Benchmarking light new physics FPC approach

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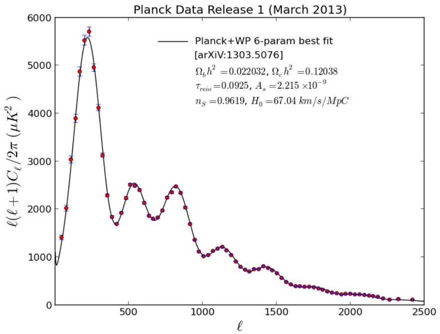
Plan

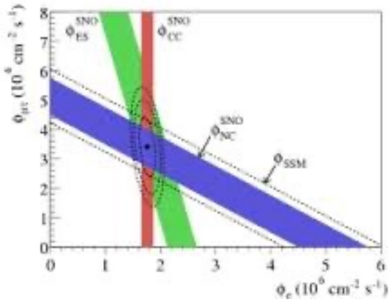
1. Long intro. Variety of experimental activity around the world.
2. Benchmarks for MeV-GeV new physics. Is similar work possible for ultra-light physics?
3. Proposed models for ultra-light New Physics.
4. Outlook

Motivations for new physics

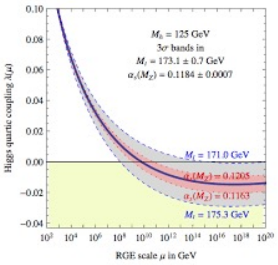
1. *Precision cosmology:* 6 parameter model (Λ-CDM) correctly describes statistics of 10^6 CMB patches. Existence of dark matter and dark energy. Strong evidence for inflation.



2. *Neutrino masses and mixing:* Give us a clue [perhaps] that there are new matter fields beyond SM. Some of them are not charged under SM, and can lead to lepton number violation.



3. *Theoretical puzzles:* Strong CP problem, vacuum stability, hints on unification, smallness of m_h relative to highest scales (GUT, M_{Planck})



4. *"Anomalous results":* muon g-2, B-physics anomalies, SBN neutrino anomalies, Hubble constant tension etc.

SM as an Effective Field Theory

Standard Model Lagrangian includes all terms of canonical dimension 4 and less, consistent with three generations of quarks and leptons and the SU(3)*SU(2)*U(1) gauge structure at classical and quantum levels.

$\mathcal{L}_{2020\text{s}} = - m_H^2 \, (H^+_{SM} H_{SM}) + \text{all dim 4 terms } (A_{SM}, \; \psi_{SM}, \; H_{SM}) +$

Neutrino mass operators (e.g. effective Dim=5)

+(W.coeff. $/\Lambda^2$) × Dim 6 etc $(A_{SM}, \; \psi_{SM}, \; H_{SM})$ + …

all lowest dimension portals $(A_{SM}, \; \psi_{SM}, \; H, \; A_{DS}, \; \psi_{DS}, \; H_{DS})$ × portal couplings

+ dark sector interactions $(A_{DS}, \; \psi_{DS}, \; H_{DS})$

SM -- Standard Model

DS – Dark Sector or FIPs

How to look for New Physics ?

1. High energy colliders.

$$\frac{1}{\Lambda^2}(\bar{e}e)(\bar{q}q) \;\rightarrow\; \sigma \propto \frac{E^2}{\Lambda^4} \;\rightarrow\; \Lambda > 10\,\mathrm{TeV}$$

2. Precision measurements (especially when a symmetry is broken)

$$\frac{1}{\Lambda_{\rm CP}^2}(\bar{e}i\gamma_5 e)(\bar{q}q) \;\rightarrow\; \mathrm{EDM},\, \frac{1}{\Lambda_{\rm CP}^2} < 10^{-10}G_F \;\rightarrow\; \Lambda_{\rm CP} > 10^7\,\mathrm{GeV}$$

3. Intensity frontier experiments where abnormal to SM appearance or disappearence can be searched.

$$pp \;\rightarrow\; \pi, K, B \;\rightarrow\; HNL + X \;\rightarrow\; HNL\ \text{decay to SM}$$

4. DM searches *Atoms + DM → visible energy*

(*Magnetized cavity + axion → EM radiation*)

All four strategies are being actively pursued by particle physics community.

PBC benchmarks for MeV - M_W window

Benchmark Cases (PBC, 2018)

PBC – “Physics Beyond Colliders”

1. *Dark photon*
2. *Dark photon + light dark matter*
3. *Millicharged particles*
4. *Singlet scalar mixed with Higgs*
5. *Quartic-dominated singlet scalar*
6. *HNL, e-flavour dominance*
7. *HNL, μ-flavour dominance*
8. *HNL, τ-flavour dominance*
9. *ALPs, coupling to photons*
10. *ALPs, coupling to fermion*
11. *ALPs, coupling to gluons*

……

Vector

scalar

HNL

ALPs

Experimental proposals, mostly CERN

SHiP	*Beam Dump*
NA62+	*Flavour, possible BD*
FASER	*LHC add-on*
MATHUSLA	*large LHC add-on*
Codex-B	*LHC add-on*
MilliQan	*LHC add-on*
NA64	*missing momentum*
KLEVER	*flavour*
REDTOP	*fixed target*
IAXO	*axion exp*
ALPs-II	*axion exp*
……..	

PBC benchmarks help to focus efforts *on new of sub-EW New Physics, and helps to compare sensitivity of existing and proposed experiments*

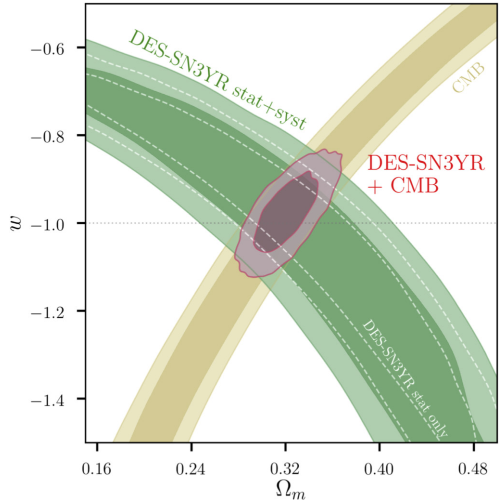
Experimental probes of ultra-light [sub-eV] fields

Ultra-light fields (ULFs) offer additional signatures: coherent forces (e.g. correction to Newton/Einstein gravity) due to ϕ exchange, non-trivial evolution of ϕ in time, and as a consequence e.g. $\alpha(\phi(t))$, breaking of spatial anisotropy by $\nabla\phi(x)$ etc.

- Precision cosmology (and astrophysics)
- Cavity searches of axions and dark photons
- Precision tests of gravitational interaction and equivalence principle
- Precision spectroscopy, clock comparison and search of "changing couplings"
- Search of "Lorentz violation" and preferred direction in Hughes-Drever type experiments.
- Search of CPT violation in experiments with antimatter.

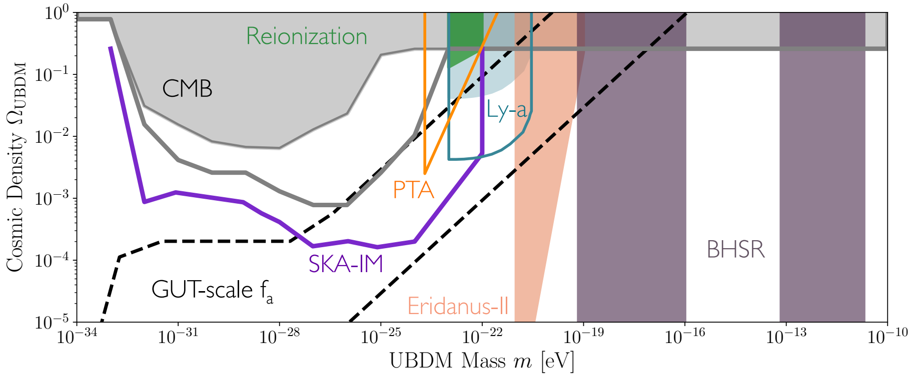
Cosmology constrains evolving scalar fields

▪ Time-dependent dark energy



- Cosmology puts strong limits on ultra-light evolving scalar/vector fields, by constraining the equation of state for dark energy (DE). So far DE shows consistency with Λ [and w will be tested to O(1%) level], but given other internal tensions (H_0 and σ_8) modifications by ultra-light fields are still a possibility.

▪ Ultra-light dark matter

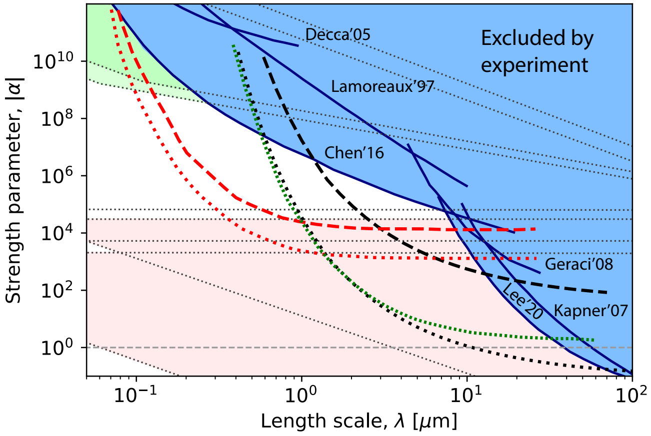


- Ultralight & very weakly interacting fields can still be constrained in astrophysics and cosmology, as their clustering properties differ from “WIMP-style” DM. In certain mass range, ULFs can extract angular momentum from BH via super-radiance.

From Marsh and Hoof, 2021

ULF can modify gravitational interactions

- Tests of gravitational forces, on the ground,



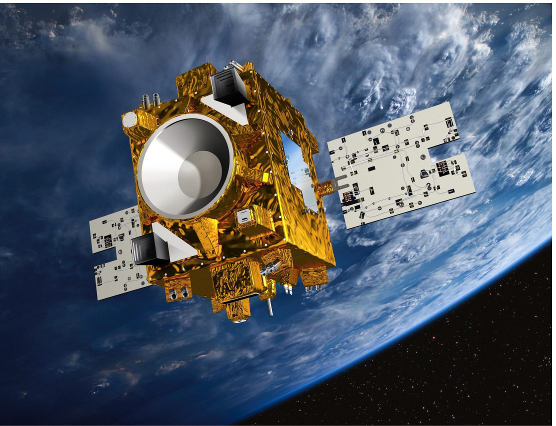
Moore and Geraci, 2021

- New technologies are emerging: atomic interferometry; levitated microspheres. Allows to probe gravity at shorter distances

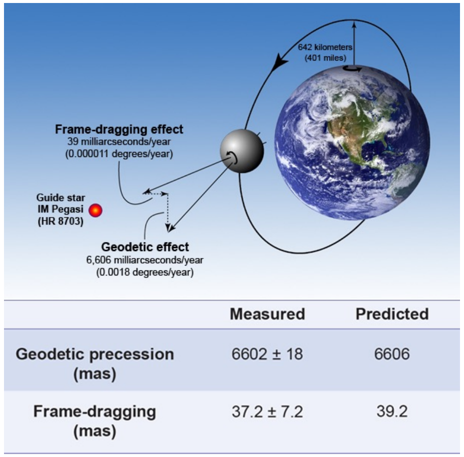
- and in space

MICROSCOPE mission: final results of the test of the Equivalence Principle

$$\eta(\mathrm{Ti},\mathrm{Pt}) \;=\; [-1.5 \pm 2.3\ (\mathrm{stat}) \pm 1.5\ (\mathrm{syst})]\ \times 10^{-15}$$



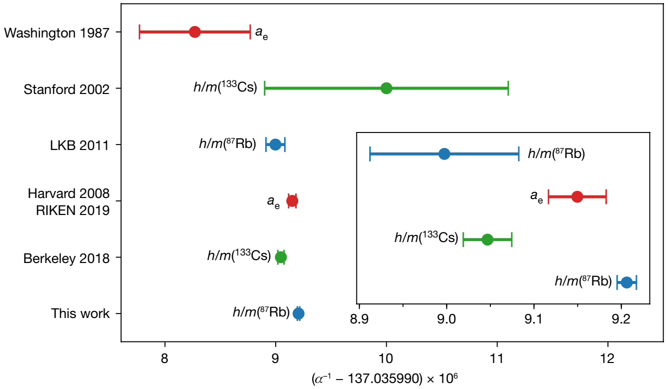
- Gravity Probe B, and especially MICROSCOPE have shown how much sensitivity can be gained in space. Future missions may perfect tests of GR, and have a new breakthrough sensitivity to ULFs.



	Measured	Predicted
Geodetic precession (mas)	6602 ± 18	6606
Frame-dragging (mas)	37.2 ± 7.2	39.2

Breakthroughs in AMO → constraints on changing couplings

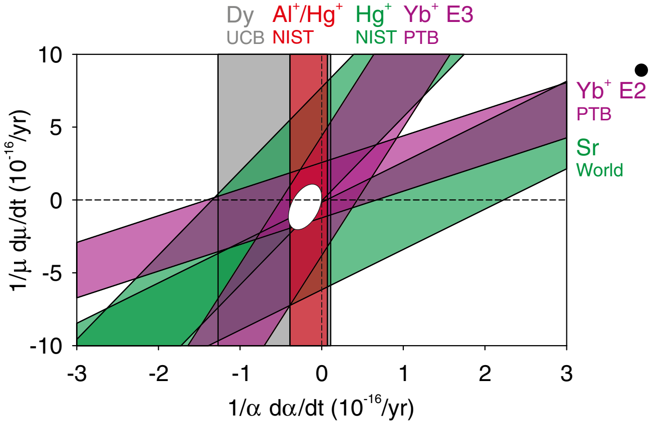
- Ever more precise clocks/ atomic interferometry.



Morel et al, 2020

- New results in recent years on precision spectroscopy allows to refine values of SM couplings, including α_{EM} and proton charge radius.

- Tests of constancy of couplings.

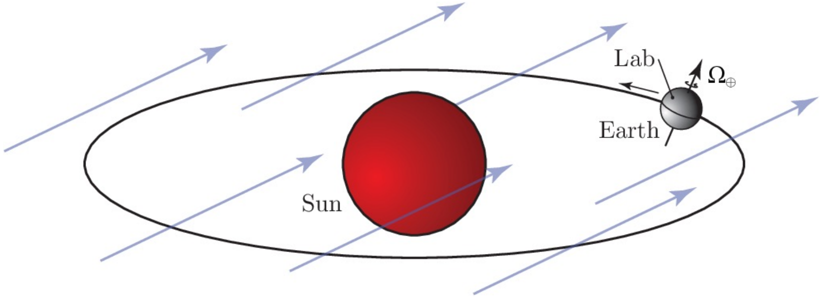


Huntemann et al, 2014

- Progress with clocks translates to probes ULF models that renormalize couplings and evolve in time (drift, oscillate, experience transient shift). Precision results on the ground can be compared to distant (z~1) absorption lines (Flambaum et al).

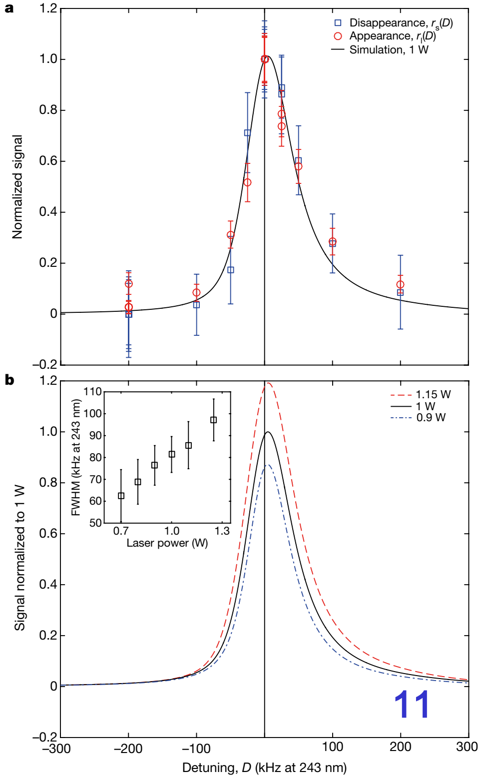
Precision magnetometry, tests of CPT

- Search of anisotropy/ Lorentz-violation in the Hughes-Drever type experiments.



- Search of preferred directions (caused e.g. by a gradient of the scalar field) has reach the level of sensitivity ~ 10^{-33} GeV for the energy associated with anisotropic shift. (Brown et al, 2010)

- Experiments with antiparticles.
  - *ALPHA collaboration* at CERN has performed precision measurements of atomic transitions in anti-hydrogen, complementing existing sensitive searches in Kaon and B-meson systems, as well as p-anti-p. Next frontier – *gravitational universality of antimatter.* Challenge for theorists: is there a well-motivated physics (in ULF context or otherwise) that can lead to apparent CPT violation AND not being tested with ordinary matter?



Possible Interactions

Let us call by ϕ, ϕ_1, ϕ_2, … - ultra-light scalar fields. (Perhaps evolving on cosmic scales, or perhaps oscillating around a minimum – contributing to the Ω_{matter}). Let us represent SM field by an electron, and a nucleon.

Interactions can be organized as "portals": coeff × $O_{\text{dark}}O_{\text{SM}}$.

$$\frac{\partial_\mu \phi}{f_a} \sum_{\text{SM particles}} c_\psi \bar{\psi}\gamma_\mu\gamma_5\psi \quad \text{axionic portal}$$

Torque on spin

$$\frac{\phi}{M_*} \sum_{\text{SM particles}} c_\psi^{(s)} m_\psi \bar{\psi}\psi \quad \text{scalar portal}$$

Shift of ω + extra gr. force

$$\frac{\phi_1^2+\phi_2^2}{M_*^2} \sum_{\text{SM particles}} c_\psi^{(2s)} m_\psi \bar{\psi}\psi \quad \text{quadratic scalar portal}$$

Shift of ω + extra force

$$\frac{\phi_1 \partial_\mu \phi_2}{M_*^2} \sum_{\text{SM particles}} g_\psi \bar{\psi}\gamma_\mu\psi \quad \text{current – current portal}$$

Extra force

1. Can we use a similar to PBC strategy and highlight a set of ULF benchmark models?

2. How to approach the problem of classifying them?

Main principles behind existing PBC benchmarks

1. Relative simplicity (a few BSM particles added), parameter space: 2-4 parameters.
2. Renormalizability for all but axion models. Low(est) dimension portals = no obvious UV suppression.
3. Technical naturalness in many cases (i.e. radiative corrections to masses of e.g. dark photon, or HNLs are under control.).

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Sub-eV benchmark models ?

(Will be tailored to mostly cover new fields eV-and-below physics)

1. Relative simplicity (a few BSM particles added), parameter space: 2-4 parameters.
2. ~~Renormalizability for all but axion models. Low(est) dimension portals = no obvious UV suppression.~~
3. Technical naturalness in many cases (i.e. radiative corrections to masses of e.g. dark photon, or HNLs are under control.).

- Simplicity is not a bad criterion *to get organized*.
- Renormalizability is not a criterion here: $\frac{h_{\alpha\beta}}{M_{Planck}}\ T_{\alpha\beta}$ - gravity itself is not renormalizable.

The issue of technical naturalness

Non-derivative interactions of light bosonic fields generate correction to bosonic self interaction (e.g. mass term) orders of magnitude larger than the assumed value for the mass: necessitates fine-tuned cancellations.

Large fraction of light new physics models suffers from this problem.

Maybe we could view technical naturalness as a "soft criterion": give some more visibility to models where it is manifest, but not entirely discard models where it is violated. Among unnatural models, state caveats, pick those that lead to the most interesting physical effects.

(See A. Hook's work for some ”Houdini tricks” to get out of straightjacket of technical naturalness)

Another closely related issue: low scale of UV completion, many models often *require* Λ to be below the weak scale, and it is a problem.

Tentative list (blue color – obeying naturalness)

- Non-interacting light scalar/vector fields modifying cosmology/astrophysics.
- ALPs + mass term + pseudoscalar coupling to photons and spins. (Softly broken shift symmetry). Maybe DM.
- ALPs with non-derivative couplings, such as to EDM etc.
- "Disformal couplings" = light scalar coupled derivatively to stress energy tensor: $T_{\alpha\beta}\,\partial_\beta\varphi\partial_\alpha\,\varphi/\Lambda^4$. $H^\dagger H\partial_\beta\varphi\partial_\alpha\,\varphi/\Lambda^2$
- Scalar field models (oscillating scalar, or smoothly evolving scalar) + couplings a. Higgs portal (relaxion), b. to $T_{\alpha\alpha}$, c. to spins, d. to $F_{\alpha\beta}\,F_{\alpha\beta}$ etc. Saturating dark matter is an option. (Some versions could be natural is cutoff is low.)
- Dark vector dark matter: a dark photon saturating dark matter, b dark B-L saturating dark matter.
- Light thermal freeze-in dark matter (Mass > keV), with possibly sub-eV light mediators.
- Chameleon-type models: a Simplest $\frac{T_{\alpha\alpha}\varphi^2}{\Lambda^2}$, b Chameleon with additional matter couplings?
- Models with nontrivial spatial pattern: DM out of lumps of light fields (Q-balls)

Examples of models & parameter space

M0. $\mathcal{L} = \frac{1}{2}(\partial\phi)^2 - V(\phi)$. It is reasonable to try several generic possibilities. E.g. models with "late motion of field" when there is a constant linear forcing, and the value of the field is $\phi(z = 0) = 0$ by construction. Also possible is to have B: some massive field with some initial condition at early times,

$$A: \ V(\phi) = V_0 + V'\phi, \quad \phi(z=0) = 0, \tag{1}$$

$$B: \ V(\phi) = V_0 + \frac{1}{2}m_0^2(\phi)^2, \quad \phi(\text{large } z) = \phi_0 \tag{2}$$

$$C: \quad V(\phi) = V_0 + V_1\cos(\phi/f), \quad \phi(\text{large } z) \sim f \tag{3}$$

M1: ALP models (obeying technical natural)

$$\mathcal{L} = \frac{1}{2}(\partial a)^2 - \frac{1}{2}m_a^2 a^2 - \frac{a}{4f_\gamma}F_{\mu\nu}\tilde{F}_{\mu\nu} - \sum_{i=e,p,n}\frac{\partial_\mu a}{f_i}\bar{\psi}_i\gamma_\mu\gamma_5\psi_i.$$

NB: KSVZ and DFSZ choices are totally adequate.

These models are thoroughly analyzed with last caveats of ULF-style dark matter being sorted out.

Examples of models & parameter space

M0, Case A, i.e. linear potential: Recasting constraints on w_{DE} and measurement of Ω_Λ onto the constraint on V_0 and V'.

$$\dot{\phi} \simeq \frac{V'}{3H_0}; \quad w = \frac{p}{\rho} = \frac{-V + (\dot{\phi})^2/2}{V + (\dot{\phi})^2/2} \simeq -1 + \frac{(\dot{\phi})^2}{V_0}$$

10% constraint on w ($-1 < w < -0.9$) implies small value of V'

$$\boxed{\left|\frac{V'}{V_0}\right| < \frac{1}{\bar{M}_{Pl}} \times \frac{\sqrt{0.3}}{\Omega_\Lambda^{1/2}}}$$

For the purpose of comparing experiments, this is the simplest model for an evolving scalar that one can use.

Examples of models & parameter space

M2. Ultra-light vector fields can have the following Lagrangian:

$$A: \quad \mathcal{L} = -\frac{1}{4}V_{\mu\nu}^2 - \frac{\epsilon}{2}V_{\mu\nu}F_{\mu\nu} + \frac{1}{2}m_V^2 V_\mu^2$$

$$B: \quad \mathcal{L} = -\frac{1}{4}V_{\mu\nu}^2 + \frac{1}{2}m_V^2 + \mathcal{L}_{SM}(D_\mu \to D_\mu - iQ_{B-L}g_{B-L}V_\mu).$$

The parameter space is evidently $\{m_V, \epsilon\}$ and $\{m_V, g_{B-L}\}$. (If m_V is tiny, the model may prefer Dirac SM neutrinos).

Some interest to these models in connection with DM and tests of gravity

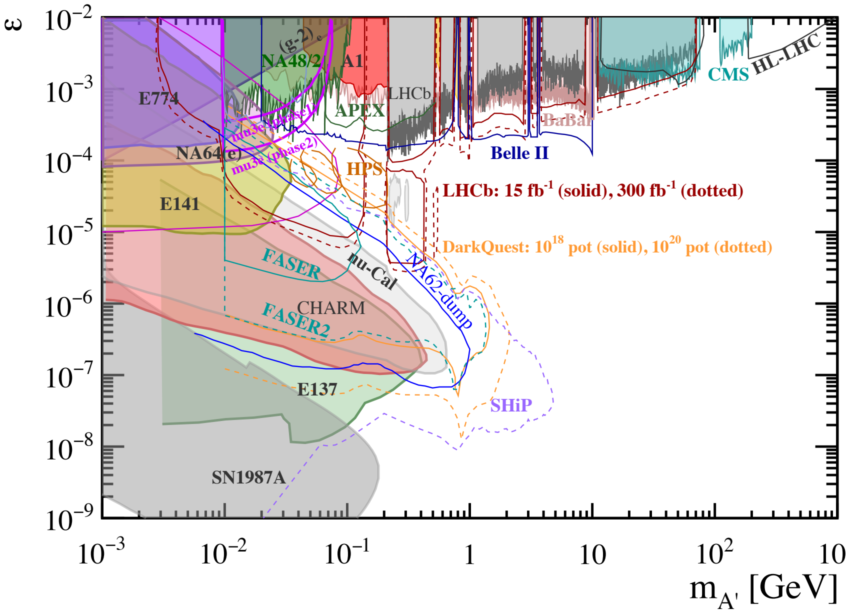
M3. The model has the same parameter set as Benchmark model 2 (PBC set). Specifically, one takes small $m_{A'}$, and $m_\chi > O(\text{keV})$:

$$\mathcal{L} = -\frac{1}{4}V_{\mu\nu}^2 - \frac{\epsilon}{2}V_{\mu\nu}F_{\mu\nu} + \frac{1}{2}m_V^2 + \bar{\chi}(i\gamma_\mu D_\mu - m_\chi)\chi,$$

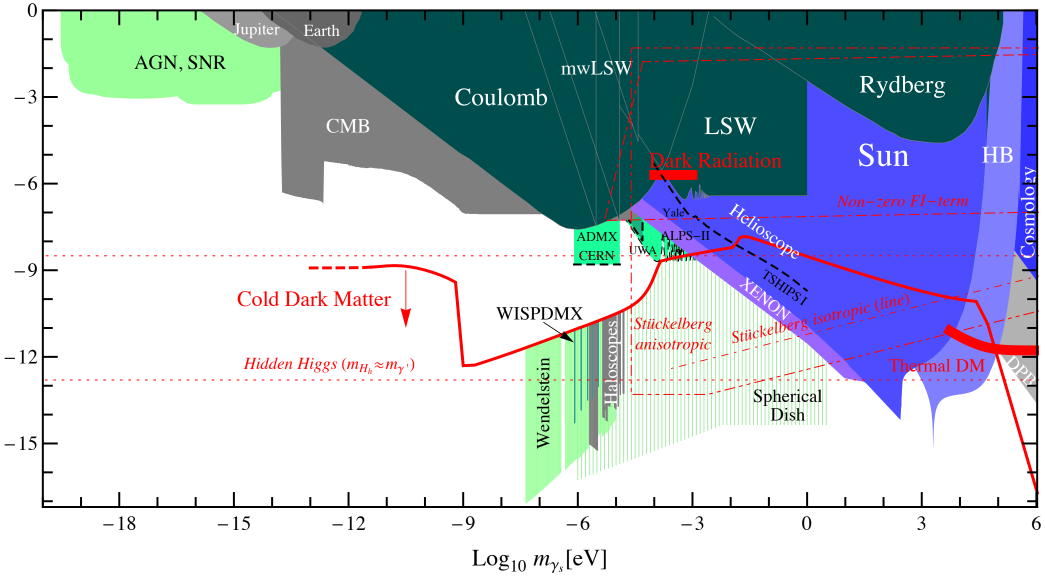
parameter space is $\{m_V, \epsilon, m_\chi, g_d\}$

Very low m_V and keV-to-MeV scale m_χ has been a "go-to" model for freeze-in DM, with large efforts in light WIMP direct detection community to meet an meV-to-eV energy release challenge.

Examples of models & parameter space



PBC, MeV and above dark photon plot (BC-1)



Dark photon below MeV, Jaeckel et al.

Examples of models & parameter space

M4. To the scalar models encountered before (M0) we add

$$A: \quad \mathcal{L}_{int} = A\phi(H^\dagger H - \langle H^\dagger H \rangle)$$

$$B: \quad \mathcal{L}_{int} = \frac{\phi}{M_T} \times T^\mu_\mu(SM)$$

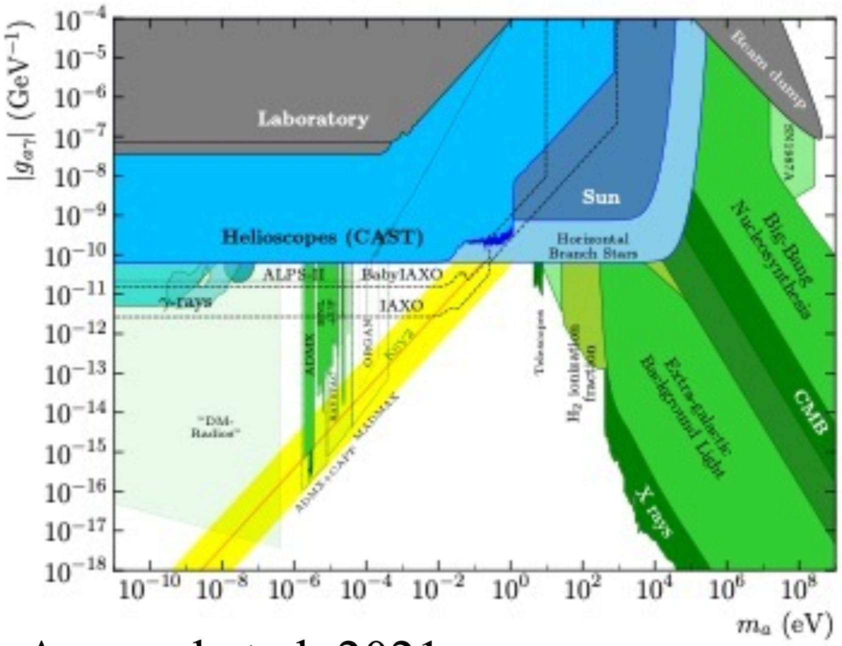
$$C: \quad \mathcal{L}_{int} = \frac{\phi}{4M_\gamma} \times (F^{EM}_{\mu\nu})^2 + \frac{\phi}{4M_e} \times \bar{e}e + \frac{\phi}{4M_N}\bar{N}N$$

$$D: \quad \mathcal{L}_{int} = -\sum_{i=e,p,n} \frac{\partial_\mu \phi}{M_i} \bar{\psi}_i \gamma_\mu \gamma_5 \psi_i$$

$$E: \quad \text{?? Same structures with } \phi \to \phi^2.$$

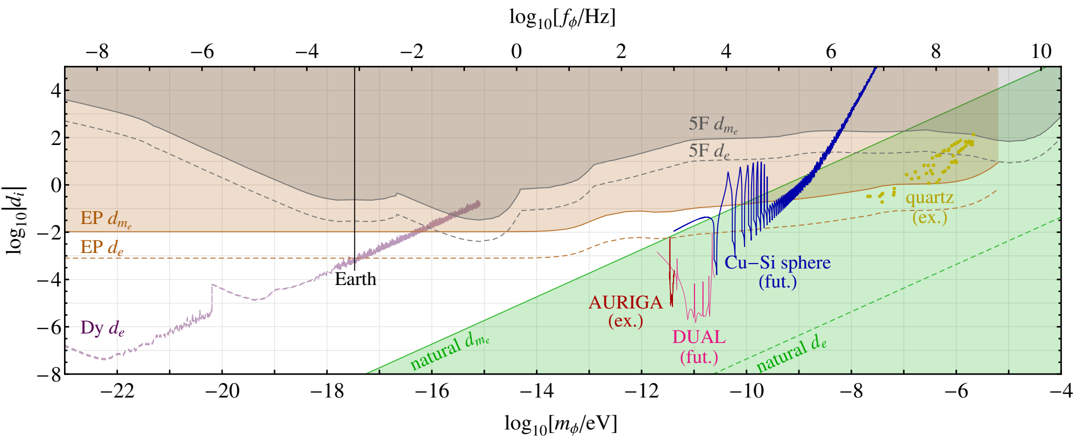
This is phenomenologically most diverse class, leading to a variety of interesting phenomena.

Axion and dark scalar



Agrawal et al, 2021

ALP , ALP as DM plot. Any point can be considered “natural” if mass m_a is supplied by hand. *Loop feedback on mass is small.*



”Relaxion”-type plot: mostly unnatural regions are probed by ongoing atomic exp. *Loop feedback on mass is large.*

Arvanitaki et al., 2015

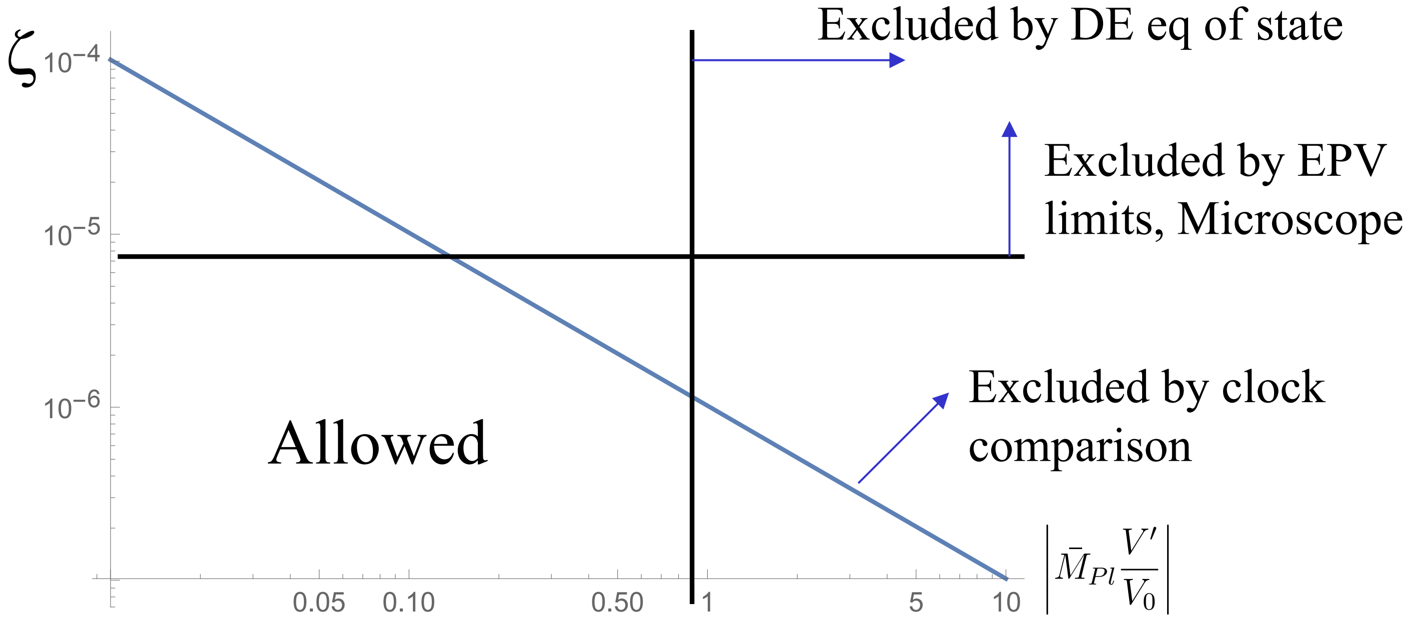
Modified Bekenstein model

Combining simplest potential and simplest coupling, we get:

$$\mathcal{L} = \frac{1}{2}(\partial_\mu \phi)^2 - (V_0 + V'\phi) + \frac{\phi \times \zeta}{4\bar{M}_{Pl}} \times (F^{EM}_{\mu\nu})^2$$

This model predicts: 1. w >-1, 2. new attractive force violating equivalence principle, 3. Linear change of EM fine structure constant in time.

$$\frac{1}{H_0}\frac{\dot{\alpha}}{\alpha} = \zeta\Omega_\Lambda \times \bar{M}_{Pl}\frac{V'}{V_0}$$



Excluded by DE eq of state

Excluded by EPV limits, Microscope

Excluded by clock comparison

Nice complementarity of cosmological, gravitational and AMO probe

Examples of models & parameter space

M5. The parameter space is the mass of "disformal" scalar and its coupling, $\{m_\phi, \Lambda\}$. (Representative couplings are given by $T_{\alpha\beta}\partial_\beta\phi\partial_\alpha\phi/\Lambda^4$ or $H^\dagger H\partial_\alpha\phi\partial_\alpha\phi/\Lambda^2$). On theoretical grounds, we expect that coupling Λ is larger than the EW scale.

Most probes of the model are colliders, as well as via $N_{\rm eff}$ (Weinberg)

M6. Chameleon or "symmetron"-type models have a large variety. For example, one can consider

$$\mathcal{L} = \frac{1}{2}(\partial\phi)^2 - \frac{1}{2}m_\phi^2\phi^2 - \lambda_\phi\phi^4 + \lambda_{H\phi}(H^\dagger H - \langle H^\dagger H\rangle)\phi^2.$$

In-medium value of $H^\dagger H - \langle H^\dagger H\rangle$ is non-zero, and if m_ϕ^2 is small, it has consequences for spatial distribution of ϕ, especially if it is dark matter. If m_ϕ^2 is negative, ϕ field will have a nonzero v.e.v. in vacuum, and matter effects can restore symmetry.

Motivates comparing experiments in rarified vs dense environments.

Examples of models & parameter space

M7. Parameter space of models with extended DM objects are difficult to describe in a few numbers. Let us approximate DM field profile inside a "defect " by some Gaussian field:

$$\phi(r) = \phi_0 \times \exp(-r^2/(2R^2))$$

ϕ_0 and R will describe the amplitude and the extent of the field configuration, that will have a mass $\propto \phi_0^2 R$, so that number density of these objects n should obey $\sim n\phi_0^2 R \leq \rho_{DM}$. The interaction of such an object with matter can be described by Eqs. (7)-(11). Gives transient effects

M8. Finally, an ULF coupling to an EDM can be described as

$$\mathcal{L}_{\mathrm{EDM}\phi} = \sum_{i=e,n,p} \phi \frac{d_i}{f} \psi_i \sigma_{\mu\nu} \tilde{F}_{\mu\nu} \psi_i$$

Gives an oscillating EDM

The parameter space of the model is then $\{m_\phi, d_i/f, \Omega_\phi\}$.

M9. Models with eV and sub-eV sterile neutrinos.

A lot more work is needed to map out constraints on parameter space of all benchmarks

Conclusions

1. Because of the increased experimental activity, the community may want to expand “benchmark models” into the sub-eV regime. (These cases apply only to a small subset of PBC experiments)

2. One should rethink the main criteria how these benchmark cases are assembled. (E.g. renormalizability is no longer a criterion, but some semblance of simplicity still is. *How to approach technical naturalness*?)

3. If O(10-15) new sub-eV benchmark cases are assembled, it may start playing “focussing role” (as PBC benchmarks play). It is worth pursuing.