THE UNIVERSITY OF SYDNEY

ARC CENTRE OF EXCELLENCE FOR DARK MATTER PARTICLE PHYSICS

Dark photon limits: a cookbook

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2105.04565

Dark photons

Extend SM gauge group: $\mathrm{SU}(3)_c \times \mathrm{SU}(2)_L \times \mathrm{U}(1)_Y \times U(1)'$

with vector X^μ

Below EW $\rightarrow$ $\mathcal{L} \supset -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} - \frac{1}{4}X_{\mu\nu}X^{\mu\nu} \boxed{-\frac{\chi}{2}F_{\mu\nu}X^{\mu\nu}} + \frac{m_X^2}{2}X_\mu X^\mu + j_\mu A^\mu$

"Kinetic mixing"

$A^\mu \rightarrow A^\mu - \chi X^\mu$:

$$\frac{m_X^2}{2}X_\mu X^\mu + j_\mu(A^\mu - \chi X^\mu)$$

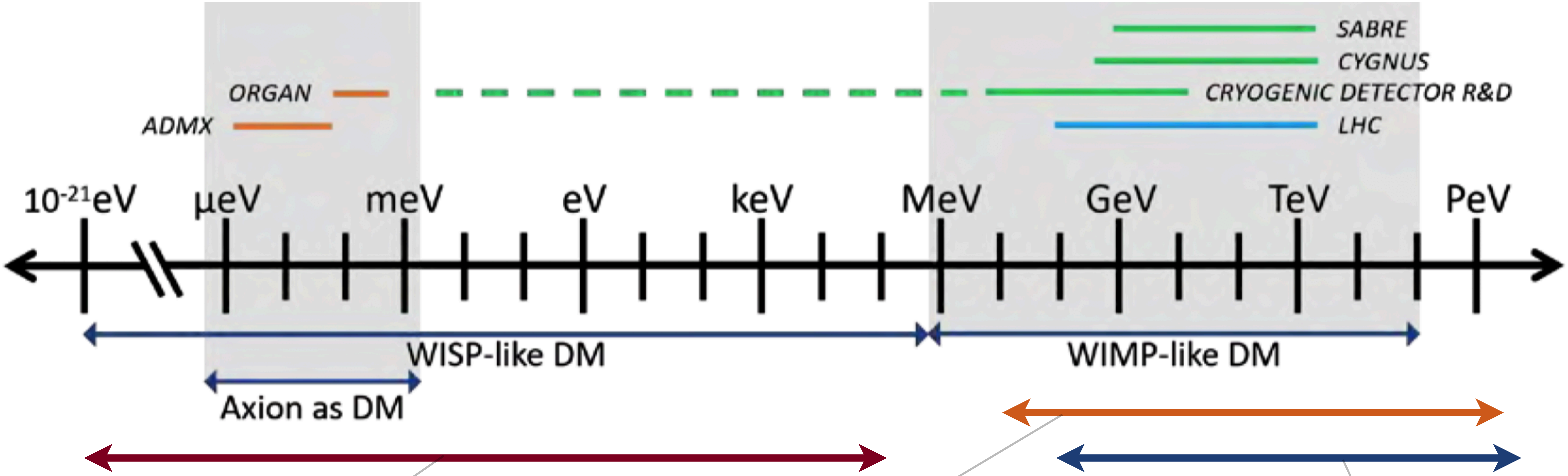
→ X is massive force carrying vector,
→ SM Particles get dark millicharge ~ χe
→ Can also be coupled to other dark sector particles to create millicharged DM

$X^\mu \rightarrow X^\mu - \chi A^\mu$:

$$\frac{m_X^2}{2}(X_\mu X^\mu - 2\chi X_\mu A^\mu + \chi^2 A_\mu A^\mu) + j_\mu A^\mu$$

→ Non-diagonal mass term
→ SM photon-dark photon mixing

Dark matter mass scales



Light dark photons as wave-like dark matter

→ Focus of this talk

millicharged DM particles coupled to SM via dark photon mediator

(See e.g. [hep-ph/0311189, 1311.2600, 1908.06986])

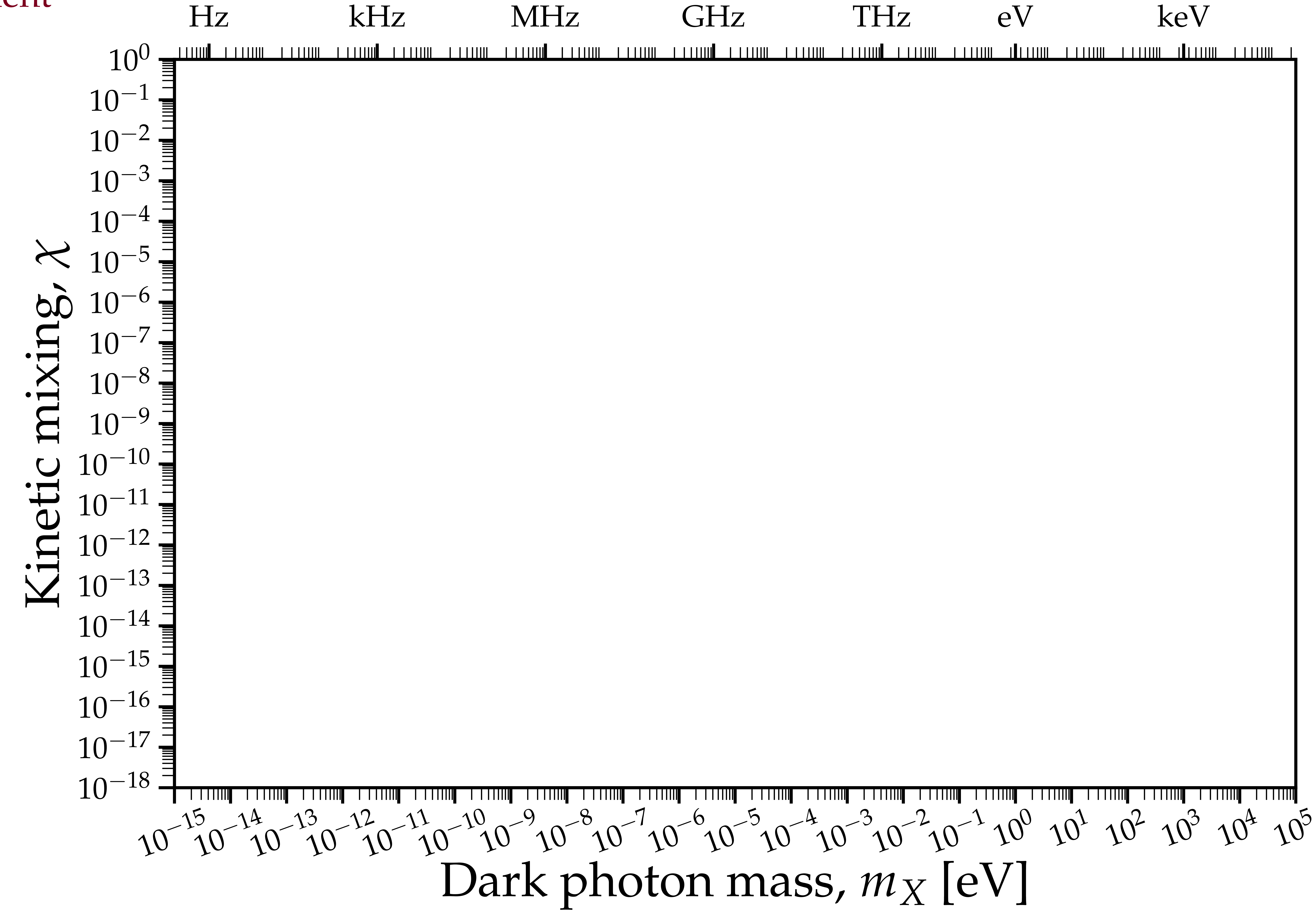
Dark photons in colliders e.g. SHiP, LHCb, Belle II, NA64, SeaQuest + many more

(See e.g. [2005.01515])

Green = Astrophysics
Blue = Cosmology
Red = Experiment

Bounds on dark photons

Plots+limit data available at
https://cajohare.github.io/AxionLimits/



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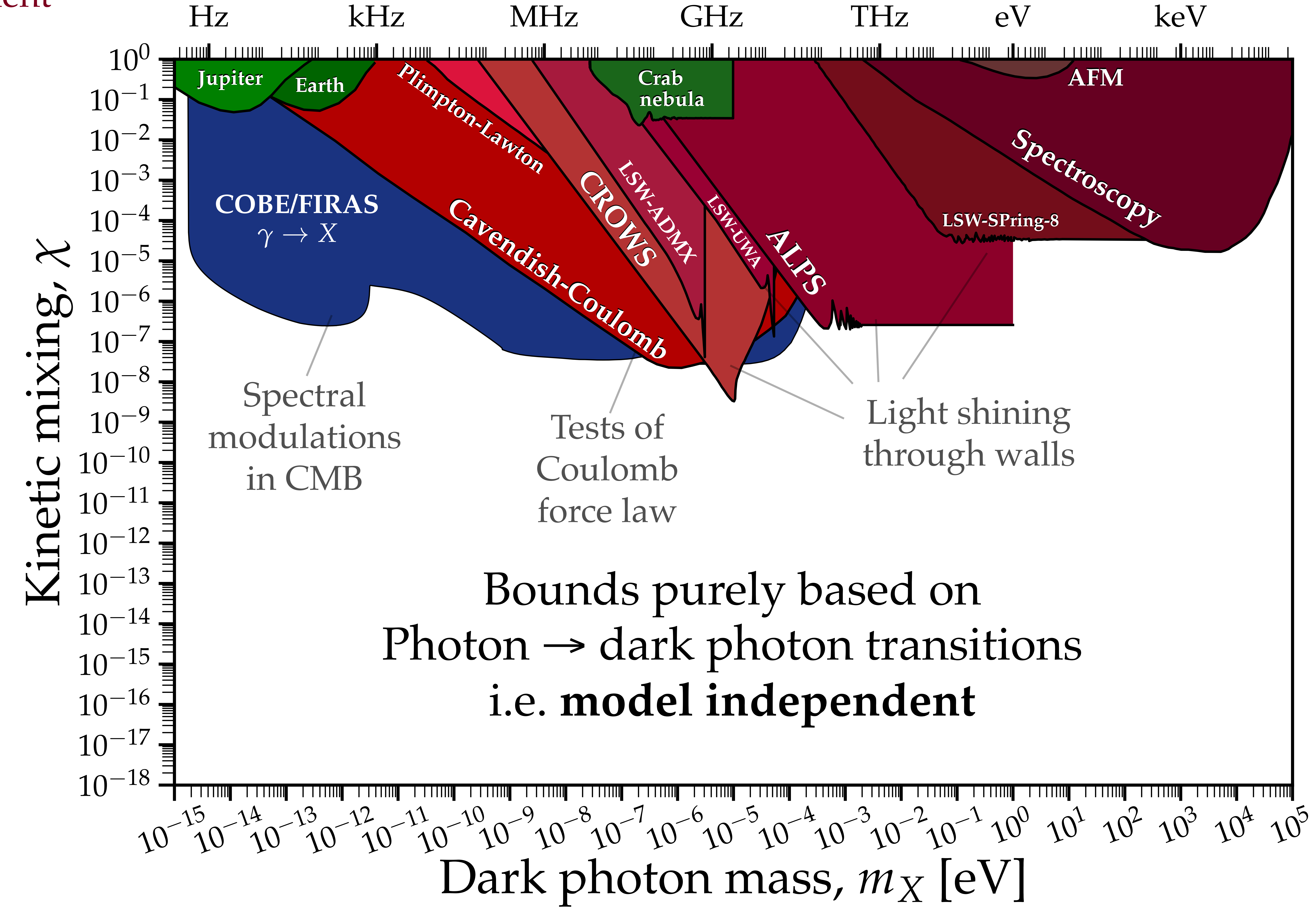

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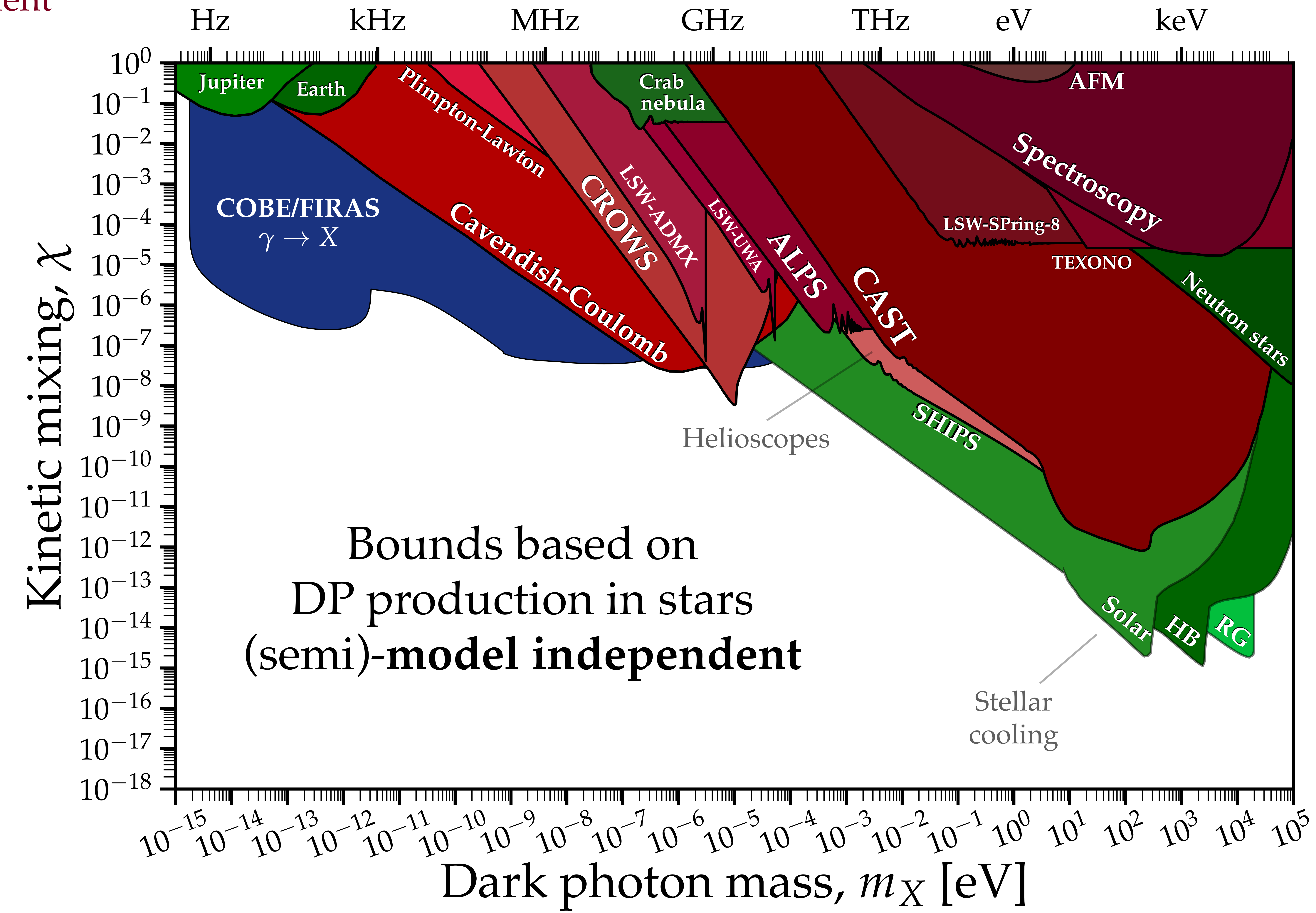

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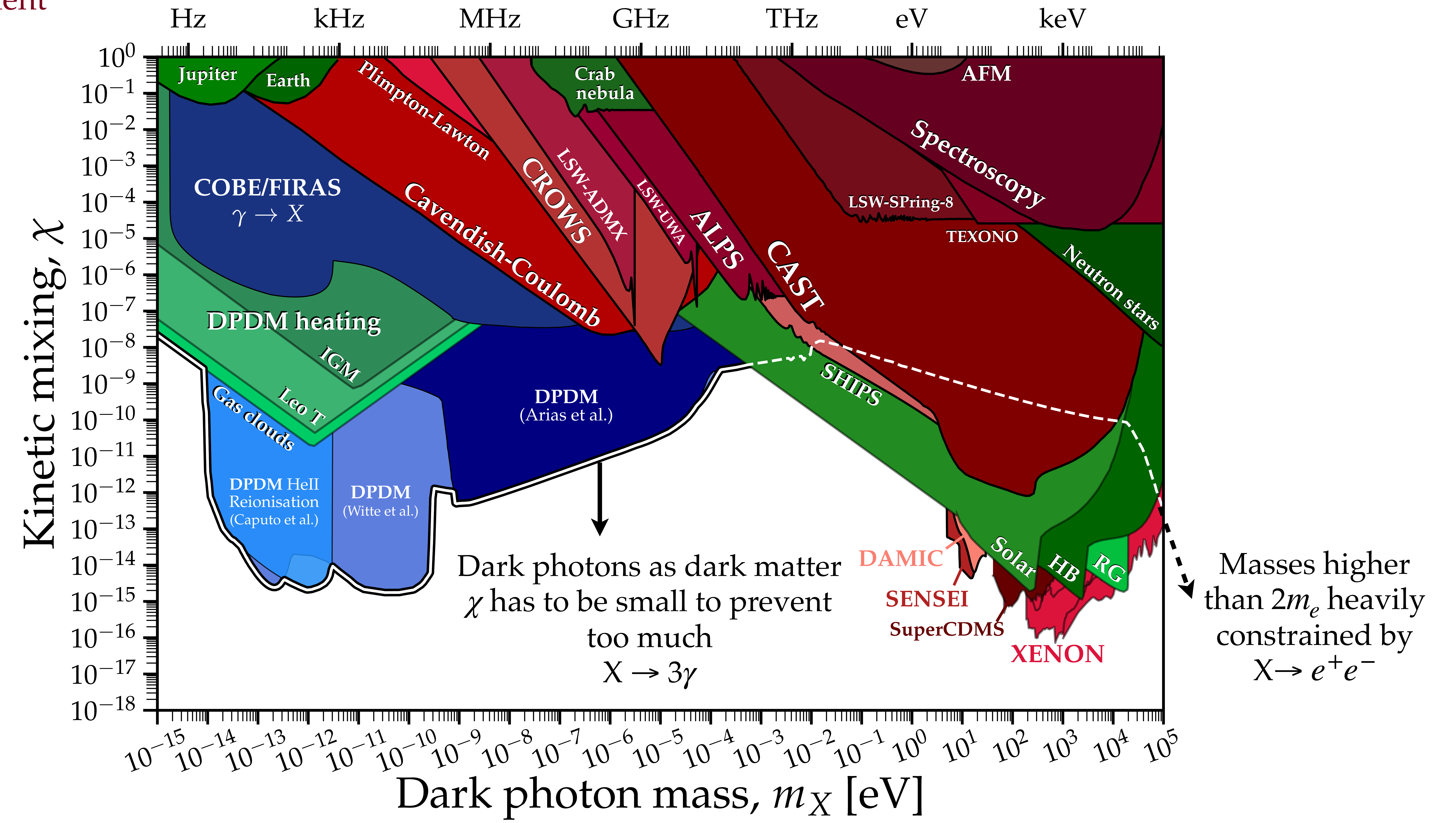
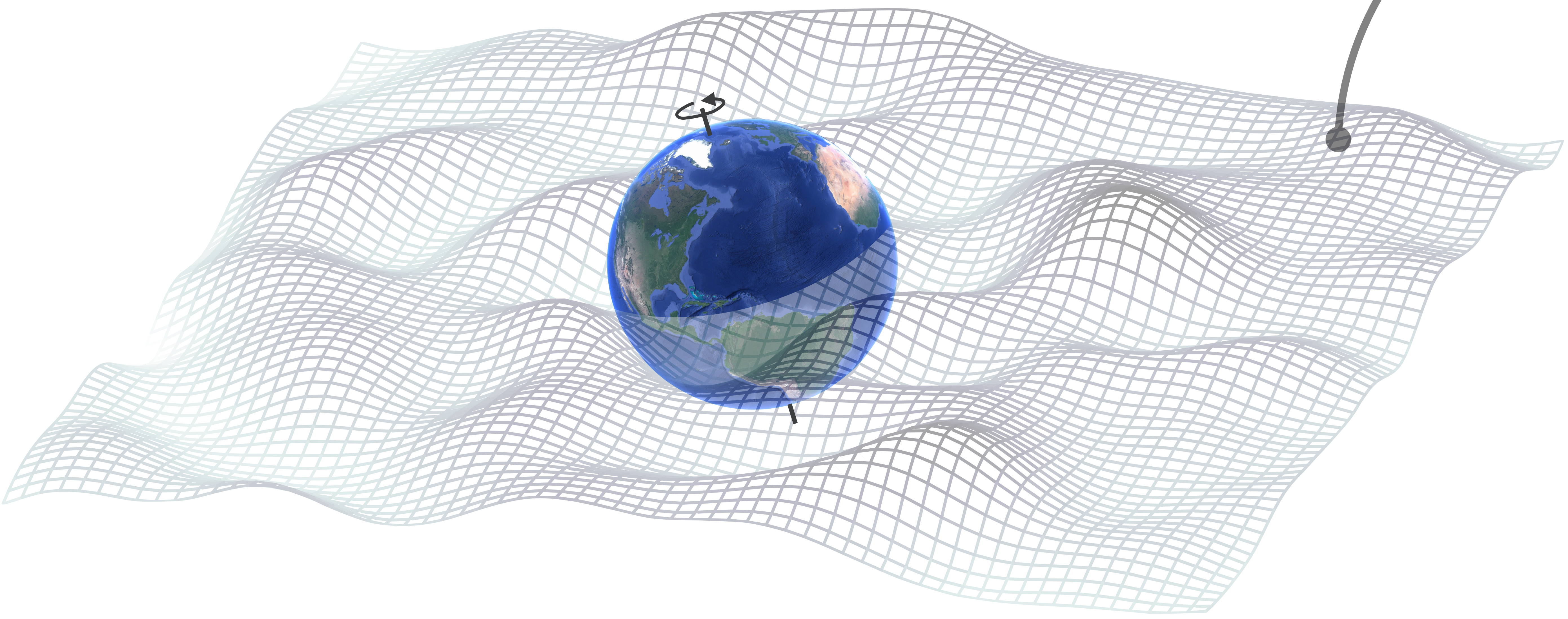


Wave-like dark matter

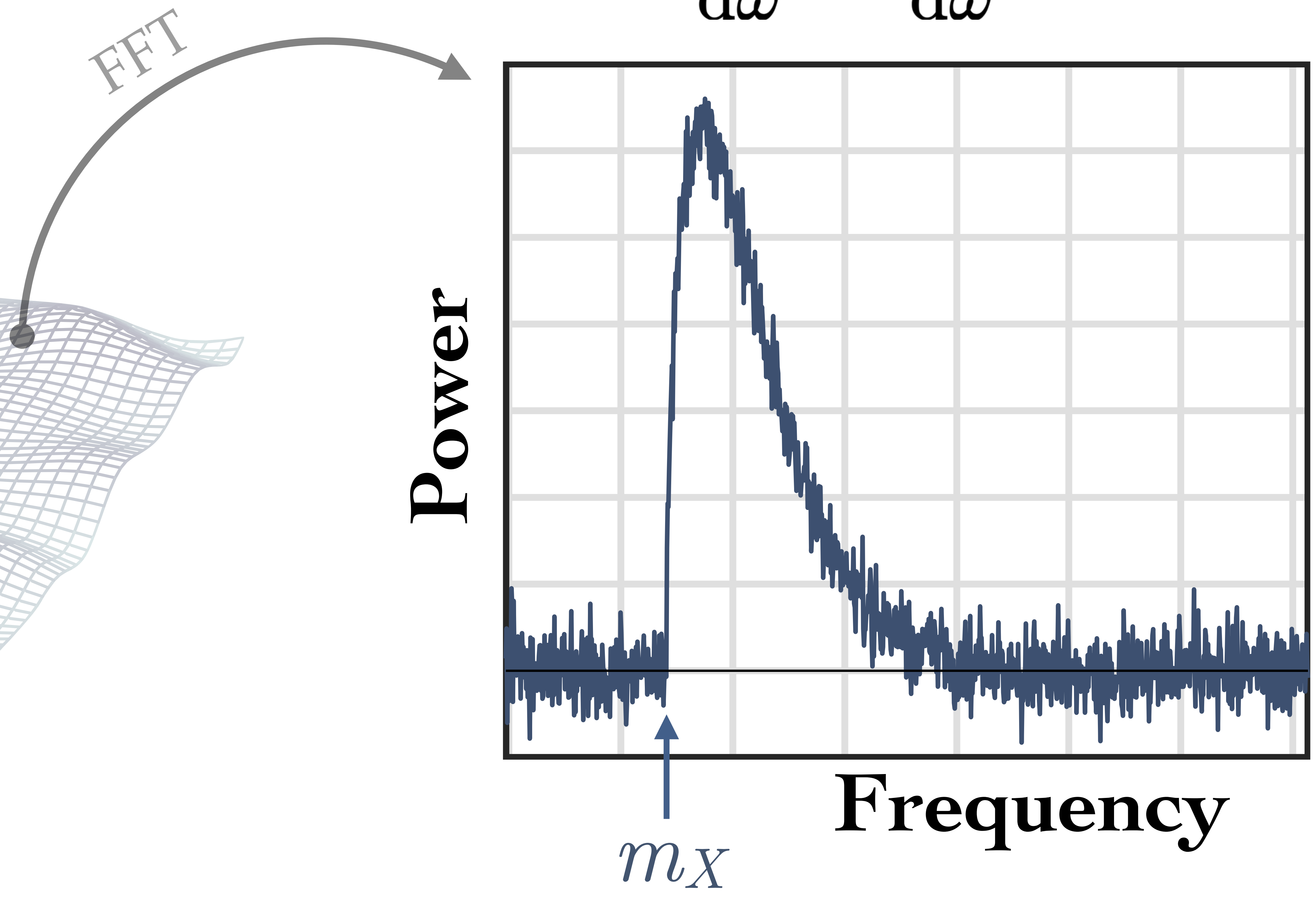
→ continuously oscillating signal with spectral lineshape given by galactic DM velocity distribution

Amplitude: $A = \frac{\sqrt{2\rho}}{m_X}$

Frequency: $\omega = m_X + \frac{1}{2} m_X v^2$



$$\frac{\mathrm{d}P}{\mathrm{d}\omega} \propto \frac{\mathrm{d}v}{\mathrm{d}\omega} f(v)$$



Dark photon electrodynamics

DP-photon
Mixing

$$\mathcal{L} \supset -\frac{1}{4}F_{\mu v}F^{\mu v} - \frac{1}{4}X_{\mu v}X^{\mu v} + eJ^{\mu}_{\mathrm{EM}}A_{\mu} + \frac{m_X^2}{2}(X^{\mu}X_{\mu} + 2\chi X_{\mu}A^{\mu})$$

Solution is a wave equation: $-K^2 A^{\mu} = \chi m_X^2 X^{\mu}$ $K = (\omega, \mathbf{k})$

$$\Downarrow$$

$$|\mathbf{E}| = \left|\frac{\chi m_X}{\epsilon}\mathbf{X}\right|$$

Dark photon sources E-field with direction given by the DP polarisation, **X**

Dark photon electrodynamics versus Axion electrodynamics

Axions source an effective current in a similar way, but via $a\,\mathbf{E}\cdot\mathbf{B}_{\rm ext}$ meaning DPs can searched for with exactly the same techniques only they do not require a B-field to convert into photons

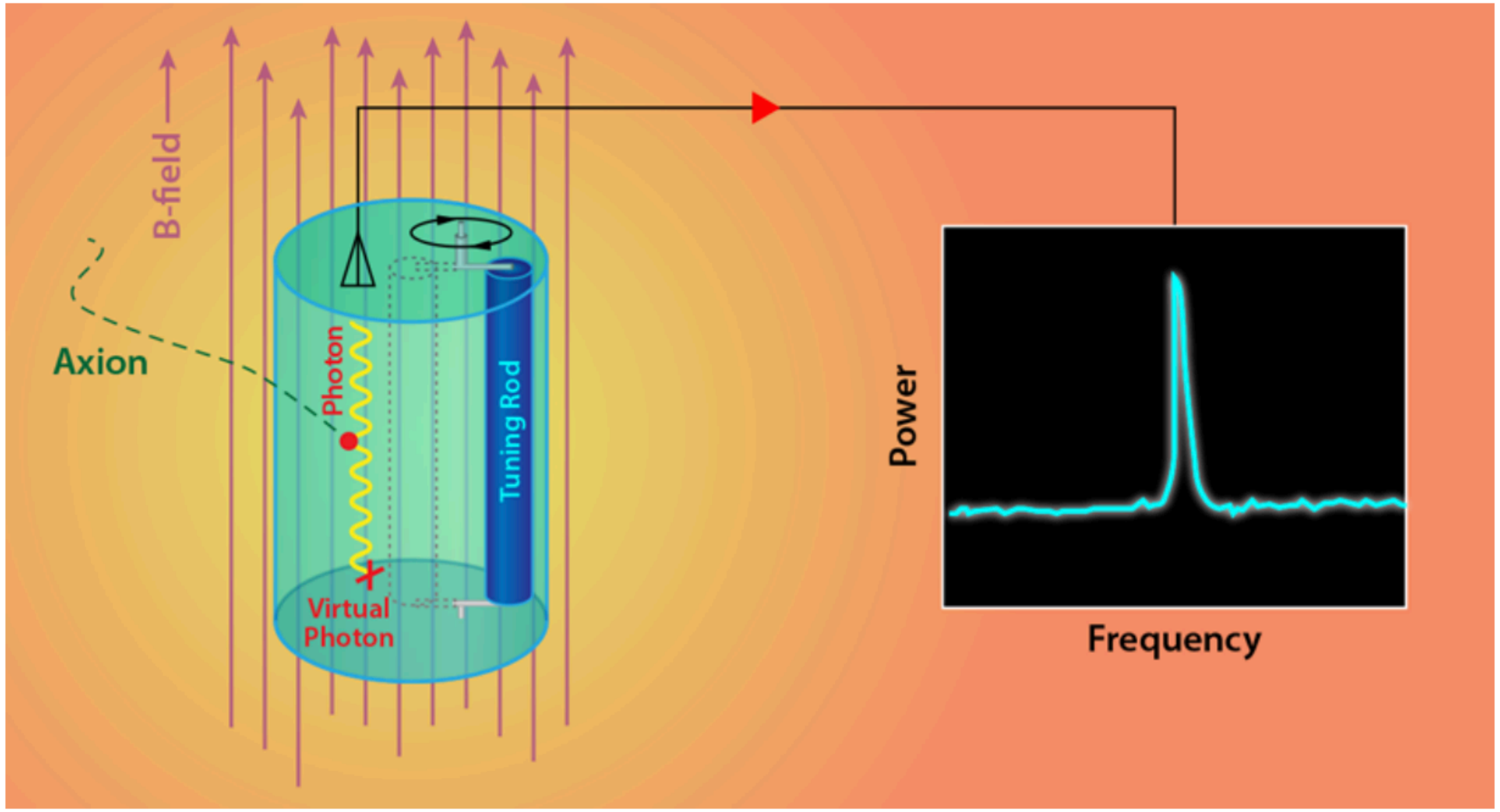
<u>Example: cavity haloscope</u>

Sikivie formula for resonant cavity power from axions:

$$P_{\rm axion} = \kappa\,\mathcal{G}\,V Q \rho_{\rm DM}\,\frac{g_{a\gamma}^2 B^2}{m_a}$$

$$P_{\rm DP} = \kappa\,\mathcal{G}\,V Q \rho_{\rm DM}\,\chi^2 m_X$$

$$\boxed{\chi m_X \leftrightarrow g_{a\gamma} B}$$



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Have to be careful!

There is a very subtle difference between these formulae

$$P_{\rm DP} = \kappa \mathcal{G} V Q \rho_{\rm DM}\, \chi^2 m_X$$

$$P_{\rm axion} = \kappa \mathcal{G} V Q \rho_{\rm DM}\, \frac{g_{a\gamma}^2 B^2}{m_a}$$

Cavity form factor

$$\mathcal{G}^{\rm axion} = \frac{\left(\int dV \mathbf{E}_\alpha \cdot \mathbf{B}_{\rm ext}\right)^2}{V B^2 \frac{1}{2}\int dV \epsilon(\mathbf{x})\mathbf{E}_\alpha^2 + \mathbf{B}_\alpha^2}$$

Axion case relies on overlap between the cavity mode $\mathbf{E}_\alpha$ and applied B-field

→ **Dependent only on the cavity itself**

$$\mathcal{G}^{\rm DP} = \frac{\left(\int dV \mathbf{E}_\alpha \cdot \hat{\mathbf{X}}\right)^2}{V \frac{1}{2}\int dV \epsilon(\mathbf{x})\mathbf{E}_\alpha^2 + \mathbf{B}_\alpha^2}$$

Appearing here is the DP polarisation!

Axions differ from dark photons in two respects
1) Dark photons don't require an applied B-field.
2) Dark photon signal depends upon its polarisation state.

So the actual recasting looks like this:

$$\chi m_X |\cos\theta| \leftrightarrow g_{a\gamma} B$$

In the cavity example $\cos\theta$ is the angle between the DP polarisation and the applied B-field.

But what is the DP polarisation???

But what is the dark photon's polarisation state?

…No one seems to know

Seems to be a badly understudied aspect of DPDM, but we can bound some possibilities:

Scenario 1: The DP polarisation is totally random in every coherence time, i.e. a random direction is drawn every $\sim 10^6$ oscillations.

Scenario 2: The DP polarisation is fixed over length/time-scales probed by experiments, i.e. $t <$ year, and $L <$ mpc

(A mixture of purely random and purely fixed is possible of course, but these two scenarios are the extremes)

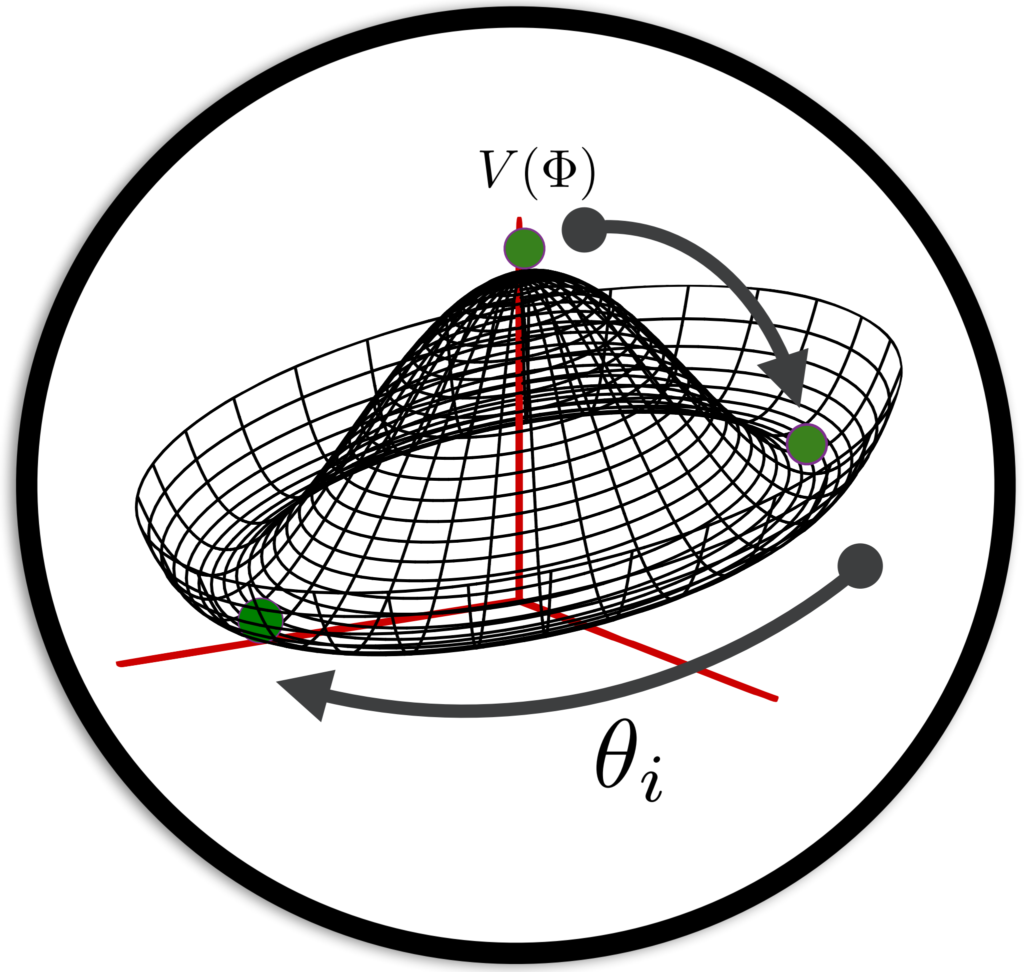
Which scenario is correct?

The answer depends on:

1) DP production mechanism → What was the primordial polarisation distribution?
2) Structure formation → Can gravity rotate the DP polarisation?

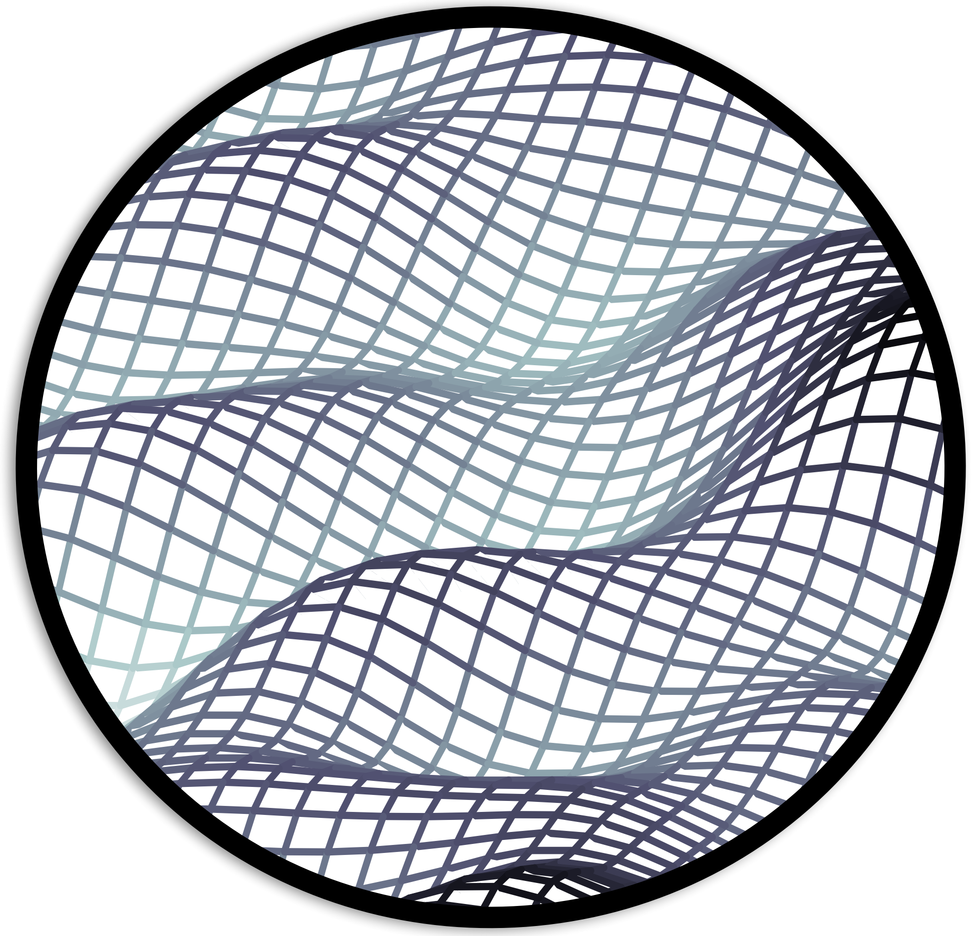
Misalignment mechanism

e.g. 1201.5902, 1905.09836



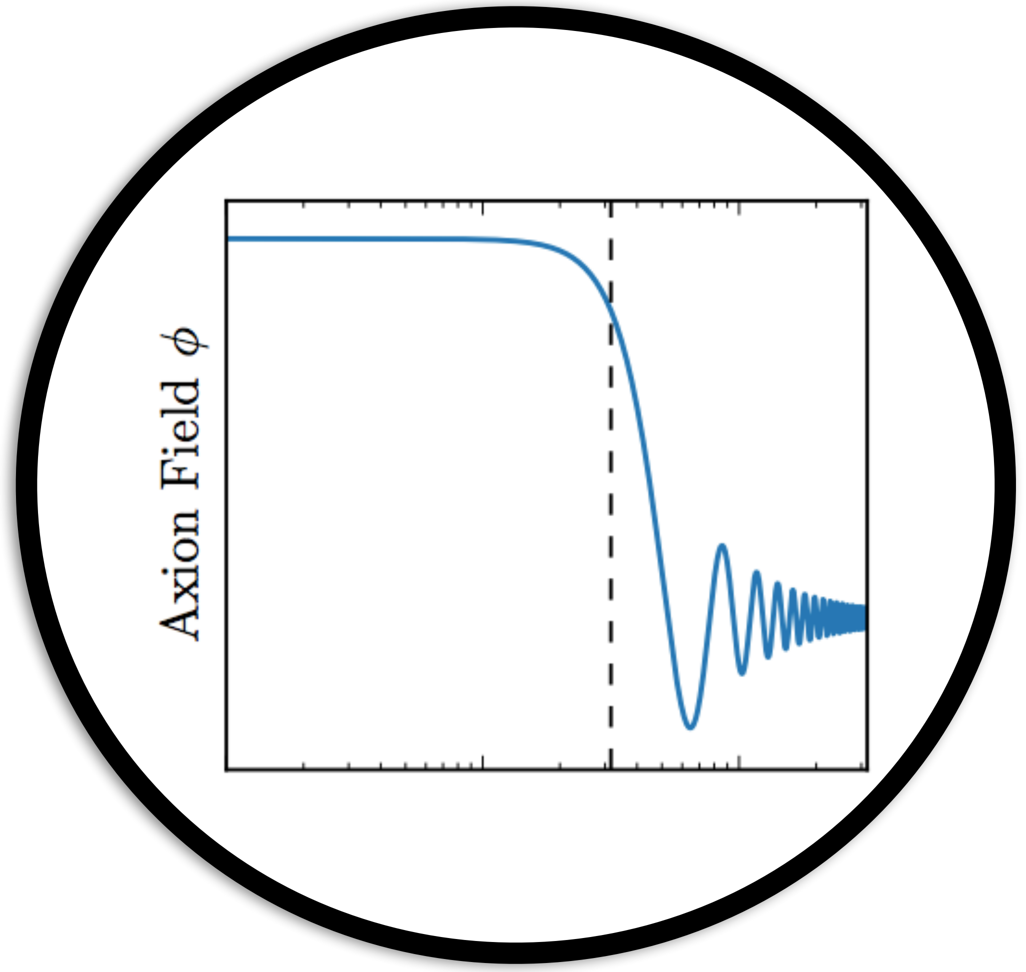
Inflationary perturbations

e.g. 1504.02102, 2009.03828, 2005.01766, 2004.10743



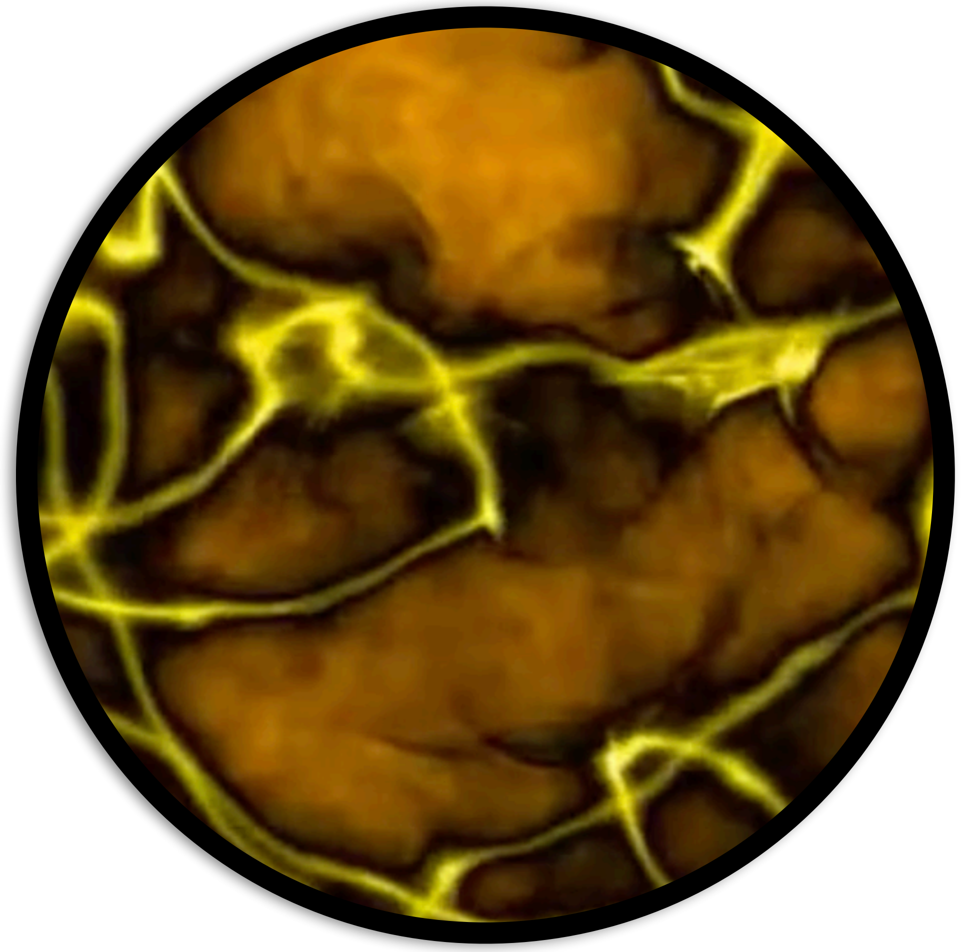
Via an axion

e.g. 1810.07188, 1810.07196



Cosmic string decay

e.g. 1901.03312



Probably fixed polarisation inside horizon (Scenario 1) → Probably more randomised polarisation inside horizon (Scenario 2)

How to account for the DP polarisation: Scenario 1

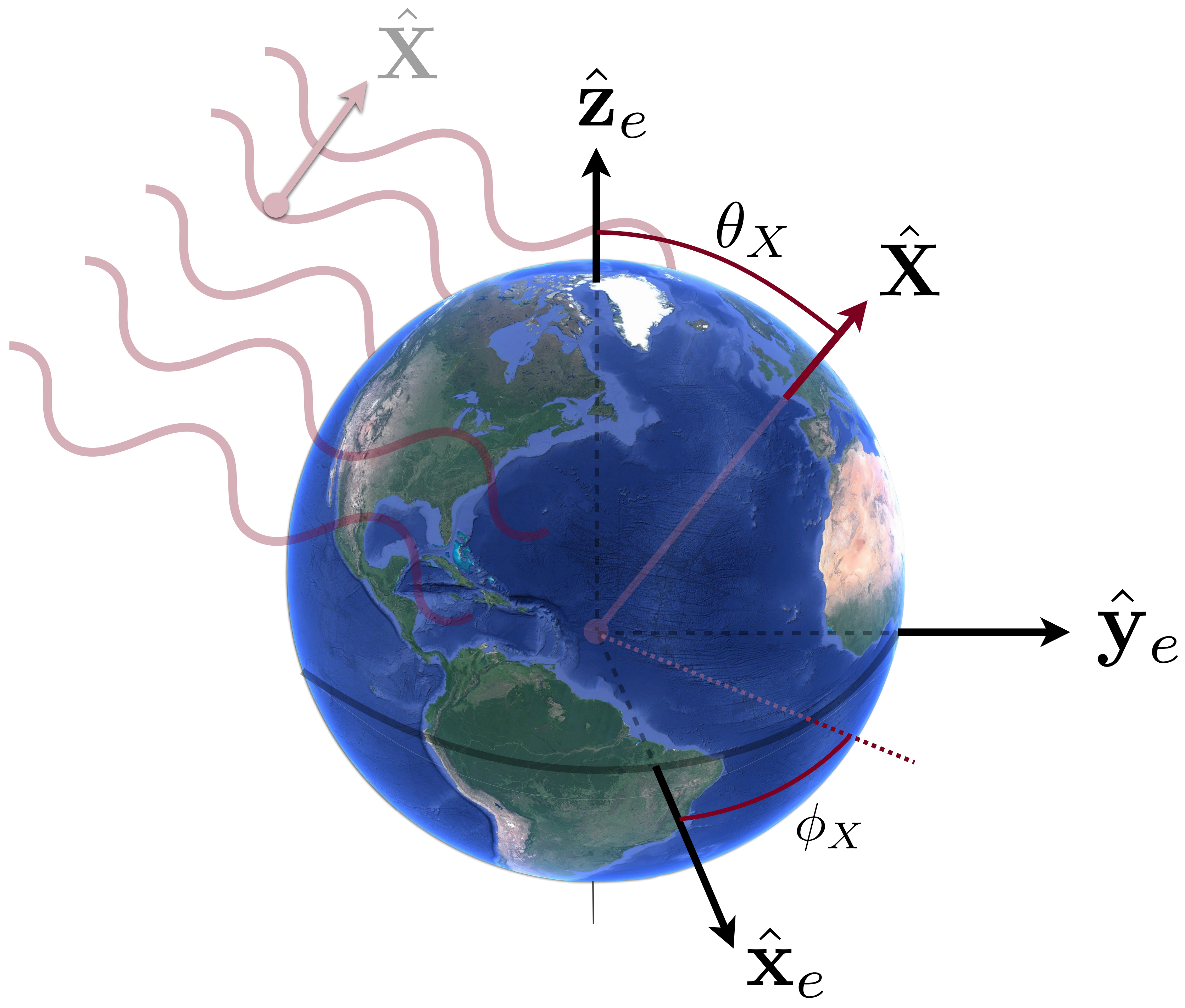
Measured power is proportional to $\langle\cos^2\theta\rangle_T$ which is the time-averaged DP polarisation angle over the duration of the measurement being made

If measurements last many coherence times (they will for all experiments here) and we randomly sample angles across the sky, then $\langle\cos^2\theta\rangle_T = 1/3$
(answer is $2/3$ if expt. is sensitive to 2 polarisations)

And we're done.

How to account for the DP polarisation: Scenario 1

The Earth rotates with respect to the DP polarisation axis which is **fixed**, so $\cos^2\theta$ depends upon time/orientation in a non-trivial, but predictable way



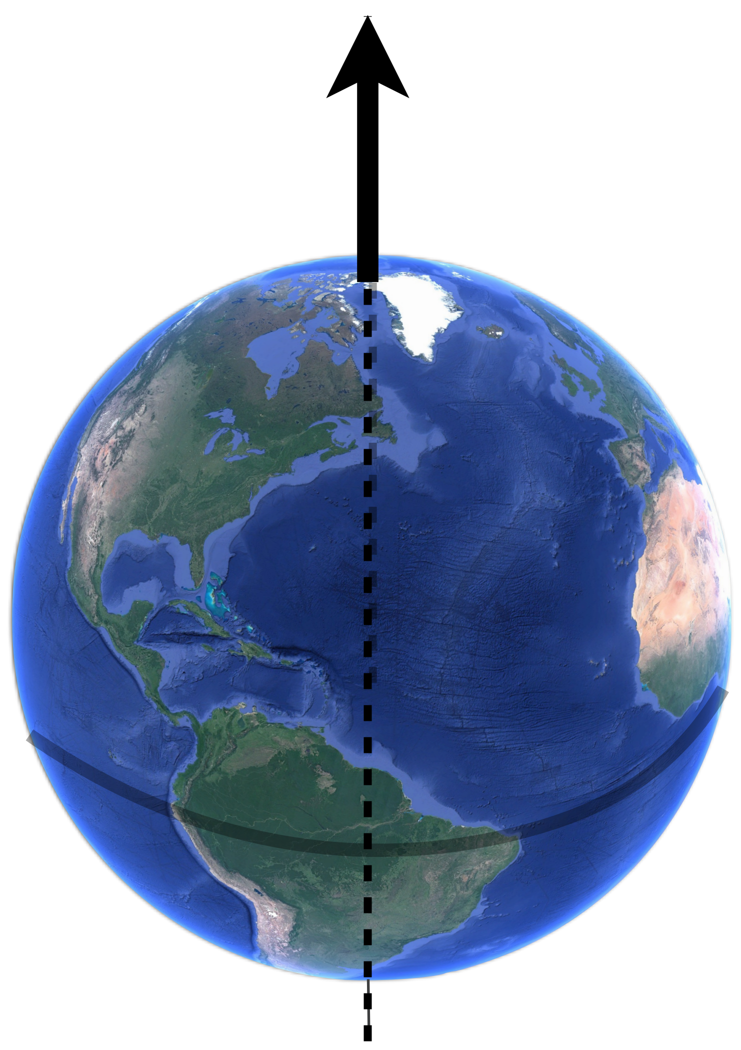
Since the DP signal is weaker in Scenario 2, it is always the more conservative option, worthwhile to use it as a baseline

Scenario 2

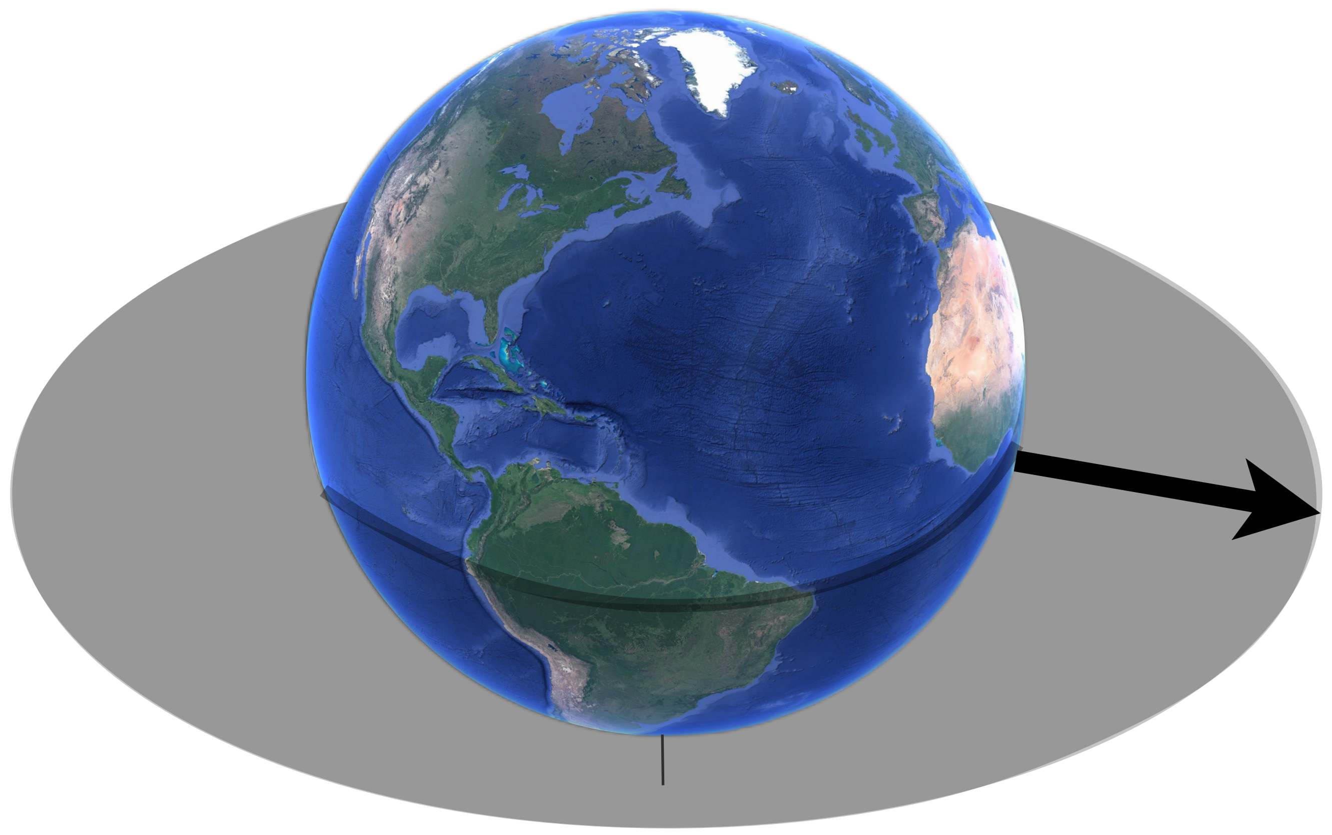
This also means that the sensitivity of a DP search strongly depends upon the duration of observation, the location, and the orientation of the experiment

Take a **Zenith-pointing** experiment (e.g. a cavity with vertical B-field):

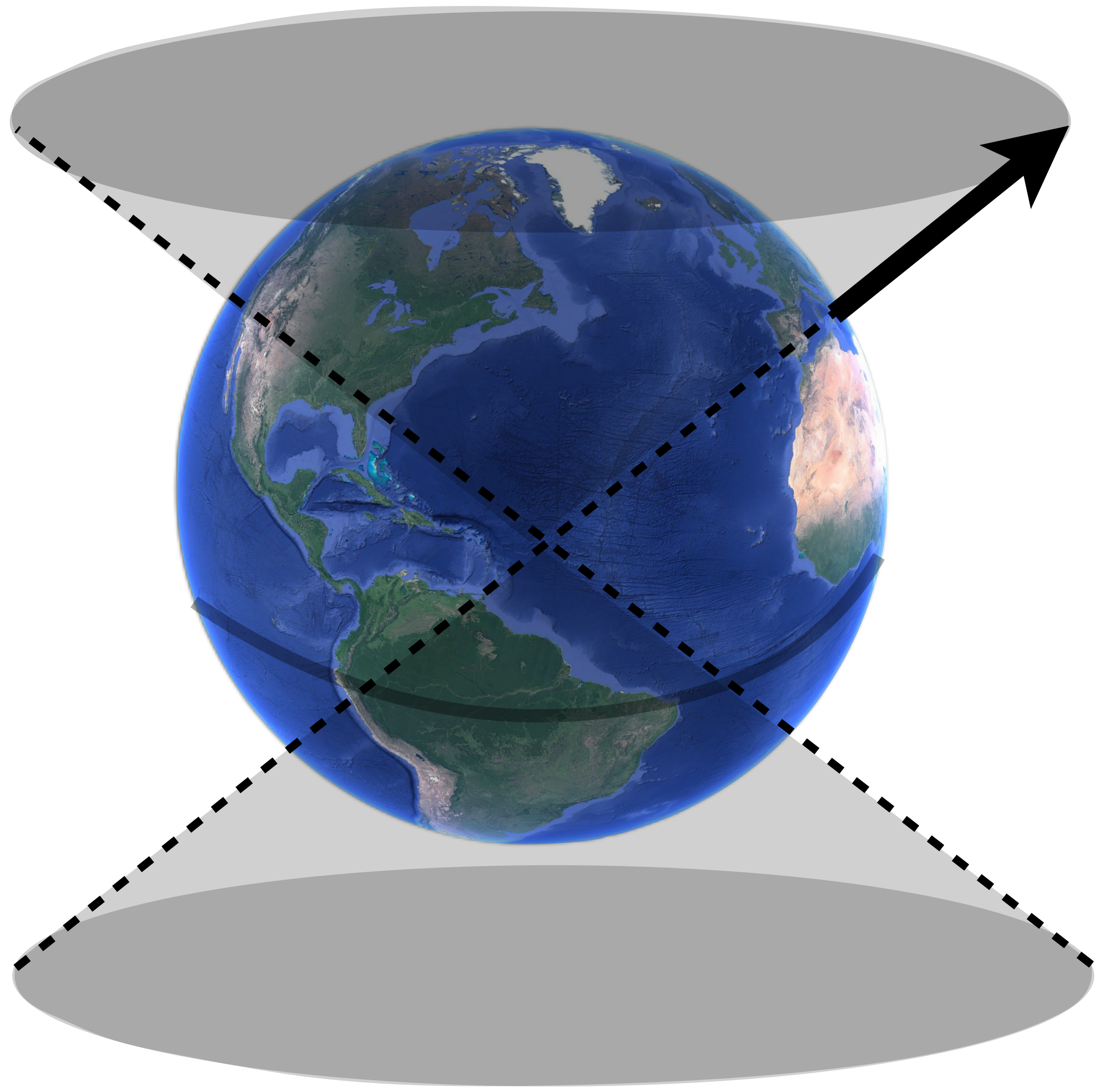
North Pole: **Worst**



Equator: **Bad**

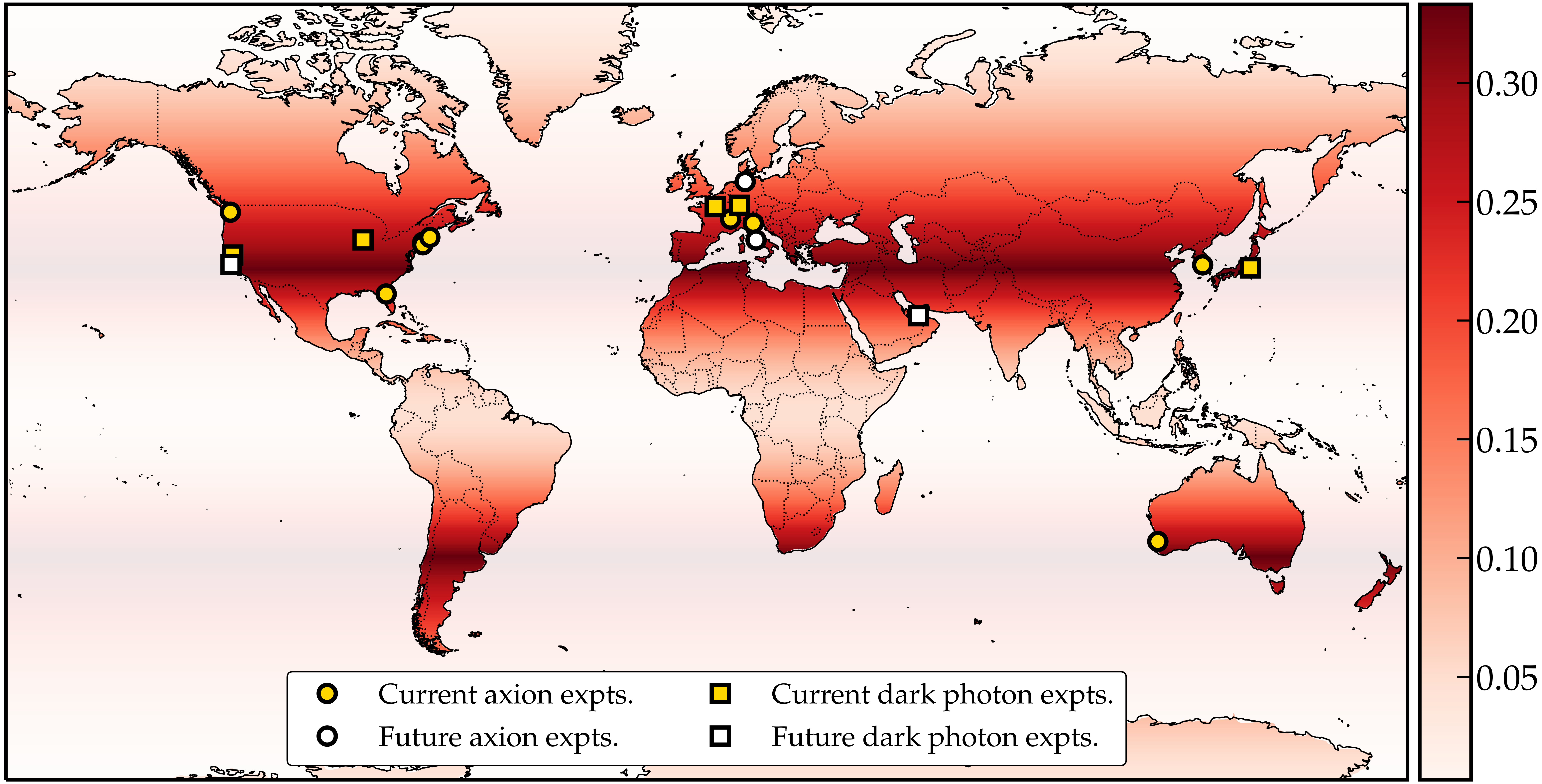


Latitude~35°: **Best**



Location dependence

Zenith-pointing experiments (e.g. most cavities)

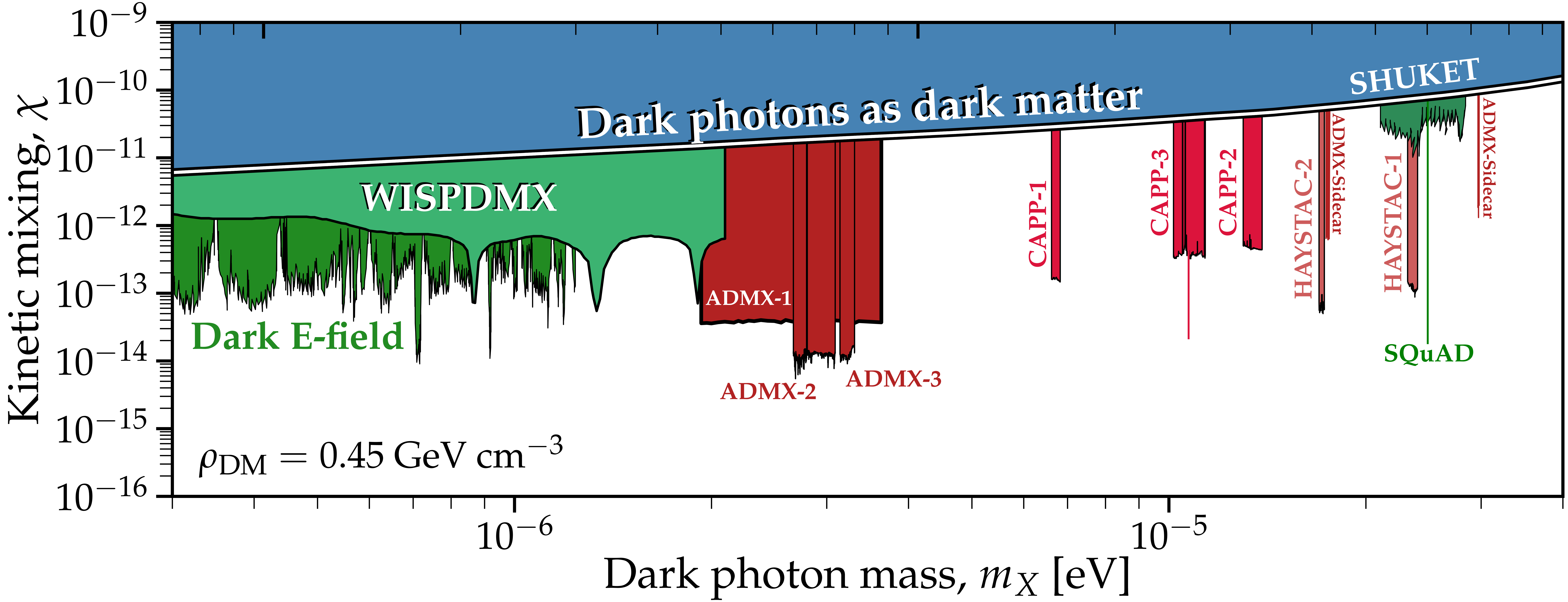


Can calculate the relevant **conversion factors** for most past experiments

Note: Some experiments veto candidate signals by turning off the magnetic field. This precludes us from reinterpreting their results in terms of DPs, but does not mean they are not sensitive to them.

	Experiment		Magnetic field [T]	Latitude [°]	Measurement time, T	Directionality	$\langle \cos^2\theta \rangle_T^{95\%}$
Cavities	ADMX-1	[106]	7.6	47.66	$\mathcal{O}$(min)	$\hat{\mathcal{Z}}$-pointing	~0.0025
	ADMX-2	[107]	6.8	47.66	$\mathcal{O}$(min)	$\hat{\mathcal{Z}}$-pointing	~0.0025
	ADMX-3	[109]	7.6	47.66	$\mathcal{O}$(min)	$\hat{\mathcal{Z}}$-pointing	~0.0025
	ADMX Sidecar	[108]	3.11[a]	47.66	$\mathcal{O}$(min)	$\hat{\mathcal{Z}}$-pointing	~0.0025
	HAYSTAC-1	[110]	9	41.32	$\mathcal{O}$(min)	$\hat{\mathcal{Z}}$-pointing	~0.0025
	HAYSTAC-2	[111]	9	41.32	$\mathcal{O}$(min)	$\hat{\mathcal{Z}}$-pointing	~0.0025
	CAPP-1	[112]	7.3	36.35	$\mathcal{O}$(min)	$\hat{\mathcal{Z}}$-pointing	~0.0025
	CAPP-2	[150]	7.8	36.35	$\mathcal{O}$(min)	$\hat{\mathcal{Z}}$-pointing	~0.0025
	CAPP-3	[151]	7.2 and 7.9	36.35	90 s	$\hat{\mathcal{Z}}$-pointing	~0.0025
	CAPP-3 [KSVZ]	[151]	7.2	36.35	15 hr	$\hat{\mathcal{Z}}$-pointing	0.11
	QUAX-$\alpha\gamma$	[113]	8.1	45.35	4203 s	$\hat{\mathcal{Z}}$-pointing	0.0046
	†KLASH	[152]	0.6	41.80	$\mathcal{O}$(min)	$\hat{\mathcal{Z}}$-pointing	~0.0025
	RBF	[114]	Magnetic field veto				
	UF	[115]	Magnetic field veto				
	ORGAN	[116]	Magnetic field veto				
	RADES	[153]	Magnetic field veto				
LC-circuits	ADMX SLIC-1	[154]	4.5	29.64	$\mathcal{O}$(min)	$\hat{\mathcal{N}}/\hat{\mathcal{W}}$-facing	~0.0975
	ADMX SLIC-2	[154]	5	29.64	$\mathcal{O}$(min)	$\hat{\mathcal{N}}/\hat{\mathcal{W}}$-facing	~0.0975
	ADMX SLIC-3	[154]	7	29.64	$\mathcal{O}$(min)	$\hat{\mathcal{N}}/\hat{\mathcal{W}}$-facing	~0.0975
	ABRACADABRA	[117]	Magnetic field veto				
	SHAFT	[118]	Magnetic field veto				
Plasmas	†ALPHA	[155]	10	Unknown	$\mathcal{O}$(week)	$\hat{\mathcal{Z}}$-pointing	0.2–0.26
Dielectrics	†MADMAX	[156]	10	53.57	$\mathcal{O}$(week)	$\hat{\mathcal{Z}}$-pointing or $\hat{\mathcal{N}}/\hat{\mathcal{W}}$-facing	0.18 or 0.49–0.65[b]
	†LAMPOST	[36]	10	Unknown	$\mathcal{O}$(week)	Any-facing	0.37–0.66
	†DALI	[157]	9	28.49	$\mathcal{O}$(month)	Any-facing[c]	0.38–0.66
Dish antenna	†BRASS	[109]	1	53.57	$\mathcal{O}$(100 days)	Any-facing	0.38–0.66
Topological insulators	†TOORAD	[158]	10[d]	Unknown	$\mathcal{O}$(day)	Any-pointing	0.05–0.3

New limits on dark photons from axion experiments taking into account the daily modulation for the first time



Main messages

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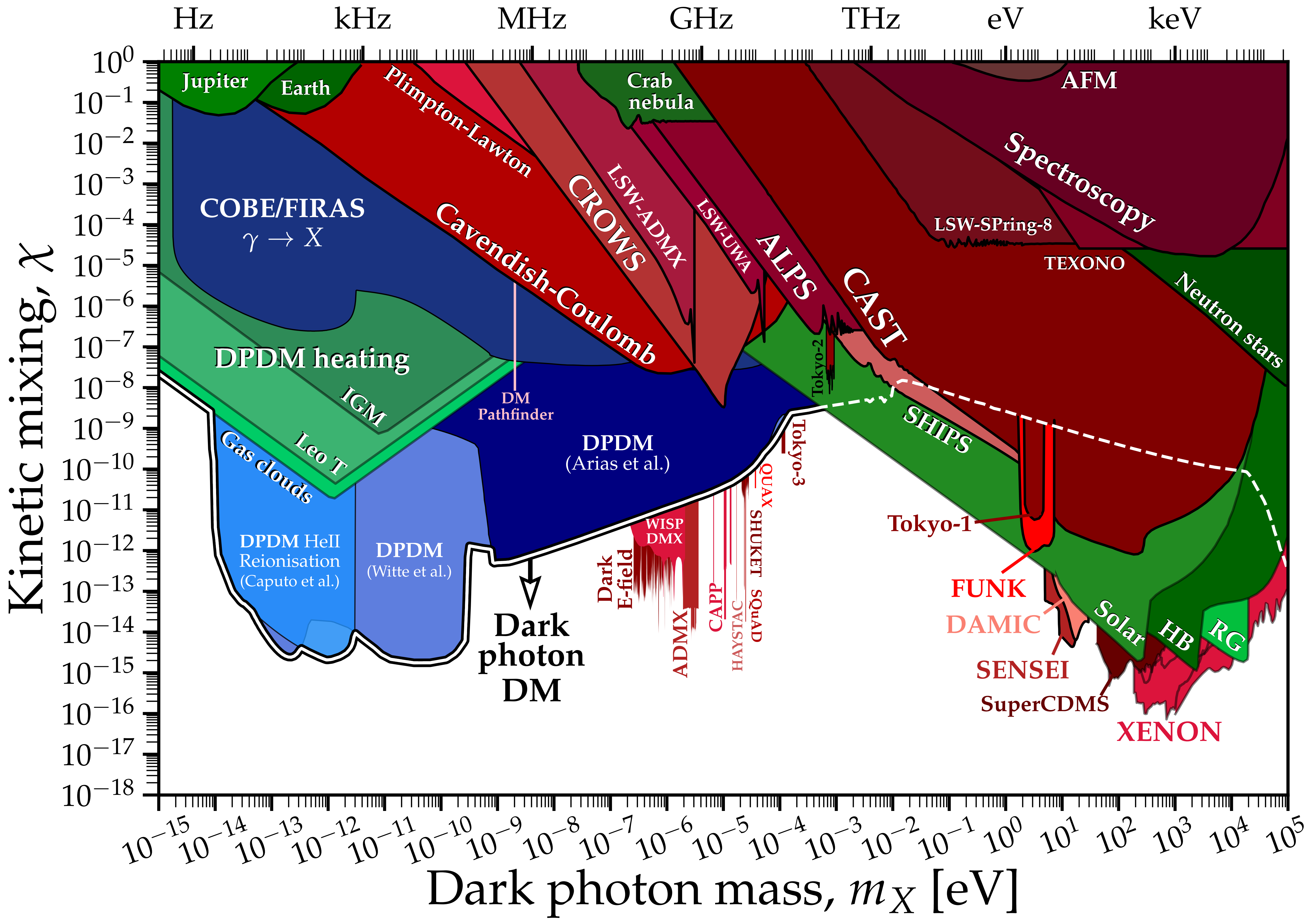
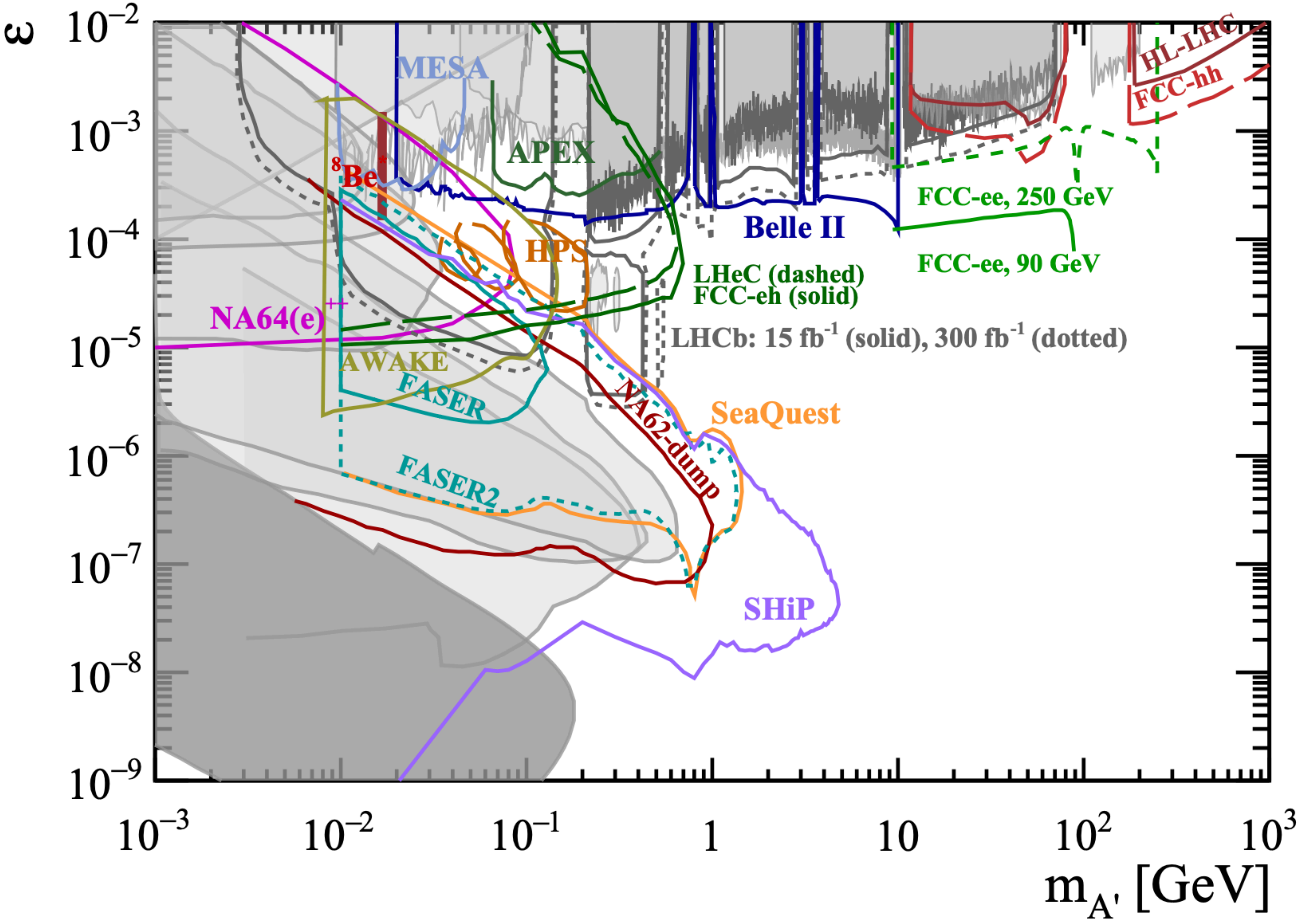
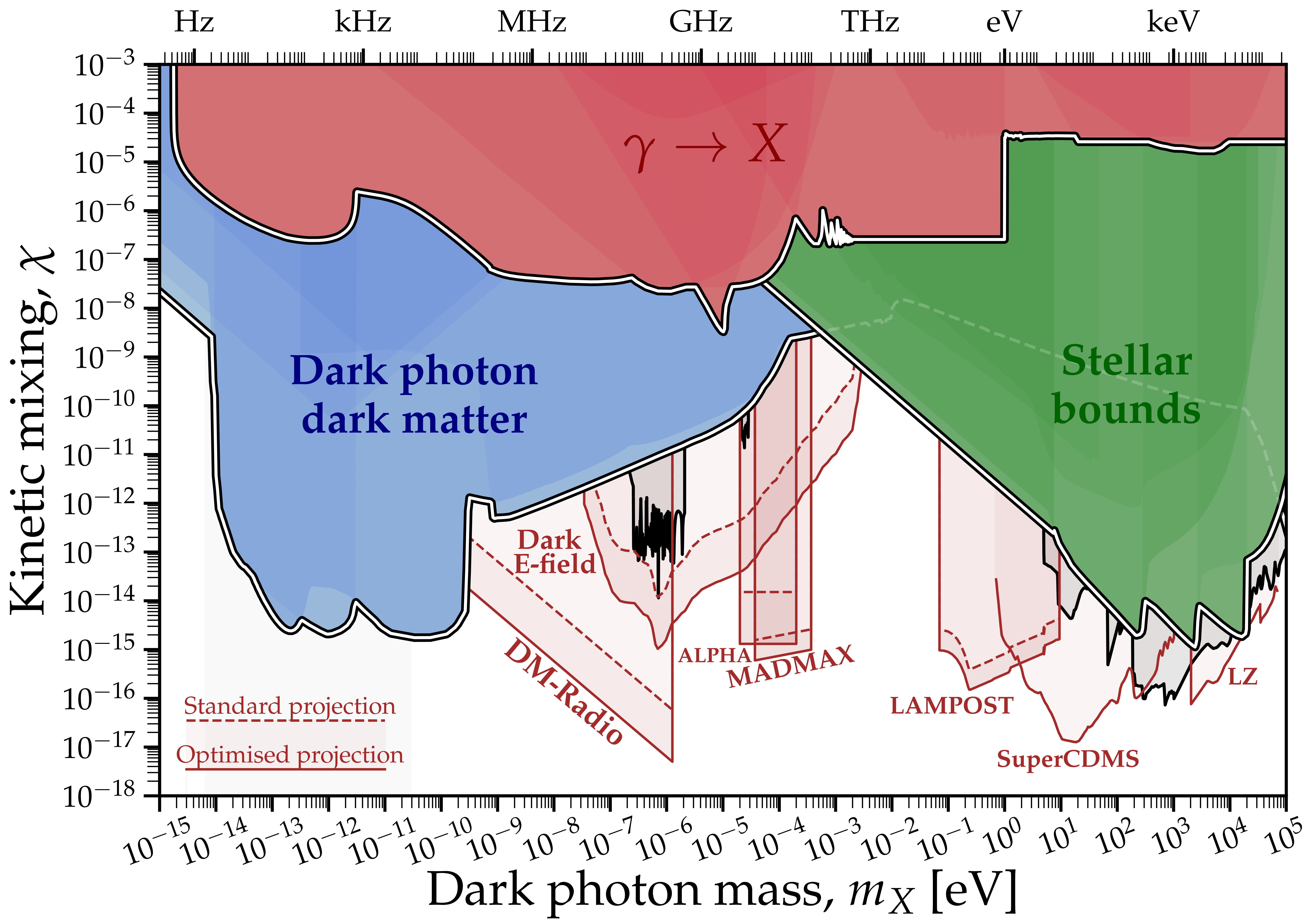
1. Most axion experiments can set limits on dark photons “for free”
2. Limits are dependent on the DP polarisation state which is not known. Being conservative necessarily means needing to account for timing and directional data that is not usually made public
3. Axion experimental collaborations can and should set their own limits on DPs and likely have the data to do so already
4. (Not discussed here) a future experimental campaign can gain over an order of magnitude improvement in sensitivity for no increase in observation time, just requires some strategic scanning (see our paper)




ε
MESA
APEX
8Be
HPS
Belle II
LHeC (dashed)
FCC-eh (solid)
LHCb: 15 fb-1 (solid), 300 fb-1 (dotted)
FCC-ee, 250 GeV
FCC-ee, 90 GeV
HL-LHC
FCC-hh
NA64(e)++
AWAKE
FASER
FASER2
NA62-dump
SeaQuest
SHiP
m_A' [GeV]

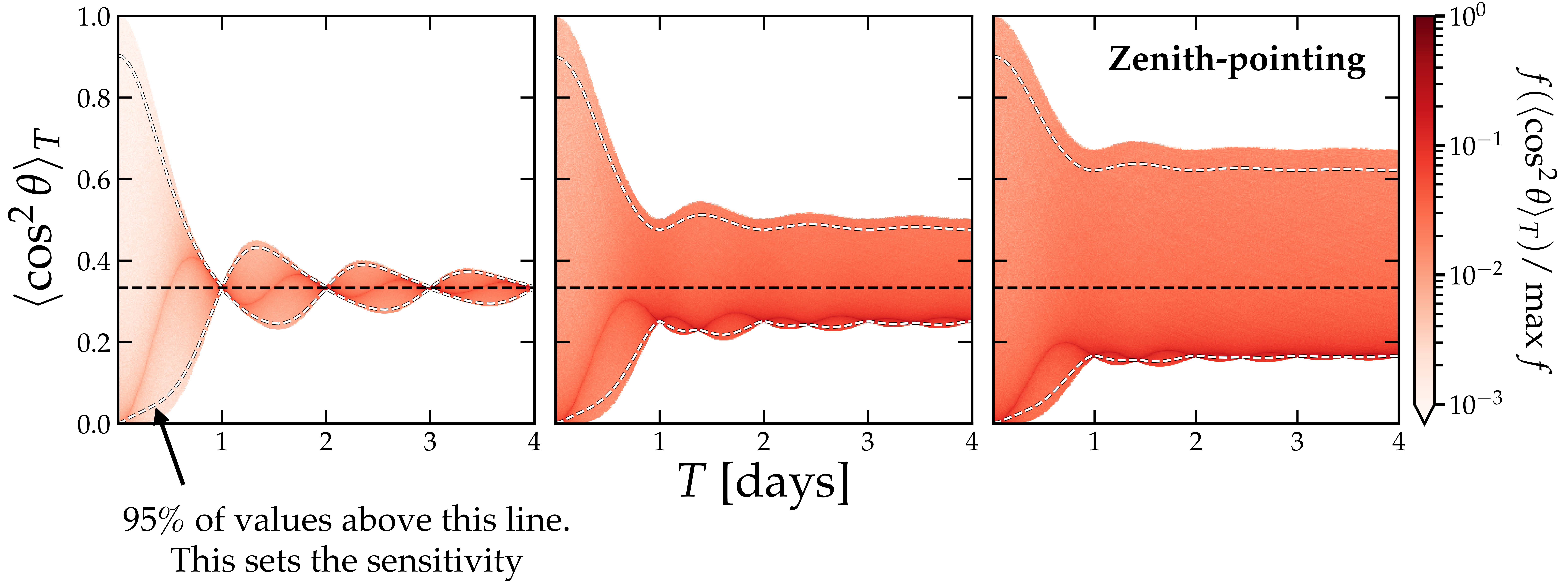
2005.01515



Hz
kHz
MHz
GHz
THz
eV
keV
$\gamma \to X$
Dark photon
dark matter
Stellar
bounds
Dark
E-field
DM-Radio
ALPHA
MADMAX
LAMPOST
SuperCDMS
LZ
Standard projection
Optimised projection
Kinetic mixing, χ
Dark photon mass, m_X [eV]

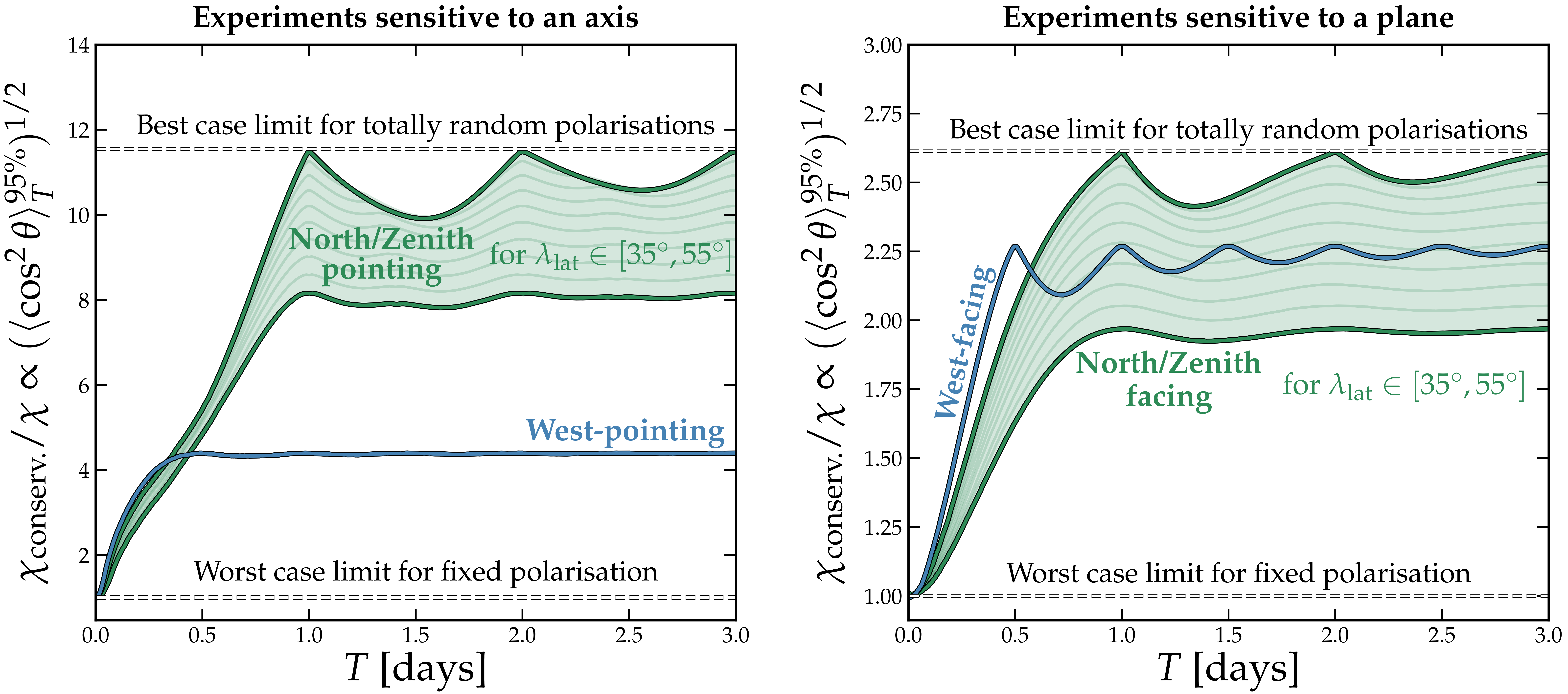
Distribution of time-averaged $\cos^2\theta$ versus the duration of observation

→ day-long measurements always optimal



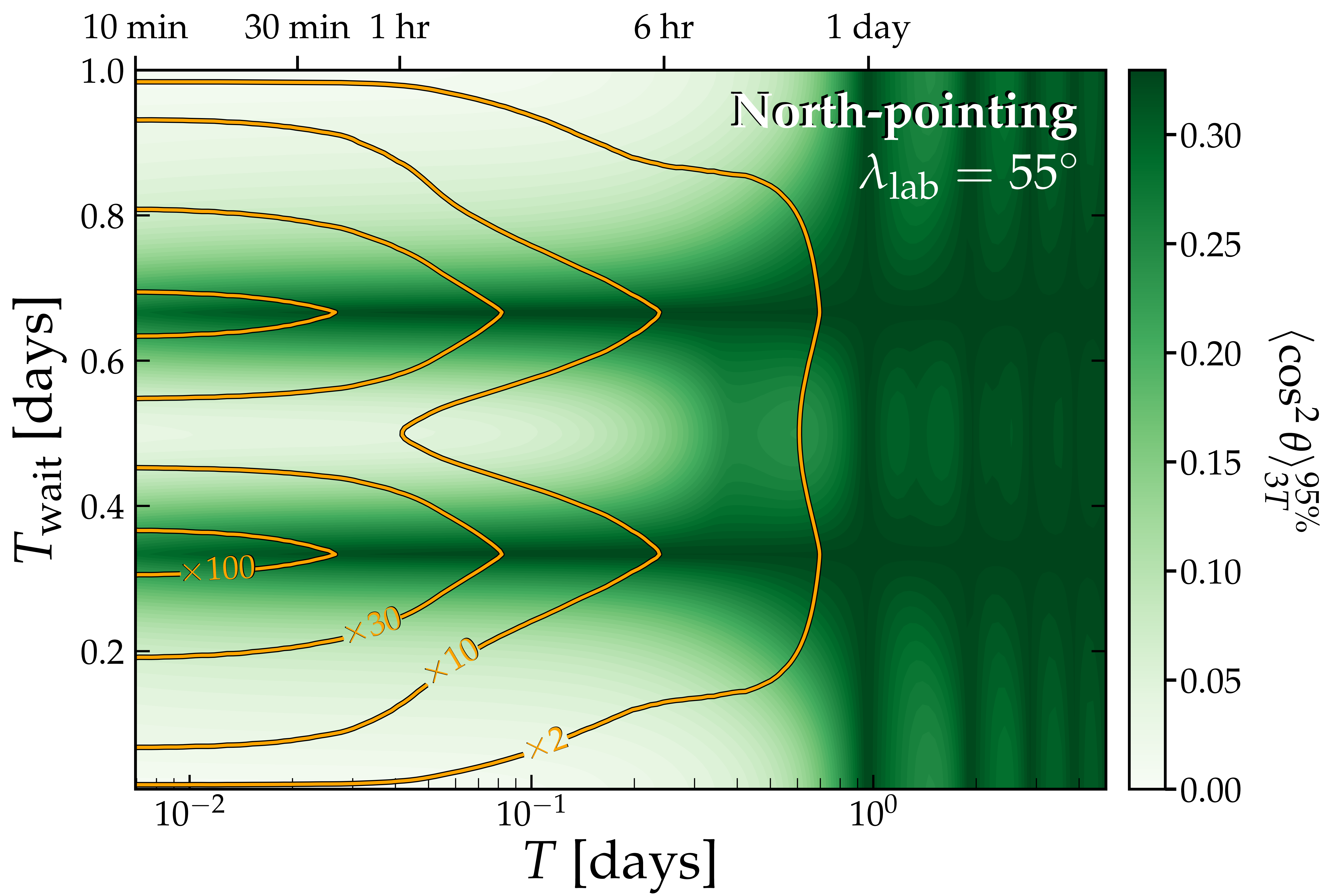
Sensitivity enhancement versus observation time

→ day long measurements always optimal



Sensitivity enhancement gained by doing three measurements separated by some time T_{wait}

→ don't need to spend a day doing measurements, just do three short measurements separated by a few hours



Can also measure the polarisation direction