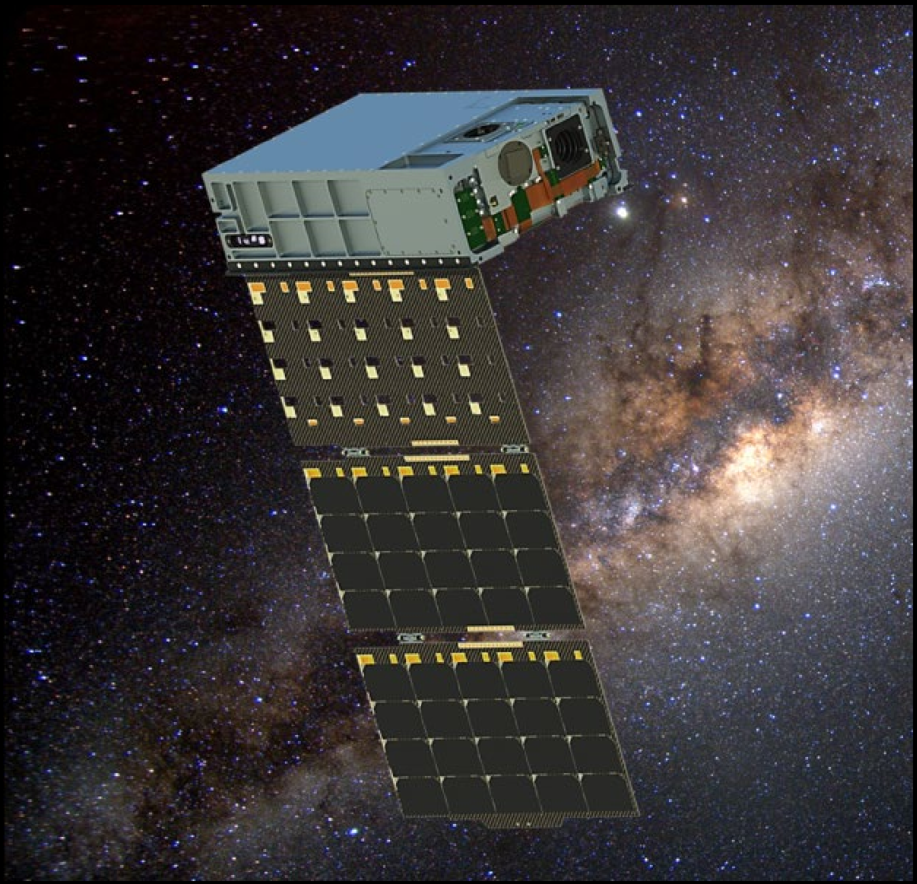
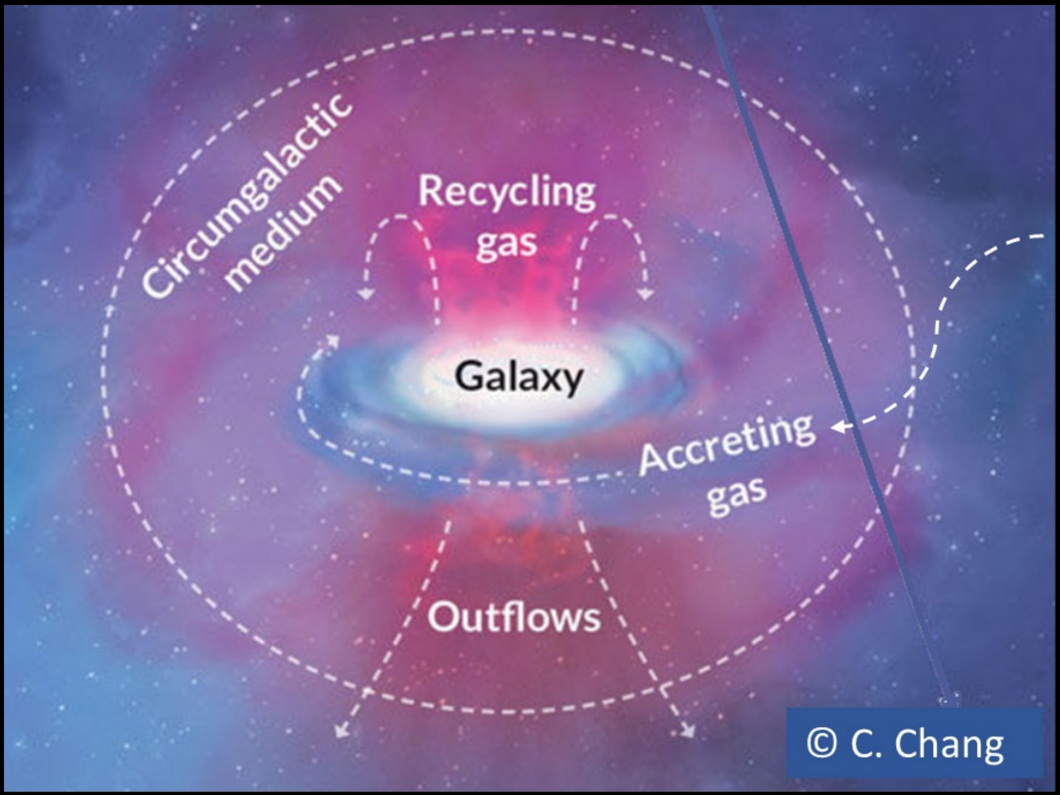
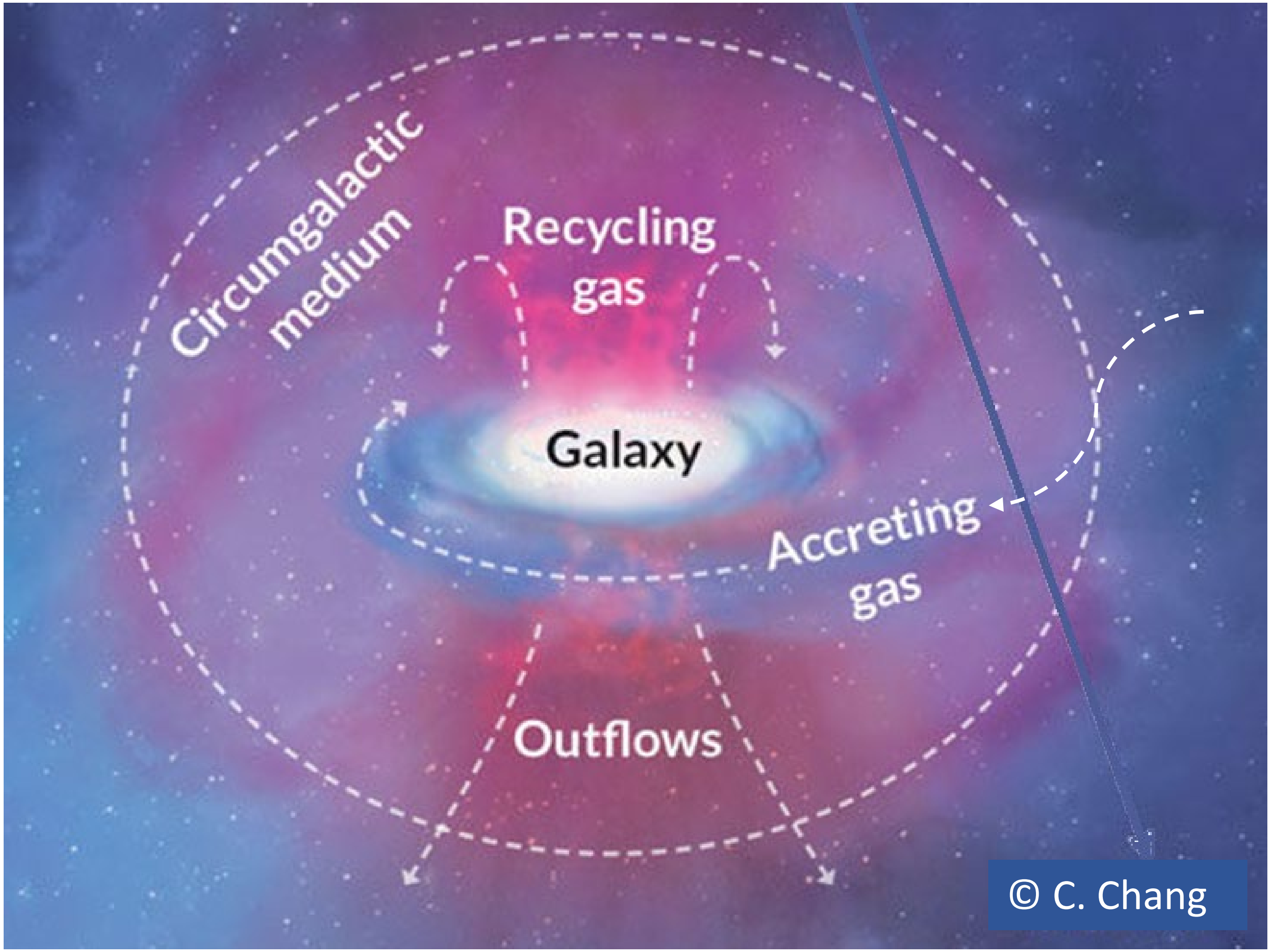
Observing the Galactic Halo with HaloSat

Philip Kaaret (University of Iowa)
for the HaloSat Team





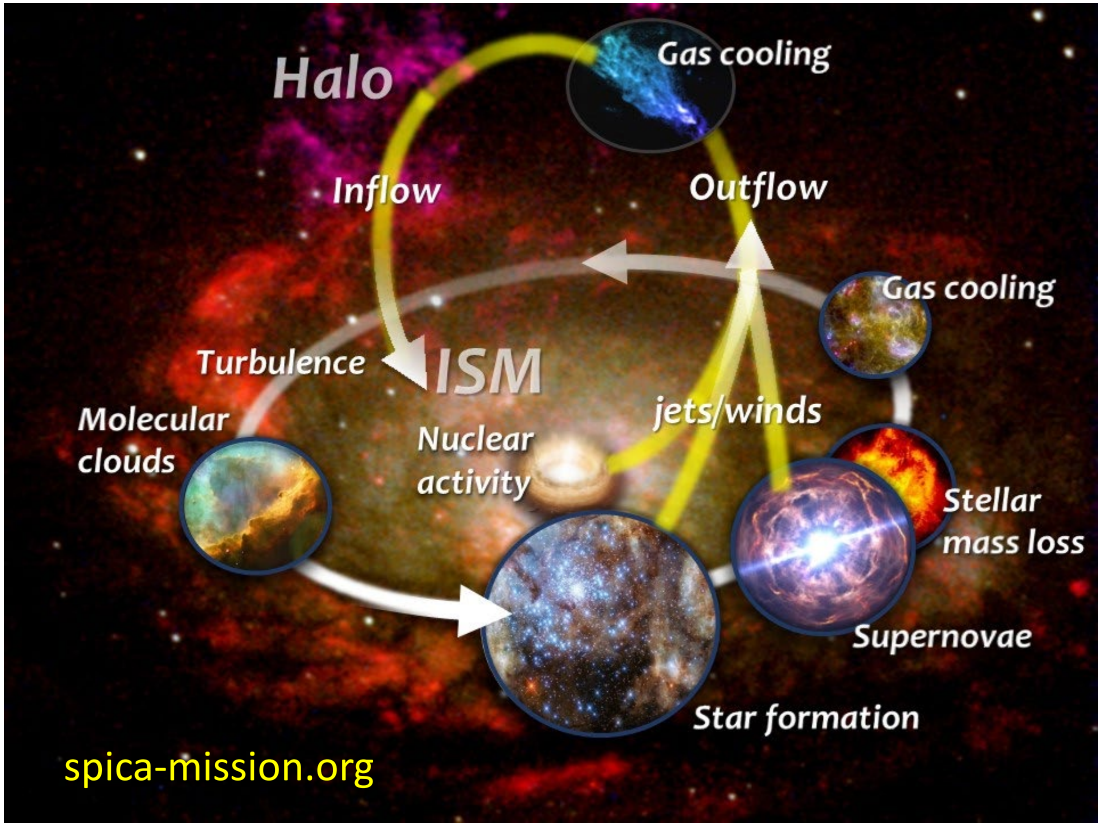
Halo = Circumgalactic Medium



Milky Way sits in gas at ~2×10^6 K.

- Accreted from intergalactic medium
- Recycled from disk by stars and nuclear activity

Feedback



Feedback –

1) gas from CGM cools,falls into disk of galaxy,

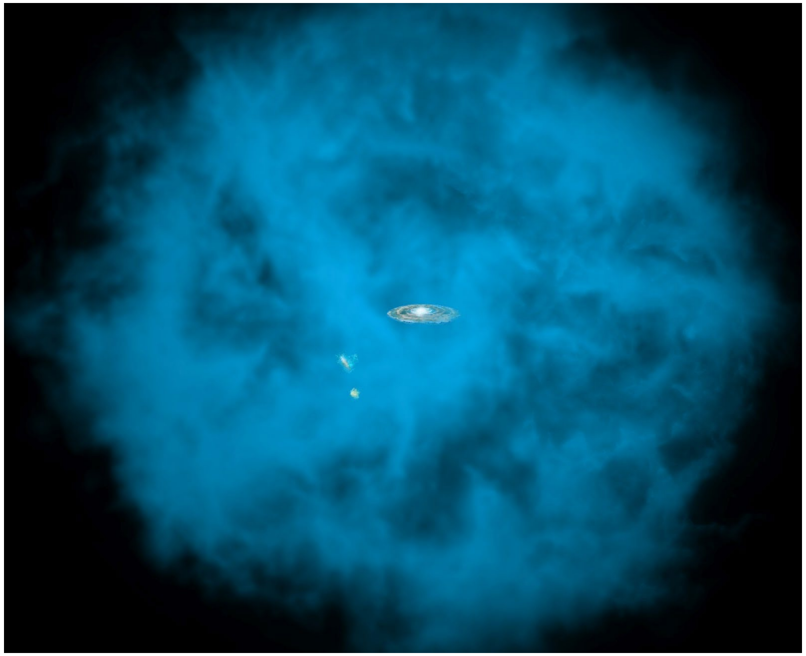
2a) cools further to make stars, stars make winds and explode,

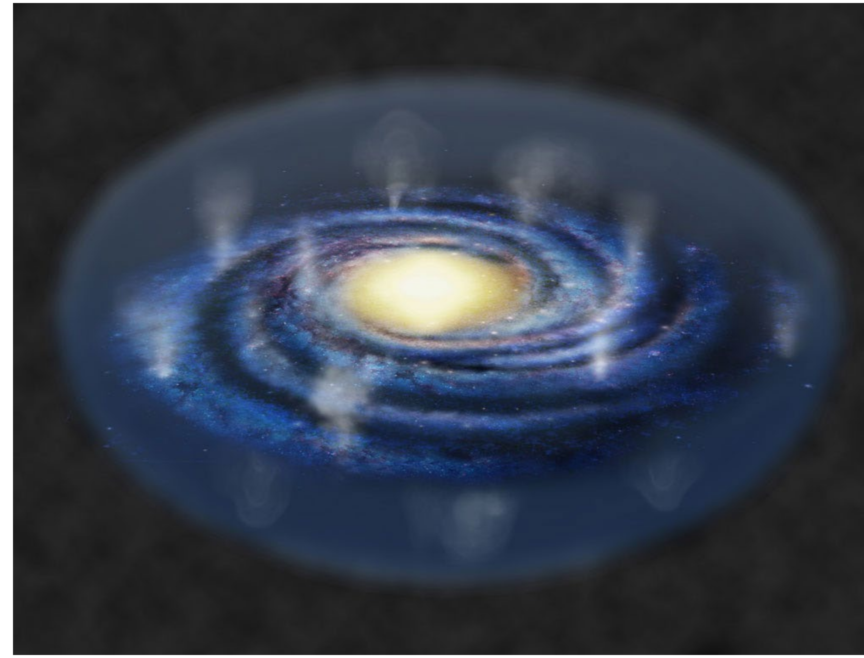
2b) falls towards supermassive black hole causes nuclear activity,

3) both energize the interstellar medium driving outflows into the CGM.

Feedback is an essential process in galaxy evolution.

Halo = Circumgalactic Medium





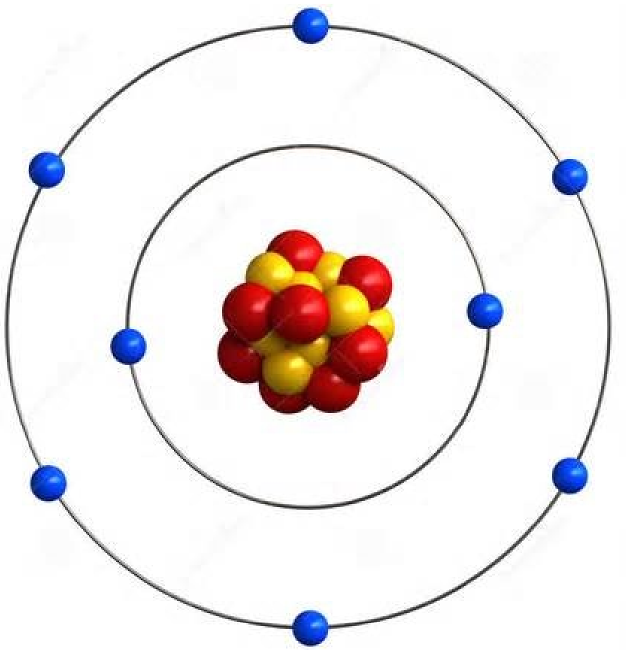
Questions:

- How CGM fed and energized?
- Is the CGM smooth and spherical or clumpy and anisotropic?
- Does the CGM have enough mass to solve the missing baryon problem?

Approach

- Look at gas in emission (not absorption)
- Look at Milky Way (not external galaxies)

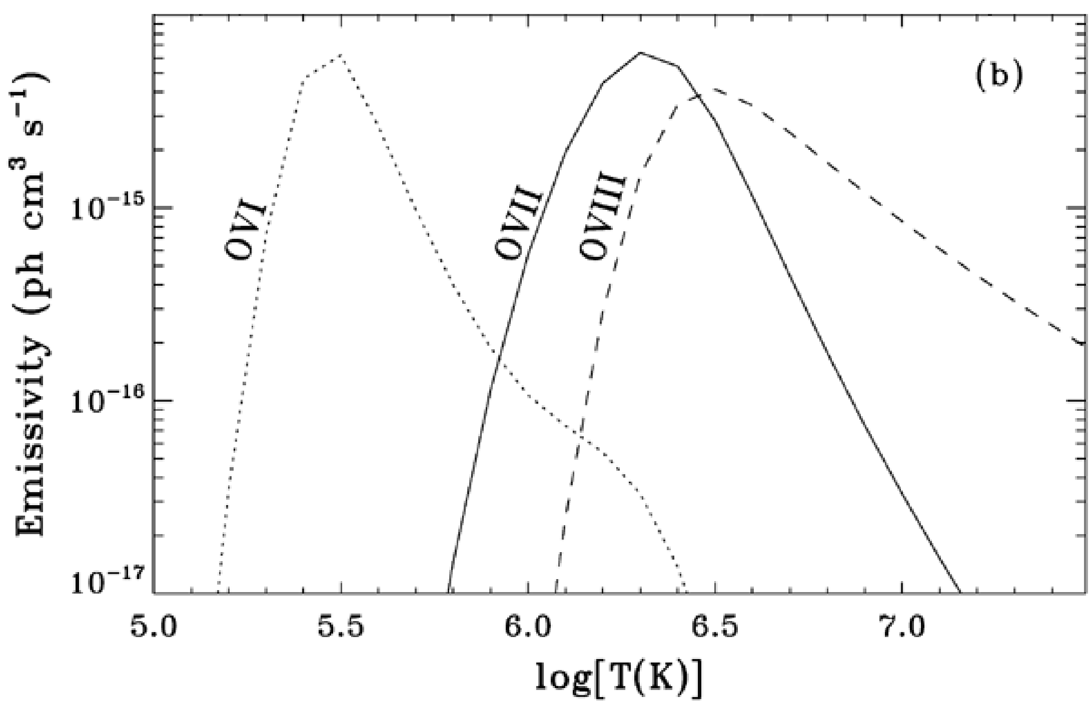
How to measure gas at ~10^6 K?



- **Goal: measure hot gas at ~10^6 K**
- **Technique: look for X-rays from oxygen atoms**
    - O VII triplet at ~560 eV
    - O VIII at 653 eV

- **O I = neutral**
- **O II = one e- gone**
- **O III = two e- gone**

  …



What is the distribution of hot gas in the Milky Way's halo?

- Requirement: measure hot gas at ~10^6 K
  - Detect X-rays from oxygen atoms
  - O VII at 561 eV, O VIII at 653 eV
  - Sensitive in 0.4-2 keV band with $\Delta E < 100$ eV at 600 eV
- Requirement: determine geometry of halo
  - Observe whole sky (or most of sky)
  - Angular resolution of 15º is sufficient
- Requirement: obtain sufficient X-ray counts
  - View large part of sky at once (10º fields)
  - Long duration mission
  - Allows use of small detectors (25 mm^2)

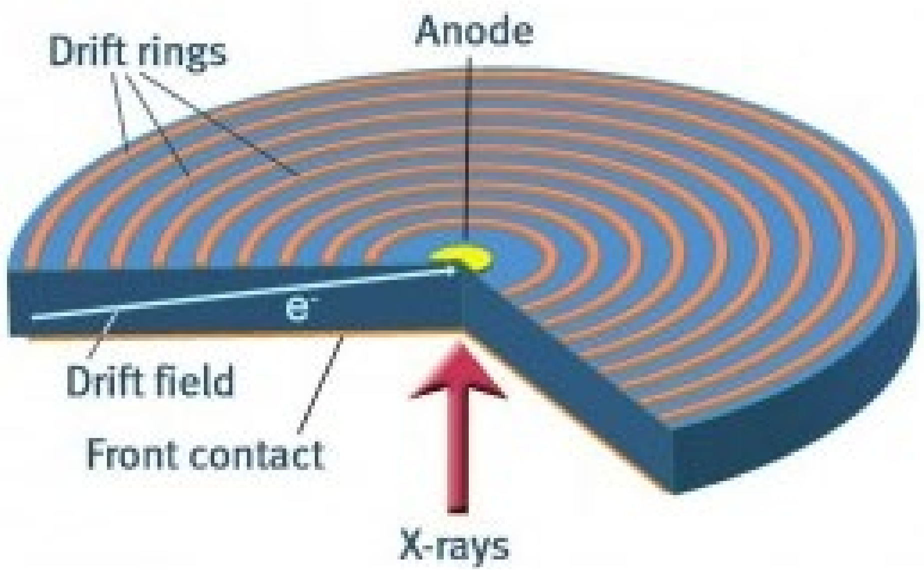
Lessons Learned

- **Flow from science question to requirements to design and back.**

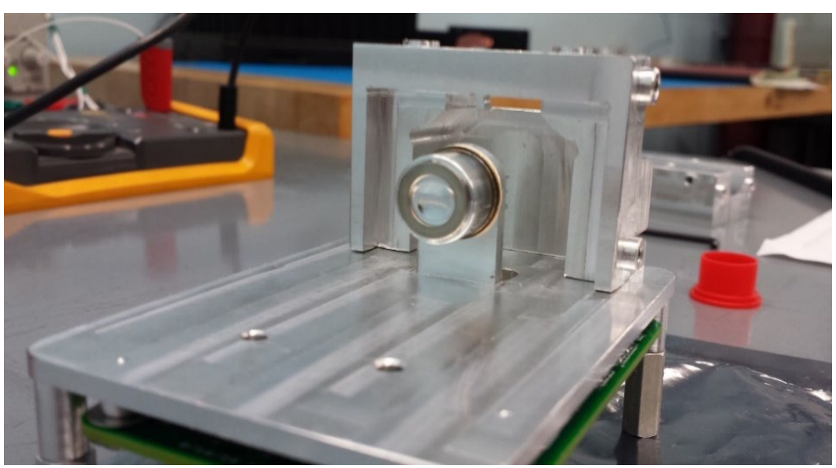
  You need an interesting and clearly stated science question to be selected. There should be a clear flow from the science question, to the science requirements, to the mission requirements, to the mission design.

  For CubeSats, it is ok to go both ways. If you can’t quite fit a mission into the CubeSat format, think about what you can fit. Can you address part of your scientific goals or somewhat different scientific goals? CubeSat are selected for “niche” or very specific science goals.

X-Ray Detector



- X-ray interacts in silicon
- Number electrons $\propto$ X-ray energy
- Electrons are collected at anode.



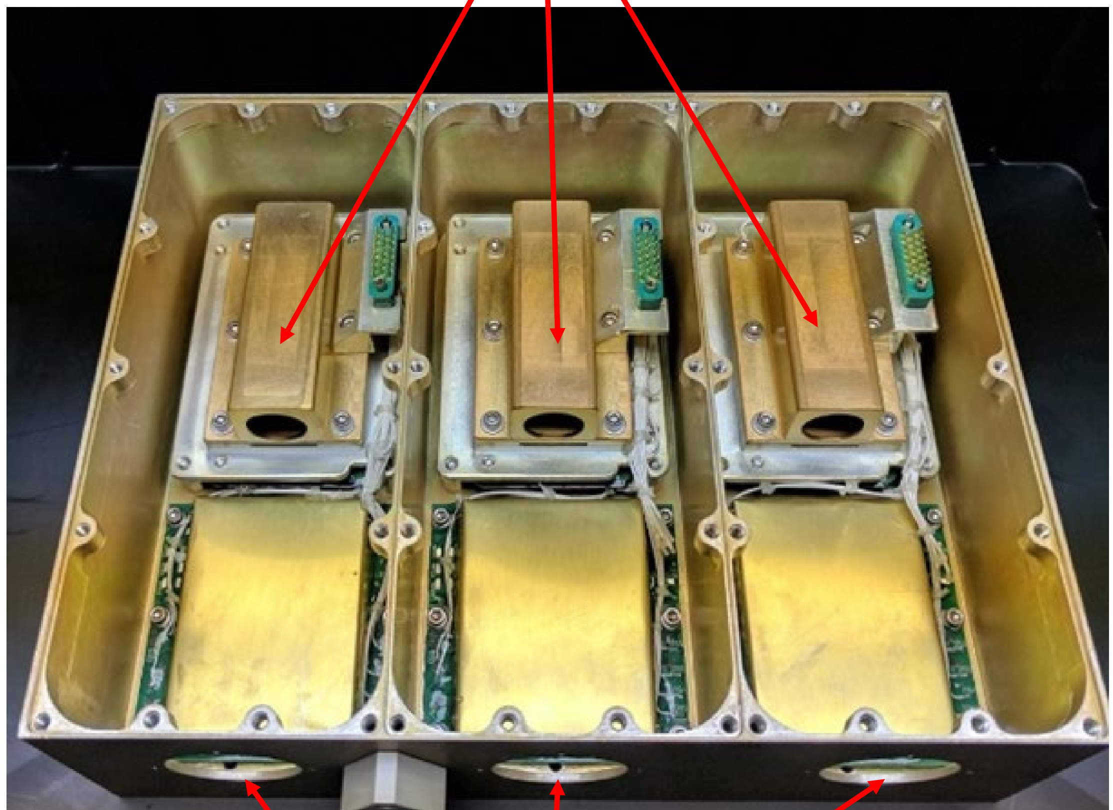
- X-ray detectors from Amptek, Inc.
- Active area of 17 mm^2
- Si_3N_4 window.
- Cooled by a thermoelectric cooler inside sealed can.

Instrument Design

All three detectors in one instrument enclosure

Sensor assembly

Copper-tungsten shield plated with gold



X-ray aperture

Field of view is 10° full response, 14° zero response.

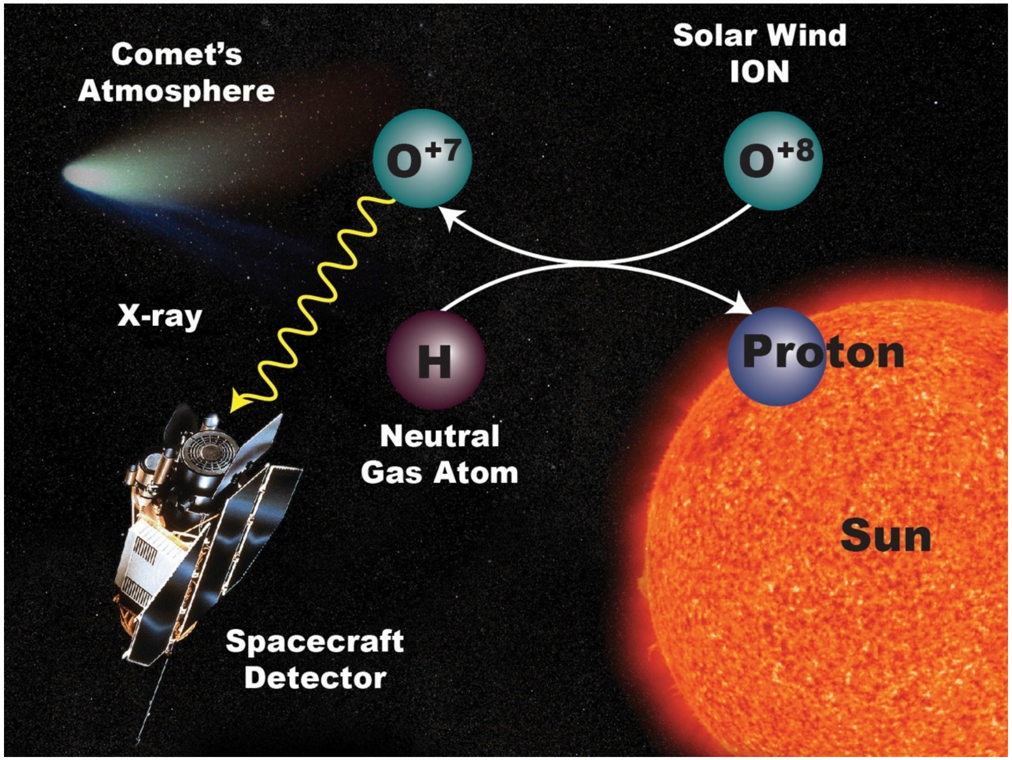
Sensitivity for Diffuse X-Ray Emission

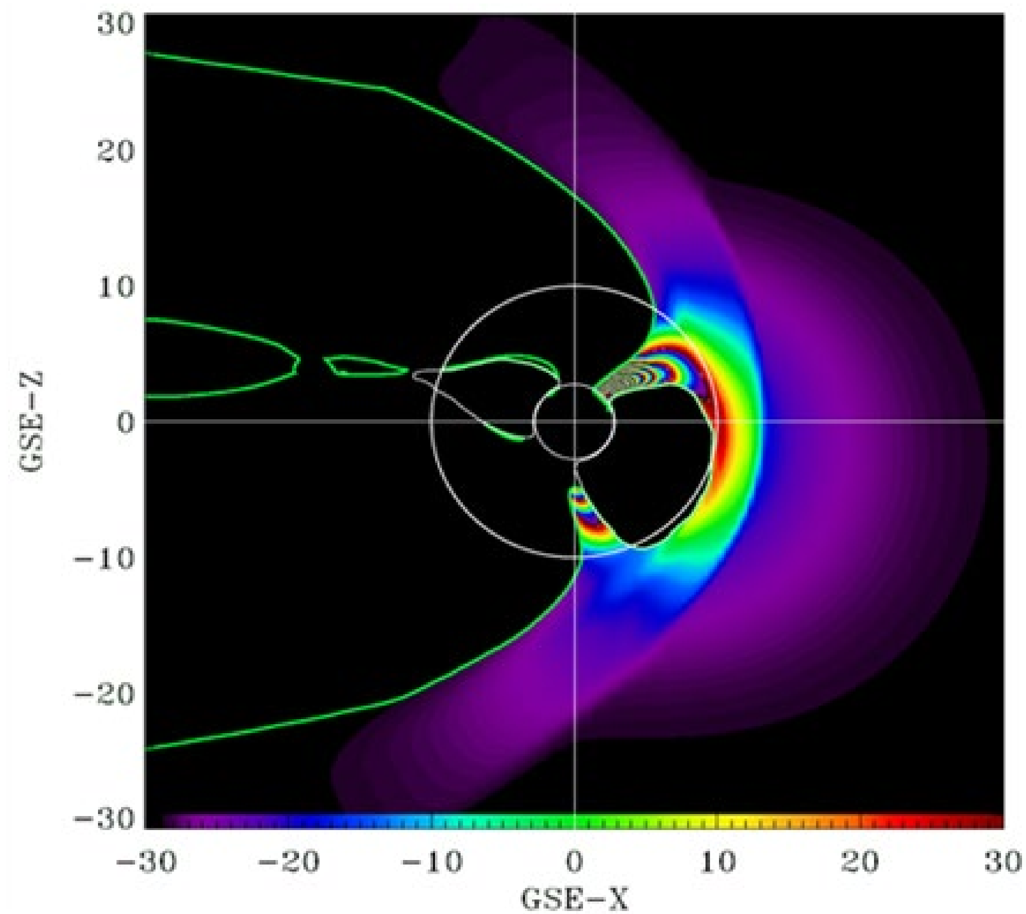
or why is a cheap, little satellite useful when there are big, expensive satellites already in orbit?

The figure of merit for observing diffuse emission, survey grasp, is the product of effective area and solid angle of the field of view, $A\Omega$. HaloSat has a small effective area, but a large field of view, giving it a grasp competitive with major missions.

Instrument	**Grasp (cm^2 deg^2)**
HaloSat	17.6
Chandra	8.7
XMM-Newton (MOS)	73

Other Sources of Oxygen X-Rays





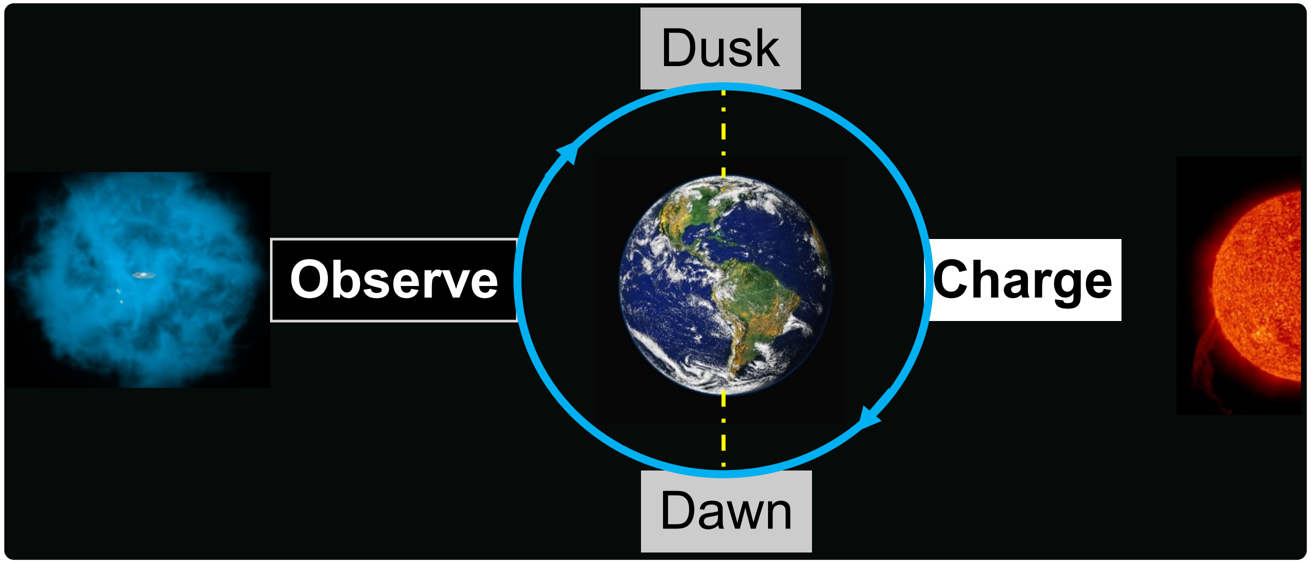
Kuntz (2019)

Accuracy of halo emission measurements are limited by foregrounds due to solar wind charge exchange emission (SWCX) from the magnetosphere and the heliosphere.

Minimizing Foreground Emission

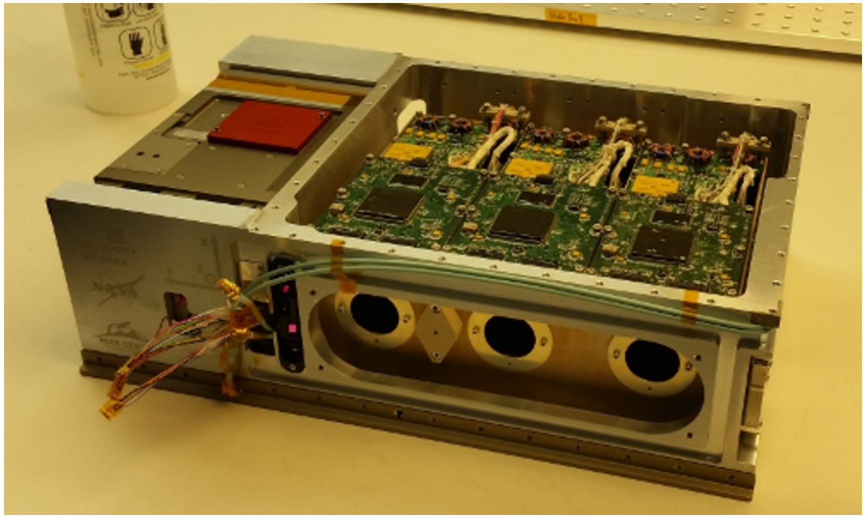
or what can a cheap, little, focused mission do better than a big, expensive, general purpose mission?

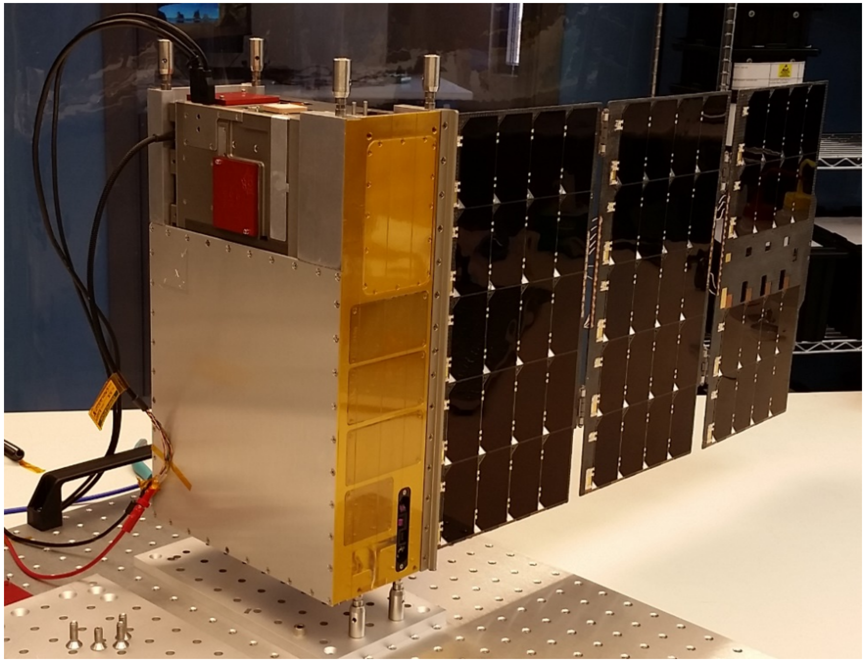
- HaloSat observes only at spacecraft night and at targets within 70° of anti-Sun to minimize foreground emission.
- Observations on night side, two ~1300 s exposures per orbit
- We also do observations to study SWCX (of interest to heliophysics)



6U CubeSat

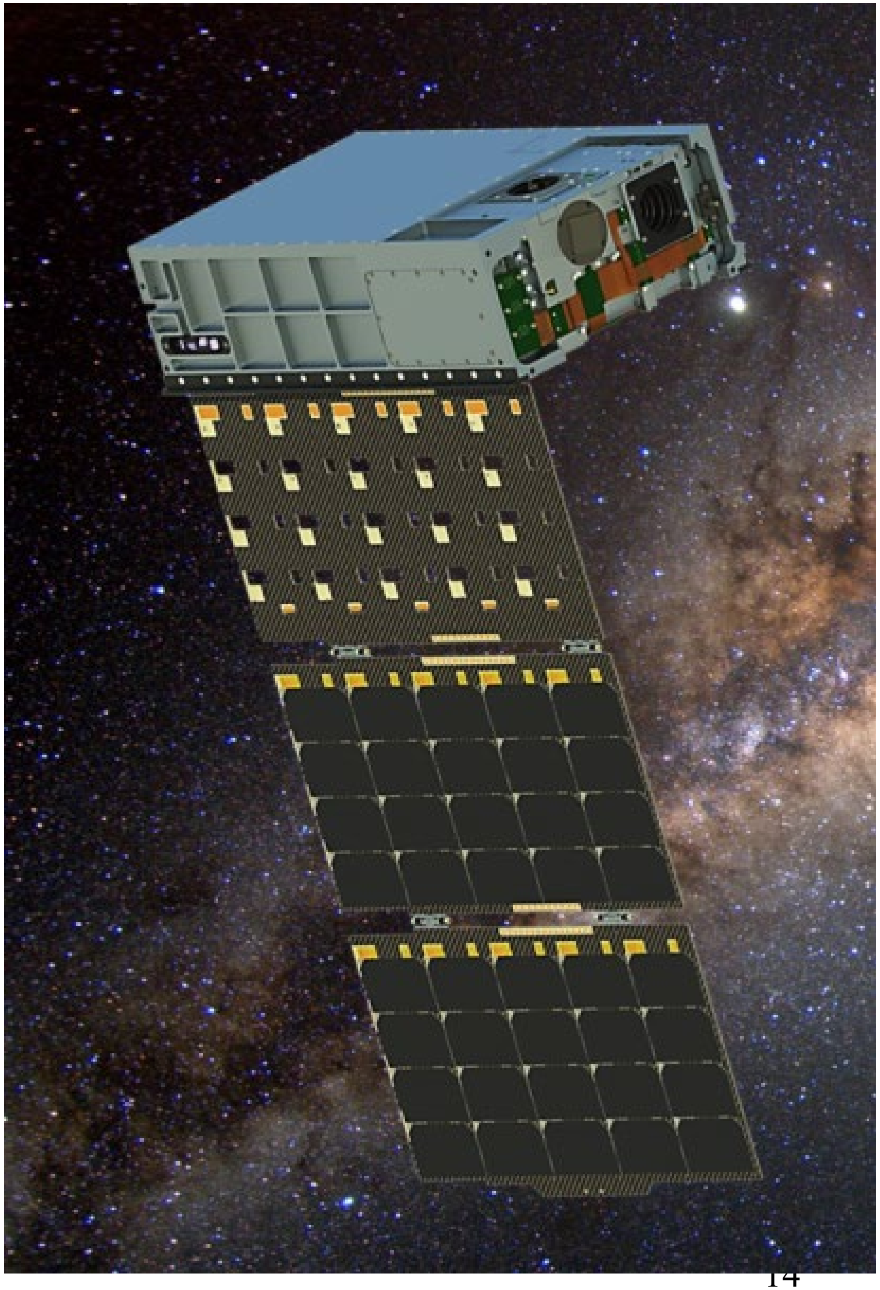
- Spacecraft bus from Blue Canyon Technologies, Inc.
- 6U format, 10.5×22.5×36.5 cm^3
- 4U volume allocated for the science payload, 2U volume allocated for avionics and payload-to-spacecraft interface
- Equipped with deployable solar panels, battery
- Pointing accuracy of $\pm 0.002^\circ$
- Slew rate of 2°/sec
- Equipped with two radios (Cadet and GlobalStar).





Schedule

- **Funding started 1/2016.**
- Prototyped in 2016.
- Built 1-7/2017.
- Tested 8-10/2017.
- **Integrated instrument with spacecraft 10/2017.**
- Tested 11/2016 to 2/2018.
- Launched to ISS 5/21/2018.
- **Deployed from ISS 7/13/2018.**
- Commissioning complete 10/15/2018.
- **Science observations for 2 years.**
- Re-entered atmosphere on 1/4/2021.
- Delivered full archive to NASA 3/2021.



Lessons Learned

- **Make your development as flight-like as possible**

  We took early delivery of a spacecraft simulator (EDU) from BCT, used it during instrument development (including flight model calibration), and changed our DAQ/monitoring software to use COSMOS as used by BCT. This enabled us to work out all compatibility issues early (hardware and software) and enabled rapid integration of our flight instrument with the flight spacecraft. (Kudos to Tom Johnson for including the EDU in the BCT contract).

- **Accept existing components with no modifications.**

  Minimizing costs requires accepting already engineered solutions with no modifications. We had to compete our bus; designing to a specific bus beginning at funding start would have saved time and money.

- **Small, dedicated teams are effective.**

  Gather a small group devoted to the project and don't let them do anything else.

Pre-Launch

The day before the launch, the Iowa HaloSat team met Astronaut Kay Hire. She is holding the 'Tiki'.

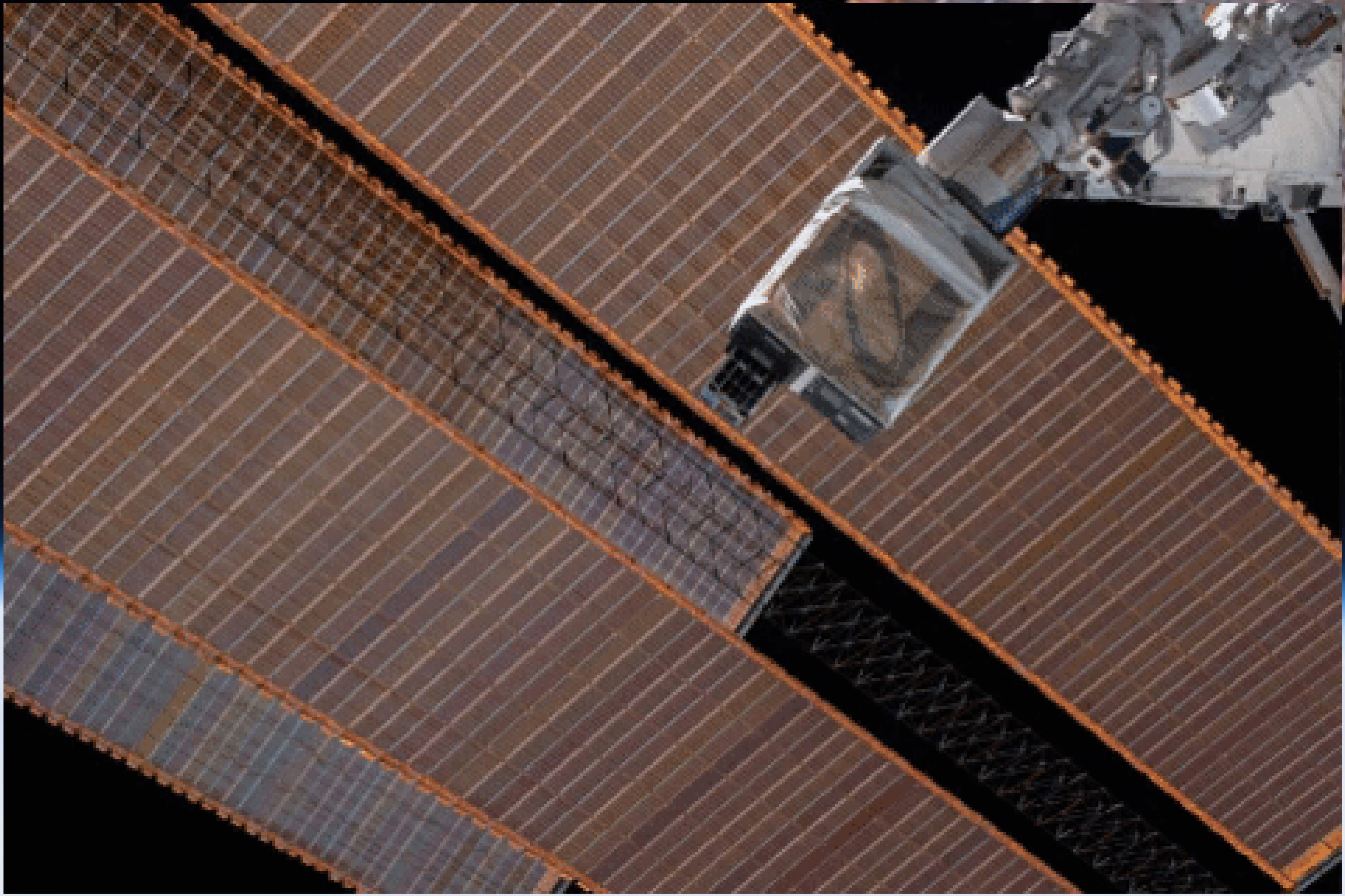
Launch – May 21 at 4:44 am

On an Orbital-ATK rocket (mission OA-9) from the Mid-Atlantic Spaceport on Wallops Island, VA.

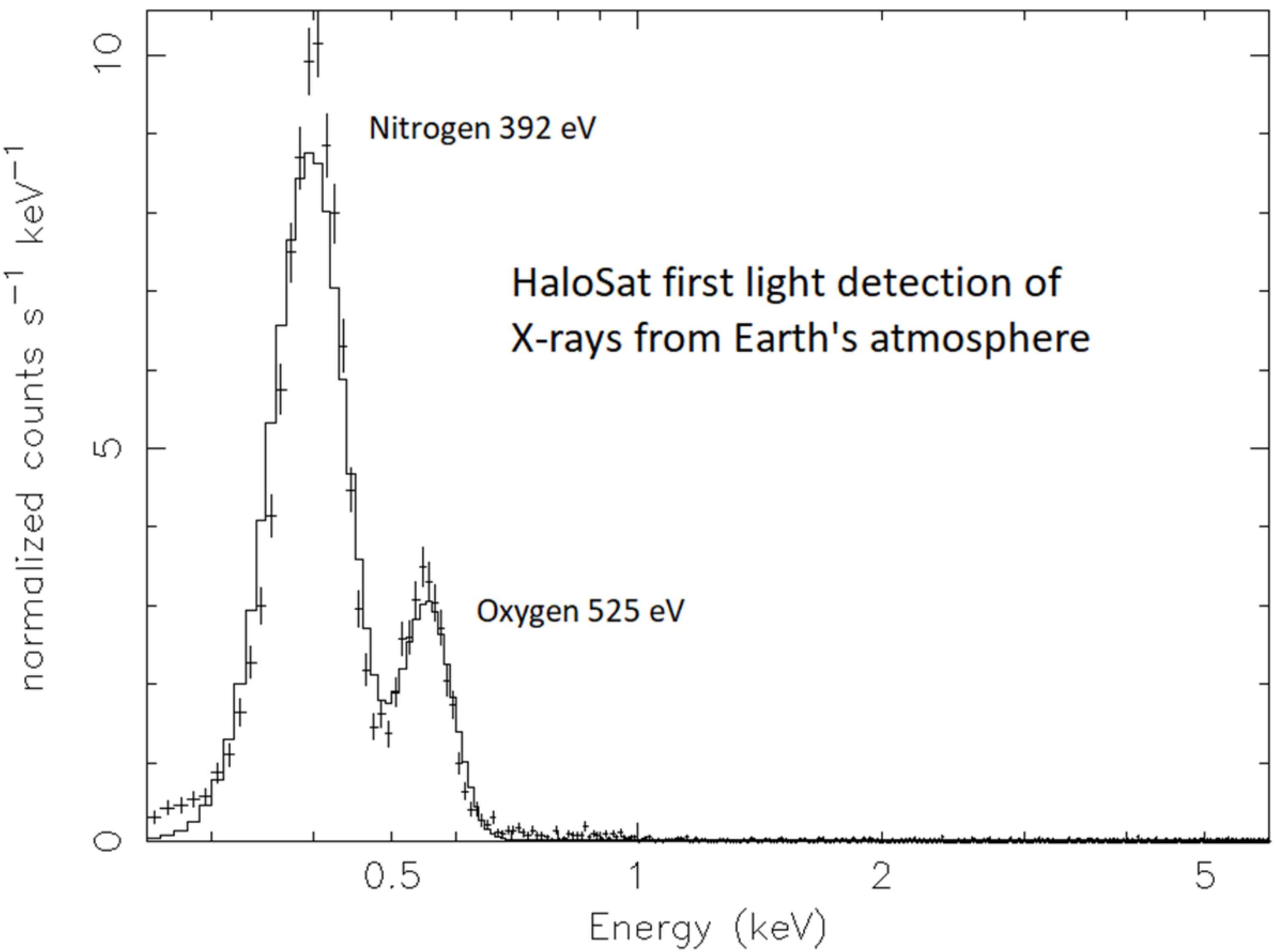
Launch – May 21 at 4:44 am

On an Orbital-ATK rocket (mission OA-9) from the Mid-Atlantic Spaceport on Wallops Island, VA.

Deployment – July 13 at 3:05 am



HaloSat First Light



Observed bright Earth, detected X-rays neutral N and O, verifying spectroscopic performance for all 3 detectors.

Lessons Learned

- **Buy two radios.**

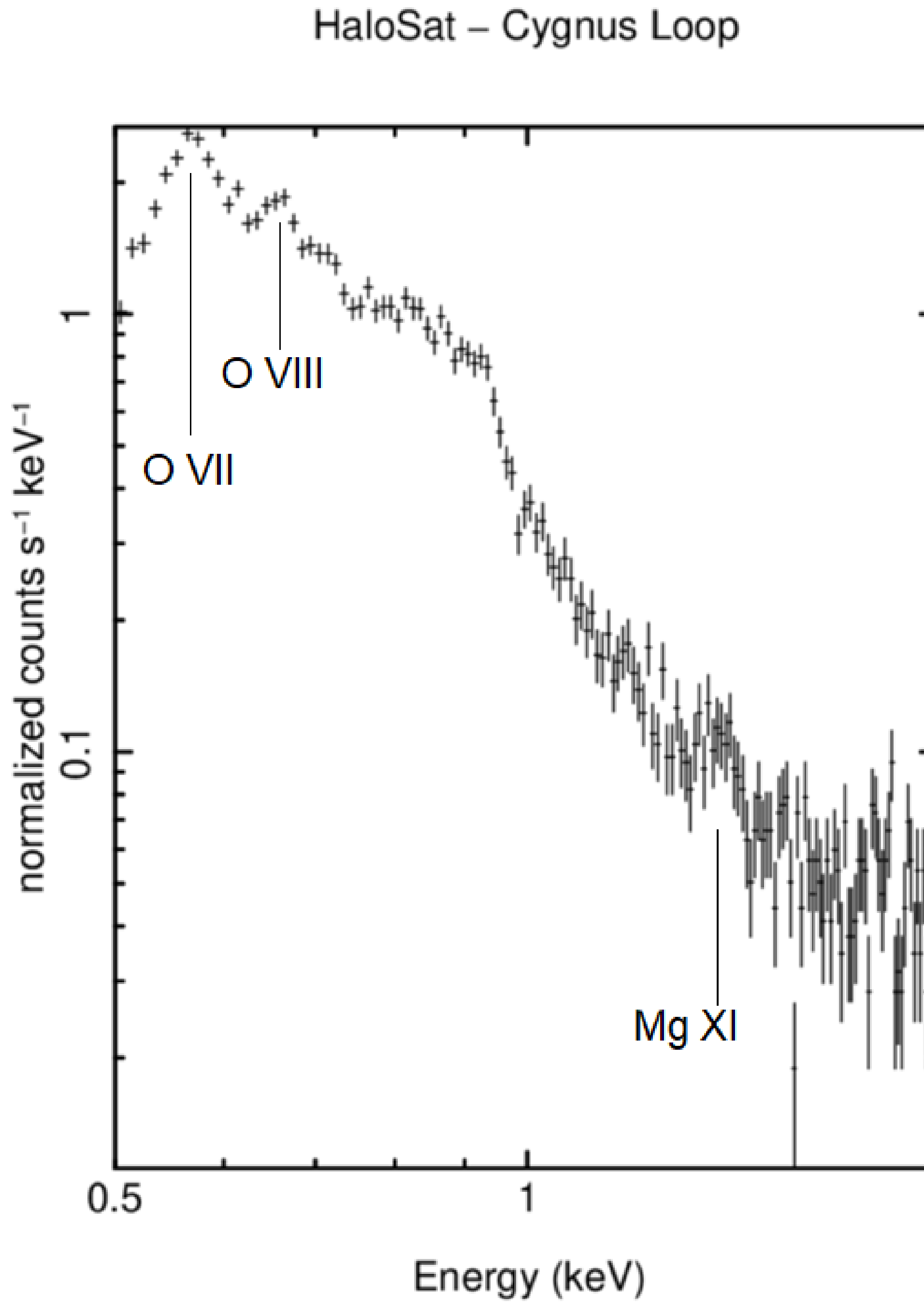
The majority of our on-orbit issues were related to communications. Many people complain about the Cadet, but offer no better alternative. Use of a single ground station is a single-point failure mode, due to antenna issues, weather, and scheduling conflicts. We averaged less than one packet per day with the GlobalStar network.

To support a robust SmallSat program, NASA would be well advised to invest in SmallSat radio development and a network of ground stations with standard interfaces.

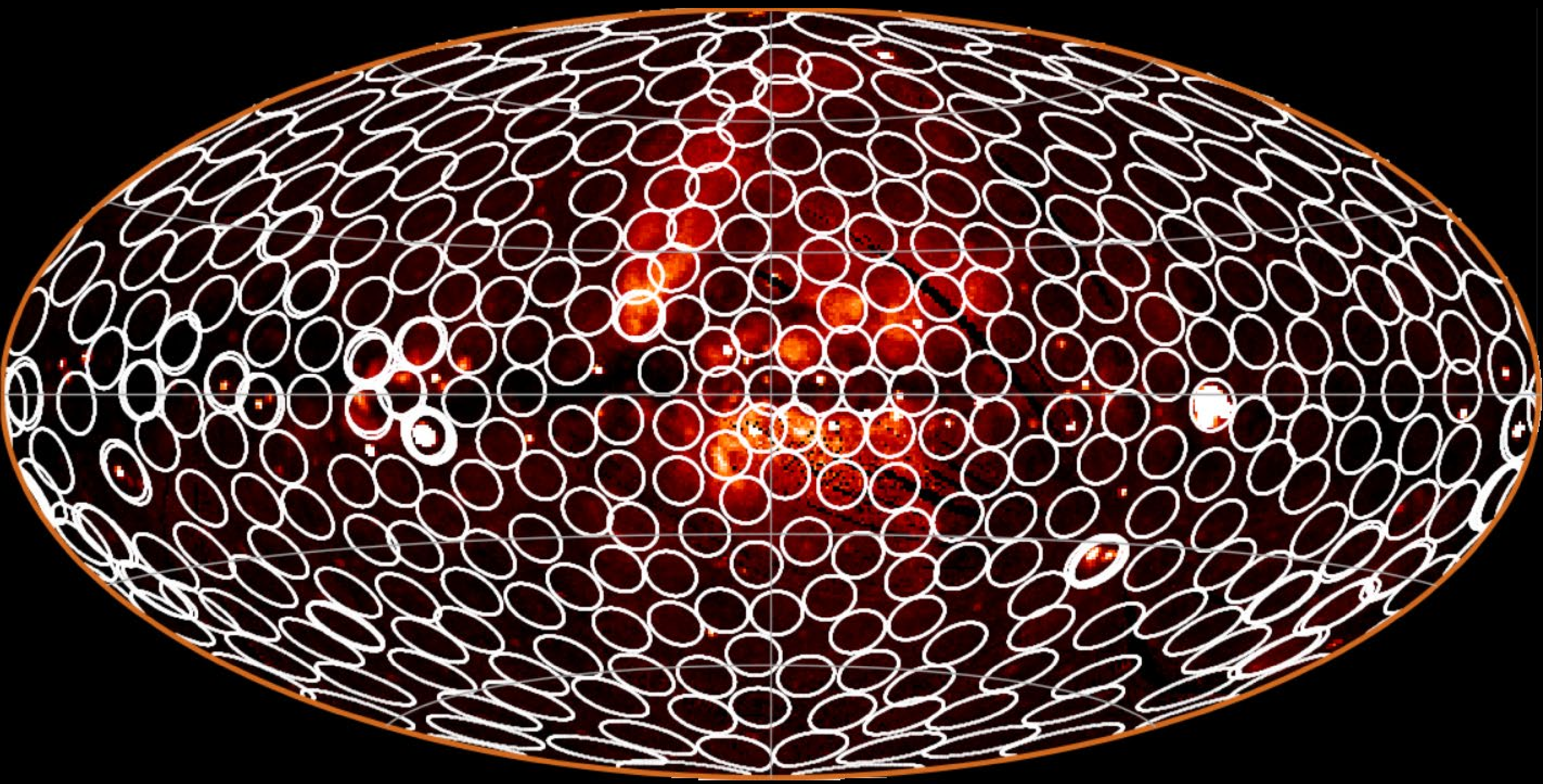
- **Make good mistakes.**

First Astrophysics Target – Cygnus Loop

- Nearby (1500 ly) supernova remnant.
- Spans 3 degrees on the sky.
- Shell is heated to 3×10^6 K.
- Strong soft X-ray source.
- Clear detection of O VII and OVIII in HaloSat spectrum.



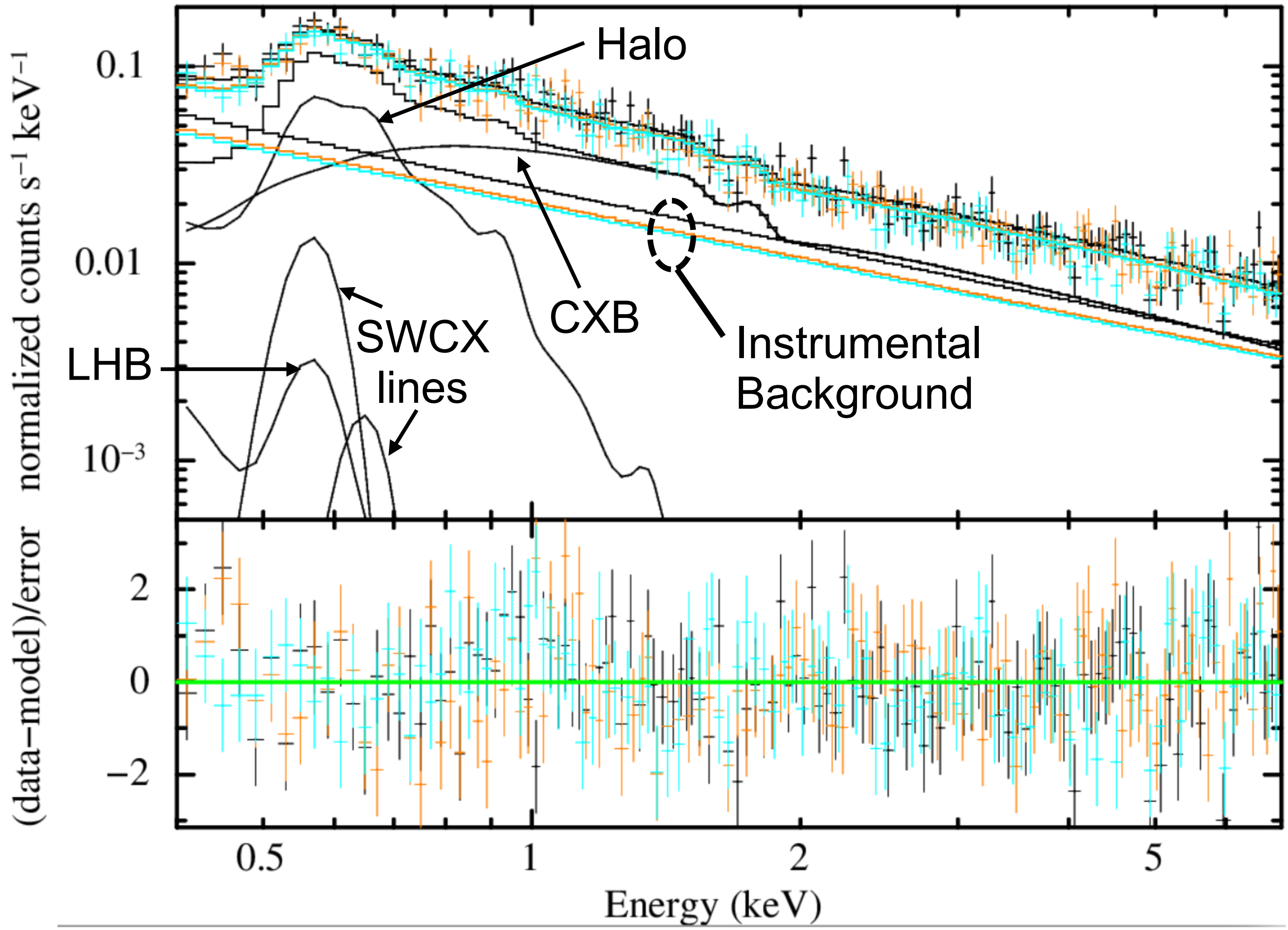
All Sky Survey



Halo Spectrum

l = 123°, b = -55°

28 ks exposure



Model:

- Thermal plasma for halo (free emission measure = EM, temperature = kT)
- *Model OVII and OVIII Heliospheric SWCX lines using ACE/SWICS data*
- Thermal plasma for local hot bubble (LHB) with parameters from Liu et al. (2017)
- Powerlaw for cosmic X-ray background from Cappelluti et al. (2017)
- Powerlaw for particle background (free normalization for each detector).

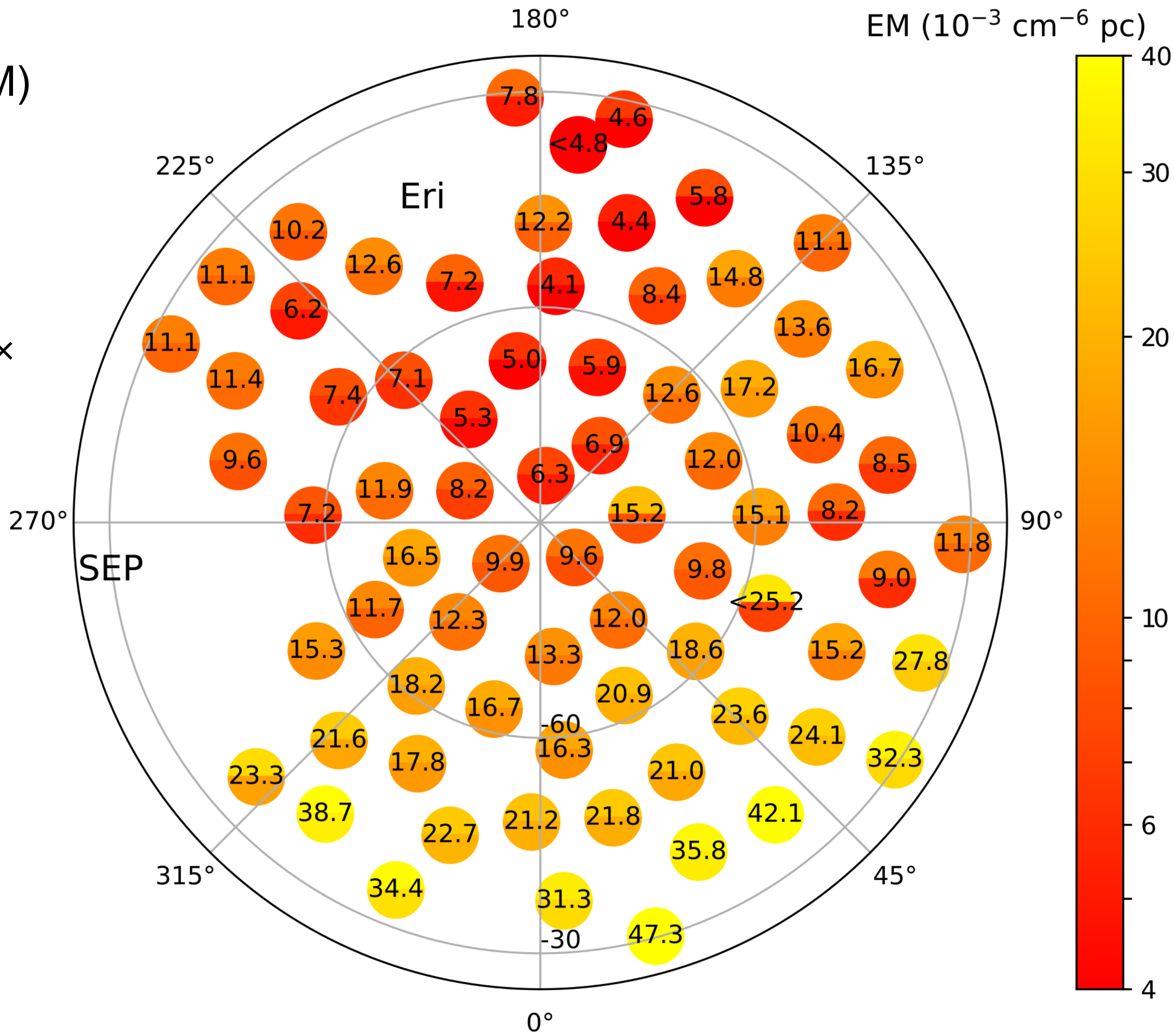
Results on Southern Halo

'Emission measure' (EM) measures flux of field,

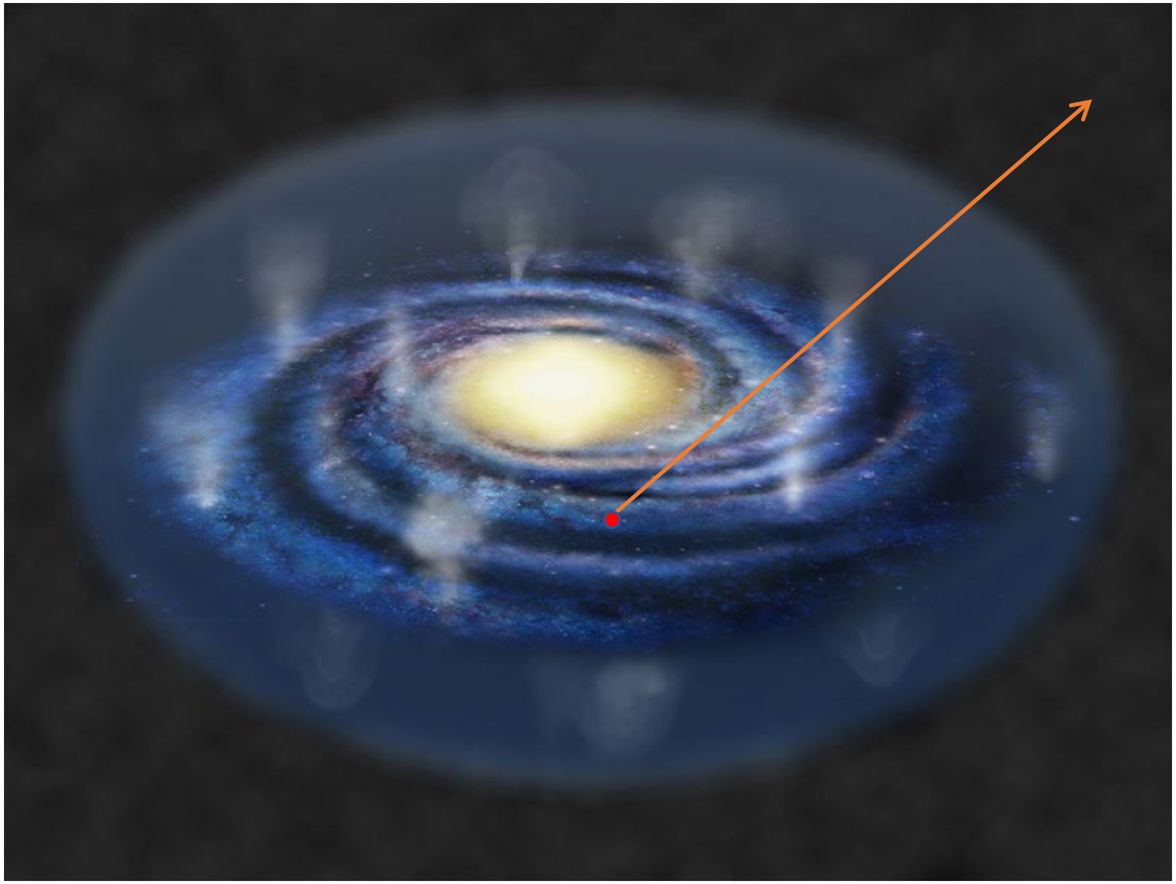
$$EM \propto \int n_e n_H \, dl$$

- Large variations ~10×
- Clumpy ~10°-20°
- Brighter towards Galactic center.

Temperatures
$kT \approx 0.23$ keV

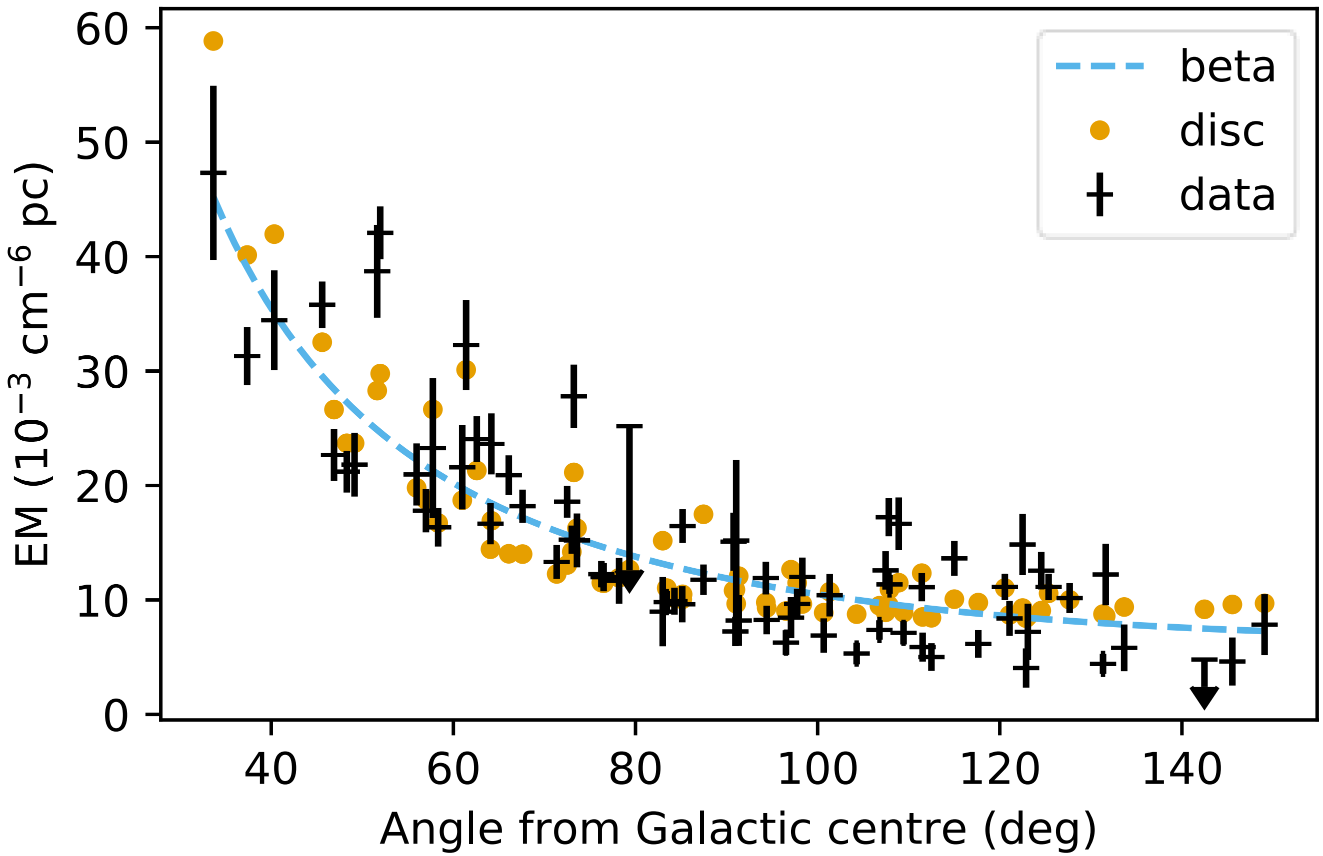


Fitting models of CGM density distribution



- Assume model for distribution of hot gas $n(r)$ or $n(R, z)$ where n = gas density, r = distance from Galactic center, R = distance from GC in plane, z = height out of plane
- Emission measure ∝ density squared
- Integrate $\int n^2(s)\, ds$ along line of sight, compare to EM

Fitting models of CGM density distribution



- Beta-model $n(r) = n_c(r/r_c)^{-3\beta}$
- Disk $n(R, z) = n_0 e^{-R/R_0} e^{-z/z_0}$
- Empirical disk model – based on tracer of star formation rate (H_2).
- Empirical disk model is preferred, suggesting relation to star formation.

Science Results

Soft X-ray emission from the halo/CGM

- is clumpy (~10°-20°) and factor ~10 variations,
- has large-scale variations well described by an empirical model of star-formation surface density,
- clumpiness is naturally explained by local variations in star formation,
- is dominated by disk emission near the Galactic plane, and therefore
- should be an excellent tool to study feedback within the Milky Way.

Additional data are needed to constrain the extended, low-density halo.

Other Results from HaloSat

The Astrophysical Journal, 904:54 (11pp), 2020 November 20 https://doi.org/10.3847/1538-4357/abbdfd

CrossMark

An Analysis of the North Polar Spur Using HaloSat

Daniel M. LaRocca[1], Philip Kaaret[1], K. D. Kuntz[2,3], Edmund Hodges-Kluck[2], Anna Zajczyk[1,2,4], Jesse Bluem[1], Rebecca Ringuette[1], and Keith M. Jahoda[2]
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...ember 29; accepted 2020 October 2; published 2020 November 20

The Astrophysical Journal, 905:91 (10pp), 2020 December 20 https://doi.org/10.3847/1538-4357/abc41b

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A HaloSat Analysis of the Cygnus Superbubble

Jesse Bluem[1], Philip Kaaret[1], William Fuelberth[1], Anna Zajczyk[1,2,3], Daniel M. LaRocca[1], R. Ringuette[1], Keith M. Jahoda[2], and K. D. Kuntz[2,4]
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Received 2020 September 16; revised 2020 October 13; accepted 202...

The Astronomical Journal, 160:20 (7pp), 2020 July https://doi.org/10.3847/1538-3881/ab93d3

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Global X-Ray Properties of the Vela and Puppis A Supernova Remnants

E. M. Silich[1], P. Kaaret[1], A. Zajczyk[1,2,3], D. M. LaRocca[1], J. Bluem[1], R. Ringuette[1], K. Jahoda[2], and K. D. Kuntz[4]
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The Astronomical Journal, 161:57 (6pp), 2021 February https://doi.org/10.3847/1538-3881/abccd0

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Total X-Ray Emission from the LMC Observed with HaloSat

H. Gulick[1], P. Kaaret[1], A. Zajczyk[1,2,3], D. M. LaRocca[1], J. Bluem[1], R. Ringuette[1], K. Jahoda[2], and K. D. Kuntz[4]
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A Search for the 3.5 keV Line from the Milky Way's Dark Matter Halo with HaloSat

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10 HaloSat papers in referred journals to date.

Lessons Learned

- **Budget to do science.**

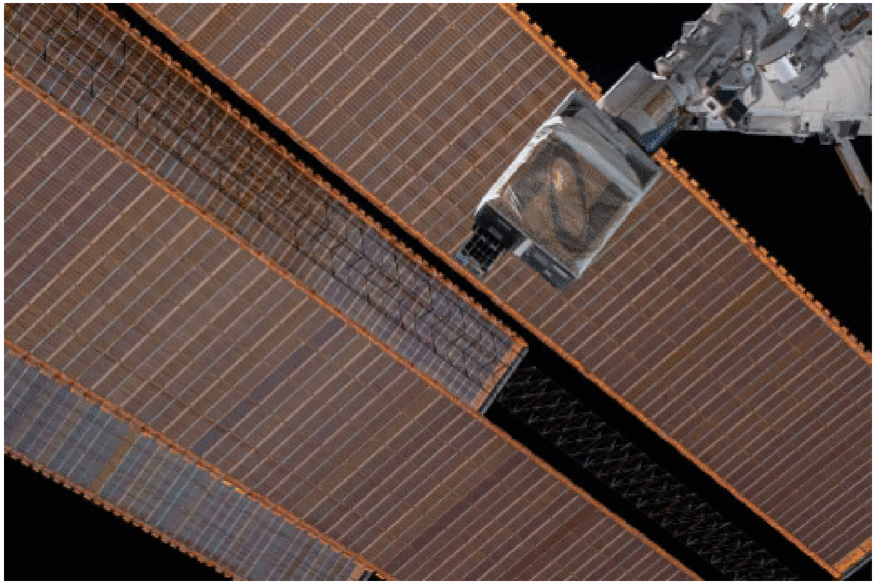
  Make sure that you have enough time and money after flight to analyze your data and write up your results. We need science coming out of CubeSats. Also, please write up your technical/engineering papers. This is a good way to transmit lessons learned. This is also a good way to get your students and junior personnel jobs.

- **Pick a good orbit.**

  The ISS orbit is not favorable to X-ray astrophysics instruments due to the high background at high latitudes. Development of options for low inclination orbits would enhance the potential science return (and would require ground stations at low latitudes).

HaloSat Team

- **University of Iowa**: Donald Kirchner, William Robison, **Anna Zajczyk**, **Daniel LaRocca**, *Jesse Bluem*, Rebecca Ringuette, Hannah Gulick, William Fuelberth, Emily Silich, Ross McCurdy, Tyler Roth, *Jacob Richardson*, Drew Miles, Keith White

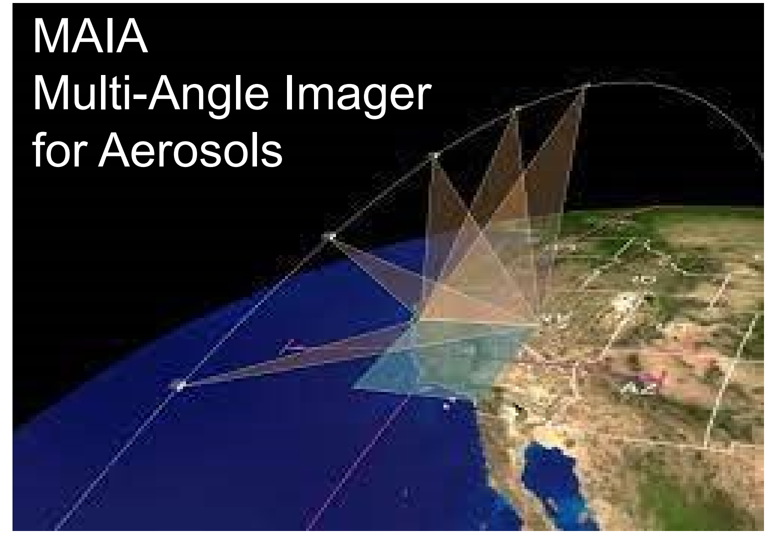


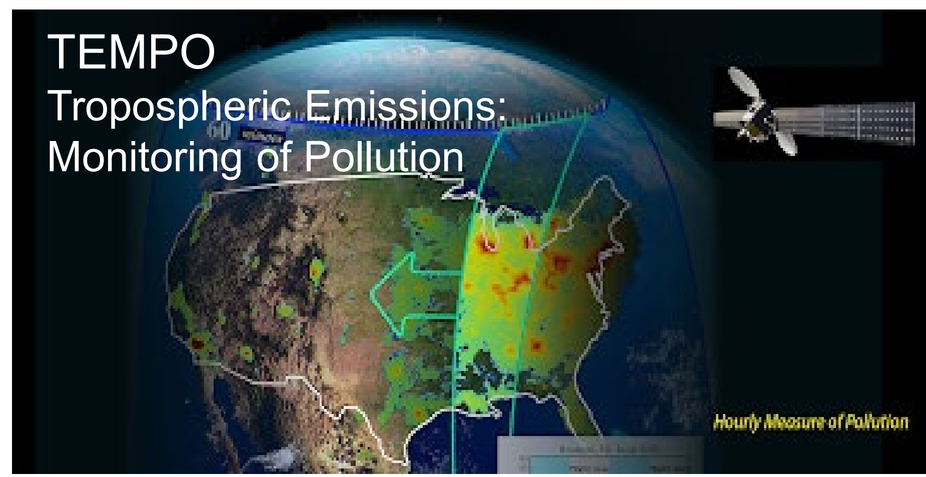
- **LAMTOS**: Dimitra Koutroumpa
- **NASA/Wallops**: Thomas Johnson, Luis Santos, Michael Matthews, Brenda Dingwall
- **NASA/GSFC**: Keith Jahoda, Anna Z, Edmund Hodges-Kluck
- **Johns Hopkins**: K.D. Kuntz
- **Blue Canyon Technologies:** Steve Schneider, Nancy Gaytan, Doug Laczkowski, Chris Esser, Scott Inlow, Tom Golden, Karl Hansen, Kristen Hanslik, John Carvo, Rebecca Walter, Charles Dumont, Matt Pallas

Open-rank faculty position in Earth Observation

Iowa's excellence in Earth observation

1. Participating (co-Is) of two Earth Venture Missions (MAIA and TEMPO)
2. PI of an EVM proposal under review
3. Multiple NASA satellite and field campaign science team memberships





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