Polarized Dark photon Analysis of GigaBREAD Data

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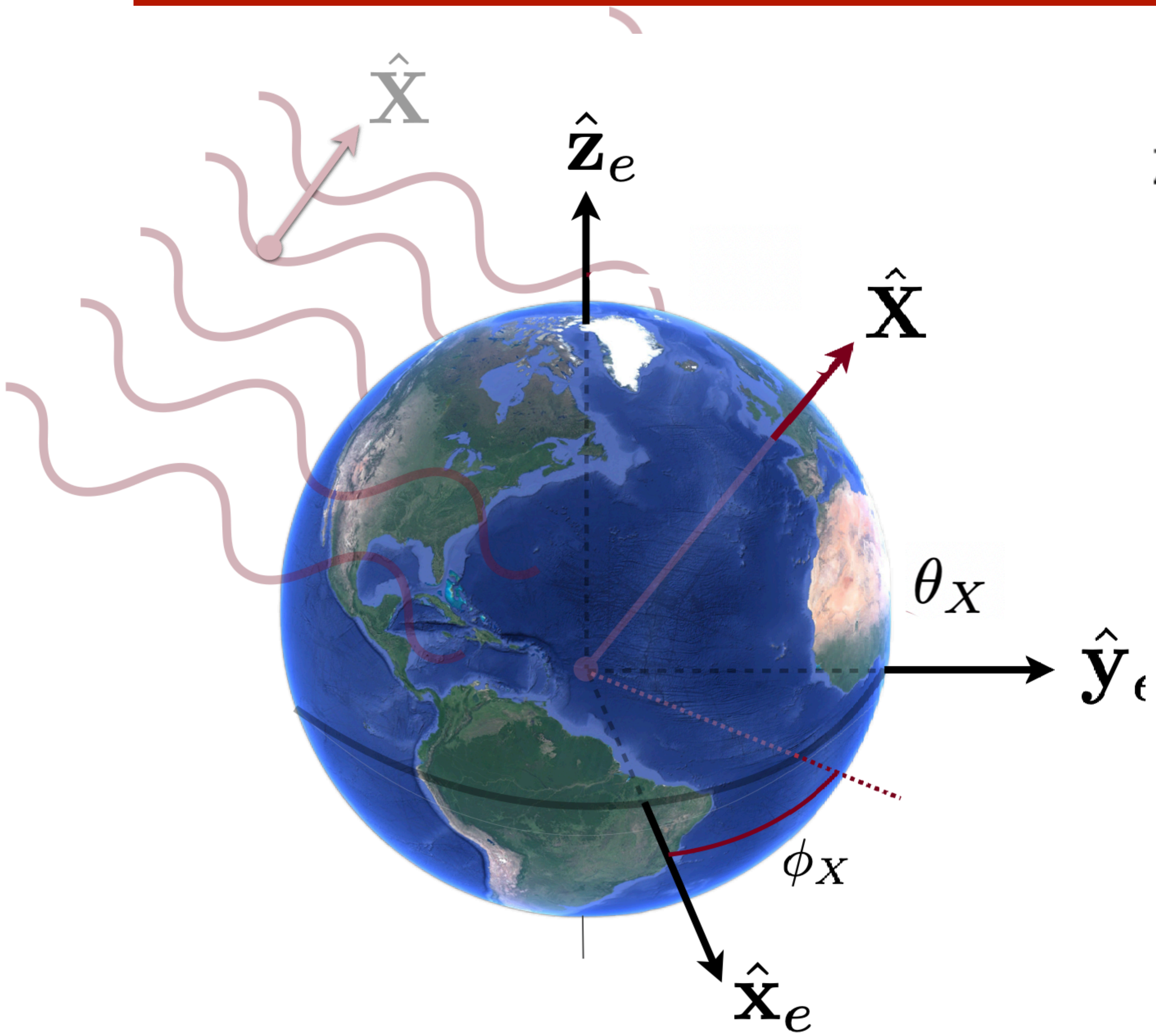
Polarized dark photon signal

- Dark photon are vector bosons with polarization
- Usually experiments assume dark photon are randomly polarized.
- Misalignment mechanism may cause DP has fixed polarization within the cosmological horizon.
- Since we don’t really know what kind of polarization DP have, its important to take a consider of the “fixed polarization scenario”.

Caputo et al., Phys. Rev. D 104, 095029 (2021).

How fix polarization affect DP signal

DP signal power: $P(t) = P_X \cos^2\theta(t)$; where: $\cos^2\theta(t) = \left(\hat{X}\cdot\hat{D}(t)\right)^2$



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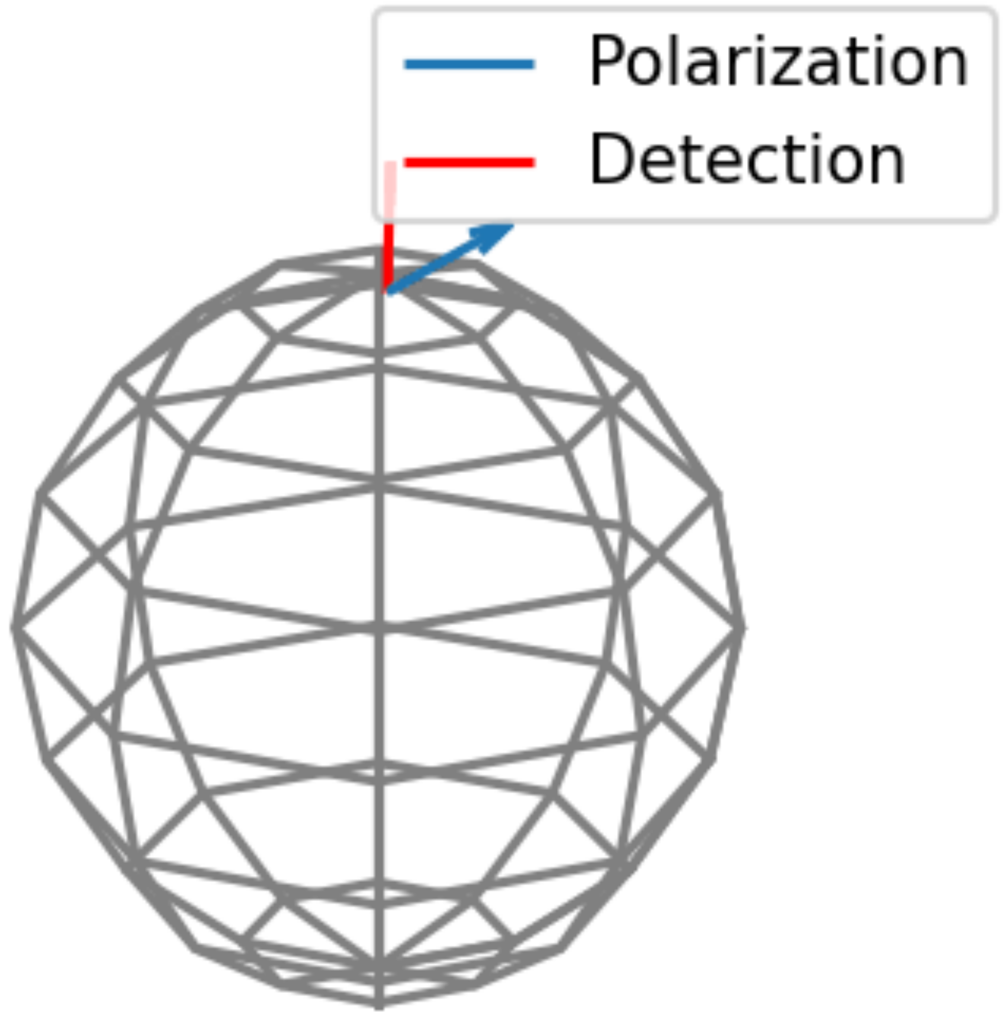
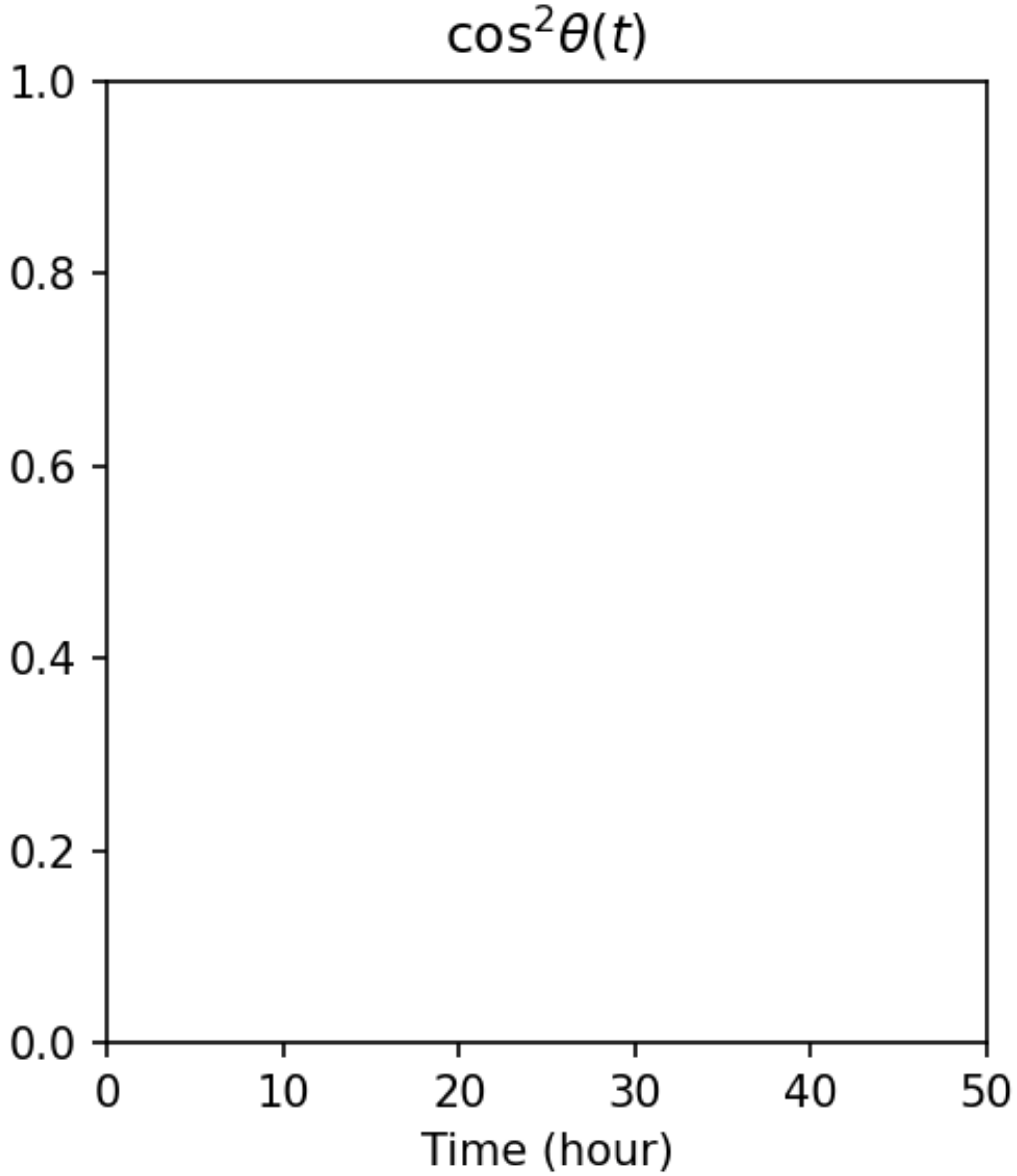




How fix polarization affect DP signal

Fix polarization

$$X = \begin{pmatrix} \cos\theta_X \cos\phi_X \\ \cos\theta_X \sin\phi_X \\ \sin\theta_X \end{pmatrix}$$

Vertical Detection

$$\hat{Z}(t) = \begin{pmatrix} \cos\lambda \cos\omega_\oplus t \\ \cos\lambda \sin\omega_\oplus t \\ \sin\lambda \end{pmatrix}$$

$$P = P_0 |\hat{X} \cdot \hat{D}(t)|^2$$

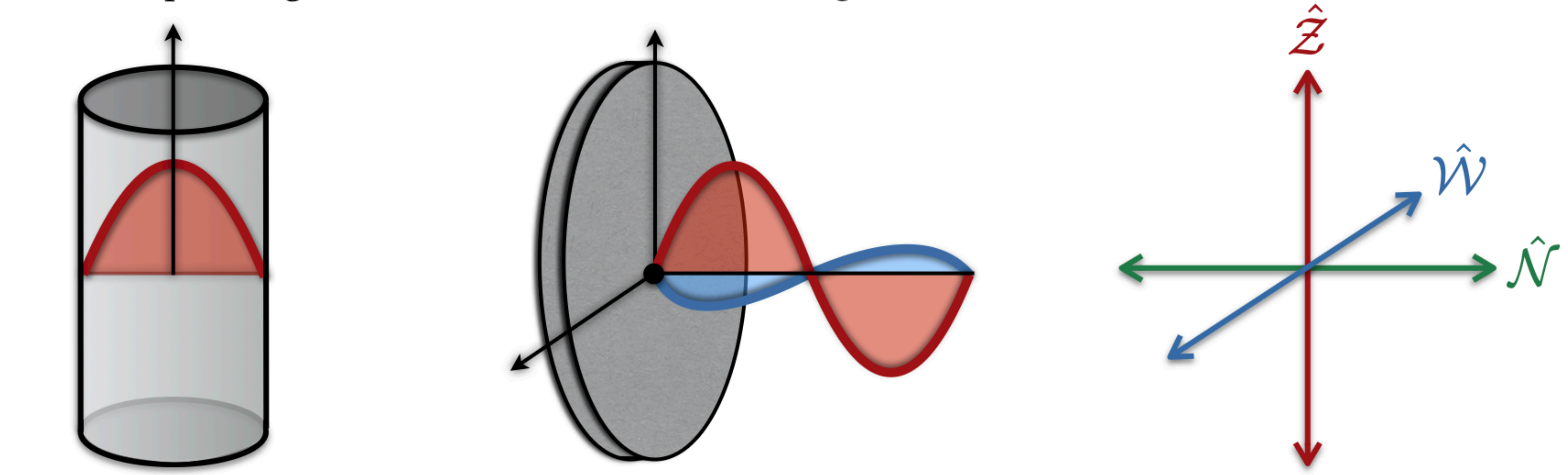
Horizontal Detection

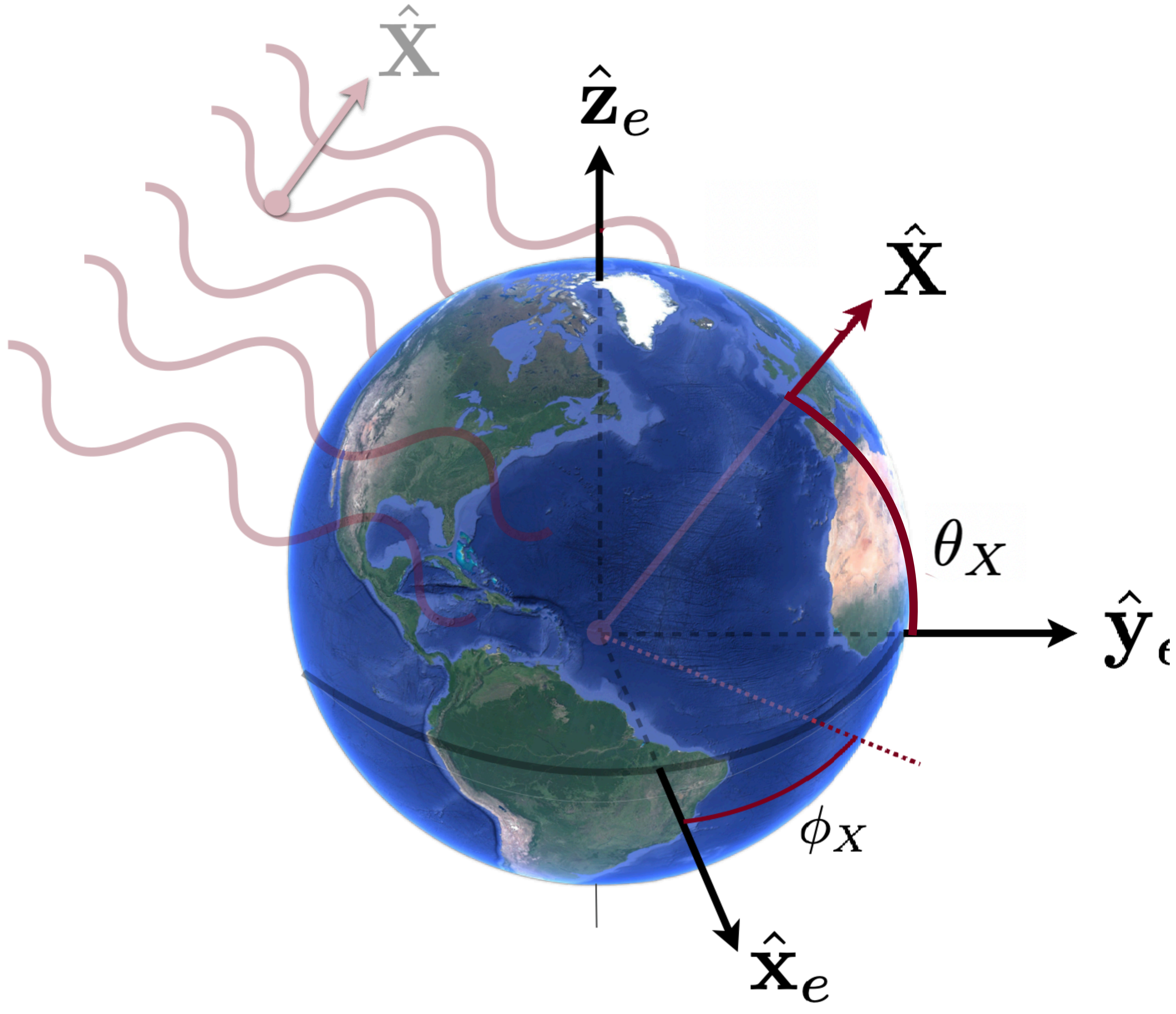
$$\mathbf{V}(\phi, t) = \begin{pmatrix} \cos\phi_d \sin\lambda \cos\omega_\oplus t + \sin\phi_d \sin\omega_\oplus t \\ \cos\phi_d \sin\lambda \sin\omega_\oplus t - \sin\phi_d \cos\omega_\oplus t \\ -\cos\phi_d \cos\lambda \end{pmatrix}$$

Axial experiment (Zenith-pointing)

Planar experiment (North-facing)

Possible DP Polarisations





Caputo et al., Phys. Rev. D 104, 095029 (2021).

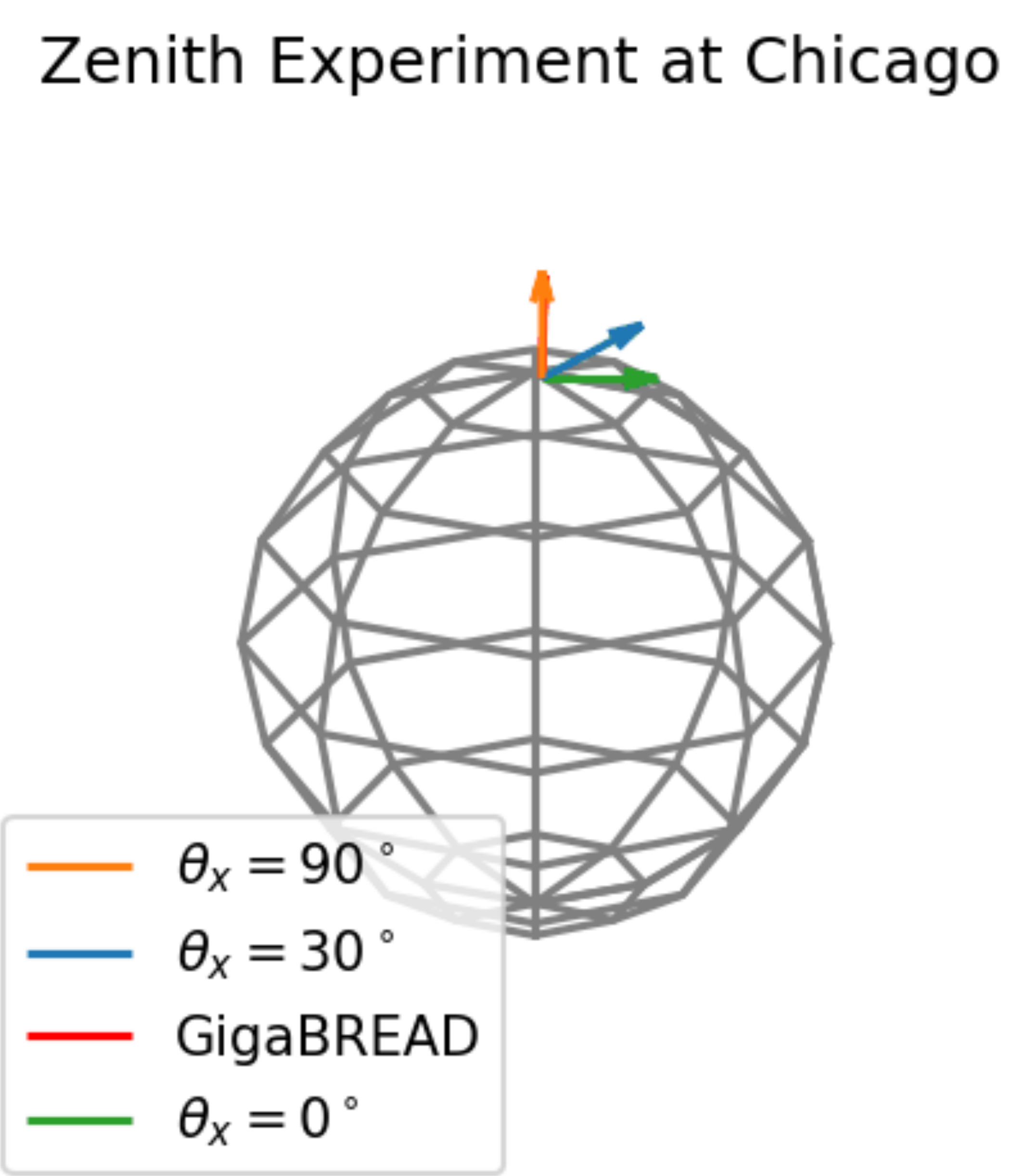
How fix polarization affect DP signal

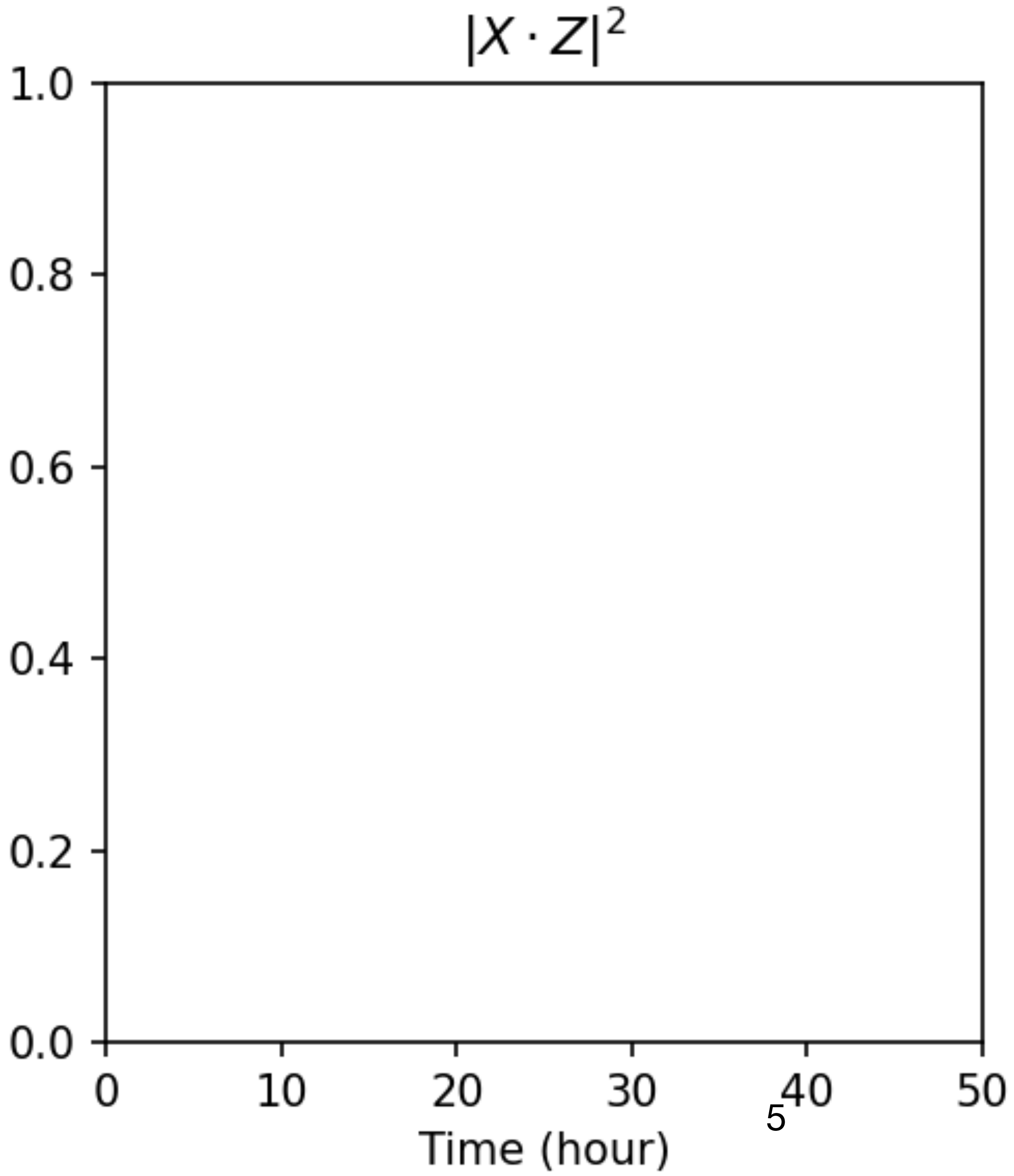
$$|X \cdot Z|^2 = \frac{1}{2}\cos^2\lambda\cos^2\theta_X + sin^2\lambda\sin^2\theta_X$$ Constant

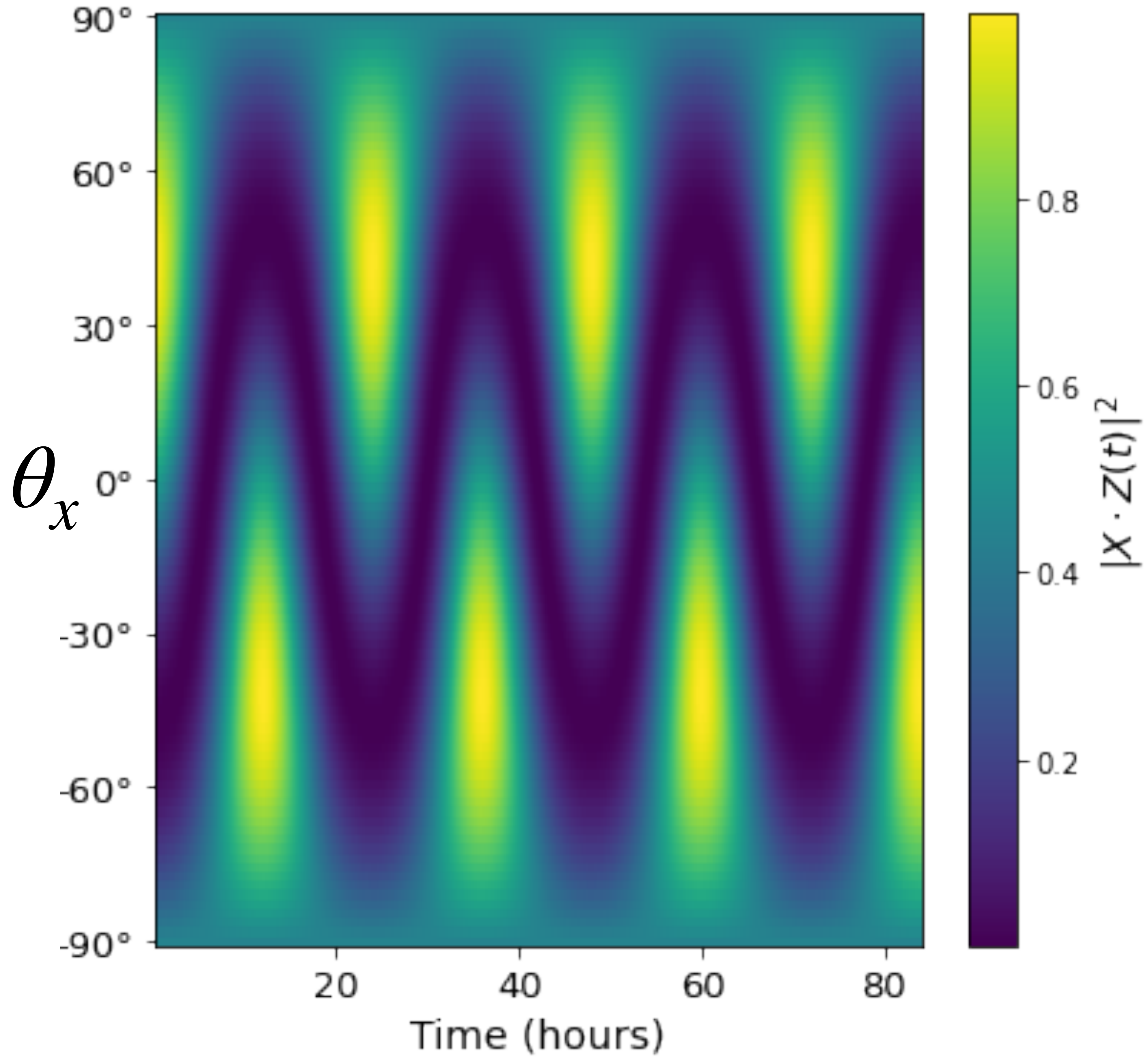
Daily Modulation: $+\ 2\cos\lambda\sin\lambda\cos\theta_X\sin\theta_X\cos(\omega t - \phi_X)$

2*Daily Modulation: $+\ \frac{1}{2}\cos^2\lambda\cos^2\theta_X\cos(2\omega t - 2\phi_X)$

Chicago: (42° N, 88° W)







Polarization-matched Likelihood

k: spectrum index (each spectrum taken at time t_k).
j: frequency bin index,

$y_{k,j}$: measured Signal

$\sigma_{k,j}$: std of measuredSignal

$\mathcal{S}_{k,j}$: Expected DP signal

$$\mathscr{L} = exp[-\frac{1}{2}\sum_{k,j}\left(\frac{y_{k,j} - \mathcal{S}_{k,j}}{\sigma_{k,j}}\right)^2]$$

TABLE I. Data–set summary used in the analysis.

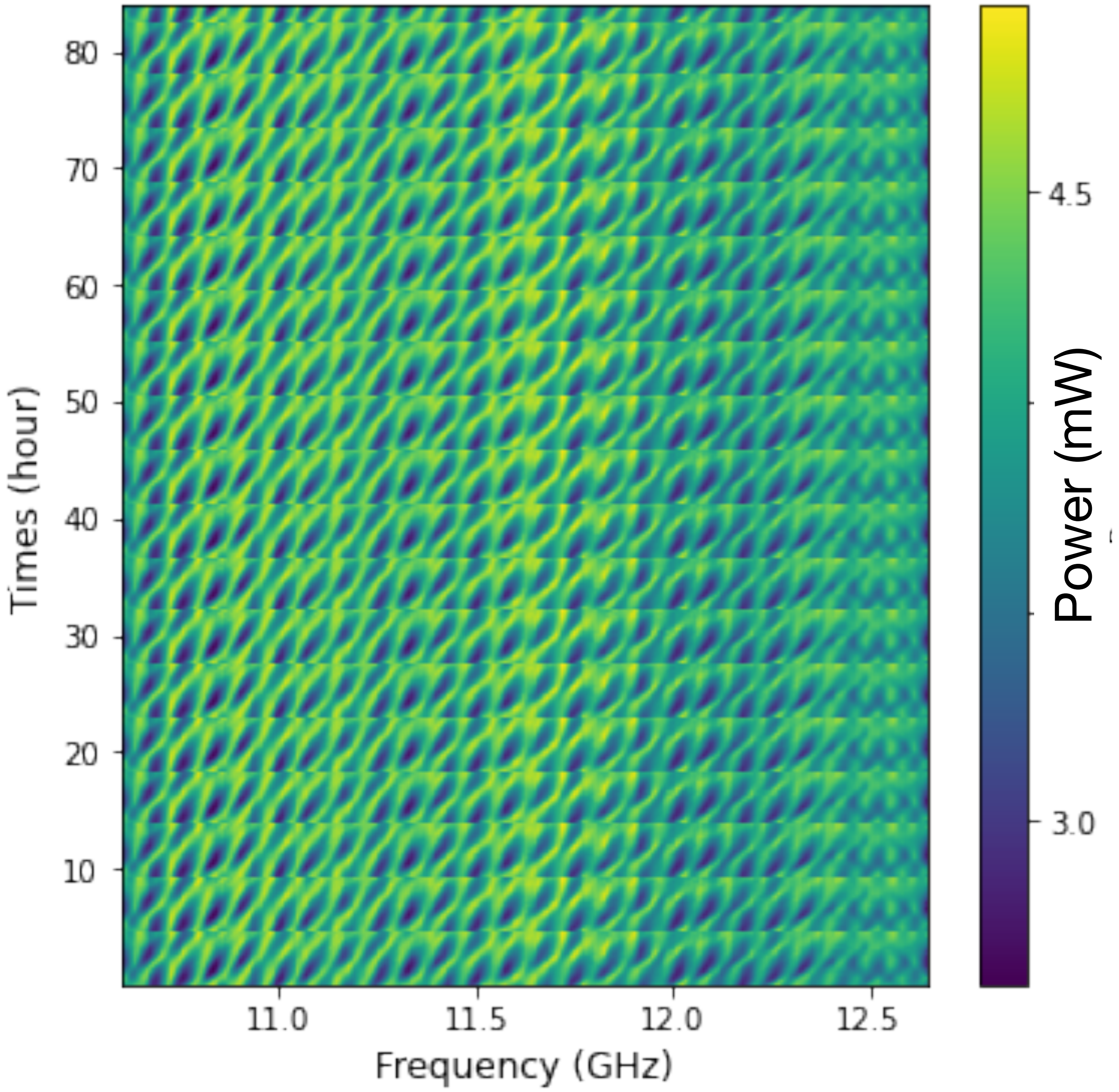
Run	Latitude	Longitude	Geometry	ϕ_d	Band (GHz)	$\Delta f_{\rm bin}$
UChicago	41.79°N	87.60°W	Zenith	—	10.7–12.5	7.8 kHz
ANL	41.71°N	87.98°W	Planar	−55°	10.7–12.5	7.8 kHz

$PSA_{k,j}$: Power spectrum

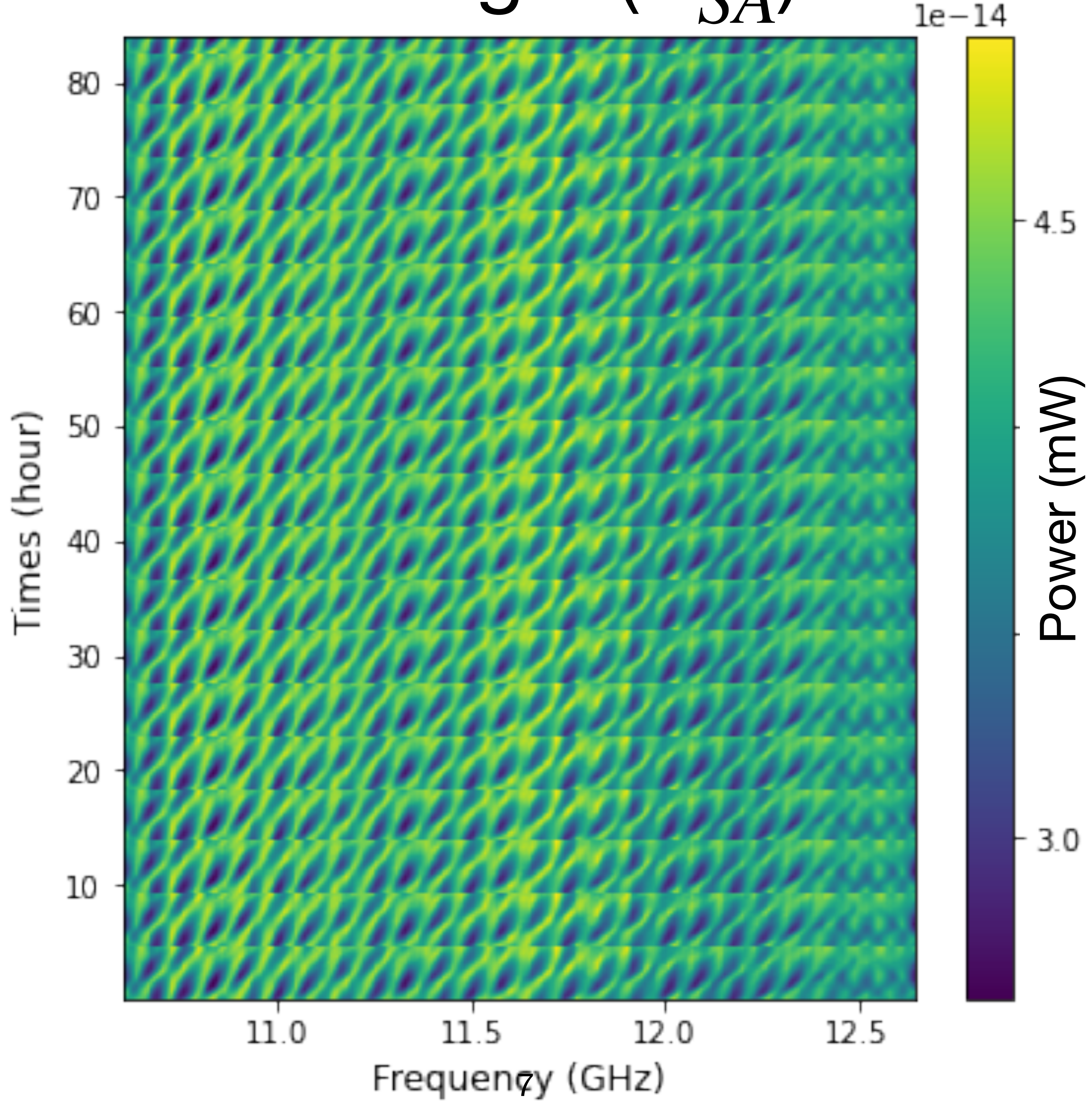
$\sigma_{k,j}$: savgol$_j(P_{SA})/\sqrt{N}$

$y_{k,j}$: P_{SA} − savgol$_j(P_{SA})$

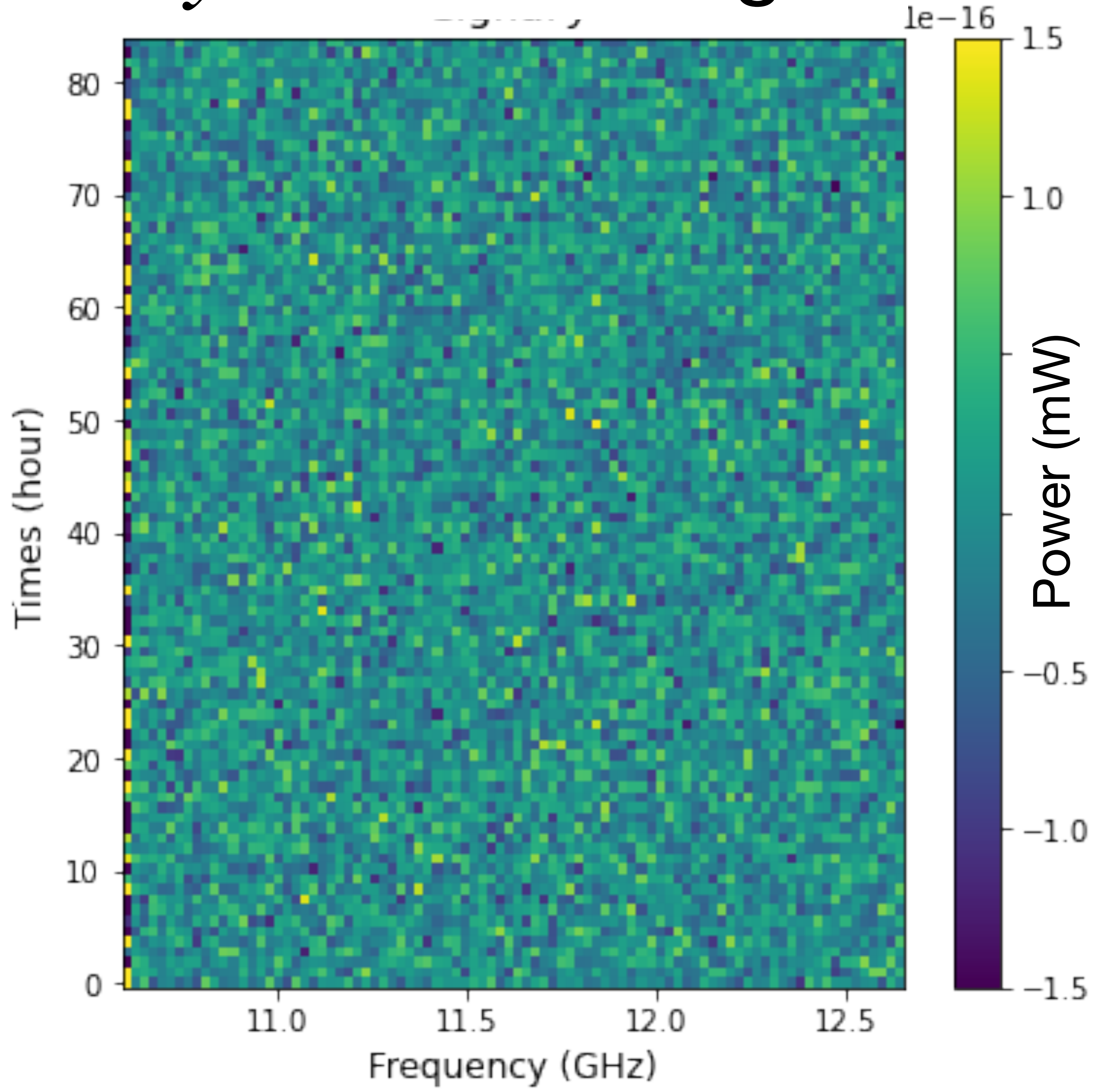
P_{SA}: Power Spec



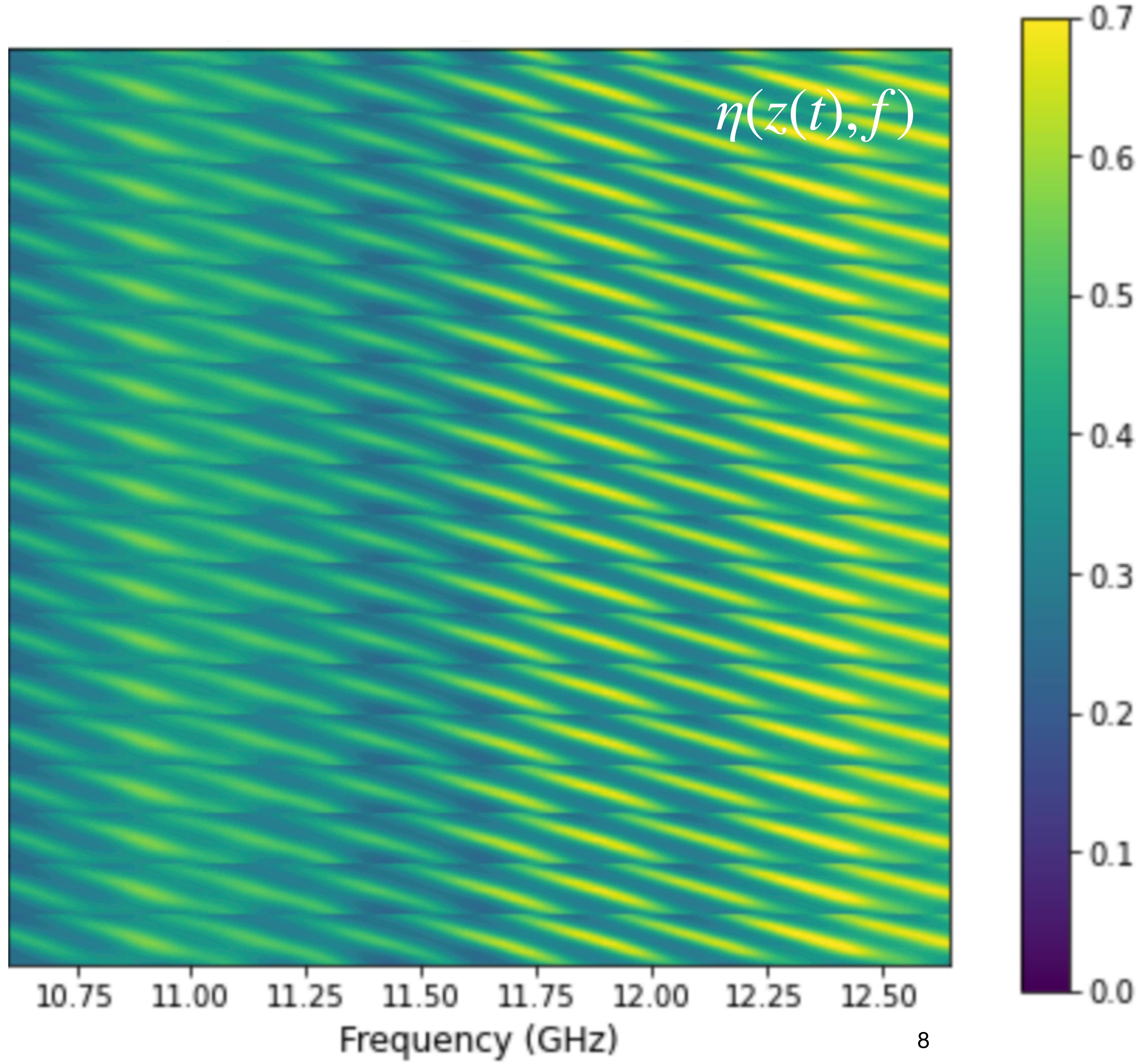
Savgol (P_{SA})

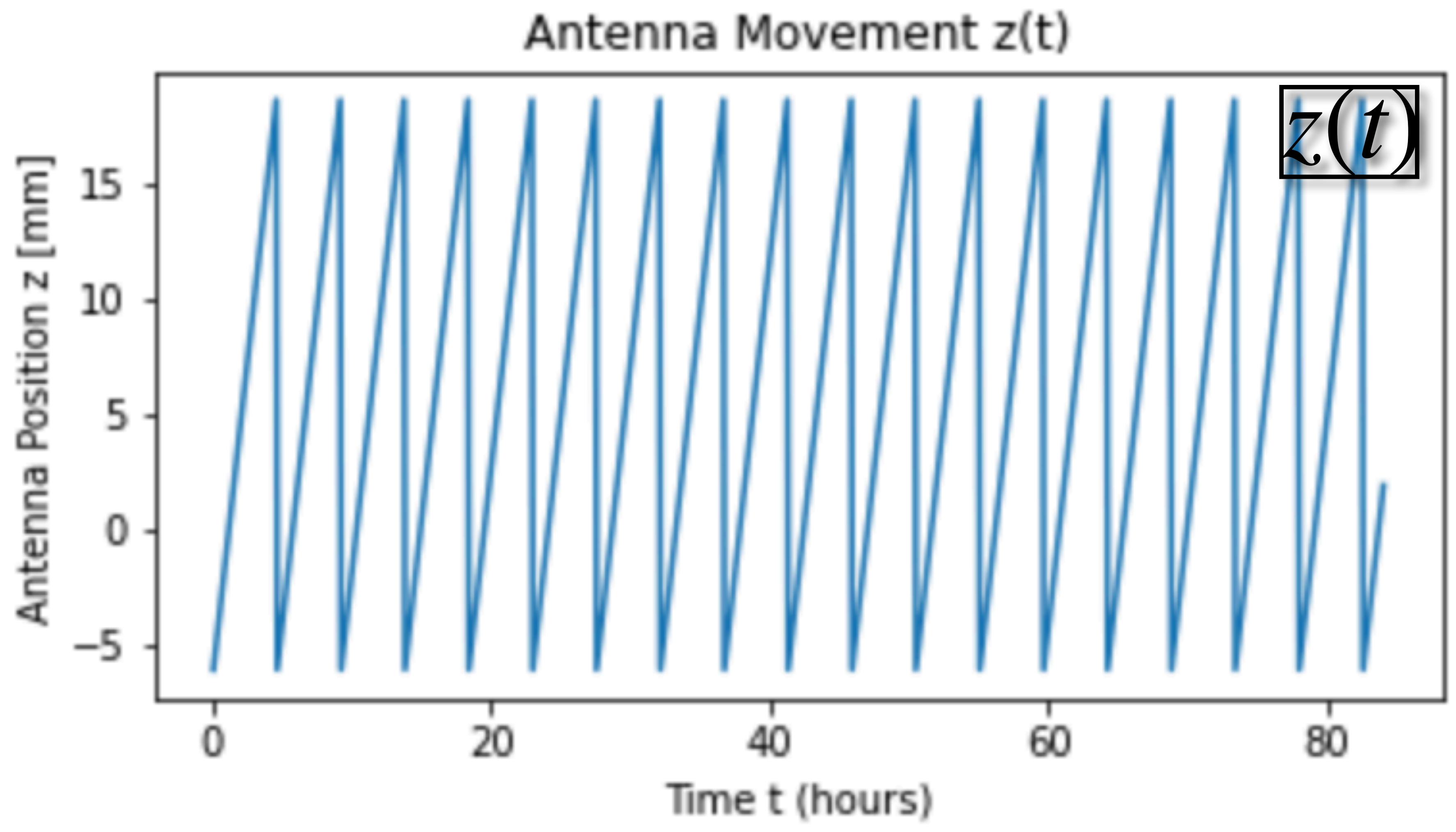


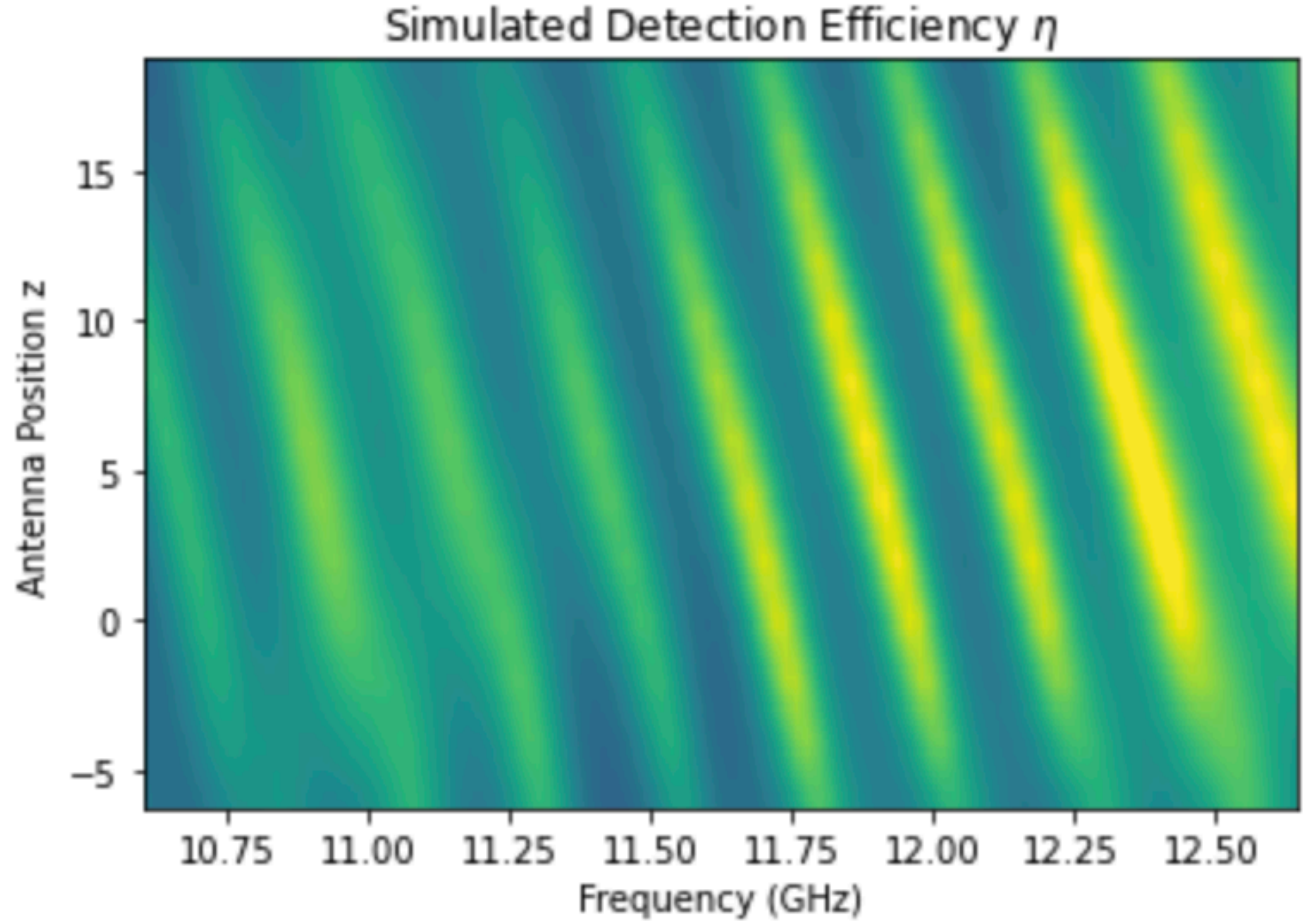
y:Measured signal



DP signal Modulation overtime







Cross Correlated

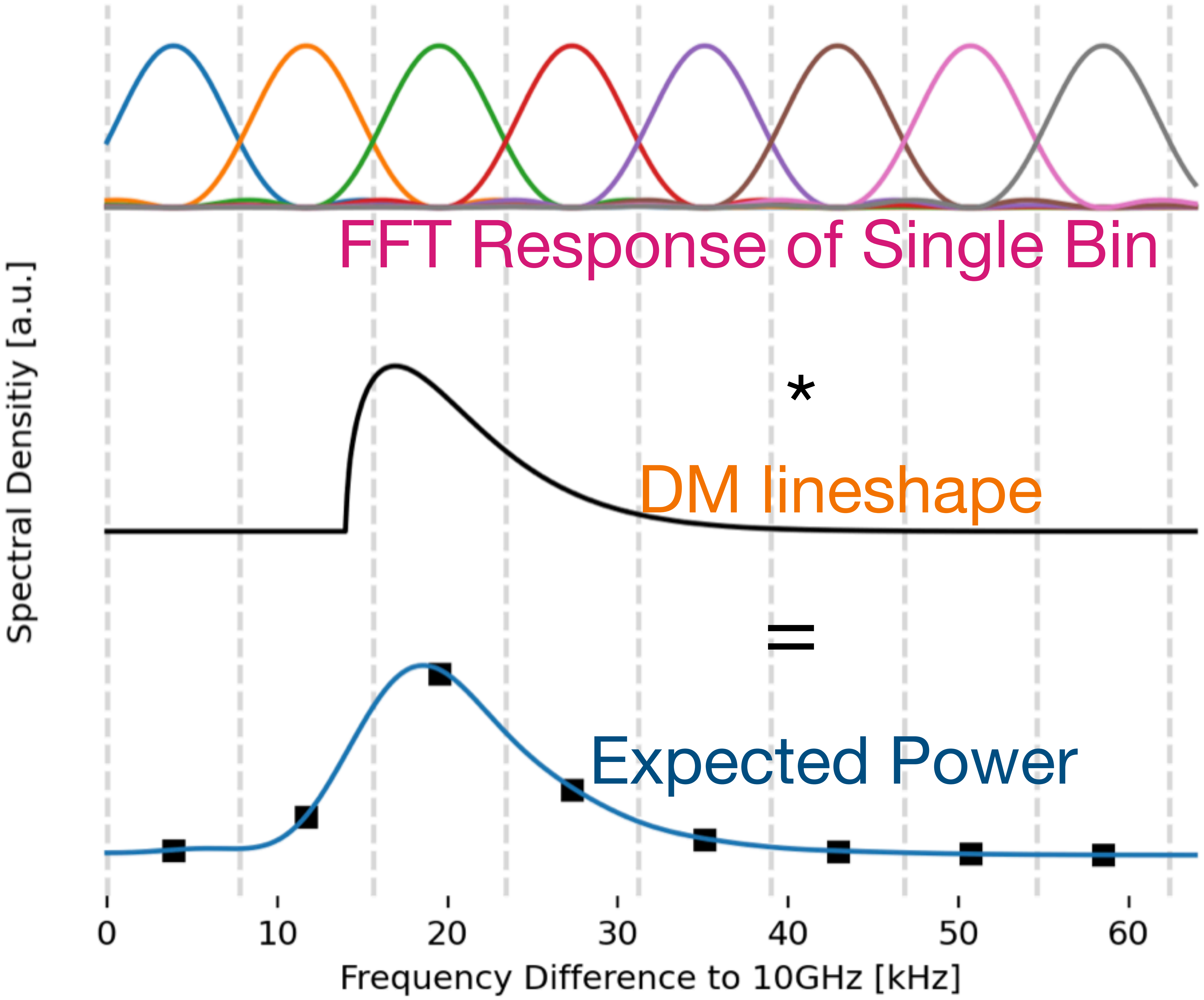


Figure From Stefan's talk

$$B_j(f) = \left| \text{sinc}\left(\frac{f - f_j}{\Delta f_{bin}}\right) \right|^2,$$

$$S(f; f') \propto \sinh\left[3r\sqrt{\frac{2|f - f'|}{f'\beta_2}}\right] \exp\left[-\frac{3(f - f')}{f'\beta_2} - \frac{3r^2}{2}\right],$$

$$O_j(f') = \int S(f; f')\, B_j(f)\, df\,.$$

$$\mathscr{C}_j(f') = \frac{O_j(f')}{\sum_{j'} O_{j'}(f')}$$

Likelihood Equation

k: spectrum index (each spectrum taken at time t_k).
j: frequency bin index,

$$\mathscr{L} = exp[-\frac{1}{2}\sum_{k,j}\left(\frac{y_{k,j} - \mathcal{S}_{k,j}}{\sigma_{k,j}}\right)^2]$$

$y_{k,j}$: measured Signal

$\sigma_{k,j}$: std of measuredSignal

$\mathcal{S}_{k,j}$: Expected DP signal

Probability of observing an DP signal with amplitude P, polarization orientation (θ_x, ϕ_x) at trial frequency f' can be described by $\mathscr{L}(D\,|\,P, \theta, \phi, f')$:

$$\log \mathscr{L}(D\,|\,f', \theta_x, \phi_x, P) = -\frac{1}{2}\sum_{k,j}\left(\frac{y_{kj} - P\,\eta_{kj}\,\mathscr{C}_j(f')\,\cos^2\theta(\theta_X, \phi_X, t_k)}{\sigma_{kj}}\right)^2$$

- f': **1M+** steps
- θ_x: **21** steps
- ϕ_x: **21** steps
- P: **501** steps
- k: **25451** terms
- j: **6** terms

$j \in [j_0 - 1, j_0 + 4]$

$\mathcal{S}_{k,j}(f, P_0, \theta, \phi)$ would need to store data for an array with dimensions **1M×501×21×21x25451x6**

In double precision, this array would require **250PB+** of memory

We need a way to simplify this calculation

Harmonic factorization

$$\log \mathscr{L} = -\frac{1}{2}\sum_{k,j}\frac{y_{kj}^2}{\sigma_{kj}^2} + P\sum_j \mathscr{C}_j \sum_k \frac{y_{kj}\eta_{kj}\cos^2\theta(\theta_X,\phi_X,t_k)}{\sigma_{kj}^2} - \frac{1}{2}P^2\sum_j \mathscr{C}_j^2 \sum_k \frac{\eta_{kj}^2\cos^4\theta(\theta_X,\phi_X,t_k)}{\sigma_{kj}^2}$$

Term0 Term1 Term2

$$\log \mathscr{L}(f',\theta_x,\phi_x,P) = \text{Const} + P \times \text{Term1}(f',\theta_x,\phi_x) - \frac{1}{2}P^2 \times \text{Term2}(f',\theta_x,\phi_x)$$

$$\text{STD} = \frac{1}{\sqrt{\text{Term2}}}$$

$$\text{P0} = \frac{\text{Term1}}{\text{Term2}}$$

$$\text{Sig} = \frac{\text{Term1}}{\sqrt{\text{Term2}}}$$

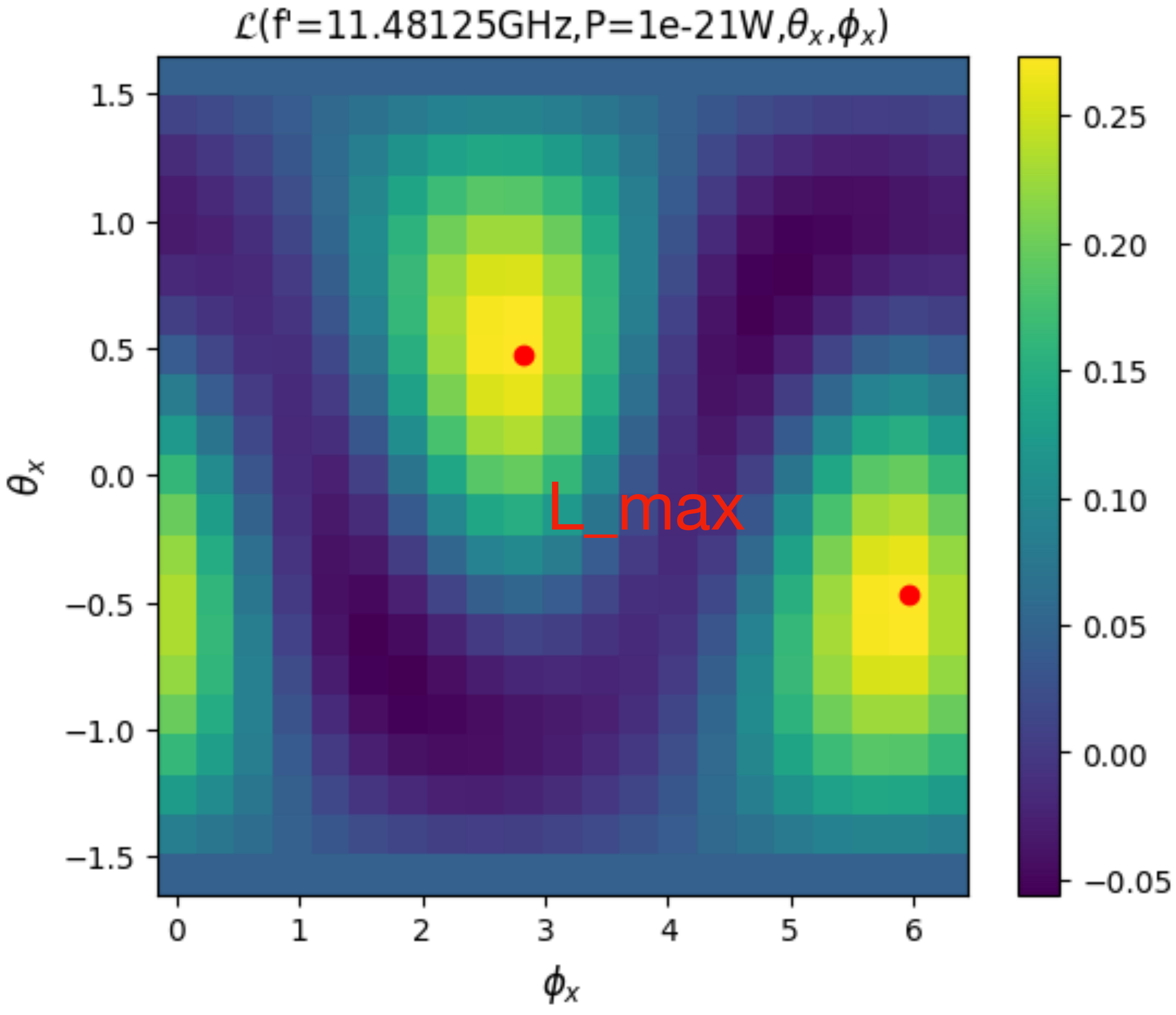
$$C_{n,2}^{(j)} = \sum_k \frac{y_{kj}\eta_{kj}}{\sigma_{kj}^2}\cos(n\omega_\oplus t_k)$$

$$S_{n,2}^{(j)} = \sum_k \frac{y_{kj}\eta_{kj}}{\sigma_{kj}^2}\sin(n\omega_\oplus t_k)$$

$$C_{n,4}^{(j)} = \sum_k \frac{\eta_{kj}^2}{\sigma_{kj}^2}\cos(n\omega_\oplus t_k)$$

$$S_{n,4}^{(j)} = \sum_k \frac{\eta_{kj}^2}{\sigma_{kj}^2}\sin(n\omega_\oplus t_k)$$

Likelihood Framework



For unknown polarization angle (θ_x, ϕ_x), How could we deal with nuisance parameter to find the $L(D|f, P)$?

$$L_{\text{Bayes}}(D \mid f, P) = \int d\theta\, \pi(\theta) \prod_{n_{\text{run}}} \int d\phi\ L_{n_{\text{run}}}(D \mid f, \theta, \phi, P)\,.$$

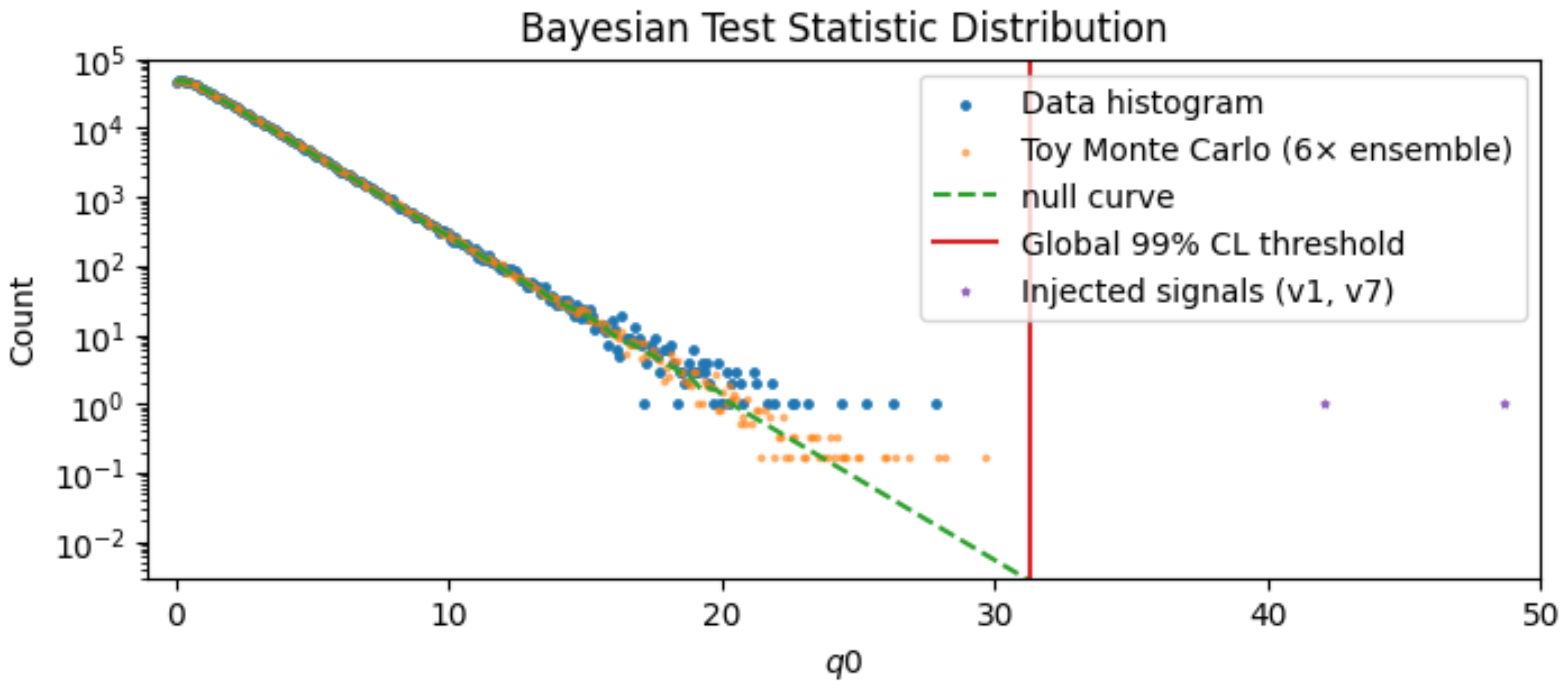
$$L_{\text{Freq}}(D \mid f, P) = \max_{\theta} \prod_{n_{run}} \max_{\phi} L_{n_{run}}(D \mid f, \theta, \phi, P)\,.$$

Absolute time stamps in GigaBREAD2023 were not recorded

Did we see Dark photon?

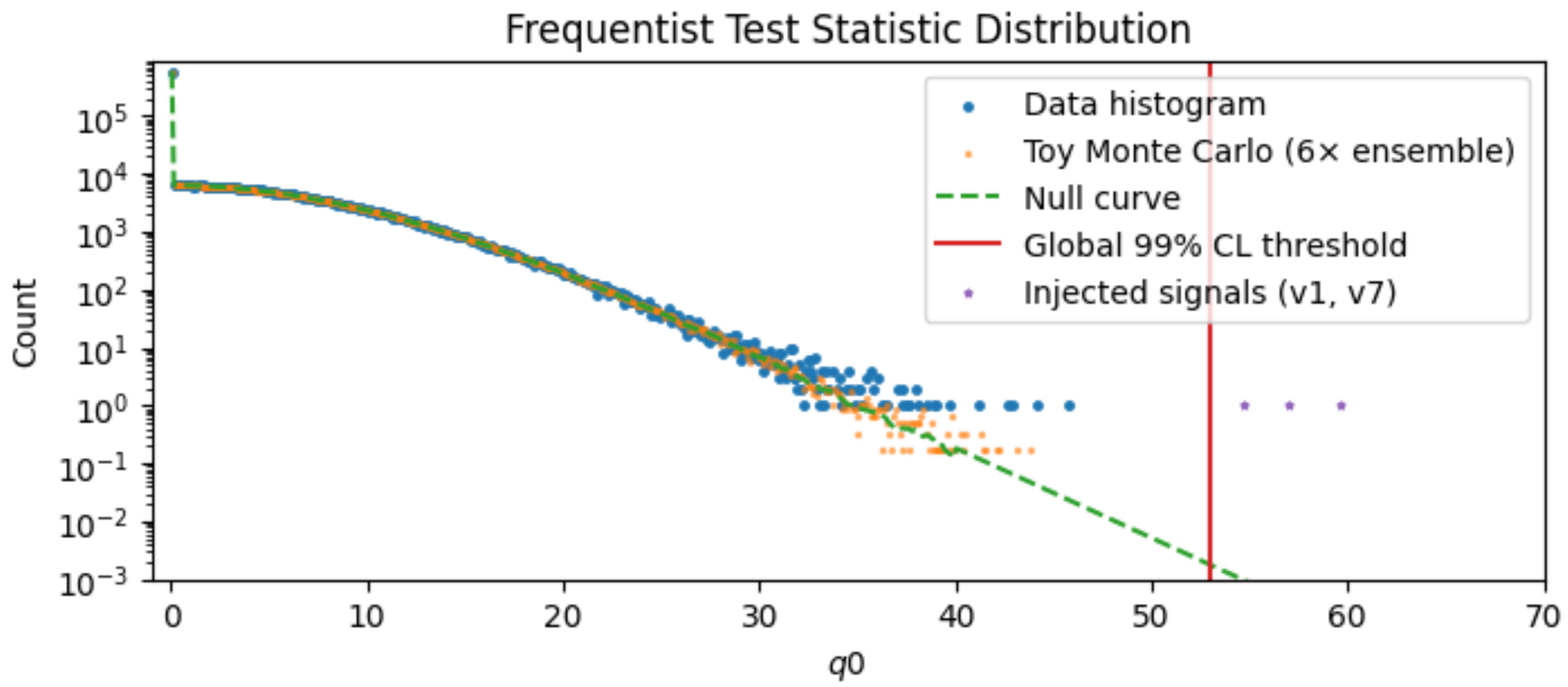
Bayesian Test Statistic

$$q_0 = -2\ln \frac{\int_{P_{\rm conv}\le 0} \mathscr{L}(P_{\rm conv})\, dP_{\rm conv}}{\int_{P_{\rm conv}\in\mathbb{R}} \mathscr{L}(P_{\rm conv})\, dP_{\rm conv}}.$$

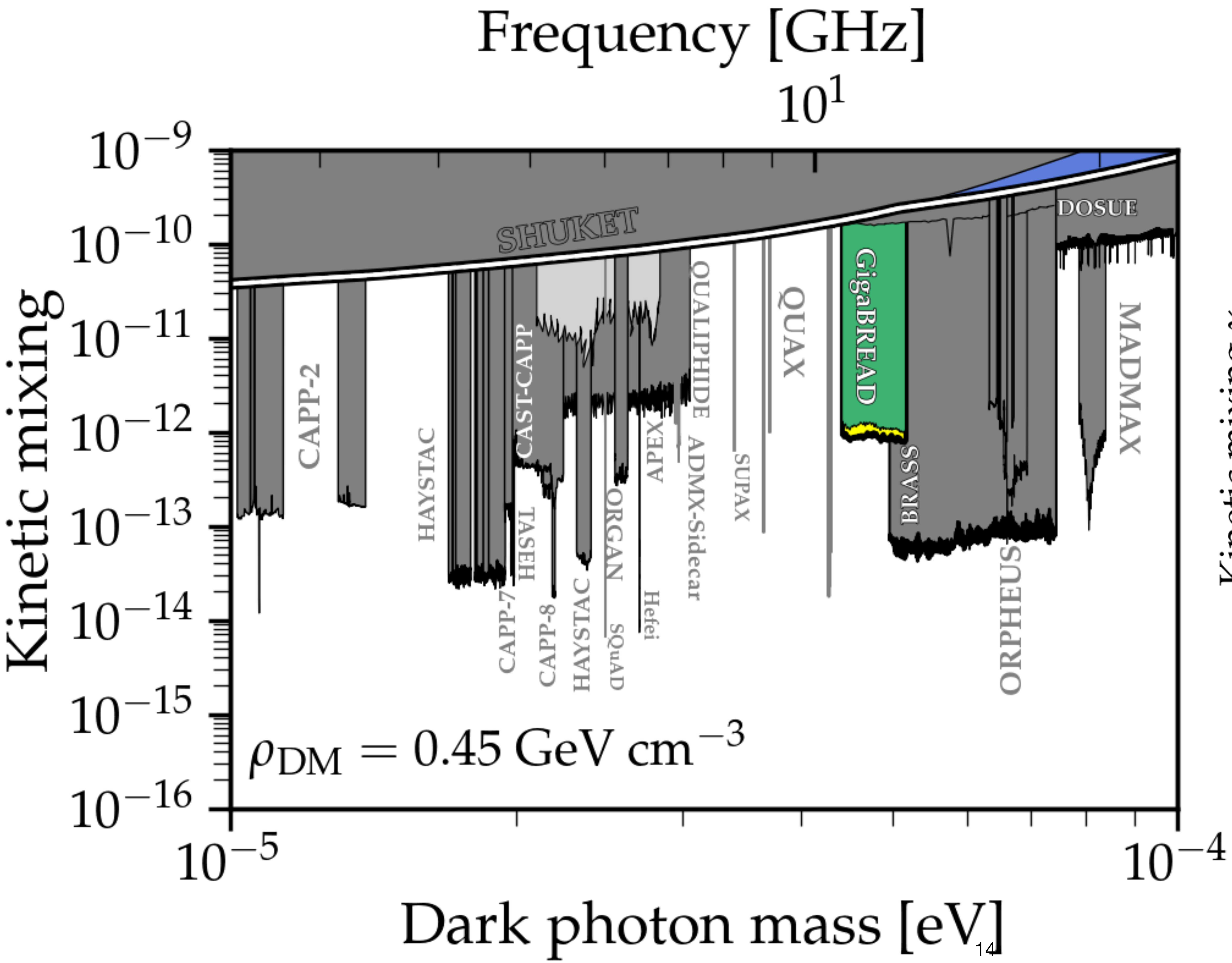


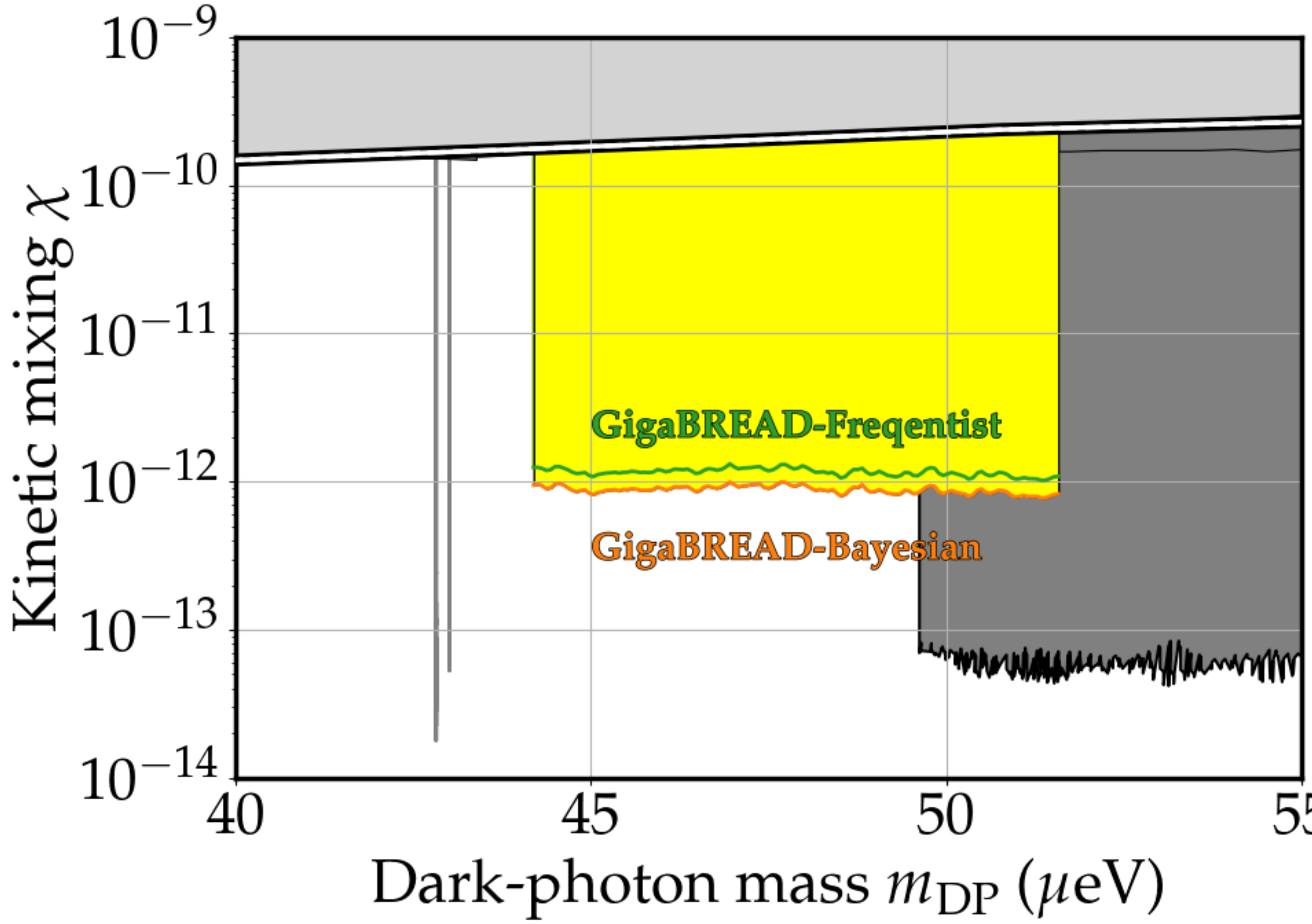
Frequentist Test Statistic

$$q_0 = -2\ln \frac{\sup_{P_{\rm conv}\le 0} \mathscr{L}(P_{\rm conv})}{\sup_{P_{\rm conv}\in\mathbb{R}} \mathscr{L}(P_{\rm conv})}$$



Seems like we didn't


Frequency [GHz]
10^1
Kinetic mixing
Dark photon mass [eV]
SHUKET
DOSUE
GigaBREAD
QUAX
QUALIPHIDE
CAPP-2
HAYSTAC
CAST-CAPP
TASEH
CAPP-7
CAPP-8
HAYSTAC
ORGAN
SQuAD
APEX
Hefei
ADMX-Sidecar
SUPAX
BRASS
ORPHEUS
MADMAX
ρDM = 0.45 GeV cm−3


Kinetic mixing χ
Dark-photon mass mDP (μeV)
GigaBREAD-Freqentist
GigaBREAD-Bayesian

Thank you!