Direct Detection of Dark Energy,
or
searching for dark energy off the beaten track

Sunny Vagnozzi & Anne-Christine Davis

New Frontiers in Astrophysics: a KICC Perspective

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20 May 2022

Dark Energy: wanted since 1998

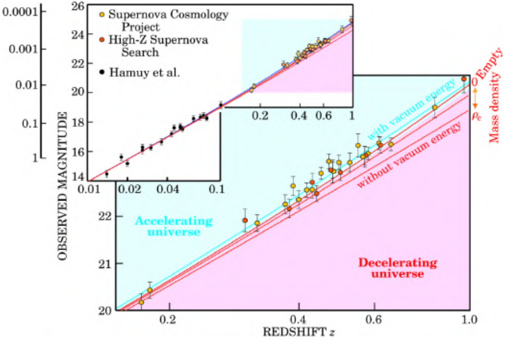
Credits: Symmetry Magazine and Sandbox Studio, Chicago

We're both older than dark energy

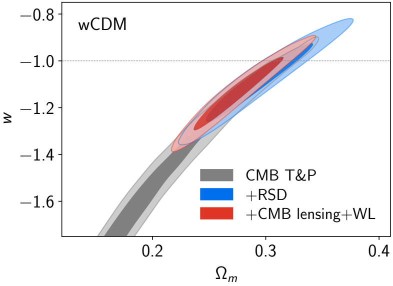
Back in $\simeq 1998^{+3}_{-1}$... (68% C.L.)

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 $w_{\rm DE} = P_{\rm DE}/\rho_{\rm DE}$ (~ -1?)



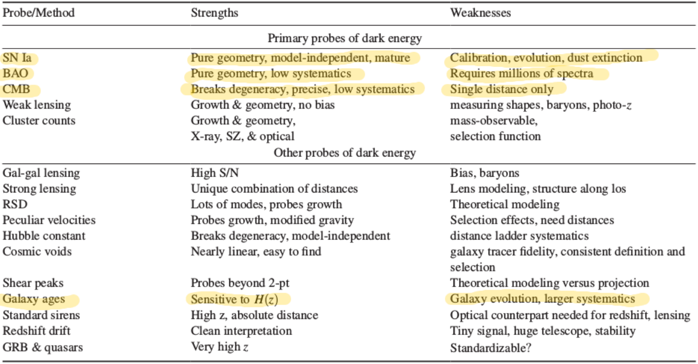
Credits: Perlmutter, Physics Today 56 (2003) 53



eBOSS collaboration, PRD 103 (2021) 083533

Not only SNeIa: evidence for cosmic acceleration is sound

Evidence for cosmic acceleration does **not** only come from SNeIa



Probe/Method	Strengths	Weaknesses
	Primary probes of dark energy	
SN Ia	Pure geometry, model-independent, mature	Calibration, evolution, dust extinction
BAO	Pure geometry, low systematics	Requires millions of spectra
CMB	Breaks degeneracy, precise, low systematics	Single distance only
Weak lensing	Growth & geometry, no bias	measuring shapes, baryons, photo-z
Cluster counts	Growth & geometry, X-ray, SZ, & optical	mass-observable, selection function
	Other probes of dark energy	
Gal-gal lensing	High S/N	Bias, baryons
Strong lensing	Unique combination of distances	Lens modeling, structure along los
RSD	Lots of modes, probes growth	Theoretical modeling
Peculiar velocities	Probes growth, modified gravity	Selection effects, need distances
Hubble constant	Breaks degeneracy, model-independent	distance ladder systematics
Cosmic voids	Nearly linear, easy to find	galaxy tracer fidelity, consistent definition and selection
Shear peaks	Probes beyond 2-pt	Theoretical modeling versus projection
Galaxy ages	Sensitive to $H(z)$	Galaxy evolution, larger systematics
Standard sirens	High z, absolute distance	Optical counterpart needed for redshift, lensing
Redshift drift	Clean interpretation	Tiny signal, huge telescope, stability
GRB & quasars	Very high z	Standardizable?

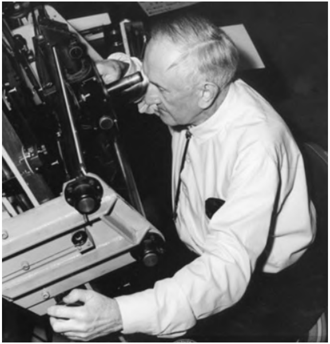
Huterer & Shafer, Rept. Prog. Phys. 81 (2018) 016901

Crucially all these observations are probing (to zeroth order) DE's gravitational signatures

Are gravitational signatures all there is?

Take a step aside: dark matter

Zwicky: Coma Cluster



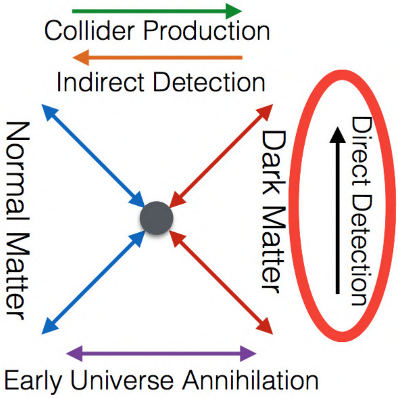
Rubin: galaxy rotation curves

Credits: Caltech archives

Credits: Carnegie Institution for Science

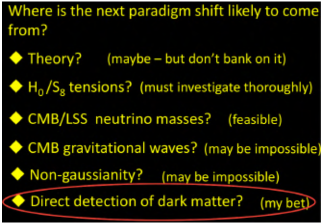
Are gravitational signatures all there is?

Three-pronged approach towards dark matter detection/discovery



Credits: (adapted from) Matt Buckley

George's bet



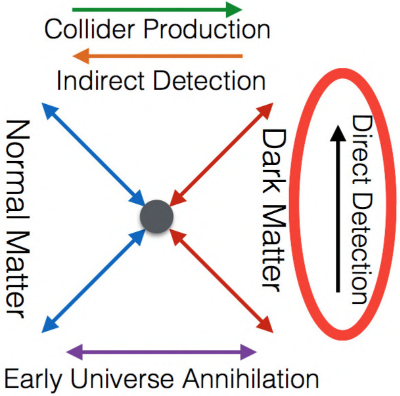
Where is the next paradigm shift likely to come from?

- ◆ Theory? (maybe – but don't bank on it)
- ◆ H_0/S_8 tensions? (must investigate thoroughly)
- ◆ CMB/LSS neutrino masses? (feasible)
- ◆ CMB gravitational waves? (may be impossible)
- ◆ Non-gaussianity? (may be impossible)
- ◆ Direct detection of dark matter? (my bet)

Credits: George Efstathiou, in this same talk series (Feb 2022)

Are gravitational signatures all there is?

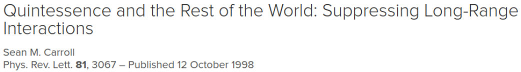
Three-pronged approach towards dark matter detection/discovery



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

Coupled quintessence

Luca Amendola
Phys. Rev. D **62**, 043511 – Published 24 July 2000

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!

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

Dark Energy vs Cosmological Constant

A cosmological constant could be dark energy provided

$$\Lambda \approx (H_0 M_{pl})^2 \approx (Mev)^4$$

A scalar field could act a dark energy provided its mass today

$$m_\phi < H_0 \approx 10^{-33} eV$$

We only know dark energy dominates today

For a scalar field

$$\rho_\phi = 1/2\dot{\phi}^2 + V(\phi)$$ kinetic energy + potential energy

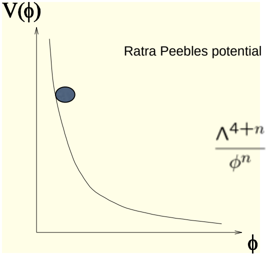
$$p_\phi = 1/2\dot{\phi}^2 - V(\phi)$$ kinetic energy - potential energy

If the potential dominates then

$$p_\phi \approx -\rho_\phi$$

so the scalar field plays the role of an effective cosmological constant. Since it's dynamical, this wouldn't have been the case for all times in the universe. We only need the scalar field to dominate the energy density of the universe today

This modifies our theory to



Field rolling down a runaway potential, reaching large values now.

Deviations from Newton's
Laws parametrised by

$$\Phi_N = -G_N/r(1 + 2\beta^2 e^{-r/\lambda})$$

First term gives Newton's inverse square law, second term is deviation from standard gravity

tightest constraint comes from satellite experiments

$$\beta^2 \leq 4 \cdot 10^{-5}$$

Fifth force must be screened

Screening: a quick preview

How to satisfy fifth-force tests?

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

(At least) 3 ways to screen

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

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

Two general classes of theories

1) Chameleon type screening. Can be tested in the lab, in the solar system, astrophysics and cosmology. Does not affect speed of gravitational waves, so no test from LIGO/VIRGO or eLISA

2) Vainshtein screening. For example Galileons, Horndeski, massive gravity, k-mouflage. Vainshtein radius is very large, so no laboratory tests, but astrophysical and cosmological tests. Some models give speed of gravitational waves to be different from that of photons, so severely constrained by LIGO/VIRGO and will be even more constrained by eLISA

Screened Modified Gravity

Khoury, Wellman PRD 69 (2004) 044026

consider the chameleon action

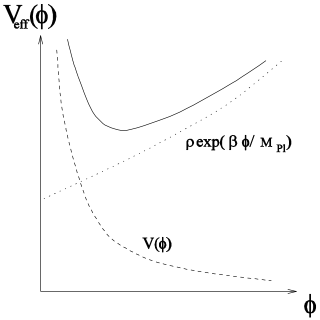
$$S = \int d^4x\sqrt{-g}(\frac{R}{16\pi G_N} - \frac{(\partial\phi)^2}{2} - V(\phi)) + S_m(\psi_i, A^2(\phi)g_{\mu\nu})$$

gives the effective potential

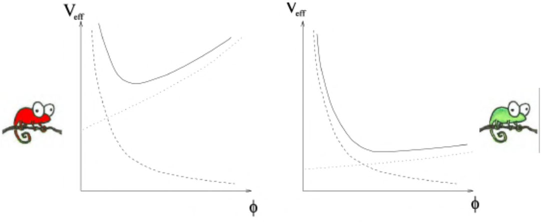
$$V_{\text{eff}}(\phi) = V(\phi) - (A(\phi) - 1)T$$

This should give fifth forces, but these are screened. Two types of screening. Chameleons - the mass depends on the environment; symmetrons - the coupling to matter depends on the environment. They have been constrained by solar system and lab tests.

There is an environmental effect: when coupled to matter the potential depends on the ambient matter density as well



$$V_{eff}(\phi) = V(\phi) + \rho_m A(\phi)$$

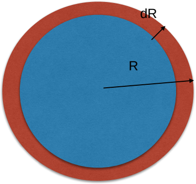


Large ρ Small ρ

mass is proportional to the second derivative of minimum of the potential
Hence it can be heavy when ρ is large and light when ρ is small

$$m_\phi^2(\rho) = \partial^2 V(\rho)/\partial\phi^2$$

To screen fifth forces in the solar system one needs the thin shell effect.



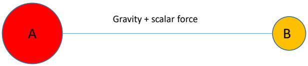
The fifth force is
proportional to the size of
the thin shell where the
field varies

$$F_\phi \approx \frac{\Delta R}{R\Phi_N}$$

Due to the scalar interaction, within the Compton wavelength of the scalar field, the inertial and gravitational masses differ for screened objects:

$$G_{A,B} = G_N(1 + 2Q_AQ_B)$$

Interaction rate depending on the objects



Value of the field far away

$$Q_A = \frac{\phi_\infty}{2m_{\rm Pl}\Phi_A}$$

Newtonian potential at the surface of the body.

$$Q_A \leq \beta_\infty$$

Screening criterion for compact objects

Massive bodies with differ scalar charges fall differently. Hence a violation of the strong equivalence principle.

Testing the Equivalence Principle

Do large objects and small objects fall at the same rate?

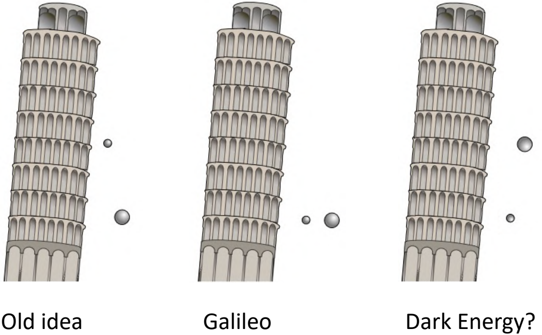


Image credit: Theresa Knott

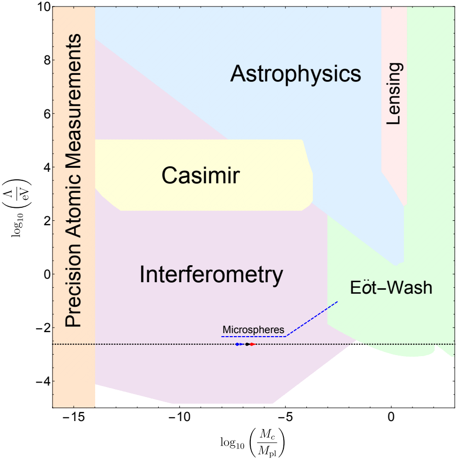
The most general coupling of the scalar field to matter in scalar-tensor gravity is due to Bekenstein

$$g_{\mu\nu} = A^2(\phi) g^E_{\mu\nu} + B^2(\phi, X) \partial_\mu \phi \partial_\nu \phi$$

$$A(\phi) = e^{\beta\phi/m_{\rm Pl}} \qquad B(\phi, X) = \frac{1}{M^4}$$

A is the conformal and B the disformal coupling

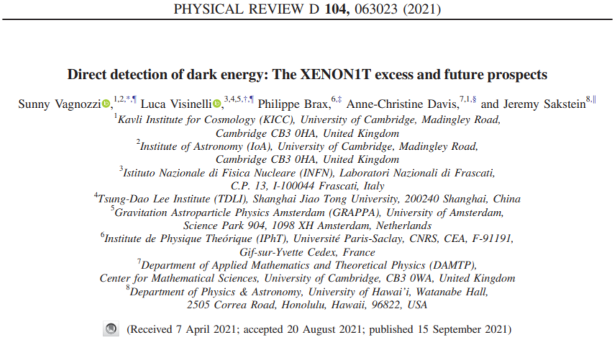
There are strict constraints on the chameleon parameters, even with screening. For the conformal coupling these come from a variety of experiments on a range of scales. Constraints on the disformal coupling come from collider constraints



Burrage and Sakstein review
Living Rev.Rel. 21 (2018) 1, 1 •
e-Print: 1709.09071

Direct detection of dark energy

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



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

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

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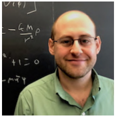
Luca Visinelli (Shanghai)

Phil Brax (IPhT, Saclay)

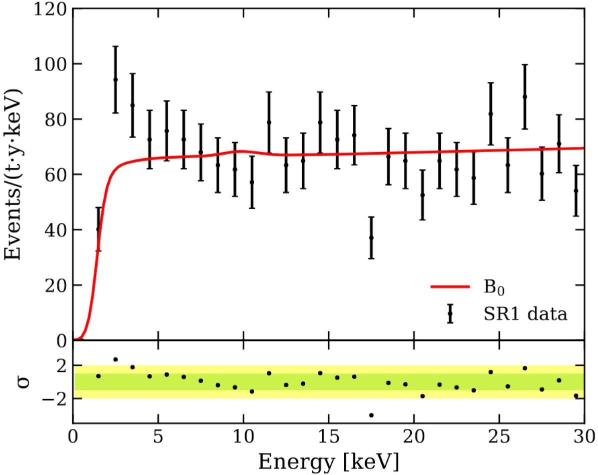


Jeremy Sakstein (Hawaii)

The XENON1T experiment

Credits: Roberto Corrieri and Patrick De Perio

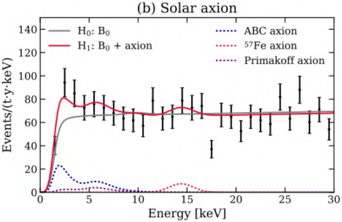
June 17, 2020: the XENON1T excess



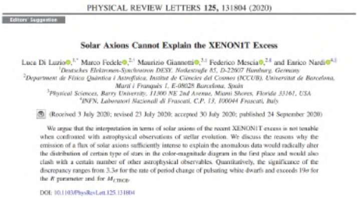
Credits: XENON1T collaboration, PRD 102 (2020) 072004

Axions for the XENON1T excess?

Absorption of solar axions by electrons (axioelectric effect)?



Credits: XENON1T collaboration, PRD 102 (2020) 072004


PHYSICAL REVIEW LETTERS **125,** 131804 (2020)

Editors' Suggestion

Solar Axions Cannot Explain the XENON1T Excess

Luca Di Luzio,[1,*] Marco Fedele,[2,†] Maurizio Giannotti,[3,‡] Federico Mescia,[2,§] and Enrico Nardi[4,∥]
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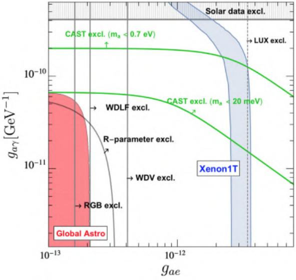
[2] *Departament de Física Quàntica i Astrofísica, Institut de Ciències del Cosmos (ICCUB), Universitat de Barcelona, Martí i Franquès 1, E-08028 Barcelona, Spain*
[3] *Physical Sciences, Barry University, 11300 NE 2nd Avenue, Miami Shores, Florida 33161, USA*
[4] *INFN, Laboratori Nazionali di Frascati, C.P. 13, I00044 Frascati, Italy*

(Received 3 July 2020; revised 23 July 2020; accepted 30 July 2020; published 24 September 2020)

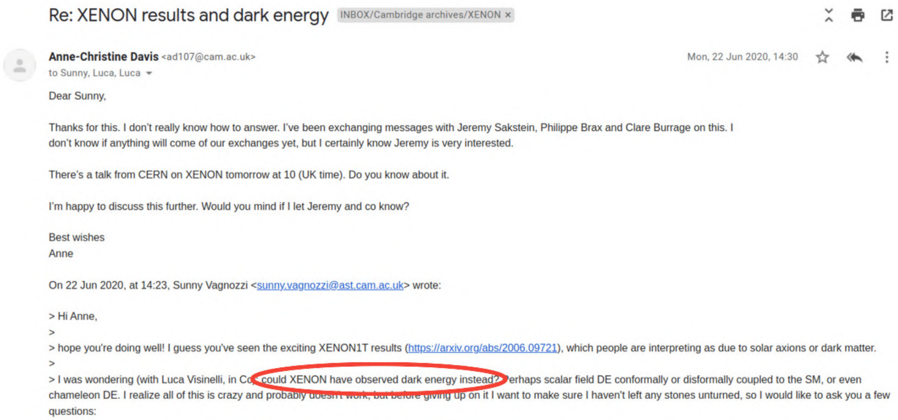
We argue that the interpretation in terms of solar axions of the recent XENON1T excess is not tenable when confronted with astrophysical observations of stellar evolution. We discuss the reasons why the emission of a flux of solar axions sufficiently intense to explain the anomalous data would radically alter the distribution of certain type of stars in the color-magnitude diagram in the first place and would also clash with a certain number of other astrophysical observables. Quantitatively, the significance of the discrepancy ranges from 3.3σ for the rate of period change of pulsating white dwarfs and exceeds 19σ for the R parameter and for $M_{I,\mathrm{TRGB}}$.

DOI: 10.1103/PhysRevLett.125.131804



Credits: Di Luzio *et al.*, PRL 125 (2020) 131804

June 22, 2020: direct detection of dark energy?



Re: XENON results and dark energy

Anne-Christine Davis <ad107@cam.ac.uk>
to Sunny, Luca, Luca

Mon, 22 Jun 2020, 14:30

Dear Sunny,

Thanks for this. I don't really know how to answer. I've been exchanging messages with Jeremy Sakstein, Philippe Brax and Clare Burrage on this. I don't know if anything will come of our exchanges yet, but I certainly know Jeremy is very interested.

There's a talk from CERN on XENON tomorrow at 10 (UK time). Do you know about it.

I'm happy to discuss this further. Would you mind if I let Jeremy and co know?

Best wishes
Anne

On 22 Jun 2020, at 14:23, Sunny Vagnozzi <sunny.vagnozzi@ast.cam.ac.uk> wrote:

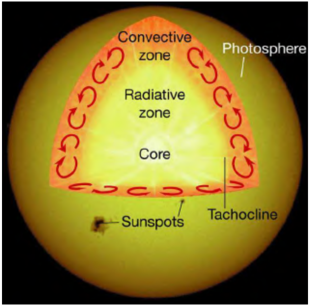
> Hi Anne,
>
> hope you're doing well! I guess you've seen the exciting XENON1T results (https://arxiv.org/abs/2006.09721), which people are interpreting as due to solar axions or dark matter.
>
> I was wondering (with Luca Visinelli, in Co could XENON have observed dark energy instead? Perhaps scalar field DE conformally or disformally coupled to the SM, or even chameleon DE. I realize all of this is crazy and probably doesn't work, but before giving up on it I want to make sure I haven't left any stones unturned, so I would like to ask you a few questions:

Direct detection of dark energy

Production

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

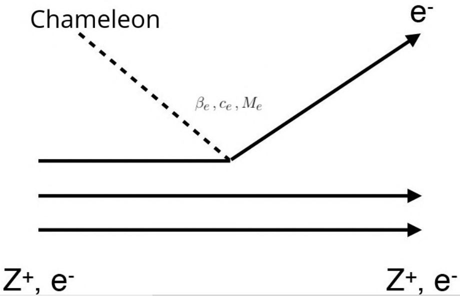
Production in strong magnetic fields of the tachocline



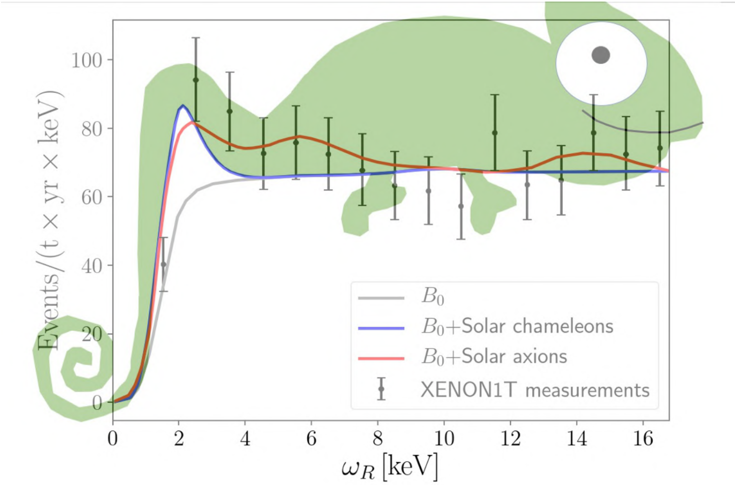
Detection

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

Analogous to photoelectric and axioelectric effects



Direct detection of (chameleon-screened) dark energy



SV *et al.*, PRD 104 (2021) 063023 Image editing credits: Cristina Ghirardini

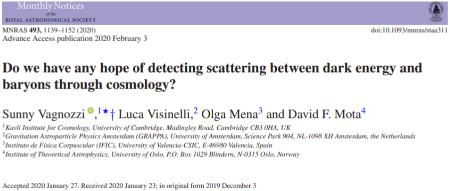
Two birds with one stone?

Follow-up work/future research directions

- Understand complementary cosmological signatures
- Understand complementary astrophysical signatures: BH mass gap?
- Refine solar production calculation, include other Lagrangian terms
- Mixed DM-DE axion-chameleon scenario?
- S2-only analysis of XENON1T data: lower threshold, resolve chameleon peak better?
- Complementary/updated laboratory constraints
- ...lots more!

Complementary cosmological signatures

If DE and baryons really talk to/scatter with each other, what are the cosmological implications?



Monthly Notices of the ROYAL ASTRONOMICAL SOCIETY
MNRAS **493,** 1139–1152 (2020) doi:10.1093/mnras/staa311
Advance Access publication 2020 February 3

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

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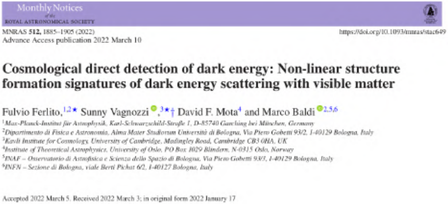

Monthly Notices of the ROYAL ASTRONOMICAL SOCIETY
MNRAS **512,** 1885–1905 (2022) https://doi.org/10.1093/mnras/stac649
Advance Access publication 2022 March 10

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

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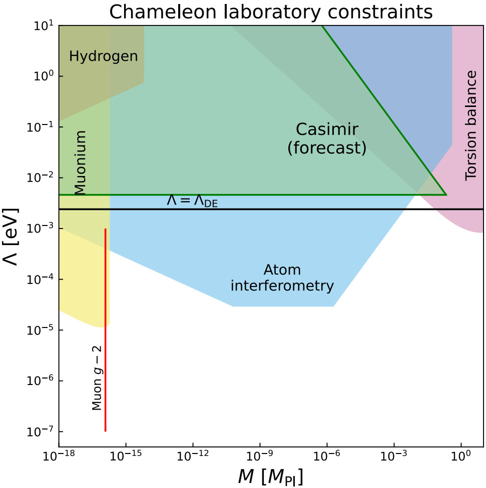
David Mota (Oslo)

Fulvio Ferlito (Garching)

Marco Baldi (Bologna)



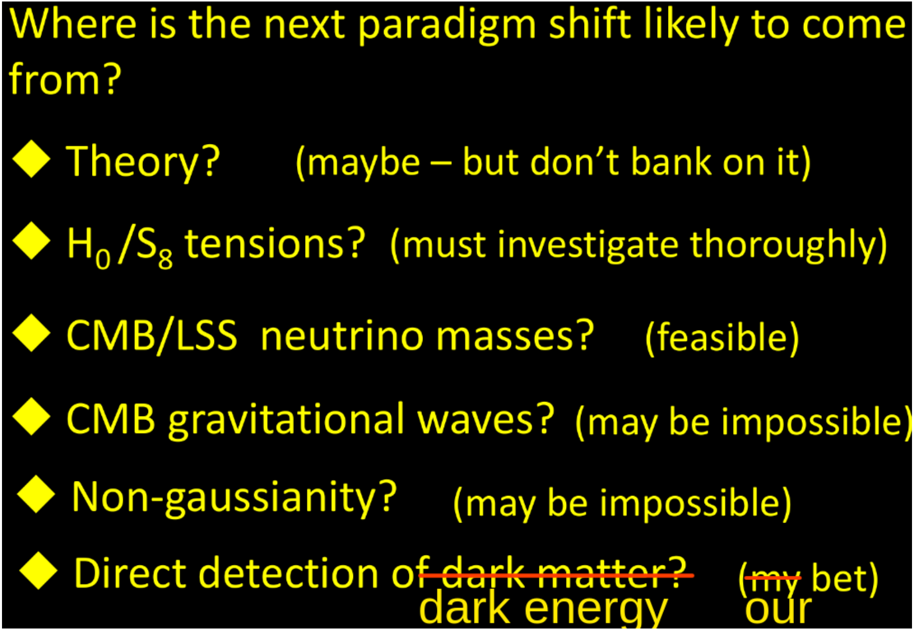
Brax, Elder,
ACD to appear

Constraints on the disformal coupling come from collider physics. The disformal coupling allows the production of chameleons in the LHC via the coupling to standard model gauge bosons. One uses standard model physics, but with the addition of the extra scalar field to the Feynman diagrams. Assuming a strictly massless scalar, the best constraint on the parameter M comes from ATLAS

$$M > 1\ \text{GeV}$$

If chameleons are produced inside a body they are will not be strictly massless as their mass is density dependent and this bound can be relaxed

In fact muonium now gives the best constraint - Brax, ACD, Elder to appear

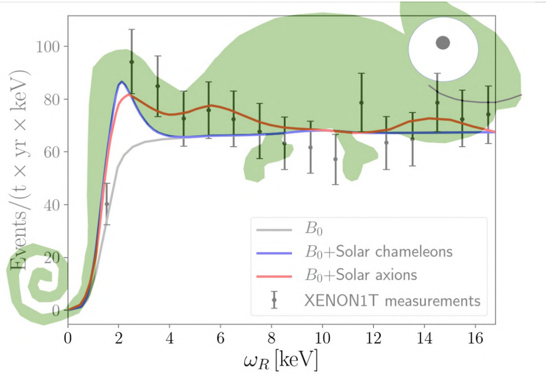


Where is the next paradigm shift likely to come from?

- Theory? (maybe – but don’t bank on it)
- H_0/S_8 tensions? (must investigate thoroughly)
- CMB/LSS neutrino masses? (feasible)
- CMB gravitational waves? (may be impossible)
- Non-gaussianity? (may be impossible)
- Direct detection of ~~dark matter?~~ dark energy (~~my~~ our bet)

Conclusions

Lots of unharvested potential in dark matter direct detection experiments



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