DHOST to unify Dark Matter and Dark Energy

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Based upon

- Laudato E., Salzano V. & Umetsu K., *"Multicomponent DHOST analysis in galaxy clusters"*, MNRAS 511 (2022) 2, 1878-1892;
- Laudato E. & Salzano V., *"DHOST gravity in Ultra-diffuse galaxies - Part I: the case of NGC1052-DF2"*, EPJC 82 (2022) 7, 935;
- Laudato E. & Salzano V., *"DHOST gravity in Ultra-diffuse galaxies - Part II: NGC 1052-DF4 and Dragonfly 44"*, to be submitted.

Extended Theories of Gravity (ETGs)

- GR has theoretical and observational issues
  - Remind: "consensus" model (ΛCDM)
- GR tested directly only in the Solar System
  - Inference over 60 order of magnitudes in scale
- Dark Energy and Dark Matter
  - They are everywhere ($\sim 95\%$) in the Universe
- But... what are they?
  - DE: too many ideas $\equiv$ no idea?
  - DM: no detection so far (sooner or later?)

Existence of DM - DE $\between$ GR as THE gravity theory

ETGs: cons and pros

Cons (to make ETGs' opponents happy):

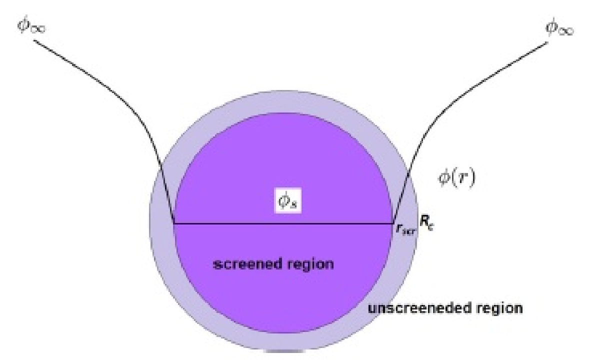
- too many possibilities!
- observations tune them almost undistinguishable from GR models
- how to discriminate among ETGs and GR? No smoking gun!
- statistically speaking, mostly disfavoured with respect to GR

Pros (to make me happy):

- the more ETGs are discarded, the more GR is confirmed (!)
- statistics is not everything
- solving "tensions" is more valuable (?)
- **DM and DE could be expression of totally NEW physics!**

ETGs: challenges

- ETGs are generally NOT proposed for DM, but mostly for DE
- once you modify GR on large scales, you use Screening Mechanisms to avoid influences also on smaller scales



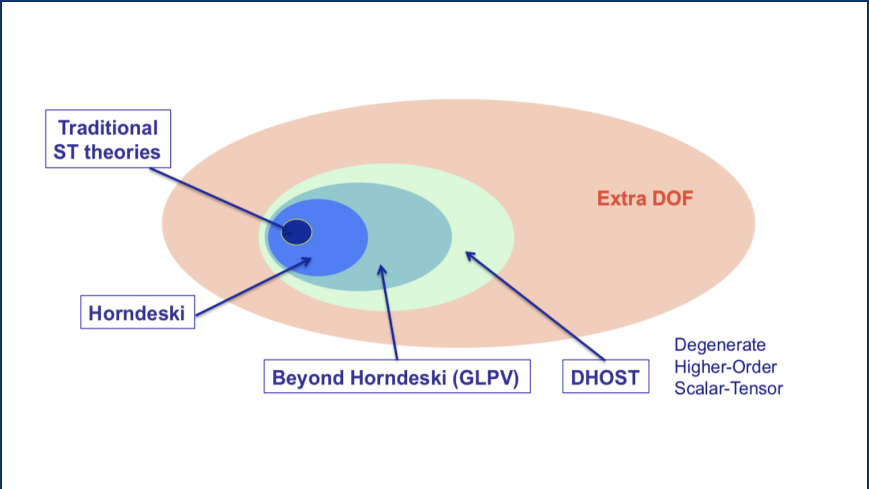
Key Idea: WHAT IF...

... Screening is partially broken, and ETGs effects might leak also into astrophysical scales?

- this is possible, but authors try to "heal" it
- when not, you might have a theory behaving as DE on cosmological scales and mimicking DM on smaller scales
- this would be a plus w.r.t. to GR, because you would unify the dark sector
- we will test this idea
  - Scenario 1: ETG as DE only, plus DM
  - Scenario 2: ETG as both DE and DM (no DM added!)

Our works: theoretical background

- DHOST: Degenerate Higher-Order Scalar-Tensor theories



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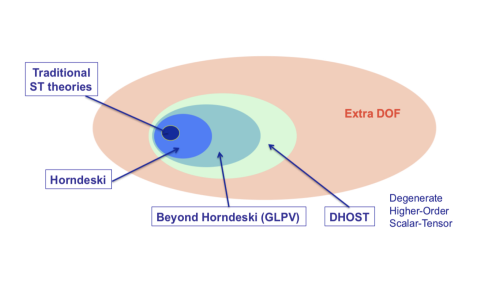

- The most general Lagrangian is (1711.06661):

$$\mathcal{L} = F_{(2)}(\phi, X)^{(4)}R + \sum_{i=1}^{5} A_i(\phi, X)\mathcal{L}^{(2)}_{i,\phi}$$

Our works: theoretical background

- DHOST: Degenerate Higher-Order Scalar-Tensor theories
- partially broken (Vainshtein) screening (1712.04731)
- Gravitational and the metric potentials look like

$$\frac{d\Phi}{dr} = \frac{G_N M(r)}{r^2} + \Xi_1 M''(r)$$

$$\frac{d\Psi}{dr} = \frac{G_N M(r)}{r^2} + \Xi_2 \frac{M'(r)}{r} + \Xi_3 M''(r)$$

- With EFT parameters: (1712.04731)

$$\Xi_1 = -\frac{1}{2}\frac{(\alpha_H + c_T^2\beta_1)^2}{c_T^2(1+\alpha_V-4\beta_1)-\alpha_H-1}$$

$$\Xi_2 = -\frac{\alpha_H\left(\alpha_H-\alpha_V+2\left(1+c_T^2\right)\beta_1\right)+\beta_1\left(c_T^2-1\right)\left(1+c_T^2\beta_1\right)}{c_T^2(1+\alpha_V-4\beta_1)-\alpha_H-1}$$

$$\Xi_3 = -\frac{(\alpha_H + c_T^2\beta_1)}{c_T^2(1+\alpha_V-4\beta_1)-\alpha_H-1}, \quad \gamma_0 = \alpha_V - 3\beta_1, \quad G_N = \frac{G}{1+\gamma_0}$$

Our works: theoretical background

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$$\frac{d\Phi}{dr} = \frac{G_N M(r)}{r^2} + \Xi_1 M''(r)$$

$$\frac{d\Psi}{dr} = \frac{G_N M(r)}{r^2} + \Xi_2 \frac{M'(r)}{r} + \Xi_3 M''(r)$$

- With EFT parameters (1712.04731) + constraints from GWs (1710.05834):

$$\Xi_1 = -\frac{(\alpha_H + \beta_1)^2}{2(\alpha_H + 2\beta_1)}, \qquad \Xi_2 = \alpha_H,$$

$$\Xi_3 = -\frac{\beta_1(\alpha_H + \beta_1)^2}{2(\alpha_H + 2\beta_1)}, \qquad \gamma_0 = -\alpha_H - 3\beta_1, \qquad G_N = \frac{G}{1 + \gamma_0}$$

Our works: data - clusters of galaxies

- **galaxy clusters**: sample of 16 objects from CLASH
- why galaxy clusters?
  - in between cosmological and astrophysical scales
    - more sensitive to large scale DE effects
    - DM and DE effects must coexist
  - multi-messenger approach:
    - X-ray astronomy
    - optical

Our works: data - clusters of galaxies

- **galaxy clusters**: sample of 16 objects from CLASH
- galaxy clusters: X-ray observations ⇒ hot gas
  - spherical symmetry + hydrostatic equilibrium ⇒ collisionless Boltzmann eq:

$$-\frac{d\Phi(r)}{dr} = \frac{kT_{gas}(r)}{\mu m_p r}\left[\frac{d\ln\rho_{gas}(r)}{d\ln r} + \frac{d\ln T_{gas}(r)}{d\ln r}\right]$$

$$M_{tot}(r) = \frac{r^2}{G_N}\frac{d\Phi(r)}{dr} = -\frac{kT_{gas}(r)}{\mu m_p G_N} r\left[\frac{d\ln\rho_{gas}(r)}{d\ln r} + \frac{d\ln T_{gas}(r)}{d\ln r}\right]$$

$$M_{tot}(r) = M_{gas}(r) + M_{gal}(r) + M_{DM}(r) \qquad (GR)$$

$$M_{tot}(r) = M_{gas}(r) + M_{gal}(r) + corr.\ terms \quad (DHOST)$$

  - matter densities are provided by observations (gas, galaxies) or models (NFW dark matter)
  - **caveat**: nongravitational effects can **bias** mass estimation

Our works: data - clusters of galaxies

- **galaxy clusters**: sample of 16 objects from CLASH
- galaxy clusters: optical $\Rightarrow$ gravitational lensing
  - convergence map

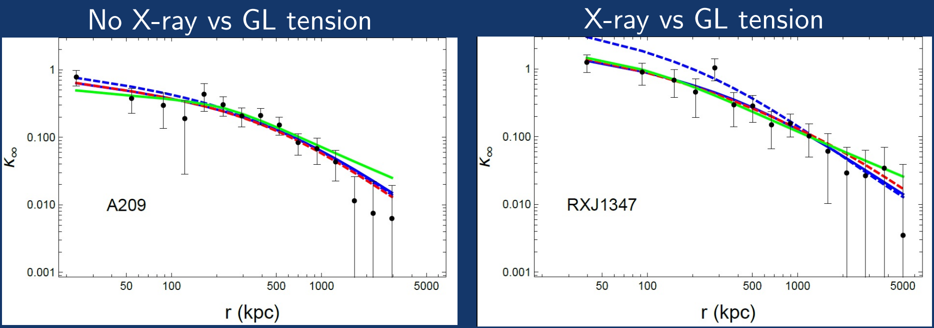
$$\kappa(R) = \frac{1}{c^2}\frac{D_l D_{ls}}{D_s}\int_{-\infty}^{+\infty}\nabla_r\left(\frac{\Phi(R,z)+\Psi(R,z)}{2}\right)\,dz$$

  - **unbiased** mass estimation
  - in GR: tension between X-ray and lensing mass
    - known thermal local disturbances contribute by $10-20\%$
    - tension is larger and with radial dependence
  - how can we solve this tension?

Results: clusters of galaxies

Scenario 1: DHOST as DE + DM

- DHOST as DE can solve tension!
- Statistically (Bayesian Evidence) favored w.r.t. GR!!



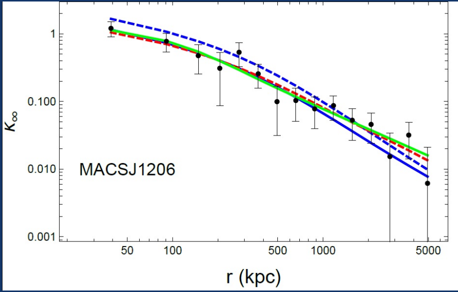
_ _ GR:X+lens; — GR:lens; _ _ DHOST+DM; — DHOST-noDM

Results: clusters of galaxies

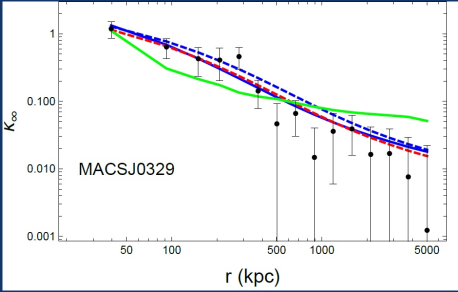
Scenario 2: DHOST as DE and DM

- Statistically disfavoured compared to GR in most of the cases
- Much more sensitive to mass components modeling!

Slightly better than GR



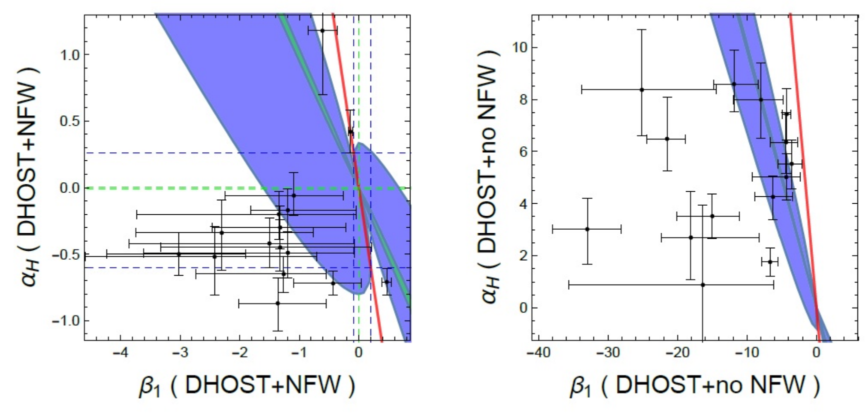
Mass modeling issues



GR:X+lens; GR:lens; DHOST+DM; DHOST-noDM

Results: clusters of galaxies

- Blue lines: stellar stability + Hulse-Taylor pulsar (red line) (1712.04731)
- Green lines: helioseismology + Hulse-Taylor pulsar (red line) (1909.02552)



Our works: data - Ultra-diffuse galaxies

- **UDGs**: 3 from observations of the Dragonfly Telescope Array
  - NGC1052-DF2 (DF2) and NGC1052-DF4 (DF4): lack of DM ($\sim 1\%$)
  - Dragonfly44: DM dominated ($\sim 99\%$)
- mass modelling: stars + DM
- data: velocity dispersions $\Rightarrow$ Jeans eq. (in GR)

$$\frac{d(\ell\sigma_r^2)}{dr} + \frac{\beta(r)}{r}(\ell\sigma_r^2) = \ell(r)\frac{d\Phi(r)}{dr}$$

$$integrating \quad \Rightarrow \quad \ell(r)\sigma_r^2 = \frac{1}{f(r)}\int_r^{\infty} ds\, f(s)\ell(s)\frac{M(s)}{s^2},$$

with $f(r) = d\log f(r)/d\log r = 2\beta(r)$. The observational quantity is

$$\sigma_{los}^2(R) = \frac{2}{I(R)}\left[\int_R^{\infty} dr\, r\frac{\ell(r)\sigma_r^2}{\sqrt{r^2 - R^2}} - R^2\int_R^{\infty} dr\beta(r)\frac{\ell(r)\sigma_r^2}{\sqrt{r^2 - R^2}}\right]$$

Our works: data - Ultra-diffuse galaxies

- **UDGs**: 3 from observations of the Dragonfly Telescope Array
  - NGC1052-DF2 (DF2) and NGC1052-DF4 (DF4): lack of DM ($\sim 1\%$)
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- mass modelling: stars + DM
- data: velocity dispersions $\Rightarrow$ Jeans eq. (in DHOST)

$$\sigma^2_{los}(R) = \frac{2G_N}{I(R)} \int_R^\infty dr\, K\left(\frac{r}{R}\right) \ell(r) \frac{M(r)}{r} \qquad (GR)$$

$$\sigma^2_{los}(R) = \frac{2G_N}{I(R)} \int_R^\infty dr\, K\left(\frac{r}{R}\right) \ell(r) \frac{M_{eff}(r)}{r} \qquad (DHOST)$$

$$M_{eff}(r) = M(r) + r^2 \Xi_1 M''(r)$$

Our works: data - Ultra-diffuse galaxies

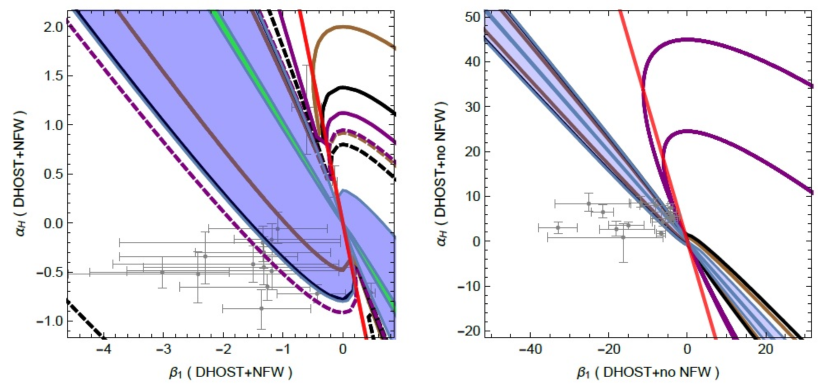
- **UDGs**: 3 from observations of the Dragonfly Telescope Array
  - NGC1052-DF2 (DF2) and NGC1052-DF4 (DF4): lack of DM ($\sim$ 1%)
  - Dragonfly44: DM dominated ($\sim$ 99%)
- mass modelling: stars + DM
- data: velocity dispersions $\Rightarrow$ Jeans eq. (in DHOST)
- Anisotropy parameter $\beta(r)$: two models (1501.03167)

$$\beta \equiv \beta_c \, ; \quad \beta(r) = \beta_0 + (\beta_\infty - \beta_0)\frac{r}{r + r_a}$$

- Relation between stars and DM
  - Stellar-to-halo mass relation (SHMR) (1703.04542)
  - Stellar and DM component decoupled

Results: data - Ultra-diffuse galaxies

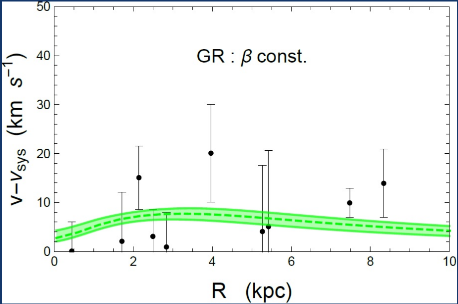
- EFT constraints: DF2 (black), DF4 (brown) and DF44 (purple)



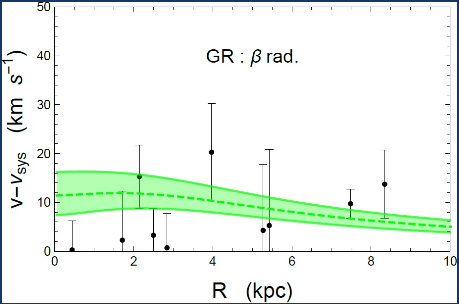
Results: data - Ultra-diffuse galaxies

- DF2: Baryonic case - GR

Reference case



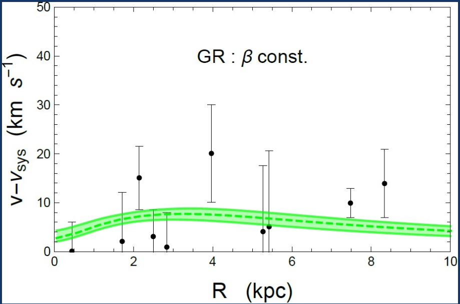
Statistically disfavoured



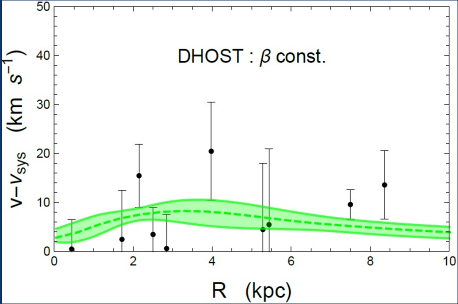
Results: data - Ultra-diffuse galaxies

- DF2: Baryonic case - GR vs DHOST (no DM!)

Reference case

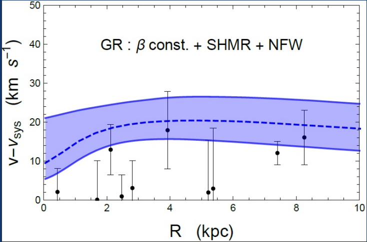


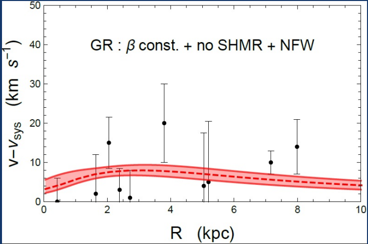
Statistically equivalent!

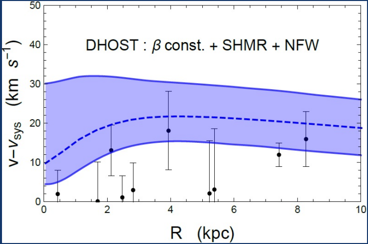


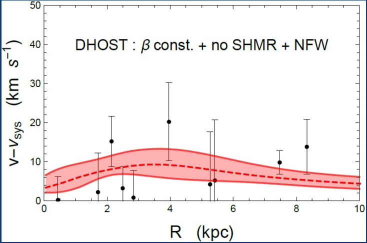
Results: data - Ultra-diffuse galaxies

- DF2: DM case - GR vs DHOST





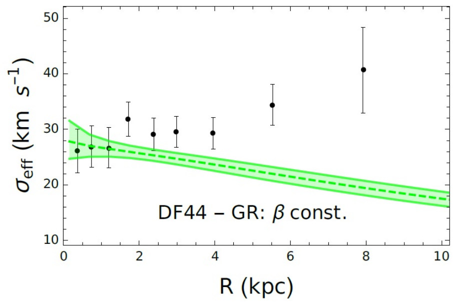




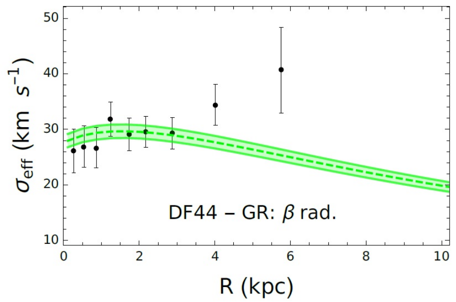
Results: data - Ultra-diffuse galaxies

- Dragonfly44: Baryonic case - GR

Unable to fit data!



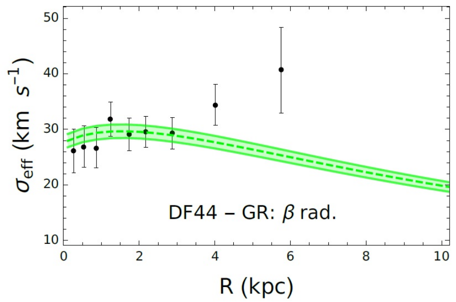
Unable to fit data!



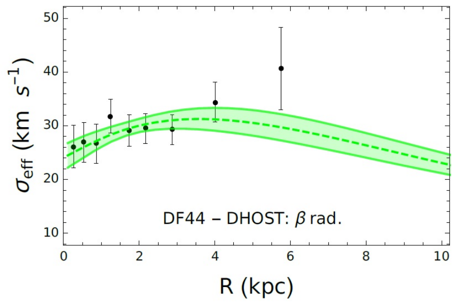
Results: data - Ultra-diffuse galaxies

- Dragonfly44: Baryonic case - GR vs DHOST (no DM!)

Unable to fit data!

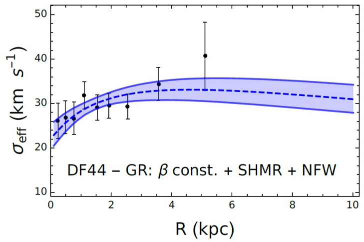


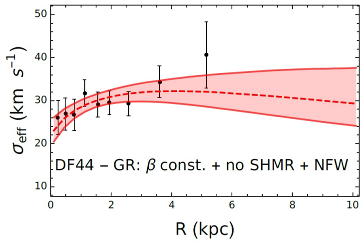
Better, but unable to fit data!

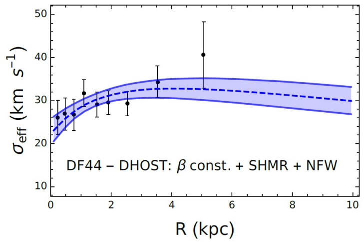


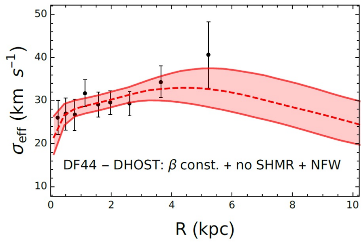
Results: data - Ultra-diffuse galaxies

- DF44: DM case - GR vs DHOST









Conclusions

From clusters of galaxies:

- Below 5 Mpc the screening mechanism is partially broken $\Rightarrow$ DHOST can mimic the role of DE in galaxy clusters
- DHOST as DE can solve the natural tension between X-rays/lensing
- DHOST as DM is statistically disfavored compared to GR

From Ultra-diffuse galaxies:

- Lacking-DM galaxies (DF2 and DF4) are compatible with a pure baryonic mass modeling
- DHOST as DE does not produce significant changes w.r.t. GR $\Rightarrow$ DE does not play a key role at galactic scales
- DHOST as DM
  - As successful as GR for lacking DM galaxies (DF2, DF4)
  - Unable to reproduce DM effects $\Rightarrow$ DM is needed (Dragonfly44)

DZIĘKUJĘ BARDZO!