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Direct detection experiments and light Chameleons

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Based on: 2103.15834
With:

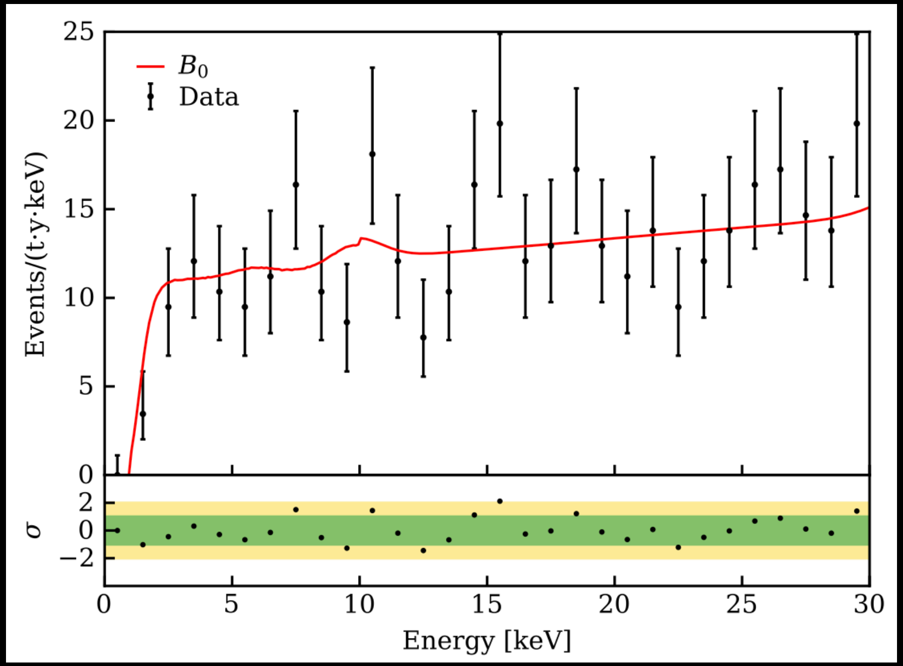
Sunny Vagnozzi Philippe Brax Anne-Christine Davis Jeremy Sakstein

Warning!

The talk is based on a result from 2021

The “Xenon excess” has been retracted since then:

XENONnT [2207.11330]



However, we salvage two important messages:
1) the methodology still applies and we can learn from it;
2) the relevant region has yet to be explored

How can we detect dark energy?

To date, very little is known about DE (compared to DM)

A cosmological constant Λ could serve as DE if

$$\Lambda \sim (H_0 M_{\rm Pl})^2 \sim ({\rm meV})^4$$

However, theory expects a much larger value $\Lambda \sim M_{\rm Pl}^4$

A scalar field ϕ of mass m_ϕ would also behave as DE today if

$$m_\phi \lesssim H_0 \sim 10^{-33}\,{\rm eV}$$

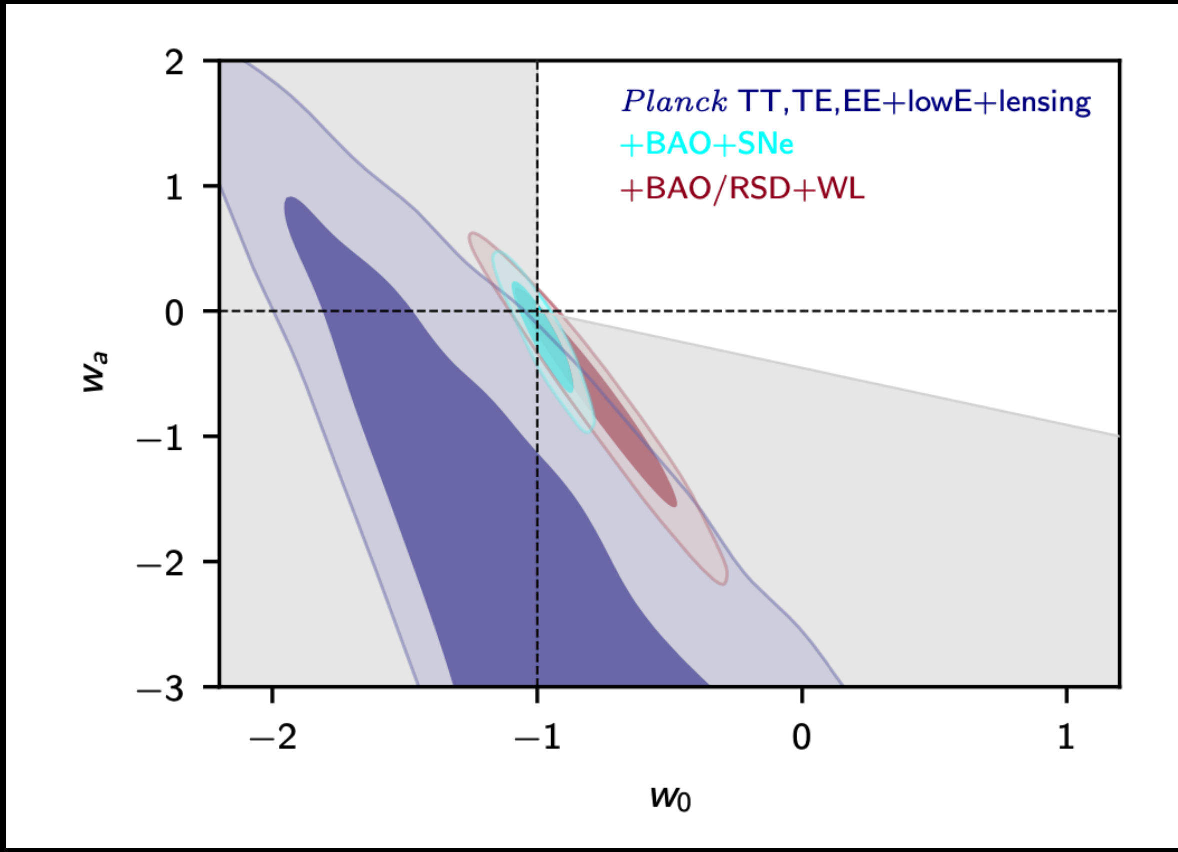
see e.g.
LV & Vagnozzi 19 [1809.06382];
Choi, Lin, **LV**, Yanagida 21 [2106.12602]

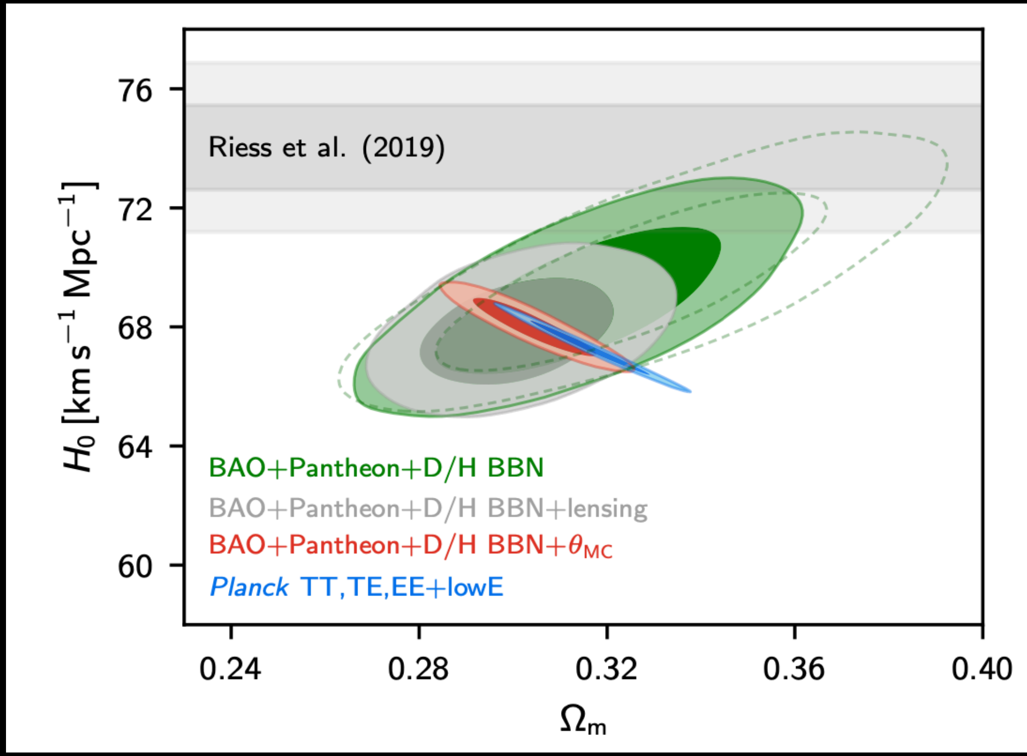
The picture is not as simple as expected

e.g. DE model with e.o.s.

$$w(a) = w_0 + w_a(1-a)$$

Data do not favor a CC





Mismatch between the H_0 coming from early- and late-time measurements

(Planck18: 1807.06211)

Baryon - dark energy scattering

What can we learn from collider searches?

DE is modeled as a scalar field ϕ of mass $\ll \mathrm{SM}$

Possible scattering operators:

$$\mathcal{L}_1 = \frac{\partial_\mu\phi\partial^\mu\phi}{M_1^4} T^\nu{}_\nu \quad \text{(conformal)} \longrightarrow \sigma_1 \sim \frac{p_\phi^4\, m_{\rm SM}^2}{M_1^8}$$

$$\mathcal{L}_2 = \frac{\partial_\mu\phi\partial_\nu\phi}{M_2^4} T^{\mu\nu} \quad \text{(disformal)} \longrightarrow \sigma_2 \sim \frac{p_\phi^4\, p_{\rm SM}^2}{M_2^8}$$

$M_1 \gtrsim 200\,\mathrm{GeV}\,;\; M_2 \gtrsim 1.2\,\mathrm{TeV}$ (Brax+16; ATLAS19)

$\boxed{\text{We generally expect } \alpha_{xb} \ll 1}$

Excess electronic recoil events in XENON1T

XENON Collaboration • E. Aprile (Columbia U.) Show All(139)

Jun 17, 2020

We report results from searches for new physics with low-energy electronic recoil data recorded with the XENON1T detector. With an exposure of 0.65 tonne-years and an unprecedentedly low background rate of 76±2stat events/(tonne×year×keV) between 1 and 30 keV, the data enable one of the most sensitive searches for solar axions, an enhanced neutrino magnetic moment using solar neutrinos, and bosonic dark matter. An excess over known backgrounds is observed at low energies and most prominent between 2 and 3 keV. The solar axion model has a 3.4σ significance, and a three-dimensional 90% confidence surface is reported for axion couplings to electrons, photons, and nucleons. This surface is inscribed in the cuboid defined by gae<3.8×10-12, gaeganeff<4.8×10-18, and gaegaγ<7.7×10-22 GeV-1, and excludes either gae=0 or gaegaγ=gaeganeff=0. The neutrino magnetic moment signal is similarly favored over background at 3.2σ, and a confidence interval of μν∈(1.4,2.9)×10-11 μB (90% C.L.) is reported. Both results are in strong tension with stellar constraints. The excess can also be explained by β decays of tritium at 3.2σ significance with a corresponding tritium concentration in xenon of (6.2±2.0)×10-25 mol/mol. Such a trace amount can neither be confirmed nor excluded with current knowledge of its production and reduction mechanisms. The significances of the solar axion and neutrino magnetic moment hypotheses are decreased to 2.0σ and 0.9σ, respectively, if an unconstrained tritium component is included in the fitting. With respect to bosonic dark matter, the excess favors a monoenergetic peak at (2.3±0.2) keV (68% C.L.) with a 3.0σ global (4.0σ local) significance over background. This analysis sets the most restrictive direct constraints to date on pseudoscalar and vector bosonic dark matter for most masses between 1 and 210 keV/c2. We also consider the possibility that Ar37 may be present in the detector, yielding a 2.82 keV peak from electron capture. Contrary to tritium, the Ar37 concentration can be tightly constrained and is found to be negligible.

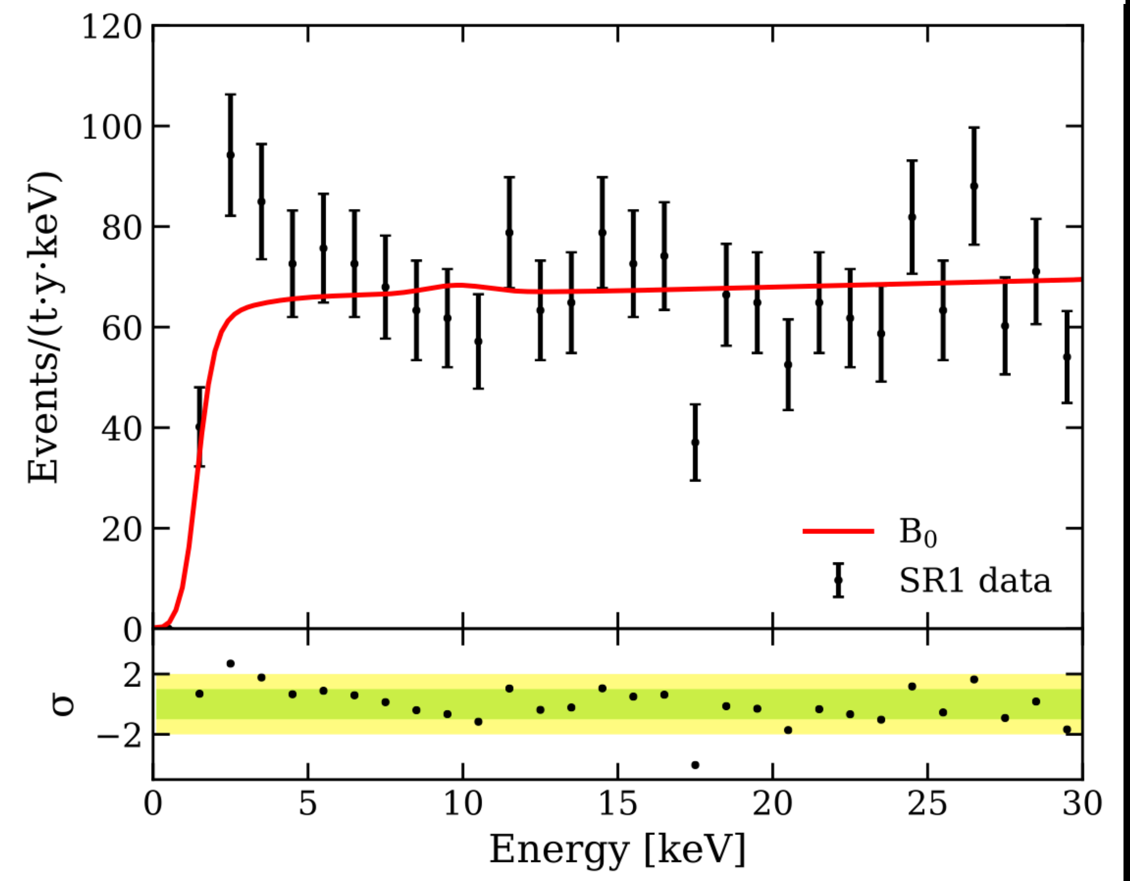
26 pages

Published in: *Phys.Rev.D* 102 (2020) 7, 072004

e-Print: 2006.09721 [hep-ex]

DOI: 10.1103/PhysRevD.102.072004

Experiments: XENON1T



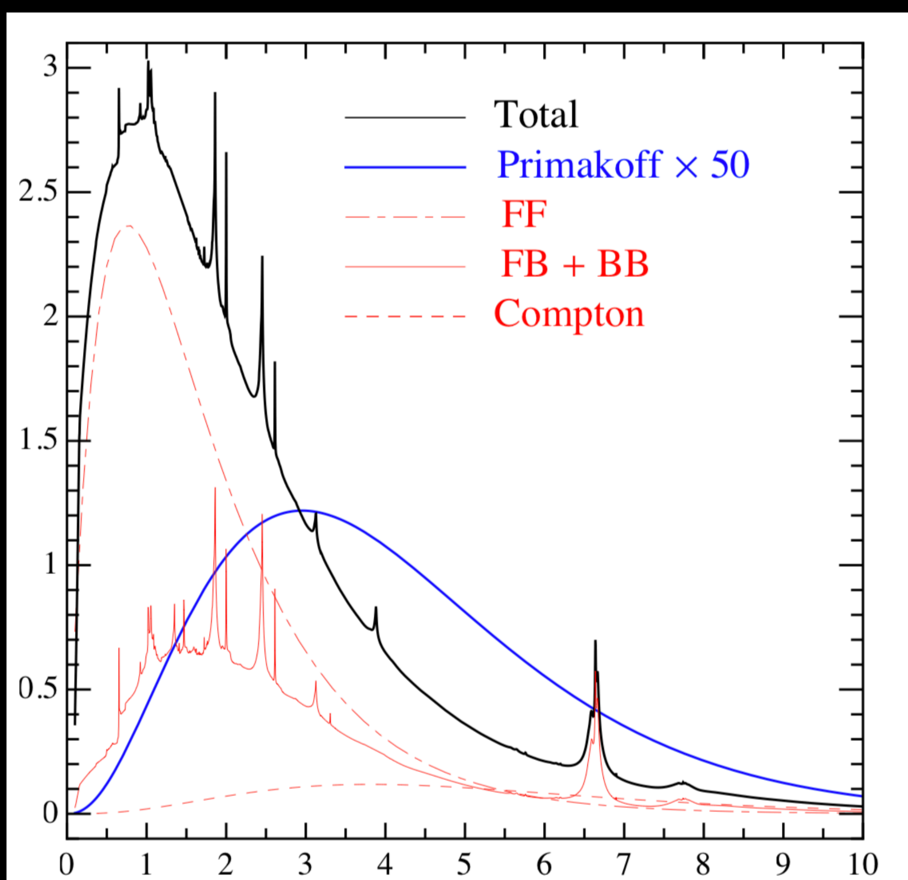
$$\mathcal{L}_{\rm int} = \frac{1}{4} g_{a\gamma} a F_{\mu\nu}\tilde{F}^{\mu\nu} + g_{ae}\frac{\partial_\mu a}{2m_e}\bar{e}\gamma^\mu\gamma_5 e\,,$$

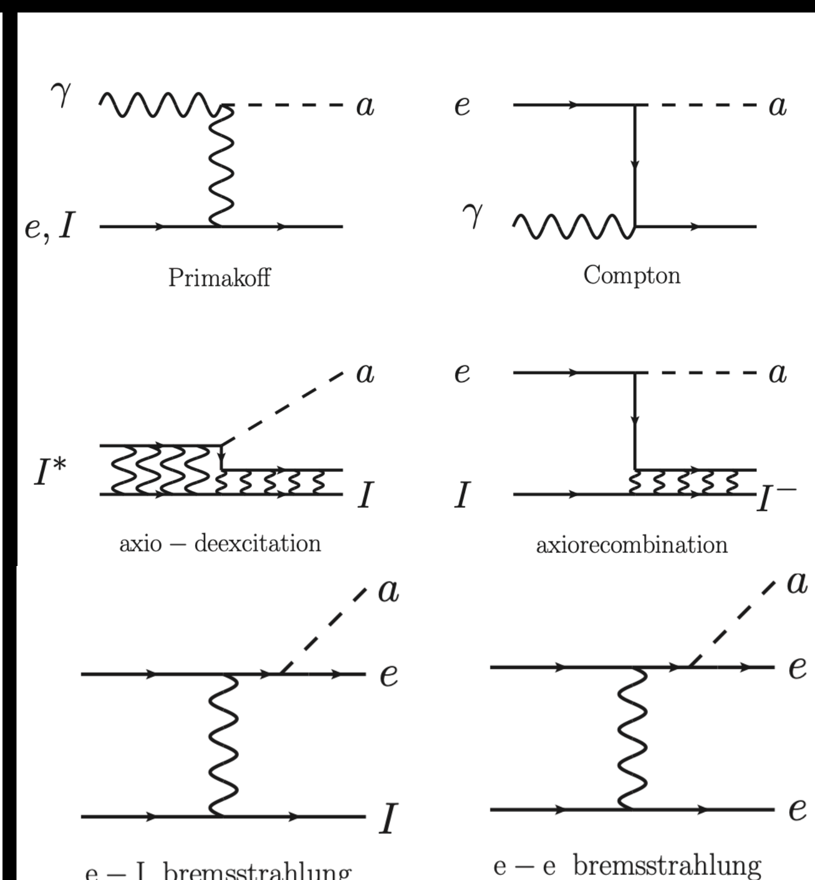
Solar axion flux from the axion-electron coupling

Javier Redondo

See Raffelt '87, Redondo '13 work

ABC (g_{ae}) + Primakoff ($g_{a\gamma}$)





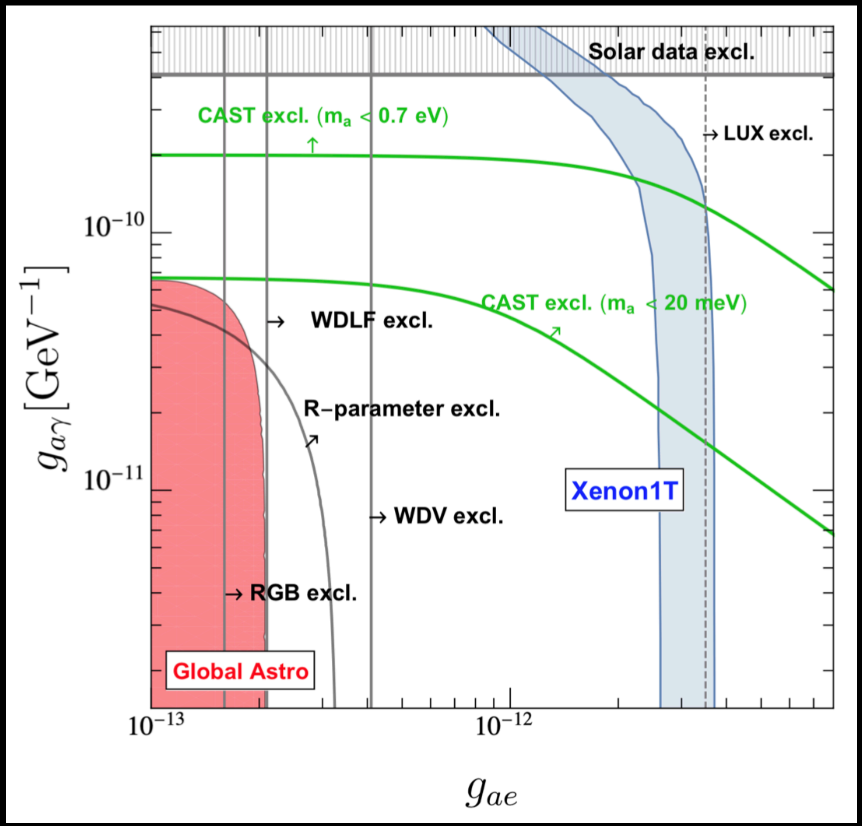
$$\frac{d\Phi_{\rm a}^{\rm Prim}}{dE_{\rm a}} = \left(\frac{g_{a\gamma}}{\rm GeV^{-1}}\right)^2\left(\frac{E_{\rm a}}{\rm keV}\right)^{2.481} e^{-E_{\rm a}/(1.205\ \rm keV)} \times 6\times10^{30}\ \ {\rm cm^{-2}s^{-1}keV^{-1}},$$

$$\Phi_{\rm a}^{\rm ABC} \propto g_{\rm ae}^2$$

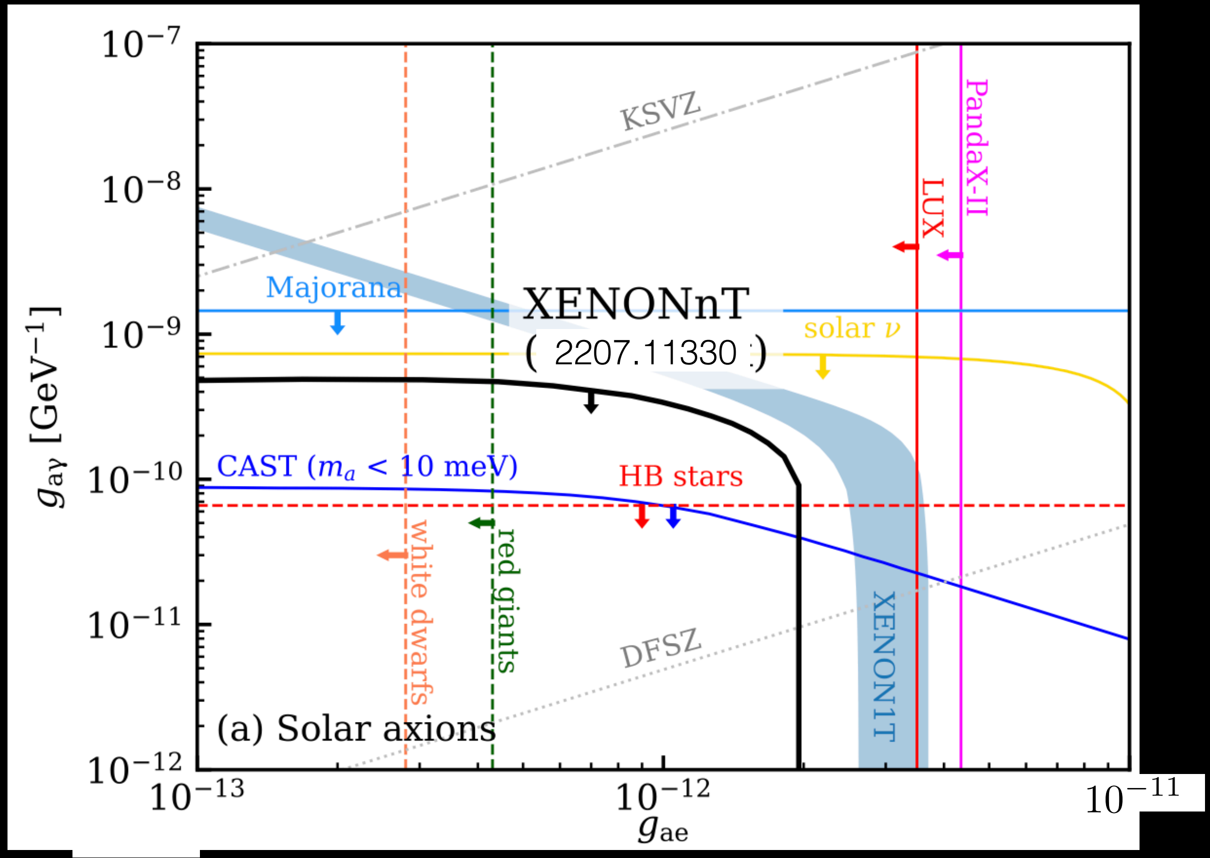
DFSZ models: axion couples at tree level to electron (ABC dominates)
KSVZ models: axion couples to electrons through loops (Primakoff dominates)

Stellar bounds

The axion interpretation of the XENON1T excess is disfavored once the best-fit region is compared to what is expected from stellar production in RGB and white dwarfs



Di Luzio + 20



The latest results from XENONnT 2022 reconcile the tension

Baryon - dark energy scattering

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

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

We explore the prospects for direct detection of dark energy by current and upcoming terrestrial dark matter direct detection experiments. If dark energy is driven by a new light degree of freedom coupled to matter and photons then dark energy quanta are predicted to be produced in the Sun. These quanta free-stream towards Earth where they can interact with Standard Model particles in the detection chambers of direct detection experiments, presenting the possibility that these experiments could be used to test dark energy. Screening mechanisms, which suppress fifth forces associated with new light particles, and are a necessary feature of many dark energy models, prevent production processes from occurring in the core of the Sun, and similarly, in the cores of red giant, horizontal branch, and white dwarf stars. Instead, the coupling of dark energy to photons leads to production in the strong magnetic field of the solar tachocline via a mechanism analogous to the Primakoff process. This then allows for detectable signals on Earth while evading the strong constraints that would typically result from stellar probes of new light particles. As an example, we examine whether the electron recoil excess recently reported by the XENON1T collaboration can be explained by chameleon-screened dark energy, and find that such a model is preferred over the background-only hypothesis at the 2.0σ level, in a large range of parameter space not excluded by stellar (or other) probes. This raises the tantalizing possibility that XENON1T may have achieved the first direct detection of dark energy. Finally, we study the prospects for confirming this scenario using planned future detectors such as XENONnT, PandaX-4T, and LUX-ZEPLIN.

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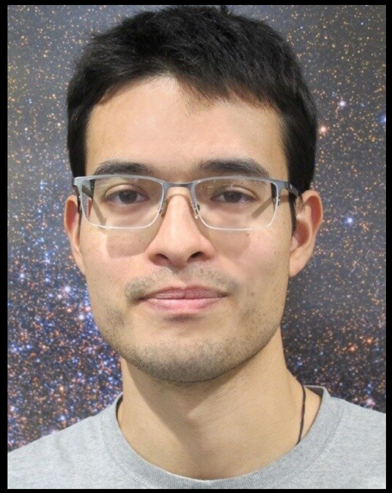
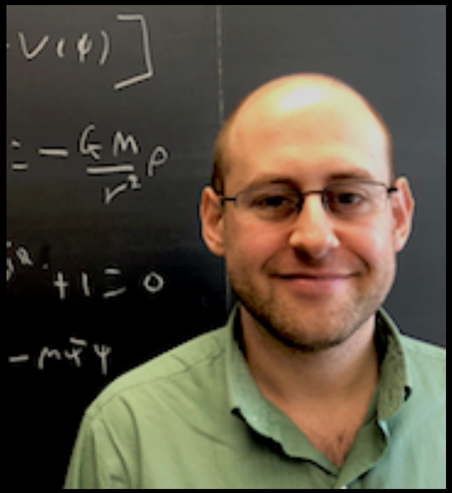


Sunny Vagnozzi

Philippe Brax

Anne-C. Davis



Jeremy Sakstein

Baryon - dark energy scattering

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 (inevitable unless protected by a symmetry!)

Result/immediate obstacle: long-range fifth forces!

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

Baryon - dark energy scattering

How to satisfy fifth-force tests?

- Tune the coupling to be extremely weak $[M \ll M_{\rm Pl}]$
- 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

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

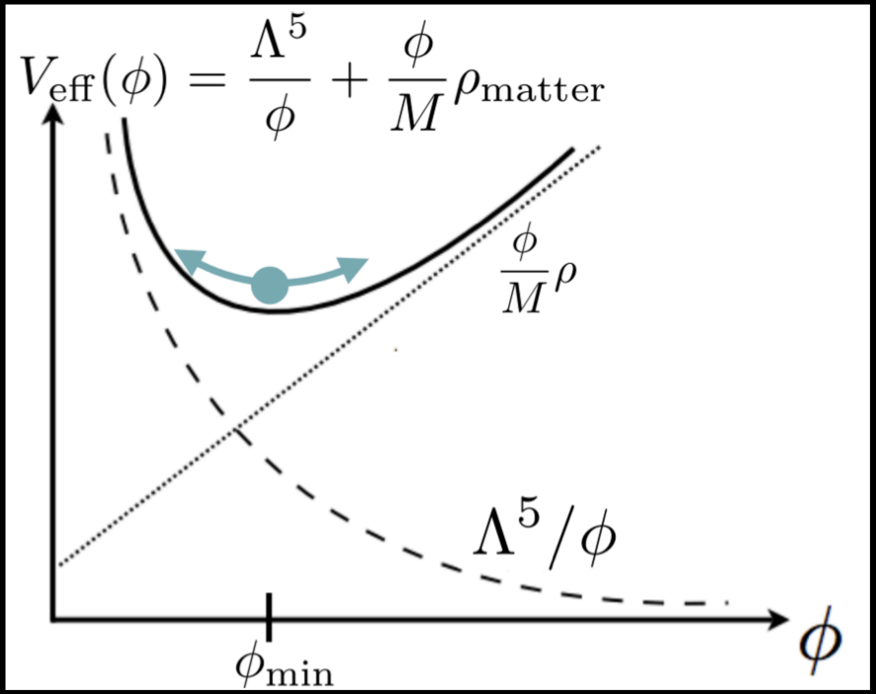
- $\lambda_5(\mathbf{x}) \to$ **chameleon** screening (short range in dense environments)
- $M_5(\mathbf{x}) \to$ symmetron screening (weak coupling in dense environments)
- $n(\mathbf{x}) \to$ Vainshtein (force drops faster than $1/r^2$ around objects)

Baryon - dark energy scattering

Direct detection: chameleons

The chameleon is characterized by a density-dependent mass

$$m_\phi = m_\phi(\rho)$$



The mass results from the effective potential

$$V_{\rm eff}(\phi) = V(\phi) + \rho \exp\left(\frac{\beta_m \phi}{M_{\rm Pl}}\right)$$

$V(\phi)$ Bare potential

β_m Chameleon coupling with the species of density ρ

Example: for $V(\phi) \propto \phi^{-n}$ it is $m_\phi^2 \propto \rho^{\frac{2+n}{1+n}}$

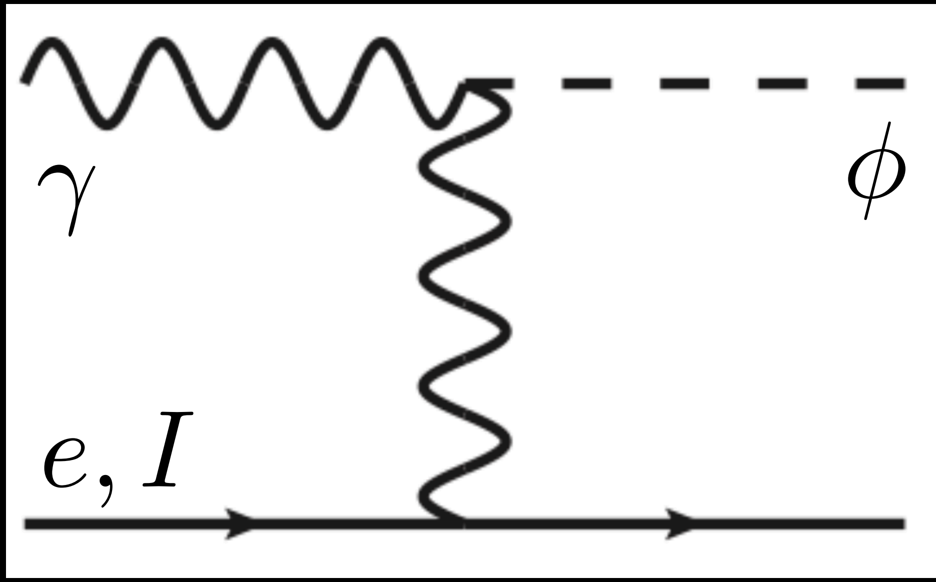
Chameleon production in the Sun

Chameleon production in the Sun differs from the axion case

$$S_{\phi\gamma} = \int \mathrm{d}^4x\sqrt{-g}\left[-\frac{1}{4}F^{\mu\nu}F_{\mu\nu} - \underbrace{\beta_\gamma\frac{\phi}{M_{\rm Pl}}F^{\mu\nu}F_{\mu\nu}}_{\text{(conformal)}} + \underbrace{\frac{1}{M_\gamma^4}T_\gamma^{\mu\nu}\partial_\mu\phi\partial_\nu\phi}_{\text{(disformal)}}\right]$$

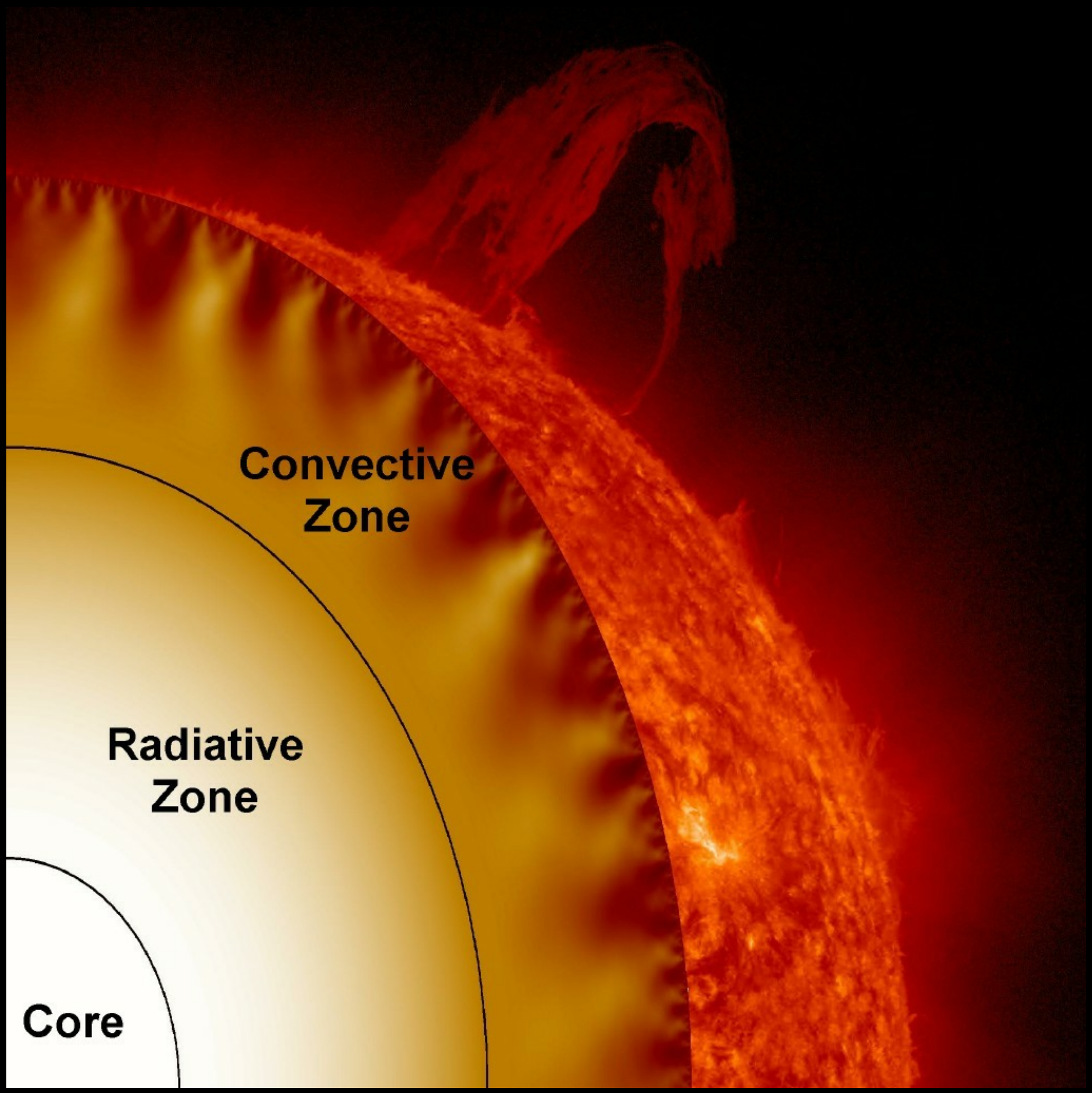
In practice, the disformal case is irrelevant in most of the space

Production through Primakoff effect (Brax+ 1110.2583; 1505.01020)



$$\frac{\mathrm{d}\Phi_{\rm Earth}}{\mathrm{d}\omega} \propto \beta_\gamma^2\,\omega^{3/2}$$

Chameleon production in the Sun



Mostly occurs within a narrow region at the Solar tachocline $R \sim 0.7 R_\odot$

Detection of solar chameleons

Cross section $\sigma_{\phi e} = \sigma_{\phi e,\,\mathrm{disf}} + \sigma_{\phi e,\,\mathrm{conf}}$

The conformal coupling is negligible $\sigma_{\phi e,\,\mathrm{conf}} \ll \sigma_{\phi e,\,\mathrm{disf}}$

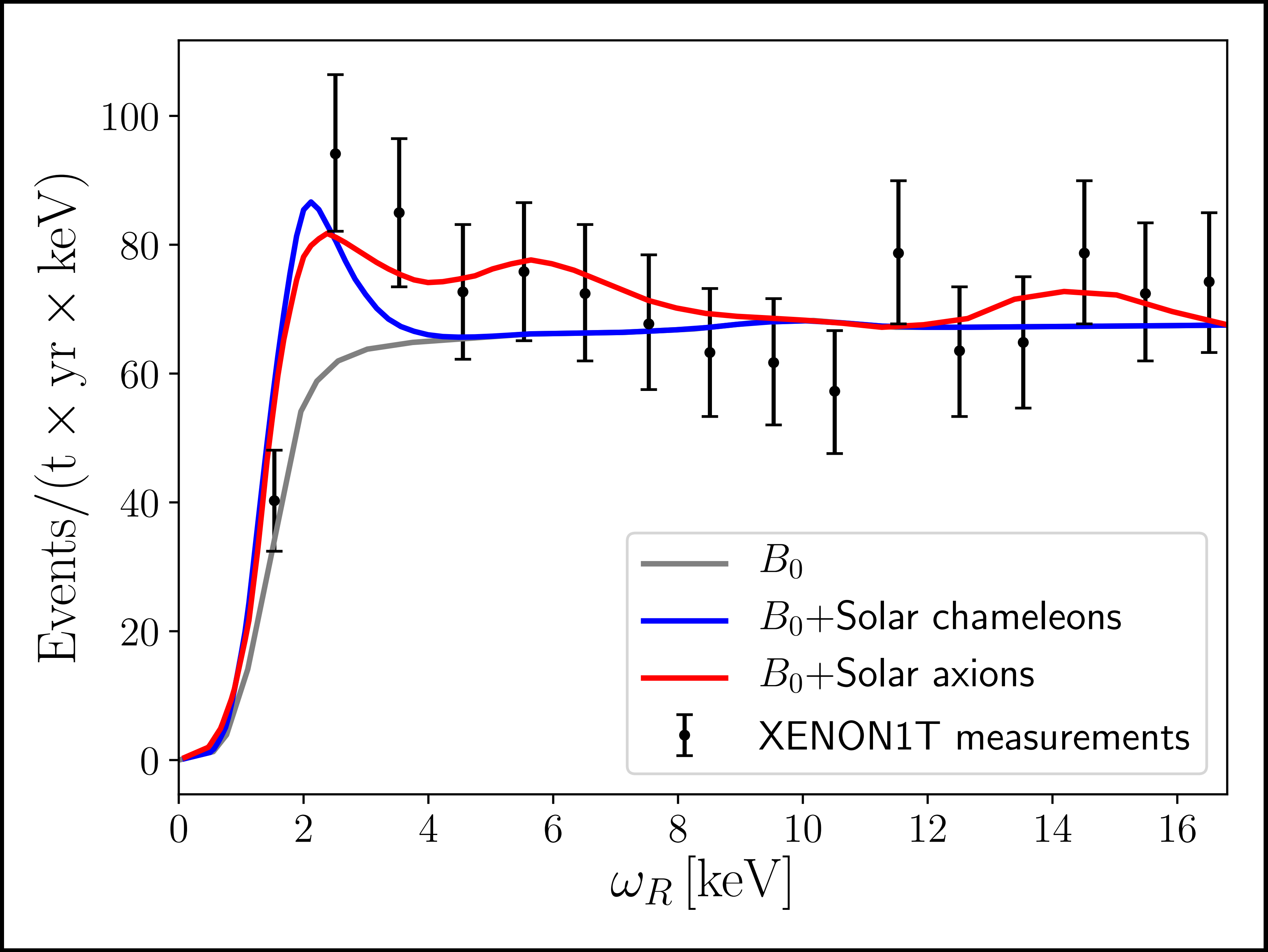
Disformal coupling $\mathcal{L} \supset \sqrt{-g}\frac{1}{M_e^4}\partial_\mu\phi\partial_\nu\phi T_e^{\mu\nu}$

Leads to the cross section $\sigma_{\phi e,\,\mathrm{disf}} = \dfrac{m_e^2\omega^4}{8\pi^2 M_e^8}$

Vagnozzi, **LV**, Brax, Davis, Sakstein 21

Detection of solar chameleons

$$\frac{\mathrm{d}R_0(\omega)}{\mathrm{d}\omega} = N_{\mathrm{Xe}} \frac{\mathrm{d}\Phi_{\mathrm{Earth}}}{\mathrm{d}\omega} \sigma_{\phi e}$$



Benchmark:

$$\beta_e = 10^2$$

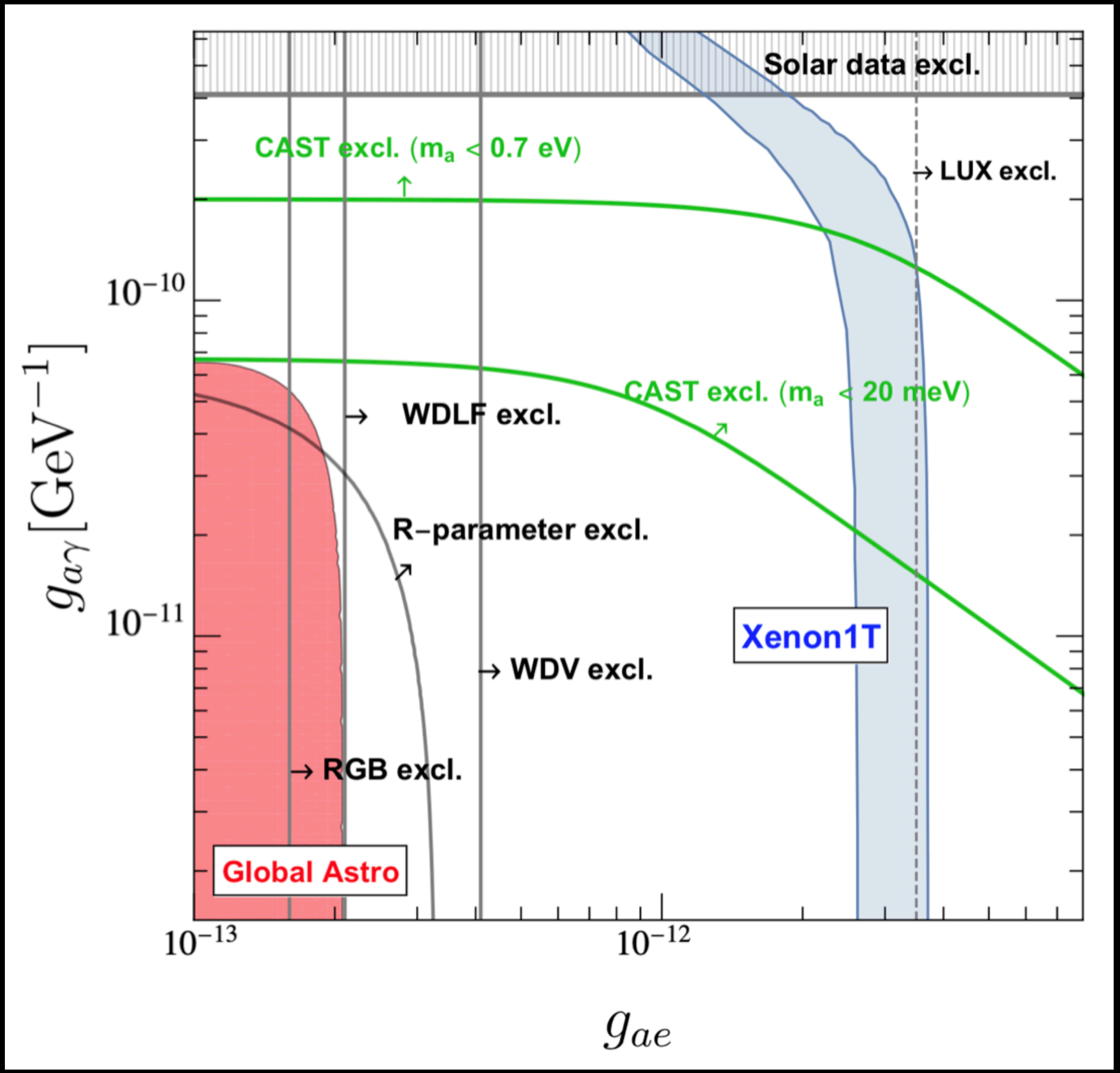
$$\boxed{\begin{aligned} M_e &= 10^{3.7}\,\mathrm{keV} \\ \beta_\gamma &= 10^{10} \end{aligned}}$$

$$M_\gamma = 1000\,\mathrm{TeV}$$

Vagnozzi+21

Stellar bounds

The axion interpretation of the XENON1T excess is disfavored once the best-fit region is compared to what is expected from stellar production in RGB and white dwarfs



di Luzio+20

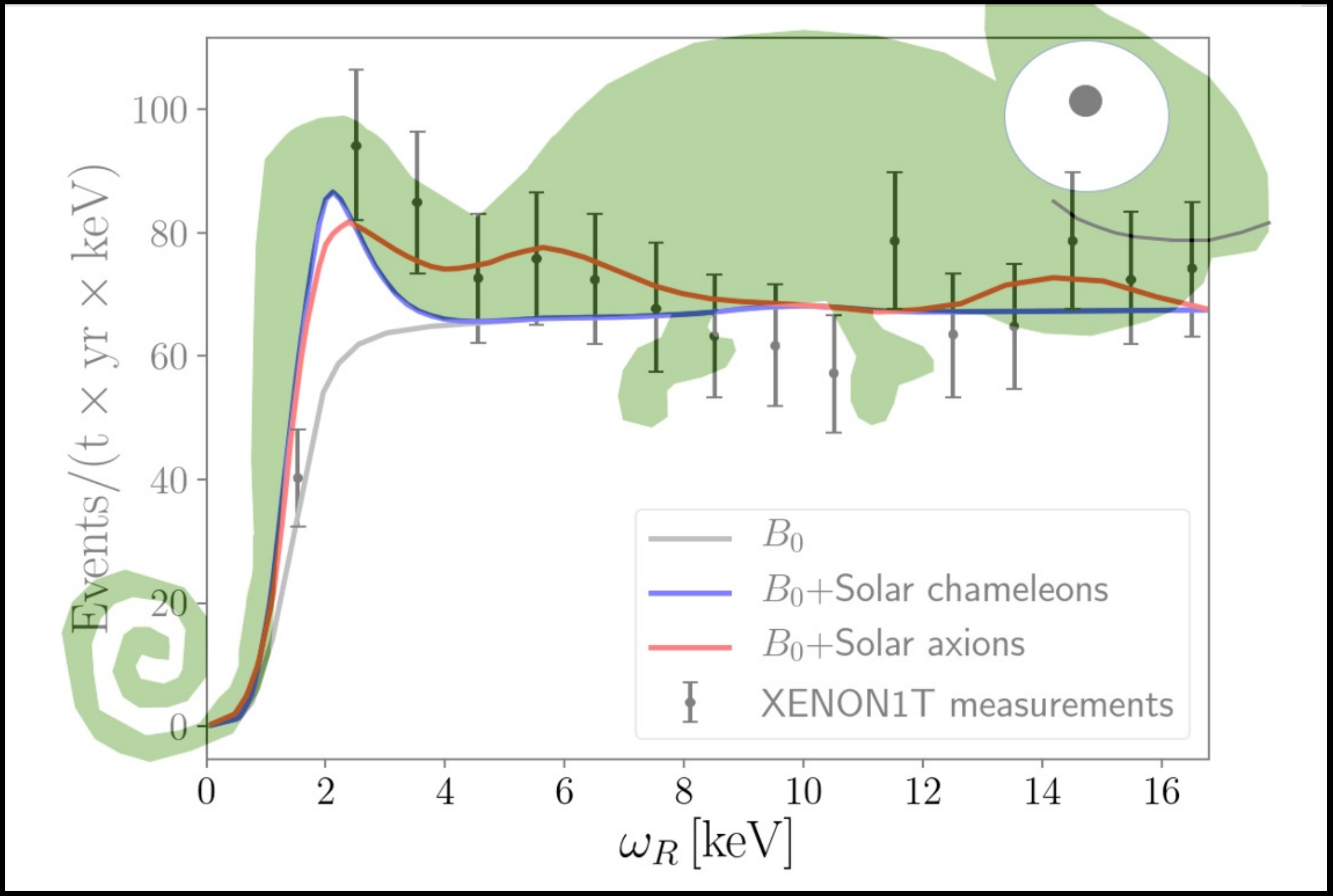
Chameleons are not affected by stellar cooling bounds because of the density-dependence of their mass:

Chameleons are not produced in the cores of stars because of kinematic suppression $m_\phi \gg T_{\rm core}$

Conclusions

The dark energy section can be probed in the future by:

- Cosmological probes
- Collider searches
- Direct detection experiments



The chameleon model could already be accessible in the next generation of DD searches

Its unique features could lead to an identification using complementary searches (ADMX)