NuSTAR solar observations and implications for axions and ALPs

Axions in the Universe and the IAXO experiment Workshop

INFN Frascati, Italy,
April 18-19, 2016

Julia Vogel (LLNL)
for the NuSTAR solar axion team

LLNL-PRES-689538
This work was performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under contract DE-AC52-07NA27344. Lawrence Livermore National Security, LLC

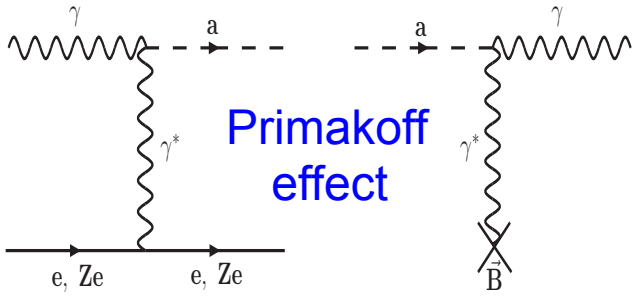
Lawrence Livermore National Laboratory

Axions in a nutshell

What are axions?

- Fundamental particles
- Proposed to solve strong CP-problem (Peccei & Quinn, 1977)
- Dark matter by definition

Class of particles:
Axions (also referred to as QCD axions)
& Axion-like particles (ALPs or non-QCD axions)



Most important axion feature

- Generic coupling to two photons
- Mass unknown $m_a \propto g_{a\gamma}$,

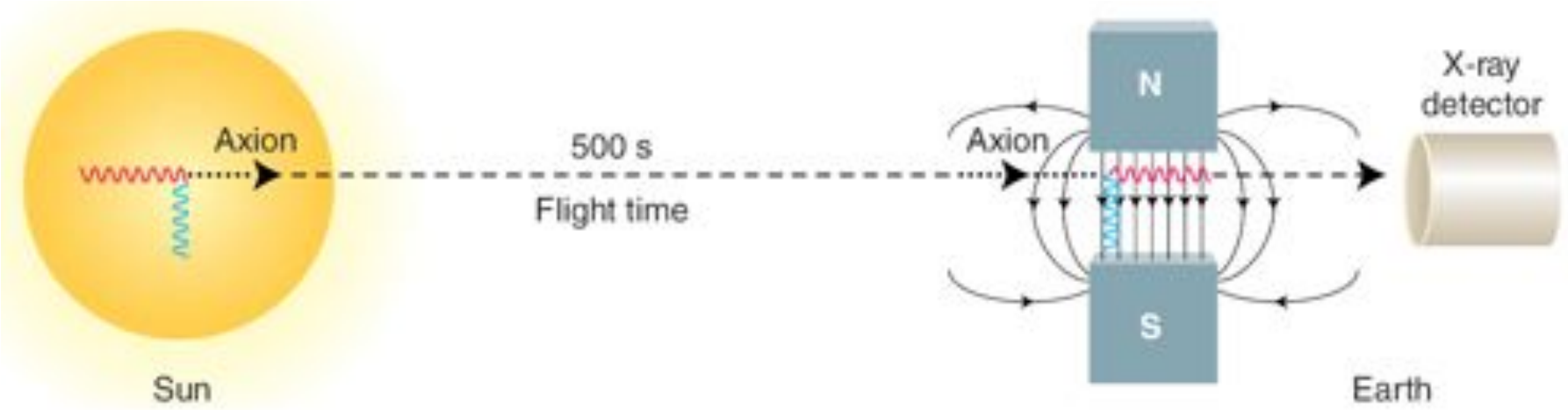
Three birds with one stone:
Strong CP-problem
& dark matter + Sun

Axion production and detection

- First axion helioscope proposed by P. Sikivie

Sikivie *PRL* 51:1415 (1983)

  - Blackbody photons (keV) in solar core can be converted into axions in the presence of strong electromagentic fields in the plasma
  - Reconversions of axions into x-ray photons possible in strong laboratory magnetic field

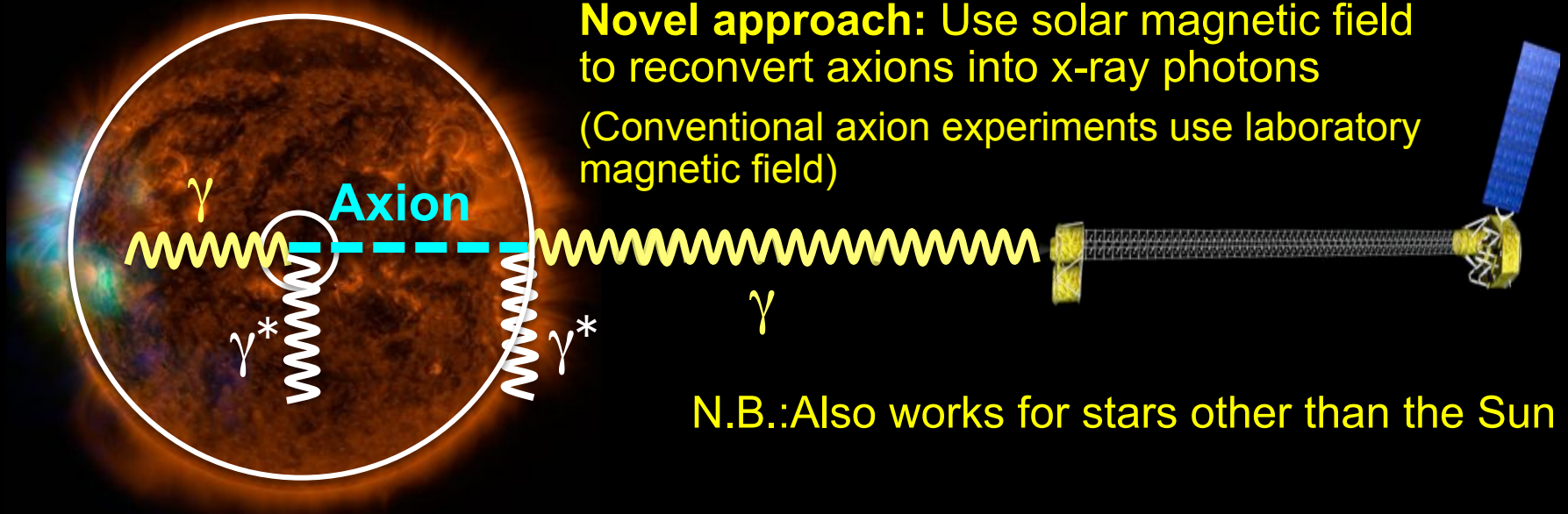


- Idea refined by K. van Bibber by using buffer gas to restore coherence over long magnetic field

Van Bibber et al. *Phys.Rev. D* 39:2089 (1989)

NuSTAR solar observations

- **Search for axions from the solar core using NuSTAR**



Novel approach: Use solar magnetic field to reconvert axions into x-ray photons

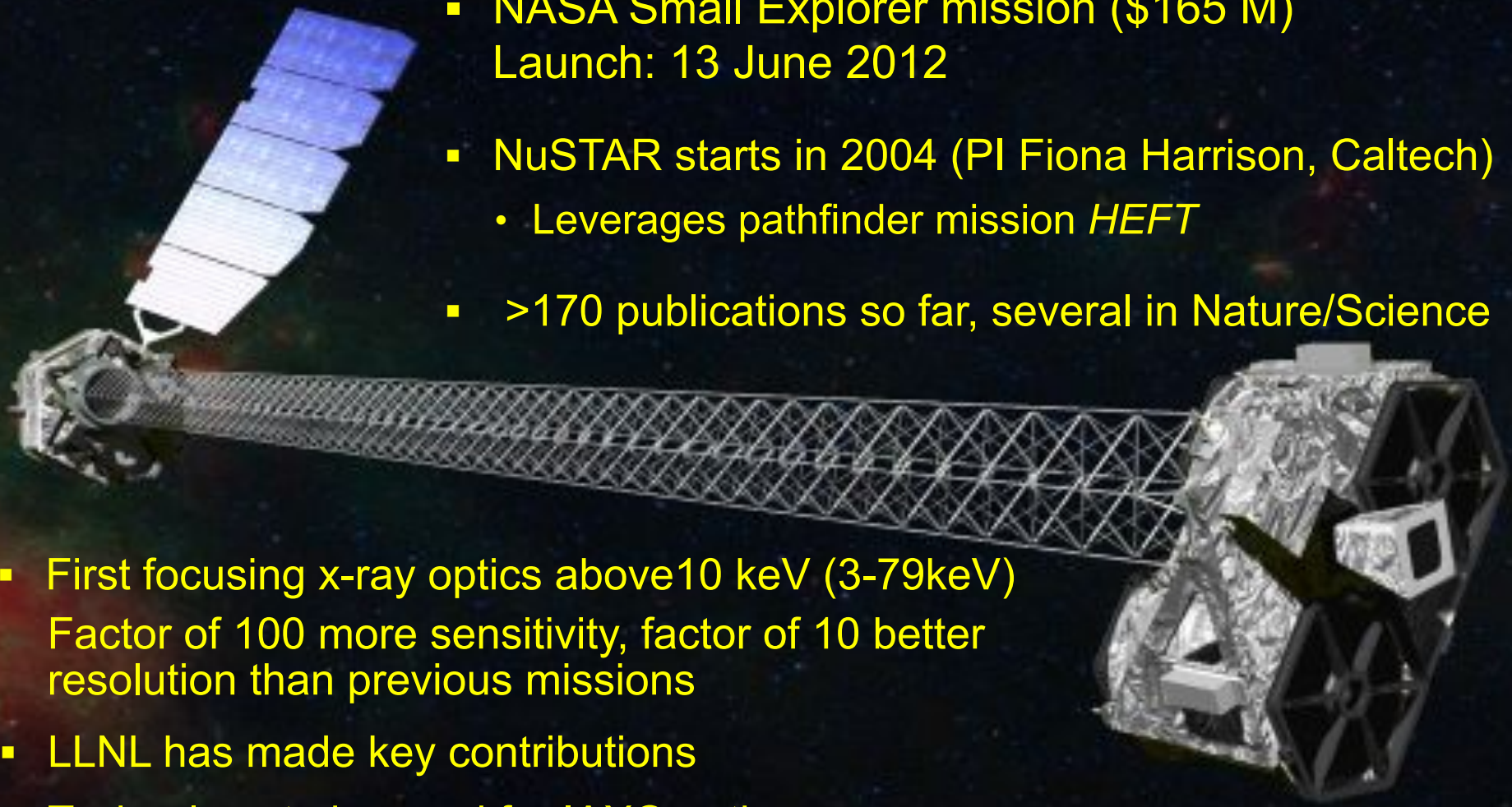
(Conventional axion experiments use laboratory magnetic field)

N.B.:Also works for stars other than the Sun

- **Why should we do this?**
  - Might find dark matter, but even in absence of signal: new stringent axion limits!
  - NuSTAR can explore significant regions of viable parameter space NOW, while conventional searches will get there in the coming decades
  - NuSTAR is complementary to traditional searches and providing first look

Nuclear Spectroscopic Telescope Array (NuSTAR)

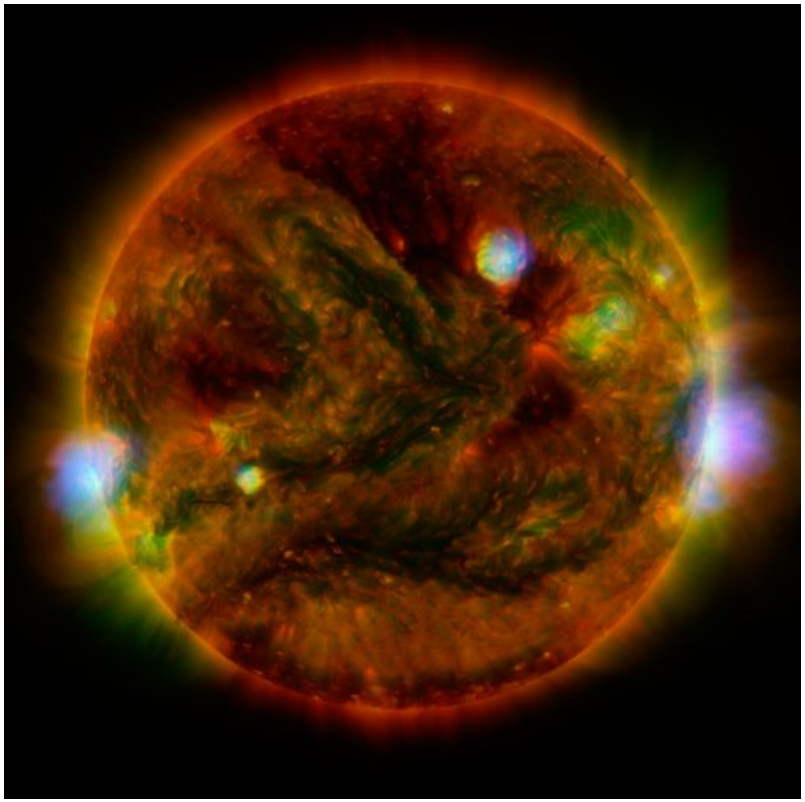
- NASA Small Explorer mission ($165 M)
  Launch: 13 June 2012
- NuSTAR starts in 2004 (PI Fiona Harrison, Caltech)
  - Leverages pathfinder mission *HEFT*
- >170 publications so far, several in Nature/Science



- First focusing x-ray optics above10 keV (3-79keV)
  Factor of 100 more sensitivity, factor of 10 better resolution than previous missions
- LLNL has made key contributions
- Technology to be used for IAXO optics

Axions/ALPs with NuSTAR

- NuSTAR ideal mission for axions:
  - Large efficiency
  - Instrument is able to look at the Sun
- Solar observations (and neutron star) observations are part of NuSTAR‘s science observation plan
  - Several solar pointings completed
- Data for these objects is acquired to conduct standard science
- We can use the same data to search for axions!

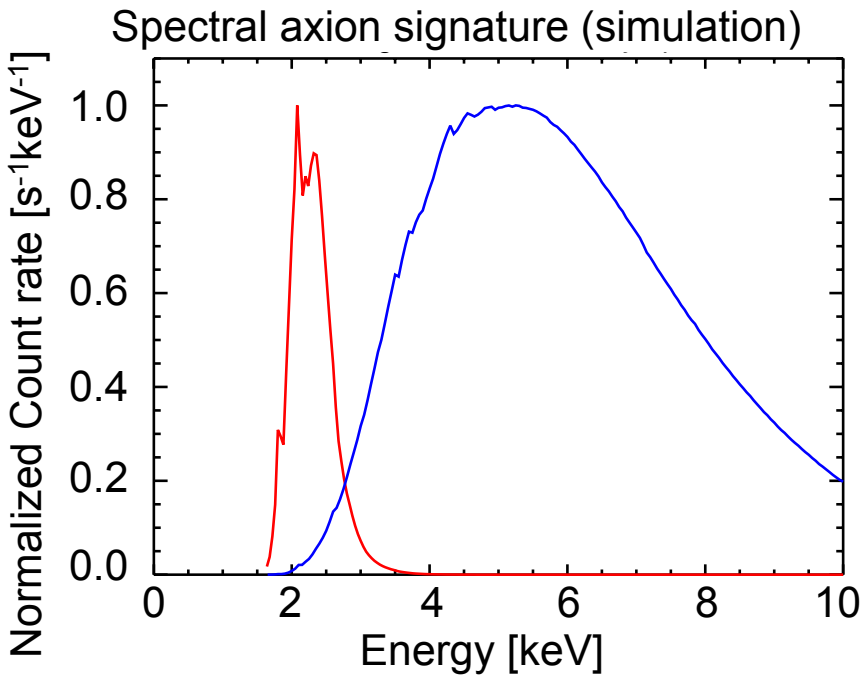


→ **Careful background selection needed**

→ **Use temporal/spatial/spectral axion signature**

Solar axion signatures for satellite searches

- Novel, satellite-based approach to solar axion searches making use of reconversion of low-mass axions in solar photosphere (no magnetic field near detector)
  - High sensitivity to low masses
  - Well-defined axion signature in X-rays: temporal, spatial, spectral
  - Main source of solar background expected to be thermal in nature (mostly T<0.5 keV) apart from flare periods
- Main challenges:
  - Solar density profile and magnetic field strength not precisely known, but valid approximations can be made and will fully suffice
  - Need quite Sun (minimize ghost-rays)



Signal would be first CDM signature ever!

Analysis steps

- **Operations**

Consultating in target selection during future solar observing sessions assuring data are acquired in axion-sensitive conditions.

- **NuSTAR Data reduction**

Different solar data sets need to be preprocessed using the NuSTAR pipeline plus additional corrections

- **Solar ancillary data collection**

Relevant solar observations (sunspots, bright points and ephemeral active regions, signatures of the network, etc.) will be organized for correlation with the *NuSTAR* spatial and temporal signal distributions.

- **Exploitation of signatures**

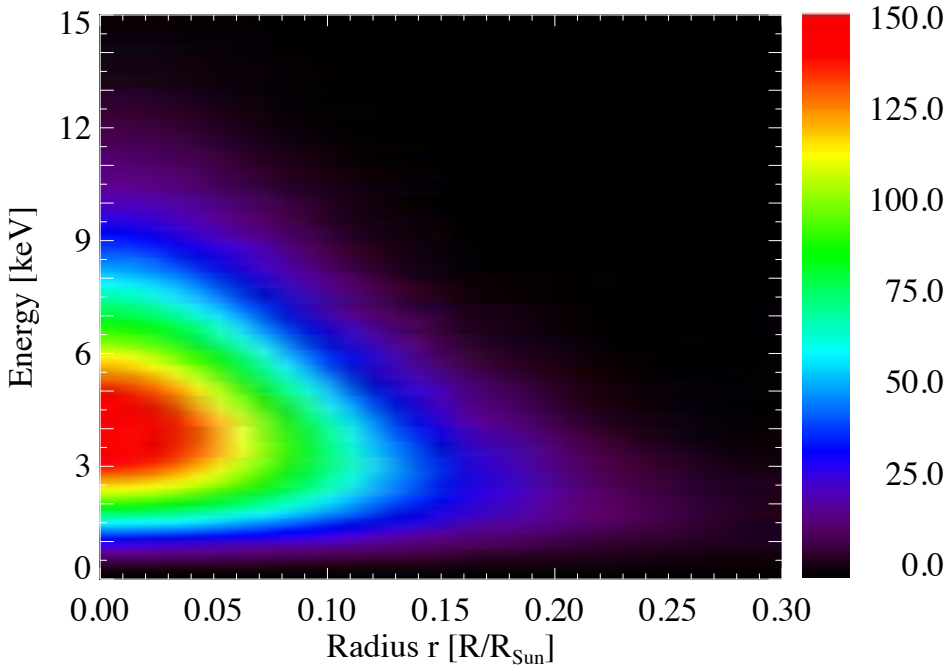
The *NuSTAR* observations will be screened against the solar ancillary data via spectral, spatial, and temporal signatures to optimize the axion detection.

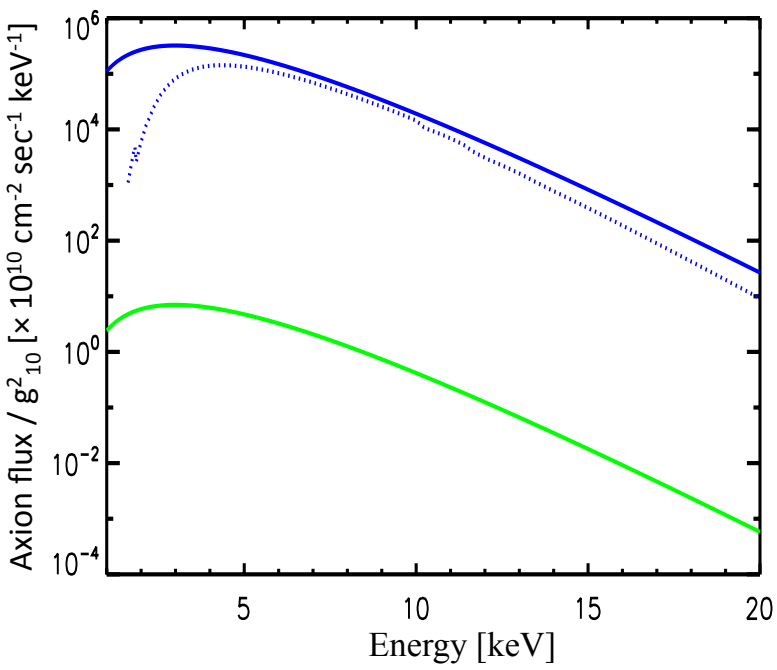
- **Analysis and interpretation**

Computing definitive upper limits on fluxes or coupling constants for any axion component in case no signal above background is observed and interpreting results in the context of current and new models and potential implications for solar physics.

Where we gain in satellite mission searches…

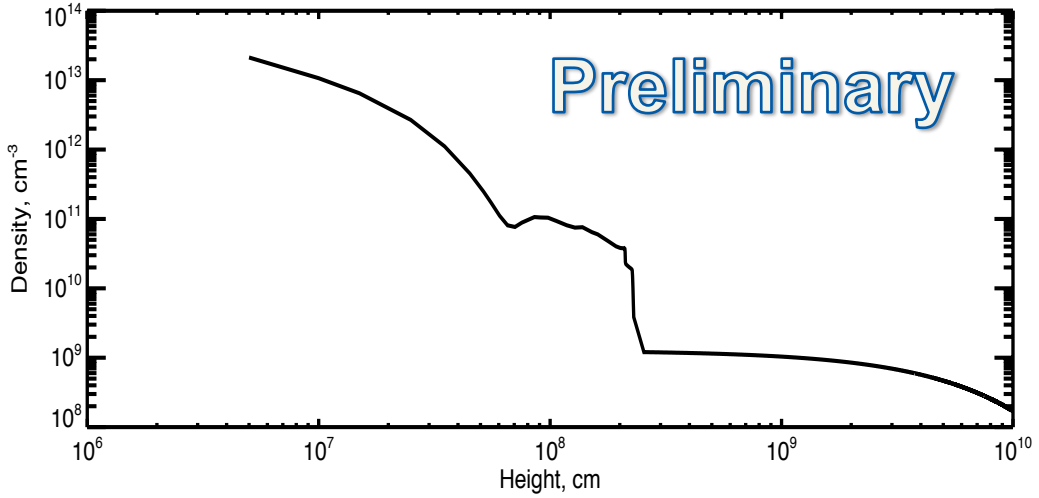
- Flux larger due to smaller distance from axion origin
- NuSTAR has sensitivity below 5 keV

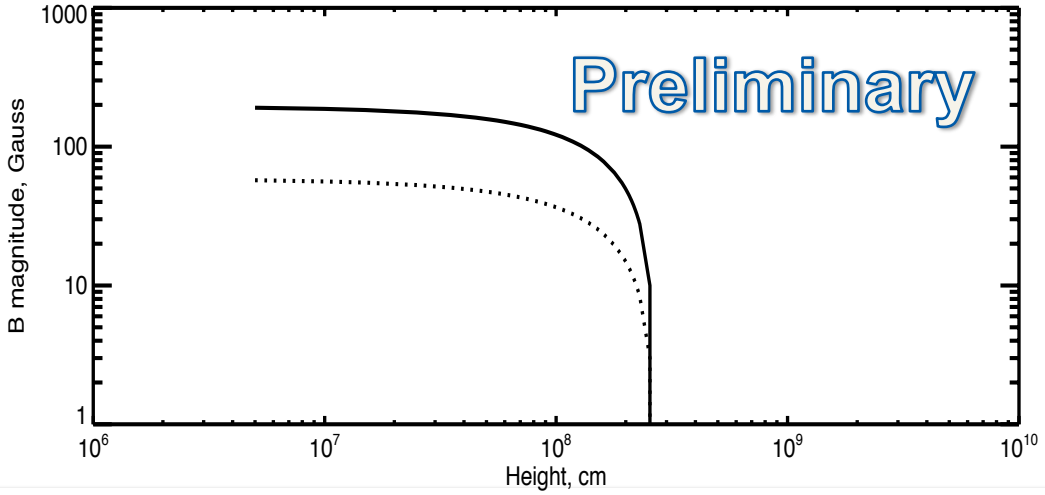




The general challenges…

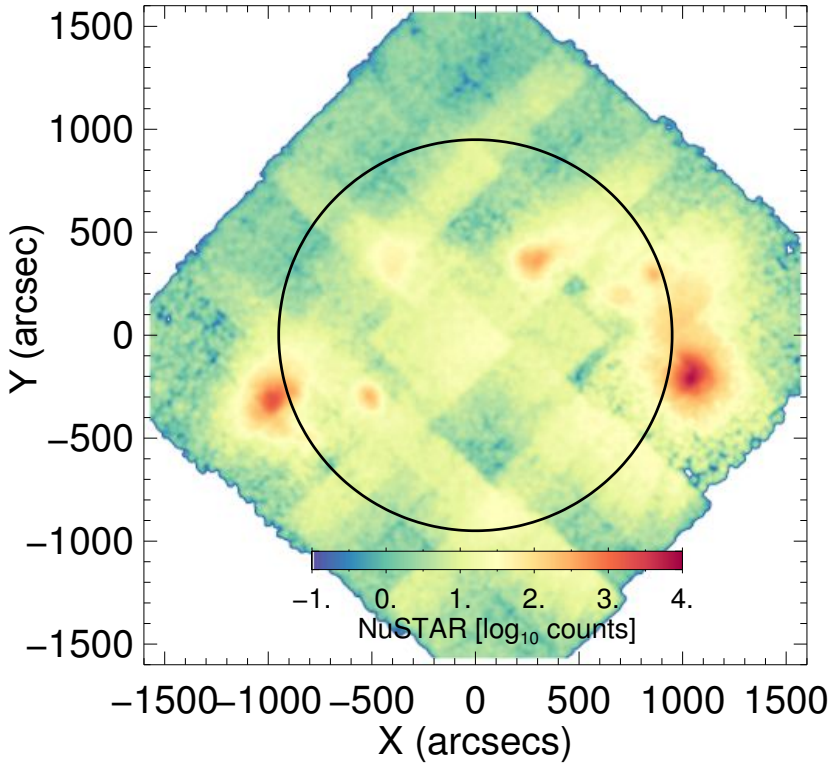
- B-field smaller than laboratory fields such as CAST/IAXO on Earth
- Significant uncertainties in solar magnetic field, density and extension
- Length of magnetic field exceeds the laboratory ones by far





First NuSTAR solar data

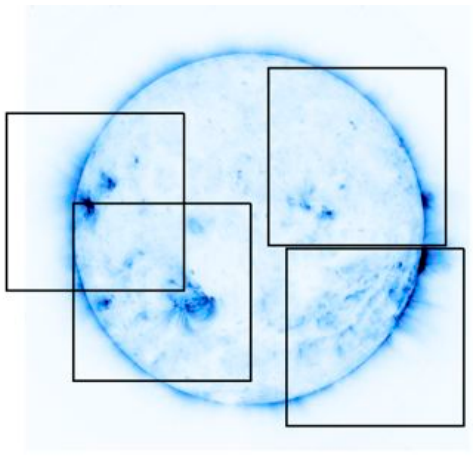
- First *NuSTAR* solar observations (Sept/Nov/Dec 2014, Apr/Sept 2015, more in 2016) confirm the capability of the instrument to observe the Sun.
- Some of currently available NuSTAR solar data include solar disk center
- Solar conditions were not optimal (high magnetic activity → elevated dead times + single-reflection "ghost ray" interference)
- Now working on using existing data to obtain preliminary estimates and to optimize a future, dedicated observing session
- Anticipation to have appropriate conditions (not necessarily true sunspot minimum, but generally minimal activity levels) starting in 2016
- Plan is to establish initial limits based on the test data, but any detection of an axion signal is unlikely at this early stage.



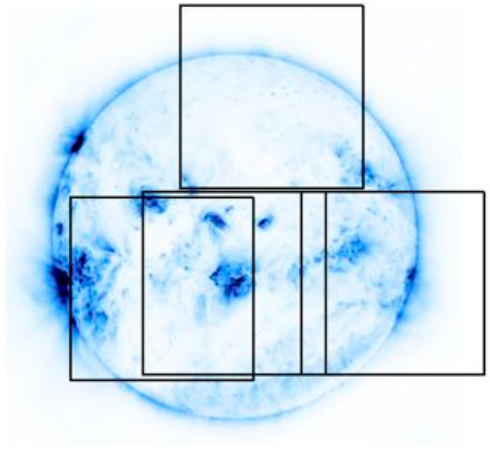
Alternative data: FOXSI

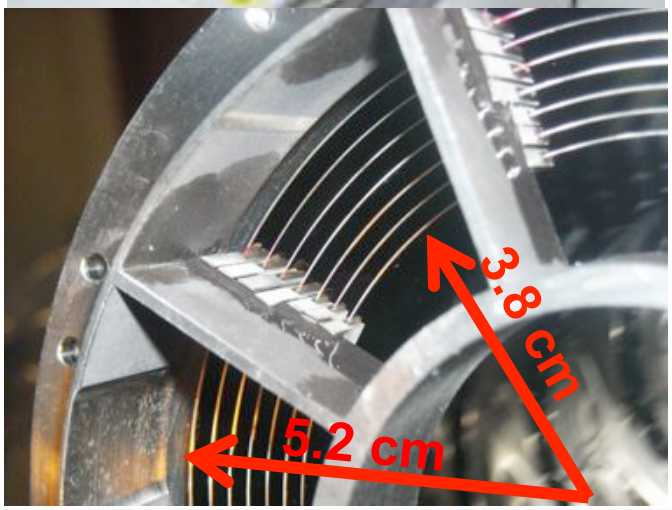
- FOXSI (Focusing Optics X-ray Solar Imager) is sounding rocket payload to study solar nanoflares
- 3× better spatial resolution and 10-100× better dynamic range than previous solar missions
- Data for solar disk center available, 4-15 keV
- Ghost-ray mostly outside region of interest

FOXSI-1
(Nov 2012)



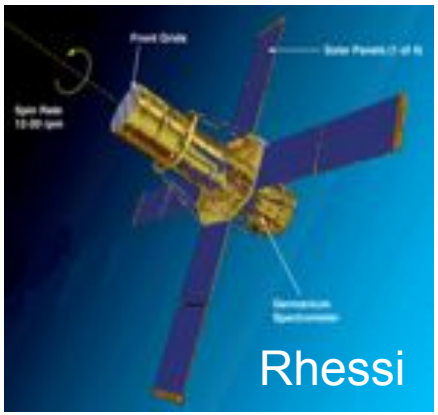
FOXSI-2
(Dec 2014)





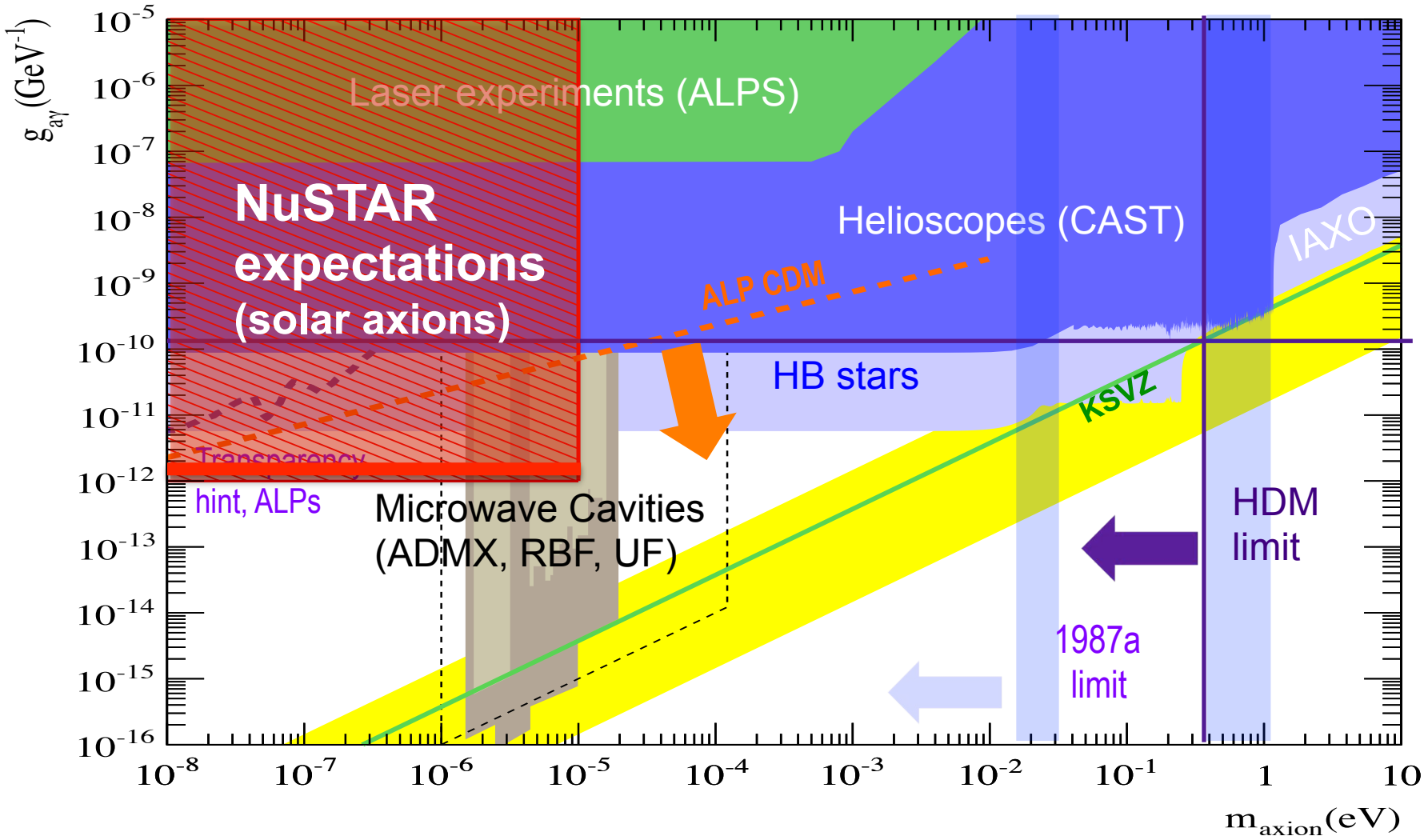
What were previous satellite missions able to do?

Instrument (Method)	E [keV]	Flux limit [ph/(cm^2 s keV]	$g_{a\gamma}$ limit @1 μeV [$\times 10^{-10}$GeV^{-1}]
GOES (long)	3.6	-	-
GOES (short)	4.8	-	-
Yohkoh (AlMg)	2.04	1.2	0.4
RHESSI (offpoint)	5	340	1.8
RHESSI (direct)	5	-	-
Hinode (energy)	1.53	0.1	0.3
Hinode (histogram)	1.53	0.01	0.2



Hudson et al. *ASP Conf. Series* 455, 25 (2012)

NuSTAR observations in the axion landscape



Summary

- Satellite mission offer alternative approach to solar axion searches (and axions from other objects)
- Expect good sensitivity to non-QCD axions at the low mass range
- First NuSTAR and FOXSI data available but needs additional work
  → Biggest challenge due to single-bounce photons ("ghost-rays")
- As we are approaching solar minimum, expect that Sun will be quiet enough for better observations in the near future
- Stay tuned for first results from existing data and upcoming observations


Lawrence Livermore
National Laboratory