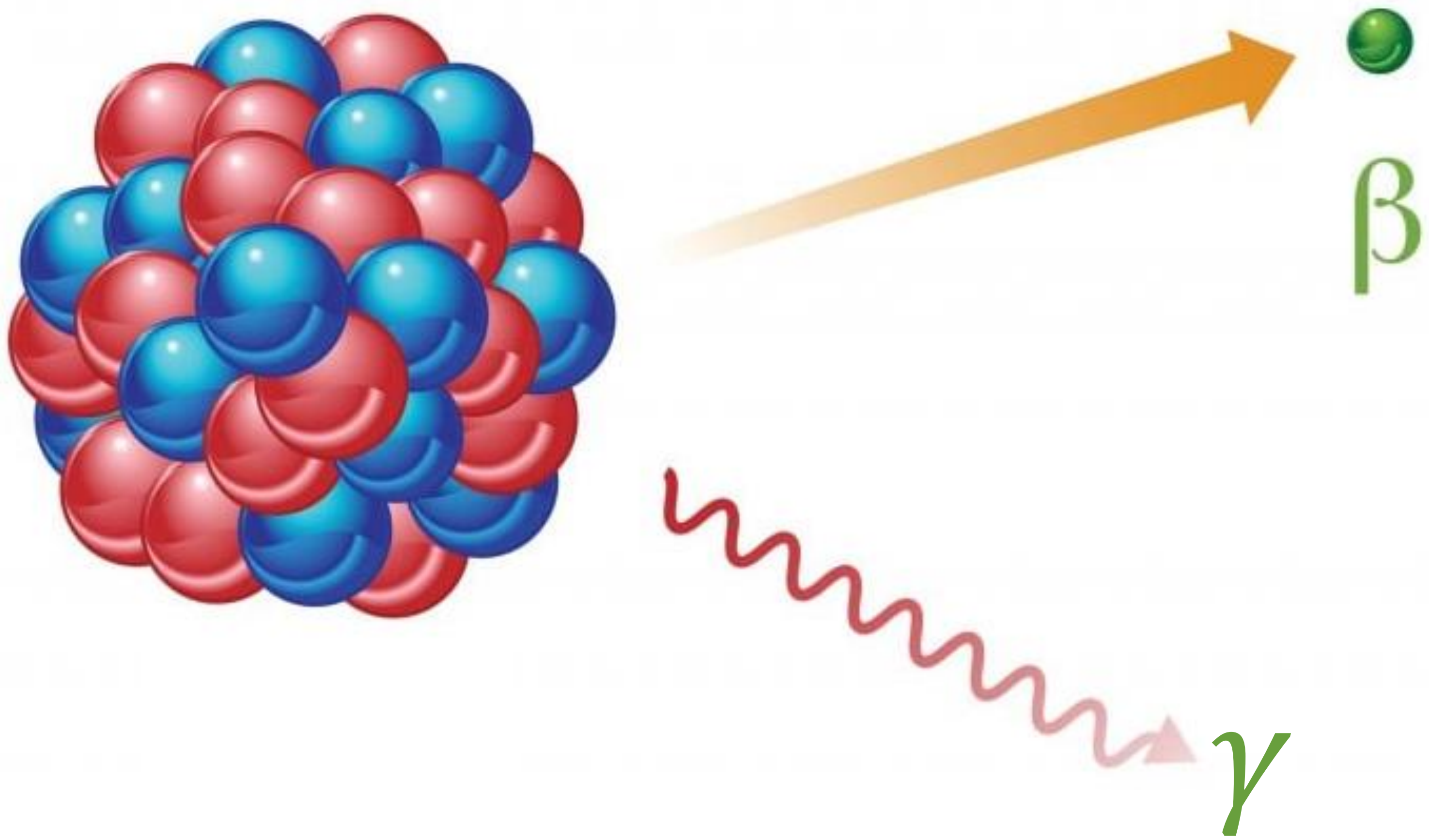
Nuclear decay anomalies as a signature of axion dark matter



Xin Zhang, Liaoning Normal University,

Based on 2303.09865, Phys. Rev. D 108 (7) (2023) L071101

In collaboration with Nick Houston (Beijing University of Technology) and Tianjun Li (ITP-CAS)

第三届高能物理理论与实验融合发展研讨会, November2 2024 , zhangxin@nao.cas.cn

The big picture

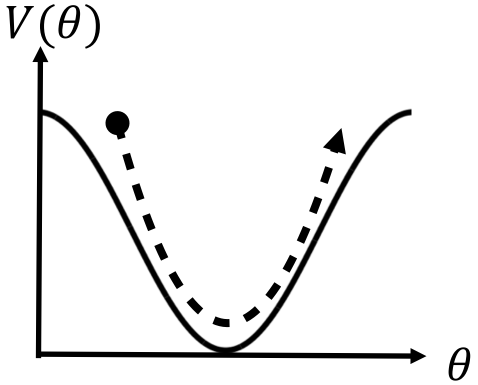
- Fundamentally, we believe that nuclear decay is **random** and **spontaneous**
- However, we also expect QCD axion DM will lead to an oscillating θ-angle
- As θ modifies nuclear physics, this can lead to non-random decay behaviour
- This talk is about using nuclear decay data to search for axion DM

Motivation

- New experimental strategies for axion DM detection
- Explanation of existing nuclear decay anomalies?

Axion and the misalignment mechanism

$$\mathscr{L}_\theta = -\theta \frac{\alpha_S}{8\pi} G^i_{\mu\nu} \tilde{G}^{\mu\nu i} \longrightarrow \theta \equiv \frac{a}{f_a} \longrightarrow$$



- For QCD axions with initial condition $\theta_{a,i}$ we typically have

$$\Omega_a h^2 \sim 2 \times 10^4 \left(\frac{f_a}{10^{16}\mathrm{GeV}} \right)^{7/6} \langle \theta^2_{a,i} \rangle, \quad \theta \simeq \sqrt{\frac{2\rho_{DM}}{m_a^2 f_a^2}} \cos(\omega t + \vec{p} \cdot \vec{x} + \phi)$$

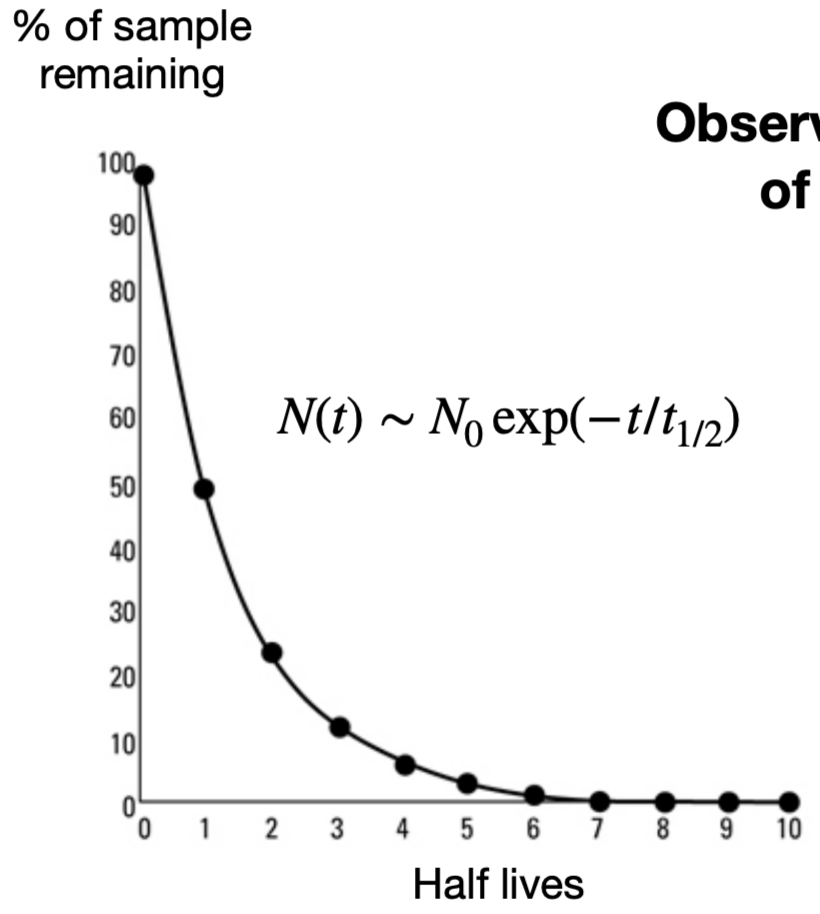
- Many aspects of nuclear physics depend on θ, for example:

$$d_n \simeq \frac{g_{\pi NN}}{4\pi} \left(\frac{e}{m_p f_\pi} \right) \ln\left(\frac{m_\rho}{m_\pi} \right) \left(\frac{m_u m_d}{m_u + m_d} \right) \theta$$

$$M_\pi^2(\theta) = M_\pi^2 \cos\frac{\theta}{2} \sqrt{1 + \varepsilon^2 \tan^2 \frac{\theta}{2}}$$

$$m_n - m_p \simeq \left(1.29 + 0.21\theta^2 + \mathcal{O}\big(\theta^4\big)\right) \mathrm{MeV}$$

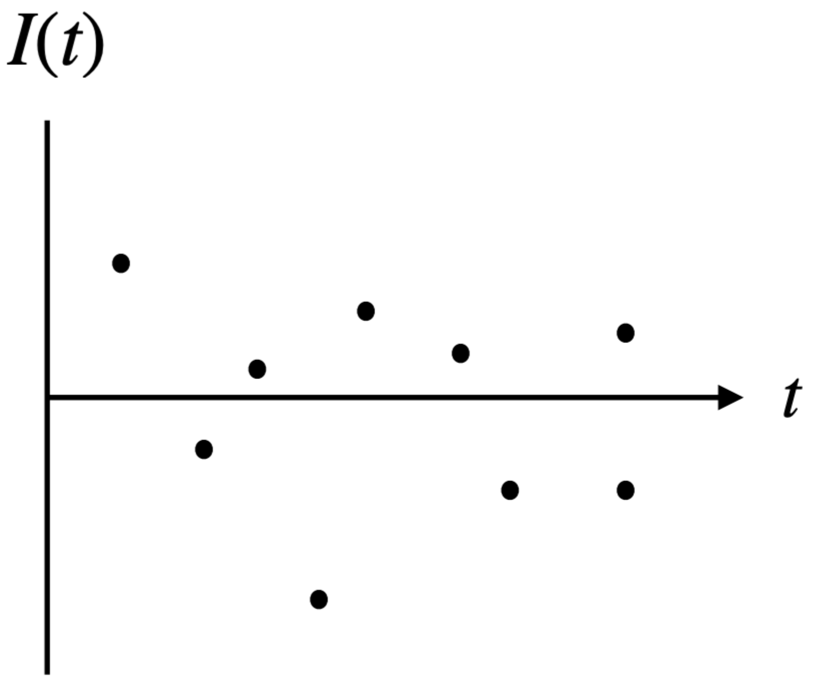
Nuclear decay is random and spontaneous:



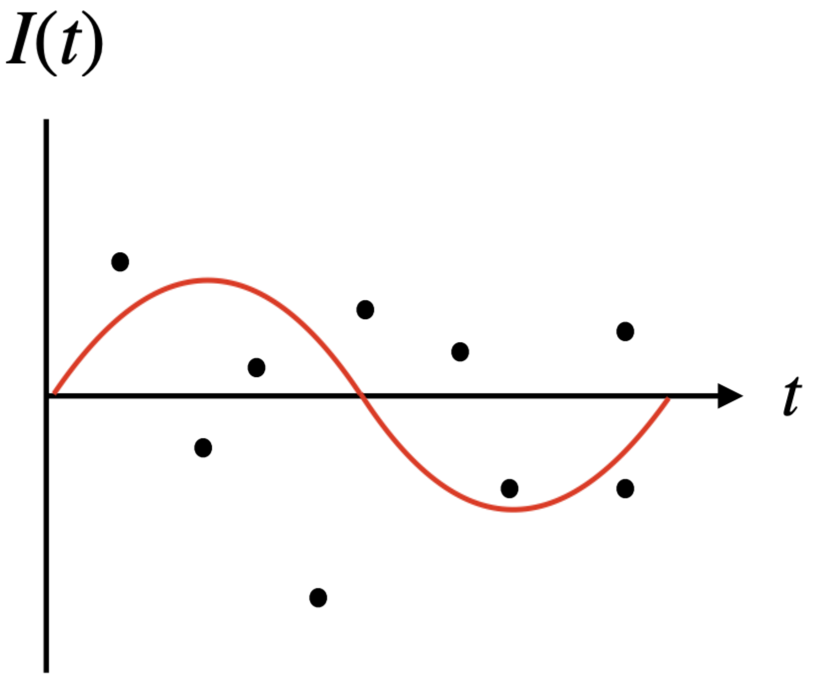
Observed number of decays

Expected number of decays

$$I(t) \equiv \frac{N(t) - \langle N \rangle}{\langle N \rangle}$$

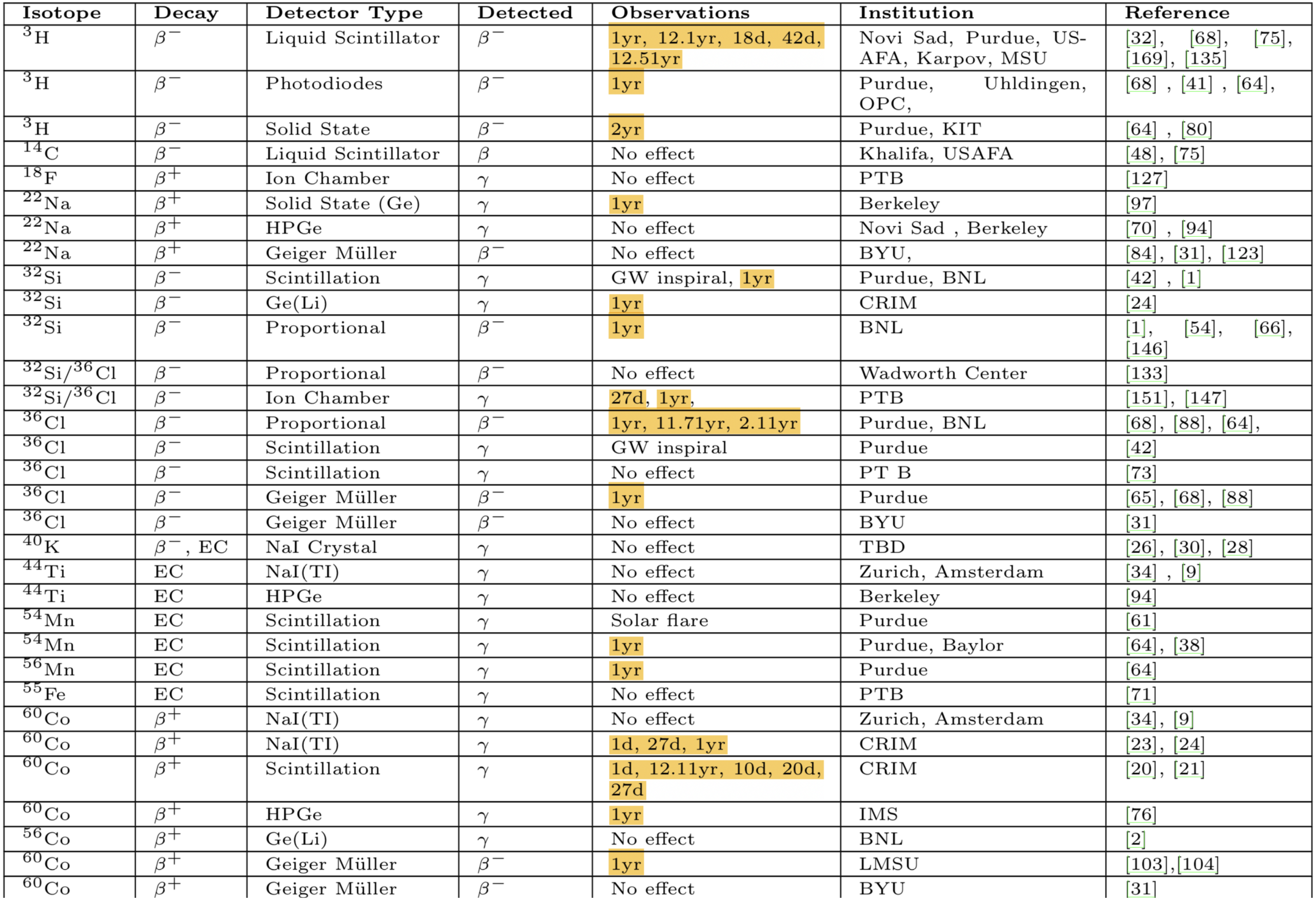


With $\theta \sim \cos(\omega t)$, nuclear decay rates will also oscillate:



A signature we can use to search for axion DM

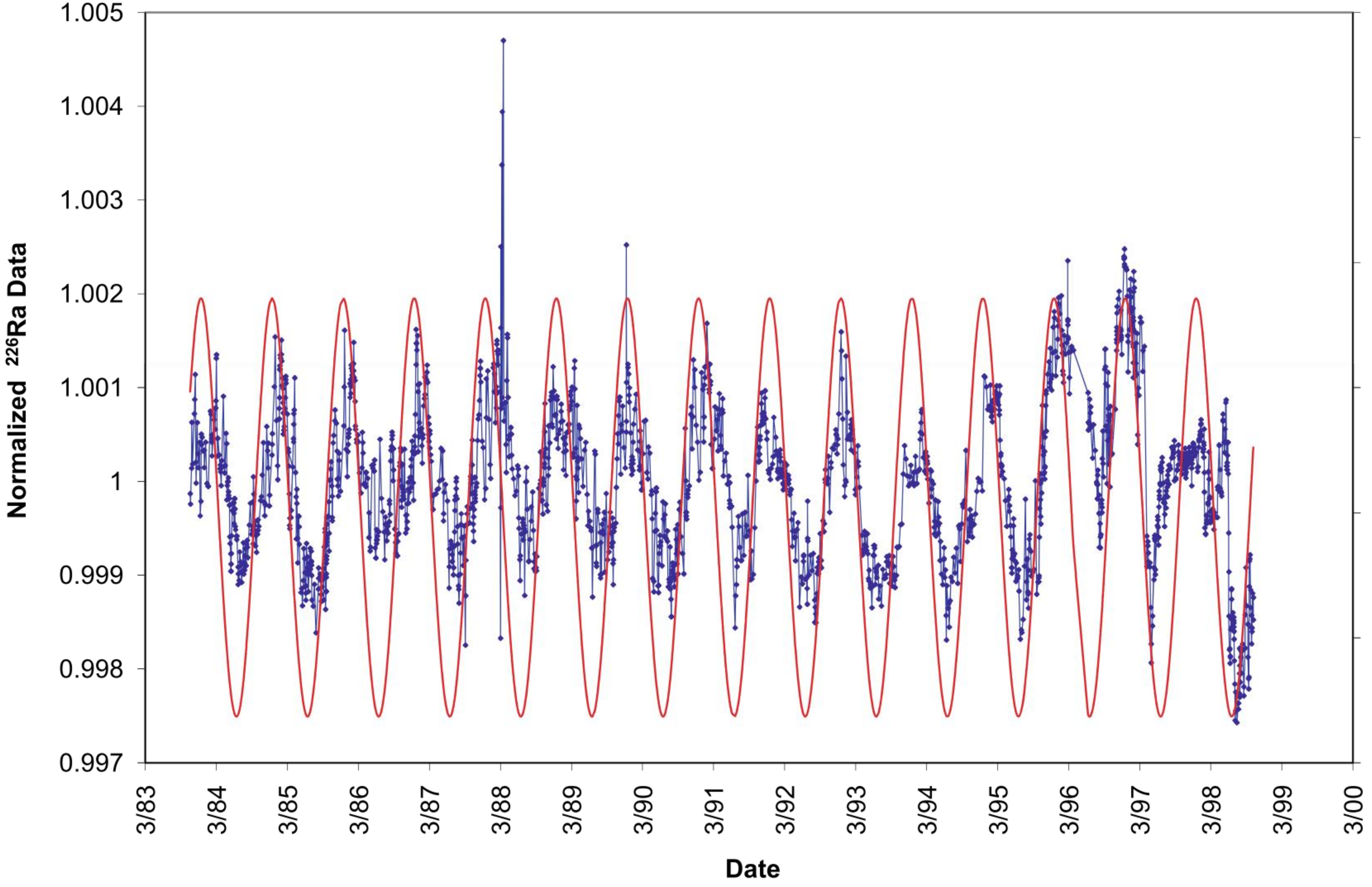
Is there any evidence for this phenomenon?



Isotope	Decay	Detector Type	Detected	Observations	Institution	Reference
^{3}H	β^-	Liquid Scintillator	β^-	1yr, 12.1yr, 18d, 42d, 12.51yr	Novi Sad, Purdue, USAFA, Karpov, MSU	[32], [68], [75], [169], [135]
^{3}H	β^-	Photodiodes	β^-	1yr	Purdue, Uhldingen, OPC,	[68] , [41] , [64],
^{3}H	β^-	Solid State	β^-	2yr	Purdue, KIT	[64] , [80]
^{14}C	β^-	Liquid Scintillator	β	No effect	Khalifa, USAFA	[48], [75]
^{18}F	β^+	Ion Chamber	γ	No effect	PTB	[127]
^{22}Na	β^+	Solid State (Ge)	γ	1yr	Berkeley	[97]
^{22}Na	β^+	HPGe	γ	No effect	Novi Sad , Berkeley	[70] , [94]
^{22}Na	β^+	Geiger Müller	β^-	No effect	BYU,	[84], [31], [123]
^{32}Si	β^-	Scintillation	γ	GW inspiral, 1yr	Purdue, BNL	[42] , [1]
^{32}Si	β^-	Ge(Li)	γ	1yr	CRIM	[24]
^{32}Si	β^-	Proportional	β^-	1yr	BNL	[1], [54], [66], [146]
^{32}Si/^{36}Cl	β^-	Proportional	β^-	No effect	Wadworth Center	[133]
^{32}Si/^{36}Cl	β^-	Ion Chamber	γ	27d, 1yr,	PTB	[151], [147]
^{36}Cl	β^-	Proportional	β^-	1yr, 11.71yr, 2.11yr	Purdue, BNL	[68], [88], [64],
^{36}Cl	β^-	Scintillation	γ	GW inspiral	Purdue	[42]
^{36}Cl	β^-	Scintillation	γ	No effect	PT B	[73]
^{36}Cl	β^-	Geiger Müller	β^-	1yr	Purdue	[65], [68], [88]
^{36}Cl	β^-	Geiger Müller	β^-	No effect	BYU	[31]
^{40}K	β^-, EC	NaI Crystal	γ	No effect	TBD	[26], [30], [28]
^{44}Ti	EC	NaI(TI)	γ	No effect	Zurich, Amsterdam	[34] , [9]
^{44}Ti	EC	HPGe	γ	No effect	Berkeley	[94]
^{54}Mn	EC	Scintillation	γ	Solar flare	Purdue	[61]
^{54}Mn	EC	Scintillation	γ	1yr	Purdue, Baylor	[64], [38]
^{56}Mn	EC	Scintillation	γ	1yr	Purdue	[64]
^{55}Fe	EC	Scintillation	γ	No effect	PTB	[71]
^{60}Co	β^+	NaI(TI)	γ	No effect	Zurich, Amsterdam	[34], [9]
^{60}Co	β^+	NaI(TI)	γ	1d, 27d, 1yr	CRIM	[23], [24]
^{60}Co	β^+	Scintillation	γ	1d, 12.11yr, 10d, 20d, 27d	CRIM	[20], [21]
^{60}Co	β^+	HPGe	γ	1yr	IMS	[76]
^{56}Co	β^+	Ge(Li)	γ	No effect	BNL	[2]
^{60}Co	β^+	Geiger Müller	β^-	1yr	LMSU	[103],[104]
^{60}Co	β^+	Geiger Müller	β^-	No effect	BYU	[31]

“Anomalies in Radioactive Decay Rates: A Bibliography of Measurements and Theory”, arxiv: 2012.00153

A typical example: Radium-226



“Time-dependent nuclear decay parameters: New evidence for new forces?”, *Space Sci.Rev.* 145 (2009) 285-335
“Anomalies in Radioactive Decay Rates: A Bibliography of Measurements and Theory”, arxiv: 2012.00153

Reasons to be skeptical

- Explanations exist which don’t require rewriting the foundations of physics
- Did seasonal variations in atmospheric conditions influence these experiments
- The data analysis here is quite subtle
- Is it possible these anomalies are due to incorrect statistical treatment?

Let’s do our own analysis!

Tritium decay

- For simple nuclei, θ-dependence is calculable, let's consider tritium decay:

$$^3H \rightarrow {}^3\mathrm{He} + e^- + \bar{\nu}_e, t_{1/2} \simeq 12.3 \text{ years}, Q = 18.6\mathrm{keV}$$

$$\Gamma^\beta(^3\mathrm{H}) = \frac{1}{2\pi^3} m_e (G_\beta m_e^2)^2 \left(B_F(^3\mathrm{H}) + B_{GT}(^3\mathrm{H})\right) \boxed{I^\beta(^3\mathrm{H})}$$

$$I^\beta\left(^3\mathrm{H}\right) = \frac{1}{m_e^5} \int_{m_e}^{E_{\max}} F_0\left(Z+1, E_e\right) p_e E_e (E_{\max} - E_e)^2 dE_e$$

The underlying quantity of interest is the fractional change in the beta decay rate:

$$I_0(\theta) \equiv \frac{\Gamma(\theta) - \Gamma(0)}{\Gamma(0)}$$

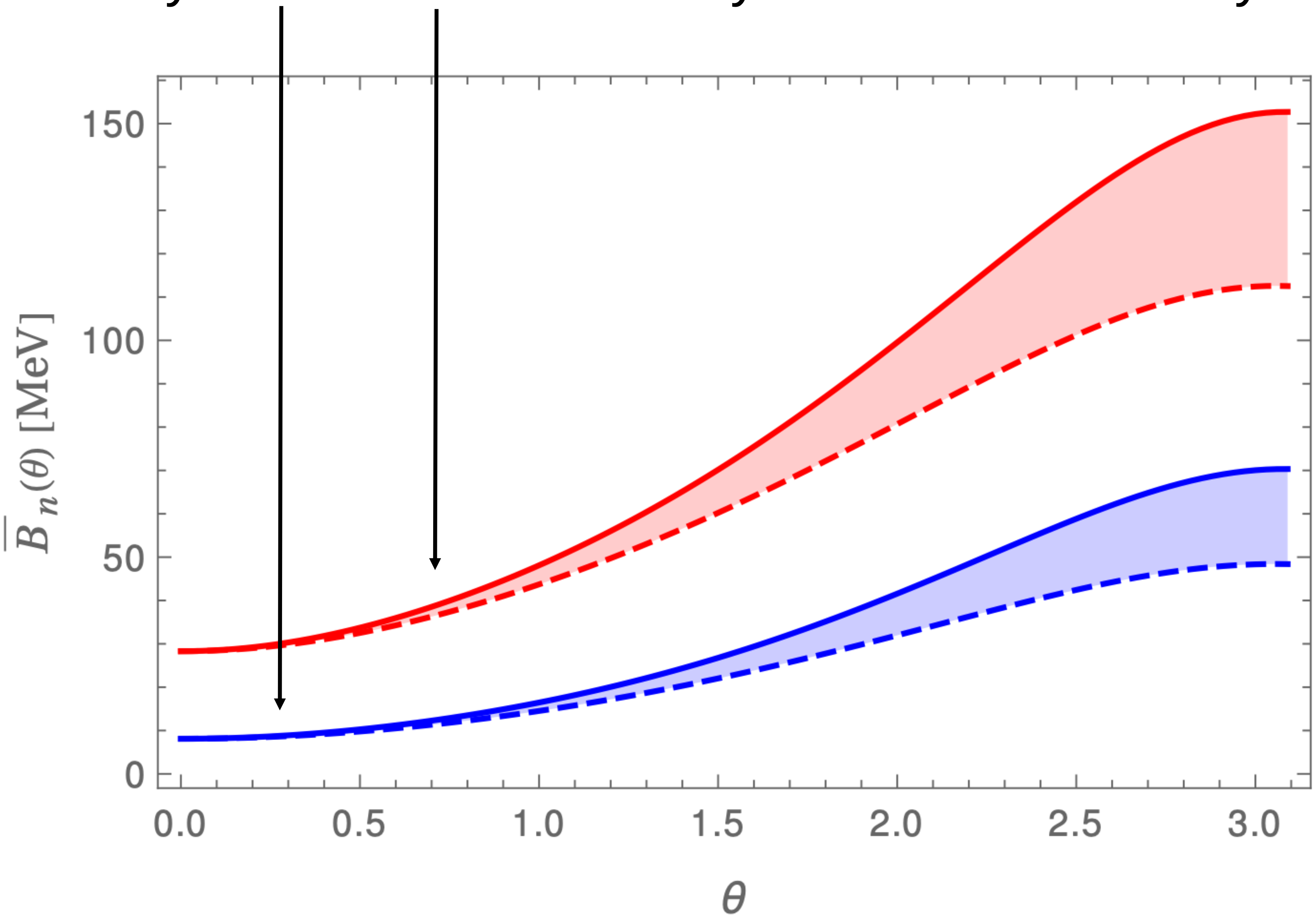
- Where does θ-dependence primarily enter?

$$I^\beta\left(^3\mathrm{H}\right) = \frac{1}{m_e^5} \int_{m_e}^{\underline{E_{\max}}} F_0\left(Z+1, E_e\right) p_e E_e (\underline{E_{\max}} - E_e)^2 dE_e$$

Emax is the maximum possible electron energy

- θ changes the decay rate here by modifying $^3\mathrm{H}/^3\mathrm{He}$ binding energies
- Fortunately for 3 and 4 nucleon systems this is already estimated

Binding energy



three and four-nucleon systems the n-nucleon binding energy satisfies :

$$\bar{B}_n(\theta)^{1/4} - \bar{B}_2(\theta)^{1/4} = \bar{B}_n(0)^{1/4} - \bar{B}_2(0)^{1/4}$$

θ-dependence of light nuclei and nucleosynthesis, 2006.12321

Knowing the θ-dependence of the binding energy, we can then calculate the energy shift by add a perturbation $\delta E(\theta)$ to Emax :

$$E_{\max} = \frac{M_i^2 + m_e^2 - (M_f + m_v)^2}{2M_i}$$

Mi and Mf are the masses of the initial and final nuclear states:

$$M_{i/f} = \sum_N m_N(\theta) - B(\theta)_{i/f}$$

$$E_{\max} \simeq E_{\max}\big|_{\delta M_{i/f}=0} + \boxed{\delta M_i \frac{M_i^2 - m_e^2 + (M_f + m_v)^2}{2M_i^2} - \delta M_f \frac{M_f + m_v}{M_i}}$$

$$E_{\max} \simeq E_{\max}\big|_{\delta M_{i/f}=0} + \boxed{\delta M_i - \delta M_f}$$

The corresponding shift in the decay energy: $\delta E(\theta) \simeq \delta M_i - \delta M_f$

$$E_{\max}(\theta) \simeq E_{\max}(0) + \delta E(\theta)$$

$$= (m_n - m_p)(\theta) - B_i(\theta) + B_f(\theta) \simeq 0.53 - 0.51\theta^2 \mathrm{MeV}$$

- Add a perturbation $\delta E(\theta)$ to $E_i - E_f$: $\Gamma(\theta) = \int_{m_e}^{E_{\max}+\delta E(\theta)} dE_e \frac{d\Gamma}{dE_e}$

$$I_0(\theta) \equiv \frac{\Gamma(\theta) - \Gamma(0)}{\Gamma(0)} \simeq \frac{\delta I^{\beta}(\theta)}{I^{\beta}(0)}$$

$$\frac{\delta\Gamma^{\beta}}{\Gamma^{\beta}} = 1 - \frac{5\delta E(\theta)\Big(E_f^2 - 2E_f(E_i + m_e) + E_i^2 + 2E_i m_e + 3m_e^2\Big)}{(E_f - E_i + m_e)\Big(3m_e(E_i - E_f) + (E_f - E_i)^2 + 6m_e^2\Big)} + \mathcal{O}\big(\delta E^2\big)$$

(Using Primakoff-Rosen approximation for F_0)

- From the previous slide, we know how δE depends on θ, and the corresponding shift in the decay energy is:

$$\delta E \simeq \mu\text{eV}\left(\frac{\rho_{DM}}{0.4\text{GeV}/\text{cm}^3}\right)\left(\frac{10^{16}\text{GeV}}{f_a}\right)^2\left(\frac{10^{-22}\text{eV}}{m_a}\right)^2\cos(2\omega t)$$

$$I_0(\theta)\big|_{{}^3H} \simeq 0.18\left(\frac{\delta E(\theta)}{\text{keV}}\right)$$

- So, now all we need is some tritium data…

Why Tritium?

- Decays with smaller $Q \equiv M_i - M_f - m_e$ resulted in a larger fractional change in the beta decay rate.

  Candidates for Low Q nuclides:

  H-3, Q=18.6keV
  Re-187, Q=2.6keV
  Pu-241, Q=20.8keV

$$\left.\frac{\delta\Gamma}{\Gamma_0}\right|_{^3\mathrm{H}} = \frac{\int_{m_e}^{E_i-E_f+\delta E} F_0\left(Z+1, E_e\right) p_e E_e (E_i - E_f + \delta E - E_e)^2 \, \mathrm{d}E_e}{\int_{m_e}^{E_i-E_f} F_0\left(Z+1, E_e\right) p_e E_e (E_i - E_f - E_e)^2 \, \mathrm{d}E_e}$$

$$\boxed{\approx 0.18428 \times \left(\frac{\delta E}{1\mathrm{keV}}\right), \qquad |\delta E| \ll 18.6\mathrm{keV}}$$

$$\left.\frac{\delta\Gamma}{\Gamma_0}\right|_{^{187}\mathrm{Re}} = \frac{\int_{m_e}^{E_i-E_f+\delta E^2} F_1\left(Z+1, E_e\right) p_e^3 E_e (E_i - E_f + \delta E - E_e)^2 \, \mathrm{d}E_e}{\int_{m_e}^{E_i-E_f} F_1\left(Z+1, E_e\right) p_e^3 E_e (E_i - E_f - E_e)^2 \, \mathrm{d}E_e}$$

$$\boxed{\approx 1.15896 \times \left(\frac{\delta E}{1\mathrm{keV}}\right), \qquad |\delta E| \ll 2.6\mathrm{keV}}$$

Experimental setup

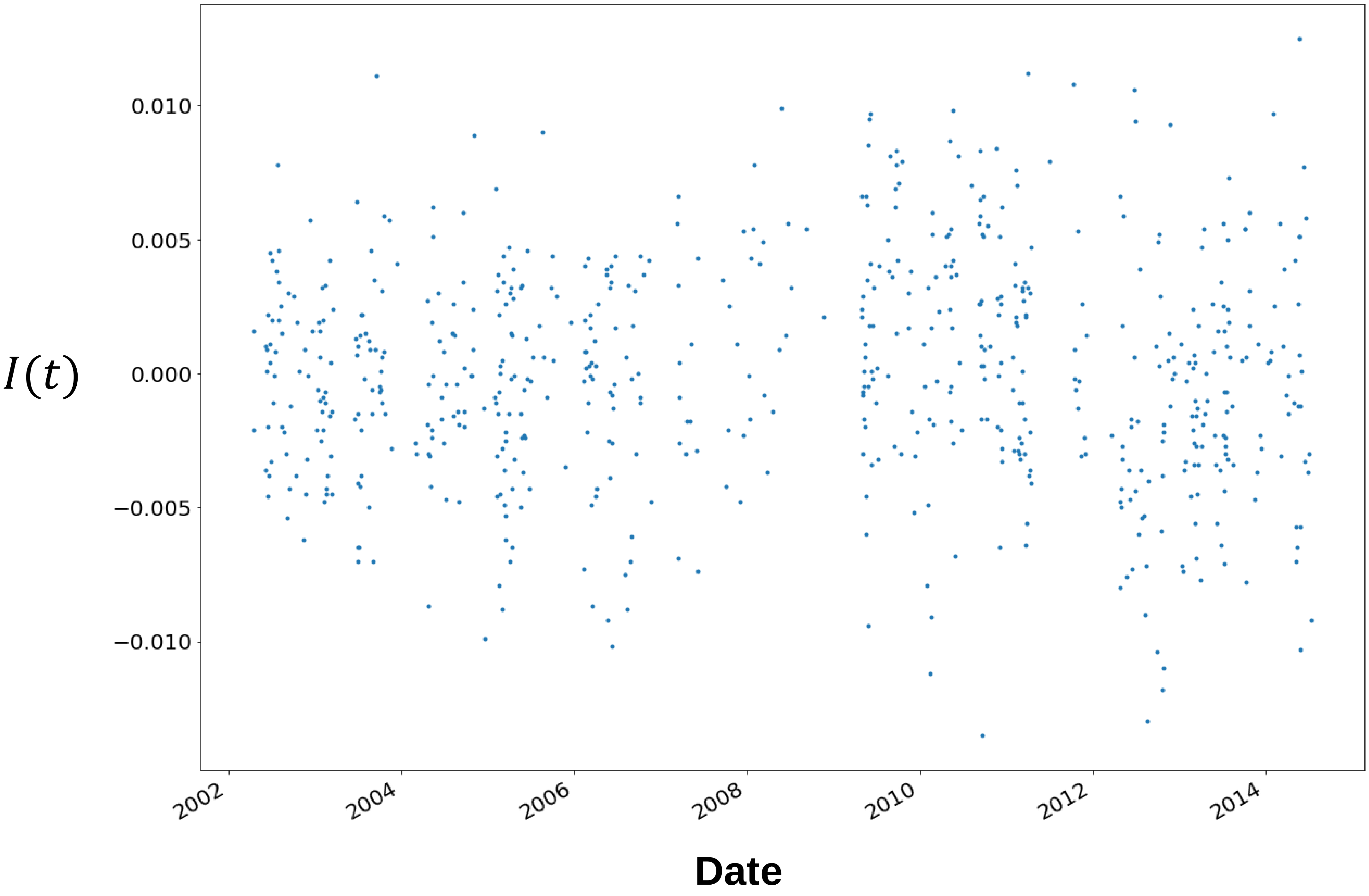
Laboratory liquid scintillator counter

+

1 microcurie of tritium

Courtesy of the European Union’s Joint Research Centre,
at the Directorate for Nuclear Safety and Security in Belgium

Tritium decay data



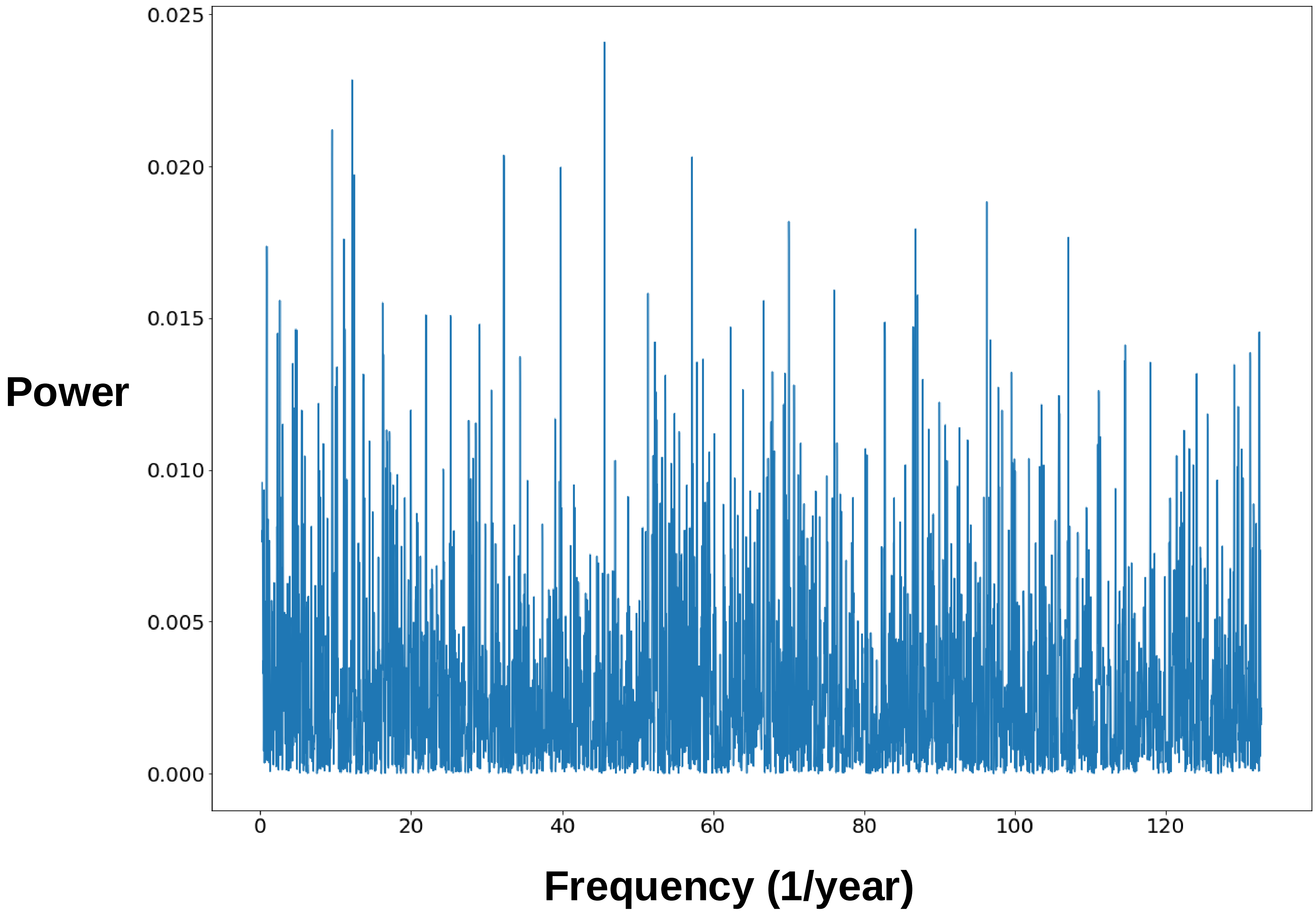
$$I(t) \equiv \frac{N(t) - \langle N \rangle}{\langle N \rangle}$$

Data is from the European Union’s Joint Research Centre, at the Directorate for Nuclear Safety and Security in Belgium

Lomb-Scargle periodogram

Least Squares Spectral Analysis (LSSA) method

- Let’s convert the data into frequency space:



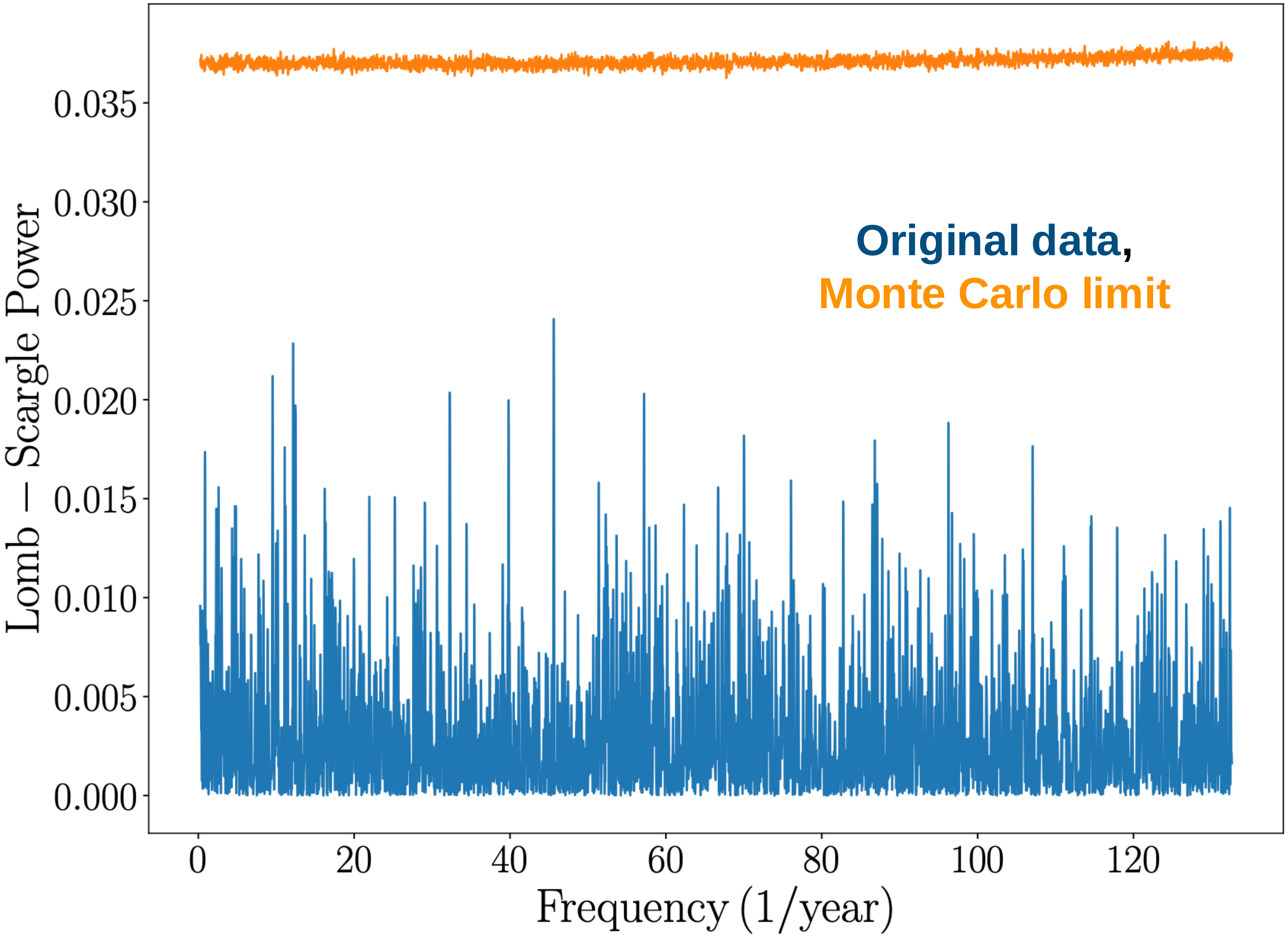
- Is there evidence of periodic effects here?

- Let’s compare the real data to Monte Carlo simulations:

1. Generate N datasets with randomly generated $I(t)$
2. For each dataset, convert to frequency space
3. Construct the CDF at each frequency
4. Find the 95 % CL limit (including look-elsewhere)
5. Compare to the real power at that frequency

- For example:

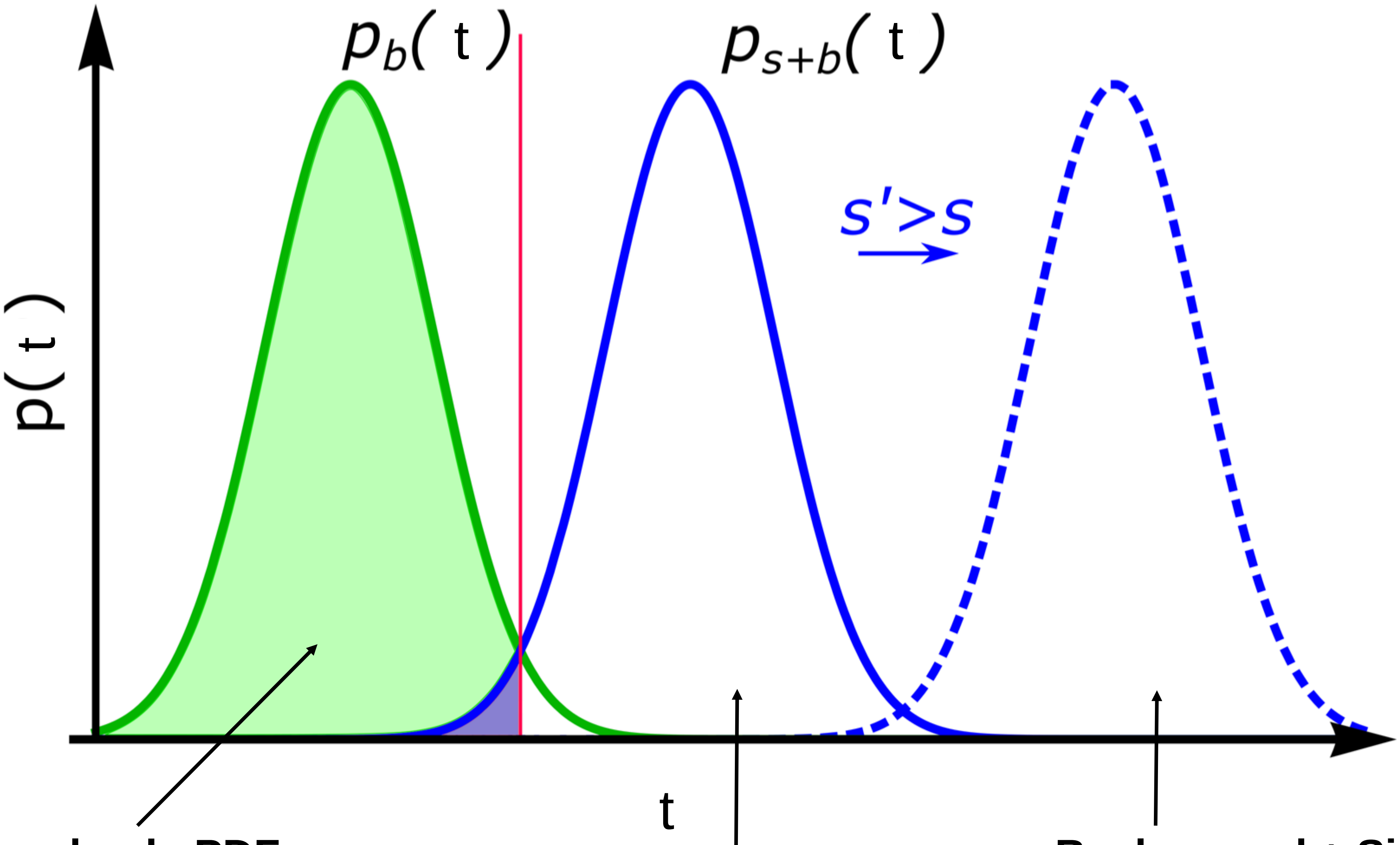
- From Monte Carlo simulations:



- We can see that the real data points (blue) are all below the 95 % CL limit (orange), and hence well-modelled by random noise

No evidence of non-random behaviour

- Repeating this with an injected axion signal:



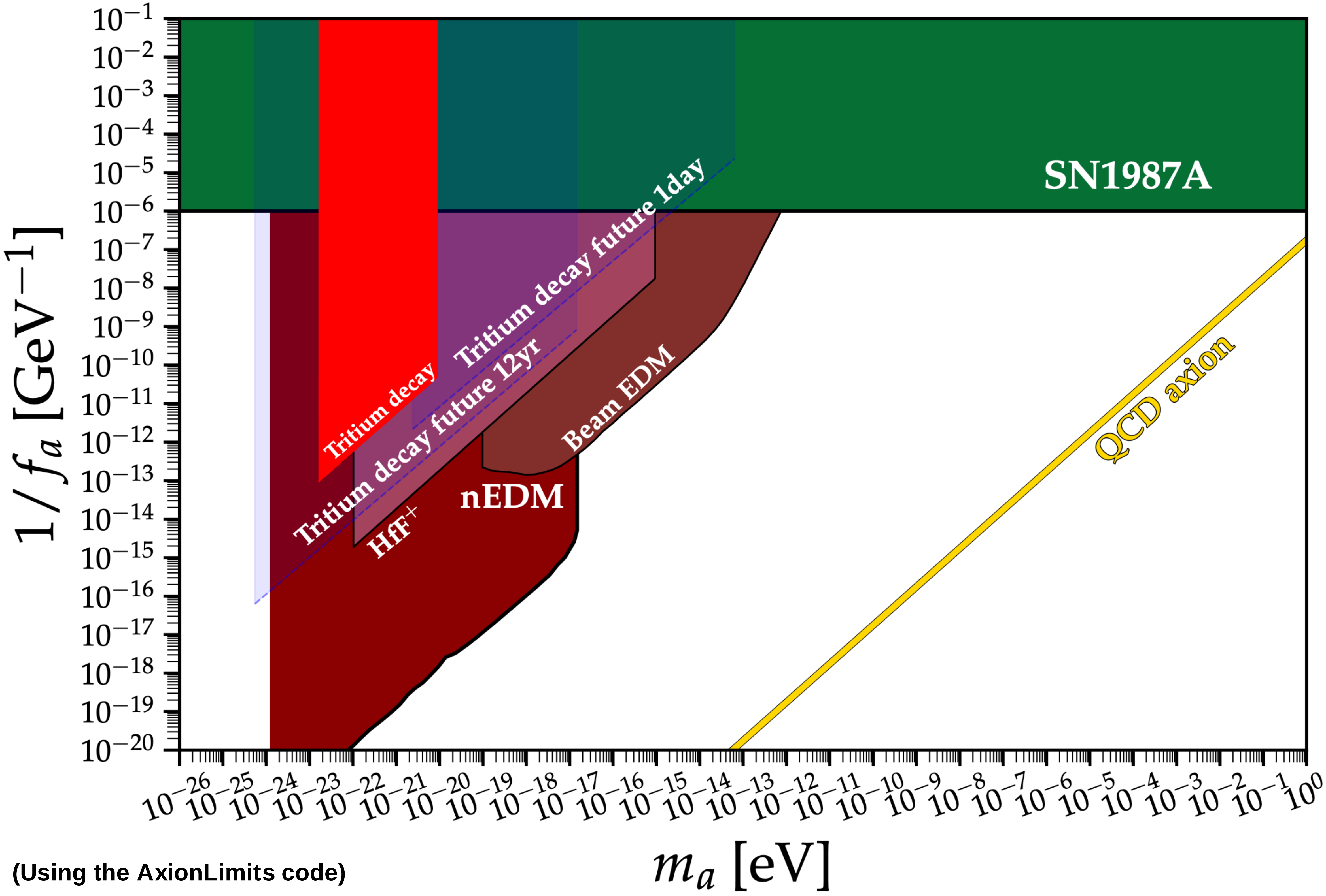
Background only PDF compatible with data

Background + Signal PDF threshold

Background + Signal PDF excluded by data

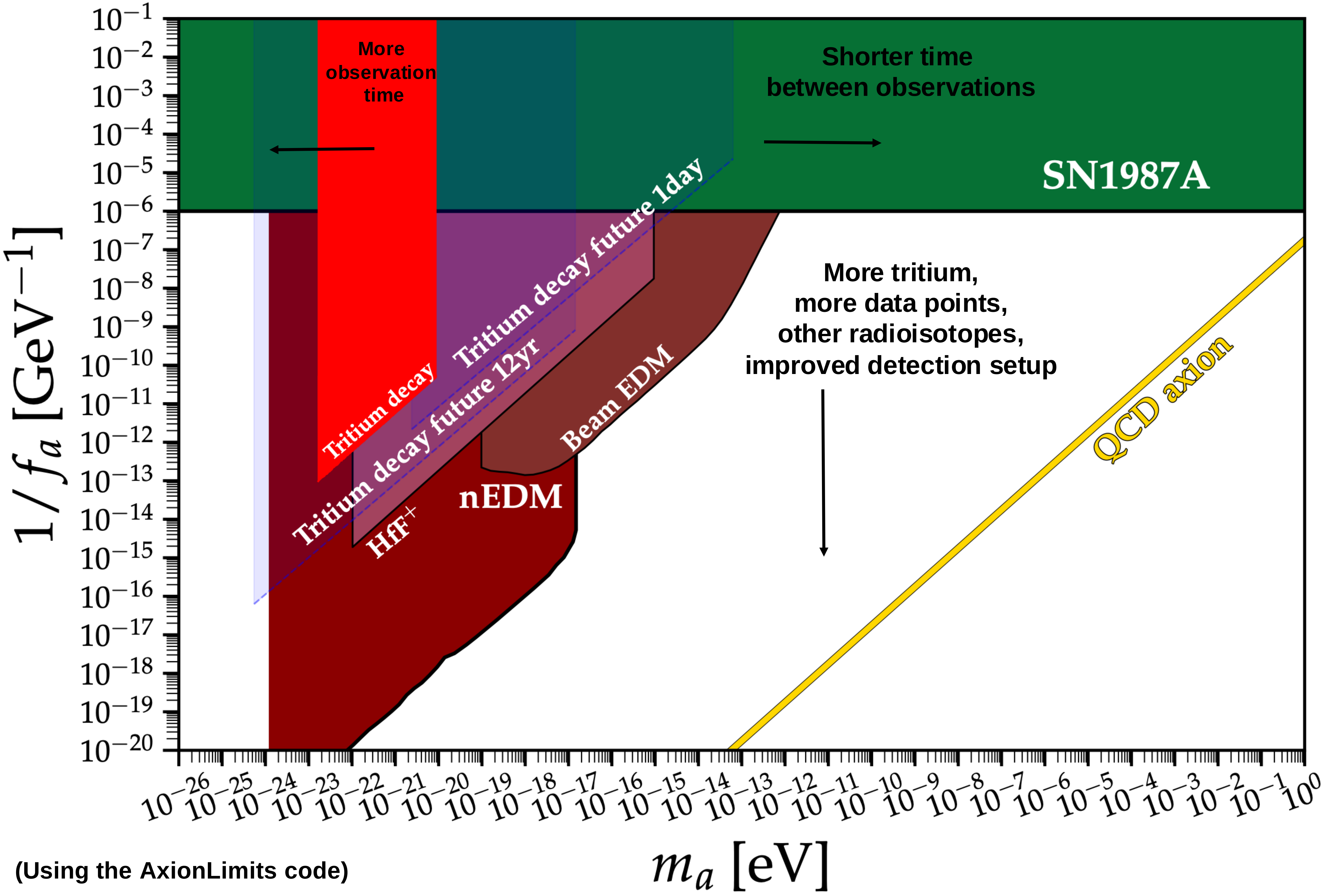
- Varying the axion coupling allows us to find the threshold values

Resulting constraint



(Using the AxionLimits code)

Resulting constraint



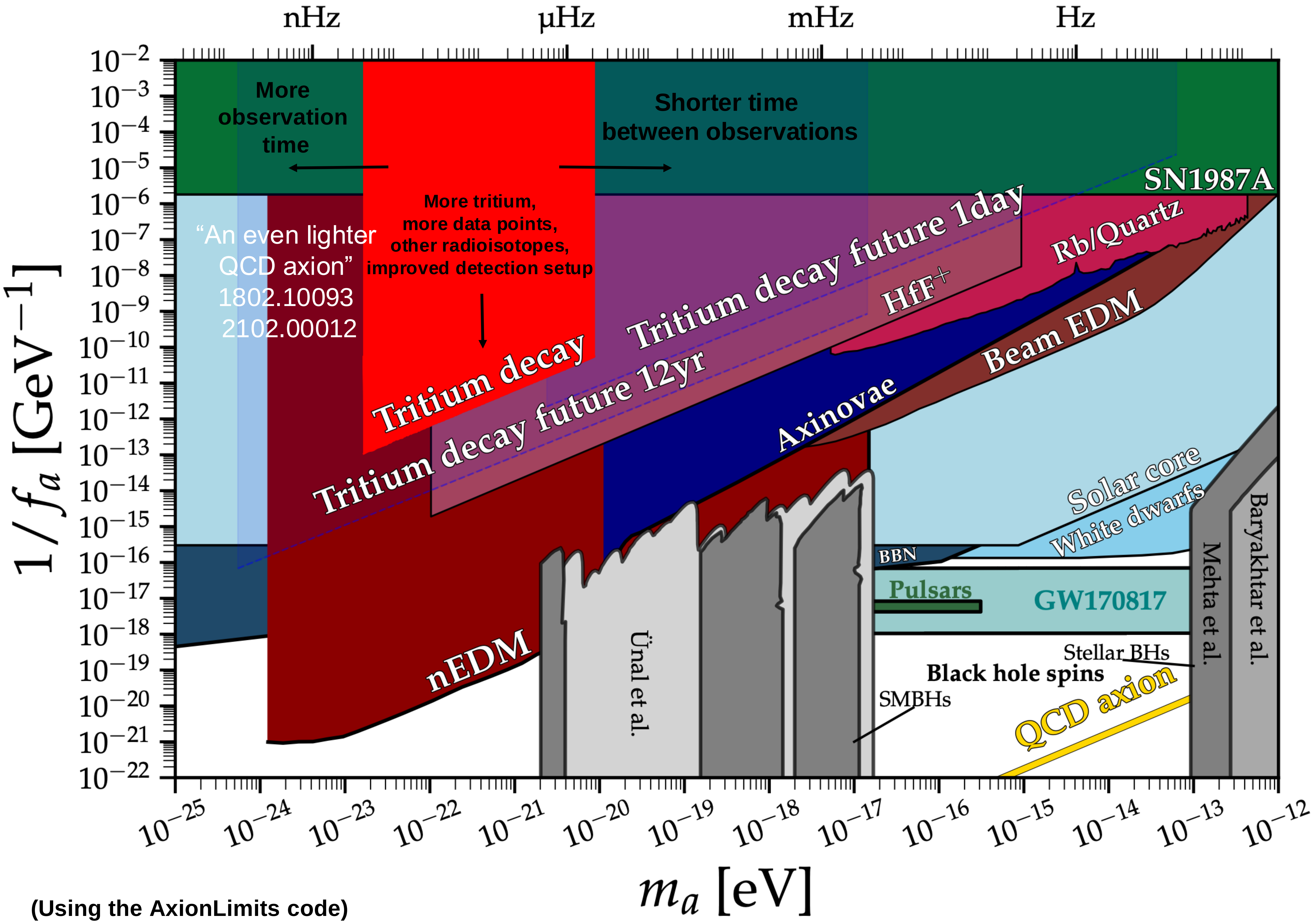
More observation time

Shorter time between observations

More tritium, more data points, other radioisotopes, improved detection setup

(Using the AxionLimits code)

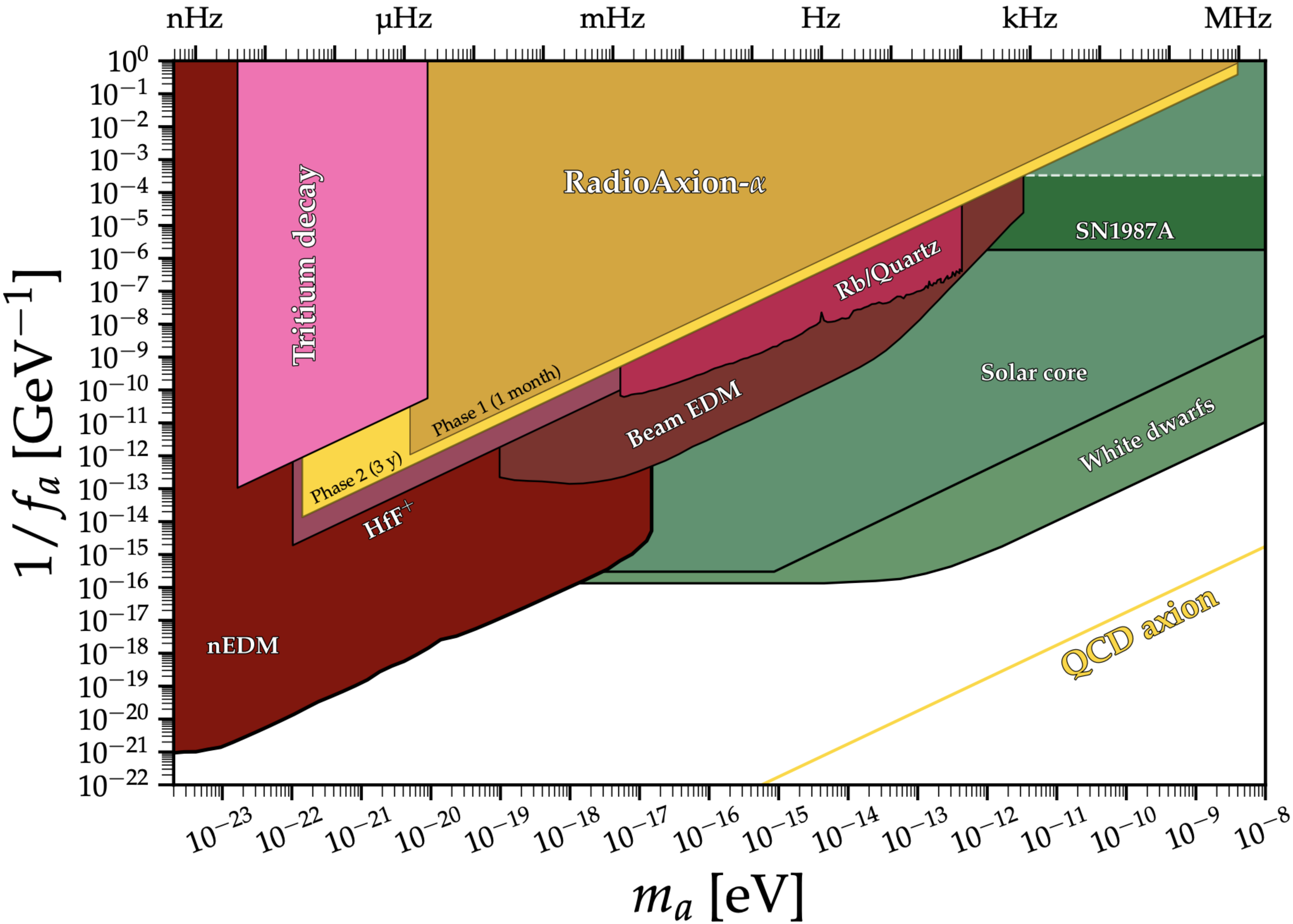
Resulting constraint



(Using the AxionLimits code)

Interesting follow up work: α-decay of Americium-241

$$^{241}\mathrm{Am} \rightarrow {}^{237}\mathrm{Np} + \alpha + \gamma(59.5\mathrm{keV})$$



Carlo Broggini, Giuseppe Di Carlo, Luca Di Luzio, Claudio 2404.18993

Discussion and conclusions

- We have explored a new experimental signature for axion DM
- In 12 years of tritium decay data we find no evidence of this phenomenon
- We used the data to place constraints on axion DM
- Is nuclear decay random and spontaneous? Yes, probably…

More details in 2303.09865

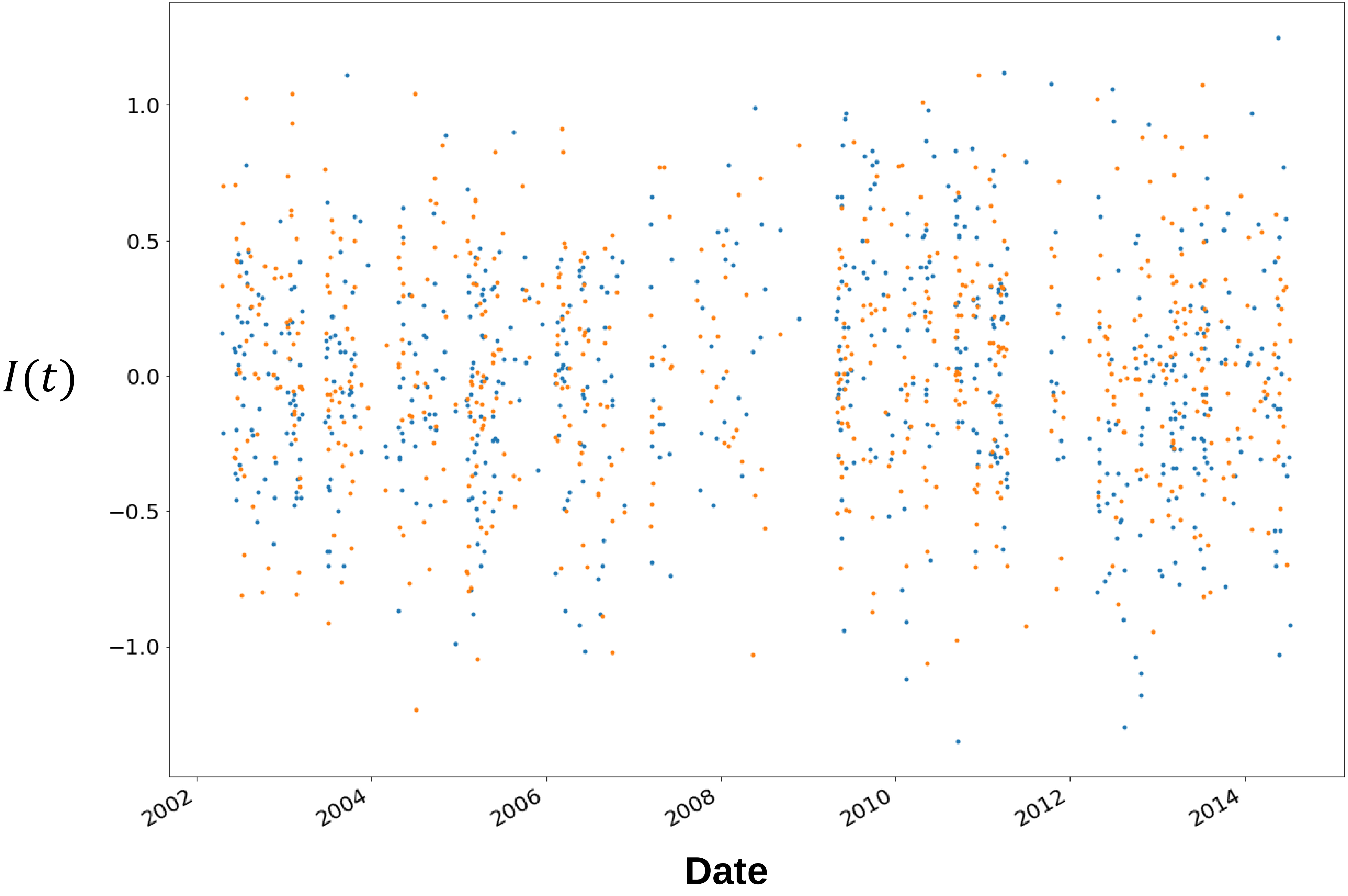
Thanks for listening!

Appendix

Compare the real data to Monte Carlo simulations:

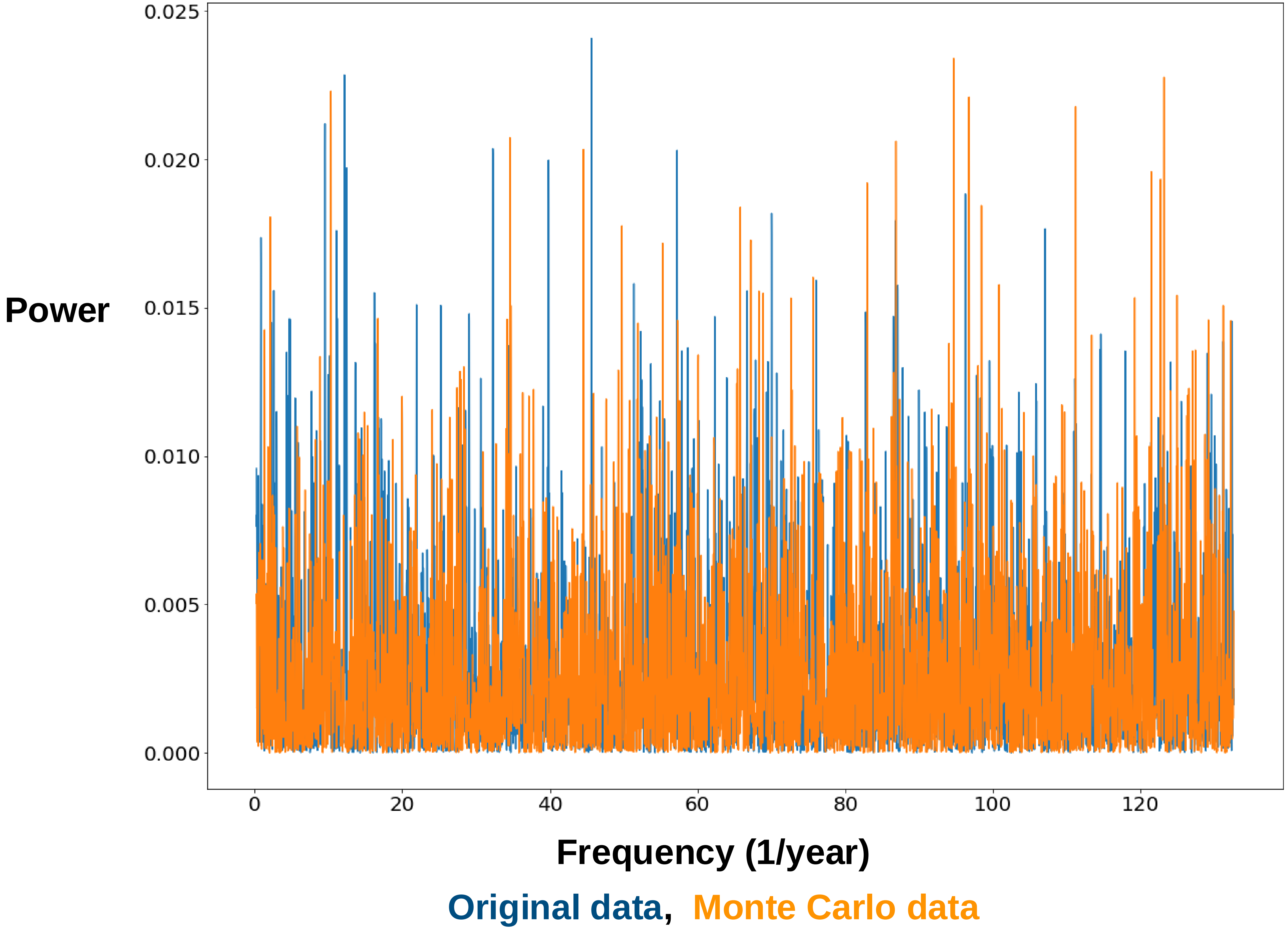
1. Generate N datasets with randomly generated $I(t)$
2. For each dataset, convert to frequency space
3. Construct the CDF at each frequency
4. Find the 95 % CL limit (including look-elsewhere)
5. Compare to the real power at that frequency

- For example:

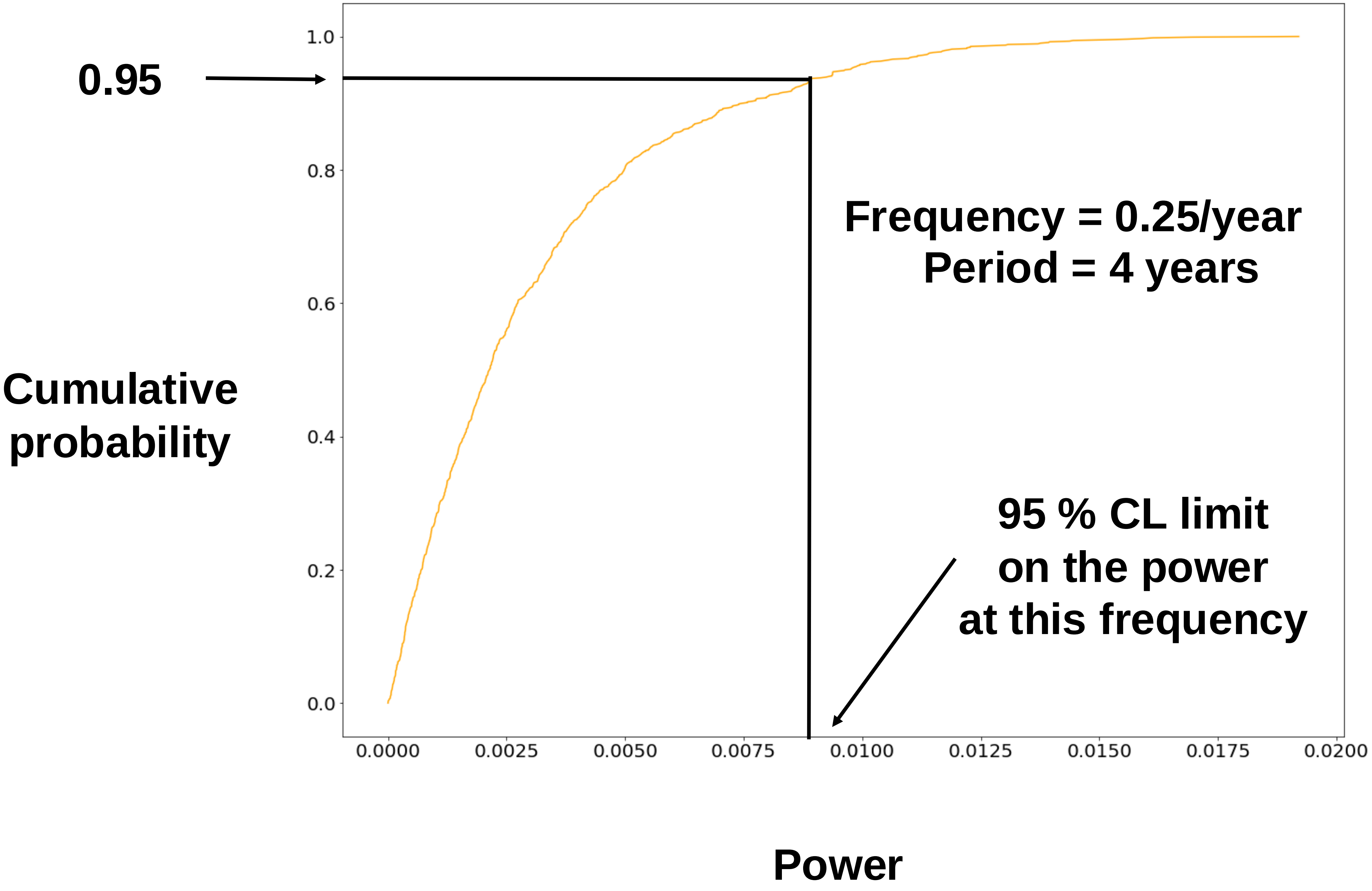


Original data, **Monte Carlo data**

Lomb-Scargle periodogram



- Repeat N times to estimate the power PDF at each frequency
- Integrate to get the power CDF:



0.95

Cumulative probability

Frequency = 0.25/year
Period = 4 years

95 % CL limit on the power at this frequency

Power