Cosmic acceleration: now, then, and back then

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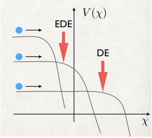
UniVersum IV, Trento, 2 February 2023

UNIVERSITÀ DI TRENTO
Dipartimento di Fisica

Three (or more?) epochs of cosmic acceleration?

In order of increasing "speculativeness":

- Dark energy (now, $t \sim 10^{10}$ yrs)
- Inflation (back then, $t \sim 10^{-36}$ s)
- Early dark energy (then, $t \sim 10^{4}$ yrs)



Credits: Vivian Poulin

Credits: (adapted from) The Open University

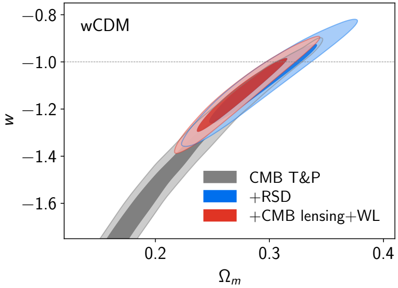
Note: blue → (Master's/PhD) students, red → postdocs

Student's name (student's institution)

Postdoc's name (postdoc's institution)

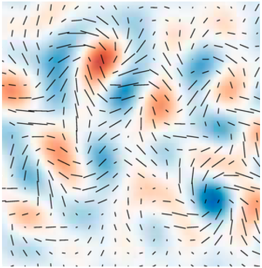
If this were a standard review talk...(simplifying a bit)

Latest on searches for dark energy *gravitational* effects (constraining w via background/growth of structure)



eBOSS collaboration, PRD 103 (2021) 083533

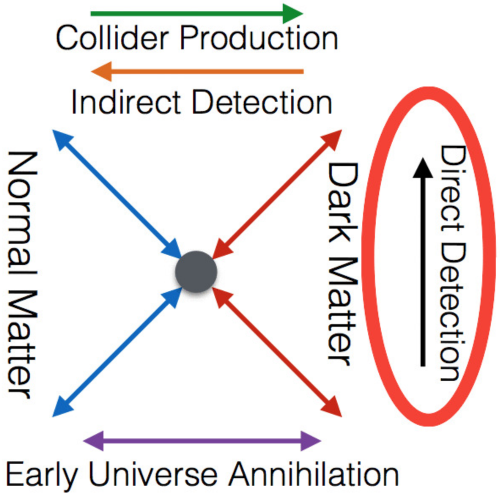
Latest on searches for low-frequency ($\sim 10^{-18}$ Hz) inflationary GWs via CMB B-modes (upper limits on r)



Credits: BICEP2 collaboration

Dark Energy

Are gravitational signatures all there is?



What about dark energy?

Credits: (adapted from) Matt Buckley

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

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

- Tune the coupling to be extremely weak [$M \gg M_{\mathrm{Pl}}$]
- 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**!

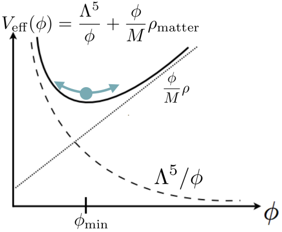
Chameleon screening

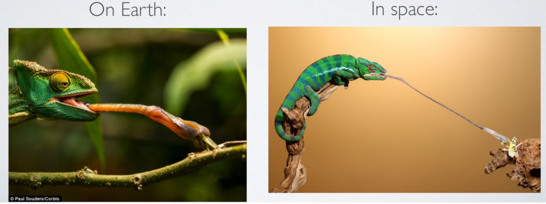
$$F_5 = -\frac{1}{M_5^2(x)} \frac{m_1 m_2}{r^{2-n(x)}} e^{-r/\lambda_5(x)}$$

- $\lambda_5(x) \rightarrow$ **chameleon** screening
- $M_5(x) \rightarrow$ symmetron screening
- $n(x) \rightarrow$ Vainshtein screening

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

$$m_{\rm eff}^2 = \frac{d^2 V_{\rm eff}}{d\phi^2}\Big|_{\phi=\phi_{\rm min}} \propto \rho_m^n \,, \; n > 0$$





Credits: Ben Elder

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 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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[2]*Institute of Astronomy (IoA), University of Cambridge, Madingley Road, Cambridge CB3 0HA, United Kingdom*
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[7]*Department of Applied Mathematics and Theoretical Physics (DAMTP), Center for Mathematical Sciences, University of Cambridge, CB3 0WA, United Kingdom*
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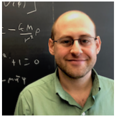
Luca Visinelli (Shanghai)


Phil Brax (IPhT, Saclay)


Anne Davis (Cambridge)

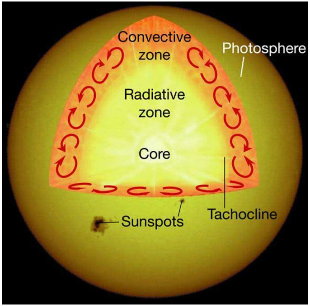

Jeremy Sakstein (Hawaii)

Direct detection of dark energy

Production

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

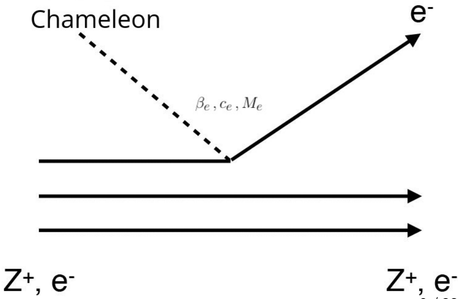
Production in strong magnetic fields of the tachocline



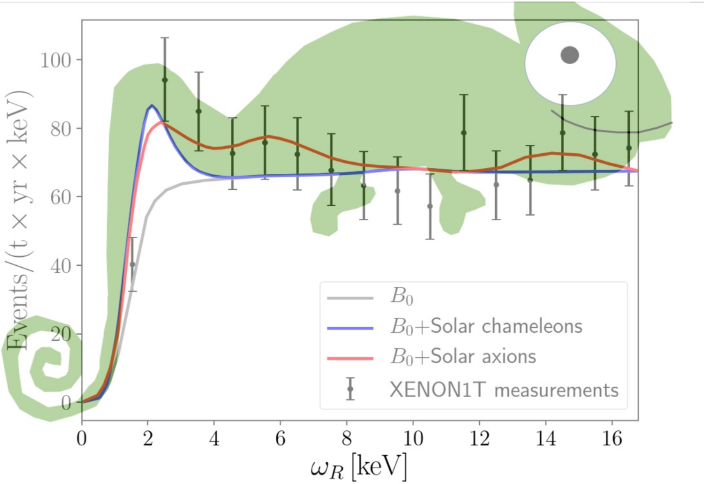
Detection

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

Analogous to photoelectric and axioelectric effects



Direct detection of (chameleon-screened) dark energy



SV *et al.*, PRD 104 (2021) 063023, winner of the 2021 *Buchalter Cosmology Prize*. 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?

Sunny Vagnozzi,[1★†] Luca Visinelli,[2] Olga Mena[3] and David F. Mota[4]

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[2]*Gravitation Astroparticle Physics Amsterdam (GRAPPA), University of Amsterdam, Science Park 904, NL-1098 XH Amsterdam, the Netherlands*
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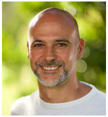
Surprisingly not!

Luca Visinelli (Shanghai)

Olga Mena (Valencia)

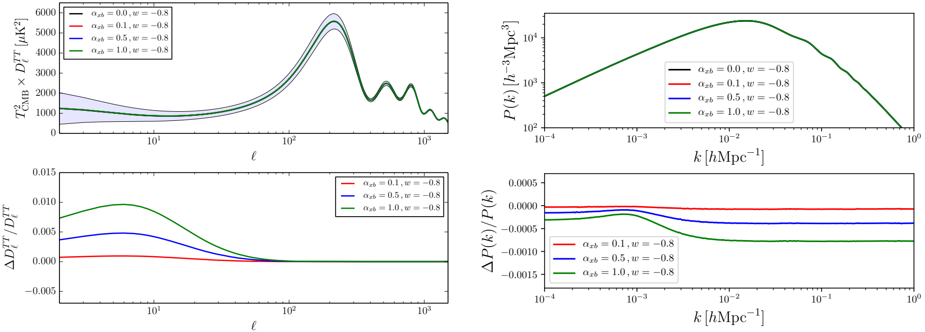


David Mota (Oslo)

Cosmological direct detection of dark energy?

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

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 scattering

What about the non-linear regime?

Monthly Notices of the ROYAL ASTRONOMICAL SOCIETY

MNRAS **512,** 1885–1905 (2022) https://doi.org/10.1093/mnras/stac649
Advance Access publication 2022 March 10

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

Fulvio Ferlito,[1,2★] Sunny Vagnozzi,[3★†] David F. Mota[4] and Marco Baldi[2,5,6]

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[3]*Kavli Institute for Cosmology, University of Cambridge, Madingley Road, Cambridge CB3 0HA, UK*
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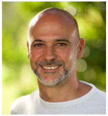
Accepted 2022 March 5. Received 2022 March 3; in original form 2022 January 17

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

Fulvio Ferlito (MPA Garching)



David Mota (Oslo)

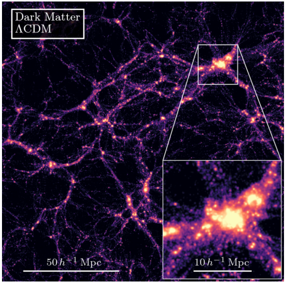
Marco Baldi (Bologna)

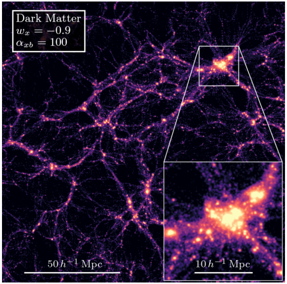
N-body simulations of DE-baryon scattering

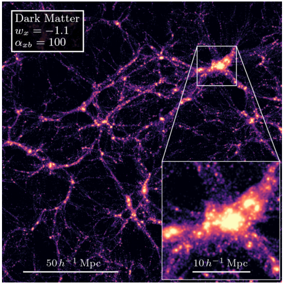
Simulation snapshots:

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

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

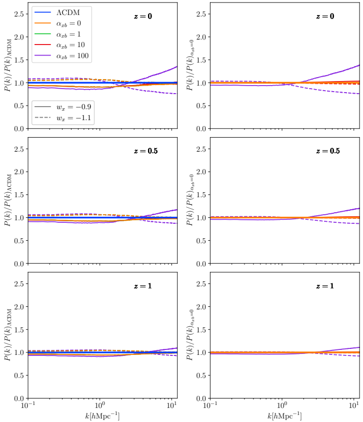




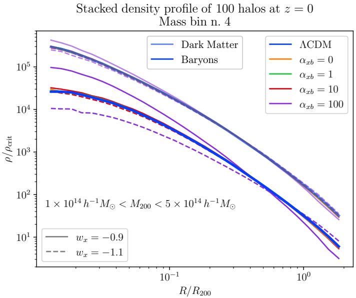


N-body simulations of DE-baryon scattering

Matter power spectrum relative to ΛCDM (left) and no-scattering wCDM (right)



Baryon fraction profiles



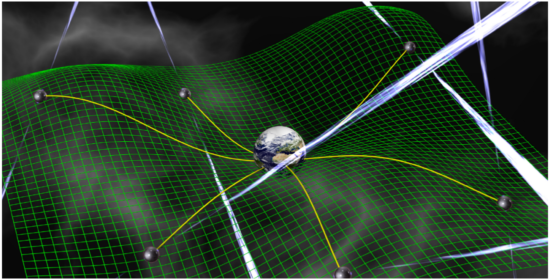
Other observables:

- (Cumulative) halo mass function
- Halo density profiles

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

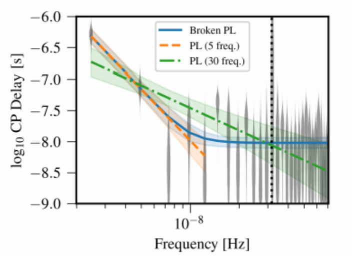
Inflation

Pulsar timing arrays



Hints of stochastic GW background detection by NANOGrav (confirmed by PPTA, EPTA, IPTA)?

NANOGrav collaboration, ApJ Lett. 905 (2020) L34; PPTA collaboration, ApJ Lett. 917 (2021) L19; EPTA collaboration, MNRAS 508 (2021) 4970; IPTA collaboration, MNRAS 510 (2022) 4873.



NANOGrav collaboration, ApJ Lett. 905 (2020) L34

Did NANOGrav see inflationary GWs?

Monthly Notices of the ROYAL ASTRONOMICAL SOCIETY
MNRAS **502,** L11–L15 (2021) doi:10.1093/mnrasl/slaa203
Advance Access publication 2020 December 21

Implications of the NANOGrav results for inflation

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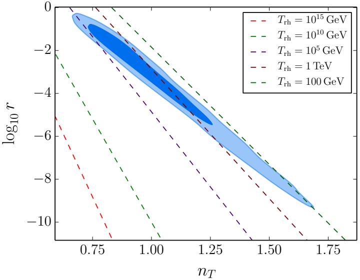
Accepted 2020 December 11. Received 2020 December 8; in original form 2020 October 7

Did NANOGrav detect an inflationary SGWB? $P_T \propto rA_s k^{n_T}$



SV, MNRAS Lett. 502 (2021) L11

- Very blue spectrum, $n_T \sim 1 \rightarrow$, violates consistency relation $r = -8n_T$, cannot come from single-field slow-roll inflation
- Very low reheating temperature, $T_{\rm rh} \lesssim \mathcal{O}(\text{TeV})$

Did NANOGrav see inflationary GWs?

Primordial gravitational waves from NANOGrav: A broken power-law approach

Micol Benetti[1,2,*] Leila L. Graef[3,†] and Sunny Vagnozzi[4,‡]
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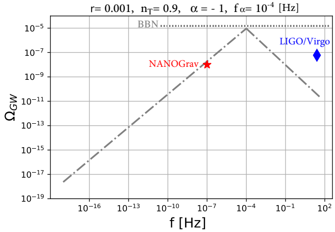
[2]Istituto Nazionale di Fisica Nucleare (INFN), Sezione di Napoli, Via Cinthia 9, I-80126 Napoli, Italy
[3]Instituto de Física, Universidade Federal Fluminense, Avenida General Milton Tavares de Souza s/n, Gragoatá, 24210-346 Niterói, Rio de Janeiro, Brazil
[4]Kavli Institute for Cosmology (KICC) and Institute of Astronomy, University of Cambridge, Madingley Road, Cambridge CB3 0HA, United Kingdom

(Received 12 November 2021; accepted 5 January 2022; published 11 February 2022)



Benetti, Graef, SV, PRD 105 (2022) 043520

Broken power-law spectrum can mimic:

- Non-standard pre-BBN era ($w \neq 1/3$: early matter domination, kination,...)
- Late-time entropy production
- Change in n_T associated to blue GW generation mechanism
- ...

Micol Benetti (SSM, Naples)

Leila Graef (Fluminense)

The swampland

Are inflation, string theory, and cosmological data mutually incompatible?

The zoo plot meets the swampland: mutual (in)consistency of single-field inflation, string conjectures, and cosmological data

William H Kinney[1,2], **Sunny Vagnozzi**[1,3,5] **and Luca Visinelli**[1,3,4]

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Accepted for publication 29 April 2019
Published 13 May 2019

CrossMark

Quite possibly, at least for the simplest inflationary models!

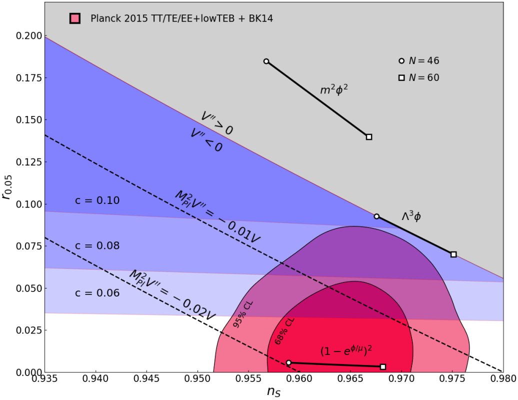
Will Kinney (SUNY Buffalo)

Luca Visinelli (Shanghai)

Are inflation and string theory incompatible?

Swampland conjectures: Obied *et al.*, arXiv:1806.08362

$$\frac{|\Delta\phi|}{M_{\rm Pl}} \lesssim \Delta \sim \mathcal{O}(1) \qquad M_{\rm Pl}\frac{|V_\phi|}{V} \gtrsim c \sim \mathcal{O}(1)$$



Kinney, SV, Visinelli, CQG 36 (2019) 117001

Ruling out inflation via the cosmic graviton background?

THE ASTROPHYSICAL JOURNAL LETTERS, 939:L22 (5pp), 2022 November 10
https://doi.org/10.3847/2041-8213/ac9b0e

The Challenge of Ruling Out Inflation via the Primordial Graviton Background

Sunny Vagnozzi[1,2] and Abraham Loeb[3]
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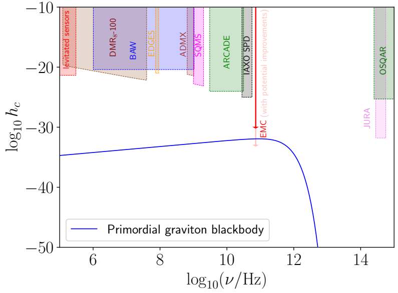
Received 2022 April 28; revised 2022 October 16; accepted 2022 October 17; published 2022 November 3



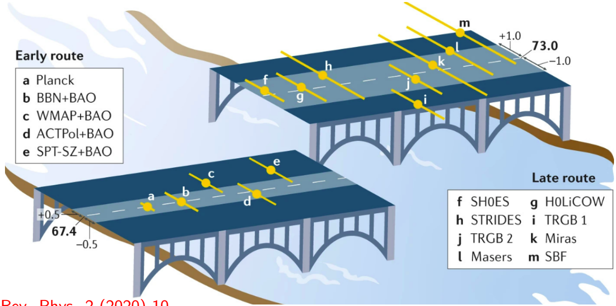
Vagnozzi & Loeb, ApJ Lett. 939 (2022) L22

- Produced at $t \sim t_{\rm Pl}$
- Gives correction $\Delta N_{\rm eff} \simeq 0.054$ (detectable in near future)
- Stochastic GW background at $\sim 100\,\mathrm{GHz}$ also potentially detectable

Avi Loeb (Harvard)

Early dark energy

Viewing the Hubble tension ocean with different eyeglasses



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

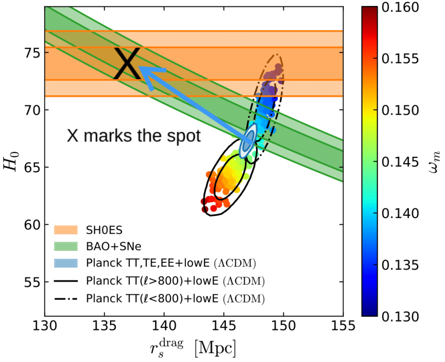
Why does ΛCDM fit data so well? Do we really need new physics? If so, at what time(s), and with what ingredients?

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 $\approx 12\%$ (!!!) 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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(Received 15 June 2021; accepted 22 July 2021; published 15 September 2021)

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

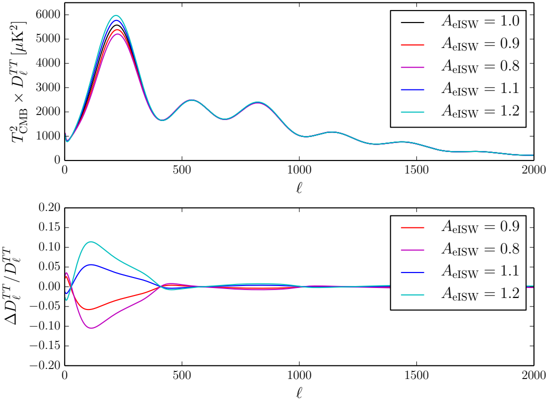
$$\Theta_\ell^{\rm ISW}(k) = \underbrace{\int_0^{\eta_m} d\eta\, e^{-\tau} \left(\dot{\Psi} - \dot{\Phi}\right) j_\ell(k\Delta\eta)}_{\text{early ISW}} + \underbrace{\int_{\eta_m}^{\eta_0} d\eta\, e^{-\tau} \left(\dot{\Psi} - \dot{\Phi}\right) j_\ell(k\Delta\eta)}_{\text{late ISW}}$$

(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 $A_{\rm eISW}$:

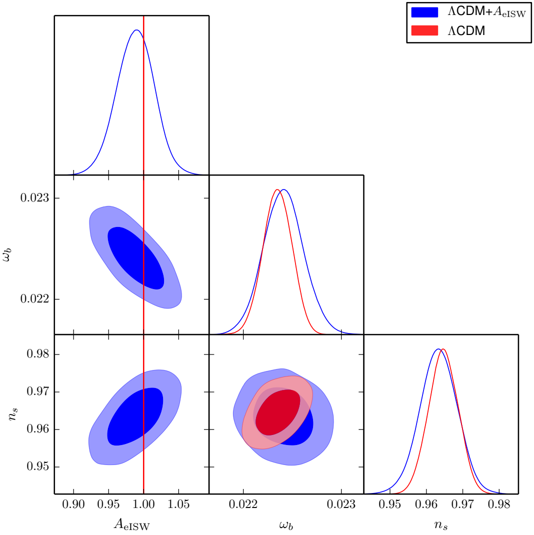
$$\Theta_\ell^{\rm eISW}(k) = {\color{red}A_{\rm eISW}} \int_0^{\eta_m} d\eta\, e^{-\tau} \left(\dot{\Psi} - \dot{\Phi}\right) j_\ell(k\Delta\eta)$$



SV, PRD 104 (2021) 063524

eISW consistency test

Is *Planck* data consistent with the expectation $A_{\rm eISW} = 1$?



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

Implications for early-time new physics: EDE case study

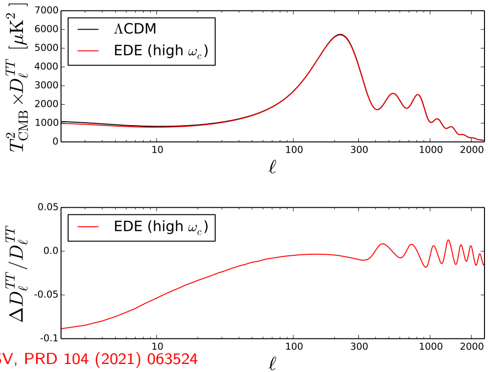
High H_0 EDE fit to CMB at the cost of increase in $\omega_c \rightarrow$ worsens tension with WL/LSS data? Hill *et al.*, PRD 102 (2020) 043507; Ivanov *et al.*, PRD 102 (2020) 103502; D'Amico *et al.*, JCAP 2105 (2021) 072; see also Gómez-Valent *et al.*, PRD 104 (2021) 083536; see partial rebuttals in: Murgia *et al.*, PRD 103 (2021) 063502; Smith *et al.*, PRD 103 (2021) 123542; Herold *et al.*, ApJ Lett. 929 (2022) L16; Gómez-Valent, PRD 106 (2022) 063506; Herold & Ferreira, arXiv:2210.16296

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

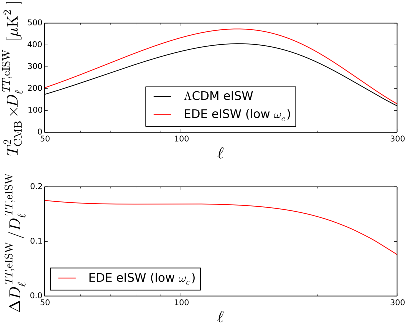


SV, PRD 104 (2021) 063524

Implications for early-time new physics: EDE case study

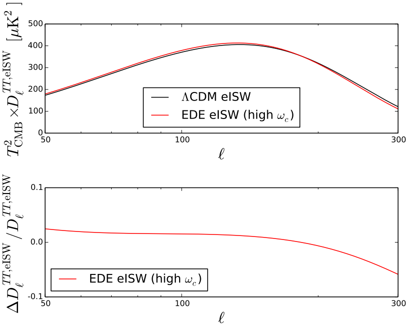
Let's extract only the eISW contribution to temperature anisotropies...

Low ω_c



Almost 20% eISW excess!

High ω_c



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

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

Rescuing early dark energy with massive neutrinos?

Restoring cosmological concordance with early dark energy and massive neutrinos?

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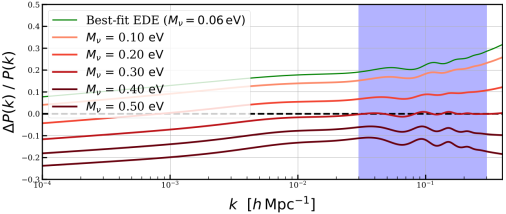


Reeves, Herold, SV, Sherwin, Ferreira, arXiv:2207.01501 (to appear in MNRAS). Plot credits: Alex Reeves

Alex Reeves (ETH Zürich)

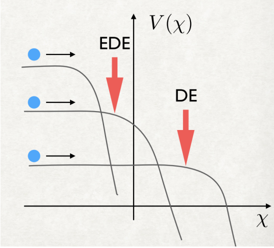
Laura Herold (MPA Garching)

Blake Sherwin (Cambridge)

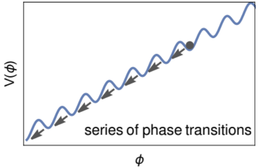
Elisa Ferreira (Tokyo)

Conclusions

- Many new ways to probe "cosmic acceleration" beyond the standard ones...
- ...which will soon be put to use on new data!
- Are inflation, dark energy, early dark energy (and beyond) just different faces of the same medal? (string axiverse?)



Credits: Vivian Poulin



Credits: Freese & Winkler, PRD 104 (2021) 083533

Thank you for your attention!