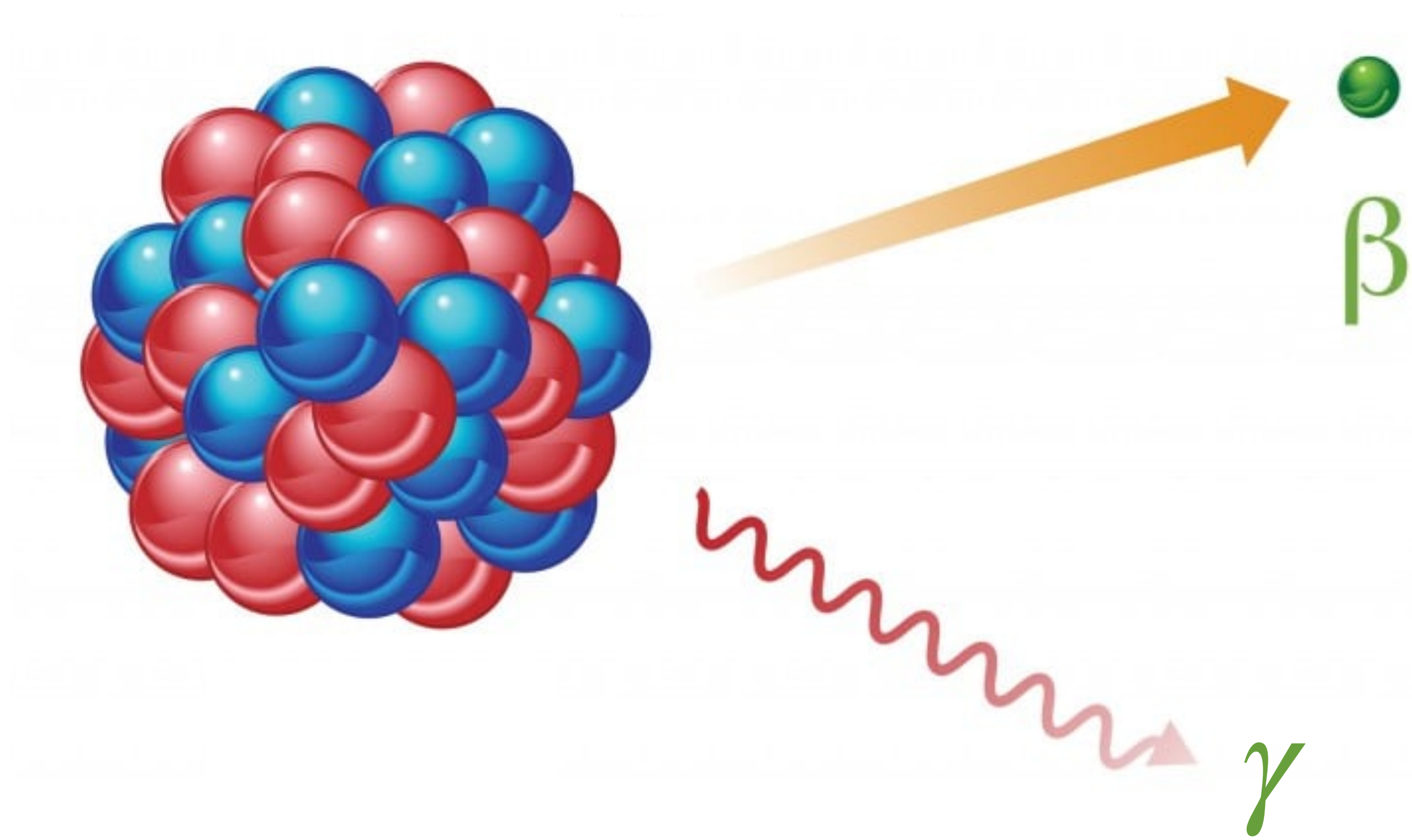
Nuclear decay anomalies as a signature of axion dark matter



Nick Houston, Beijing University of Technology

Based on 2303.09865, In collaboration with Xin Zhang (NAOC) and Tianjun Li (ITP-CAS)

Galileo Galilei Institute axion workshop, May 2023 , nhouston@bjut.edu.cn

The big picture

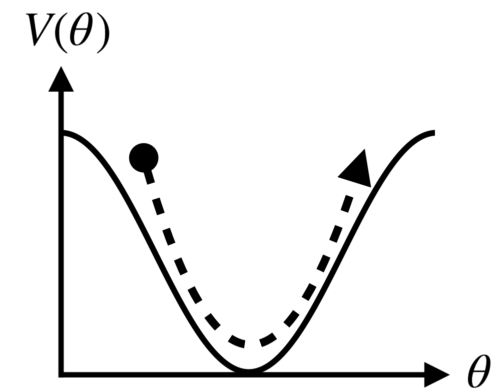
- Fundamentally, we believe that nuclear decay is **random** and **spontaneous**
- However, we also expect QCD axion DM will lead to an oscillating θ-angle
- As θ modifies nuclear physics, this can lead to non-random decay behaviour
- This talk is about using nuclear decay data to search for axion DM

Motivation

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

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

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

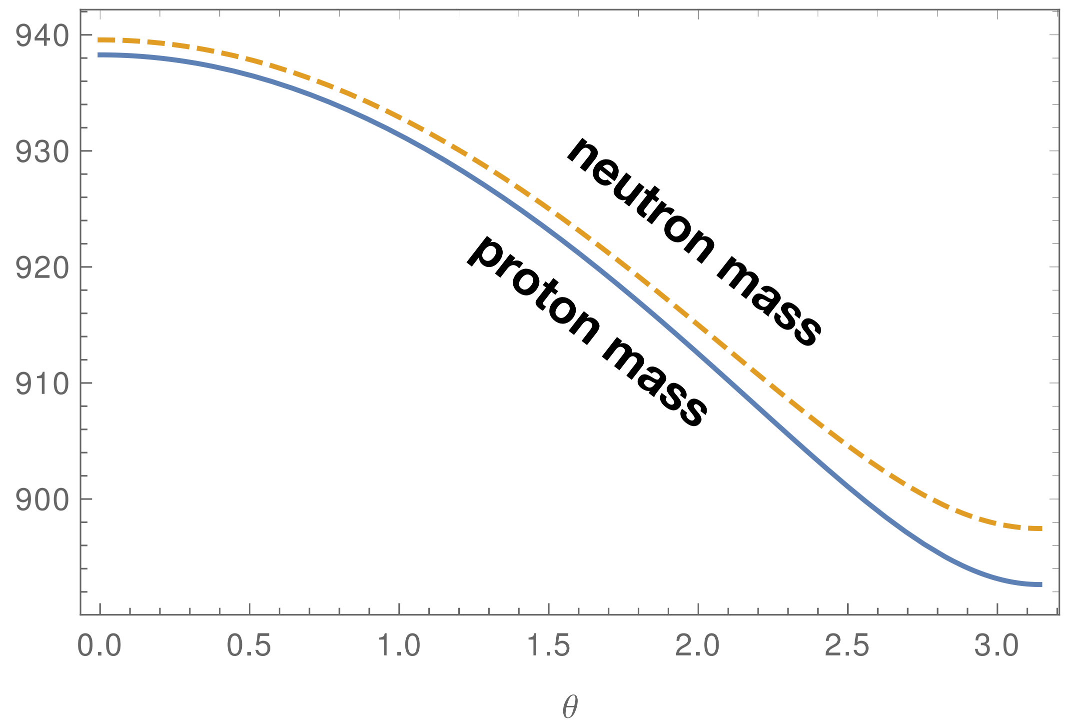
- Many aspects of nuclear physics depend on θ, for example:

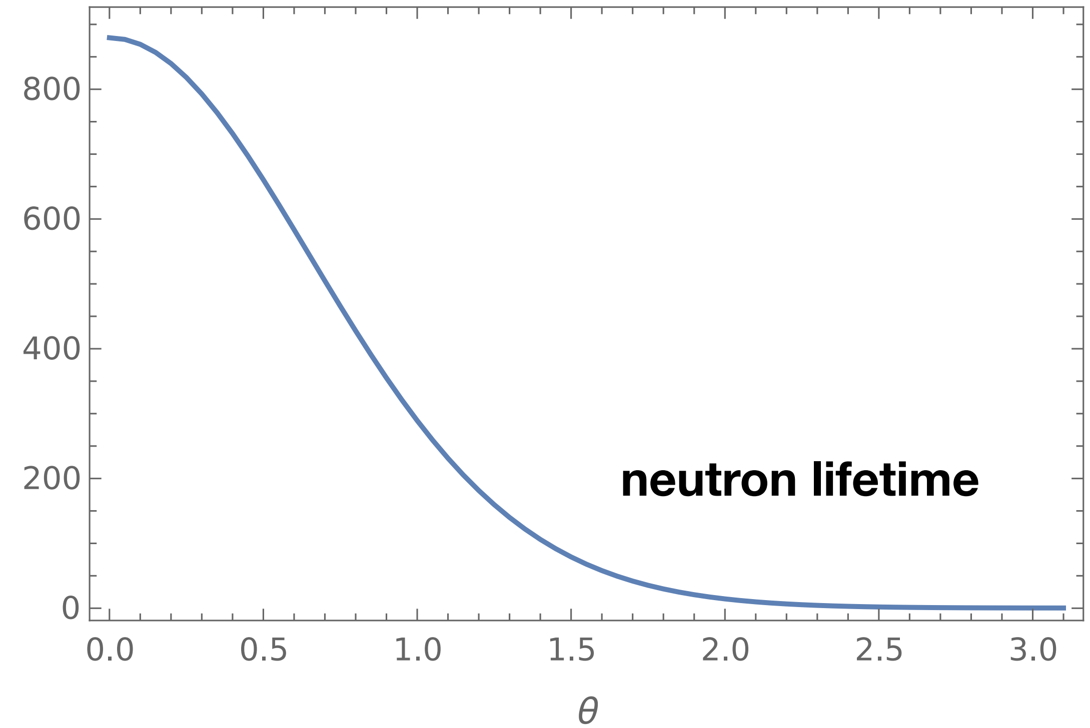
$$d_n \simeq \frac{g_{\pi NN}}{4\pi} \left(\frac{e}{m_p f_\pi} \right) \ln \left(\frac{m_\rho}{m_\pi} \right) \left(\frac{m_u m_d}{m_u + m_d} \right) \theta$$

The misalignment mechanism

- By modifying nuclear binding energies, θ can also change decay rates:

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

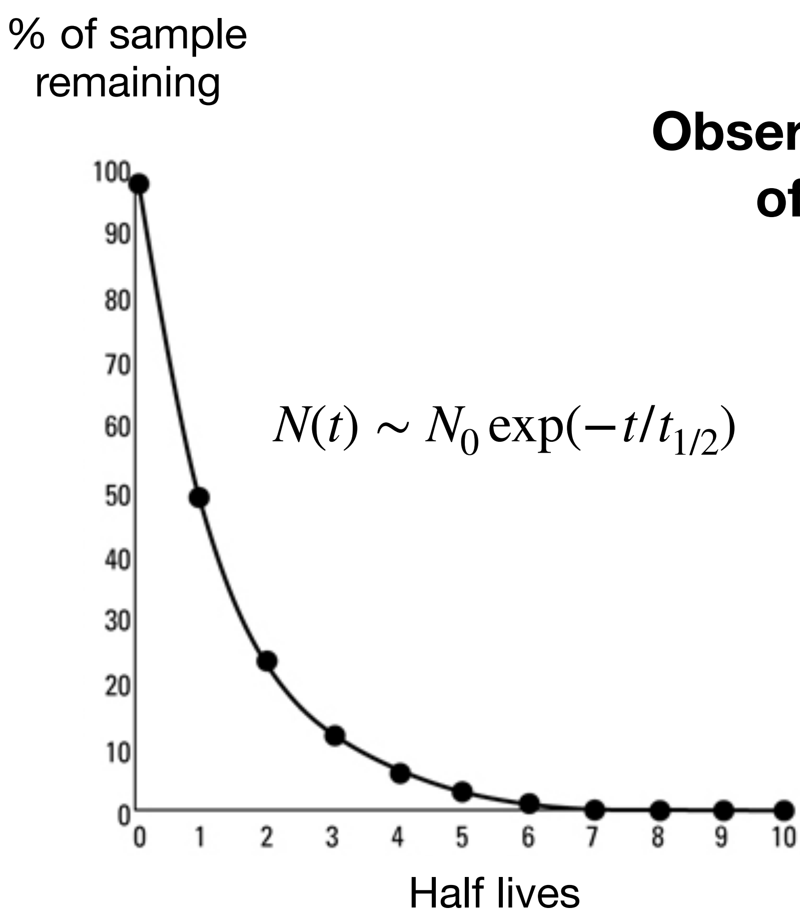




θ-dependence of light nuclei and nucleosynthesis, 2006.12321

The misalignment mechanism

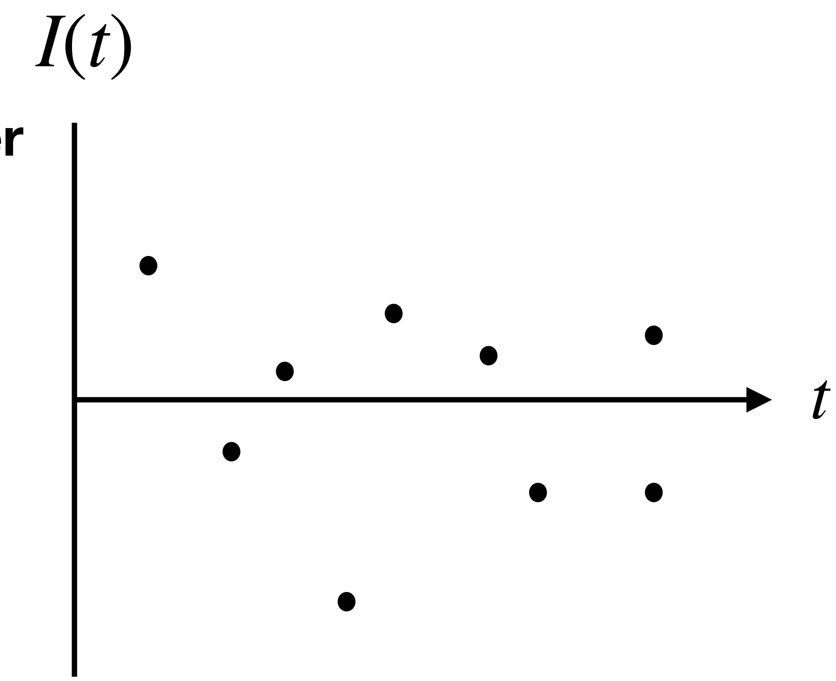
- With $\theta \sim \cos(\omega t)$, nuclear decay rates will also oscillate



Observed number of decays

Expected number of decays

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



The misalignment mechanism

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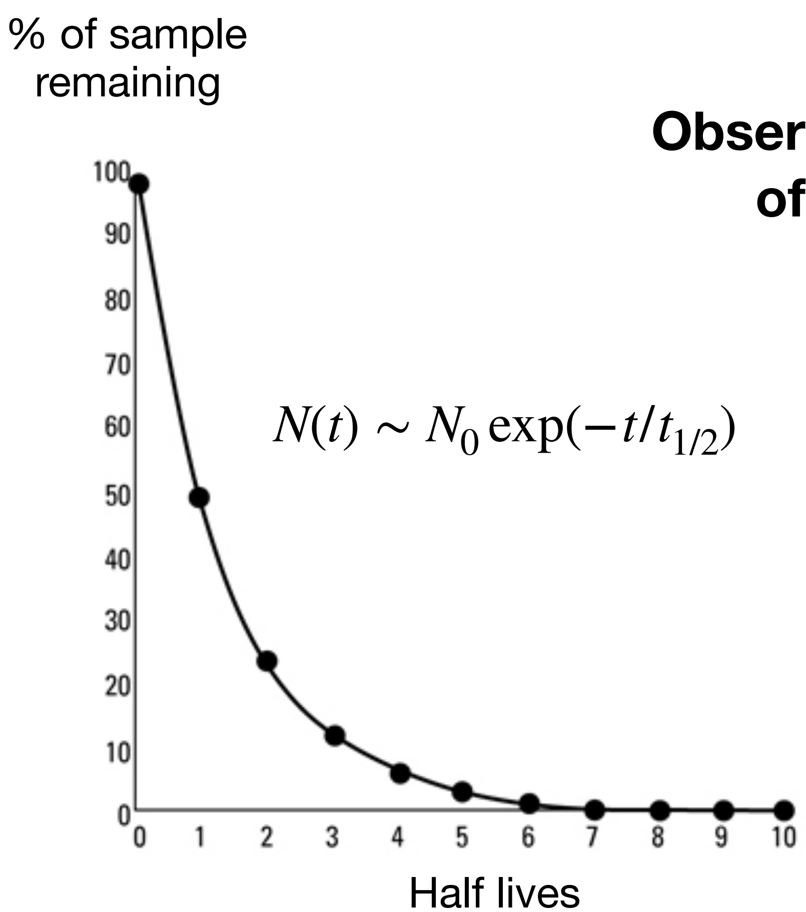

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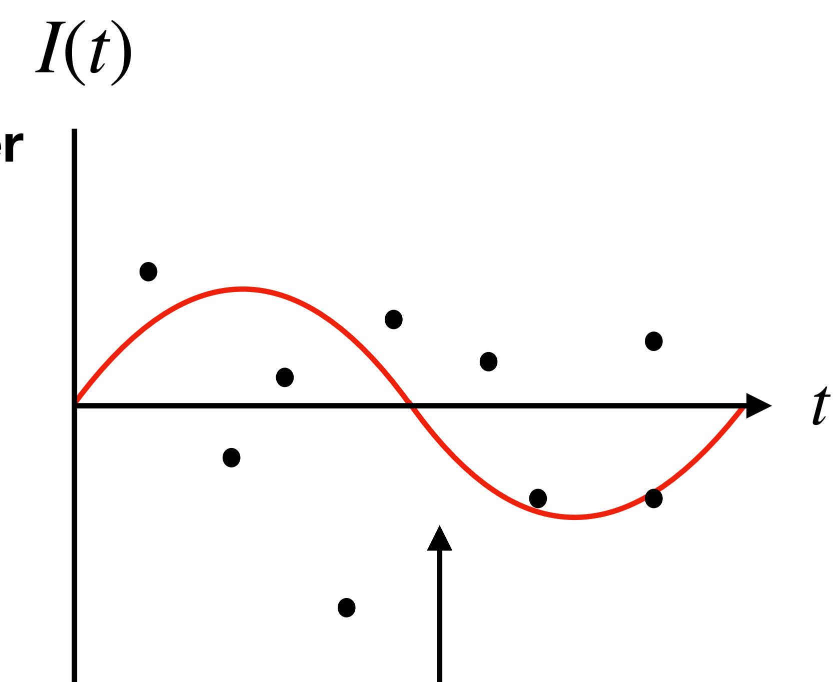
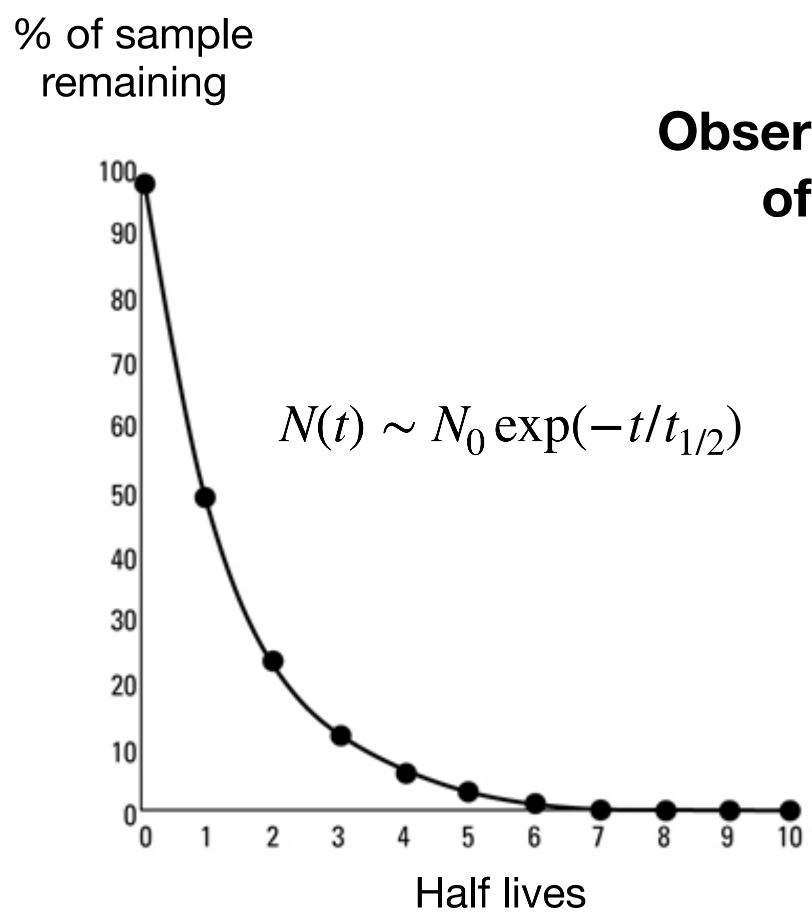


A signature we can use to search for axion DM

The misalignment mechanism

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



Observed number of decays **Expected number of decays**

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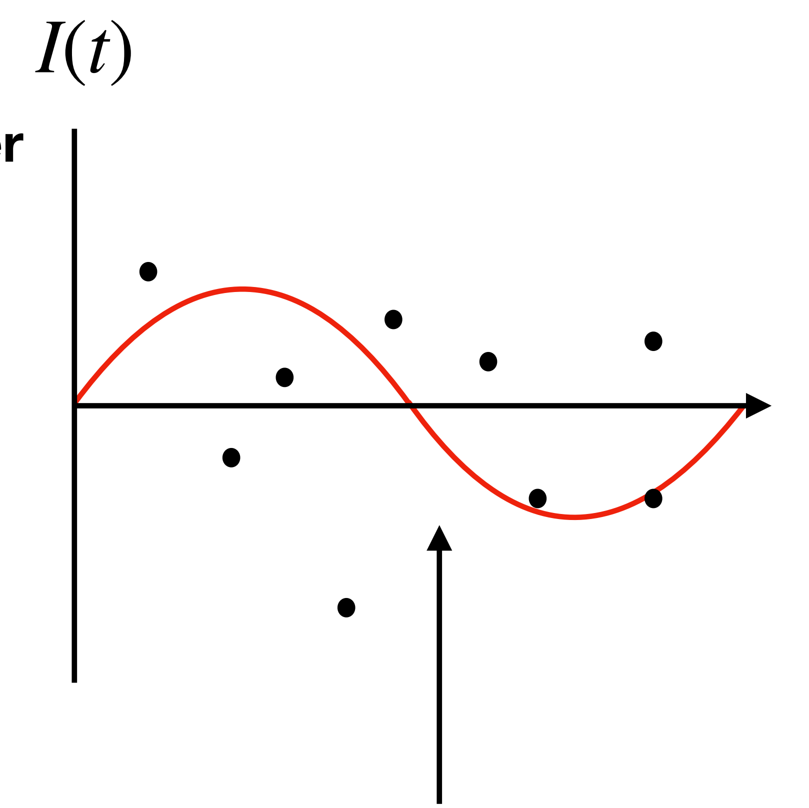

A signature we can use to search for axion DM

- Is there any evidence for this phenomenon?

Anomalies in Radioactive Decay Rates: A Bibliography of Measurements and Theory

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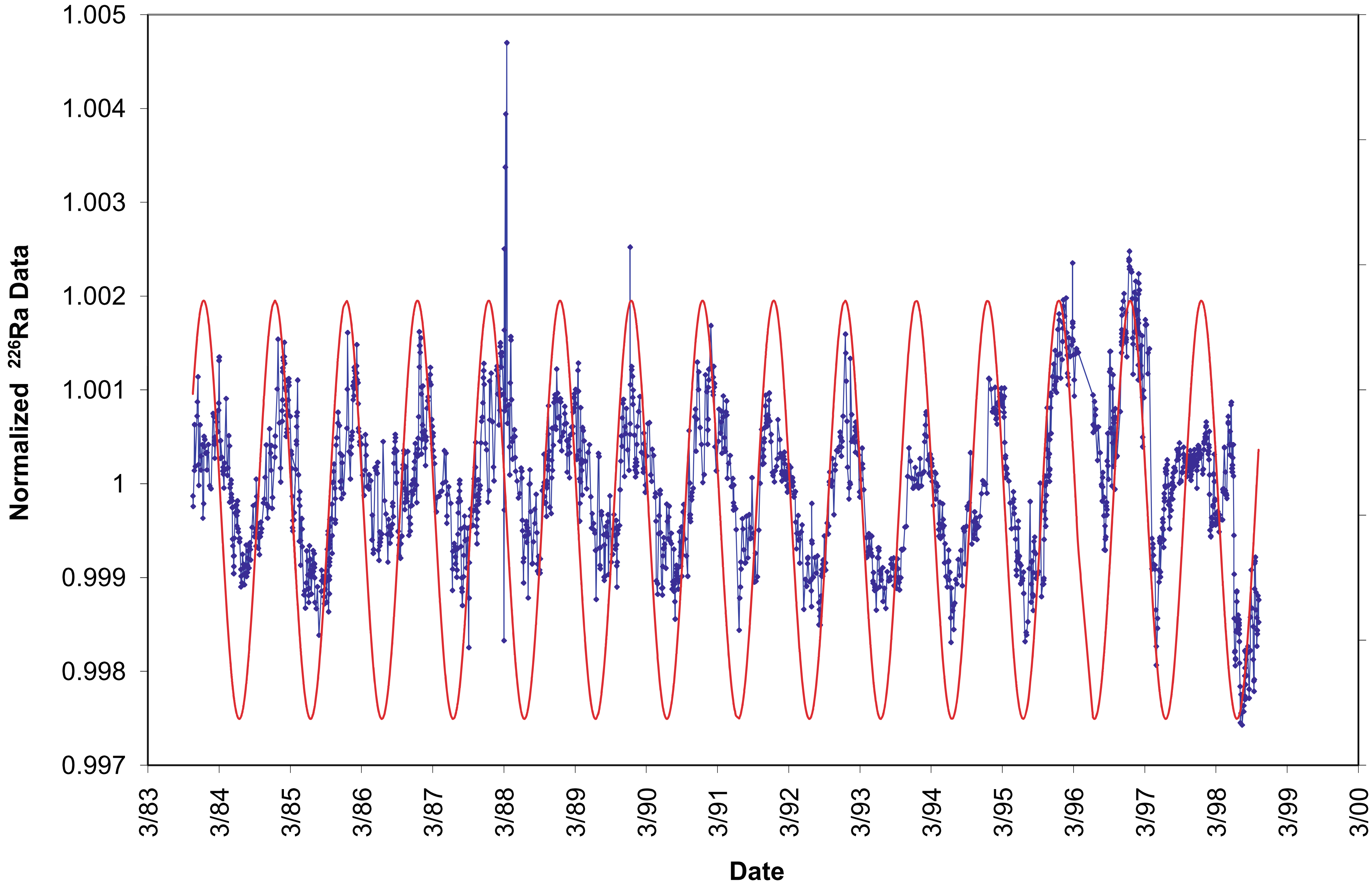
7 December 2020

Abstract. Knowledge of the decay rates (or half-lives) of radioisotopes is critical in many fields, including medicine, archeology, and nuclear physics, to name just a few. Central to the many uses of radioisotopes is the belief that decay rates are fundamental constants of nature, just as the masses of the radioisotopes themselves are. Recently, the belief that decay rates are fundamental constants has been called into question following the observation of various reported anomalies in decay rates, such as apparent periodic variations. The purpose of this bibliography is to collect in one place the relevant literature on both sides of this issue in the expectation that doing so will deepen our understanding of the available data.

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:



“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:

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

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

$$B_F(^3H) = g_V^2\ |M_F|^2 = g_V^2\ \tfrac{1}{2} \left|{}_{^3He}\langle(1/2)^+ \parallel \textstyle\sum_n \tau_n^+ (1/2)^+\rangle_{^3H}\right|^2 ,$$
$$B_{GT}(^3H) = g_A^2\ |M_{GT}|^2 = g_A^2\ \tfrac{1}{2} \left|{}_{^3He}\langle(1/2)^+ \parallel \textstyle\sum_n \tau_n^+ \sigma_n (1/2)^+\rangle_{^3H}\right|^2$$

$$I^\beta(^3\mathrm{H}) = \frac{1}{m_e^5} \int_{m_e}^{E_i - E_f} F_0(Z+1,\, E_e) p_e E_e (E_i - E_f - E_e)^2 \, \mathrm{d}E_e$$

- Where does θ-dependence primarily enter?

Tritium decay

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$$B_F(^3H) = g_V^2\ |M_F|^2 = g_V^2\ \tfrac{1}{2} \left|{}_{^3He}\langle (1/2)^+ \parallel \textstyle\sum_n \tau_n^+ (1/2)^+ \rangle_{^3H}\right|^2 ,$$
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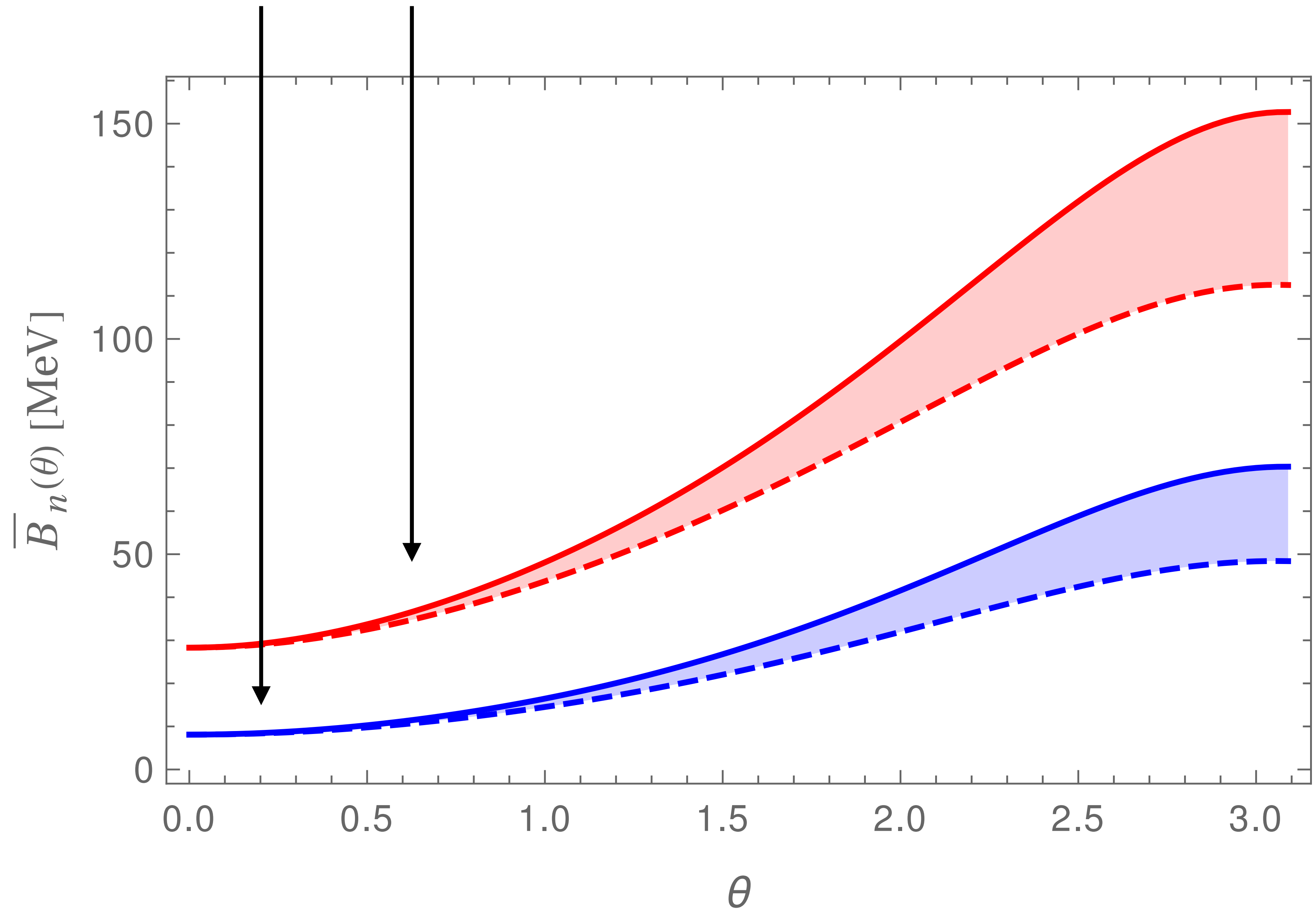
$$I^\beta(^3\text{H}) = \frac{1}{m_e^5} \int_{m_e}^{\underline{E_i - E_f}} F_0(Z+1,\, E_e)\, p_e E_e (\underline{E_i - E_f} - E_e)^2\, \mathrm{d}E_e$$

- Where does θ-dependence primarily enter?

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

Binding energy



θ-dependence of light nuclei and nucleosynthesis, 2006.12321

Tritium decay

- So, let's add a perturbation $\delta E(\theta)$ to $E_i - E_f$:

(Using Primakoff-Rosen approximation for F_0)

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

- From the previous slide, we know how δE depends on θ, and so

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

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

Experimental setup

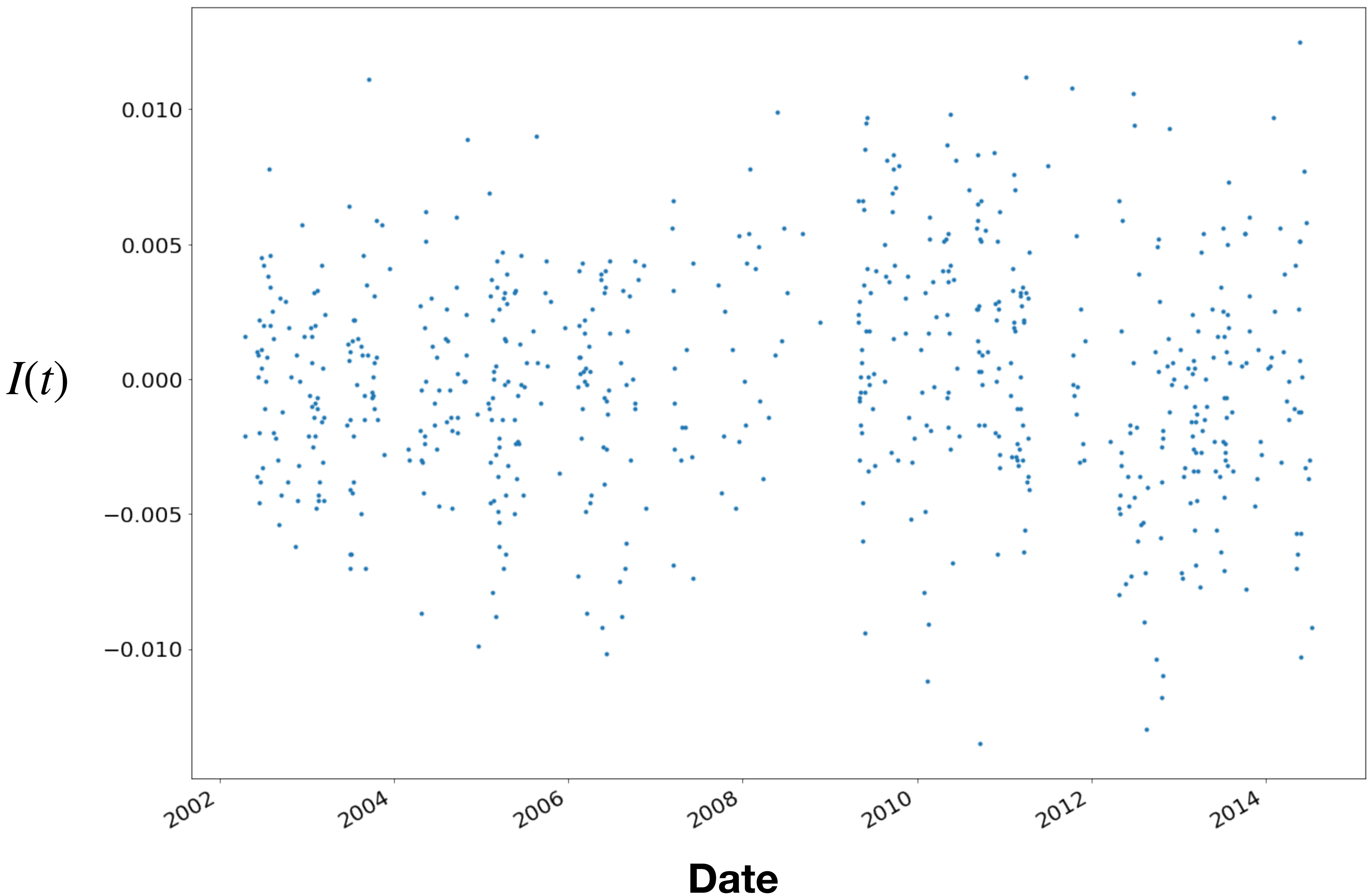
Laboratory liquid scintillator counter
(~ 10,000 USD)

+

1 microcurie of tritium
(~ 3 USD/curie)

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

Tritium decay data



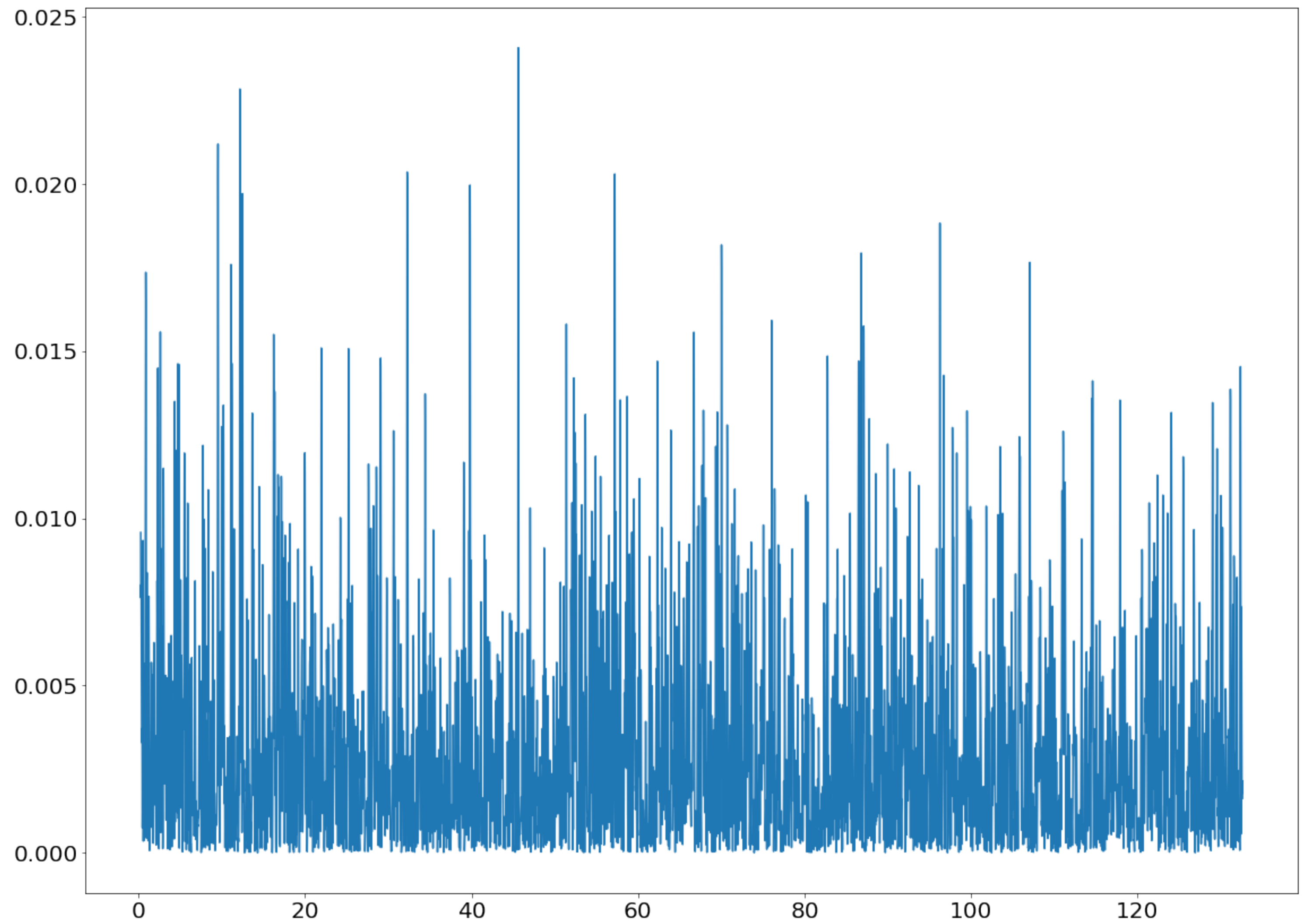
$$I(t) \equiv \frac{N(t) - \langle N \rangle}{\langle N \rangle}$$

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

Lomb-Scargle periodogram

- Let's convert the data into frequency space:

Power



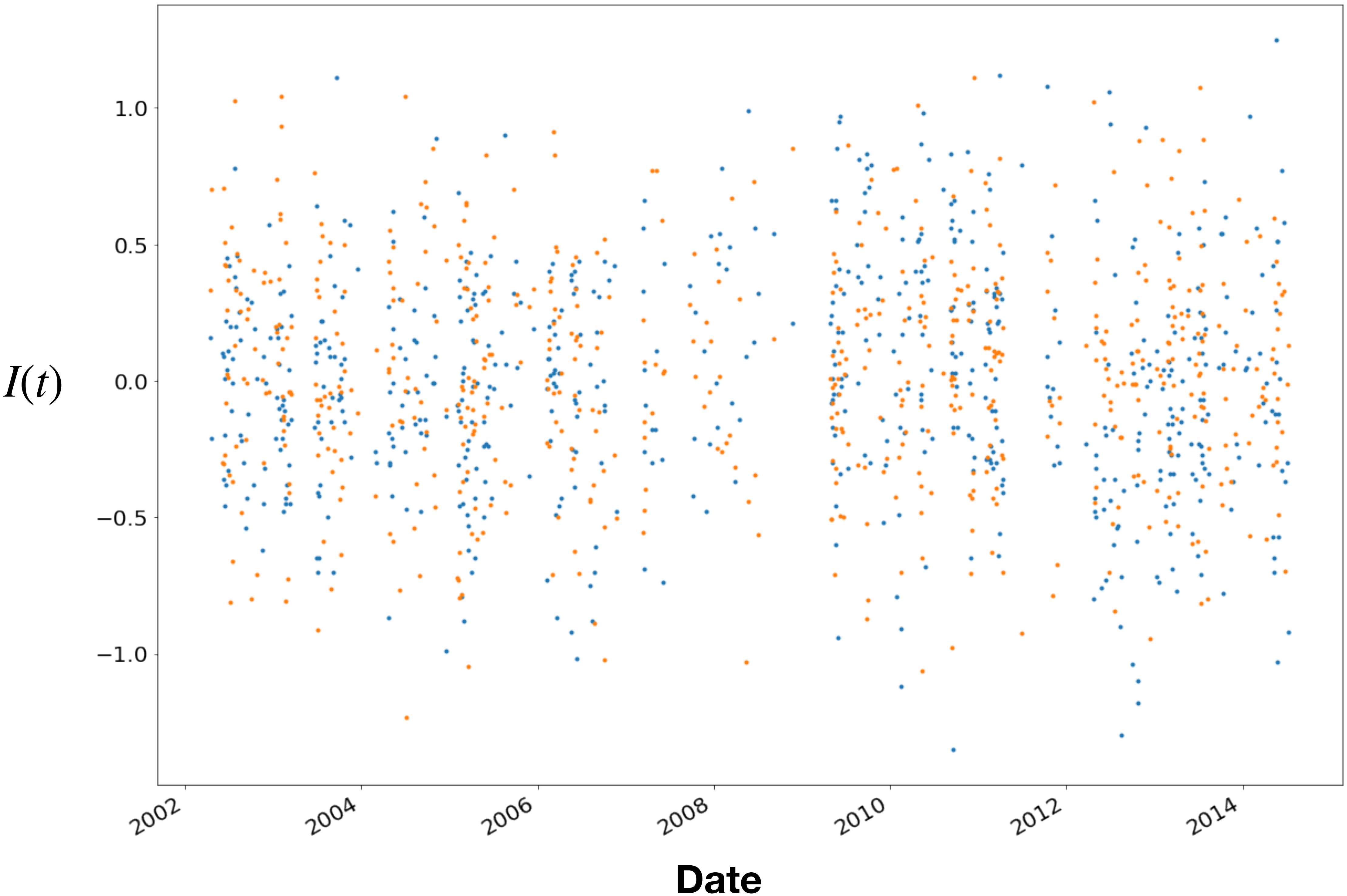
Frequency (1/year)

- Is there evidence of periodic effects here?

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

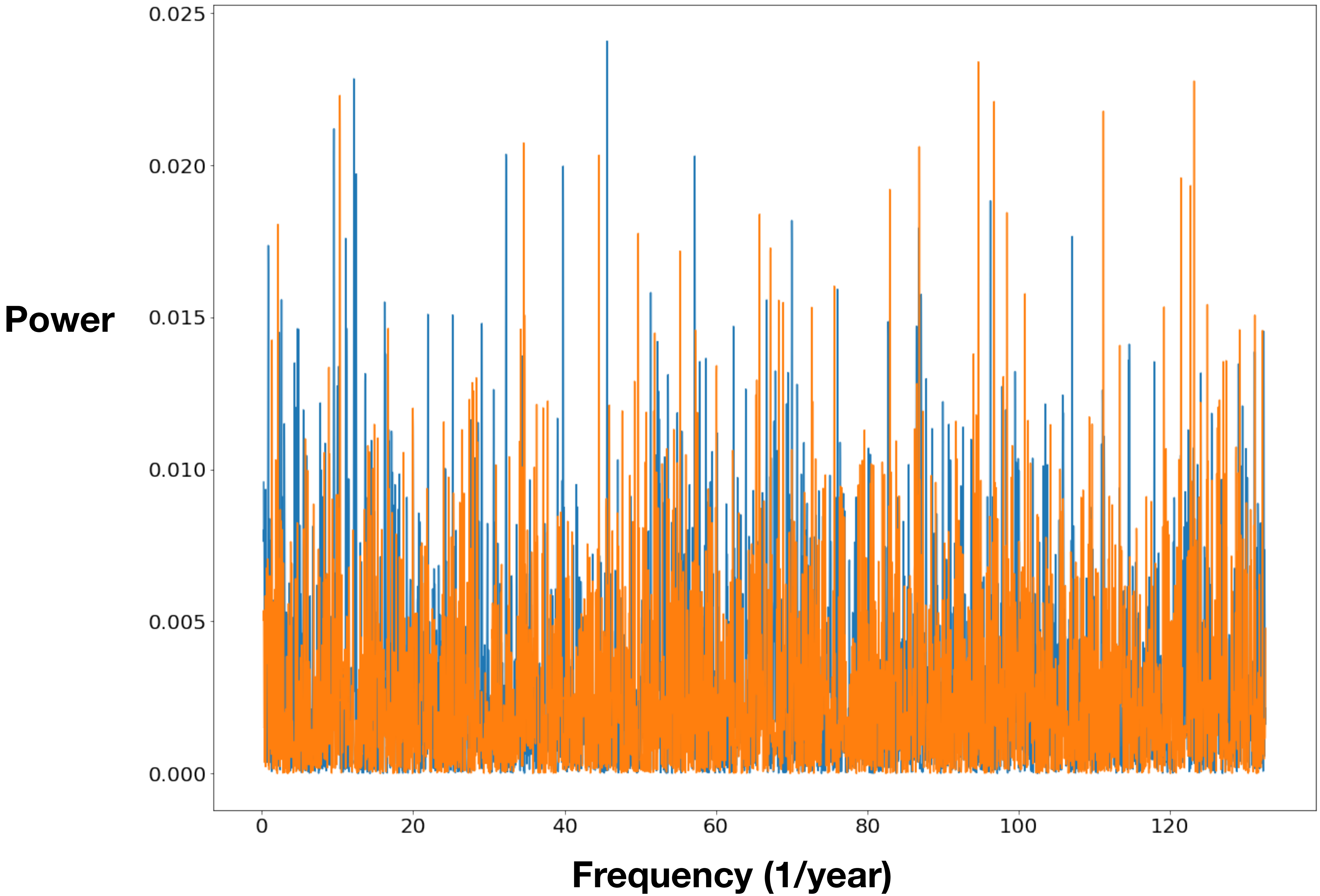
1. Generate N datasets with randomly generated $I(t)$
2. For each dataset, convert to frequency space
3. Construct the CDF at each frequency
4. Find the 95 % CL limit (including look-elsewhere)
5. Compare to the real power at that frequency

- For example:



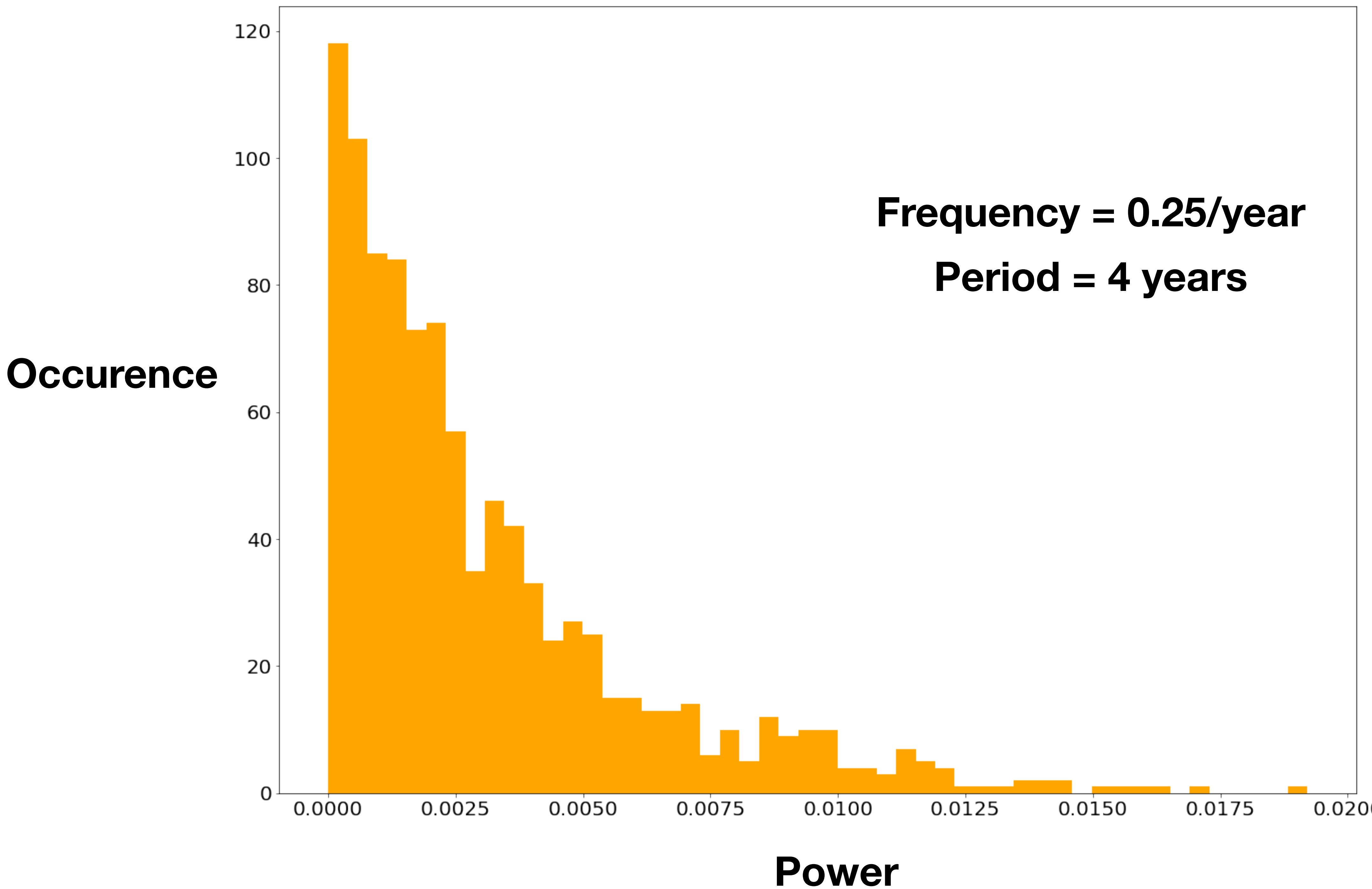
Original data, Monte Carlo data

Lomb-Scargle periodogram



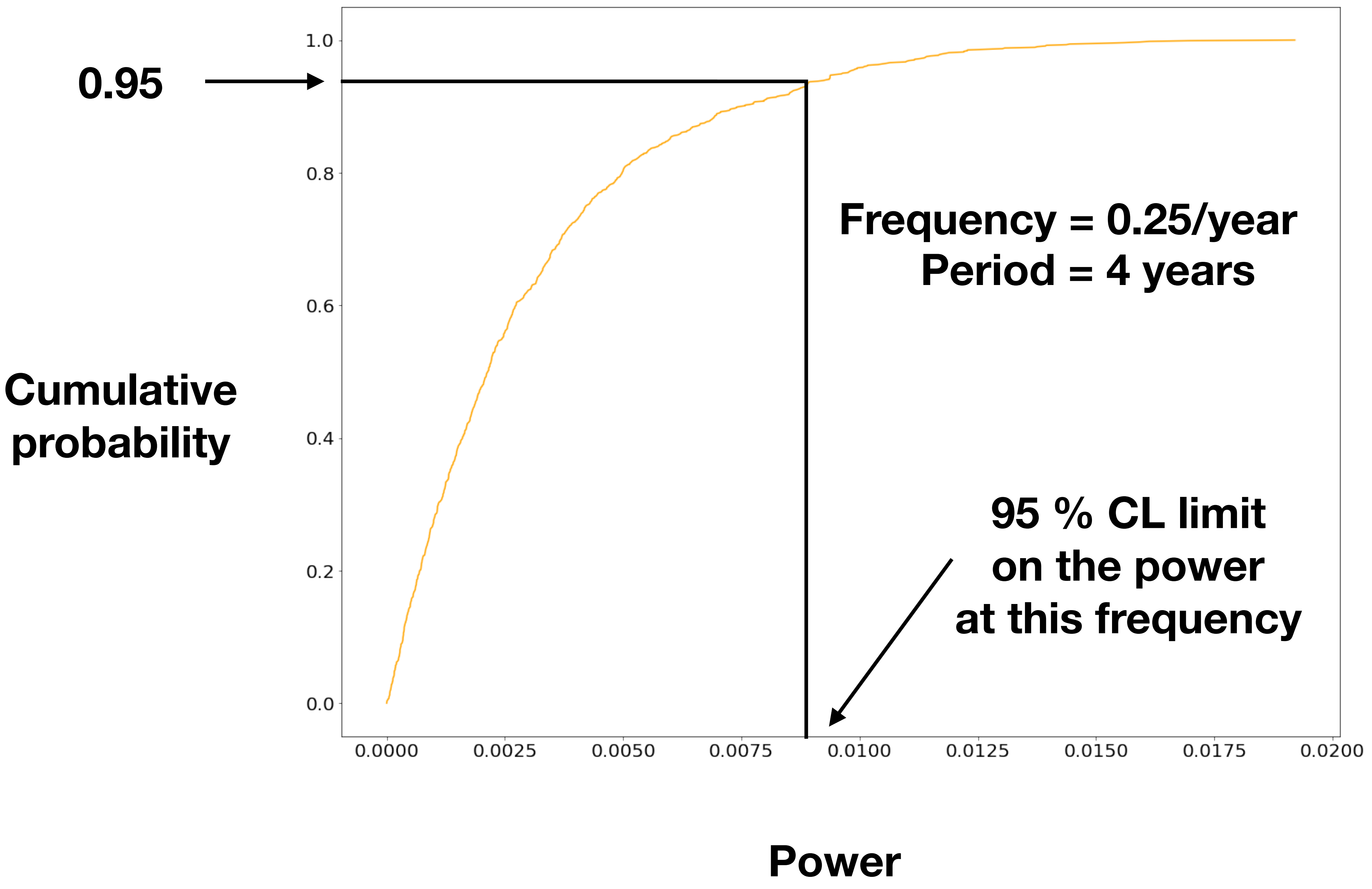
Original data, **Monte Carlo data**

- Repeat N times to estimate the power PDF at each frequency

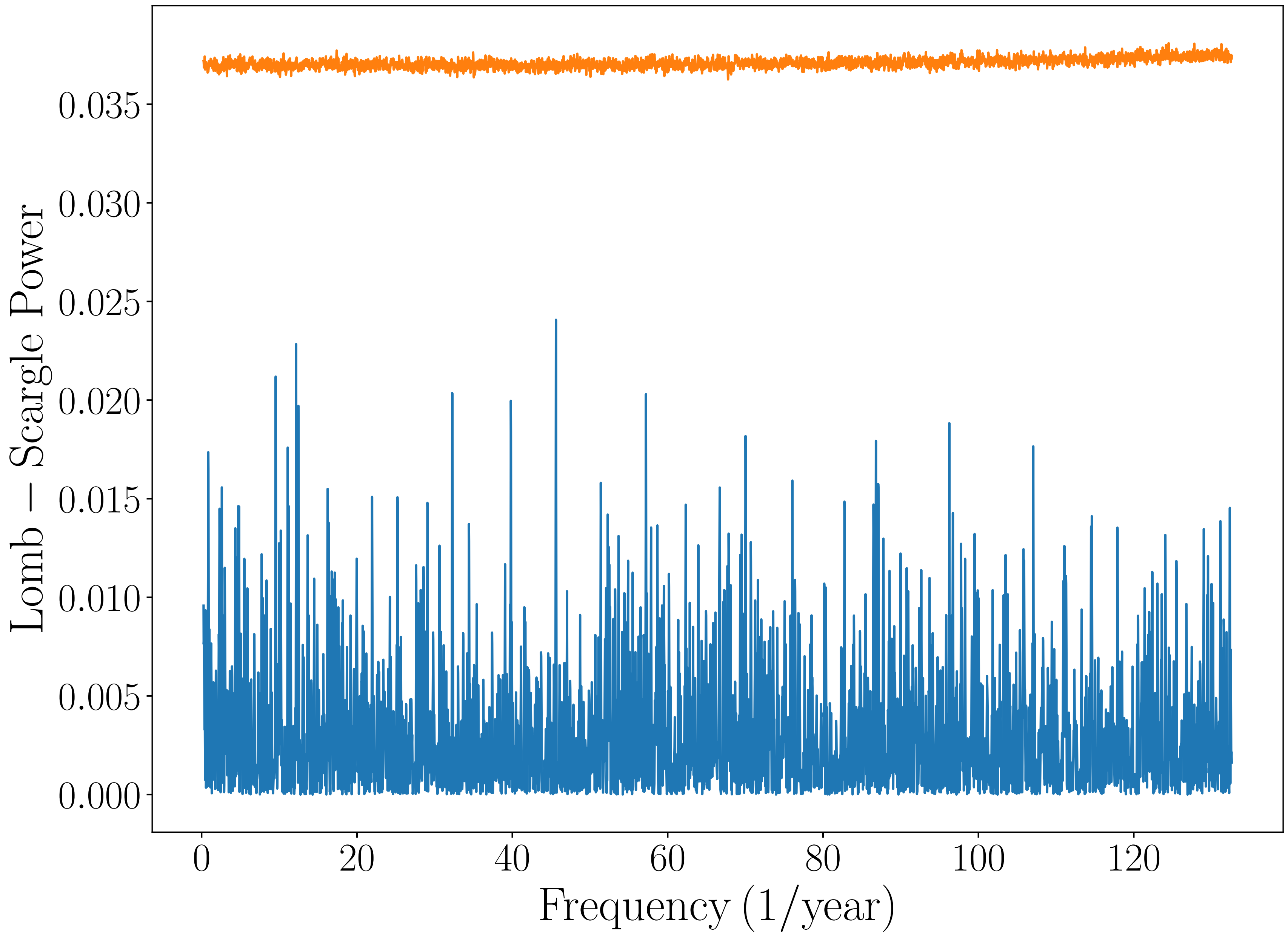


Monte Carlo data

- Integrate to get the power CDF:



- Repeating this at each frequency:



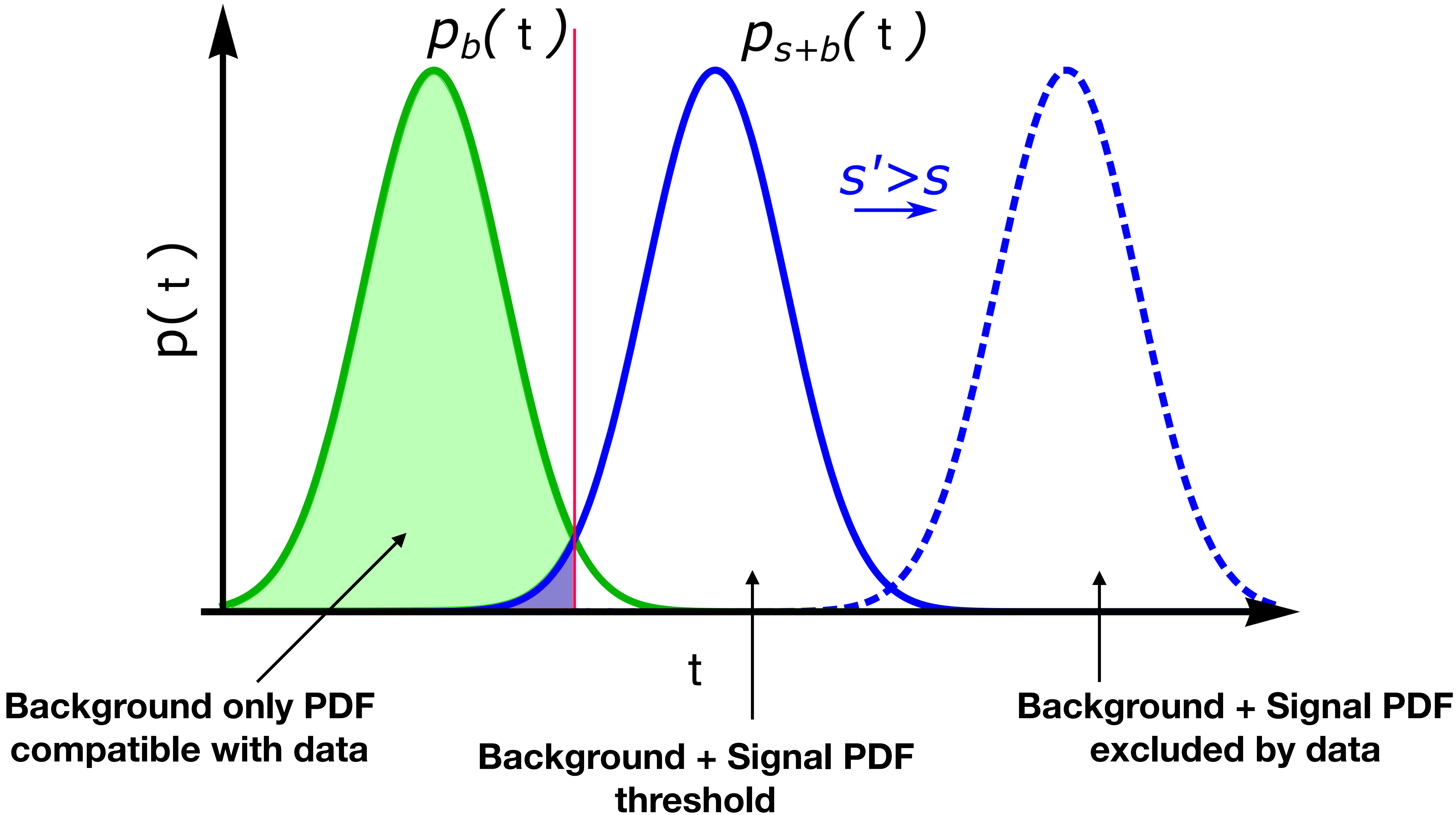
Original data, Monte Carlo limit

- 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

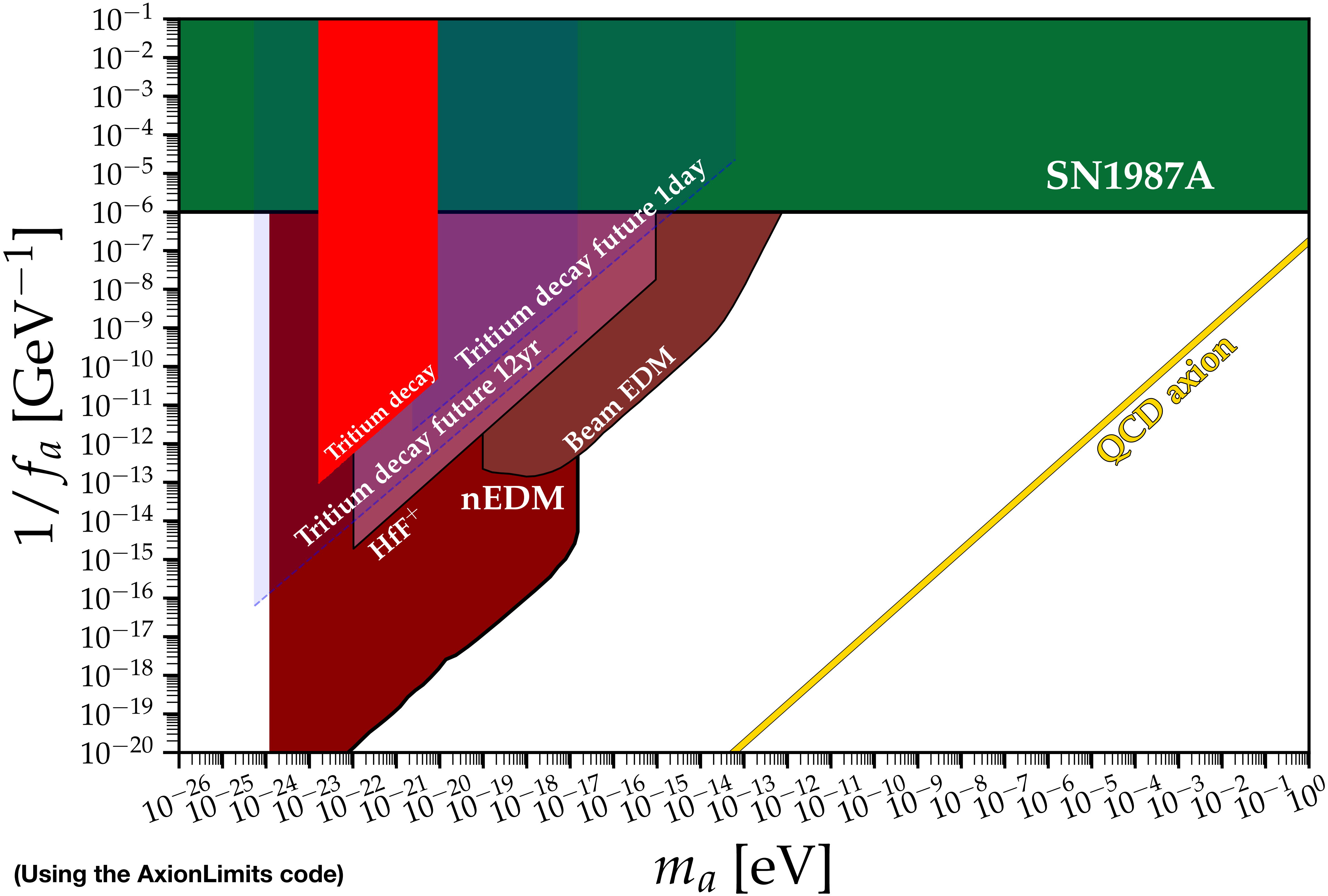
(Figure via 1905.13650)

- Repeating this with an injected axion signal:



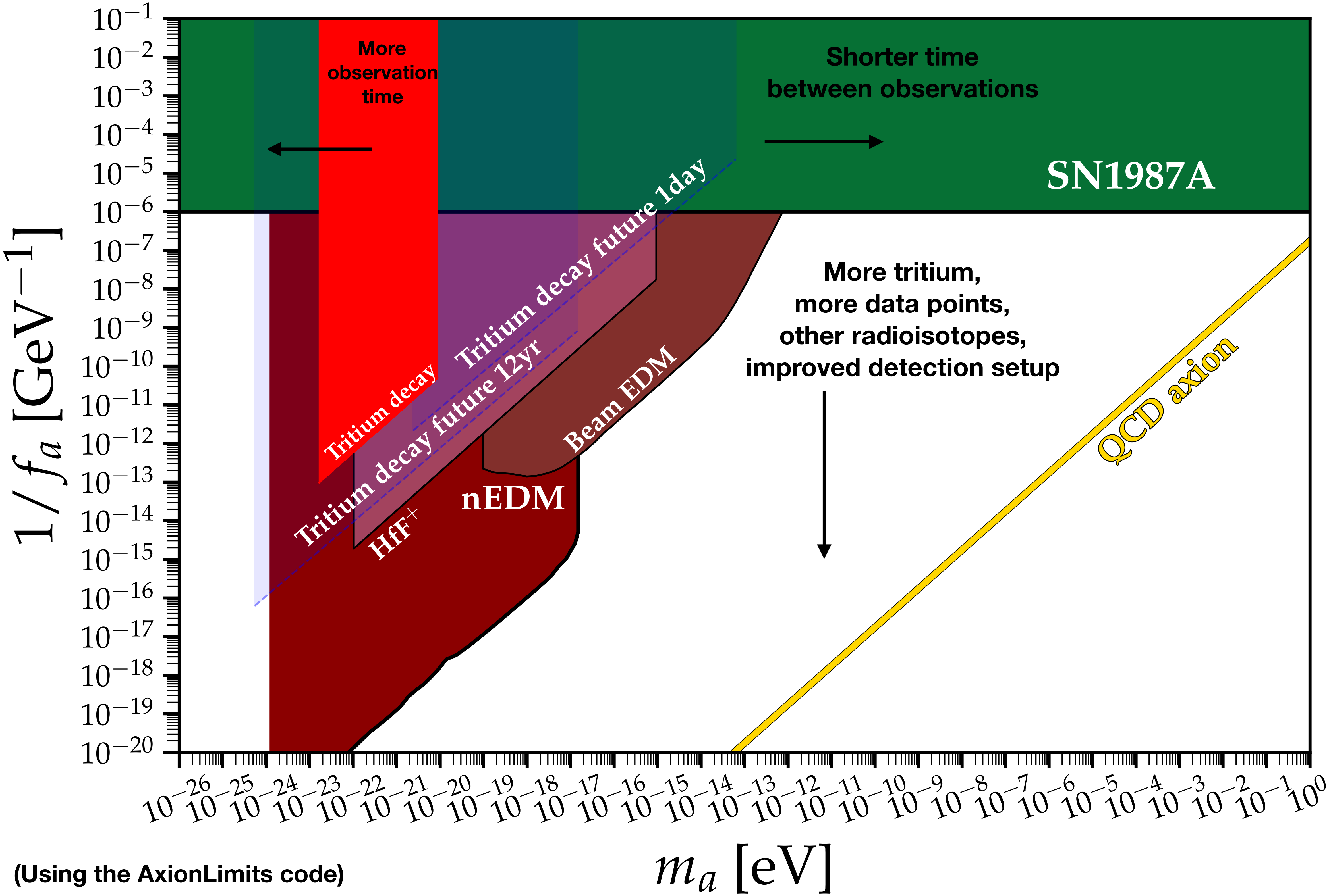
- Varying the axion coupling allows us to find the threshold values

Resulting constraint



(Using the AxionLimits code)

Resulting constraint



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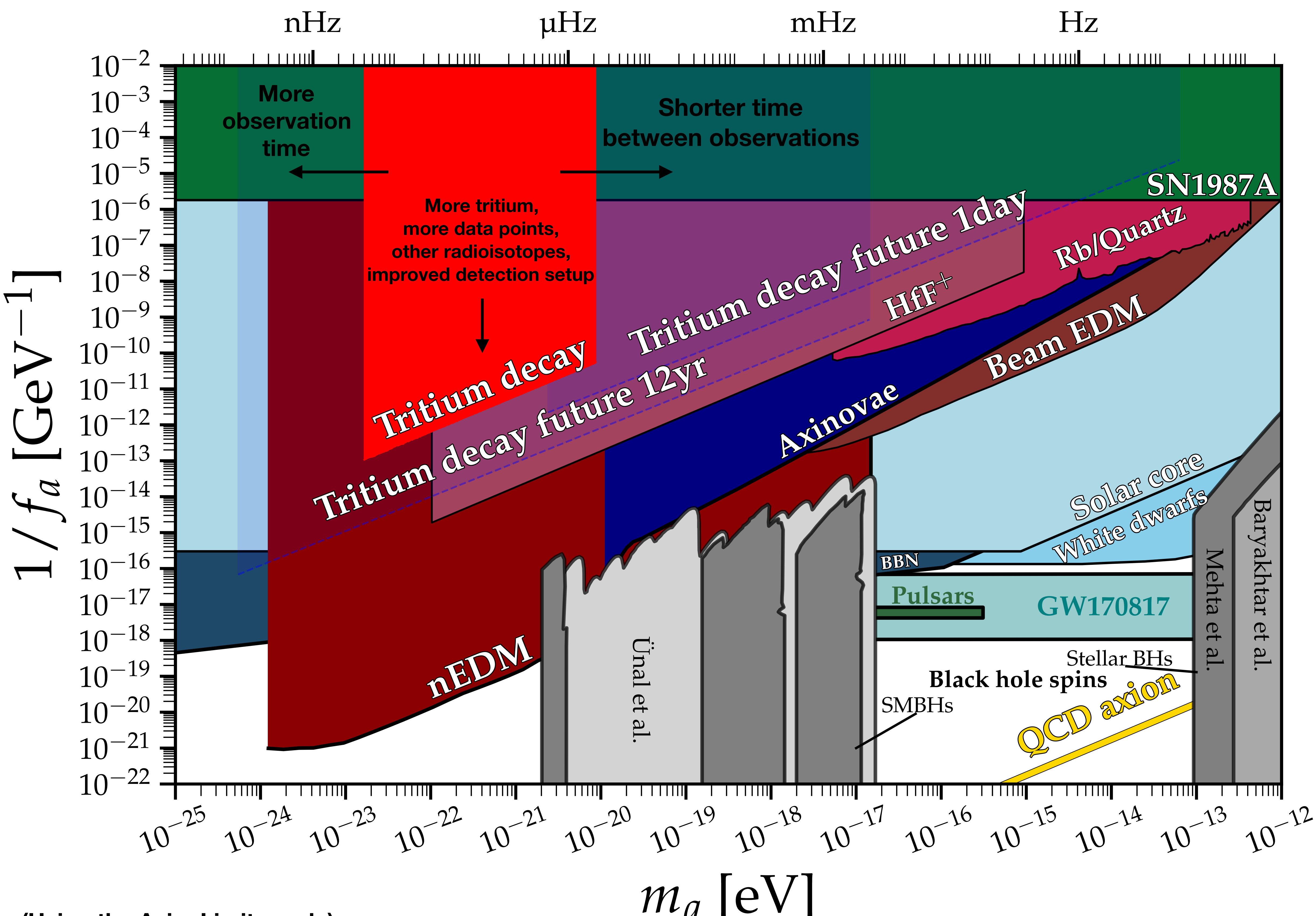

(Using the AxionLimits code)

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!