New probes for new physics

Sunny Vagnozzi

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OKC Colloquium, 28 September 2021

Outline

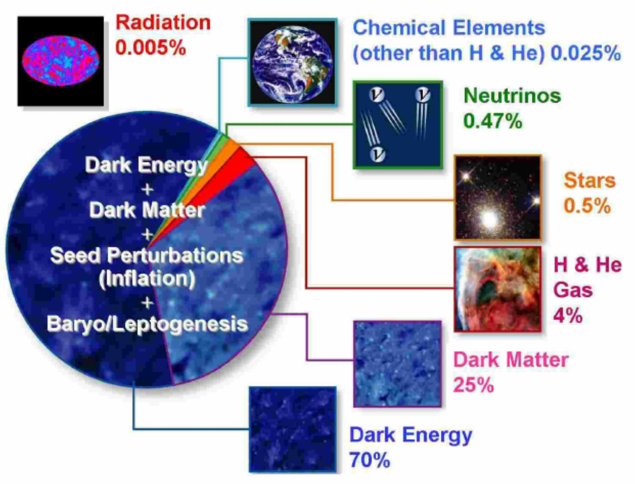
- Dark energy
- Inflation
- Black holes
- Dark matter and new (ultra)light particles
- Cosmic tensions (?)

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

Student's name (student's institution)

Postdoc's name (postdoc's institution)

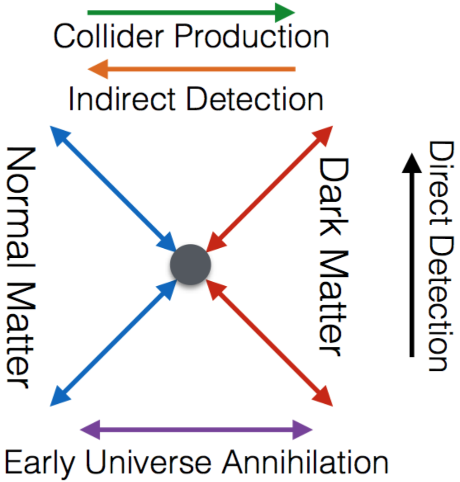
Our dark Universe



Credits: Rocky Kolb

Searching for dark matter

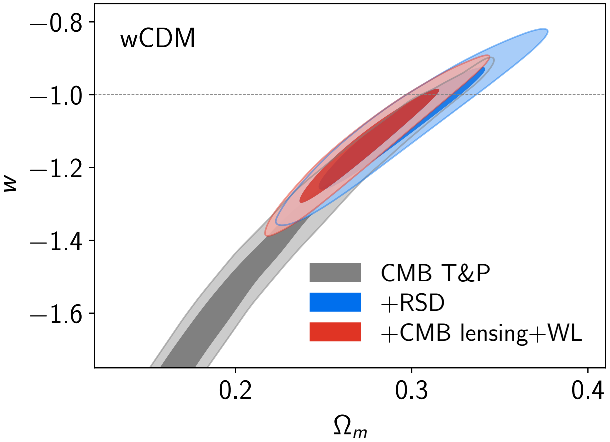
3-pronged approach towards detecting DM's *non-gravitational* signatures



Credits: Matt Buckley

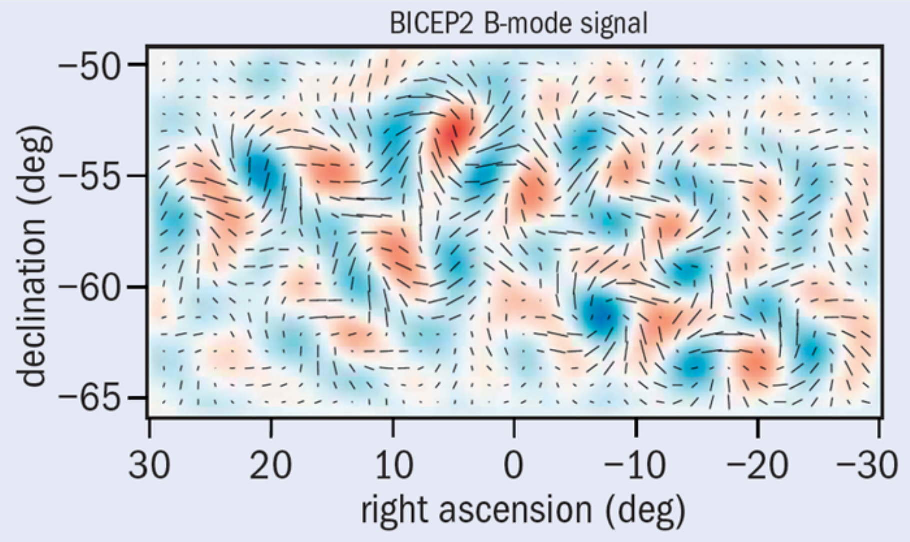
Searching for dark energy's gravitational signatures

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

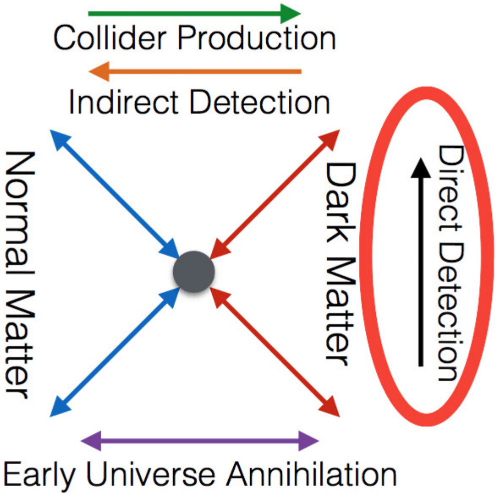
Searching for B-modes from inflation



Credits: BICEP2 collaboration

Part 1: 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**!

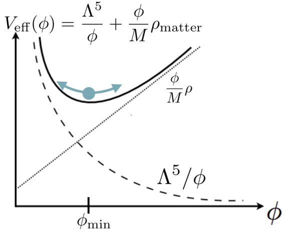
Chameleon screening

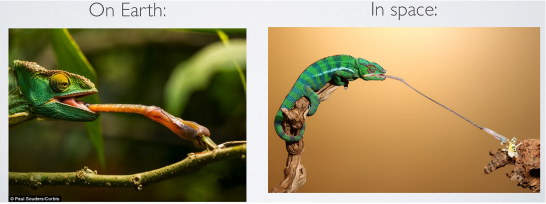
$$F_5 = -\frac{1}{M_5^2(\mathbf{x})}\frac{m_1 m_2}{r^{2-n(\mathbf{x})}} e^{-r/\lambda_5(\mathbf{x})}$$

- $\lambda_5(\mathbf{x}) \to$ **chameleon** screening
- $M_5(\mathbf{x}) \to$ symmetron screening
- $n(\mathbf{x}) \to$ Vainshtein screening

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

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





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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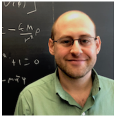
Luca Visinelli (INFN Frascati)

Phil Brax (IPhT, Saclay)

Anne Davis (Cambridge)



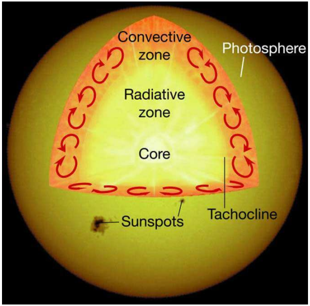
Jeremy Sakstein (Hawaii)

Direct detection of dark energy

Production

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

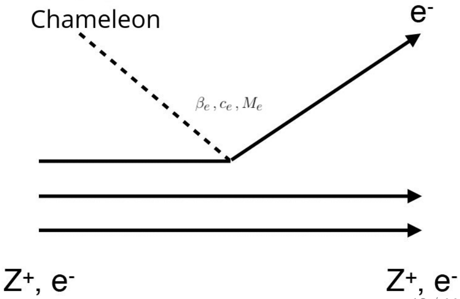
Production in strong magnetic fields of the tachocline



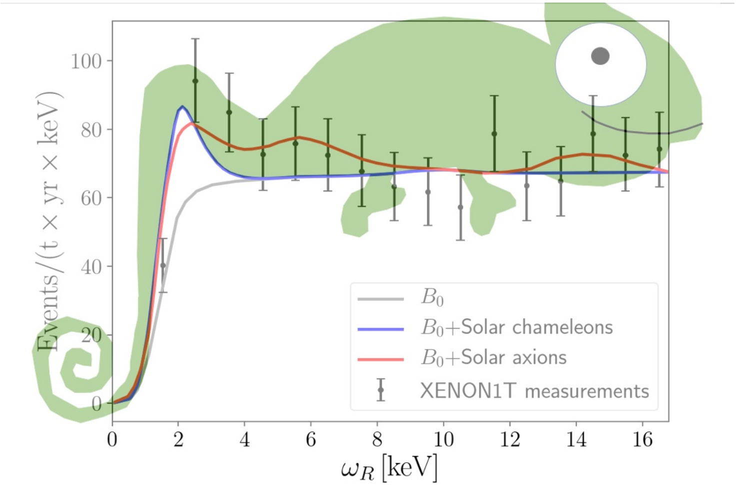
Detection

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

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?

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

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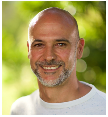
Accepted 2020 January 27. Received 2020 January 23; in original form 2019 December 3

Surprisingly not!


Luca Visinelli (INFN Frascati)


Olga Mena (Valencia)

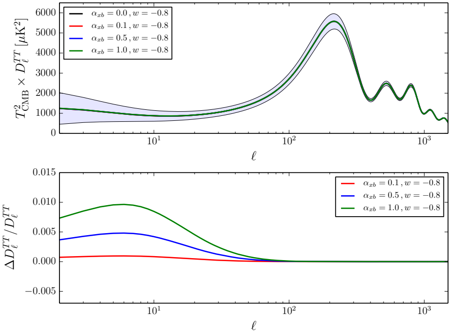

David Mota (Oslo)

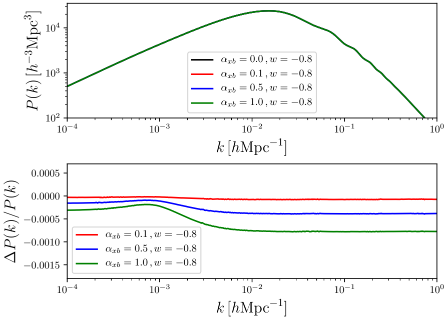
Cosmological direct detection of dark energy?

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

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

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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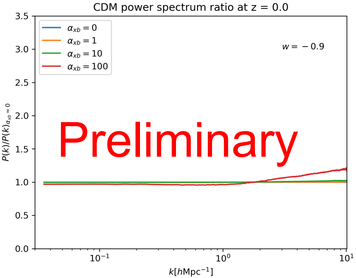
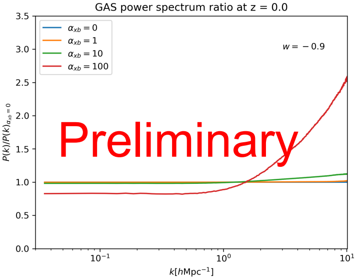


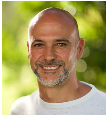
Ferlito, SV, Baldi, Mota, in preparation



Ferlito, SV, Baldi, Mota, in preparation

Fulvio Ferlito (Garching)

Marco Baldi (Bologna)



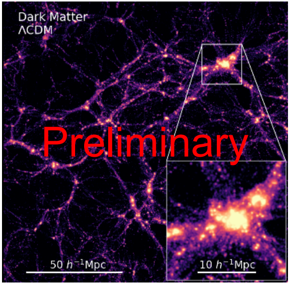
David Mota (Oslo)

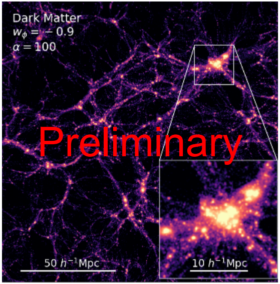
N-body simulations of DE-baryon interactions

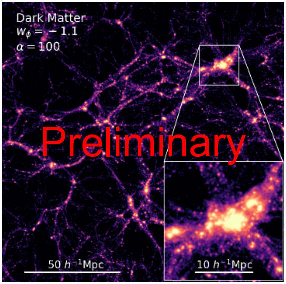
Simulation snapshots:

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

Ferlito, SV, Baldi, Mota, in preparation

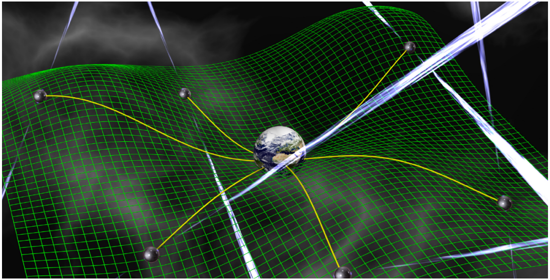






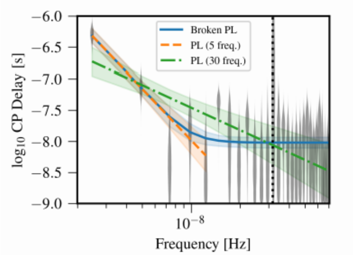
Part 2: Inflation

Pulsar timing arrays



Hints of stochastic GW background detection by NANOGrav (possibly confirmed by PPTA)?

NANOGrav collaboration, ApJ Lett. 905 (2020) L34; PPTA collaboration, ApJ Lett. 917 (2021) L19



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

Sunny Vagnozzi ★†
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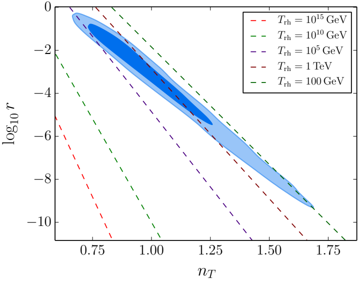
Accepted 2020 December 11. Received 2020 December 8; in original form 2020 October 7

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?

Inflationary gravitational waves from NANOGrav revisited

Micol Benetti,[1,2,3,*] Leila L. Graef,[4,†] and Sunny Vagnozzi[5,‡]
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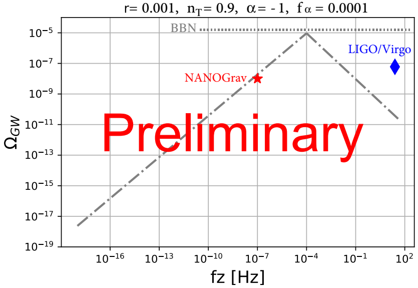
[5]*Kavli Institute for Cosmology (KICC) and Institute of Astronomy, University of Cambridge, Madingley Road, Cambridge CB3 0HA, United Kingdom*

(Dated: September 23, 2021)



Benetti, Graef, SV, in preparation

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 (e.g. gauge field production from $\phi F\tilde{F}$)
- ...

Micol Benetti (Naples)

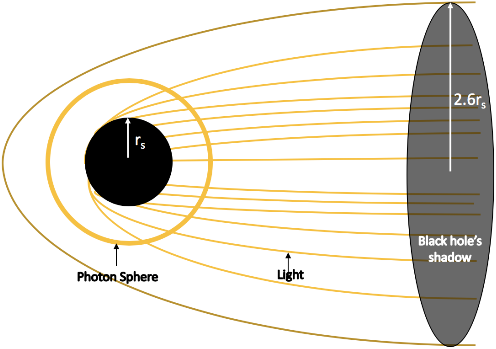
Leila Graef (Fluminense)

Part 3: Black holes

Black hole shadows

For Schwarzschild BH shadow radius $3\sqrt{3}M$

Credits: Event Horizon Telescope collaboration



For advection-dominated hot (geometrically thick optically thin) accretion flow, edge of BH shadow robust to accretion flow details, only influenced by space-time geometry Narayan *et al.*, ApJ Lett. 885 (2019) L33; Bronzwaer & Falcke, arXiv:2108.03966

$\Longrightarrow$ we can use BH shadows to test fundamental physics!

Testing fundamental physics from black hole shadows?

Known information for M87*:

- Diameter of shadow δ, distance to mass ratio D/M
  $\rightarrow d = D\delta/M \sim 11.0 \pm 1.5$
- Deviation from circularity $\Delta C \lesssim 10\%$
- Axis ratio $\Delta y/\Delta x \lesssim 4/3$
- $\epsilon \equiv \Delta Q/Q_{\rm Kerr} \lesssim 4$, $Q_{\rm Kerr} = Ma^2$

Recipe: compute d and ΔC for BHs in your favourite theory, then impose these constraints

Testing the rotational nature of the supermassive object M87* from the circularity and size of its first image

Cosimo Bambi, Katherine Freese, Sunny Vagnozzi, and Luca Visinelli
Phys. Rev. D **100**, 044057 – Published 29 August 2019

Hunting for extra dimensions in the shadow of M87*

Sunny Vagnozzi and Luca Visinelli
Phys. Rev. D **100**, 024020 – Published 12 July 2019

Magnetically charged black holes from non-linear electrodynamics and the Event Horizon Telescope

Alireza Allahyari[1], Mohsen Khodadi[1], Sunny Vagnozzi[2] and David F. Mota[3]
Published 4 February 2020 • © 2020 IOP Publishing Ltd and Sissa Medialab
Journal of Cosmology and Astroparticle Physics, Volume 2020, February 2020
Citation Alireza Allahyari *et al* JCAP02(2020)003

Concerns regarding the use of black hole shadows as standard rulers

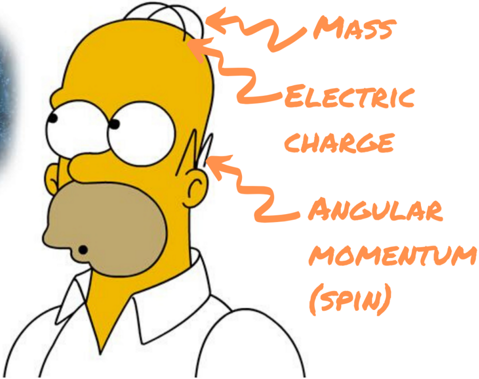
Sunny Vagnozzi[4,1], Cosimo Bambi[2] and Luca Visinelli[3]
Published 25 March 2020 • © 2020 IOP Publishing Ltd
Classical and Quantum Gravity, Volume 37, Number 8
Citation Sunny Vagnozzi *et al* 2020 *Class. Quantum Grav.* **37** 087001

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

Mohsen Khodadi[1], Alireza Allahyari[1], Sunny Vagnozzi[2] and David F. Mota[3]
Published 14 September 2020 • © 2020 IOP Publishing Ltd and Sissa Medialab
Journal of Cosmology and Astroparticle Physics, Volume 2020, September 2020
Citation Mohsen Khodadi *et al* JCAP09(2020)026

The no-hair theorem

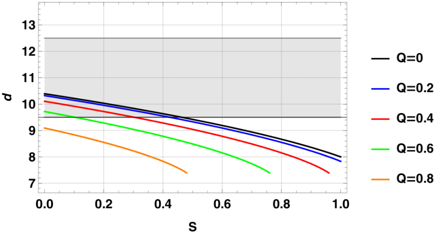
Black holes have at most three hairs ($3 \approx 0$)



Credits: Medium.com

An example of no-hair theorem violation

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



Journal of Cosmology and Astroparticle Physics
An IOP and SISSA journal

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

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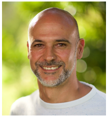
Alireza Allahyari (KIAA Beijing)



David Mota (Oslo)

Part 4: Dark matter and new (ultra)light particles

Superradiance-induced black hole shadow evolution

Superradiance evolution of black hole shadows revisited

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

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[4] *Gravitation Astroparticle Physics Amsterdam (GRAPPA), University of Amsterdam, Science Park 904, 1098 XH Amsterdam, The Netherlands*
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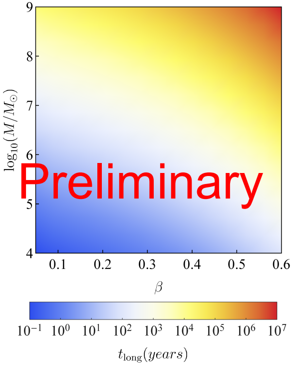


Evolution in shadow size $\Delta\theta \sim \mathcal{O}(1)\mu\text{as}$ due to superradiance potentially observable on human timescales $[\mathcal{O}(10)\,\text{yr}]$

Rittick Roy

(Fudan)

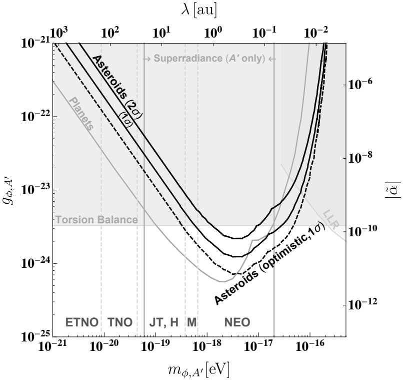
Luca Visinelli

(INFN Frascati)

Roy, SV, Visinelli, in preparation

Precession of planetary objects and new light particles

Precession from new light (gauged) mediators-induced fifth force



Tsai, Wu, SV, Visinelli, arXiv:2107.04038

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

Yu-Dai Tsai,[1,2,*] Youjia Wu,[3,†] Sunny Vagnozzi,[4,‡] and Luca Visinelli[5,6,§]

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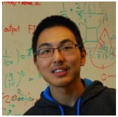
- Planetary objects: asteroids, (exo)planets, TNOs
- Competitive with torsion balance tests

Yu-Dai Tsai (Fermilab/KICP, Chicago)

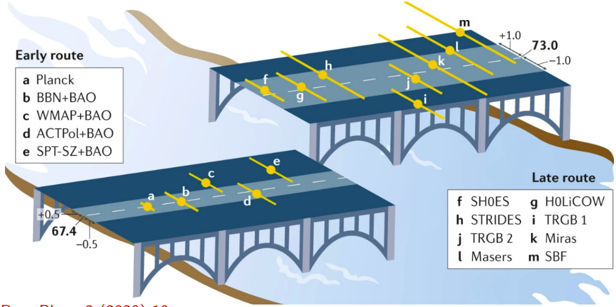


Youjia Wu (Michigan)

Luca Visinelli (INFN Frascati)

Part 5: Cosmic tensions (?)

Viewing the Hubble tension ocean with different eyeglasses



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

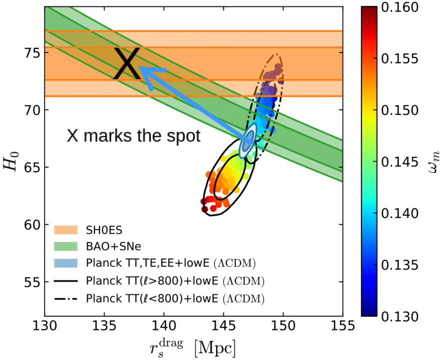
Why does ΛCDM fit data so well? Do we really need new physics? If so, at what time(s), and with what ingredients?

Early times: early ISW effect $\Longleftrightarrow$ *Consistency tests of ΛCDM* $\Longleftrightarrow$ *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 ≈ 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

Sunny Vagnozzi*
Kavli Institute for Cosmology (KICC) and Institute of Astronomy, University of Cambridge, Madingley Road, Cambridge CB3 0HA, United Kingdom

(Received 15 June 2021; accepted 22 July 2021; published 15 September 2021)

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

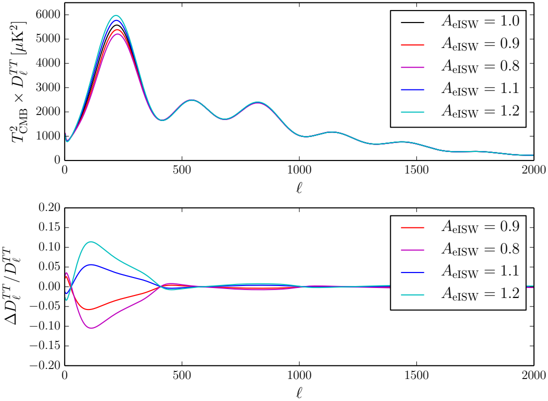
$$\Theta_\ell^{\text{ISW}}(k) = \underbrace{\int_0^{\eta_m} d\eta \, e^{-\tau} \left(\dot{\Psi} - \dot{\Phi}\right) j_\ell(k\Delta\eta)}_{\text{early ISW}} + \underbrace{\int_{\eta_m}^{\eta_0} d\eta \, e^{-\tau} \left(\dot{\Psi} - \dot{\Phi}\right) j_\ell(k\Delta\eta)}_{\text{late ISW}}$$

(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

Introduce scaling amplitude/fudge factor A_{eISW}:

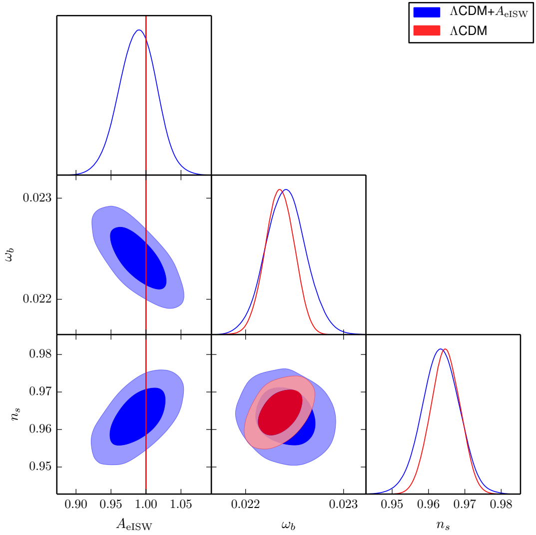
$$\Theta_\ell^{\mathrm{eISW}}(k) = A_{\mathrm{eISW}} \int_0^{\eta_m} d\eta\, e^{-\tau} \left(\dot{\Psi} - \dot{\Phi}\right) j_\ell(k\Delta\eta)$$



SV, PRD 104 (2021) 063524

eISW consistency test

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



Yes!

Parameter	*Planck*	
	ΛCDM	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

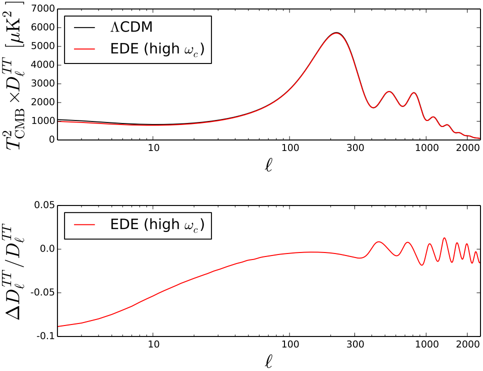
High H_0 EDE fit to CMB at cost of ω_c increase $\to$ worsens S_8 tension with WL/LSS data? Hill *et al.*, PRD 102 (2020) 043507; Ivanov *et al.*, PRD 102 (2020) 103502; D'Amico *et al.*, JCAP 2105 (2021) 072; partial rebuttals in: Murgia *et al.*, PRD 103 (2021) 063502; Smith *et al.*, PRD 103 (2021) 123542

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

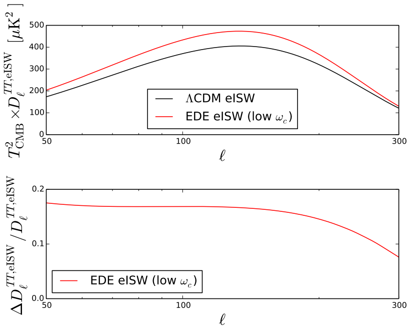


SV, PRD 104 (2021) 063524

Implications for early-time new physics: EDE case study

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

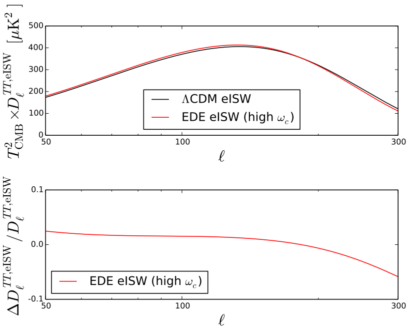
Low ω_c



SV, PRD 104 (2021) 063524

Almost 20% eISW excess!

High ω_c



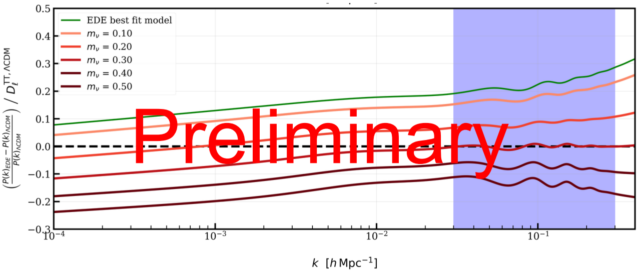
SV, PRD 104 (2021) 063524

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

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

Solving early dark energy's problems beyond ΛCDM?

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



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

Neutrinos actually turn out not to work – other possible ingredients: decaying DM, DM-dark radiation interactions (work in progress)

Alex Reeves (Cambridge → ETH)

Blake Sherwin (Cambridge)

George Efstathiou (Cambridge)

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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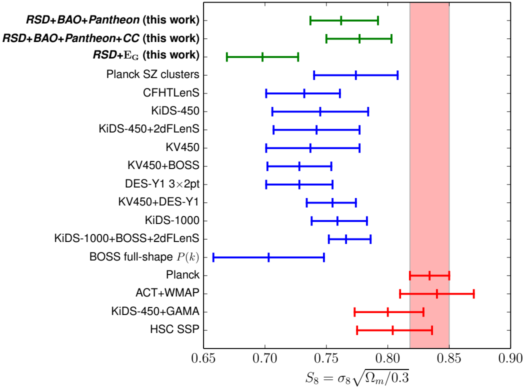
[2]*Kavli Institute for Cosmology (KICC), University of Cambridge, Madingley Road, Cambridge CB3 0HA, UK*



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

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

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,‡]
[1]*Kavli Institute for Cosmology (KICC) and Institute of Astronomy, University of Cambridge, Madingley Road, Cambridge CB3 0HA, United Kingdom*
[2]*Center for Astrophysics | Harvard & Smithsonian, Cambridge, MA 02138, USA*
[3]*Black Hole Initiative, Harvard University, Cambridge, MA 02138, USA*

$$t_U(z) = \int_z^\infty \frac{dz'}{(1+z')H(z')} \propto \frac{1}{H_0}$$

Pros and cons:

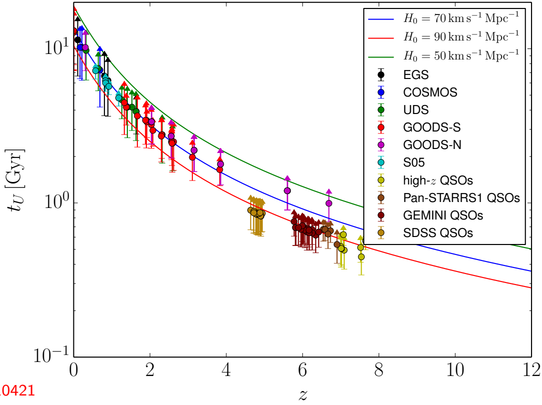
- OAO cannot be older than the Universe $\rightarrow$ **upper limit on $\mathbf{H_0}$**
- $t_U(z)$ integral insensitive to early-time cosmology
- $\implies$ **early-time-independent ΛCDM consistency test**!
- Ages of astrophysical objects at $z > 0$ hard to estimate robustly ⚠

Fabio Pacucci (Harvard)

Avi Loeb (Harvard)

OAO age-redshift diagram

Age-redshift diagram up to $z \sim 8$ (galaxy ages estimated mostly by CANDELS team via SED fitting)

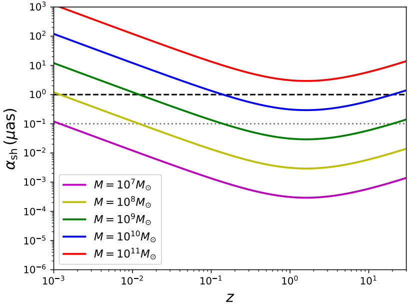


SV *et al.*, arXiv:2105.10421

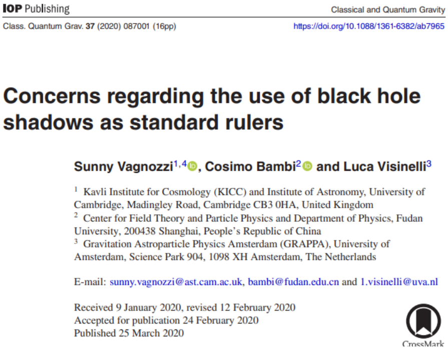
$H_0 < 73.2\,\mathrm{km/s/Mpc}$ (95% C.L.) $\rightarrow$ hints for some amount of late-time new physics (in relation to the H_0 tension)?

Black hole shadows as standard rulers?

$$\alpha_{\rm sh}(z) \simeq \frac{3\sqrt{3}M}{D_A(z)}$$



SV *et al.*, CQG 37 (2020) 087001



IOP Publishing — Classical and Quantum Gravity

Class. Quantum Grav. **37** (2020) 087001 (16pp) https://doi.org/10.1088/1361-6382/ab7965

Concerns regarding the use of black hole shadows as standard rulers

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[3] Gravitation Astroparticle Physics Amsterdam (GRAPPA), University of Amsterdam, Science Park 904, 1098 XH Amsterdam, The Netherlands

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Received 9 January 2020, revised 12 February 2020
Accepted for publication 24 February 2020
Published 25 March 2020

CrossMark

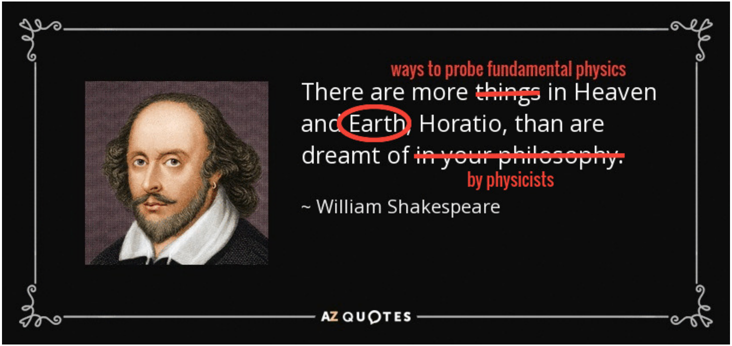
Cosimo Bambi (Fudan)

Luca Visinelli (INFN Frascati)

Problems:

- Reliably determining M
- Model-dependence (beyond GR)
- Understand high-z SMBHs well?

Conclusions



Tack för uppmärksamheten!