Searching for dark energy off the beaten track

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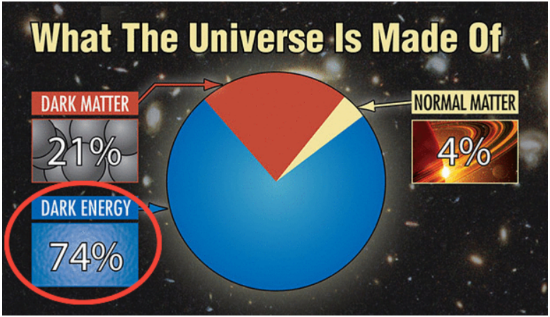
6 September 2023

Dark Energy



- Part I: non-standard cosmological searches for dark energy
- Part II: (terrestrial and cosmological) direct detection of dark energy

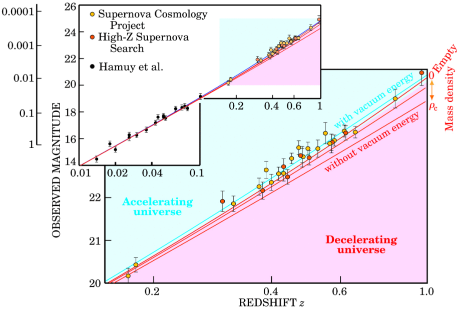
Note: blue → (Master's/PhD) students, red → postdocs

Student's name (student's institution)

Postdoc's name (postdoc's institution)

The beaten track

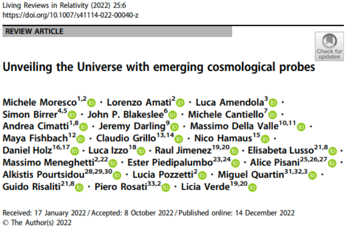
Gravitational signatures (effect of DE energy density on background expansion or growth of structure) probed by **standard cosmological observations**, with particular focus on the **equation of state** *w*



Credits: Perlmutter, Physics Today 56 (2003) 53

Standard cosmological observations:

- CMB
- BAO
- Hubble flow SNeIa



Living Reviews in Relativity (2022) 25:6
https://doi.org/10.1007/s41114-022-00040-z

REVIEW ARTICLE

Check for updates

Unveiling the Universe with emerging cosmological probes

Michele Moresco[1,2] · Lorenzo Amati[2] · Luca Amendola[3] ·
Simon Birrer[4,5] · John P. Blakeslee[6] · Michele Cantiello[7] ·
Andrea Cimatti[1,8] · Jeremy Darling[9] · Massimo Della Valle[10,11] ·
Maya Fishbach[12] · Claudio Grillo[13,14] · Nico Hamaus[15] ·
Daniel Holz[16,17] · Luca Izzo[18] · Raul Jimenez[19,20] · Elisabeta Lusso[21,8] ·
Massimo Meneghetti[2,22] · Ester Piedipalumbo[23,24] · Alice Pisani[25,26,27] ·
Alkistis Pourtsidou[28,29,30] · Lucia Pozzetti[2] · Miguel Quartin[31,32,3] ·
Guido Risaliti[21,8] · Piero Rosati[33,2] · Licia Verde[19,20]

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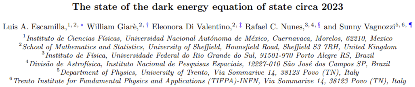
Moresco *et al.*, Living Rev. Relativ. 25 (2022) 6

Part I:
non-standard cosmological searches for dark energy

The state of the dark energy equation of state



The state of the dark energy equation of state circa 2023

Luis A. Escamilla,[1,2,*] William Giarè,[2,†] Eleonora Di Valentino,[2,‡] Rafael C. Nunes,[3,4,§] and Sunny Vagnozzi[5,6,¶]
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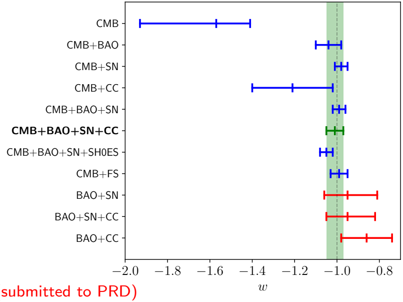


Escamilla *et al.*, arXiv:2307.14802 (submitted to PRD)


Luis Escamilla

(UNAM, Mexico)


William Giarè

(Sheffield)


Eleonora Di Valentino

(Sheffield)


Rafael Nunes

(UFRGS, Brazil)

Old astrophysical objects at high redshift

Where to break a model? Where it is tested the least! For ΛCDM, this means $2 \lesssim z \lesssim 10$

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

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

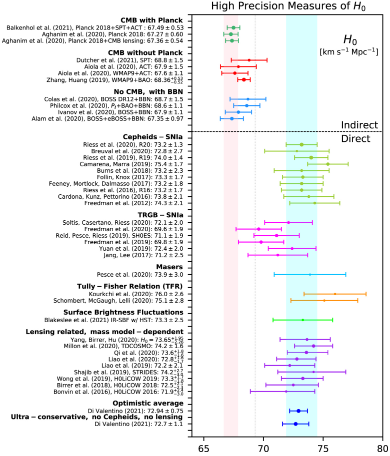
What can old astrophysical objects do for cosmology in the 2020s?

The H_0 tension

Can old astrophysical objects say something about the H_0 tension?

Overall trend:

- "early-time" model-dependent measurements prefer low H_0
- "late-time" direct measurements prefer high H_0



Review by Di Valentino *et al.*, CQG 38 (2021) 153001

Often heard "mantra" (?): H_0 tension calls for early-Universe new physics

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?

Journal of High Energy Astrophysics 36 (2022) 27–35

Contents lists available at ScienceDirect

Journal of High Energy Astrophysics

journal homepage: www.elsevier.com/locate/jheap

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

Sunny Vagnozzi [a,*], Fabio Pacucci [b,c], Abraham Loeb [b,c]

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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:

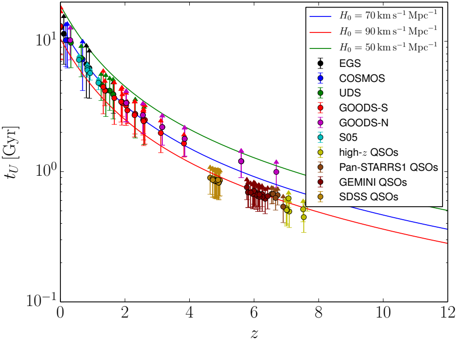
- OAO cannot be older than the Universe → **upper limit on** H_0
- $t_U(z)$ integral insensitive to early-time cosmology
- $\implies$ **late-time consistency test for ΛCDM independent of the early-time expansion**!
- Ages of astrophysical objects at $z > 0$ hard to estimate robustly ⚠

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

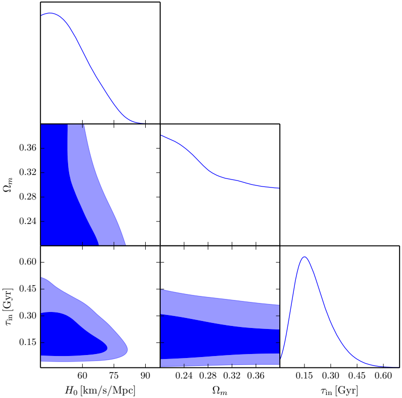
OAO age-redshift diagram

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



SV, Pacucci & Loeb, JHEAp 36 (2022) 27

Constraints on H_0 and Ω_m



SV, Pacucci & Loeb, JHEAp 36 (2022) 27

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

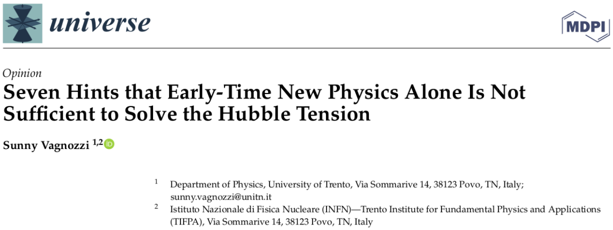
Implications for dark energy and the Hubble tension

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

1. ΛCDM may not be the end of the story at $z \lesssim 10$ (need something in the direction of phantom DE)
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? SV, Universe 9 (2023) 393



universe

MDPI

Opinion

Seven Hints that Early-Time New Physics Alone Is Not Sufficient to Solve the Hubble Tension

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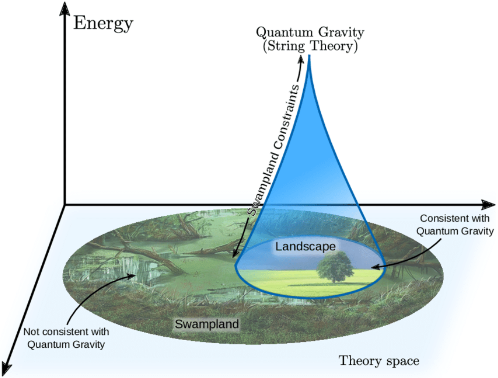
Negative dark energy density?

International Journal of Modern Physics D | Vol. 27, No. 12, 1830007 (2018) | Review Paper

What if string theory has no de Sitter vacua?

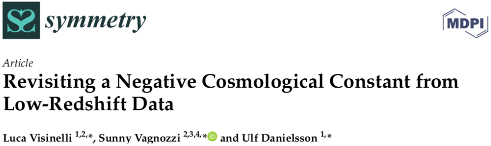
Ulf H. Danielsson and Thomas Van Riet

https://doi.org/10.1142/S0218271818300070 | **Cited by:** 238



Credits: Delaram Mirfendereski

Negative cosmological constant is consistent with data



symmetry

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Article

Revisiting a Negative Cosmological Constant from Low-Redshift Data

Luca Visinelli [1,2,*], **Sunny Vagnozzi** [2,3,4,*] **and Ulf Danielsson** [1,*]

$$H(z) = H_0\sqrt{\Omega_{\rm nCC} + \Omega_{\rm DE,0}(1+z)^{3(1+w)} + \Omega_{m,0}(1+z)^3 + \Omega_r(z)}$$

$$\Omega_{\rm nCC} < 0\,, \quad \Omega_{\rm DE,0} > 0\,, \quad \Omega_{\rm nCC} + \Omega_{\rm DE,0} \sim 0.7$$

This is in principle **perfectly consistent** with late-time cosmological data:

$$\begin{aligned} |\Omega_{\rm nCC}| &\lesssim \mathcal{O}(10) \quad \text{[BAO+SNeIa]} \\ |\Omega_{\rm nCC}| &\lesssim \mathcal{O}(1) \quad \text{[(geometrical) CMB+BAO+SNeIa]} \end{aligned}$$

Luca Visinelli (Shanghai)

Ulf Danielsson (Uppsala)

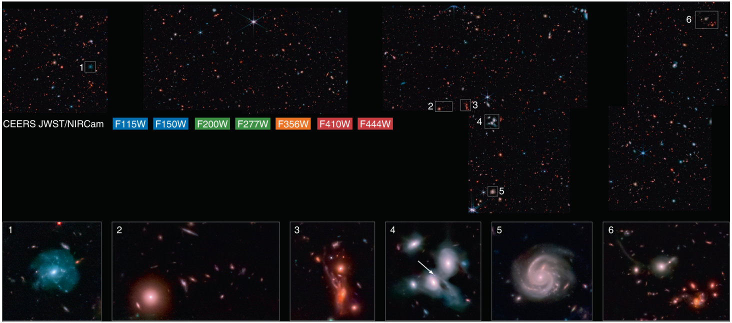
Early JWST observations: a challenge to ΛCDM?

Too many galaxies which are too massive at too high redshift!

A population of red candidate massive galaxies ~600 Myr after the Big Bang

Ivo Labbé ✉, Pieter van Dokkum, Erica Nelson, Rachel Bezanson, Katherine A. Suess, Joel Leja, Gabriel Brammer, Katherine Whitaker, Elijah Mathews, Mauro Stefanon & Bingjie Wang

Nature **616**, 266–269 (2023) | Cite this article



Credits: NASA/STScI/CEERS/TACC/S. Finkelstein/M. Bagley/R. Larson/Z. Levay

Negative cosmological constant to the rescue

Can a negative CC help with the "JWST tension"?

Dark energy in light of the early JWST observations: case for a negative cosmological constant?

Shahnawaz A. Adil,[a] **Upala Mukhopadhyay,**[b] **Anjan A. Sen,**[b] **and Sunny Vagnozzi**[c,d]

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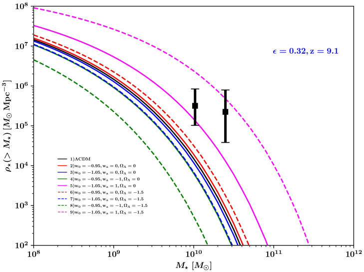
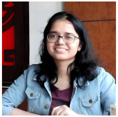


Adil *et al.* (incl. SV), arXiv:2307.12763 (submitted to JCAP)

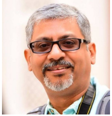
Shahnawaz Adil

(Jamia Millia Islamia)



Upala Mukhopadhyay

(Jamia Millia Islamia)

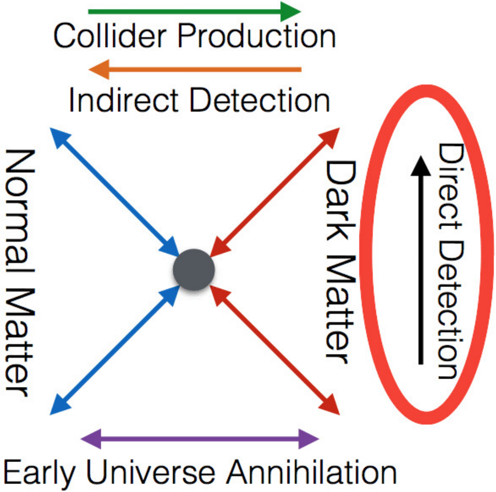


Anjan Sen

(Jamia Millia Islamia)

Part II:
(terrestrial and cosmological) direct detection of dark energy

Are gravitational signatures all there is?



Collider Production

Indirect Detection

Normal Matter

Dark Matter

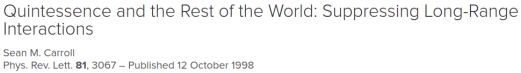
Direct Detection

Early Universe Annihilation

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 [$M \gg M_{\mathrm{Pl}}$]
- 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**!

(At least) 3 ways to screen

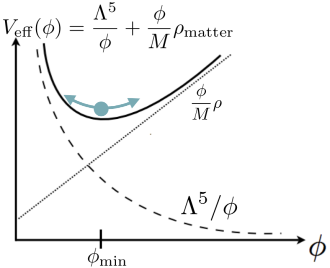
$$F_5 = -\frac{1}{M_5^2(\mathrm{x})} \frac{m_1 m_2}{r^{2-n(\mathrm{x})}} e^{-r/\lambda_5(\mathrm{x})}$$

- $\lambda_5(\mathrm{x}) \rightarrow$ **chameleon** screening (short range in dense environments)
- $M_5(\mathrm{x}) \rightarrow$ symmetron screening (weak coupling in dense environments)
- $n(\mathrm{x}) \rightarrow$ 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

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



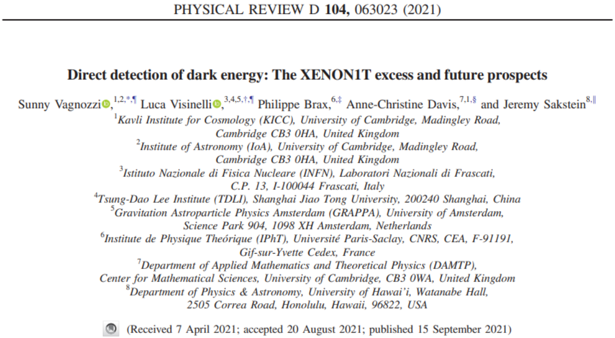
On Earth:

In space:

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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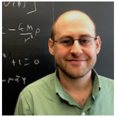


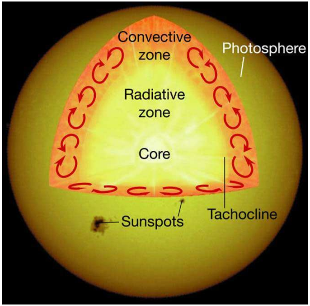
Jeremy Sakstein (Hawaii)

Direct detection of dark energy

Production

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

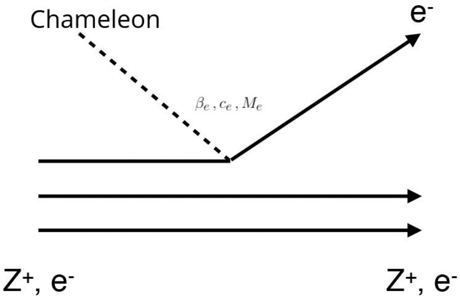
Production in strong magnetic fields of the tachocline



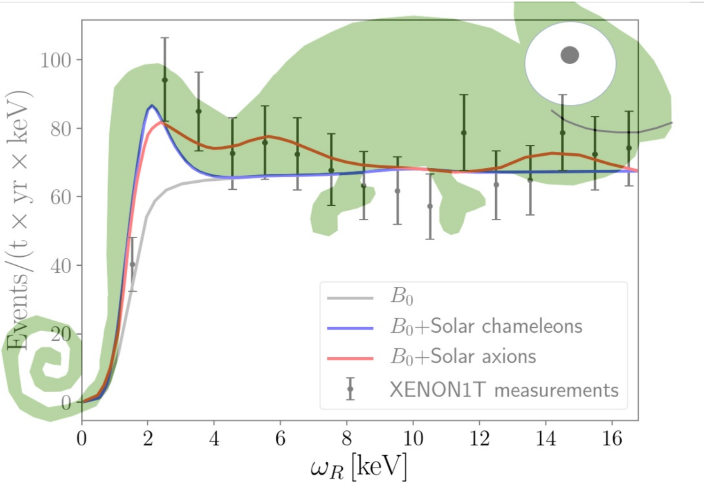
Detection

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

Analogous to photoelectric and axioelectric effects



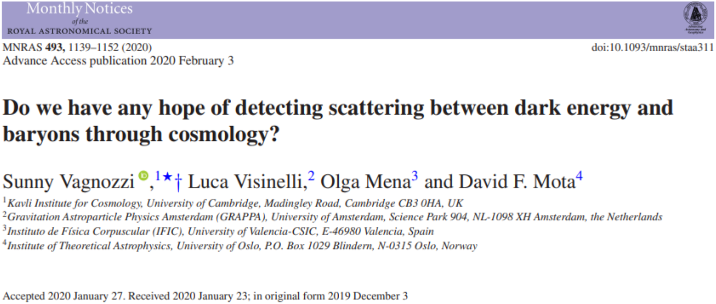
Direct detection of (chameleon-screened) dark energy



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)
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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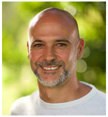
Olga Mena (Valencia)

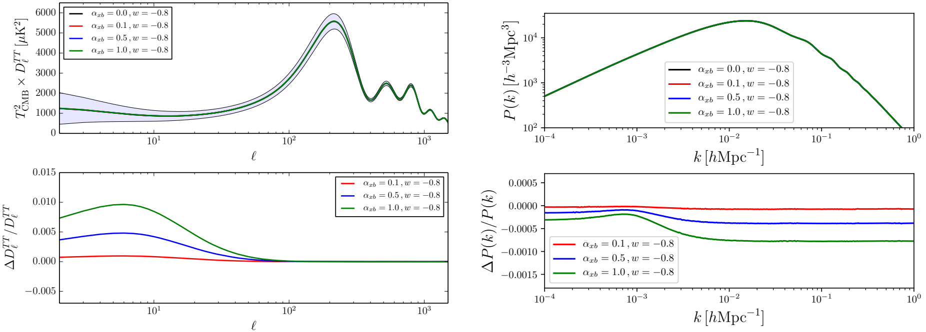


David Mota (Oslo)

Cosmological direct detection of dark energy?

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

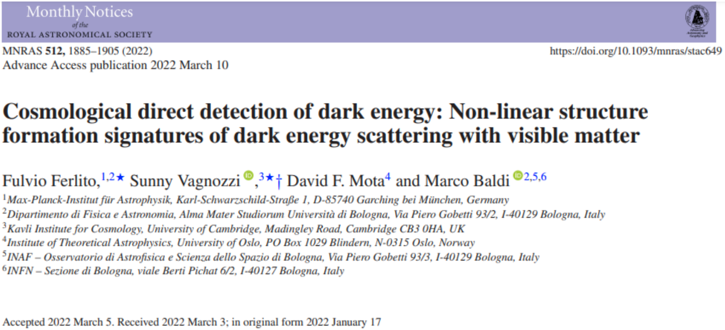
Impact on CMB and *linear* matter power spectrum ($\alpha = \sigma_{xb}/\sigma_T$)



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)
Advance Access publication 2022 March 10

https://doi.org/10.1093/mnras/stac649

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

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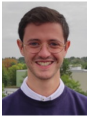
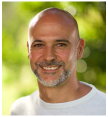


Fulvio Ferlito (MPA Garching)



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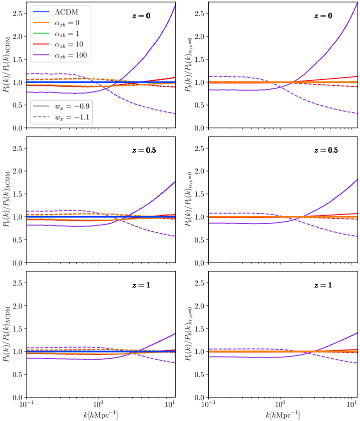
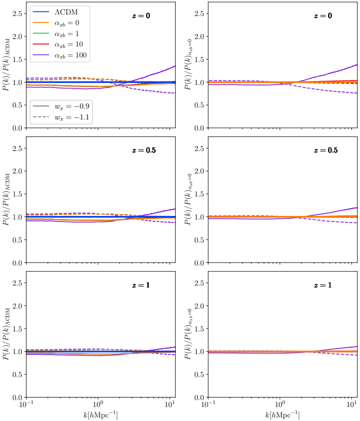
N-body simulations of DE-baryon scattering

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



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



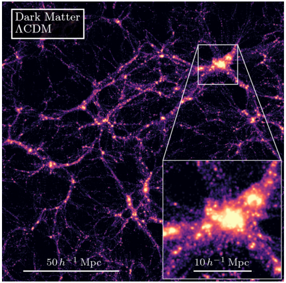
Ferlito, SV, Mota, Baldi, MNRAS 512 (2022) 1885

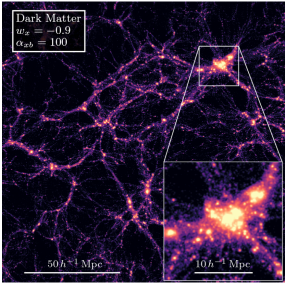
N-body simulations of DE-baryon scattering

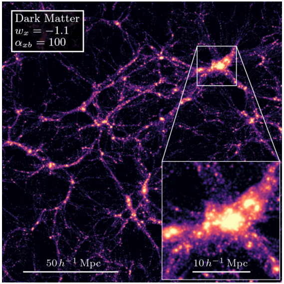
Simulation snapshots:

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

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



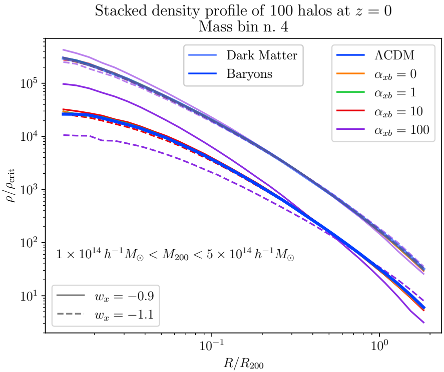




N-body simulations of DE-baryon scattering

Other observables:

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



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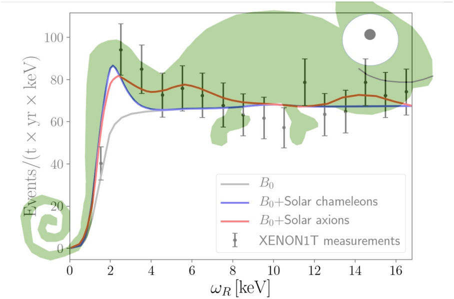
Baryon profiles most promising observable to probe DE-baryon scattering

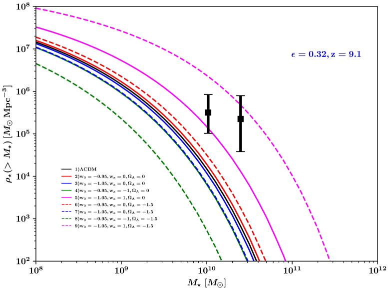
Conclusions

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



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

My cosmological take: Λ will eventually be broken by high-($z \gtrsim 2$) and not low-z data



Adil *et al.* (incl. SV), arXiv:2307.12763 (submitted to JCAP)

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