Searching for dark energy off the beaten track

Sunny Vagnozzi

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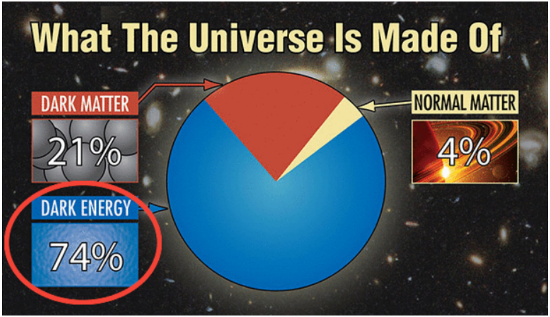
3PAC seminar, Imperial College London, 8 October 2021

Dark Energy



- Part I: direct detection of dark energy
- Part II: (early and late) consistency tests of ΛCDM and what we might learn about (early and late) dark energy

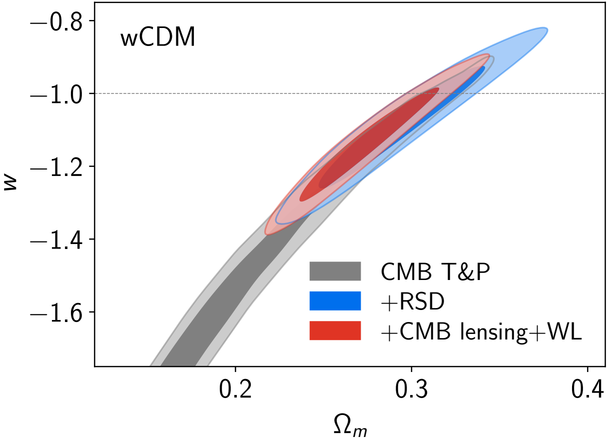
Note: blue → (Master's/PhD) students, red → postdocs

Student's name (student's institution)

Postdoc's name (postdoc's institution)

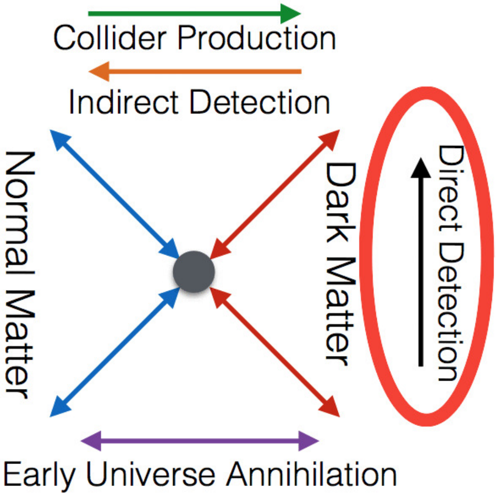
Understanding dark energy's properties

Lots of focus on understanding *gravitational* signatures of dark energy, and in particular constraining its equation of state w



eBOSS collaboration, PRD 103 (2021) 083533

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

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

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

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

Chameleon screening

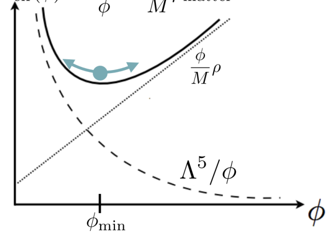
Fifth force range $\lambda(\mathbf{x})$ becomes short in dense environments, scalar field minimizes effective potential determined by coupling to matter

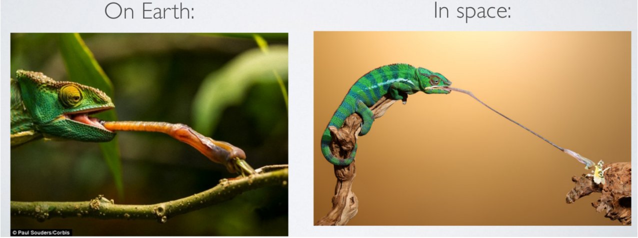
$$V_{\text{eff}} = V(\phi) + \phi\rho_m/M$$

$$m^2_{\text{eff}} = \frac{d^2 V_{\text{eff}}}{d\phi^2}\Big|_{\phi=\phi_{\text{min}}} \propto \rho^n \, , \, n > 0$$

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

$$V_{\text{eff}}(\phi) = \frac{\Lambda^5}{\phi} + \frac{\phi}{M}\rho_{\text{matter}}$$





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

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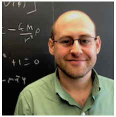
Luca Visinelli (INFN Frascati)

Phil Brax (IPhT, Saclay)

Anne Davis (Cambridge)



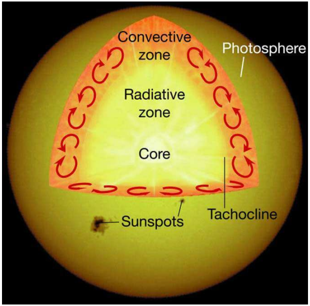
Jeremy Sakstein (Hawaii)

Direct detection of dark energy

Production

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

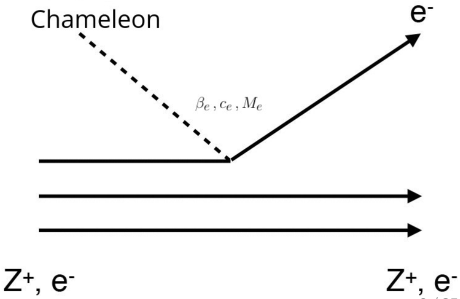
Production in strong magnetic fields of the tachocline



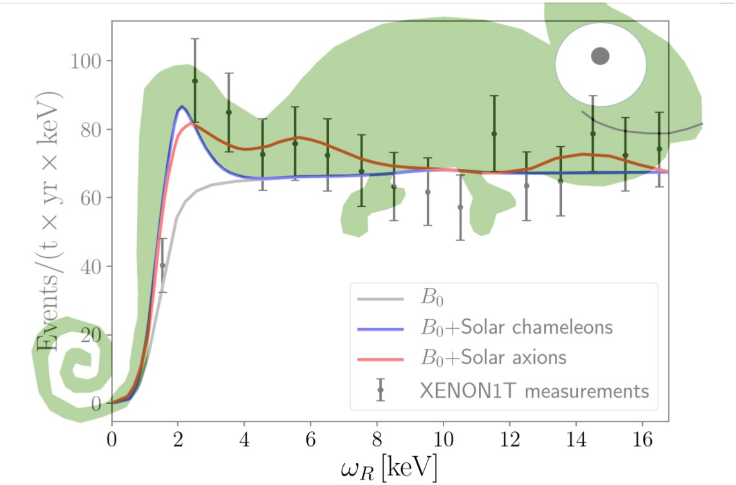
Detection

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

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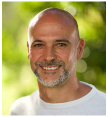
Accepted 2020 January 27. Received 2020 January 23; in original form 2019 December 3

Surprisingly not!

Luca Visinelli (INFN Frascati)

Olga Mena (Valencia)



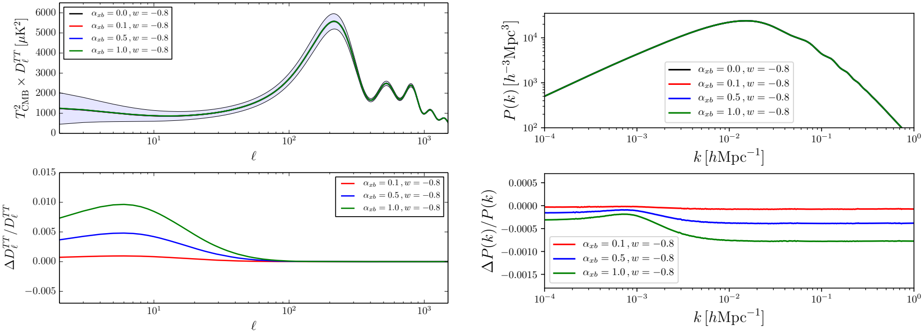
David Mota (Oslo)

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

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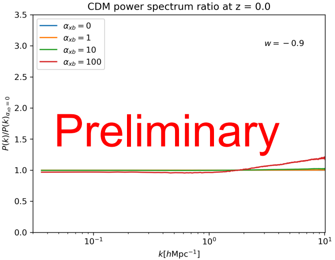
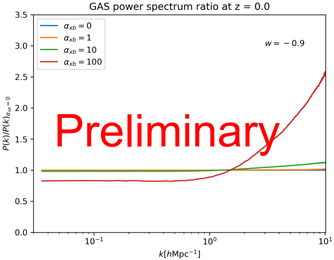


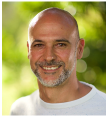
Ferlito, SV, Baldi, Mota, in preparation



Ferlito, SV, Baldi, Mota, in preparation

Fulvio Ferlito (Bologna → Garching)

Marco Baldi (Bologna)



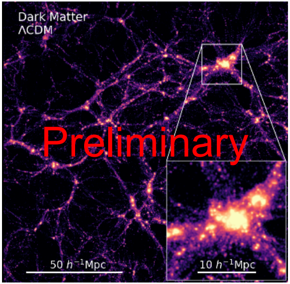
David Mota (Oslo)

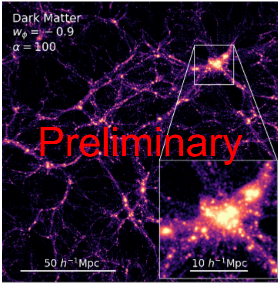
N-body simulations of DE-baryon interactions

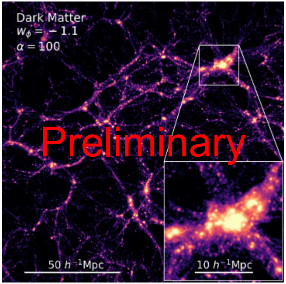
Simulation snapshots:

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

Ferlito, SV, Baldi, Mota, in preparation



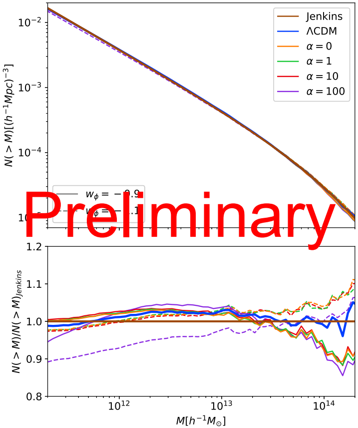




N-body simulations of DE-baryon interactions

Other observables:

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



Ferlito, SV, Baldi, Mota, in preparation

Recap

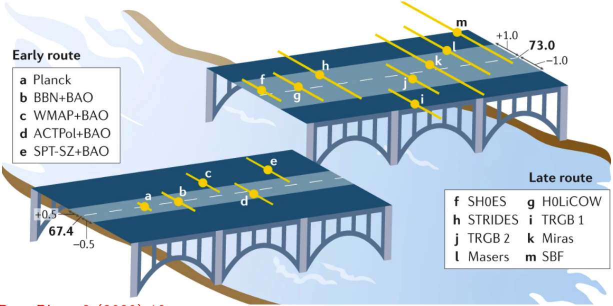
Direct detection of dark energy

- 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 and late times)?

Perhaps from the Hubble tension!

Viewing the Hubble tension ocean with different eyeglasses



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

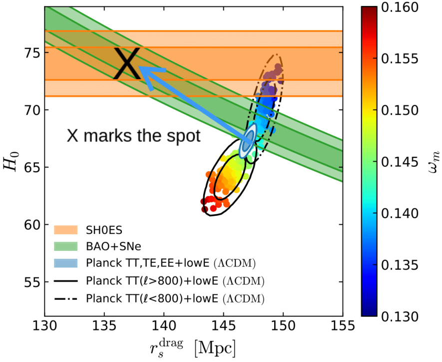
Why does ΛCDM fit data so well? Do we really need new physics? If so, at what time(s), and with what ingredients?

Early times: early ISW effect ⟺ *Consistency tests of ΛCDM* ⟺ *Late times: ages of old objects*

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?

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

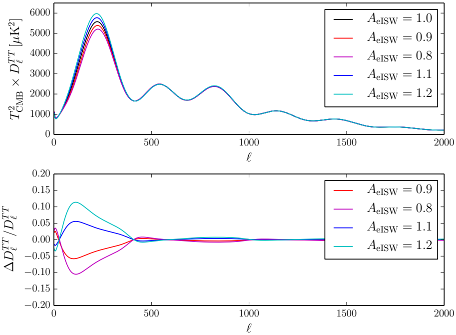
$$\Theta = \int_0^{\eta_0} d\eta \left[\underbrace{\propto g(\Theta_0 + \Psi)}_{\text{Sachs-Wolfe}} + \underbrace{\propto g v_b \frac{d}{d\eta}}_{\text{Doppler}} + \underbrace{\propto e^{-\tau}(\dot{\Psi} - \dot{\Phi})}_{\text{ISW}} + \underbrace{\propto (g\Pi + [g\ddot{\Pi}])}_{\text{Polarization}}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

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

(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

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

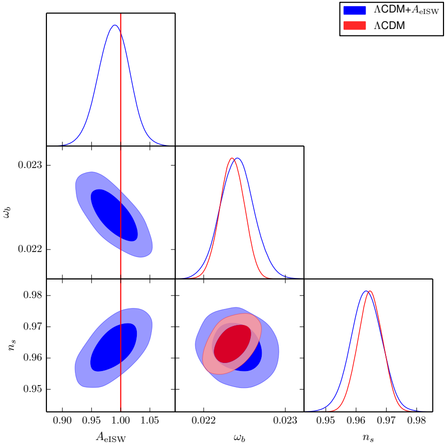


SV, PRD 104 (2021) 063524

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

Implications for early-time new physics: EDE case study

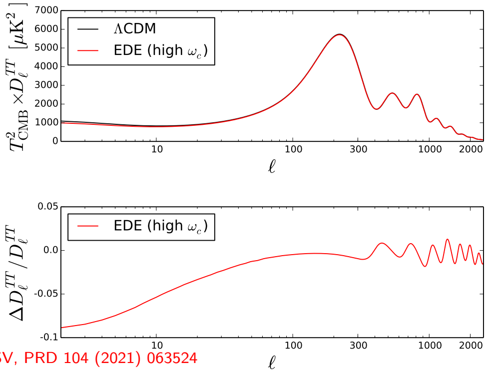
High H_0 EDE fit to CMB at the cost of increase in $\omega_c \to$ worsens tension with WL/LSS data? Hill *et al.*, PRD 102 (2020) 043507; Ivanov *et al.*, PRD 102 (2020) 103502; D'Amico *et al.*, JCAP 2105 (2021) 072; see partial rebuttals in: Murgia *et al.*, PRD 103 (2021) 063502; Smith *et al.*, arXiv:2009.10740

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

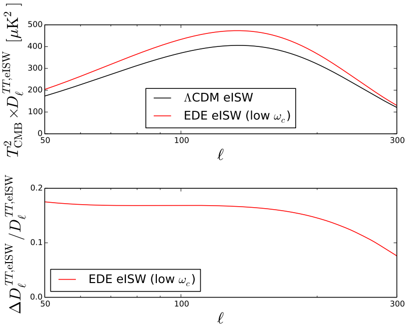


SV, PRD 104 (2021) 063524

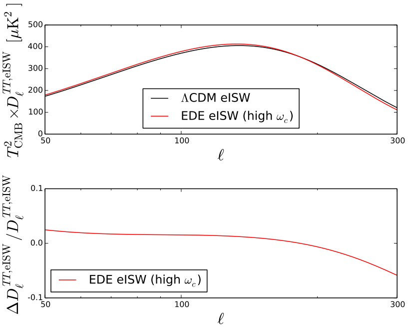
Implications for early-time new physics: EDE case study

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

Low ω_c



High ω_c



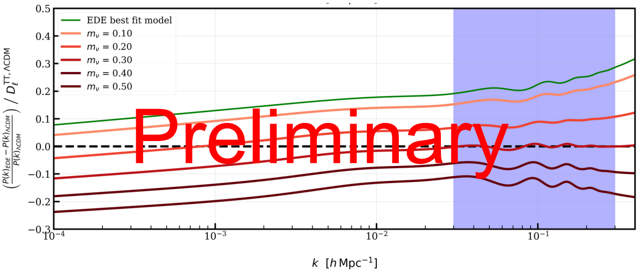
Almost 20% eISW excess!

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)

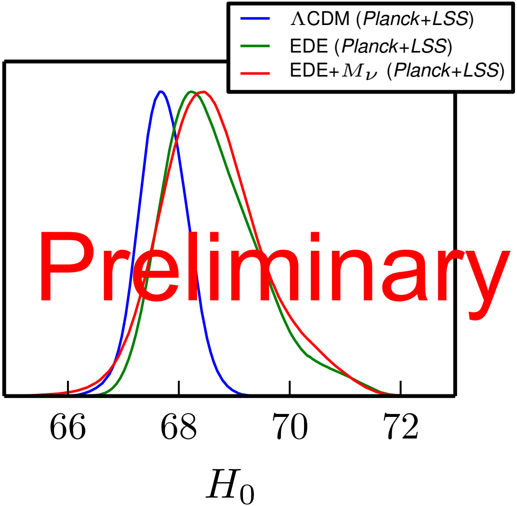

George Efstathiou (Cambridge)


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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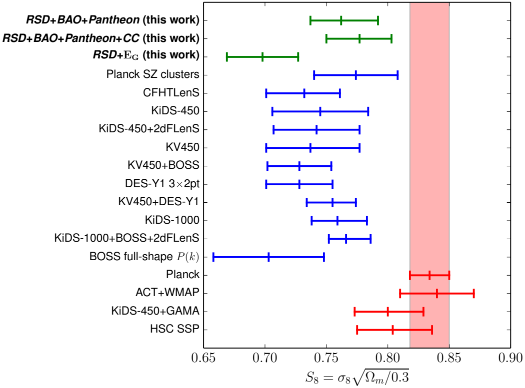

From the growth rate ($f\sigma_8$) point of view, S_8 discrepancy perfectly compatible with a statistical fluctuation!

Rafael Nunes (INPE, Brazil)

Nunes & SV, MNRAS 505 (2021) 5427

Late-time consistency tests of ΛCDM

Is ΛCDM really all there is at late times?

↓

(Try to) Test ΛCDM 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

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Potentially yes!

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:

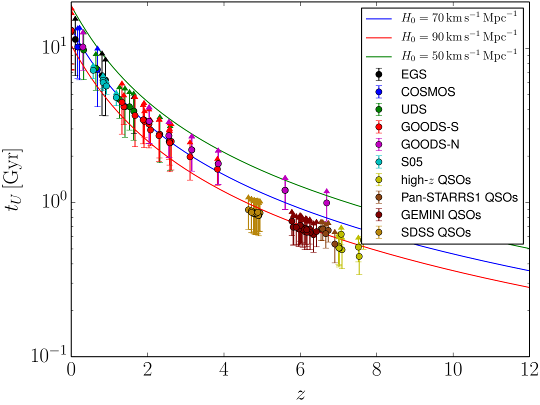
- OAO cannot be older than the Universe $\rightarrow$ **upper limit on $\mathbf{H_0}$**
- $t_U(z)$ integral insensitive to early-time cosmology
- $\Longrightarrow$ **late-time consistency test for ΛCDM independent of the early-time expansion**!
- Ages of astrophysical objects at $z > 0$ hard to estimate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

OAO age-redshift diagram

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

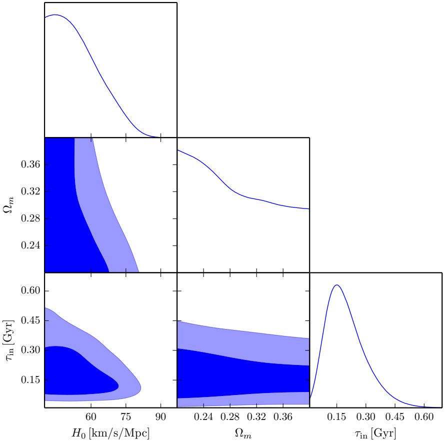


SV *et al.*, arXiv:2105.10421

Results

Assume ΛCDM at late times, constrain H_0, Ω_m, and incubation time $\tau_{\rm in}$

Prior for $\tau_{\rm in}$ following Jiménez *et al.*, JCAP 1903 (2019) 043; Valcin *et al.*, JCAP 2012 (2020) 022



SV *et al.*, arXiv:2105.10421

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

Implications for the Hubble tension

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

- #1: ΛCDM may not be the end of the story at $z \lesssim 10$
- #2: Nothing wrong with ΛCDM 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 2σ 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; Lin *et al.*, arXiv:2102.05701; Dainotti *et al.*, ApJ 912 (2021) 150

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

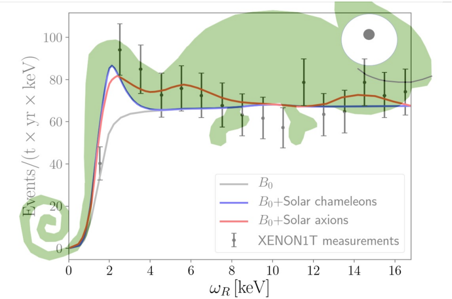
Karsten Jedamzik, Levon Pogosian & Gong-Bo Zhao

Communications Physics **4**, Article number: 123 (2021) | Cite this article

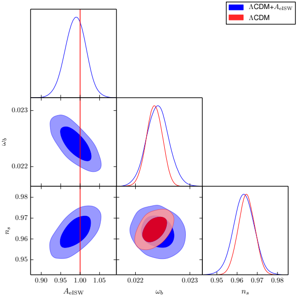
1461 Accesses | **1** Citations | **10** Altmetric | Metrics

Conclusions

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



Consistency tests of ΛCDM: do we need new dark energy physics both before and after recombination?



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