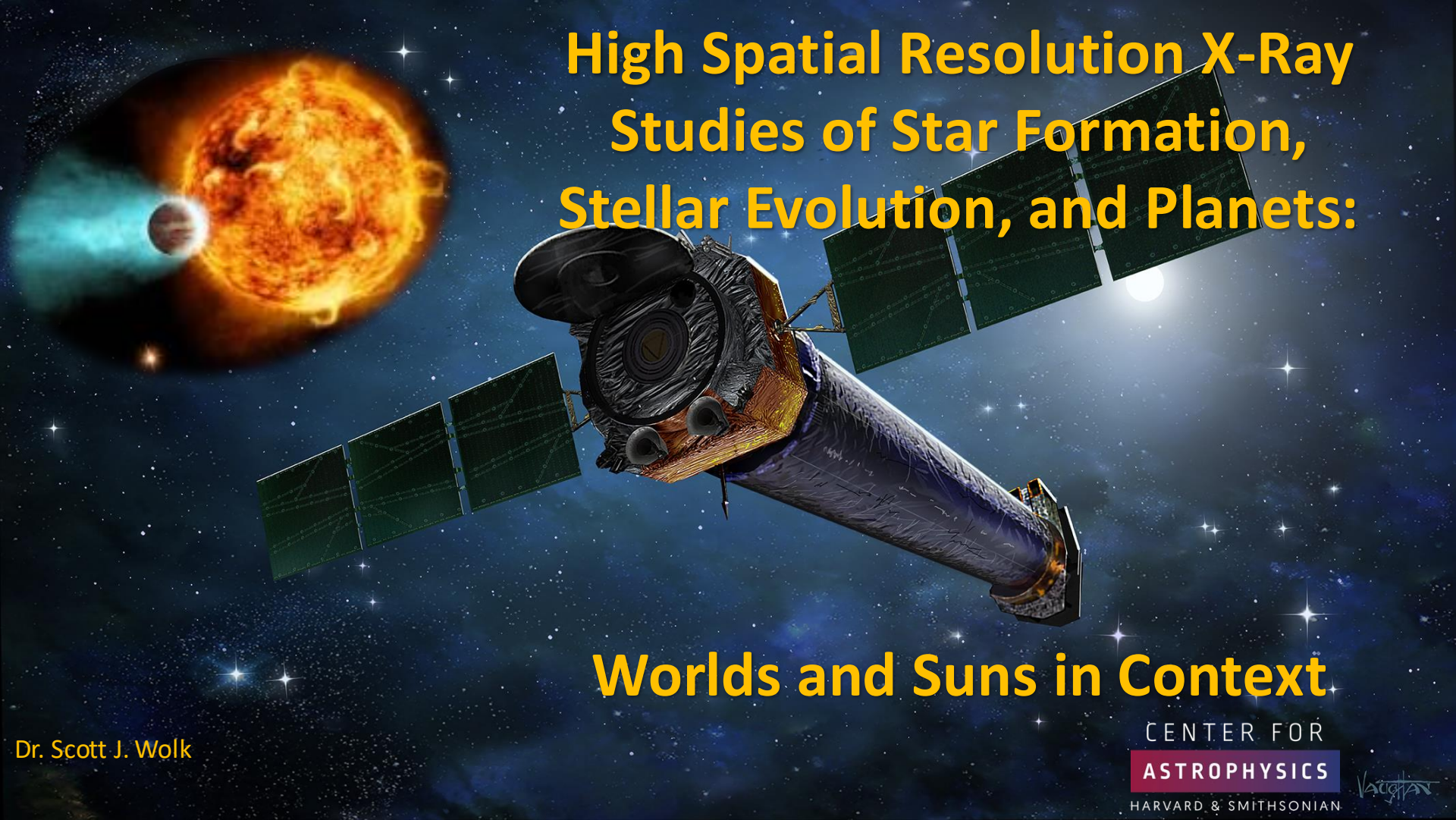




High Spatial Resolution X-Ray Studies of Star Formation, Stellar Evolution, and Planets:

Worlds and Suns in Context

Dr. Scott J. Wolk

CENTER FOR
ASTROPHYSICS

HARVARD & SMITHSONIAN

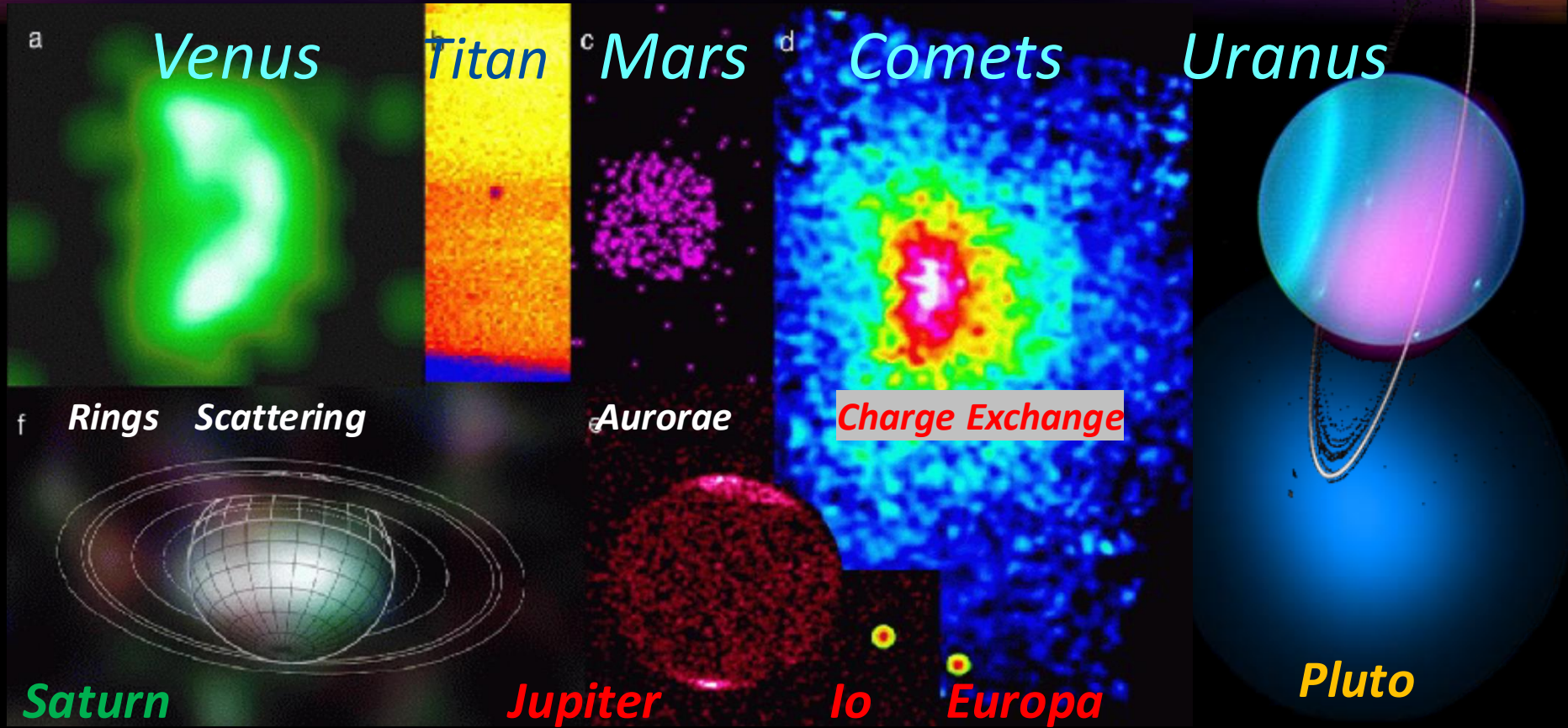
Vaughan

HiReX White Paper.

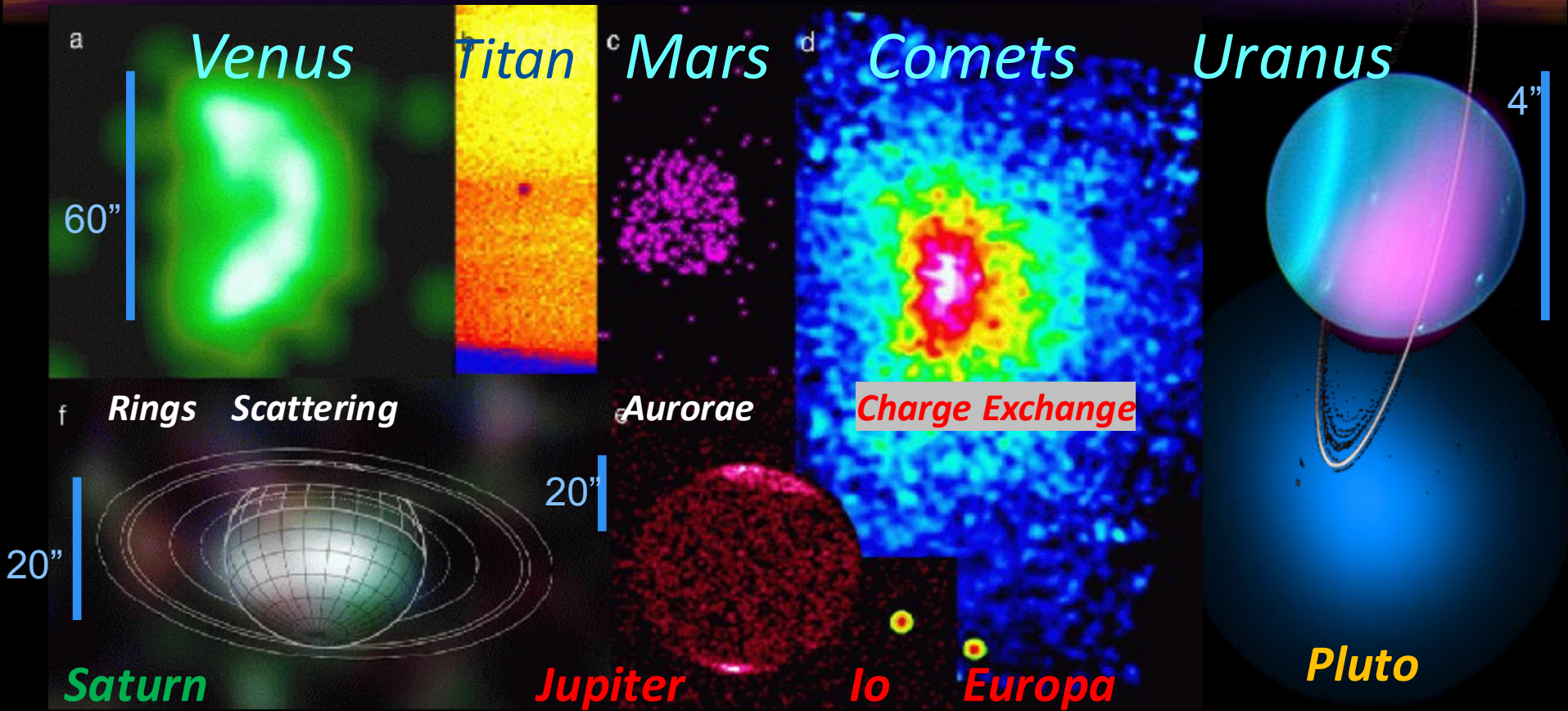
Topic	Science Case	Resolution	Other Requirements
Solar System	Resolve comets	$0.1''$	large A_{eff}
	Planetary Aurorae	$0.005''$	
Planetary Nebulae	Observe mixing in fast wind and nebula, radial distribution of hot bubble mission	$0.1''$	soft $A_{\text{eff}} > 10 \times \text{Chandra}$ for faint features, FOV: arcmin, 0.2–2 keV
Star Formation	Proto-stellar jet launching	$0.01''$	0.5–2.0 keV
	distant young stellar clusters	$0.01''$	
Novae	Resolve ejecta from super-soft source	$0.05''$	0.1–2 keV, TOO: hours, then repeat visits over weeks/months
	Locate X-rays emission between WD and MS star	$0.01''$	
(Exo-)planets	Exoplanet plasmoid	$0.001''$	7
Activity	Astrospheres	$0.1''$	0.2–2.0 keV
	Resolving stellar coronae	$10^{-5}''$	large A_{eff}
	Coronal superflares	$10^{-5}''$	FOV: $> \text{arcmin}^2$ or TOO: hours, 2–7 keV
	Extreme coronal mass ejections (CMEs)	$10^{-5}''$	
Magnetic CVs	Magnetically interacting binary stars	$< 10^{-4}''$	
	Resolve accretion column	$10^{-4}''$	
Massive Stars	Distribution of wind shocks	$10^{-4}''$	0.2–2.0 keV
	Structure of colliding wind binary shock cones	$\leq 10^{-4}''$	More distance limited; repeat over orbital period
	Topology of magnetic fields	$10^{-4}''$	large A_{eff}

Günther+ (2026)
Randall+ (2026)

~30 years of The Study of Solar System X-rays is a Very Rich Field, Still Developing. Low Lx but important physical processes.



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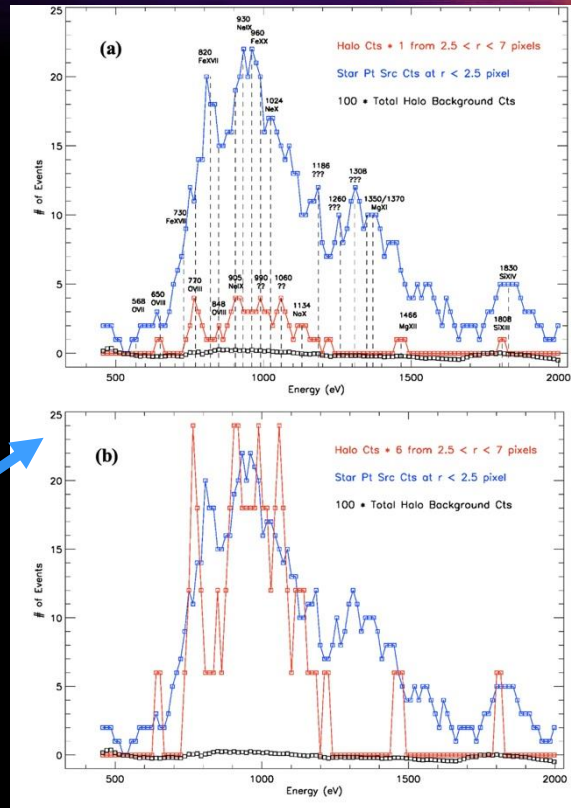
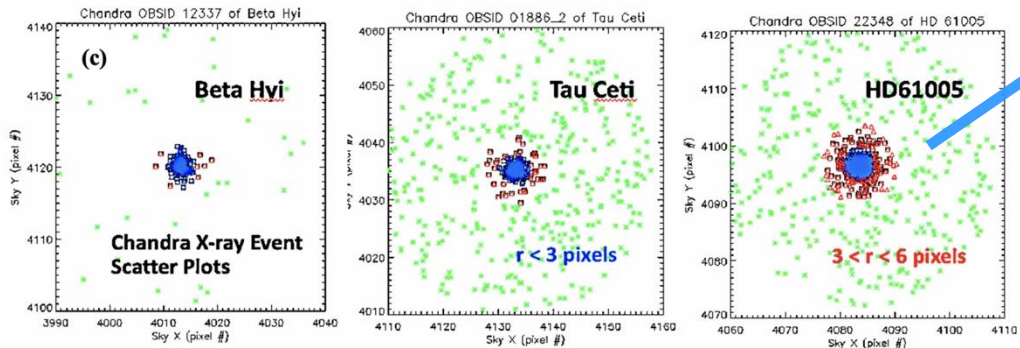
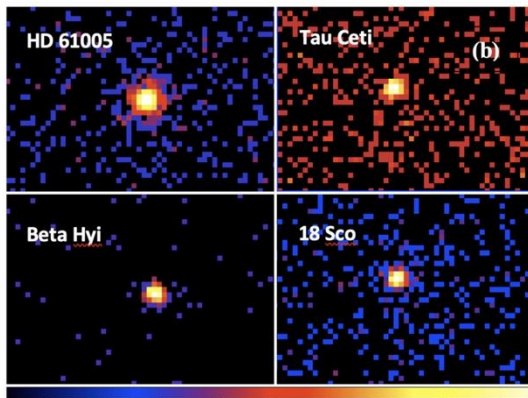
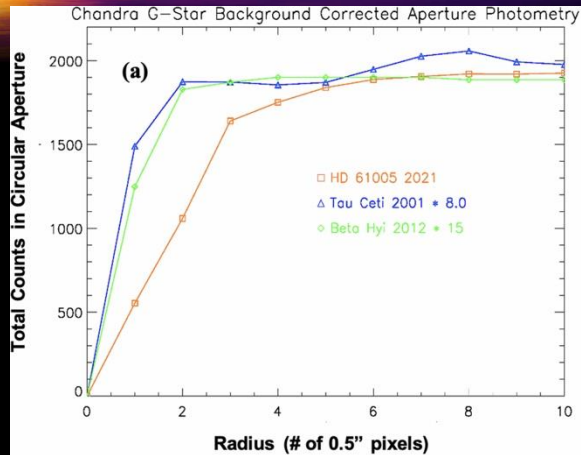


Low hanging solar system fruit for a high spatial resolution mission

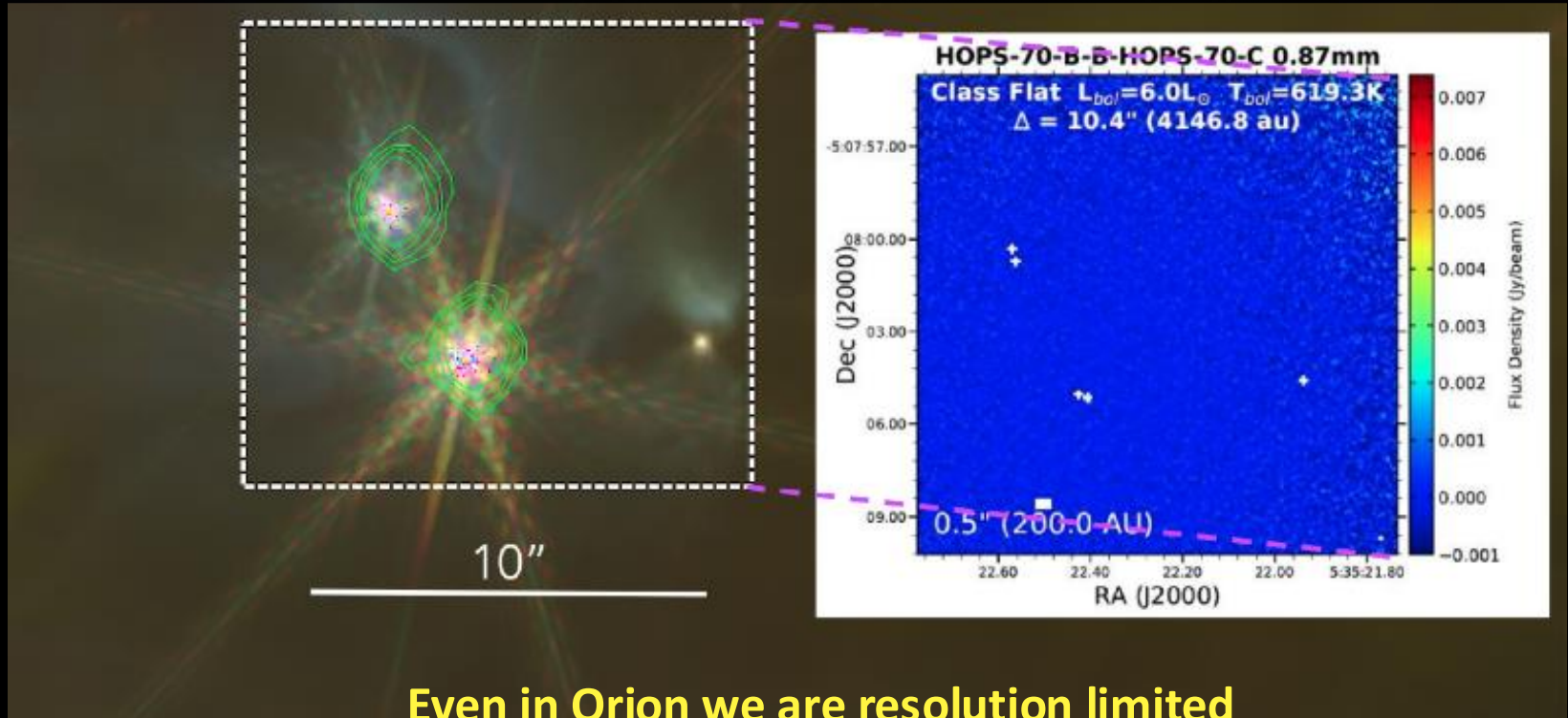
- 1st detection of X-ray Emission from Uranus, Neptune, examples of the most common type of exoplanets.
- 1st detection of Saturnian Aurora X-ray emission.
- Confirm the excess O emission from the western ring of Saturn.
- Confirm the nature of the emission from Pluto
- Tracking the motion of flares & CMEs through the Solar System
- Understand the hard emission from Jupiter's poles.
- Learn why the north Jupiter pole doesn't have a pulsation and study the structure of the Io plasma torus.
- Study the effect of the solar cycle on Martian atmospheric loss.
- Minerology of Luna, Io, Europa and Ceres.
 - Obtain high-spatial resolution elemental composition maps of the surface to complement Clementine, Lunar Prospector maps.
- Study solar X-ray-induced chemistry & stripping of planetary atmospheres
- Exospheres around other stars.

Note that many of these are complementary with Planetary Directorate missions including the Europa mission and The Uranus mission, as well as planned missions to the moon and asteroids.

On the cusp: Astrospheres

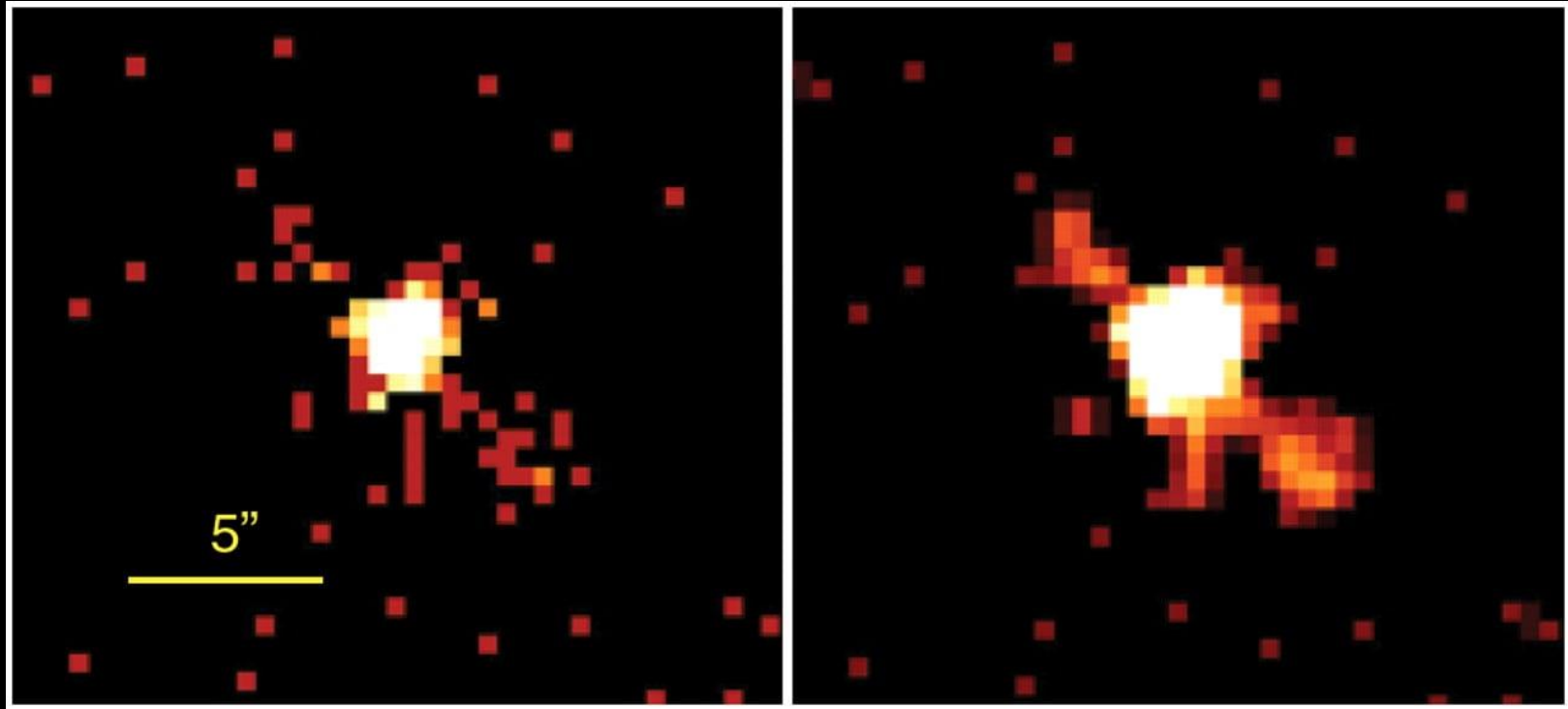


On the cusp: Stellar Hierarchy

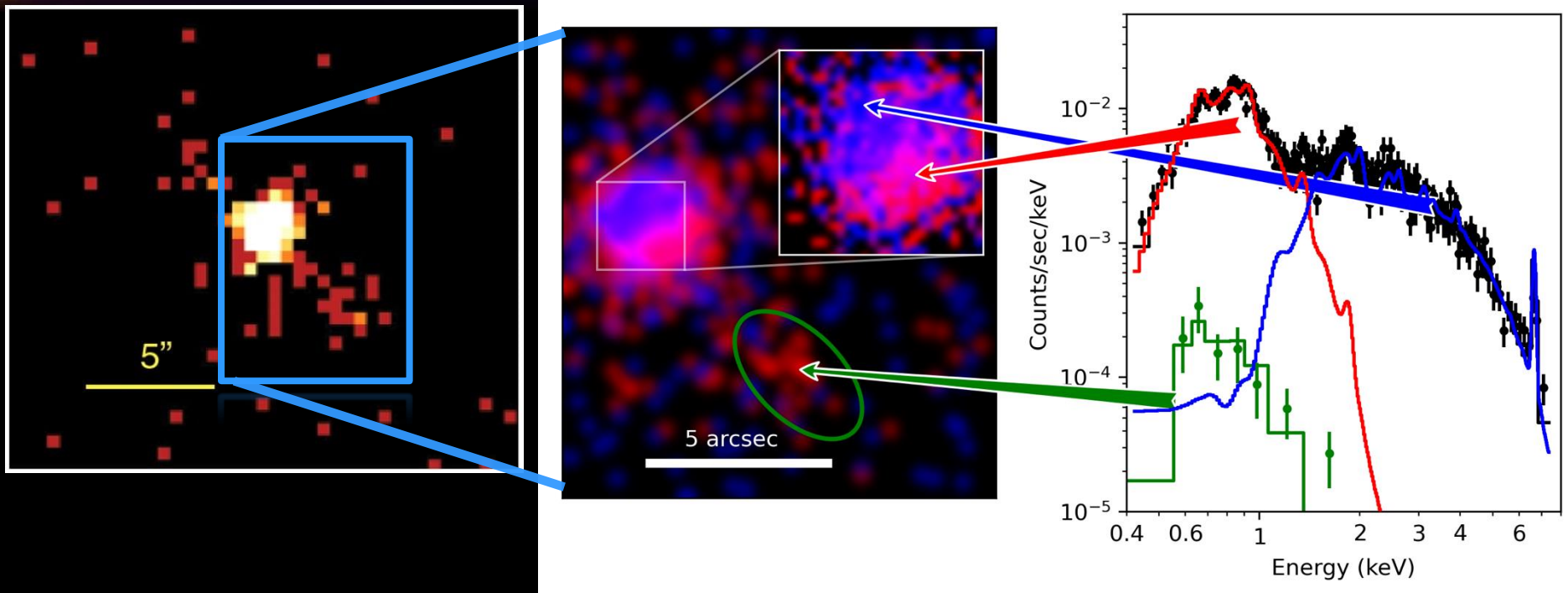


Even in Orion we are resolution limited

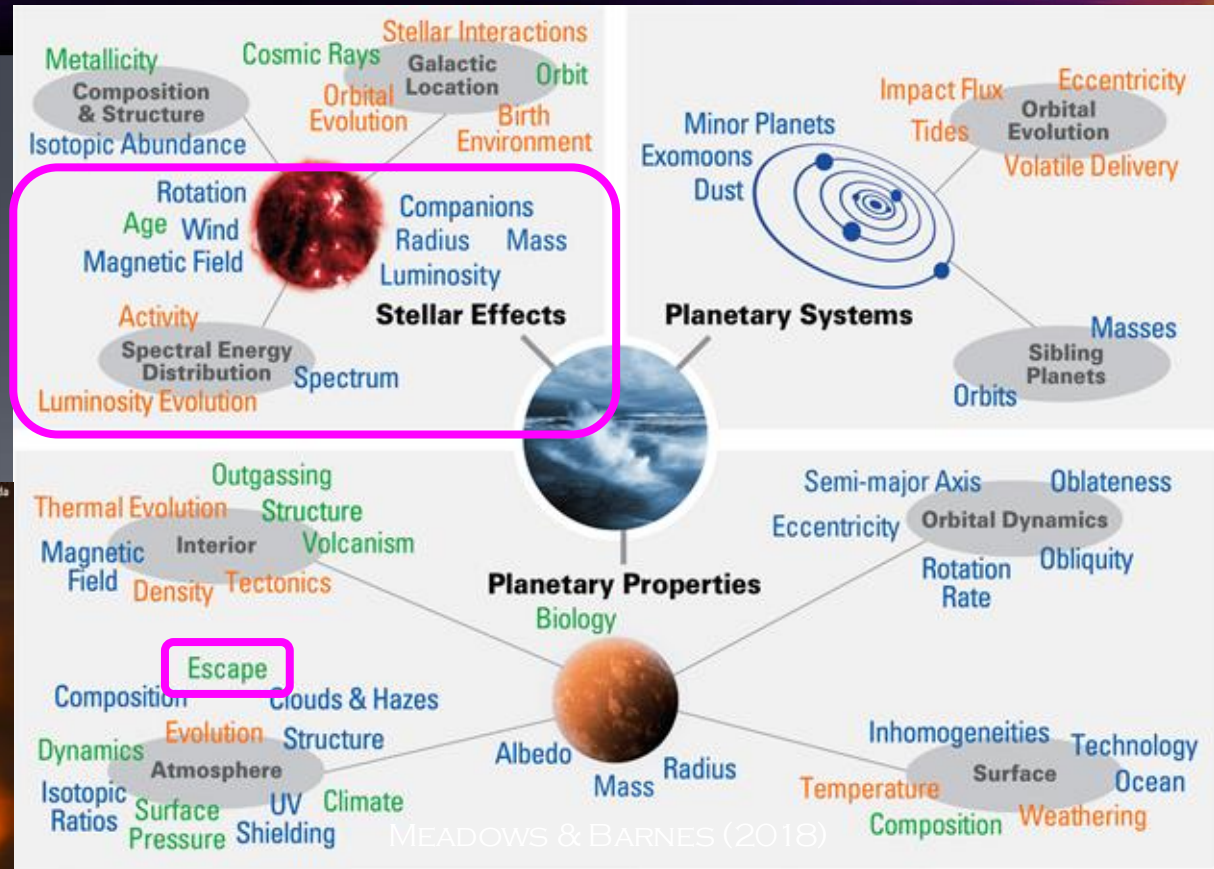
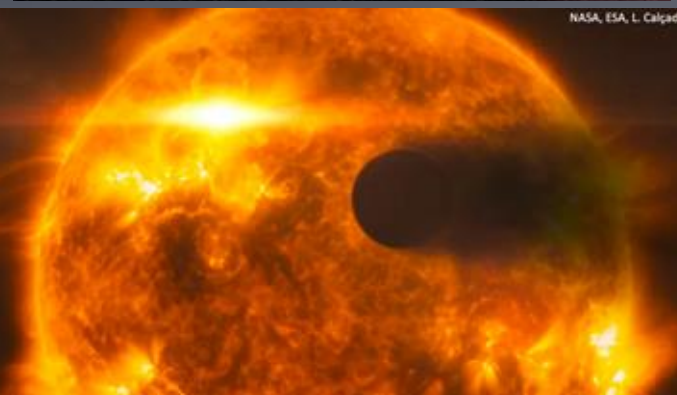
On the Cusp: Stellar Jets



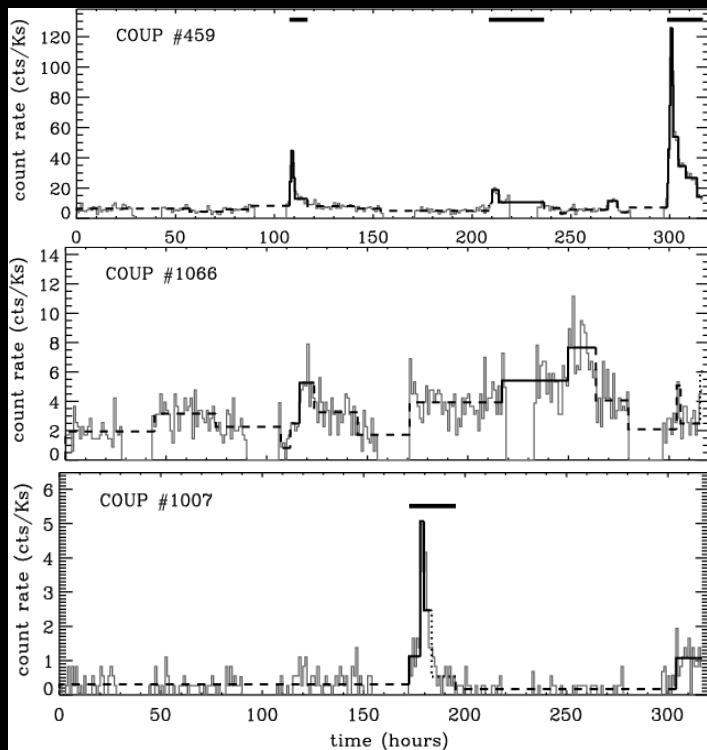
DG Tau (140 pc)



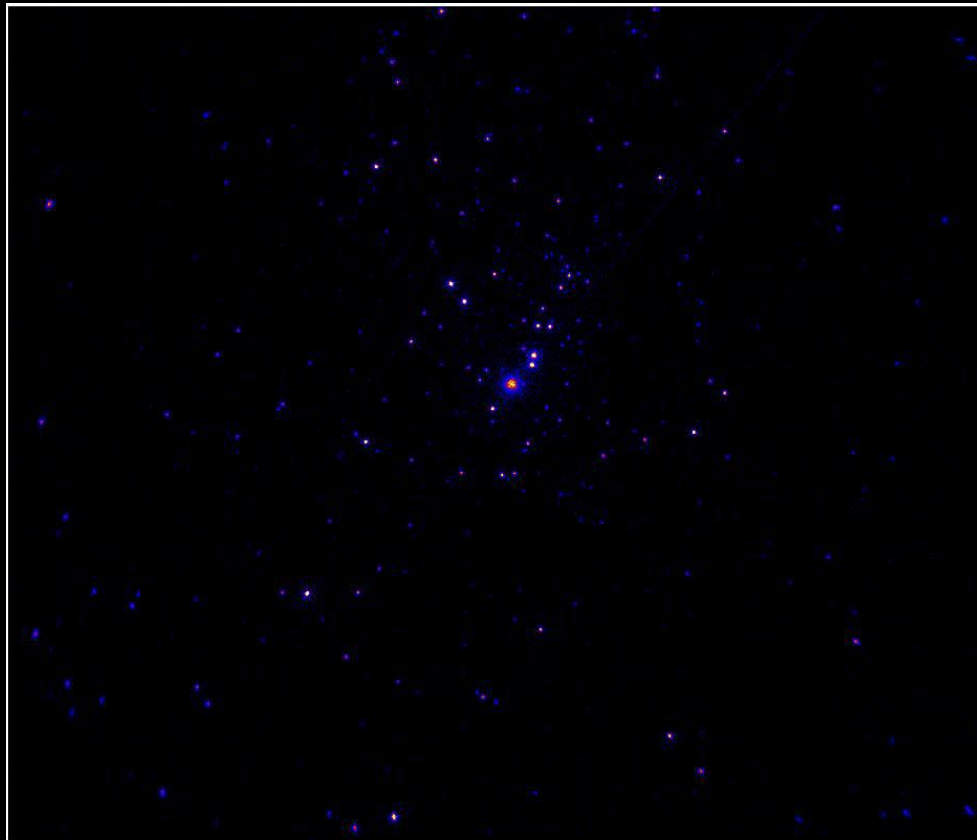
High energy characterization of stars and stellar activity is of high importance for assessing habitability



Impact of stellar activity on habitability



M stars: ~ 1 flare/800 ks at 3 Myr.



Orion

Description: A damped magneto acoustic oscillation in the flaring loop.

[see Mitra-Kraev et al. (2005)]

$$\Delta I/I \sim 4 \pi n k_B T / B^2$$

$$T \sim 12 \text{ MK}$$

$$n: \text{ density} = 5 \times 10^{10} \text{ cm}^{-3}$$

$$B \longrightarrow 40\text{-}100 \text{ G}$$

$$\tau \sim \text{Length} / c_s$$

$$c_s = \sim T^{0.5}$$

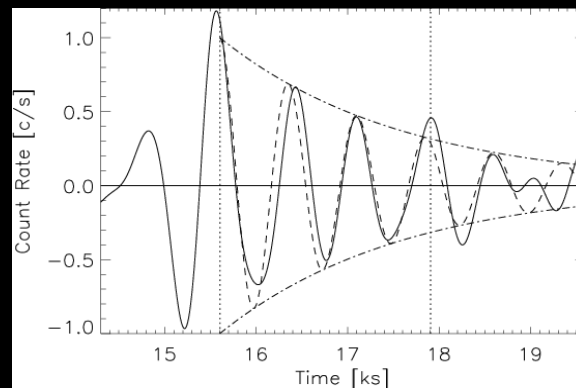
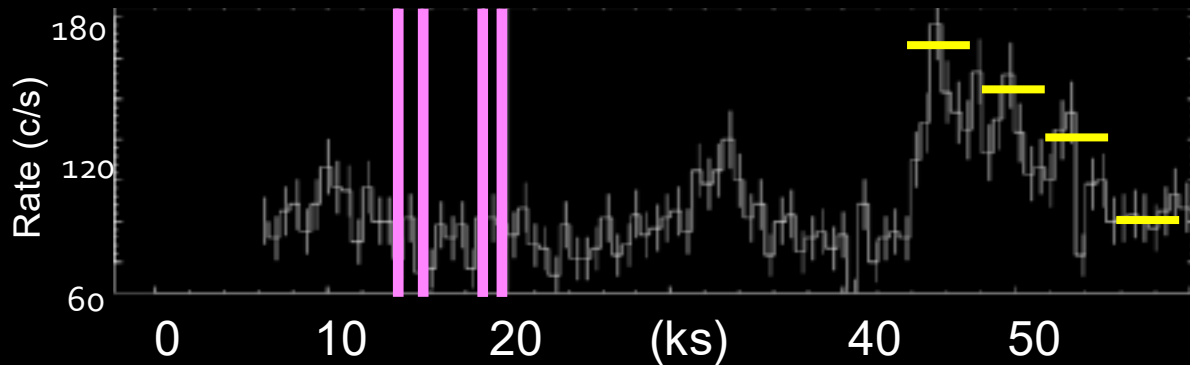
$$\tau = \text{oscillation period} \sim 4 \text{ ks}$$

$$L = \text{Const.} \times \tau_{\text{osc}} N T^{0.5}$$

assuming $N=1$

$$L \longrightarrow 2\text{-}4 R_*$$

$$\sim 3 \text{ MKm} \sim 2 \text{ milliarcsec at } 10 \text{ pc}$$



Active, emission-line red dwarfs in the solar neighborhood

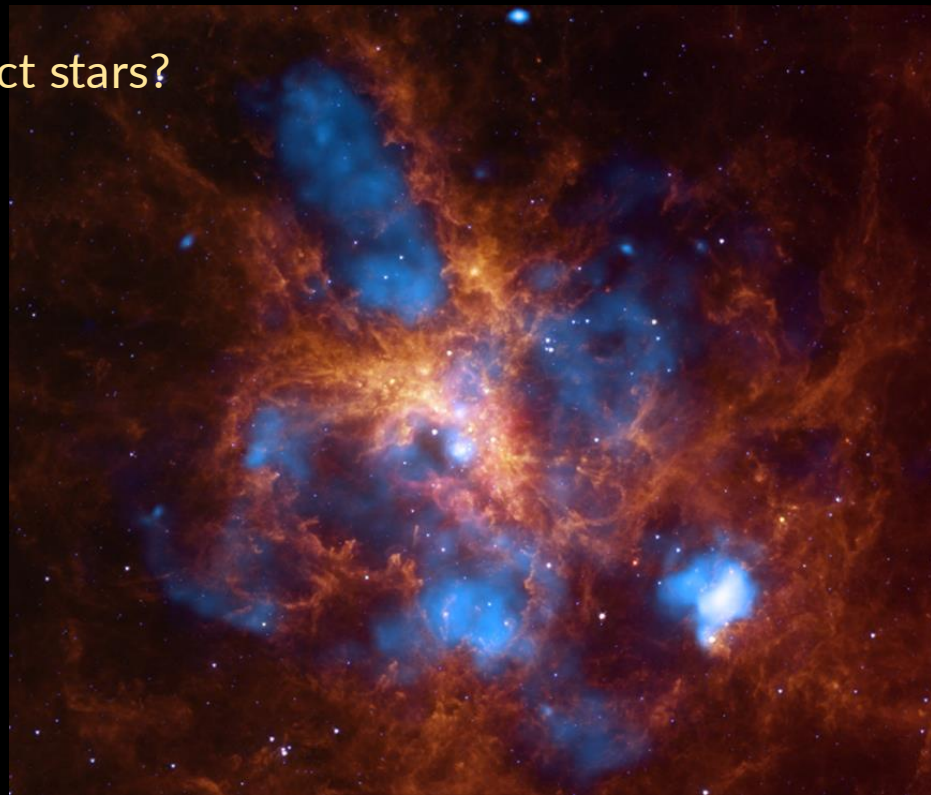
Star	Spectral type	Distance (pc)	Notes
Proxima Centauri	<i>dM5.5e</i>	1.30	Nearest star to the Sun; frequent flarer
BL/UV Cet	<i>2x dM5.5e</i>	2.62	Half of the UV Ceti binary/Prototype of the flare-star class
Wolf 359 (CN Leo)	<i>dM6e</i>	2.41	Famous, very active flare star
Ross 154	<i>dM4.5e</i>	2.97	Frequent flarer
Ross 248 (HH And)	<i>dM5.5e</i>	3.16	Weak / occasional H α emission
DX Cancrī	<i>dM6e</i>	3.58	Active flare star
YZ Canis Minoris	<i>dM4.5e</i>	~5.9	Well-studied flare star
AD Leonis	<i>dM3e</i>	~4.9	One of the most-observed flare stars
EV Lacertae	<i>dM3.5e</i>	~5.1	Very active, young, fast rotator
EQ Pegasi A/B	<i>dM3.5e /dM4.5e</i>	~6.2	Active binary pair
AU Microscopii	<i>dM1e</i>	~9.8	Young (~20 Myr), debris disk, strong flares

The Decadal Pillar: Worlds and Suns in Context

entails the study of Star formation, evolution, exoplanets and planetary systems, which are now discovered as a matter of routine but remain difficult to study in detail.

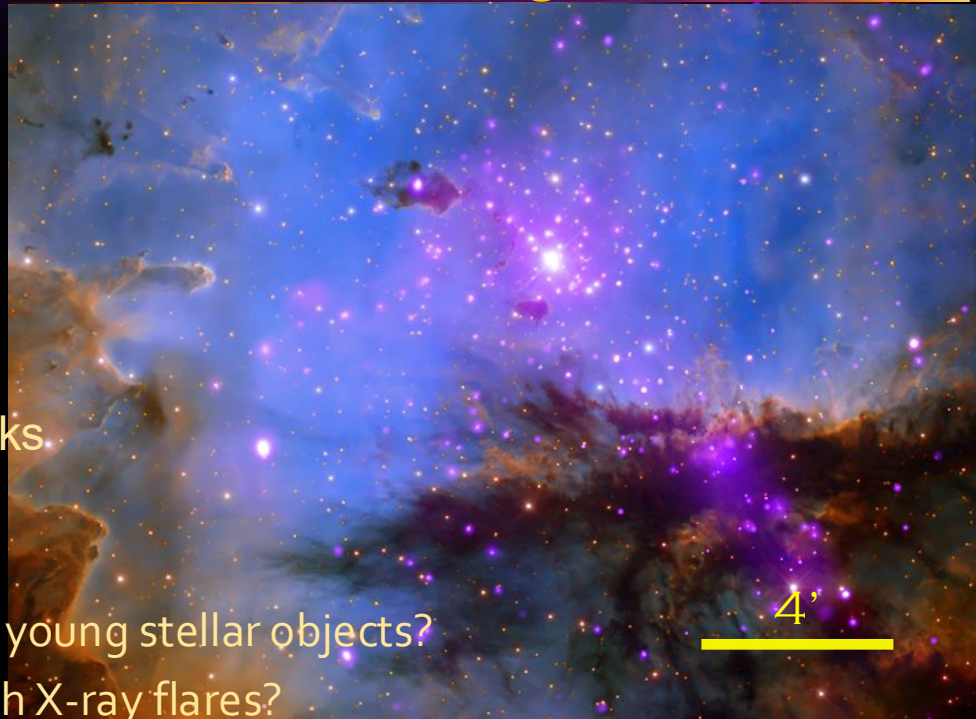
- How do rotation and magnetic fields affect stars?
 - How does the dynamo work?
 - How is the corona heated?
- How do stars form?
- How do circumstellar disks evolve, form planetary systems?
- How diverse are planetary systems?
- Do habitable worlds exist on other stars?

X-rays inform each of these topics, are vital for understanding how stars work and how they interact with their environment



Specific Science Goals for Star Formation Regions

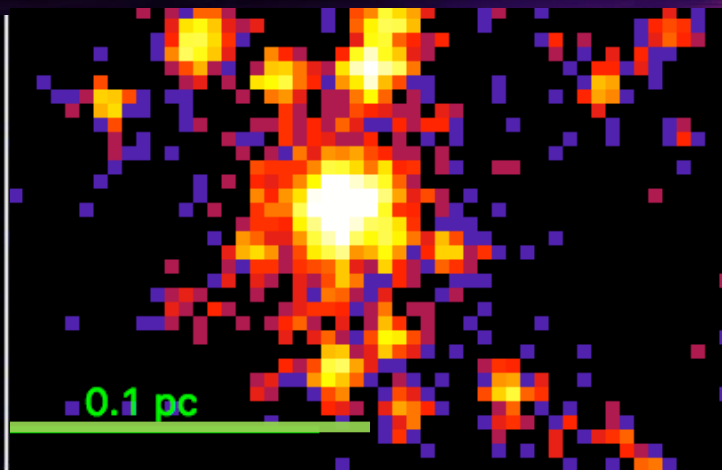
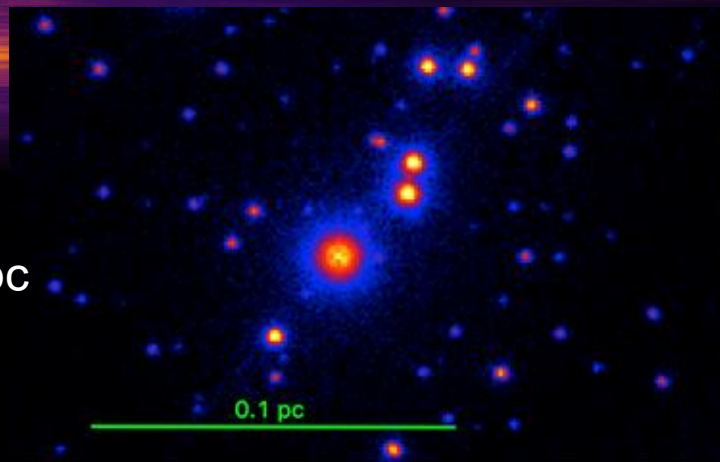
- ❖ Cluster Census
- ❖ Transition disk timescales
- ❖ X-ray effects on cluster morphology
- ❖ Detecting grain evolution
- ❖ X-rays from protostars
- ❖ Effect of X-rays on forming planets disks.
 - ❖ Especially flares.
- ❖ Understanding the magnetic fields.
- ❖ What are the statistics of radio flaring for young stellar objects?
- ❖ Are radio and optical flares correlated with X-ray flares?
- ❖ Understanding diffuse emission and feedback.
- ❖ What is the relationship between X-rays and radio emission from YSOs?



ONC

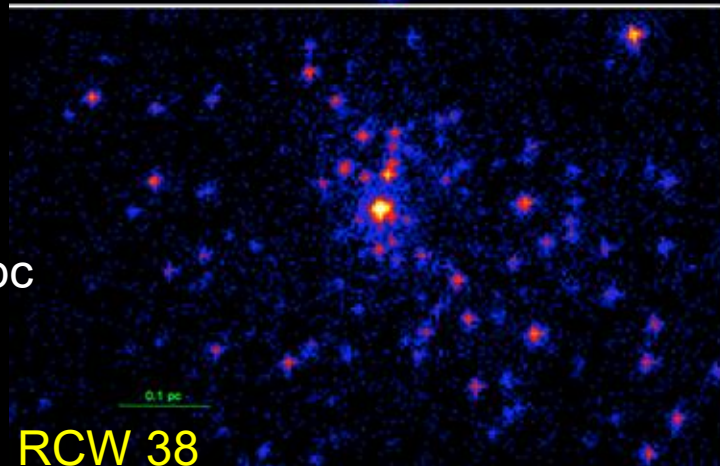
RCW 38

0.5"
@ 400 pc

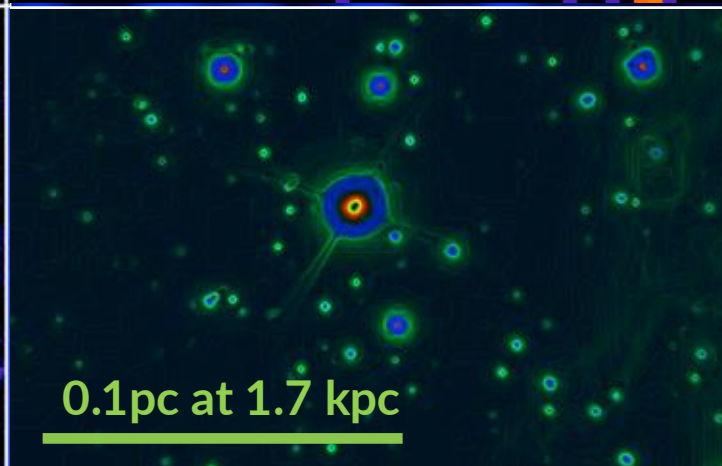


0.5"

0.5"
@ 1.7 kpc



RCW 38



0.1"

Sample program: Study Nearby Massive Star Formation Regions

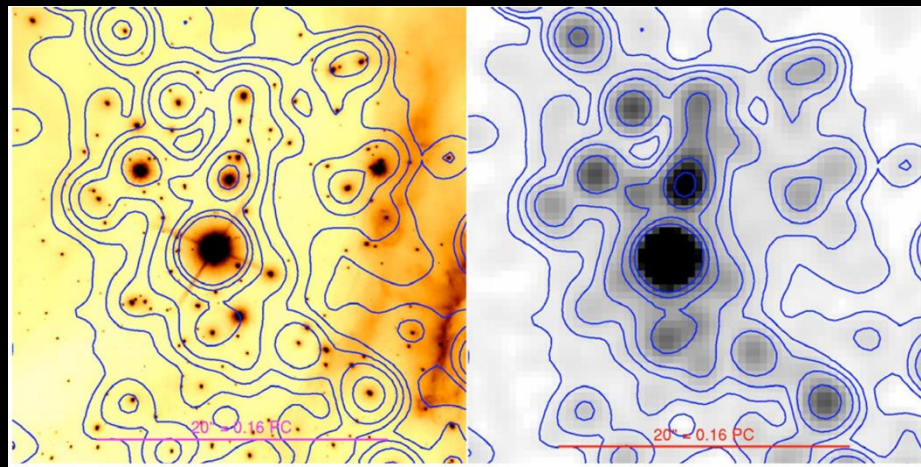
- **Goals**

- ❖ Cluster Census
- ❖ Transition disk timescales
- ❖ X-ray effects on cluster morphology
- ❖ Detecting grain evolution
- ❖ X-rays from protostars
- ❖ Effect of X-rays on planets and forming disks
 - Especially flares.
 - Understanding the magnetic fields.
- ❖ Understanding diffuse emission and feedback.

- **Targets**

- ❖ RCW 38 (1700pc)
- ❖ Carina (2400 pc)
- ❖ Westerlund 1 (4250 pc)
- ❖ NGC 3603 (6900 pc)
- ❖ ARCHES (~8000pc)
- ❖ 30 Dor (LMC)
- ❖ Etc.

RCW 38
100mas Left,
0.5" (Chandra) Right

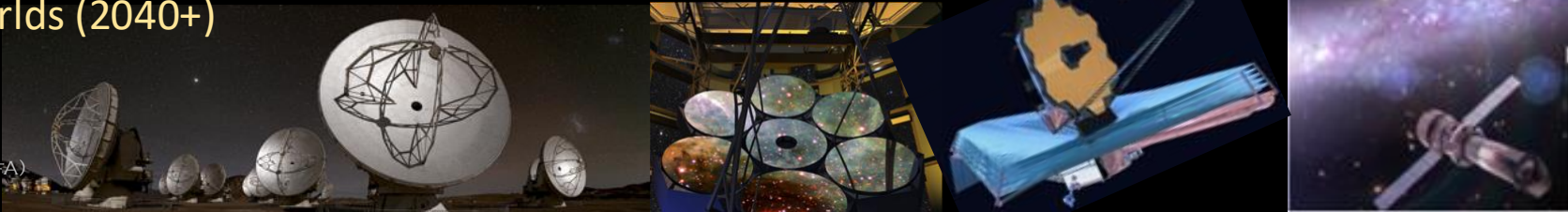


Concluding thoughts:

- Spatial resolution is intimately tied to effective area. You might have $0.1''$ resolution, but if you only get 4 photons per $1''$ then your resolution is $\sim 1''$.
- Solar system bodies have different physics occurring on all spatial scales.
- Current resolution limitations ($0.5''$) leave us on the precipice of the discovery of multiple astrospheres, exoplanet atmospheres, proper motion measurements, and stellar jets.
- $0.1''$ resolution will allow us to resolve almost all star formation within 3.5 kpc.
 - 10 milli arcsecond resolution is about what is needed for the center of the galaxy.
- Large flares in the solar neighborhood require milli arc seconds to resolve.

Science Landscape of the 2030s

- ❖ JWST, Roman– Deep IR imaging and spectroscopy. constraints on stellar populations in crowded stellar clusters down to the H-burning limit, properties of starspots in transiting exoplanet systems
- ❖ Plato (2027), ARIEL (2031) – Survey millions of stars to find exoplanets.
- ❖ ALMA (wideband), SKA (2028+), ngVLA (2030+), – Radio telescopes will study chemistry and dynamics of planet-forming disks, non thermal stellar processes.
- ❖ E-ELT, TMT GMT (2028+) – Ground based optical and NIR telescopes will map surface magnetic fields in a variety of stars
- ❖ Athena (2035) – sensitive $R \sim 200\text{-}500$ X-ray spectroscopy (as far as stars are concerned). PSF limits utility in crowded regions.
- ❖ LISA (2035) – gravitational wave observatory. Not much for stars and planets.
- ❖ HabWorlds (2040+)



What is the Diffuse Emission?

- Diffuse Emission has now been reported in about half a dozen regions of massive star formation
- An X-ray halo around IRS 2?
 - ✧ Diffuse flux is much harder than that of IRS 2.
- Thermal emission?
 - ✧ Would need to be hot $\sim 10\text{keV}$ electrons.
 - ✧ Pressure would be high leading to shocks.
 - ✧ No lines seen.
 - ✧ Wind driven models of diffuse emission tend have cooler & thermal emission profiles.
- filling the cavity. (ad hoc)
- SPECTRUM DOMINATED BY POWER-LAW.
 - SYNCHROTRON $\rightarrow$ B FIELD TO EXCITE ELECTRONS
 - COMMON IN SNR BUT LACK OF LINES IMPLIES A SHELL TYPE SNR, NOT CONSISTENT WITH THE MORPHOLOGY.
 - ENERGETICS
 - $L_x \sim 3 \times 10^{32}$ ERGS/SEC
 - ASSUMING EQUIPARTITION
 - $B \sim 4.9 \mu\text{G}$
 - 2.2×10^{44} ERGS IN RELATIVISTIC ELECTRONS
 - e^- SHOULD DECAY IN 20,000 YEARS (UNIQUE AMONG STAR FORMING REGIONS)
 - CAUSED BY RECENT SN? OR...
 - REPLENISHED BY COLLIDING WINDS ?
 - SHELL SUPERNOVAE REMNANTS TEND TO BE SYMMETRIC.
- PHOTOIONIZATION
- PERHAPS THIS IS A SHELL SUPERNOVA WITH A MASSIVE O STAR WIND

Discussion Notes

- How large a format μ cal would be useful?
 - ✧ Measuring velocities over regions will be valuable.
- Only μ cal (smaller FOV)
 - ✧ or multiple μ cal (one small and high spectral res. + other bigger with less resolution)
 - ✧ or μ cal + CCD for wide field (2 instruments) ?
 - ✧ Possible “sacred” soft (sub eV resolution) pixels.
 - ✧ Notional mission will help with this trade.
- Don’t forget fast timing
 - ✧ (but in the Athena program)
- Angular resolution drivers.
 - ✧ $<0.3''$ very difficult, but should be kept as a goal ($z=1$ normal galaxies and star formation both benefit) .
 - ✧ $<0.5''$ near technical limit.
 - ✧ Going below 0.5 gives away some of the details we know exist from Chandra...e.g proper motion studies

Discussion Notes

- Angular resolution cont'd....
 - ✧ HPD 0.5" gets us to 100's of km/s proper motions in the galactic center. Resolving structures and faint point sources are key to the pillars. Going below 1" is required to do this.
 - ✧ Below 0.25" might be photon starved, could be demonstrated through simulation.
 - ✧ Localizes centroids to much better, especially if the PSF is well calibrated across the FOV.
 - ✧ Other wavelengths are sub arcsec (except mid-IR?)

Discussion Notes

- Timeline
 - ✧ Mission Study due to NASA May? 2019.
 - ✧ Decadal call for white papers (science questions) late 2018.
 - ❖ Formally not tied to missions, but...
 - ✧ Science pillars, two identified so far, but discussing a third, needs to be focused soon.
 - ❖ What is our core message to the whole community?
 - ✧ Chandra cycle 20/21...
 - ❖ What can Chandra do to support the Lynx science case?
 - ❖ Would an Chandra initiative for this be useful?
 - ❖ Prioritize theory money?????
- Link to fundamental physics.
 - ✧ Lots of mission already working on e.g. cosmology. So hard to imagine what the key questions will be in 2030'a