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

Sunny Vagnozzi

Newton-Kavli Fellow (2019–2022)

✉ sunny.vagnozzi@ast.cam.ac.uk  🏡 www.sunnyvagnozzi.com

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?

Example: early dark energy

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

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

Credits: Knox & Millea, PRD 101 (2020) 043533
The early ISW (eISW) effect

\[ \Theta = \int_0^{\eta_0} d\eta \left[ \alpha \left( g(\Theta_0 + \Psi) + gV_b \frac{d}{d\eta} + e^{-\tau}(\dot{\Psi} - \dot{\Phi}) + (g\Pi + [g\Pi]) \right) j_\ell(k\Delta \eta) \right] \]

\[ \Theta_{\ell}^{\text{ISW}}(k) = \int_0^{\eta_m} d\eta e^{-\tau}(\dot{\Psi} - \dot{\Phi}) j_\ell(k\Delta \eta) + \int_{\eta_m}^{\eta_0} d\eta e^{-\tau}(\dot{\Psi} - \dot{\Phi}) j_\ell(k\Delta \eta) \]

(A substantial amount of) New physics increasing \( H(z) \) around \( z_{eq}/z_\star \) should leave an imprint on the eISW effect!
Introduce scaling amplitude/fudge factor $A_{\text{eISW}}$:

$$\Theta_{\ell}^{\text{eISW}}(k) = A_{\text{eISW}} \int_{0}^{\eta_m} d\eta \, e^{-\tau} \left( \dot{\psi} - \dot{\Phi} \right) j_\ell(k\Delta\eta)$$

SV, PRD 104 (2021) 063524
More new physics to solve EDE’s problems?

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

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

Plot credits: Alex Reeves (Part III project)
From the growth rate \((f\sigma_8)\) point of view, \(S_8\) discrepancy perfectly compatible with a statistical fluctuation!
Non-parametric test of spatial curvature

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

Suhail Dhawan, Justin Alsing, Sunny Vagnozzi

$H_0d_L = \frac{c(1+z)}{\sqrt{|\Omega_K|}} \sin n \left( \sqrt{|\Omega_K|} \int_0^z \frac{dz'}{E(z')} \right)$

$H_0d_L$: uncalibrated SNeIa
$E(z)$: cosmic chronometers
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 XENONIIT excess and future prospects

Sunny Vagnozzi, Luca Visinelli, Philippe Brax, Anne-Christine Davis, and Jeremy Sakstein

1Kavli Institute for Cosmology (KICC), University of Cambridge, Madingley Road, Cambridge CB3 0HA, United Kingdom
2Institute of Astronomy (IoA), University of Cambridge, Madingley Road, Cambridge CB3 0HA, United Kingdom
3Istituto Nazionale di Fisica Nucleare (INFN), Laboratori Nazionali di Frascati, C.P. 13, I-100044 Frascati, Italy
4Tsung-Dao Lee Institute (TDLI), Shanghai Jiao Tong University, 200240 Shanghai, China
5Gravitation Astroparticle Physics Amsterdam (GRAPPA), University of Amsterdam, Science Park 904, 1098 XH Amsterdam, Netherlands
6Institute de Physique Théorique (IPhT), Université Paris-Saclay, CNRS, CEA, F-91191, Gif-sur-Yvette Cedex, France
7Department of Applied Mathematics and Theoretical Physics (DAMTP), Center for Mathematical Sciences, University of Cambridge, CB3 0WA, United Kingdom
8Department of Physics & Astronomy, University of Hawai‘i, Watanabe Hall, 2505 Correa Road, Honolulu, Hawaii, 96822, USA

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See University of Cambridge’s press release!
Direct detection of (chameleon-screened) dark energy

Production

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

Production in strong magnetic fields of the tachocline

Detection

\[ \mathcal{L}_{\phi_i} \supset \beta_i \frac{\phi T_i}{M_{\text{Pl}}^4} - c_i \frac{\partial^{\mu} \phi \partial_{\mu} \phi}{M^4} T_i + \frac{T_{i}^{\mu\nu} \partial_{\mu} \phi \partial_{\nu} \phi}{M_{i}^4} \]

Analogous to photoelectric and axioelectric effects
Direct detection of (chameleon-screened) dark energy

Intriguing hints in XENON1T?
Part 3: Black holes
Black hole shadows

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

Can we use BH shadows to test fundamental physics?
Known information for M87*:

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

Recipe: compute $d$ and $\Delta C$ for BHs in your favourite theory, then impose these constraints.
The no-hair theorem

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

Credits: Medium.com
An example of no-hair theorem violation

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

Khodadi, Allahyari, SV, Mota, JCAP 2009 (2020) 026
Superradiance-induced black hole shadow evolution

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

Roy, SV, Visinelli, in preparation