Hunting Dark Energy on Astrophysical Scales

The Dark Side of the Universe
DSU 2022 – UNSW 08-12
Gravity – Dark Energy session

Leonardo Giani
The University of Queensland

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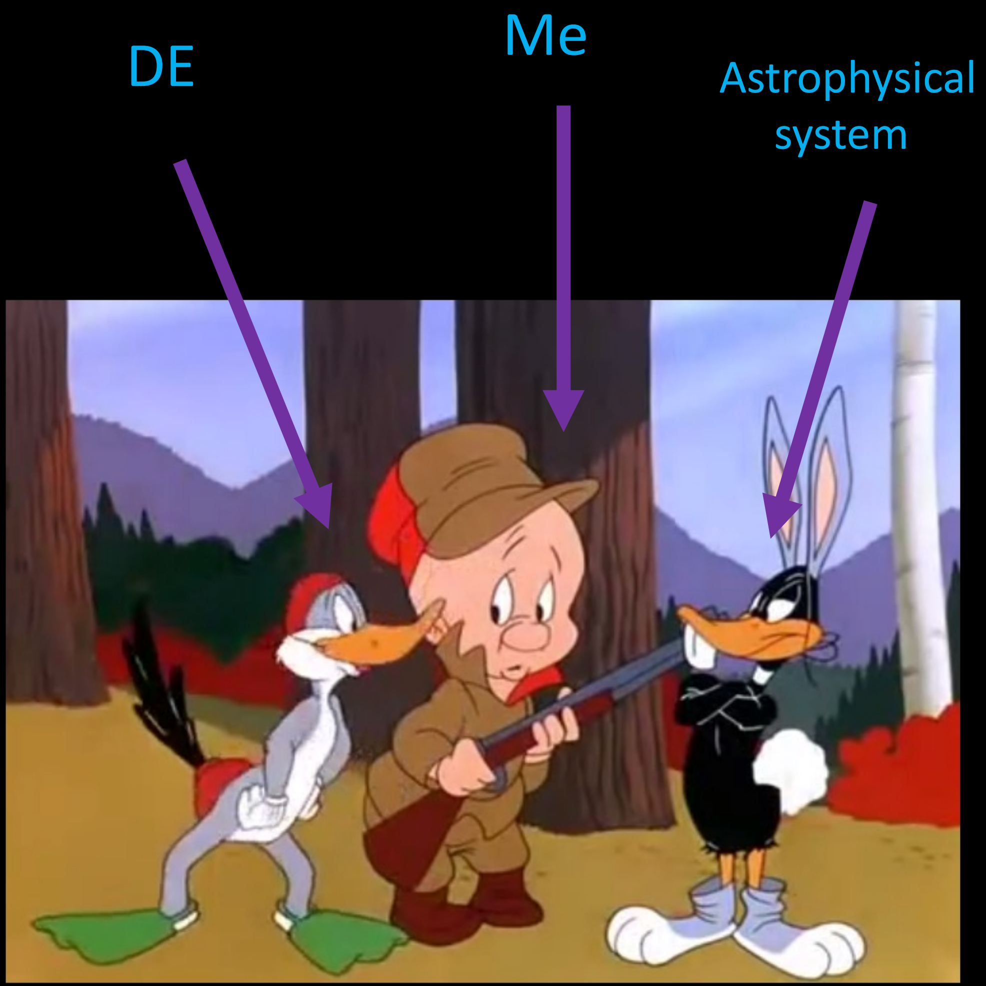


There is a general consensus on accepting the ΛCDM model as the most effective and simple description of our Universe.

-GR Based

-Flat and Democratic (Cosmological Principle)

-Cold Dark Matter + Cosmological constant + a bunch of Bright leftovers

On the other hand, scientist are known for their polemic attitude..

– Small scale problems of the ΛCDM model: a short review, 1606.07790
– Small-Scale Challenges to the ΛCDM Paradigm, 1707.04256
– Beyond ΛCDM: problems, solutions and the road ahead 1512.05356
– Simultaneous falsification of ΛCDM and Quintessence with massive, distant clusters, 1101.0004
– Putting Flat ΛCDM in the (Redshift) Bin, 2206.11447
– Challenges for ΛCDM: An update, 2105.0528
– Revealing intrinsic Flat ΛCDM biases with standardizable candles, 2203.10558

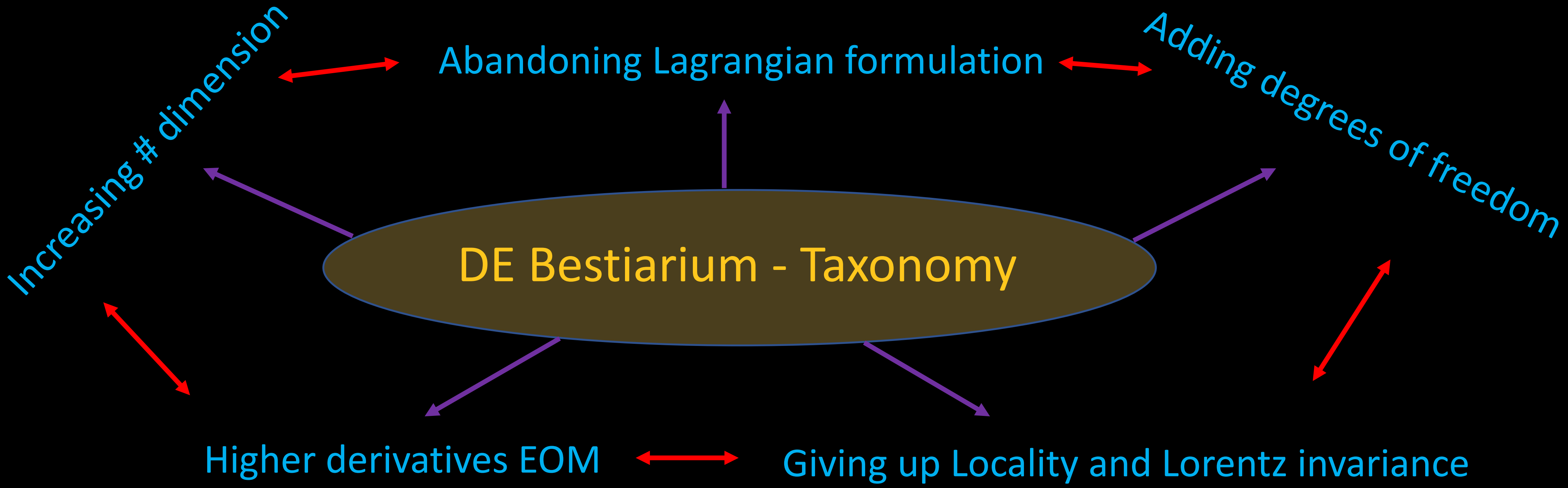
..maybe, sometimes, overreacting a bit: The missing satellites problem

– Where are the missing galactic satellites?, astro-ph/9901240
– Dwarf Galaxies of the Local Group, astro-ph/9901240
– There is No Missing Satellites Problem, 1711.06267
– Hundreds of Milky Way Satellites? Luminosity Bias in the Satellite Luminosity Function, 0806.4381

Lovelock Theorem

Theorem 1 *The only possible second-order Euler-Lagrange expression obtainable in a four dimensional space from a scalar density of the form $\mathcal{L} = \mathcal{L}(g_{\mu\nu})$ is:*

$$E^{\mu\nu} = \alpha\sqrt{-g}\left[R^{\mu\nu} - \frac{1}{2}Rg^{\mu\nu}\right] + \sqrt{-g}g^{\mu\nu}\Lambda \ ,$$



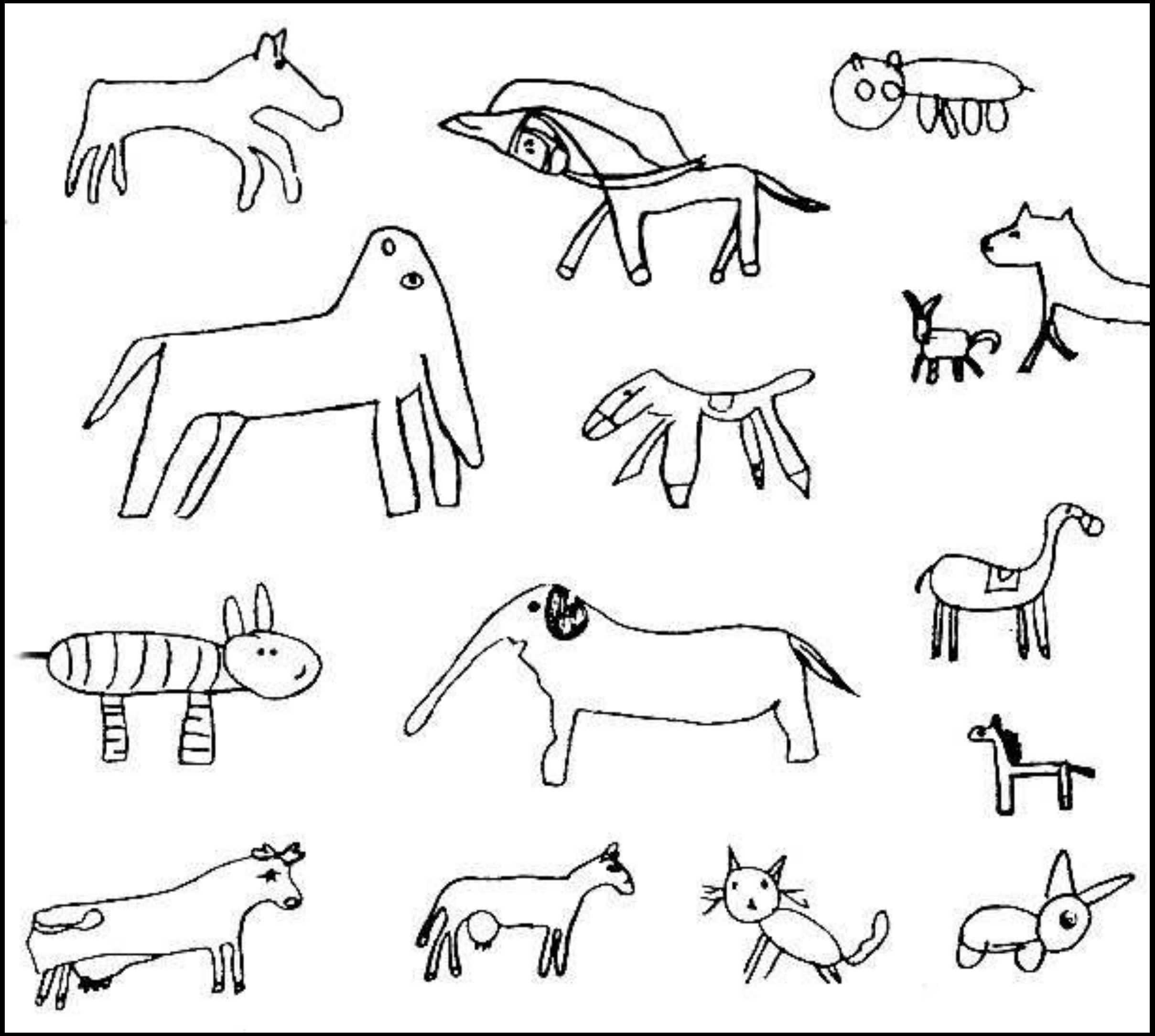
DE Bestiarium - Ethology

Sort of Universal EFT features, as discussed in the talk by Shinji Mukohyama

-Different gravity for Rel. and non Rel matter
$(Y, \eta \quad or \quad \Sigma, \mu)$

- Perturbations and structure formation
  $(\alpha_K, \alpha_B, \alpha_M, \alpha_T)$

- Violations of Equivalence principle
  (e.g. through coupling with matter)



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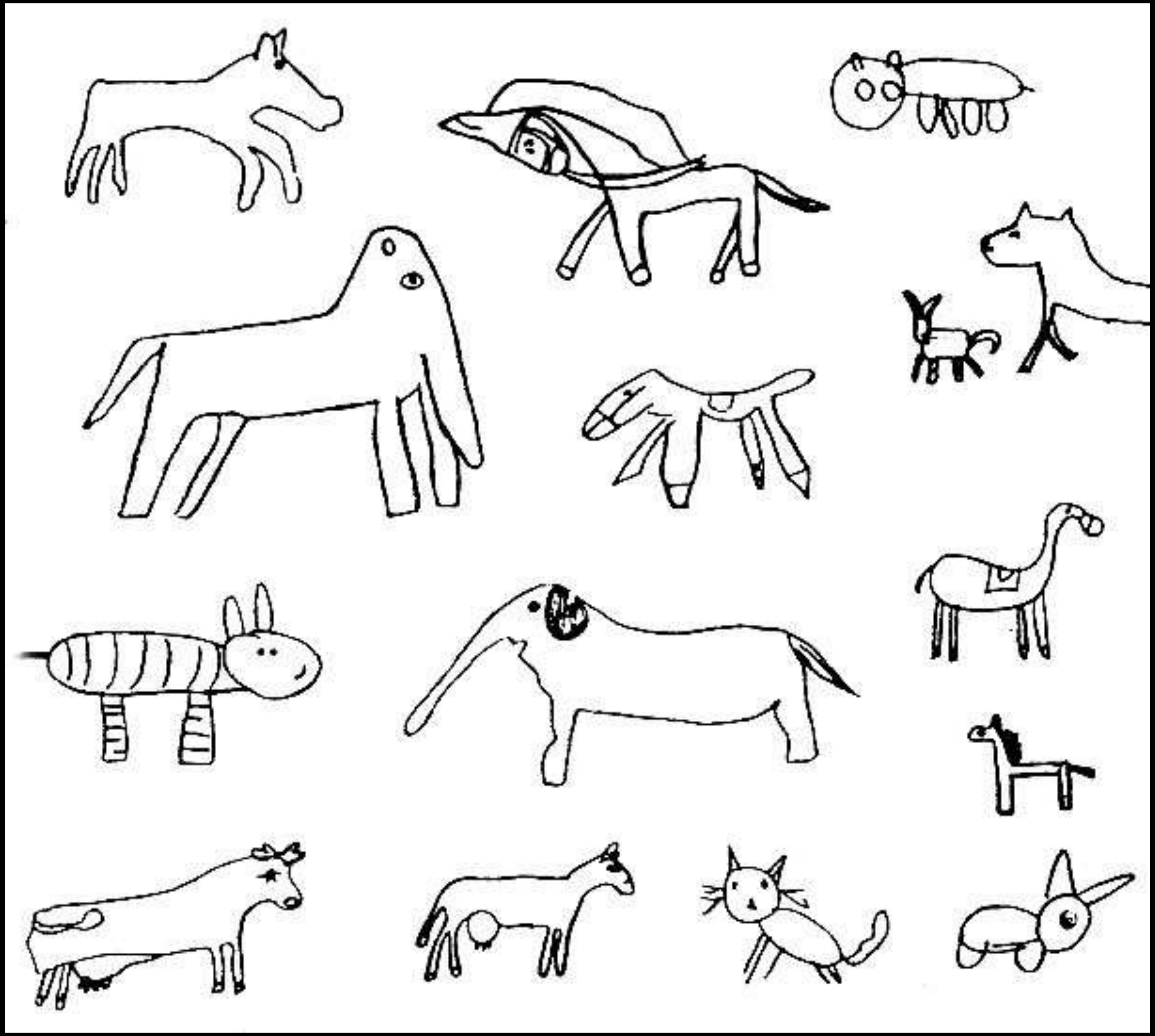
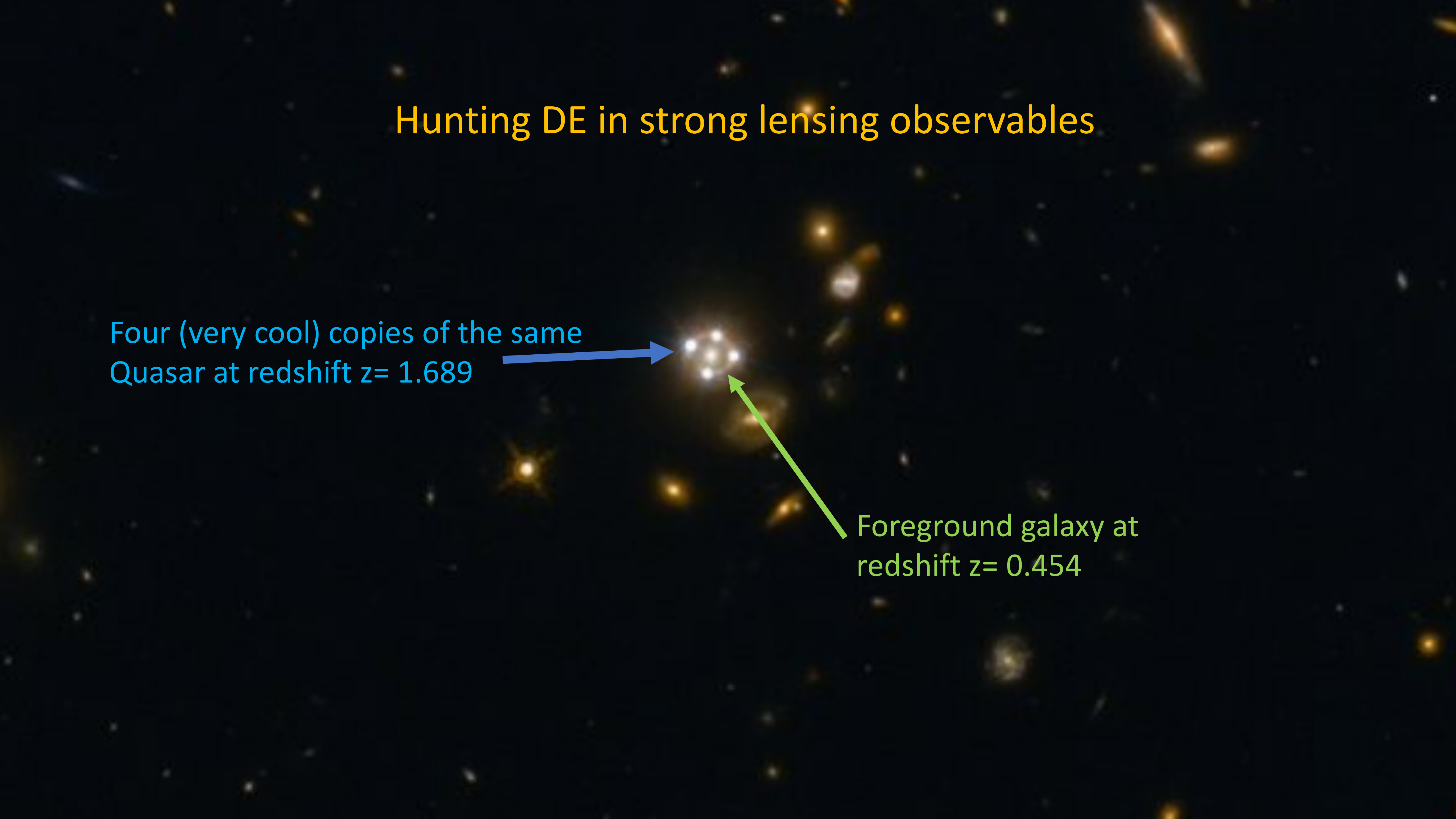


Looking for signatures of DE with legs

Focus on DE violating the EP on astrophysical scales

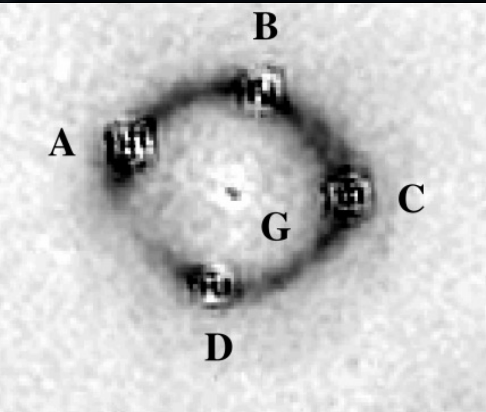
Hunting DE in strong lensing observables



Hunting DE in strong lensing observables

Four (very cool) copies of the same Quasar at redshift z= 1.689

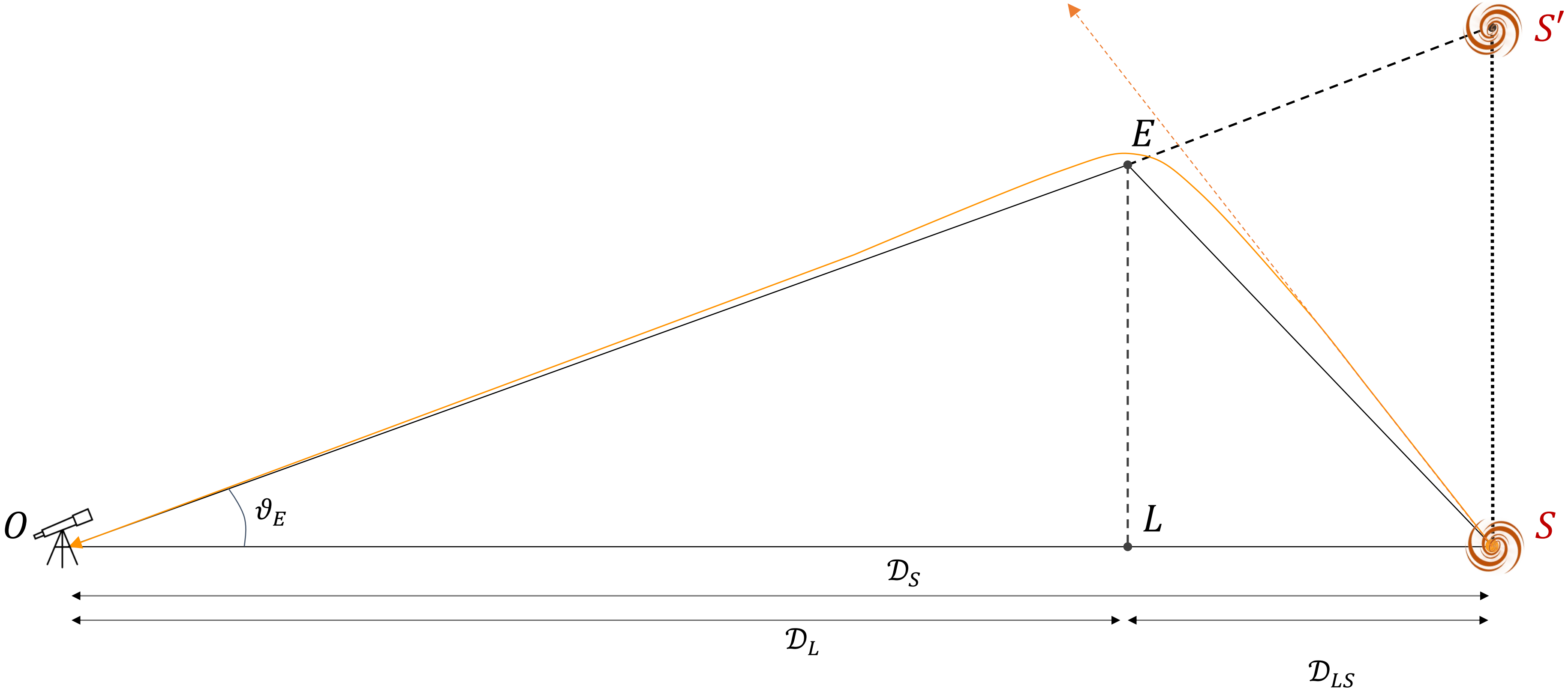
Foreground galaxy at redshift z= 0.454



Einstein Ring in the H band from the galaxy host of the quasar

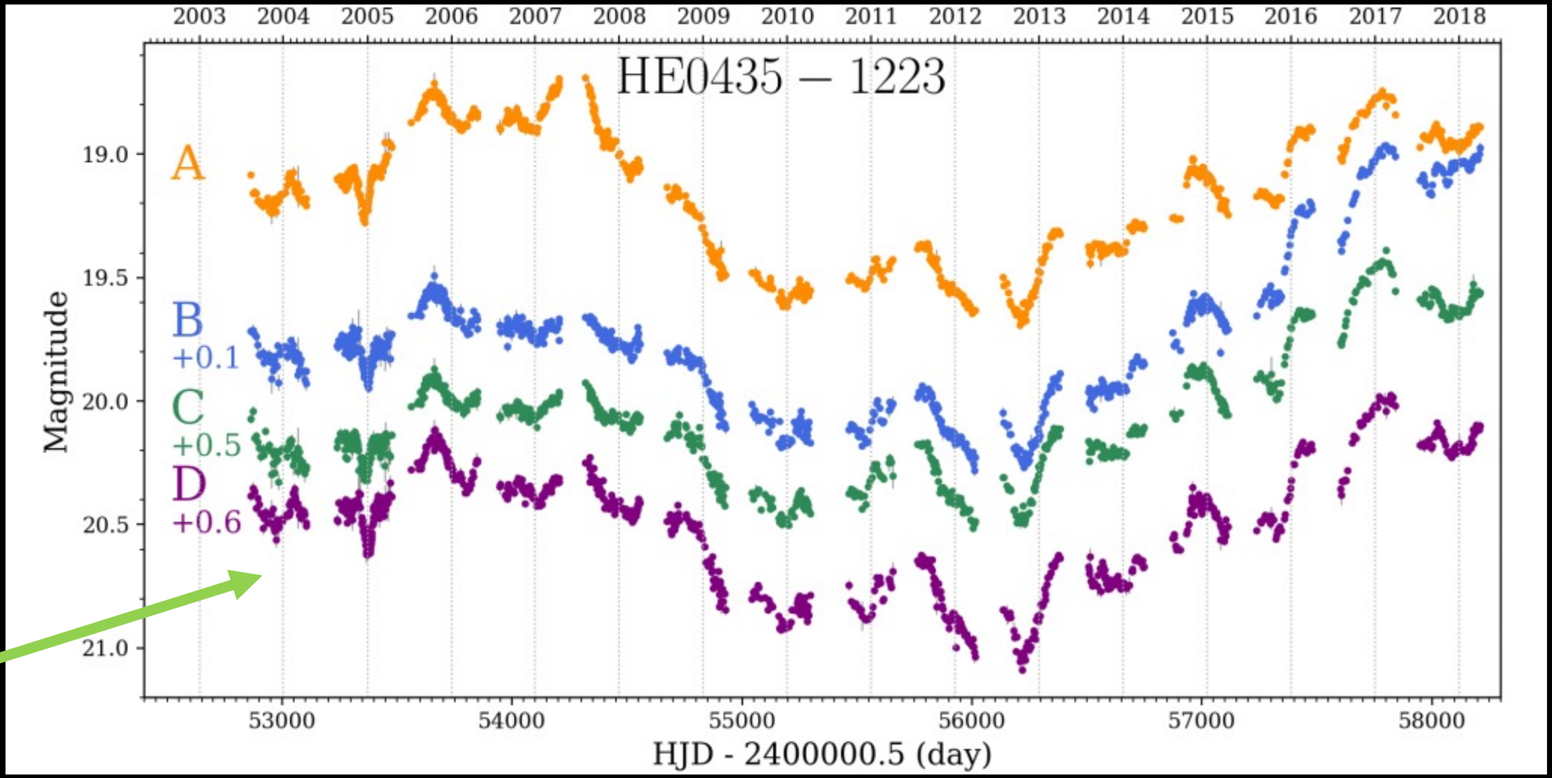
Hunting DE in strong lensing observables

$$\theta_E^2 = 4GM(1+z_L)\left(\frac{1}{\chi_L} - \frac{1}{\chi_S}\right)$$



Hunting DE in strong lensing observables

Lensed photons travel different optical paths (at the same speed c), and arrive at the observer slightly delayed



The horizontal shift between these light curves is the "time delay"

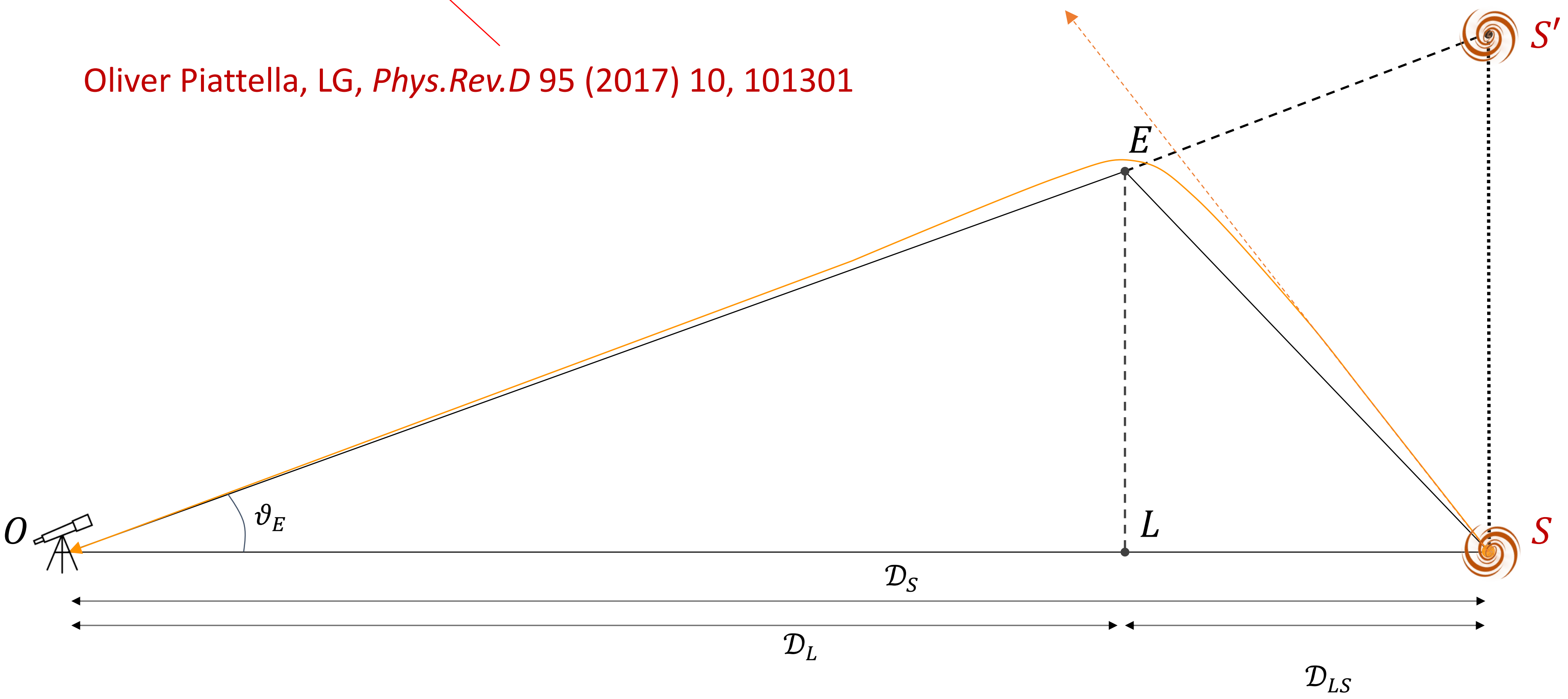
$$\Delta_{ij} = \frac{D_{\Delta_t}}{c}\left(\frac{(\boldsymbol{\beta}_i-\boldsymbol{\alpha})^2}{2} - \frac{(\boldsymbol{\beta_j}-\boldsymbol{\alpha})^2}{2} + \psi(\boldsymbol{\beta_j}) - \psi(\boldsymbol{\beta_i})\right)$$

$$\psi(\boldsymbol{\beta}) \equiv \frac{2}{c^2}\frac{\mathcal{D}_{LS}}{\mathcal{D}_L\mathcal{D}_S}\int_{\boldsymbol{\beta}} d\lambda\, \Phi\ ,$$

Hunting DE in strong lensing observables

$$\theta_E^2 = 4GM(1+z_L)\left(\frac{1}{\chi_L} - \frac{1}{\chi_S}\right)$$

Oliver Piattella, LG, *Phys.Rev.D* 95 (2017) 10, 101301



Hunting DE in strong lensing observables

If $G \rightarrow G_{eff}(t)$

$$\frac{\dot{\Delta}_{ij}}{\Delta_{ij}} = \left(\frac{\dot{G}}{G} + H_0 - \frac{H(z_L)}{1+z_L}\right)\left[1 + \frac{D_{\Delta t}\left(\boldsymbol{\beta}_i - \boldsymbol{\alpha}\right)^2}{2c\Delta_{ij}} - \frac{D_{\Delta t}\left(\boldsymbol{\beta}_j - \boldsymbol{\alpha}\right)^2}{2c\Delta_{ij}}\right] - \frac{\dot{\kappa}_{ext}}{1-\kappa_{ext}}$$

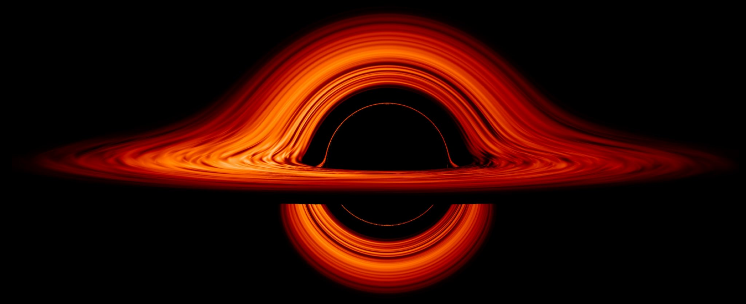
Using the quasar DES J0408-5354 we found constraint of order $\frac{\dot{G}_{eff}}{G_{eff}} < 10^{-1}, 10^{-2}\, yr^{-1}$

(LG, Emmanuel Frion, JCAP 09 (2020) 008)

-Ridiculously small (10 orders of magnitude) compared to constraint from other probes, but at least in an unexplored redshift range (Extragalactic scales)

-Promising if TD measurements boost their precision (For example SL repeating FRB may give TD measurements of $\sim O(sec)$ rather than $\sim O(days)$, improving constraints of a factor 10^5)

Hunting DE in lensing observables around BH



$\approx$

Lensed photons in unstable orbits around the BH can reach us, revealing its silhouette (BH Shadow)

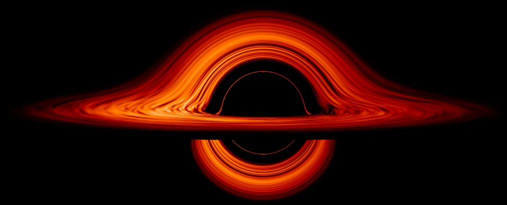
The size of the shadow at a cosmological distance can be written:

$$\alpha_{\rm cosm}(R_O) = \frac{3\sqrt{3}m}{D_A(z)}$$

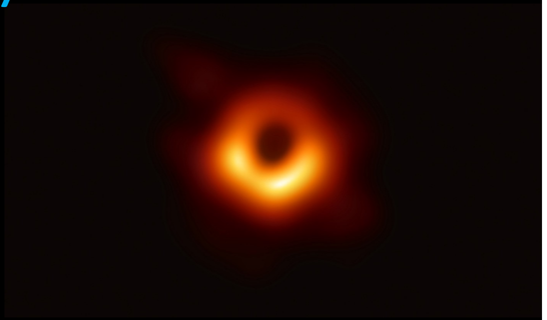
O. Y. Tsupko and G. S. Bisnovatyi-Kogan, First analytical calculation of black hole shadow in McVittie metric, Int. J. Mod. Phys. D 29 (2020)

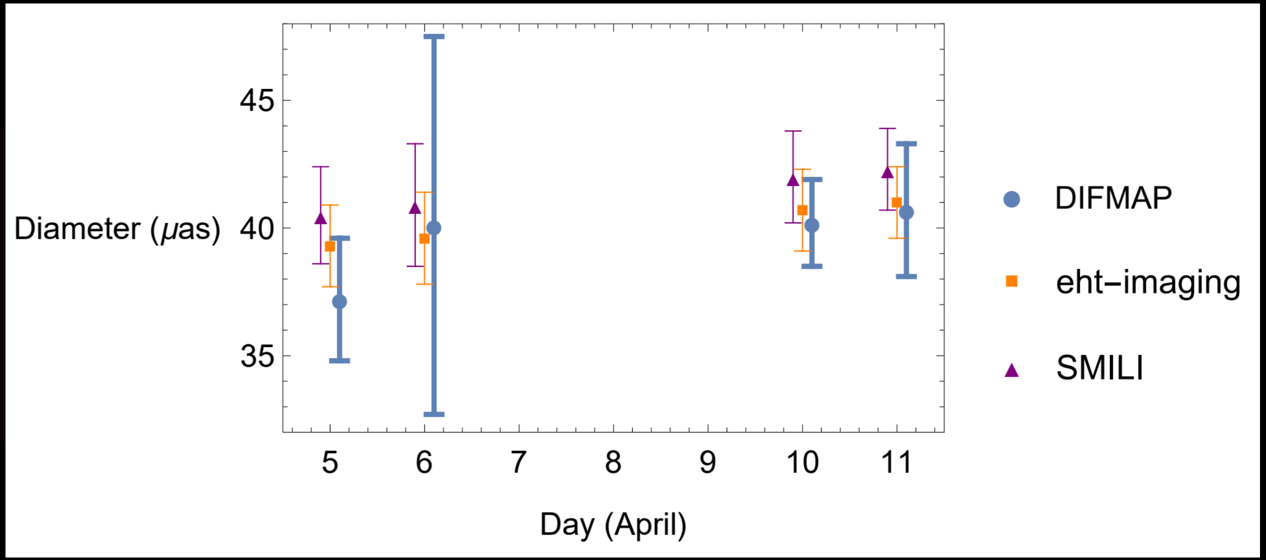
Hunting DE in lensing observables around BH

M87



$\approx$





$$\frac{\dot{\alpha}}{\alpha} = H_0 - \frac{H(z)}{1+z} + \frac{\dot{G}}{G} \, .$$

$$\frac{\dot{G}_{eff}}{G_{eff}} < \; 10^{-4} \, yr^{-1}$$

Still very small (we are slow learner), but slightly better and still from an unexplored redshift range (Extragalactic scales)

Emmanuel Frion, LG, Tays Miranda, *Open J.Astrophys.* 4 (2021)

Hunting DE around BH from spectral Lines

Bekenstein Coupling :

$$S = \frac{1}{2}\int d^4x\sqrt{-g}R + \int d^4x\sqrt{-g}\left[\frac{1}{2}\partial^\mu\varphi\partial_\mu\varphi - V(\varphi)\right] - \frac{1}{4}\int d^4x\sqrt{-g}B_F F_{\mu\nu}F^{\mu\nu} \ .$$

Varying with respect to φ yields the following equation of motion:

$$\Box\varphi + V_\varphi + \frac{1}{4}B_{F\varphi}F_{\mu\nu}F^{\mu\nu} = 0 \ ,$$

From which we get an effective Fine structure constant

$$\alpha(t,r) = \frac{\alpha_0}{B_F(\varphi(t,r))} \ ,$$

$$\frac{\Delta\alpha}{\alpha} \equiv \frac{\alpha(t,r) - \alpha_0}{\alpha_0} = \frac{1}{B_F(\varphi(t,r))} - 1 \ ,$$

Hunting DE around BH from spectral Lines

The previous action expanded up to first order linear perturbations over a flat FLRW background gives the following equations:

$$-\frac{2}{a^2}\nabla^2\Phi + 6H\dot{\Phi} = \rho\delta + V_{,\varphi}\delta\varphi + \Psi\left(2V + 2\rho\right) + \dot{\varphi}\dot{\delta\varphi}\ ,$$

$$2\left[\frac{1}{3a^2}\nabla^2\left(\Psi + \Phi\right) + H\left(\dot{\Psi} - 3\dot{\Phi}\right) - \ddot{\Phi}\right] = -2\Psi\left(V - w\rho\right) + p - V_{,\varphi}\delta\varphi + \dot{\varphi}\dot{\delta\varphi}\ ,$$

$$\ddot{\delta\varphi} + 3H\dot{\delta\varphi} - \frac{\nabla^2}{a^2}\delta\varphi + V_{,\varphi\varphi}\delta\varphi = -2\Psi V_{,\varphi} + \dot{\varphi}\left(\dot{\Psi} - 3\dot{\Phi}\right)\ ,$$

$$\dot{\delta} + 3H\delta\left(-w + \frac{p}{\delta\rho}\right) + (1+w)\left(3\dot{\Phi} + \frac{v^i_{,i}}{a}\right) = 0\ . \quad \dot{\theta} + 2H\theta = \frac{\nabla^2}{a^2}\Phi - \frac{\nabla^2}{a^2}\frac{p}{\rho\left(1+w\right)}$$

Cosmological constant
$w - 1$

Slow Rolling Quintessence
$w \approx -1$

(close to a massive structure)

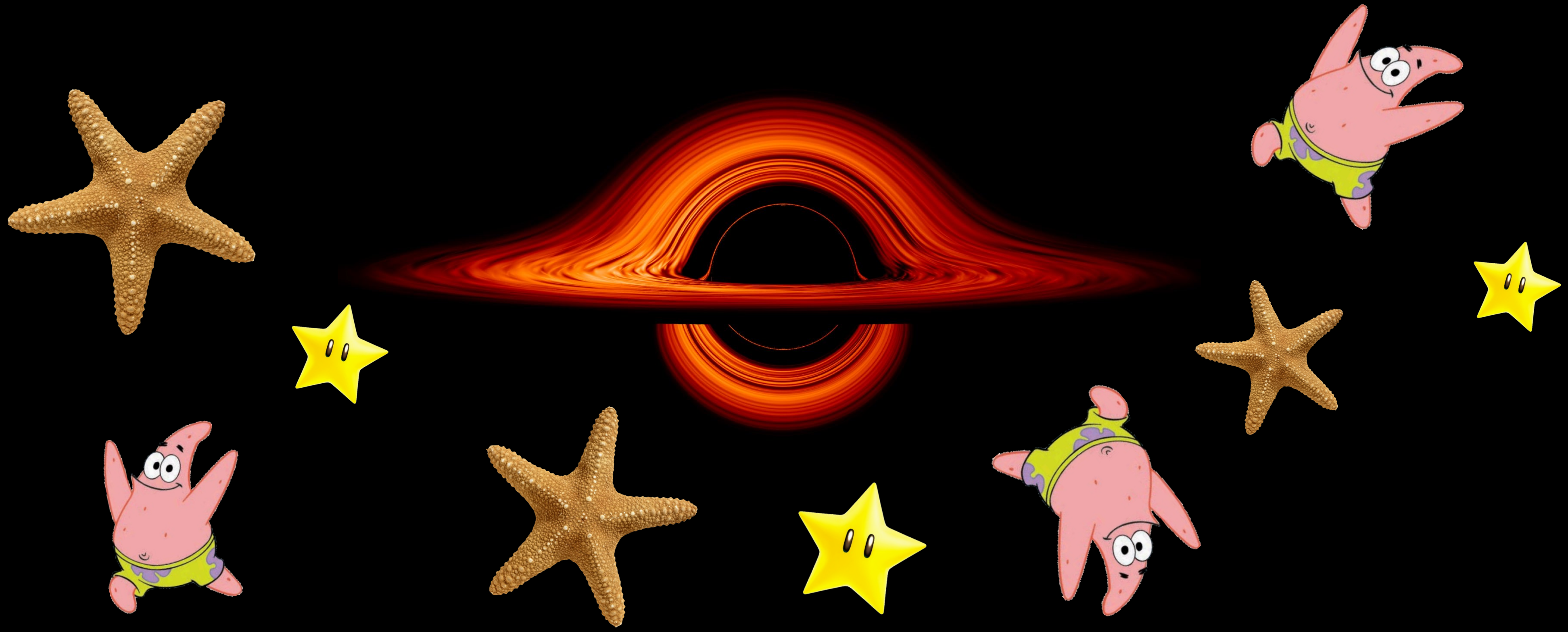
We considered the above equations with a Scalar field in slow roll to mimic a cosmological constant
(i.e. as close as possible to a LCDM cosmology today)

Hunting DE around BH from spectral Lines

Solving the above mess for Spherically symmetric and static distribution of matter ($\dot{\delta} = 0$) we found:

$$\frac{\delta\alpha}{\alpha}(r) \propto \frac{1}{r} \ .$$

Thus, around a spherically symmetric object, we found that a quintessential field would induce a 1/r dependence on the fine structure constant.



Hunting DE around BH from spectral Lines

$$\frac{\delta\alpha}{\alpha}(r) \propto \frac{1}{r} \, .$$

Star	$\Delta\alpha_{star}/\alpha_{ref}$	r_{star} $[arcsec]$
S0-6	$1.0 \pm 1.2 \times 10^{-4}$	0.36
S0-12	$-0.3 \pm 1.4 \times 10^{-4}$	0.69
S0-13	$0.03 \pm 3.5 \times 10^{-4}$	0.69
S1-5	$-0.7 \pm 2.4 \times 10^{-4}$	0.95
S1-23	$0.9 \pm 5.8 \times 10^{-6}$	1.74

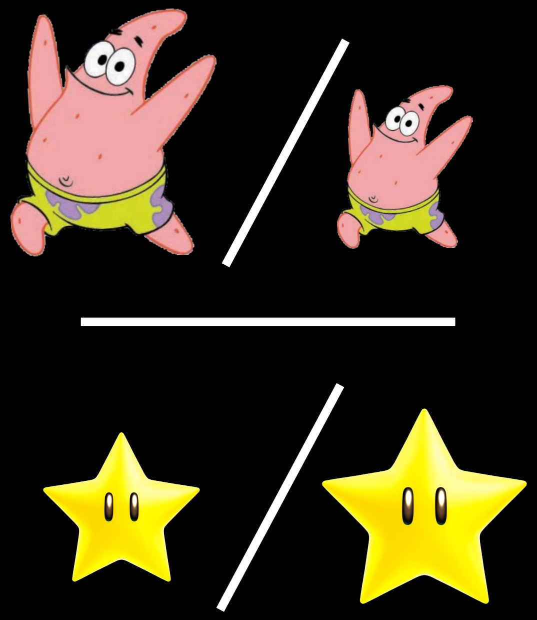
A. Hees et al., Phys. Rev. Lett. 124, 081101 (2020)

One of these et al. is Benjamin Roberts, which gave us a brilliant and enlightening talk on how to get those measurements Monday.

Thanks Ben!

Hunting DE around BH from spectral Lines

In principle, we can use the ratio of these upper bounds to test whether there actually is a 1/r dependence of the fine structure constant



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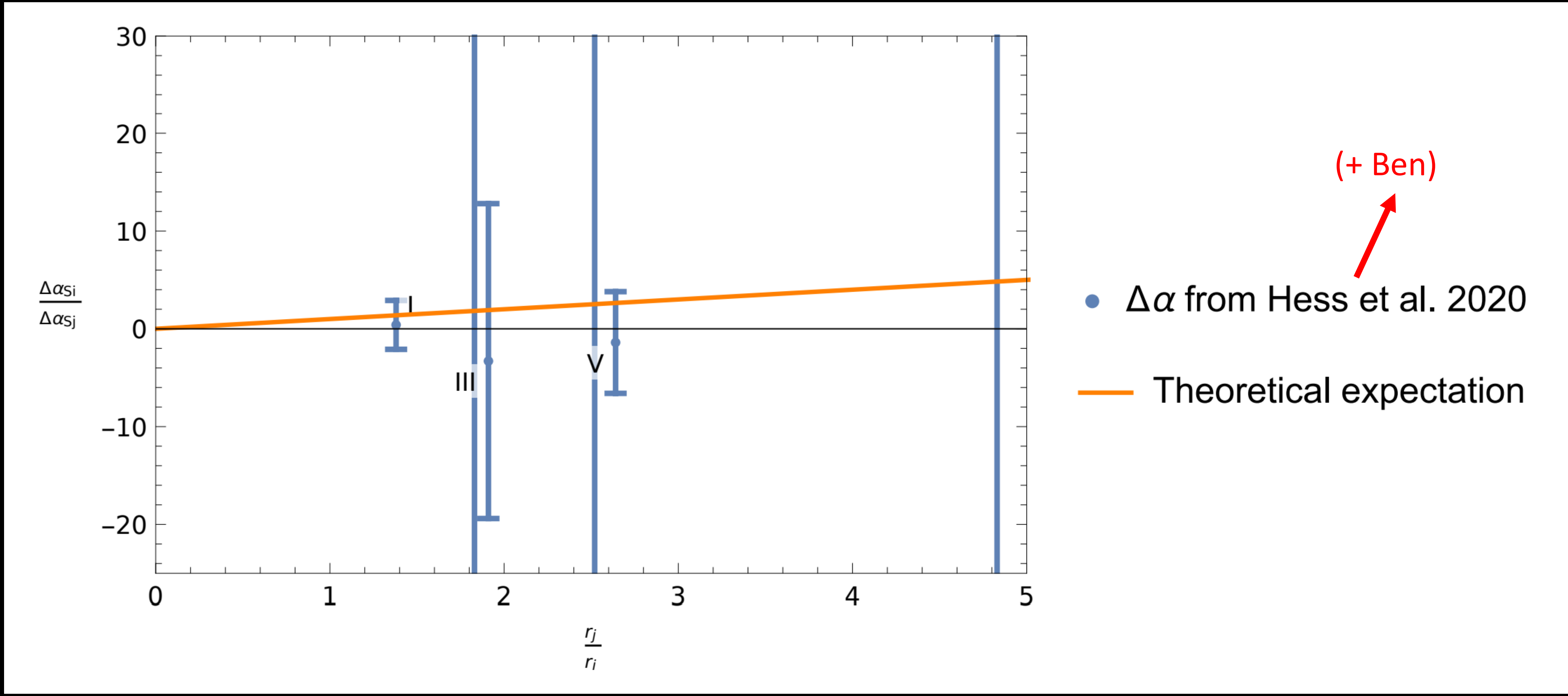
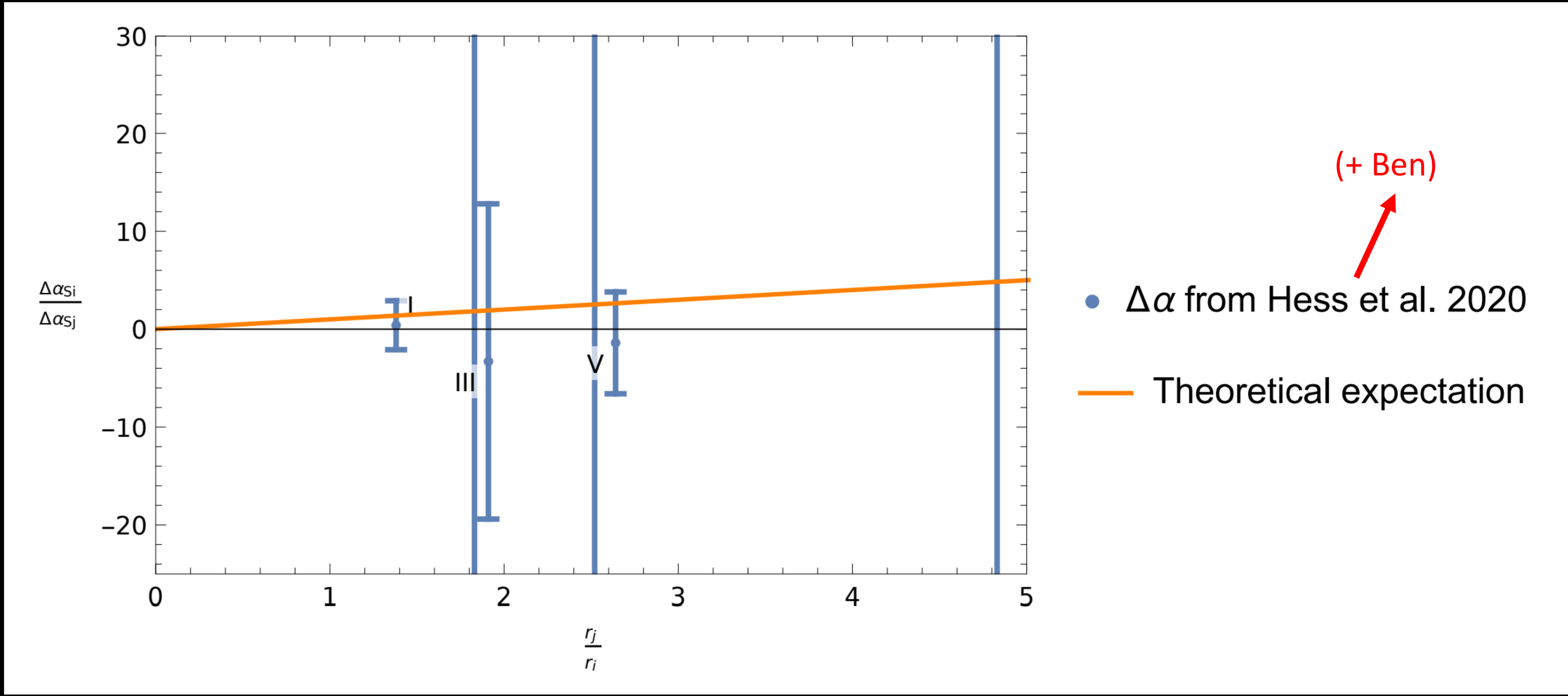
Pair of Stars S_i, S_j	$\Delta\alpha_{Si}/\Delta\alpha_{Sj}$	r_j/r_i
I (S0-12,S1-5)	0.4 ± 2.5	1.38
II (S1-5,S1-23)	-77.8 ± 567.9	1.83
III (S0-6,S0-12)	-3.3 ± 16.0	1.91
IV (S0-12,S1-23)	-33.3 ± 264.9	2.52
V (S0-6,S1-5)	-1.4 ± 5.2	2.64
VI (S0-6,S1-23)	111.1 ± 728.4	4.83

Hunting DE around BH from spectral Lines



(+ Ben)

Hunting DE around BH from spectral Lines



(+ Ben)

Summary

-Dynamical DE manifests at scales
smaller than cosmological ones

- Astrophysical systems can be used
to constrain its properties on scales
where DE is usually unexplored

-As you saw its not so hard.
Can you think of something else?

-With some luck and better
measurements, the constraints
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Summary

Astrophysical systems

-Dynamical DE manifests at scales smaller than cosmological ones

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Can you think of something else?

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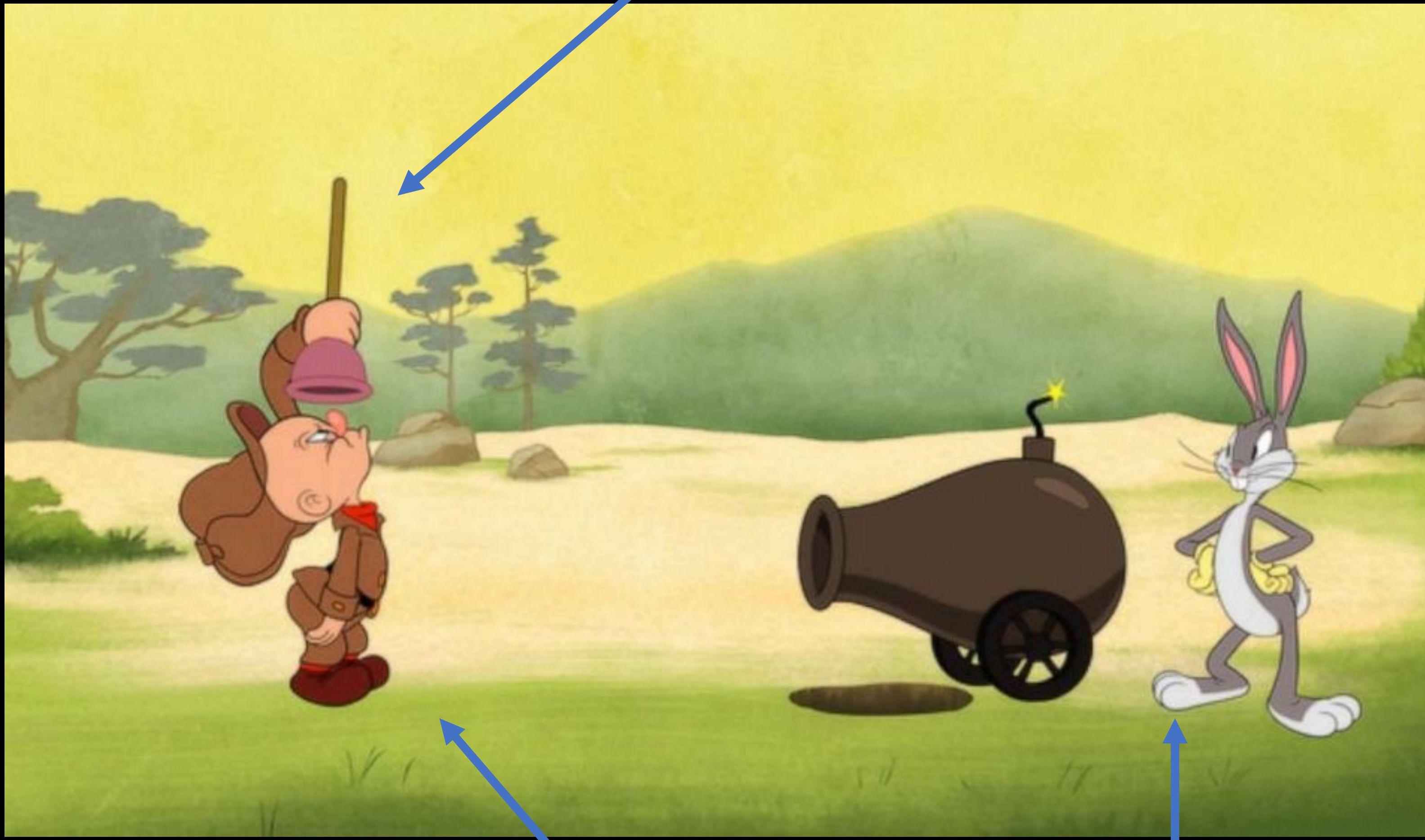

.. Even if so far…

Still
Me

DE