

# Searching for dark energy off the beaten track

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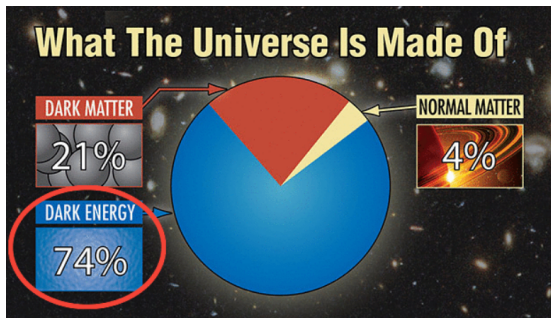
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CRAG Seminar, University of Sheffield  
11 May 2022



# Dark Energy



- Part I: direct detection of DE on Earth
- Part II: consistency tests of  $\Lambda$ CDM, implications for (early and late) DE
- Part III: new ways to search for light particles (related or not to DE?)

Note: blue → (Master's/PhD) students, red → postdocs



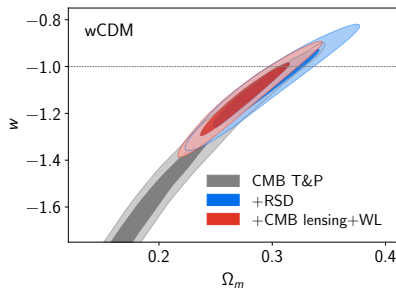
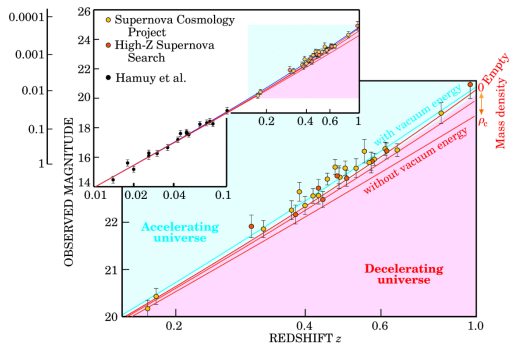
Student's name (student's institution)



Postdoc's name (postdoc's institution)

# The beaten track

*Gravitational* signatures of DE: the effect of DE's energy density on the background expansion or the growth of structure, probed by standard cosmological observations, with particular focus on DE's equation of state  $w_{\text{DE}} = P_{\text{DE}}/\rho_{\text{DE}}$  ( $\sim -1$ ?)

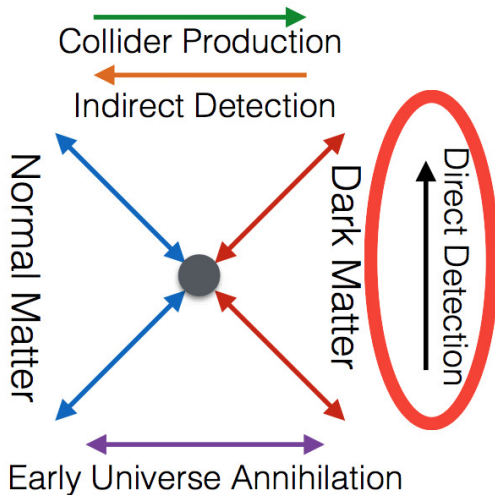


eBOSS collaboration, PRD 103 (2021) 083533

Credits: Perlmutter, Physics Today 56 (2003) 53

*Part I:  
direct detection of dark energy*

# Are gravitational signatures all there is?



What about dark energy?



# Can dark energy and visible matter talk to each other?

Quintessence and the Rest of the World: Suppressing Long-Range Interactions

Sean M. Carroll  
Phys. Rev. Lett. **81**, 3067 – Published 12 October 1998

Coupled quintessence

Luca Amendola  
Phys. Rev. D **62**, 043511 – Published 24 July 2000

If DE due to a new particle, this typically will:

- be very light [ $m \sim H_0 \sim \mathcal{O}(10^{-33})$  eV]
- have gravitational-strength coupling to matter

Result/immediate obstacle: long-range fifth forces!

$$F_5 = -\frac{1}{M_5^2} \frac{m_1 m_2}{r^2} e^{-r/\lambda_5}, \quad M_5 \sim M_{\text{Pl}}, \quad \lambda_5 \sim m^{-1} \sim H_0^{-1}$$

# Screening

How to satisfy fifth-force tests?

- Tune the coupling to be extremely weak [ $M \gg M_{\text{Pl}}$ ]
- Tune the range to be extremely short [ $\lambda \ll \mathcal{O}(\text{mm})$ ]
- Tune the dynamics so the force weakens based on its environment  
→ **screening!**

(At least) 3 ways to screen

$$F_5 = -\frac{1}{M_5^2(x)} \frac{m_1 m_2}{r^{2-n(x)}} e^{-r/\lambda_5(x)}$$

- $\lambda_5(x)$  → **chameleon** screening (short range in dense environments)
- $M_5(x)$  → symmetron screening (weak coupling in dense environments)
- $n(x)$  → Vainshtein (force drops faster than  $1/r^2$  around objects)

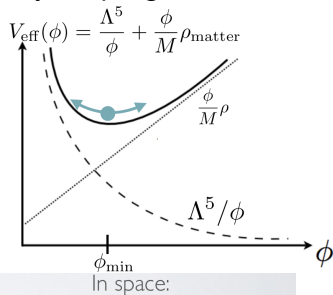
# Chameleon screening

Fifth force range  $\lambda(x)$  becomes short in dense environments, scalar field minimizes effective potential determined by coupling to matter

$$V_{\text{eff}} = V(\phi) + \phi \rho_m / M$$

$$m_{\text{eff}}^2 = \left. \frac{d^2 V_{\text{eff}}}{d\phi^2} \right|_{\phi=\phi_{\text{min}}} \propto \rho^n, n > 0$$

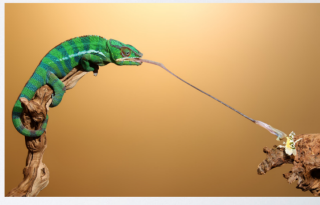
$$\lambda \sim 1/m_{\text{eff}} \propto \rho^{-n/2}$$



On Earth:



In space:





# Direct detection of dark energy

Can we detect (screened) DE in DM direct detection experiments?

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

## Direct detection of dark energy: The XENONIT excess and future prospects

Sunny Vagnozzi<sup>1,2,\*</sup>, Luca Visinelli<sup>3,4,5,\*</sup>, Philippe Brax<sup>6,†</sup>, Anne-Christine Davis<sup>7,1,§</sup> and Jeremy Sakstein<sup>8,¶</sup>

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 (Received 7 April 2021; accepted 20 August 2021; published 15 September 2021)



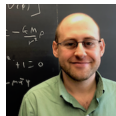
Luca Visinelli (Shanghai)



Phil Brax (IPhT, Saclay)



Anne Davis (Cambridge)



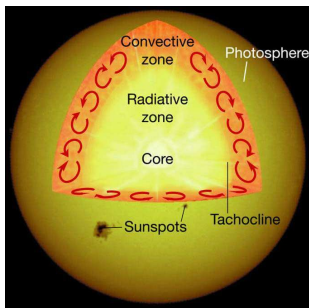
Jeremy Sakstein (Hawaii)

# Direct detection of dark energy

## Production

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

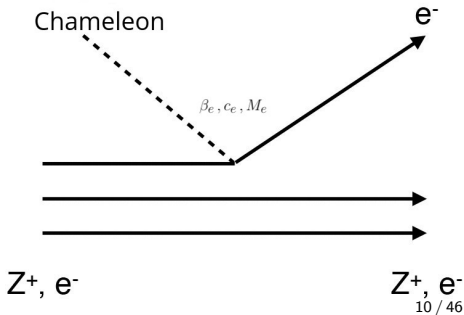
Production in strong magnetic fields of the tachocline



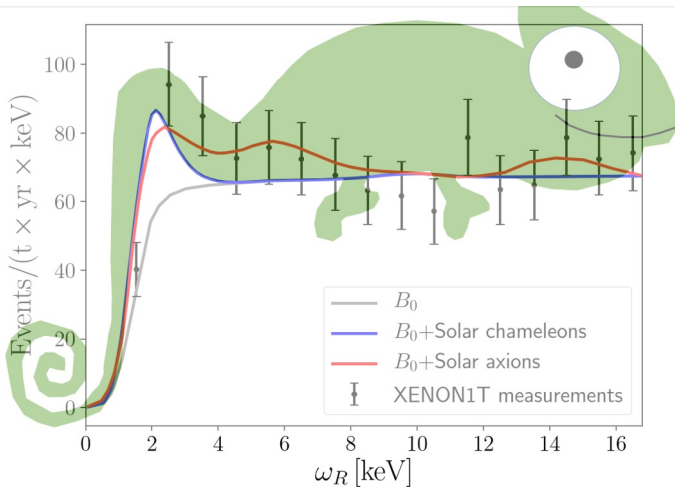
## Detection

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

Analogous to photoelectric and axioelectric effects



# Direct detection of (chameleon-screened) dark energy



# Cosmological direct detection of dark energy

Wouldn't scattering between DE and baryons mess up cosmology?

Monthly Notices

of the  
ROYAL ASTRONOMICAL SOCIETY

MNRAS **493**, 1139–1152 (2020)

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doi:10.1093/mnras/staa311

## Do we have any hope of detecting scattering between dark energy and baryons through cosmology?

Sunny Vagnozzi<sup>1</sup>,<sup>1</sup>\*<sup>†</sup> Luca Visinelli,<sup>2</sup> Olga Mena<sup>3</sup> and David F. Mota<sup>4</sup>

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<sup>4</sup>*Institute of Theoretical Astrophysics, University of Oslo, P.O. Box 1029 Blindern, N-0315 Oslo, Norway*

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Surprisingly not!



Luca Visinelli (Shanghai)



Olga Mena (Valencia)



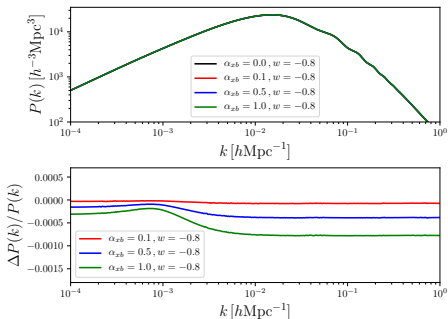
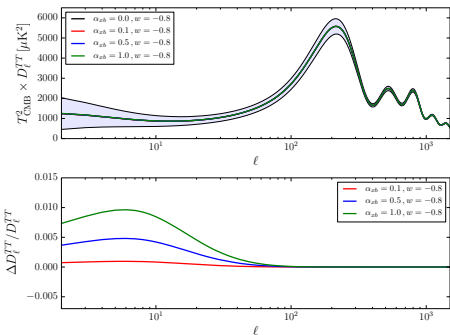
David Mota (Oslo)

# Cosmological direct detection of dark energy?

$$\dot{\theta}_b = -\mathcal{H}\theta_b + c_s^2 k^2 \delta_b + \frac{4\rho_\gamma}{3\rho_b} an_e \sigma_T (\theta_\gamma - \theta_b) + (1 + w_x) \frac{\rho_x}{\rho_b} an_e \sigma_{xb} (\theta_x - \theta_b)$$

$$\dot{\theta}_x = -\mathcal{H}(1 - 3c_s^2)\theta_x + \frac{c_s^2 k^2}{1 + w_x} \delta_x + an_e \sigma_{xb} (\theta_b - \theta_x)$$

Impact on CMB and *linear* matter power spectrum ( $\alpha = \sigma_{xb}/\sigma_T$ )



# N-body simulations of DE-baryon scattering

What about the non-linear regime?

## Cosmological direct detection of dark energy: Non-linear structure formation signatures of dark energy scattering with visible matter

Fulvio Ferlito,<sup>1,2★</sup> Sunny Vagnozzi<sup>①</sup>,<sup>3★†</sup> David F. Mota<sup>4</sup> and Marco Baldi<sup>②</sup><sup>2,5,6</sup>

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<sup>2</sup>Dipartimento di Fisica e Astronomia, Alma Mater Studiorum Università di Bologna, Via Piero Gobetti 93/2, I-40129 Bologna, Italy

<sup>3</sup>Kavli Institute for Cosmology, University of Cambridge, Madingley Road, Cambridge CB3 0HA, UK

<sup>4</sup>Institute of Theoretical Astrophysics, University of Oslo, PO Box 1029 Blindern, N-0315 Oslo, Norway

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<sup>6</sup>INFN – Sezione di Bologna, viale Berti Pichat 6/2, I-40127 Bologna, Italy

Only one way to find out: run N-body simulations!



Fulvio Ferlito (MPA Garching)



David Mota (Oslo)

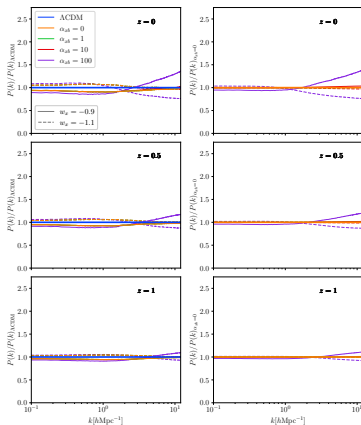
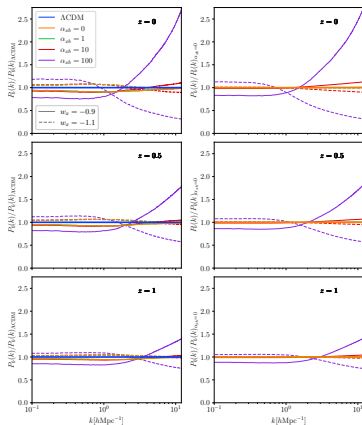


Marco Baldi (Bologna)

# N-body simulations of DE-baryon scattering

Baryon power spectrum relative to  $\Lambda$ CDM (left) and no-scattering  $w$ CDM (right)

Matter power spectrum relative to  $\Lambda$ CDM (left) and no-scattering  $w$ CDM (right)

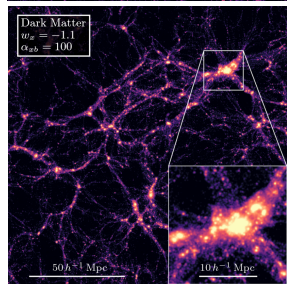
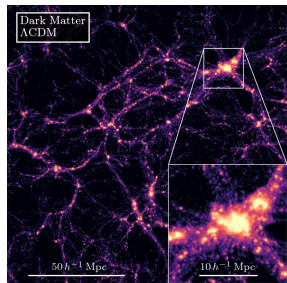
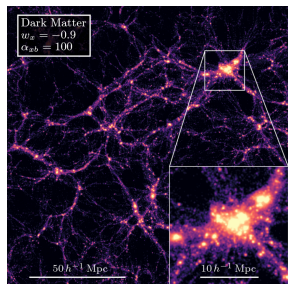


# N-body simulations of DE-baryon scattering

Simulation snapshots:

- $\sigma = 100\sigma_T$
- $w = -0.9, -1, -1.1$

Ferlito, SV, Mota, Baldi, MNRAS 512 (2022) 1885

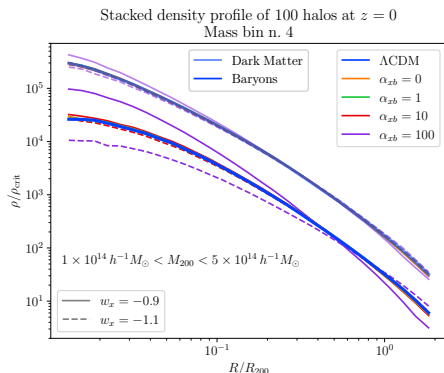




# N-body simulations of DE-baryon scattering

Other observables:

- (Cumulative) halo mass function
- (Stacked) halo density profiles
- Baryon fraction profiles
- Future work: Bullet-like systems, higher-order correlators, galaxy bias



Ferlito, SV, Mota, Baldi, MNRAS 512 (2022) 1885

Baryon profiles most promising observable to probe DE-baryon scattering

## Recap

### Direct detection of dark energy

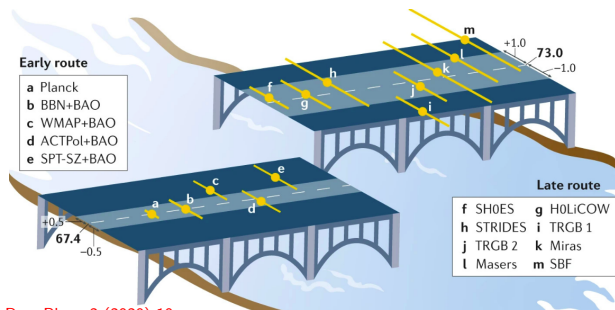
- Potentially lots of unharvested potential for direct detection of dark energy in dark matter direct detection experiments
- Room for large dark energy-baryons interactions in cosmology...
- ...possibly tightly constrained by (non-linear) LSS clustering and other astrophysical observations!

*Where else might we learn something about dark energy (at early and late times)?*

Perhaps from the Hubble tension!

*Part II:  
consistency tests of  $\Lambda$ CDM and  
implications for (early and late) DE*

# Viewing the Hubble tension ocean with different eyeglasses



Credits: Riess, Nat. Rev. Phys. 2 (2020) 10

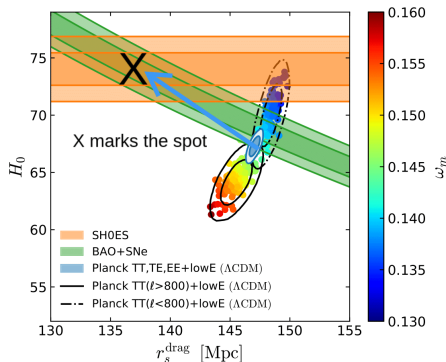
Why does  $\Lambda$ CDM fit data so well? Do we really need new physics? If so, at what time(s), and with what ingredients?

## Consistency tests of $\Lambda$ CDM

# The Hubble tension and new physics

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

Increasing  $H(z)$  just prior to  $z_*$ :  
“least unlikely” proposal?



Example: early dark energy (some debate as to how much it works)

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  $z_{\text{eq}}$  ↓↓

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

see also Gómez-Valent *et al.*, PRD 104 (2021) 083536


Caveat: true prior to ACT DR4 and SPT-3G?

# Early-time consistency tests of $\Lambda$ CDM

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

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## Consistency tests of $\Lambda$ CDM from the early integrated Sachs-Wolfe effect: Implications for early-time new physics and the Hubble tension

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 (Received 15 June 2021; accepted 22 July 2021; published 15 September 2021)

*No clear sign of early-time new physics in CMB data alone*



*Why does  $\Lambda$ CDM fit CMB data so well?*



*(Early-time) Consistency tests of  $\Lambda$ CDM*

## The early ISW (eISW) effect

Around recombination: Universe not fully matter dominated  $\implies$  residual decay of gravitational potentials  $\implies$  eISW effect sources anisotropies

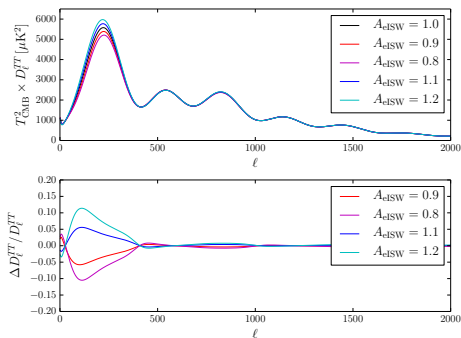
$$\Theta = \int_0^{\eta_0} d\eta \left[ \underbrace{\propto g(\Theta_0 + \Psi)}_{\text{Sachs-Wolfe}} + \underbrace{\propto g v_b \frac{d}{d\eta}}_{\text{Doppler}} + \underbrace{\propto e^{-\tau} (\dot{\Psi} - \dot{\Phi})}_{\text{ISW}} + \underbrace{\propto (g\Pi + [g\ddot{\Pi}])}_{\text{Polarization}}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

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

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

## eISW consistency test

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



SV, PRD 104 (2021) 063524

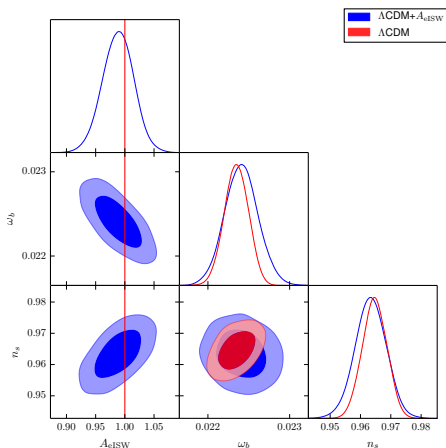
Consistency check: within  $\Lambda\text{CDM}$ , data consistent with  $A_{\text{eISW}} = 1$ ?



# eISW consistency test

Is the data consistent with  $A_{eISW} = 1$ ? (7-parameter  $\Lambda$ CDM+ $A_{eISW}$ )

Yes!



Parameter	<i>Planck</i>	
	$\Lambda$ CDM	$\Lambda$ CDM+ $A_{eISW}$
$100\omega_b$	$2.235 \pm 0.015$	$2.241 \pm 0.020$
$\omega_c$	$0.1202 \pm 0.0013$	$0.1203 \pm 0.0014$
$\theta_s$	$1.0409 \pm 0.0003$	$1.0409 \pm 0.0003$
$\tau$	$0.0544 \pm 0.0078$	$0.0541 \pm 0.0078$
$\ln(10^{10}A_s)$	$3.045 \pm 0.016$	$3.046 \pm 0.016$
$n_s$	$0.965 \pm 0.004$	$0.963 \pm 0.005$
$A_{eISW}$	1.0	$0.988 \pm 0.027$
$H_0$ [km/s/Mpc]	$67.26 \pm 0.57$	$67.28 \pm 0.62$
$\Omega_m$	$0.317 \pm 0.008$	$0.317 \pm 0.009$

SV, PRD 104 (2021) 063524

Other parameter constraints very stable, no more than  $\approx 0.3\sigma$  shifts

SV, PRD 104 (2021) 063524

# Implications for early-time new physics: EDE case study

High  $H_0$  EDE fit to CMB at the cost of increase in  $\omega_c \rightarrow$  worsens tension with WL/LSS data? Hill *et al.*, PRD 102 (2020) 043507; Ivanov *et al.*, PRD 102 (2020) 103502; D'Amico *et al.*,

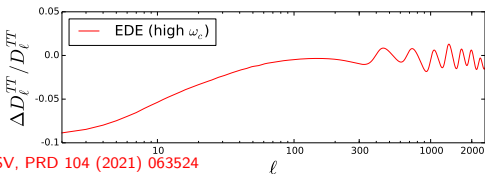
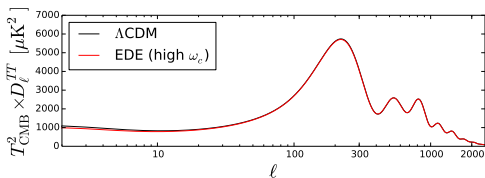
JCAP 2105 (2021) 072; see also Gómez-Valent *et al.*, PRD 104 (2021) 083536; see partial rebuttals in: Murgia *et al.*, PRD 103 (2021) 063502; Smith *et al.*, PRD 103 (2021) 123542; Herold *et al.*, ApJ Lett. 929 (2022) L16

## Editor's 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

Parameter	$\Lambda$ CDM	EDE (high $\omega_c$ )	EDE (low $\omega_c$ )
$100\omega_b$	2.253	2.253	2.253
$\omega_c$	0.1177	0.1322	0.1177
$H_0$ [km/s/Mpc]	68.21	72.19	72.19
$\tau$	0.085	0.072	0.072
$\ln(10^{10} A_s)$	3.0983	3.0978	3.0978
$n_s$	0.9686	0.9889	0.9889
$f_{\text{EDE}}$	–	0.122	0.122
$\log_{10} z_c$	–	3.562	3.562
$\theta_i$	–	2.83	2.83
$n$	–	3	3

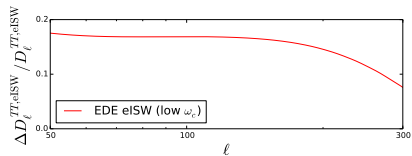
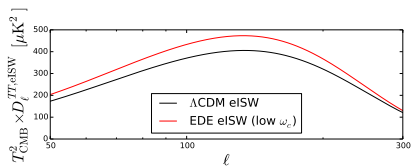


SV, PRD 104 (2021) 063524

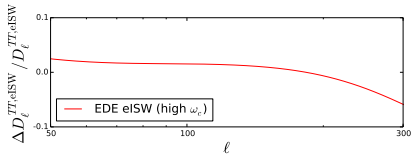
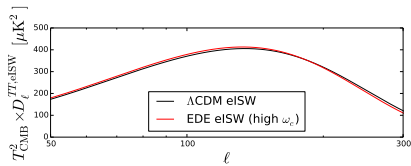
# Implications for early-time new physics: EDE case study

Let's extract only the eISW contribution to temperature anisotropies...

Low  $\omega_c$



High  $\omega_c$



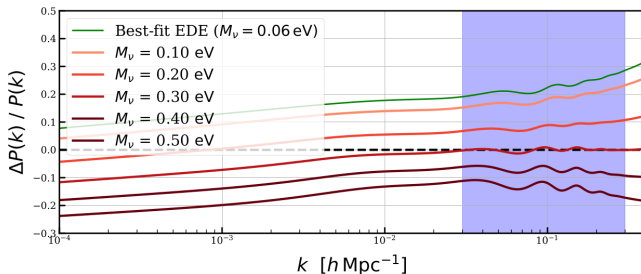
Almost 20% eISW excess!

No more than  $\lesssim$  3-5% eISW excess

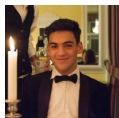
Generic to models increasing pre-recombination  $H(z)$ , not just EDE

# Rescuing early dark energy with additional new physics?

Example: neutrino mass (nominally need  $M_\nu \sim 0.3 \text{ eV}$  to rescue EDE!)



Reeves, Herold, SV, Sherwin, Ferreira, in preparation. Plot credits: Alex Reeves



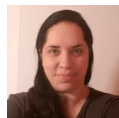
Alex Reeves (ETH Zürich)



Laura Herold (MPA Garching)



Blake Sherwin (Cambridge)



Elisa Ferreira (Tokyo)

# Massive neutrinos (not) rescuing early dark energy

Restoring cosmological concordance with early dark energy and massive neutrinos?

Alexander Reeves,<sup>1\*</sup> Laura Herold,<sup>2</sup> Sunny Vagnozzi,<sup>3</sup> Blake D. Sherwin,<sup>3,4</sup>  
and Elisa G. M. Ferreira<sup>5,6</sup>

<sup>1</sup>Institute for Particle Physics and Astrophysics, ETH Zürich, Wolfgang-Pauli-Straße 27, CH-8093 Zürich, Switzerland

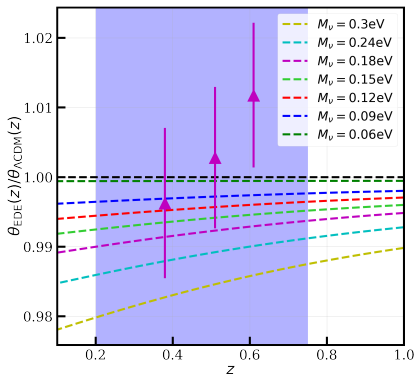
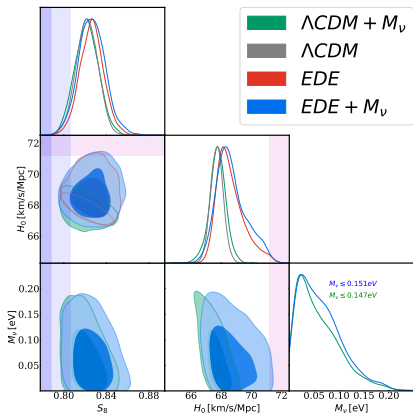
<sup>2</sup>Max-Planck-Institut für Astrophysik, Karl-Schwarzschild-Straße 1, D-85740 Garching bei München, Germany

<sup>3</sup>Kavli Institute for Cosmology, University of Cambridge, Madingley Road, Cambridge CB3 0HA, UK

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## Late-time consistency tests of $\Lambda$ CDM

*Is  $\Lambda$ CDM really all there is at late times?*



*(Try to) Test  $\Lambda$ CDM making no assumptions about early-time physics*



*Learn something about  $H_0$  in the process?*

# Old astrophysical objects at high redshift

Historically (1960s-1998) high- $z$  OAO provided the first hints for the existence of dark energy ( $\Omega \neq 1$ ,  $\Omega_\Lambda > 0$ )

## **A 3.5-Gyr-old galaxy at redshift 1.55**

James Dunlop, John Peacock, Hyron Spinrad, Arjun Dey, Raul Jimenez, Daniel Stern & Rogier Windhorst

*Nature* **381**, 581–584 (1996) | [Cite this article](#)

## **Conflict over the age of the Universe**

M. Bolte & C. J. Hogan

*Nature* **376**, 399–402 (1995) | [Cite this article](#)

## **The observational case for a low-density Universe with a non-zero cosmological constant**

J. P. Ostriker & Paul J. Steinhardt

*Nature* **377**, 600–602 (1995) | [Cite this article](#)

What can OAO do for cosmology in the 2020s?

# Cosmology with old astrophysical objects

Can the ages of the oldest inhabitants of the Universe teach us something about the Universe's contents (including DE) and the Hubble tension?

Implications for the Hubble tension from the ages of the oldest astrophysical objects

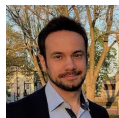
Sunny Vagnozzi,<sup>1,\*</sup> Fabio Pacucci,<sup>2,3,†</sup> and Abraham Loeb<sup>2,3,‡</sup>

<sup>1</sup>*Kavli Institute for Cosmology (KICC) and Institute of Astronomy,  
University of Cambridge, Madingley Road, Cambridge CB3 0HA, United Kingdom*

<sup>2</sup>*Center for Astrophysics | Harvard & Smithsonian, Cambridge, MA 02138, USA*

<sup>3</sup>*Black Hole Initiative, Harvard University, Cambridge, MA 02138, USA*

Potentially yes!



Fabio Pacucci (Harvard)




Avi Loeb (Harvard)



## Cosmology with old astrophysical objects

$$t_U(z) = \int_z^\infty \frac{dz'}{(1+z')H(z')} \propto \frac{1}{H_0}$$

Pros and cons:

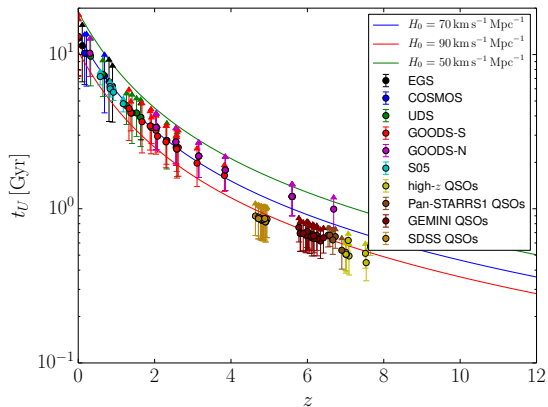
- OAO cannot be older than the Universe  $\rightarrow$  **upper limit on  $H_0$**
- $t_U(z)$  integral insensitive to early-time cosmology
- $\implies$  **late-time consistency test for  $\Lambda$ CDM independent of the early-time expansion!**
- **Ages of astrophysical objects at  $z > 0$  hard to estimate robustly** 

Usefulness in relation to the Hubble tension:

- Contradiction between OAO upper limit on  $H_0$  and local  $H_0$  measurements could indicate the need for non-standard late-time ( $z \lesssim 10$ ) physics, or non-standard local physics
- Conclusions completely independent of pre-recombination physics

# OA0 age-redshift diagram

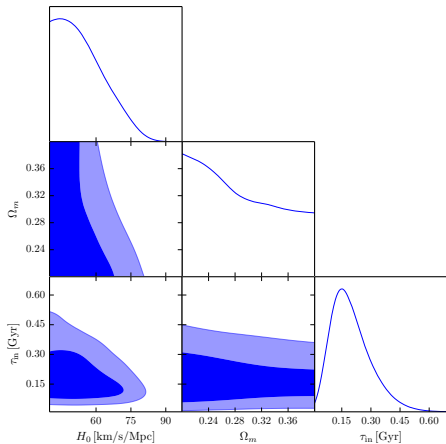
Age-redshift diagram up to  $z \sim 8$



# Results

Assume  $\Lambda$ CDM at late times, constrain  $H_0$ ,  $\Omega_m$ , and incubation time  $\tau_{\text{in}}$

Prior for  $\tau_{\text{in}}$  following Jiménez *et al.*, JCAP 1903 (2019) 043; Valcin *et al.*, JCAP 1212 (2020) 022



SV *et al.*, arXiv:2105.10421 (submitted to PRL)

$H_0 < 73.2$  (95% C.L.)

# Implications for the Hubble tension

**CAVEAT** – if the OAO ages are reliable, possible explanations include:

- #1:  $\Lambda$ CDM may not be the end of the story at  $z \lesssim 10$
- #2: Nothing wrong with  $\Lambda$ CDM at  $z \lesssim 10$ , need local new physics...

Examples: screened 5th forces (Desmond *et al.*, PRD 100 (2019) 043537; Desmond & Sakstein, PRD 102 (2020) 023007), breakdown of FLRW (Krishnan *et al.*, CQG 38 (2021) 184001; arXiv:2106.02532),++

- #3: Just a boring  $2\sigma$  fluke or systematics?

Is this a hint that pre-recombination new physics alone is not enough to solve the Hubble tension? Krishnan *et al.*, PRD 102 (2020) 103525; Jedamzik *et al.*, Commun. Phys. 4 (2021) 123; Haridasu *et al.*, PRD 103 (2021) 063539; Lin *et al.*, ApJ 920 (2021) 159; Dainotti *et al.*, ApJ 912 (2021) 150

Article | [Open Access](#) | [Published: 08 June 2021](#)

## Why reducing the cosmic sound horizon alone can not fully resolve the Hubble tension

[Karsten Jedamzik](#), [Levon Pogosian](#) & [Gong-Bo Zhao](#) 

[Communications Physics](#) 4, Article number: 123 (2021) | [Cite this article](#)

1461 Accesses | 1 Citations | 10 Altmetric | [Metrics](#)

# Recap

## Early-time consistency tests of $\Lambda$ CDM

- eISW effect sets tight constraints on new pre-recombination physics
- Models which raise pre-recombination  $H(z)$  will typically overpredict amplitude of eISW effect
- Example: early dark energy (need additional post-recombination new physics to solve “ $S_8$  tension”?)

## Late-time consistency tests of $\Lambda$ CDM

- Ages of old astrophysical objects can set upper limit on  $H_0$
- Late-time consistency test of  $\Lambda$ CDM completely independent of pre-recombination assumptions
- Need new physics at  $z \lesssim 10$  or on local scales?

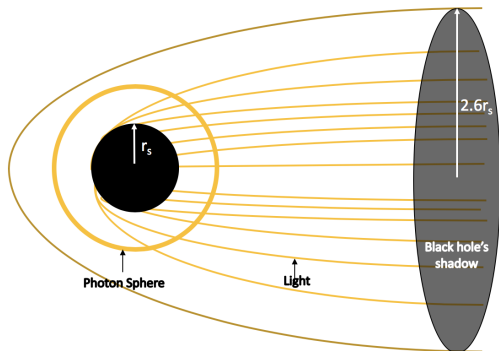
*Part III:  
new searches for light particles  
(dark energy-related or not)*

# Black hole shadows

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



Credits: Event Horizon Telescope collaboration



For advection-dominated hot (geometrically thick optically thin) accretion flow, edge of BH shadow robust to accretion flow details, only influenced by space-time geometry [Narayan et al., ApJ Lett. 885 \(2019\) L33](#); [Bronzwaer & Falcke, ApJ 920 \(2021\) 155](#)

⇒ we can use BH shadows to test fundamental physics!

# Testing fundamental physics from black hole shadows?

## Known information for M87\*:

- Diameter of shadow  $\delta$ , distance to mass ratio  $D/M$   
 $\rightarrow d = D\delta/M \sim 11.0 \pm 1.5$
- Deviation from circularity  $\Delta C \lesssim 10\%$
- Axis ratio  $\Delta y/\Delta x \lesssim 4/3$
- $\epsilon \equiv \Delta Q/Q_{\text{Kerr}} \lesssim 4$ ,  
 $Q_{\text{Kerr}} = Ma^2$

Recipe: compute  $d$  and  $\Delta C$  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<sup>1</sup>, Mohsen Khodadi<sup>1</sup>, Sunny Vagnozzi<sup>2</sup> and David F. Mota<sup>3</sup>  
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<sup>4,1</sup>, Cosimo Bambi<sup>2</sup> and Luca Visinelli<sup>3</sup>  
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

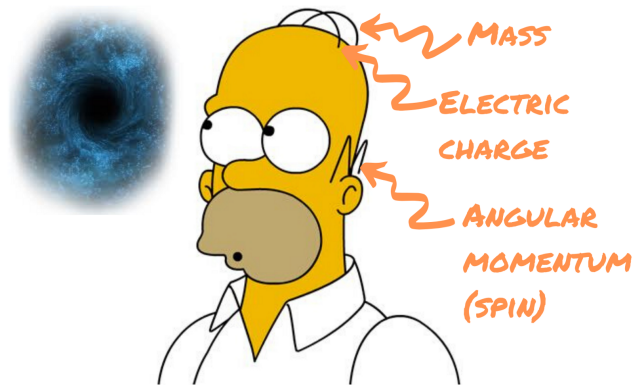
Mohsen Khodadi<sup>1</sup>, Alireza Allahyari<sup>1</sup>, Sunny Vagnozzi<sup>2</sup> and David F. Mota<sup>3</sup>  
Published 14 September 2020 • © 2020 IOP Publishing Ltd and Sissa Medialab  
[Journal of Cosmology and Astroparticle Physics, Volume 2020, September 2020](#)

Citation Mohsen Khodadi et al JCAP09(2020)026



# The no-hair theorem

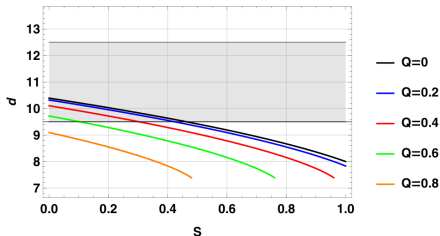
Black holes have at most three hairs ( $3 \approx 0$ )



# An example of no-hair theorem violation

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

**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

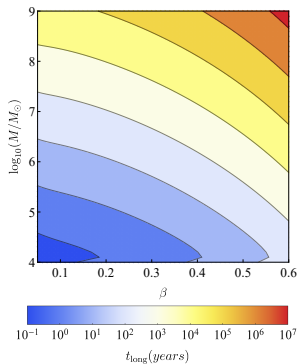
Rittick Roy<sup>1,\*</sup>, Sunny Vagnozzi<sup>2,1</sup> and Luca Visinelli<sup>3,4,‡</sup>

<sup>1</sup>Center for Field Theory and Particle Physics and Department of Physics, Fudan University, 200438 Shanghai, People's Republic of China

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<sup>4</sup>INFN, Laboratori Nazionali di Frascati, C.P. 13, 100044 Frascati, Italy



- Consistent modelling of superradiant instability in the presence of gas accretion and GW emission
- Evolution in size of SgrA\* shadow  $\Delta\theta \sim \mathcal{O}(1)\mu\text{as}$  due to superradiance potentially observable on human timescales [ $\mathcal{O}(10)\text{yr}$ ]



Rittick Roy (Fudan)



Luca Visinelli (Shanghai)

# Precession of planetary objects and new light particles

Asteroid astrometry as a fifth-force and ultralight dark sector probe

Yu-Dai Tsai,<sup>1,2,\*</sup> Youjia Wu,<sup>3,†</sup> Sunny Vagnozzi,<sup>4,‡</sup> and Luca Visinelli<sup>5,6,§</sup>

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<sup>6</sup>Tsung-Dao Lee Institute (TDLI), Shanghai Jiao Tong University, 200240 Shanghai, China

Yukawa potential from new light particle, e.g. new scalar or vector mediator from gauged  $U(1)'$  sector [ $U(1)_B$ ,  $U(1)_{B-L}$ ,  $L_\mu - L_{e,\tau}, \dots$ ]:

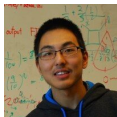
$$V(r) = \tilde{\alpha} \frac{GM_\odot M_*}{r} \exp\left[-\frac{r}{\lambda}\right] \rightarrow \frac{g^2}{4\pi} \frac{Q_\odot Q_*}{r} \exp\left[-\frac{mc^2}{\hbar c} r\right],$$

Several GR calculations later, in the light mediator limit ( $m \ll \hbar/ac$ )...

$$|\Delta\varphi| \simeq \frac{2\pi}{1 + \frac{g^2}{4\pi Gm_p^2}} \frac{g^2}{4\pi Gm_p^2} \left(\frac{amc}{\hbar}\right)^2 (1 - e)$$



Yu-Dai Tsai (Fermilab → Irvine)



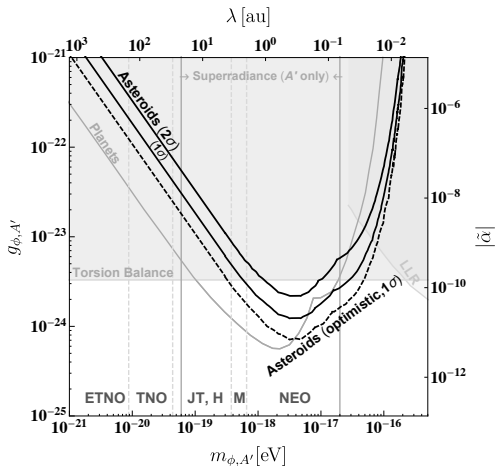
Youjia Wu (Michigan)



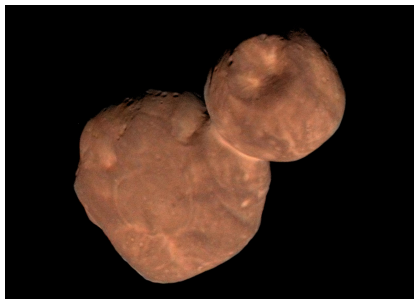
Luca Visinelli (Shanghai)

# Precession of planetary objects and new light particles

Results from planets and 9 well-tracked (i.e. dangerous) asteroids



Asteroid 66391 Moshup  
( $\sim 1.3$  km in diameter)

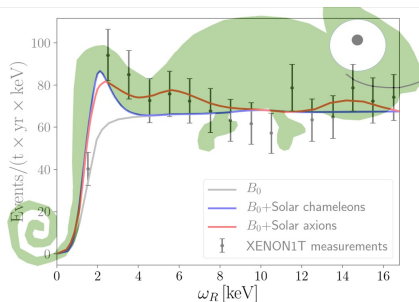


Credits: Wikiwand

Tsai, Wu, SV, Visinelli, arXiv:2107.04038 (submitted to Nat. Astron.)

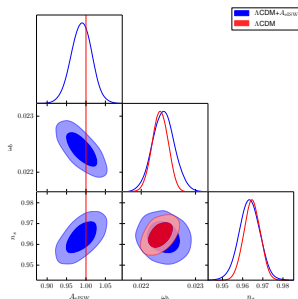
## Conclusions

Direct detection of dark energy: lots of unharvested potential in dark matter direct detection experiments



SV *et al.*, PRD 104 (2021) 063023

Consistency tests of  $\Lambda$ CDM: pre-recombination new physics tightly constrained by eISW effect



SV, PRD 104 (2021) 063524

*Much to be learned about dark energy beyond “standard” cosmological searches for its gravitational interactions*