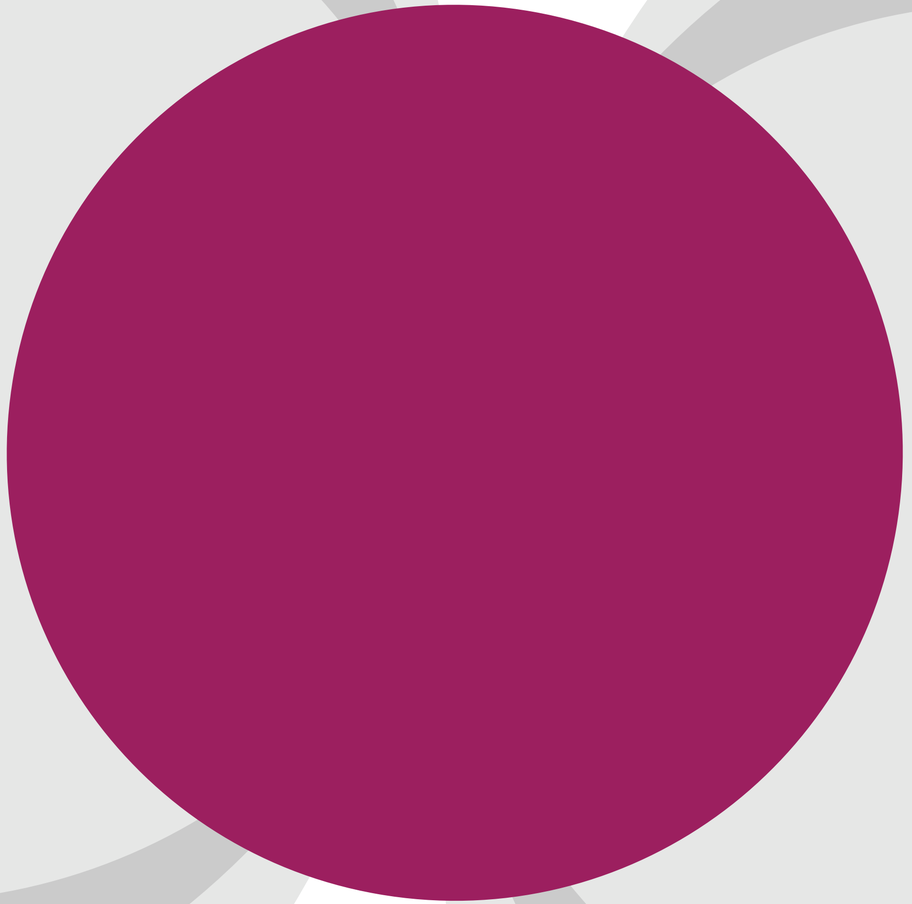
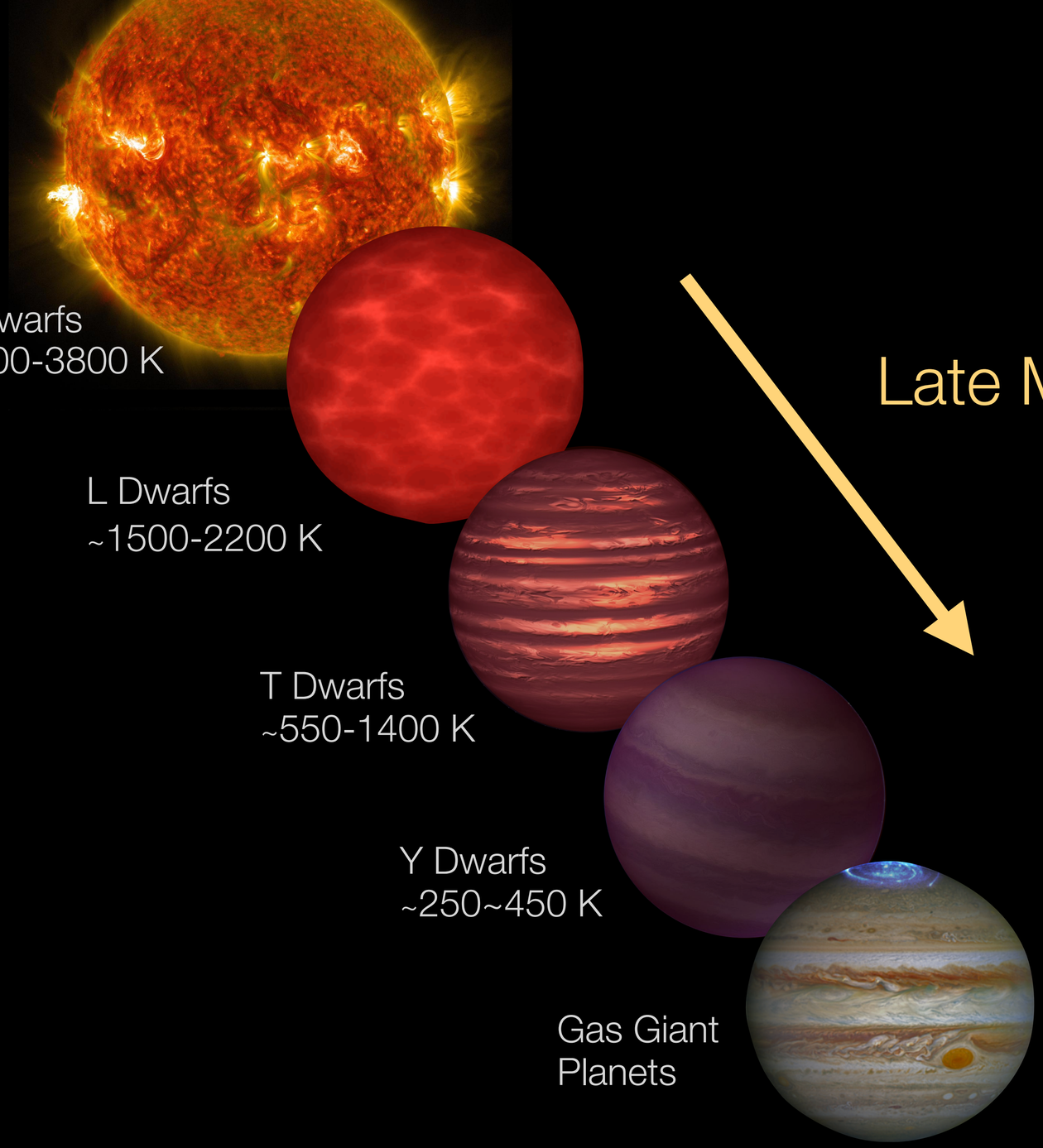
Ultracool dwarfs and Star-Planet Interactions



Melodie Kao
Lowell Observatory



Ultracool dwarfs:
Late M dwarf through brown dwarfs

Melodie Kao (mkao@lowell.edu)

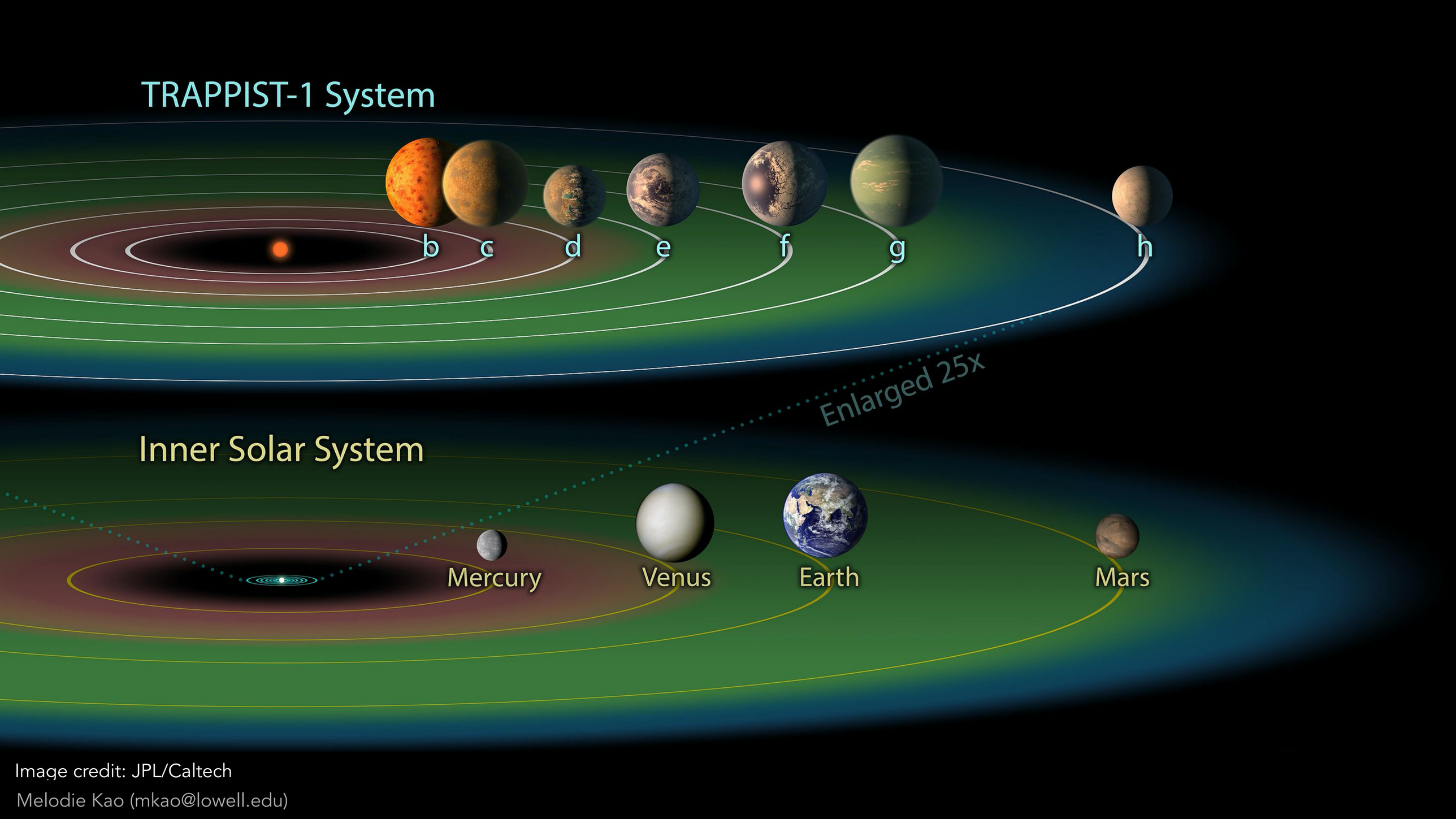
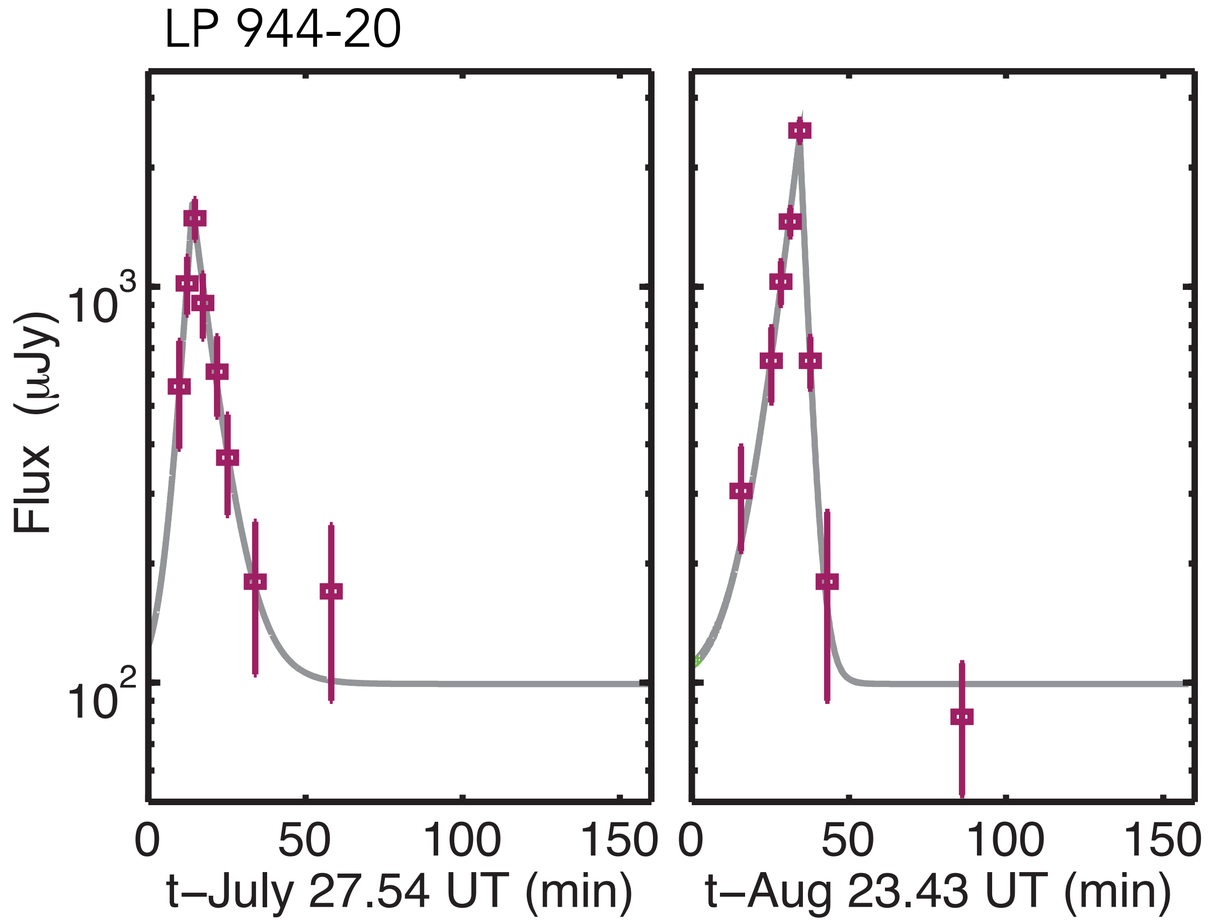
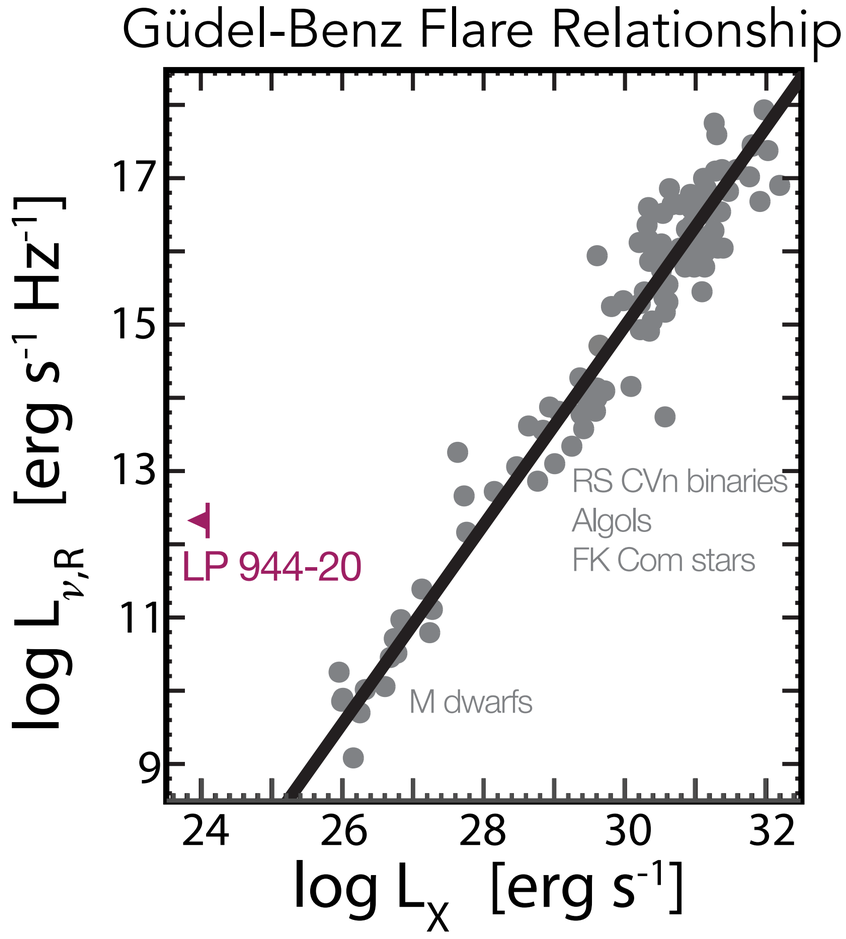


Image credit: JPL/Caltech

Melodie Kao (mkao@lowell.edu)

Surprisingly bright brown dwarf radio bursts

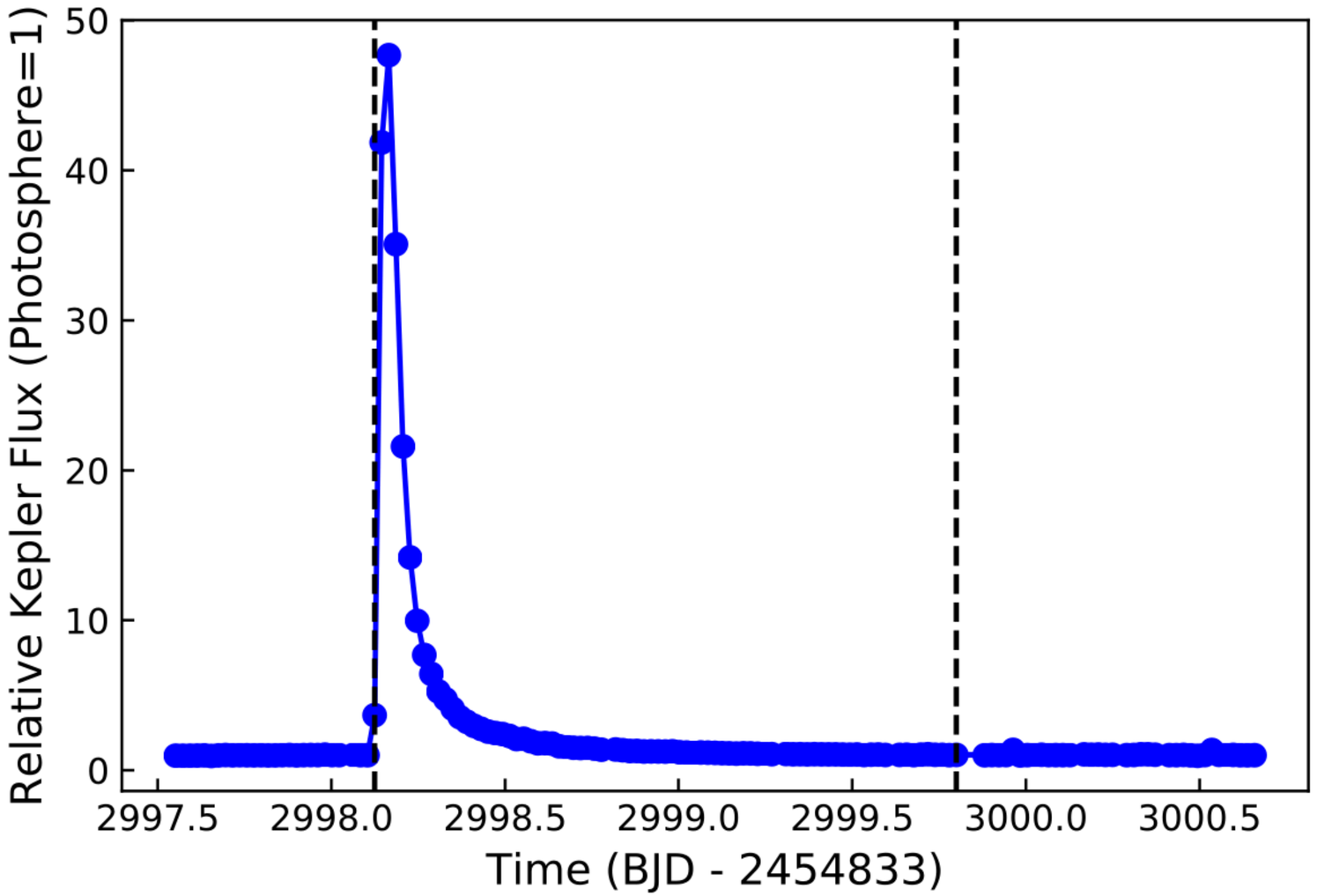




Berger+ (2001)

adapted from Williams+ (2014)

Brown dwarfs can flare!



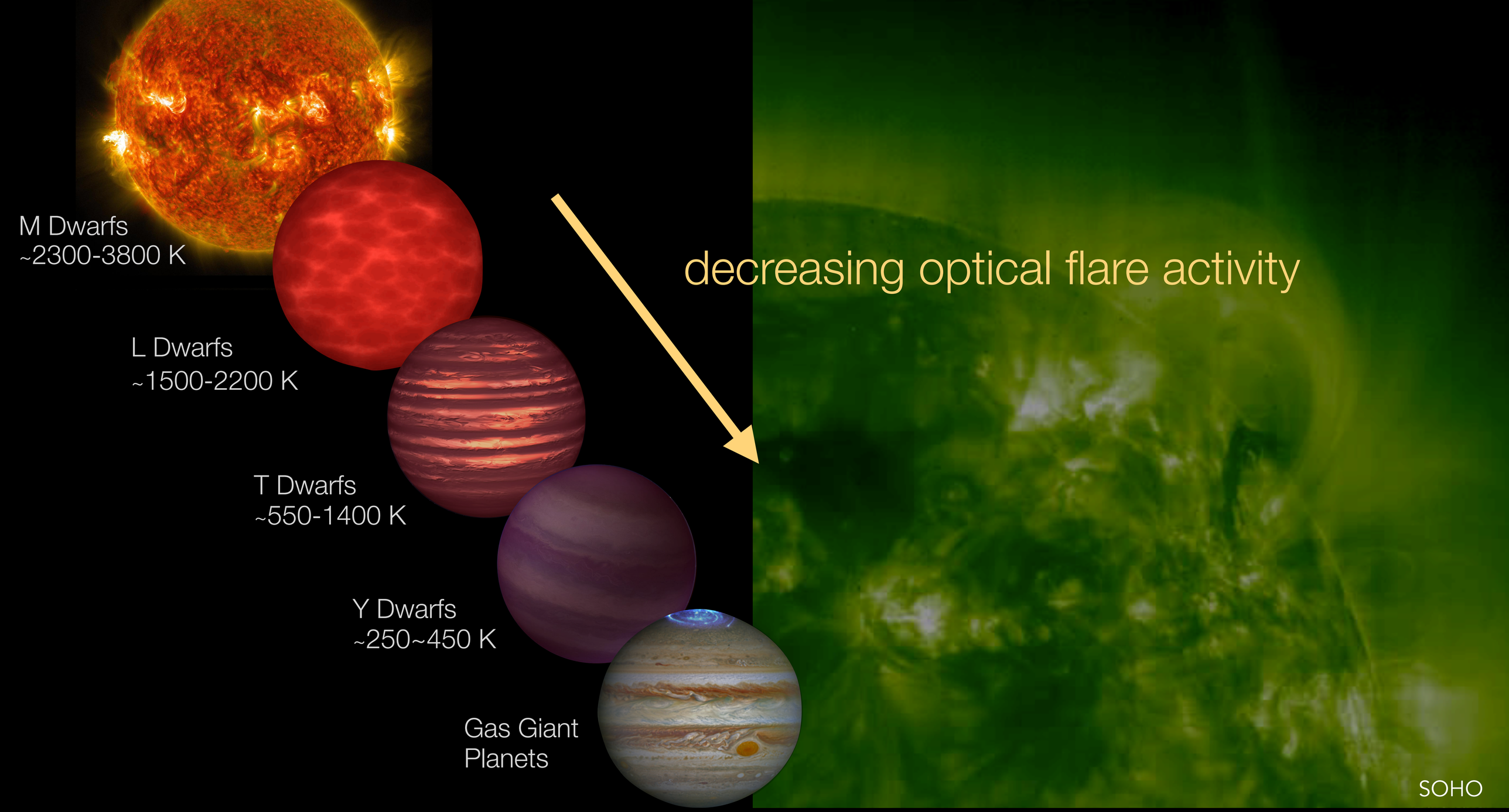
CFHT-BD-Tau 4

~67 M_J

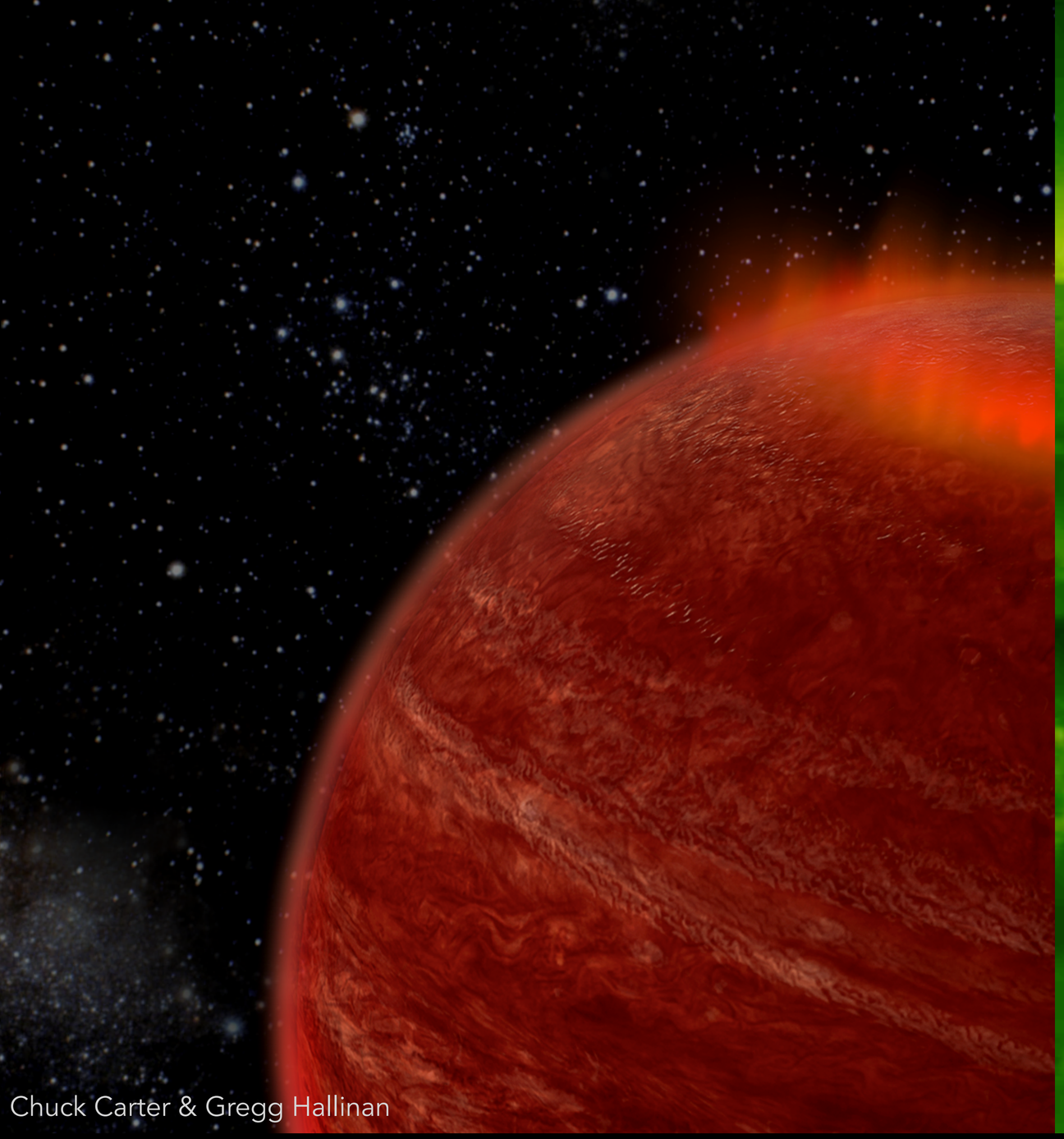
~2900 K (M7)

~1 Myr

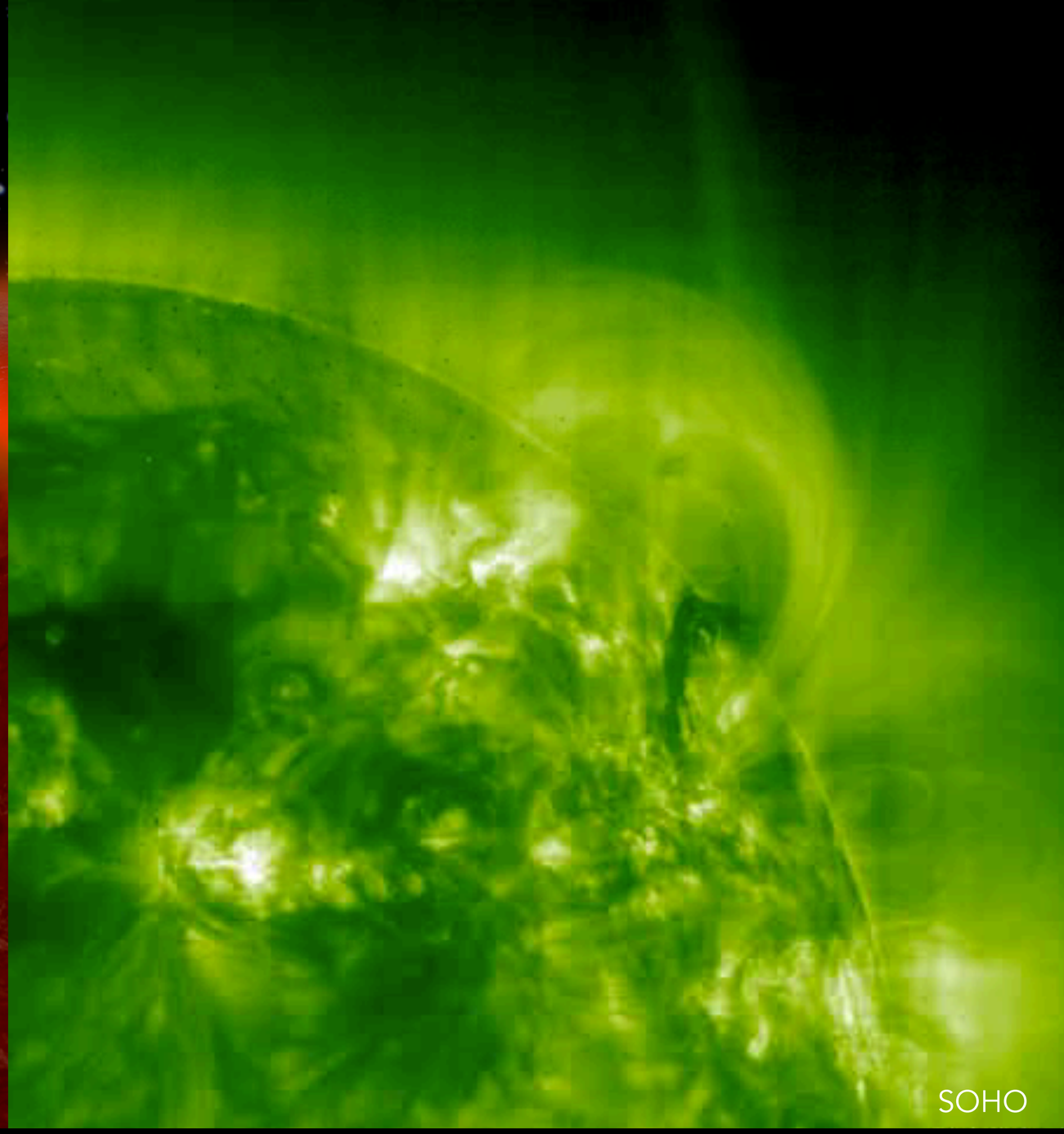
Paudel+ (2018b)



Melodie Kao (mkao@lowell.edu)

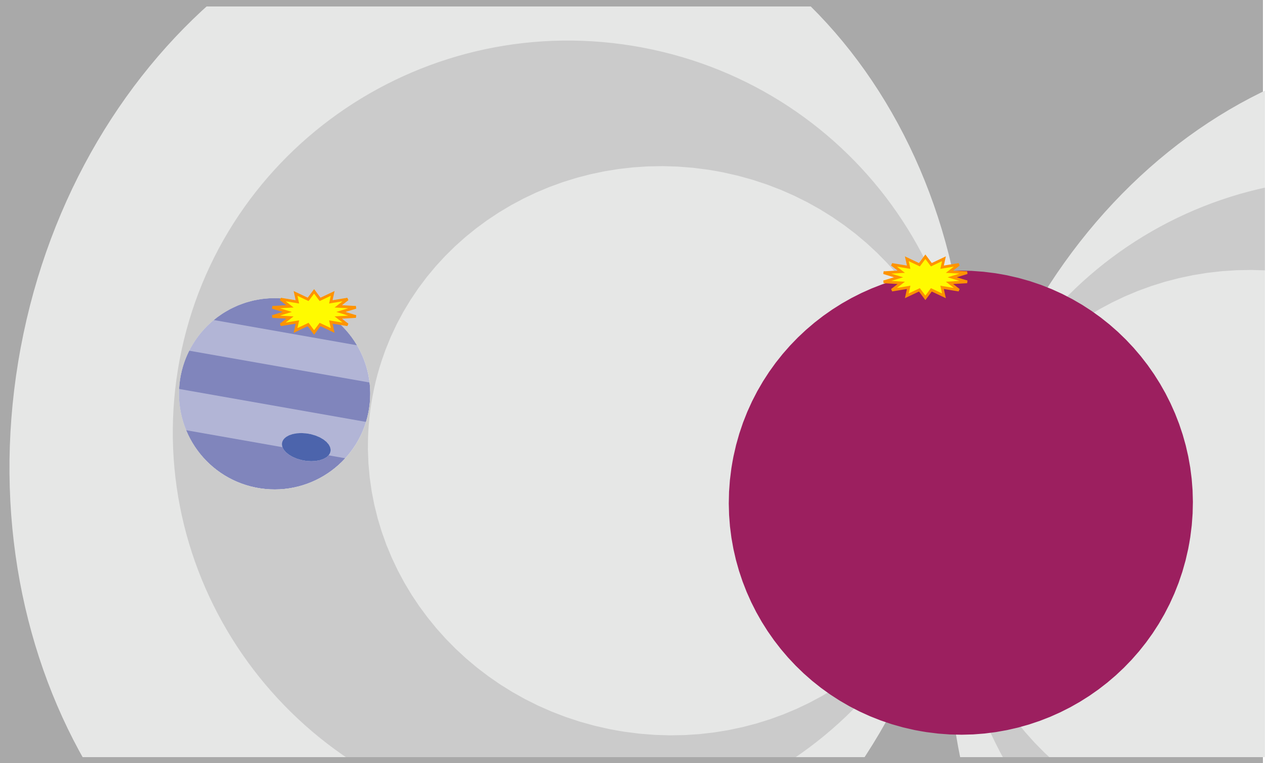


Chuck Carter & Gregg Hallinan

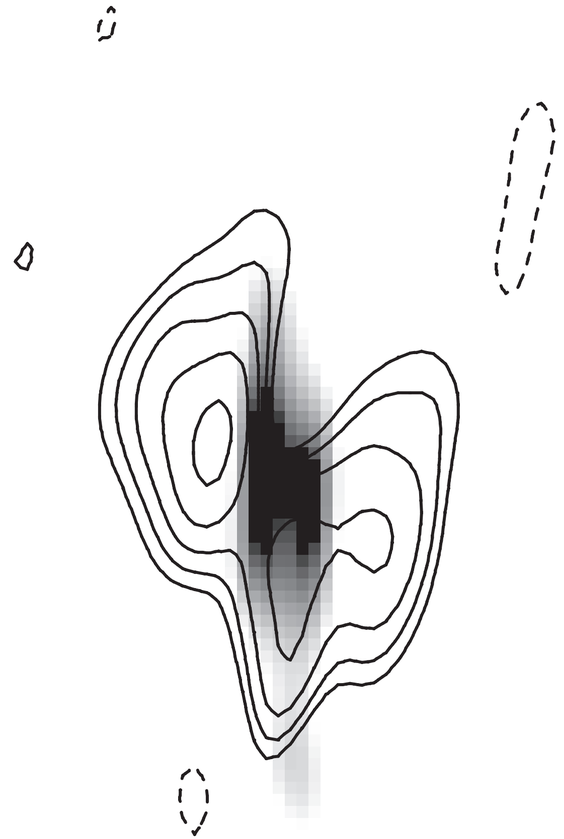


SOHO

Melodie Kao (mkao@lowell.edu)

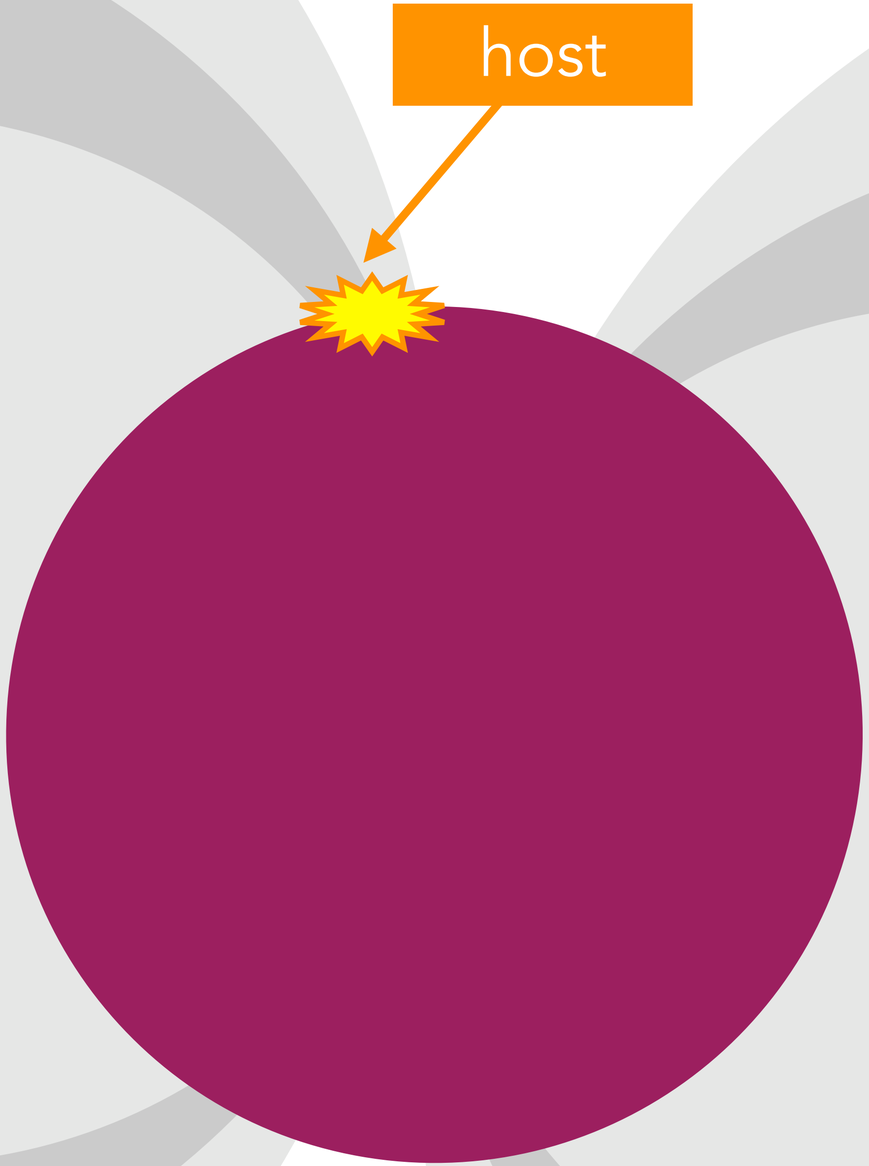


Star-Planet Interactions



Radiation Belts

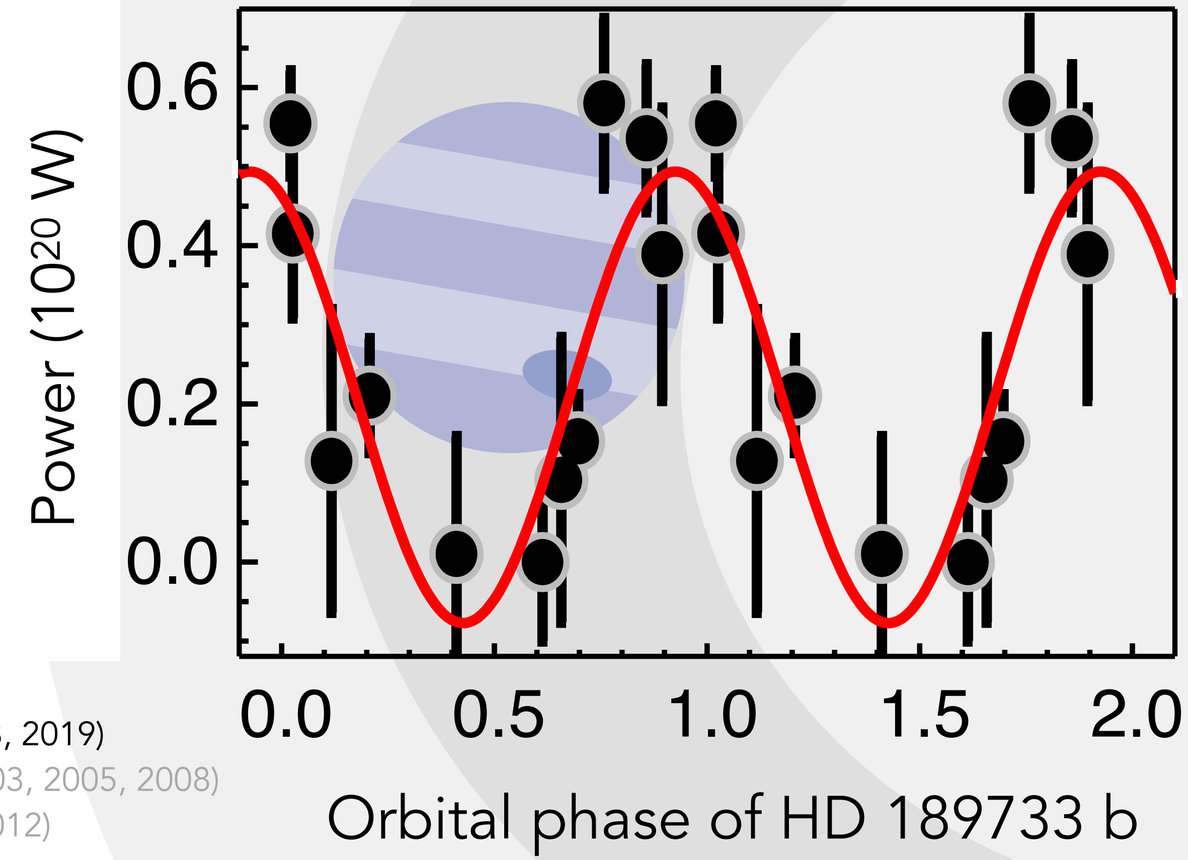
Melodie Kao (mkao@lowell.edu)

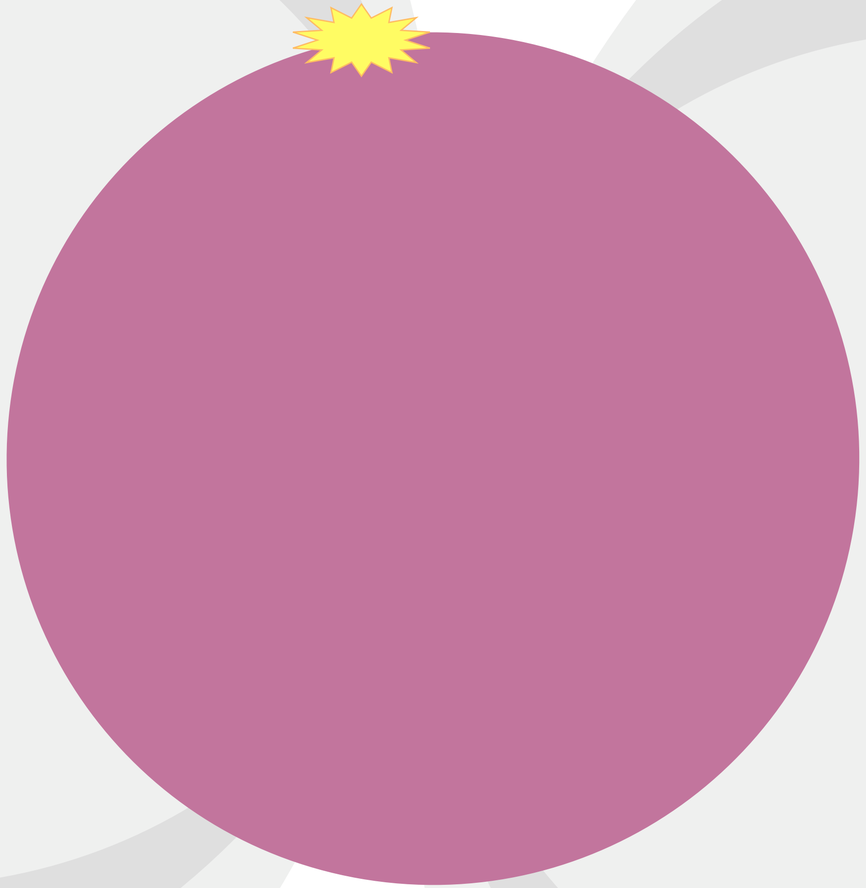


Melodie Kao (mkao@lowell.edu)

Indirect: Optical Star-planet interactions

$$\text{Power} \sim v_{rel}\, R^2\, (B_{planet})^{2/3}\, B_*^{4/3}$$

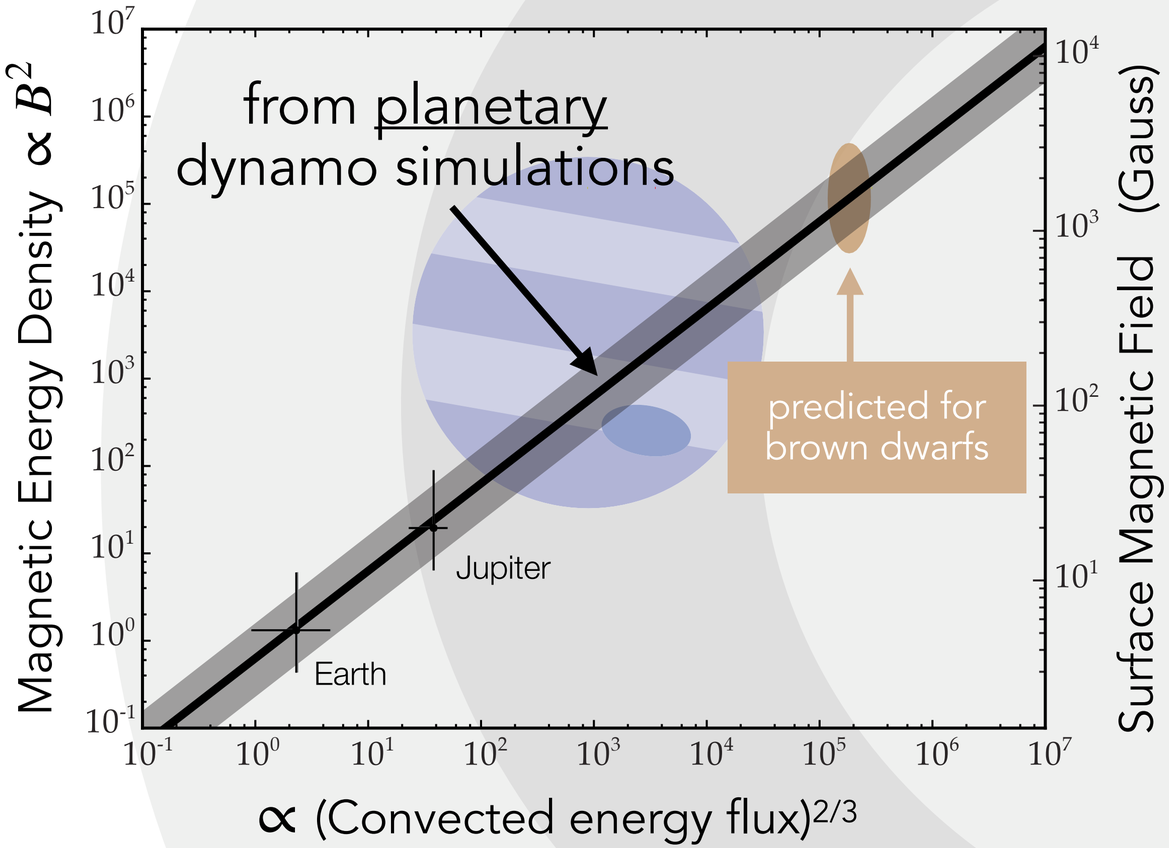


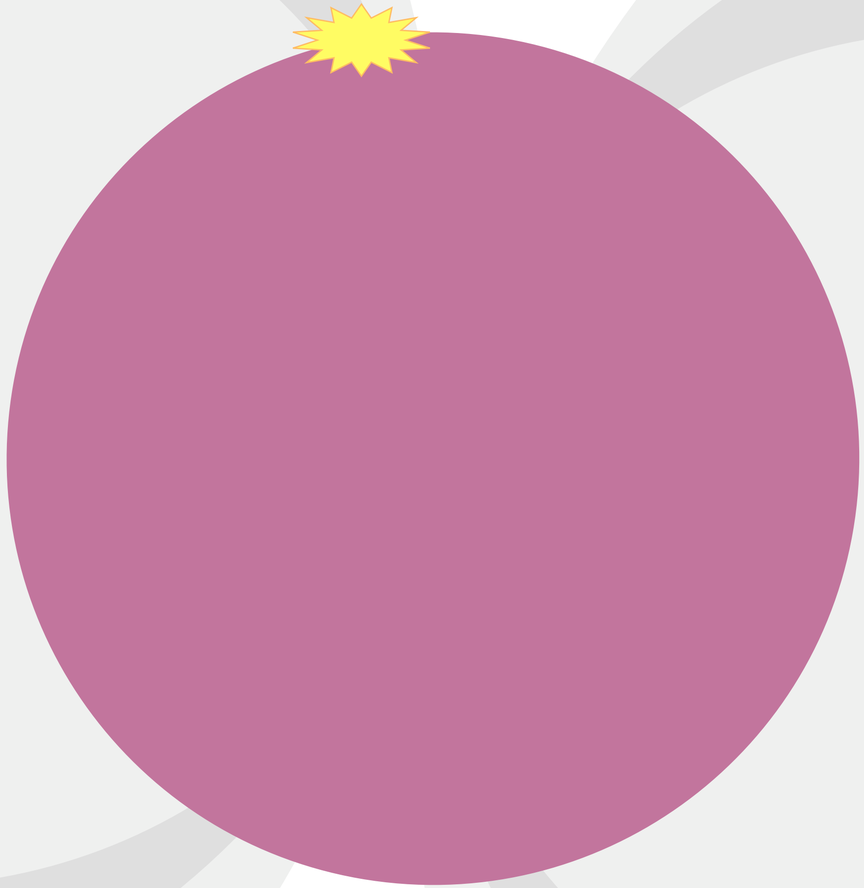


Cauley+ (2018, 2019)
Shkolnik+ (2003, 2005, 2008)
Gurdemir+ (2012)
Lanza+ (2012)
Saur+ (2013)

Indirect: Optical Star-planet interactions

Power ~ $v_{rel}\, R^2\, (B_{planet})^{2/3}\, B_*^{4/3}$

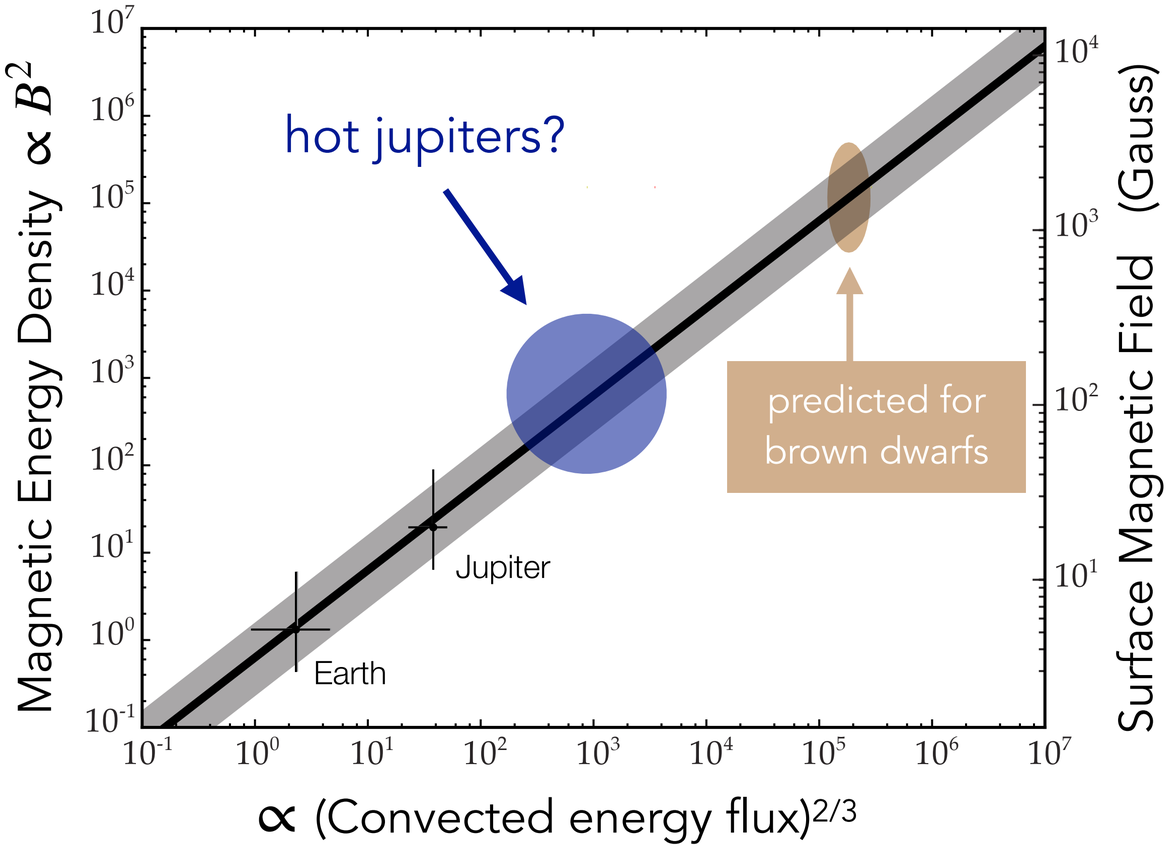




Christensen+ (2009)
See also: Yadav & Thorngren (2017)

Indirect: Optical Star-planet interactions

Power ~ $v_{rel}\, R^2\, (B_{planet})^{2/3}\, B_*^{4/3}$



hot Jupiters receive
extra thermal energy from host stars

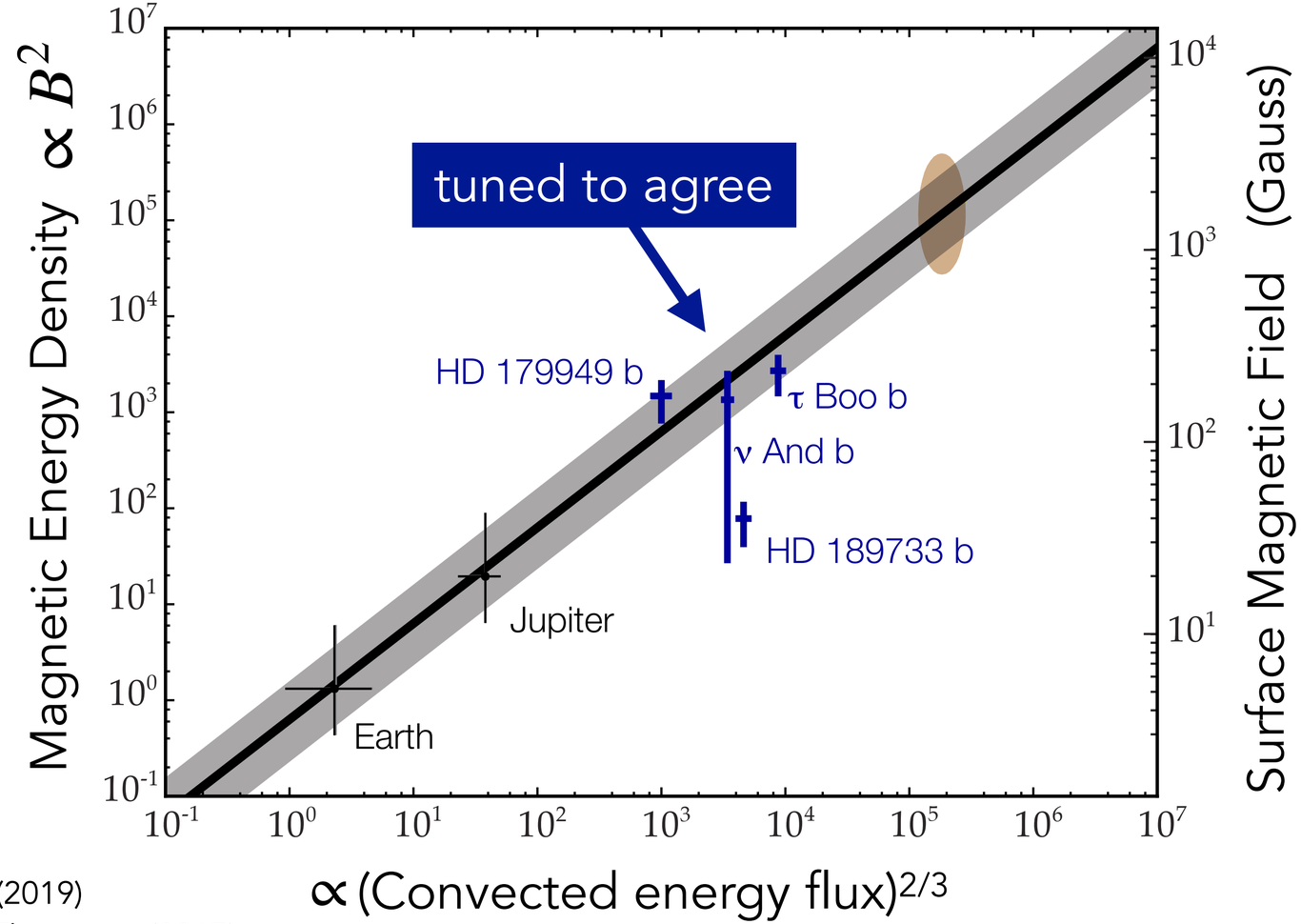
Christensen+ (2009)
See also: Yadav & Thorngren (2017)

(ultra)Hot Jupiters may have strong magnetic fields.

Melodie Kao (mkao@lowell.edu)

Indirect: Optical Star-planet interactions

Power ~ $v_{rel}\, R^2\, (B_{planet})^{2/3}\, B_*^{4/3}$

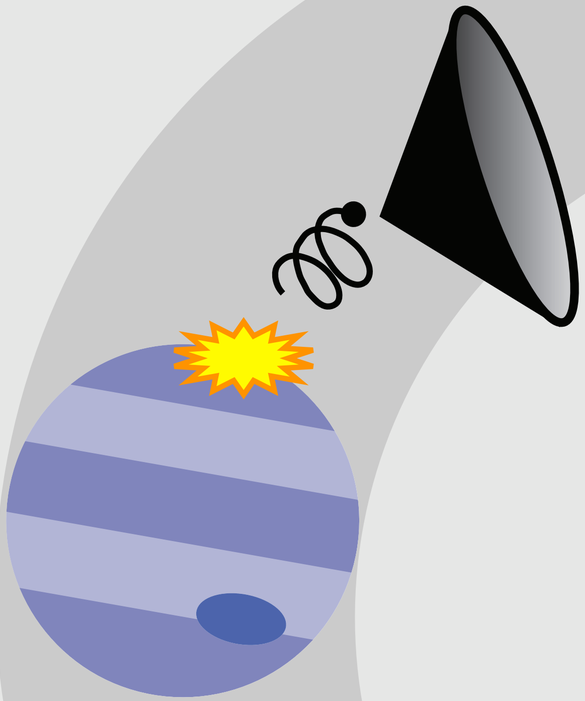


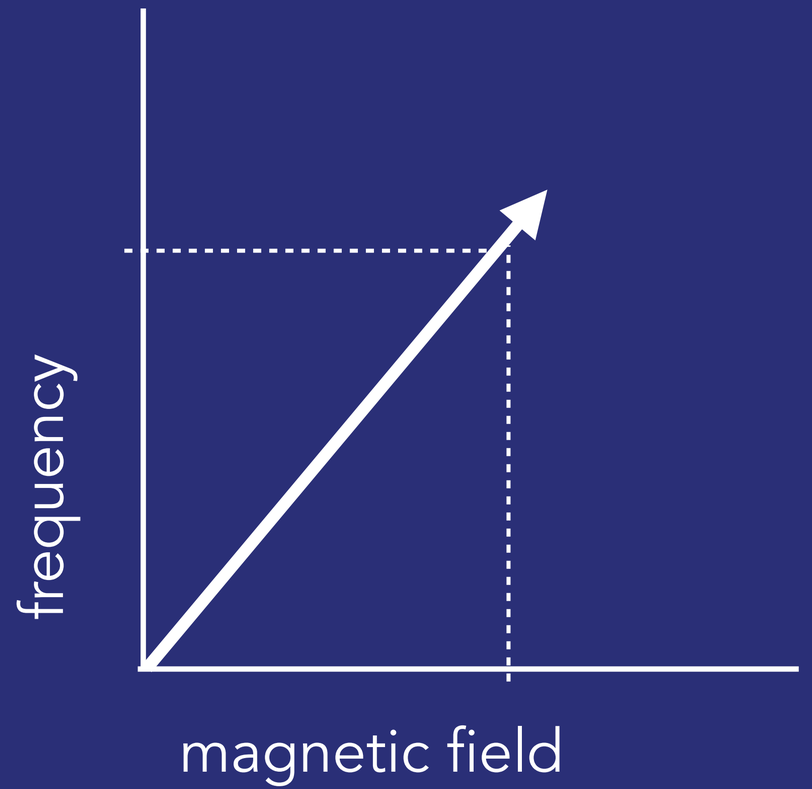
hot Jupiters receive
extra thermal energy from host stars

Cauley+ (2019)
Yadav & Thorngren (2017)

Direct: Radio Aurorae

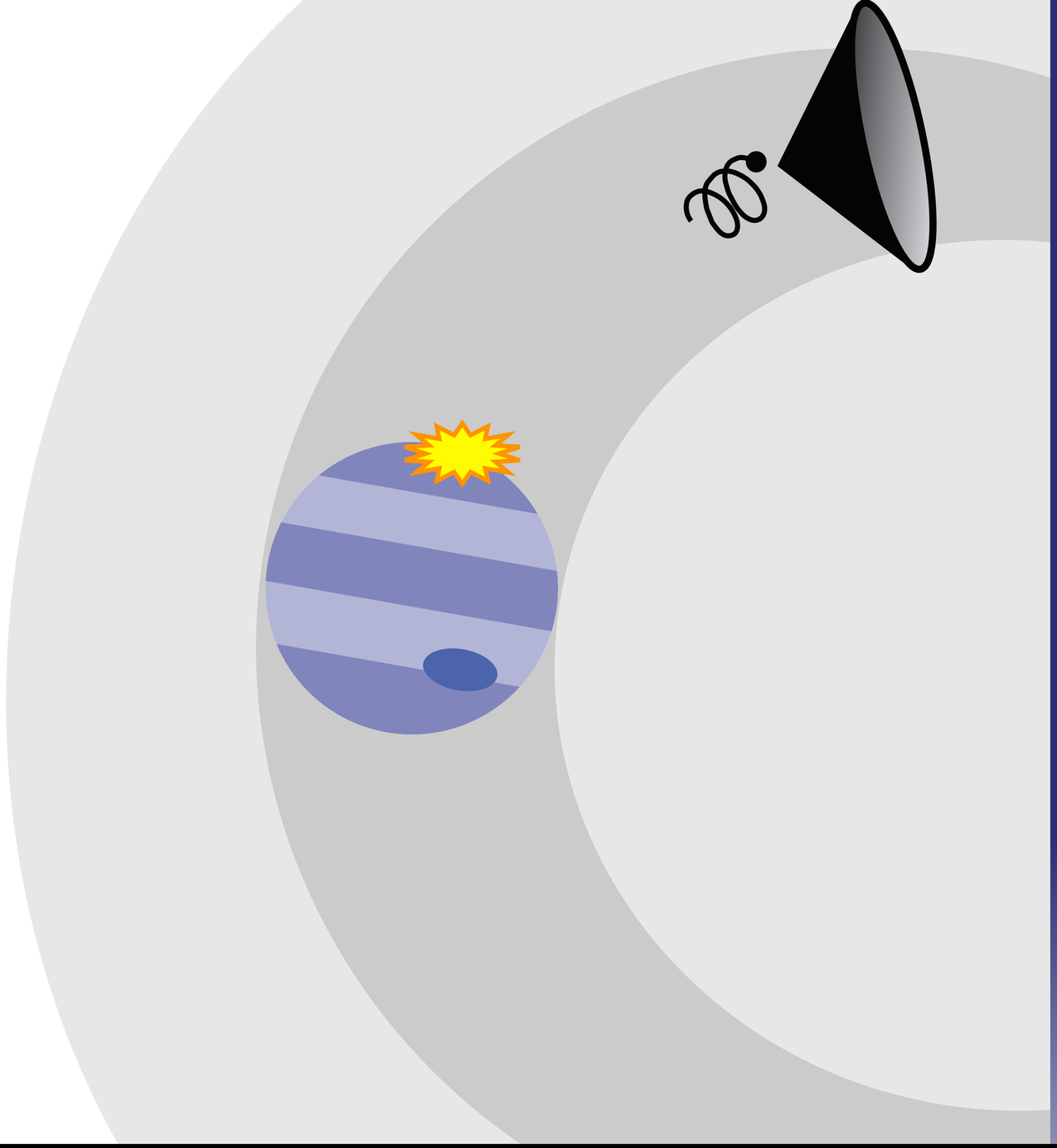
$\nu_{[\mathrm{MHz}]} \approx 2.8\ \mathbf{B_{planet\ [Gauss]}}$

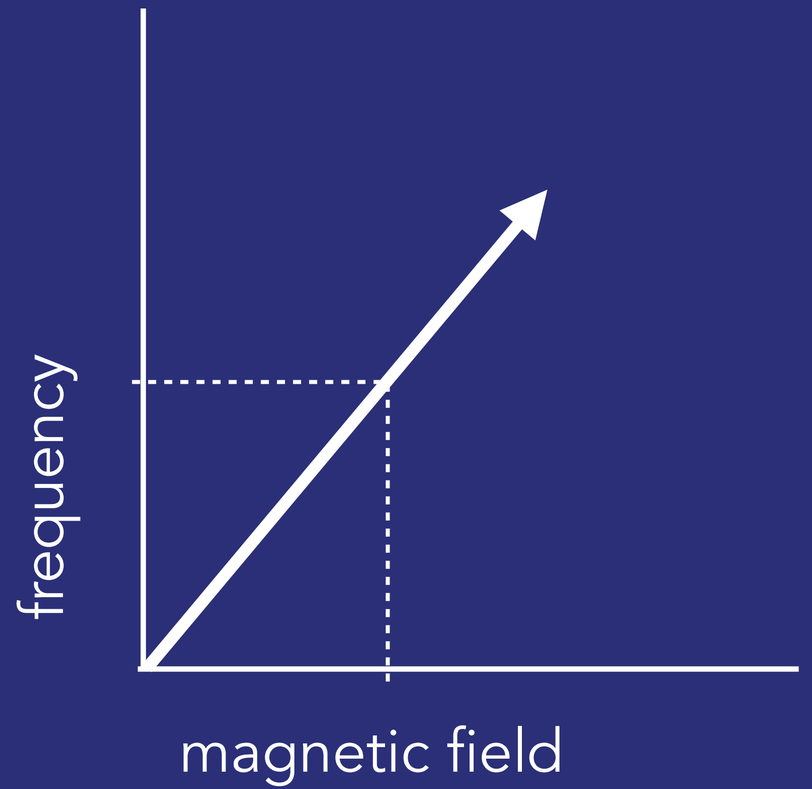




$$\nu_{\mathrm{MHz}} \approx 2.8\, B_{\mathrm{Gauss}}$$

Melodie Kao (mkao@lowell.edu)





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

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)

Saur+ 2013

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

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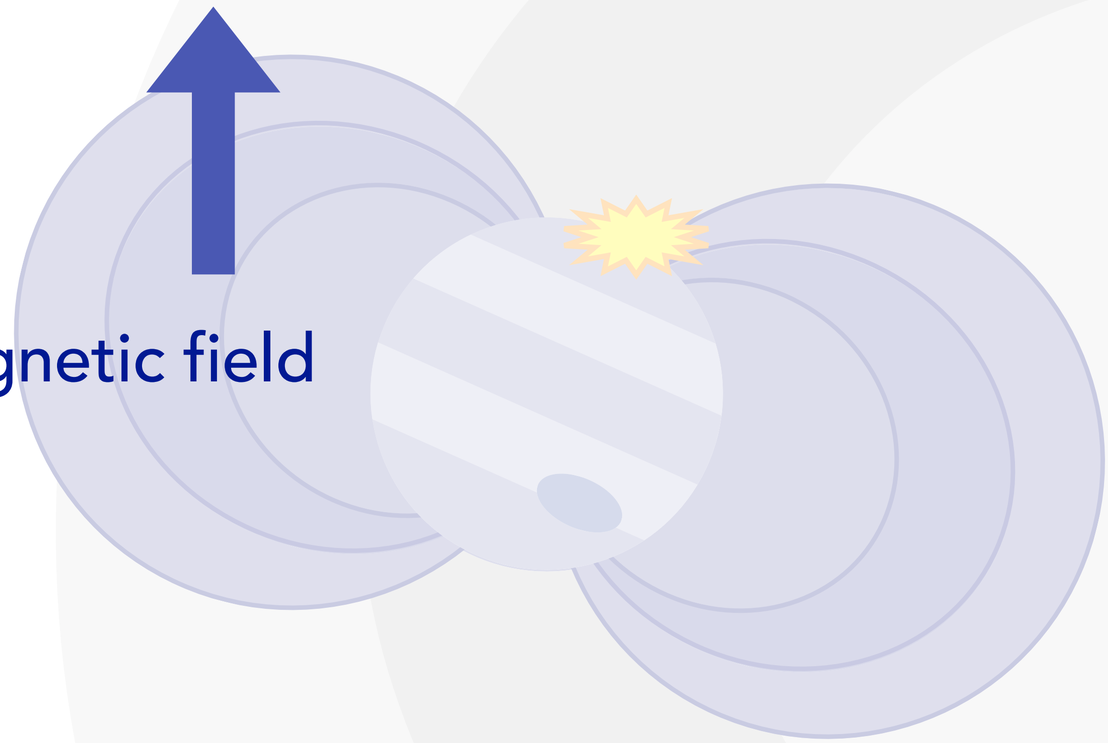


planet magnetic field

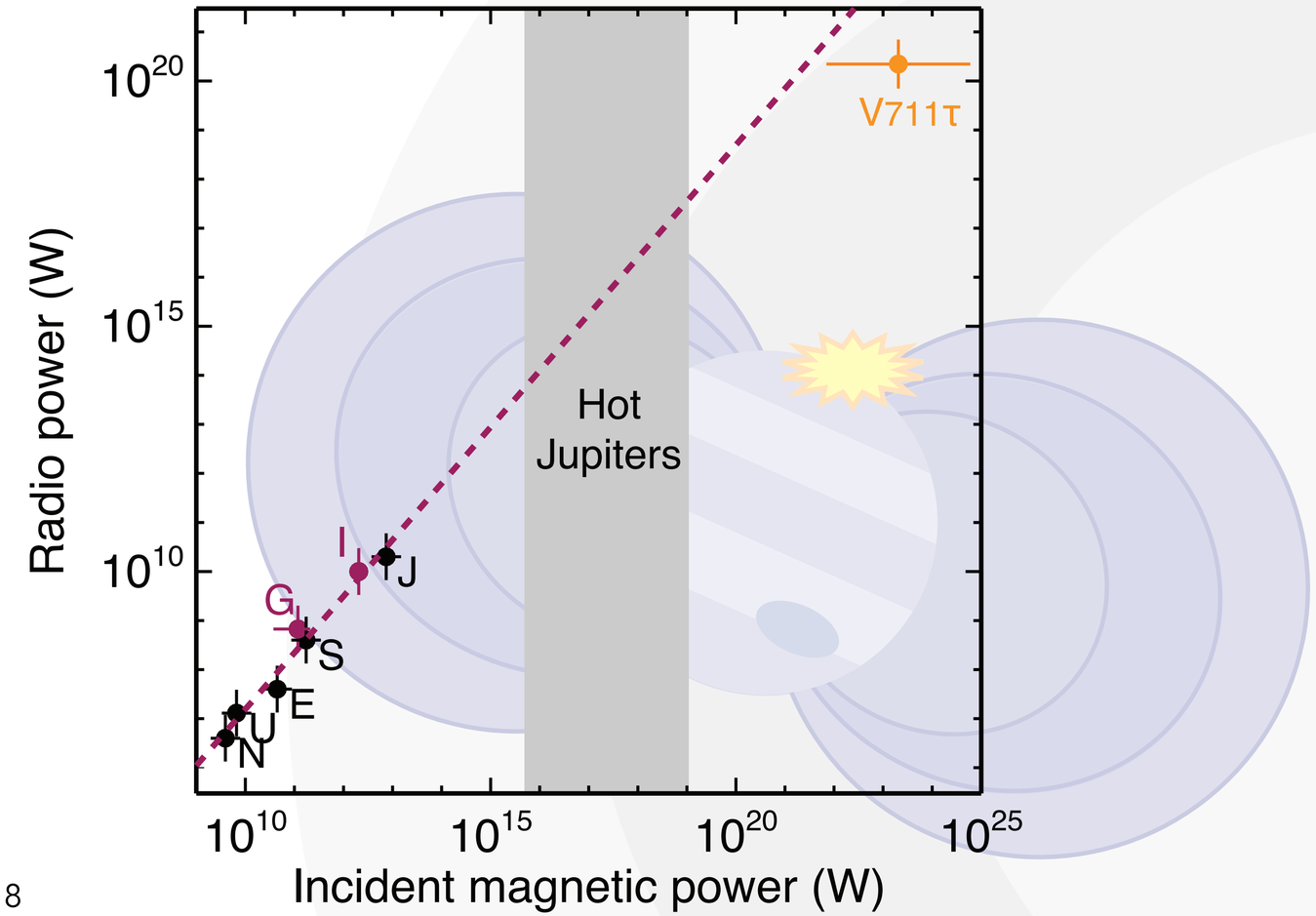
Saur+ 2013

Melodie Kao (mkao@lowell.edu)

$S \propto$ power dissipated

R_o^2 obstacle size

$B_{\mathrm{wind}}\ \Delta u^2\ \sin^2\theta\ \sqrt{\rho_{\mathrm{wind}}}$ (magnetospheric plasma flow properties)



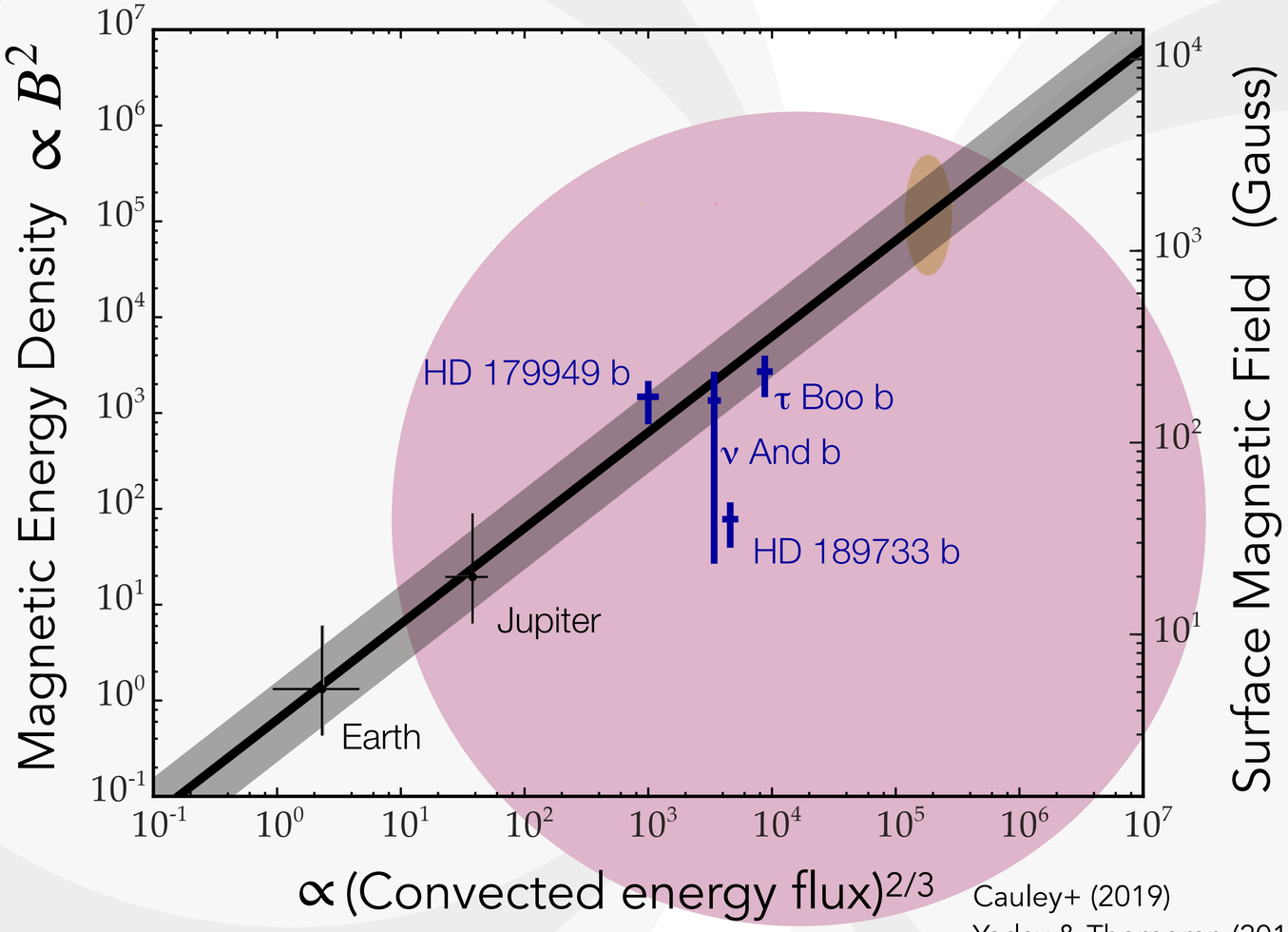
Zarka+ 2018

Melodie Kao (mkao@lowell.edu)

Direct: Radio Aurorae

$\nu_{[MHz]} \approx 2.8\ B_{planet\ [Gauss]}$

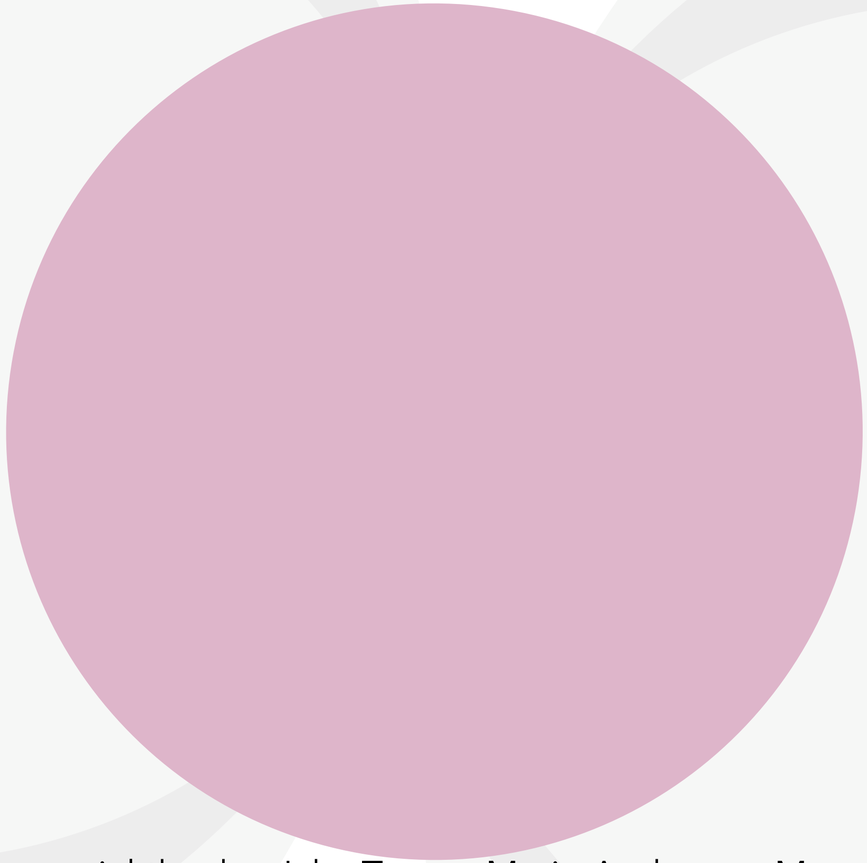
test inferred fields



Cauley+ (2019)
Yadav & Thorngren (2017)

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

Melodie Kao (mkao@lowell.edu)

Yantis+ 1977
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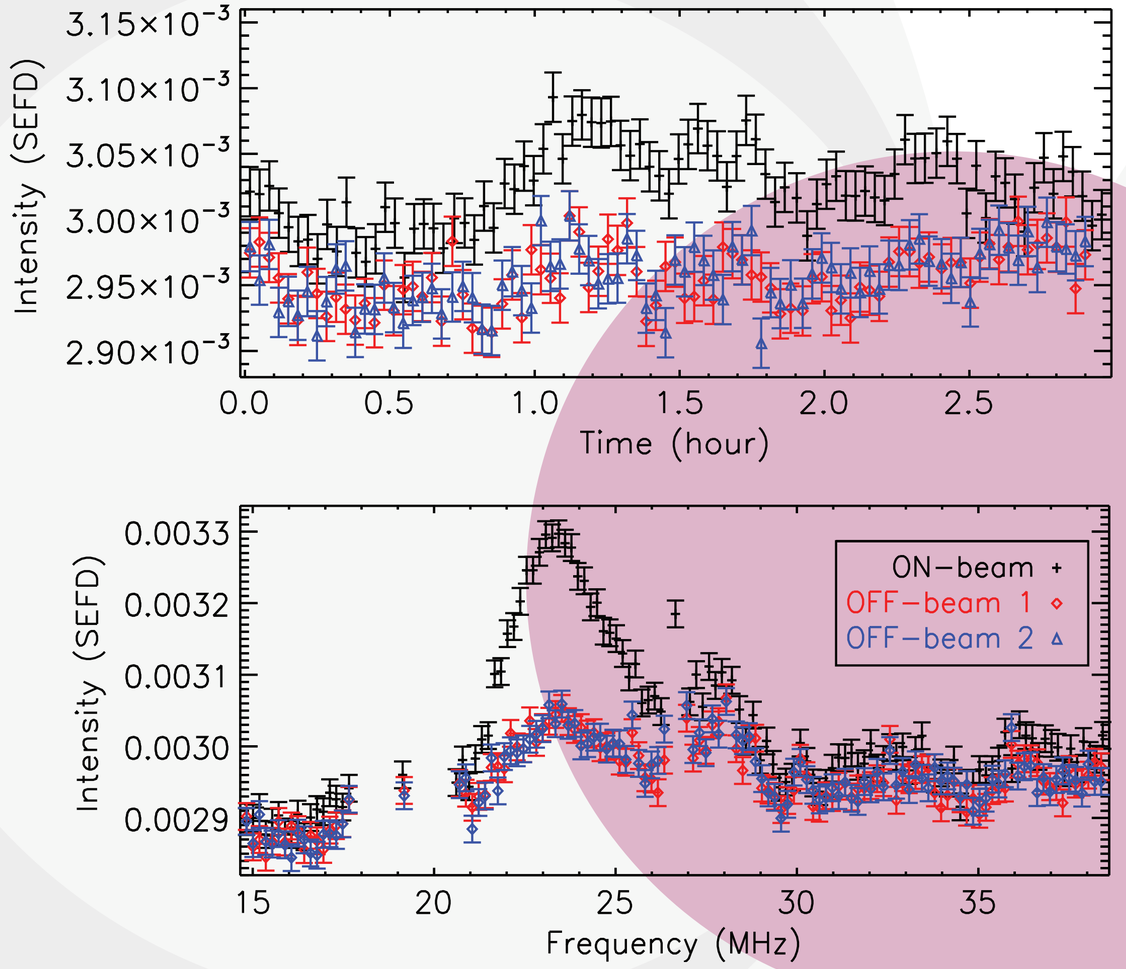
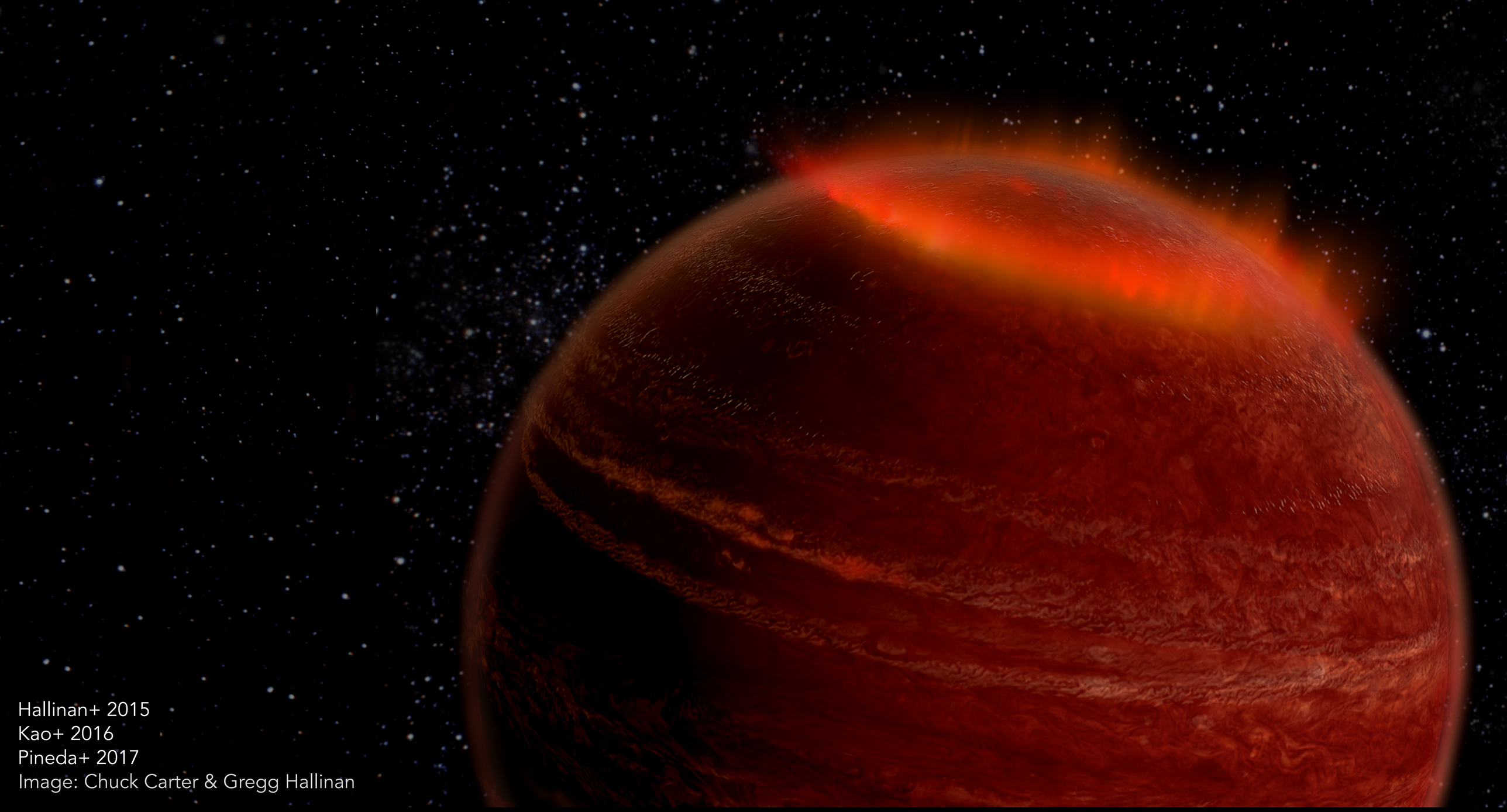
Bastian+ 2018
O'Gorman+ 2018
de Gasperin+ 2020
Green+ 2021
Narang+ 2021

Turner+ 2021

a candidate exoplanet aurorae.

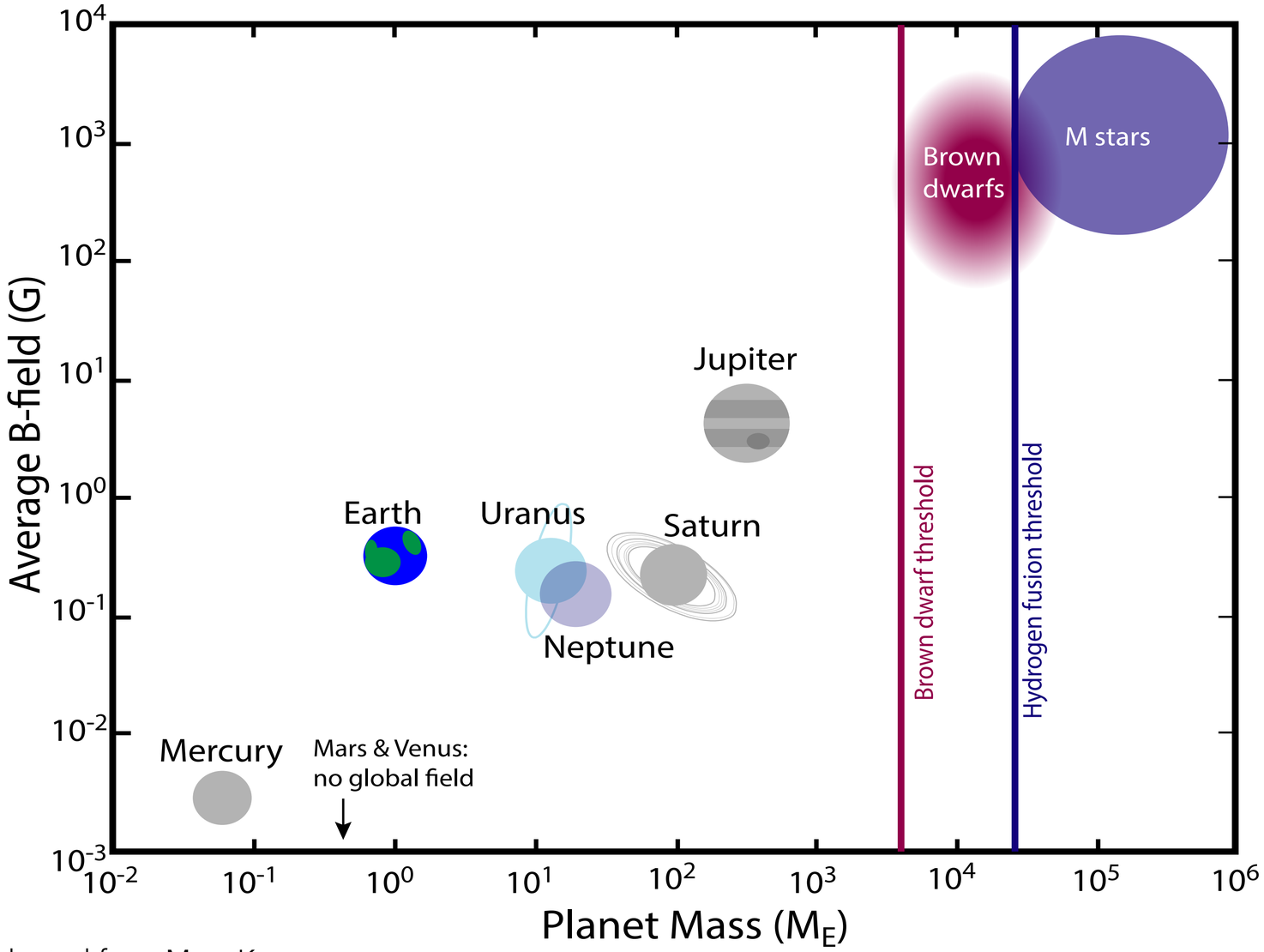




Hallinan+ 2015
Kao+ 2016
Pineda+ 2017
Image: Chuck Carter & Gregg Hallinan

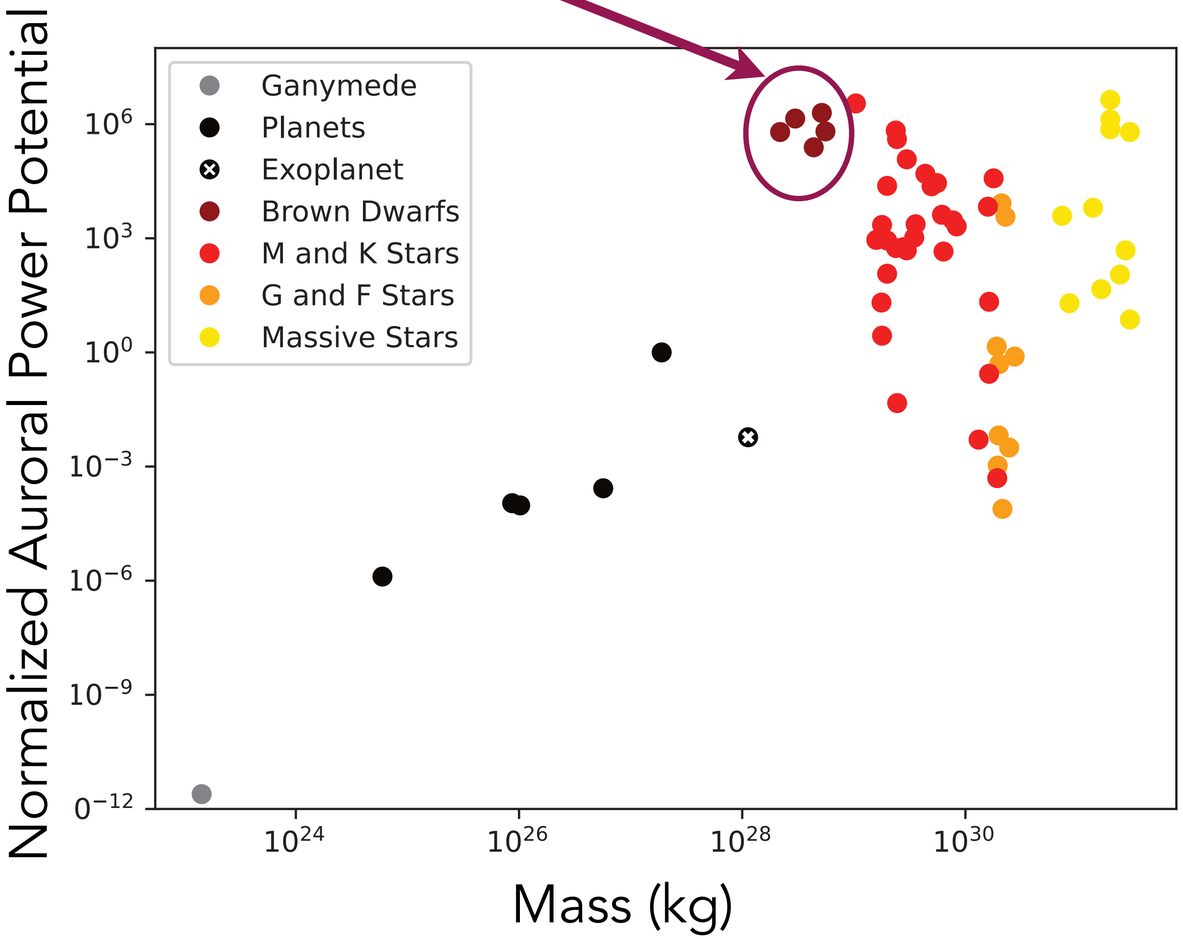
Melodie Kao (mkao@lowell.edu)

Brown dwarfs: Magnetic analogs to gas giant planets



Adapted from Mary Knapp

Brown dwarfs: high potential to power aurorae.

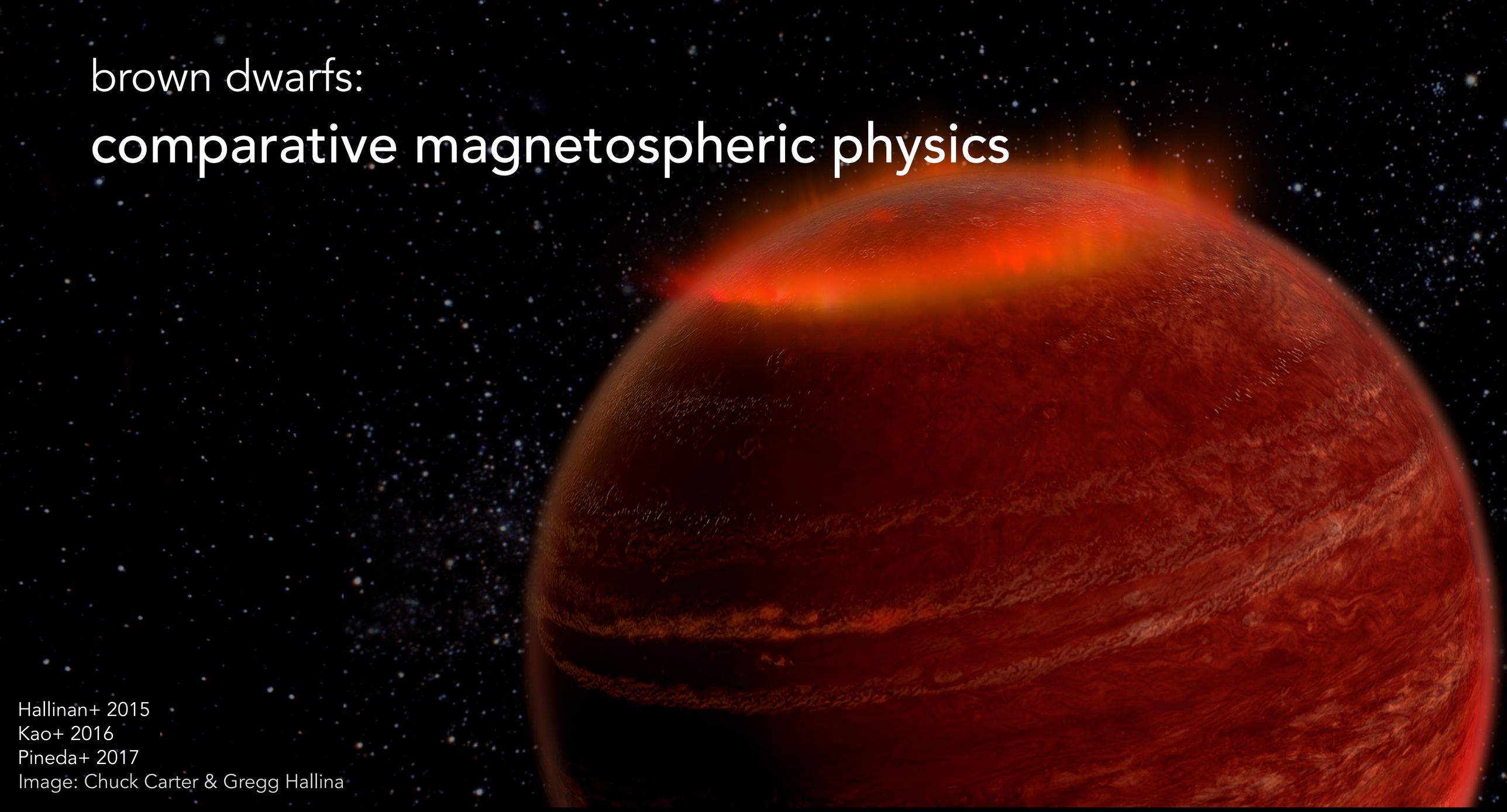


$$S \propto B_{\text{host}}^2 \, \Omega_{\text{host}}^2 \, R_{\text{host}}^2$$

- S: Power dissipated
- B_{host}^2: auroral host's polar magnetic field
- Ω_{host}^2: auroral host's angular velocity
- R_{host}^2: auroral host's radius

Saur+ 2021

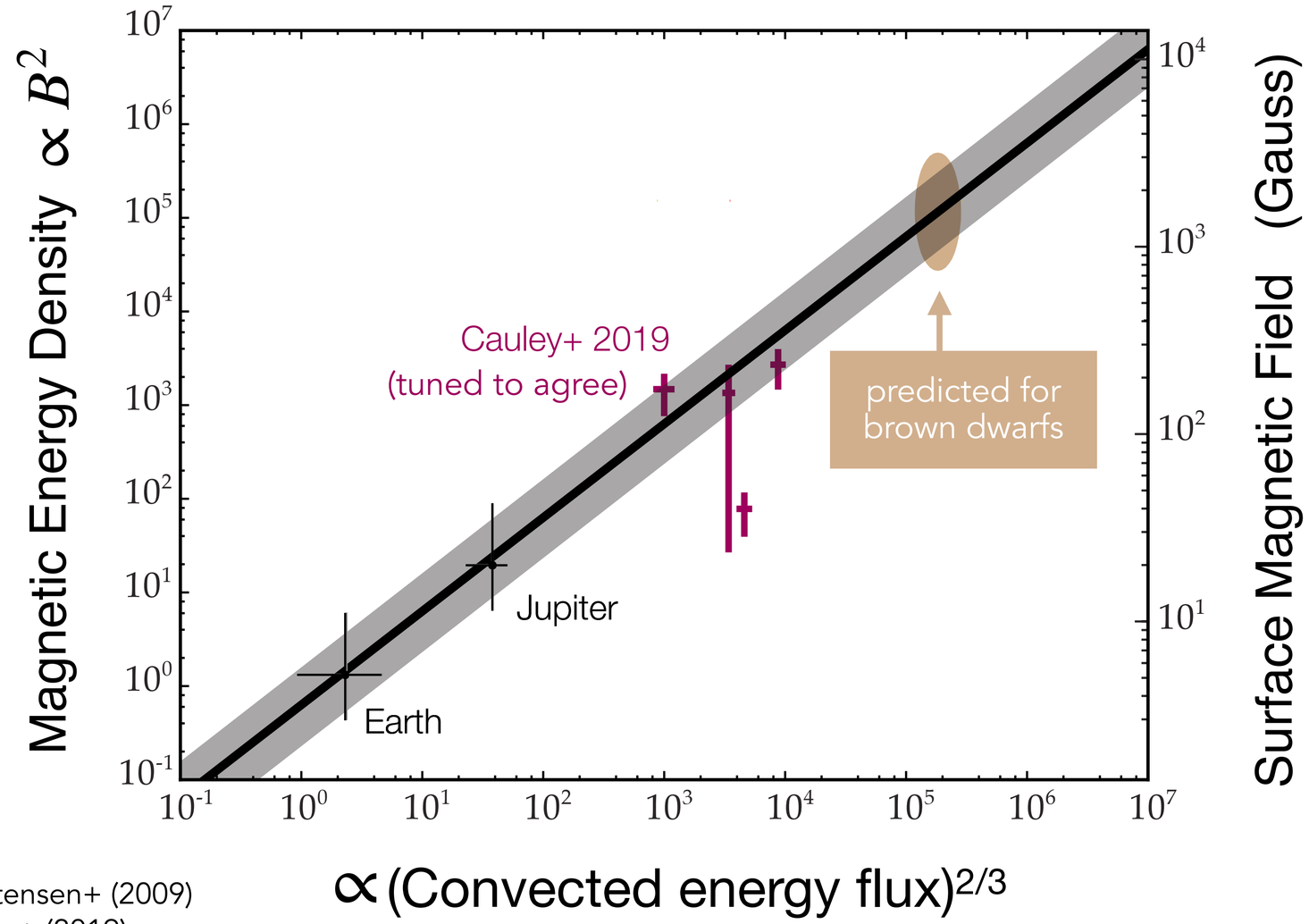
brown dwarfs:
comparative magnetospheric physics

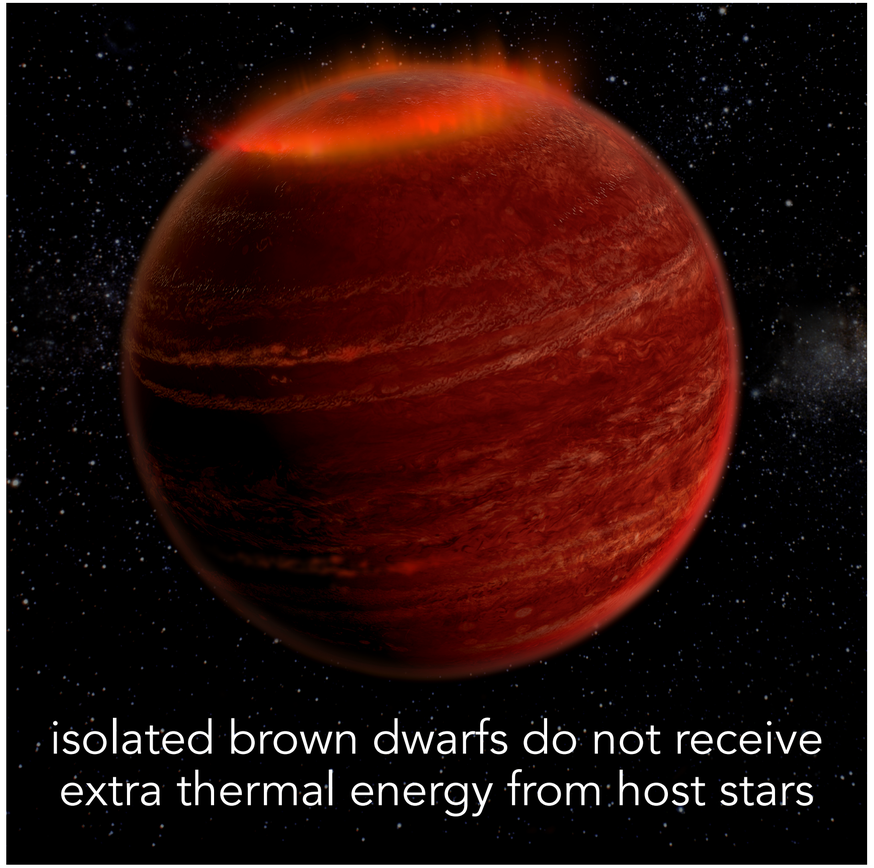


Hallinan+ 2015
Kao+ 2016
Pineda+ 2017
Image: Chuck Carter & Gregg Hallina

Melodie Kao (mkao@lowell.edu)

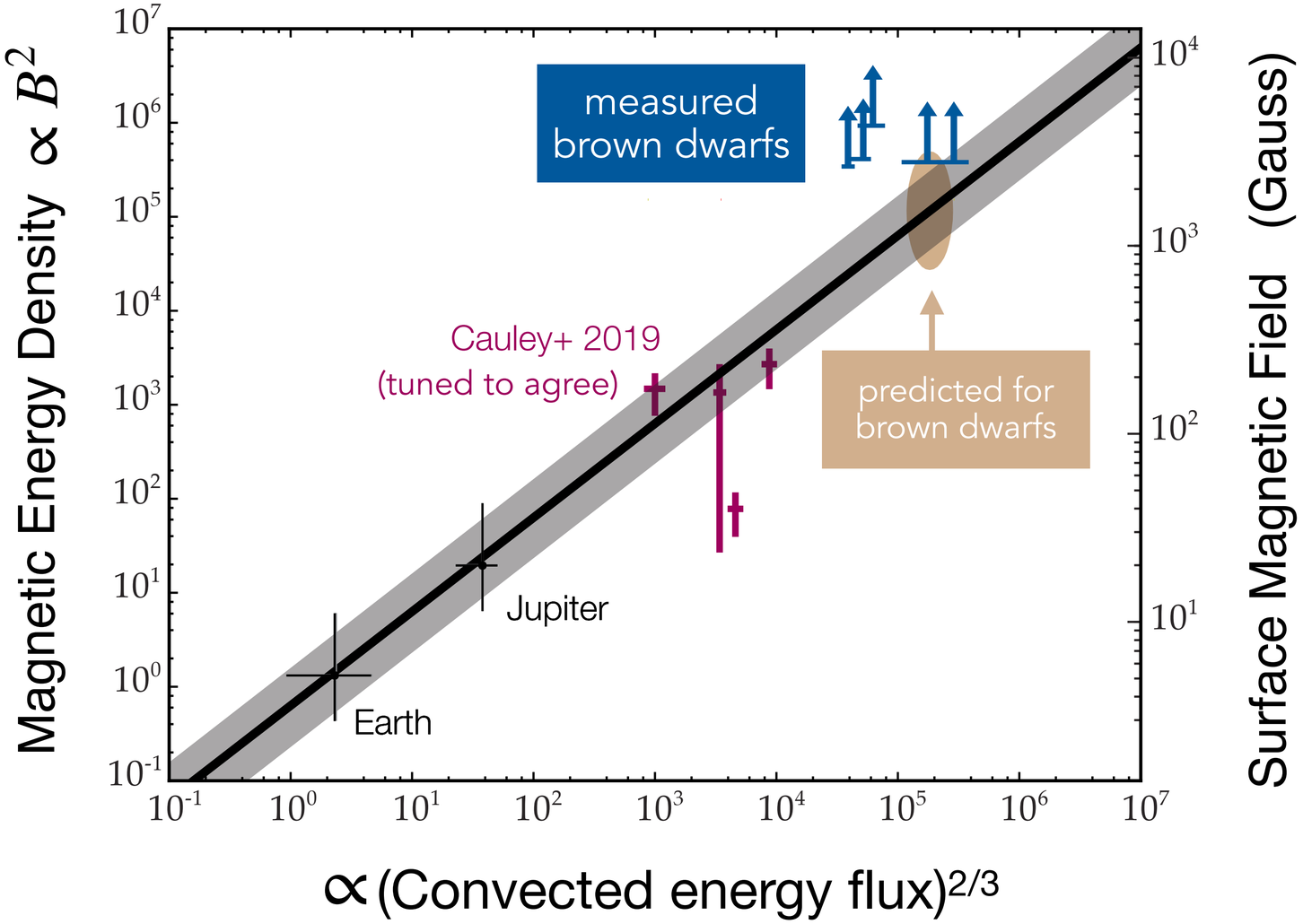
Convected thermal energy sets magnetic field?

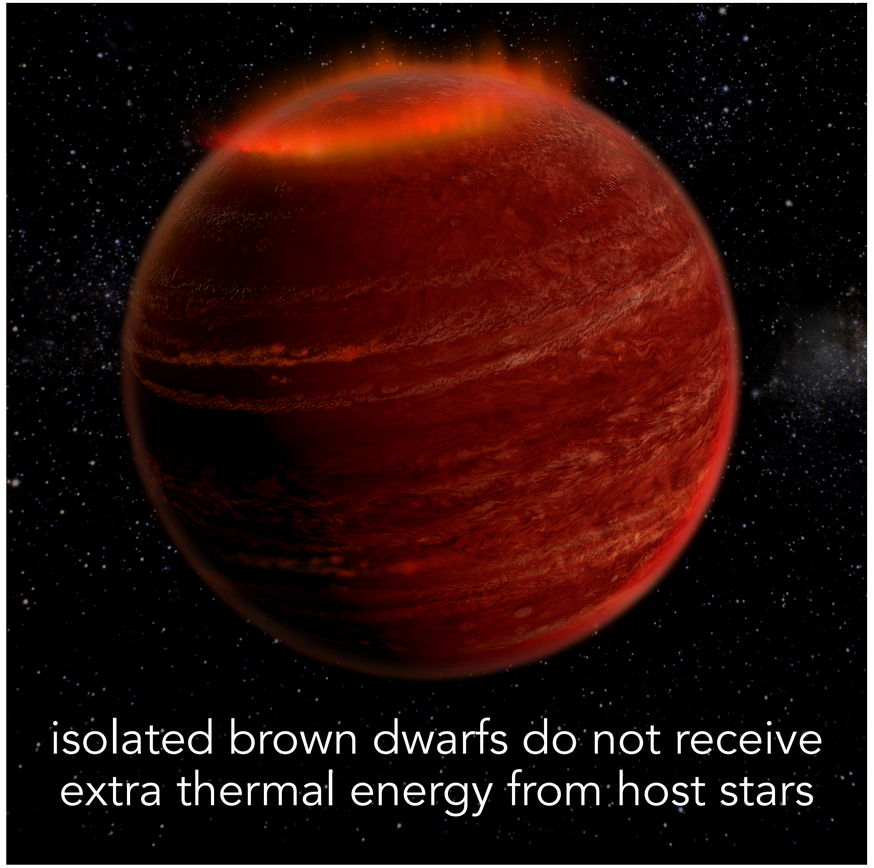




Christensen+ (2009)
Cauley+ (2019)
Yadav & Thorngren (2017)

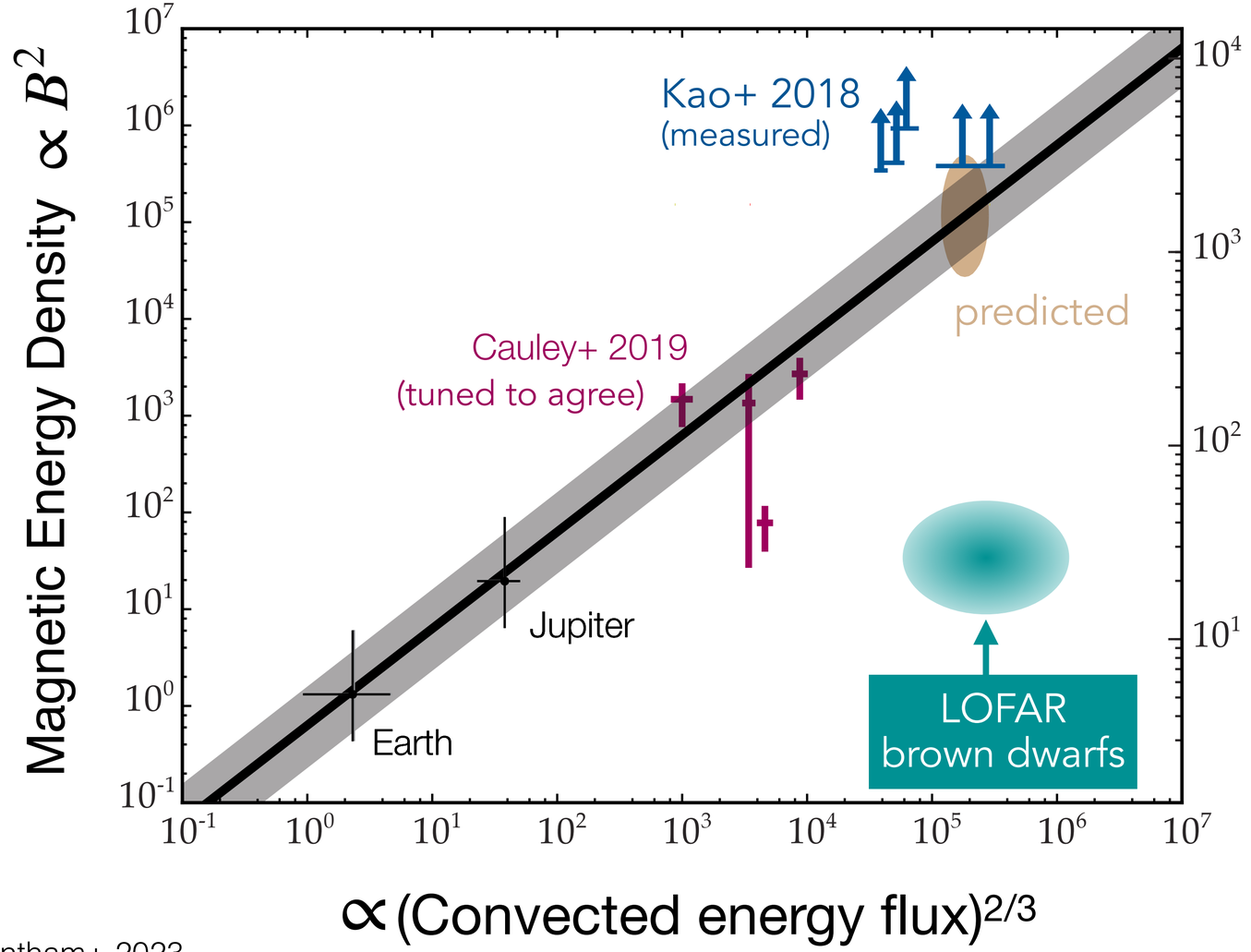
Convected thermal energy sets magnetic field? **Maybe not.**

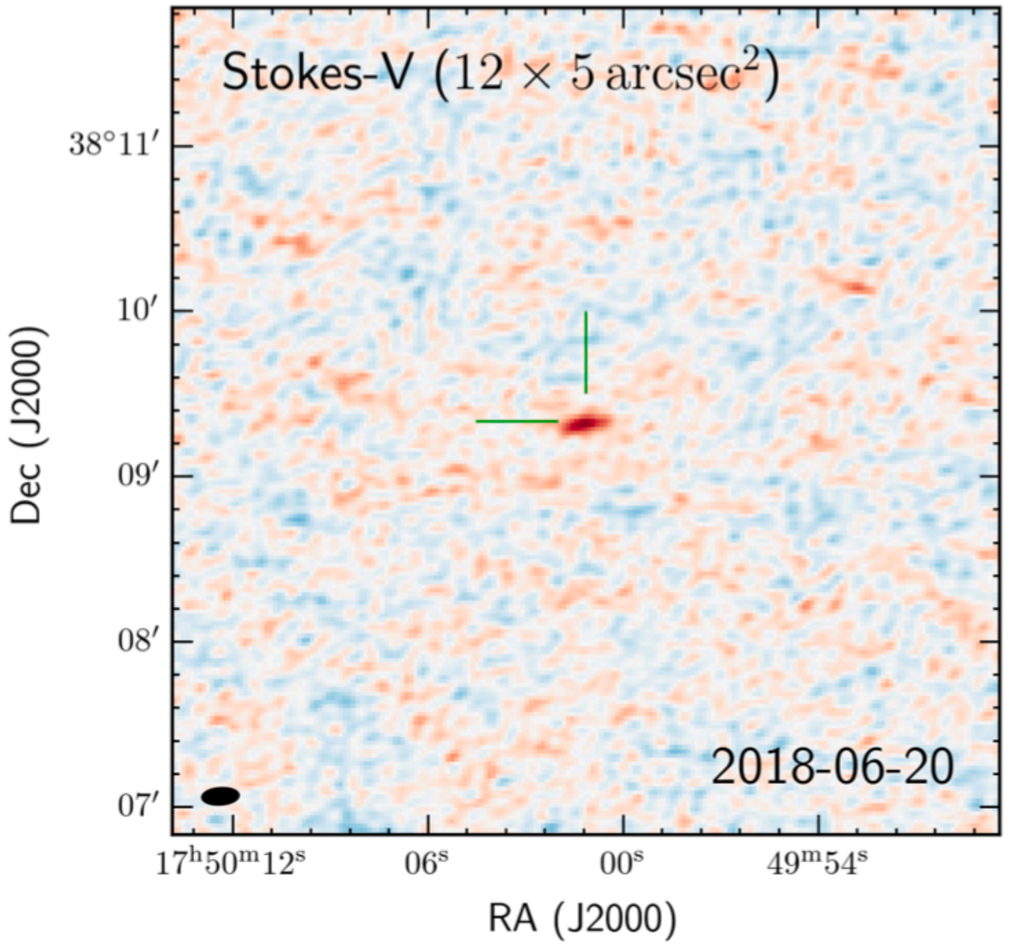




Kao+ (2018)

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

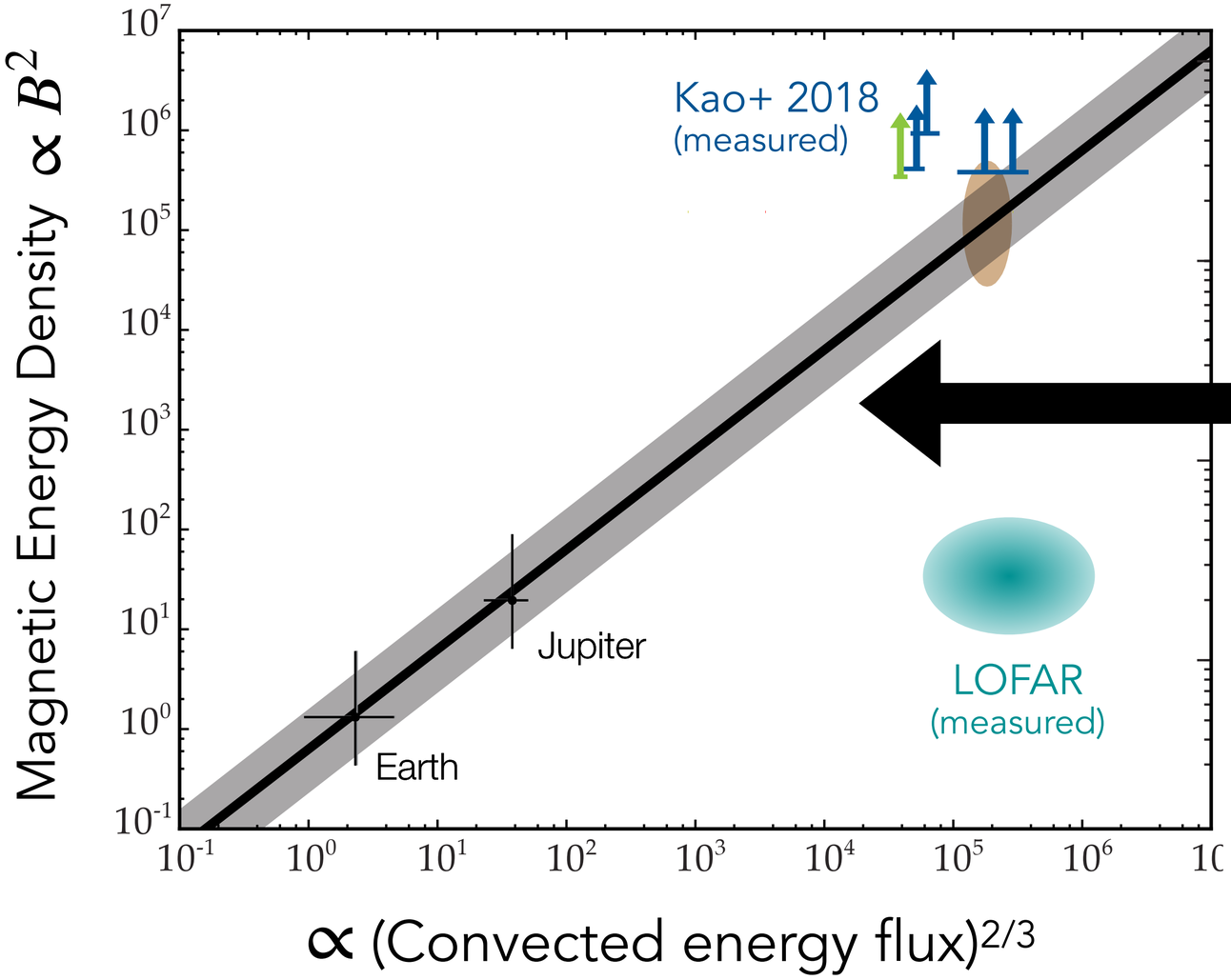




Vedantham+ 2023

Vedantham+ 2020b

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

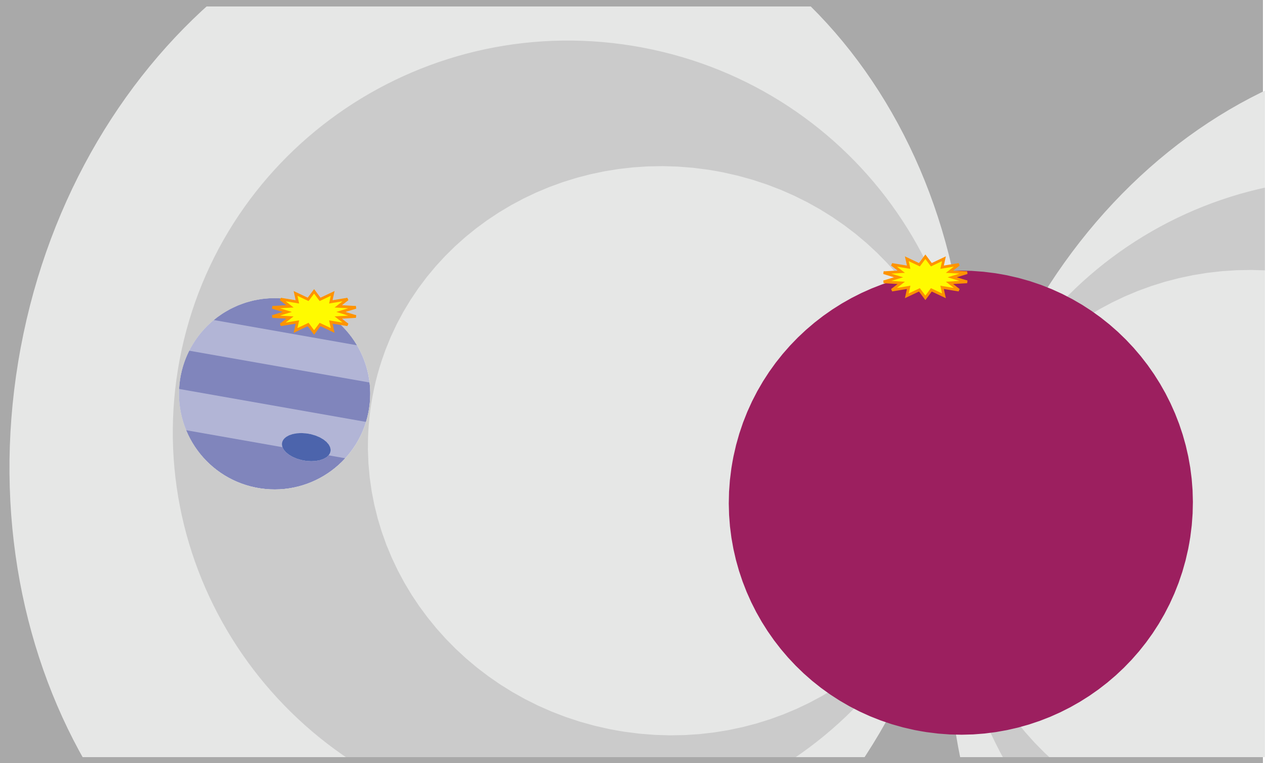


for: dipole-dominated

Kao+ (2018)

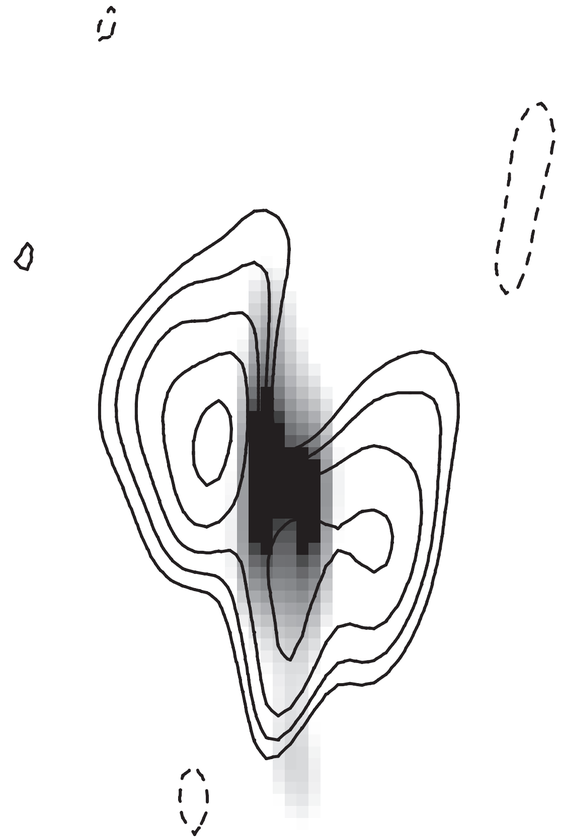
What **shapes** are exoplanet magnetic fields?

Melodie Kao (mkao@lowell.edu)



Star-Planet Interactions

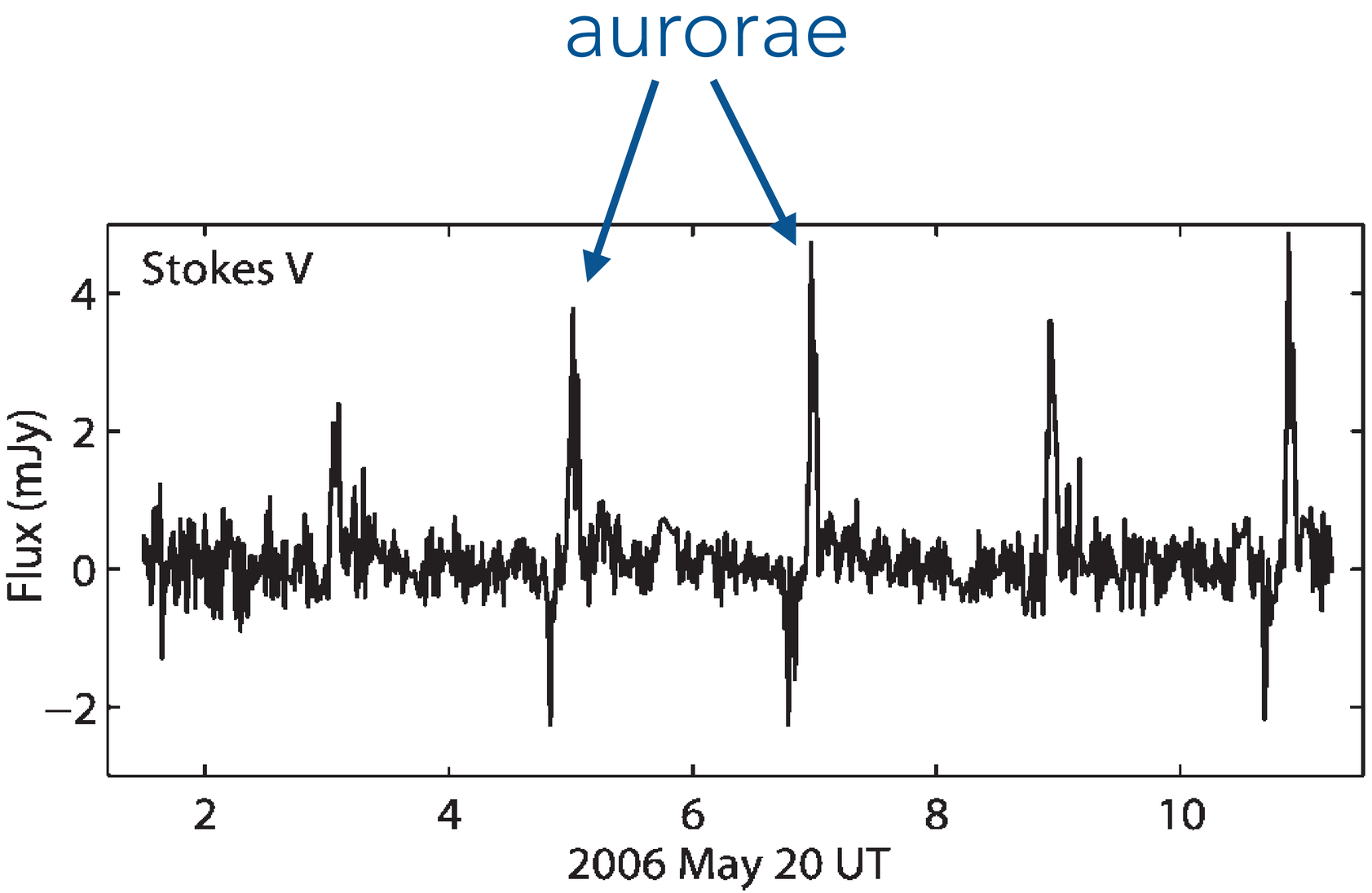
(strength)



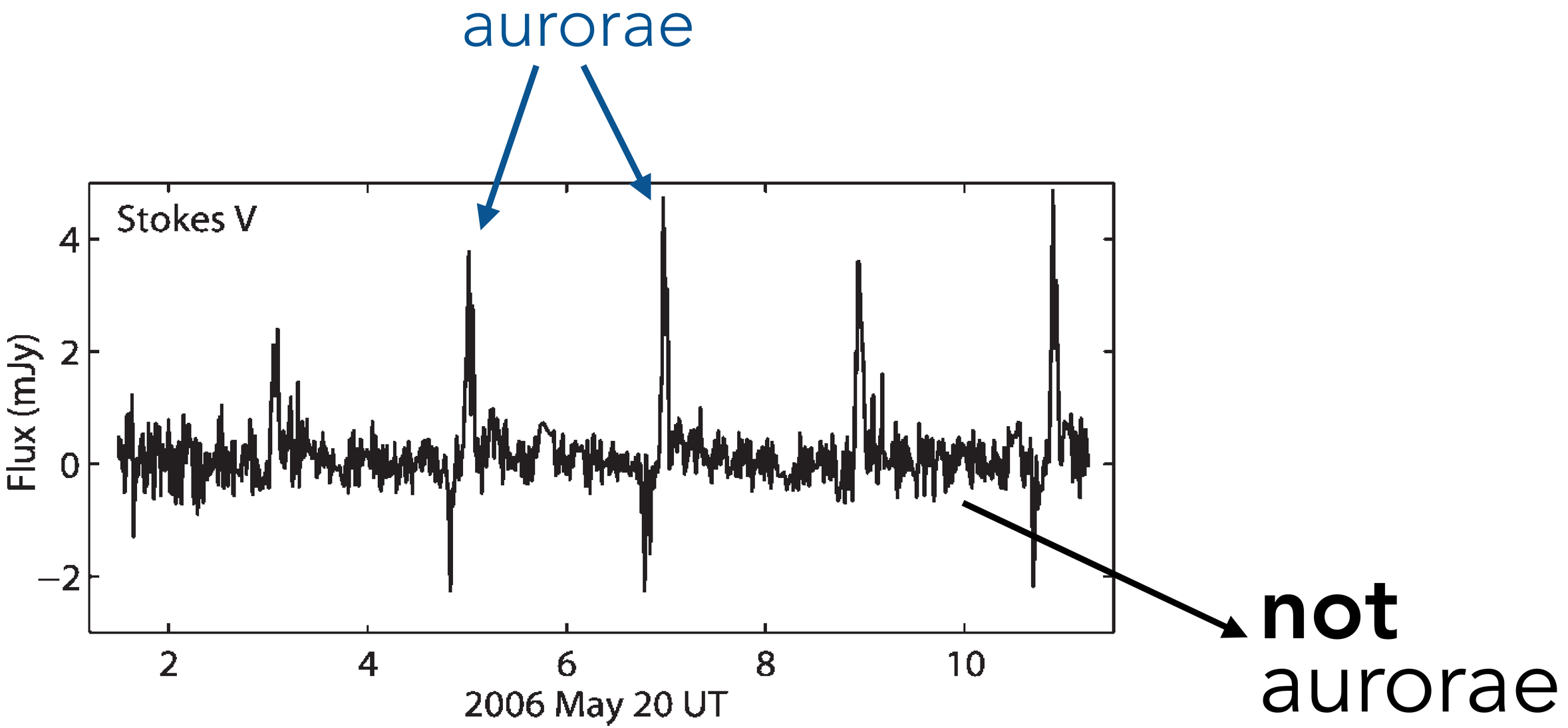
Radiation Belts

(shape)

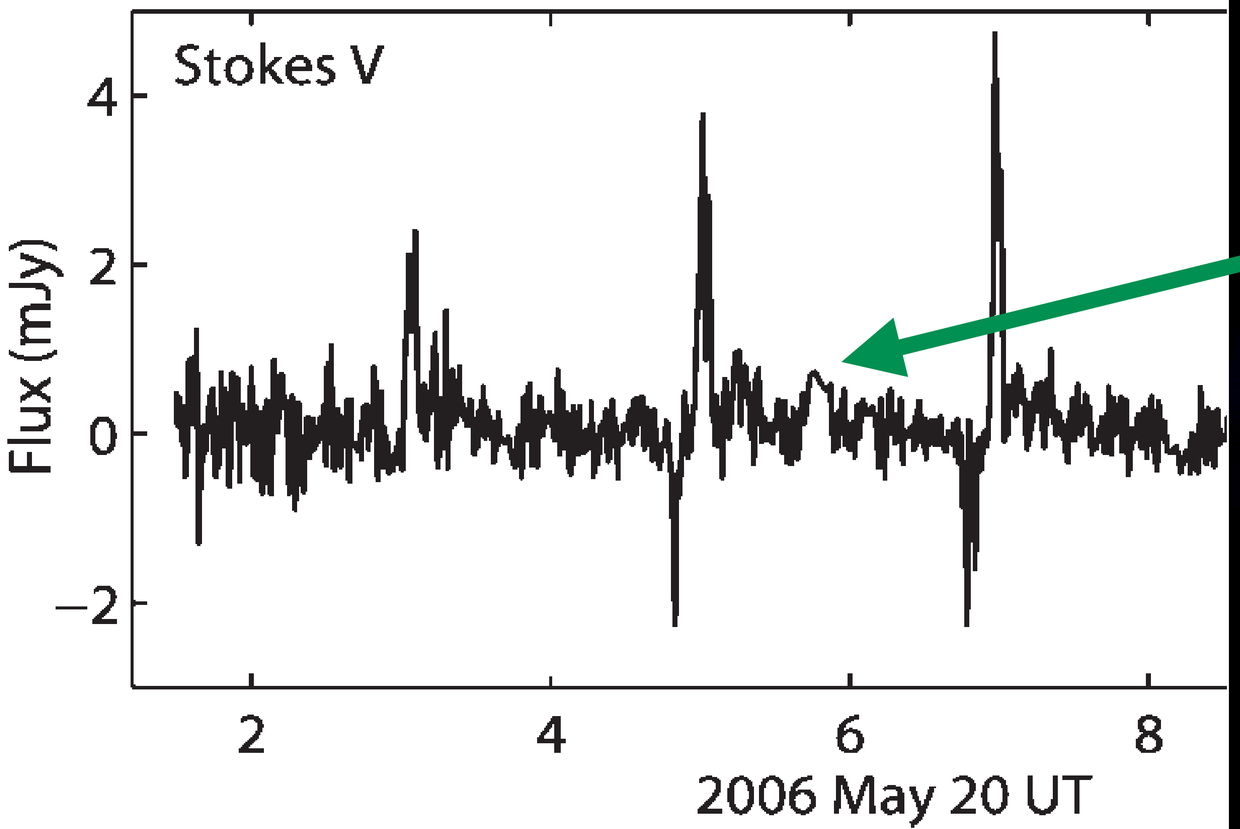
Melodie Kao (mkao@lowell.edu)



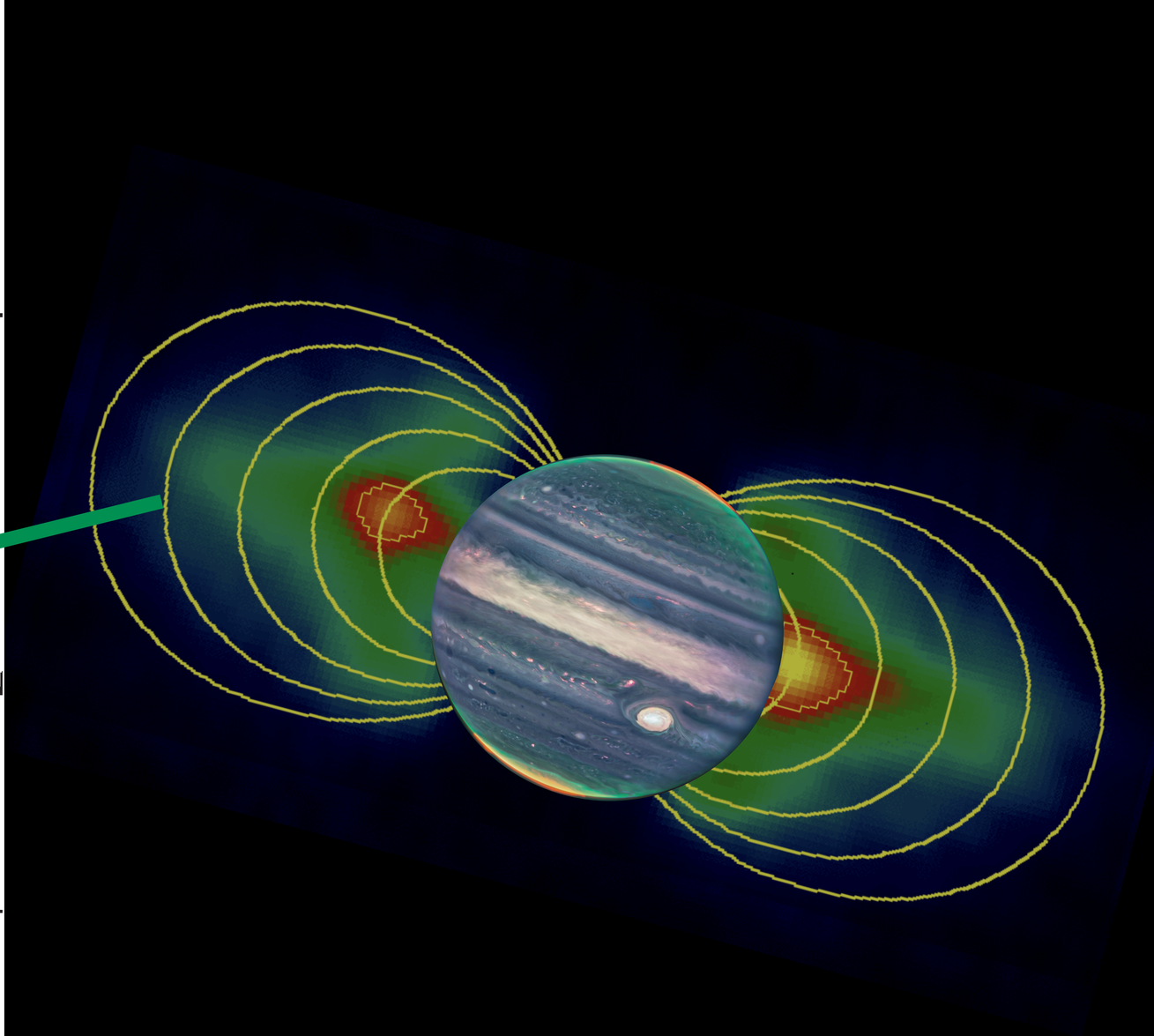
Hallinan+ 2007



Hallinan+ 2007



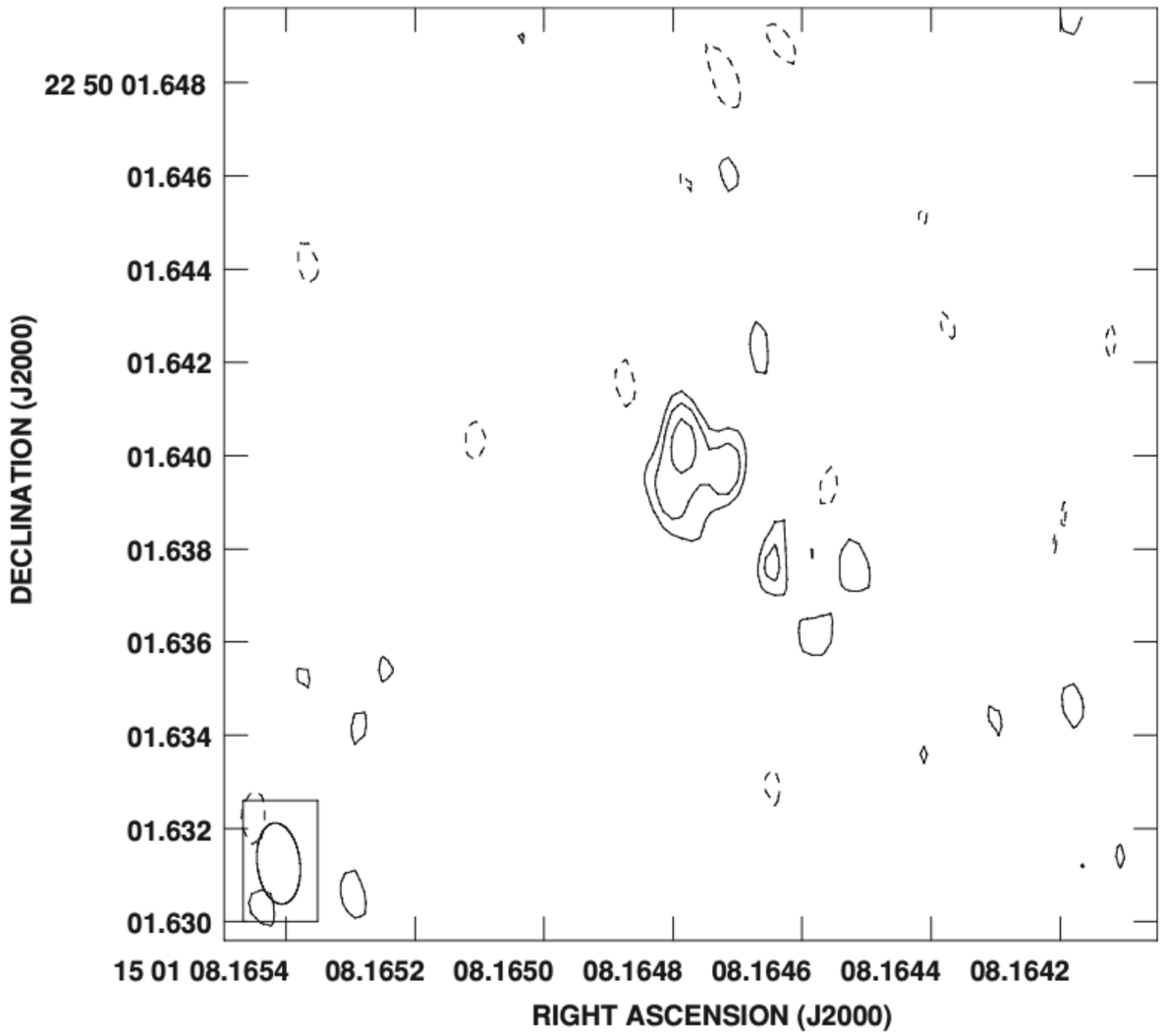
Hallinan+ 2007



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

Melodie Kao (mkao@lowell.edu)

TVLM 513-46546



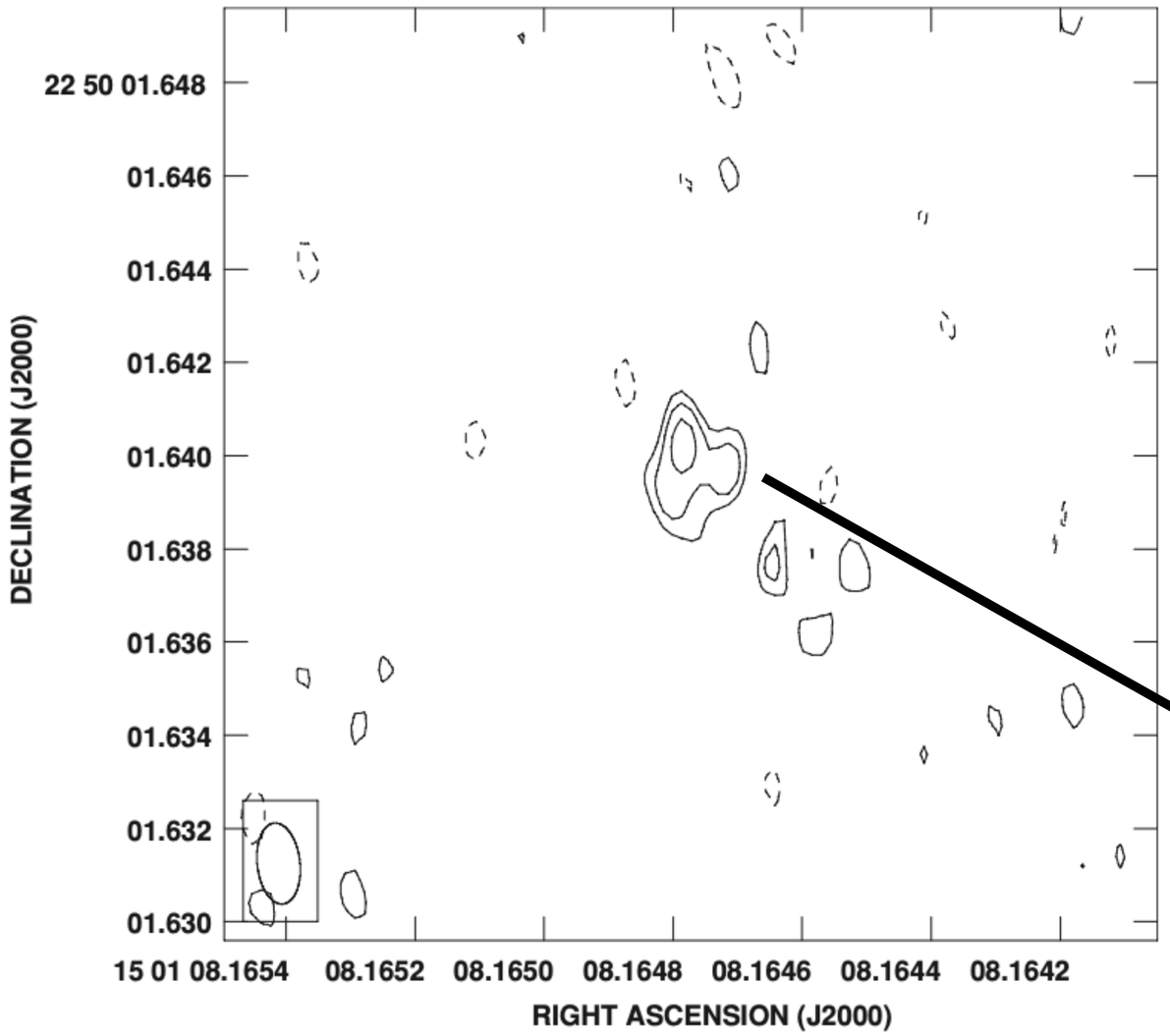
Radio search for companions:

Marginally resolved ~20 R_{UCD}

Forbrich & Berger 2009

See also:
Zhang & Hallinan (2020)
Curiel+ (2020)

TVLM 513-46546



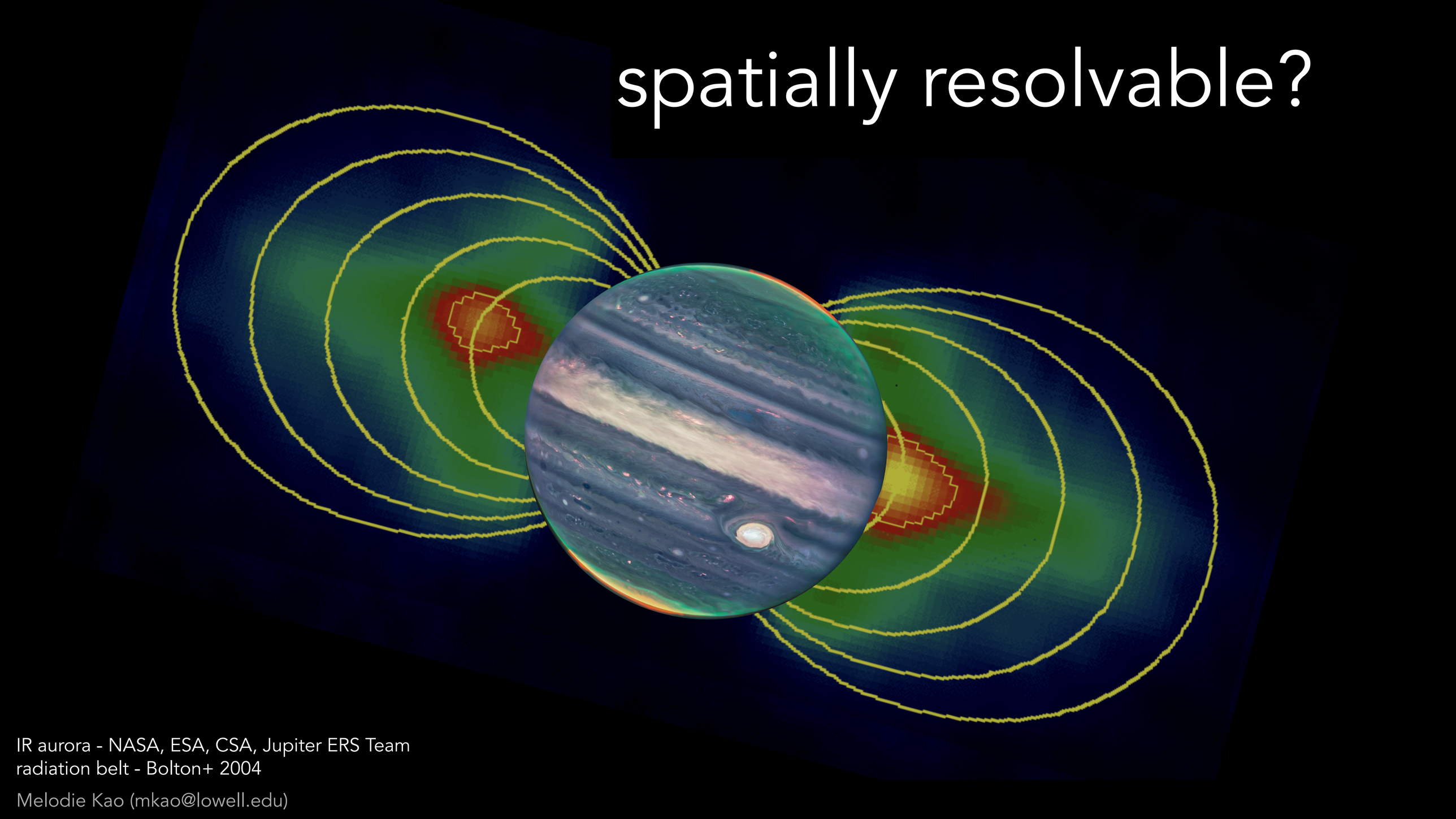
Radio search for companions:

Marginally resolved ~20 R_{UCD}

radiation belt? :)

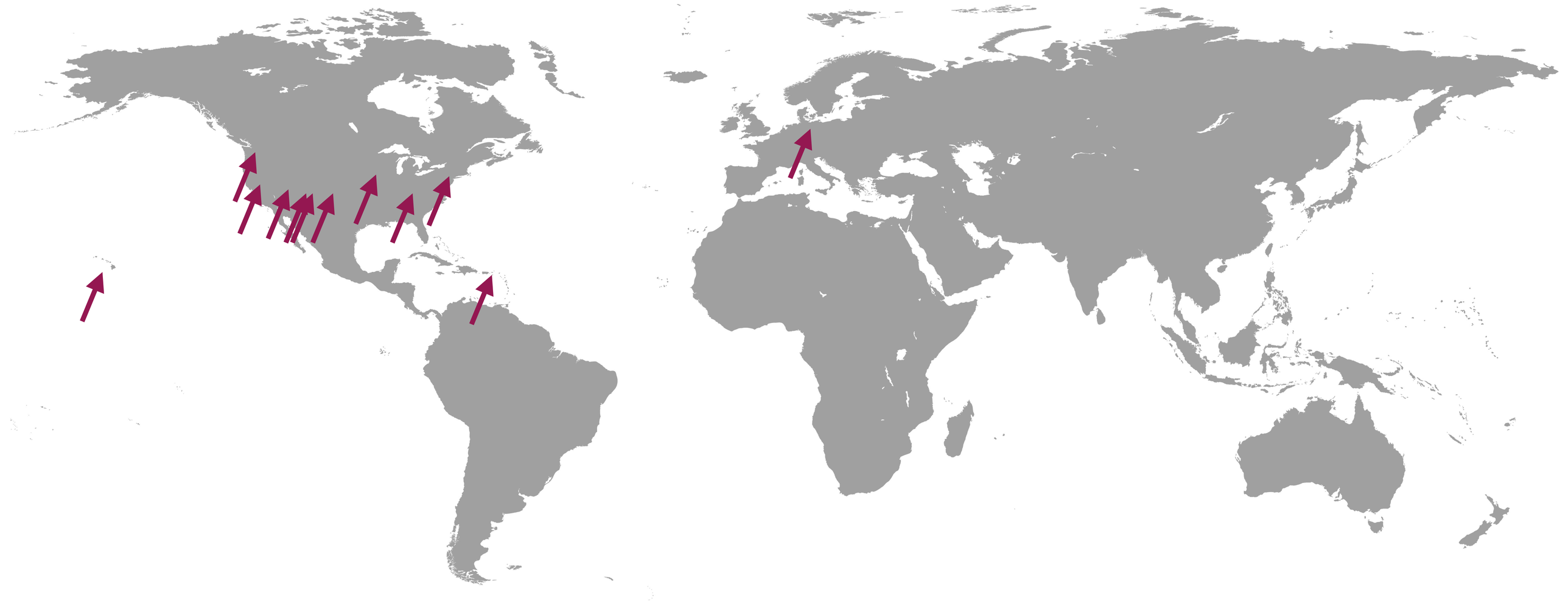
Forbrich & Berger 2009

spatially resolvable?



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

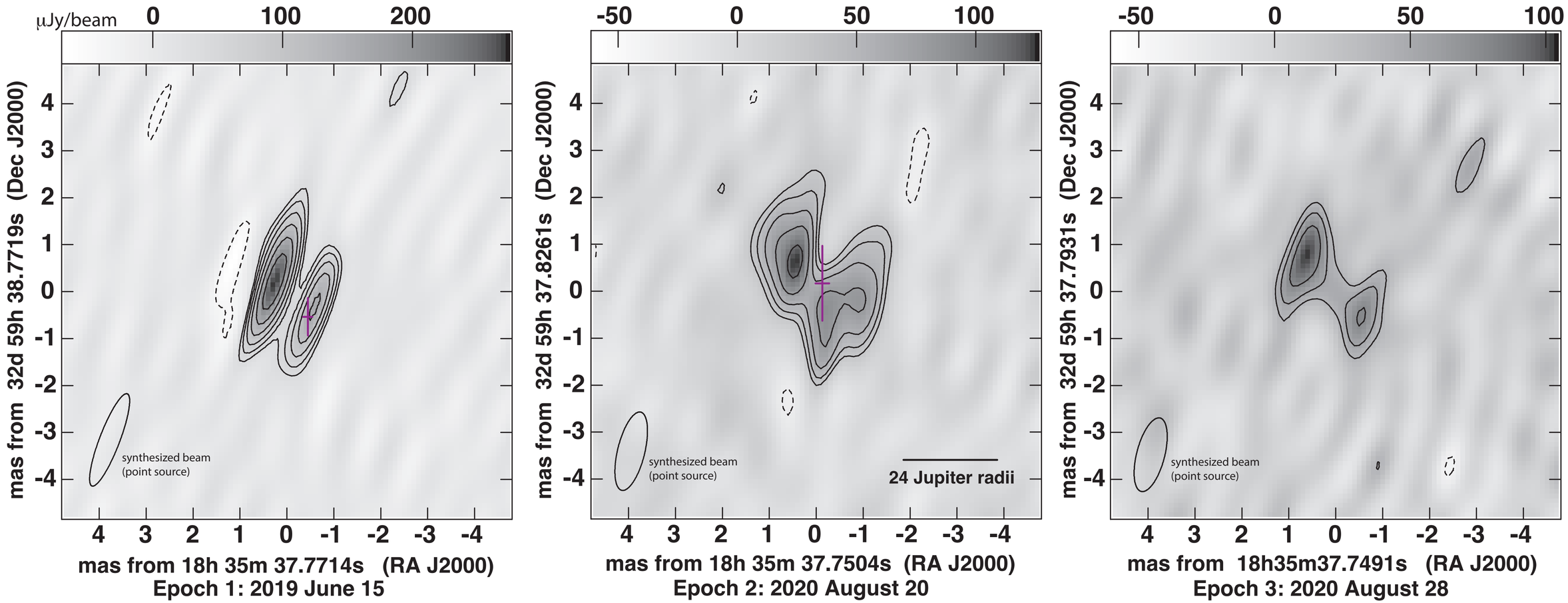
Melodie Kao (mkao@lowell.edu)



High Sensitivity Array: VLA + VLBA + Greenbank + Effelsburg

Melodie Kao (mkao@lowell.edu)

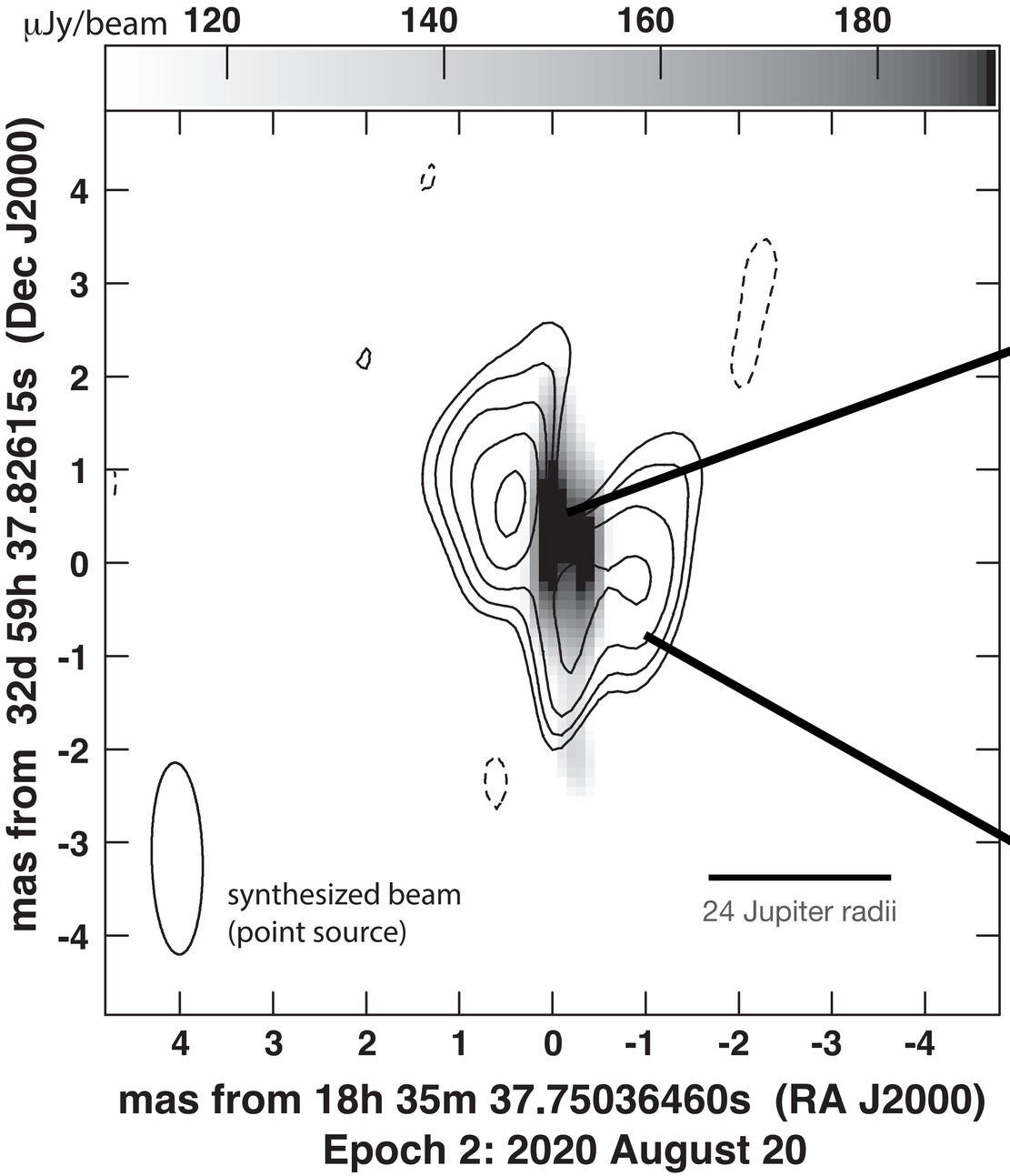
39 Dishes: 27x **25m** 10x **25m** 1x **100m** 1x **100m**



extended + long-lived

Download paper!

Kao, Mioduszewski, Villadsen & Shkolnik (Nature 2023)

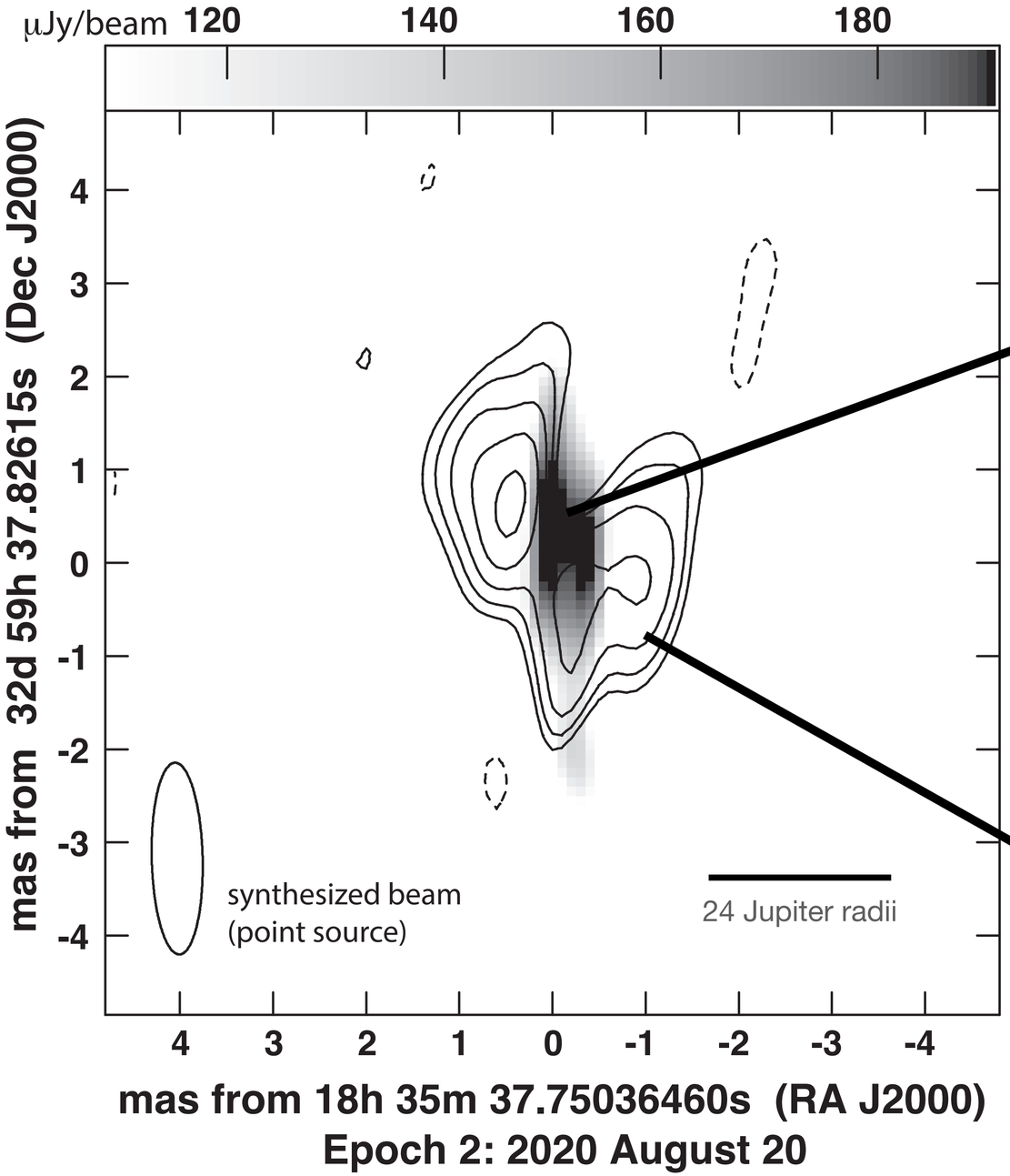


aurorae

not aurorae

Kao, Mioduszewski, Villadsen & Shkolnik (Nature 2023)

see also: Climent+ (Science 2023)



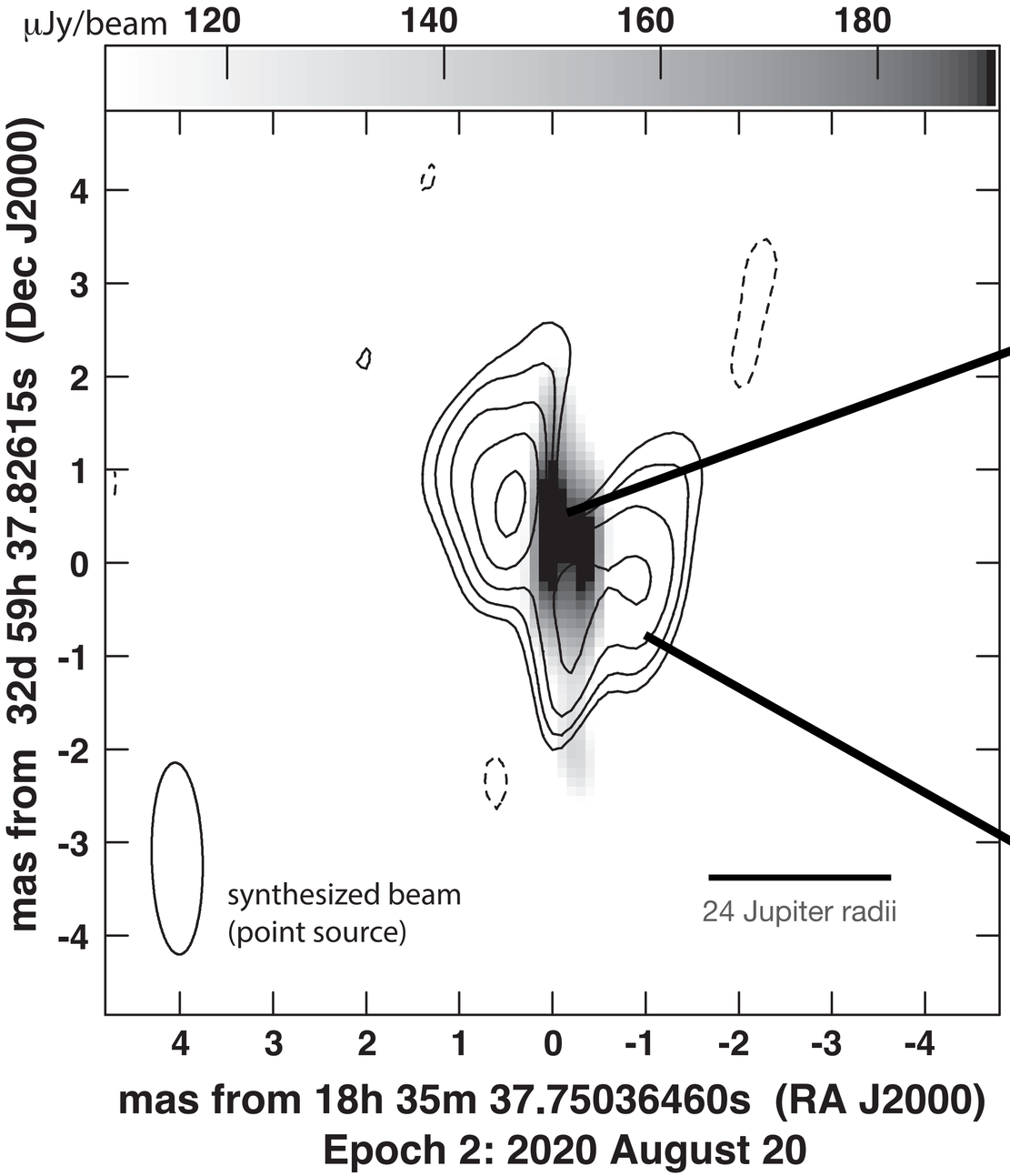
aurorae

3 kiloGauss

not aurorae

Kao, Mioduszewski, Villadsen & Shkolnik (Nature 2023)

see also: Climent+ (Science 2023)



aurorae

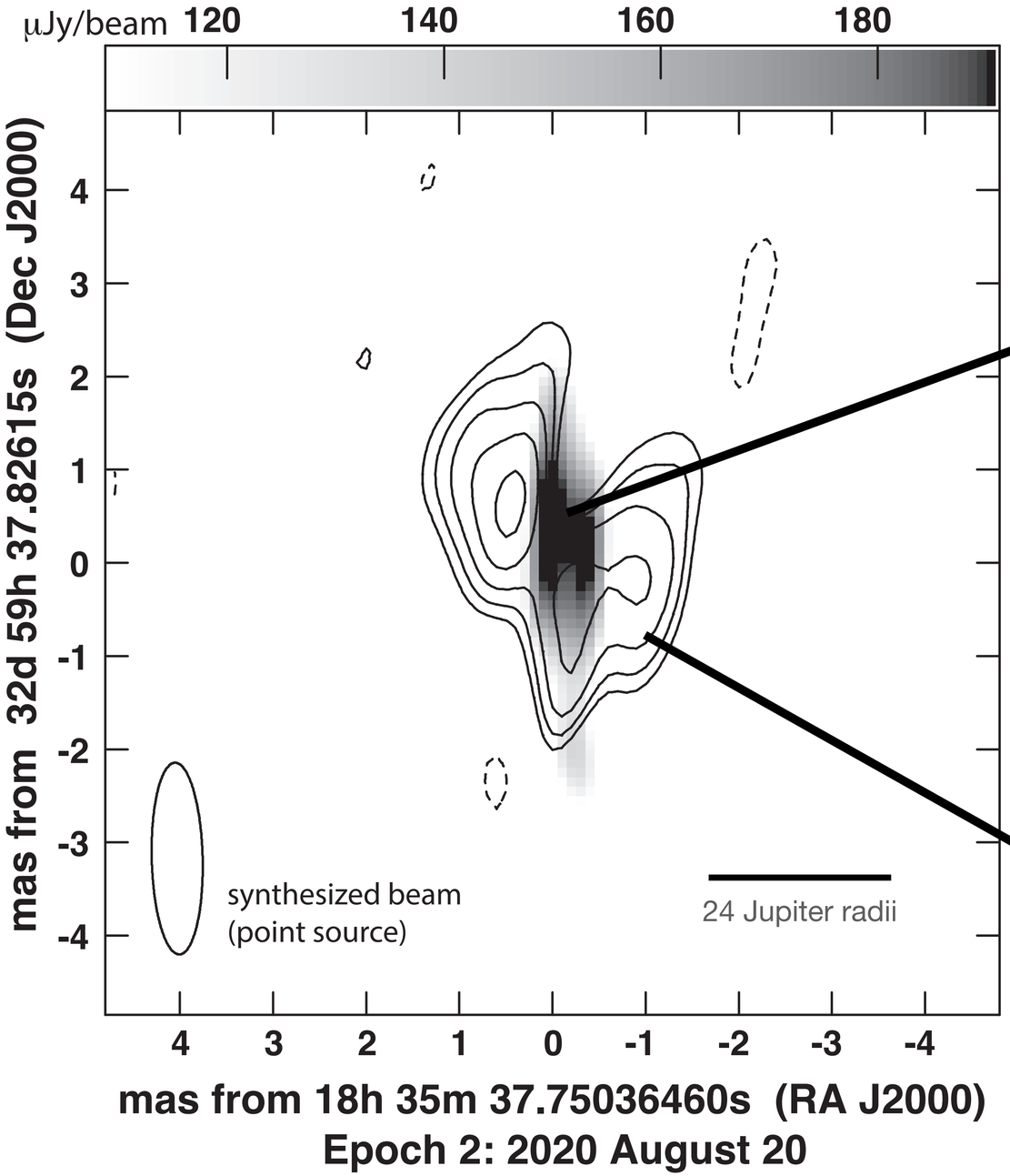
3 kiloGauss

not aurorae

@ 2 Gauss

Kao, Mioduszewski, Villadsen & Shkolnik (Nature 2023)

see also: Climent+ (Science 2023)



aurorae

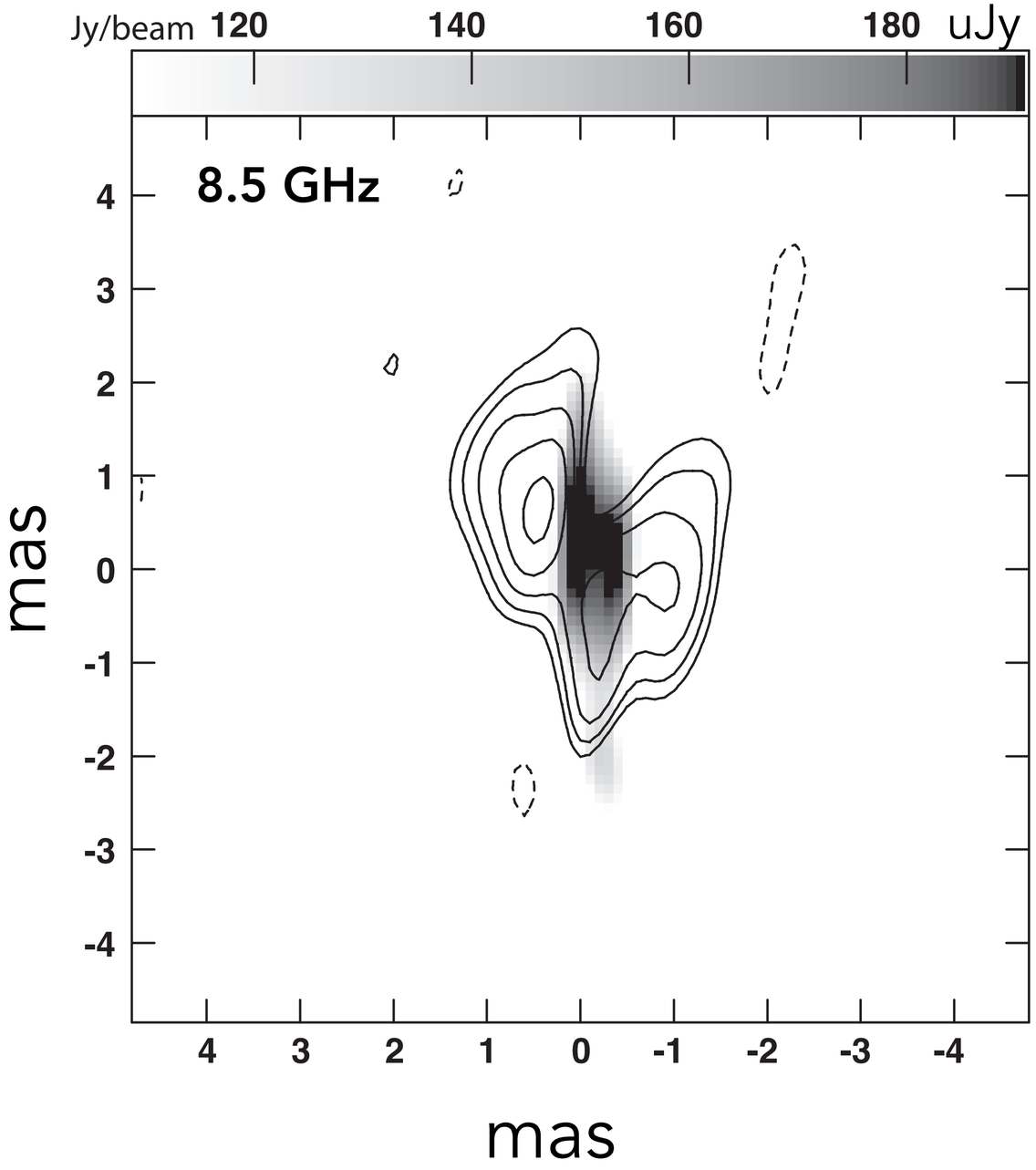
3 kiloGauss

8.4 gigahertz synchrotron @ 2 Gauss

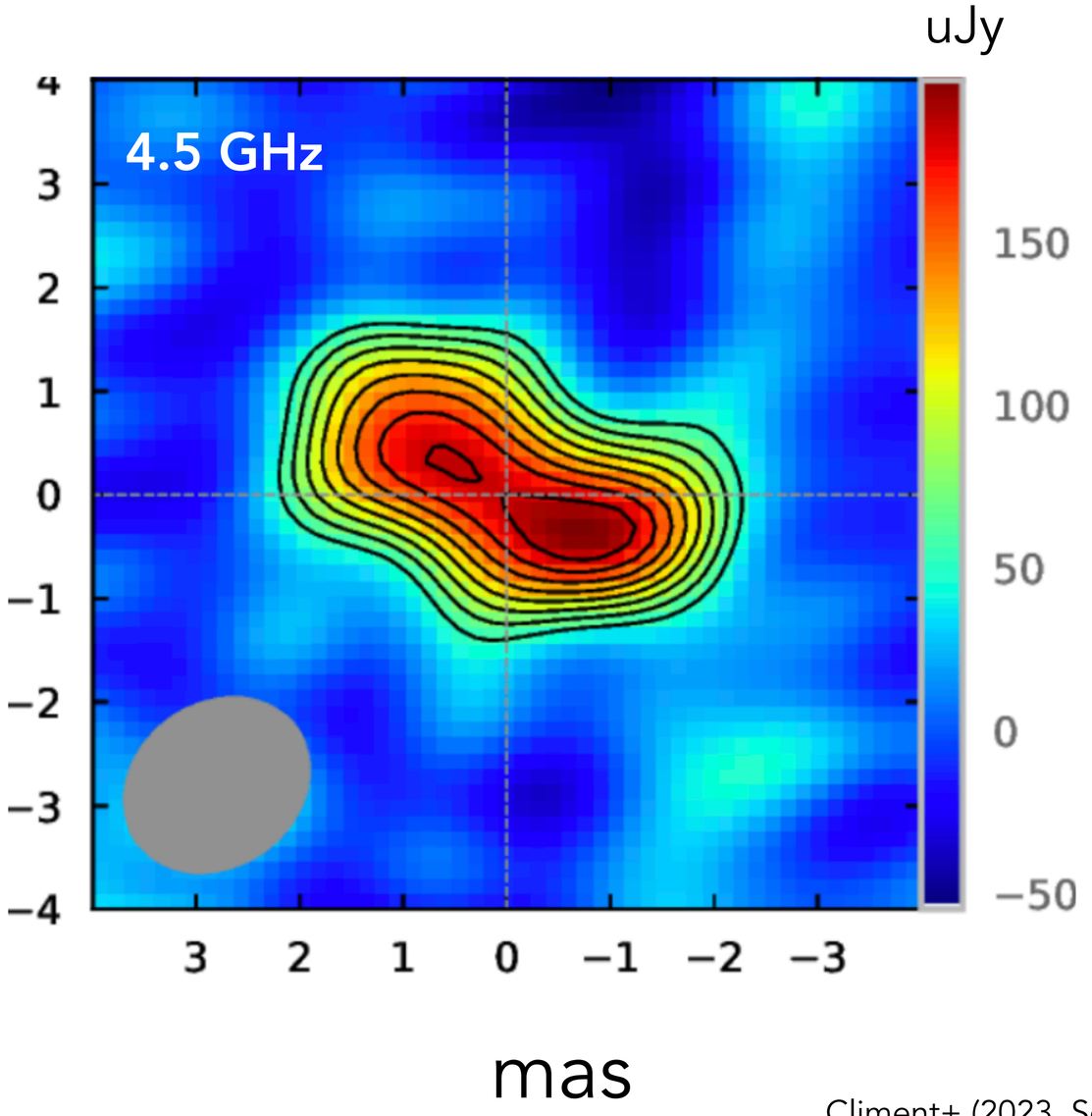
15 MeV

Kao, Mioduszewski, Villadsen & Shkolnik (Nature 2023)

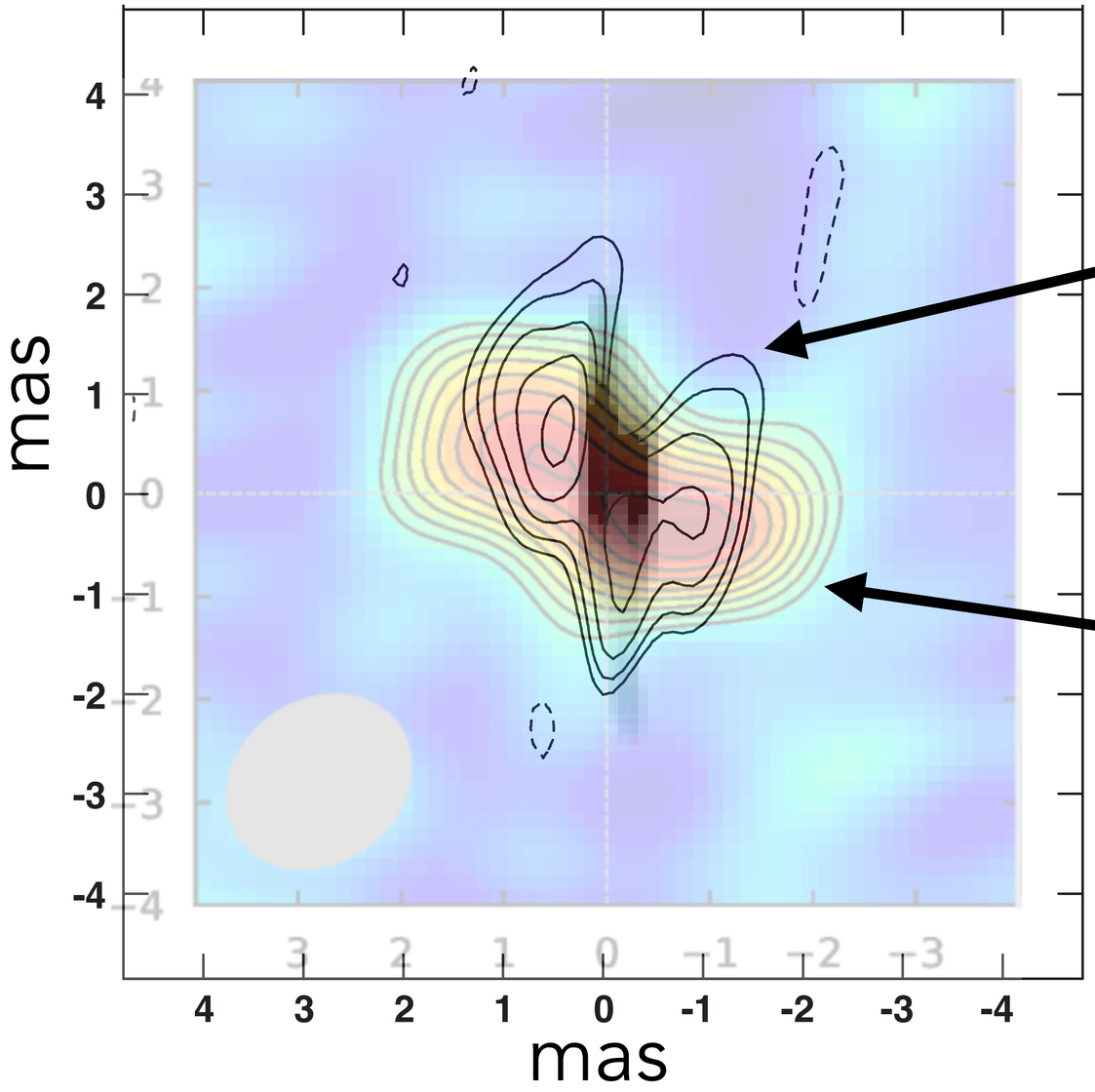
see also: Climent+ (Science 2023)



Kao, Mioduszewski+ (2023)



Climent+ (2023, Science)

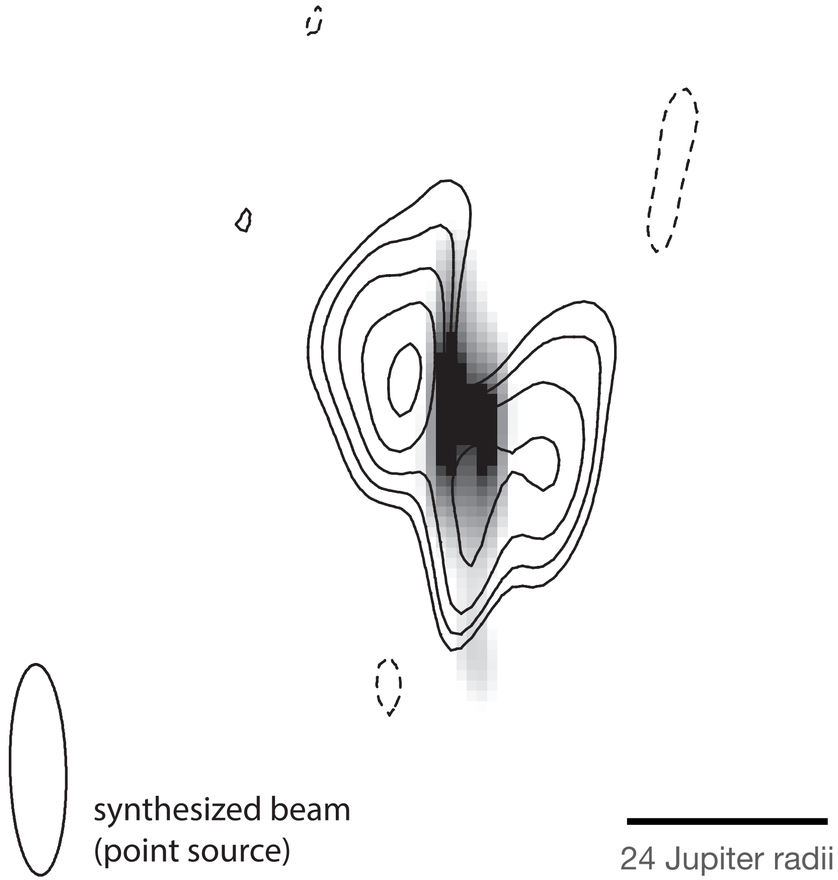


higher energy e-
(more compact)

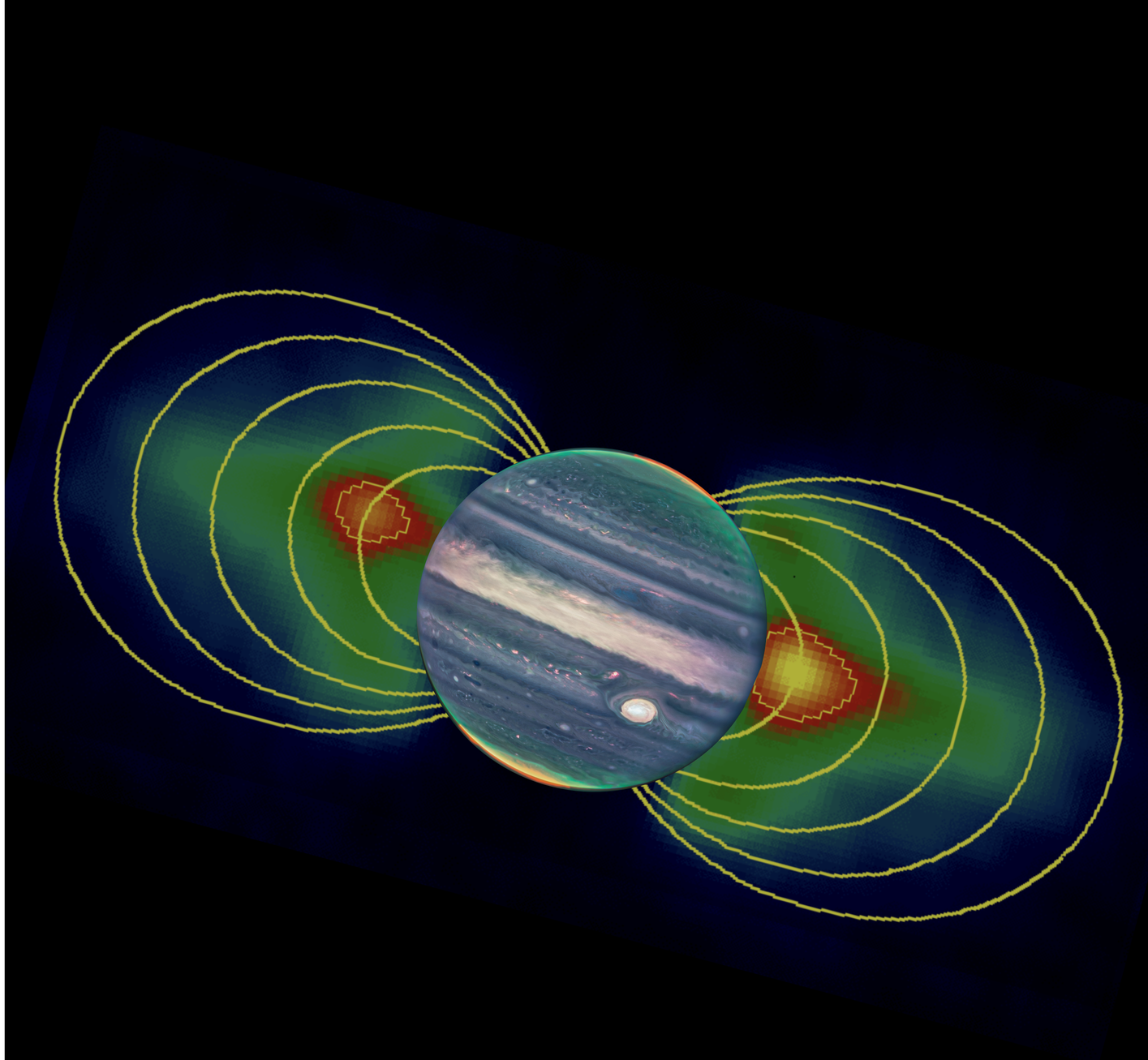
lower energy e-

Climent+ (2023, Science)

Kao, Mioduszewski+ (2023, Nature)



Kao, Mioduszewski, Villadsen & Shkolnik (Nature 2023)



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

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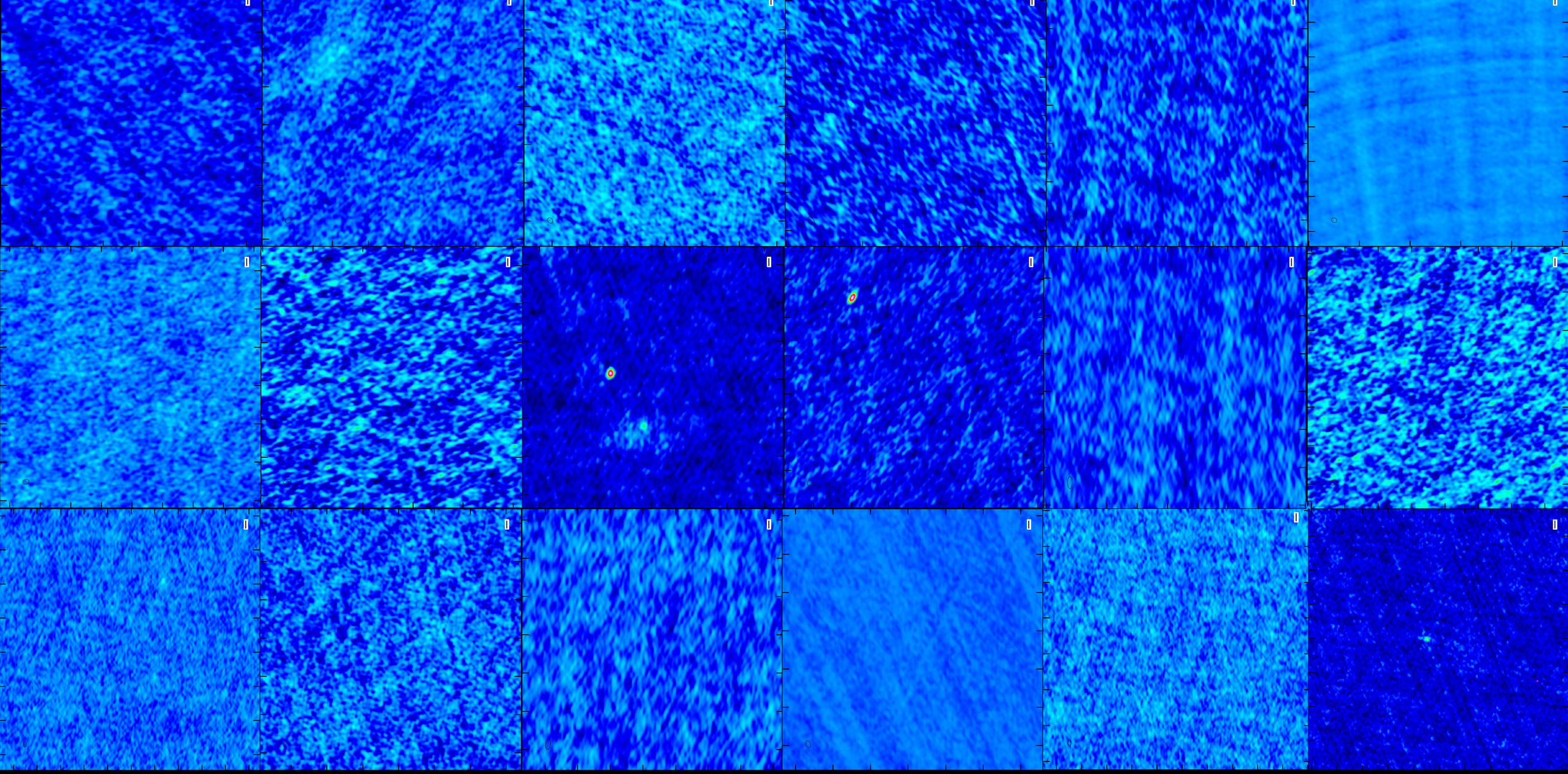
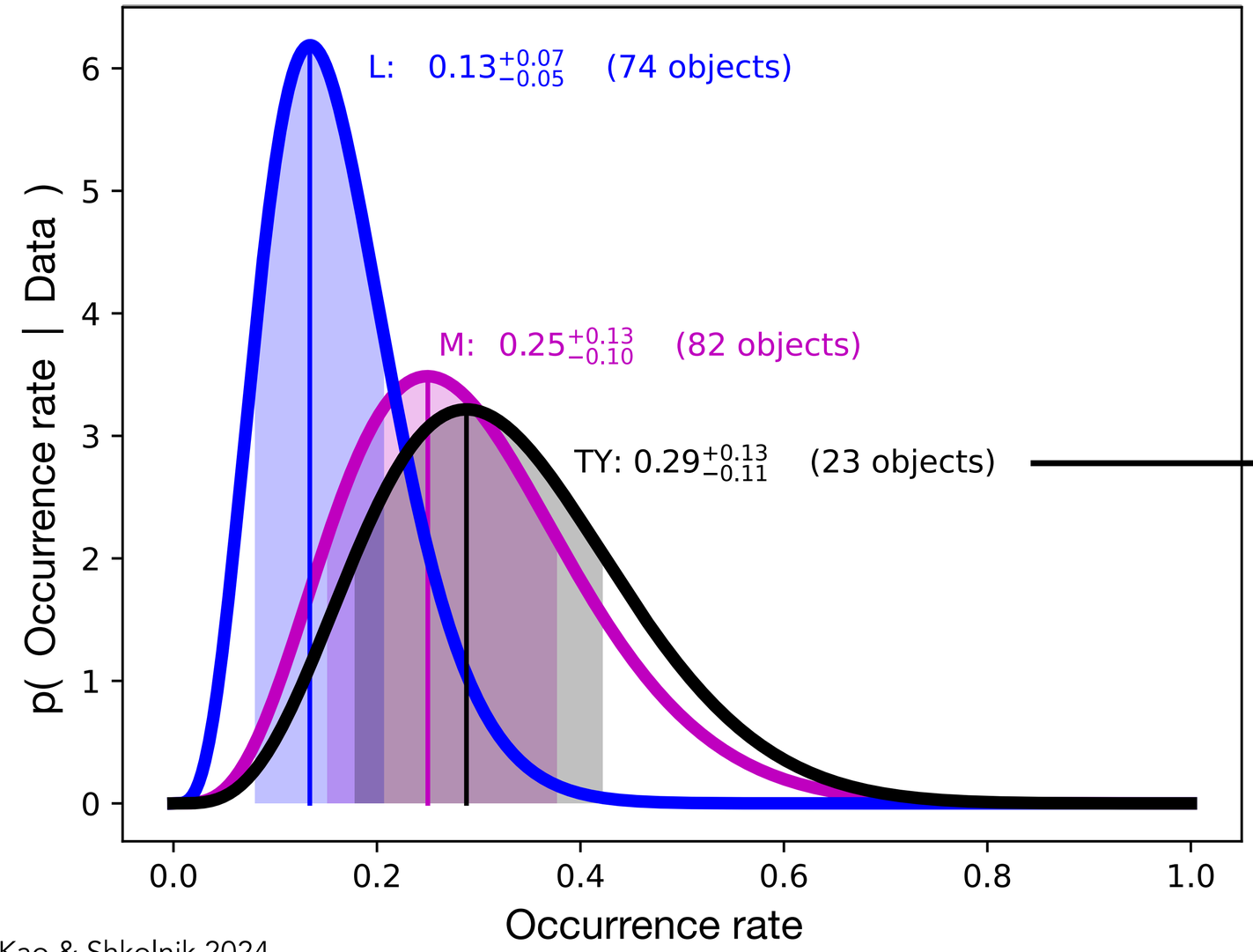


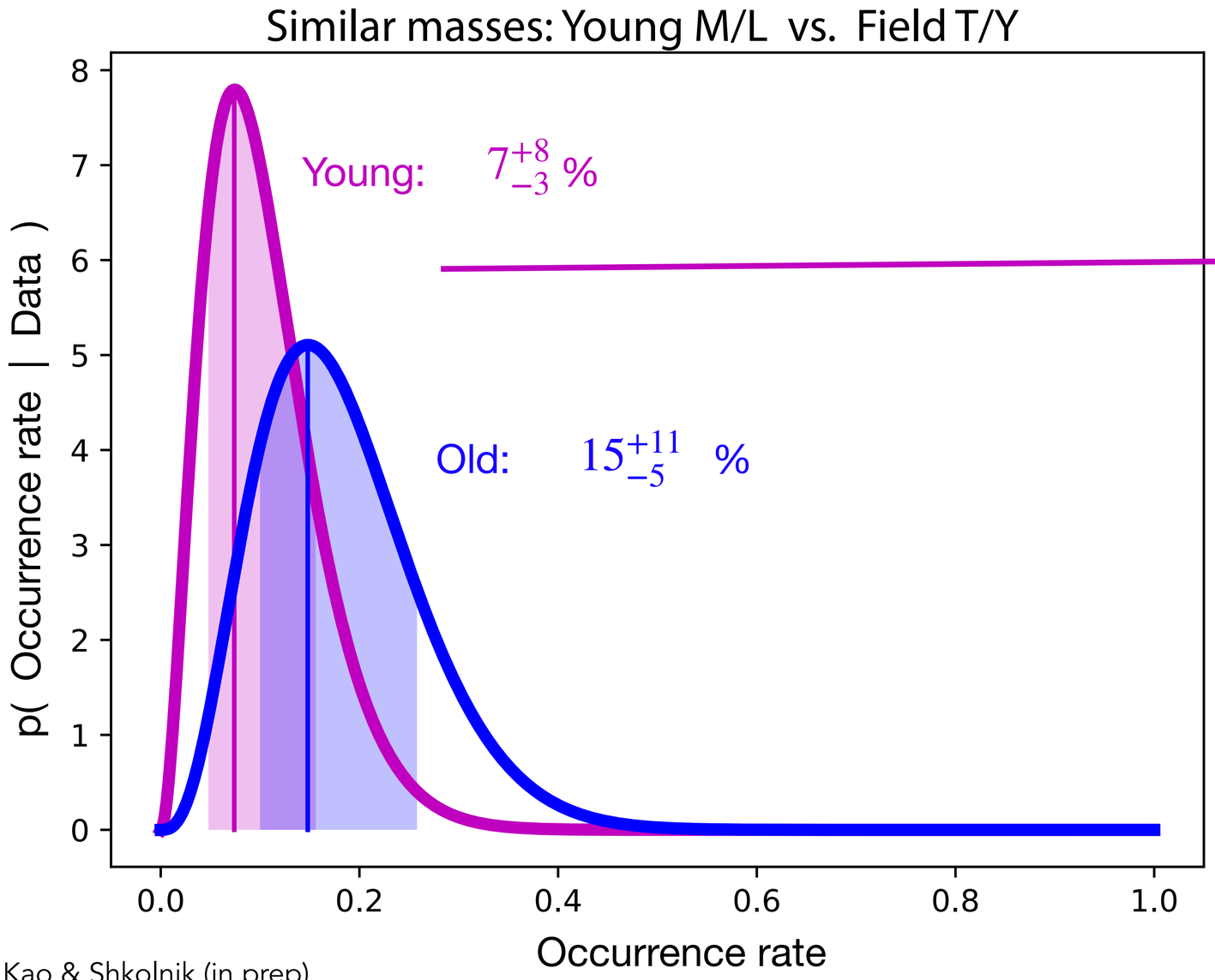
Kao & Shkolnik (in prep)

Melodie Kao (mkao@lowell.edu)



~30% have radiation belts

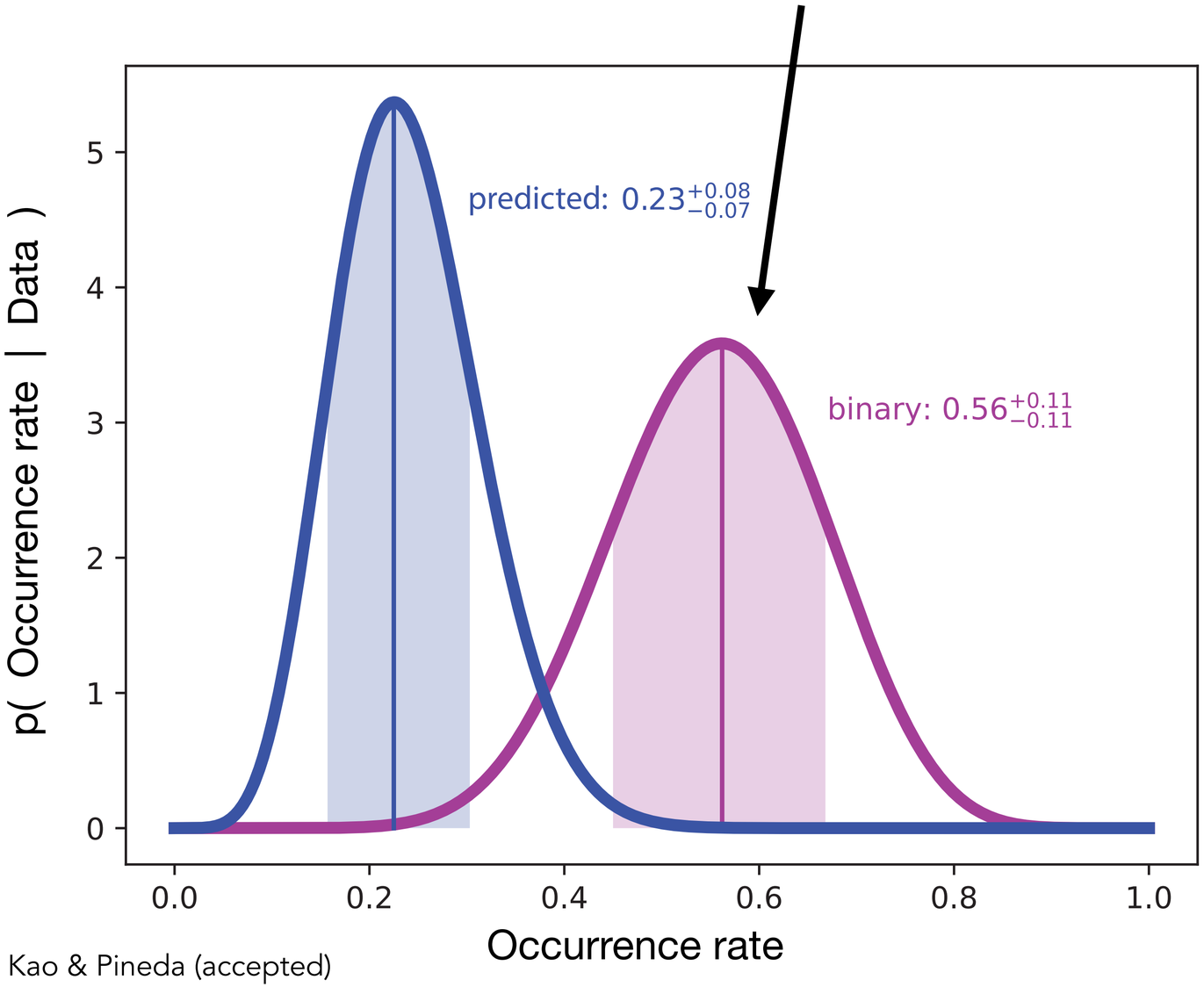
Kao & Shkolnik 2024



Kao & Shkolnik (in prep)

hot, younger objects
not more likely to have
radiation belts

Binarity **enhances** radiation belt occurrence rate.



Kao & Pineda (accepted)

Download paper!

Melodie Kao (mkao@lowell.edu)

https://arxiv.org/abs/2403.08860

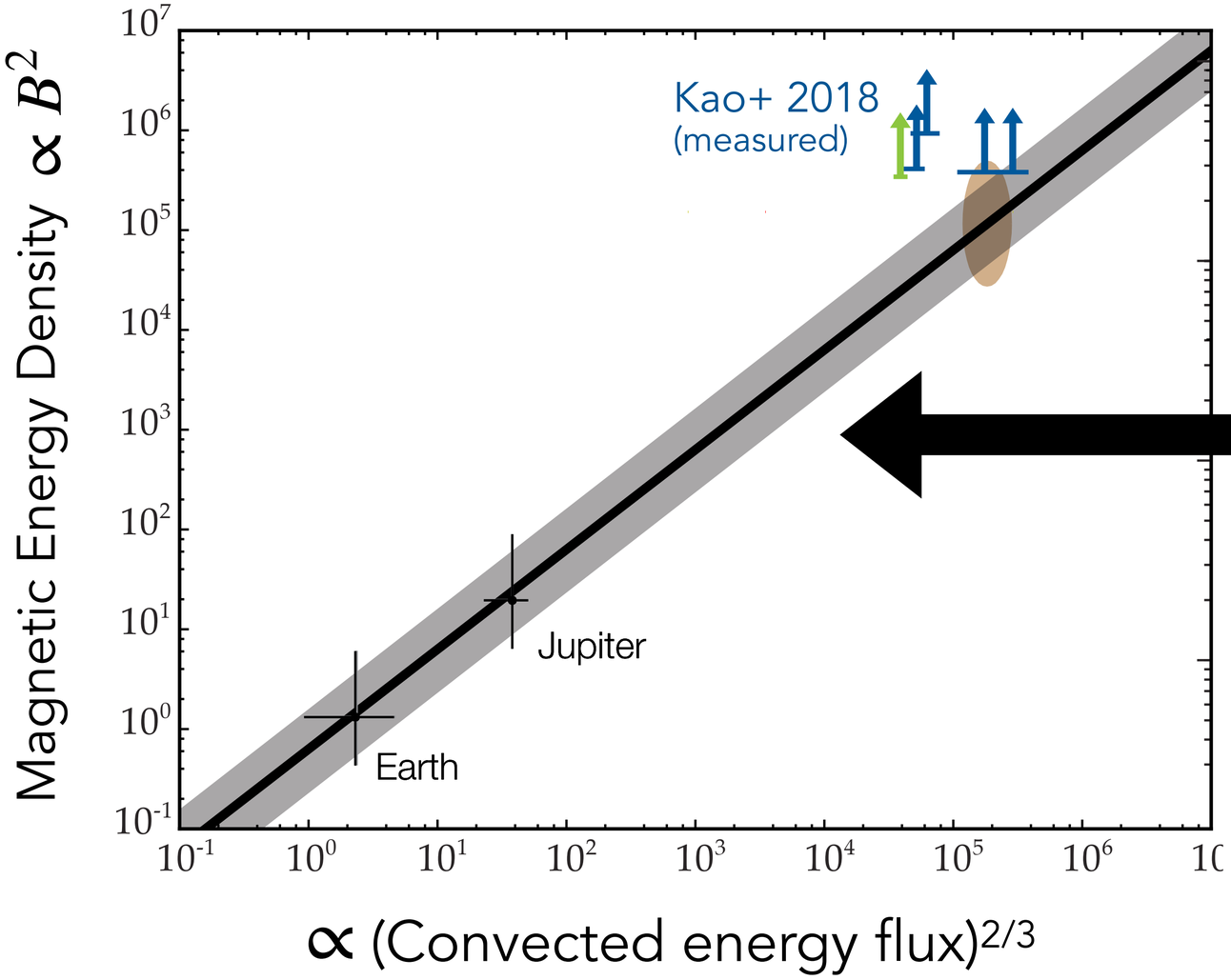
radiation belts may be ubiquitous:

planets
brown dwarfs
low mass stars
massive stars

Leto+ (2021)
Owoki+ (2022)

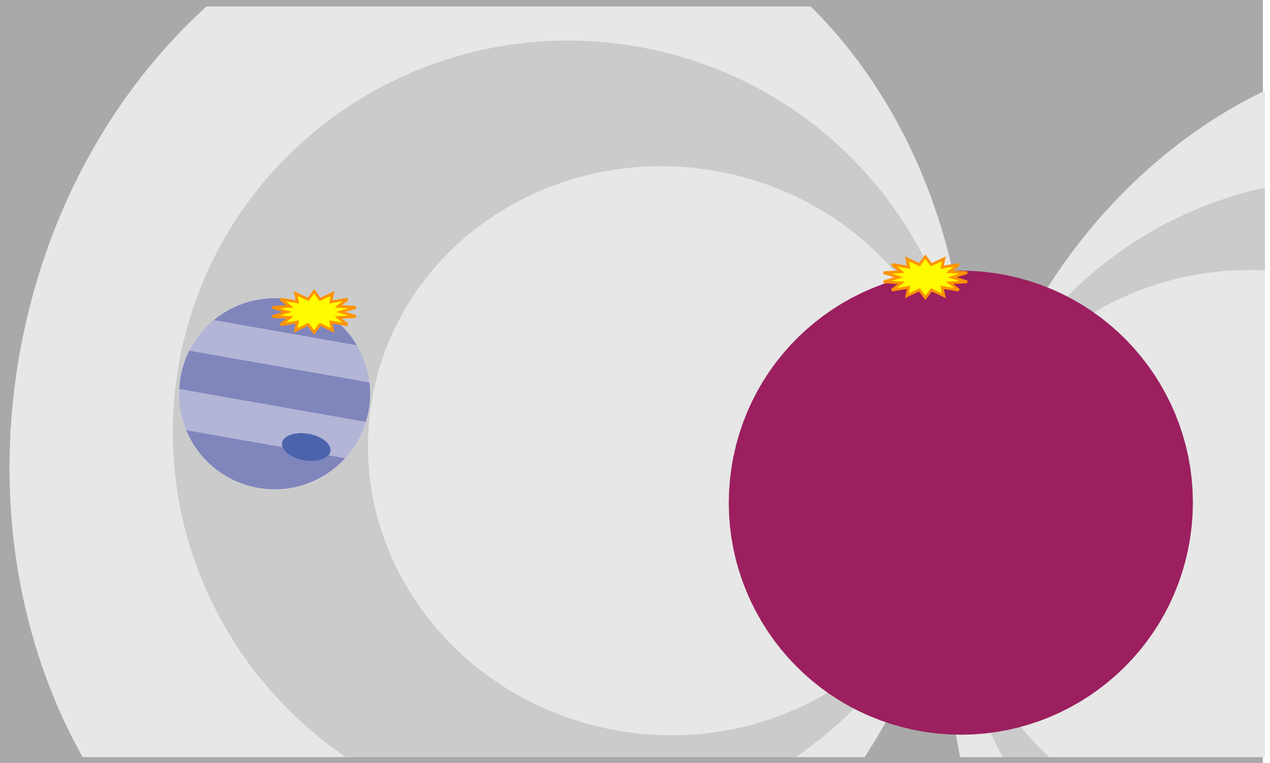
see Barnali Das' invited review tomorrow!

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



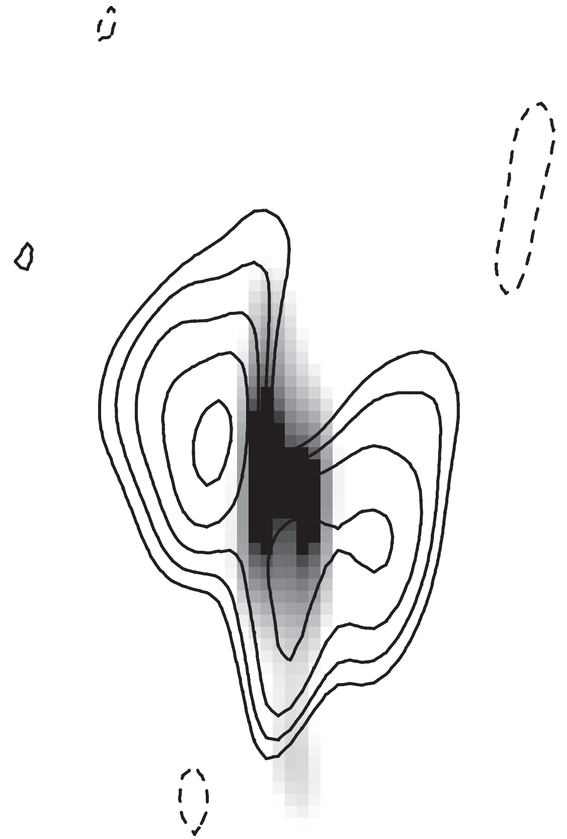
for: dipole-dominated ✓

Kao+ (2018)



Star-Planet Interactions

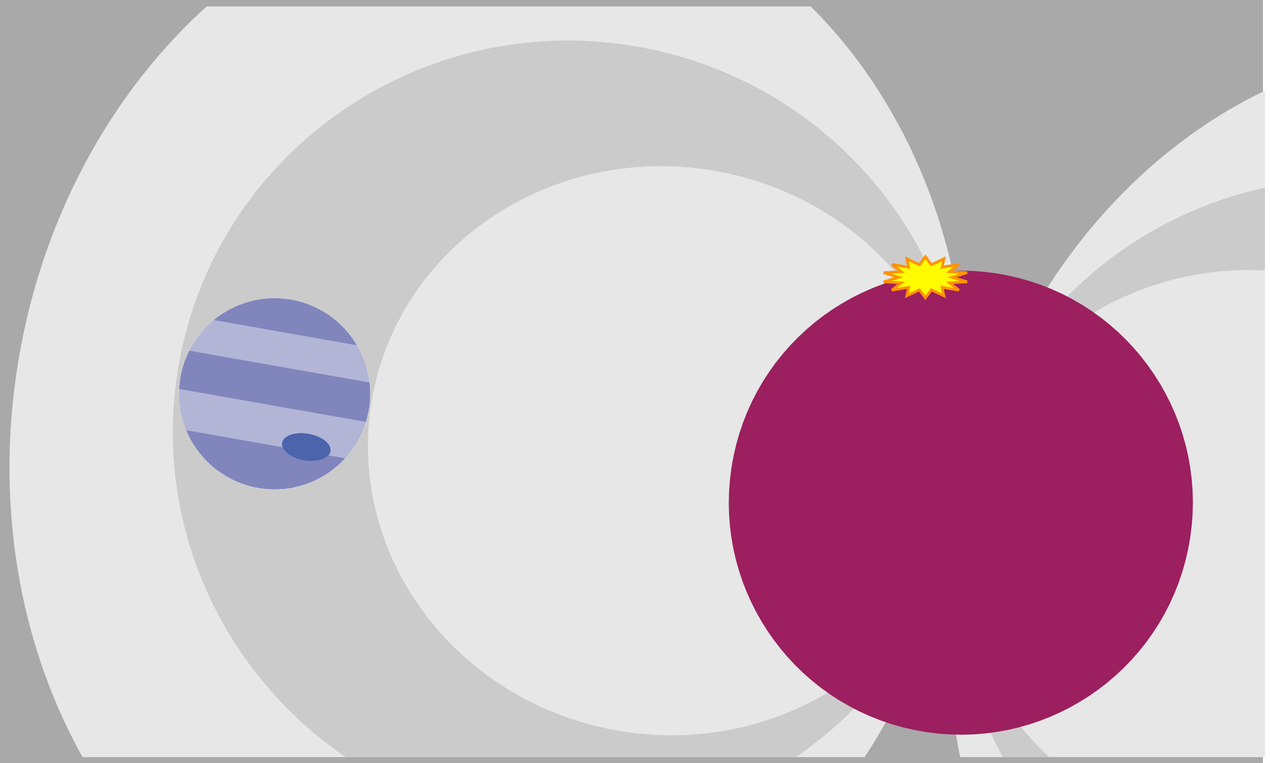
(strength, shape)



Radiation Belts

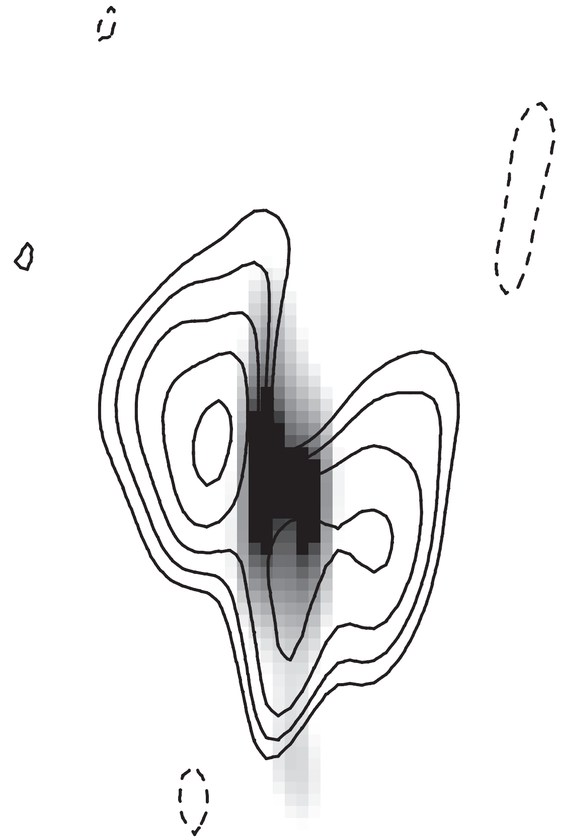
(shape)

Melodie Kao (mkao@lowell.edu)



Host-Satellite Interactions

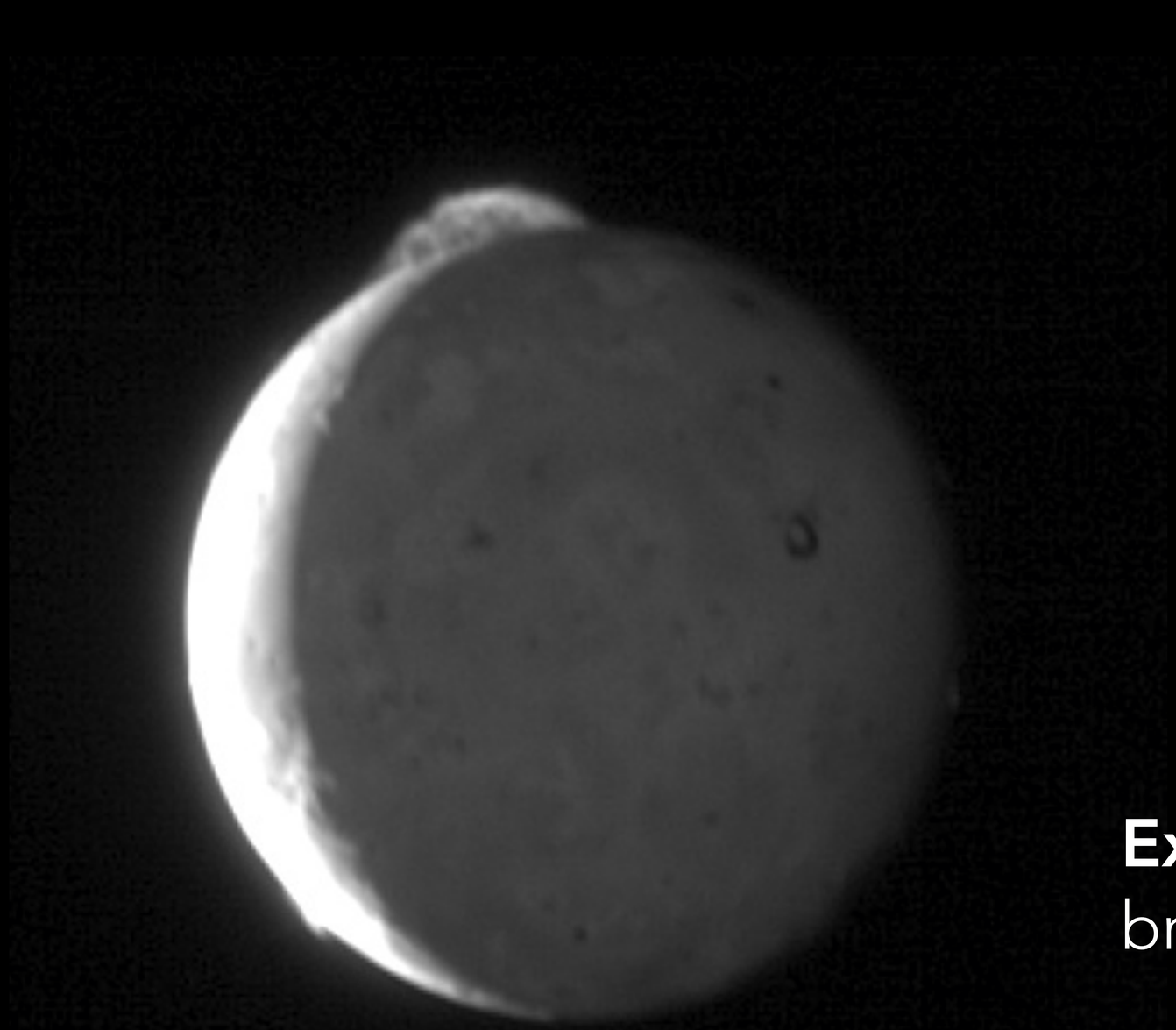
(strength, shape)



Radiation Belts

(shape)

Melodie Kao (mkao@lowell.edu)



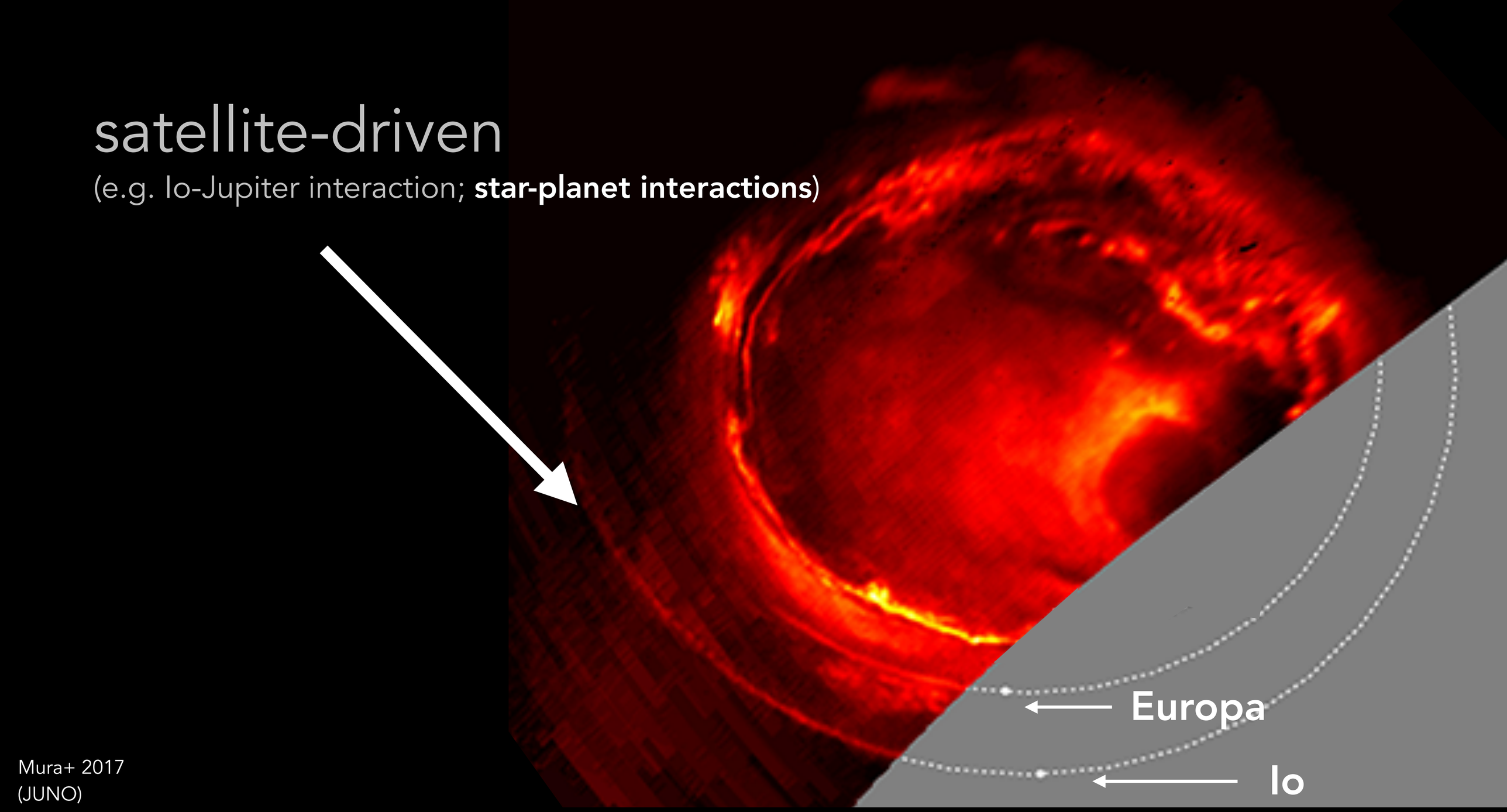
Exo-volcanism seeding brown dwarf magnetospheres?

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

Melodie Kao (mkao@lowell.edu)

satellite-driven

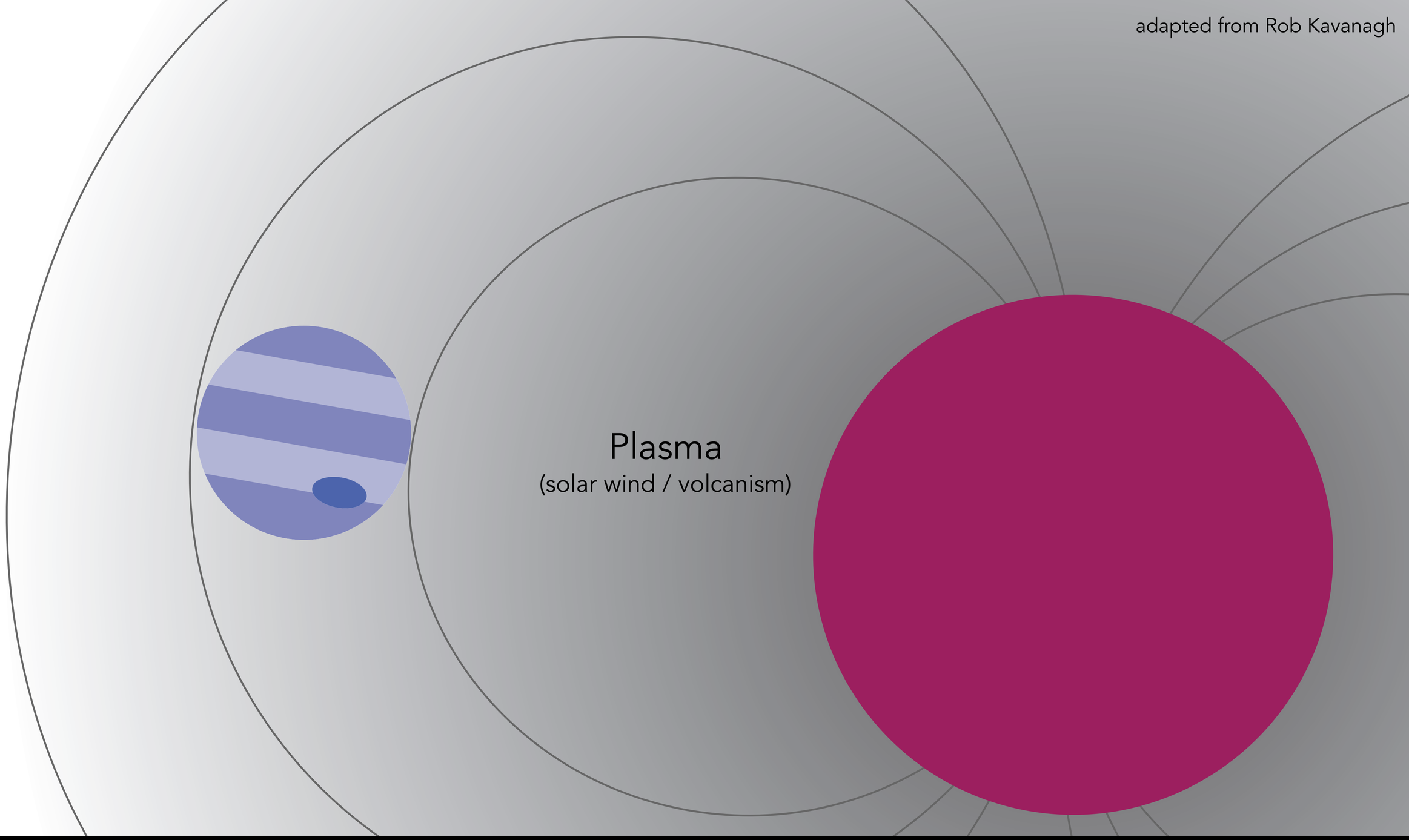
(e.g. Io-Jupiter interaction; **star-planet interactions**)



Mura+ 2017
(JUNO)

Melodie Kao (mkao@lowell.edu)

adapted from Rob Kavanagh



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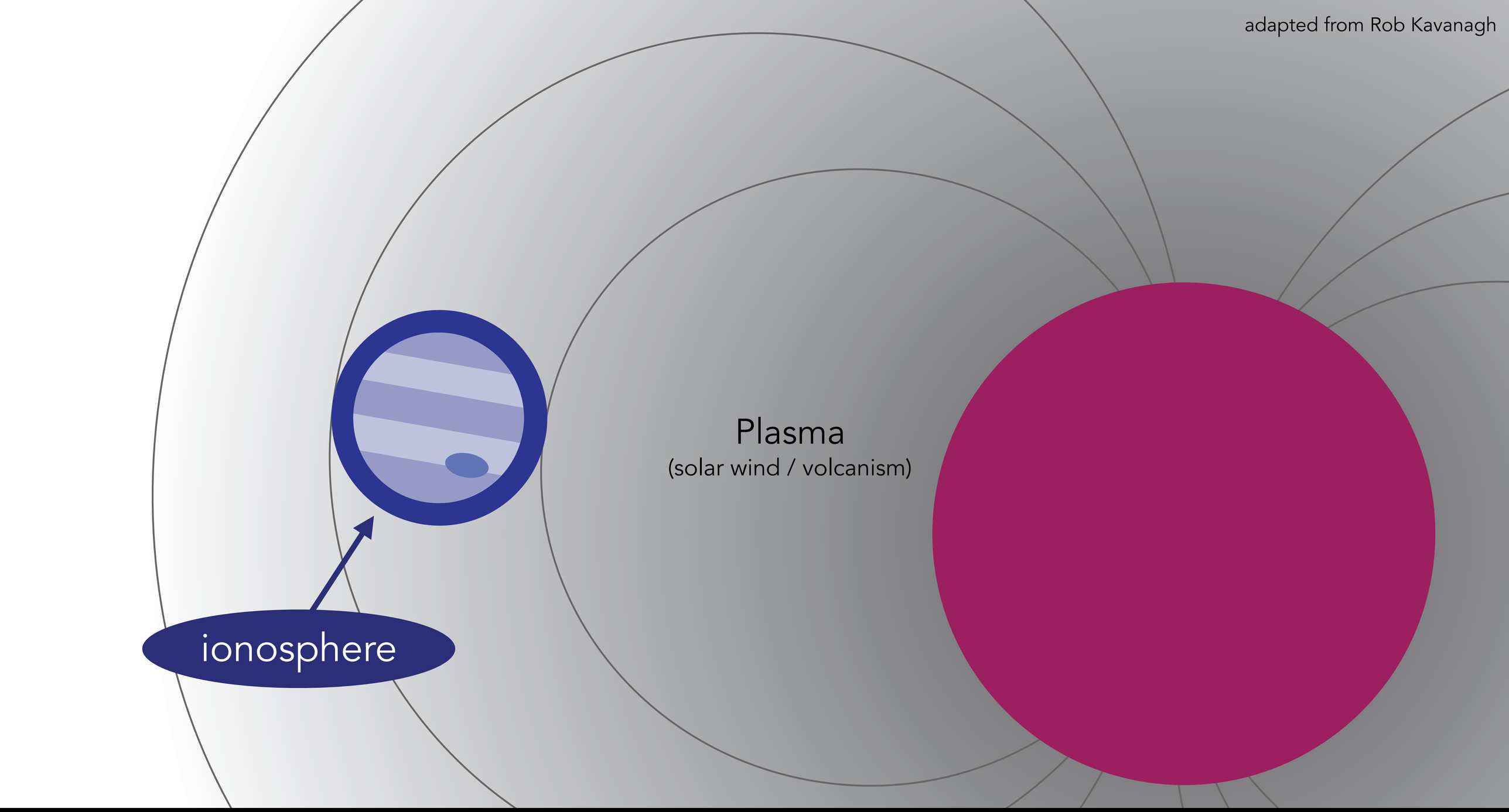

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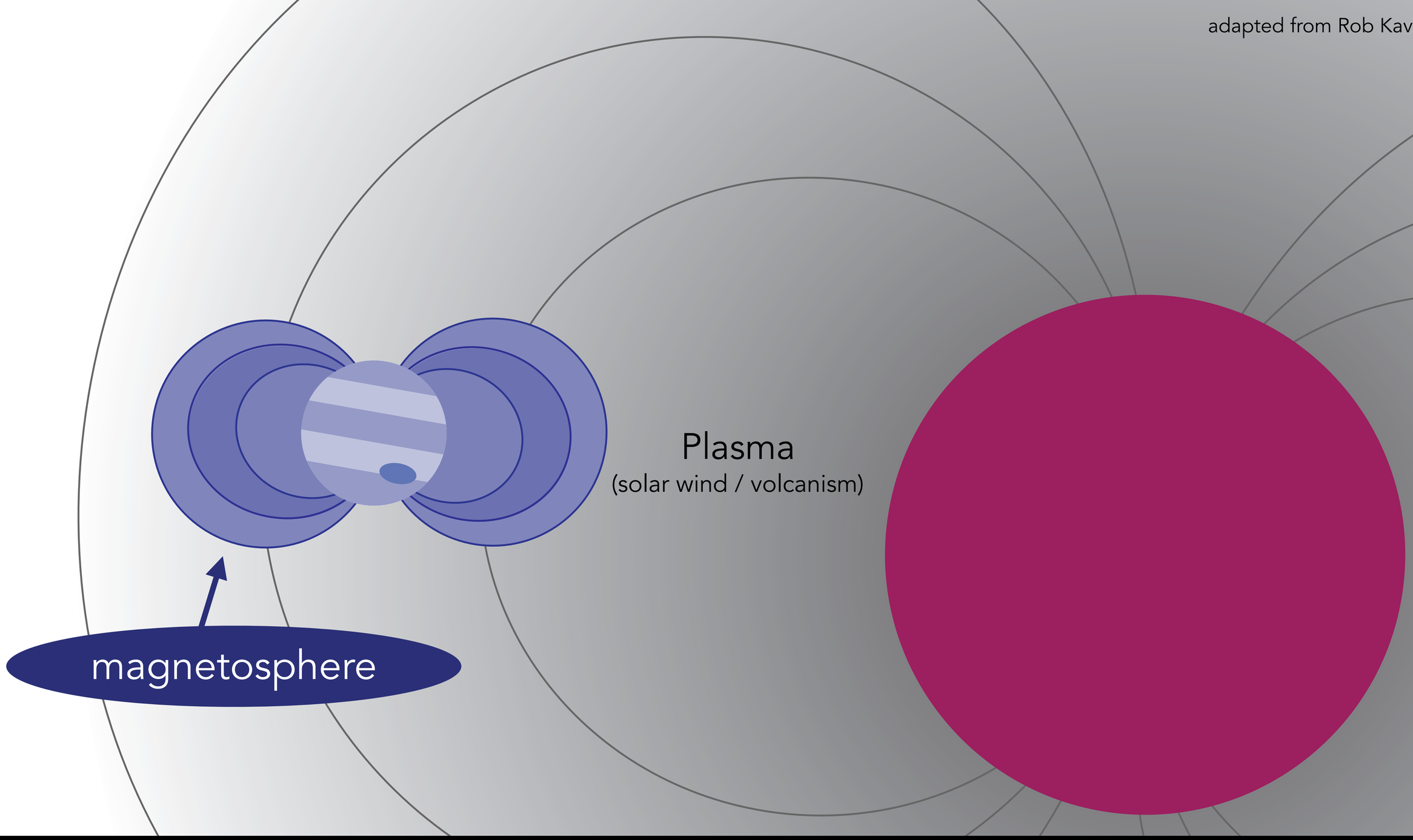

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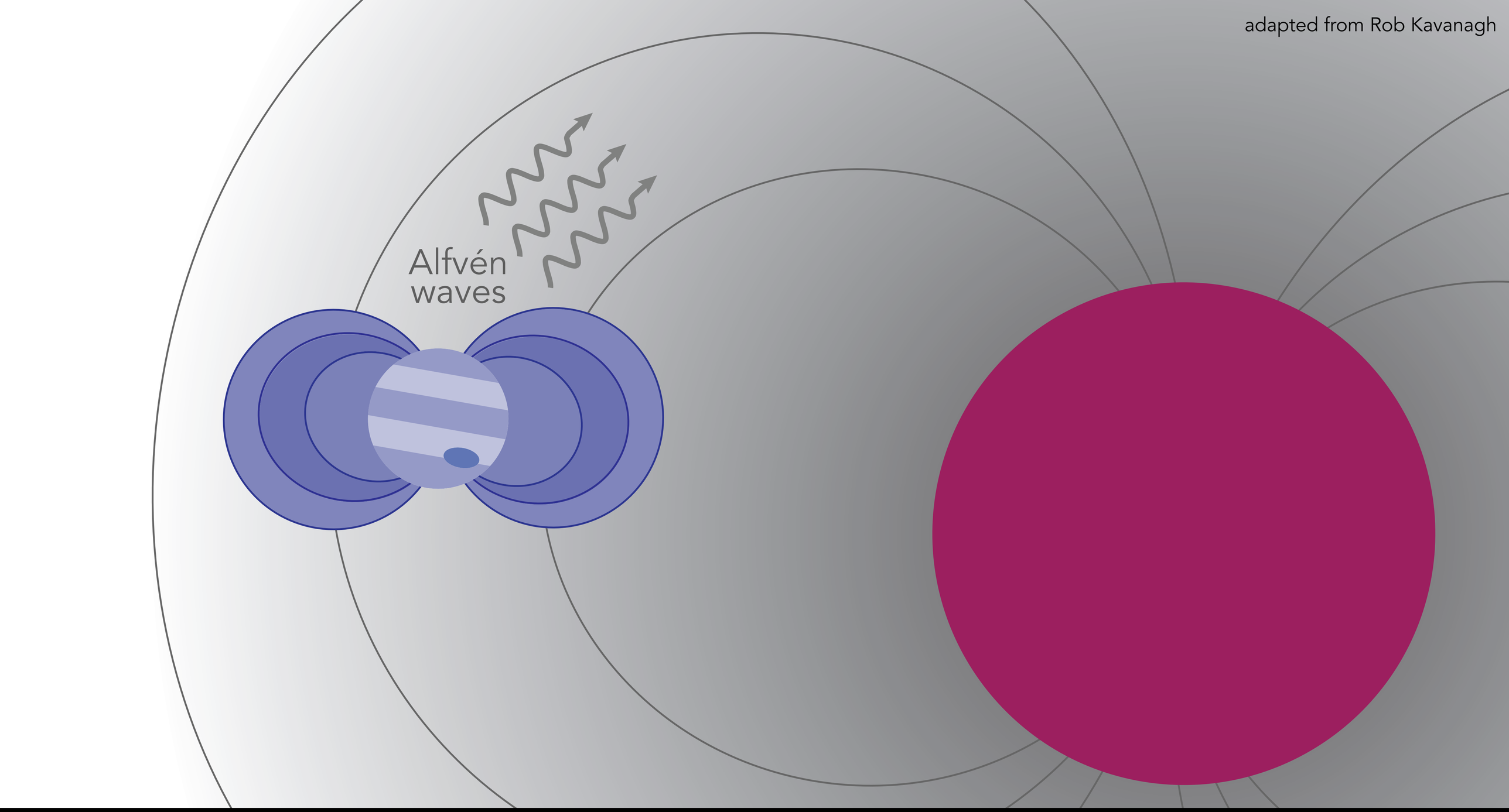

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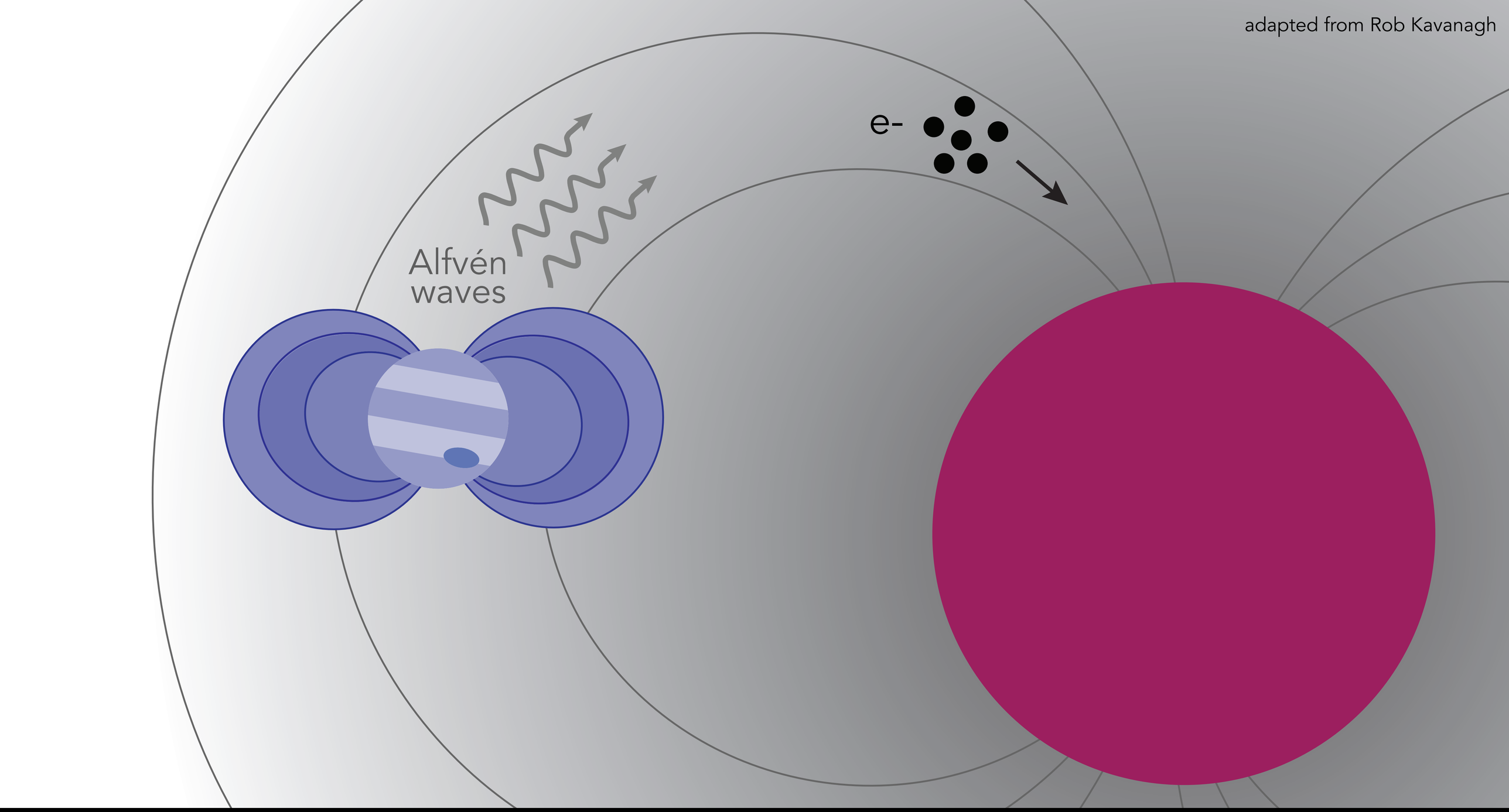

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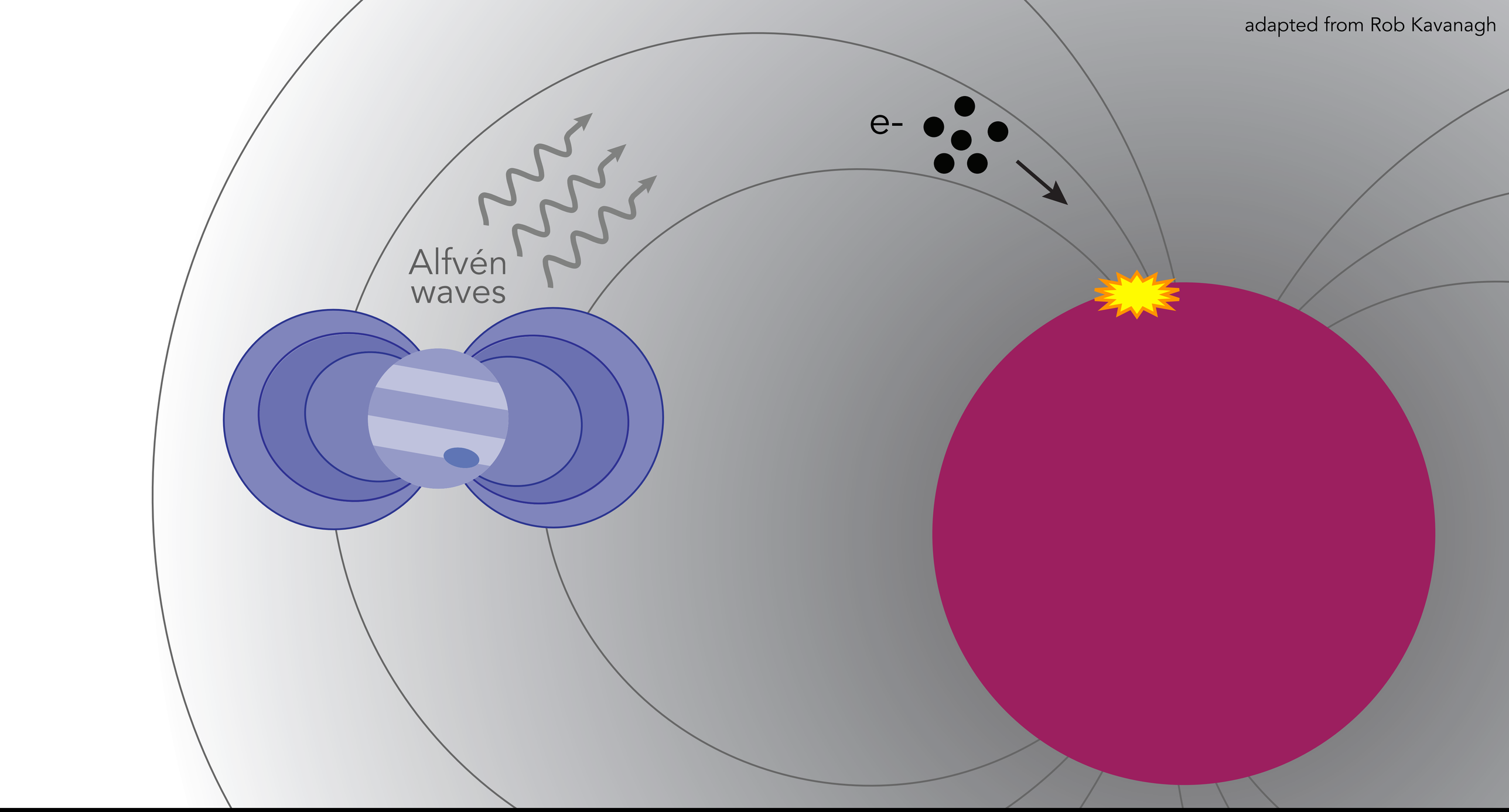

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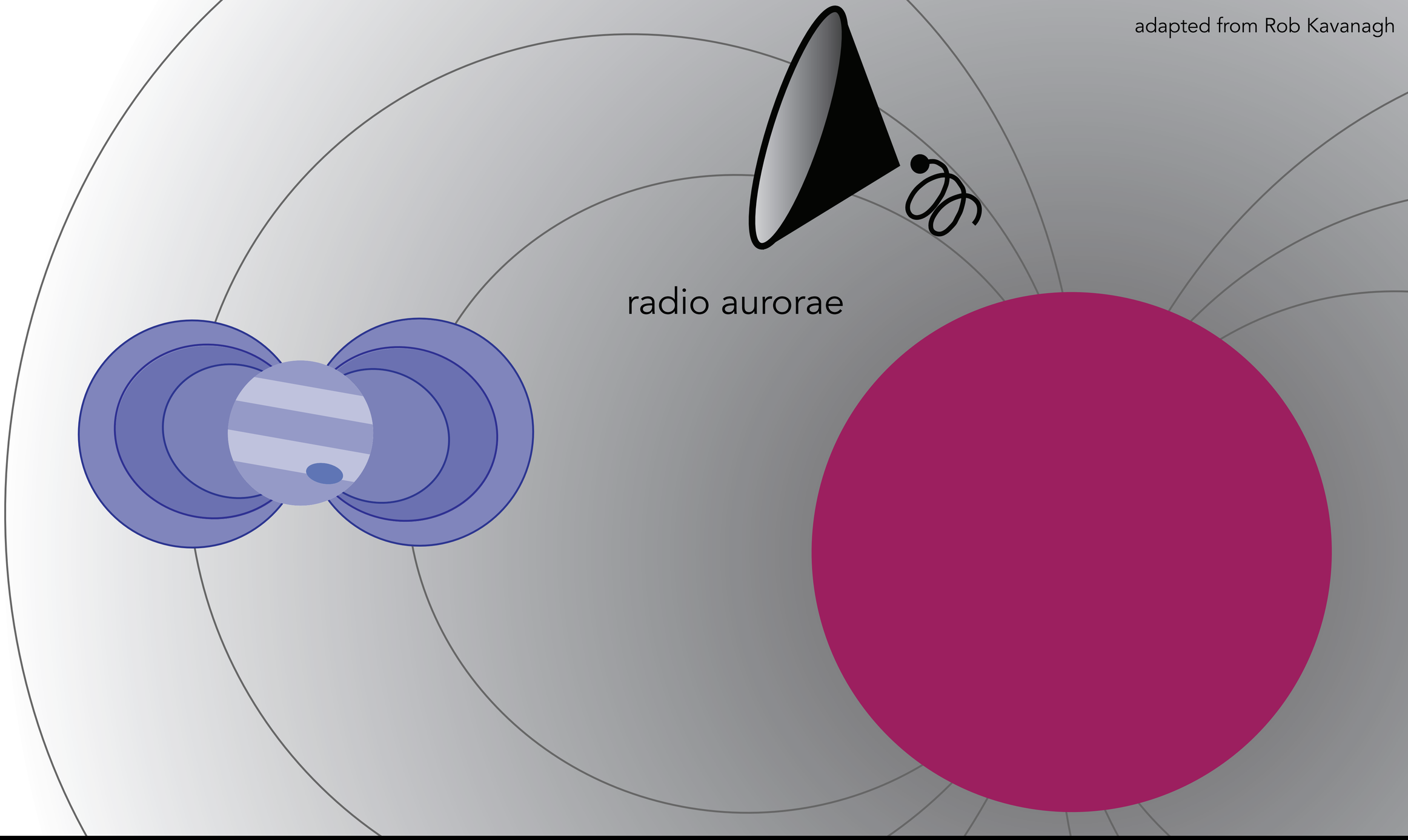
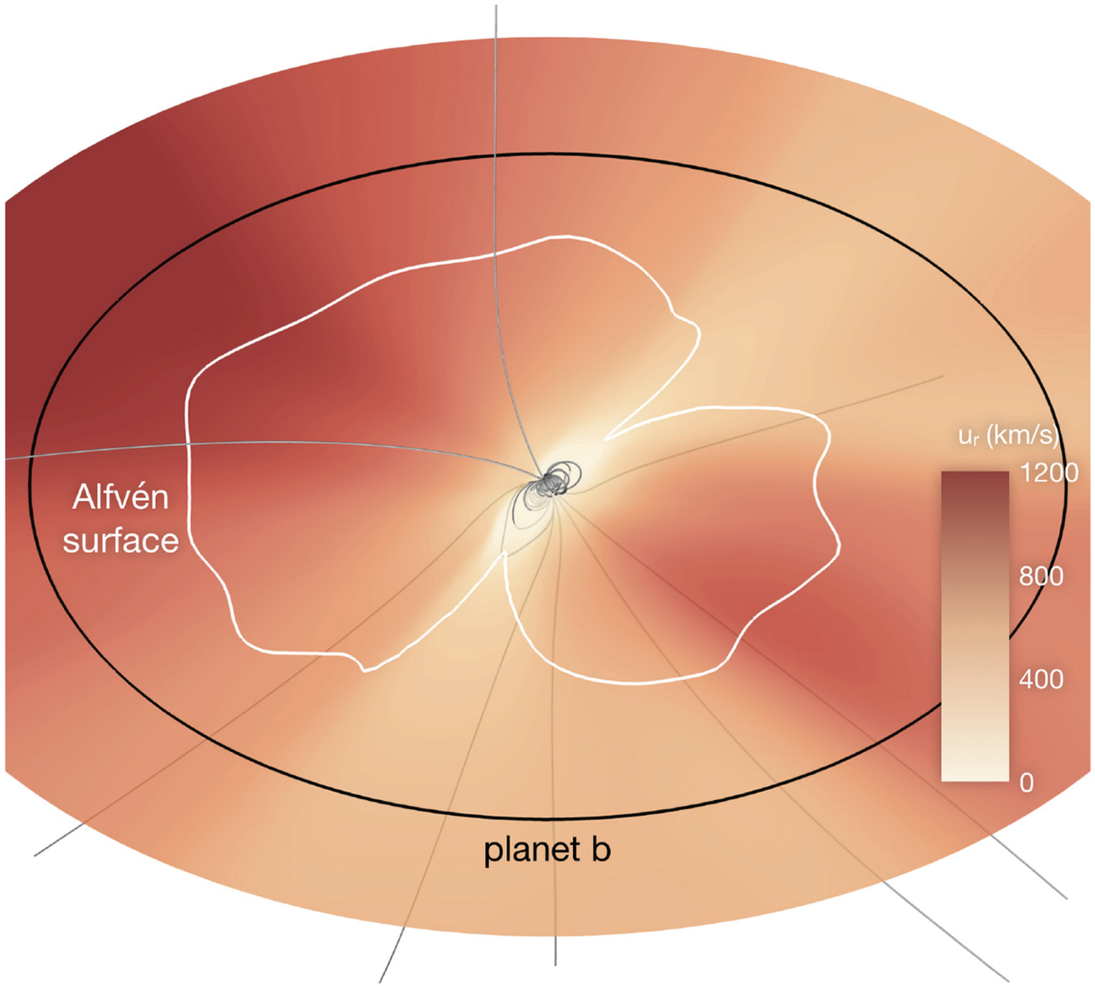
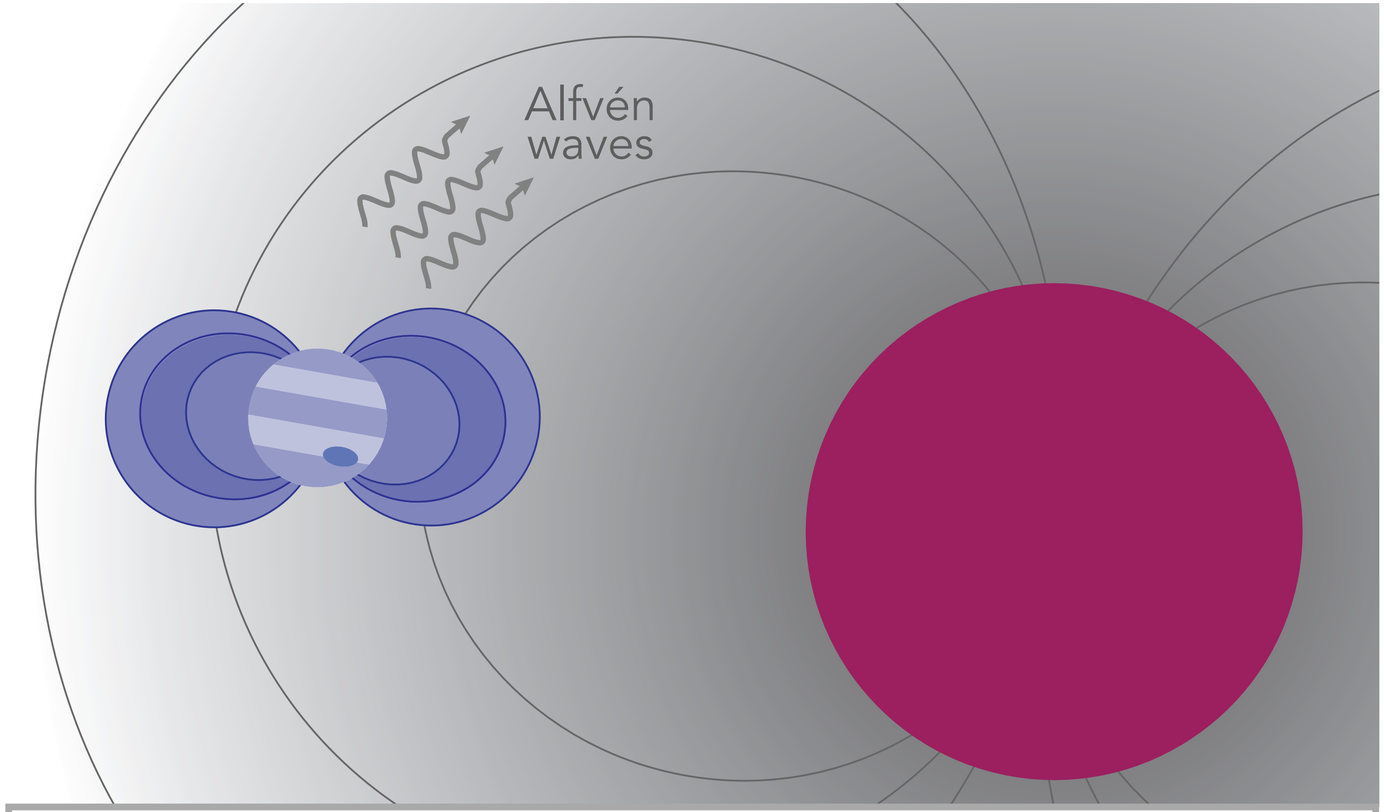


Melodie Kao (mkao@lowell.edu)

Proxima Centauri: Radio SPI? Perez-Torres+ 2021

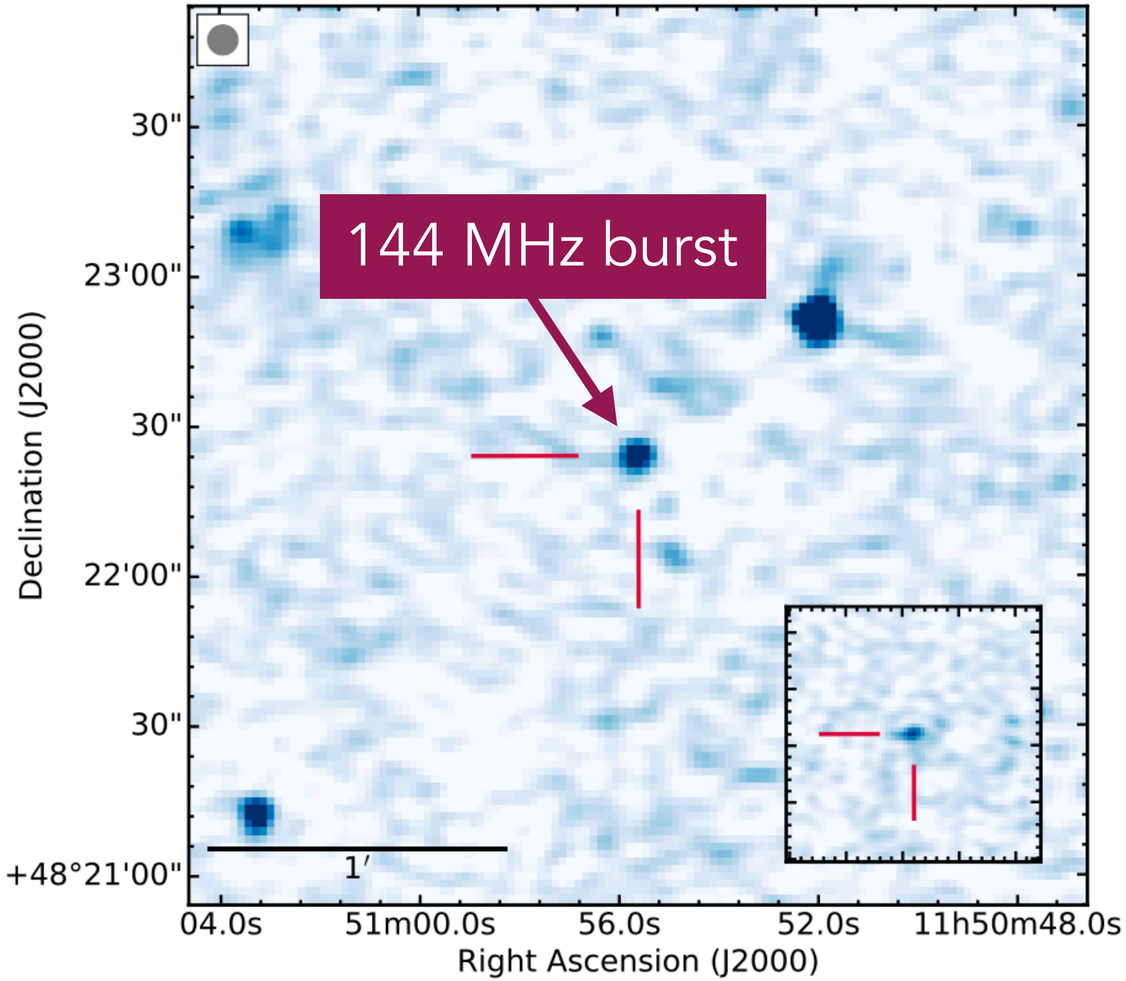




"No feasible scenario where the planet can induce radio emission in the star's corona"

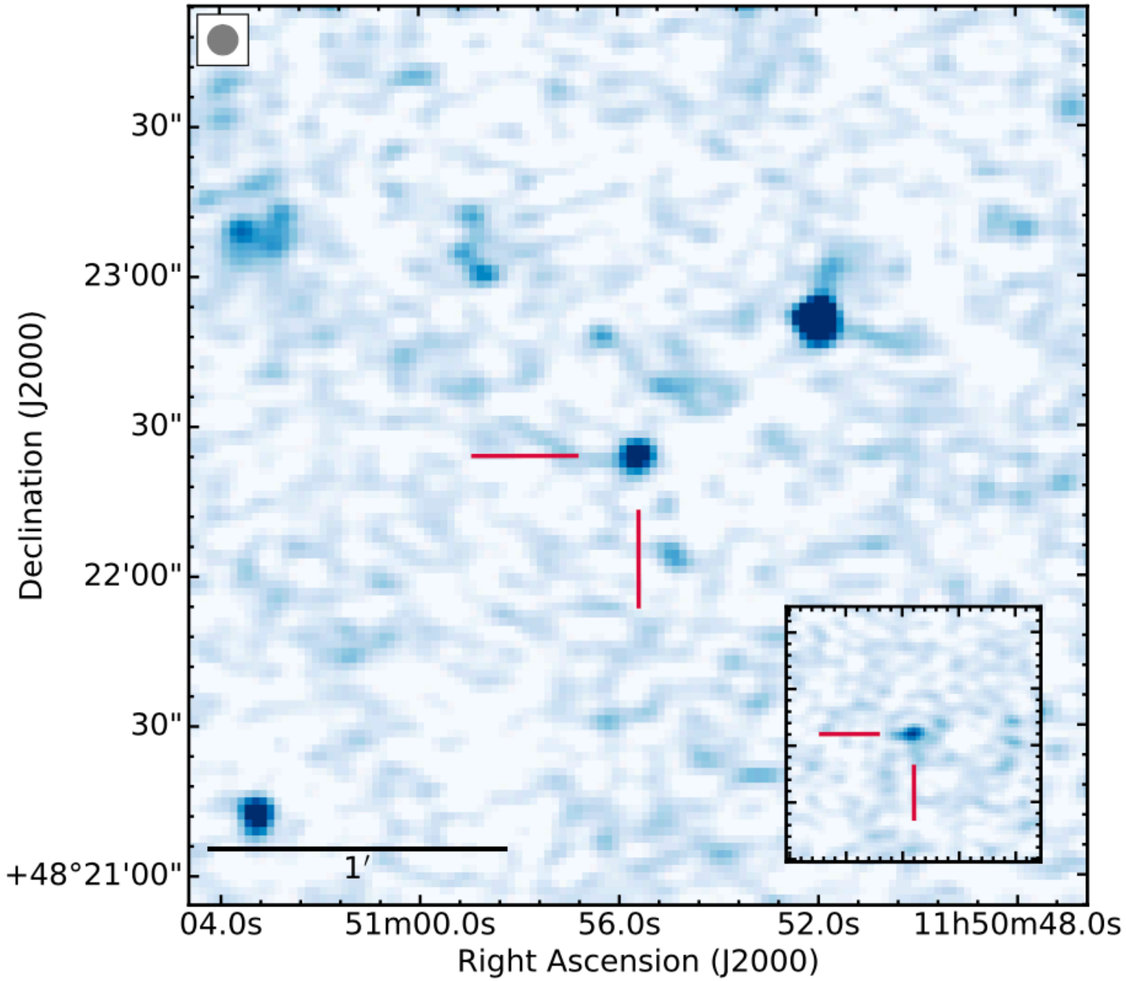
Kavanagh+ 2021

Alfvén velocity **>** outflowing plasma velocity



Close-in Earth-sized planet powering radio emission?

Vedantham+ 2020



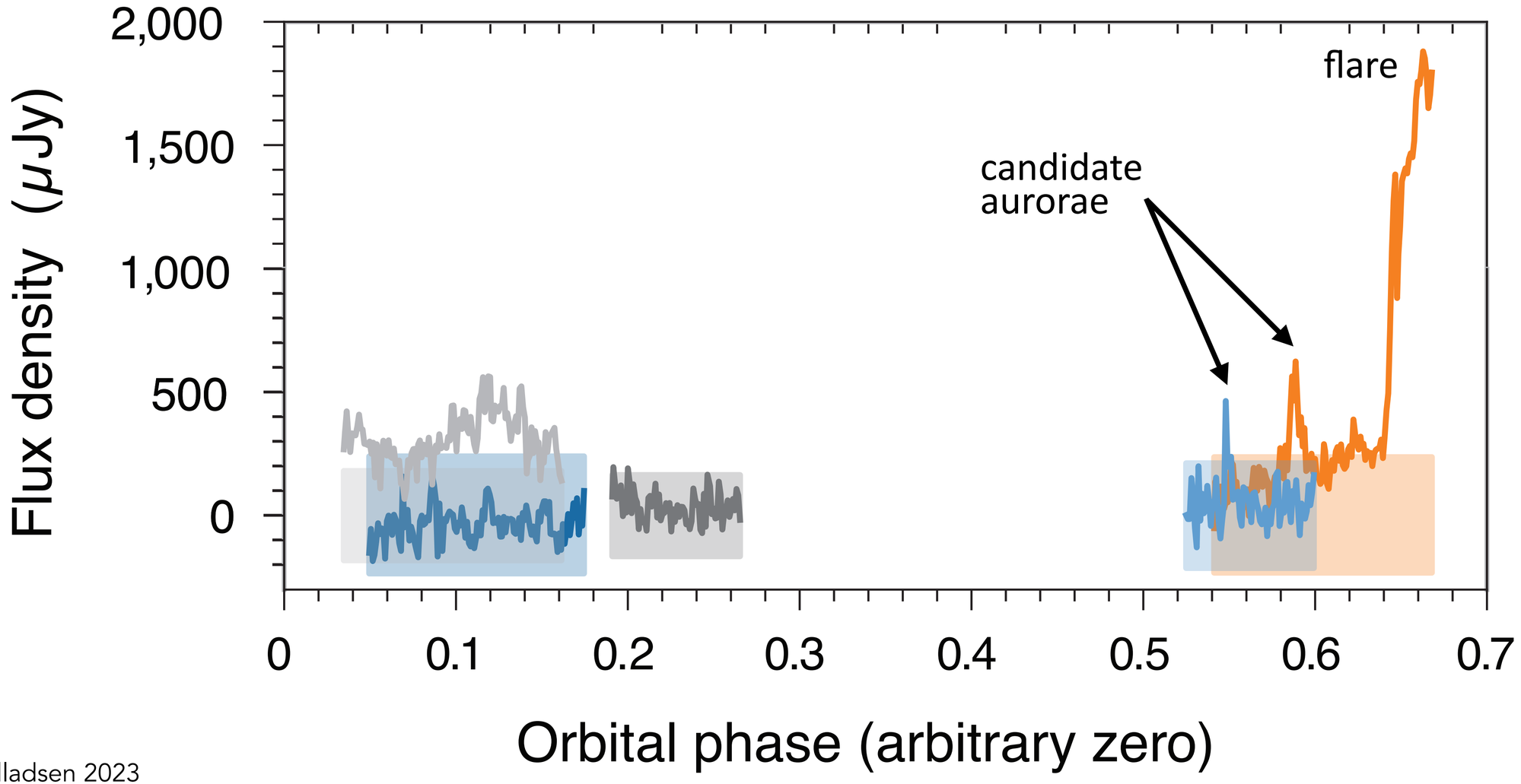
Vedantham+ 2020

Close-in Earth-sized planet could power observed flux densities

RV follow-up rules out massive planets

(Pope+ 2020, Perger+ 2021)

YZ Ceti: Radio SPI?



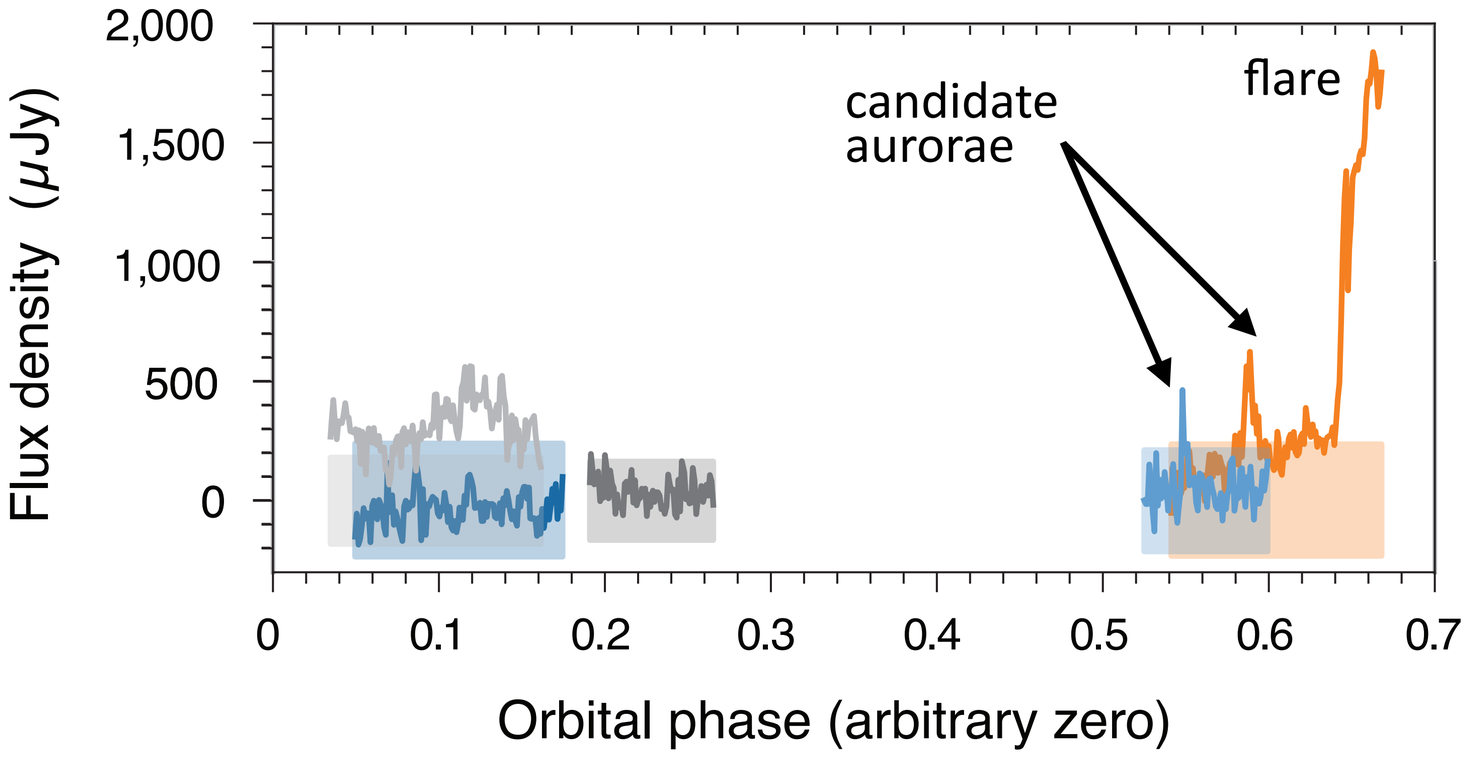
Pineda & Villadsen 2023

see also: Triglio+ 2023

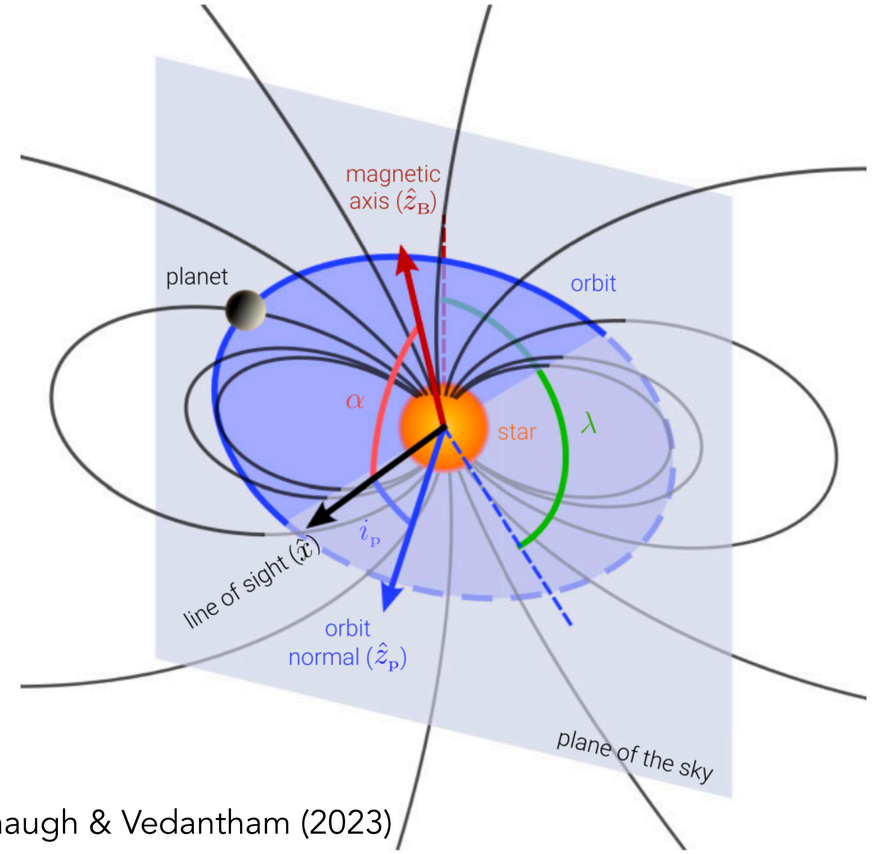
$S \propto$ power dissipated

R_o^2 obstacle size

$B_{\rm wind}\ \Delta u^2\ \sin^2\theta\ \sqrt{\rho_{\rm wind}}$ (magnetospheric plasma flow properties)

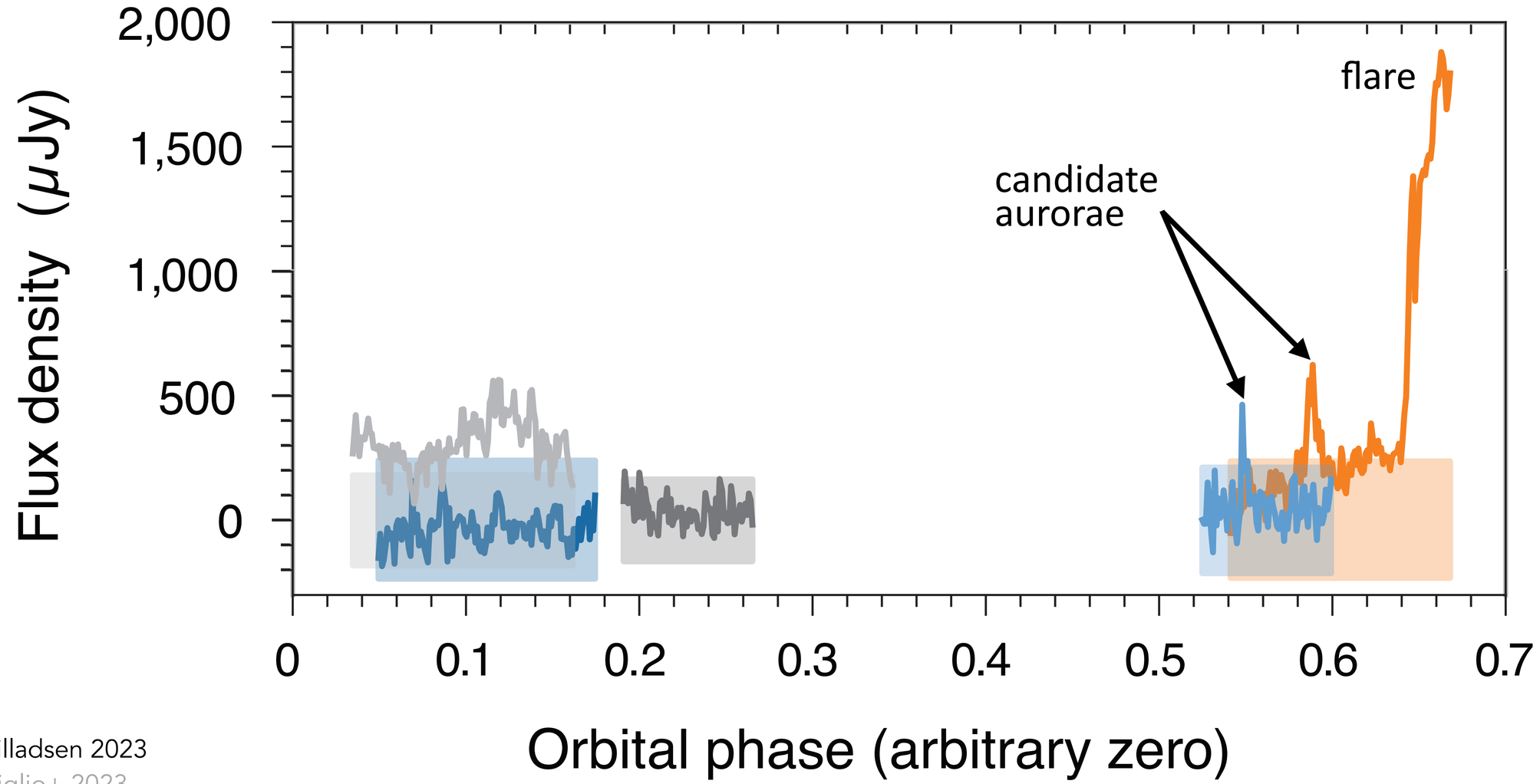


Hess+ (2008)



Kavanaugh & Vedantham (2023)
see also Lynch + (2016)
see also Rob Kavanaugh's poster, conference room across the hall

Stay tuned for Cool Stars!



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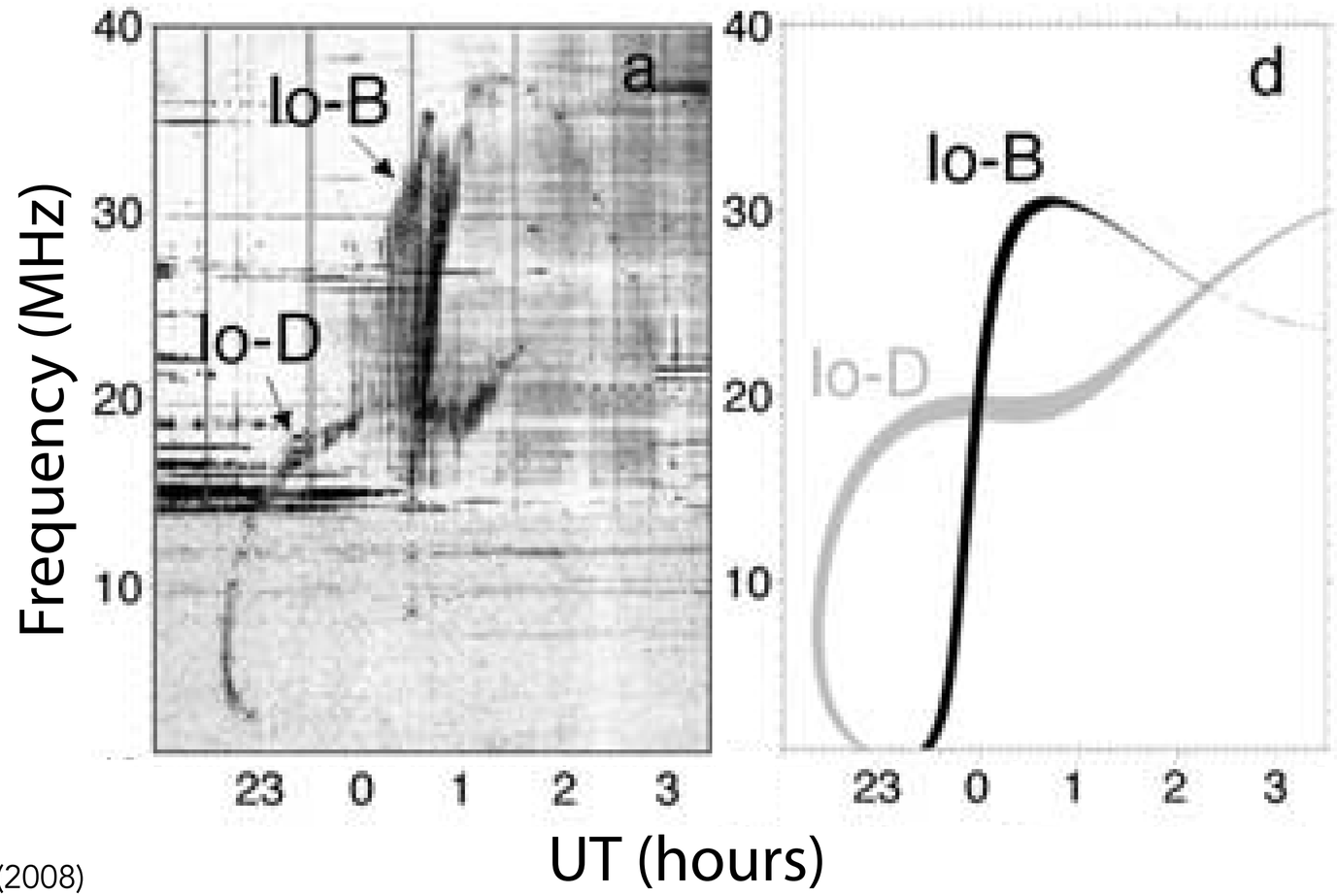

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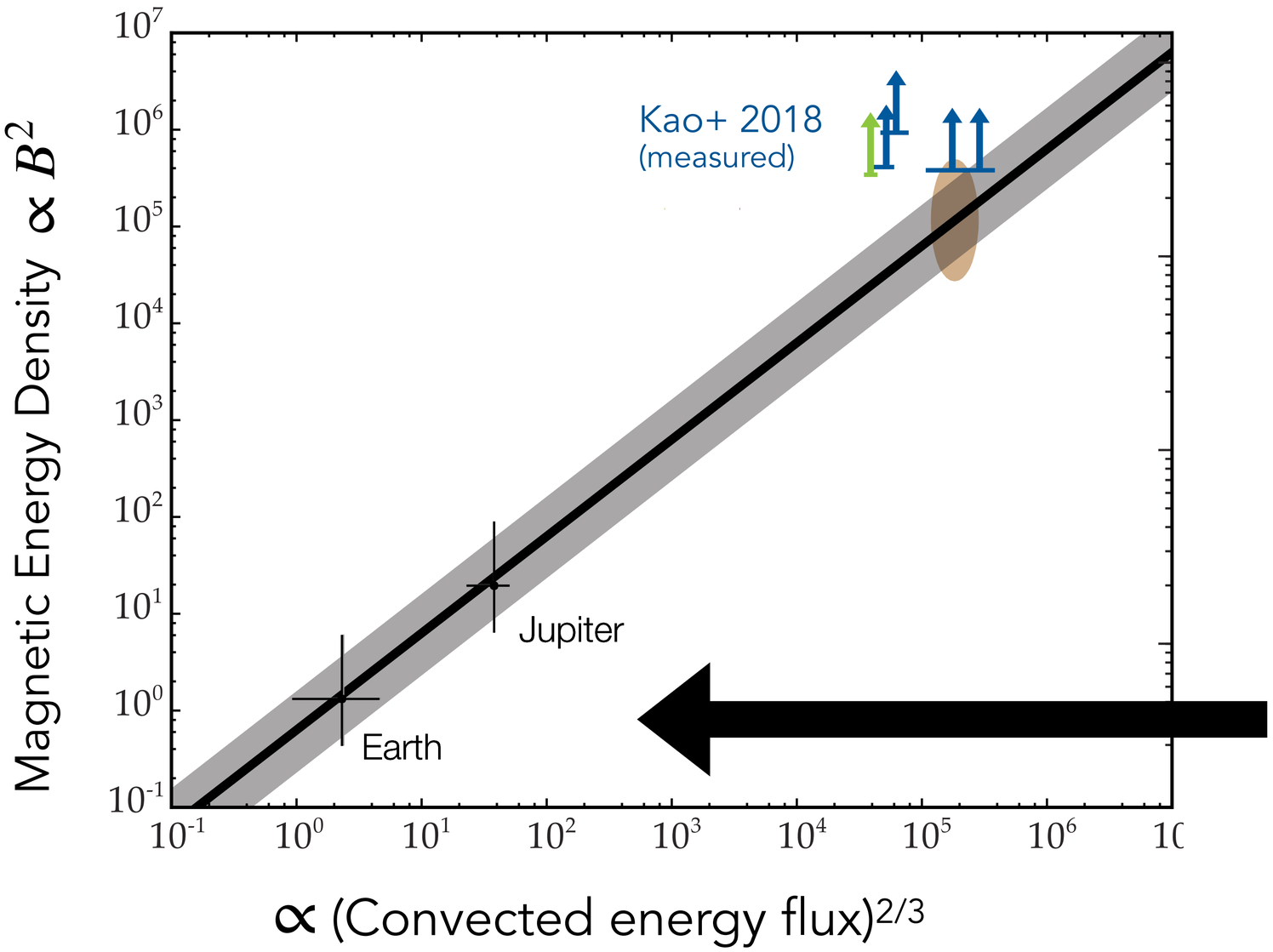
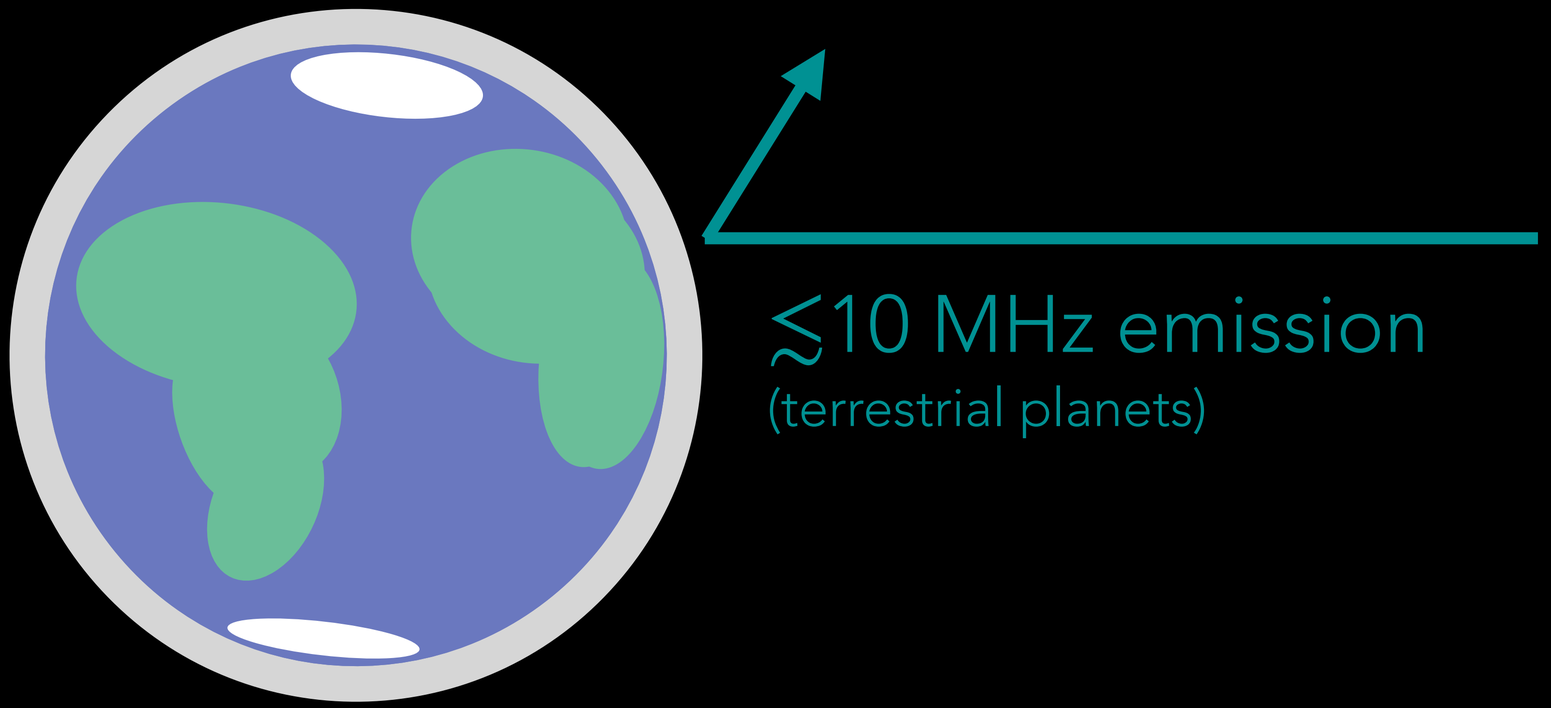


terrestrial satellites
around brown dwarfs



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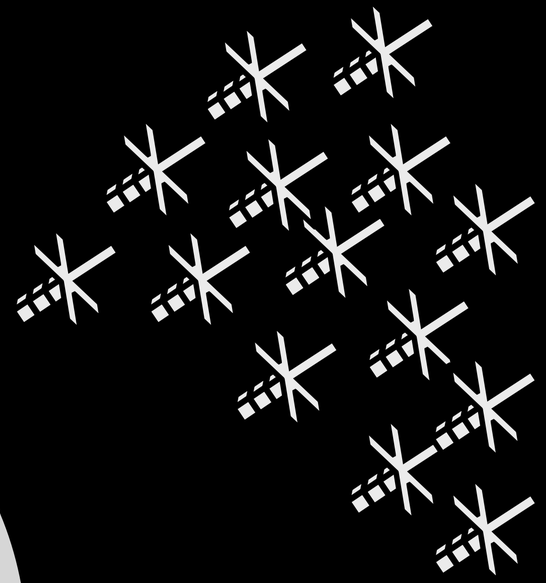


≲10 MHz emission
(terrestrial planets)

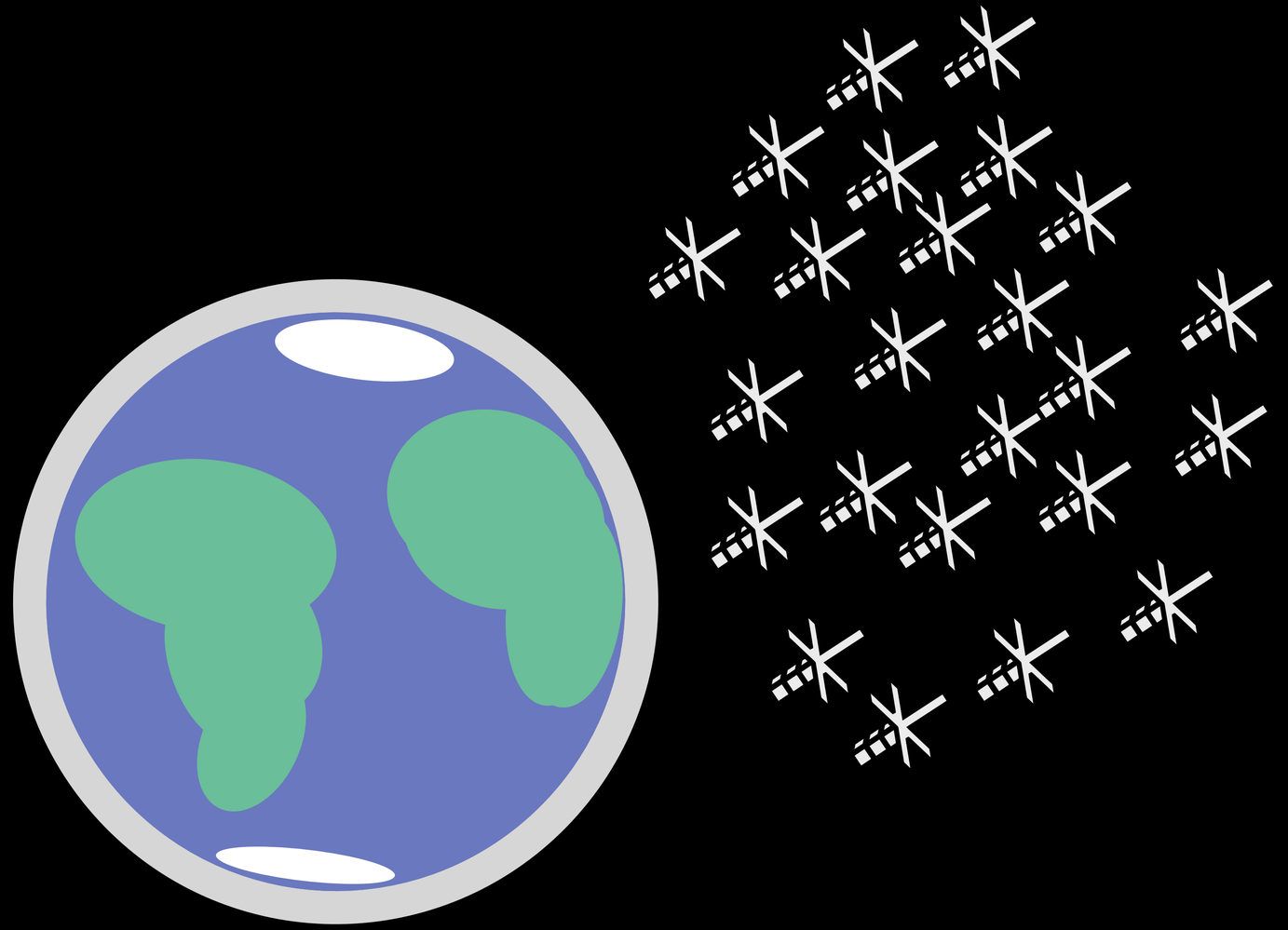
GO-LoW

Great Observatory at Long Wavelengths

https://arxiv.org/abs/2404.08432

Knapp, Paritsky, Kononov, Kao (2024 NIAC)

Melodie Kao (mkao@lowell.edu)



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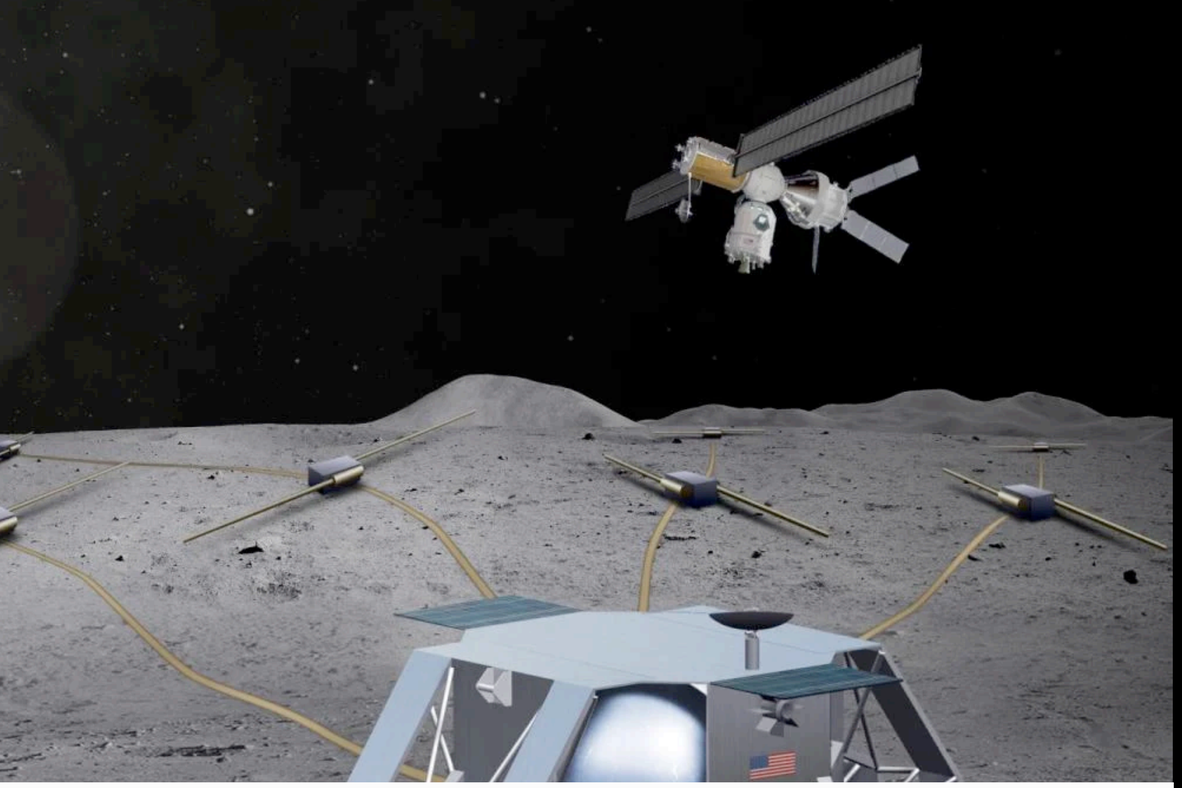
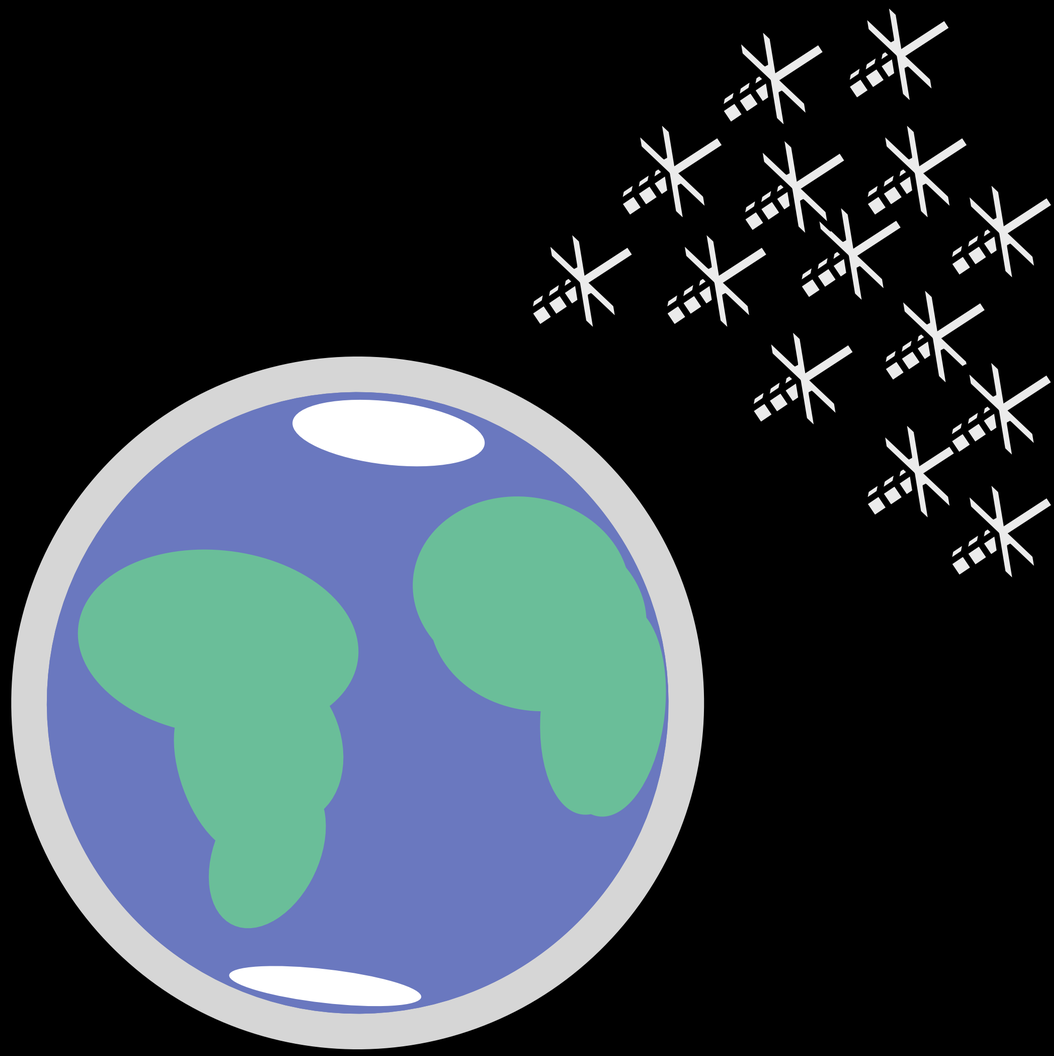


FARSIDE

Burns+ (2021)



GO-LoW

Knapp, Paritsky, Kononov, Kao (2024 NIAC)

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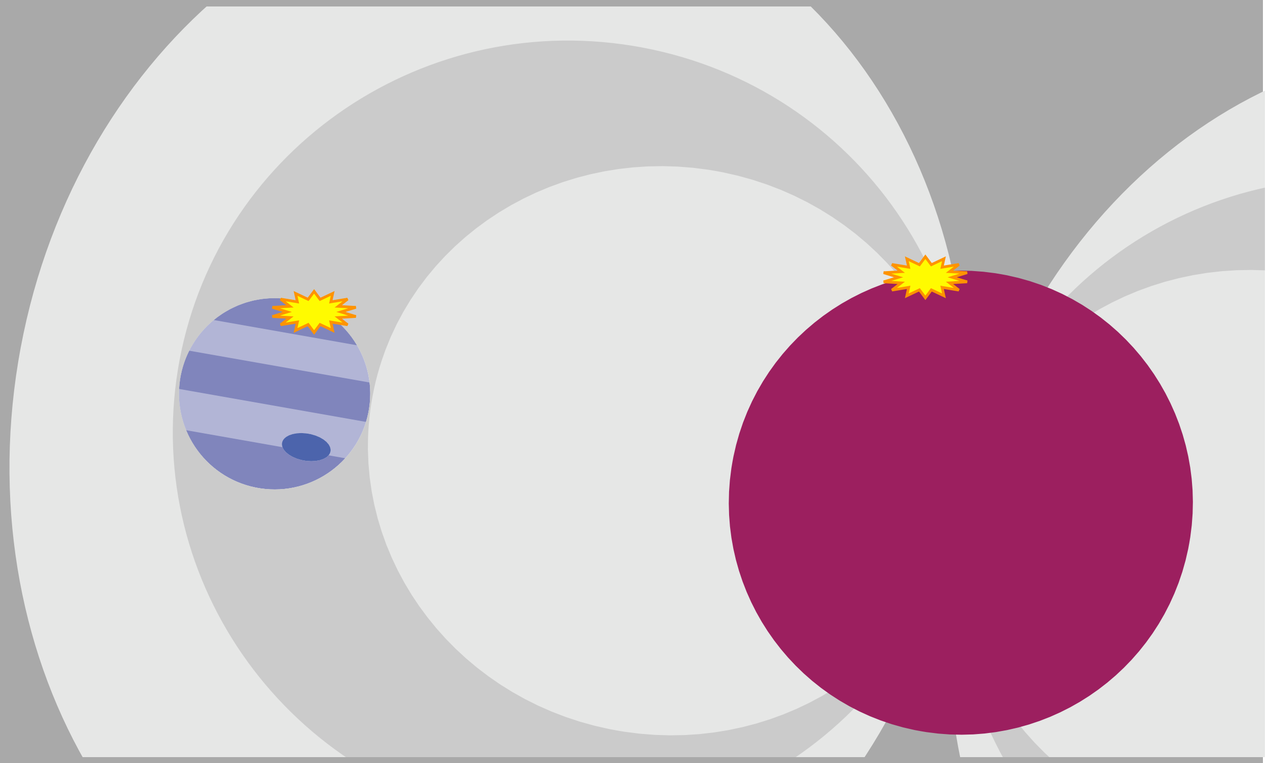
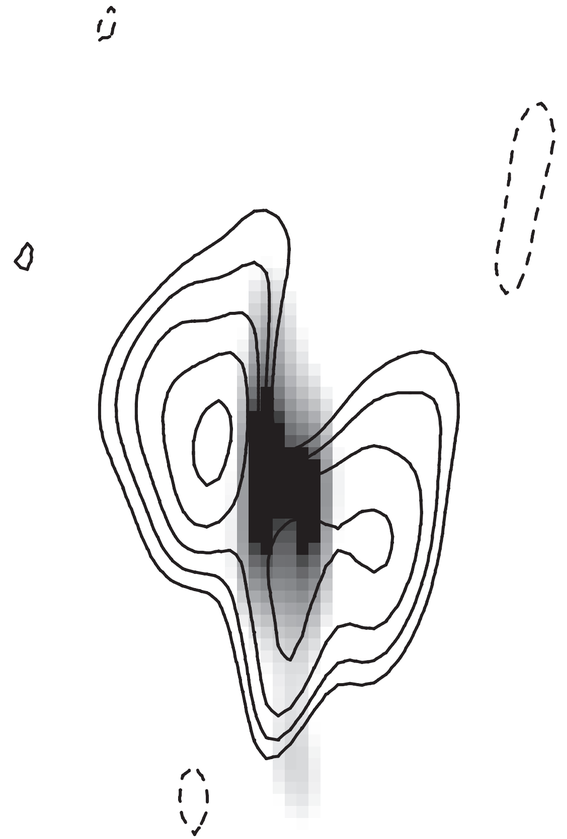


Star-Planet Interactions

(strength, shape)



Radiation Belts

(shape)

Melodie Kao (mkao@lowell.edu)

extra slides