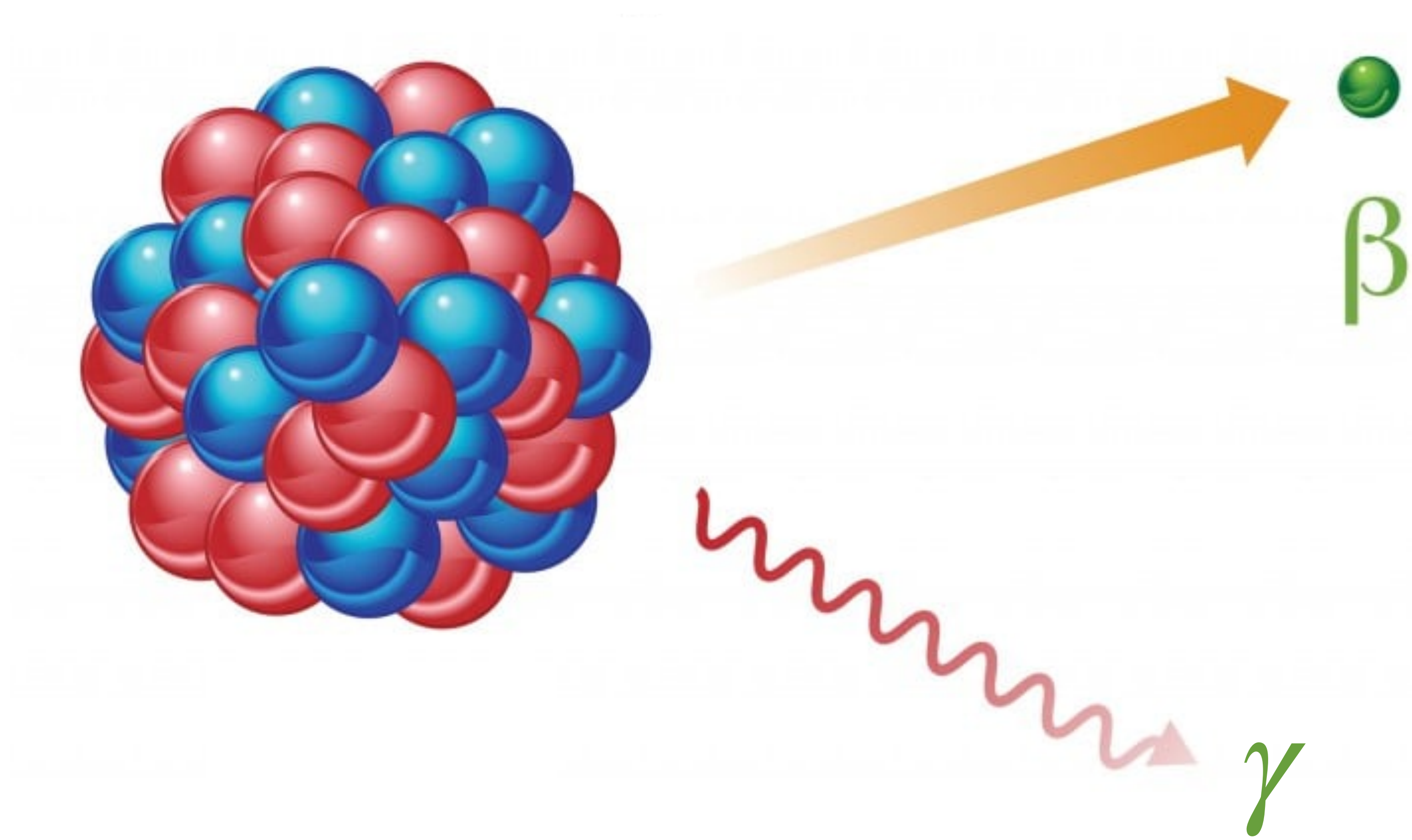
Searching for axion dark matter via nuclear decay anomalies



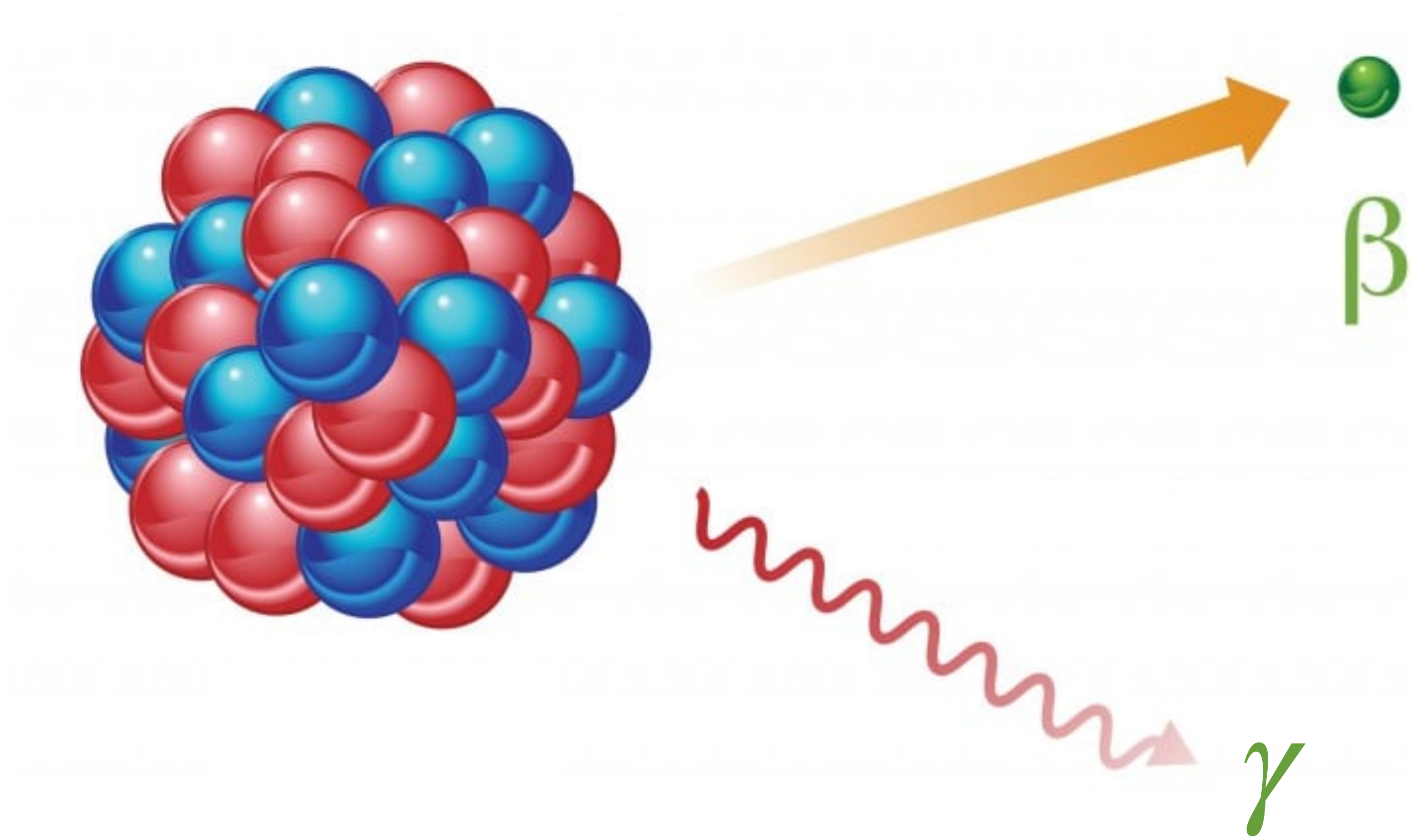
Nick Houston, Beijing University of Technology

In collaboration with Xin Zhang (NAOC) and Tianjun Li (ITP-CAS)

Based on 2212.XXXX

Axion 2022, Nov 2022 , nhouston@bjut.edu.cn

The big picture



Fundamentally, we believe that nuclear decay is **random** and **spontaneous**

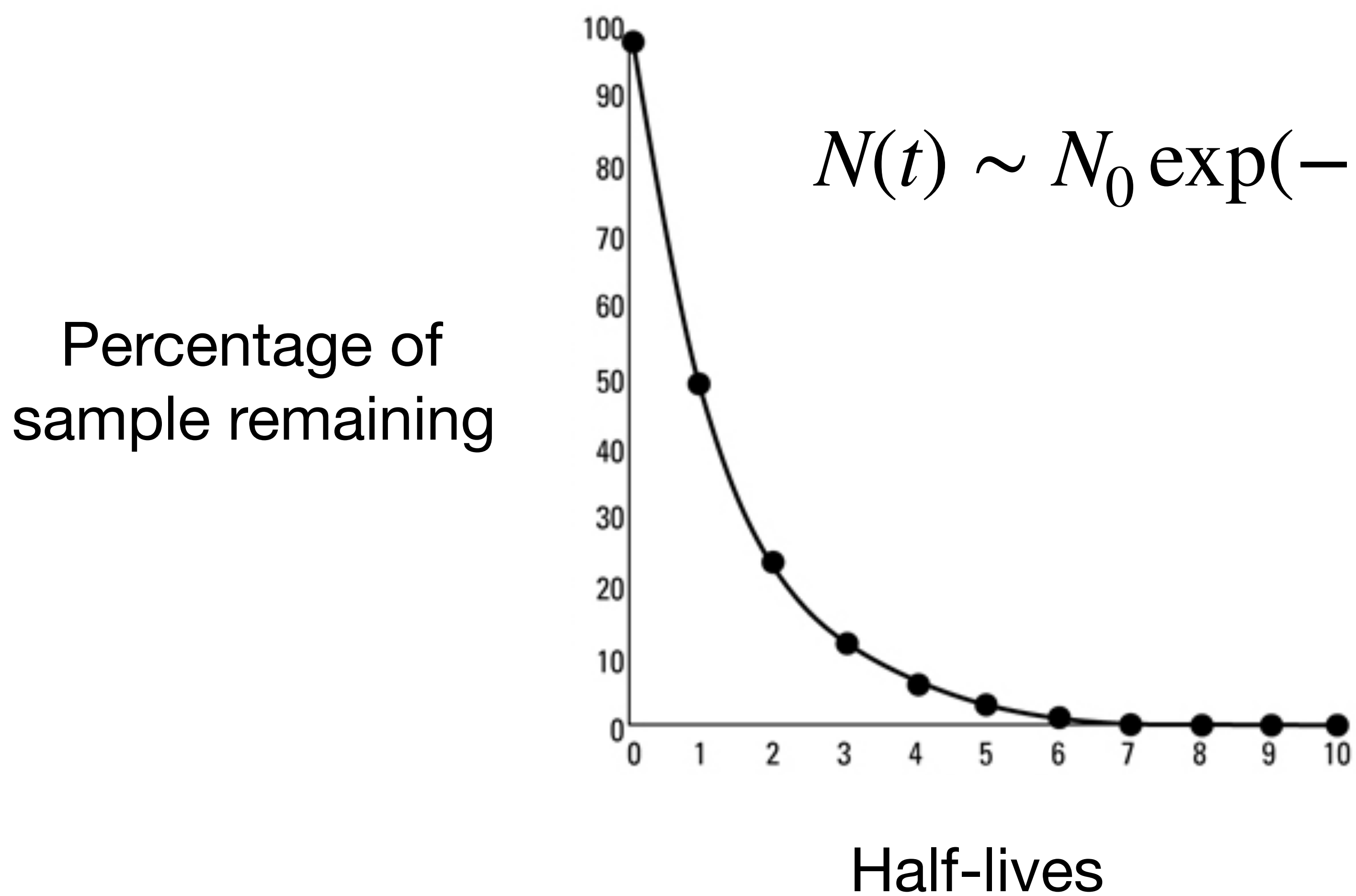
However, we also expect QCD axion DM will lead to an oscillating θ-angle

As θ modifies nuclear physics, this can lead to non-random decay behaviour

What is nuclear decay?

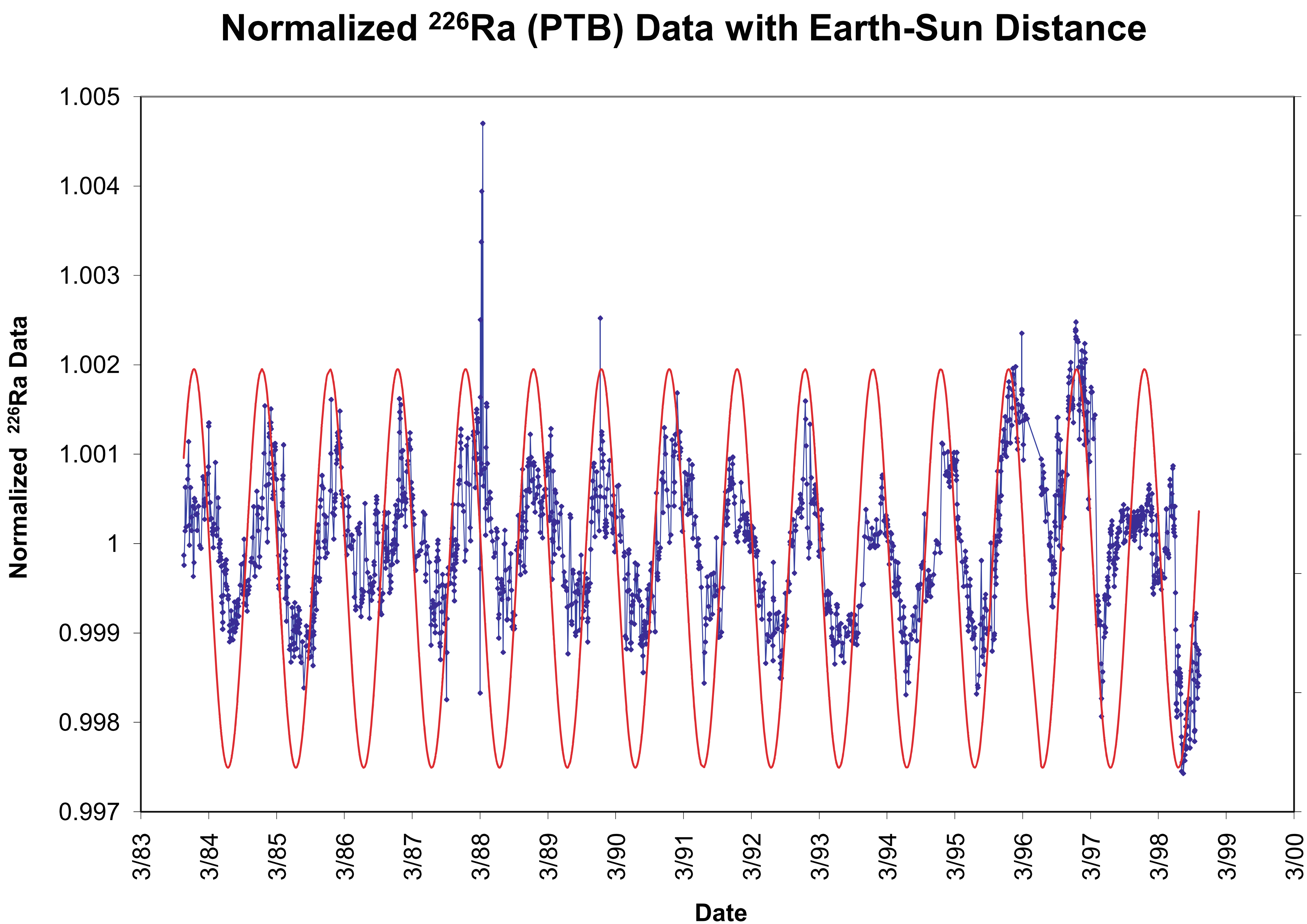
- "Nuclear decay is the process by which an unstable atom loses energy by emitting radiation, generally changing the number of protons and neutrons in the nucleus"

- We can only predict how often this will happen on average



$$N(t) \sim N_0 \exp(-t/t_{1/2})$$

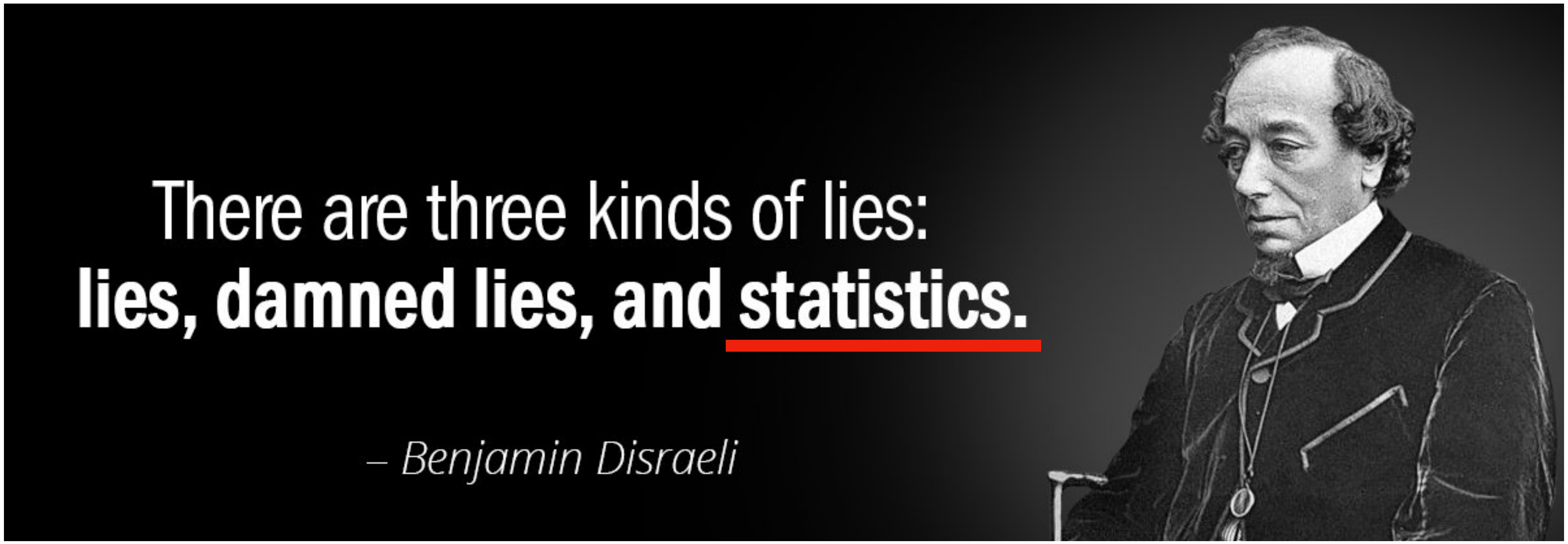
- This is well established science, why should we question this?



- Should we believe this?

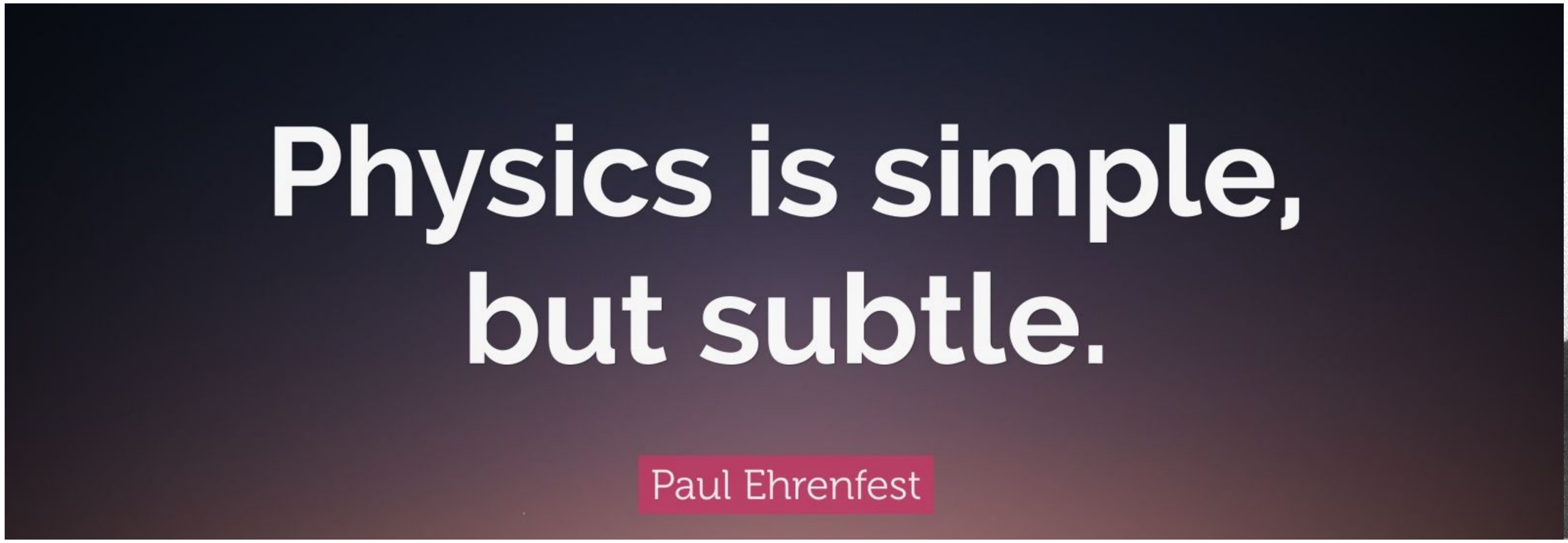
"Time-dependent nuclear decay parameters: New evidence for new forces?", ***Space Sci.Rev.*** **145 (2009) 285-335**
"Anomalies in Radioactive Decay Rates: A Bibliography of Measurements and Theory", arxiv: 2111.03149

Reasons to be skeptical: 1



- The data analysis here is quite subtle
- Is it possible these anomalies are due to incorrect statistics?

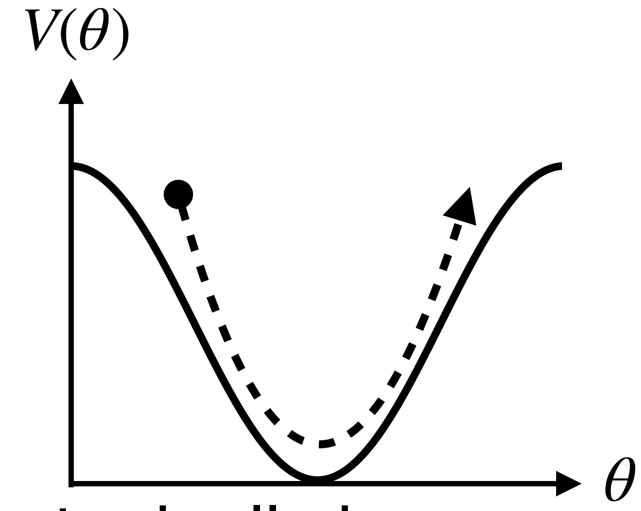
Reasons to be skeptical: 2



- Can we explain these anomalies without rewriting the laws of physics?
- Did seasonal variations in temperature influence the experiment?
- Is there any possible explanation in terms of fundamental physics?

Recall: 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

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

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

$$d_n = \frac{g_{\pi NN}}{4\pi} \left(\frac{e}{m_p f_\pi} \right) \ln \left(\frac{m_\rho}{m_\pi} \right) \left(\frac{m_u m_d}{m_u + m_d} \right) \theta, \; m_n - m_p \simeq \left(1.29 + 0.37\, \theta^2 \right) \mathrm{MeV}$$

- By modifying nuclear binding energies, θ changes decay rates

Tritium decay

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

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

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

$$B_F(^3\mathrm{H}) = \frac{1}{2} \left| {}_{^3\mathrm{He}}\langle (1/2)^+ \parallel \sum_n \tau_n^+ \parallel (1/2)^+ \rangle_{^3\mathrm{H}} \right|^2, \quad B_{GT}(^3\mathrm{H}) = g_A^2 \frac{1}{2} \left| {}_{^3\mathrm{He}}\langle (1/2)^+ \parallel \sum_n \tau_n^+ \sigma_n \parallel (1/2)^+ \rangle_{^3\mathrm{H}} \right|^2$$

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

- Where does θ-dependence enter?

Tritium decay

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

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

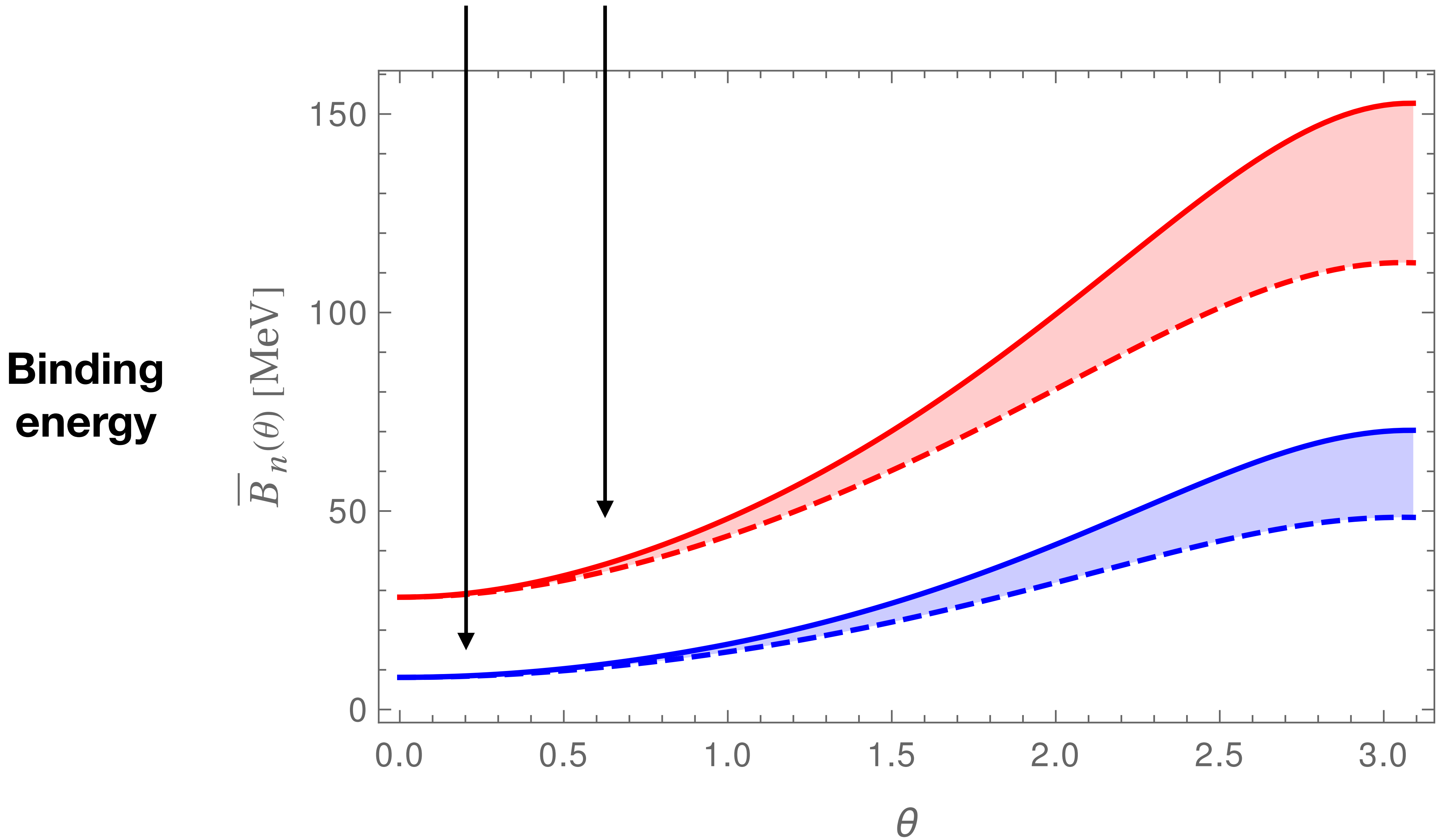
$$\Gamma^\beta(^3\mathrm{H}) = \frac{1}{2\pi^3} m_e \left(G_\beta m_e^2\right)^2 \left(B_F(^3\mathrm{H}) + B_{GT}(^3\mathrm{H})\right) I^\beta(^3\mathrm{H})$$

$$B_F(^3\mathrm{H}) = \frac{1}{2}\left|{}_{^3\mathrm{He}}\langle(1/2)^+ \parallel \sum_n \tau_n^+ \parallel (1/2)^+\rangle_{^3\mathrm{H}}\right|^2,\quad B_{GT}(^3\mathrm{H}) = g_A^2 \frac{1}{2}\left|{}_{^3\mathrm{He}}\langle(1/2)^+ \parallel \sum_n \tau_n^+ \sigma_n \parallel (1/2)^+\rangle_{^3\mathrm{H}}\right|^2$$

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

- Where does θ-dependence enter?

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



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)**

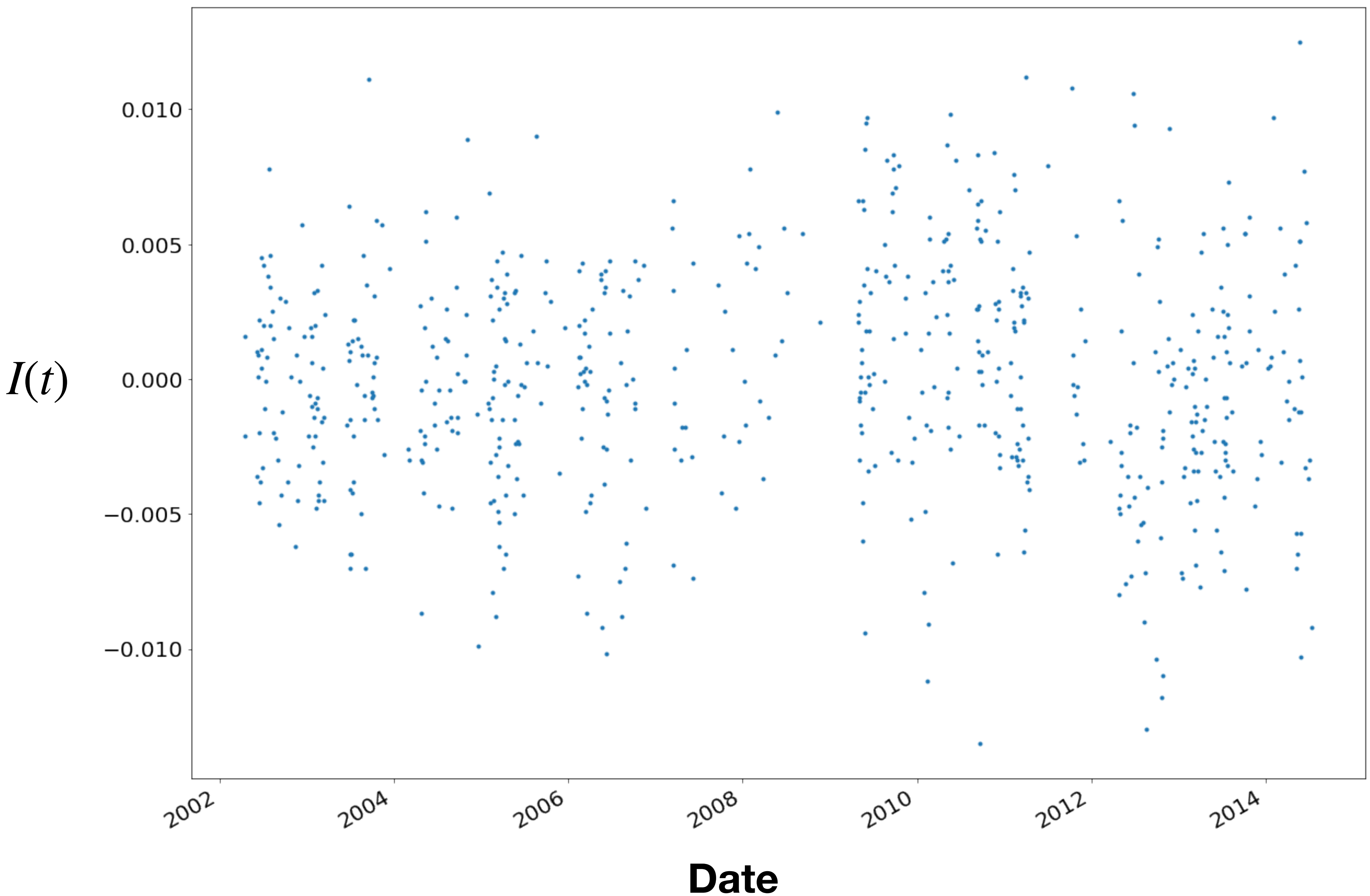
$$\frac{\delta\Gamma^\beta}{\Gamma^\beta} = 1 - \frac{5\delta E(\theta)\left(E_f^2 - 2E_f(E_i + m_e) + E_i^2 + 2E_i m_e + 3m_e^2\right)}{(E_f - E_i + m_e)\left(3m_e(E_i - E_f) + (E_f - E_i)^2 + 6m_e^2\right)} + \mathcal{O}(\delta E^2)$$

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

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

- So, now all we need is some tritium…

Tritium decay data



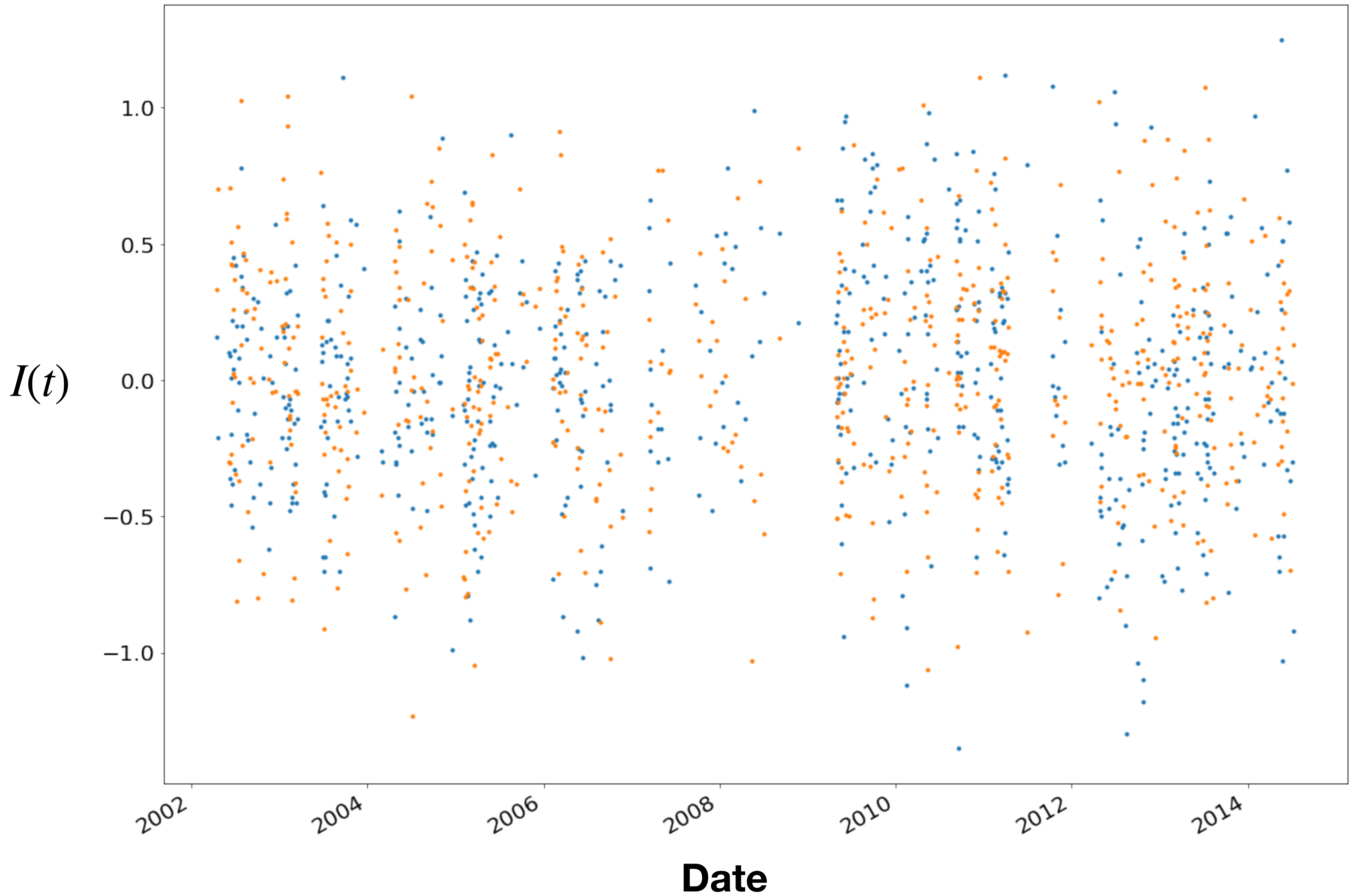
$$I(t) \equiv \frac{N(t) - \langle N \rangle}{\langle N \rangle}$$

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

- 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
5. Compare to the real power at that frequency

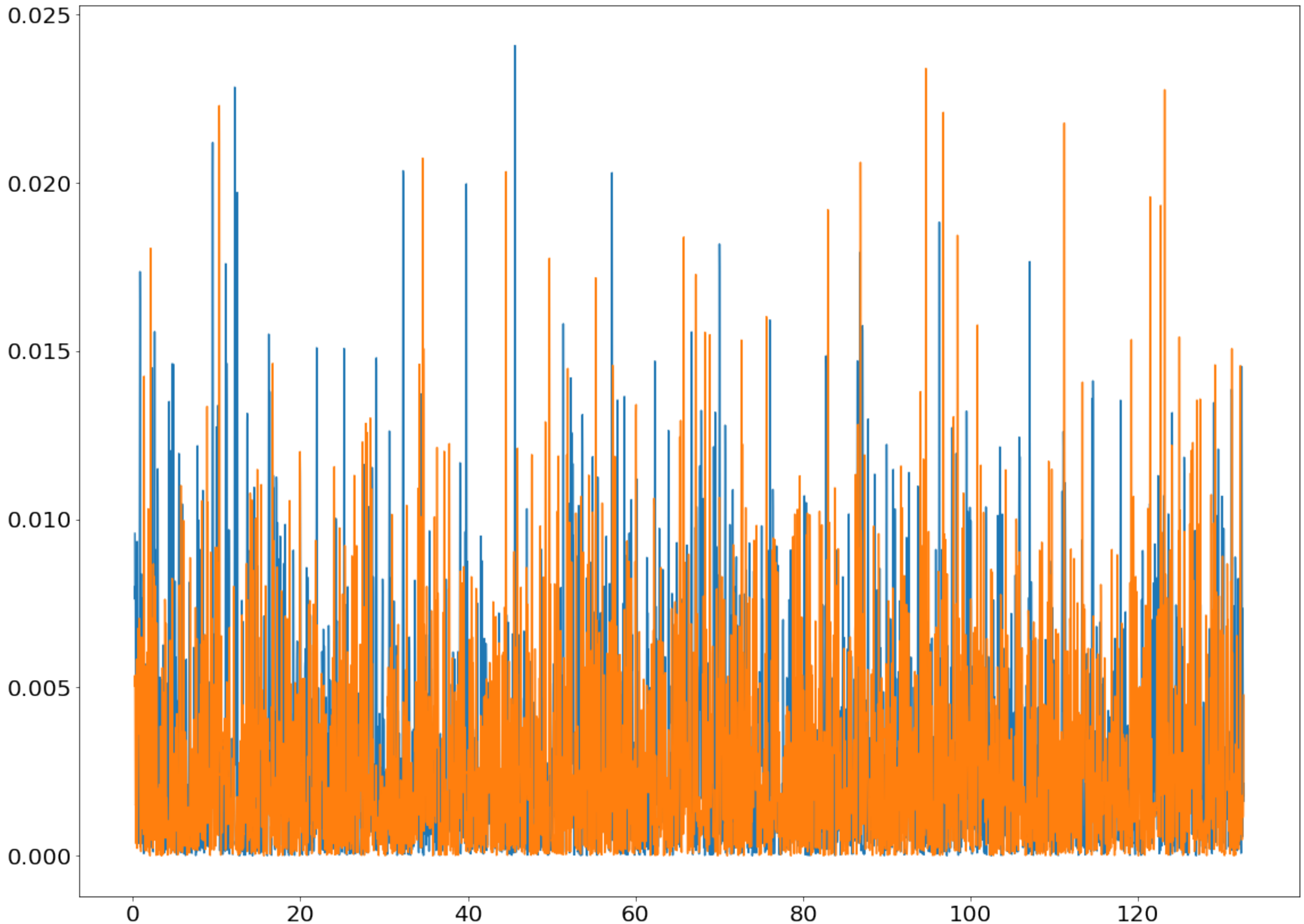
- For example:



Original data, **Monte Carlo data**

Lomb-Scargle periodogram

Power

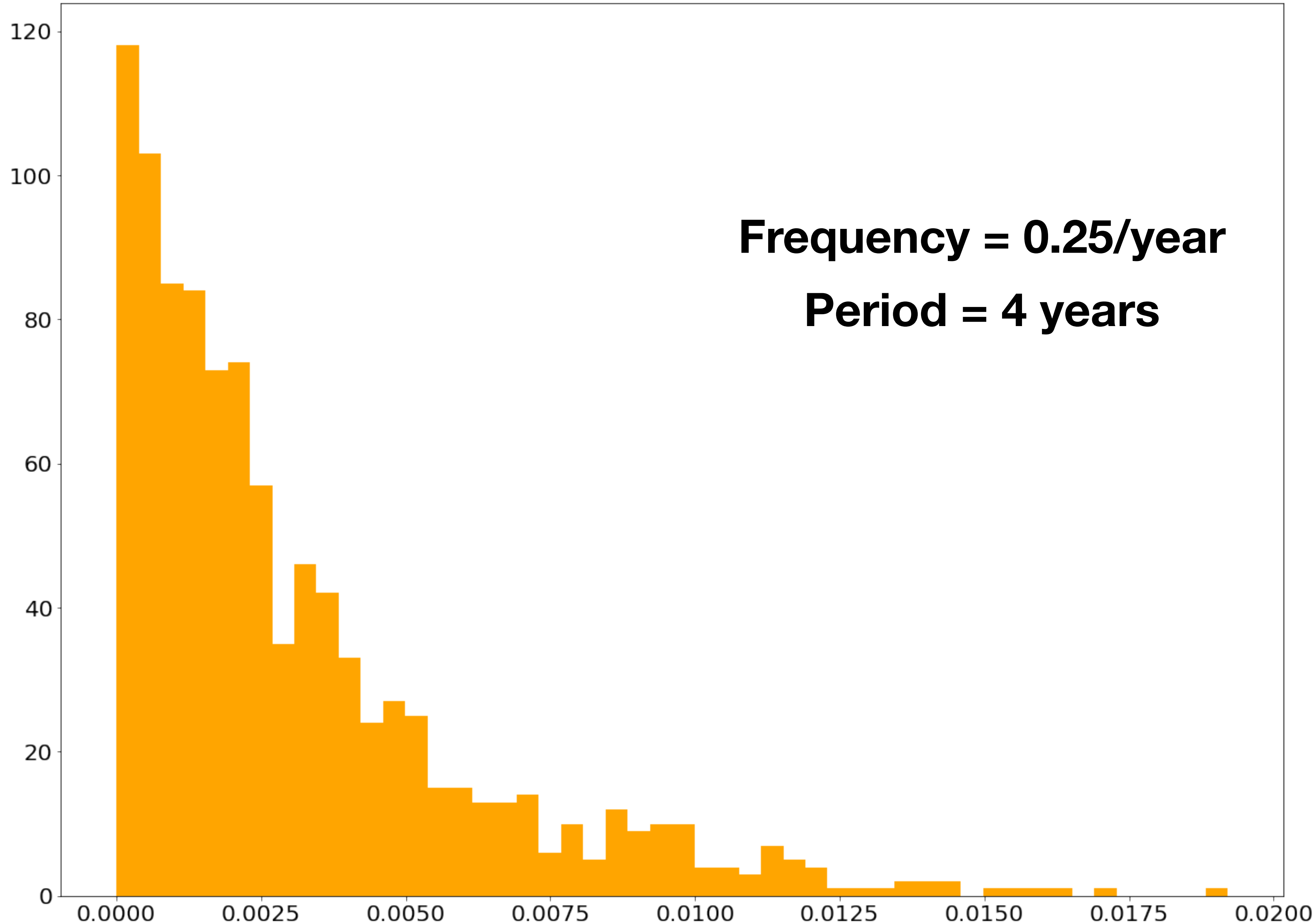


Frequency (1/year)

Original data, Monte Carlo data

- Repeating this process N times allows us to estimate the probability distribution function (PDF) of power at each frequency

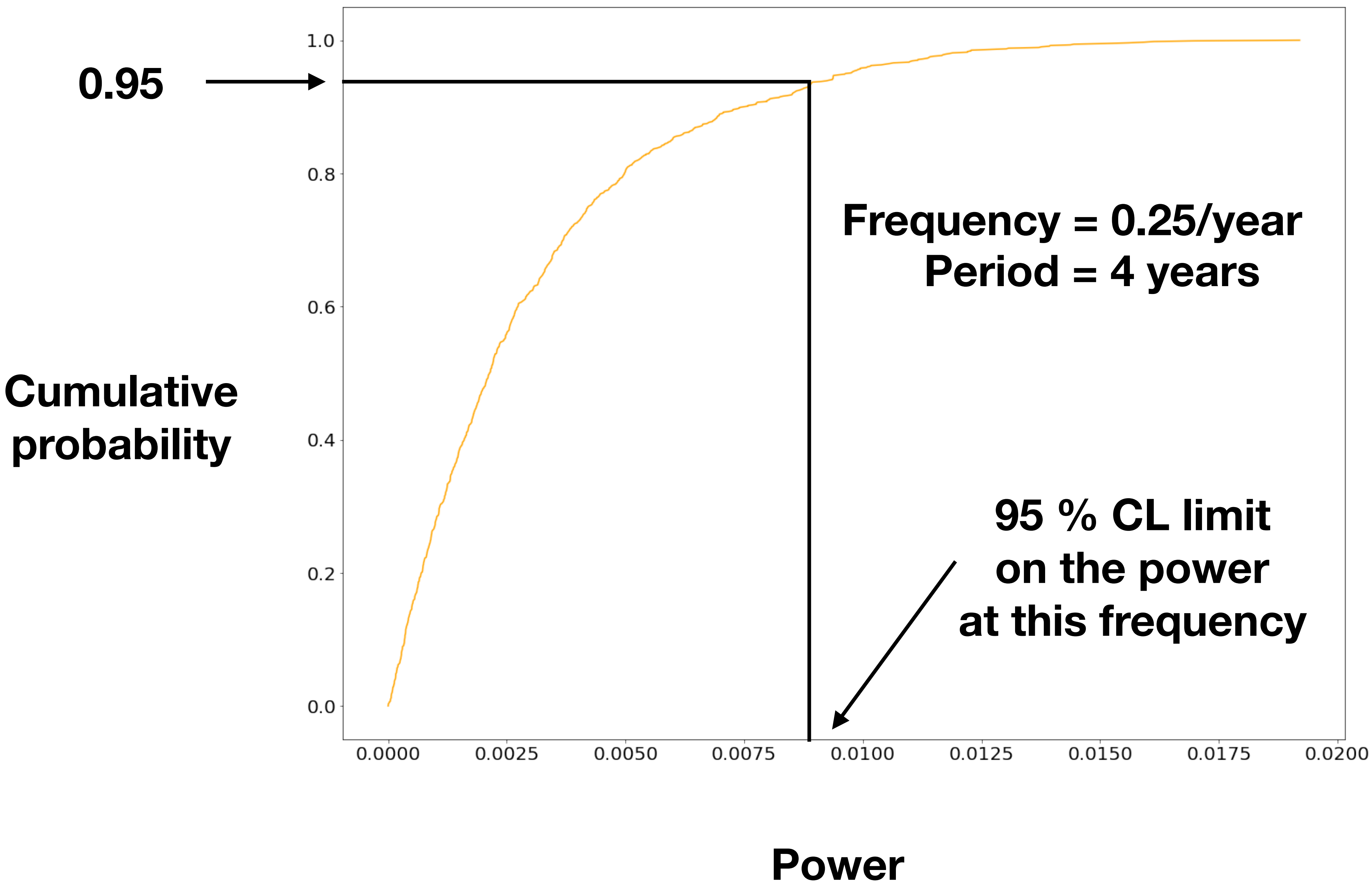
Occurence



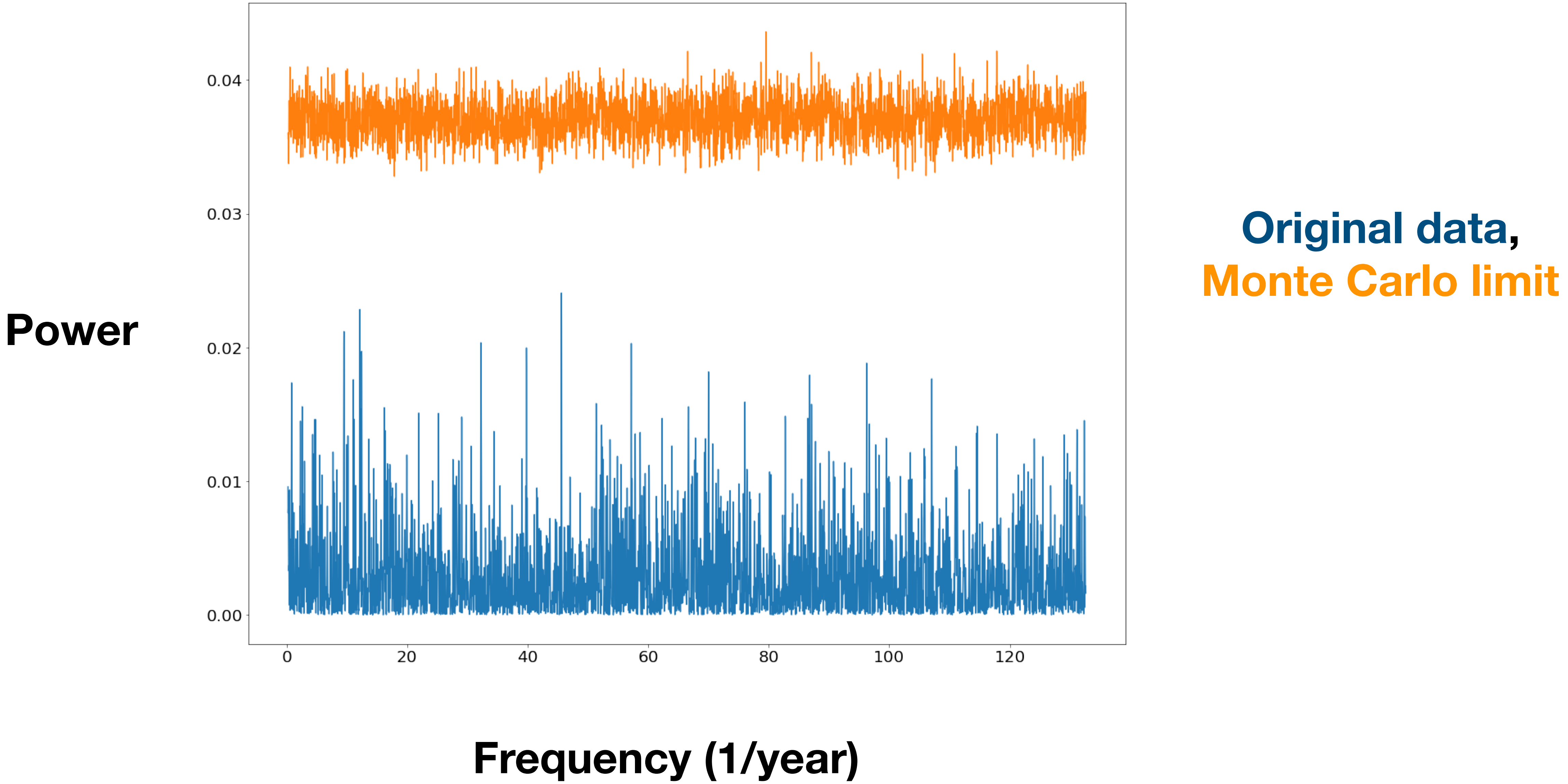
Power

Monte Carlo data

- This PDF integrates to give a cumulative probability distribution (CDF):



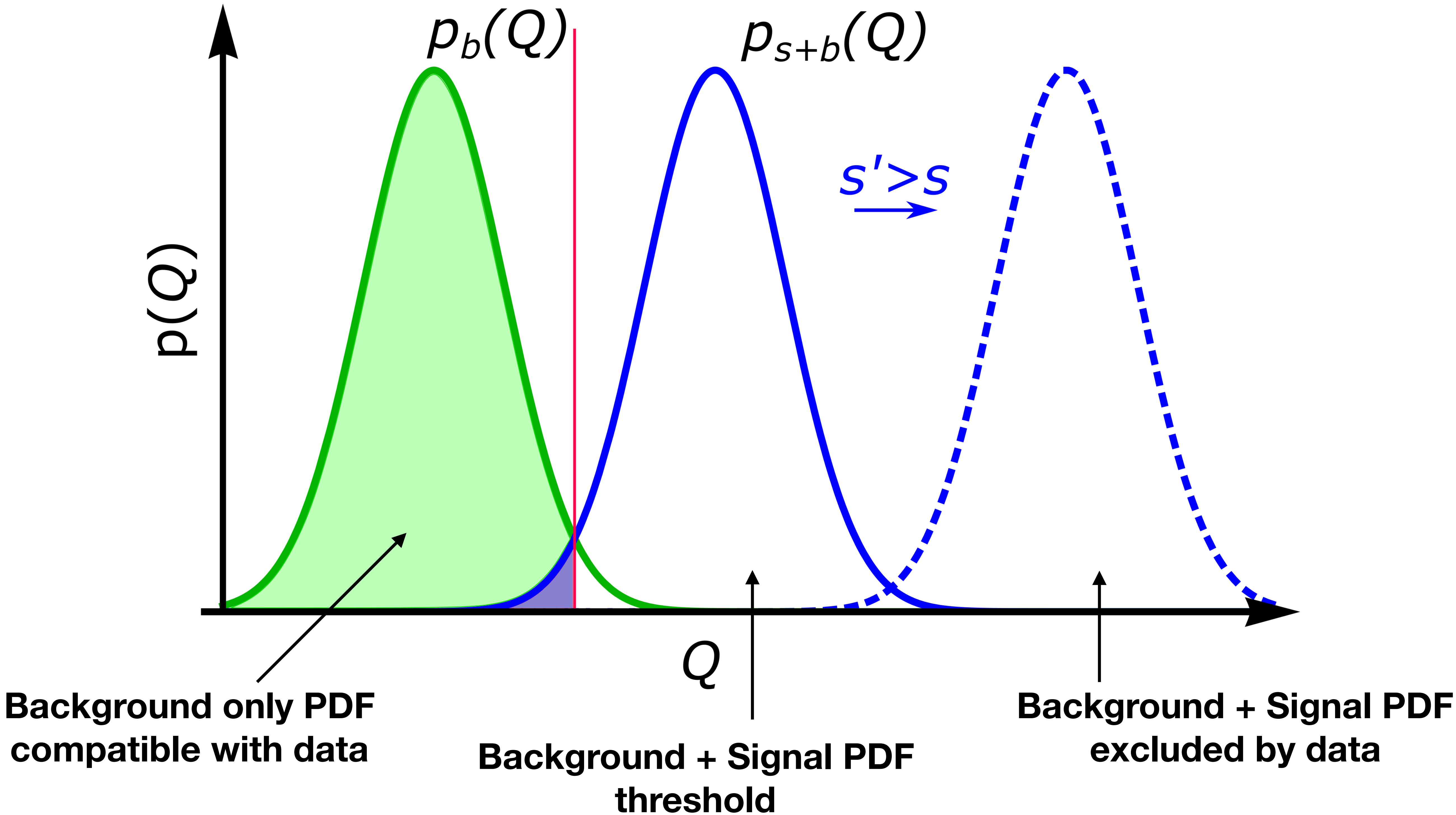
- Repeating this at each frequency:



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

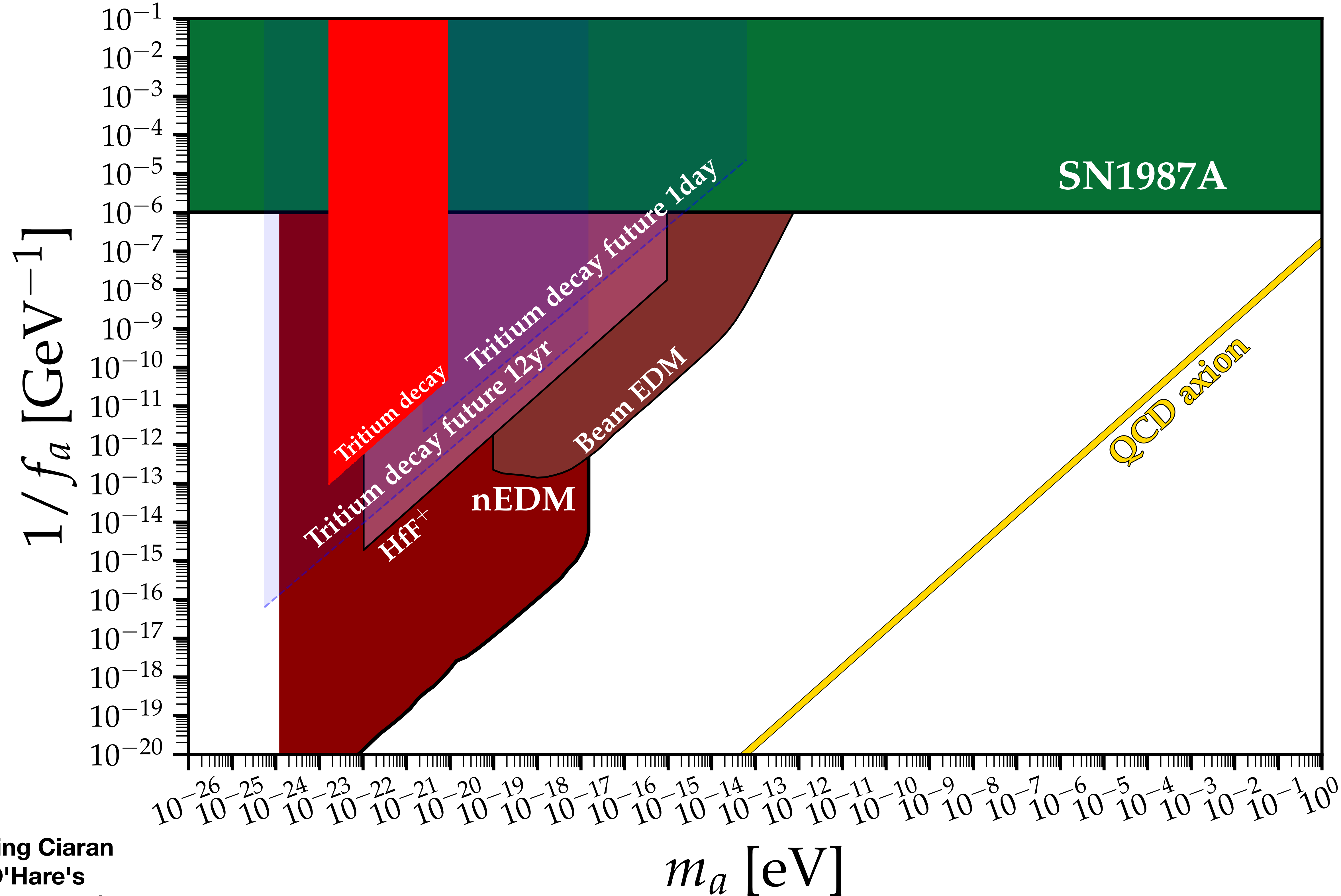
No evidence of non-random behaviour!

- Repeating this with an injected axion signal:



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

Resulting constraint

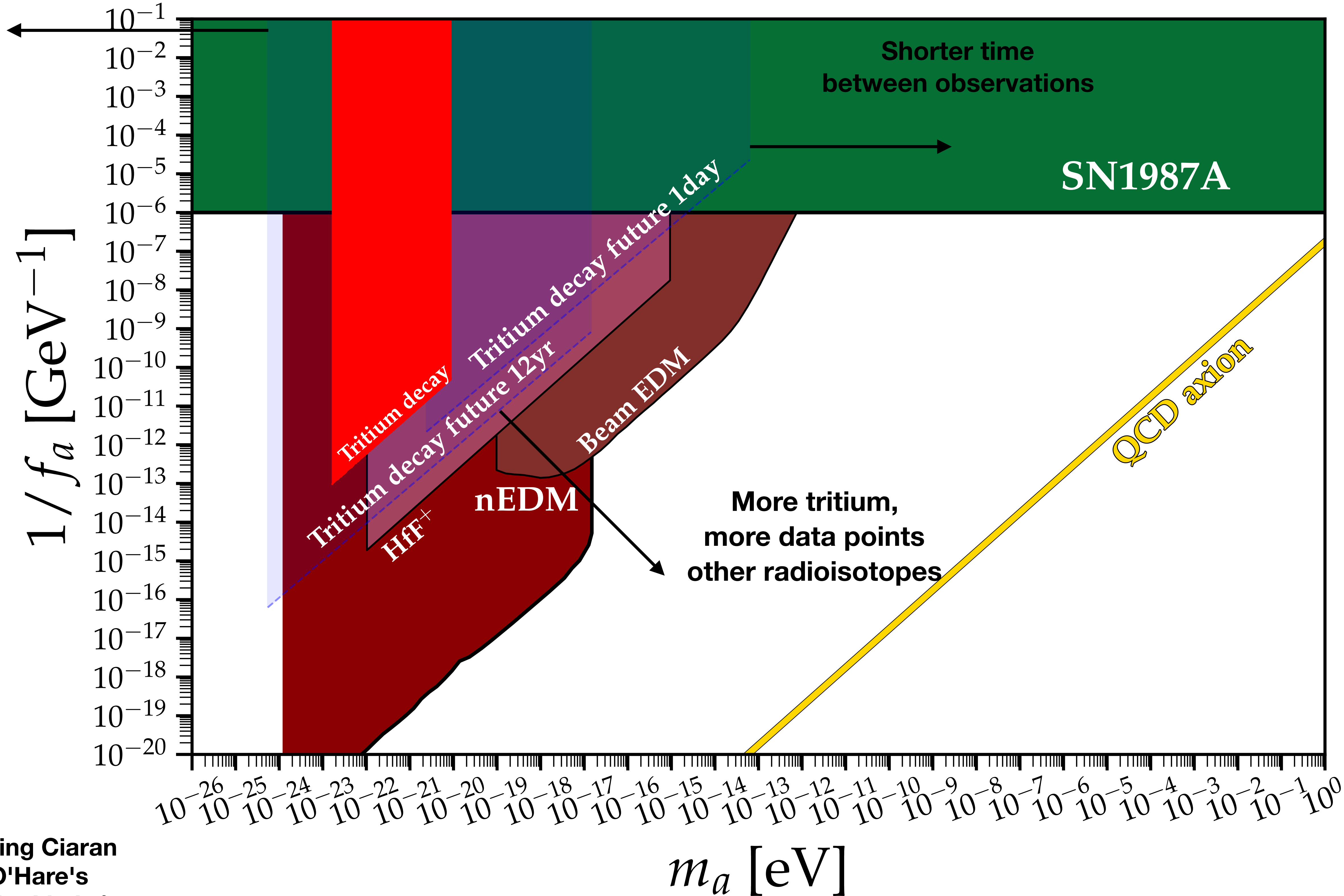


(Using Ciaran O'Hare's AxionLimits)

Can we talk about these effects so far away from the QCD axion band?
See Luca Di Luzio's talk from yesterday

Resulting constraint

More observation time



(Using Ciaran O'Hare's AxionLimits)

Can we talk about these effects so far away from the QCD axion band?
See Luca Di Luzio's talk from yesterday

Discussion and conclusions

- We have examined reports of non-random behaviour in nuclear decay
- 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? Yes, probably…

More details in a paper soon to appear online!

Discussion and conclusions

- We have examined reports of non-random behaviour in nuclear decay
- 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? Yes, probably…

More details in a paper soon to appear online!

Thanks for listening!