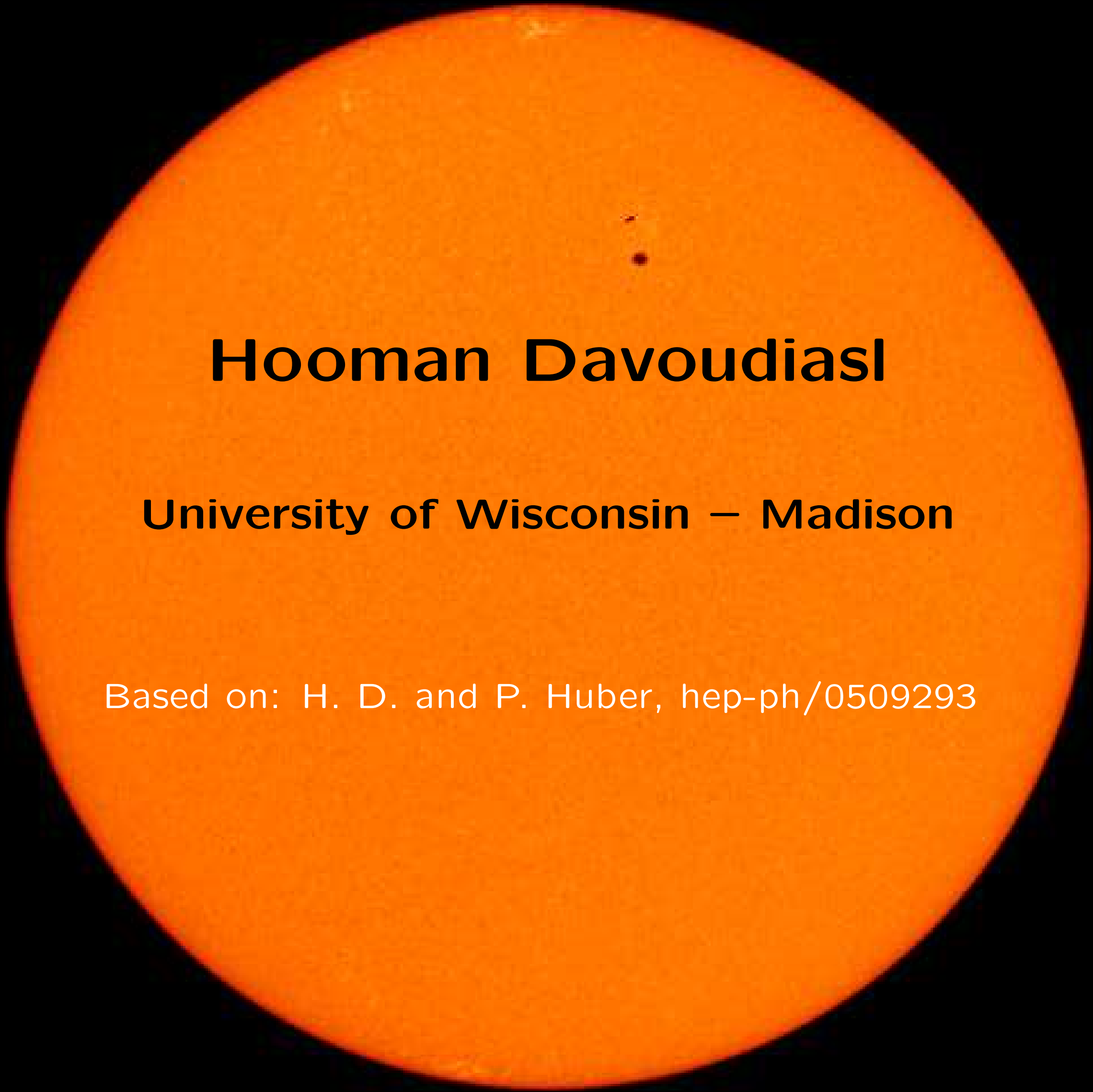
Detecting Solar Axions Using Earth's Magnetic Field



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Based on: H. D. and P. Huber, hep-ph/0509293

★ Weakly-coupled light pseudo-scalars:

- Strong CP problem; QCD: $\theta_{\mathrm{QCD}} \leq 10^{-10}$. Peccei, Quinn (1977)
- Cosmology.
- Ubiquitous in String Theory.

★ Axion-photon coupling at low energies:

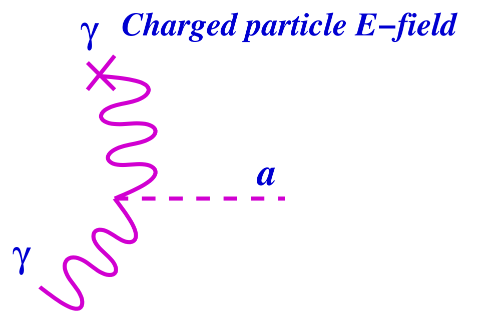
$$\mathcal{L}_{a\gamma} = -\frac{1}{4}\, g_{a\gamma}\, a F_{\mu\nu} \tilde{F}^{\mu\nu}$$

$g_{a\gamma}^{-1} \sim (\pi/\alpha) f_a$, f_a axion scale, and $\alpha \simeq 1/137$.

★ Plasma axion-emission, Primakoff effect:

- Solar axion flux: $\langle \omega_a \rangle \simeq 4.2$ keV.

van Bibber, McIntyre, Morris, Raffelt (1989)



- Reverse: axion $\rightarrow$ photon in transverse B-filed. Sikivie (1983)

$\Rightarrow$ Solar axions convert to X-rays: $\langle \omega_\gamma \rangle \simeq 4.2$ keV.

Axion-photon conversion: $p_\gamma(L) = \frac{1}{2}\left(g_{a\gamma}B/q\right)^2\left[1-\cos(qL)\right]$

Raffelt, Stodolsky (1988)

van Bibber, McIntyre, Morris, Raffelt (1989)

- L: path length; $\ell = 2\pi/q$: oscillation length.
- $q = m_a^2/(2\omega_a)$. (vacuum propagation).
- m_a: axion mass

The CAST Experiment:

Most recent solar axion bound on $g_{a\gamma}$.

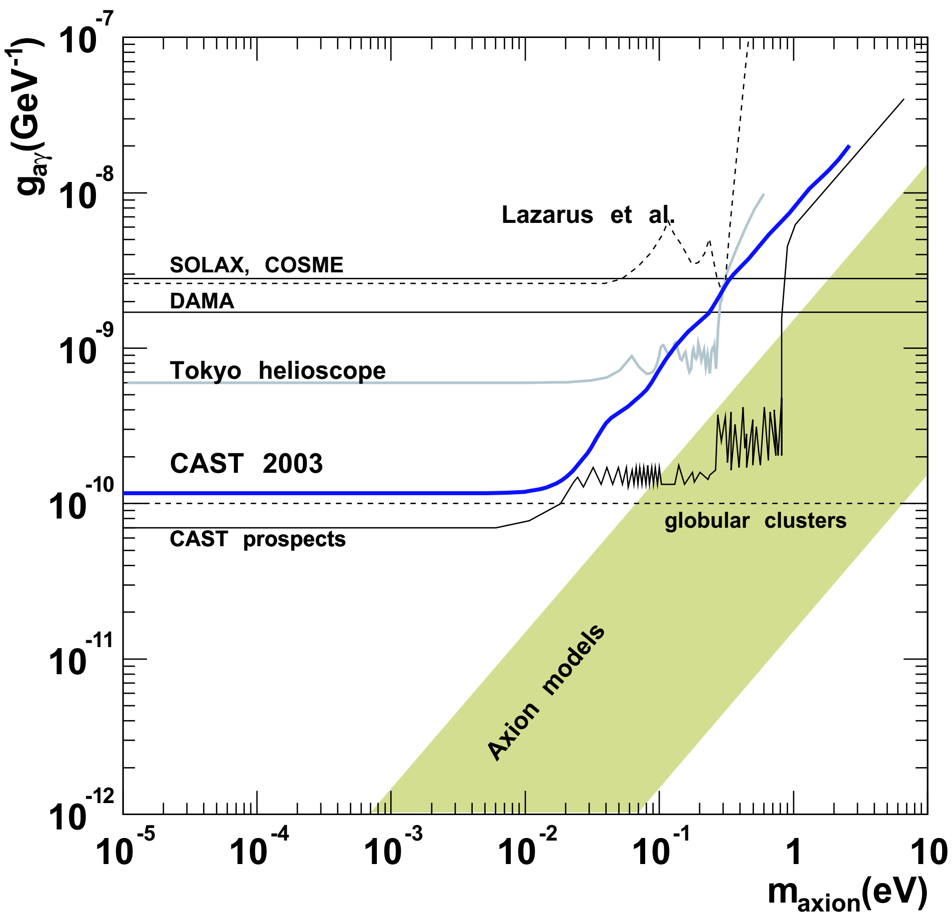
$B = 9.0$ T ; Length $= 9.26$ m.

$A = 2 \times 14.5$ cm^2 (two pipes).

S. Andriamonje *et al.* [CAST Collaboration], Phys. Rev. Lett. **94**, 121301 (2005).

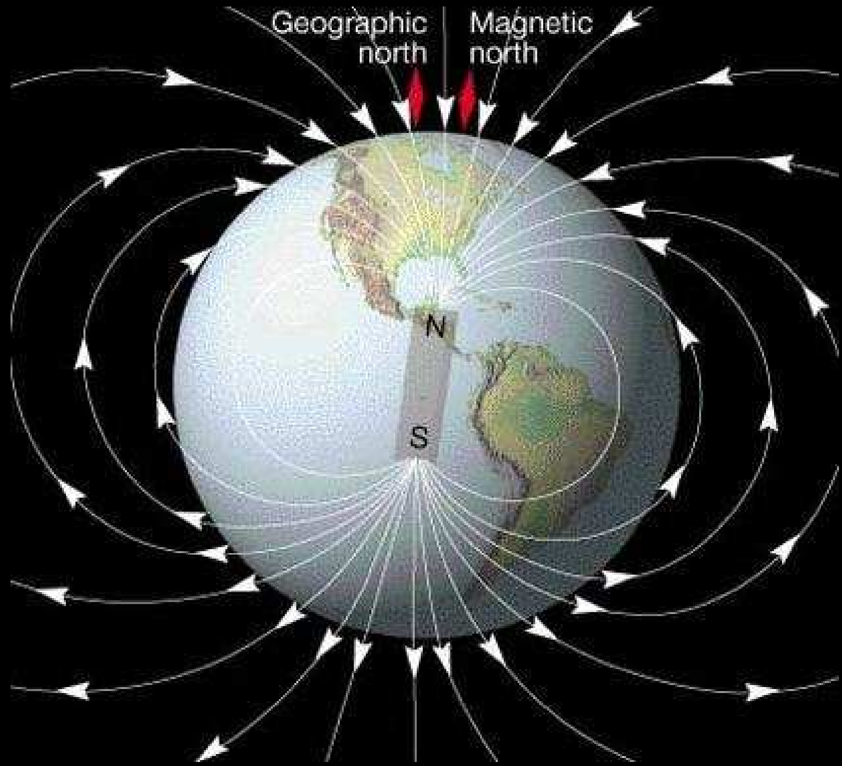
$p_\gamma(L) \approx (g_{a\gamma}BL/2)^2$ (for $q \ll 1/L$).

Figure of merit: $\mathcal{F} \equiv (BL)^2$.



Key Observation

- Earth's magnetic field: $B_\oplus \simeq 0.3$ G.
- $B_\oplus \propto 1/r^3$
- $L \ll R_\oplus \approx 6400$ km $\Rightarrow B_\oplus \simeq$ Constant.
- We will use $L_\oplus \simeq 1000$ km.



Earth as the conversion region:

$\Rightarrow \mathcal{F}_\oplus \simeq 900$ T^2 m^2.

$\mathcal{F}$(CAST) $\simeq 7000$ T^2 m^2.

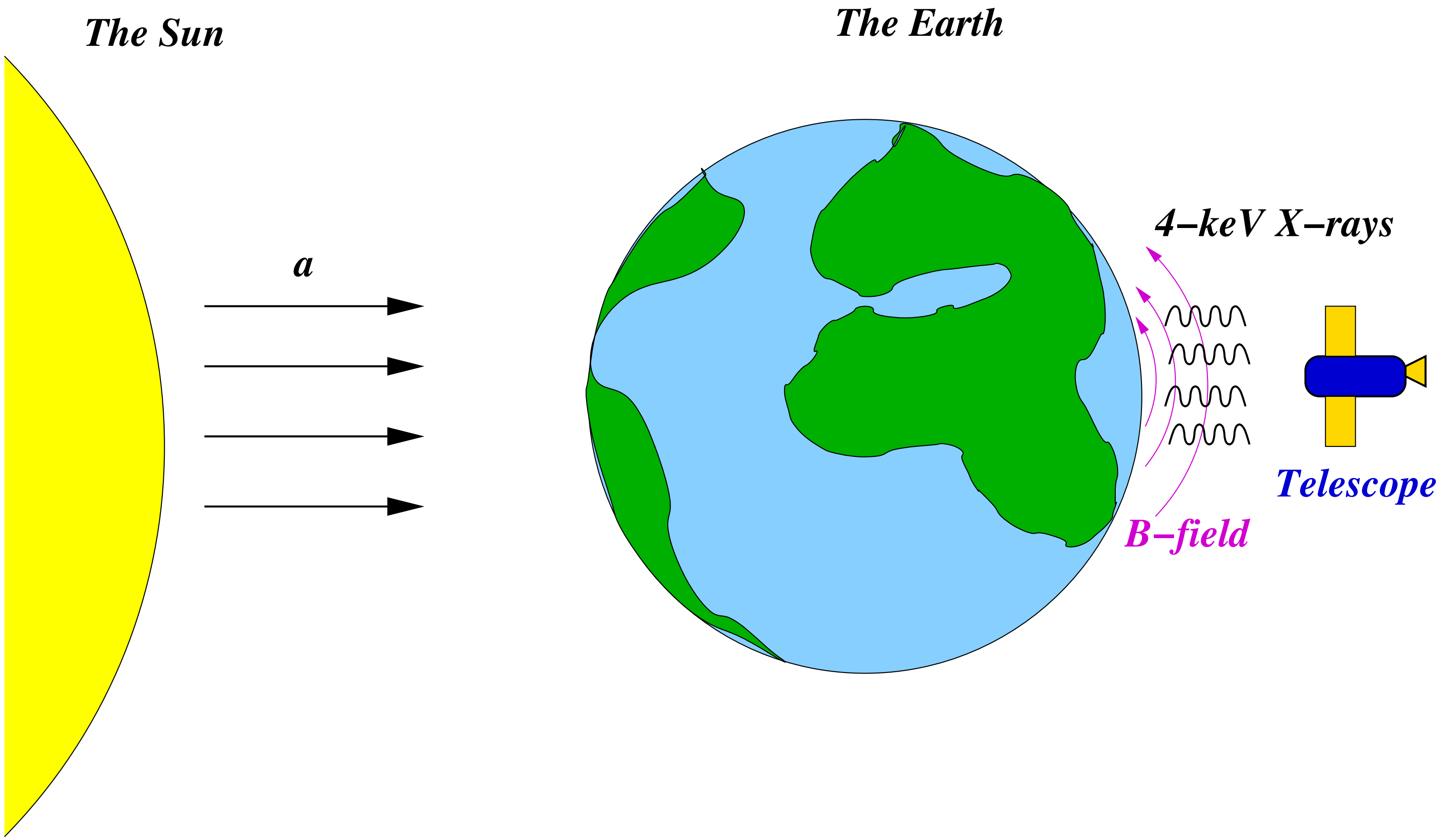
$\mathcal{F}_\oplus \approx (1/8)\mathcal{F}$(CAST)

Conversion of high energy cosmic axions in $B_\oplus$:

Zioutas, Thompson, Paschos (1998).

$\therefore$ A low-earth-orbit X-ray telescope with $A \gg 10A_{\rm CAST}$ can outperform CAST ($m_a \lesssim 10^{-4}$ eV).

Geomagnetic Conversion of Solar Axions to X-rays (GECOSAX)



Detection:

Using the Earth to shield from solar X-rays. ⇒ Collect data on the night side.

Numerical inputs:

- $B_\oplus = 3 \times 10^{-5}$ T, $\omega_a = 4$ keV, $g_{a\gamma} = 10^{-10}$ GeV^{-1}.
- $L_\oplus = 600\,\text{km} < R_\oplus/10 \Rightarrow m_a \leq 10^{-4}$ eV. *Note: Above ~ 150 km, atmosphere negligible.*

$\Rightarrow\ p_\gamma(L_\oplus) \approx 10^{-18}$.

Solar-axion flux at Earth: $\Phi_a = 3.67 \times 10^{11} \left(\frac{g_{a\gamma}}{10^{-10}\,\text{GeV}^{-1}}\right)^2 \text{cm}^{-2}\,\text{s}^{-1}$

X-ray flux at $L_\oplus \simeq 600\,\text{km}$:

$$\boldsymbol{\Phi_\gamma(L_\oplus) \approx 4 \times 10^{-7}\,\text{cm}^{-2}\,\text{s}^{-1}.}$$

Q: Can we observe this flux?

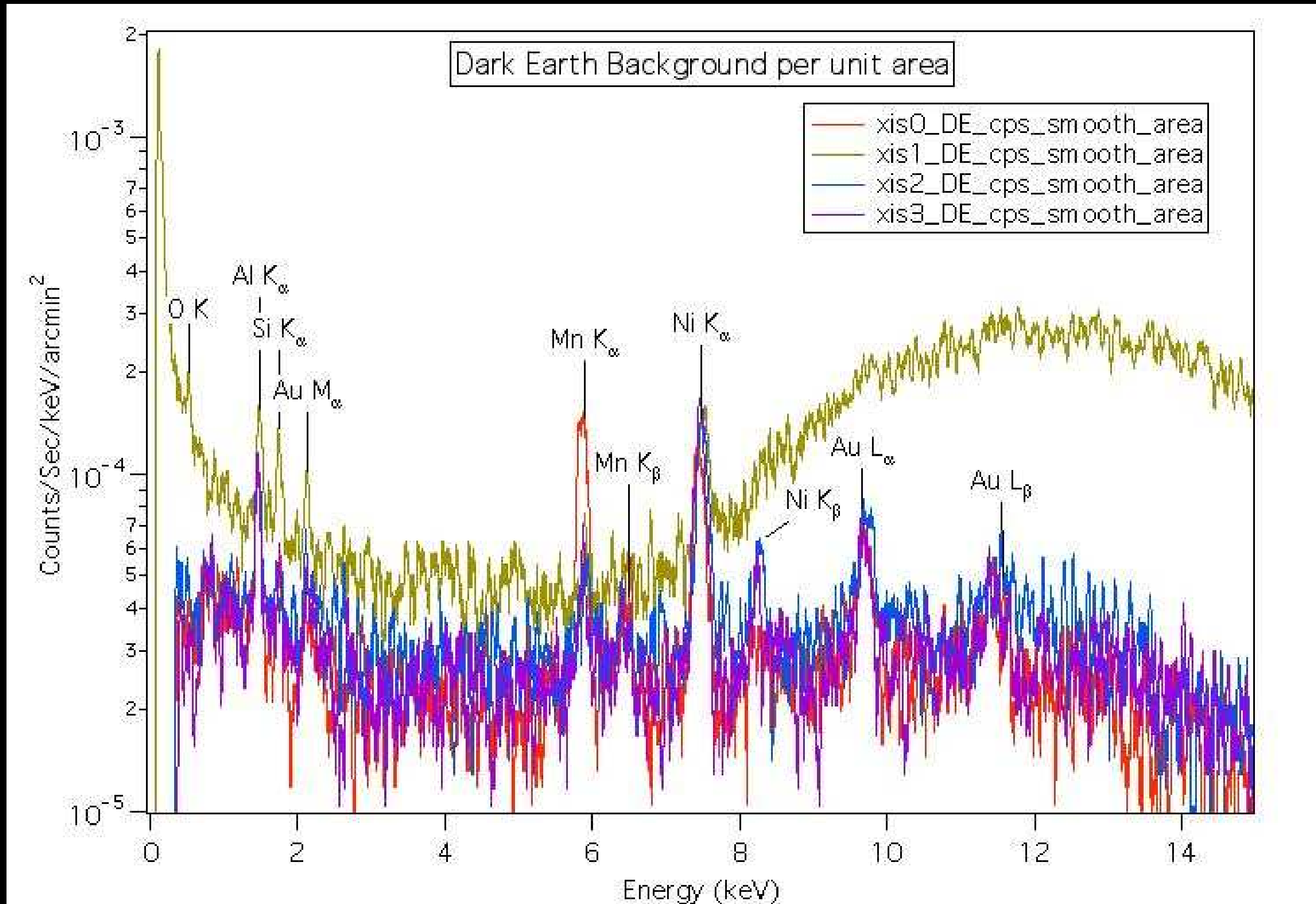
A: Yes!

Initial estimate based on the RXTE X-ray telescope:

1996-1999: $\delta t \simeq 2.5 \times 10^4$ s of dark earth data. Background: 3 counts s^{-1}. $A_{\text{eff}} \sim 7000$ cm^2, $E_\gamma \in [2, 10]$ keV.

RXTE Sensitivity: $\sqrt{N}_B/(\delta t\, A_{\text{eff}}) \sim 1.5 \times 10^{-6}$ cm^{-2} s^{-1}.

Suzaku X-ray Mission: Recent Data



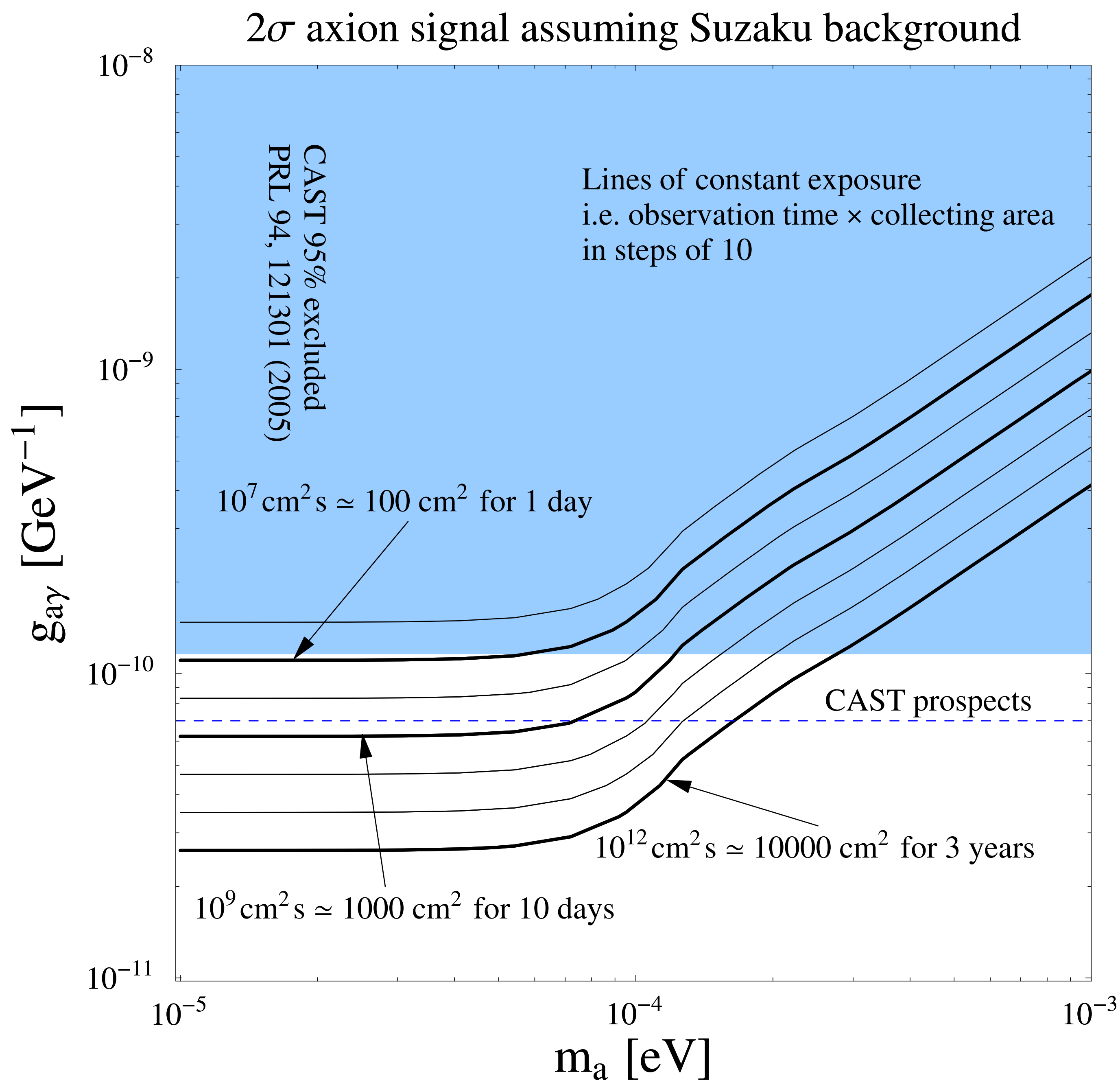
Courtesy of Suzaku team

Suzaku Satellite:

- Circular orbit: 575 km, 33°.
- Resolution: 1'.

Suzaku team: $A_{eff} \sim$ 300 cm^2 over 2-7 keV.

With 3×10^5 s of data, $g_{a\gamma} < 10^{-10}$ GeV^{-1} at 4σ could have been possible.



2σ axion signal assuming Suzaku background
CAST 95% excluded
PRL 94, 121301 (2005)
Lines of constant exposure
i.e. observation time × collecting area
in steps of 10
10^7 cm^2 s ≃ 100 cm^2 for 1 day
CAST prospects
10^12 cm^2 s ≃ 10000 cm^2 for 3 years
10^9 cm^2 s ≃ 1000 cm^2 for 10 days
g_aγ [GeV^-1]
m_a [eV]
10^-8
10^-9
10^-10
10^-11
10^-5
10^-4
10^-3

Concluding Remarks

- Axions: theoretically well-motivated; important potential role in Nature.
- Promising discovery path: solar axion detection in magnetic fields.
- **GECOSAX:** efficient due to large magnetized volume.
- Present orbiting X-ray telescopes can search for GECOSAX.
- X-ray signatures are distinct:
  - Direction of the solar core (3').
  - Black-body distributed with $T \simeq 1.1$ keV.
  - Flux variations: annual (Earth-Sun distance) and orbital ($B_\oplus$).
- For $m_a \leq 10^{-4}$ eV, orbital observation of GECOSAX significantly more powerful than current laboratory solar axion experiments.

Unambiguous Discovery:

Viewing the Solar Core in X-rays through the Earth!