Hunting solar axions in low Earth orbit

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based on

H. Davoudiasl and PH, PRL **97**, 141302 (2006).

and arXiv:0804.3543.

Outline

- gecosax
- geometry
- satellite orbits
- geomagnetic field
- earth atmosphere
- typical and optimal orbits
- results
- outlook

Helioscope – CAST

The Cern Axion Solar Telescope

decomissioned LHC test magnet with $L \simeq 9.3\,\mathrm{m}$ and $B \simeq 9.0\,\mathrm{T}$ and an area of $2 \times 14.5\,\mathrm{cm}^2$

$$B^2 L^2 \simeq 7\,000\,\mathrm{T}^2\,\mathrm{m}^2$$

The idea

Geomagnetic conversion of solar axions into x-rays (GECOSAX), is based on the fact that the Earth is a relatively weak but fairly large magnet.

The conversion probability for an axion into a photon depends (in the massless limit) only on $L^2 B^2$.

Assuming an conversion region of 1/10th of an Earth radius, $L \sim 600\,\mathrm{km}$ and a constant perpendicular B-field corresponding to the geomagnetic field at the equator of $B = 3 \times 10^{-5}\,\mathrm{T}$, one obtains

$$B^2 L^2 \simeq 325\,\mathrm{T}^2\,\mathrm{m}^2$$

Comparison with CAST

CAST

$$B^2L^2 \simeq 7\,000\,\mathrm{T}^2\,\mathrm{m}^2 \text{ and } A \simeq 30\,\mathrm{cm}^2$$

GECOSAX

$$B^2L^2 \simeq 325\,\mathrm{T}^2\,\mathrm{m}^2$$

which is about 20 times less than for CAST, but if A is 20 times larger...

Flux estimate

$m_a = 10^{-4}\,\mathrm{eV}$ and $E_a = 4\,\mathrm{keV}$ the oscillation length $L = \pi/q$ is $600\,\mathrm{km}$.

Using $g_{a\gamma} = g_{10}$ we get $p_\gamma \simeq 10^{-18}$.

If we integrate the axions flux from the sun over an energy range from $1 - 10\,\mathrm{keV}$ we obtain $\simeq 4 \times 10^{11}\mathrm{axions\,cm^{-2}\,s^{-1}}$

This yields a x-ray fluence of

$$4 \times 10^{-7}\,\mathrm{photons\,cm^{-2}\,s^{-1}}$$

Taking an observation time of $t = 10^7\,\mathrm{s}$ and collecting area of $A = 10^4\,\mathrm{cm}^2$ we get 10^4 x-ray photons, where the signal is proportional to g_{10}^4.

Solar x-rays

Even the quiet Sun emits large amounts of soft x-rays $(0.5 - 4\,\mathrm{keV})$, typical fluxes are of the order

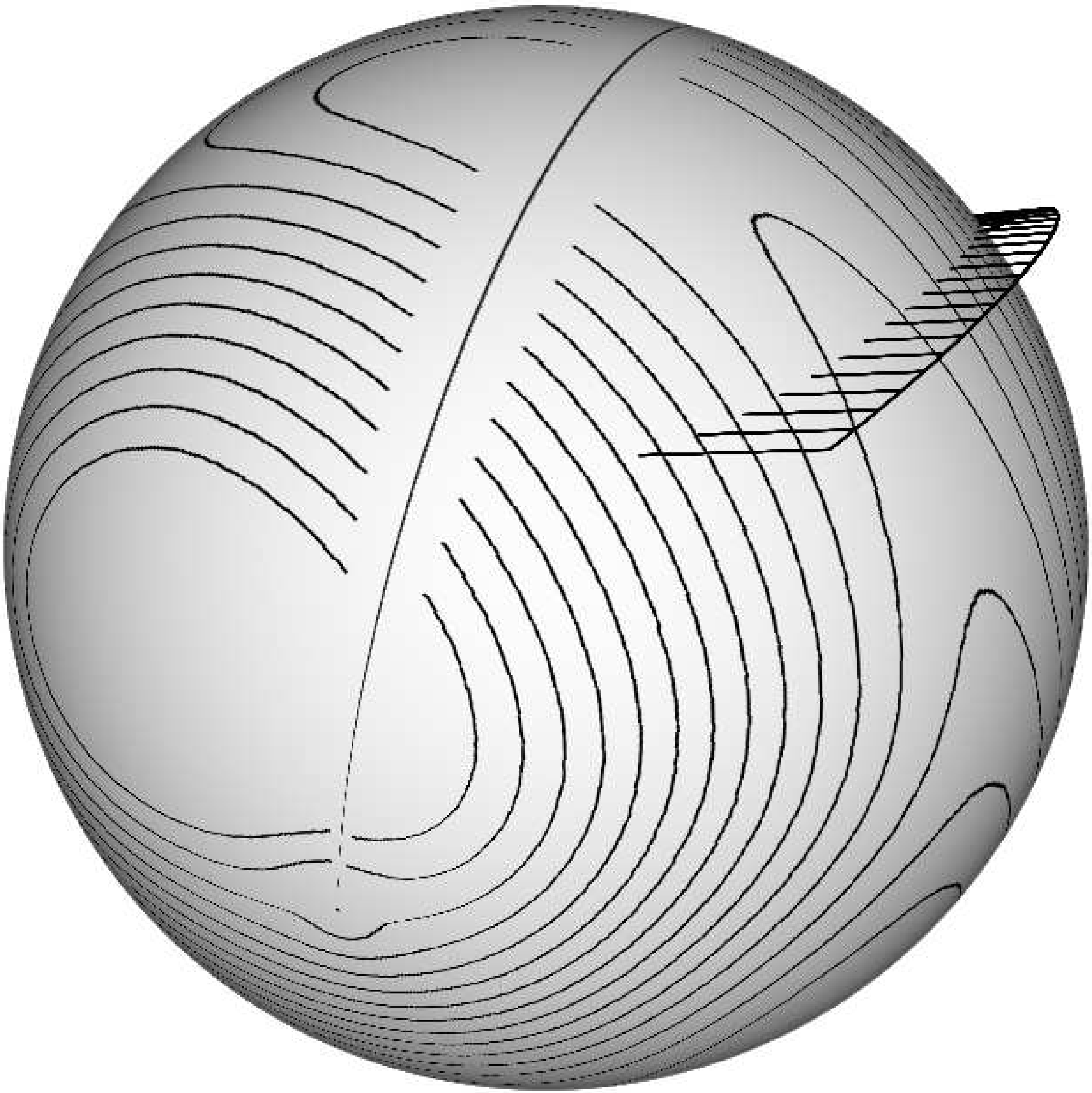
$$10^9 - 10^{10}\,\mathrm{eV\,cm^{-2}\,s^{-1}}$$

yielding a photon flux of approximately $10^6\,\mathrm{photons\,cm^{-2}\,s^{-1}}$, which is about 13 orders of magnitude larger than the GECOSAX signal...

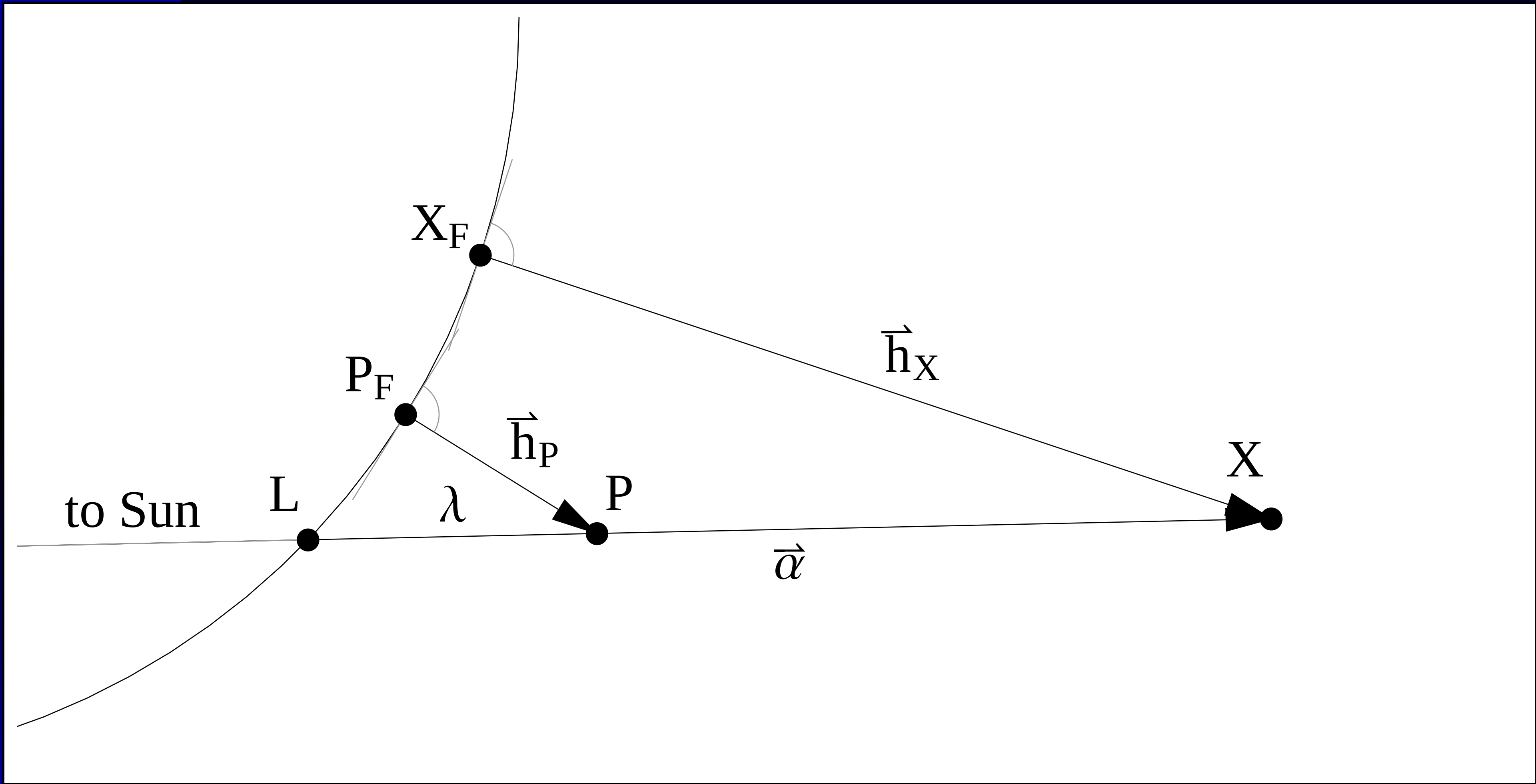
Solar x-rays, continued

However, where there is light, there is shadow (and vice versa)!

The night side of the Earth is not reached by solar x-rays. Solar axions on the other hand can traverse the entire Earth without being absorbed. Therefore, on the night side of the Earth, there is a steady upward going stream of solar axions but no solar x-rays.



Geometry



Note, that the line of sight (LOS) $\vec{\alpha}$ is always longer than the altitude of the satellite $\vec{h}_X$.

Satellite orbits

In order to be able compute the line of sight, we need to know the relative positions of the Earth, the Sun and the satellite. All of those can be obtained from classical Newtonian mechanics, but a simplified two body treatment of the satellite-Earth system is not sufficient:

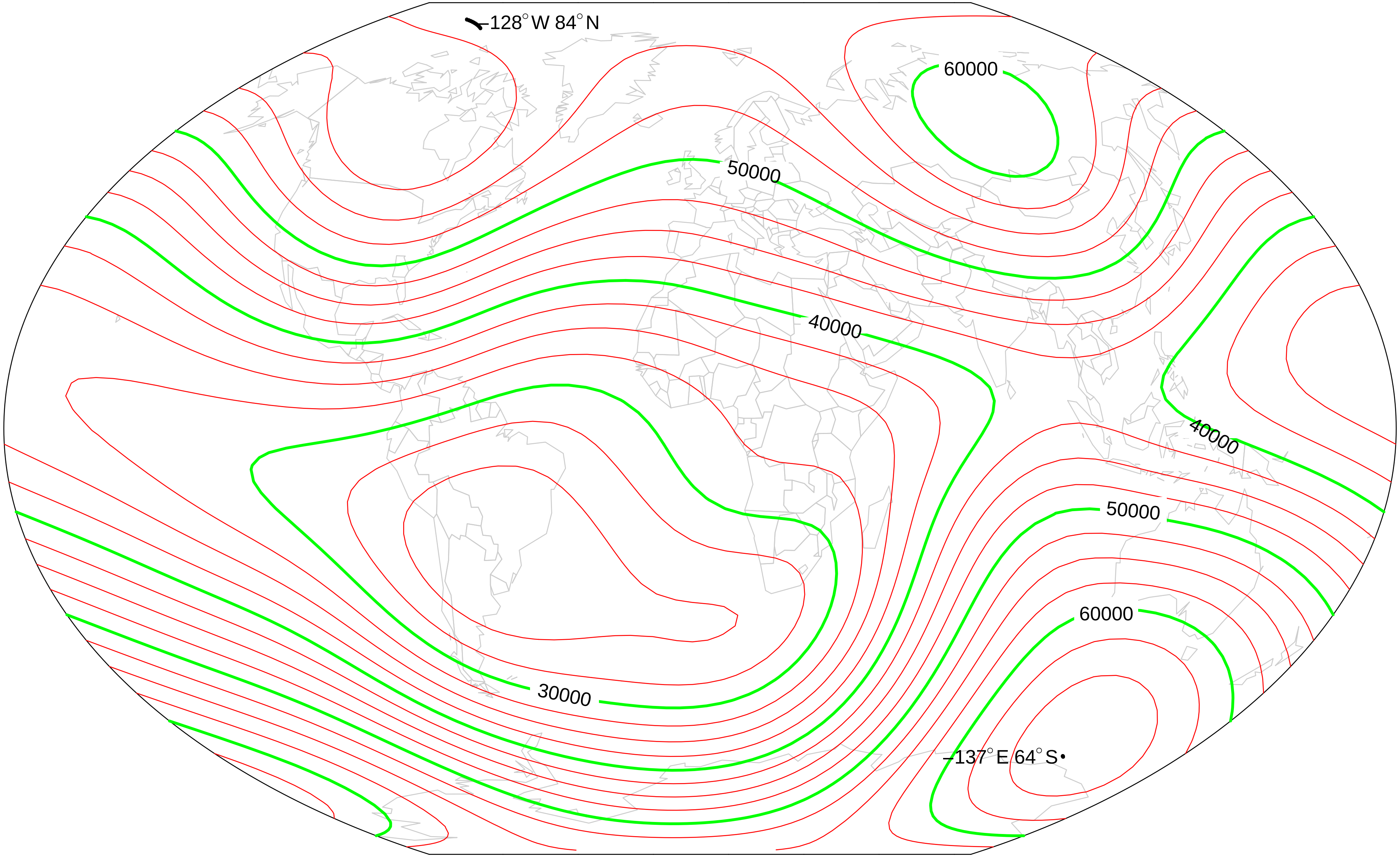
- influence of the moon and sun is non-negligible.
- in a low Earth orbit drag from the atmosphere
- Earth’s gravitational field is not spherical symmetric

Geomagnetic field

The geomagnetic field is only approximately a dipole and the geographic and magnetic poles do not coincide. Spatial variation can be few 10%. Also, there secular variations at the level of a few 100 nT.

However, there is general (military) need for an accurate magnetic model. A consortium of the United States National Geospatial-Intelligence Agency (NGA), the U.S. National Geophysical Data Center (NGDC) and the British Geological Survey (BGS) produces such a model every 5 years. We use the World Magnetic Model (WMM) 2005.

Geomagnetic field



X-rays in air

Refraction

$$m_\gamma = 0.64 \left(\frac{\rho}{\mathrm{kg\,m^{-3}}} \right)^{1/2}$$

Absorption

$$T = \exp\left(-\rho\mu x\right)$$

with μ being the mass absorption coefficient, which is energy dependent. At $4\,\mathrm{keV}$, $\mu \simeq 8\,\mathrm{kg\,m^2}$, which yields a mean free path at sea level ($\rho = 1.2\,\mathrm{kg\,m^{-3}}$) of about $0.1\,\mathrm{m}$.

Density variations

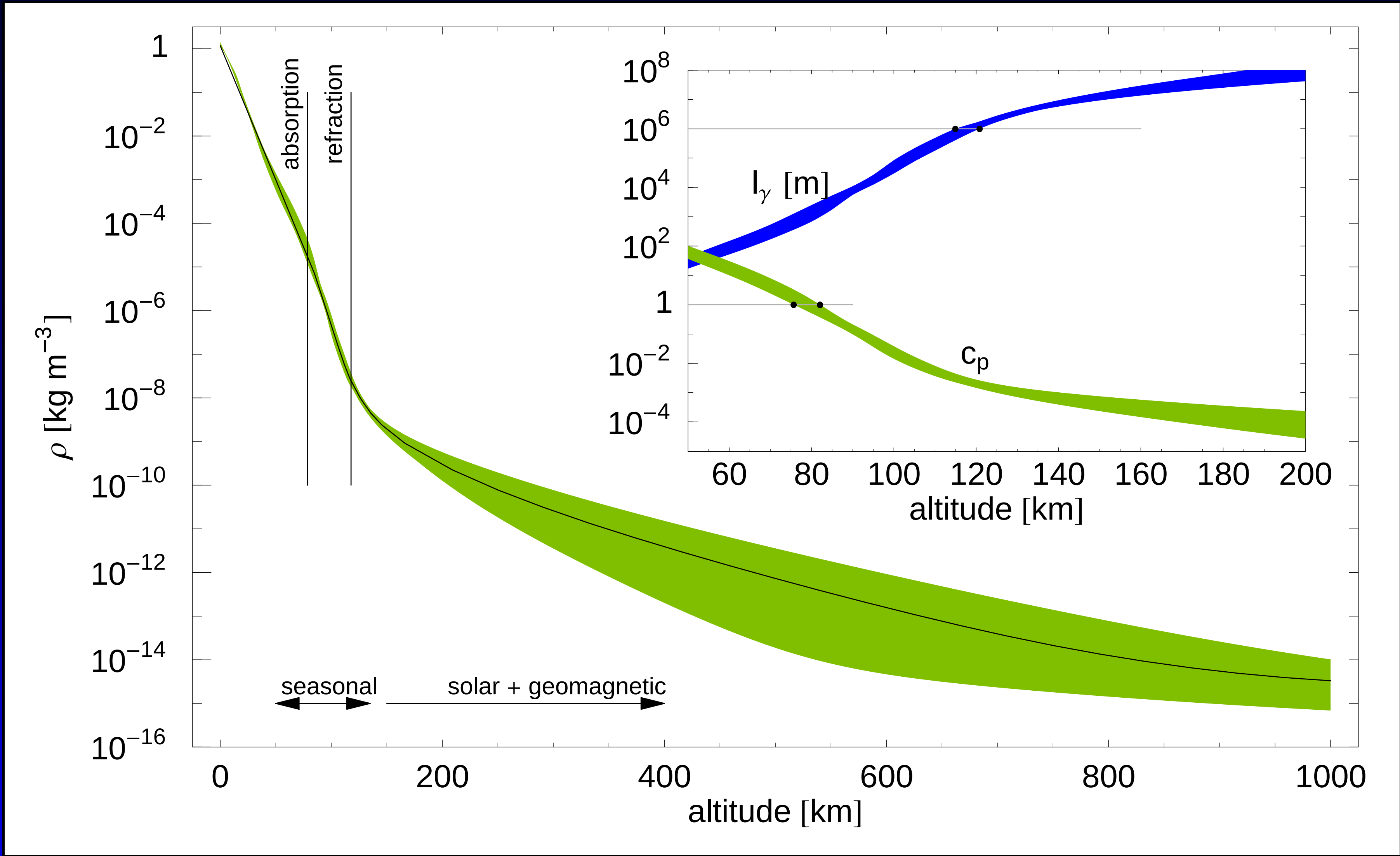
In order to estimate the impact of density variations on the axion conversion probability we define:

- $\eta_{\rm esc}$, which is that altitude at which the probability for a 4keV x-ray to escape to infinity reaches $1/e$
- η_γ, which is that altitude at which the oscillation length to due the finite photon mass becomes $1000\,\mathrm{km}$.

Varying the inputs to the atmospheric model over one full year and the whole Earth, and taking the extremes for $F_{10.5}$ and A_p we find that:

$$\eta_{\rm esc} = 78^{+4}_{-3}\,\mathrm{km} \qquad \eta_\gamma = 118 \pm 3\,\mathrm{km}$$

X-rays in the atmosphere



Signal computation

In computing the signal flux we use

- axion flux from current solar standard model
- WMM 2005 for the magnetic field
- x-ray absorption and refraction in a standardized, average atmosphere
- NORAD orbits
- proper ephemeris for the sun and the Earth

to compute the path dependence of B, m_γ, Γ for a given time t. In the next time step the satellite has moved, a new path has to be found and the new dependence of B, m_γ, Γ.

Observation modes

Fixed mode

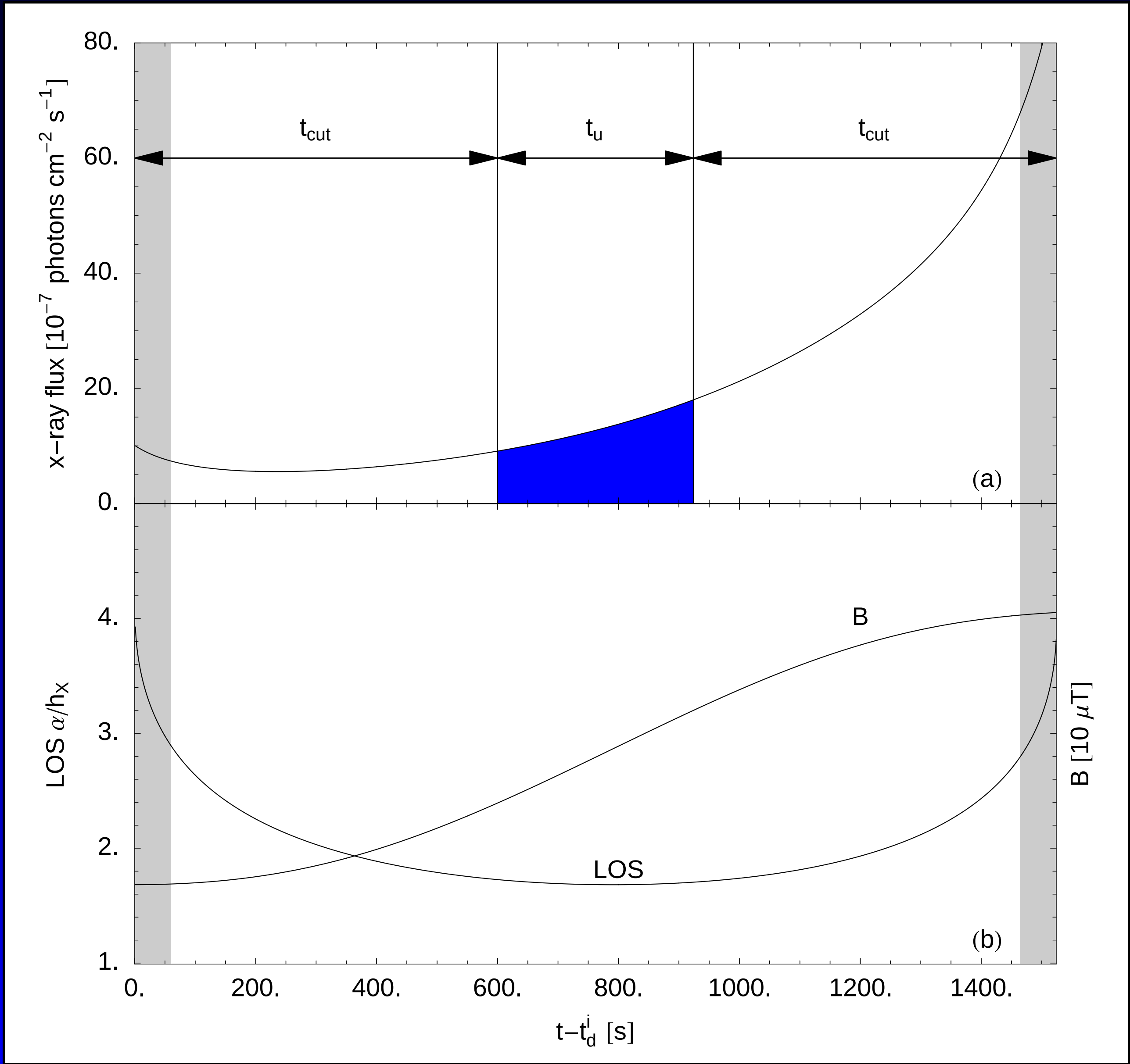
Some x-ray detectors can withstand direct solar radiation and hence need not be turned away. Since the all uncertainties tend to accumulate at the entry and exit point in/from Earth shadow we discard the first and last 1 minute.

Observation modes, continued

Turning mode

Many sensitive x-ray detectors must not be pointed towards the sun since this would lead to severe damage. They can start turning towards the sun only once they are in the Earth shadow and have to turn away before the leave the Earth shadow, the time in the shadow is determined by the orbit. Given typical slew rate of $6^\circ, \mathrm{minute}^{-1}$ and sun avoidance angles of 30°, the first and last 5 minutes of each dark orbit are unusable. To allow for some safety margin, we cut the first and last 10 minutes.

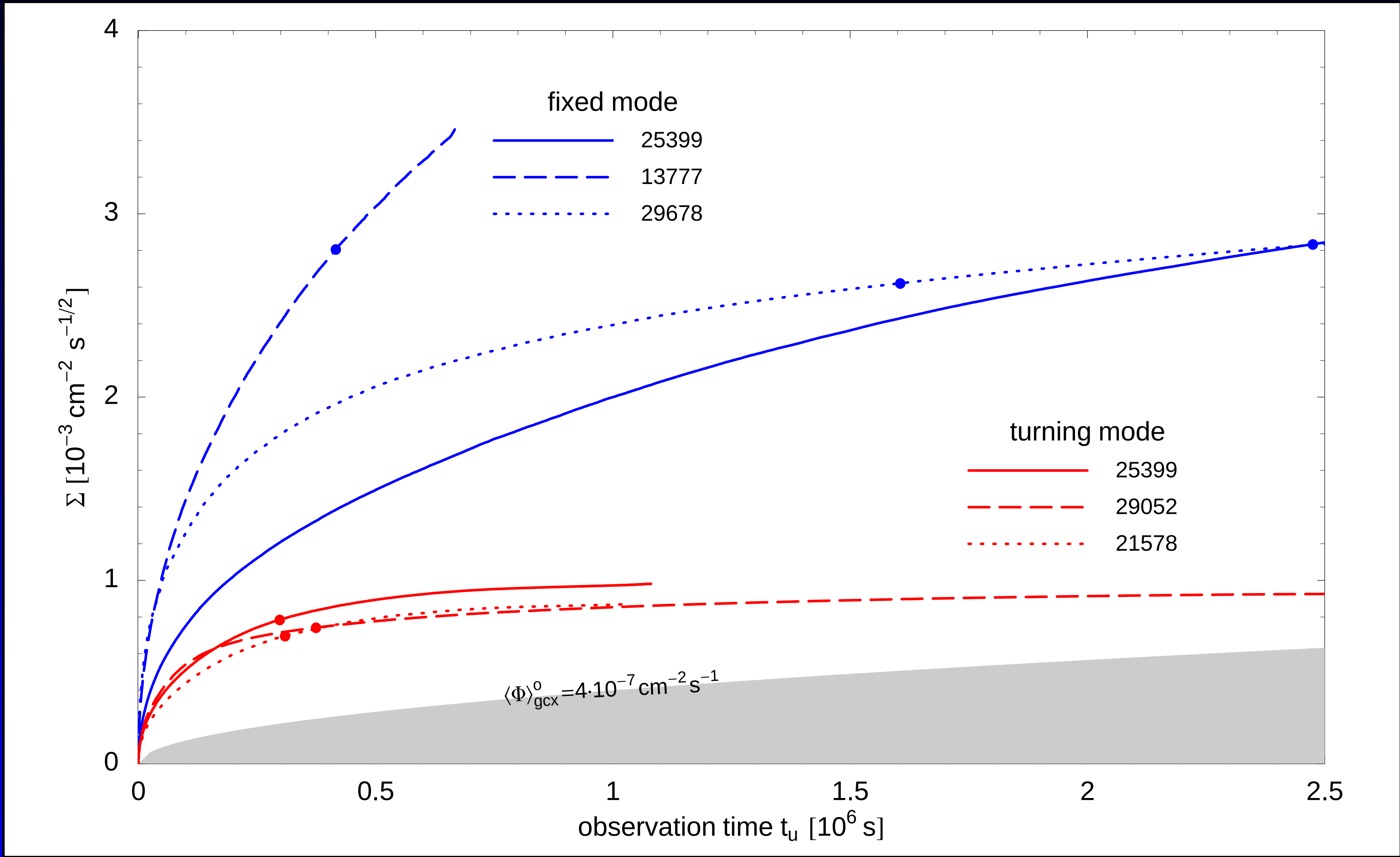
Typical orbit



Optimal orbits

Naively, one would like to have orbits which have long duration dark orbits with a long LOS and a high magnetic field. Since, there will be some background, we want to optimize $s/\sqrt{b}$.
Instead of designing an optimal orbit, we took the orbits of 50 currently operating scientific satellites with apogees below $1\,000\,\mathrm{km}$ and computed the axion flux for each dark orbit in 1 whole year. Then we sorted these orbits in descending order of their $s/\sqrt{b}$ values and use the first I orbits to compute the total significance or sensitivity.

Optimal orbits



X-ray satellites

- Collecting areas range from a few $100\mathrm{cm}^2$ up to a $50\,000\,\mathrm{cm}^2$
- Altitudes range from several $100\,\mathrm{km}$ up to several $10\,000\,\mathrm{km}$
- Background rates from $(8-4000)\cdot 10^{-6}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$
- Imaging vs non-imaging detectors

Combining these factors, we find values for Q in the range $300-80\,000\,\mathrm{cm}^2\,\mathrm{s}^{1/2}$.

Suzaku

Suzaku (formerly know as ASTRO-EII) was launched in 2005 into a low Earth orbit with altitudes $250 - 560\,\mathrm{km}$. The main instrument is the X-ray Imaging Spectrometer with an effective total area of $\sim 300\,\mathrm{cm}^2$. Its maximum slew rate is $6^\circ\,\mathrm{min}^{-1}$. SUZAKU has a measured background rate while observing the dark Earth of $7.6 \cdot 10^{-6}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$.

Sensitivity

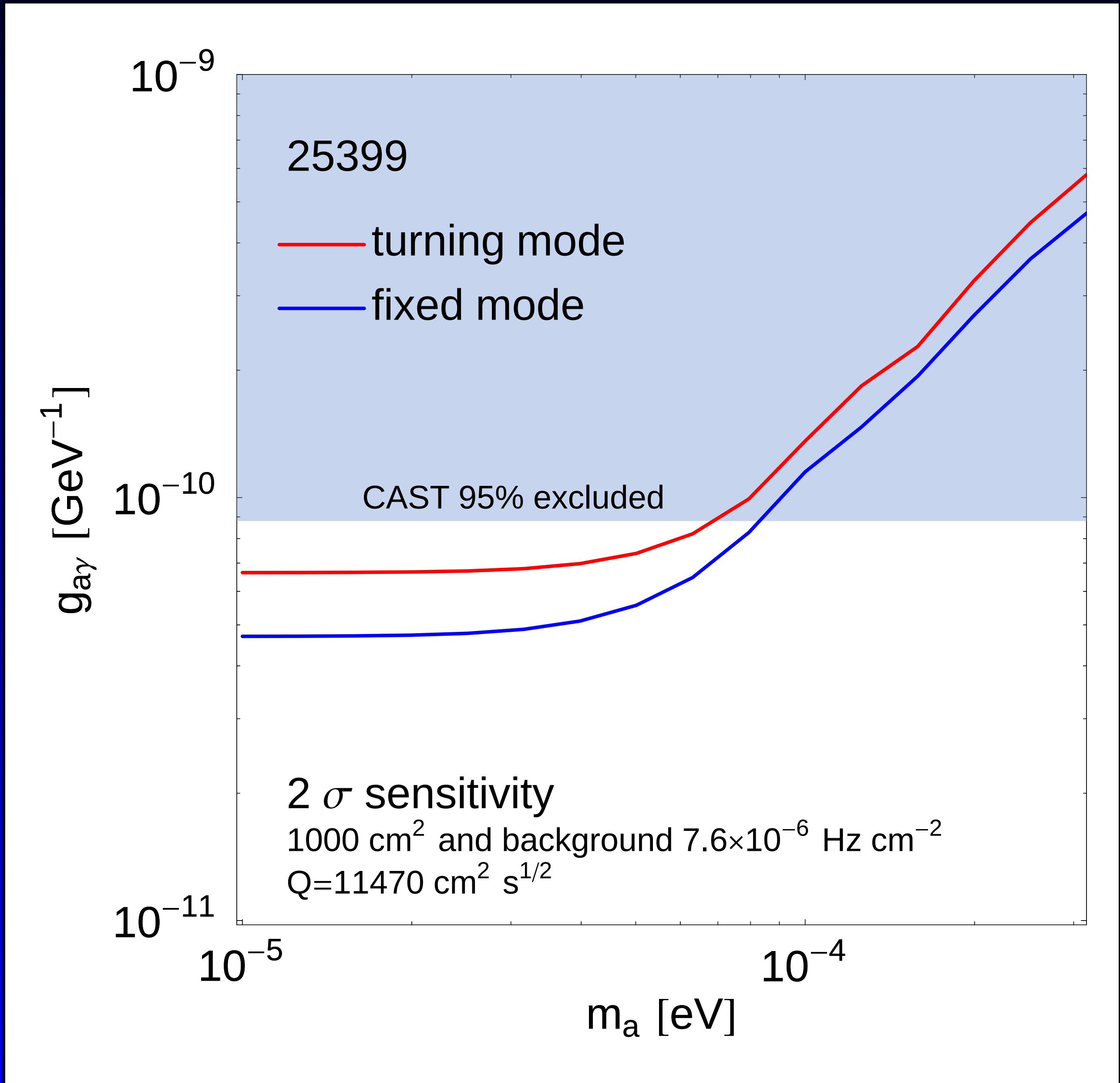
The obtainable $N\,\sigma$ CL bound on $g_{a\gamma}$ is approximately given by

$$\left(\frac{g_{a\gamma}}{10^{-10}\mathrm{GeV}^{-1}}\right) = \left(\frac{\Sigma Q}{N}\right)^{-1/4} \,.$$

A full binned likelihood analysis yields a 5-10% better limit. Taking the extreme values for $\Sigma = 0.0035\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1/2}$ and $Q = 80\,000\,\mathrm{cm}^{2}\,\mathrm{s}^{1/2}$ we get at $2\,\sigma$

$$g_{a\gamma} < 2.9 \cdot 10^{-11}\,\mathrm{GeV}^{-1}$$

Comparison with CAST



Outlook

- the web and google are very powerful tools
- gecosax can work in practice – requires the right satellite
- the flux calculation presented is accurate to 10-20%
- a possible signal would have very distinct features