Hidden Photon Limits: A Cookbook

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arXiv:2105.04565

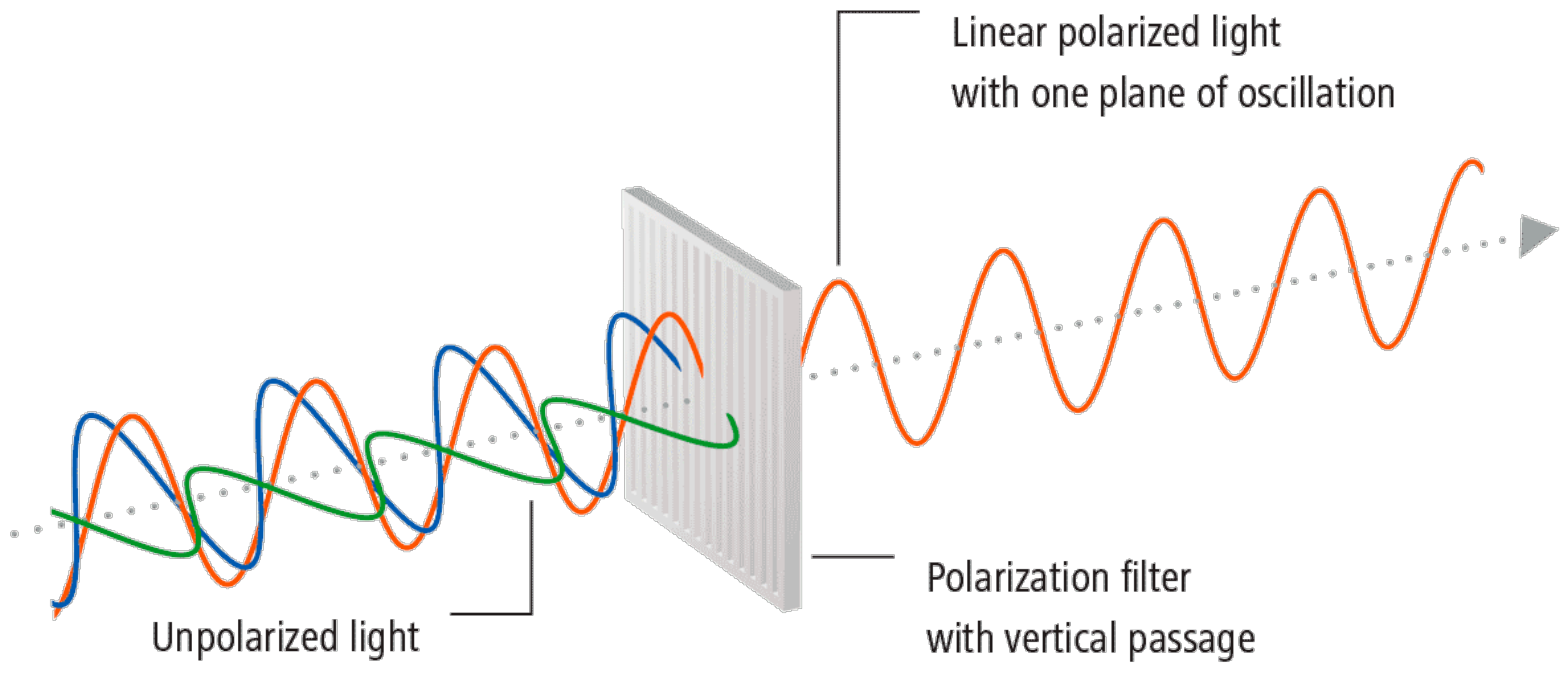
Hidden/Dark photons

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

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

Hidden Photons vs ALPs

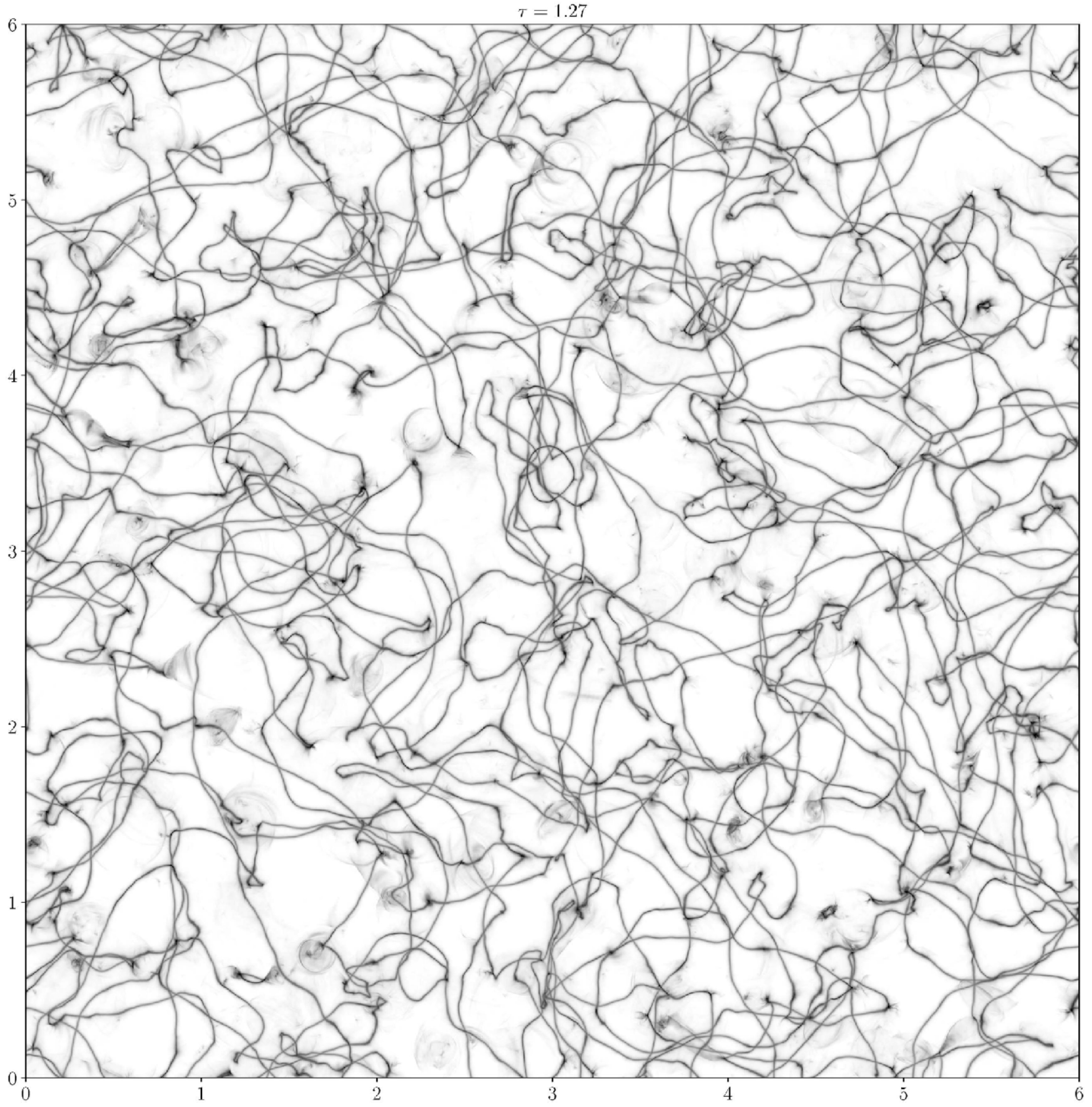
- Key difference: HP doesn't need B-field!
- Key difference: HP has a polarisation!
- May be randomised or fixed depending on the production mechanism (or somewhere in-between)
- Structure formation may change this, but no detailed studies



Hidden Photon Production

- Misalignment (can be before/after inflation)
- Quantum fluctuations during inflation
- Tachyonic instabilities
- Decay of topological defects like cosmic strings
- Rough estimates indicate polarisation should be unchanged over galactic timescales

$$\frac{\delta S}{S} \sim 4 \times 10^{-3} \left(\frac{v}{2 \times 10^{-3}}\right)^3 \frac{T}{13 \times 10^9 \,\mathrm{yr}} \frac{8\,\mathrm{kpc}}{R},$$

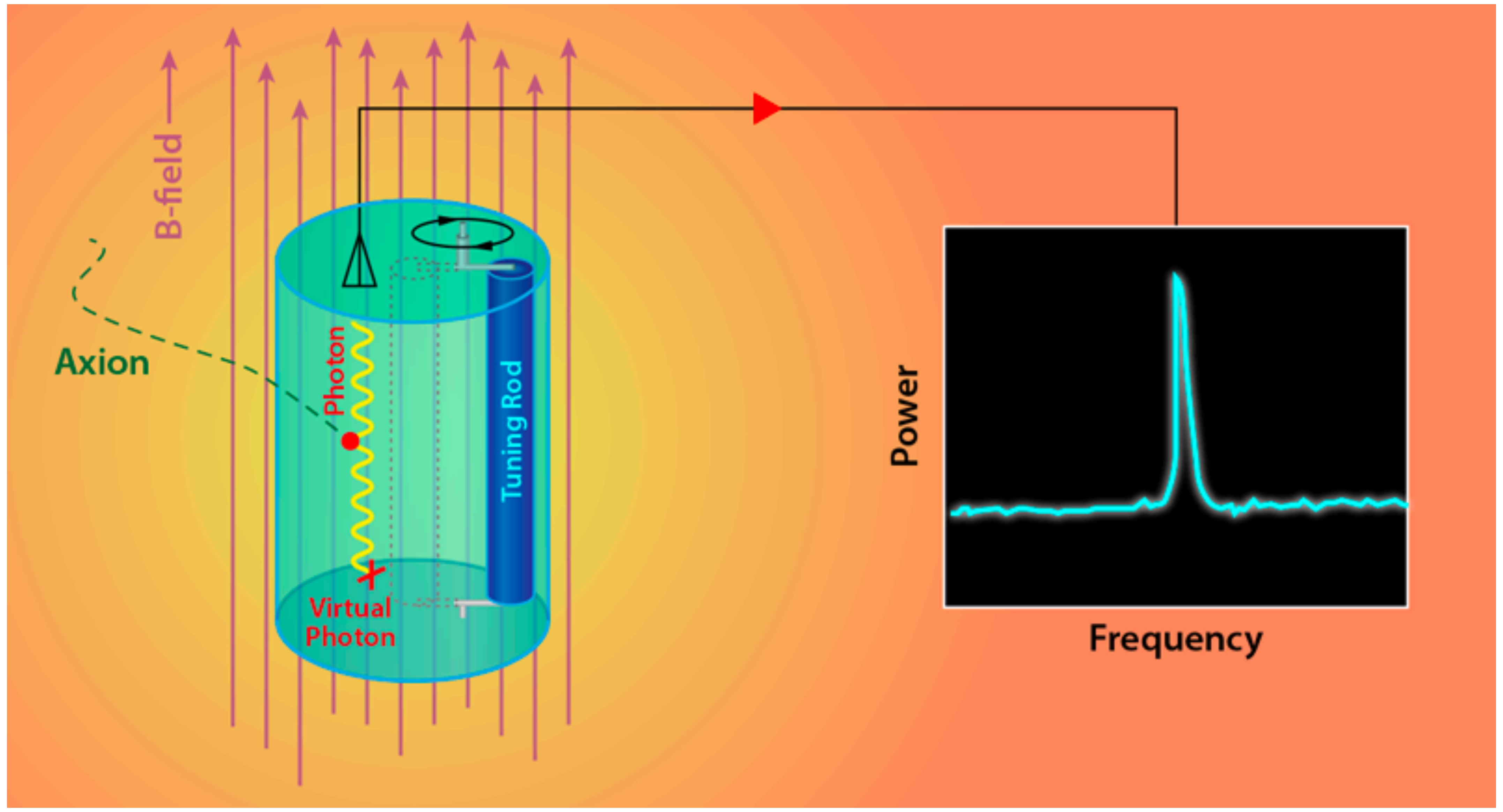


arXiv:1809.09241

Haloscopes for HP DM

- Almost axion haloscope using axion-photon mixing is sensitive to HPs
- 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	$\langle \cos^2\theta \rangle_T^{\text{excl.}}$
Cavities	ADMX-1	[107]	7.6	47.66	$\mathcal{O}$(min)	$\hat{\mathcal{Z}}$-pointing	∼0.025
	ADMX-2	[108]	6.8	47.66	$\mathcal{O}$(min)	$\hat{\mathcal{Z}}$-pointing	∼0.019
	ADMX-3	[110]	7.6	47.66	$\mathcal{O}$(min)	$\hat{\mathcal{Z}}$-pointing	∼0.019
	ADMX Sidecar	[109]	3.11[a]	47.66	$\mathcal{O}$(min)	$\hat{\mathcal{Z}}$-pointing	∼0.019
	HAYSTAC-1	[111]	9	41.32	$\mathcal{O}$(min)	$\hat{\mathcal{Z}}$-pointing	∼0.019
	HAYSTAC-2	[112]	9	41.32	$\mathcal{O}$(min)	$\hat{\mathcal{Z}}$-pointing	∼0.019
	CAPP-1	[113]	7.3	36.35	$\mathcal{O}$(min)	$\hat{\mathcal{Z}}$-pointing	∼0.019
	CAPP-2	[154]	7.8	36.35	$\mathcal{O}$(min)	$\hat{\mathcal{Z}}$-pointing	∼0.019
	CAPP-3	[155]	7.2 and 7.9	36.35	90 s	$\hat{\mathcal{Z}}$-pointing	∼0.019
	CAPP-3 [KSVZ]	[155]	7.2	36.35	15 hr	$\hat{\mathcal{Z}}$-pointing	0.20
	QUAX-$\alpha\gamma$	[114]	8.1	45.35	4203 s	$\hat{\mathcal{Z}}$-pointing	0.023
	†KLASH	[156]	0.6	41.80	$\mathcal{O}$(min)	$\hat{\mathcal{Z}}$-pointing	∼0.019
	RBF	[115]	Magnetic field veto				
	UF	[116]	Magnetic field veto				
	ORGAN	[117]	Magnetic field veto				
	RADES	[157]	Magnetic field veto				
LC-circuits	ADMX SLIC-1	[158]	4.5	29.64	$\mathcal{O}$(min)	$\hat{\mathcal{N}}/\hat{\mathcal{W}}$-facing	∼0.19
	ADMX SLIC-2	[158]	5	29.64	$\mathcal{O}$(min)	$\hat{\mathcal{N}}/\hat{\mathcal{W}}$-facing	∼0.19
	ADMX SLIC-3	[158]	7	29.64	$\mathcal{O}$(min)	$\hat{\mathcal{N}}/\hat{\mathcal{W}}$-facing	∼0.19
	ABRACADABRA	[118]	Magnetic field veto				
	SHAFT	[119]	Magnetic field veto				
Plasmas	†ALPHA	[159]	10	Unknown	$\mathcal{O}$(week)	$\hat{\mathcal{Z}}$-pointing	0.28–0.33
Dielectrics	†MADMAX	[160]	10	53.57	$\mathcal{O}$(week)	$\hat{\mathcal{Z}}$-pointing or $\hat{\mathcal{N}}/\hat{\mathcal{W}}$-facing	0.26 or 0.62–0.66[b]
	†LAMPOST	[36]	10	Unknown	$\mathcal{O}$(week)	Any-facing	0.61–0.66
	†DALI	[161]	9	28.49	$\mathcal{O}$(month)	Any-facing[c]	0.61–0.66
Dish antenna	†BRASS	[162]	1	53.57	$\mathcal{O}$(100 days)	Any-facing	0.61–0.66
Topological insulators	†TOORAD	[163]	10[d]	Unknown	$\mathcal{O}$(day)	Any-pointing	0.18–0.33

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 $\langle\cos^2\theta\rangle_T$	$\langle\cos^2\theta\rangle_T^{\text{excl.}}$
Cavities	WISPDMX	[32]	46.14	$\mathcal{O}$(day)	$(0.92\hat{\mathcal{N}}+0.38\hat{\mathcal{W}})$-pointing	1/3	0.23
	SQuAD	[93]	41.88	12.81 s	Unspecified	1/3	0.019
Dielectrics	†NYU Abu Dhabi	[164]	24.45	$\mathcal{O}$(day)	$\hat{\mathcal{Z}}$-facing	N/A	0.65
Dish antennae	Tokyo-1	[28]	35.68	29 days[a]	$\hat{\mathcal{W}}$-facing	2/3	0.62
	Tokyo-2	[30]	36.06	$\mathcal{O}$(week)	Axial, $\hat{\mathcal{N}}/\hat{\mathcal{W}}$-pointing	1/3	0.15–0.2
	Tokyo-3	[34]	36.13	12 hr	$\hat{\mathcal{N}}/\hat{\mathcal{W}}$-pointing or $\hat{\mathcal{Z}}$-facing	Unspecified	0.15 or 0.62
	SHUKET	[31]	48.86	8000 s	$\hat{\mathcal{Z}}$-pointing	1/3	0.04
	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	0.56
LC-circuits	DM Pathfinder	[90]	37.42	5.14 hr	$\hat{\mathcal{Z}}$-pointing	1[b]	0.075
	Dark E-field	[35]	38.54	3.8 hr [c]	$\hat{\mathcal{W}}$-pointing	1/3	0.29
	Dark E-field spots	[35]	38.54	5.8 days[d]	$\hat{\mathcal{W}}$-pointing	1/3	0.58

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?

Statistics of Exclusion/Discovery

- Usually expressed as a 95% CL
- Defined so that 95% of signals would be higher than the noise
- Need to marginalise over the polarisation distribution

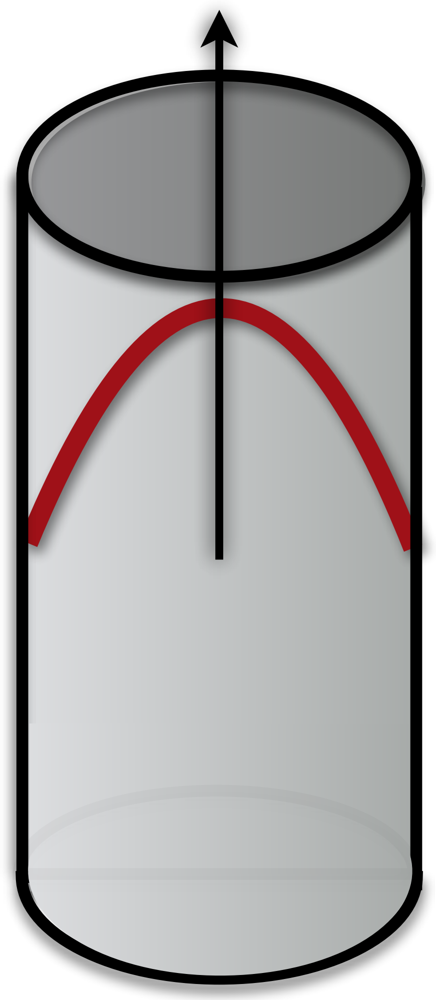
$$\Phi[0] \equiv \int_{-\infty}^{+\infty} \mathrm{d}P_X \int_{-\infty}^{0-P_X} \mathrm{d}N\, f(P_X) f(N) = 1 - 0.95$$

- Allows us to define the angle that gives a 95% CL, $\langle \cos^2 \theta \rangle_T^{\text{excl.}}$
- More like 0.025 or 0.37 for short measurements
- Stricter claim need for most experiments to expect a 5 sigma signal
- We define the angle so that 95% of experiments would make a discovery $\langle \cos^2 \theta \rangle_T^{\text{disc.}}$

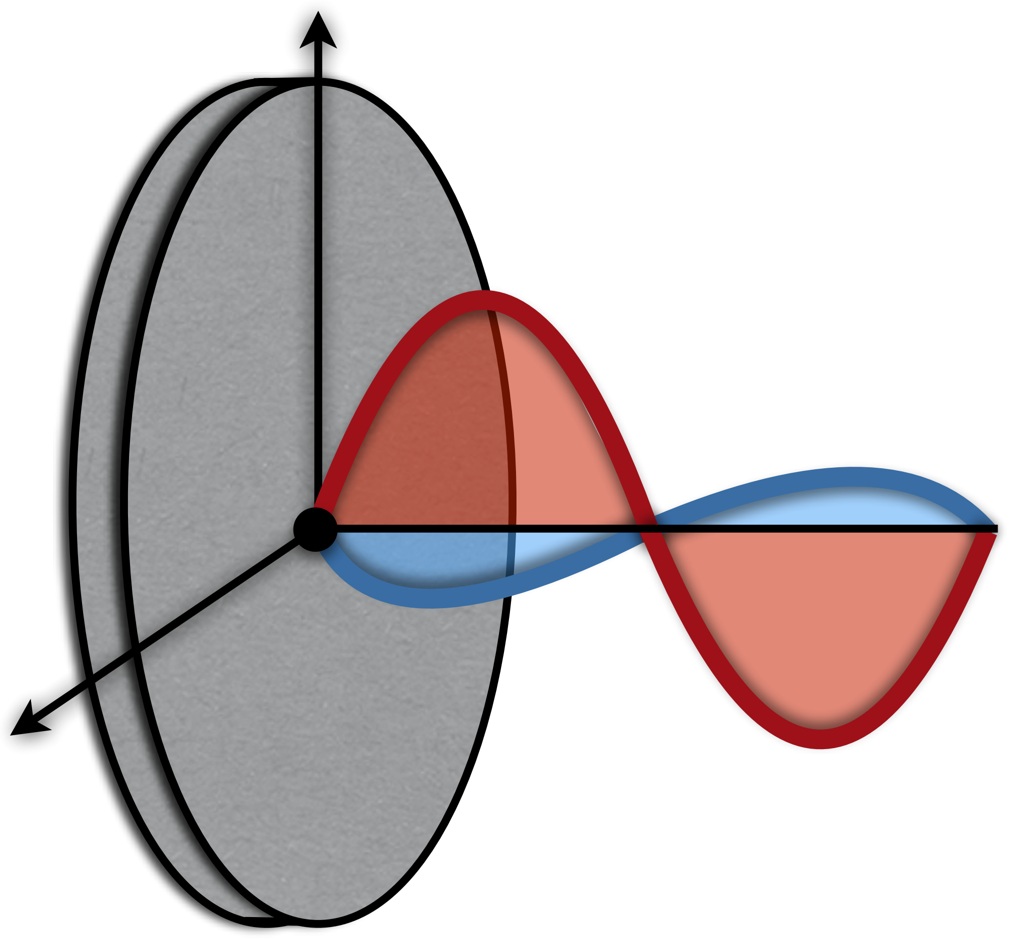
HP Polarisations

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

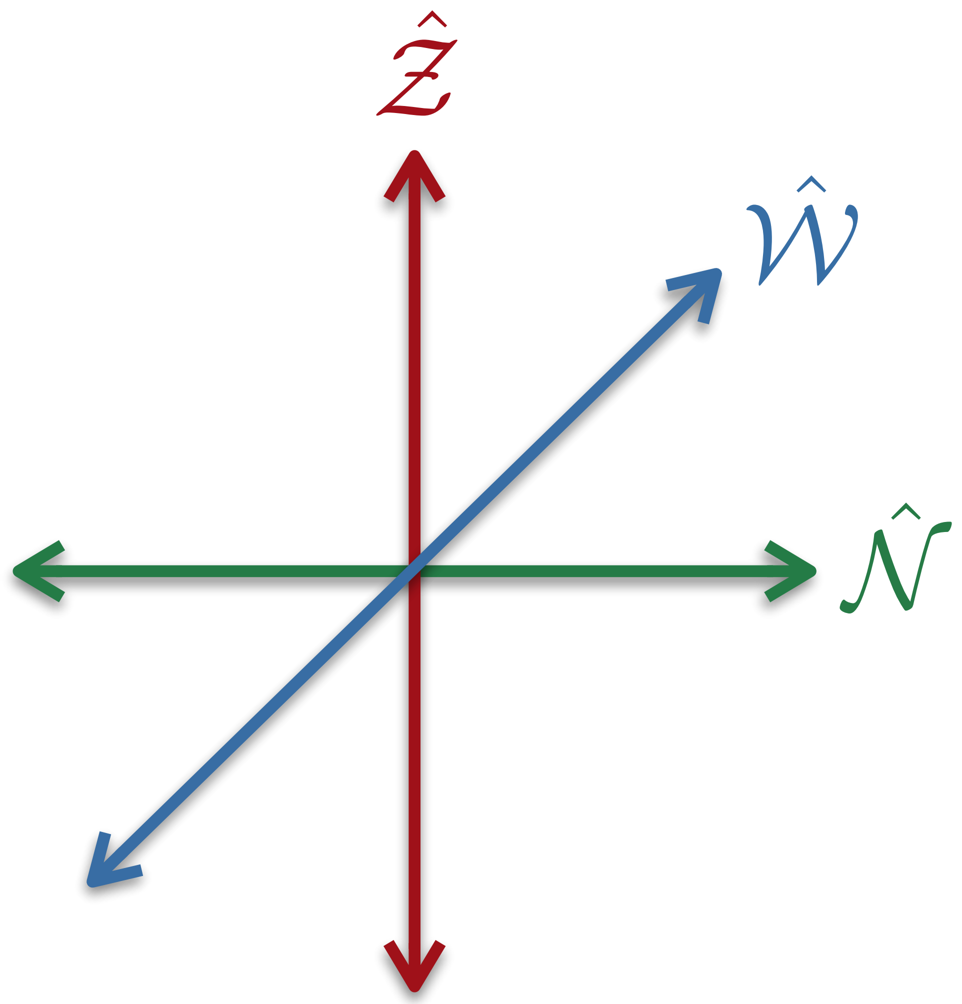
Axial experiment
(Zenith-pointing)



Planar experiment
(North-facing)



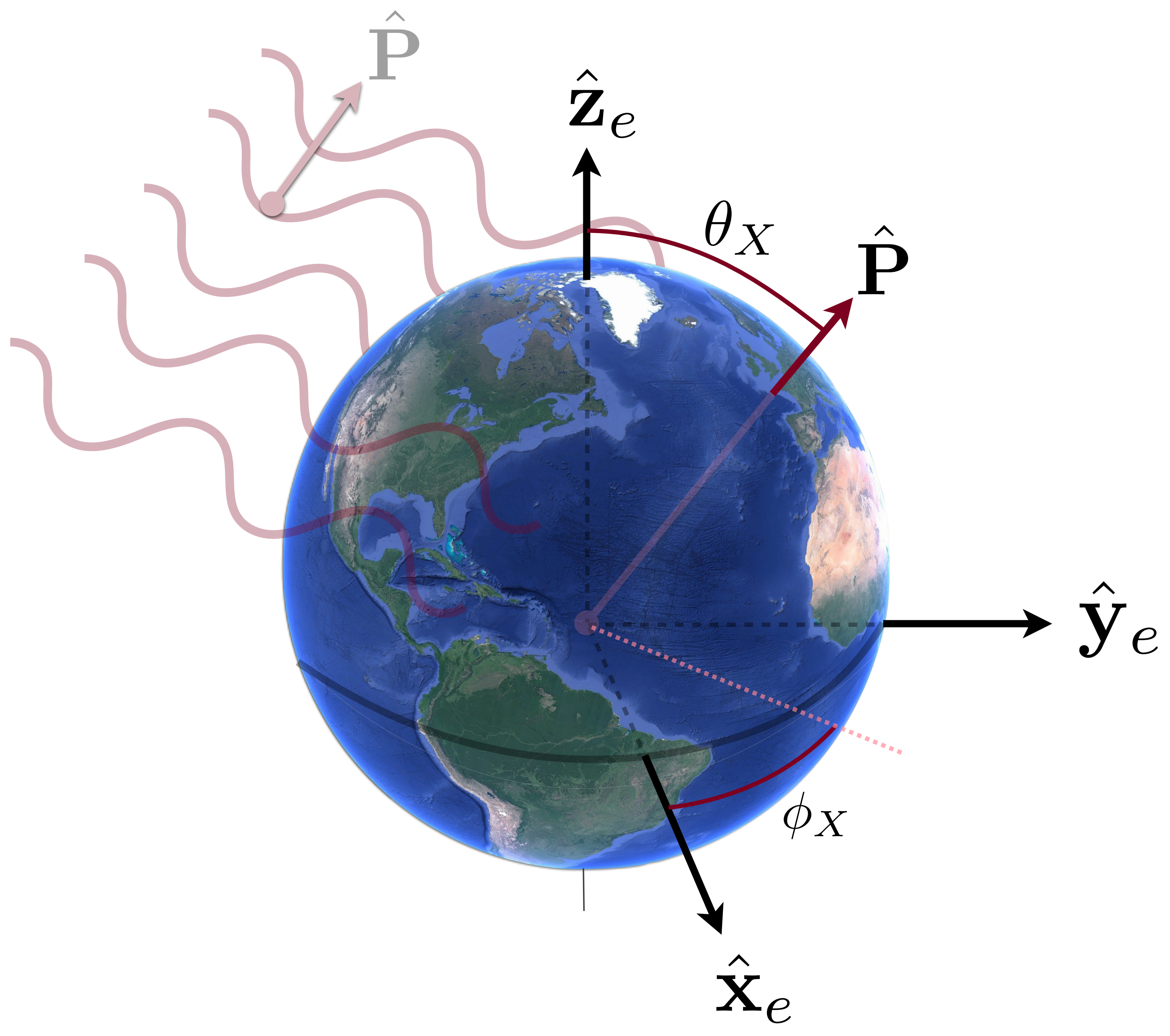
Possible DP Polarisations



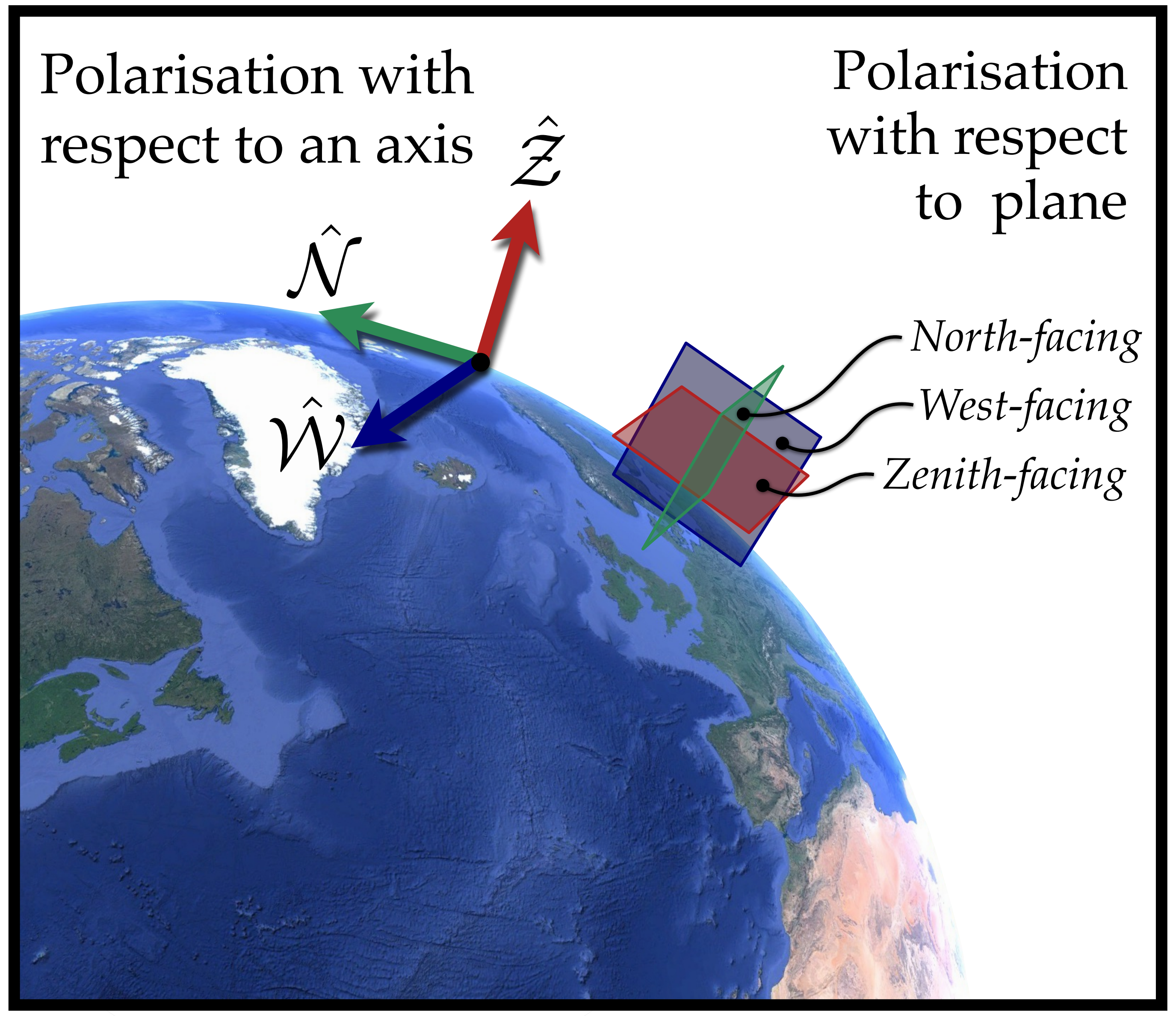
HP Polarisations

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

Geocentric coordinates

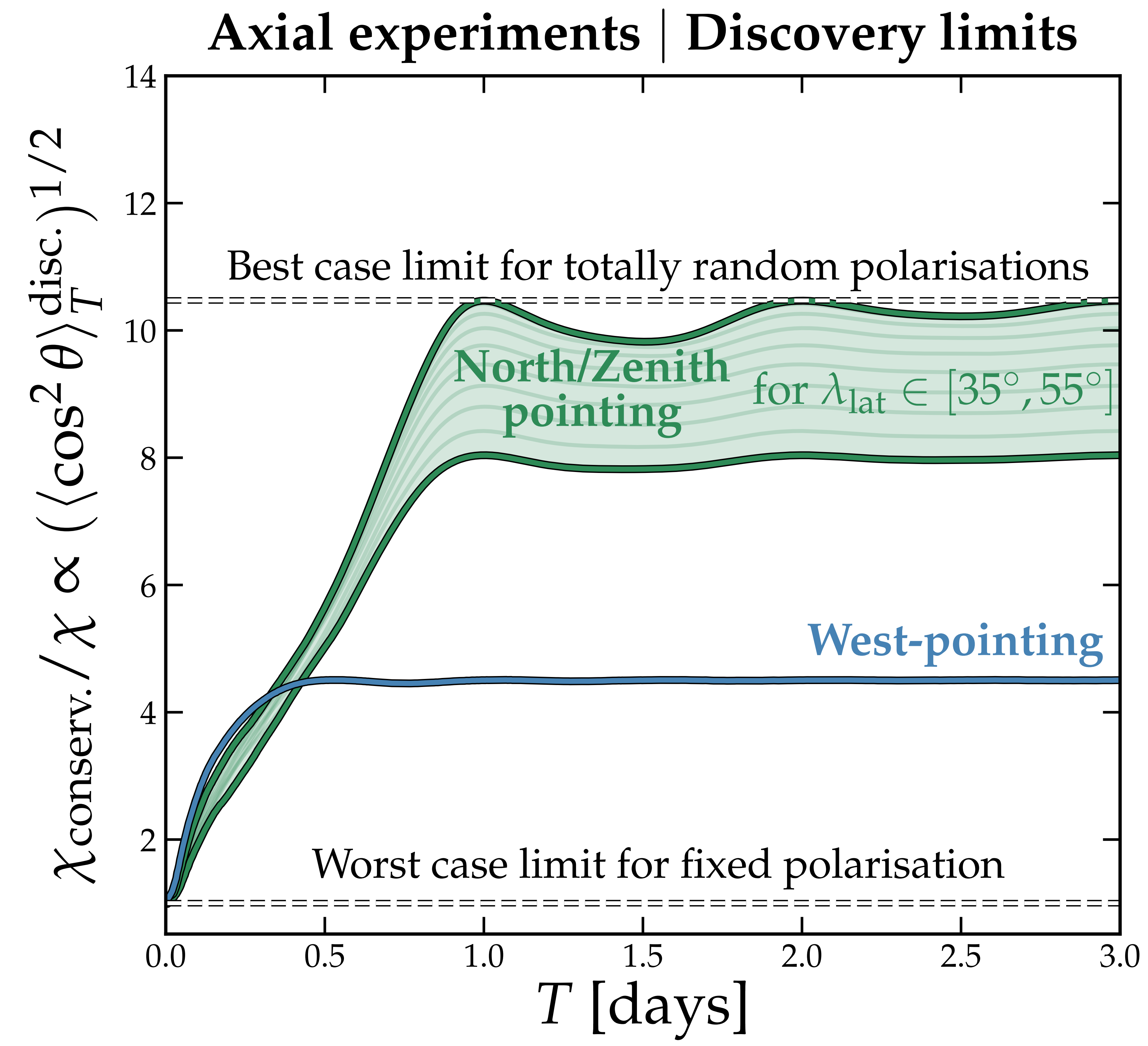


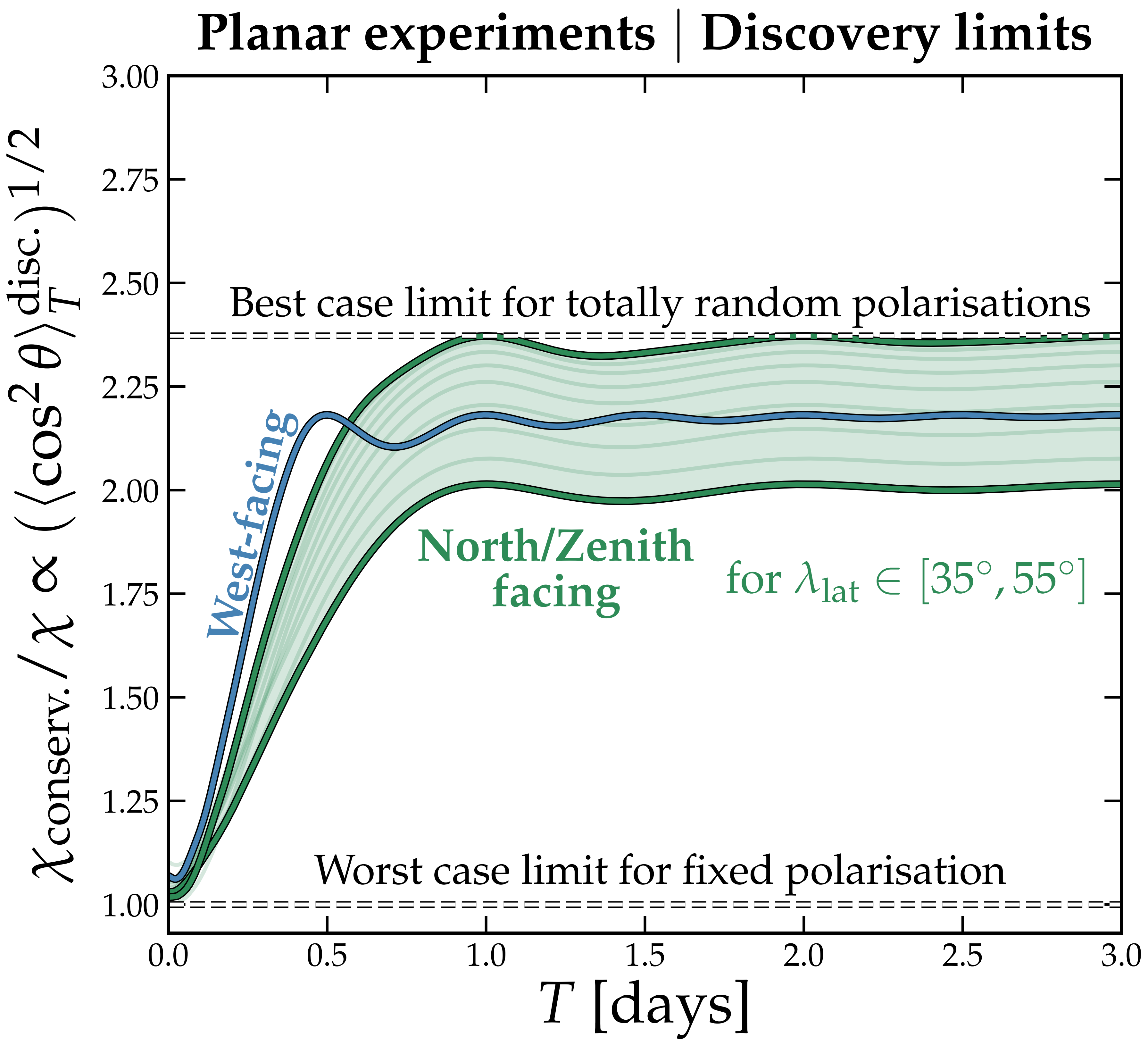
Detector-centric coordinates



Improvement with long measurements

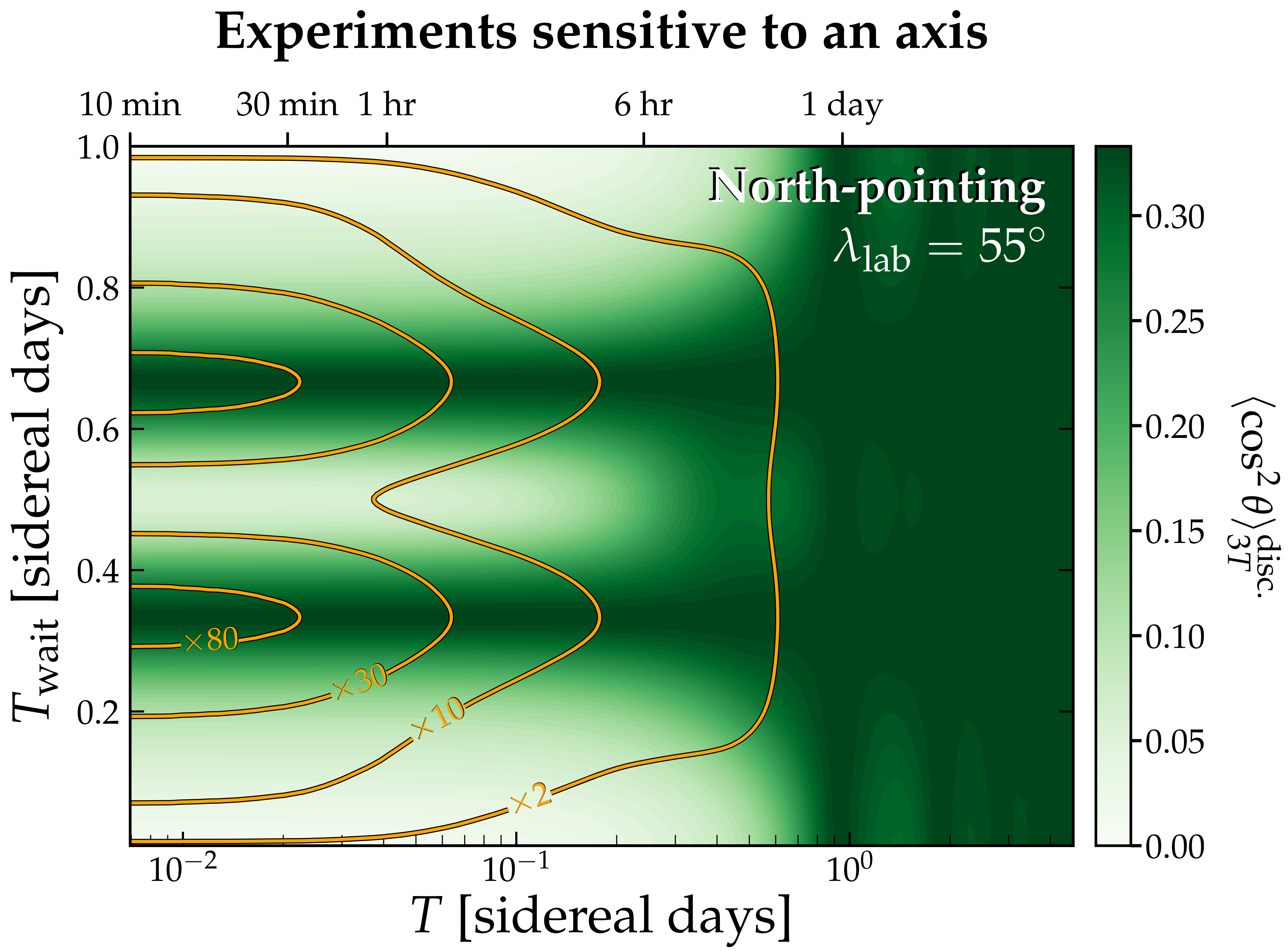
- Up to an order of magnitude improvement on discovery projections

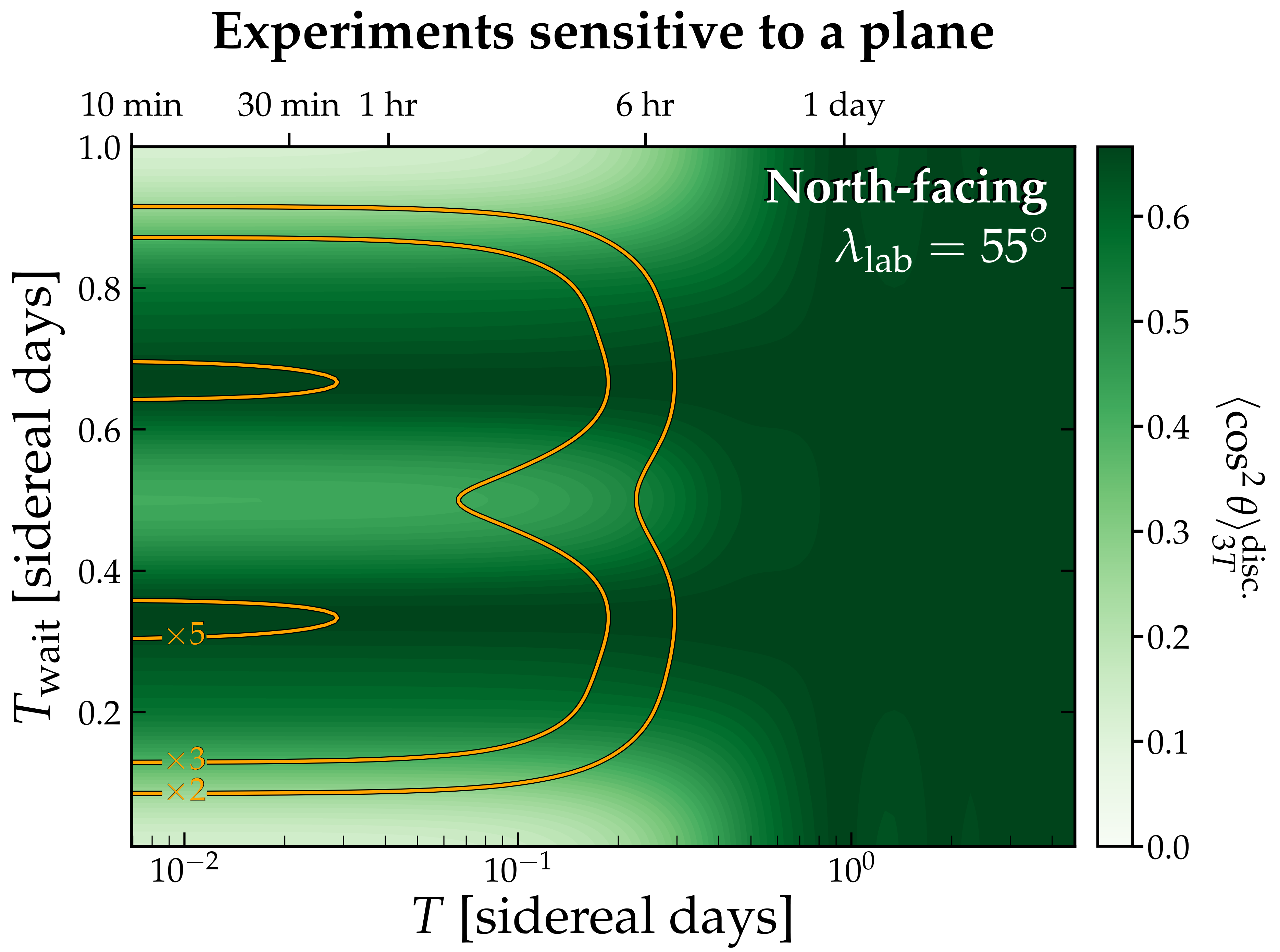




What about for short measurements?

- 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





What about for short measurements?

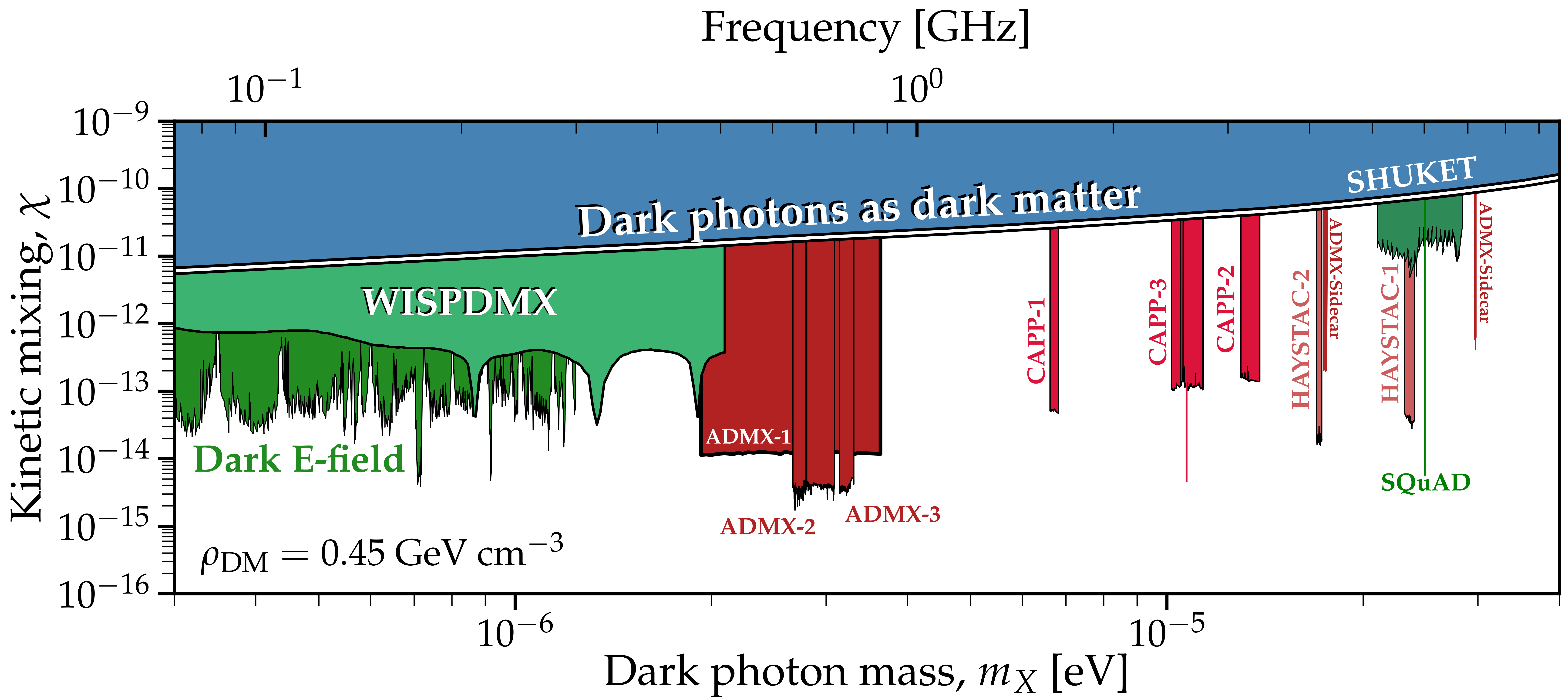
- Order of magnitude improvement on coupling just from three measurements!
- Does not increase overall data taking time
- Also have to be careful of rescans

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

- Always rescan with the same alignment

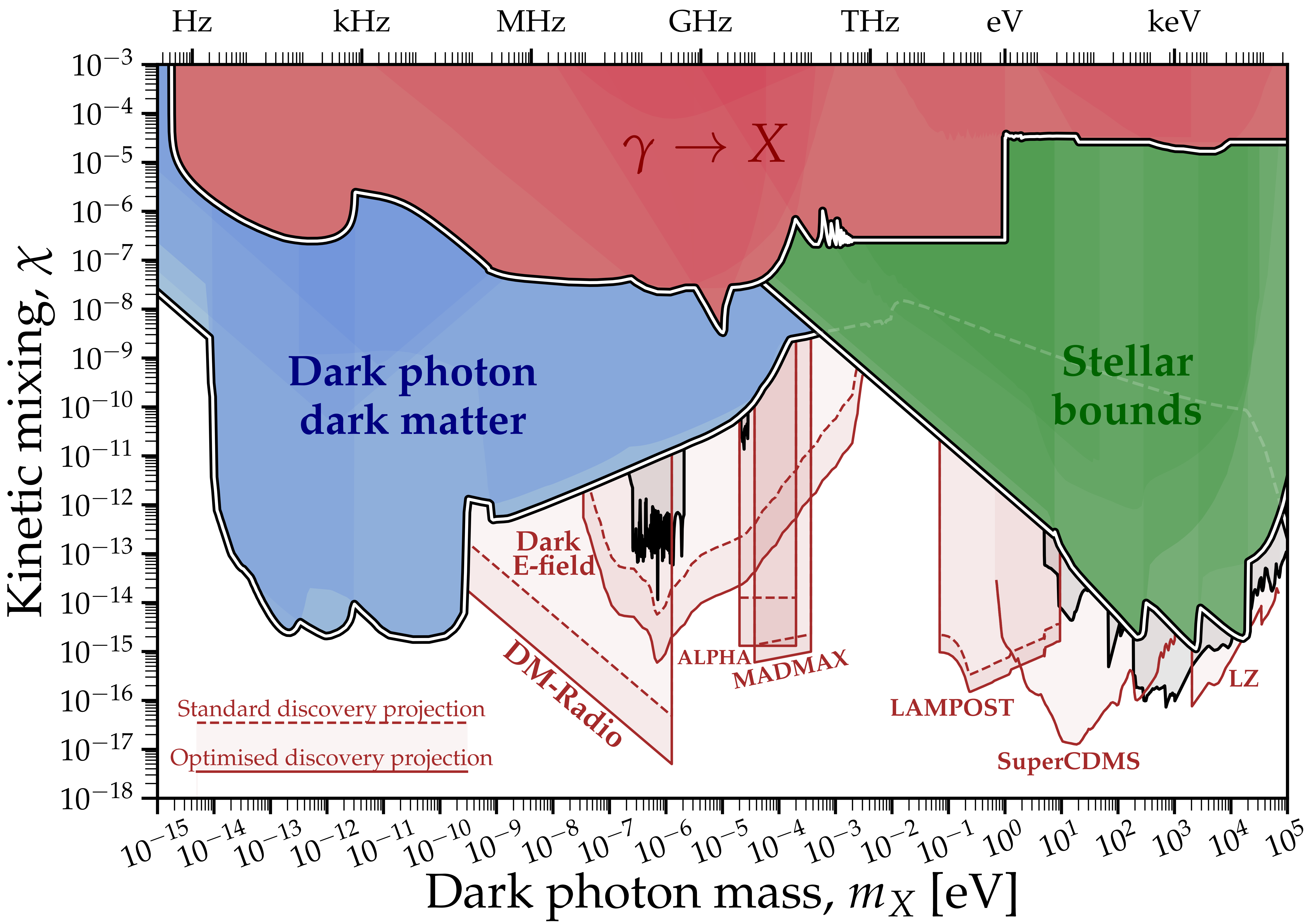
Current HP Limits

- Rescaled for fixed polarisation (conservative case)



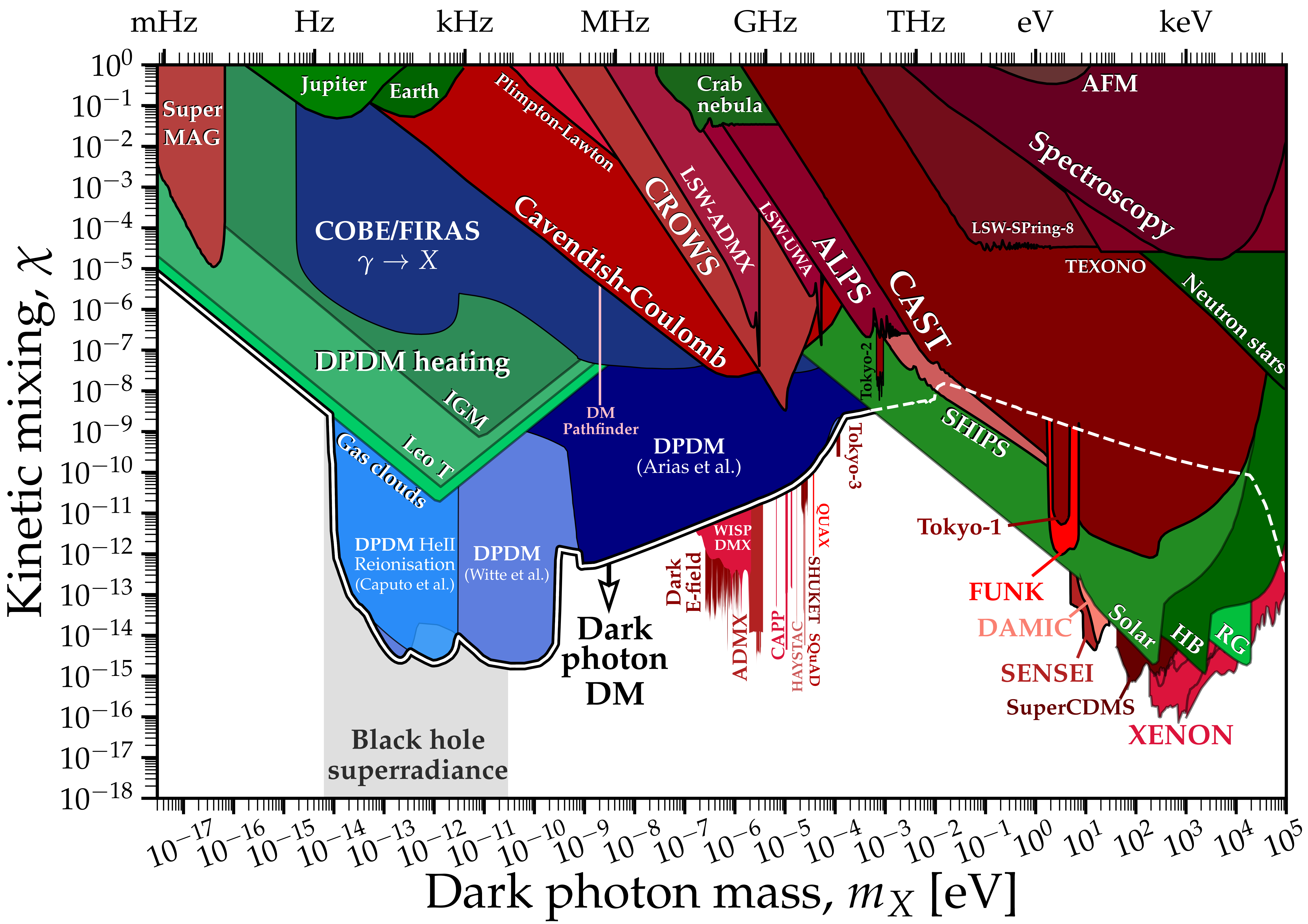
Future experiments

- 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

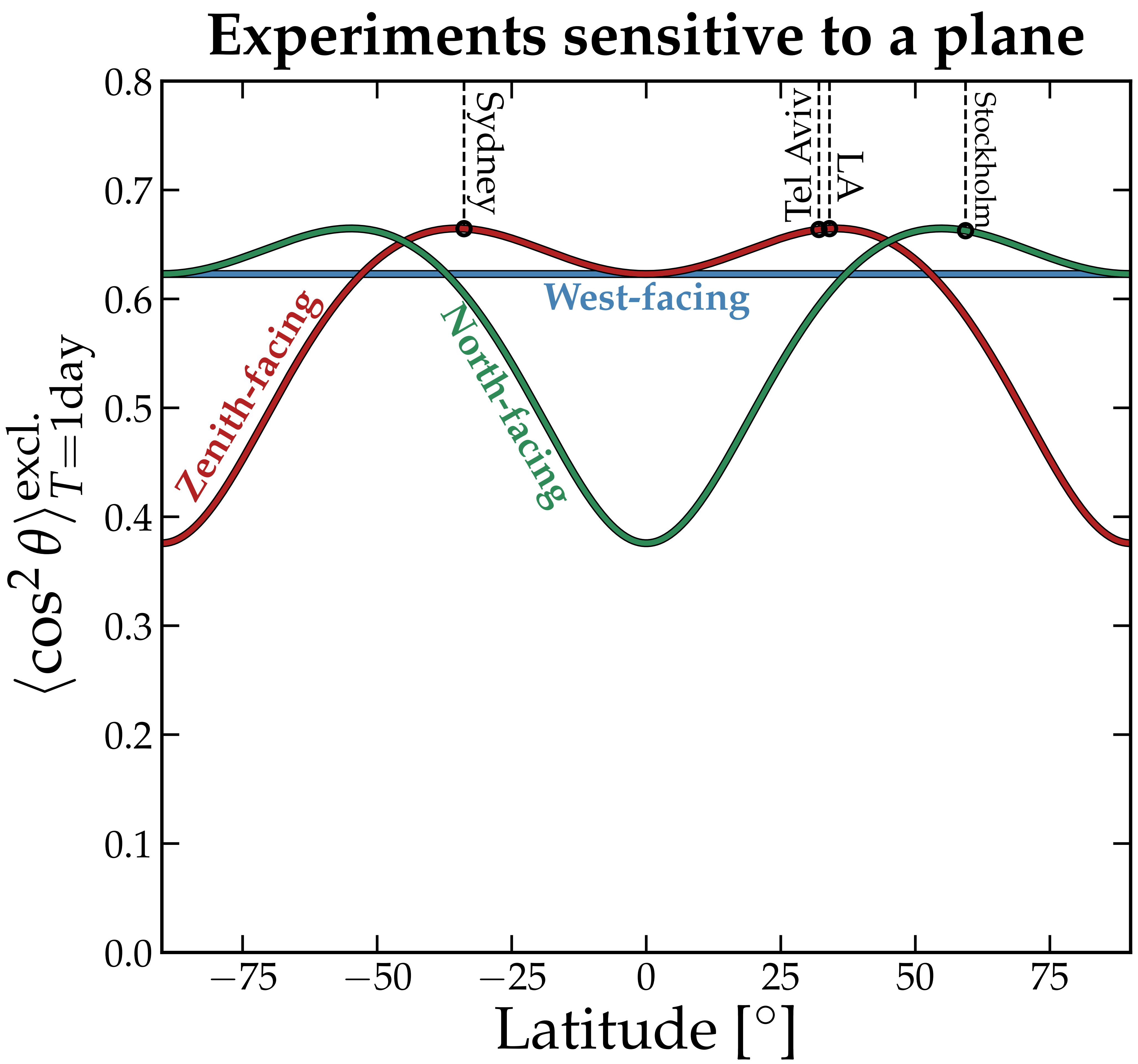


HP Polarisation

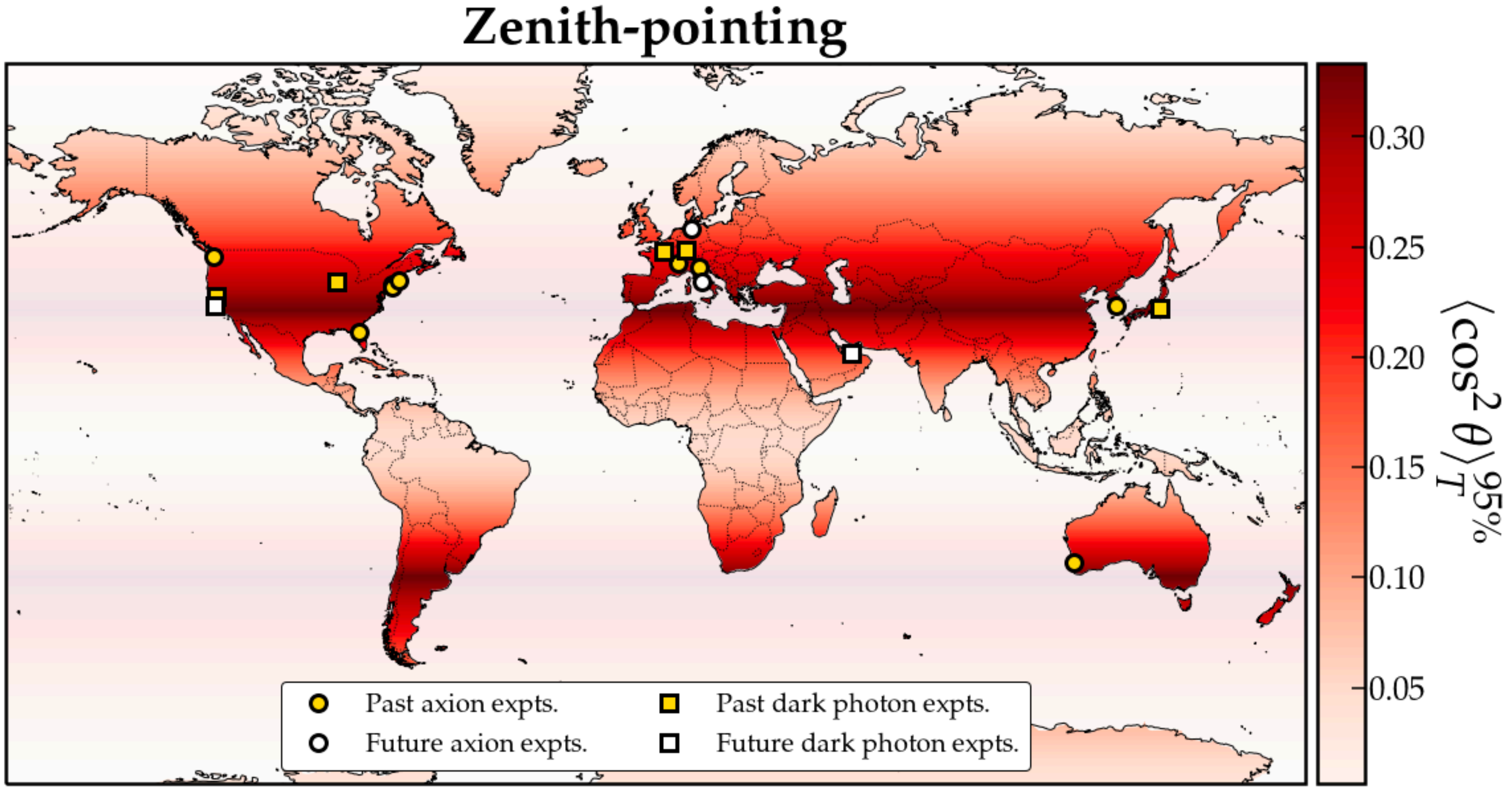
- Need find the distribution of angles over some measurement

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

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

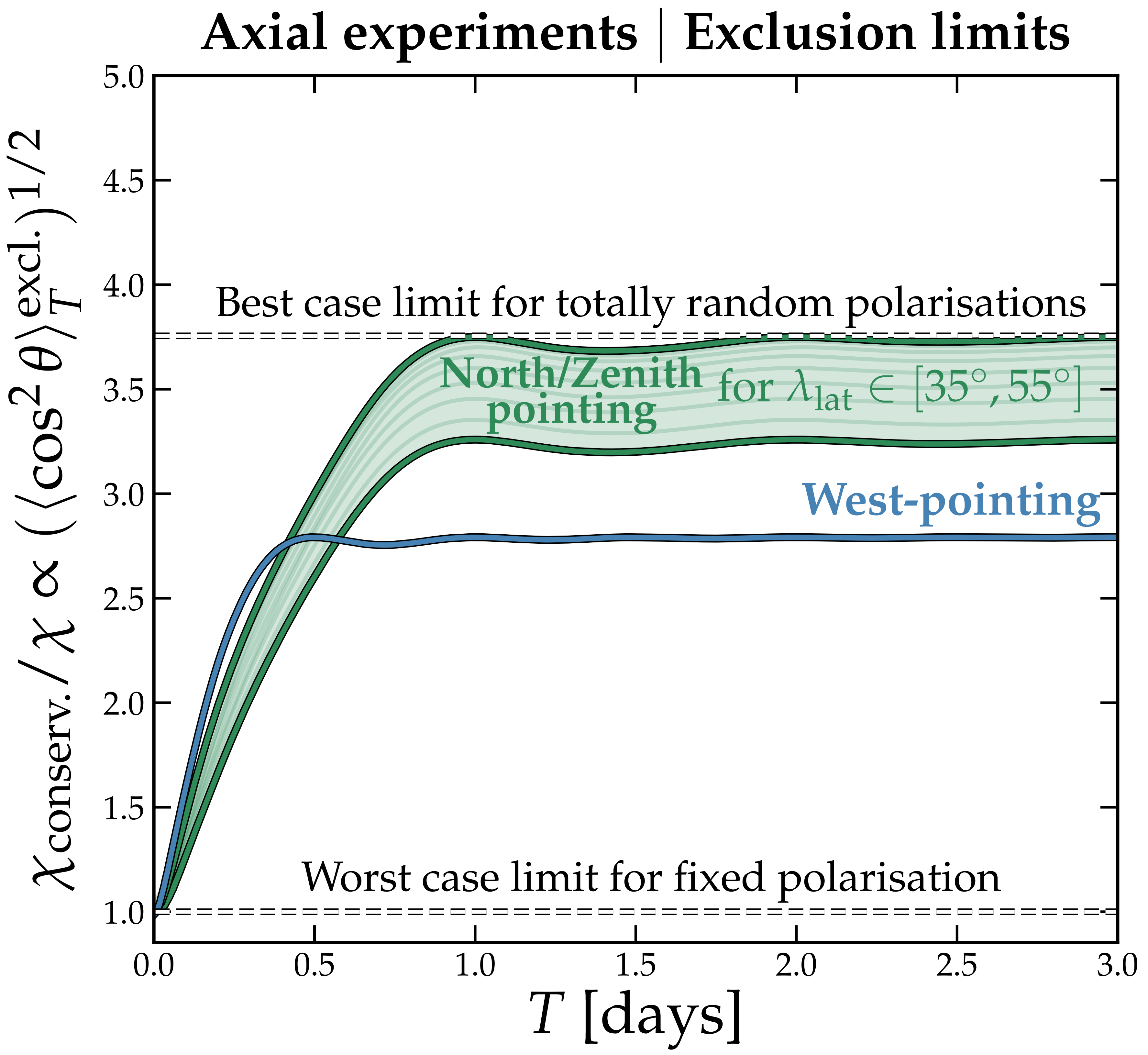


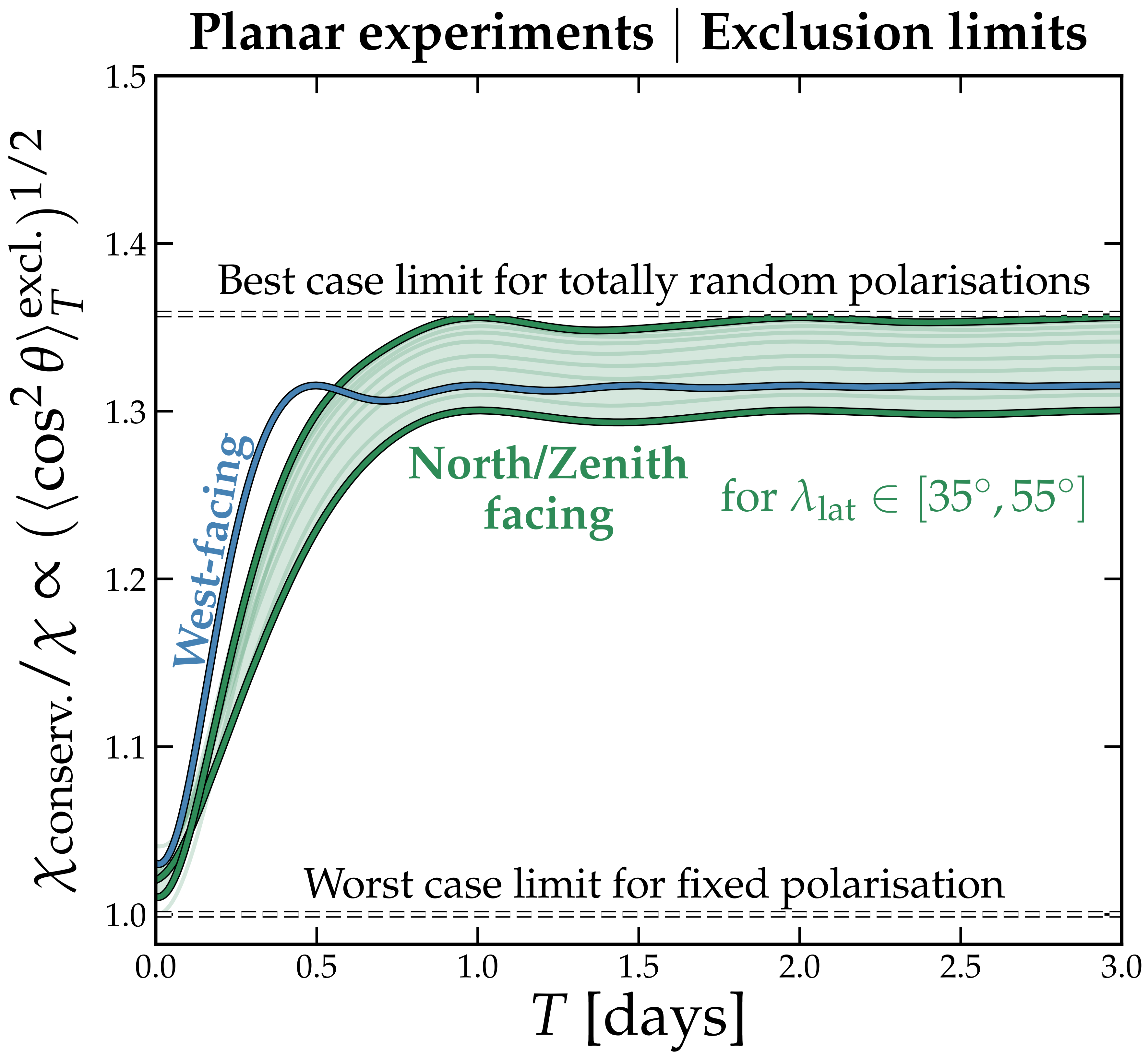
Experiment Locations



Improvement with long measurements

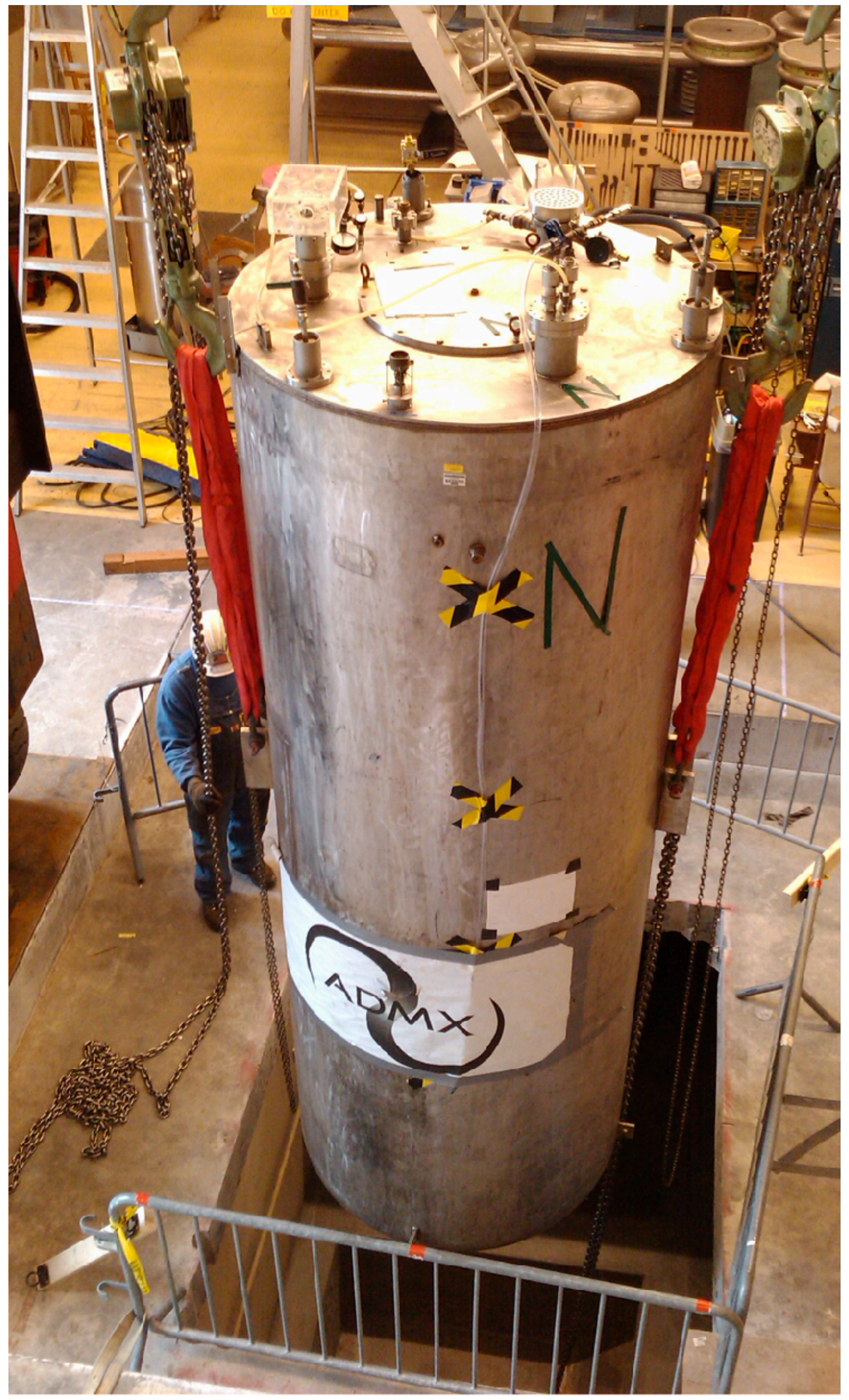
- Up to a a factor of three improvement on exclusion limit





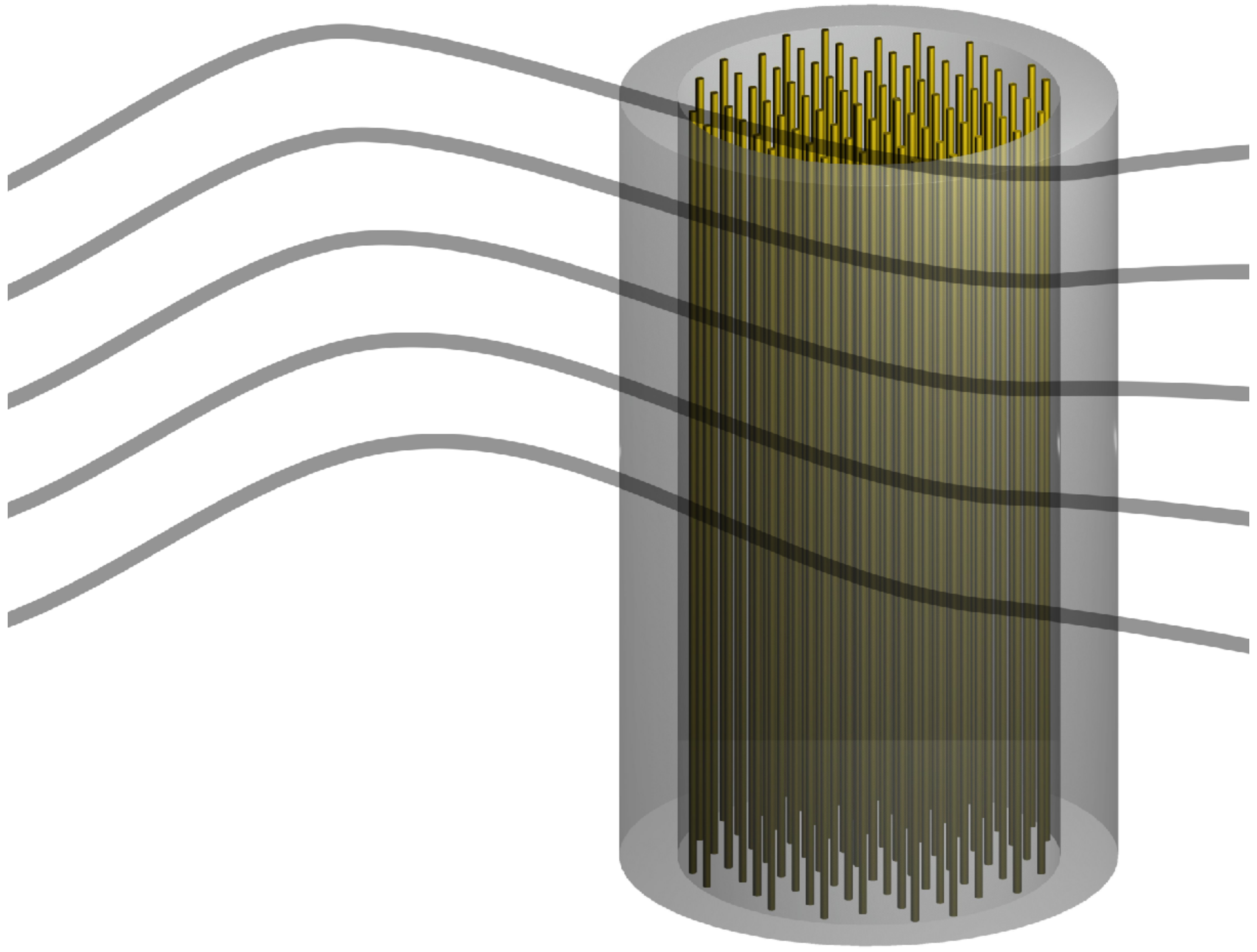
Cavity Haloscopes

- Originally introduced to search for the axion
- Oldest and most established method (proposed by Sikivie)
- Build a cavity matching the Compton wavelength of DM to resonantly break translation invariance
- Requires large volume – hard to do for large axions masses (small wavelengths)
- Examples include ADMX, HAYSTAC, CULTASK, RADES…



Plasma Haloscopes

- Why break translation invariance?
- Just match the photon and DM masses: plasma!
- Strong possibilities using thin wire meta materials (arXiv:1904.11872)
- Not limited by the Compton wavelength!
- Should allow for higher masses to be searched
- Being pursued by ALPHA



arXiv:1904.11872

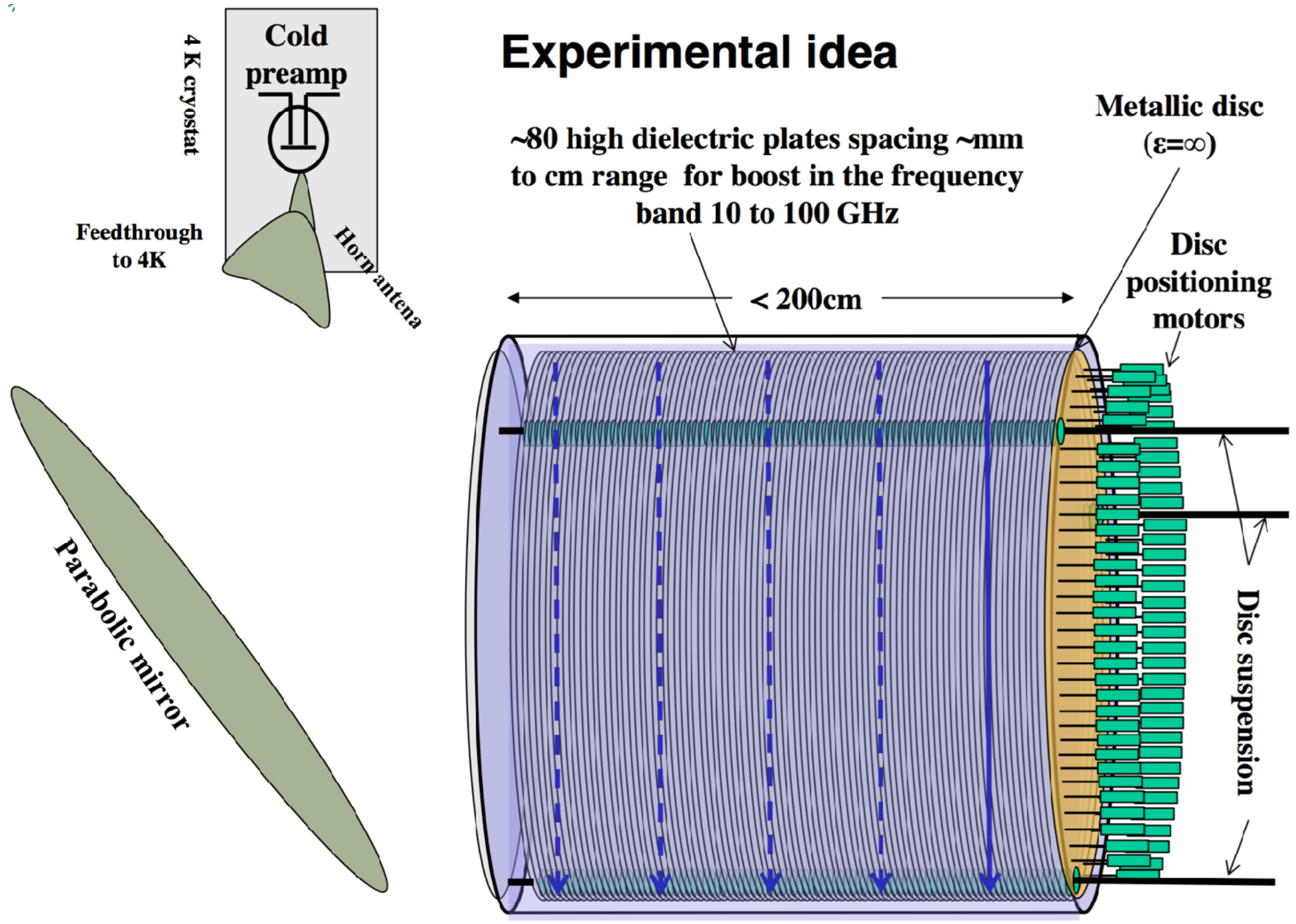
Dish Antenna

- Breaks translation invariance with a mirror (arXiv:1212.2970)
- No resonance!
- Completely broadband response
- Focus a large area onto a detector to increase S/N
- Experiments like FUNK, Tokyo, SHUKET…

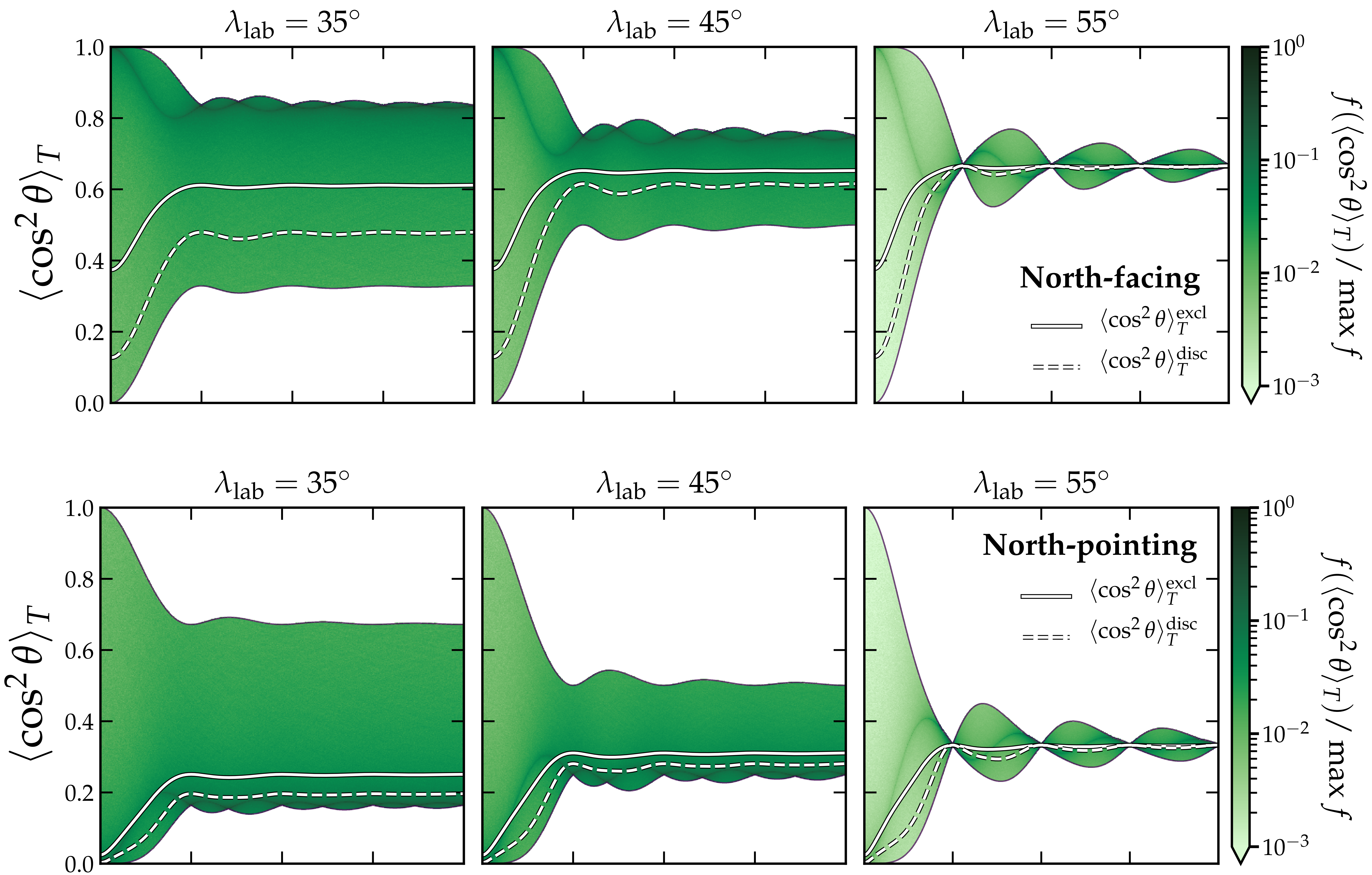
arXiv:2003.13144

Dielectric Haloscopes

- Dish antenna on steroids (arXiv:1611.05865)
- Use many dielectric layers, each creating waves which constructively interfere
- Tune frequencies by controlling disk spacings
- Lots of freedom over frequency response!
- Very large volumes
- Being pursued by MADMAX, LAMPOST and at Abu Dhabi



Polarisation Distributions



LC Circuits

- Rather than measure E, create a circuit that measures B (1310.8545, 1602.01086)
- Can create geometries that generate B (but not E) in the presence of DM
- Can be made broadband or resonant
- Works sub-wavelength: good for low frequencies!
- ABRACADABRA and DM Radio are typical examples