Hidden Photon Limits: A Cookbook

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arXiv:2105.04565

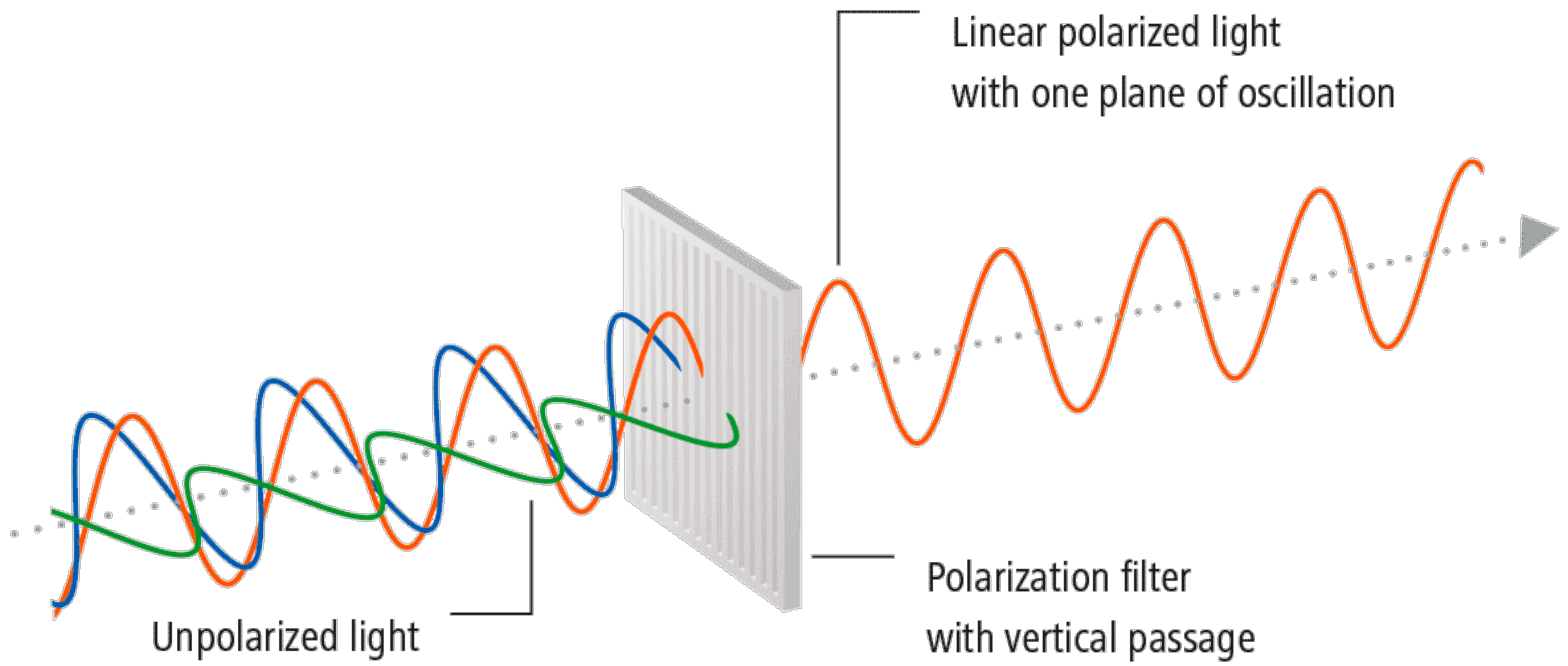
Hidden/Dark photons

- New U(1) gauge boson with tiny kinetic mixing with the visible photon
- Can be non-thermally produced as a good dark matter candidate
- Very similar behaviour to axions

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

Hidden Photons vs ALPs

- Key difference: HP has a polarisation!
- May be randomised or fixed depending on the production mechanism (or somewhere in-between)
- Structure formation may change this, but no detailed studies



Haloscopes for HP DM

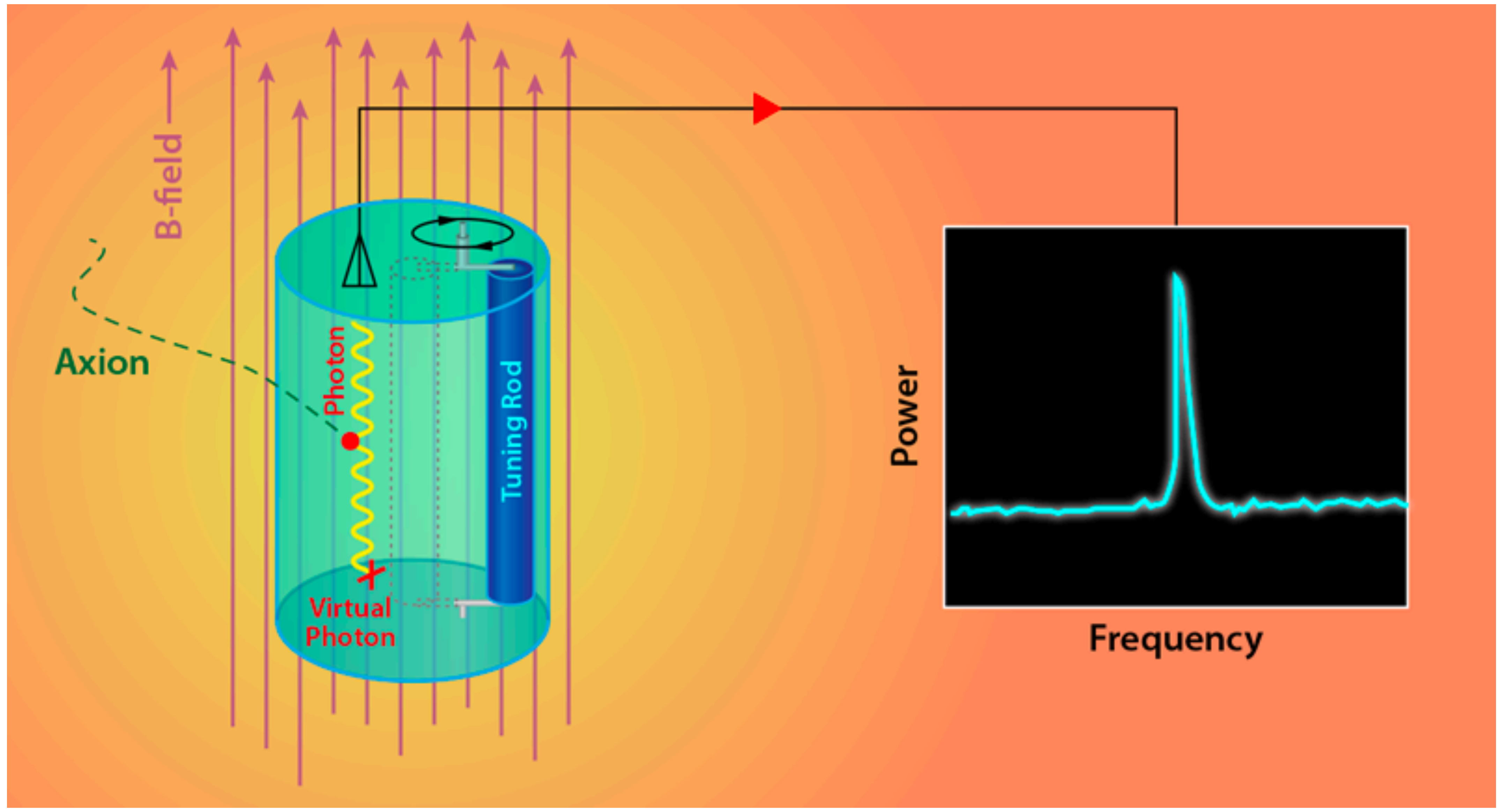
- In principle, any axion haloscope using axion-photon mixing is sensitive to HPs
- For an example, take a cavity haloscope

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

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

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

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



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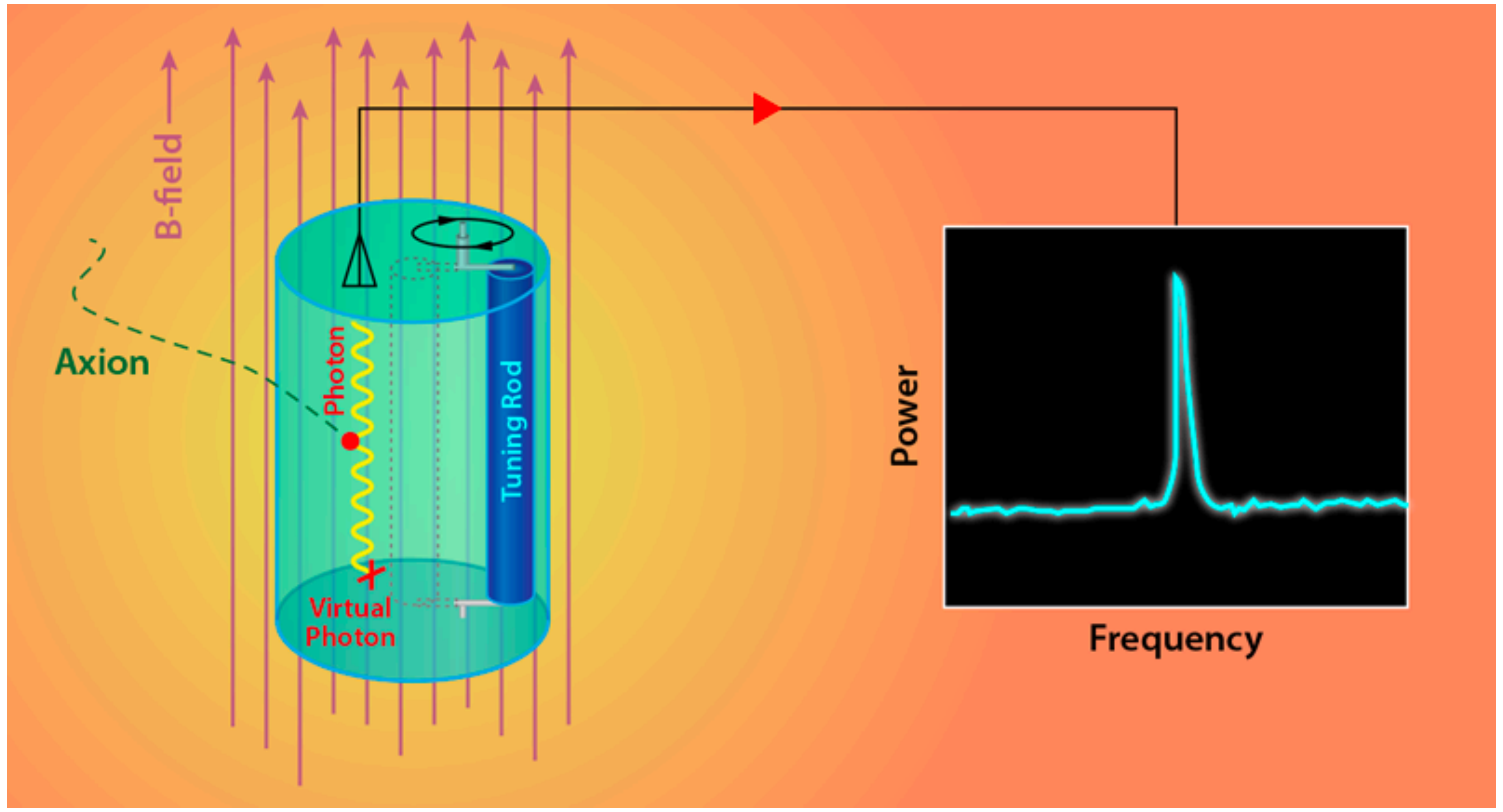
Haloscopes for HP DM

- Two key differences
- HP does not need a B-field
- The polarisation direction of the HP matters
- (Usually) easy to convert between the two sensitivities

$$\chi = g_{a\gamma} \frac{B}{m_X |\cos\theta|}, \qquad \cos\theta = \hat{\mathbf{X}} \cdot \hat{\mathbf{B}}.$$



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Reinterpreting axion experiments

- Actually need to be very careful: many experiments use B-field vetos which people have neglected before now
- Polarisations can give a highly non-trivial time varying signal
- Timing and directional data rarely given

	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-$a\gamma$	[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	Unknown	$\mathcal{O}$(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

Current HP Experiments

- Currently HP experiments make lots of different assumptions
- Some assume fixed, some random: few provide enough information in the results to properly calculate a limit for fixed polarisations

Experiment			Latitude [°]	Measurement time, T	Directionality	Assumed $\langle \cos^2\theta \rangle_T$	$\langle \cos^2\theta \rangle_T^{95\%}$
Cavities	WISPDMX	[32]	46.14	$\mathcal{O}$(day)	$(0.92\hat{\mathcal{N}} + 0.38\hat{\mathcal{W}})$-pointing	1/3	0.079–0.081
	SQuAD	[92]	41.88	12.81 s	Unspecified	1/3	0.0025
Dielectrics	†NYU Abu Dhabi	[159]	24.45	$\mathcal{O}$(day)	$\hat{\mathcal{Z}}$-facing	N/A	0.54–0.58
Dish antennae	Tokyo-1	[28]	35.68	29 days[a]	$\hat{\mathcal{W}}$-facing	2/3	0.50
	Tokyo-2	[30]	36.06	$\mathcal{O}$(week)	Axial, $\hat{\mathcal{N}}/\hat{\mathcal{W}}$-pointing	1/3	0.048–0.17
	Tokyo-3	[34]	36.13	12 hr	$\hat{\mathcal{N}}/\hat{\mathcal{W}}$-pointing or $\hat{\mathcal{Z}}$-facing	Unspecified	0.05 or 0.47
	SHUKET	[31]	48.86	8000 s	$\hat{\mathcal{Z}}$-pointing	1/3	0.0086
	FUNK	[33]	49.10	$\mathcal{O}$(month)	$(-0.5\hat{\mathcal{N}} - 0.87\hat{\mathcal{W}} + 0.28\hat{\mathcal{Z}})$-facing	2/3	0.27
LC-circuits	DM Pathfinder	[89]	37.42	5.14 hr	$\hat{\mathcal{Z}}$-pointing	1[b]	0.028
	Dark E-field	[35]	38.54	3.8 hr [c]	$\hat{\mathcal{W}}$-pointing	1/3	0.027
	Dark E-field spots	[35]	38.54	5.8 days[d]	$\hat{\mathcal{W}}$-pointing	1/3	0.049

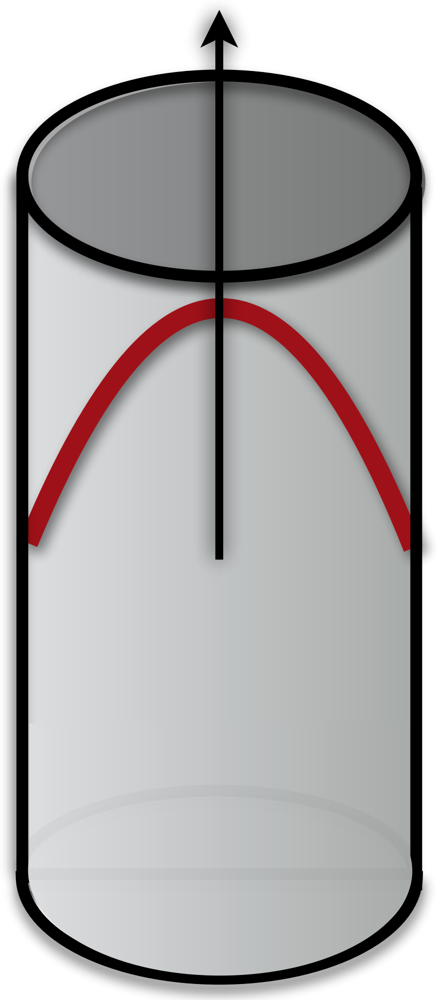
What should an experiment assume?

- Totally randomised is the most optimistic (just factors of 1/3 or 2/3 for $\cos^2\theta$)
- Totally constant polarisation is the trickiest scenario
- Simplest analysis (arXiv:1201.5902) gives factors of 0.0025 or 0.0975
- Both time varying and constant signals should be considered
- How do we make our worse case scenario match the best case scenario?

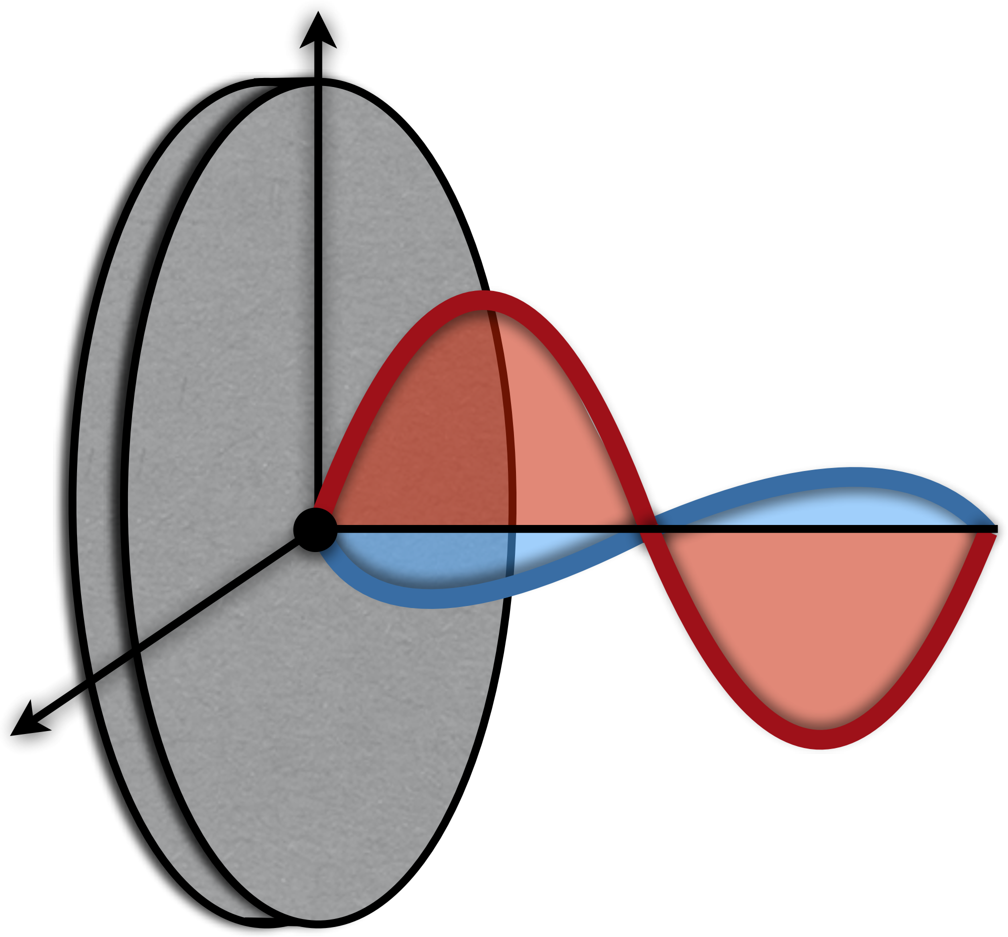
HP Polarisations

- How do you deal with a fixed polarisation?
- Experiments are sensitive to an axis or a plane

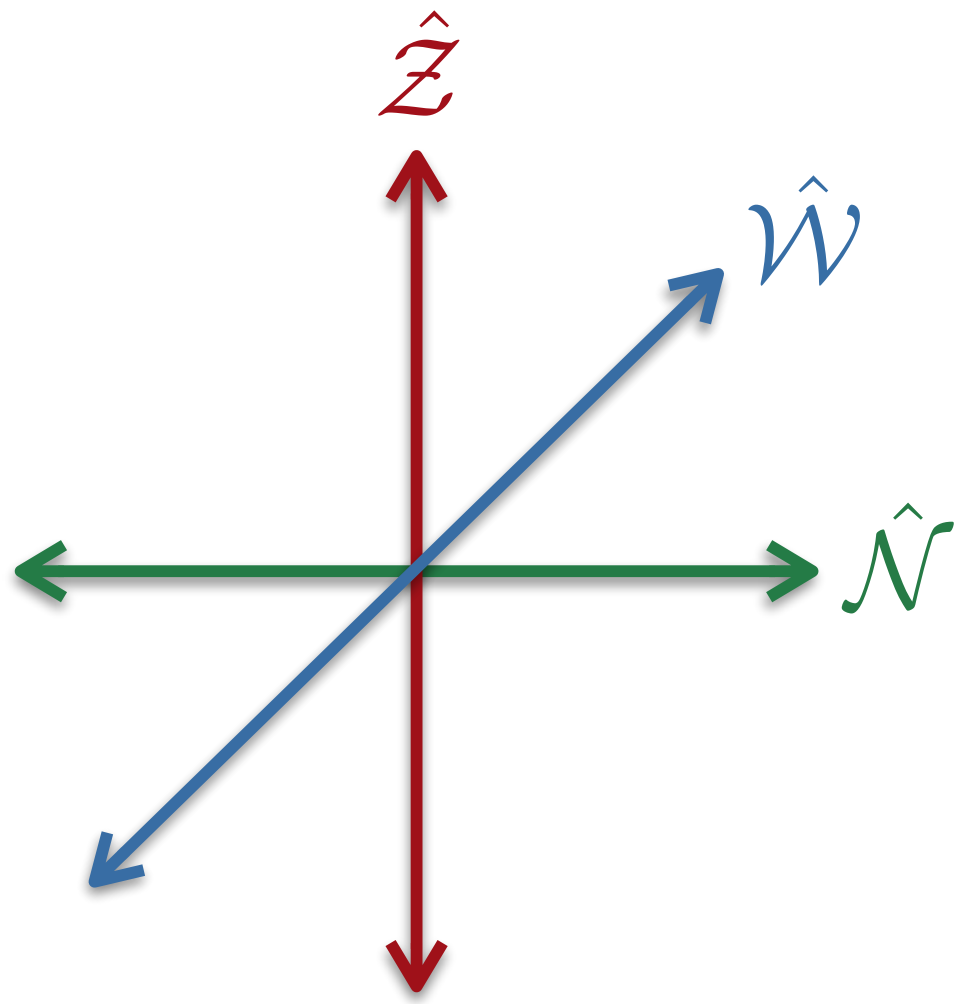
Axial experiment
(Zenith-pointing)



Planar experiment
(North-facing)



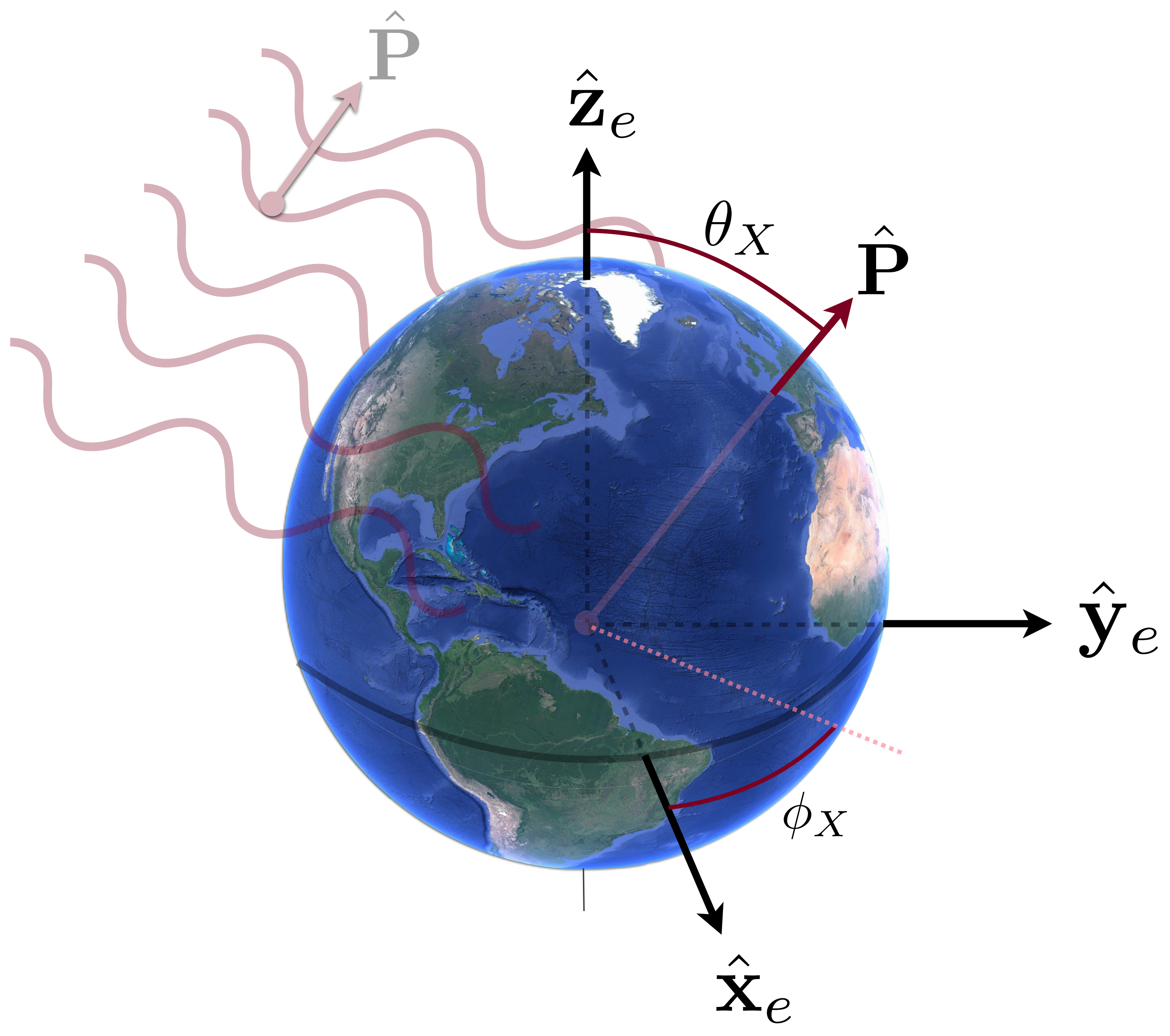
Possible DP Polarisations



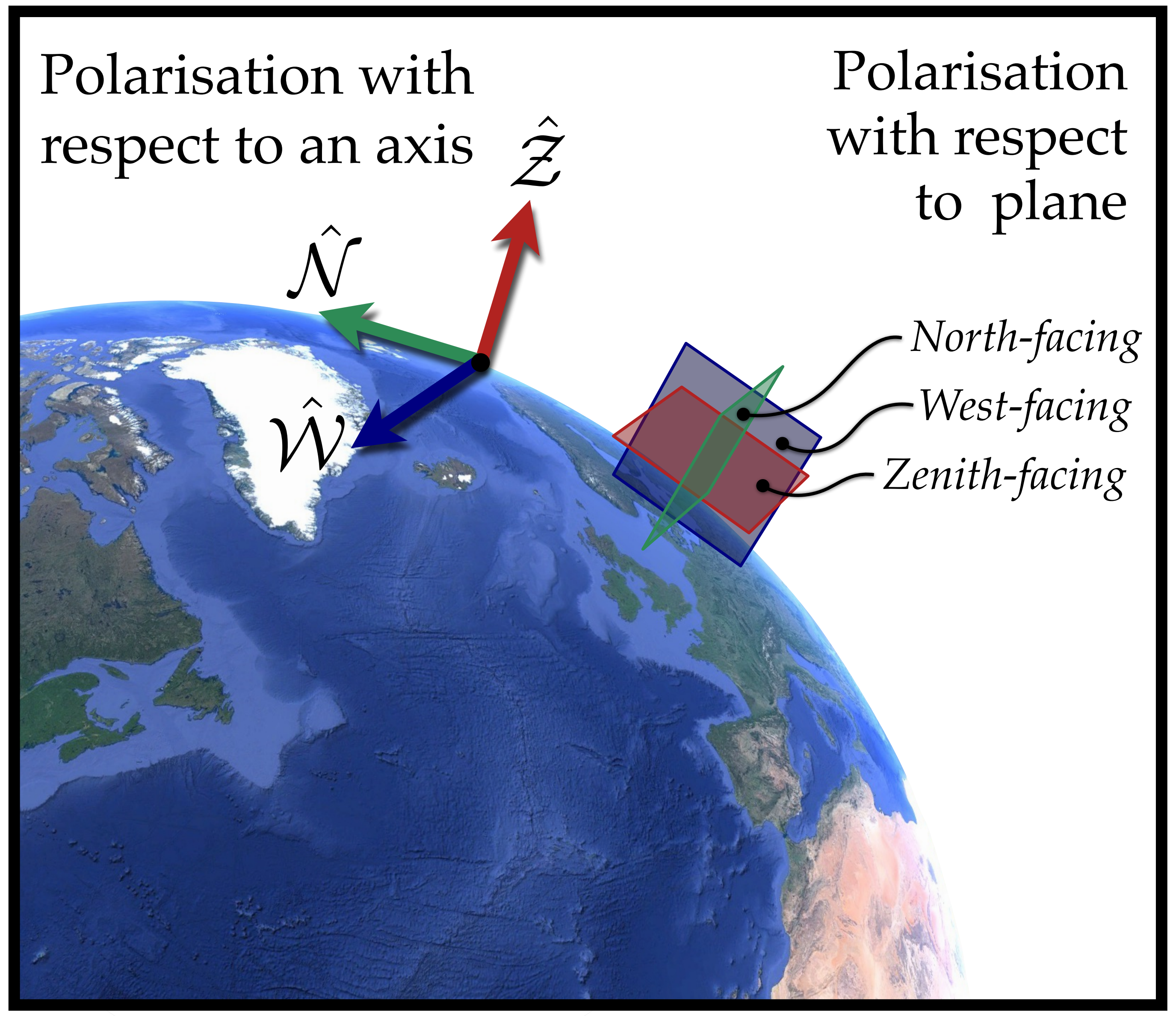
HP Polarisations

- Earth rotates!
- Long measurements sample a cone (or analogue)
- Short measurements sample a single random direction (very bad)

Geocentric coordinates

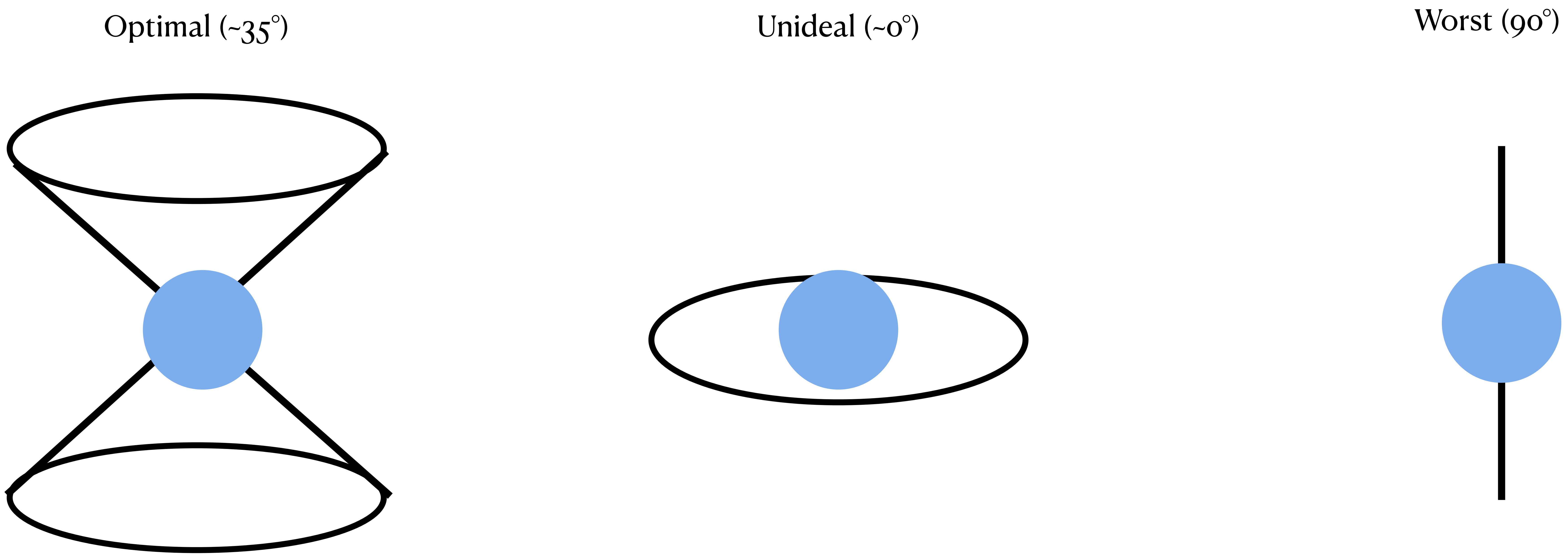


Detector-centric coordinates



Day long measurements

- To get a sense, one can take the simplest case: measurements lasting n-days exactly
- Experiments sensitive to an axis sweep out a cone (sensitive to a plane is simply the compliment)

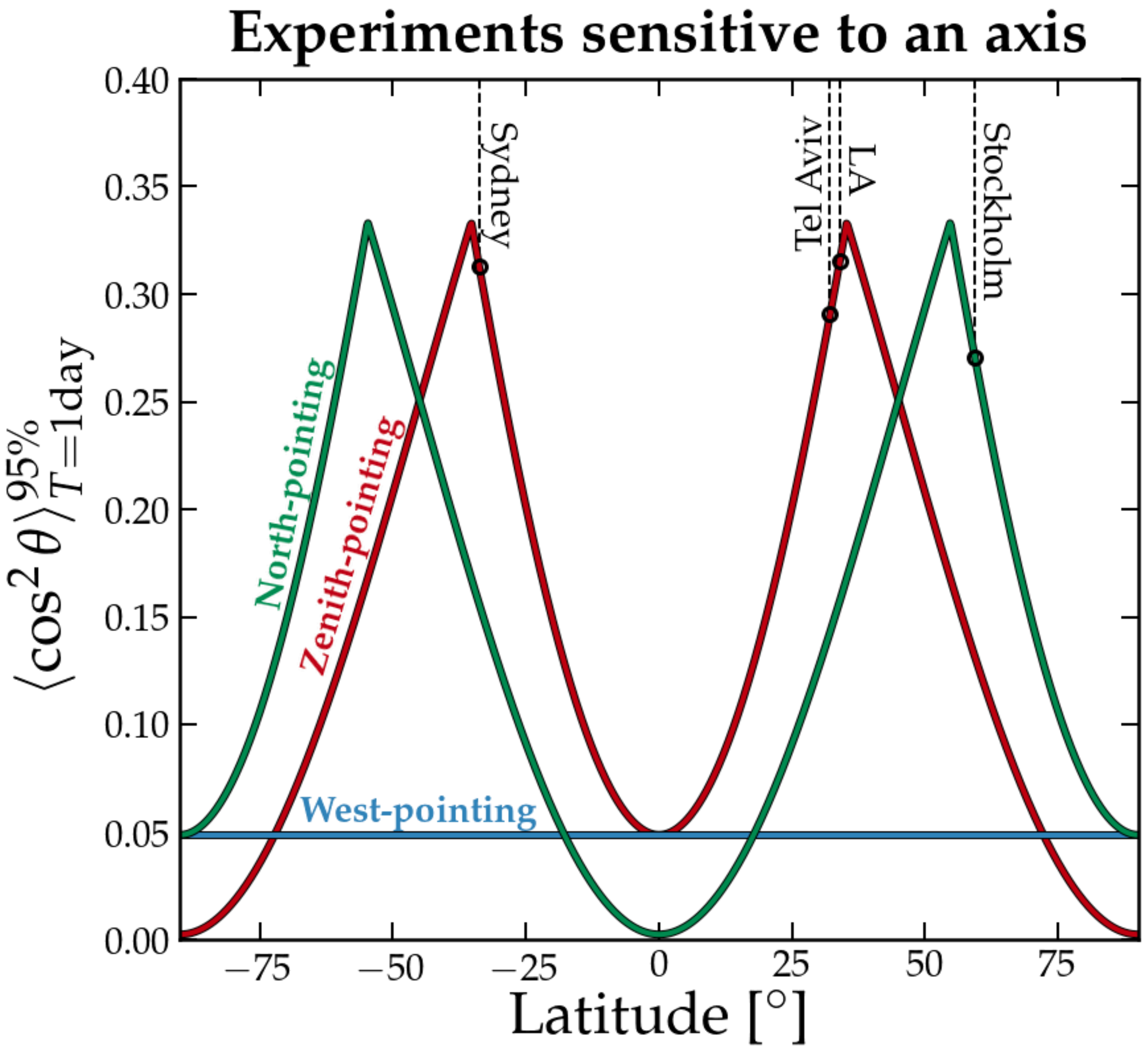


Day long measurements

- Need find the distribution of angles over some measurement

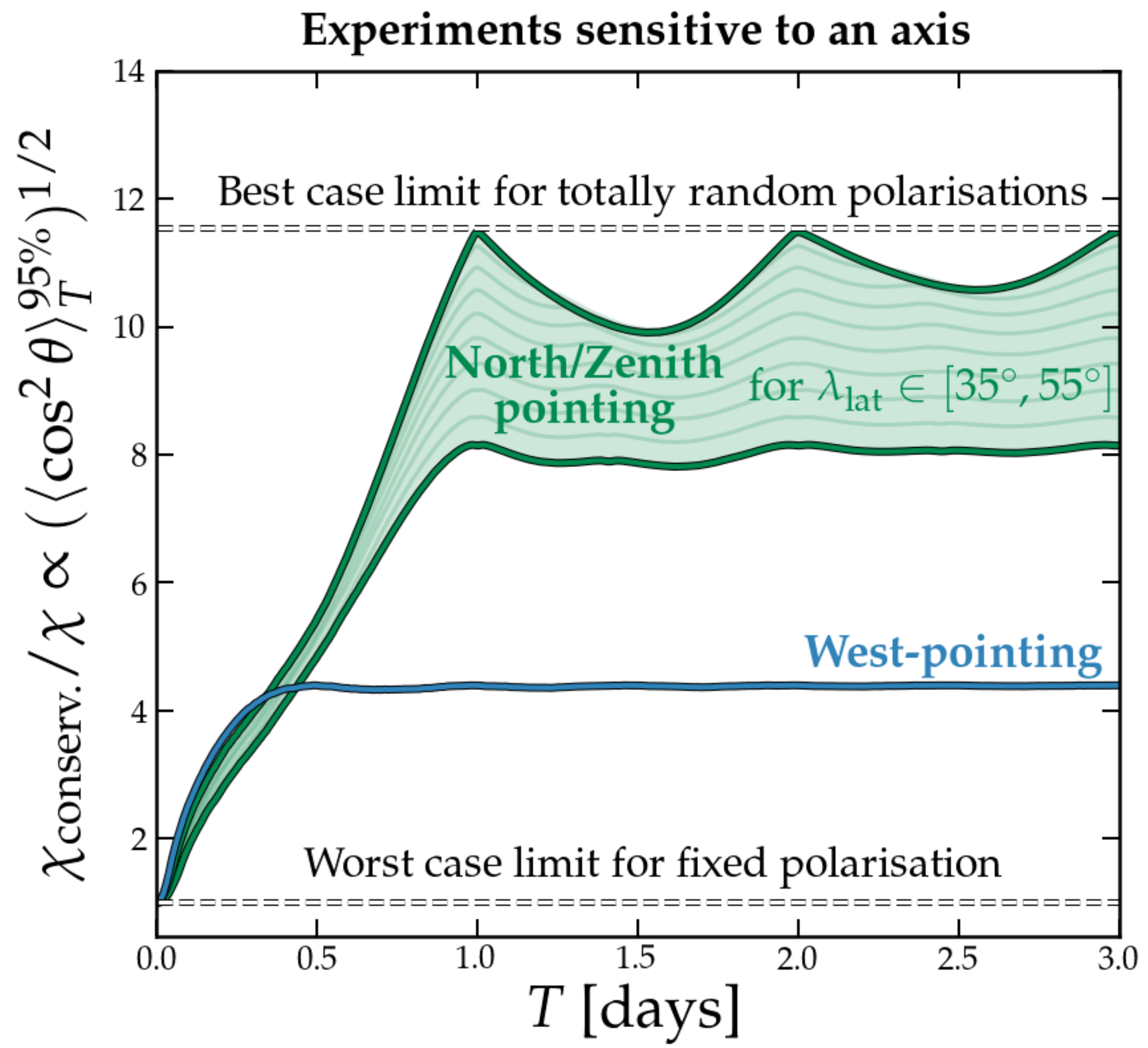
$$\langle \cos^2\theta(t)\rangle_T \equiv \frac{1}{T}\int_0^T \cos^2\theta(t)\mathrm{d}t$$

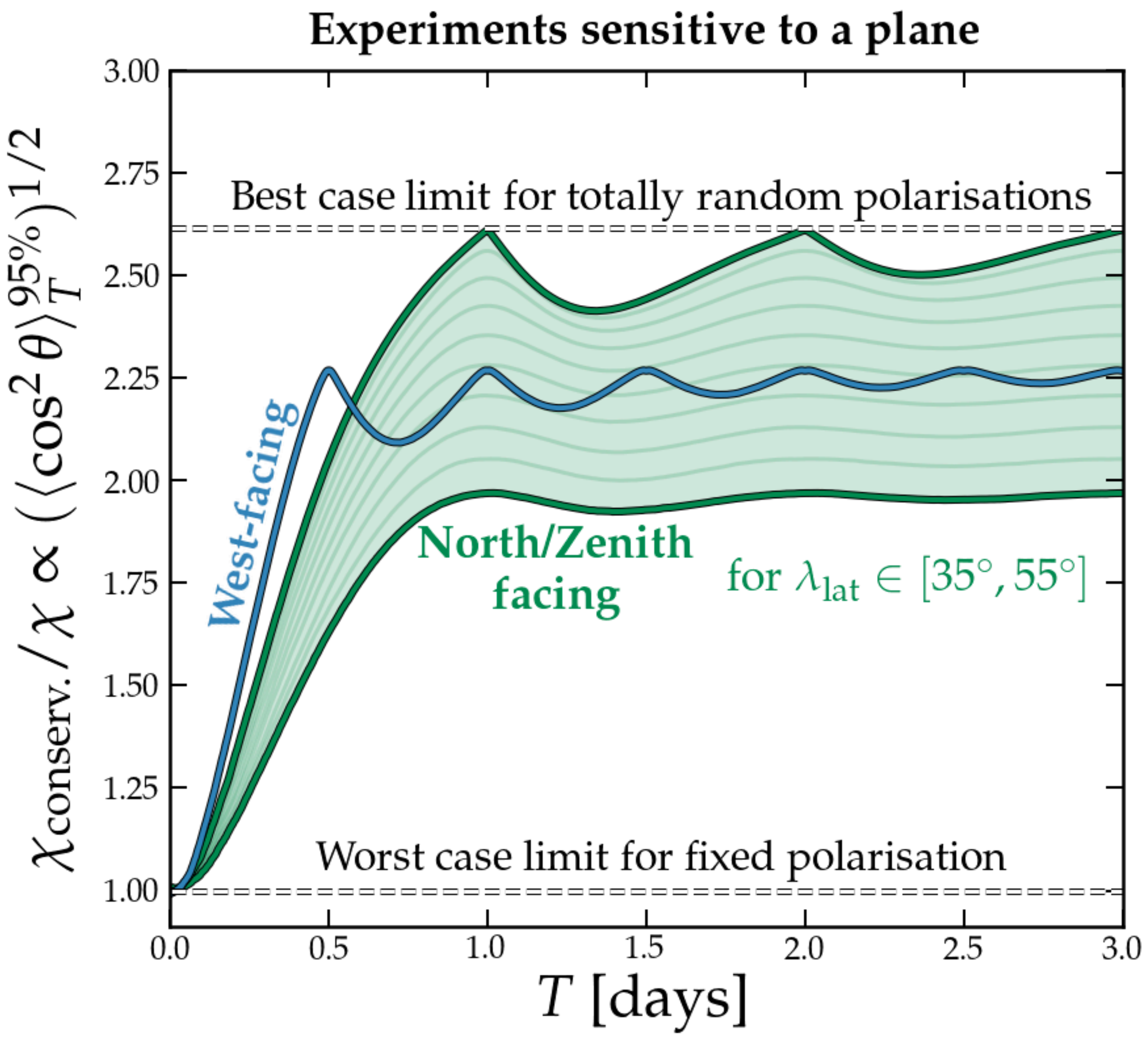
- Depends strongly on alignment and location (basically, there is a perfect angle with the pole around 35°)



Improvement with long measurements

- Up to an order of magnitude improvement on limits for long measurements

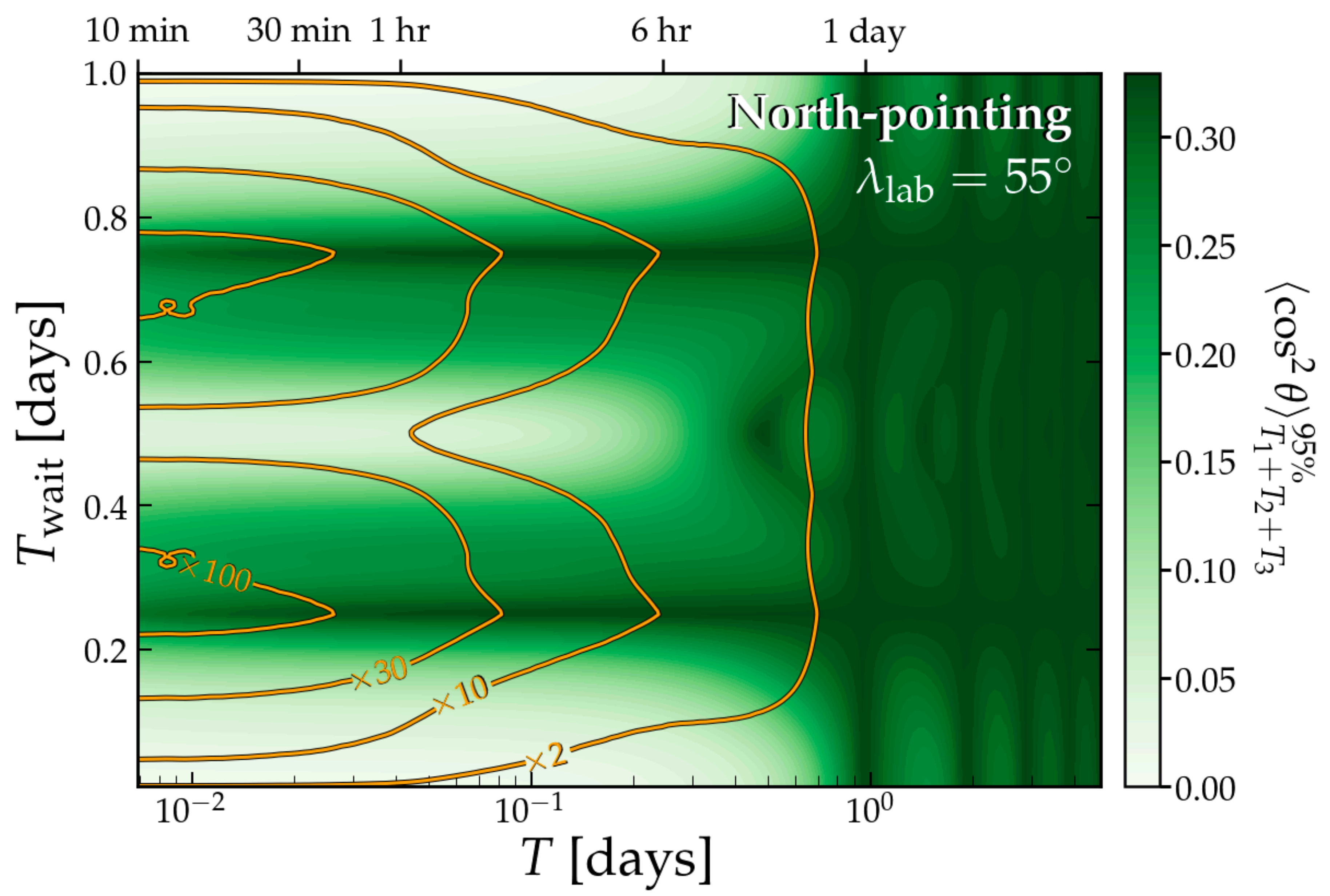




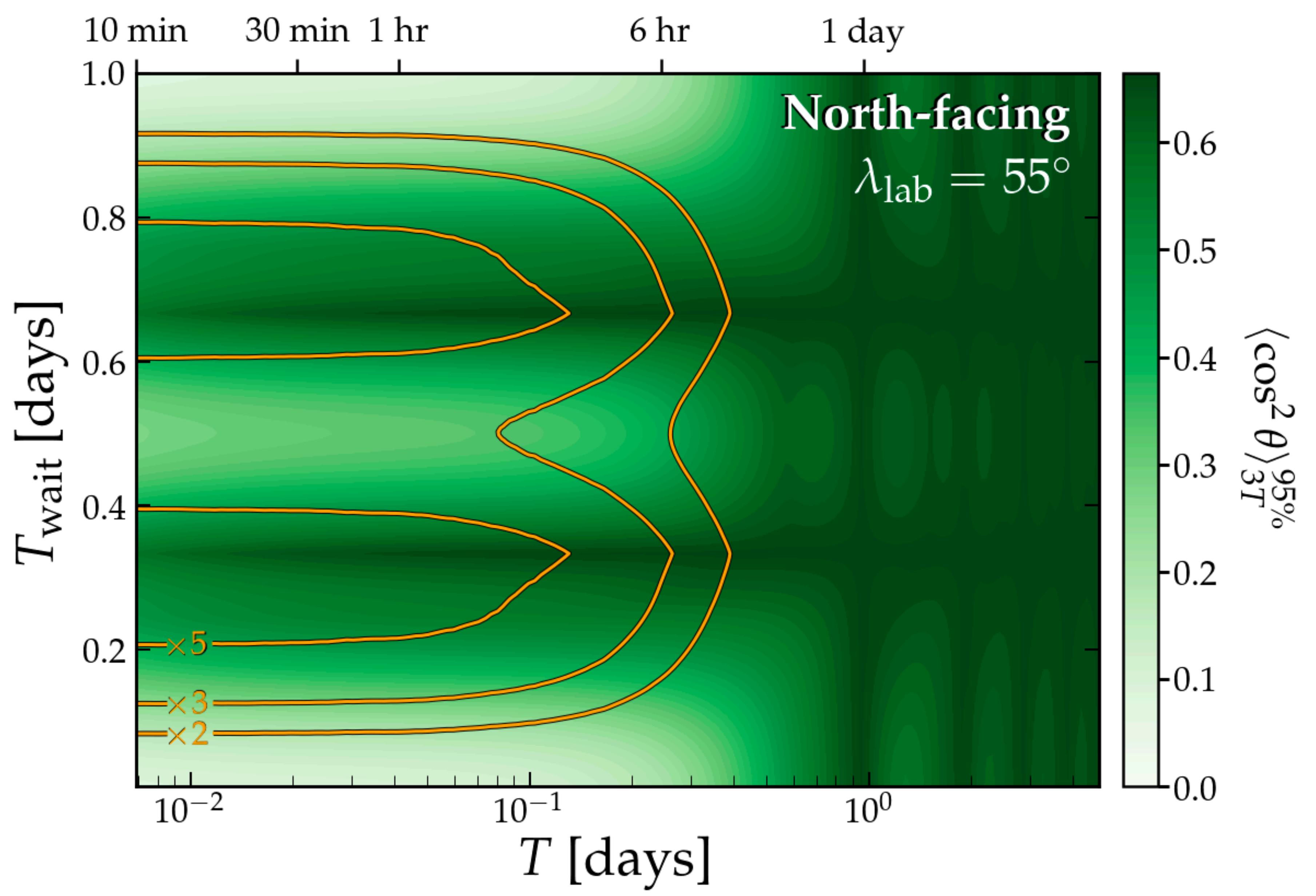
What about for short measurements?

- Most experiments do single, short measurements
- Can be made better!
- Split each measurement into parts, and space those parts over the course of a day
- Best results: three if sensitive to an axis, two if sensitive to a plane

Experiments sensitive to an axis



Experiments sensitive to a plane



What about for short measurements?

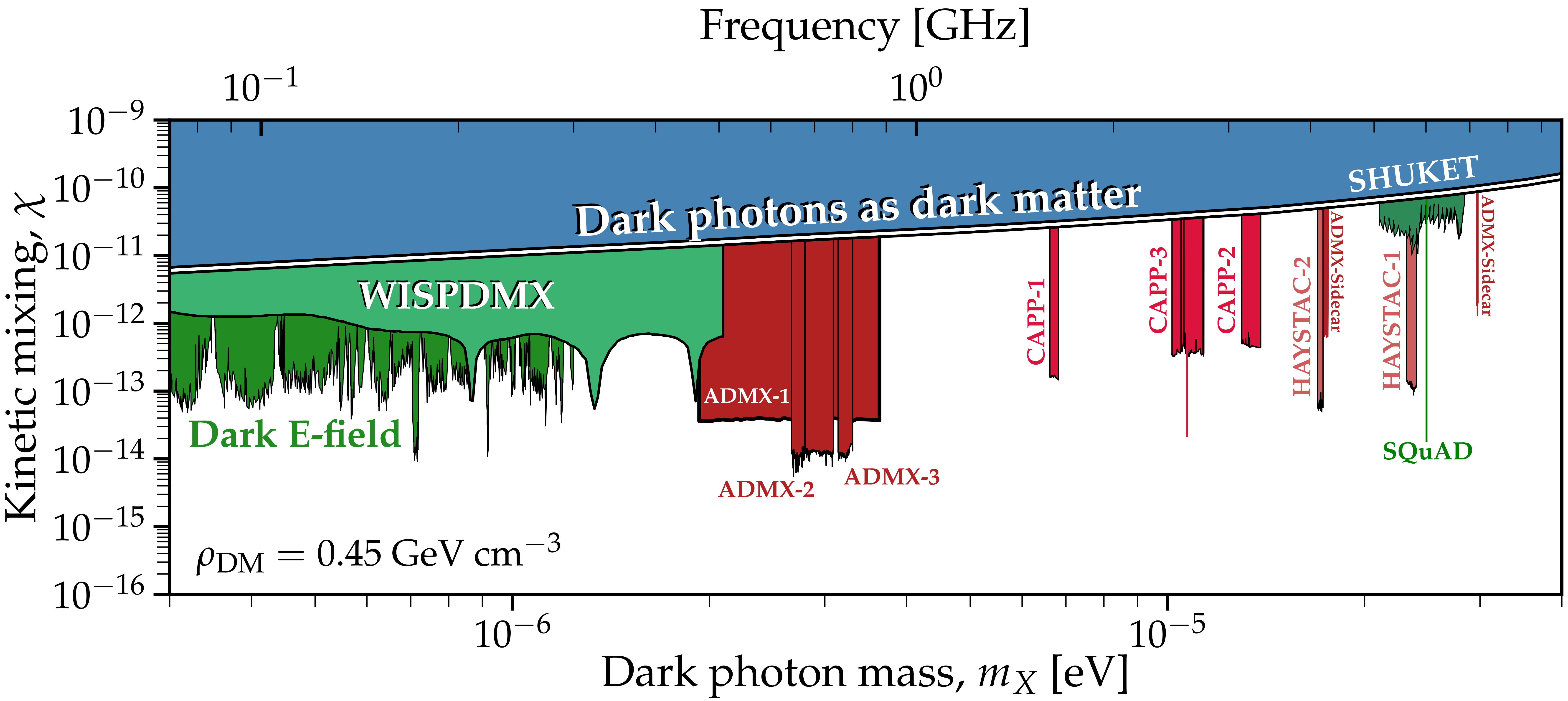
- Order of magnitude improvement on coupling just from three measurements!
- Does not increase overall data taking time
- Also have to be careful of rescans

$$\frac{S}{N} \simeq \frac{S_1 + S_2}{\sqrt{2N_1}} \propto \int_0^T dt P(t) + \int_{T_{\text{wait}}}^{T_{\text{wait}}+T} dt P(t)$$

- Always rescan with the same alignment

Current HP Limits

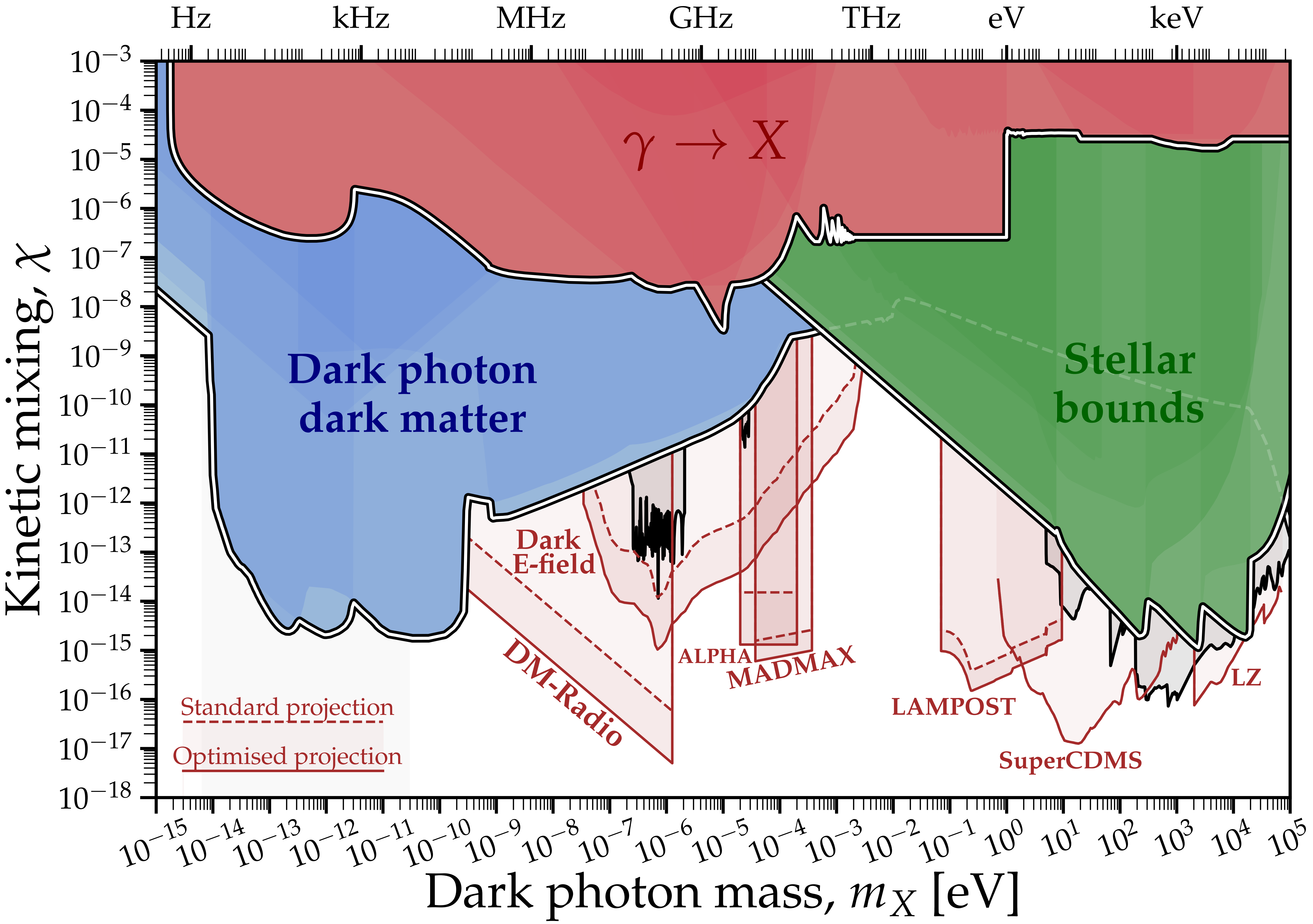
- Rescaled for fixed polarisation (conservative case)



- *Dark E-field assumes time varying signal so may not apply to randomly polarised HP

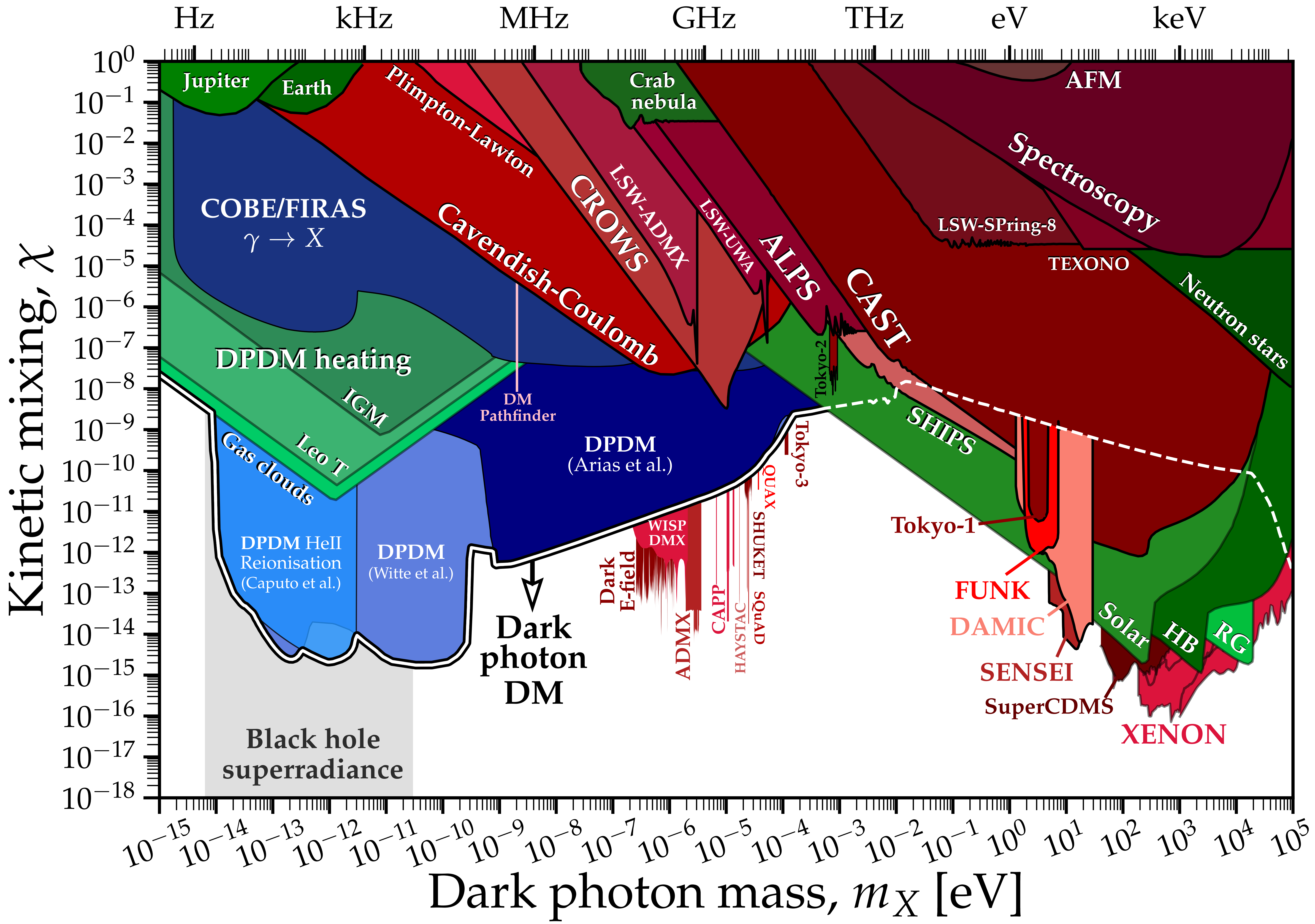
Future experiments

- Many more axion and HP experiments coming soon
- We should optimise scanning strategies to ensure robust limits regardless of DP scenario
- Need dedicated HP analyses!

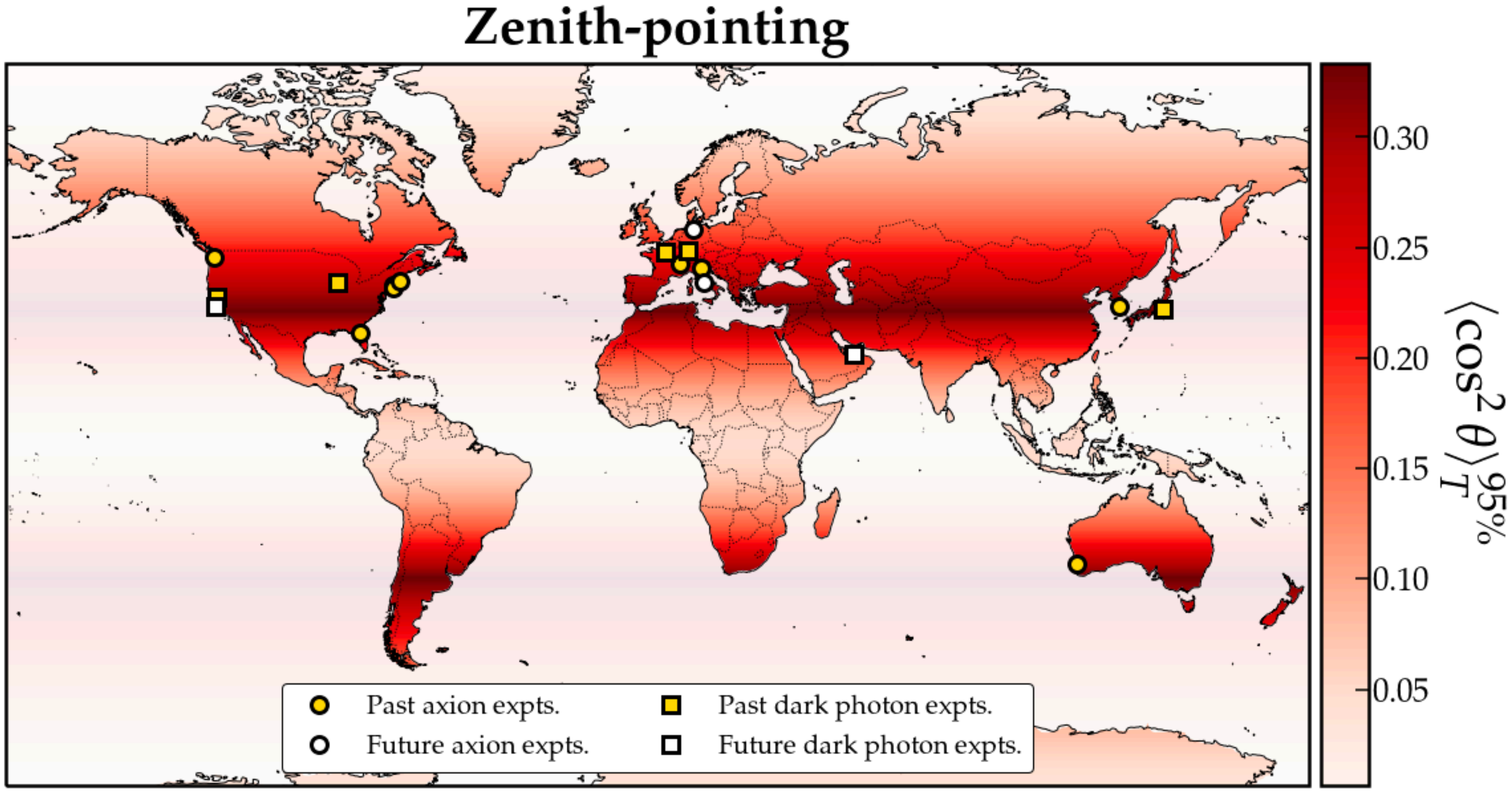


Conclusions

- Most important message: axion experiments should do dedicated analysis, not just leave them for people to try to reinterpret them
- Polarisation can be very non-trivial: detailed timing and directional data is needed
- Can improve limits be an order of magnitude
- Effects of structure formation should be simulated



Experiment Locations



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