mass discrepancy and acceleration in galaxies

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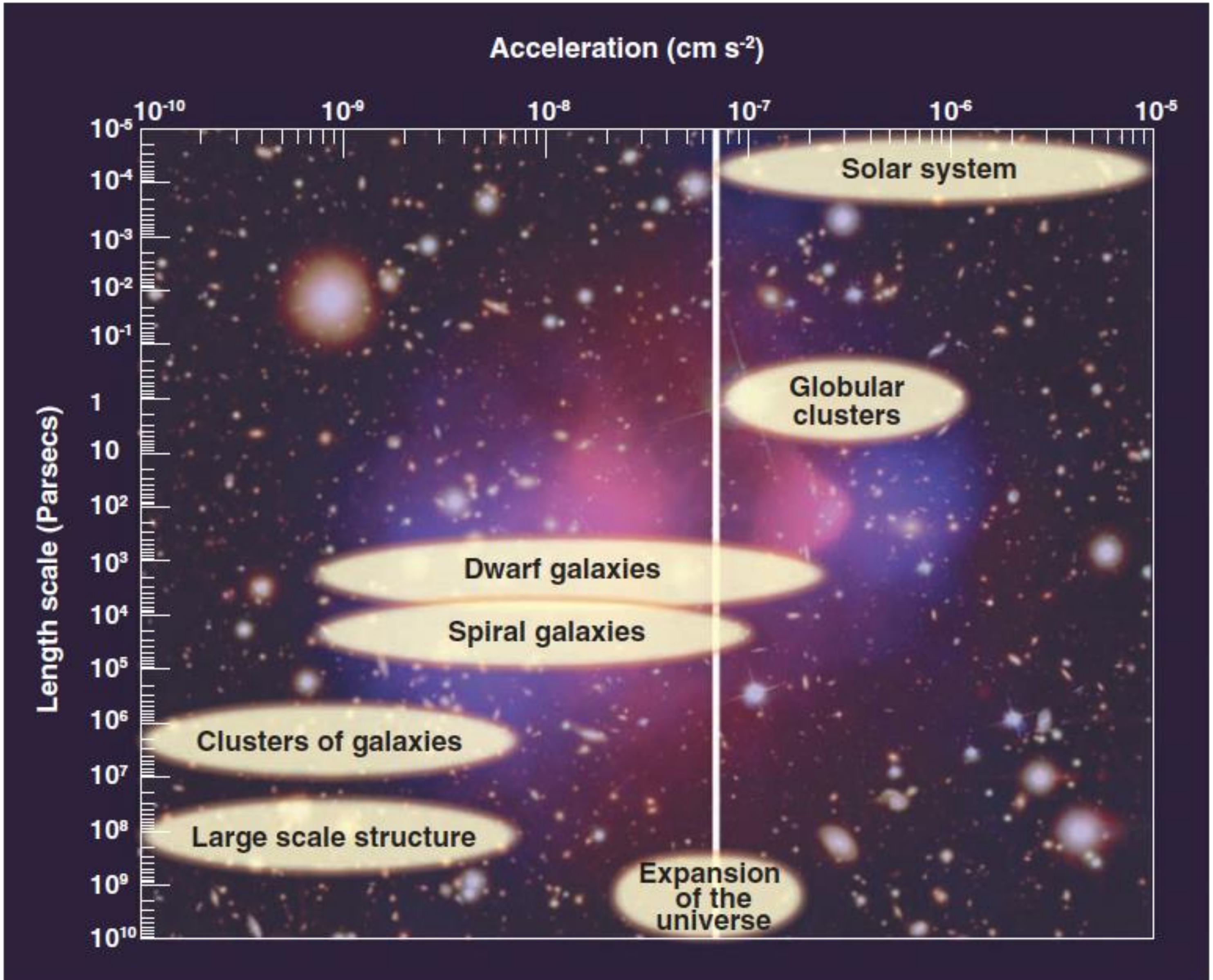
a discussion on

- mass and acceleration
- mass discrepancy
- relations
- interpretations?

mass and acceleration



Ferreira & Starkman (2009)

(Newtonian) dynamics

- cause and effect

$$m_{\rm g}\mathbf{g} = \mathbf{F} = m_{\rm I}\mathbf{a}$$

gravitational field, where the object is submerged

acceleration, response of the object

- equivalence principle

$$m_{\rm g} = m_{\rm I} = m$$

mass of the object or test particle

mass

- dynamical mass
  - observe motion then infer mass
  - direct (if we know the dynamics)
- luminous mass
  - observe luminosity then infer mass
  - indirect (sometimes involve many physics)
  - ideally, calibrate with dynamical mass (if we believe the dynamics)

acceleration

- acceleration of object
  - measured by its motion
- gravitational field or acceleration
  - from the distribution of matter and a theory of gravity
  - if light traces matter, then distribution of matter can be deduced from brightness distribution

what if they don't agree? $\boxed{\mathrm{g} \neq \mathrm{a}}$

- under Newtonian gravity and Newtonian dynamics
- dynamical mass is often larger than luminous mass
- acceleration is often larger than gravitational field (by luminous matter)
- excess acceleration unaccounted for

what if they don't agree? $\boxed{\mathrm{g} \neq \mathrm{a}}$

- some matters are not luminous $\mathrm{g} = \mathrm{a}$?
  - what are they? light is not a good tracer of mass? more physics is needed?
- gravity theory is not what we expected $\mathrm{g} = \mathrm{a}$?
  - modified gravity?
- law of motion is not what we expected $\mathrm{g} = \mathrm{a}$?
  - what to do?

mass discrepancy

minute discrepancy

- existence of Neptune
  - confirmation of dynamical mass by luminous mass (seeing is believing?)
  - successful story of missing mass
- exoplanets
  - believing even not seeing
- perihelion of Mercury
  - Einstein’s general relativity
  - successful story for modified gravity

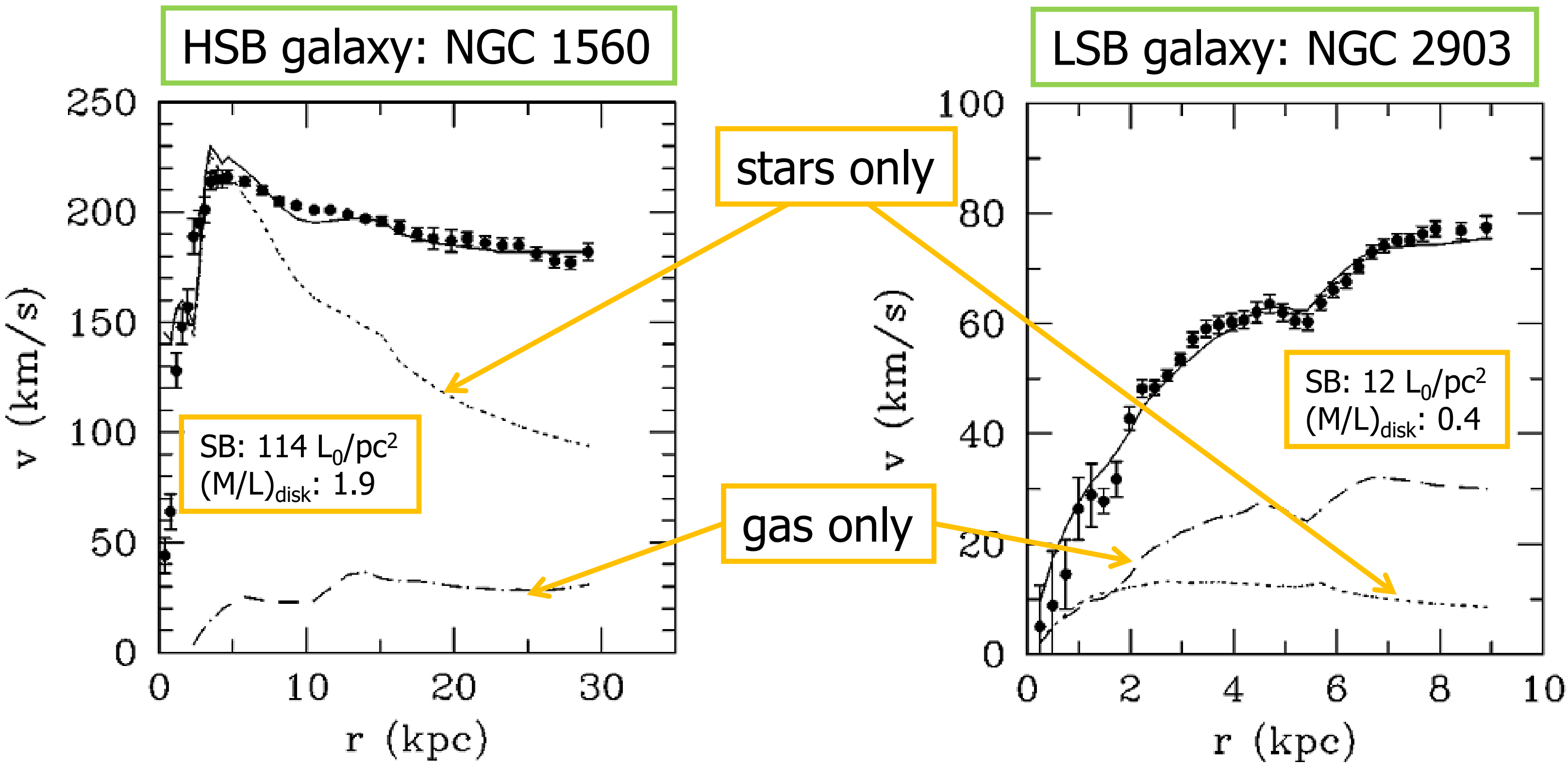
large discrepancy (O(1) or more)

- Oort (1932): acceleration of stars perpendicular to Galactic disk
- Zwicky (1933): radial velocity of galaxies in Coma cluster
- Babcock (1939), Mayall (1951): rotation curve of M31
- Kahn & Woltjer (1959): M31 approaches Milky Way against expansion of universe

large discrepancy (O(1) or more)

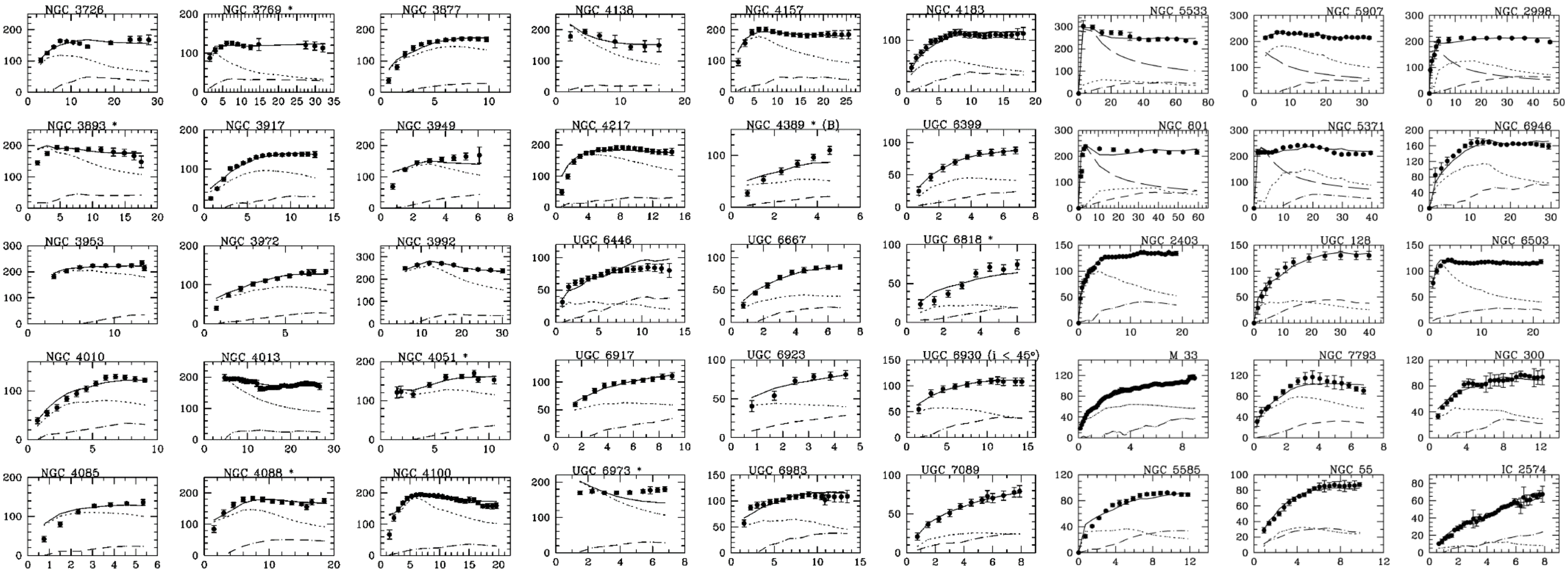
- Rogstad & Shostak (1972): rotation curve beyond optical disk of spirals from 21 cm
- Rubin et al. (1980): rotation curve of optical disk of spirals
- …
- proper motion of stars near galactic centre (Eckart & Genzel 1997, Ghez et al. 1998)
- …

rotation curve of spirals



Sanders & McGaugh (2002)

many more rotation curves



Sanders & McGaugh (2002)

relations

mass and acc discrepancy

- mass and acceleration discrepancy
  - the ratio between “observed” quantity to the “deduced” quantity (“total” to “baryon”?)
  - “observed” refers to dynamical mass and the corresponding acceleration
  - “deduced” refers to luminous mass and the inferred acceleration

spiral galaxies

$\boxed{\text{cold disc}}$ $$\frac{v_{\mathrm{c}}^2}{r} = g = \frac{Gm}{r^2}$$

- rotationally supported systems
  - dynamics relatively simple
- dynamical mass (“total” matter)
  - circular velocity of stars (or other entities)
  - related in a simple way to the gravitational acceleration at that radius
  - gravitational acceleration is given by the mass enclosed within that radius

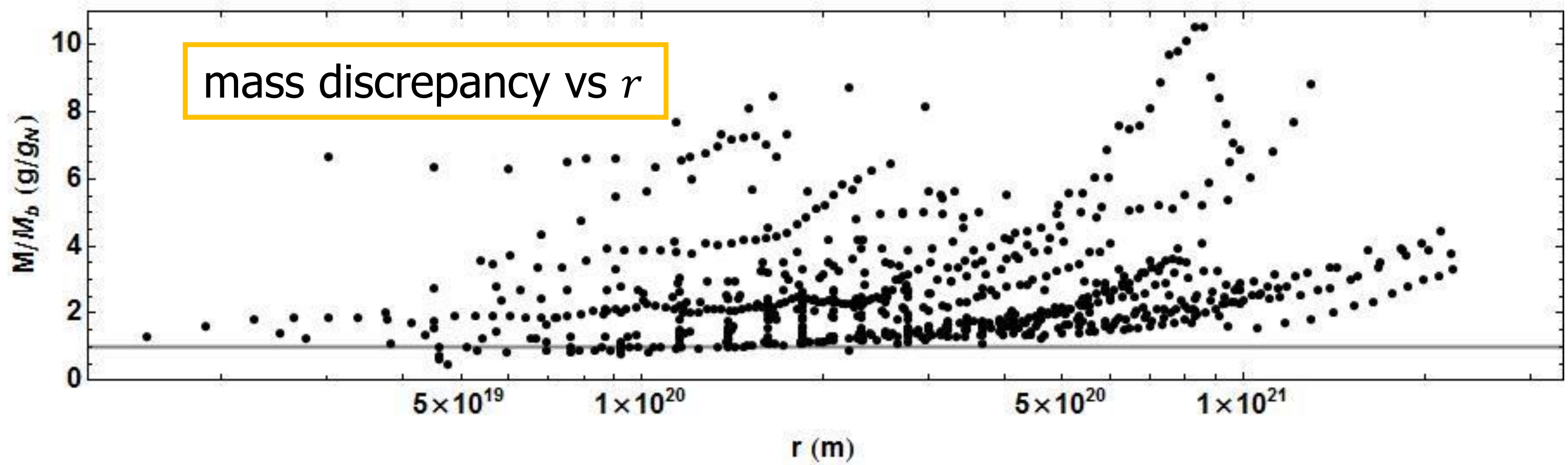
spiral galaxies

- luminous mass (baryonic matter)
  - stars, gas
  - population synthesis, … SED, …mass-to-light ratio, …
  - kind of complicated

- in spirals, characteristic acceleration is easier to define

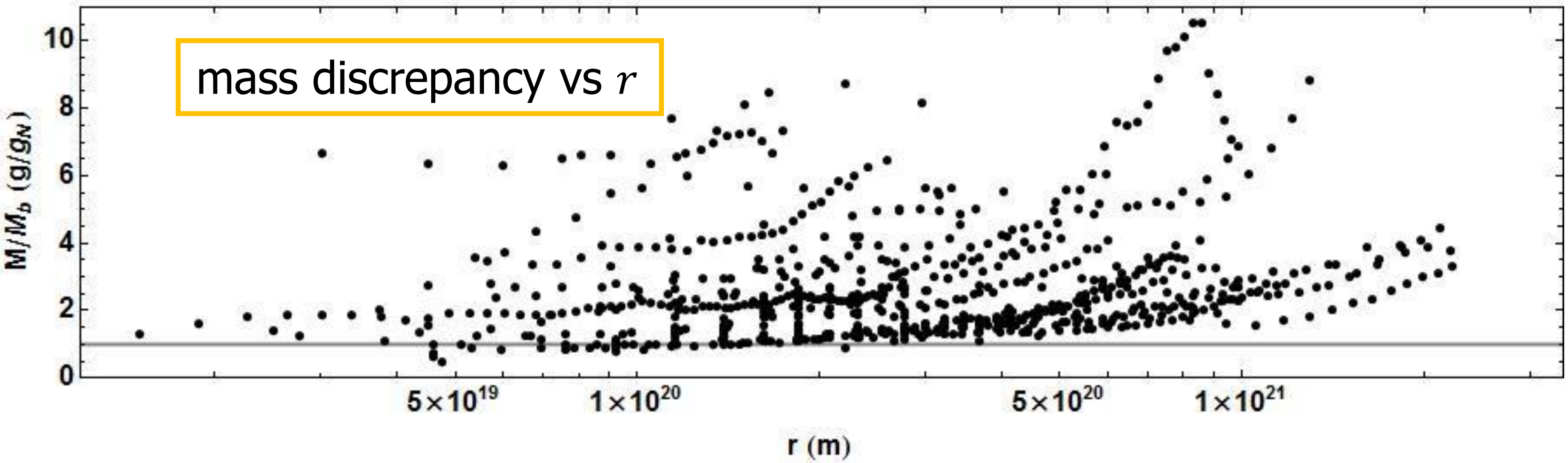
relations

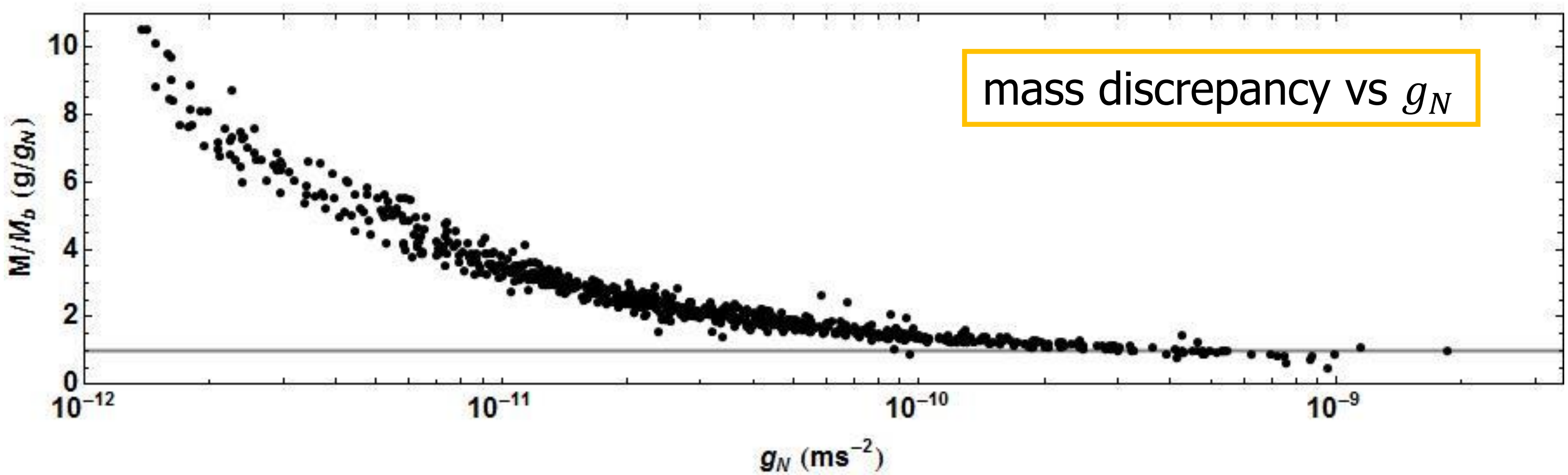
Famaey & McGaugh (2012)



relations

Famaey & McGaugh (2012)

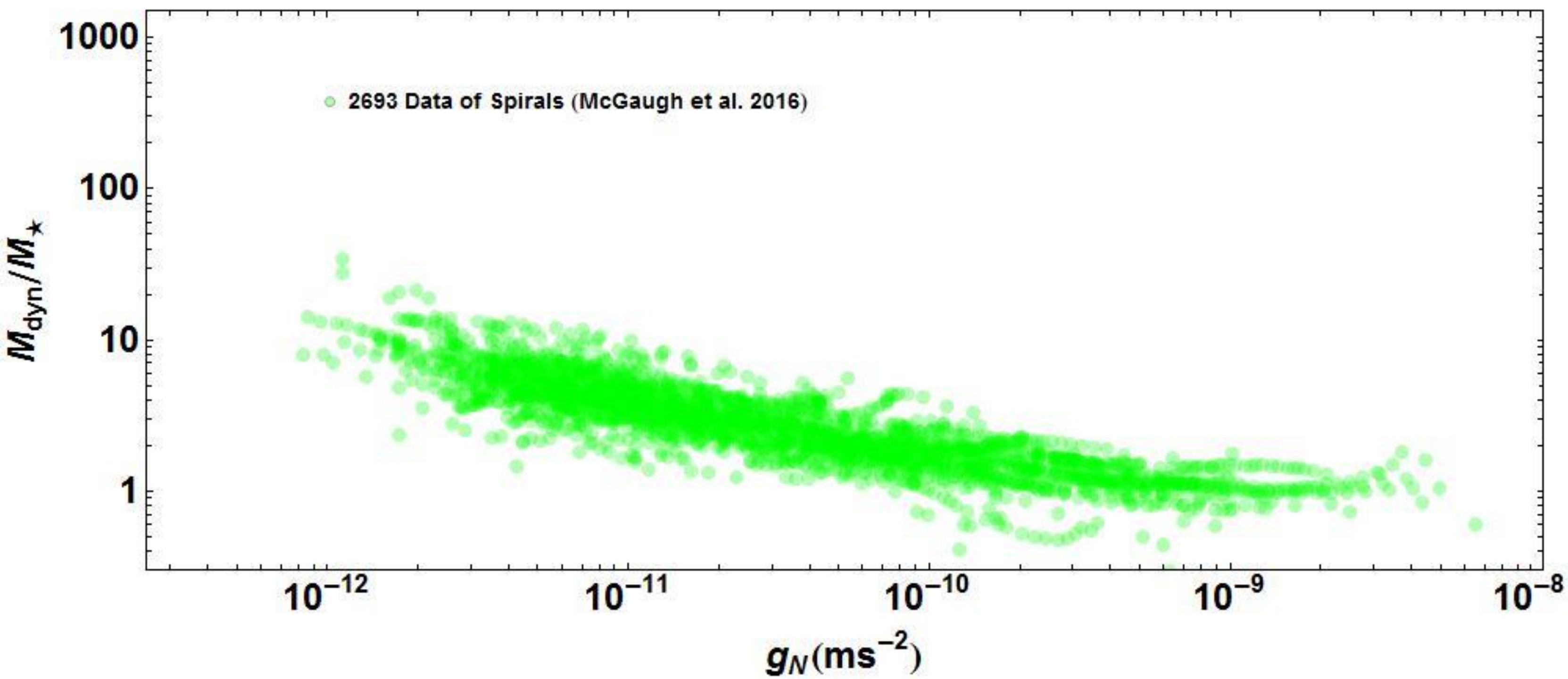




mass discrepancy

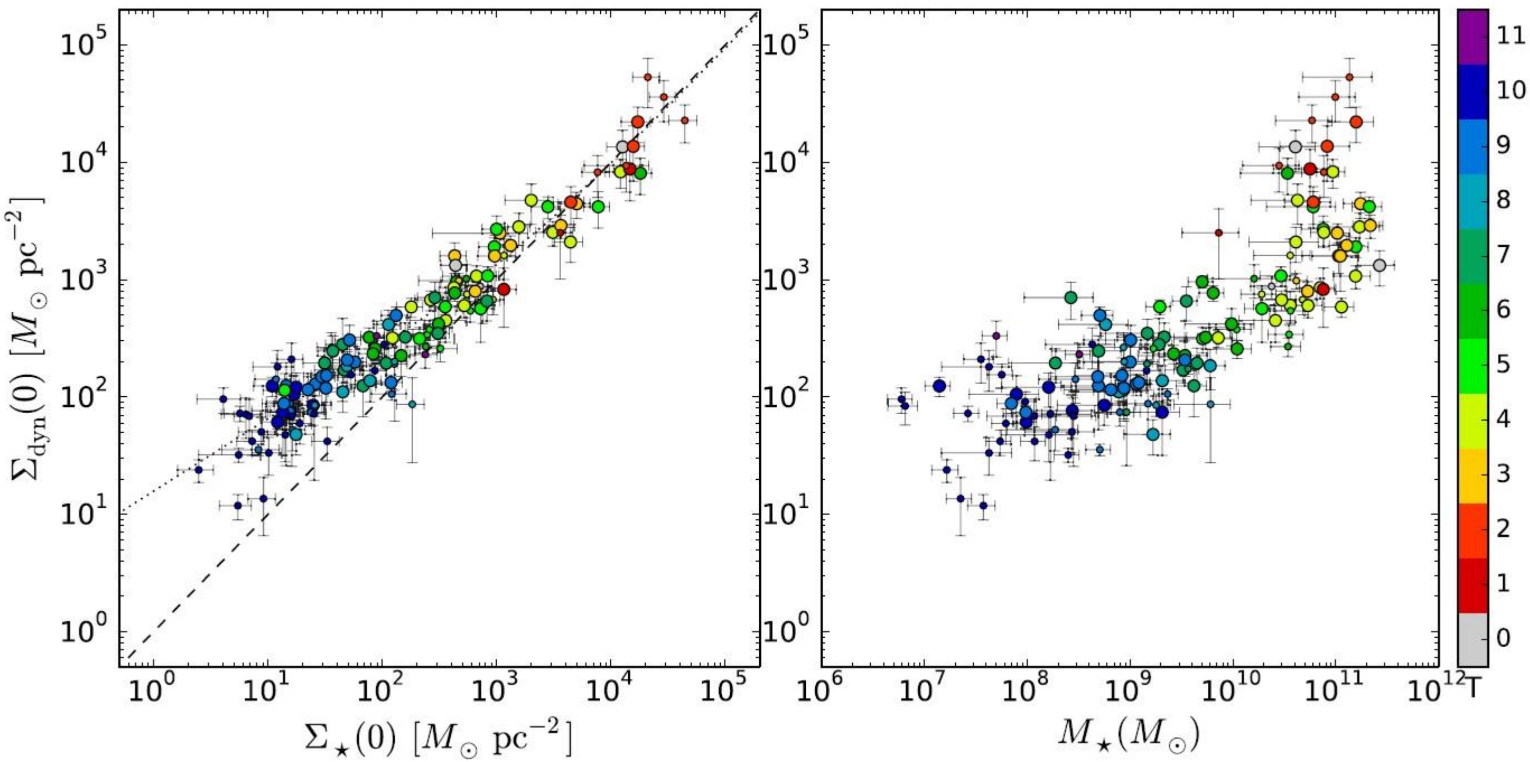
- relation between mass discrepancy and acceleration
- mass discrepancy is unnoticeable at large acceleration
- mass discrepancy becomes larger as acceleration becomes smaller
- deviation around $10^{-10}\ \mathrm{m/s^2}$
- *mass discrepancy acceleration relation*

Mass Discrepancy Acc Relation



McGaugh et al. (2016)

dynamical vs luminous mass



Lelli et al. (2016)

surface mass density

- relation between surface mass density of dynamical mass and baryonic mass
- for high surface density, both densities are close to each other
- at low surface density, dynamical mass surface density is systematically larger than luminous mass surface density

elliptical galaxies

- pressure supported systems
  - dynamics more complex
- dynamical mass (“total” matter)
  - velocity dispersion of stars
  - convolution of gravity and density
  - mass model (Hernquist, singular isothermal…)
  - anisotropy

elliptical galaxies

- velocity dispersion

anisotropy

$$\sigma_r^2 = \frac{1}{\rho}\int_r^{\infty} \rho g \exp\left(\int_r^{r'} \frac{2\beta}{r''}\,\mathrm{d}r''\right)\,\mathrm{d}r'$$

mass model

- projected velocity dispersion

mass-to-light ratio

$$\sigma_I^2(R) = \frac{2}{I(R)}\int_R^{\infty} \frac{\sigma_r^2(r)\rho(r)}{\Upsilon}\frac{r\,\mathrm{d}r}{\sqrt{r^2-R^2}} \qquad I(R) = 2\int_R^{\infty}\frac{\rho(r)}{\Upsilon}\frac{r\,\mathrm{d}r}{\sqrt{r^2-R^2}}$$

$$\sigma_S^2(R) = \frac{2}{S(R)}\int_0^{R} \sigma_I^2(R')I(R')2\pi R'^{\,2}\,\mathrm{d}R' \qquad S(R) = \int_0^{R} I(R')2\pi R'^{\,2}\,\mathrm{d}R'$$

elliptical galaxies

- lensing mass ("total" matter)
  - deflection angle of background object
  - depends on the contribution of gravitational acceleration along the light path

$$\frac{1}{\theta_{\mathrm{E}}^2} = \frac{[\chi(\theta_+) + \chi(\theta_-)]}{(\theta_+ + \theta_-)}$$

$$r_\pm^2 = D_{\mathrm{L}}^2 \theta_\pm^2 + \zeta^2$$

$$\chi(\theta_\pm) = \int_0^\infty \frac{\theta_\pm \tilde{g}(r_\pm)}{r_\pm} \, \mathrm{d}\zeta$$

$$\tilde{g} = \frac{D_{\mathrm{L}}^2 \, g}{G\mathcal{M}}$$

mass model, gravity, etc.

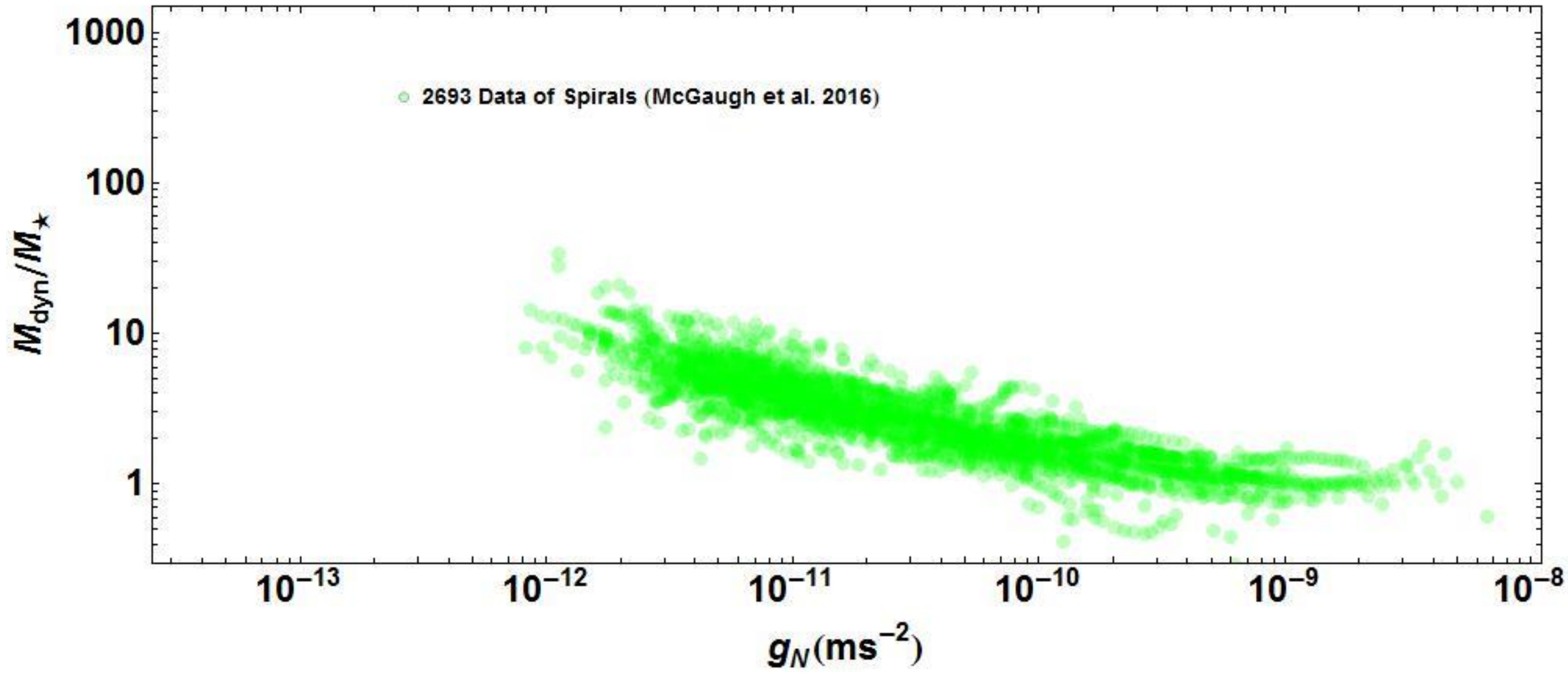
elliptical galaxies

- luminous mass (baryonic matter)
  - stars (only?)
  - population synthesis, … SED, …mass-to-light ratio, … (complicated!)

- in ellipticals, characteristic acceleration is not easy to define
  - may depend on mass model, anisotropy

Mass Discrepancy Acc Relation

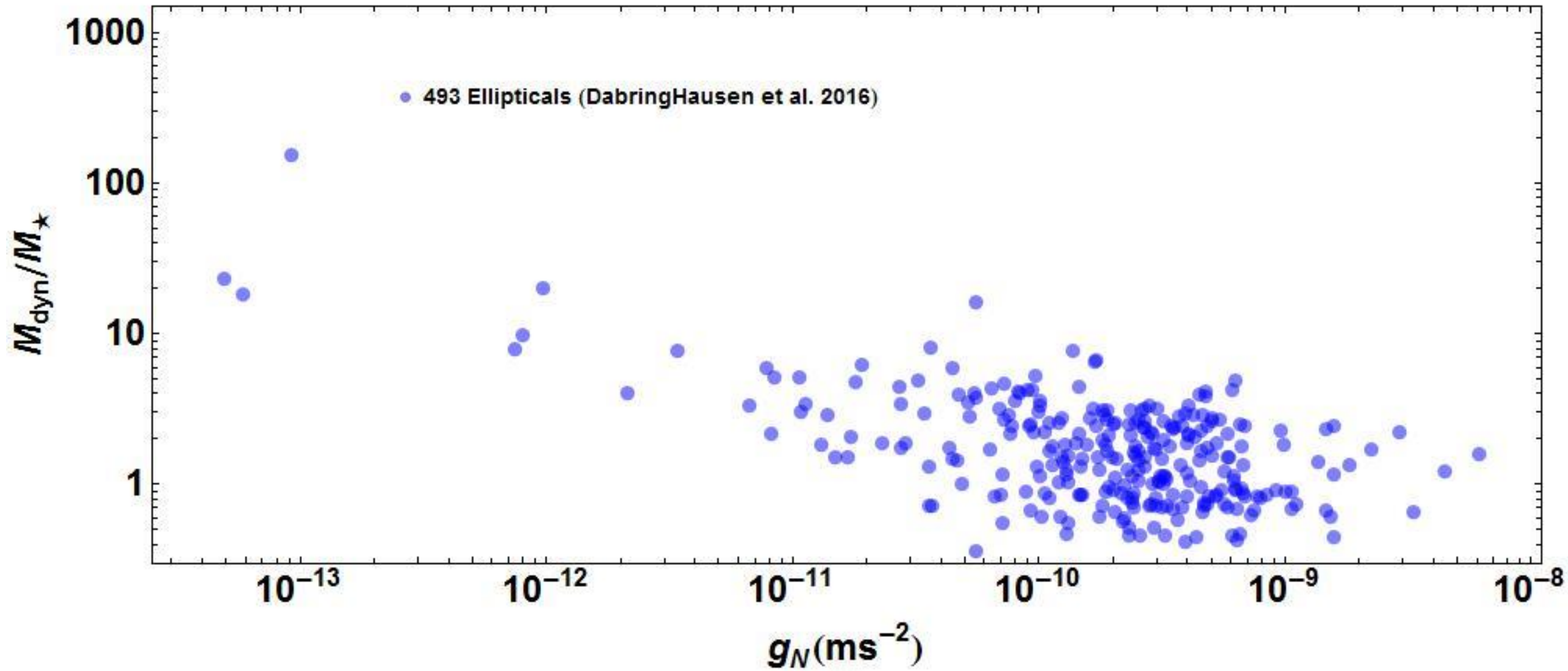
spirals



McGaugh et al. (2016)

Mass Discrepancy Acc Relation

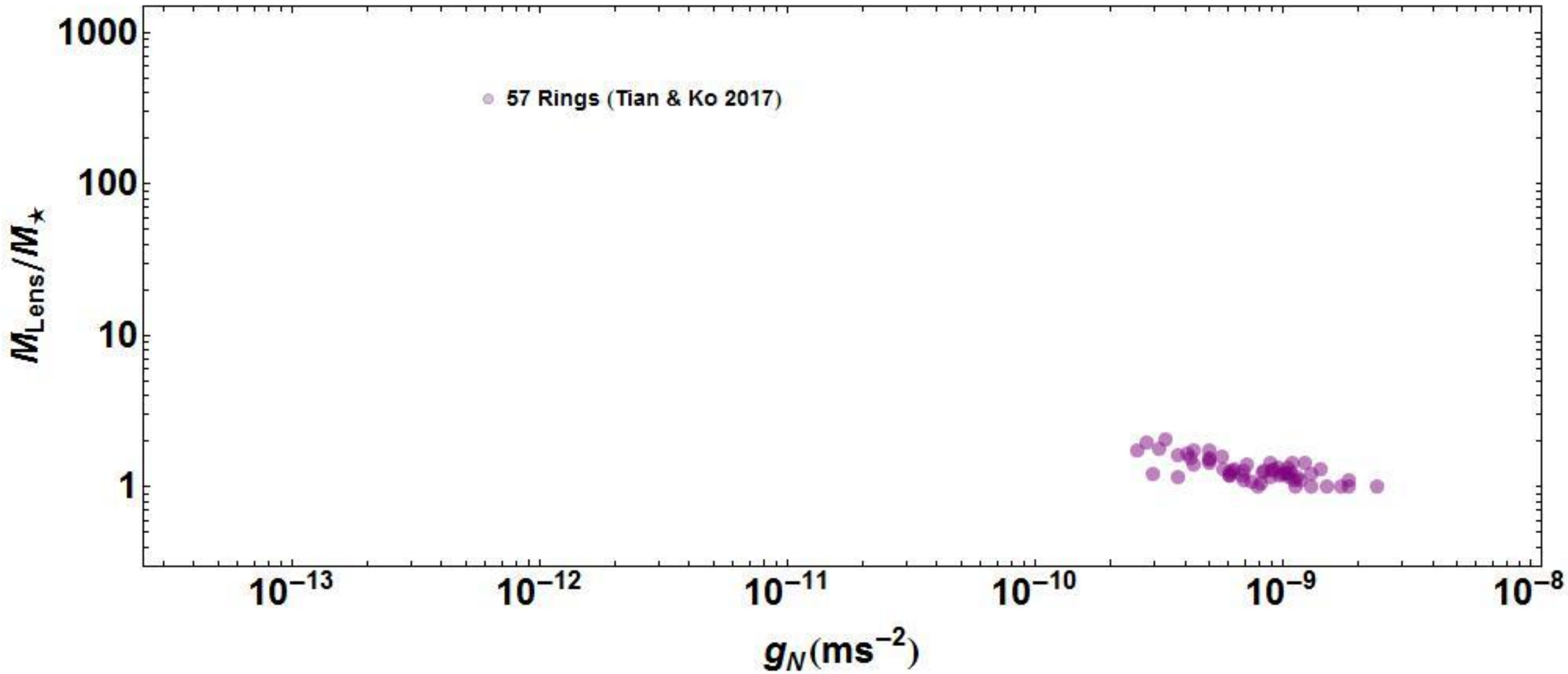
ellipticals (virial)



Tian & Ko (in prep.)

Mass Discrepancy Acc Relation

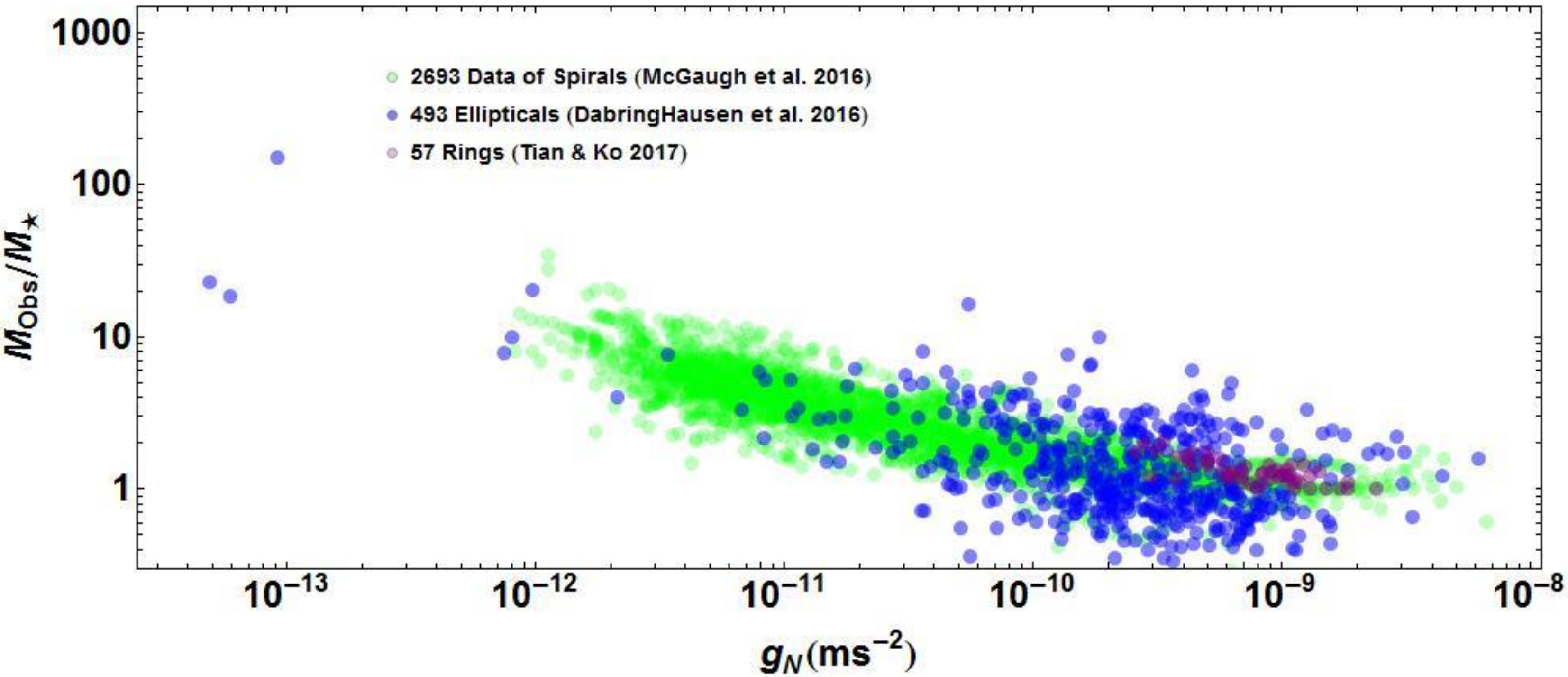
ellipticals (Einstein ring)



Tian & Ko (submitted)

Mass Discrepancy Acc Relation

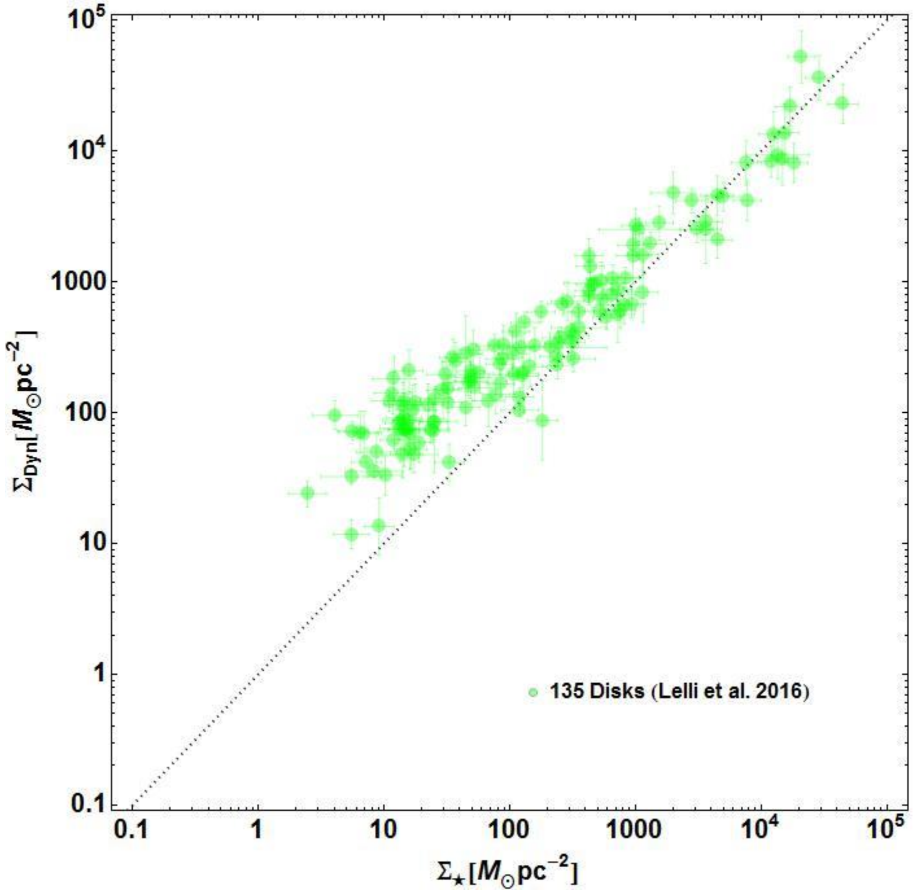
spirals + ellipticals (virial) + ellipticals (Einstein ring)



Tian & Ko (in prep.)

surface mass density

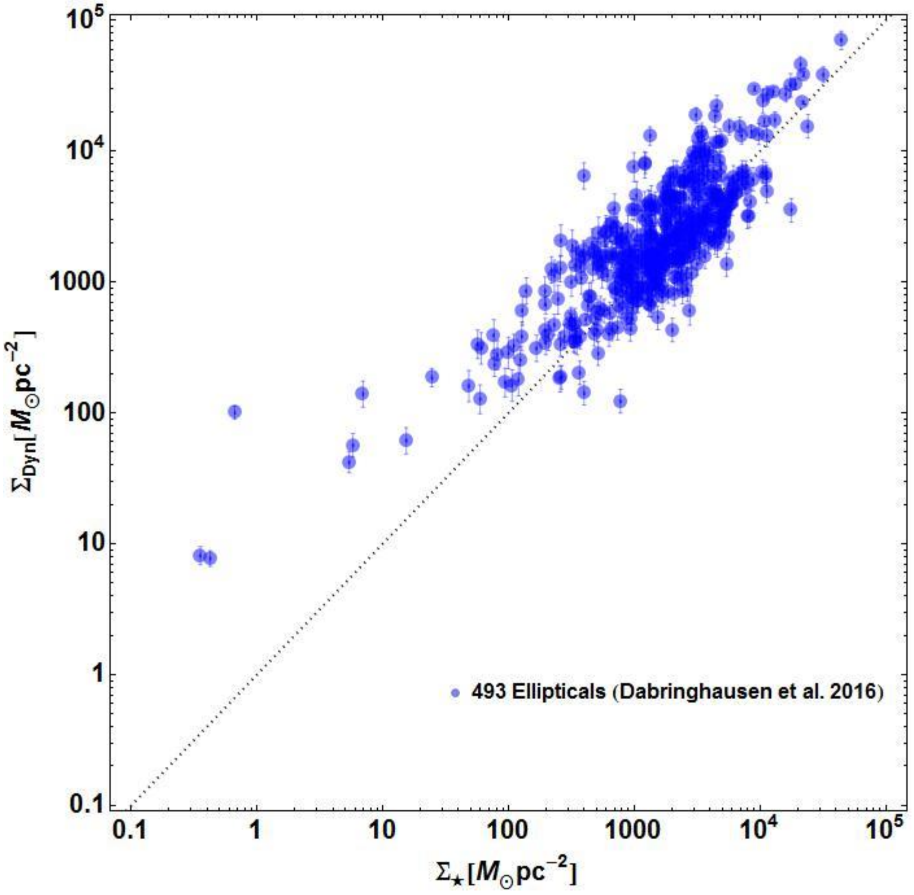
spirals



Lelli et al. (2016)

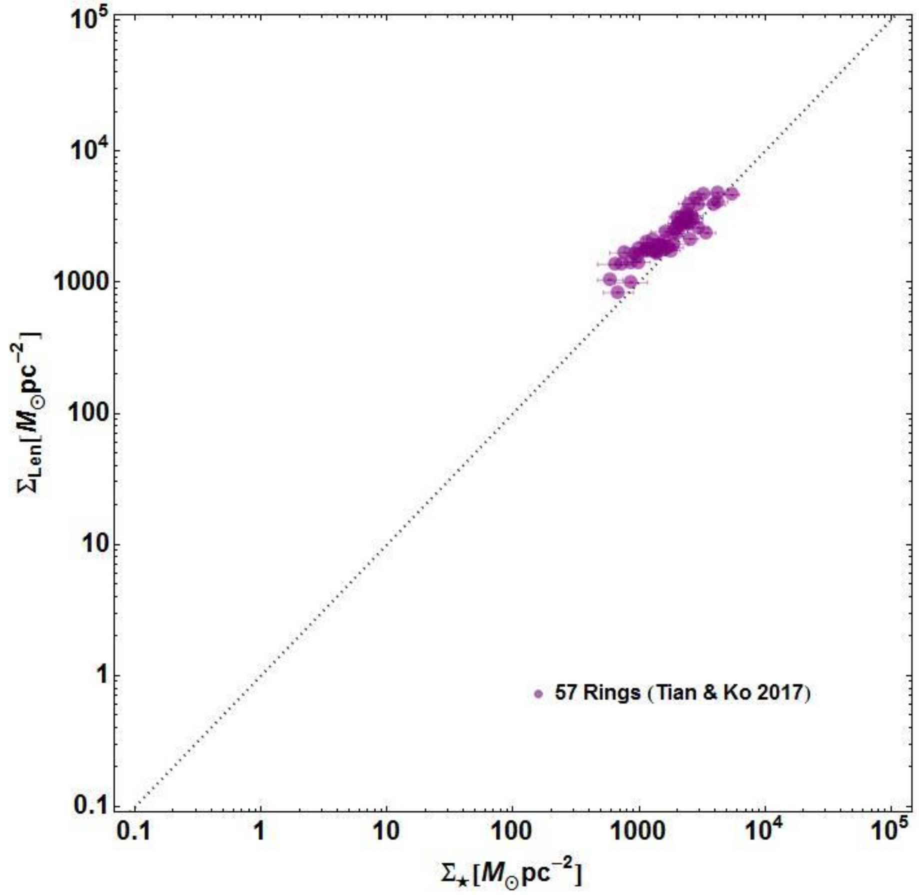
surface mass density

ellipticals
(virial)



Tian & Ko (in prep.)

surface mass density

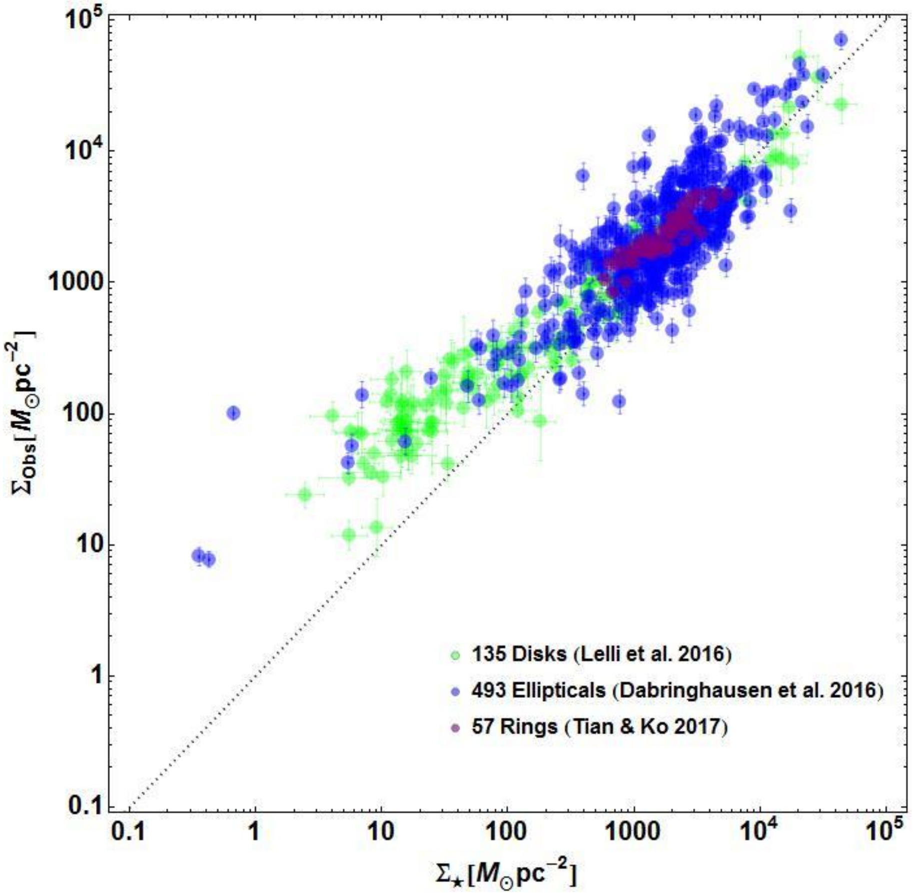


ellipticals
(Einstein ring)

Tian & Ko (submitted)

surface mass density

spirals
+
ellipticals (virial)
+
ellipticals (Einstein ring)



Tian & Ko (in prep.)

interpretations?

two masses don't agree

$\boxed{g \neq a}$

- some matters are not luminous $g = a$?
  - what are they? light is not a good tracer of mass? more physics is needed?
- gravity theory is not what we expected $g = a$?
  - modified gravity?
- law of motion is not what we expected $g = a$?
  - what to do?

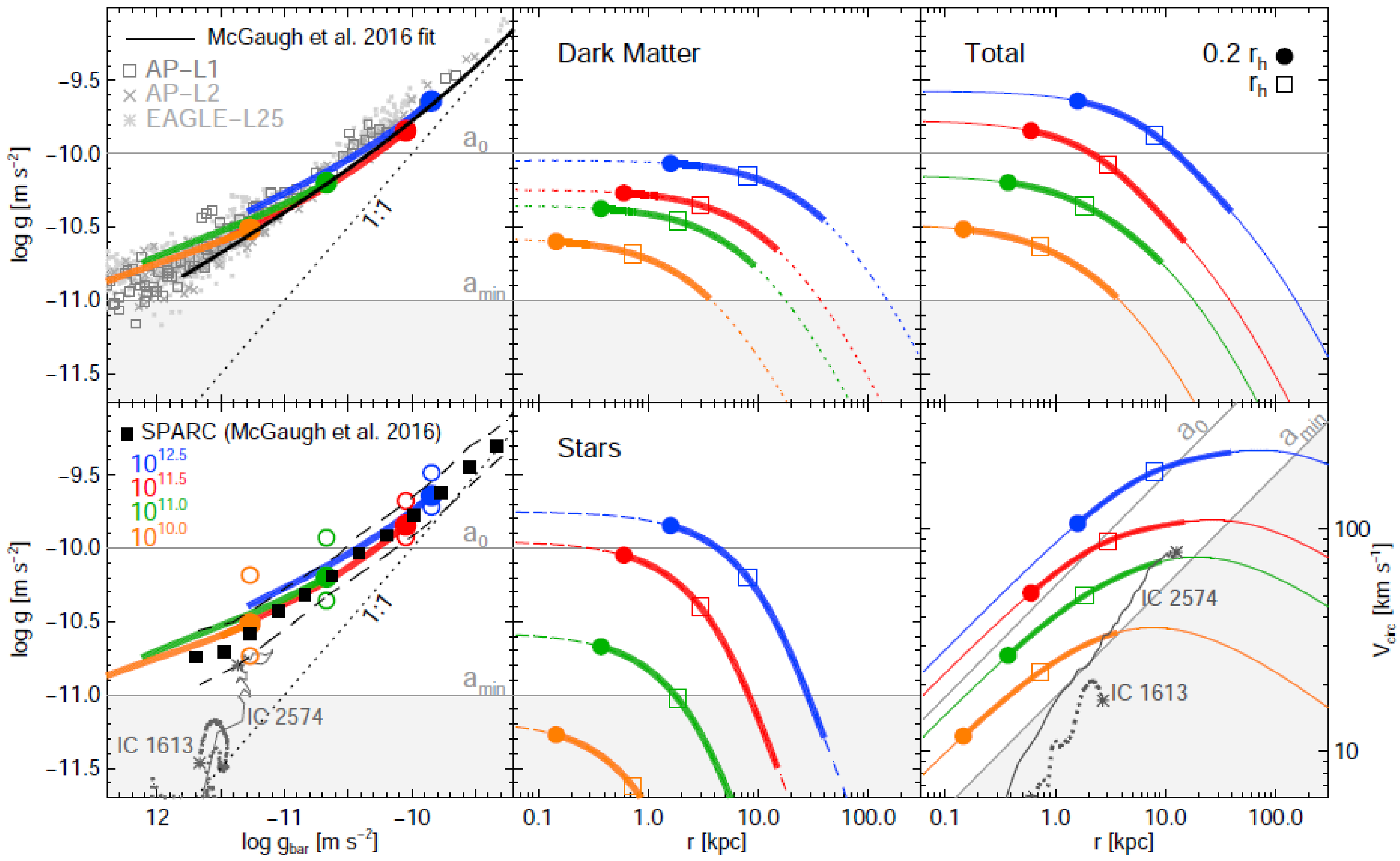
Dark Matter

$g = a$
?

- Navarro et al. (arXiv:1612.06239v1)
  - dark halo acceleration has a broad maximum between $10^{-11} \sim 10^{-10}\ \mathrm{m/s^2}$
  - halo mass and (galaxy) baryon mass are tightly related (due to galaxy formation process)
  - disc galaxies form at centre of DM halos spanning a narrow range of virial velocity
- also Di Cintio & Lelli (2016)

Dark Matter

Navarro et al. (arXiv:1612.06239v1)



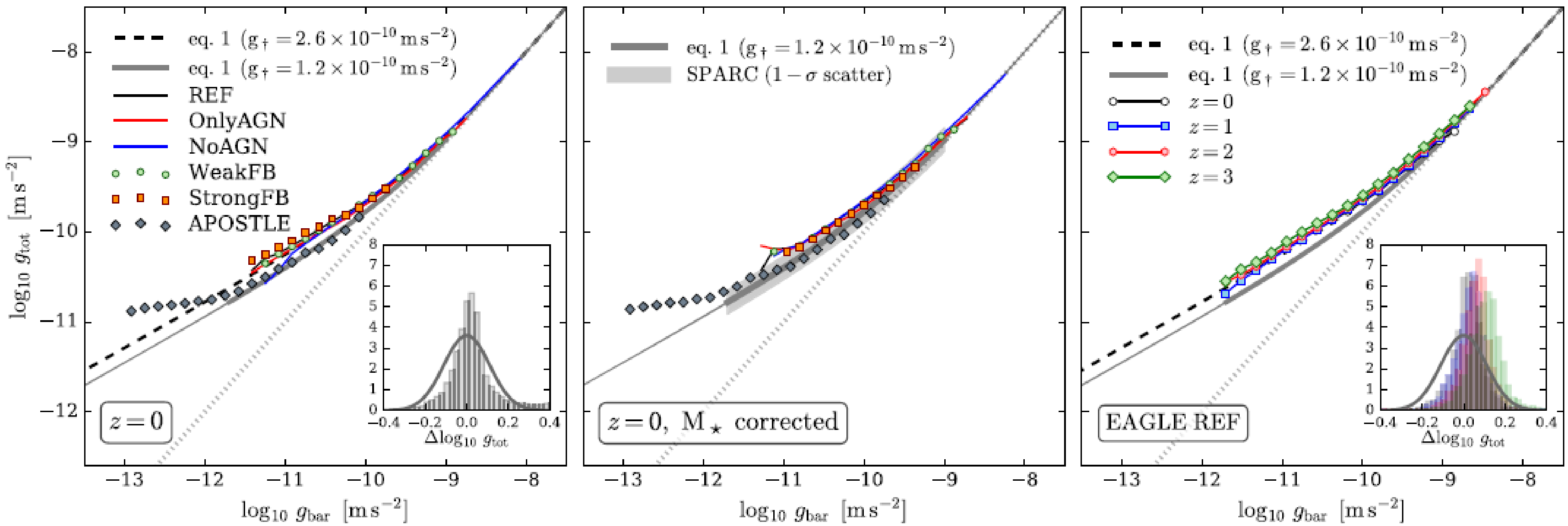
Dark Matter

$\mathrm{g} = \mathrm{a}$

?

- Ludlow et al. (2017)
  - standard cold dark matter paradigm
  - hydrodynamic simulation (EAGLE)
  - sub-grid physics so that simulations reproduce observed scaling relations
  - explain MDAR and its small scatter
- also Santos-Santos et al. (2016), Keller & Wadsley (2017), etc.

Dark Matter



Ludlow et al. (2017)

MOdified Newtonian Dynamics

$$\mathrm{g} = \mathrm{a}$$

?

- MOND is a form of modify gravity
- when acceleration is small, gravity is stronger than Newtonian

MONDian gravity

$$\nabla \cdot \left[\tilde{\mu}\left(|\mathrm{g}|/a_0\right)\mathrm{g}\right] = \nabla \cdot \mathrm{g}_\mathrm{N} = -4\pi G\rho$$

nonlinear Poisson equation

Newtonian gravity

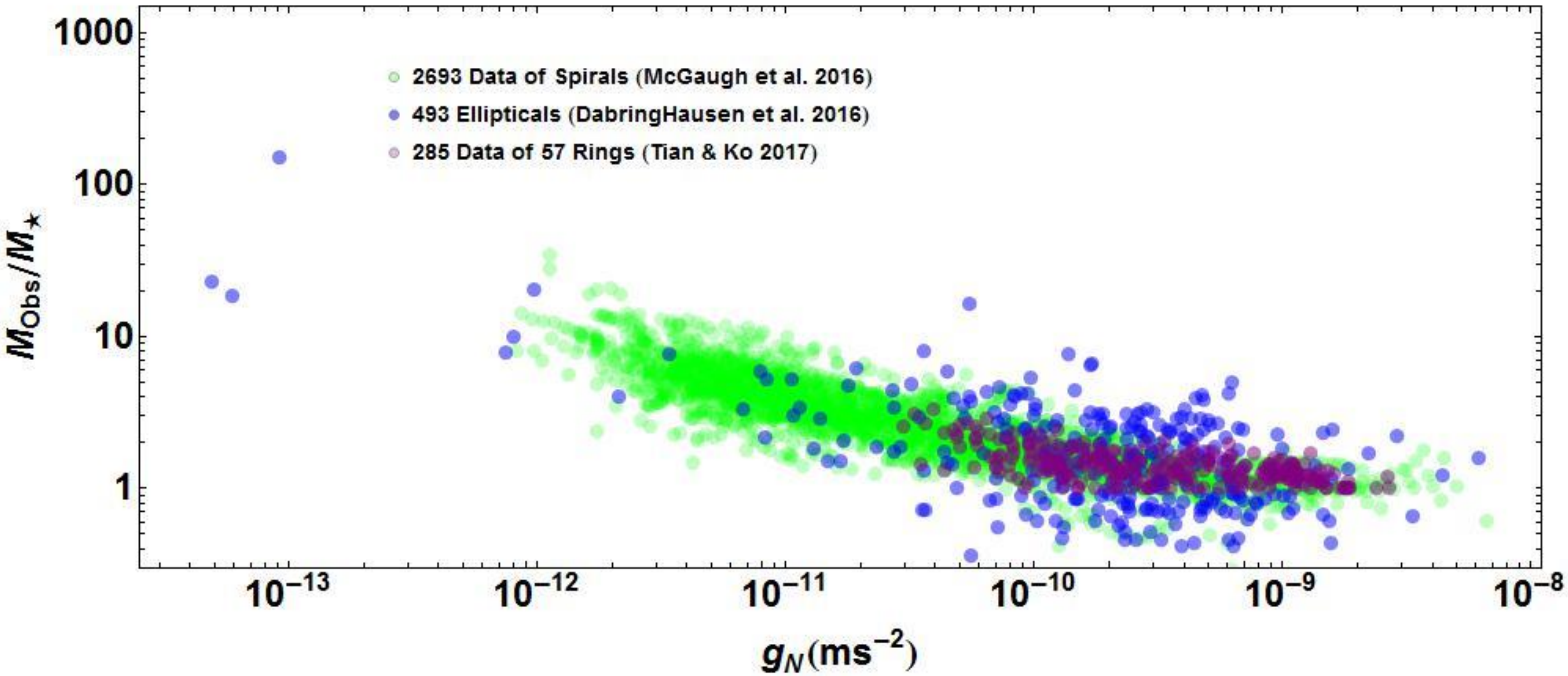
$$\tilde{\mu}(x) \rightarrow \begin{cases} 1 & \text{for } x \gg 1 \quad \text{Newtonian} \\ x & \text{for } x \ll 1 \quad \text{deep MOND} \end{cases}$$

interpolation function

- relativistic version for lensing (TeVeS, ...)

Mass Discrepancy Acc Relation

spirals + ellipticals (virial) + ellipticals (Einstein ring)



Tian & Ko (in prep.)

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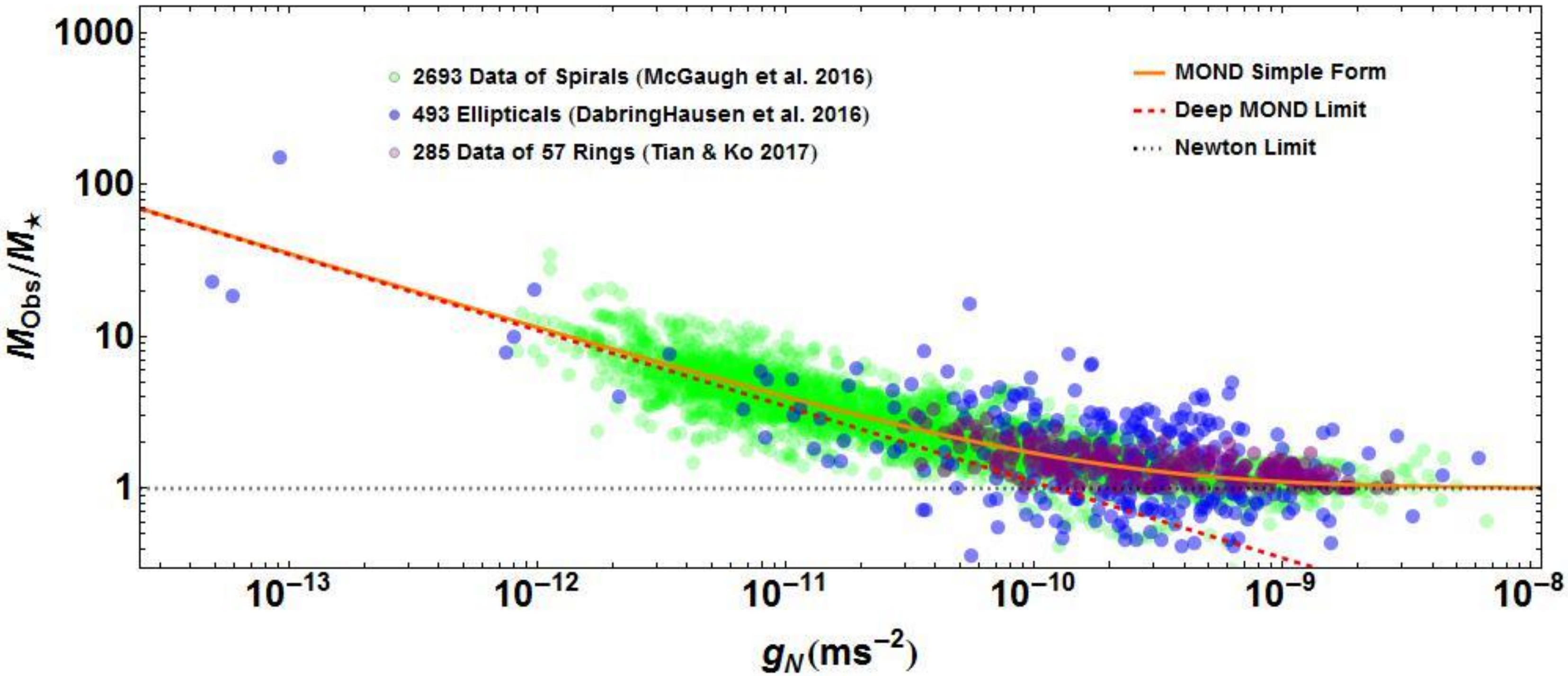
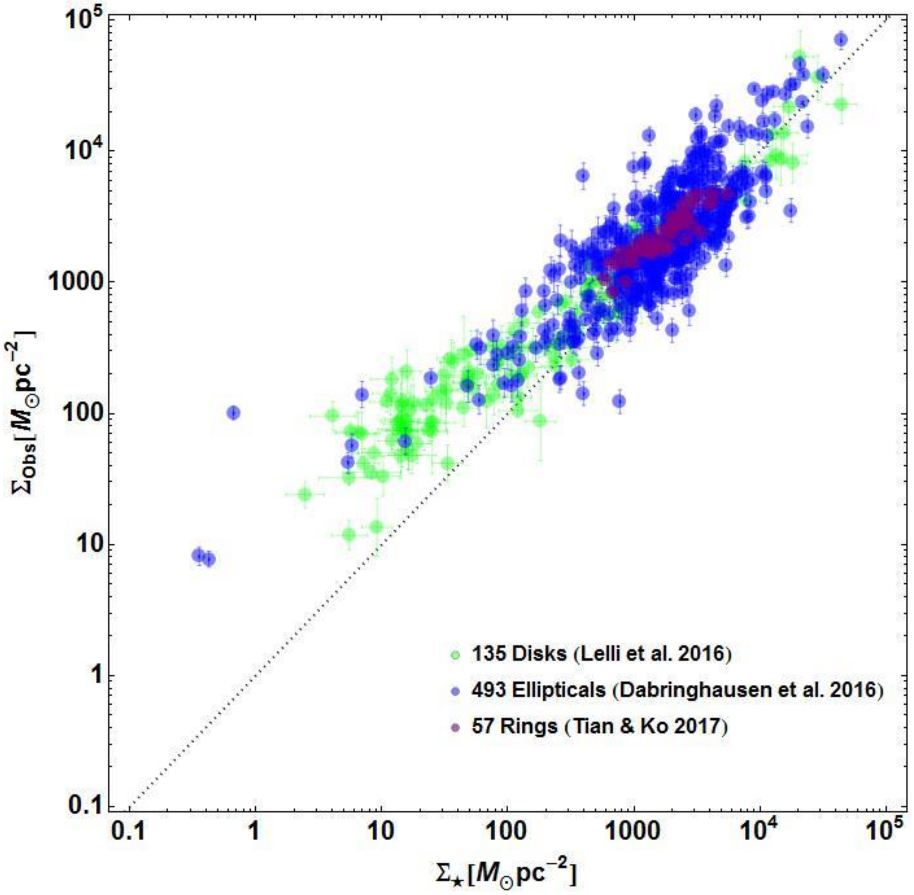


Tian & Ko (in prep.)

surface mass density

spirals
+
ellipticals
(virial)
+
ellipticals
(Einstein ring)



Tian & Ko (in prep.)

surface mass density

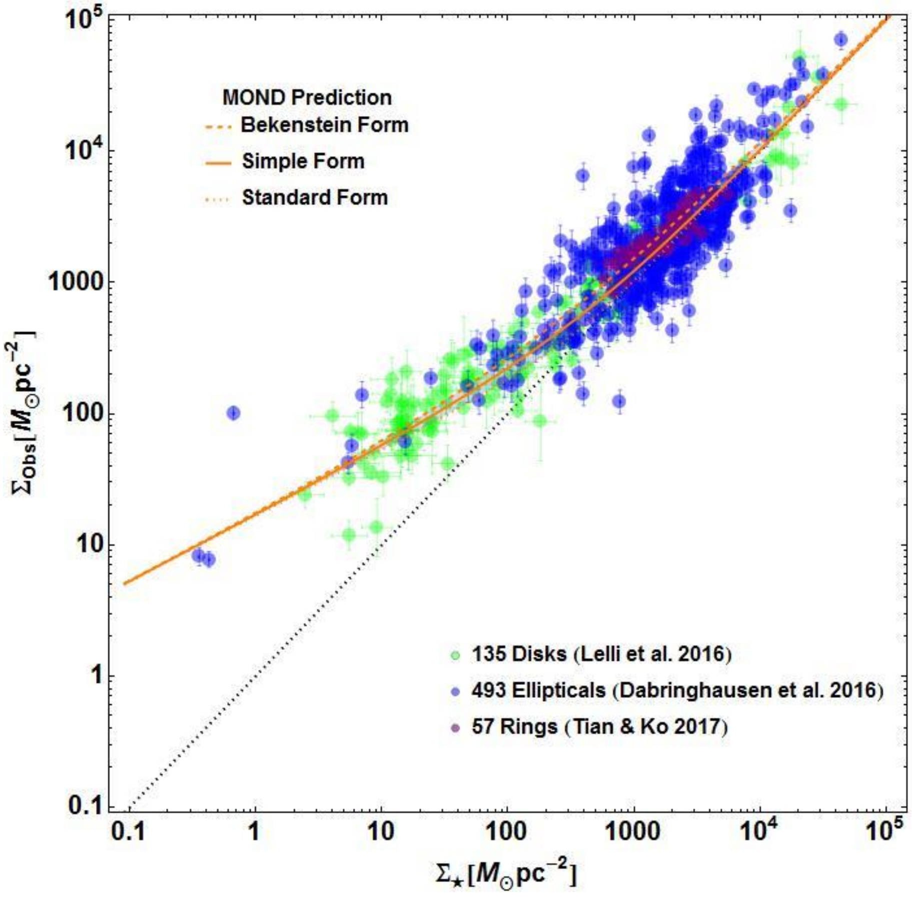
spirals

+

ellipticals (virial)

+

ellipticals (Einstein ring)



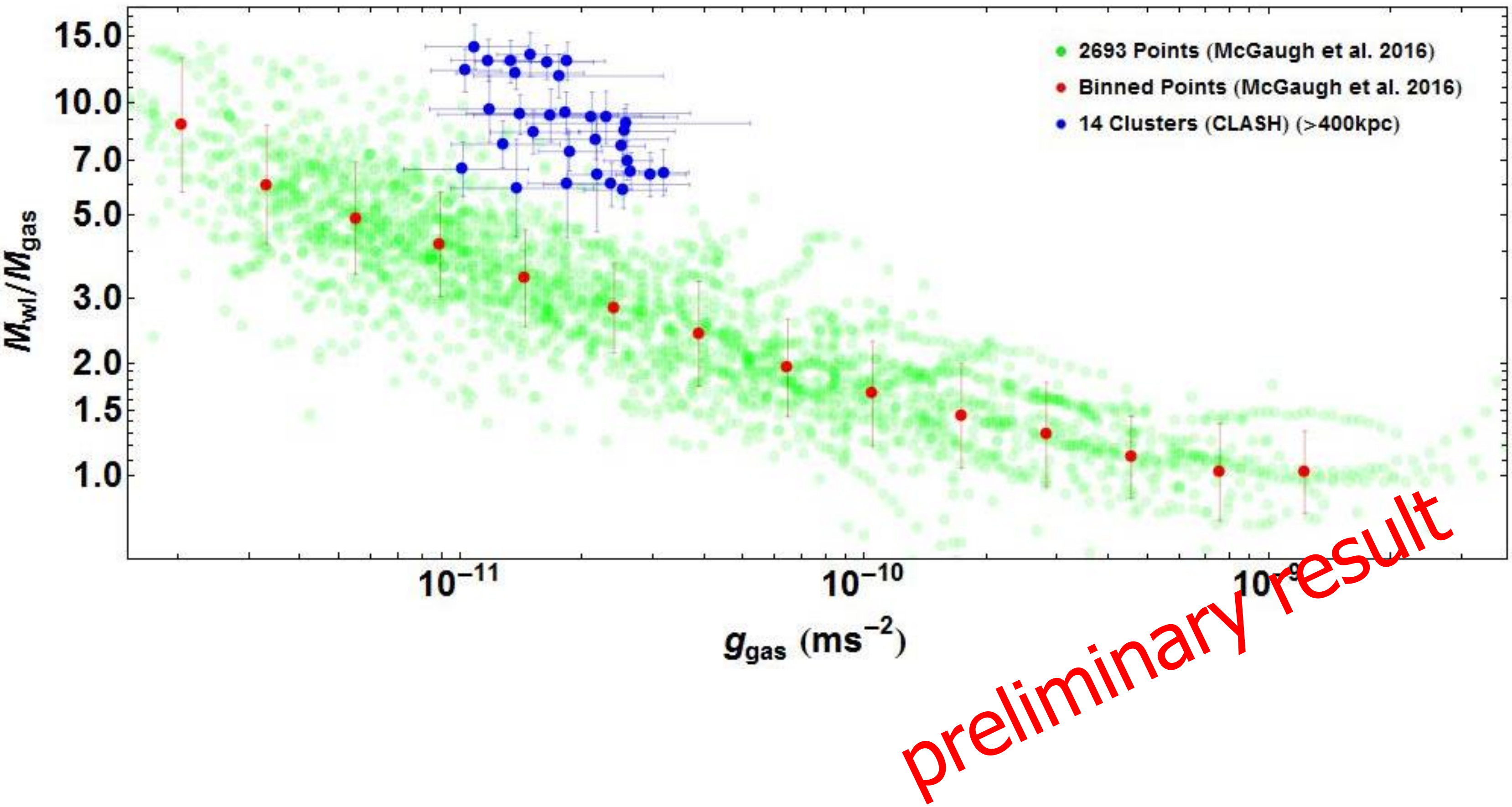
Tian & Ko (in prep.)

remarks

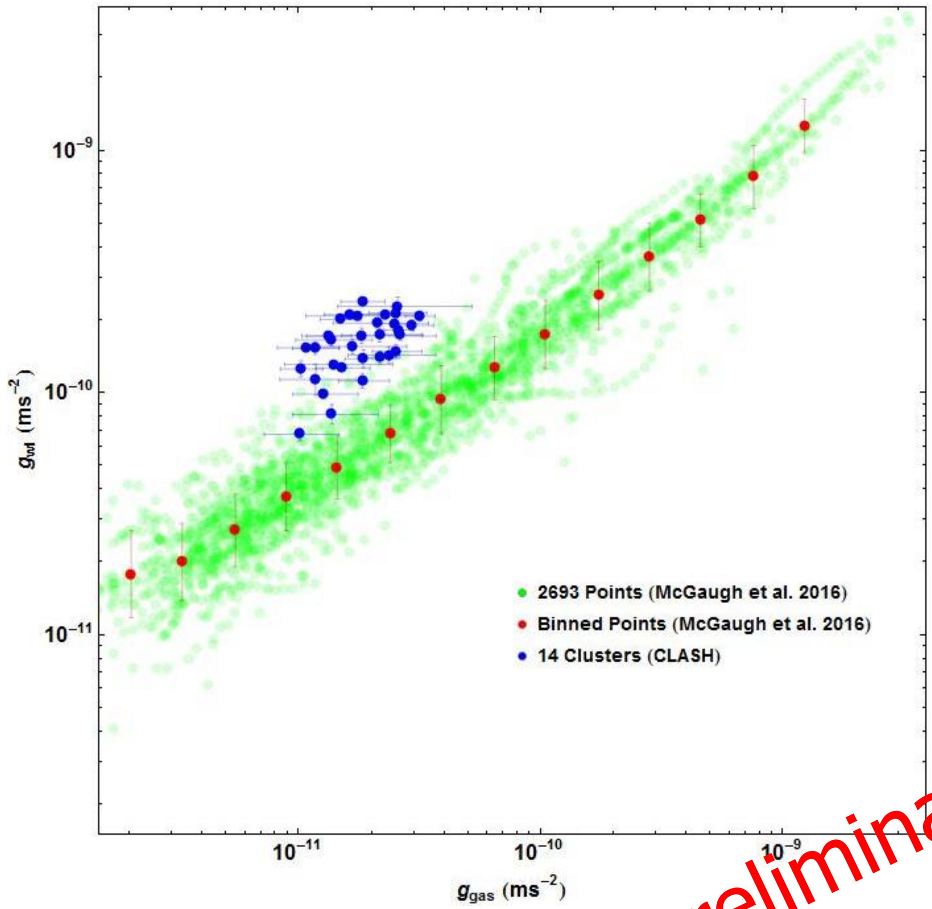
- MDAR exists in spirals and ellipticals
- both LCDM (with proper galaxy formation process and feedback) and MOND can explain MDAR
- maybe MOND is an “empirical law” as a consequence of LCDM

clusters of galaxies

Mass Discrepancy Acc Relation



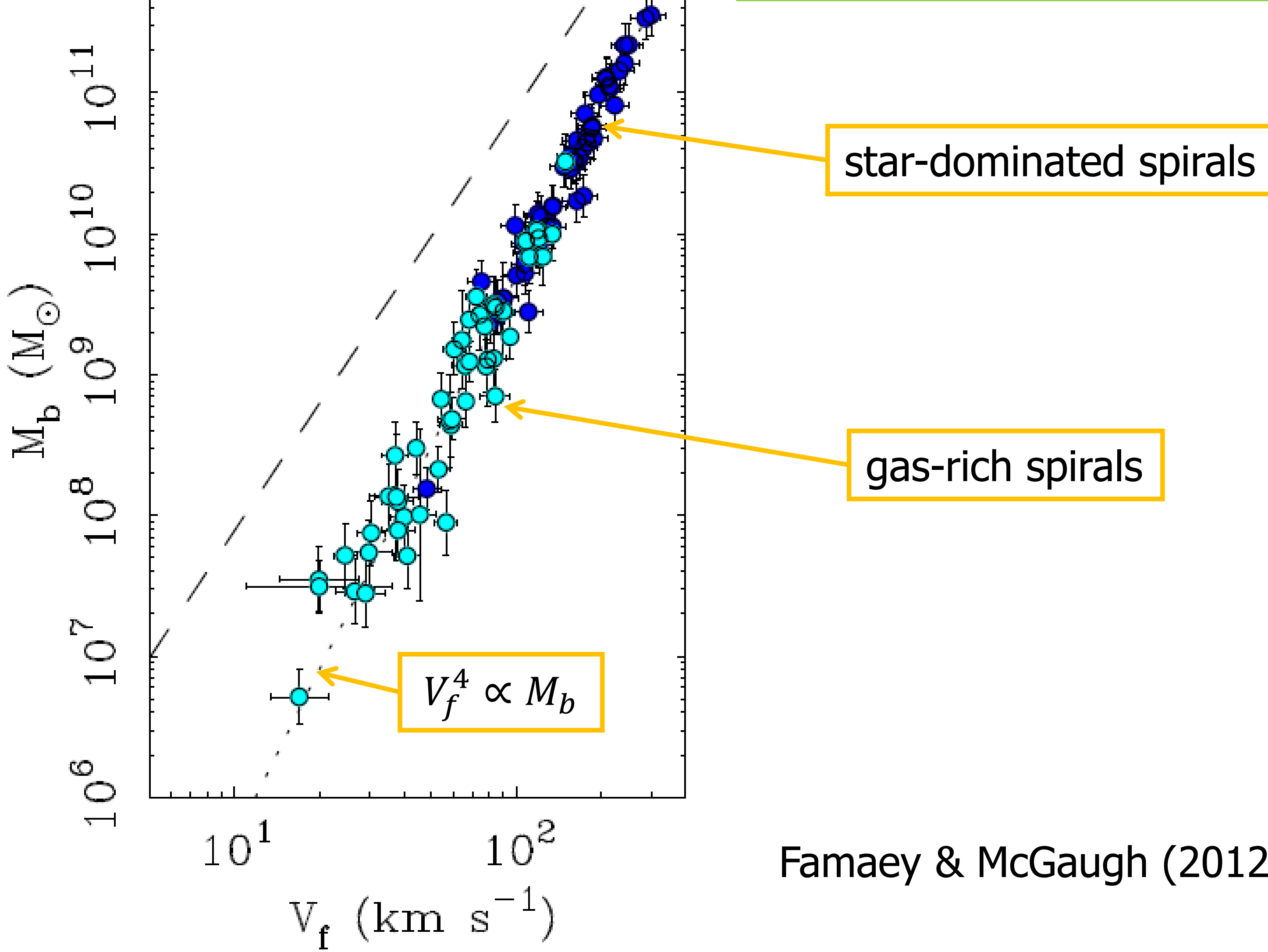
radial acceleration



preliminary result

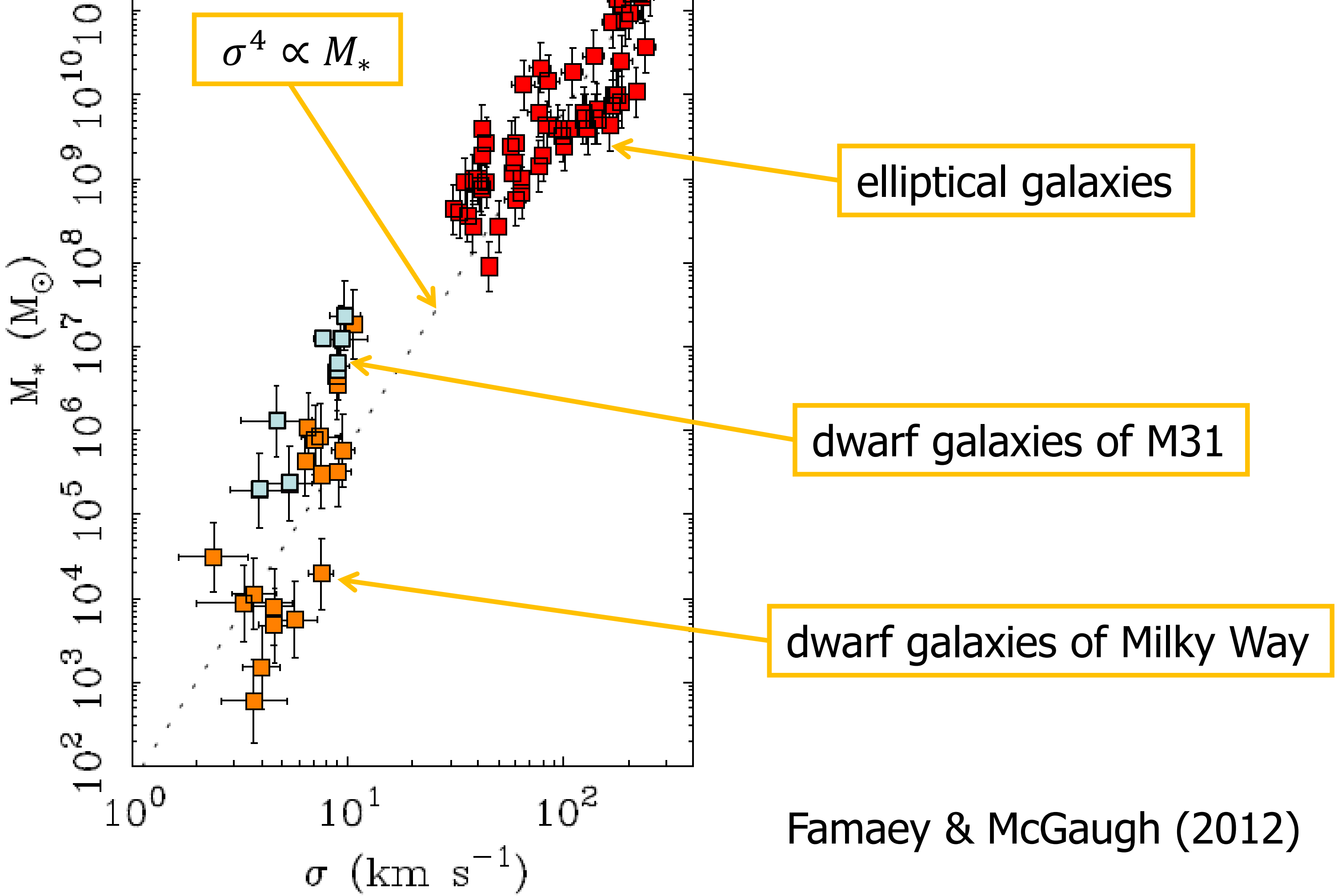
backup slides

Baryonic Tully-Fisher relation



Famaey & McGaugh (2012)

Faber-Jackson relation



Famaey & McGaugh (2012)

- both dark matter and MOdified Newtonian Dynamics (MOND) can explain the acceleration (or mass) discrepancy in many situations
- perhaps MOND is better than dark better in galaxy scales while dark matter is better at larger scales

acceleration scale?

- it seems that the acceleration (or mass) discrepancy occurs when acceleration is smaller than a certain value, and not according to some length scale or mass scale
- of the order of cH_0 (a coincidence?)

dynamical mass vs lensing mass

- 57 Einstein rings from SLACS
- MOND?