New probes for new physics

Sunny Vagnozzi

Newton-Kavli Fellow @ KICC, University of Cambridge

sunny.vagnozzi@ast.cam.ac.uk www.sunnyvagnozzi.com

RAMSIA-2022, GLA University, Mathura
23 June 2022

Outline

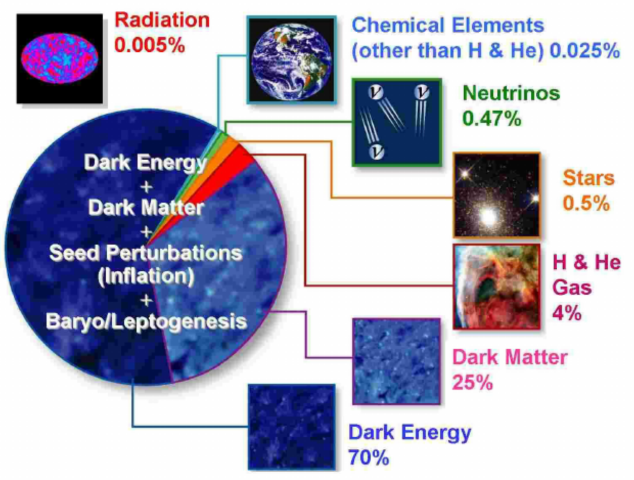
- Dark energy
- Inflation
- Black holes
- Dark matter and new (ultra)light particles
- Cosmic tensions (?)

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

Student's name (student's institution)

Postdoc's name (postdoc's institution)

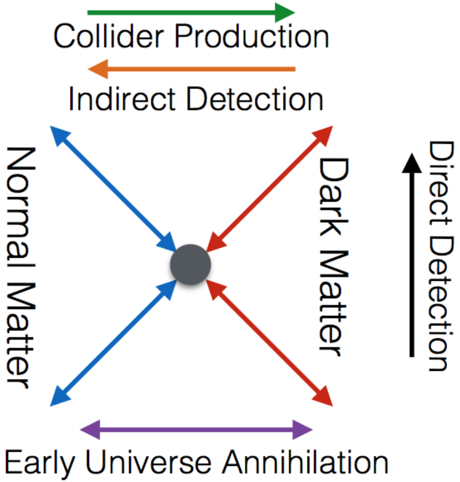
Our dark Universe



Credits: Rocky Kolb

Searching for dark matter

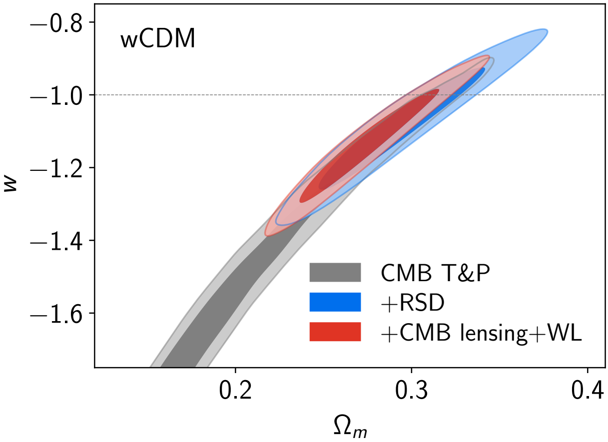
3-pronged approach towards detecting DM's *non-gravitational* signatures



Credits: Matt Buckley

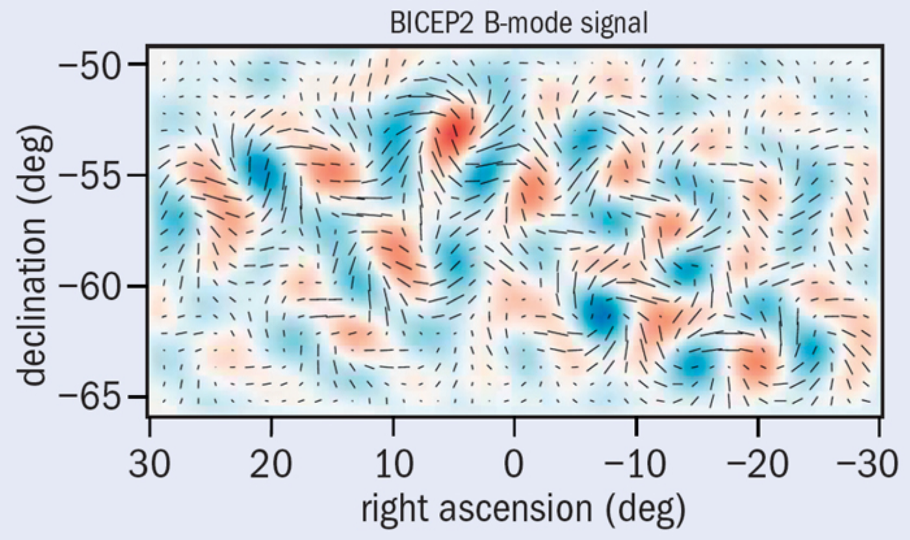
Searching for dark energy's gravitational signatures

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

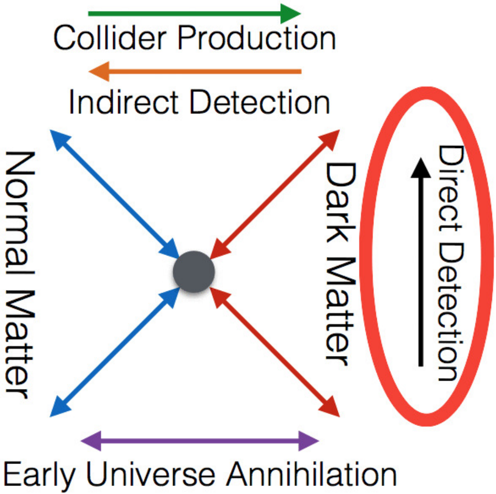
Searching for B-modes from inflation



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

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

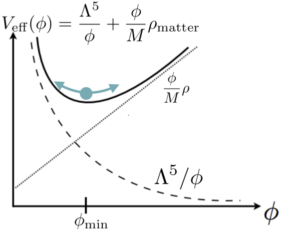
- Tune the coupling to be extremely weak [$M \gg M_{\mathrm{Pl}}$]
- Tune the range to be extremely short [$\lambda \ll \mathcal{O}(\mathrm{mm})$]
- Tune the dynamics so the force weakens based on its environment $\longrightarrow$ **screening**!

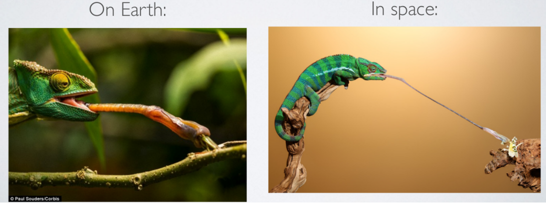
Chameleon screening

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

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

$$V_{\rm eff} = V(\phi) + \phi\rho_m/M$$
$$m_{\rm eff}^2 = \frac{d^2 V_{\rm eff}}{d\phi^2}\Big|_{\phi=\phi_{\rm min}} \propto \rho_m^n \, , n > 0$$





Credits: Ben Elder

Direct detection of dark energy

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

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

Direct detection of dark energy: The XENON1T excess and future prospects

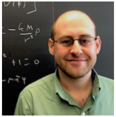
Sunny Vagnozzi,[1,2,*,¶] Luca Visinelli,[3,4,5,†,¶] Philippe Brax,[6,‡] Anne-Christine Davis,[7,1,§] and Jeremy Sakstein[8,‖]
[1]*Kavli Institute for Cosmology (KICC), University of Cambridge, Madingley Road, Cambridge CB3 0HA, United Kingdom*
[2]*Institute of Astronomy (IoA), University of Cambridge, Madingley Road, Cambridge CB3 0HA, United Kingdom*
[3]*Istituto Nazionale di Fisica Nucleare (INFN), Laboratori Nazionali di Frascati, C.P. 13, I-100044 Frascati, Italy*
[4]*Tsung-Dao Lee Institute (TDLI), Shanghai Jiao Tong University, 200240 Shanghai, China*
[5]*Gravitation Astroparticle Physics Amsterdam (GRAPPA), University of Amsterdam, Science Park 904, 1098 XH Amsterdam, Netherlands*
[6]*Institute de Physique Theórique (IPhT), Université Paris-Saclay, CNRS, CEA, F-91191, Gif-sur-Yvette Cedex, France*
[7]*Department of Applied Mathematics and Theoretical Physics (DAMTP), Center for Mathematical Sciences, University of Cambridge, CB3 0WA, United Kingdom*
[8]*Department of Physics & Astronomy, University of Hawai'i, Watanabe Hall, 2505 Correa Road, Honolulu, Hawaii, 96822, USA*

(Received 7 April 2021; accepted 20 August 2021; published 15 September 2021)


Luca Visinelli (Shanghai)


Phil Brax (IPhT, Saclay)


Anne Davis (Cambridge)

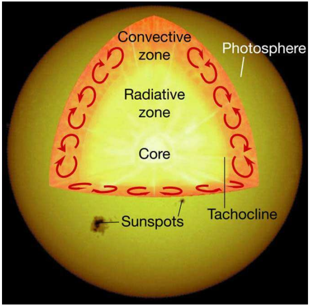

Jeremy Sakstein (Hawaii)

Direct detection of dark energy

Production

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

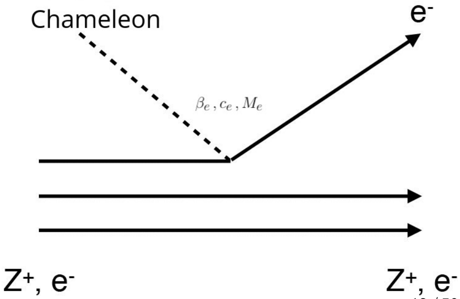
Production in strong magnetic fields of the tachocline



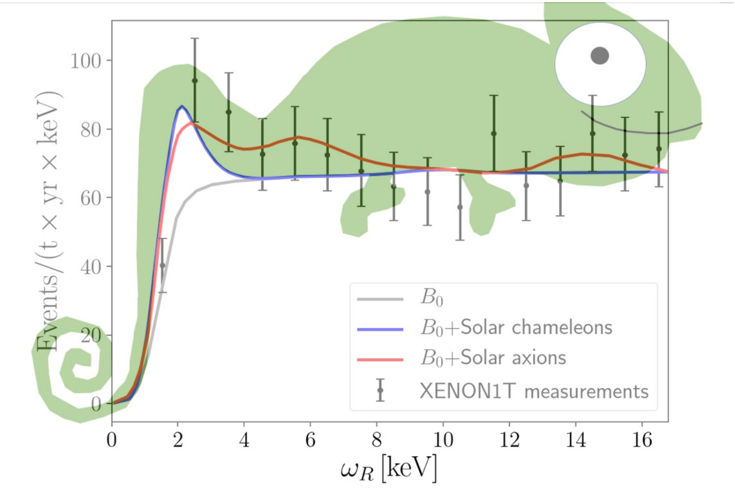
Detection

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

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]

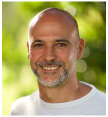
[1] *Kavli Institute for Cosmology, University of Cambridge, Madingley Road, Cambridge CB3 0HA, UK*
[2] *Gravitation Astroparticle Physics Amsterdam (GRAPPA), University of Amsterdam, Science Park 904, NL-1098 XH Amsterdam, the Netherlands*
[3] *Instituto de Física Corpuscular (IFIC), University of Valencia-CSIC, E-46980 Valencia, Spain*
[4] *Institute of Theoretical Astrophysics, University of Oslo, P.O. Box 1029 Blindern, N-0315 Oslo, Norway*

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

Surprisingly not!

Luca Visinelli (Shanghai)

Olga Mena (Valencia)



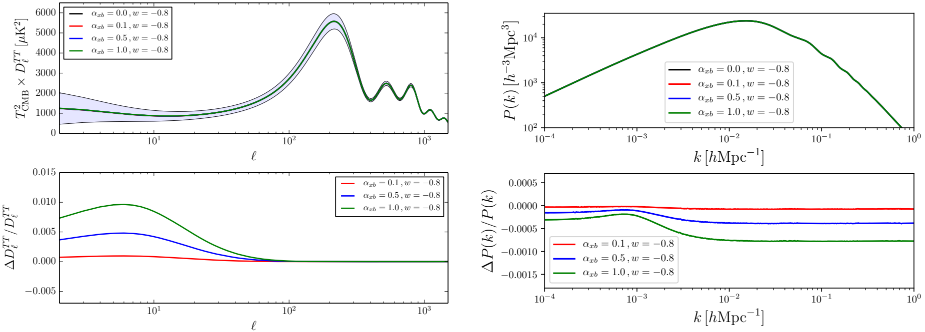
David Mota (Oslo)

Cosmological direct detection of dark energy?

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

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

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 scattering

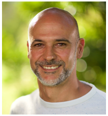
What about the non-linear regime?

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. Mota[4] and Marco Baldi[2,5,6]
[1]*Max-Planck-Institut für Astrophysik, Karl-Schwarzschild-Straße 1, D-85740 Garching bei München, Germany*
[2]*Dipartimento di Fisica e Astronomia, Alma Mater Studiorum Università di Bologna, Via Piero Gobetti 93/2, I-40129 Bologna, Italy*
[3]*Kavli Institute for Cosmology, University of Cambridge, Madingley Road, Cambridge CB3 0HA, UK*
[4]*Institute of Theoretical Astrophysics, University of Oslo, PO Box 1029 Blindern, N-0315 Oslo, Norway*
[5]*INAF – Osservatorio di Astrofisica e Scienza dello Spazio di Bologna, Via Piero Gobetti 93/3, I-40129 Bologna, Italy*
[6]*INFN – 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)


David Mota (Oslo)

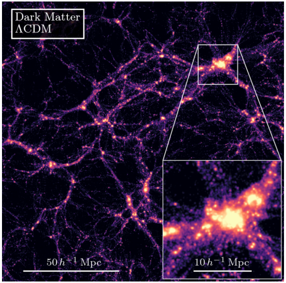

Marco Baldi (Bologna)

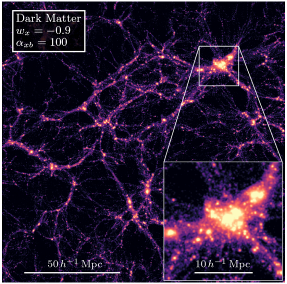
N-body simulations of DE-baryon scattering

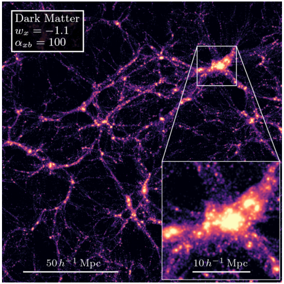
Simulation snapshots:

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

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

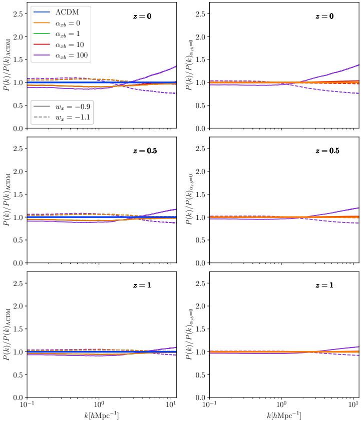




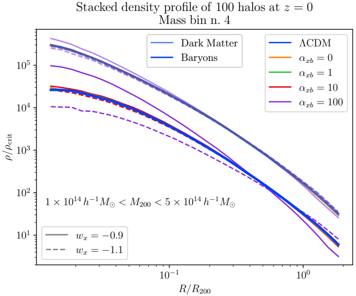


N-body simulations of DE-baryon scattering

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



Baryon fraction profiles (combine lensing, kSZ, and tSZ)



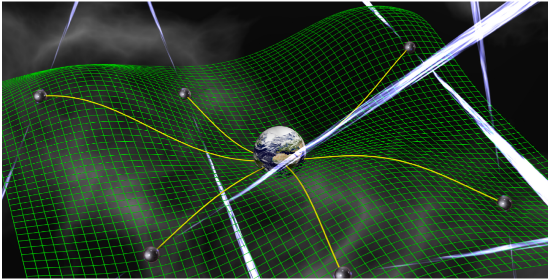
Other observables:

- (Cumulative) halo mass function
- (Stacked) halo density profiles
- Future work: Bullet-like systems

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

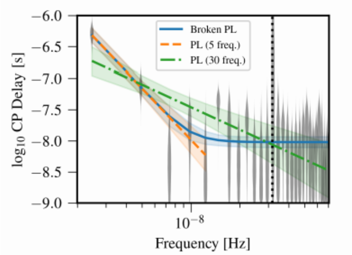
Part 2: Inflation

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?

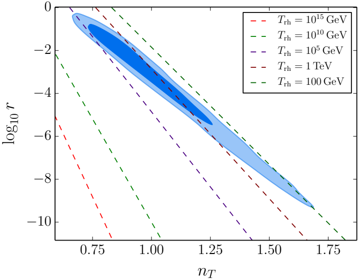
Monthly Notices of the ROYAL ASTRONOMICAL SOCIETY
MNRAS **502,** L11–L15 (2021) doi:10.1093/mnrasl/slaa203
Advance Access publication 2020 December 21

Implications of the NANOGrav results for inflation

Sunny Vagnozzi ★†
Kavli Institute for Cosmology, University of Cambridge, Madingley Road, Cambridge CB3 0HA, UK

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

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



SV, MNRAS Lett. 502 (2021) L11

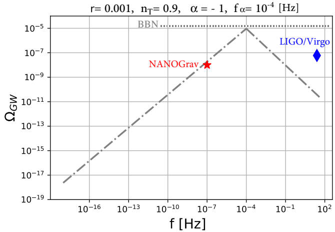
- Very blue spectrum, $n_T \sim 1 \rightarrow$, violates consistency relation $r = -8n_T$, cannot come from single-field slow-roll inflation
- Very low reheating temperature, $T_{\rm rh} \lesssim \mathcal{O}(\text{TeV})$

Did NANOGrav see inflationary GWs?

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

Micol Benetti,[1,2,*] Leila L. Graef,[3,†] and Sunny Vagnozzi[4,‡]
[1]*Scuola Superiore Meridionale (SSM), Università di Napoli "Federico II," Largo San Marcellino 10, I-80138 Napoli, Italy*
[2]*Istituto Nazionale di Fisica Nucleare (INFN), Sezione di Napoli, Via Cinthia 9, I-80126 Napoli, Italy*
[3]*Instituto de Física, Universidade Federal Fluminense, Avenida General Milton Tavares de Souza s/n, Gragoatá, 24210-346 Niterói, Rio de Janeiro, Brazil*
[4]*Kavli Institute for Cosmology (KICC) and Institute of Astronomy, University of Cambridge, Madingley Road, Cambridge CB3 0HA, United Kingdom*

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



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

Broken power-law spectrum can mimic:

- Non-standard pre-BBN era ($w \neq 1/3$: early matter domination, kination,...)
- Late-time entropy production
- Change in n_T associated to blue GW generation mechanism (e.g. gauge field production from $\phi F\tilde{F}$)
- ...

Micol Benetti (Naples)

Leila Graef (Fluminense)

The swampland

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

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

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

[1] The Oskar Klein Centre for Cosmoparticle Physics, Department of Physics, Stockholm University, Roslagstullsbacken 21A, 10691 Stockholm, Sweden
[2] Department of Physics, University at Buffalo, Buffalo, NY 14260, United States of America
[3] The Nordic Institute for Theoretical Physics (NORDITA), Roslagstullsbacken 23, 10691 Stockholm, Sweden
[4] Department of Physics and Astronomy, Uppsala University, Lägerhyddsvägen 1, 75120 Uppsala, Sweden

E-mail: whkinney@buffalo.edu, sunny.vagnozzi@fysik.su.se and luca.visinelli@physics.uu.se

Received 25 January 2019, revised 25 March 2019
Accepted for publication 29 April 2019
Published 13 May 2019

CrossMark

Quite possibly, at least for the simplest inflationary models!

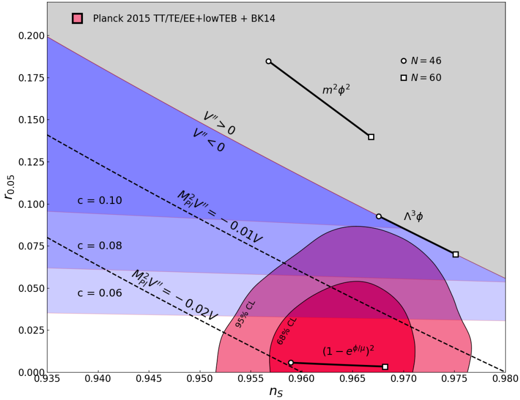
Will Kinney (SUNY Buffalo)

Luca Visinelli (Shanghai)

Are inflation and string theory incompatible?

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

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



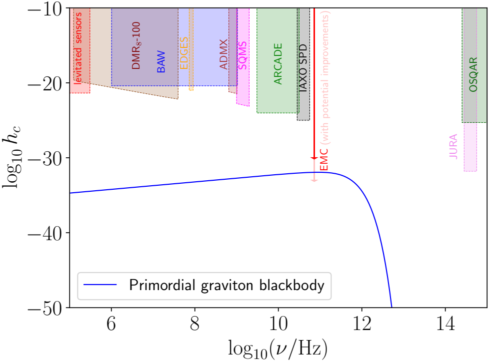
Kinney, SV, Visinelli, CQG 36 (2019) 117001

Ruling out inflation via the cosmic graviton background?

The challenge of ruling out inflation via the primordial graviton background

Sunny Vagnozzi[1] and Abraham Loeb[2]

[1] Kavli Institute for Cosmology, University of Cambridge, Madingley Road, Cambridge CB3 0HA, United Kingdom
[2] Department of Astronomy, Harvard University, 60 Garden Street, Cambridge, MA 02138, USA



Vagnozzi & Loeb, under review in ApJ Lett.

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

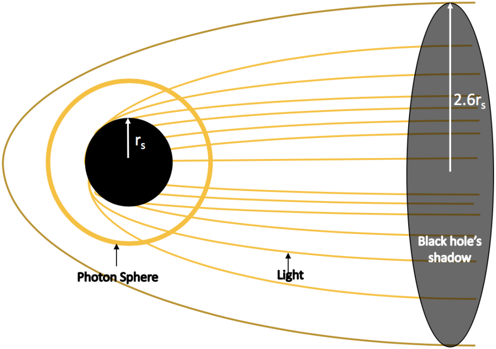
Avi Loeb (Harvard)

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, ApJ 920 (2021) 155

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

Testing fundamental physics from M87*'s shadow?

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

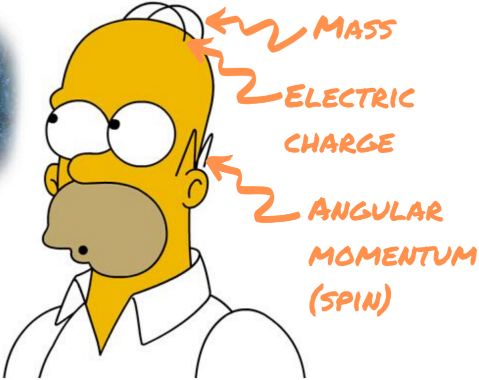
Sunny Vagnozzi[4,1], Cosimo Bambi[2] and Luca Visinelli[3]
Published 25 March 2020 • © 2020 IOP Publishing Ltd
Classical and Quantum Gravity, Volume 37, Number 8
Citation Sunny Vagnozzi *et al* 2020 *Class. Quantum Grav.* **37** 087001

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

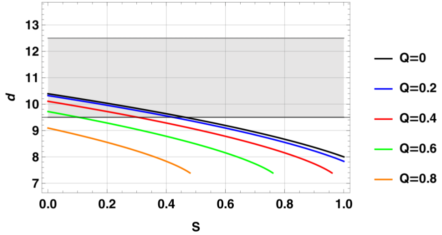
Black holes have at most three hairs ($3 \approx 0$)



Credits: Medium.com

An example of no-hair theorem violation

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



Journal of Cosmology and Astroparticle Physics
An IOP and SISSA journal

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

Mohsen Khodadi,[a] Alireza Allahyari,[a] Sunny Vagnozzi[b] and David F. Mota[c]

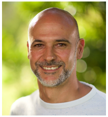
[a]School of Astronomy, Institute for Research in Fundamental Sciences (IPM), P.O. Box 19395-5531, Tehran, Iran
[b]Kavli Institute for Cosmology (KICC) and Institute of Astronomy, University of Cambridge, Madingley Road, Cambridge CB3 0HA, U.K.
[c]Institute of Theoretical Astrophysics, University of Oslo, P.O. Box 1029 Blindern, N-0315 Oslo, Norway

E-mail: m.khodadi@ipm.ir, alireza.al@ipm.ir, sunny.vagnozzi@ast.cam.ac.uk, d.f.mota@astro.uio.no

Received May 18, 2020
Accepted August 8, 2020
Published September 14, 2020

Mohsen Khodadi (IPM Tehran)

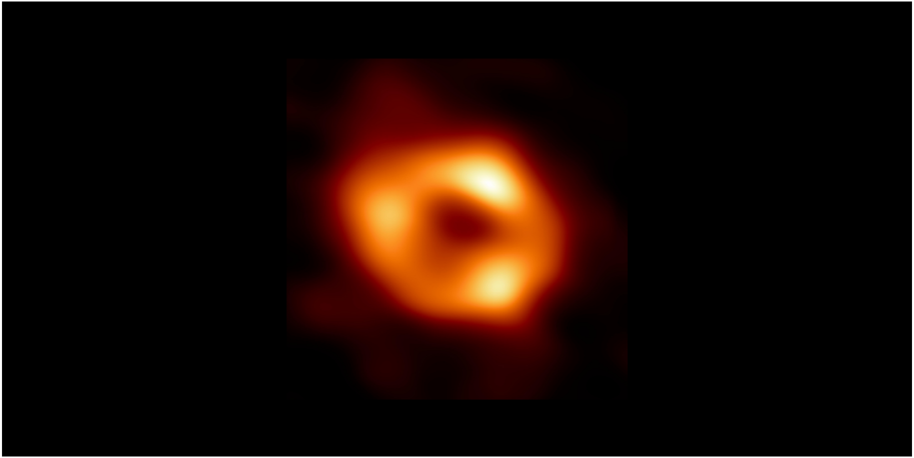
Alireza Allahyari (Kharazmi)



David Mota (Oslo)

Sagittarius A*

Supermassive BH at the center of the Milky Way



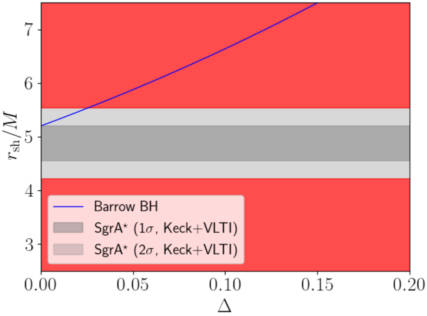
Credits: Event Horizon Telescope collaboration

Fundamental physics tests from Sagittarius A*'s shadow

Horizon-scale tests of gravity theories and fundamental physics from the Event Horizon Telescope image of Sagittarius A*

Sunny Vagnozzi,[1,*] Rittick Roy,[2,†] Yu-Dai Tsai,[3,‡] and Luca Visinelli[4,5,§]
[1] *Kavli Institute for Cosmology (KICC) and Institute of Astronomy, University of Cambridge, Madingley Road, Cambridge CB3 0HA, United Kingdom*
[2] *Center for Field Theory and Particle Physics and Department of Physics, Fudan University, 200438 Shanghai, P. R. China*
[3] *Department of Physics and Astronomy, University of California, Irvine, CA 92697-4575, USA*
[4] *Tsung-Dao Lee Institute (TDLI), 520 Shengrong Road, 201210 Shanghai, P. R. China*
[5] *School of Physics and Astronomy, Shanghai Jiao Tong University, 800 Dongchuan Road, 200240 Shanghai, P. R. China*
(Dated: May 17, 2022)

Example: Barrow entropy $S = (A/4)^{1+\Delta/2}$



Studied 20+ fundamental physics scenarios (hairy BHs, gravity theories, wormholes, naked singularities, modified entropies,...)


Rittick Roy (Fudan)


Yu-Dai Tsai (UC Irvine)


Luca Visinelli (Shanghai)

SV, Roy, Tsai, Visinelli, arXiv:2205.07787

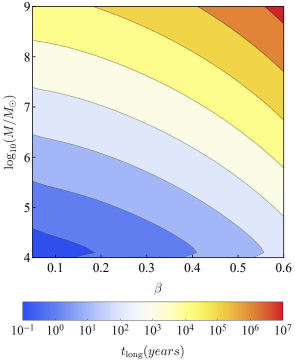
Part 4: Dark matter and new (ultra)light particles

Superradiance-induced black hole shadow evolution

Superradiance evolution of black hole shadows revisited

Rittick Roy[1,*] Sunny Vagnozzi[2,†] and Luca Visinelli[3,4,‡]
[1]Center for Field Theory and Particle Physics and Department of Physics, Fudan University, 200438 Shanghai, People's Republic of China
[2]Kavli Institute for Cosmology (KICC) and Institute of Astronomy, University of Cambridge, Madingley Road, Cambridge CB3 0HA, United Kingdom
[3]Tsung-Dao Lee Institute (TDLI) and School of Physics and Astronomy, Shanghai Jiao Tong University, 200240 Shanghai, People's Republic of China
[4]INFN, Laboratori Nazionali di Frascati, C.P. 13, 100044 Frascati, Italy

(Received 19 December 2021; accepted 15 March 2022; published 12 April 2022)



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

Rittick Roy

(Fudan)

Luca Visinelli

(Shanghai)

Roy, SV, Visinelli, PRD 105 (2022) 083002

Superradiance-induced black hole shadow evolution

Superradiant evolution of the shadow and photon ring of Sgr A*

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

[1] *CAS Key Laboratory of Theoretical Physics, Institute of Theoretical Physics, Chinese Academy of Sciences, 100190 Beijing, P. R. China*

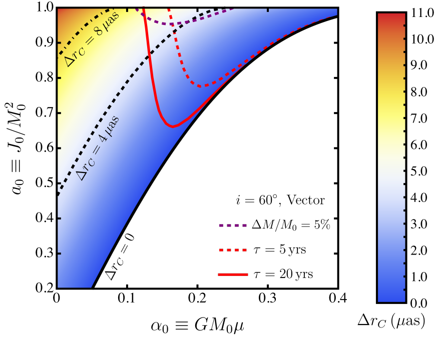
[2] *Center for Field Theory and Particle Physics and Department of Physics, Fudan University, 200438 Shanghai, P. R. China*

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

[4] *Tsung-Dao Lee Institute (TDLI), 520 Shengrong Road, 201210 Shanghai, P. R. China*

[5] *School of Physics and Astronomy, Shanghai Jiao Tong University, 800 Dongchuan Road, 200240 Shanghai, P. R. China*

(Dated: May 13, 2022)



Chen, Roy, SV, Visinelli, arXiv:2205.06238 (under review in PRL)

- Vector and tensor superradiance more easily observable!
- Potentially cleaner signatures in the photon ring auto-correlation

Yifan Chen

(Beijing)

Rittick Roy

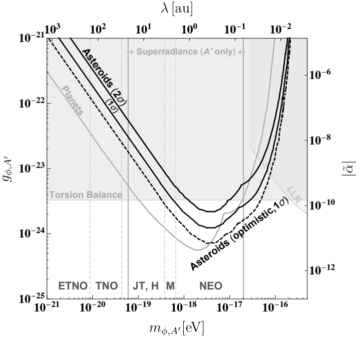
(Fudan)

Luca Visinelli

(Shanghai)

Precession of planetary objects and new light particles

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



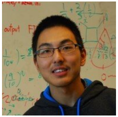
Tsai, Wu, SV, Visinelli, arXiv:2107.04038 (under review in Nat. Astron.)

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,§]
[1] *Fermi National Accelerator Laboratory (Fermilab), Batavia, IL 60510, USA*
[2] *Kavli Institute for Cosmological Physics (KICP), University of Chicago, Chicago, IL 60637, USA*
[3] *Leinweber Center for Theoretical Physics, University of Michigan, Ann Arbor, MI 48109, USA*
[4] *Kavli Institute for Cosmology (KICC), University of Cambridge, Cambridge CB3 0HA, United Kingdom*
[5] *INFN, Laboratori Nazionali di Frascati, C.P. 13, I-100044 Frascati, Italy*
[6] *Tsung-Dao Lee Institute (TDLI), Shanghai Jiao Tong University, 200240 Shanghai, China*

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

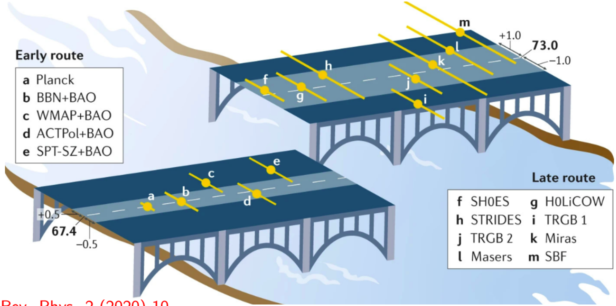

Yu-Dai Tsai (UC Irvine)


Youjia Wu (Michigan)


Luca Visinelli (Shanghai)

Part 5: Cosmic tensions (?)

Viewing the Hubble tension ocean with different eyeglasses



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

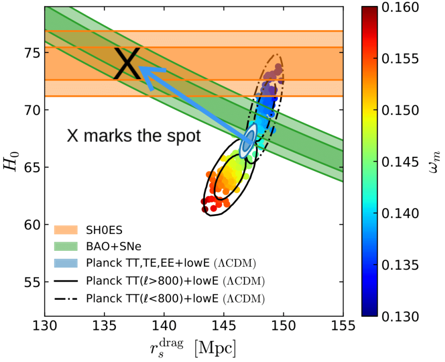
Why does ΛCDM fit data so well? Do we really need new physics? If so, at what time(s), and with what ingredients?

Early times: early ISW effect	⟺	*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 ≈ 12% (!!!) EDE around $z_{\rm eq}$ ⇓

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)

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

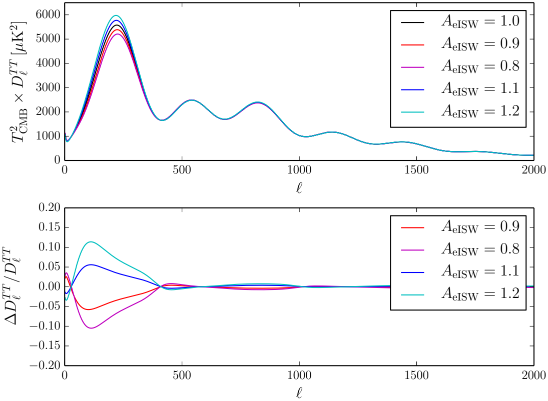
$$\Theta_\ell^{\text{ISW}}(k) = \underbrace{\int_0^{\eta_m} d\eta\, e^{-\tau} \left(\dot{\Psi} - \dot{\Phi}\right) j_\ell(k\Delta\eta)}_{\text{early ISW}} + \underbrace{\int_{\eta_m}^{\eta_0} d\eta\, e^{-\tau} \left(\dot{\Psi} - \dot{\Phi}\right) j_\ell(k\Delta\eta)}_{\text{late ISW}}$$

(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 $A_{\rm eISW}$:

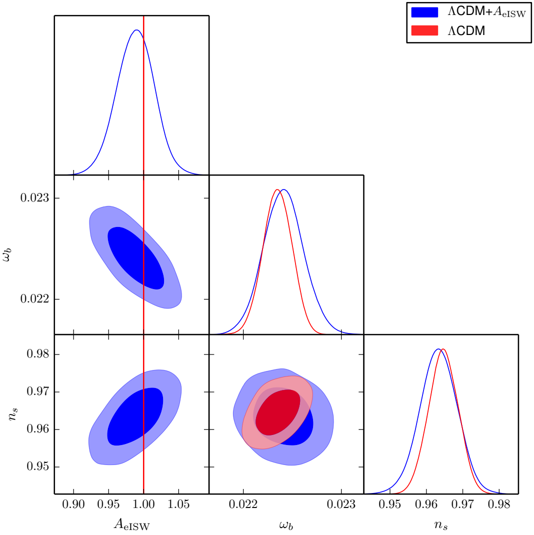
$$\Theta_\ell^{\rm eISW}(k) = A_{\rm eISW} \int_0^{\eta_m} d\eta \, e^{-\tau} \left(\dot{\Psi} - \dot{\Phi}\right) j_\ell(k\Delta\eta)$$



SV, PRD 104 (2021) 063524

eISW consistency test

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



Yes!

Parameter	*Planck* ΛCDM	*Planck* ΛCDM+$A_{\rm eISW}$
$100\omega_b$	2.235 ± 0.015	2.241 ± 0.020
ω_c	0.1202 ± 0.0013	0.1203 ± 0.0014
θ_s	1.0409 ± 0.0003	1.0409 ± 0.0003
τ	0.0544 ± 0.0078	0.0541 ± 0.0078
$\ln(10^{10} A_s)$	3.045 ± 0.016	3.046 ± 0.016
n_s	0.965 ± 0.004	0.963 ± 0.005
$A_{\rm eISW}$	1.0	0.988 ± 0.027
H_0 [km/s/Mpc]	67.26 ± 0.57	67.28 ± 0.62
Ω_m	0.317 ± 0.008	0.317 ± 0.009

SV, PRD 104 (2021) 063524

Implications for early-time new physics: EDE case study

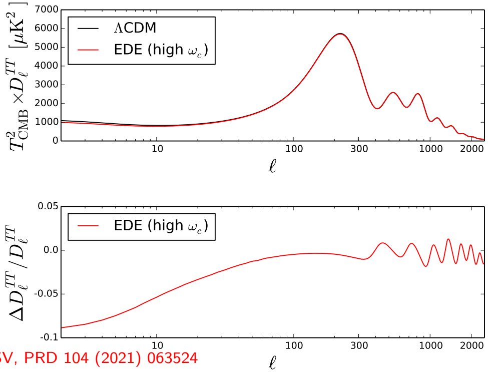
High H_0 EDE fit to CMB at the cost of increase in ω_c → worsens tension with WL/LSS data? Hill *et al.*, PRD 102 (2020) 043507; Ivanov *et al.*, PRD 102 (2020) 103502; D'Amico *et al.*, JCAP 2105 (2021) 072; see also Gómez-Valent *et al.*, PRD 104 (2021) 083536; see partial rebuttals in: Murgia *et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

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

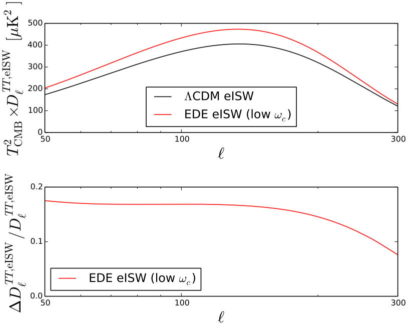


SV, PRD 104 (2021) 063524

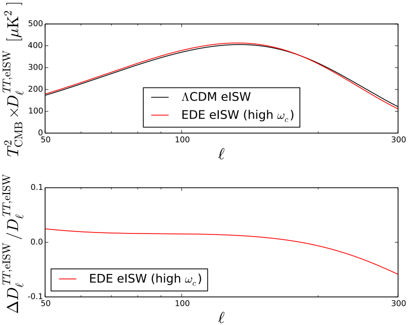
Implications for early-time new physics: EDE case study

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

Low ω_c



High ω_c



Almost 20% eISW excess!

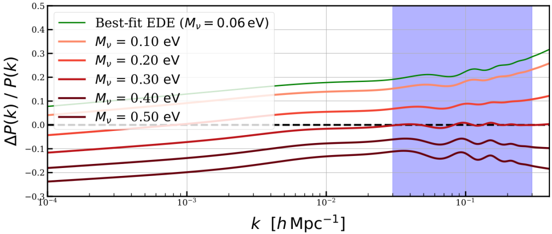
No more than $\lesssim$ 3-5% eISW excess

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

Rescuing early dark energy with massive neutrinos?

Restoring cosmological concordance with early dark energy and massive neutrinos?

Alexander Reeves,[1⋆] Laura Herold,[2] Sunny Vagnozzi,[3] Blake D. Sherwin,[3,4] and Elisa G. M. Ferreira[5,6]
[1] *Institute for Particle Physics and Astrophysics, ETH Zürich, Wolfgang-Pauli-Straße 27, CH-8093 Zürich, Switzerland*
[2] *Max-Planck-Institut für Astrophysik, Karl-Schwarzschild-Straße 1, D-85740 Garching bei München, Germany*
[3] *Kavli Institute for Cosmology, University of Cambridge, Madingley Road, Cambridge CB3 0HA, UK*
[4] *Department of Applied Mathematics and Theoretical Physics, University of Cambridge, Wilberforce Road, Cambridge CB3 0WA, UK*
[5] *Kavli IPMU (WPI), UTIAS, The University of Tokyo, 5-1-5 Kashiwanoha, Kashiwa, Chiba 277-8583, Japan*
[6] *Instituto de Física, Universidade de São Paulo, Rua do Matão 1371, Butantã, 05508-090, São Paulo, Brazil*



Reeves, Herold, SV, Sherwin, Ferreira, in preparation. Plot credits: Alex Reeves

Alex Reeves (ETH Zürich)

Laura Herold (MPA Garching)

Blake Sherwin (Cambridge)

Elisa Ferreira (Tokyo)

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:

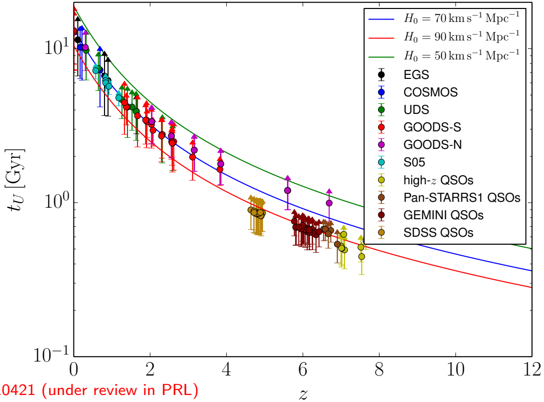
- OAO cannot be older than the Universe $\rightarrow$ **upper limit on** H_0
- $t_U(z)$ integral insensitive to early-time cosmology
- $\Longrightarrow$ **early-time-independent ΛCDM consistency test**!
- Ages of astrophysical objects at $z > 0$ hard to estimate robustly ⚠

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)

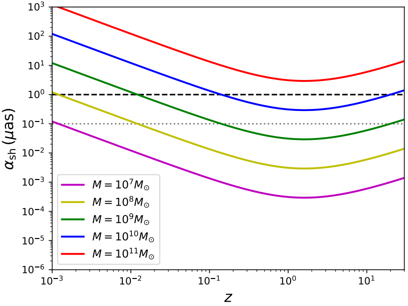


SV *et al.*, arXiv:2105.10421 (under review in PRL)

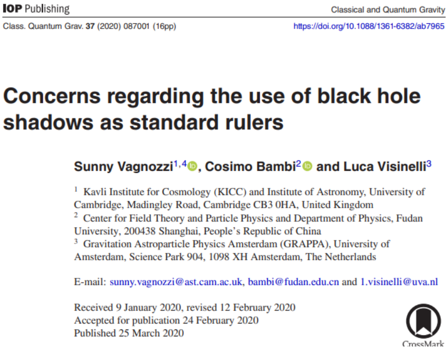
$H_0 < 73.2\,\mathrm{km/s/Mpc}$ (95% C.L.) $\rightarrow$ hints for some amount of late-time new physics (in relation to the H_0 tension)?

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

Sunny Vagnozzi[1,4], Cosimo Bambi[2] and Luca Visinelli[3]

[1] Kavli Institute for Cosmology (KICC) and Institute of Astronomy, University of Cambridge, Madingley Road, Cambridge CB3 0HA, United Kingdom
[2] Center for Field Theory and Particle Physics and Department of Physics, Fudan University, 200438 Shanghai, People's Republic of China
[3] Gravitation Astroparticle Physics Amsterdam (GRAPPA), University of Amsterdam, Science Park 904, 1098 XH Amsterdam, The Netherlands

E-mail: sunny.vagnozzi@ast.cam.ac.uk, bambi@fudan.edu.cn and l.visinelli@uva.nl

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

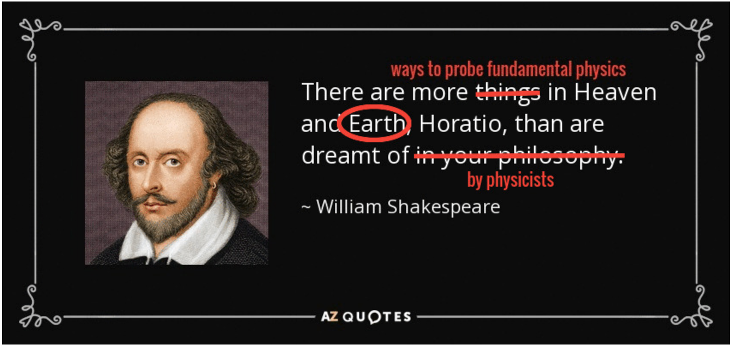
CrossMark

Problems:

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

Cosimo Bambi (Fudan)

Luca Visinelli (Shanghai)



Thank you for your attention!