Towards new constraints on light, dark sectors through EIC studies

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See Justin Cammarota's talk at this workshop (yesterday)!

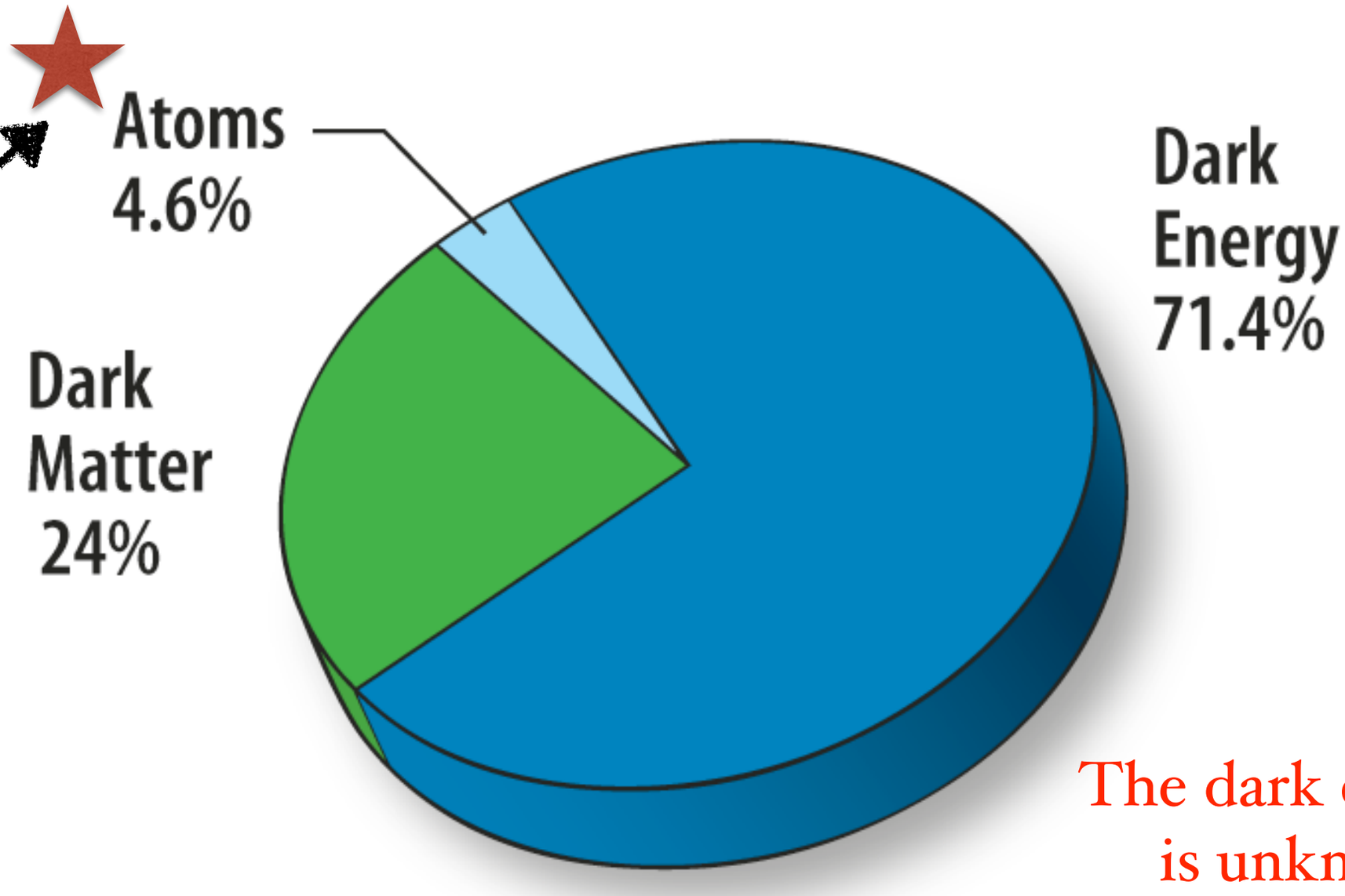
``New opportunities for beyond-the-Standard Model searches at the EIC"
Center for Frontiers in Nuclear Science
July 24, 2025

Research supported by the U.S. Dept. of Energy Office of Nuclear Physics
under DE-FG02-96ER40989

A Dark-Dominated Universe

Two different numbers speak to new physics

[map.gsfc.nasa.gov/universe/uni_matter.html]



The dark content is unknown

a baryon **excess**: TODAY

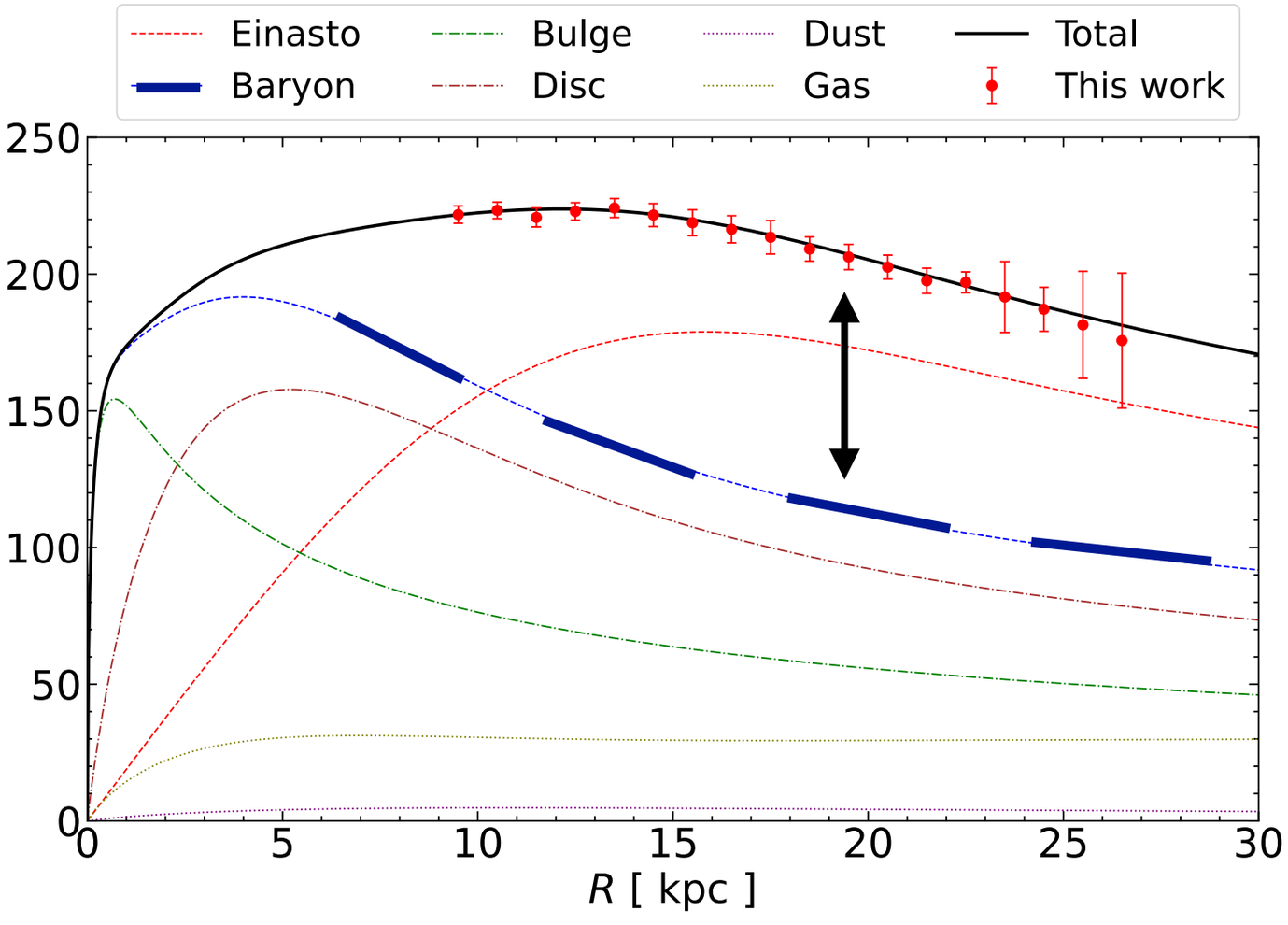
$$\eta = n_{\text{baryon}}/n_{\text{photon}} = (6.12 \pm 0.04) \times 10^{-10}$$

N.B. primordial D/H abundance…

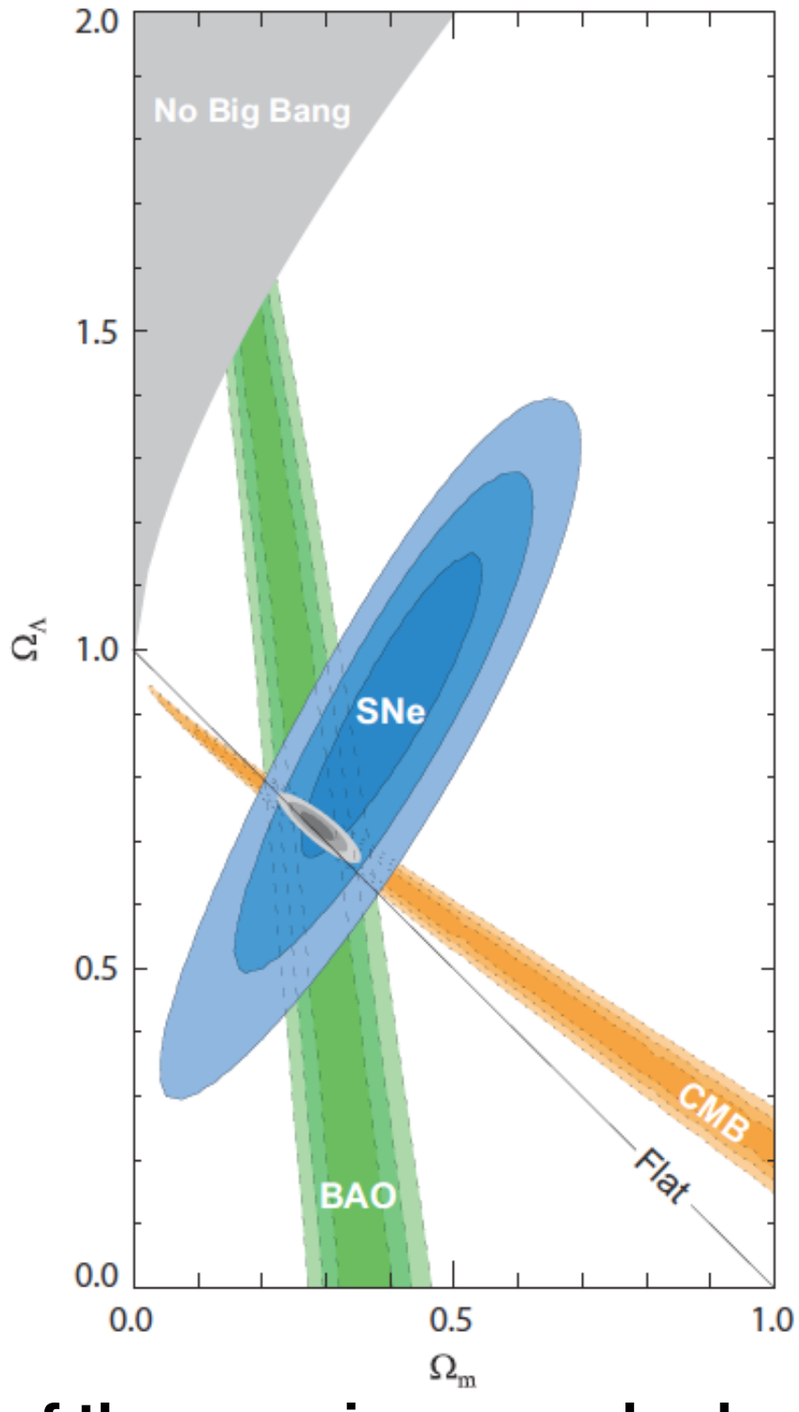
[Planck, 2020; PDG, 2022]

Observational Evidence for Dark Matter ranges from “local” to cosmic scales

Rotation Curve of our Milky Way with Gaia DR3!
Jiao et al., A&A, 2023



The observed circular speed does not track the luminous mass.



[PDG, RPP, 2017]

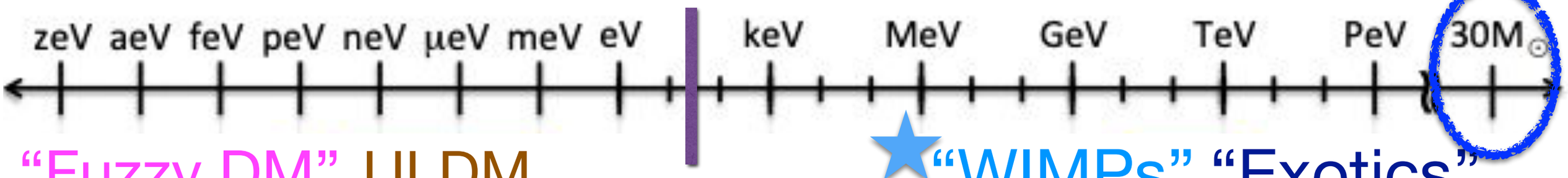
Most of the cosmic energy budget is of an unknown form!

A Vast Range of Dark Matter Candidates

Particle Masses

Fits in Galaxy

Elementary Particle



"Fuzzy DM" ULDM

★"WIMPs" "Exotics"

Phenomenology controlled by deBroglie λ at the Sun's location:

$n_{DM} \lambda_{dB}^3 >> 1$

Wave-like!

$n_{DM} \lambda_{dB}^3 << 1$

Particle-like!

"Black Holes"!

DM direct detection experiments assume a "Standard Halo Model" (& steady state)

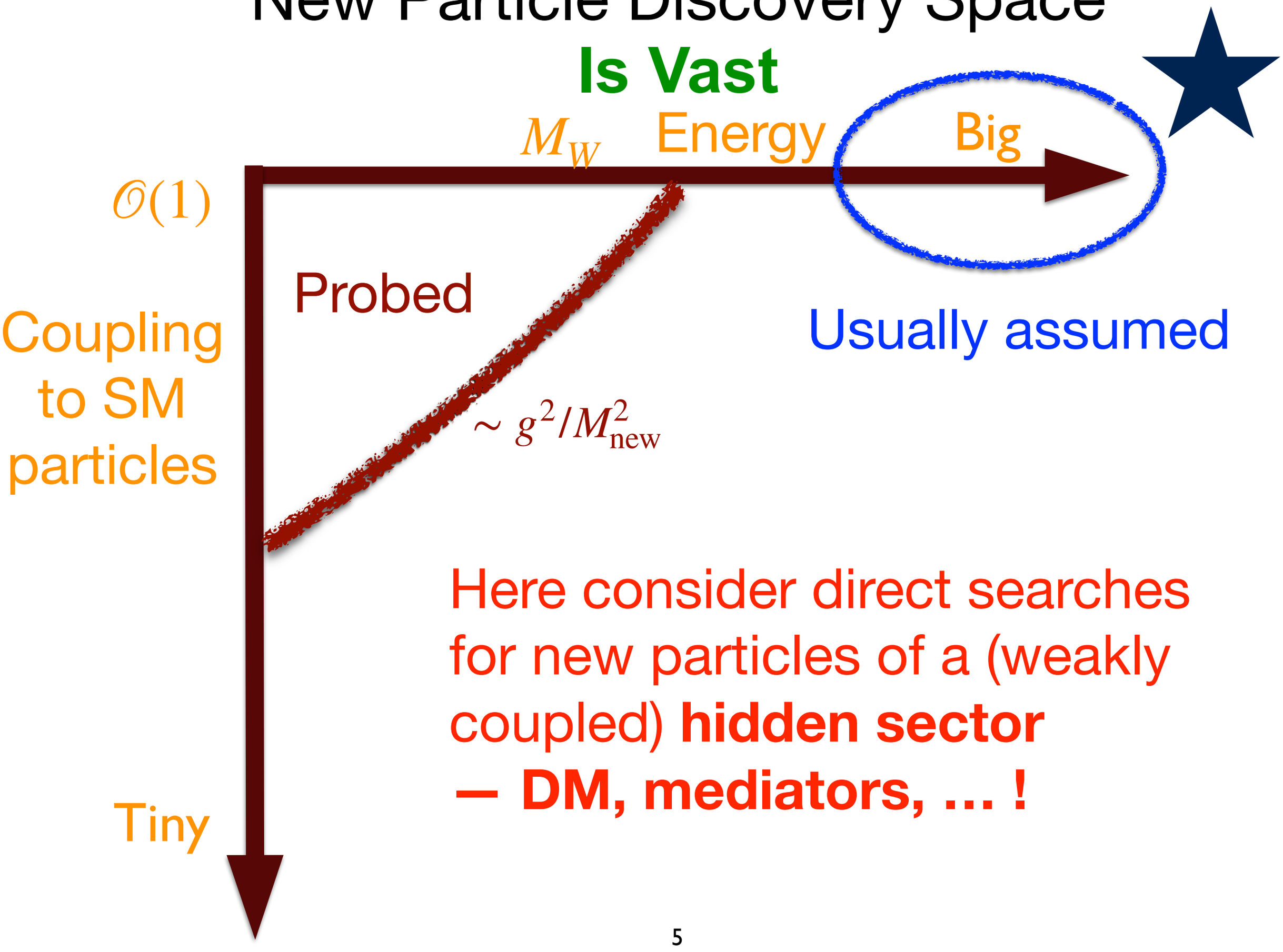
Cosmic small-scale structure not known! [Bechtol et al., arXiv:2203.07354]

Non-steady-state effects exist! [Widrow, SG, Yanny, Dodelson, & Chen, 2012; Yanny & SG, 2013...; SG, Hinkel, Yanny, 2020]

Motivates DM (and more) searches at accelerators!

New Particle Discovery Space

Is Vast



Here consider direct searches for new particles of a (weakly coupled) **hidden sector**

— DM, mediators, … !

Hidden-Sector Portals

Different Connectors are Possible

$$\mathcal{L}_{\dim\leq 4} = \kappa B^{\mu\nu} V_{\mu\nu} - H^\dagger H (AS + \lambda S^2) - Y_N L H N$$

[Batell, Pospelov, and Ritz, 2009; Le Dall, Pospelov, Ritz, 2015]

N.B. hidden sector particles

Enter the **dark photon** A'^{μ} and its field strength tensor $V^{\mu\nu}$

→ With "kinetic mixing" of visible & hidden sectors, e.g.

$$\mathscr{L} = -\frac{1}{4} F_{\mu\nu} F^{\mu\nu} - \frac{1}{4} V_{\mu\nu} V^{\mu\nu} + \frac{1}{2} m_{A'}^2 A'^2$$ dark matter

$$- \sum_f q_f e (A_\mu + \varepsilon A'_\mu) \bar{f} \gamma^\mu f - g_X A'_\mu \bar{X} \gamma^\mu X + \ldots \text{ for } M_{A'} \ll M_Z$$

[Feng, Smolinsky, Tanedo, "dark sunshine", 2016]

Gauge Theories of the Hidden Sector

There are many possible vector portals – but only some are anomaly free

Typical to consider Abelian groups as $F^{\mu\nu}$ is gauge invariant

- $U(1)_Y$ or $U(1)_{em}$: enter the dark photon and $A - A'$ mixing [Holdom, 1986...]

- $U(1)_Y$ with an extended Higgs sector : now mixing with both the photon and Z occurs – enter the Z_d [Davoudiasl, Lee, Marciano, 2014]
- $U(1)_B$ but not anomaly free [Nelson & Tetradis, 1989; Tulin, 2014; Dobrescu & Frugiuele, 2014...]

$$\mathcal{L}_{B'} = g^u_{B'} \bar{u} \gamma^\mu u B'_\mu + g^d_{B'} \bar{d} \gamma^\mu d B'_\mu + \ldots$$

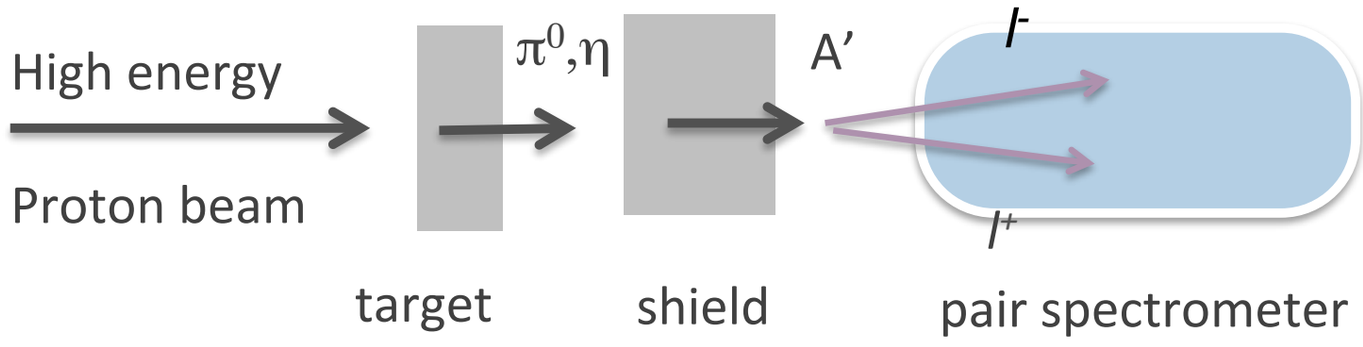
- $U(1)_{B\text{-}L}$ [Feng et al., 2017...]

$$\mathcal{L}_B = \frac{1}{3} \bar{q} \gamma^\mu q B_\mu$$

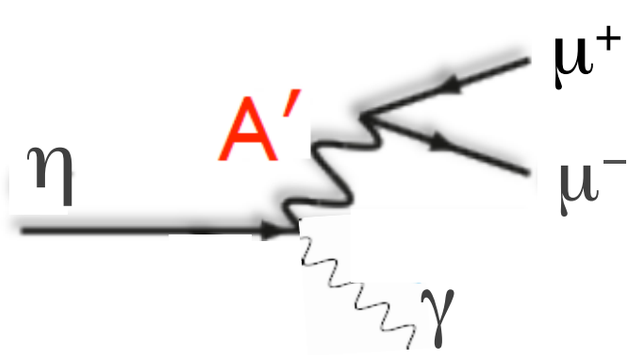
- $U(1)_{\mu\text{-}\tau}$ [Altsmannshofer, Gori, Pospelov, & Yavin, 2014]

Dark Photon Searches

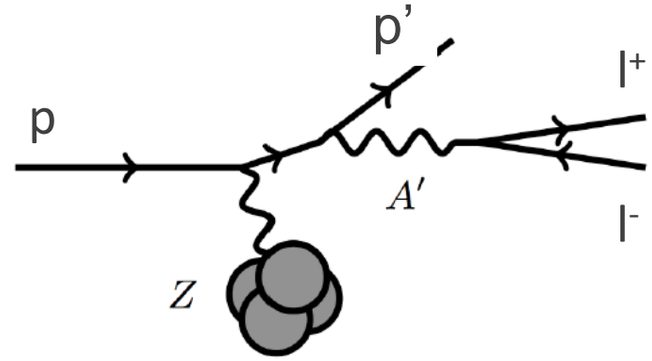
Searches for displaced vertices



[Liu & Reimer, Fermilab E906/SeaQuest]



[Batell, Pospelov, and Ritz, 2009; Gninenko, 2011]
[SG, Holt, Tadepalli, 2015]



[Bluemlein and Brunner, 2011 & 2013]

or "bump hunts" to sample $(\varepsilon, M_{A'})$ phase space

[cf. Bjorken, Essig, Schuster, and Toro ("BEST"), 2009]

Can look for scalars and more….

Special Opportunities at an EIC

for light, weak coupled particle searches

The EIC is a high-intensity electron-**ion** collider; its planned detector can also detect **forward** particles

[N.B. https://www.jlab.org/conference/EPIC]

Thus, BSM searches at the EIC…

- favor particles with couplings to first-generation fermions (& can access weaker couplings)
- gives a Z^2 signal boost via coherent production
- can probe "visible" or "invisible" final states
- sensitivity to particles at the MeV-GeV scale….

[Davoudiasl, Marcarelli, & Neil, 2023; Balkin et al., 2024; Davoudiasl & Liu, 2025…]

“Light” New Physics Searches

— some possibilities —

[N.B. many papers!]

Scalars:

$$\mathscr{L}_S = g_V^e \phi \bar{e} e + g_S^\chi \phi \bar{\chi} \chi$$

Vectors:

$$\mathscr{L}_V = g_V^e \phi_\mu \bar{e} \gamma^\mu e + g_V^\chi \phi_\mu \bar{\chi} \gamma^\mu \chi$$

$$m_\chi < m_\phi / 2$$

“invisible” final states possible!

[Davoudiasl & Liu, 2025]

The QCD axion, or axion-like particles (ALPs)….

The QCD Axion

Converting a problem into an experimental opportunity

QCD *could have* included a P, T (CP) odd term through $G\tilde{G}$ — but the experimental limits on d_n constrains its appearance severely!

[Baluni, 1979; Crewther et al., 1979]

Why does it not appear?

[Peccei & Quinn, 1977]

One solution: there is a Peccei-Quinn symmetry.

If it is spontaneously broken, then the **axion** can appear, and we have

$\theta \to \frac{a}{f_a}$ "the strong CP problem is washed away"

[Weinberg, 1978; Wilczek, 1978]

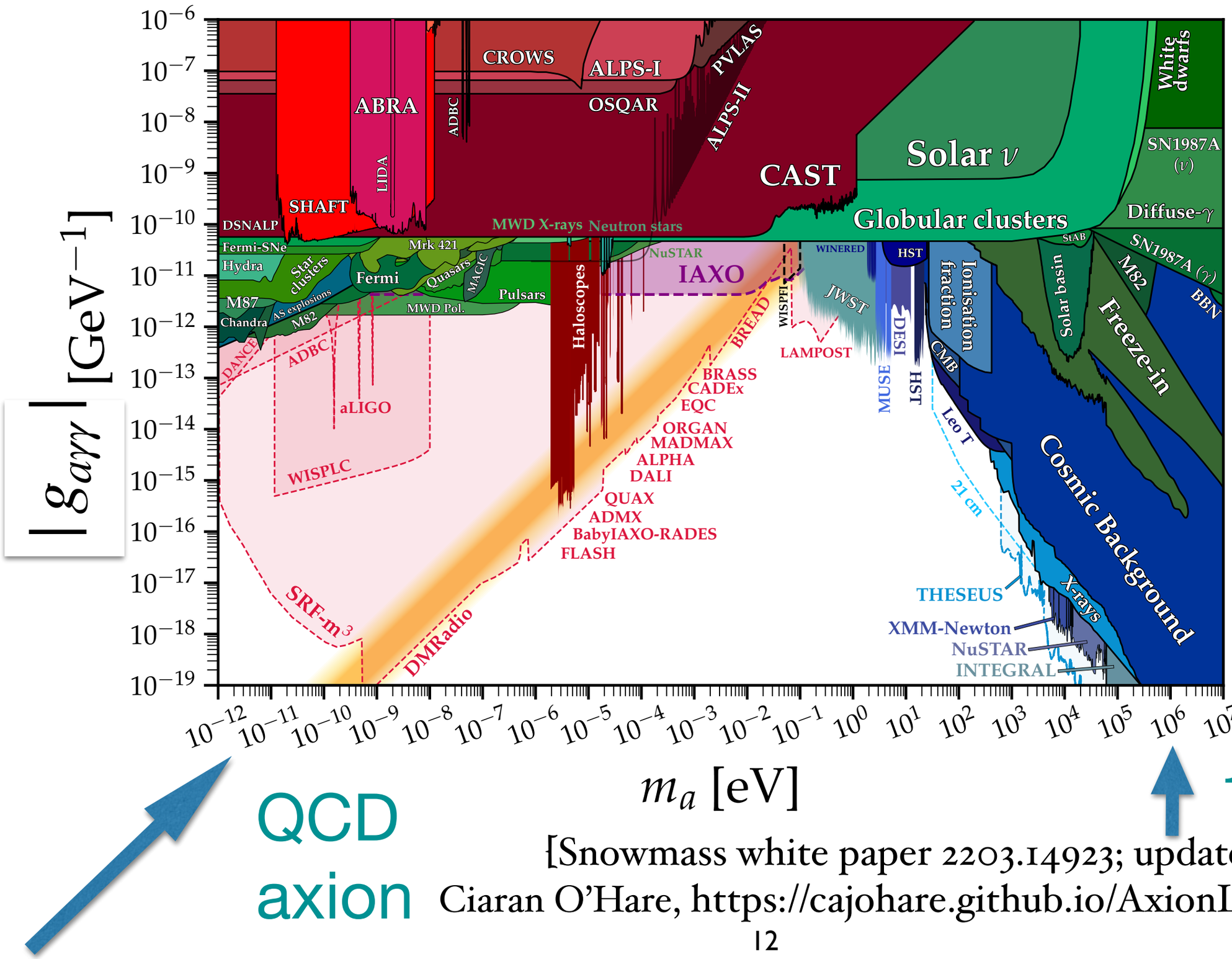
Couplings to fermions, photons also can appear

N.B. many new schemes to detect them!

[e.g., with phonons: Mitridate, Trickle, Zhang, Zurek, 2020; with magnetized media: Berlin & Trickle, 2023; ALPHA: Millar et al., 2023]

Constraints on axion-photon couplings

Assuming (astro) it is all of the dark matter $\mathscr{L}^{\rm em}_{\rm axion} = -\frac{g_{a\gamma\gamma}}{4} aF\tilde{F}$



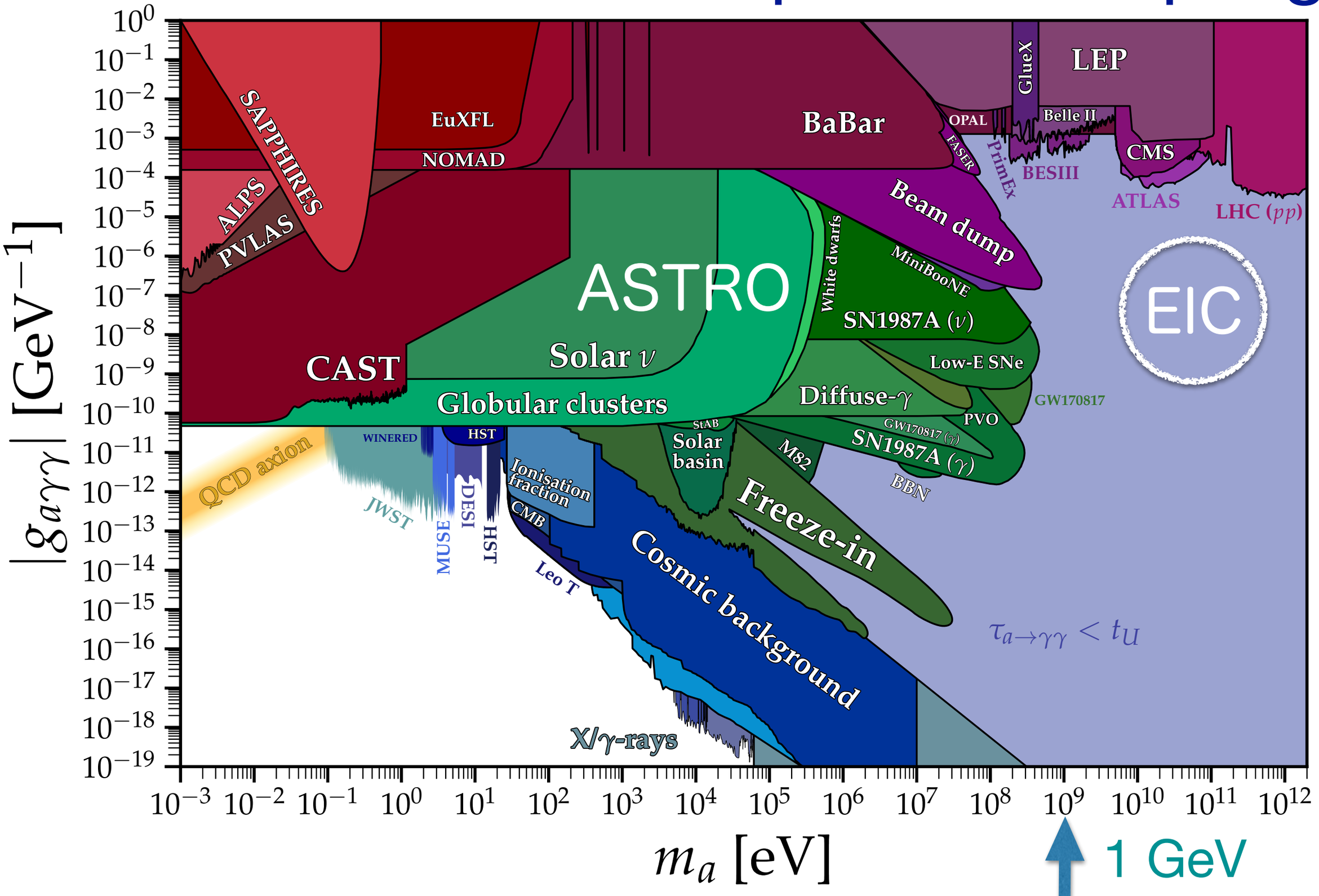
Pale red shaded regions are forecasts

QCD axion

10 MeV

[Snowmass white paper 2203.14923; update (June, 2025), Ciaran O'Hare, https://cajohare.github.io/AxionLimits/docs/ap.html]

Constraints on axion-photon couplings



[Ciaran O'Hare, https://cajohare.github.io/AxionLimits/docs/ap.html]

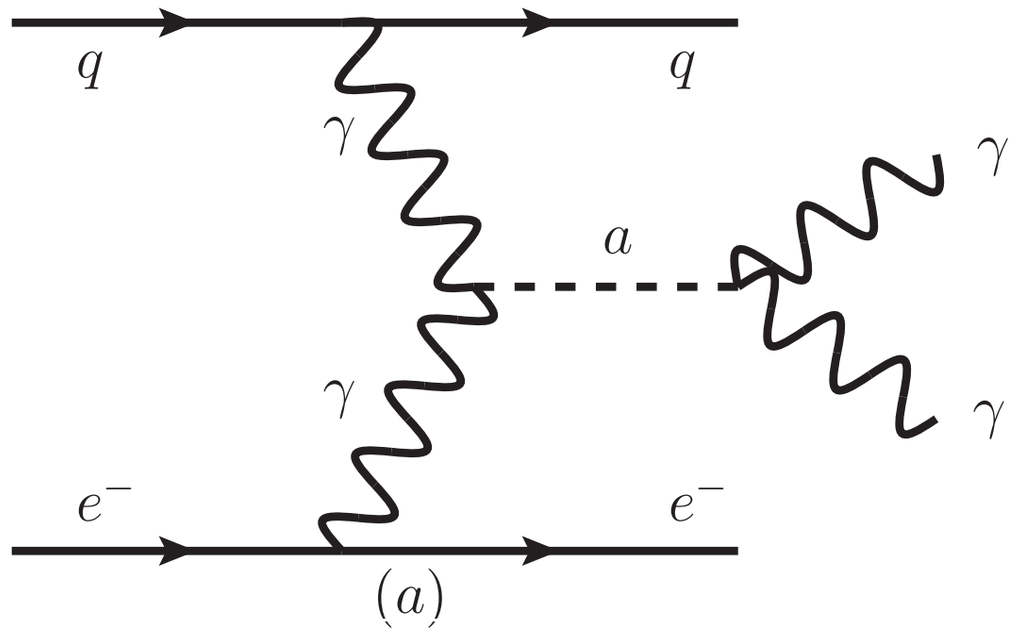
ALP production studies at the EIC

Focus thus far on axion-photon coupling constraints

$$\frac{1}{2}(\partial_\mu a)^2 - \frac{1}{2}m_a^2 a^2 - \frac{g_{a\gamma\gamma}}{4} a F_{\mu\nu}\tilde{F}^{\mu\nu}$$

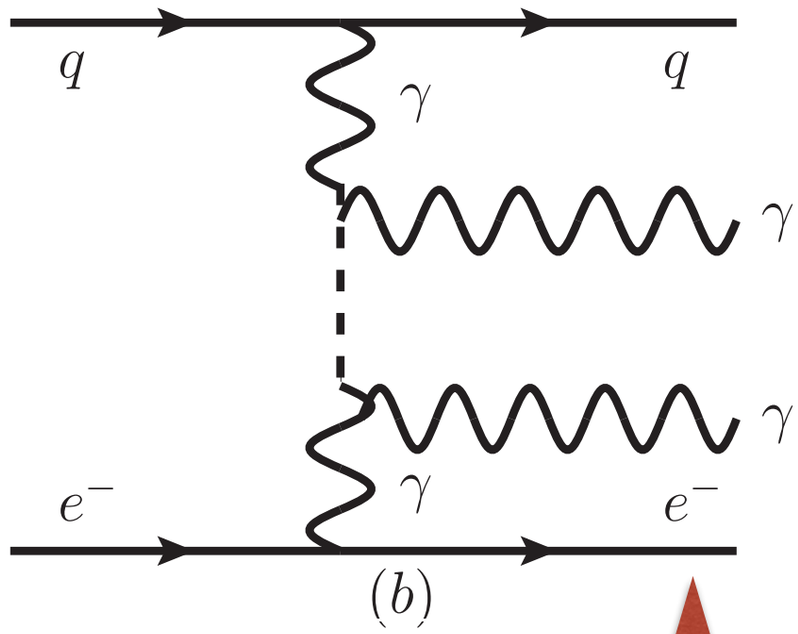
for $e^- q \to e^- j\gamma\gamma$...

[Liu & Yan, 2021; N.B. PDG notation]



$\mathcal{O}(g_{a\gamma\gamma}^2)(\mathrm{Br}(a \to \gamma\gamma))$

Set $= 1$ (Strong CP?!)

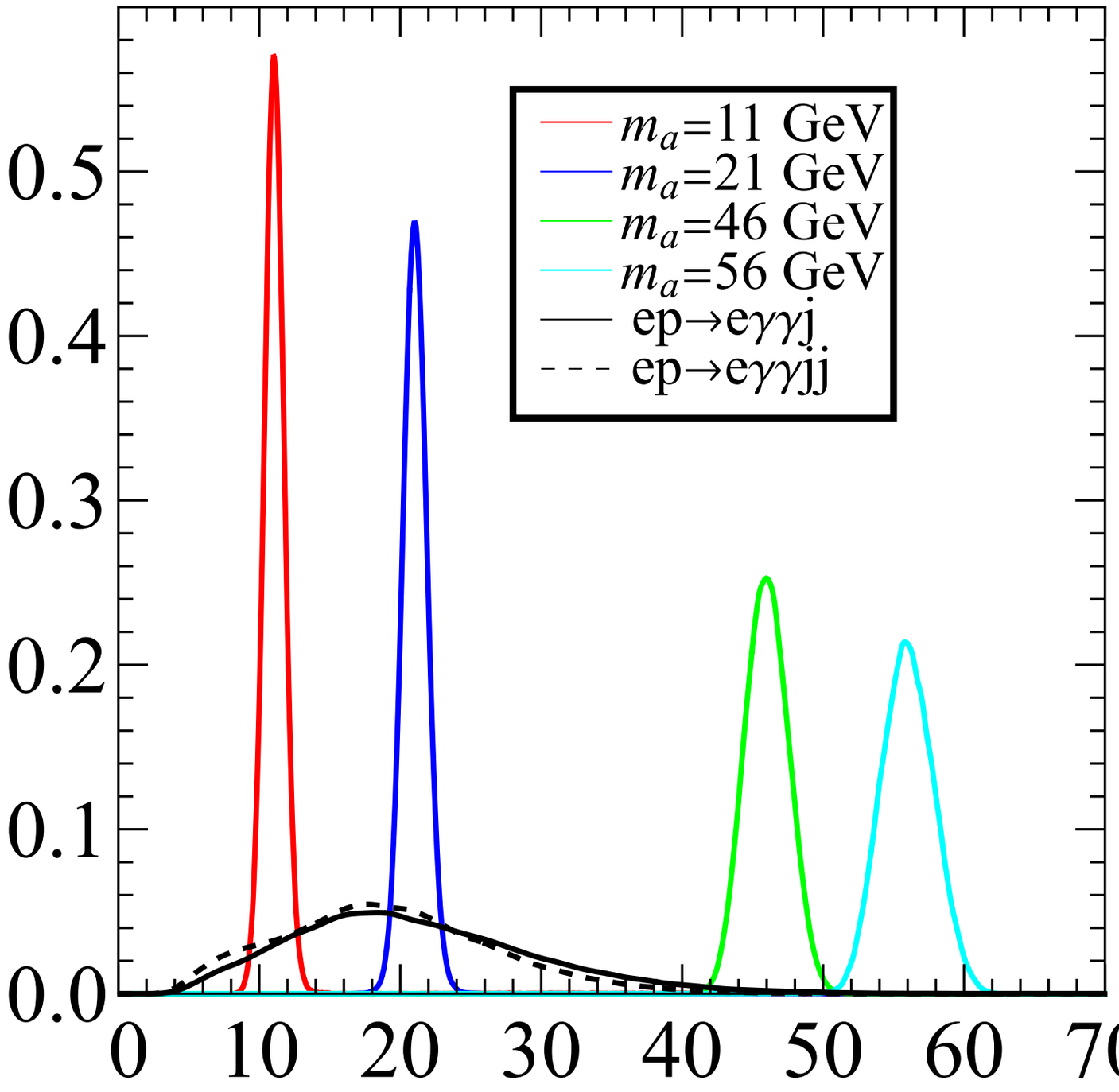


$\mathcal{O}(g_{a\gamma\gamma}^4)$ ★

Still need to detect $\gamma\gamma$!

ALP production studies at the EIC

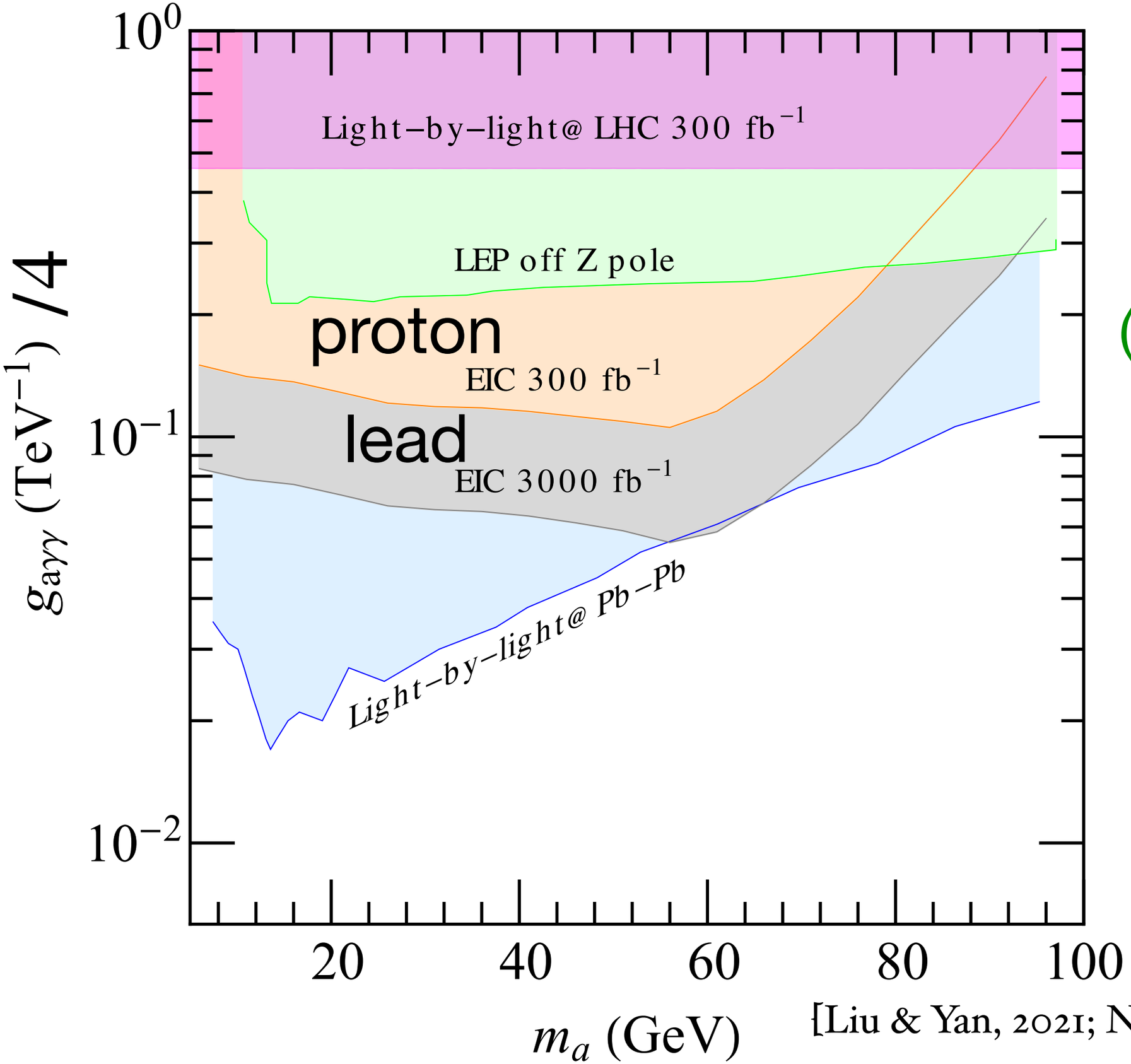
"Bump hunts"



After kinematic cuts

[Liu & Yan, 2021]

ALP production studies at the EIC



Prompt Decay

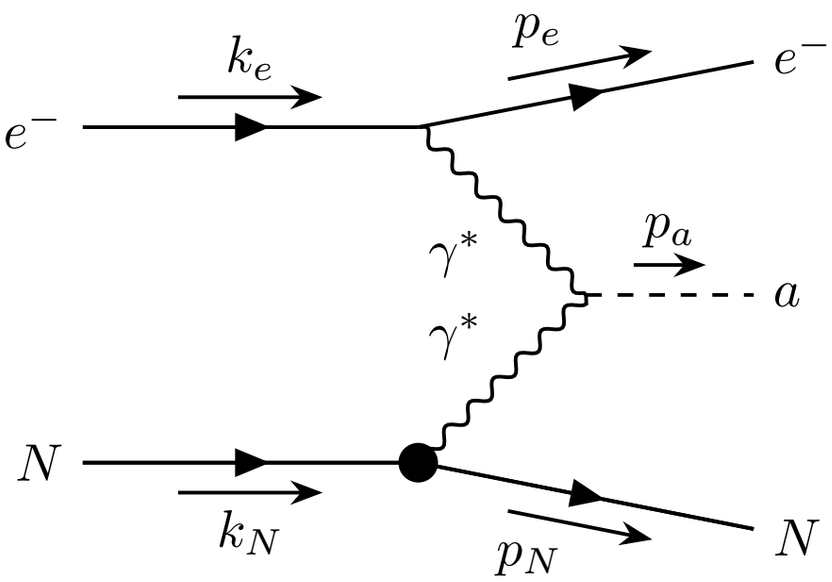
(Bump hunts)

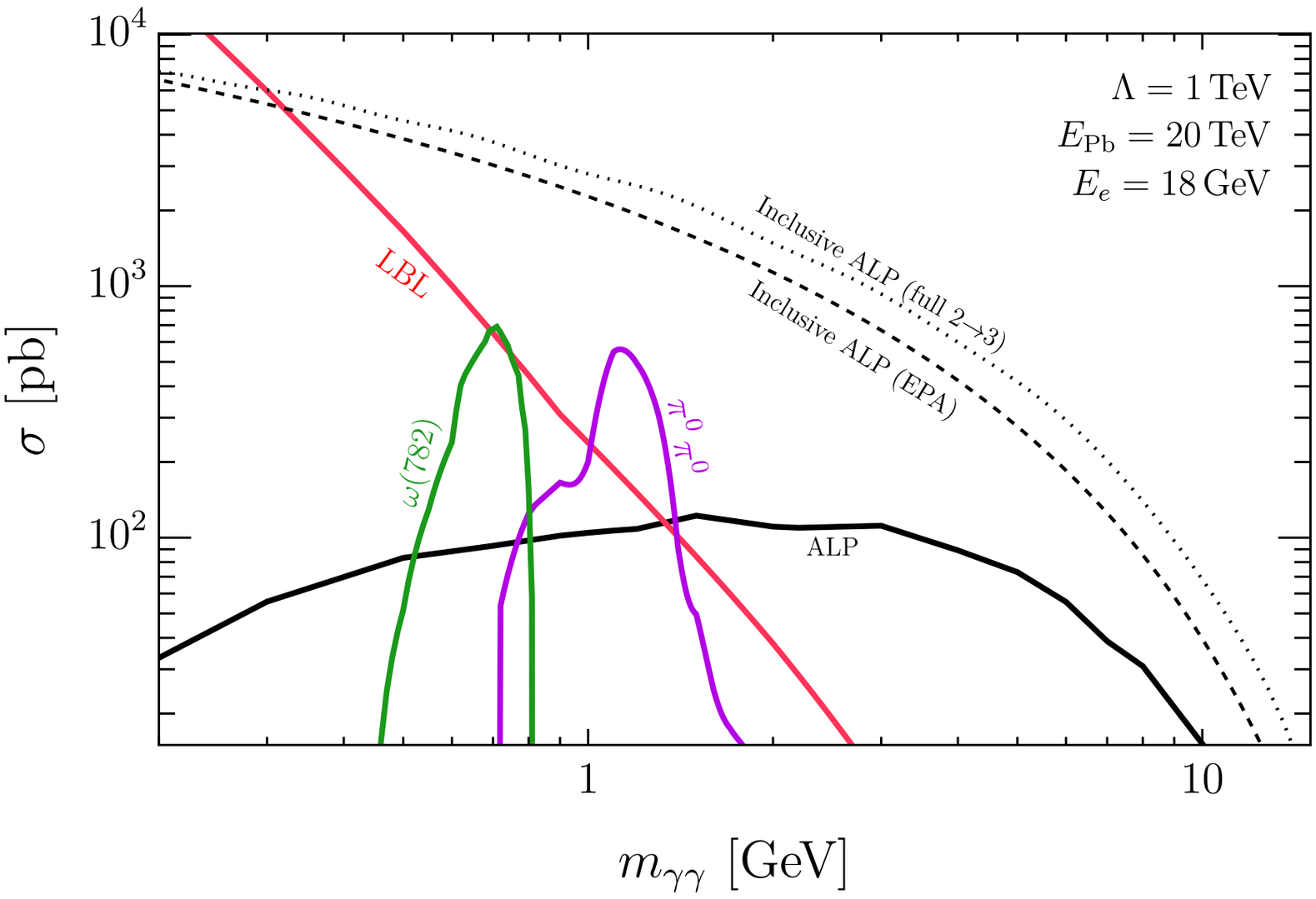
Bkgds computed

[Liu & Yan, 2021; N.B. PDG notation]

ALP production studies at the EIC

Study of s-channel axion production





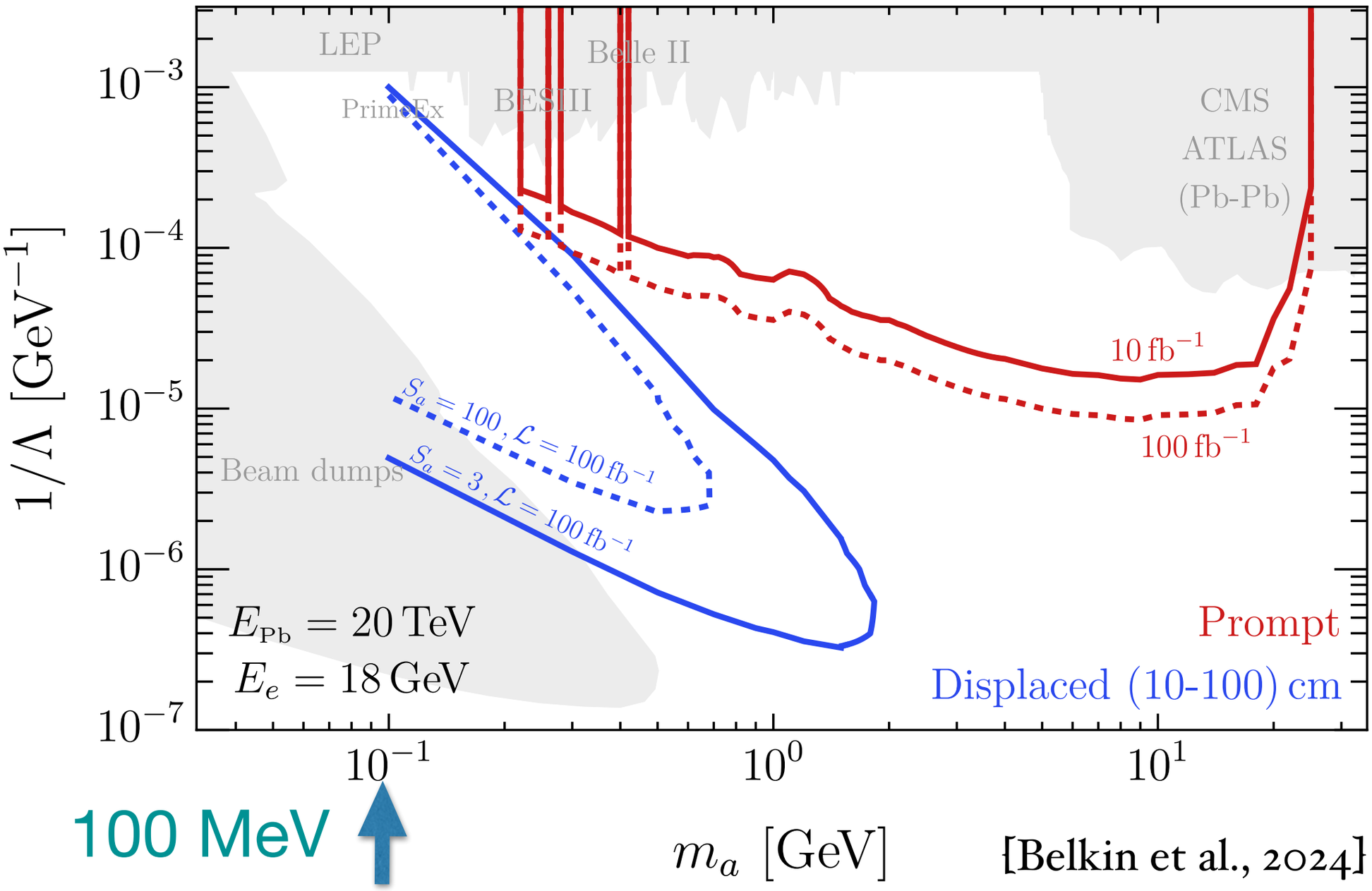
Assumes

$\mathrm{Br}(a \to \gamma\gamma) \approx 100\,\%$

[Belkin et al., 2024]

ALP production studies at the EIC

$$g_{a\gamma\gamma} \equiv 1/\Lambda$$



[Belkin et al., 2024]

What if the axion decays invisibly?

ALP production studies at the EIC

New possibilities using QCD + QED factorization

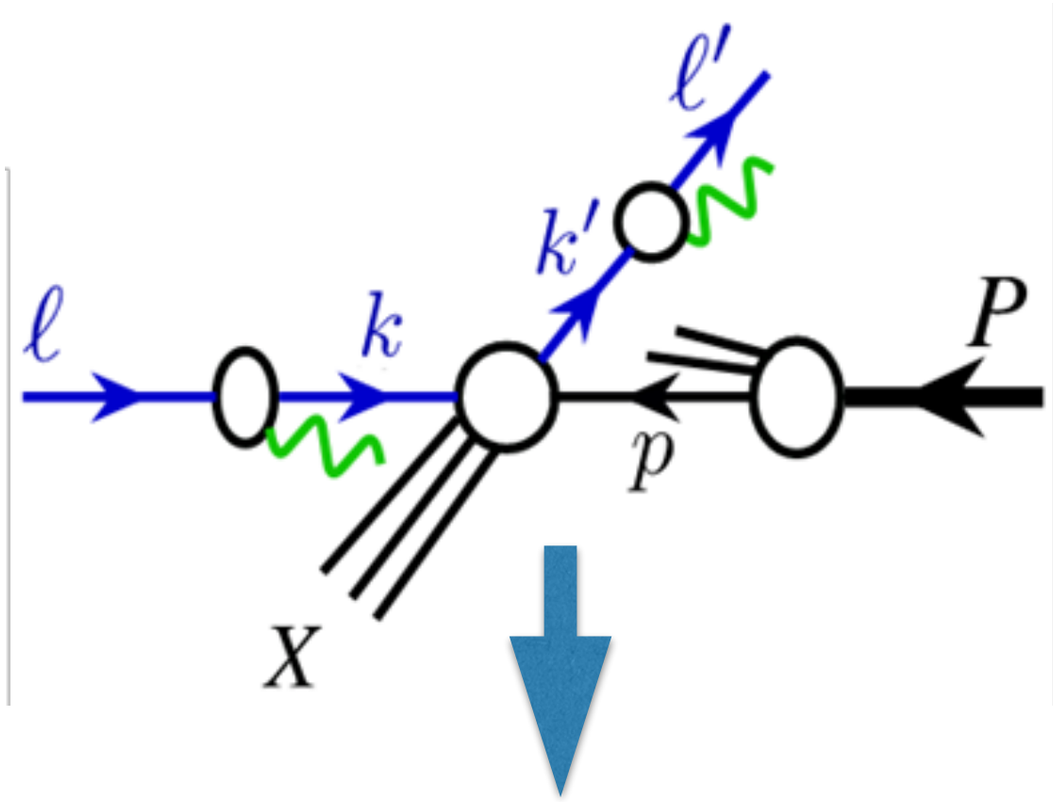
See Justin Cammarota's talk at this workshop (yesterday)!

- Refines computations of DIS and SIDIS cross sections & their kinematic variations
- Cross-section shapes can be modified in $\mathcal{O}(g_{a\gamma\gamma}^2)$ via "invisible" axion emission
- Limits on axion-fermion couplings also possible

Thus far, the factorization analysis assumes real photon emission…

ALP production studies at the EIC

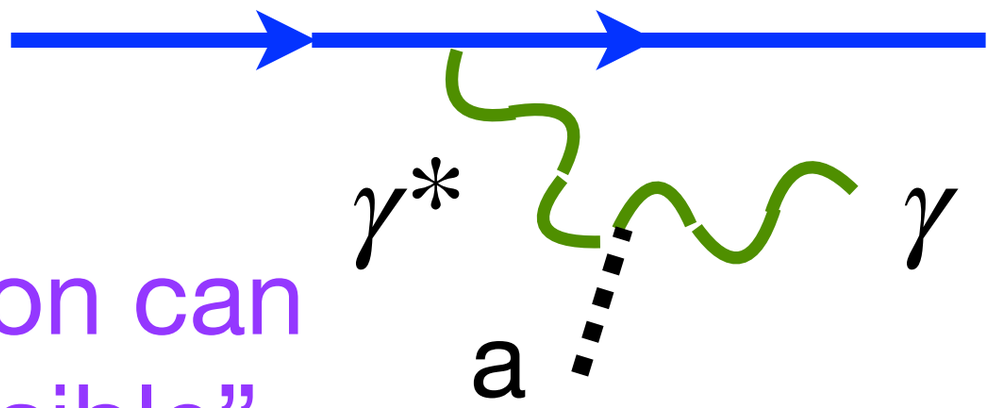
e.g., in DIS with QCD + QED factorization



[Liu et al., 2021; Cammorata et al., 2024]

PDFs / LDFs are blended QCD+QED objects

Can add, e.g., $\gamma^* \to \gamma a$ to any charged fermion line



and can add a direct coupling to fermion f with the precise weighting to depend on the **model**….

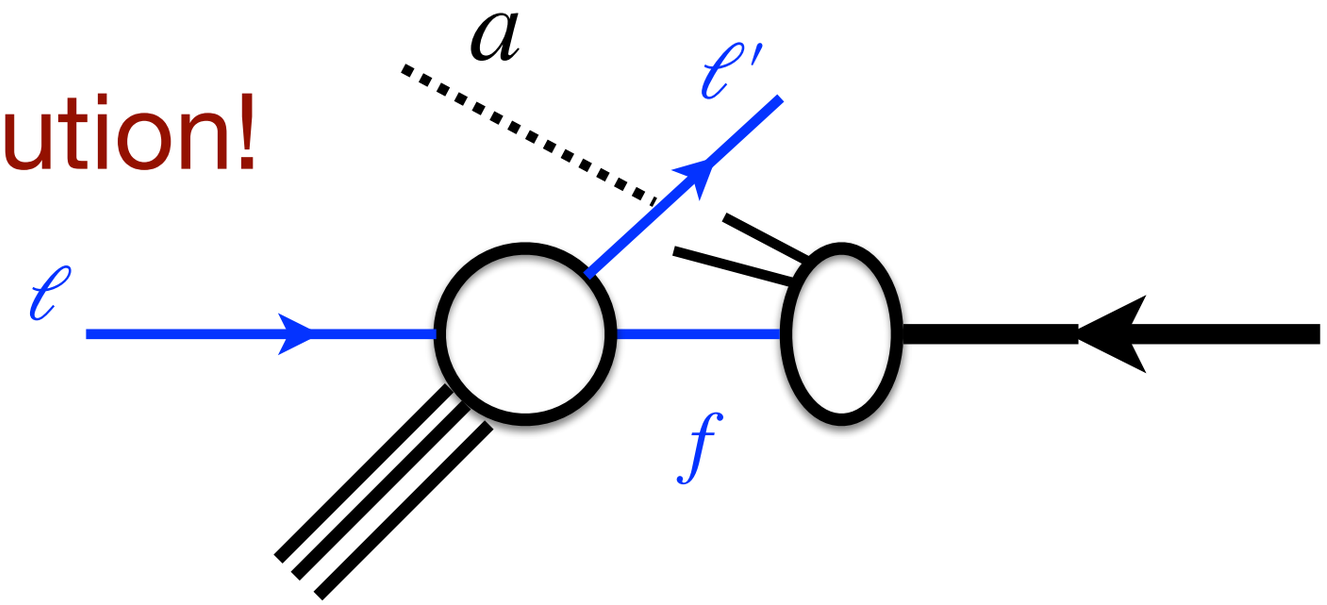
The axion can be “invisible”

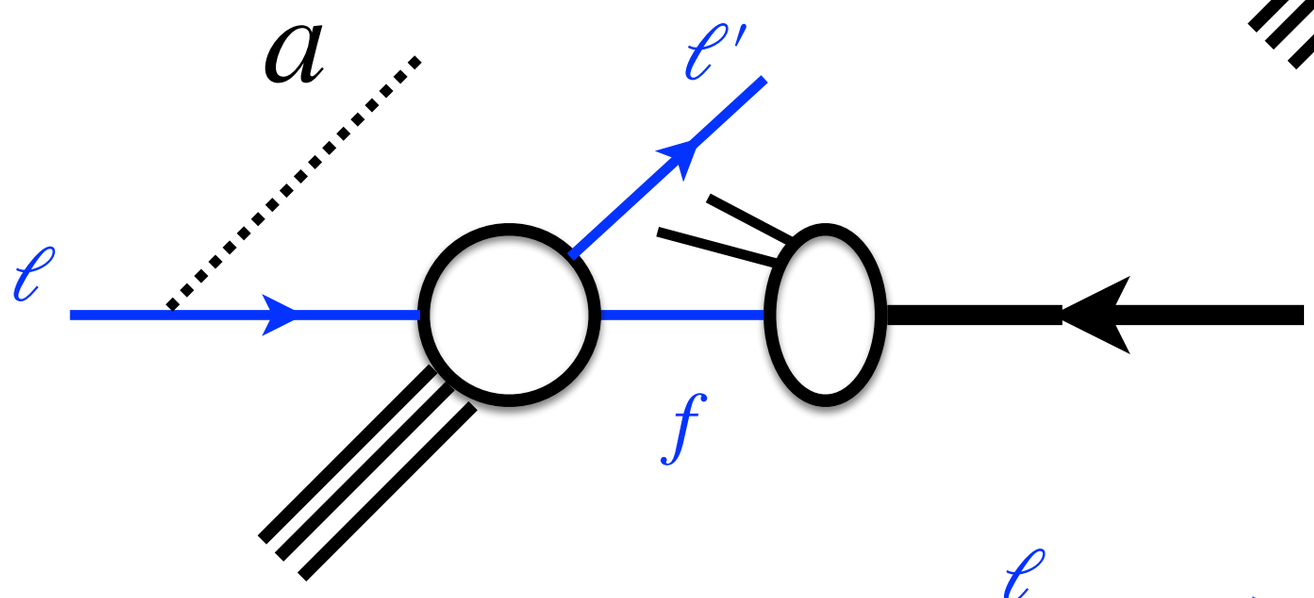
ALPs & QCD+QED factorization

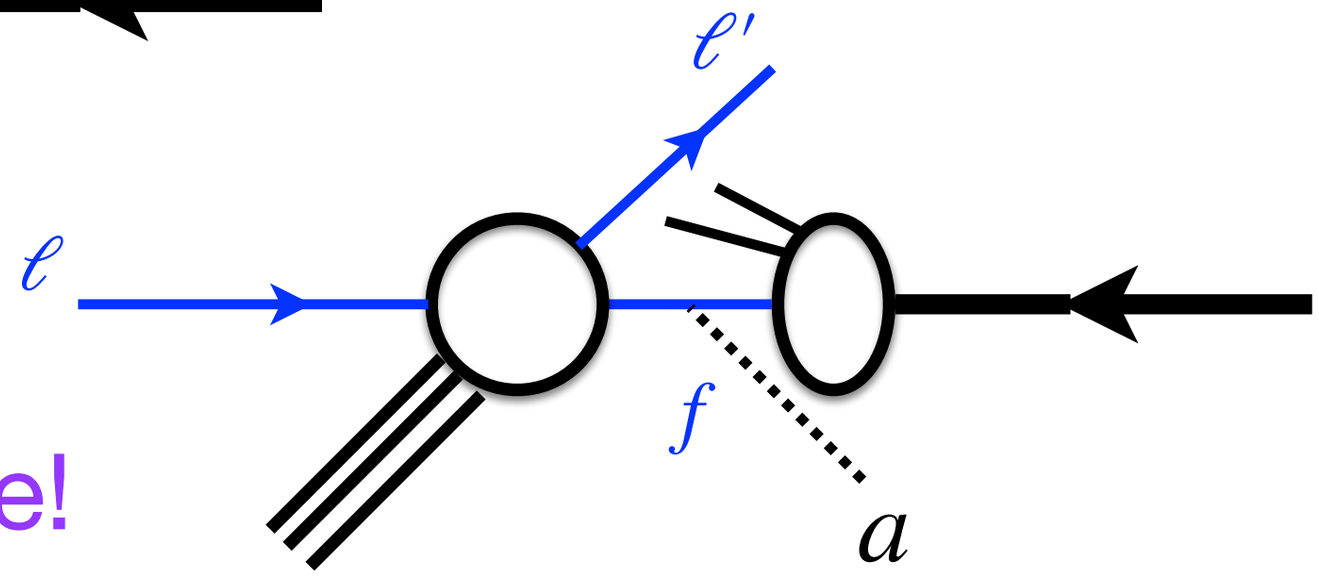
ALP models: input couplings at Λ + RNG flow!

Impacts LDF/PDF evolution!

no m_a threshold!







N.B. changes of shape!

Coda: Probes of MeV-Scale Axions

via rare η meson decays

Beam dump experiments offer strong constraints on $g_{a\gamma\gamma}$

However, we can also consider $a \to e^+e^-$, though the axion must decay **promptly** enough to be detected as in, e.g.,

$$\eta(\eta') \to \pi\pi(a \to e^+e^-)$$

[Alves & Gonzalez-Solis, 2024]

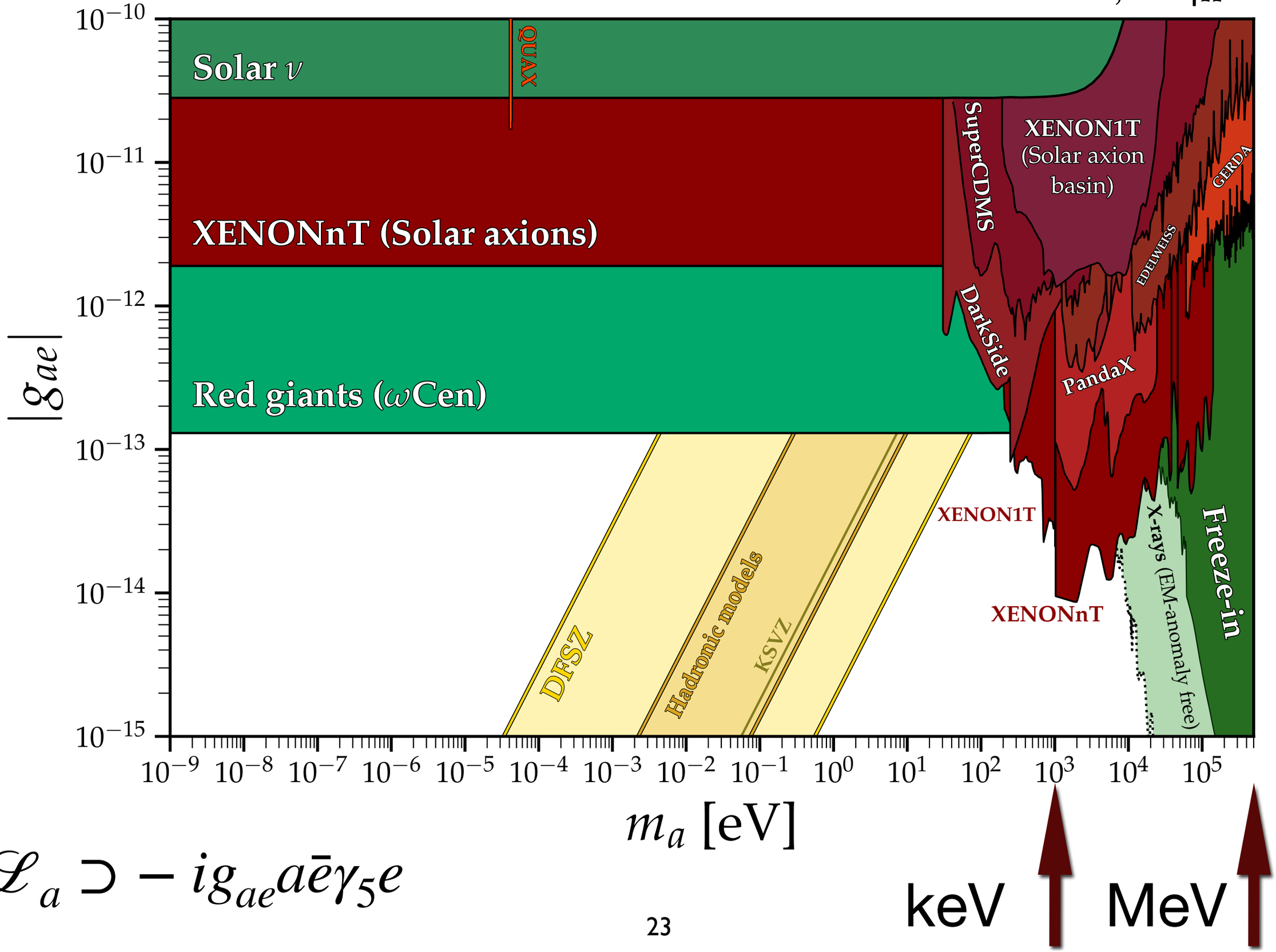
Possible if axion-pion mixing is suppressed….

[Alves & Weiner, 2018; Alves, 2021; Hostert & Pospelov, 2023]

In these searches the axion decays “visibly”!

Axion Constraints

[PDG axion review, 2024; Ciaran O'Hare; note also Berlin et al., 2024]]



$$\mathscr{L}_a \supset -ig_{ae}a\bar{e}\gamma_5 e$$

keV MeV

Summary

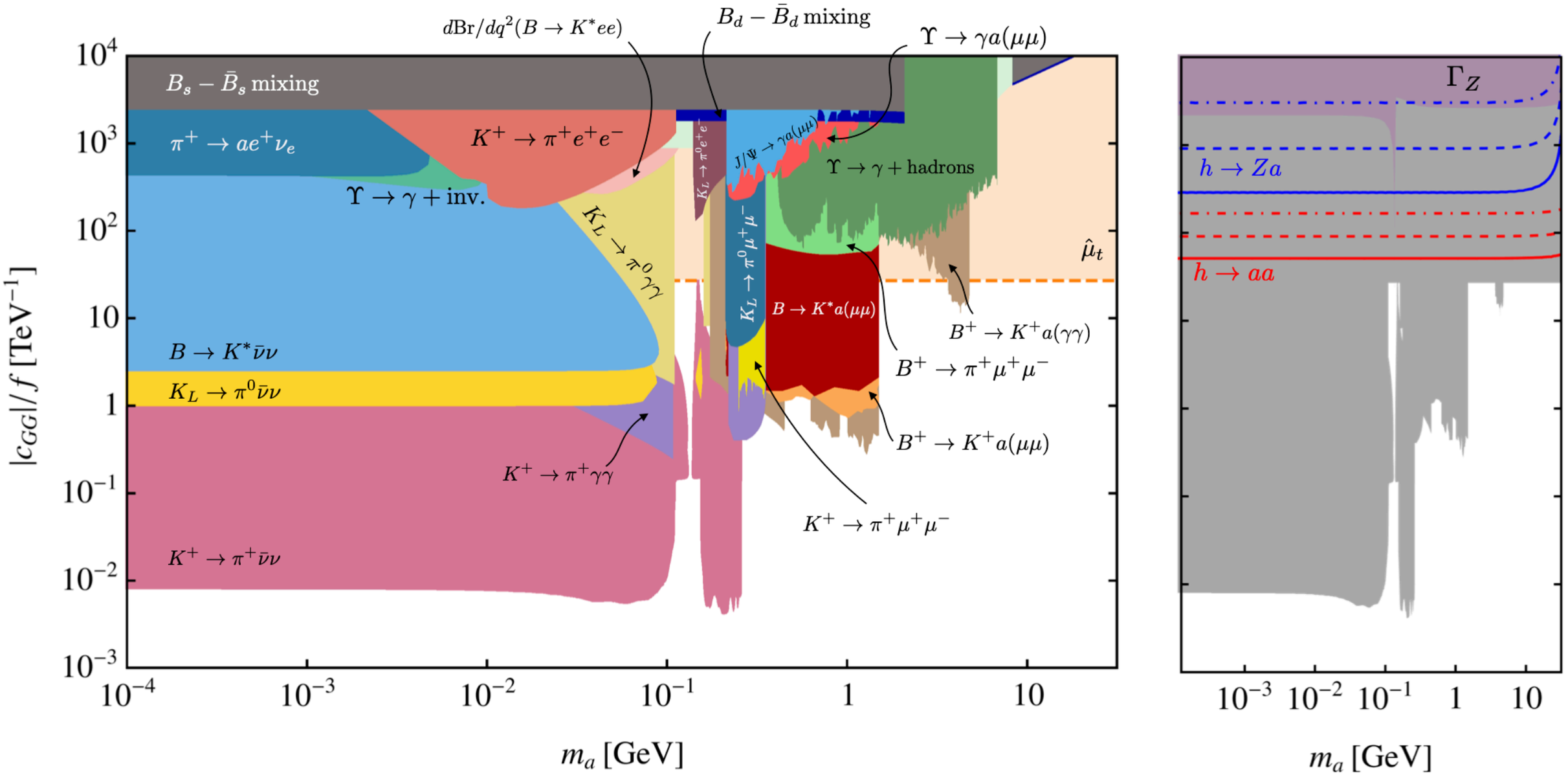
We have considered new searches for axion-like particles at the EIC (as an example)

- Prompt and displaced vertex studies of visible axions-like particles have been made
- The combined QCD+QED factorization framework opens new windows on such searches, as the ALP s can decay invisibly & still be probed (via PDF/LDF **shapes**!)
- Potentially models with different axion-fermion couplings can be probed simultaneously….

I thank Justin Cammarota for discussions!

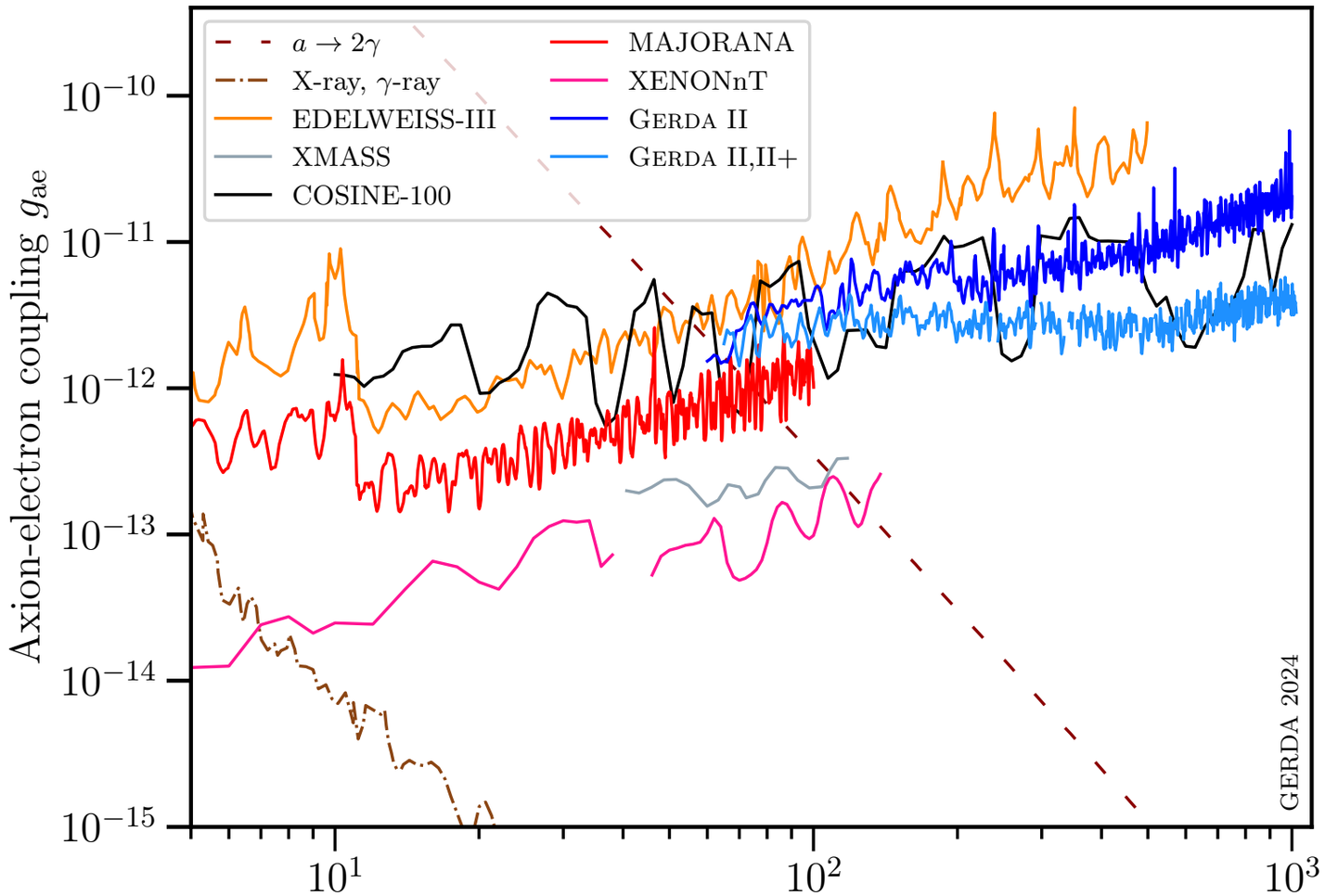
Backup Slides

Flavor Probes of ALP Couplings



[Bauer, Neubert, Renner, Schnubel, Thamm, 2022]

Model: glue only at $f = 4\pi(1\ \mathrm{TeV})$

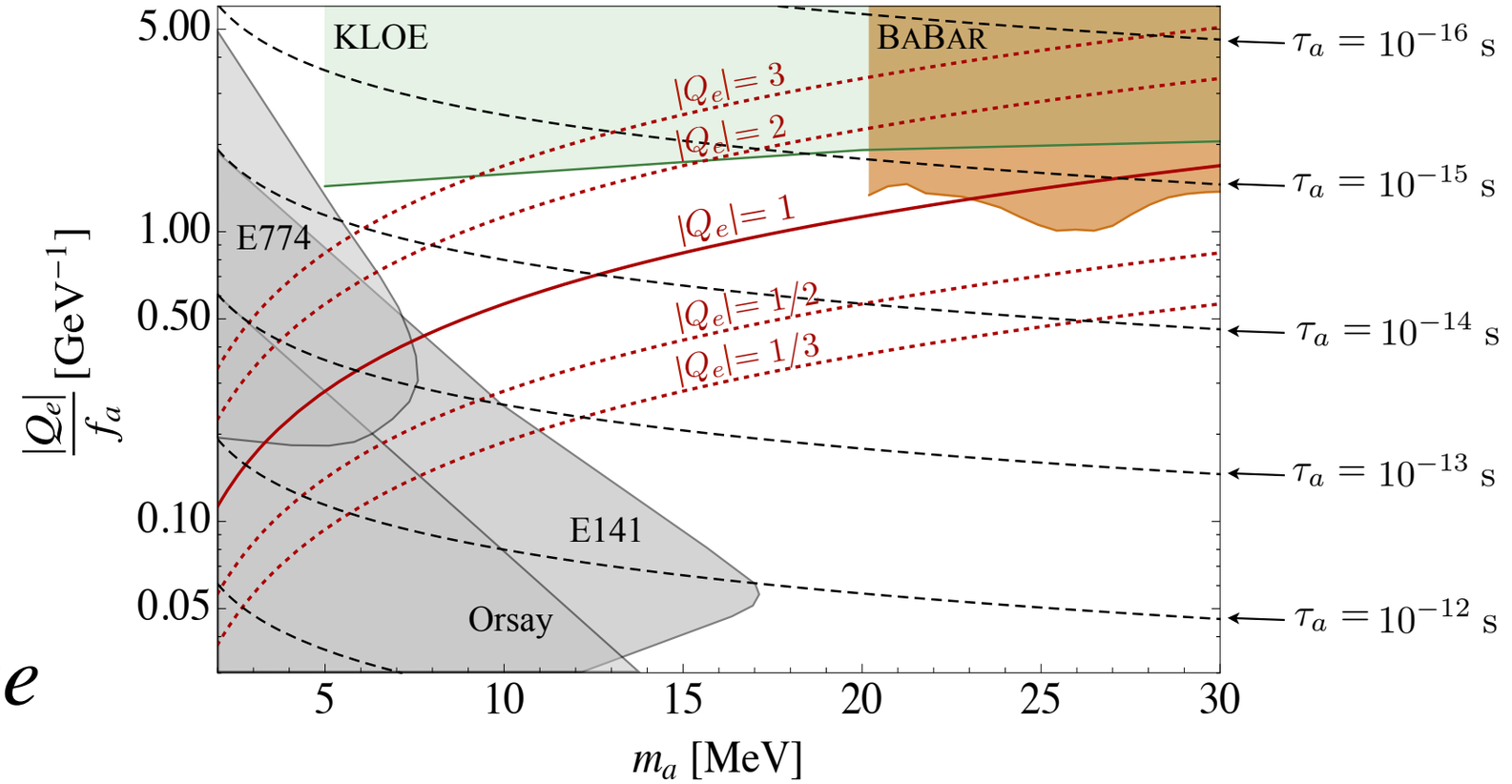


[GERDA, 2405.15954]

$\times m_a \Longrightarrow g_{ae}$

DD constraints are more sensitive; could $a \to e^+e^-$ not be prompt?

[Alves & Weiner, 2018]



Ultralight Axion-like Dark Matter

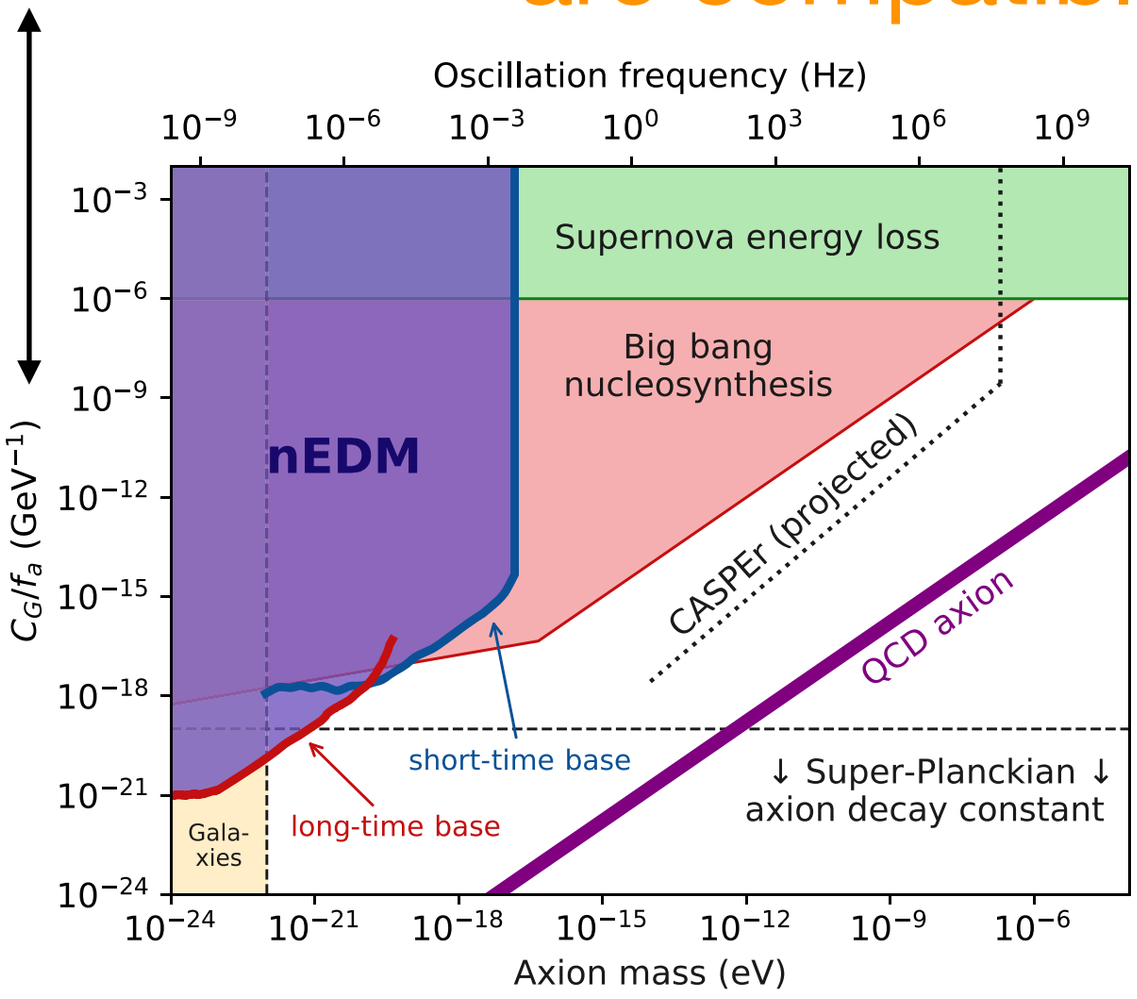
Can be compatible with our cosmic history if DM "overproduction" is erased by inflation

[cf. Lee & Weinberg, 1977]

Current CMB observations (B mode polarization) are compatible with this

[Ade et al., 2016 (BICEP2 + Keck + Planck)]

from $aG\tilde{G}$



[Abel et al., PRX, 2017]

Hadronic matrix element can be estimated

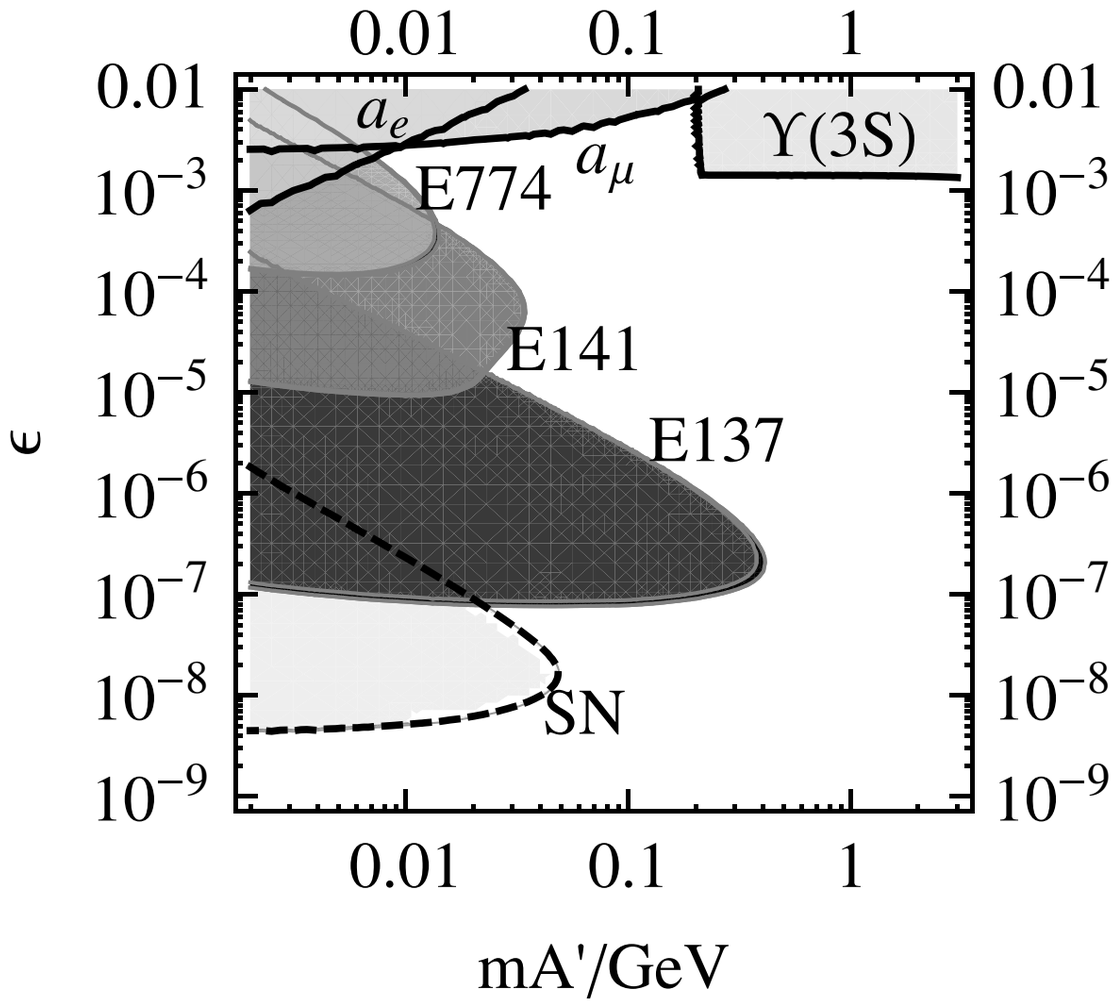
$$d_n(t) \approx 2.4 \times 10^{-16} \frac{C_G a_0}{f_a} \cos(m_a t)\, e\,\mathrm{cm}$$

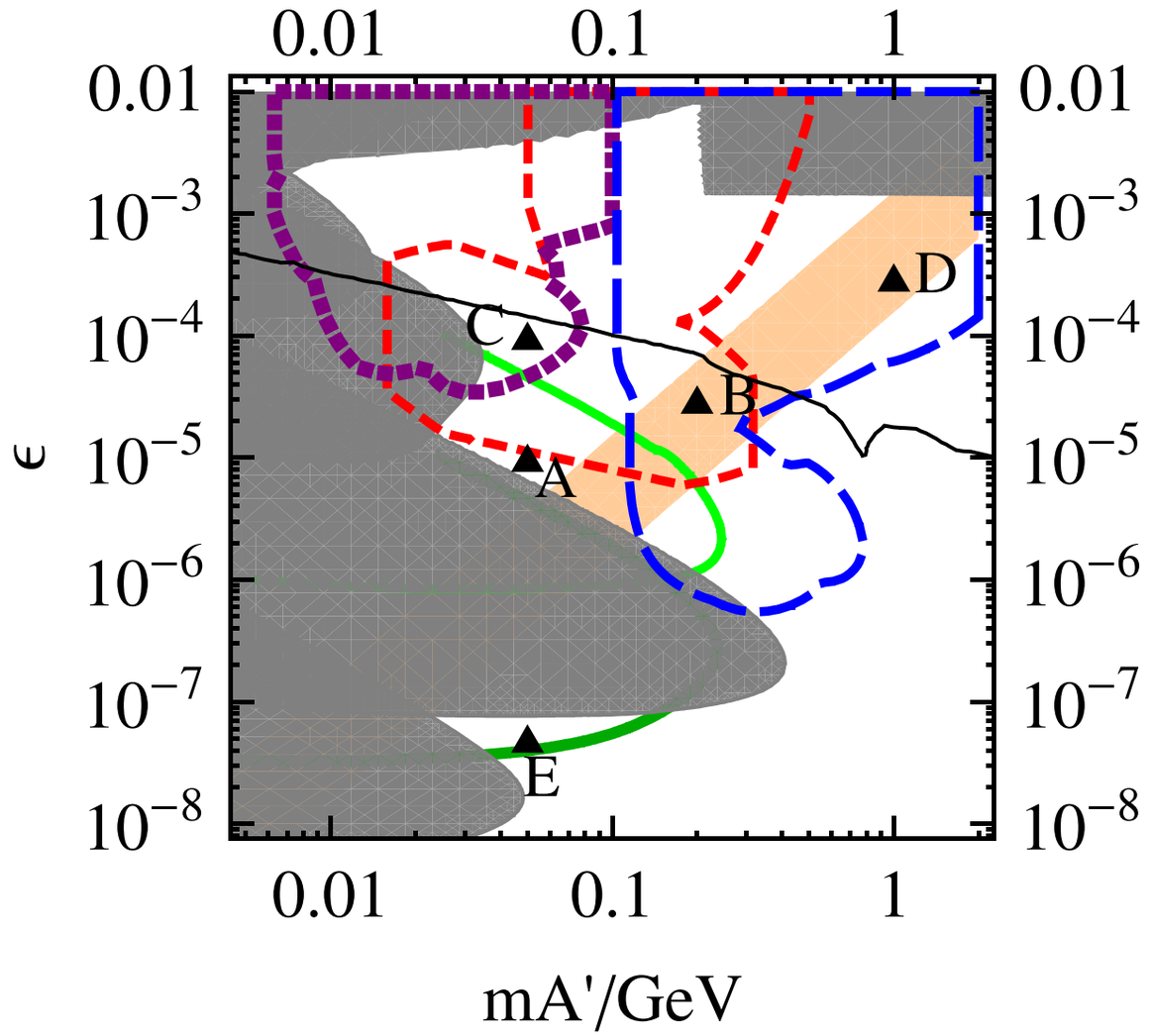
[Crewther et al., 1979]

[Graham & Rajendran, 2011; also CASPer experiment, Budker et al., 2014]

Dark Photon Parameter Space is Vast

Different experimental strategies for different regions





[Bjorken, Essig, Schuster, and Toro ("BEST"), 2009]

"Beam dump" (displaced production & detection vertices in matter) studies yield powerful constraints