David Benisty

Dark Energy in two body problem

D. Benisty **A&A 656, A129 (2021);** D. Benisty; A-Davis, W. Evans ***Astrophys.J.Lett.* 953 (2023) 1, L2**

D. Benisty, E. Vasiliev, W. Evans, A. Davis, O. Hartl, L. Strigari **Astrophys.J.Lett. 928 (2022) 1, L5**

Signs for Dark Energy

- “Pantheon” - Type Ia Super Nova

Astrophys. J. 859, 101 (2018)

- Cosmic Chronometers

Jimenez & Loeb (2002)

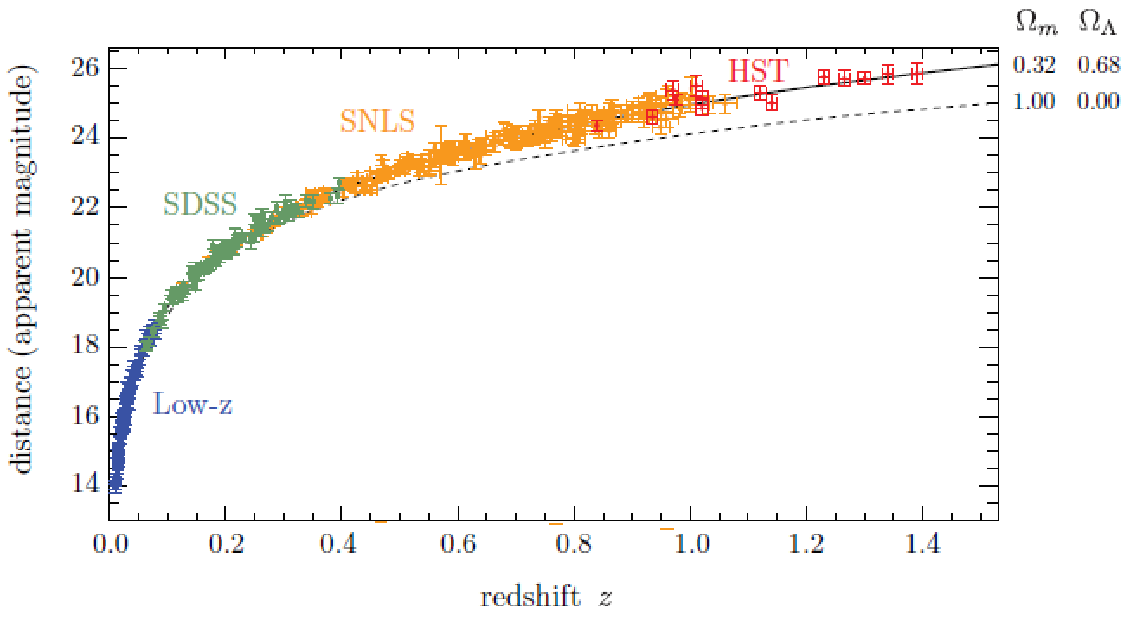
- Baryon Acoustic Oscillations

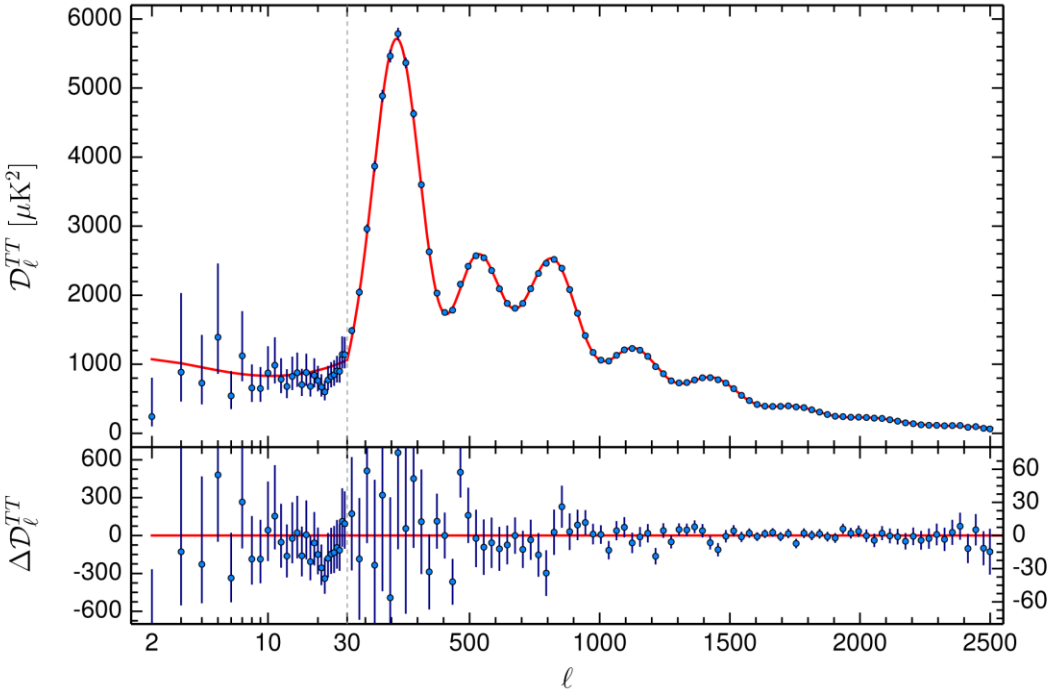
Phys. Rev. D 92, 123516 (2015)

- Cosmic Microwave Background

(Planck 2018)

- LSST, Others…





Einstein’s biggest Blunder & the Cosmological constant problem

***Physical Review D*. 37 (12): 3406–3427**

$$\mathcal{L} = \frac{1}{2}R - \frac{1}{2}g^{\mu\nu}\phi_{,\mu}\phi_{,\nu} - V(\phi) \implies \mathcal{L} = \frac{1}{16\pi G}(R - 2\Lambda)$$

- Quintessence is an extension to GR + Lambda.

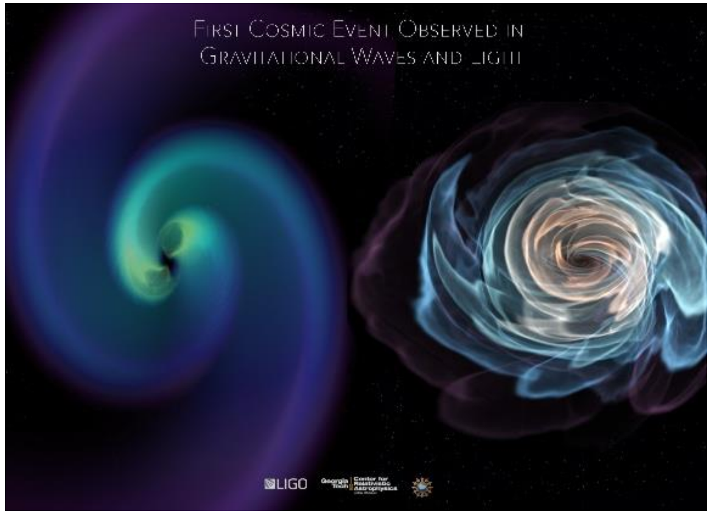
$$3H^2 = \frac{1}{2}\dot{\phi}^2 + V(\phi) \implies 3H^2 = \Lambda$$

$$-3H^2 - 2\dot{H} = \frac{1}{2}\dot{\phi}^2 - V(\phi) \implies -3H^2 - 2\dot{H} = -\Lambda$$

- Slow-roll approximation:

$$\frac{1}{2}\dot{\phi}^2 \ll V(\phi)$$

Einstein's biggest Blunder



- GR needs to be modified: $\mathcal{L} = \frac{1}{16\pi G}(R - 2\Lambda)$

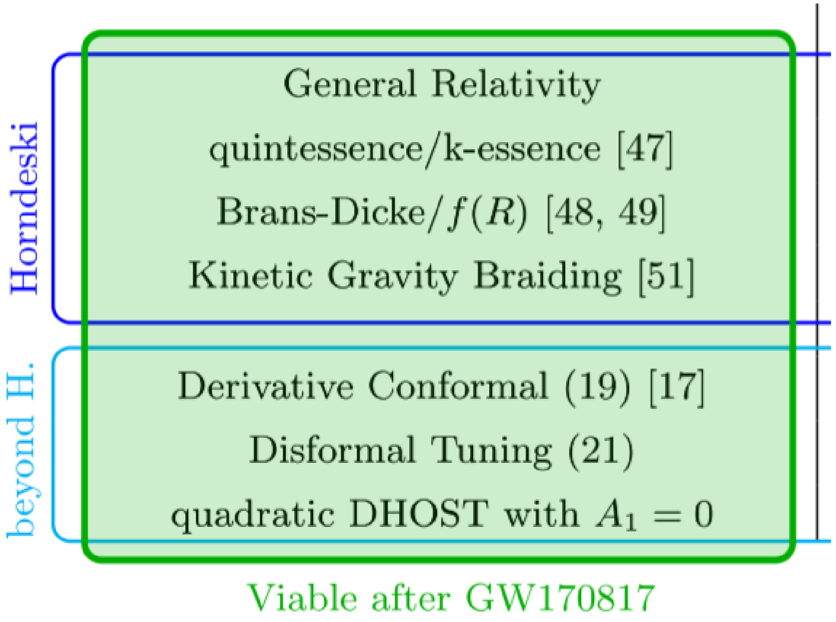
$$-3 \times 10^{-15} \leq c_g/c - 1 \leq 7 \times 10^{-16}$$

- GW170817 and modified gravity.

Phys. Rev. Lett. **119** 161101

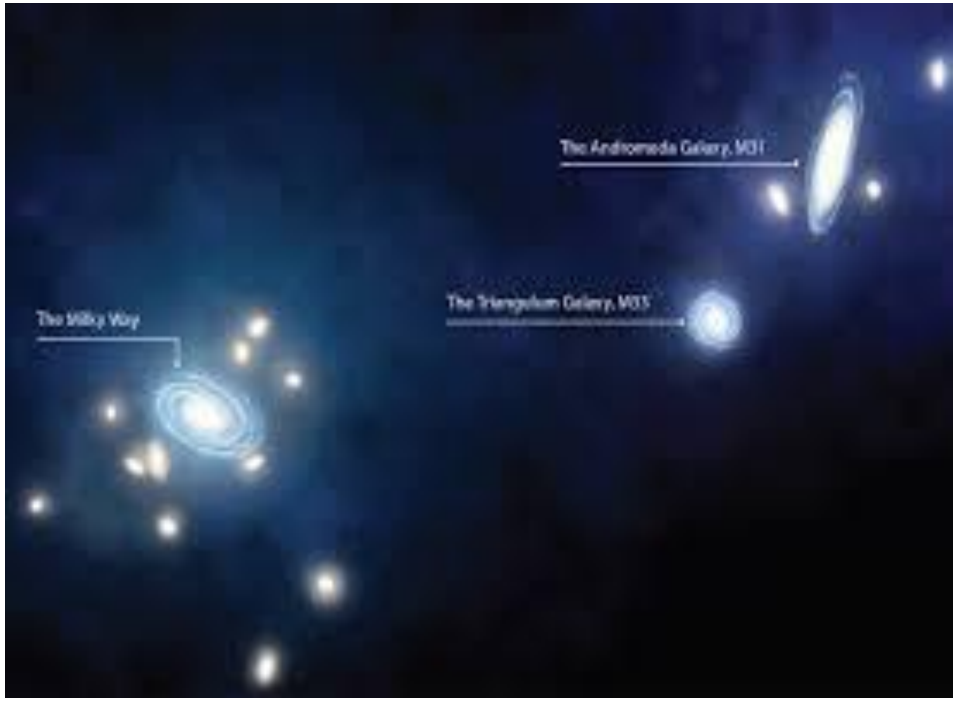
Horndeski

$$\mathcal{L}_2 = K(\phi, X),$$
$$\mathcal{L}_3 = -G_3(\phi, X)\Box\phi,$$
$$\mathcal{L}_4 = G_4(\phi, X)R + G_{4X}(\phi, X)\left[(\Box\phi)^2 - \phi_{;\mu\nu}\phi^{;\mu\nu}\right],$$
$$\mathcal{L}_5 = G_5(\phi, X)G_{\mu\nu}\phi^{;\mu\nu} - \frac{1}{6}G_{5X}(\phi, X)\left[(\Box\phi)^3 + 2\phi_{;\mu}{}^{\nu}\phi_{;\nu}{}^{\alpha}\phi_{;\alpha}{}^{\mu} - 3\phi_{;\mu\nu}\phi^{;\mu\nu}\Box\phi\right]$$



Phys. Rev. Lett. **119**, 251301

The Local group



An illustration of the Local Group of galaxies. The picture was made by Ezzy Pearson from: www.skyatnightmagazine.com/space-science/local-group-guide-galaxy-neighbourhood/

- The Local group includes the Milky Way galaxy, M31 and several smaller galaxies.
- A good approximation for the LG considers only the MW and M31.
- $M_{m31} \approx 2\ M_{MW}$

  Phelps S., Nusser A., Desjacques V., 2013, ApJ, 775, 102

- How can we estimate the mass of the LG?

van der Marel R. et al., 2012, ApJ, 753, 8

Data of the LG

- The measured physical values of M31:

$r = 0.77 \pm 0.04\ Mpc$

$v_{rad} = -109.4 \pm 4.4 \frac{km}{s}$

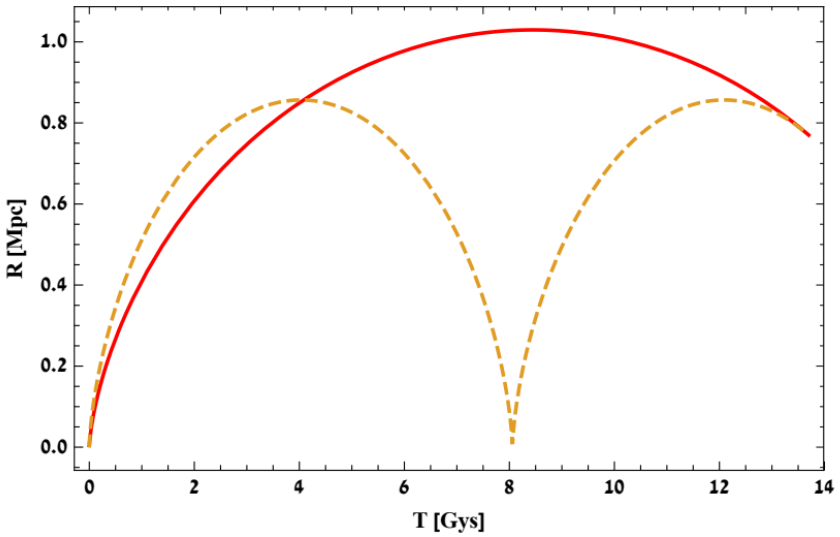
R. P. van der Marel, M. A. Fardal, S. T. Sohn, E. Patel, G. Besla, A. del Pino, J. Sahlmann, and L. L. Watkins, JCAP 872, 24 (2019)

- Tangential velocities:

$v_{tan} < 17 \frac{km}{s}$, $v_{tan} = 59^{+38}_{-42} \frac{km}{s}$, $v_{tan} = 82^{+35}_{-38} \frac{km}{s}$

van der Marel R. et al., 2015 Salomon et al. 2022

The timing argument



- The galaxies are modeled as point particles.
- Galaxy pairs are isolated; there is no external gravitational field.
- Galaxies start their orbits in the early universe close to $r(t = 0) = 0$.
- What are the equations of motion?

$\mathbf{\Lambda \sim 10^{-52} km^{-2}}$

G.R. in low energy limit

The Einstein Hilbert action: $\tilde{\mathcal{L}} = \sqrt{-g}(R - 2\Lambda)$

In the weak field limit, yields the spherically symmetric potential:

$\phi = -\frac{GM}{r} + \frac{\Lambda c^2}{3} r$ gives $\ddot{r} = -\frac{GM}{r^2} + \frac{\Lambda c^2}{3} r + \frac{l^2}{r^3}$

- Dark Energy in the solar system? From $\dot{\omega} = \frac{\Lambda c^2 P}{4\,\pi}\sqrt{1 - e^2}$ in the solar system $\Lambda < 10^{-37}\, m^{-2}$.

Physics Letters B 634 (2006) 465–470

Local Group and Λ

- The measured physical values of M31: 2012, ApJ, 753, 8

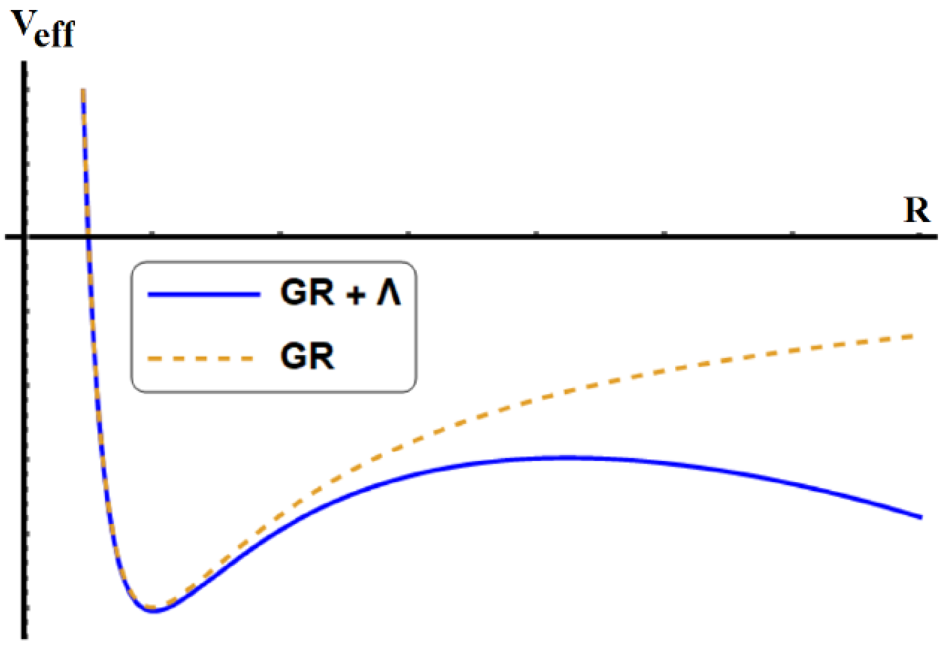
$$r = 0.77 \pm 0.04\ Mpc$$
$$v_{rad} = -109.4 \pm 4.4 \frac{km}{s}$$
$$v_{tan} = 82.5 \text{ km/s (Salomon et al. 2021)}$$

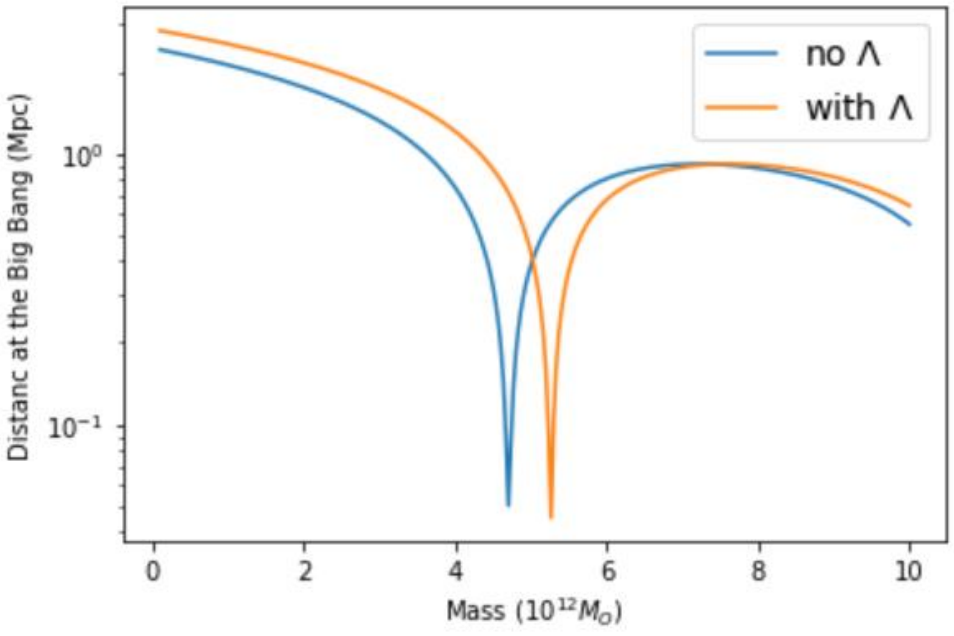
where $t_u = 13.7$ G. years
$$\ddot{r} = -\frac{GM}{r^2} + \frac{\Lambda c^2}{3} r + \frac{l^2}{r^3}$$

- Timing Argument - Galaxies start their orbits in the early universe close to $r(t = 0) = 0$. (Kahn & Woltjer 1959)

- <u>The Λ change in the LG: 10%</u>

Partridge, C., Lahav, O., & Hoffman, Y. 2013, MNRAS, 436, 45



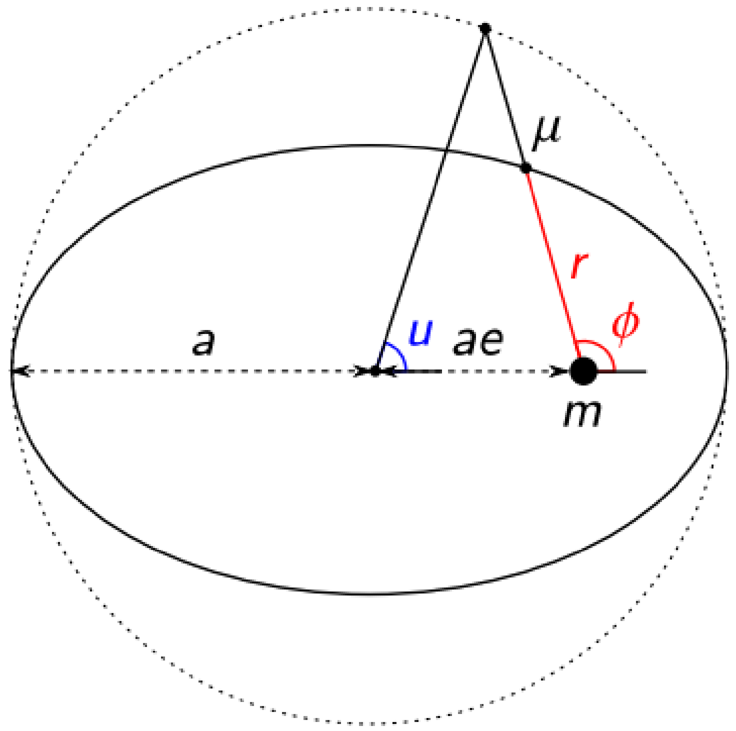


Two body problem – Mean η vs. true anomaly ϕ

- An elegant solution for the Newtonian two body problem.

$$r = a(1 - e\cos\eta)$$
$$n \cdot (t - t_0) = \eta - e\sin\eta$$
$$\phi = 2\arctan\left[\sqrt{\frac{1+e}{1-e}}\tan\left(\frac{\eta}{2}\right)\right]$$

- Keplerian 3rd law $n = \sqrt{\frac{GM}{a^3}}$. Equivalent to $r = a\,\frac{1-e^2}{1+e\cos\phi}$



$$\varepsilon = \frac{1}{2}\dot{r}^2 + j^2/2r^3 - \frac{GM}{r}, \quad j = r^2\dot{\theta},$$

General relativistic celestial mechanics of binary systems. I. The post-Newtonian motion

Annales de l'I. H. P., section A, tome 43, nº 1 (1985), p. 107-132.

T. DAMOUR
N. DERUELLE

1st Post Newtonian Solution

- With PN expansion $\frac{GM}{R\,c^2} \ll 1.$

$$L_{1PN} = L_N + \frac{1}{c^2}L_2. \quad L_2 = \frac{1}{8}mv^4 + \frac{1}{8}m'v'^4 + \frac{Gmm'}{2R}\left(3v^2 + 3v'^2 - 7\vec{v}\vec{v}' - (\vec{N}\vec{v})(\vec{N}\vec{v}') - G\frac{m+m'}{R}\right)$$

- EoM:

$$\left(\frac{dR}{dt}\right)^2 = A + 2B/R + C/R^2 + D/R^3$$

$$\frac{d\theta}{dt} = H/R^2 + I/R^3$$

1st Post Newtonian Solution

The Keplerian Solution

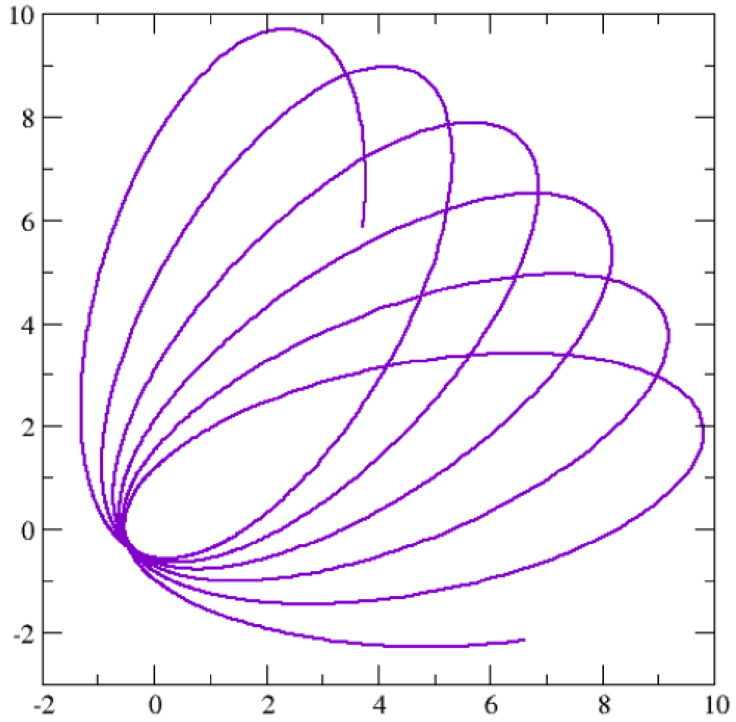
$$r = \mathrm{a}(1 - \mathrm{e}\cos\eta)$$
$$\mathrm{n}\cdot(\mathrm{t}-\mathrm{t}_0) = \eta - \mathrm{e}\sin\eta$$

- The mean anomaly gives elegant solution:

$$r = \mathrm{a}(1 - \mathrm{e}\cos\eta),$$
$$\mathrm{n}\cdot(\mathrm{t}-\mathrm{t}_0) = \eta - \mathrm{e}_\mathrm{t}\sin\eta,$$
$$\tilde{\nu} = 2\arctan\left[\sqrt{\frac{1+\mathrm{e}}{1-\mathrm{e}}}\tan\left(\frac{\eta}{2}\right)\right], \qquad \theta = \frac{\Phi}{2\pi}\tilde{\nu}$$

- The modified properties: $\frac{e_R}{e_t} = 1 + \frac{GM}{a_R c^2}\left(4 - \frac{3}{2}\frac{\mu}{M}\right)$

And $\Delta\Phi = \frac{6\,\pi\,G\,M}{ac^2(1-e_R^2)}$



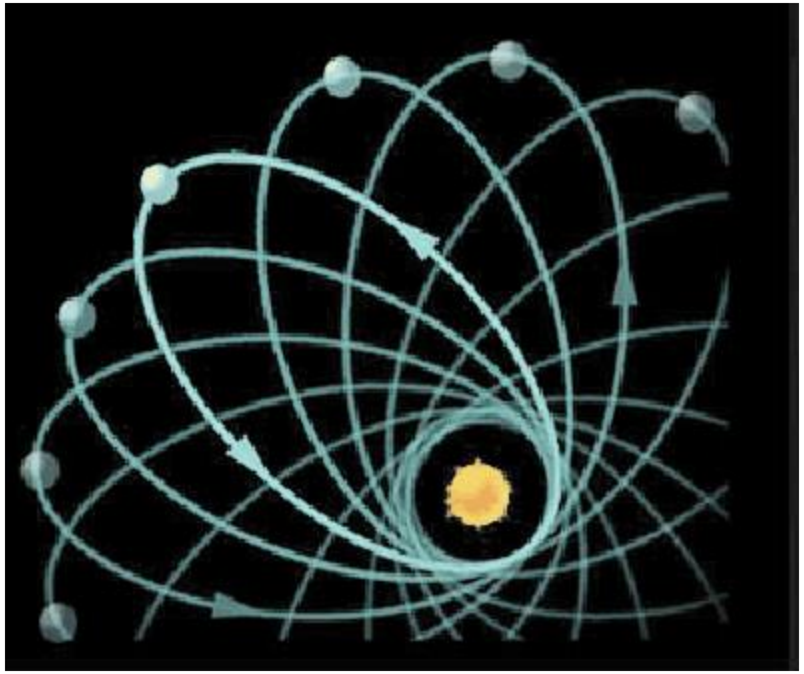
Precession

- Any perturbation over the Newtonian solution yields a precession.

- Mercury precession: 43 arc seconds per century.

- Pulsars: 16.899323(13)

PHYSICAL REVIEW X 11, 041050 (2021)



Analytical Solutions

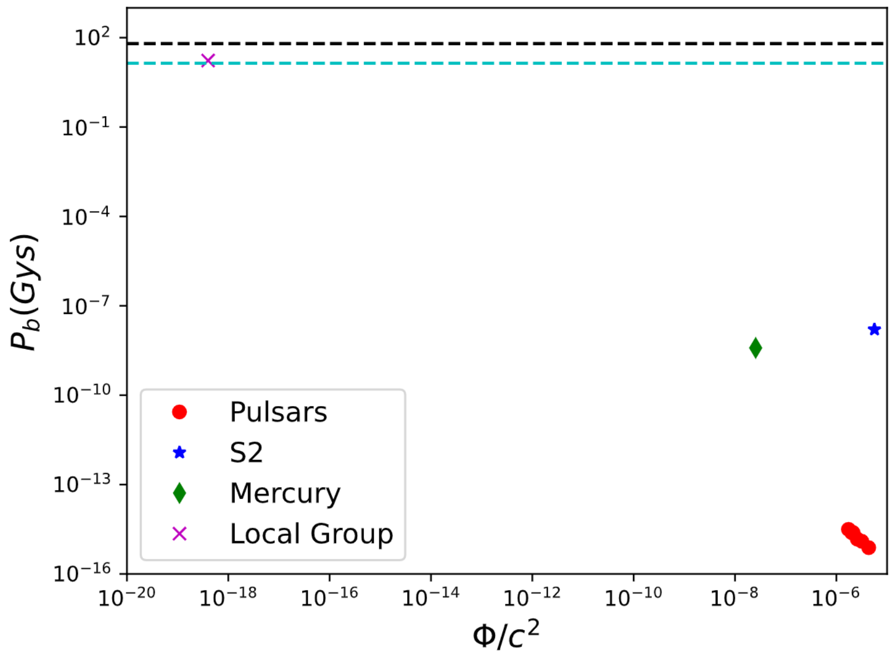
- The modification for the Newtonian case:

$$\lambda := \frac{a^3 c^2}{GM}\Lambda = \left(\frac{T_{Kep}}{63.2\ Gys}\right)^2$$

- The perturbed solution:

$$\frac{2\pi}{T}(t - t_0) = \eta - e_t \sin\eta - \lambda\left(\frac{5e^2}{24}s_2 - \frac{e^3}{72}s_3\right)$$

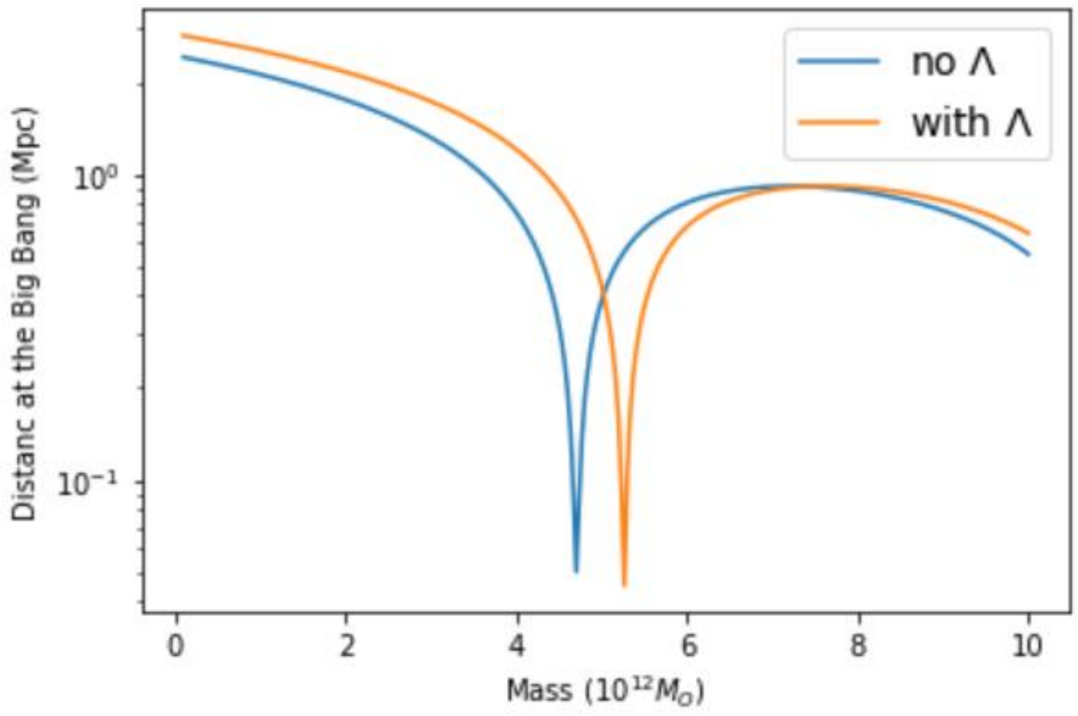
$$\frac{e_t}{e} = 1 - \frac{16 - 7e^2}{24}\lambda, \quad \frac{1}{T} = \frac{1}{T_{\rm Kep}}\left[1 - \frac{8 + 3e^2}{12}\lambda\right]$$



Timing Argument implementations

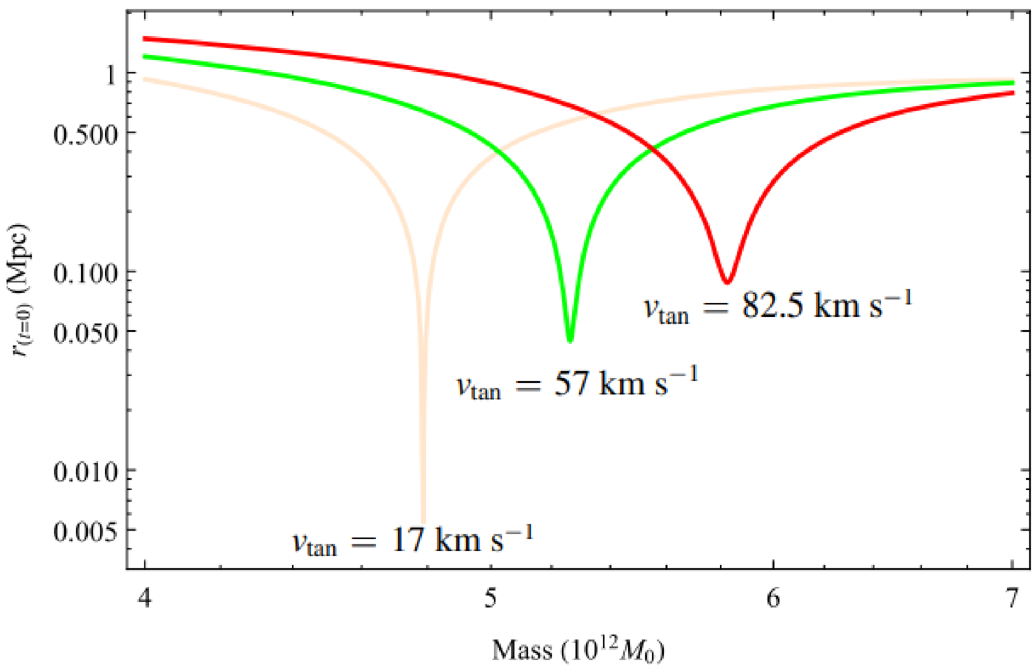
- Initial conditions: $r(t = 0) = 0$.
- Velocities and location
- $\lambda = 0.103 \pm 0.01$

- Prior r, v_r, v_t, t, Λ
- Posterior a, e, ν, T

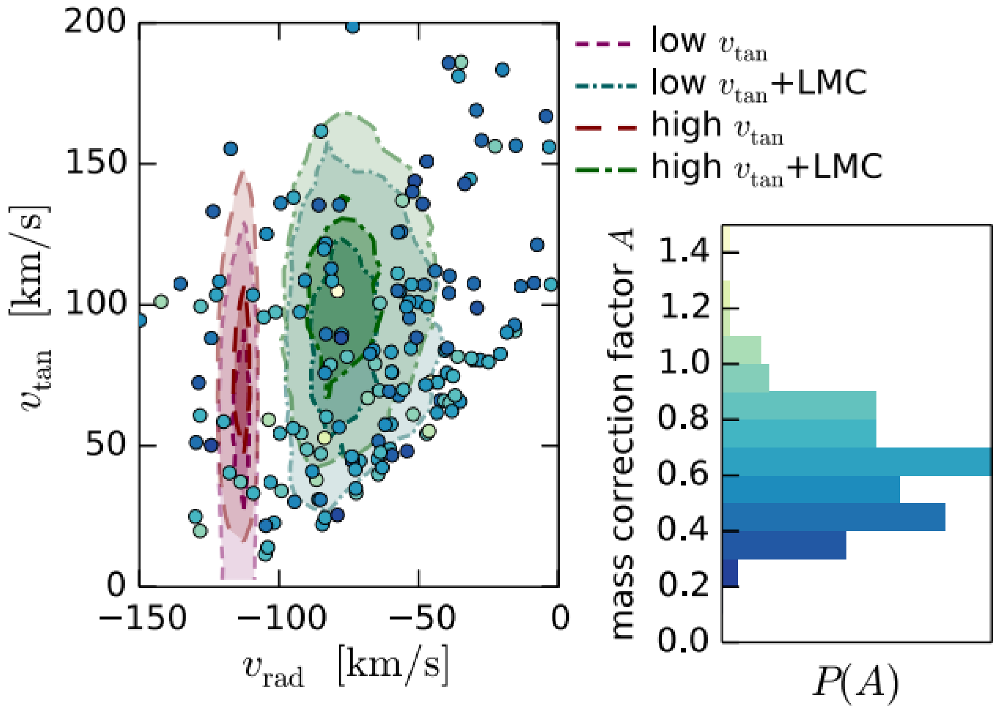


TA with the CB from simulations

- Different Vt – Different mass



- The cosmic bias dependence

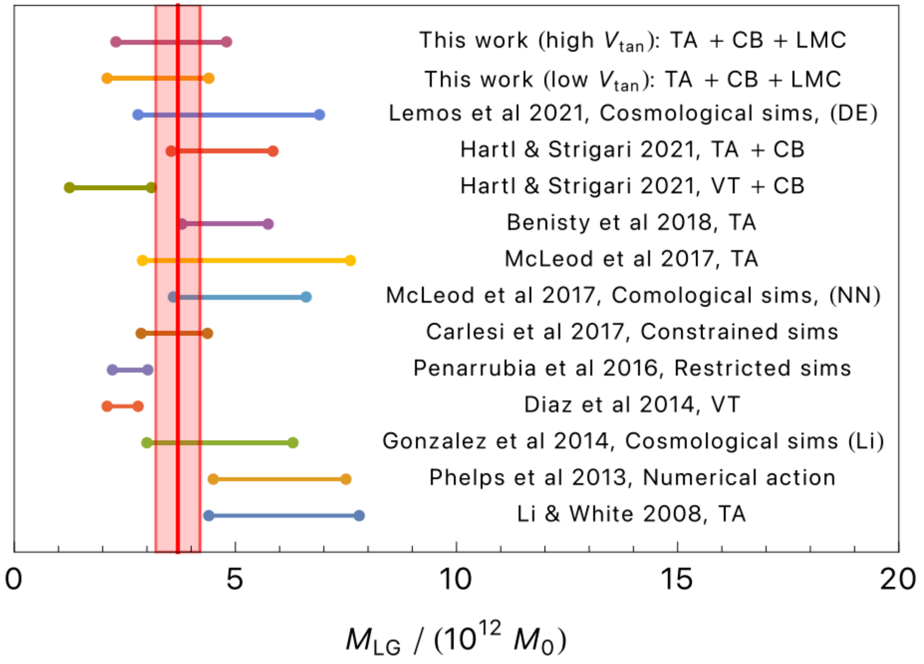


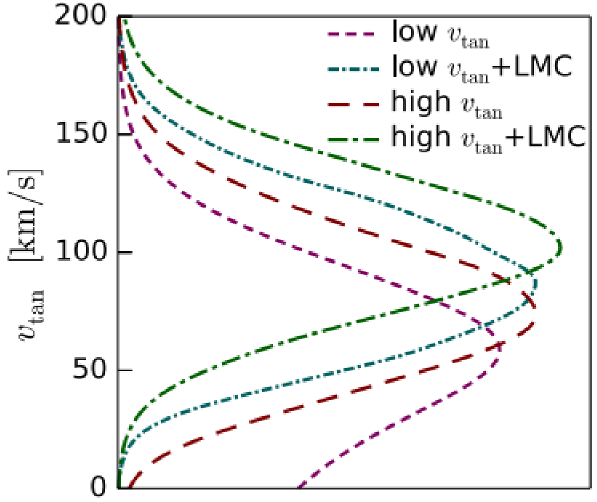
David Benisty[1,2,3], Eugene Vasiliev[4], N. Wyn Evans[4], Anne-Christine Davis[1,2], Odelia V. Hartl[5] and Louis E. Strigari[5]

Benisty *et al.* 2022 *ApJL* 928 L5

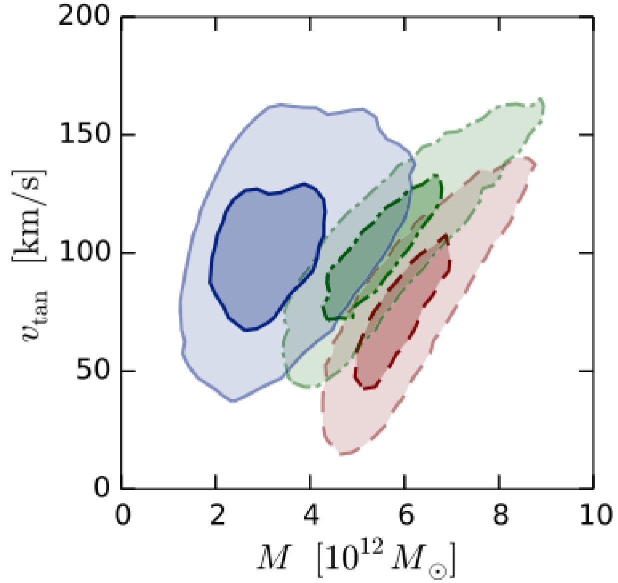
The Local Group Mass in the Light of Gaia

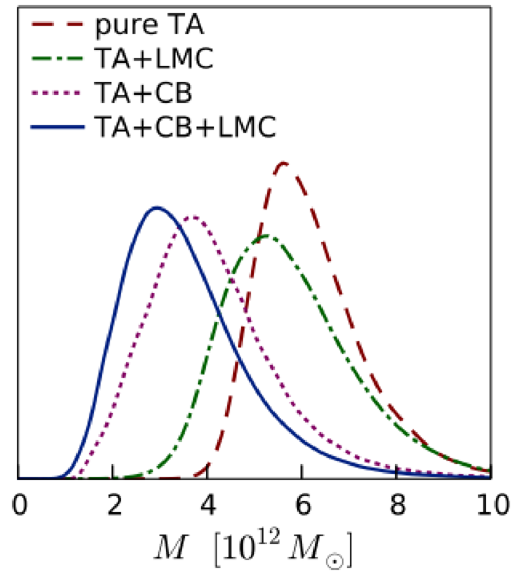
- Local Group analogs in cosmological simulations based on stellar mass and kinematic criteria. **Hartl & Strigari 2021**
- The **Cosmic Bias**
- No Past Encounter.





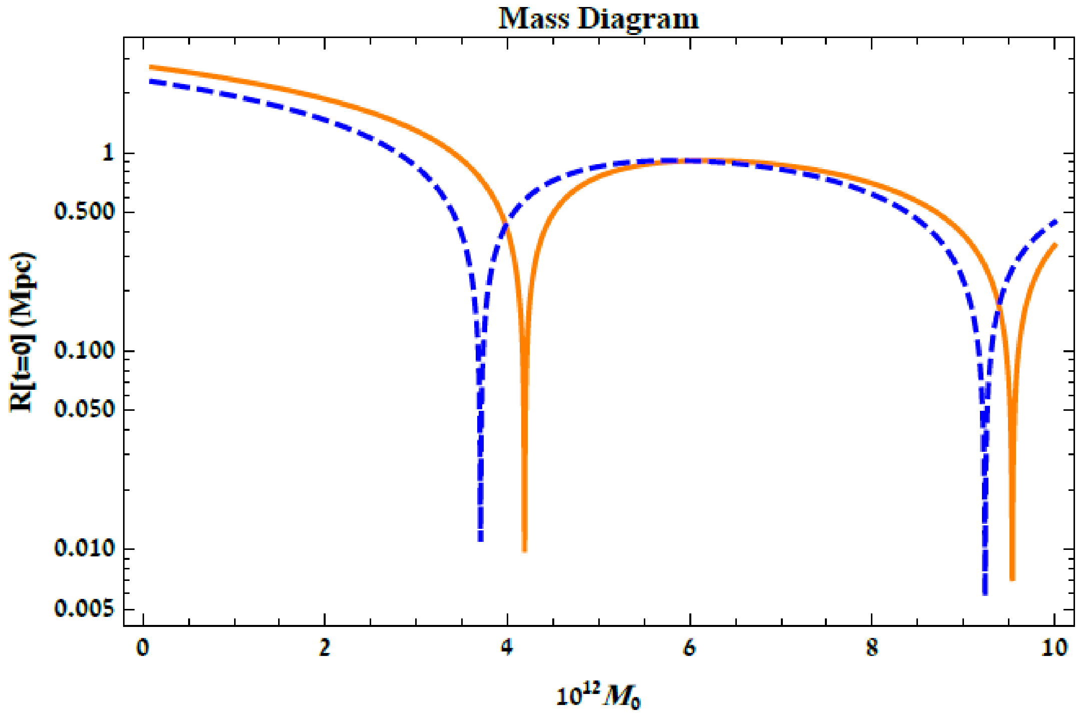
Model	$M(10^{12}M_\odot)$
pure TA	$6.0^{+1.3}_{-0.9}$
TA+LMC	$5.6^{+1.6}_{-1.2}$
TA+CB	$3.9^{+1.5}_{-1.1}$
TA+CB+LMC	$3.4^{+1.4}_{-1.1}$
same, low v_{tan}	$3.1^{+1.3}_{-1.0}$

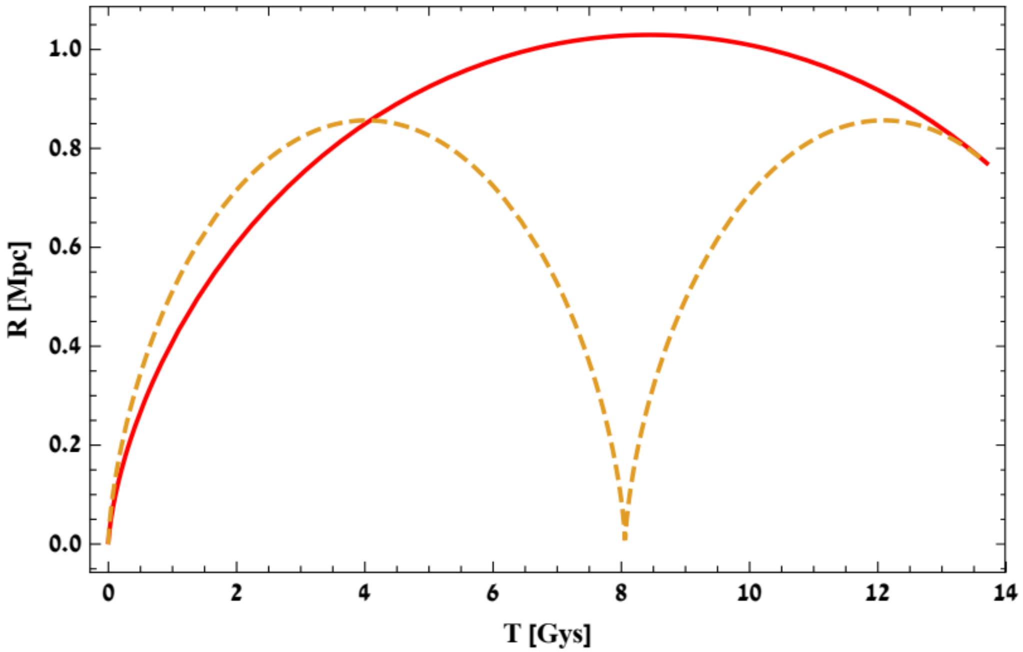


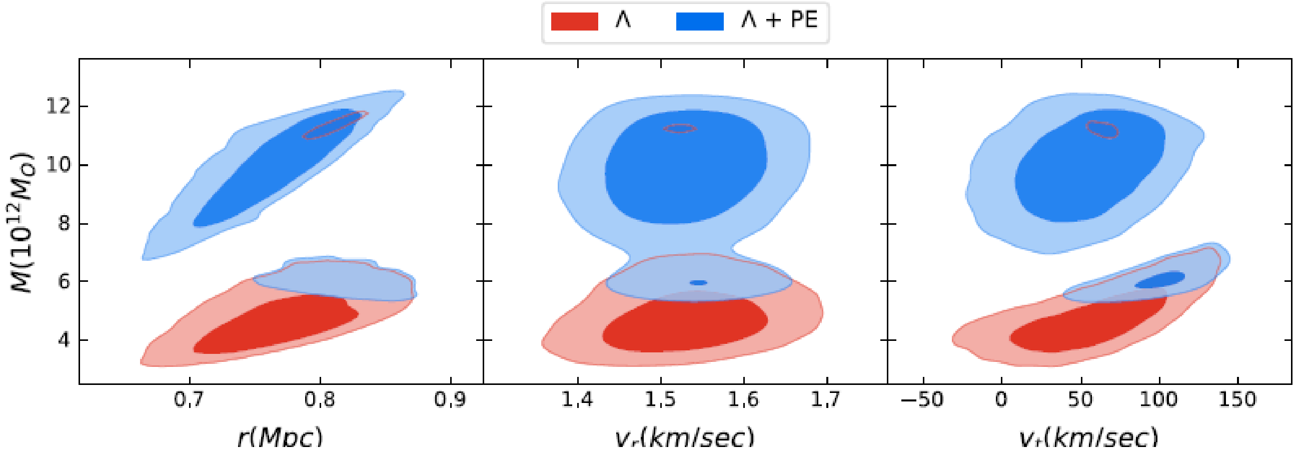


D. Benisty MW & M31 Past Encounter: A&A 656, A129 (2021)

TA – No Past Encounter





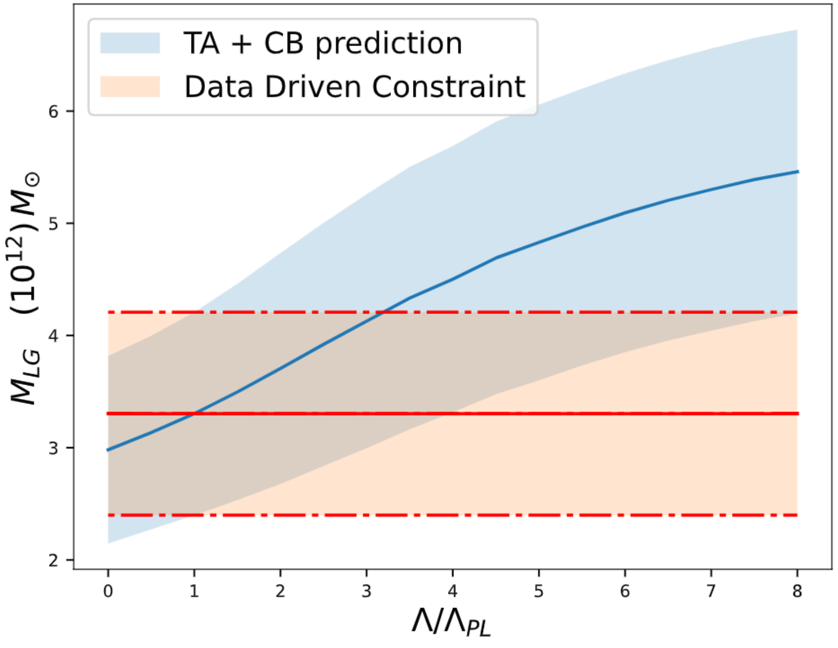


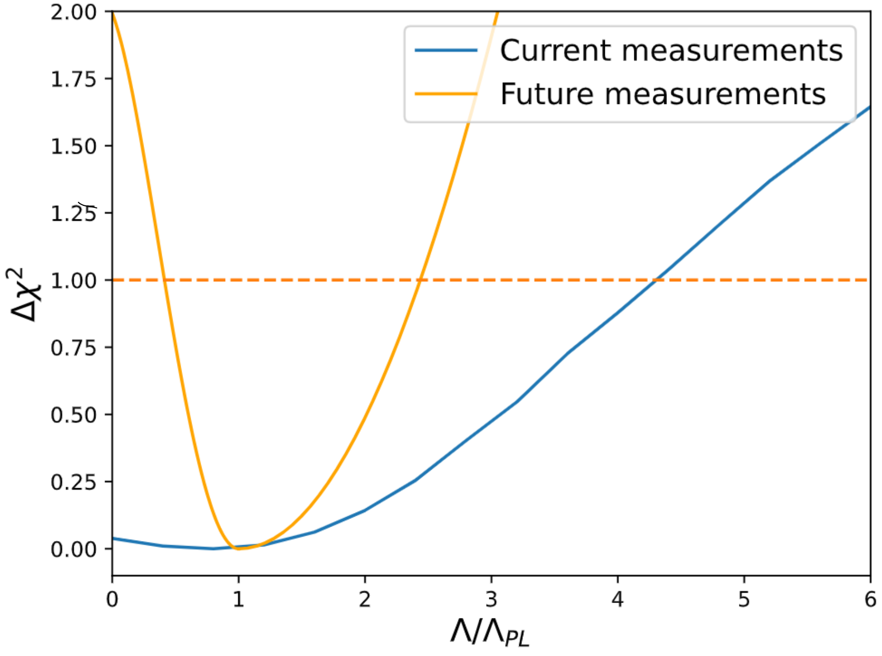
Case	$M(10^{12}\ M_\odot)$
No Λ, no PE	4.13 ± 0.78
With Λ, no PE	4.61 ± 1.39
No Λ, with PE	9.63 ± 2.14
With Λ, with PE	9.77 ± 2.47

Bounding DE from the LG

- The dependence between the TA mass and Λ.

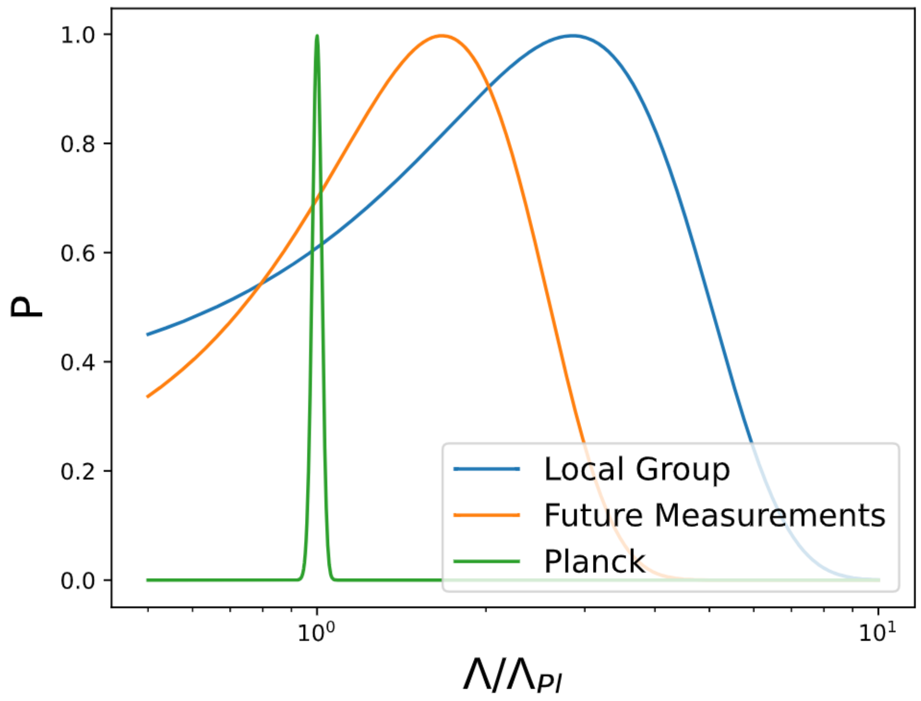
- Λ from the known mass : $\Lambda/\Lambda_{Pl} = 3.074 \pm 2.369$.





Future measurements

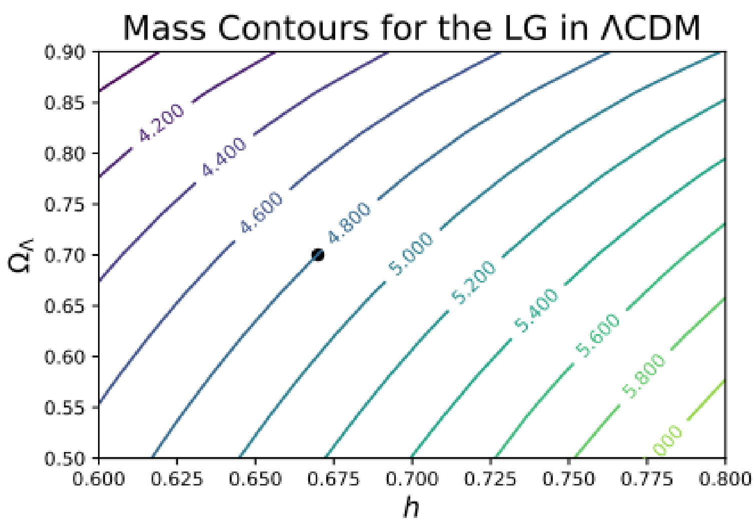
- δr = 5.2%, δvr = 4%, δvt = 37.86%
- With JWST the upper bound will be $= (1.670 \pm 0.794)\ \Lambda_{Pl}$
- Do we really measure Λ?



McLeod & Lahav *JCAP* 09 (2020) 056

Modified Gravity and LG mass

The Two Body Problem in the Presence of Dark Energy and Modified Gravity: Application to the Local Group



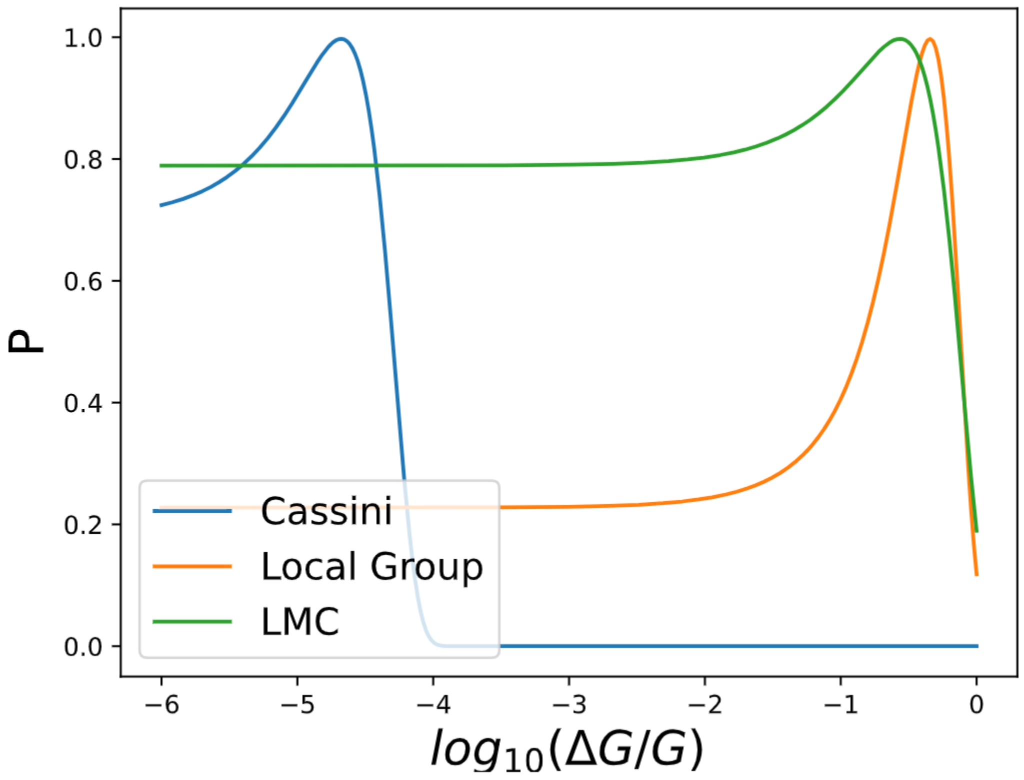
Model	Parameters	M_{LG} / $10^{12} M_\odot$
ΛCDM	$h = 0.67,\ \Omega_\Lambda = 0.7$	4.80
ΛCDM	$h = 0.63,\ \Omega_\Lambda = 0.7$	4.55
ΛCDM	$h = 0.76,\ \Omega_\Lambda = 0.7$	5.43
wCDM	$h = 0.67,\ \Omega_f = 0.7,\ w = -1.1$	4.79
wCDM	$h = 0.67,\ \Omega_f = 0.7,\ w = -0.9$	4.81
Symmetron + Λ	$\mu = 2.46 \times 10^{-58}$ GeV, $\lambda = 10^{-109}$, $S = 0.015$	3.34
MOND	$a_0 = 1.2 \times 10^{-10}\,\mathrm{m\,s^{-2}}$, $t_u = 13.69$ Gyr	0.027

Modified Gravity

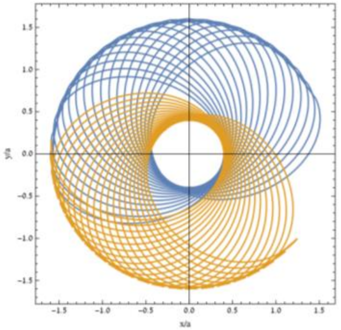
- Dynamical G could emerge from many theories. $G \sim \frac{1}{f(R)}$.

- Cassini constraint: (Nature, 425, 374)
  $(2.1 \pm 2.5) \times 10^{-5}$

- $\Delta G/G = 0.264 \pm 0.454$



F(R) gravity



Benisty, Capozziello 2022 Under Review

Capozziello et al. 2022 *Phys.Rev.D* 76 (2007) 104019

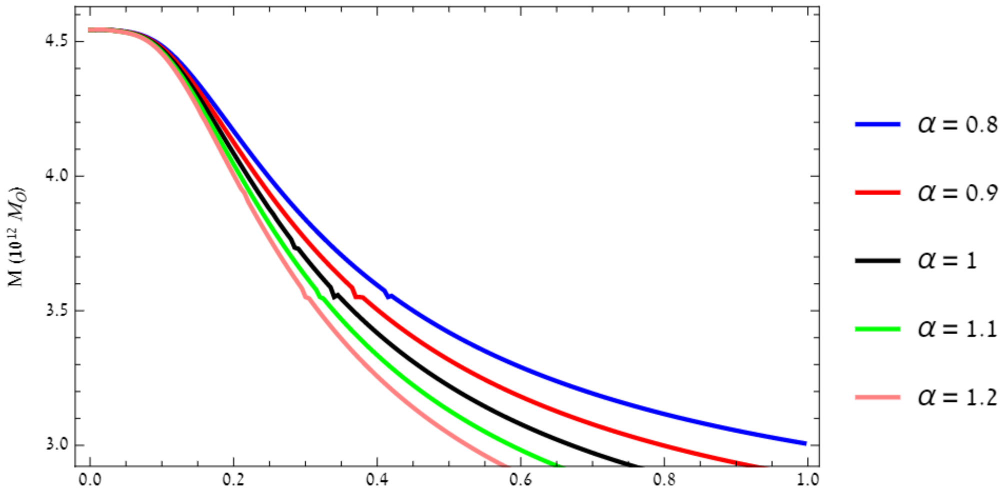
- In the low energy limit the theories screens Yukawa Type potential.

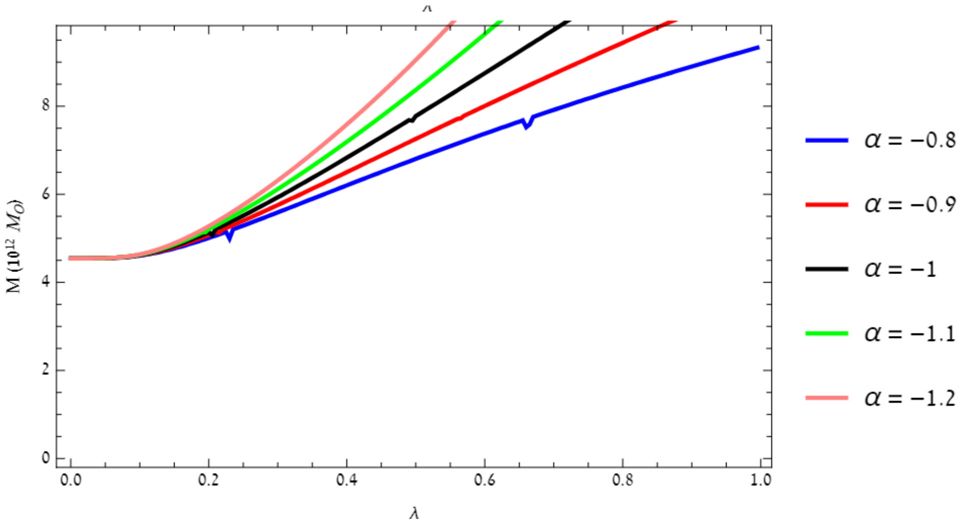
$$\Phi(r) = -G\,\frac{M}{r}\,\frac{1+\alpha\, e^{-r/\lambda}}{1+\alpha}$$

$$L^{-1} \precsim 0.3 \pm 9.9\, Kpc^{-1},$$
$$\alpha \precsim 4.9 \pm 4.7 \cdot 10^{-3}.$$

With $\alpha = 1 - f',\ \ \lambda^2 = -6\,\frac{f''}{f'}.$

<u>Some analytical Solutions</u> *D. Benisty Phys.Rev.D* 106 (2022) 4, 043001





Summery

- Post Encounters require higher mass for the LG.
- The cosmological constant requires higher mass.
- Binary motion gives constraints on Λ and MoG.
- Do we really measure the cosmological constant?