Status of Dark Photons

Jim Cline, McGill University

with G. Alonso-Álvarez et al.

arXiv:2107.07524, 2111.04744,

2301.04152, 2309.13105, 2401.14450

Moriond EW&UT, 29 March, 2024

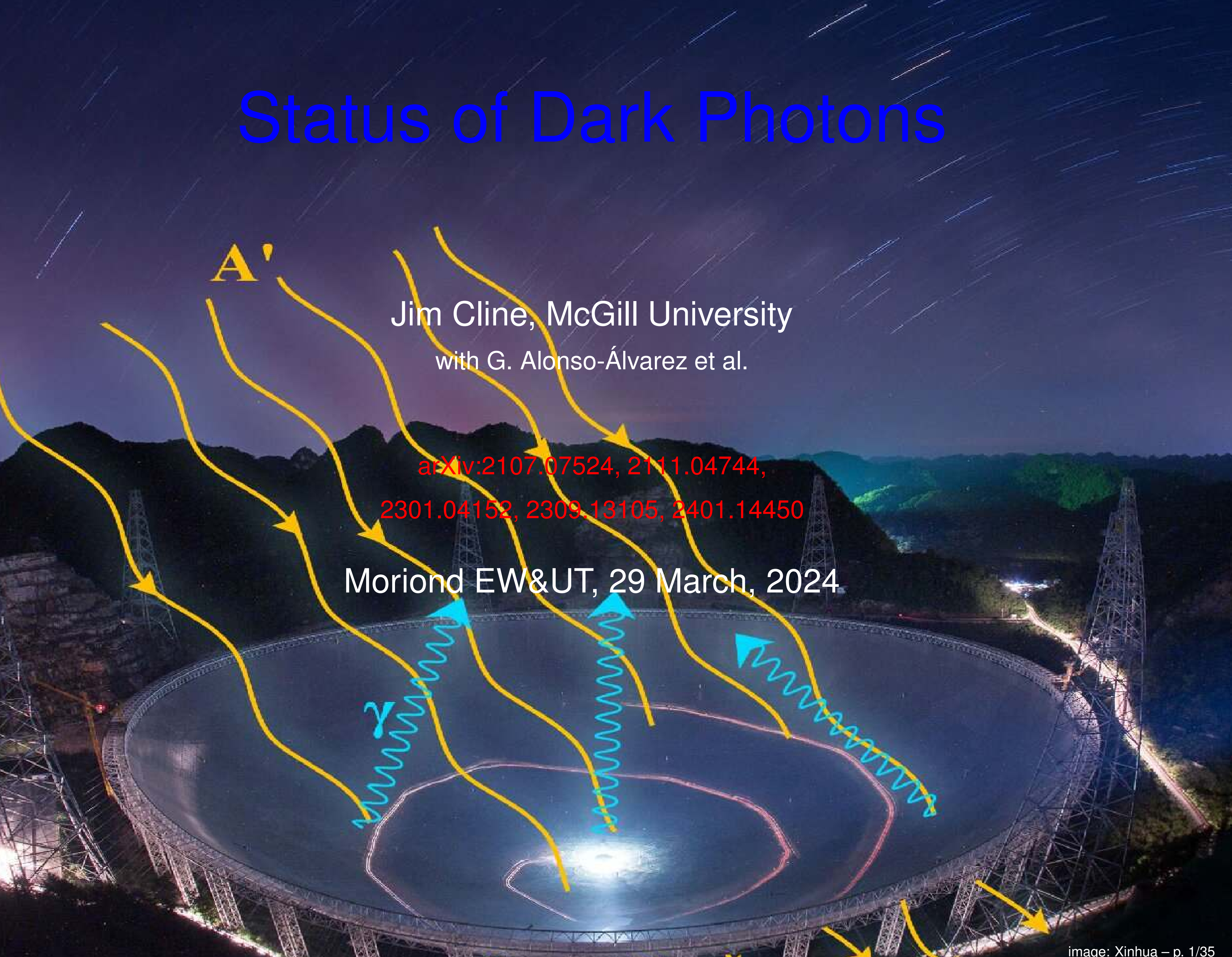
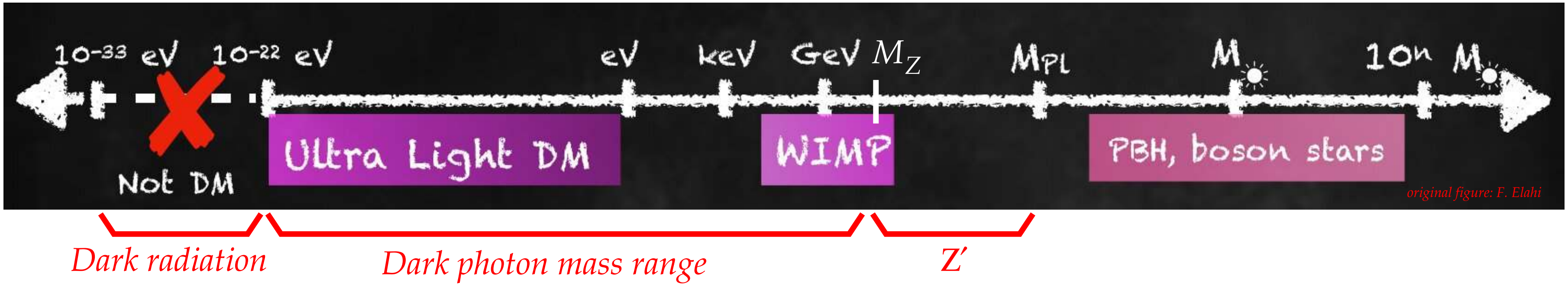


image: Xinhua

What qualifies as a dark photon?



I take

$$10^{-22}\,\mathrm{eV} < m_{A'} < m_Z;$$

I will not discuss massless A' (relevant for dark atoms & millicharged particles)

Dark photon can function as:

- dark matter
- dark force mediator
- both!

Can interact with SM via:

- kinetic mixing
- direct gauge coupling

Kinetic mixing

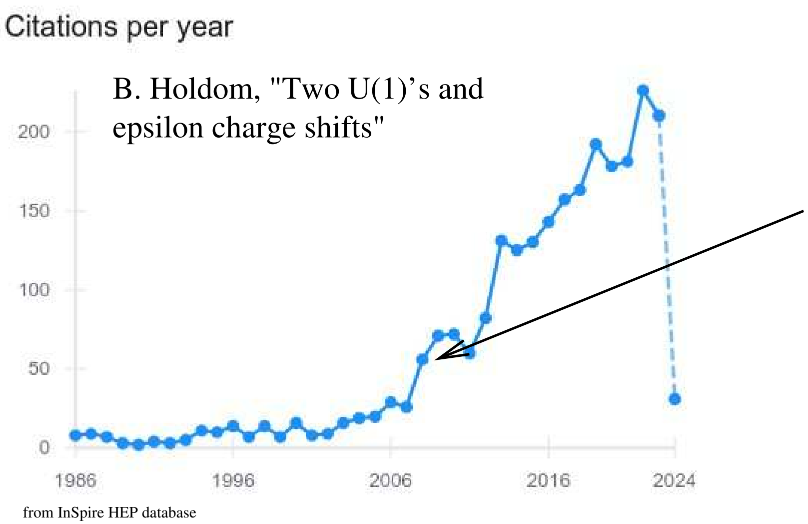
Massive U(1) vector A'_μ can mix with photon (B. Holdom, 1986)

$$\mathcal{L} = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} - \frac{1}{4}F'_{\mu\nu}F'^{\mu\nu} - \frac{1}{2}\epsilon F_{\mu\nu}F'^{\mu\nu} - \frac{1}{2}m_{A'}^2 A'_\mu A'^\mu$$

Diagonalize kinetic term (to $O(\epsilon^2)$) via $A_\mu \to A_\mu - \epsilon A'_\mu$.

$\Longrightarrow$ Dark photon couples to charged particles with strength $\epsilon q e$.

If $m_{A'} = 0$, diagonalize instead via $A'_\mu \to A'_\mu + \epsilon A_\mu$; particles coupling to A' become millicharged: dark Higgs looks millicharged in limit of small $m_{A'}$, leading to strong limits

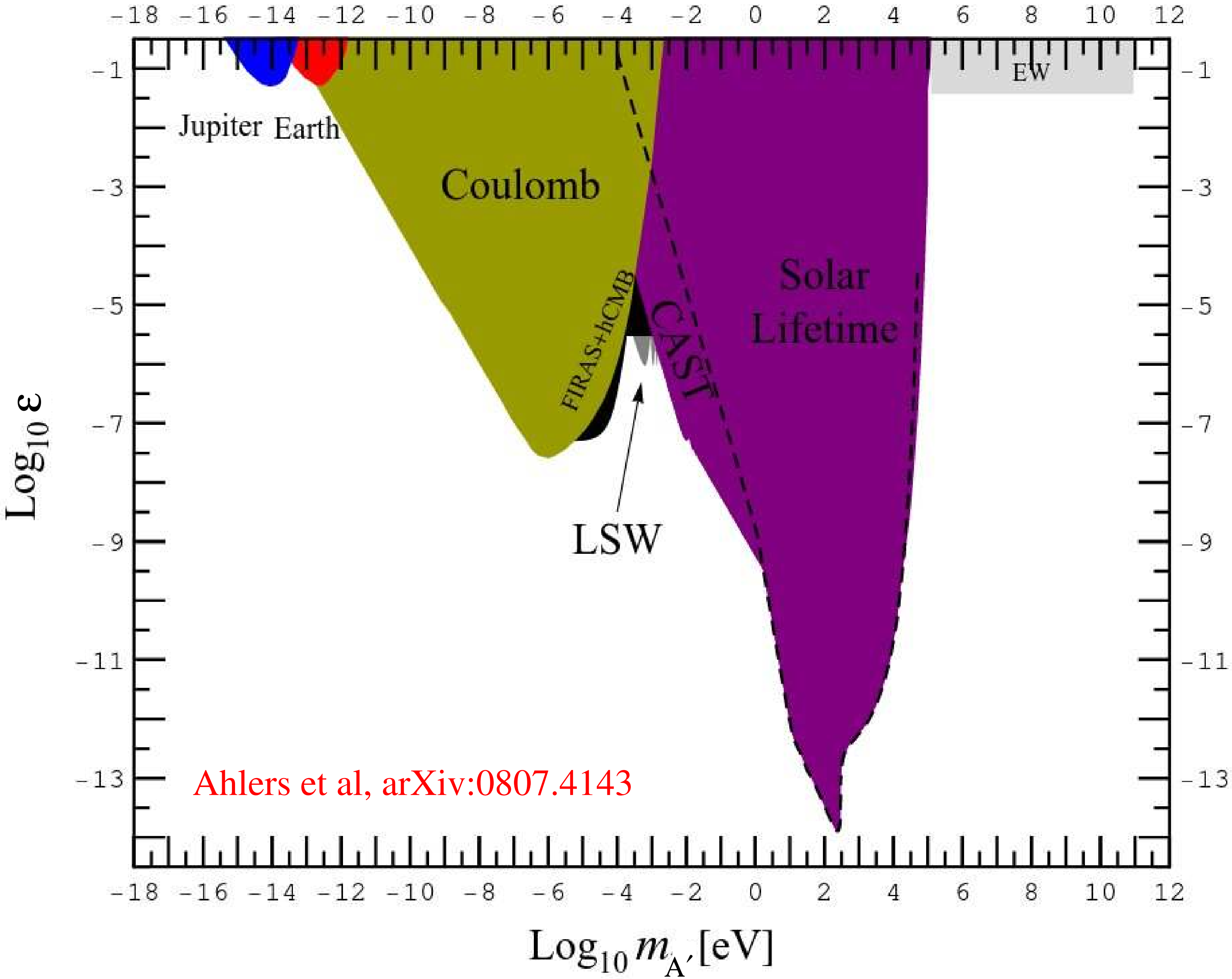


2008: appearance of

Arkani-Hamed et al., "A theory of dark matter,"
Pospelov et al., "Secluded WIMP dark matter"

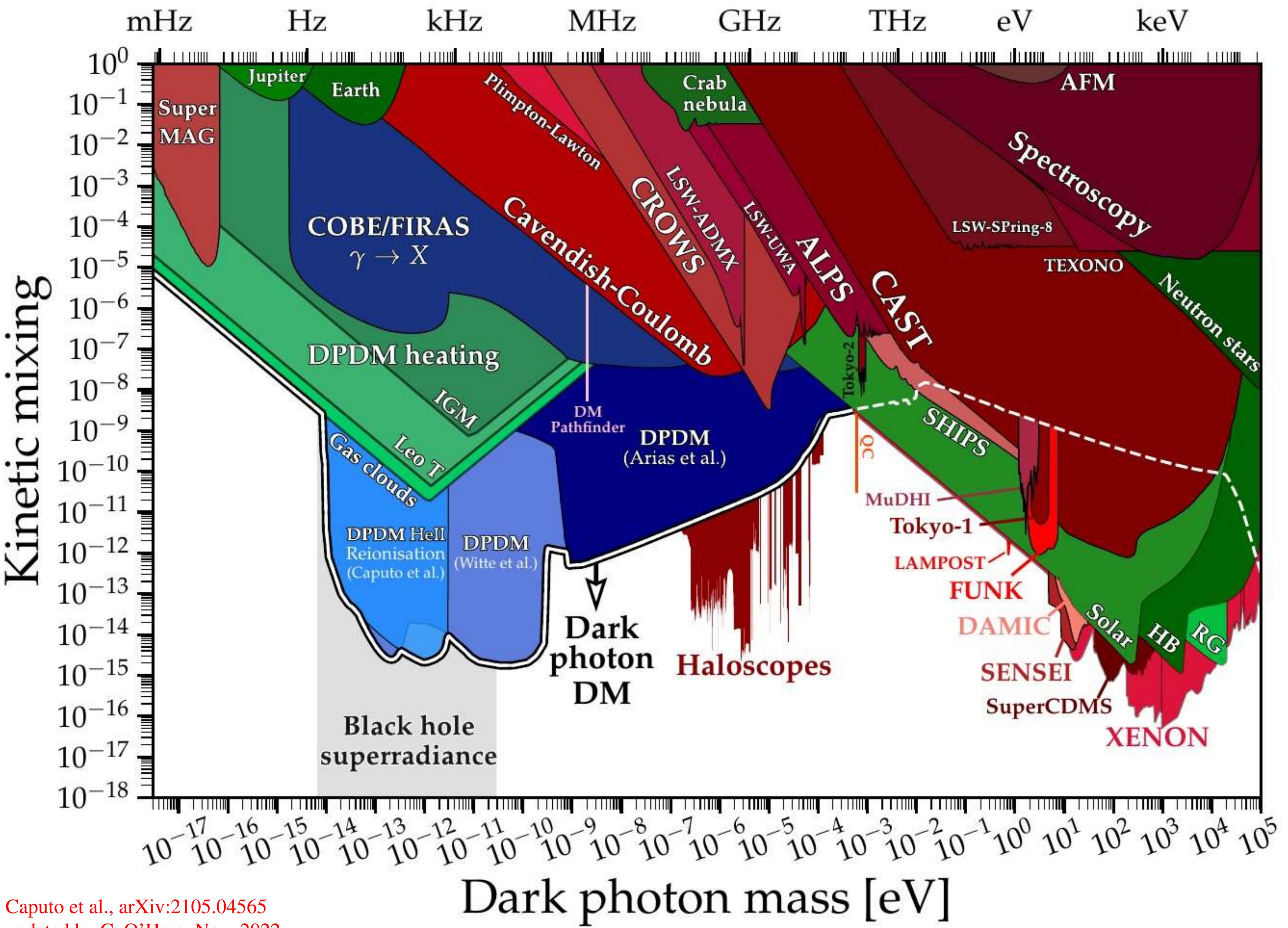
highlighting kinetic mixing

Constraints on kinetic mixing, 2008



Constraints on kinetic mixing, 2024

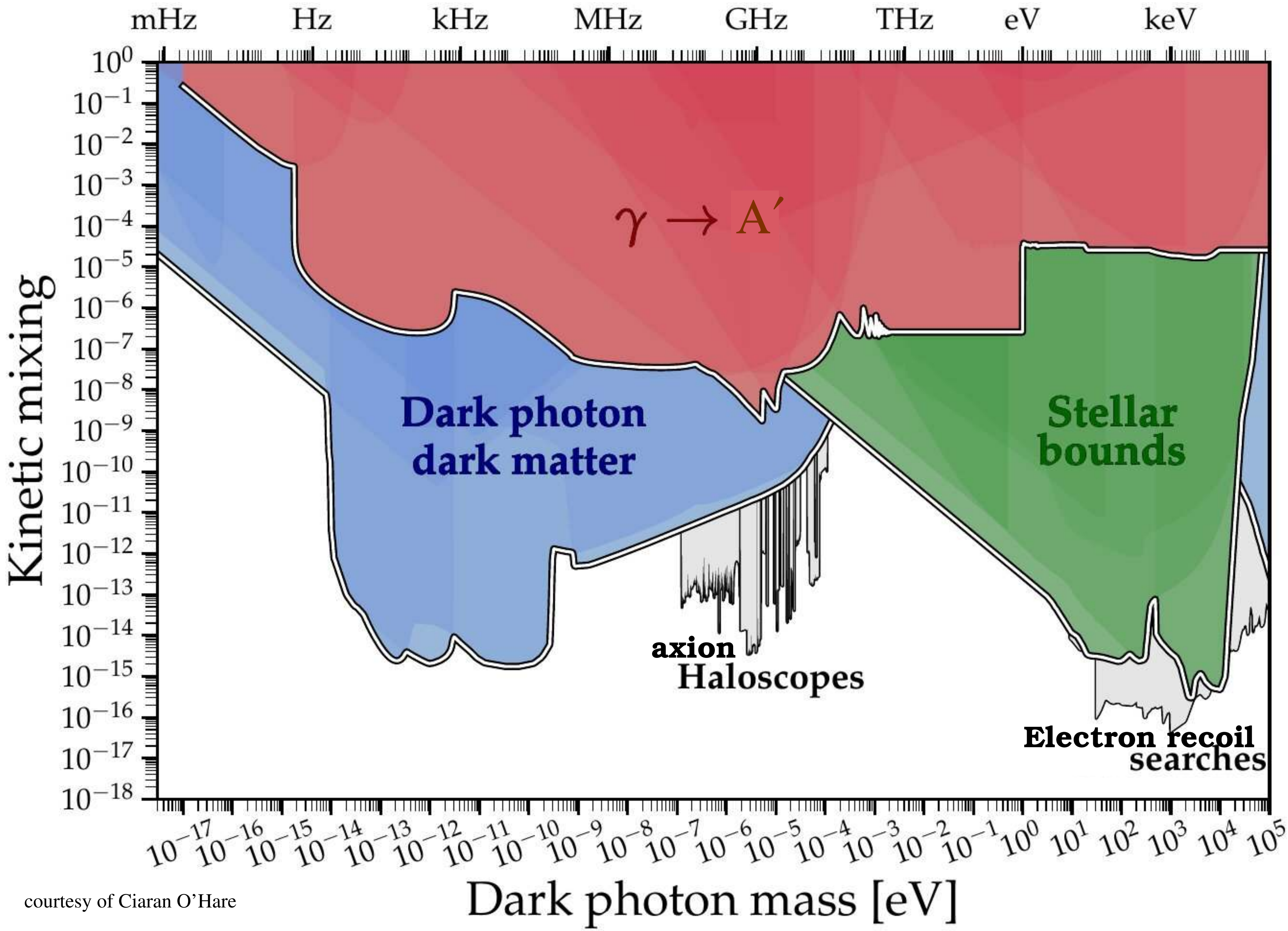
Individual limits



Caputo et al., arXiv:2105.04565
updated by C. O'Hare, Nov. 2022

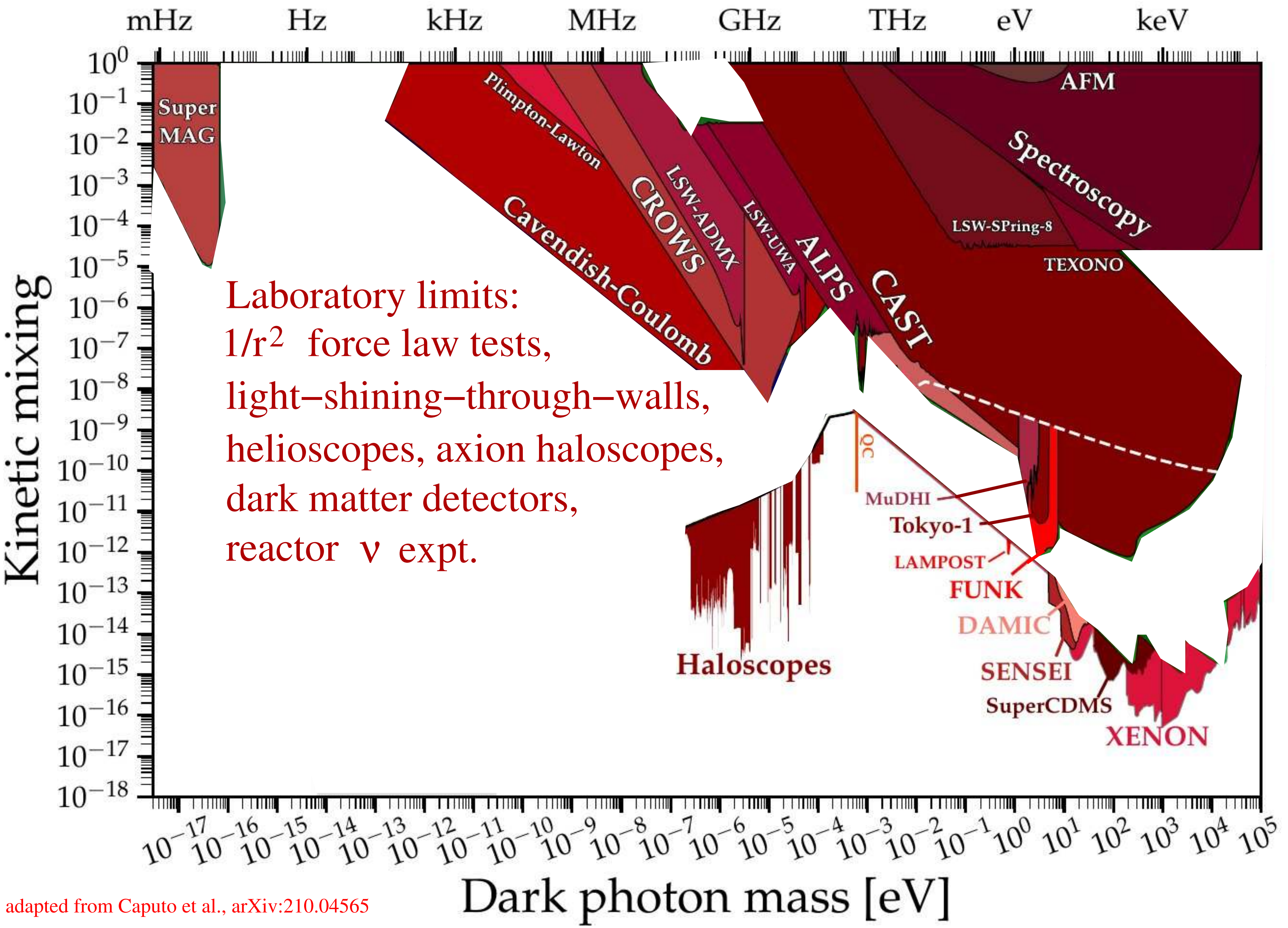
Constraints on kinetic mixing, 2024

Categories of constraints



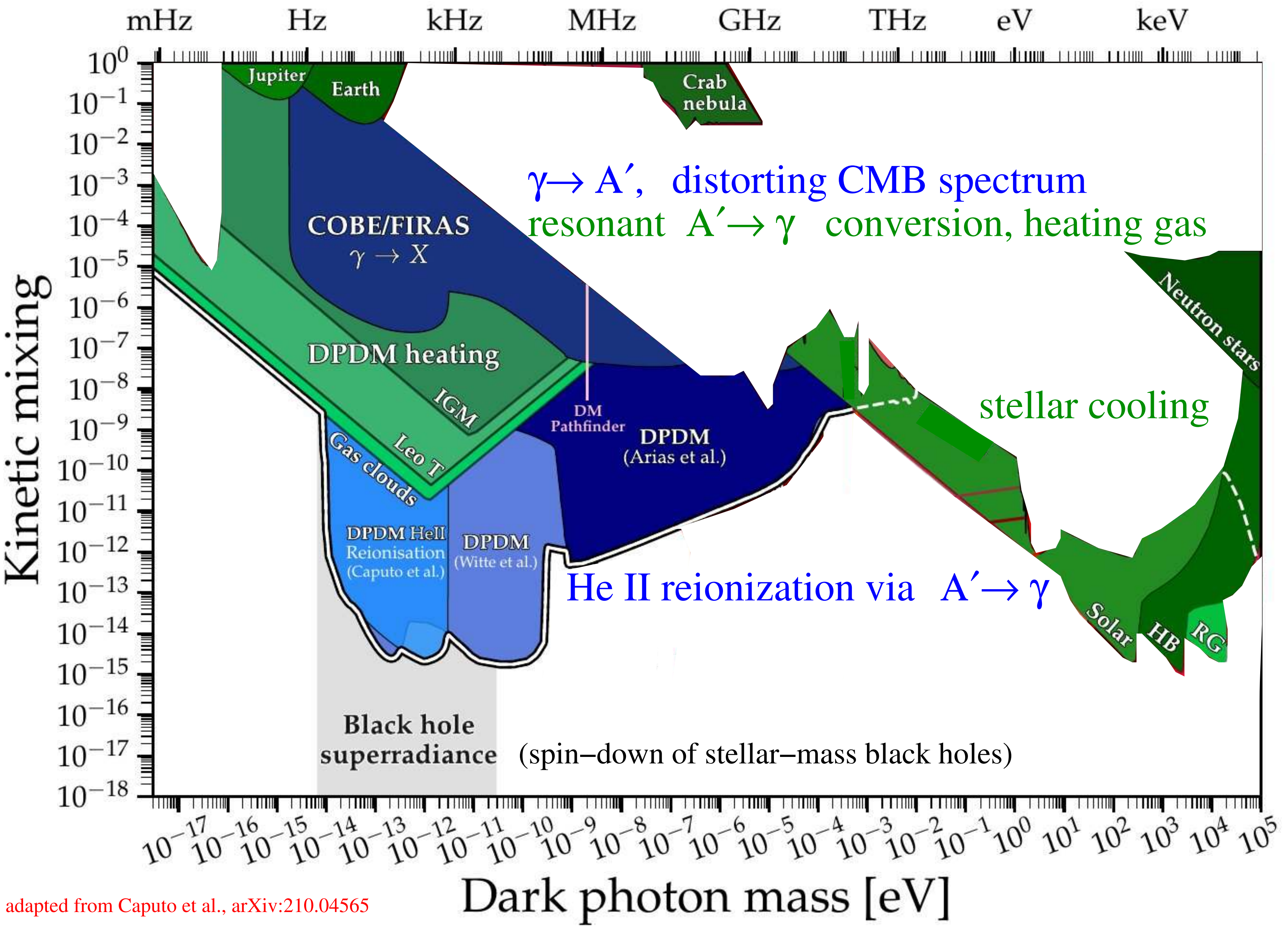
courtesy of Ciaran O'Hare

Lab constraints on kinetic mixing



adapted from Caputo et al., arXiv:210.04565

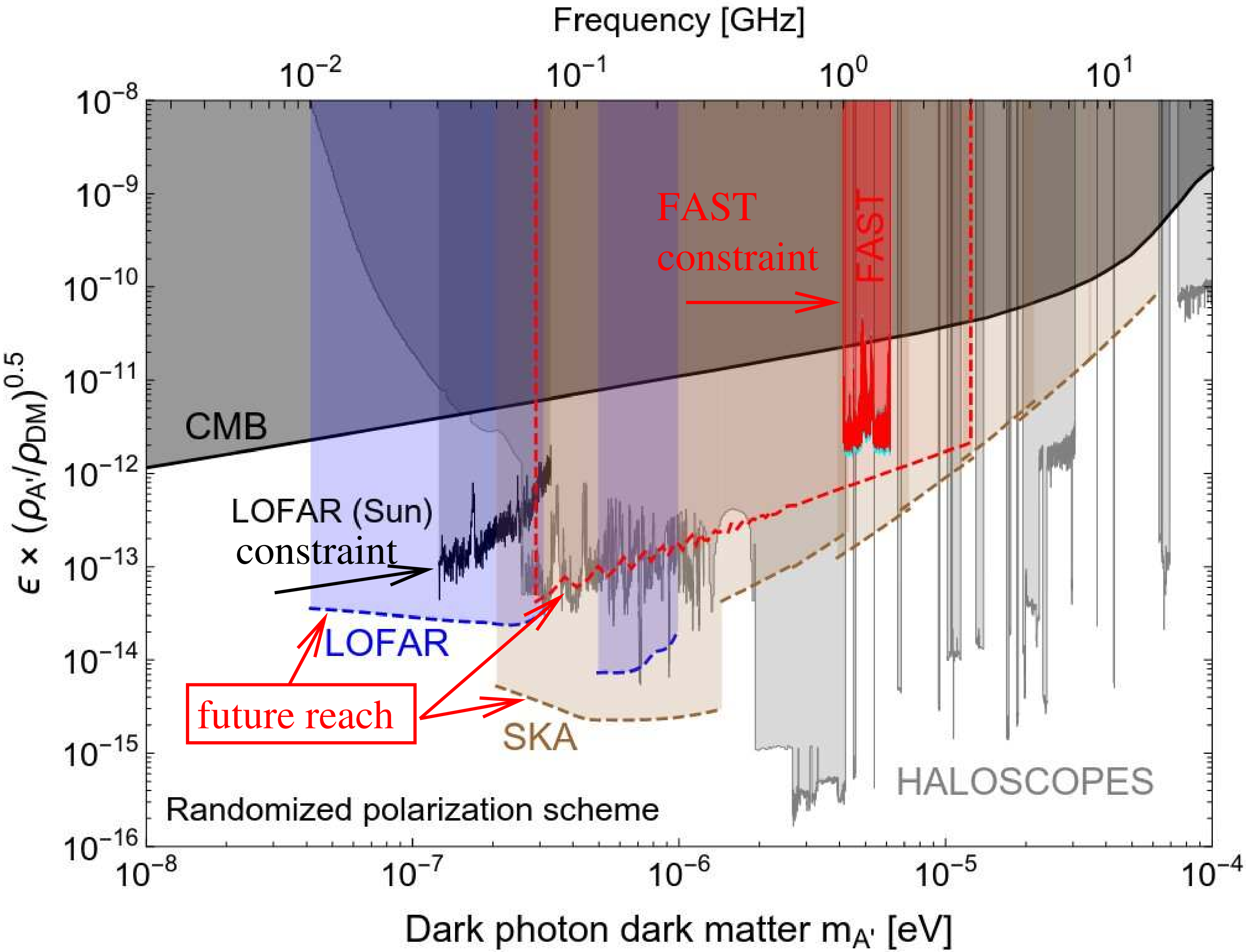
Astro + cosmo constraints on ϵ



adapted from Caputo et al., arXiv:210.04565

Constraints from radio telescopes

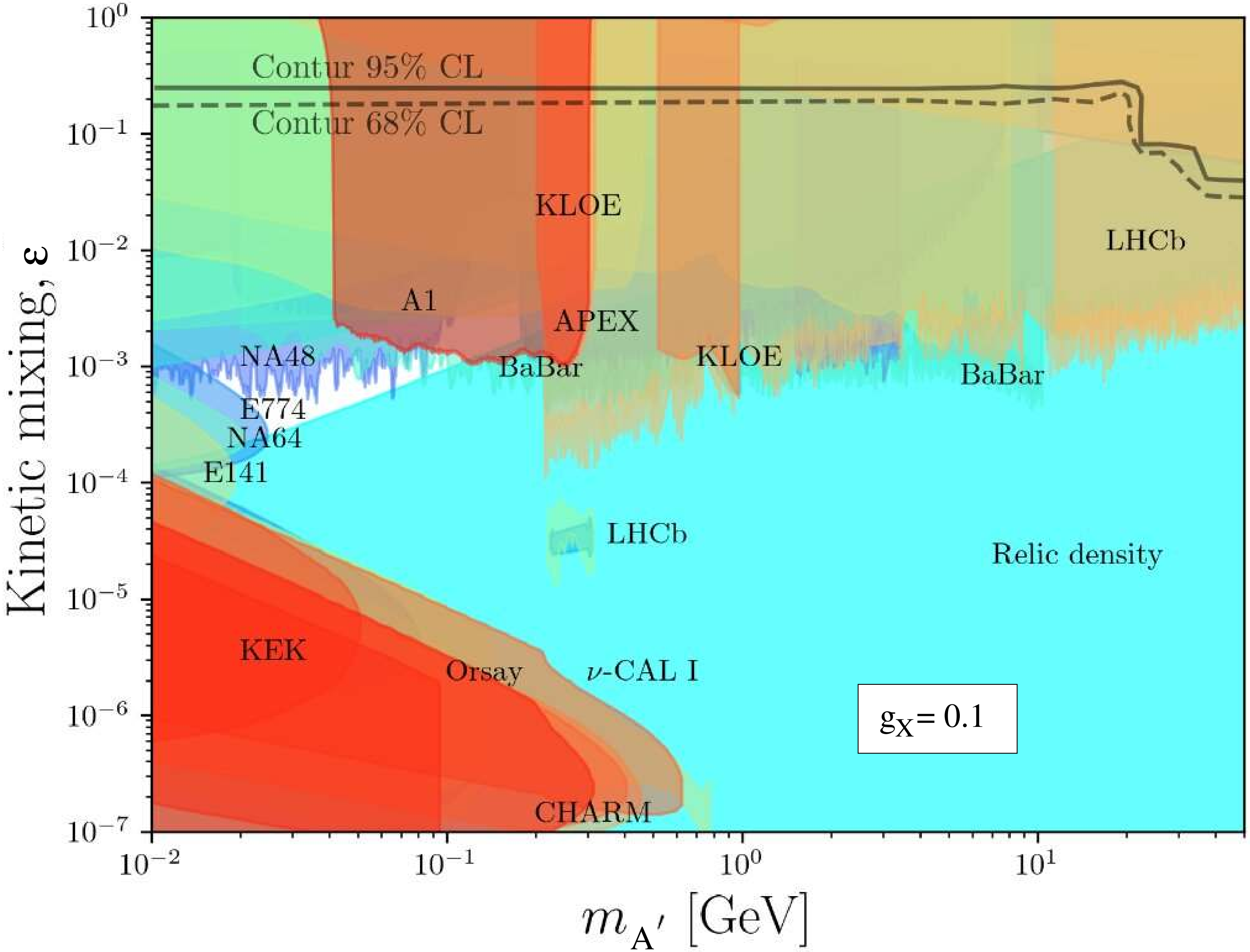
An et al., 2207.05767, 2301.03622: absorption of A' in solar corona or in radio telescope dish can lead to signal:



An et al., 2402.17140: similar technique constrains $m_{A'} \sim 0.05{-}2\,$eV in IR using James Webb Space Telescope

Heavier A' constraints

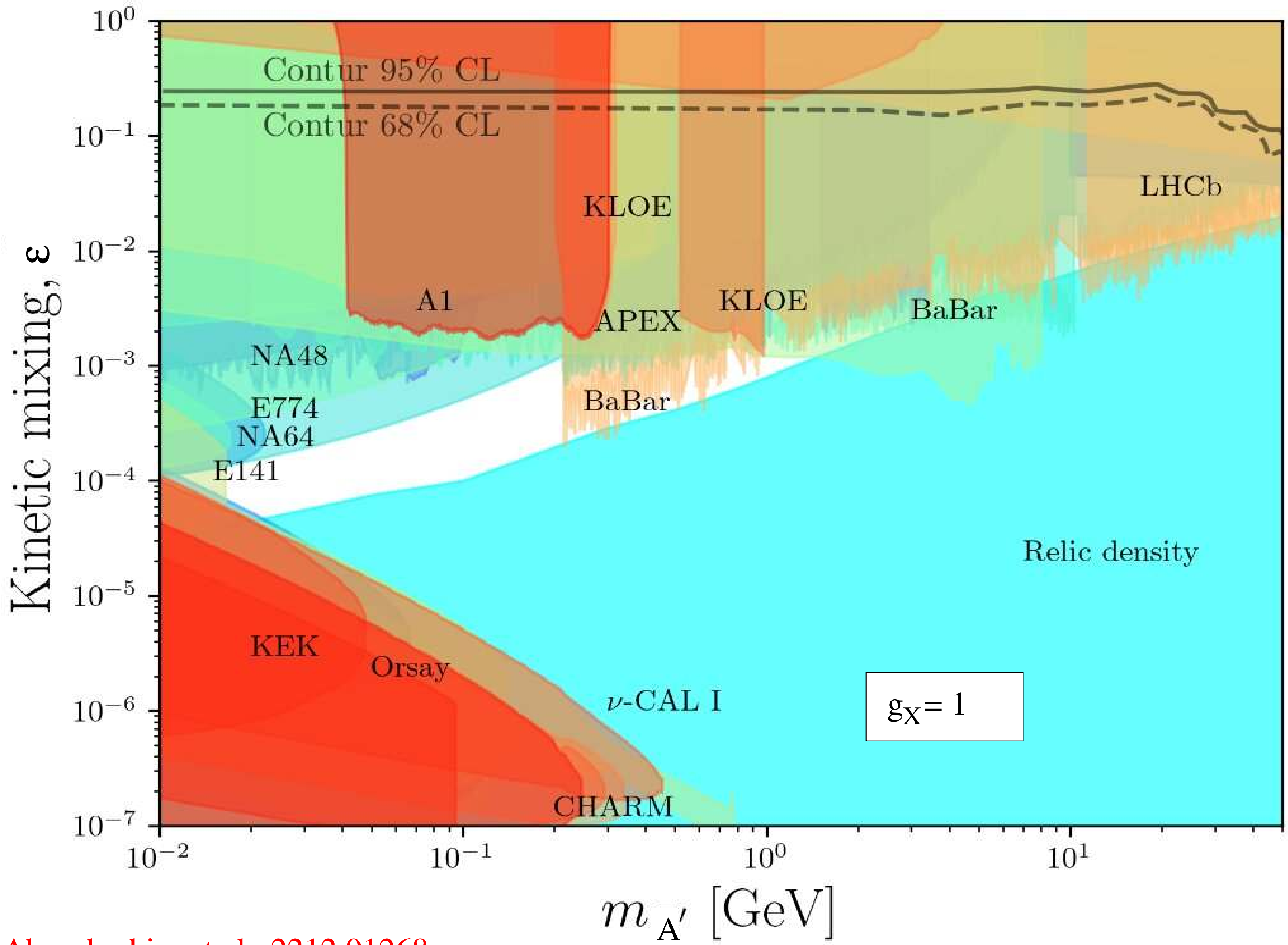
Assumes A' couples to DM with strength $g_X = 0.1$, and can decay invisibly



Abrouhrahim et al., 2212.01268

Heavier A' constraints

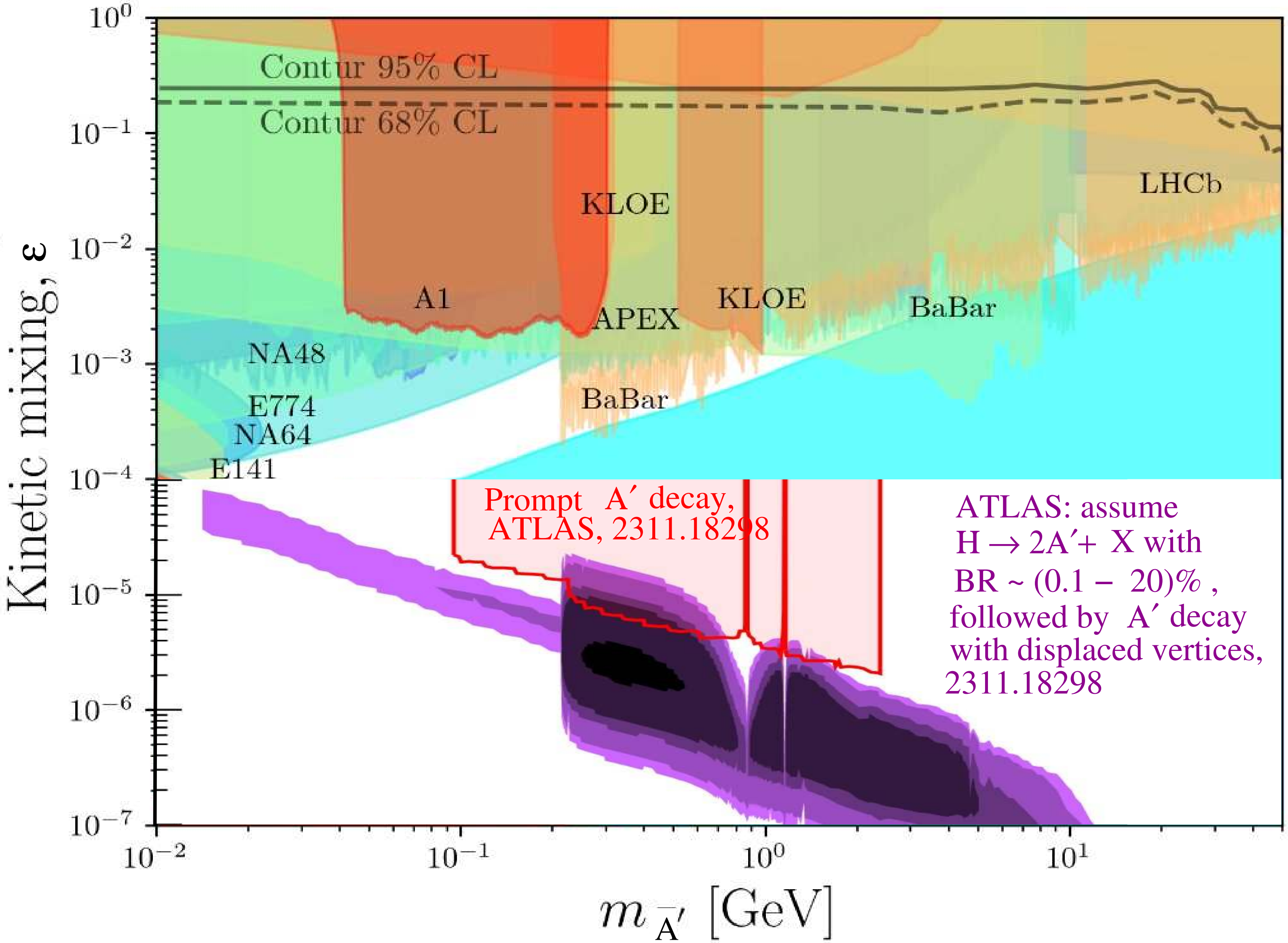
Assumes A' couples to DM with strength $g_X = 1$, and can decay invisibly



Abrouhrahim et al., 2212.01268

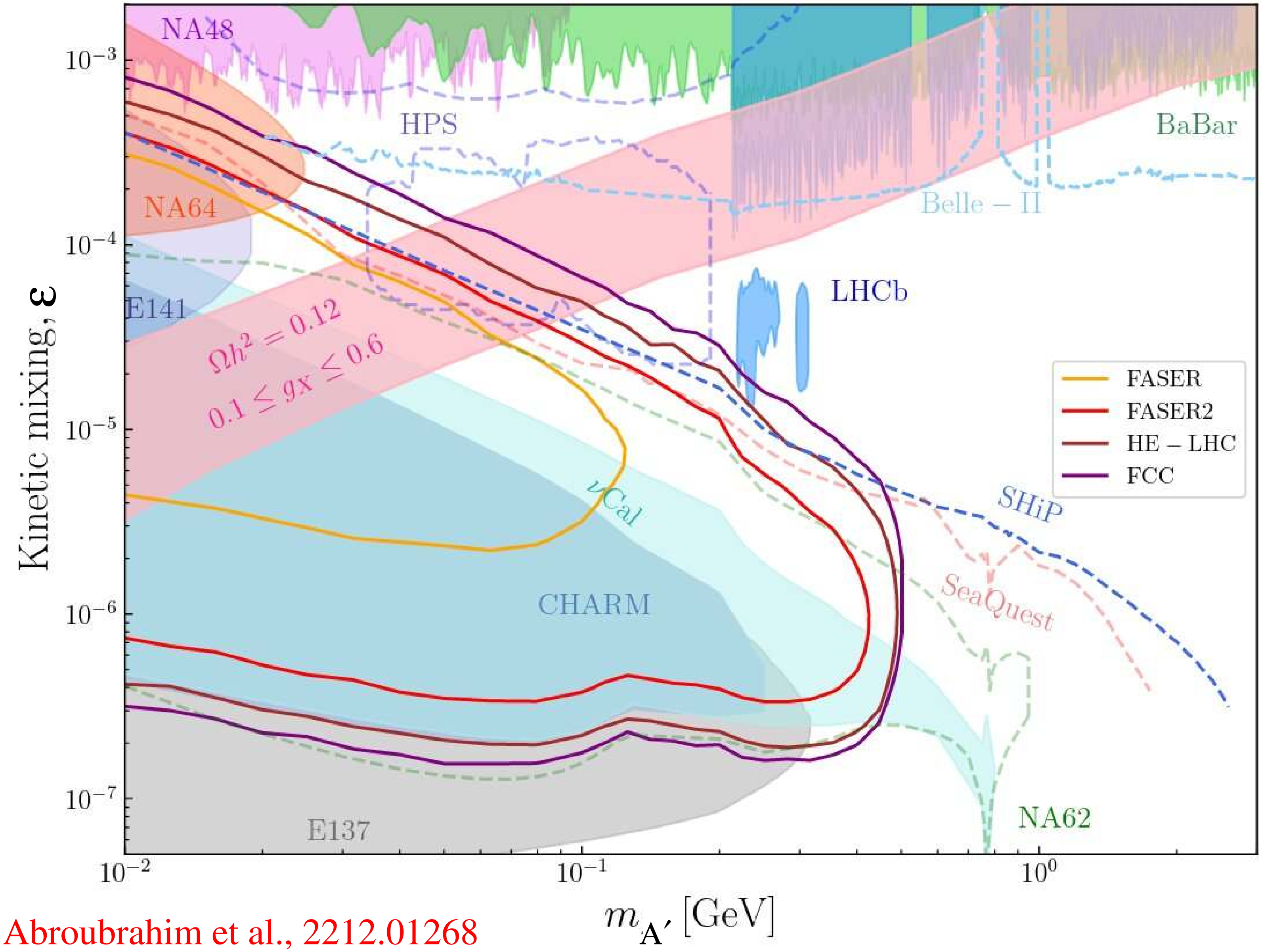
Exotic Higgs decays to A'

Shown at this conference:



Future experimental sensitivity

Proposed and existing experiments HPS, FASER, SHiP, SeaQUEST, HE-LHC, FCC . . . will improve limits:



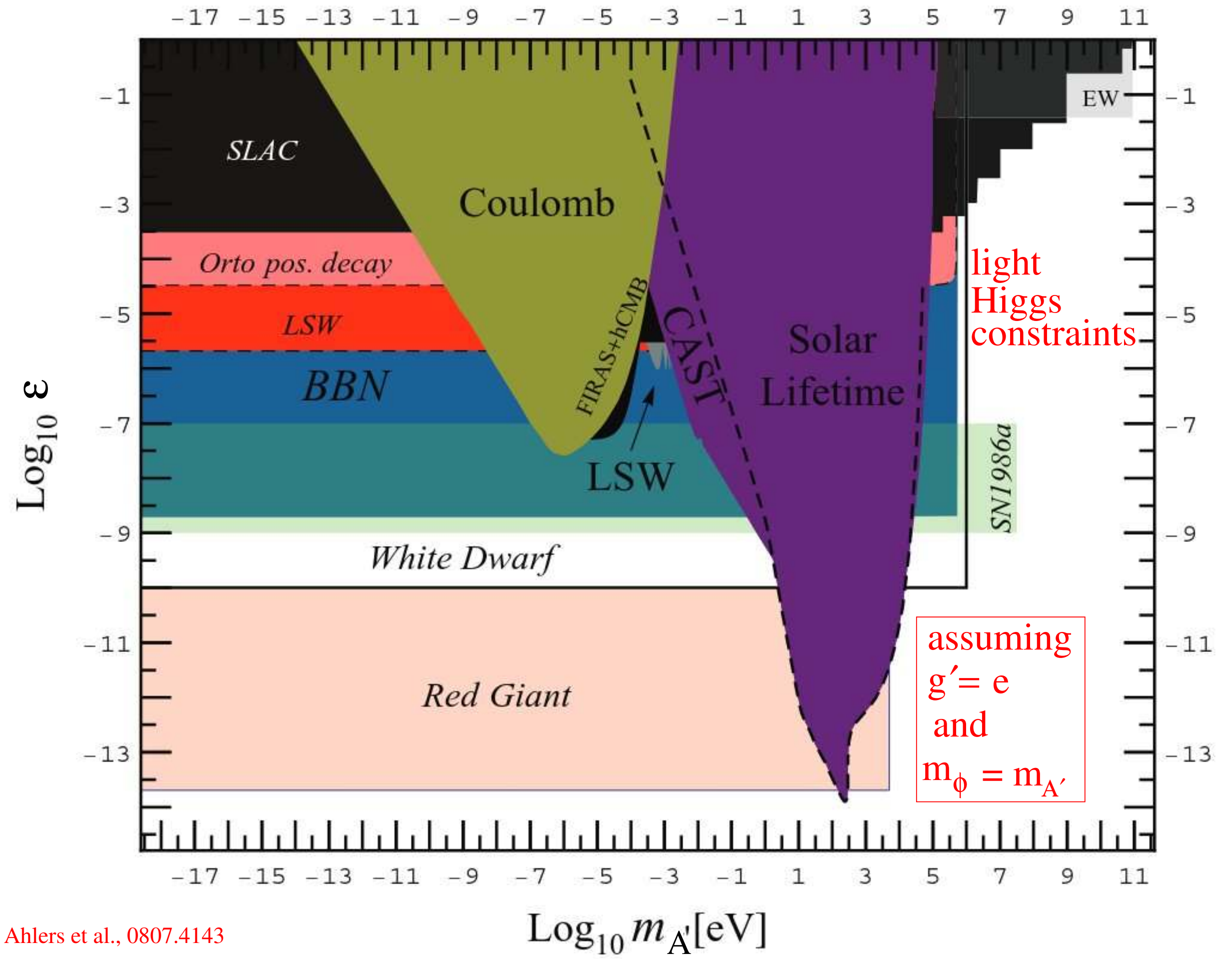
Abroubrahim et al., 2212.01268

Origin of $m_{A'}$: Higgs or Stueckelberg?

Previous bounds assume Stueckelberg mass. Alternatively $m_{A'} \sim g'v'$ can come from dark Higgs VEV $\langle\phi\rangle = v'$.

If $g' \ll 1$, swampland bounds may be important (M. Reece, 1808.09966)

If $g' \sim 1$, light A' $\implies$ light ϕ $\implies$ additional constraints:



Ahlers et al., 0807.4143

Ahlers et al., 0807.4143

Dark Higgs effectively becomes millicharged, removing most of parameter space.

If $g' \ll e$, ϕ becomes heavier than A', new bounds move up and to left by factor $\log_{10}(e/g')$.

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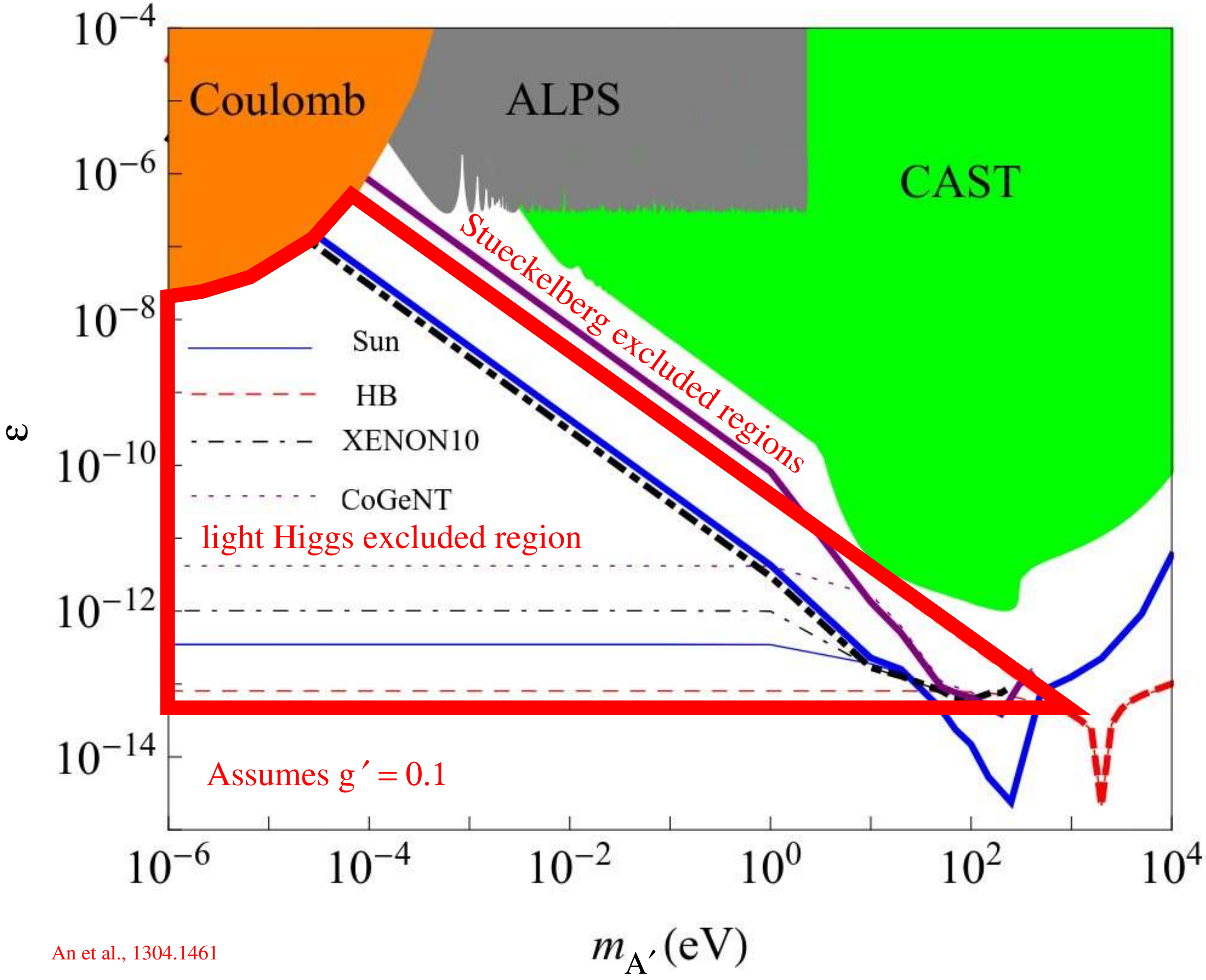


An, Pospelov, Pradler, 1304.3461

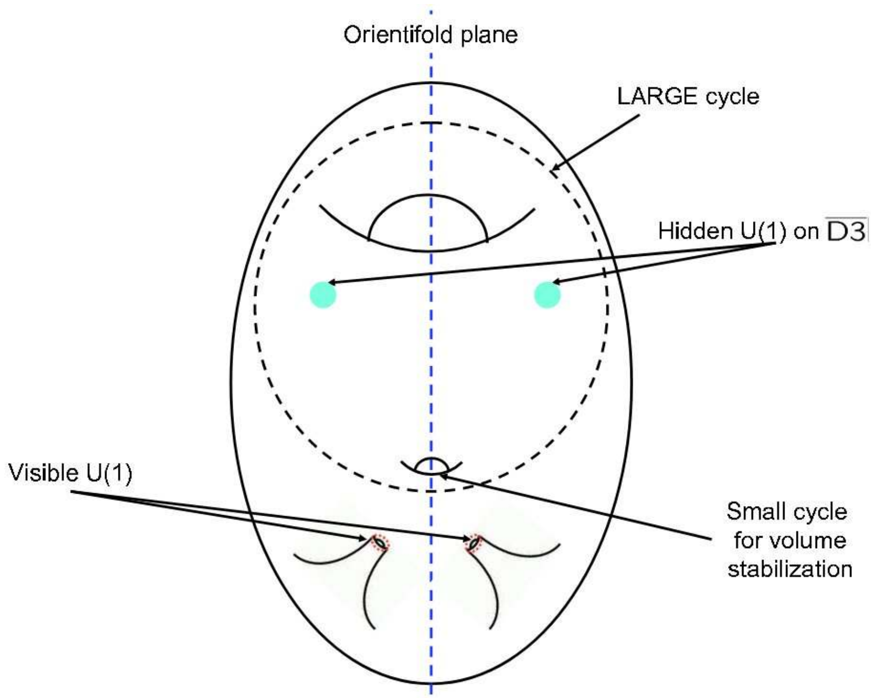
Similarly, light millicharged dark Higgs is produced in DM direct detectors (as well as stars), ruling out region to the left

Stueckelberg dark photon mass

Stueckelberg mechanism can give light $m_{A'}$ regardless of g', by adding extra field θ

$$\tfrac{1}{2} m_{A'}^2 \left(A'_\mu - \partial_\mu \theta\right)^2$$

to action. In string compactifications, θ comes with radial field analogous to ϕ, but with no VEV. Limit $m_{A'} \to 0$ is singular: kinetic term for ϕ diverges.



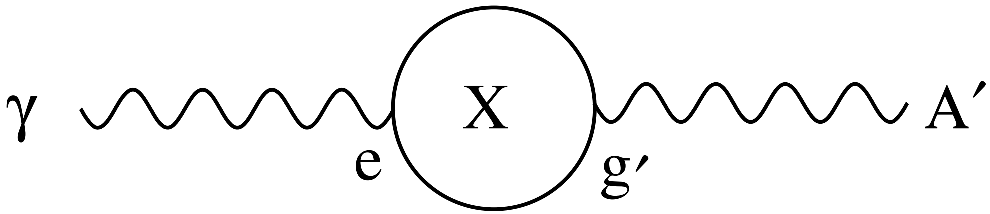
Goodsell et al., 0909.0515:

String compactifications with large volume $\mathcal{V} \lesssim 10^{27}$ ($m_s \gtrsim \text{TeV}$) can give light Stueckelberg masses

$$m_{A'} \sim g_s^{3/2} \frac{M_p}{\mathcal{V}} \gtrsim g_s^{3/2}\,\text{eV} \gtrsim 1\,\text{meV}$$

Origin of ϵ: heavy particle in loop?

ϵ can be put in by hand, or come from loop effect,

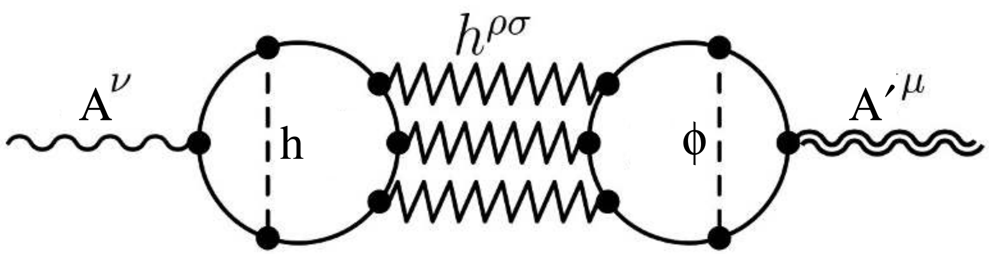


$\sim \frac{e\, g'}{16\pi^2}$

Need $g' \lesssim 10^{-11}$—not possible if gauge groups are unified at high scale—or forbid matter charged under both $U(1)$'s†

Gherghetta et al., 1909.00696: can build models where ϵ appears at higher loops. Pure gravity+Higgs mediation requires 6 loops

(Higgs insertions needed for nonzero result due to gravitational anomaly cancellation)

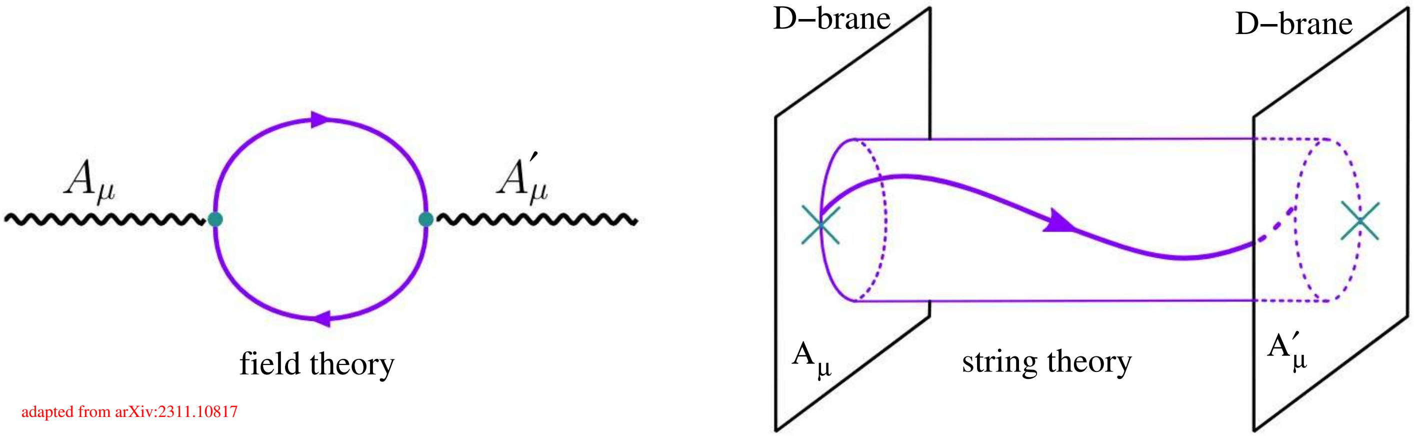


$\leq 10^{-13}$

† Strong version of weak gravity conjecture does not admit this option

String theoretic origin of ϵ

Exact cancellation of one-loop contributions can occur in some compactifications (Obied, Parikh, 2109.07913; Hebecker et al., 2311.10817)



Small kinetic mixing can arise from large volume compactifications, (Conlon et al., hep-th/ 0505076)

$$\mathcal{V} = (2\pi R)^6 \gg 1 \quad \text{(string length units, } \ell_s = 2\pi\sqrt{\alpha'}\text{)}$$

with light volume modulus of mass $m_{\mathcal{V}} \sim M_P \mathcal{V}^{-3/2}$.
Hebecker et al., 2311.10817; see also Goodsell et al., 0909.0515:

$$\epsilon \gtrsim 10^{-16} \left(\frac{m_{\mathcal{V}}}{2m_H}\right)^{8/9} \qquad \text{close to XENON constraint!}$$

Need $m_{\mathcal{V}} > 2m_H$ to avoid cosmological moduli decay problems.

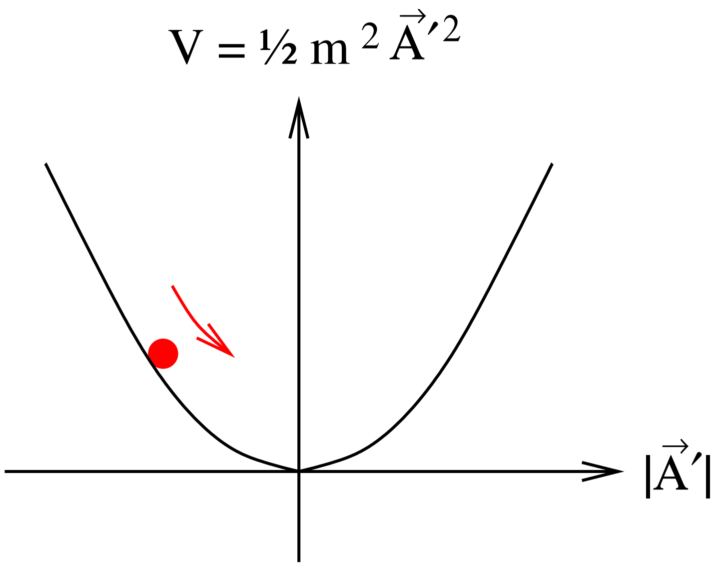
A' as DM: obtaining relic density?

Nonthermal mechanism is needed to populate A' in the early universe.

Graham et al., 1504.02102: inflationary fluctuations of A' give the right relic density if

$$m_{A'} \cong 6 \times 10^{-6}\,\mathrm{eV} \left(\frac{10^{14}\,\mathrm{GeV}}{\mathrm{H_I}}\right)^4$$

where $H_I =$ Hubble rate during inflation.



Misalignment mechanism is problematic for vectors;

Nonminimal coupling to gravity $RA'_\mu A'_\mu$ is needed to get large enough density (Arias et al., 1201.5902; Golovnev et al., 0802.2068)

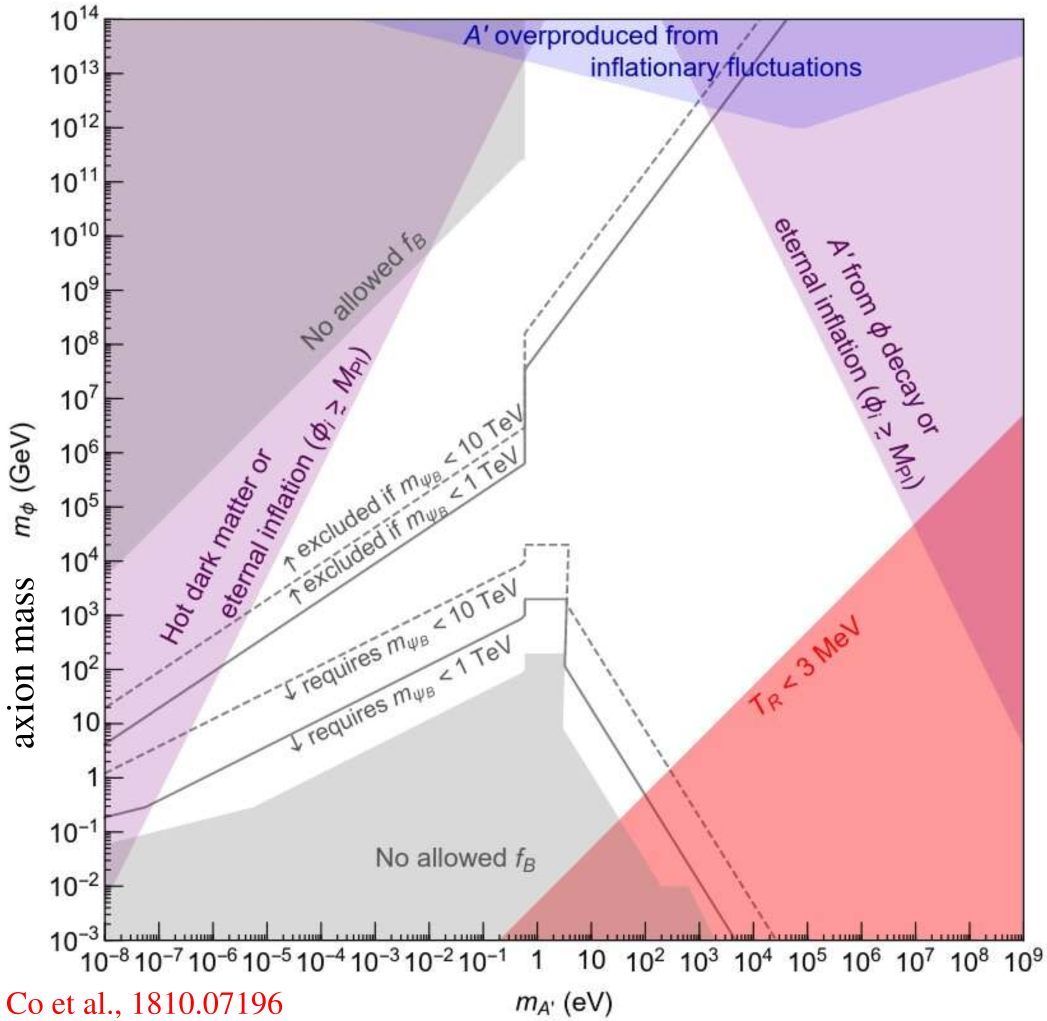
The nonminimal coupling makes longitudinal polarization ghost-like for some momenta (Lyth et al., 1007.1426)

Can be overcome with modified kinetic term $f(\phi)F'_{\mu\nu}F'^{\mu\nu}$ (Nakayama, 1907.06243)

Relic dark photons from axions

Agrawal et al., 1810.07188; Co et al., 1810.07196: Suppose axion a is initial dark matter via misalignment, and couples to dark photon,

$$\mathcal{L} = -\frac{\beta}{f_a}\, a\, F'_{\mu\nu} F'^{\mu\nu}$$



Co et al., 1810.07196

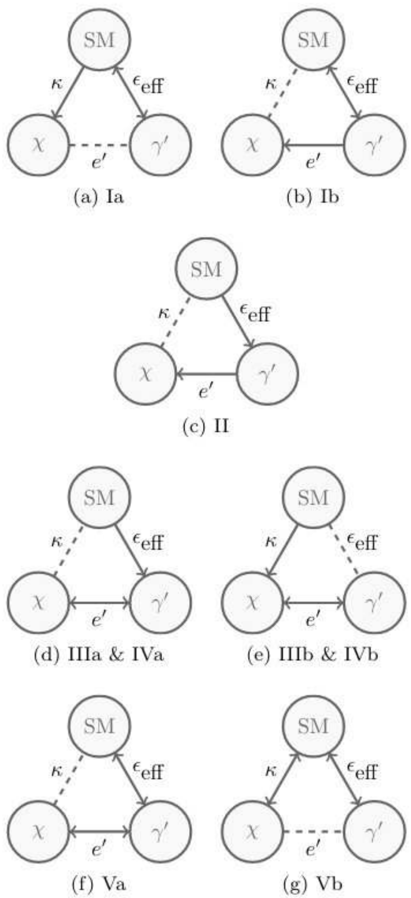
When a oscillates, tachyonic instability quickly transfers energy from a to A'_μ, for range of axion/A'_μ masses $m_{A'} \sim (10^{-7} - 10^{7})\,\mathrm{eV}$.

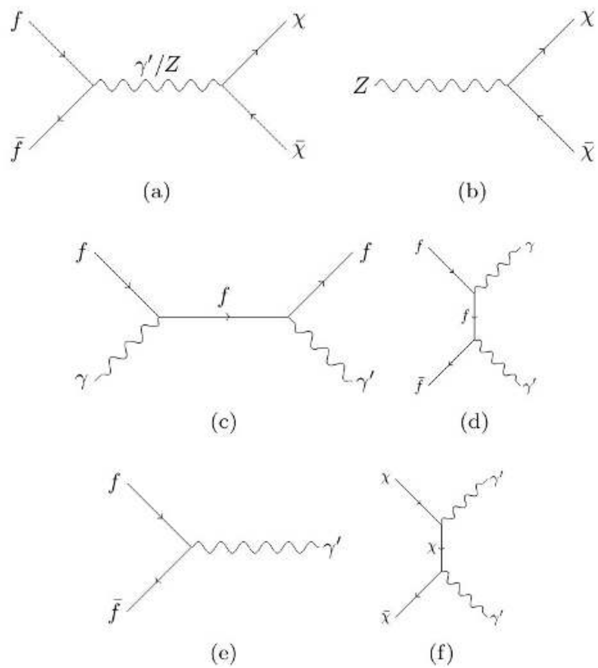
Can similarly produce A'_μ from dark Higgs oscillations by parametric resonance if ϕ couples to A'_μ (Dror et al., 1810.07195)

A' as mediator for DM relic density

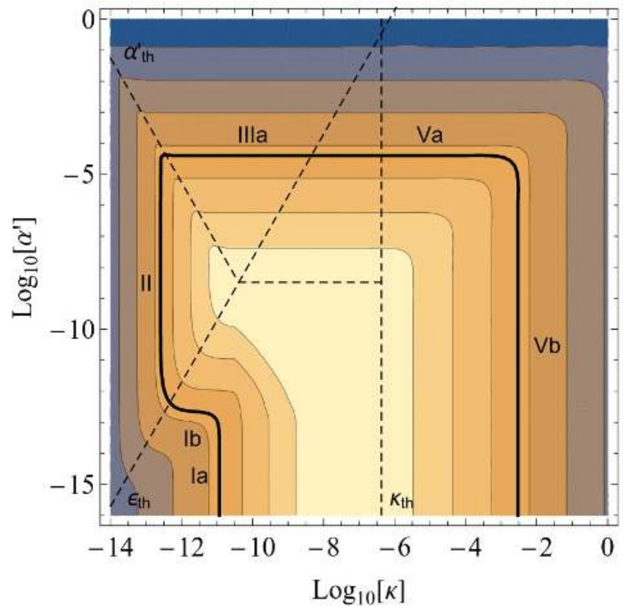
A' can enable thermal freezeout of DM by $\chi\bar\chi \to A'A'$ or $\chi\bar\chi \to A'^* \to f\bar f$. But in general there are many other possibilities depending on which sectors are in thermal equilibrium

(Hambye et al., 1908.09864)





E.g., kinetic mixing can be enhanced by resonant A→A′ at finite T, due to photon plasmon mass



DM relic density enabled by various regimes of dark photon interactions

Swampland constraints

Weak gravity conjecture (Arkani-Hamed et al., hep-th/0601001) has strong evidence, and its variants are well motivated by string theory/quantum gravity arguments.

Reece, 1808.09966: WGC bounds on Stueckelberg mass imply limit on EFT cutoff

$$\Lambda \lesssim \min\left[\sqrt{M_P\, m_{A'}/g'},\; g'^{1/3} M_P\right]$$

hence arbitrarily small g' is disfavored.

If A' DM is produced by inflationary fluctuations, need $\Lambda > H_I$, implies $m_{A'} \gtrsim 0.3\,\mathrm{eV}$, a significant restriction!

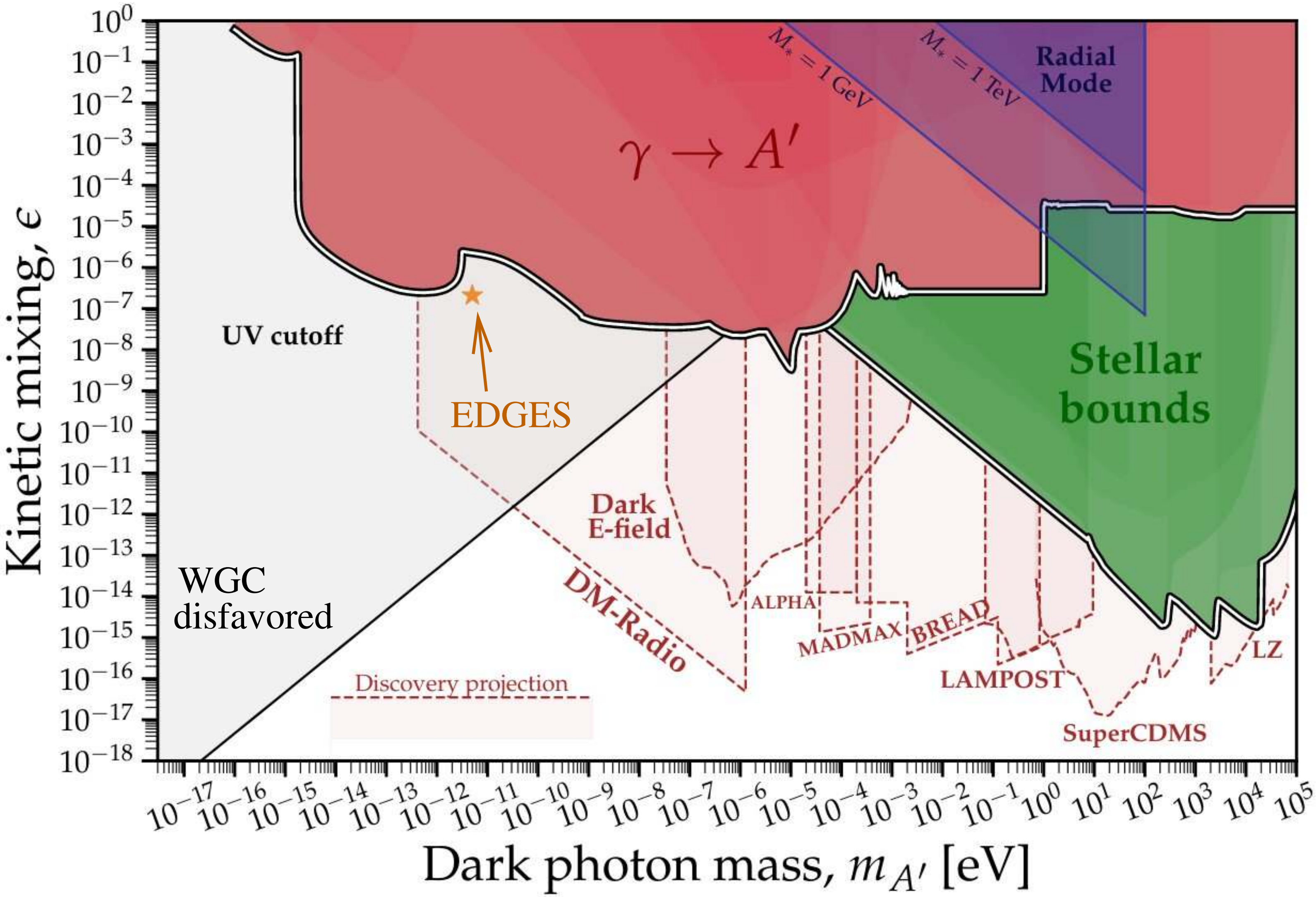
Benakli et al., 2007.02655: WGC implies UV cutoff (with XENON10 $\epsilon \lesssim 10^{-16}$)

$$\Lambda \lesssim g' M_p \sim \frac{16\pi^2}{e}\epsilon M_p \sim 100\,\mathrm{TeV},$$

hence new states accessible to Future Circular Collider. ($g' \sim 1/(R\, m_s)^3$ in large volume string compactifications.)

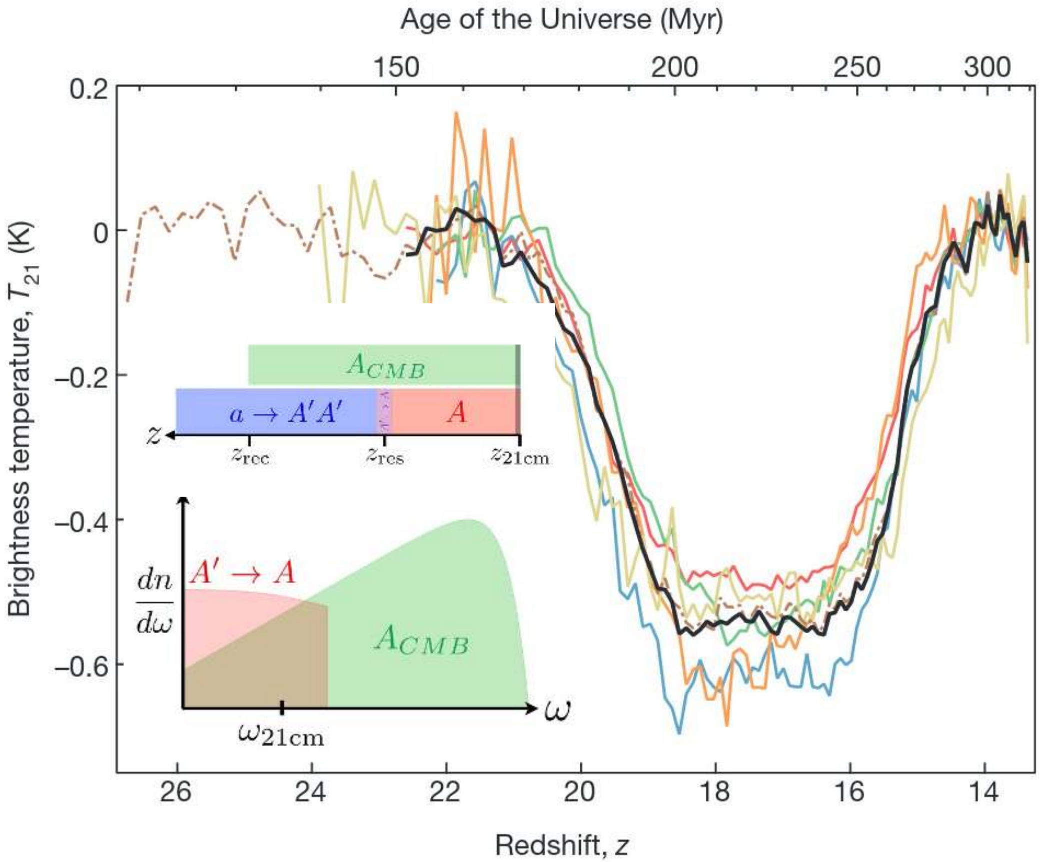
Swampland constraints

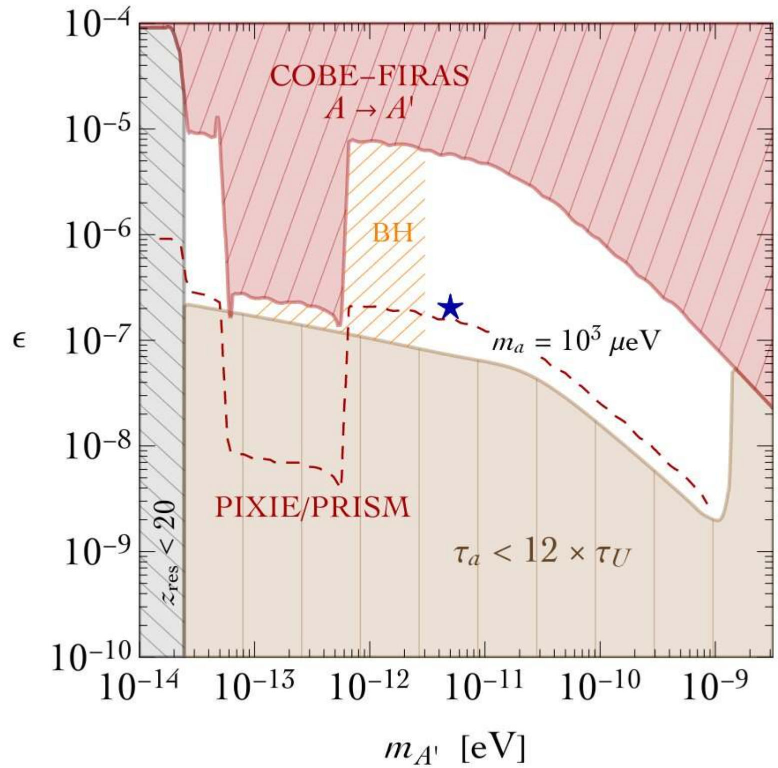
Montero et al., 2207.09448: "Magnetic " WGC bound $\Lambda < \sqrt{M_P m_{A'}/g'}$ combined with LHC bound $\Lambda \gtrsim 10\,\mathrm{TeV}$, and 1-loop estimate $\epsilon \sim eg'/16\pi^2$ rules out grey region:



A'_μ origin of EDGES anomaly

Pospelov et al., 1803.07048; Caputo et al., 2009.03899: Axion decays $a \to A'A'$ followed by $A' \to A$ resonant oscillations can boost low-frequency CMB photons, suppressing 21 cm signal as seen by EDGES





BH: disfavored by superradiance;

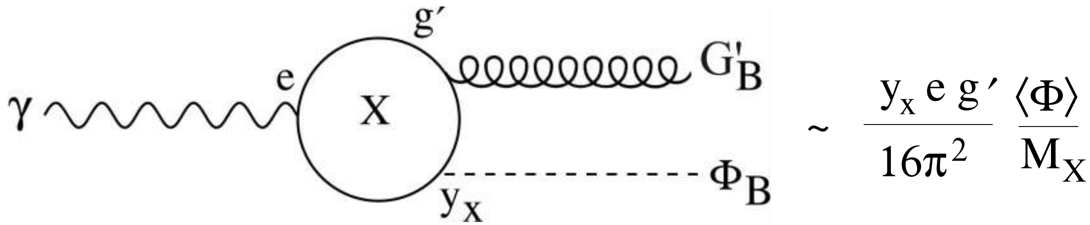
star: fiducial model

SARAS (Singh et al., 2212.00464) does not yet detect the 21 cm signal, $\sim 2\sigma$ tension

Nonabelian origin for dark photon

A dark gluon can become a dark photon if nonabelian gauge symmetry breaks spontaneously, e.g. by VEV of octet scalar Φ.

Kinetic mixing arises as dimension-5 operator,



Can parametrically suppress ϵ without needing small g'.

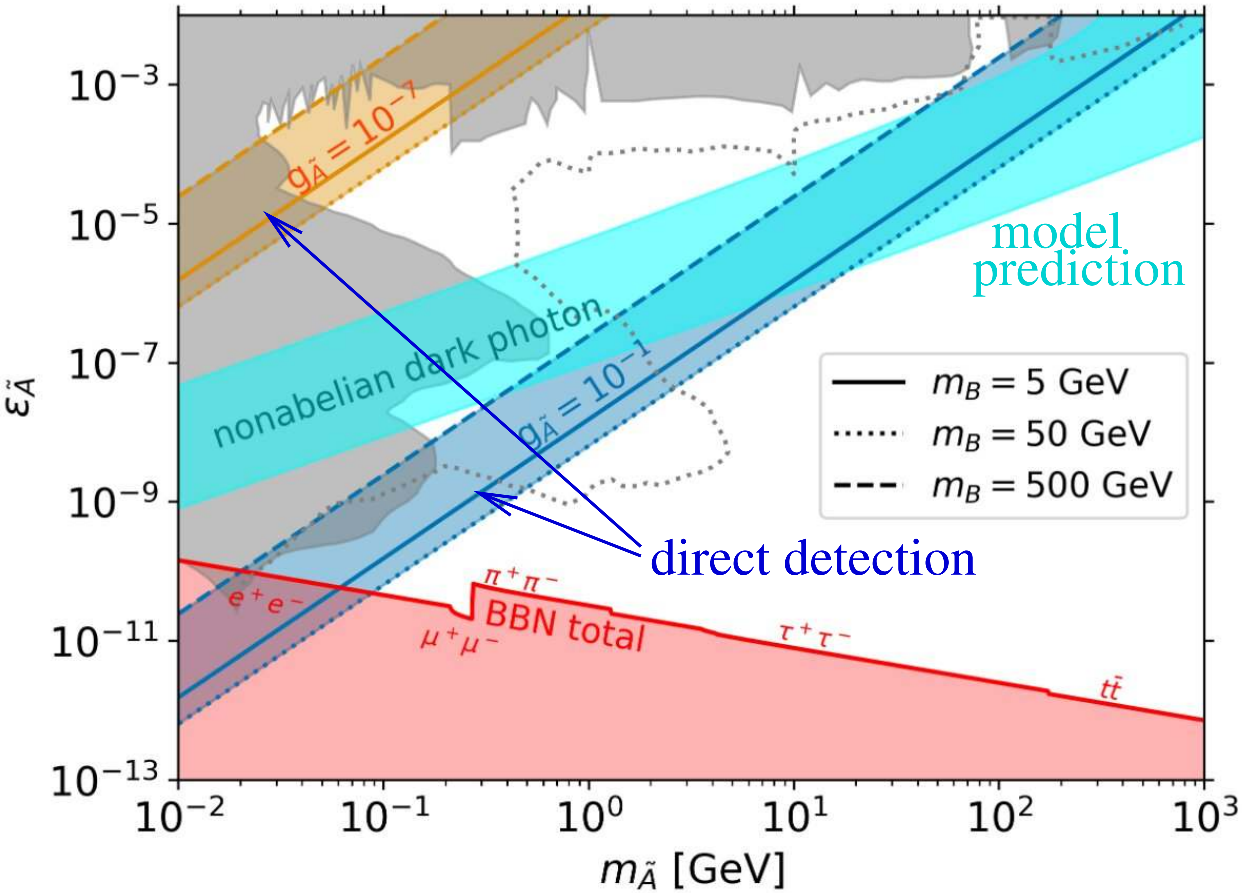
Can also get ϵ with $\langle\Phi\rangle = 0$ in confining phase of dark gauge theory: dark gluon G' and scalar Φ form bound state, composite dark photon $\tilde{A}^\mu$ (Alonso-Álvarez, JC et al., 2309.13105):

$$\epsilon \sim \frac{\sqrt{\alpha\,\alpha'} y_X \Lambda}{4\pi m_X}$$

where $\Lambda =$ dark confinement scale.

Composite dark photon

Alonso-Álvarez, JC et al., 2309.13105: $m_{\tilde{A}}$ and $\epsilon_{\tilde{A}}$ can be correlated in composite model. Dark gauge coupling is not free parameter, $\alpha' \sim 1/\ln\Lambda$ in confining gauge theory.



"model prediction" assumes $y_X = 1$, $m_\Phi \sim \Lambda$, $m_X = (0.2 - 10)$ TeV

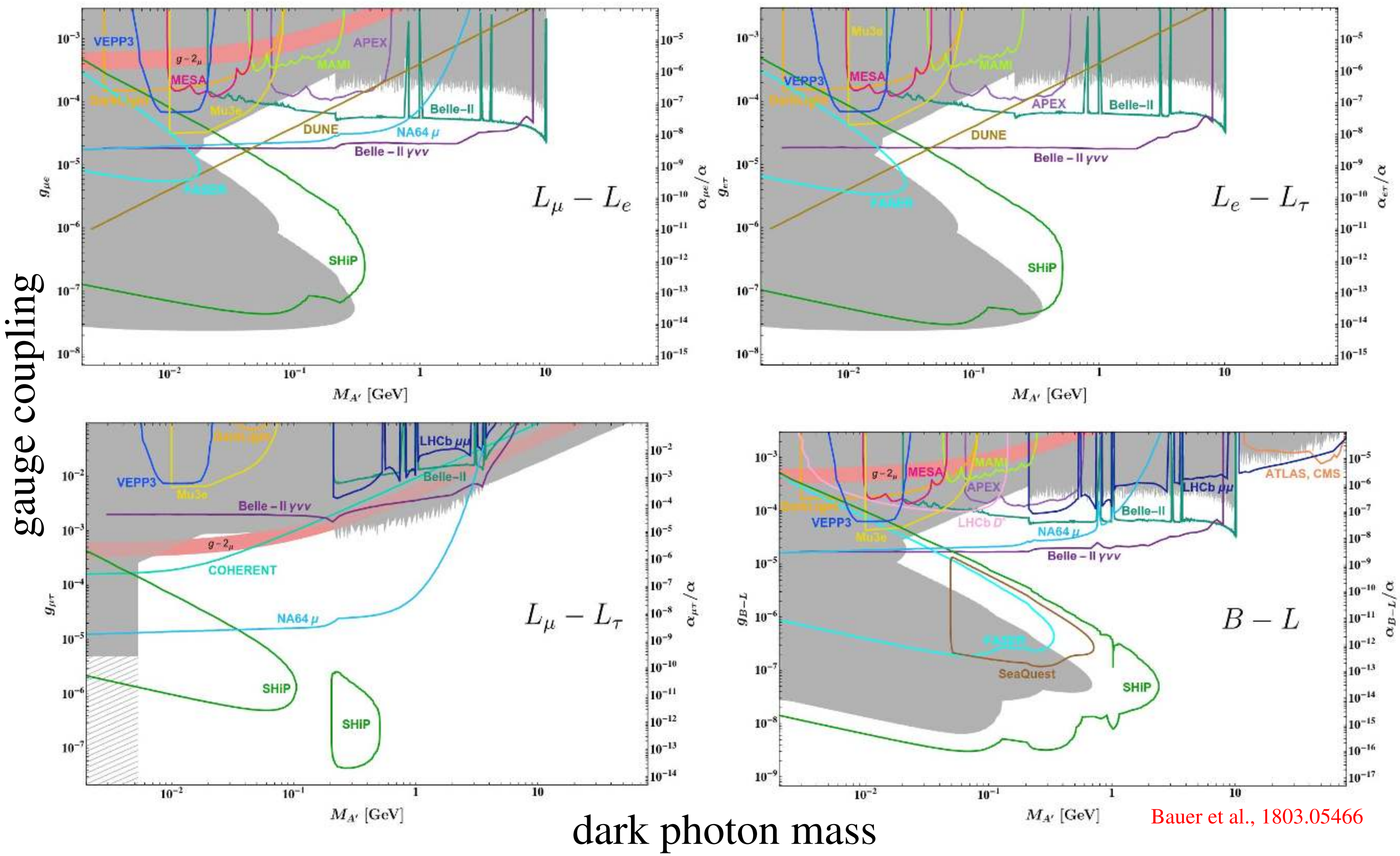
direct detection limit depends on coupling $g_{\tilde{A}}$ of $\tilde{A}$ to composite dark baryon

BBN limit comes from $\tilde{A} \to f\bar{f}$ decays

Gauging standard model symmetries

The extra U(1) need not be totally dark; one could gauge global symmetries of the SM. Kinetic mixing ϵ is calculable and small.*

Anomaly free choices are $L_e - L_\mu$, $L_\mu - L_\tau$, $L_\tau - L_e$, $B - L$ (with 3 right-handed neutrinos)

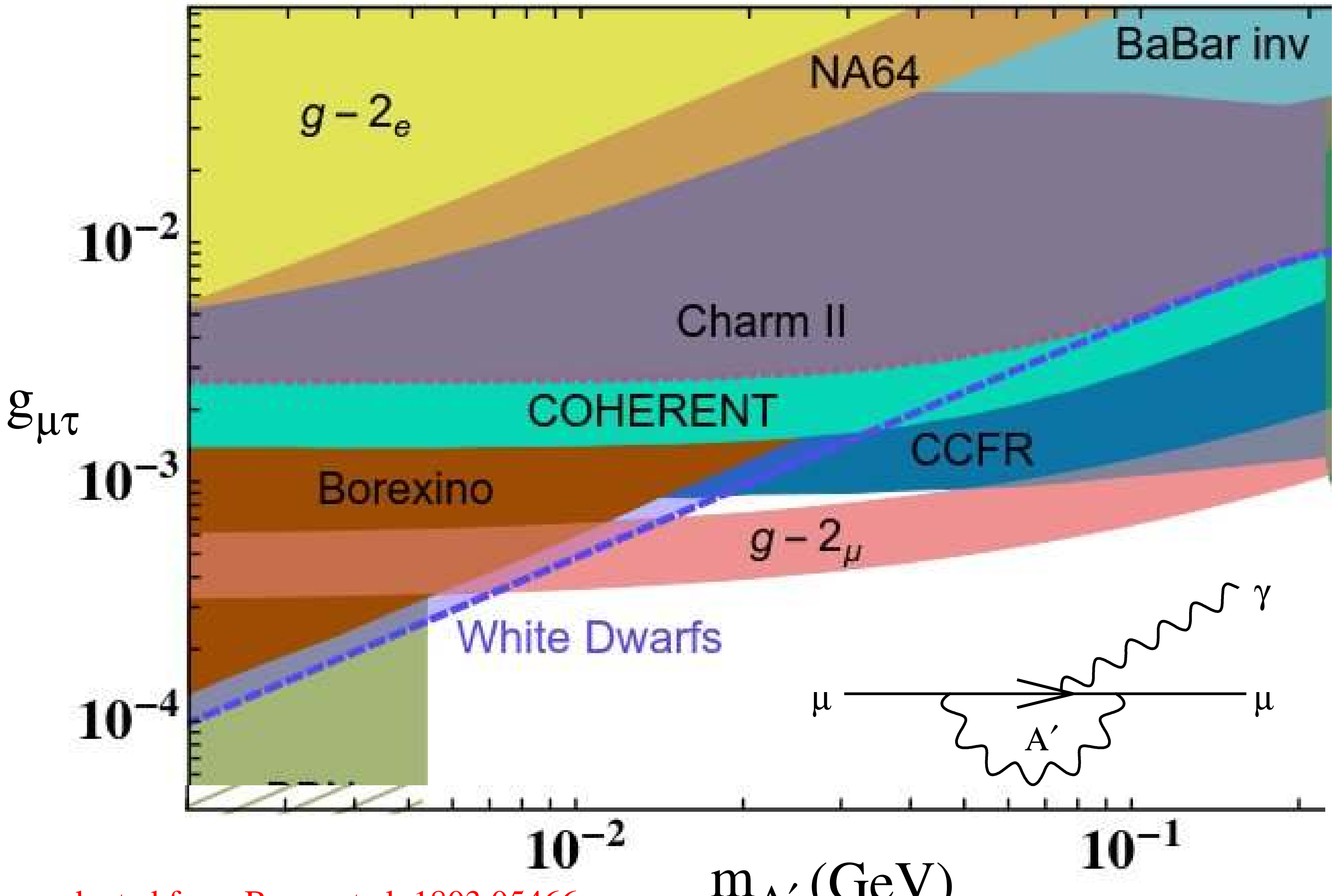


Bauer et al., 1803.05466

* E.g., for $L_\mu - L_\tau$, $\epsilon = 0.02\, g'$ at momentum transfer $q^2 = 0$

Muon anomalous magnetic moment

Kinetically mixed A' is ruled out for $(g-2)_\mu$ (but see Mohlabeng 2019), and other gauged models, but still viable for gauged $L_\mu - L_\tau$,

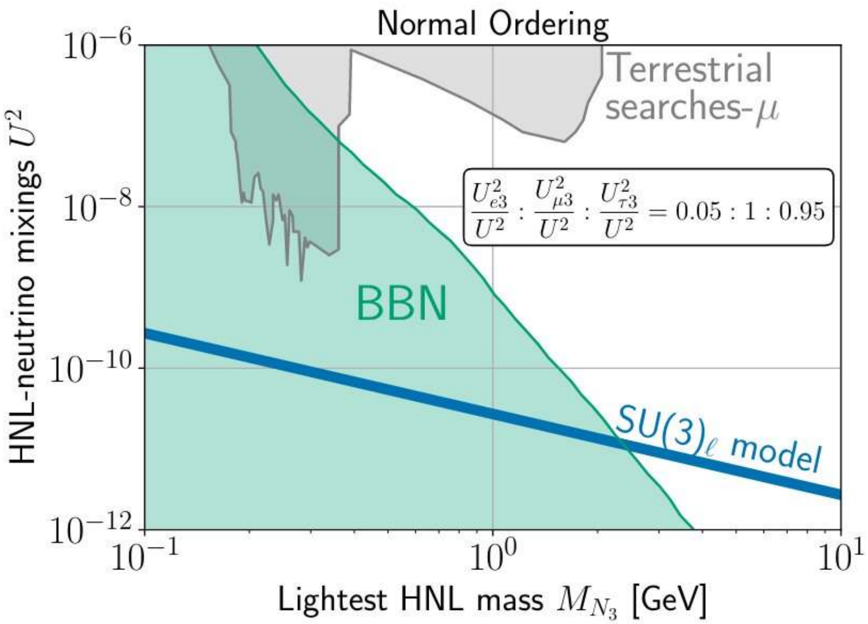


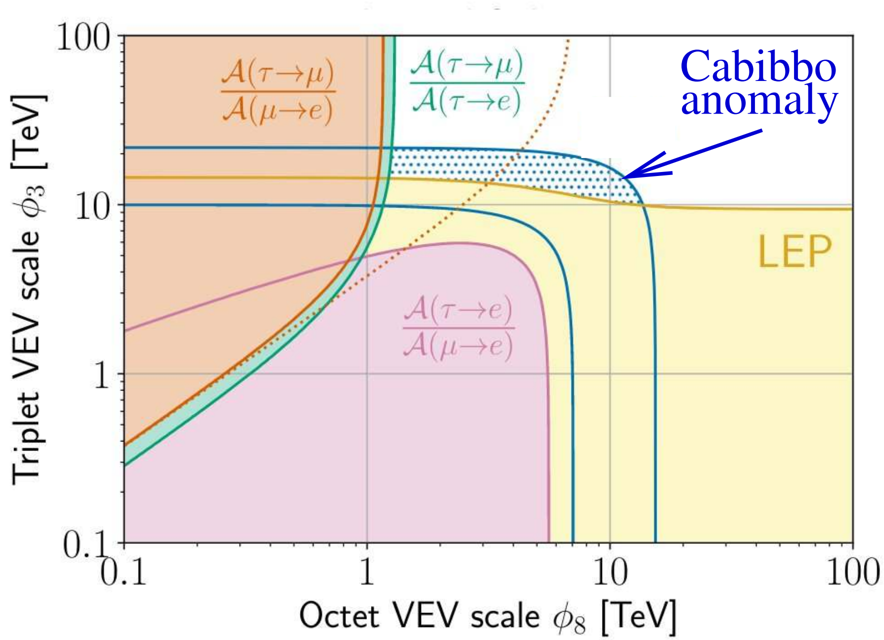
adapted from Bauer et al, 1803.05466

A'_μ from gauged SU(3)$_\ell$ lepton flavor

G. Alonso-Álvarez, JC, 2111.04744: $L_\mu - L_\tau$ dark photon can come from gauging SU(3) of lepton flavor, broken at $5-10$ TeV scale*, consistent with $(g-2)_\mu$. Can also explain Cabibbo (CKM) anomaly.

Model predicts heavy neutral leptons at the GeV scale, constrained by big bang nucleosynthesis



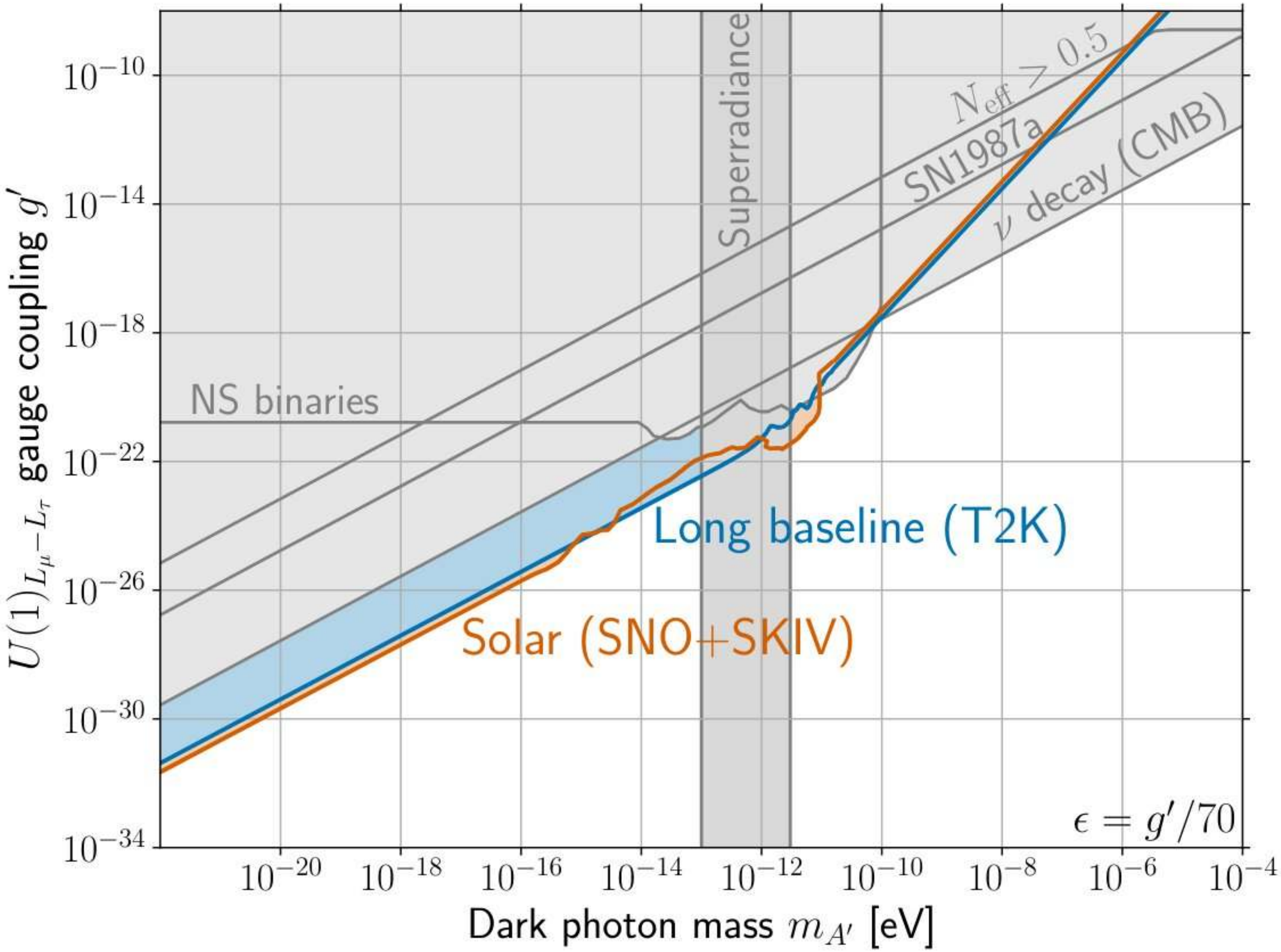


Lightest ν mass is predicted to be $\gtrsim 10^{-4}\,\mathrm{eV}$.

*except for one scalar with $\langle\phi_6\rangle \sim 20-200\,\mathrm{GeV}$

$L_\mu - L_\tau$ dark A'_μ effect on ν oscillations

If A'_μ from gauged $L_\mu - L_\tau$ is the dark matter, it can give a $g'\bar\nu \not{A}'(t)\nu$ time-dependent effective mass to ν_μ and ν_τ: distorts ν oscillations.

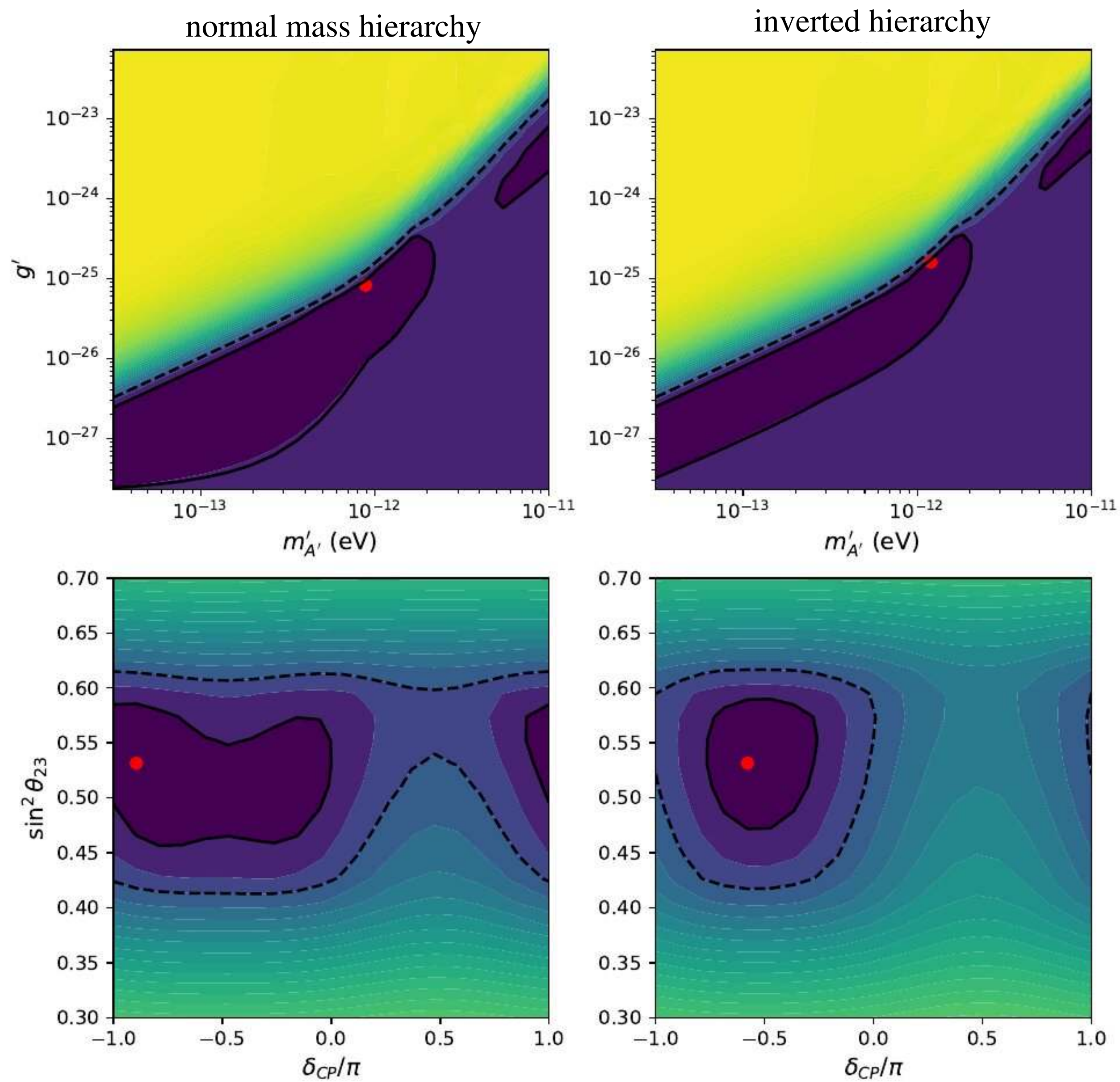


G. Alonso-Álvarez, K. Bleau, JC, 2301.04152

Long baseline and solar ν oscillations give new constraints on $L_\mu - L_\tau$ dark photon dark matter

Reconciling long baseline ν tensions

NOνA and T2K ν oscillation experiments have some tensions; $L_\mu - L_\tau$ dark photon effect can mildly ameliorate them



G. Alonso-Álvarez, B. Laurent, JC, U. Rahaman, to appear

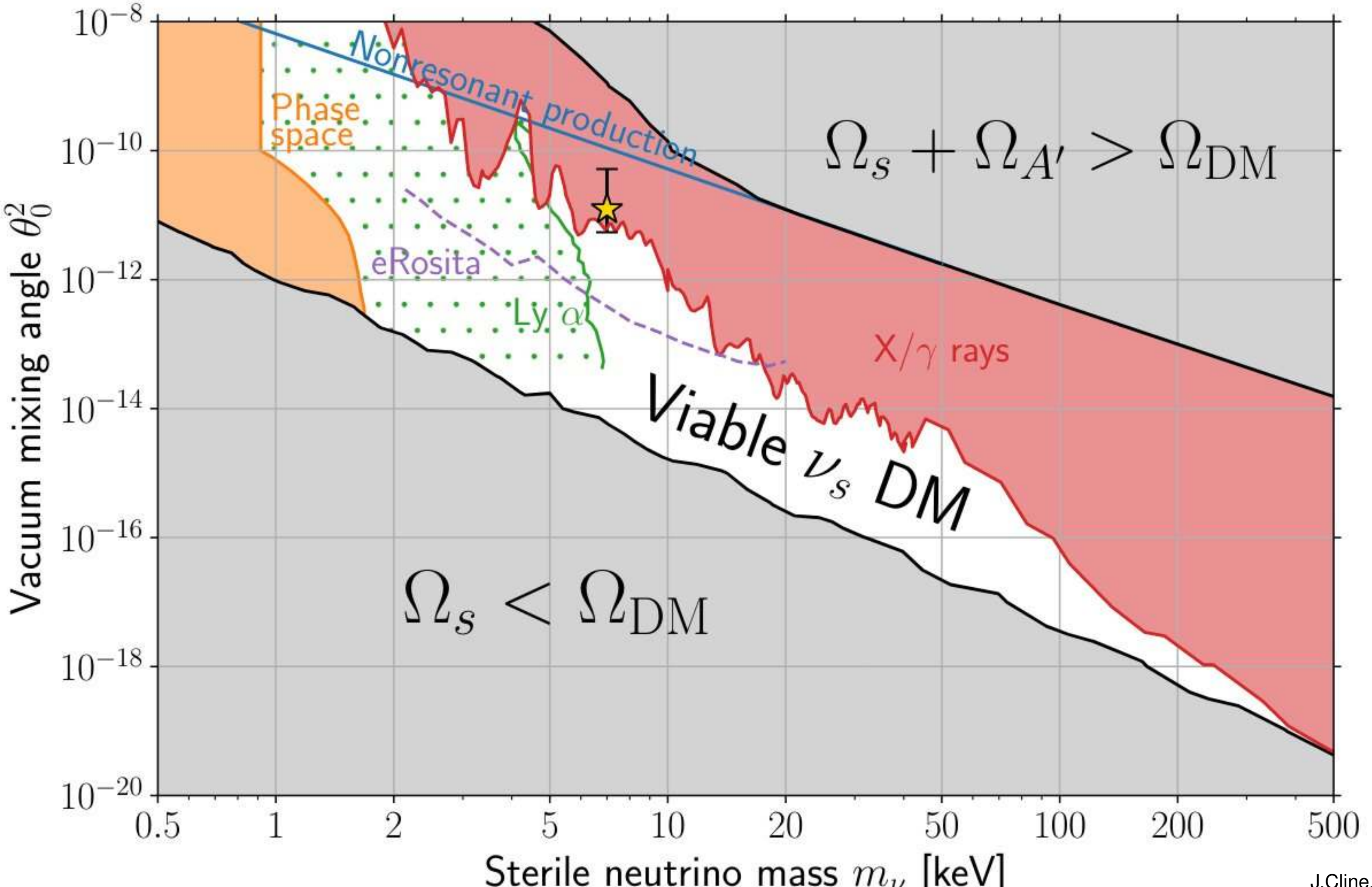
preferred $m_{A'} \sim 10^{-12}\,\mathrm{eV}$, $g' \sim 10^{-25}$

Inverted ν mass hierarchy is mildly preferred with $\Delta\chi^2 = 2$;

A' preferred over SM by $\Delta\chi^2 = 2.3$

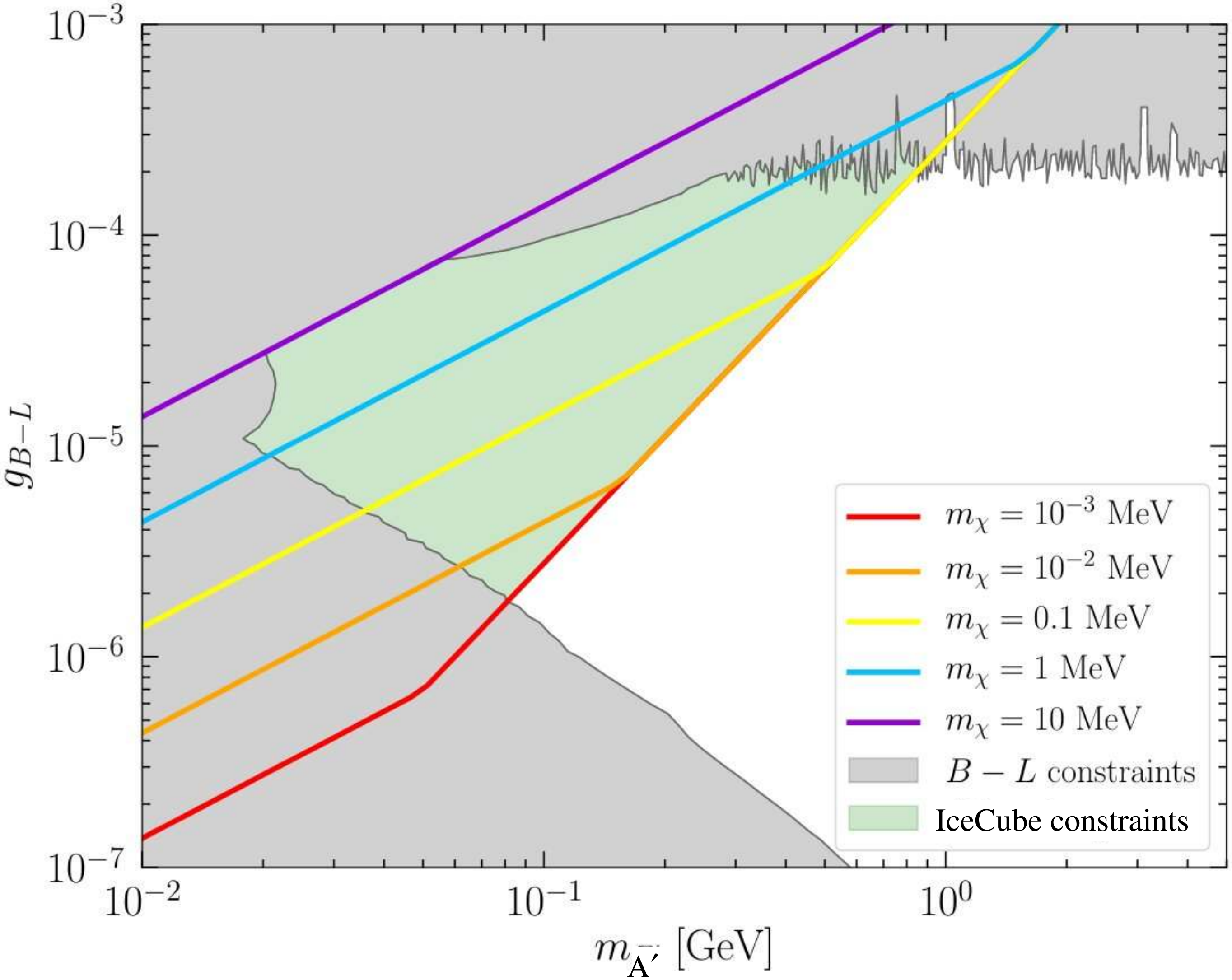
Enabling sterile ν dark matter

Sterile ν DM ν_s is ruled out by cosmological + x-ray constraints. Effective ν_τ, ν_μ masses from $L_\mu - L_\tau$ background dark photon can make $\nu_{\mu,\tau} \to \nu_s$ resonant at smaller mixing angles, opening new parameter space for ν_s DM (G. Alonso-Álvarez + JC, 2107.07524)



IceCube limit on ν-DM scattering

IceCube sees νs from active galactic nuclei. Suppose DM couples to $B - L$ dark photon.* AGN νs will be attenuated by DM spike around supermassive black hole.



JC, M. Puel, 2301.0875

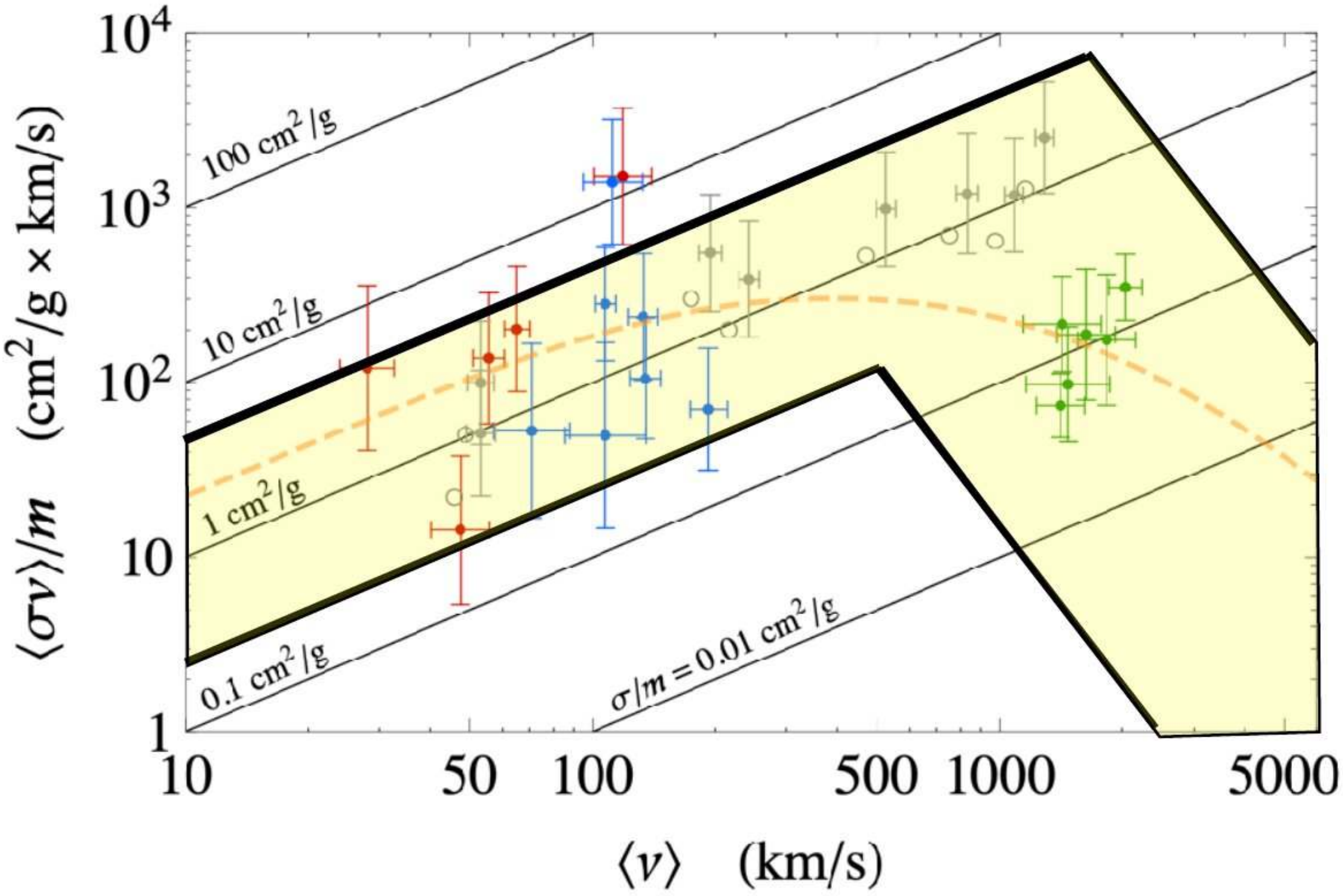
New constraint depends on DM mass,

$m_\chi \in [10^{-3}, 10]$ MeV

* with strength $g = 1$

Dark matter self-interactions

Dark photon is natural mediator of DM self-interactions. Motivated by small scale structure problems of CDM (Tulin, Yu, 1705.02358) and final parsec problem of SMBH mergers, desired to explain NANOGrav GW signal (G. Alonso-Álvarez, JC, C. Dewar, 2401.14450)



DM friction speeds SMBH merger; SIDM needed for DM spike to survive

Turn-over v suggests $m_{A'} \sim 10^{-3}\, m_\chi$

Good overlap to simultaneously solve final pc problem and CDM small-scale structure problems

original figure: Kaplinghat et al., 1508.03339

Conclusions

Dark photons: an extremely rich field, theoretically and experimentally

Dark photons can be dark matter or enable DM

They can explain anomalies: $(g-2)_\mu$, EDGES 21 cm dip, CDM small scale structure, SMBH mergers $\dots$

Huge parameter space: consistency of UV completions with gravity can provide guidance

E.g., Stueckelberg mass mechanism does imply new heavy physics at some scale, implies UV cutoff

Higgs mass mechanism can lead to much stronger constraints