Probing fundamental physics with data from every corner of the (dark) Universe

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Newton-Kavli Fellow (2019–2022)

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Kavli Fellows' Science Day, 30 September 2021

My past 18 months

3 research highlights today:

- Cosmic tensions (?), model-agnostic tests
- Direct detection of dark energy
- Black holes as probes of fundamental physics

2 non-research highlights:

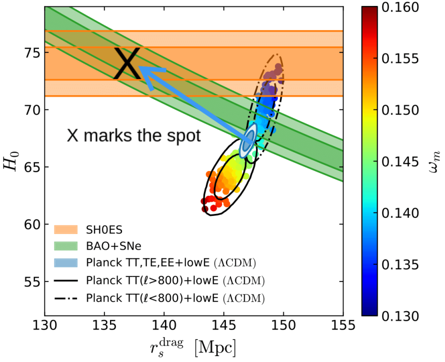
- New family member since May 22, 2021
- Euro 2021

Part 1: Cosmic tensions and model-agnostic cosmological tests

The Hubble tension and new physics

Hubble tension *appears* to call for (substantial) early-time new physics...

Increasing $H(z)$ just prior to $z_\star$:
"least unlikely" proposal?



Credits: Knox & Millea, PRD 101 (2020) 043533

Example: early dark energy

Featured in Physics | Editors' Suggestion

Early Dark Energy can Resolve the Hubble Tension

Vivian Poulin, Tristan L. Smith, Tanvi Karwal, and Marc Kamionkowski
Phys. Rev. Lett. **122**, 221301 – Published 4 June 2019

Editors' Suggestion

Early dark energy does not restore cosmological concordance

J. Colin Hill, Evan McDonough, Michael W. Toomey, and Stephon Alexander
Phys. Rev. D **102**, 043507 – Published 5 August 2020

Need $\approx 12\%$ (!!!) EDE around $z_{\rm eq}$ $\Downarrow$

Why is there no **clear** *sign of new physics in CMB data alone?*

Caveat: true prior to ACT DR4?

The early ISW (eISW) effect

PHYSICAL REVIEW D **104,** 063524 (2021)

Consistency tests of ΛCDM from the early integrated Sachs-Wolfe effect: Implications for early-time new physics and the Hubble tension

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$$\Theta = \int_0^{\eta_0} d\eta \left[\underbrace{\propto g(\Theta_0 + \Psi)}_{\text{Sachs-Wolfe}} + \underbrace{\propto g v_b \frac{d}{d\eta}}_{\text{Doppler}} + \underbrace{\propto e^{-\tau}(\dot{\Psi} - \dot{\Phi})}_{\text{ISW}} + \underbrace{\propto (g\Pi + [\ddot{g\Pi}])}_{\text{Polarization}} \right] j_\ell(k\Delta\eta)$$

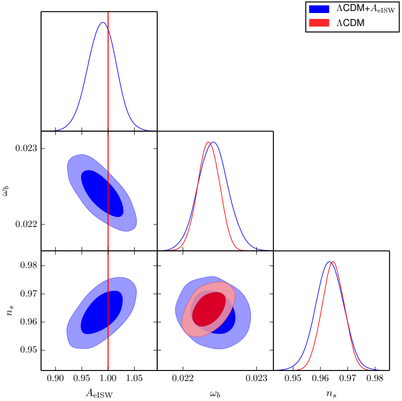
$$\Theta_\ell^{\rm ISW}(k) = \underbrace{\int_0^{\eta_m} d\eta\, e^{-\tau} \left(\dot{\Psi} - \dot{\Phi}\right) j_\ell(k\Delta\eta)}_{\text{early ISW}} + \underbrace{\int_{\eta_m}^{\eta_0} d\eta\, e^{-\tau} \left(\dot{\Psi} - \dot{\Phi}\right) j_\ell(k\Delta\eta)}_{\text{late ISW}}$$

(A substantial amount of) New physics increasing $H(z)$ around $z_{\rm eq}/z_\star$ *should* leave an imprint on the eISW effect!

eISW consistency test

Introduce scaling amplitude/fudge factor A_{eISW}:

$$\Theta_\ell^{\mathrm{eISW}}(k) = A_{\mathrm{eISW}} \int_0^{\eta_m} d\eta \, e^{-\tau} \left(\dot{\Psi} - \dot{\Phi} \right) j_\ell(k\Delta\eta)$$

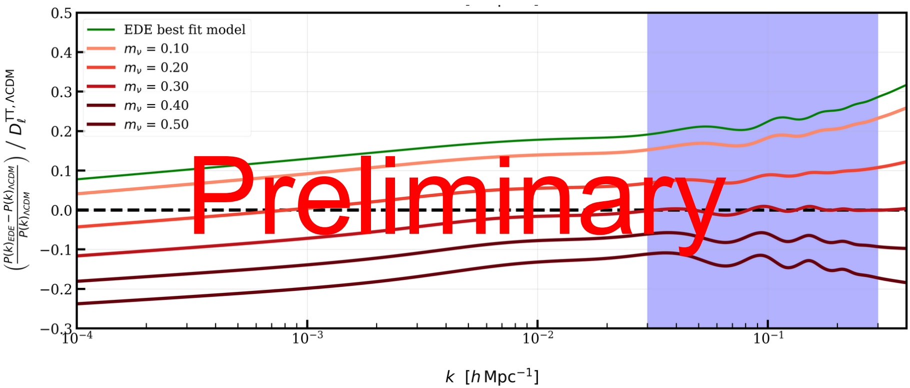


Parameter	*Planck*	
	ΛCDM	ΛCDM+A_{eISW}
$100\omega_b$	2.235 ± 0.015	2.241 ± 0.020
ω_c	0.1202 ± 0.0013	0.1203 ± 0.0014
θ_s	1.0409 ± 0.0003	1.0409 ± 0.0003
τ	0.0544 ± 0.0078	0.0541 ± 0.0078
$\ln(10^{10} A_s)$	3.045 ± 0.016	3.046 ± 0.016
n_s	0.965 ± 0.004	0.963 ± 0.005
A_{eISW}	1.0	0.988 ± 0.027
H_0 [km/s/Mpc]	67.26 ± 0.57	67.28 ± 0.62
Ω_m	0.317 ± 0.008	0.317 ± 0.009

SV, PRD 104 (2021) 063524

More new physics to solve EDE's problems?

Massive neutrinos? Looks like $M_\nu \sim 0.3\,\mathrm{eV}$ needed to rescue EDE!



Plot credits: Alex Reeves (Part III project)

Massive neutrinos actually turn out not to work (still trying to fully understand why...)

S_8 discrepancy – something to get excited about?

Monthly Notices of the ROYAL ASTRONOMICAL SOCIETY
MNRAS 505, 5427–5437 (2021)
Advance Access publication 2021 June 5
https://doi.org/10.1093/mnras/stab1613

Arbitrating the S_8 discrepancy with growth rate measurements from redshift-space distortions

Rafael C. Nunes[1★] and Sunny Vagnozzi[2†]
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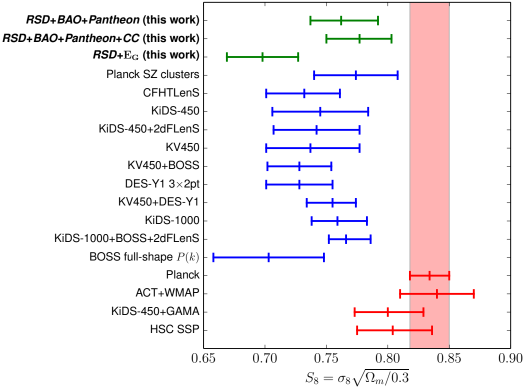
[2]*Kavli Institute for Cosmology (KICC), University of Cambridge, Madingley Road, Cambridge CB3 0HA, UK*



From the growth rate ($f\sigma_8$) point of view, S_8 discrepancy perfectly compatible with a statistical fluctuation!

Nunes & SV, MNRAS 505 (2021) 5427

Non-parametric test of spatial curvature

Monthly Notices of the ROYAL ASTRONOMICAL SOCIETY

MNRAS **506,** L1–L5 (2021) https://doi.org/10.1093/mnrasl/slab058
Advance Access publication 2021 June 04

Non-parametric spatial curvature inference using late-Universe cosmological probes

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[2] *The Oskar Klein Centre for Cosmoparticle Physics, Department of Physics, Stockholm University, SE-10691 Stockholm, Sweden*
[3] *Imperial Centre for Inference and Cosmology, Astrophysics Group, Imperial College London, Blackett Laboratory, Prince Consort Road, London SW7 2AZ, UK*

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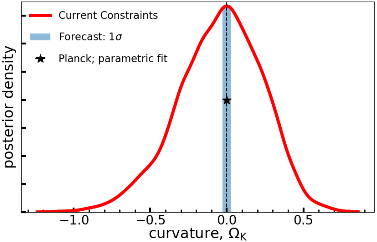
$$H_0 d_L = \frac{c(1+z)}{\sqrt{|\Omega_K|}} \,\mathrm{sinn}\left(\sqrt{|\Omega_K|}\int_0^z \frac{dz'}{E(z')}\right)$$

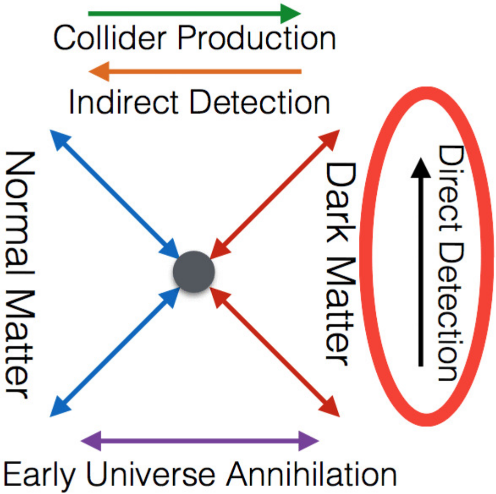
$H_0 d_L$: *uncalibrated* SNeIa
$E(z)$: cosmic chronometers



Dhawan, Alsing, SV, MNRAS Lett. 506 (2021) L1

Part 2: Direct detection of Dark Energy

Are gravitational signatures of dark energy all there is?



What about dark energy?

Credits: (adapted from) Matt Buckley

Direct detection of (screened) dark energy

PHYSICAL REVIEW D **104**, 063023 (2021)

Direct detection of dark energy: The XENON1T excess and future prospects

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[3]Istituto Nazionale di Fisica Nucleare (INFN), Laboratori Nazionali di Frascati, C.P. 13, I-100044 Frascati, Italy
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Have we detected dark energy? Cambridge scientists say it's a possibility

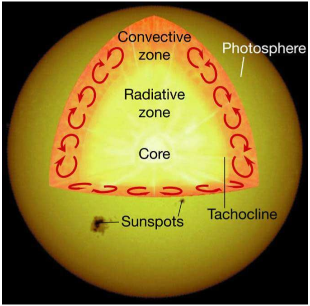
See University of Cambridge's press release!

Direct detection of (chameleon-screened) dark energy

Production

$$\mathcal{L}_{\phi\gamma} \supset -\beta_\gamma \frac{\phi}{M_{\rm Pl}} F_{\mu\nu}F^{\mu\nu} + \underbrace{\frac{T_\gamma^{\mu\nu}\partial_\mu\phi\partial_\nu\phi}{M_\gamma^4}}_{\text{disformal}}$$

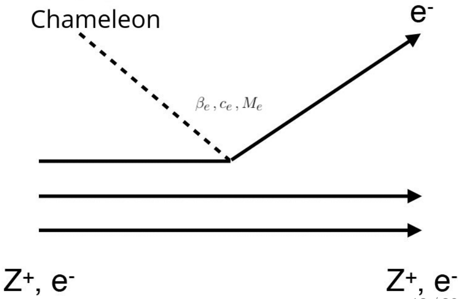
Production in strong magnetic fields of the tachocline



Detection

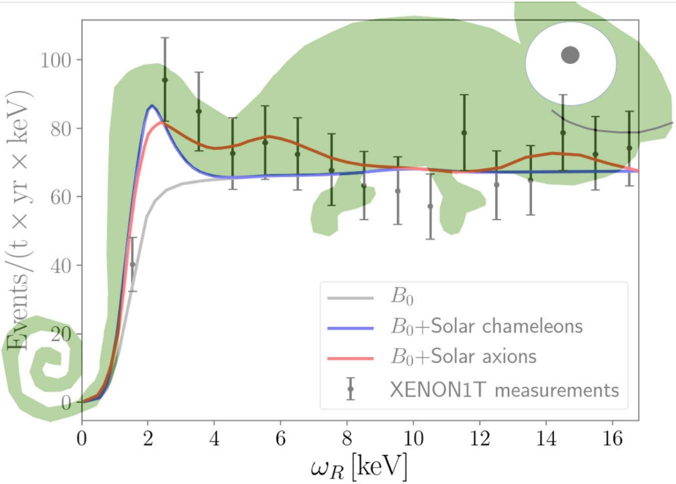
$$\mathcal{L}_{\phi i} \supset \underbrace{\beta_i \frac{\phi T_i}{M_{\rm Pl}}}_{\text{conformal}} - \underbrace{c_i \frac{\partial^\mu\phi\partial_\mu\phi}{M^4}}_{\text{kinetic-conformal}} T_i + \underbrace{\frac{T_i^{\mu\nu}\partial_\mu\phi\partial_\nu\phi}{M_i^4}}_{\text{disformal}}$$

Analogous to photoelectric and axioelectric effects



Direct detection of (chameleon-screened) dark energy

Intriguing hints in XENON1T?



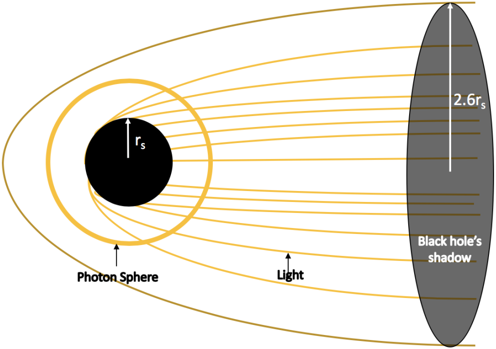
SV *et al.*, PRD 104 (2021) 063023 Image editing credits: Cristina Ghirardini

Part 3: Black holes

Black hole shadows

Credits: Event Horizon Telescope collaboration

For Schwarzschild BH shadow radius $3\sqrt{3}M$



Can we use BH shadows to test fundamental physics?

Testing fundamental physics from black hole shadows?

Known information for M87*:

- Diameter of shadow δ, distance to mass ratio D/M $\rightarrow d = D\delta/M \sim 11.0 \pm 1.5$
- Deviation from circularity $\Delta C \lesssim 10\%$

Recipe: compute d and ΔC for BHs in your favourite theory, then impose these constraints

Testing the rotational nature of the supermassive object M87* from the circularity and size of its first image

Cosimo Bambi, Katherine Freese, Sunny Vagnozzi, and Luca Visinelli
Phys. Rev. D **100**, 044057 – Published 29 August 2019

Hunting for extra dimensions in the shadow of M87*

Sunny Vagnozzi and Luca Visinelli
Phys. Rev. D **100**, 024020 – Published 12 July 2019

Magnetically charged black holes from non-linear electrodynamics and the Event Horizon Telescope

Alireza Allahyari[1], Mohsen Khodadi[1], Sunny Vagnozzi[2] and David F. Mota[3]
Published 4 February 2020 • © 2020 IOP Publishing Ltd and Sissa Medialab
Journal of Cosmology and Astroparticle Physics, Volume 2020, February 2020
Citation Alireza Allahyari *et al* JCAP02(2020)003

Concerns regarding the use of black hole shadows as standard rulers

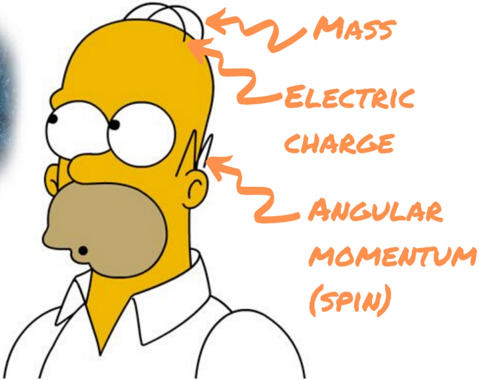
Sunny Vagnozzi[4,1], Cosimo Bambi[2] and Luca Visinelli[3]
Published 25 March 2020 • © 2020 IOP Publishing Ltd
Classical and Quantum Gravity, Volume 37, Number 8
Citation Sunny Vagnozzi *et al* 2020 *Class. Quantum Grav.* **37** 087001

Black holes with scalar hair in light of the Event Horizon Telescope

Mohsen Khodadi[1], Alireza Allahyari[1], Sunny Vagnozzi[2] and David F. Mota[3]
Published 14 September 2020 • © 2020 IOP Publishing Ltd and Sissa Medialab
Journal of Cosmology and Astroparticle Physics, Volume 2020, September 2020
Citation Mohsen Khodadi *et al* JCAP09(2020)026

The no-hair theorem

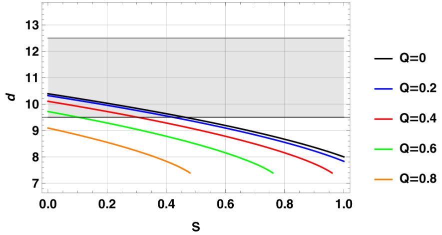
Black holes have at most three hairs ($3 \approx 0$)



Credits: Medium.com

An example of no-hair theorem violation

$$\mathcal{L} = \mathcal{L}_{\rm EH} + \mathcal{L}_{\rm Maxwell} - \left(\frac{1}{6}\phi^2 R + \partial_\mu \phi \partial^\mu \phi \right)$$



Khodadi, Allahyari, SV, Mota, JCAP 2009 (2020) 026

Journal of Cosmology and Astroparticle Physics
An IOP and SISSA journal

Black holes with scalar hair in light of the Event Horizon Telescope

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Superradiance-induced black hole shadow evolution

Superradiance evolution of black hole shadows revisited

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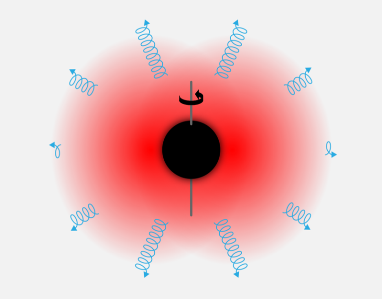

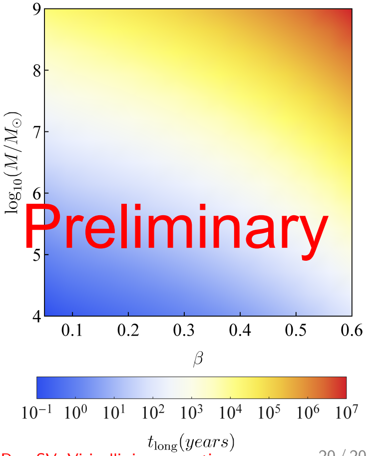

Evolution in shadow size $\Delta\theta \sim \mathcal{O}(1)\mu$as due to superradiance potentially observable on human timescales $[\mathcal{O}(10)\,\mathrm{yr}]$

Roy, SV, Visinelli, in preparation