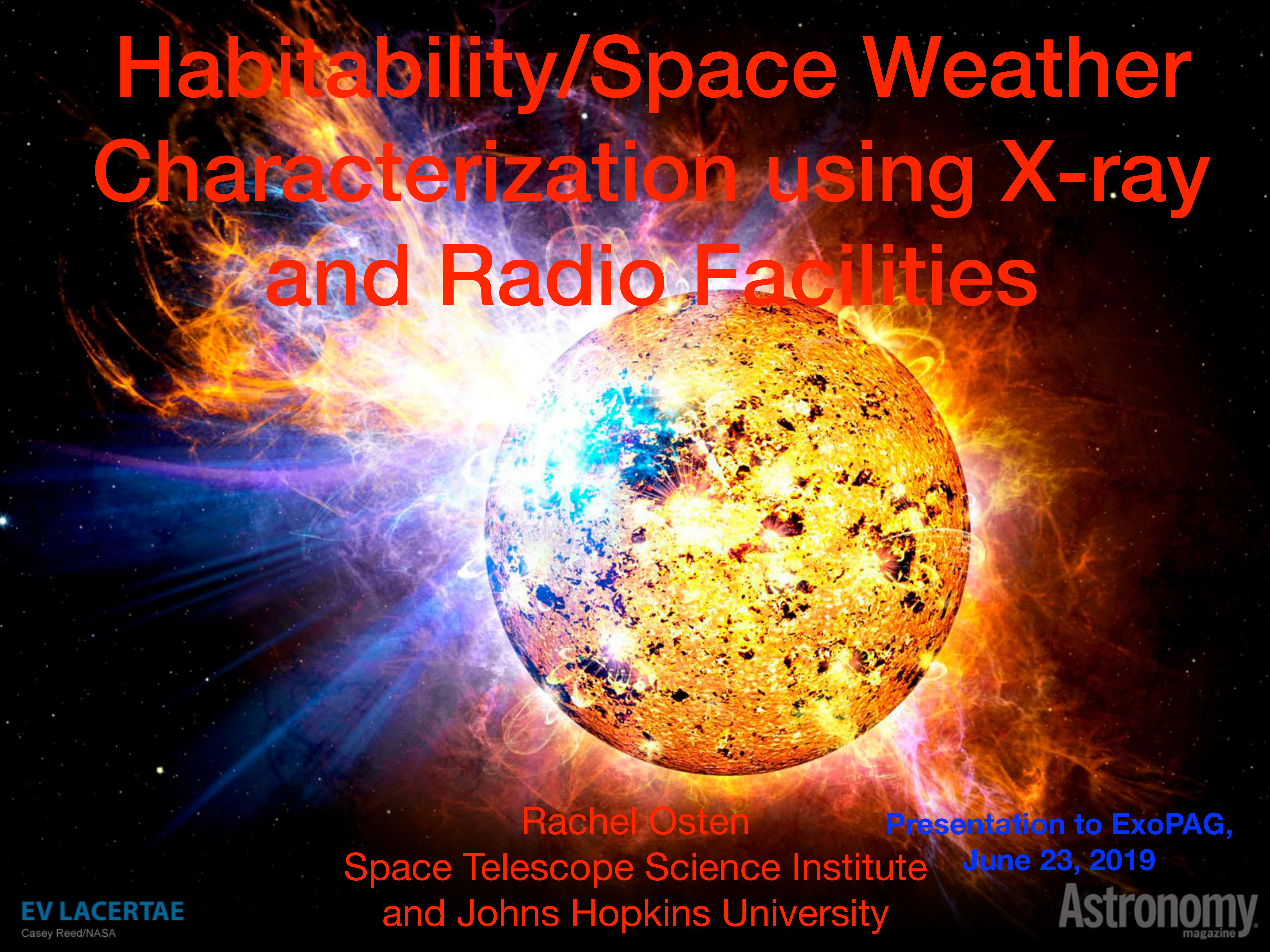
Habitability/Space Weather Characterization using X-ray and Radio Facilities



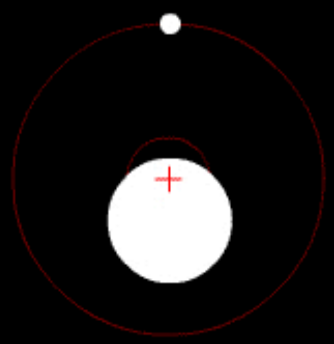
Rachel Osten
Space Telescope Science Institute
and Johns Hopkins University

Presentation to ExoPAG, June 23, 2019

Outline

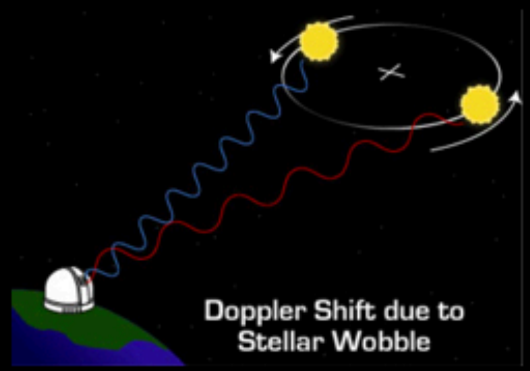
- Unifying scientific themes
- X-ray facilities (Athena, Lynx): capabilities, comparison
- Radio facilities (SKA, ngVLA): capabilities, comparison
- Key questions and avenues to answer them

Exoplanet Science: Detection

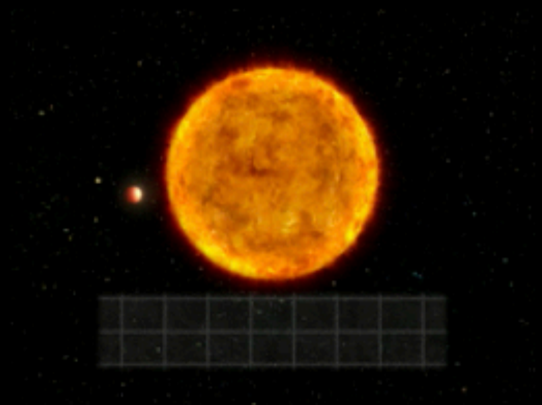


astrometry — seeing the reflex motion of the star due to star+planet system

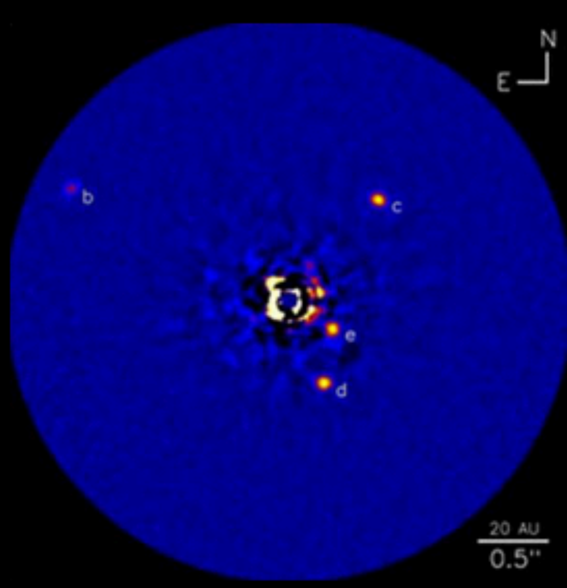
radial velocity — velocity shift of a star due to star+planet



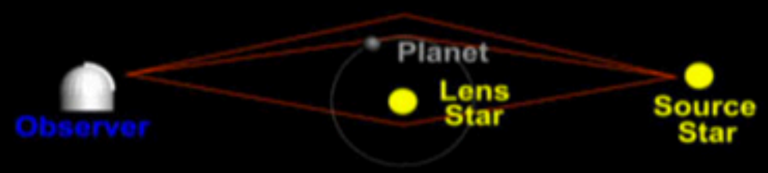
transit — decrease in stellar light



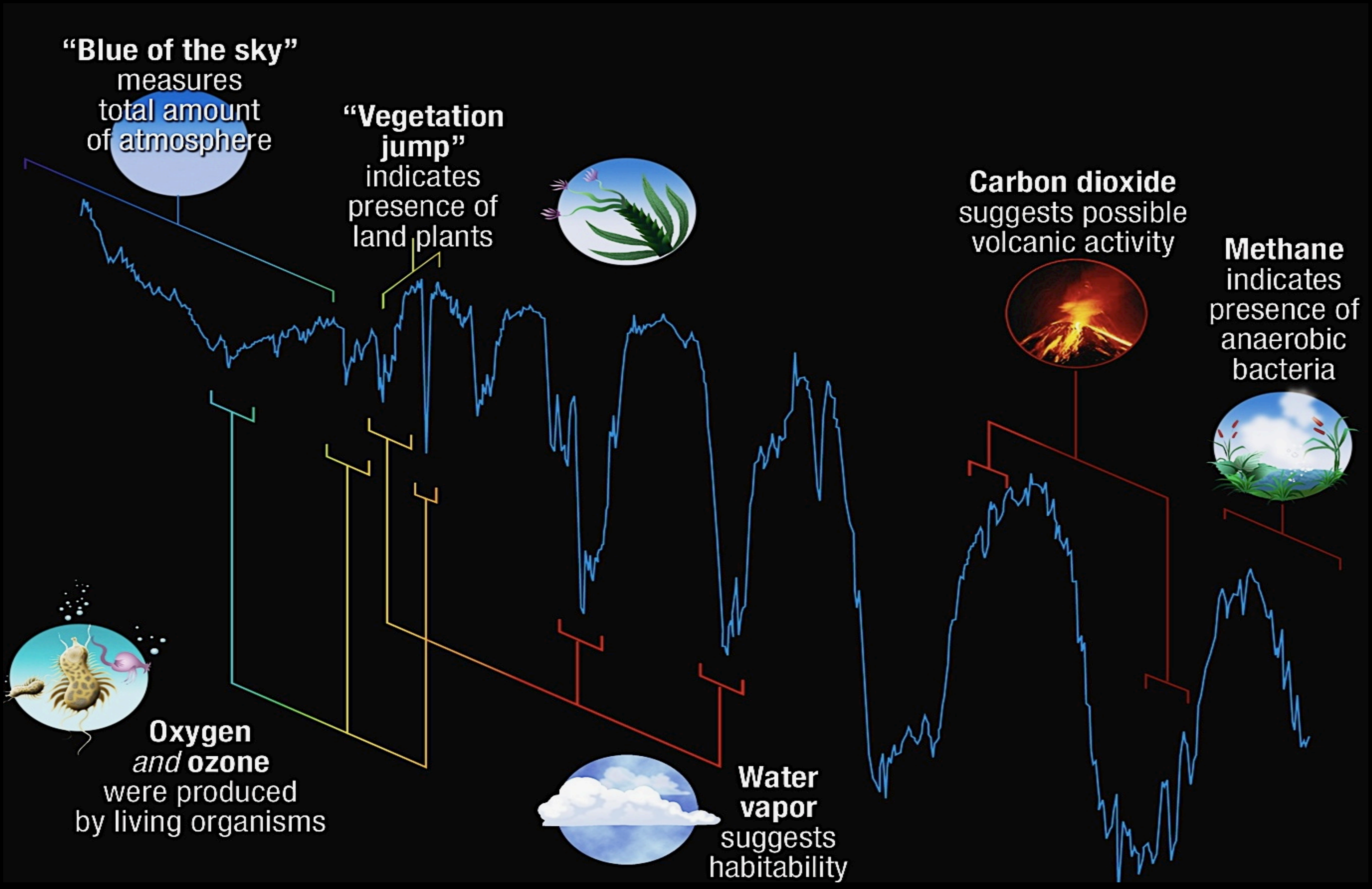
direct imaging — block out the light of the star to see the planet directly



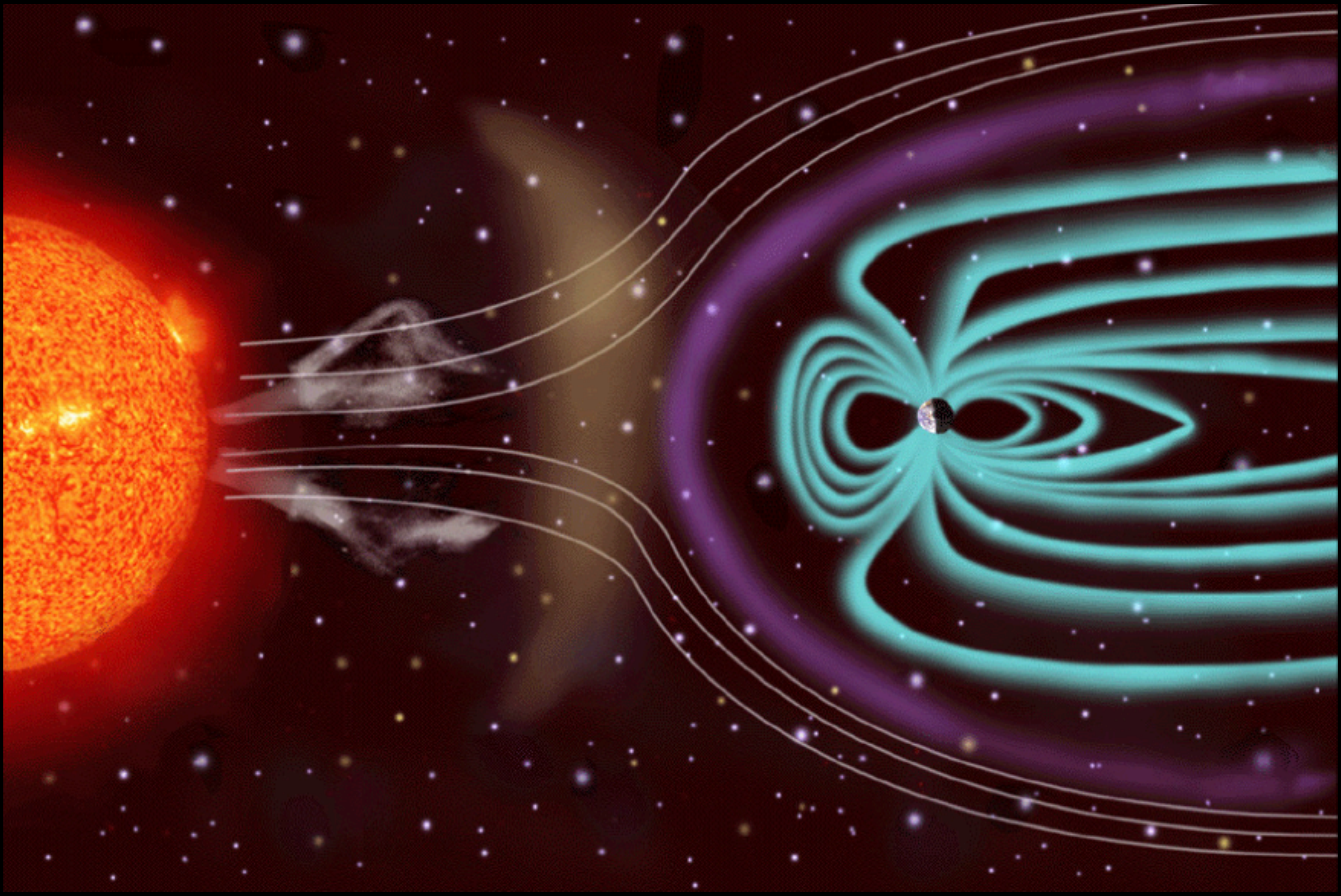
microlensing — gravitational lensing due to star+planet system passing in front of a background star



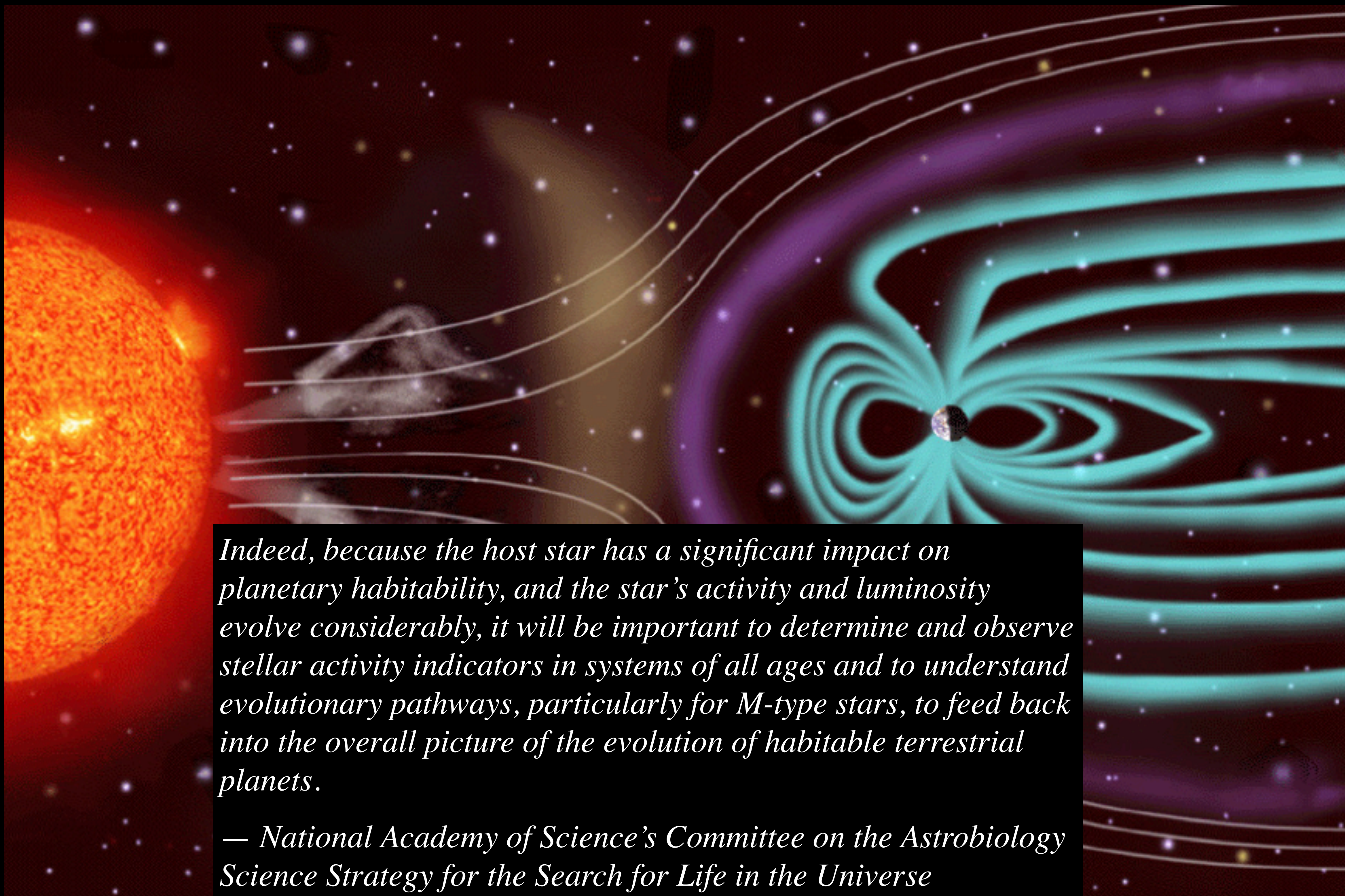
Exoplanet Science: Characterization



Exoplanet Science: Environment



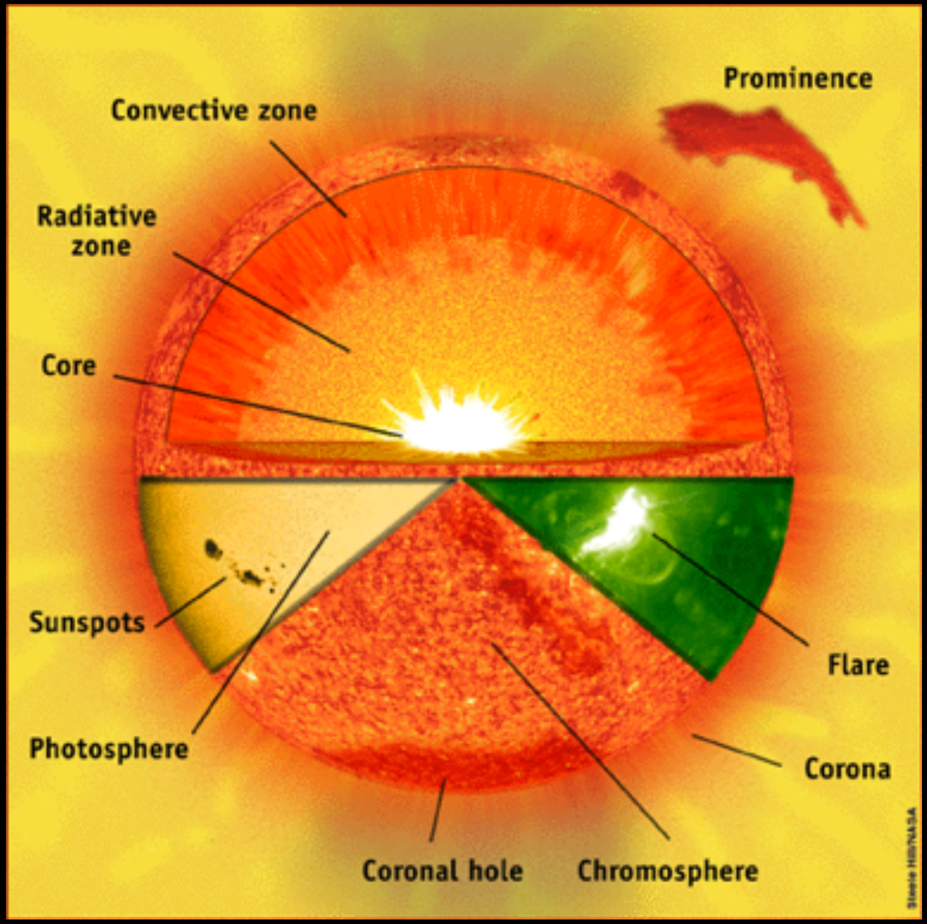
Exoplanet Science: Environment

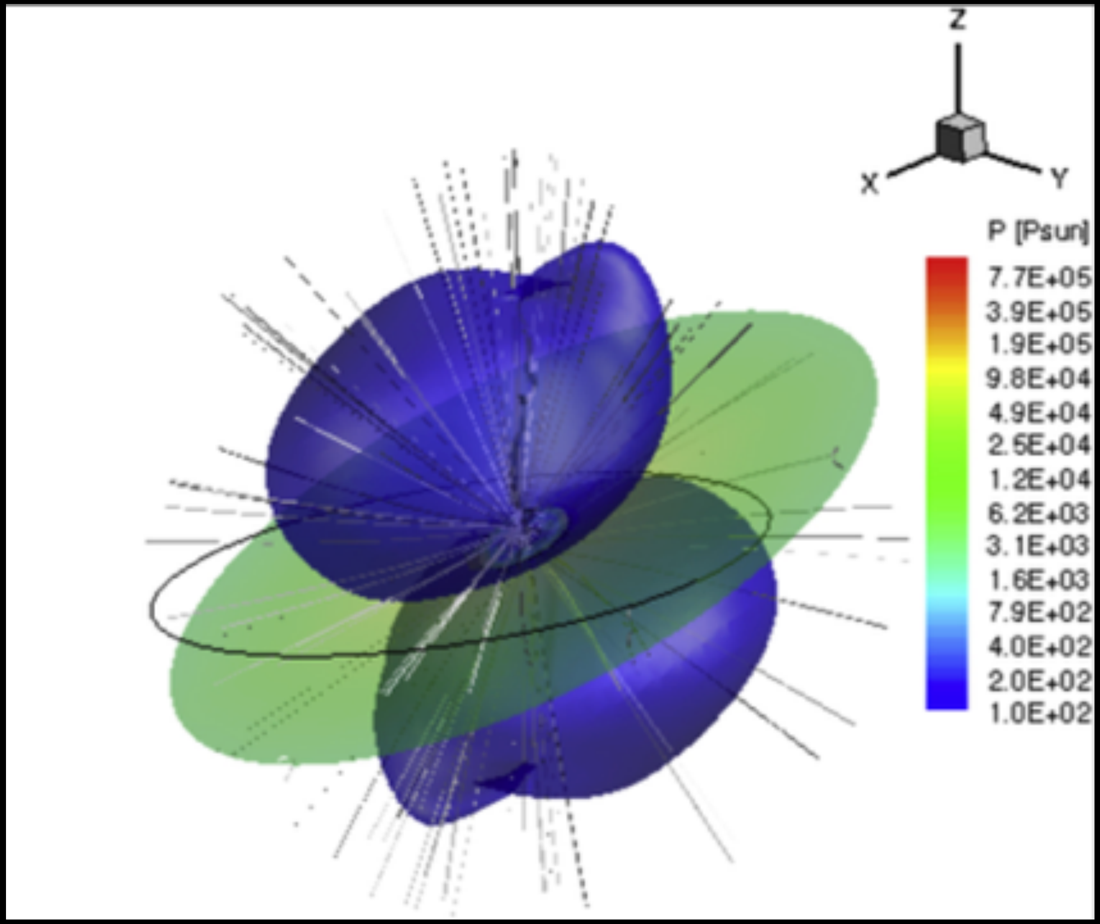


Indeed, because the host star has a significant impact on planetary habitability, and the star's activity and luminosity evolve considerably, it will be important to determine and observe stellar activity indicators in systems of all ages and to understand evolutionary pathways, particularly for M-type stars, to feed back into the overall picture of the evolution of habitable terrestrial planets.

— National Academy of Science's Committee on the Astrobiology Science Strategy for the Search for Life in the Universe

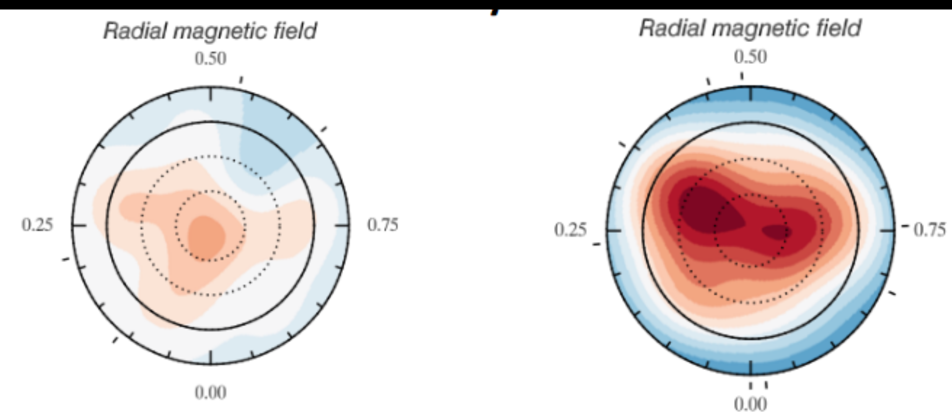
The Importance of Being Magnetic





- The star's magnetic field creates an ecosystem which helps to set the environment that planets (and life) experience (Lingam & Loeb 2018)
- Stellar magnetospheres influence the inner edge of the traditional habitable zone (Garaffo et al. 2016, 2017).
- Coronal mass ejections and proton events have the biggest impact in determining the effect of reconnection events on planetary atmospheres, but require scaling from the Sun

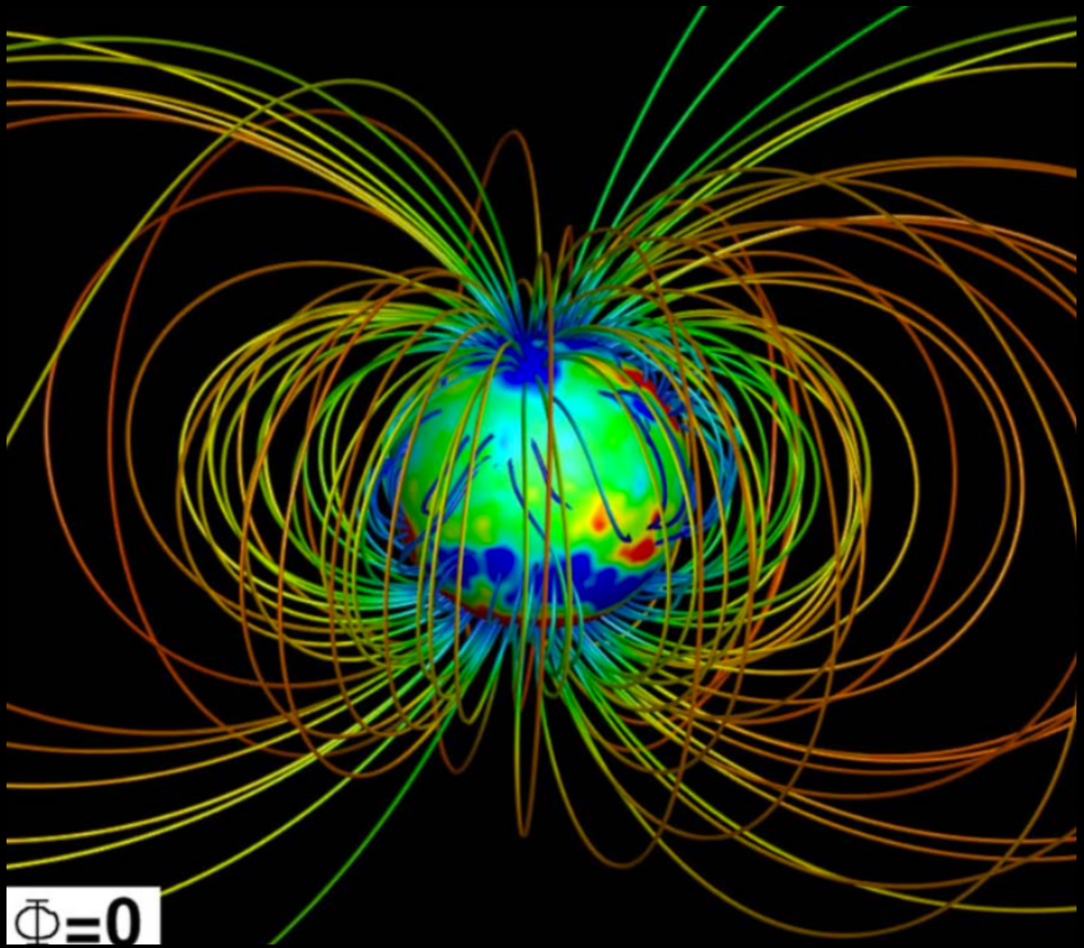
The Importance of Being Magnetic



	Gl 65A	Gl 65B
Spectral class	M5.5Ve	M6Ve
Mass	0.1225 $M_\odot$	0.1195 $M_\odot$
Radius	0.165 $R_\odot$	0.159 $R_\odot$
Rot. vsini	28.5 km/s	30.6 km/s
Rot. period	5.86 hr	5.45 hr
Metall. [Fe/H]	-0.03	-0.12
<Bf> Stokes I	**5.2 kG**	**6.7 kG**
B_{dip} strength V	**0.3 kG**	**1.3 kG**
	complex, non-axisymmetric	**axisymmetric dipole**

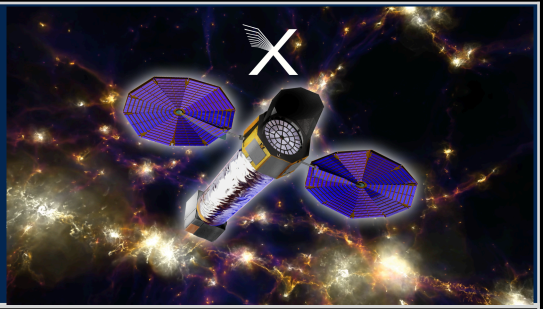
Kervella et al. 2016, Barnes et al. 2016, Kochukhov et al. 2017, Lynch et al. 2017

larger amplitude X-ray & radio variability

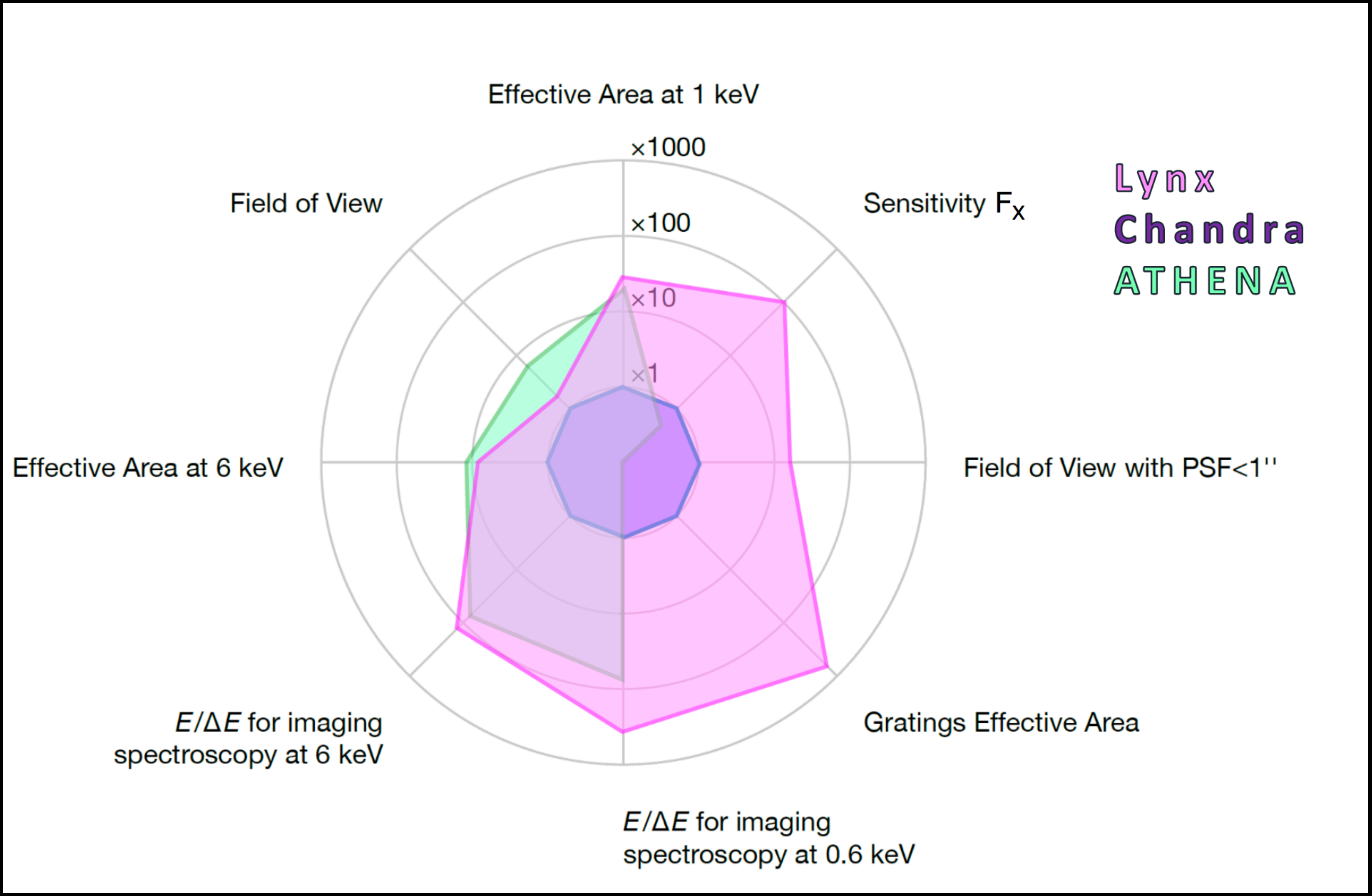


Cohen et al. (2017) dynamo simulation

- Stellar twins are not magnetic twins; radio and X-ray activity level & variability are tied to magnetic field structure
- Planetary atmospheric evolution is fundamentally linked to XEUV emission
- X-rays trace magnetic structure directly

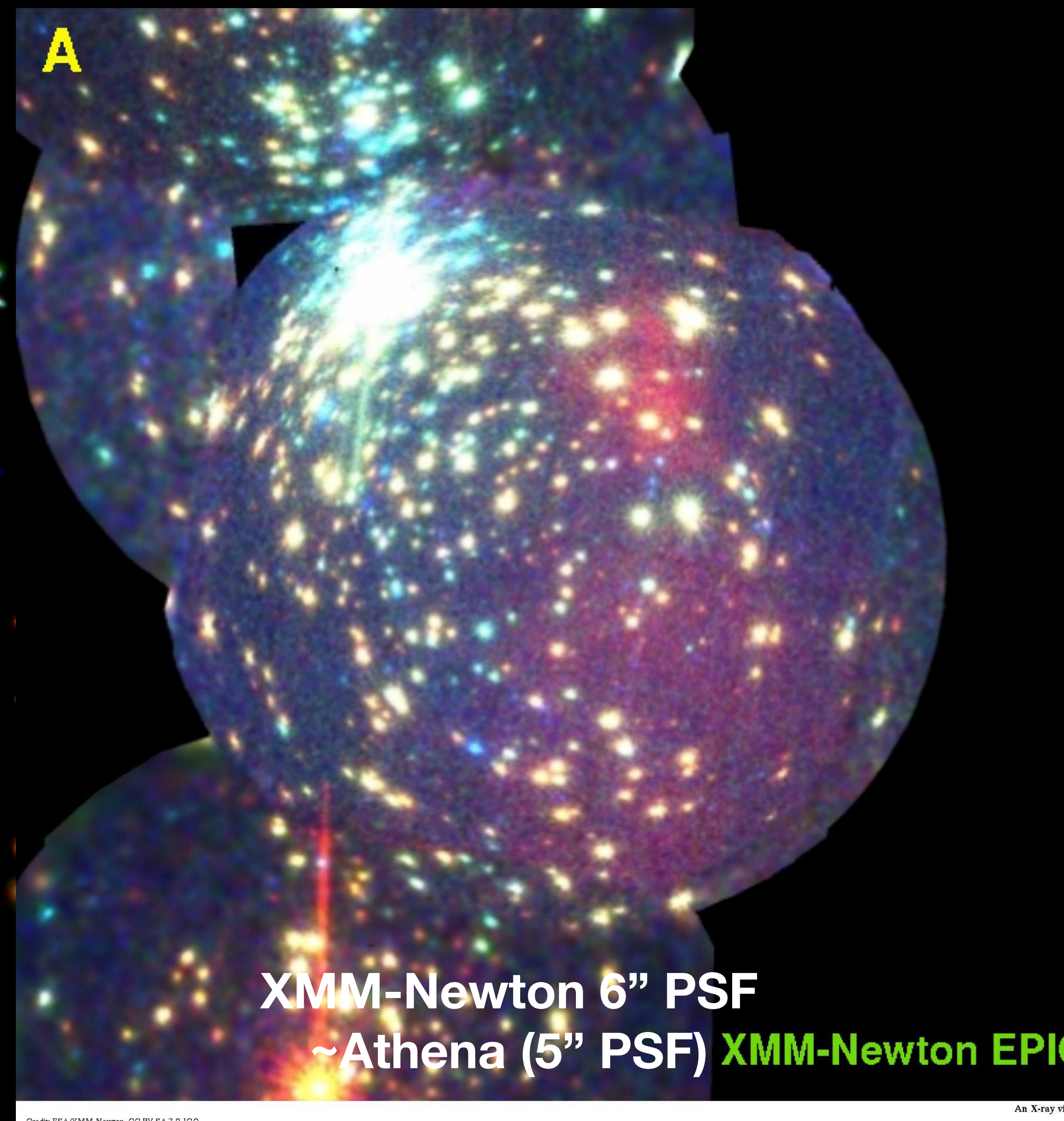
X-ray Facilities	ATHENA	Lynx 
Status	ESA approved L2 mission (w/NASA contributions); launch in 2031?	NASA Large mission Concept
Angular Resolution	5”	0.5”
Wavelength/ Energy Grasp	0.1-12 keV	0.3-10 keV
Instrument Characteristics	**X-ray Microcalorimeter Spectrometer:** ΔE=3 eV @ 6 keV, 2’x2’ **Wide Field Imager:** ΔE=150 eV @6 keV, 24’x24'	**X-ray Microcalorimeter:** ΔE=3 eV, 0.2-7 keV w/1” pixels **High Definition X-ray Imager:** 0.3” pixels, ΔE=100 eV, 20’x20’ **X-ray Grating Spectrometer:** R=5000 over 0.2-2 keV
Science Pillars/ Key Science	1. Mapping hot gas structures and determining their physical properties 2. Searching for supermassive black holes	1. The Dawn of Black Holes 2. Revealing the Invisible Drivers of Galaxy Formation and Evolution 3. The Energetic Side of Stellar Evolution and Stellar Ecosystems
More Info	https://www.the-athena-x-ray-observatory.eu/	https://www.lynxobservatory.com/

X-ray Facilities Comparison



X-ray Facilities Comparison

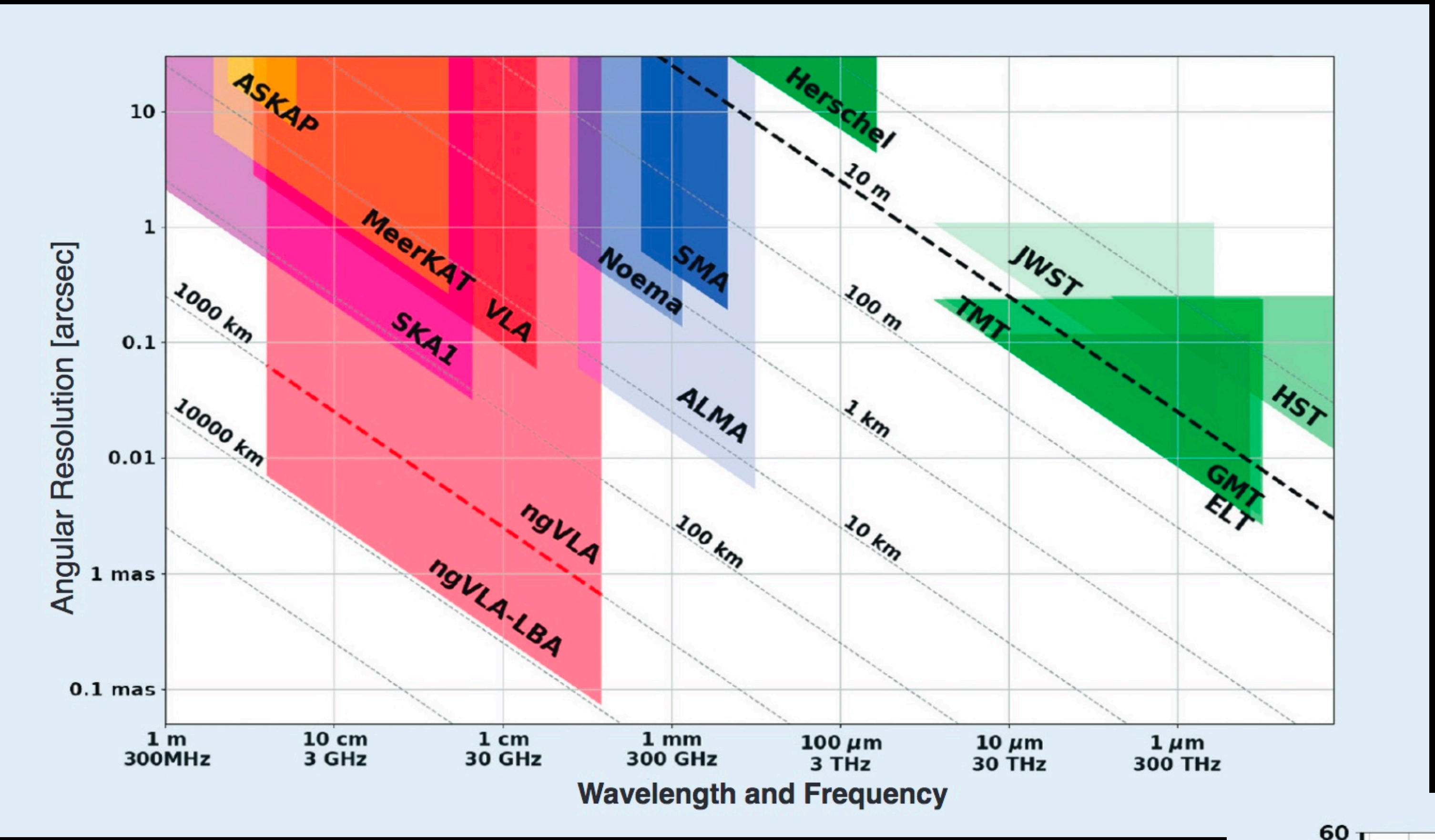
Chandra 0.5” PSF
~Lynx

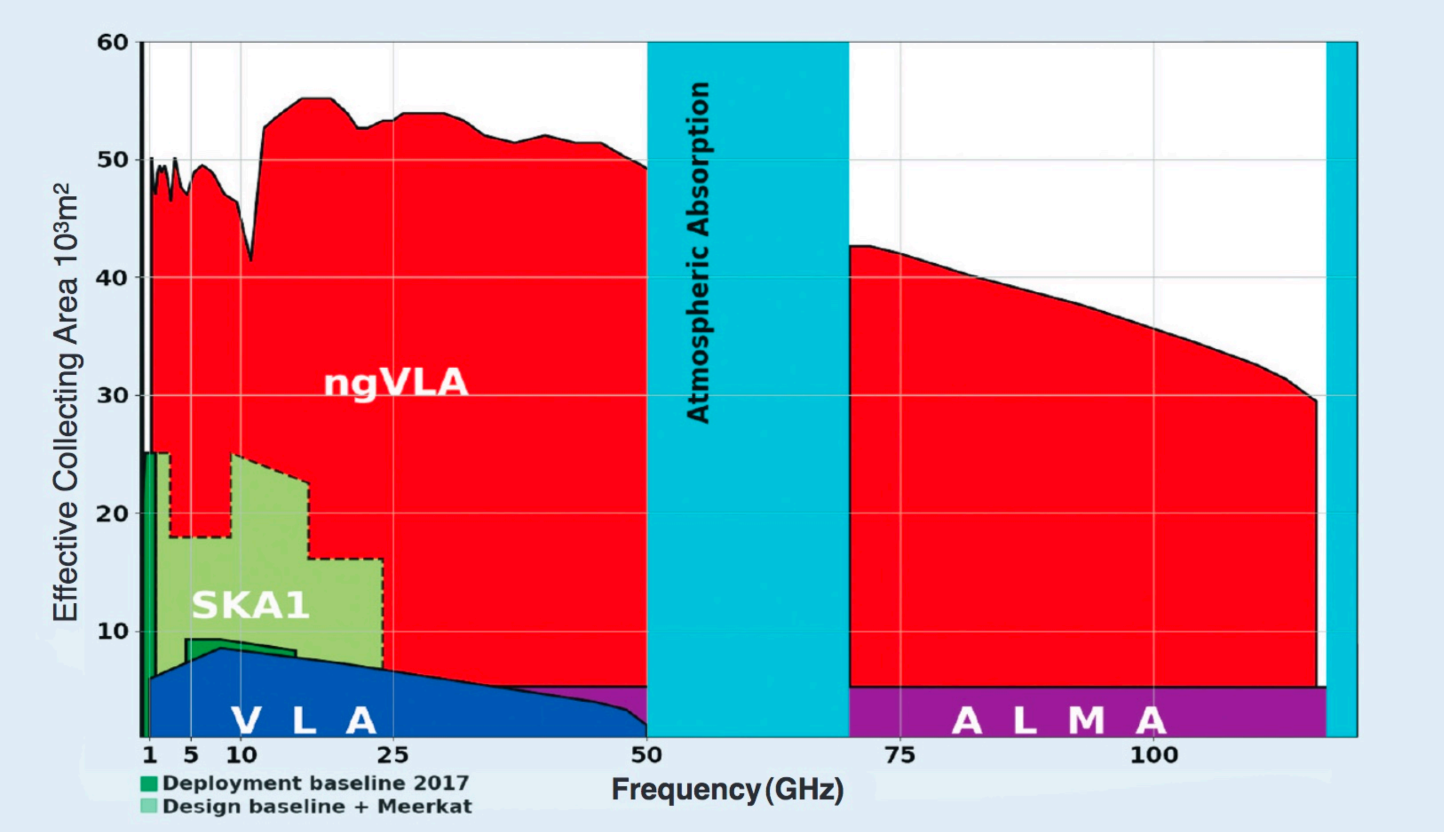


XMM-Newton 6” PSF
~Athena (5” PSF)

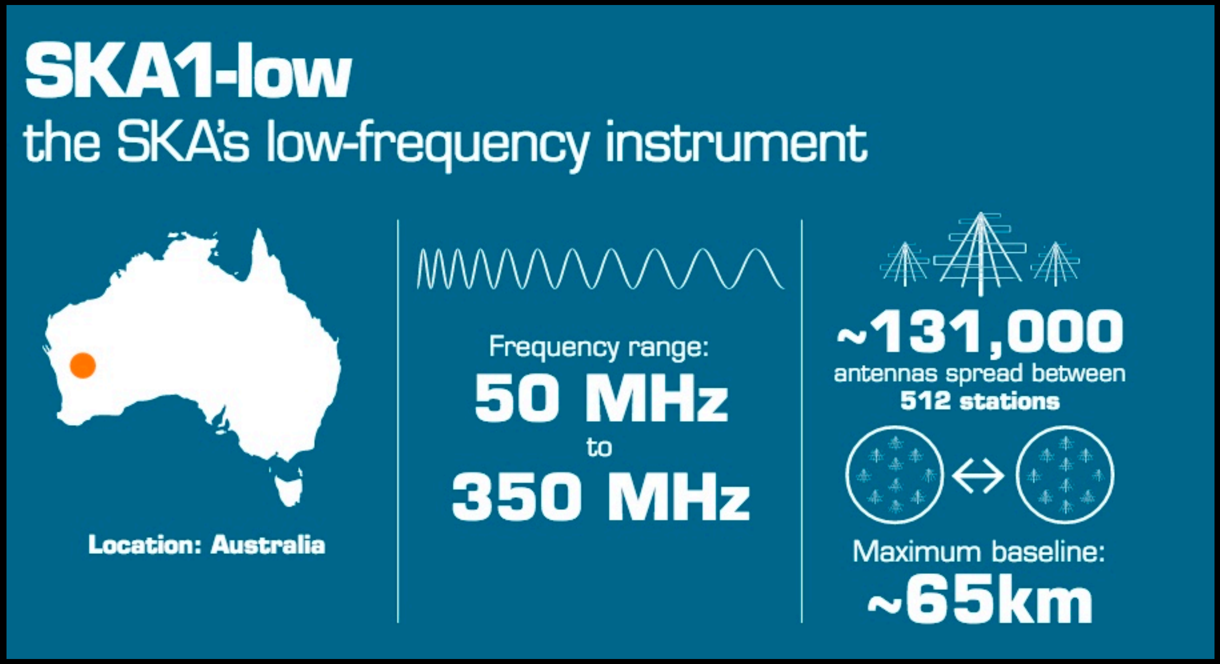
Radio Facilities	Square Kilometer Array	next generation VLA
Status	Funding from member countries of SKA Organization; Phase I construction 2018-2023	NSF design & development funds; construction 2024, early science 2028
Max. Angular Resolution	40 mas @12.5 GHz	0.2 mas @ 30GHz
Wavelength Grasp	110 MHz-15.3 GHz	1.2-116 GHz
Science Pillars/ Key Science	1. How do galaxies evolve? What is dark energy? 2. Was Einstein right about gravity? 3. What generates giant magnetic fields in space? 4. How were the first black holes and stars formed? 5. Are we alone?	1. Unveiling the Formation of Solar System Analogs on Terrestrial Scales 2. Probing the Initial Conditions for Planetary Systems and Life with Astrochemistry 3. Charting the Assembly, Structure, and Evolution of Galaxies from the First Billion Years to the Present 4. Tracing Galactic Center Pulsars for a Fundamental Test of Gravity 5. Understanding the Formation and Evolution of Stellar and Supermassive Black Holes in the Era of Multi-Messenger Astronomy
More Info	https://www.skatelescope.org/	https://ngvla.nrao.edu/

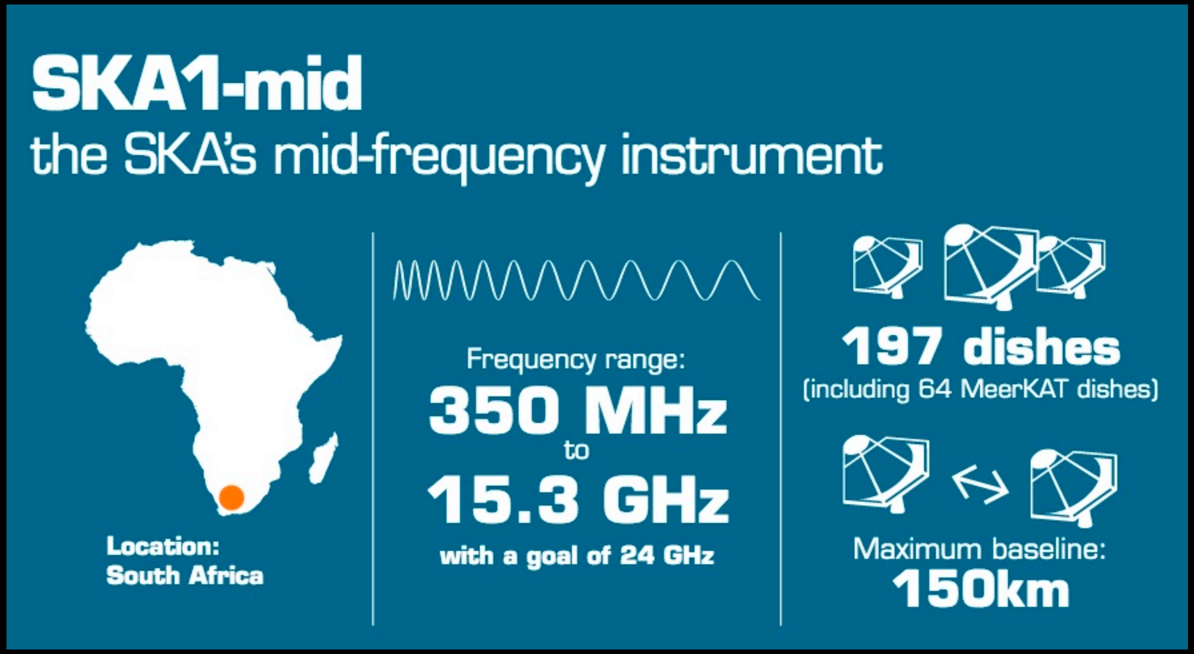
Radio Facilities Comparison

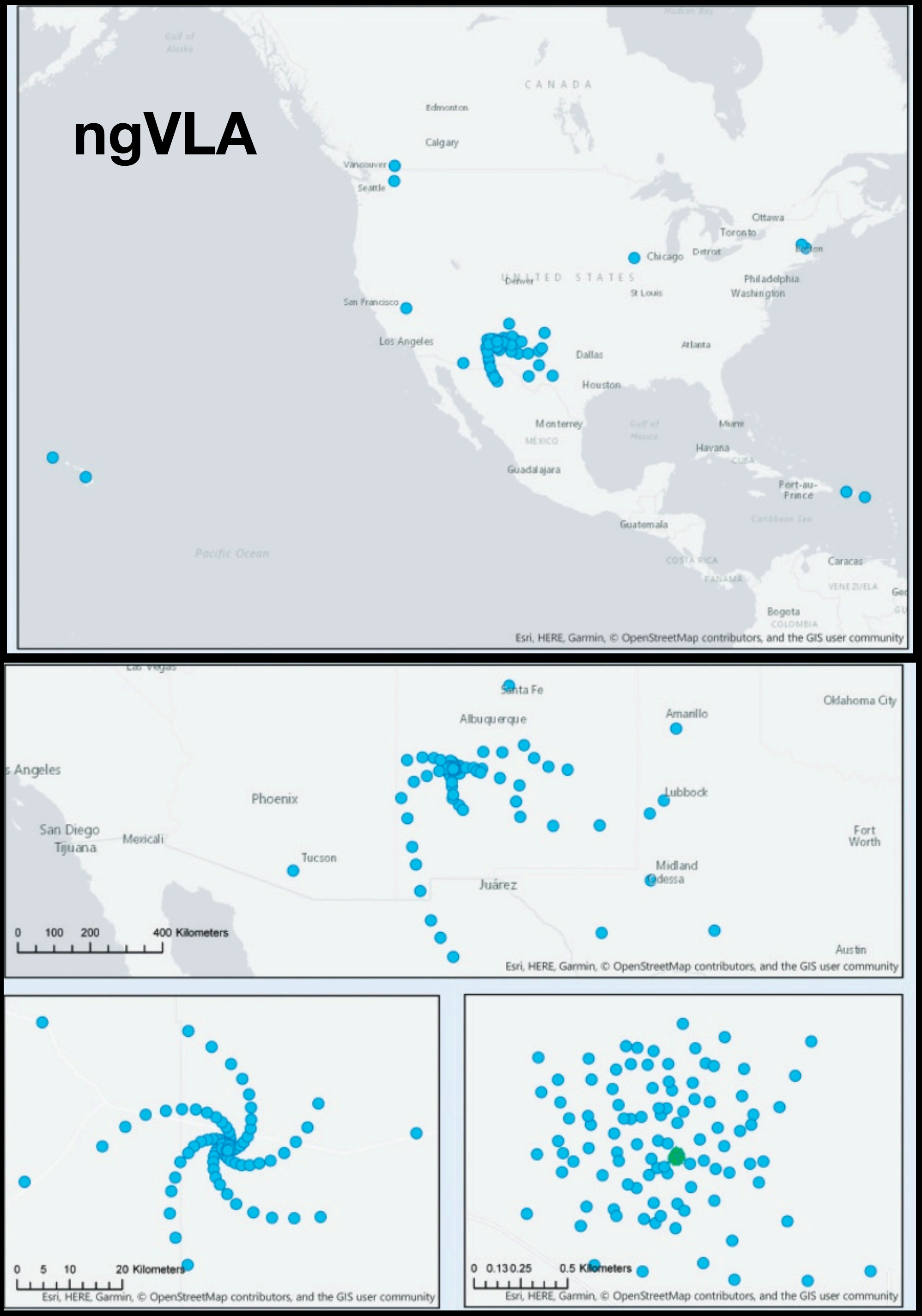




Radio Facilities Comparison





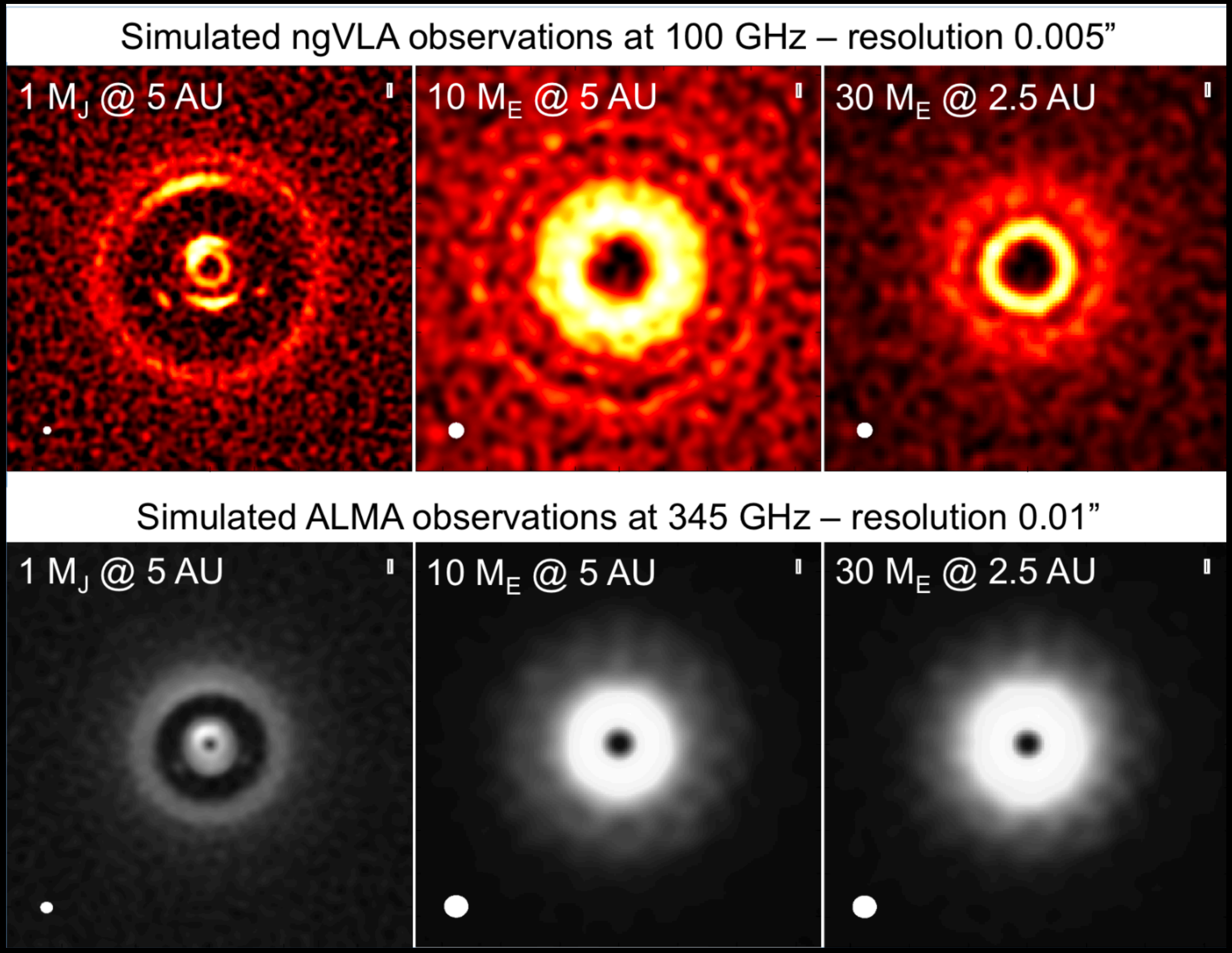


Key Questions Relevant to Habitability/ Space Weather Characterization

- Where do planets form? Where do they migrate?
- How does the coronal emission of stars affect exoplanets?
- How do the characteristics of flares change with time, and what impact does this have on exoplanet conditions?
- How do stellar winds change with time, and what impact does this have on exoplanet conditions?

Where do planets form? Where do they migrate?

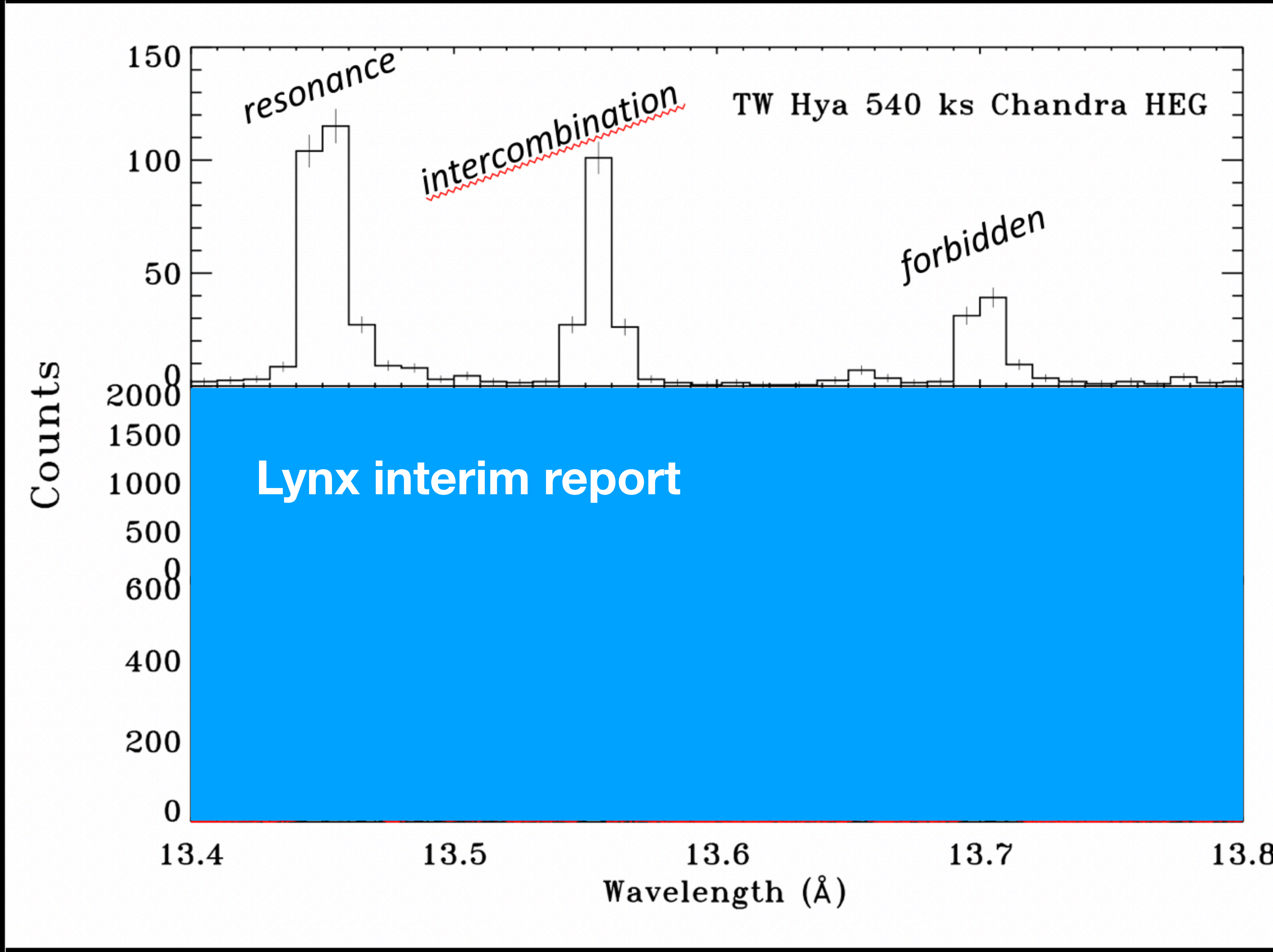
- Angular resolution & sensitivity currently limited to probing planets more massive than Neptune, >20-30 au
- ALMA observations optically thick dust emission
- Increasing angular resolution and sensitivity enables study of formation of super Earths and more massive planets, orbital motions of structures on monthly timescales, circumplanetary disks + Trojan satellites



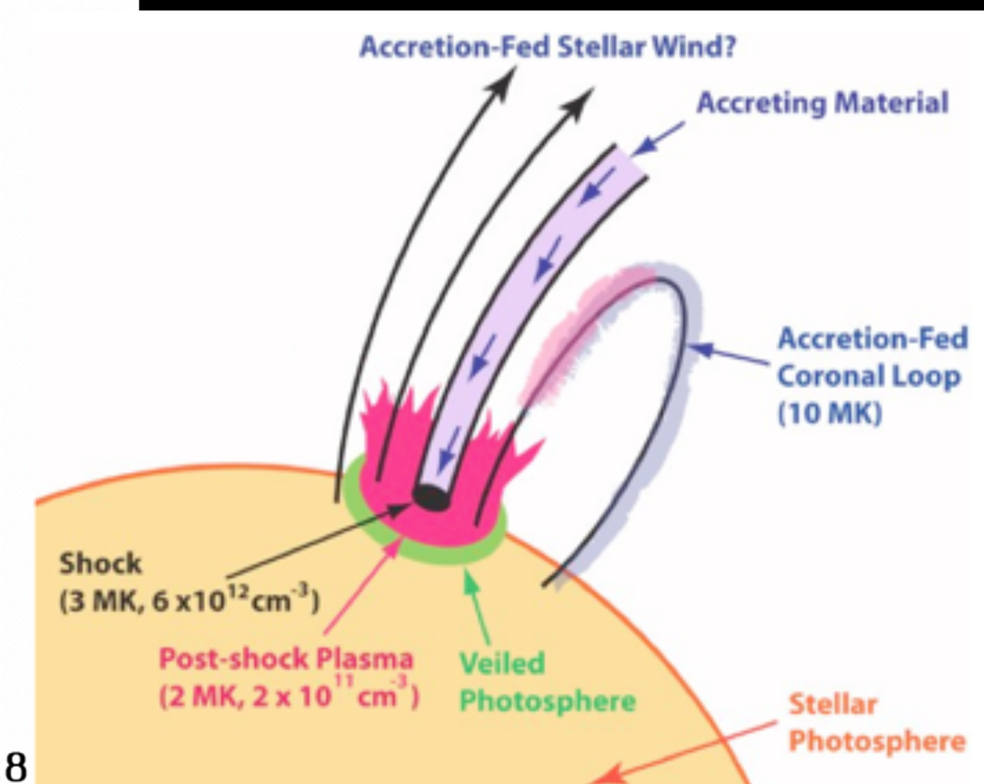
Ricci et al. (2018)

Where do planets form? Where do they migrate?

- X-ray spectra of young stars show more than accretion plus magnetic activity



One of the deepest, highest resolution X-ray spectra of a young star ever taken



Brickhouse et al. (2010)

The impact of a high quality X-ray spectrum: need more than accretion source + coronal source to explain all the miriad diagnostics (electron density, electron temperature, absorbing column)

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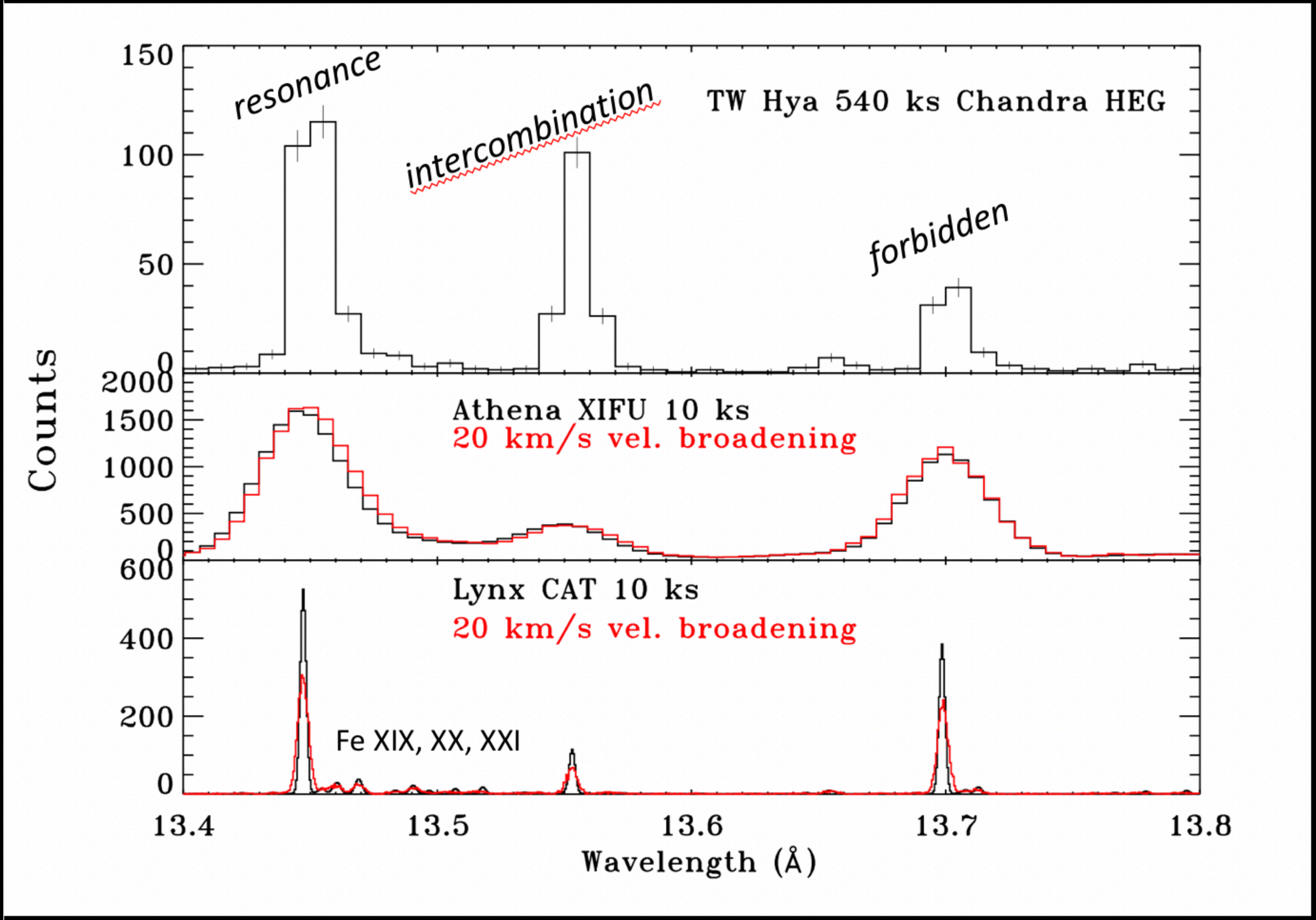


One of the deepest, highest resolution X-ray spectra of a young star ever taken

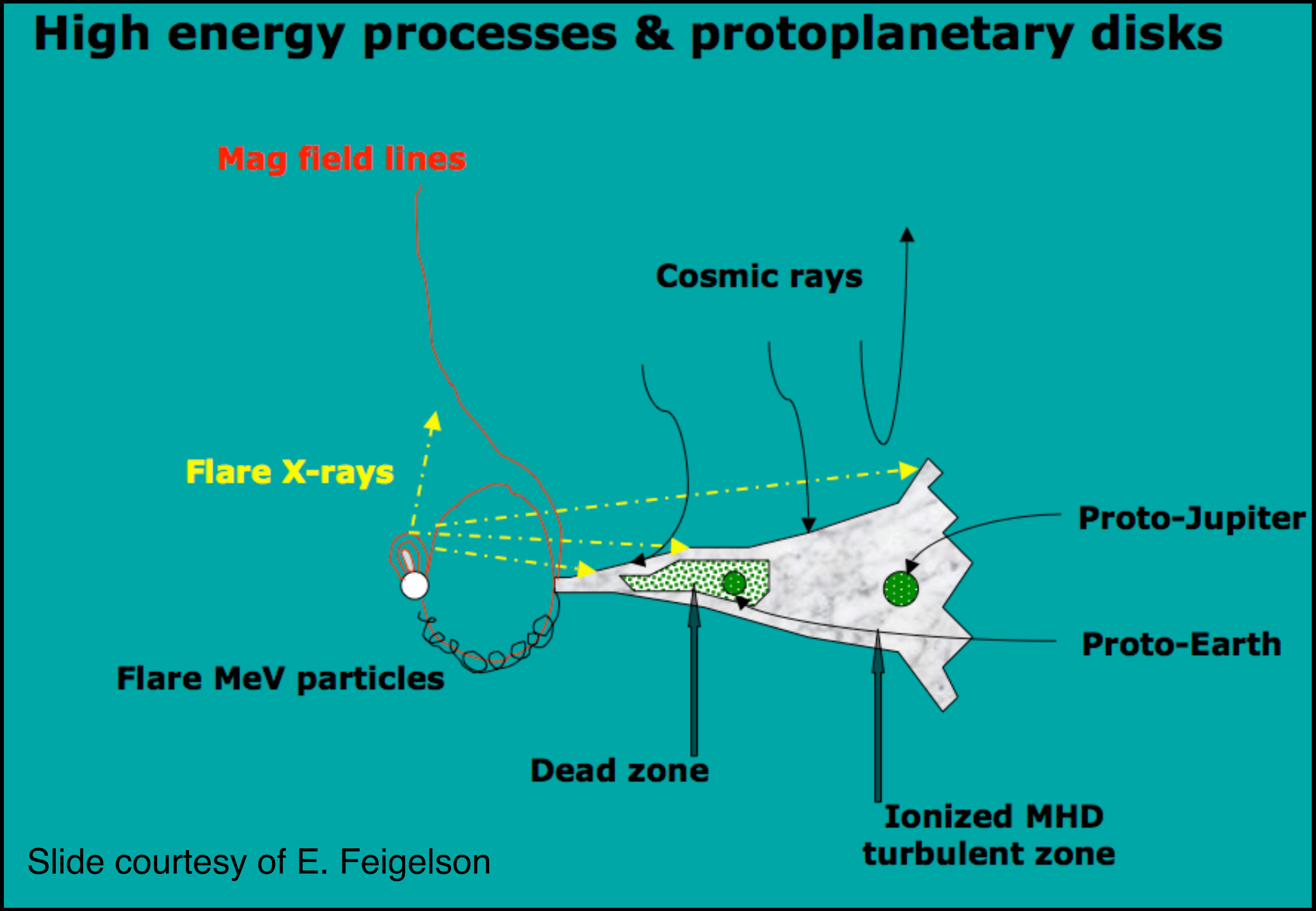
Athena issues
-- continuum placement for measurement of triplet lines
--blending lines

Lynx
--similar quality to Chandra exposure in 1 ks in Taurus-Auriga objects, 10 ks at Orion

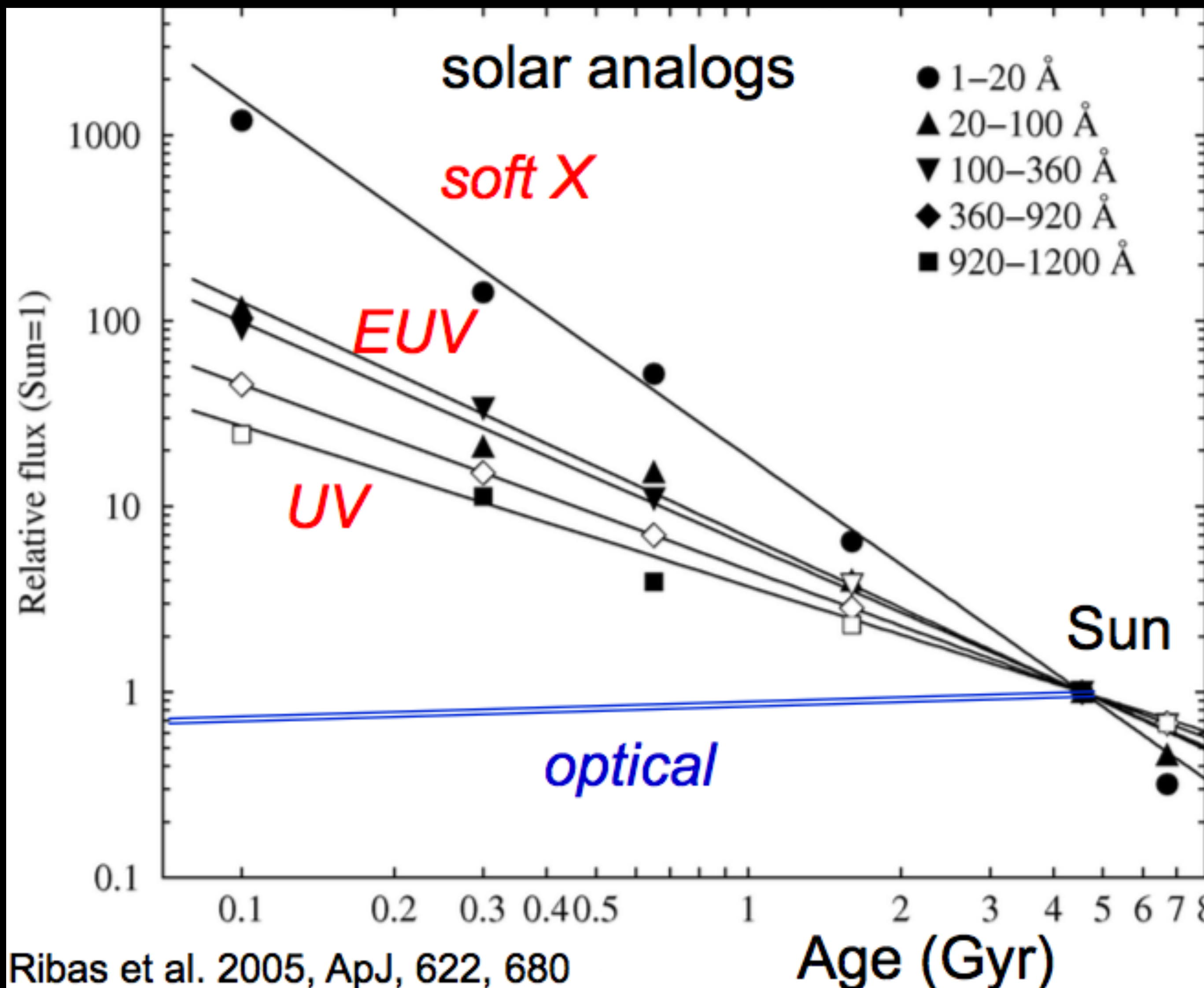
The impact of a high quality X-ray spectrum: need more than accretion source + coronal source to explain all the miriad diagnostics (electron density, electron temperature, absorbing column)

Where do planets form? Where do they migrate?

- X-ray spectra of young stars show more than accretion plus magnetic activity
- X-rays implicated in rapid heating of protoplanetary disks
- After stars lose their disks X-ray surveys are the only way to find young stellar objects



How does the coronal emission of stars affect exoplanets?



- Stellar twins are not magnetic twins; star's X-ray emission at early ages is a much larger factor in planetary irradiation
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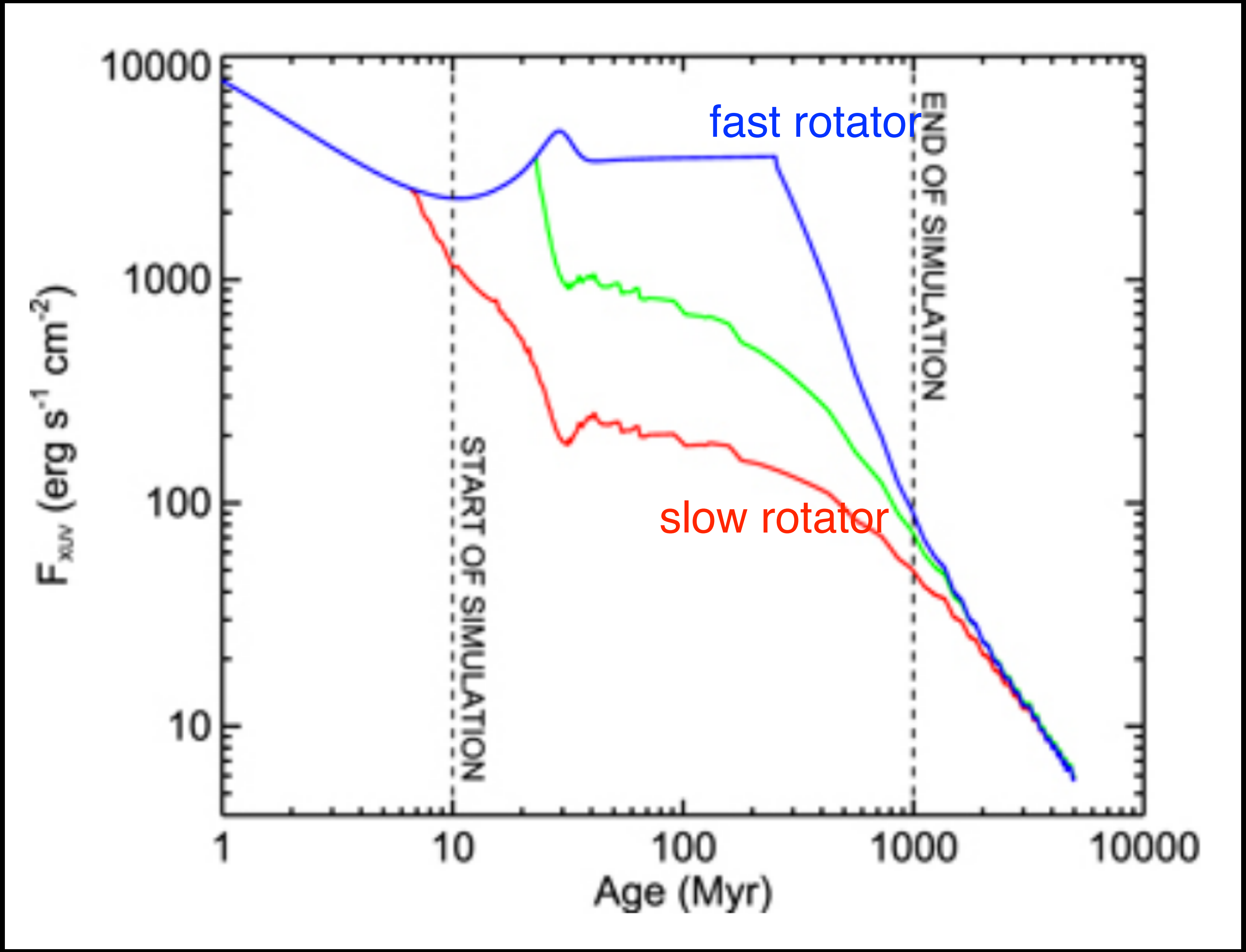

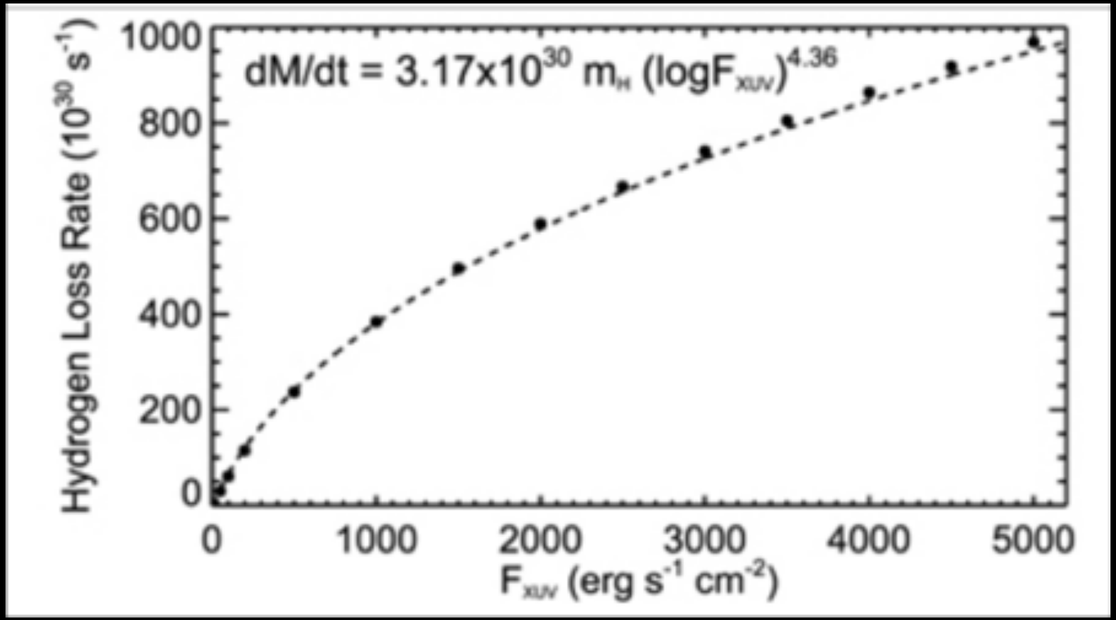

Johnstone et al. (2015)

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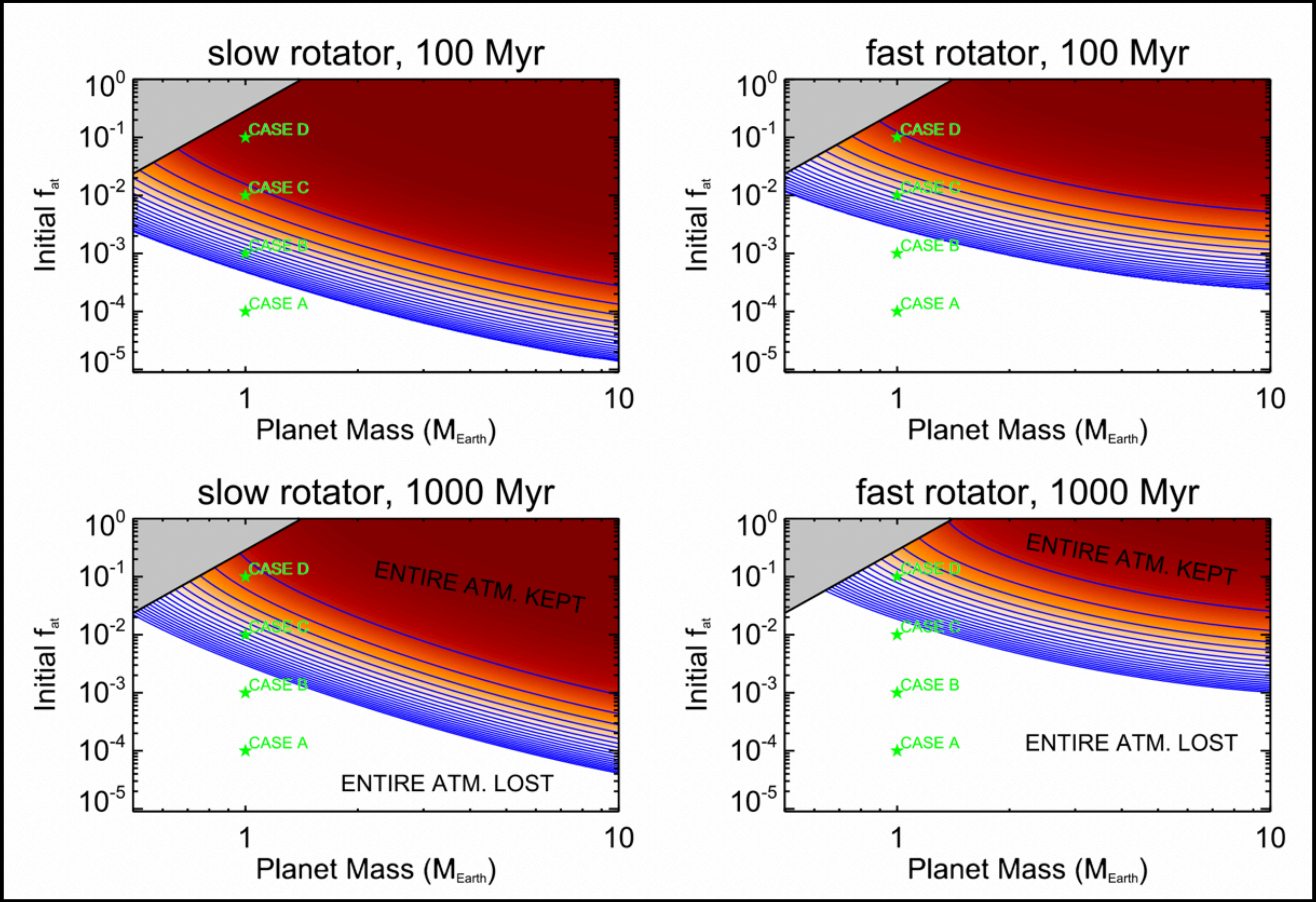
How does the coronal emission of stars affect exoplanets?

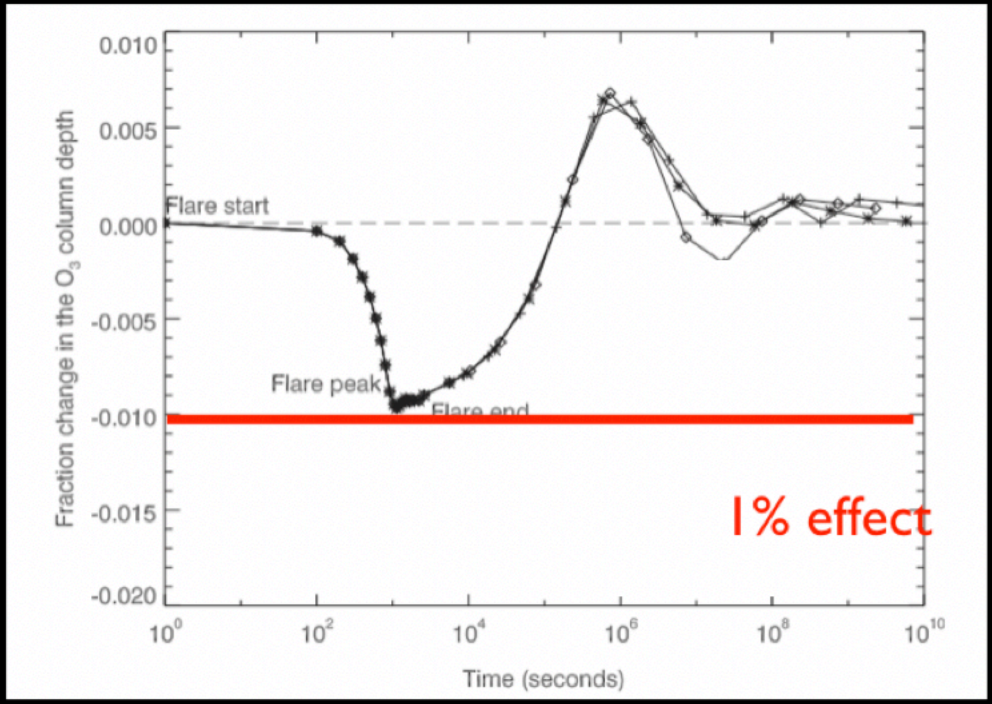
F_{at}=$M_{atmosphere}$/M_{planet}



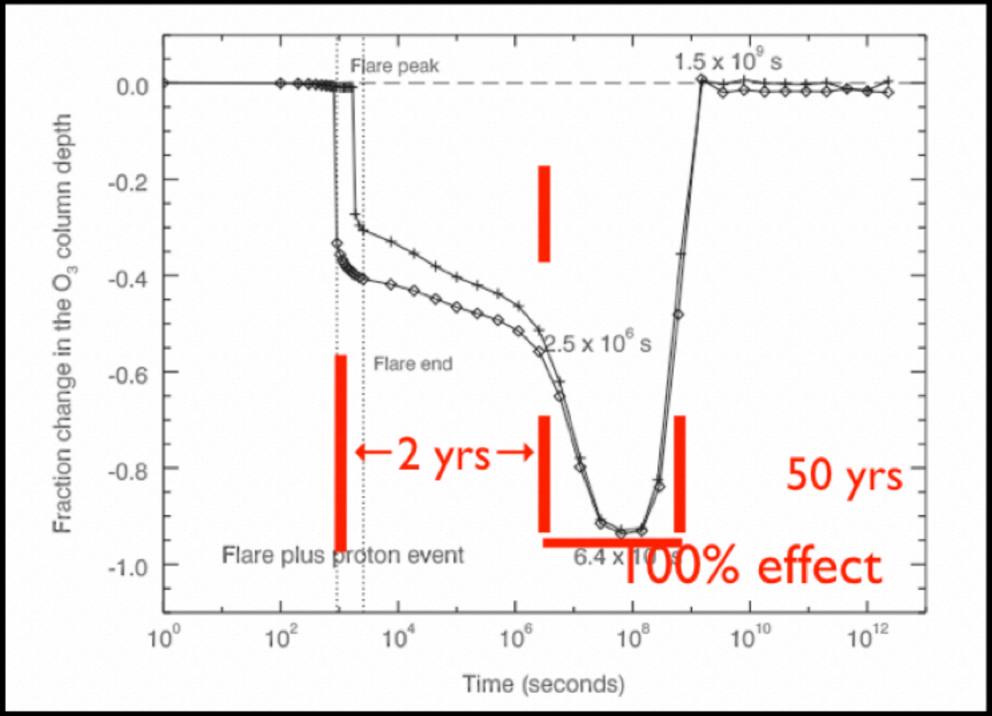
Johnstone et al. (2015)

How do the characteristics of flares change with time, and what impact does this have on exoplanet conditions?

- Systematic change of T_{max}, E_{flare}, $L_{x,max}$ on flares of stars with varying mass, age, magnetic configuration as input to evolution of planetary irradiation
- Influence of energetic particles inferred from line profiles



A UV flare only has a 1% effect on the depletion of the ozone layer of an Earth-like planet in the habitable zone of an M dwarf



A UV flare + proton event (>10 MeV) inferred from scaling from solar events, results in complete destruction of the ozone layer in the atmosphere of an Earth-like planet in the habitable zone of an M dwarf

Segura et al. (2010)

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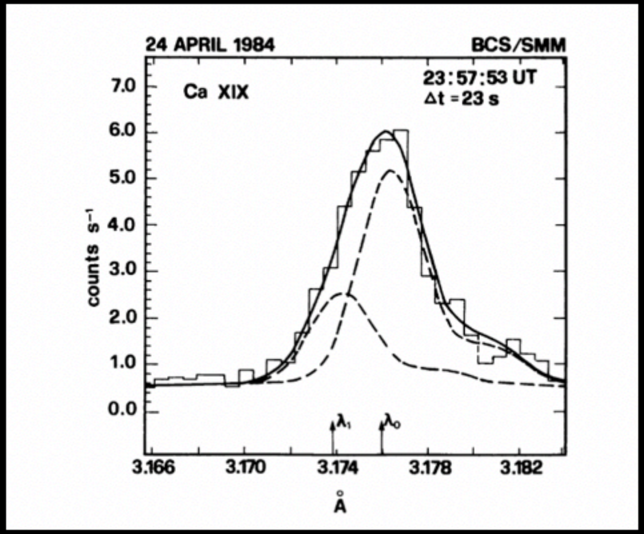
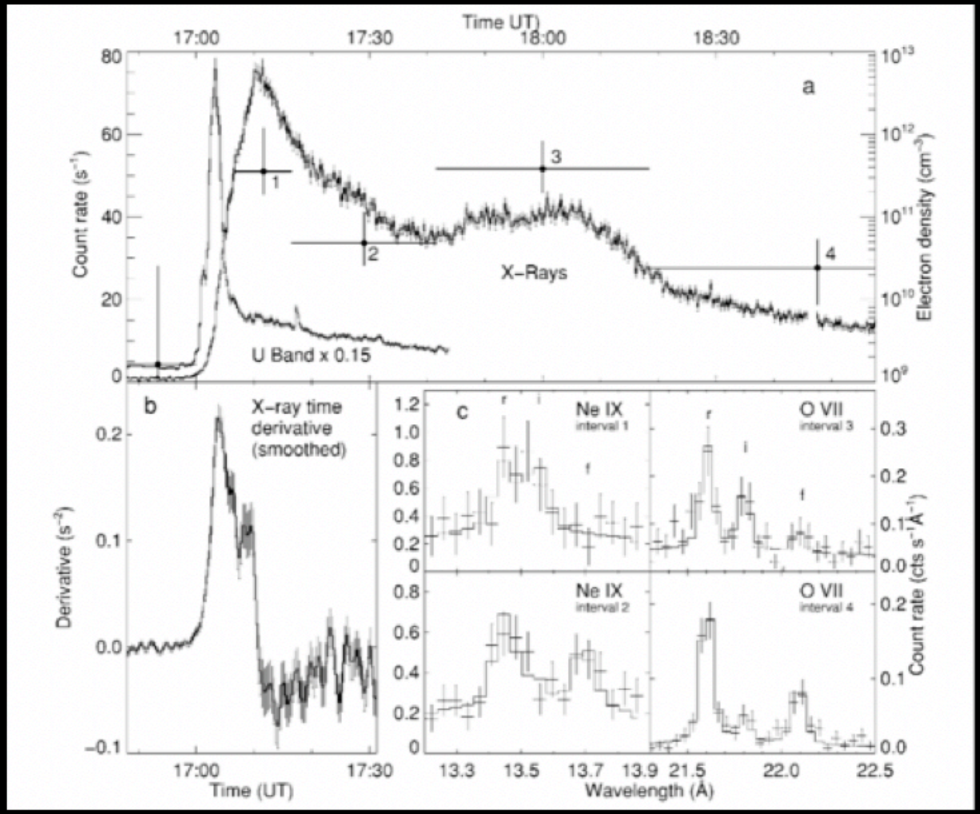


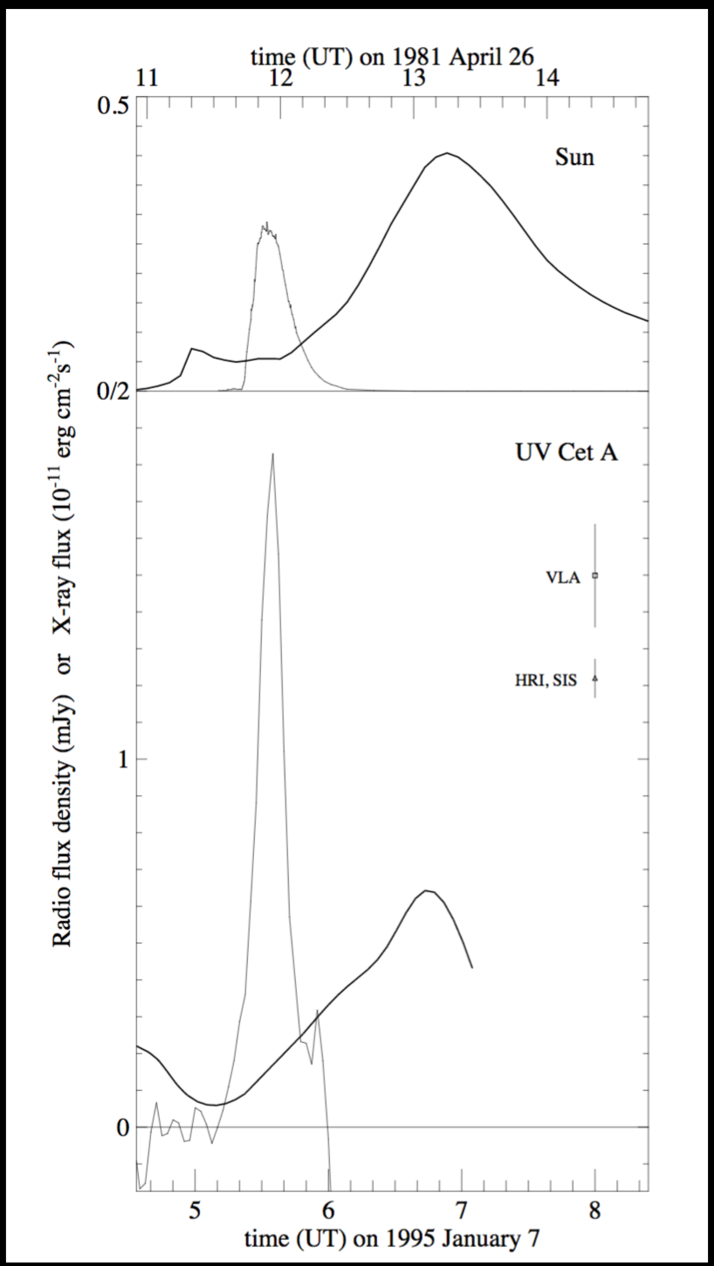
Antonucci et al. (1990)



Large flare on Proxima
Güdel et al. (2002)

- Blueshifts in solar flares up to several hundred km/s, coincide with start of nonthermal hard X-ray emission from accelerated particles (Antonucci et al. 1990)
- Peak in nonthermal line broadening occurs at same time as maximum amount of hard X-ray emission (Antonucci et al. 1982)

How do the characteristics of flares change with time, and what impact does this have on exoplanet conditions?



- Stellar flare white-light emission is produced deep in the photosphere, characterized by a hot black-body >>T_{eff}; this is ubiquitous
- Allred et al. (2005, 2006) showed difficulty in reproducing M dwarf white light flare with solar-like electron beam
- Kowalski et al. (2015) showed that increasing the beam flux by two orders of magnitude from the largest beam flux seen in a solar flare can do the trick. There are problems, however, with return currents.
- Optically thin radio emission (ν> 10 GHz) during stellar flares reveals distribution of accelerated particles

Relative to the flare X-ray emission, stellar flares produce larger radio amplitudes than for solar flares (Güdel et al. 1996)

How do stellar winds change with time, and what impact does this have on exoplanet conditions?

- Stellar wind mass loss critical to atmospheric escape process
- Detect charge exchange emission from nearest ~20 stars to constrain $\dot{M}$
- Coronal mass ejections play an important role in potential habitability; need a way to constrain them

Credit: NASA MAVEN mission

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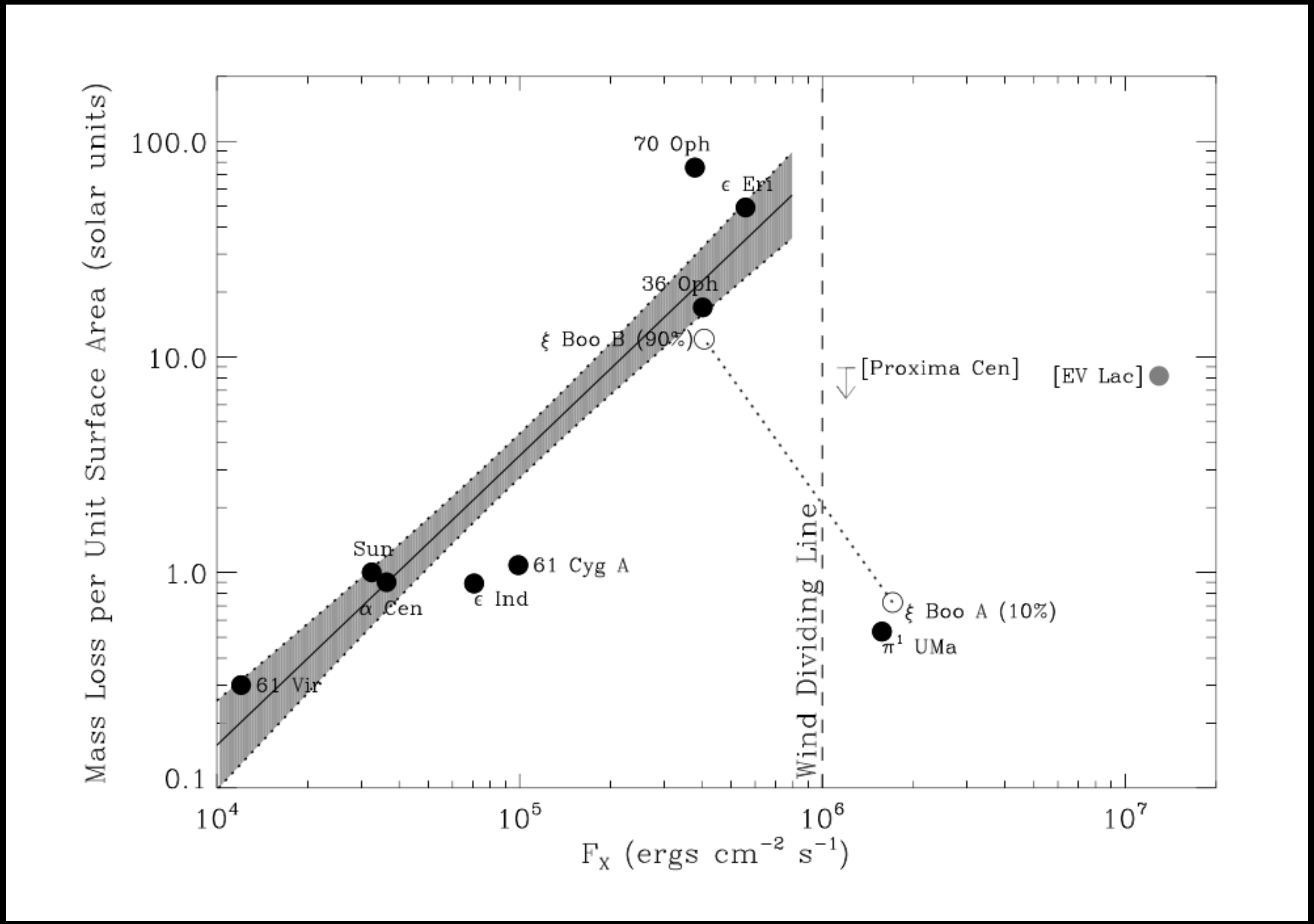

Wood et al. (2004) indirect measures of stellar mass loss

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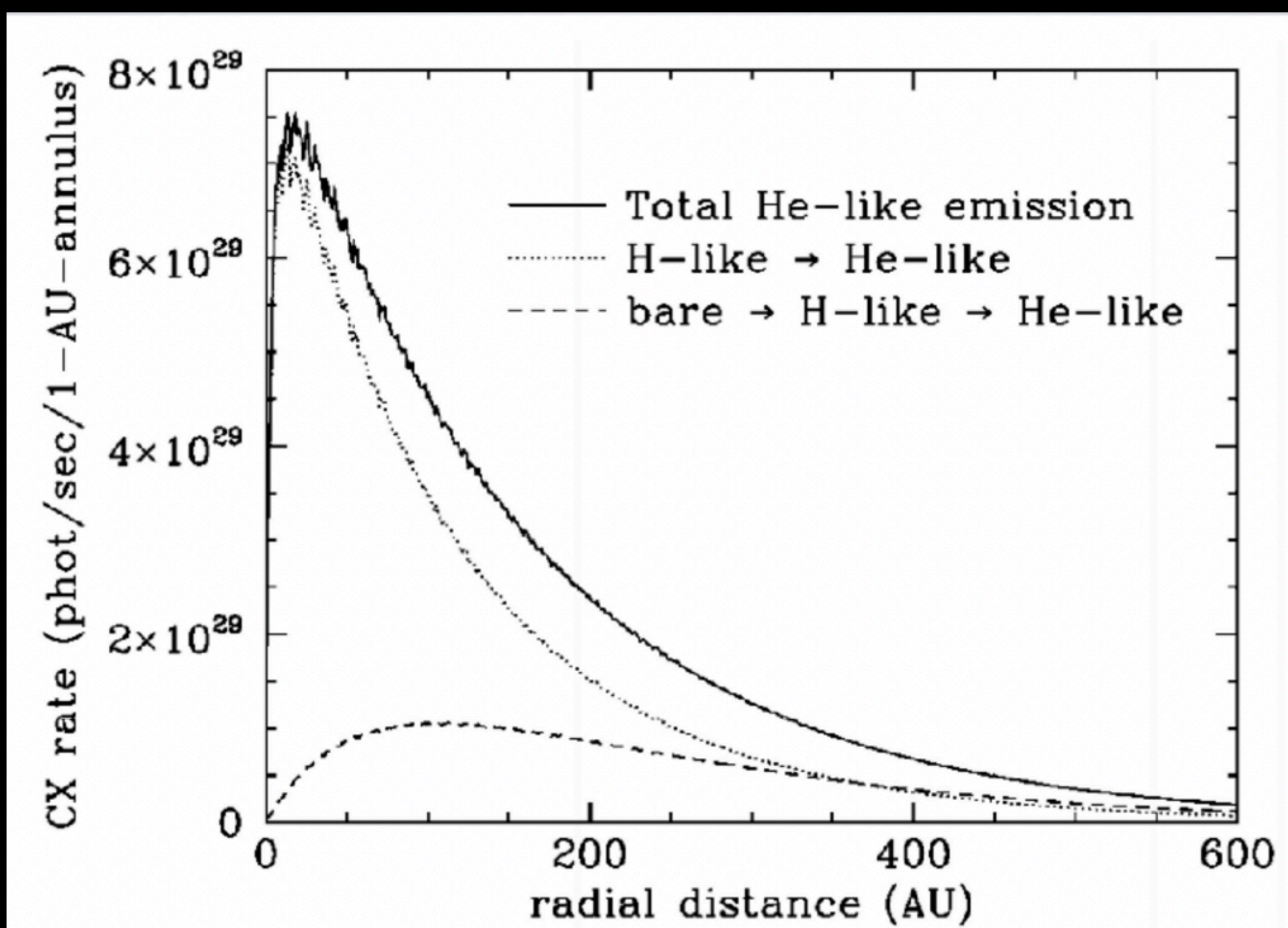

Wargelin & Drake (2001)
Upper limit on mass loss rate of Proxima from charge-exchange emission from interaction of stellar wind with ISM

Requires spatial resolution <0.5” to resolve CX from central point source
Applicable to ~20 nearby stars.

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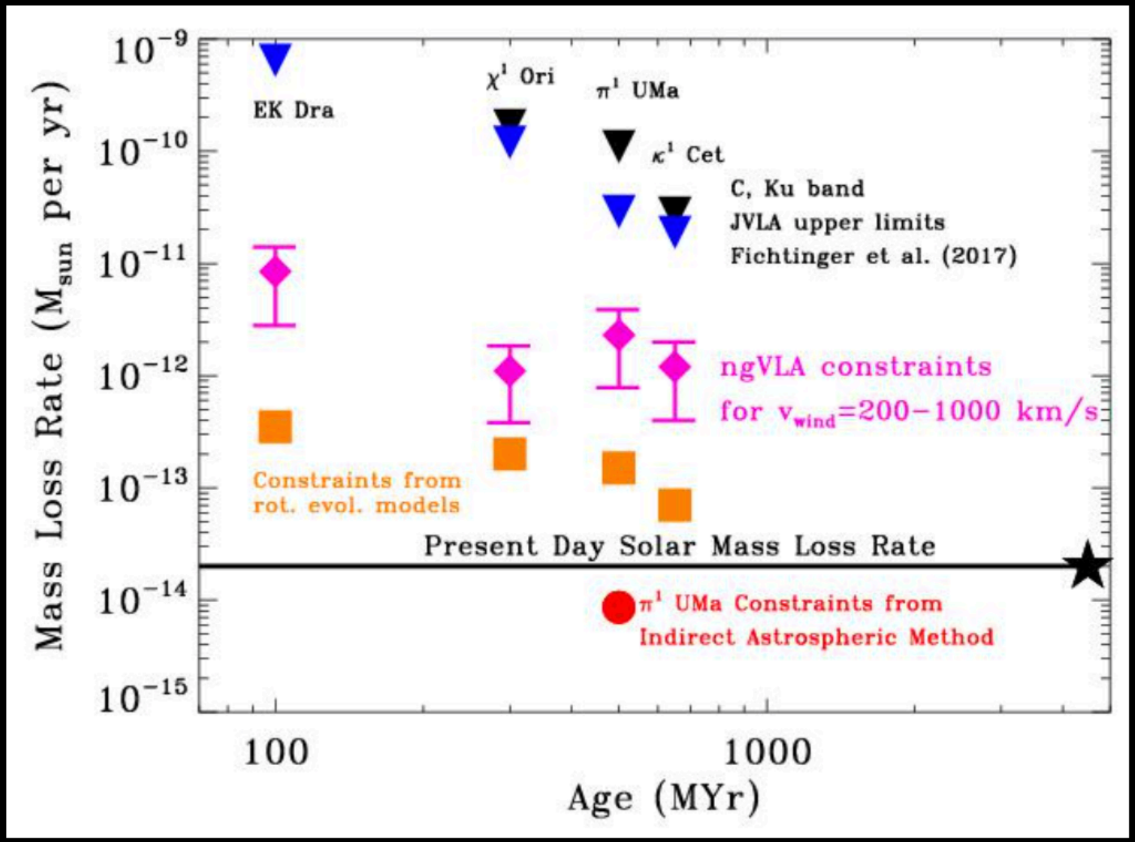

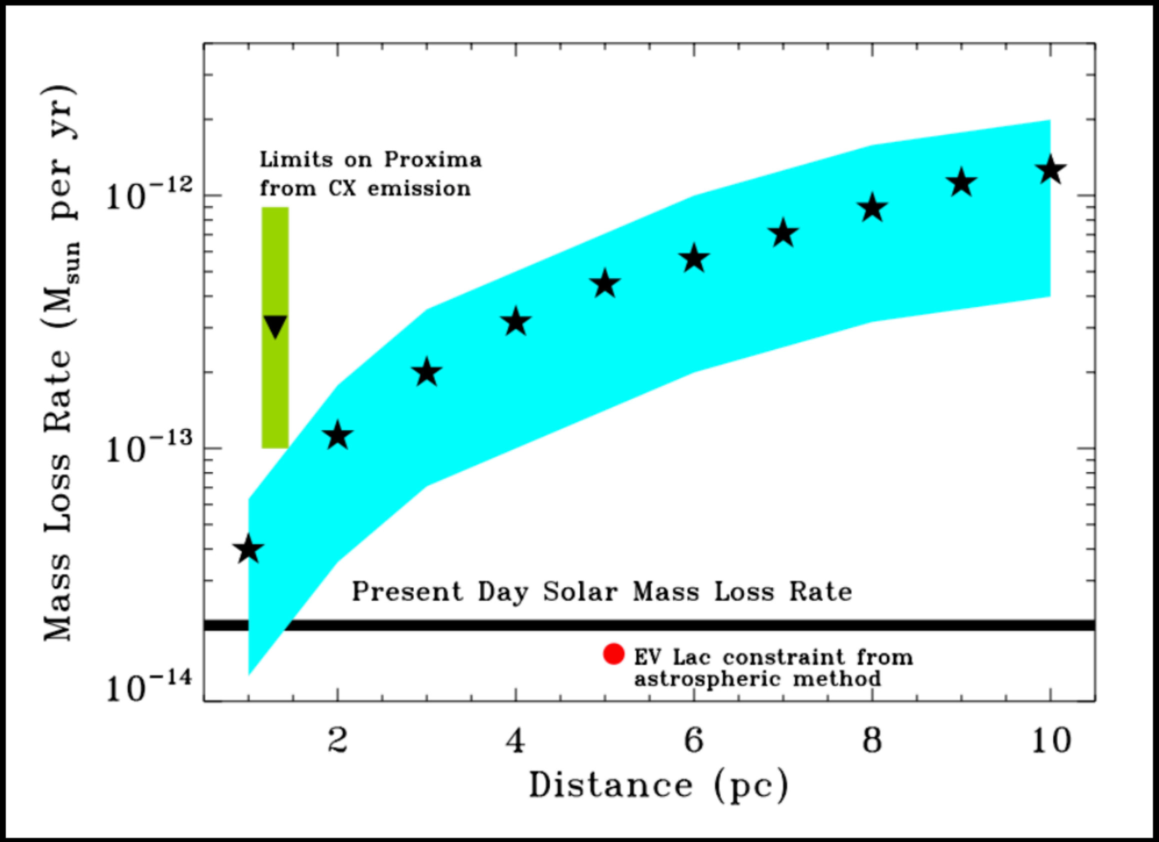

Detect or constrain radio emission from an ionized stellar wind, improving current radio upper limits for solar analogues by ~two orders of magnitude, sensitive surveys of nearby planet-hosting M dwarfs

ngVLA Memo #31 the ngVLA and Exo-Space Weather

How do stellar winds change with time, and what impact does this have on exoplanet conditions?

Jakosky et al. (2015)
impact of an interplanetary coronal mass ejection on Mars

Detection of stellar coronal mass ejections:

- Changes in column density during a flare
- Detection of mass-loss coronal dimming during a flare
- Velocity signatures in the line profile of flare-heated plasma
- Detection of low-frequency emission with characteristic shape of intensity w/frequency and time expected for CMEs

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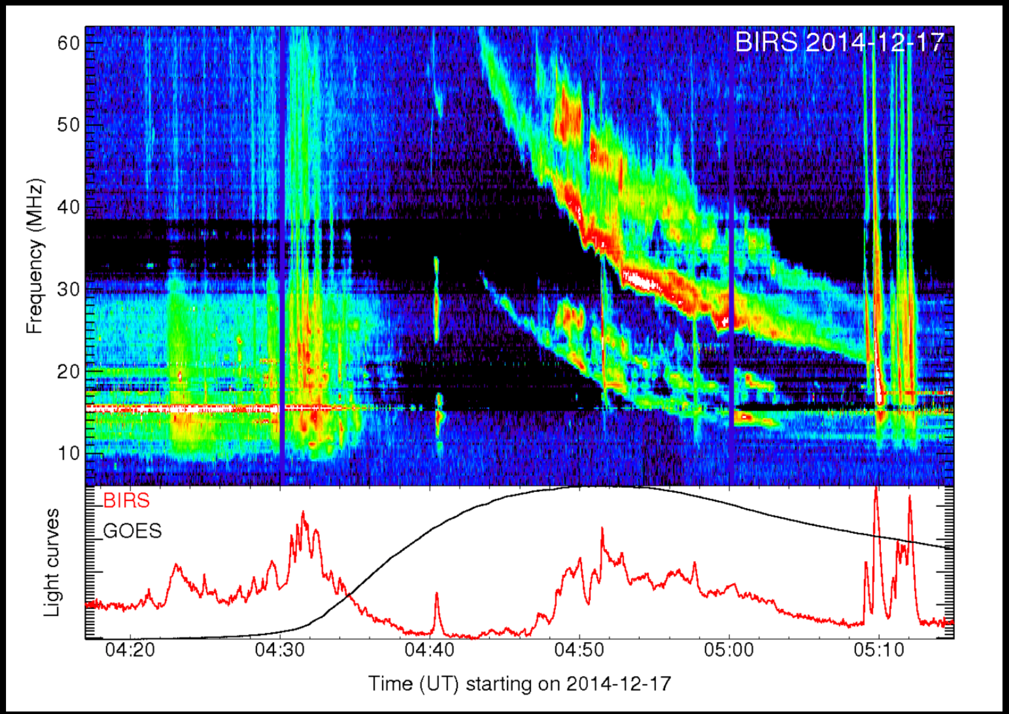

Conclusions

- Stars impact their near-environment due to the presence and action of magnetic fields (plasma heating, particle acceleration); this is the source of space weather/habitability for exoplanets
- Understanding how these processes work on stars other than the Sun is vital for the Search for Life
- Radio and X-ray facilities of the future will be able to make these measurements, with increased sensitivity, spatial and spectral resolution