David Benisty

Bounding Dark Energy from the Local Universe

D. Benisty **A&A 656, A129 (2021);** D. Benisty; A-Davis, W. Evans 2306.14963

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)

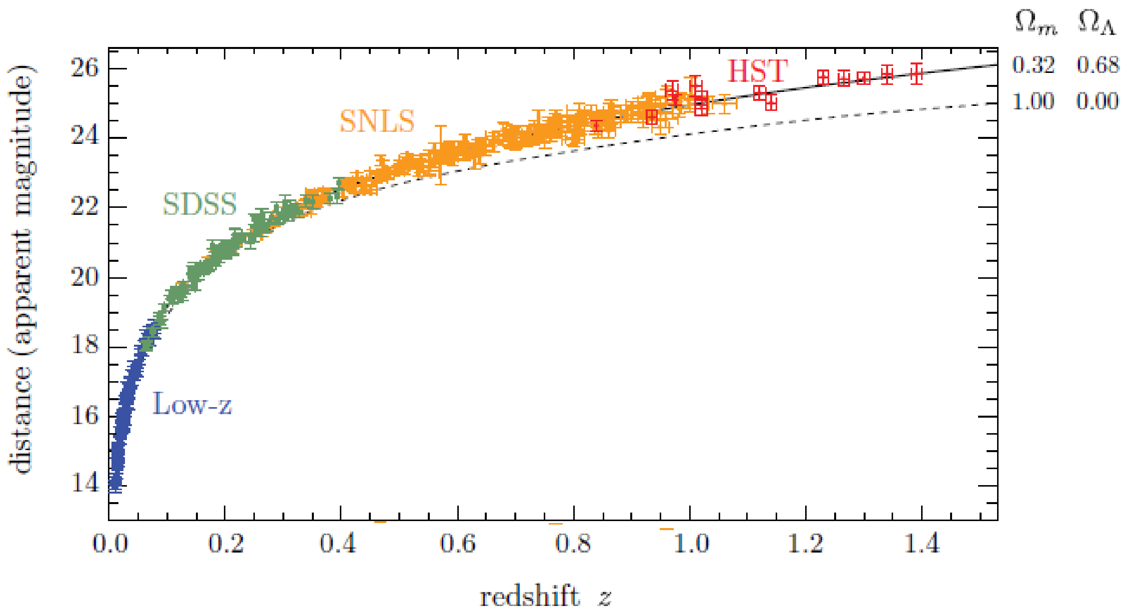
- Baryon Acoustic Oscillations

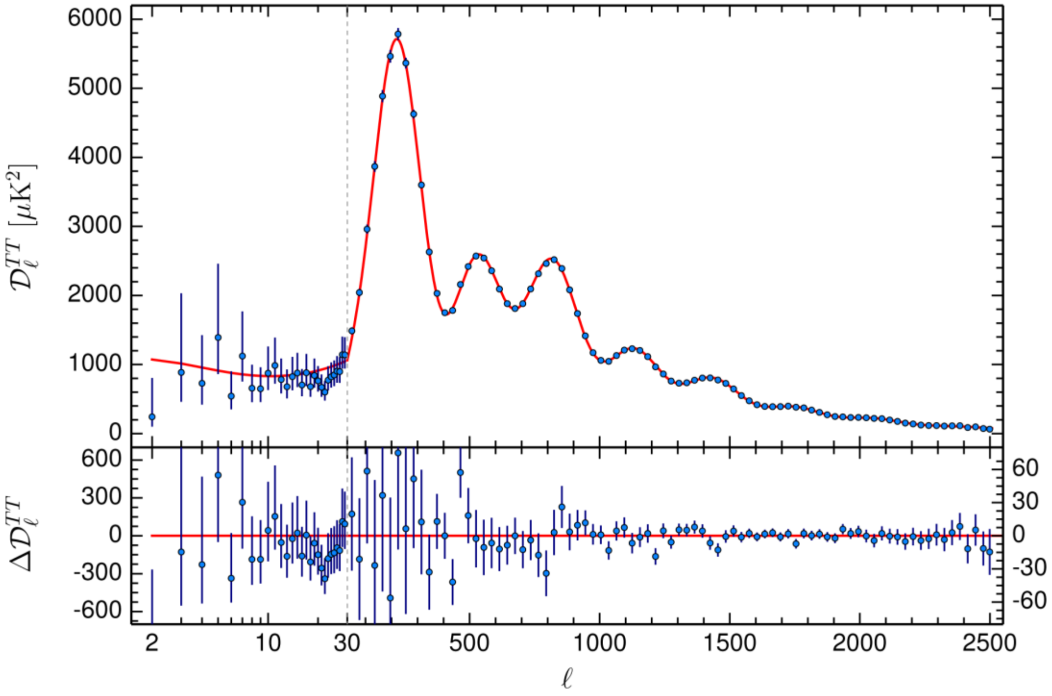
Phys. Rev. D 92, 123516 (2015)

- Cosmic Microwave Background

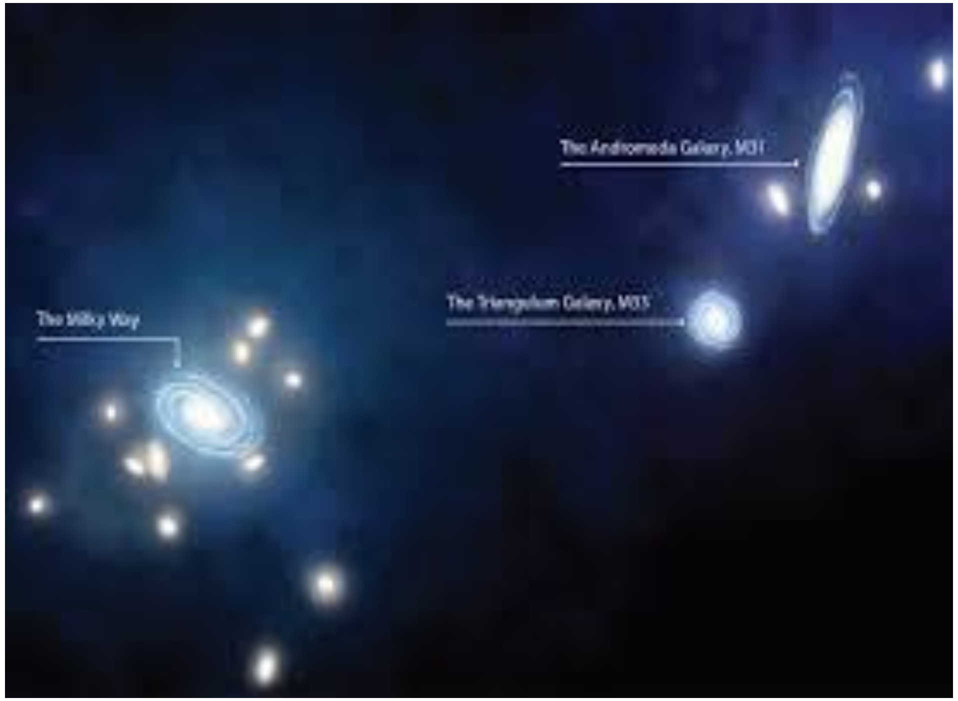
(Planck 2018)

- LSST, Others…





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:

$r = 0.77 \pm 0.04\ Mpc$

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

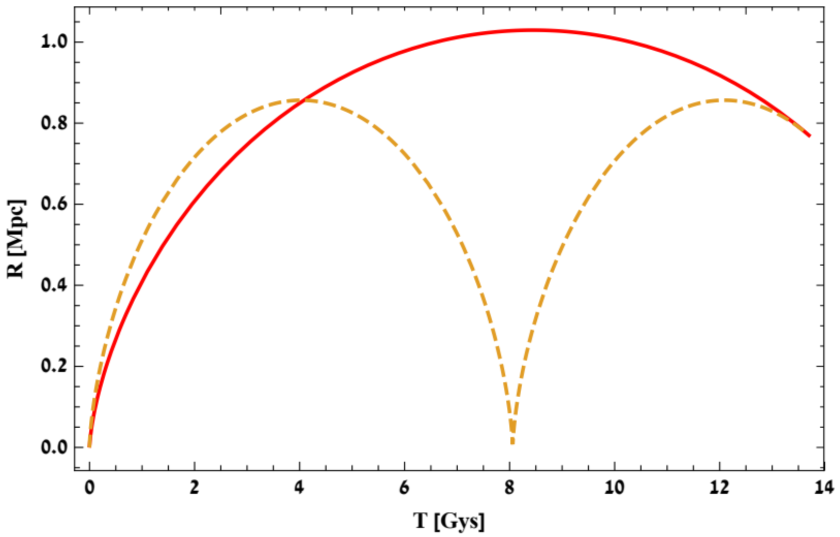
R. P. van der Marel, M. A. Fardal, S. T. Sohn, E. Patel, G. Besla, A. del Pino, J. Sahlmann, and L. L. Watkins, JCAP 872, 24 (2019)

- 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)

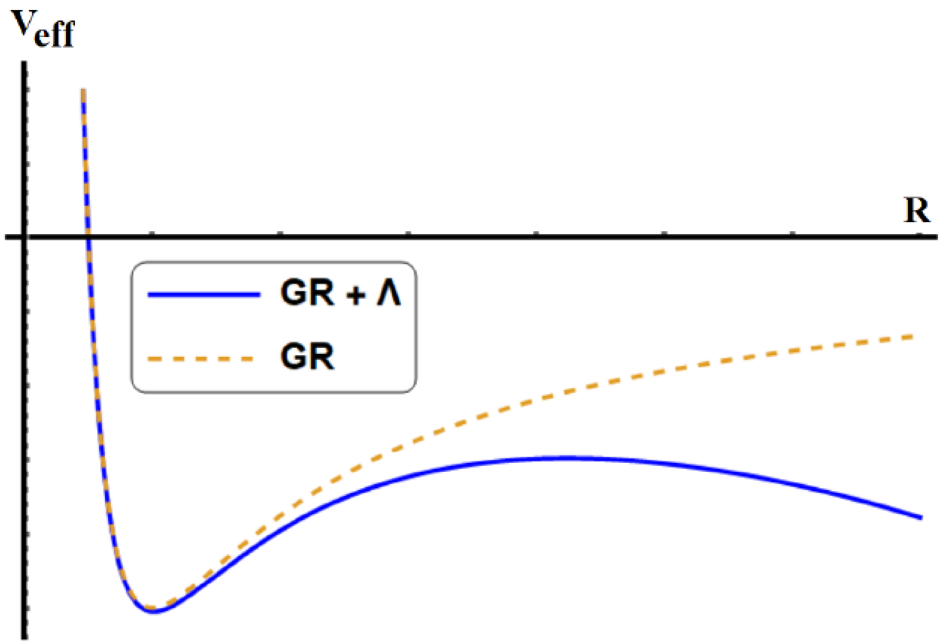
where $t_u = 13.7$ G. years

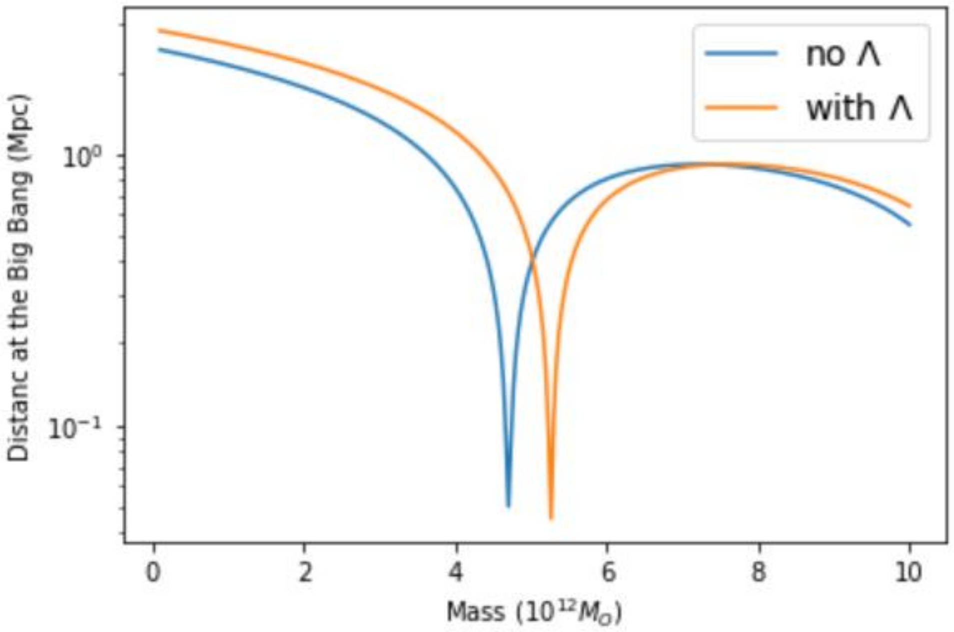
$$\ddot{r} = -\frac{GM}{r^2} + \frac{\Lambda c^2}{3} r + \frac{l^2}{r^3}$$

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

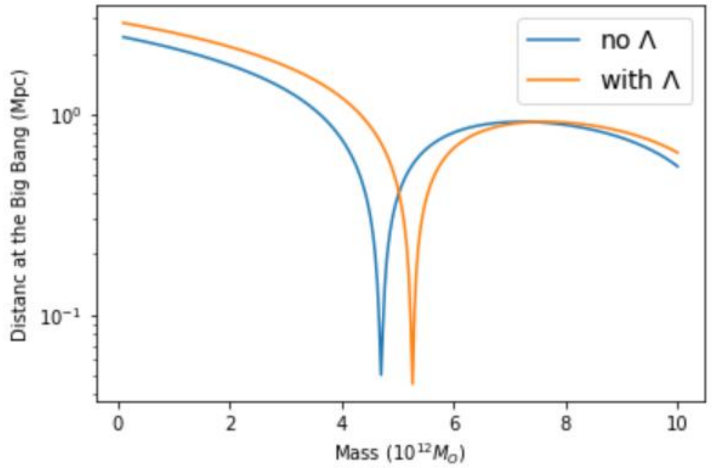
- <u>The Λ change in the LG: 10%</u>

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





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: $\lambda = 0.103 \pm 0.01$

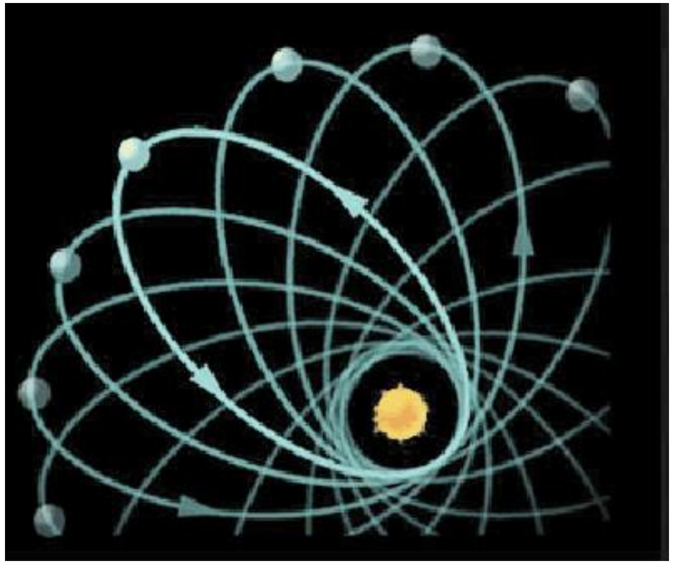
$$\frac{2\pi}{T}(t - t_0) = \eta - e_t \sin\eta - \lambda\left(\frac{5e^2}{24}s_2 - \frac{e^3}{72}s_3\right)$$

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

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)

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

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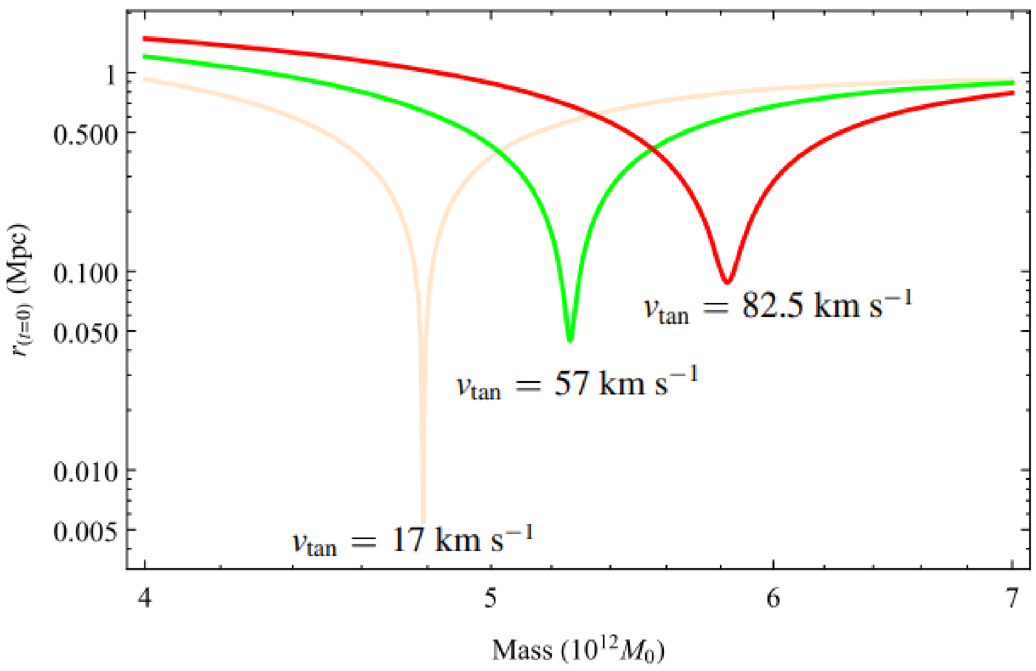
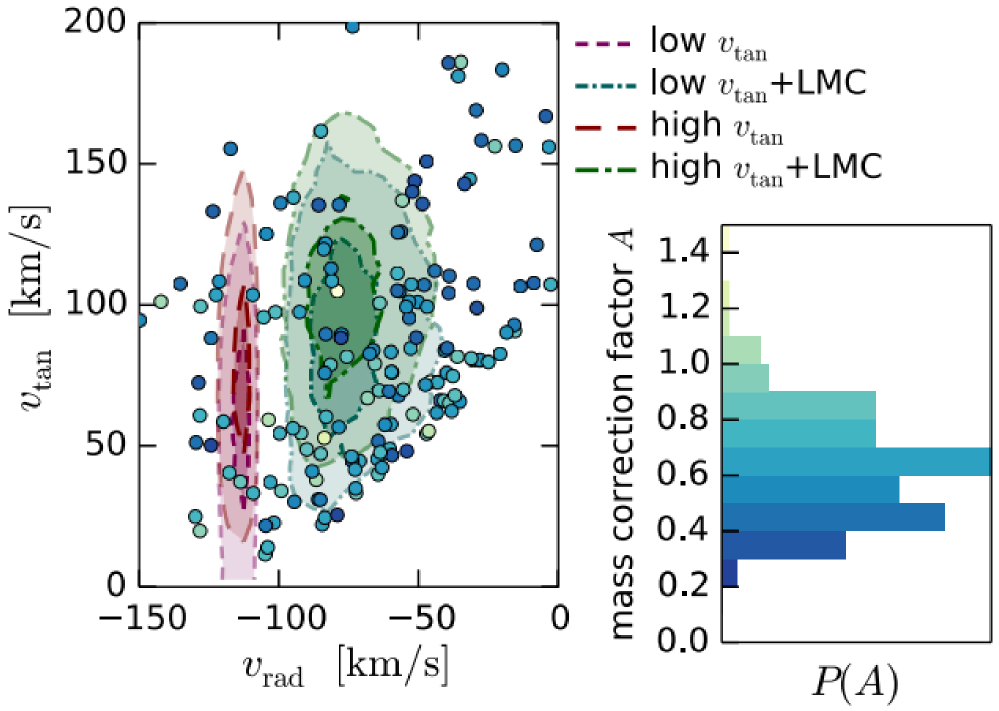
TA with the CB from simulations

- Different Vt – Different mass



- The cosmic bias dependence

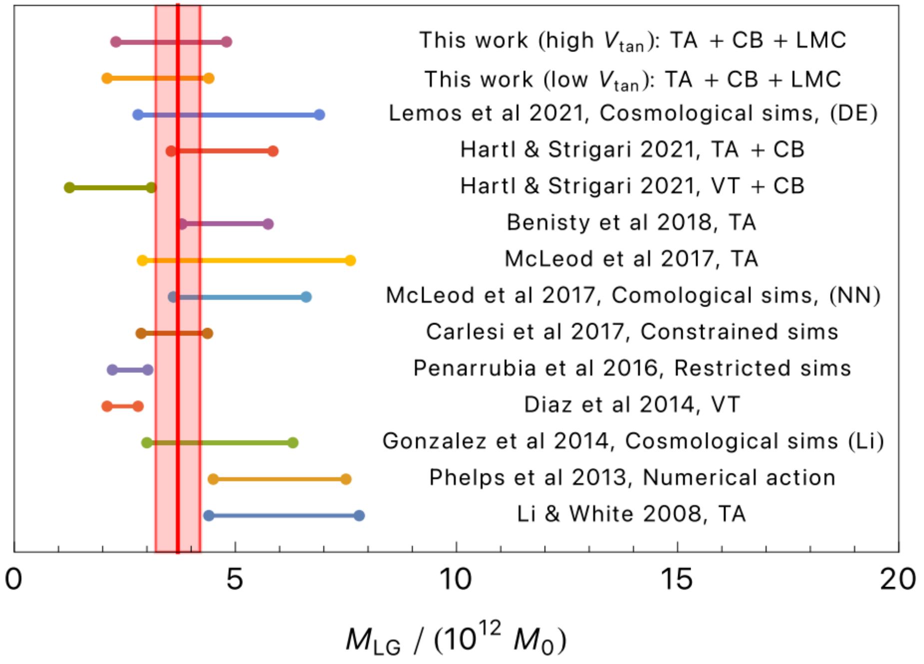


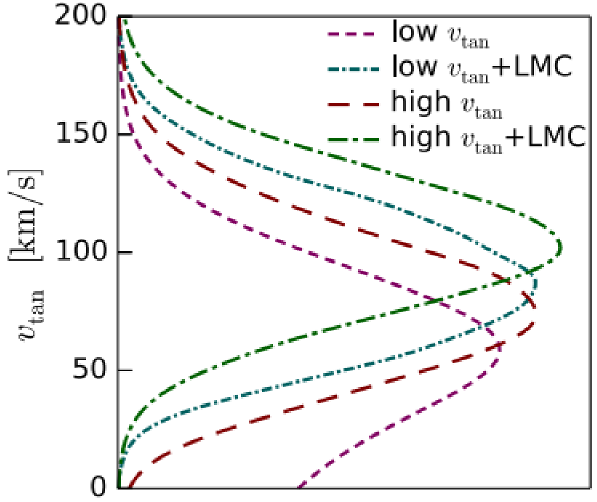
David Benisty[1,2,3], Eugene Vasiliev[4], N. Wyn Evans[4], Anne-Christine Davis[1,2], Odelia V. Hartl[5] and Louis E. Strigari[5]

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

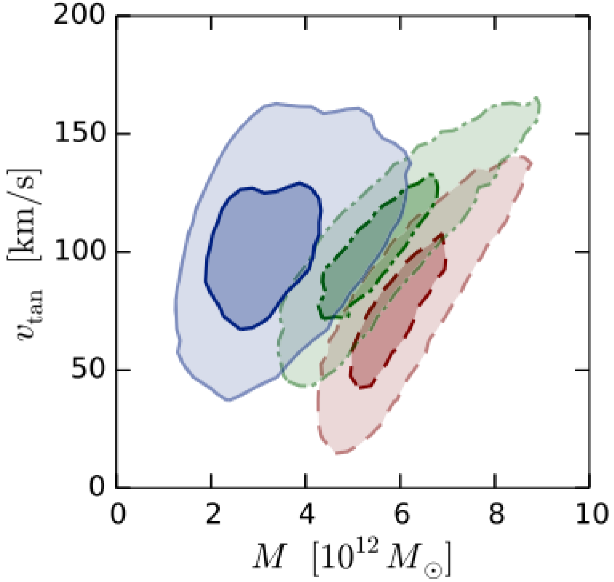
The Local Group Mass in the Light of Gaia

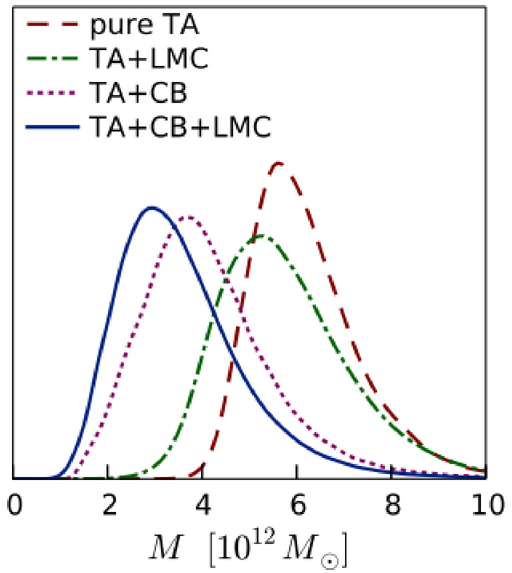
- Local Group analogs in cosmological simulations based on stellar mass and kinematic criteria. **Hartl & Strigari 2021**
- The **Cosmic Bias**
- No Past Encounter.





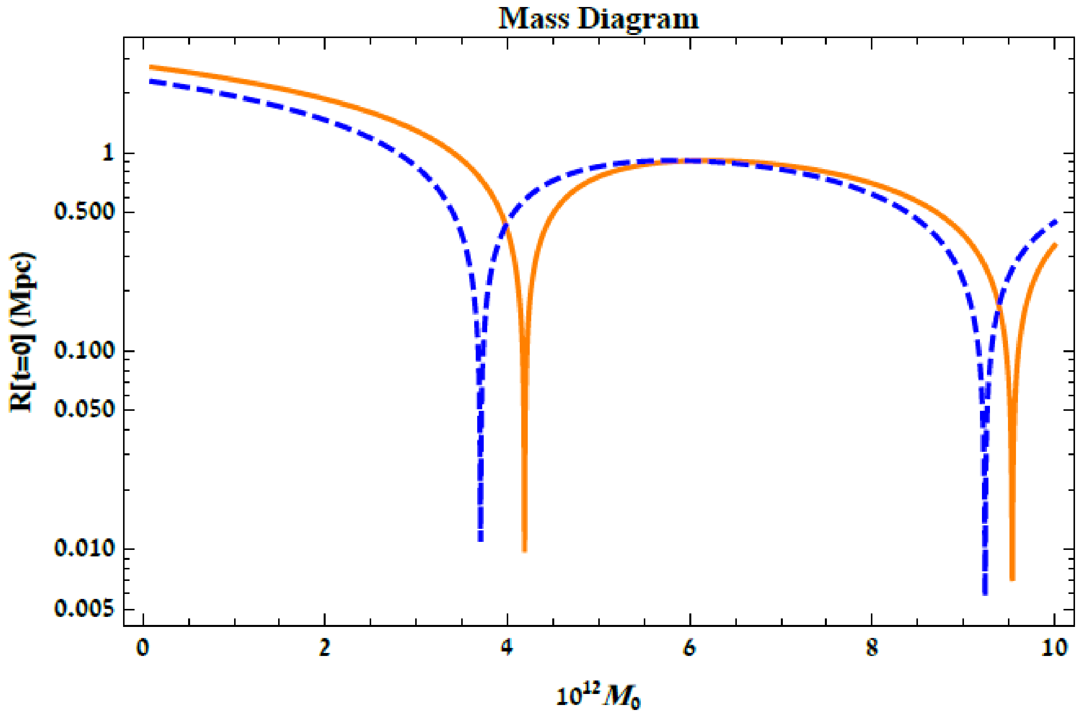
Model	$M(10^{12}M_\odot)$
pure TA	$6.0^{+1.3}_{-0.9}$
TA+LMC	$5.6^{+1.6}_{-1.2}$
TA+CB	$3.9^{+1.5}_{-1.1}$
TA+CB+LMC	$3.4^{+1.4}_{-1.1}$
same, low v_{tan}	$3.1^{+1.3}_{-1.0}$

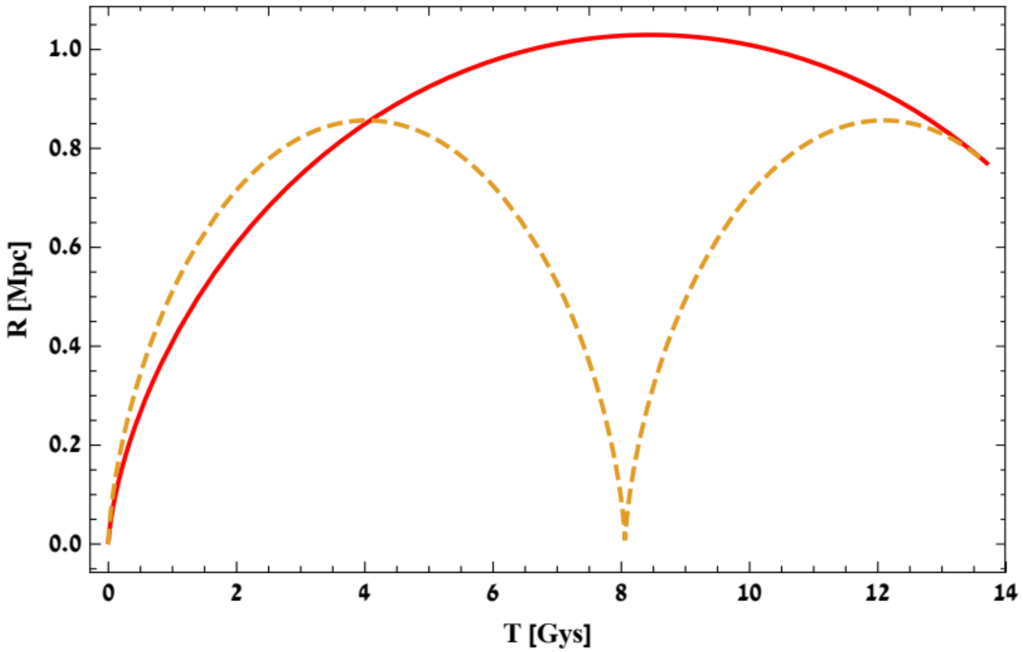




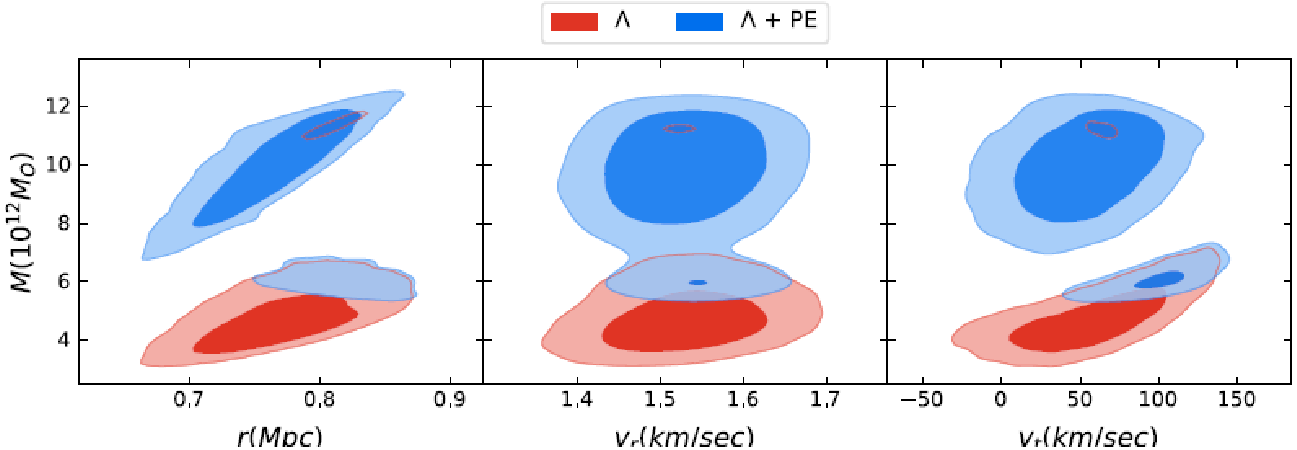
D. Benisty MW & M31 Past Encounter: A&A 656, A129 (2021)

TA – No Past Encounter



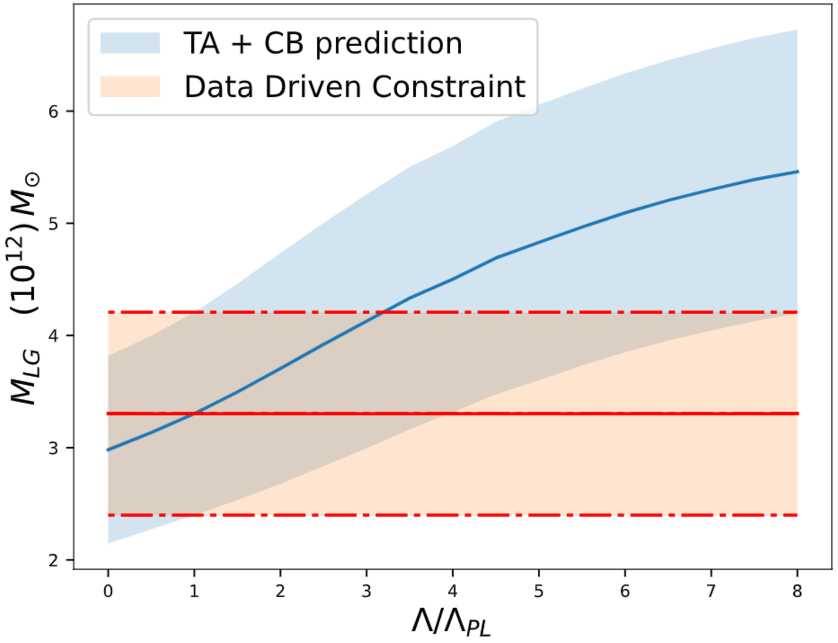


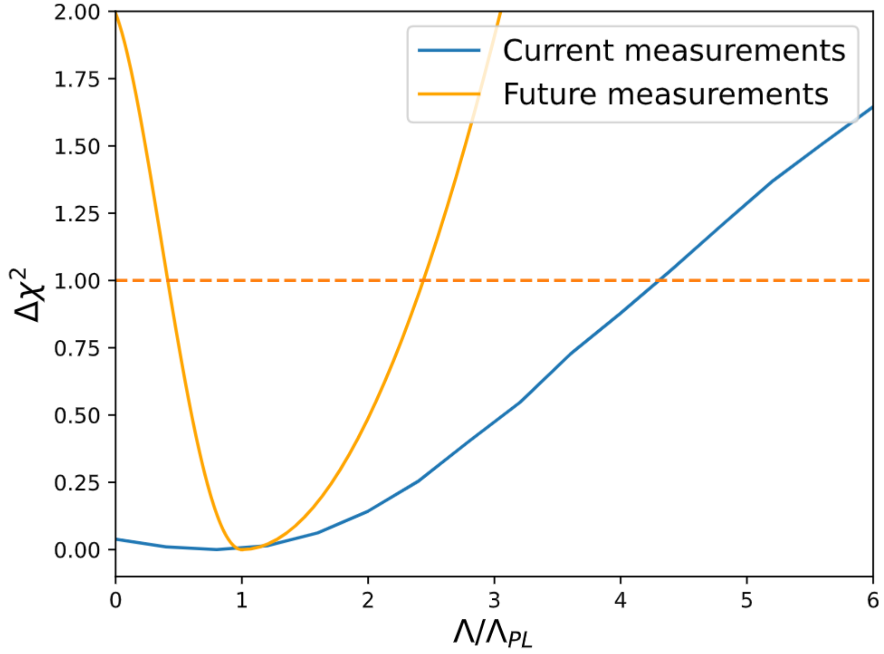
Case	$M(10^{12}\,M_\odot)$
No Λ, no PE	4.13 ± 0.78
With Λ, no PE	4.61 ± 1.39
No Λ, with PE	9.63 ± 2.14
With Λ, with PE	9.77 ± 2.47



Bounding DE from the LG

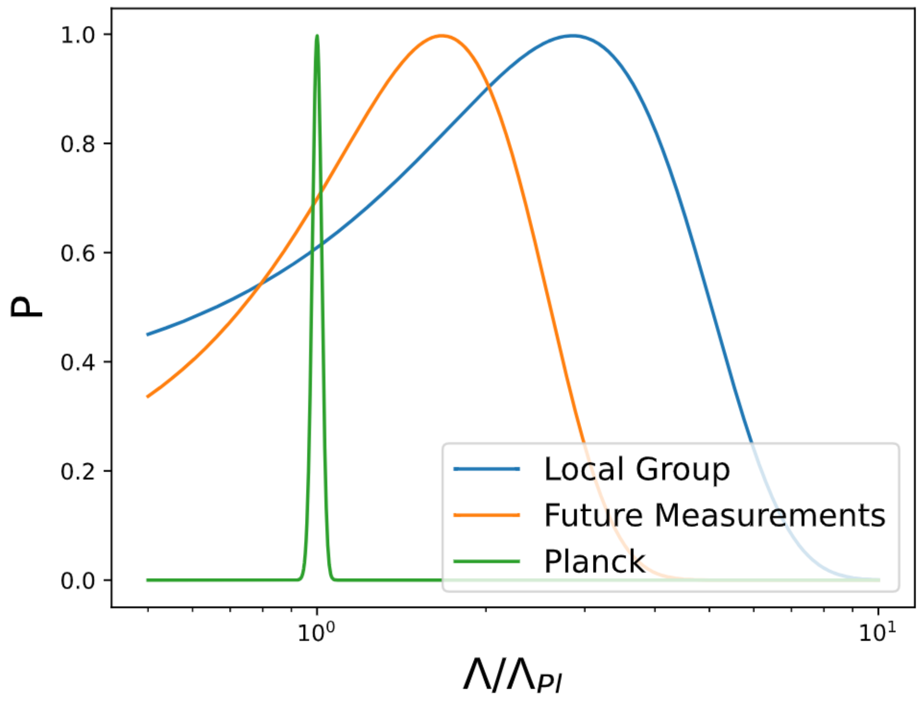
- The dependence between the TA mass and Λ.
- Λ from the known mass : $\Lambda/\Lambda_{Pl} = 3.074 \pm 2.369$.





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?



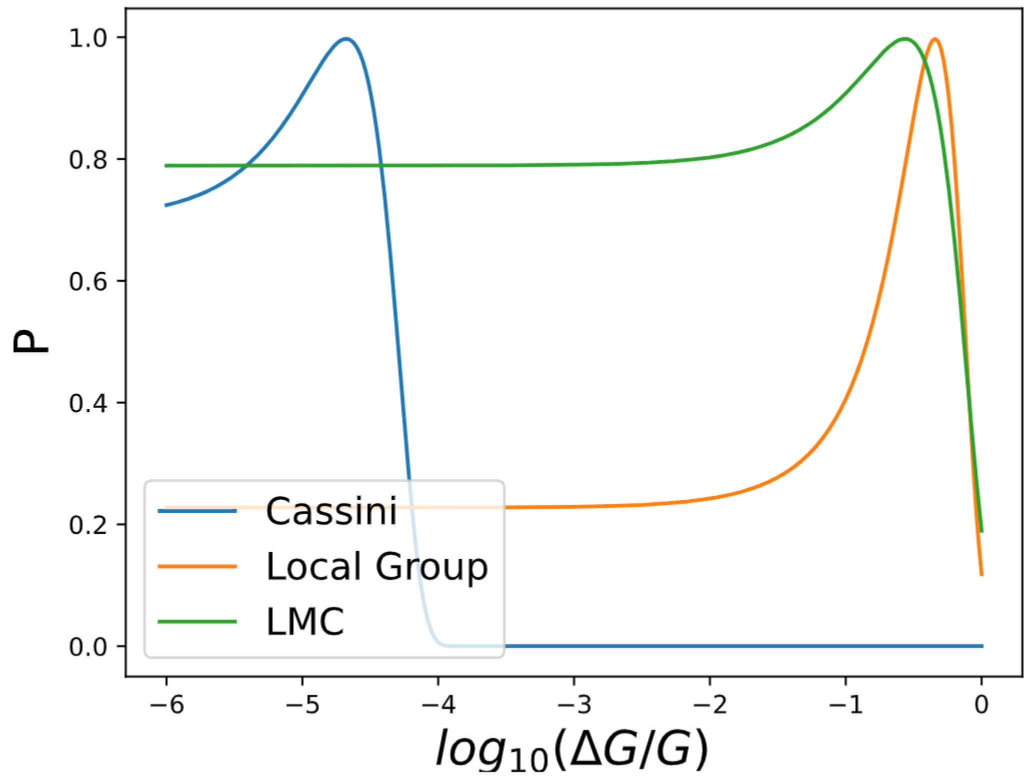
Modified Gravity

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

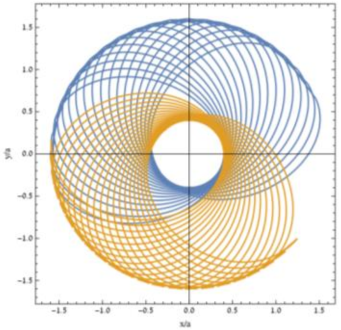
- Cassini constraint: (Nature, 425, 374)

$(2.1 \pm\ 2.5\ ) \times\ 10^{-5}$

- ΔG/G = 0.264 ± 0.454



F(R) gravity



Benisty, Capozziello 2022 Under Review

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

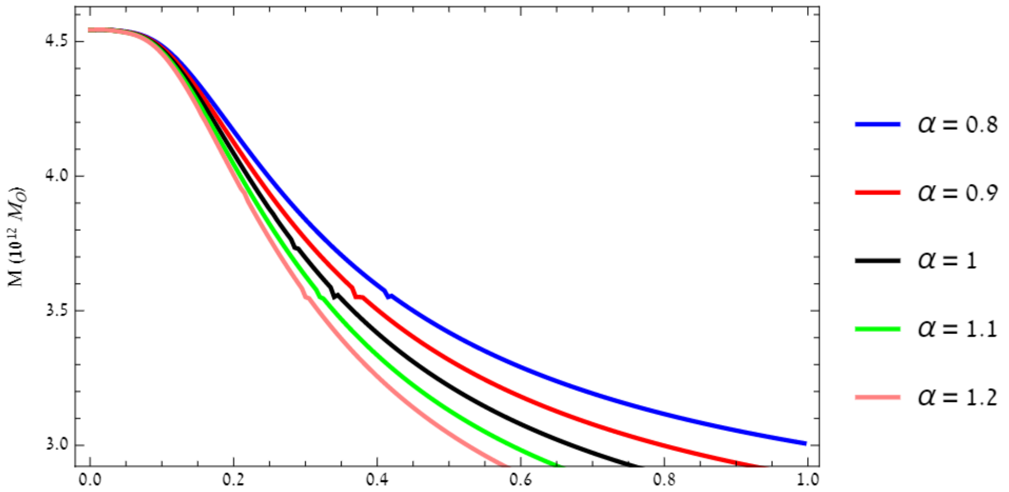
- In the low energy limit the theories screens Yukawa Type potential.

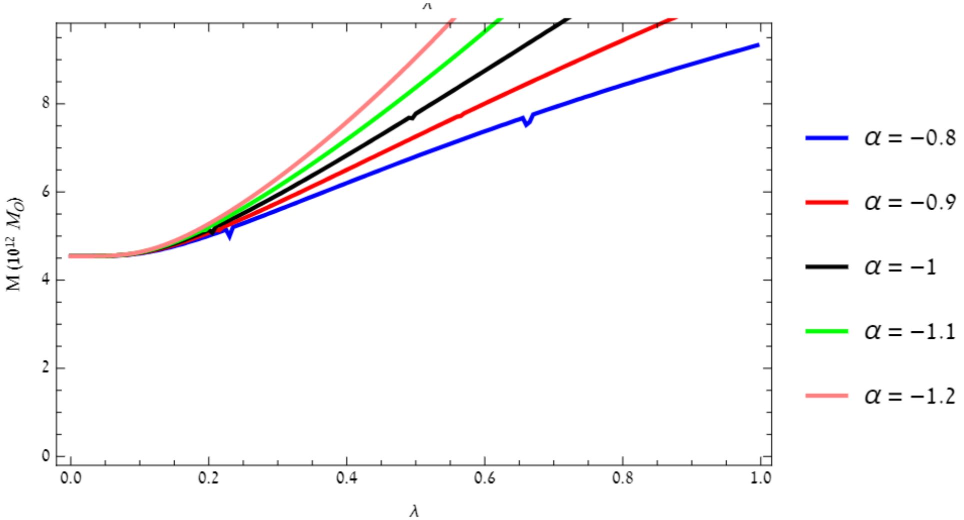
$$\Phi(r) = -G\,\frac{M}{r}\,\frac{1+\alpha\, e^{-r/\lambda}}{1+\alpha}$$

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

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?