

Searching for dark energy off the beaten track

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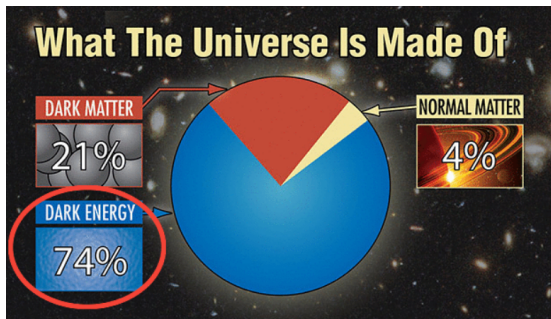
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Cosmology and Gravitation Seminar, Perimeter Institute
25 January 2022

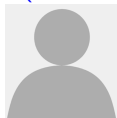


Dark Energy



- Part I: direct detection of DE on Earth
- Part II: consistency tests of Λ CDM, implications for (early and late) DE

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



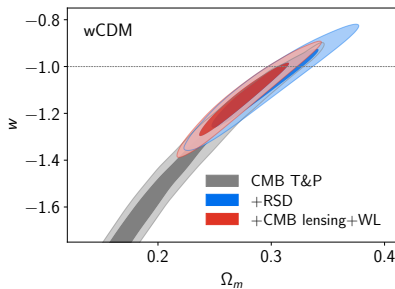
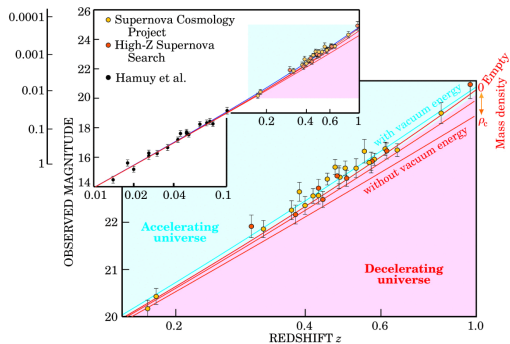
Student's name (student's institution)



Postdoc's name (postdoc's institution)

The beaten track

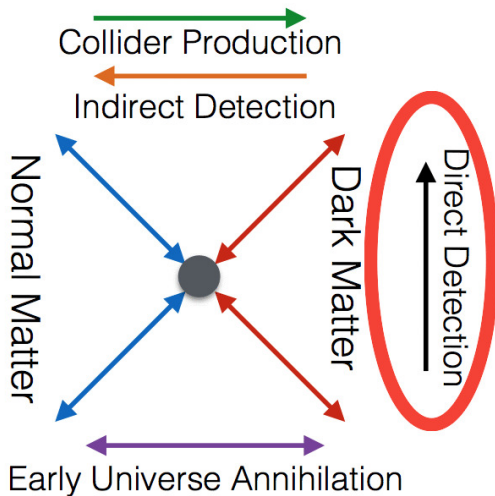
Gravitational signatures of DE: the effect of DE's energy density on the background expansion or the growth of structure, probed by standard cosmological observations, with particular focus on DE's equation of state $w_{\text{DE}} = P_{\text{DE}}/\rho_{\text{DE}}$ (~ -1 ?)



eBOSS collaboration, PRD 103 (2021) 083533

*Part I:
direct detection of dark energy*

Are gravitational signatures all there is?



What about dark energy?



Are gravitational signatures all there is?

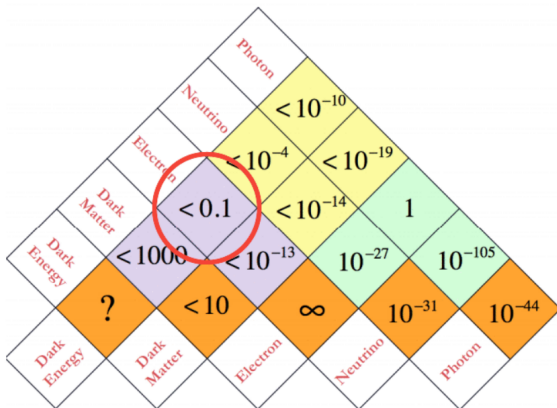
PHYSICAL REVIEW D **82**, 083505 (2010)

Scattering of dark matter and dark energy

Fergus Simpson*

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Edinburgh EH9 3HJ, United Kingdom*

(Received 2 August 2010; published 7 October 2010)



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 [$m \sim H_0 \sim \mathcal{O}(10^{-33})$ 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)

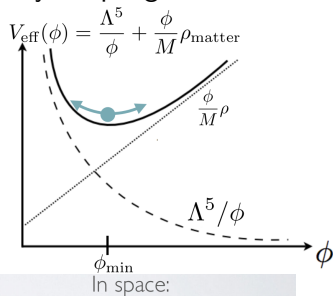
Chameleon screening

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

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

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

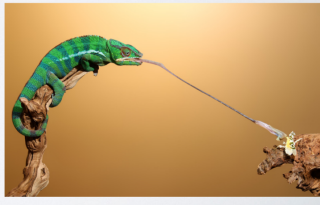
$$\lambda \sim 1/m_{\text{eff}} \propto \rho^{-n/2}$$



On Earth:



In space:



Direct detection of dark energy

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

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Scientists may have accidentally detected dark energy

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

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

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

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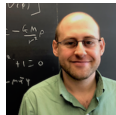
Luca Visinelli (Shanghai)



Phil Brax (IPhT, Saclay)



Anne Davis (Cambridge)



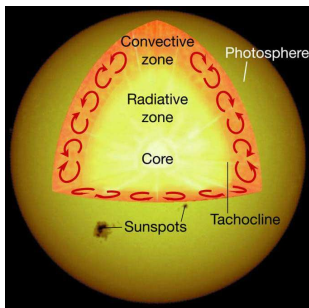
Jeremy Sakstein (Hawaii)

Direct detection of dark energy

Production

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

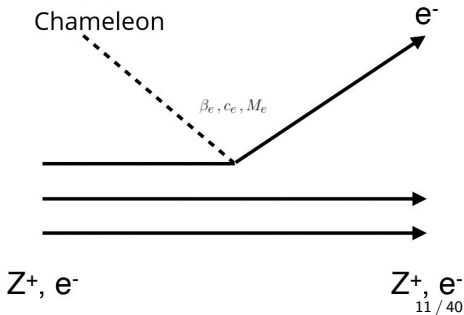
Production in strong magnetic fields of the tachocline



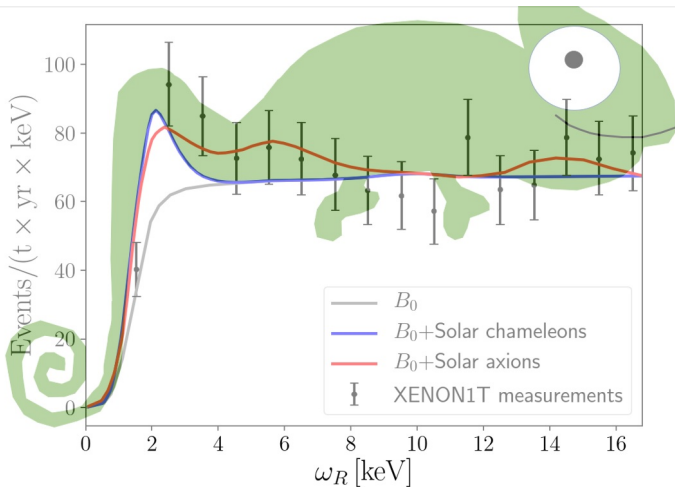
Detection

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

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)

Advance Access publication 2020 February 3



doi:10.1093/mnras/staa311

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

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Surprisingly not!



Luca Visinelli (Shanghai)



Olga Mena (Valencia)



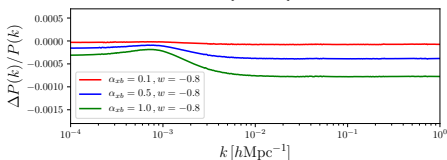
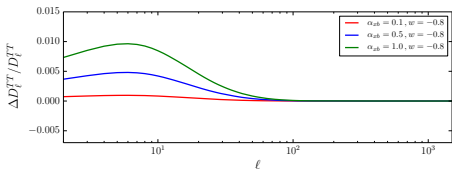
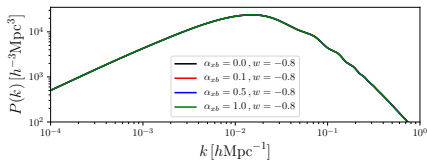
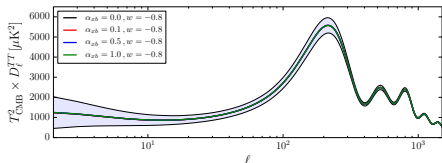
David Mota (Oslo)

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,^{1,2*} Sunny Vagnozzi,^{3,†‡} David F. Mota⁴ and Marco Baldi^{2,5,6}

¹Max-Planck-Institut für Astrophysik, Karl-Schwarzschild-Straße 1, D-85740 Garching bei München, Germany

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

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⁶INFN - 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)



Marco Baldi (Bologna)

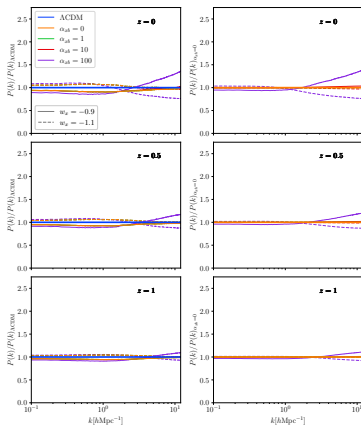
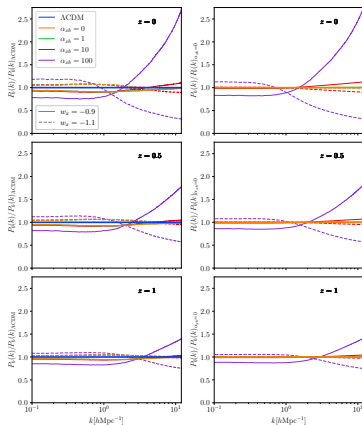


David Mota (Oslo)

N-body simulations of DE-baryon scattering

Baryon power spectrum relative to Λ CDM (left) and no-scattering w CDM (right)

Matter power spectrum relative to Λ CDM (left) and no-scattering w CDM (right)

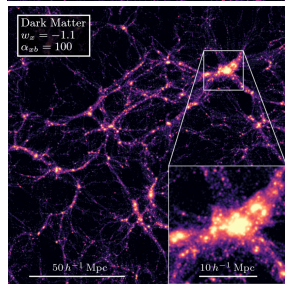
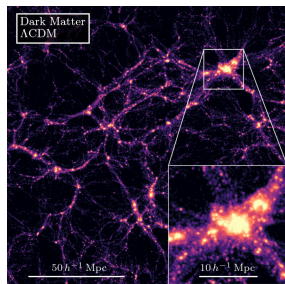
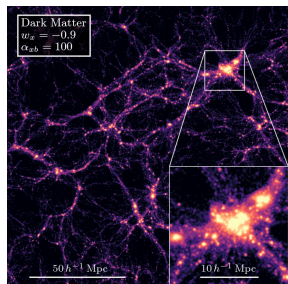


N-body simulations of DE-baryon scattering

Simulation snapshots:

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

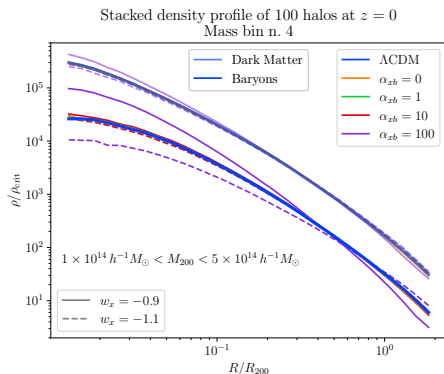
Ferlito, SV, Mota, Baldi, arXiv:2201.04528 (submitted to MNRAS)



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, arXiv:2201.04528 (submitted to MNRAS)

Baryon profiles most promising observable to probe DE-baryon scattering

Recap

Direct detection of dark energy

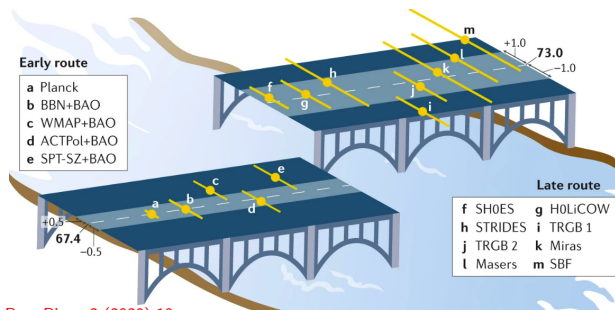
- Potentially lots of unharvested potential for direct detection of dark energy in dark matter direct detection experiments
- Room for large dark energy-baryons interactions in cosmology...
- ...possibly tightly constrained by (non-linear) LSS clustering and other astrophysical observations!

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

Perhaps from the Hubble tension!

*Part II:
consistency tests of Λ 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 Λ CDM fit data so well? Do we really need new physics? If so, at what time(s), and with what ingredients?

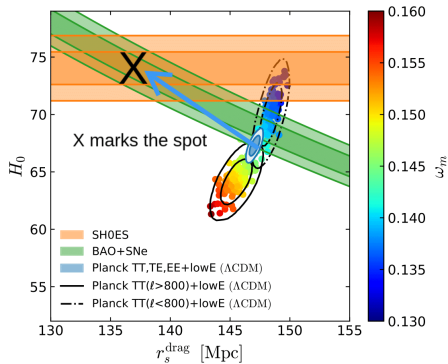
Consistency tests of Λ CDM

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_{eq} ↓↓

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


Early-time consistency tests of Λ CDM

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

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

Sunny Vagnozzi 

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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 Λ CDM fit CMB data so well?



(Early-time) Consistency tests of Λ CDM

The early ISW (eISW) effect

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

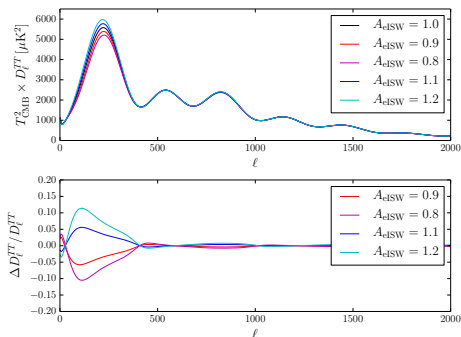
$$\Theta = \int_0^{\eta_0} d\eta \left[\underbrace{\propto g(\Theta_0 + \Psi)}_{\text{Sachs-Wolfe}} + \underbrace{\propto gv_b \frac{d}{d\eta}}_{\text{Doppler}} + \underbrace{\propto e^{-\tau}(\dot{\Psi} - \dot{\Phi})}_{\text{ISW}} + \underbrace{\propto (g\Pi + [g\ddot{\Pi}])}_{\text{Polarization}} \right]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

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

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

eISW consistency test

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



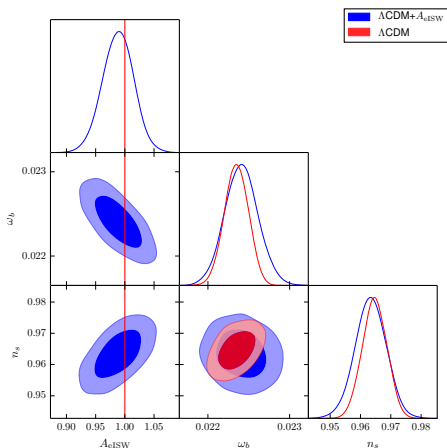
SV, PRD 104 (2021) 063524

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

eISW consistency test

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

Yes!



| Parameter | <i>Planck</i> | |
|--------------------|---------------------|---------------------------|
| | Λ CDM | Λ CDM+ A_{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_{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

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.*,

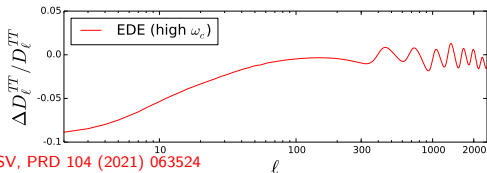
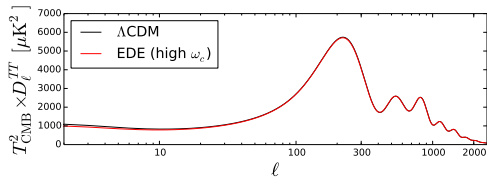
JCAP 2105 (2021) 072; see partial rebuttals in: Murgia *et al.*, PRD 103 (2021) 063502; Smith *et al.*, PRD 103 (2021) 123542

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 | Λ CDM | 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_{EDE} | – | 0.122 | 0.122 |
| $\log_{10} z_c$ | – | 3.562 | 3.562 |
| θ_i | – | 2.83 | 2.83 |
| n | – | 3 | 3 |

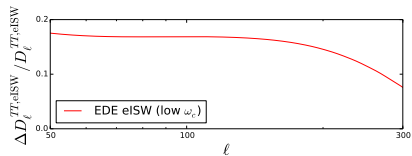
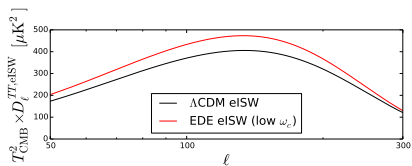


SV, PRD 104 (2021) 063524

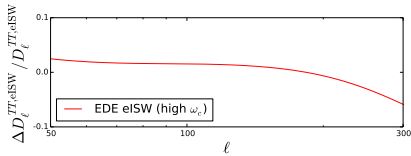
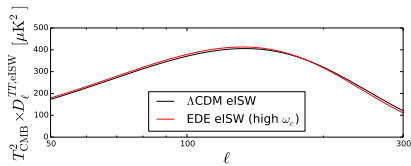
Implications for early-time new physics: EDE case study

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

Low ω_c



High ω_c



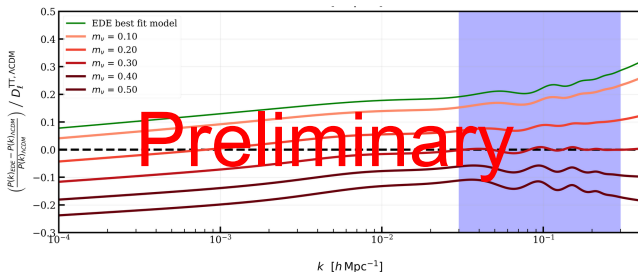
Almost 20% eISW excess!

No more than \lesssim 3-5% eISW excess

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

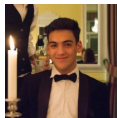
Early dark energy problems

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



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

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



Alex Reeves (ETH Zürich)



George Efstathiou (Cambridge)

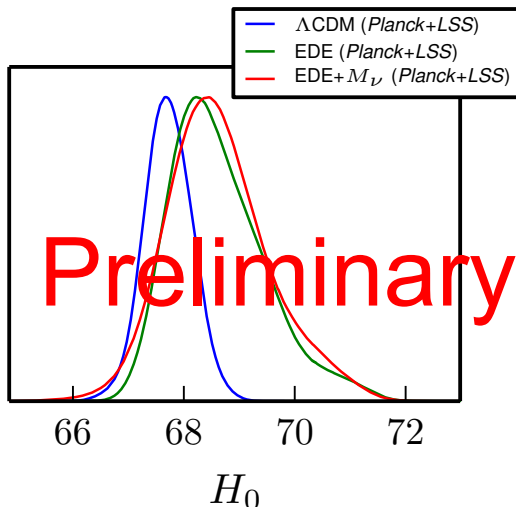


Blake Sherwin (Cambridge)

Early dark energy problems

Massive neutrinos actually turn out not to work:

- Increase in S_8 (worsens S_8 discrepancy)
- M_ν negatively correlated with H_0 for CMB
- Need $M_\nu \sim 0.3$ eV, very hard to accommodate in LSS data
- Worsen fit to BAO data
- Maybe EDE not such a bad fit after all (prior volume effects)?



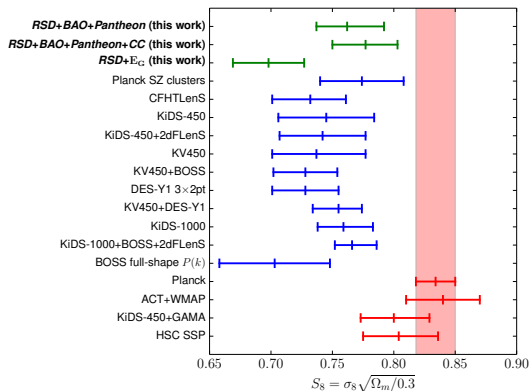
Reeves, SV, Efstathiou, Sherwin, in preparation. Plot credits: Alex Reeves

S_8 discrepancy – something to get excited about?

Arbitrating the S_8 discrepancy with growth rate measurements from redshift-space distortions

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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)

Late-time consistency tests of Λ CDM

Is Λ CDM really all there is at late times?



(Try to) Test Λ 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

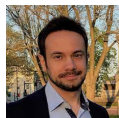
Sunny Vagnozzi,^{1,*} Fabio Pacucci,^{2,3,†} and Abraham Loeb^{2,3,‡}

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³*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:

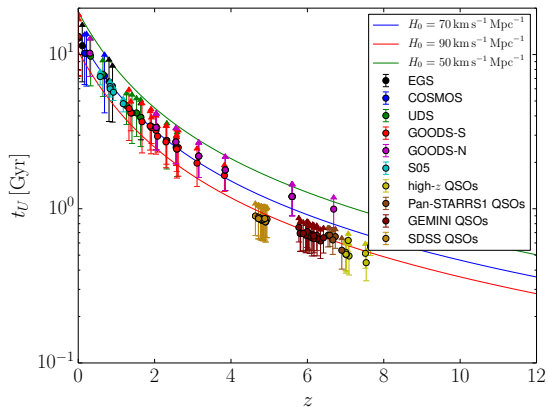
- OAO cannot be older than the Universe \rightarrow **upper limit on H_0**
- $t_U(z)$ integral insensitive to early-time cosmology
- \implies **late-time consistency test for Λ CDM independent of the early-time expansion!**
- **Ages of astrophysical objects at $z > 0$ hard to estimate robustly** 

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

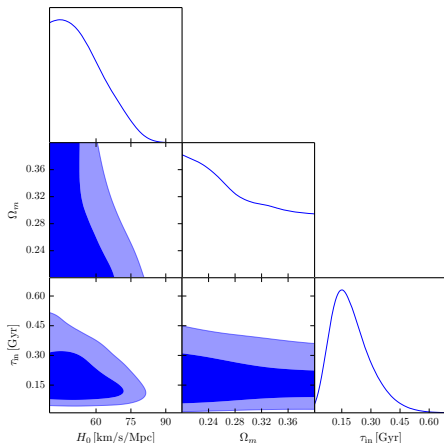
Age-redshift diagram up to $z \sim 8$



Results

Assume Λ CDM at late times, constrain H_0 , Ω_m , and incubation time τ_{in}

Prior for τ_{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)

$H_0 < 73.2 \text{ km/s/Mpc}$ (95% C.L.)

Implications for the Hubble tension

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

- #1: Λ CDM may not be the end of the story at $z \lesssim 10$
- #2: Nothing wrong with Λ 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 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; 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 Altmeteric | [Metrics](#)

Recap

Early-time consistency tests of Λ CDM

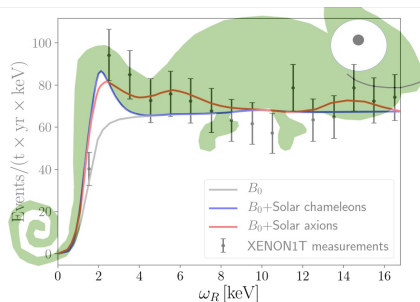
- eISW effect sets tight constraints on new pre-recombination physics
- Models which raise pre-recombination $H(z)$ will typically overpredict amplitude of eISW effect
- Example: early dark energy (need additional post-recombination new physics to solve “ S_8 tension”?)
- Early-time new physics alone not enough to solve the Hubble tension?

Late-time consistency tests of Λ CDM

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

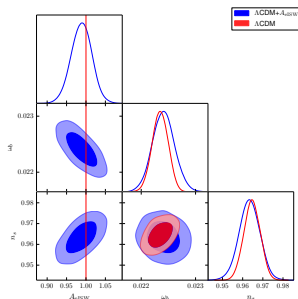
Conclusions

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 Λ 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