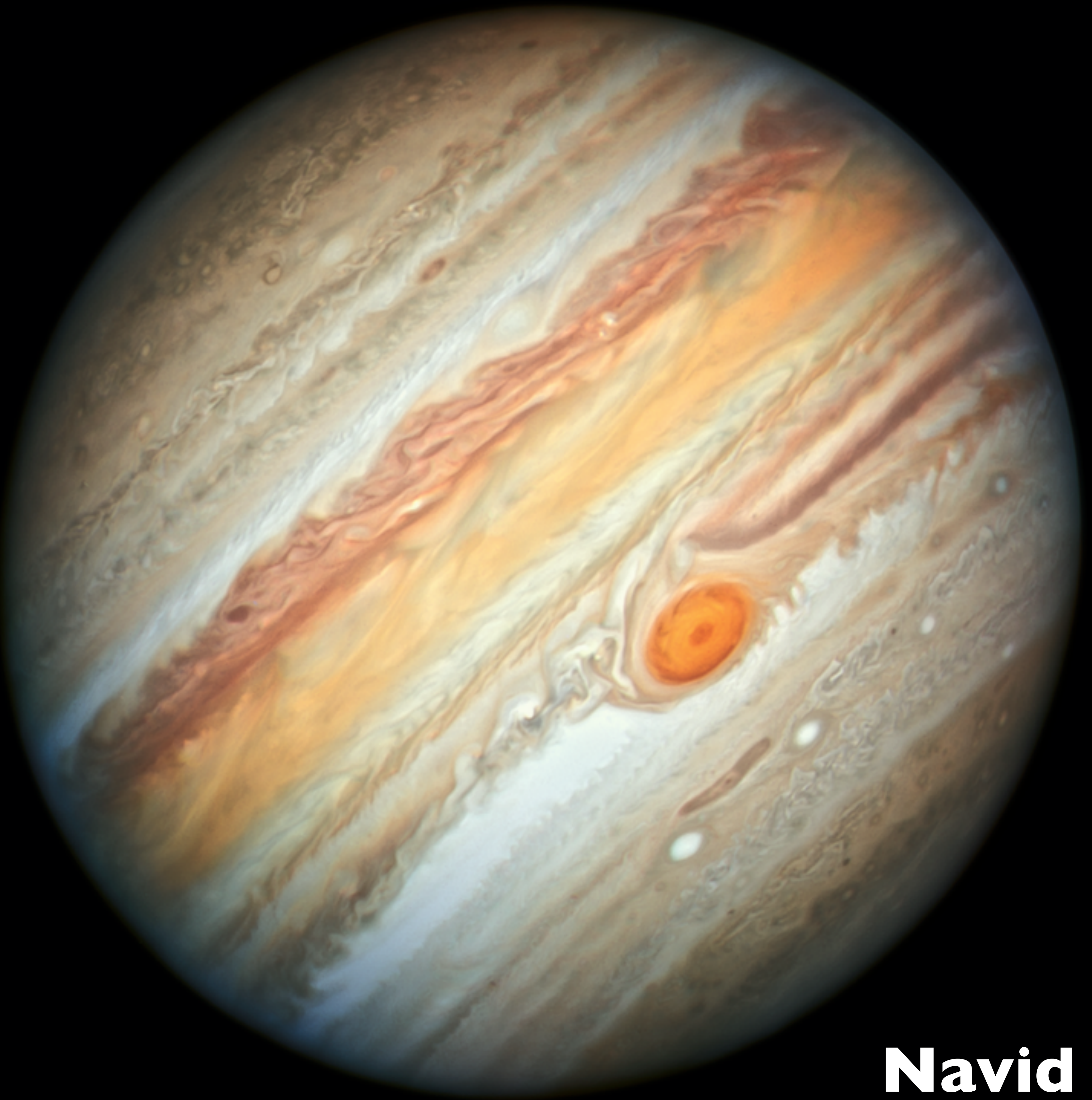
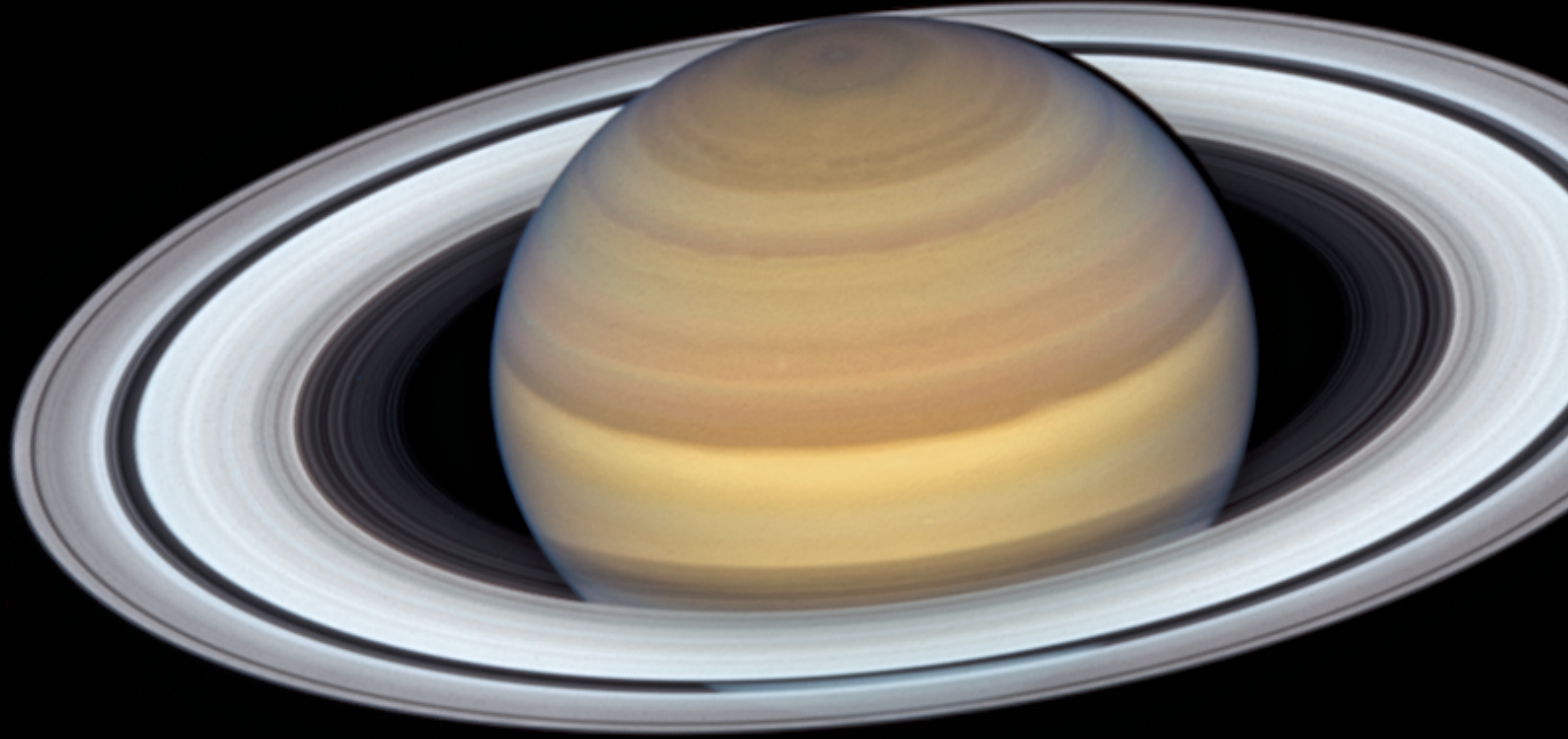
Australian National University

What's underneath Jupiter's and Saturn's stripes?

clex
ARC Centre of Excellence for Climate Extremes





Navid Constantinou

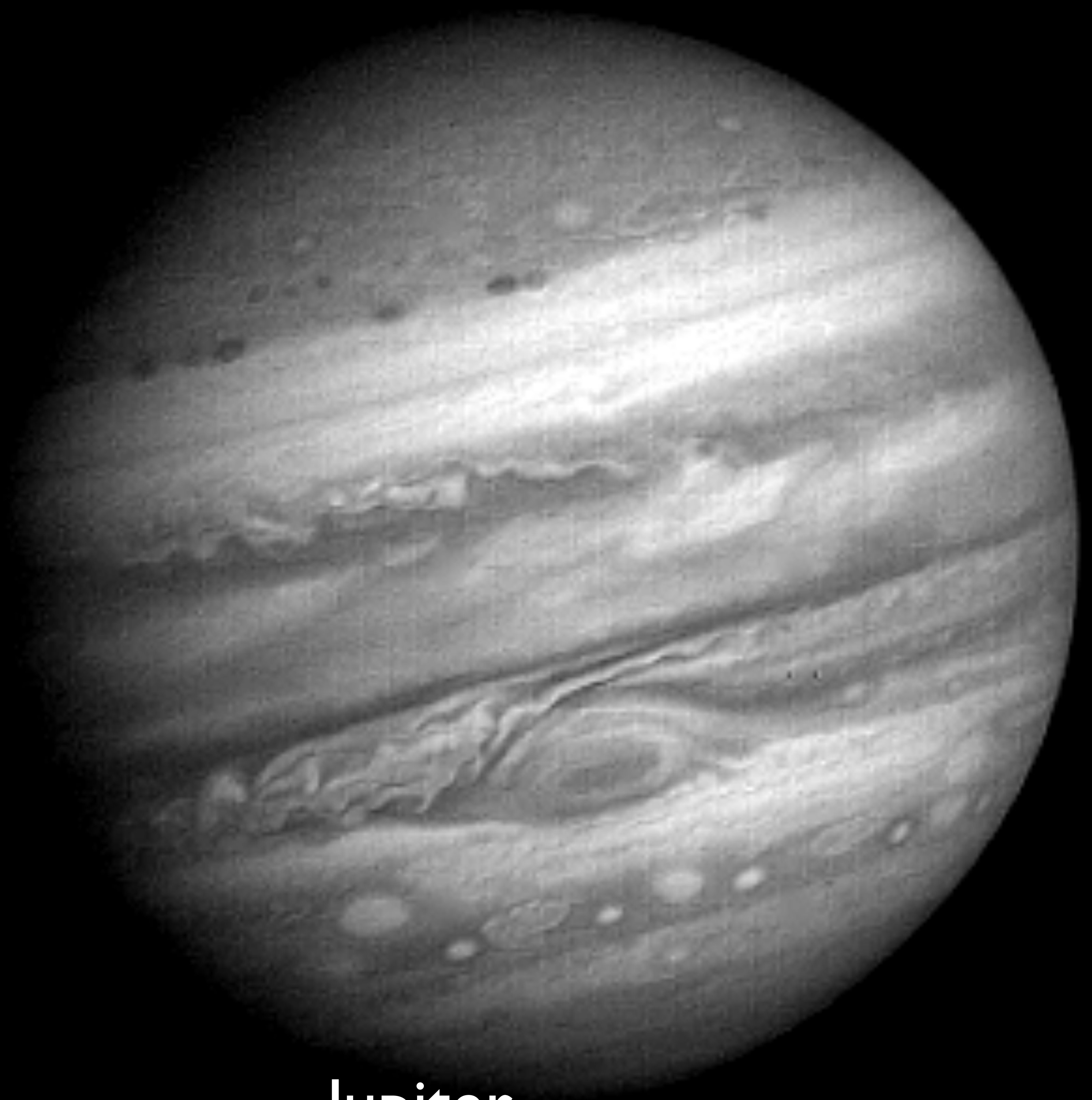
FEARS, RSAA @ ANU

29 October 2019

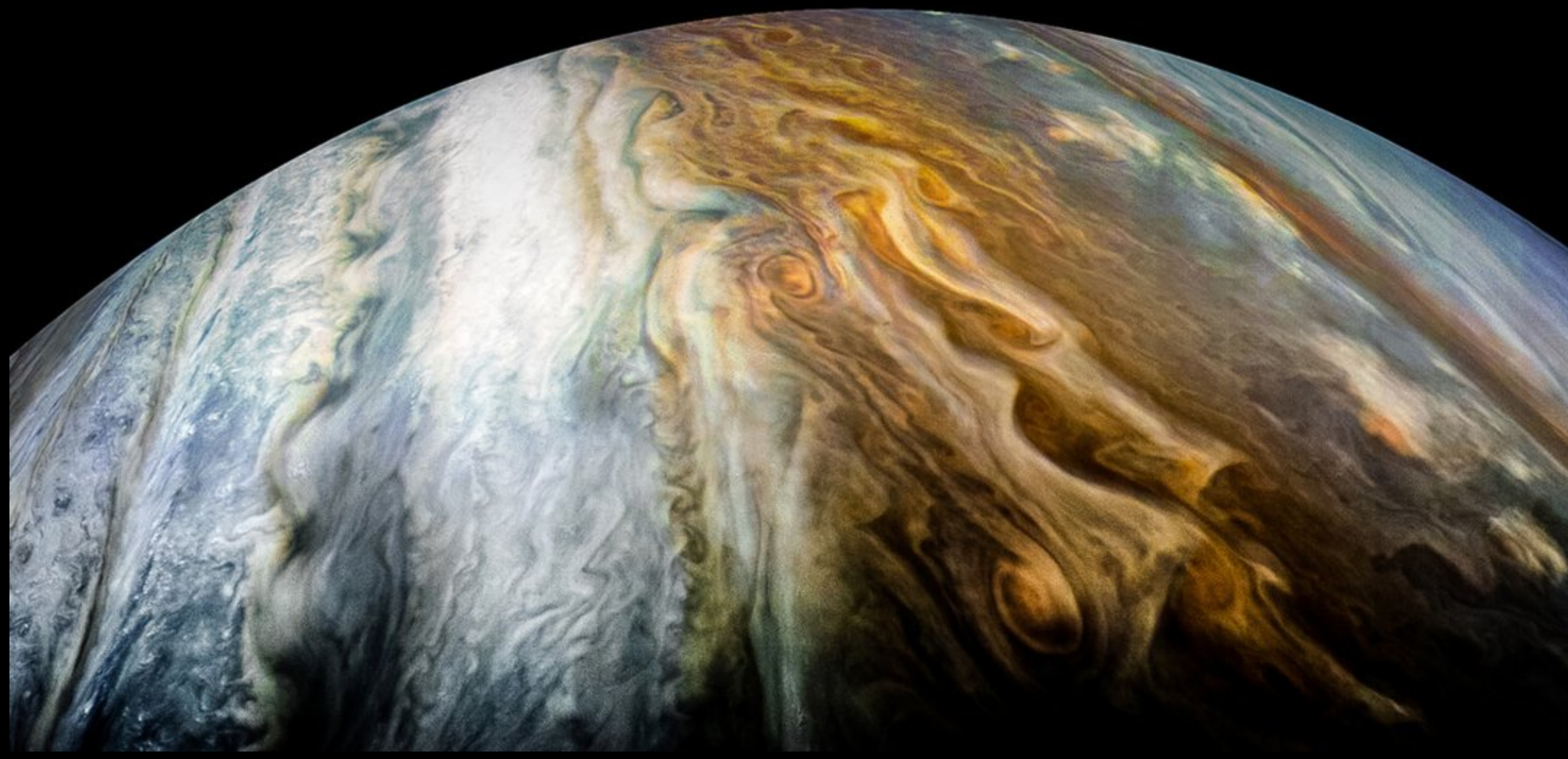
Jupiter
Hubble telescope, NASA
(Aug 2019)

Saturn
Hubble telescope, NASA
(Sep 2019)

jets coexist with vigorous turbulence



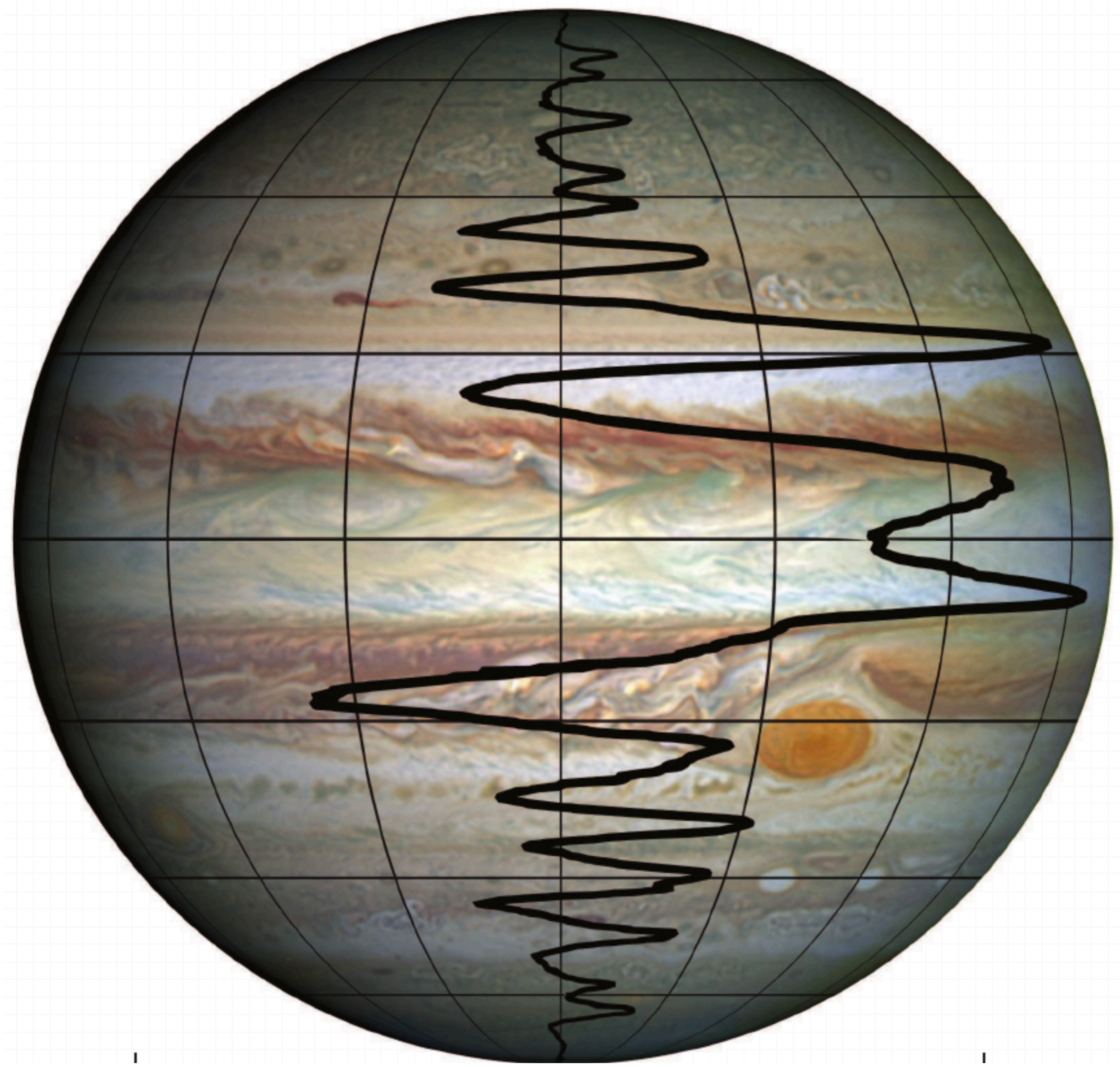
Jupiter
by *Voyager*
(1980)



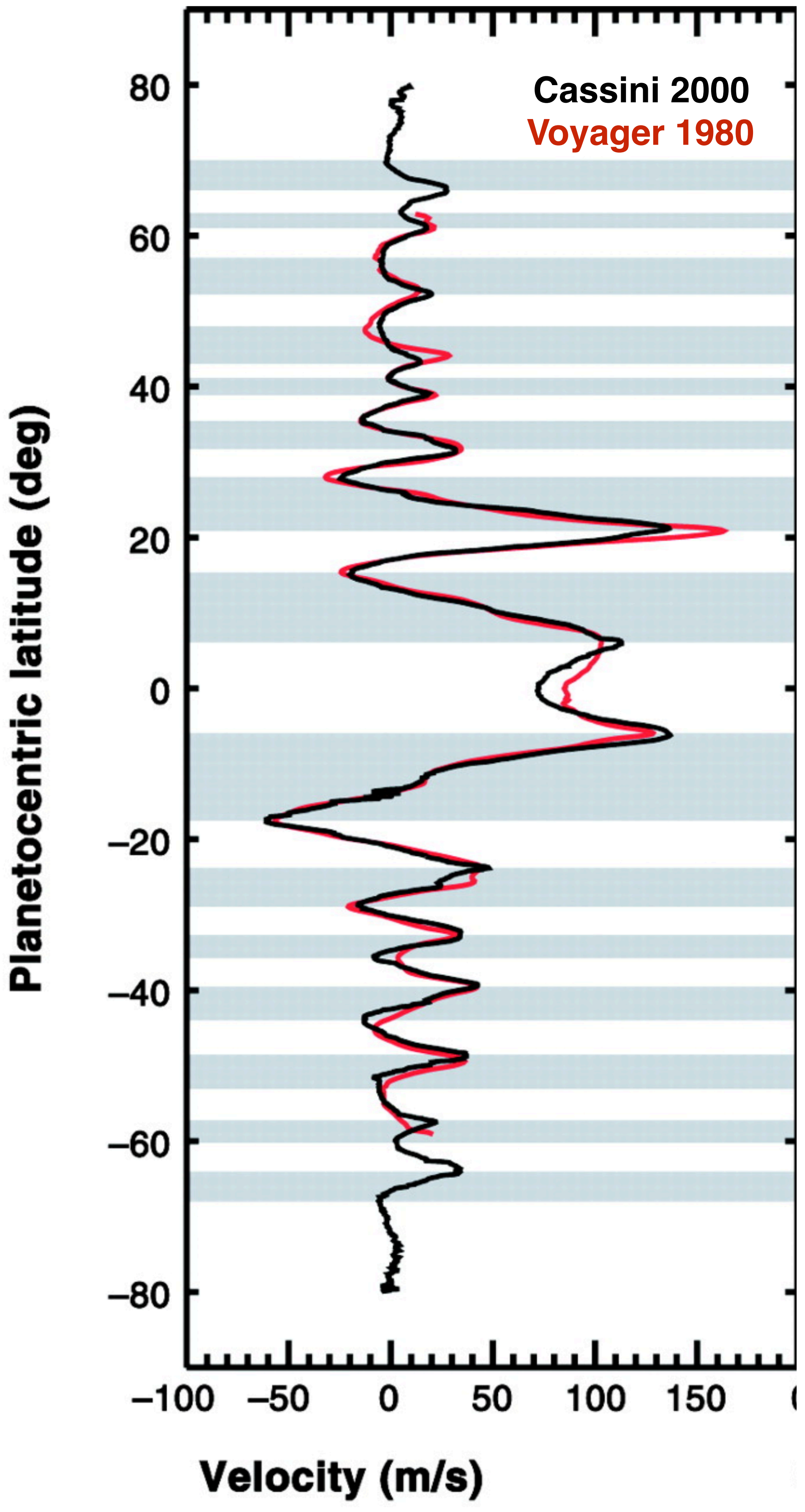
Jupiter
by *Juno*
(2015)

jets appear to be "steady"

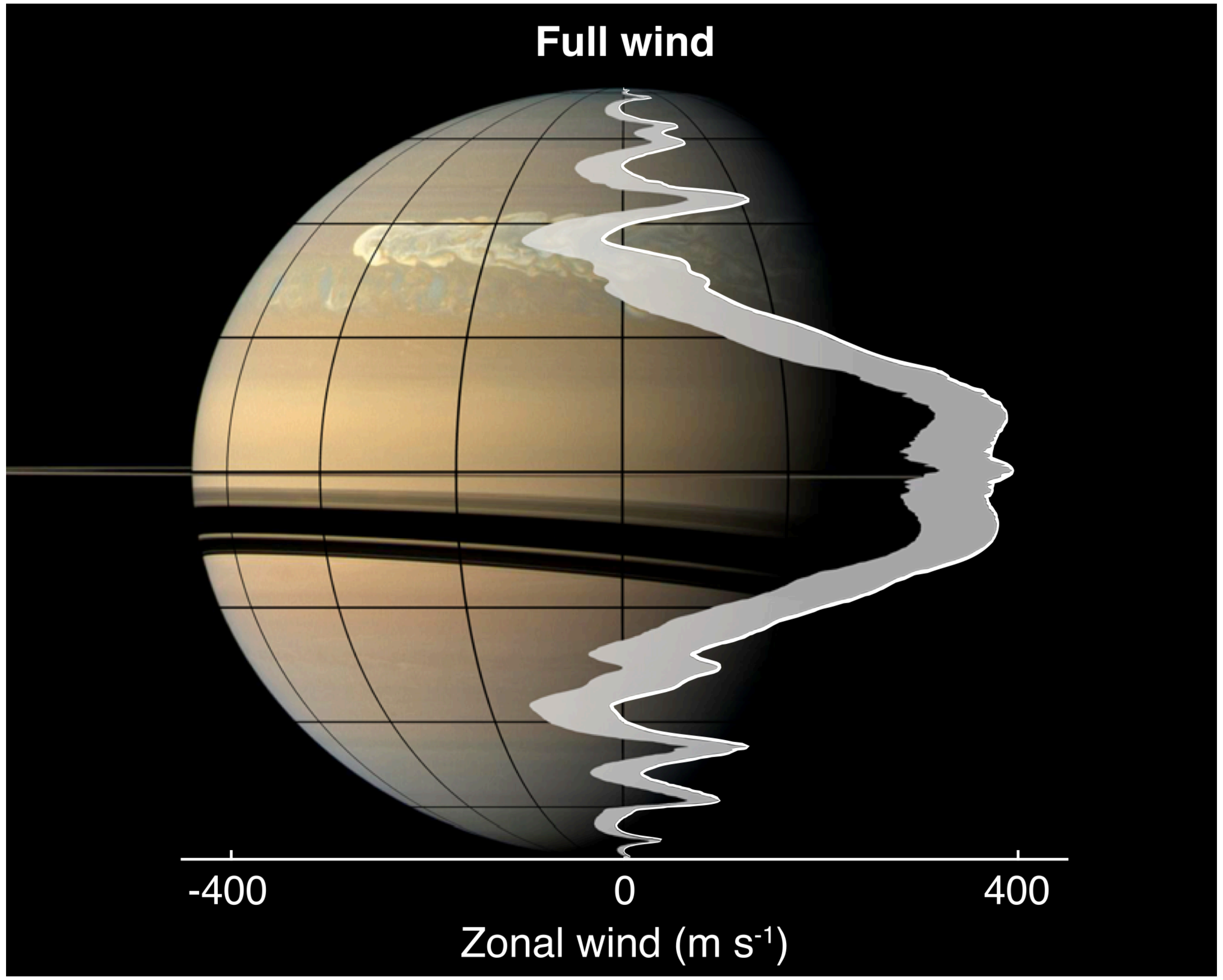
Jupiter



Jovian winds



Saturn



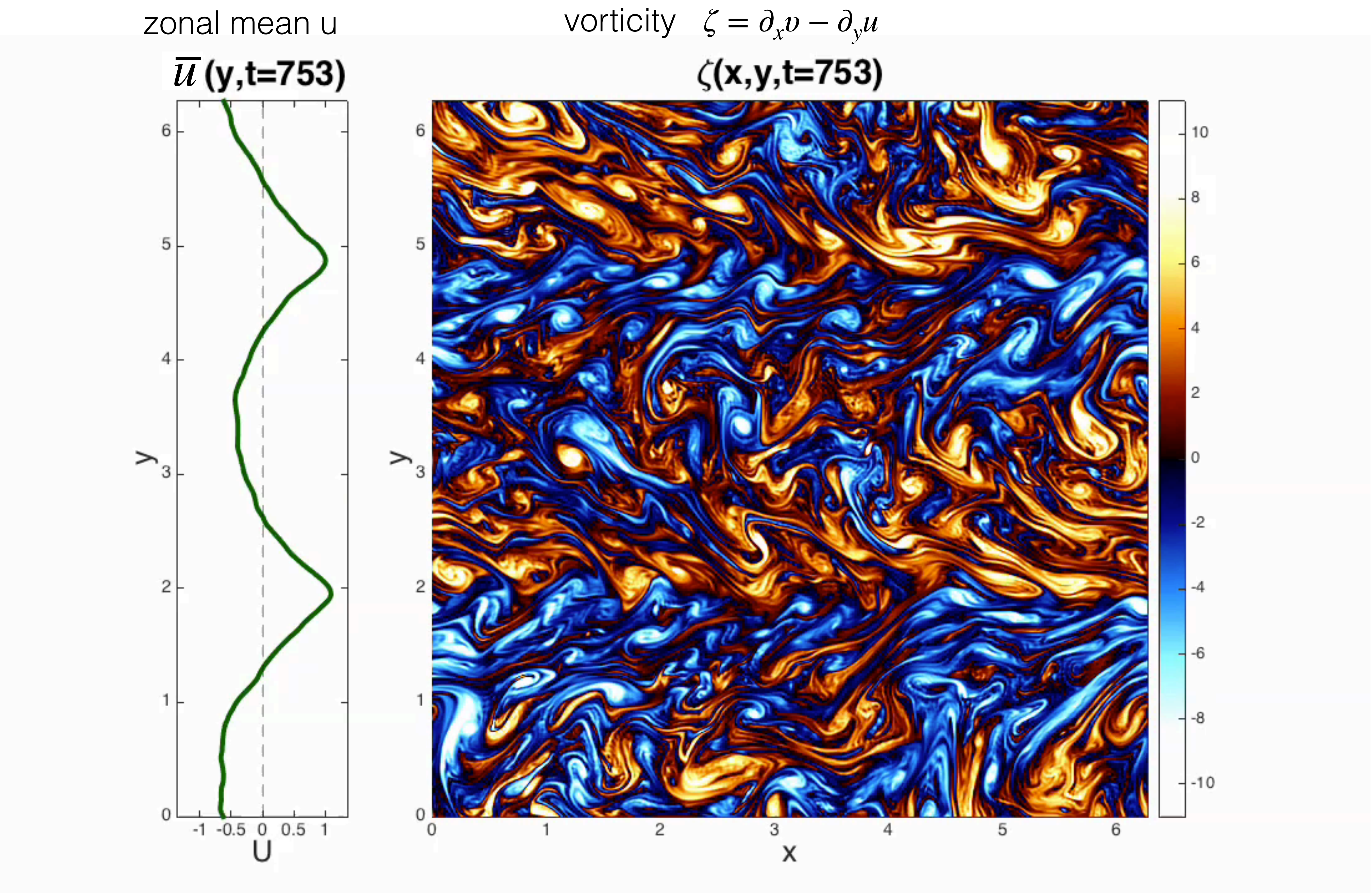
towards a theory for understanding outer-atmosphere jets

$$\boldsymbol{u} = \big(u(\boldsymbol{x},t)\,,v(\boldsymbol{x},t)\big)$$

$$u = \overline{u} + u'$$

jets — eddies (=turbulence)

$$\overline{u} \equiv \frac{1}{L_x}\int_0^{L_x} u\,\mathrm{d}x$$

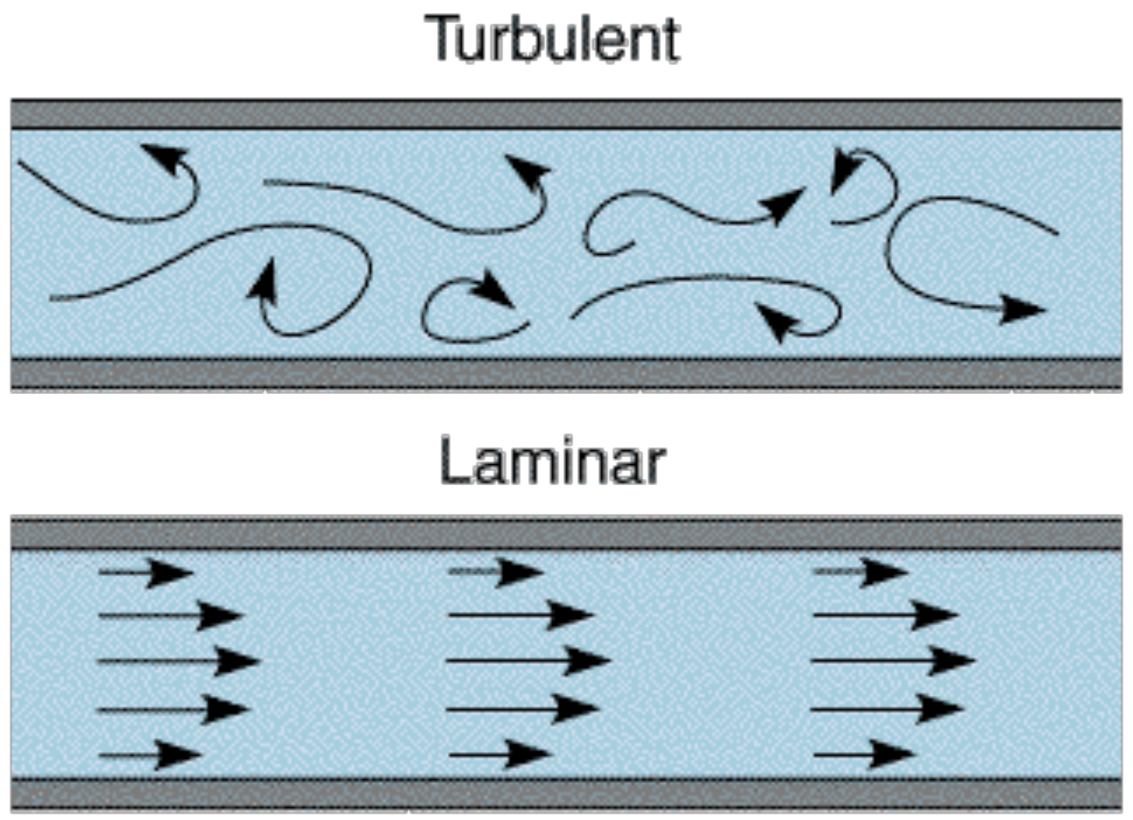


small-scale motions
self-organise
to large-scale coherent jets

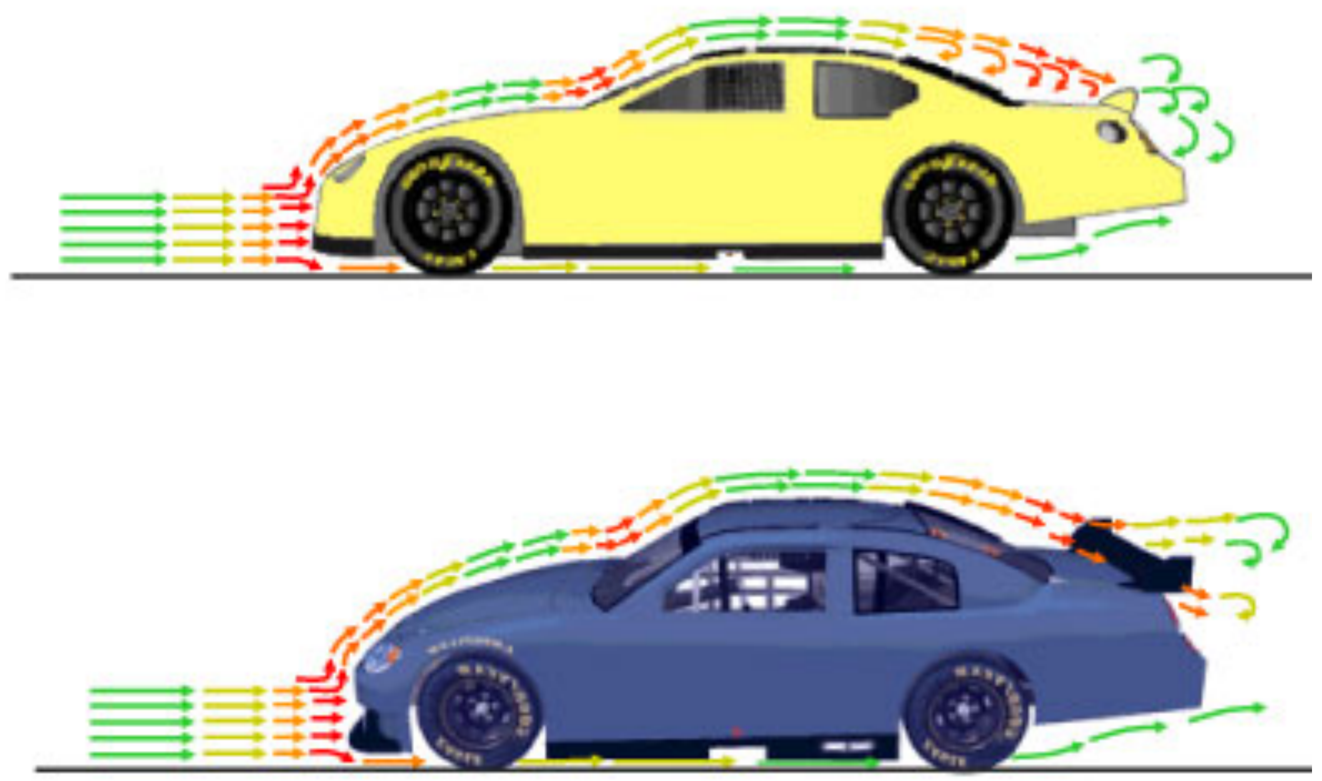
How are the zonal jets fueled?

The eddies (=turbulence) feed the jets with momentum!

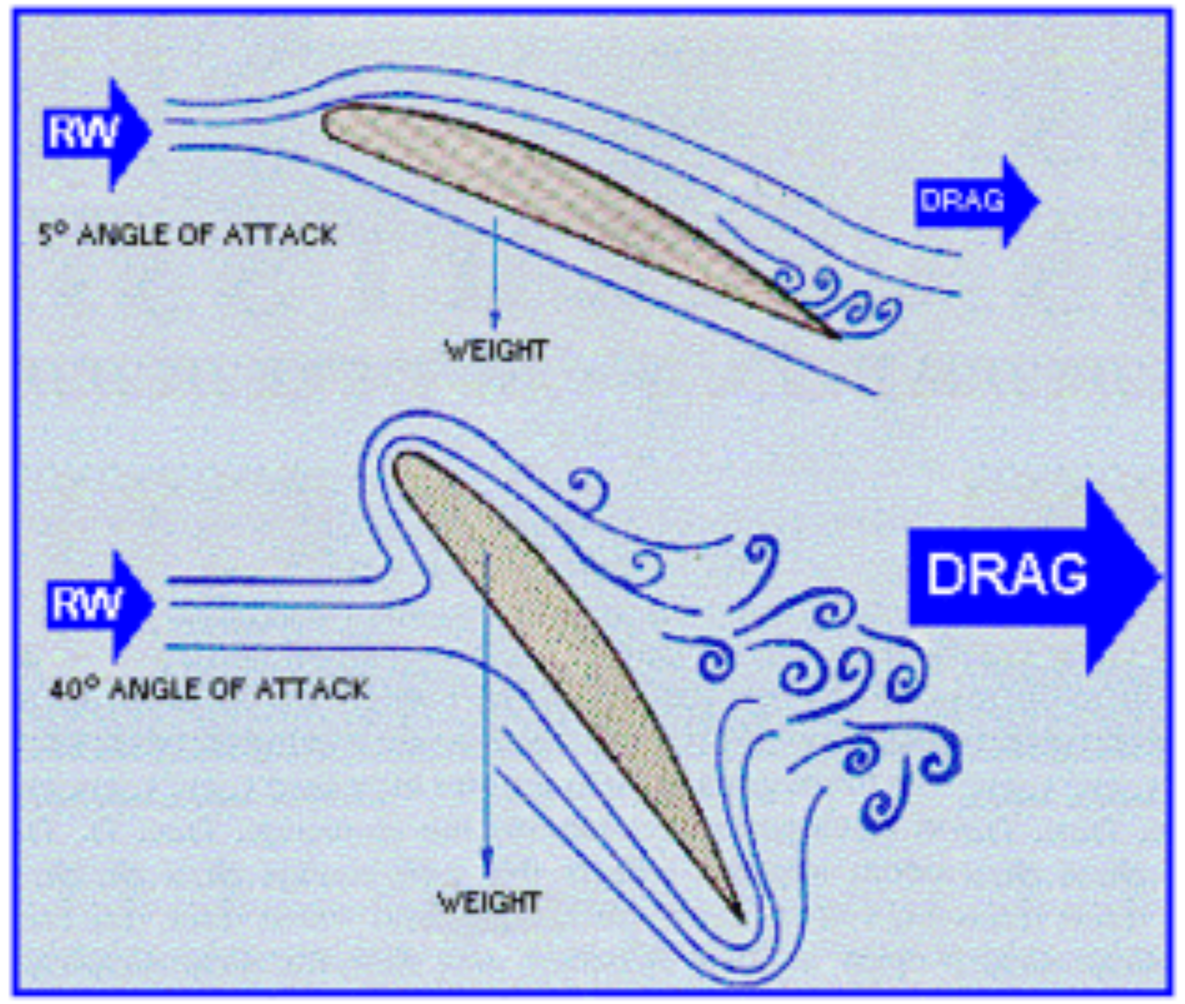
turbulence usually is "drag"



wall-bounded
flow



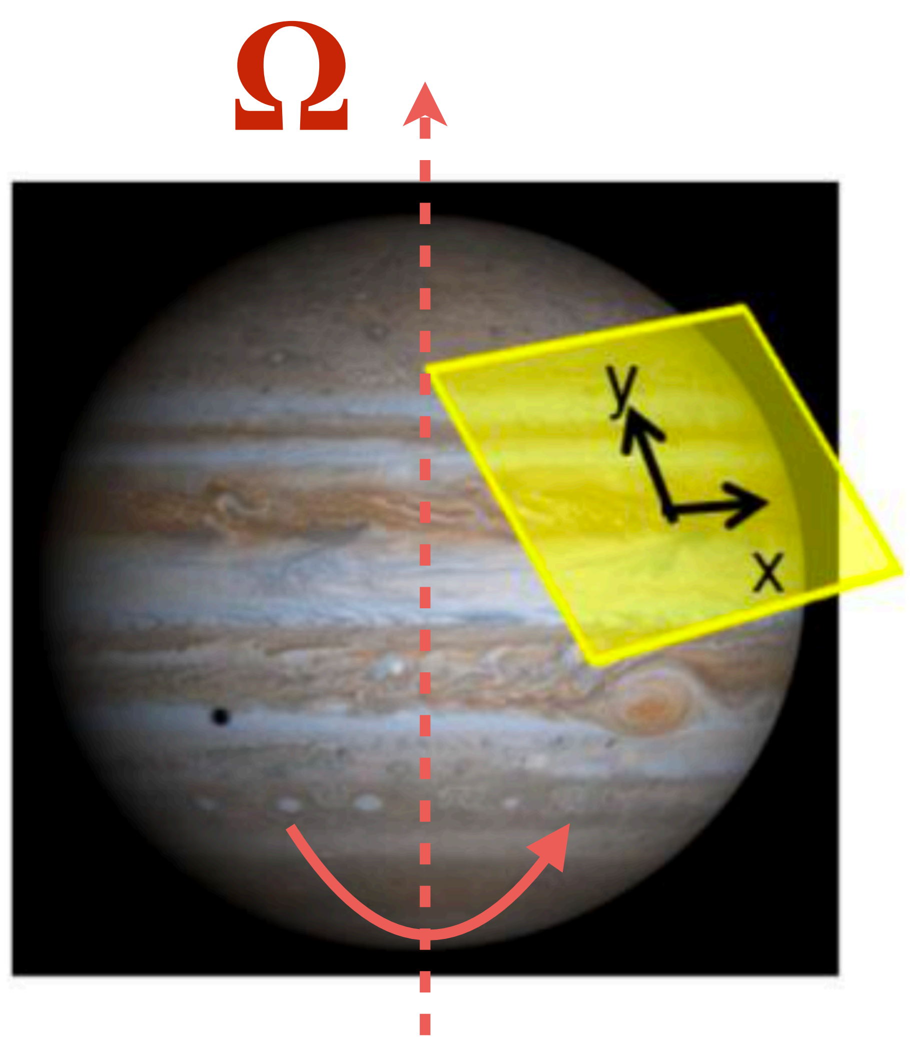
airflow over
vehicle



airflow over airfoil

Can turbulence ***reinforce*** flows?

towards a theory for understanding outer-atmosphere jets



$\boldsymbol{x} = (x\,,y)$

$\boldsymbol{u} = \big(u(\boldsymbol{x},t)\,,v(\boldsymbol{x},t)\big)$

Navier-Stokes eq. for incompressible fluid
(Newton's 2nd law)

$$\underbrace{\rho\left(\frac{\partial \boldsymbol{u}}{\partial t} + \boldsymbol{u}\cdot\nabla\boldsymbol{u}\right)}_{\text{mass} \times \text{acceleration}} = \underbrace{-\nabla\phi - 2\rho\boldsymbol{\Omega}\times\boldsymbol{u} + \nu\,\rho\,\nabla^2\boldsymbol{u} + \boldsymbol{\xi}}_{\text{“forces”}}$$

reduced pressure gradient — Coriolis force — viscosity (dissipation) — forcing (small-scale noise; $\overline{\boldsymbol{\xi}} = 0$)

$$u = \overline{u} + u'$$

jets — eddies (=turbulence)

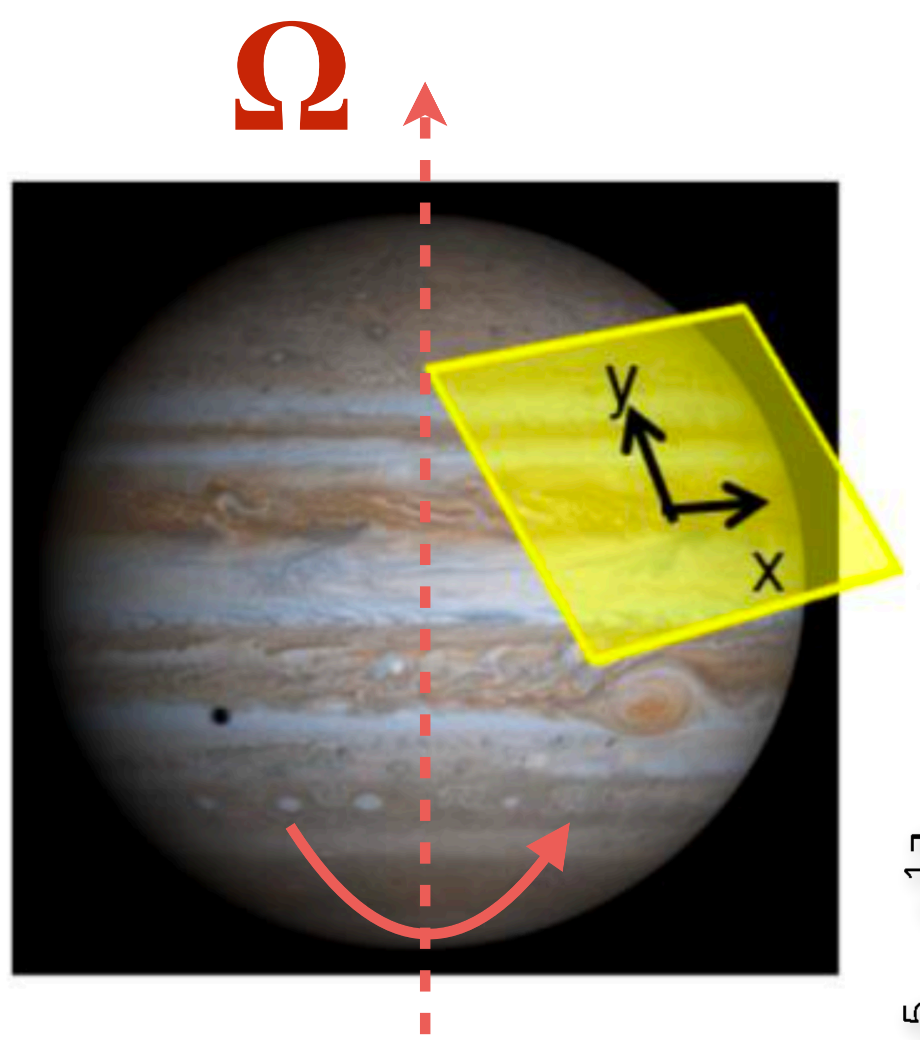
and after some fiddling:

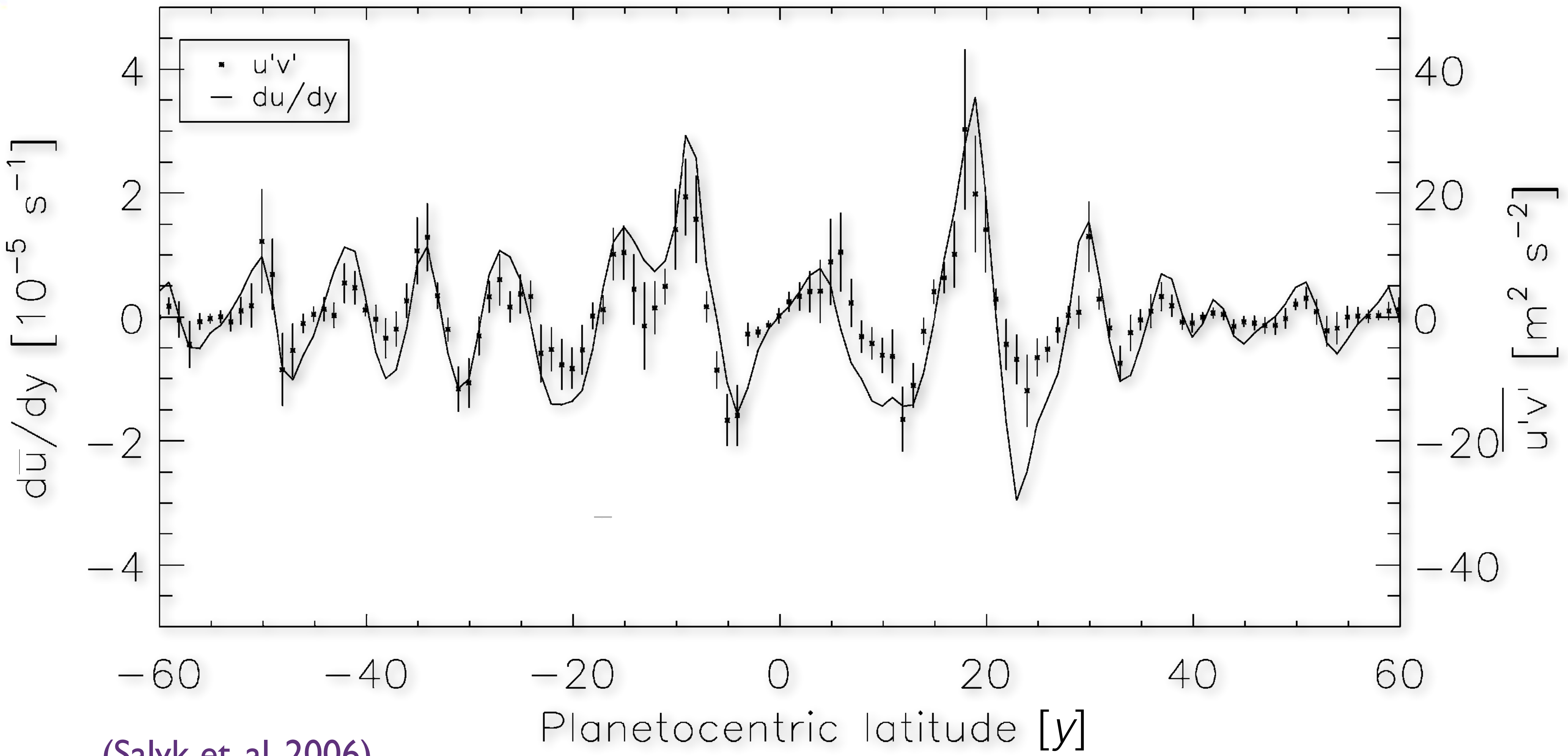
$$\frac{\partial \overline{u}}{\partial t} = -\frac{\partial}{\partial y}\overline{u'v'} + \nu\,\nabla^2\overline{u}$$

Reynolds stresses — viscosity (dissipation)

(divergence of energy-momentum tensor)

jets are eddy-driven





(Salyk et. al. 2006)

$$\overline{u'v'} \approx \kappa \frac{\partial \overline{u}}{\partial y}$$

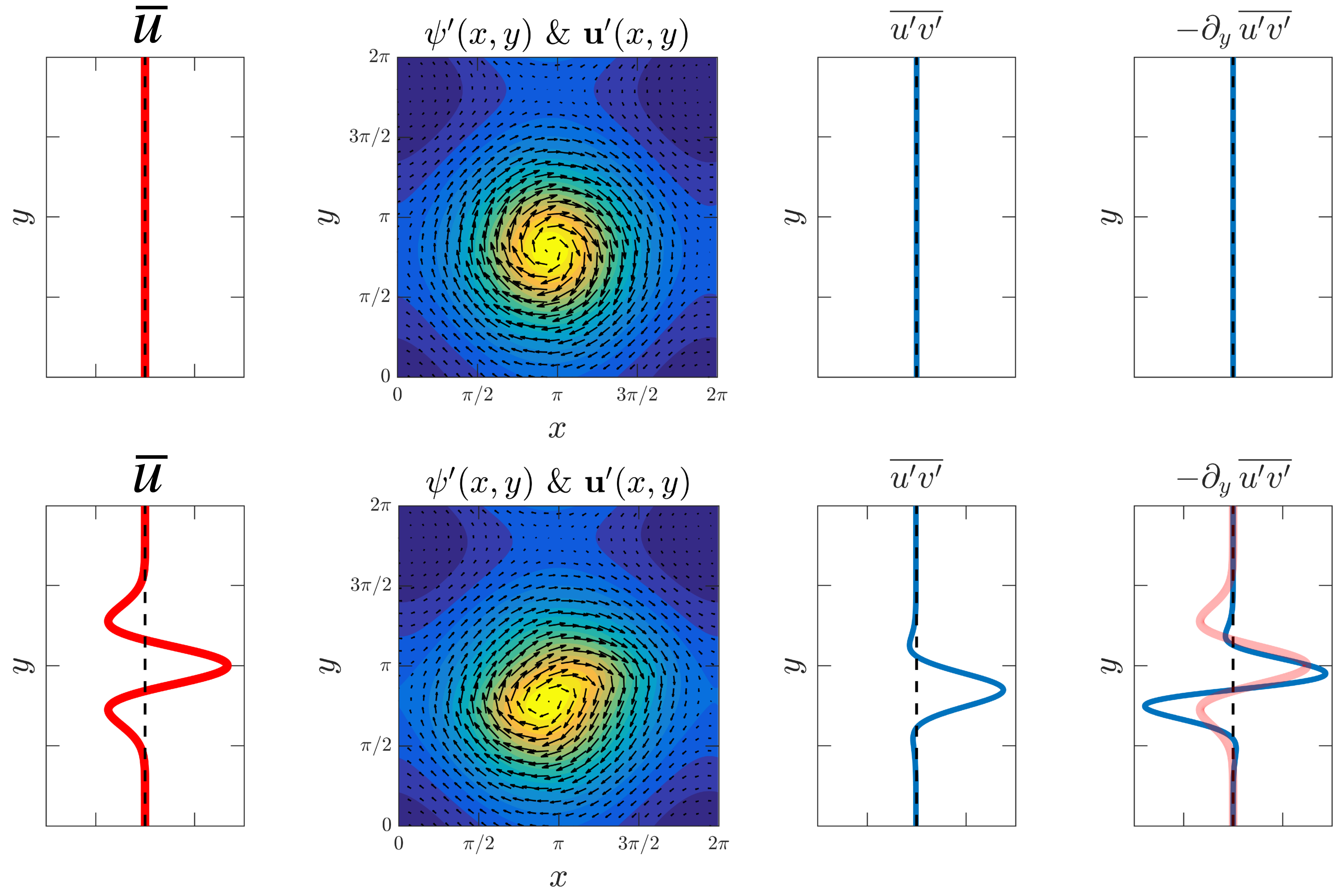
$$\kappa \approx 10^6 \, \mathrm{m^2 s^{-1}}$$

$$\frac{\partial \overline{u}}{\partial t} = -\frac{\partial}{\partial y}\overline{u'v'} = \frac{\partial}{\partial y}\left(-\kappa\frac{\partial \overline{u}}{\partial y}\right)$$

anti-diffusion
(or negative viscosity)

turbulence acts anti-diffusively and gives momentum to jets

$$\frac{\partial \overline{u}}{\partial t} = -\frac{\partial}{\partial y}\overline{u'v'}$$



$\overline{u}(y)$ & homogeneous u', v' $\xrightarrow{\text{advect for } \Delta t}$ $\overline{u'v'} \propto \Delta t\, \overline{v'^2}\, \partial_y \overline{u}$

$$\Longrightarrow -\partial_y \overline{u'v'} = \partial_y \big(\underbrace{-\gamma \Delta t\, \overline{v'^2}}_{} \, \partial_y \overline{u} \big)$$

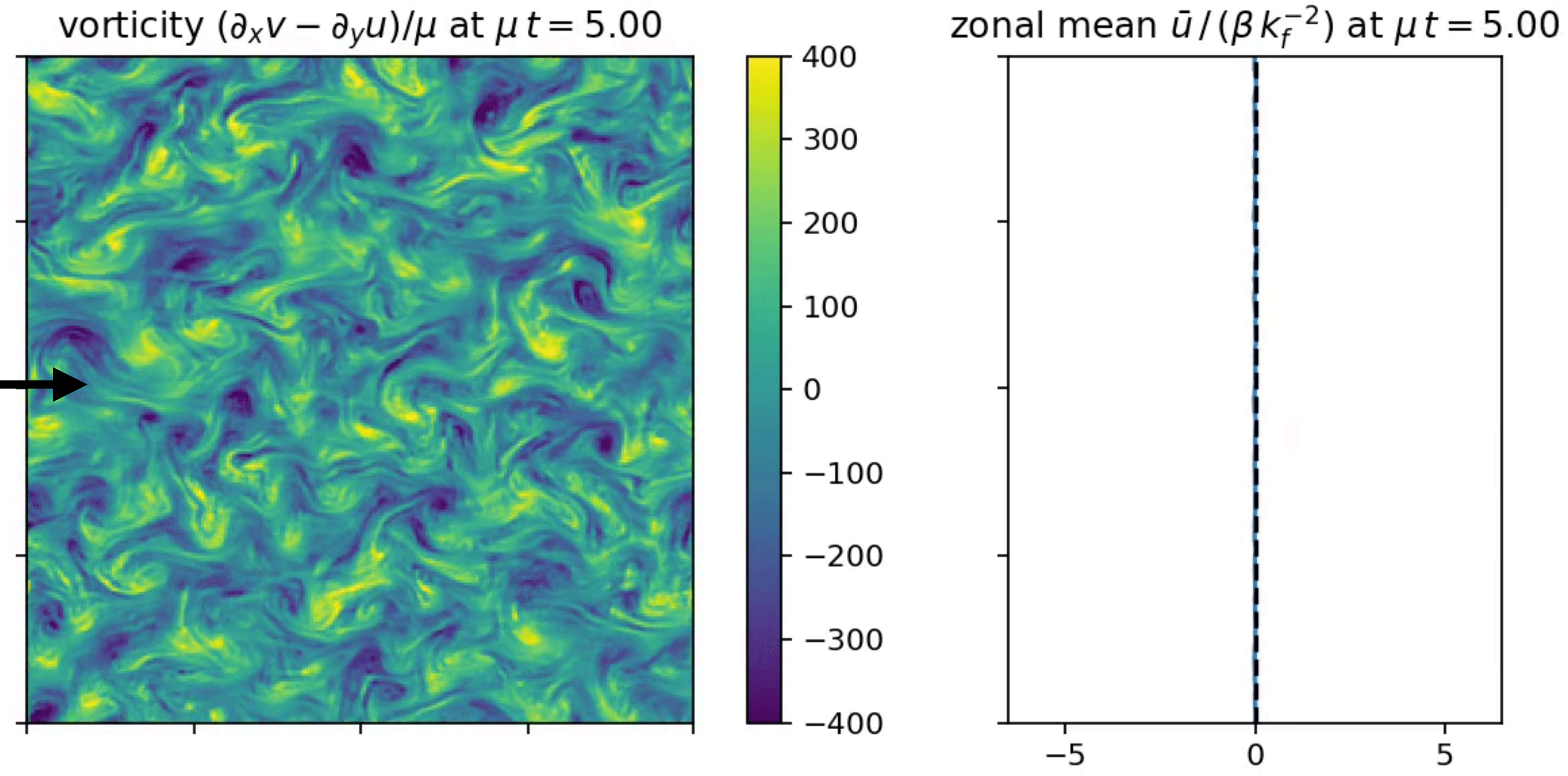
negative turbulent viscosity

$\gamma =$ nondim constant of $O(1)$

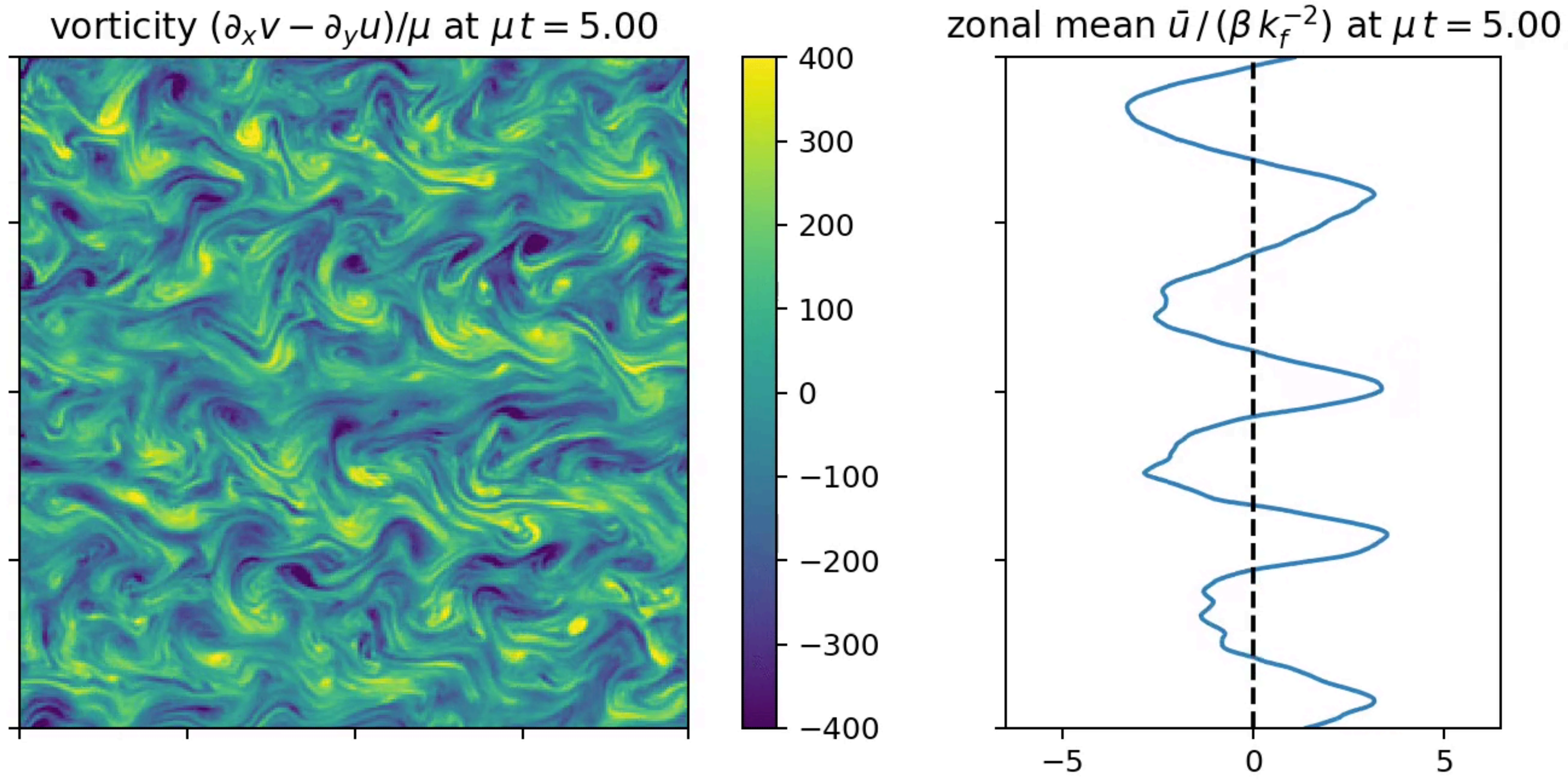
how can we perform stability of turbulent flows?

how do we show that a flow like this ...

[simulation in which at each time step we "kill" the zonal-mean component]



... is ***unstable*** leading to forming four jets?



the need for a new framework

To understand the underlying dynamics of jet formation
we need to change framework...

dynamics of flow realizations
(e.g. Navier-Stokes, ...)

$\boldsymbol{u}(\boldsymbol{x}, t)\ , \ldots$

dynamics that govern the same-time statistics of the flow fields

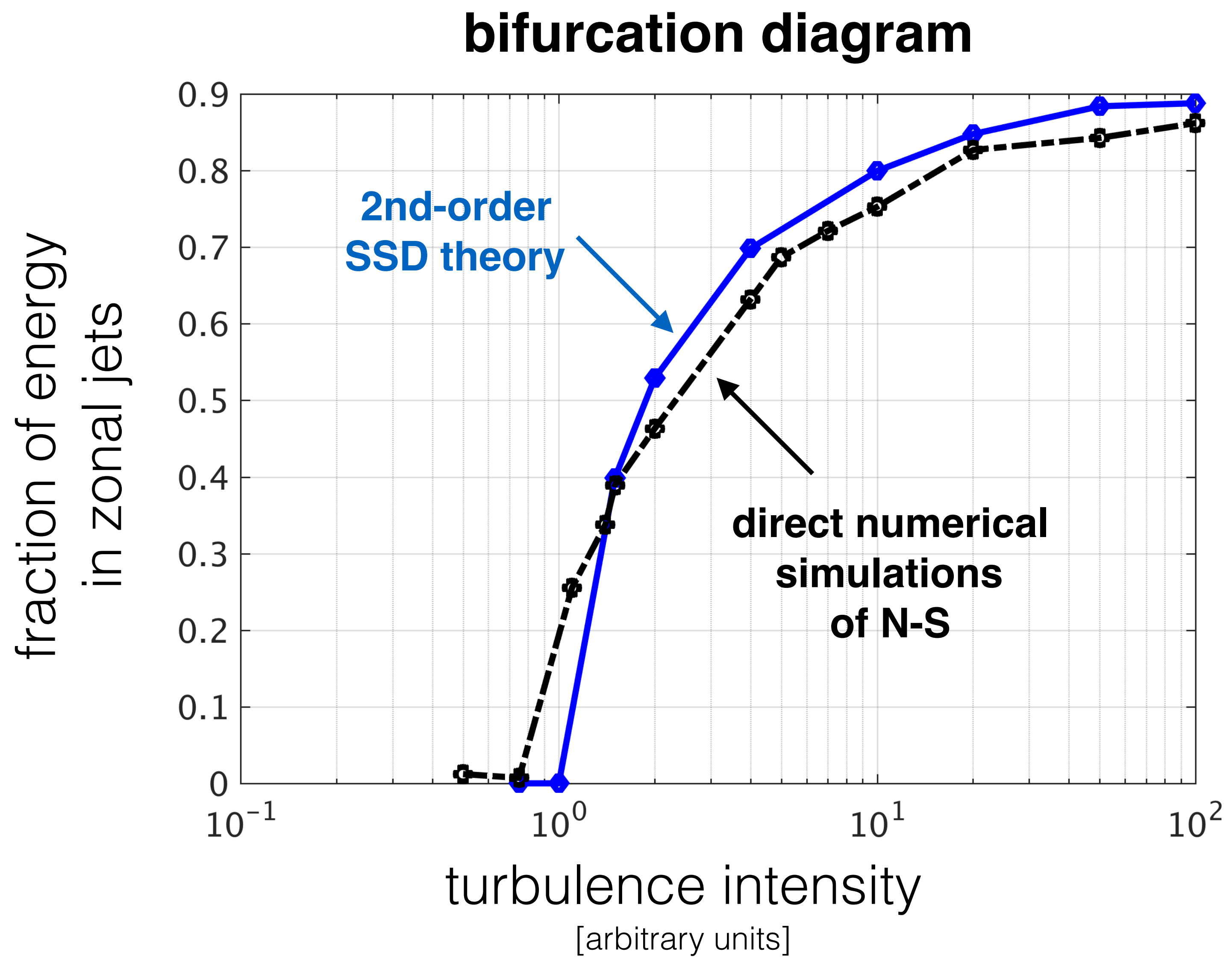
$\overline{\boldsymbol{u}(\boldsymbol{x}, t)}\ ,\ \ \overline{\boldsymbol{u}'(\boldsymbol{x}_1, t)\boldsymbol{u}'(\boldsymbol{x}_2, t)}, \ldots$

Statistical State Dynamics

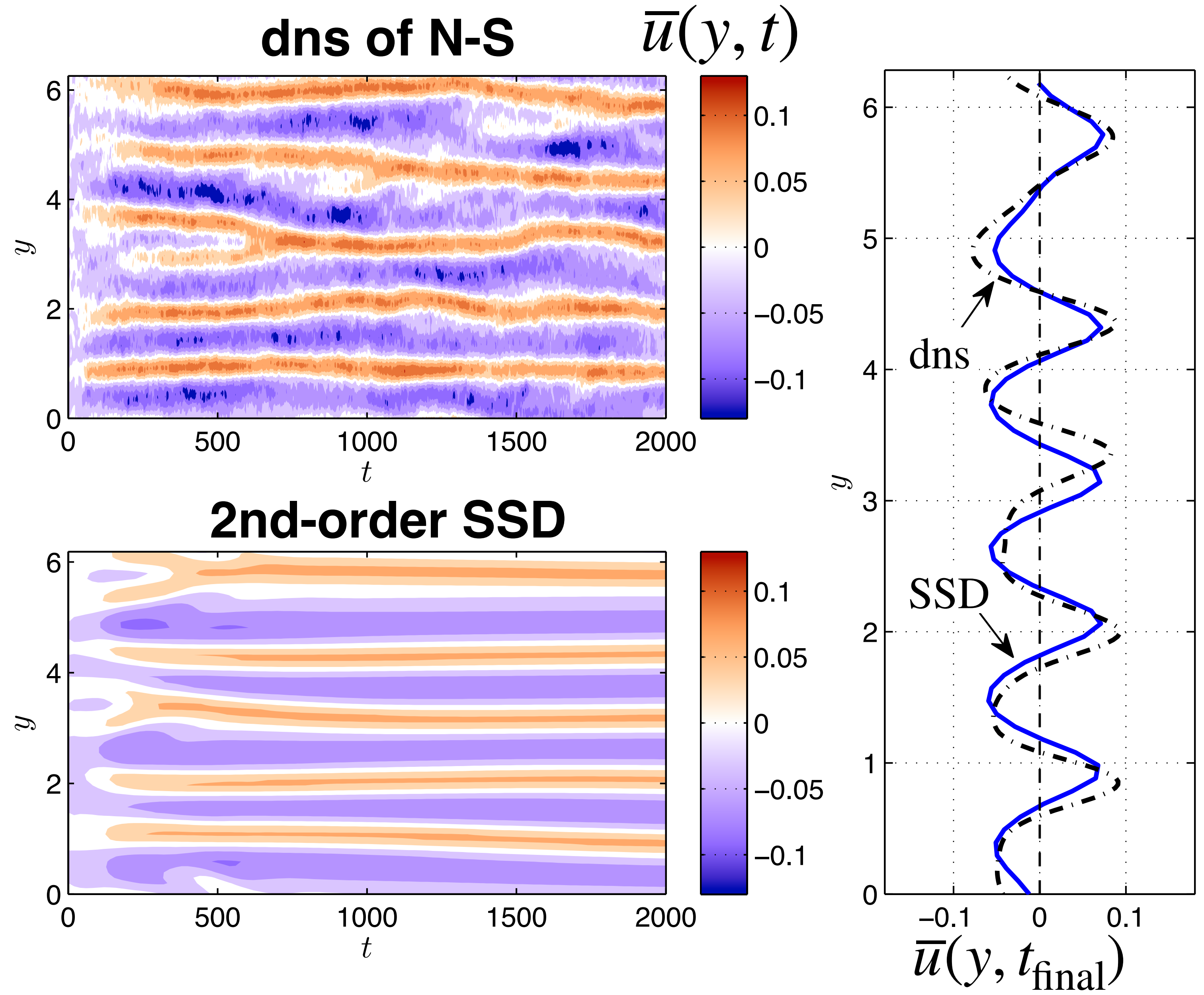
Farrell & Ioannou (2003) *JAS*

Statistical State Dynamics allows us linearize about a turbulent flow!

outer-atmosphere jets
[a theory for their formation]



jets emerge through a "phase change" that occurs as turbulence intensity increases



Flow realizations (dns) exhibit jet formation,
but its analytic expression appears only the SSD.

Predicting critical turbulence intensity or the structure of the emergent jet is **not** possible through N-S dynamics

Constantinou et al. (2014) *JAS*
Constantinou (2015), PhD thesis

We understand how outer-atmosphere jet form and maintain.

But what's happening below the clouds?

For example: how deep these jets continue below the clouds?

how deep the jets go below the clouds?

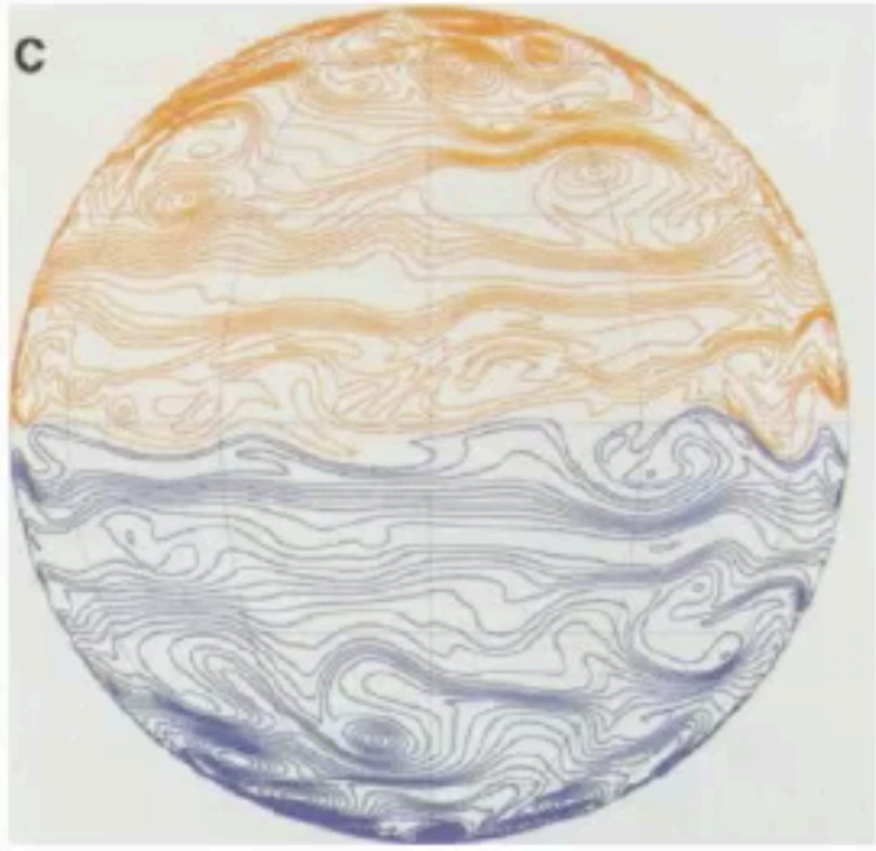
outstanding question
rooted deep in debate among various theories

shallow-jet theories

jets exist only within
the top-atmospheric layer ~100km

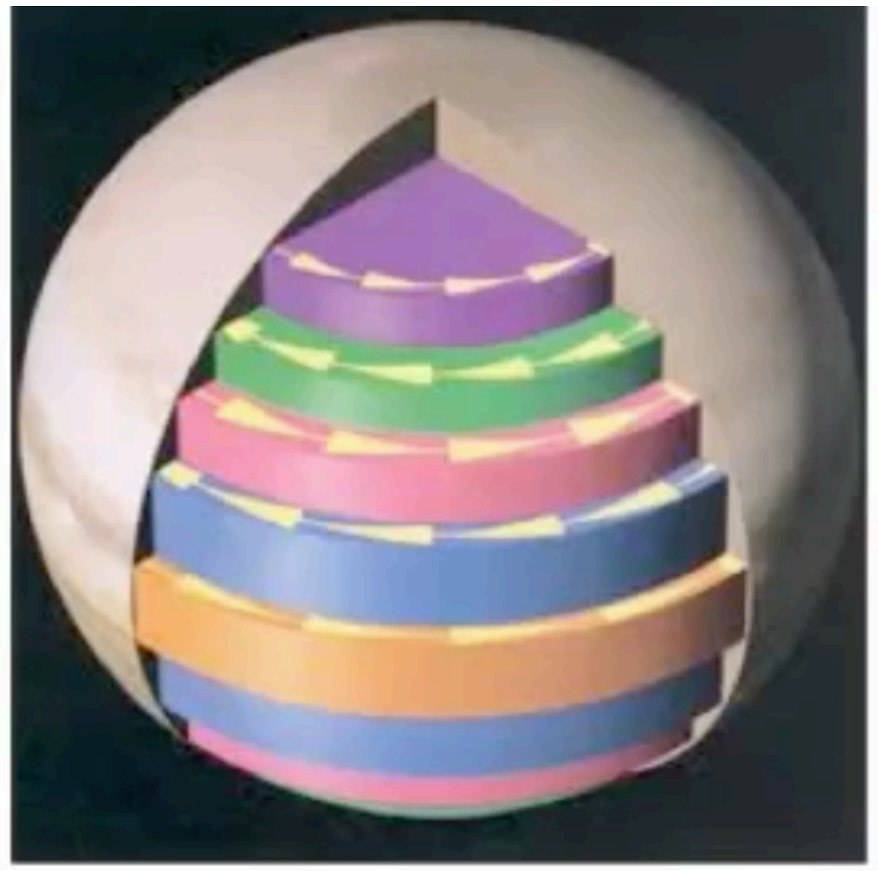
deep-jet theories

jets reach the centre of the planet
"Taylor columns"



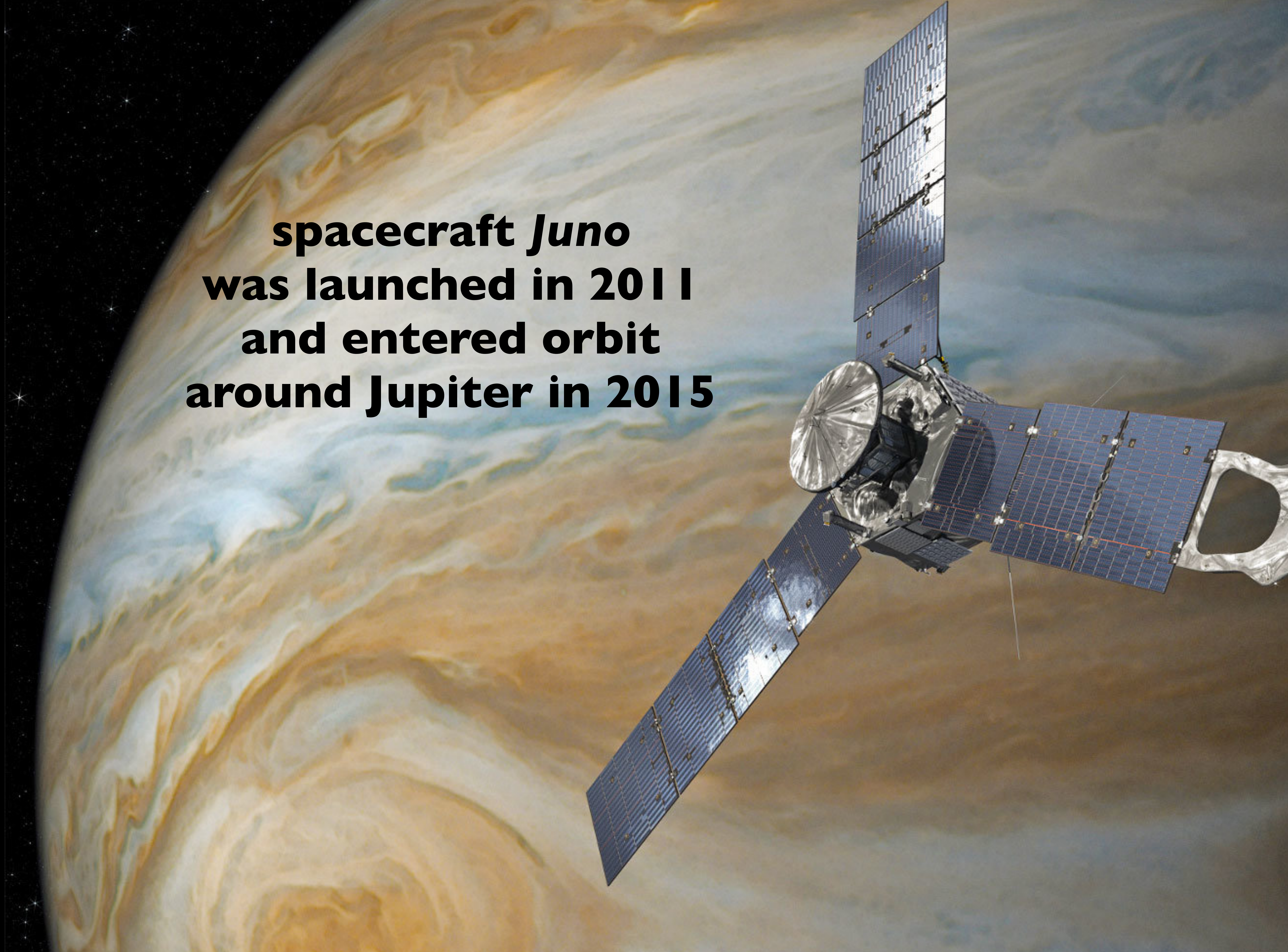
Shallow geostrophic turbulence
(Rhines, 1975, Cho & Polvani 1996)

Shallow or deep?



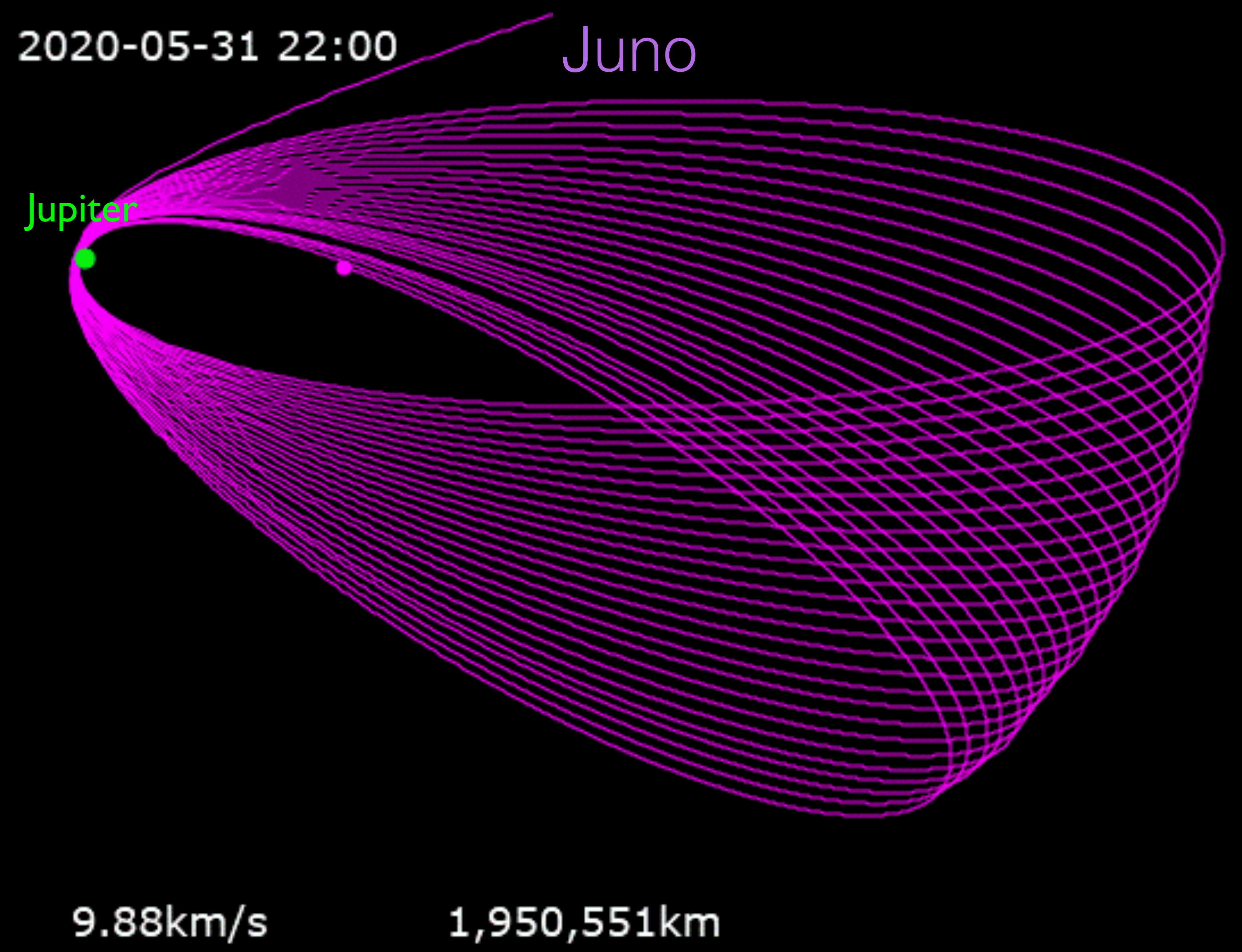
Deep internal convection
(Busse, 1976, Heimpel et al, 2005
Fig. from Ingersoll, 1990)

spacecraft *Juno*
was launched in 2011
and entered orbit
around Jupiter in 2015



JUNO

Juno's mission



make detailed measurements of
Jupiter's **gravitational** and
magnetic fields

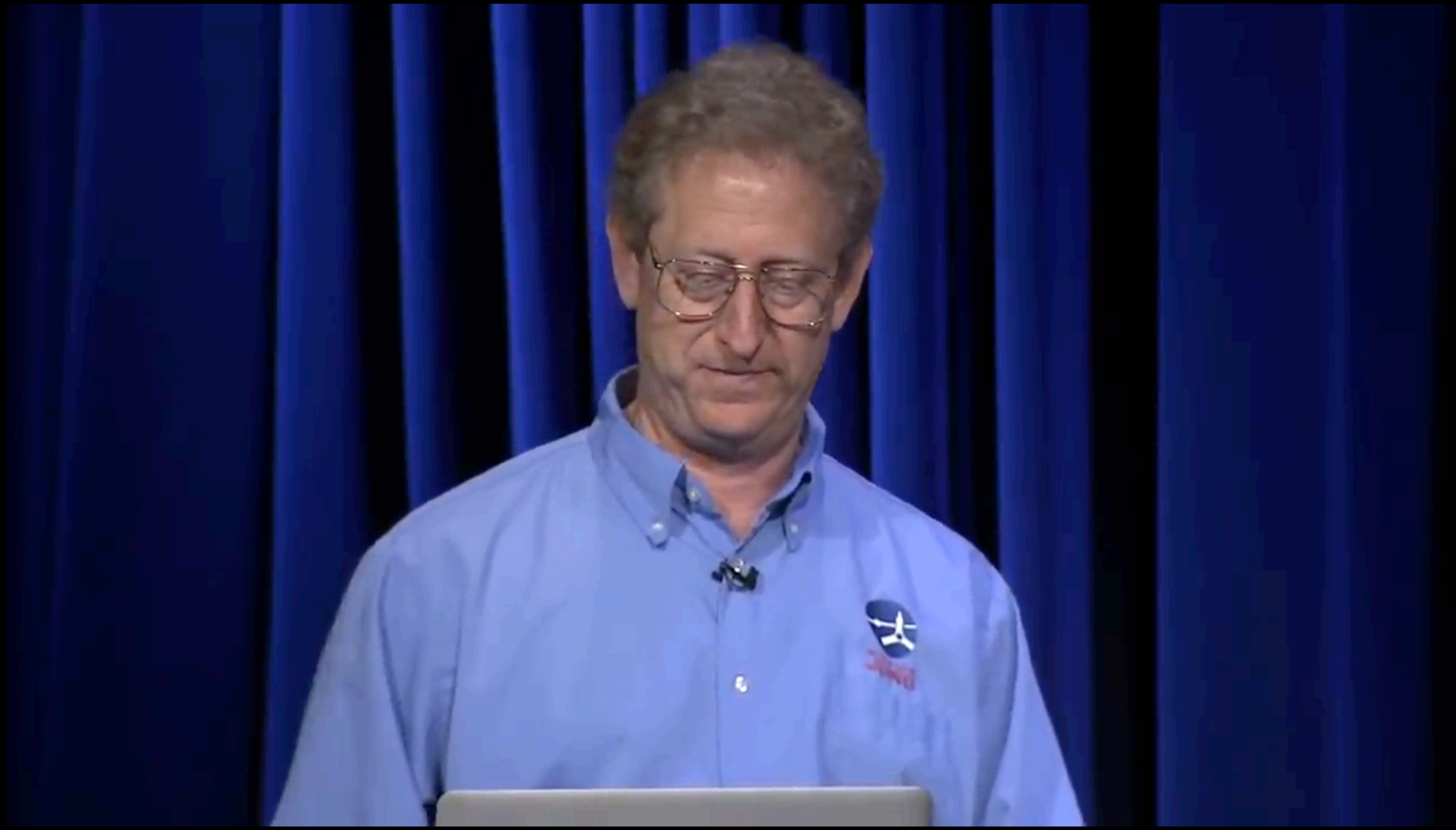
Jupiter's background radiation is ***EXTREME!***
(around 5×10^7 times stronger of that here on Earth)

Strategy: Go in close; get the data; get out quick!

At its closest point it reaches
only ~4500km over the cloud tops
(that's about the distance from Athens to Iceland)

What did *Juno* discover?

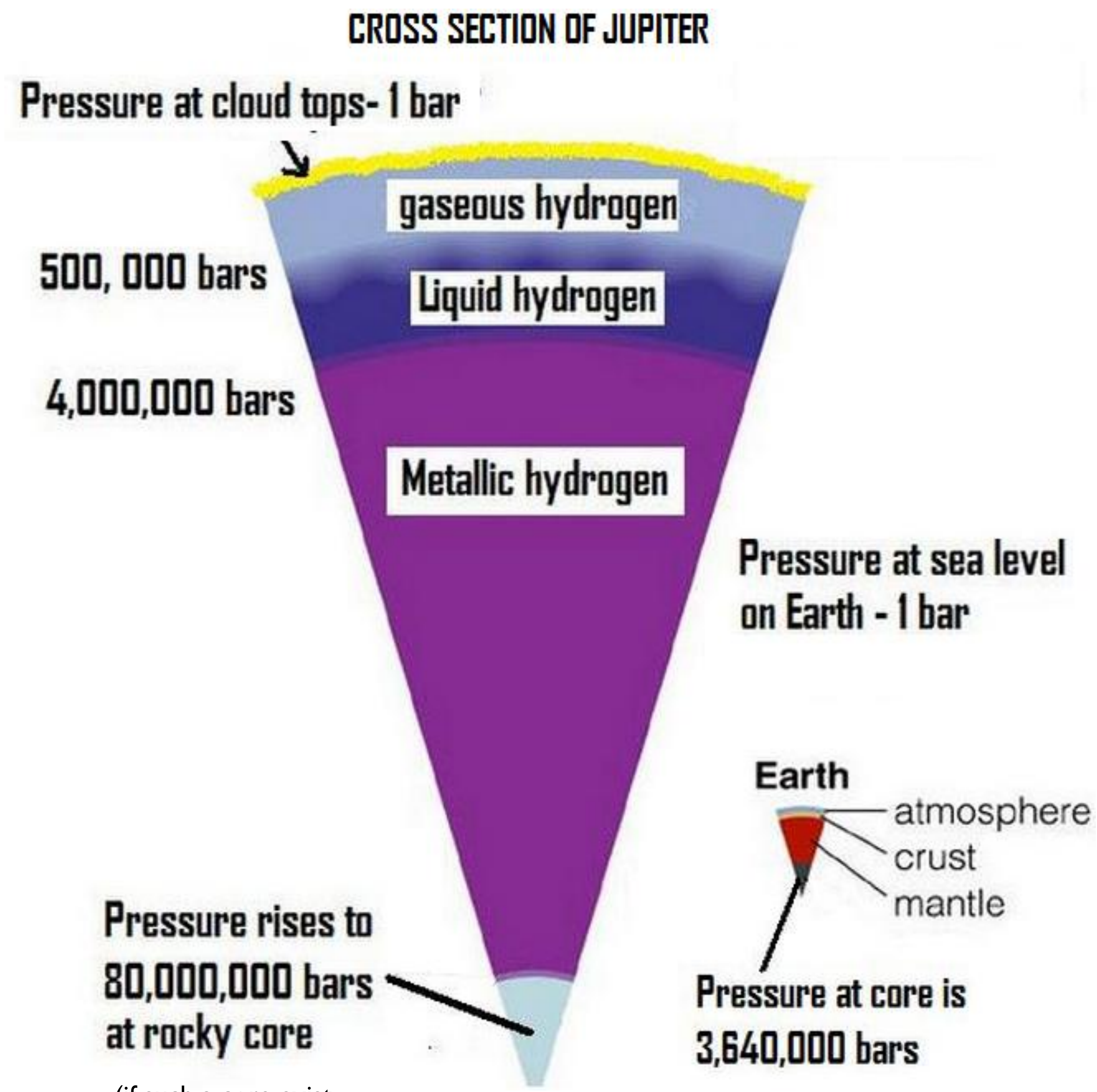
[Excerpt from NASA Jet Propulsion Laboratory public announcement, May 2018]



Dr. Steve Levin
Juno Project Scientist
NASA JPL

"...magnetic field has something to do with why the belts and zones only go that deep (…)
*But we don't know this yet; **it's speculation**."*

deep inside the gas giants fluid becomes conducting



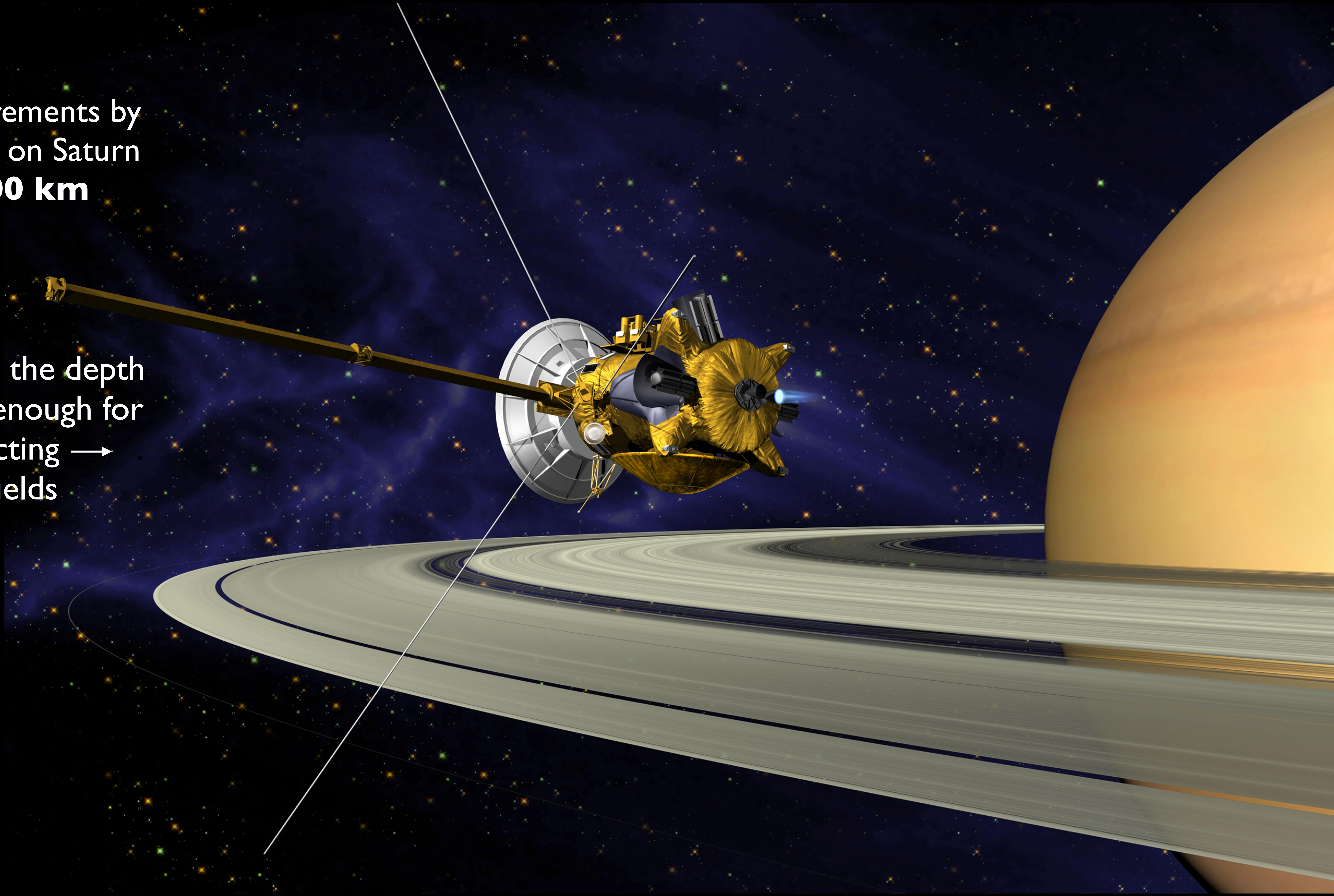
(if such a core exist
Juno's findings suggest
there is no rocky core)

as we go deeper inside Jupiter
pressure rises **dramatically**

electrons escape the molecules
and the fluid **becomes conducting**

conducting moving fluid ⟶
⟶ currents ⟶ magnetic fields

Btw, same story in Saturn...



Gravitometric measurements by *Cassini* reveal that jets on Saturn go as deep as **8500 km**

and again that's about the depth that pressure is high enough for the fluid to be conducting ⟶

⟶ magnetic fields

here's where me and Jeff Parker come into the story...

Jeffrey Parker
Lawrence Livermore
National Laboratory
CA, USA

Magnetic fields bring about new terms in equations of motion

N-S → MHD $\rho \frac{\partial \boldsymbol{u}}{\partial t} + \ldots = \boldsymbol{J} \times \boldsymbol{B} + \ldots$ $\frac{\partial \boldsymbol{B}}{\partial t} = \ldots$ $\boldsymbol{B} = (B_x, B_y)$

Lorentz force

induction equation
Faraday's law

$\mu_0 \boldsymbol{J} = \nabla \times \boldsymbol{B}$ Ampére's law (ignoring displacement current)

[... some fiddling]
now zonal flow obeys:

$$\frac{\partial \overline{\rho u}}{\partial t} = \frac{1}{\mu_0} \frac{\partial \overline{B_x' B_y'}}{\partial y} - \frac{\partial \overline{\rho u' v'}}{\partial y} + \text{dissipation}$$

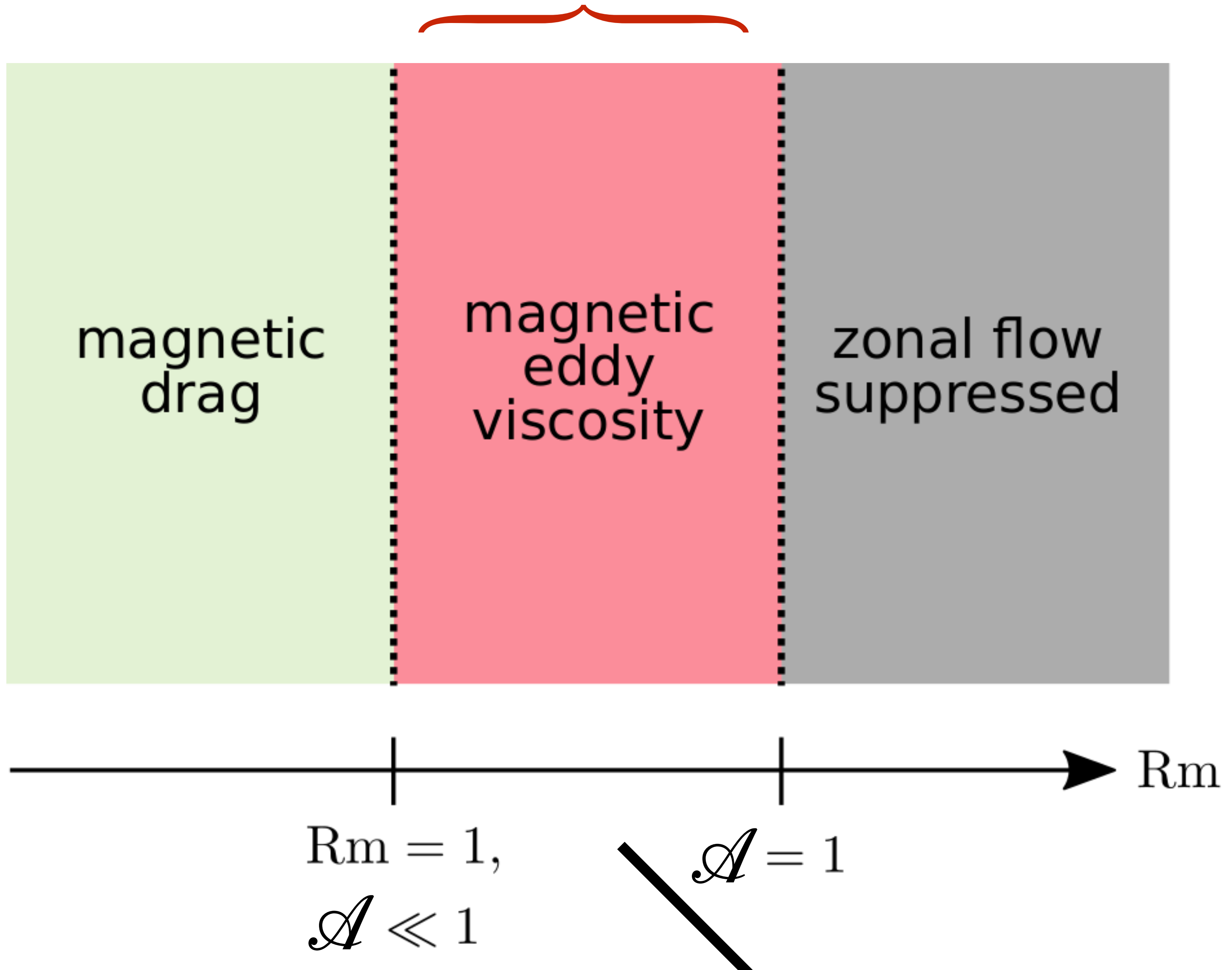
Maxwell stresses

Reynolds stresses

We point out a new regime of *magnetic eddy viscosity*

$$\mathscr{A} = \frac{|\boldsymbol{J} \times \boldsymbol{B}|}{|\rho \boldsymbol{u} \cdot \nabla \boldsymbol{u}|} = \frac{\text{Lorentz force}}{\text{inertial force}}$$

Collective effect of a mean shear flow to the magnetic fluctuations acts effectively to increase the fluid's viscosity



this is exactly the regime where zonal jets start being suppressed

$$\mathrm{Rm} = \frac{LV}{\eta} = \frac{\text{inertial force}}{\text{viscous force}}$$

η → magnetic diffusivity

Parker & Constantinou, *Phys. Rev. Fluids*, 2019

We point out a new regime of *magnetic eddy viscosity*

Collective effect of a mean shear flow to the magnetic fluctuations acts effectively to increase the fluid's viscosity

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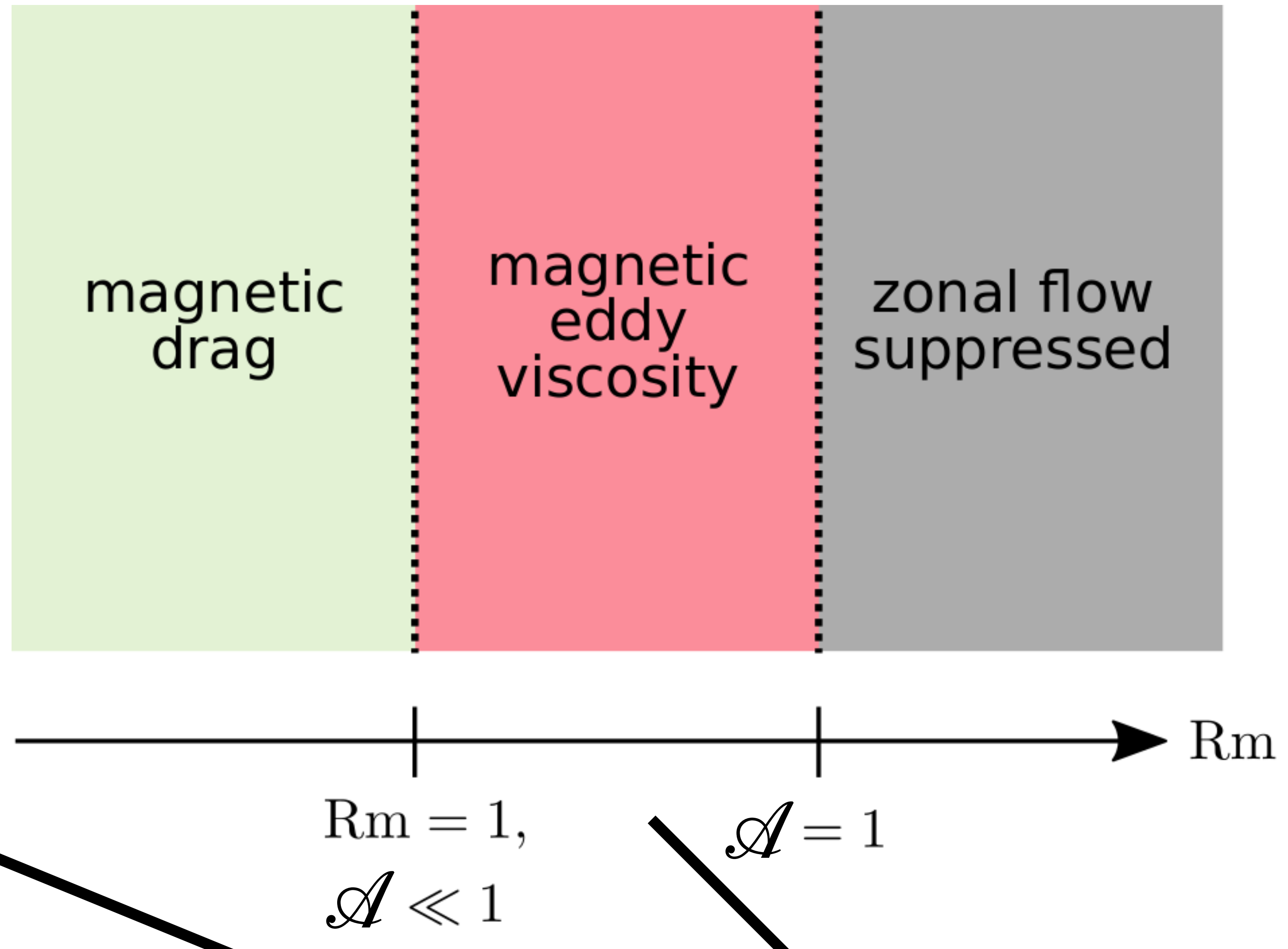
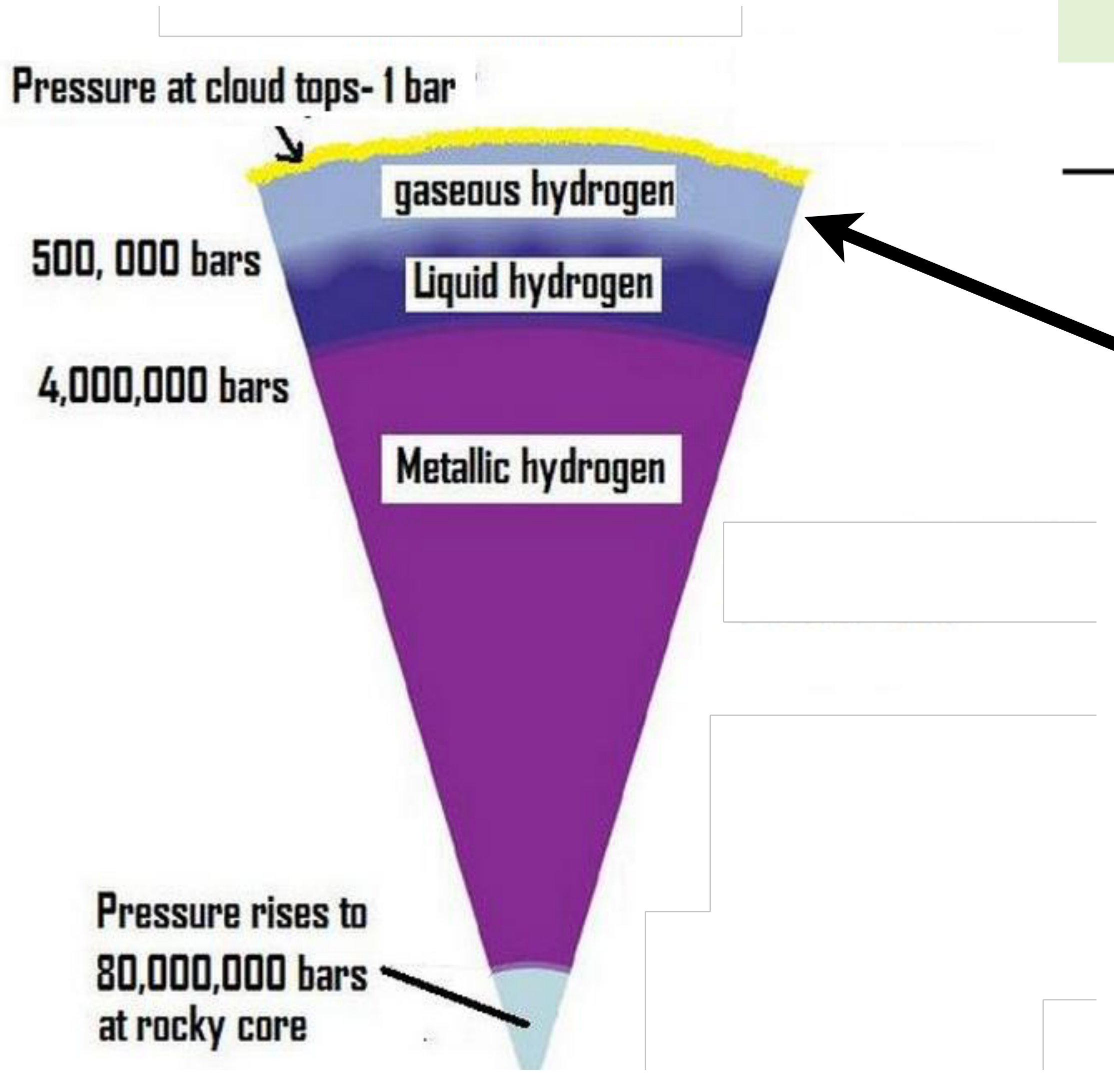


$$\mathrm{Rm} = \frac{LV}{\eta} = \frac{\text{inertial force}}{\text{viscous force}}$$

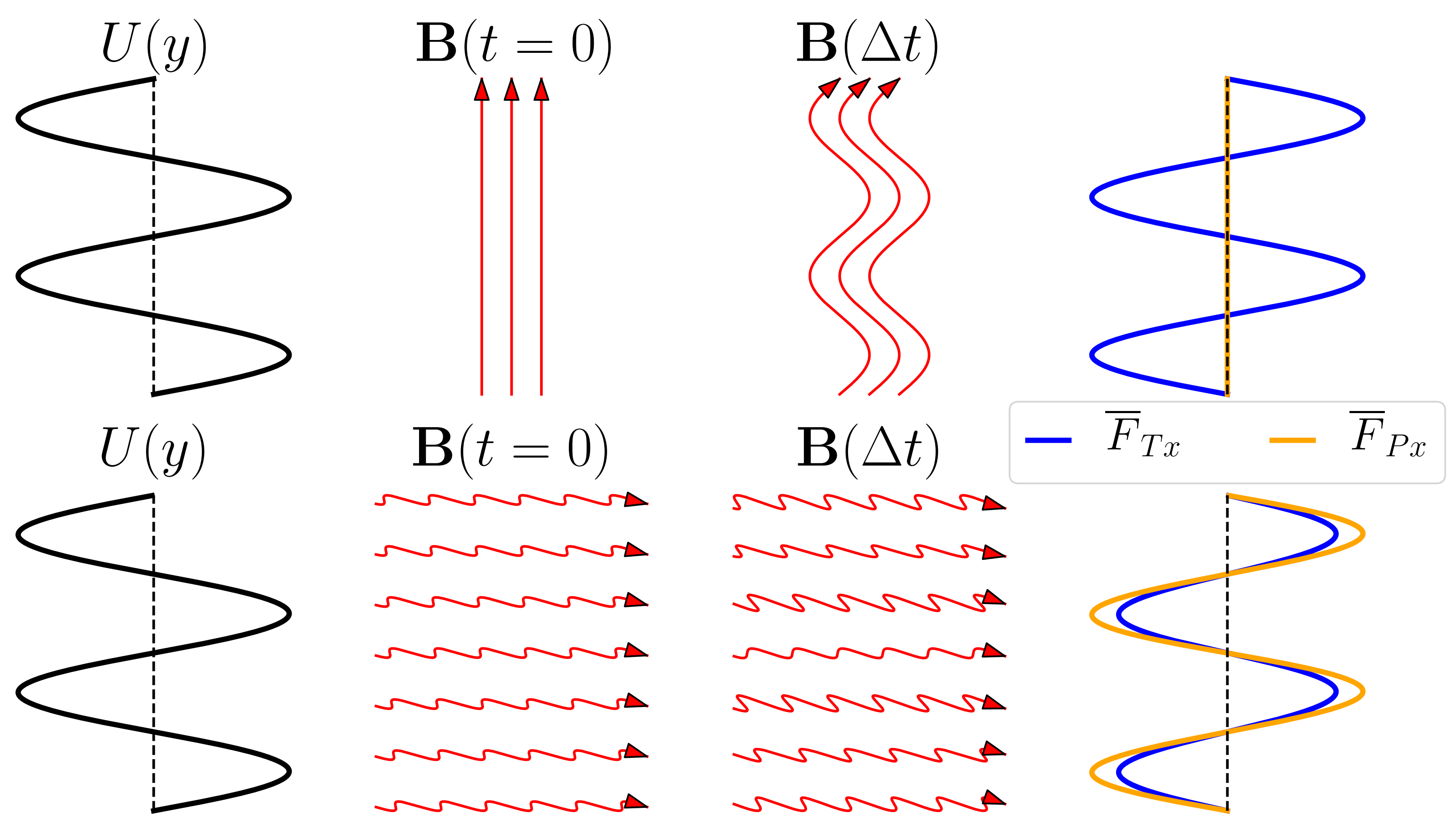
η → magnetic diffusivity



this is exactly the regime where zonal jets start being suppressed

Parker & Constantinou, *Phys. Rev. Fluids*, 2019

We derive magnetic viscosity from simple physical arguments



$\overline{u}(y)$ & homogeneous B'_x, B'_y $\xrightarrow{\text{advect for } \Delta t}$ $\overline{B'_x B'_y} \propto \Delta t\, \overline{B'^2_y}\, \partial_y \overline{u}$

$$\Longrightarrow \frac{1}{\mu_0}\partial_y \overline{B'_x B'_y} = \partial_y\Big(\underbrace{\alpha \frac{1}{\mu_0}\Delta t\, \overline{B^2_y}}_{\text{magnetic viscosity}}\ \partial_y \overline{u}\Big)$$

$\alpha =$ nondim constant of $O(1)$

Parker & Constantinou, *Phys. Rev. Fluids*, 2019

Putting it all together

zonal flow equation:

$$\frac{\partial \overline{\rho u}}{\partial t} = \frac{1}{\mu_0}\frac{\partial \overline{B_x' B_y'}}{\partial y} - \frac{\partial \overline{\rho u' v'}}{\partial y} + \ldots$$

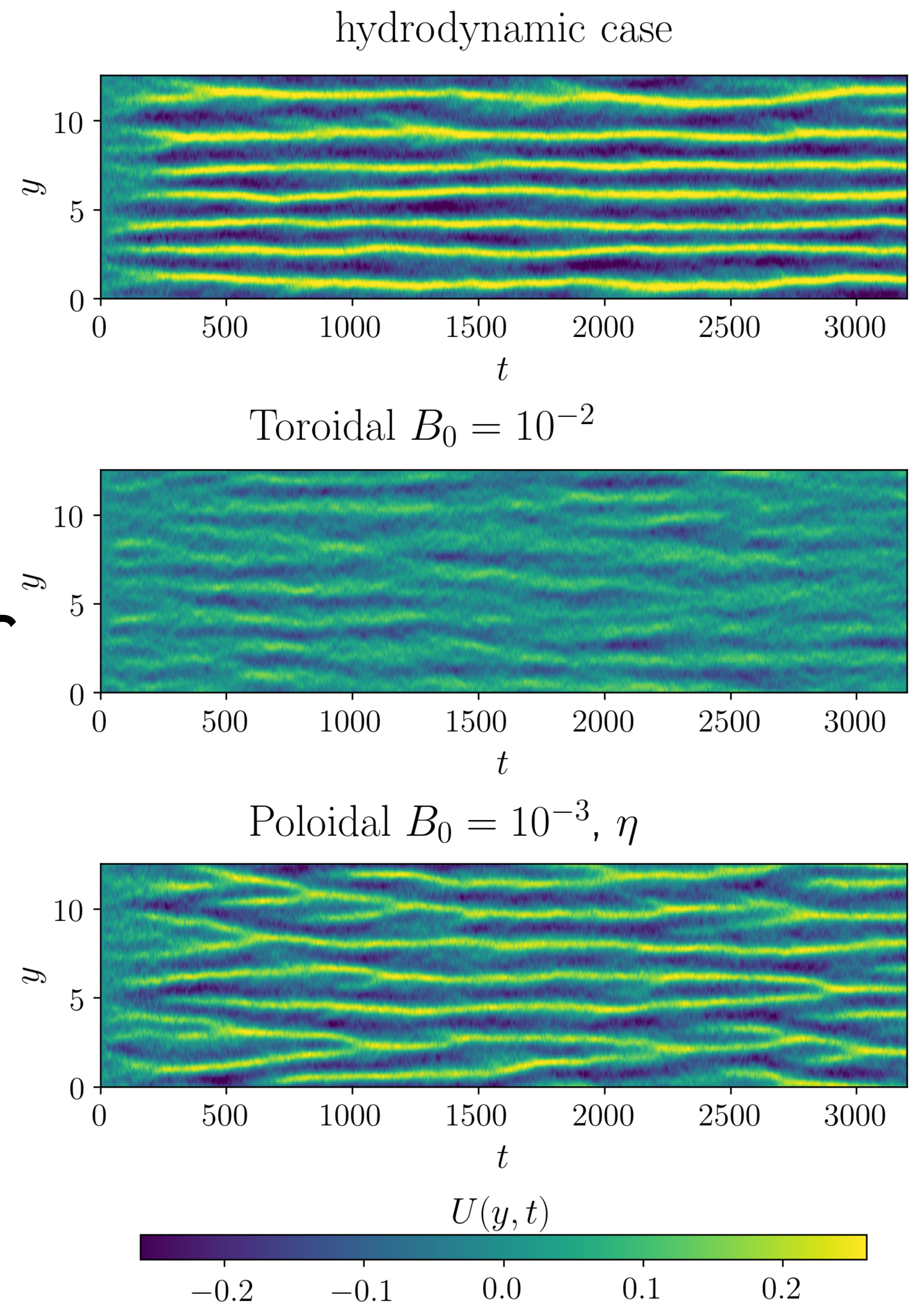
$$= \frac{\partial}{\partial y}\Bigg[\underbrace{\Bigg(\alpha\frac{\overline{B_y'^2}}{\mu_0} - \gamma\rho\overline{v'^2}\Bigg)\tau_{\mathrm{corr}}}_{\text{total turbulent viscosity}}\frac{\partial \overline{u}}{\partial y}\Bigg] + \ldots$$

$\alpha, \gamma =$ nondim constants of $O(1)$

Parker & Constantinou, *Phys. Rev. Fluids*, 2019

Magnetic fields tend to suppress zonal jets in 2D magnetohydrodynamic simulations

spacetime diagrams of jets



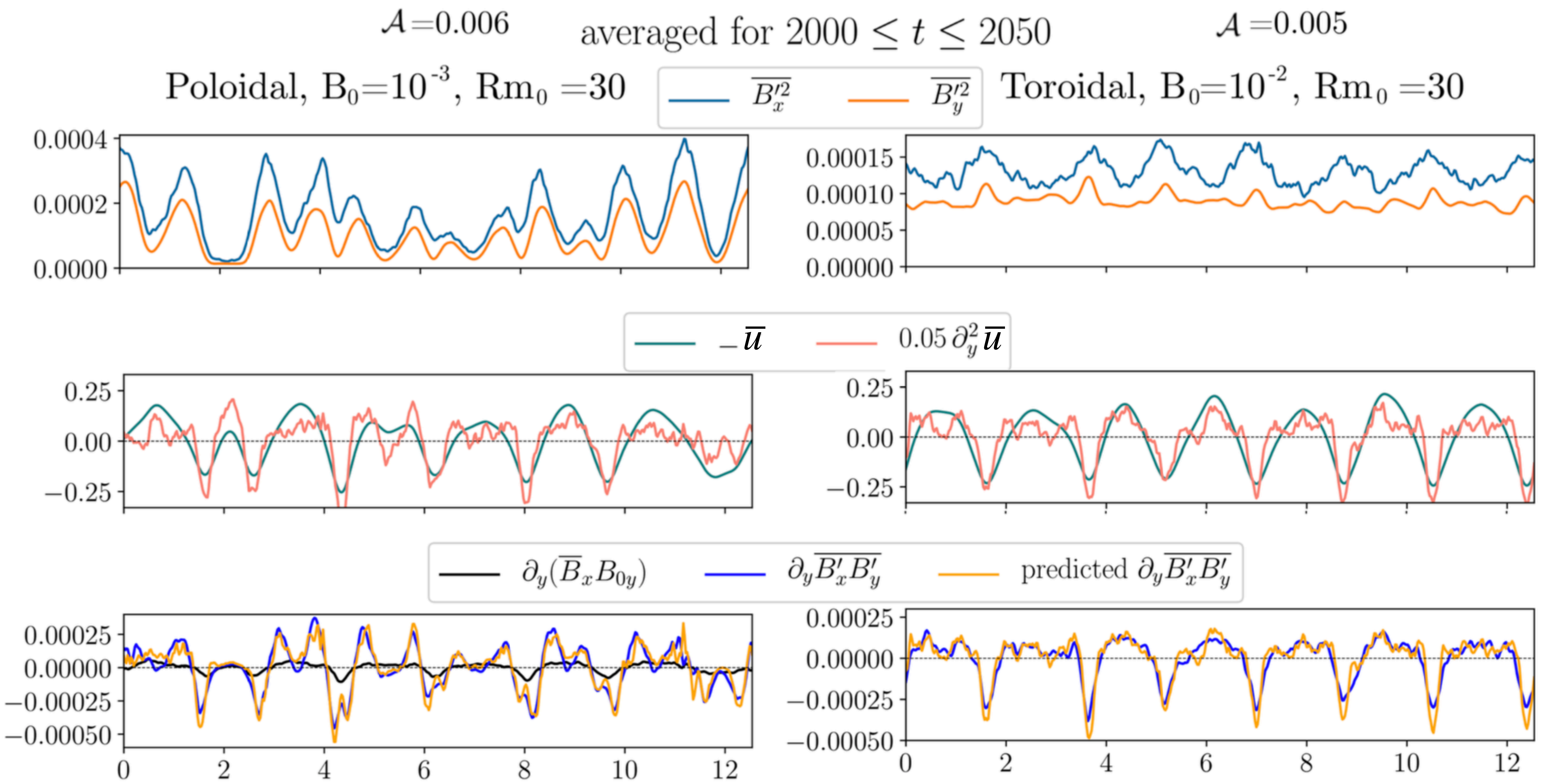
strong, coherent jets

weaker & less coherent jets

Parker & Constantinou, *Phys. Rev. Fluids*, 2019

We verify magnetic viscosity in 2D magnetohydrodynamic simulations

our prediction $$\frac{\partial \overline{B_x' B_y'}}{\partial y} = \frac{\partial}{\partial y}\left(\alpha \overline{B_y'^2}\, \tau_{\text{corr}} \frac{\partial \overline{u}}{\partial y}\right)$$

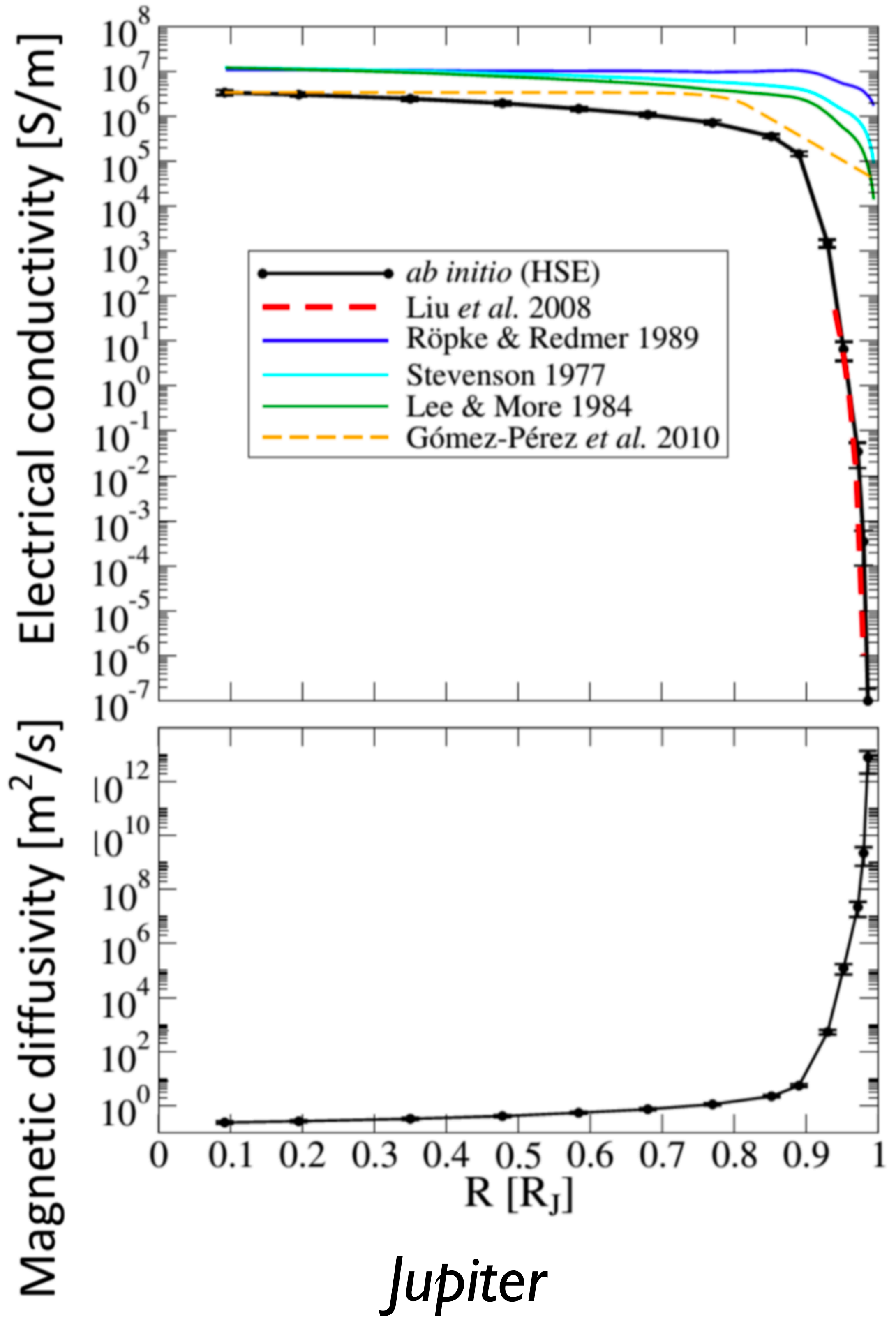


Parker & Constantinou, *Phys. Rev. Fluids*, 2019

Ready for a leap of faith?

Use $$\frac{\partial \overline{\rho u}}{\partial t} = \frac{\partial}{\partial y}\left[\left(\alpha \frac{\overline{B_y'^2}}{\mu_0} - \gamma \rho \overline{v'^2}\right)\tau_{\rm corr}\frac{\partial \overline{u}}{\partial y}\right] + \ldots$$

to predict how deep the jets in Jupiter & Saturn should go.



Jupiter

[French et al., *ApJ Supp. S.* (2012)]

- Use typical flow values from cloud tops
- Use B^2 = Rm B_0^2 (empirical relation) to get a critical Rm ⟶ critical η
- Use current internal structure models for each gas giant to compute the depth that corresponds to the $\eta_{\rm crit}$ value

We get: Jupiter 3500 km Saturn 8000 km

[*Juno* ⟶ Jupiter 3000 km *Cassini* ⟶ Saturn 8500 km]

coincidence?

Parker & Constantinou, *Phys. Rev. Fluids*, 2019

take home messages

Identified an MHD regime ($\mathrm{Rm} \gg 1$ & $\mathscr{A} \ll 1$) in which there is *magnetic eddy viscosity* of mean shear flow

Simple derivation with clear physical picture:
Shear flow + MHD frozen-in law + "short" decorrelation due to turbulence

Confirmed in 2D incompressible MHD simulations

Magnetic eddy viscosity may explain for the depth-extent of the zonal jets in Jupiter and Saturn

thanks

Constantinou and Parker (2018). Magnetic suppression of zonal flows on a beta plane. *Astrophysical Journal*, **863**, 46
Parker and Constantinou (2019). Magnetic eddy viscosity of mean shear flows in two-dimensional magnetohydrodynamics. *Physical Review Fluids*, **4**, 083701

Constantinou (2018). Jupiter's magnetic fields may stop its wind bands from going deep into the gas giant, *The Conversation*, August 10th, 2018