SPECTRAL DISTORTIONS OF ASTROPHYSICAL BLACKBODIES AS AXION PROBES

Based on:

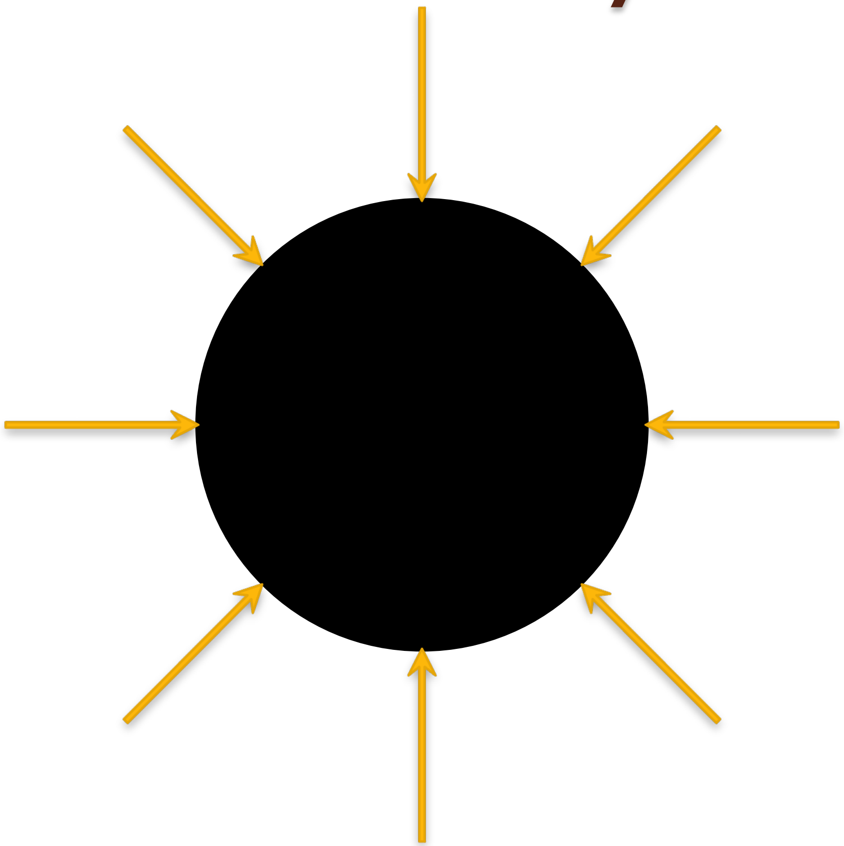
JHC, Reza Ebadi, Xuheng Luo, and Erwin H. Tanin, arXiv:2305.03749

Jae Hyeok Chang

Fermilab and UIC

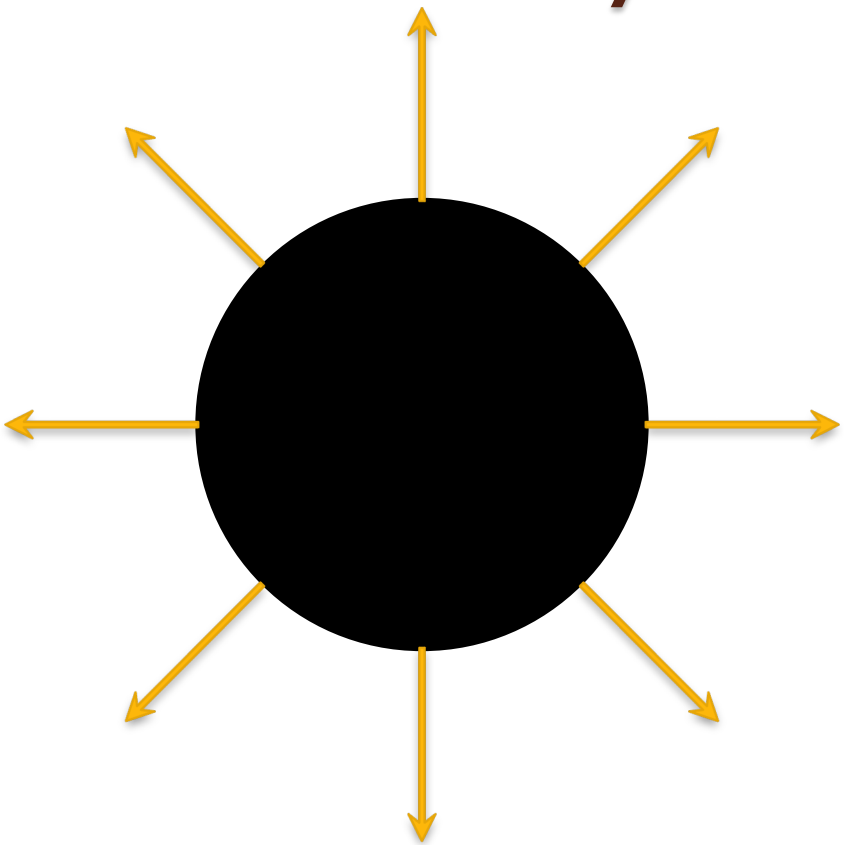
12/05/2023 PNU-IBS Workshop on Axion Physics : Search for axions

Blackbody



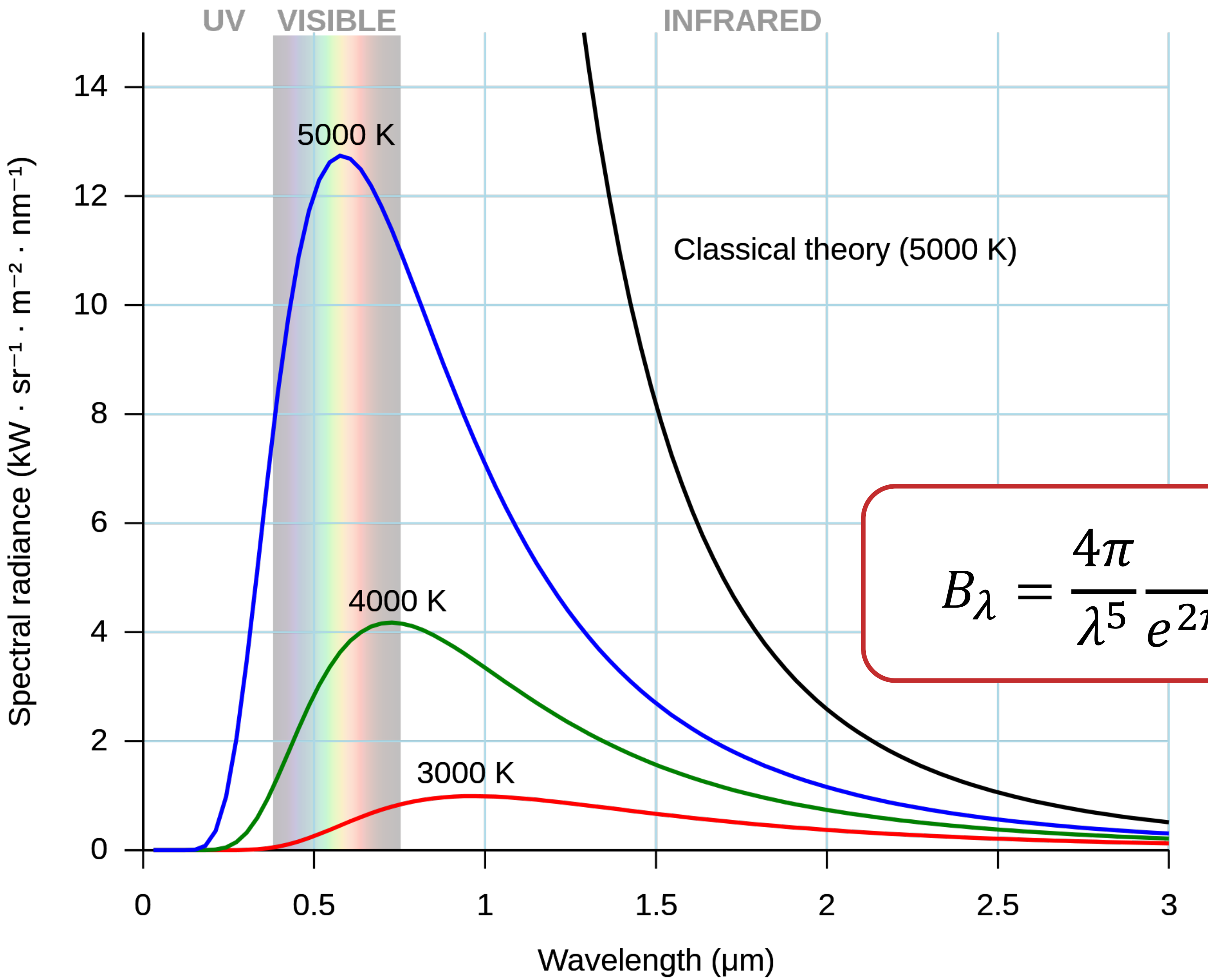
- absorbs all incident electromagnetic radiation

Blackbody



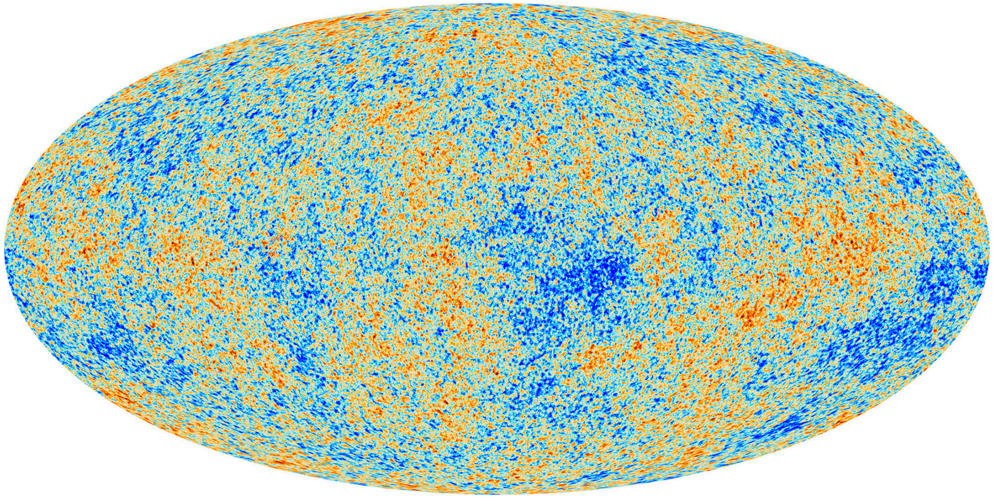
- absorbs all incident electromagnetic radiation
- emits thermally equilibrated radiation
- Blackbody spectrum is determined by temperature alone

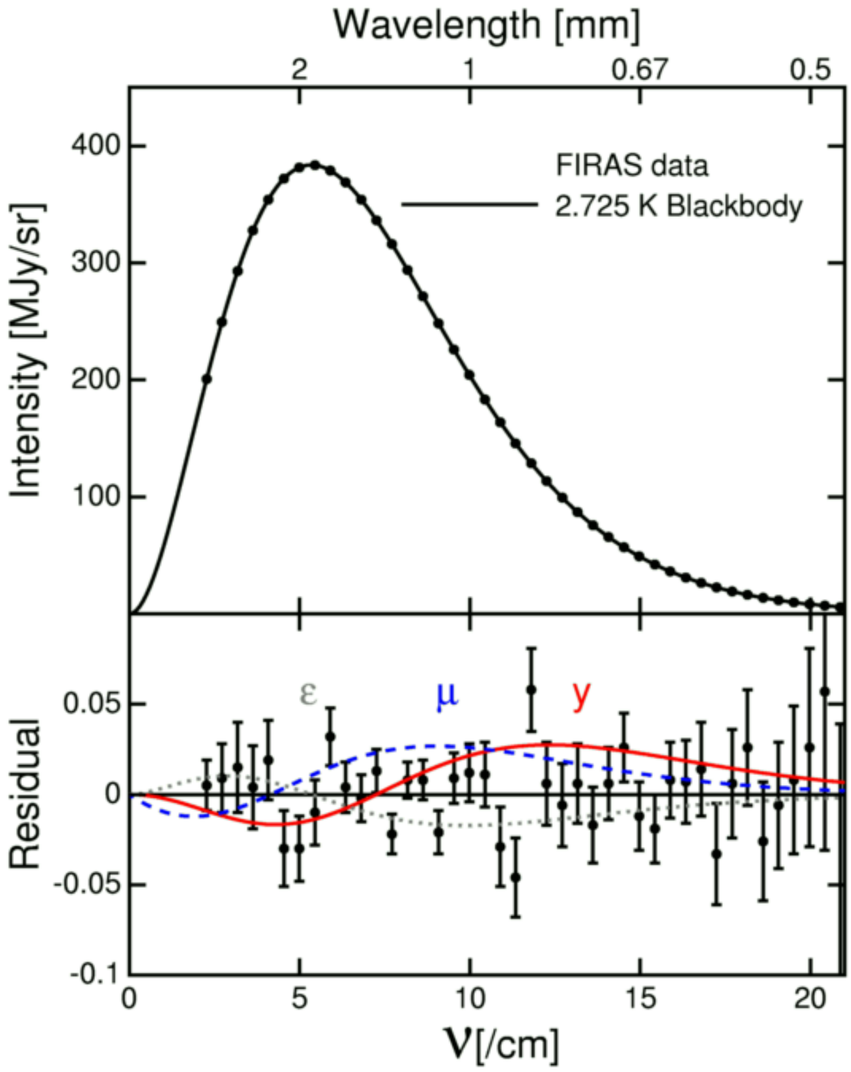
Blackbody spectrum



$$B_\lambda = \frac{4\pi}{\lambda^5}\frac{1}{e^{2\pi/\lambda T} - 1}$$

Best blackbody we know



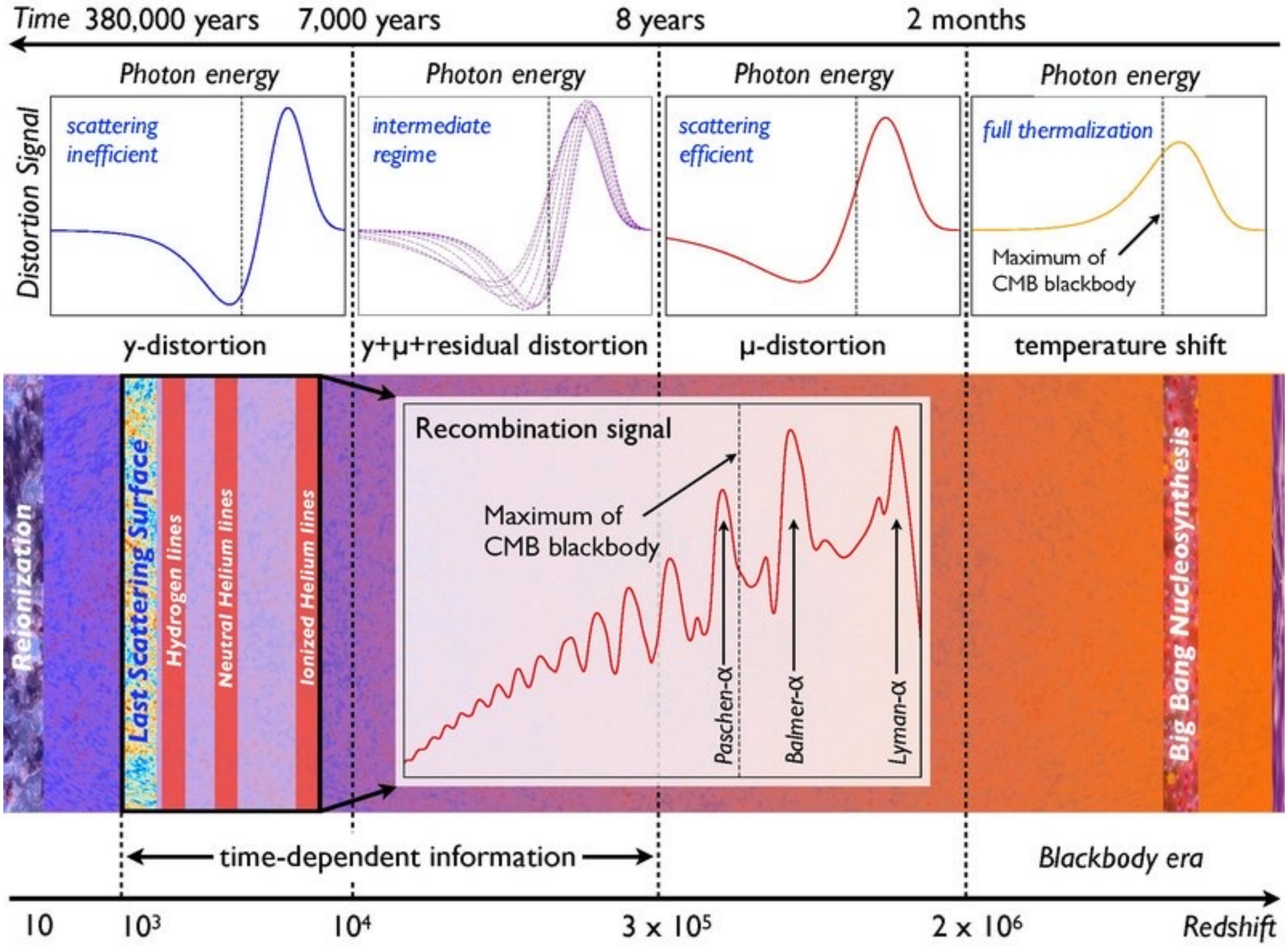


Cosmic Microwave Background!

$$T = 2.725 \pm 0.002\ K$$

$$|\mu| < 9\times 10^{-5}, |y| < 1.5\times 10^{-5}$$

Spectral distortions of CMB

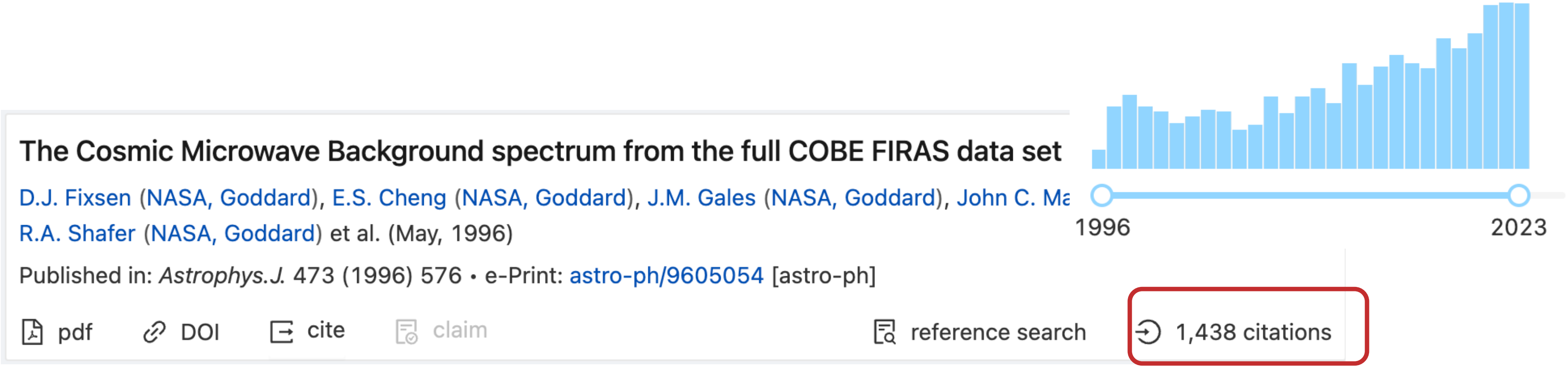


What do we learn from CMB distortions?

- There is no energy injection to CMB after $z = 2{\times}10^6$

- We can rule out BSM models that give this energy injection

- COBE-FIRAS data are still widely used

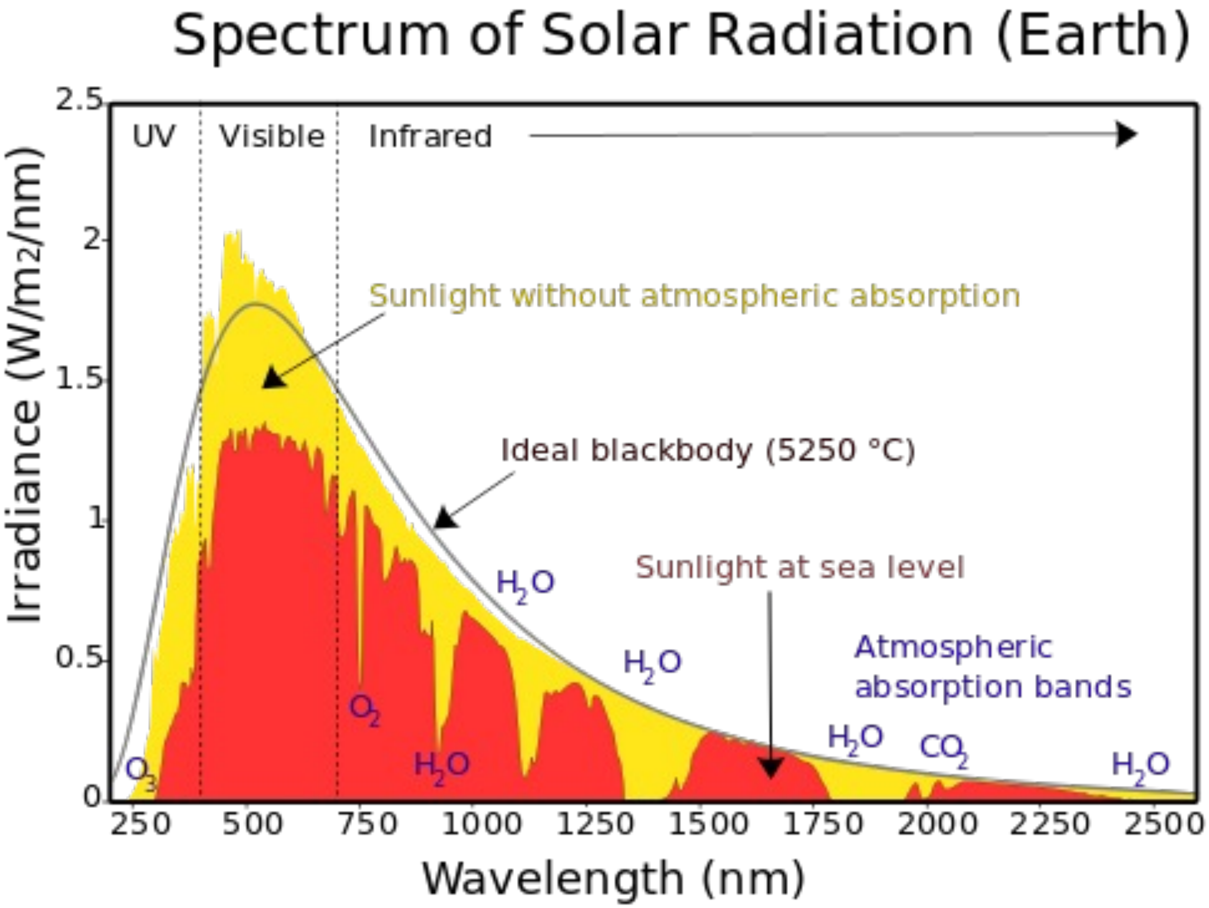


The Cosmic Microwave Background spectrum from the full COBE FIRAS data set

D.J. Fixsen (NASA, Goddard), E.S. Cheng (NASA, Goddard), J.M. Gales (NASA, Goddard), John C. Ma
R.A. Shafer (NASA, Goddard) et al. (May, 1996)

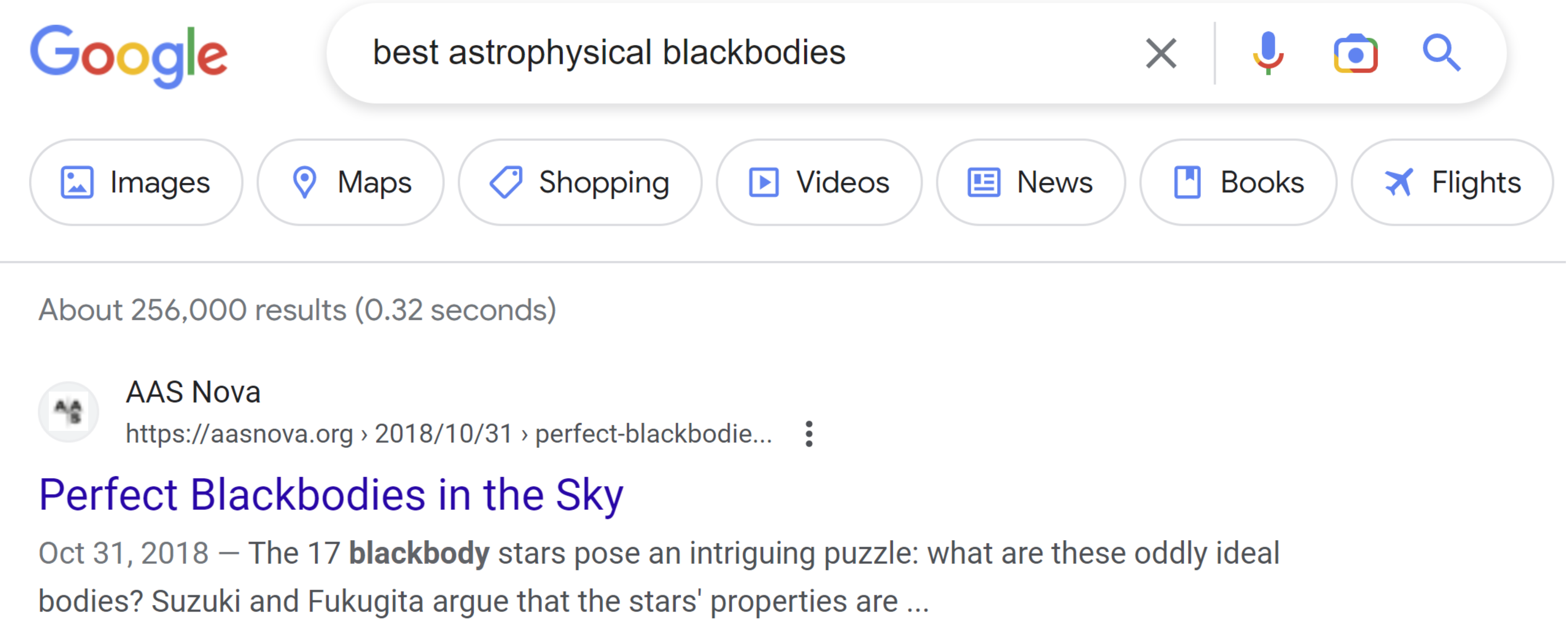
Published in: *Astrophys.J.* 473 (1996) 576 • e-Print: astro-ph/9605054 [astro-ph]

Can we do something similar with another blackbodies?



The Sun is not a perfect blackbody

Can we do something similar with another blackbodies?



best astrophysical blackbodies

About 256,000 results (0.32 seconds)

AAS Nova

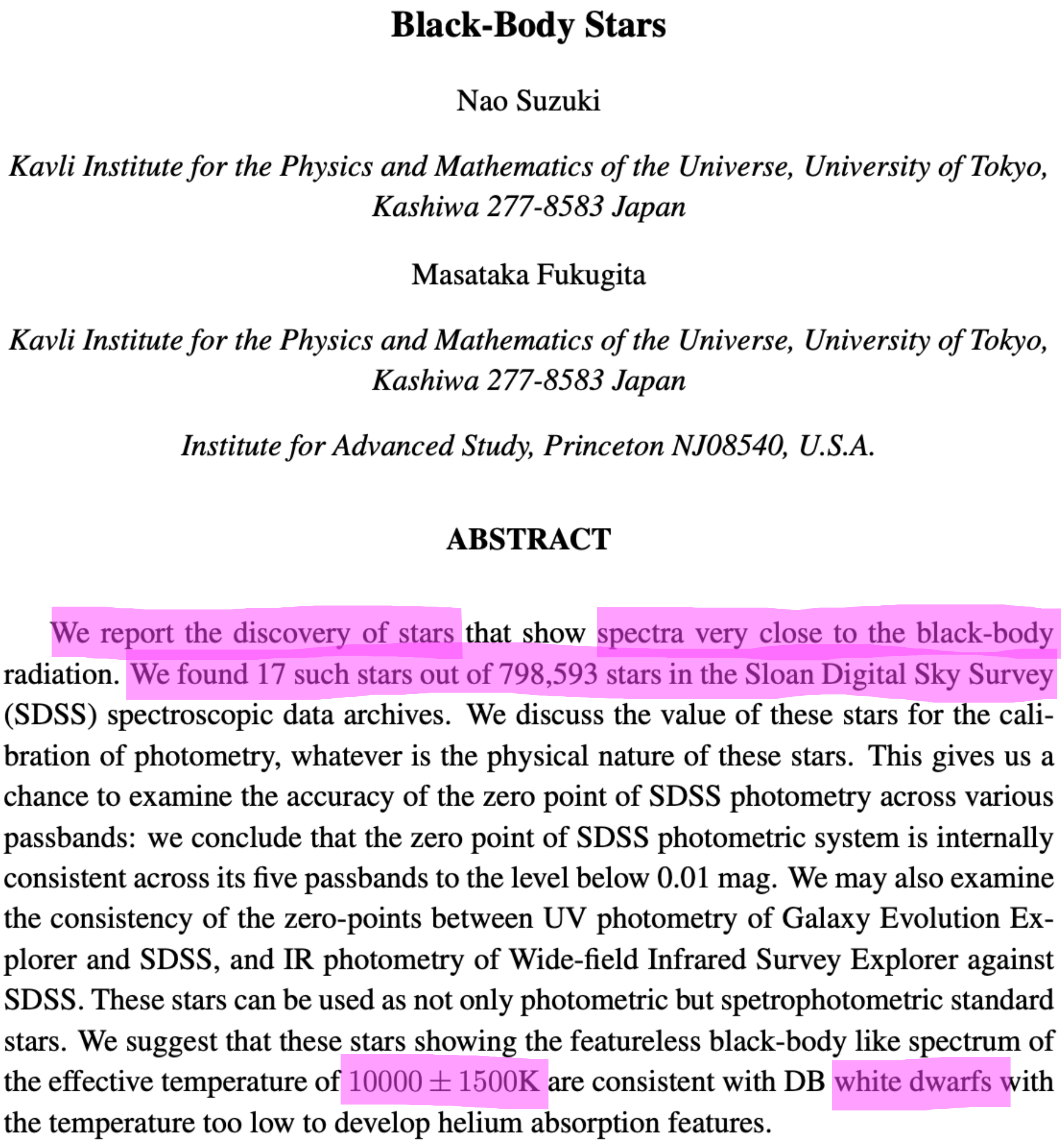
https://aasnova.org › 2018/10/31 › perfect-blackbodie...

Perfect Blackbodies in the Sky

Oct 31, 2018 — The 17 **blackbody** stars pose an intriguing puzzle: what are these oddly ideal bodies? Suzuki and Fukugita argue that the stars' properties are ...

We can ask Google

1711.01122



Black-Body Stars

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Kashiwa 277-8583 Japan

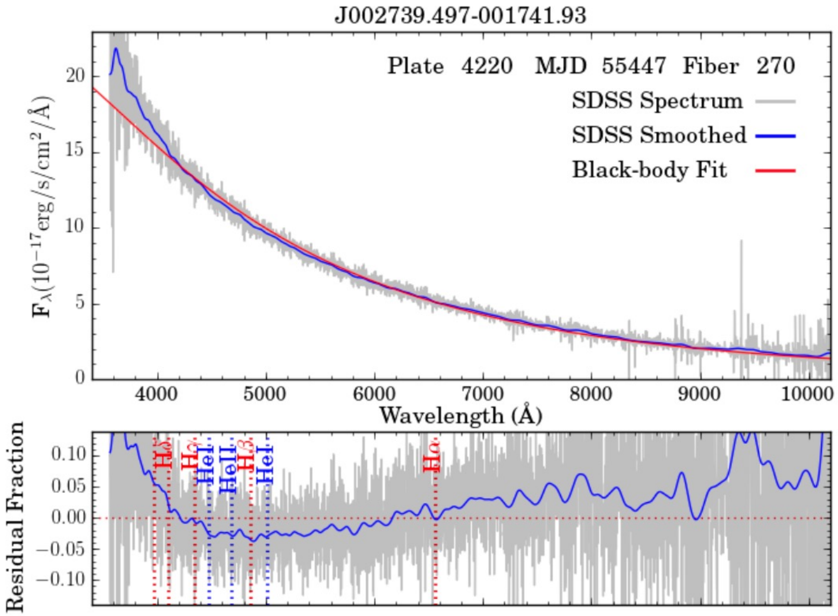
Institute for Advanced Study, Princeton NJ08540, U.S.A.

ABSTRACT

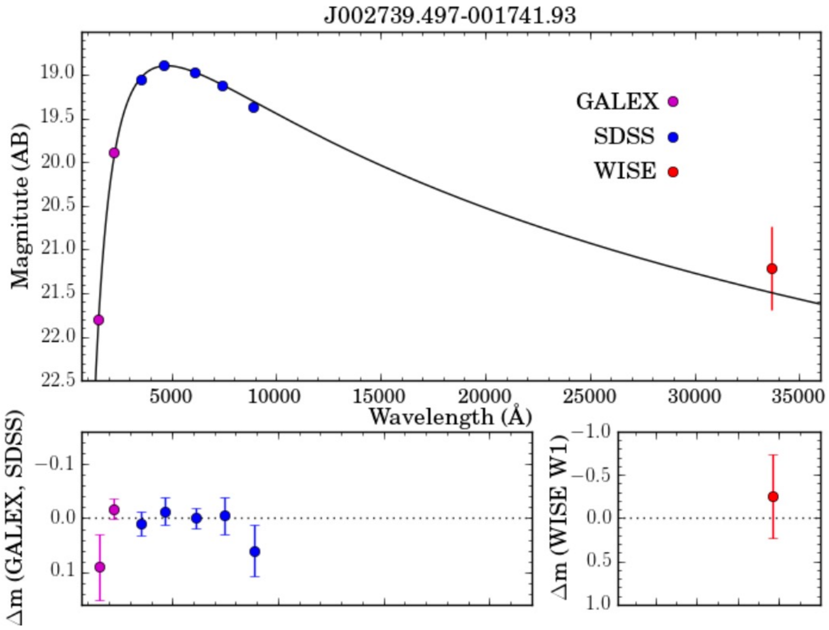
We report the discovery of stars that show spectra very close to the black-body radiation. We found 17 such stars out of 798,593 stars in the Sloan Digital Sky Survey (SDSS) spectroscopic data archives. We discuss the value of these stars for the calibration of photometry, whatever is the physical nature of these stars. This gives us a chance to examine the accuracy of the zero point of SDSS photometry across various passbands: we conclude that the zero point of SDSS photometric system is internally consistent across its five passbands to the level below 0.01 mag. We may also examine the consistency of the zero-points between UV photometry of Galaxy Evolution Explorer and SDSS, and IR photometry of Wide-field Infrared Survey Explorer against SDSS. These stars can be used as not only photometric but spetrophotometric standard stars. We suggest that these stars showing the featureless black-body like spectrum of the effective temperature of 10000 ± 1500K are consistent with DB white dwarfs with the temperature too low to develop helium absorption features.

Blackbody Stars

Spectrometry

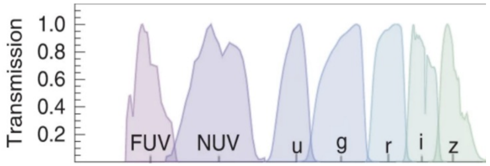


Photometry



$$T = 10662 \pm 60 \;\; \mathrm{K}$$

$$\chi^2/\mathrm{d.o.f} = 0.84$$



Blackbody Stars

- 17 blackbody stars in SDSS data
- DC-type (featureless) white dwarfs
- Low-temperature $T \approx 10{,}000K$
- Helium-rich atmosphere

  $-6 < \log(N_H/N_{He}) < -5.4$ 1804.01236
- Located $70 - 200$ pc away

Similar to CMB distortions,
we can use distortions of
the spectrum of blackbody stars

We put constraints on
axion-like particles (ALP)
as an example

Axion electrodynamics

$$\mathcal{L}_a \supset \frac{1}{2}(\partial_\mu a)^2 - \frac{1}{2}m_a^2 a^2 - \frac{g_{a\gamma\gamma}}{4} a\, F_{\mu\nu}\tilde{F}^{\mu\nu}$$

$$F_{\mu\nu}\tilde{F}^{\mu\nu} = \vec{E}\cdot\vec{B}$$

$$\nabla\cdot E = g_{a\gamma\gamma}\nabla a\cdot B$$

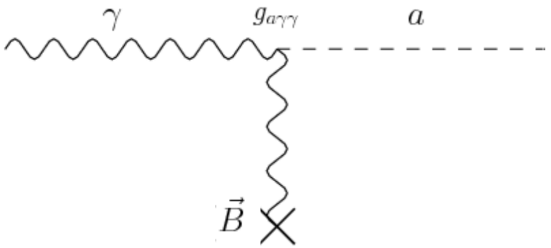
$$\nabla\cdot B = 0$$

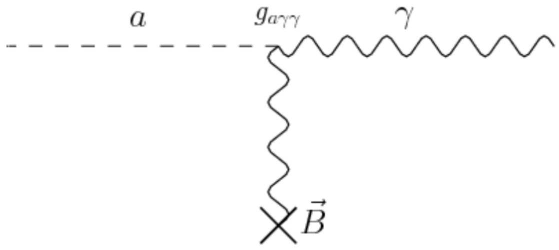
$$\nabla\times E + \partial_t B = 0$$

$$\nabla\times B - \partial_t E = -g_{a\gamma\gamma}[(\partial_t a)B + \nabla a\times E]$$

$$\partial^2 a + m_a^2 a + \frac{1}{4} g_{a\gamma\gamma} F\tilde{F} = 0$$

- In a magnetic field, photons can be converted to axion and vice versa





- Leads photon/axion oscillations

Photon/axion oscillations in a B-field

$$i\partial_z \begin{pmatrix} A_\parallel \\ a \end{pmatrix} = \begin{pmatrix} \omega - \frac{\omega_p^2}{2\omega} & \frac{g_{a\gamma\gamma} B_{\text{ext}}}{2} \\ \frac{g_{a\gamma\gamma} B_{\text{ext}}}{2} & \omega - \frac{m_a^2}{2\omega} \end{pmatrix} \begin{pmatrix} A_\parallel \\ a \end{pmatrix}$$

- Linearized equation under assumption of relativistic particles ($\omega \gg \omega_p, m_a$)

Photon/axion oscillations in a B-field

$$i\partial_z \begin{pmatrix} A_\parallel \\ a \end{pmatrix} = \begin{pmatrix} \omega - \frac{\omega_p^2}{2\omega} & \frac{g_{a\gamma\gamma}B_{\text{ext}}}{2} \\ \frac{g_{a\gamma\gamma}B_{\text{ext}}}{2} & \omega - \frac{m_a^2}{2\omega} \end{pmatrix} \begin{pmatrix} A_\parallel \\ a \end{pmatrix}$$

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- Plasma frequency of the photon in a medium

Photon/axion oscillations in a B-field

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- Linearized equation under assumption of relativistic particles ($\omega \gg \omega_p, m_a$)
- Plasma frequency of the photon in a medium
- Mass of axion

Photon/axion oscillations in a B-field

$$i\partial_z \begin{pmatrix} A_\parallel \\ a \end{pmatrix} = \begin{pmatrix} \omega - \frac{\omega_p^2}{2\omega} & \frac{g_{a\gamma\gamma} B_{\text{ext}}}{2} \\ \frac{g_{a\gamma\gamma} B_{\text{ext}}}{2} & \omega - \frac{m_a^2}{2\omega} \end{pmatrix} \begin{pmatrix} A_\parallel \\ a \end{pmatrix}$$

- Linearized equation under assumption of relativistic particles ($\omega \gg \omega_p, m_a$)
- Plasma frequency of the photon in a medium
- Mass of axion
- Mixing from the interaction

Photon/axion oscillations in a B-field

$$P_{\gamma\to a}(\omega) = \frac{1}{2}\left|\frac{g_{a\gamma\gamma}}{2}\int_0^d dz' B(z') e^{i\int_0^{z'} dz'' \frac{\omega_p^2(z'') - m_a^2}{2\omega}}\right|^2$$

- We assumed $P_{\gamma\to a} \ll 1$
- Can be simplified in some specific situations

Photon/axion oscillations in a B-field

$$P_{\gamma\to a}(\omega) = \frac{1}{2}\left|\frac{g_{a\gamma\gamma}}{2}\int_0^d dz' B(z') e^{i\int_0^{z'} dz'' \frac{\omega_p^2(z'')-m_a^2}{2\omega}}\right|^2$$

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- Proportional to $g_{a\gamma\gamma}^2$

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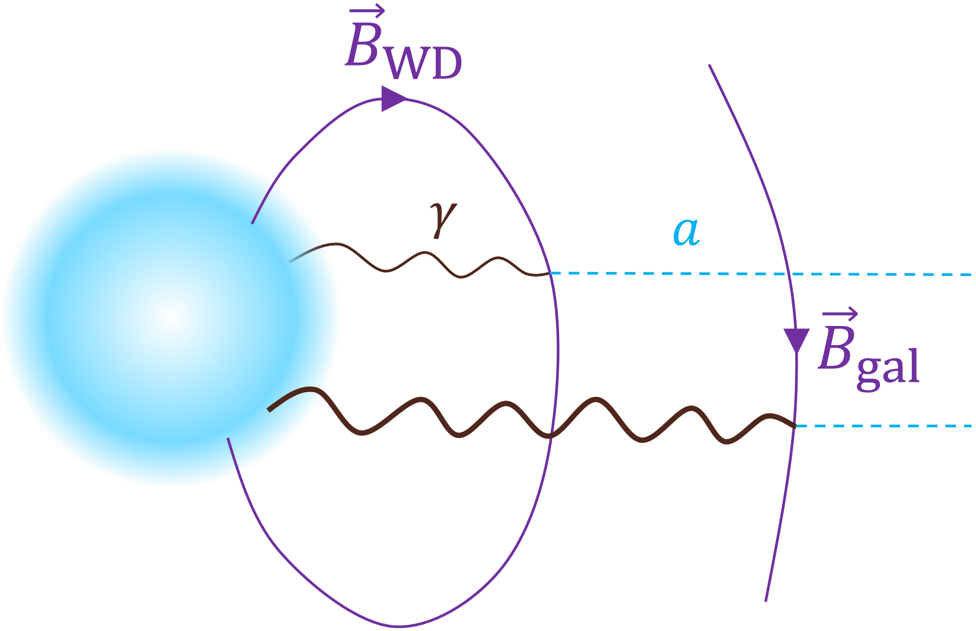
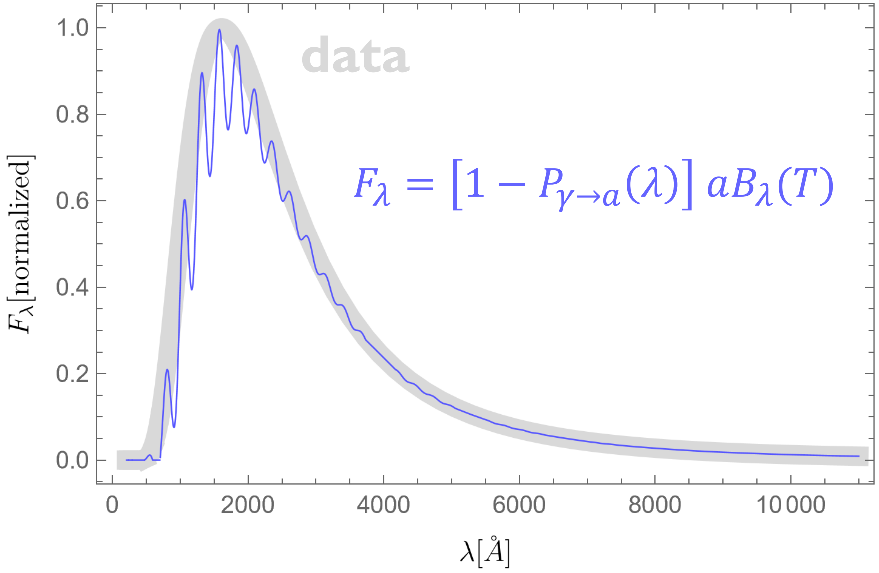
- We assumed $P_{\gamma\to a} \ll 1$
- Can be simplified in some specific situations
- Proportional to $g_{a\gamma\gamma}^2$
- Need to know $B(z)$ and $\omega_p(z)$ along the line of sight
- $P_{\gamma\to a}$ depends on frequency (ω)

Photon/axion oscillations in a B-field

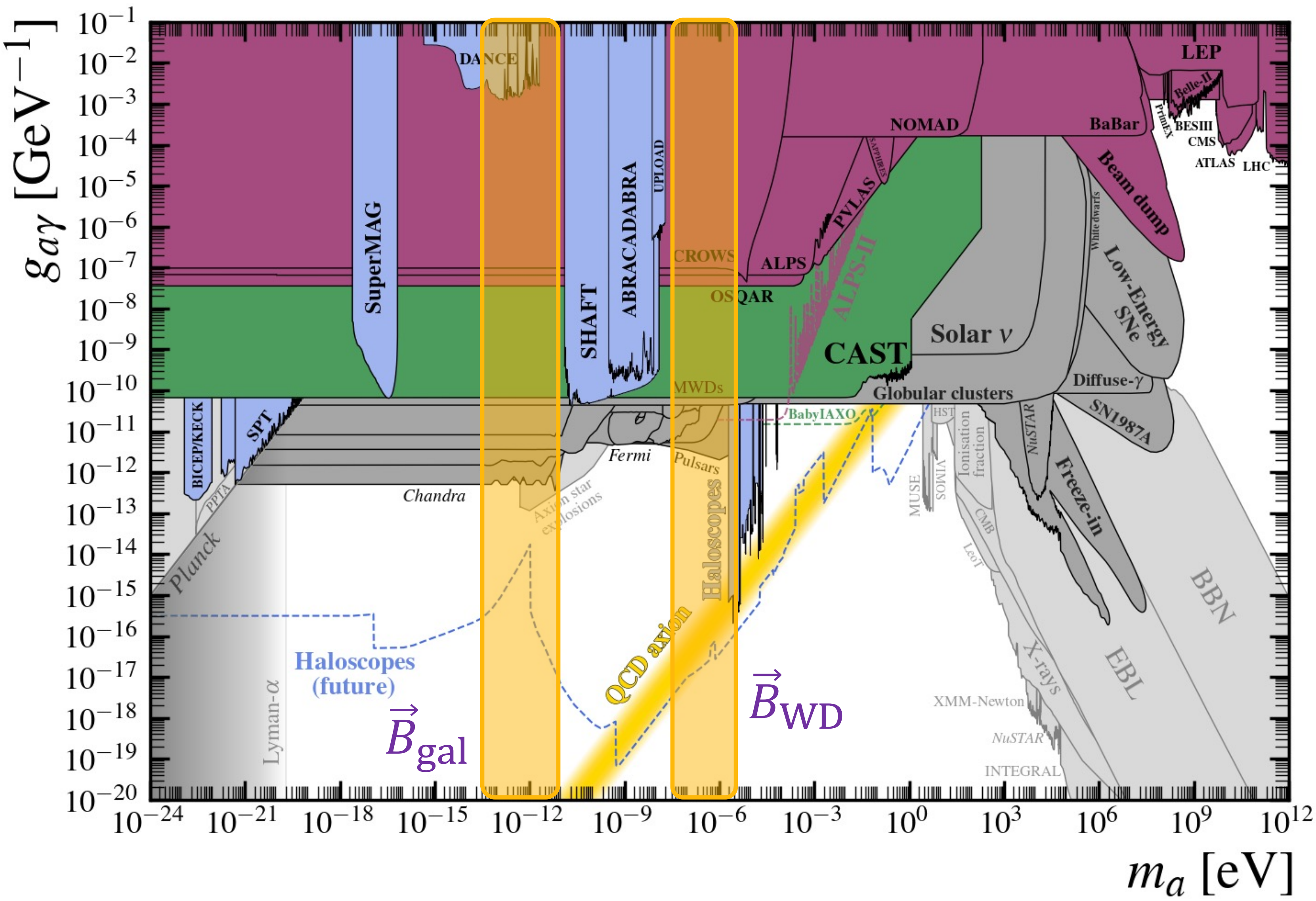
$$P_{\gamma\to a}(\omega) = \frac{1}{2}\left|\frac{g_{a\gamma\gamma}}{2}\int_0^d dz' B(z') e^{i\int_0^{z'} dz''\frac{\omega_p^2(z'')-m_a^2}{2\omega}}\right|^2$$



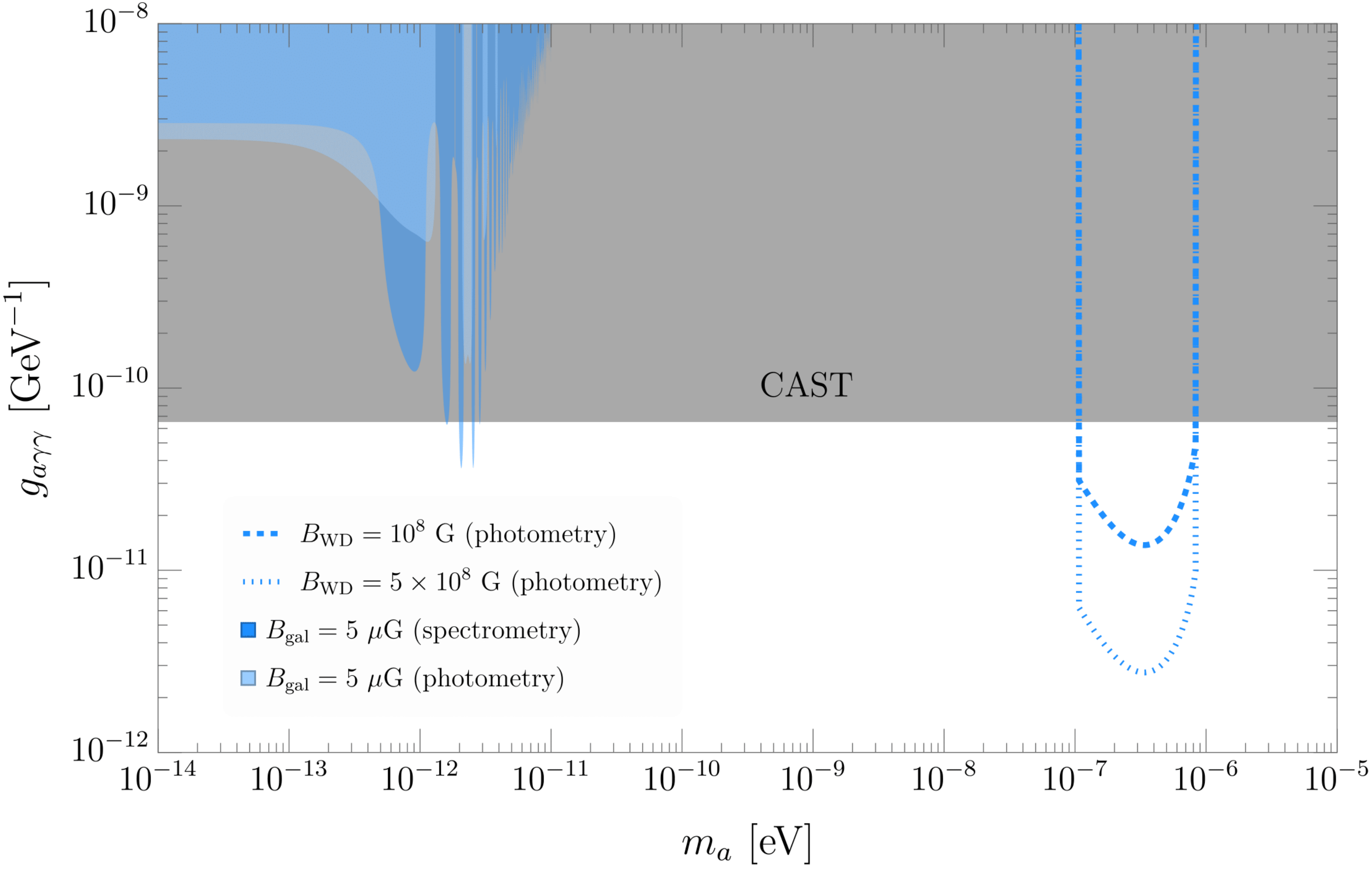


Observation of blackbody spectrum indicates that there's no such axion!

Axion constraints



Our Results

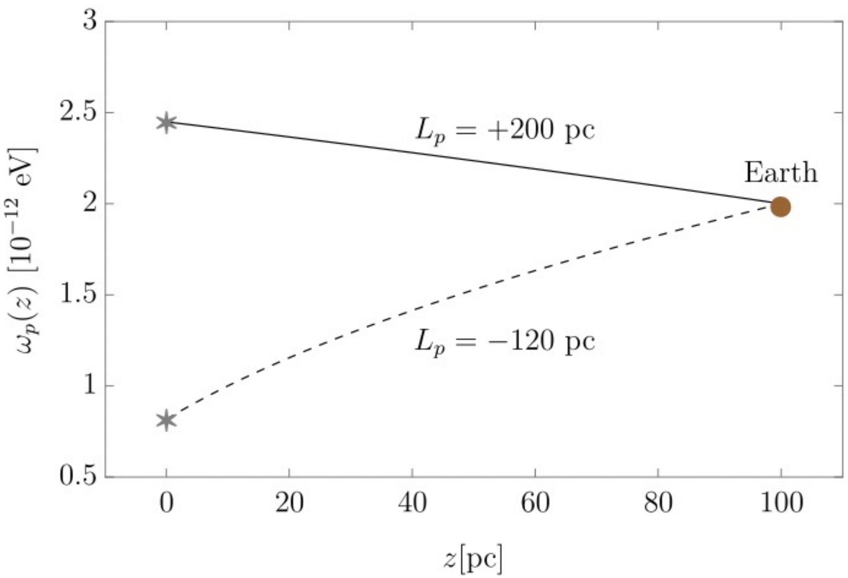


$g_{a\gamma\gamma}$ [GeV^{-1}]
10^{-8}
10^{-9}
10^{-10}
10^{-11}
10^{-12}
CAST
$B_{\mathrm{WD}} = 10^8$ G (photometry)
$B_{\mathrm{WD}} = 5 \times 10^8$ G (photometry)
$B_{\mathrm{gal}} = 5\ \mu$G (spectrometry)
$B_{\mathrm{gal}} = 5\ \mu$G (photometry)
10^{-14}
10^{-13}
10^{-12}
10^{-11}
10^{-10}
10^{-9}
10^{-8}
10^{-7}
10^{-6}
10^{-5}
m_a [eV]

Conversion from galactic B-field

- $\vec{B}_{\mathrm{gal}} \sim 5\mu G$, coherent over long distance

- "Local Bubble" of plasma medium 1610.09448
  - directional density gradient, size ~ 100 pc
  - Model: $\omega_p^2(z) = \omega_{p,0}^2\left(1 + \frac{d-z}{L_p}\right)$
  - $L_p \sim \pm 100$ pc
  - $\omega_{p,0} \approx \sqrt{\frac{4\pi\alpha n_e}{m_e}} \approx 2\times 10^{-12}$ eV

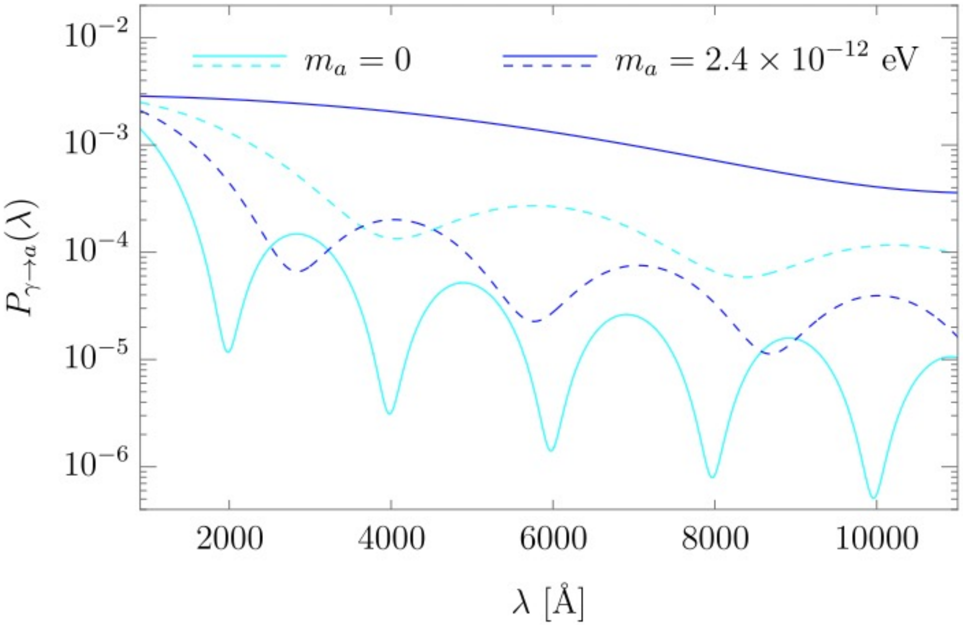


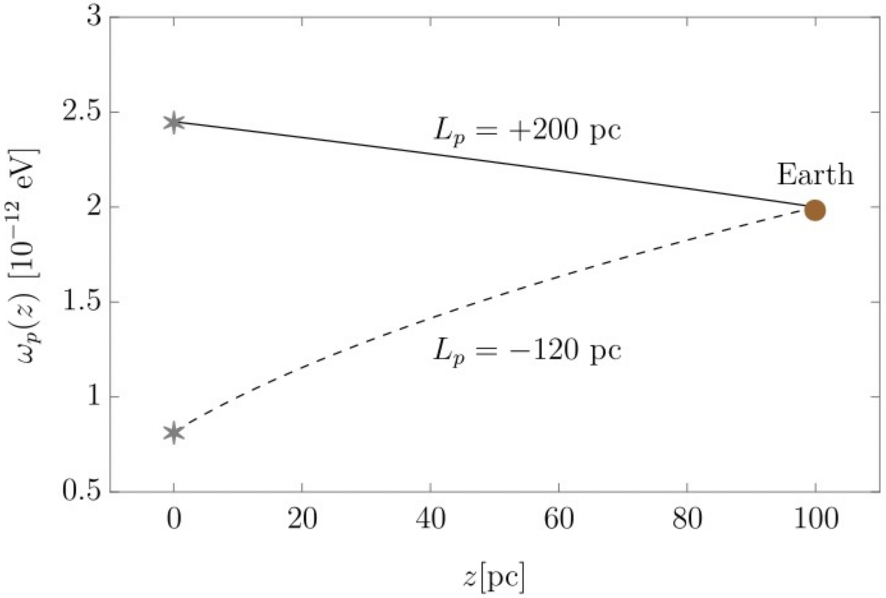
- Strongest constraints at $m_a \sim \omega_{p,0}$

Conversion Probability

$$P_{\gamma\to a}(\omega) = \frac{1}{2}\frac{\pi^2 g_{a\gamma\gamma}^2 B_{\text{gal}}^2 L_p}{2\omega_{p,0}^2\lambda}\left|\text{Erf}[\Phi(d)] - \text{Erf}[\Phi(0)]\right|^2$$

$$\Phi(z) = \sqrt{\frac{iL_p}{\omega}\frac{m_a^2-\omega_p^2(z)}{2\omega_{p,0}}}$$





Chi-squared Analysis

- Flux model

$$F_\lambda = \left[1 - P_{\gamma\to a}\left(m_a, g_{a\gamma\gamma}, \lambda\right)\right] aB_\lambda(T) \qquad aB_\lambda(T) = a\,\frac{4\pi}{\lambda^5}\,\frac{1}{e^{2\pi/\lambda T} - 1}$$

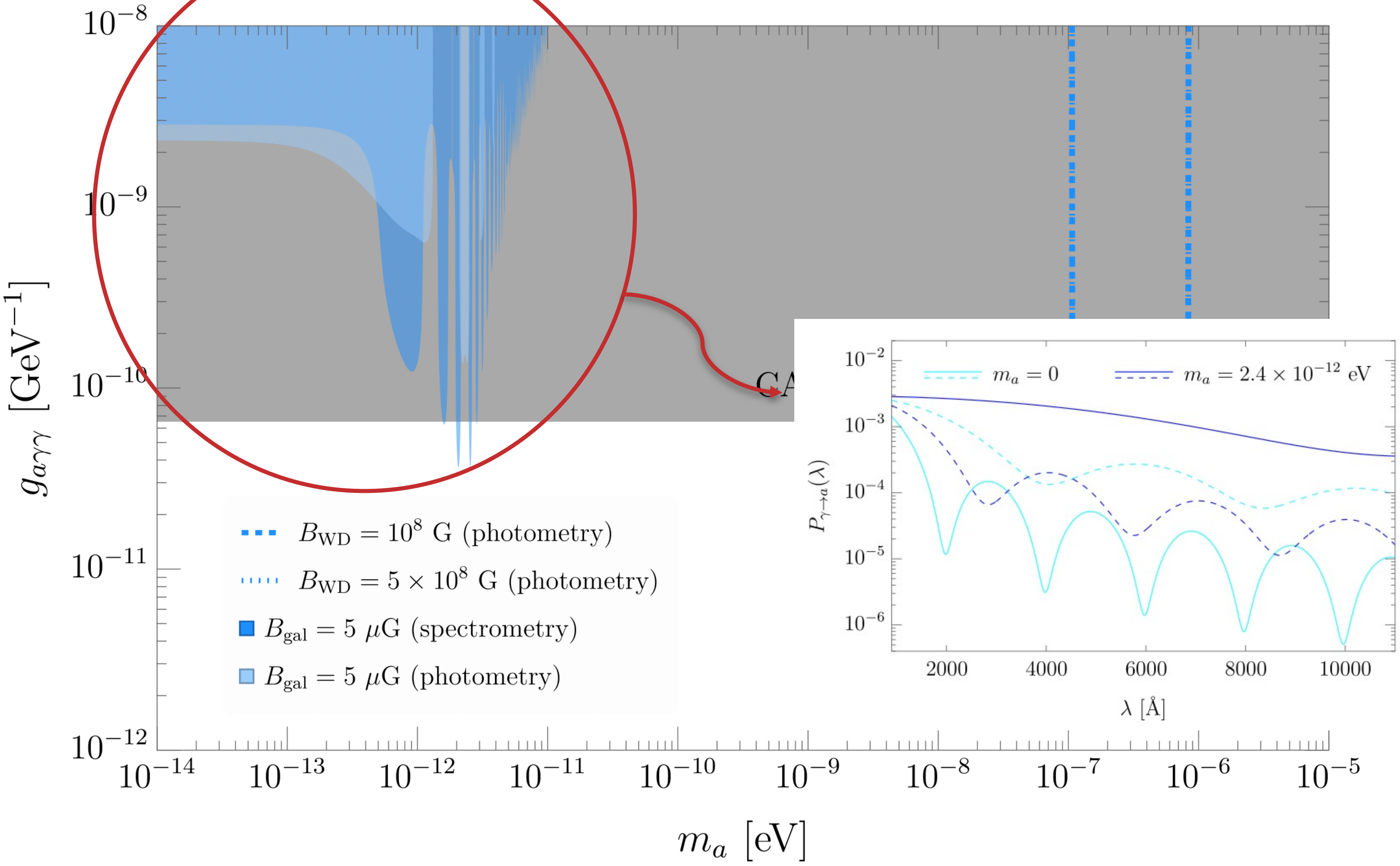
- 95% CL exclusion criterion for a given m_a (Wilk's theorem)

$$\chi^2 = \sum_{i=1}^{N_{\mathrm{bin}}} \left[\frac{F_i - F_{\lambda_i}(m_a, g_{a\gamma\gamma}, a, T)}{\sigma_{F_i}}\right]^2$$

$$\Delta\chi^2 = \left[\chi^2\left(g_{a\gamma\gamma}\right)\right]_{\mathrm{best}(a,T)} - \left[\chi^2\right]_{\mathrm{best}\left(g_{a\gamma\gamma},a,T\right)} > \left[\chi^2\right]_{95\%\ \mathrm{CL}}^{\mathrm{one-sided}} = 2.71$$

- We use both photometry and spectrometry data

Our Results: from galactic B-field



Conversion from white dwarf B-field

- Modeled as dipole magnetic field

$$\vec{B}(\vec{r}) = \frac{B_{WD} R_{WD}^3}{2r^3} (3(\hat{m} \cdot \hat{r})\hat{r} - \hat{m})$$

- $B_{WD} \sim 10^4 - 10^9\ \mathrm{G}, R_{WD} \sim 10^4\ \mathrm{km}$
- B_{WD} is not known, but distributed uniformly in log-space

2111.11174

- B_{WD} can be measured in the future with circular polarimetry
- We use $B_{WD} = 10^8\ \mathrm{G}$ and $5{\times}10^8\ \mathrm{G}$
- Plasma frequency is negligible in this case

Conversion Probability

$$P_{\gamma\to a}(\omega) = \frac{1}{2} F(\theta) \frac{\left(g_{a\gamma\gamma} B_{\mathrm{WD}} R_{\mathrm{WD}}\right)^2}{16} \left| \int_1^\infty d\tilde{r}\, \frac{e^{i\delta_a \tilde{r}}}{\tilde{r}^3} \right|^2 \qquad \delta_a = -\frac{m_a^2 R_{\mathrm{WD}}}{2\omega}$$

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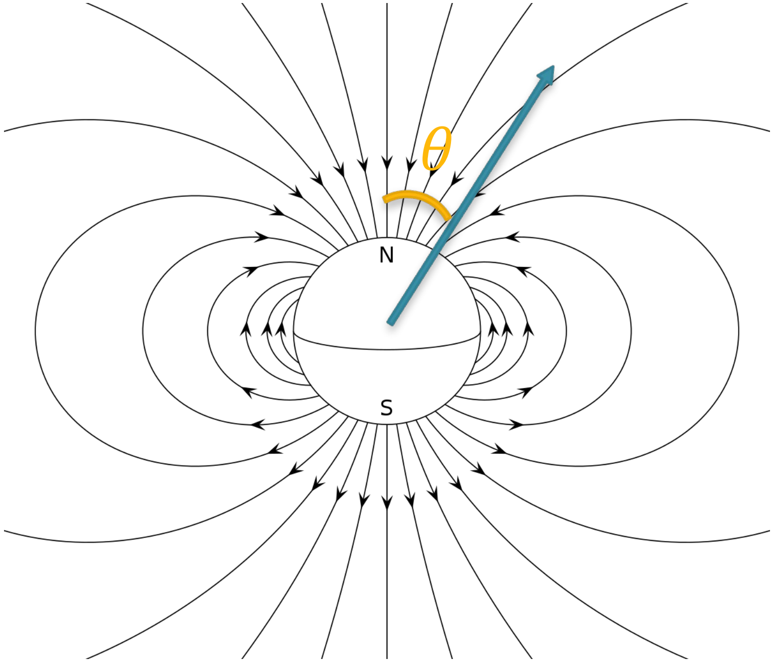
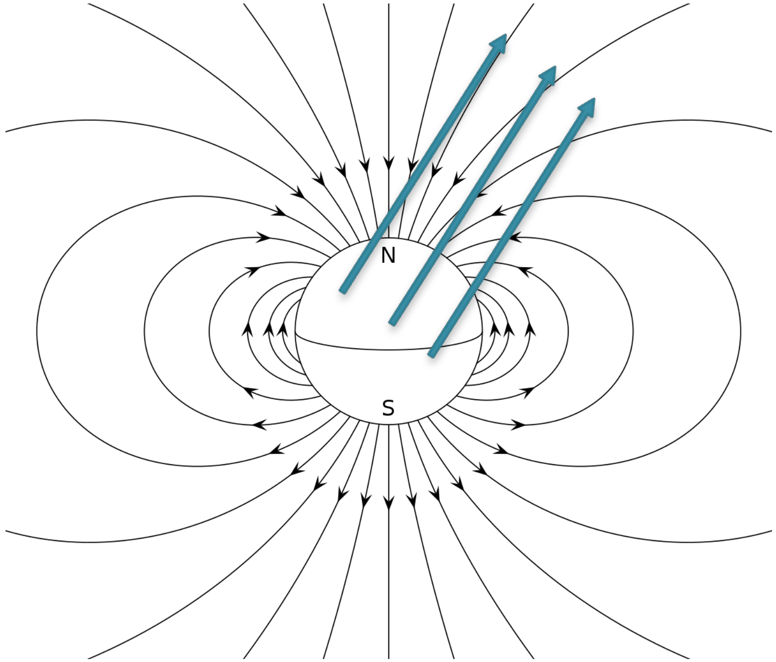


- θ is the angle between a particle and the dipole axis

- For radial direction, we can calculate $F(\theta)$ analytically

Conversion Probability

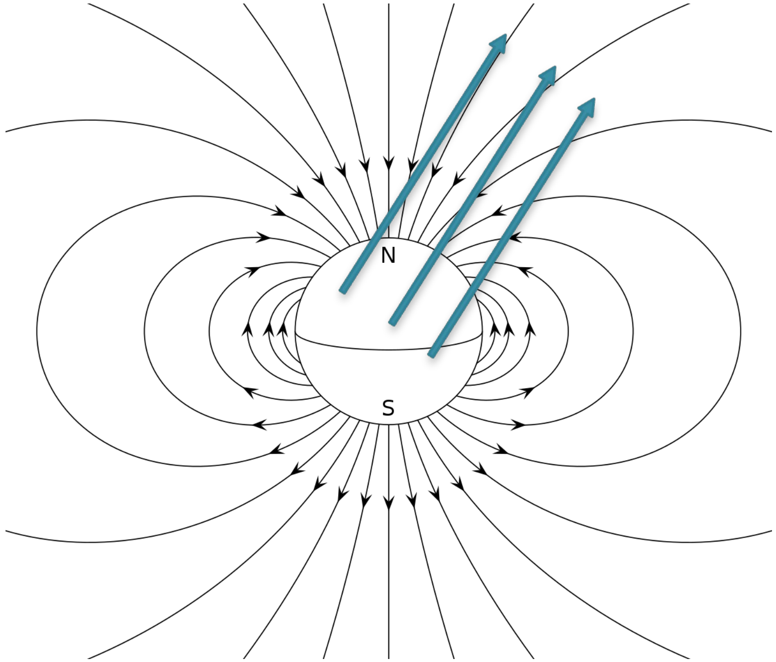
$$P_{\gamma\to a}(\omega) = \frac{1}{2}F(\theta)\frac{\left(g_{a\gamma\gamma}B_{\mathrm{WD}}R_{\mathrm{WD}}\right)^2}{16}\left|\int_1^\infty d\tilde{r}\,\frac{e^{i\delta_a\tilde{r}}}{\tilde{r}^3}\right|^2 \qquad \delta_a = -\frac{m_a^2 R_{\mathrm{WD}}}{2\omega}$$

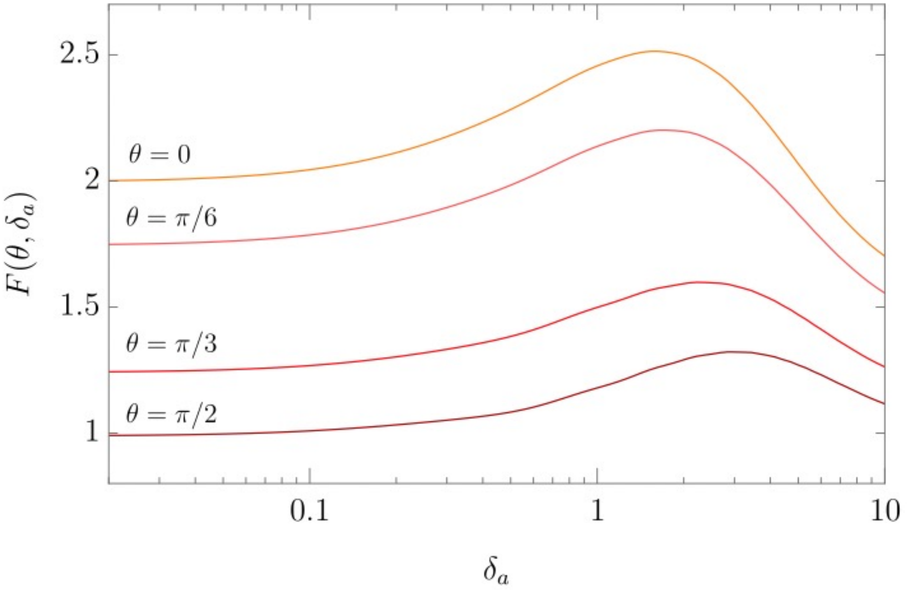


- θ is the angle between a particle and the dipole axis
- For radial direction, we can calculate $F(\theta)$ analytically
- However, particles don't propagate radially

Conversion Probability

$$P_{\gamma\to a}(\omega) = \frac{1}{2} F(\theta) \frac{\left(g_{a\gamma\gamma} B_{\mathrm{WD}} R_{\mathrm{WD}}\right)^2}{16} \left| \int_1^\infty d\tilde{r}\, \frac{e^{i\delta_a \tilde{r}}}{\tilde{r}^3} \right|^2 \qquad \delta_a = -\frac{m_a^2 R_{\mathrm{WD}}}{2\omega}$$

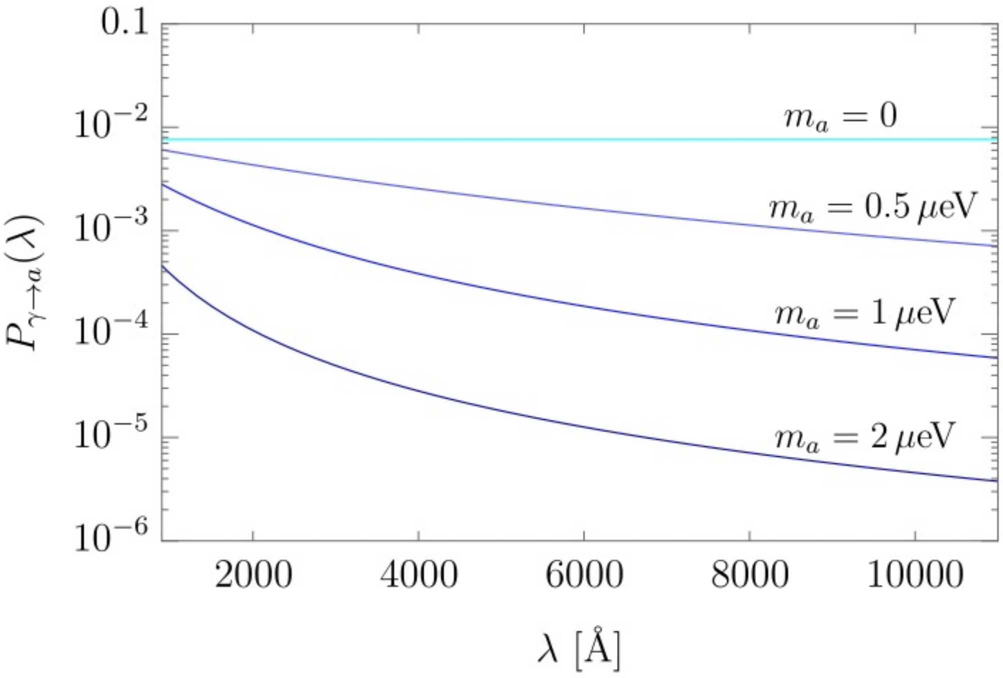




- We take a constant $F(\theta) = 2$

Conversion Probability

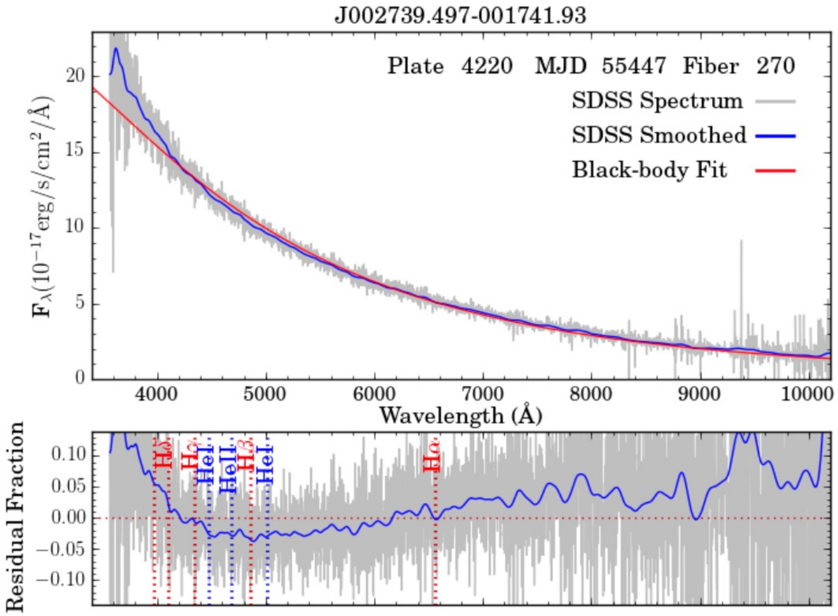
$$P_{\gamma\to a}(\omega) = \frac{1}{2}F(\theta)\frac{\left(g_{a\gamma\gamma}B_{\mathrm{WD}}R_{\mathrm{WD}}\right)^2}{16}\left|\int_1^\infty d\tilde{r}\,\frac{e^{i\delta_a\tilde{r}}}{\tilde{r}^3}\right|^2 \qquad \delta_a = -\frac{m_a^2R_{\mathrm{WD}}}{2\omega}$$



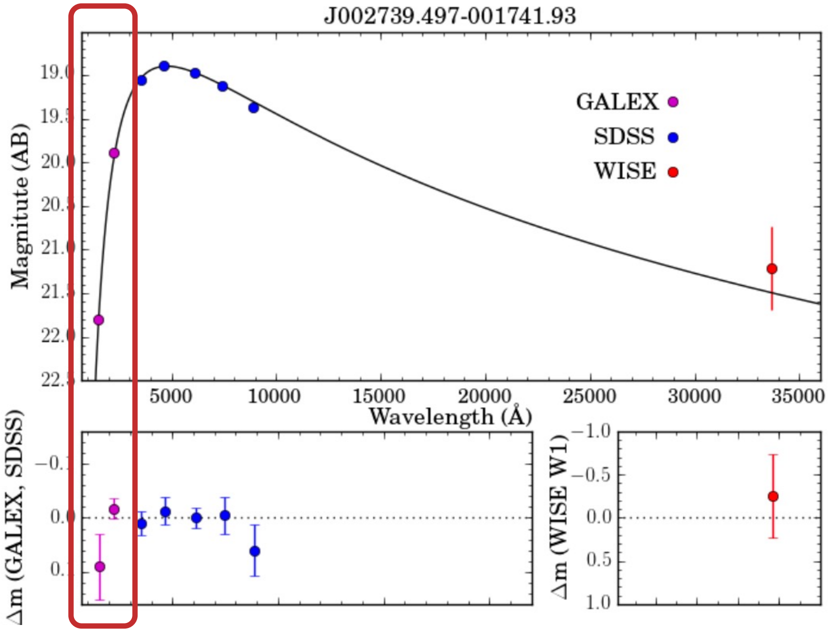
- $P_{\gamma\to a}$ is maximized for small δ_a
- However, we lose λ dependence
- Best results come from $\delta_a \approx \mathcal{O}(1)$ or $m_a \approx \sqrt{\frac{\omega}{R_{WD}}} \approx \mu\mathrm{eV}$
- No oscillation feature, only monotonic

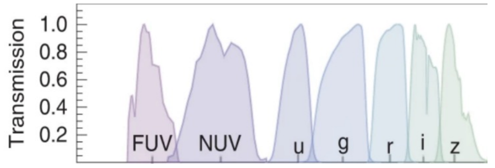
We use photometry for WD B-field

Spectrometry



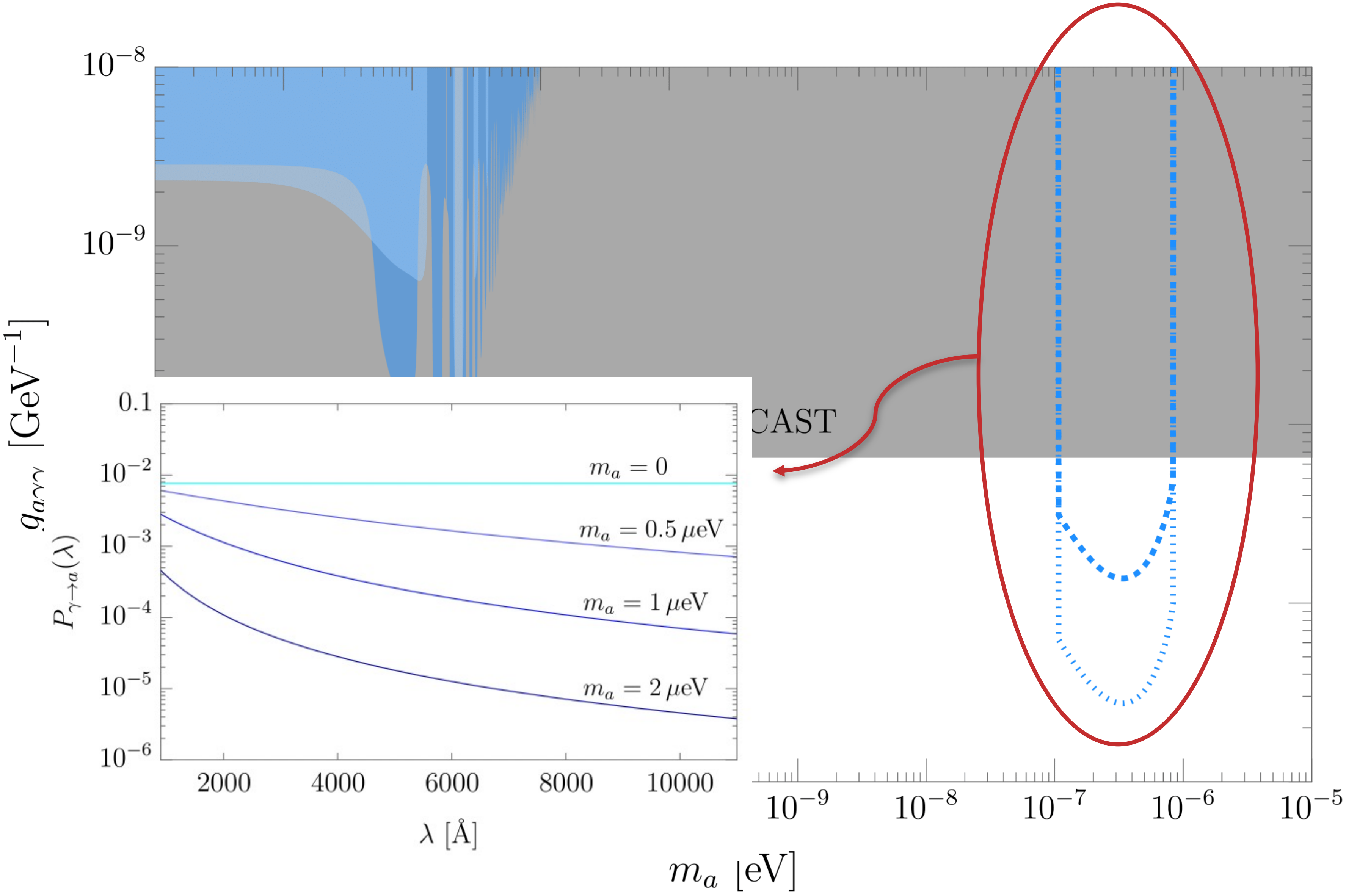
Photometry





We follow the same process to get constraints

Our Results: from WD B-field



Conclusions

- 17 blackbody stars were probed from SDSS data
- We can use spectral distortion of the blackbody stars to probe new physics
- We put constraints on axion-like particles as an example

Future Works

- Use recent telescope data
  - More blackbody stars
  - Smaller uncertainty
  - Put better constraints

- Different Models
  - Dark photons
  - Millicharged dark matter
  - ⋮

THANK YOU