Blowing Bubbles in the Galaxy: Chandra Detects the 1st Ever Resolved Astrosphere Around a Main Sequence G-Star

HD 61005 (aka "The Moth"), an ~100 Myr Old, "Opposite Side of the Local Bubble", G9V Disk-Hosting Star

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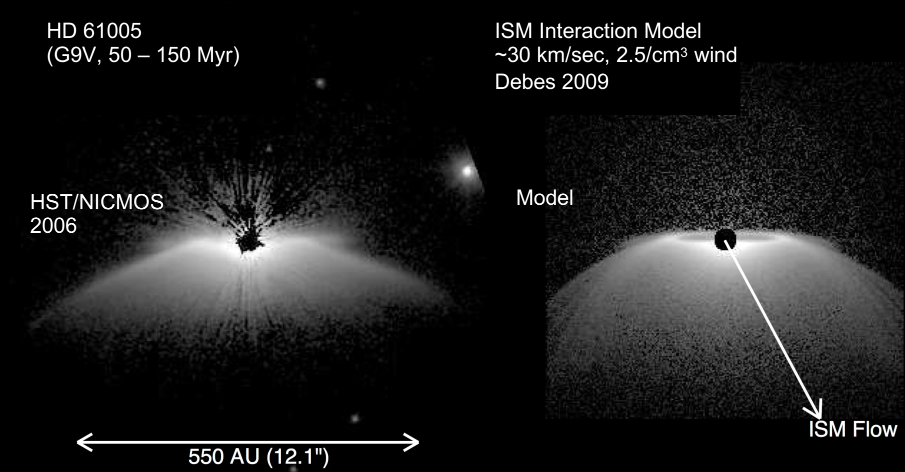
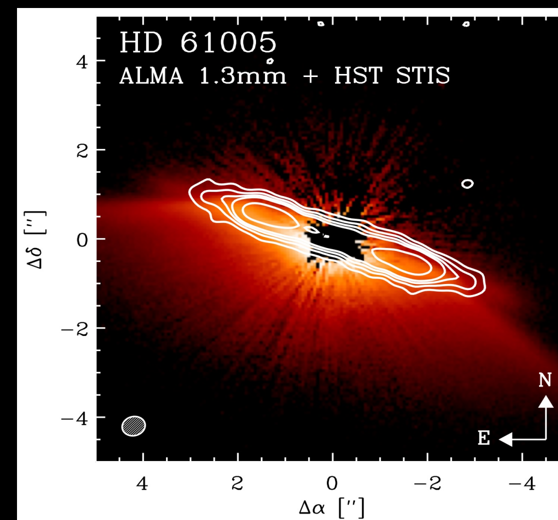
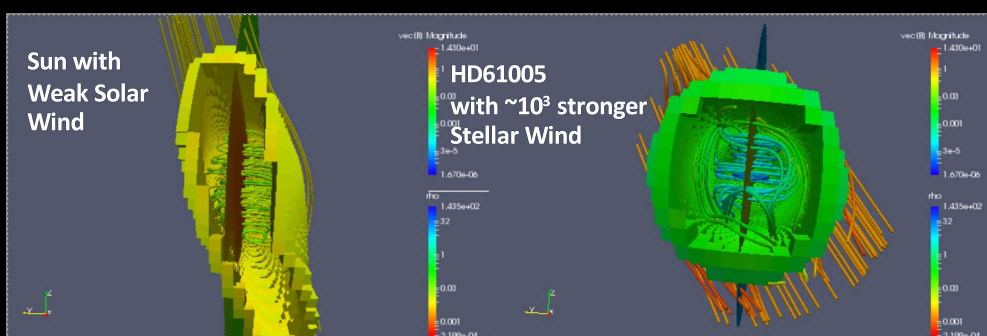


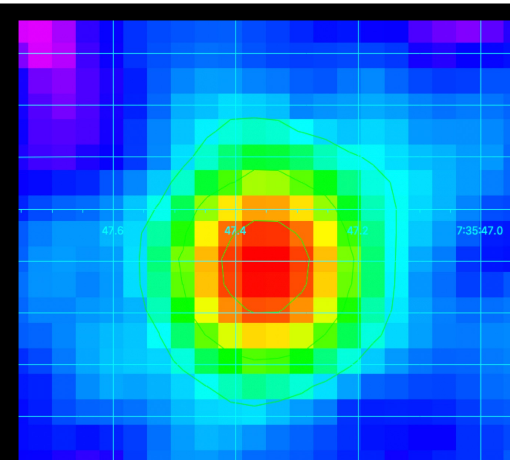
HD 61005:
Nearby (36 pc)
~100 Myr Old
G9V **Travelling**
Through a Dense
Part of the ISM
= **Our Sun** at
Zero-Age Main
Sequence Passing
Thru a GMC





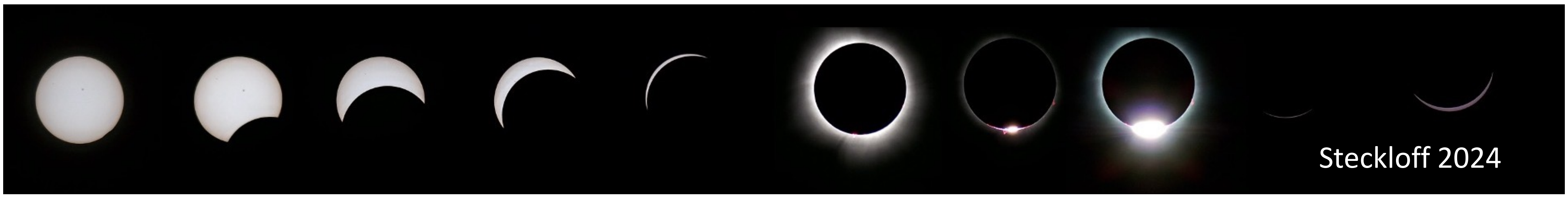
Parker 1960 Heliosphere Models

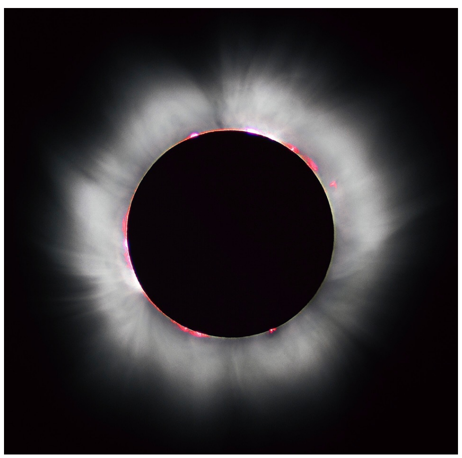
New Chandra
HD61005 X-ray
Spectral Imaging
of Extended
Astrosphere + Star
(Lisse+ 2024)

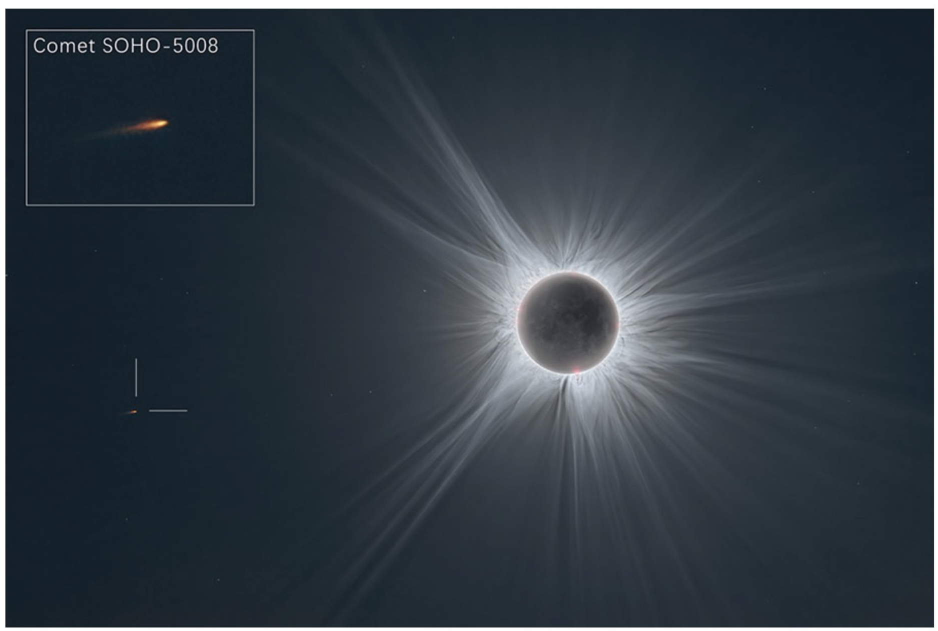


To Start: Some Quick Background, since this work combines elements of heliophysics, exodisk astronomy, and x-ray astronomy.

Stars have Coronae, or Ultra Hot (~MK), Thin Atmospheres above their Optical Surfaces that create Hot, Diffuse Wind Outflows AND emit “Coronal” x-ray radiation, dominated by a thermal x-ray continuum.

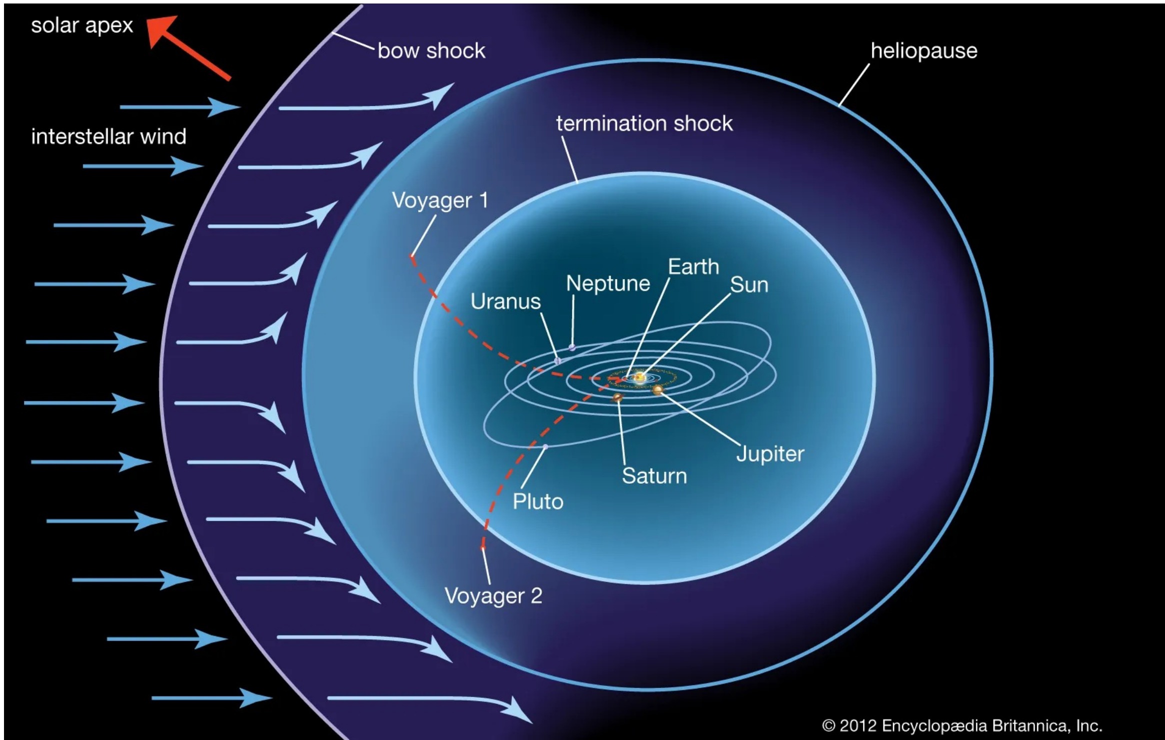


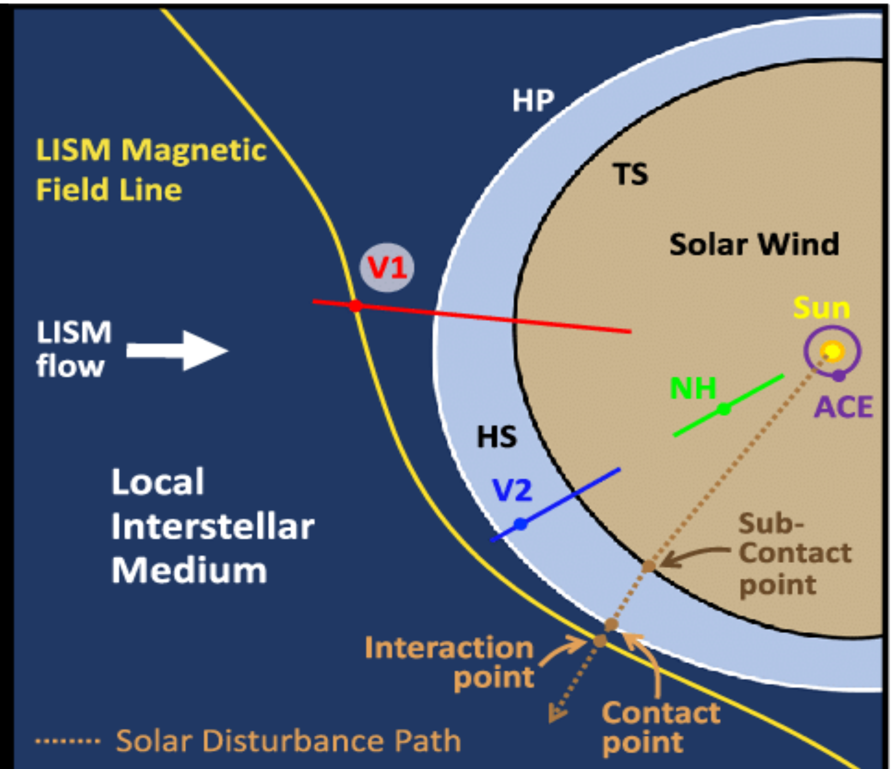


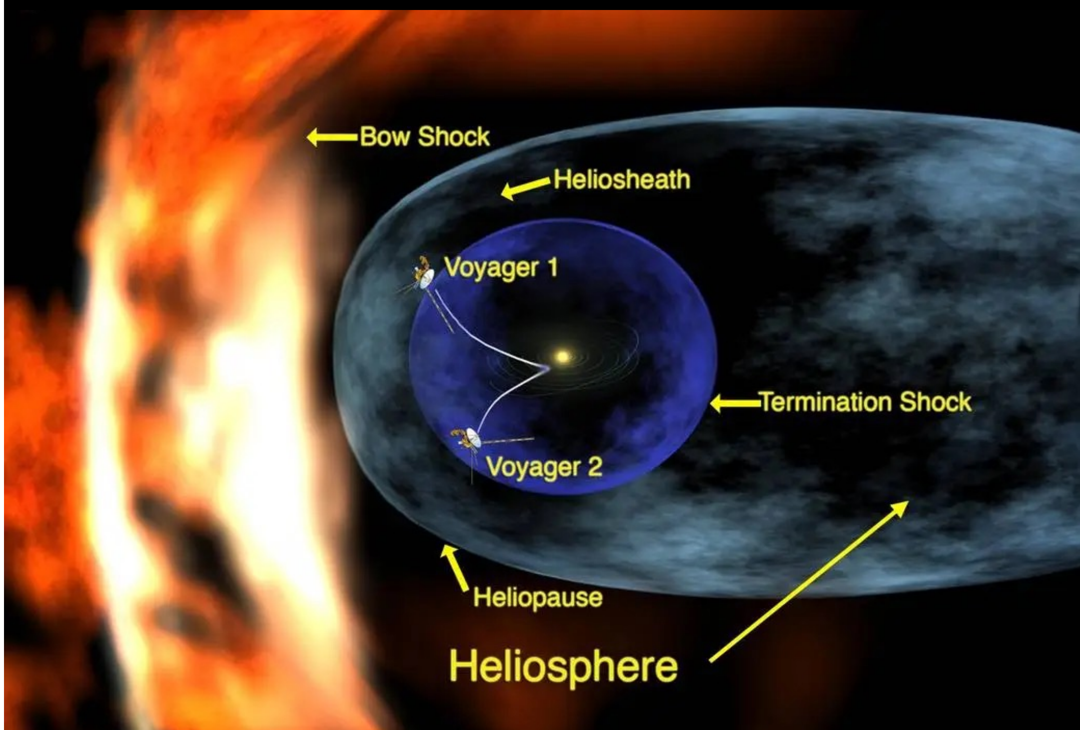


This wide-field photo of totality caught the Kreutz sungrazing comet, 5008 SOHO.
Lin Zixuan (Tsinghua University, China)

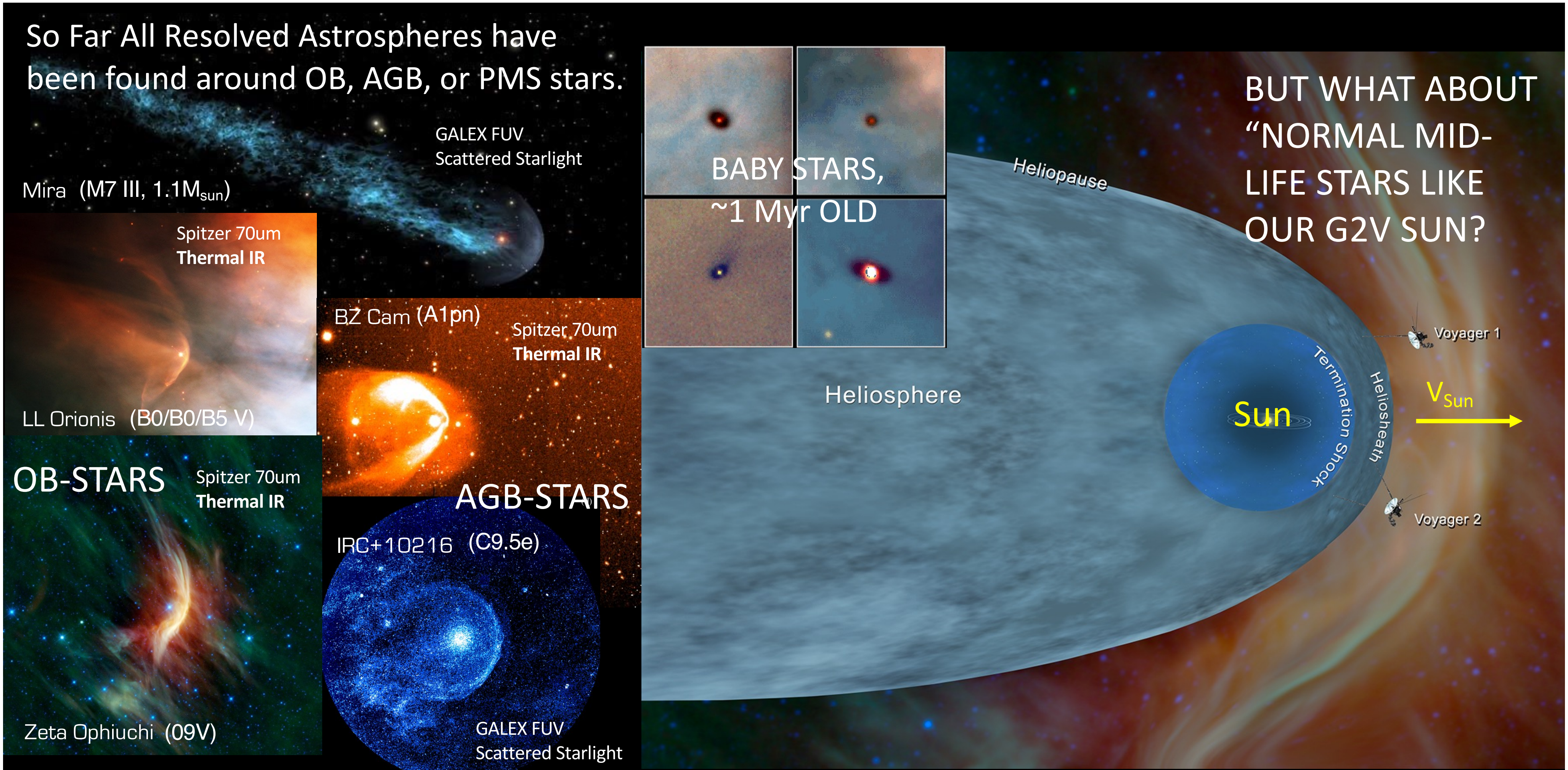
Great 08-Apr-2024 North American Solar Eclipse Directly Revealed the Actinic Light from Our Sun’s ~1.3 MK Corona.







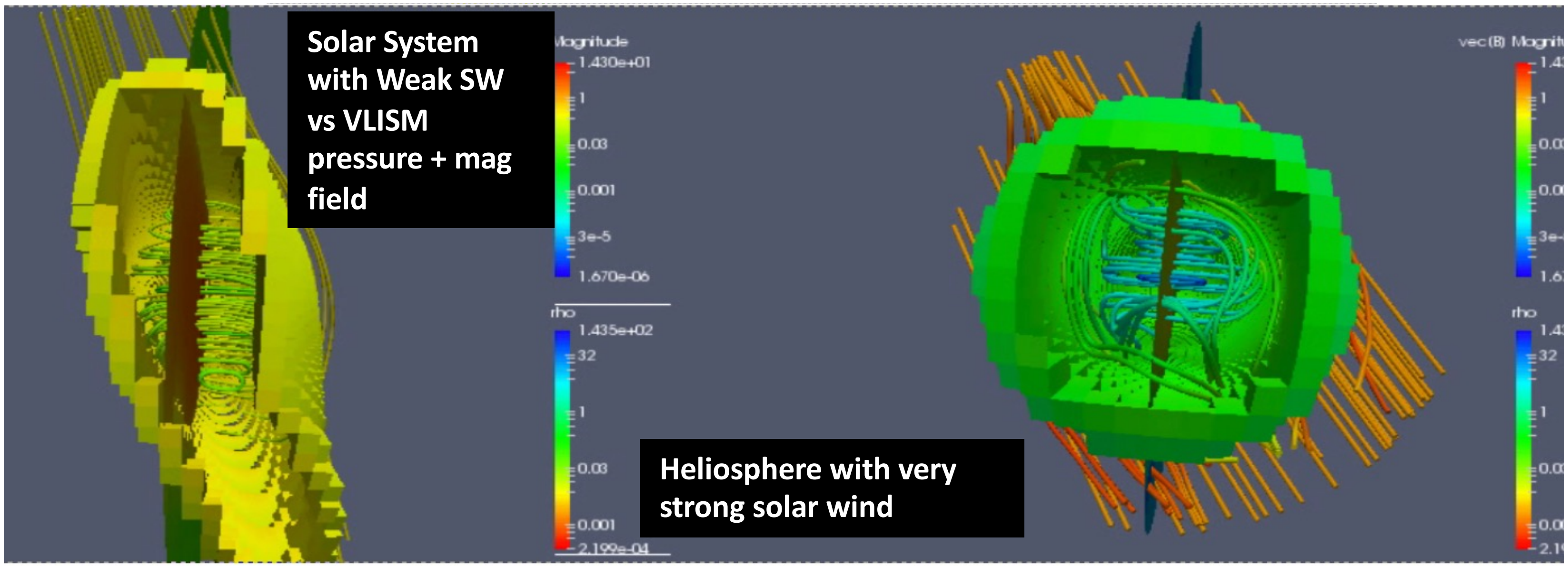
Stars also have Astrospheres, bubbles blown out of the Galaxy by the pressure of a star's stellar wind (SW). Their boundaries are defined where the pressure of the instreaming galactic material (due to the star's orbital motion through the galaxy) equals the pressure of the outflowing SW.



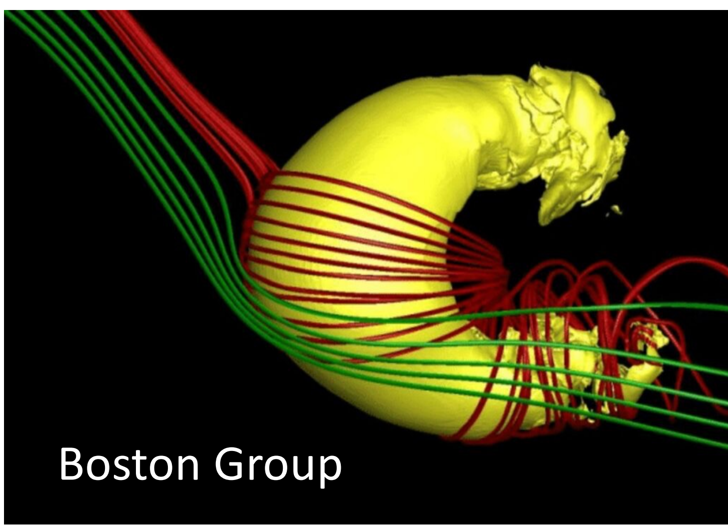
In order to understand what **our own heliosphere** is like, understanding other system's astrospheres & astroshocks is very important - but none of the O, B, or AGB star systems with known resolved astrospheres are anything like G2V Sol.

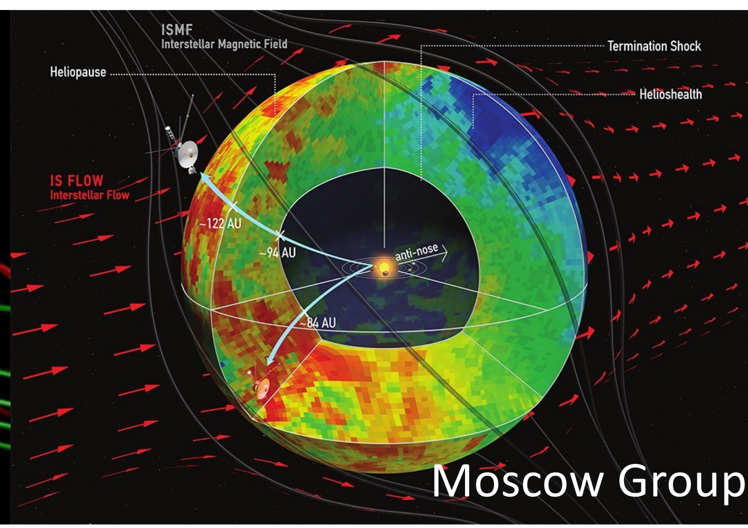
Detecting Astrospheres Around Mid-Life, Main Sequence Stars Like the Sun is Hard, even for nearby Local Bubble systems!

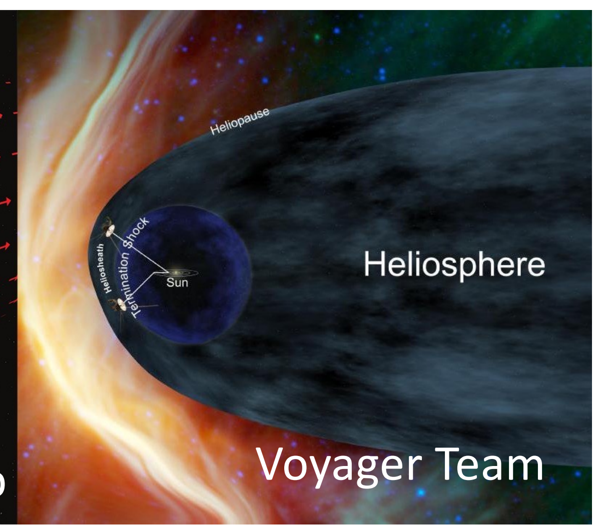
In 1960 using pressure balance $n_{SW} * v_{SW}^2 = n_{ISM} * v_{ISM}^2 + B_{ISM}^2/4\pi + P_{ISM,thermal}$, **Parker** found, with cavity radius ~10^2 AU, two limiting heliospheric morphological solutions:



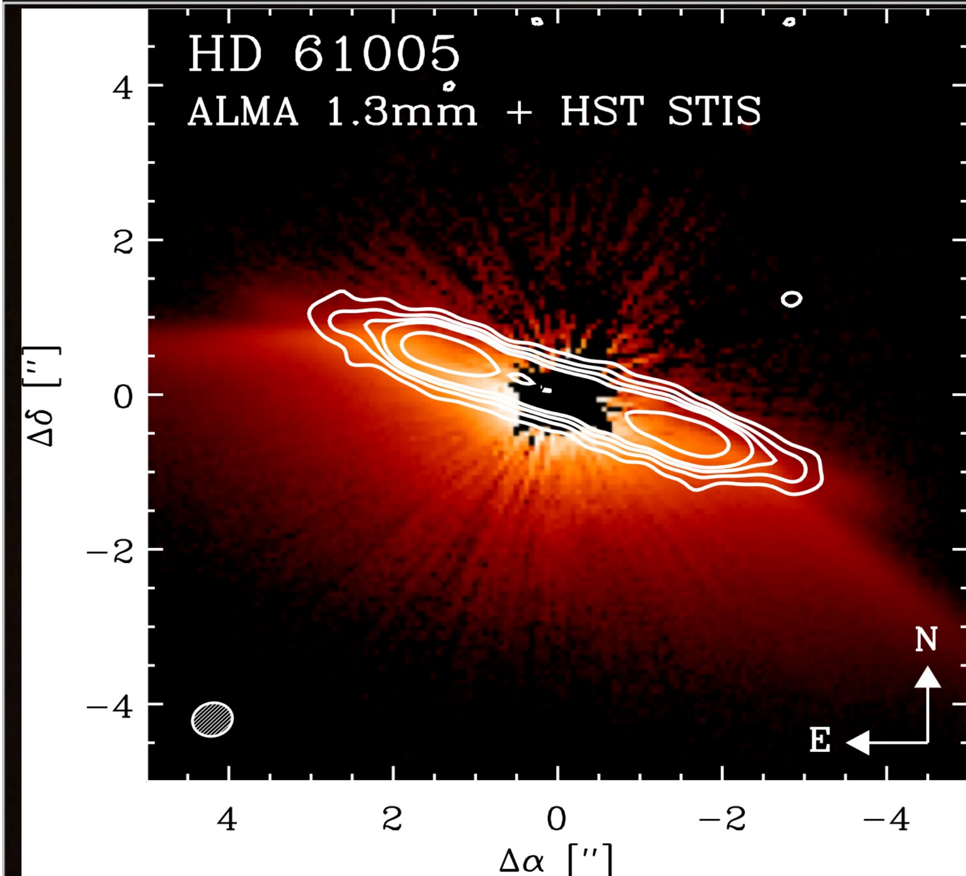
Modern Day : Very Different Models for Our Heliosphere's Morphology Still Exist





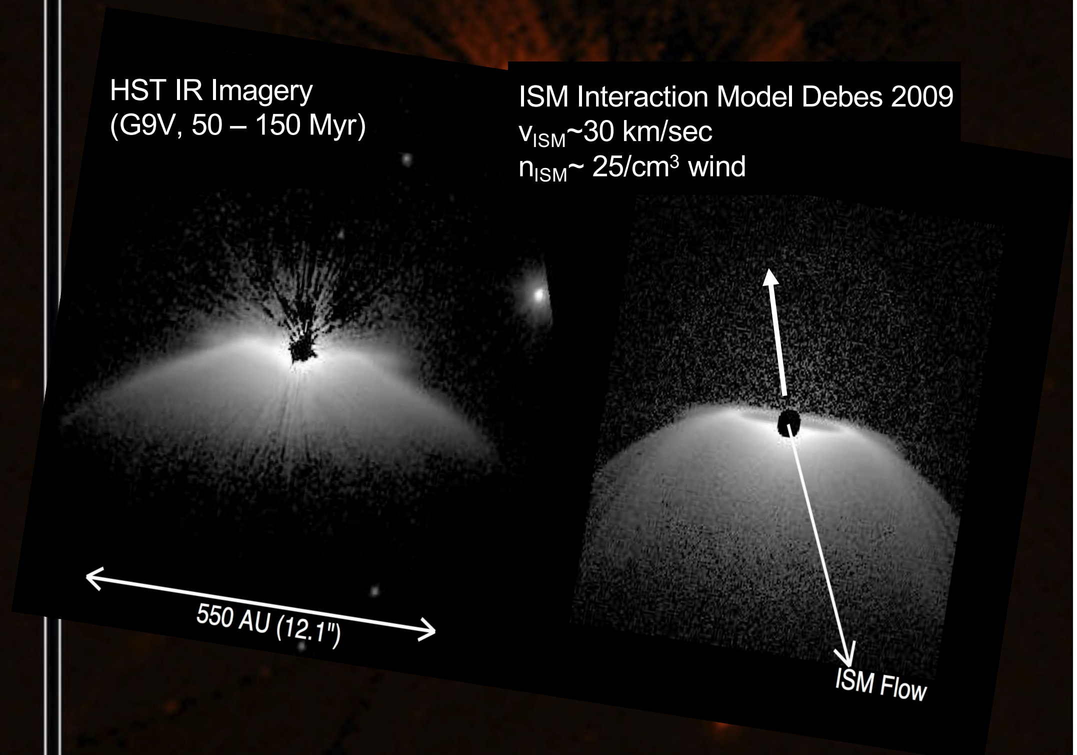


Enter HD61005 (aka "The MOTH"). A known ROSAT x-ray system harboring a Circumstellar Dust Disk with marked structure due to ISM-Disk Interactions.



150 AU

Size of Neptune's Orbit



NICMOS

MODEL

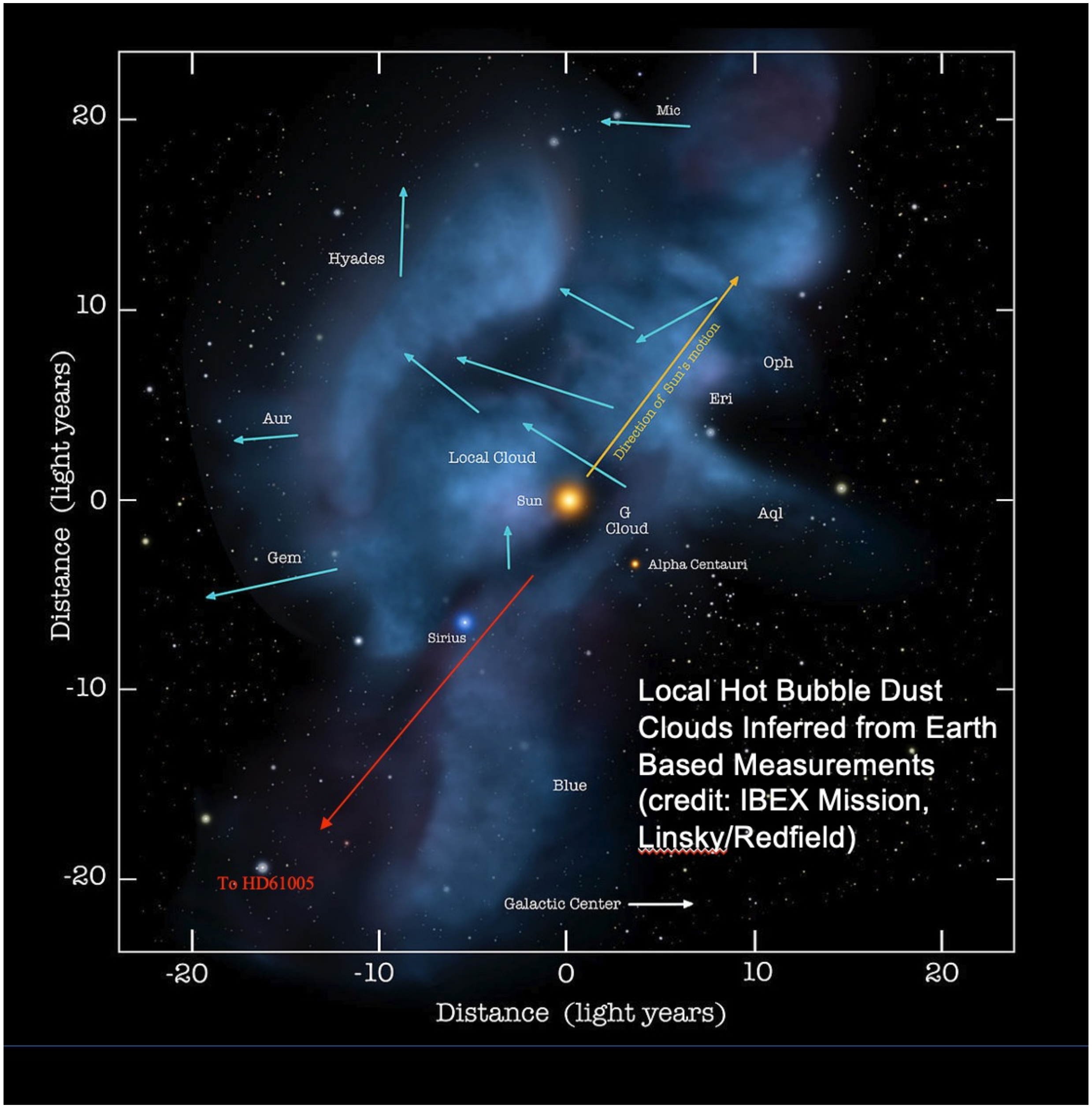
HD 61005 Circumstellar Disk ▪ The Moth

Hubble Space Telescope ▪ NICMOS

NASA, ESA, D. Hines (Space Science Institute, New Mexico), and G. Schneider (University of Arizona) 2007

STScI-PRC08-01

HD 61005 is located ~110 ly (36 pc) away, **on the Other Side of the Local Bubble**, in Puppis (close to the sky directions of Sirius and Epsilon Canis Majoris), and close to the galactic plane.



HD61005: G9V

Mass = ~0.9 M_{sun}

Luminosity = 0.7 L_{sun}

Radius = 0.86 R_{sun}

T_{eff} = 5480 K (0.95T_{sun})

Age = 50 - 100 Myr old

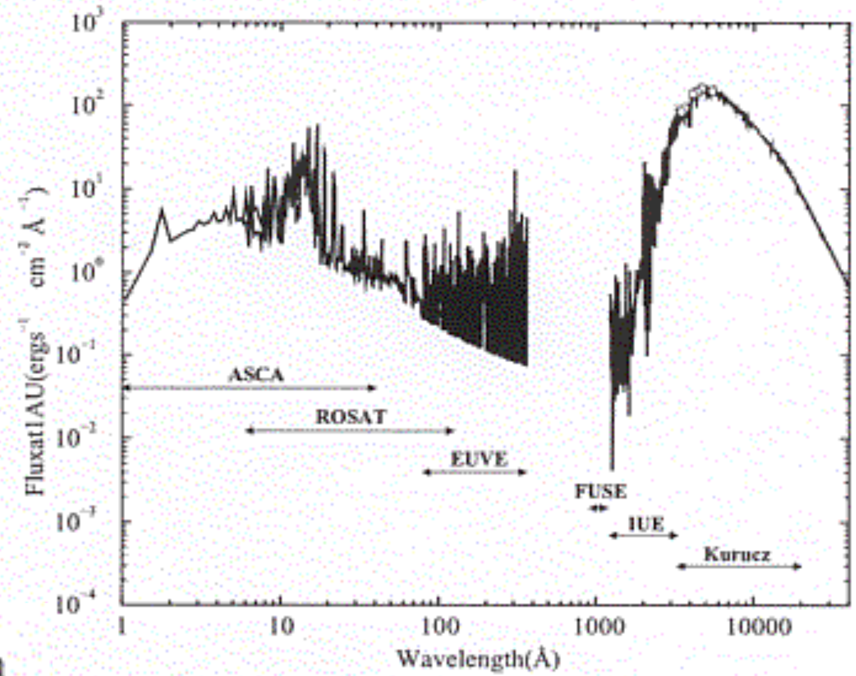
P_{rot} ~ 5 days

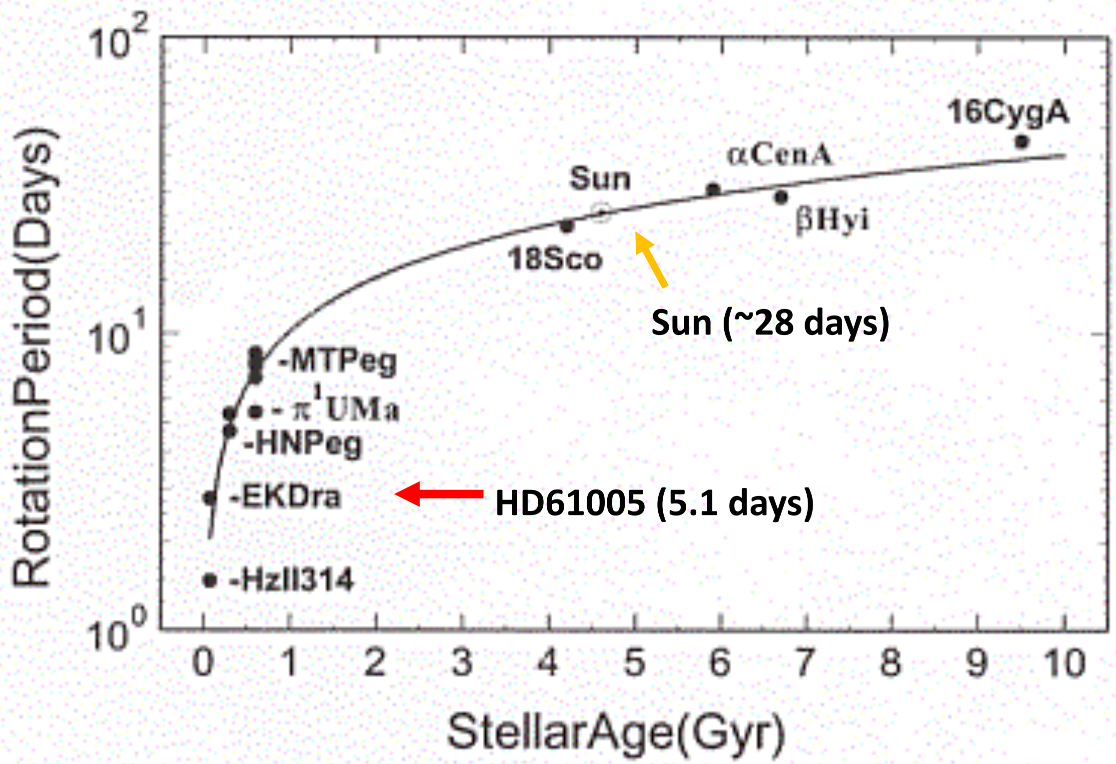
d = 36 pc distant

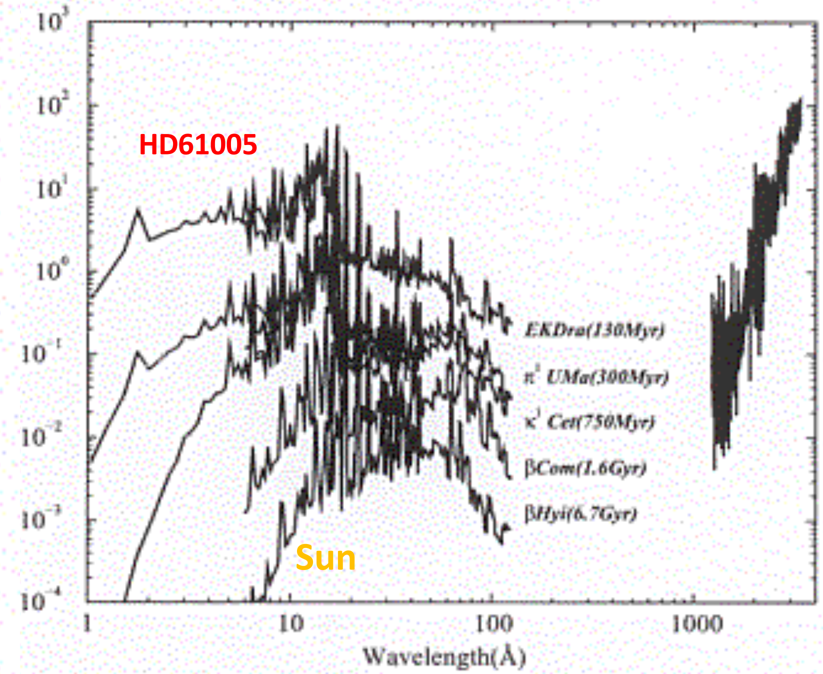
No known planets (yet)

"Sun in Time" study of G-star behavior by Guinan+ 2002, 2007 :

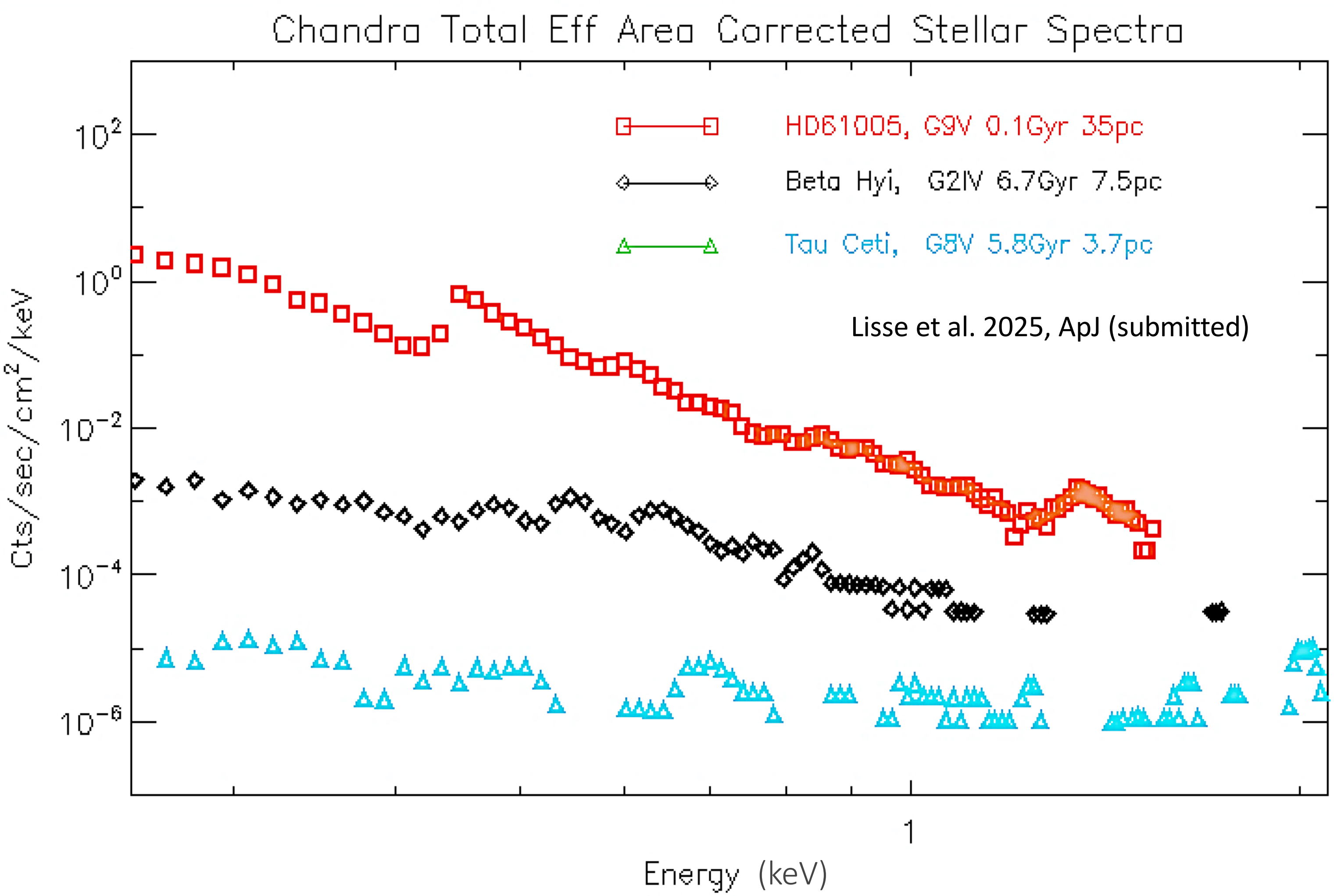
We can expect ~100 Myr old Sun-like stars (e.g. EK Dra, HD61005) should have hot coronae with 10^2-10^3 times more XUV flux & SW than the Sun





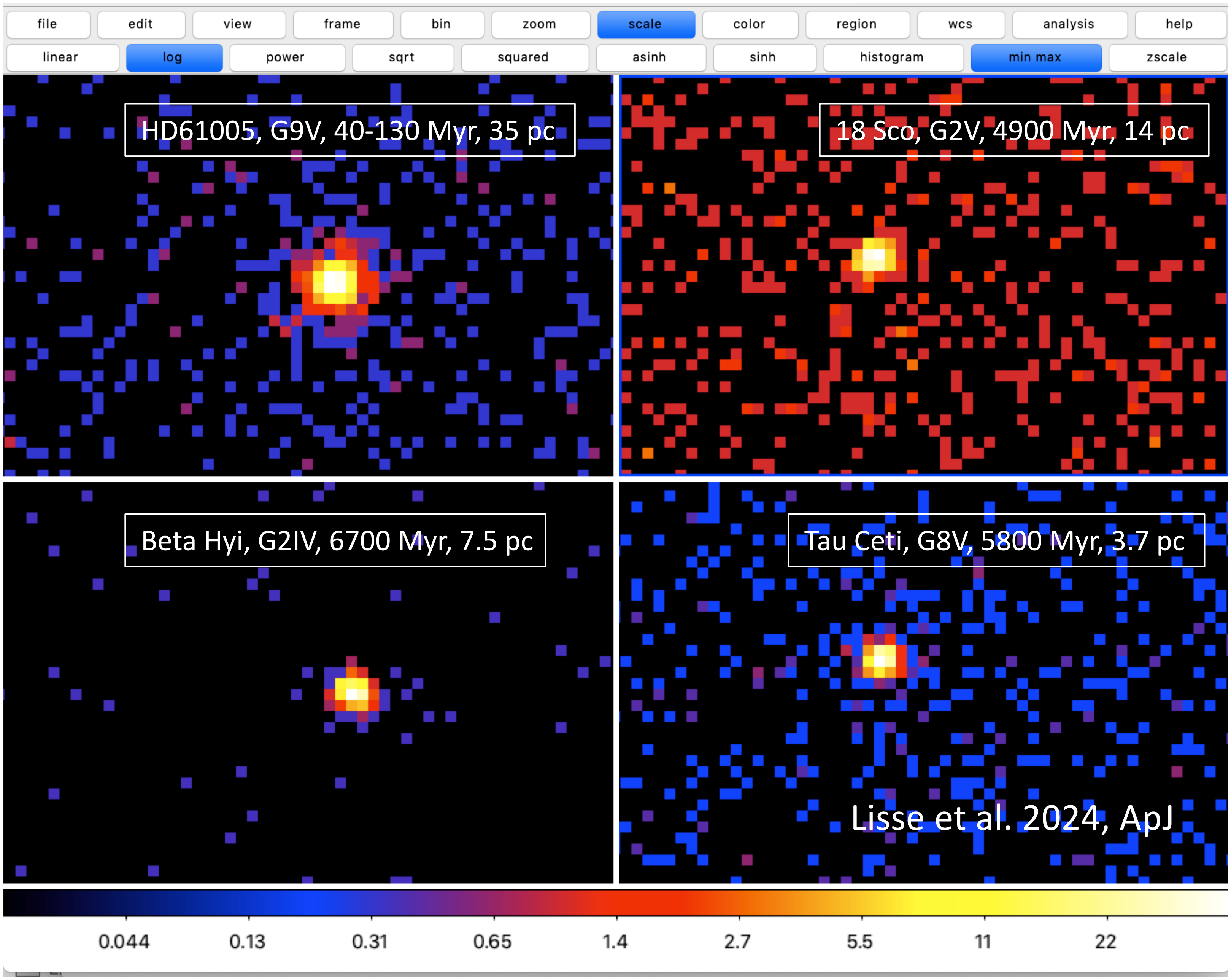


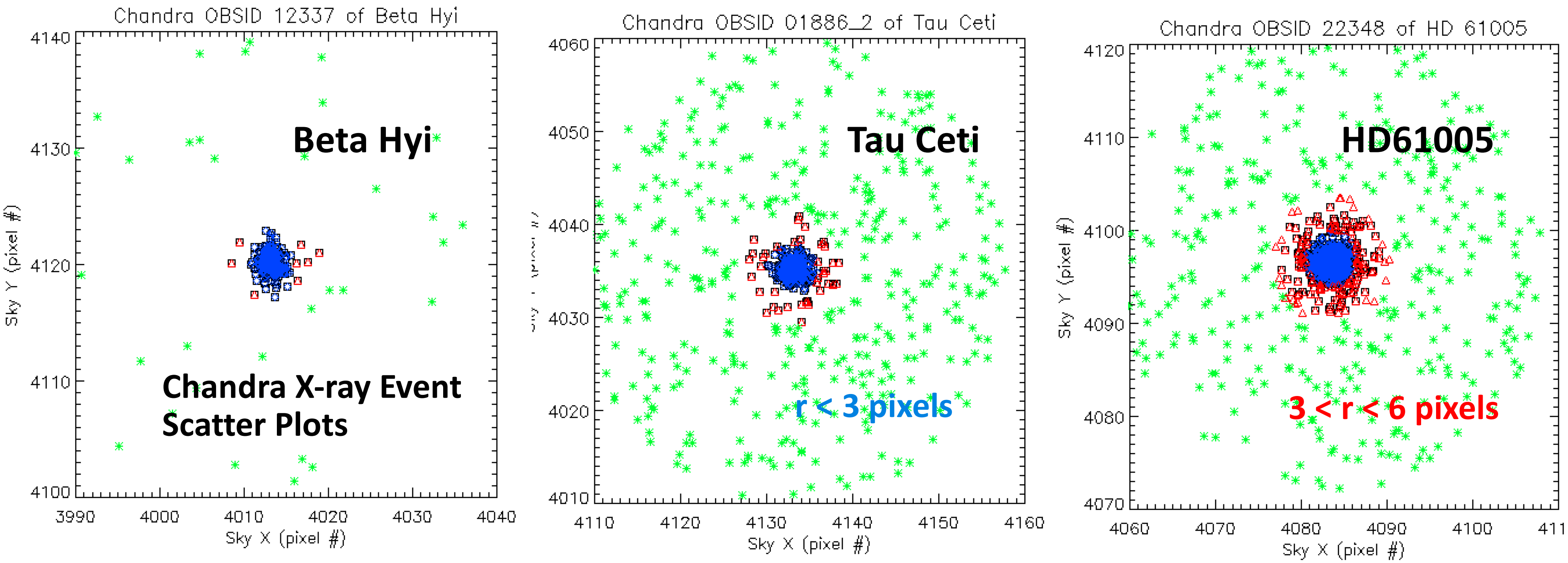
Our new *Chandra* ACIS-S observations of HD61005 in Feb 2021 show that
~0.1 Gyrs old HD61005 is 2-3 orders of magnitude more luminous in the X-ray than 6-8 Gyrs old Beta Hyi & Tau Ceti (as predicted by Guinan+ 2005, 2007)



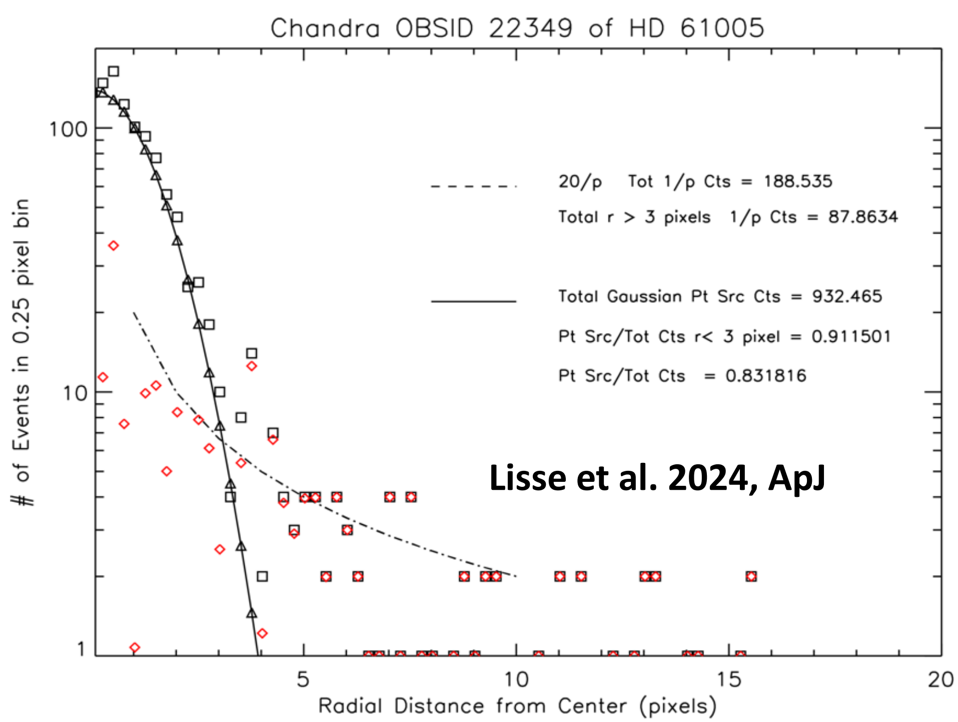
X-ray spectra for HD61005, Tau Ceti and Beta Hyi after correction for total on-target integration time, distance, and ACIS-S Effective Collecting Area.

HD61005 is clearly extended in our new Chandra ACIS-S imagery vs. archival *Chandra* images of other Sun-like G-stars.





Chandra ACIS-S images of Beta Hyi and Tau Ceti vs HD61005. Stellar coronal vs astrosphere components.

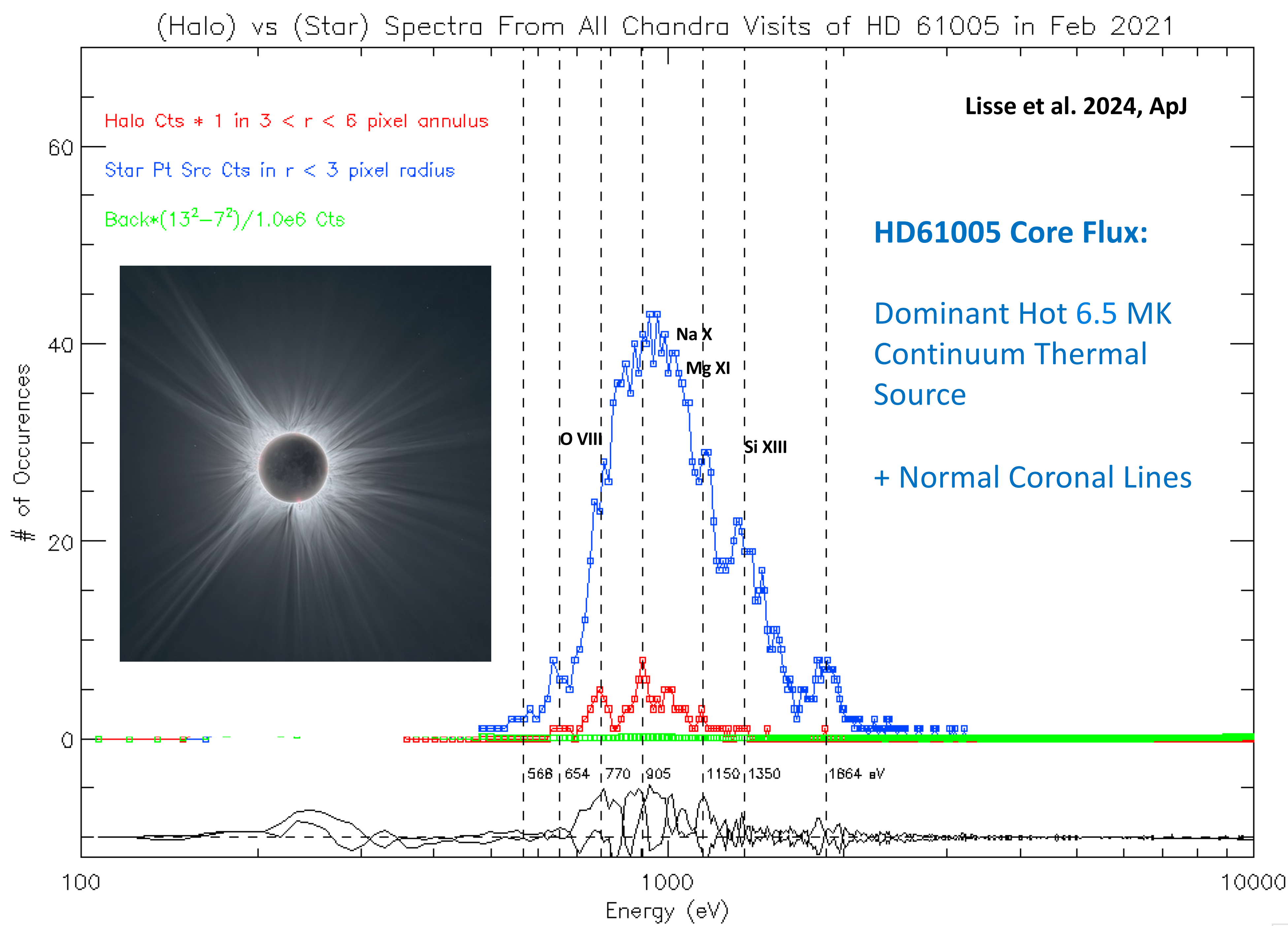


Chandra ACIS-S background-corrected radial aperture photometry. Two components are clearly seen:

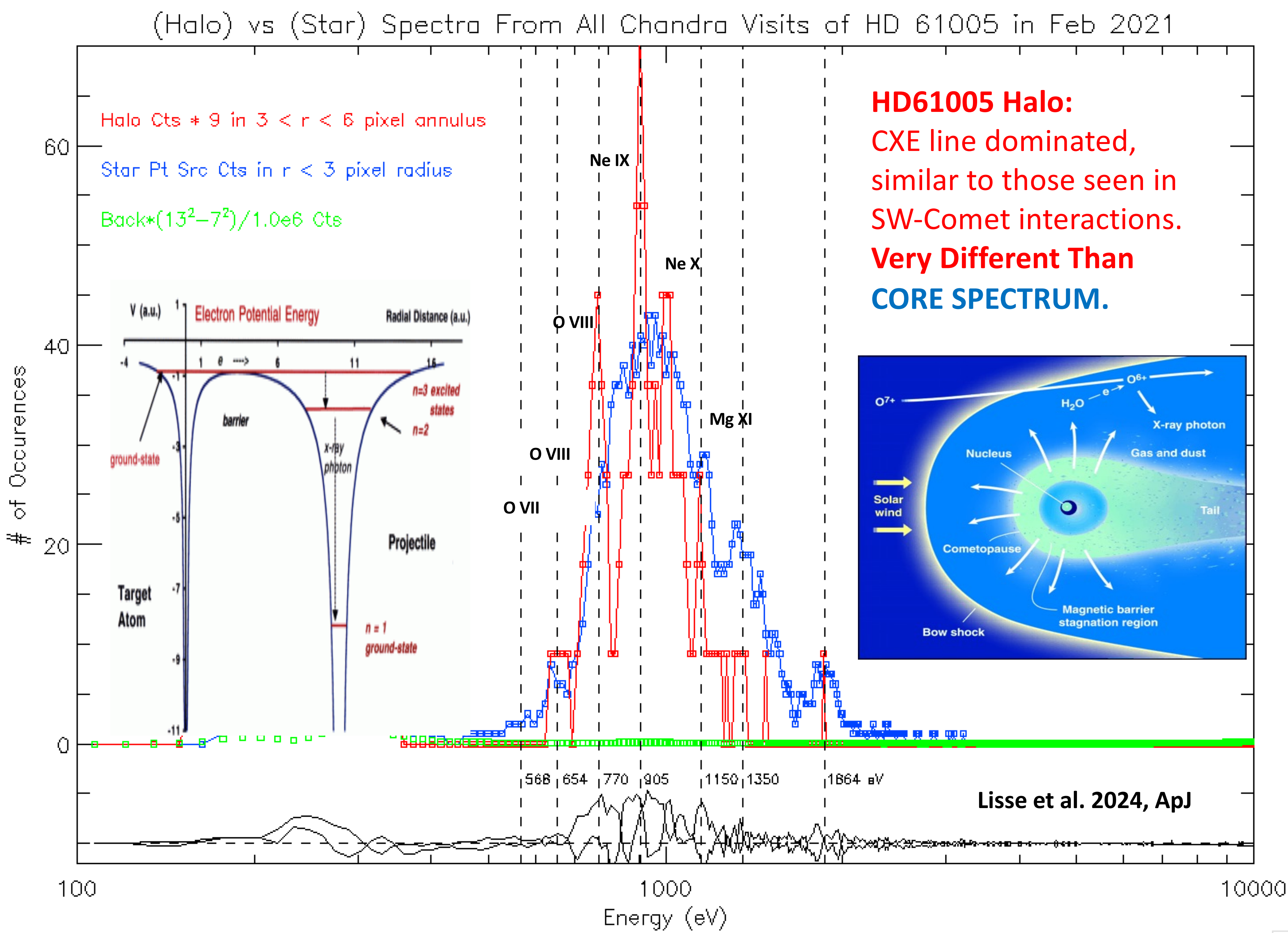
- A Point-source (Stellar Corona), dominating inside r = 2 pix

- A 1/ρ Extended Source (Halo), which dominates at r > 3 pixels.

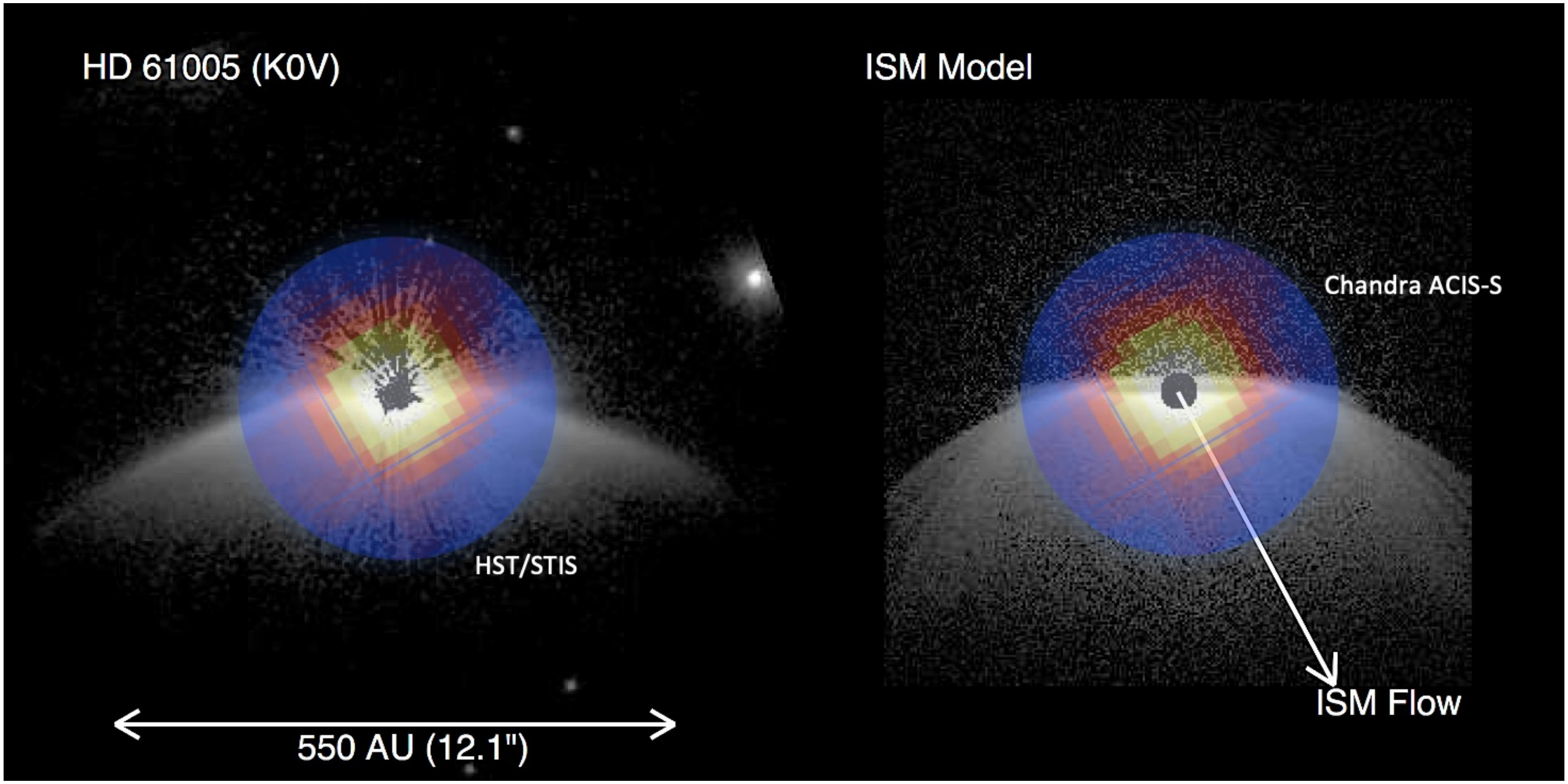
(N.B.: the log scale required to emphasize the halo skirt.)



(Halo) vs (Star) Spectra From All Chandra Visits of HD 61005 in Feb 2021
Lisse et al. 2024, ApJ
Halo Cts * 1 in 3 < r < 6 pixel annulus
Star Pt Src Cts in r < 3 pixel radius
Back*(13²−7²)/1.0e6 Cts
HD61005 Core Flux:
Dominant Hot 6.5 MK Continuum Thermal Source
+ Normal Coronal Lines
Na X
Mg XI
O VIII
Si XIII
568
654
770
905
1150
1350
1864 eV
# of Occurences
0
20
40
60
100
1000
10000
Energy (eV)

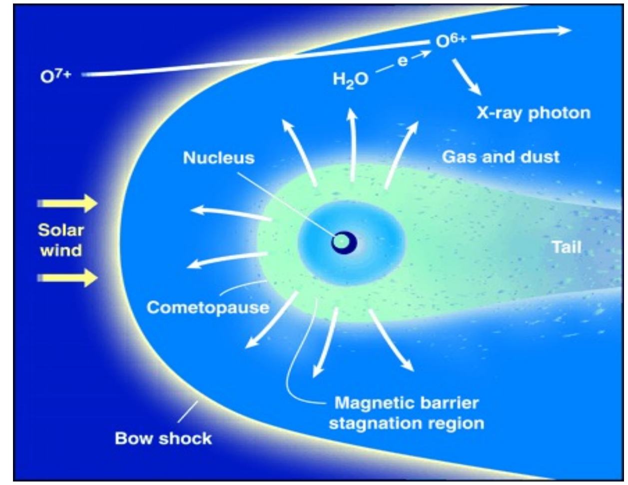

(Halo) vs (Star) Spectra From All Chandra Visits of HD 61005 in Feb 2021
Halo Cts * 9 in 3 < r < 6 pixel annulus
Star Pt Src Cts in r < 3 pixel radius
Back*(13²−7²)/1.0e6 Cts
Ne IX
Ne X
O VIII
O VIII
O VII
Mg XI
568
654
770
905
1150
1350
1864 eV
# of Occurences
Energy (eV)
100
1000
10000
0
20
40
60
Electron Potential Energy
V (a.u.)
Radial Distance (a.u.)
barrier
n=3 excited states
n=2
ground-state
x-ray photon
Projectile
Target Atom
n = 1 ground-state
O7+
O6+
H2O
e
X-ray photon
Nucleus
Gas and dust
Solar wind
Tail
Cometopause
Magnetic barrier stagnation region
Bow shock
HD61005 Halo:
CXE line dominated,
similar to those seen in
SW-Comet interactions.
Very Different Than
CORE SPECTRUM.
Lisse et al. 2024, ApJ

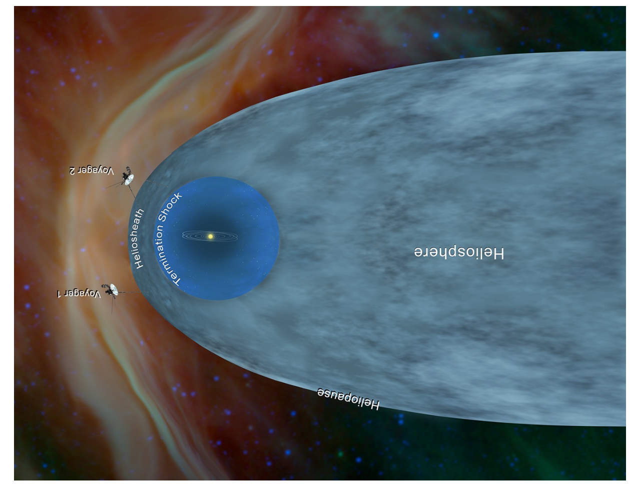
Overlay of the new Chandra imaging of HD61005 on **HST/NICMOS near-infrared imagery (*left*) and Debes+ 2009 model of the system's dust structure** (***right)*** produced by invoking ISM wind ram pressure perturbations of circumstellar dust orbits.



Noteworthy is the spherical symmetry of the x-ray emission, denoting an astrosphere morphology dominated by the strong stellar wind of the ~ 100 Myr old host G8V star; the ~100 au radial extent of the extended x-ray emission and the beginning of the NICMOS dust "wings" (f**or scale, Voyager 1 has found the heliopause in our L_x ~ $10^{27.5}$ system at ~120 AU), and the roots of the Wings at ~ the astropause distance.**

Simple Toy Model for HD61005 SW – VLISM Interaction: 2 Equations, 2 Unknowns



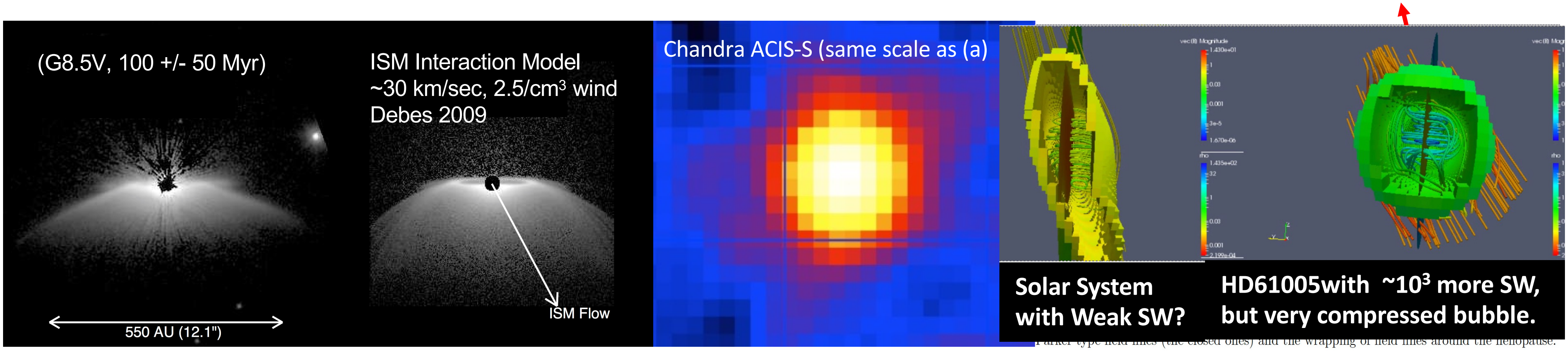


- Given **Pressure Balance** $n_{SW} * v_{SW}^2 = n_{VLISM} * v_{VLISM}^2$ (ignoring ISM magnetic and thermal pressures)

- Given $\mathbf{L_{X,CXE}} \sim \sigma_{CXE} * n_{VLISM} * n_{sw} (n_{minor}/n_H) * v_{sw} * \text{Volume}_{interaction} * \langle E_{photon} \rangle$

- And assuming $n_{sw} \sim 1/r_h^2$, $v_{ISM} = 25$ km/sec (Debes 2009), $(n_{minor}/n_H) \sim 10^{-3}$, and $V_{sw} \sim$ 1200 km/sec for an ~0.1 Gyr old G9-star
- Including constraints from our new Chandra observations: $R_{astrosphere} \sim 100$ au and $L_{X,CXE} \sim 1.3 \times 10^{29}$ erg/sec
- => We find $\mathbf{n_{VLISM}}$ **= 100 – 300/cm³ (~1000x $\mathbf{n_{VLISM,\,Sun}}$)** and $\mathbf{n_{SW}}$ **~ 2000/cm³ at 1 AU from host star (~300x solar)**

Conclusions from new Chandra ACIS-S Imaging of HD61005



- The stellar XUV activity and wind for HD61005 should be hot & high, about that observed by Guinan *et al.* for EK Dra, as HD61005 has an ~5 day stellar rotation rate. => We find an ~7 MK corona **> 200x more XUV active than the ~1 MK. ~4.5 Gyr old Sun or 6-7 Gyr G8V Tau Ceti**.

- **X-ray emission is extended out to ~100 au**, with a pronounced "Halo" not found in other point-source G-star observations. The halo's x-ray spectrum is CXE line dominated, like our heliosphere's.

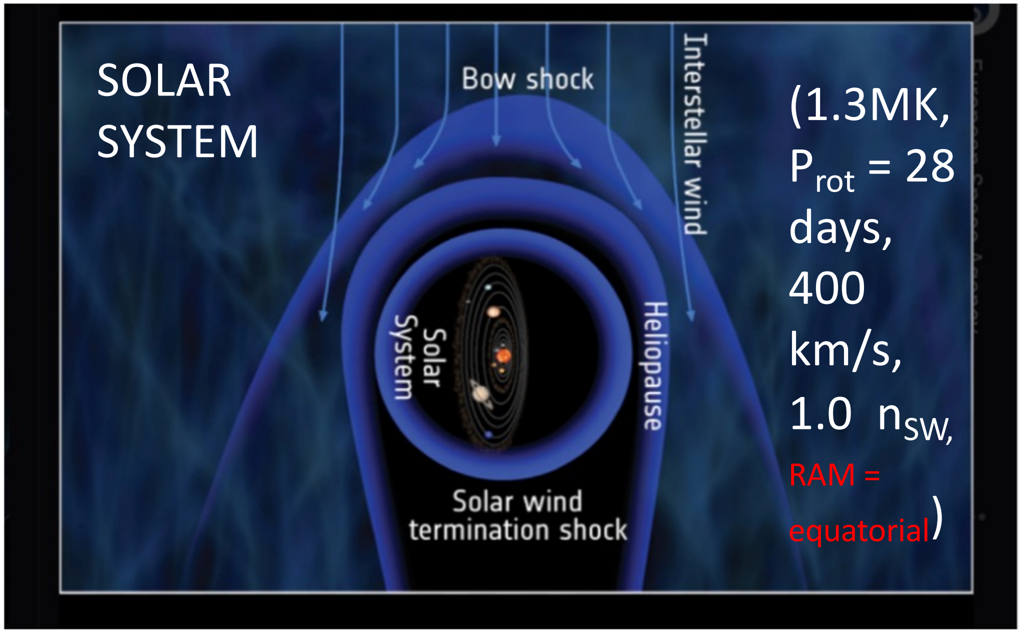
- HD61005' **local ISM must be very dense** in order for a system with $L_x \sim 10^2 F_{SW, Sun}$ to have **an astropause at only ~100 au**. => $\rho_{ISM, HD61005} = 100 - 300/cm^3$ using simple pressure balance, densities found inside GMC's like the Local Lynx Cloud (LLC).

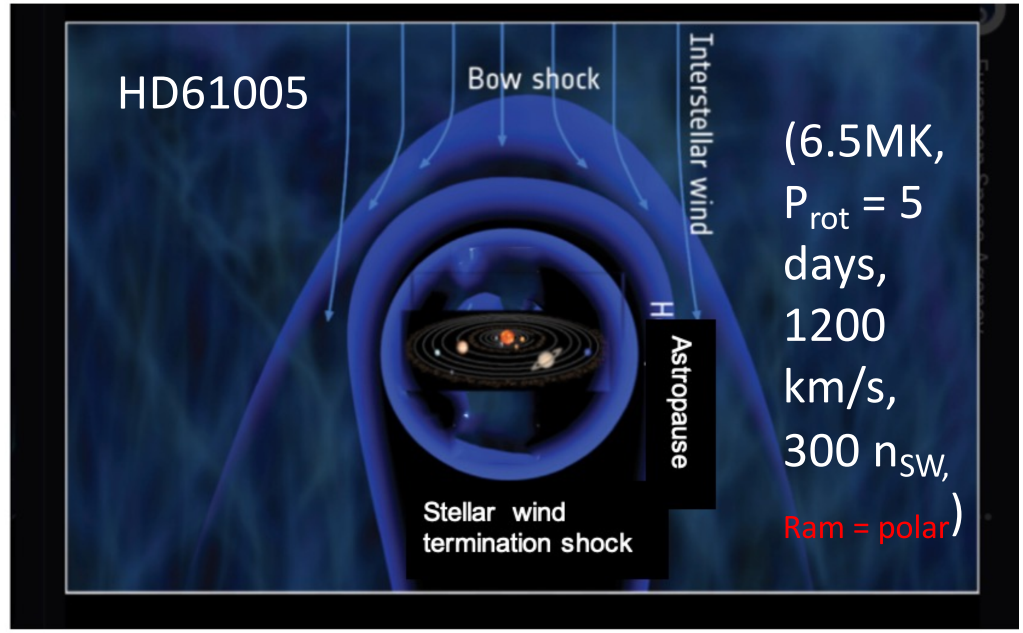
[The solar system system **TODAY** has $\rho_{VLISM, Sun} = 0.2/cm^3$ and heliopause at ~120 AU, but would have a heliopause at ~ 1000 au if the SW was 100x stronger].

- 1st ever spatially resolved G-star astrosphere: Due to **its youth** and its **dense VLISM, HD61005's CXE emission measure** $n_{sw} * v_{sw} * n_{ISM} \sim 10^6 * n_{sw,Sun} * v_{sw,Sun} * n_{ISM, Sun}$.

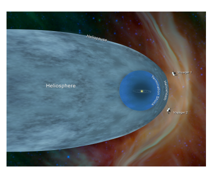
- **The resolved Halo does NOT appear to follow the well known disk + fan tail and appears spherical in nature.** This argues that the stellar wind – VLISM interaction is Parker stellar wind dominated.

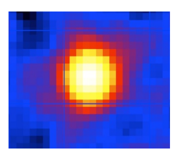
To Do & Open Questions: Apply Current Heliosphere Models to HD61005





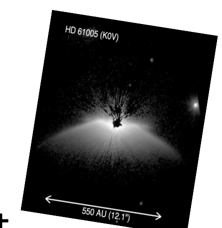
<u>Solar System Evolution</u>: At r ~ 100 au, HD61005's astrosphere is smaller than our own (r ~ 120)! => When HD61005 moves into "normal" ISM space, its astrosphere will balloon up to r ~ 1000 au (& ours will shrink down to r ~ 2-5 au when we move into its cloud as we orbit the galactic center!) (Opher *et al.* 2023, 2024)



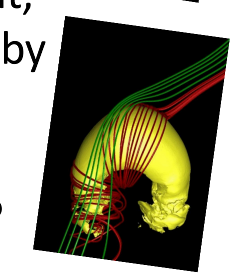


<u>Search for Other Young G-star Astrospheres?</u> Nearby, edge-on, young G1V HD107146 and G2V HD202917 disk systems seem similarly promising.

<u>Is There Hope for an Alpha Cen CXE Astrosphere Detection With NextGen X-ray Telescopes?</u> $n_{sw} * v_{sw} * n_{vlism} / d^2 = 10^2 - 10^3$ in solar units for HD61005 & ~1 for Alpha Cen. So probably not…Procyon?

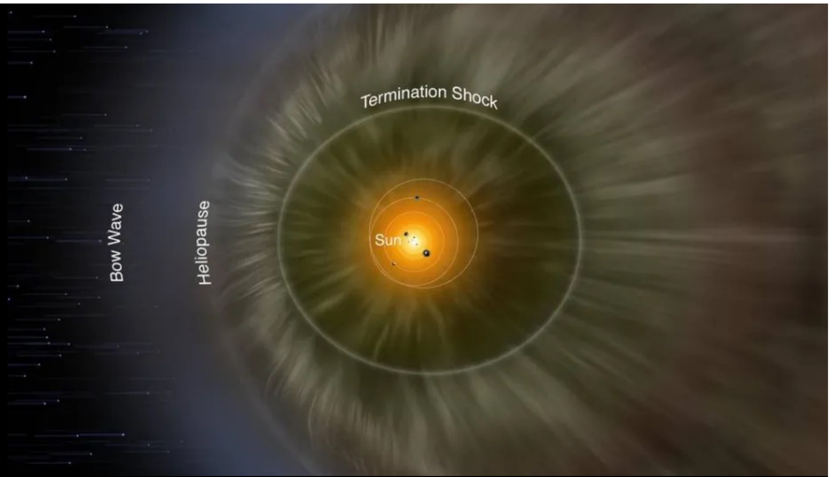


<u>The "Wings"</u> - are the "swept-back, fine particle" wings due to disk dust blowout, ISM sputtering of unprotected dust, or by exclusion of ISM neutrals? Are they coincident with the prongs of the croissant in the Boston groups models?



Supplementary Slides

Some Calculations of the Scale of the SW



Pressure of the Heliosphere:

PV = nkT or P = (n/V) kT   and

[760 torr = 1 atm = 1.01 x 10^5 Pa, => 1 torr = 133 Pa, 1 Pa = 1/133 torr]

So for Density ~ 1 H/cm^3 at 1million K Temperature, we have

P = (1 H/cm^3 * 10^6 cm^3/m^3) *1.38x10^{-23}*10^6 deg K = **1.4 x 10^{-11} Pa [or ~ 1x10^{-13} torr]**

By comparison: Fluorescent light bulb Hg plasma pressure ~ 0.8 Pa = 6 x 10^{-3} torr

Good rough pump vacuum ~ 1 x 10^{-3} torr = 1.3 x 10^{-1} Pa

Good turbopump vacuum ~ 1 x 10^{-7} torr = 1.3 x 10^{-5} Pa= Pressure on Pluto's surface, 10x Pressure in a Fusion Reactor

Ultra High Lab Vacuum = 1 x 10^{-10} to 1 x 10^{-11} torr = 1.3 x 10^{-8} Pa to 1.3 x 10^{-9} Pa

Mass of the Heliosphere:

4π/3 *<1 H/cm^3 > * (1.67 x 10^{-24} g/H-atom) * (1.5 x 10^{13} cm)^3 = 24 x 10^{15} g = **2.4e13 kg**

2.4 x 10^{13} kg is the mass of a 2.3 km radius comet of 0.5 g/cm^3 density

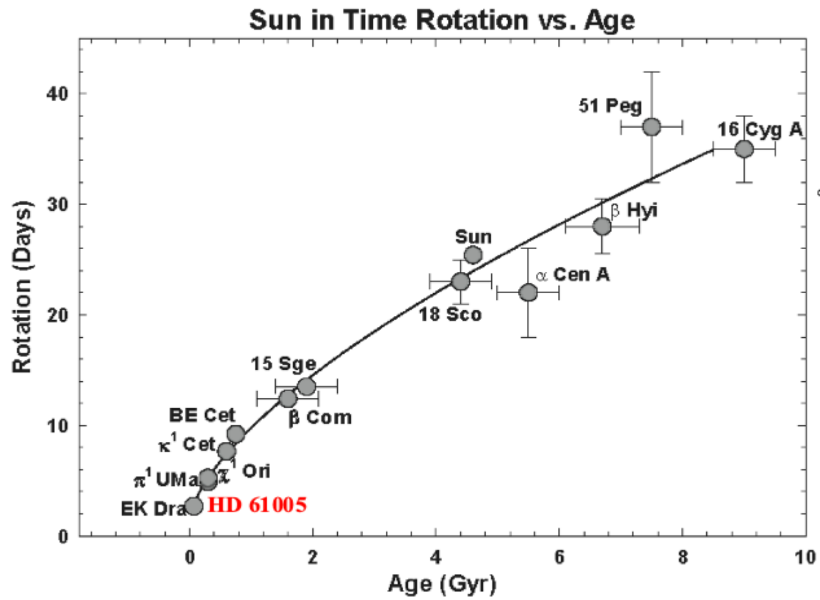
Mass Flux into the Heliosphere:

Sun loses ~2 x 10^{-14} M_{Sun}/yr =2 x 10^{-14}/yr * 2 x 10^{30} kg * /(3.1 x 10^7sec/yr) = 1.3 x 109 kg/sec

4 H/cm^3 at 1 AU * (1.67 x 10^{-27} kg/H atom) * 4π*(1.5 x 10^{13} cm/AU)^3 * 450 x 10^5cm/sec = **1.3 x 10^9 kg/sec**

1 x 10^9 kg is the mass of a large comet's coma, or of an 100 m radius comet-like body, or 500 Olympic swimming pools

Sun masses 3.3 x 10^5 M_{Earth}, so the Sun loses 7 x 10^{-8} M_{Earth}/yr, 70% of M_{earth} in 10 Myrs, ~300 M_{earth} in 4.56 Gyr (at current rates; the Sun's stellar wind was hundreds of times stronger when it was first born). Stellar winds from of low-mass stars likes the Sun do not strongly influence their evolution on THE MAIN SEQUENCE. (Pre- and Post-Main Sequence Stellar Winds CAN cause ~M_{Sun} mass losses in Myrs!)



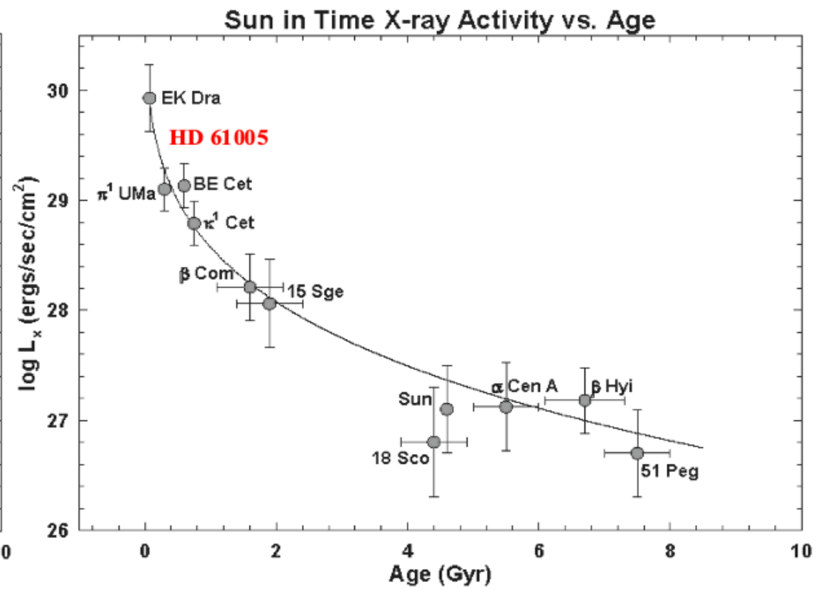


Figure 3(d) – Measured rotation rate vs stellar age for the Sun and several close solar analogues. The solid curve is a simple power law fit modeling $P_{rot} \sim Age^{0.6}$. **Figure 3(e) – As measured XUV luminosities for EK Dra, π^1 Uma, π^1 Ceti, Beta Com,** and **Beta Hyi,** ***all close solar analogue stars*****.** Notice the factor of $\sim 10^3$ higher flux between EK Dra (=HD 61005) and β Hyi (= Tau Ceti). After Guinan & Engle (2007).

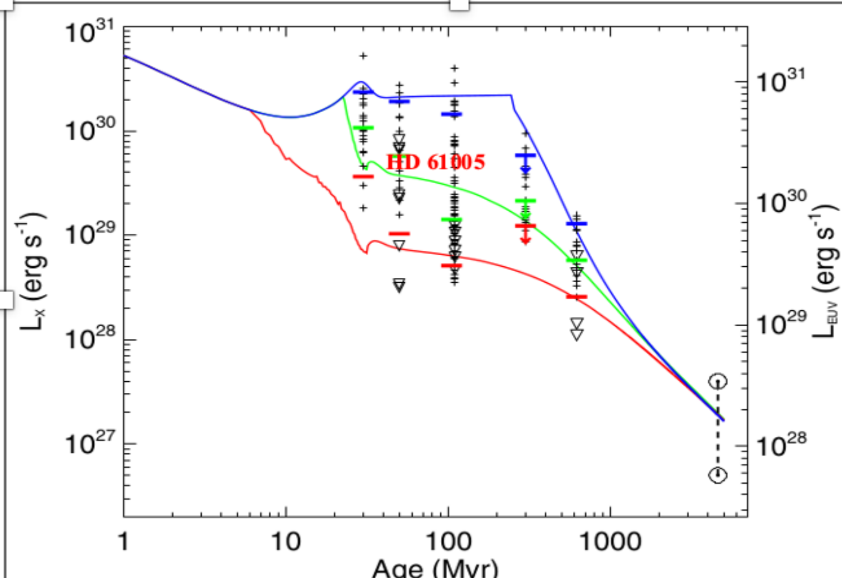
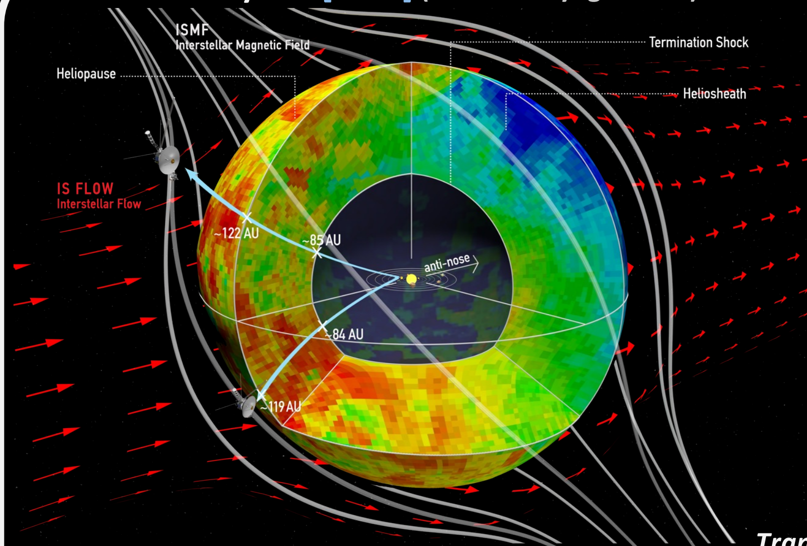


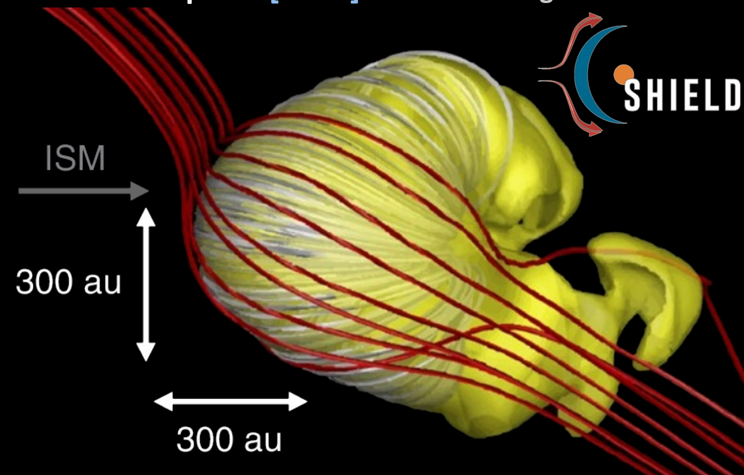
Figure 3(f) – Update of the L_x vs Age plot including an order of magnitude more G-stars and the predicted low (red), median (green) and high (blue) cases. After Tu *et al.* 2015.

Shape of the Global Heliosphere (1961-2022) // A rough diamagnetic bubble; a jets structure; a comet...

Dialynas+[2017] (INCA & Voyager data)



Opher+[2020] MHD modeling



IBEX-Lo Data (Galli+[2016; 2017])

[...] typical thickness of HS in downwind ~(220±110) AU.

IBEX-Hi Data (Reisenfeld+[2016])

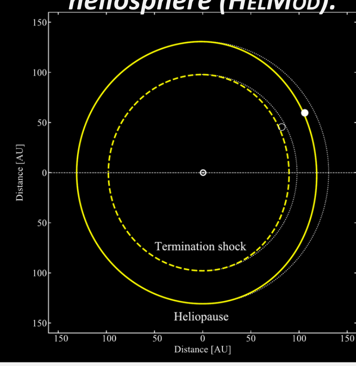
N. pole ***L_{HS}~210 AU*** *|| S. pole* ***L_{HS}~160 AU***

IBEX-Hi Data (Reisenfeld+[2021])

[...] heliosphere extends at least ***~350 AU*** *tailwards*

Boschini+[2019; 2020]

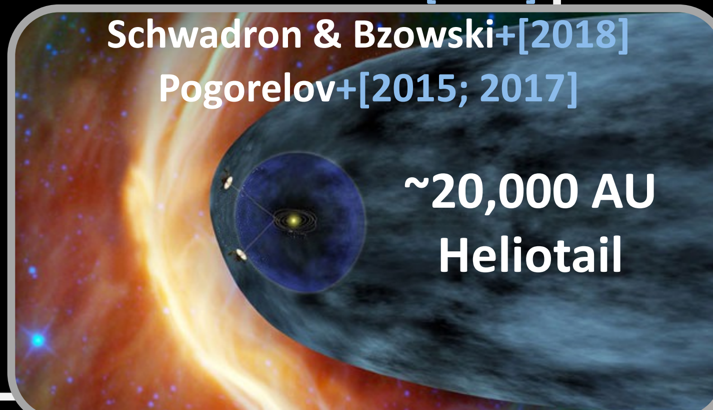
Transport of GCRs through the heliosphere (HelMod).



Czechowski+[2020]

Schwadron & Bzowski+[2018]

Pogorelov+[2015; 2017]



THE GLOBAL HELIOSPHERE A DATA-DRIVEN VIEW

Krimigis+[2019]

Combined data from V1, V2 and Cassini/INCA

Dialynas+[2022]

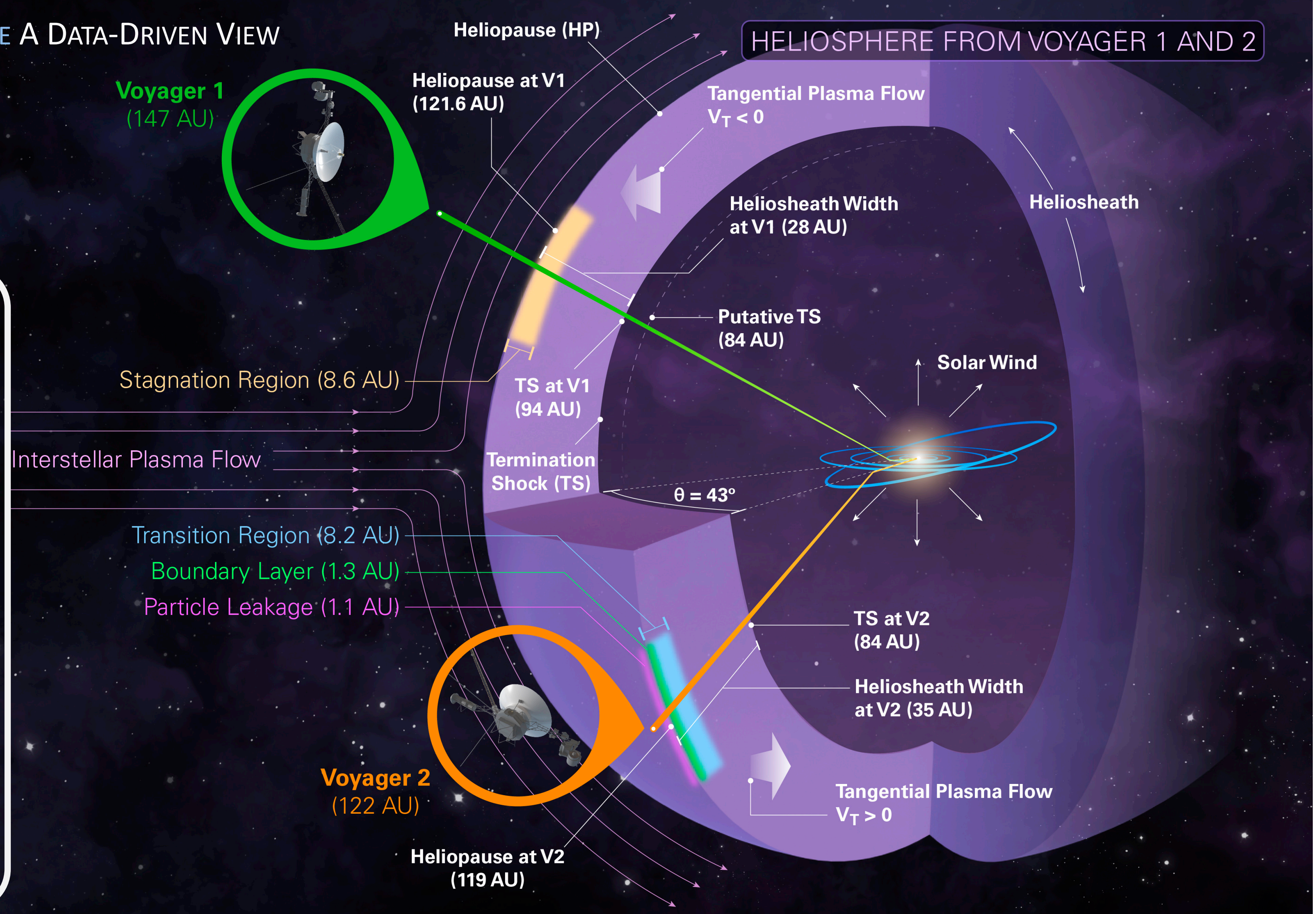
The heliosphere from the perspective of Cassini, HSTOF & Voyager measurements!

Kleimann+[2022]

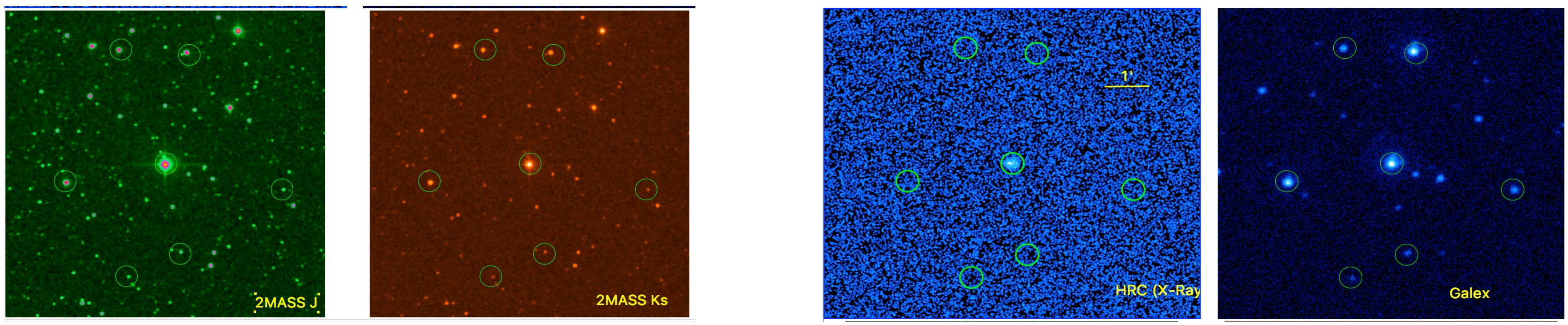
The heliosphere from the perspective of the models and comparison of models with data!

SSRv 2022

The Heliosphere in the Local Interstellar Medium *Into the Unknown*

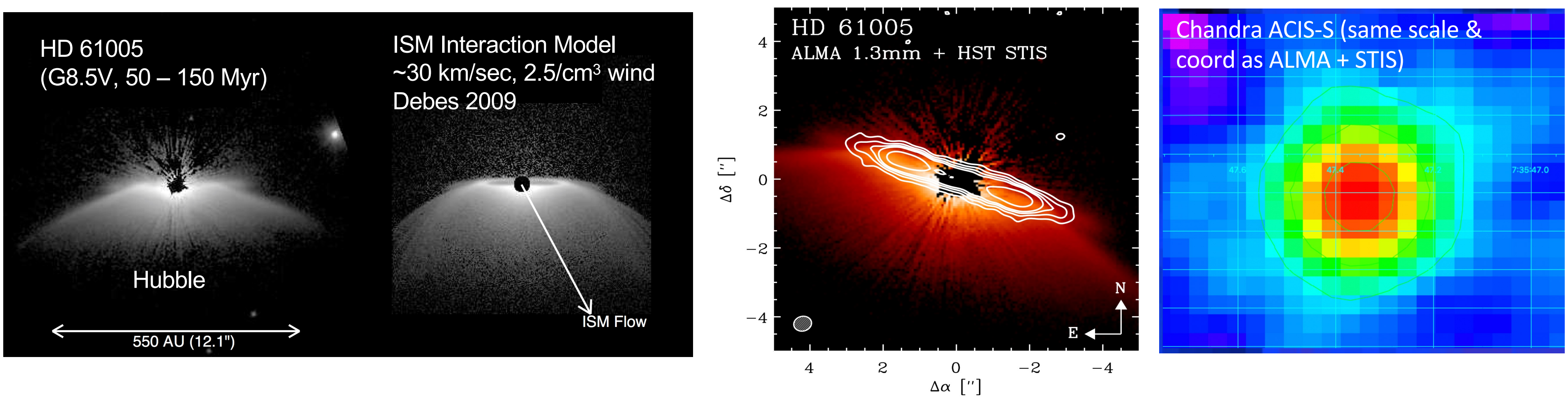


Compendium of Archival Observations of the HD61005 system.



2MASS J ***2MASS Ka*** ***4ksec Chandra/HRC*** ***GALEX***

The ~12" extent of the NICMOS NIR imagery easily fits within the HWHM of the shallow, off-axis ***Chandra/HRC.***



Archival HST/NICMOS near-infrared imagery of HD61005. ***(left)*** The swept-back wings of the outer disk can be clearly seen in contrast to the bright central flat disk running left-right in the center of the image. **Debes+ 2009 model of the system's dust structure** produced by invoking ISM wind ram pressure perturbations of circumstellar dust orbits. ***(middle)*** **Close up of HST/STIS (color) + ALMA imagery (contours) of HD61005 from MacGregor+ (2018),** which suggest that there are two components to the disk populated by both small micron-sized grains (HST) and larger mm-sized grains (ALMA): (1) a confined planetesimal belt between 42 and 67 AU with a rising surface density gradient and (2) an extended outer halo. **For scale, Voyager 1 has found the heliopause in our $L_x \sim 10^{27.5}$ system at ~150 AU. (right) New Chandra HD61005 ACIS imagery is ~6.5" pixels wide, or ~100 au in radius at 36 pc, and roughly axisymmetric.**

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look for our 2024 paper!!

First Detection of a Resolved Astrosphere Around a Main Sequence G-Star by Chandra

C.M. Lisse[1], S.J. Wolk[2], B. Snios[2], J.D. Slavin[2], R.A. Osten[3], D.C Hines[3], J.H. Debes[3], D. Koutroumpa[4], V. Kharchenko[2], M.A. MacGregor[5], J.L. Linsky[5], H.M. Günther[6], E.F. Guinan[7], S. Redfield[8], P.C. Frisch[9], K. Dennerl[10], V. Kashyap[2], K.G. Kislyakova[11], Y.R. Fernandez[12], E. Provornikova[1], C.H. Chen[3], R.L. McNutt[1], P. Brandt[1], L. Paxton[1], M. Horanyi[5], K. Dalynas[13], L. Gu[14]

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39 Pages, 10 Figures, 0 Tables

Key words: X-rays: stars; techniques: spectroscopic; stars: planetary systems: formation, debris disks; a interstellar medium