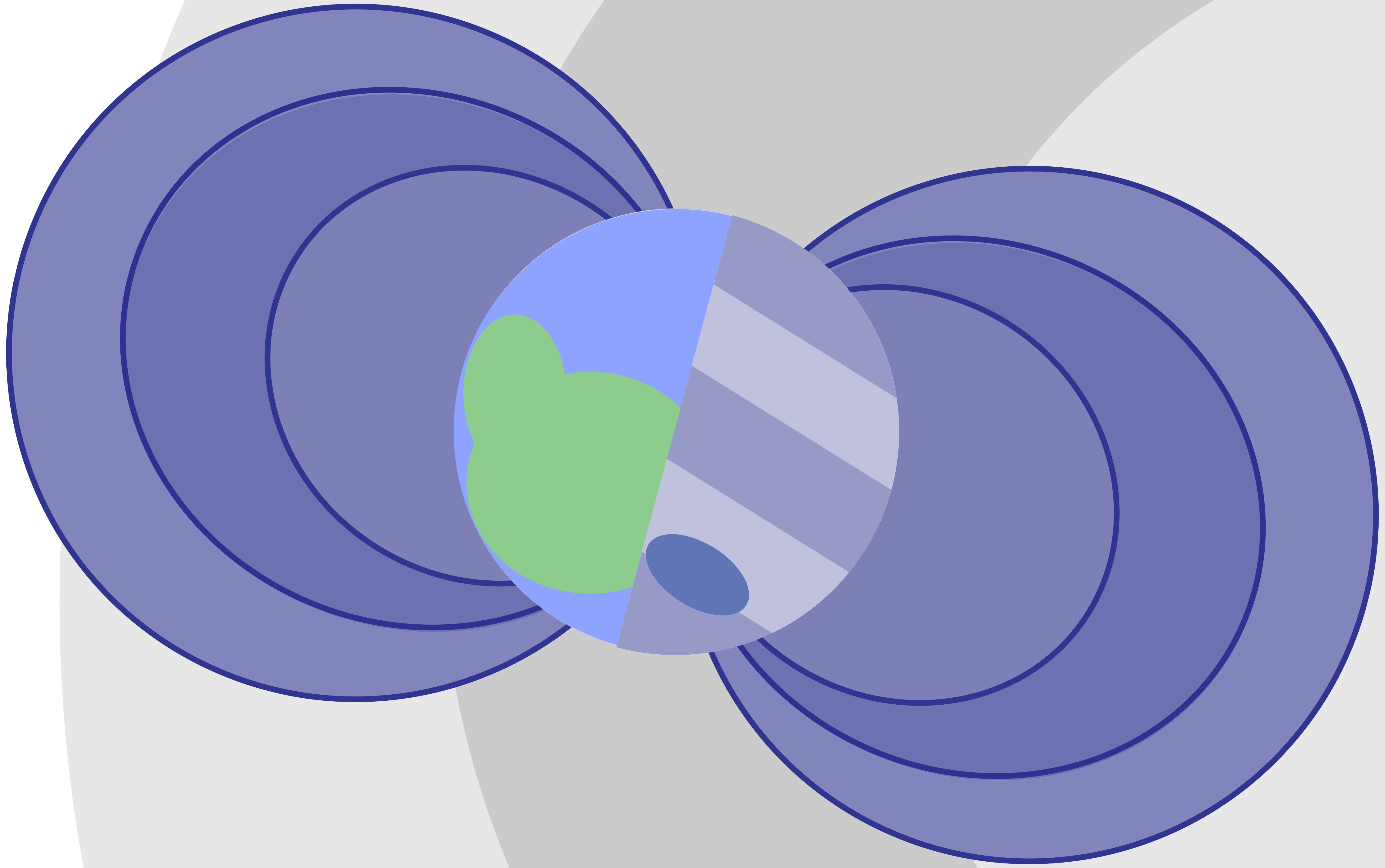
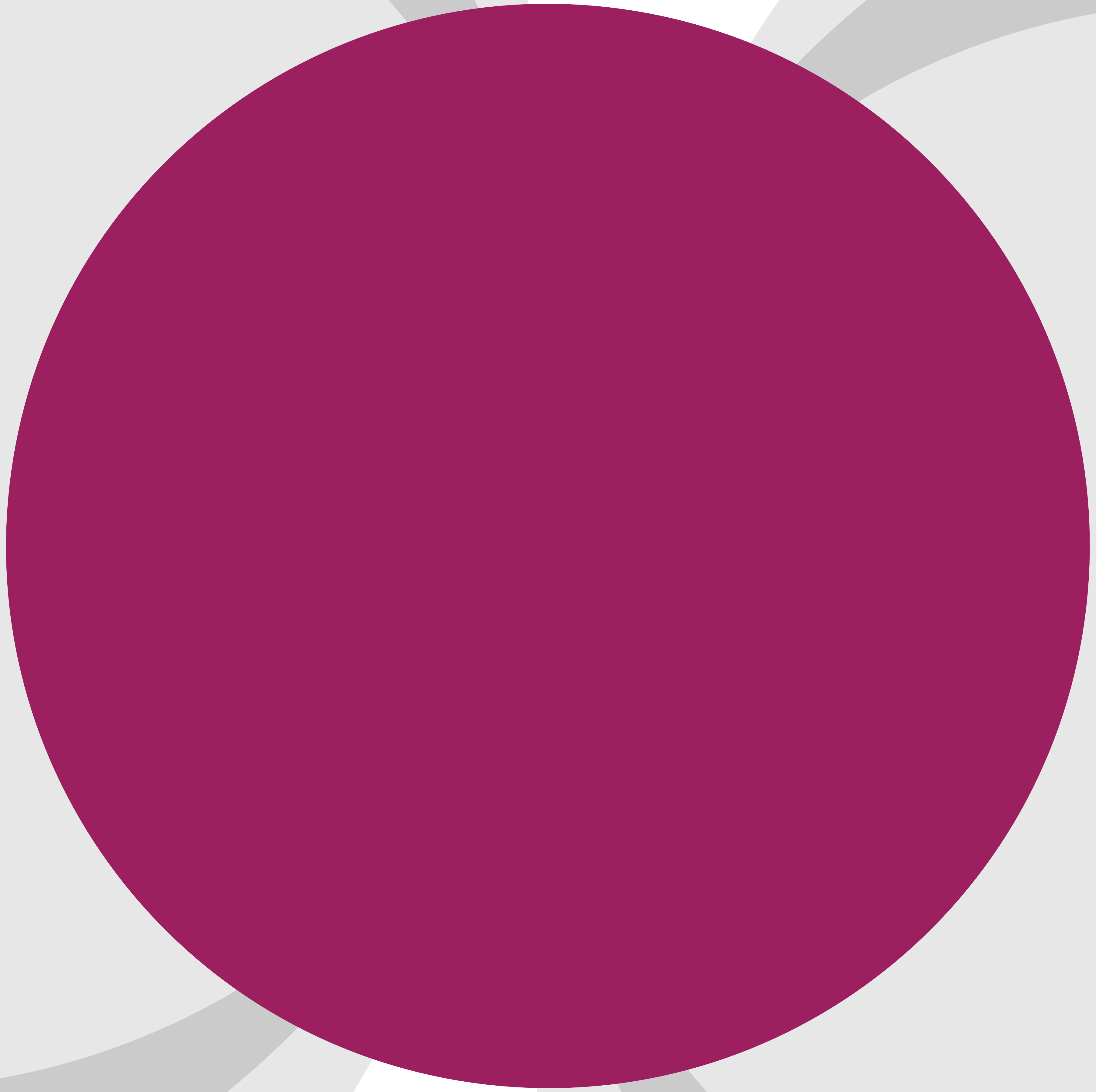
Exoplanet and Brown Dwarf Radio Emissions





Melodie Kao

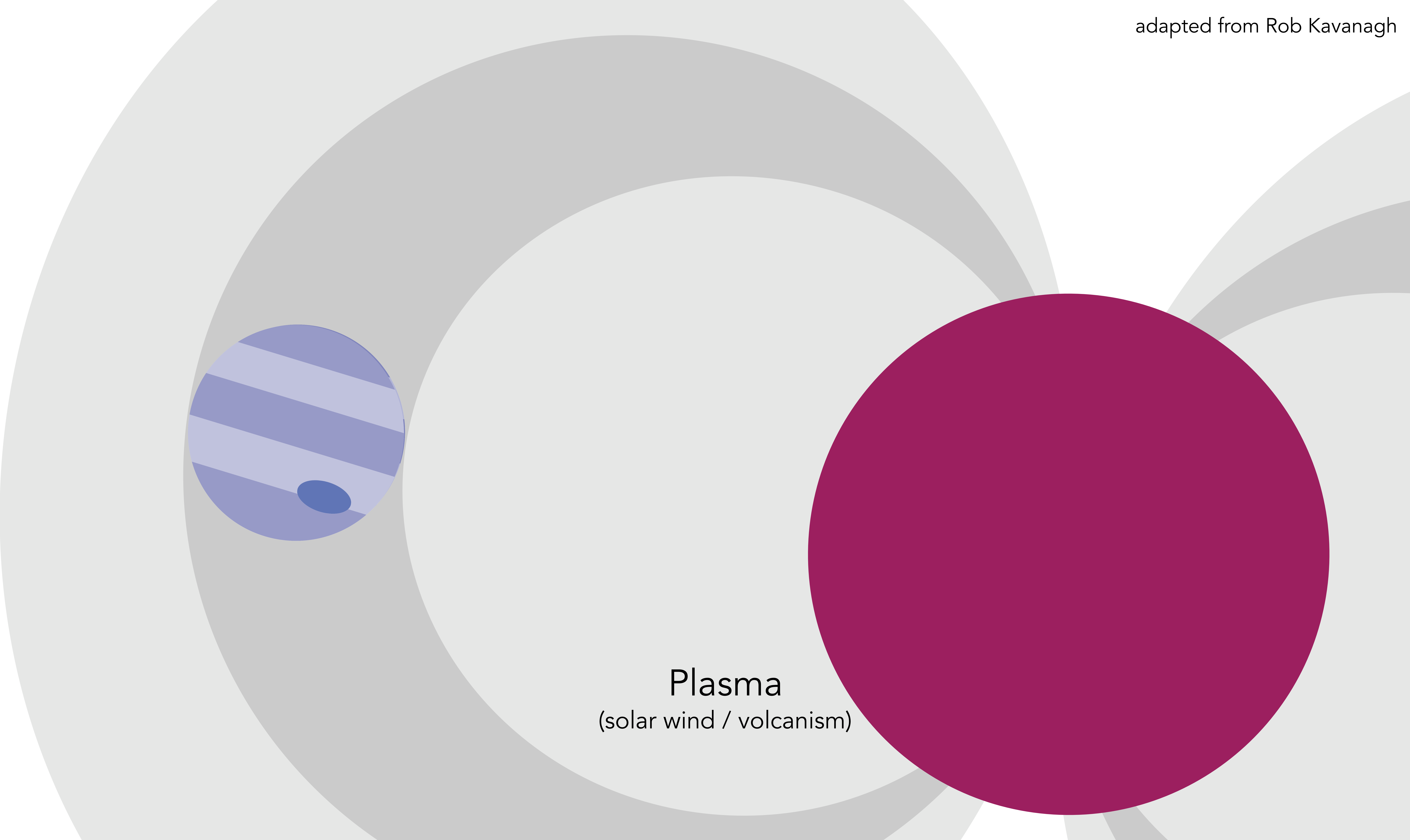
Lowell Observatory

Image credit:
UV aurora - ESA, J. Nichols
radiation belt - Bolton+ 2004
clouds - de Pater

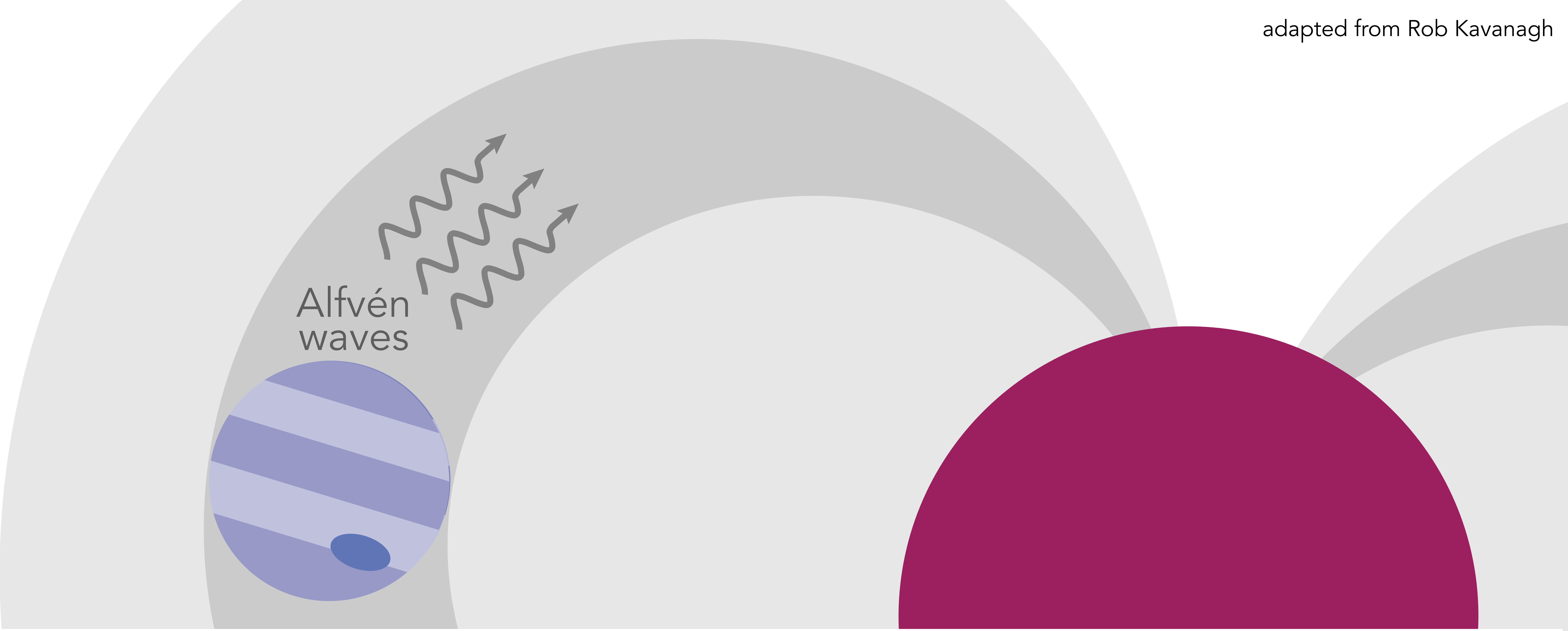
melodie.kao@ucsc.edu


INDIRECT
Host (stellar) emissions
DIRECT
Aurora: Wind-driven
DIRECT
Aurora: Spin-driven
DIRECT
Radiation belts

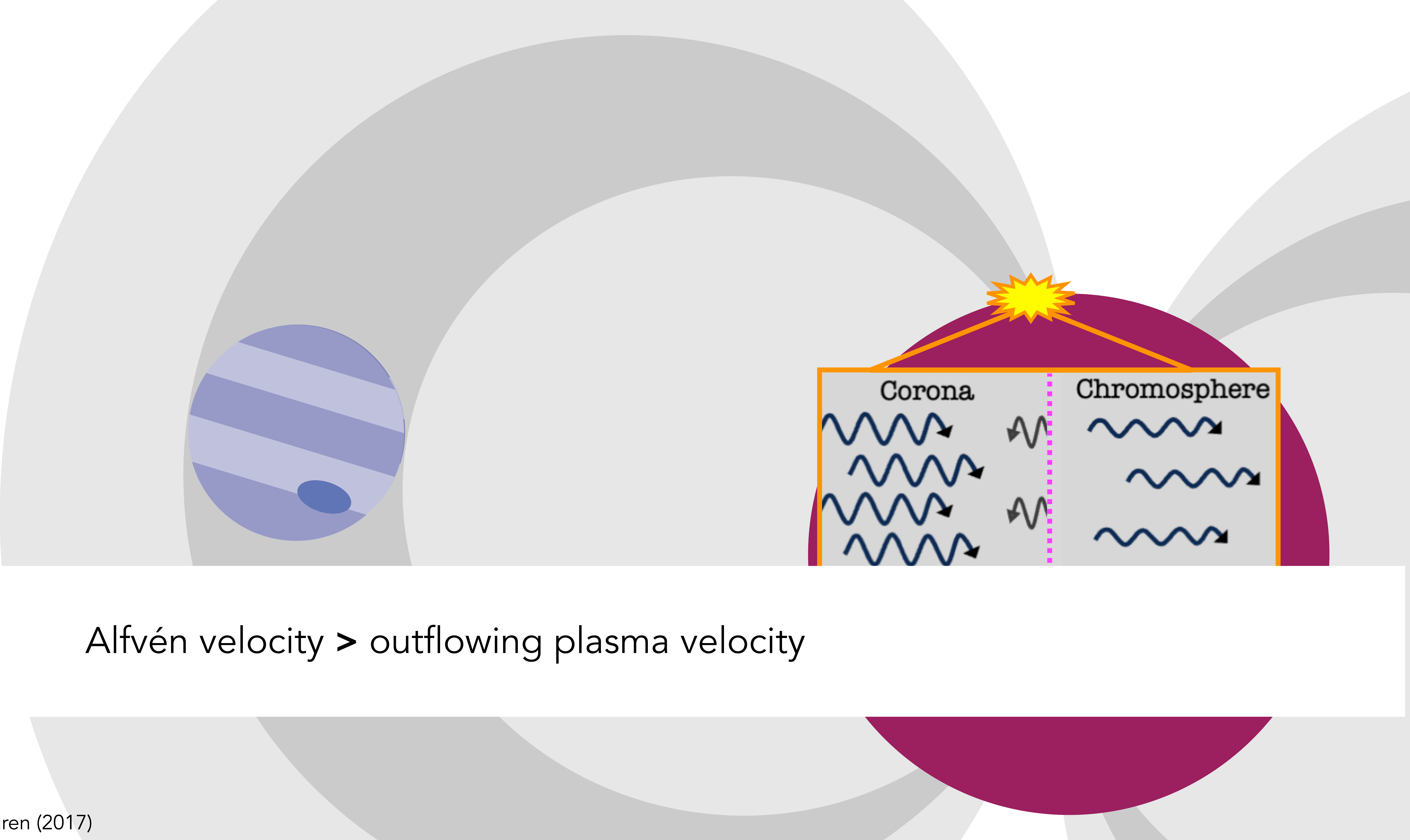
adapted from Rob Kavanagh



adapted from Rob Kavanagh



Alfvén velocity **>** outflowing plasma velocity

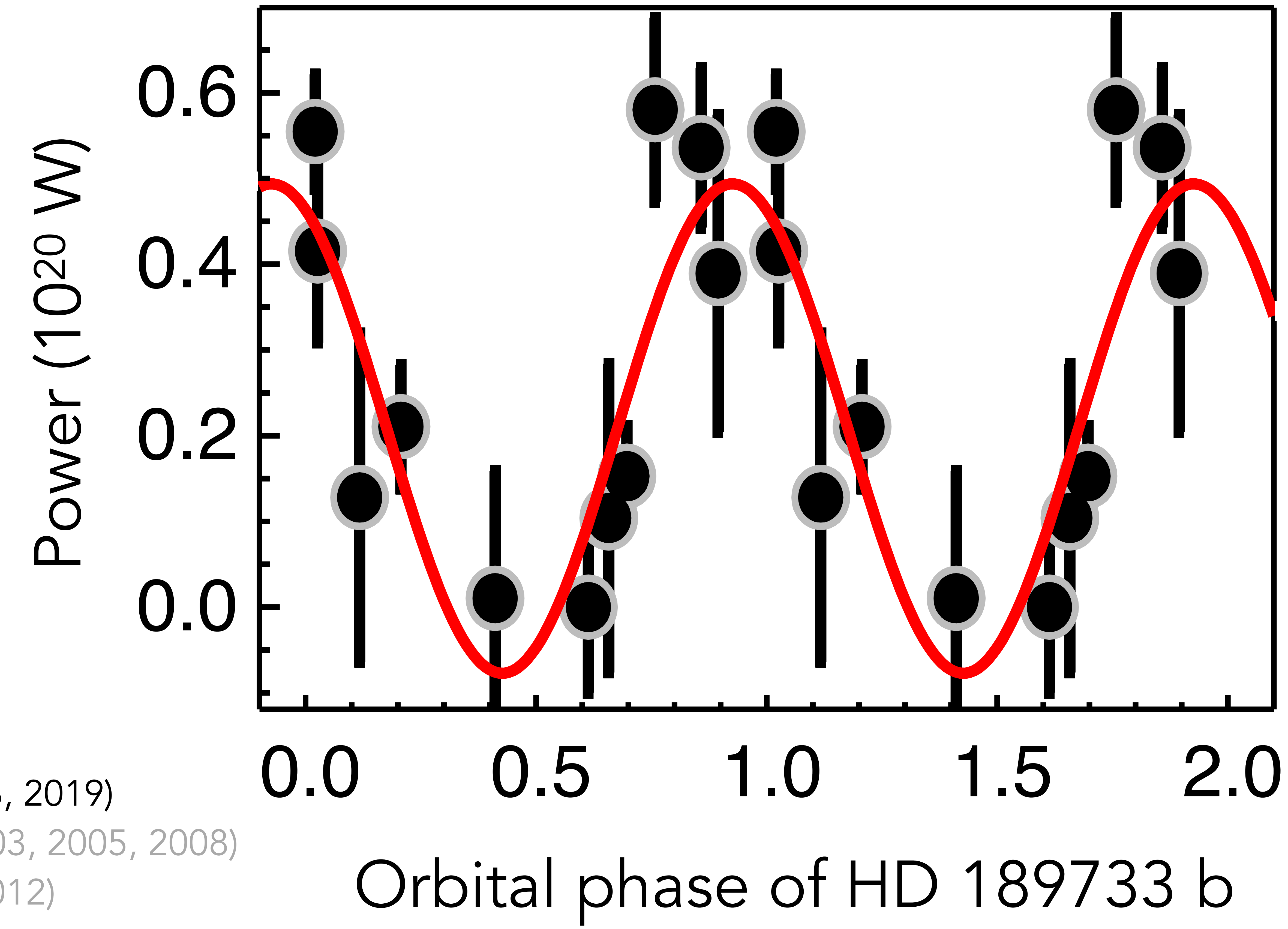


Alfvén velocity > outflowing plasma velocity

Cauley+ (2019)
Yadav & Thorngren (2017)

Indirect: Star-planet interactions

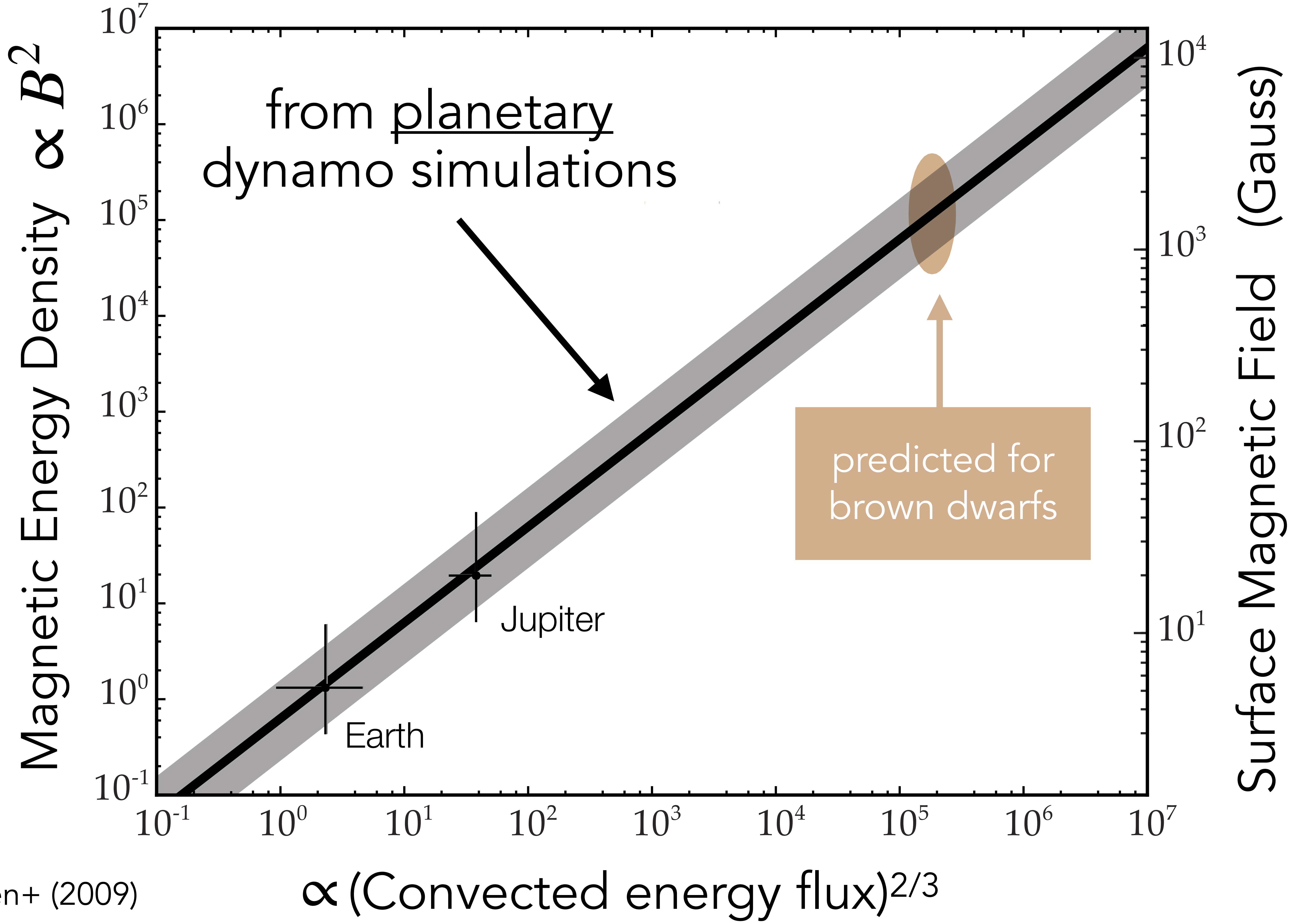
Power ~ $v_{rel} R^2 (B_{planet})^2$



Cauley+ (2018, 2019)
Shkolnik+ (2003, 2005, 2008)
Gurdemir+ (2012)
Lanza+ (2012)
Saur+ (2013)

Indirect: Star-planet interactions

Power ~ $v_{rel}\, R^2\, (B_{planet})^2$

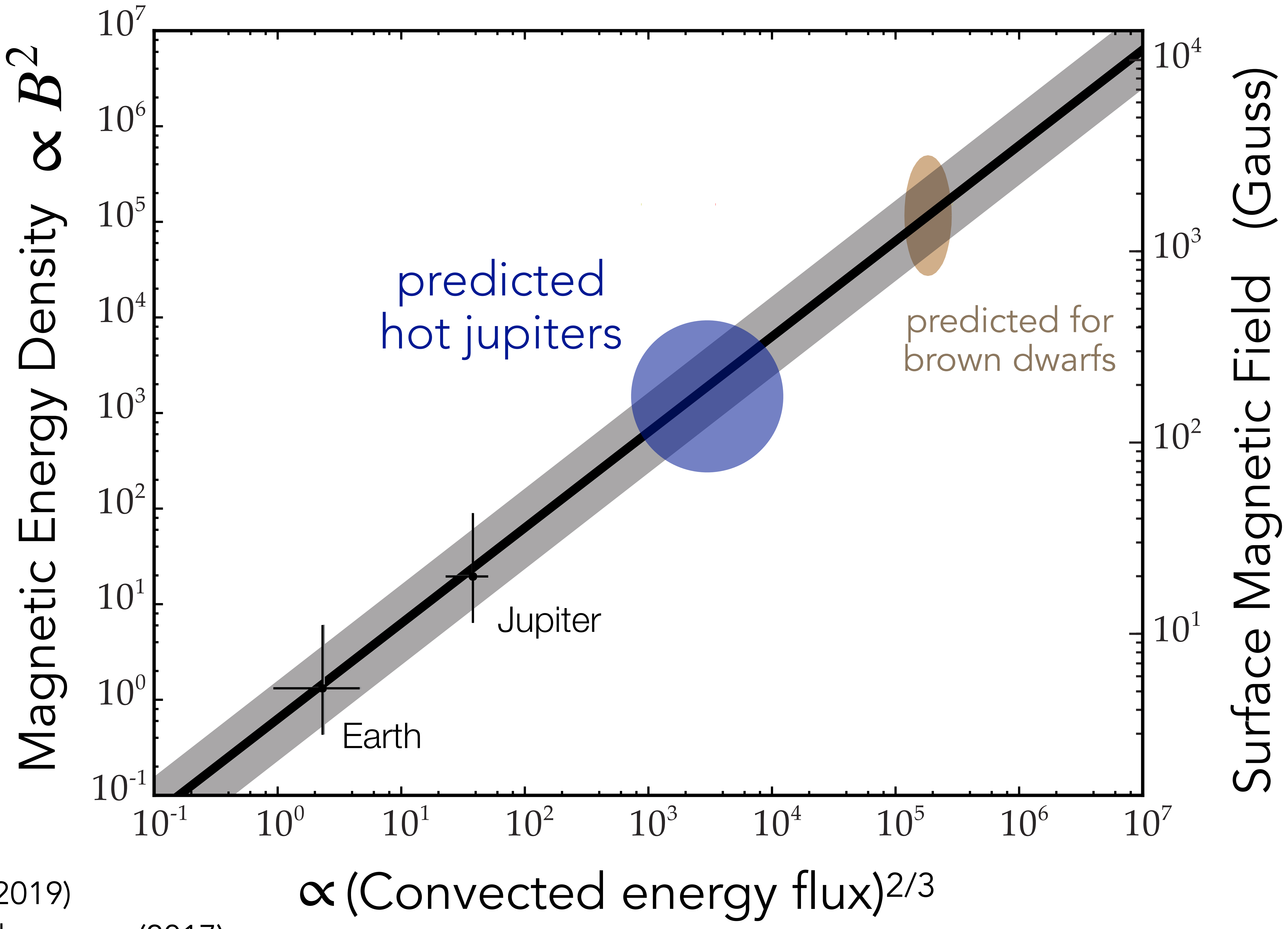


Christensen+ (2009)
See also: Yadav & Thorngren (2017)

Indirect: Star-planet interactions

Power ~ $v_{rel} R^2 (B_{planet})^2$

Lanza (2013)



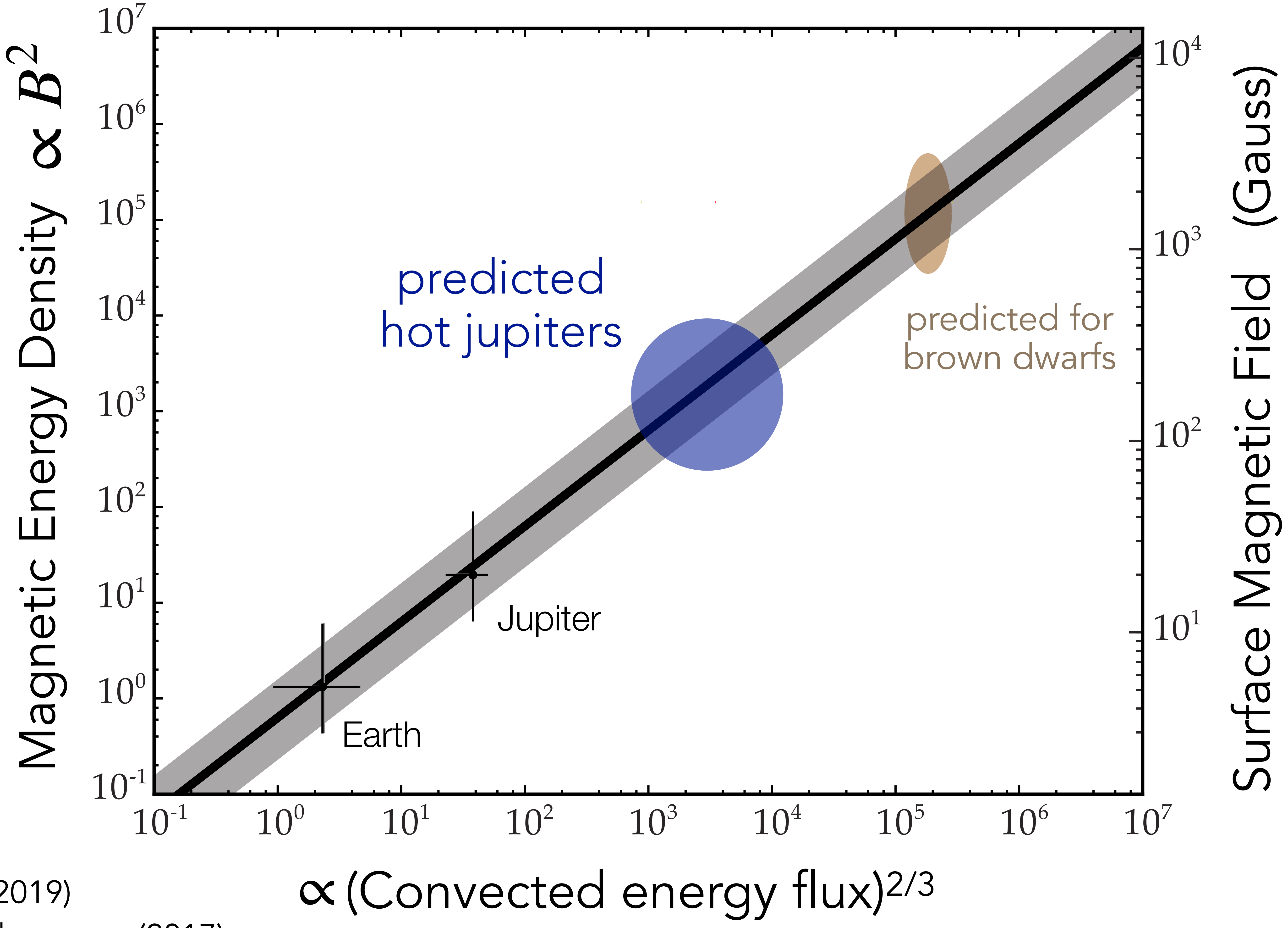
Cauley+ (2019)
Yadav & Thorngren (2017)

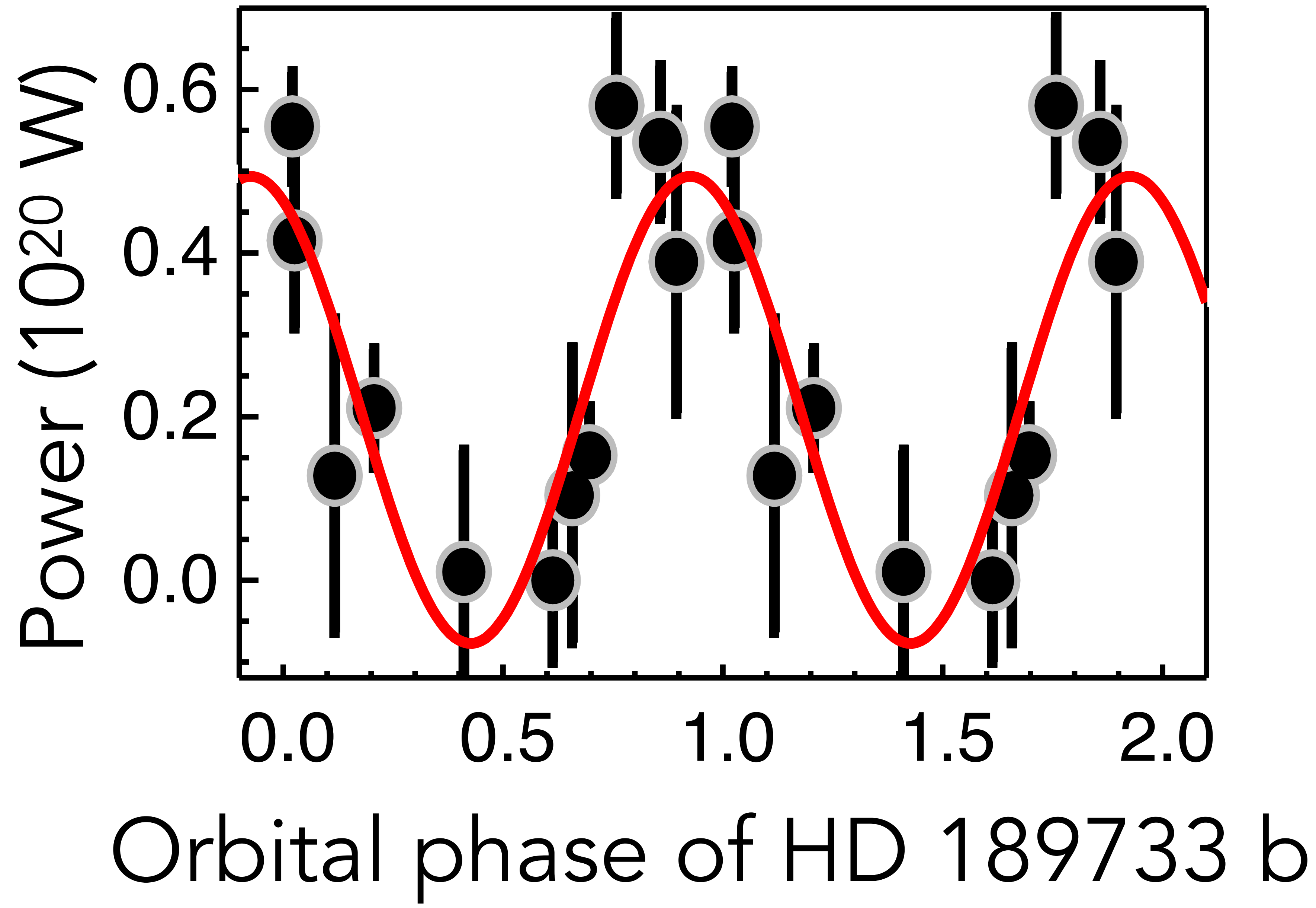
hot Jupiters receive
extra thermal energy from host stars

Indirect: Star-planet interactions

Power ~ $v_{rel} R^2 (B_{planet})^2$

Lanza (2013)





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Indirect: Star-planet interactions

Power ~ $v_{rel} R^2 (B_{planet})^2$

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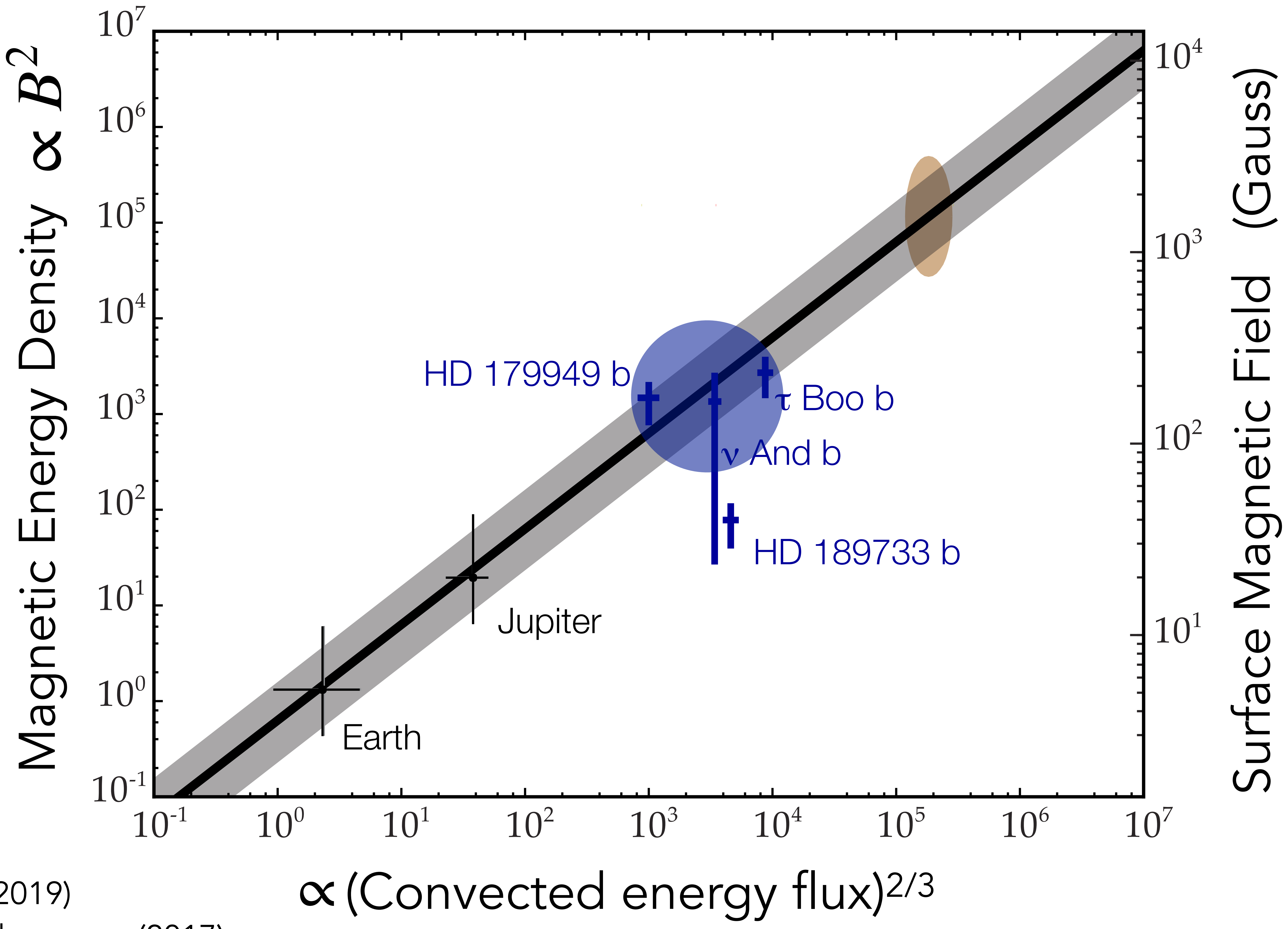
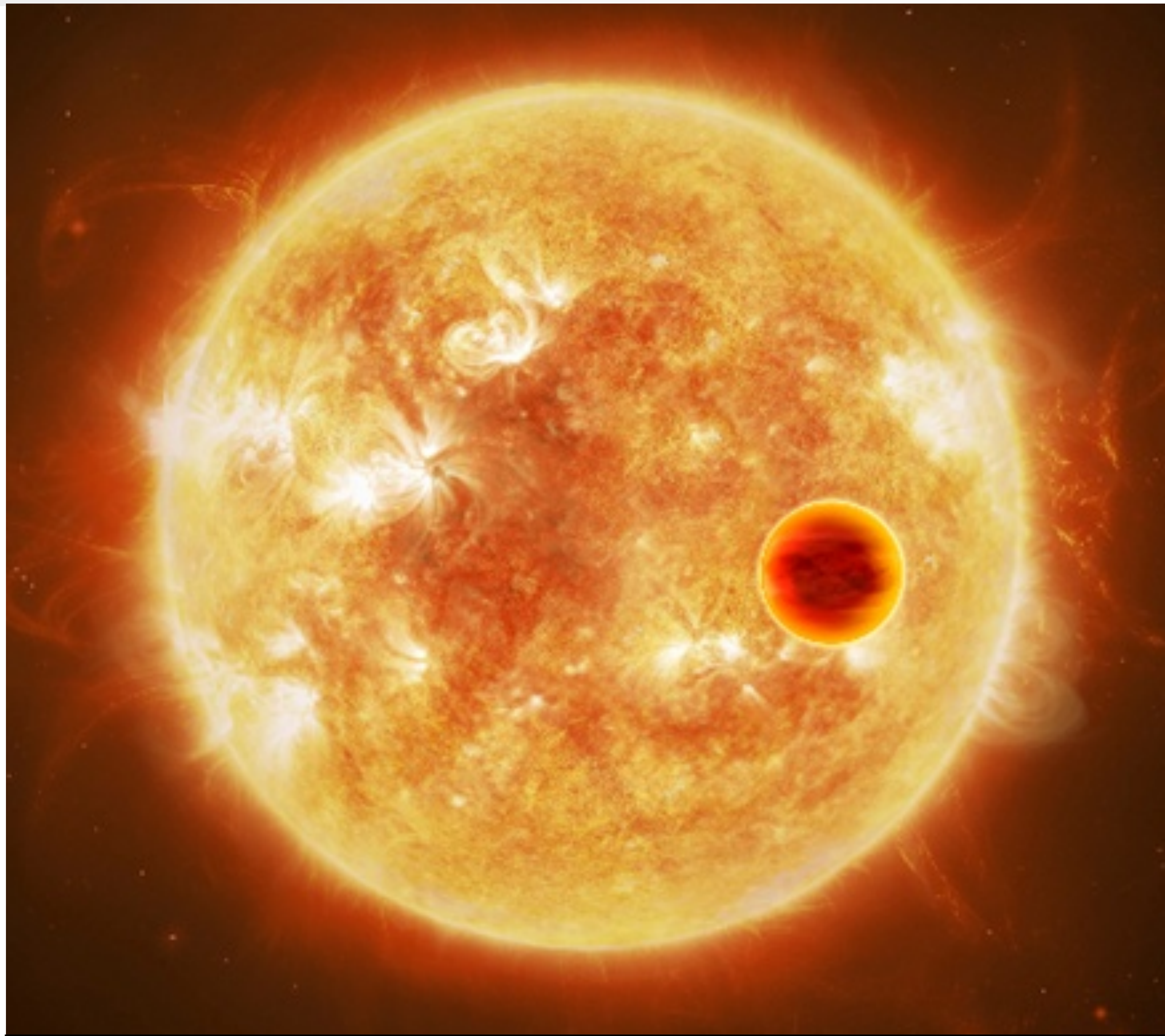




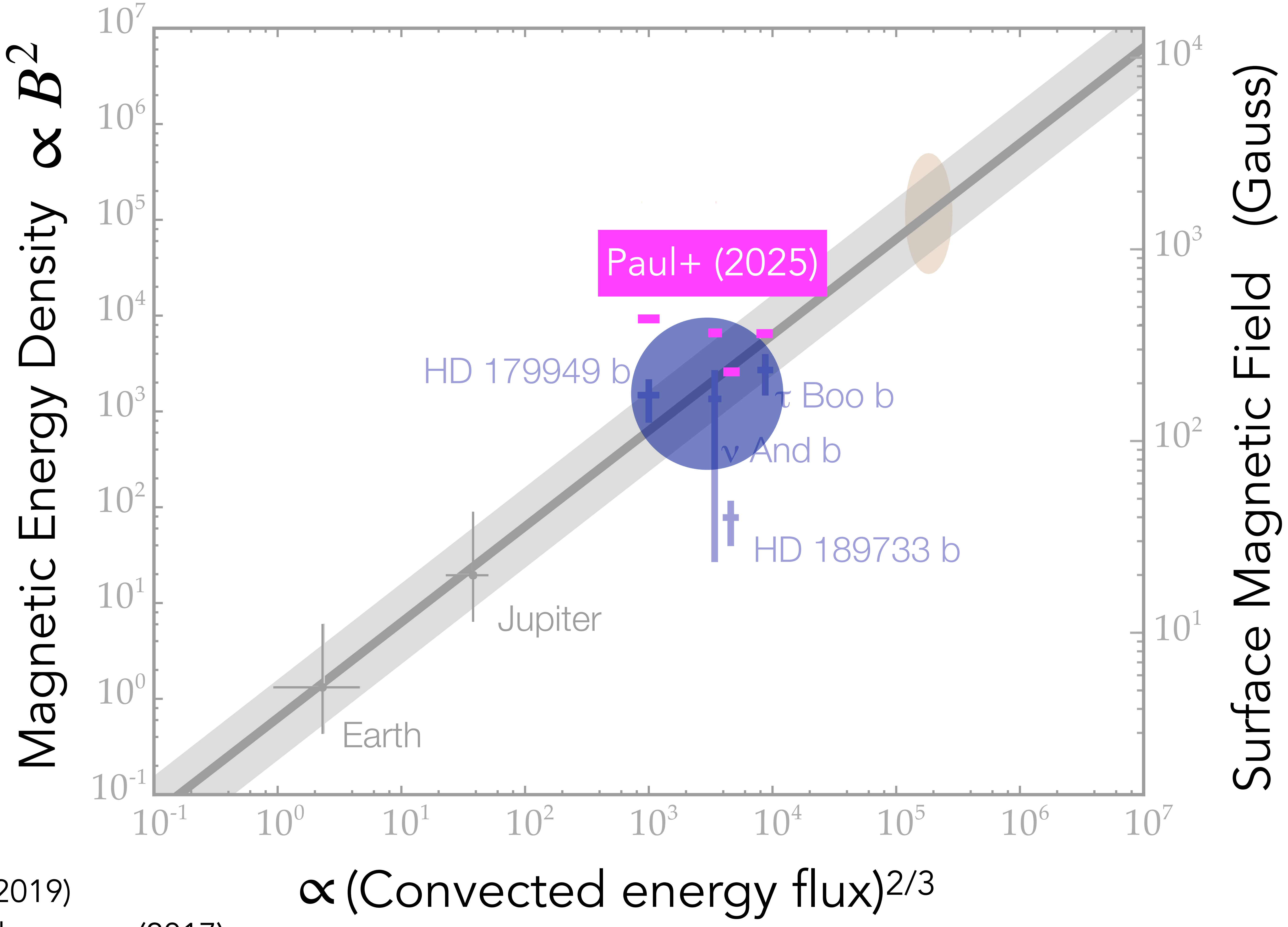
hot Jupiters receive
extra thermal energy from host stars

Cauley+ (2019)
Yadav & Thorngren (2017)

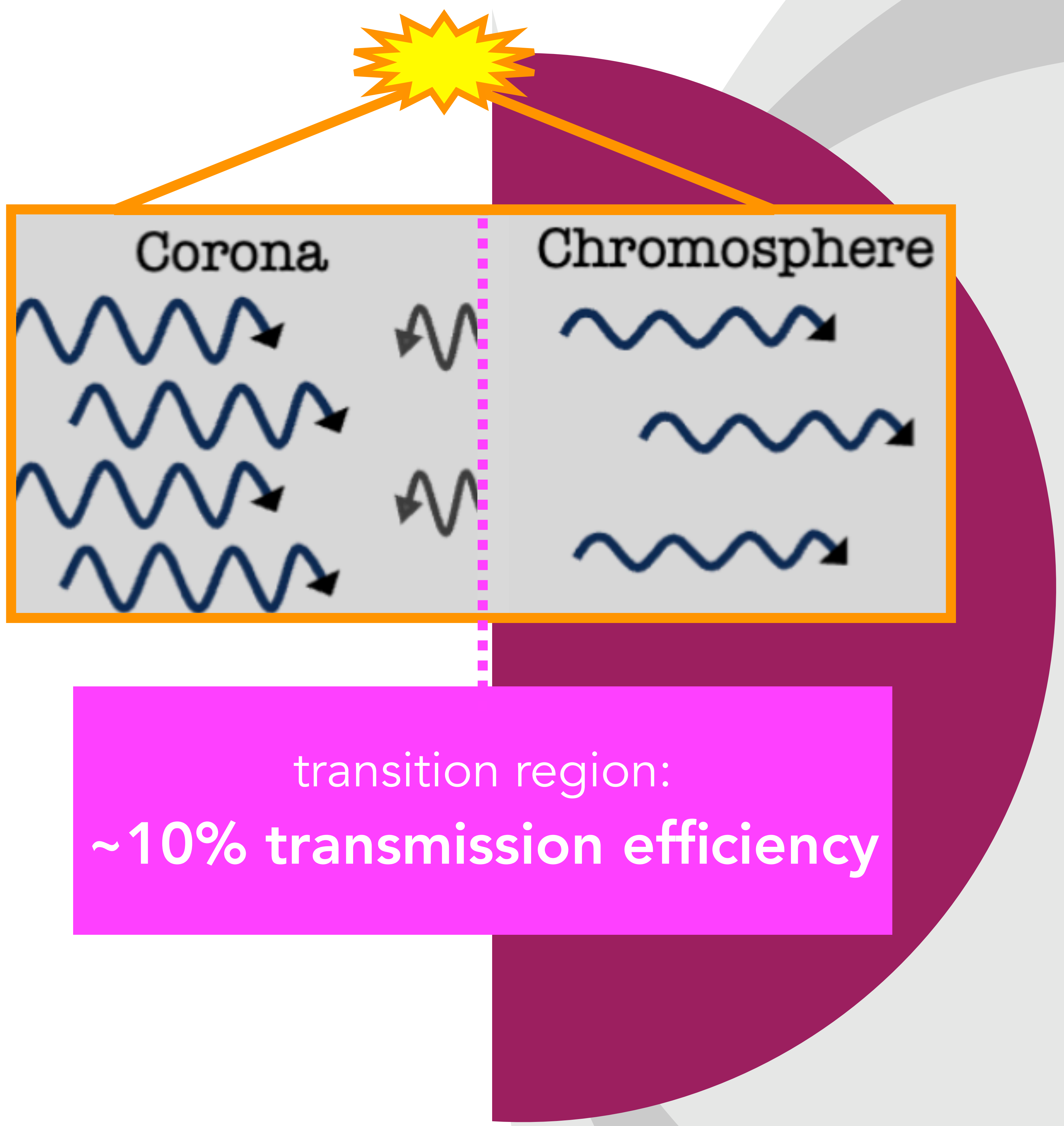
Indirect: Star-planet interactions

$$\text{Power} \sim v_{rel} R^2 (B_{planet})^2$$

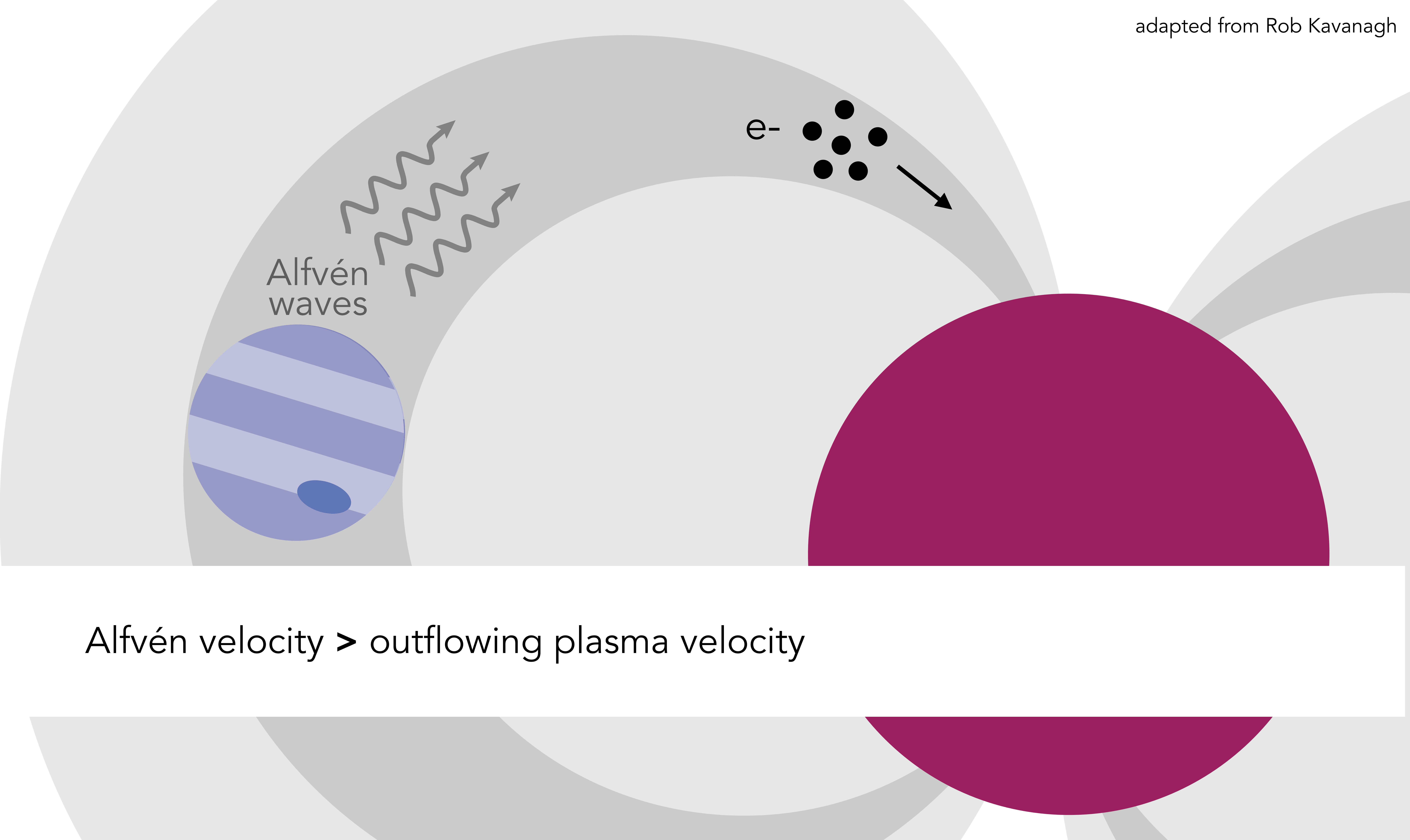
Lanza (2013)



Cauley+ (2019)
Yadav & Thorngren (2017)

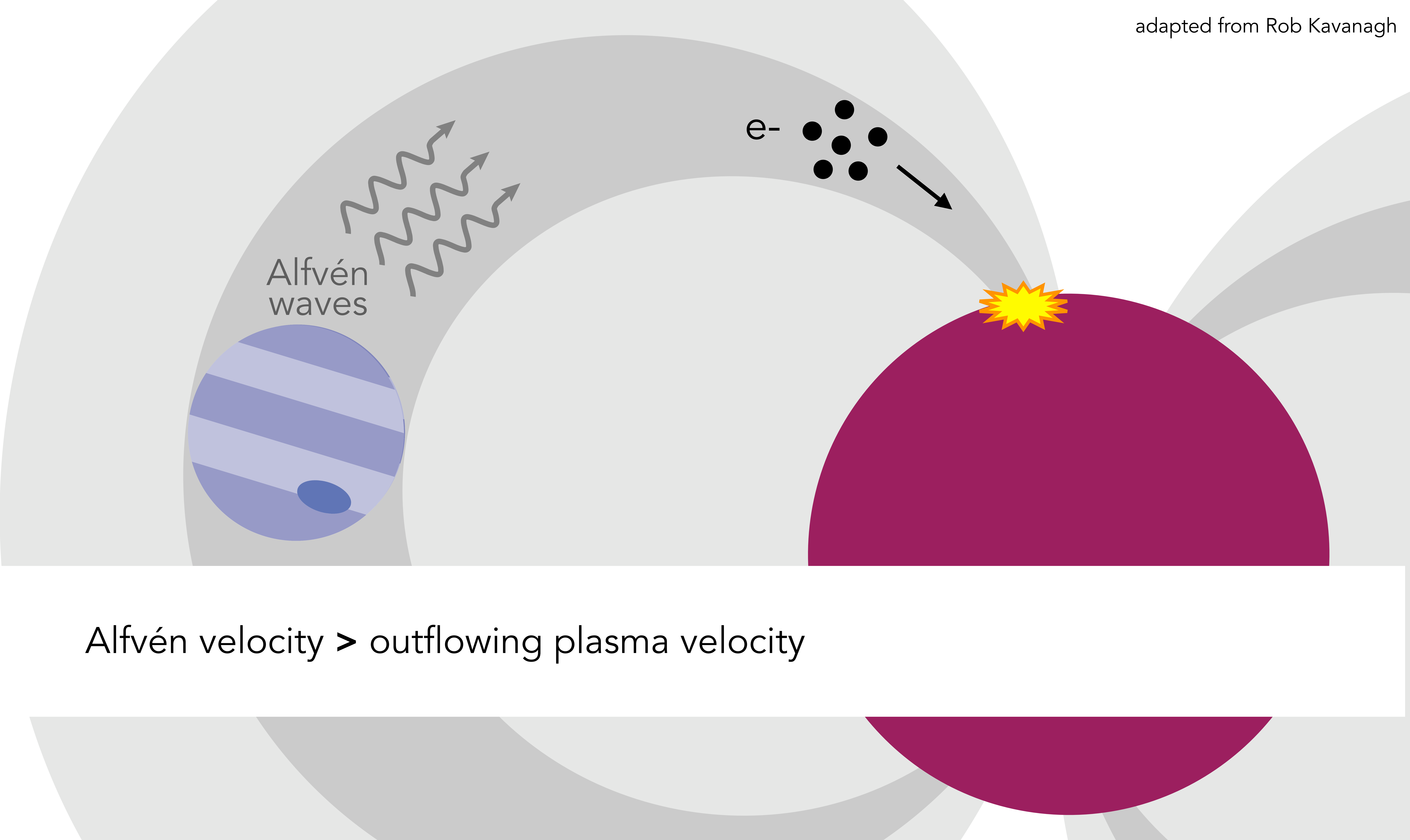


adapted from Rob Kavanagh



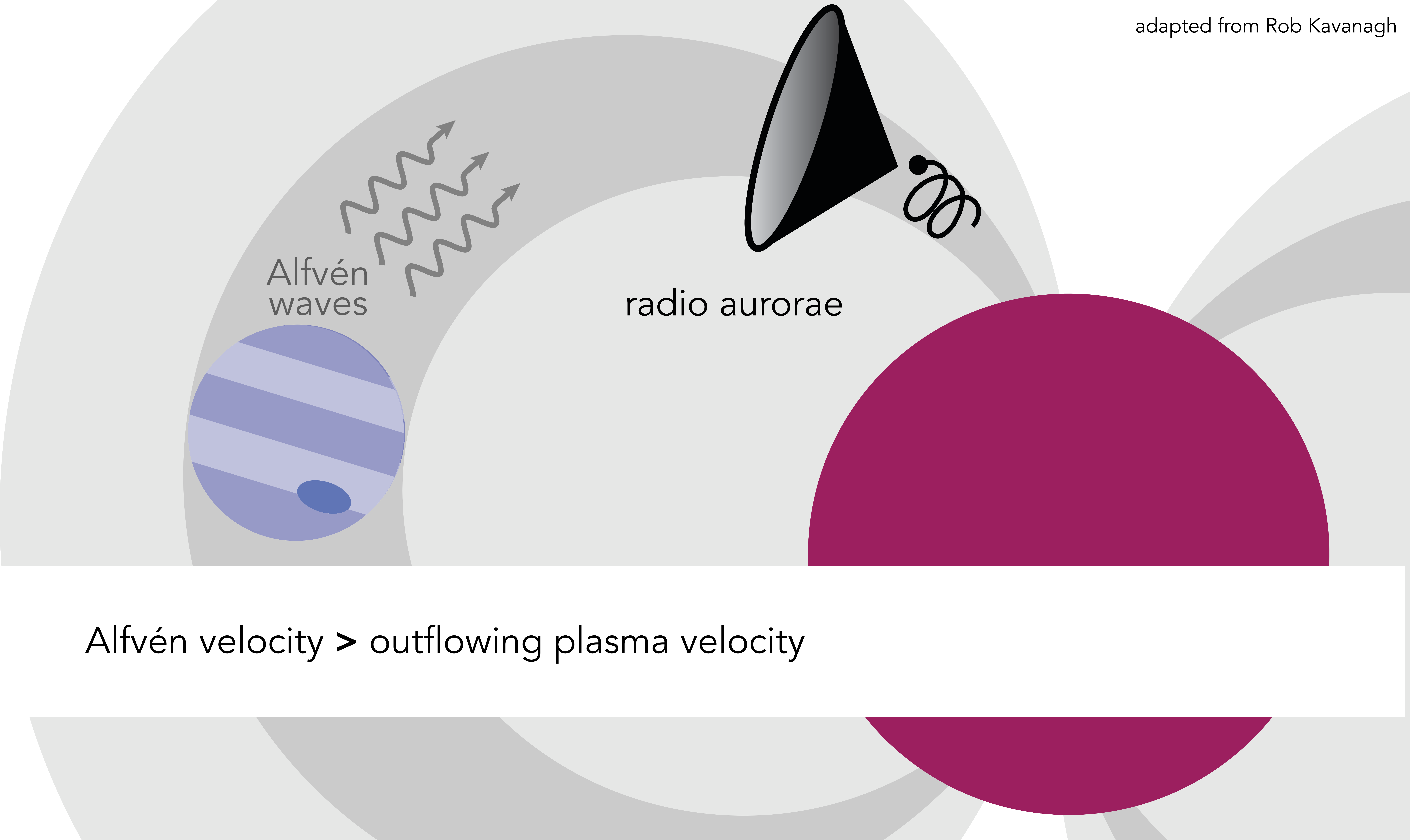
Alfvén velocity > outflowing plasma velocity

adapted from Rob Kavanagh



Alfvén velocity **>** outflowing plasma velocity

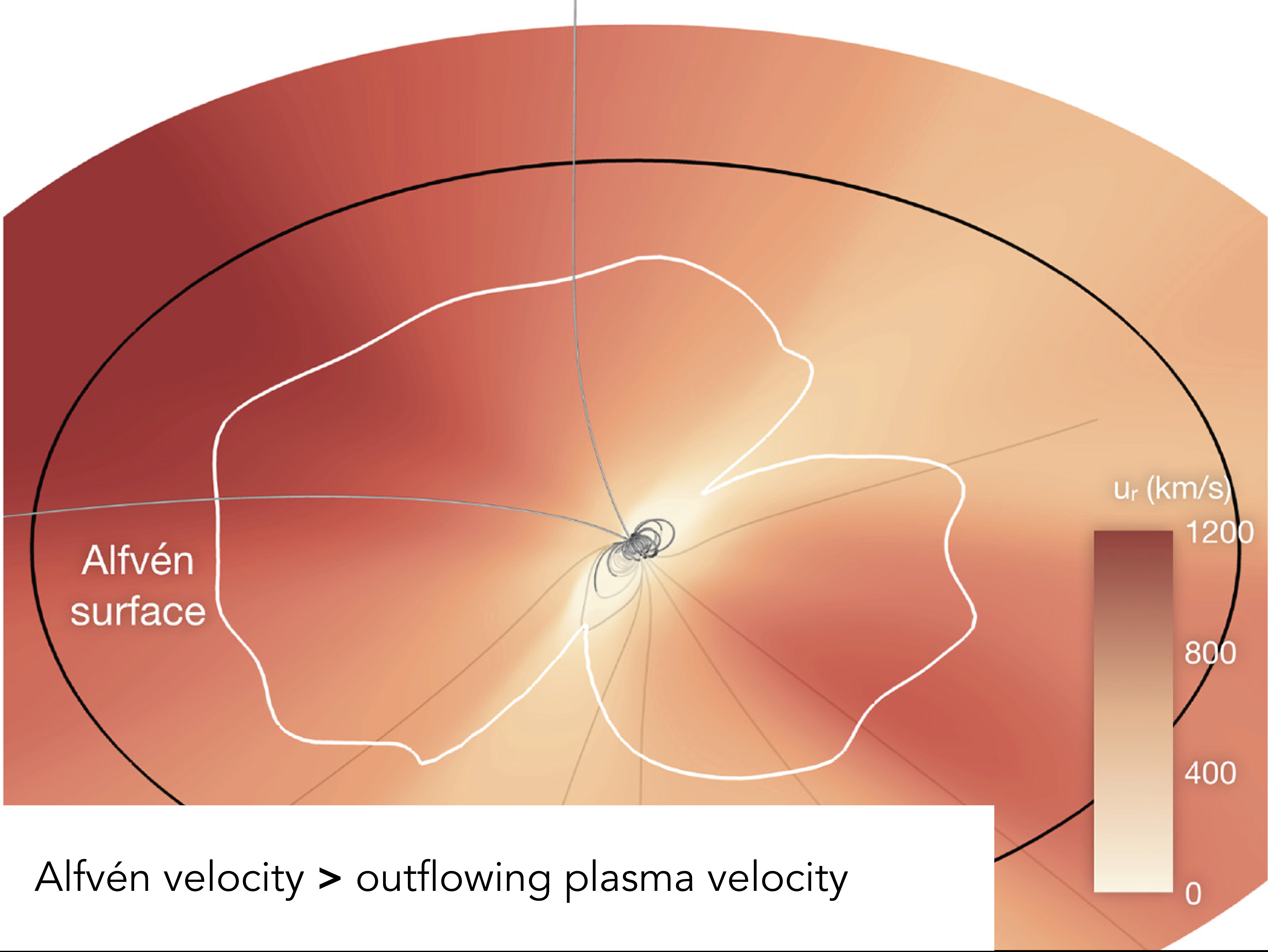
adapted from Rob Kavanagh



Alfvén velocity > outflowing plasma velocity

Recent radio SPI searches

Vedantham+ 2020
Perez-Torres+ 2021
Pineda & Villadsen+ 2023
Triglio+ 2023
(…and references therein)

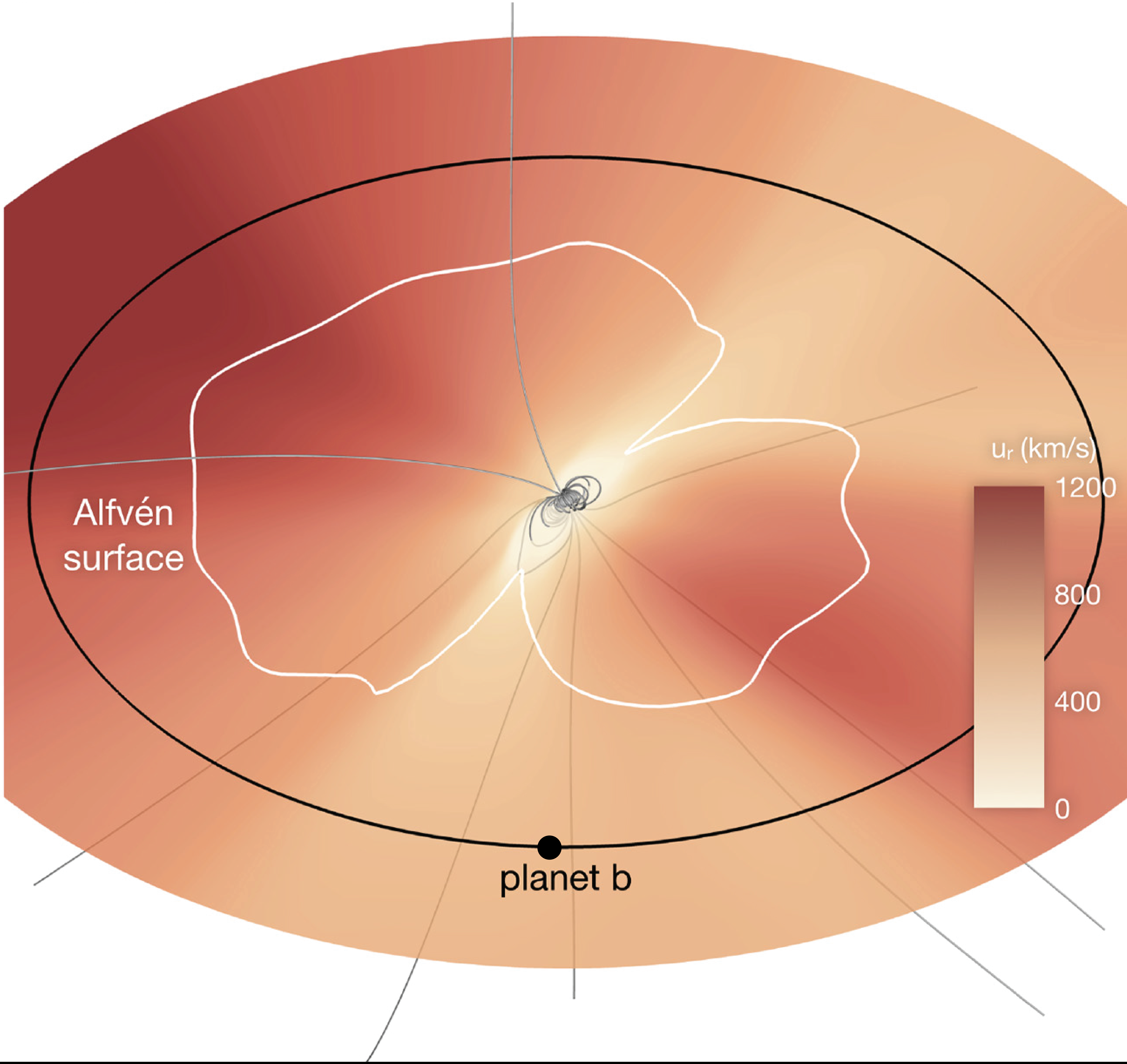


Kavanagh+ 2021

Alfvén velocity **>** outflowing plasma velocity

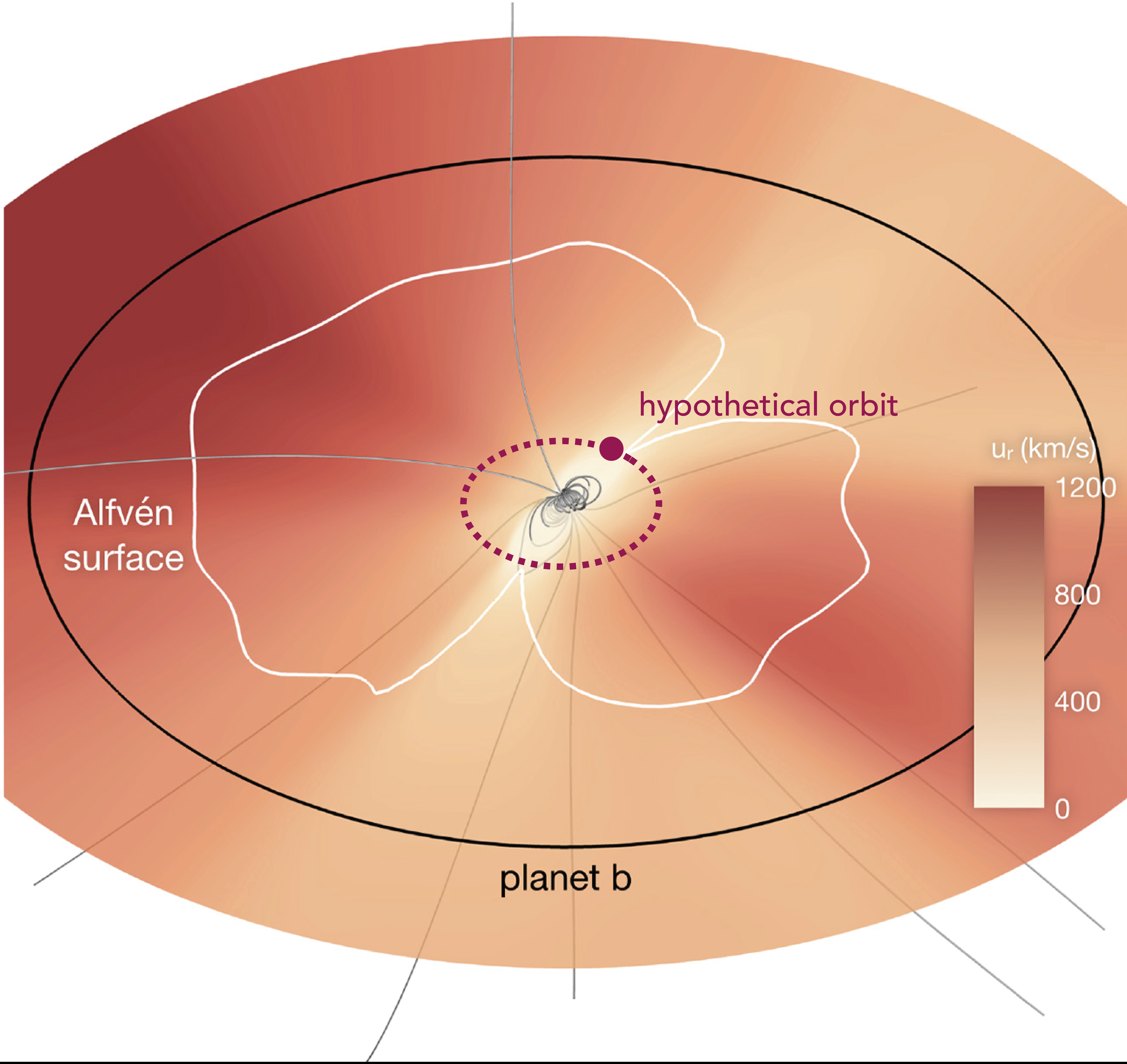
“No feasible scenario where the planet can induce radio emission in the star’s corona”

Kavanagh+ 2021



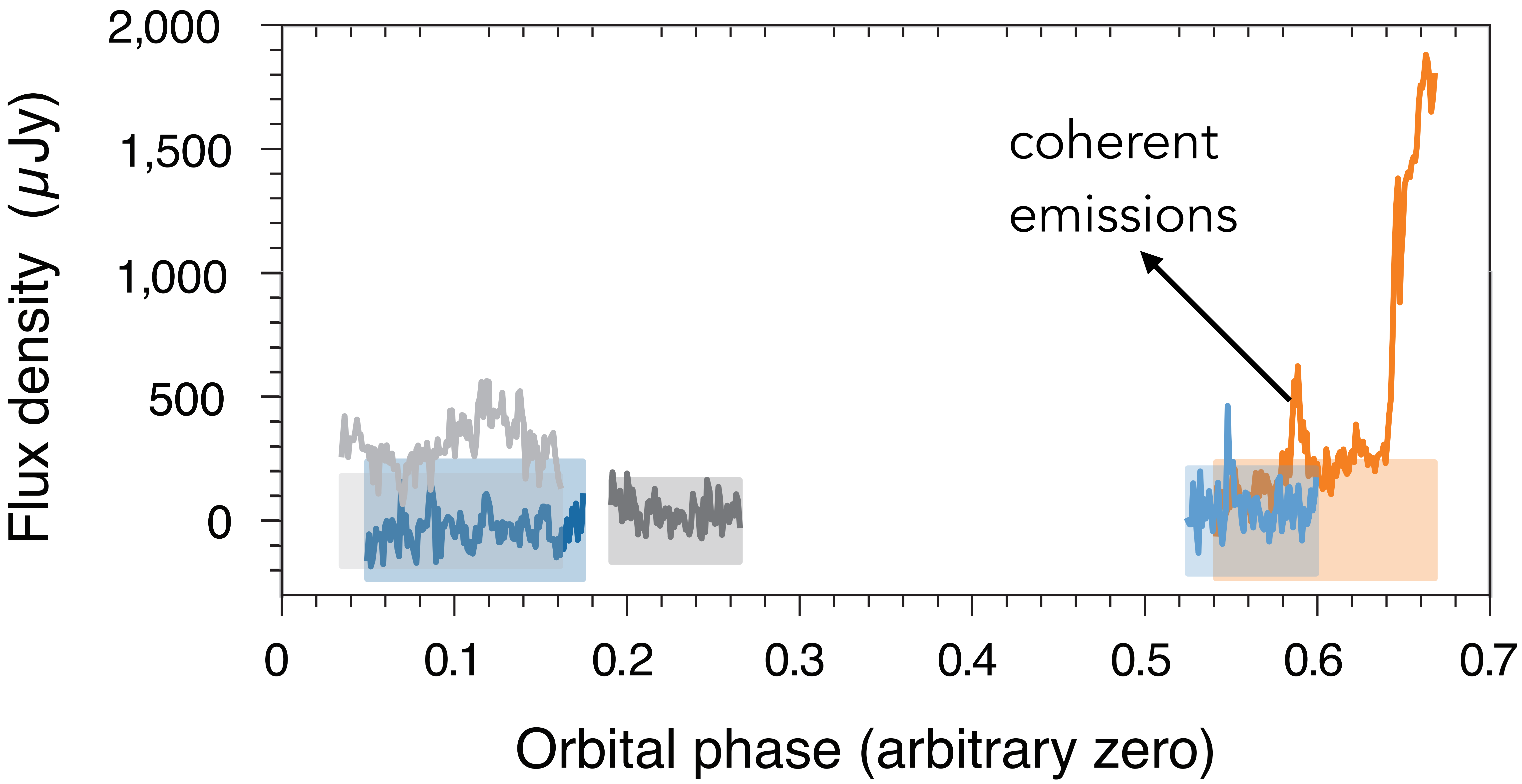
Kavanagh+ 2021

Yes!



Kavanagh+ 2021

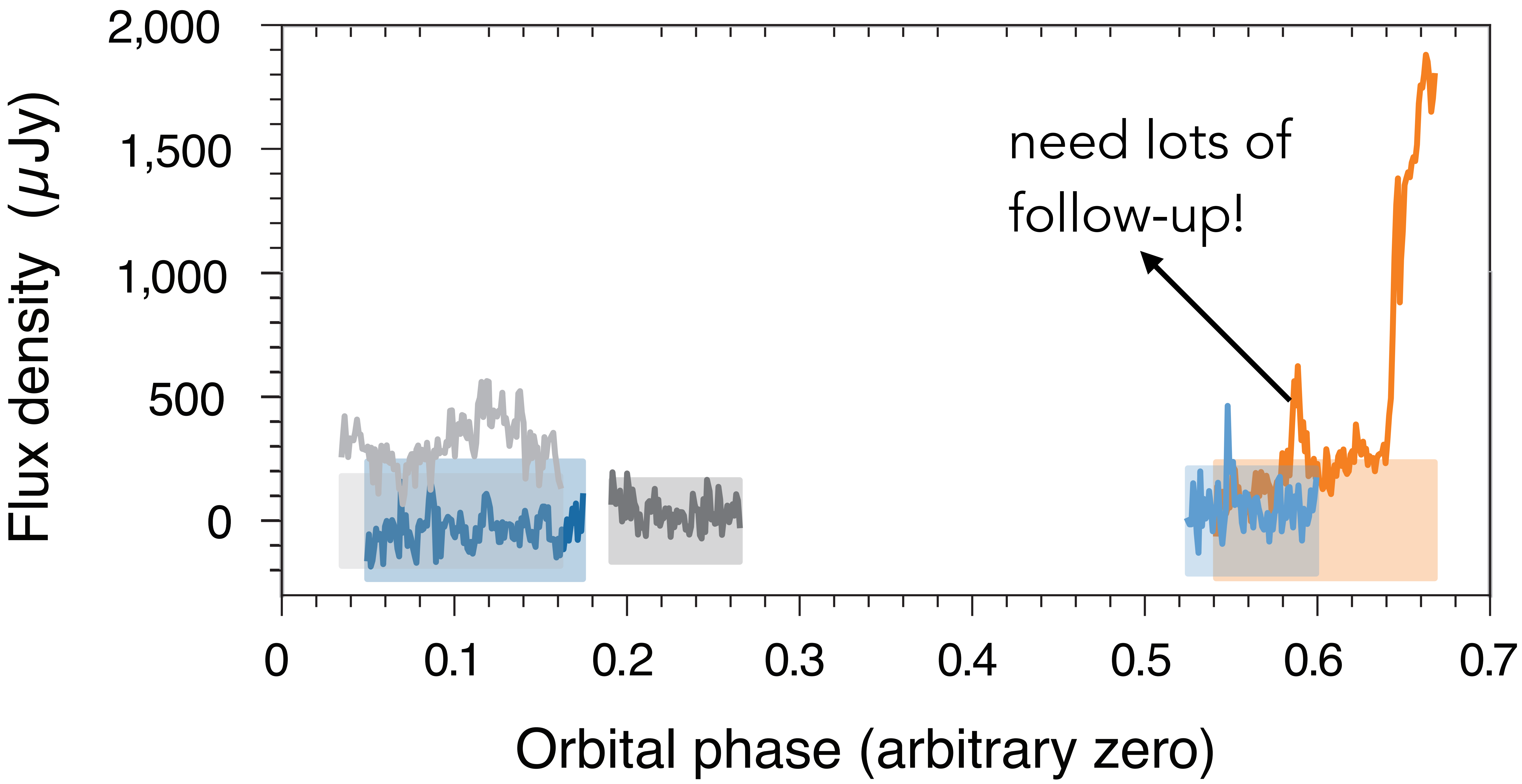
Indirect: Star-planet interactions (radio)



Pineda & Villadsen 2023

see also: Triglio+ 2023

Indirect: Star-planet interactions



Pineda & Villadsen 2023
see also: Triglio+ 2023

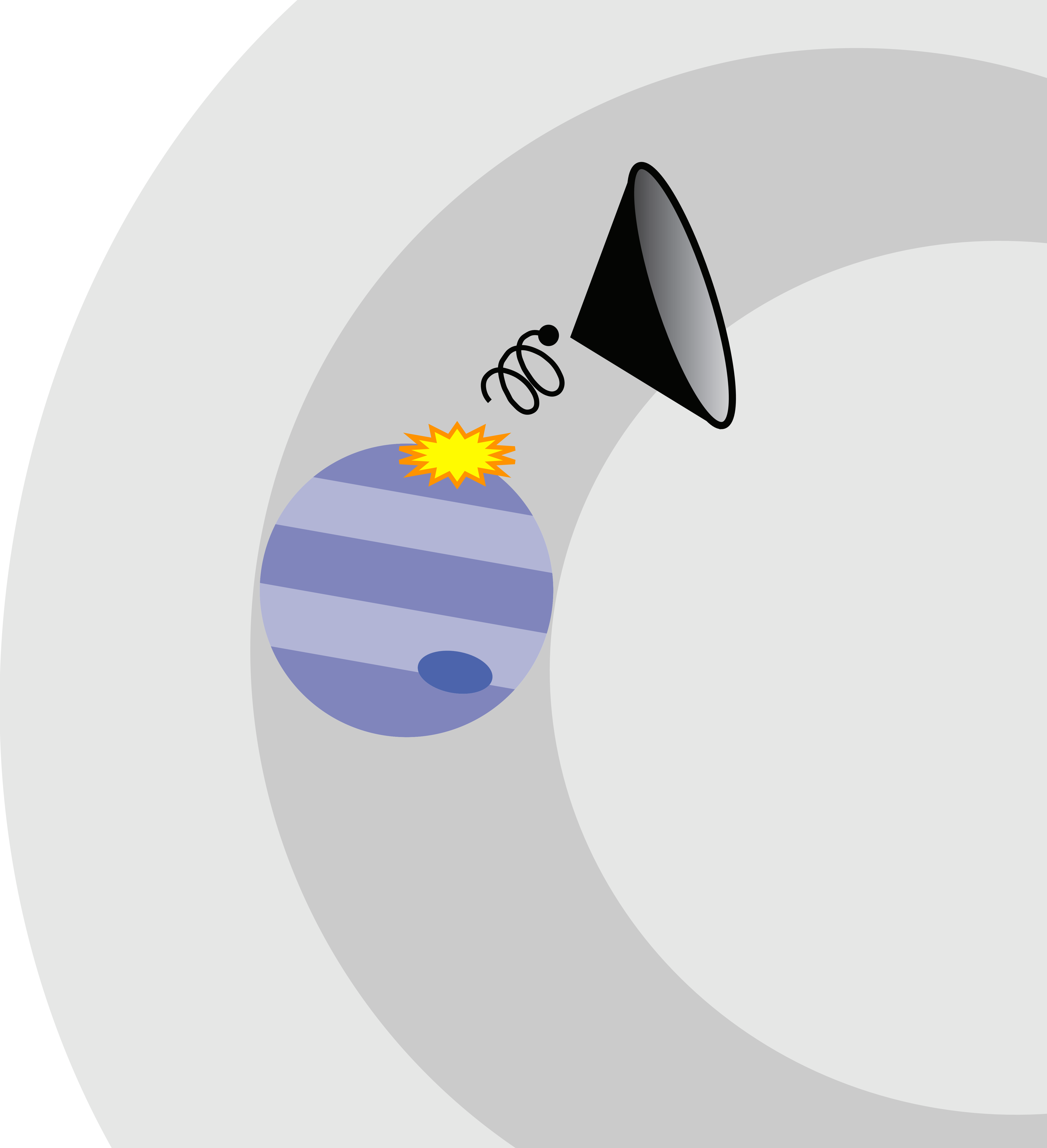
SKA

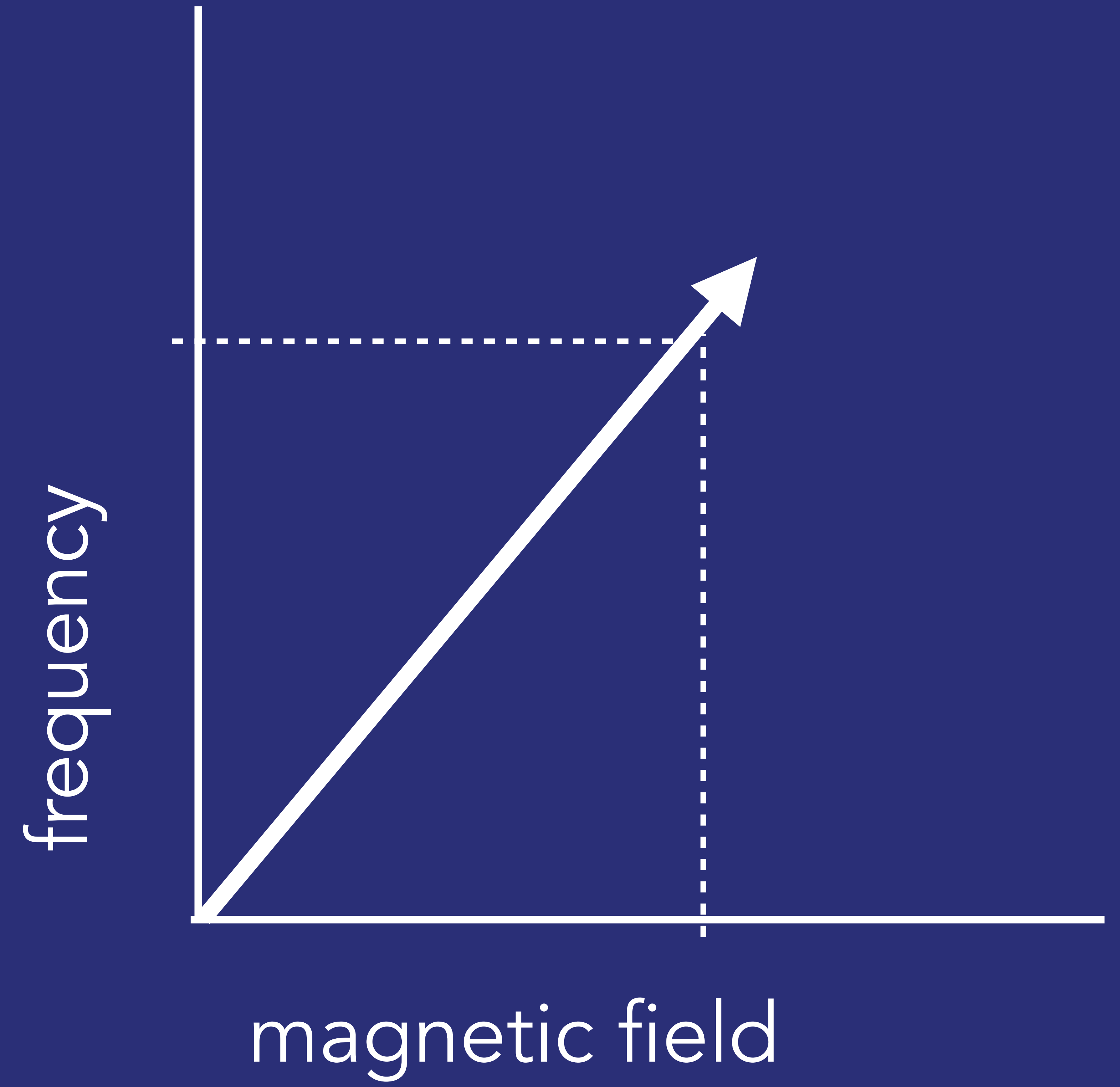
DSA-2000

INDIRECT
Host (stellar) emissions
DIRECT
Aurora: Wind-driven
DIRECT
Aurora: Rotation-driven
DIRECT
Radiation belts

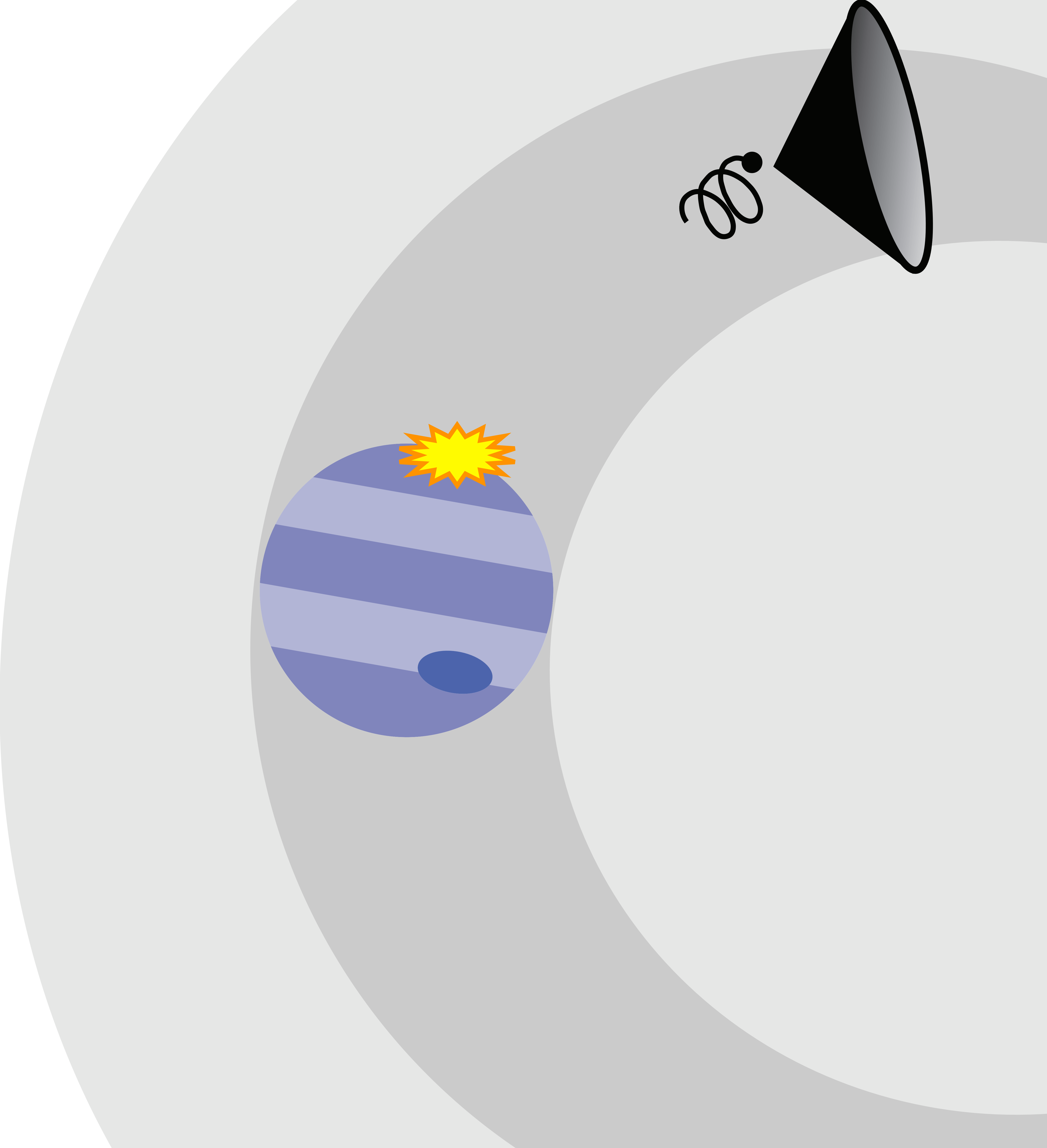
Direct: Radio Aurorae

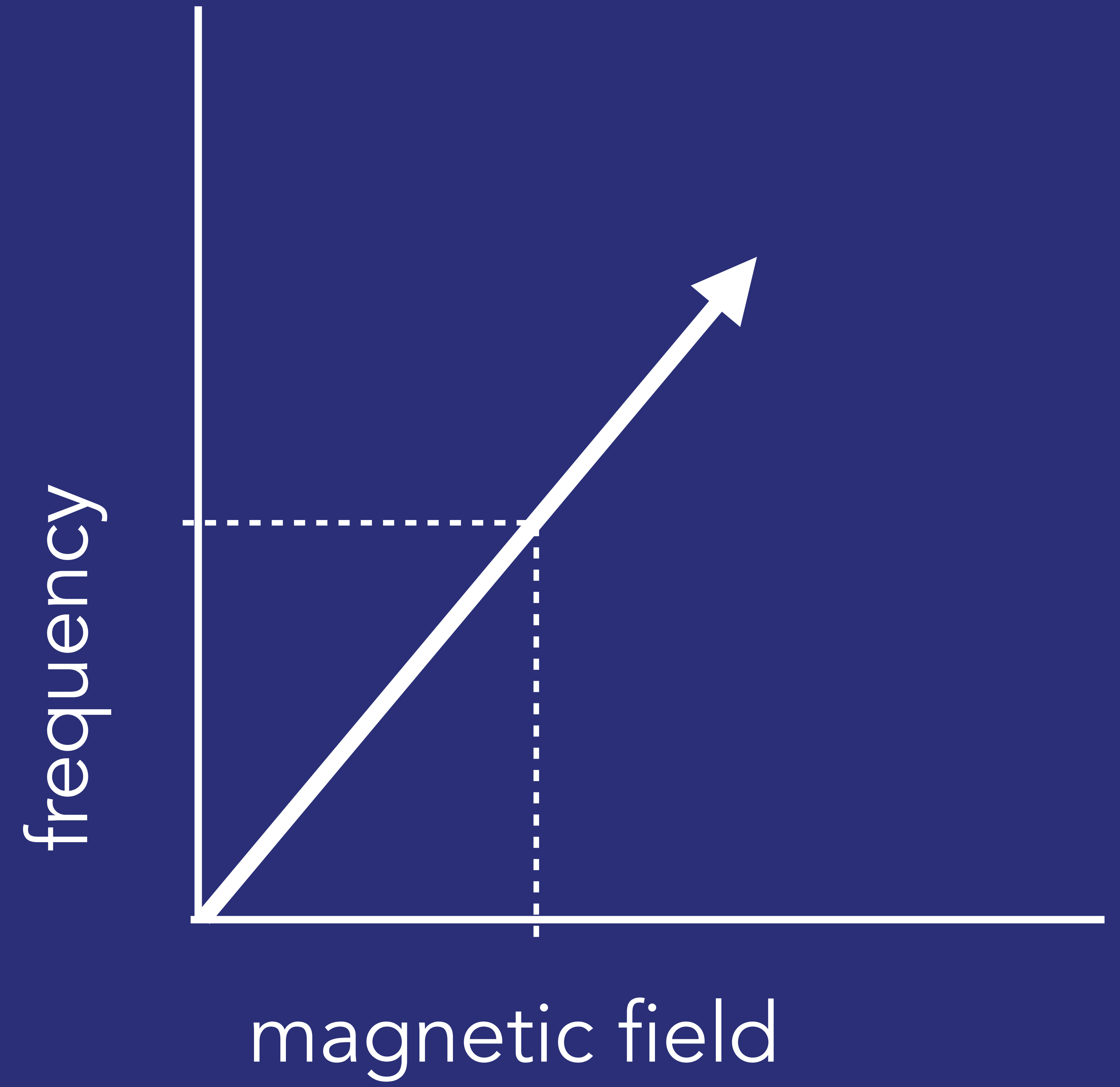
$\nu_{[\mathrm{MHz}]} \approx 2.8\ \mathbf{B}_{\mathbf{planet\ [Gauss]}}$





$$\nu_{\mathrm{MHz}} \approx 2.8\, B_{\mathrm{Gauss}}$$





$$\nu_{\mathrm{MHz}} \approx 2.8\, B_{\mathrm{Gauss}}$$

Melodie Kao (mkao@lowell.edu)

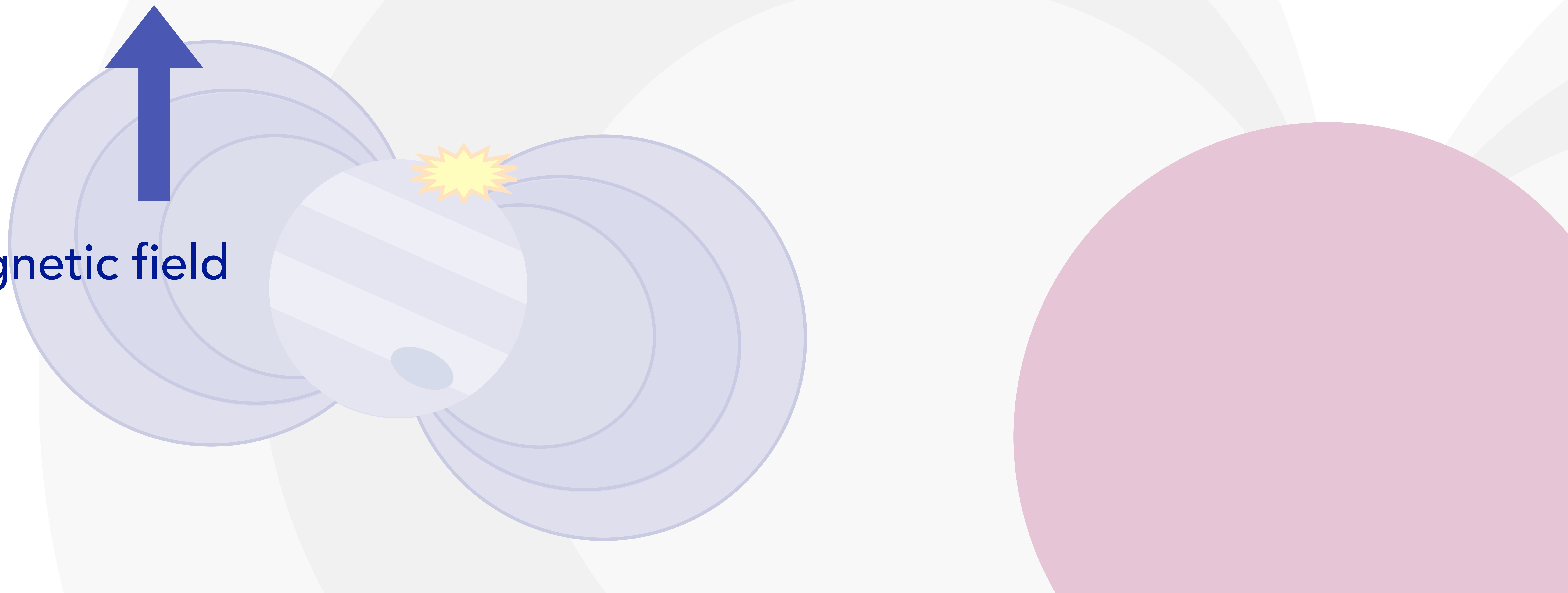
$$S \propto R_o^2 \, B_{\rm wind} \, \Delta u^2 \, \sin^2\theta \sqrt{\rho_{\rm wind}}$$

power dissipated | obstacle size | (magnetospheric plasma flow properties)

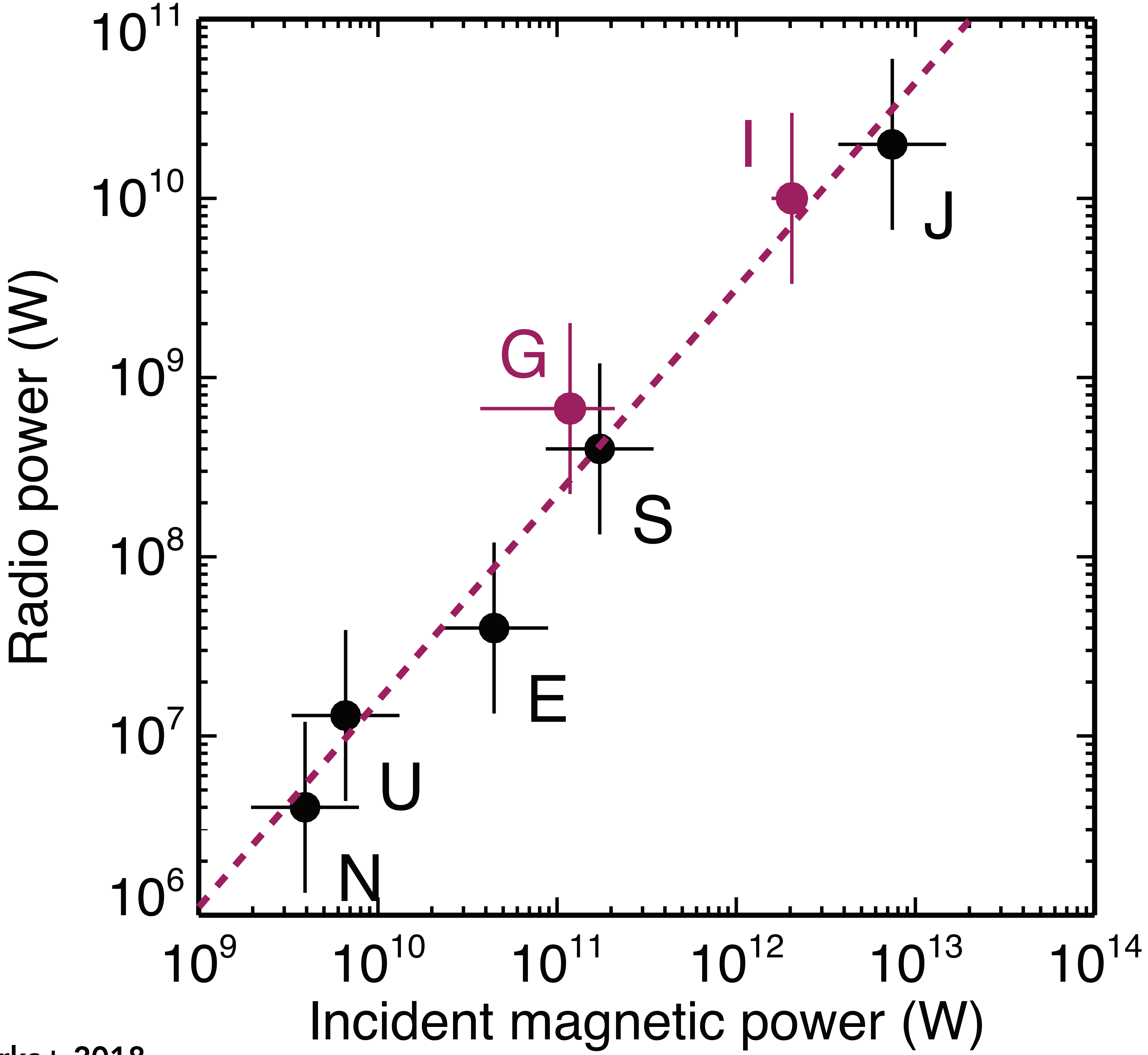
Saur+ 2013

$$S \propto R_o^2 \; B_{\mathrm{wind}} \; \Delta u^2 \; \sin^2\theta \sqrt{\rho_{\mathrm{wind}}}$$

power dissipated | obstacle size | (magnetospheric plasma flow properties)



Saur+ 2013



Zarka+ 2018
Zarka 2007

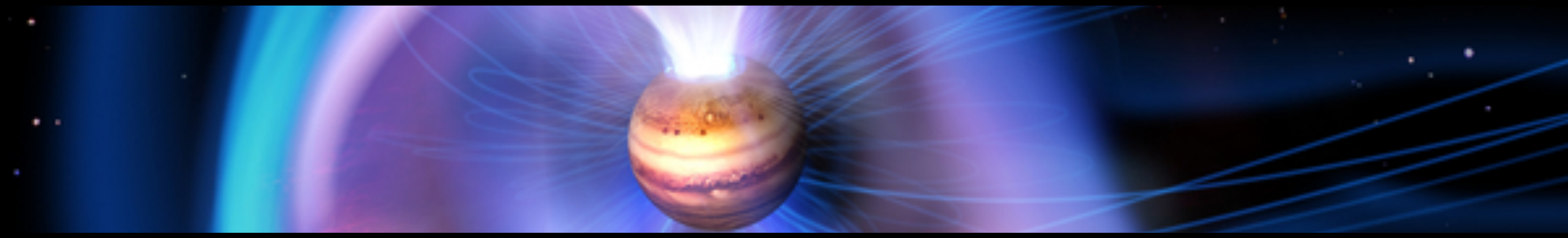
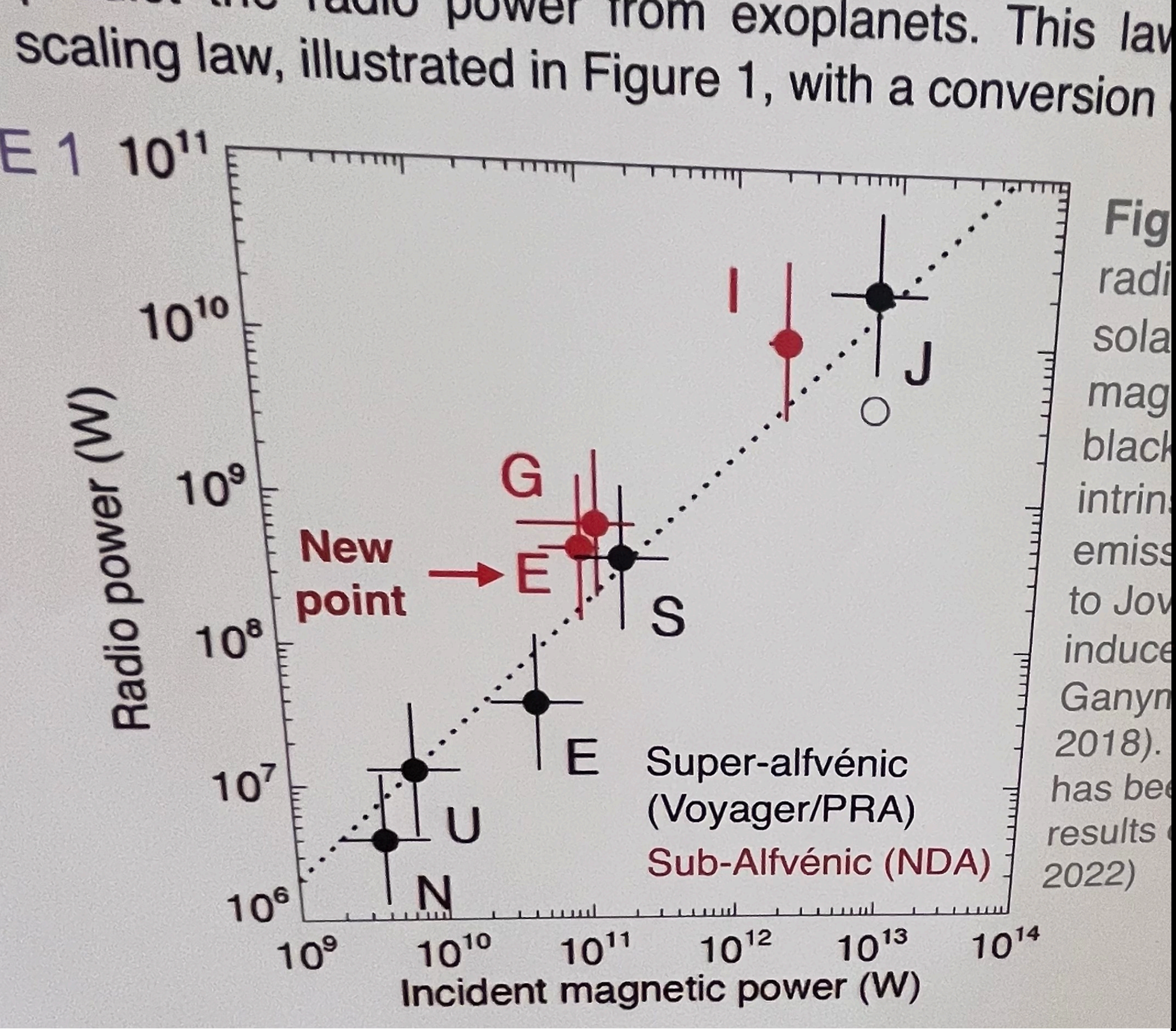


image: JAXA



Jâcome+ 2022
Zarka+ 2018
Zarka 2007

see poster by L. Lamy!

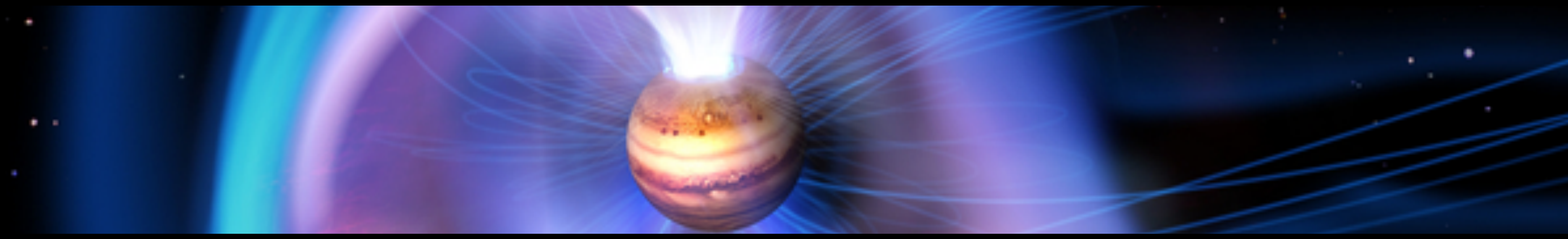


image: JAXA

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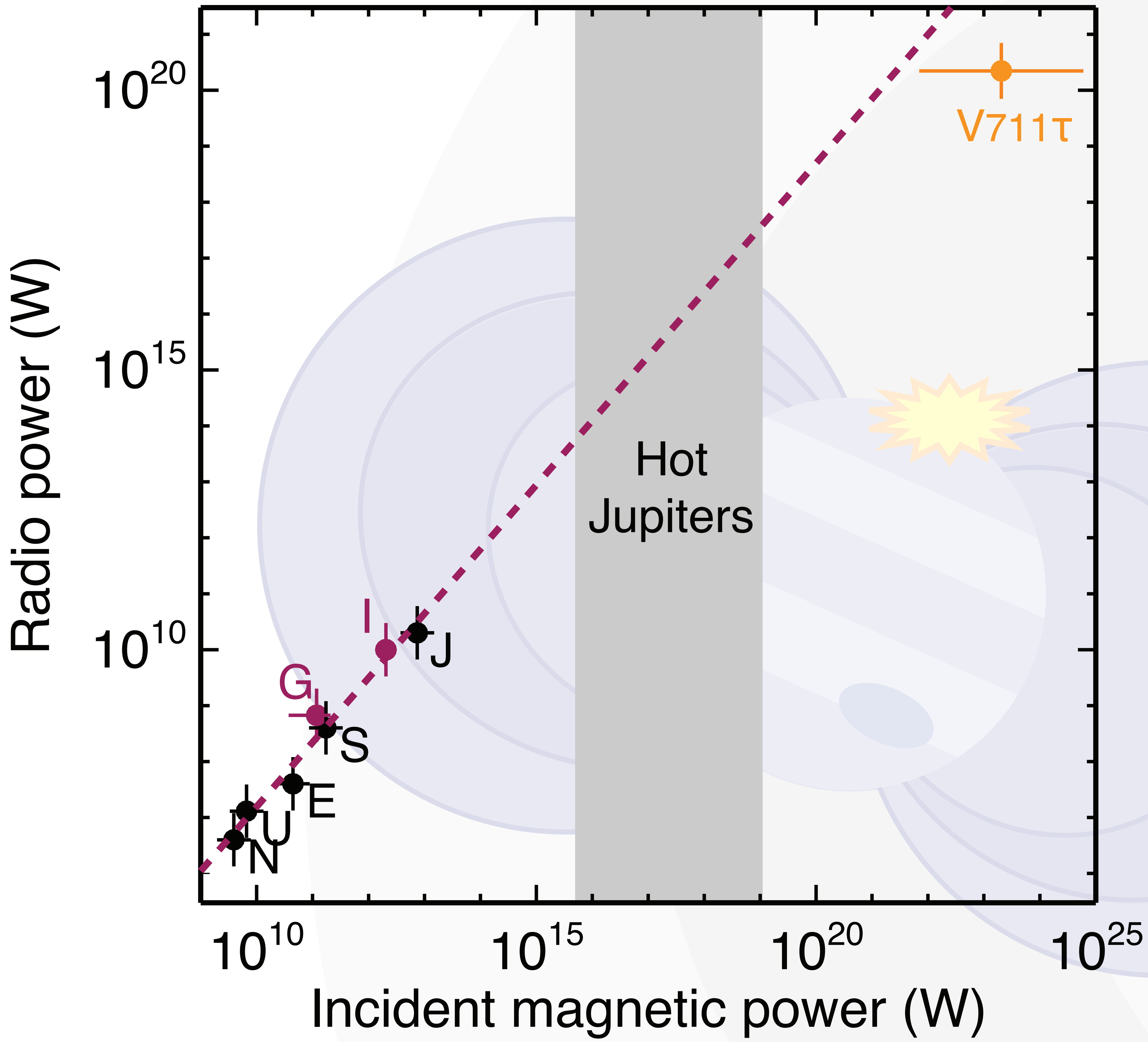
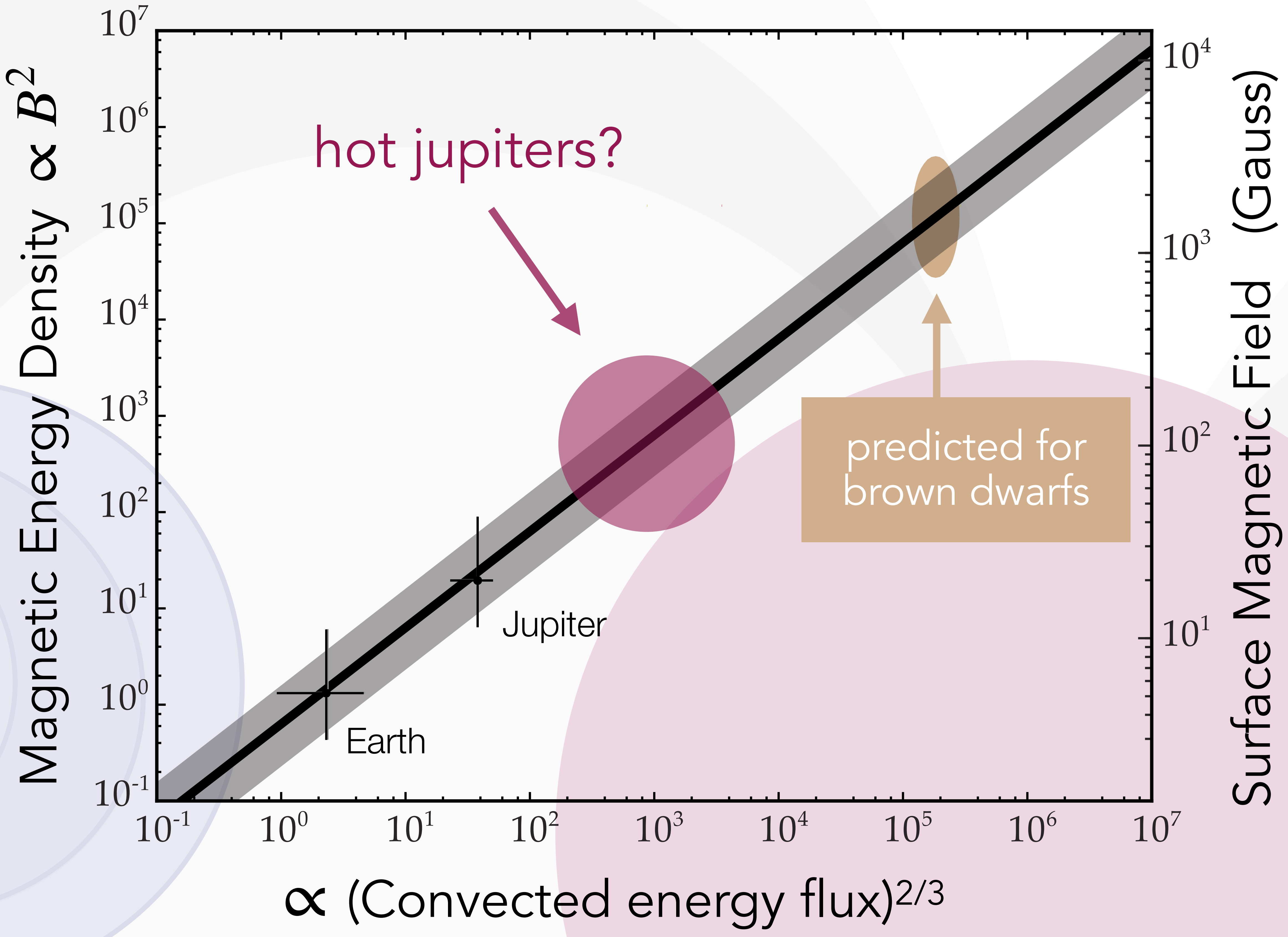
power dissipated

obstacle size

(magnetospheric plasma flow properties)



Zarka+ 2018



Christensen+ (2009)

See also: Yadav & Thorngren (2017)

Melodie Kao (mkao@lowell.edu)

Yantis+ 1977
Winglee+ 1986
Zarka+ 1997
Bastian+ 2000
Farrell+ 2003
Lazio+ 2004
Ryabov+ 2004
Guenther+ 2005
Shiratori+ 2005
Winterhalter+ 2006
Majid+ 2006
George+ 2007
Lazio+ 2007
Lecavelier Des Etangs+ 2009
Smith+ 2009
Lazio+ 2010a
Lazio+ 2010b
Zarka+ 2011
Lecavelier Des Etangs+ 2011
Stroe+ 2012
Lecavelier Des Etangs+ 2013
Hallinan+ 2013
Sirothia+ 2014
Murphy+ 2015
Vasylieva 2015
Knapp+ 2016
Turner+ 2017
Bastian+ 2018
O'Gorman+ 2018
de Gasperin+ 2020
Green+ 2021
Narang+ 2021
Turner+ 2021

No confirmed exoplanet radio aurorae.

special thanks: Jake Turner, Marin Anderson, Mary Knapp

Yantis+ 1977
Winglee+ 1986
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INDIRECT
Host (stellar) emissions
DIRECT
Aurora: Wind-driven
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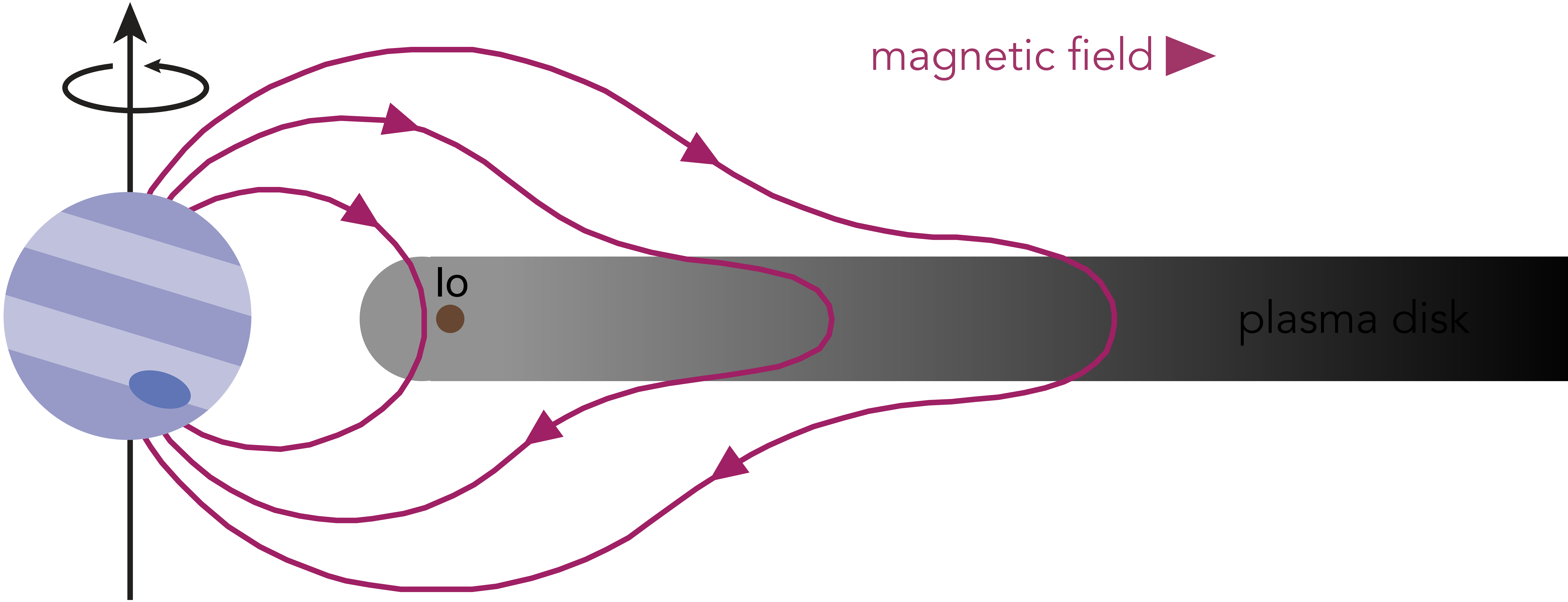
Aurora: Rotation-driven
DIRECT
Radiation belts

(Magnetospheric-Ionospheric) MI-Coupling



Bagenal+ 2014

(Magnetospheric-Ionospheric) MI-Coupling

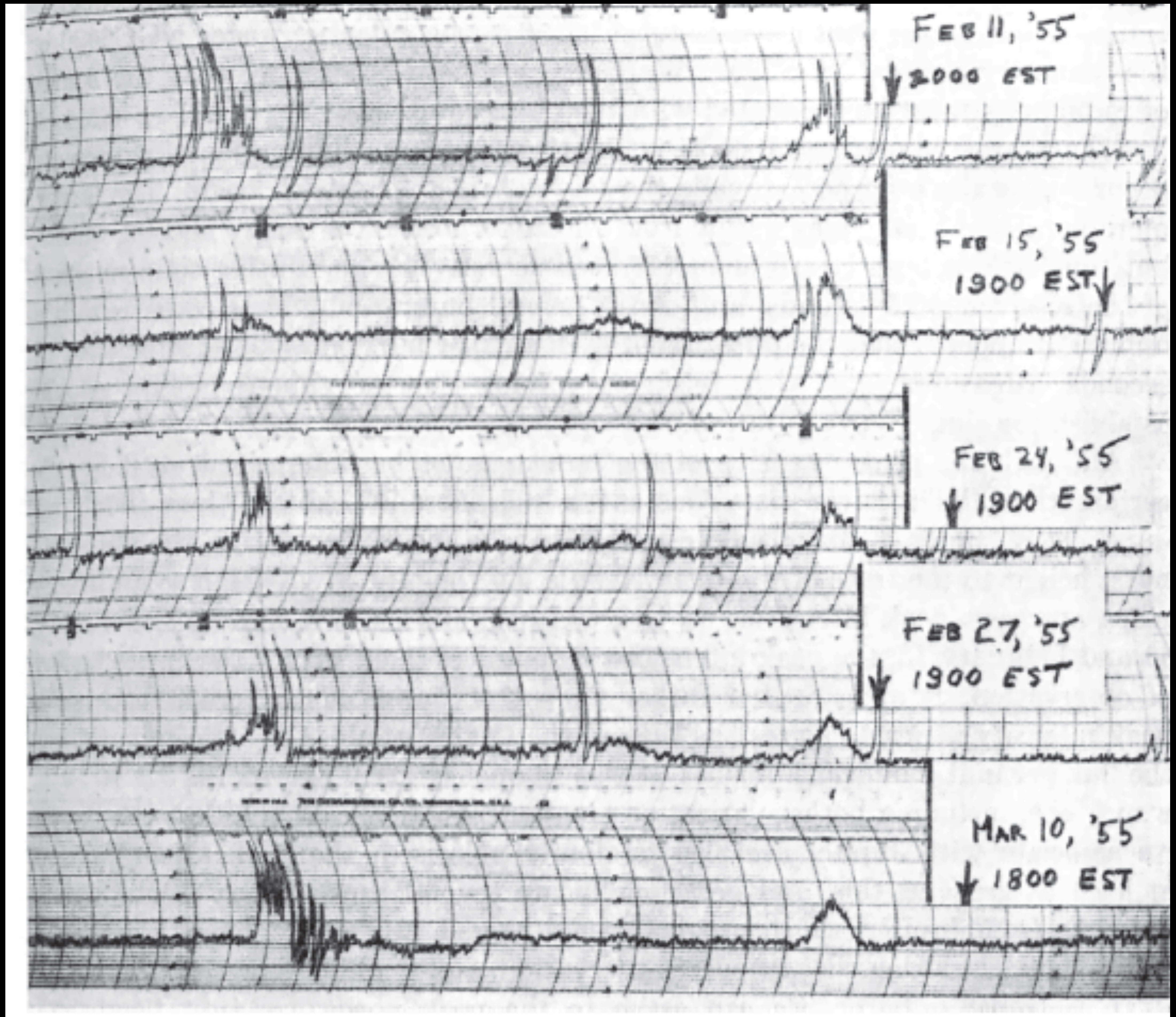
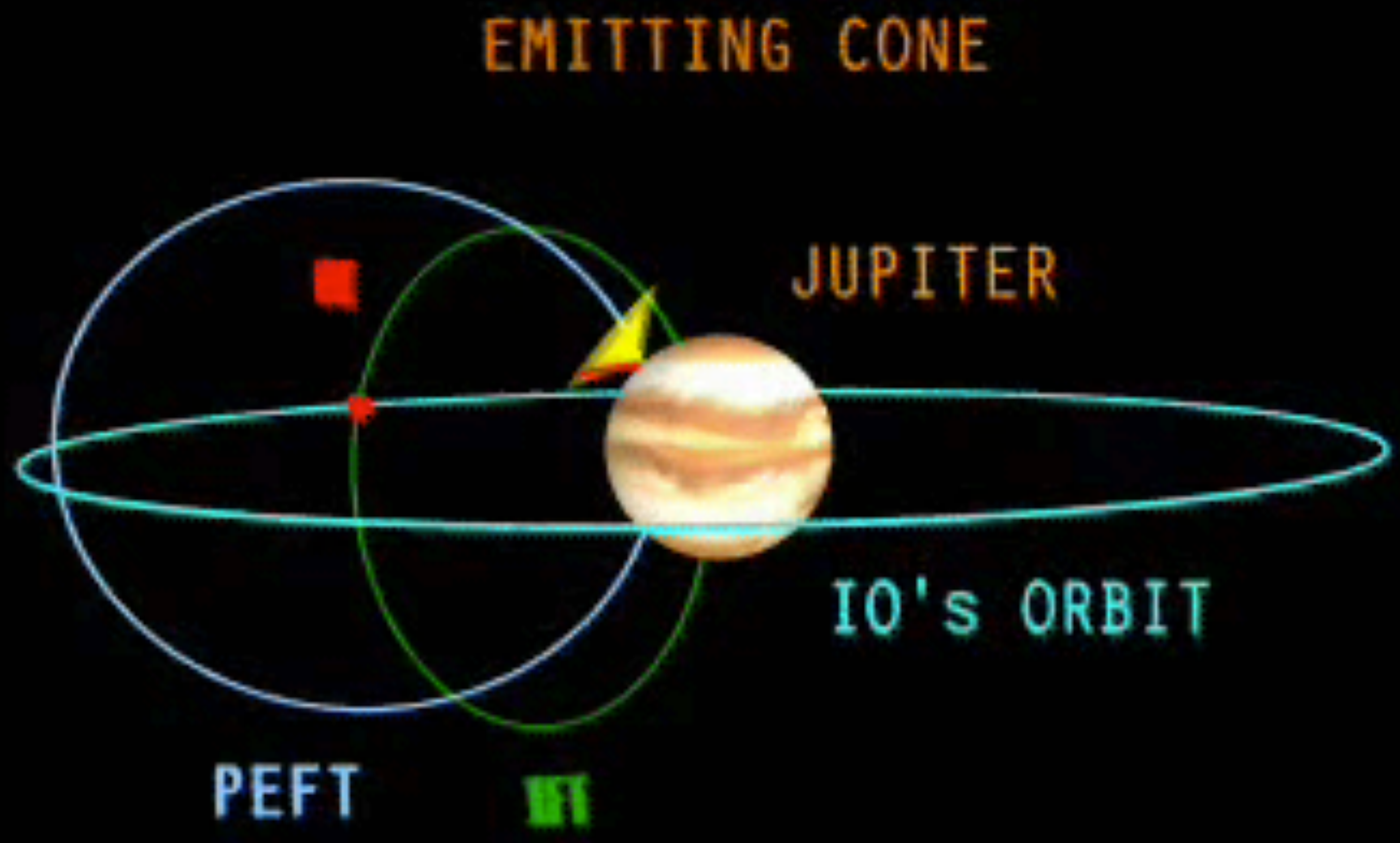


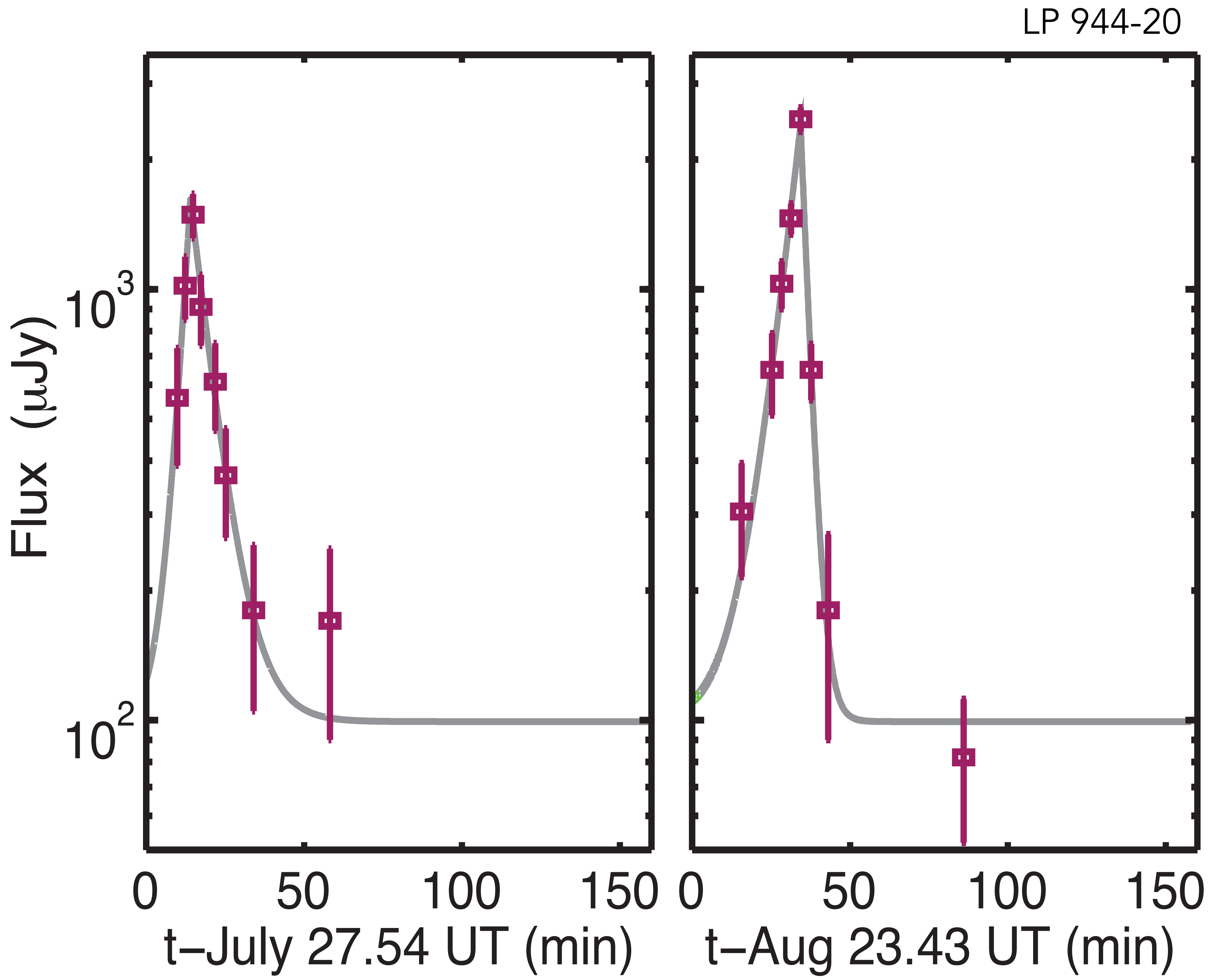
Fig. 2—Phase-switching records showing the appearance of the variable source

Franklin & Burke 1955



Imai Lab

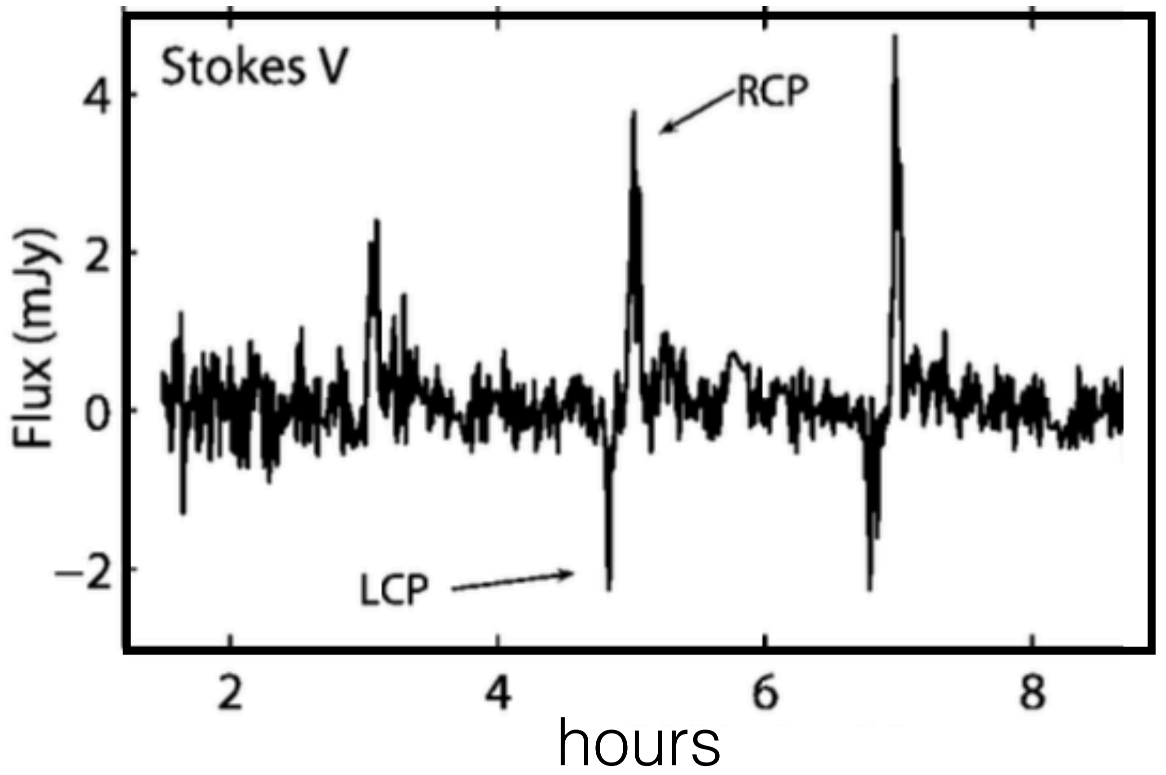
Melodie Kao (mkao@lowell.edu)



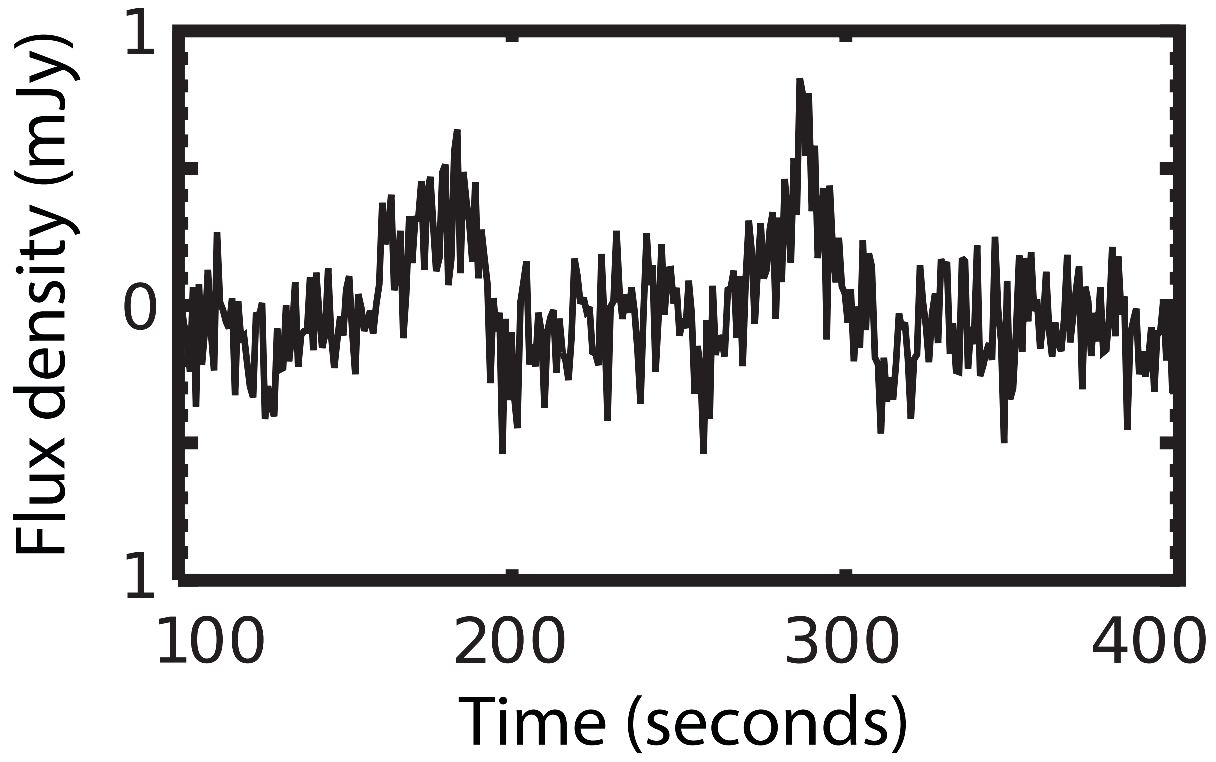
Radio bursts from a brown dwarf

Berger+ (2001)

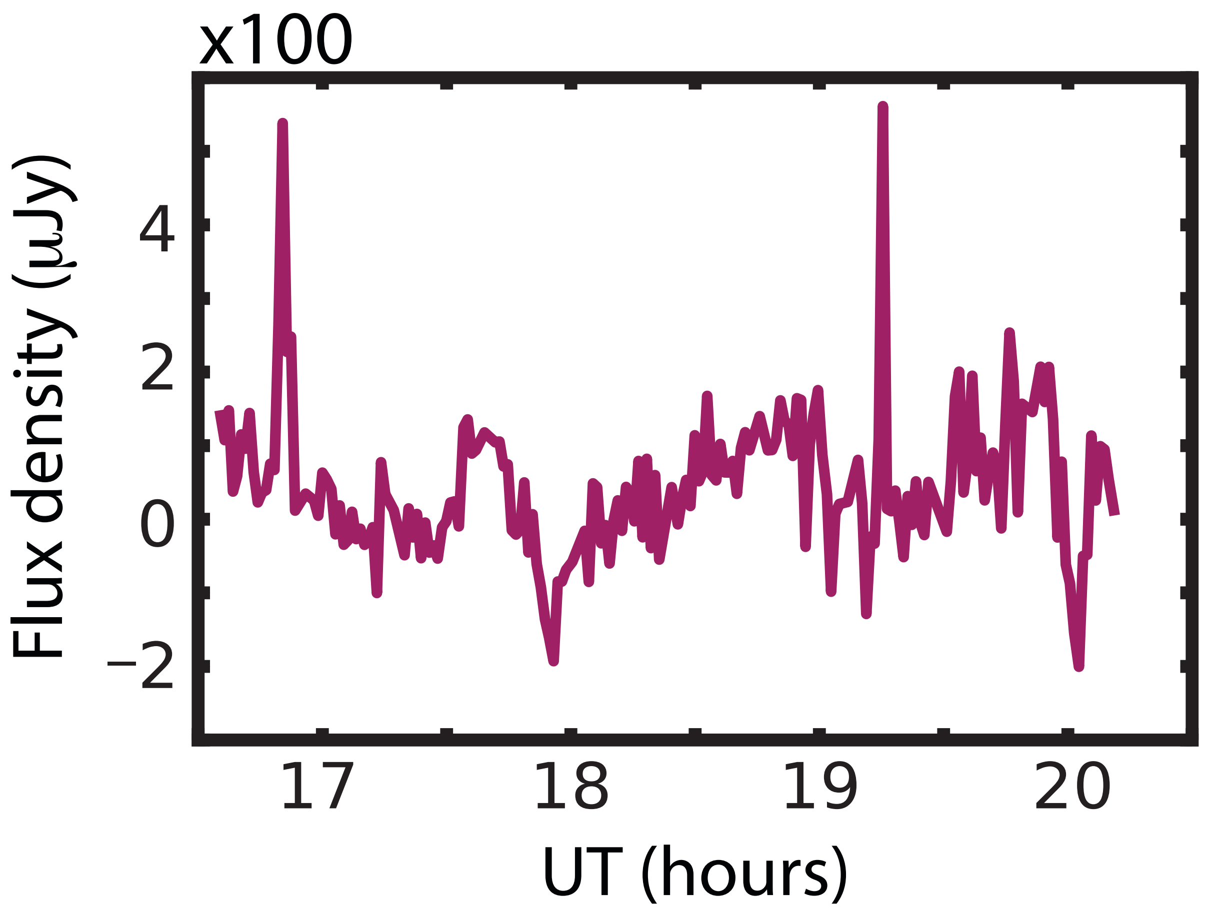
TVLM 513-46546
M9
Hallinan+ 2007



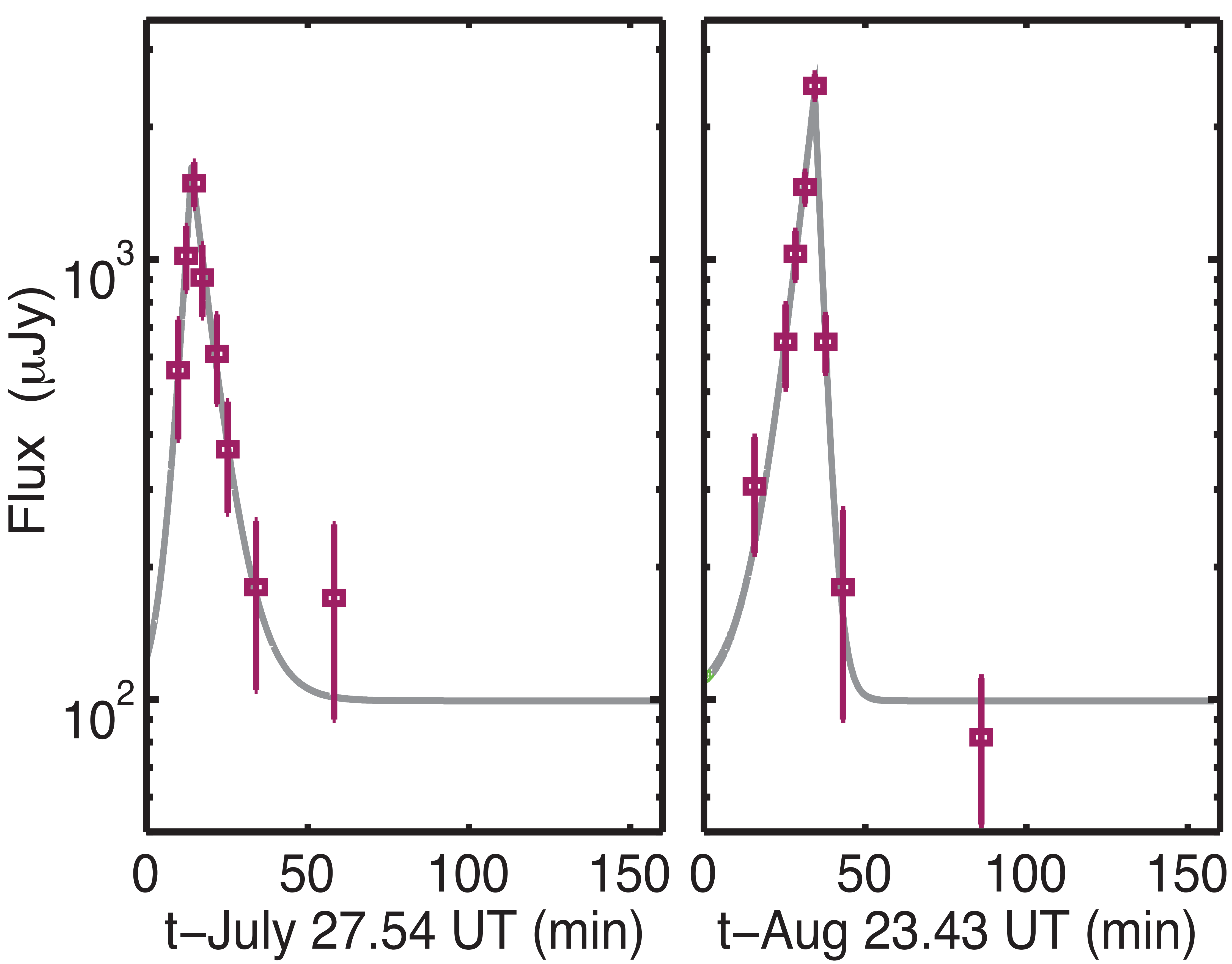
2M1047
T6.5, 900K
Route & Wolszczan 2012



SIMP0136
T2.5, 1100K, ~13 M_J
Kao+ 2016



LP 944-20



See also: Vedantham+ 2020b, 2023; Rose+ 2023

Berger+ (2001)

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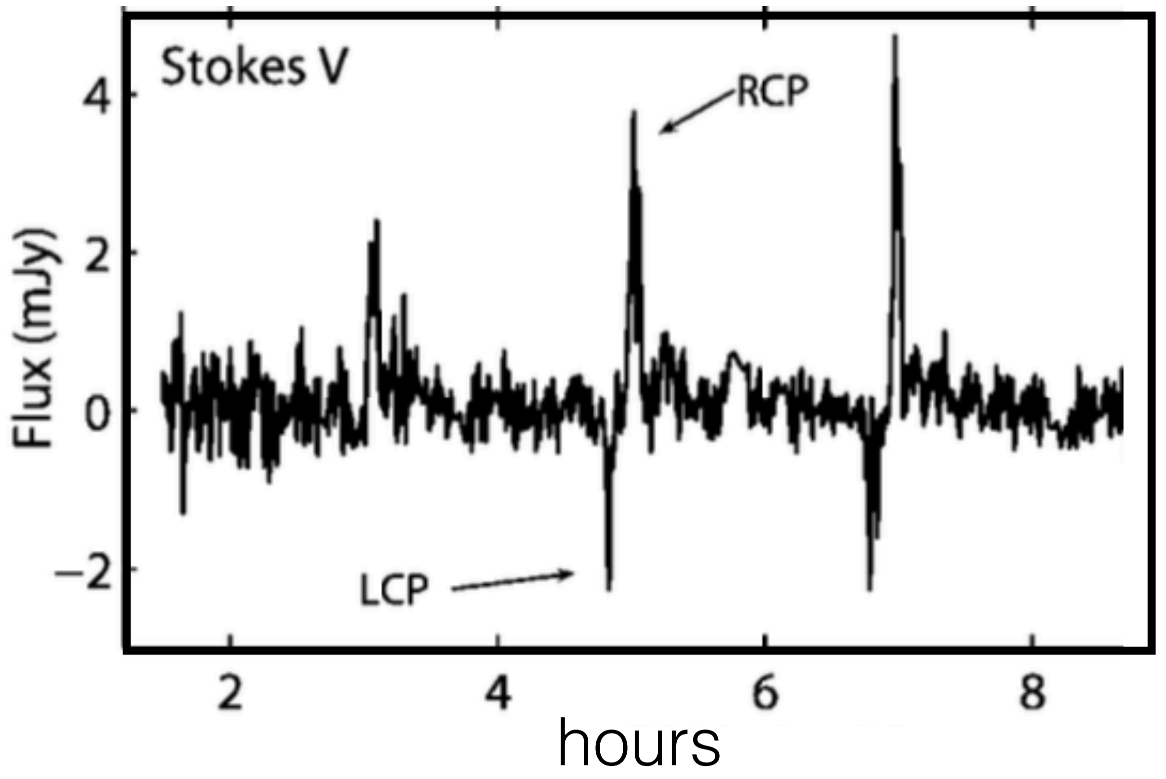

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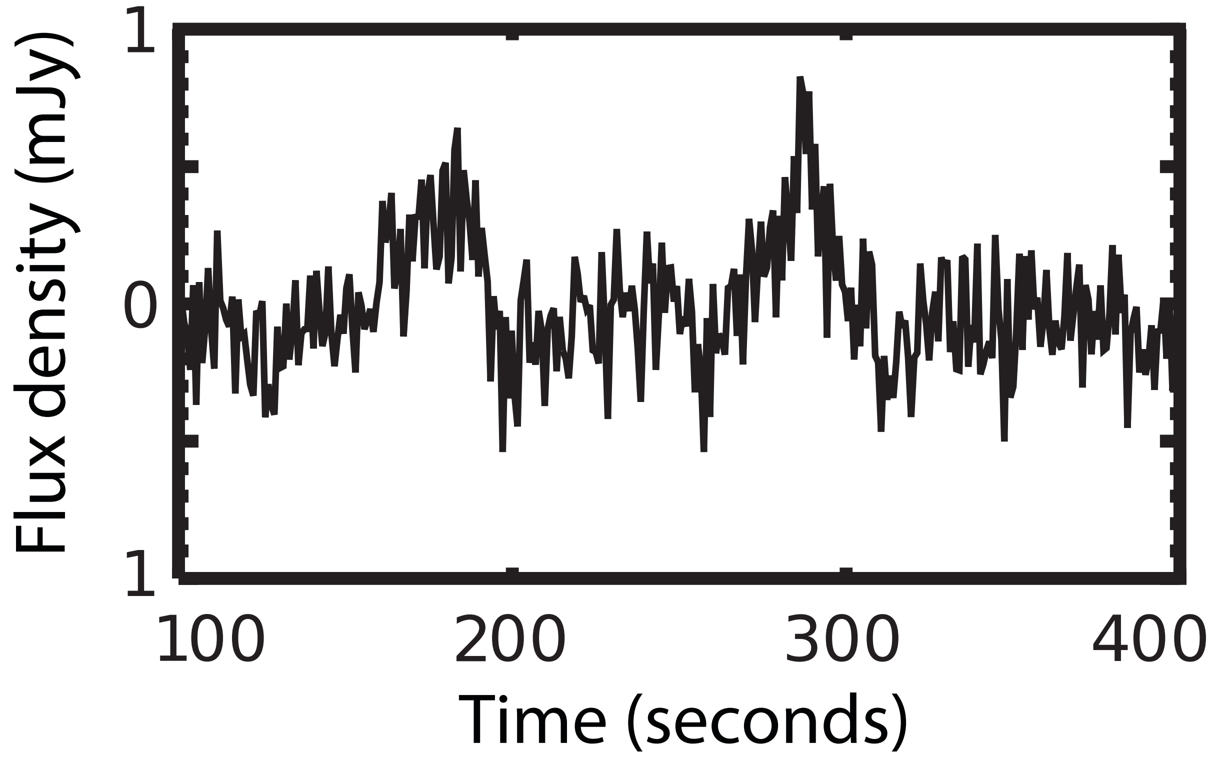

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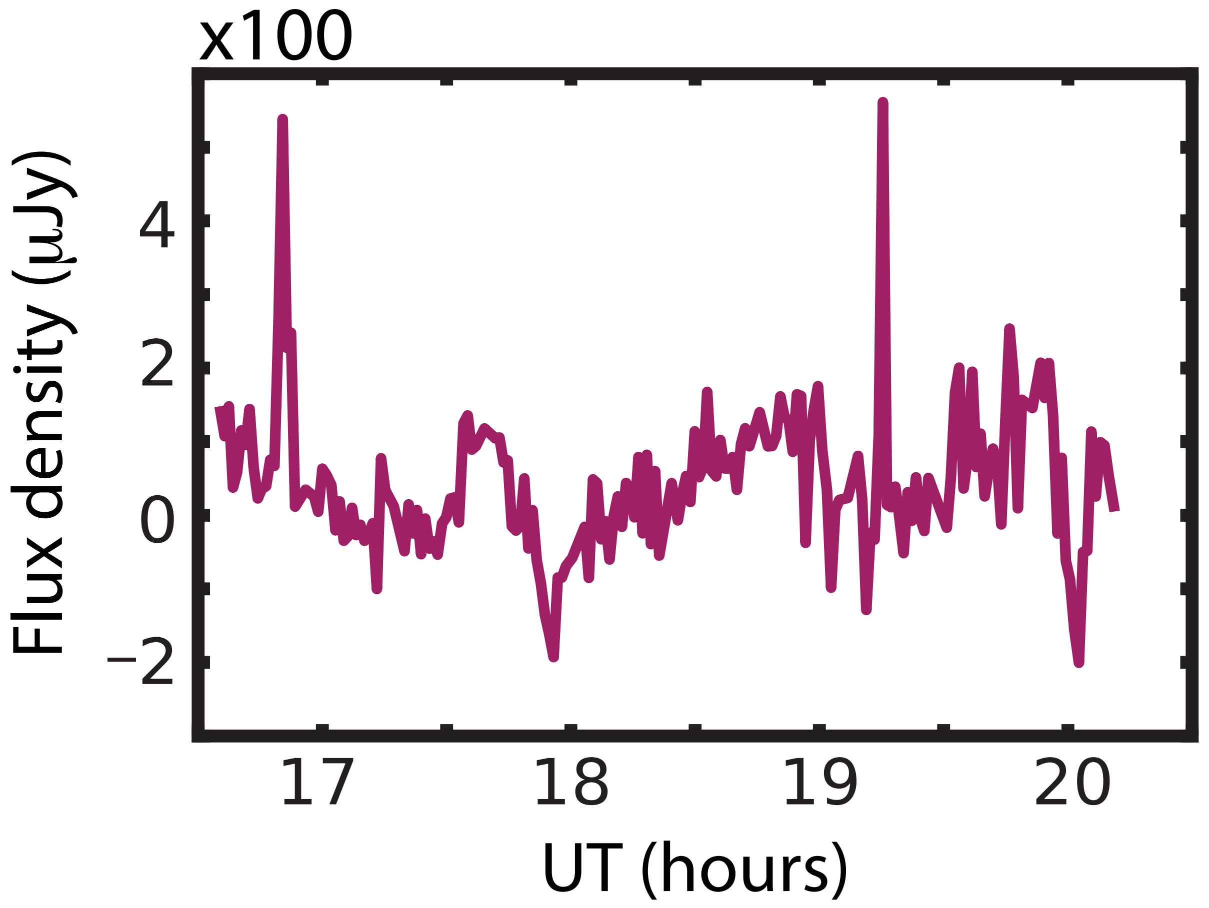
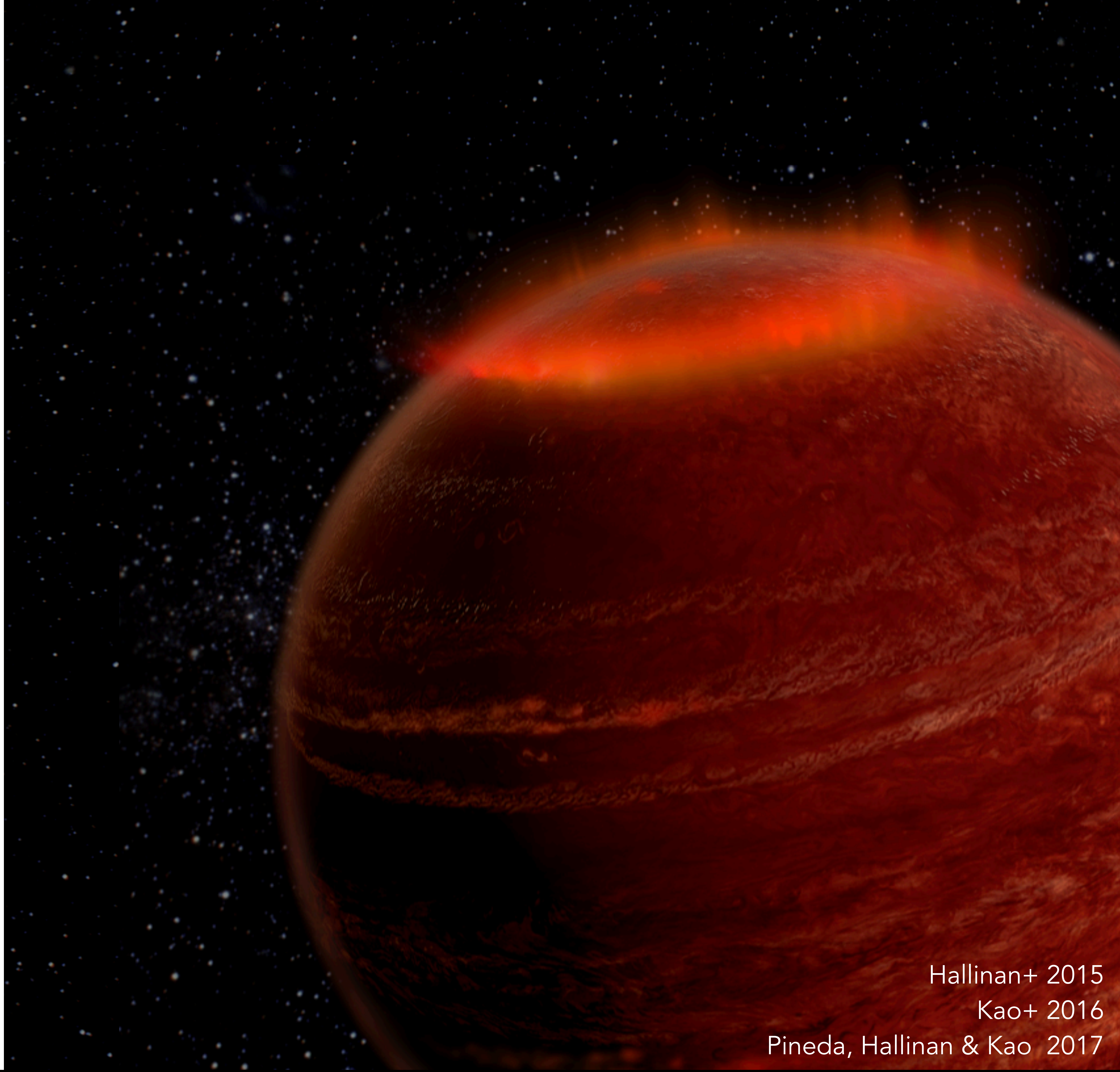
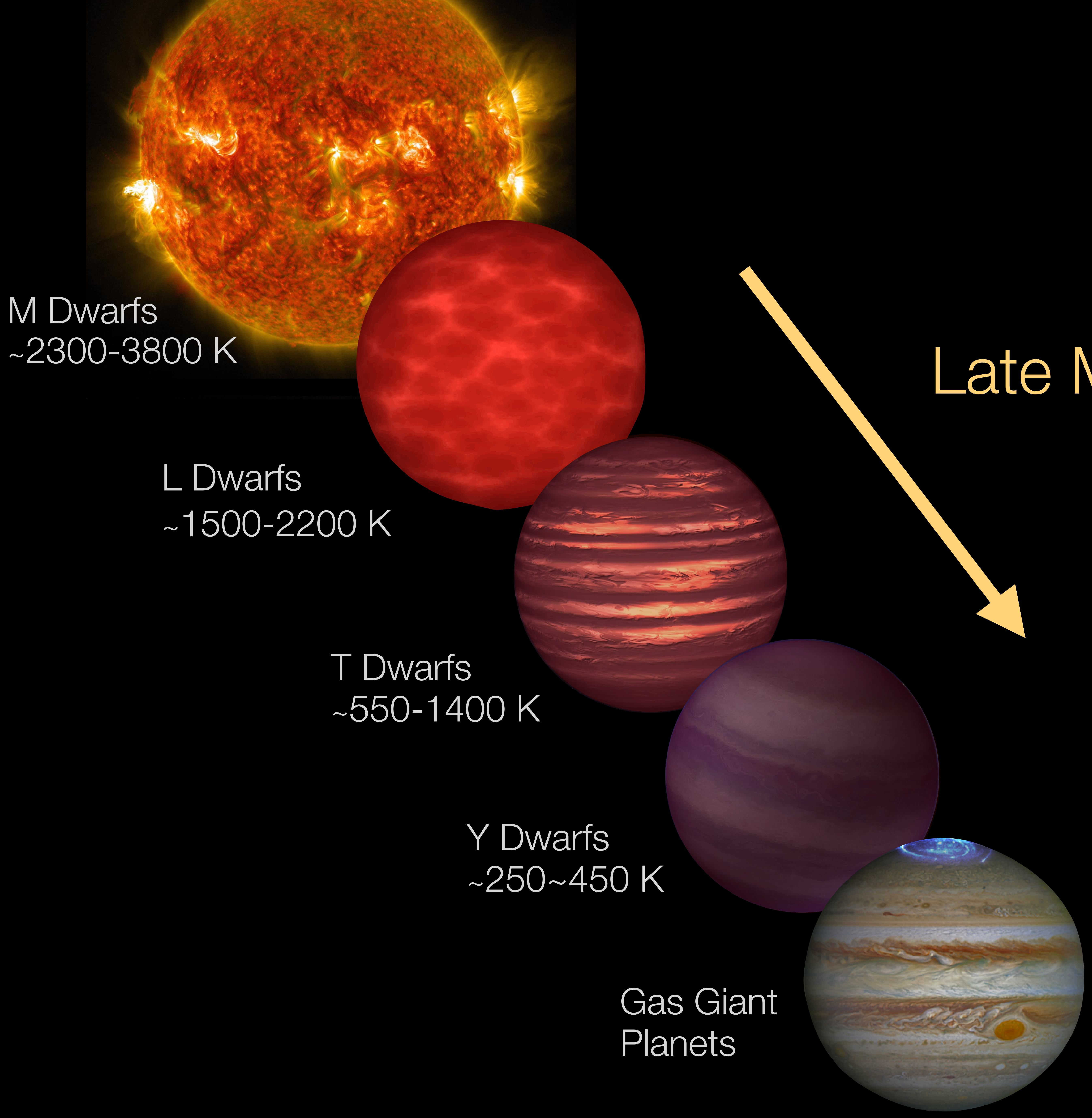


See also: Vedantham+ 2020b, 2023; Rose+ 2023

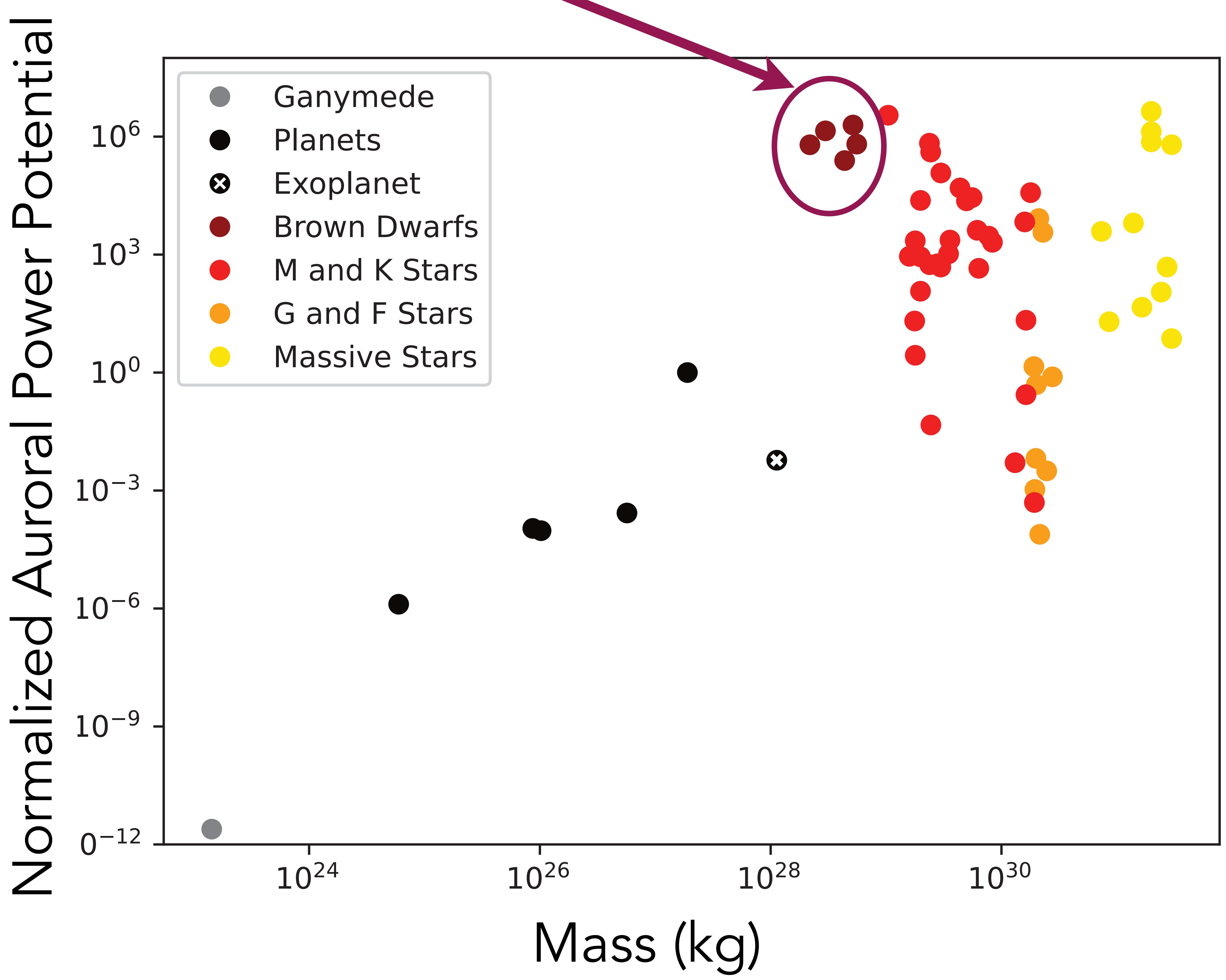




Ultracool dwarfs:
Late M dwarf through brown dwarfs

Melodie Kao (mkao@lowell.edu)

Brown dwarfs: high potential to power aurorae.



$$S \propto B_{\mathrm{host}}^2 \; \Omega_{\mathrm{host}}^2 \; R_{\mathrm{host}}^2$$

Power dissipated

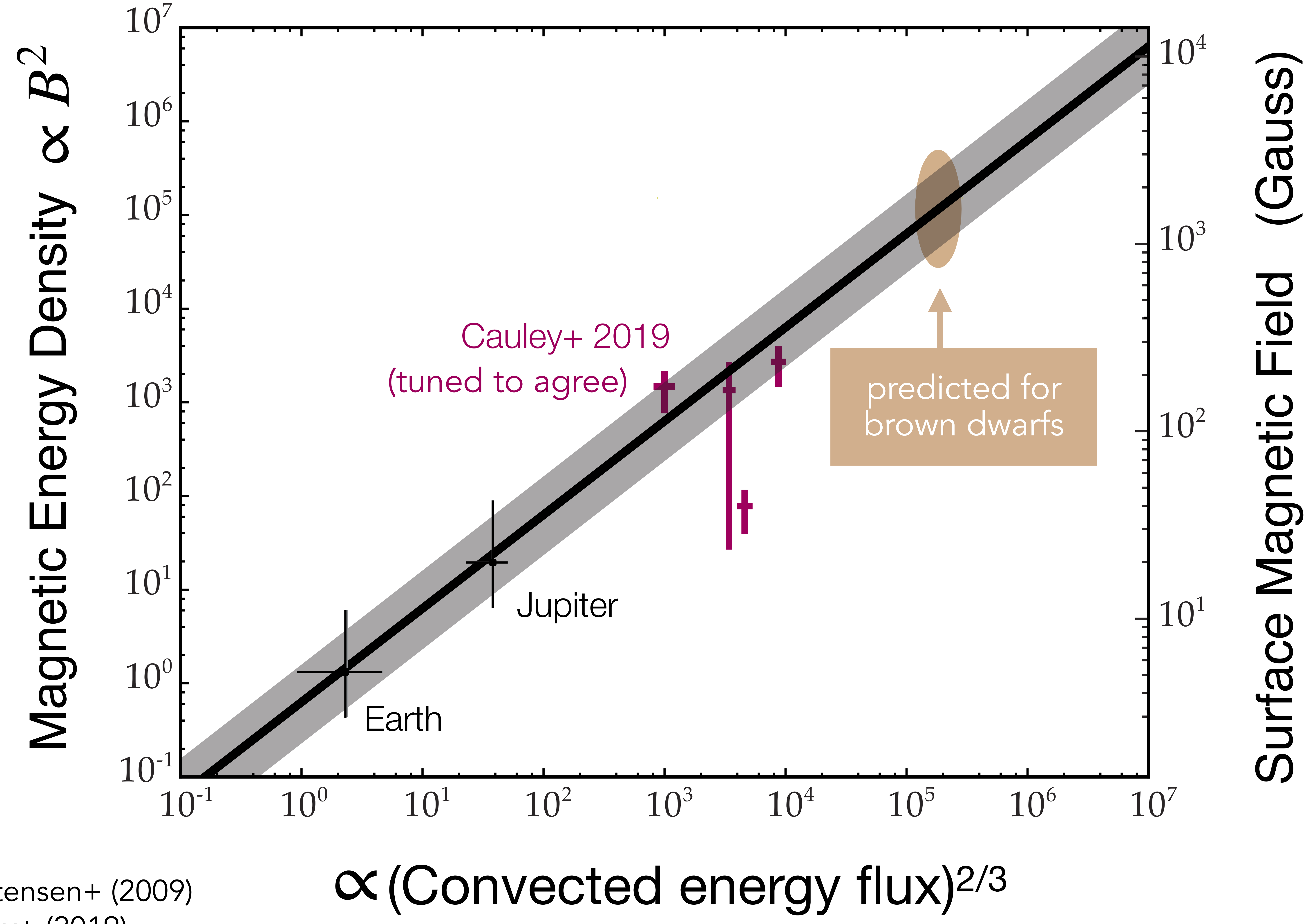
auroral host's polar magnetic field

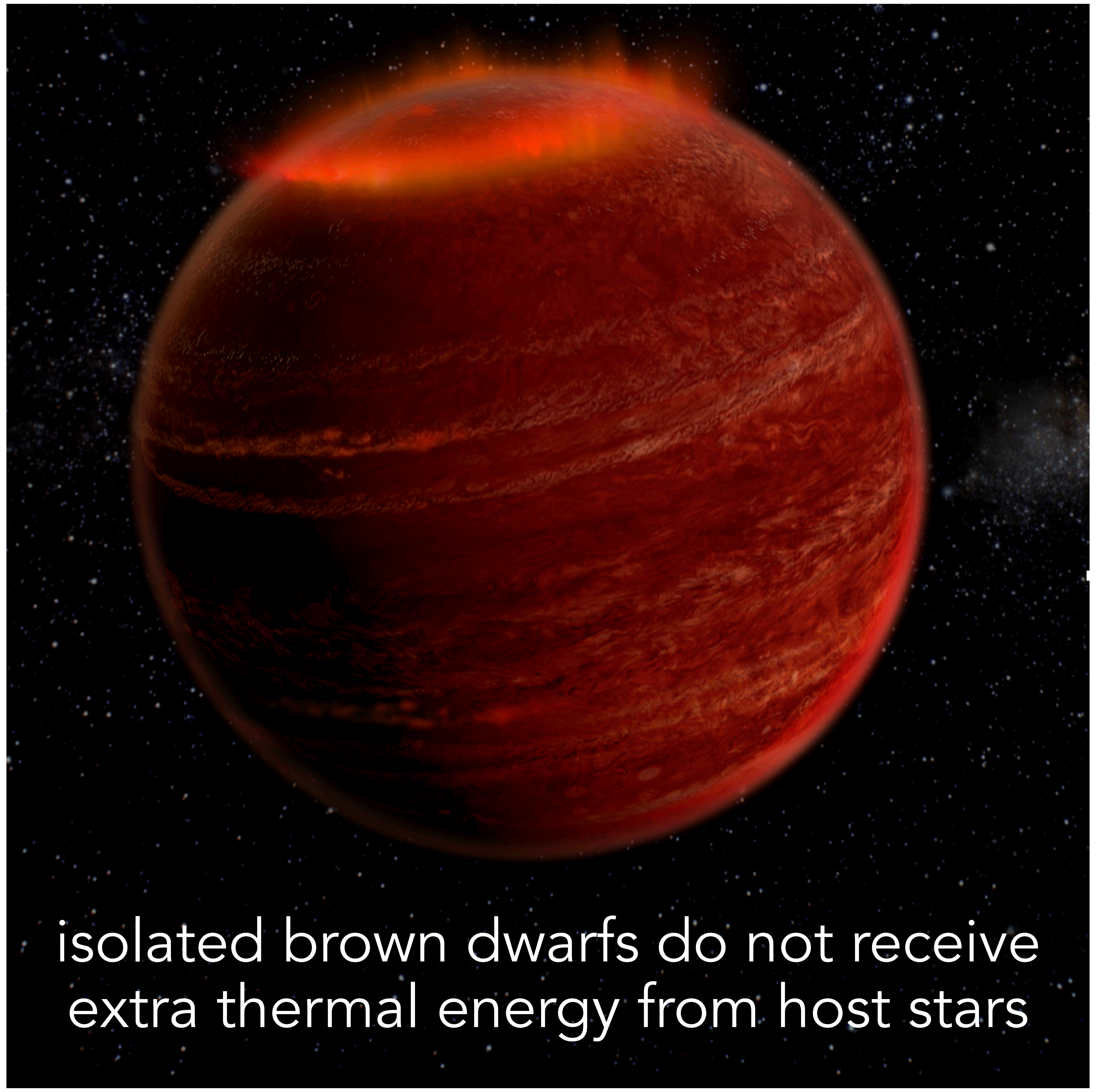
auroral host's angular velocity

auroral host's radius

Saur+ 2021

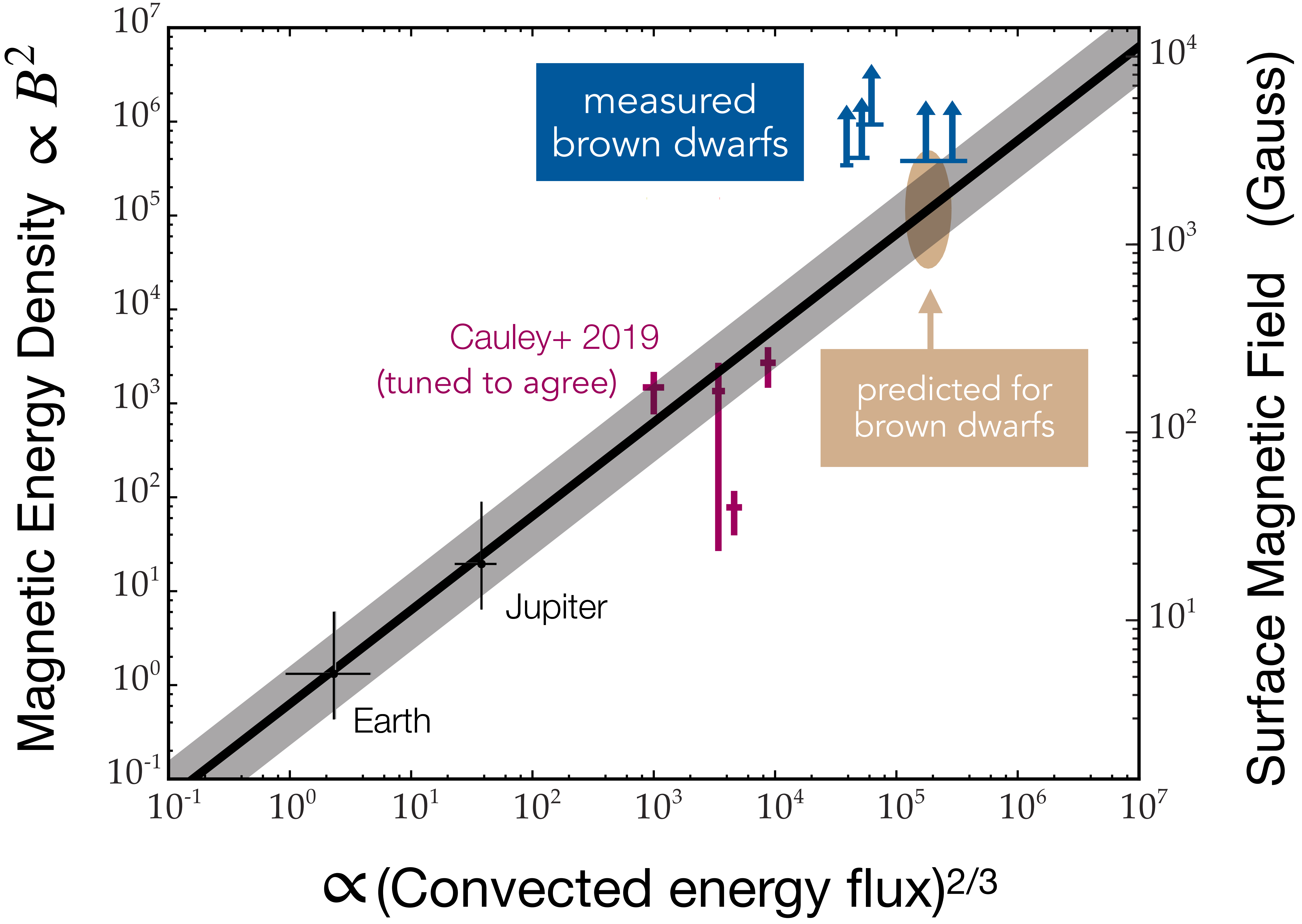
Convected thermal energy sets magnetic field?

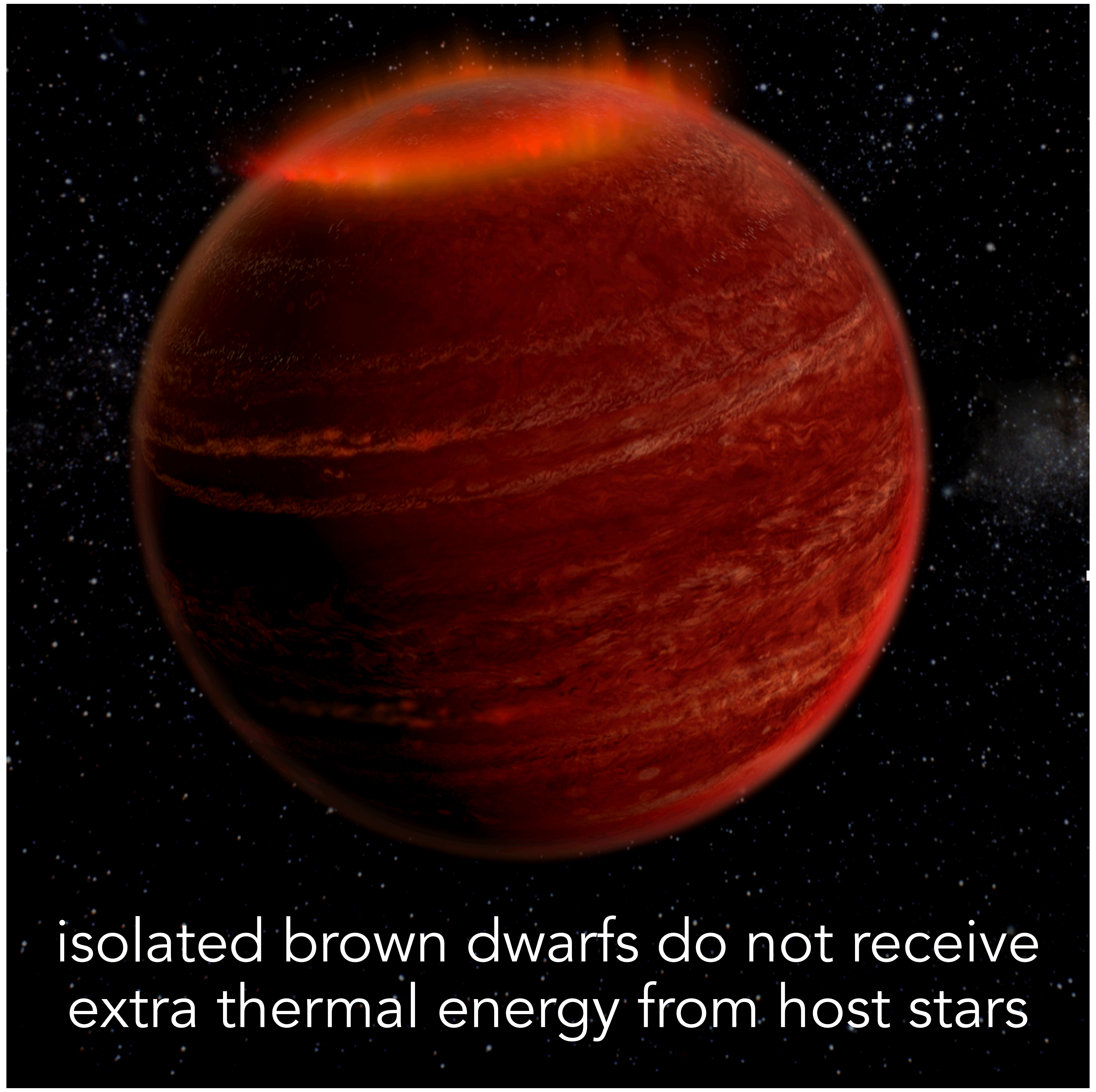




Christensen+ (2009)
Cauley+ (2019)
Yadav & Thorngren (2017)

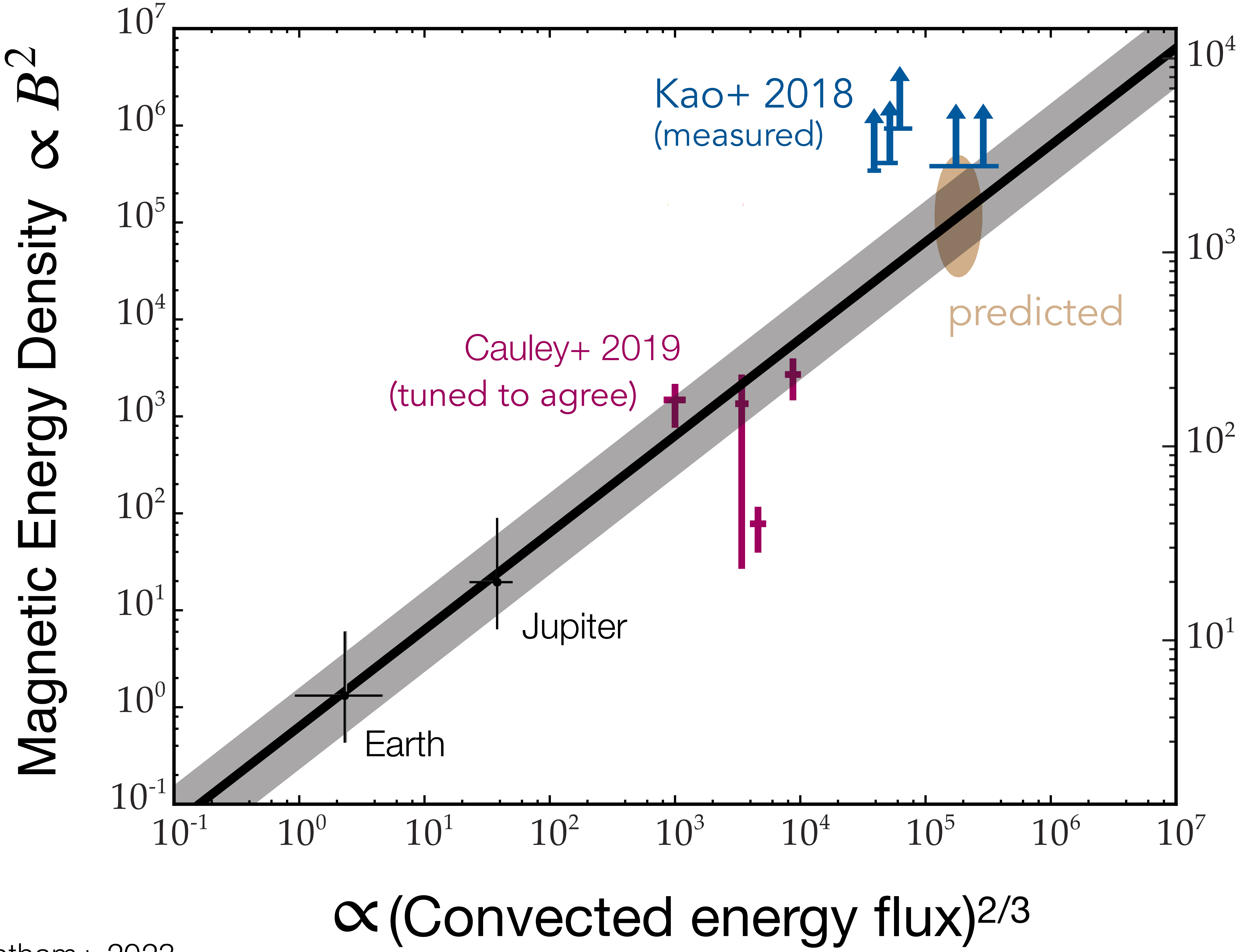
Convected thermal energy sets magnetic field? **Maybe not.**

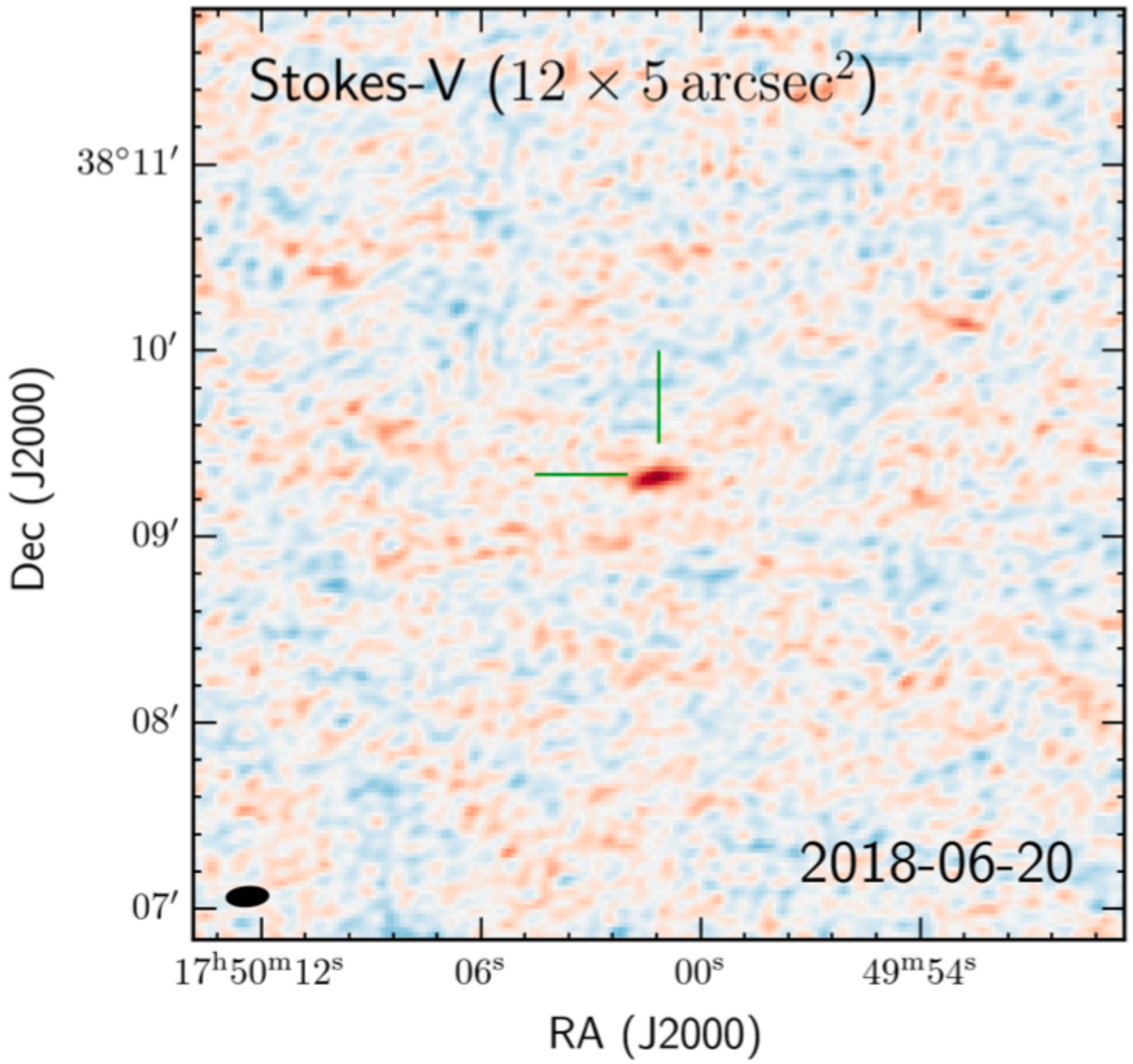




Kao+ (2018)

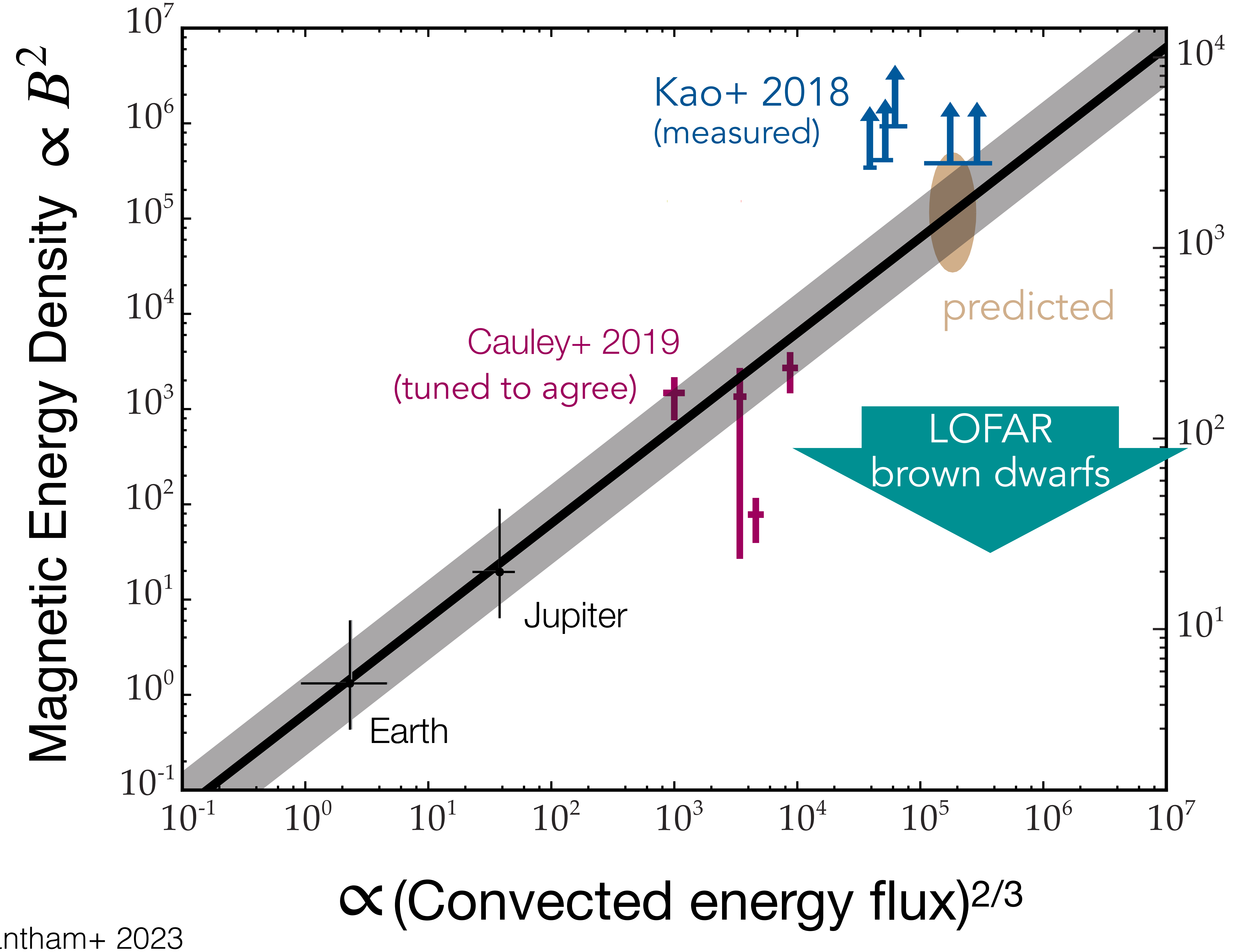
Some brown dwarfs strongly magnetized, others not. **Why?**

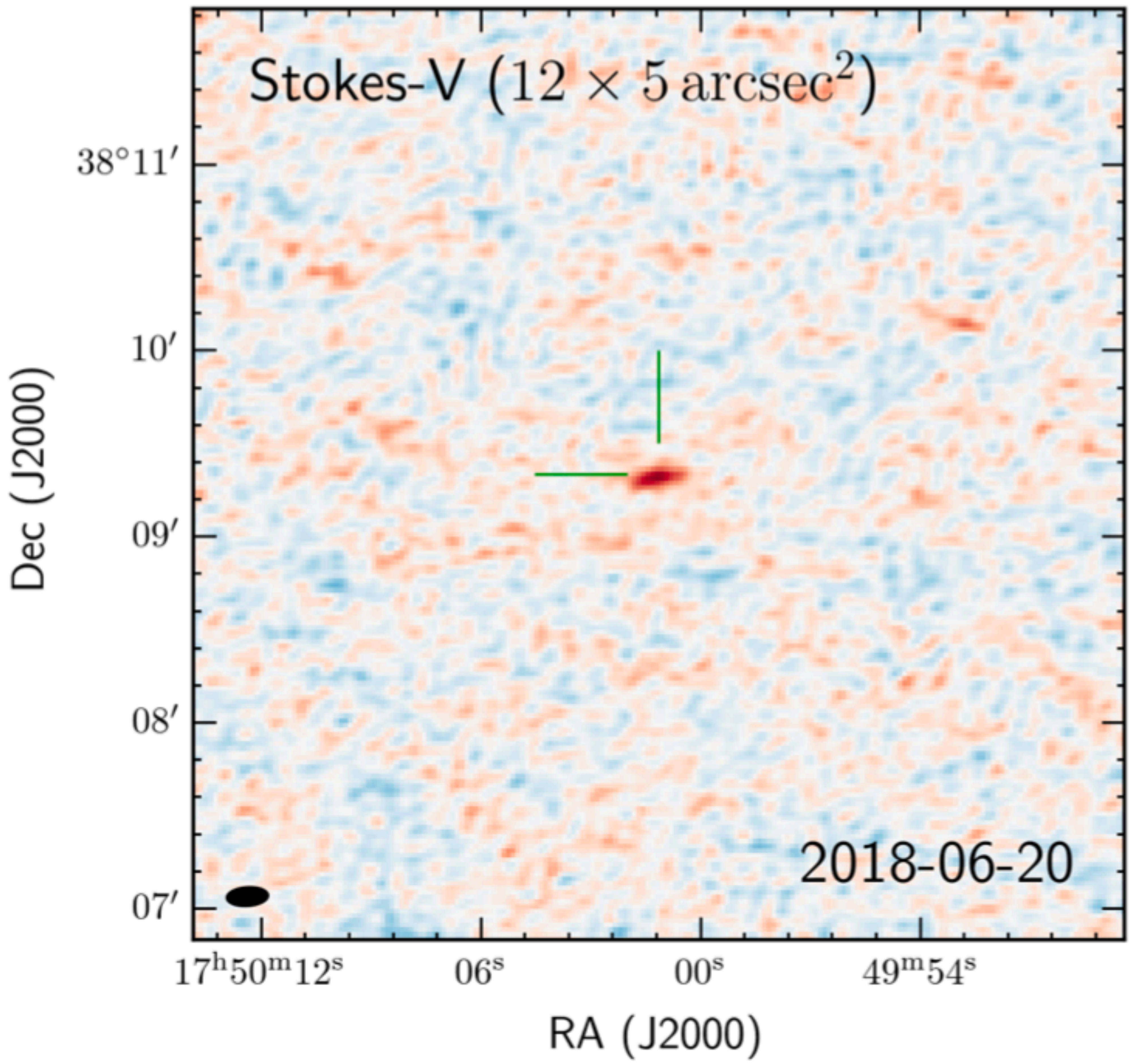




Vedantham+ 2023
Vedantham+ 2020b

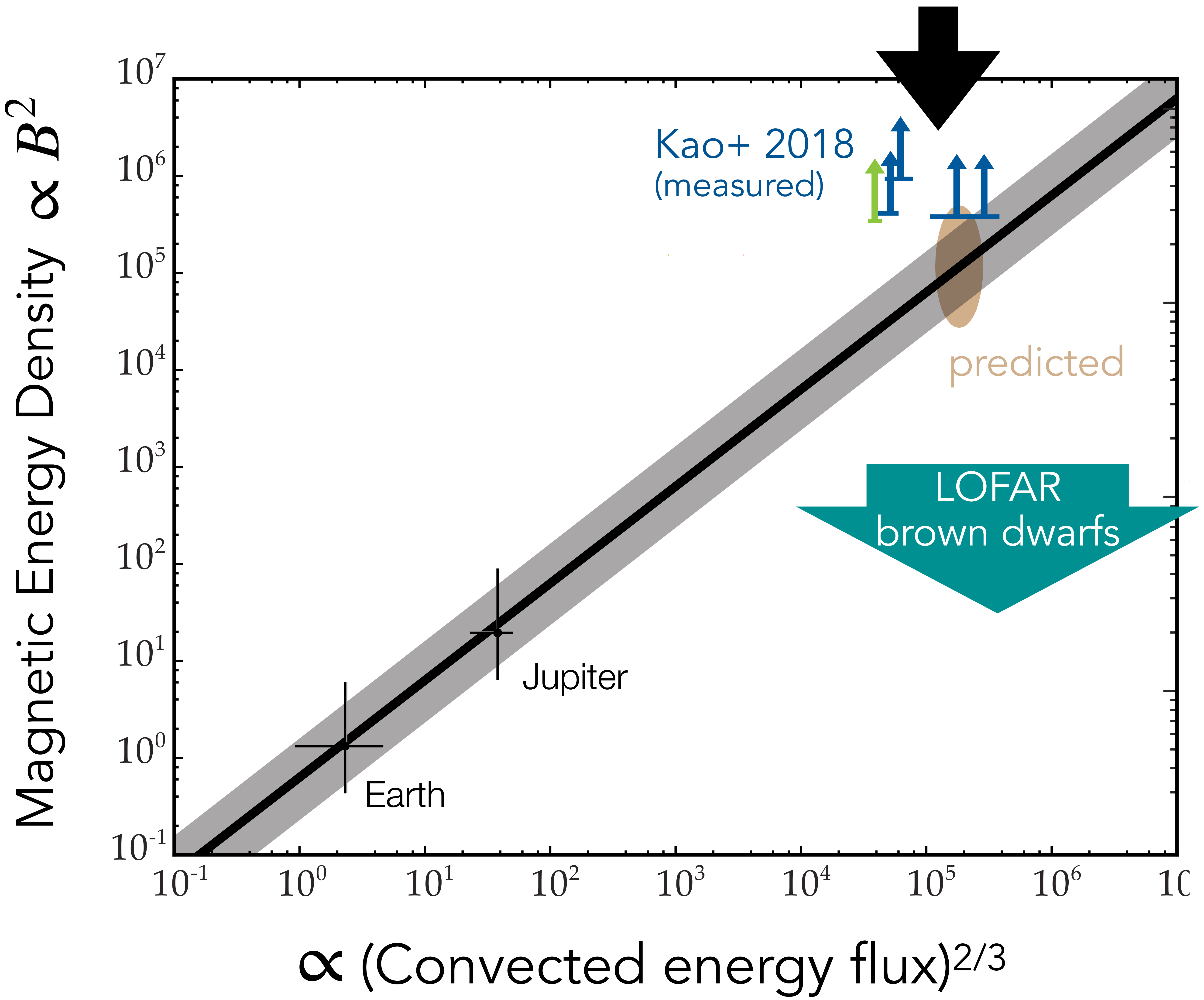
Some brown dwarfs strongly magnetized, others not. **Why?**

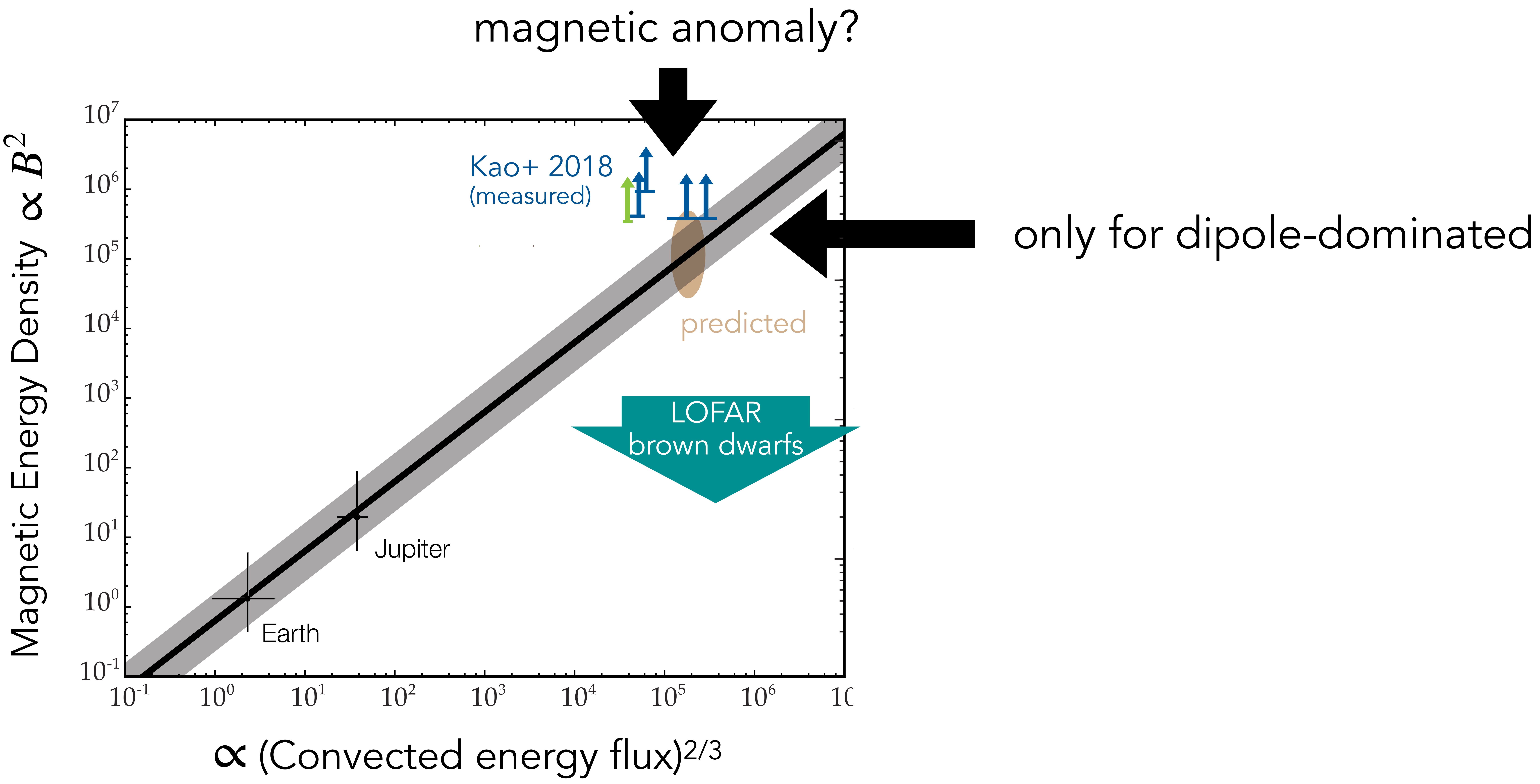




Vedantham+ 2023
Vedantham+ 2020b

magnetic anomaly?





magnetic anomaly?
only for dipole-dominated
Kao+ 2018
(measured)
predicted
LOFAR
brown dwarfs
Jupiter
Earth
Magnetic Energy Density ∝ B^2
∝ (Convected energy flux)$^{2/3}$
10^{-1}
10^{0}
10^{1}
10^{2}
10^{3}
10^{4}
10^{5}
10^{6}
10^{7}

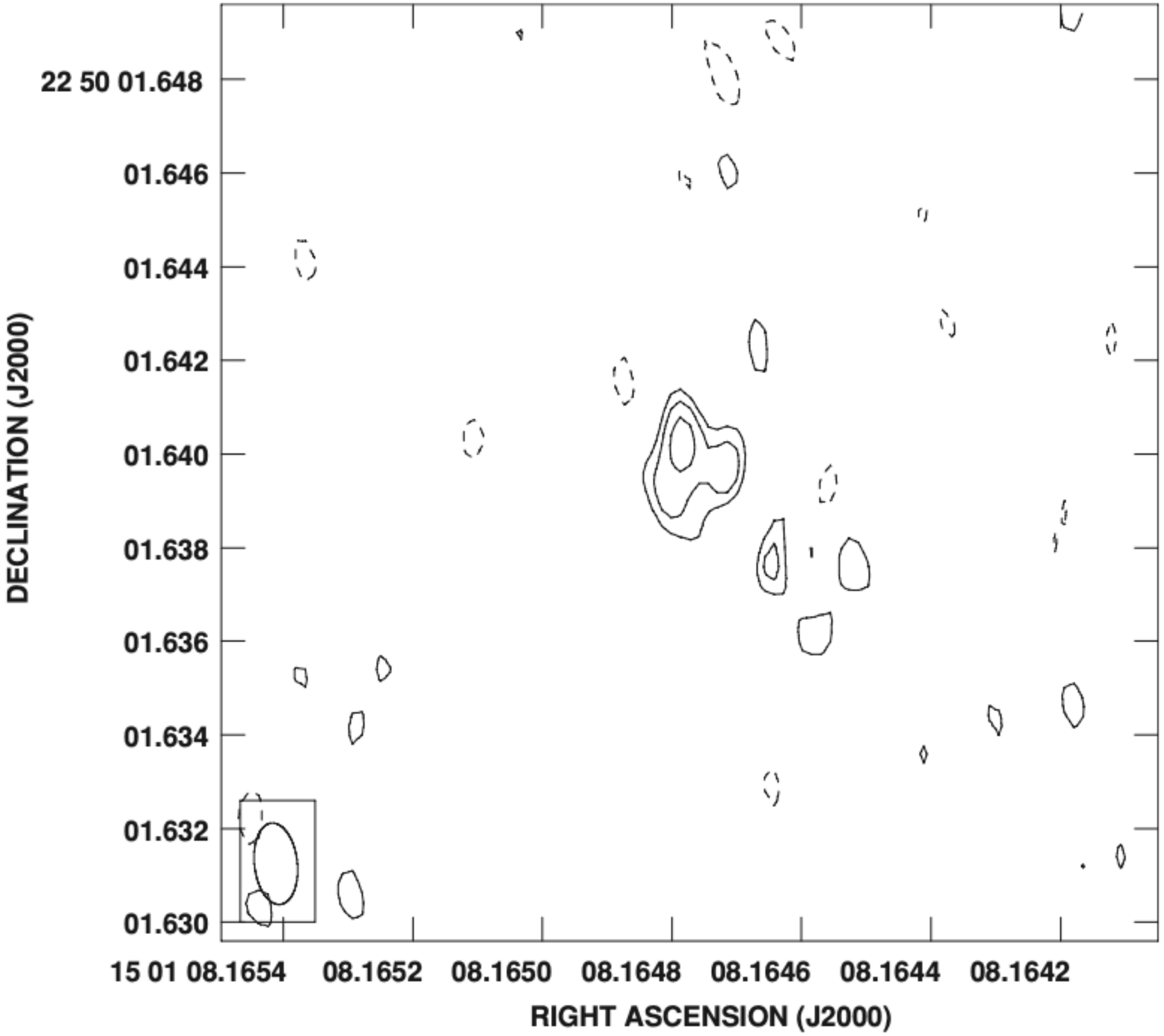
What **shape** are substellar magnetic fields?

What **shape** are substellar magnetic fields?

→ see Rob Kavanagh’s talk! ←

Radiation belts

TVLM 513-46546

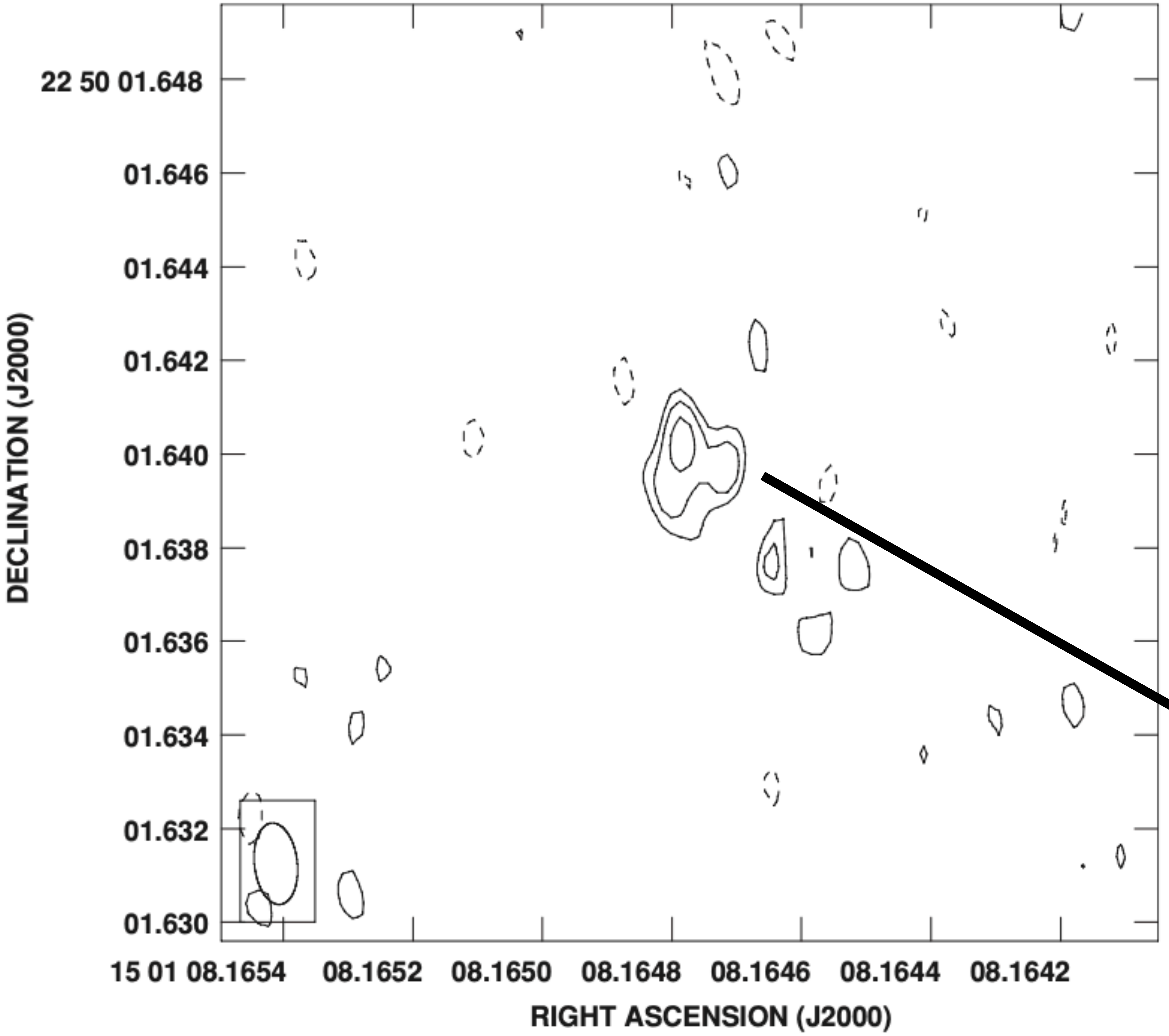


Radio search for companions:

Marginally resolved ~20 R_{UCD}

Forbrich & Berger 2009

TVLM 513-46546



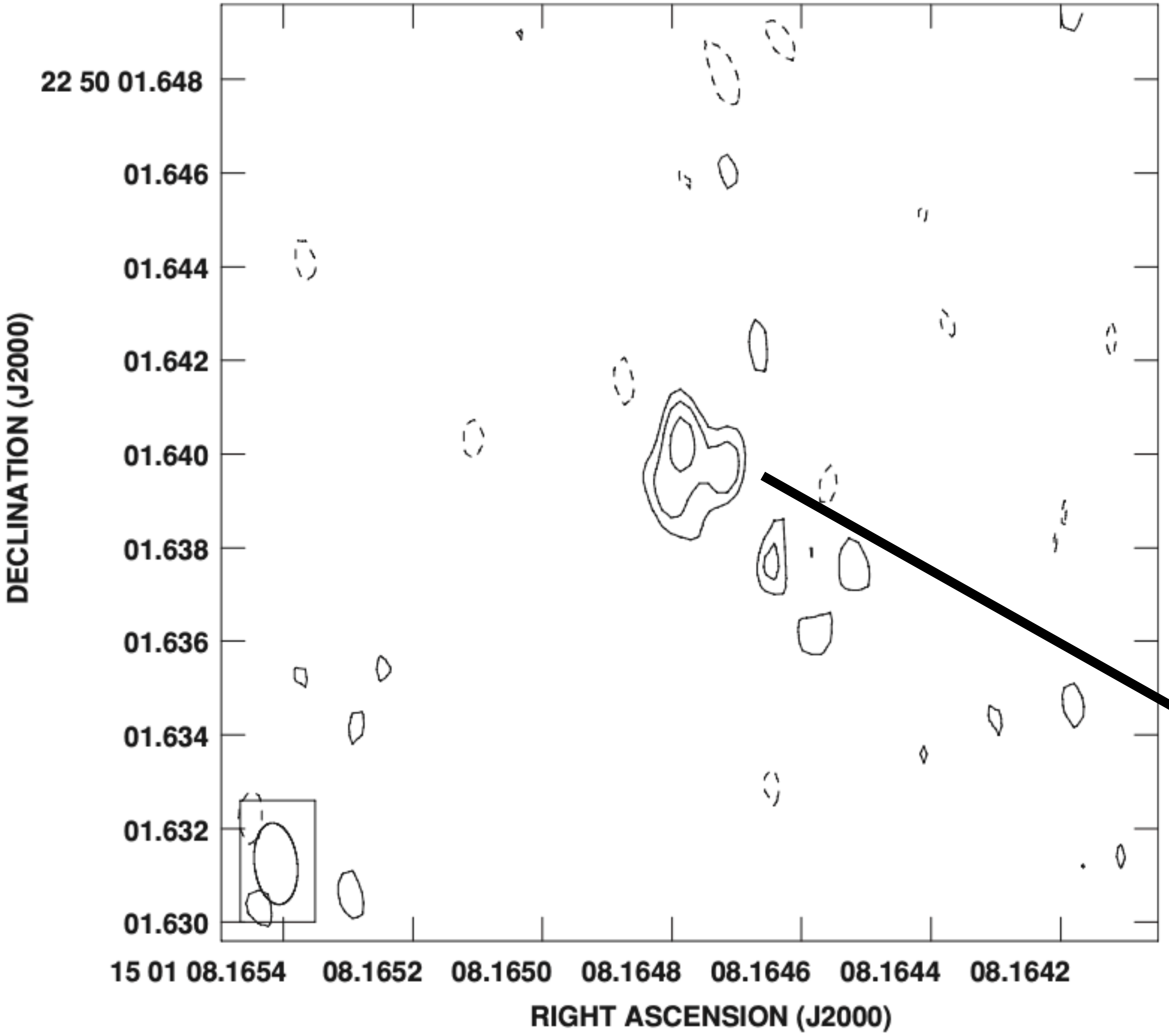
Radio search for companions:
Marginally resolved ~20 R_{UCD}

radiation belt? :-)

Forbrich & Berger 2009

melodie.kao@ucsc.edu

TVLM 513-46546



Radio search for companions:

Marginally resolved ~20 R_{UCD}

closer object

+

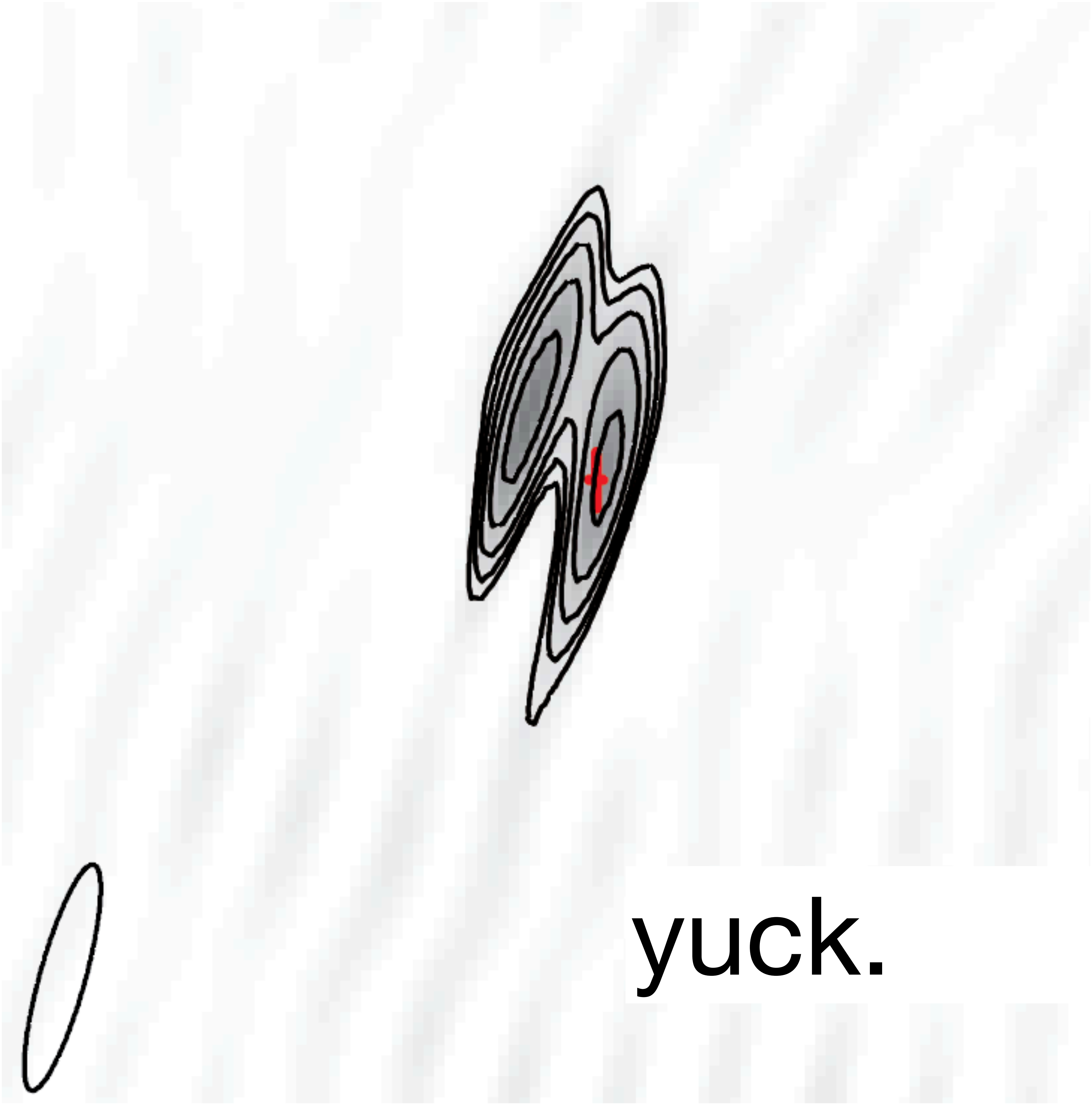
more powerful telescope

Forbrich & Berger 2009

High Sensitivity Array: VLA + VLBA + Greenbank + Effelsburg

Melodie Kao (mkao@lowell.edu)

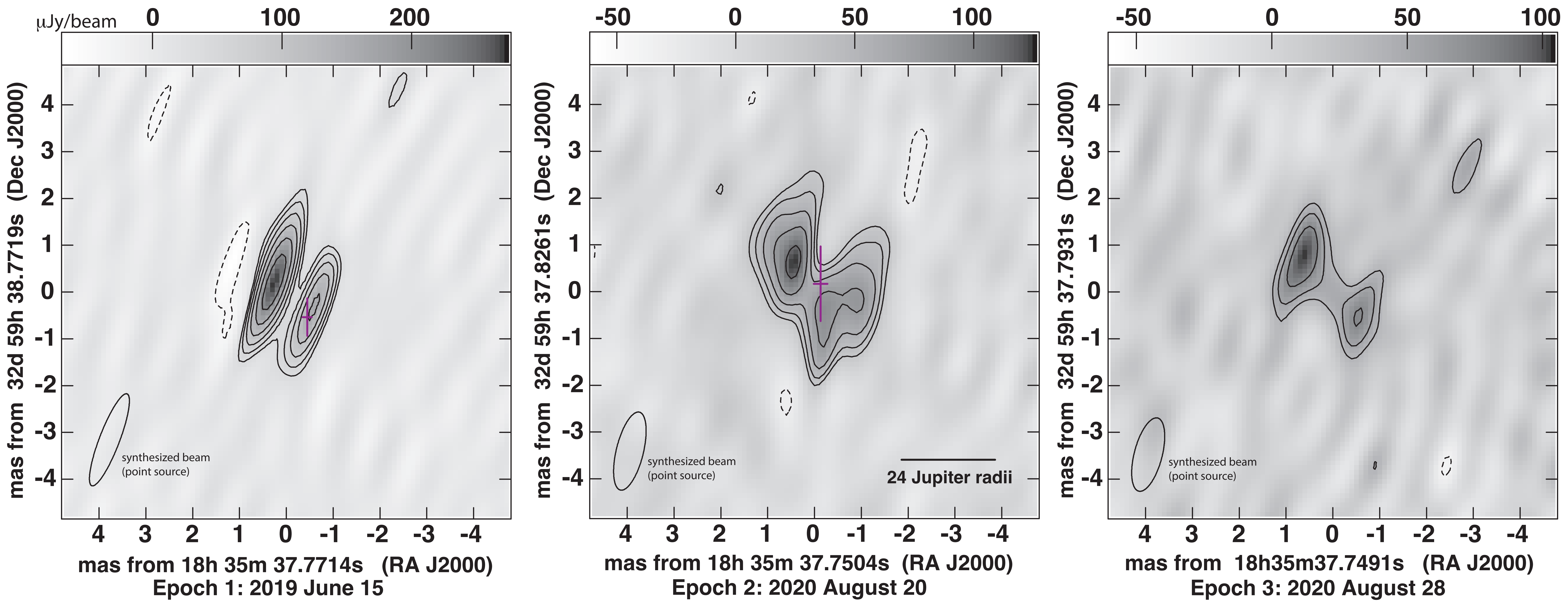
39 Dishes: 27x **25m** 10x **25m** 1x **100m** 1x **100m**



yuck.

Download paper!

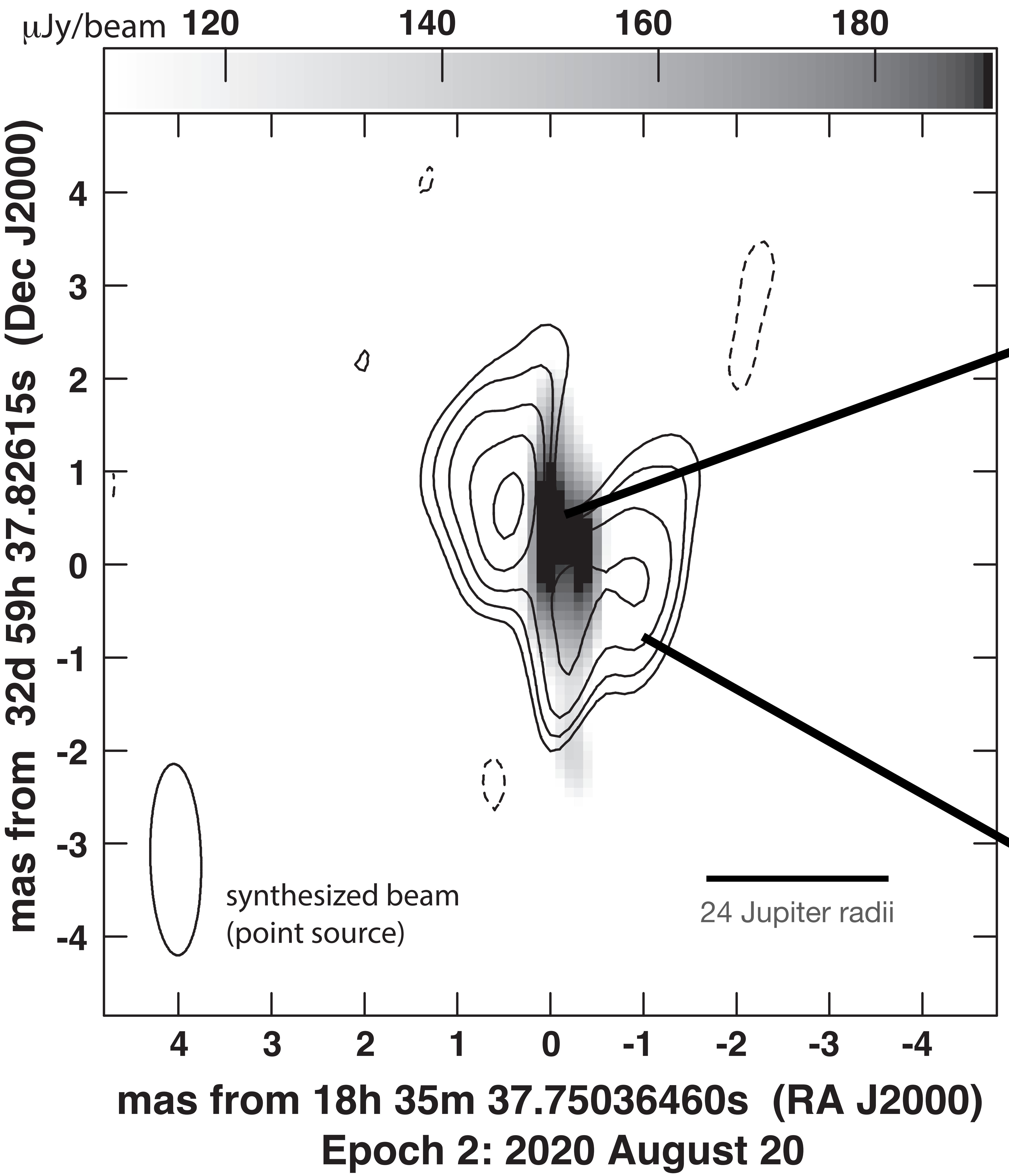
Kao, Mioduszewski, Villadsen & Shkolnik (Nature 2023)



extended + long-lived

Download paper!

Kao, Mioduszewski, Villadsen & Shkolnik (Nature 2023)

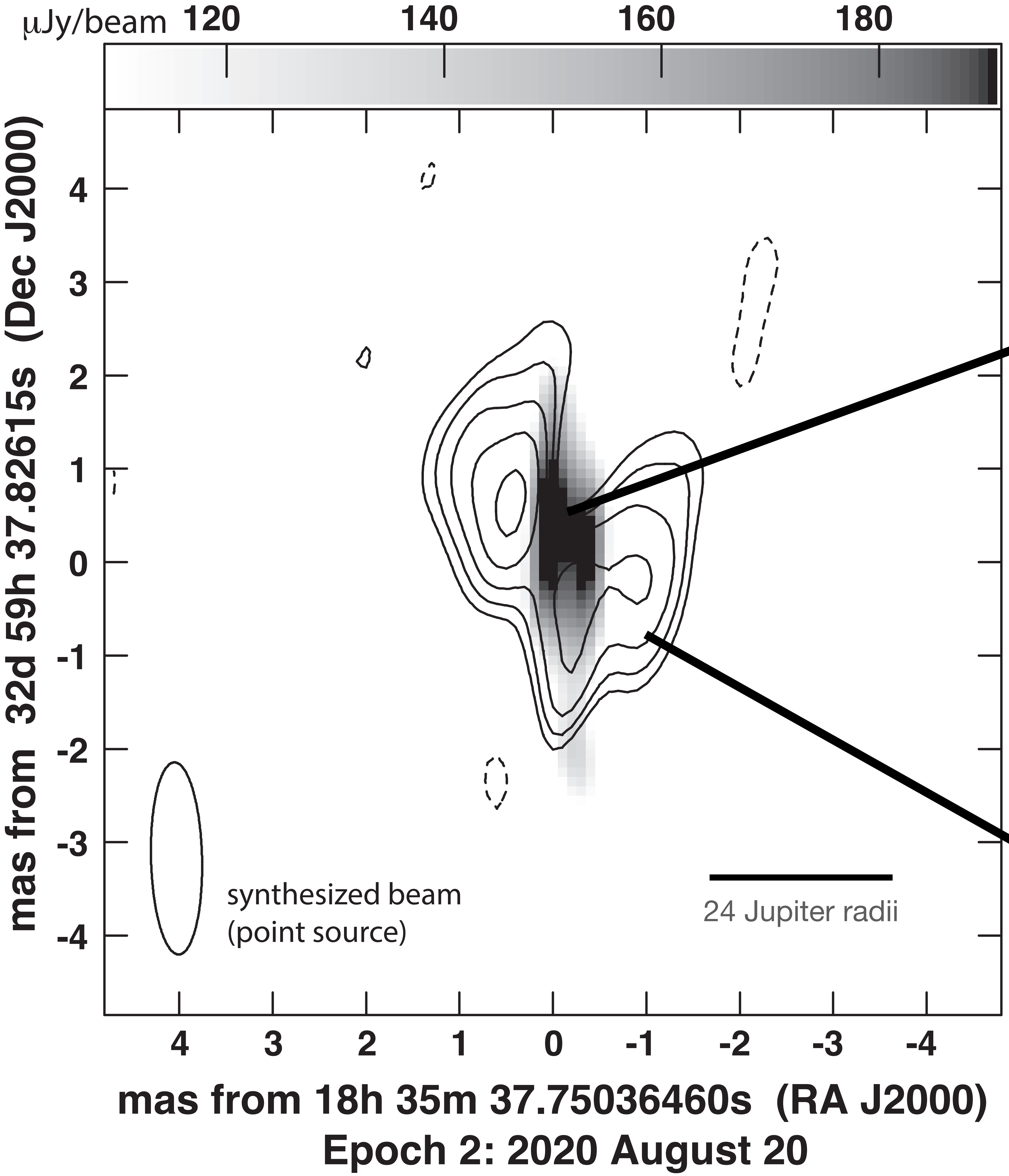


aurorae

3 kiloGauss

not aurorae

Kao, Mioduszewski, Villadsen & Shkolnik (Nature 2023)



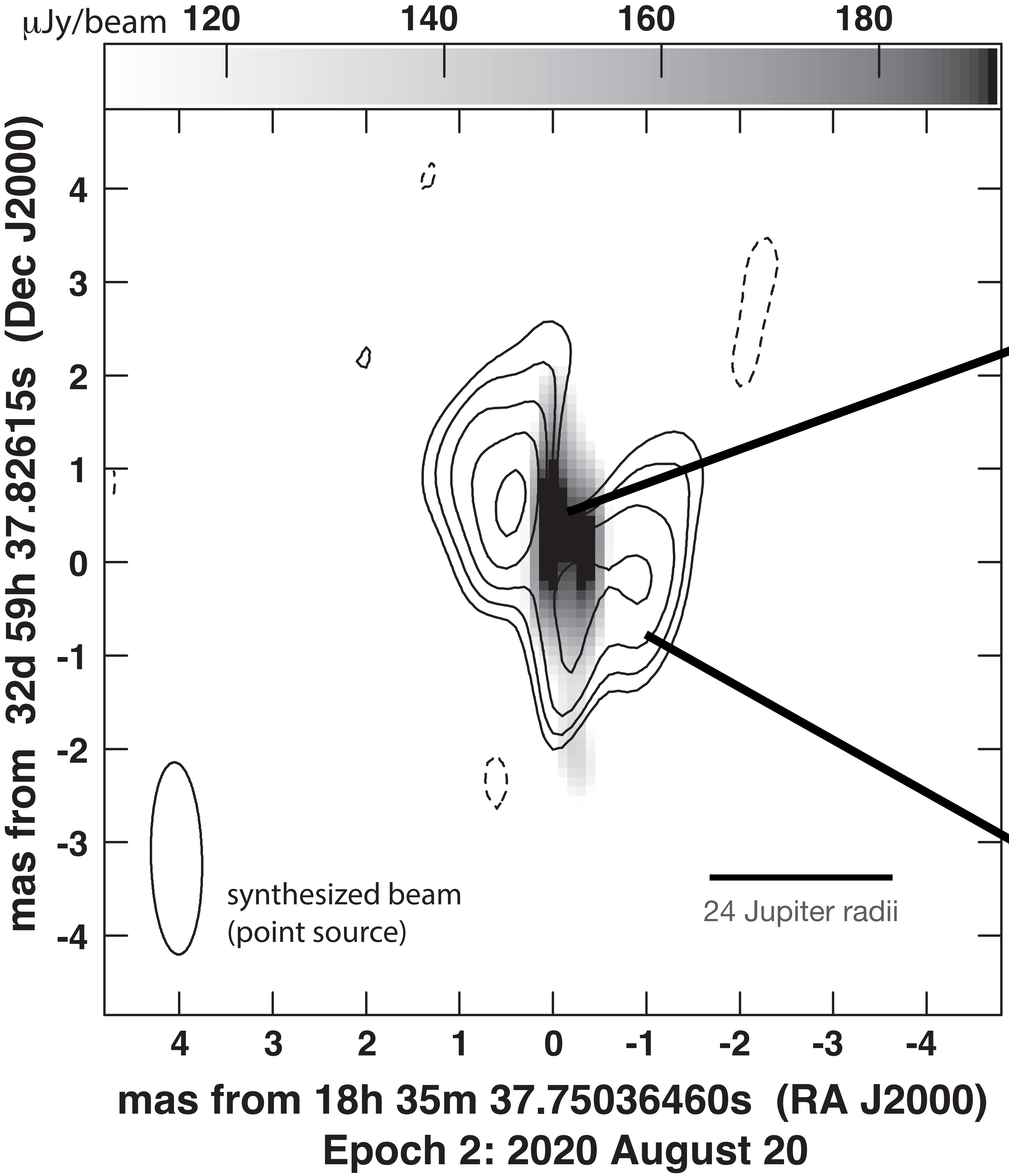
aurorae

3 kiloGauss

not aurorae

@ 2 Gauss

Kao, Mioduszewski, Villadsen & Shkolnik (Nature 2023)



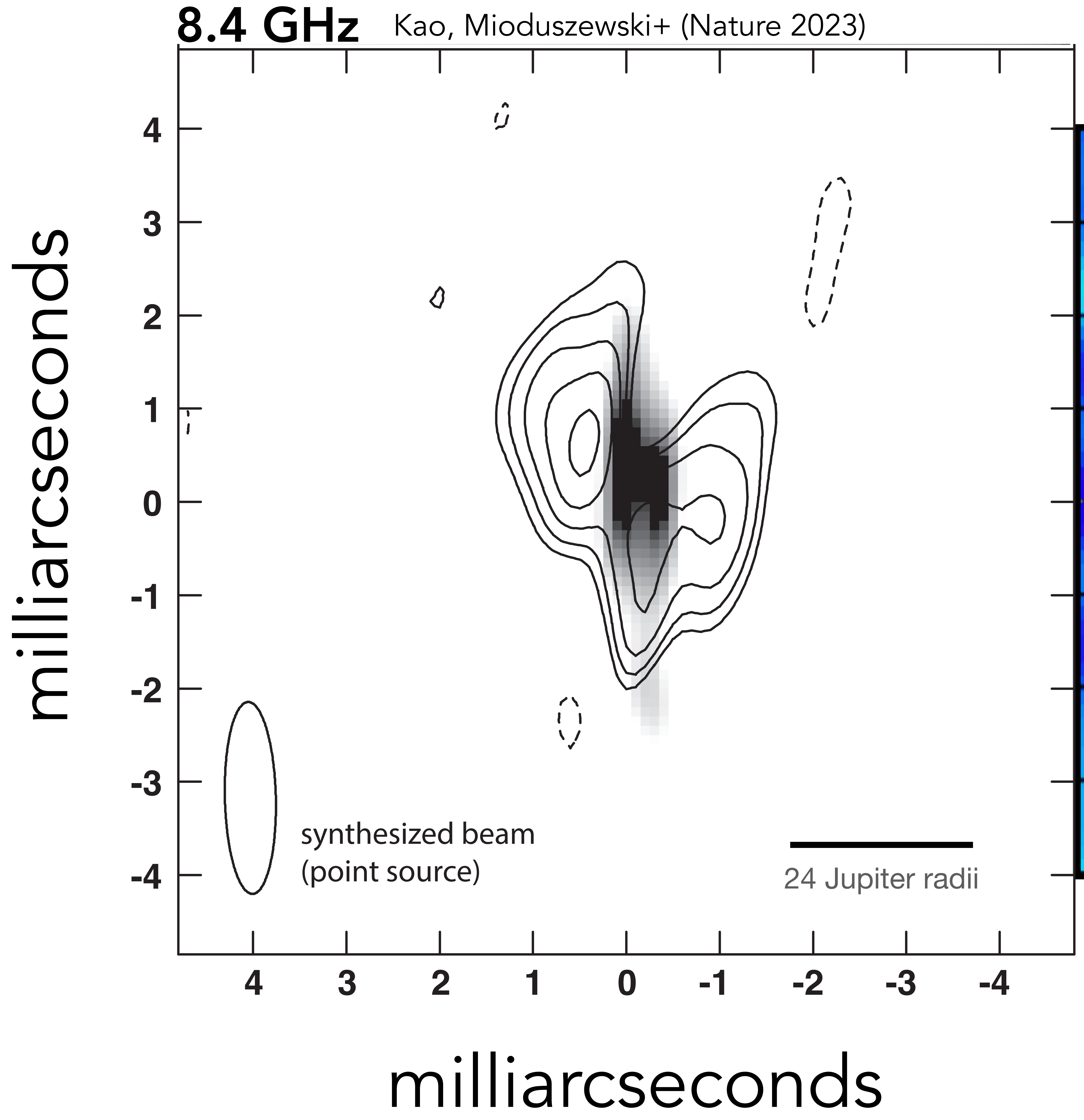
aurorae

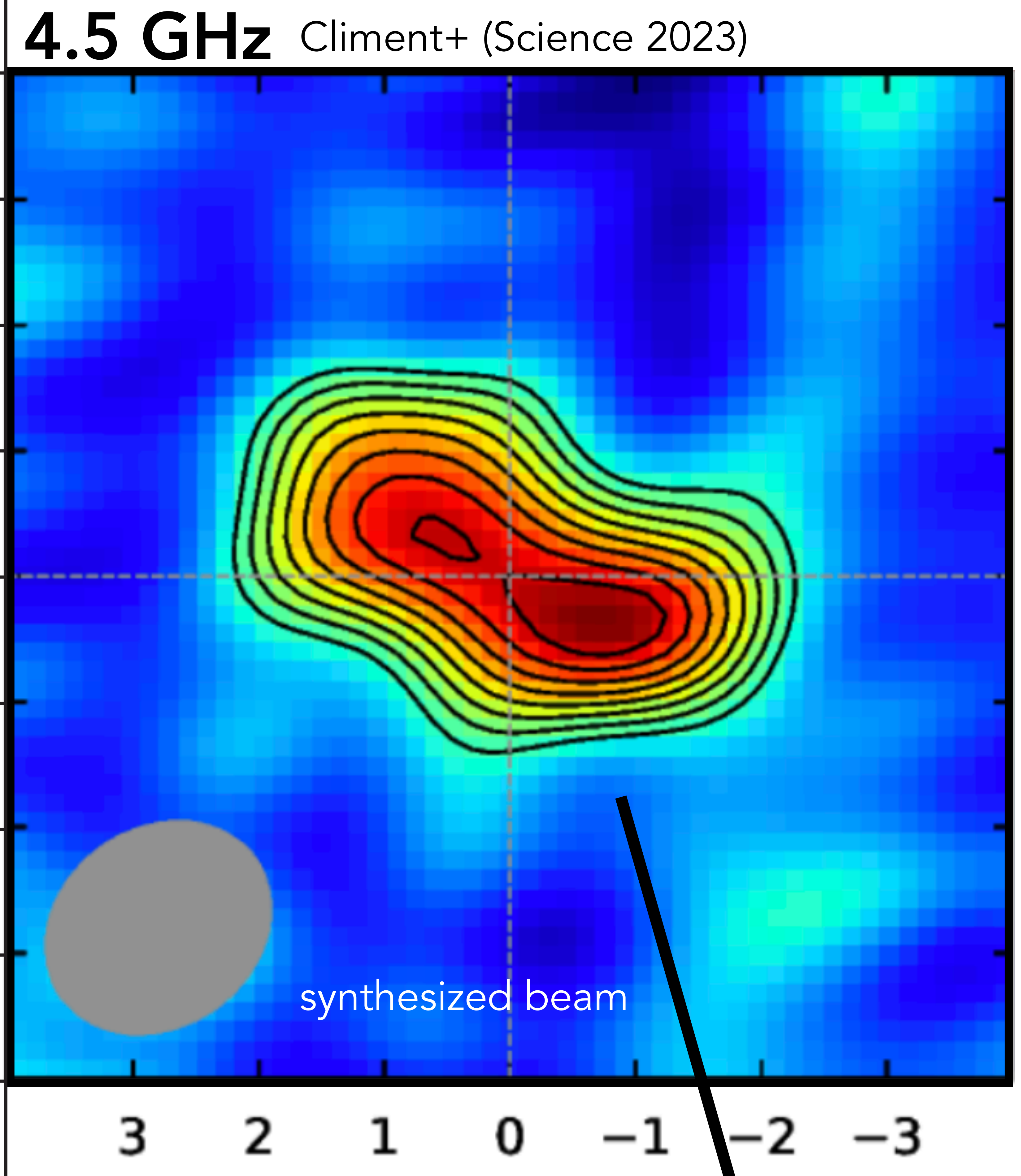
3 kiloGauss

8.4 gigahertz synchrotron @ 2 Gauss

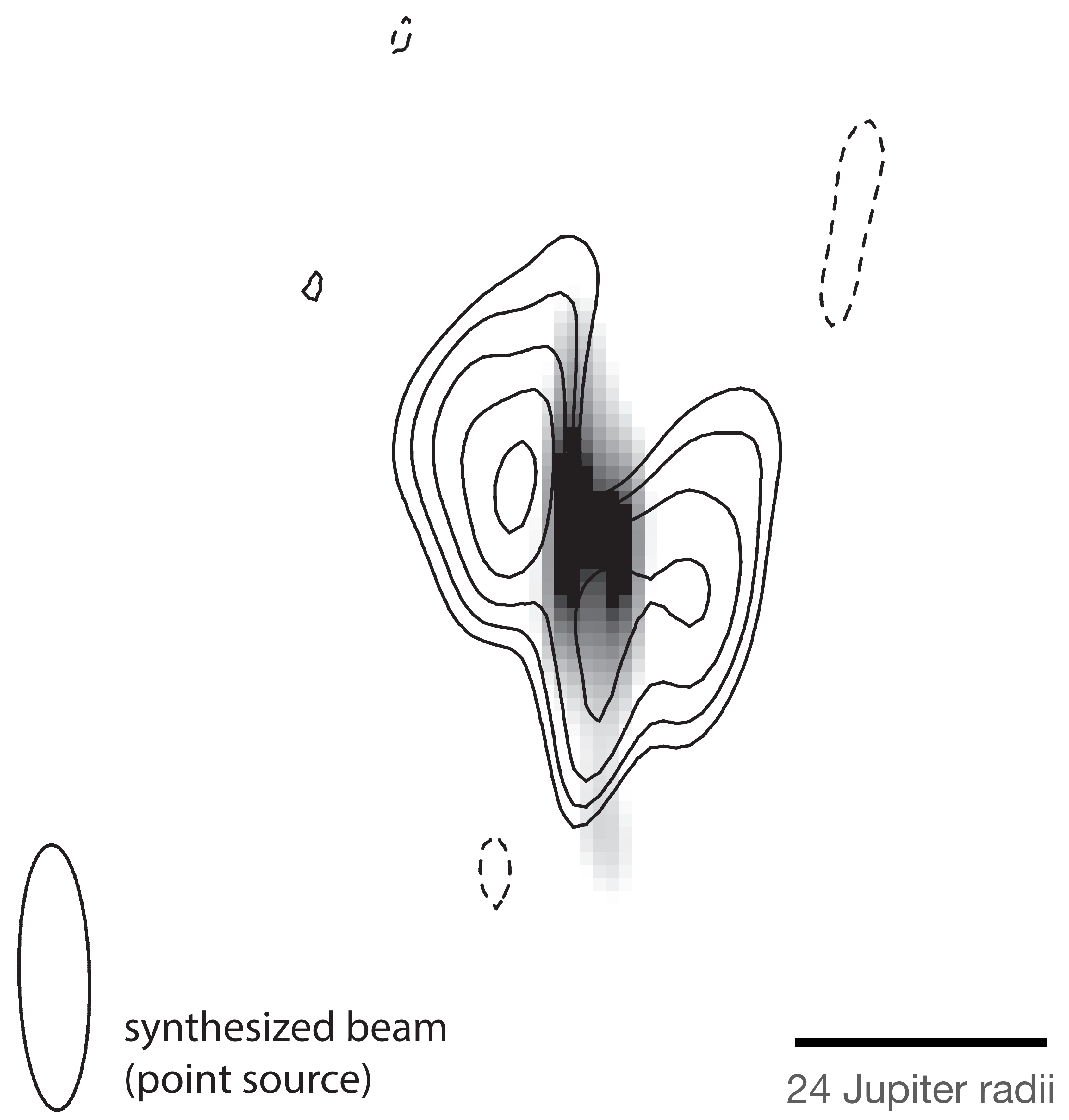
15 MeV

Kao, Mioduszewski, Villadsen & Shkolnik (Nature 2023)

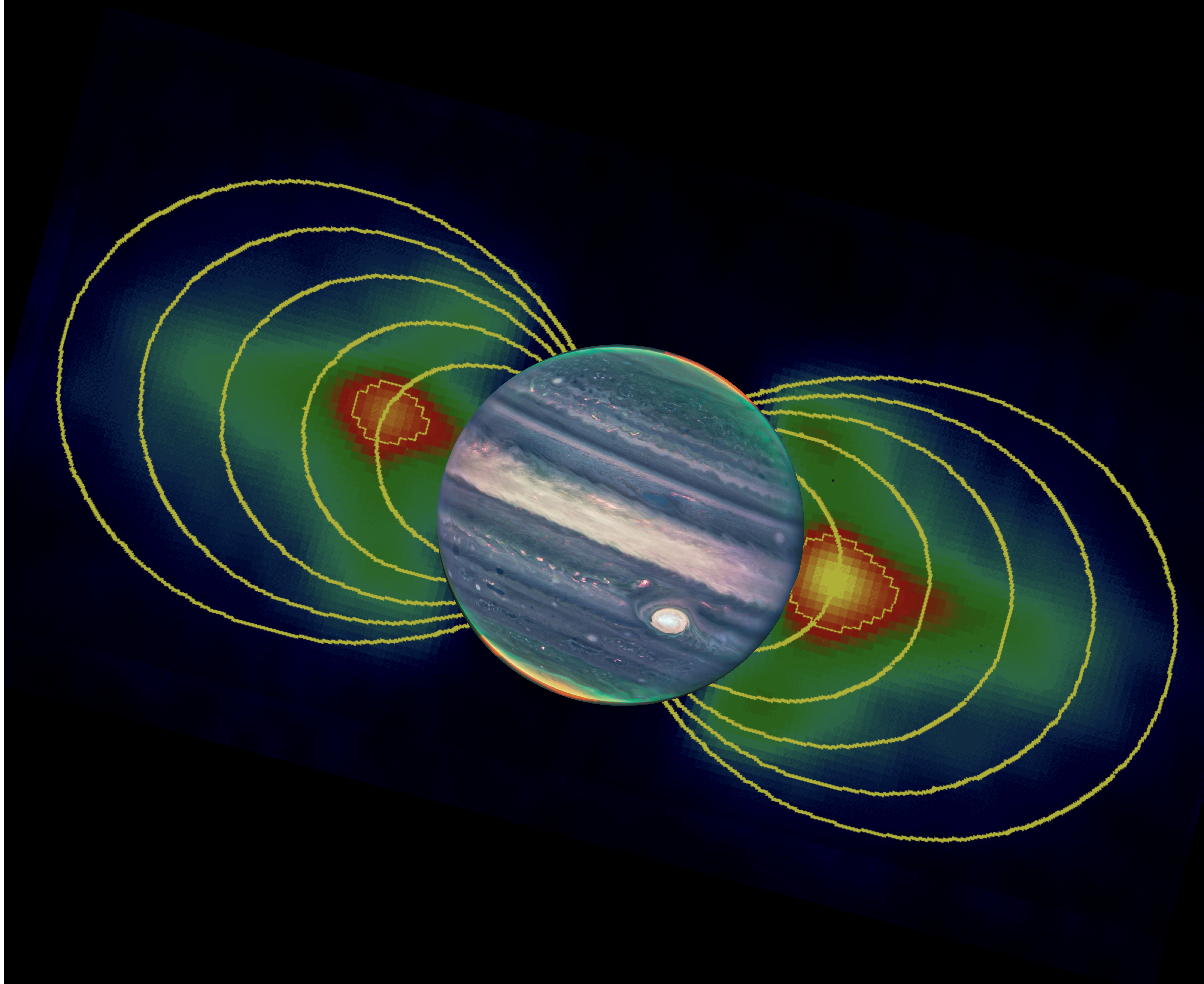




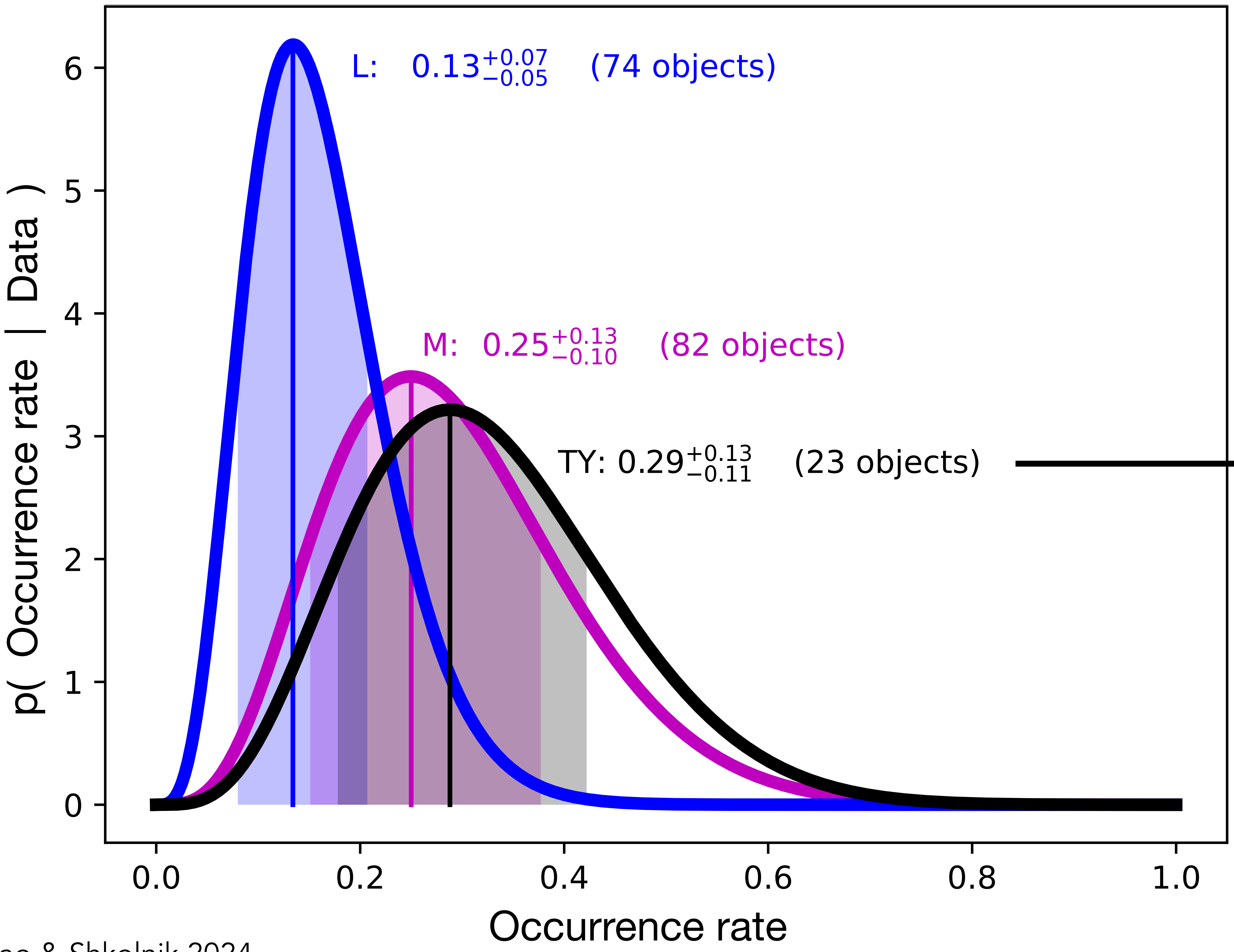
See J. B. Climent Oliver's talk!



Kao, Mioduszewski, Villadsen & Shkolnik (Nature 2023)
see also: Climent+ (Science 2023)



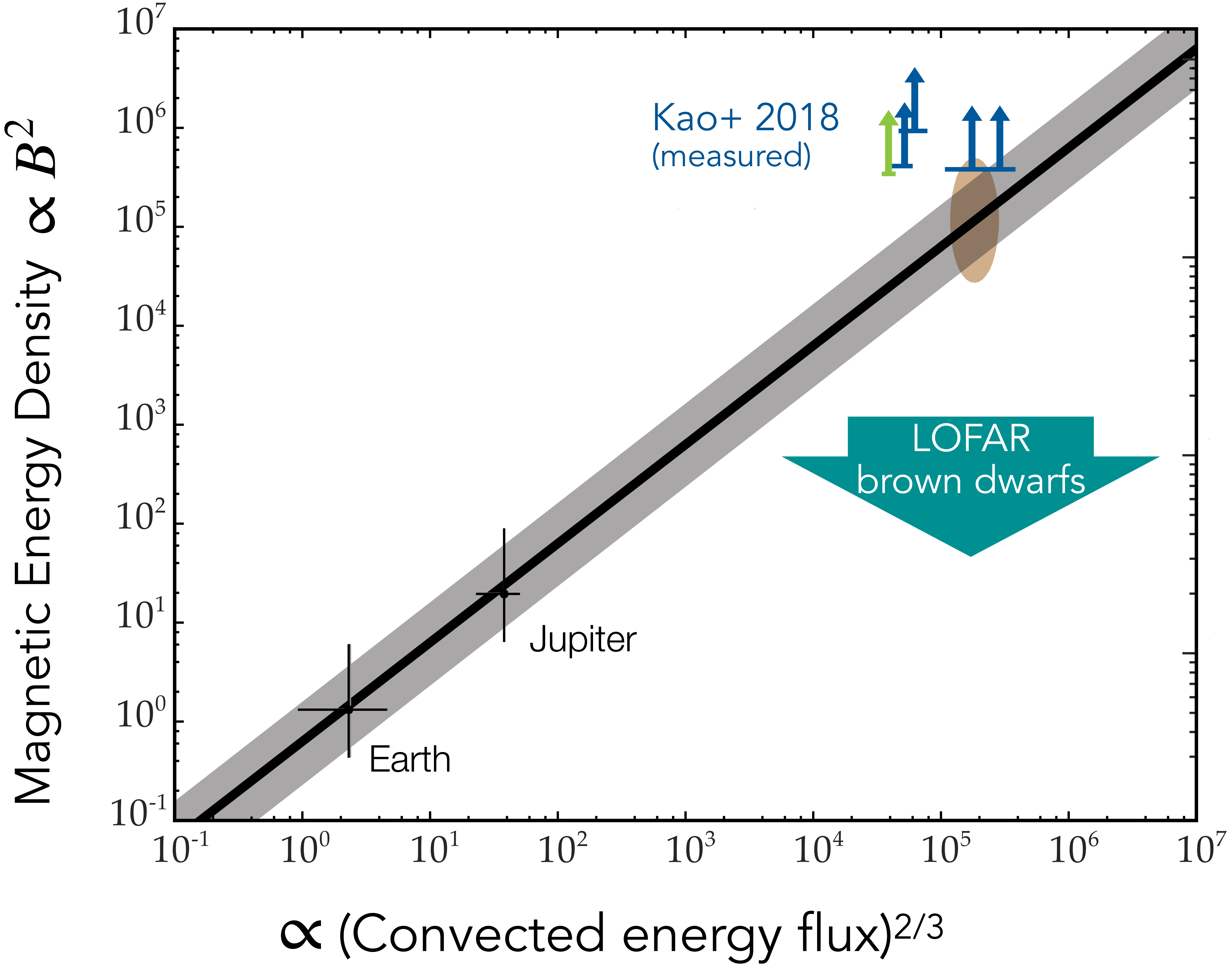
IR aurora - NASA, ESA, CSA, Jupiter ERS Team
radiation belt - Bolton+ 2004



~30% have radiation belts

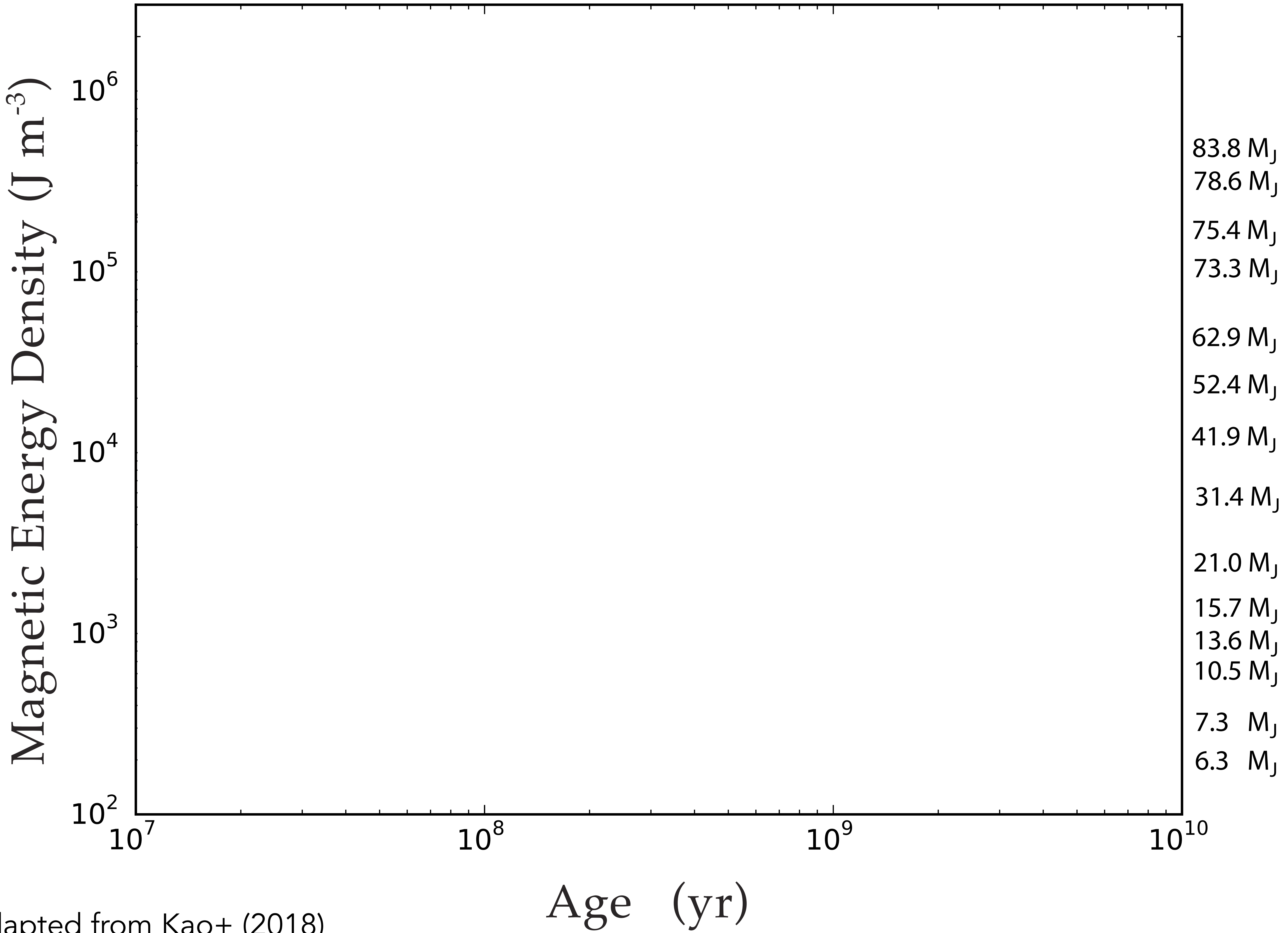
Kao & Shkolnik 2024

mkao@lowell.edu



Magnetic Energy Density ∝ B^2
∝ (Convected energy flux)$^{2/3}$
Kao+ 2018
(measured)
LOFAR
brown dwarfs
Jupiter
Earth
10^{-1}
10^{0}
10^{1}
10^{2}
10^{3}
10^{4}
10^{5}
10^{6}
10^{7}

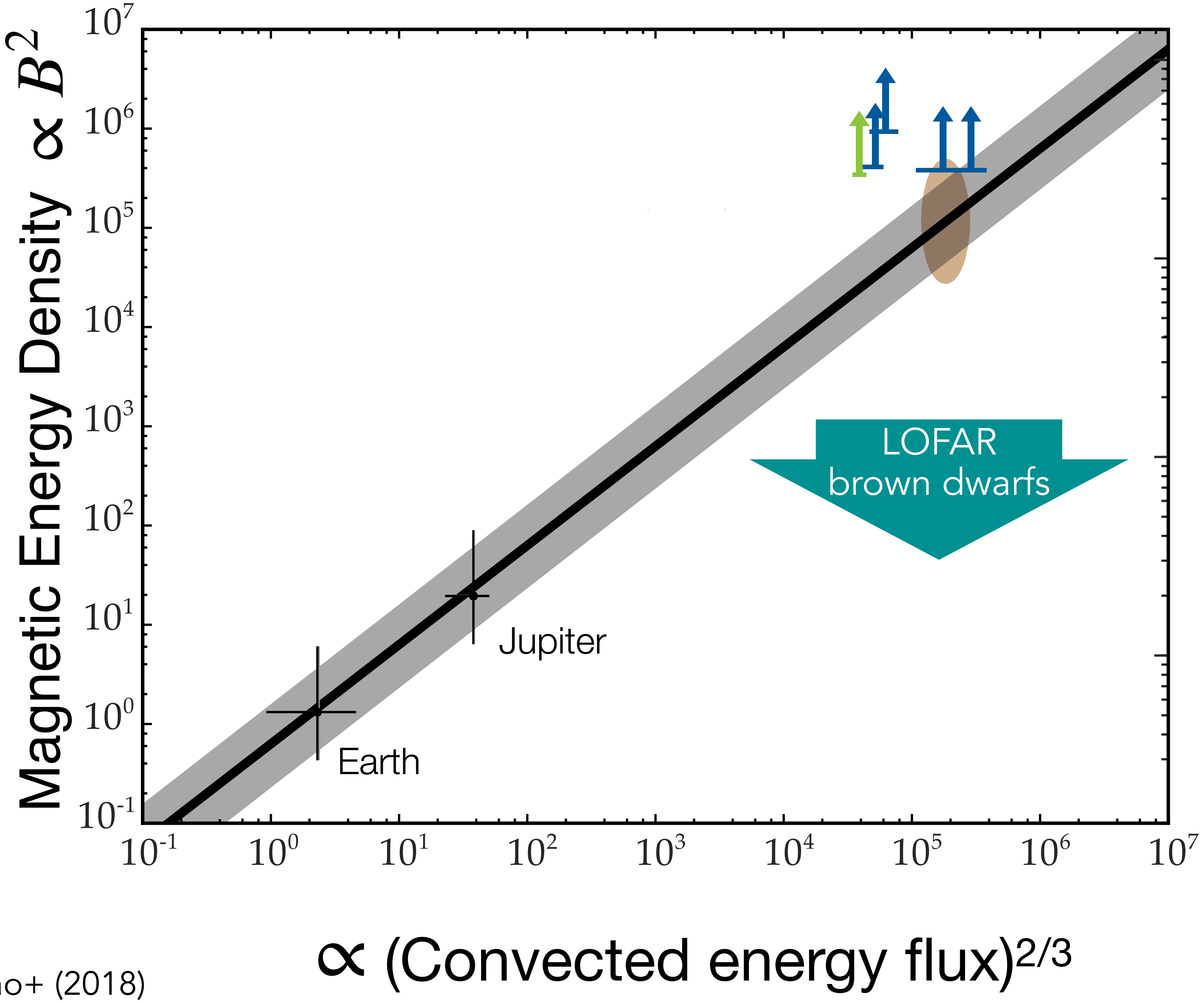
Younger, hotter: more strongly magnetized



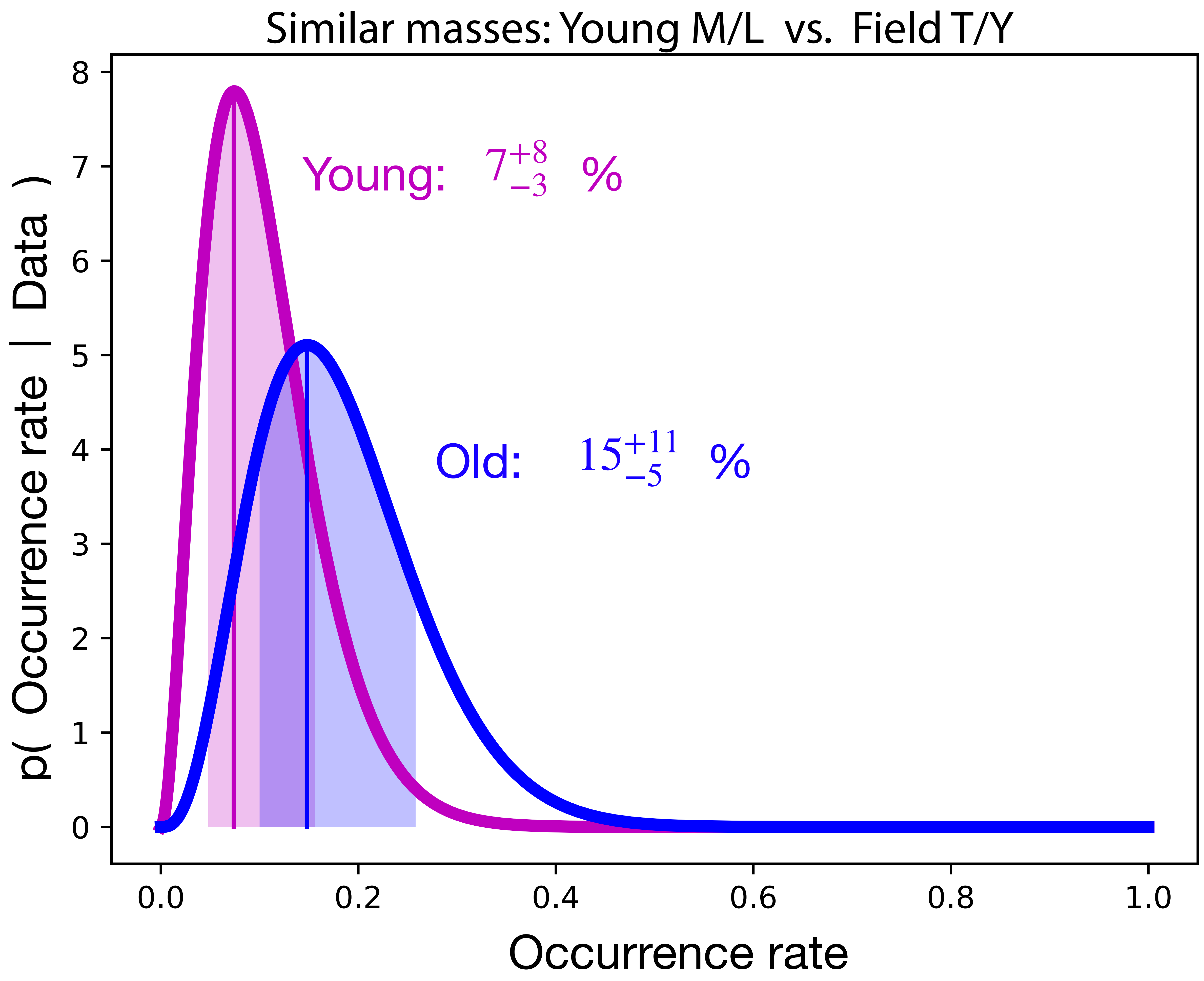
adapted from Kao+ (2018)
see also: Reiners & Christensen (2010)

Melodie Kao (mkao@lowell.edu)

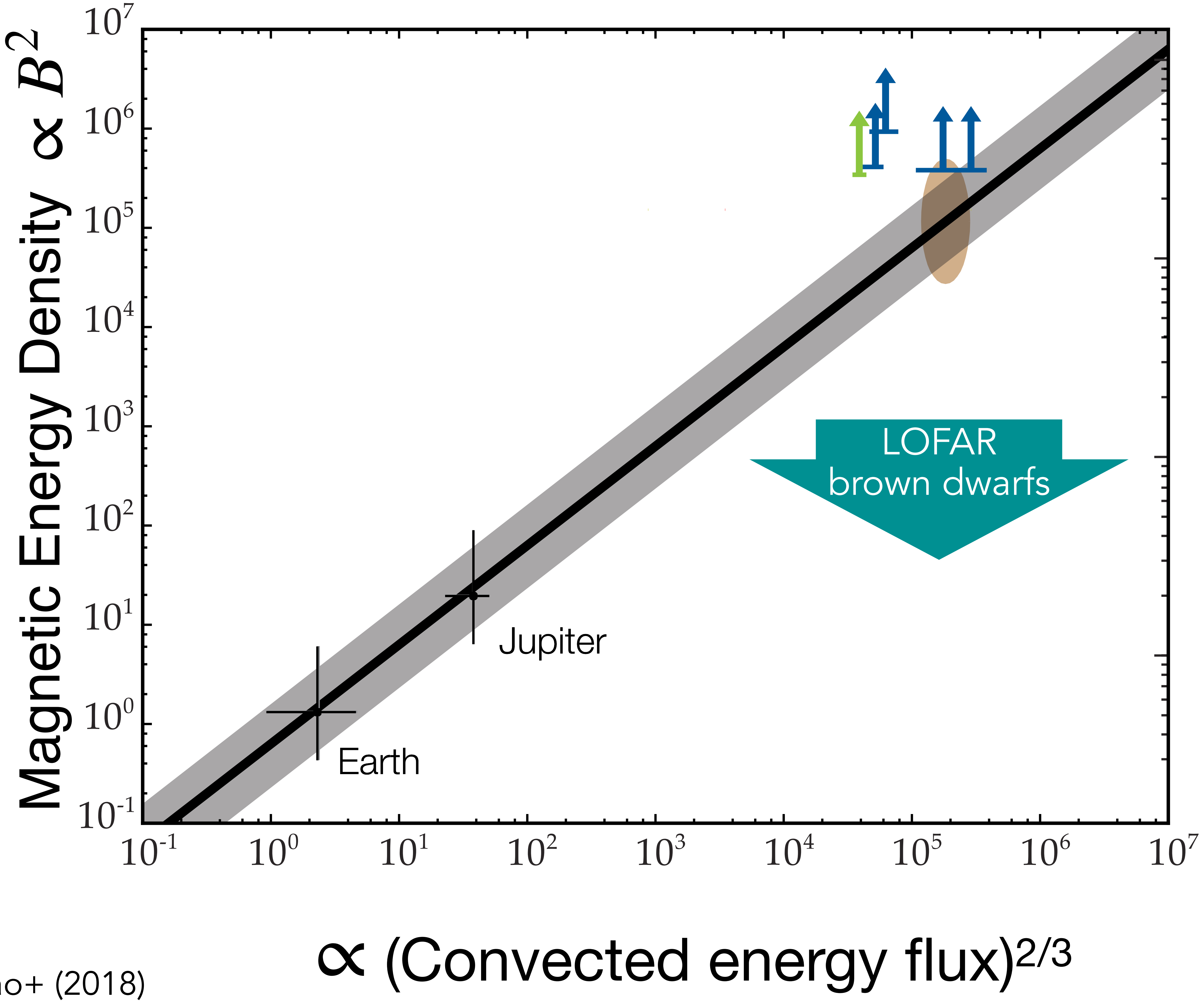
Younger, hotter: more strongly magnetized? **Maybe not.**



Kao+ (2018)



Kao & Shkolnik (in prep)



Kao+ (2018)

Kao+ (2016, 2018):

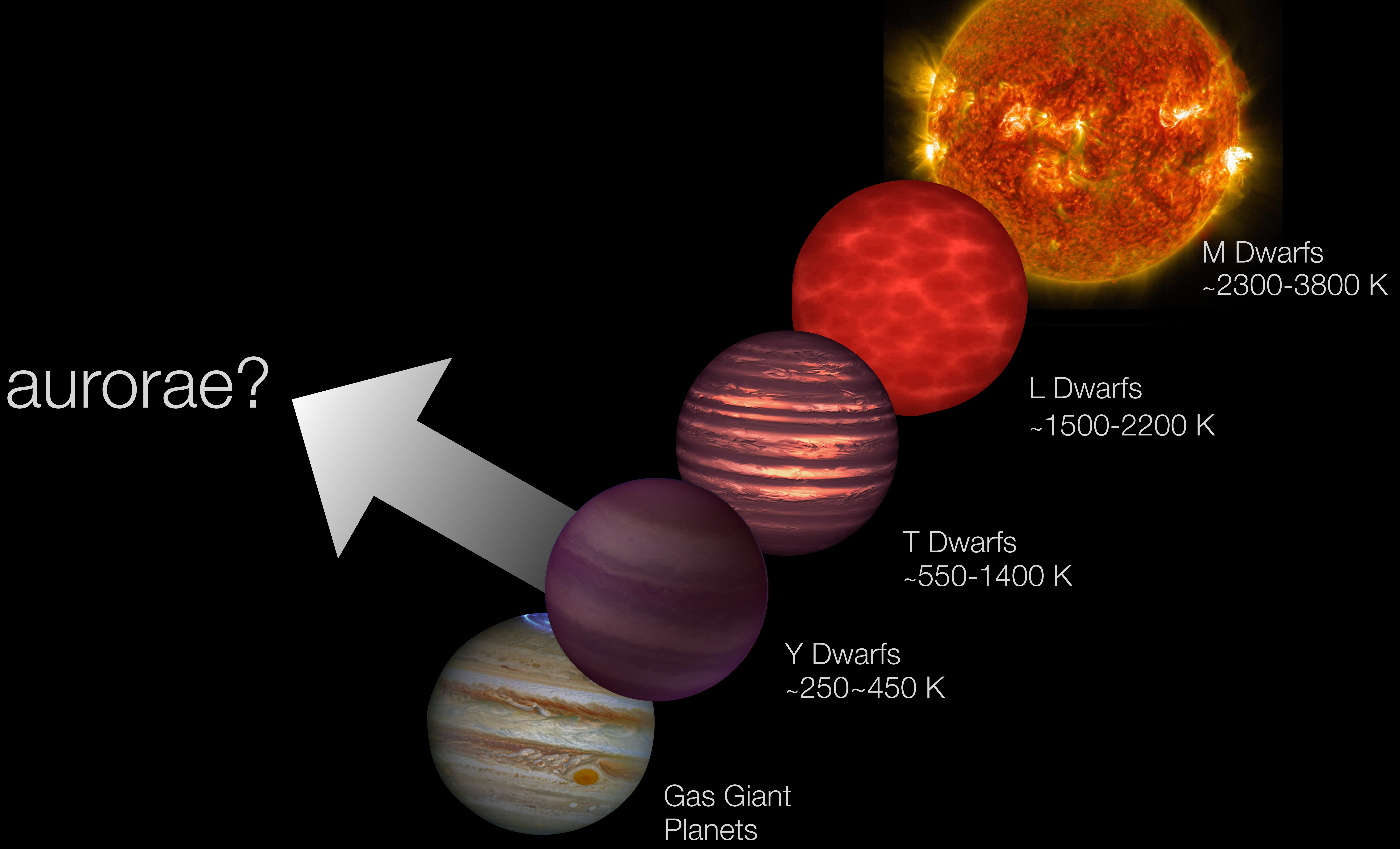
B fields exceed predictions from convected heat flux

Kao, Mioduszewski, Villadsen & Shkolnik (Nature 2023):

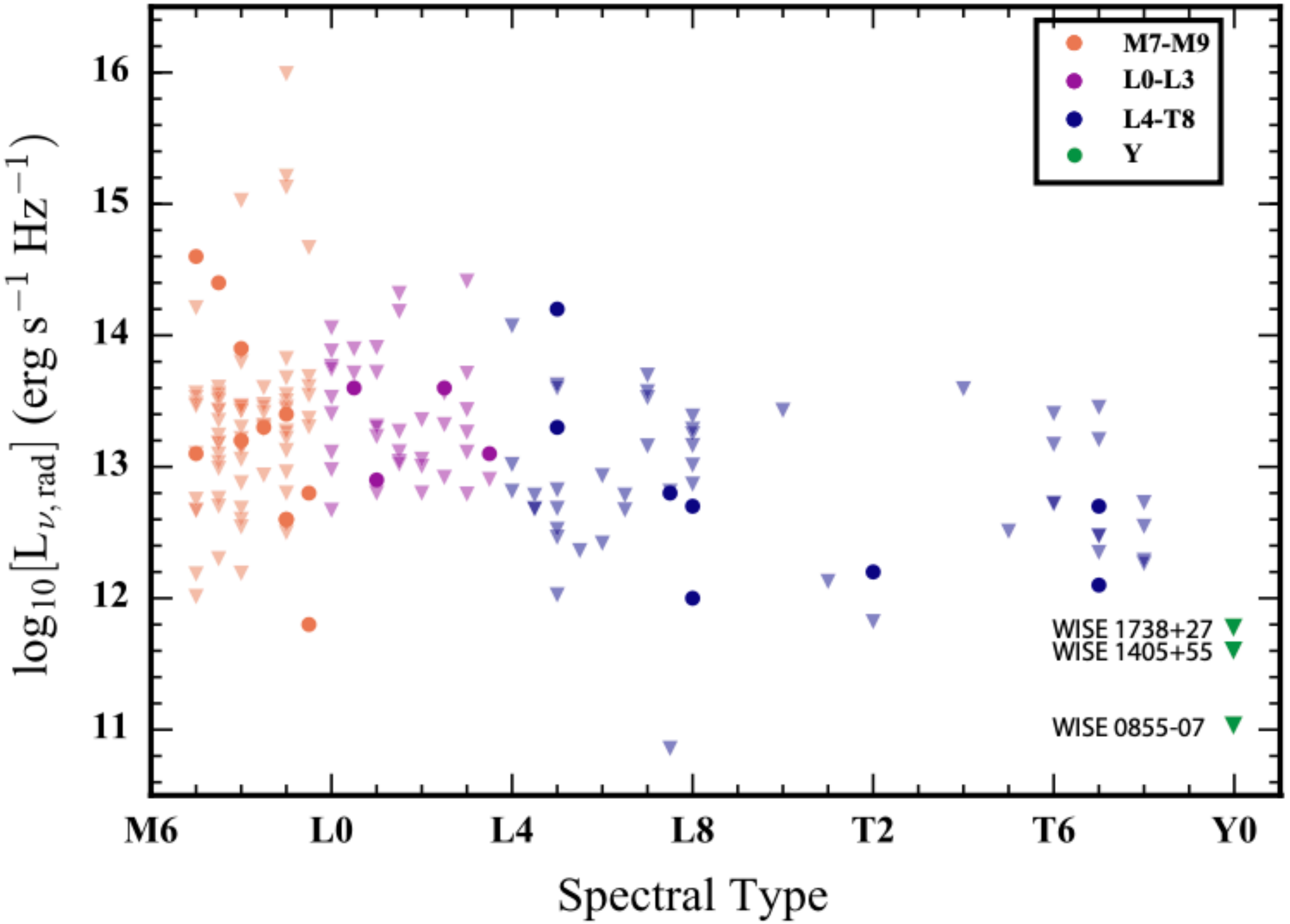
Brown dwarfs have radiation belts

Need more data:

Empirical Scaling Relationship

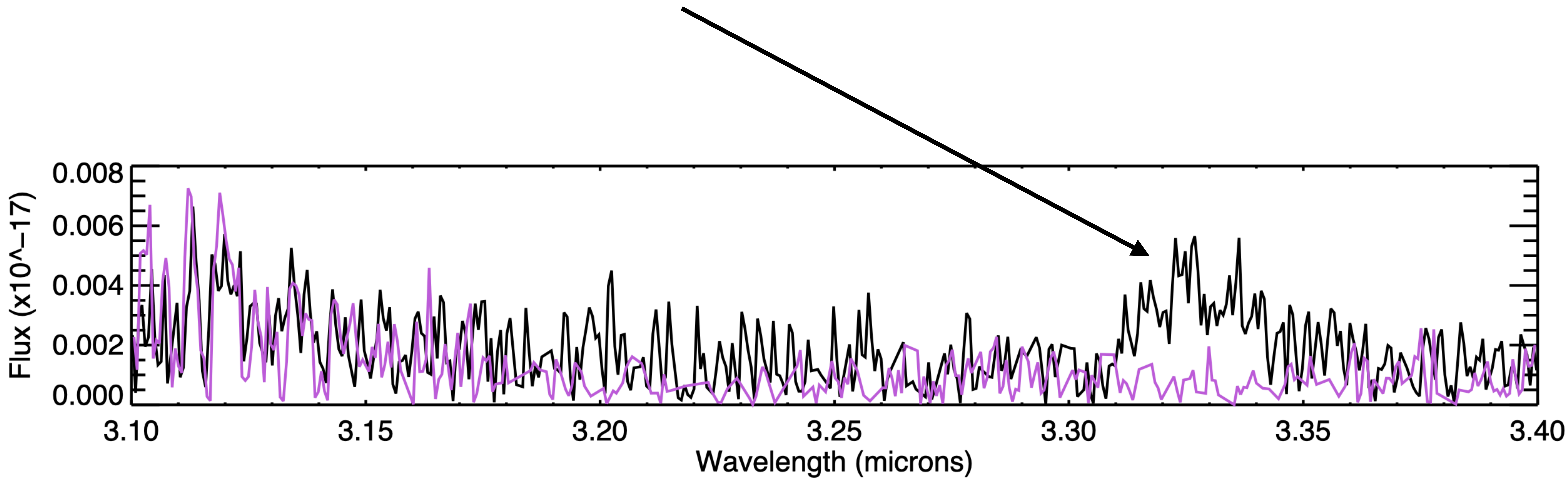


Melodie Kao (mkao@lowell.edu)


M7-M9
L0-L3
L4-T8
Y
16
15
14
13
12
11
$\log_{10}[L_{\nu,\mathrm{rad}}]$ (erg s^{-1} Hz^{-1})
WISE 1738+27
WISE 1405+55
WISE 0855-07
M6
L0
L4
L8
T2
T6
Y0
Spectral Type

Kao+ (2019)

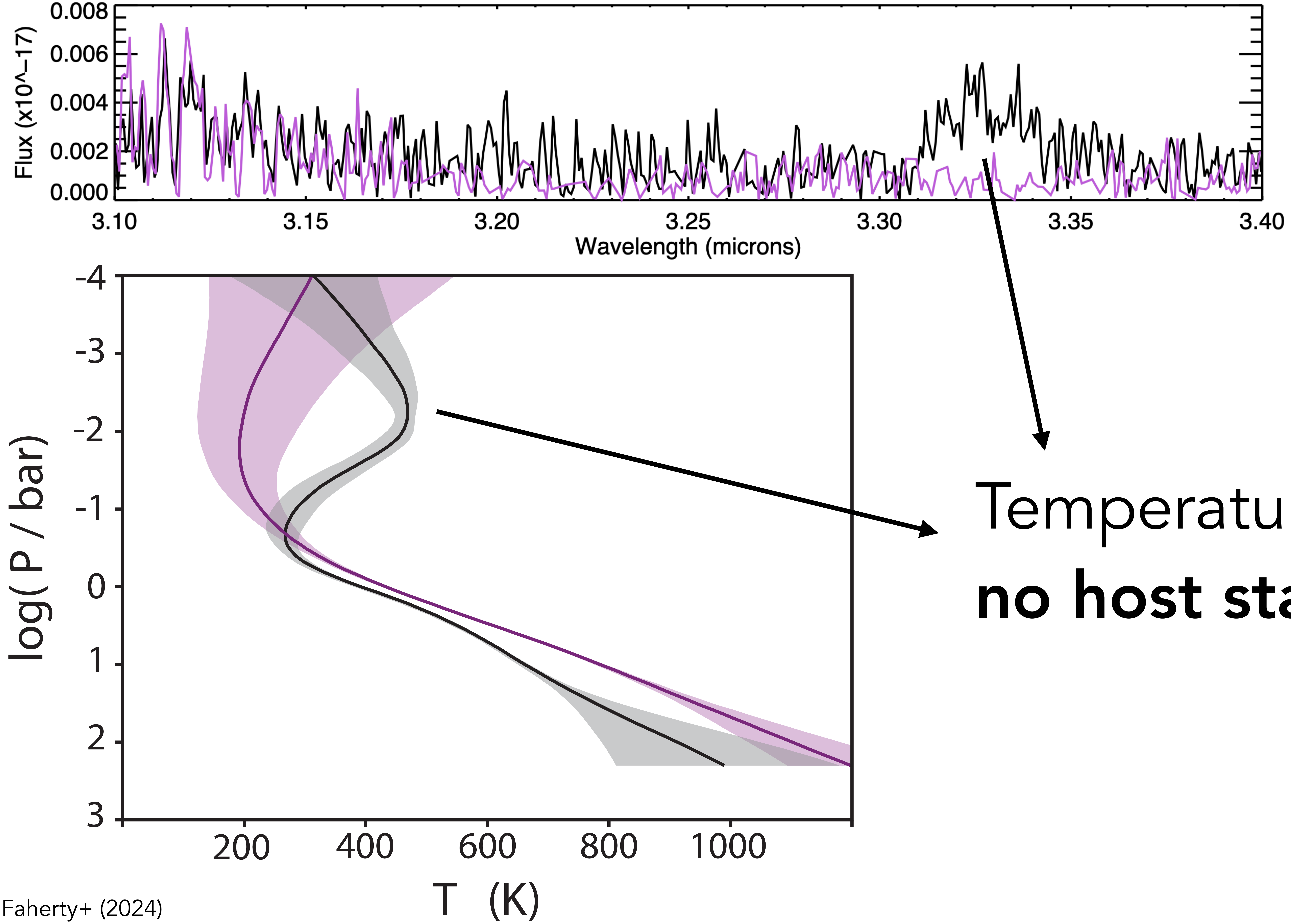
Methane emission from a Y dwarf:



Target - 487 K

Control - 487 K

Faherty+ (2024)



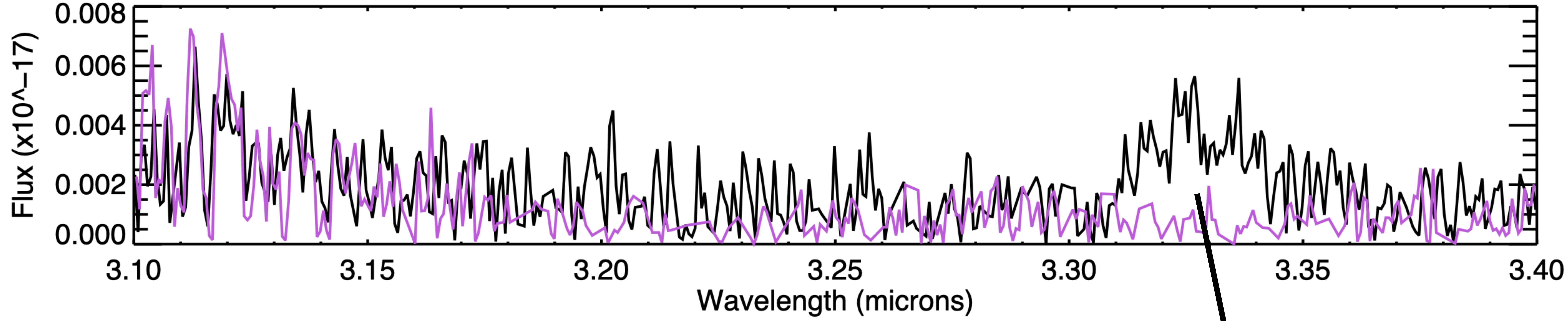
Target - 487 K

Control - 487 K

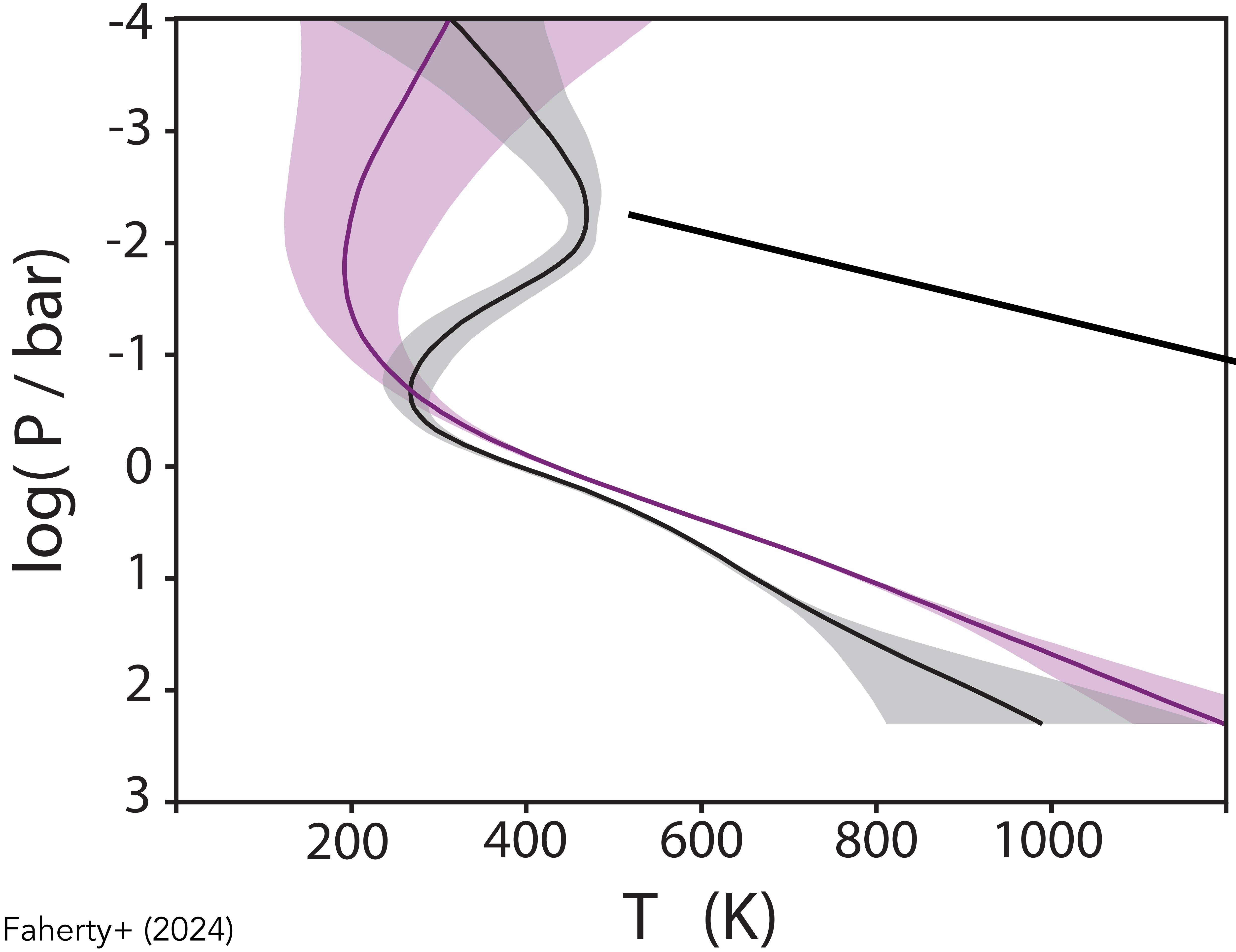
Temperature inversion …

no host star

Faherty+ (2024)

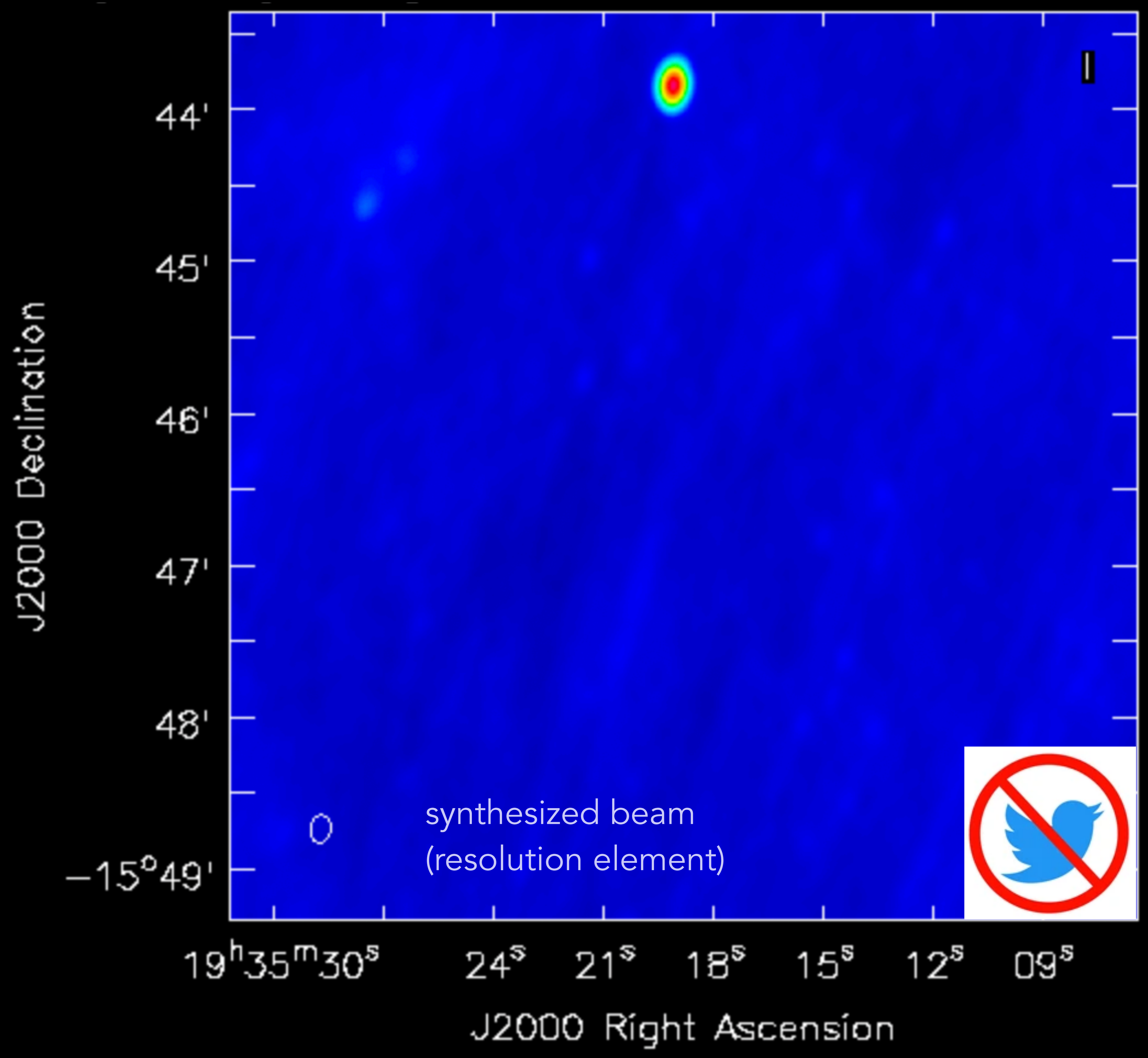


Target - 487 K
Control - 487 K



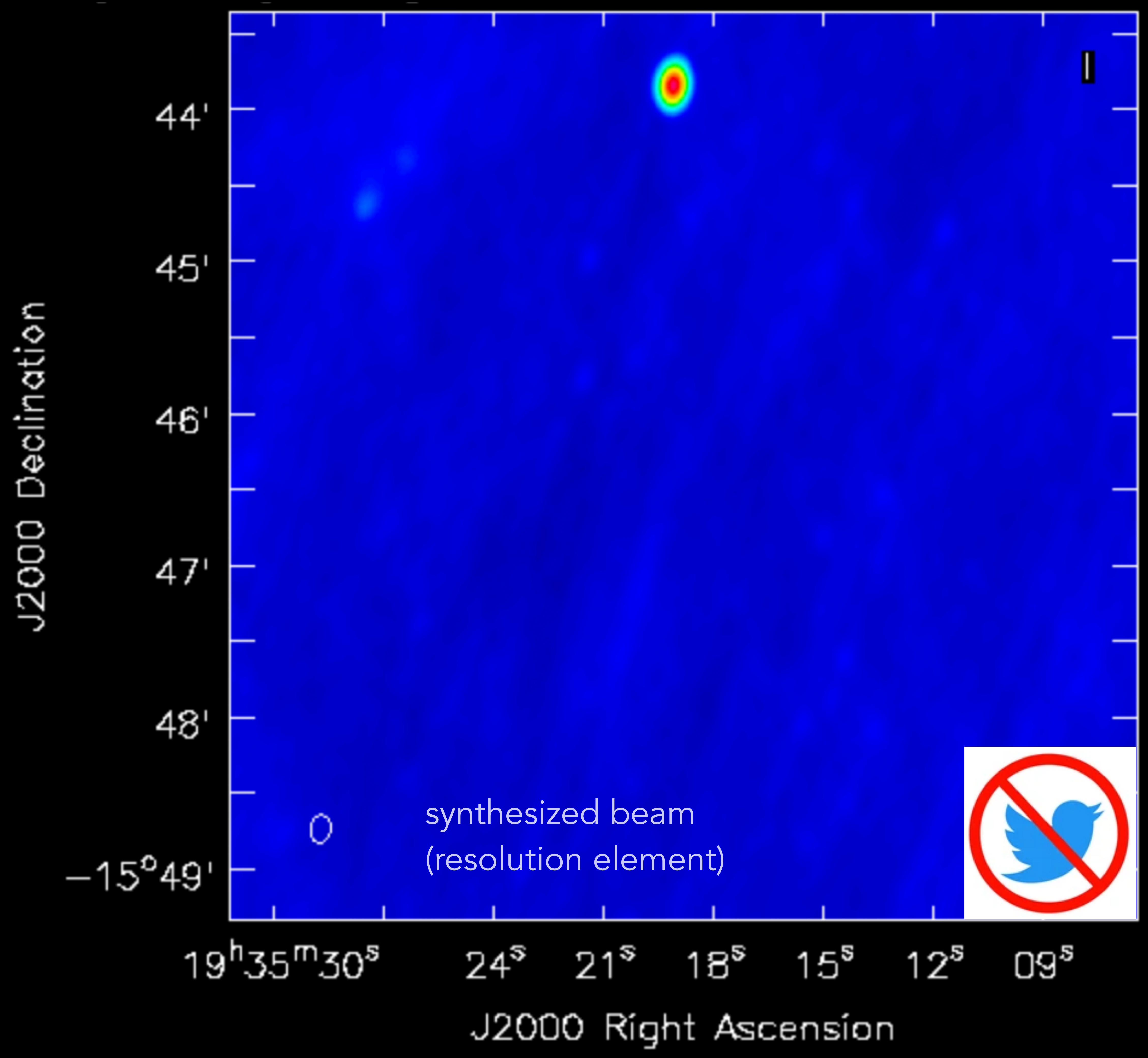
Temperature inversion:
Auroral heating?

Faherty+ (2024)



Kao, Pineda, Faherty, Vos (in prep)

Melodie Kao (mkao@lowell.edu)



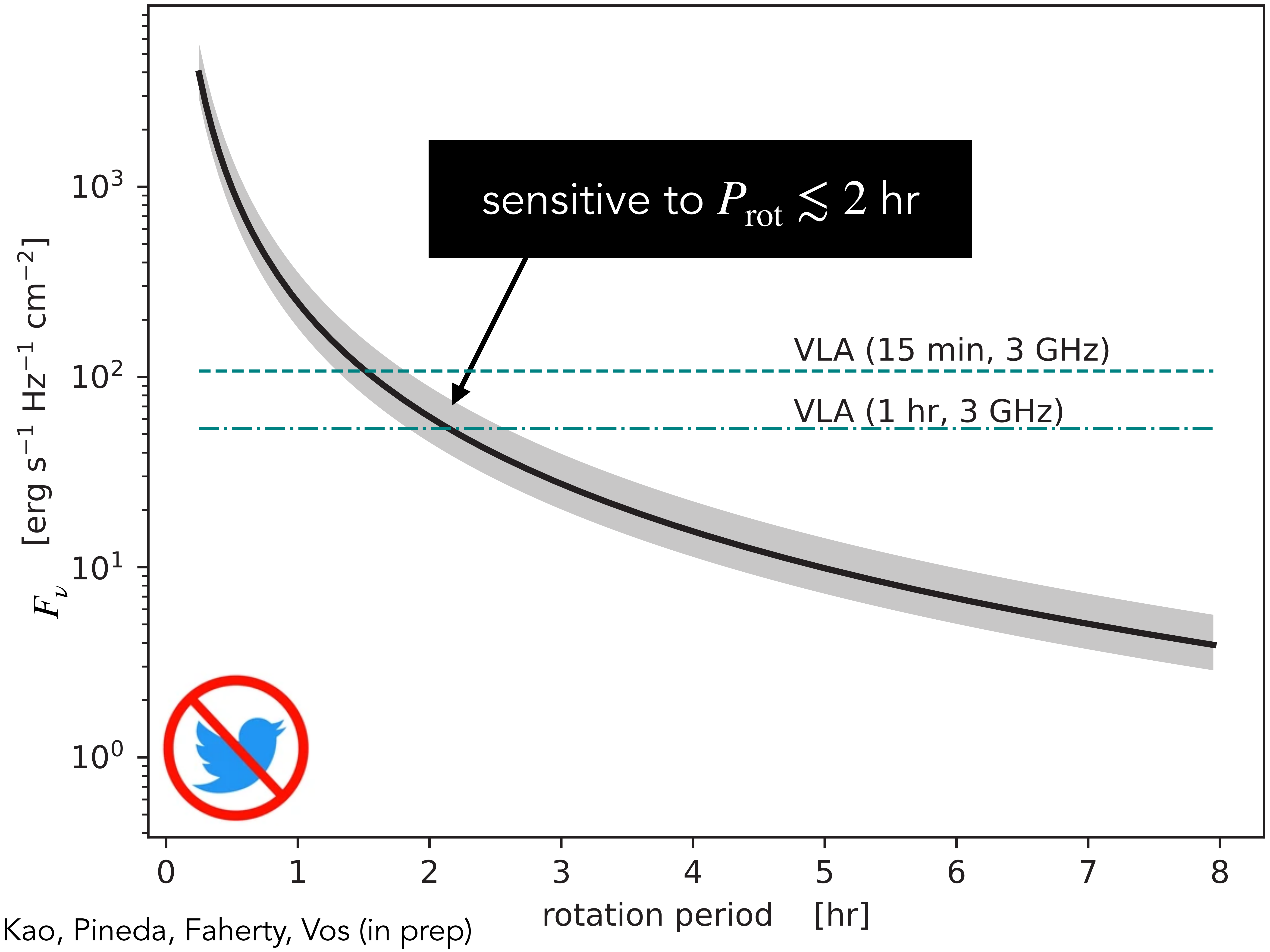
2-4 GHz (0.7 - 1.4 kiloGauss)

No detection … yet

Kao, Pineda, Faherty, Vos (in prep)

Melodie Kao (mkao@lowell.edu)

Weakly magnetized objects need to rotate faster.



Kao, Pineda, Faherty, Vos (in prep)

$$S \propto B_{\rm host}^2 \ \Omega_{\rm host}^2 \ R_{\rm host}^2$$

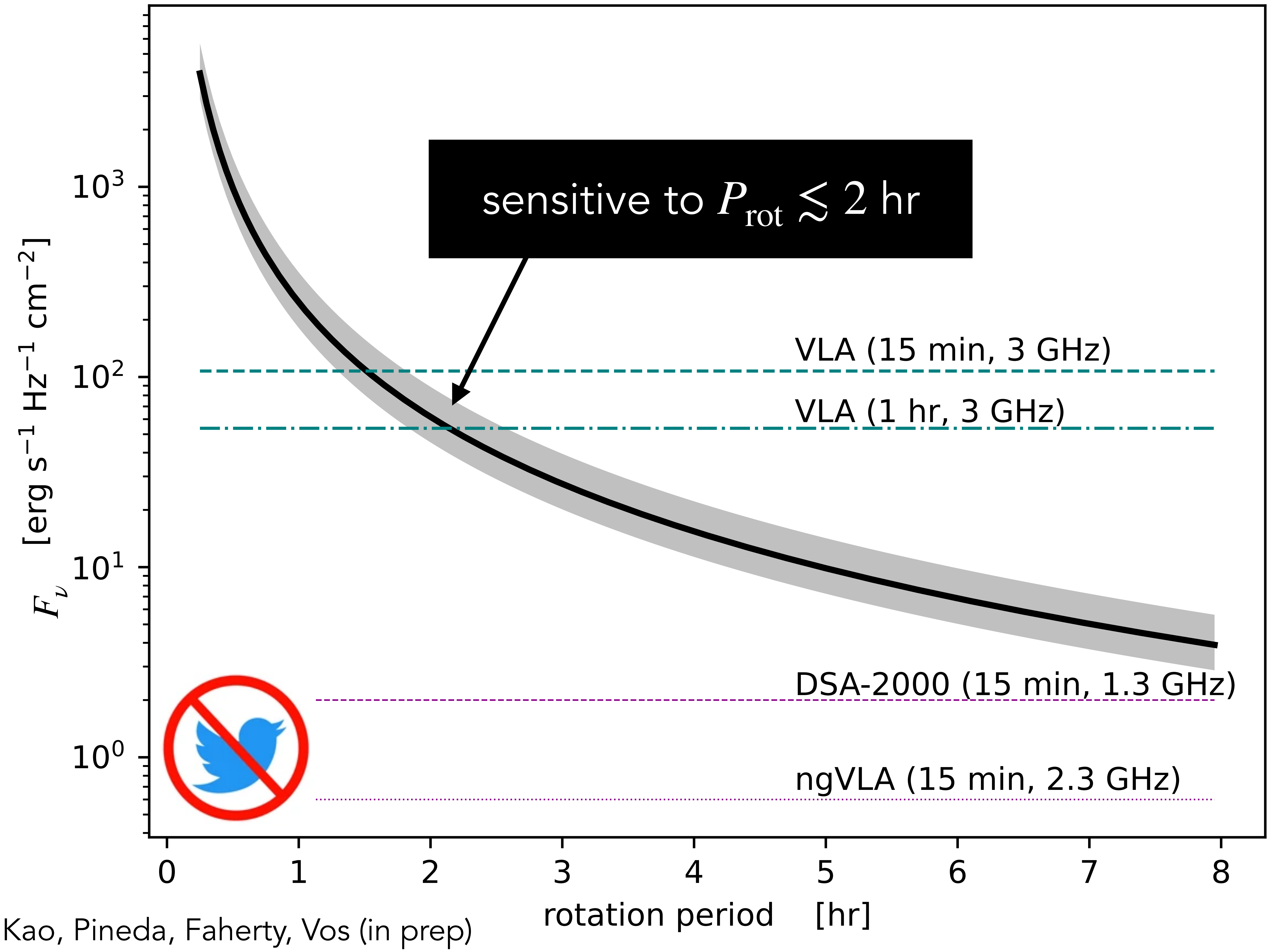
Power dissipated

auroral host's polar magnetic field

auroral host's angular velocity

auroral host's radius

Weakly magnetized objects need to rotate faster.



Kao, Pineda, Faherty, Vos (in prep)

$$S \propto B_{\rm host}^2 \, \Omega_{\rm host}^2 \, R_{\rm host}^2$$

S: Power dissipated

$B_{\rm host}$: auroral host's polar magnetic field

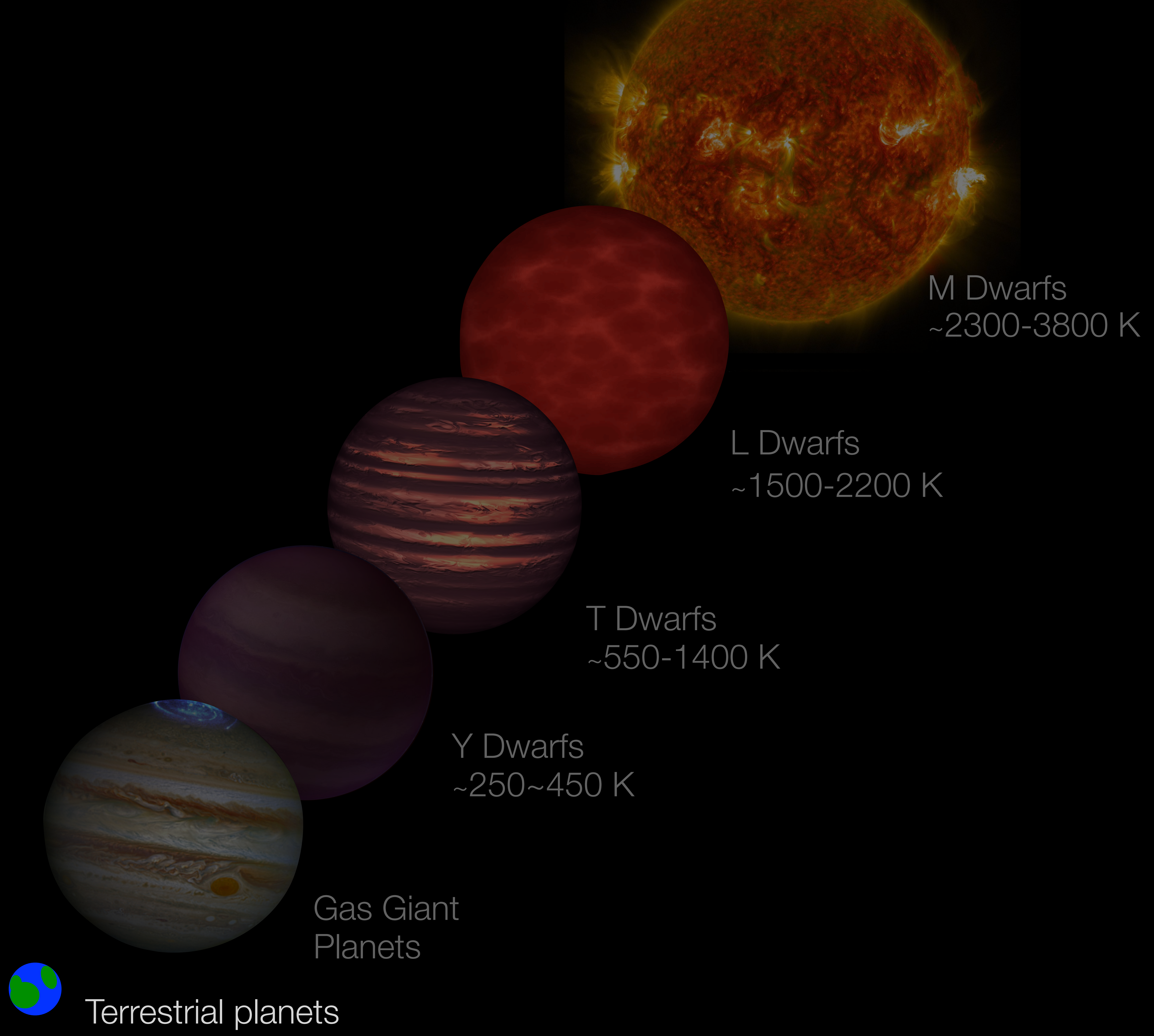
$\Omega_{\rm host}$: auroral host's angular velocity

$R_{\rm host}$: auroral host's radius

Coming soon:

Survey of Y dwarfs

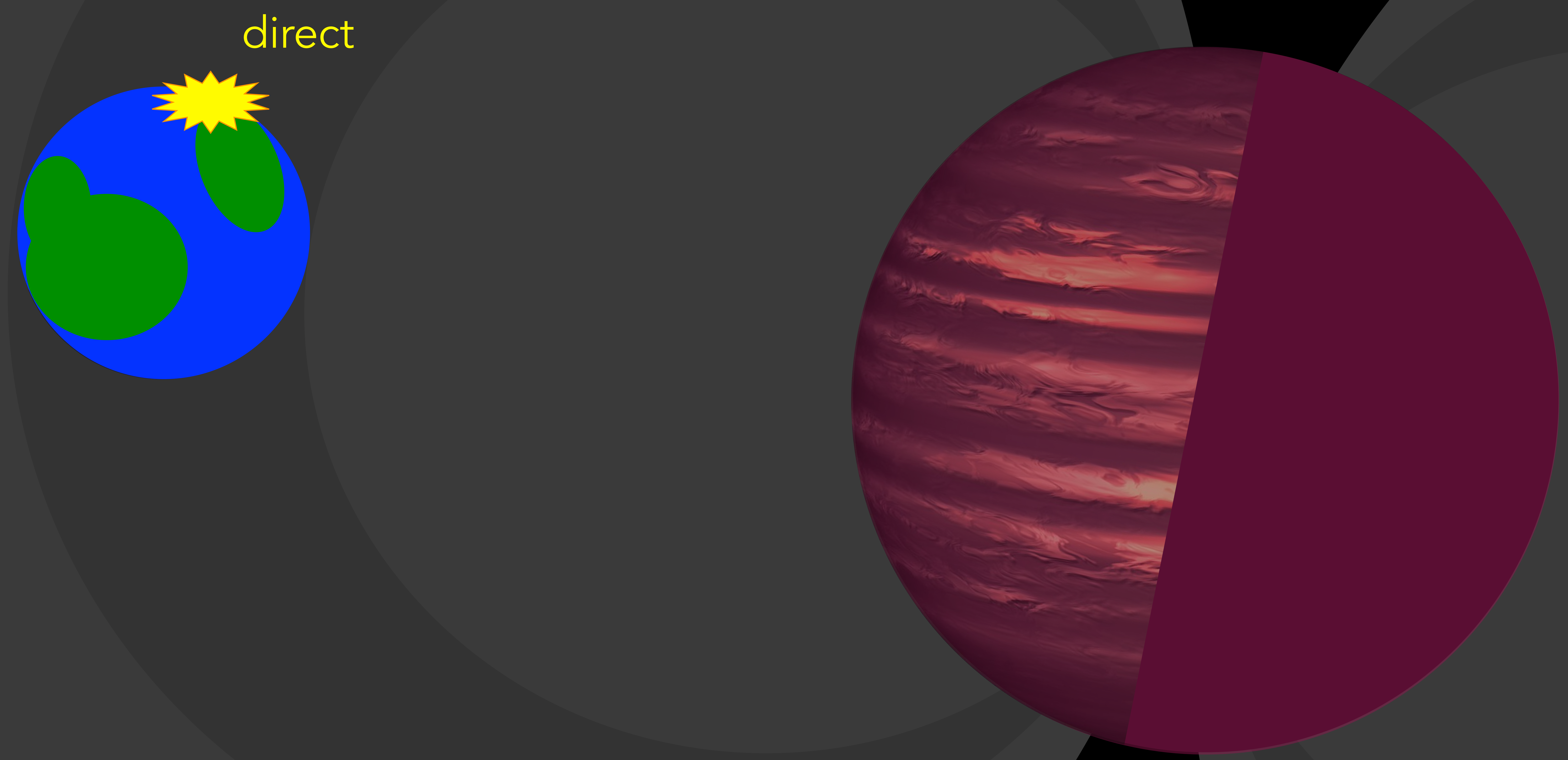
Carlos Ayala & Kao+ (in prep)

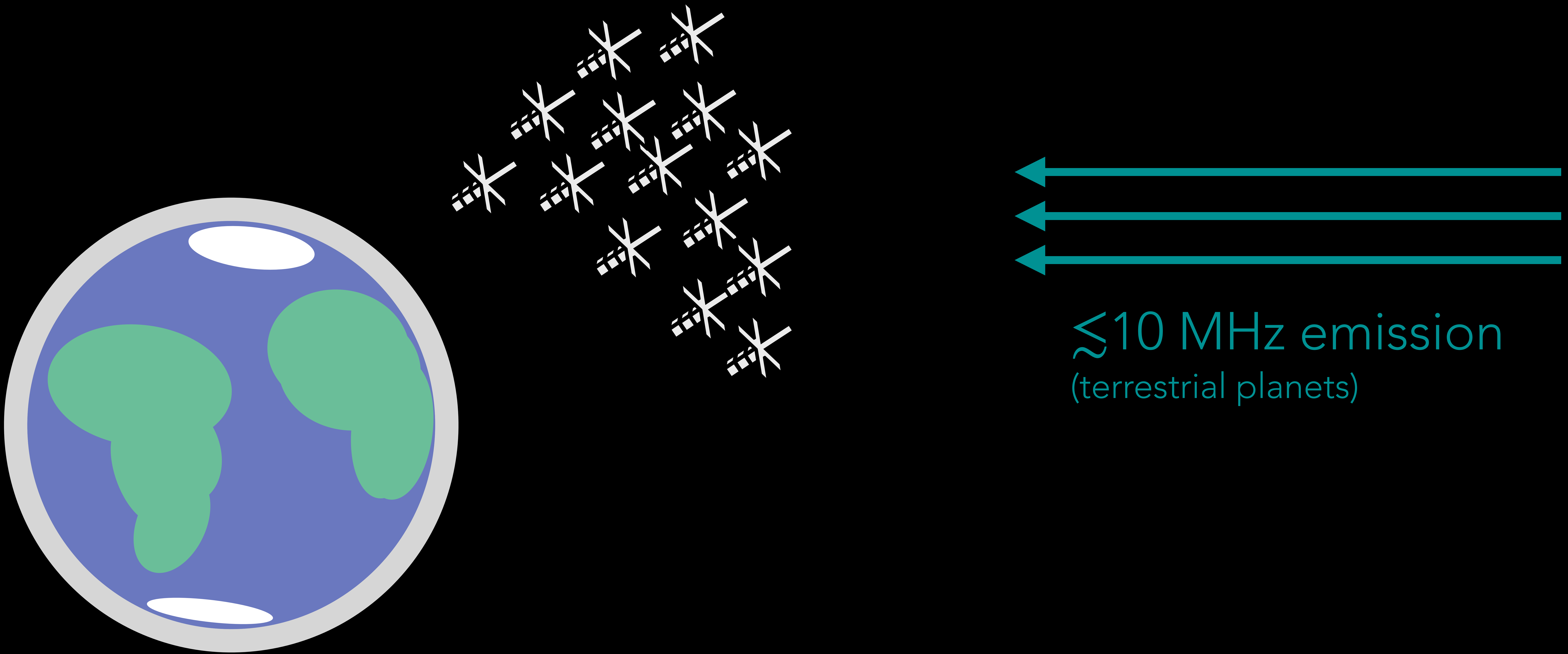


Melodie Kao (mkao@lowell.edu)

Terrestrial planets:

Interaction-driven aurorae





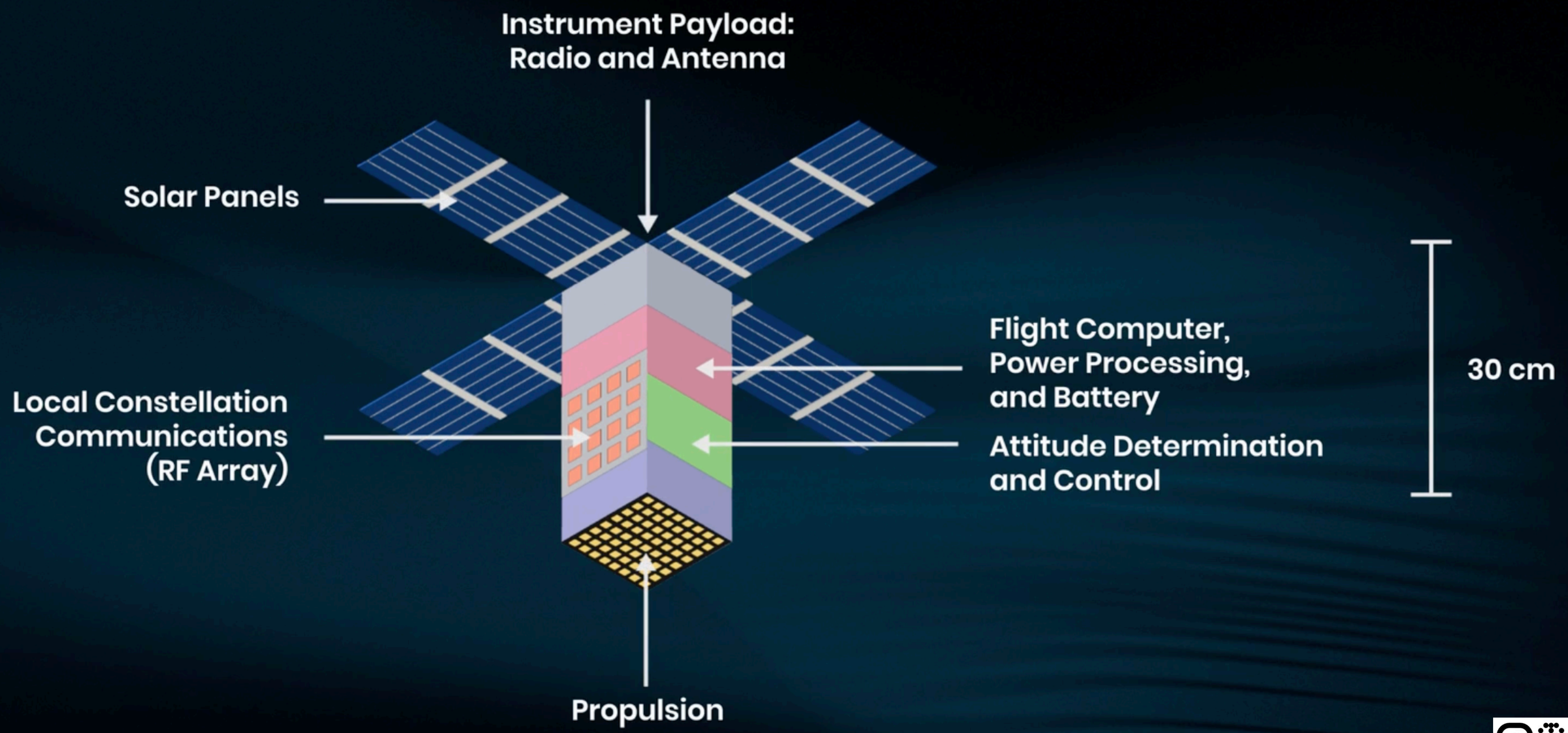
GO-LoW

Great Observatory at Long Wavelengths

Knapp, Paritsky, Kononov, Kao (2024 NIAC)

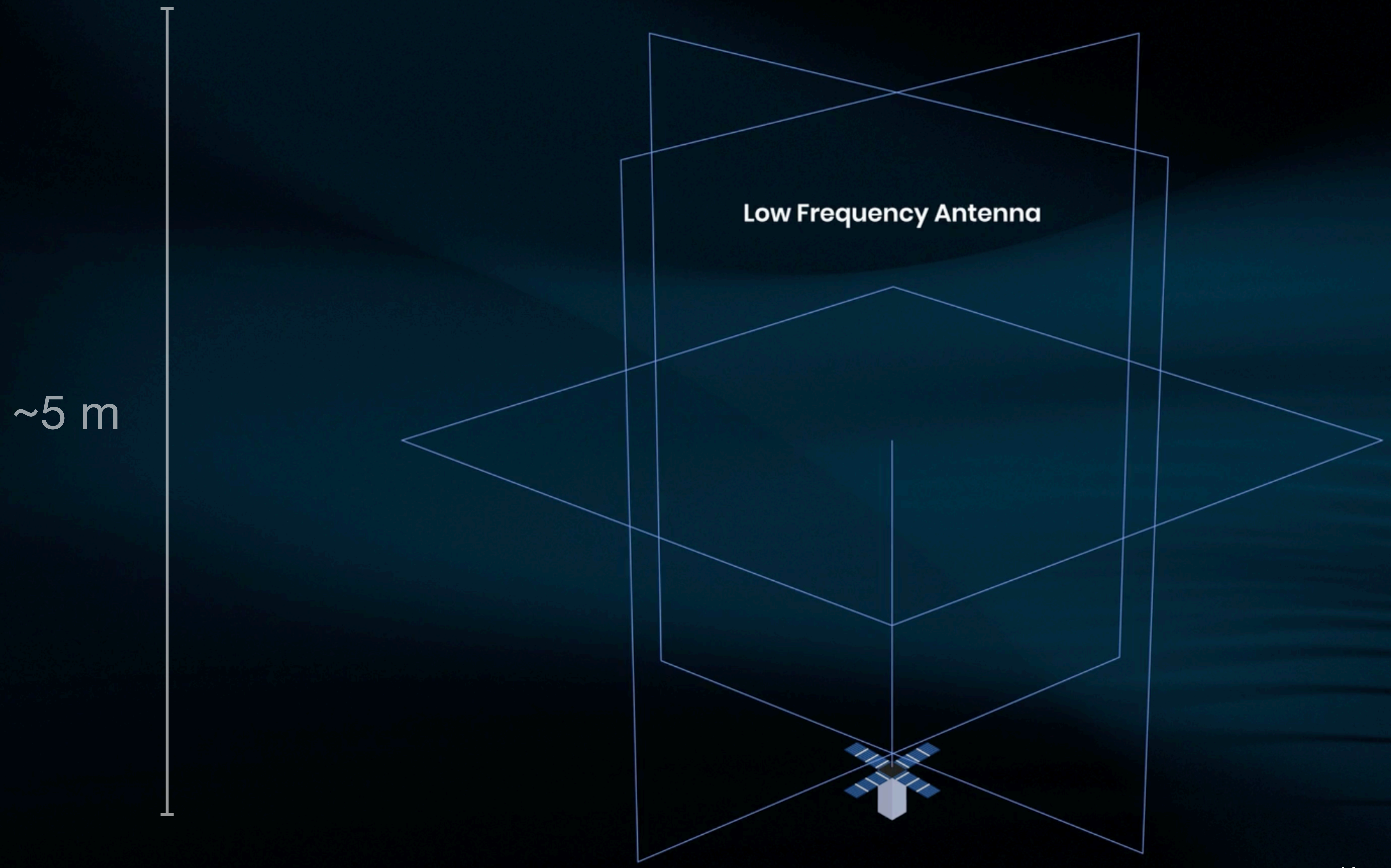
Melodie Kao (mkao@lowell.edu)

Listener Node (LN)



Knapp, Paritsky, Kononov, Kao (2024 NIAC)

Listener Node (LN)



Knapp, Paritsky, Kononov, Kao (2024 NIAC)

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GO-LoW

Great Observatory at Long Wavelengths

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GO-LoW

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GO-LoW

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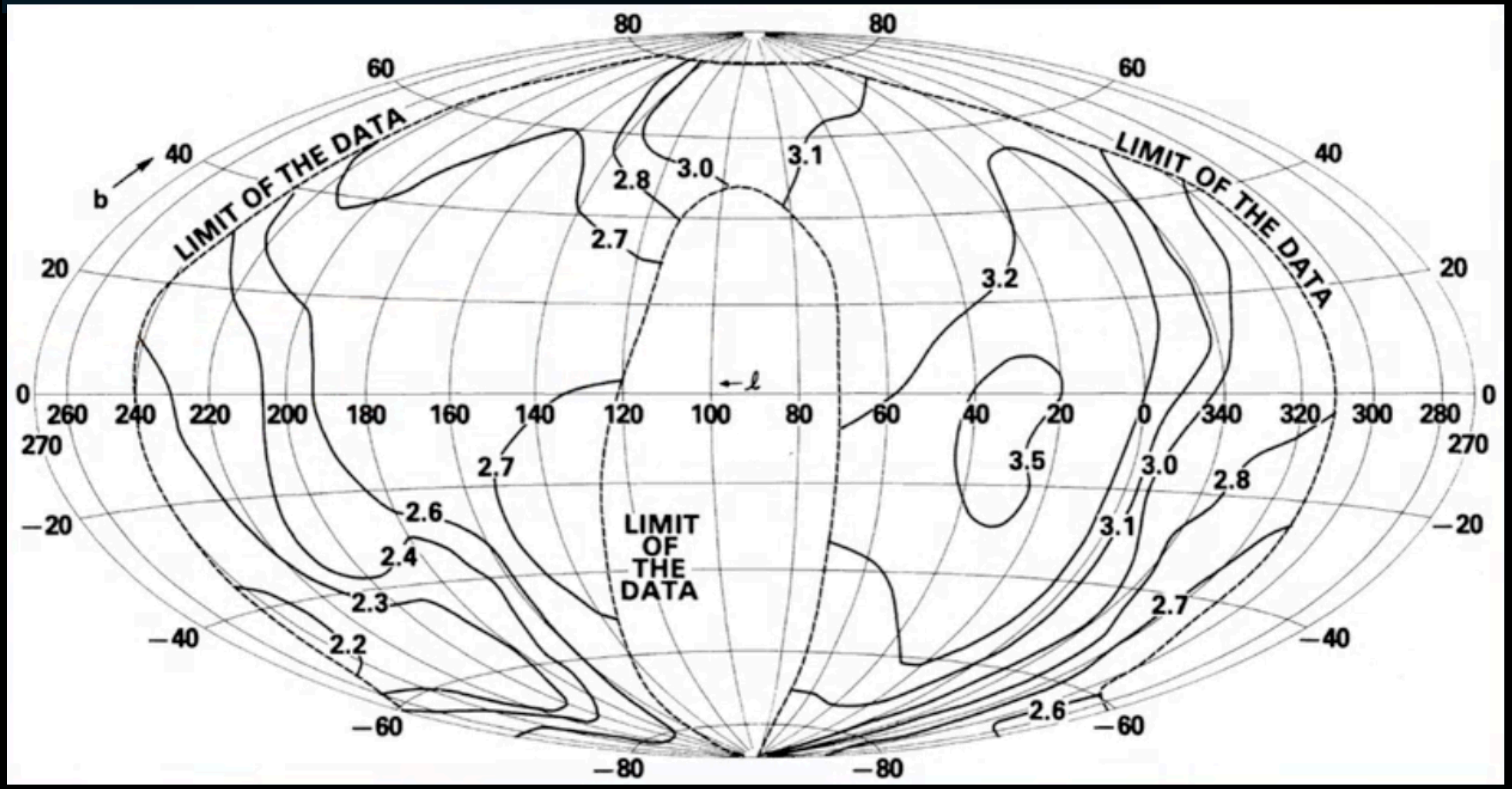
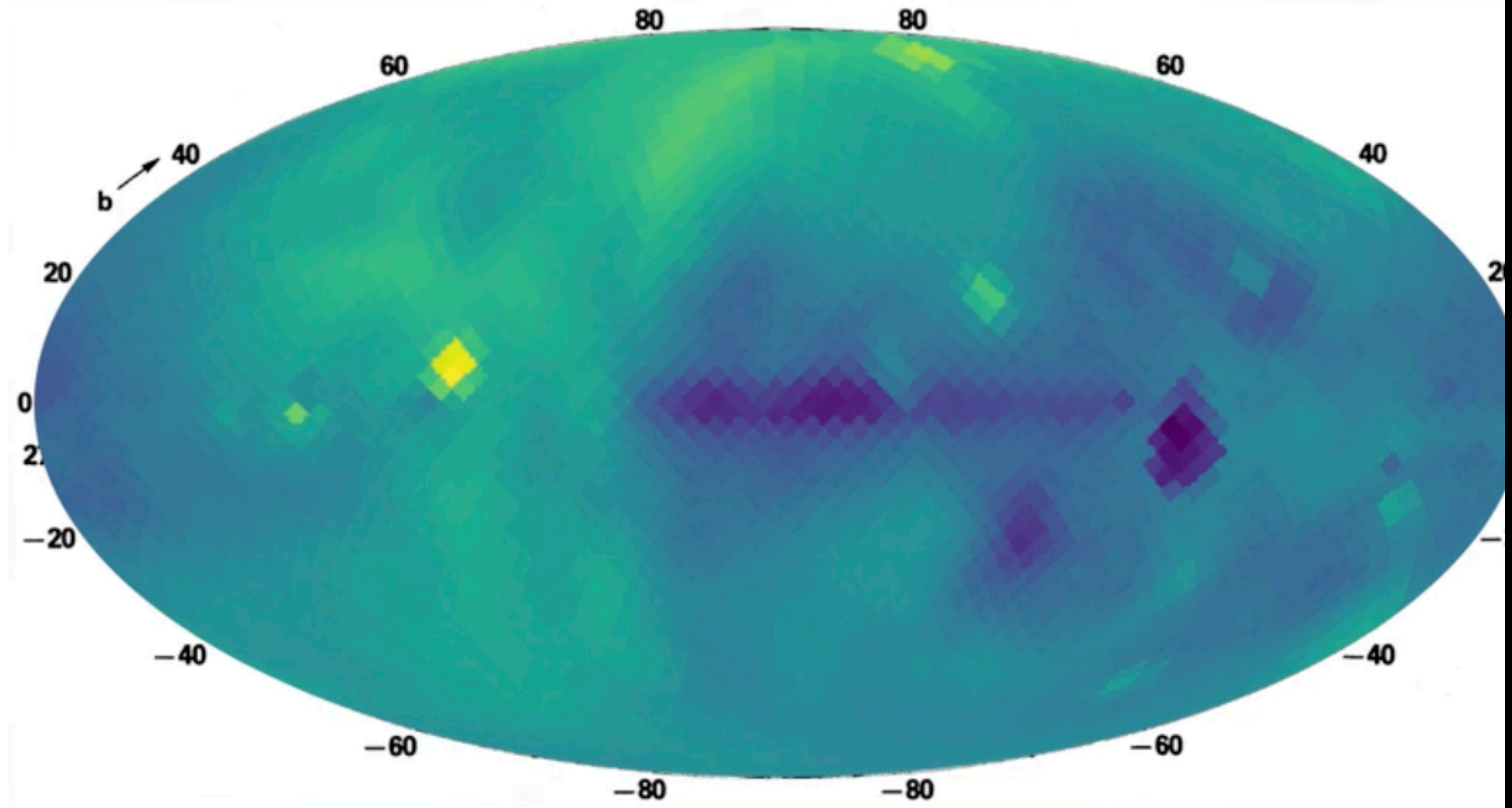
Current view

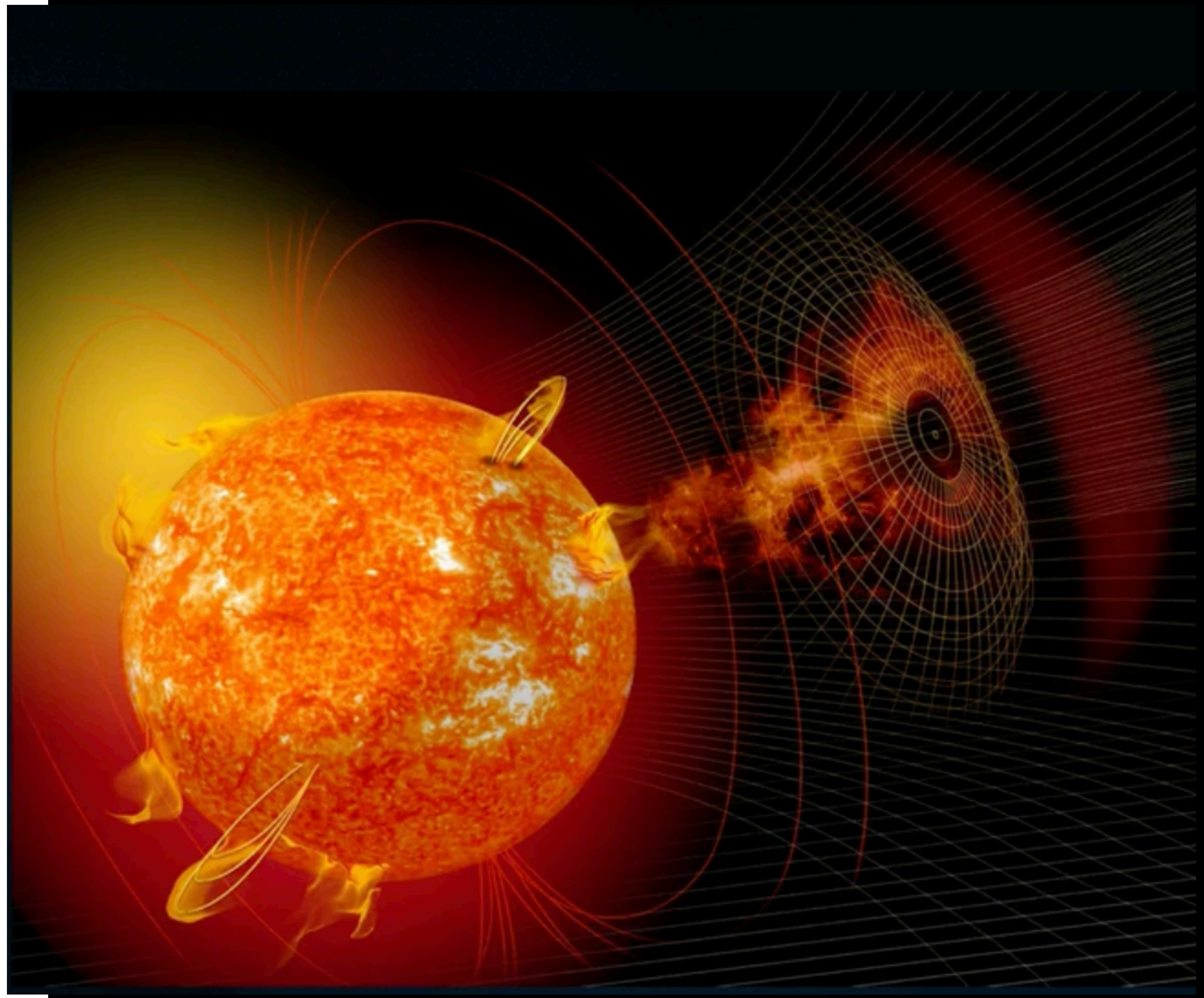


Novaco & Brown (1978)

Knapp, Paritsky, Kononov, Kao (2024 NIAC)

100 nodes

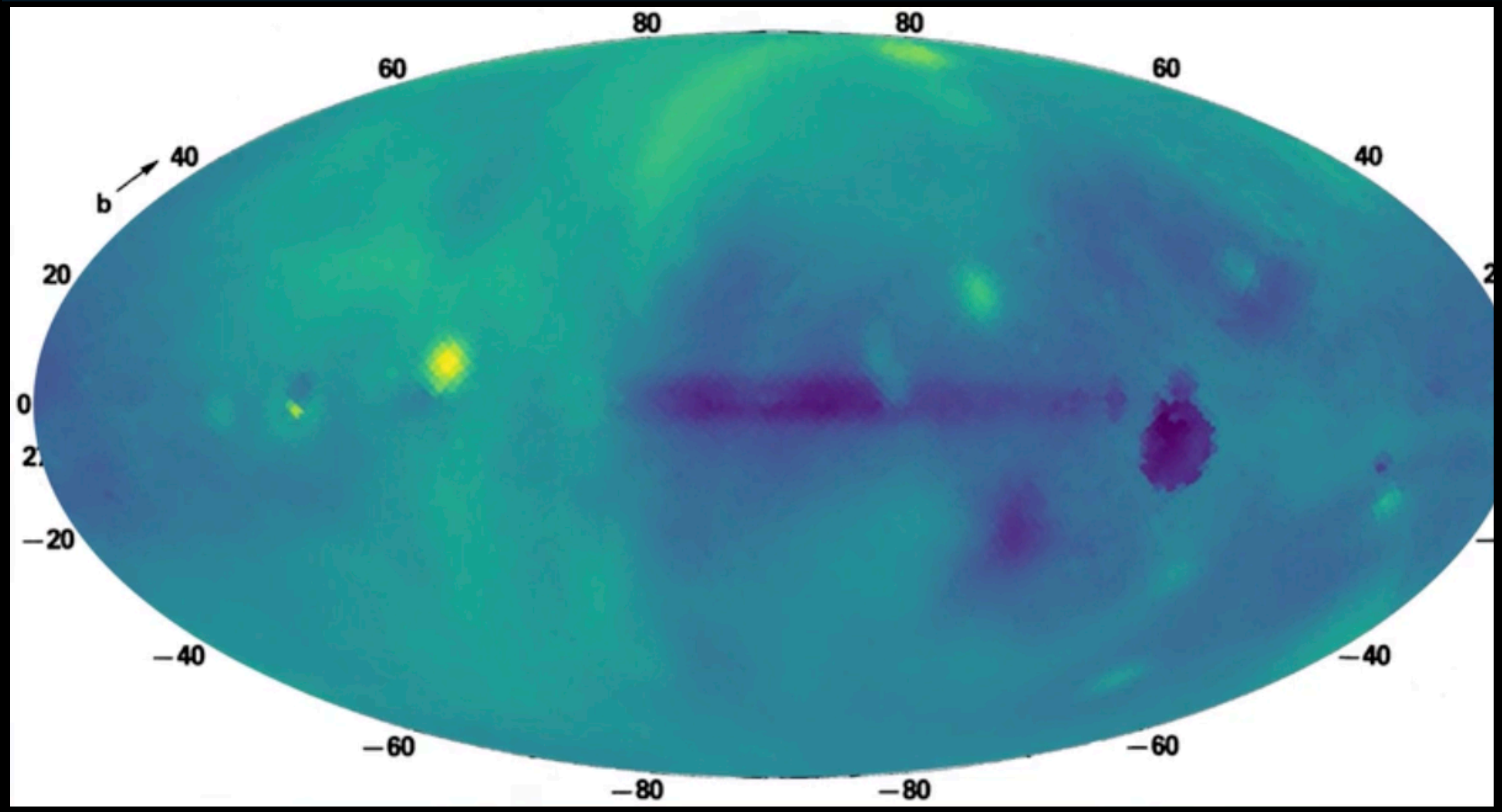




- Coronal Mass Ejections
- Gas Giants
- ce Giants
- Global 21 cm signal

Knapp, Paritsky, Kononov, Kao (2024 NIAC)

100 → 1000 - 10,000 nodes



Kononov, Knapp+ (in review)

Stellar Radio Bursts

21 cm tomography

Knapp, Paritsky, Kononov, Kao (2024 NIAC)

100,000 nodes:

Earth twin exoplanet aurorae

Knapp, Paritsky, Kononov, Kao (2024 NIAC)

Melodie Kao (mkao@lowell.edu)

Melodie Kao (mkao@lowell.edu)

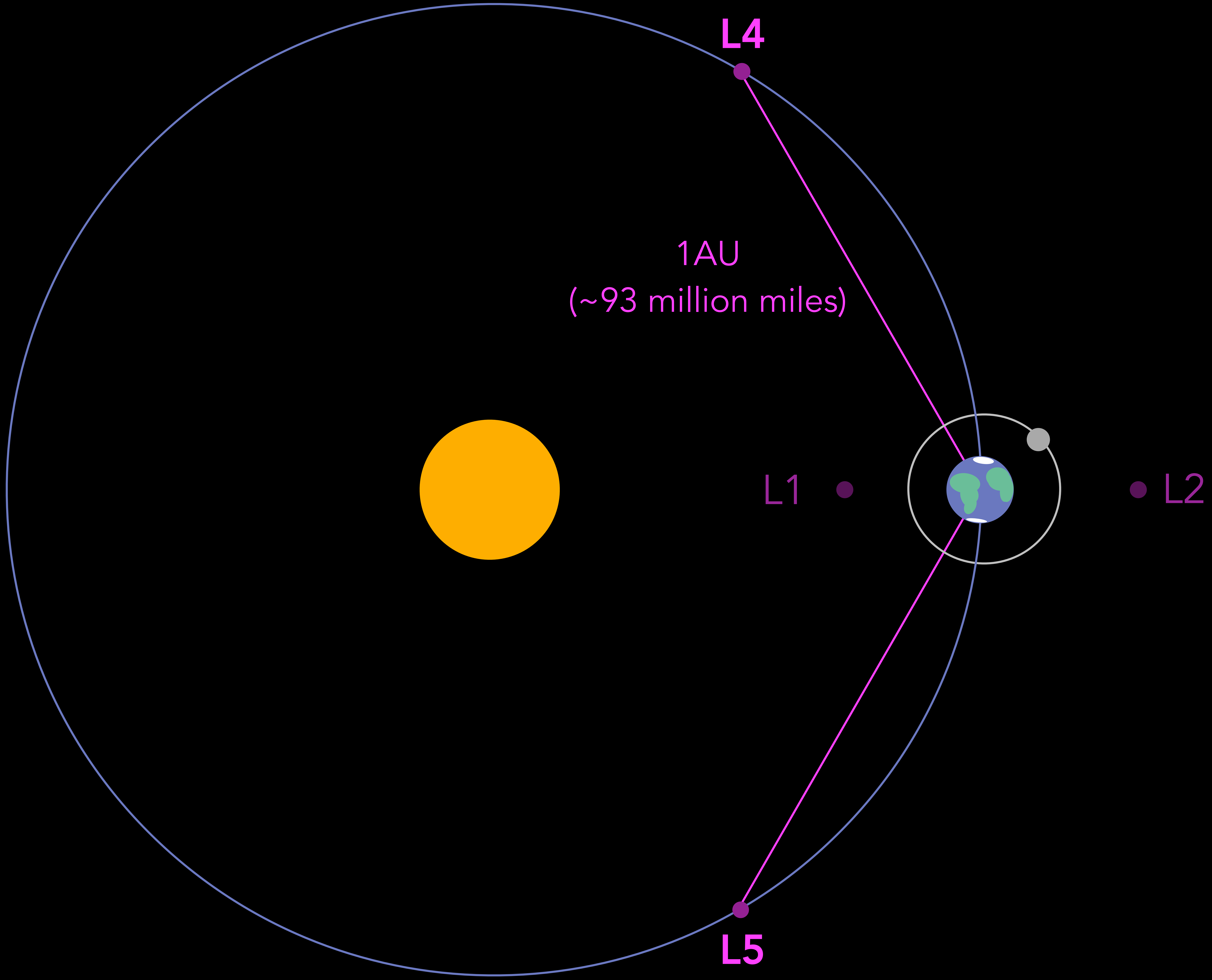
book chapter review:

Brain, Kao & O'Rourke (2024)

https://arxiv.org/abs/2404.15429

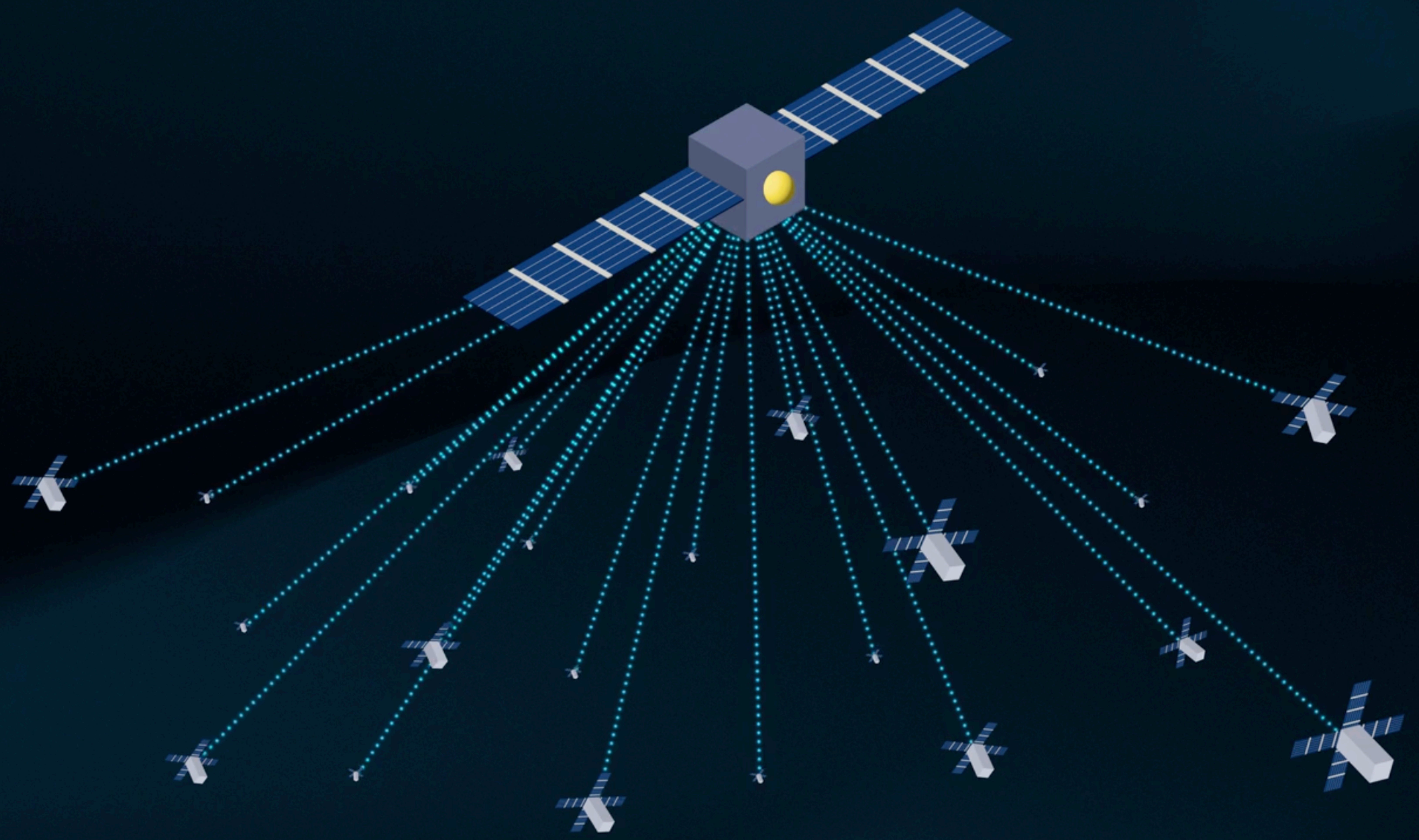
Melodie Kao (mkao@lowell.edu)

extra slides

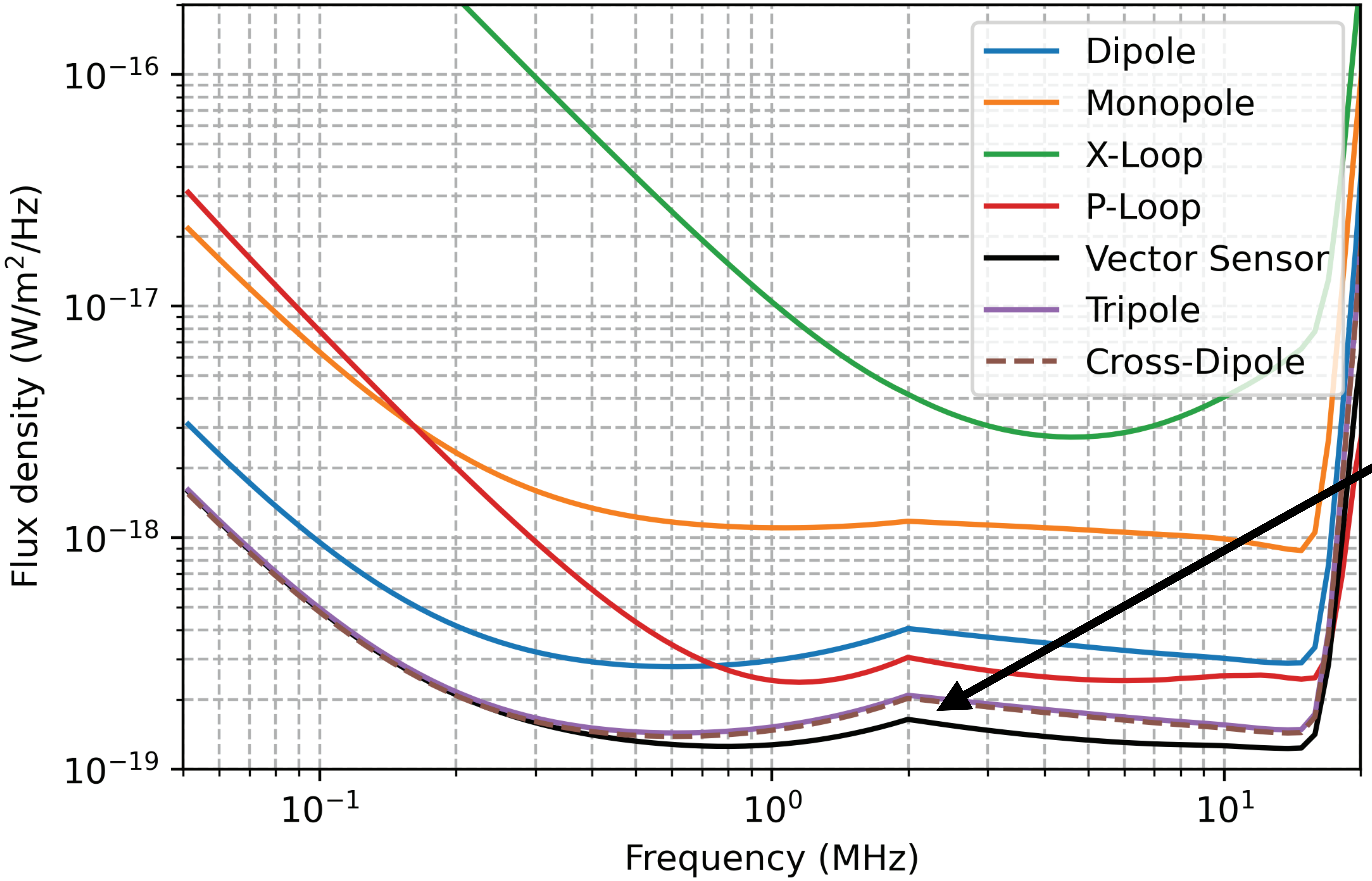


Knapp, Paritsky, Kononov, Kao (2024 NIAC)

Melodie Kao (mkao@lowell.edu)



Knapp, Paritsky, Kononov, Kao (2024 NIAC)

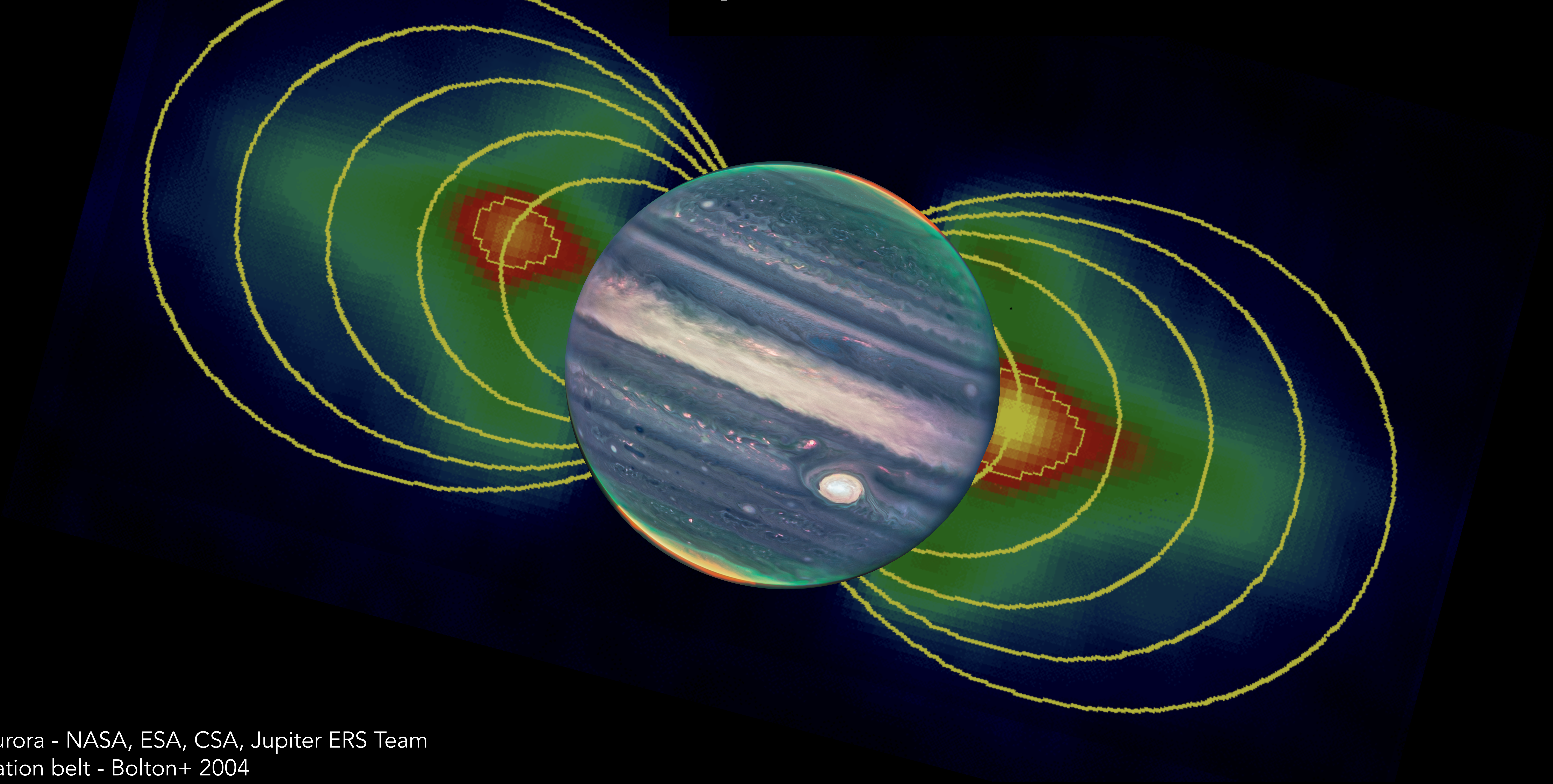


Vector Sensor Arrays:

~2x sensitive!

Kononov+ (2024)

spatially resolvable?



IR aurora - NASA, ESA, CSA, Jupiter ERS Team
radiation belt - Bolton+ 2004

Melodie Kao (mkao@lowell.edu)

$$S \propto R_o^2 \; B_{\mathrm{wind}} \, \Delta u^2 \, \sin^2\theta \sqrt{\rho_{\mathrm{wind}}}$$

power dissipated

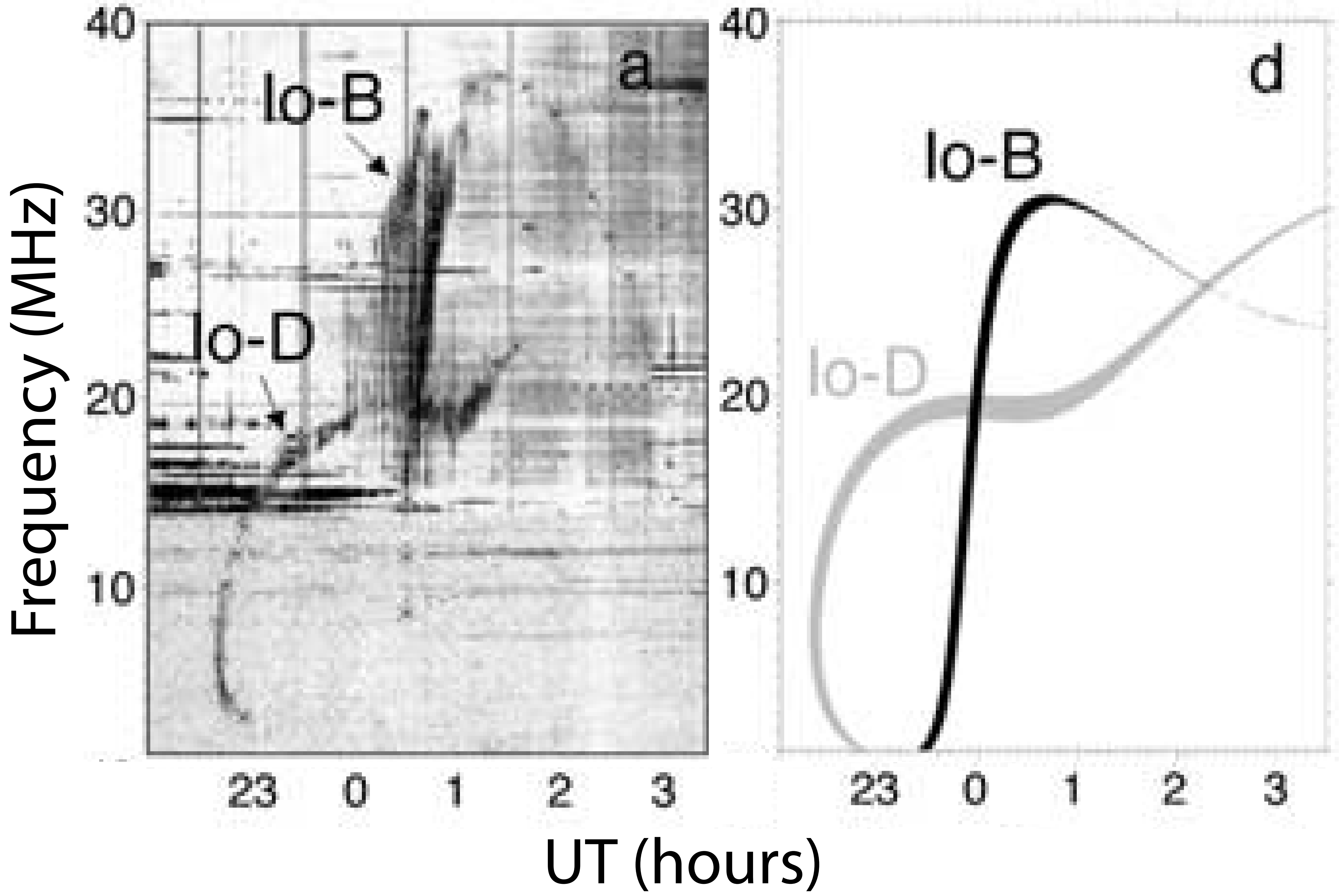
obstacle size

(magnetospheric plasma flow properties)

coming soon from ngVLA!!

satellite magnetic field

(…around brown dwarfs?)

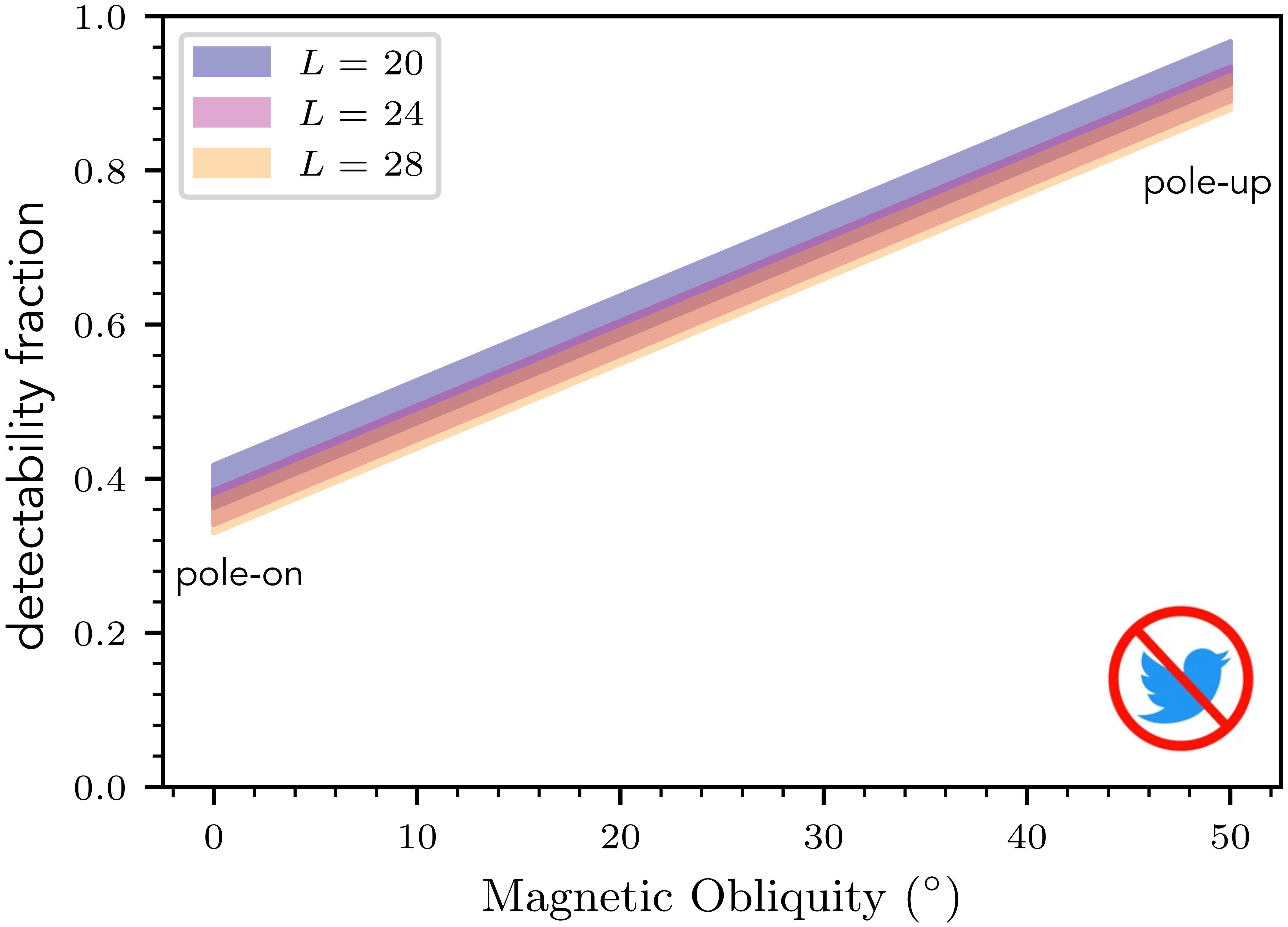


Hess+ (2008)

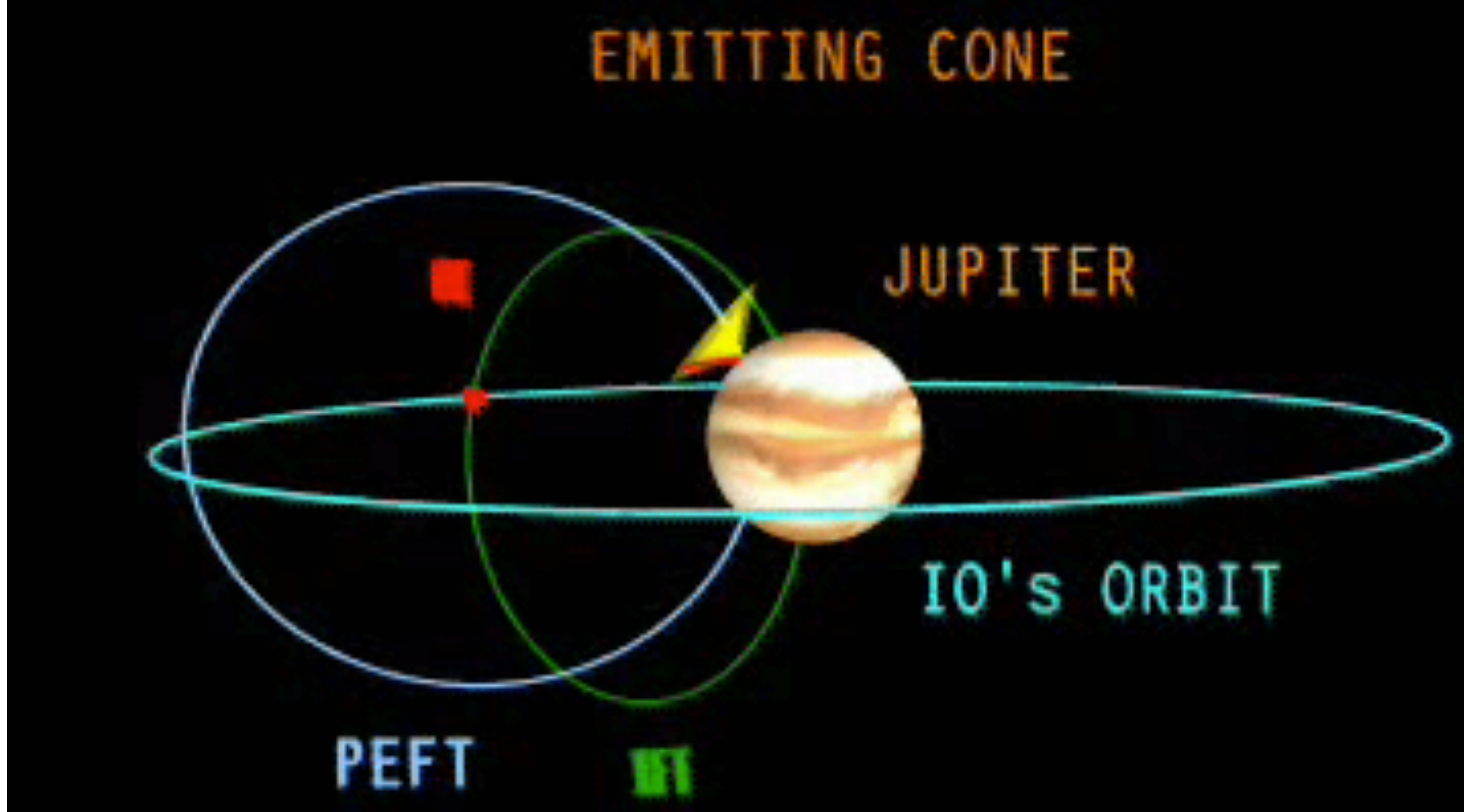
see also: Lamy+ (2008)

Louis+ (2019b)

Viewing geometry matters

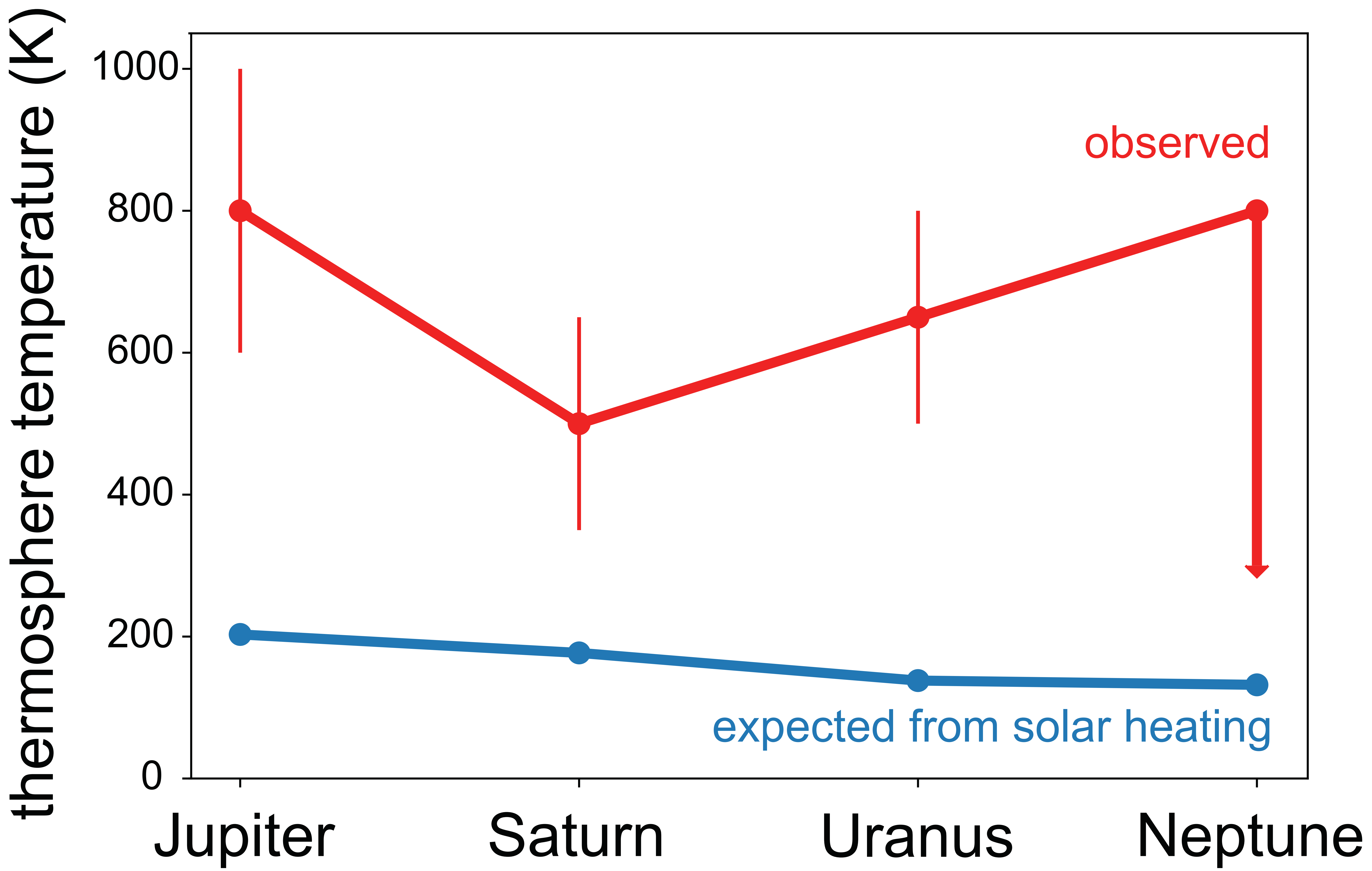


Kao, Pineda, Faherty, Vos (in prep)



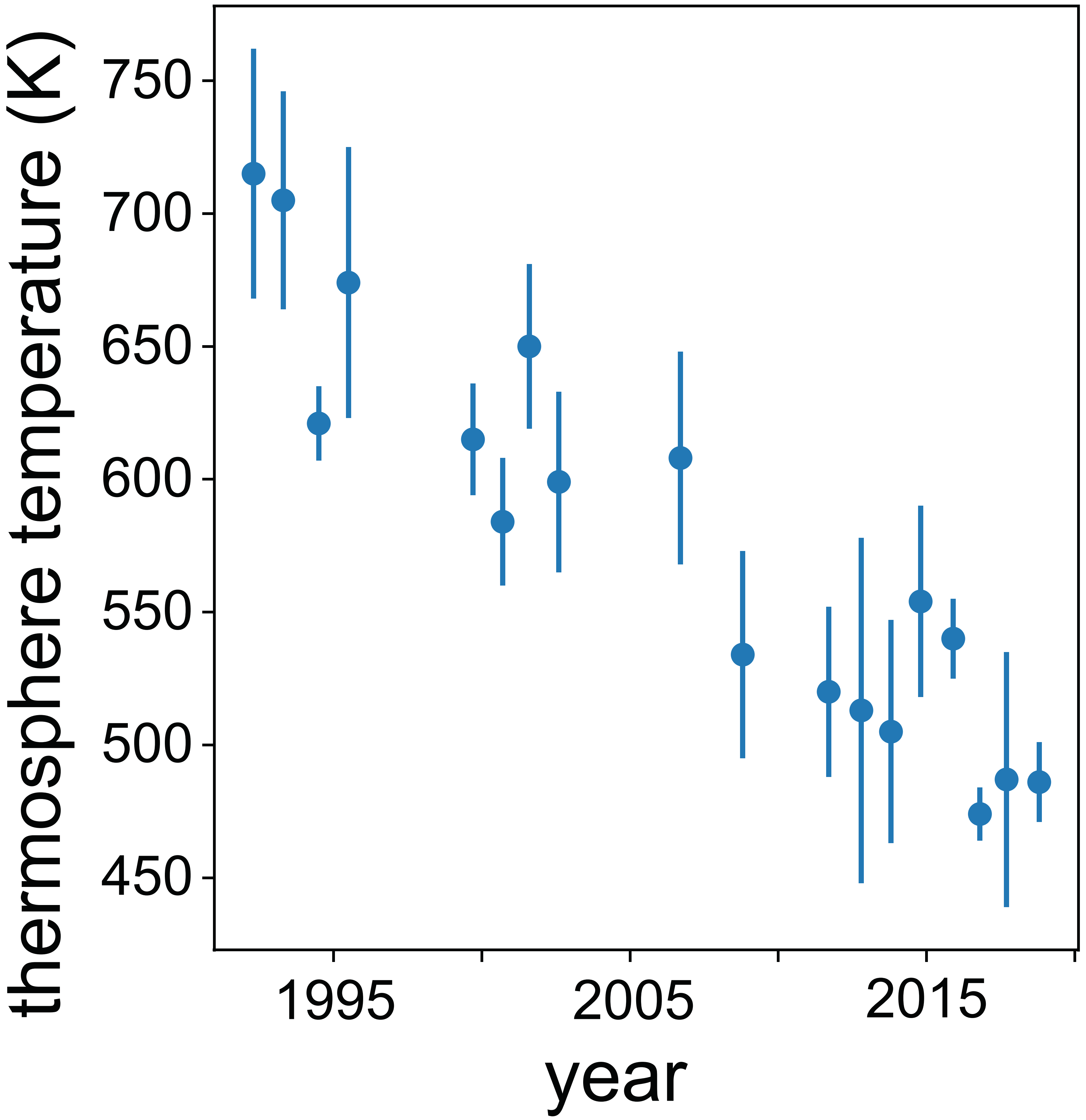
Imai Lab

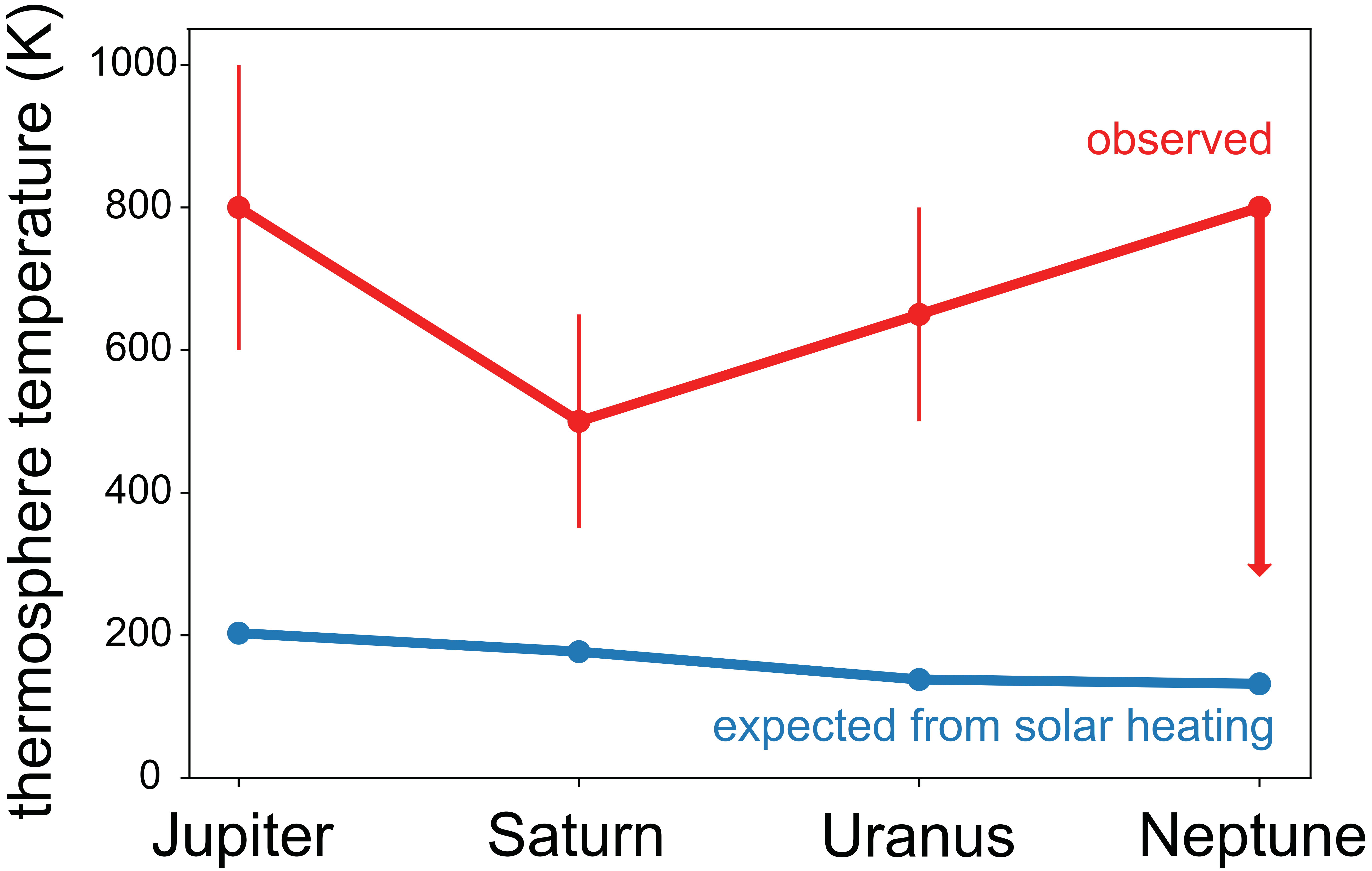
Uranus problem: a cooling ionosphere



Melin 2020

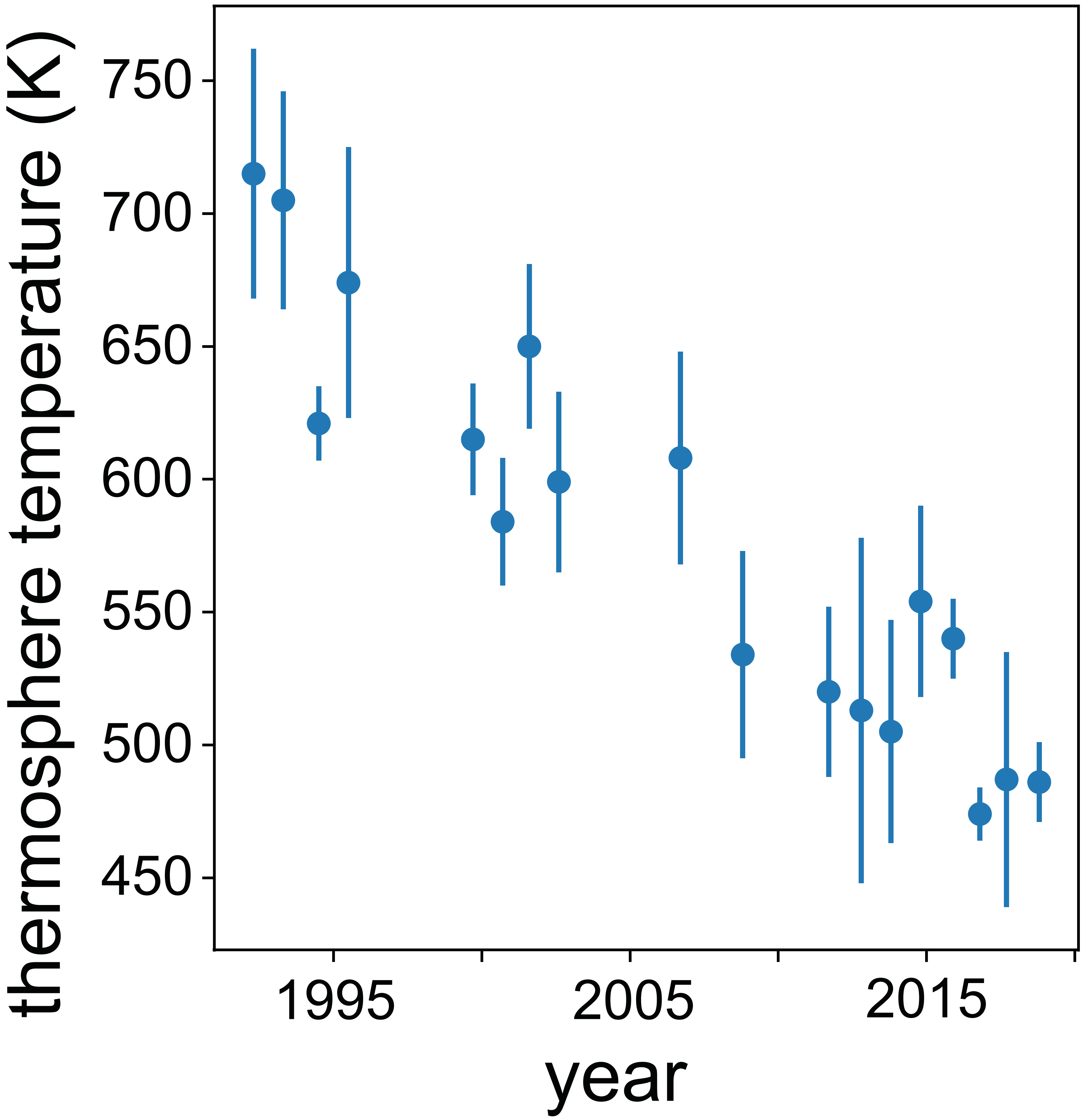
Uranus problem: a cooling ionosphere





Melin 2020

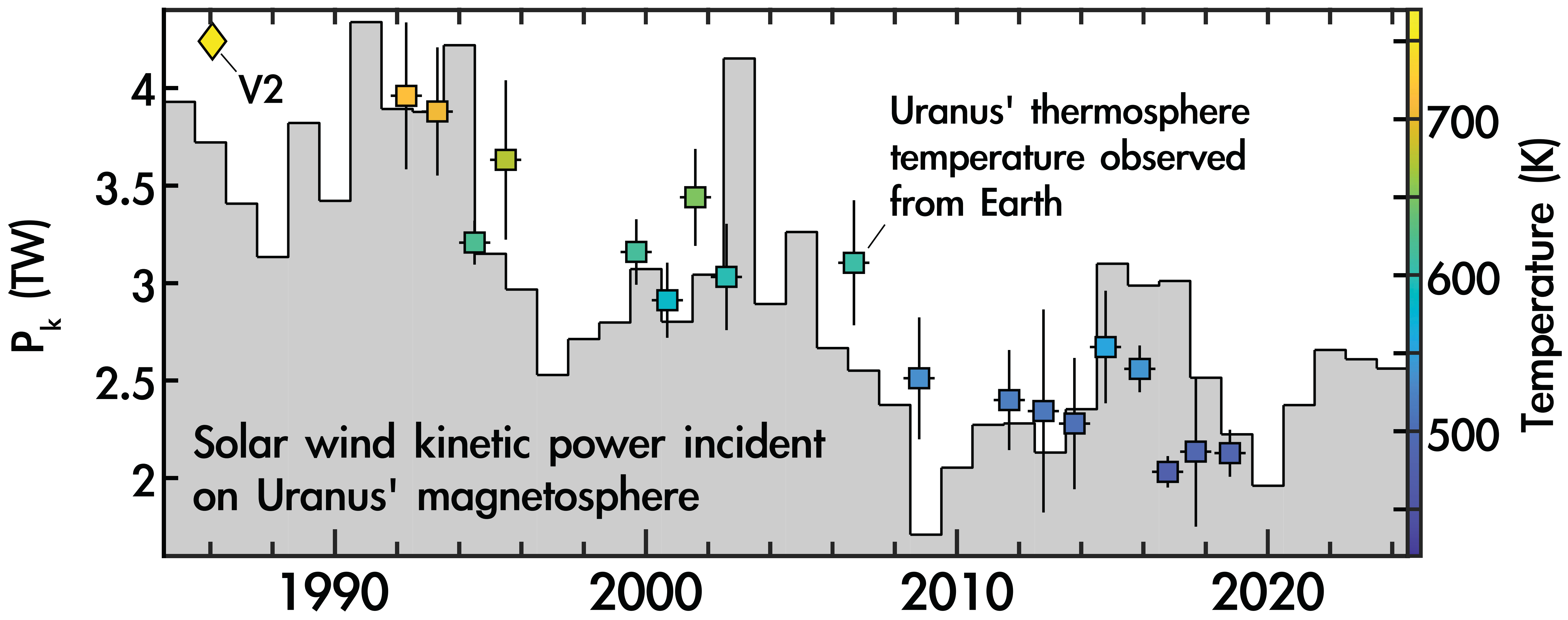
Uranus problem: a cooling ionosphere



- x solar cycle
- x seasons
- x geometric viewing effects

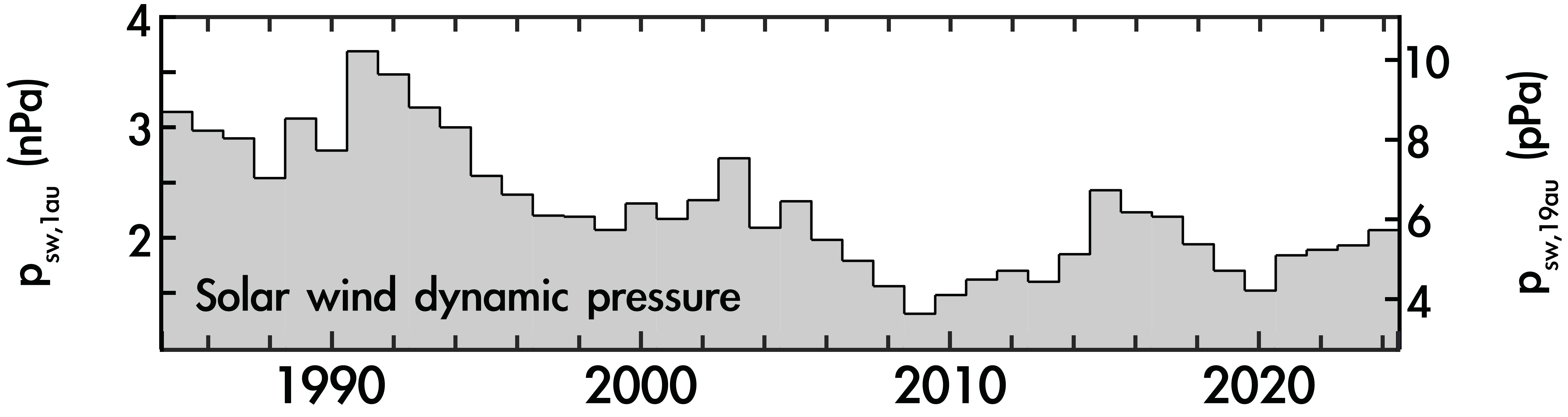
Melin 2020

Solar wind power governs Uranus thermosphere



Masters, Szalay, Zomerdijk-Russell, Kao (2024)

Solar wind power governs Uranus thermosphere



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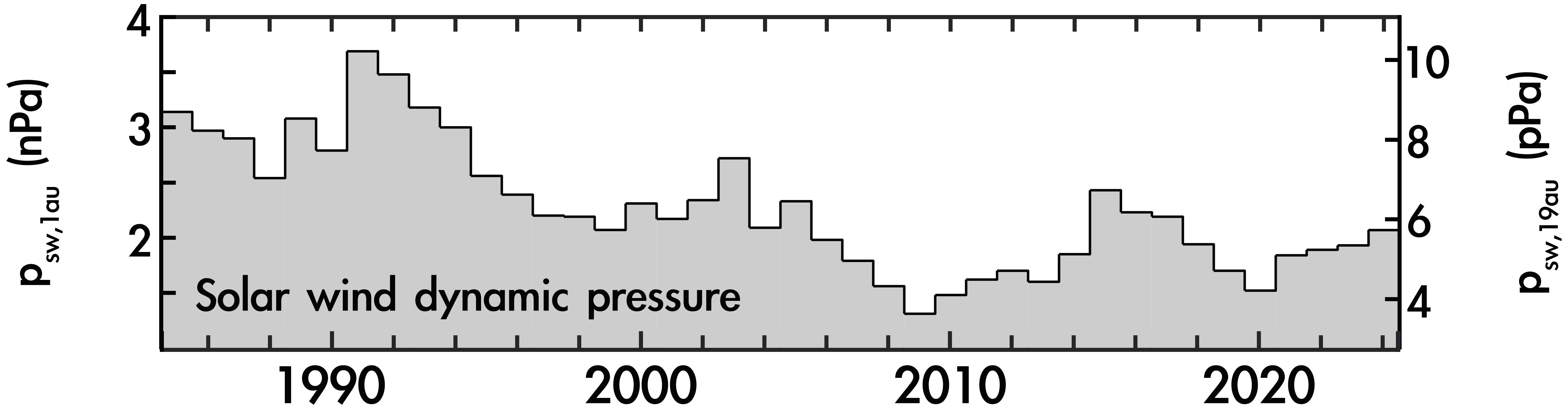
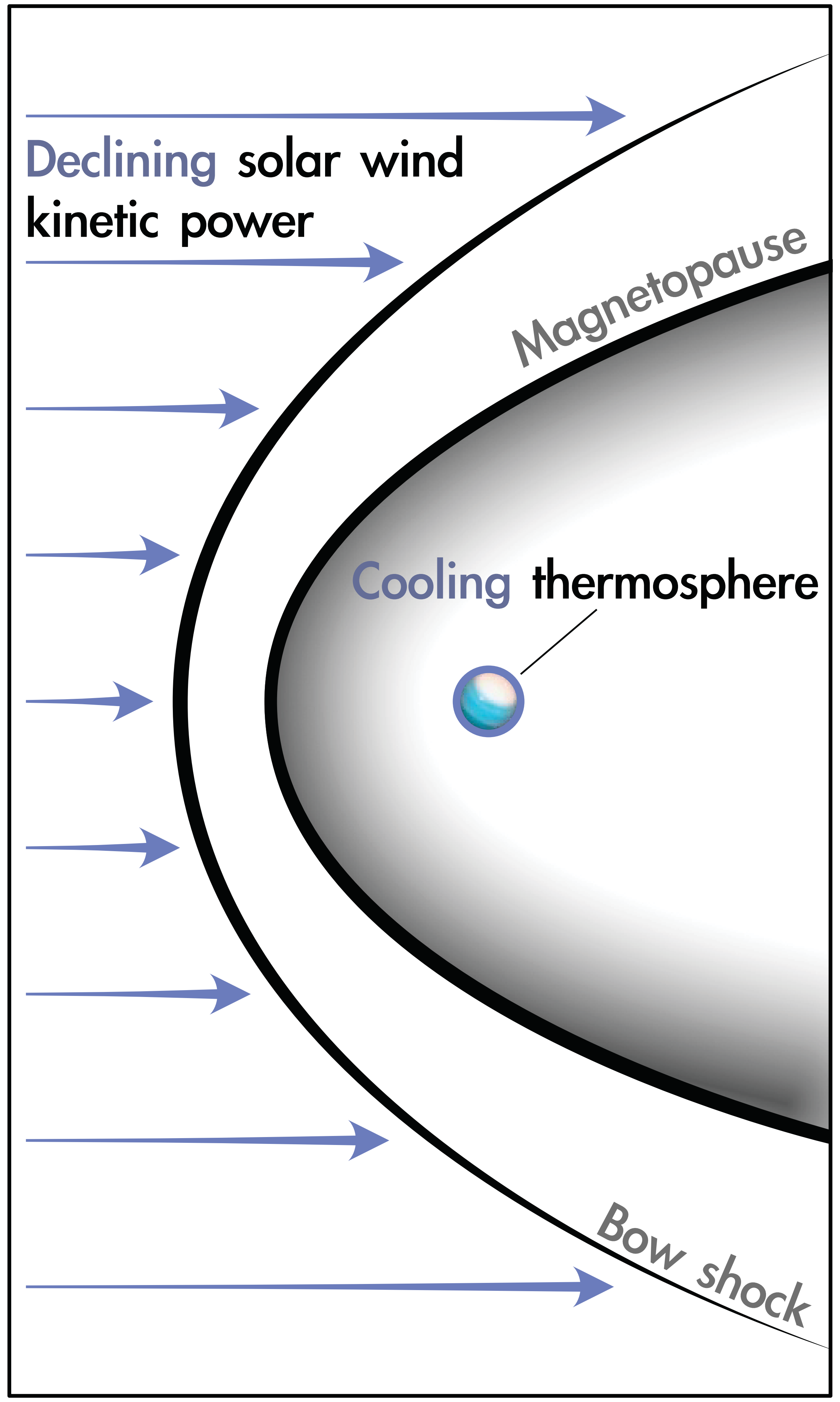
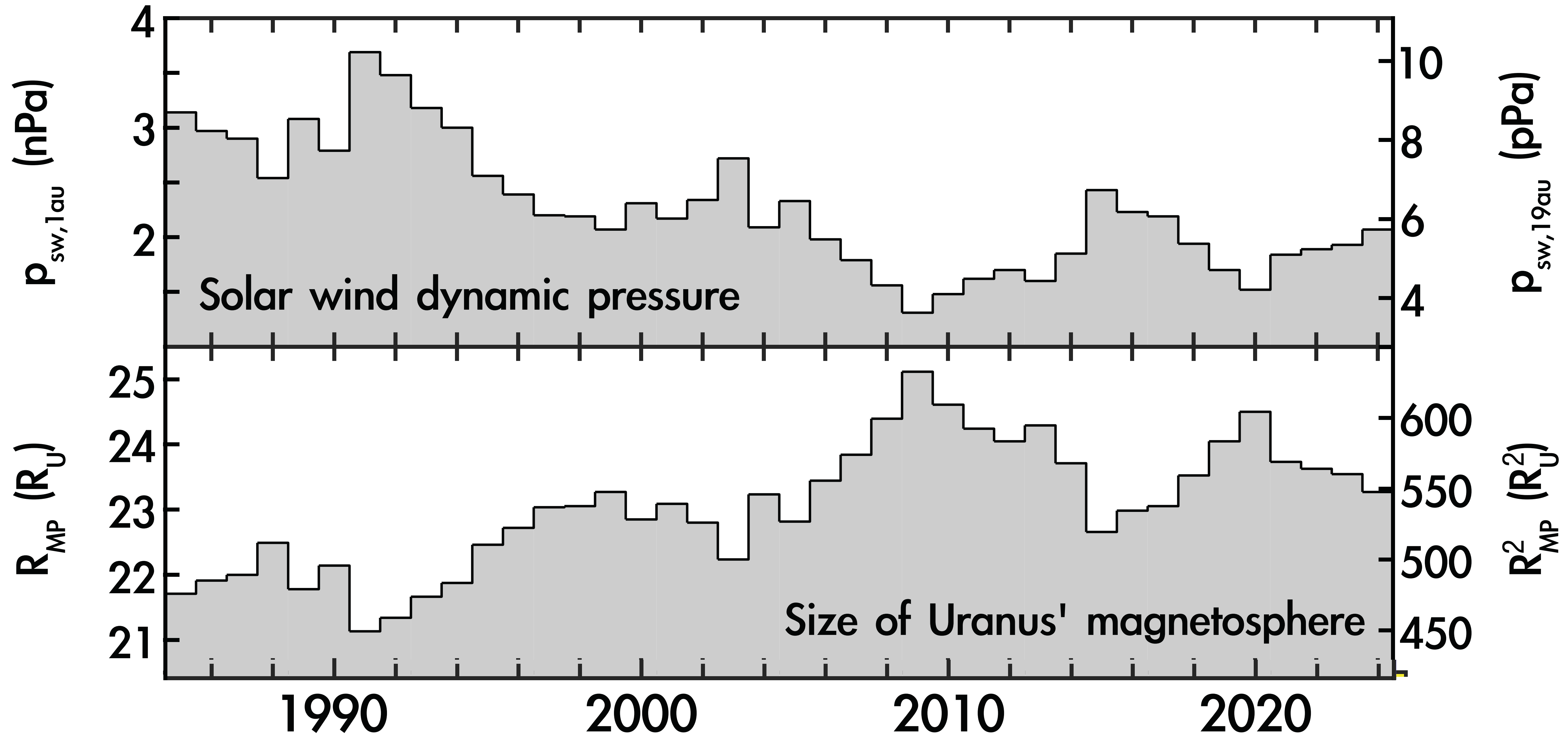
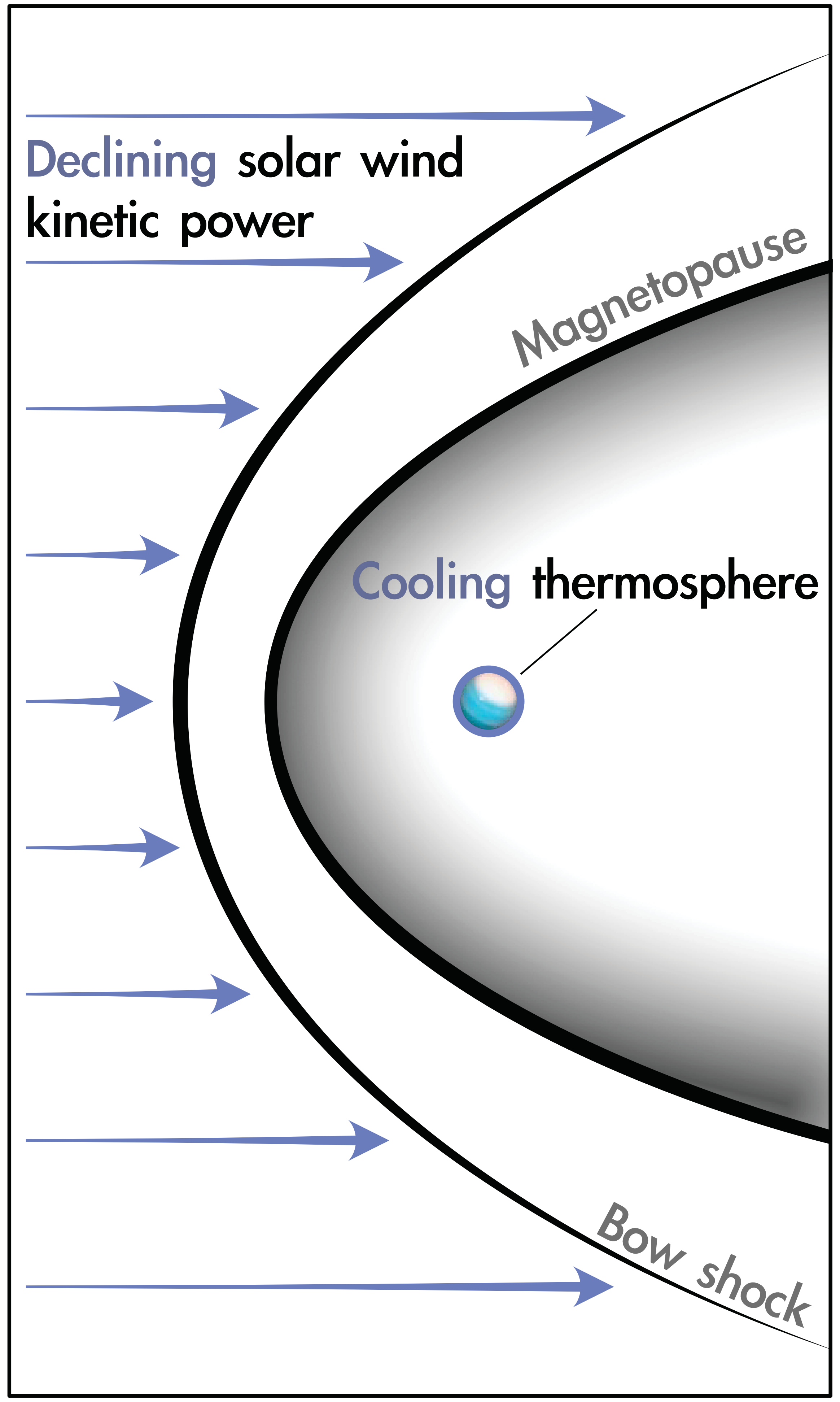




Masters, Szalay, Zomerdijk-Russell, Kao (2024)

Solar wind power governs Uranus thermosphere





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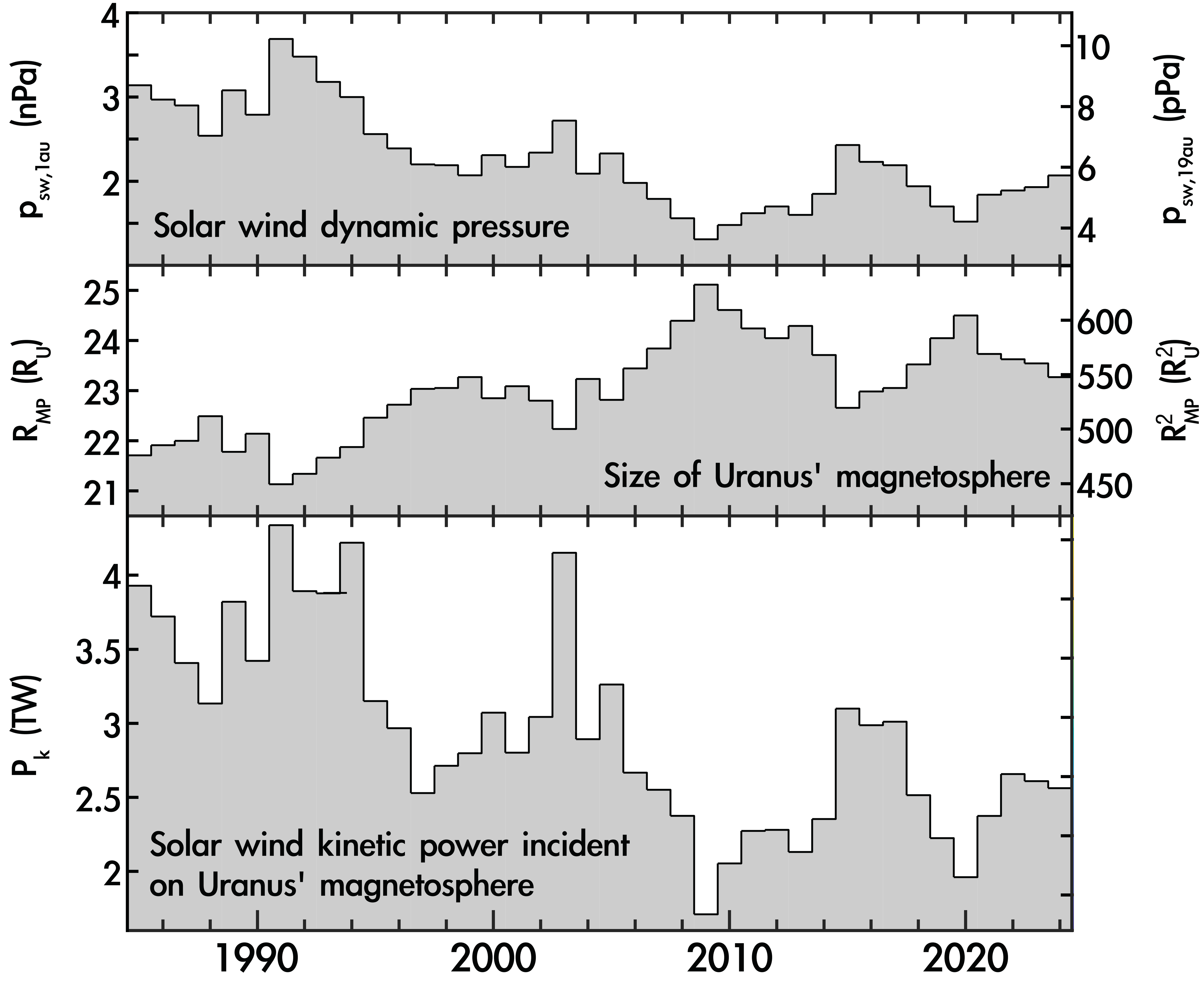

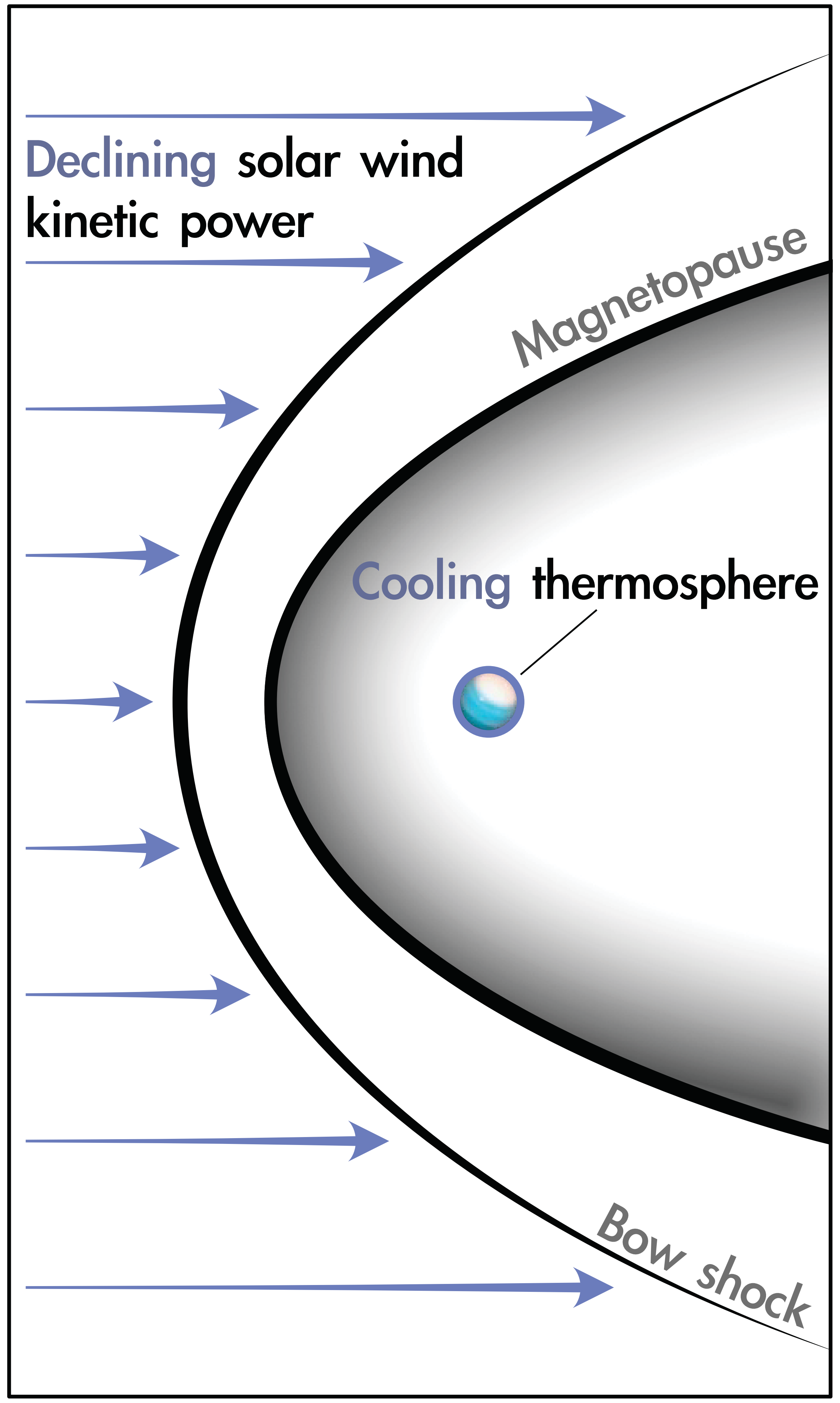

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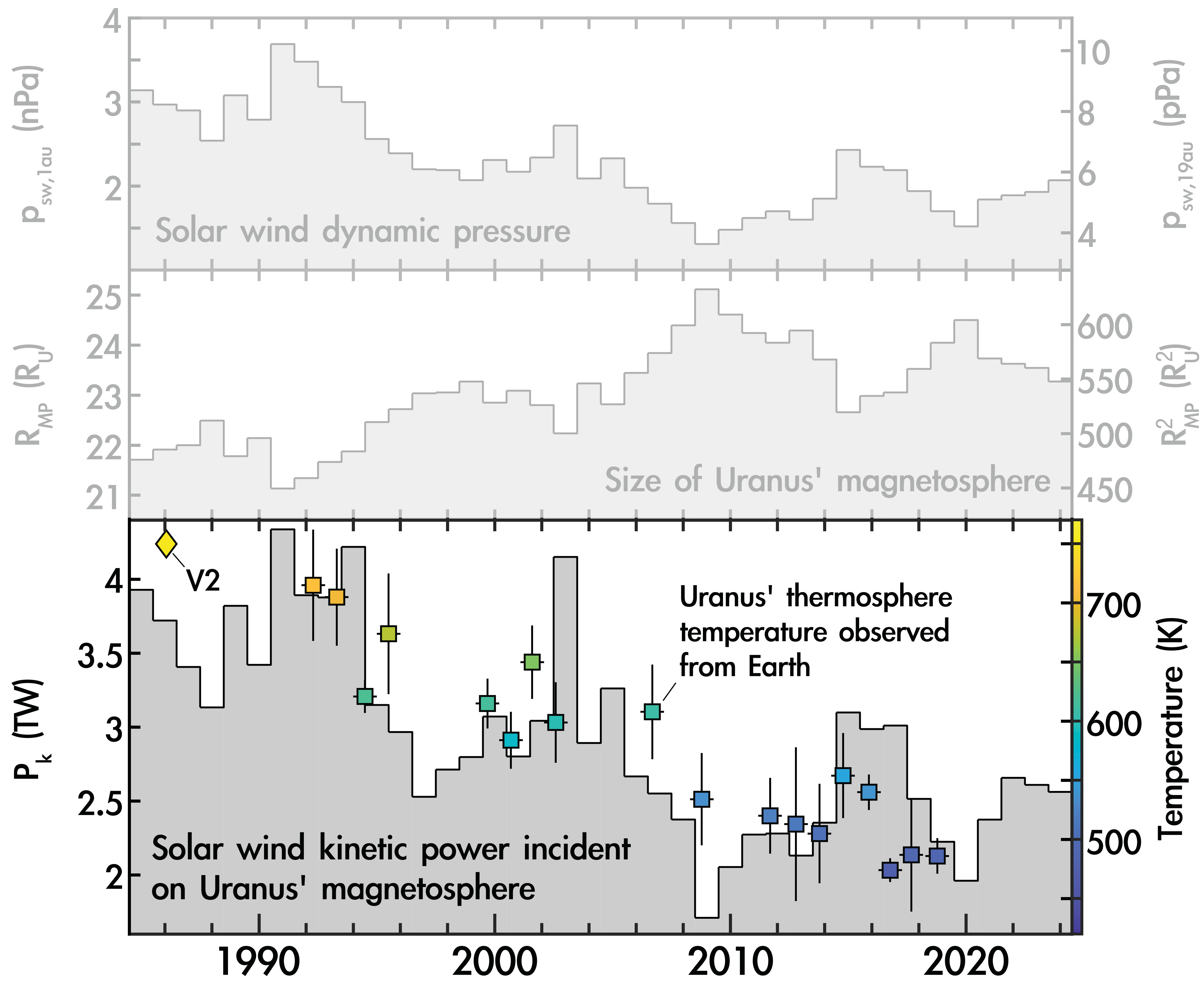
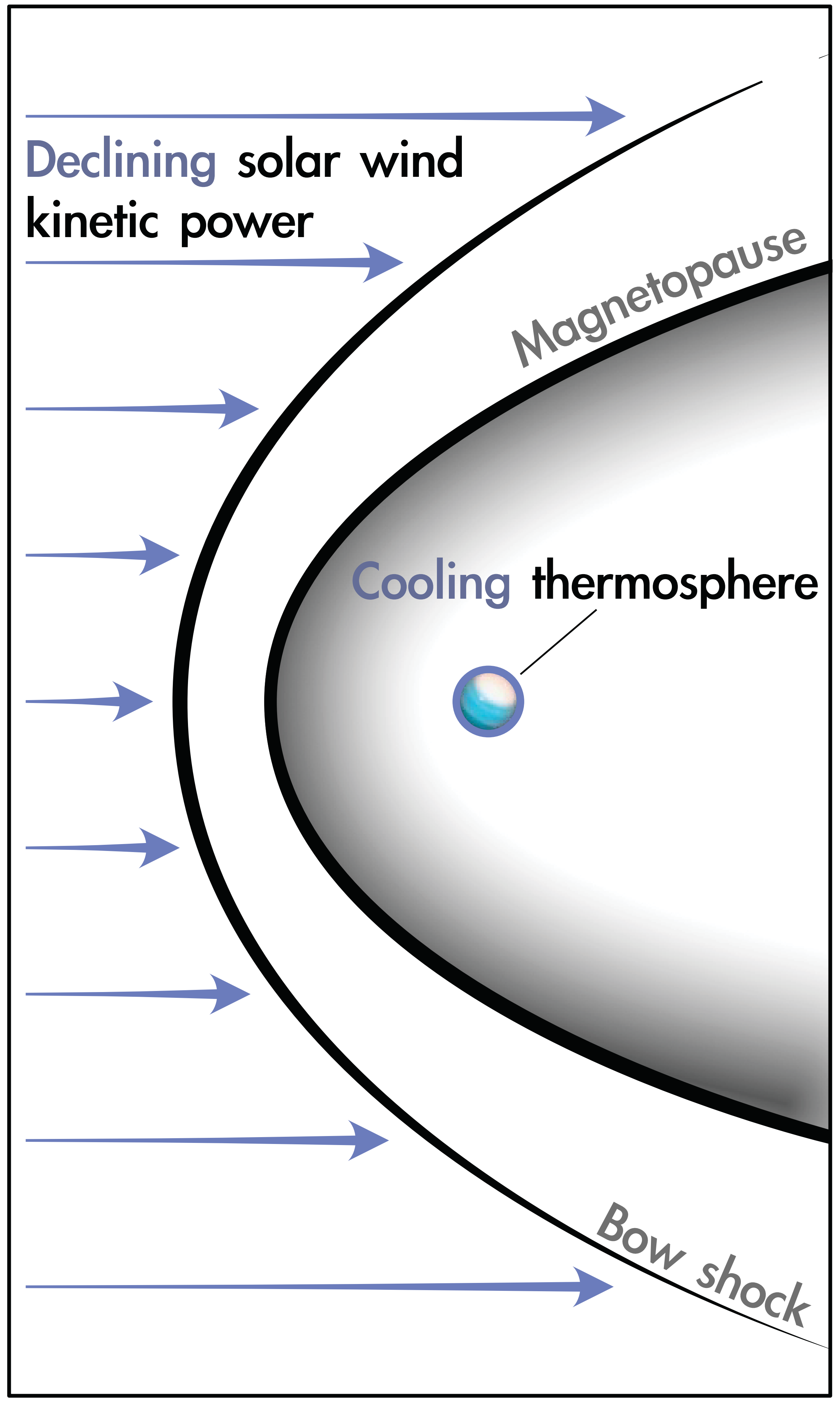
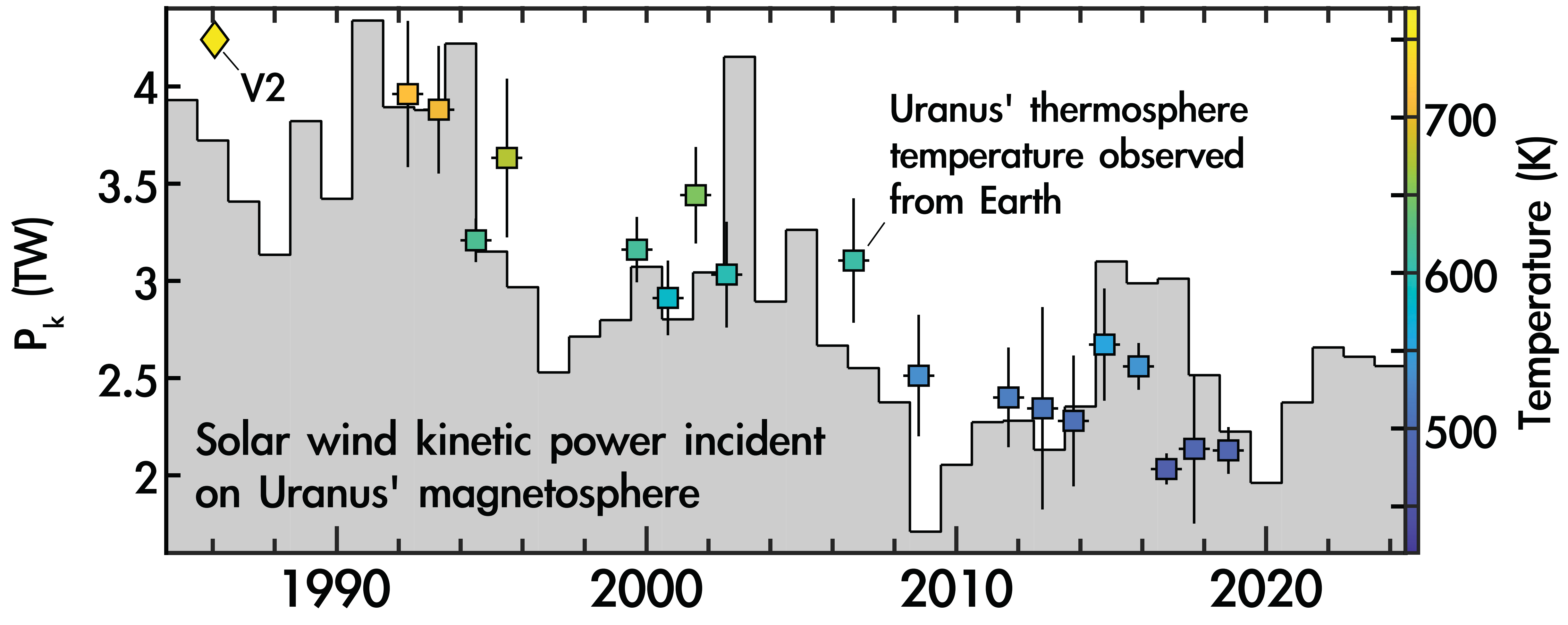




Masters, Szalay, Zomerdijk-Russell, Kao (2024)

Solar wind power governs Uranus thermosphere…

also Neptune's?



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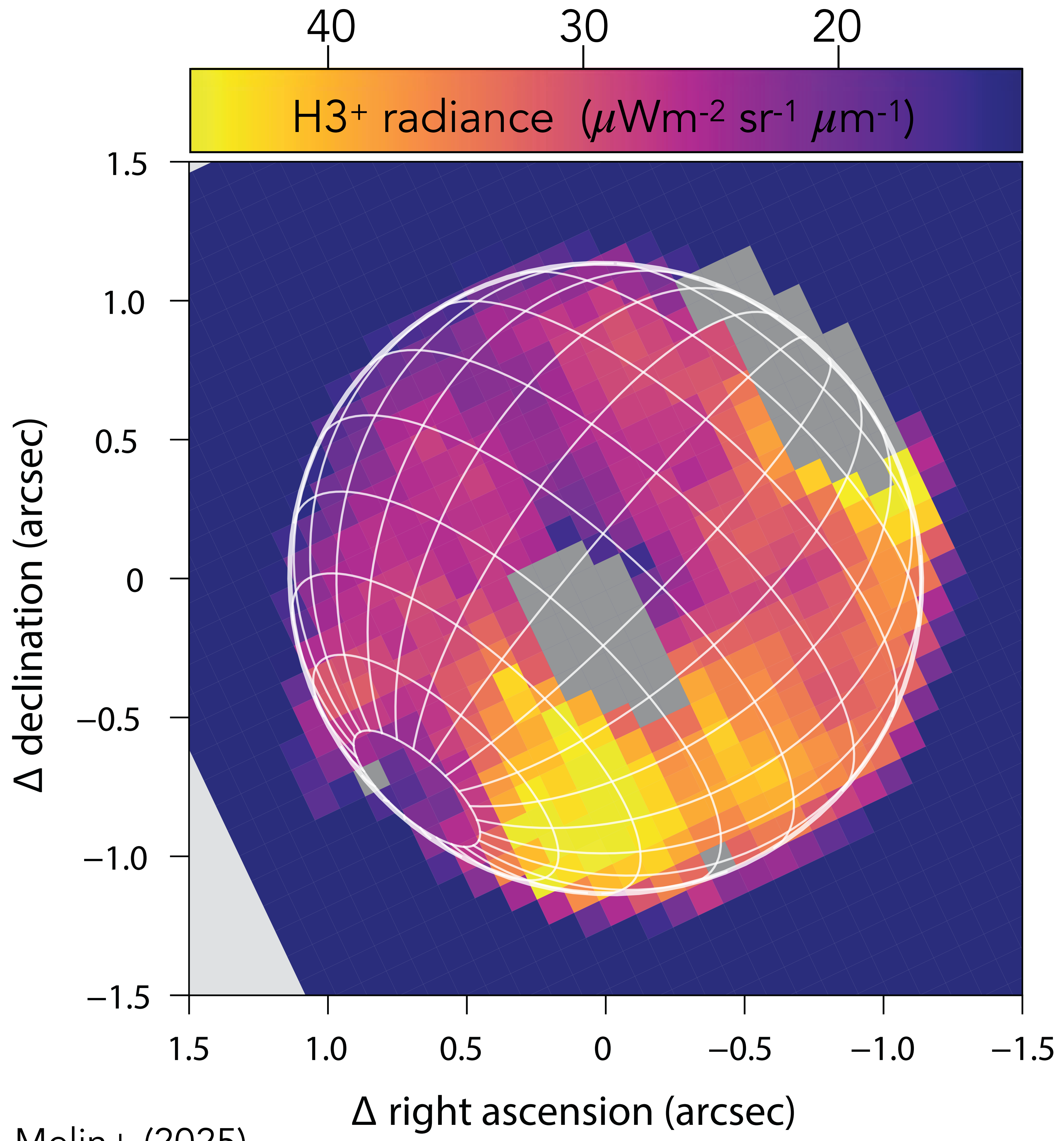
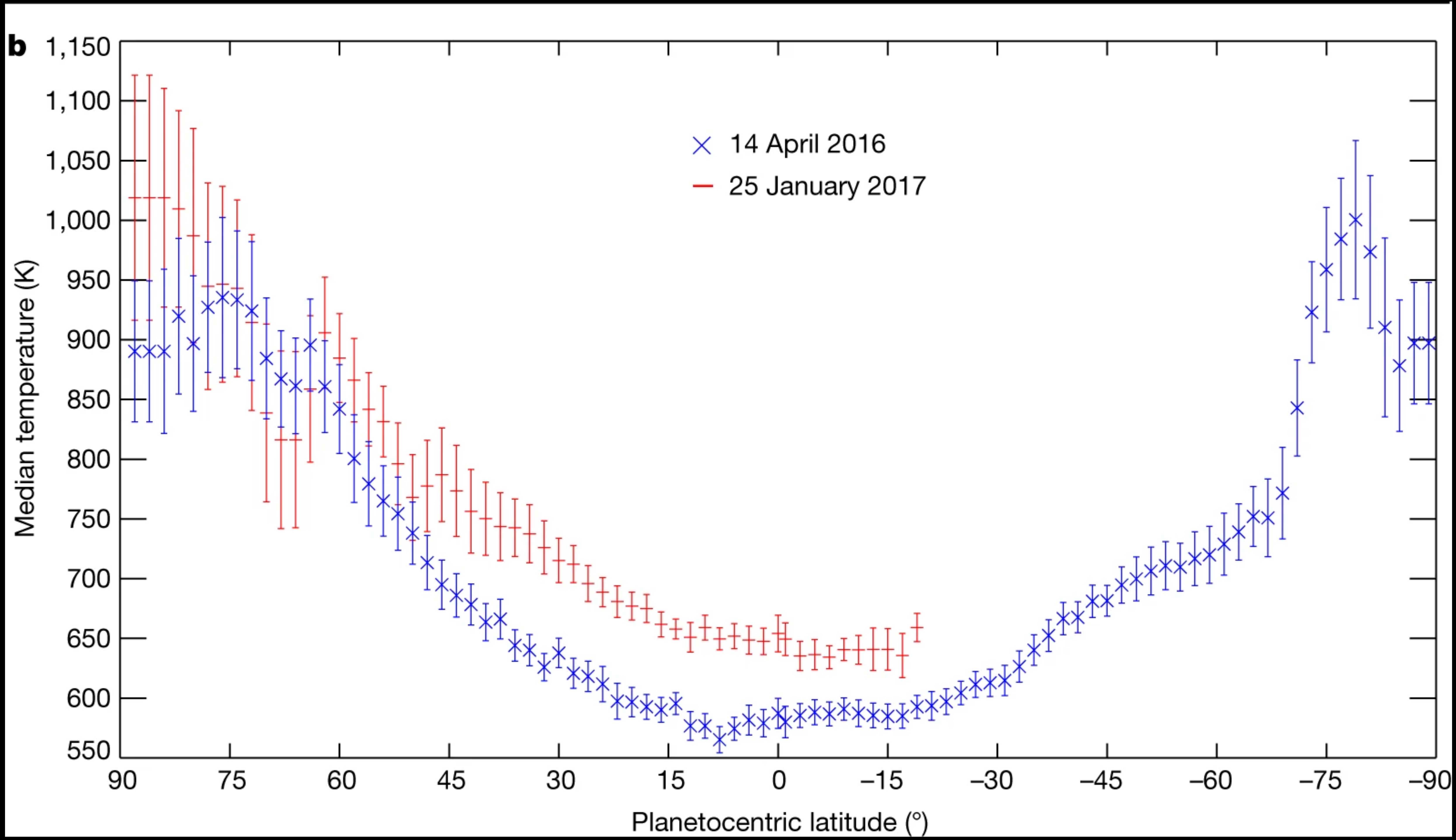


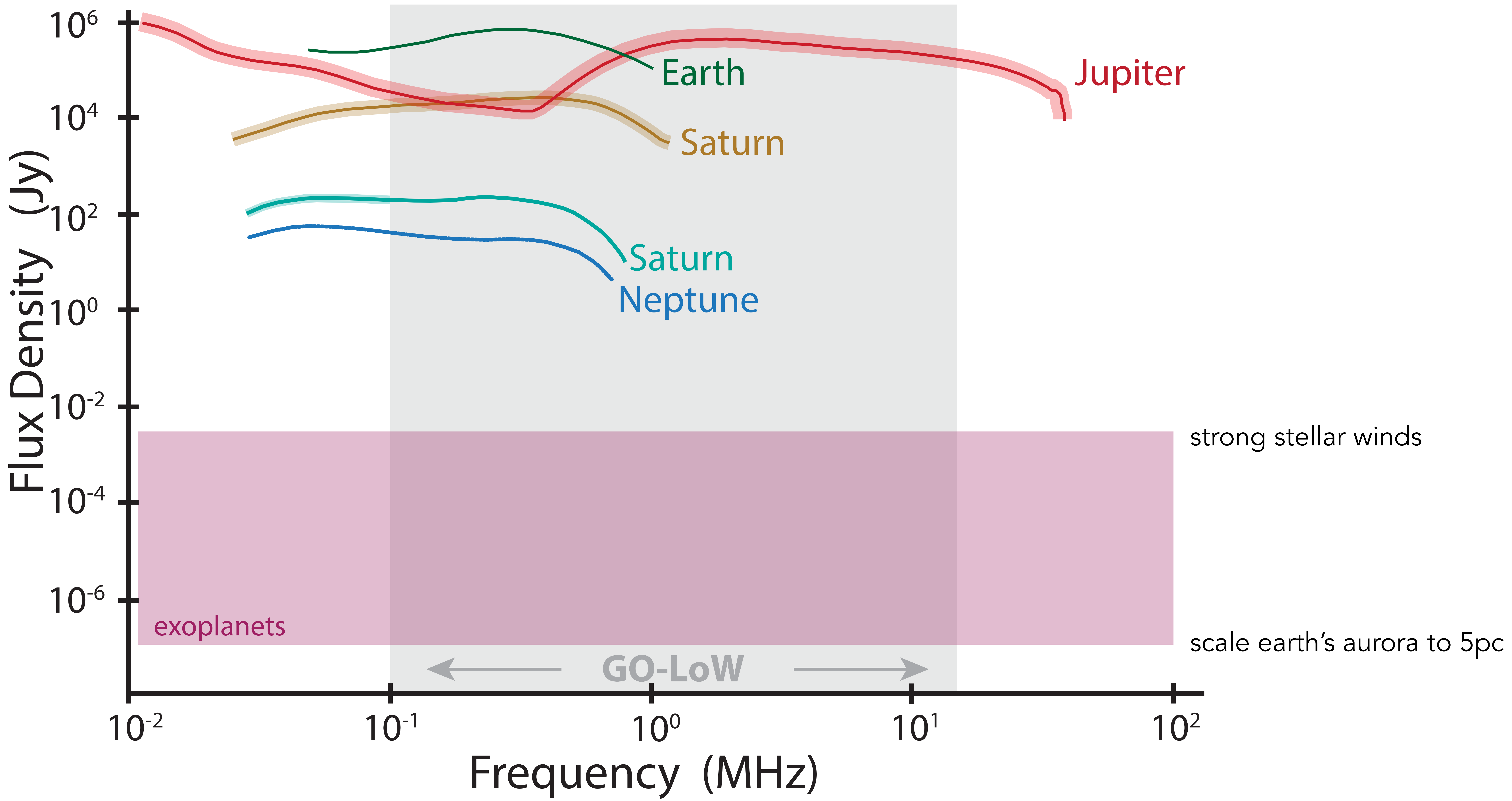
Melin+ (2025)

Yes: atmosphere <u>2x</u> cooler*

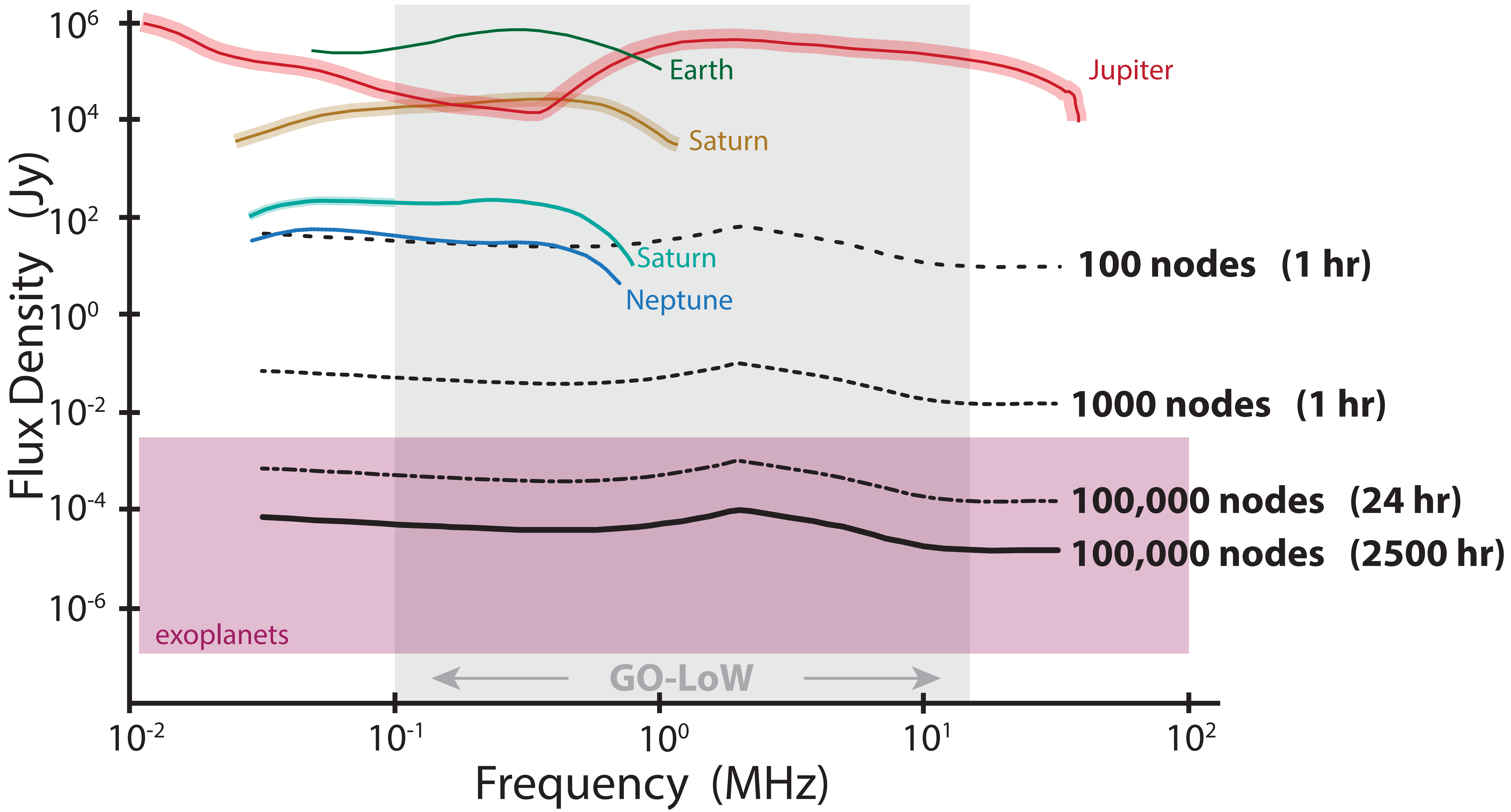


Global heating from Jovian aurorae respond to solar wind dynamic pressure

O'Donoghue+ (2021)



Kononov+ (2024)



Kononov+ (2024)

$$S \propto R_o^2 \; B_{\mathrm{wind}} \, \Delta u^2 \, \sin^2\theta \sqrt{\rho_{\mathrm{wind}}}$$

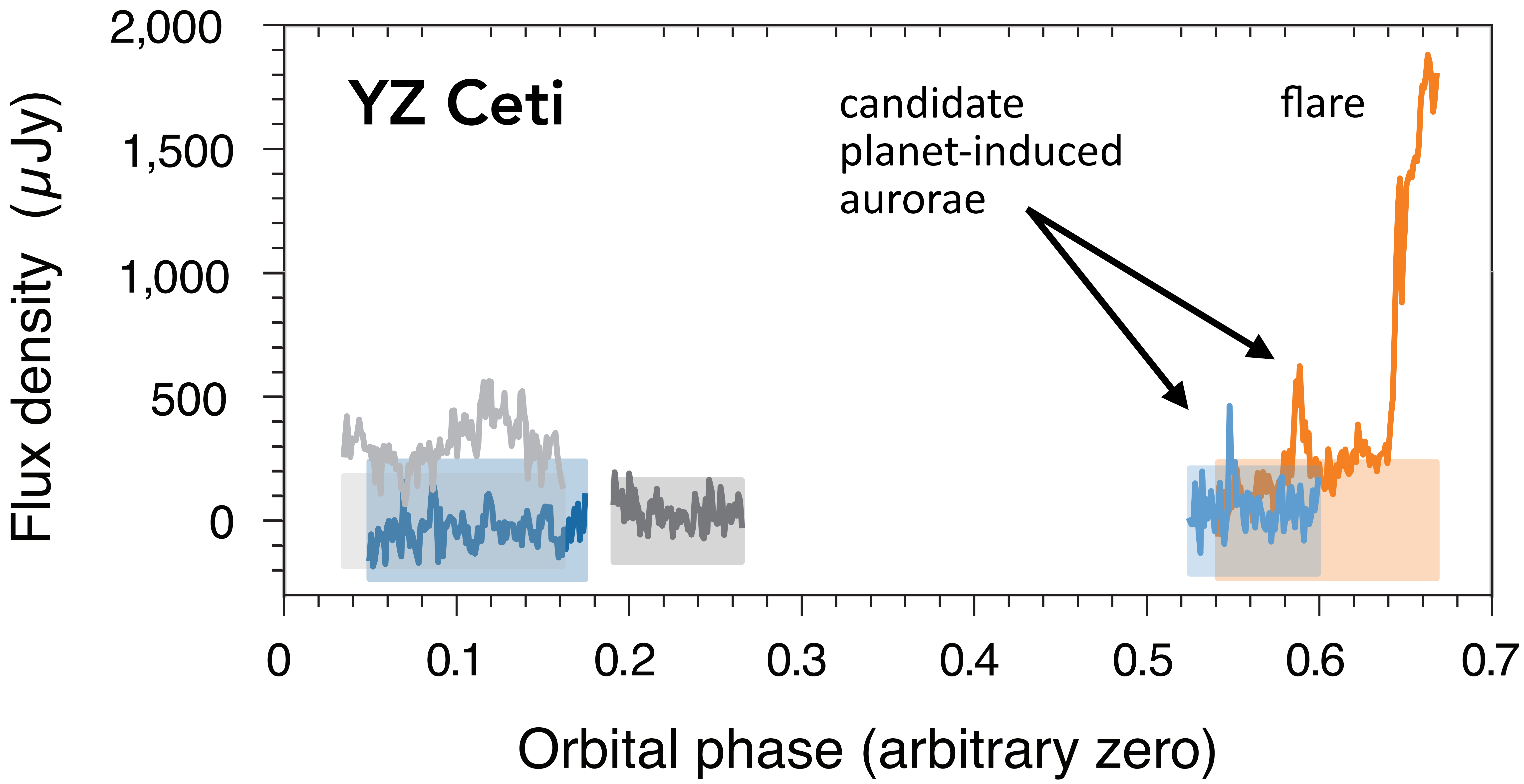
power dissipated

obstacle size

(magnetospheric plasma flow properties)

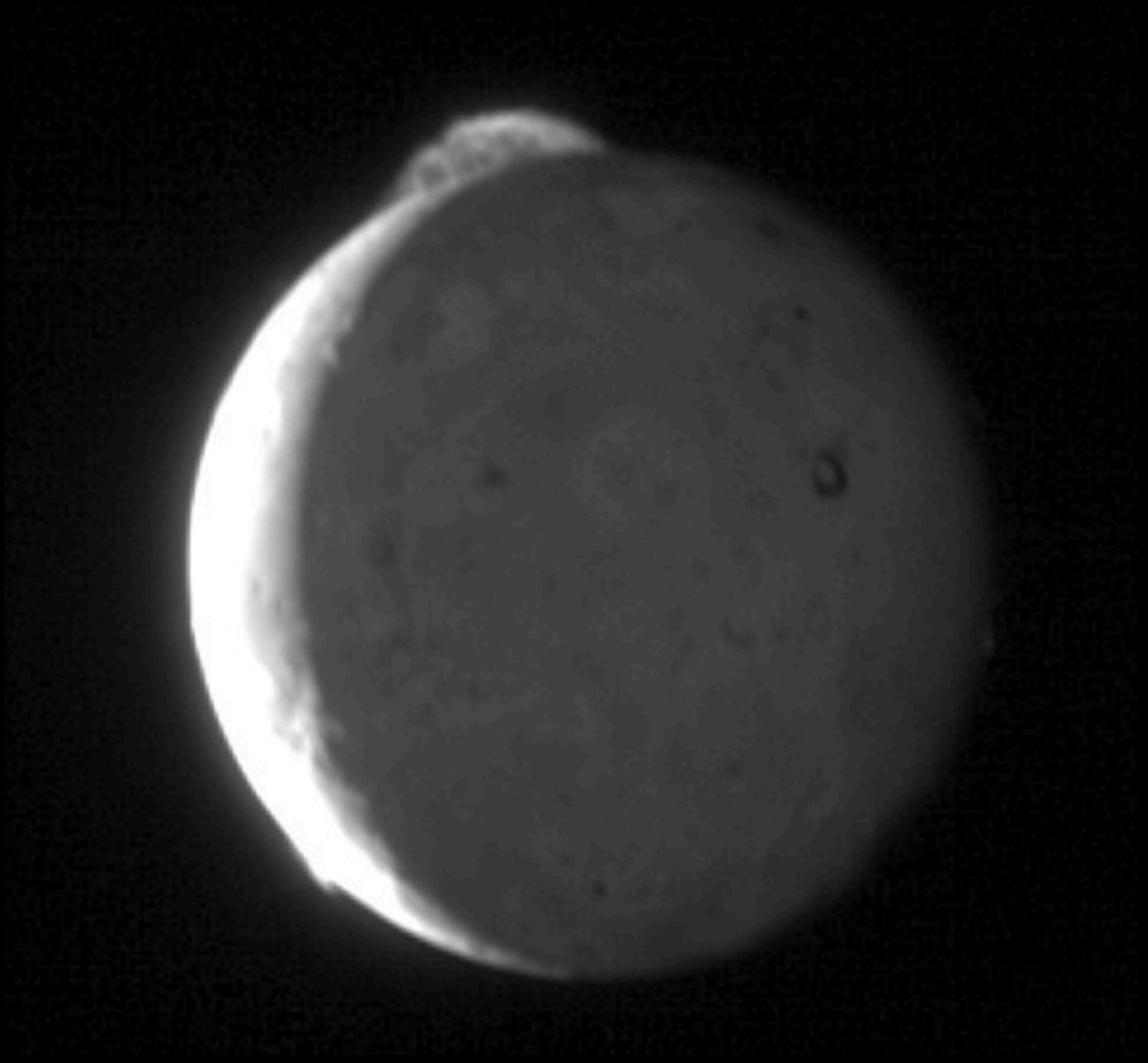
rocky planet magnetic field

(…around stars?)



Pineda & Villadsen 2023

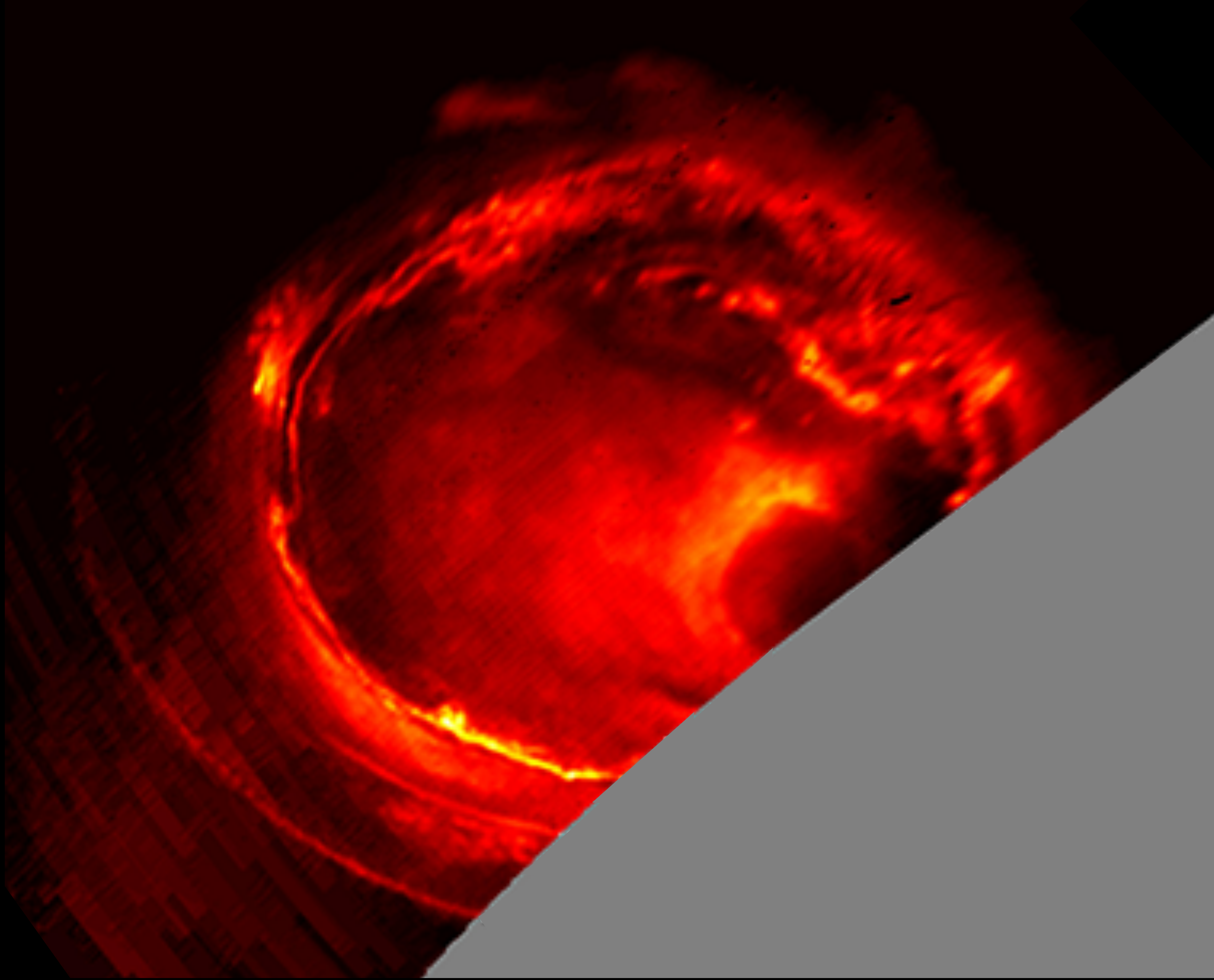
see also: Triglio+ 2023



Exo-volcanism seeding brown dwarf magnetospheres?

Hamilton+ (2013)
Image credit: NASA/Hamilton (New Horizons)

Melodie Kao (mkao@lowell.edu)

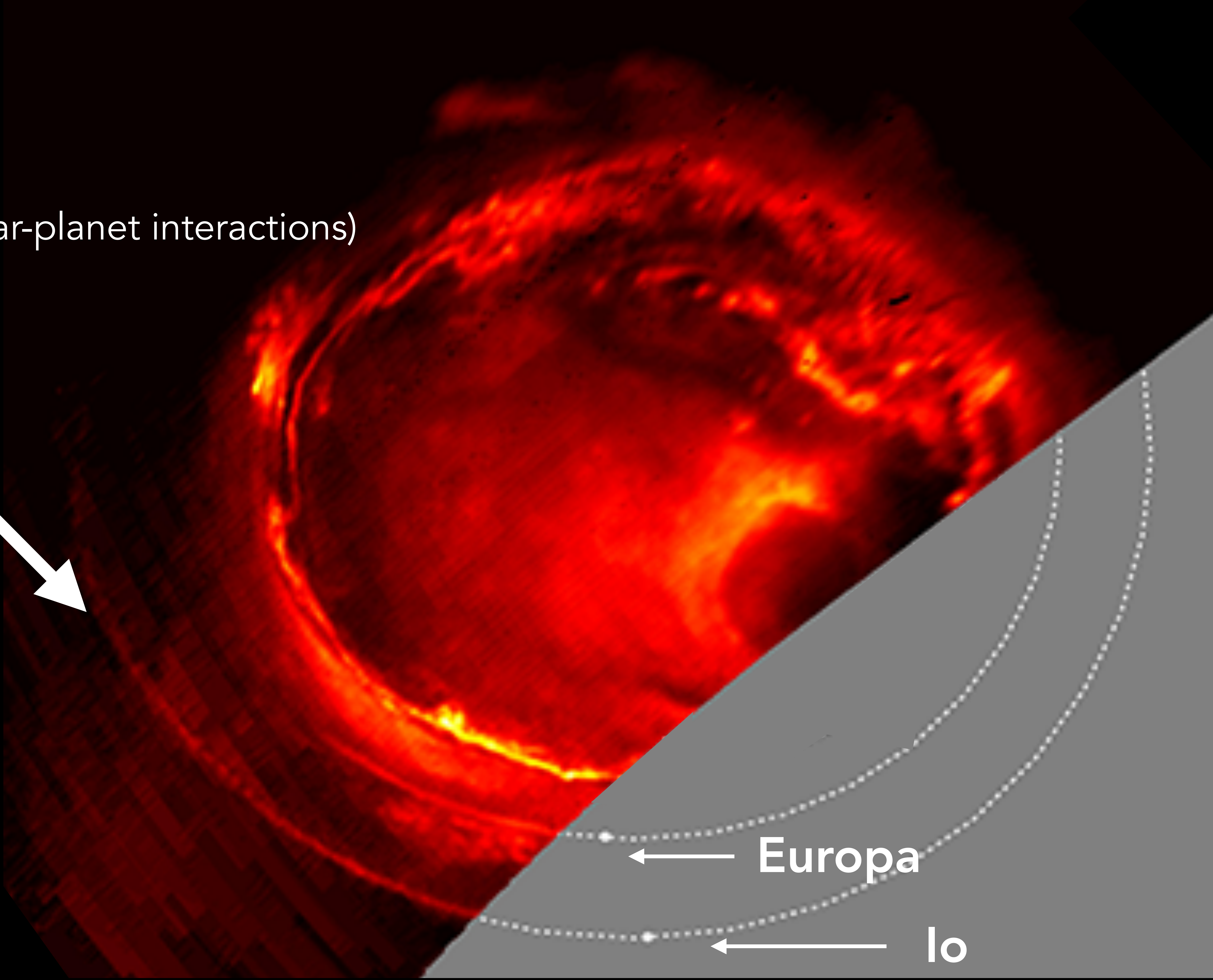


Mura+ 2017
(JUNO)

Melodie Kao (mkao@lowell.edu)

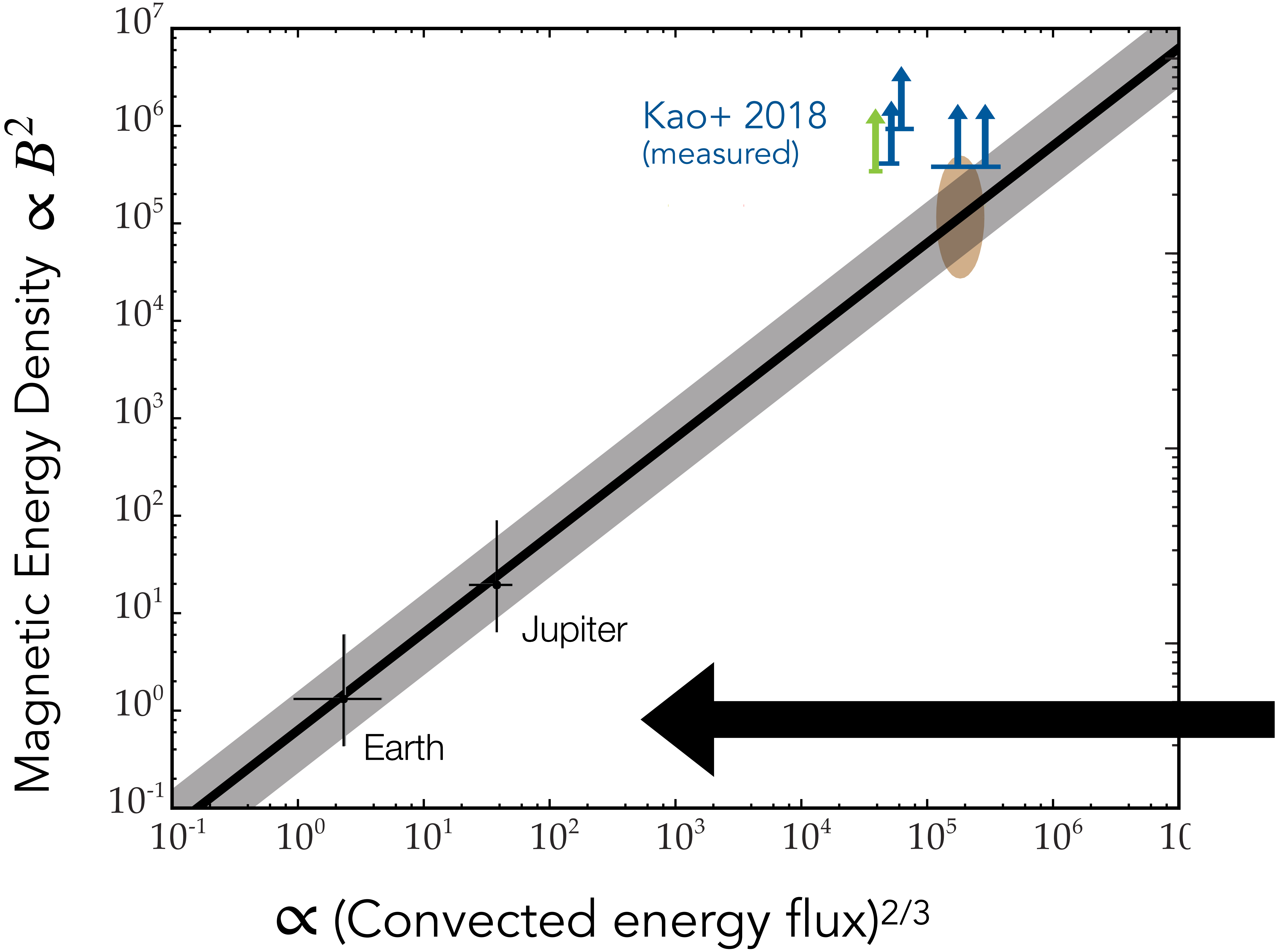
satellite-driven

(e.g. Io-Jupiter interaction; star-planet interactions)



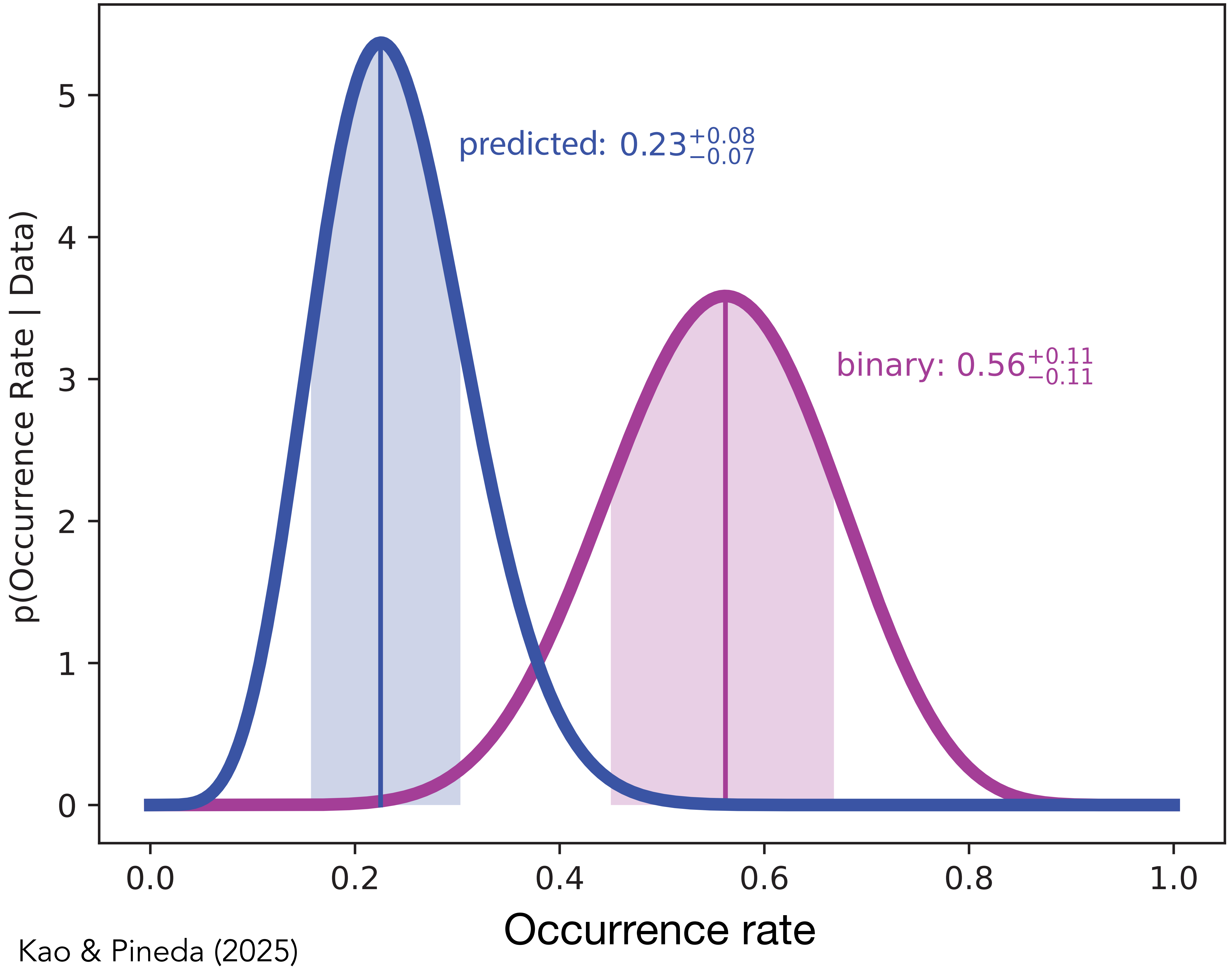
Mura+ 2017
(JUNO)

Melodie Kao (mkao@lowell.edu)



terrestrial satellites
around brown dwarfs

Binarity **enhances** binary radiation belt occurrence rate.



Kao & Pineda (2025)

$$f_p \ll f_c$$

plasma freq.
$\propto n_e^{1/2}$

cyclotron freq.
$\propto B$

radio aurorae require rarified plasma

melodie.kao@ucsc.edu

$$\frac{f_p}{f_c} \ll 1$$

plasma freq. $\propto n_e^{1/2}$

cyclotron freq. $\propto B$

radio aurorae require rarified plasma

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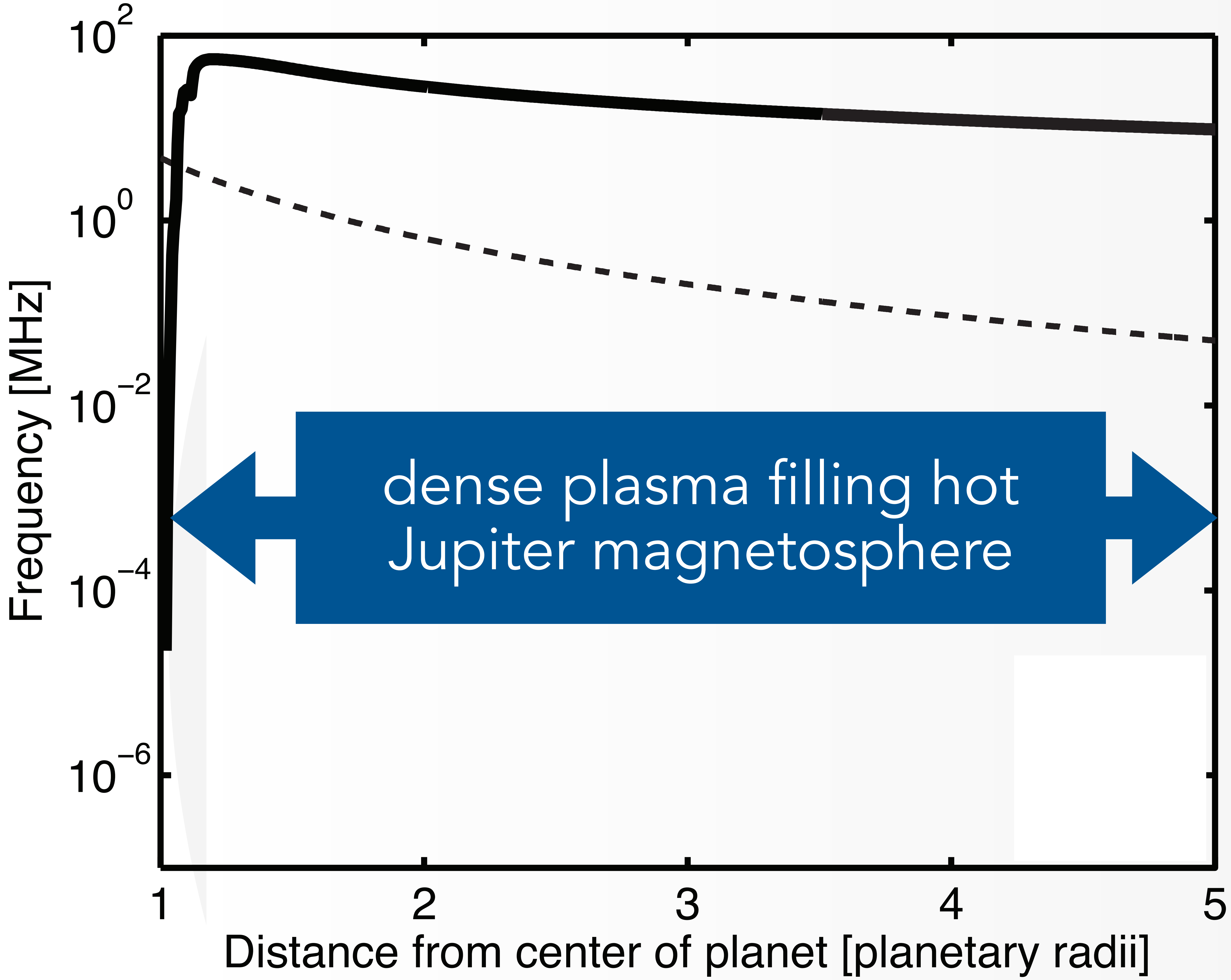
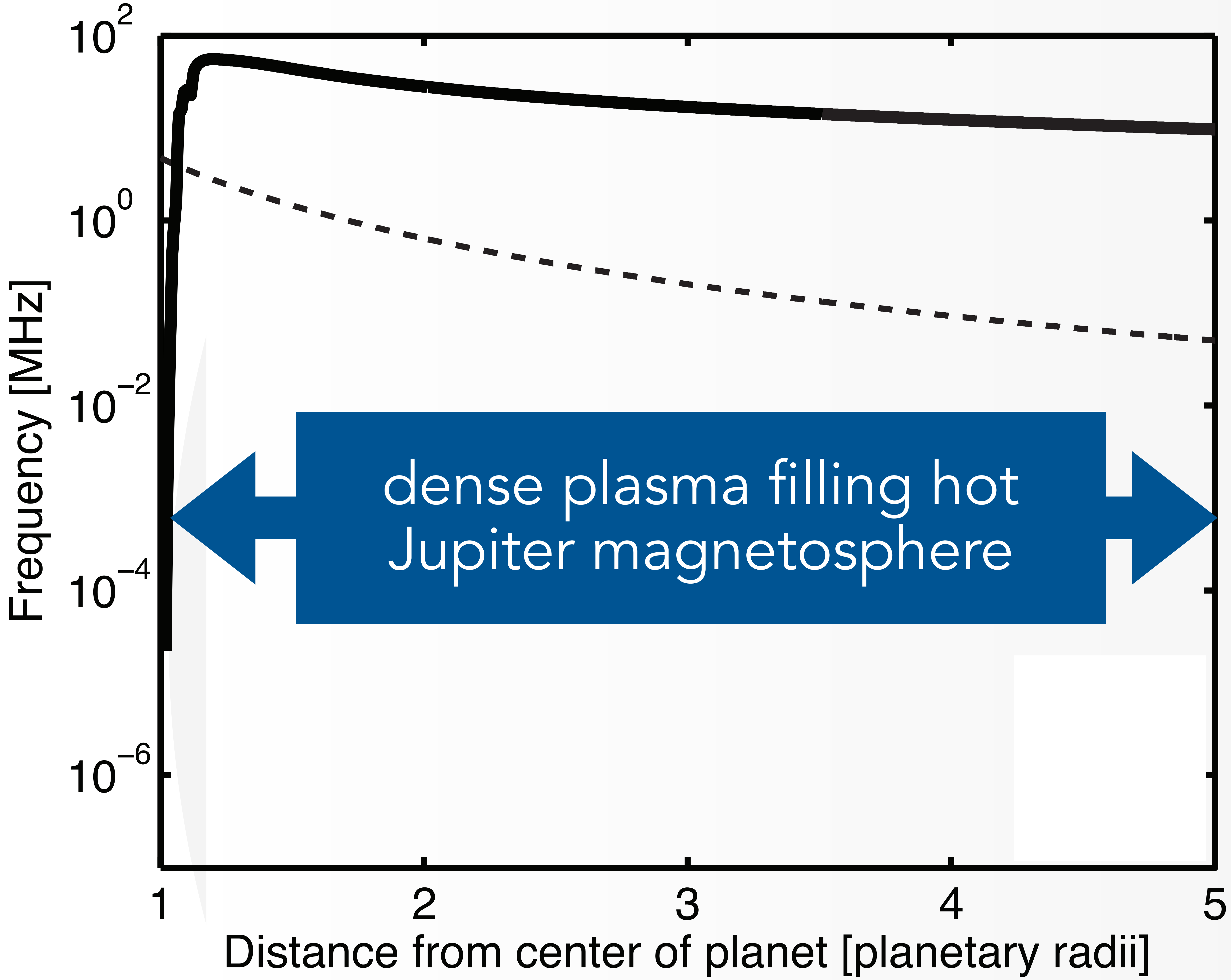


$$\frac{f_p}{f_c} \ll 1$$

plasma freq. $\propto n_e^{1/2}$

cyclotron freq. $\propto B$

Weber+ 2017; see also: Daley-Yates & Stevens 2017, 2018



$$\frac{f_p}{f_c} \gg 1$$

plasma freq. $\propto n_e^{1/2}$

cyclotron freq. $\propto B$

Weber+ 2017; see also: Daley-Yates & Stevens 2017, 2018