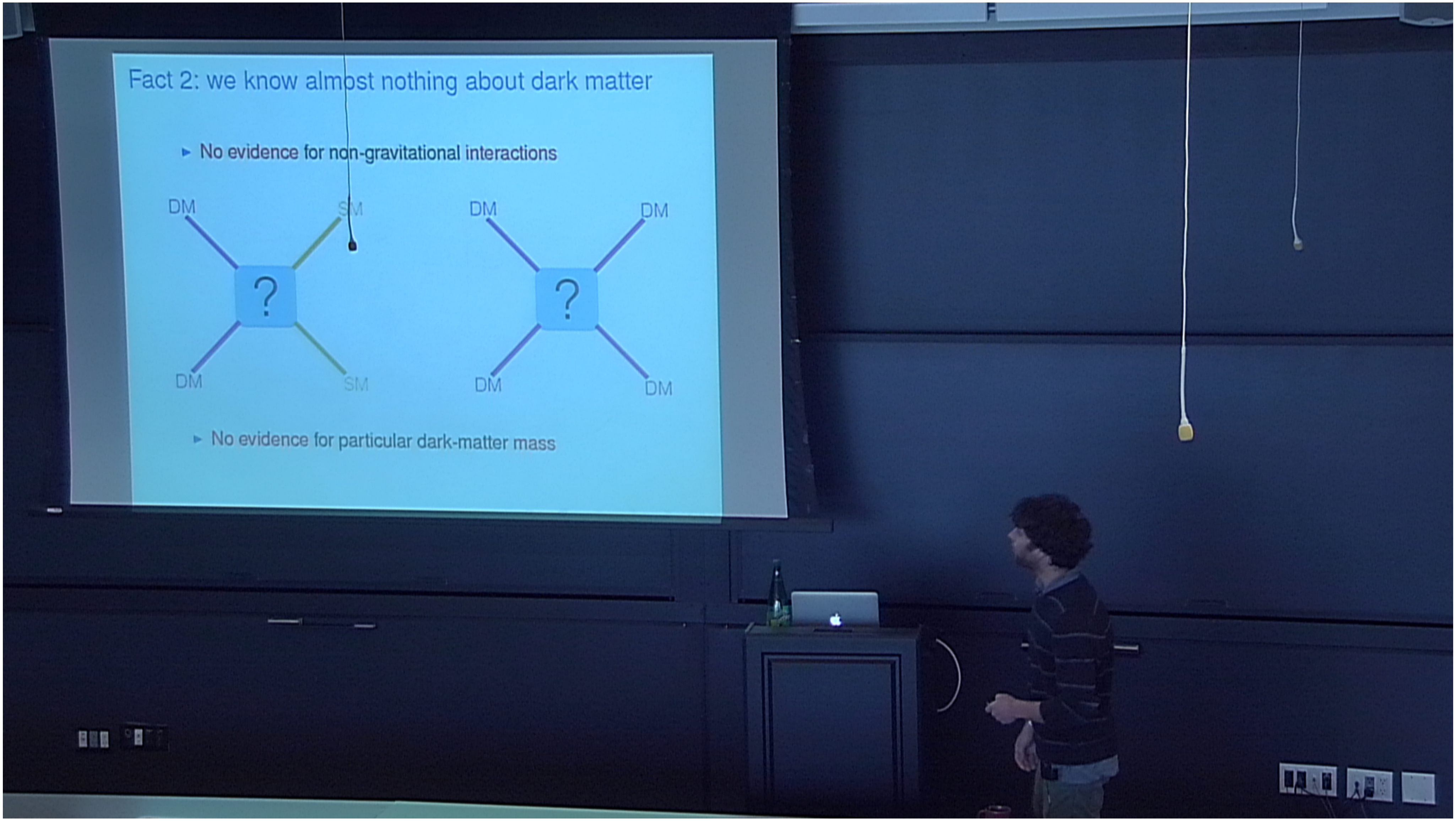
Title: A dark-matter hunterâ€™s guide to the Galaxy (and beyond)

Date: Mar 18, 2016 01:00 PM

URL: http://pirsa.org/16030123

Abstract: <p>Understanding the microscopic nature of dark matter (DM) is one of the most outstanding problems facing modern physics. There is to-date no evidence for non-gravitational interactions of DM with the rest of the Standard Model and also no hint for any particular DM mass. My talk with focus on new techniques to search for GeV-TeV scale weakly-interacting DM by looking for DM annihilating in the cosmos into cosmic rays such as gamma-rays and neutrinos. These potential signs of new physics are easily confused with standard but poorly understood astrophysical backgrounds, such as populations of dim point sources (PSs) like millisecond pulsars. I will present new methods to characterize Galactic and extra-Galactic PS populations, which have complicated DM searches in these regions. I will show that accounting for unresolved PSs in Fermi gamma ray data leads both to new constraints on the dark sector along with some unexpected surprises. I will conclude by briefly describing a new idea for a laboratory experiment able to probe ultra-light axion DM, with masses some 20 orders of magnitude smaller than the weak scale.</p>


Fact 2: we know almost nothing about dark matter
No evidence for non-gravitational interactions
DM
SM
DM
SM
?
DM
DM
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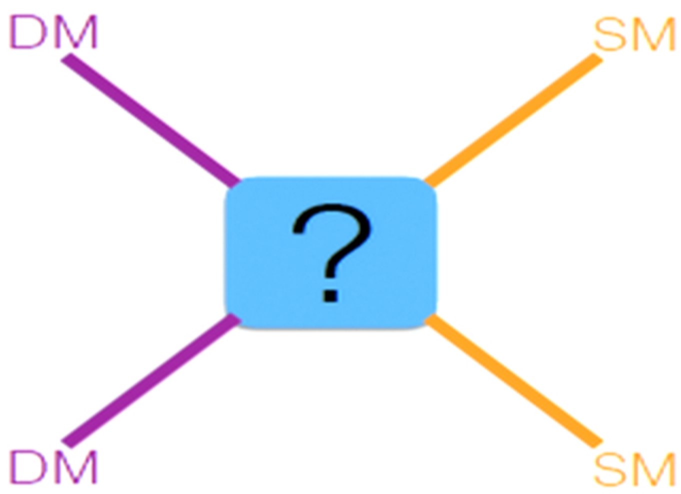
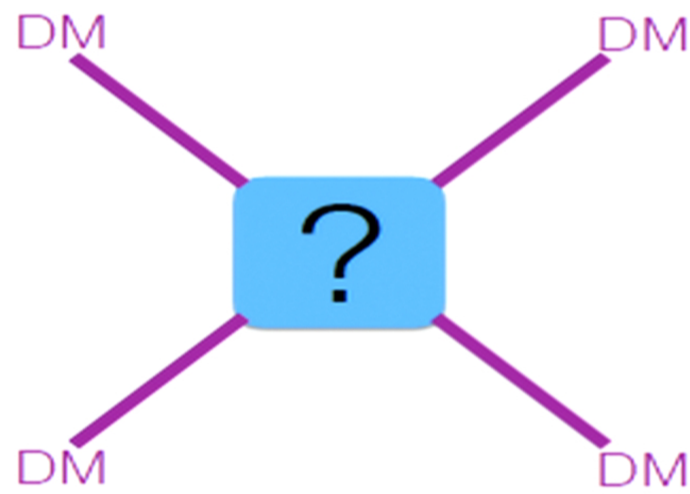
?
No evidence for particular dark-matter mass

Fact 2: we know almost nothing about dark matter

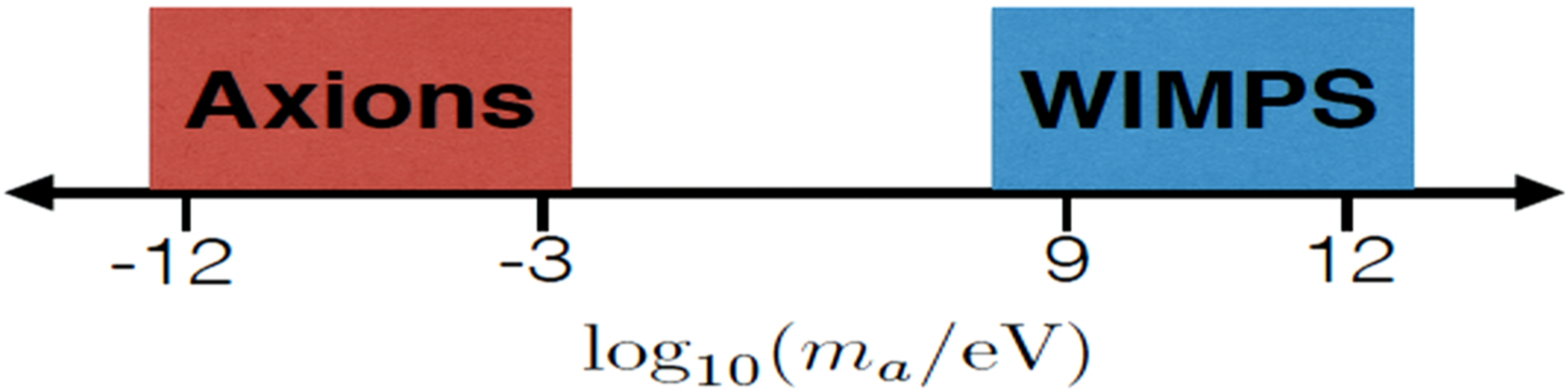
- No evidence for non-gravitational interactions

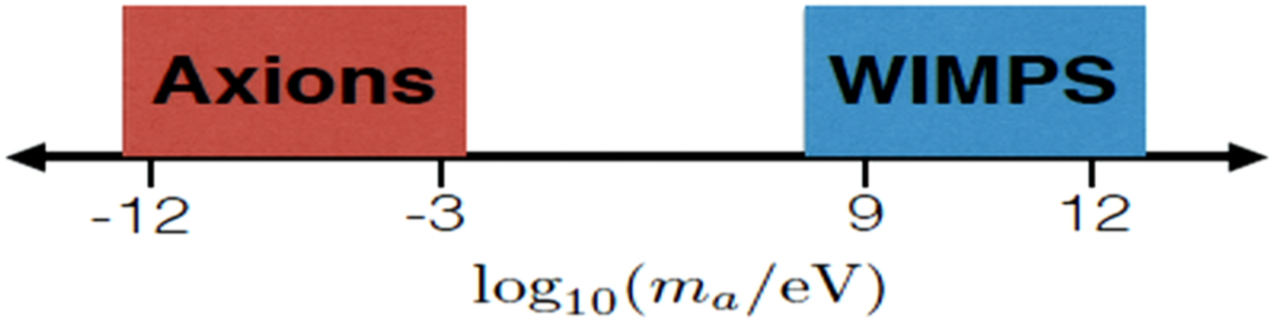




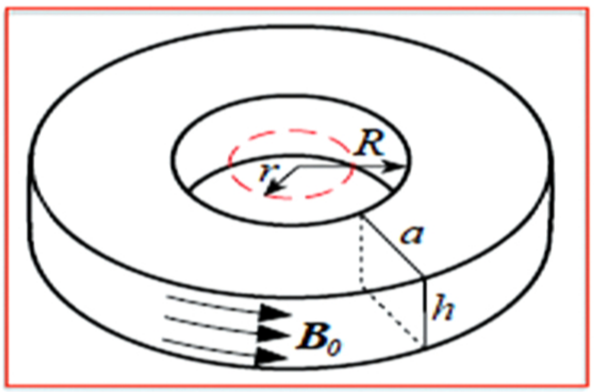
- No evidence for particular dark-matter mass

Over 20 orders of magnitude in DM mass!





Axion DM direct detection



Progress through new ideas utilizing precision frontier

Indirect Detection

A lot we can learn from existing data

Indirect detection and unresolved point sources

Dim PSs important background for dark matter searches in

- gamma-ray sky
- High-energy astrophysical neutrinos

Fermi

IceCube

Indirect detection

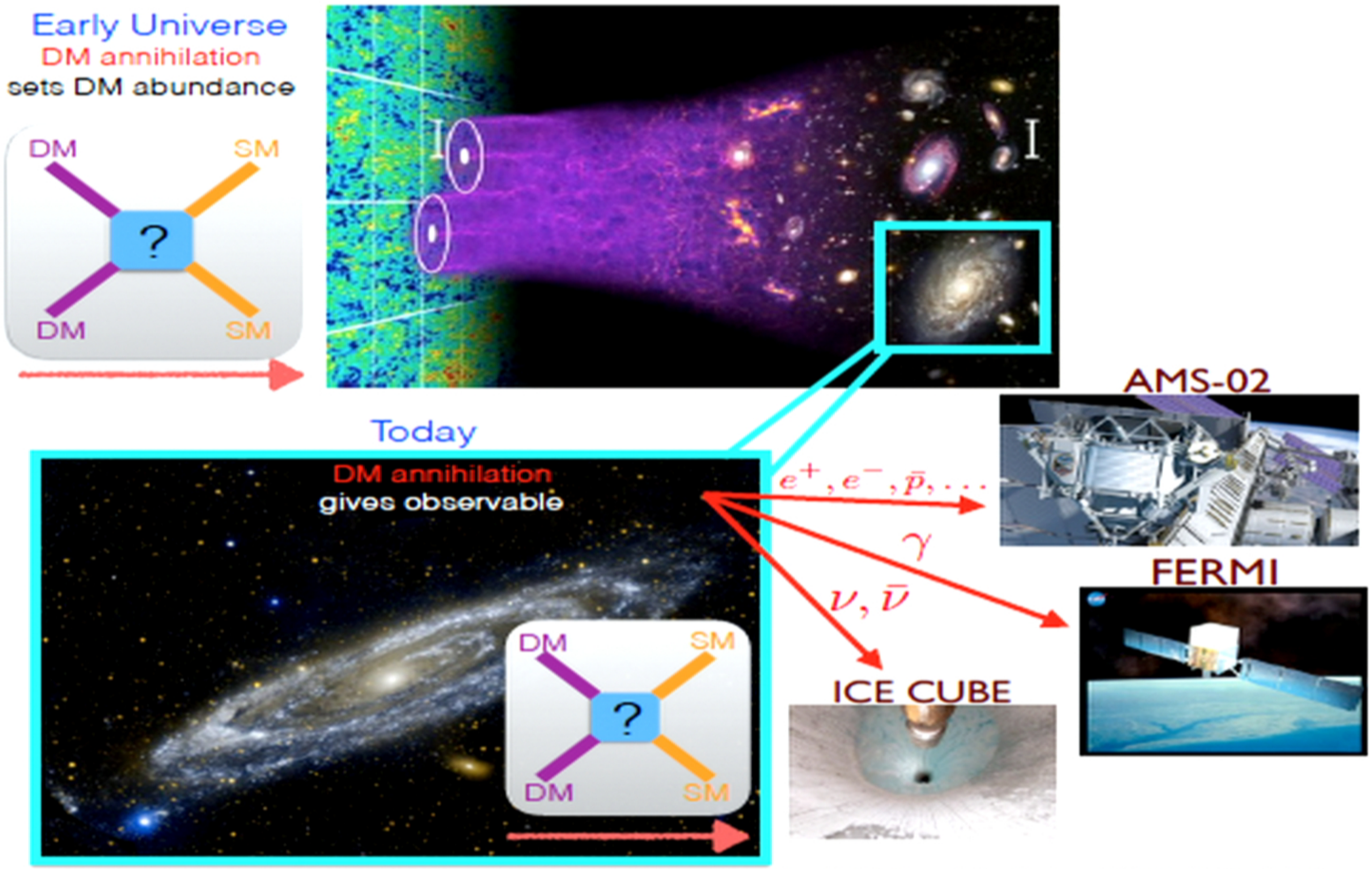
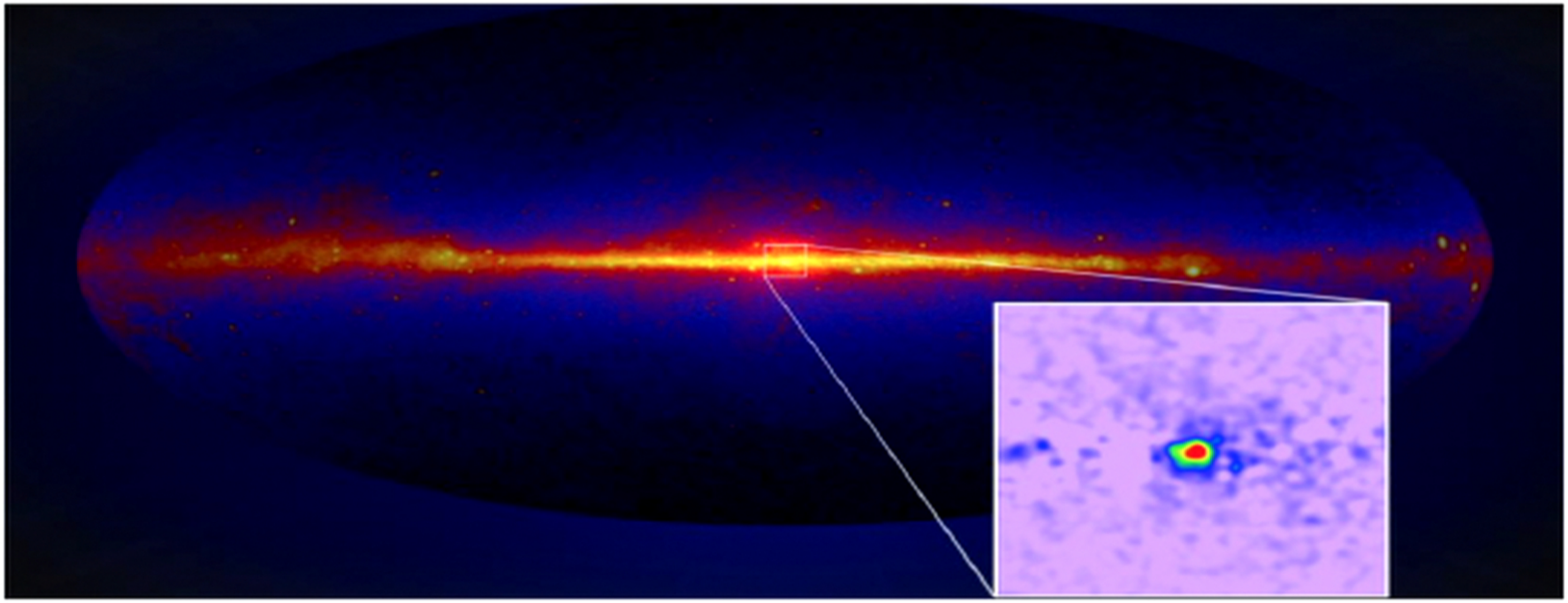


Image credits: AMS, Fermi, IceCube, NASA, *Scitechdaily*

Hints of dark matter annihilation in *Fermi* data?

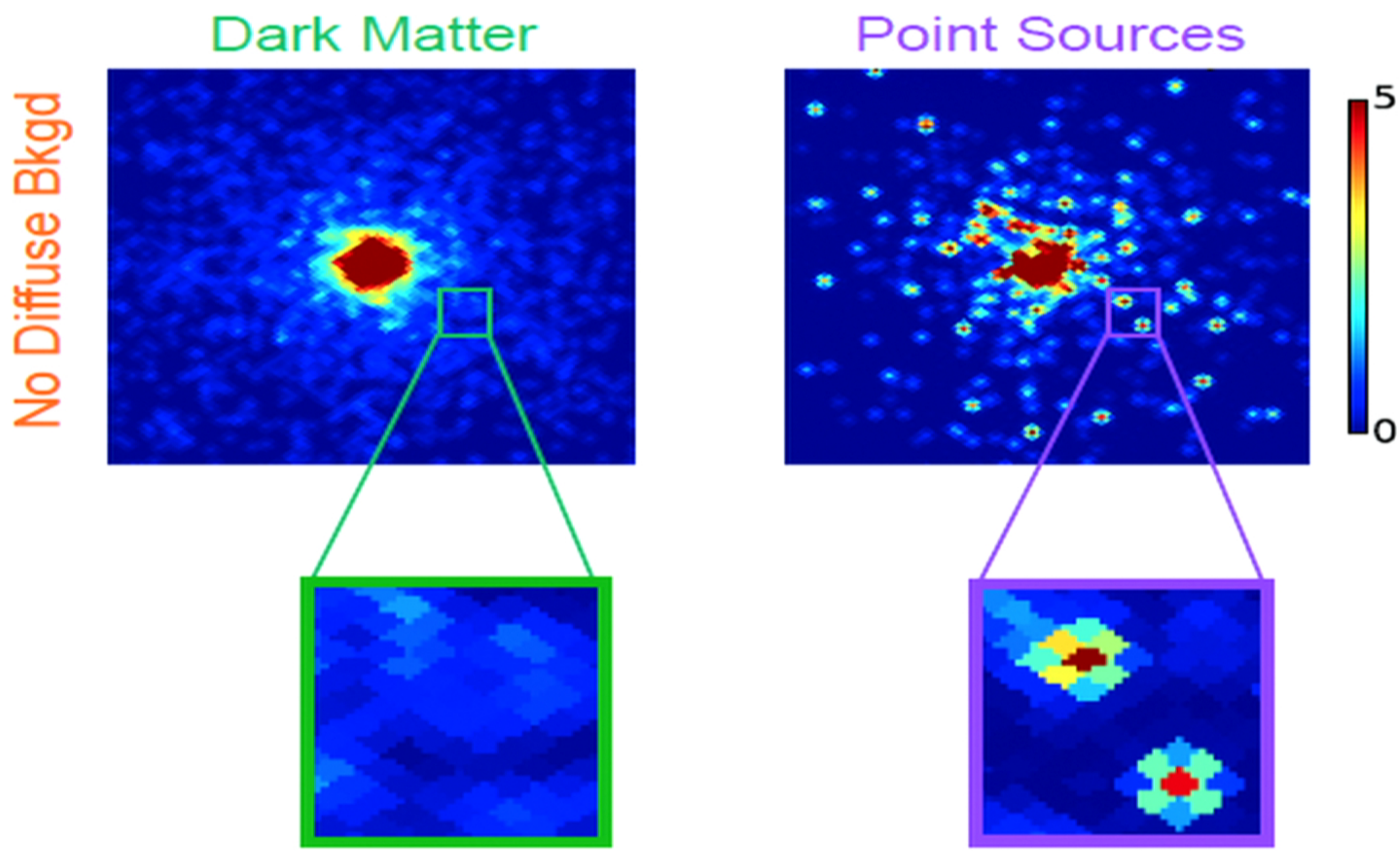


- Spherically symmetric excess (consistent with DM annihilation)

Outline

- Non Poissonian template fit (NPTF)
- Evidence for gamma-ray point sources near the Galactic Center
- Beyond the WIMP paradigm: A new idea to search for axion dark matter

Photon Statistics: DM vs. Point Sources



P(D) distribution in X-ray astronomy; Malyshev and Hogg, 2011; Lee, Lisanti, **BS** 2014

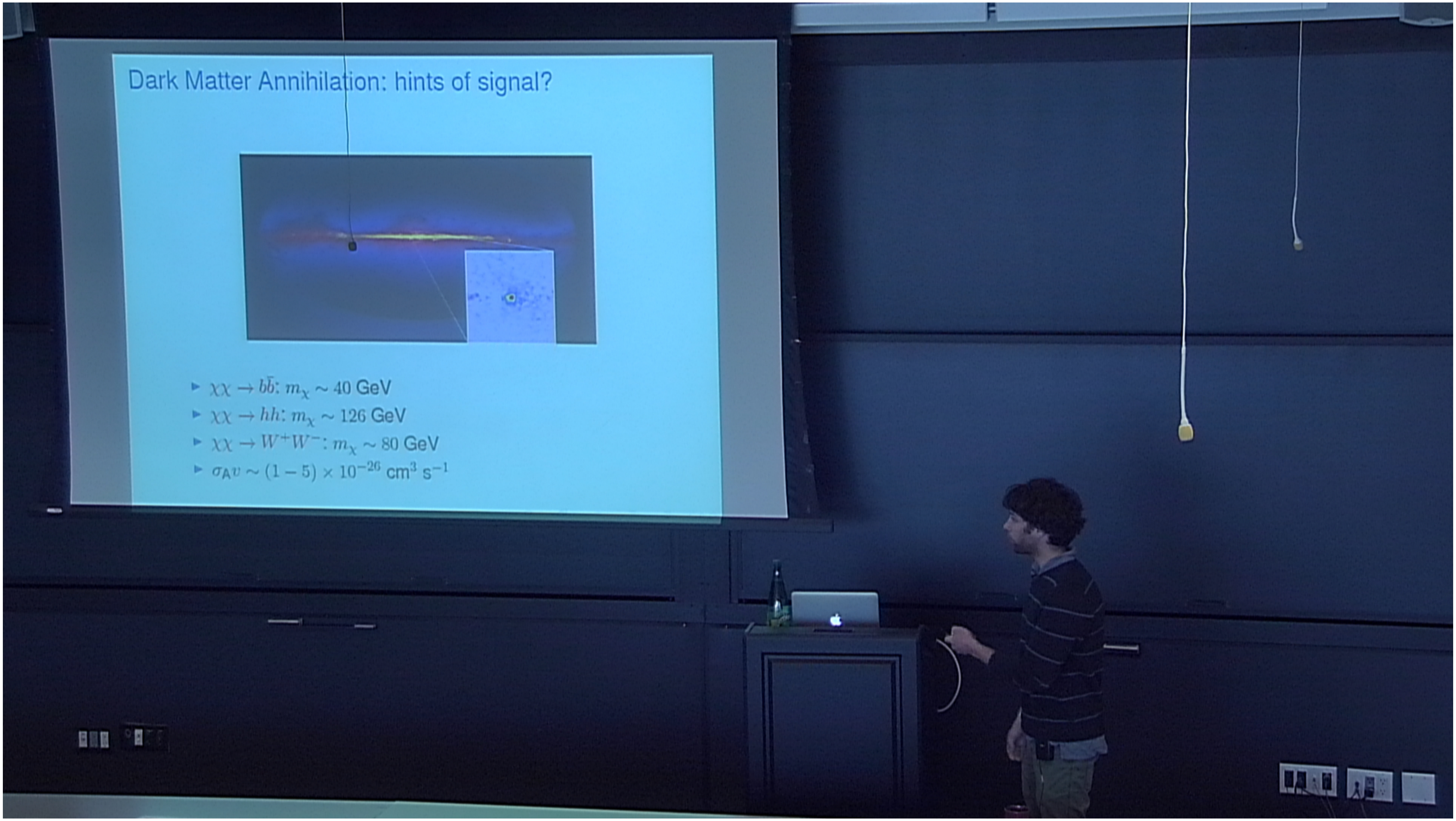
Photon Statistics: Point Sources

- $p_k^{(p)}$ = probability of finding k photons in pixel p
- Smooth emission: Poissonian counting statistics: $p_k^{(p)} = \lambda^k e^{-\lambda}/k!$
- Point-source emission: Non-Poissonian counting statistics
  - (1) What is probability to find a PS in a given pixel?
  - (2) Given a PS, what is the probability it produces k photons?
  - Source-count: $\frac{dN^{(p)}}{dF} = A^p \begin{cases} \left(\frac{F}{F_b}\right)^{-n_1}, & F \geq F_b \\ \left(\frac{F}{F_b}\right)^{-n_2}, & F < F_b \end{cases}$
  - F is average flux (photons / cm^2 / s)
  - A^p follow a spatial template

Non-Poissonian template fit (NPTF)

- data set d (counts in each pixel $\{n_p\}$)
- model $\mathcal{M}$ with parameters θ
- The likelihood function:

$$p(d|\theta, \mathcal{M}) = \prod_{\text{pixels } p} p_{n_p}^{(p)}(\theta)$$


Dark Matter Annihilation: hints of signal?
$\chi\chi \to b\bar{b}$: $m_\chi \sim 40$ GeV
$\chi\chi \to hh$: $m_\chi \sim 126$ GeV
$\chi\chi \to W^+W^-$: $m_\chi \sim 80$ GeV
$\sigma_A v \sim (1-5) \times 10^{-26}$ cm^3 s^{-1}

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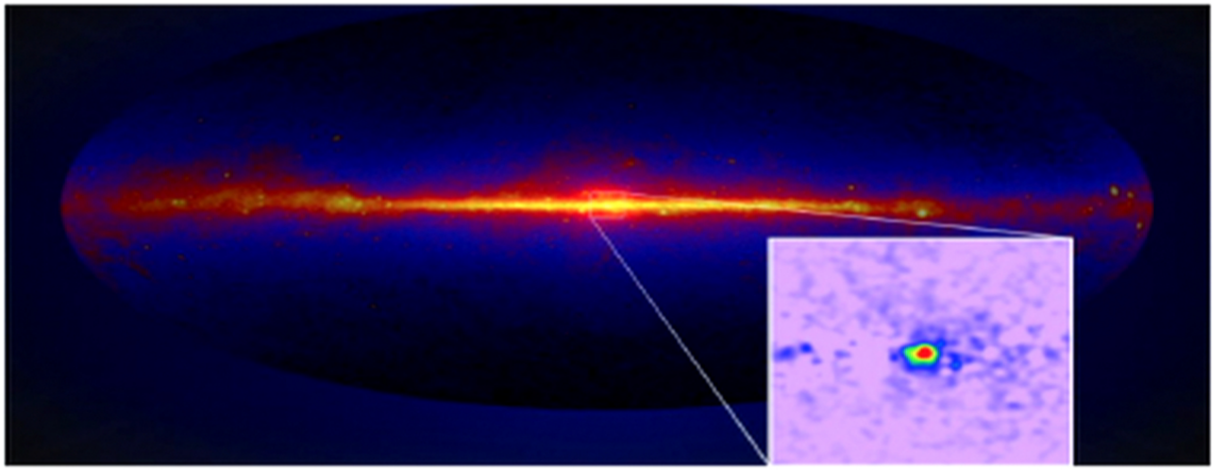

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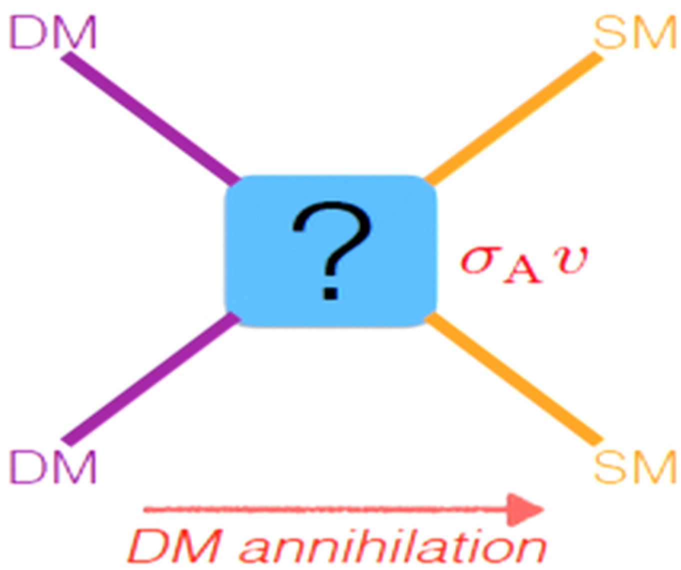
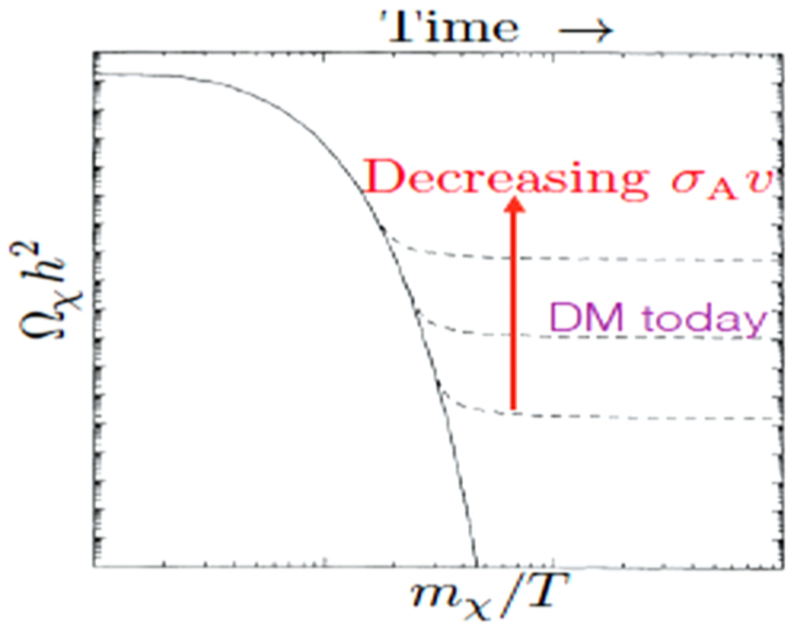
Relic abundance of thermal dark matter

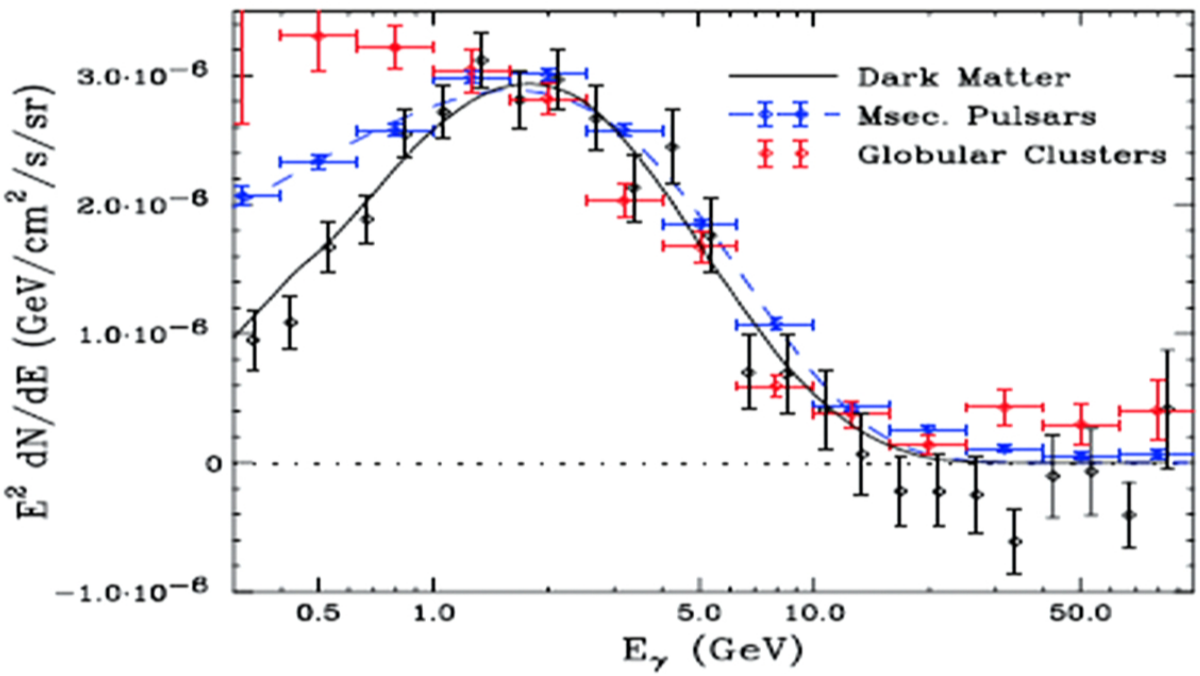




- $\Omega_\chi h^2 = 0.1199 \pm 0.0027$ (Planck + WMAP)

The case for millisecond pulsars

- Millisecond pulsar (MSP) spectrum similar to excess (from 61 millisecond pulsars and 36 globular clusters) (Cholis, Hooper, Linden 2014)



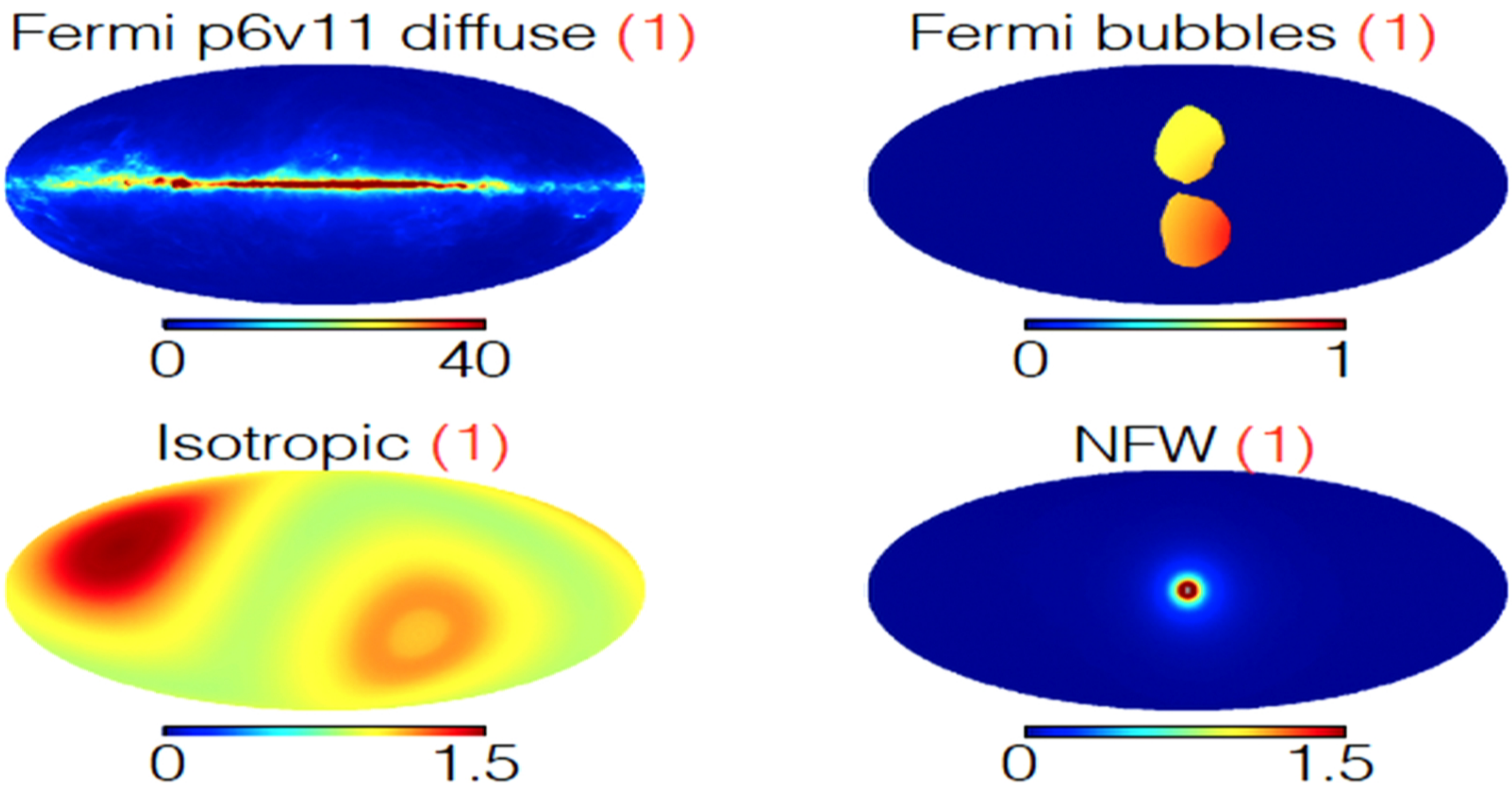
- Disrupted globular clusters can explain pulsar distribution (Brandt, Kocsis, 2015)

The *Fermi* Large-Area Telescope

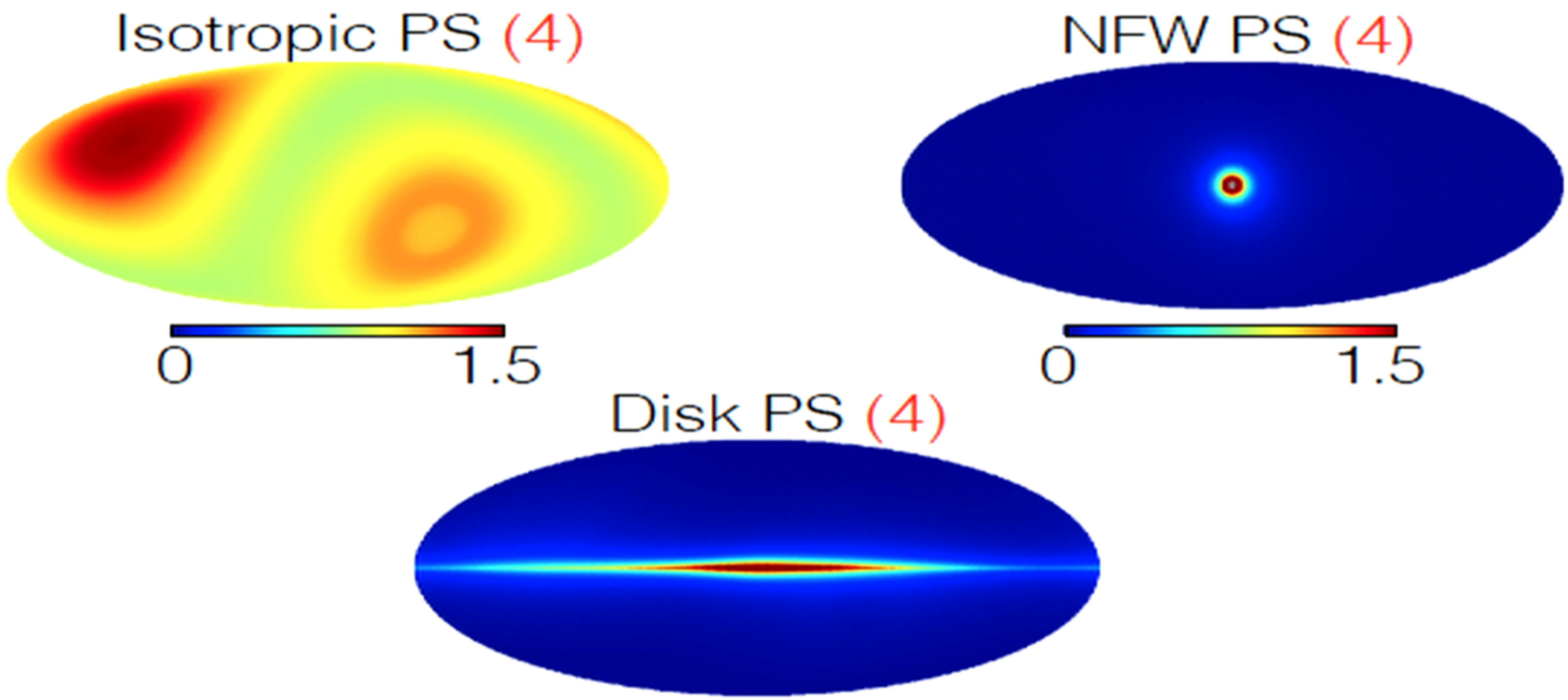

Fermi (NASA)

- Pass 8 data:
  Ultracleanveto class, top quartile by PSF (August 4, 2008—June 3, 2015)
- Energy range: ∼2–12 GeV

The models: Poissonian templates



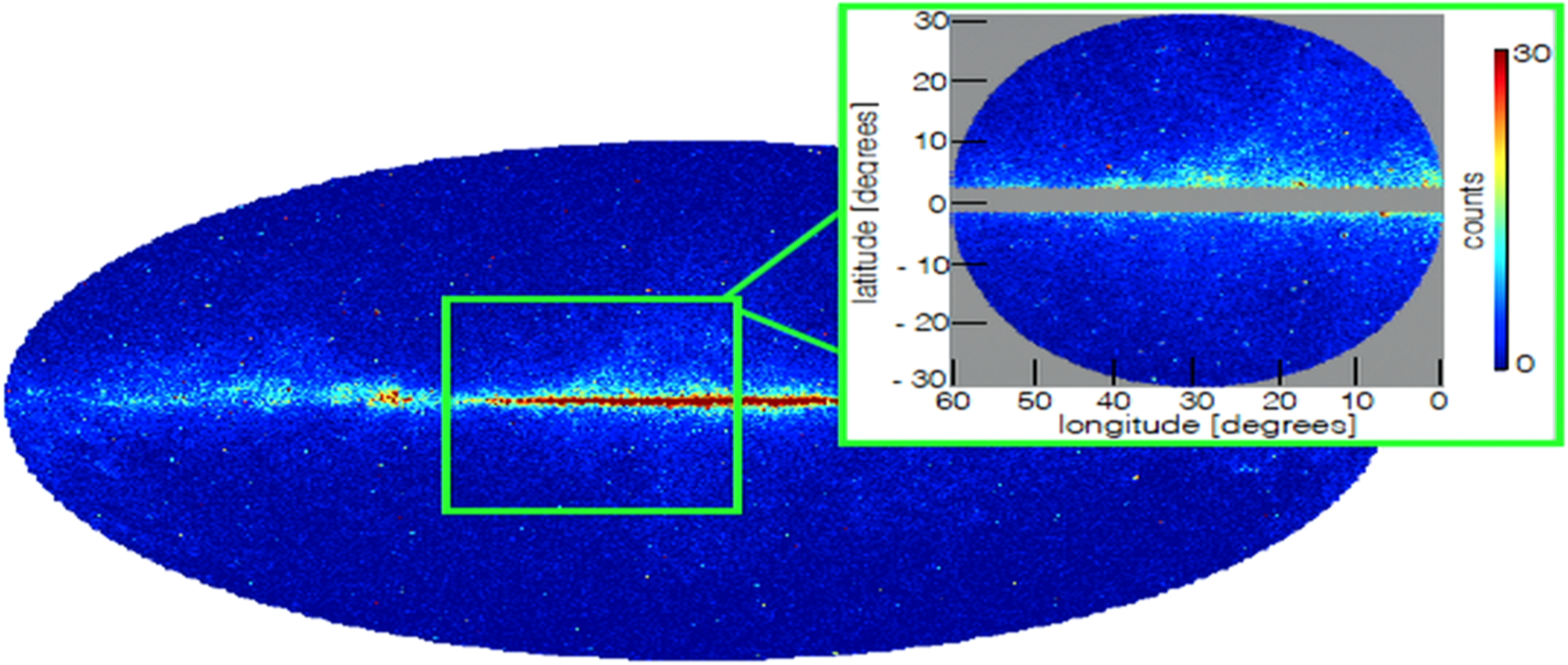
The models: Non-Poissonian templates



- Disk: $n \propto$ exp $(-R/\,5$ kpc$)$ exp $(-|z|/\,0.3$ kpc$)$

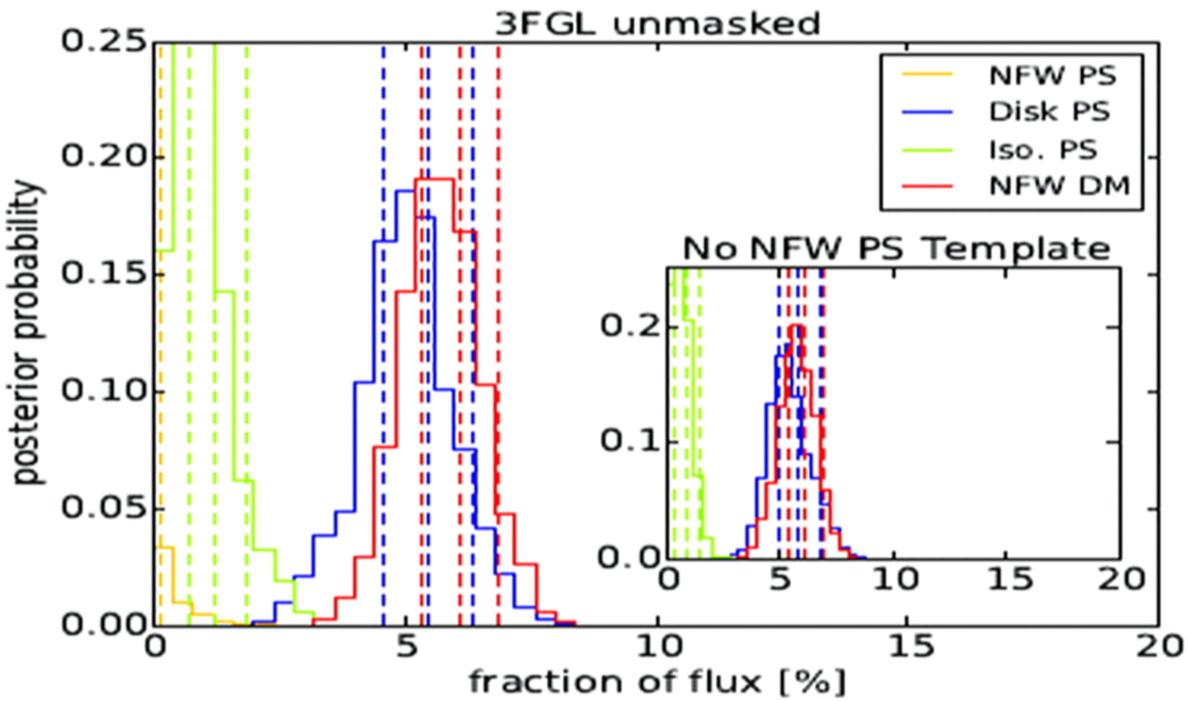
Check 1: the $\ell = 30^\circ$ excess

Mask $4°$ around plane, out to $30°$ around $\ell = 30°$

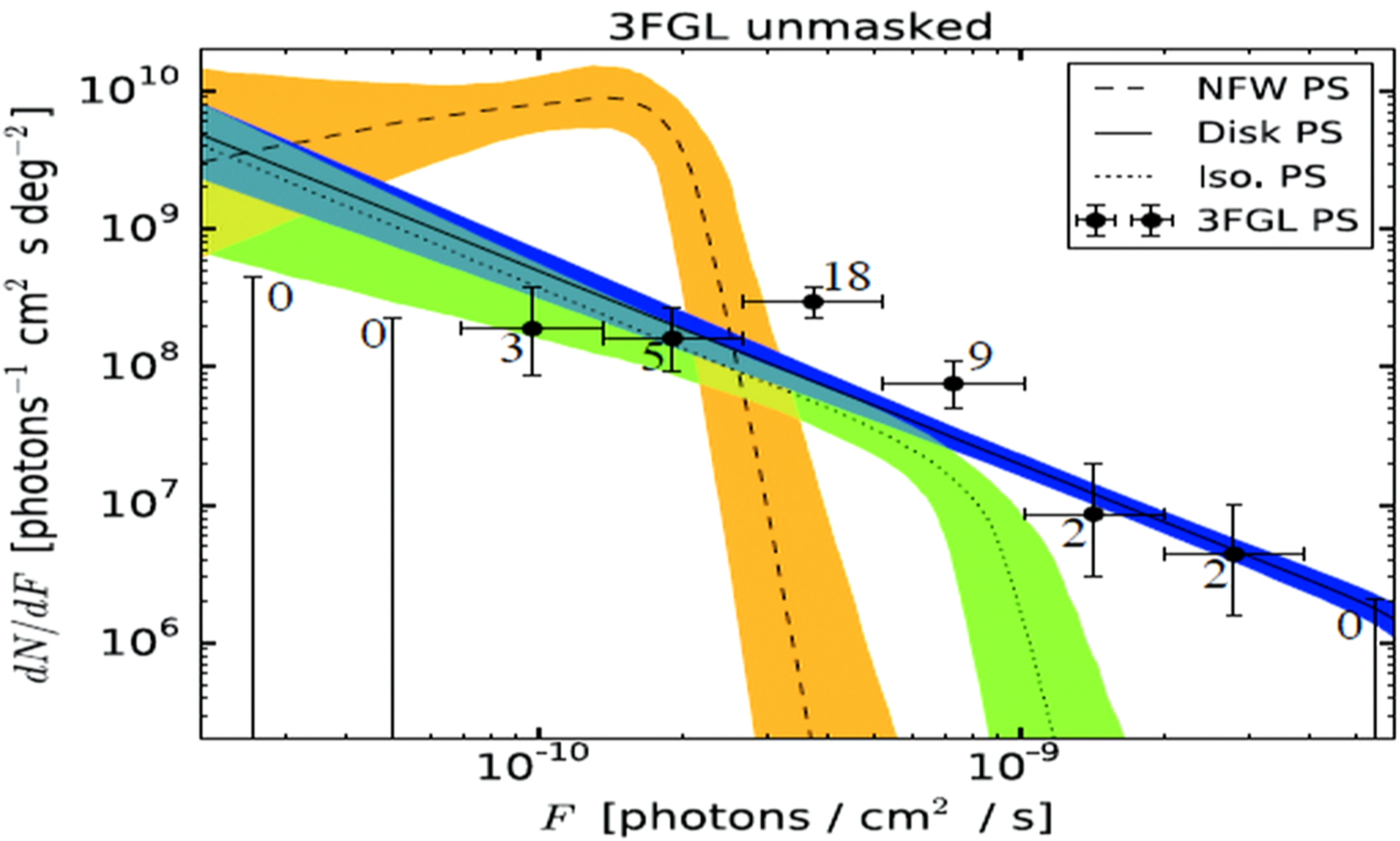


The $\ell = 30^\circ$ excess: no evidence for spherical PSs

- NFW DM, NFW PS templates centered around $\ell = 30^\circ$
- Disk template centered around $\ell = 0^\circ$



The $\ell = 0^\circ$ excess: source-count function



Where are the PSs and what are they?

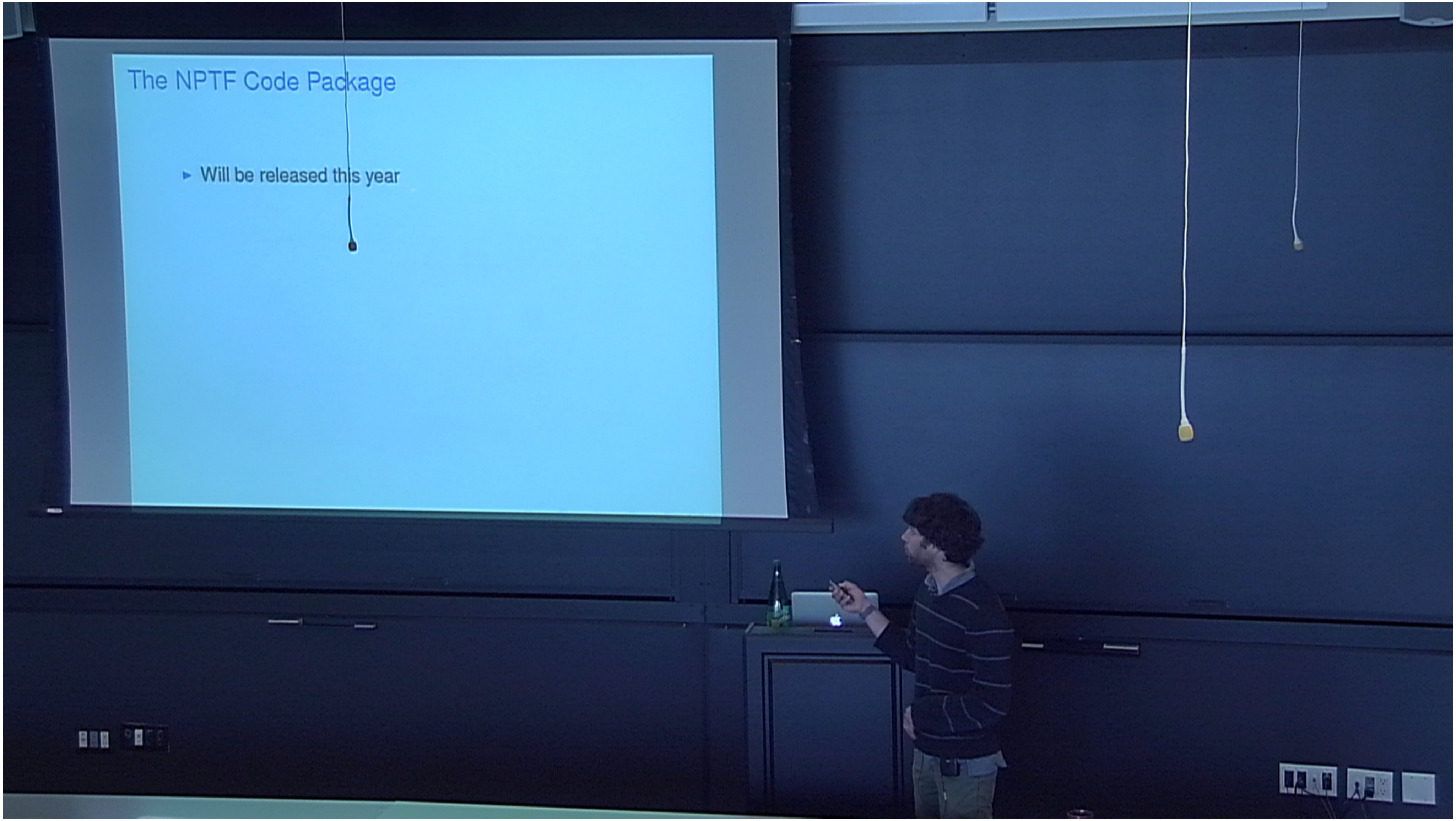
Radio followup survey

- Follow-up survey in radio (Green Bank, Parkes) for MSPs
- Submitted Last Month: *Fermi* Guest Investigator (GI) proposal for Green Bank
- Simulation results: $\sim$100 hours of observation time, find $\sim$5 MSPs in the bulge

Parkes (Australia)

Green Bank (West Virginia)

with T. Linden, S. Ransom, P. Ray, C. Weniger, . . . , *Fermi* members (E. Charles, M. Di Mauro)


The NPTF Code Package
Will be released this year

The NPTF Code Package

- Will be released this year
- Fast and semi-analytic evaluation of $p_{n_p}^{(p)}(\theta)$ and $p(d|\theta, \mathcal{M})$
  - any PSF, variety of dN/dS characterizations, arbitrary number of PS templates.
- Python interface
- Bayesian (Multinest, Polychord) and Frequentist (Minuit) options
- Applications beyond Fermi (e.g., IceCube)
- L. Necib (MIT), N. Rodd (MIT), **B.S.**, Siddharth Sharma (Princeton)

Outline

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- Beyond the WIMP paradigm: A new idea to search for axion dark matter

The axion solves the strong CP problem

$$\mathcal{L}_{\text{QCD}}^{\mathcal{CP}} = -\frac{\theta\, g^2}{32\pi^2} G_{\mu\nu}\tilde{G}^{\mu\nu} - \sum_q \bar{q}\, m_q e^{-i\phi_q\gamma_5} q$$

- $U(1)_A$ anomaly: $\quad q \to e^{-i\alpha_q\gamma_5} q$

$$\theta \to \theta + 2\sum_q \alpha_q$$

- $U(1)_\mathsf{A}$ invariant: $\bar{\theta} \equiv \theta - \sum_q \phi_q$
- Calculation: $d_n \approx 2.4 \times 10^{-16}\,\bar{\theta}$ e · cm
- Measurement: $|\bar{\theta}| < 10^{-10}$
- No anthropic argument for why $\bar{\theta}$ is so small!

Peccei, Quinn 1977; Weinberg 1978; Wilczek 1978

The axion solves the strong CP problem

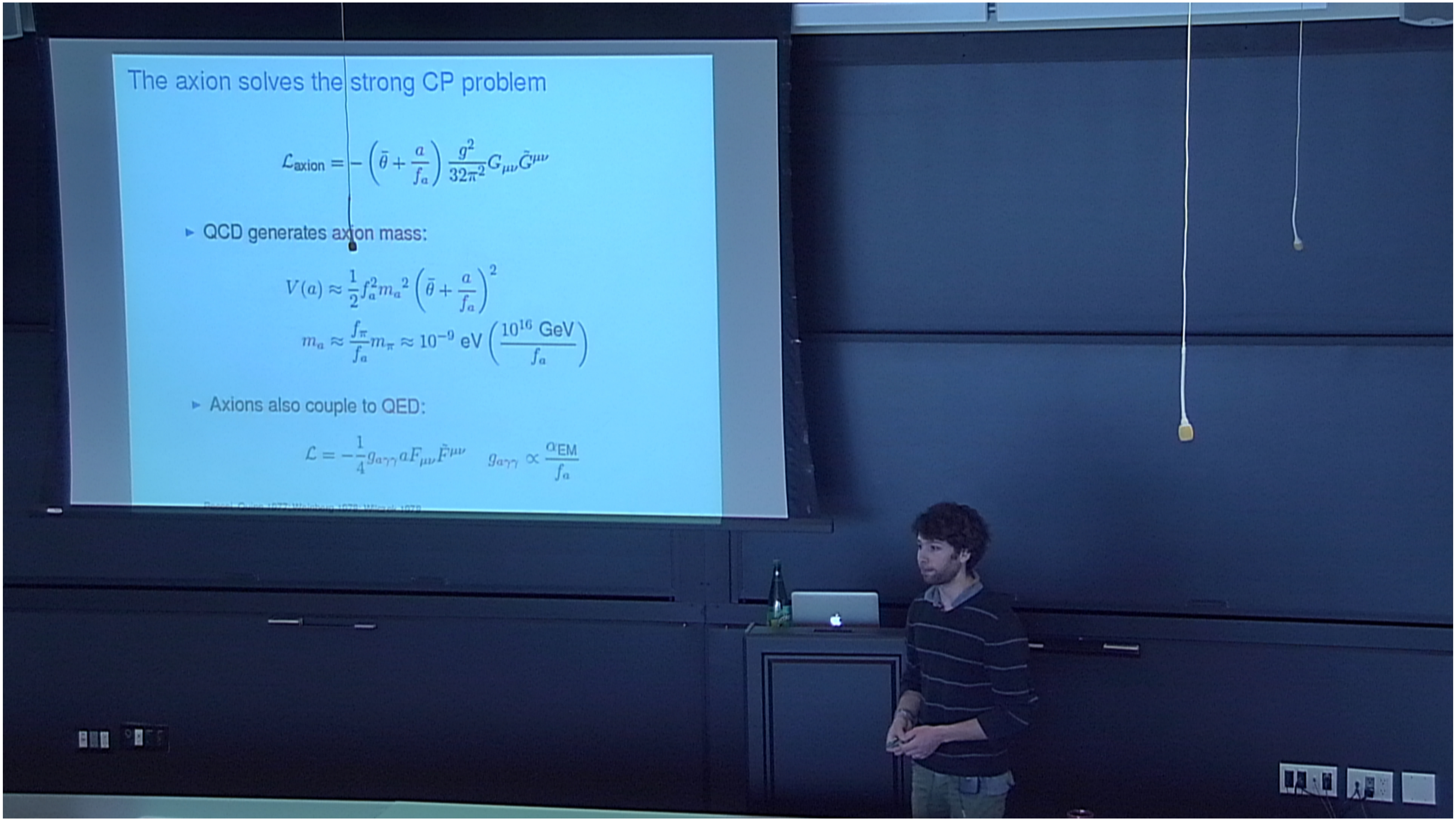
$$\mathcal{L}_{\text{axion}} = -\left(\bar{\theta} + \frac{a}{f_a}\right)\frac{g^2}{32\pi^2}G_{\mu\nu}\tilde{G}^{\mu\nu}$$

- QCD generates axion mass:

$$V(a) \approx \frac{1}{2} f_a^2 {m_a}^2 \left(\bar{\theta} + \frac{a}{f_a}\right)^2$$

$$m_a \approx \frac{f_\pi}{f_a} m_\pi \approx 10^{-9}\ \text{eV}\left(\frac{10^{16}\ \text{GeV}}{f_a}\right)$$

Peccei, Quinn 1977; Weinberg 1978; Wilczek 1978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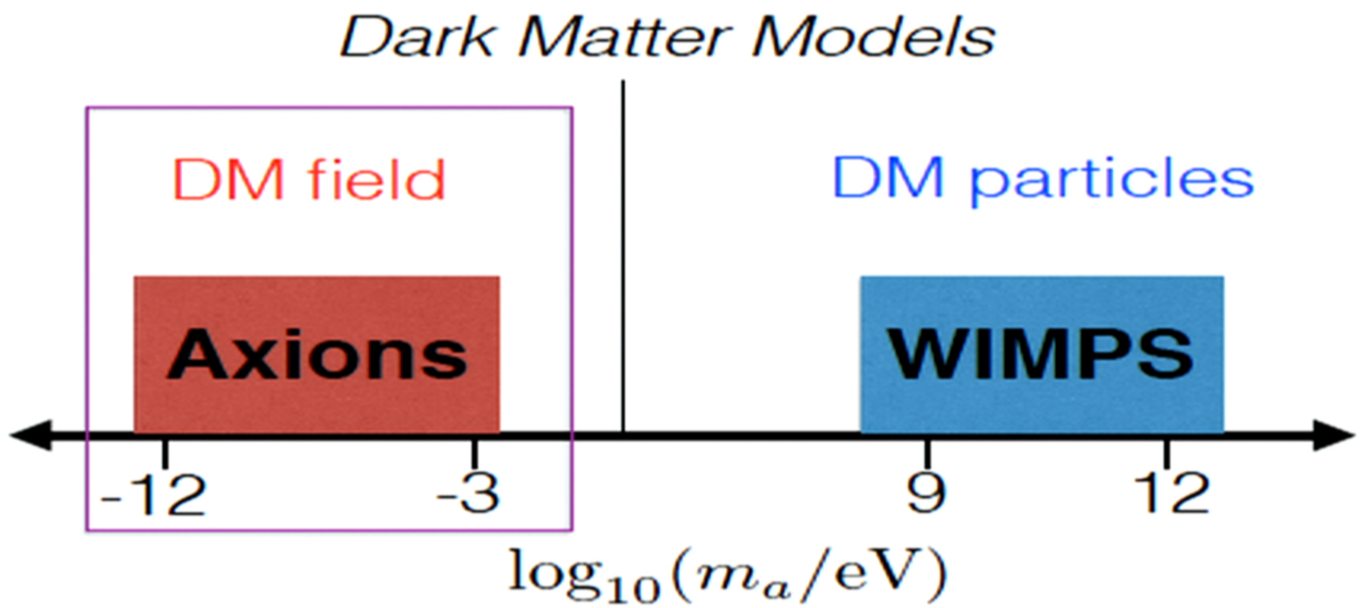
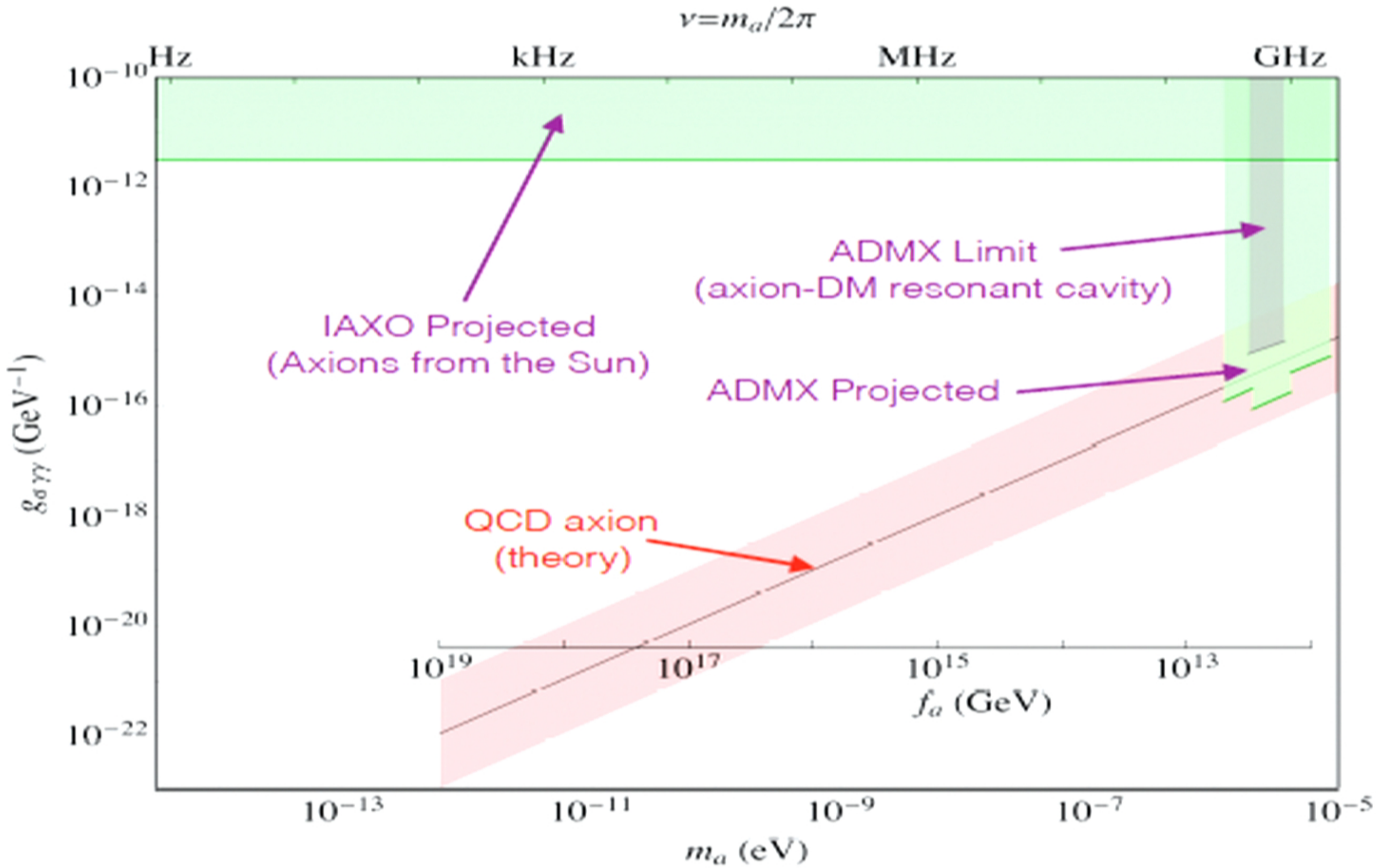
Axions also couple to QED:
$\mathcal{L} = -\frac{1}{4}g_{a\gamma\gamma}aF_{\mu\nu}\tilde{F}^{\mu\nu} \quad g_{a\gamma\gamma} \propto \frac{\alpha_{\text{EM}}}{f_a}$

How can we probe axion dark matter?



- Astrophysics/cosmology: stellar cooling, CMB, BBN (Phys. Lett. B. 2014: K. Blum, R. D'Agnolo,M. Lisanti, **B.S.**), superradiance
- Laboratory experiments: ADMX (resonant cavity), CAST (axion helioscope), . . .
- New proposal: 1602.01086 (Y. Kahn, **B.S.**, J. Thaler): A broadband approach to axion dark matter detection

How can we probe axion dark matter?



Axion dark matter modifies Maxwell's equations

- Recall axions also couple to QED:

$$\mathcal{L} = -\frac{1}{4} g_{a\gamma\gamma} a F_{\mu\nu} \tilde{F}^{\mu\nu} \qquad g_{a\gamma\gamma} \propto \frac{\alpha_{\text{EM}}}{f_a}$$

- Magnetoquasistatic approximation: new electric current that follows $\mathbf{B}$-field lines

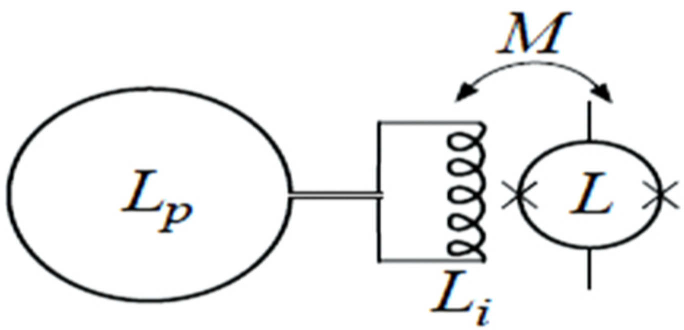
$$\nabla \times \mathbf{B} = g_{a\gamma\gamma} \mathbf{B} \frac{\partial a}{\partial t}$$

- Locally: $a(t) \approx a_0 \sin(m_a t)$ and $\frac{1}{2} m_a^2 {a_0}^2 = \rho_{\text{DM}}$
- $\mathbf{J}_{\text{eff}} = g_{a\gamma\gamma} \sqrt{2\,\rho_{\text{DM}}} \mathbf{B} \sin(m_a t)$

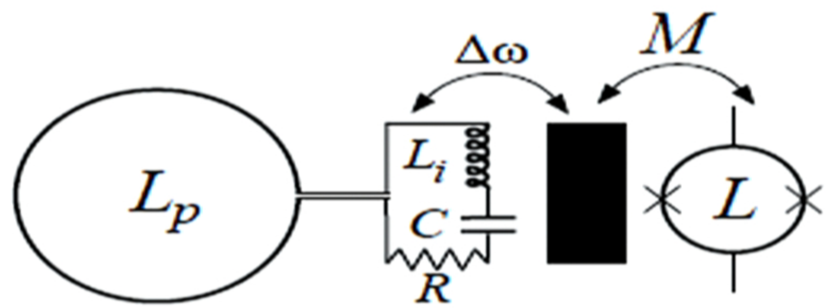

Axion dark matter generates magnetic flux
Superconducting pickup loop
R
r
a
h
B0
Estimate B-field induced through pickup loop (r = a = h = R)

Two readout strategies

Broadband



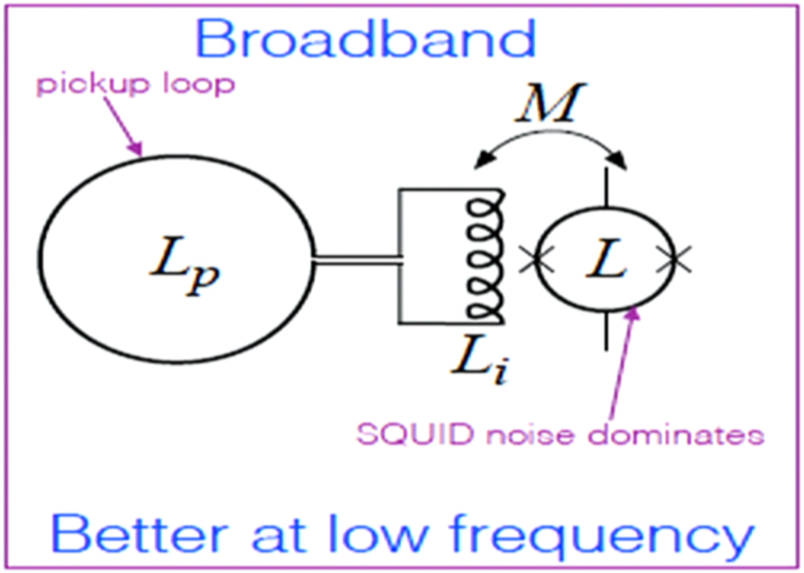
Resonant

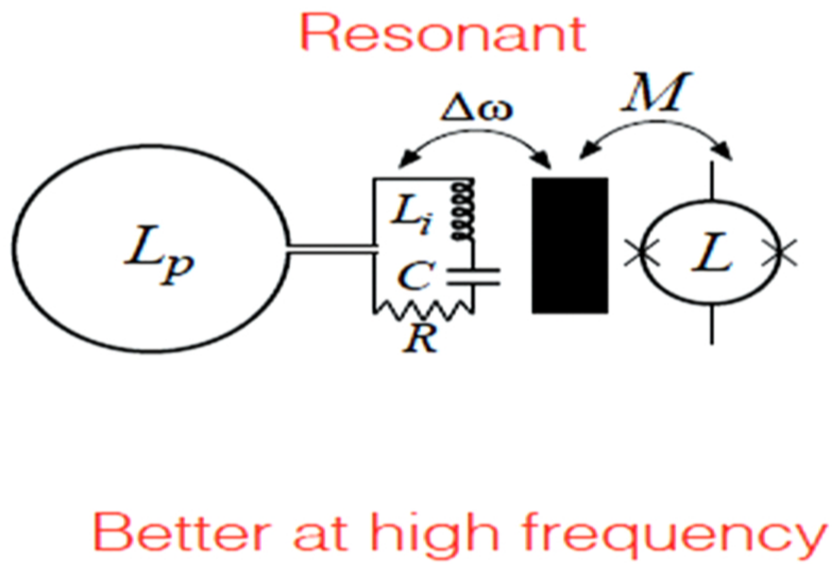


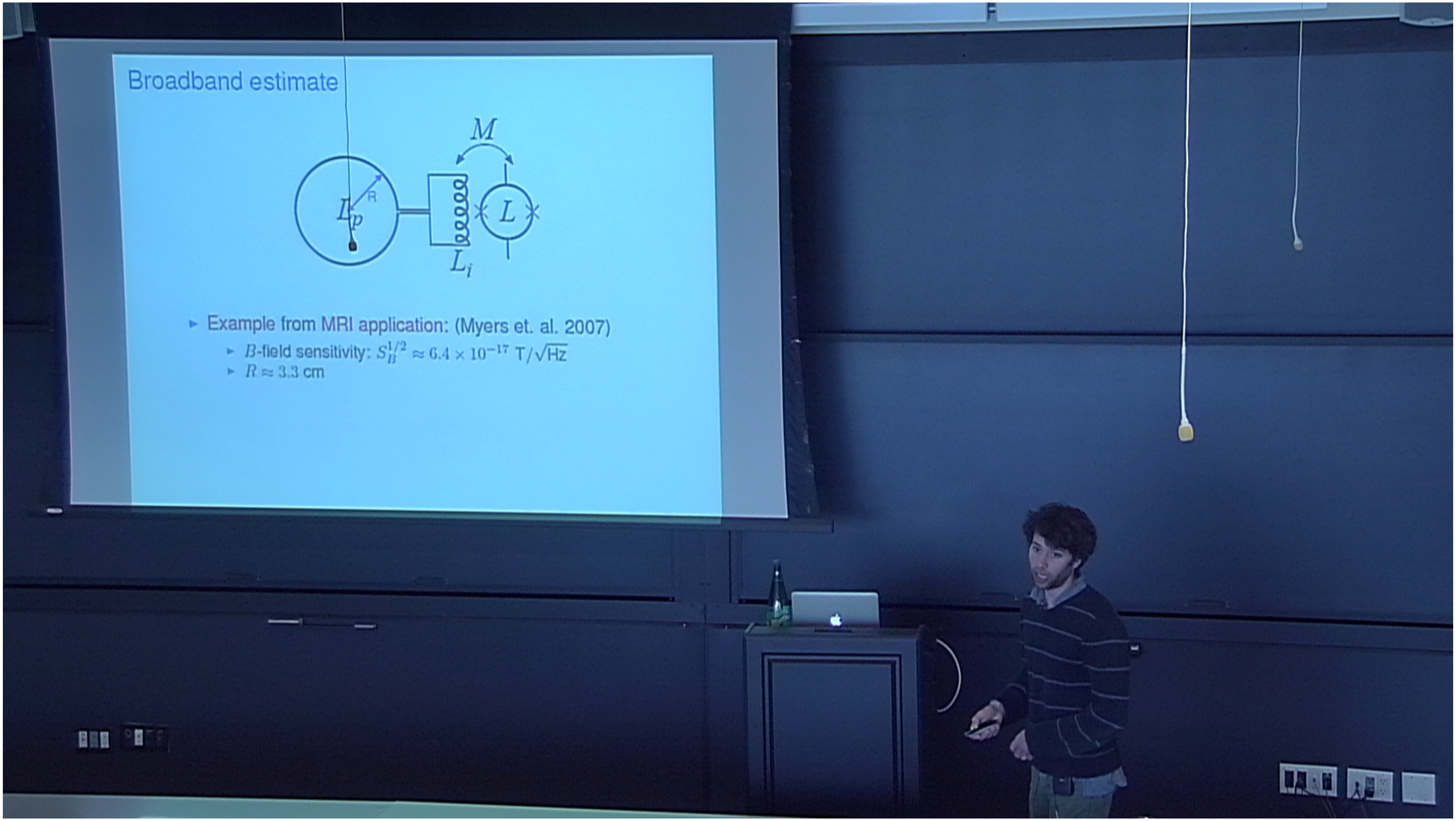
Better at low frequency

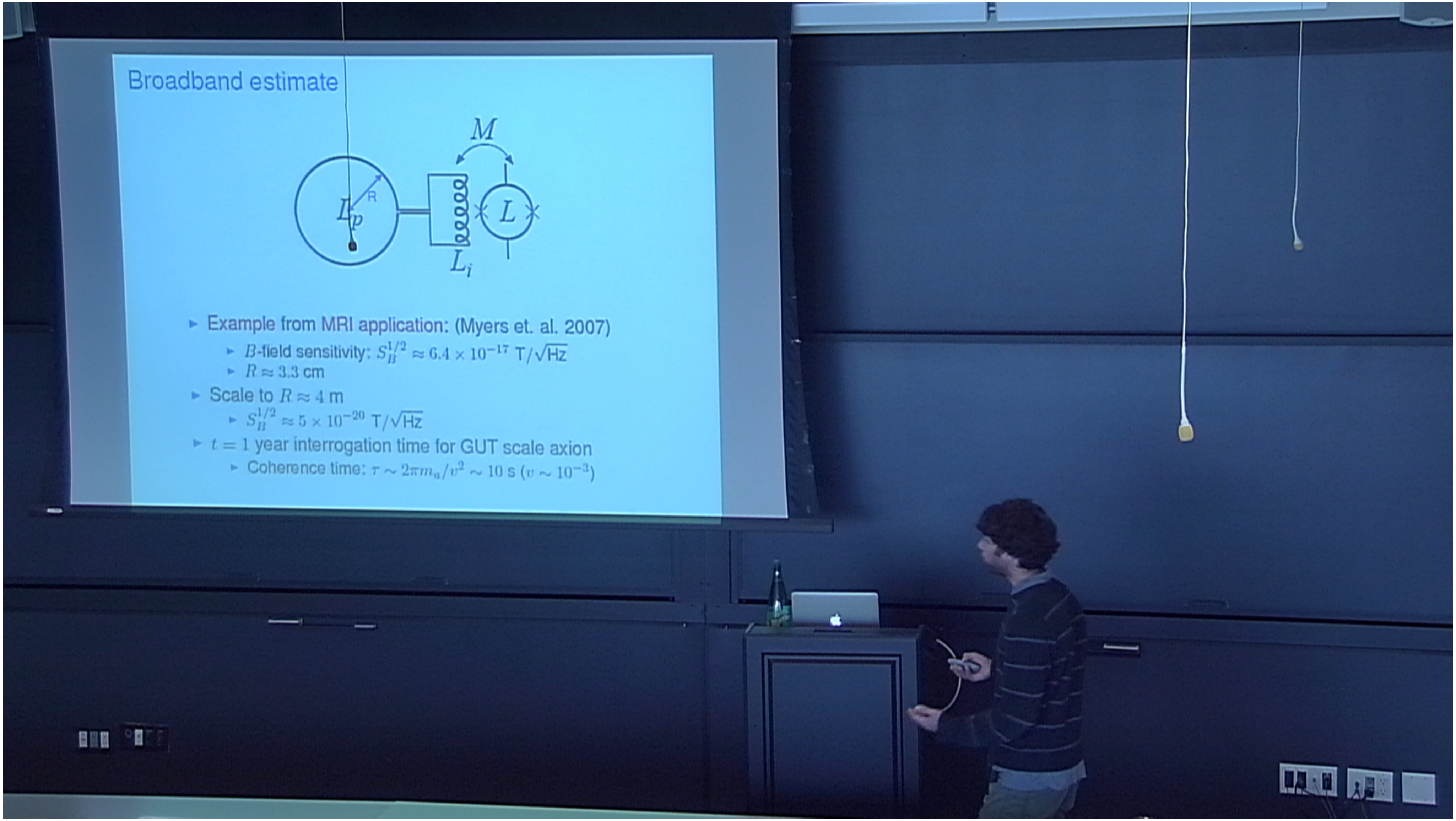
Better at high frequency

Two readout strategies






Broadband estimate
M
R
L_p
L
L_i
Example from MRI application: (Myers et. al. 2007)
B-field sensitivity: $S_B^{1/2} \approx 6.4 \times 10^{-17}$ T/$\sqrt{\text{Hz}}$
$R \approx 3.3$ cm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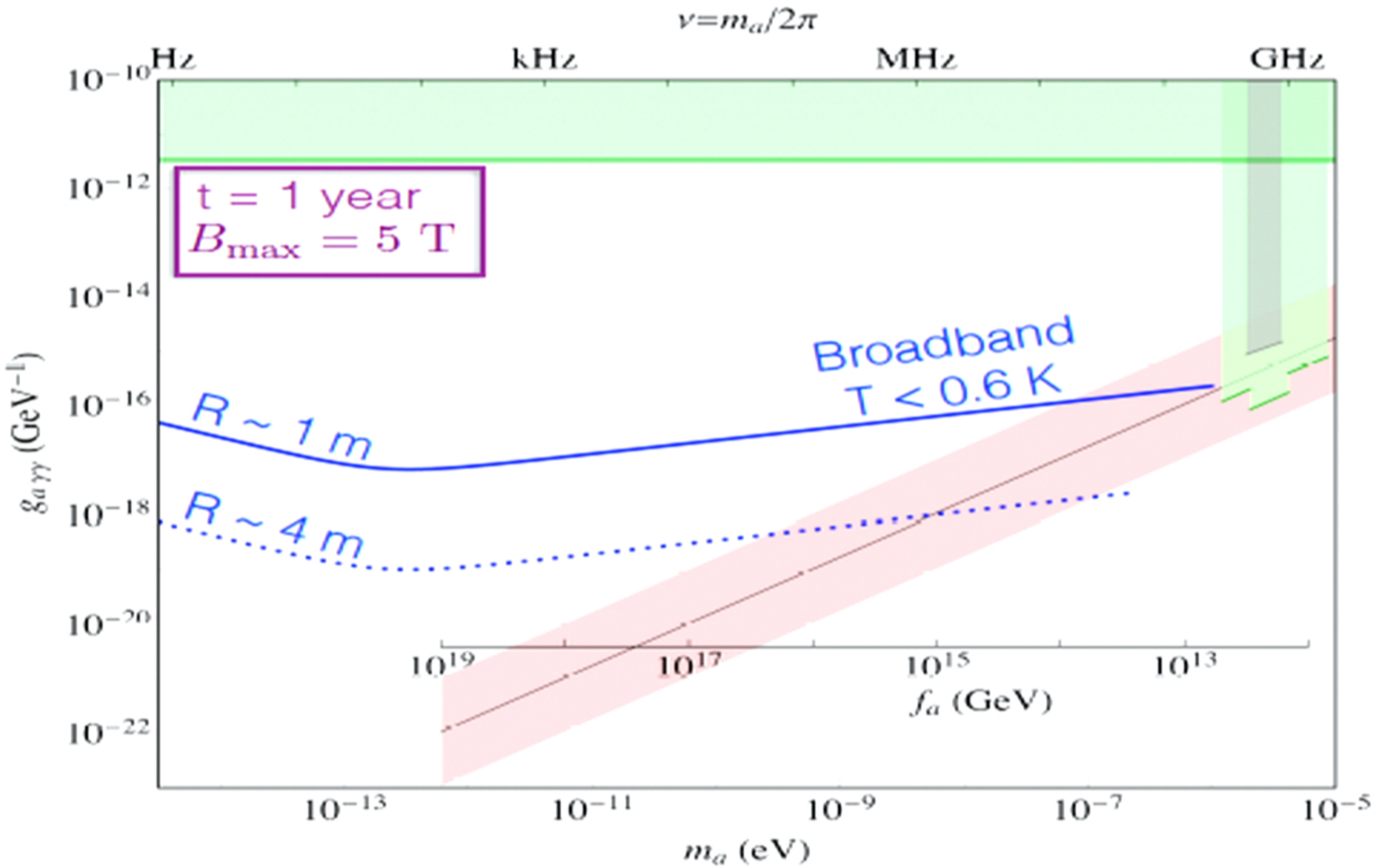
Scale to $R \approx 4$ m
$S_B^{1/2} \approx 5 \times 10^{-20}$ T/$\sqrt{\text{Hz}}$
$t = 1$ year interrogation time for GUT scale axion
Coherence time: $\tau \sim 2\pi m_a/v^2 \sim 10$ s ($v \sim 10^{-3}$)

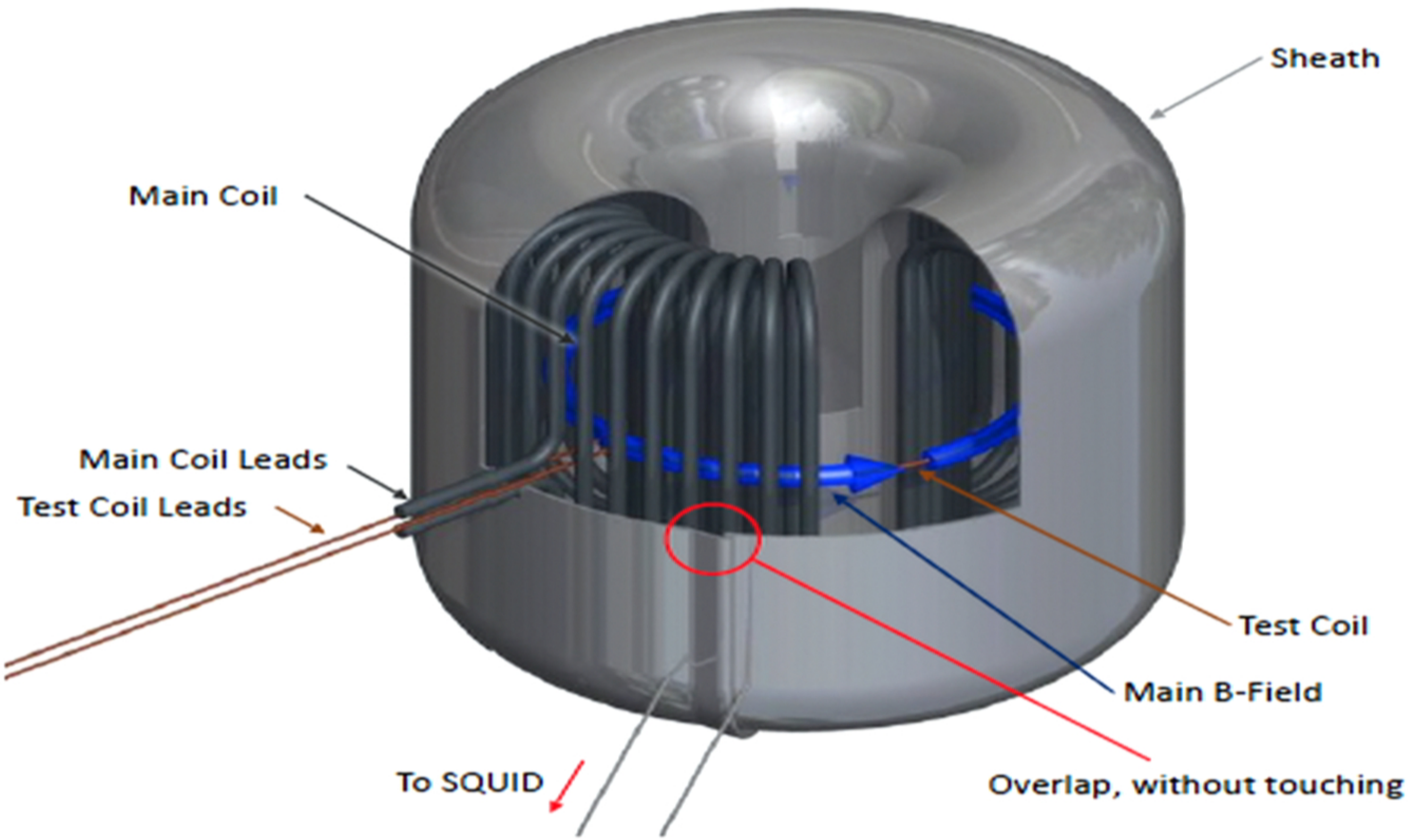
Axion dark matter projected reach



Light bosonic dark matter future

- Towards a prototype (discussions with experimentalists at MIT, Princeton, Stanford : J. Conrad, J. Formaggio, L. Page, C. Tuly, K. Irwin, . . .)
- Axions and light bosonic dark matter well motivated by high-scale physics (e.g., compactified string theory)
  - Detection may provide window to high-scale physics (GUT scale, inflation, . . .)
  - New ideas to search for ultra-light scalars, dark-photons, etc. (laboratory experiments + astrophysics)

The MIT prototype: 12 cm $\times$ 12 cm, $B = 1$ T



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