EVALUATION OF THE RADIAL ACCELERATION RELATION IN ELLIPTICAL GALAXIES AND GALAXY CLUSTERS

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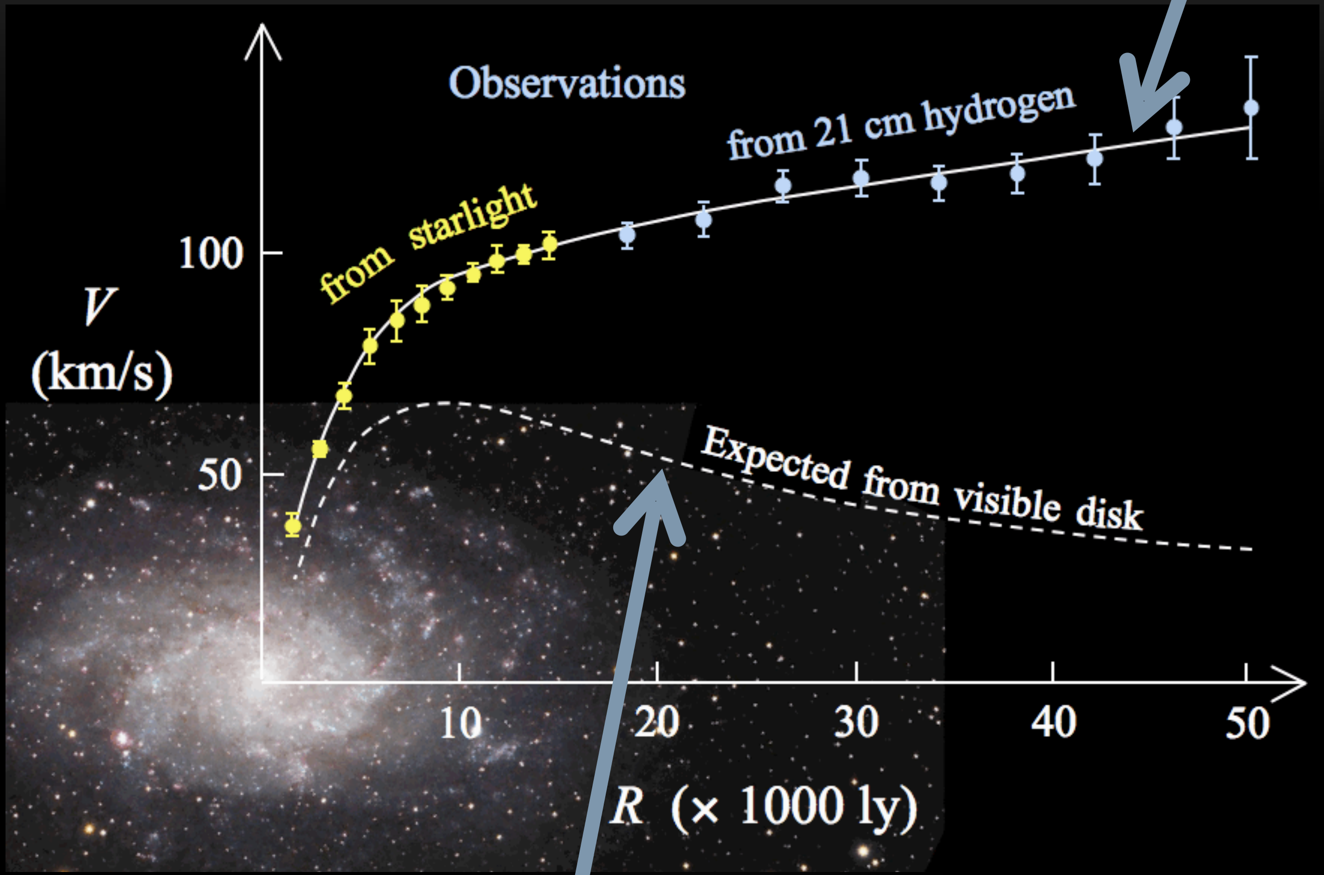
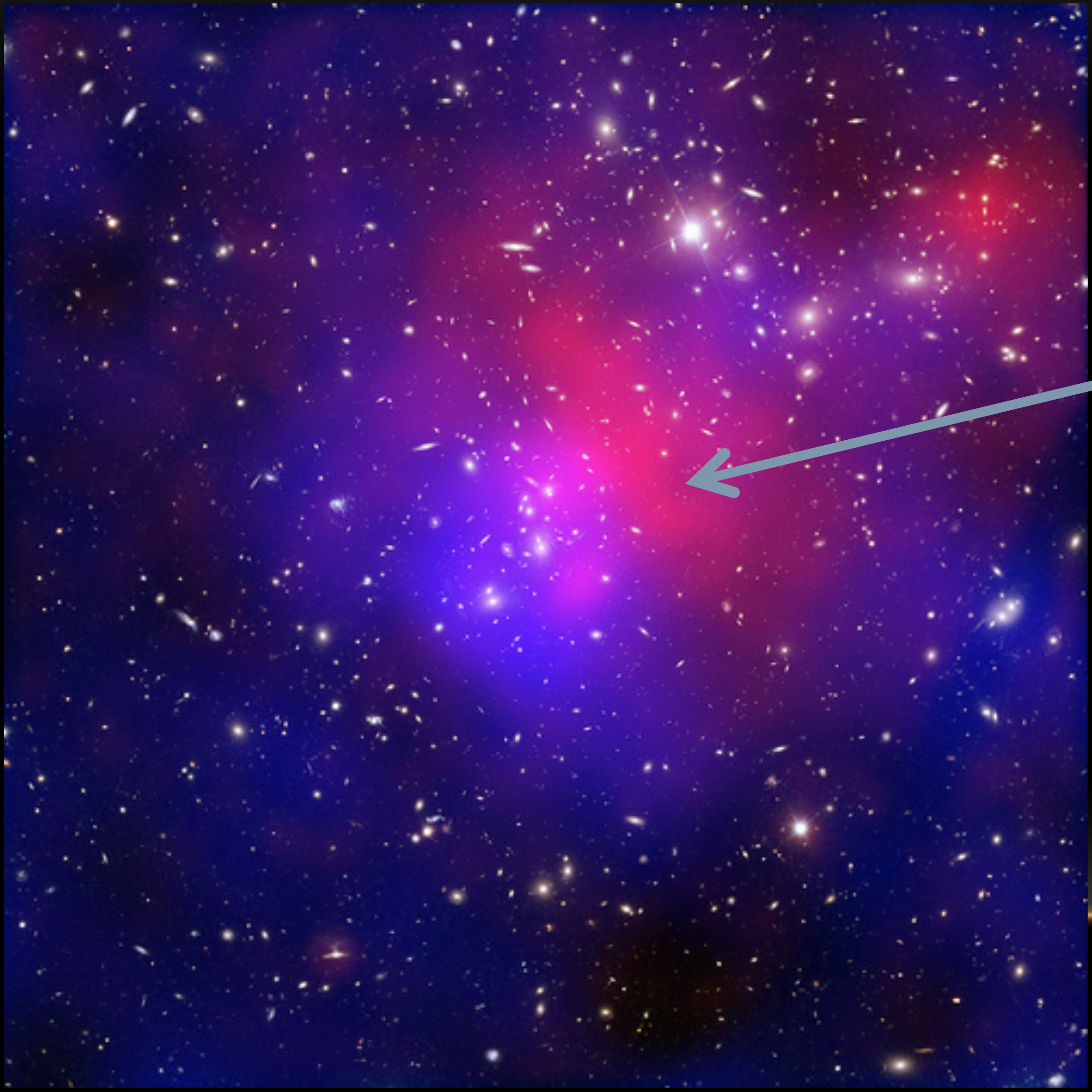
Observed rotation curve (flat)



Expected rotation curve from counting luminous mass (decaying)

$$v_{star} = \sqrt{\frac{GM_{star}}{r}}$$

DARK MATTER IN GALAXY CLUSTER

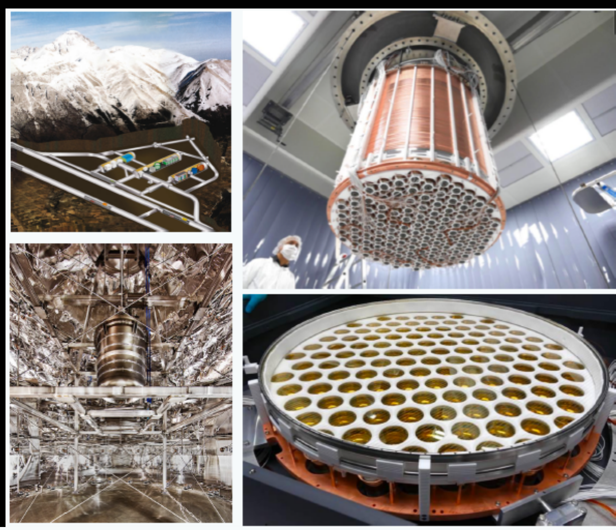


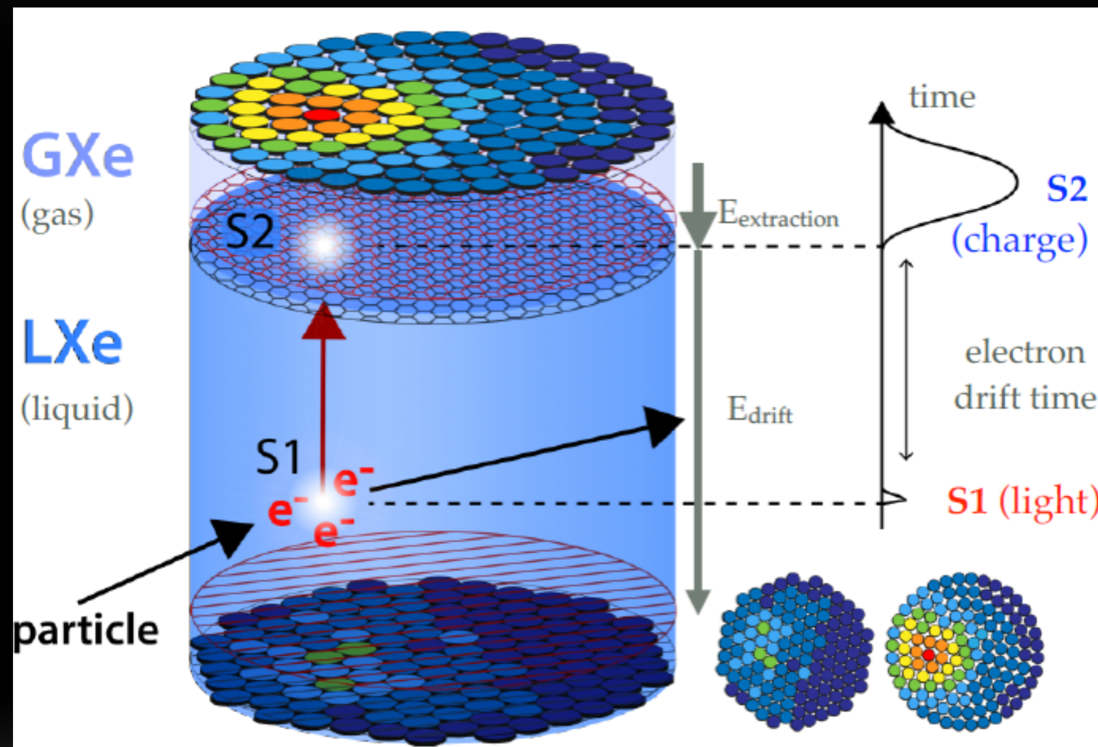
Hot gas in galaxy cluster(emit X-ray)

THE STANDARD COSMOLOGICAL MODEL

- Lambda-cold-dark-matter model (ΛCDM model)
- Dark matter exists
- Dark matter is "cold" – it becomes non-relativistic when it decouples from normal matter
- For cold dark matter, dark matter mass ~ MeV or above
- Cold dark matter is almost collisionless
- There should be no strong correlation between cold dark matter and baryonic matter

DIRECT-DETECTION EXPERIMENT

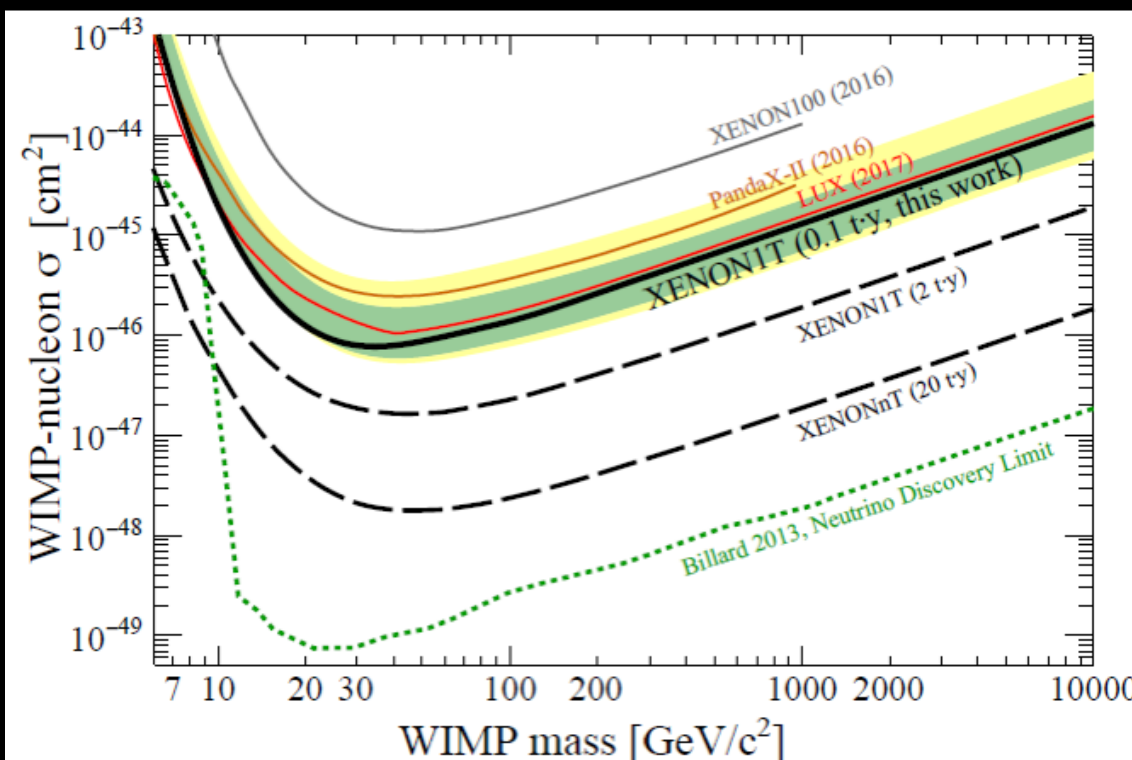


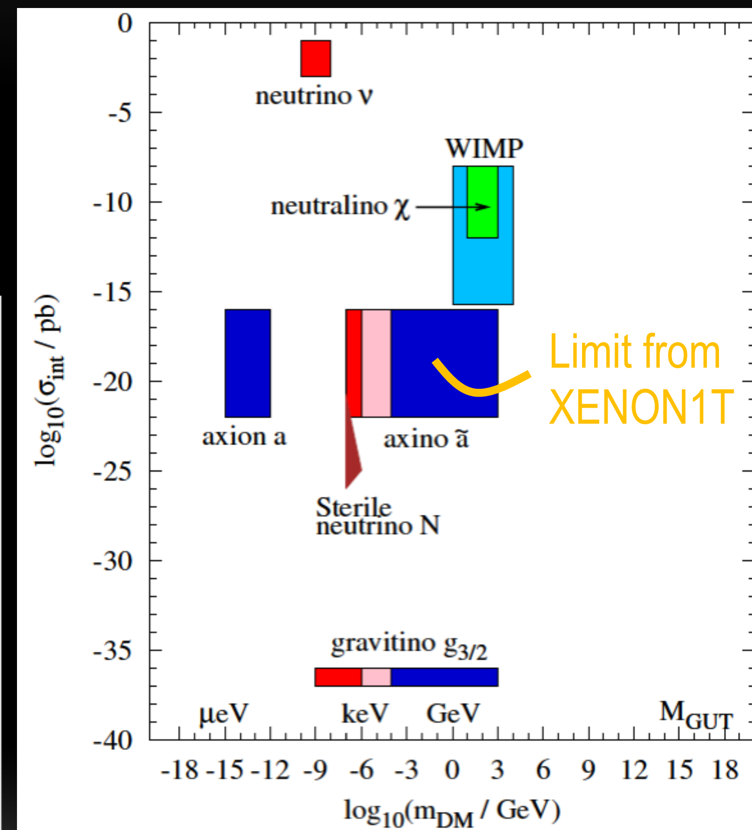


XENON1T experiment

PROBLEM OF DARK MATTER THEORY

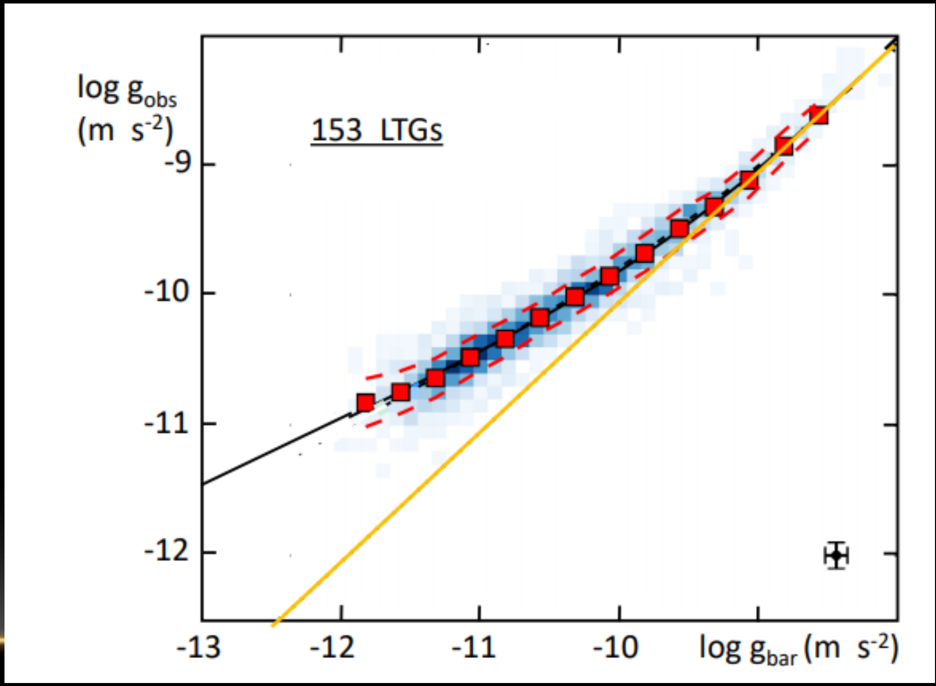
- No signal
- Great challenge to WIMP models





Credit: XENON1T; Roszkowski et al. (2018). Rept. Prog. Phys. 81, 066201

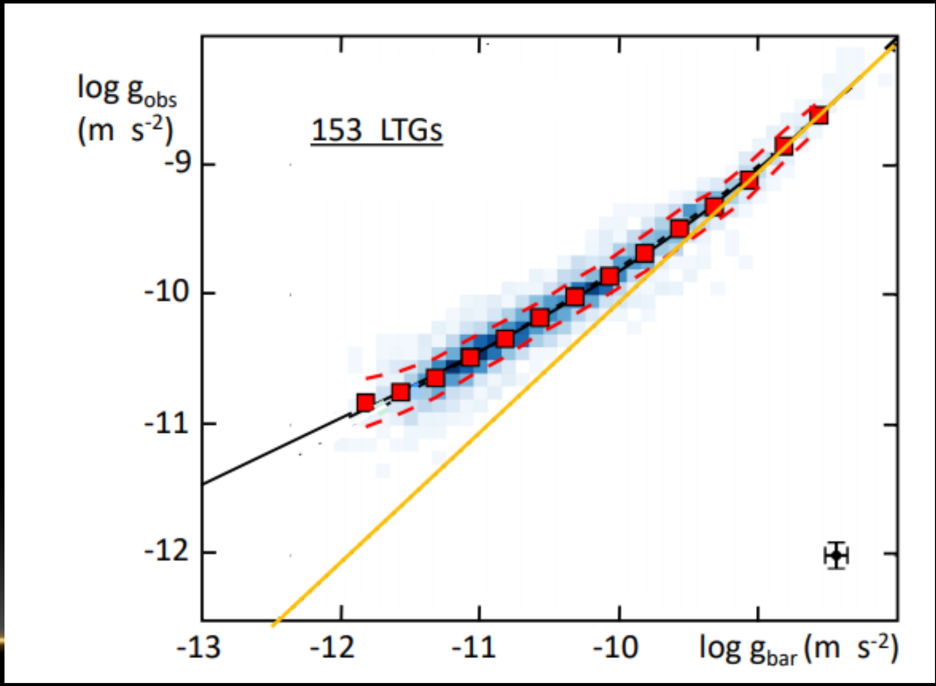
PROBLEM OF DARK MATTER THEORY



McGaugh & Lelli (2016). Phys. Rev. Lett. 117, 201101.

PROBLEM OF DARK MATTER THEORY

- Density profiles – not match!



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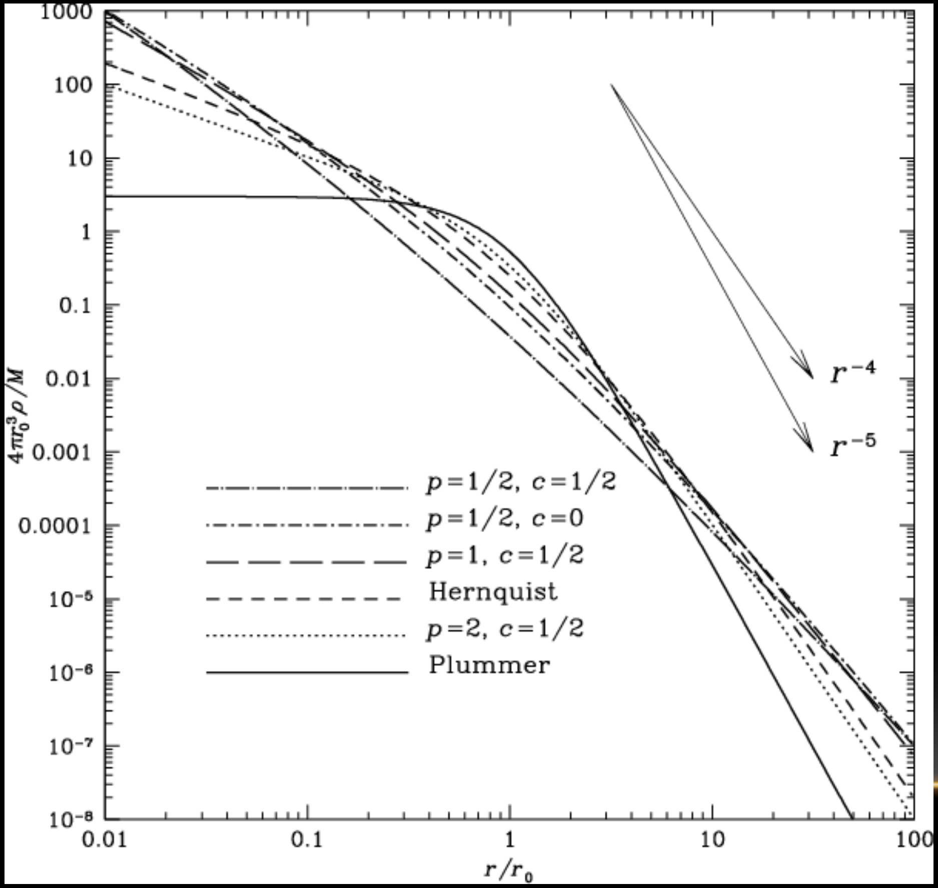

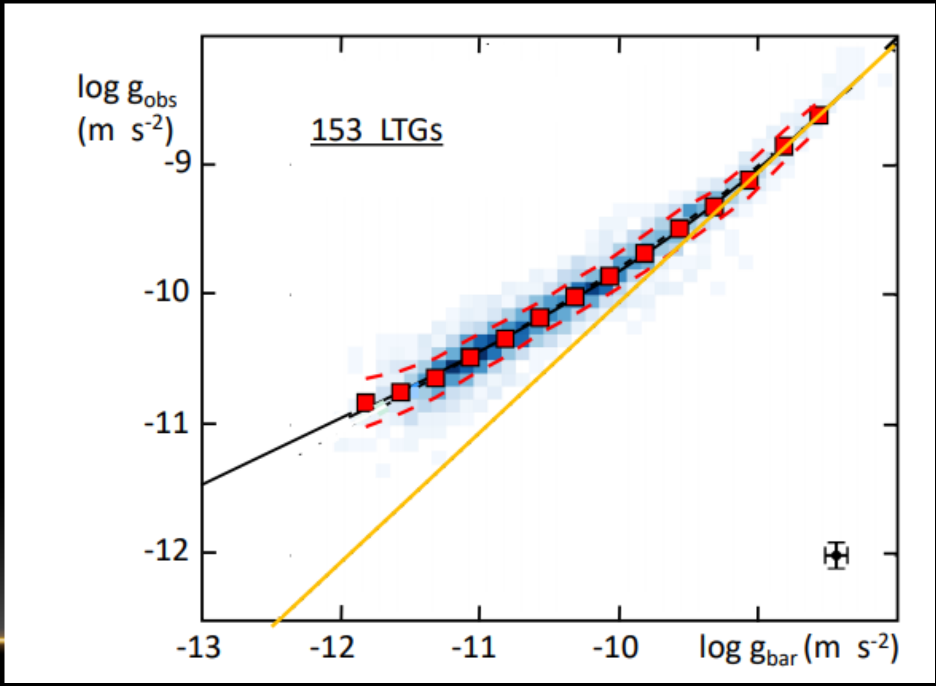

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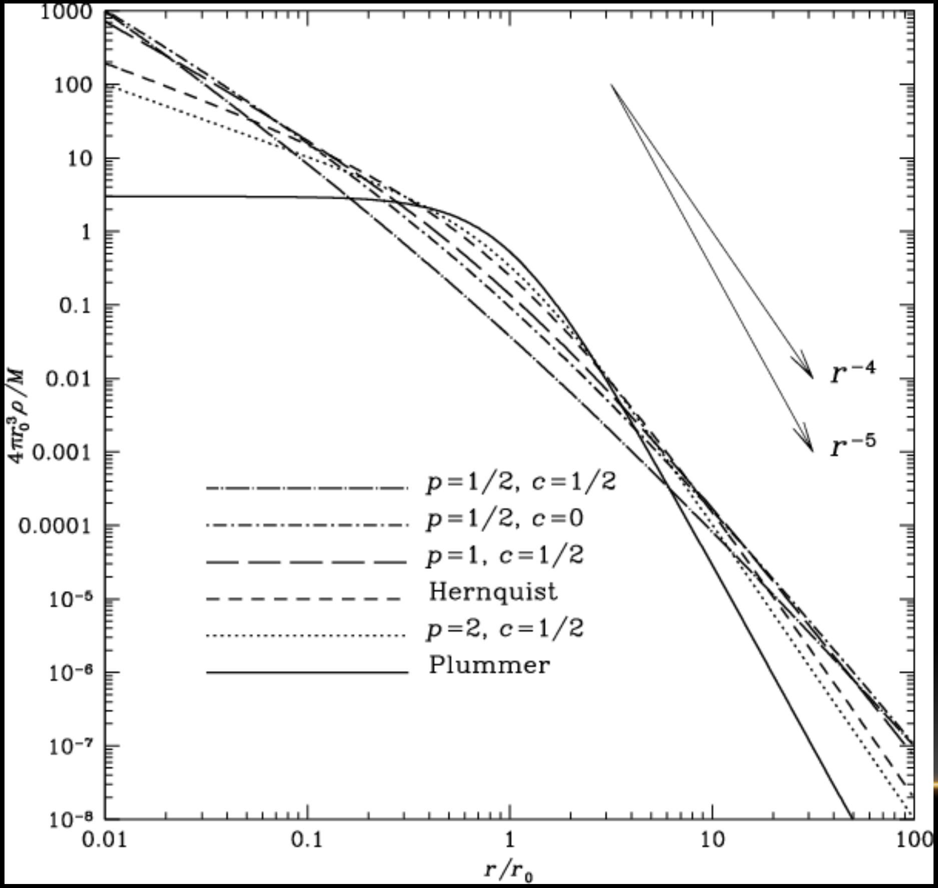
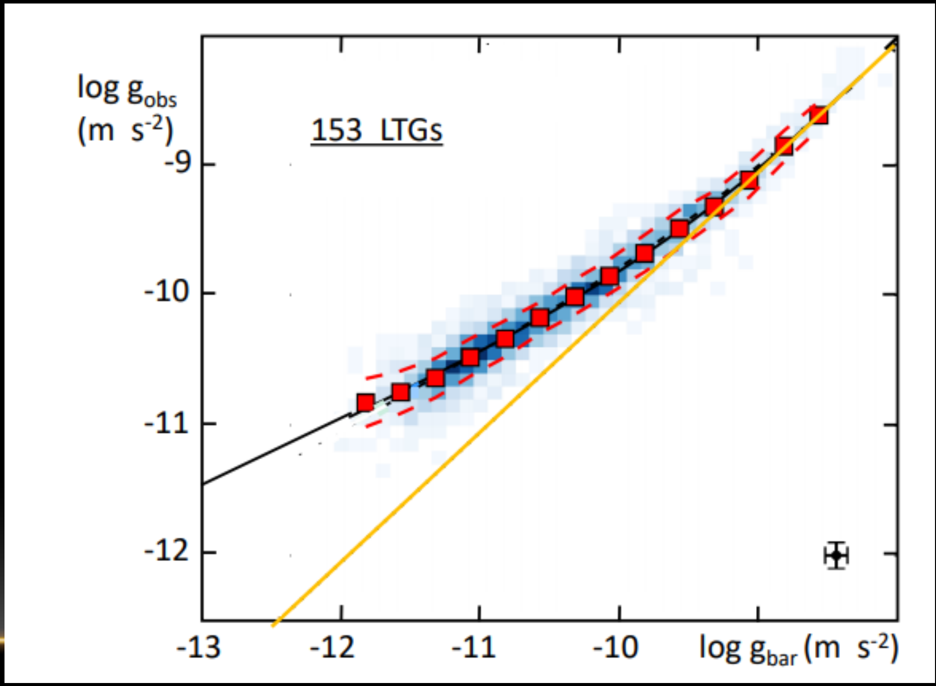


- The tight correlation: Radial Acceleration Relation



McGaugh & Lelli (2016). Phys. Rev. Lett. 117, 201101.

THE RADIAL ACCELERATION RELATION (RAR)

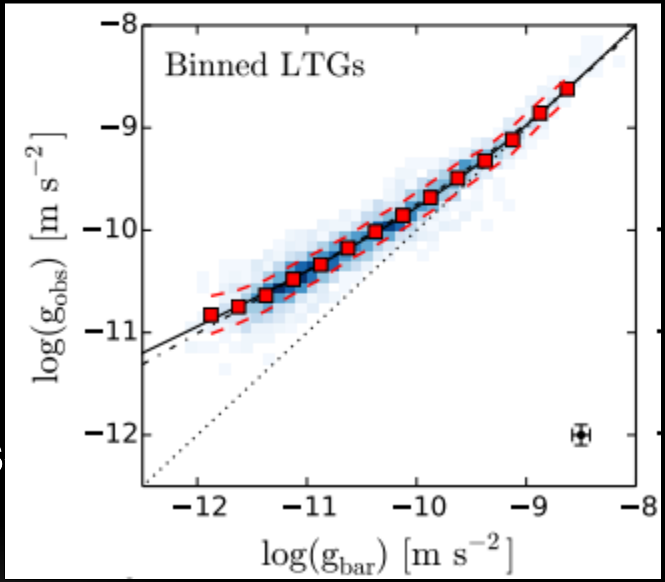
- There exists a strong correlation between the dynamical acceleration and baryonic acceleration in spiral galaxies (i.e. there is a strong correlation between dynamical mass and baryonic mass)

$$a_{dyn} = \frac{a_{bar}}{1 - e^{-\sqrt{\frac{a_{bar}}{a_0}}}}$$

$$a_{dyn} = \frac{v^2}{r}$$

$$a_{bar} = -\nabla\Phi_{bar}$$

$$a_0 = 1.20 \pm 0.02 \pm 0.04 \times 10^{-10} \text{ m/s}$$



Lelli et al. (2017), ApJ 836, 152.

CHARACTERISTICS OF THE RAR

- It has an acceleration scale a_0
- It is consistent with the Baryonic Tully-Fisher Relation
- It is generally consistent with the Modified Newtonian Dynamics (MOND)
- This has been viewed as a strong evidence of the MOND or some modified gravity theories

IS THE RAR UNIVERSAL?

- Some studies have questioned the existence of a fundamental acceleration scale (e.g. Rodrigues et al. (2018), Nature Astronomy 2, 668).
- If the RAR originates from modified gravity theories, it should be universal.
- There is a need to check the universality of the RAR or the acceleration scale.

THE RAR IN GALAXY CLUSTERS

- We performed an analysis to generate the RAR in a sample of galaxy clusters

$$a_{dyn} = \frac{GM_{dyn}}{r^2}$$

$$a_{bar} = \frac{GM_{bar}}{r^2}$$

- Under the hydrostatic equilibrium condition, we can connect a_{dyn} with a_{bar}:

$$\frac{dP}{dr} = -\frac{GM_{dyn}\rho_g}{r^2}$$

- The gas density is best-described by the beta model:

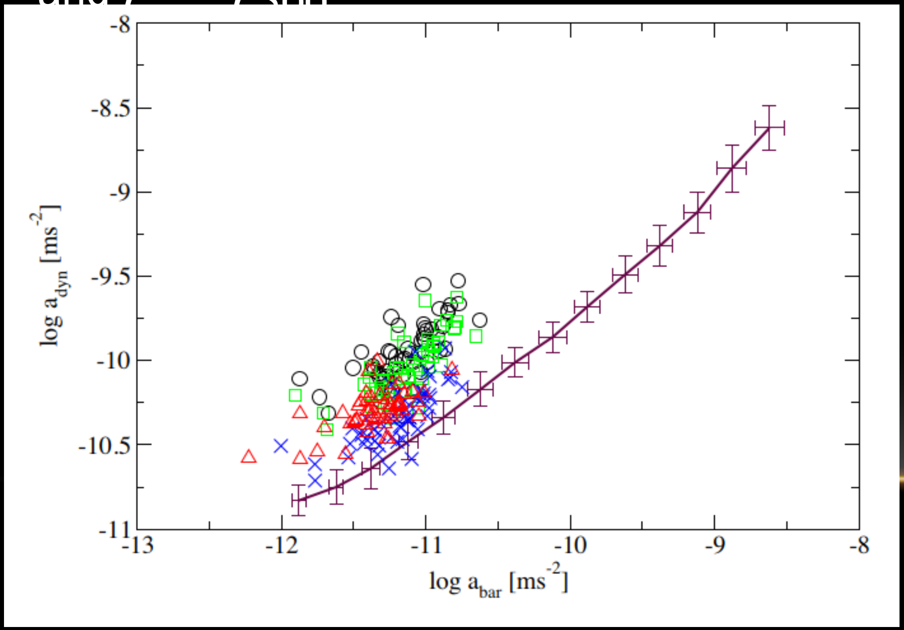
$$\rho_g = \rho_0 \left(1 + \frac{r^2}{r_c^2} \right)^{-3\beta/2}$$

THE RAR IN GALAXY CLUSTERS

- The baryonic acceleration can be calculated

$$a_{bar} = \frac{GM_{bar}}{r^2} = 4\pi G \int_0^r r^2 \rho_g dr$$

- We analyse the relation at four different positions: $r = r_c, r = 2r_c, r = 3r_c$ and $r = r_{500}$



Sample galaxy clusters:
HIFLUGCS galaxy cluster sample
52 non-cool-core clusters
Scale radius > 100 kpc

Chan and Del Popolo (2020), MNRAS, 492, 5865.

THE RAR IN GALAXY CLUSTERS

- The RAR in galaxy clusters is significantly different from the RAR in spiral galaxies
- The scatters are 0.18 dex (expected from uncertainties should be 0.13 dex) → not a tight relation!
- The best-fit acceleration scale is $a_0 = 9.5 \times 10^{-10}$ m/s², which is much greater than the one in the RAR in spiral galaxies
- Therefore, there is no clear RAR in galaxy clusters
- After a very short period of time, another group also obtained a similar result (Tian et al. 2020, ApJ 896, 70)

THE RAR IN GALAXY CLUSTERS

- We also investigate the potential analytic RAR for central region of galaxy clusters
- We use the same formalism, but we expand the baryonic mass expression in terms of the dynamical acceleration:

$$M_{gas} = \frac{4\pi m_g n_0 r^3}{3} \sum_{j=0}^{\infty} \frac{\left(\frac{3\beta}{2}\right)_j \left(\frac{3}{2}\right)_j}{\left(\frac{5}{2}\right)_j j!} \left(-\frac{r^2}{r_c^2}\right)^j$$

$$(x)_j = \frac{\Gamma(x+j)}{\Gamma(x)} = x(x+1)\ldots(x+j-1)$$

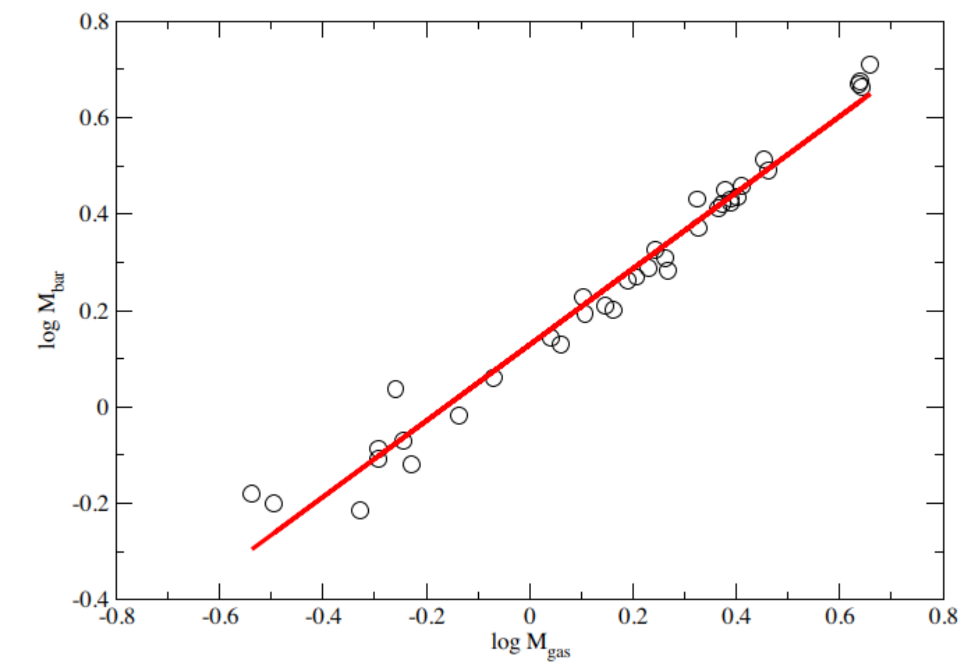
- We expand the series for small r ($r \leq r_c$):

$$a_{gas} = 4\pi G m_g n_0 r_c \left[\frac{1}{6}y + \left(\frac{1}{24} - \frac{1}{80}\beta\right)y^3 + \left(\frac{1}{48} - \frac{111}{4480}\beta + \frac{9}{1792}\beta^2\right)y^5 + O(y^7)\right]$$

with $y = \frac{a_{dyn}}{a_{max}} = \frac{2\mu m_p r_c}{3\beta kT} a_{dyn}$

THE RAR IN GALAXY CLUSTERS

- We can also include the contribution of the stellar mass in galaxy clusters (stellar mass is significant for the central region)
- There is a correlation between the hot gas mass and the stellar mass:



THE RAR IN GALAXY CLUSTERS

- Including the stellar mass, we can obtain a more precise analytic RAR relation for central region of galaxy clusters:

$$a_{bar} = a_b\left[2.4y^{0.37} + \left(0.22 - 0.14\beta\right)y^{2.37} + \left(0.093 - 0.26\beta + 0.056\beta^2\right)y^{4.37}\right]$$

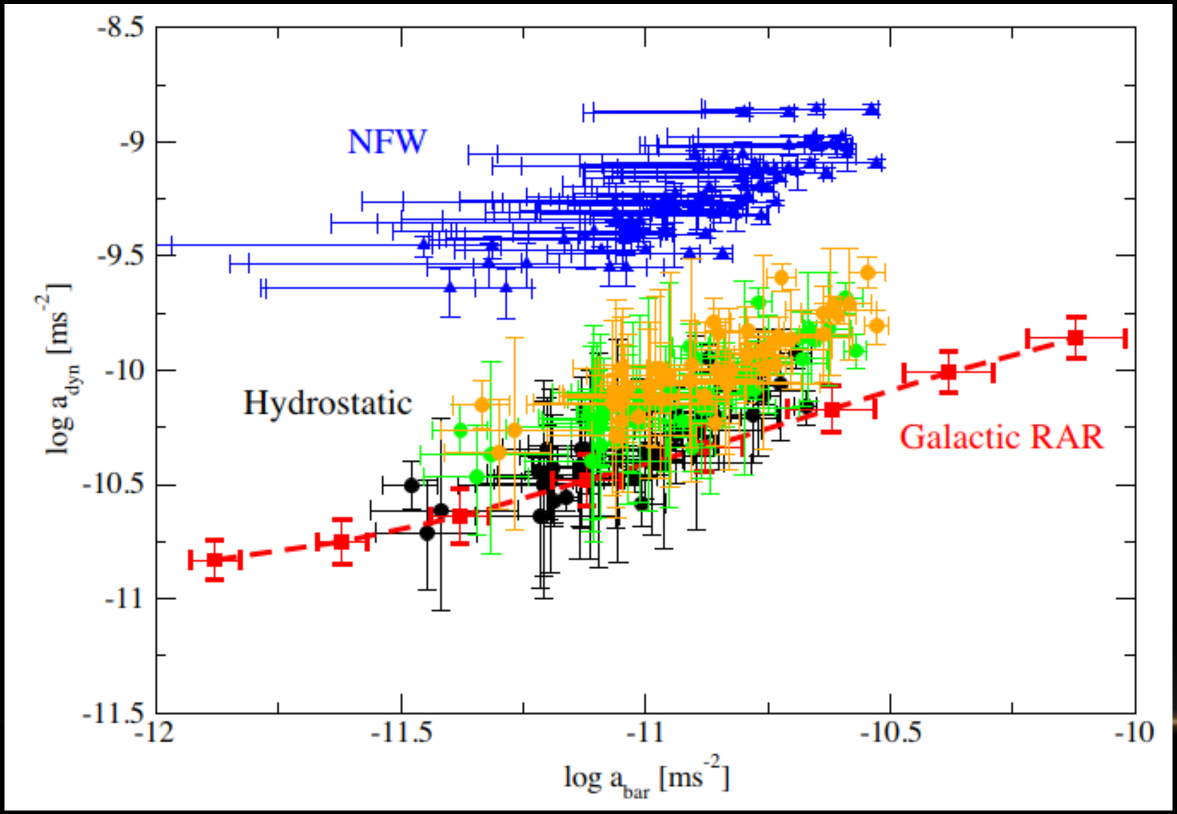
$$a_b = 1.35G\left(10^{13}M_\odot\right)^{0.2}\left(m_g n_0 r_c^3\right)^{0.8}/r_c^2$$

$$y = \frac{a_{dyn}}{a_{max}} = \frac{2\mu m_p r_c}{3\beta kT}a_{dyn}$$

- The scatter of a_b is very large. Therefore, the RAR in galaxy clusters is also very large.

THE RAR IN GALAXY CLUSTERS

- We do the same trick for the NFW profile.
- Clearly, the functional forms deviate from the RAR in spiral galaxies



52 non-cool-core clusters with scale radius > 100 kpc

Chan and Law (2022), Phys. Rev. D, 105, 083003.

THE RAR IN E0 ELLIPTICAL GALAXIES

- E0 elliptical galaxies are significantly different from the spiral galaxies (e.g. morphology)
- Most of the E0 elliptical galaxies are slow rotators (spiral galaxies are fast rotators)
- Testing the RAR in E0 elliptical galaxies is useful
- Previous studies have included only a small portion of E0 elliptical galaxies

THE RAR IN E0 ELLIPTICAL GALAXIES

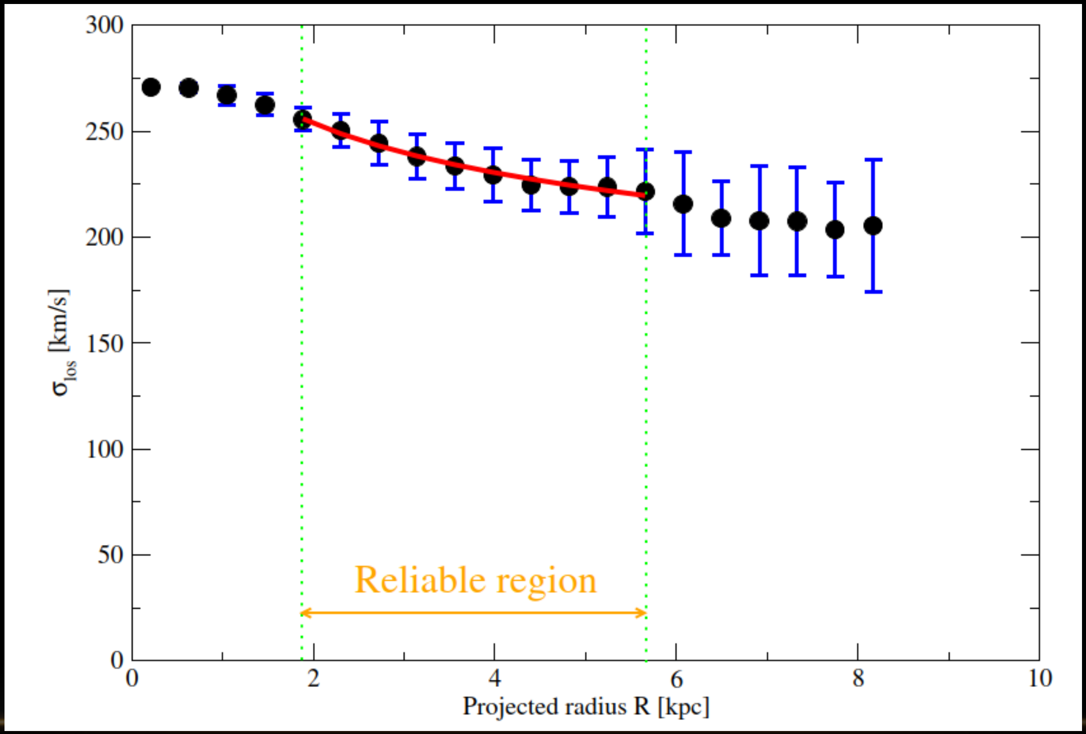
- A previous study has examined the RAR in E0 elliptical galaxies (Chae et al. 2020, ApJ 903, L31)
- However, they have assumed the MOND interpolating function to connect the dynamical acceleration and baryonic acceleration in their analysis
- This assumption would give selection bias
- We propose to use Jeans analysis to re-perform the investigation

THE RAR IN E0 ELLIPTICAL GALAXIES

- Sample galaxies: MaNGA (Aguado et al. 2019, ApJS 240, 23)
- There are 13 good E0 galaxies for analysis
- We transform the line-of-sight velocity dispersion maps into the line-of-sight velocity dispersion profile $\sigma_{los}(R)$ for each galaxy
- We take the azimuthal averaging of the velocity dispersion in concentric bins with a constant bin width 0.5”
- We discard the data with R < 2” and the data with signal-to-noise ratio < 10

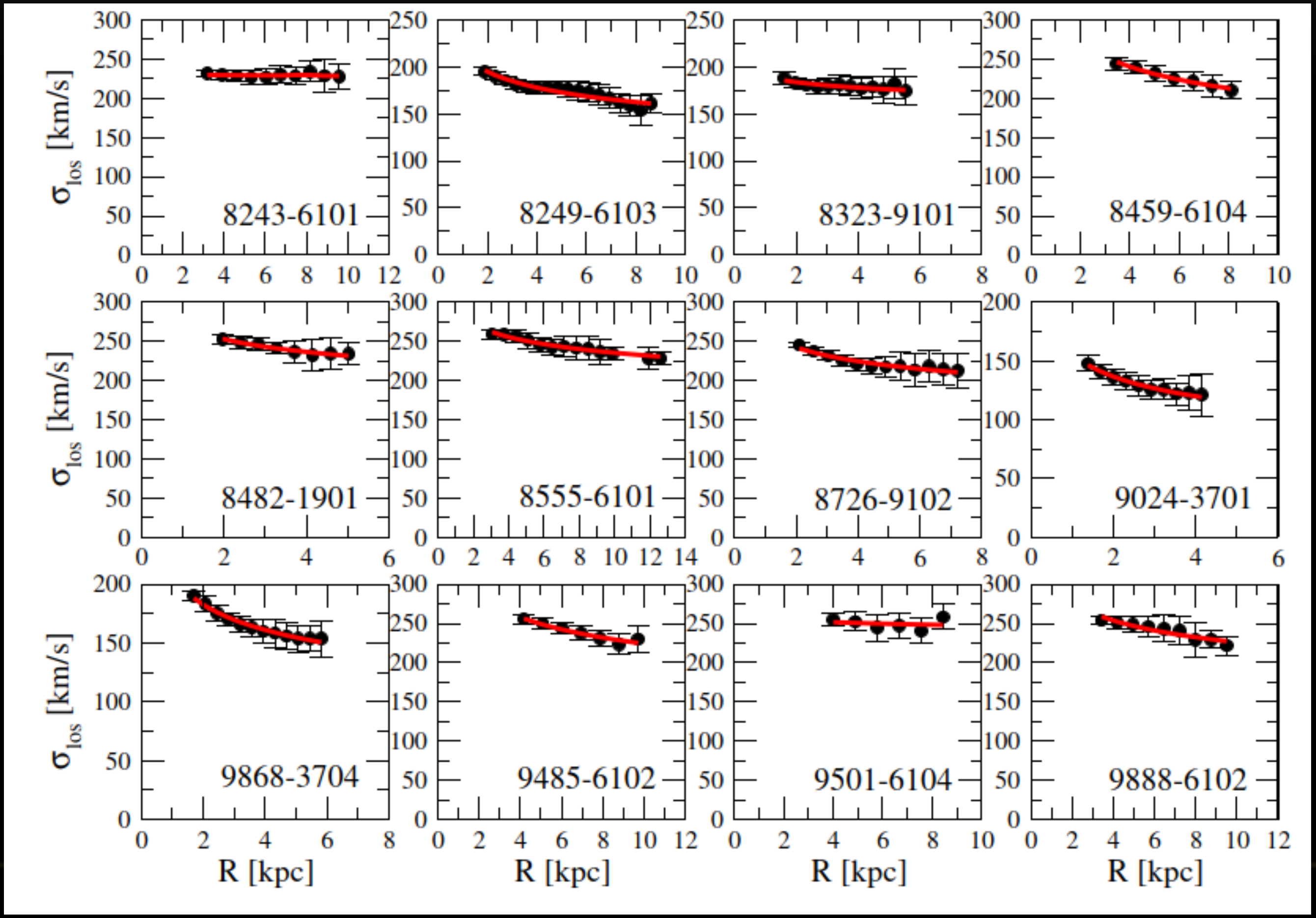
THE RAR IN E0 ELLIPTICAL GALAXIES

- The line-of-sight velocity dispersion profiles can be well fitted by a power law function $\sigma_{los} = \sigma_0{}' R^{-\gamma}$



9047-6102 galaxy

THE RAR IN E0 ELLIPTICAL GALAXIES



THE RAR IN E0 ELLIPTICAL GALAXIES

- We assume that the 3-D velocity dispersion can also be expressed in terms of a power-law

$$\sigma(r) = \sigma_0 \left(\frac{r}{r_a} \right)^{-\alpha}$$

- The relation between the 3-D velocity dispersion and the line-of-sight velocity dispersion is given by

$$\sigma_{los}^2(R) = \frac{2}{\Sigma(R)} \int_R^\infty \left(1 - \beta \frac{R^2}{r^2} \right) \frac{\sigma^2(r)\rho(r)}{\sqrt{r^2 - R^2}} r dr$$

- The surface mass density profile is written as

$$\Sigma(R) = I_0 e^{-b_n \left[\left(\frac{R}{R_e} \right)^{\frac{1}{n}} - 1 \right]} \times \Upsilon(R)$$

where

$$\Upsilon(R) = \Upsilon_0 \times \max \left\{ 1 + K \left[2.33 - 3 \left(\frac{R}{R_e} \right) \right], 1 \right\}$$

THE RAR IN E0 ELLIPTICAL GALAXIES

- The 3-D stellar mass profile is given by

$$\rho(r) = -\frac{1}{\pi}\int_0^\infty \frac{d\Sigma(R)}{dR}\frac{dR}{\sqrt{R^2 - r^2}}$$

- The anisotropy parameter is given by (Chae et al. 2020):

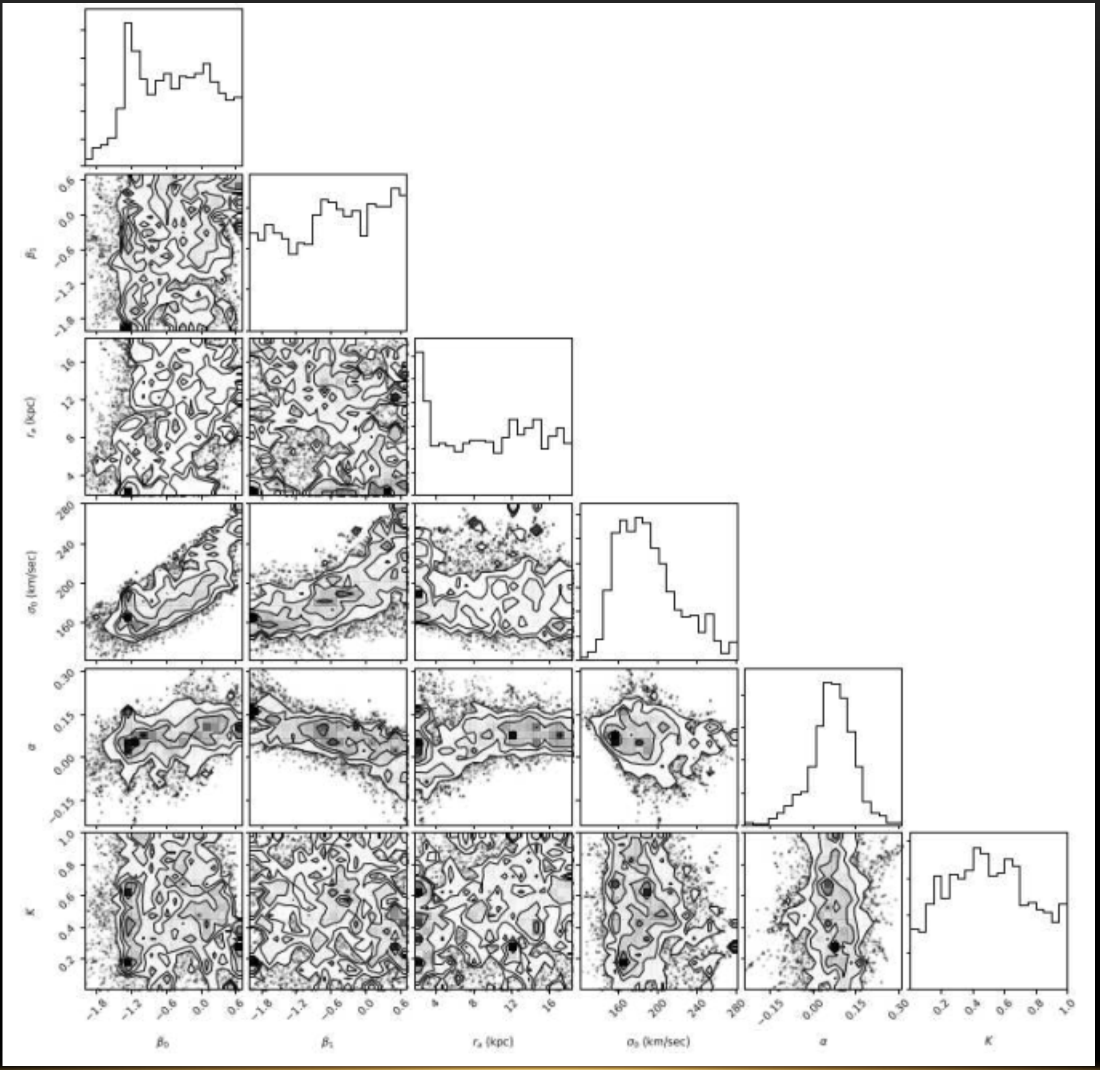
$$\beta(r) = \beta_0 + (\beta_1 - \beta_0)\frac{\left(\frac{r}{r_a}\right)^2}{1 + \left(\frac{r}{r_a}\right)^2}$$

- Therefore, altogether there are 6 independent parameters $\{K, \beta_0, \beta_1, r_a, \sigma_0, \alpha\}$ involved in the fitting of the observed $\sigma_{los}(R)$

THE RAR IN E0 ELLIPTICAL GALAXIES

- We perform the MCMC analysis, using the emcee sampler (Foreman-Mackey et al. 2013)
- We set the following priors: $K = [0,1]$, $\beta_0 = [-2, +0.7]$, $\beta_1 = [-2, +0.7]$, $r_a = [0.1R_e, R_e]$, $\sigma_0 = [50,400]$ km/s, $\alpha = [-1, +1]$

Galaxy	K	β_0	β_1	r_a (kpc)	σ_0 (km/s)	α
8243-6101	$0.479^{+0.084}_{-0.163}$	$-0.295^{+0.218}_{-0.402}$	$-0.429^{+0.445}_{-0.791}$	$11.04^{+1.82}_{-1.94}$	$193.93^{+18.50}_{-12.40}$	$0.032^{+0.108}_{-0.084}$
8249-6103	$0.510^{+0.339}_{-0.334}$	$-0.571^{+0.826}_{-0.876}$	$-0.870^{+1.036}_{-0.768}$	$4.98^{+2.62}_{-2.52}$	$144.26^{+16.23}_{-16.12}$	$0.088^{+0.125}_{-0.124}$
8323-9101	$0.584^{+0.327}_{-0.383}$	$-0.075^{+0.618}_{-1.548}$	$-0.514^{+0.863}_{-0.929}$	$4.34^{+5.31}_{-1.73}$	$158.58^{+36.68}_{-28.75}$	$-0.050^{+0.138}_{-0.086}$
8459-6104	$0.517^{+0.334}_{-0.346}$	$-0.642^{+0.919}_{-0.849}$	$-0.711^{+0.922}_{-0.897}$	$4.92^{+3.23}_{-2.71}$	$197.06^{+32.34}_{-25.22}$	$0.17^{+0.12}_{-0.14}$
8482-1901	$0.395^{+0.315}_{-0.271}$	$-0.681^{+0.809}_{-0.774}$	$-0.890^{+1.053}_{-0.723}$	$14.19^{+6.78}_{-9.90}$	$192.85^{+44.48}_{-23.77}$	$0.020^{+0.103}_{-0.080}$
8555-6101	$0.496^{+0.292}_{-0.324}$	$-0.594^{+0.562}_{-0.775}$	$-0.553^{+0.783}_{-1.033}$	$6.17^{+3.80}_{-3.65}$	$206.64^{+36.09}_{-22.61}$	$0.063^{+0.090}_{-0.085}$
8726-9102	$0.488^{+0.306}_{-0.287}$	$-0.497^{+0.747}_{-0.726}$	$0.520^{+0.864}_{-0.990}$	$9.82^{+5.73}_{-6.70}$	$185.34^{+38.18}_{-26.08}$	$0.072^{+0.063}_{-0.071}$
9024-3701	$0.393^{+0.402}_{-0.285}$	$-0.368^{+0.704}_{-0.803}$	$-0.421^{+0.618}_{-0.879}$	$2.60^{+1.32}_{-1.54}$	$103.70^{+16.85}_{-12.84}$	$0.030^{+0.142}_{-0.129}$
9047-6102	$0.543^{+0.319}_{-0.340}$	$-0.074^{+0.501}_{-0.590}$	$-0.269^{+0.660}_{-1.008}$	$6.14^{+4.95}_{-2.93}$	$209.39^{+27.37}_{-28.94}$	$0.084^{+0.130}_{-0.084}$
9485-6102	$0.530^{+0.288}_{-0.346}$	$-0.276^{+0.689}_{-1.160}$	$-0.910^{+0.953}_{-0.692}$	$6.82^{+3.87}_{-3.32}$	$201.50^{+39.44}_{-21.85}$	$0.166^{+0.168}_{-0.115}$
9501-6104	$0.423^{+0.372}_{-0.306}$	$-0.192^{+0.693}_{-1.242}$	$-0.774^{+1.081}_{-0.928}$	$8.18^{+5.39}_{-4.69}$	$218.34^{+54.69}_{-37.13}$	$0.059^{+0.125}_{-0.127}$
9868-3704	$0.329^{+0.283}_{-0.221}$	$-0.507^{+0.946}_{-0.748}$	$-0.417^{+0.724}_{-0.836}$	$2.95^{+2.27}_{-1.58}$	$140.97^{+30.13}_{-16.42}$	$0.102^{+0.099}_{-0.122}$
9888-6102	$0.478^{+0.351}_{-0.310}$	$-0.426^{+0.891}_{-0.961}$	$-1.131^{+0.739}_{-0.585}$	$5.52^{+2.75}_{-2.90}$	$201.06^{+31.32}_{-25.05}$	$0.148^{+0.132}_{-0.099}$



Corner plot of the 8726-9102 galaxy

THE RAR IN E0 ELLIPTICAL GALAXIES

- After getting the parameters, we can calculate the dynamical acceleration by the Jeans equation:

$$a_{dyn} = \frac{\sigma_r^2}{r}(\gamma_* + \gamma_\sigma - 2\beta)$$

where $\gamma_* = -\frac{d\ln\rho}{d\ln r}$ and $\gamma_\sigma = -\frac{d\ln\sigma_r^2}{d\ln r} = 2\alpha$.

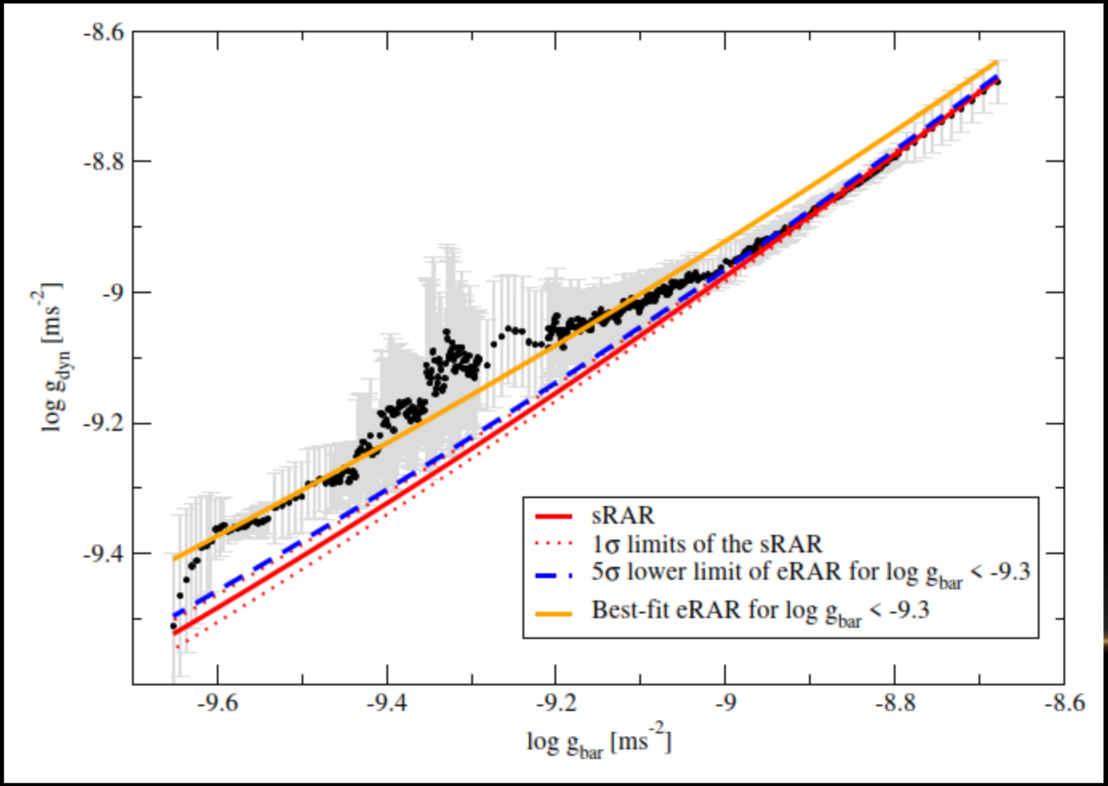
- We also calculate the baryonic acceleration:

$$a_{bar} = \frac{GM_{bar}}{r^2} = \frac{G}{r^2}\int_0^r 4\pi r'^2 \rho(r')dr'$$

- We maximize the likelihood between the observed RAR in spiral galaxies and the RAR in E0 elliptical galaxies to get the values of $\Upsilon_0 I_0$. In fact, the likelihood would be maximized when $a_{dyn} = a_{bar}$ (baryonic matter dominated)

THE RAR IN E0 ELLIPTICAL GALAXIES

- We mainly compare the RAR in E0 galaxies and the RAR in spiral galaxies for $\log a_{bar} < -9.3$ (baryonic matter no longer dominated)
- More than 5σ deviation between the two RARs



The RAR in E0 galaxies is different from the RAR in spiral galaxies

Chan, Desai & Del Popolo, in prep.

CONCLUSION

- The RAR is unlikely to be universal in galaxies as there is a large deviation between the RAR in spiral galaxies and the RAR in elliptical galaxies
- The RAR in galaxy clusters has large scatters and is different from the RAR in spiral galaxies
- There is no universal acceleration scale
- The RAR in spiral galaxies might be just an emergent phenomenon only (some CDM model can reproduce the RAR, e.g. arXiv:2102.13116).

Q&A!

Thanks!