Observing the Galactic Halo with HaloSat

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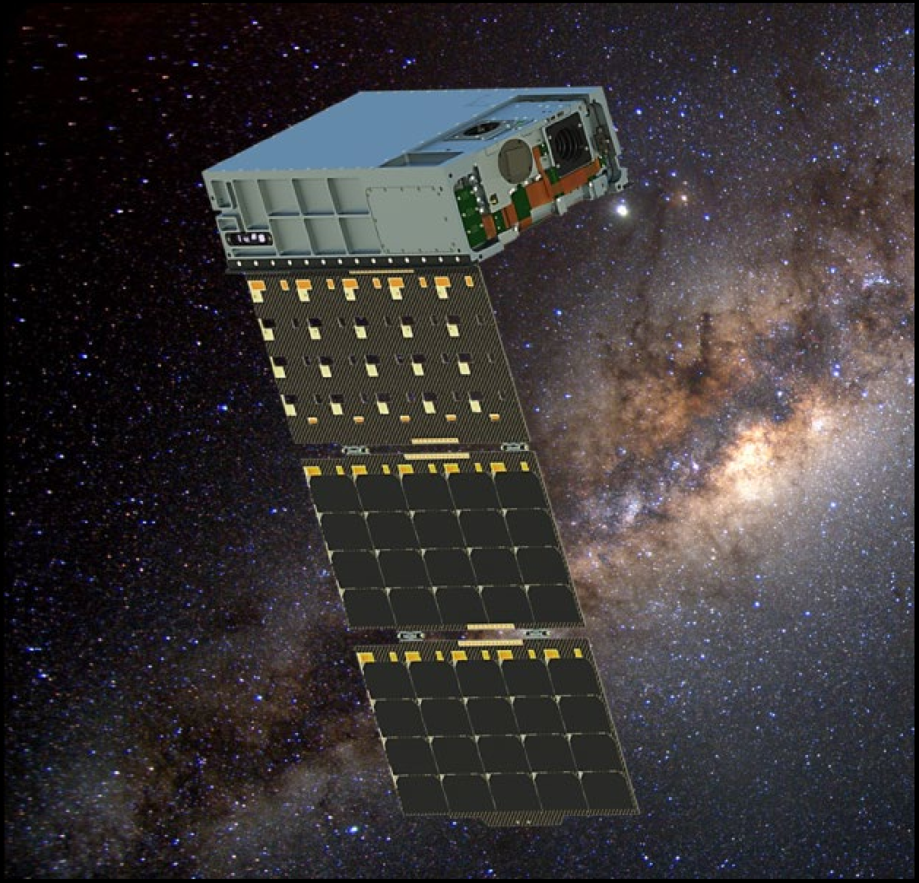
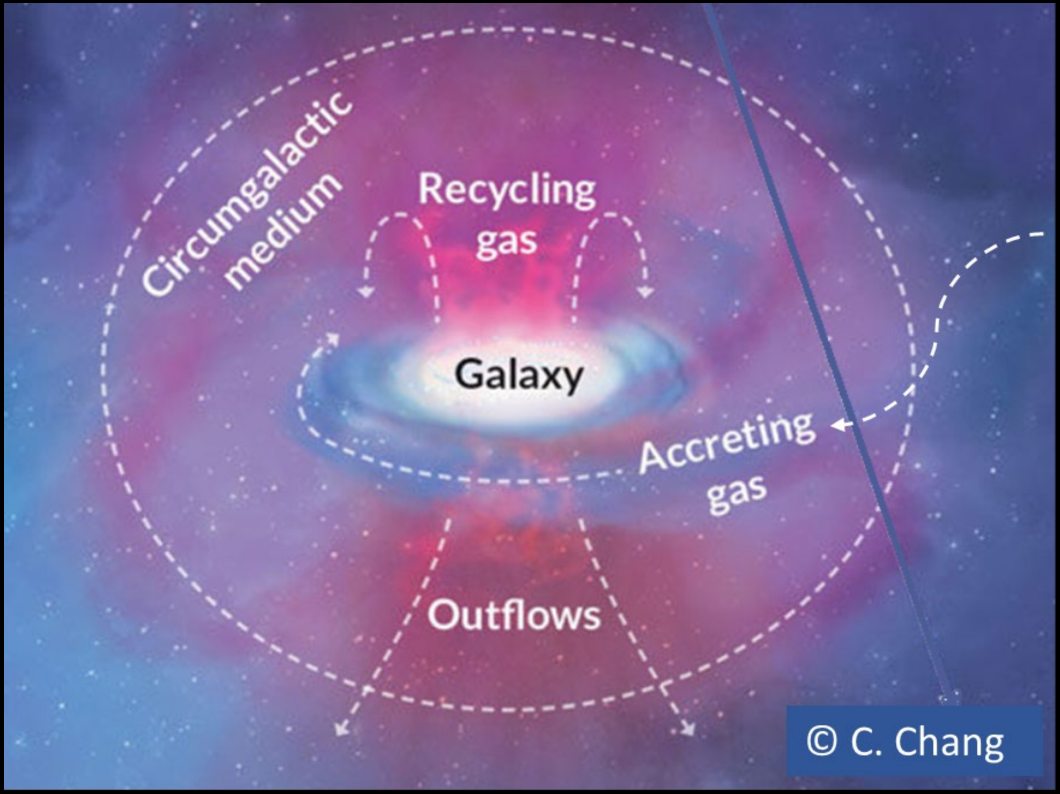
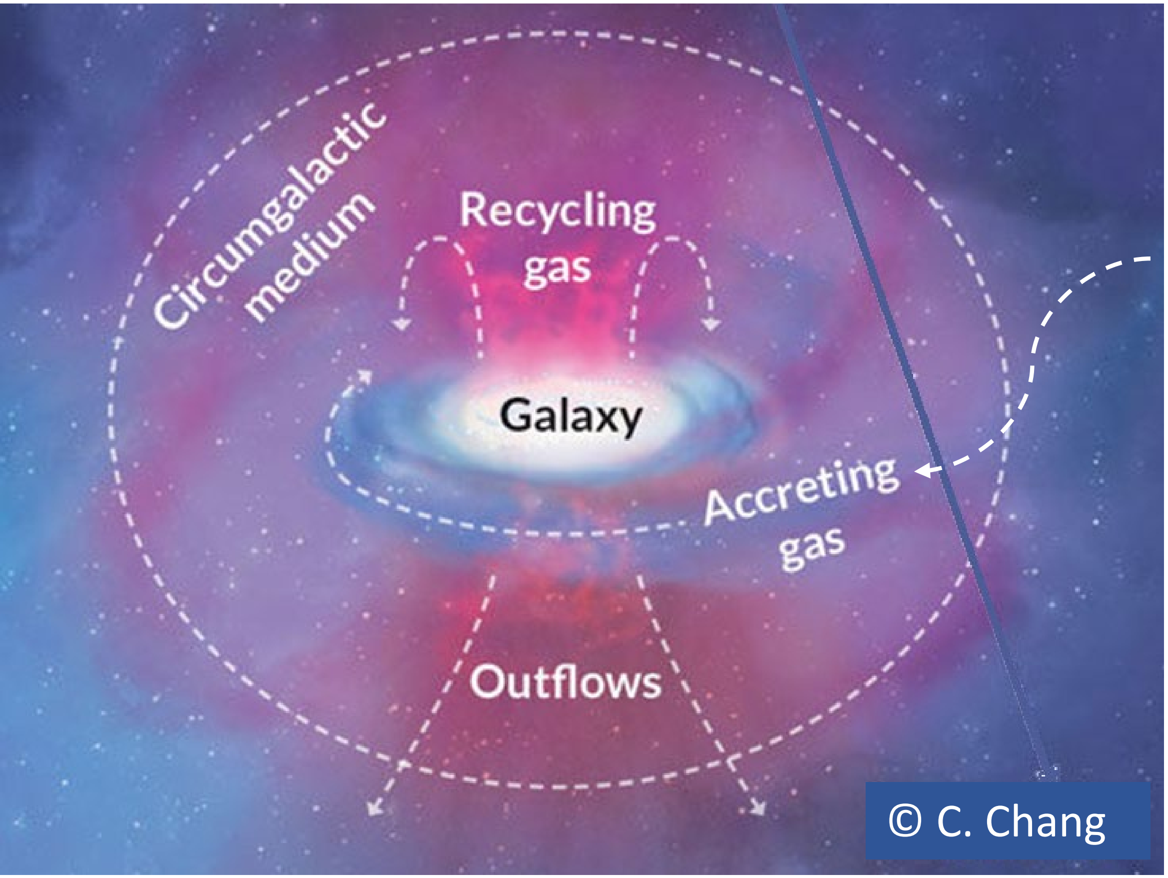
for the HaloSat Team





Halo = Circumgalactic Medium



(Tumlinson et al. 2017, Peeples et al. 2015)

Milky Way sits in gas at ~2×10^6 K.

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

Questions:

- How CGM fed and energized?
- What is the mass of the CGM?
- Does the CGM have a spherical or disk geometry?
- Is the CGM smooth or clumpy?

Observational approach:

- Survey the sky in soft X-rays to look for emission from the hot gas
- Emission dominated by lines from highly ionized oxygen (OVII)

HaloSat is Designed to Measure Diffuse X-Ray Emission

Figure of merit for observing diffuse emission is
grasp = effective area × field of view.

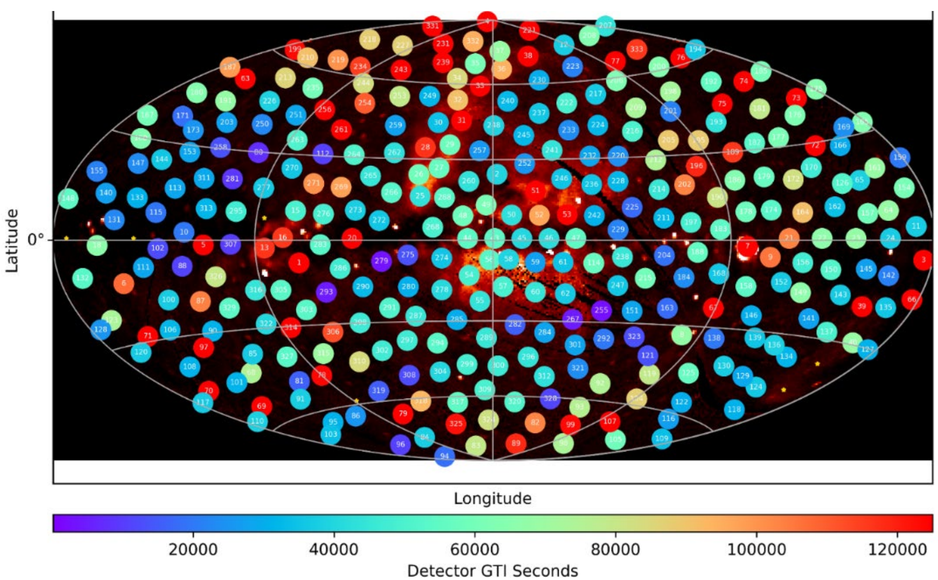
HaloSat grasp is competitive with major missions.

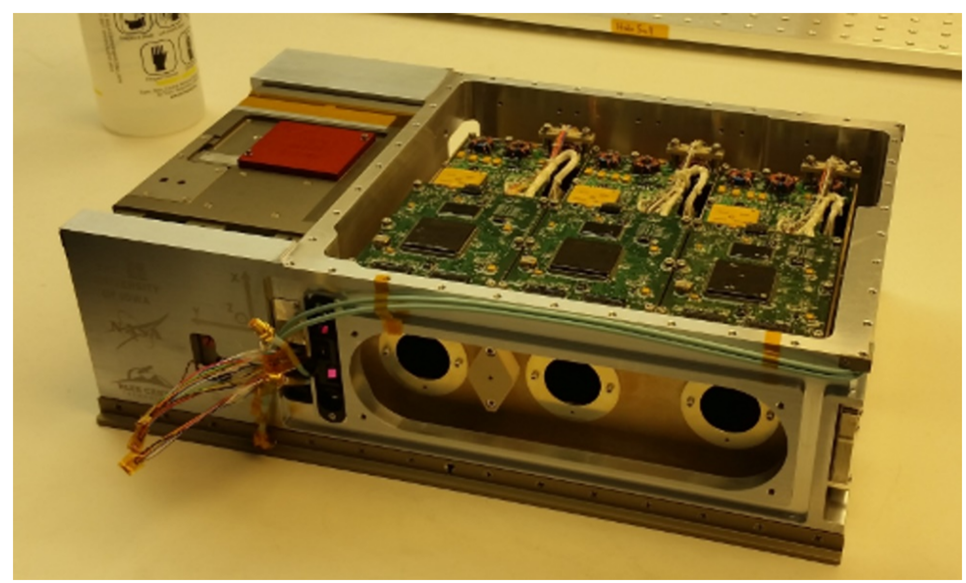
Observing strategy optimized to minimize foreground contamination due to solar wind charge exchange that limits current data.

Surveying sky since 10/2018.

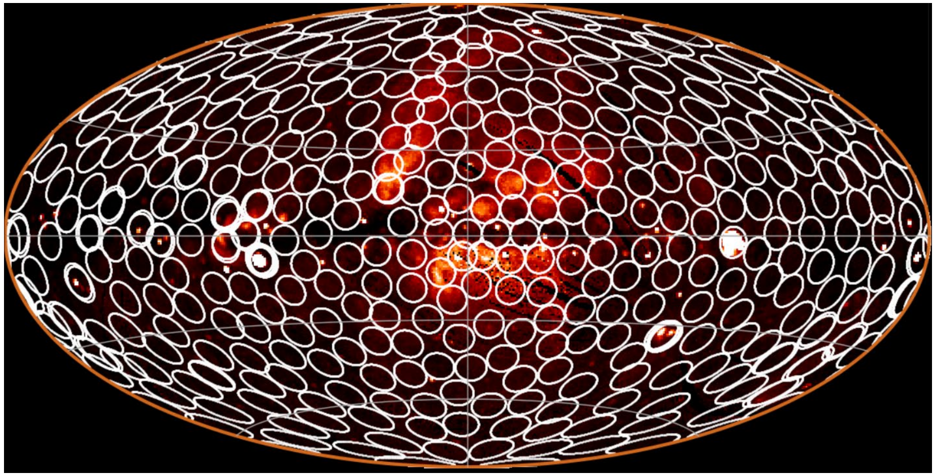
First year of data on HEASARC.

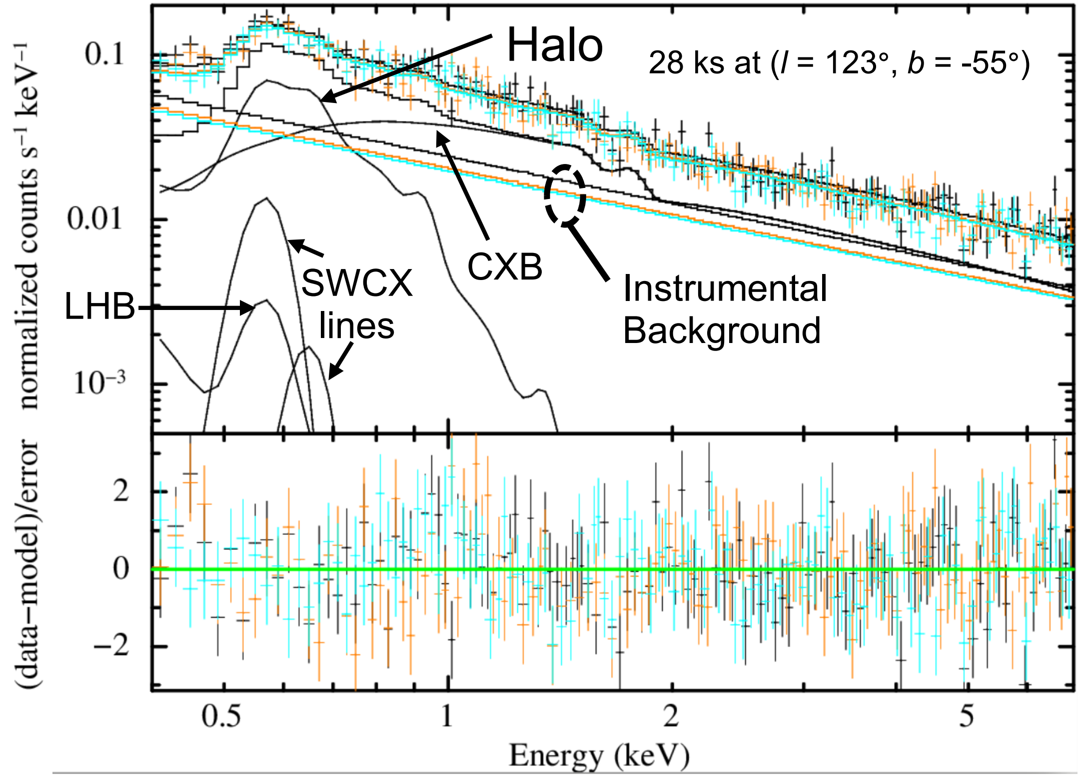
Mission	Grasp ($cm^2\ deg^2$)
HaloSat	17.6
Chandra	8.7
XMM-Newton	73.0





All Sky Survey





All sky survey with 333 fields of view (each 10° diameter)

- Acquire 3 spectra (each detector) for each field

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

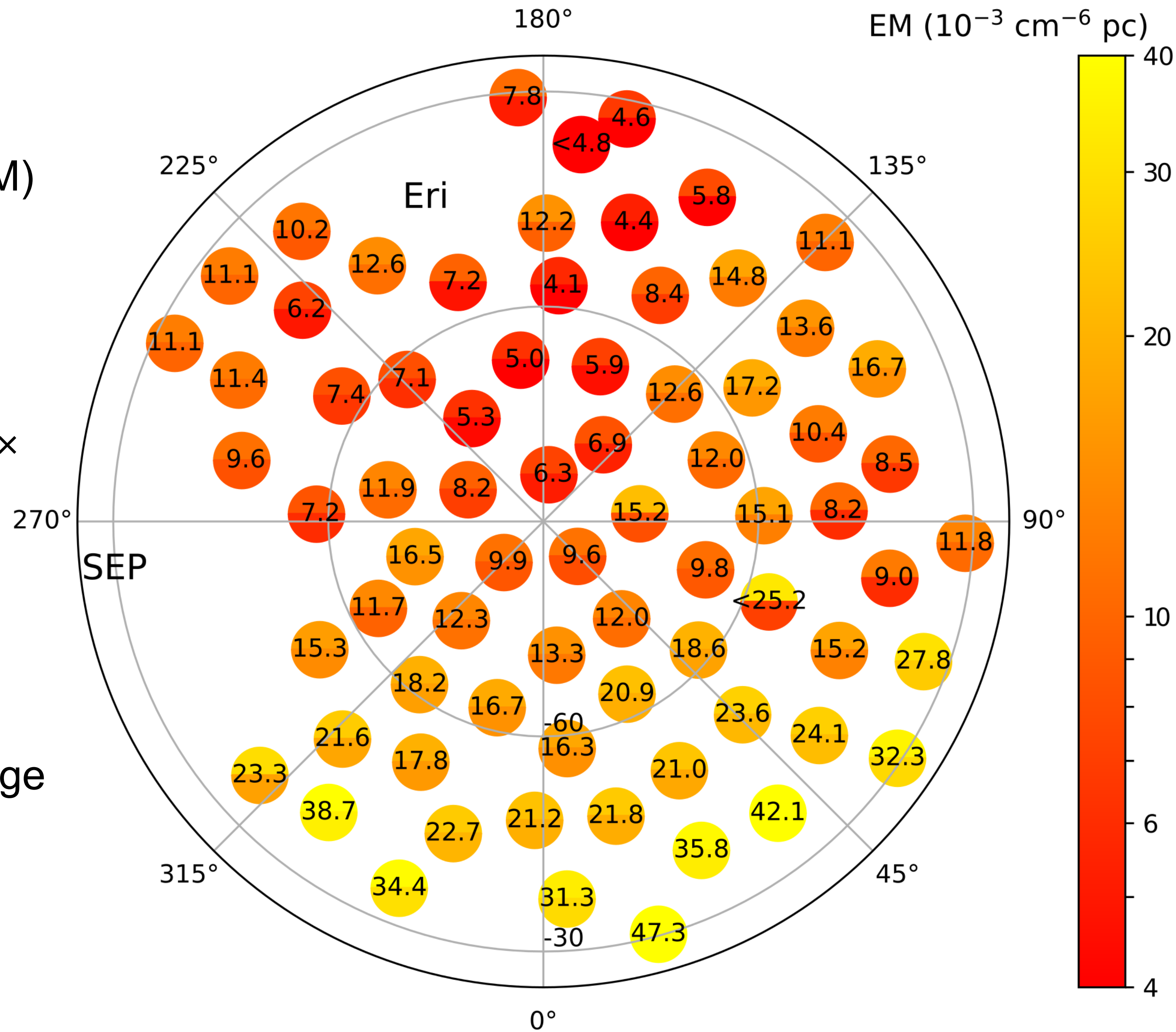
EM, *kT* of each field.

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

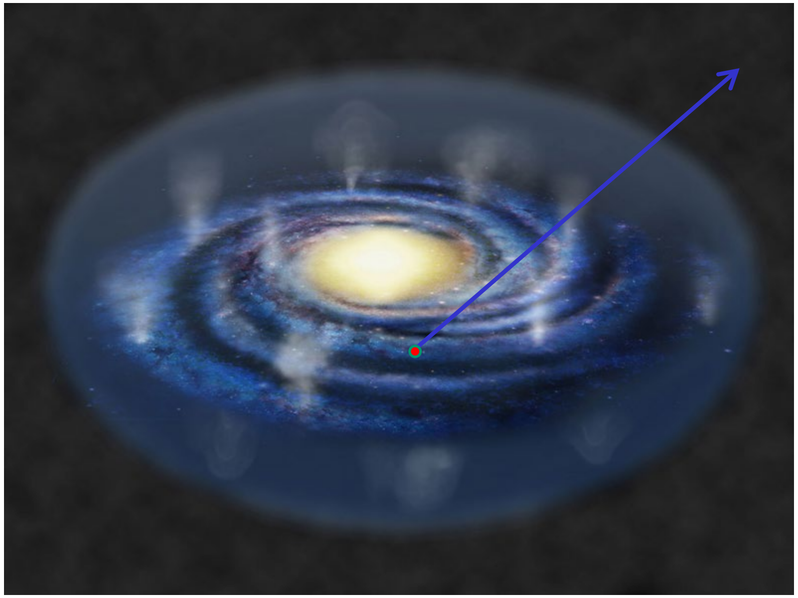
$$EM \propto \int n_e n_H \, dl$$

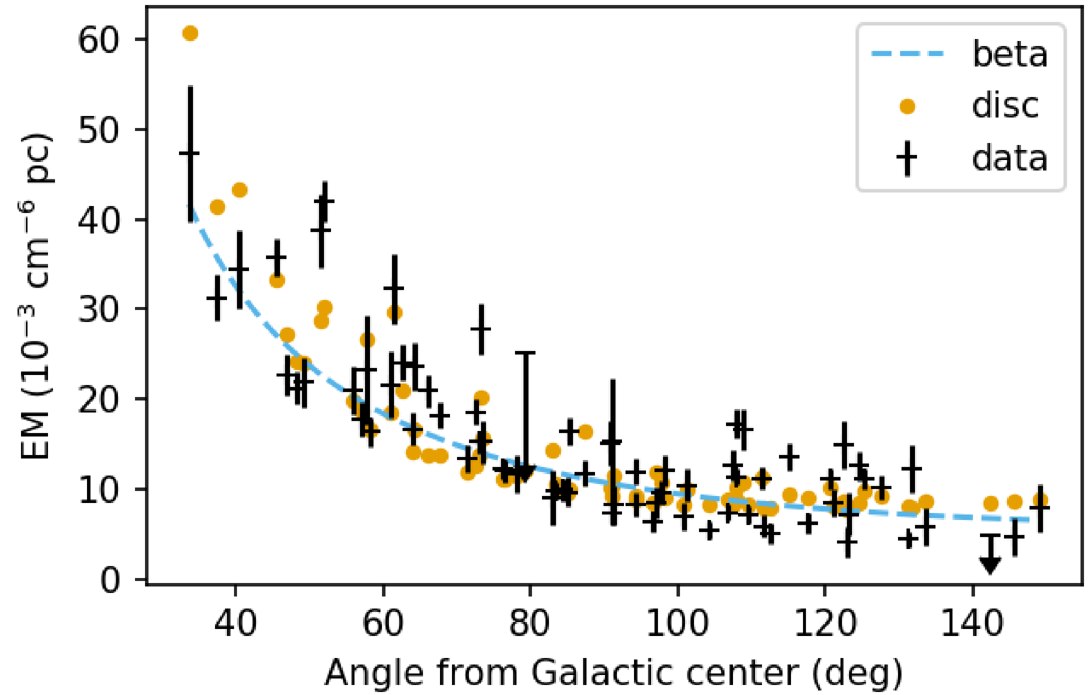
- Large variations ~10×
- Clumpy ~10°-20°
- Brighter towards Galactic center.

- Temperatures in range kT = 0.18-0.28 keV



Fitting models of CGM density distribution



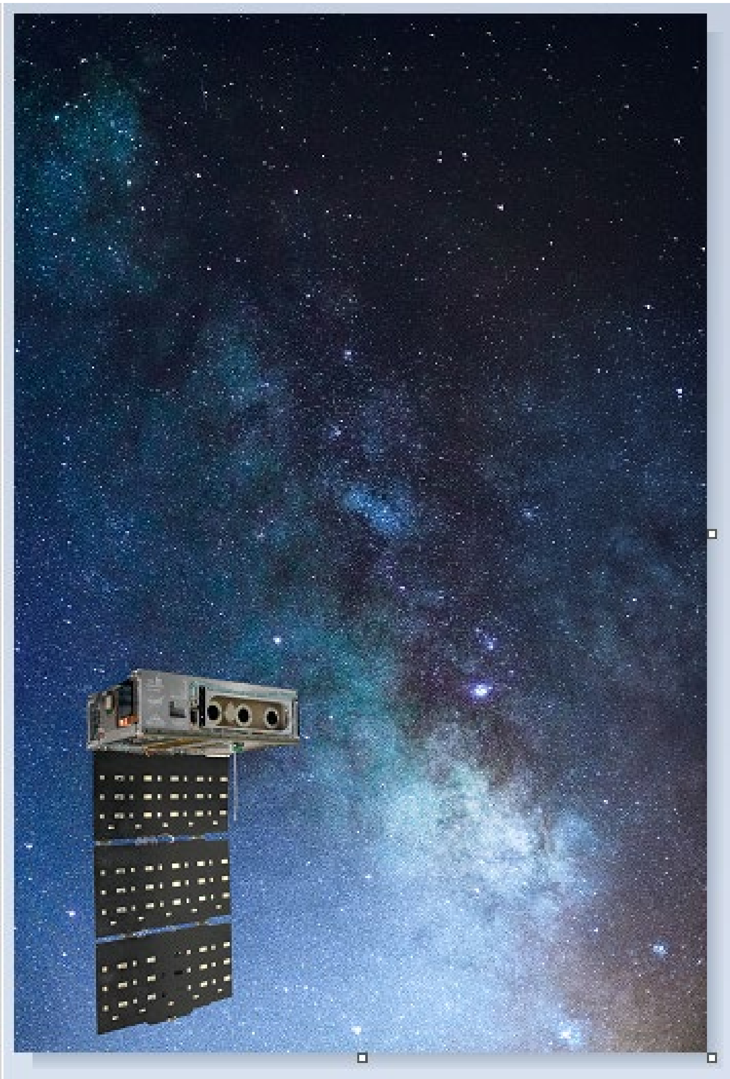


- Pick model for density distribution of hot gas: $n(R, z)$
- Integrate $\int n^2(s)\, ds$ along line of sight, compare to measured EM

- Best fit molecular hydrogen surface density $n(R, z) = n_0\, \Sigma(R)\, e^{-z/z_0}$
- F-test = 3×10^{-6} for empirical disk model vs spherical beta model.
- Scale height = 1.09±0.08 kpc.
- *Soft X-ray emission is dominated by disk emission near the Galactic plane.*

- Disk-only model underpredicts OVII absorption measurements and density in Magellanic stream → fit with added extended halo brings into agreement.

Conclusions



Soft X-ray emission from the CGM

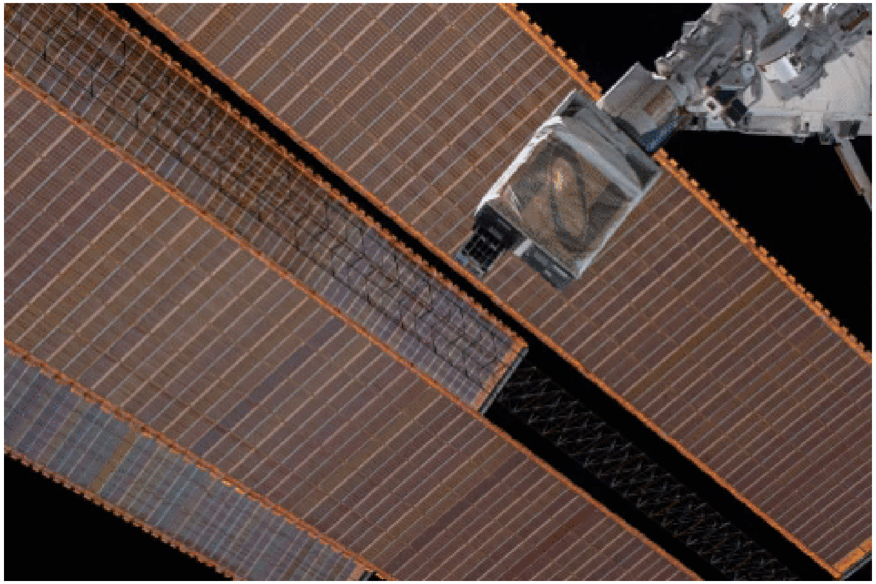
- is clumpy (~10°-20°) and factor ~10 variations,
- has large-scale variations well described by an empirical model of star-formation surface density,
- clumpiness is naturally explained by local variations in star formation,
- is dominated by disk emission near the Galactic plane, and therefore
- should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

Results to appear in Nature Astronomy:
https://www.nature.com/articles/s41550-020-01215-w

Other HaloSat papers on: North Polar Spur (*LaRocca*), Cygnus Superbubble (Bluem), Vela supernova remnant (*Silich*), Large Magellanic Cloud (Gulick)

HaloSat Team

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



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- **NASA/GSFC**: Keith Jahoda, Anna Z, Edmund Hodges-Kluck
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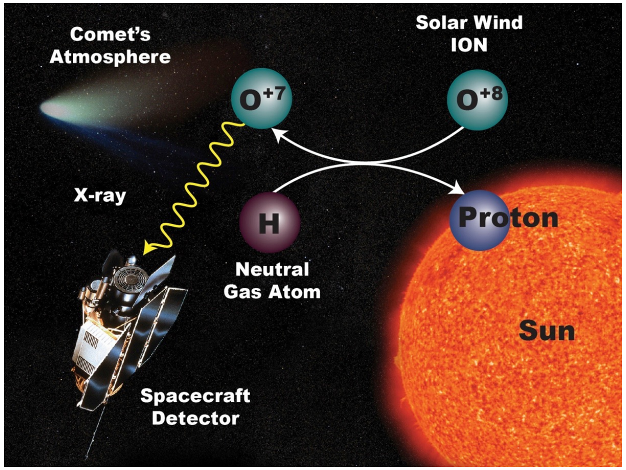
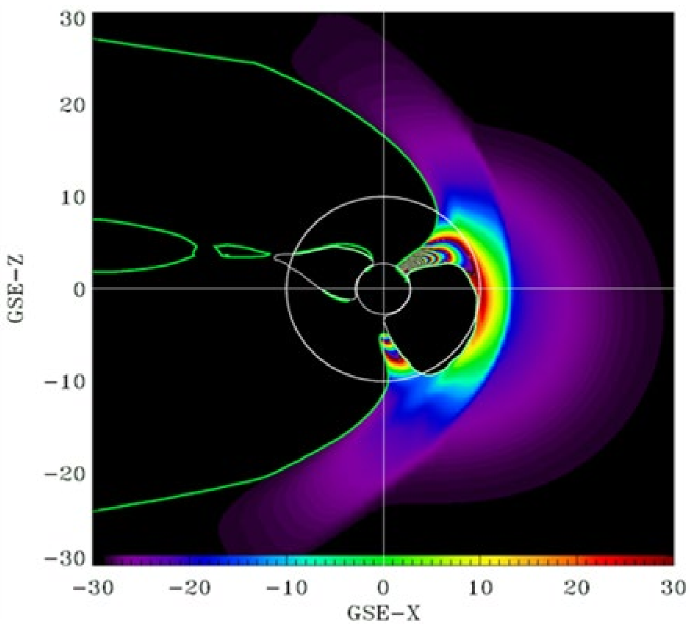
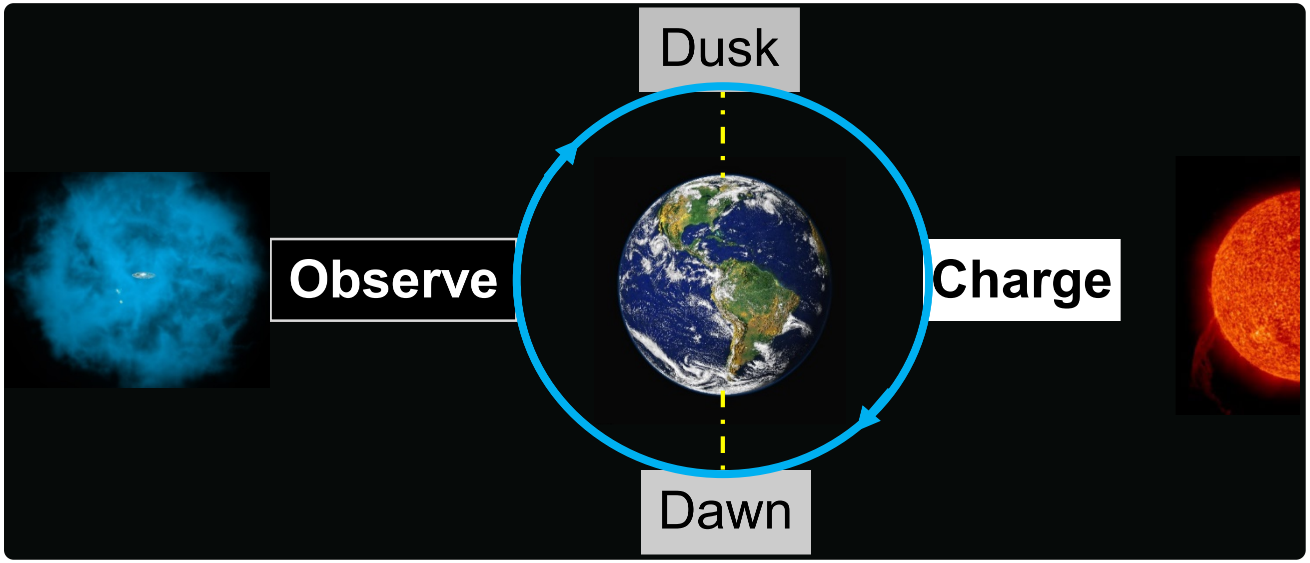
- **Blue Canyon Technologies:** Steve Schneider, Nancy Gaytan, Doug Laczkowski, Chris Esser, Scott Inlow,Tom Golden, Karl Hansen, Kristen Hanslik, John Carvo, Rebecca Walter, Charles Dumont, Matt Pallas

Minimizing Foreground Emission

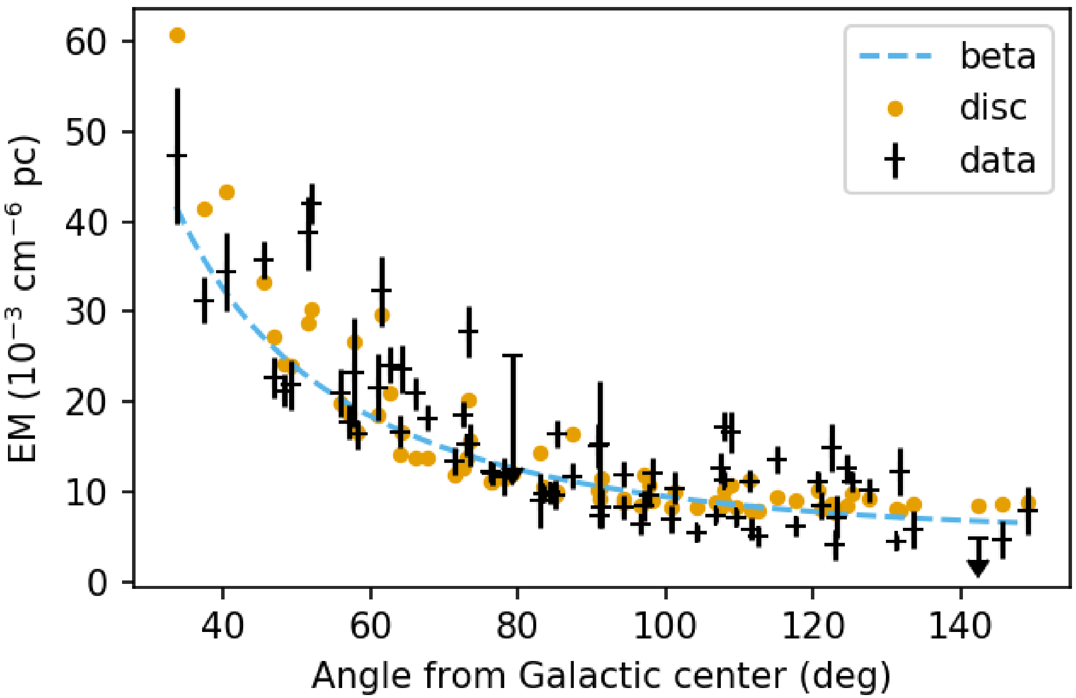
- Accuracy of halo measurements are limited by solar wind charge exchange emission (SWCX) from magnetosphere and heliosphere.
- HaloSat observes at spacecraft night and we use targets within 70° of anti-Sun to minimize foreground emission.
- We model the heliospheric SWCX for each observation using solar wind measurements

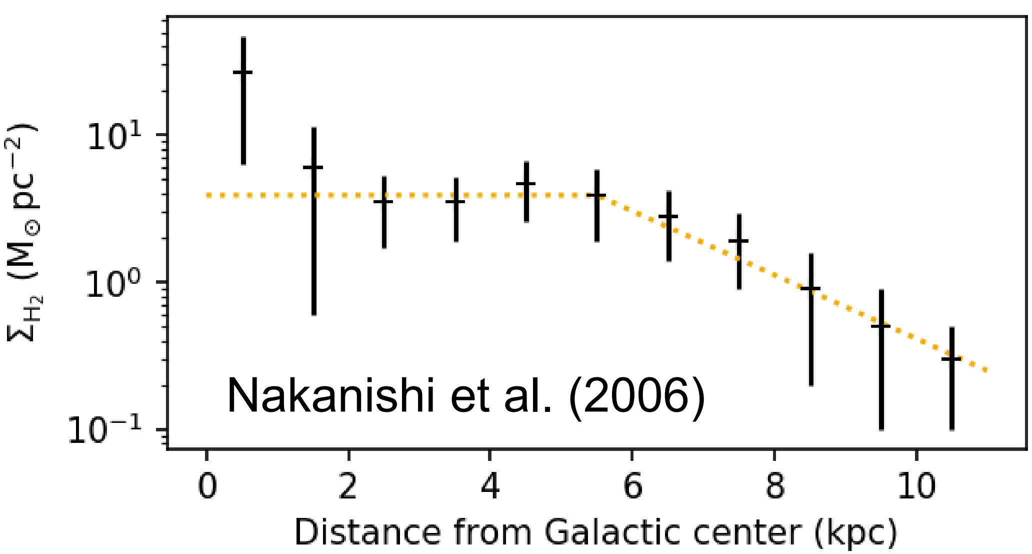






Model Fitting





- Beta-model $n(r) = n_c(r/r_c)^{-3\beta}$
- Disk $n(R,z) = n_0 e^{-R/R_0} e^{-z/z_0}$
- Disk model is preferred, suggesting relation to star formation.

- Use molecular hydrogen surface density to trace star formation → improved fit, F-test of 3×10^{-6} for empirical disk model vs beta model.
- Scale height = 1.09±0.08 kpc.

- Soft X-ray emission is dominated by disk emission near the Galactic plane.

Other Observations

- Hα emission from the Magellanic Stream and ram-pressure stripping of satellite galaxies suggest an extended halo, $n_H \sim 10^{-4}$ cm^{-3} at ~50 kpc.
- X-ray oxygen absorption line measurements are sensitive to lower density plasma, signal varies as $\int n\, dl$ instead of $\int n^2\, dl$.
- Best fit empirical disk model from emission alone underpredicts the densities inferred from these measurements → extended component required.

- Adding an extended component modeled as an adiabatic gas with polytropic index = 5/3 in hydrostatic equilibrium with the dark matter halo (Maller & Bullock 2004; Fang et al. 2013) provides agreement with these observations and permits a halo mass sufficient to account for missing baryons.