Terrestrial, cosmological, and astrophysical direct detection of dark energy

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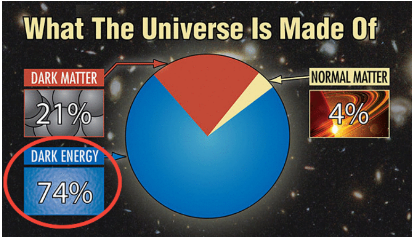
HEP Seminar, UCL, 11 February 2022

Dark Energy

Searching for dark energy off the beaten track



- Part I: what is dark energy (DE)?
- Part II: terrestrial direct detection of (screened) DE
- Part III: cosmological and astrophysical direct detection of DE

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

Student's name (student's institution)

Postdoc's name (postdoc's institution)

Part I: What is dark energy?

How to measure the expansion rate of the Universe...

...and establish cosmic acceleration?

Always a good idea in cosmology: measure distances (to infer expansion rate)

Luminosity distance:

$$d_L(z) = (1+z)\frac{1}{H_0\sqrt{\Omega_K}}\sinh\left[H_0\sqrt{\Omega_K}\int_0^z \frac{dz'}{H(z')}\right]$$

Angular diameter distance:

$$d_A(z) = \frac{1}{1+z}\frac{1}{H_0\sqrt{\Omega_K}}\sinh\left[H_0\sqrt{\Omega_K}\int_0^z \frac{dz'}{H(z')}\right]$$

Standard candles and standard rulers

In practice "infer distances" = "measure fluxes or angles"

Fluxes:

$$d_L = \sqrt{\frac{L}{4\pi f}}$$

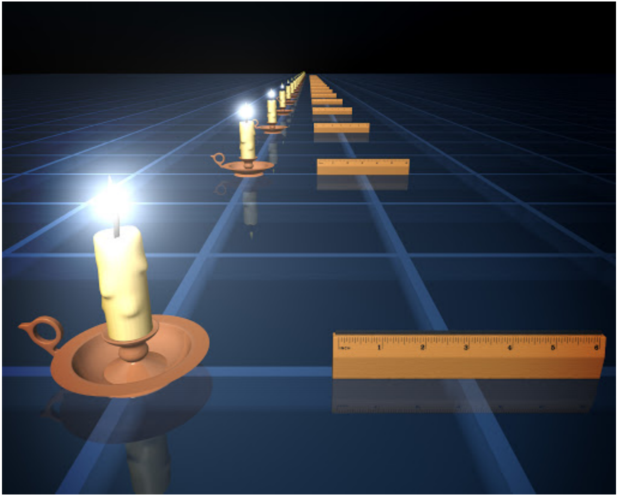
L=intrinsic luminosity

Angles:

$$d_A = \frac{x}{\theta}$$

x=intrinsic physical size

Standard candles and standard rulers



Credits: NASA/JPL-Caltech/R. Hurt (SSC)

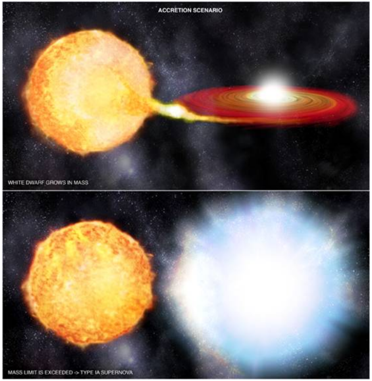
Type Ia Supernovae as standard candles

SNeIa: white dwarf accretes matter from a companion star, exceeds the Chandrasekhar mass limit ($\approx 1.4 M_\odot$), collapses, and explodes

$\implies$ mass of exploding star highly predictable

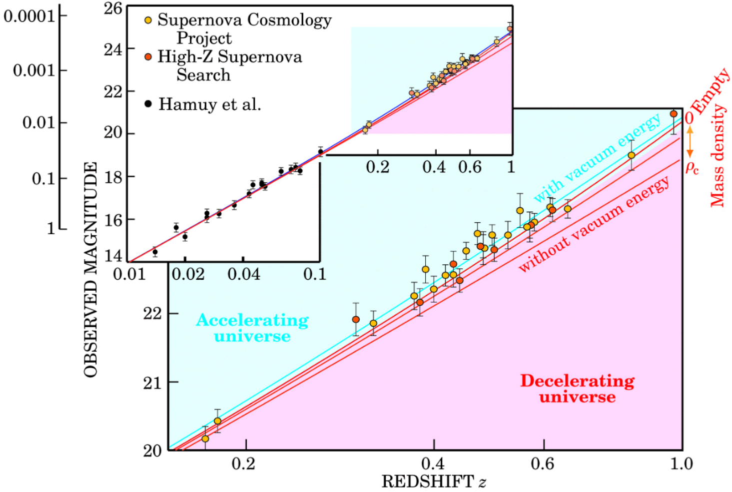
$\implies$ (peak) luminosity $\approx 4 \times 10^9 L_\odot$ highly predictable

$\implies$ SNeIa are excellent standard(izable) candles



Credits: phys.org

1998: SNeIa indicate cosmic acceleration



Credits: Perlmutter, Physics Today 56 (2003) 53

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

What is driving cosmic acceleration?

Second Friedmann equation:

$$\frac{\ddot{a}}{a} = -\frac{4\pi G}{3}(\rho + 3P) \implies w = \frac{P}{\rho} < -\frac{1}{3} \quad \text{to get} \quad \ddot{a} > 0$$

Need to violate the strong energy condition!

"Simplest" solution to get negative pressure: vacuum energy Λ:

$$\frac{\ddot{a}}{a} = [...] + \frac{\Lambda}{3} \implies w_\Lambda = -1$$

Why is $\Lambda \sim (\mathrm{meV})^4$ rather than $\sim (M_{\mathrm{Pl}})^4$? Cosmological constant problem/vacuum energy catastrophe!

What is driving cosmic acceleration?

Scalar fields can naturally produce negative pressure!

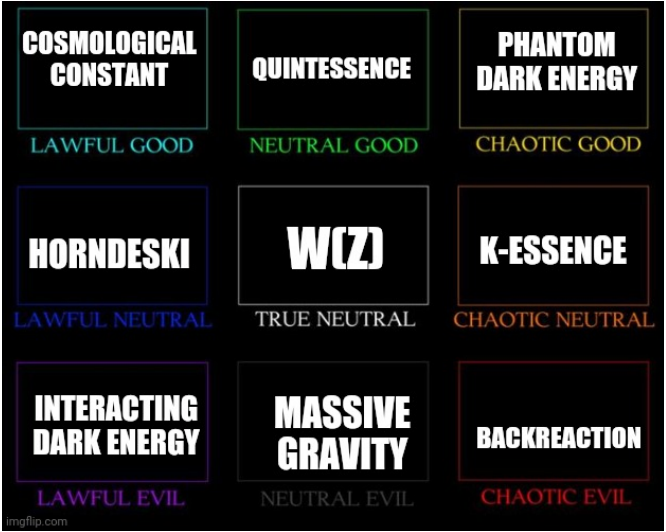
Next-to-“simplest” solution: single, minimally coupled scalar field (“*quintessence*”)

$$\mathcal{L}_\phi = \frac{1}{2}\partial^\mu\phi\partial_\mu\phi - V(\phi) \implies P_\phi = \frac{1}{2}\dot{\phi}^2 - V(\phi)$$

Equation of state:

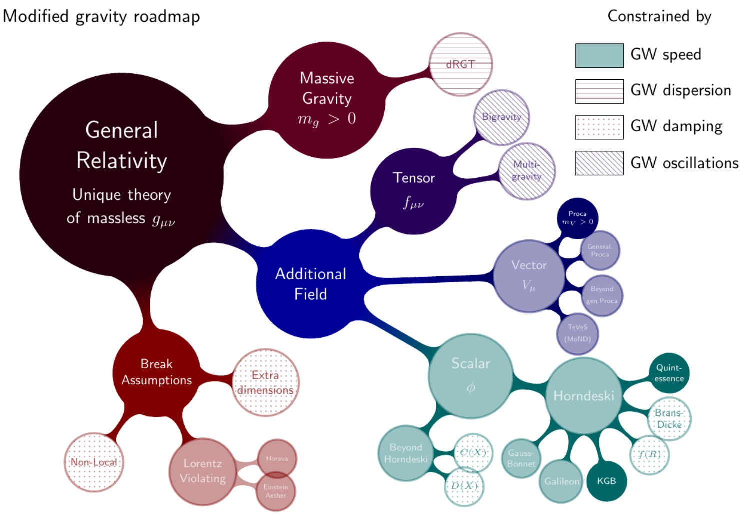
$$w_\phi \equiv \frac{P_\phi}{\rho_\phi} = \frac{\frac{1}{2}\dot{\phi}^2 - V(\phi)}{\frac{1}{2}\dot{\phi}^2 + V(\phi)} \geq -1$$

The zoo of dark energy models



Credits: Tessa Baker

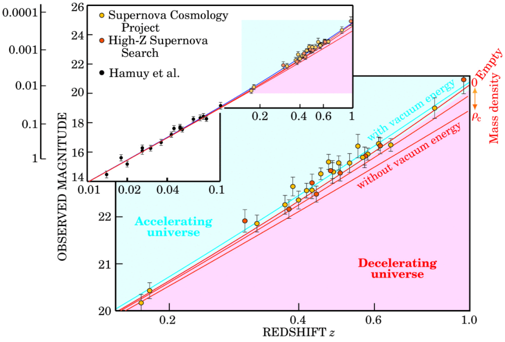
The zoo of dark energy/modified gravity models



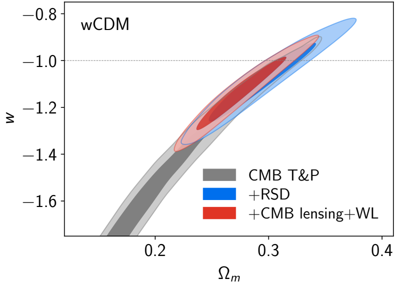
Ezquiaga & Zumalácarregui, Front. Astron. Space Sci. 5 (2018) 44

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?)



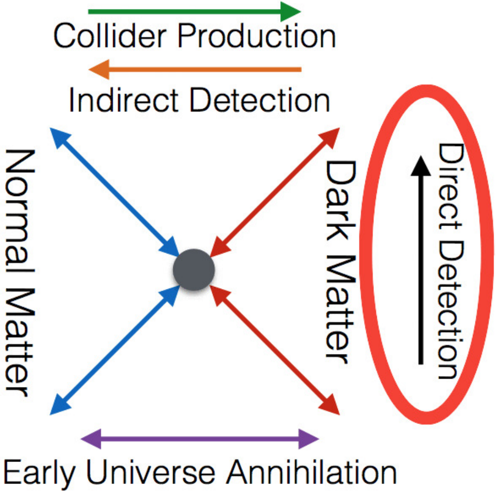
Credits: Perlmutter, Physics Today 56 (2003) 53



eBOSS collaboration, PRD 103 (2021) 083533

Part II:
Terrestrial direct detection of 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

Result/immediate obstacle: long-range fifth forces!

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

Screening

How to satisfy fifth-force tests?

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

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

- $\lambda_5(x) \rightarrow$ **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)

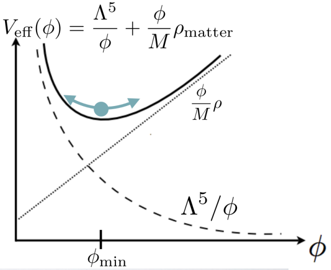
Chameleon screening

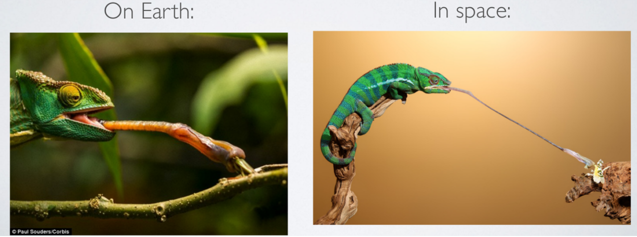
Fifth force range $\lambda(x)$ becomes short in dense environments, scalar field minimizes effective potential determined by coupling to matter

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

$$m_{\mathrm{eff}}^2 = \frac{d^2V_{\mathrm{eff}}}{d\phi^2}\Big|_{\phi=\phi_{\mathrm{min}}} \propto \rho^n\,,\ n>0$$

$$\lambda \sim 1/m_{\mathrm{eff}} \propto \rho^{-n/2}$$





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

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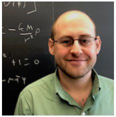
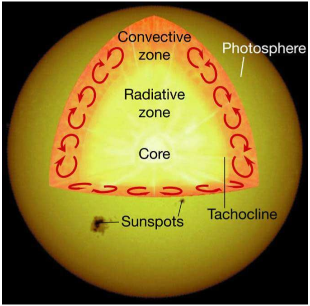

Jeremy Sakstein (Hawaii)

Direct detection of dark energy

Production

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

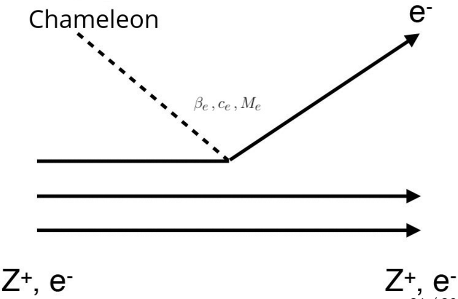
Production in strong magnetic fields of the tachocline



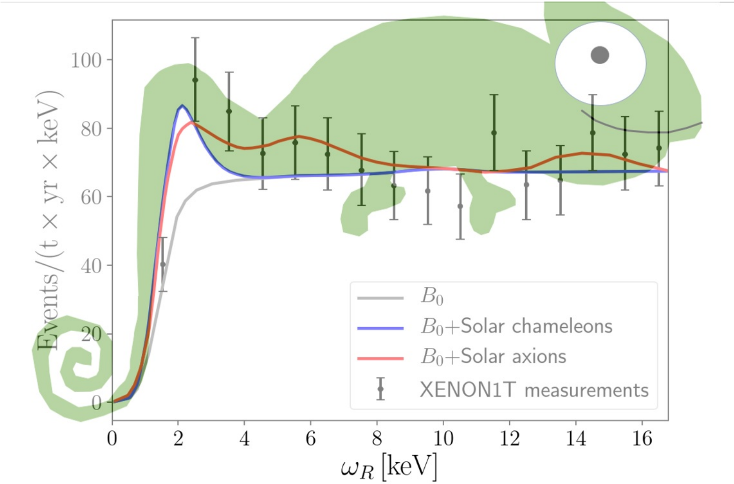
Detection

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

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

To do: think about S2-only analysis?

Part III:

Cosmological and astrophysical direct detection of dark energy

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?

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[1] *Kavli Institute for Cosmology, University of Cambridge, Madingley Road, Cambridge CB3 0HA, UK*
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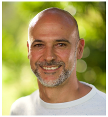
Surprisingly not!

Luca Visinelli (Shanghai)

Olga Mena (Valencia)



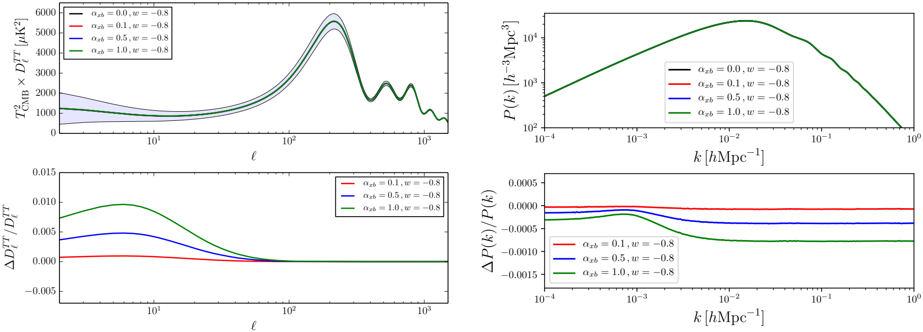
David Mota (Oslo)

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]
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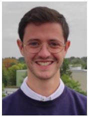
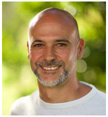
Only one way to find out: run N-body simulations!

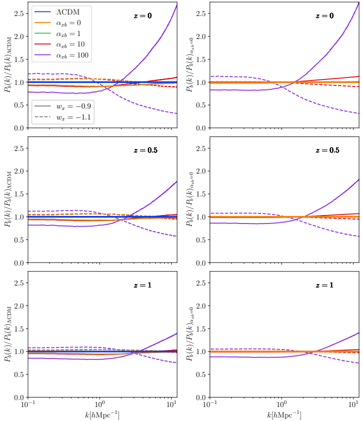

Fulvio Ferlito (MPA Garching)


Marco Baldi (Bologna)

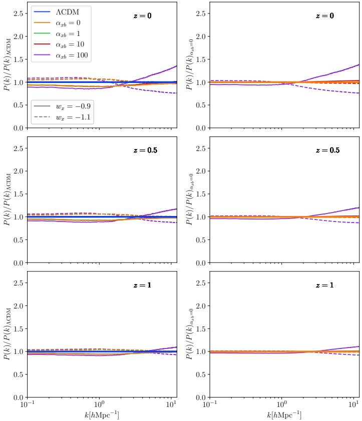

David Mota (Oslo)

N-body simulations of DE-baryon scattering

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



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



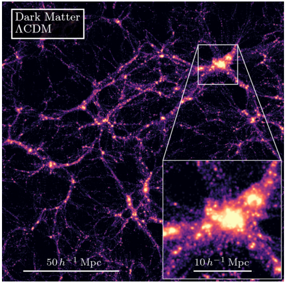
Ferlito, SV, Mota, Baldi, arXiv:2201.04528 (submitted to MNRAS)

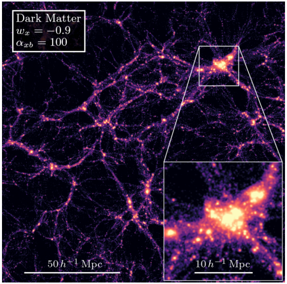
N-body simulations of DE-baryon scattering

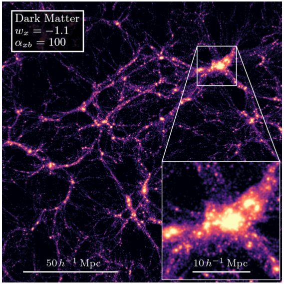
Simulation snapshots:

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

Ferlito, SV, Mota, Baldi, arXiv:2201.04528 (submitted to MNRAS)



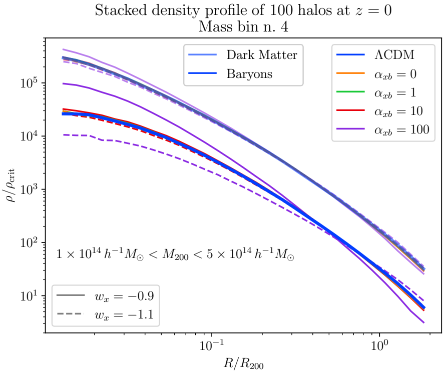




N-body simulations of DE-baryon scattering

Other observables:

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

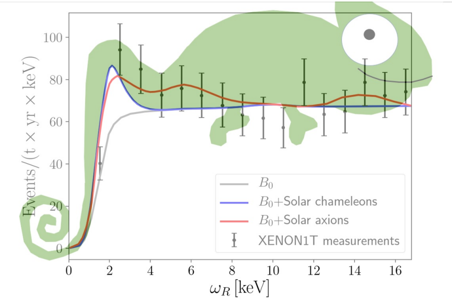


Ferlito, SV, Mota, Baldi, arXiv:2201.04528 (submitted to MNRAS)

Baryon profiles most promising observable to probe DE-baryon scattering

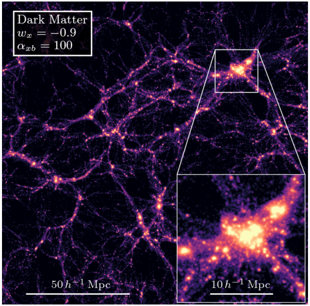
Conclusions

Terrestrial direct detection of dark energy



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

Cosmological and astrophysical direct detection of dark energy



Ferlito, SV, Mota, Baldi, arXiv:2201.04528

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