Searching for dark energy off the beaten track

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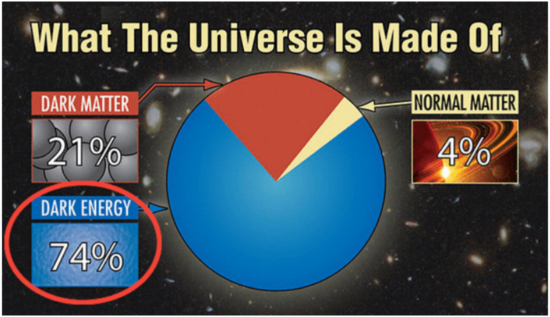
21 October 2021

Dark Energy



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

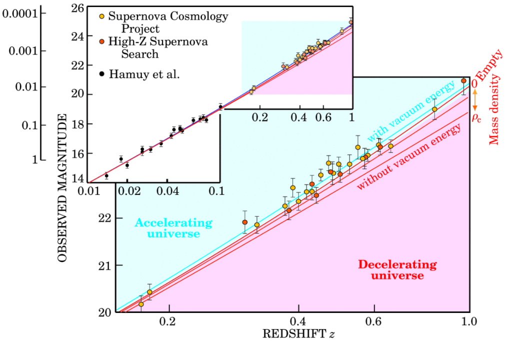
Note: blue $\rightarrow$ (Master's/PhD) students, red $\rightarrow$ postdocs

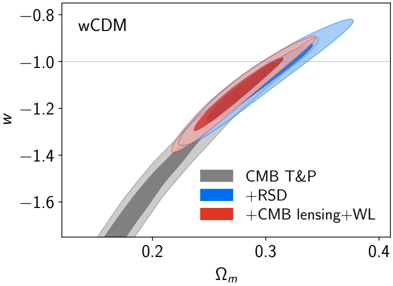
Student's name (student's institution)

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 $w_{\rm DE} = P_{\rm DE}/\rho_{\rm DE}$ $(\sim -1?)$

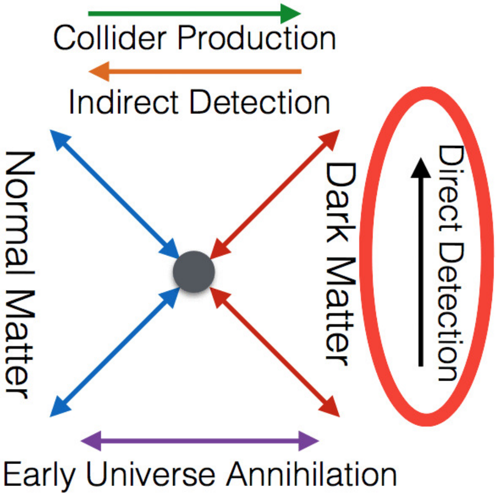




eBOSS collaboration, PRD 103 (2021) 083533

Part I:
direct detection of dark energy

Are gravitational signatures all there is?



What about dark energy?

Credits: (adapted from) Matt Buckley

Are gravitational signatures all there is?

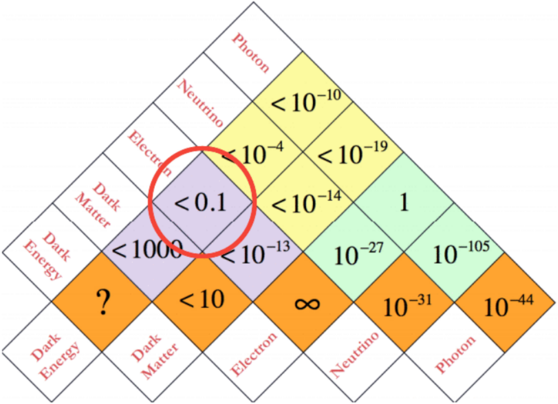
PHYSICAL REVIEW D **82,** 083505 (2010)

Scattering of dark matter and dark energy

Fergus Simpson*

SUPA, Institute for Astronomy, University of Edinburgh, Royal Observatory, Blackford Hill, Edinburgh EH9 3HJ, United Kingdom

(Received 2 August 2010; published 7 October 2010)



Simpson, PRD 82 (2010) 083505

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

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

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

Result/immediate obstacle: long-range fifth forces!

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

Screening

How to satisfy fifth-force tests?

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

(At least) 3 ways to screen

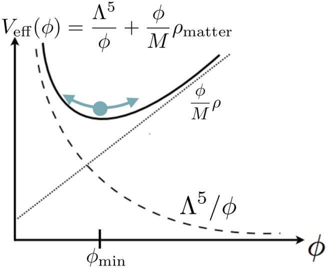
$$F_5 = -\frac{1}{M_5^2(x)} \frac{m_1 m_2}{r^{2-n(x)}} e^{-r/\lambda_5(x)}$$

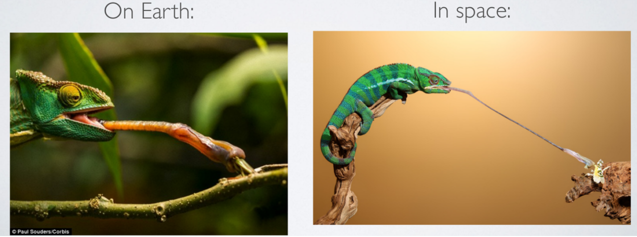
- $\lambda_5(x) \rightarrow$ **chameleon** screening (short range in dense environments)
- $M_5(x) \rightarrow$ symmetron screening (weak coupling in dense environments)
- $n(x) \rightarrow$ Vainshtein (force drops faster than $1/r^2$ around objects)

Chameleon screening

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

$$
\begin{aligned}
V_{\rm eff} &= V(\phi) + \phi\rho_m/M \\
m_{\rm eff}^2 &= \frac{d^2 V_{\rm eff}}{d\phi^2}\Big|_{\phi=\phi_{\rm min}} \propto \rho^n \,,\, n>0 \\
\lambda &\sim 1/m_{\rm eff} \propto \rho^{-n/2}
\end{aligned}
$$





Credits: Ben Elder

Direct detection of dark energy

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

ABC CIENCIA

Opinión ▾ España ▾ Economía ▾ Internacional ▾ Sociedad Deportes ▾ Cultura ▾ Historia Ciencia Gente Play ▾ EXCLUSIVO PREMIUM Estilo ▾ Más

Buscar

¿Ha causado la Energía Oscura los extraños resultados del experimento XENON1T?

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

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

Sunny Vagnozzi,[1,2,*,¶] Luca Visinelli,[3,4,5,†,¶] Philippe Brax,[6,‡] Anne-Christine Davis,[7,1,§] and Jeremy Sakstein[8,∥]

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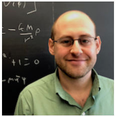
Luca Visinelli (INFN Frascati)

Phil Brax (IPhT, Saclay)

Anne Davis (Cambridge)



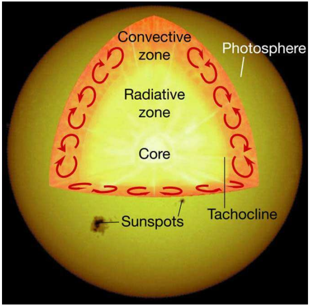
Jeremy Sakstein (Hawaii)

Direct detection of dark energy

Production

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

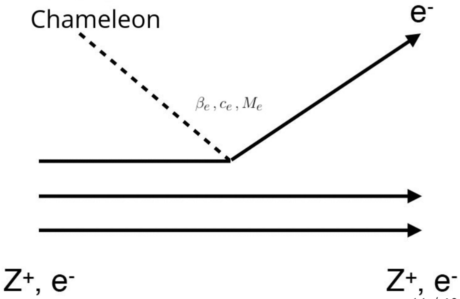
Production in strong magnetic fields of the tachocline



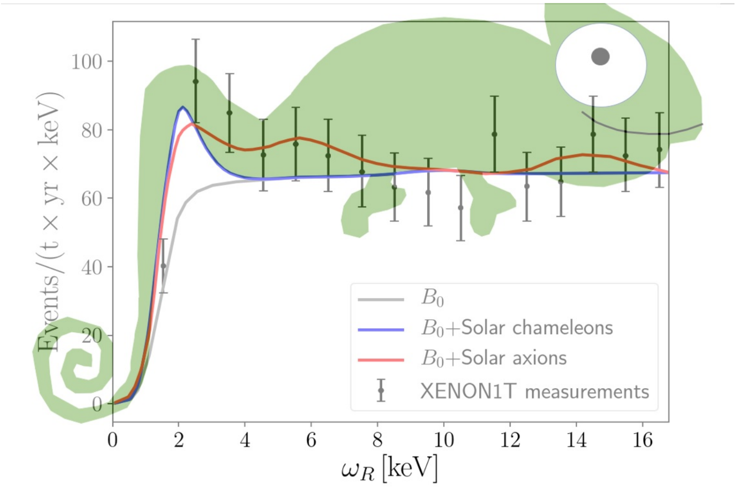
Detection

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

Analogous to photoelectric and axioelectric effects



Direct detection of (chameleon-screened) dark energy



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

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) doi:10.1093/mnras/staa311
Advance Access publication 2020 February 3

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

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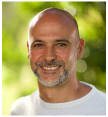
Accepted 2020 January 27. Received 2020 January 23; in original form 2019 December 3

Surprisingly not!

Luca Visinelli (INFN Frascati)

Olga Mena (Valencia)



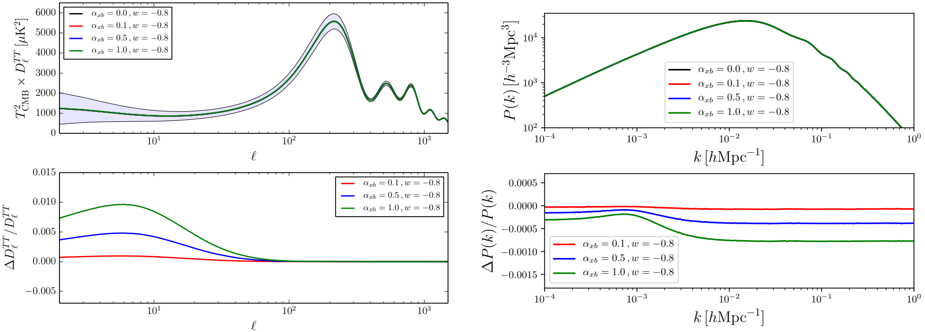
David Mota (Oslo)

Cosmological direct detection of dark energy?

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

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

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



SV *et al.*, MNRAS 493 (2020) 1139

N-body simulations of DE-baryon interactions

Structure formation with scattering between dark energy and baryons

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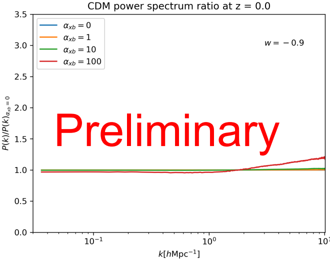
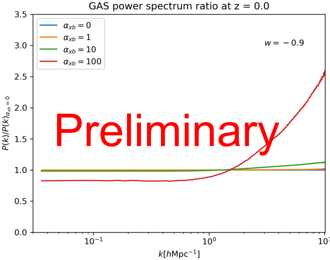


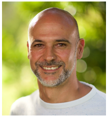
Ferlito, SV, Baldi, Mota, in preparation



Ferlito, SV, Baldi, Mota, in preparation

Fulvio Ferlito (Bologna → Garching)

Marco Baldi (Bologna)



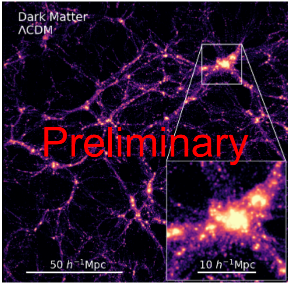
David Mota (Oslo)

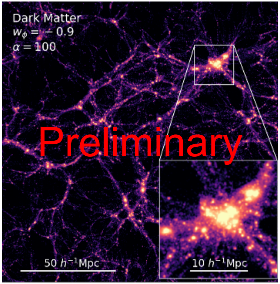
N-body simulations of DE-baryon interactions

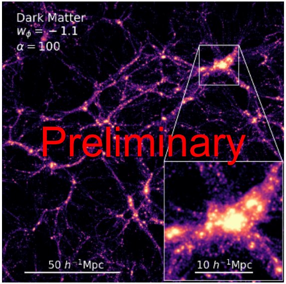
Simulation snapshots:

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

Ferlito, SV, Baldi, Mota, in preparation



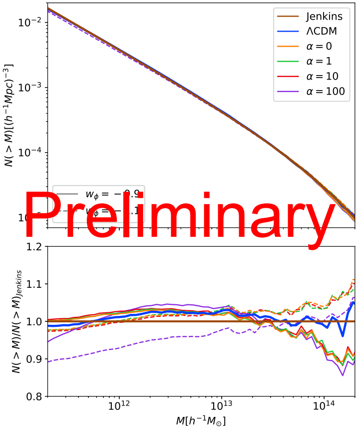




N-body simulations of DE-baryon interactions

Other observables:

- (Cumulative) halo mass function
- (Stacked) halo density profiles
- Baryon fraction profiles
- Bullet-like systems
- ...



Ferlito, SV, Baldi, Mota, in preparation

Recap

Direct detection of dark energy

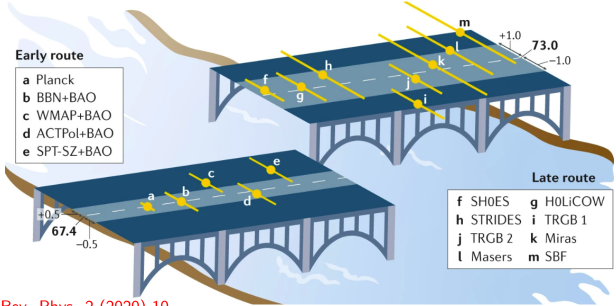
- Potentially lots of unharvested potential for direct detection of dark energy in dark matter direct detection experiments
- Room for large dark energy-baryons interactions in cosmology...
- ...possibly tightly constrained by (non-linear) LSS clustering and other astrophysical observations!

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

Perhaps from the Hubble tension!

Part II: consistency tests of ΛCDM and implications for (early) DE

Viewing the Hubble tension ocean with different eyeglasses



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

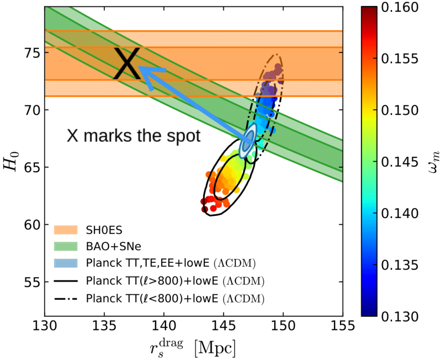
Why does ΛCDM fit data so well? Do we really need new physics? If so, at what time(s), and with what ingredients?

Consistency tests of ΛCDM

The Hubble tension and new physics

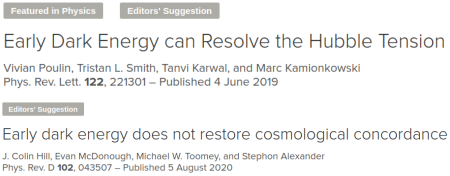
Hubble tension *appears* to call for (substantial) early-time new physics...

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



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

Example: early dark energy (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 ≈ 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?

Early-time consistency tests of ΛCDM

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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(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 ΛCDM fit CMB data so well?

↓

(Early-time) Consistency tests of ΛCDM

The early ISW (eISW) effect

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

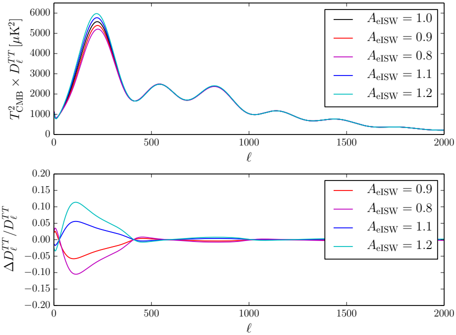
$$\Theta = \int_0^{\eta_0} d\eta \left[\underbrace{\propto g(\Theta_0 + \Psi)}_{\text{Sachs-Wolfe}} + \underbrace{\propto g v_b \frac{d}{d\eta}}_{\text{Doppler}} + \underbrace{\propto e^{-\tau}(\dot{\Psi} - \dot{\Phi})}_{\text{ISW}} + \underbrace{\propto (g\Pi + [g\ddot{\Pi}])}_{\text{Polarization}}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

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

(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

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

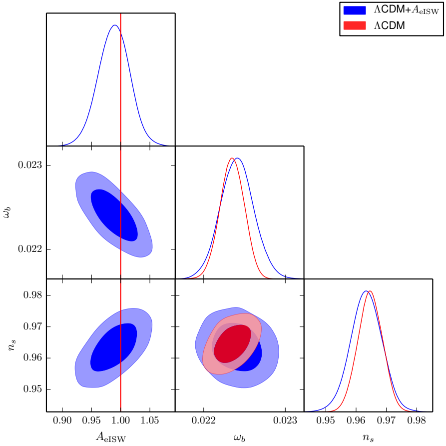


SV, PRD 104 (2021) 063524

Consistency check: within ΛCDM, data consistent with $A_{\rm eISW} = 1$?

eISW consistency test

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



SV, PRD 104 (2021) 063524

Yes!

Parameter	*Planck* ΛCDM	*Planck* ΛCDM+$A_{\rm eISW}$
$100\omega_b$	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
$A_{\rm eISW}$	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

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

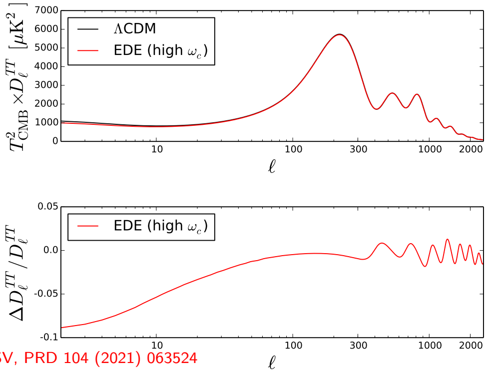
High H_0 EDE fit to CMB at the cost of increase in $\omega_c \to$ worsens tension with WL/LSS data? Hill *et al.*, PRD 102 (2020) 043507; Ivanov *et al.*, PRD 102 (2020) 103502; D'Amico *et al.*, JCAP 2105 (2021) 072; see partial rebuttals in: Murgia *et al.*, PRD 103 (2021) 063502; Smith *et al.*, arXiv:2009.10740

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

Parameter	ΛCDM	EDE (high ω_c)	EDE (low ω_c)
$100\omega_b$	2.253	2.253	2.253
ω_c	0.1177	0.1322	0.1177
H_0 [km/s/Mpc]	68.21	72.19	72.19
τ	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
$f_{\rm EDE}$	–	0.122	0.122
$\log_{10} z_c$	–	3.562	3.562
θ_i	–	2.83	2.83
n	–	3	3

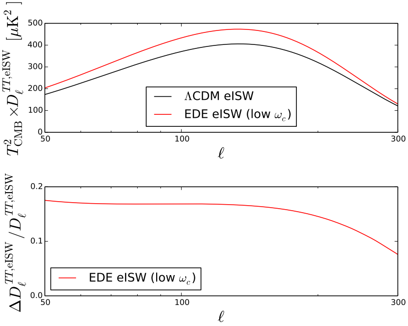


SV, PRD 104 (2021) 063524

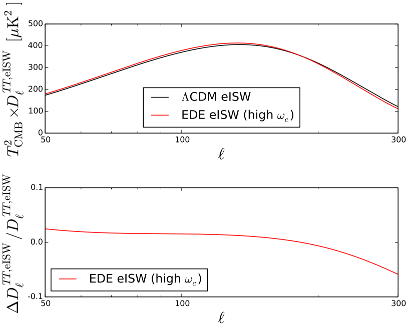
Implications for early-time new physics: EDE case study

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

Low ω_c



High ω_c



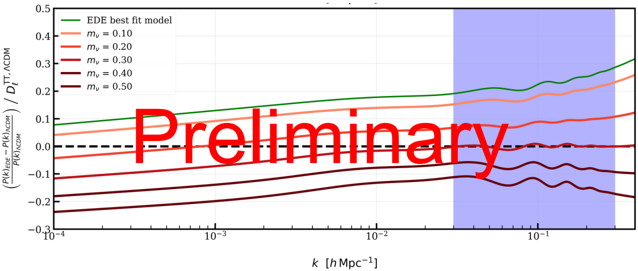
Almost 20% eISW excess!

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

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

Early dark energy problems

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



Reeves, SV, Efstathiou, Sherwin, in preparation. Plot credits: Alex Reeves

Other possible ingredients: decaying DM, DM-dark radiation interactions

Alex Reeves (Cambridge → ETH)

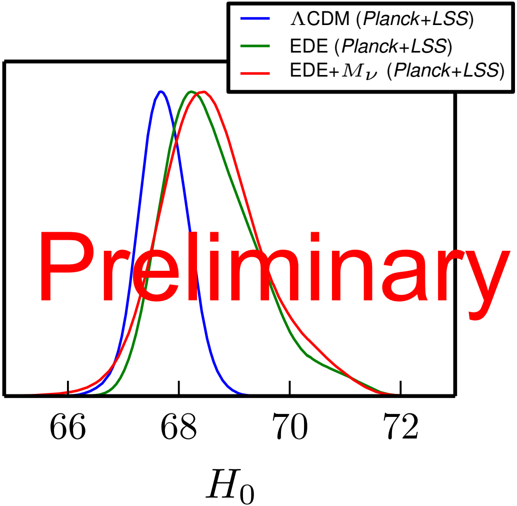
George Efstathiou (Cambridge)

Blake Sherwin (Cambridge)

Early dark energy problems

Massive neutrinos actually turn out not to work:

- Increase in S_8 (actually worsens S_8 discrepancy)
- M_ν negatively correlated with H_0 for CMB
- Need $M_\nu \sim 0.3\,\mathrm{eV}$, very hard to accommodate in LSS data



Reeves, SV, Efstathiou, Sherwin, in preparation. Plot credits: Alex Reeves

S_8 discrepancy – something to get excited about?

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

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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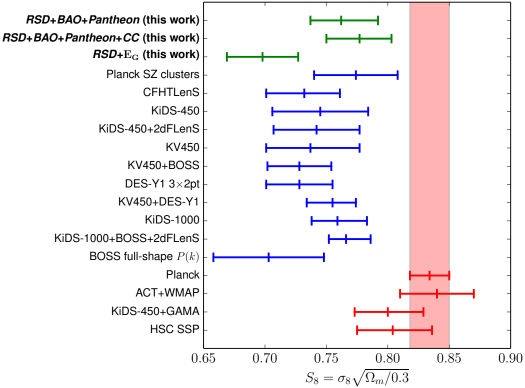


From the growth rate ($f\sigma_8$) point of view, S_8 discrepancy perfectly compatible with a statistical fluctuation!

Rafael Nunes (INPE, Brazil)

Nunes & SV, MNRAS 505 (2021) 5427

Recap

Early-time consistency tests of ΛCDM

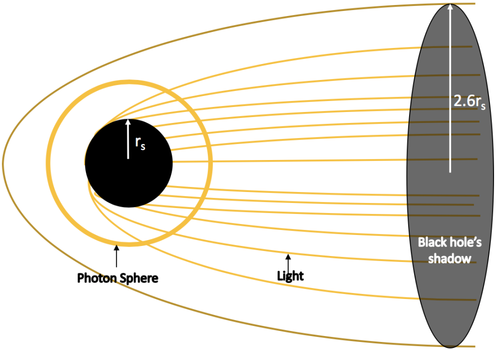
- eISW effect sets tight constraints on new pre-recombination physics
- Models which raise pre-recombination $H(z)$ will typically overpredict amplitude of eISW effect
- Example: early dark energy (need additional post-recombination new physics to solve "S_8 tension"?)

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, arXiv:2108.03966

$\Longrightarrow$ we can 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 $\Delta C \lesssim 10\%$
- Axis ratio $\Delta y/\Delta x \lesssim 4/3$
- $\epsilon \equiv \Delta Q/Q_{\rm Kerr} \lesssim 4$, $Q_{\rm Kerr} = Ma^2$

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

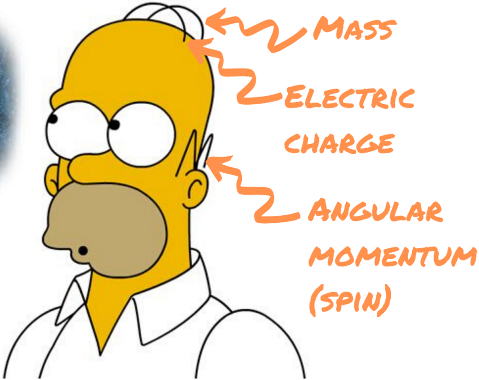
Sunny Vagnozzi[4,1], Cosimo Bambi[2] and Luca Visinelli[3]
Published 25 March 2020 • © 2020 IOP Publishing Ltd
Classical and Quantum Gravity, Volume 37, Number 8
Citation Sunny Vagnozzi *et al* 2020 *Class. Quantum Grav.* **37** 087001

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

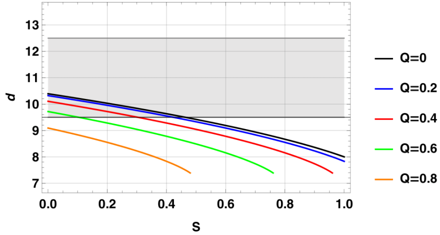
Black holes have at most three hairs ($3 \approx 0$)



Credits: Medium.com

An example of no-hair theorem violation

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



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

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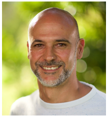
David Mota (Oslo)

Superradiance-induced black hole shadow evolution

Superradiance evolution of black hole shadows revisited

Rittick Roy,[1,*] Sunny Vagnozzi,[2,†] and Luca Visinelli[3,4,5,‡]

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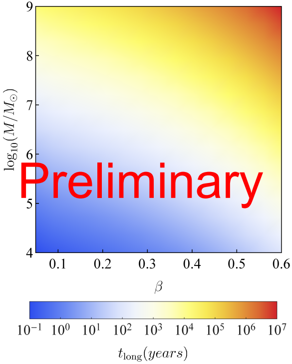

Evolution in shadow size $\Delta\theta \sim \mathcal{O}(1)\mu\mathrm{as}$ due to superradiance potentially observable on human timescales $[\mathcal{O}(10)\,\mathrm{yr}]$

Rittick Roy

(Fudan)

Luca Visinelli

(INFN Frascati)

Roy, SV, Visinelli, in preparation

Precession of planetary objects and new light particles

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

Yu-Dai Tsai,[1,2,*] Youjia Wu,[3,†] Sunny Vagnozzi,[4,‡] and Luca Visinelli[5,6,§]
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[6] *Tsung-Dao Lee Institute (TDLI), Shanghai Jiao Tong University, 200240 Shanghai, China*

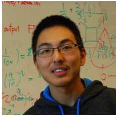
Yukawa potential from new light particle, e.g. new scalar or vector mediator from gauged $U(1)'$ sector [$U(1)_B$, $U(1)_{B-L}$, $L_\mu - L_{e,\tau}$,...]:

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

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

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

Yu-Dai Tsai (Fermilab/KICP, Chicago)

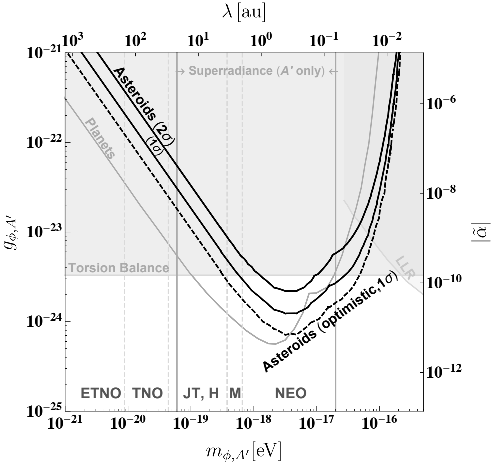


Youjia Wu (Michigan)

Luca Visinelli (INFN Frascati)

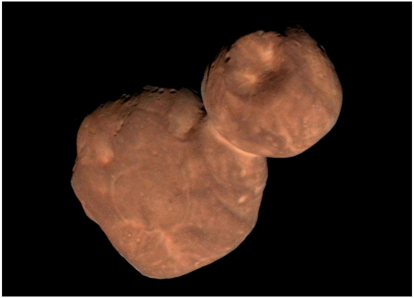
Precession of planetary objects and new light particles

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



Tsai, Wu, SV, Visinelli, arXiv:2107.04038 (submitted to PRL)

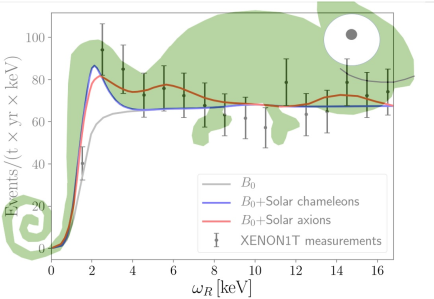
Asteroid 66391 Moshup
($\sim$ 1.3 km in diameter)



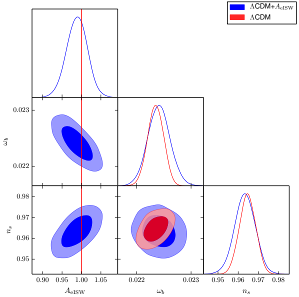
Credits: Wikiwand

Conclusions

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



Consistency tests of ΛCDM: pre-recombination new physics tightly constrained by eISW effect



Much to be learned about dark energy beyond "standard" cosmological searches for its gravitational interactions