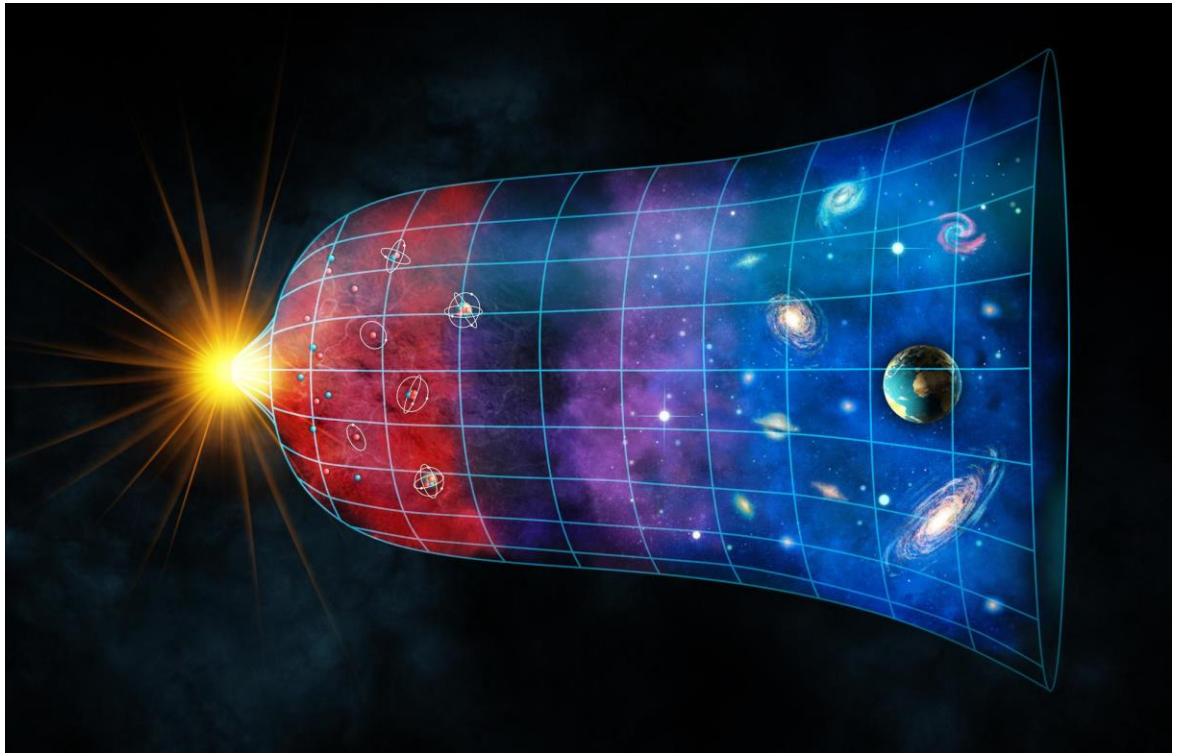


Leibniz-Institut für Astrophysik Potsdam

FIAS Frankfurt Institute for Advanced Studies

MINERVA STIFTUNG

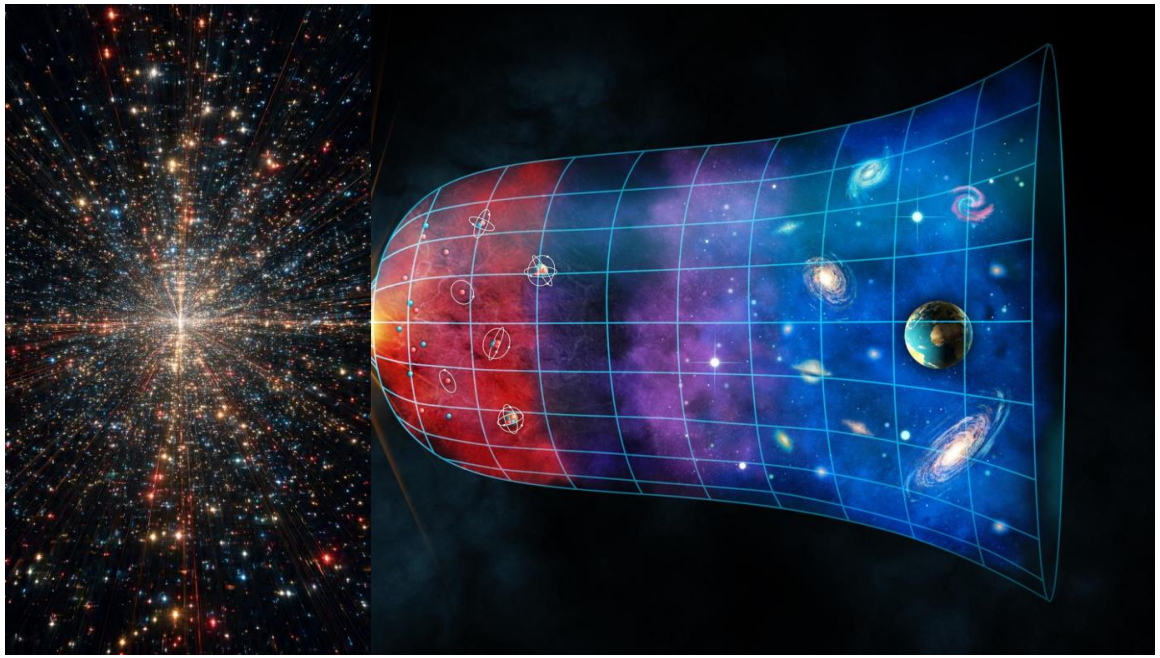
CLUES
Constrained Local UniversE Simulations

David Benisty

Illuminating Dark Energy

And let there be light

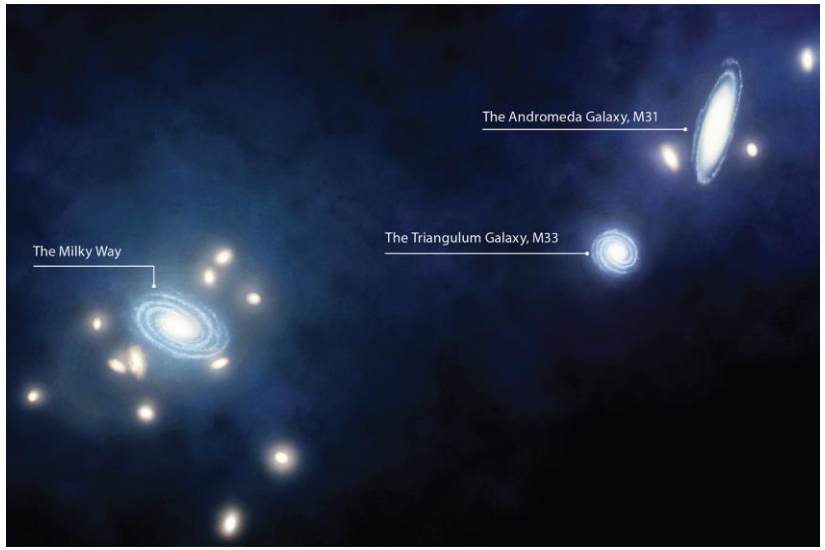
We track the dark with the light.

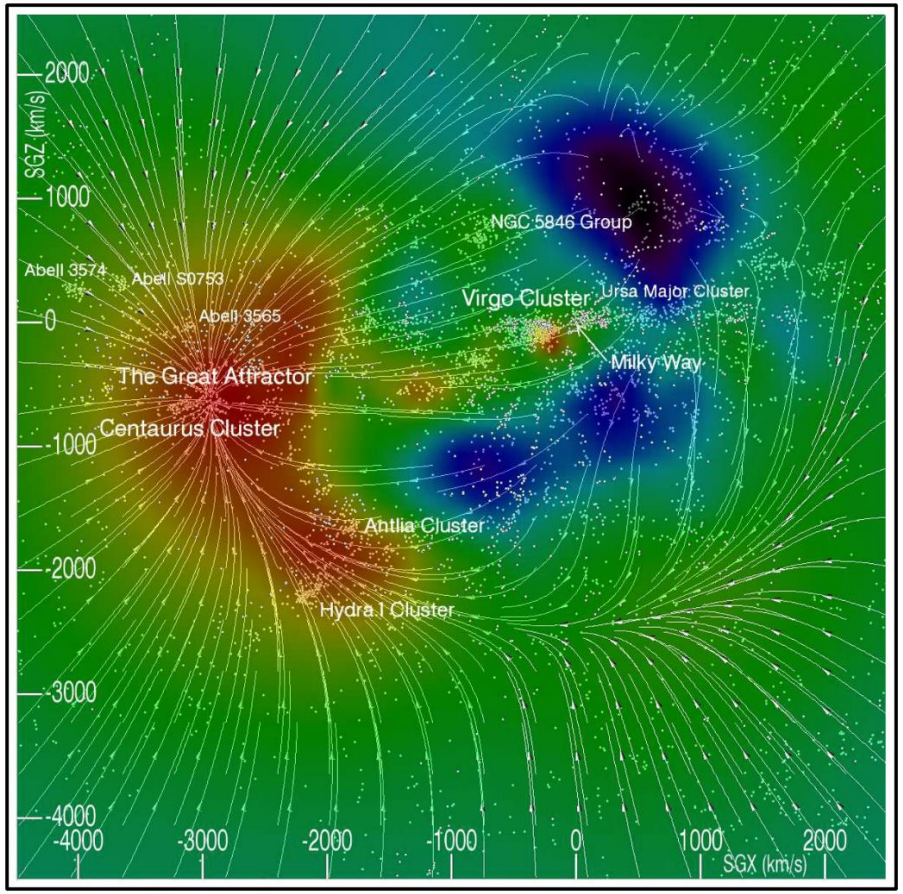


Our cosmic neighborhood

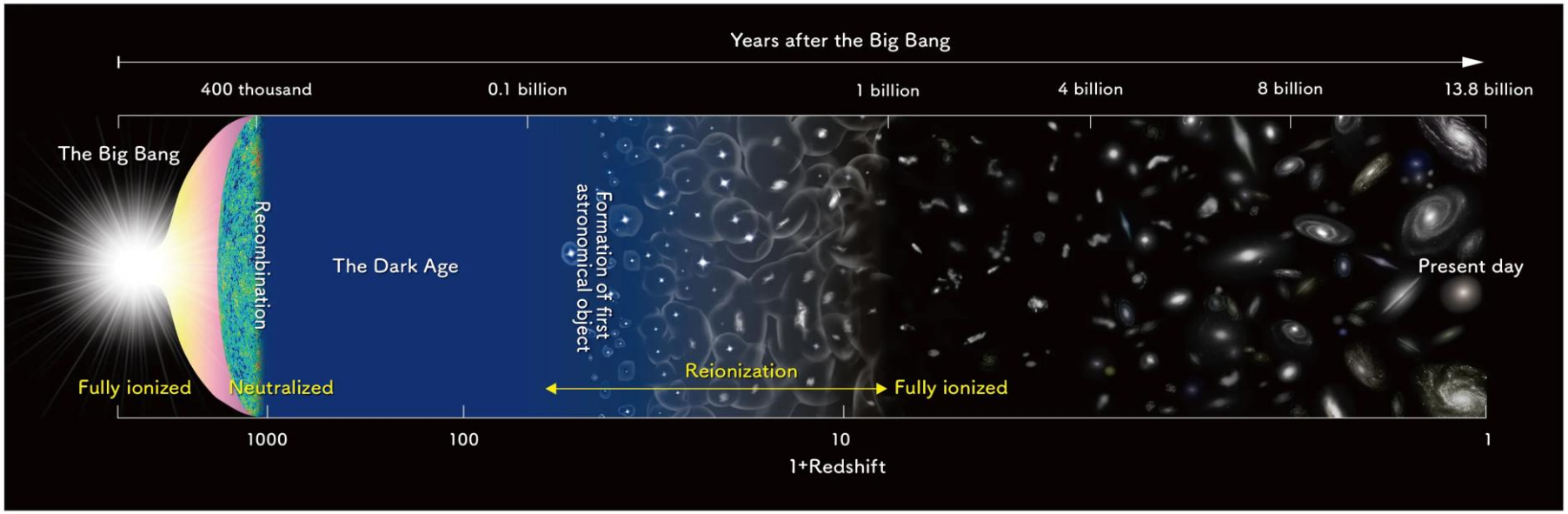
- The solar system inside the MW
- The Local Group = MW + M31
- The Local Universe – around the Virgo cluster

R. Brent Tully *et al* 2023 *ApJ* **944** 94





Redshift = velocity = backwards in time



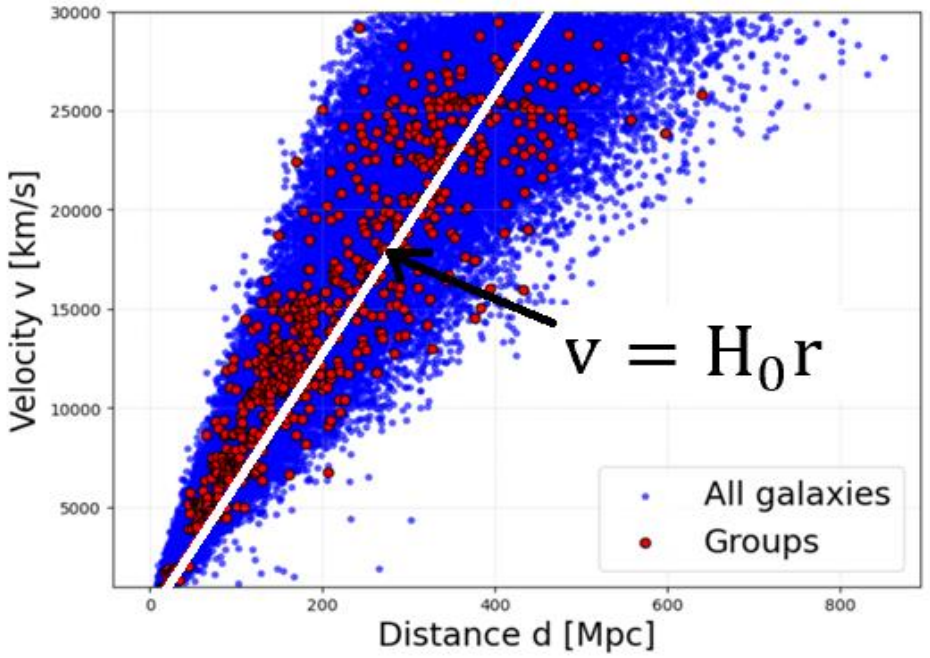
CMB		
Dark Ages	$1100 \rightarrow 30$	Hydrogen fog, no light
First Stars (Cosmic Dawn)	**~30**	**~100 million years**
First Galaxies	**~14 - 20**	**~200-300 million years**
End of Reionization	~6	1 billion years
Cosmic Noon (Peak Stars)	**~2 - 3**	**~3 billion years**
Solar System Forms	~0.4	9.2 billion years
Today	**0**	**13.8 billion years**

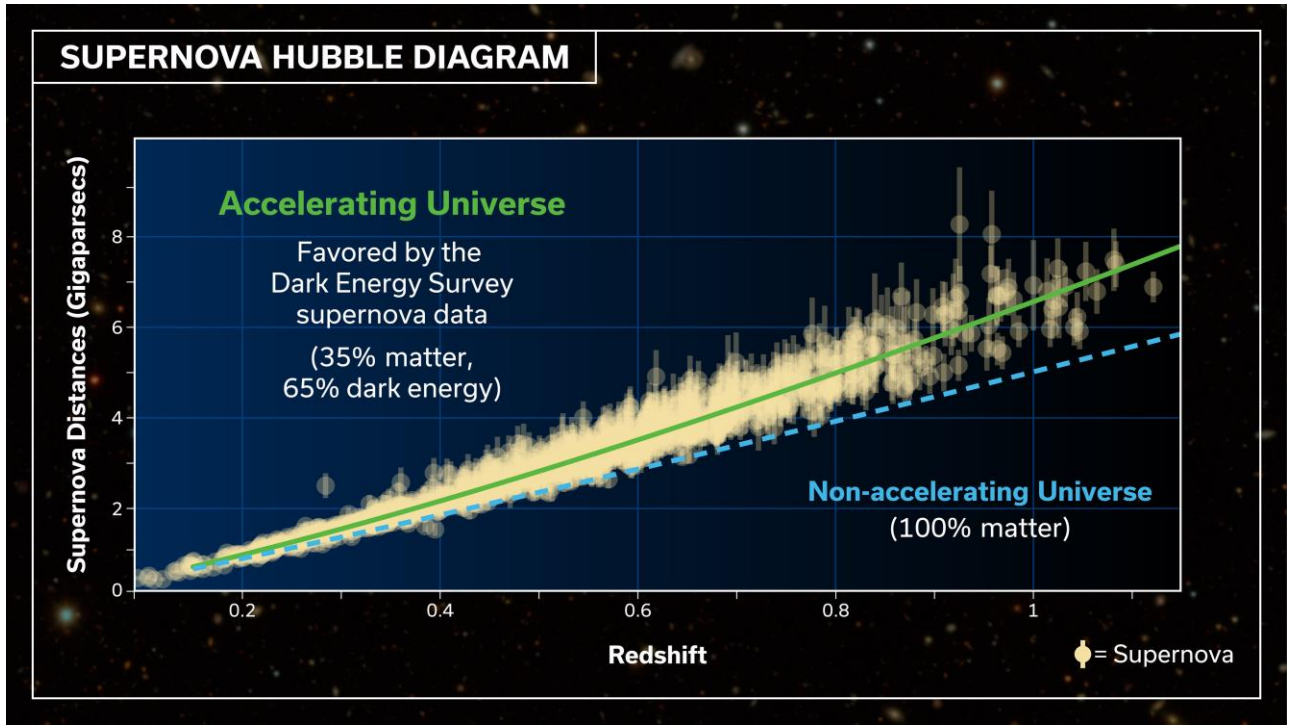
Tully et. al. ApJ. 944 (2023) 1, 94

JHEAp 34 +22 49-211 Di Valentino et. al.

From Hubble Law to the Supernova

- Hubble Law – $v_{\text{Line of Sight}} = H_0 r$, Peculiar velocity = the difference.
- Friedman Equations: $\frac{H^2}{H_0^2} = \frac{\Omega_m^0}{(1+z)^3} + \Omega_\Lambda^0$ with $\Lambda \sim \Omega_\Lambda^0 \left(\frac{H_0}{c}\right)^2 \sim 10^{-52}\, m^{-2}$





Dynamical Field

Ratra, P.; Peebles, L. (1988) PRD. 37 (12): 3406–3427
Wetterich, C. (1988-06-13). NPB. 302 (4): 668–696.

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

- Quintessence is a generalization for Λ.

Density (00): $3H^2 = \rho_m + \frac{1}{2}\dot{\phi}^2 + V(\phi) \implies 3H^2 = \Lambda$

Pressure (ii): $-3H^2 - 2\dot{H} = p_m + \frac{1}{2}\dot{\phi}^2 - V(\phi) \implies -3H^2 - 2\dot{H} = -\Lambda$

- Slow-roll approximation: $\frac{1}{2}\dot{\phi}^2 \ll V(\phi)$.

- Eos $\mathrm{w} = \mathrm{p}/\rho$. For $\Lambda = \mathrm{Const}$; $\mathrm{w} = -1$.

Kobayashi; Rept.Prog.Phys. 82 (2019) no.8, 086901

Horndeski Theories

- Free from ghost and stable $\Box\phi \equiv g^{\mu\nu}\phi_{;\mu\nu}$,$X \equiv -1/2 g^{\mu\nu}\phi_{;\mu}\phi_{;\nu}$

$$\mathcal{L}_2 = G_2(\phi,\, X)$$

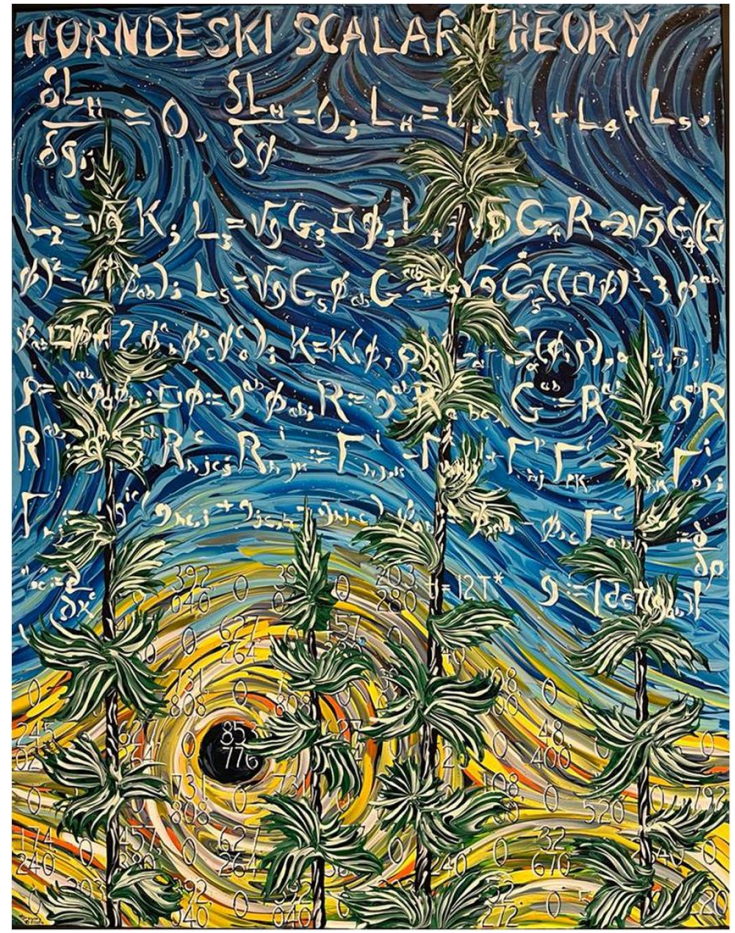
$$\mathcal{L}_3 = G_3(\phi,\, X)\Box\phi$$

$$\mathcal{L}_4 = G_4(\phi,\, X)R + G_{4,X}(\phi,\, X)\left[(\Box\phi)^2 - \phi_{;\mu\nu}\phi^{;\mu\nu}\right]$$

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

- G2 = Quintessence ($G_2 = X + V(\phi)$), K-essence $F(X)$

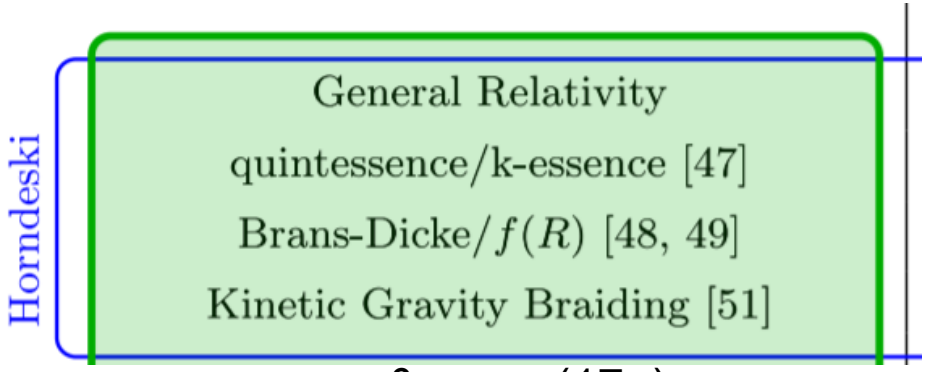
- For G4 – Yukawa type potentials.



Speed of Gravity and Speed of Light

- From GW170817:

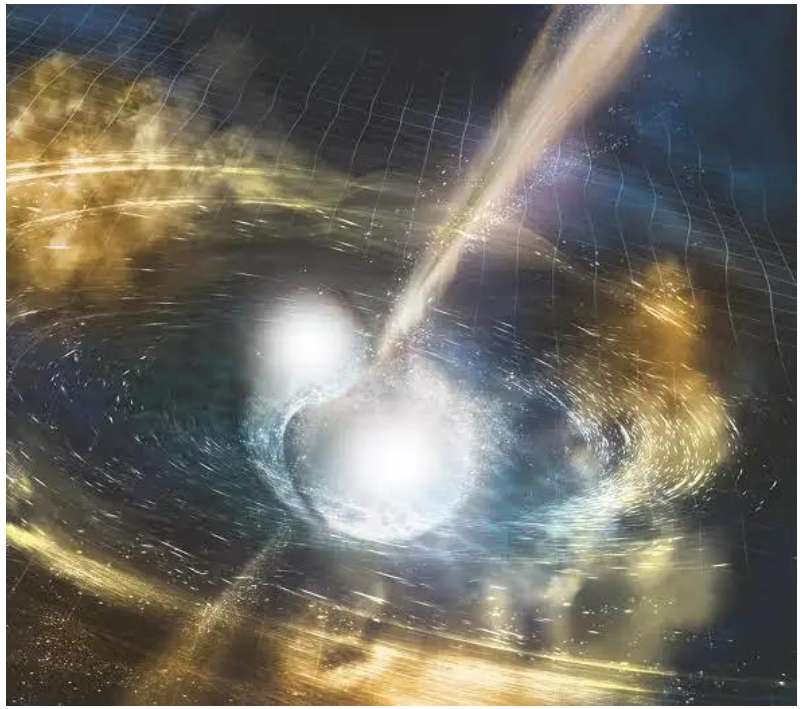
$$-3 \cdot 10^{-15} \leq c_g/c - 1 \leq 7 \cdot 10^{-16}$$



Ezquiaga & Zuma (17+)

Horndeski

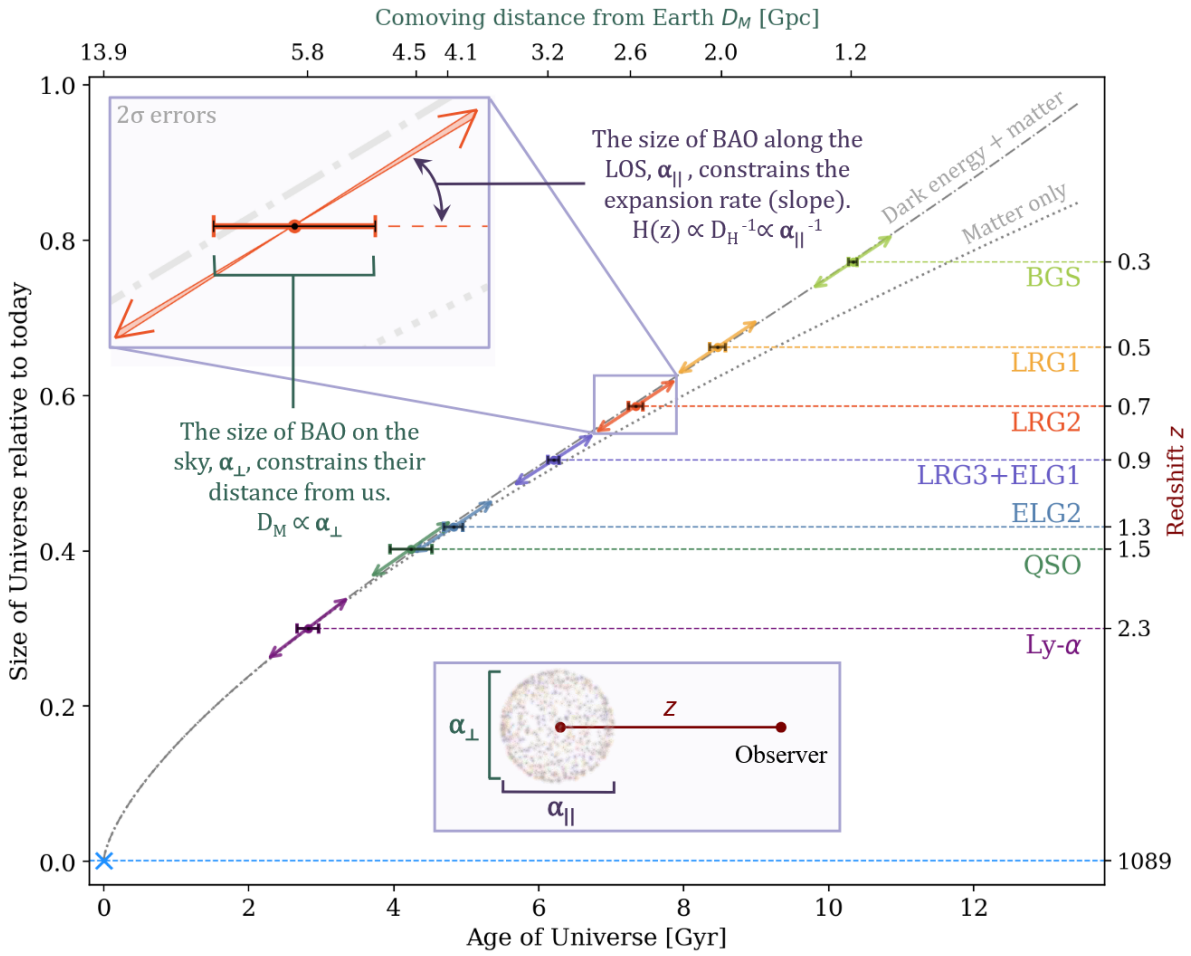
$$\mathcal{L}_2 = K(\phi, X)\,,$$
$$\mathcal{L}_3 = -G_3(\phi, X)\Box\phi\,,$$
$$\mathcal{L}_4 = G_4(\phi, X)R + G_{4X}(\phi, X)\left[(\Box\phi)^2 - \phi_{;\mu\nu}\phi^{;\mu\nu}\right]\,,$$
$$\mathcal{L}_5 = G_5(\phi, X)G_{\mu\nu}\phi^{;\mu\nu} - \frac{1}{6}G_{5X}(\phi, X)\left[(\Box\phi)^3 + 2\phi_{;\mu}{}^{\nu}\phi_{;\nu}{}^{\alpha}\phi_{;\alpha}{}^{\mu}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

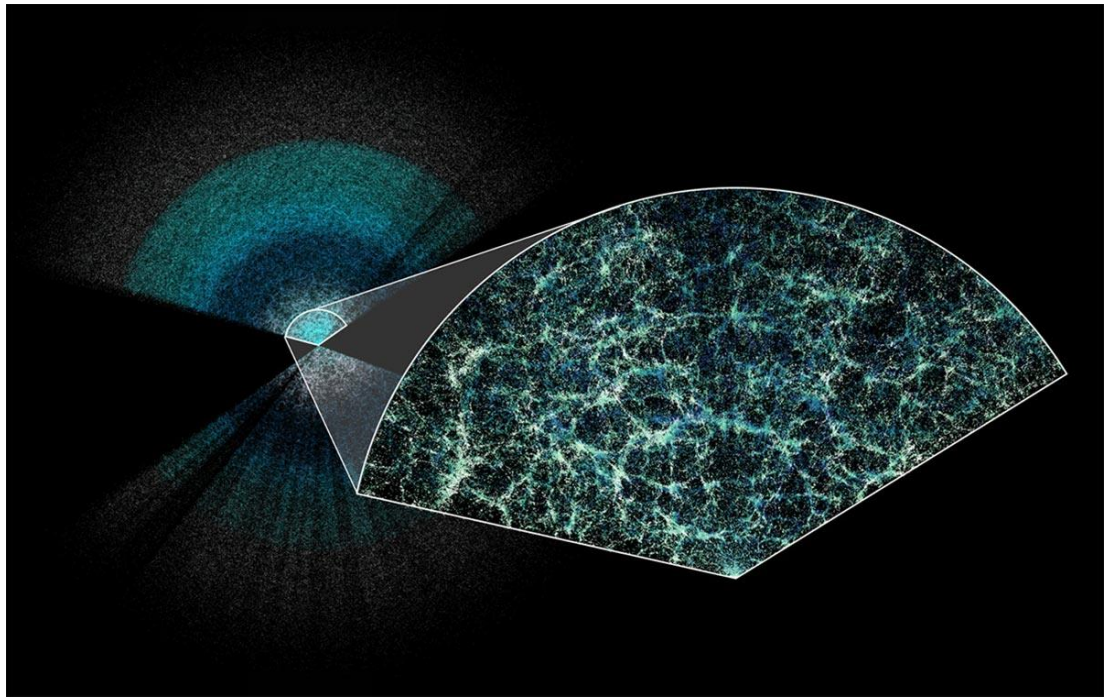


Abbott et al. (Virgo, LIGO), PRL (2017) 161101 ,119

Phys. Rev. D 112, 083515, 2025

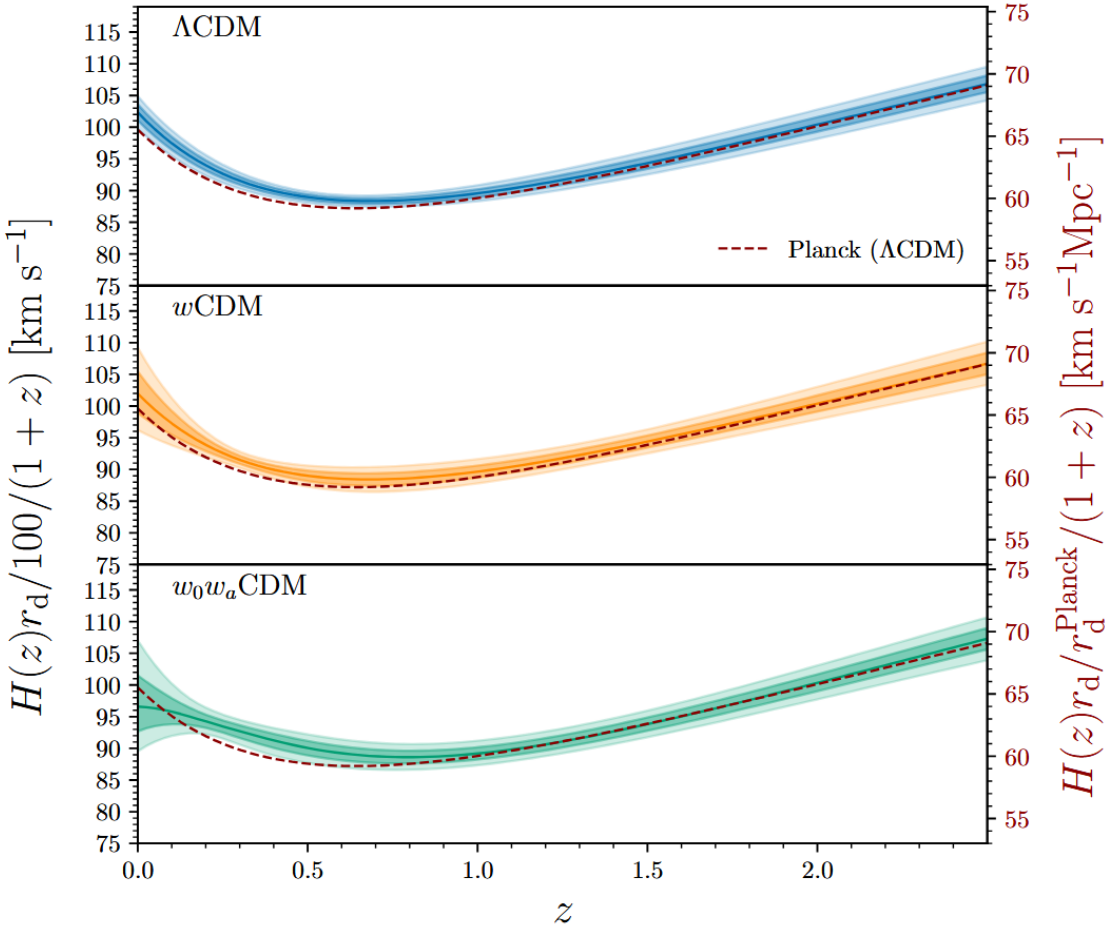
DESI BAO – New Range of Galaxies

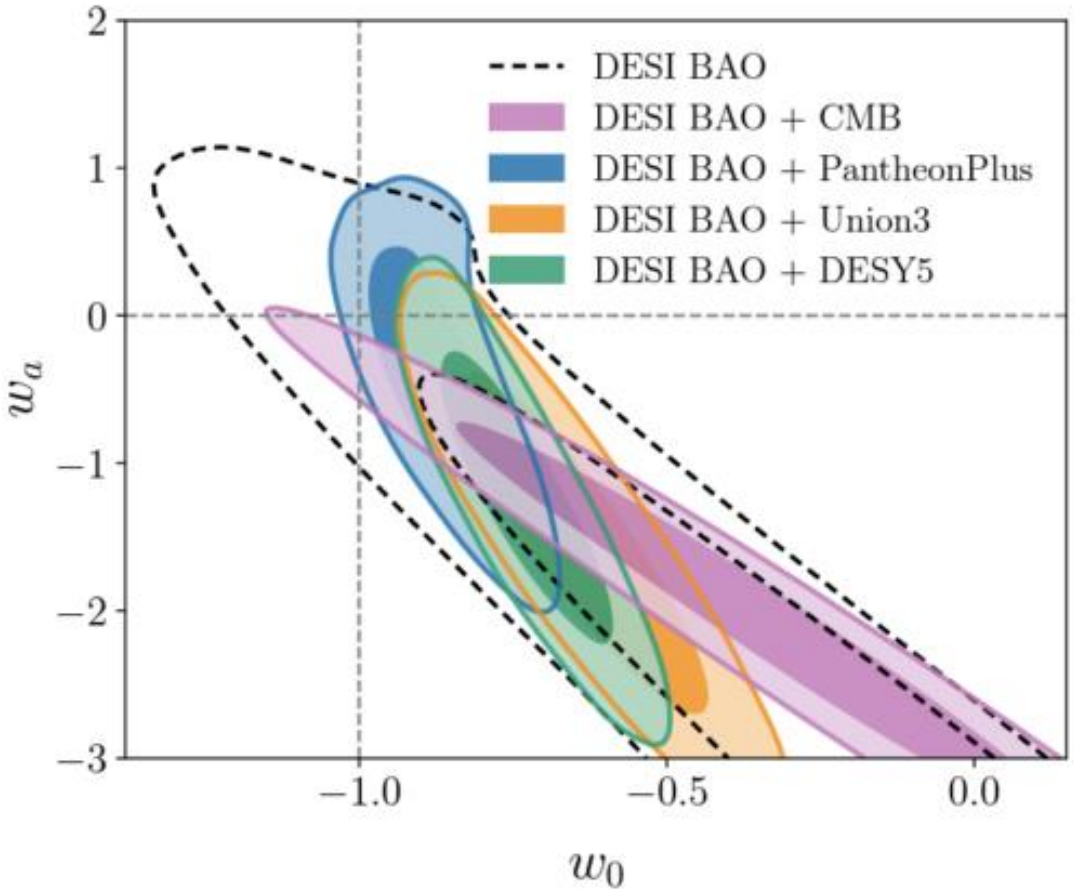




Phys. Rev. D 112, 083515, 2025

DESI BAO – Dark Energy?





Friedman Equations and Λ

- Friedman Equations $\frac{H^2}{H_0^2} = \frac{\Omega_m^0}{(1+z)^3} + \Omega_\Lambda^0$ with $\Lambda \sim \Omega_\Lambda^0 \left(\frac{H_0}{c}\right)^2 \sim 10^{-52}\, m^{-2}$

- Spherically Symmetric Solution: $\ddot{\mathrm{r}} = -\mathrm{G}\frac{\mathrm{M}}{\mathrm{r}^2} + \frac{\Lambda c^2}{3}\mathrm{r}$

- Dark Energy in the Local Universe? For the LG = almost zero.

Dark Energy in the Local Universe?

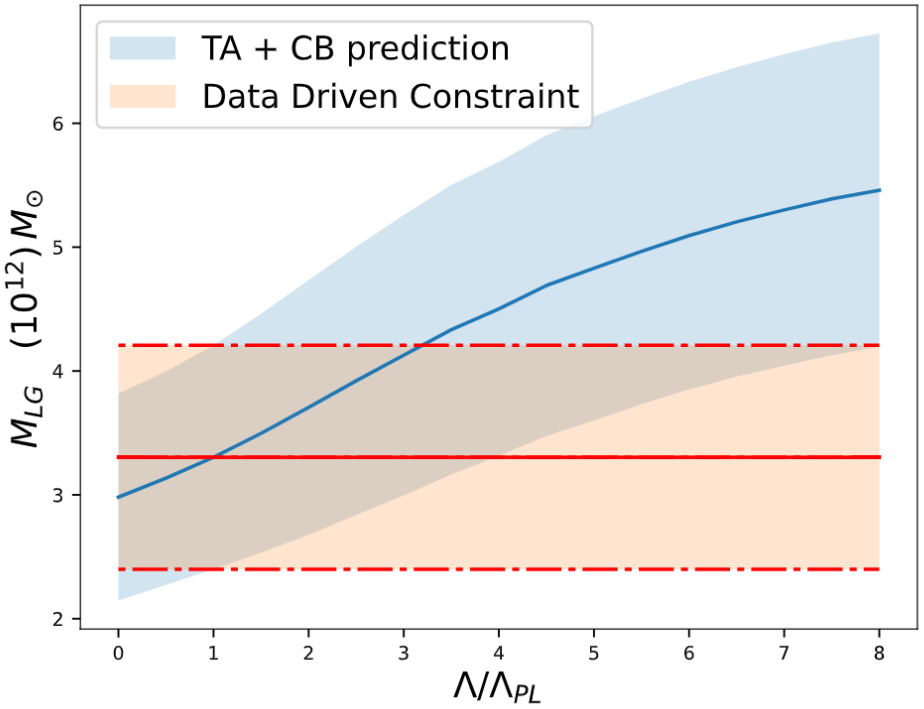
- $\ddot{r} = -\frac{GM}{r^2} + \frac{\Lambda c^2}{3} r \rightarrow$ For the LG = almost zero.

- Upper limit of $< 5.44\ \Lambda_{\mathrm{CMB}}$

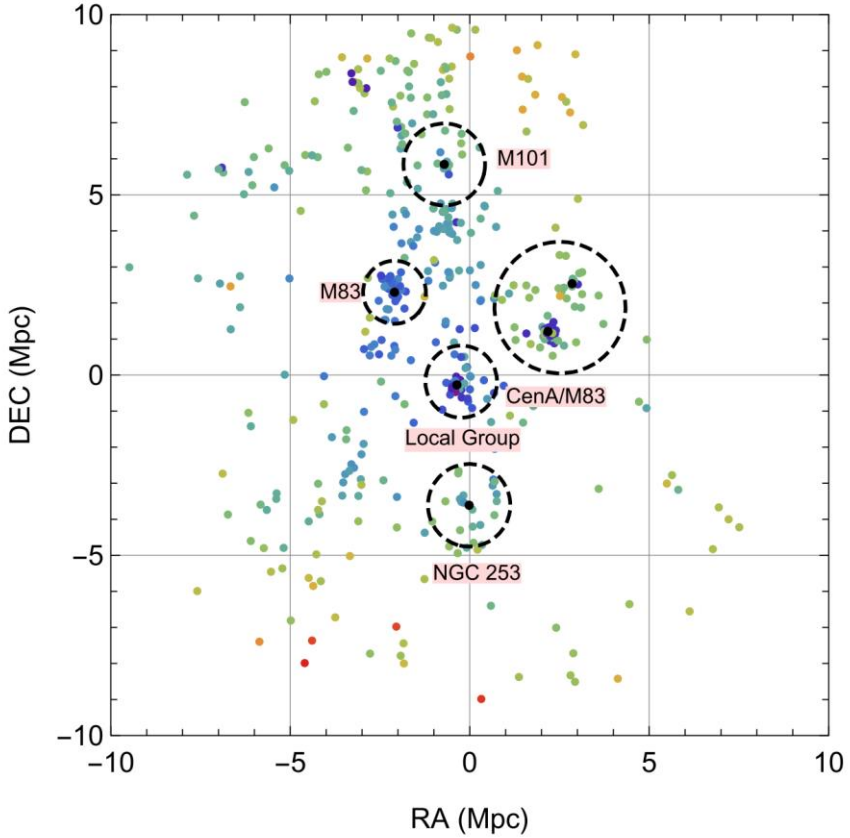
- With future JWST – detection of DE.

$$\delta v_t / v_t \approx 40\%$$

Benisty, Davis, Evans, **APJL 953 (2023) 1, L2**



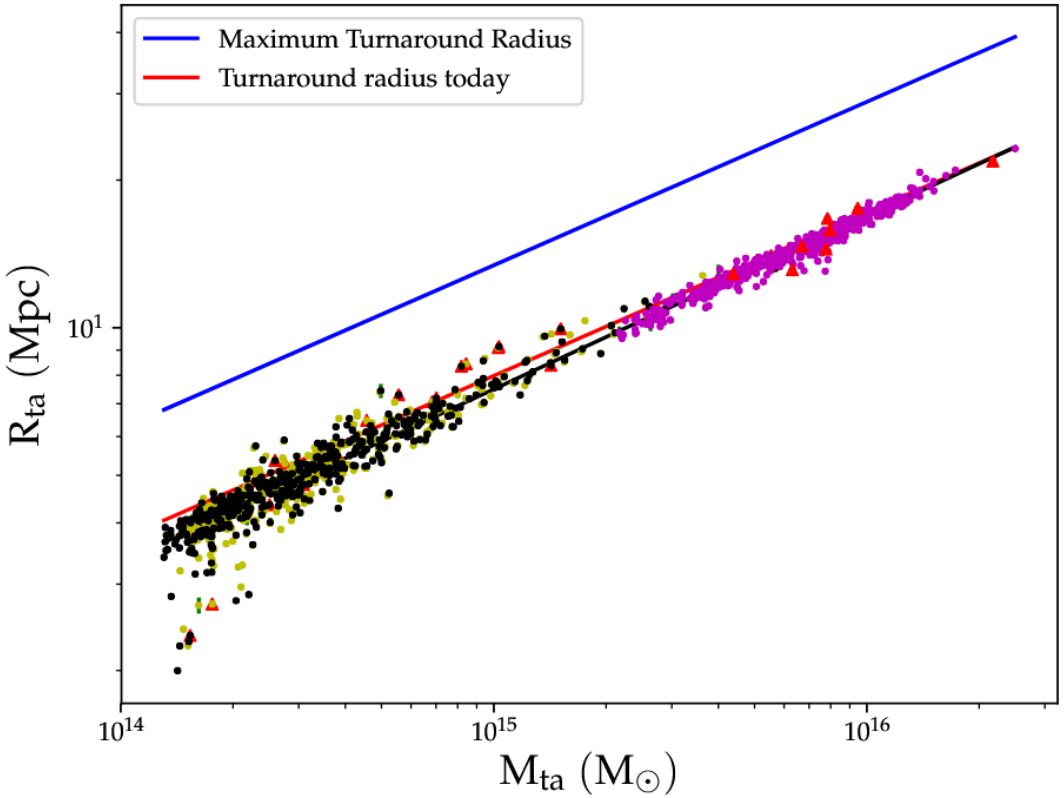
Turnaround radius & Zero-acceleration



Benisty, Chaichian, Tureanu

Phys.Lett.B 858 (2024) 139033

Turnaround radius & Zero-acceleration



Korkidis et. al. (+20) A&A 639, A122

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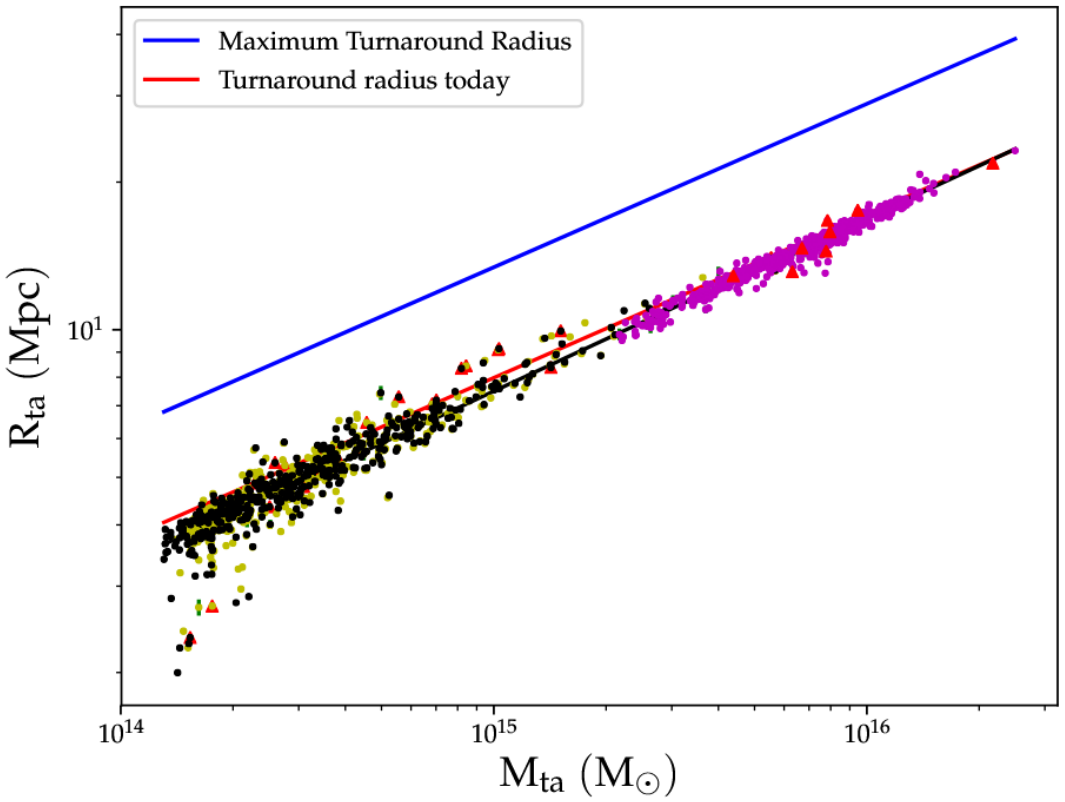
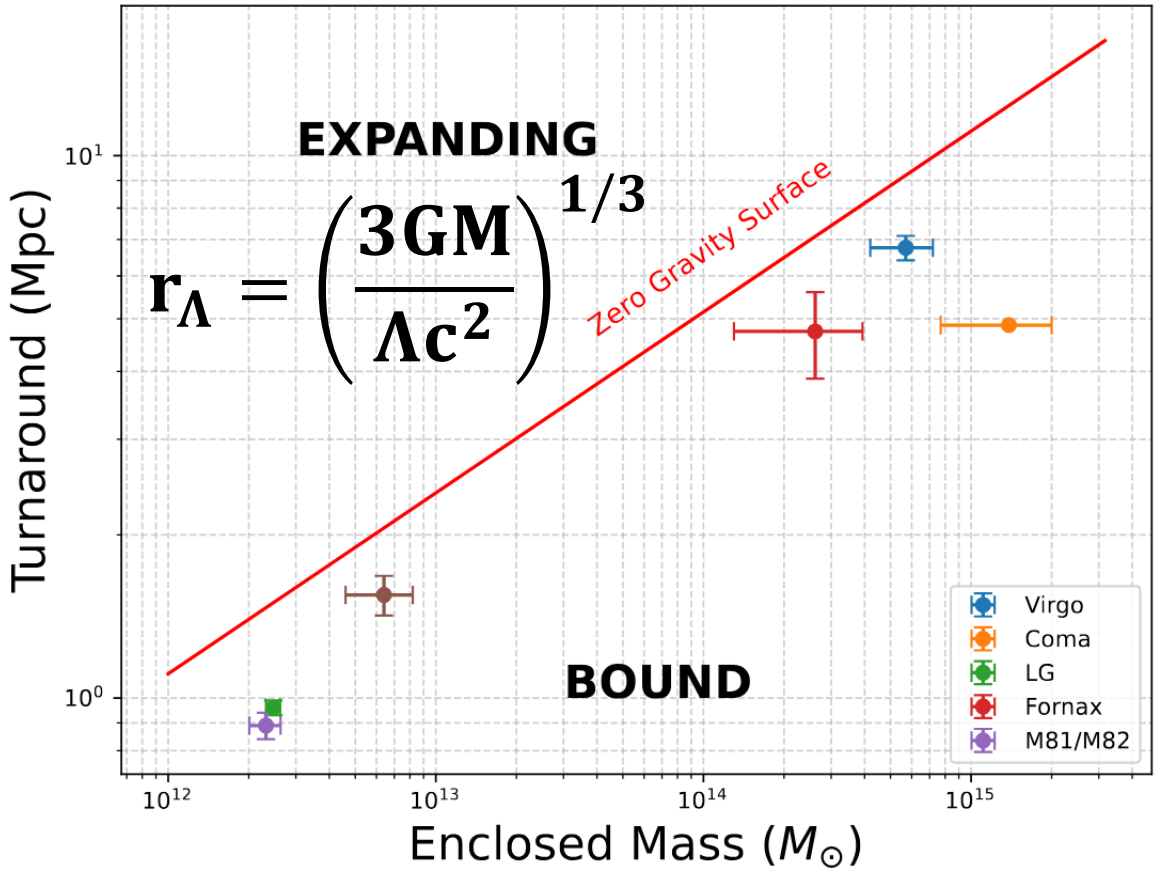


Korkidis et. al. (+20) A&A 639, A122



Pavlidou & Tomaras JCAP 09 (2014) 020

Benisty PRD 112 (2025) 8, 083557

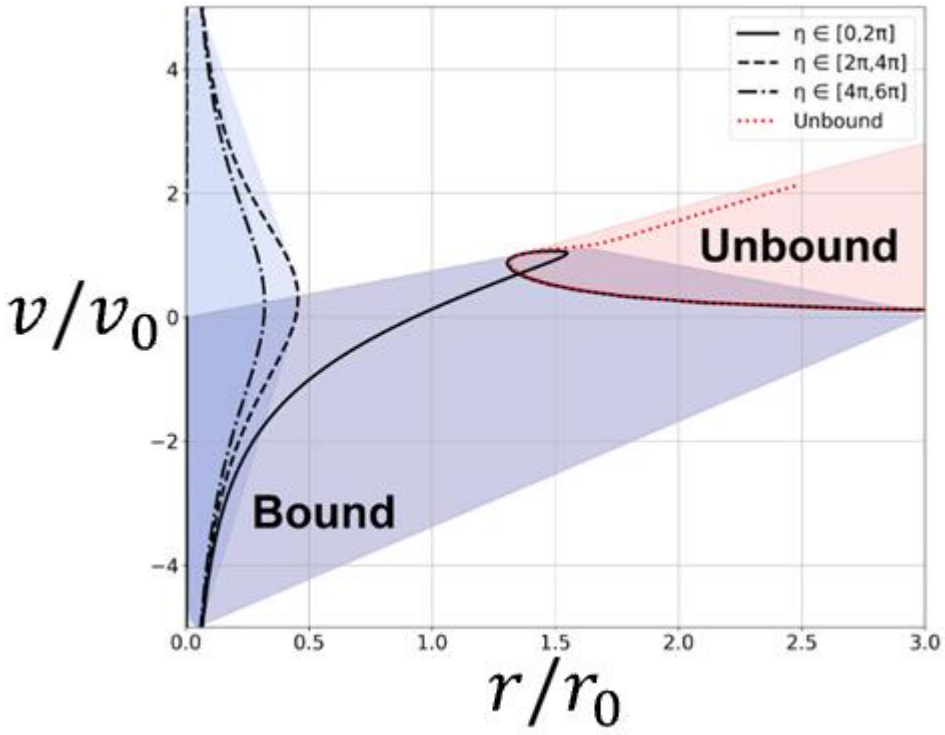
Spherical Collapse and Local Hubble Flow

Introduced in Sandage 1986, ApJ 307, 1.

- Spherical Collapse:

$$\ddot{r} = -G\frac{M}{r^2} + \frac{\Lambda c^2}{3} r \rightarrow \quad v_r = -A\sqrt{\frac{GM}{R}} + b\, H_0 R$$

Peirani & de Freitas Pacheco +06



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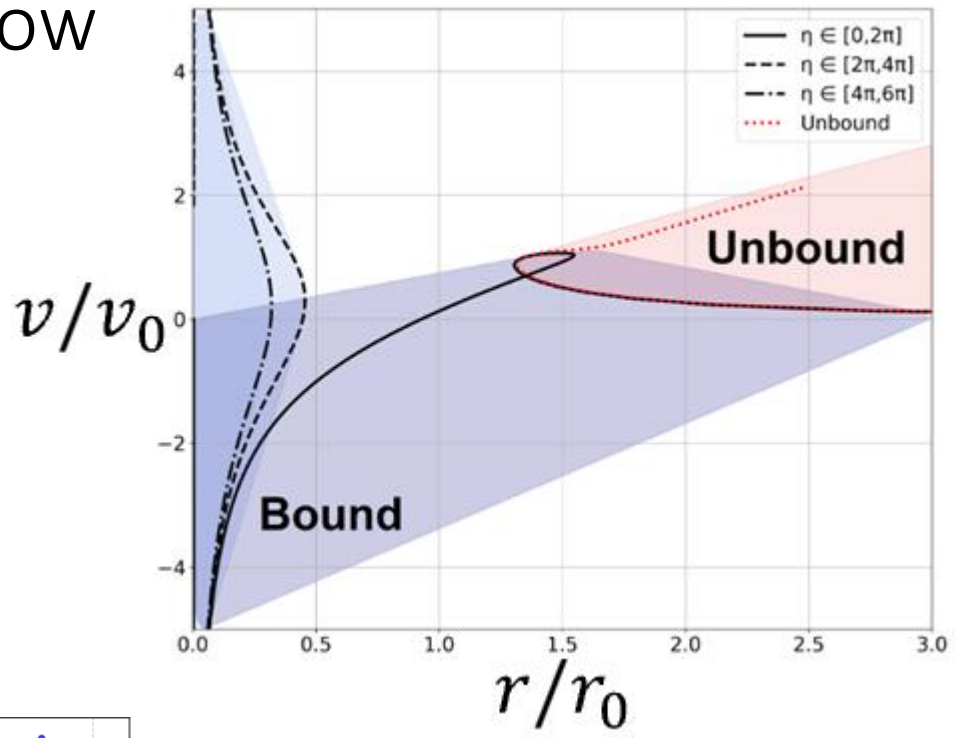
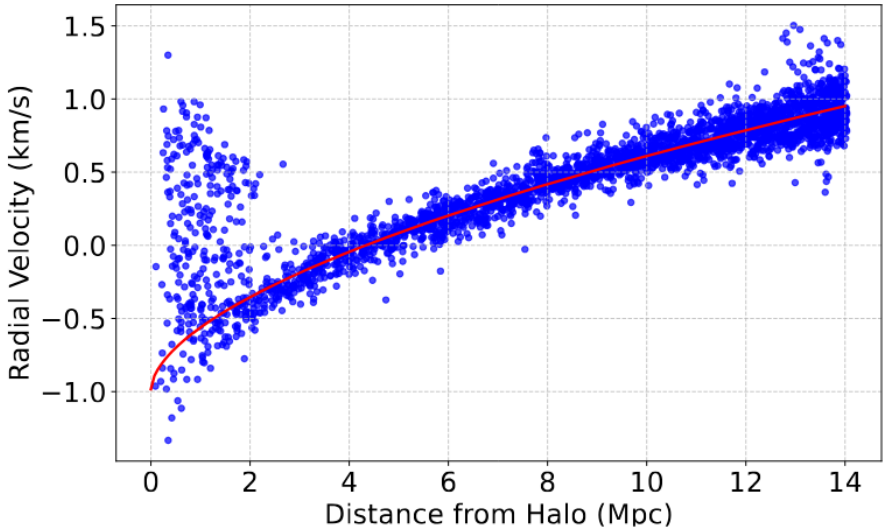
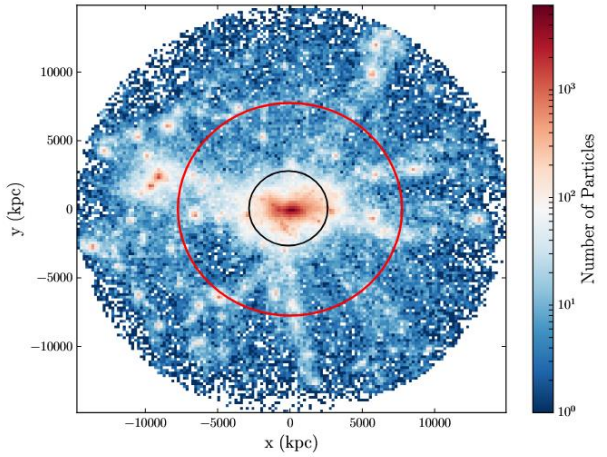


- From the TNG simulation





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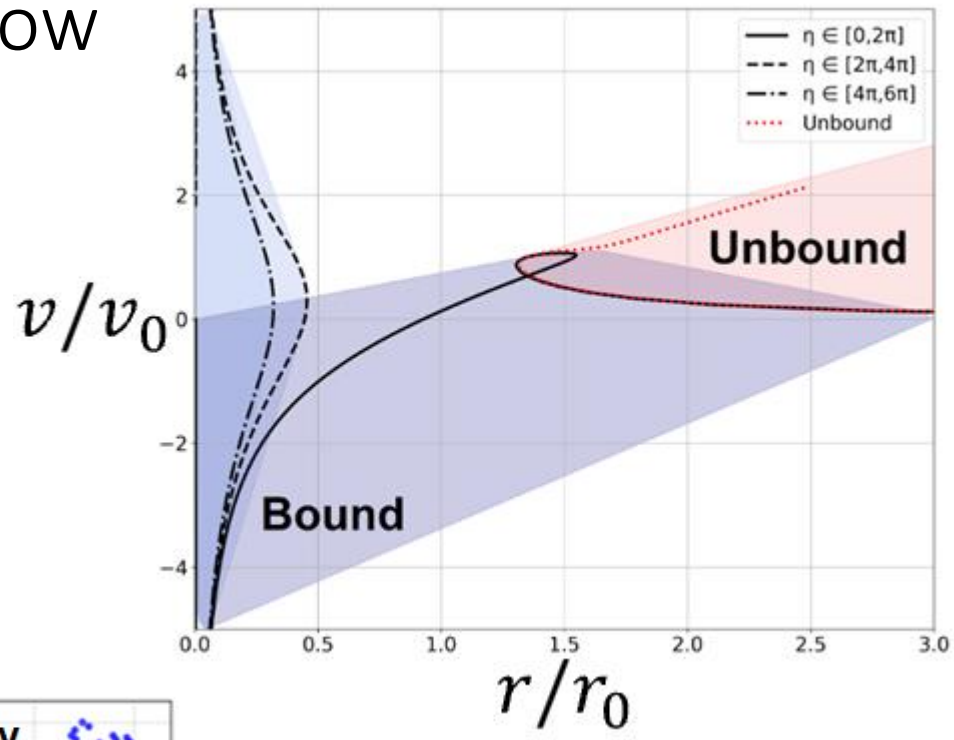
Peirani & de Freitas Pacheco +06



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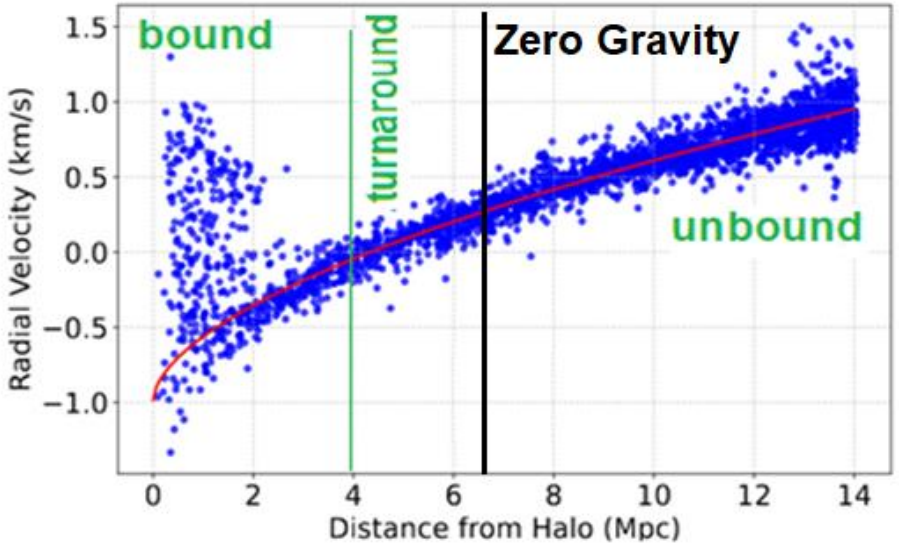

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Peirani & de Freitas Pacheco +06

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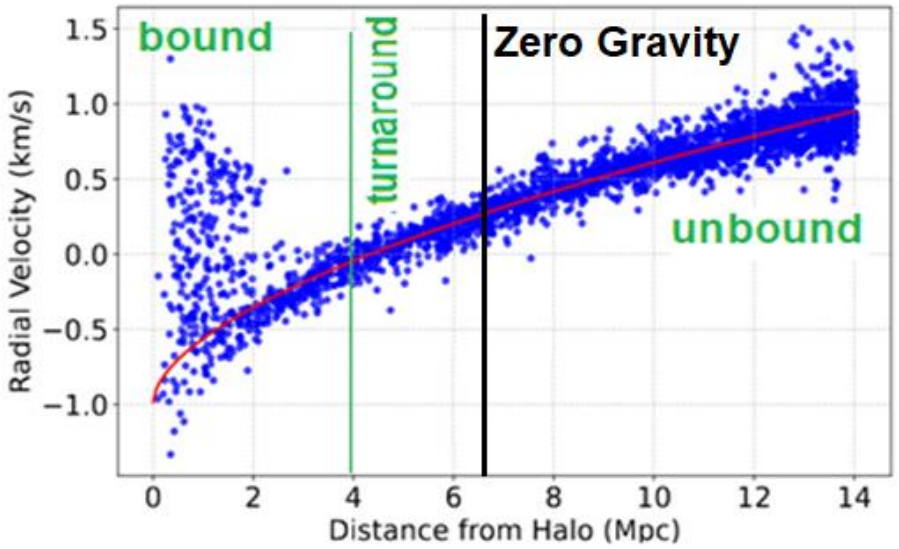
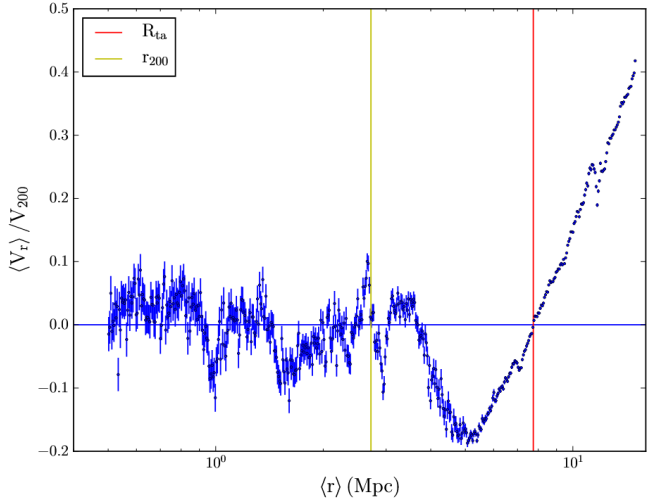
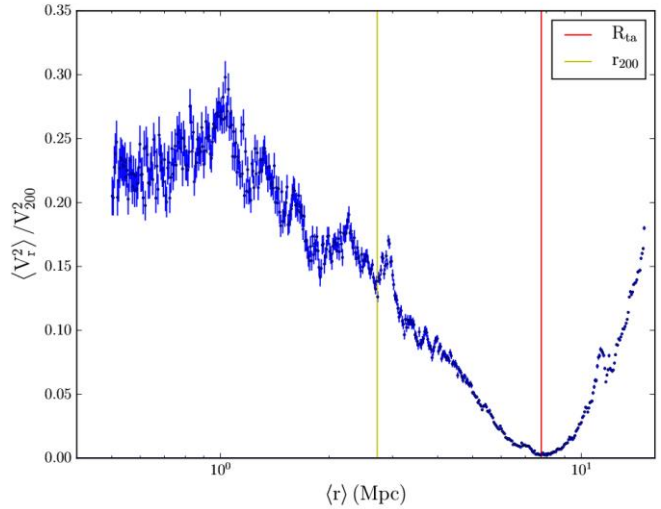




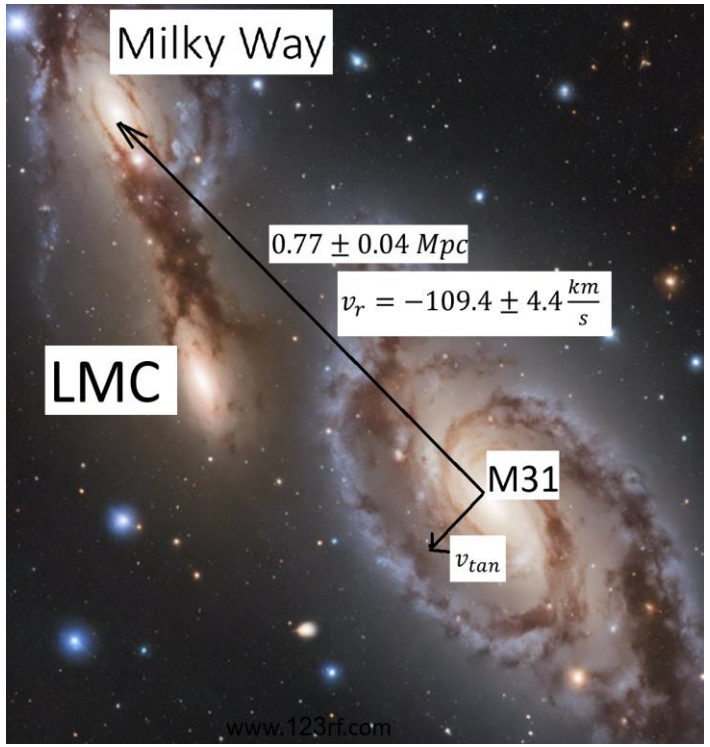


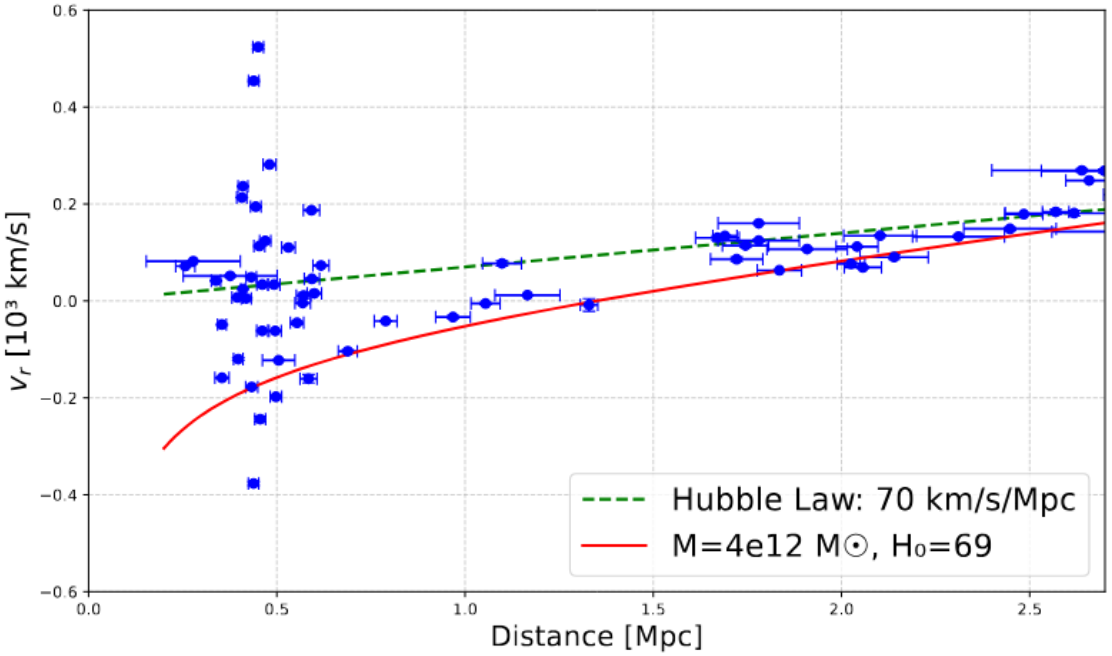
Korkidis et. al. (+20) A&A 639, A122

Example 1: Local Group in the light of Gaia

- Dominated by Milky Way and Andromeda

- From Gaia – PM for most of the galaxies.





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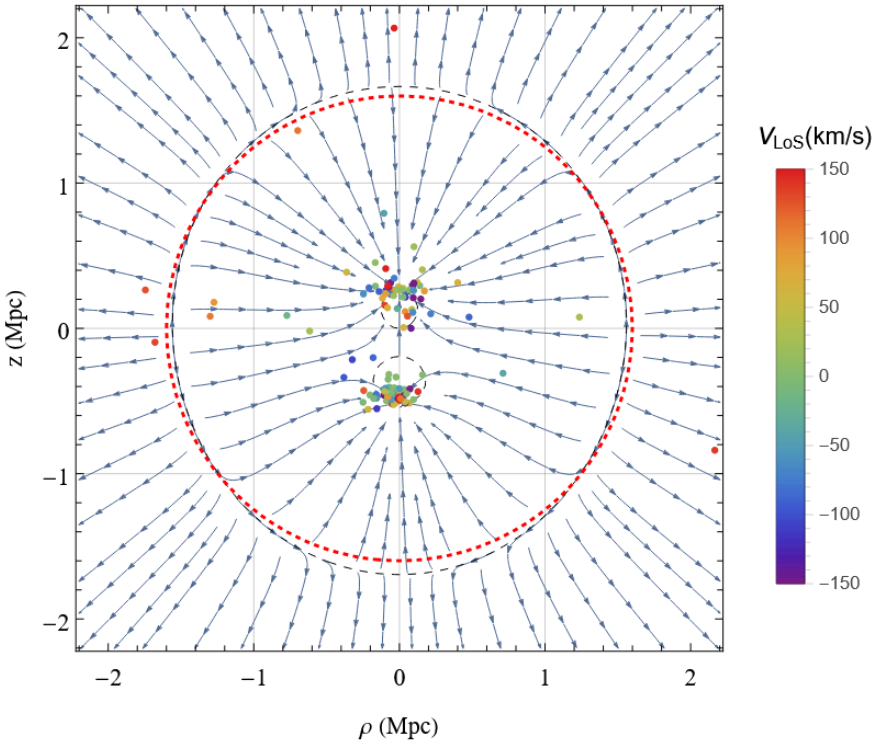

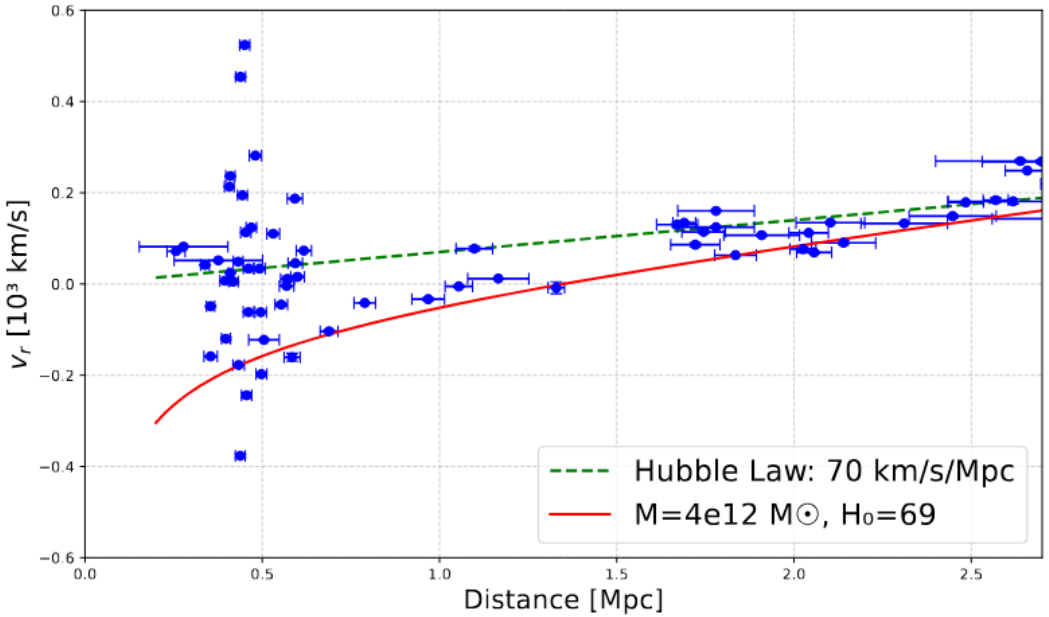

Benisty, Chaichian, Tureanu PLB 858 (2024) 139033

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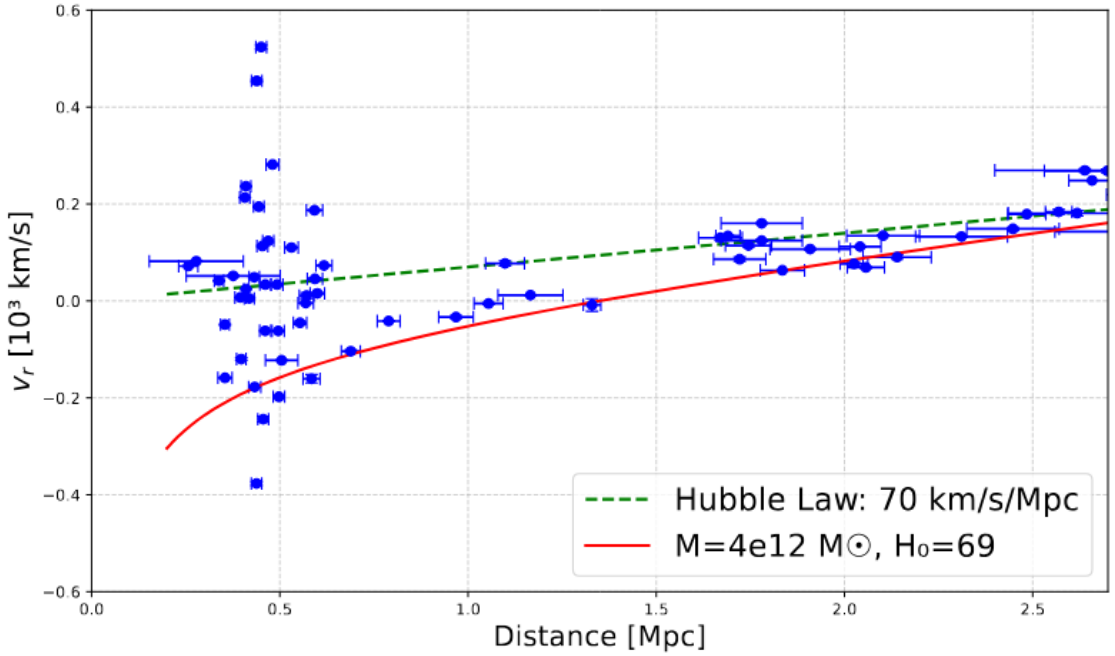
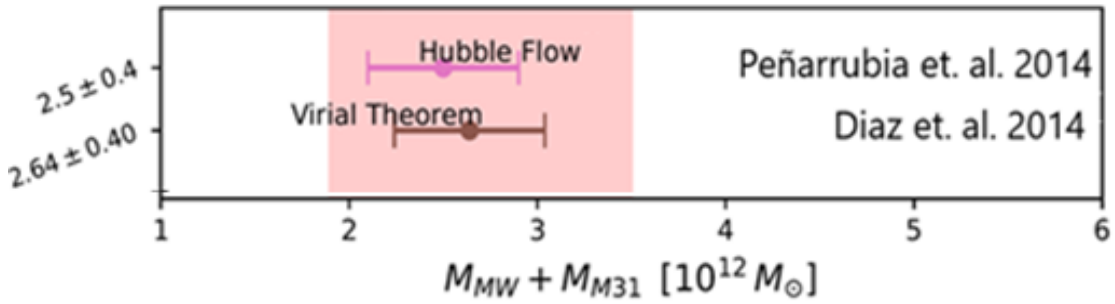
Peñarrubia et. al. 2014 (minor infall)

$$\mathbf{H_0 = 67 \pm 5 \frac{km}{s\ Mpc}}$$

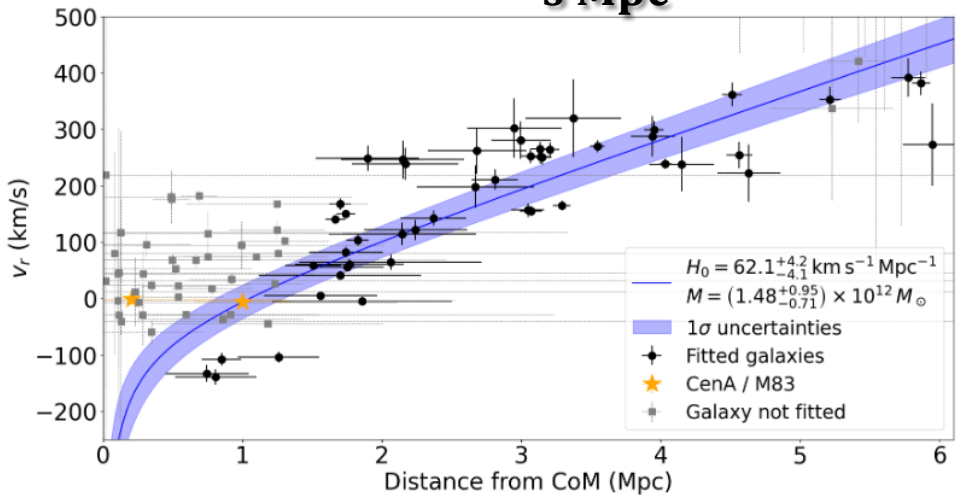




Example 2: CenA/M83

Faucher, **Benisty**, Mota +26 to be published in A&A

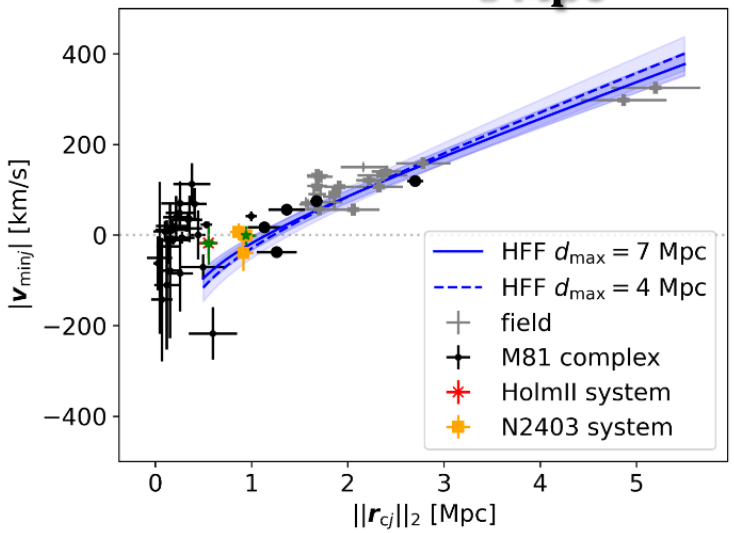
$$\mathbf{H_0 = 64 \pm 5 \frac{km}{s\ Mpc}}$$



M81/M82

Wagner, **Benisty**, Karachentsev +26 accepted in A&A

$$\mathbf{H_0 = 63 \pm 6 \frac{km}{s\ Mpc}}$$



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Faucher, **Benisty**, Mota +25 to be published A&A

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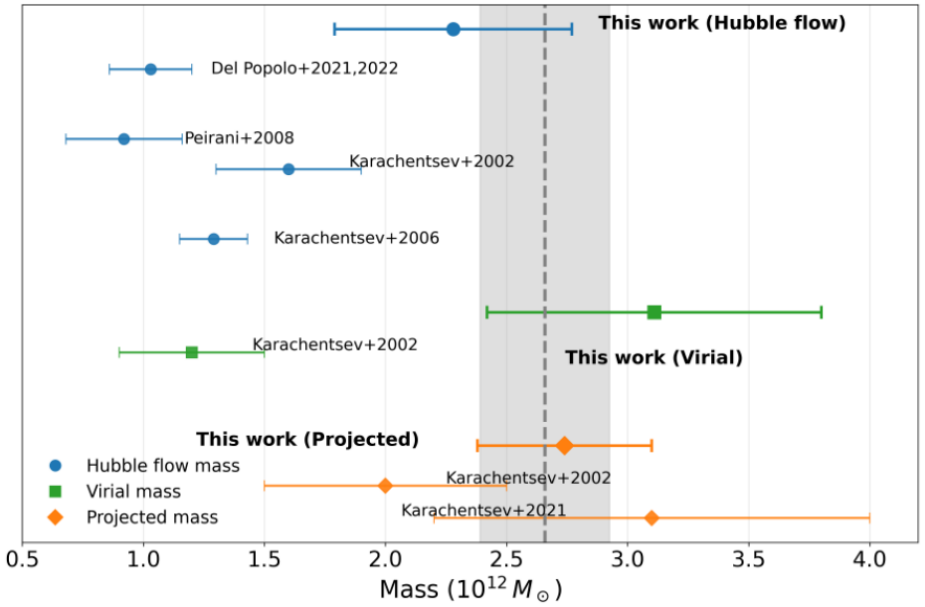
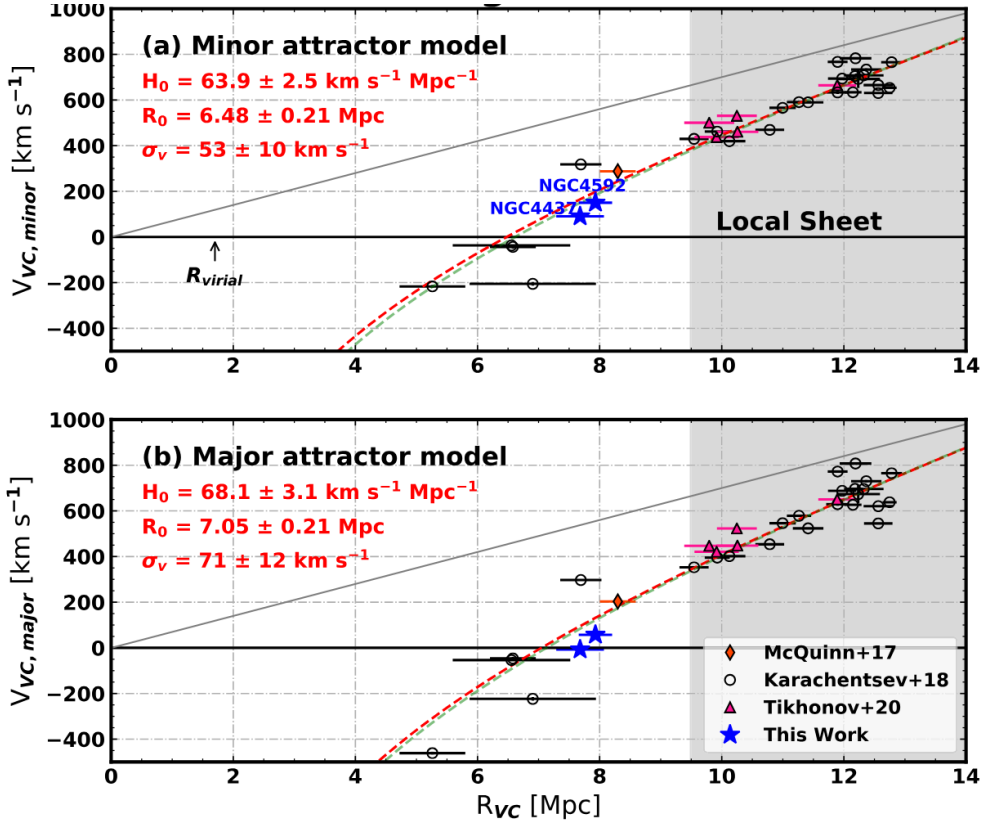
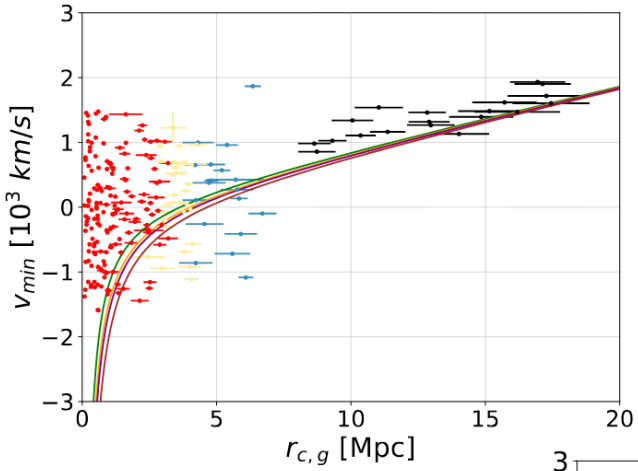


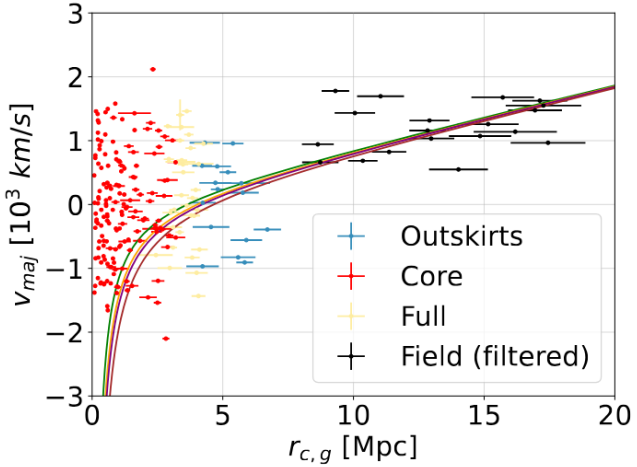
Hubble Flow around clusters

- Virgo



- Coma



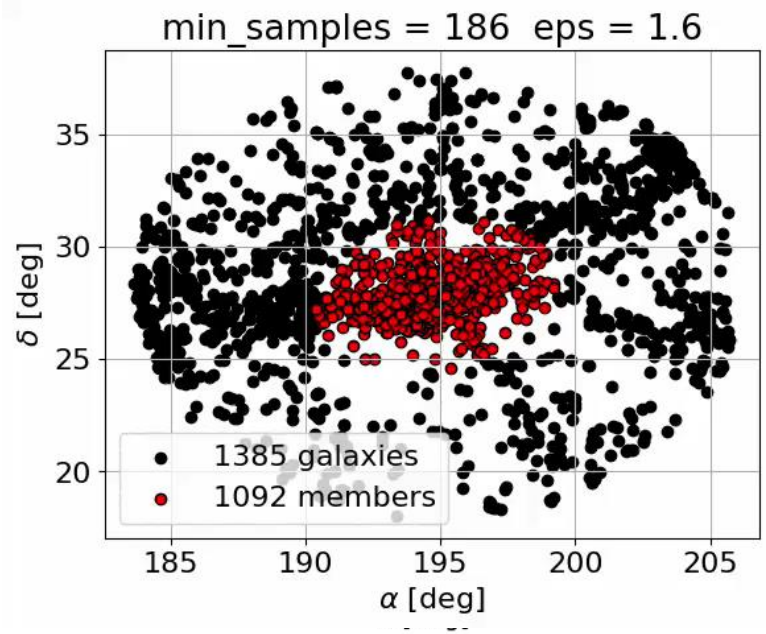


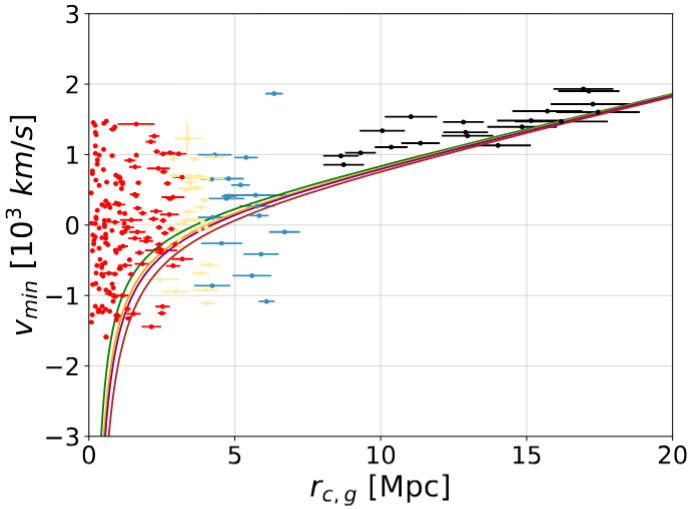
Benisty, Wagner, Haridasu, Salucci 2504.04135 to be published in JCAP

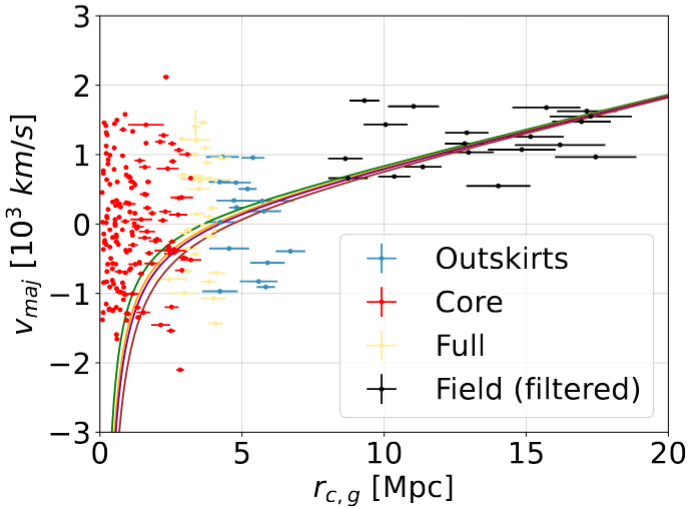
Example 3: Galaxy Clusters - Coma

- SDSS 17: z (2K)
- CF4: distances (~200)

- Density based algorithm (DBScan)



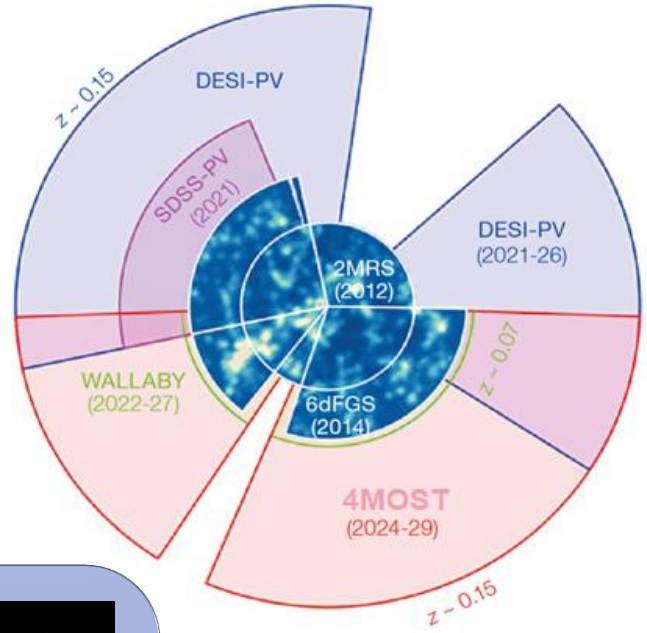


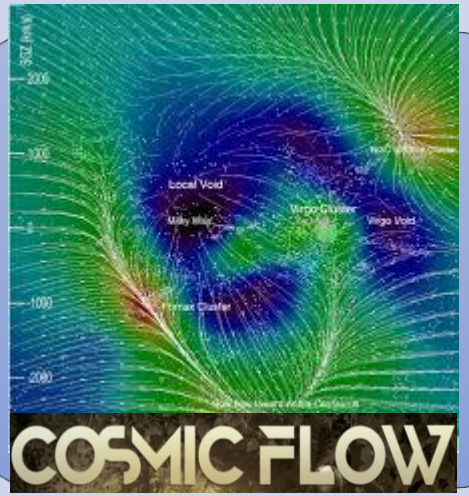


What's next?

Observational data – CF4, DESI & 4MOST

More then 10^9 sources





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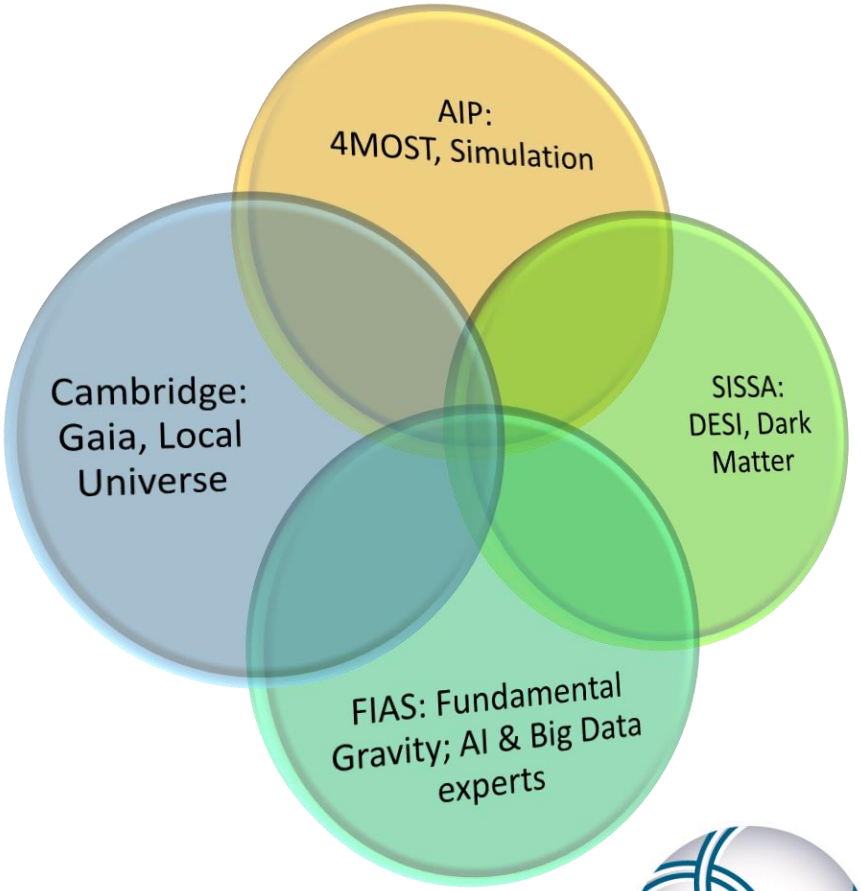

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