Developing a Technique to Differentiate Axion Signals from Radio-Frequency Interference signals in ADMX

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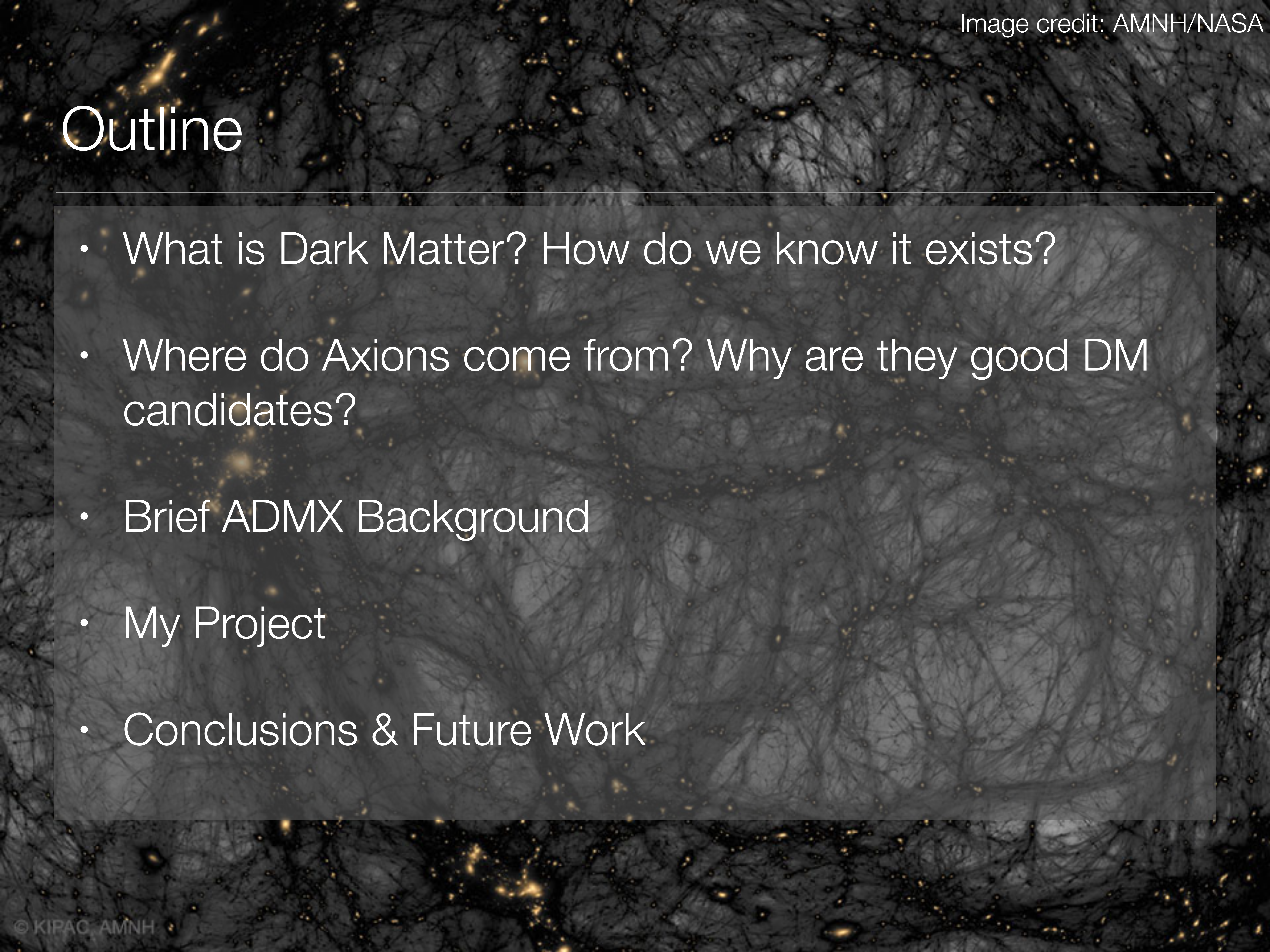


Image credit: AMNH/NASA

Outline

- What is Dark Matter? How do we know it exists?
- Where do Axions come from? Why are they good DM candidates?
- Brief ADMX Background
- My Project
- Conclusions & Future Work

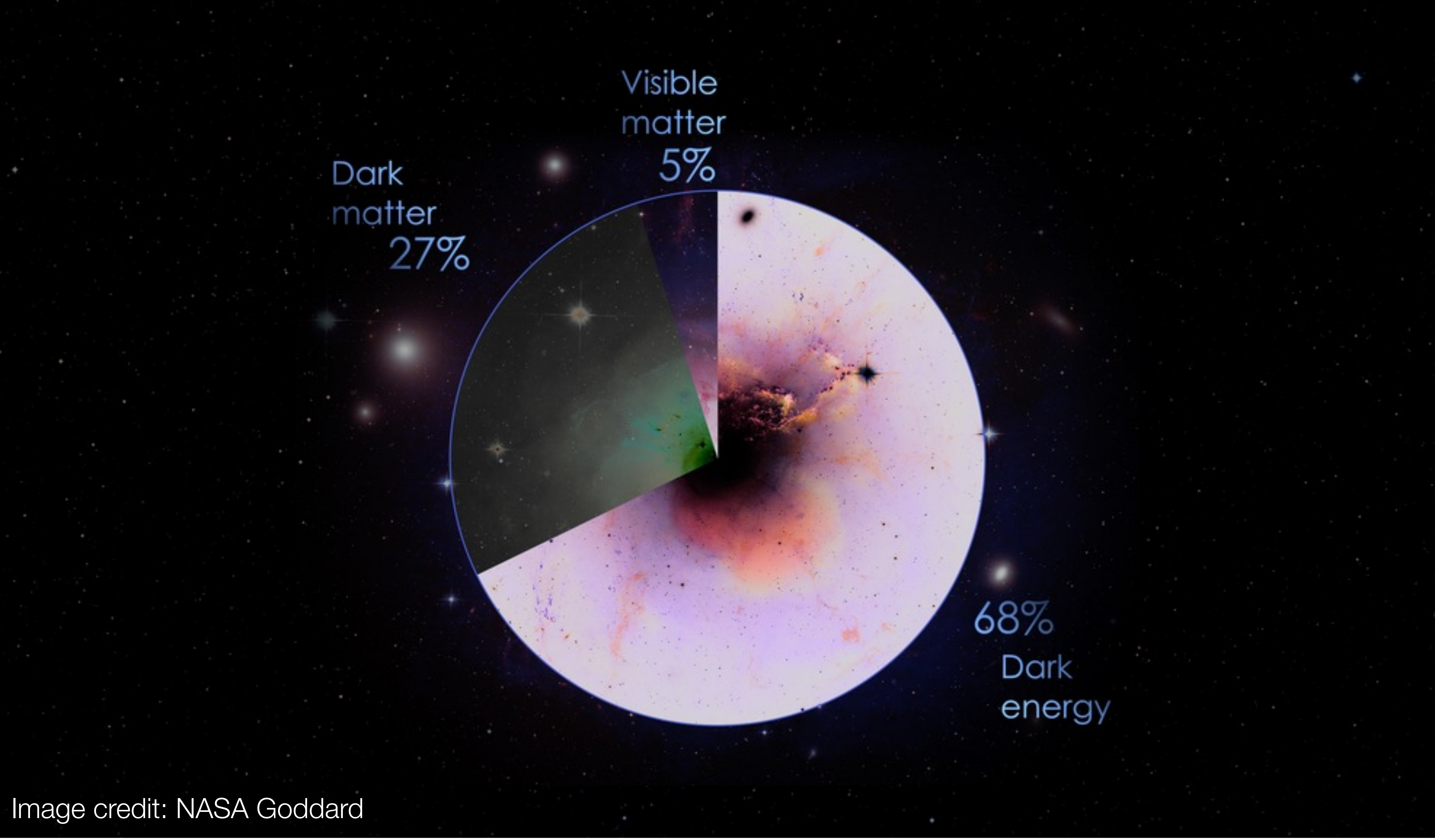


Image credit: NASA Goddard

Dark Matter

- Interacts primarily gravitationally
- Must be cold

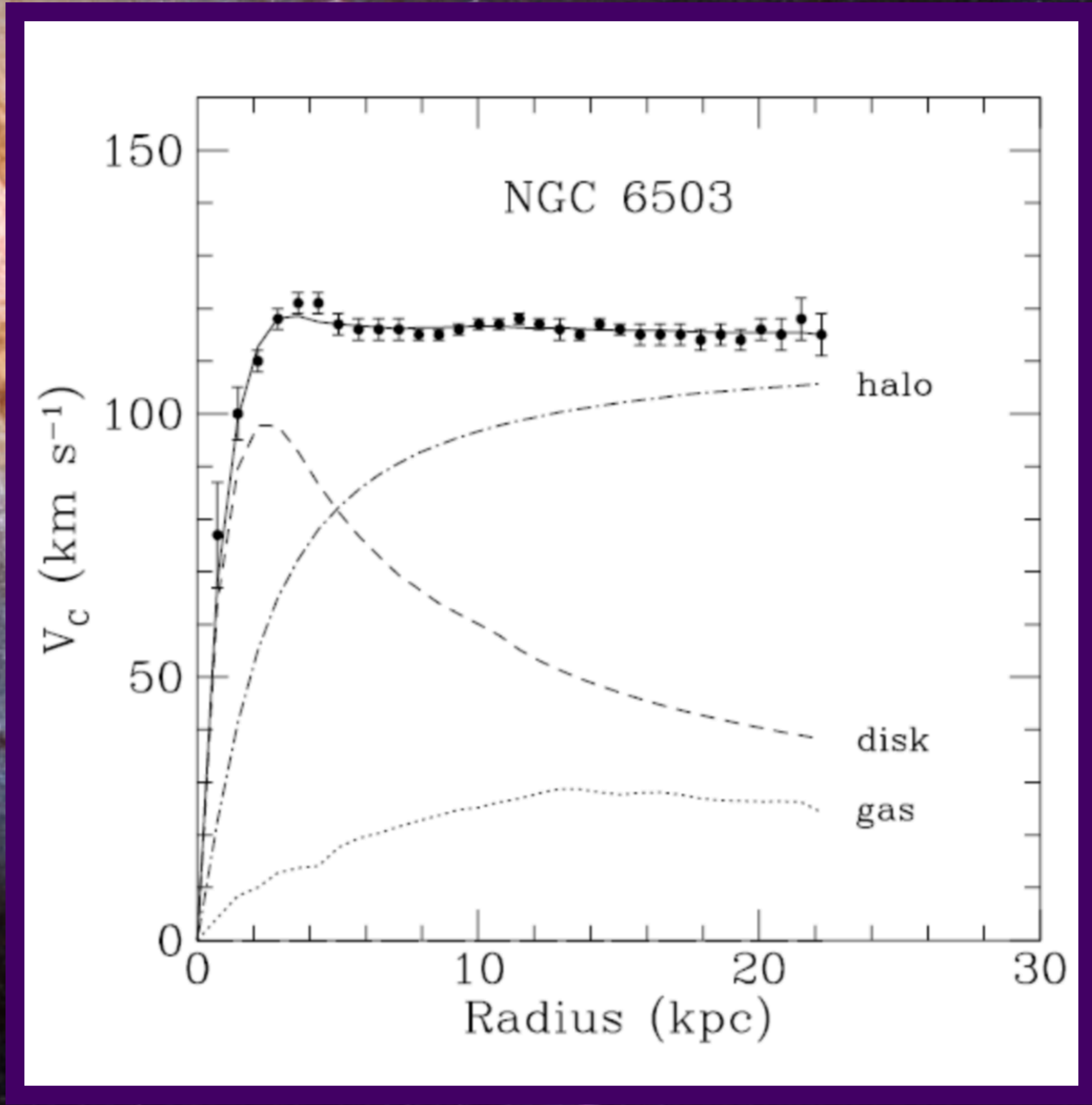
Image credit: NASA

Galactic Rotation Curves

- Expected shape for spherically symmetric mass

$$v_c(r) = \left(\frac{GM(r)}{r}\right)^{1/2}$$

- Expected contributions from the disk and gas alone do not create curves which match measured rotation curves



Begemen, K.G. 1991

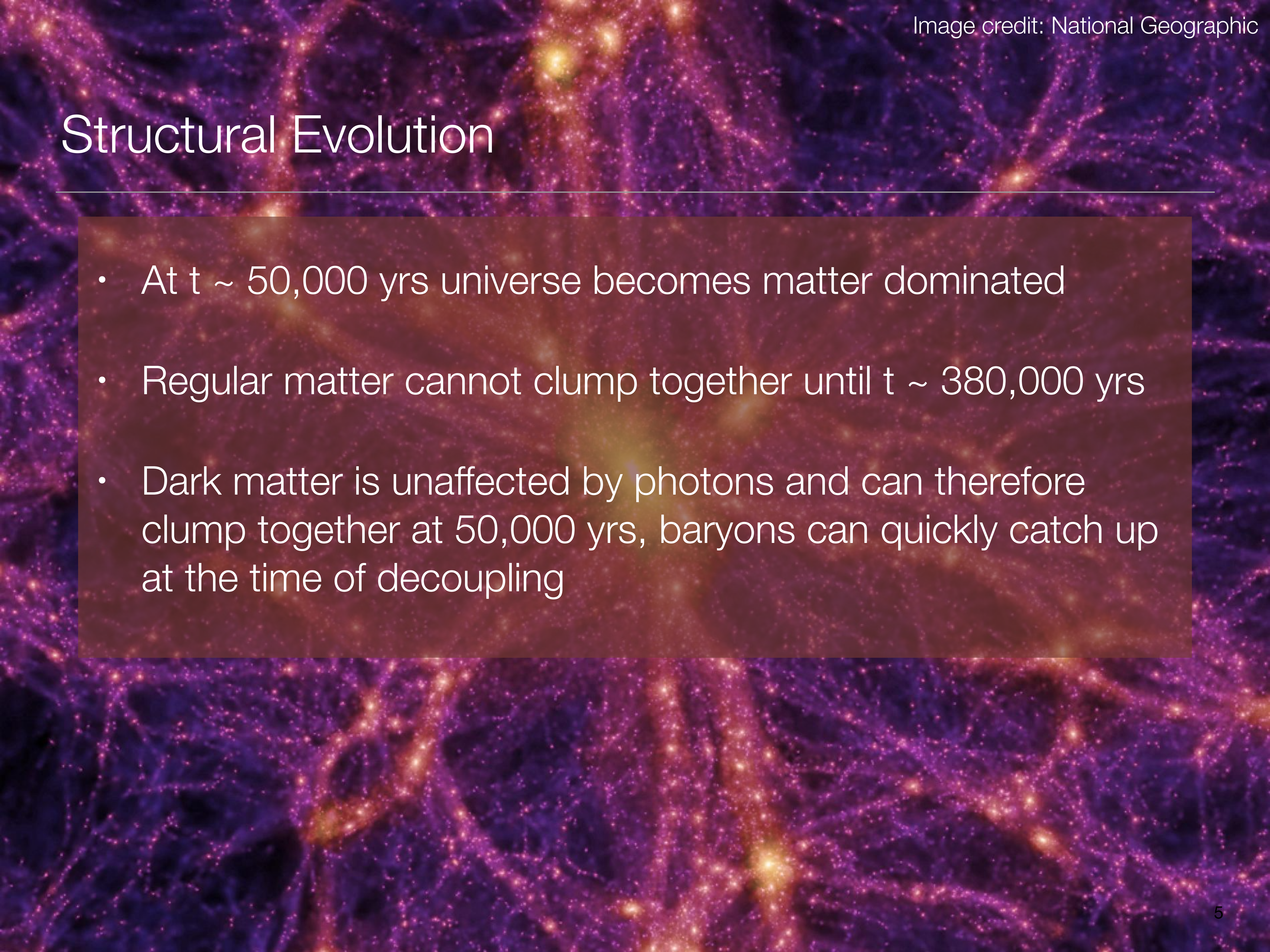


Image credit: National Geographic

Structural Evolution

- At t ~ 50,000 yrs universe becomes matter dominated
- Regular matter cannot clump together until t ~ 380,000 yrs
- Dark matter is unaffected by photons and can therefore clump together at 50,000 yrs, baryons can quickly catch up at the time of decoupling

Image credit: Symmetry Magazine

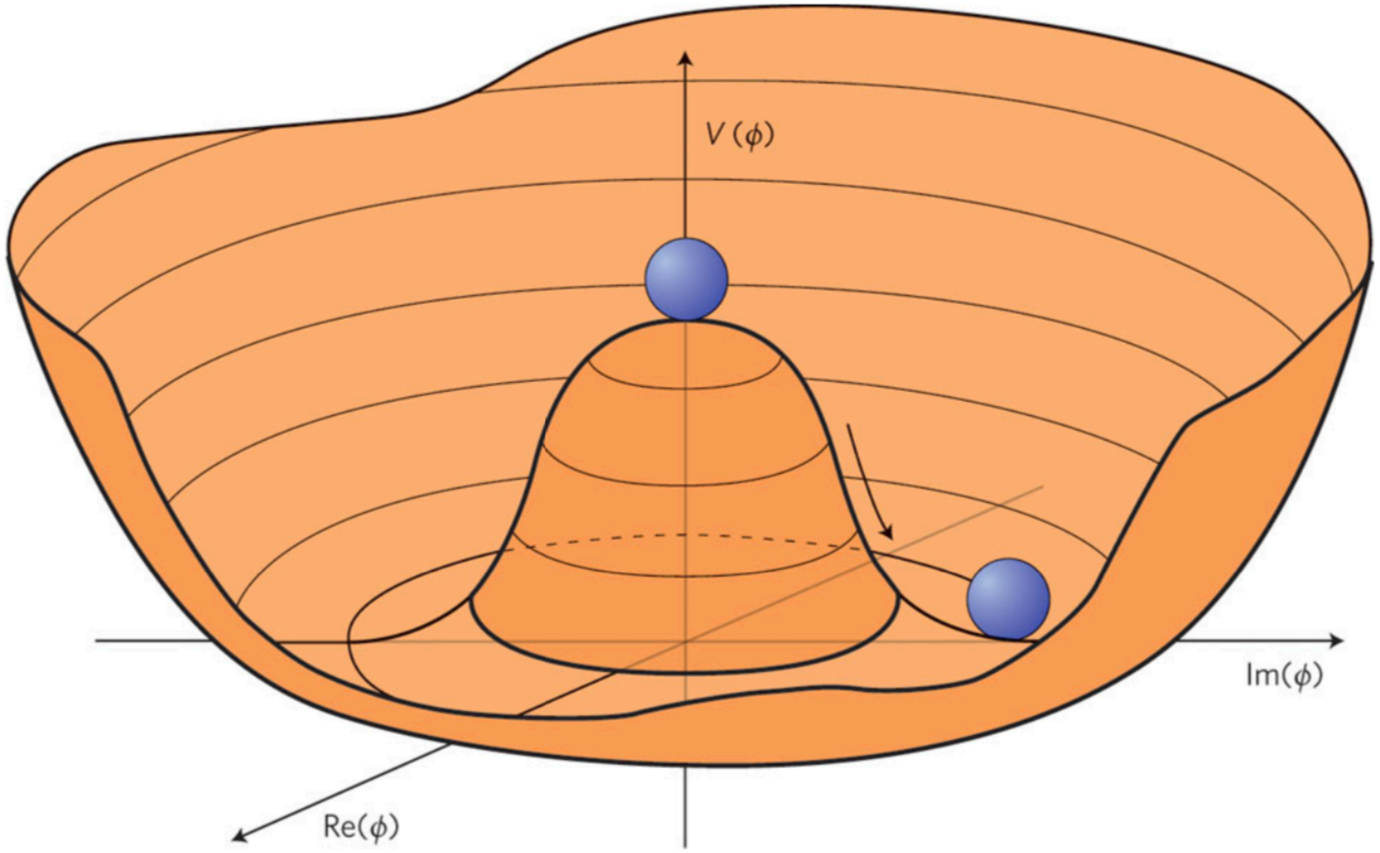
Strong CP Problem: Axions to the Rescue

$$L_\theta = \theta \frac{g^2}{32\pi^2} F_a^{\mu\nu} \tilde{F}_{a\mu\nu}$$ ← This term in the QCD Lagrangian violates P and T reversal invariance but conserves charge conjugation invariance, so it violates CP invariance

As a result, a large neutron EDM (strong CP violation) is expected, but has not been observed! This requires an “unnaturally” small ($< 10^{-10}$) value for θ.

Peccei-Quinn Solution

- Introduces a new global (PQ) symmetry and transforms θ from a parameter into a dynamic variable
- The combination of simultaneous and explicit PQ symmetry breaking creates a pseudo-Goldstone boson, namely the axion



Brubaker 2018

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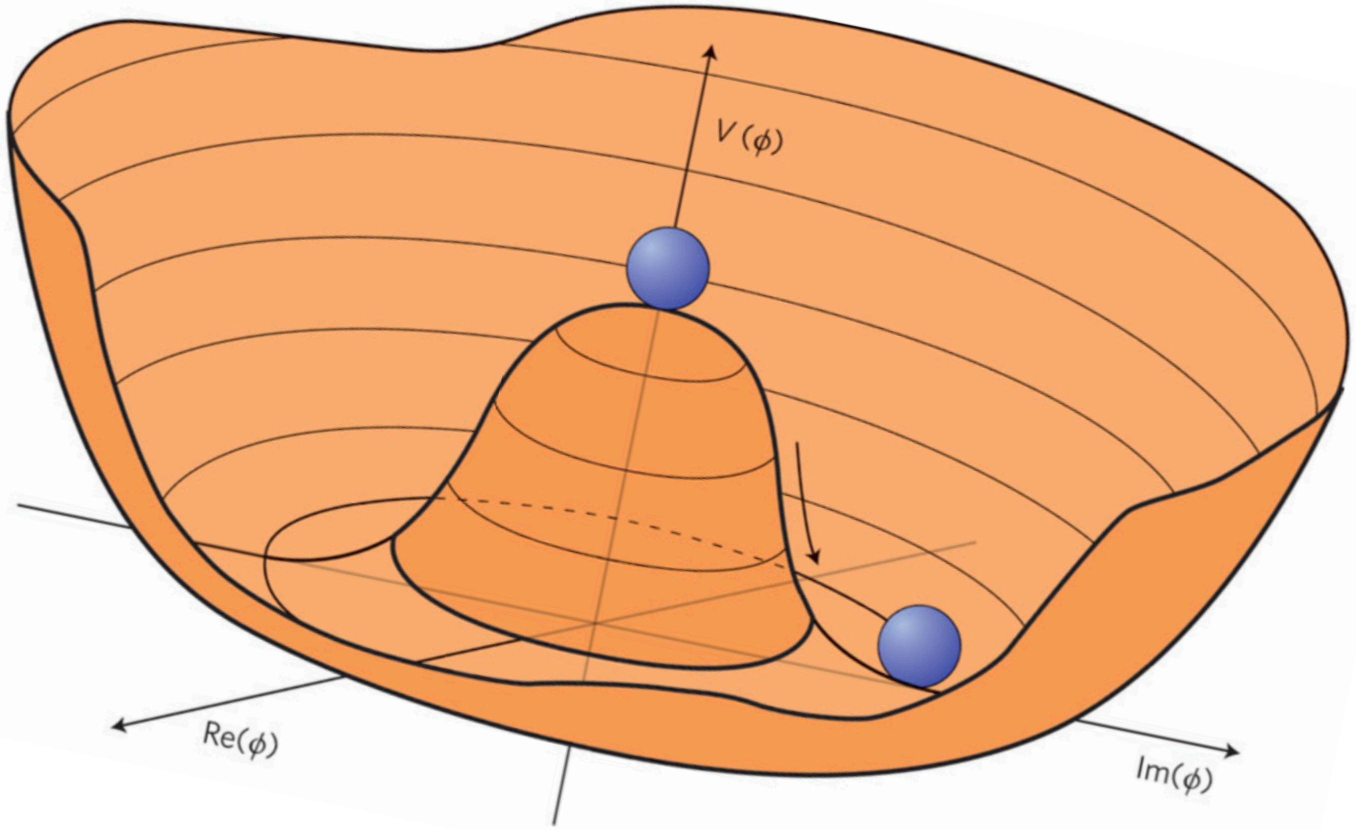
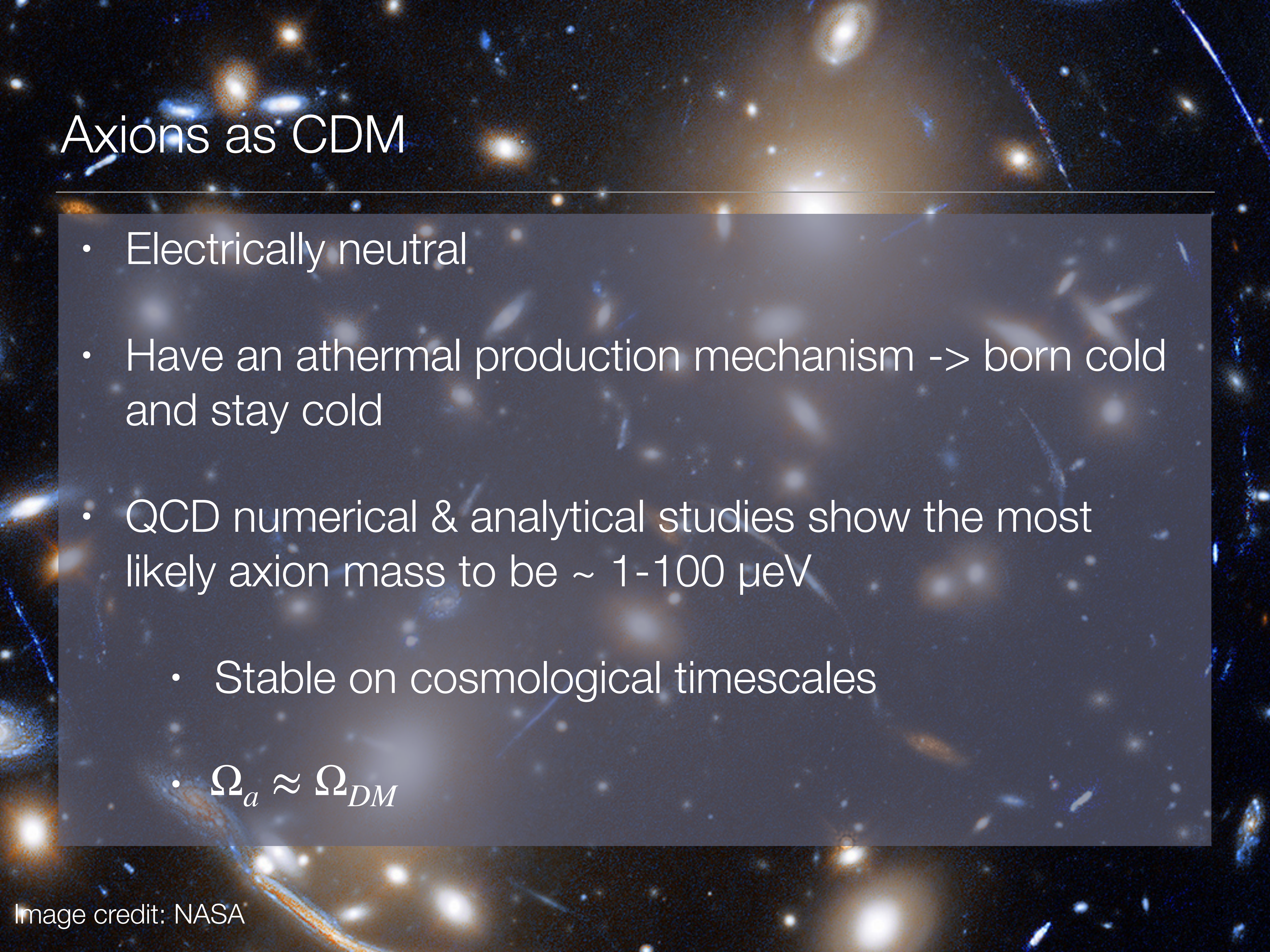


Brubaker 2018



Axions as CDM

- Electrically neutral
- Have an athermal production mechanism -> born cold and stay cold
- QCD numerical & analytical studies show the most likely axion mass to be ~ 1-100 μeV
  - Stable on cosmological timescales
  - $\Omega_a \approx \Omega_{DM}$

Image credit: NASA

ADMX

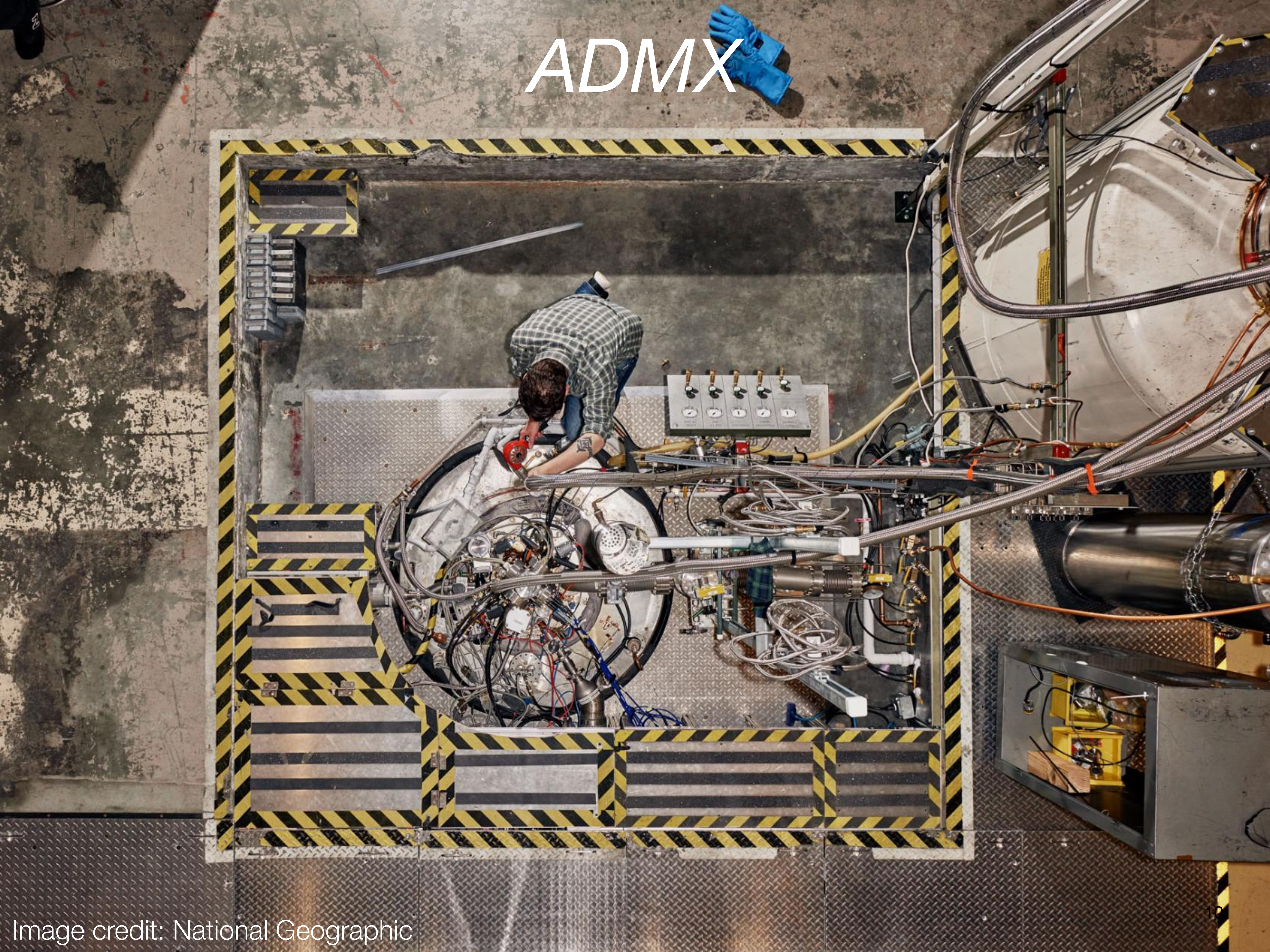
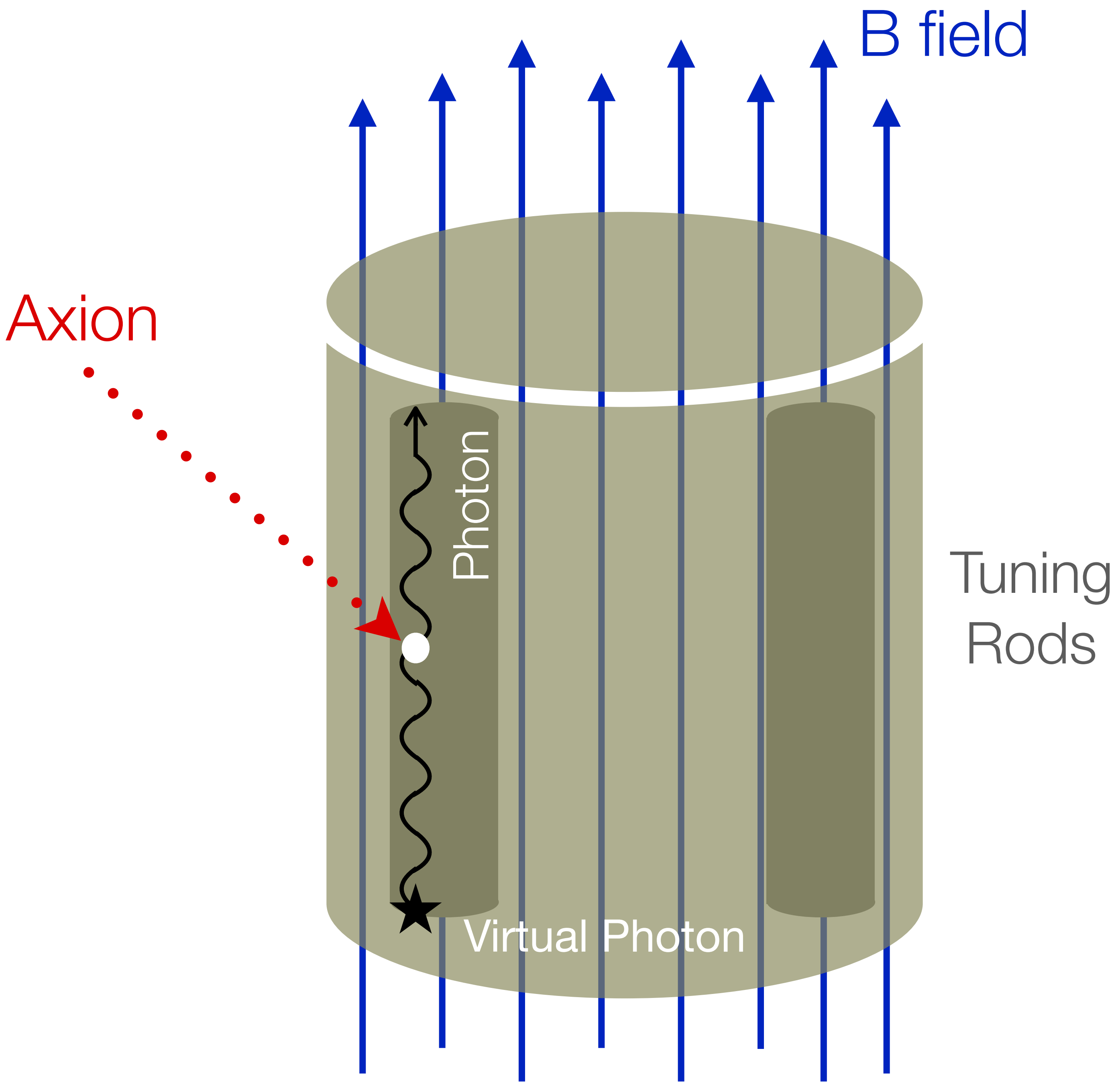


Image credit: National Geographic

Axion Haloscope

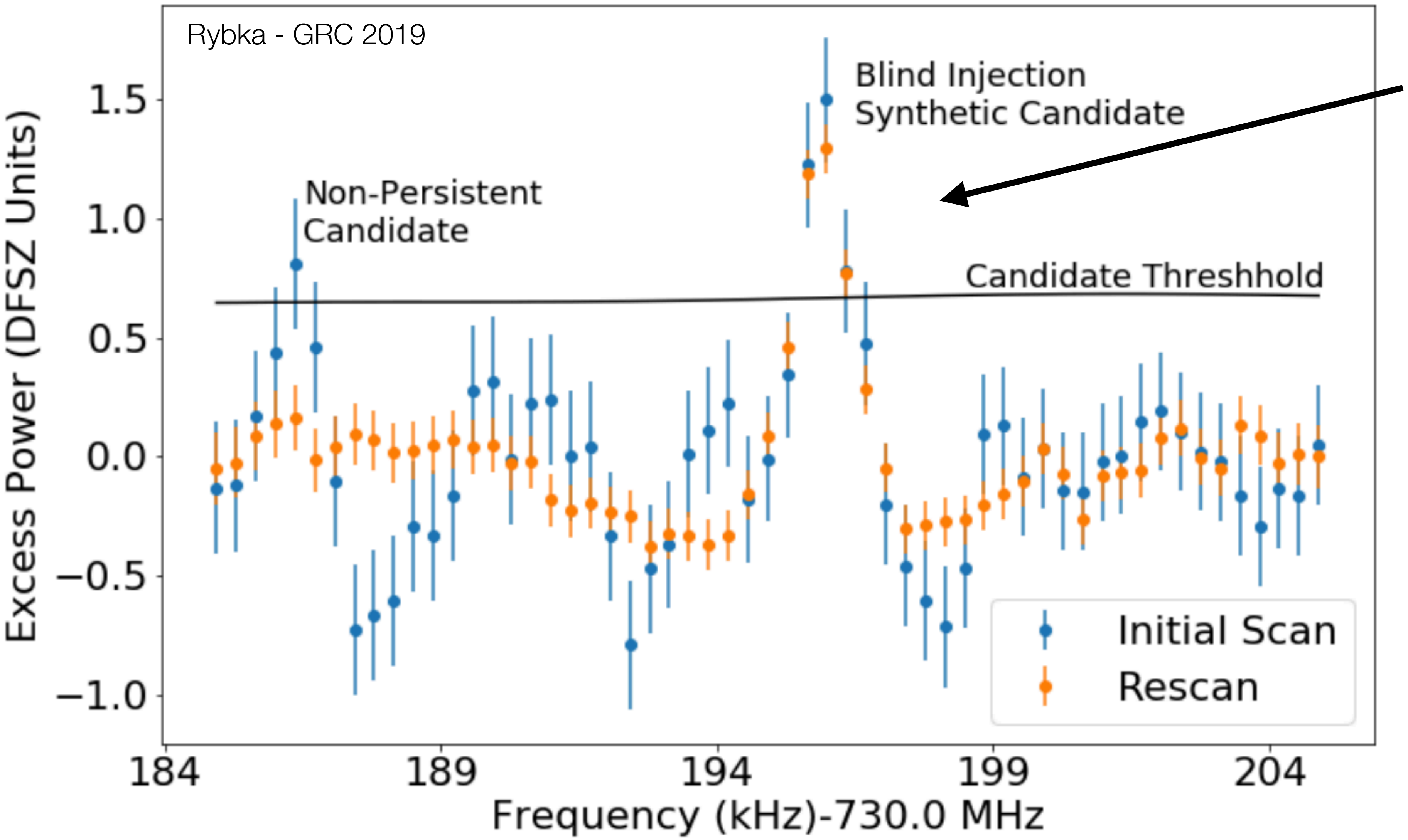


Resonant microwave cavity

- Converts invisible axions into detectable microwave photons in a large magnetic field via the inverse Primakoff effect

- Tunable so we can scan a range of frequencies

What does it mean to detect a candidate?


Rybka - GRC 2019

candidate: any excess power signal above a specified SNR threshold

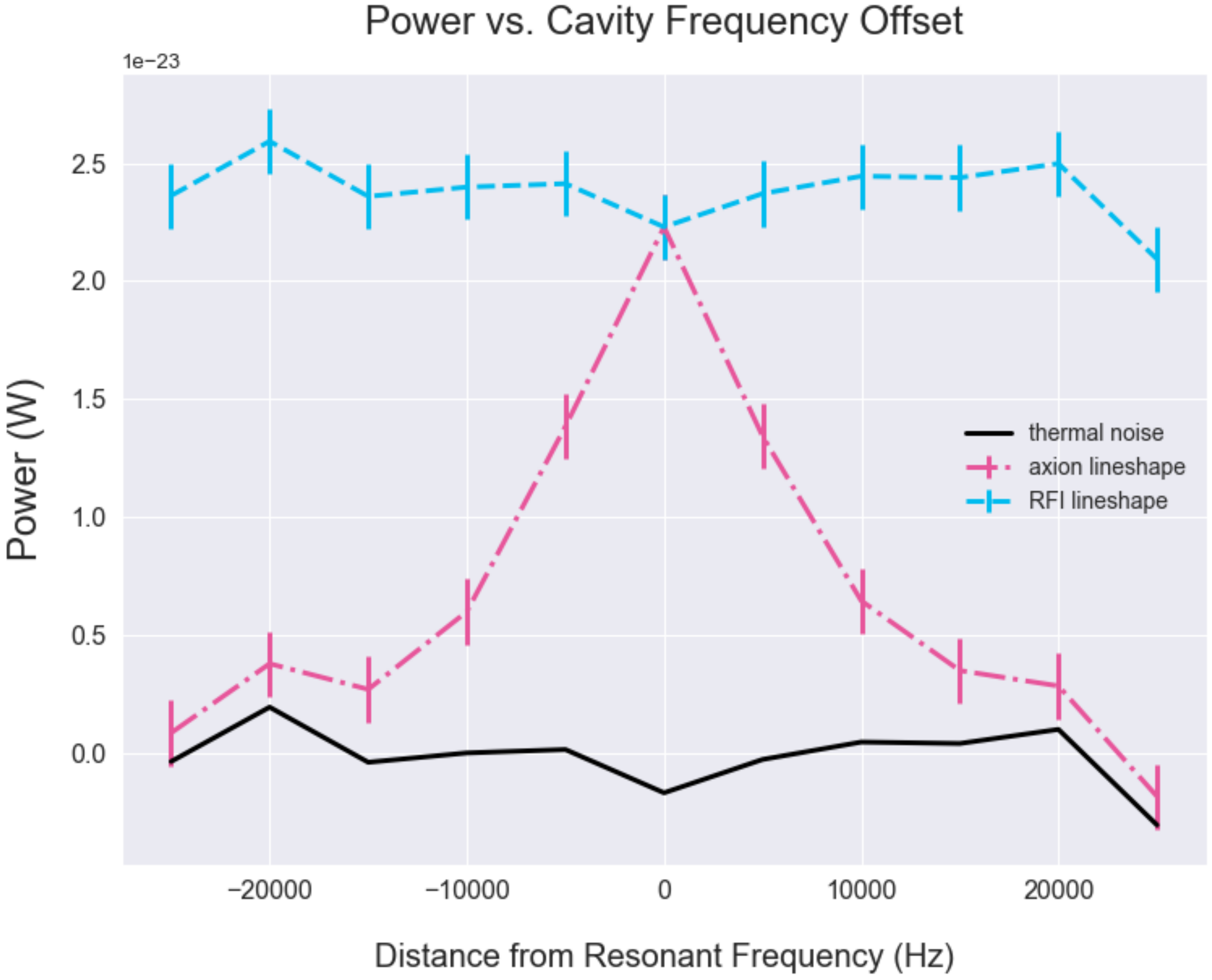
- Radio-Frequency Interference (RFI)
  - does not enter the cavity, enters somewhere in the electronics
  - does not show dependence on the cavity resonant frequency

My Goal

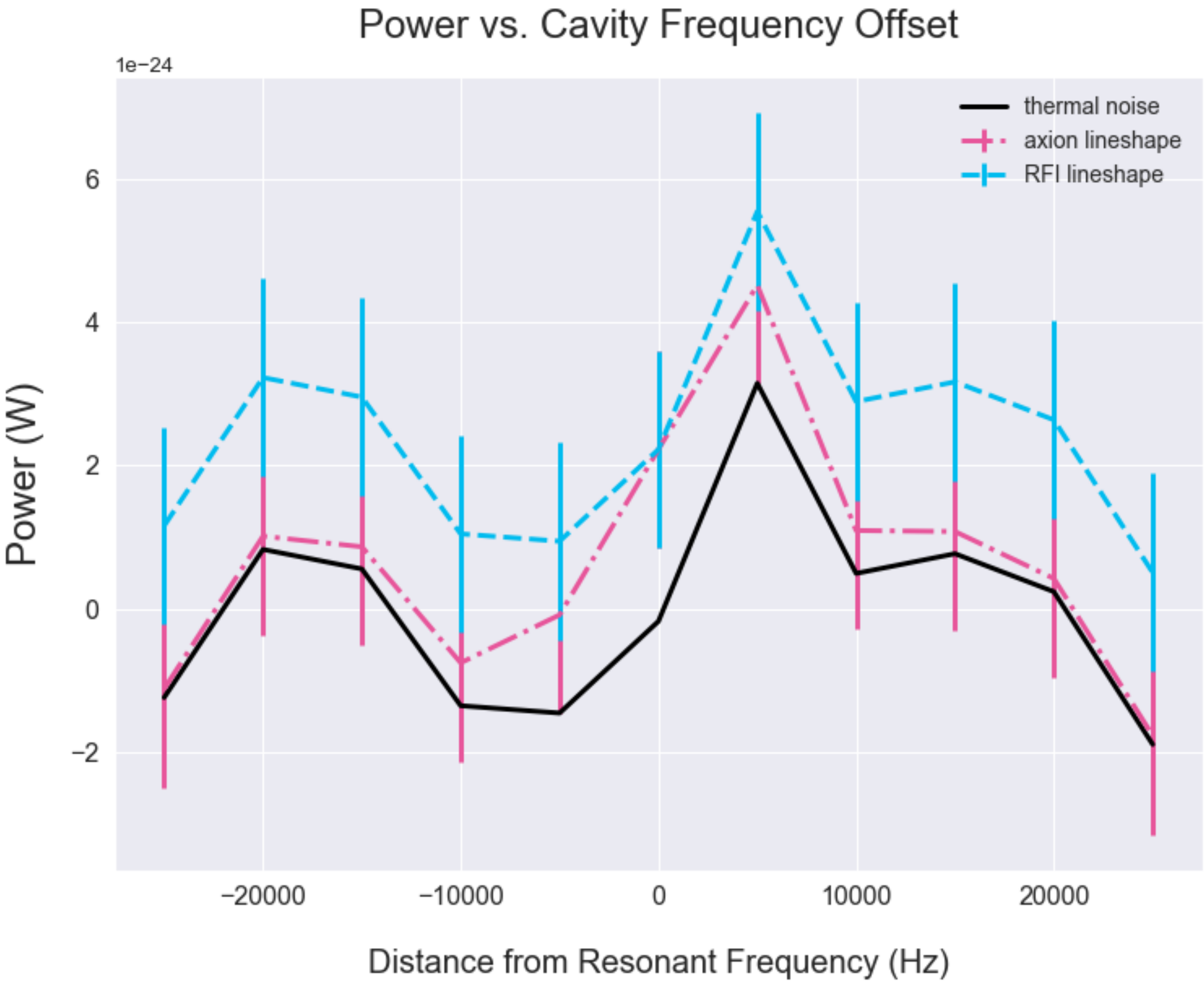
- Reduce the amount of Radio-Frequency Interference (RFI) signals we rescan as potential candidates

- Use chi-squared statistics to analyze how well a certain signal fits an axion-like cavity line shape vs. an RFI-like out-of-cavity line shape

SNR = 30


Power vs. Cavity Frequency Offset
1e−23
2.5
2.0
1.5
1.0
0.5
0.0
Power (W)
−20000
−10000
0
10000
20000
Distance from Resonant Frequency (Hz)
thermal noise
axion lineshape
RFI lineshape

SNR = 3


Power vs. Cavity Frequency Offset
1e−24
6
4
2
0
−2
Power (W)
−20000
−10000
0
10000
20000
Distance from Resonant Frequency (Hz)
thermal noise
axion lineshape
RFI lineshape

My Model

- I assume signals are either axion-like (follow the cavity line shape) or RFI-like (do not follow the cavity shape)

- I have a signal sampled at several frequency offsets from the cavity center

- I’m testing with simulated data where we have 20,000 scans within +/- 25 kHz of the cavity resonance moving in steps of 5 kHz, each scan with a Gaussian noise distribution centered on zero with a standard deviation of 1.3E-24 W

Using chi-squared statistics to distinguish low SNR signals

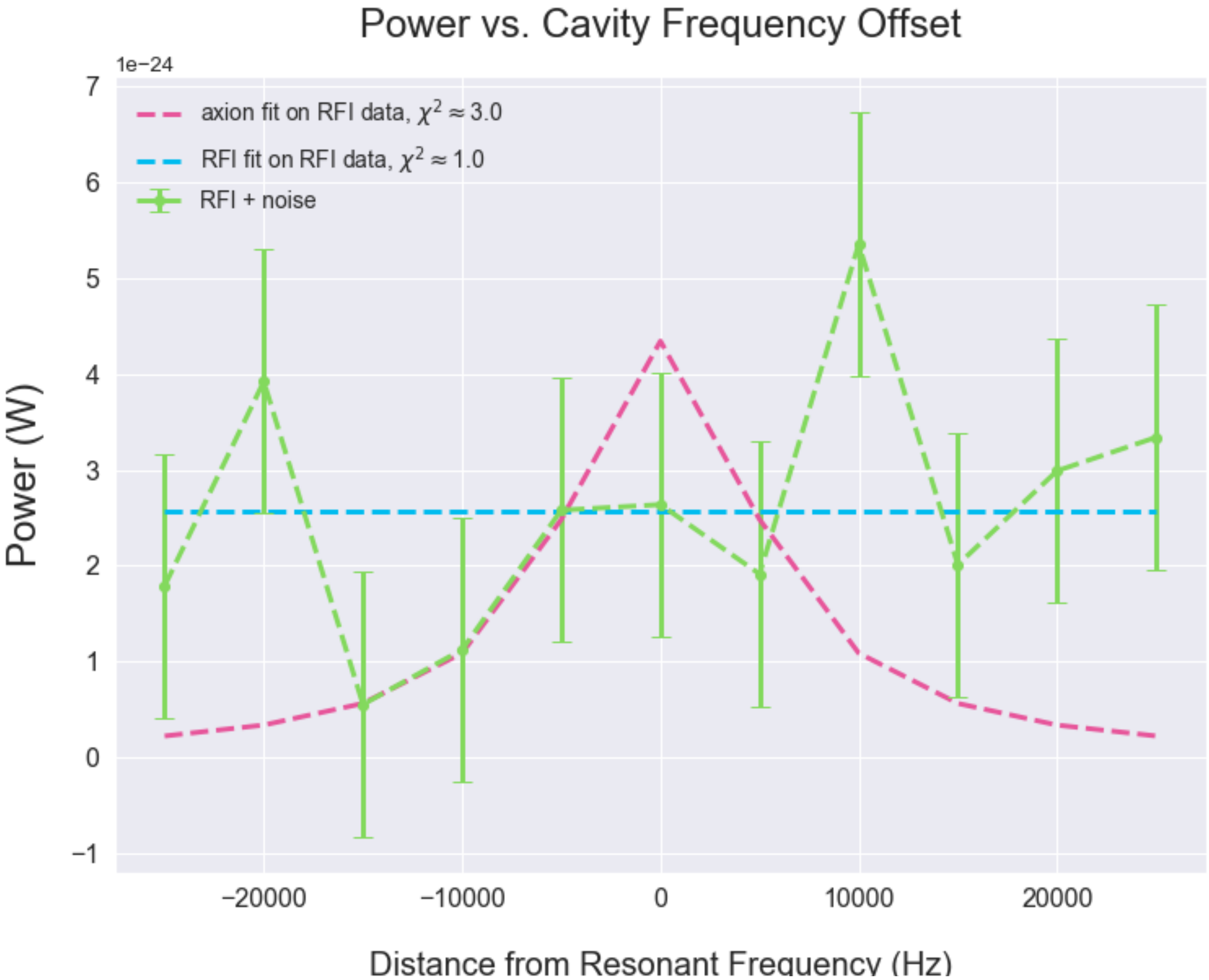
1. Fit a given signal twice, one using the axion-like (Lorentzian) function and the other using the RFI-like (constant) function

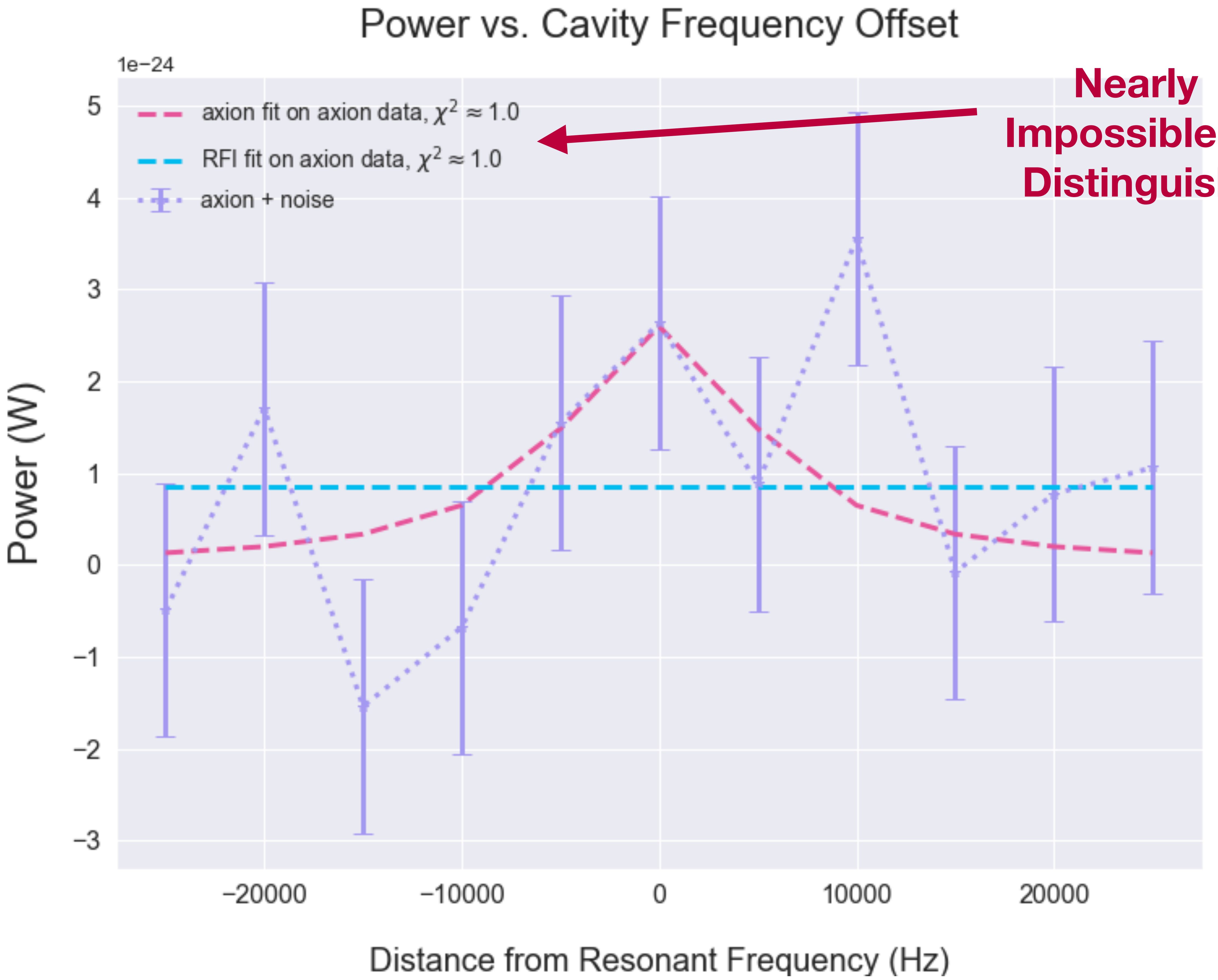
2. Calculate a chi-squared value for each of the two fits

3. Use the difference, $\chi^2_{axion} - \chi^2_{RFI}$, to categorize the signals into either axion-like or RFI-like

ex. $\chi^2_{axion} = 1 \ \chi^2_{RFI} = 2 \longrightarrow$ axion fit is better $\chi^2_{axion} - \chi^2_{RFI} = -1$

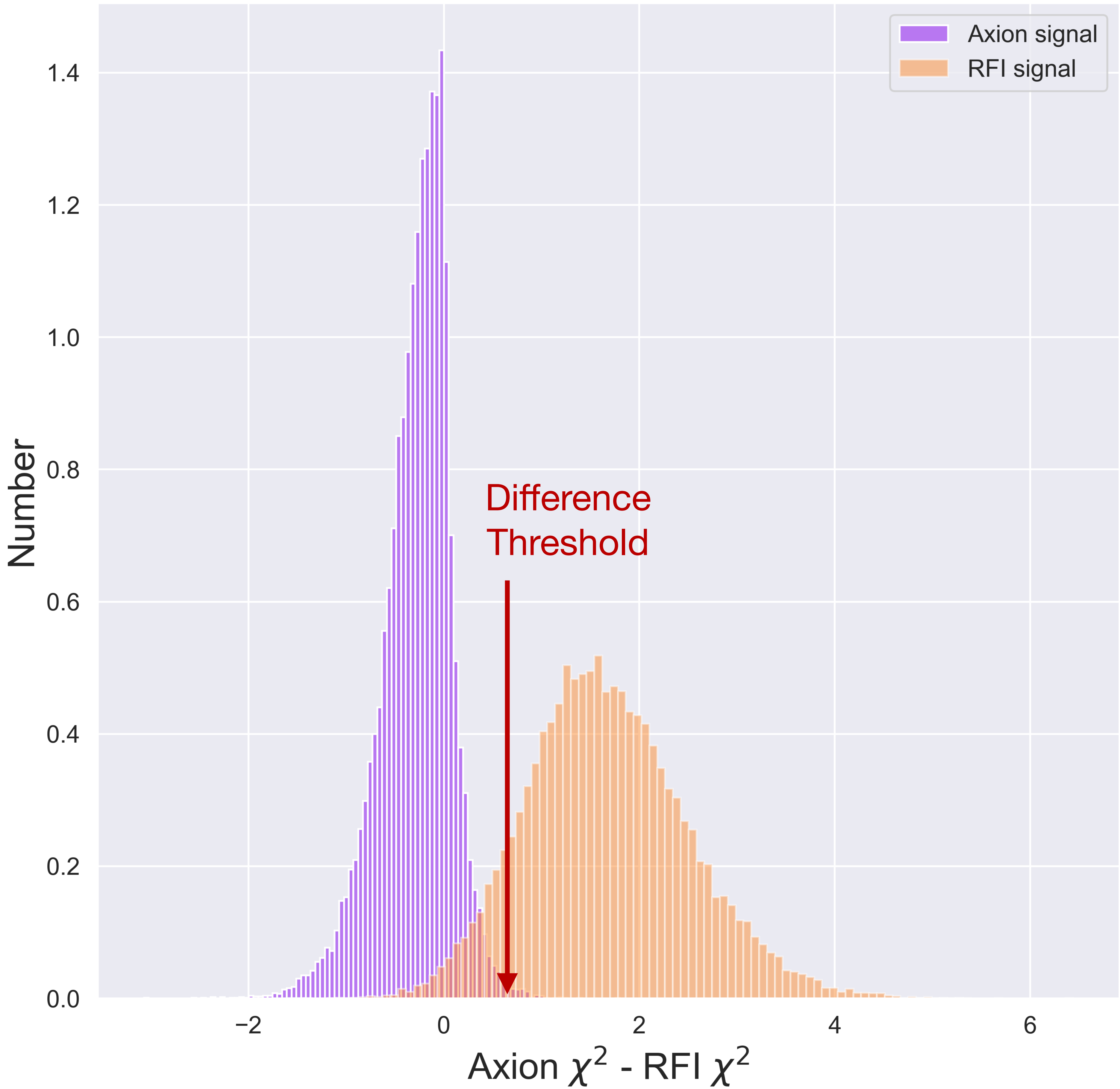
$\chi^2_{axion} = 2 \ \chi^2_{RFI} = 1 \longrightarrow$ RFI fit is better $\chi^2_{axion} - \chi^2_{RFI} = +1$

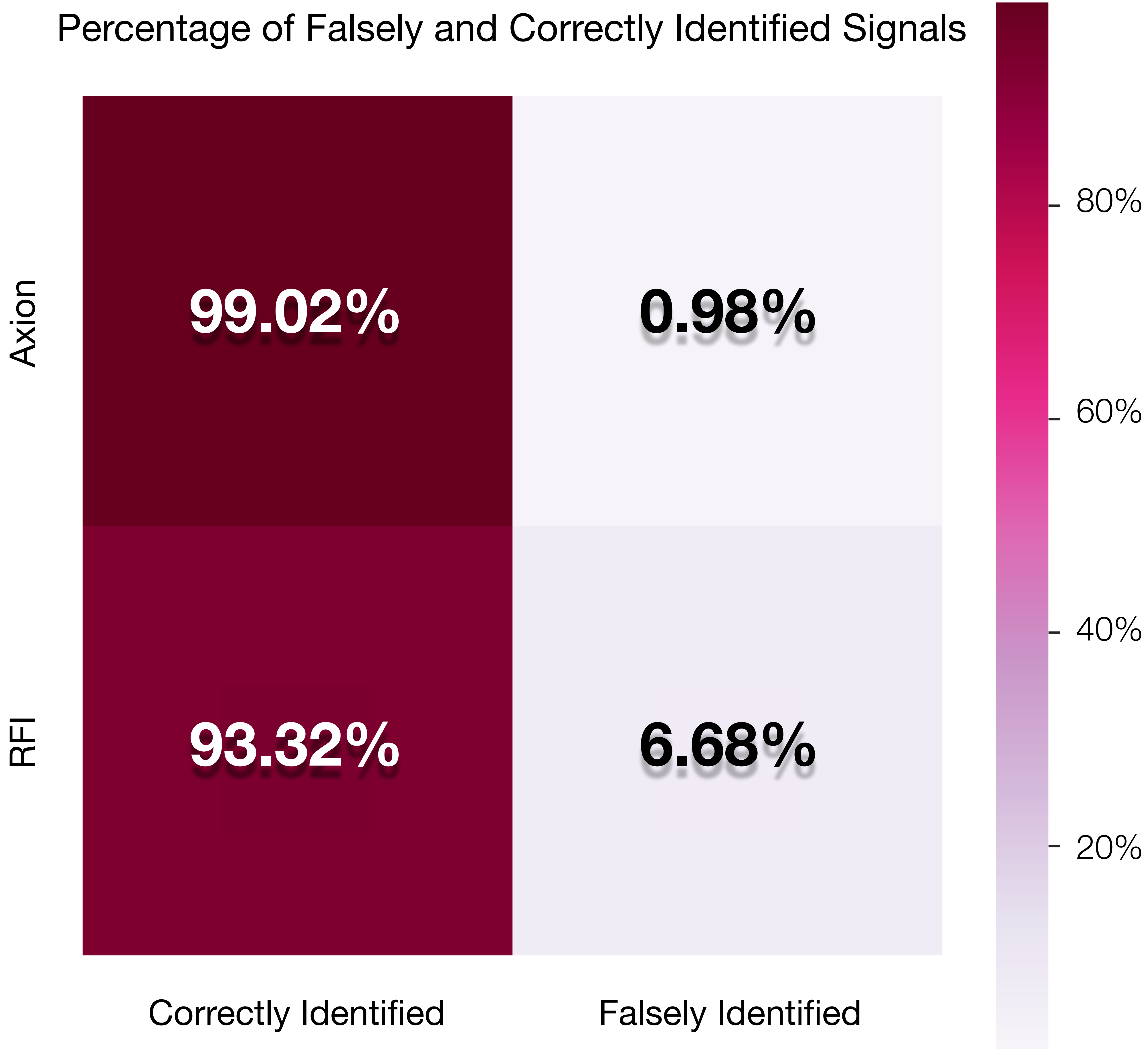

Power vs. Cavity Frequency Offset
1e−24
7
6
5
4
3
2
1
0
−1
Power (W)
axion fit on RFI data, $\chi^2 \approx 3.0$
RFI fit on RFI data, $\chi^2 \approx 1.0$
RFI + noise
−20000
−10000
0
10000
20000
Distance from Resonant Frequency (Hz)



Nearly Impossible to Distinguish!

χ^2 difference for Axion and RFI signals




Percentage of Falsely and Correctly Identified Signals
Axion
RFI
99.02%
0.98%
93.32%
6.68%
Correctly Identified
Falsely Identified
80%
60%
40%
20%

Conclusions

- Using this model we can reject ~ 93% of RFI signals for rescanning (given an SNR of 3), while still having less than a 1% chance of missing an axion. This could greatly increase scan speed.
- If the SNR is lower or there are fewer data points (bigger steps) this method still works but not quite as well. For example, if SNR = 2.2, we can only reject ~73% of RFI signals while only missing less than 1% of axions. However, this is still a great improvement from before.

Future Work

- Test this model using real data and ensure that it can be a trusted method before implementing it into the greater analysis procedure

Acknowledgements

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- ADMX Collaboration
- National Science Foundation
- The University of Washington
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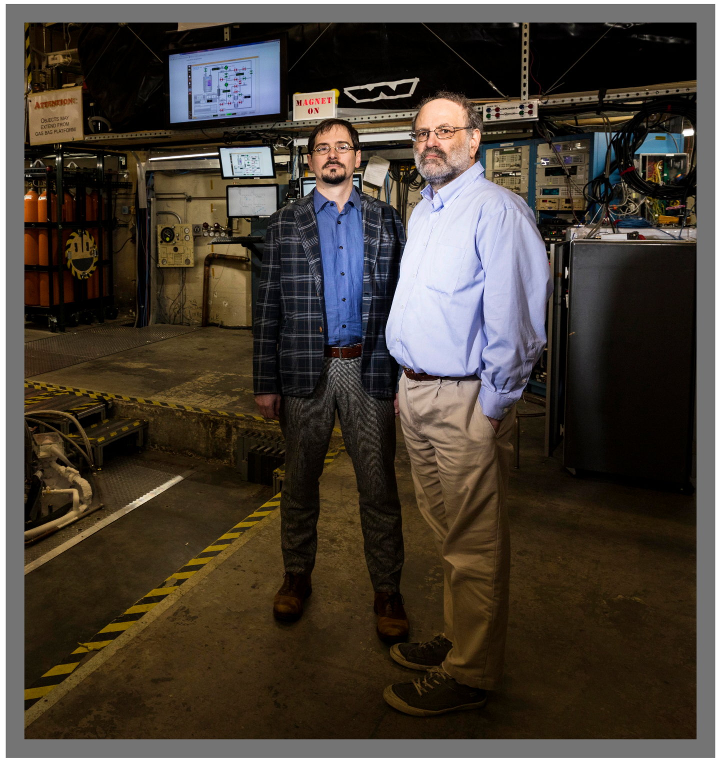

AXION DARK MATTER EXPERIMENT

References

- Brubaker, B. (2018). First results from the HAYSTAC axion search (Ph.D. Thesis).

- Du, N. et al. (ADMX Collaboration), Phys. Rev. Lett. 120, 151301 (2018).