Detecting solar axions with x-ray satellites

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based on

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

JIGSAW07

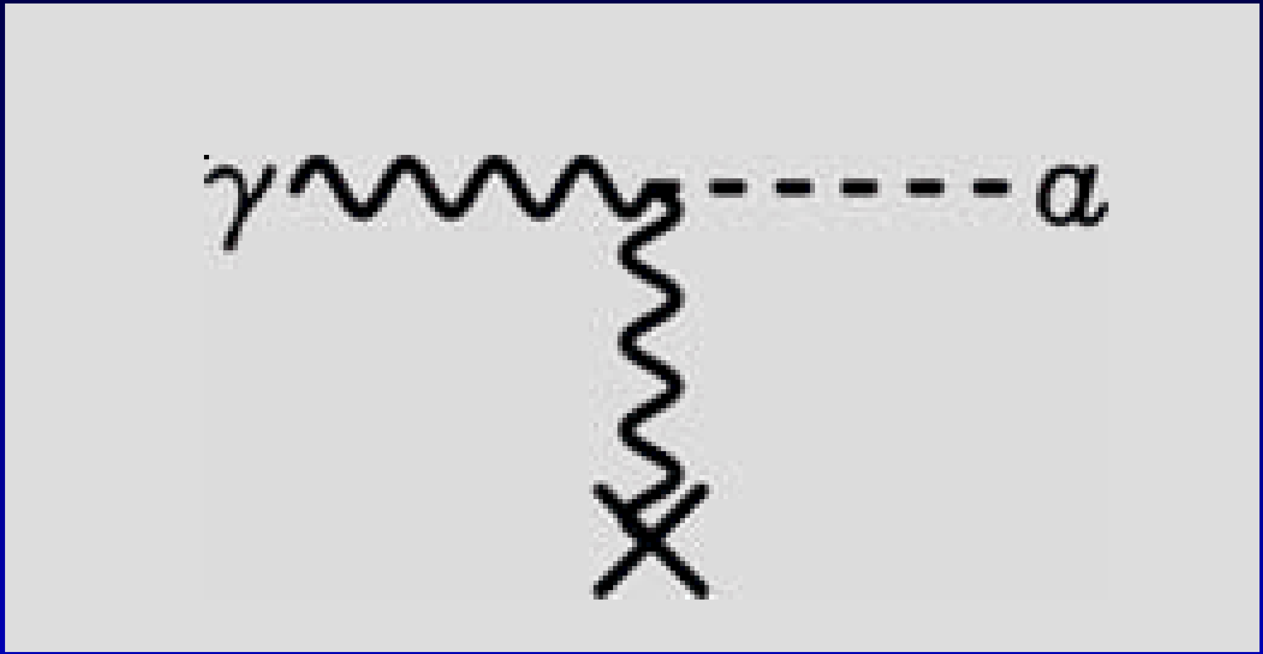
TIFR, Mumbai

Outline

- solar axions
- gecosax
  - flux estimate
  - feasibility
- results
- conclusion

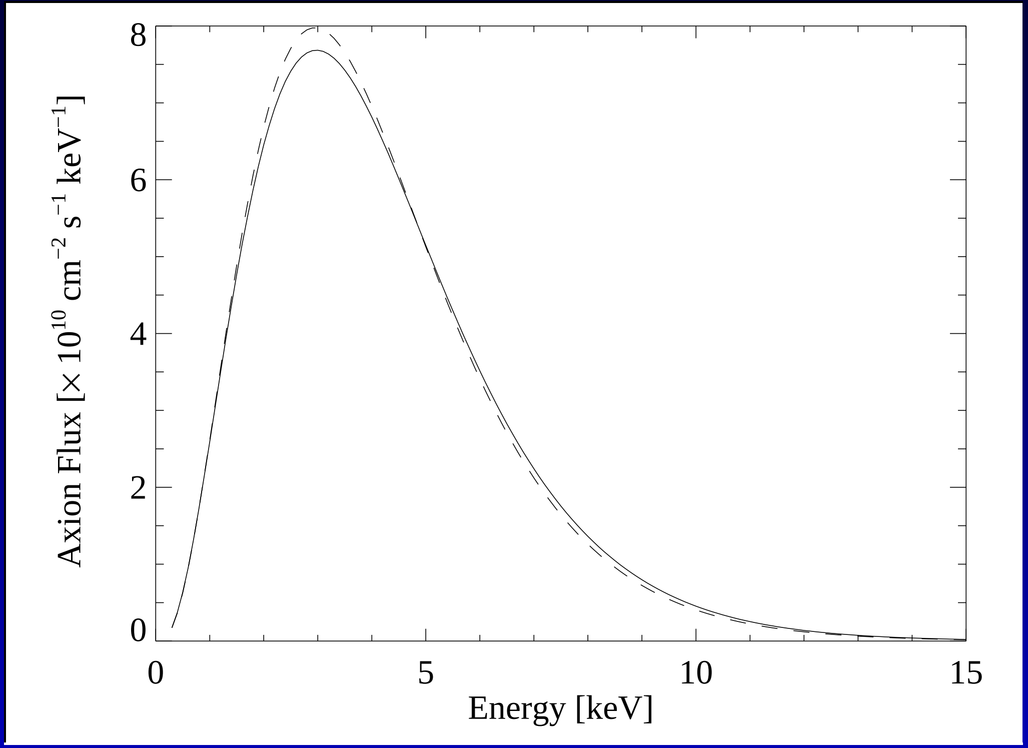
Photon-axion coupling

A pseudo-scalar can couple to photons via $g_{a\gamma}$. With this coupling one can write down the following vertex



Solar axions

Primakoff production in a plasma.



$$\frac{d\Phi}{dE} = 6.02 \times 10^{10}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}\,\mathrm{keV}^{-1} g_{10}^2 E^{2.481} \exp(-E/1.205)$$

where $g_{10} := g_{a\gamma}/(10^{-10}\mathrm{GeV}^{-1})$

CAST collaboration, hep-ex/0702006v2

Photon-axion mixing

In an external transverse magnetic field photons and axion mix, leading to photon-axion oscillations. The probability in a constant field is given by

$$p_\gamma = \frac{1}{2} g_{a\gamma}^2 B^2 \frac{1 - \cos qL}{q^2}$$

where

$$q = \frac{|m_\gamma^2 - m_a^2|}{2\omega_a}$$

In the limit $q \rightarrow 0$ we obtain

$$p_\gamma = \frac{1}{4} g_{a\gamma}^2 B^2 L^2$$

P. Sikivie, PRL **51** (1983) 1415 [Erratum-ibid. **52** (1984) 695].

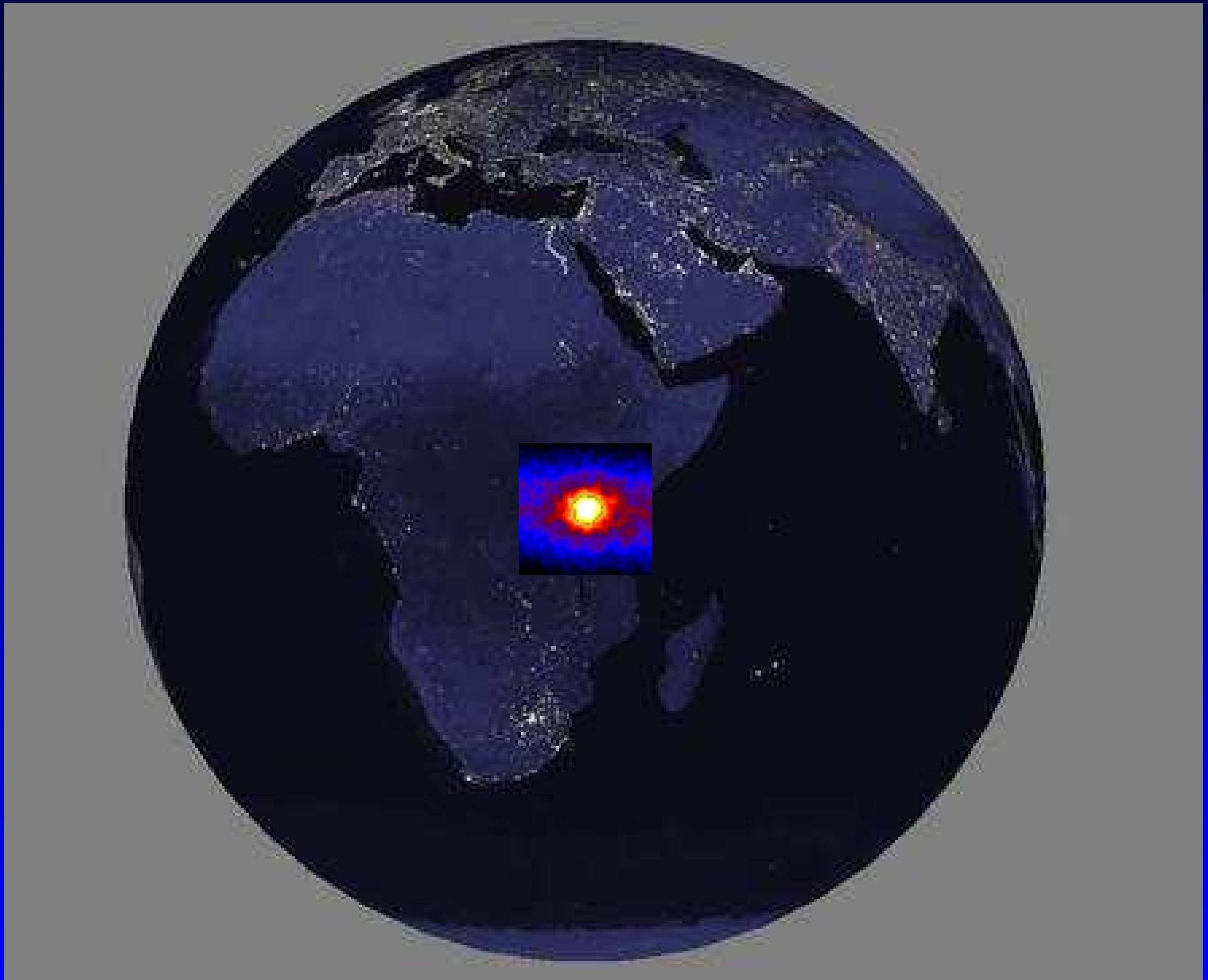
Helioscope – CAST

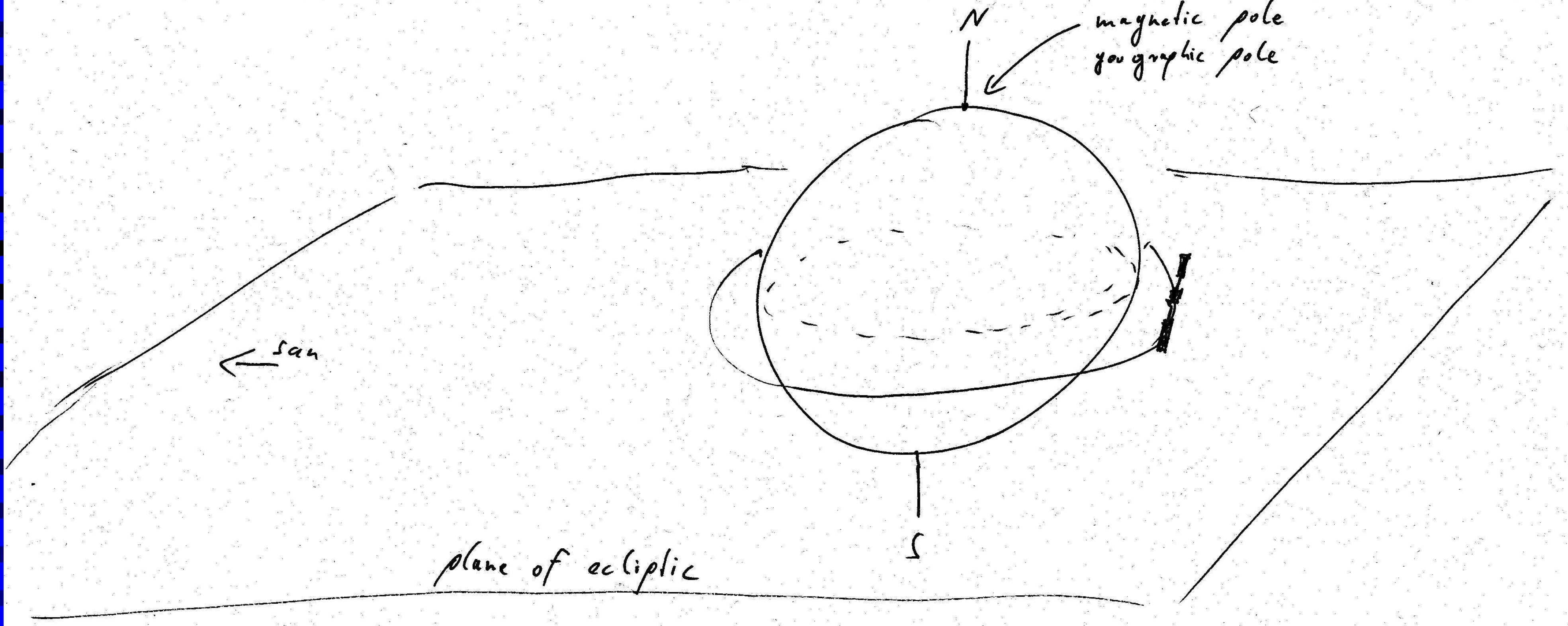
The Cern Axion Solar Telescope

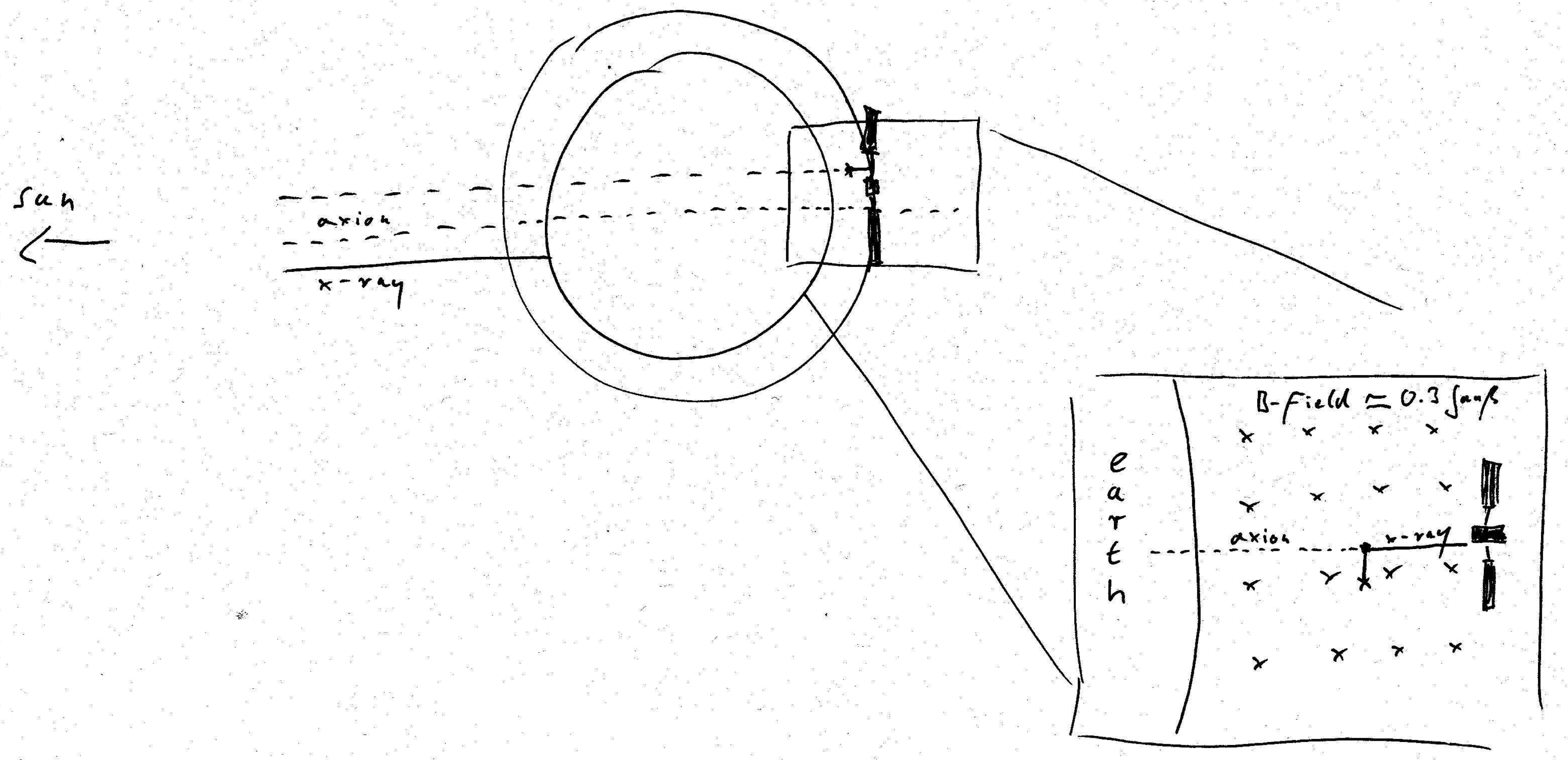
decomissioned LHC test magnet with $L = 9.26\,\mathrm{m}$ and $B = 9.0\,\mathrm{T}$ and an area of $2 \times 14.5\,\mathrm{cm}^2$

$$B^2 L^2 = 6946\,\mathrm{T}^2\,\mathrm{m}^2$$

geomagnetic conversion of solar axions into x-rays
GECOSAX




N
magnetic pole
geographic pole
sun
S
plane of ecliptic


sun
axion
x-ray
B-field ≃ 0.3 gauß
e a r t h
axion
x-ray

Comparison with CAST

CAST

$$B^2L^2 = 6946\,\mathrm{T}^2\,\mathrm{m}^2 \text{ and } A = 29\,\mathrm{cm}^2$$

GECOSAX
$B = 3 \times 10^{-5}\,\mathrm{T}$ and $L = 600\,\mathrm{km}$

$$B^2L^2 = 324\,\mathrm{T}^2\,\mathrm{m}^2$$

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

Flux estimate

$m_a = 10^{-4}$ 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. The signal is proportional to g_{10}^4.

X-ray satellites

- Collecting areas range from a few cm^2 up to a few $1000\,\mathrm{cm}^2$
- Altitudes range from several $100\,\mathrm{km}$ up to several $10\,000\,\mathrm{km}$
- Imaging vs non-imaging detectors
- Slew rate – how fast can they turn

A sensitive x-ray detector 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.

RXTE

The Rossi X-ray Timing Explorer was launched in 1995 into a low earth orbit with an average altitude of $600\,\mathrm{km}$. The main instrument is the proportional counter array with an effective total area of $7\,000\,\mathrm{cm}^2$. Its maximum slew rate is $6^\circ\,\mathrm{min}^{-1}$.

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 $6^\circ\,\mathrm{min}^{-1}$.

Objections

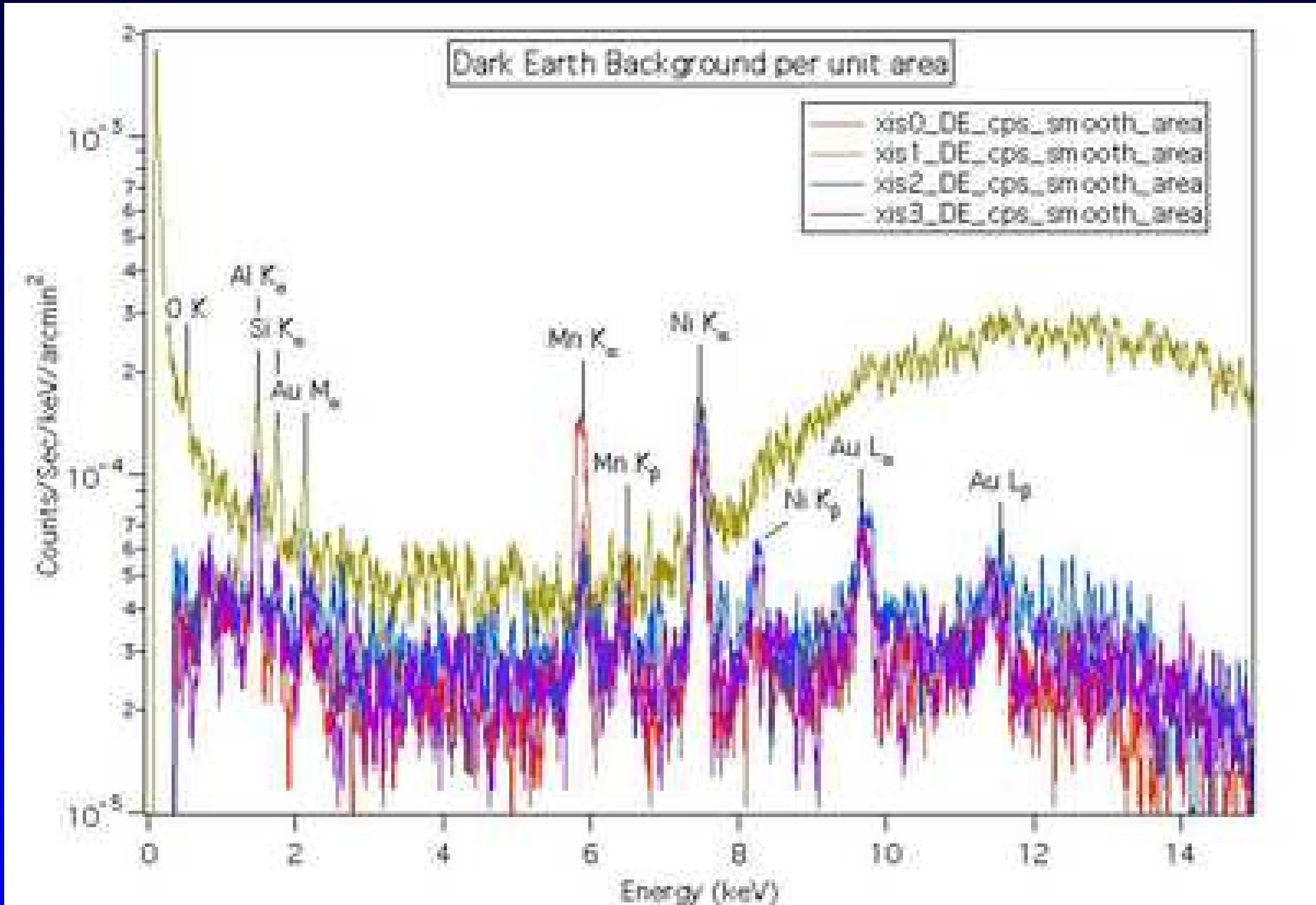
- x-ray backgrounds from the
  - Sun
  - Atmosphere
  - detector
- geomagnetic field is not a dipole (and not constant)
- effects of the atmosphere on x-ray propagation (absorption & refraction)
- …

Equally important:

proper geometry!

Suzaku data

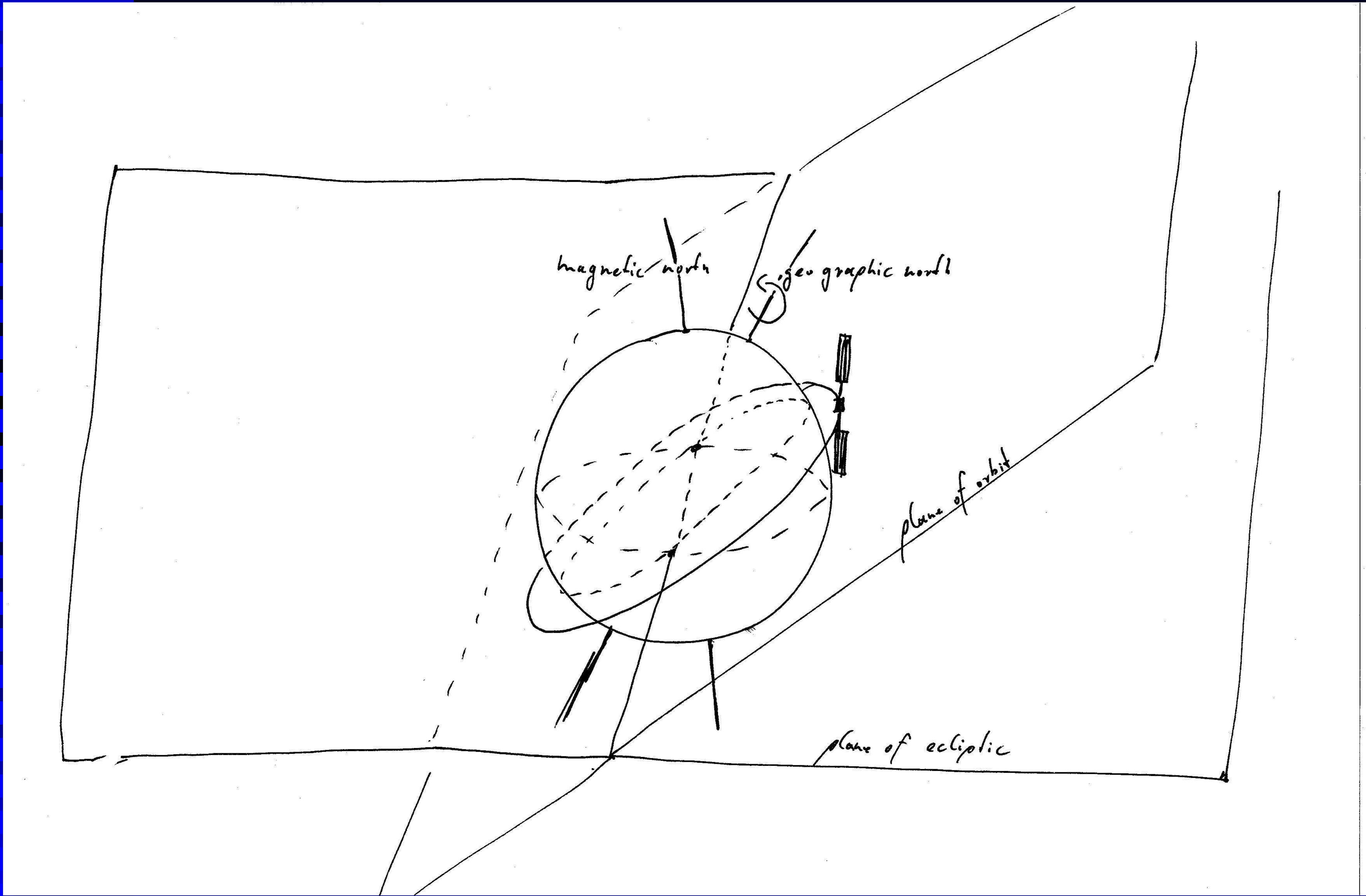
Actual data observing the dark earth



courtesy the Suzaku Team

Observation strategy

- enter earth shadow
- turn towards the sun
- observe
  - non-imaging – point on target for signal, point off target for background
  - imaging – use on-target pixels for signal, off-target pixels for background
- turn away from the sun
- exit earth shadow


magnetic north
geographic north
plane of orbit
plane of ecliptic

Satellite orbits

In principle a satellite's orbit is given by a solution to the Kepler problem. In reality, however,

- 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

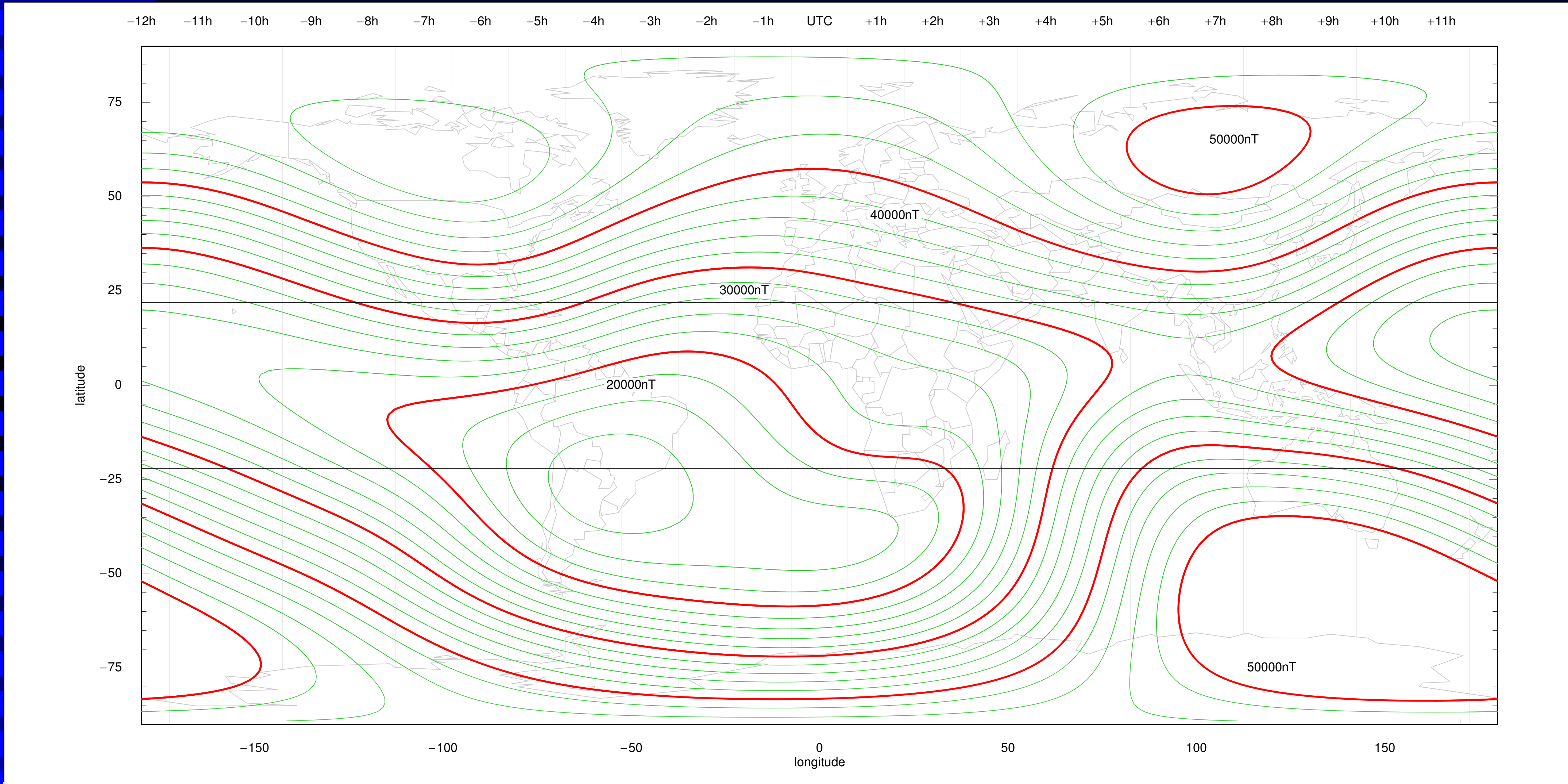
There is a specialized perturbation theory calculation parameterizing these effects and fitting the orbit with pseudo-Keplerian elements. We use the SGP4 orbit propagator and the orbital data provided by NORAD. This allows to predict the position with an accuracy of $\mathcal{O}(100\,\mathrm{m})$.

Geomagnetic field

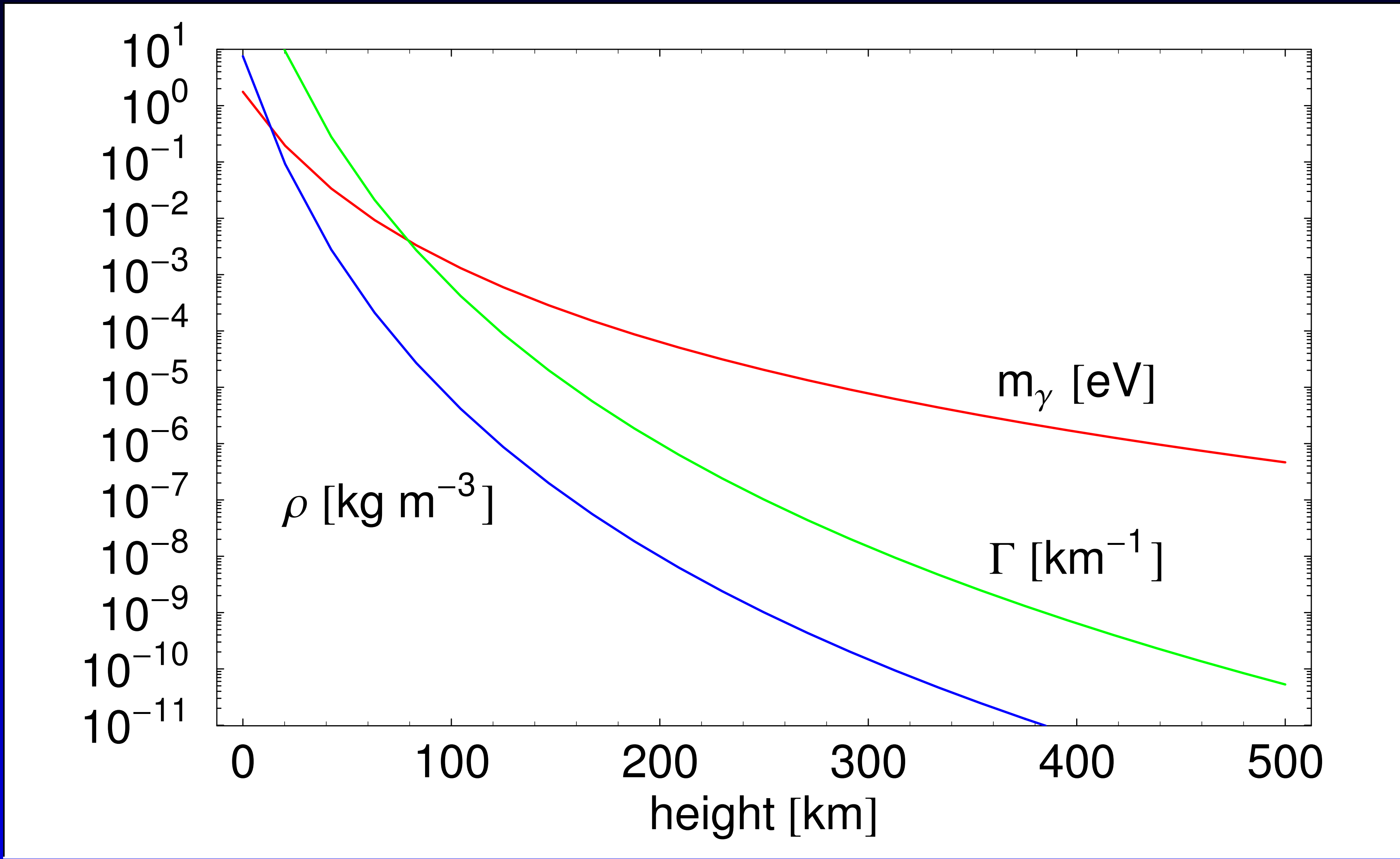
The geomagnetic field is only approximately a dipole and the geographic and magnetic poles do not coincide. Spatial variation can be few 10%. Also, there secular variations at the level of a few 100 nT.

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.
This model is accurate to better than 1%.

Geomagnetic field



X-rays in the atmosphere



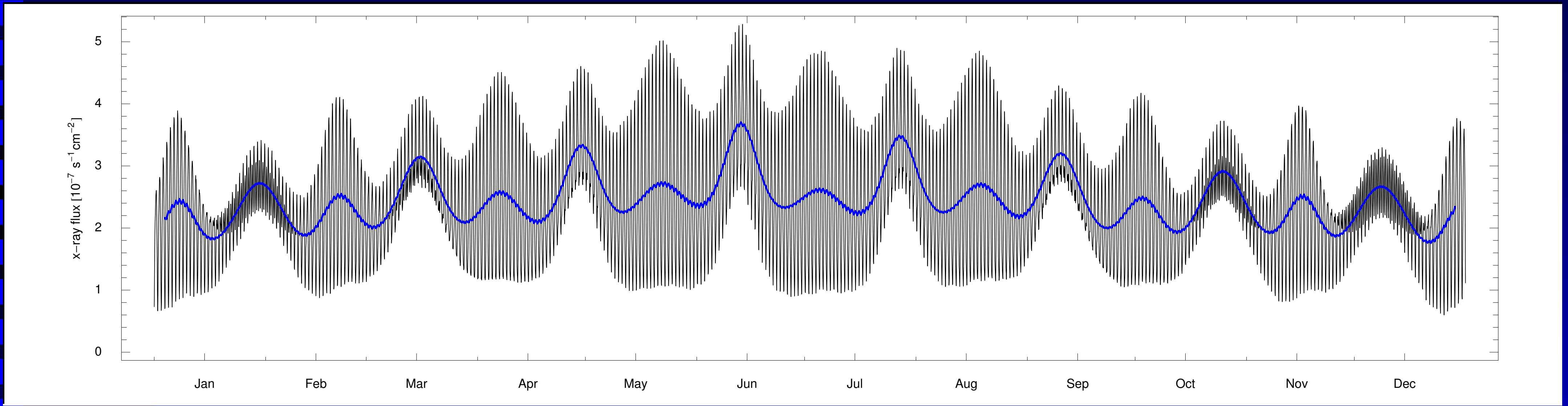
Signal computation

In computing the signal flux we use

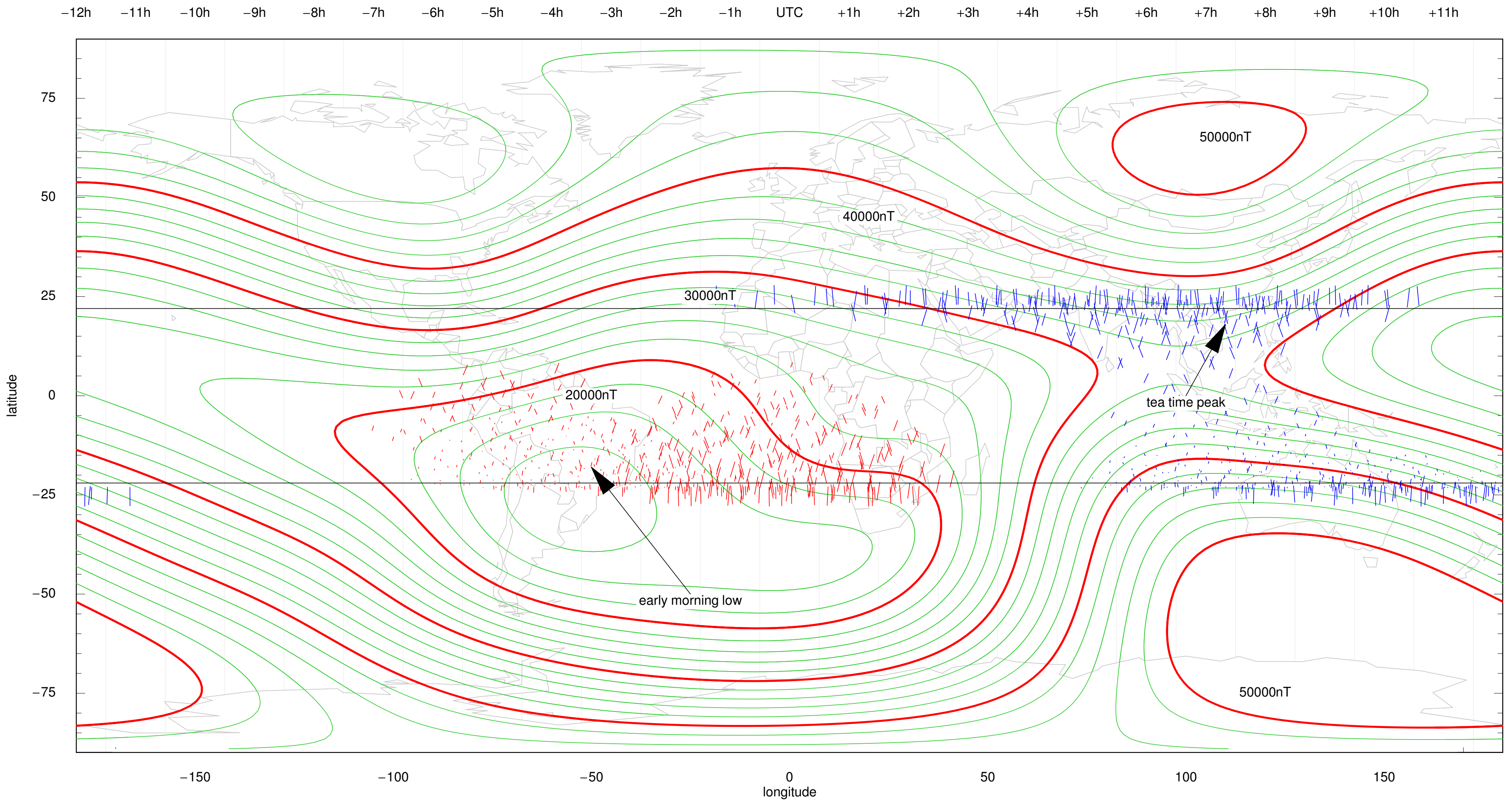
- axion flux from current solar standard model
- WMM 2005 for the magnetic field
- x-ray absorption and refraction in a standardized, average atmosphere
- NORAD orbits
- proper ephemerides for the sun and the earth

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.

Fluxes throughout the year



The world



−12h
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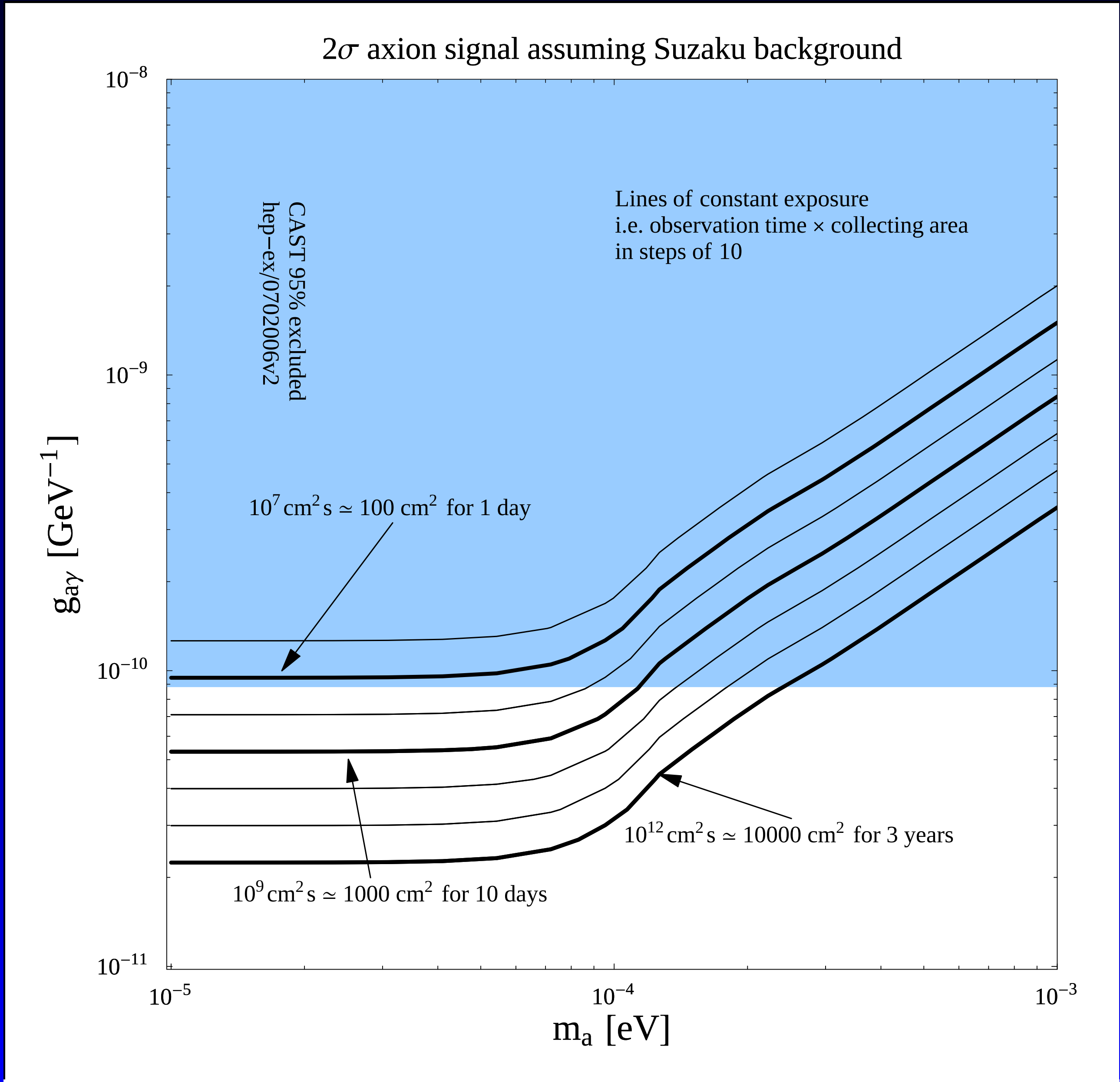
+3h
+4h
+5h
+6h
+7h
+8h
+9h
+10h
+11h
75
50
25
0
−25
−50
−75
latitude
−150
−100
−50
0
50
100
150
longitude
50000nT
40000nT
30000nT
20000nT
tea time peak
early morning low
50000nT

Comparison with CAST



Conclusion

- the web and google are very powerful tools
- axions are theoretically well motivated
- gecosax can work in practice – requires the right satellite
- a possible signal would have very distinct features

Midnight Sun