dependence
- Hope to find redshift dependence as expected
  - If not, ΛCDM may need more work to be done!