



ABRACADABRA

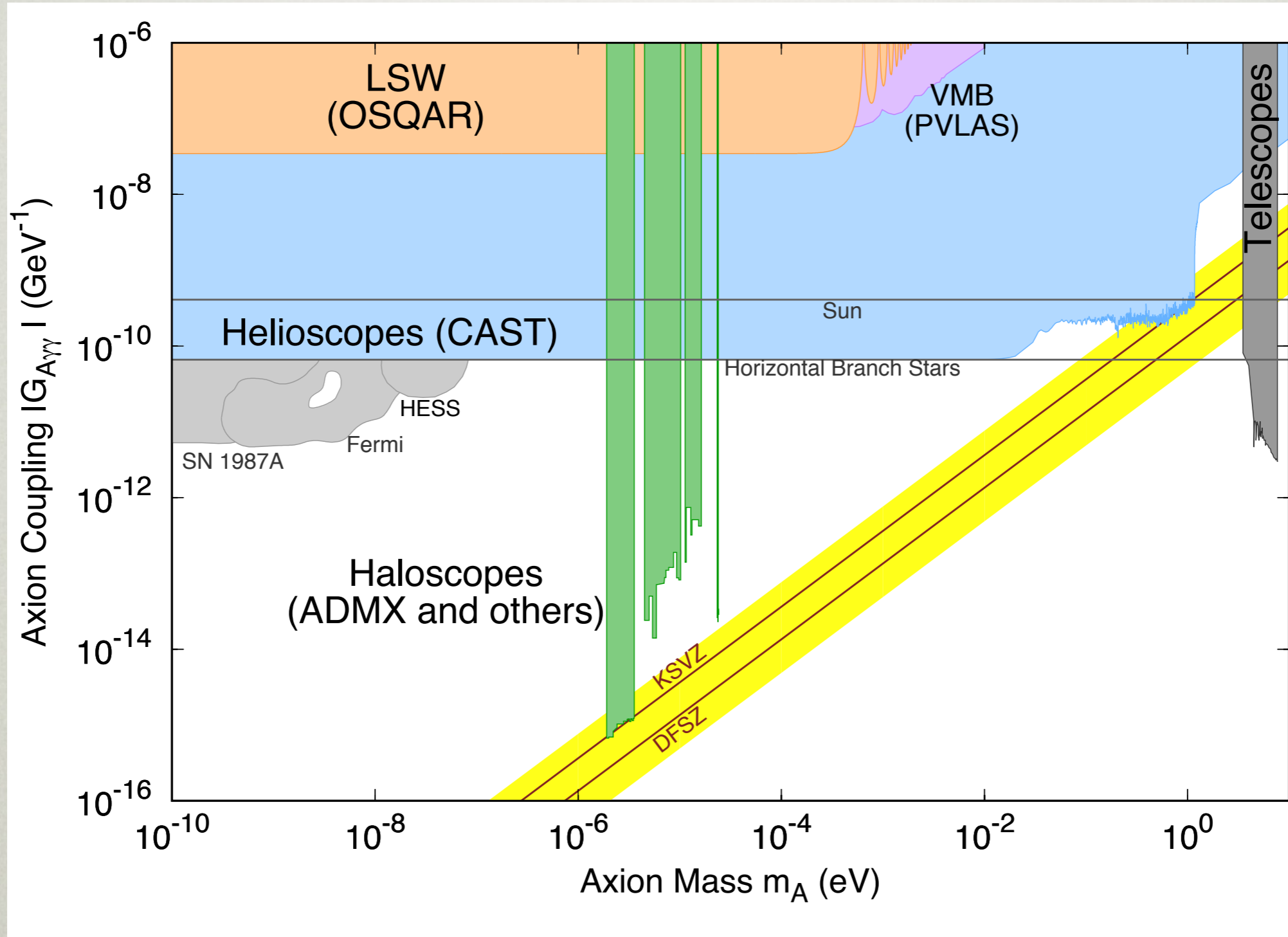
10CM RESULTS & AXION LIKELIHOOD



NICK RODD

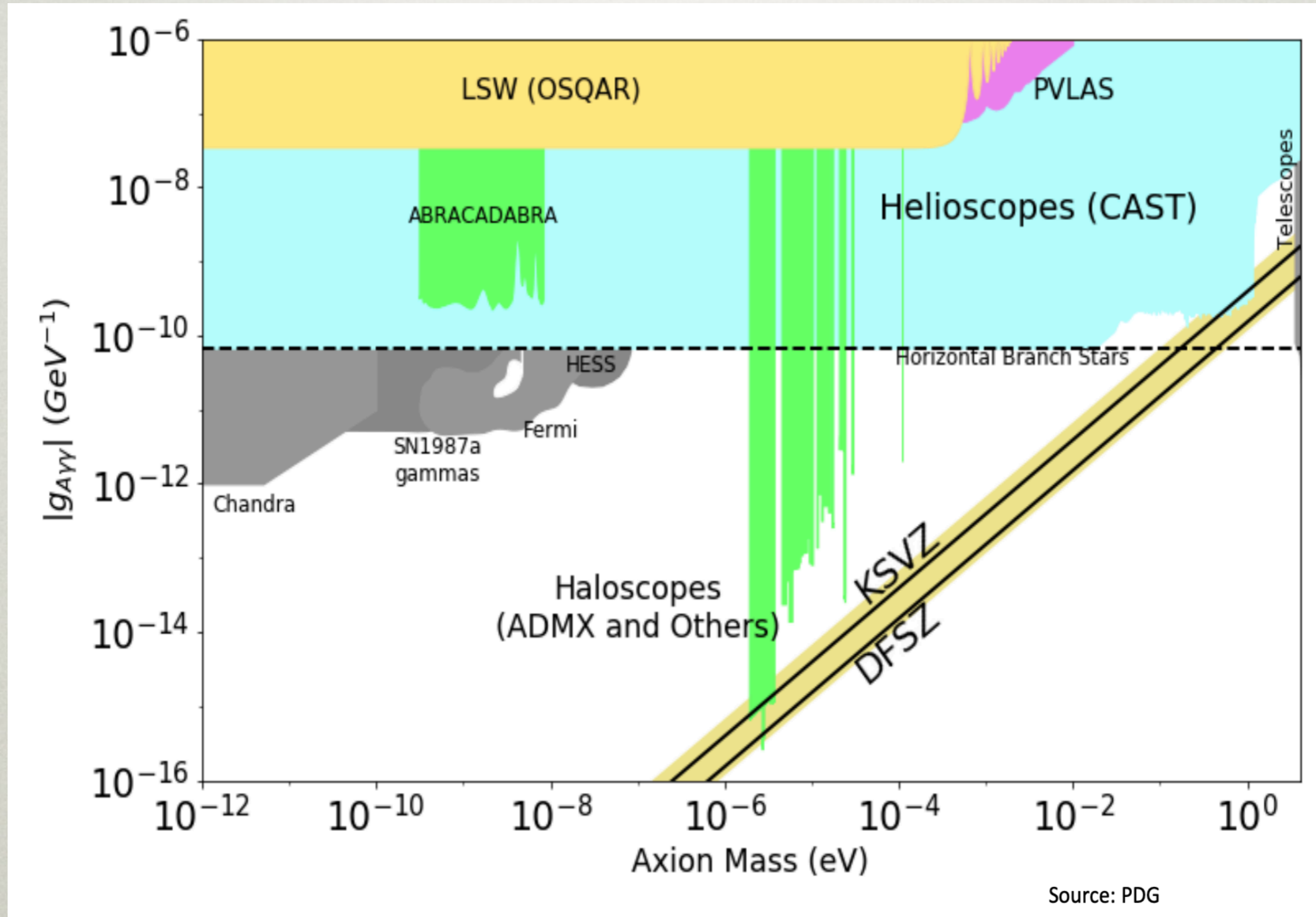
NEPLES, 23 SEPTEMBER 2019

THE RACE FOR THE AXION



[PDG 2019]

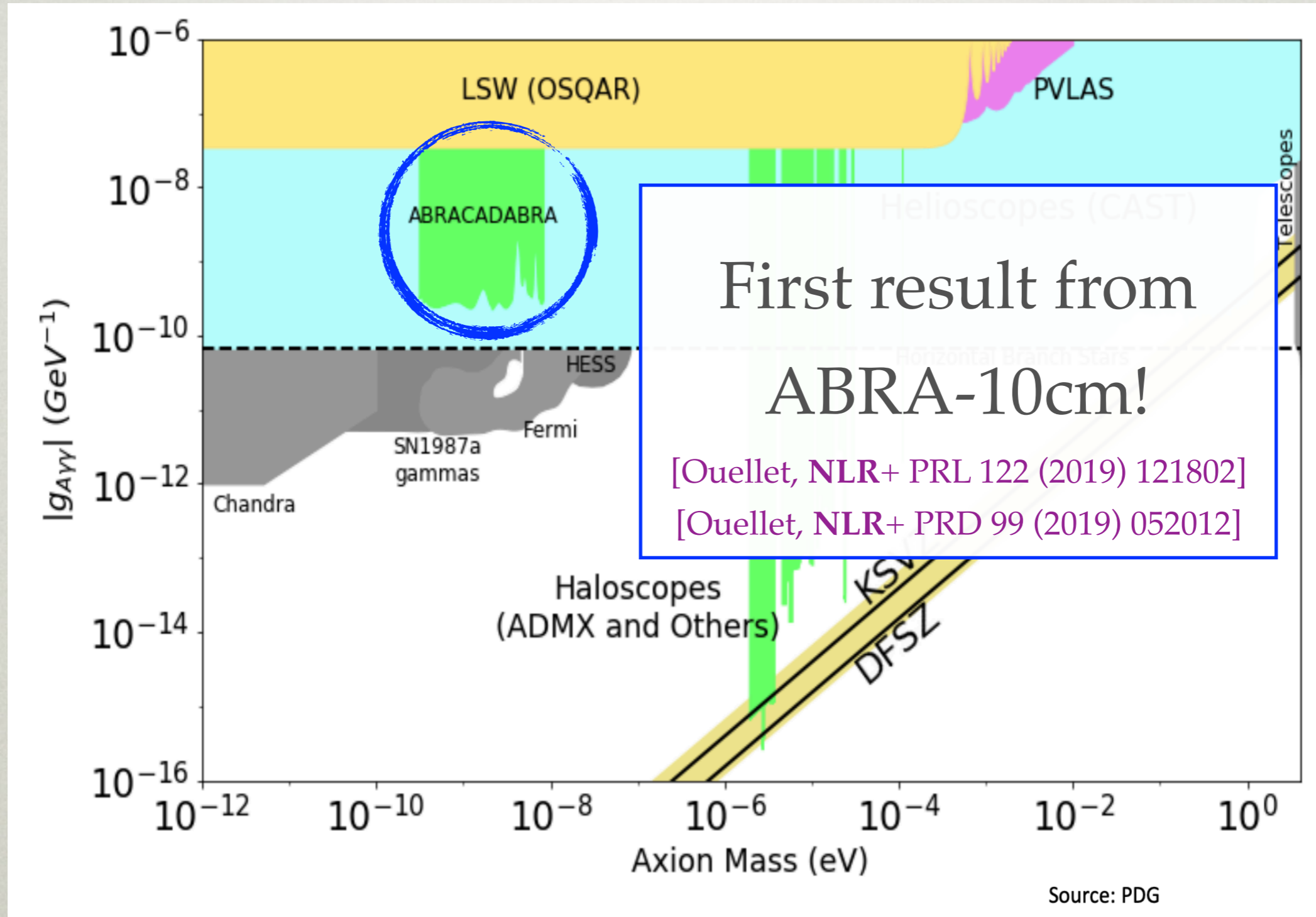
THE RACE FOR THE AXION



[PDG 2020?]

Source: Gray Rybka, TAUP 2019

THE RACE FOR THE AXION



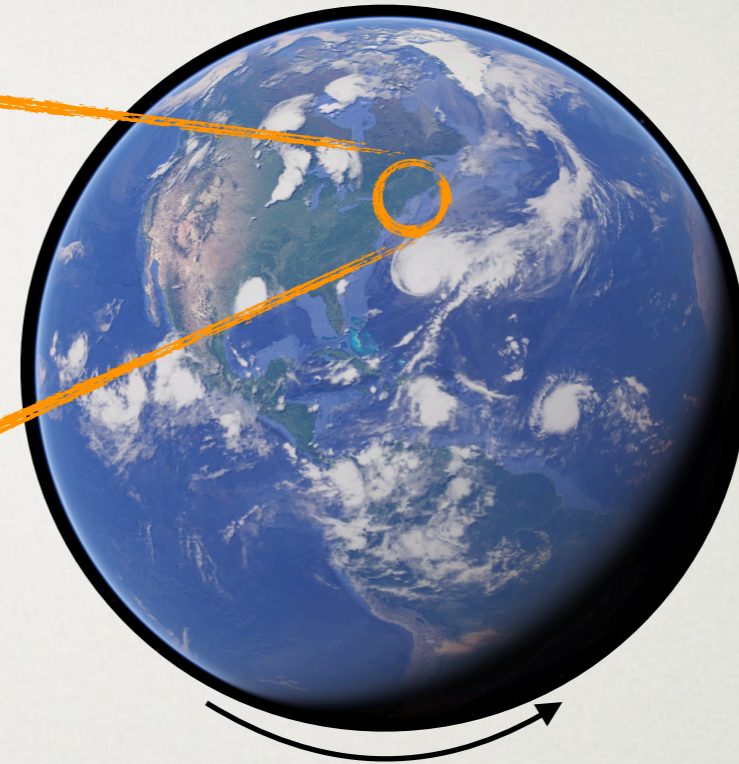
[PDG 2020?]

Source: Gray Rybka, TAUP 2019

DARK MATTER'S FINGERPRINT

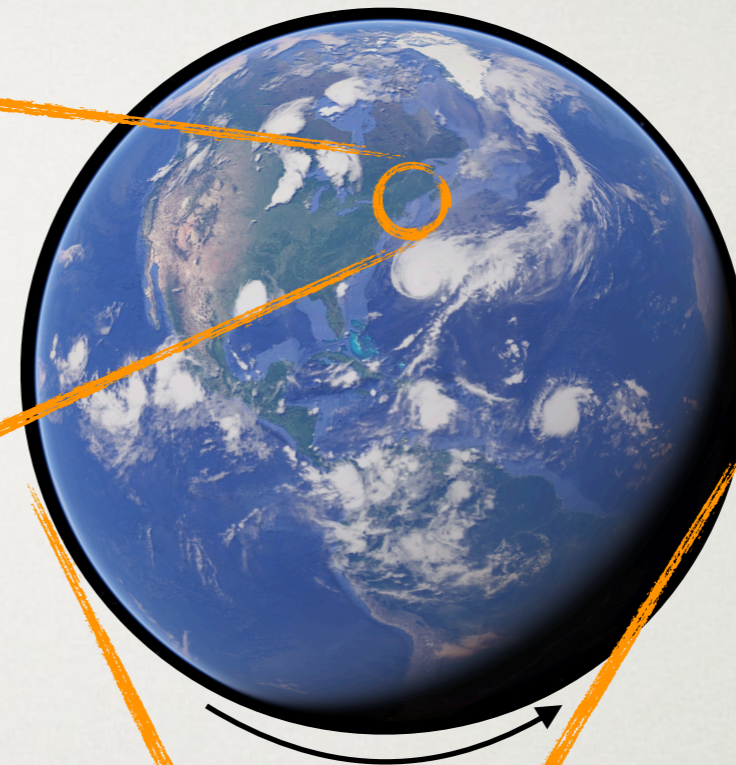


DARK MATTER'S FINGERPRINT

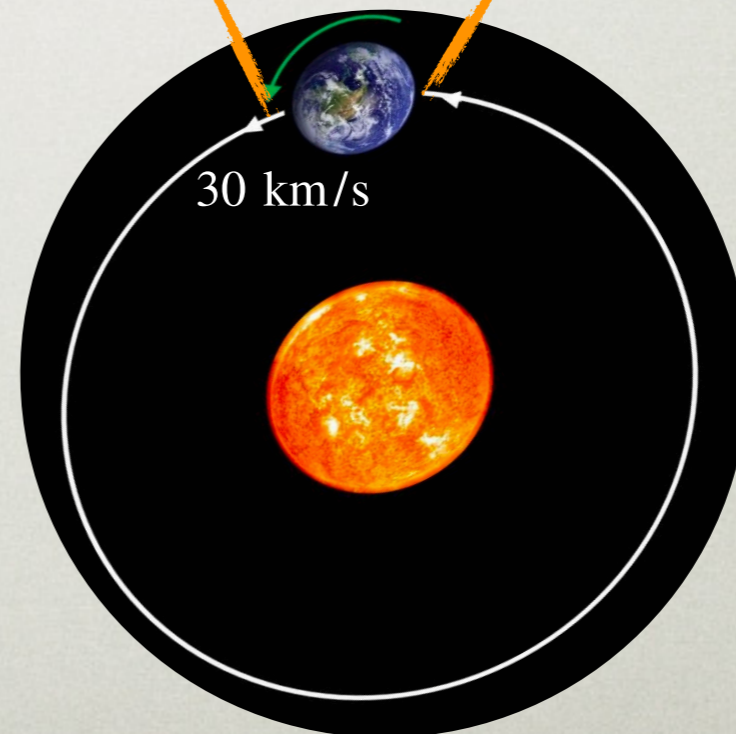


0.5 km/s

DARK MATTER'S FINGERPRINT

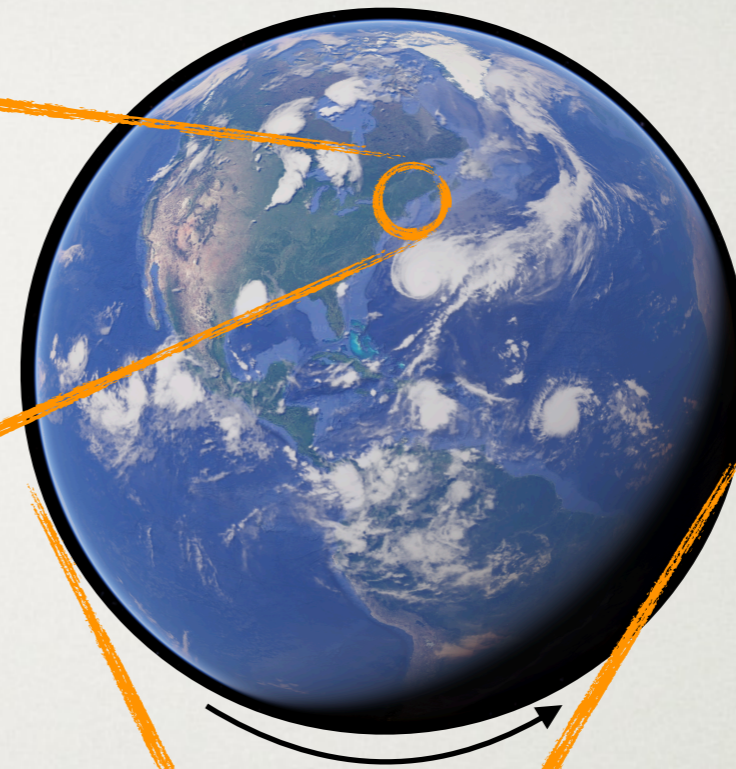


0.5 km/s

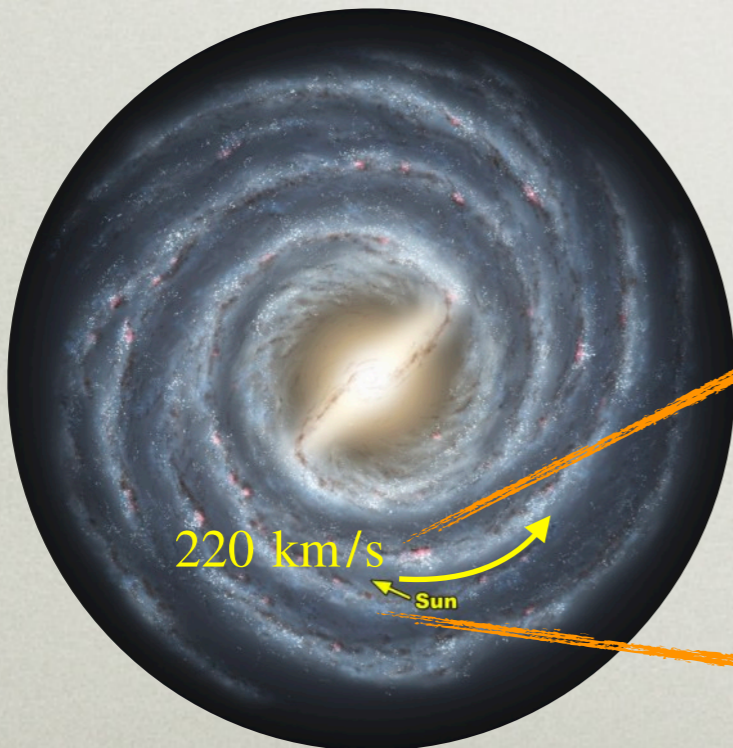


30 km/s

DARK MATTER'S FINGERPRINT

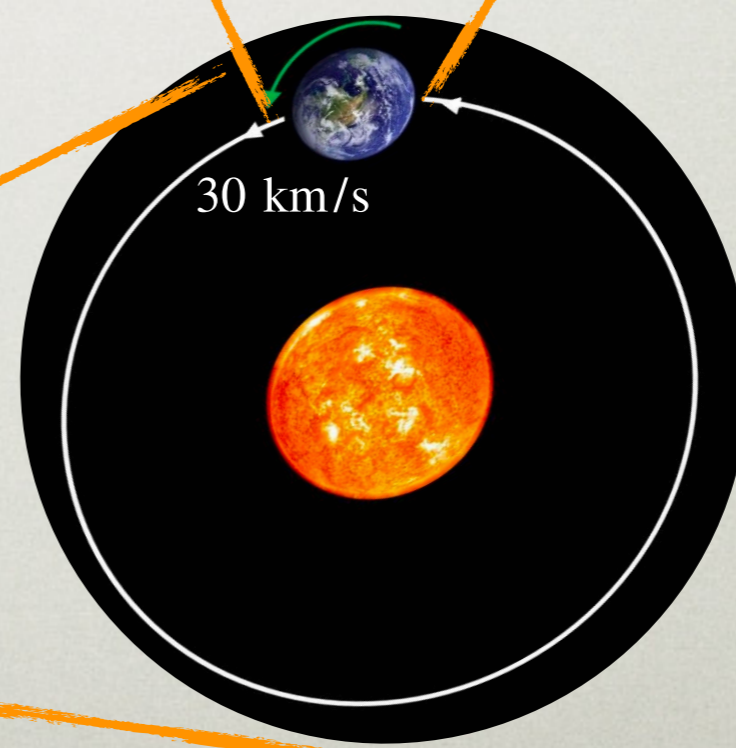


0.5 km/s



220 km/s

Sun



30 km/s

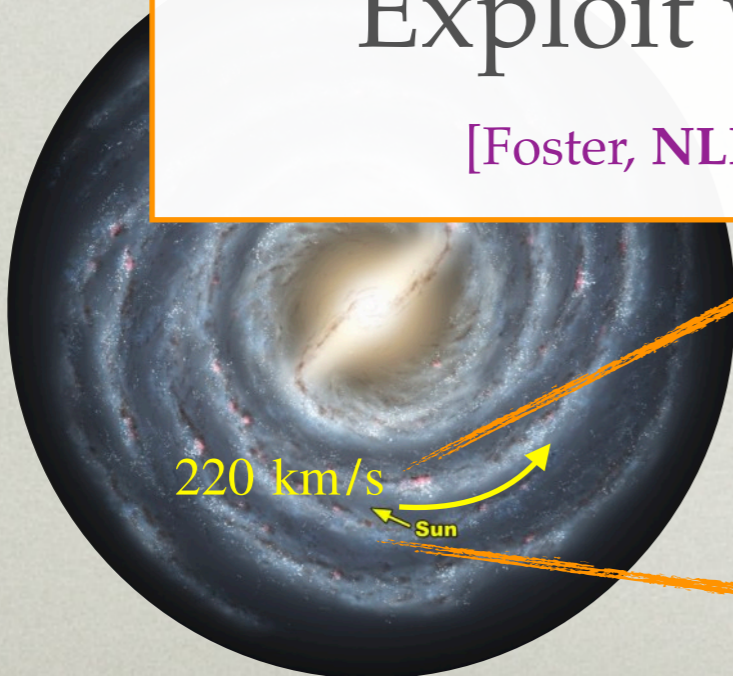
DARK MATTER'S FINGERPRINT



Dark matter leaves a unique
fingerprint in the data

Exploit with a *Likelihood*

[Foster, NLR, Safdi PRD 97 (2018) 123006]



ABRA - IN THEORY



- Modified Ampere-Maxwell equation

$$\nabla \times \mathbf{B} = \frac{\partial \mathbf{E}}{\partial t} + \mathbf{J} - g_{a\gamma\gamma} \left(\mathbf{E} \times \nabla a - \frac{\partial a}{\partial t} \mathbf{B} \right)$$

ABRA - IN THEORY



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$v \sim 10^{-3} \ll 1$

ABRA - IN THEORY



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$(m_a L_{\text{exp}})^2 \ll 1$ $v \sim 10^{-3} \ll 1$

- Displacement current suppressed for small axion masses
- For details: [Ouellet, Bogorad PRD 99 (2019) 055010]

ABRA - IN THEORY



- Modified Ampere-Maxwell equation

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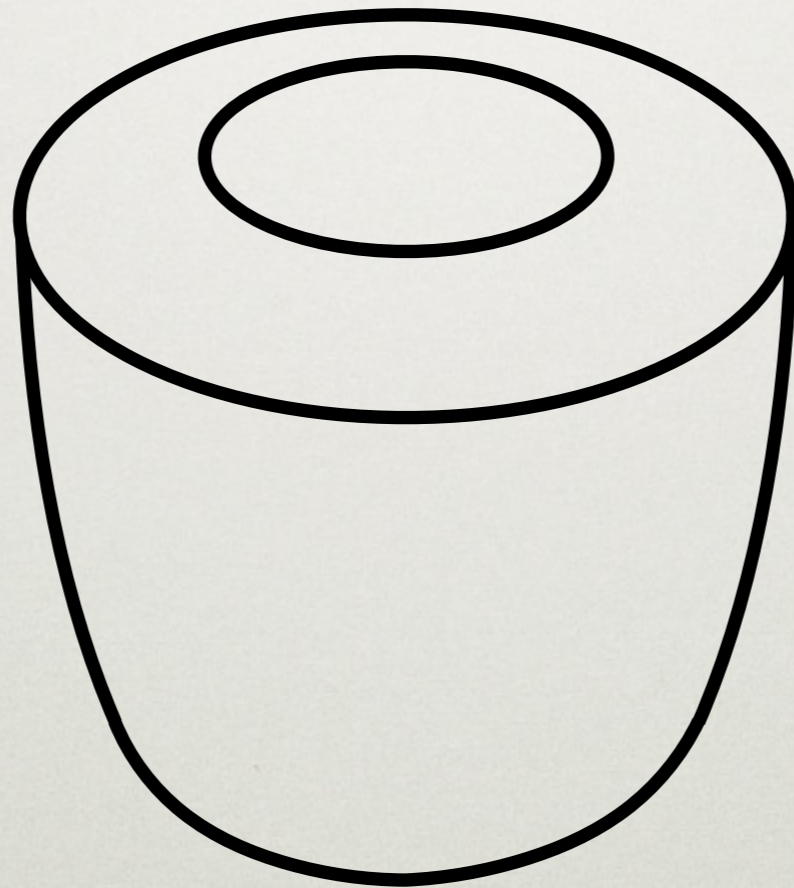
- Displacement current suppressed for small axion masses
- Leading contribution

$$\nabla \times \mathbf{B} = \mathbf{J}_{\text{eff}} = g_{a\gamma\gamma} \frac{\partial a}{\partial t} \mathbf{B}$$



ABRA - IN THEORY

$$\nabla \times \mathbf{B} = \mathbf{J}_{\text{eff}} = g_{a\gamma\gamma} \frac{\partial a}{\partial t} \mathbf{B}$$

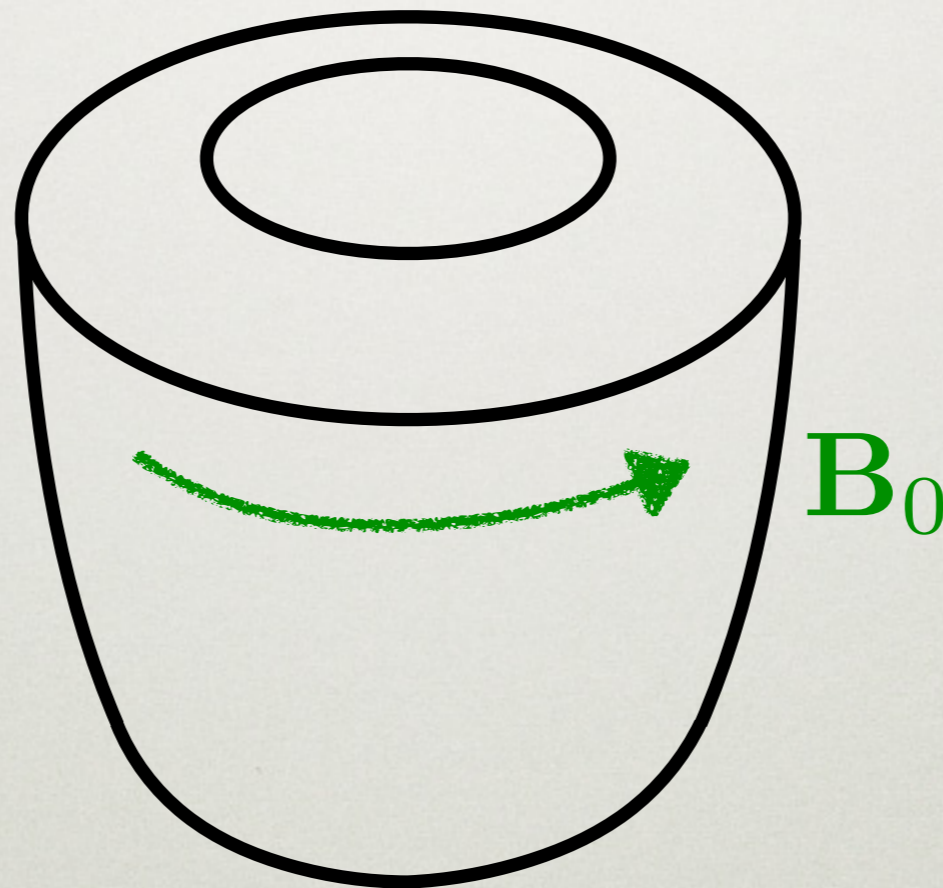


Proposal from [Kahn, Safdi, Thaler PRL 117 (2016) 141801]



ABRA - IN THEORY

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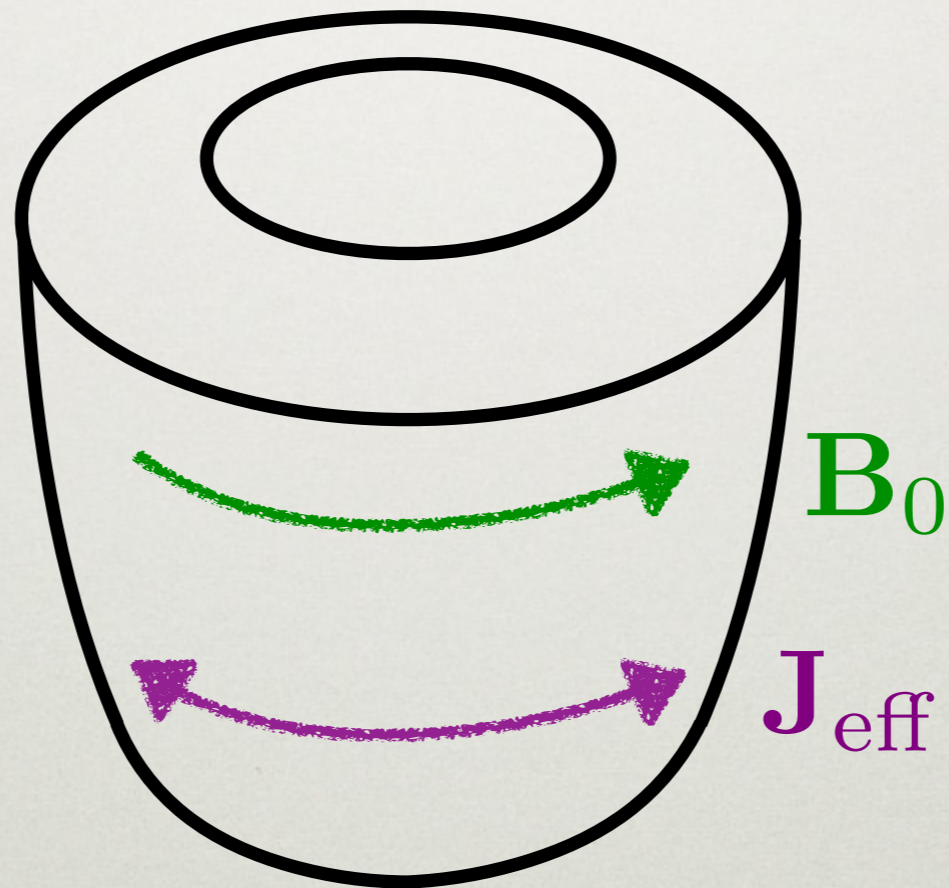


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ABRA - IN THEORY

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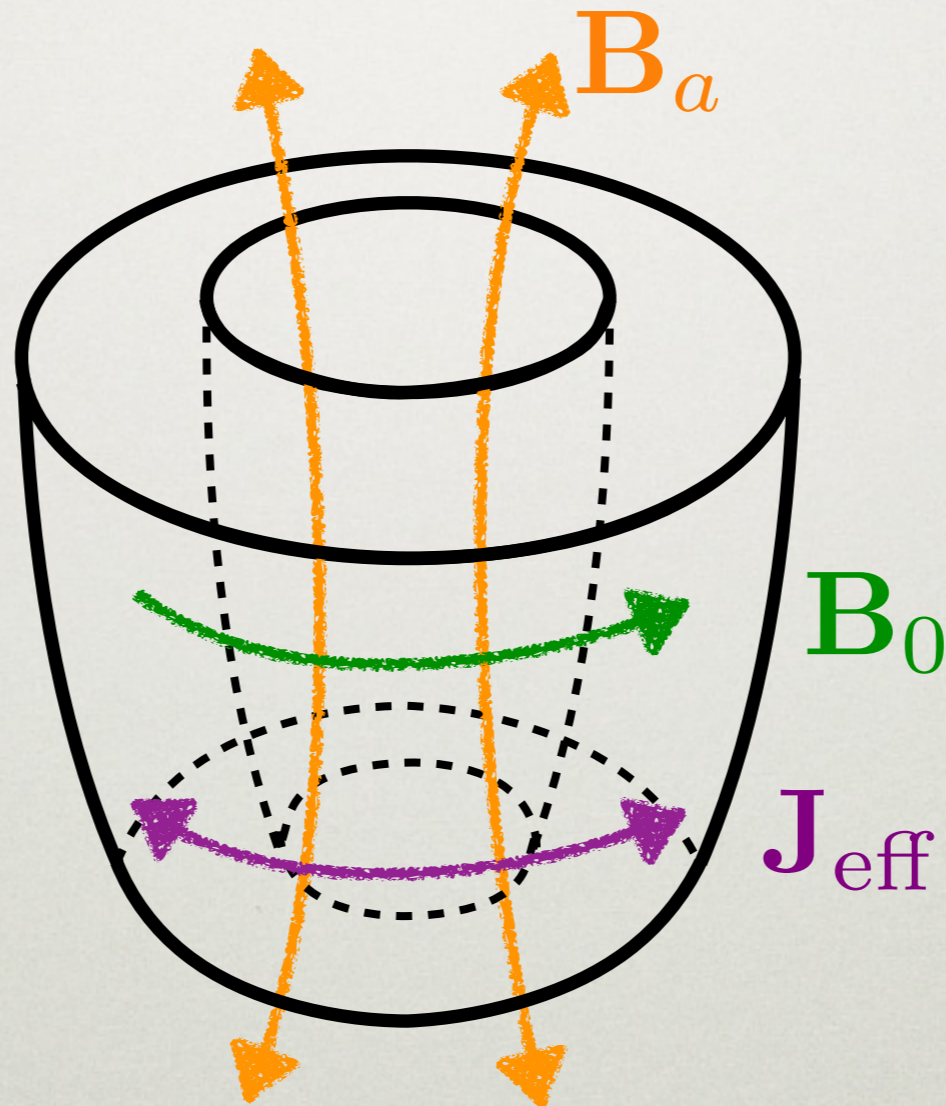


Proposal from [Kahn, Safdi, Thaler PRL 117 (2016) 141801]

ABRA - IN THEORY

$$\nabla \times \mathbf{B} = \mathbf{J}_{\text{eff}} = g_{a\gamma\gamma} \frac{\partial a}{\partial t} \mathbf{B}$$

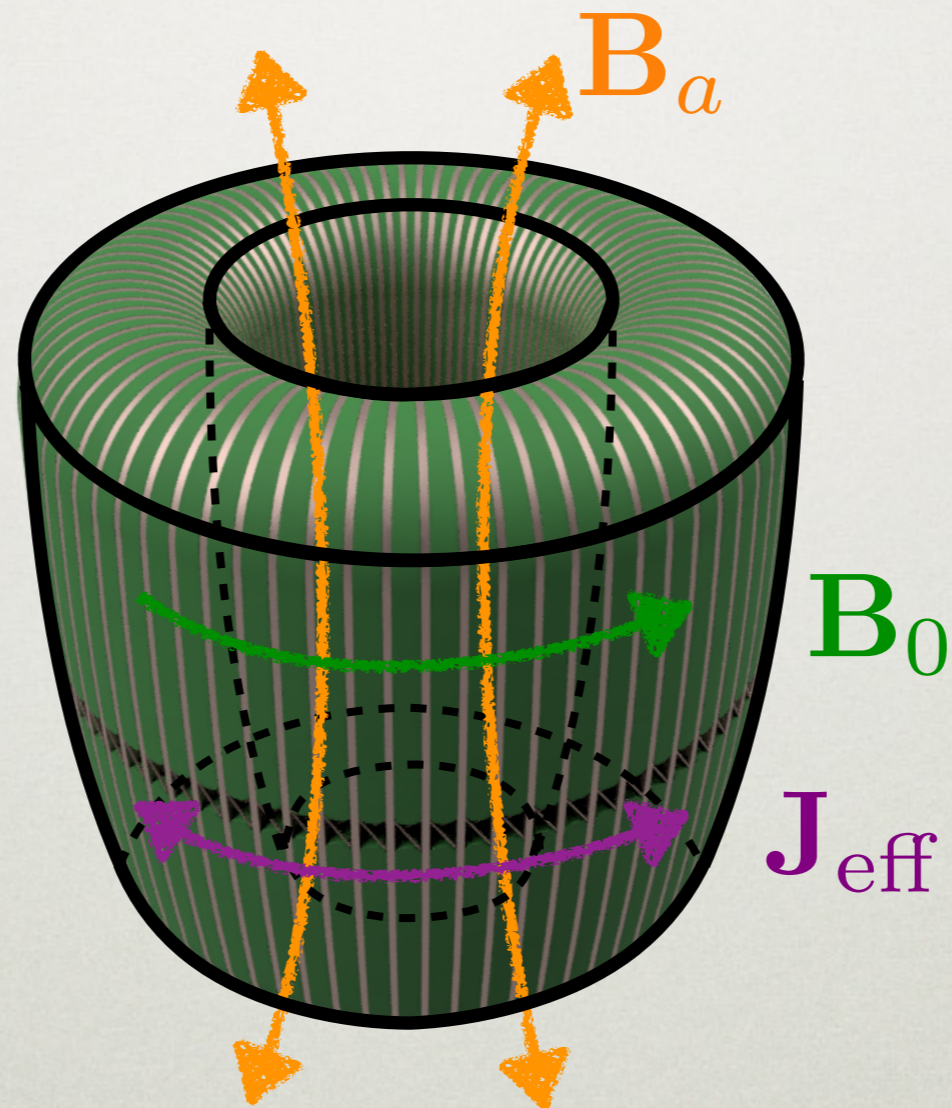
Pickup loop in
the centre reads
out $\Phi_{\mathbf{B}_a}$



Proposal from [Kahn, Safdi, Thaler PRL 117 (2016) 141801]

ABRA - EXPERIMENT

$$\nabla \times \mathbf{B} = \mathbf{J}_{\text{eff}} = g_{a\gamma\gamma} \frac{\partial a}{\partial t} \mathbf{B}$$

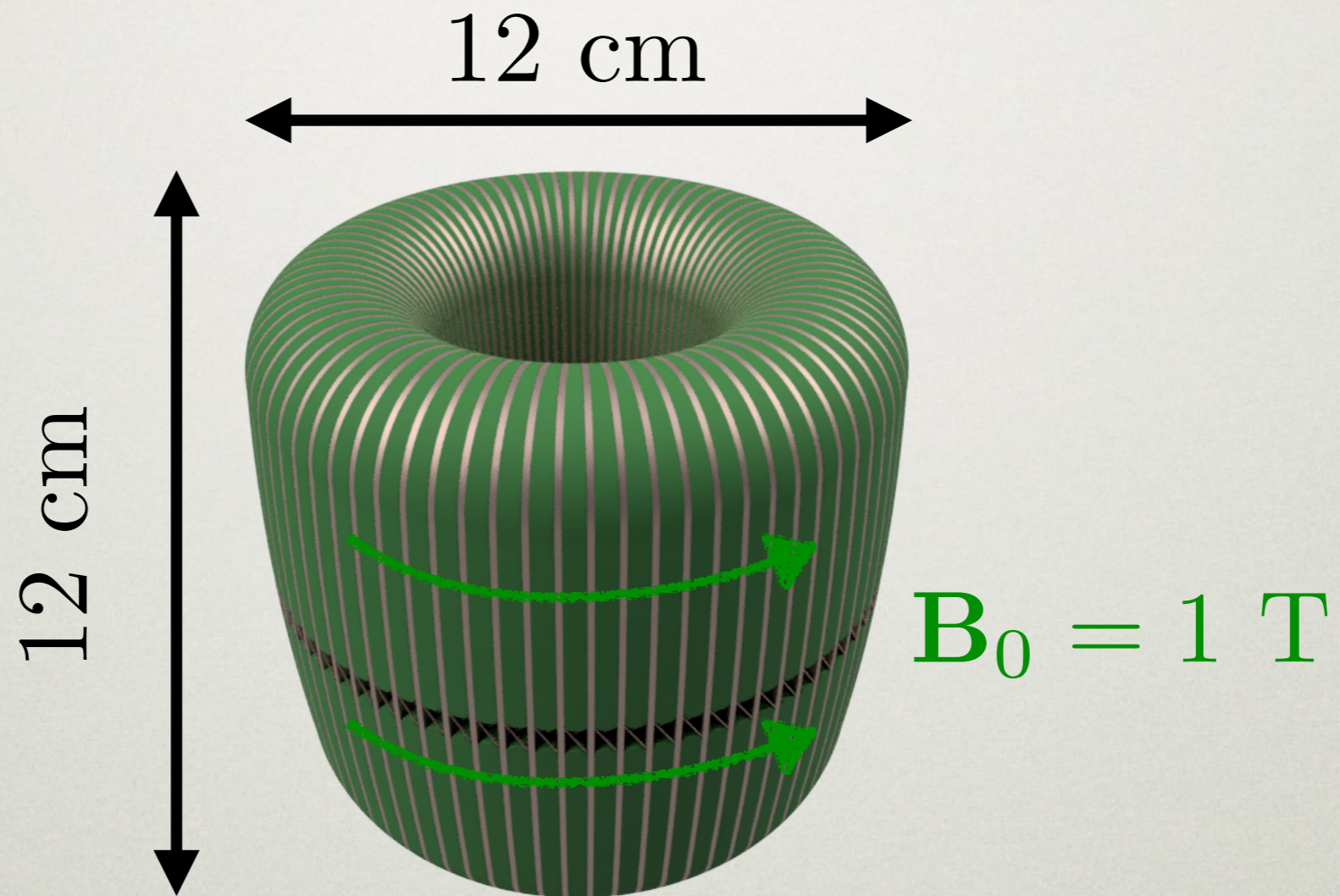


Proposal from [Kahn, Safdi, Thaler PRL 117 (2016) 141801]

ABRA - EXPERIMENT



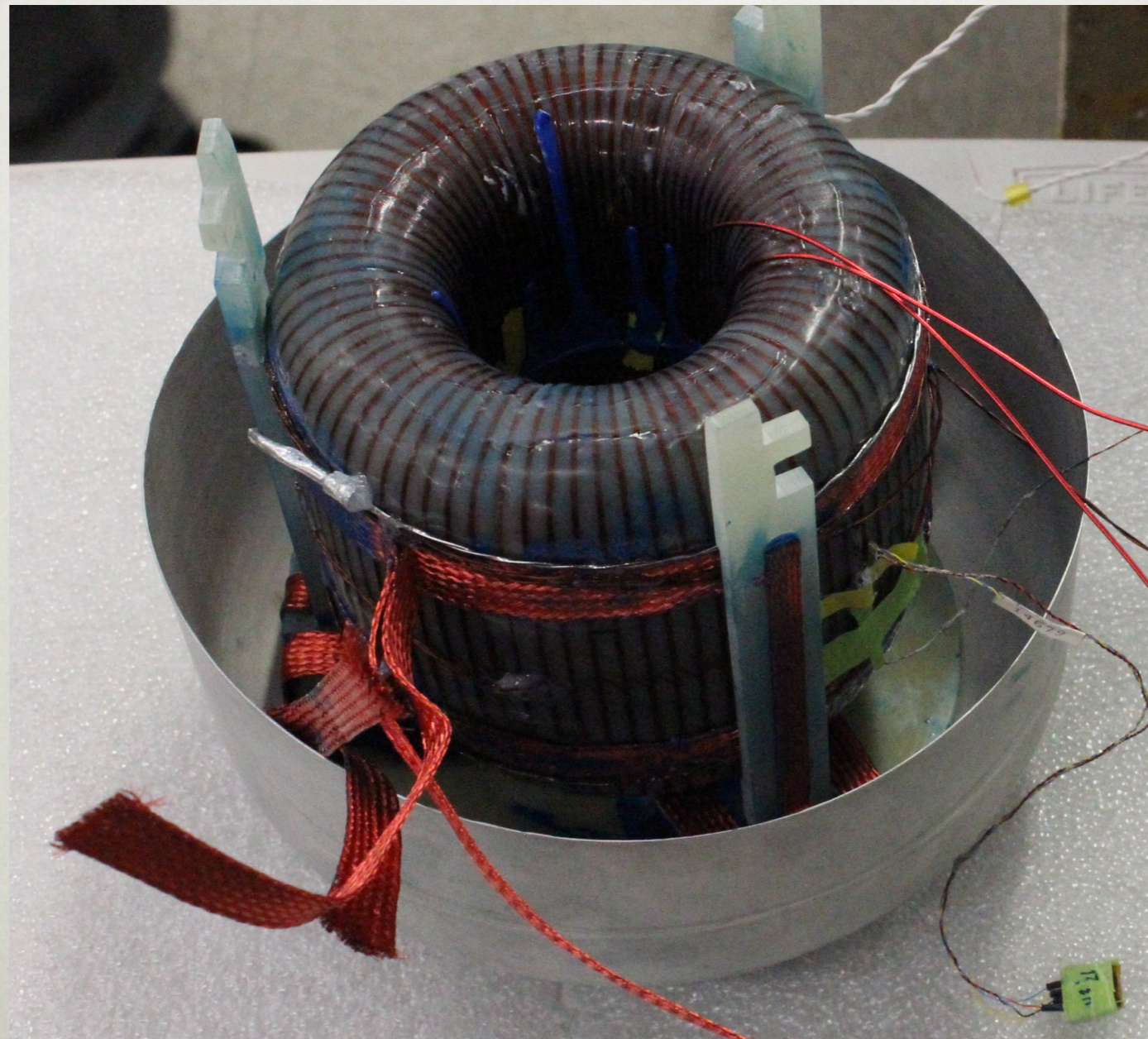
- 10cm experimental parameters



ABRA - EXPERIMENT



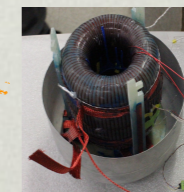
- 10cm experimental parameters
- Experiment exists!



ABRA - EXPERIMENT



- 10cm experimental parameters
- Experiment exists!



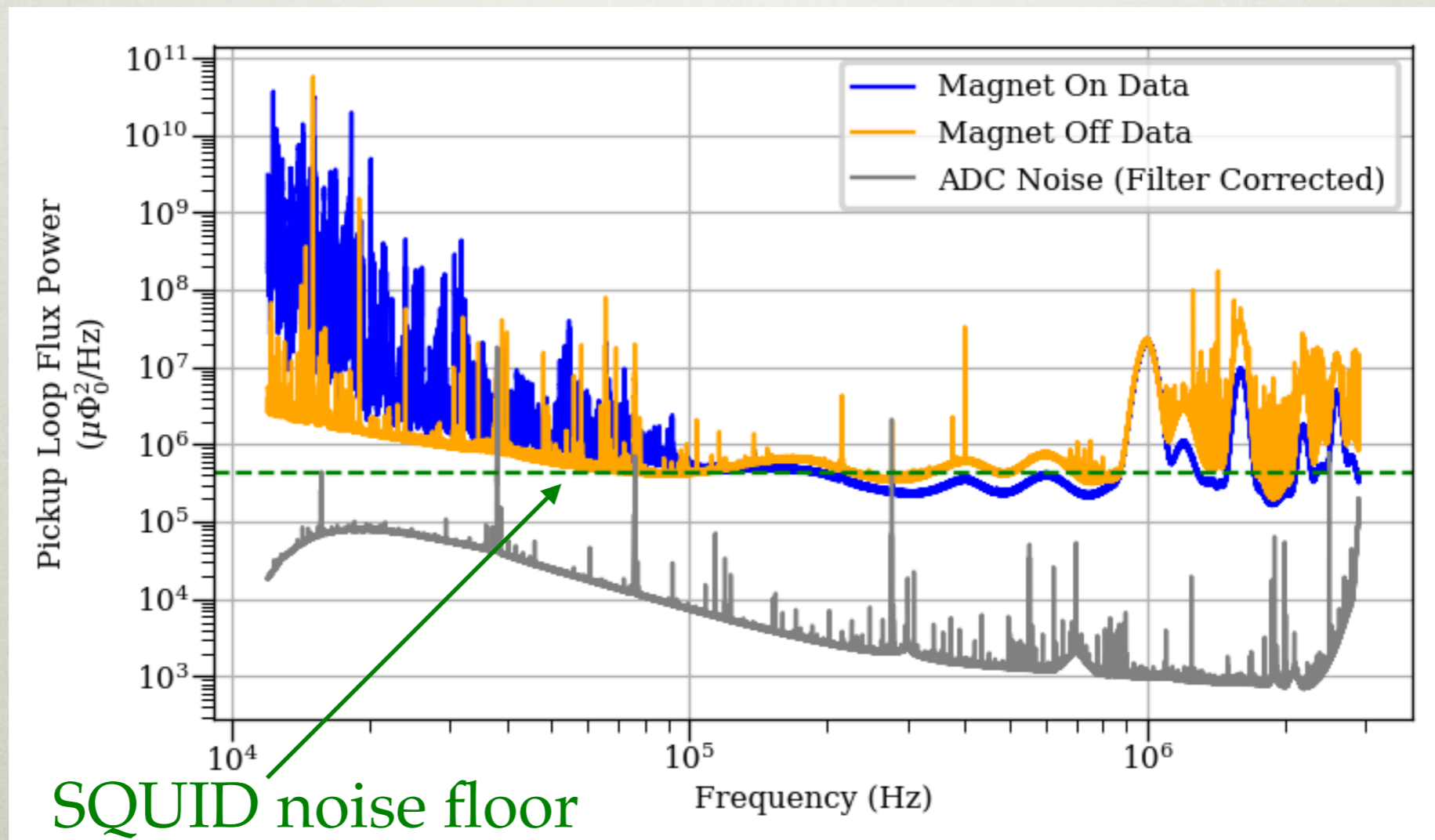
Shielded and cooled < 1 K

Experimentalists for scale

ABRA - EXPERIMENT



- Data: 1 month magnet on; 2 weeks magnet off; 10 MS/s
- Collected in the broadband readout (add resonator in future)
- For a discussion of optimal readout: [Chaudhuri+ 1904.05806]



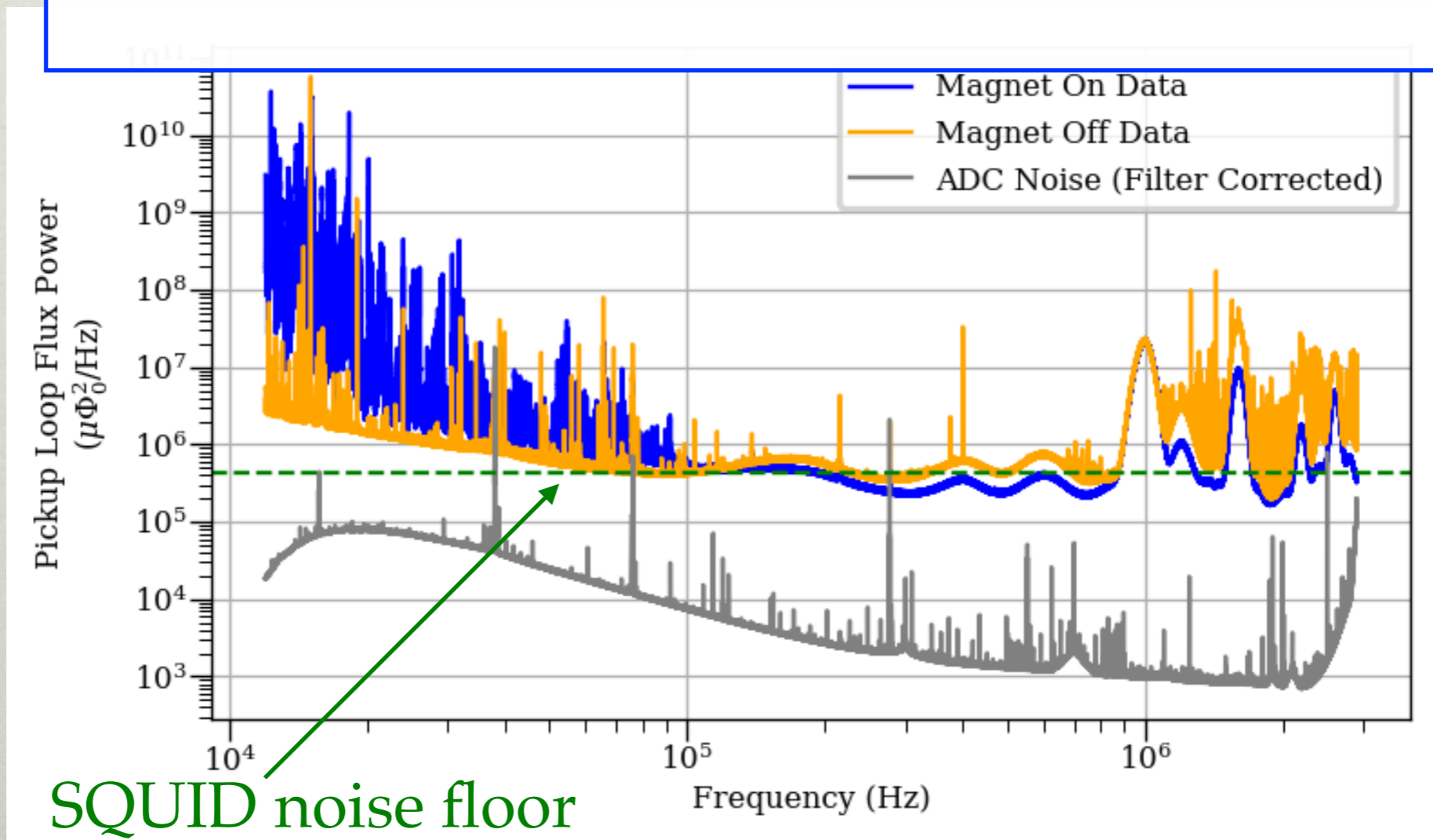
[Ouellet, NLR+ PRL 122 (2019) 121802]

[Ouellet, NLR+ PRD 99 (2019) 052012]

ABRA - EXPERIMENT



- Data: 1 month magnet on; 2 weeks magnet off; 10 MS/s
 - Collected in the broadband readout (add resonator in future)
 - For a
- Is there an axion hiding in this data?



[Ouellet, NLR+ PRL 122 (2019) 121802]

[Ouellet, NLR+ PRD 99 (2019) 052012]

ABRA - LIKELIHOOD



- Experiments all sample the local axion field

$$a(t) = \sum_{i=1}^{N_a} \frac{\sqrt{2\rho_{\text{DM}}/N_a}}{m_a} \cos \left[m_a \left(1 + \frac{v_i^2}{2} \right) t + \phi_i \right]$$

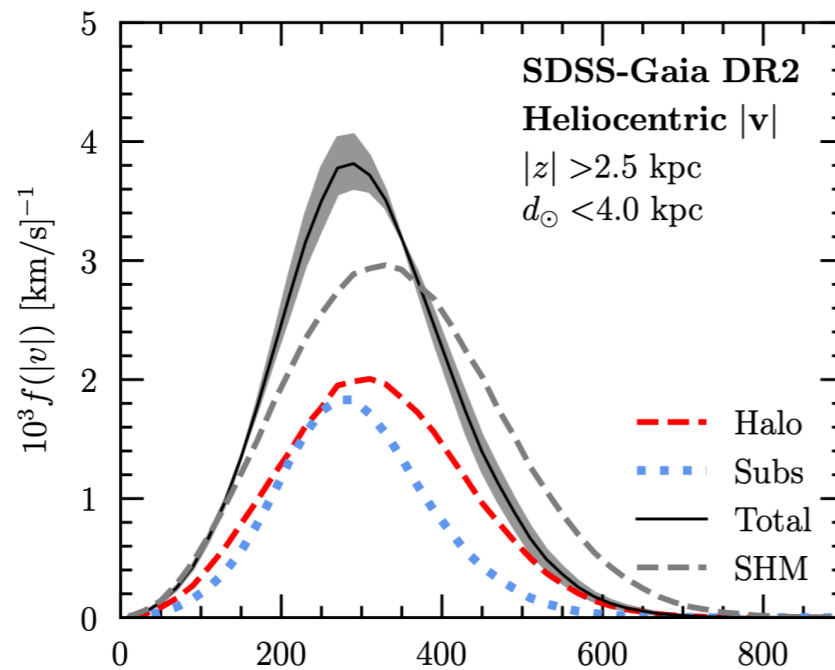
ABRA - LIKELIHOOD



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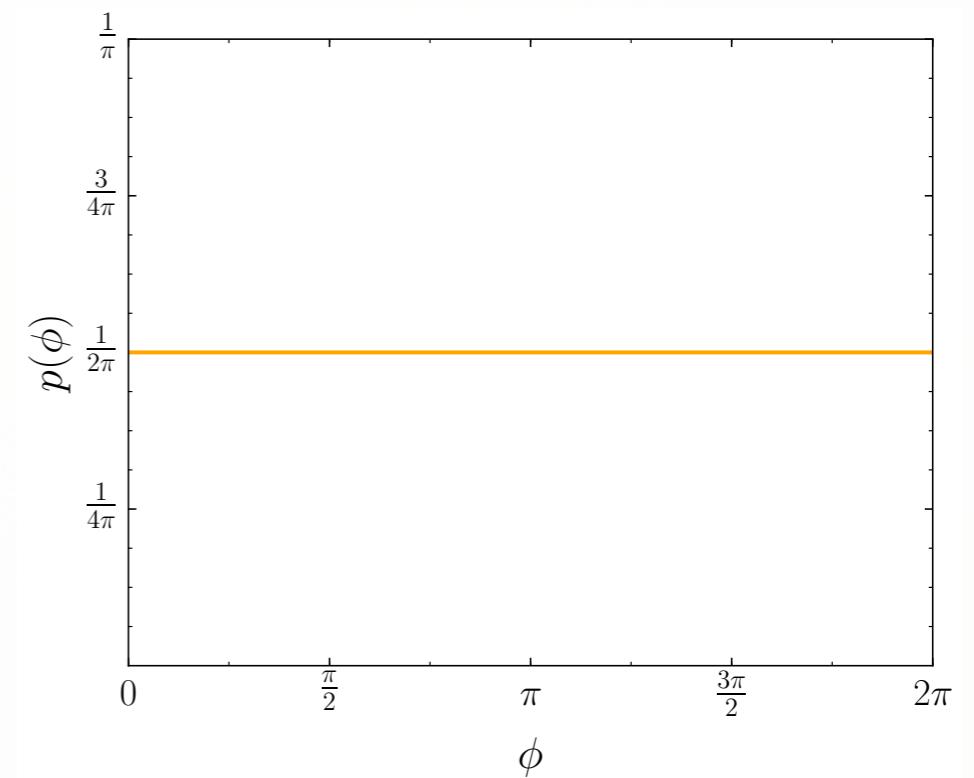
$$a(t) = \sum_{i=1}^{N_a} \frac{\sqrt{2\rho_{\text{DM}}/N_a}}{m_a} \cos \left[m_a \left(1 + \frac{v_i^2}{2} \right) t - \phi_i \right]$$

Draw from speed distribution



[Necib+ 1810.12301] |v| [km/s]

Random phase



[Foster, NLR, Safdi PRD 97 (2018) 123006]

ABRA - LIKELIHOOD



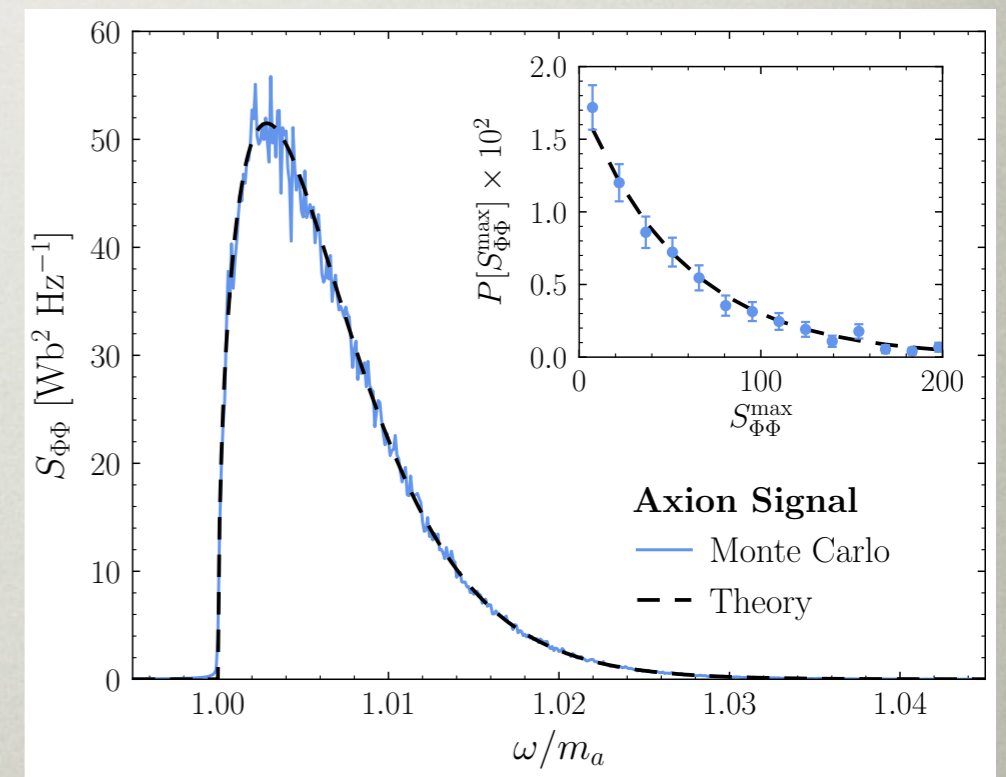
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- Axion PSD inherits an exponential distribution

$$P[S_{\Phi\Phi}(\omega)] = \frac{1}{\lambda(\omega)} e^{-S_{\Phi\Phi}(\omega)/\lambda(\omega)}$$

$$\lambda(\omega) \equiv \langle S_{\Phi\Phi}(\omega) \rangle = A \frac{\pi f(v)}{m_a v} \Big|_{v=\sqrt{2\omega/m_a-2}}$$



ABRA - LIKELIHOOD



- Experiments all sample the local axion field

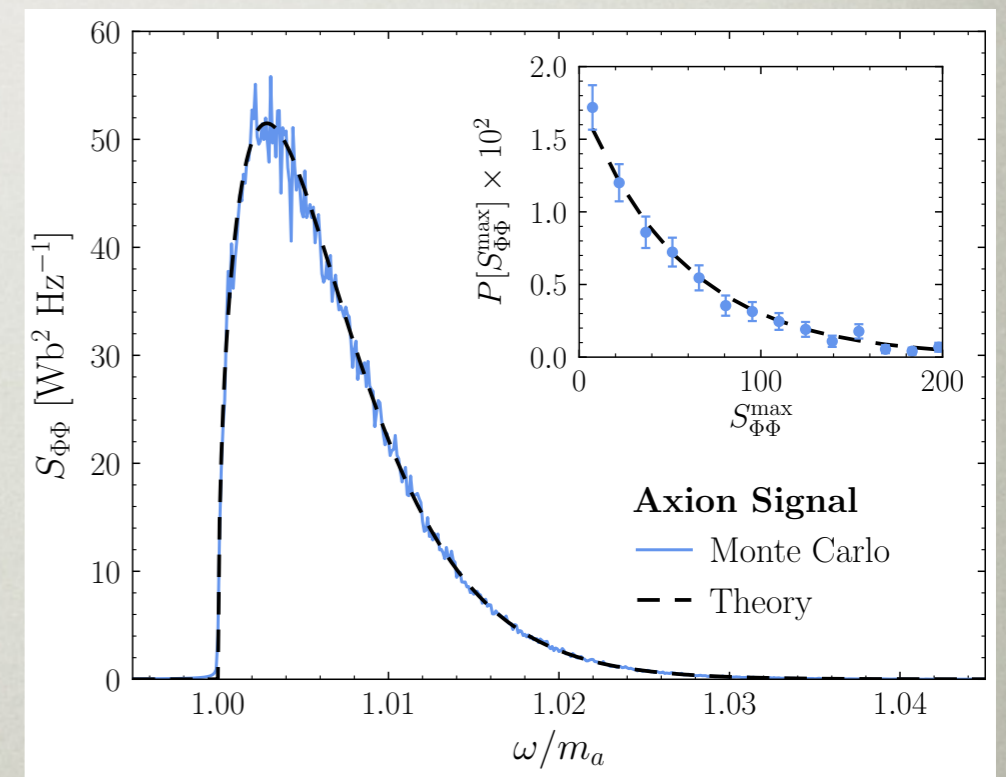
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Experimental parameters - result not unique to ABRA (or axions!)



ABRA - LIKELIHOOD



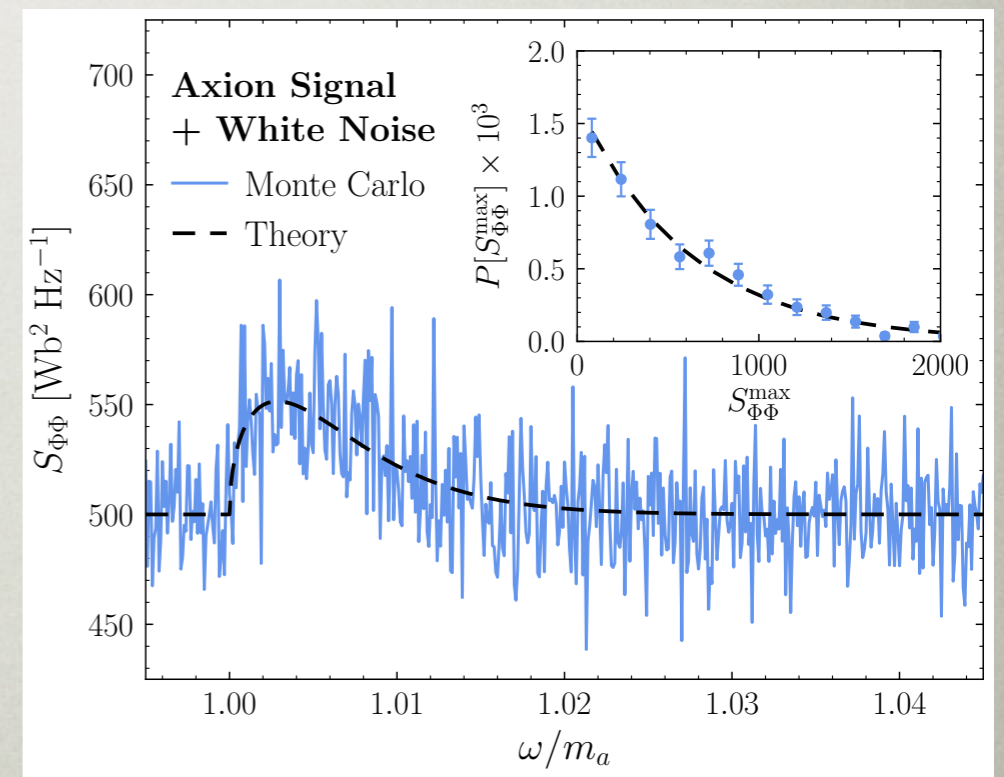
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- Axion PSD inherits an exponential distribution
- Can include Gaussian backgrounds

$$P[S_{\Phi\Phi}(\omega)] = \frac{1}{\lambda(\omega)} e^{-S_{\Phi\Phi}(\omega)/\lambda(\omega)}$$

$$\lambda(\omega) \equiv \langle S_{\Phi\Phi}(\omega) \rangle = A \frac{\pi f(v)}{m_a v} + \lambda_B$$



ABRA - LIKELIHOOD



$$\mathcal{L}(d|\mathcal{M}, \boldsymbol{\theta}) = \prod_{k=1}^{N-1} \frac{1}{\lambda_k(\boldsymbol{\theta})} e^{-S_{\Phi\Phi}^k / \lambda_k(\boldsymbol{\theta})}$$

ABRA - LIKELIHOOD



$$\mathcal{L}(d|\mathcal{M}, \boldsymbol{\theta}) = \prod_{k=1}^{N-1} \frac{1}{\lambda_k(\boldsymbol{\theta})} e^{-S_{\Phi\Phi}^k / \lambda_k(\boldsymbol{\theta})}$$

- Analytic sensitivity: Asimov
- [Cowan+ EPJ C71 (2011) 1554]

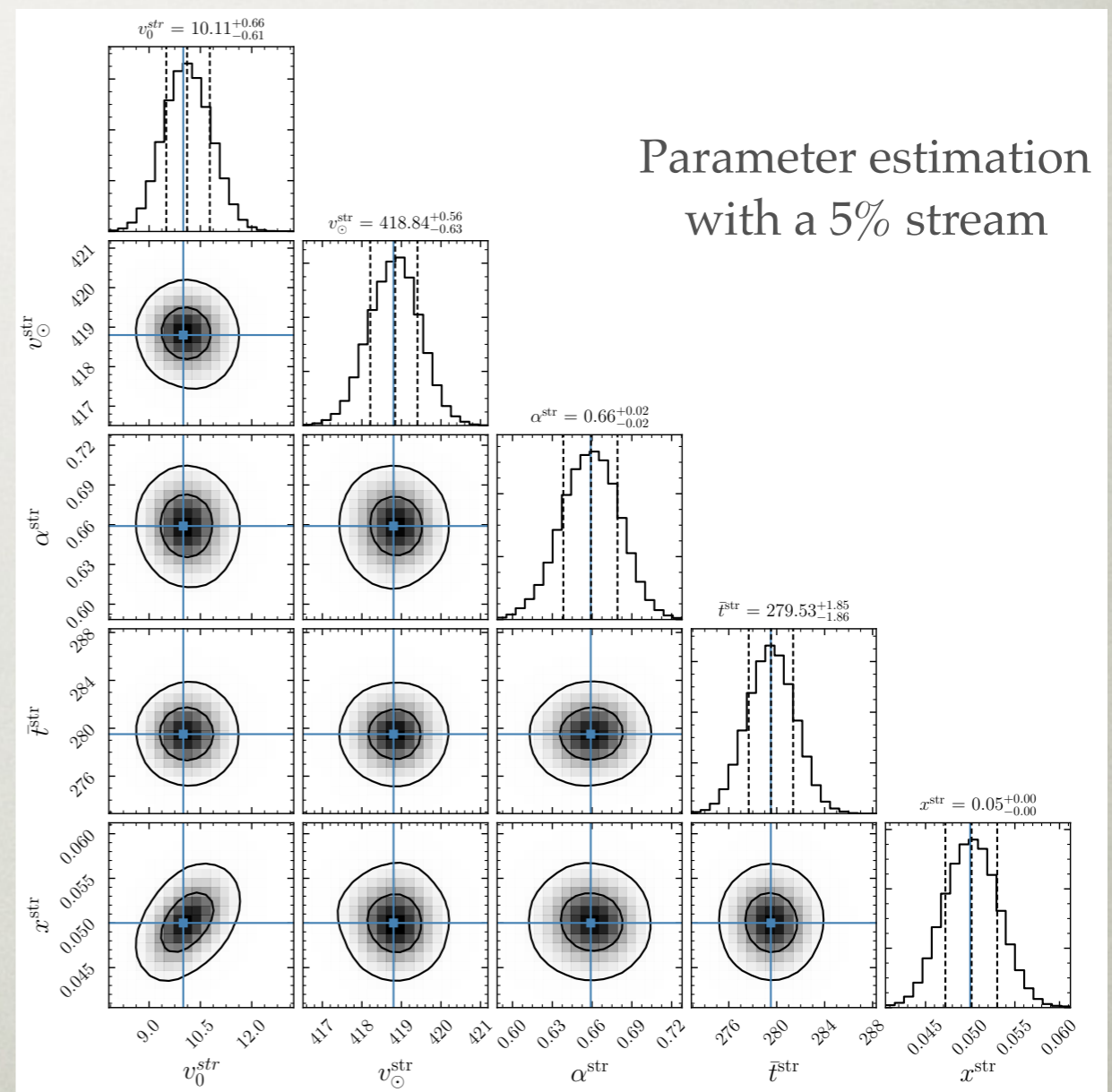
$$g_{a\gamma\gamma}^2 \sim \frac{1}{\sqrt{\int_0^\infty dv \frac{f(v)^2}{v}}} \quad (\text{Field})$$

$$\sigma_{\text{DD}} \sim \frac{1}{\int_{v_{\text{min}}}^\infty dv \frac{f(v)}{v}} \quad (\text{Particle})$$

ABRA - LIKELIHOOD

$$\mathcal{L}(d|\mathcal{M}, \boldsymbol{\theta}) = \prod_{k=1}^{N-1} \frac{1}{\lambda_k(\boldsymbol{\theta})} e^{-S_{\Phi\Phi}^k / \lambda_k(\boldsymbol{\theta})}$$

- Analytic sensitivity: Asimov
- Disentangle DM's fingerprint

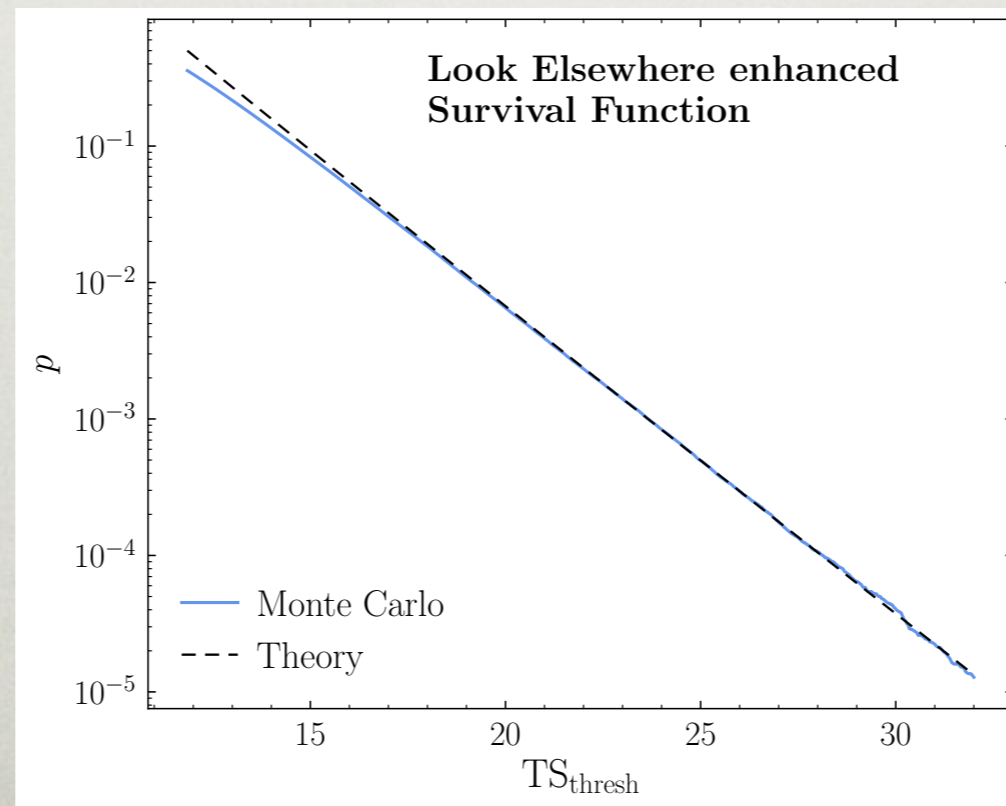




ABRA - LIKELIHOOD

$$\mathcal{L}(d|\mathcal{M}, \boldsymbol{\theta}) = \prod_{k=1}^{N-1} \frac{1}{\lambda_k(\boldsymbol{\theta})} e^{-S_{\Phi\Phi}^k / \lambda_k(\boldsymbol{\theta})}$$

- Analytic sensitivity: Asimov
- Disentangle DM's fingerprint
- Analytical look elsewhere effect



ABRA - LIKELIHOOD



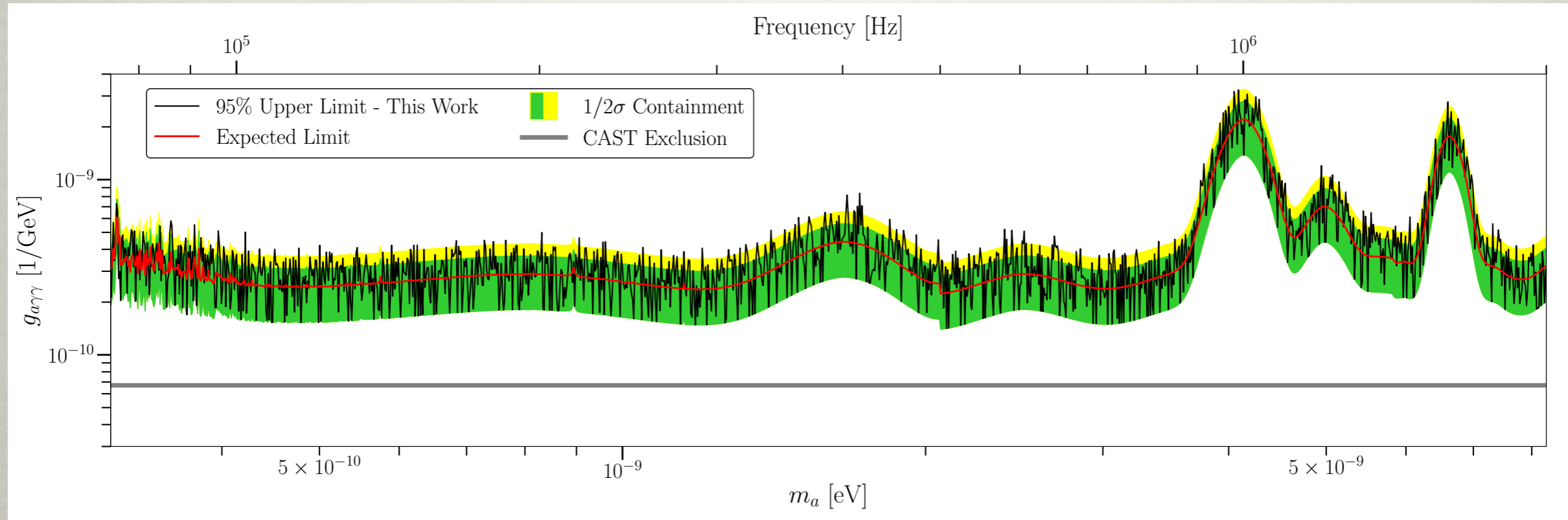
$$\mathcal{L}(d|\mathcal{M}, \boldsymbol{\theta}) = \prod_{k=1}^{N-1} \frac{1}{\lambda_k(\boldsymbol{\theta})} e^{-S_{\Phi\Phi}^k / \lambda_k(\boldsymbol{\theta})}$$

- Analytic sensitivity: Asimov
- Disentangle DM's fingerprint
- Analytical look elsewhere effect
- **Analyse experimental datasets!**
 - Establish rigorous 95% CL limits
 - Establish 5σ discovery threshold

ABRA - $\mathcal{L}(d|\mathcal{M}, \theta)$ & DATA



- ABRA data + likelihood framework

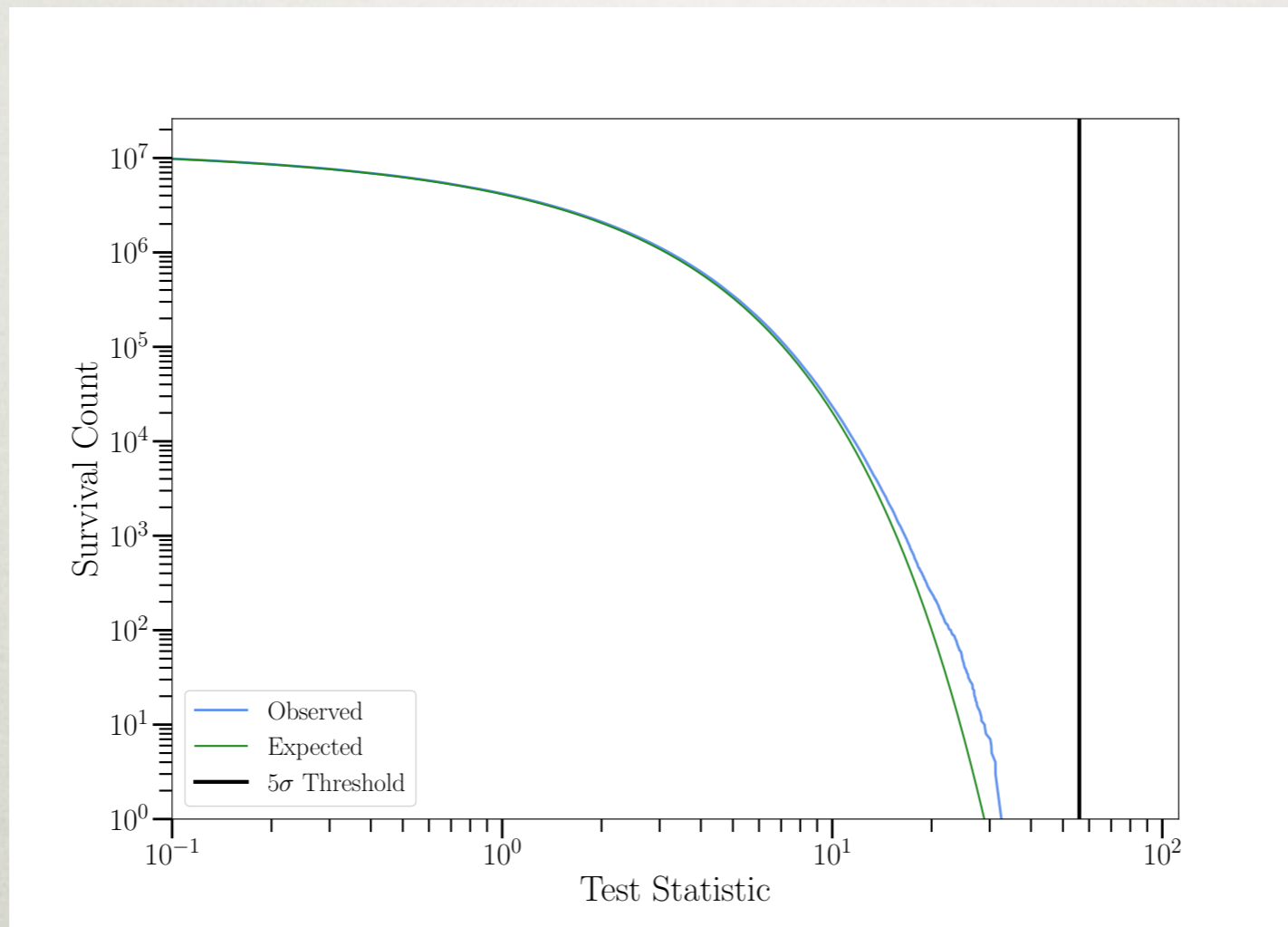


- ~10 million mass points, down sampled by a factor of 10^4
- 87 5 sigma excesses - all seen in magnet off data, so vetoed
- ~30% of the data removed due to large amounts of noise
- Confirmed this did not bias our analysis via injected signal test
[Ouellet, NLR+ PRL 122 (2019) 121802]
[Ouellet, NLR+ PRD 99 (2019) 052012]

ABRA - $\mathcal{L}(d|\mathcal{M}, \theta)$ & DATA



- Statistics in action:

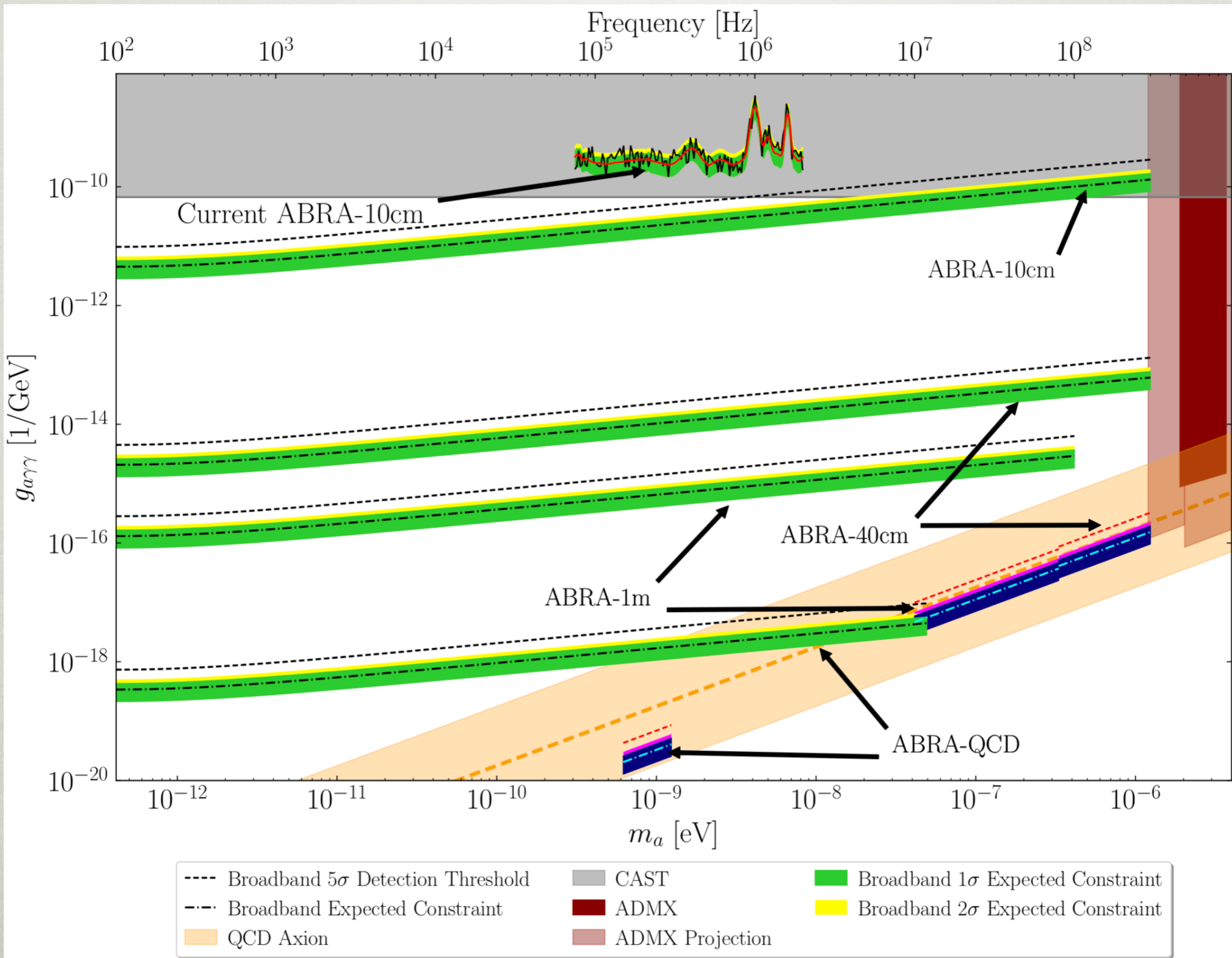


- Look elsewhere effect is included
- Extremely well described by Gaussian noise

[Ouellet, NLR+ PRL 122 (2019) 121802]

[Ouellet, NLR+ PRD 99 (2019) 052012]

ABRA - FUTURE

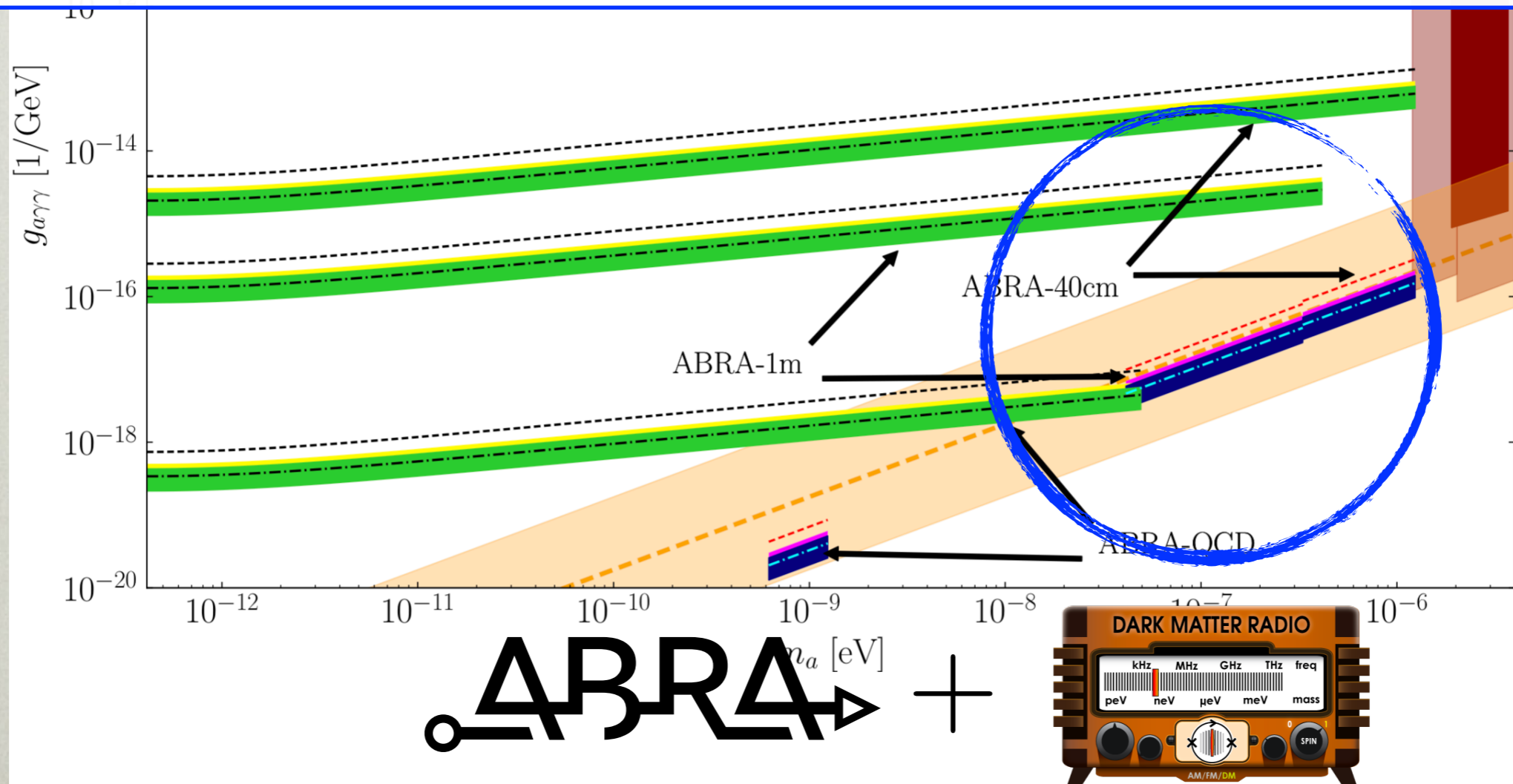


ABRA - BREAKING NEWS



Frequency [Hz]

- In the process of forming a collaborative effort with DM-radio to construct 1m³ experiment capable of probing the QCD axion
- Project has funding to begin engineering studies at SLAC





CONCLUSION

- Lots of exciting axion data in the coming years
 - In particular, new results from ABRA-10cm soon!
- A likelihood framework allows a rigorous analysis of the data
 - Uncover dark matter's fingerprint
 - Unique effects when look at multiple experiments (ongoing)
- Tools are public: <https://github.com/bsafdi/AxiScan>

