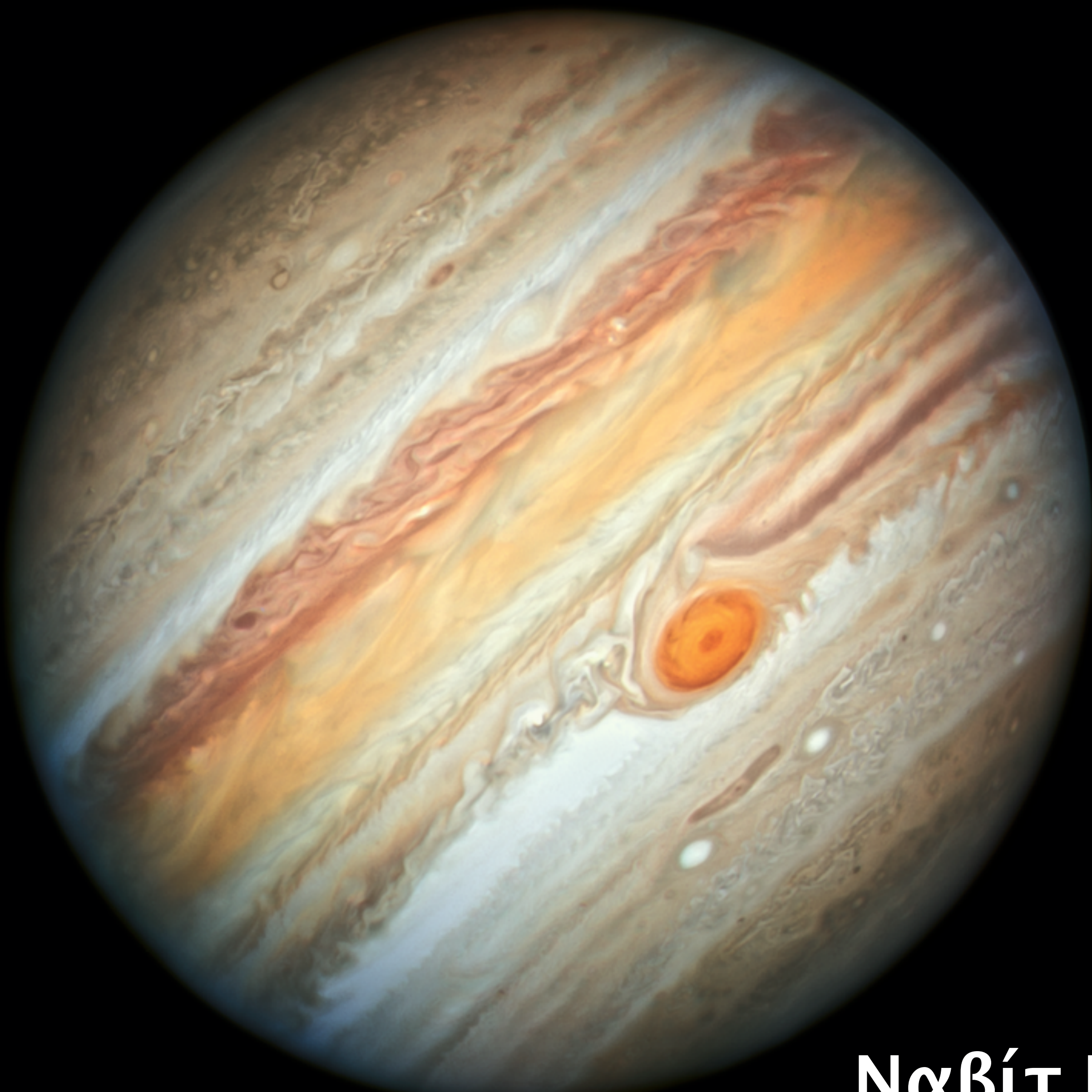
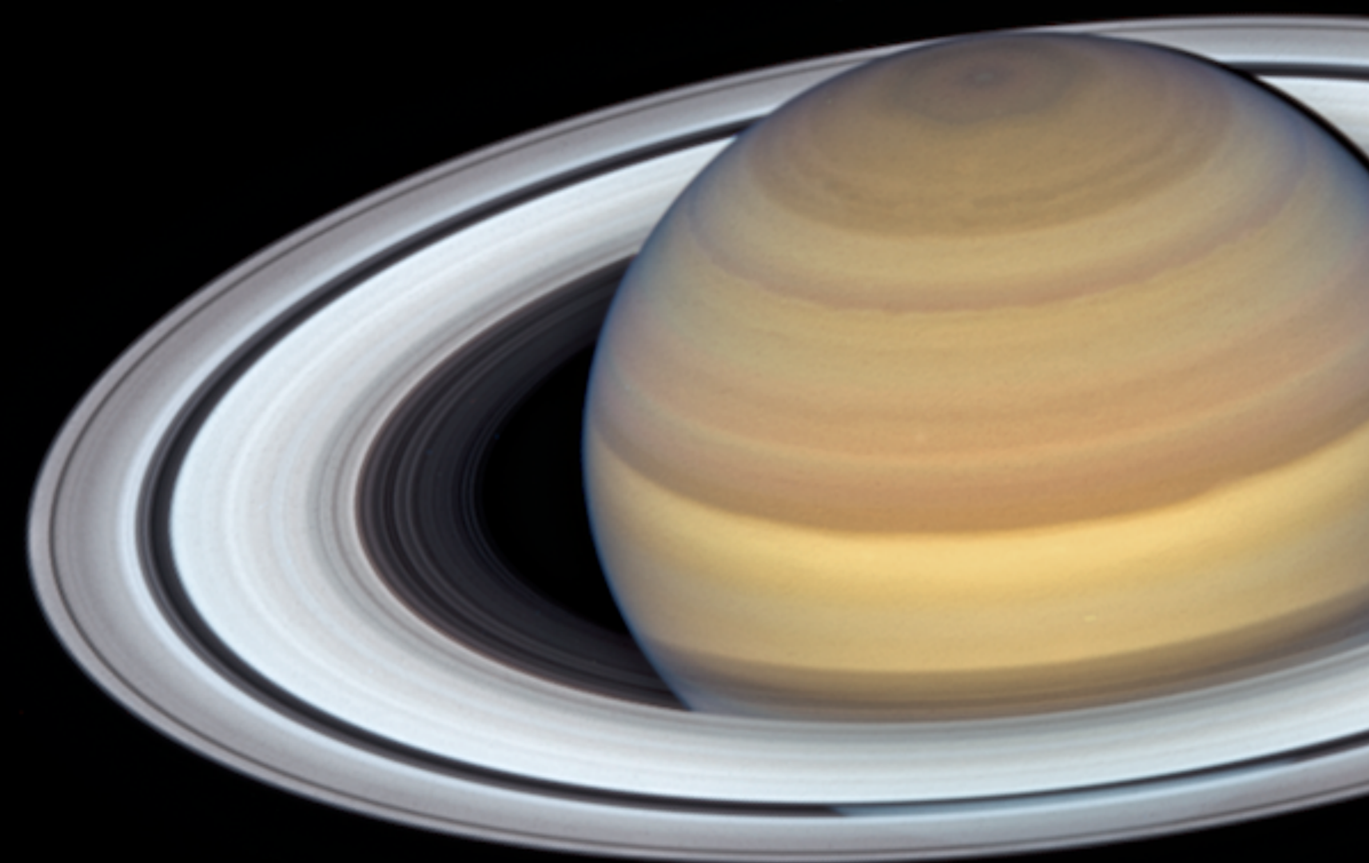
Australian National University

# Τι κρύβεται κάτω από τις ζώνες του Δία και του Κρόνου;

ARC Centre of Excellence for Climate Extremes





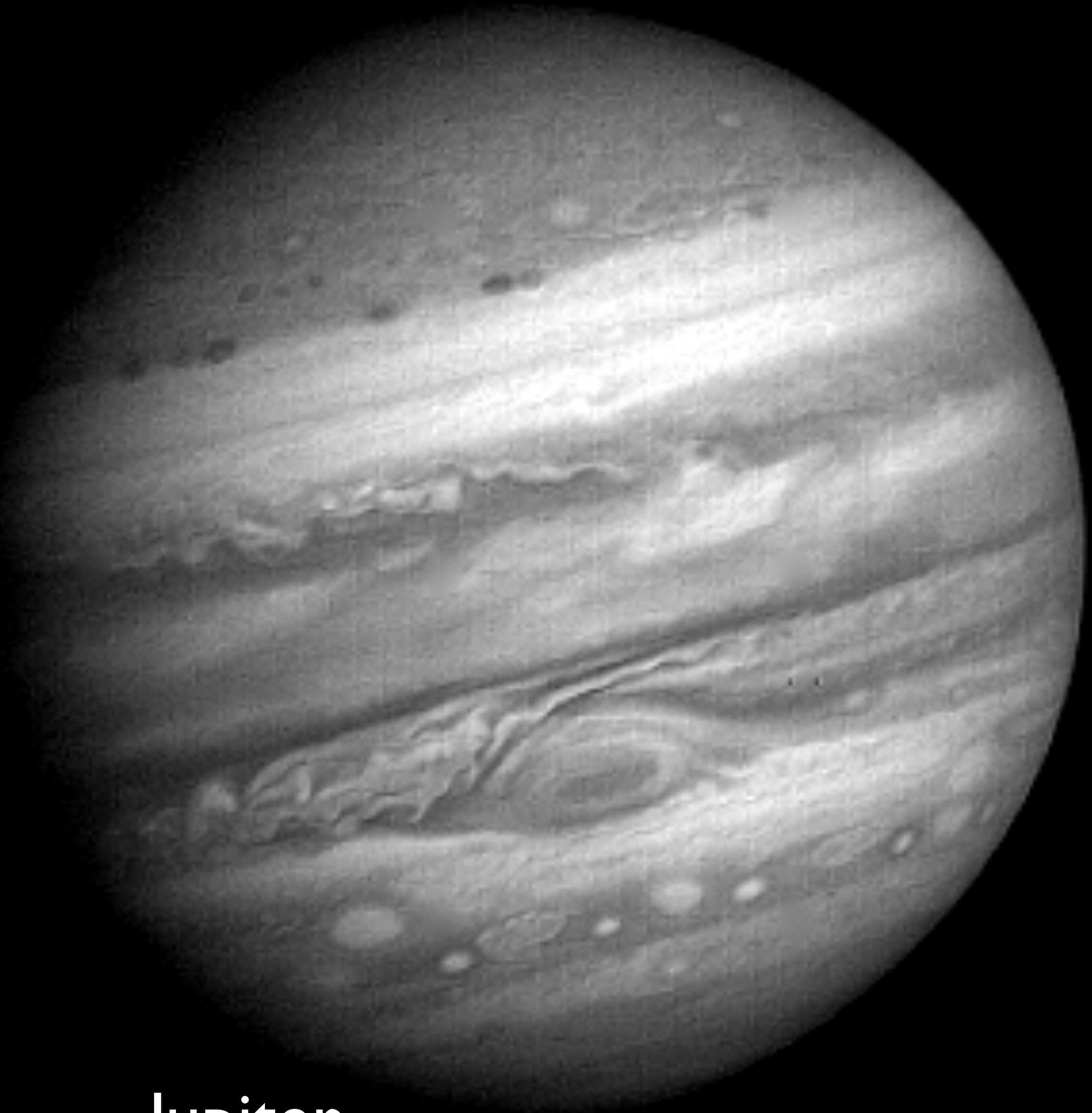
**Ναβίτ Κωνσταντίνου**

Σεμινάριο Τμήματος Φυσικής
16 Οκτωβρίου 2019

Δίας
*Hubble telescope*, NASA
(Αυγ 2019)

Κρόνος
*Hubble telescope*, NASA
(Σεπ 2019)

# jets coexist with vigorous turbulence

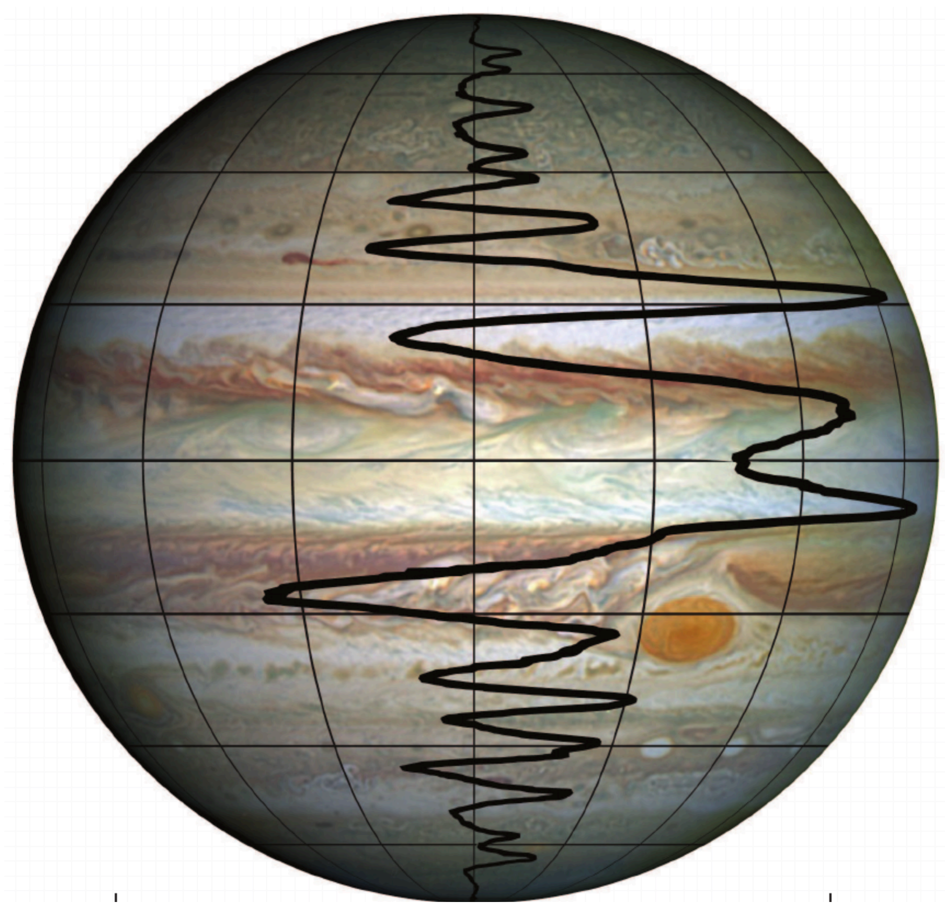


Jupiter
by *Voyager*
(1980)

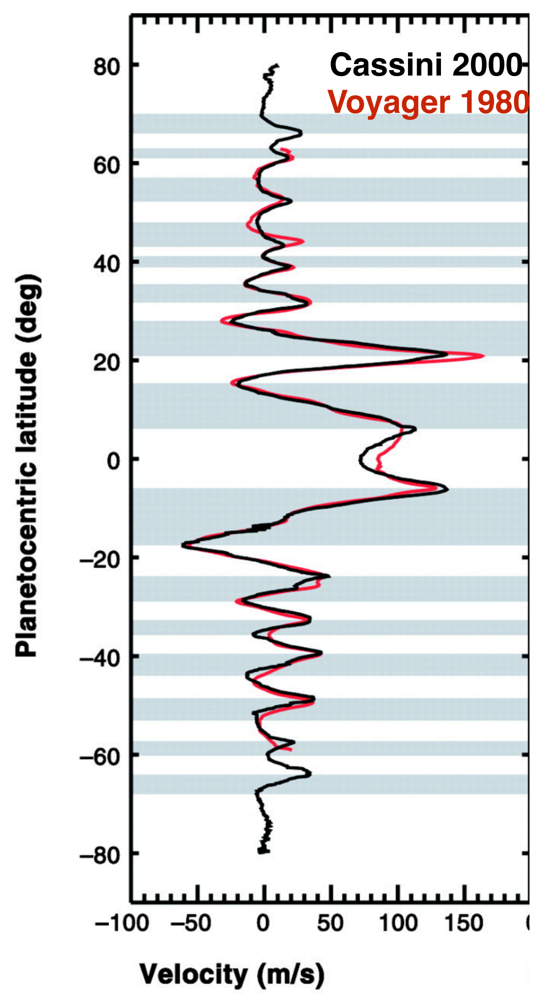
Jupiter
by *Juno*
(2015)

# jets appear to be "steady"

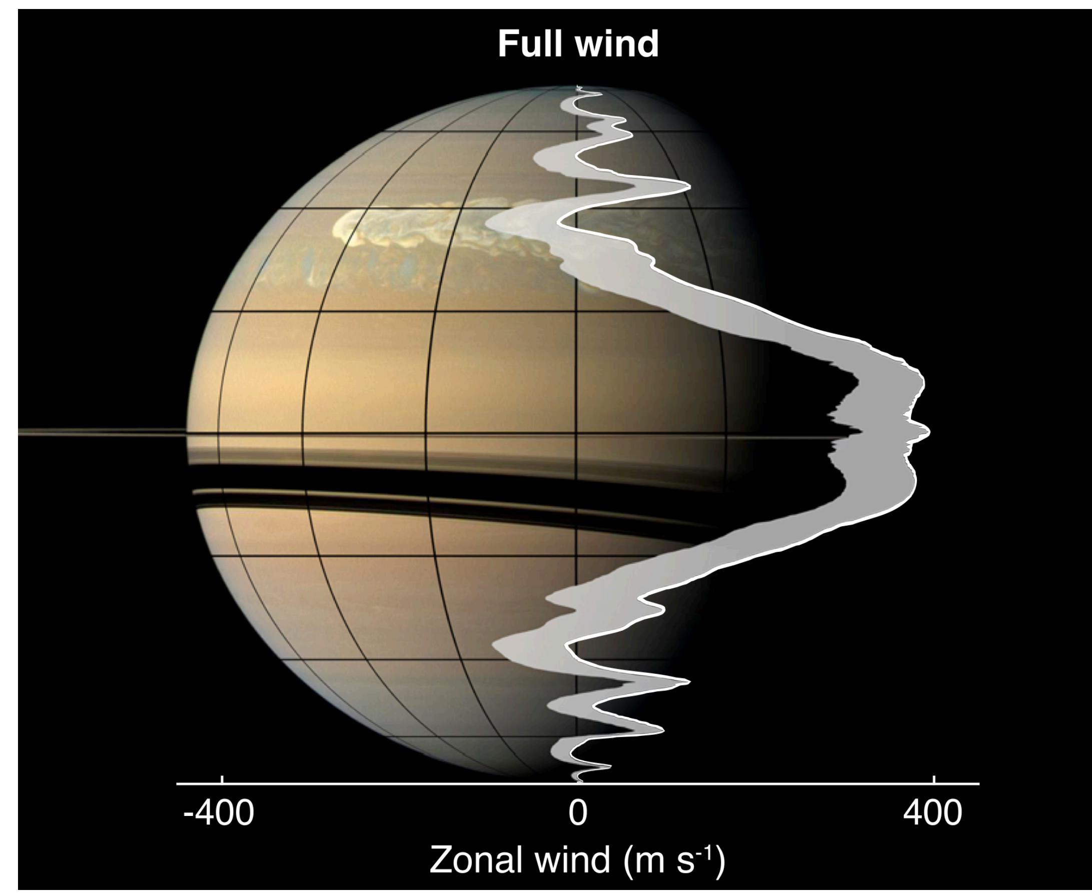
**Jupiter**



**Jovian winds**




**Saturn**



# towards a theory for understanding outer-atmosphere jets

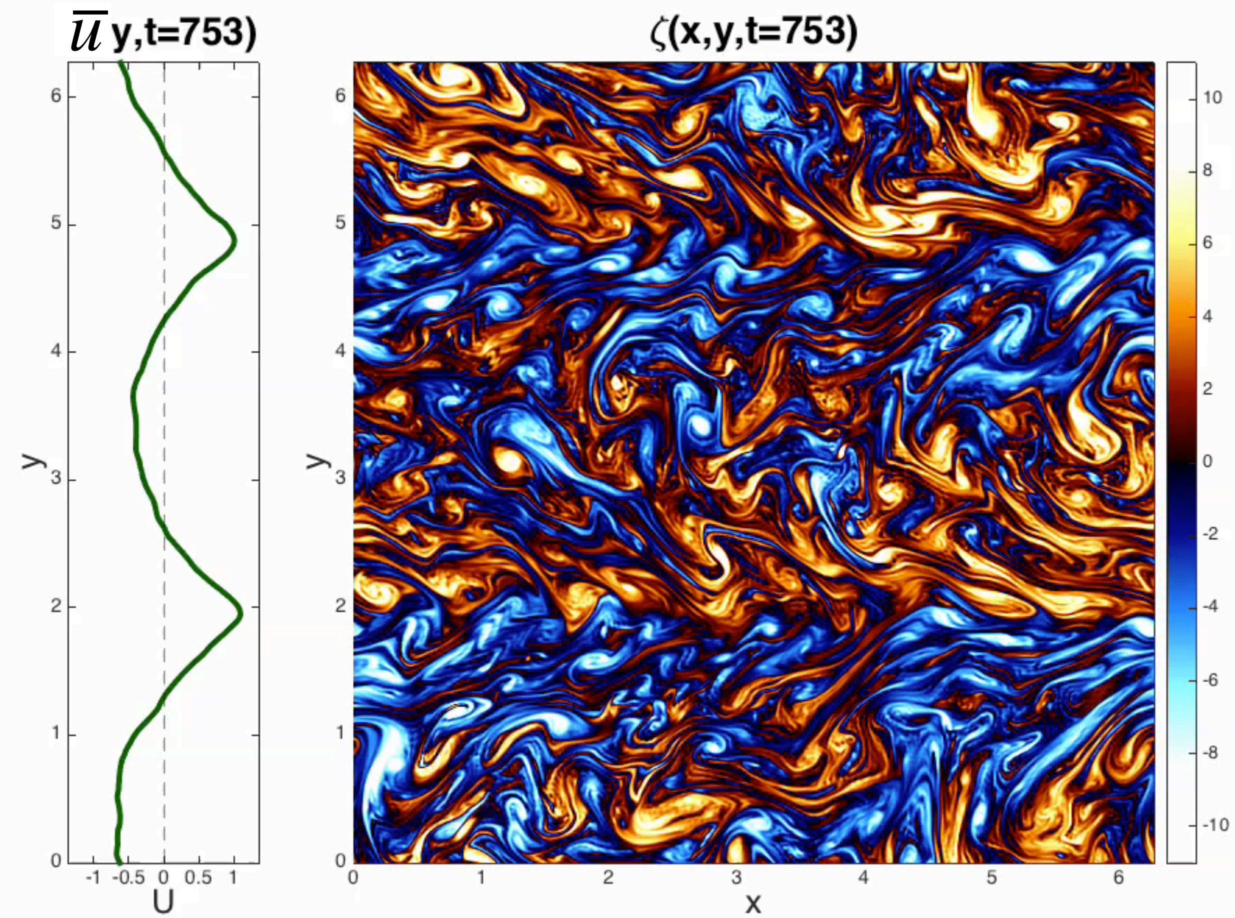

$$\boldsymbol{u} = \big(u(\boldsymbol{x},t)\,,v(\boldsymbol{x},t)\big)$$

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

jets — eddies (=turbulence)

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

zonal mean u — vorticity $\zeta = \partial_x v - \partial_y u$

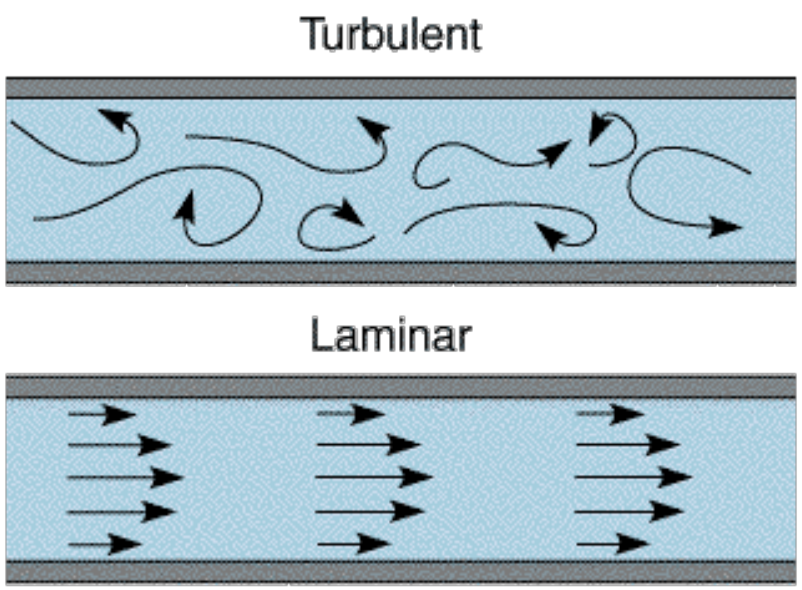



small-scale motions
self-organise
to large-scale coherent jets

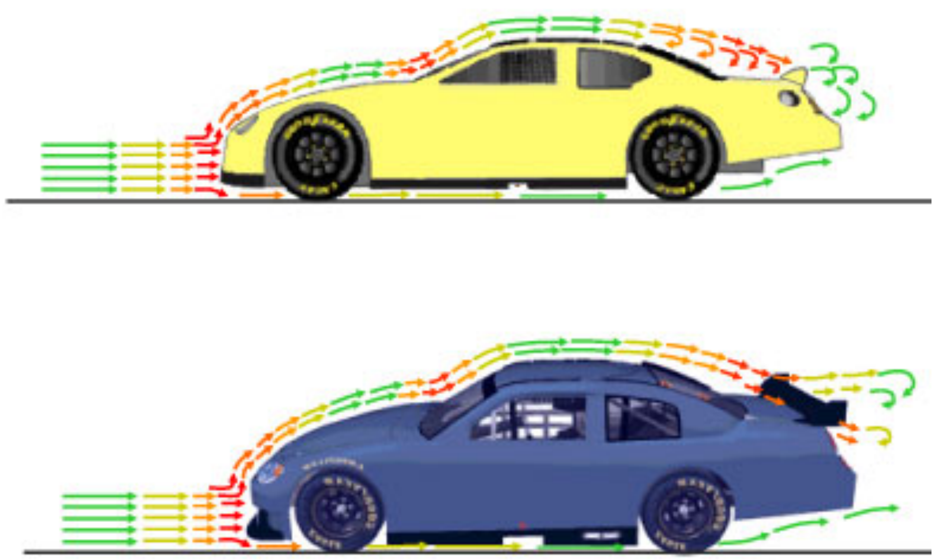
How are the zonal jets fueled?

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

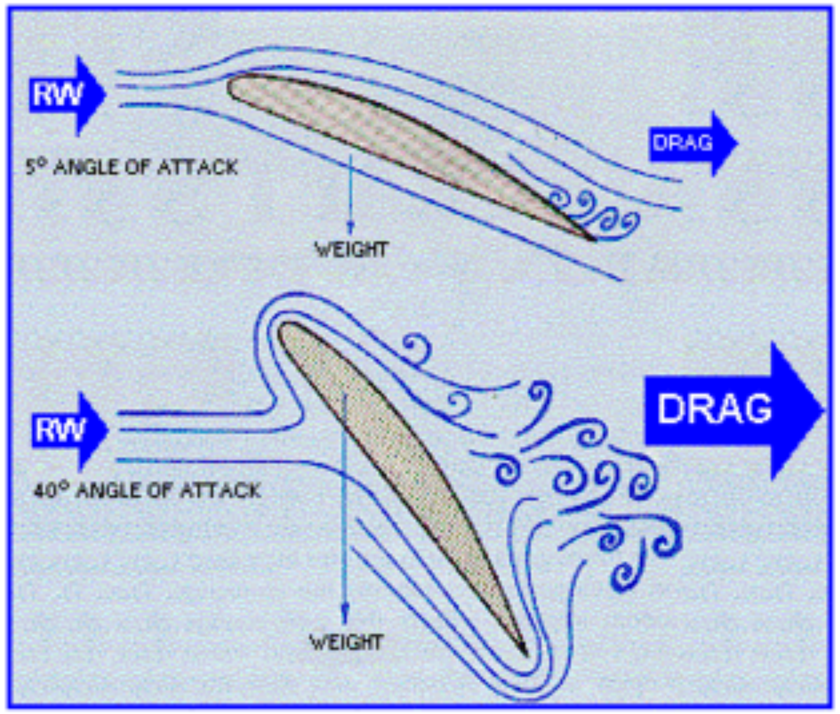
# turbulence usually acts as drag




wall-bounded
flow



airflow over
vehicle




airflow over airfoil

Can turbulence act to ***reinforce*** flows?

# towards a theory for understanding outer-atmosphere jets


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

$$\rho\left(\frac{\partial \boldsymbol{u}}{\partial t} + \boldsymbol{u}\cdot\nabla\boldsymbol{u}\right) = -\nabla\phi \;-\; 2\rho\boldsymbol{\Omega}\times\boldsymbol{u} \;+\; \nu\,\rho\,\nabla^2\boldsymbol{u} \;+\; \boldsymbol{\xi}$$

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

mass × acceleration = "forces"

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

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

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

jets — eddies (=turbulence)

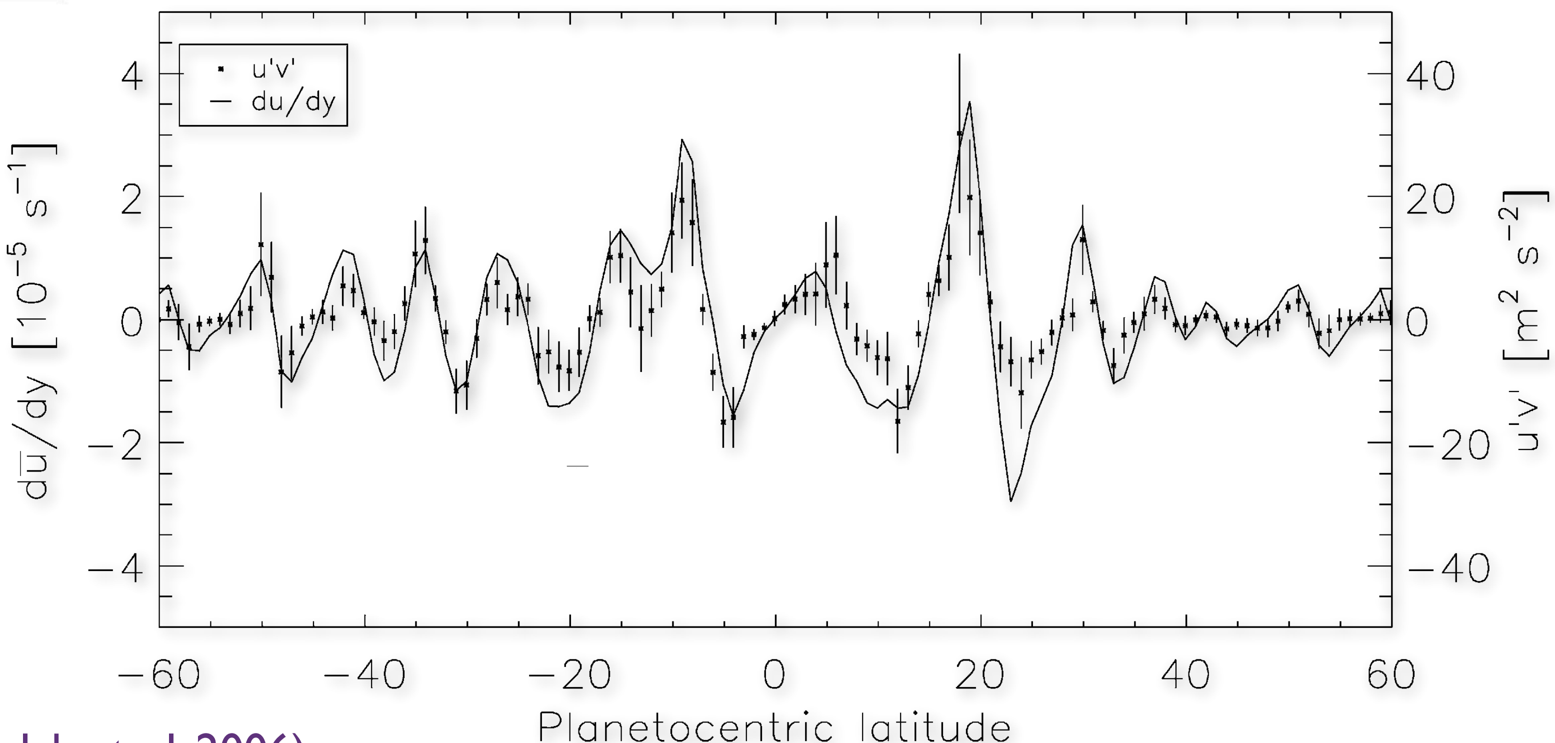
after some fiddling:

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

Reynolds stresses — viscosity

(divergence of energy-momentum tensor)

# jets are eddy-driven


(Salyk et. al. 2006)

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

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

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

anti-diffusion

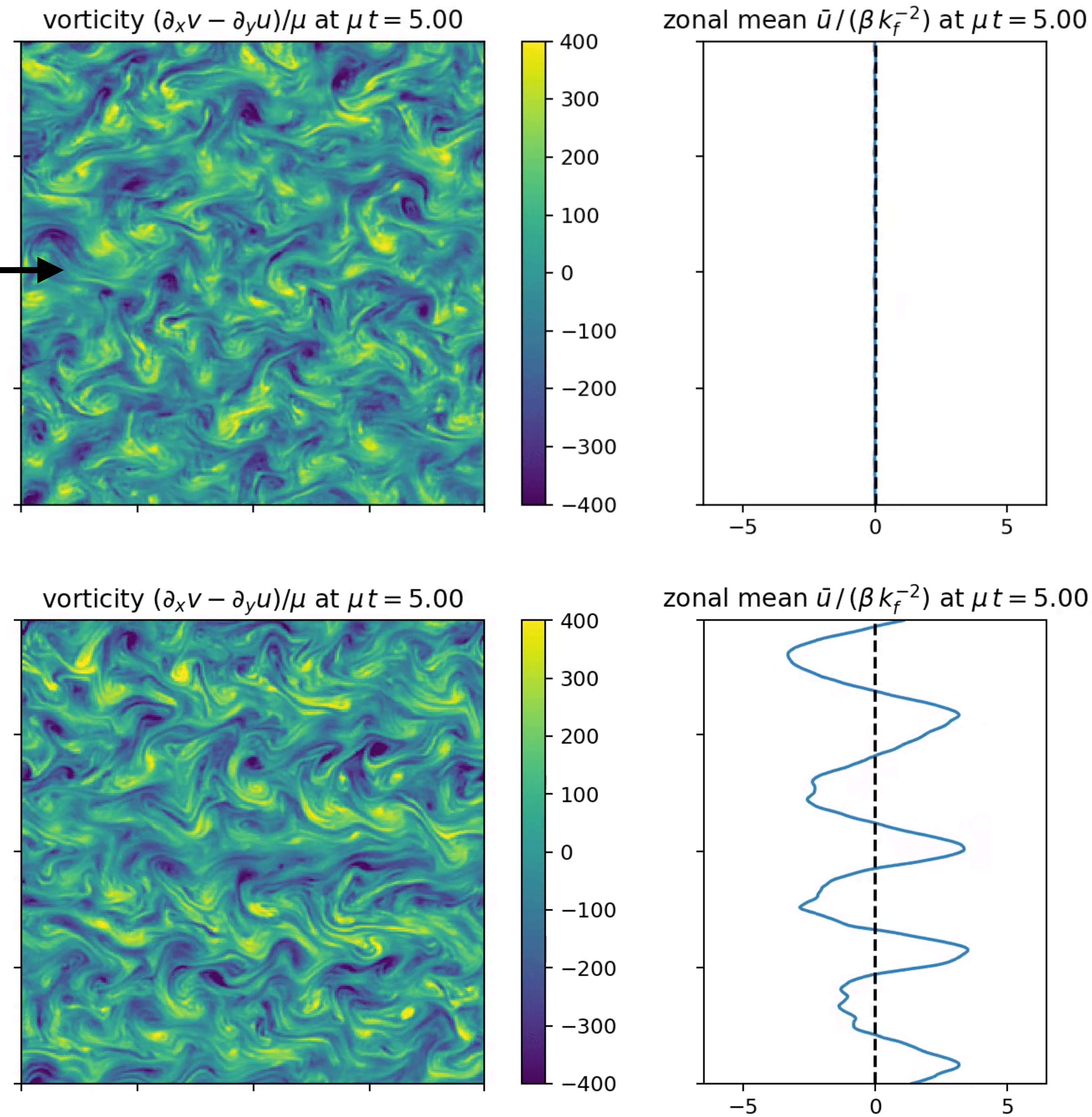
(or negative viscosity)

# 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

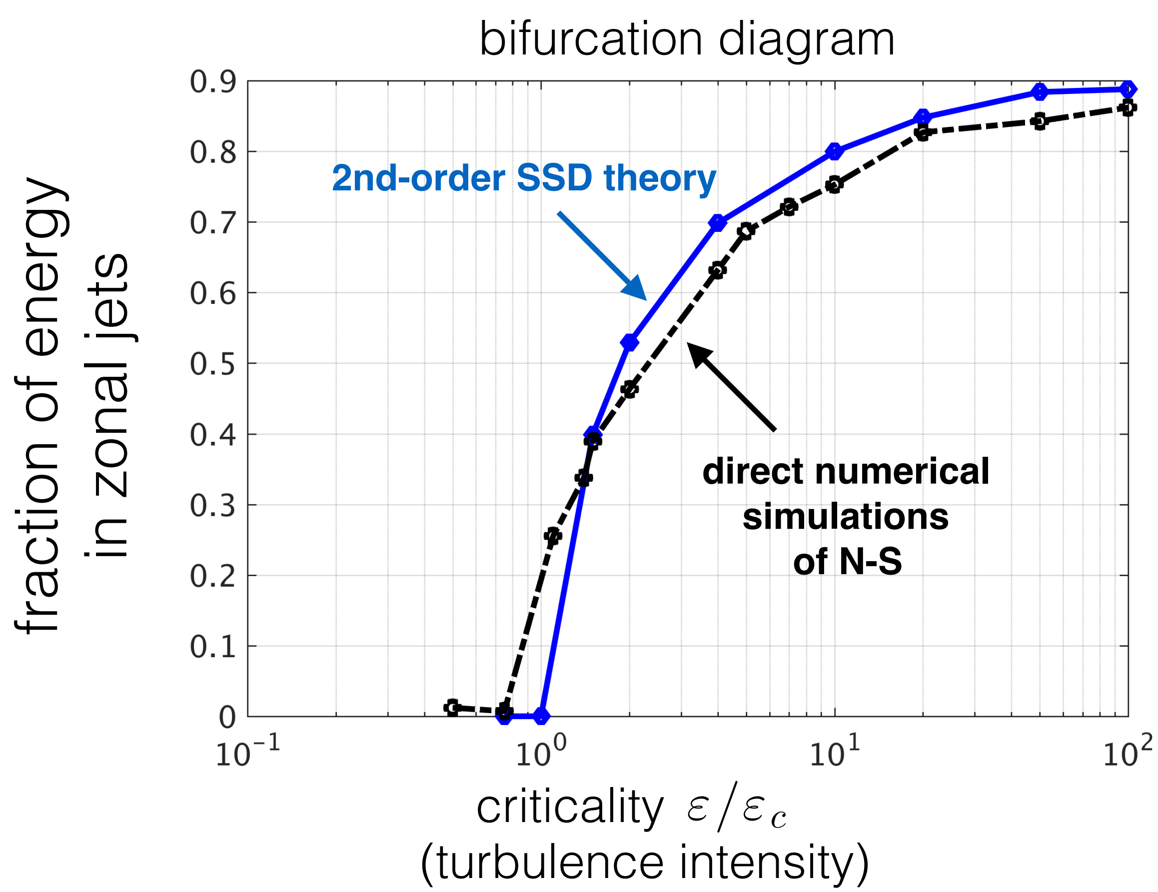
$\overline{\boldsymbol{u}(\boldsymbol{x},t)}\ ,\ \ \overline{\boldsymbol{u}'(\boldsymbol{x}_1,t)\boldsymbol{u}'(\boldsymbol{x}_2,t)},\ \ldots$

**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 $\varepsilon_c$ 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?

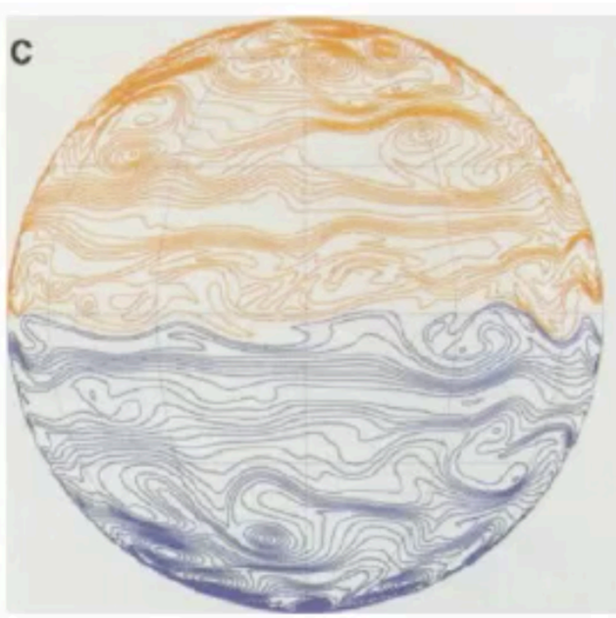
outstanding question
rooted deep in debate among various theories

*shallow-jet theories*

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

*deep-jet theories*

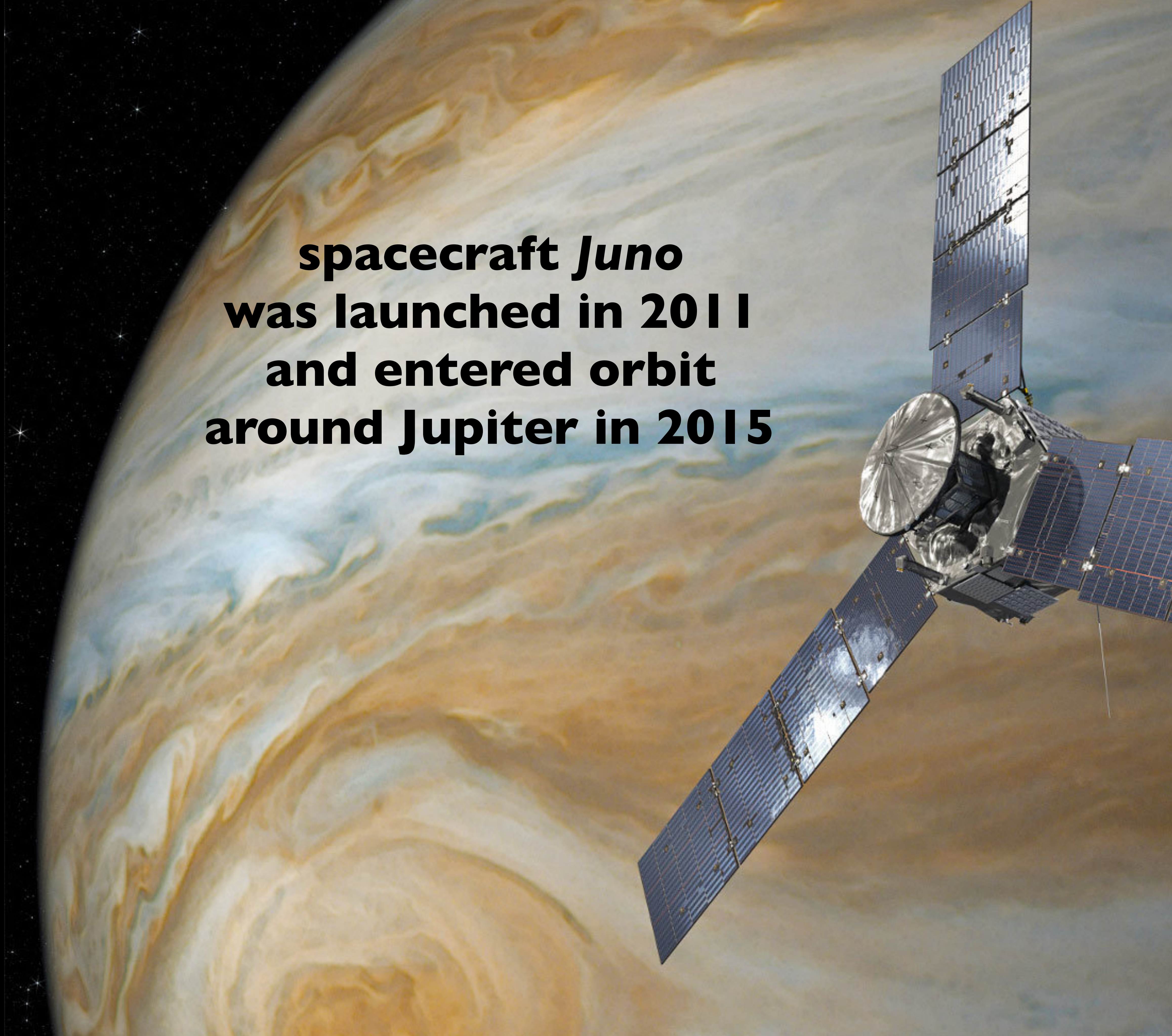
jets reach the centre of the planet
"Taylor columns"




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

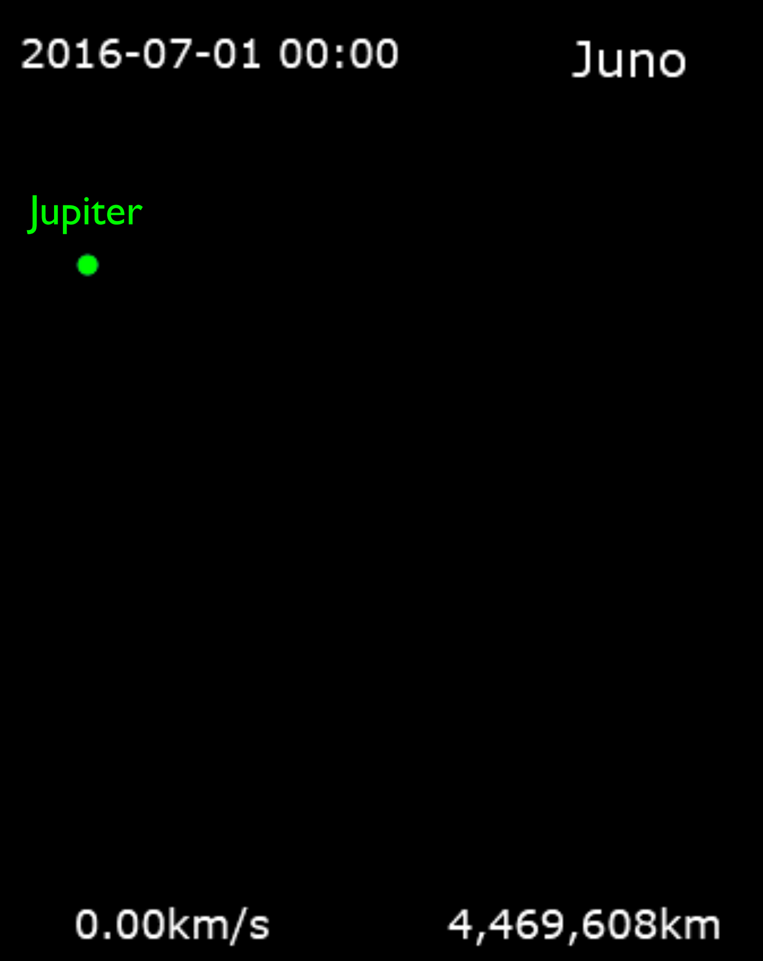
**Shallow or deep?**

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

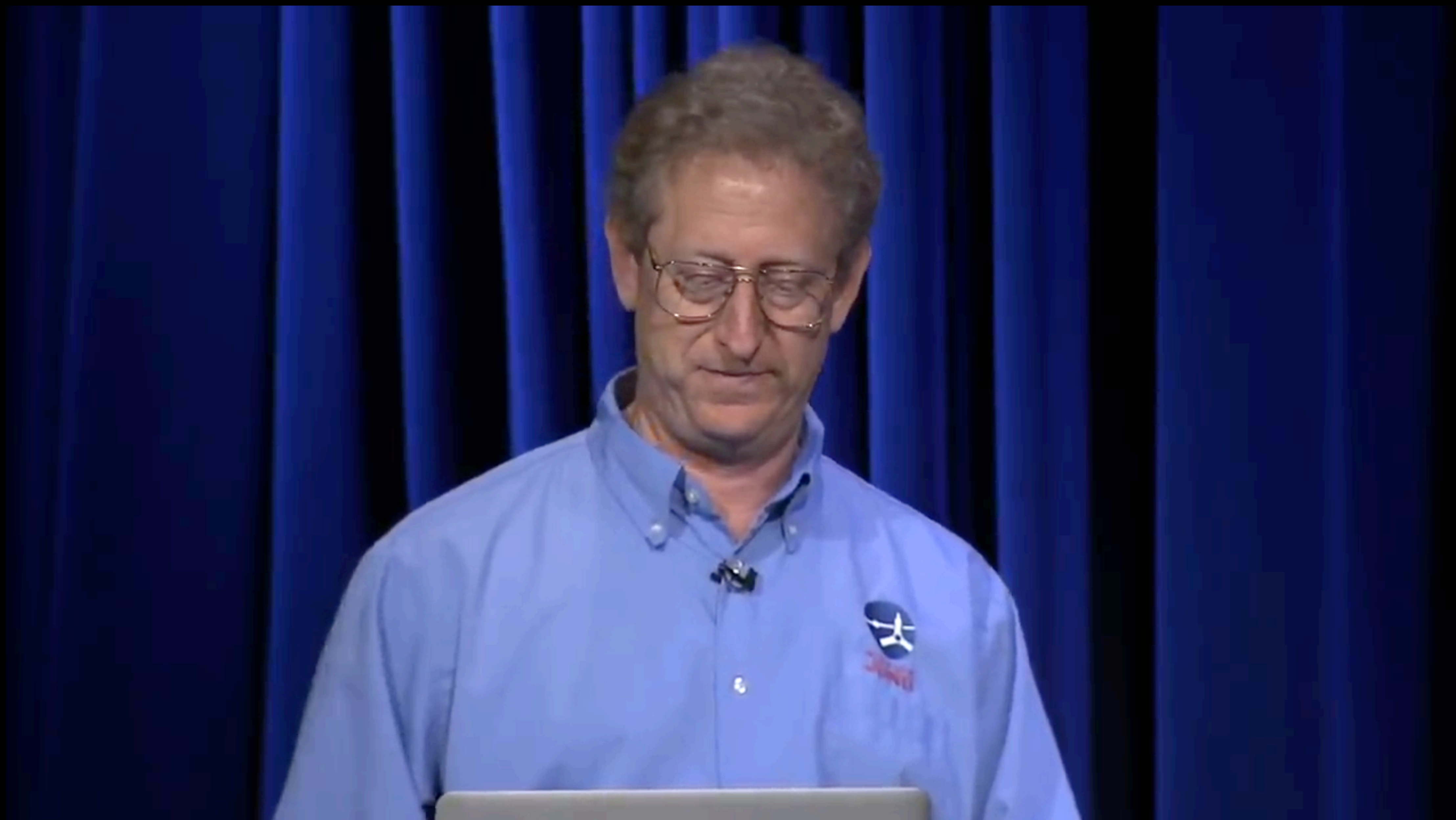
Jupiter's background radiation is ***EXTREME!***
(around $5 \times 10^{7}$ times stronger of that here on Earth)

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?

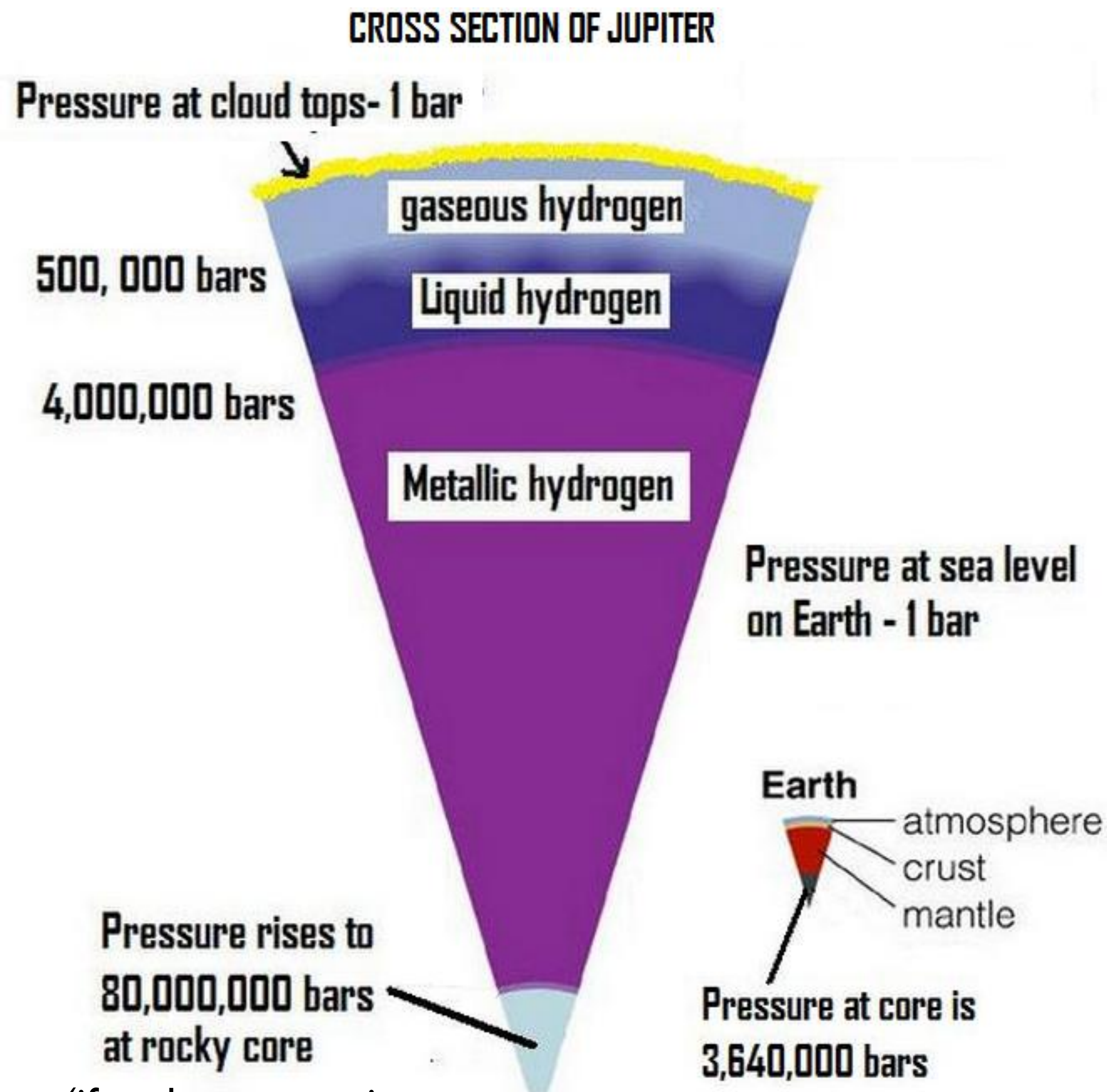
[Excerpt from NASA Jet Propulsion Laboratory public announcement, May 2018]



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**

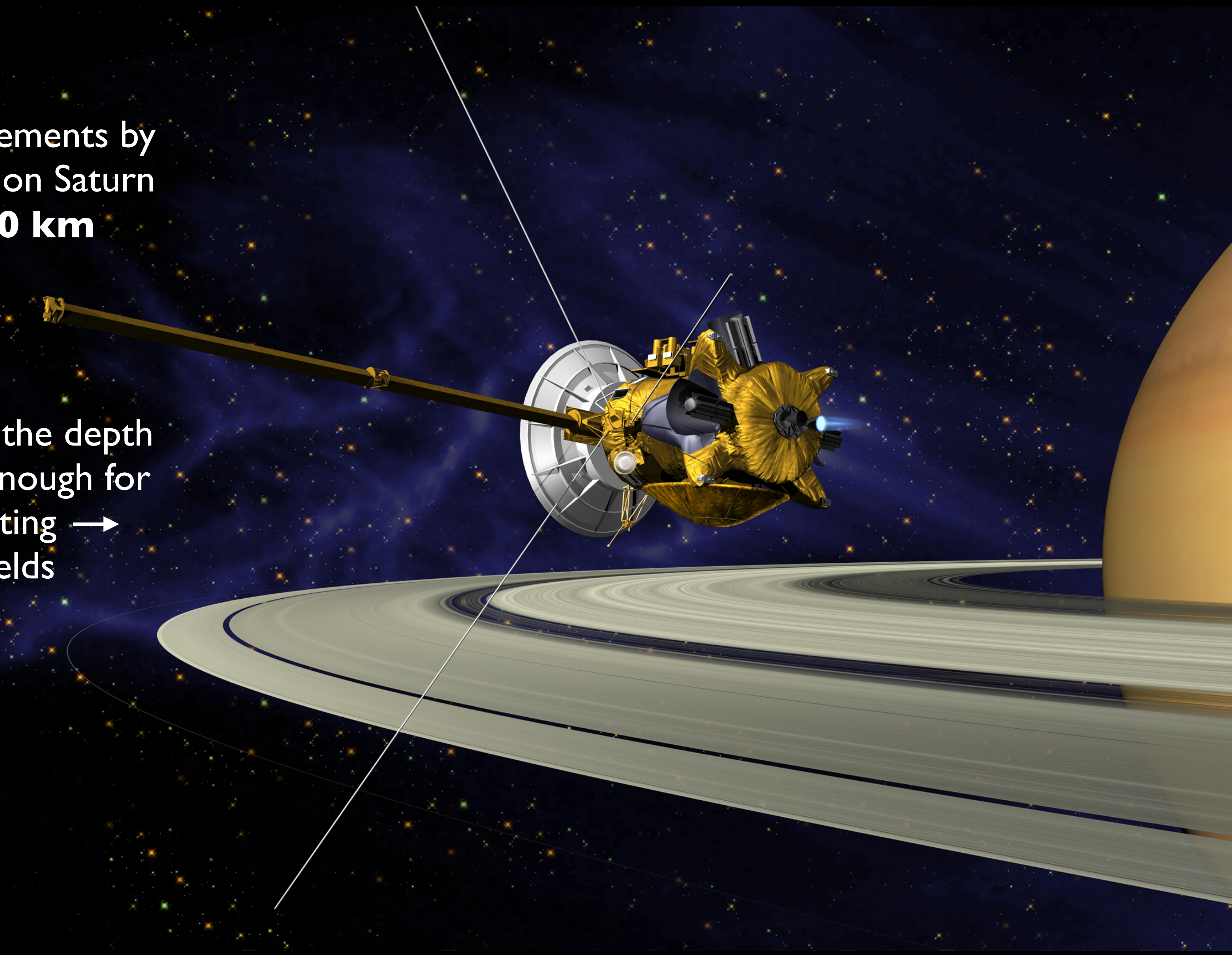
conducting moving fluid ⟶ ⟶ currents ⟶ magnetic fields

# 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 $\rho\frac{\partial \boldsymbol{u}}{\partial t} + \ldots = \boldsymbol{J} \times \boldsymbol{B} + \ldots$ $\frac{\partial \boldsymbol{B}}{\partial t} = \ldots$ $\boldsymbol{B} = \left(B_x, B_y\right)$

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:

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

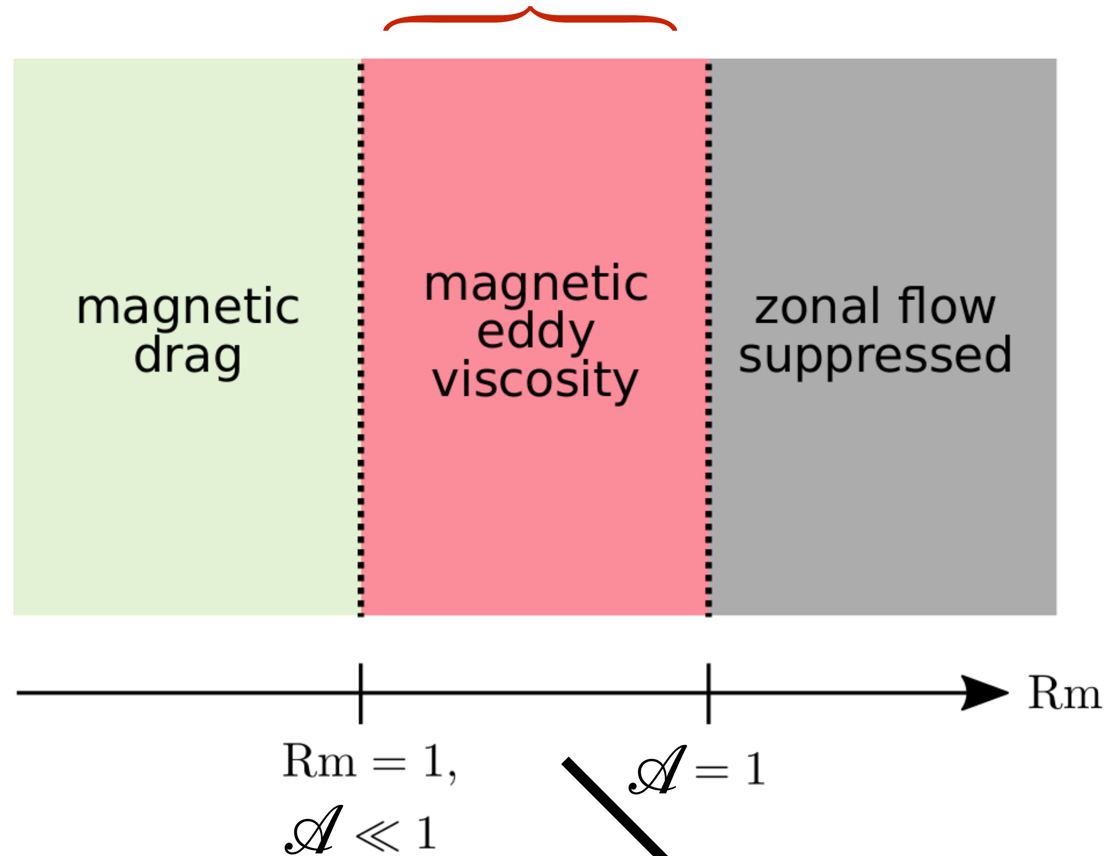
Maxwell stresses

Reynolds stresses

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

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

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




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

$\eta$ → magnetic diffusivity

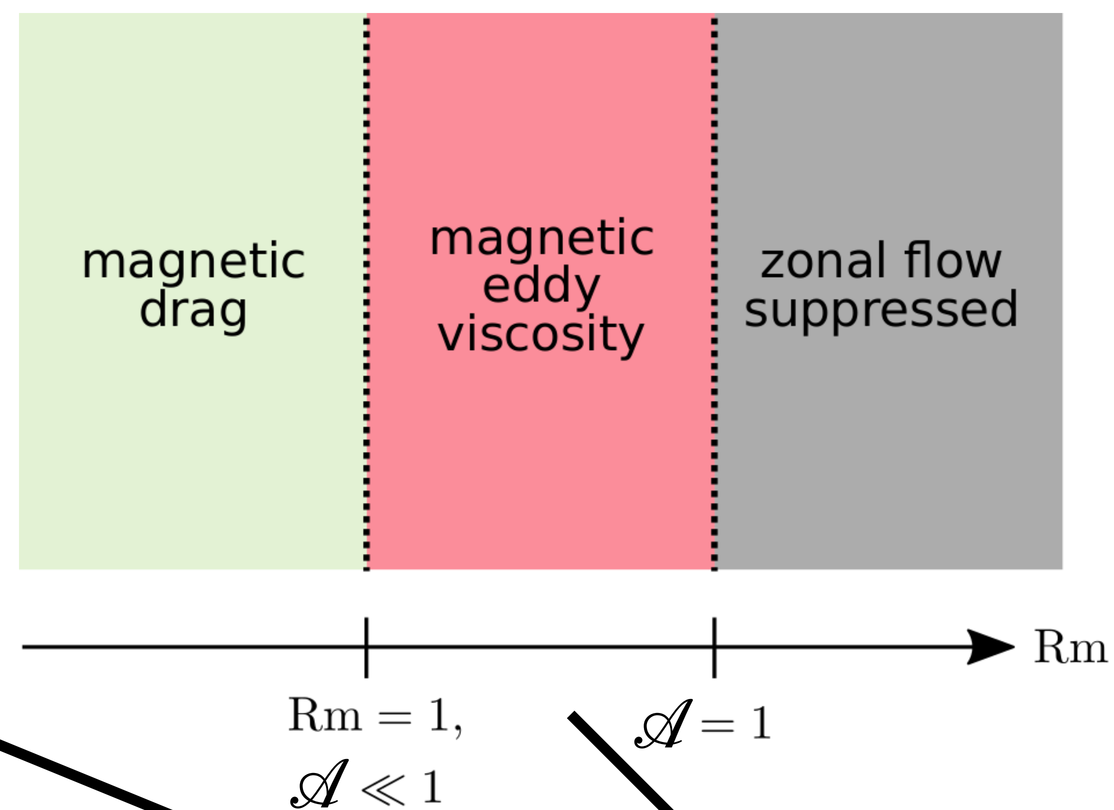
this is exactly the regime where zonal jets start being suppressed

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

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

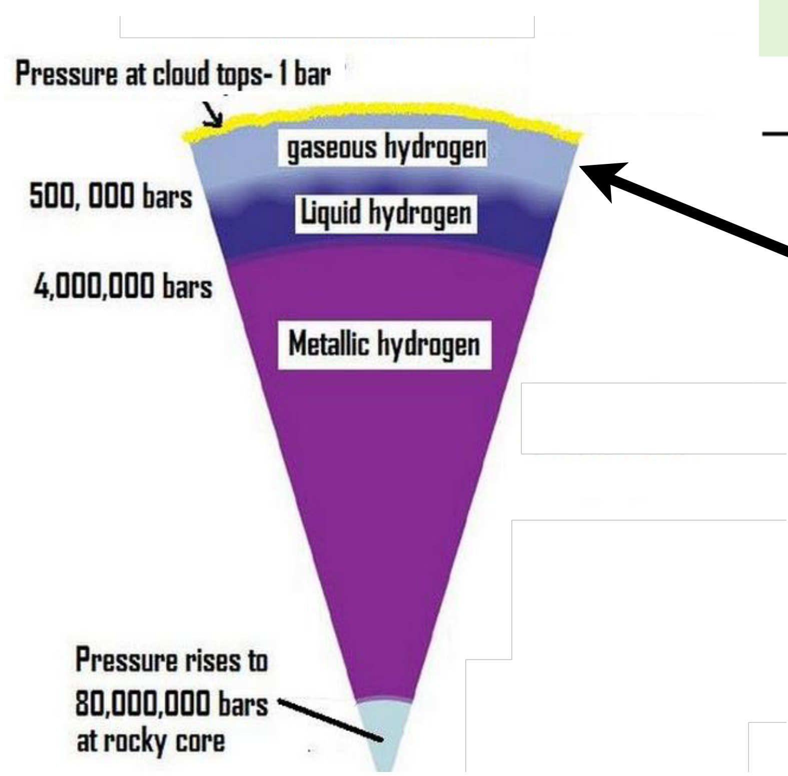
Collective effect of a mean shear flow to the magnetic fluctuations acts effectively to increase the fluid's viscosity

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




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

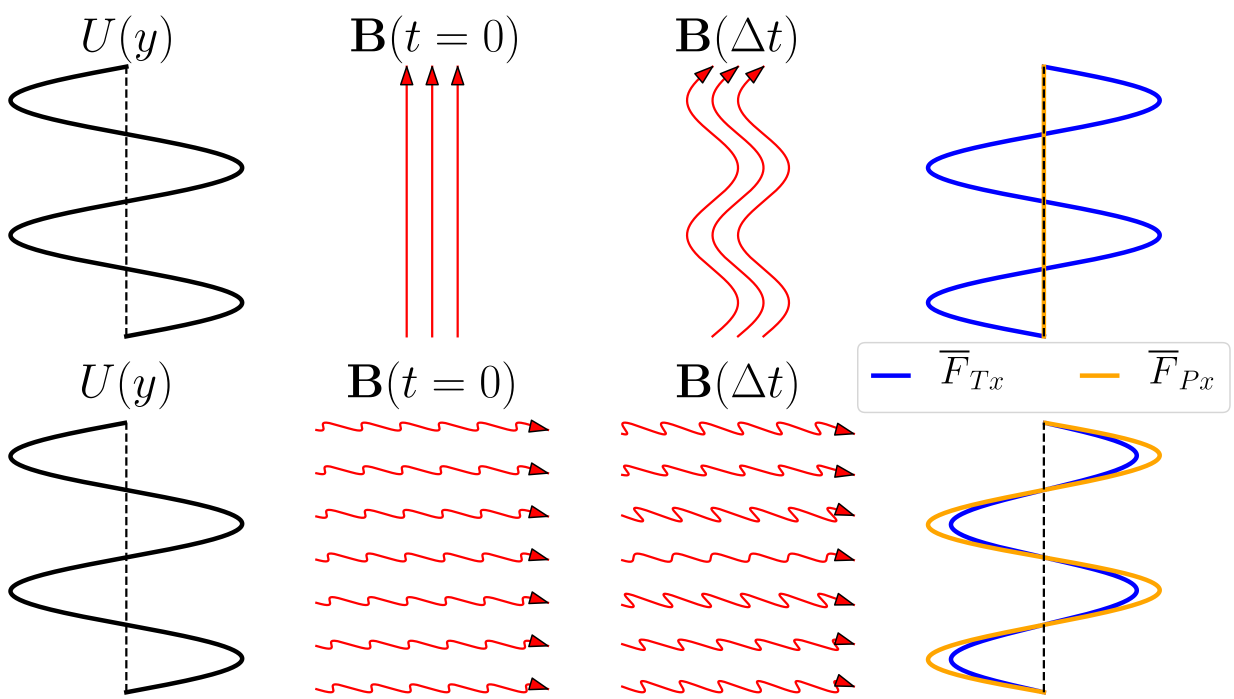
magnetic diffusivity




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




$$\boldsymbol{u}(t=0)\ \&\ U(y) \longrightarrow \Delta\overline{uv} \propto \Delta t\, \overline{v^2}\, \partial_y U$$

$$\Longrightarrow -\partial_y \overline{uv} = \partial_y \Big[ \underbrace{-\gamma \Delta t\, \overline{v^2}}\, \partial_y U \Big]$$

**negative turbulent viscosity**

$$\boldsymbol{B}(t=0)\ \&\ U(y) \longrightarrow \Delta\overline{B_x B_y} \propto \overline{B_y}^2\, \partial_y U$$

$$\Longrightarrow \frac{1}{\mu_0}\partial_y \overline{B_x B_y} = \partial_y \Big[ \underbrace{\alpha \frac{1}{\mu_0} \Delta t\, \overline{B_y^2}}\, \partial_y U \Big]$$

**magnetic viscosity**

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

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

# Putting it all together

zonal flow equation:

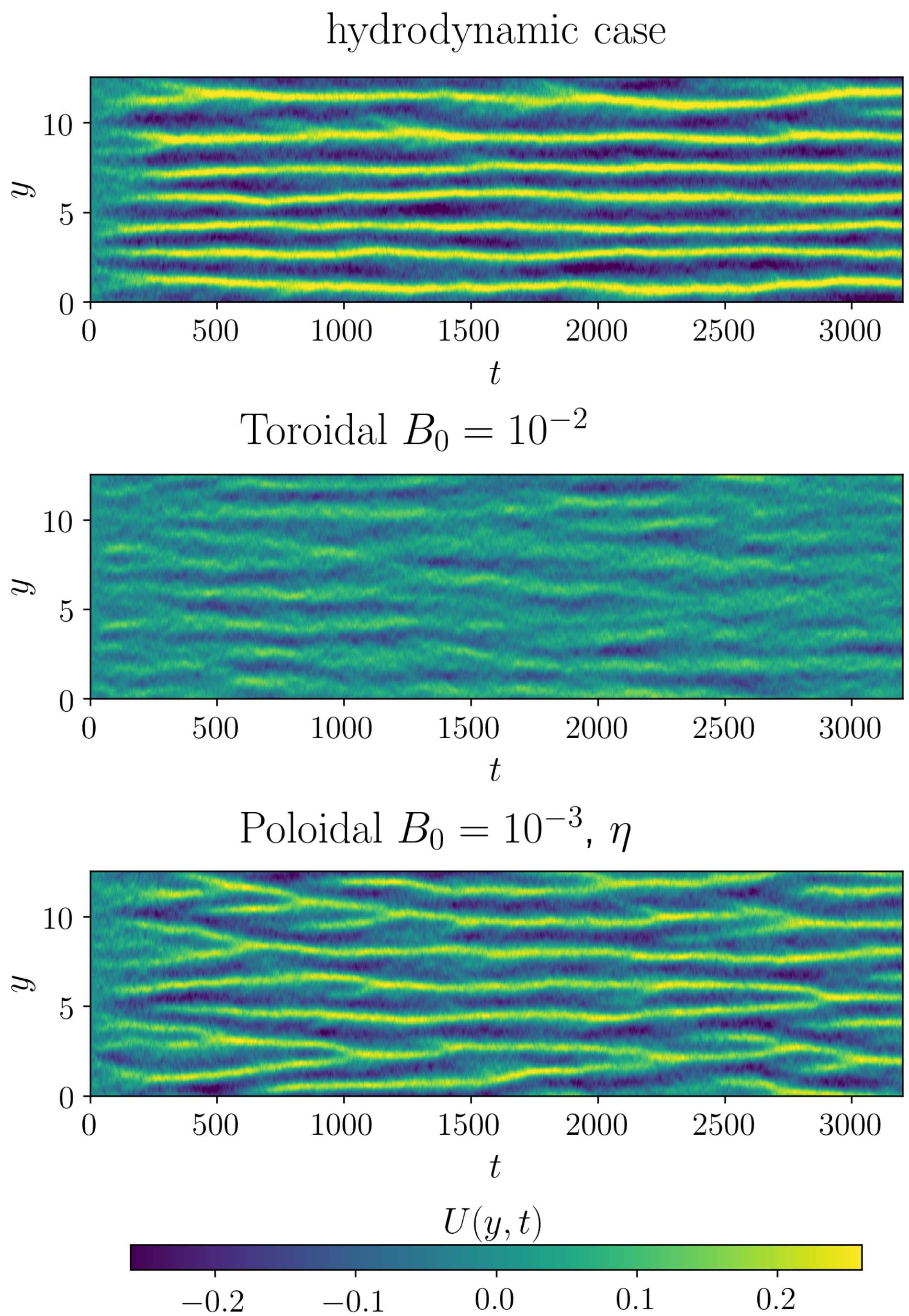
$$\frac{\partial \overline{\rho u}}{\partial t} = \frac{1}{\mu_0} \frac{\partial \overline{B_x' B_y'}}{\partial y} - \frac{\partial \overline{\rho u' v'}}{\partial y} + \dots$$

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

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

# We verify magnetic viscosity in 2D magnetohydrodynamic simulations

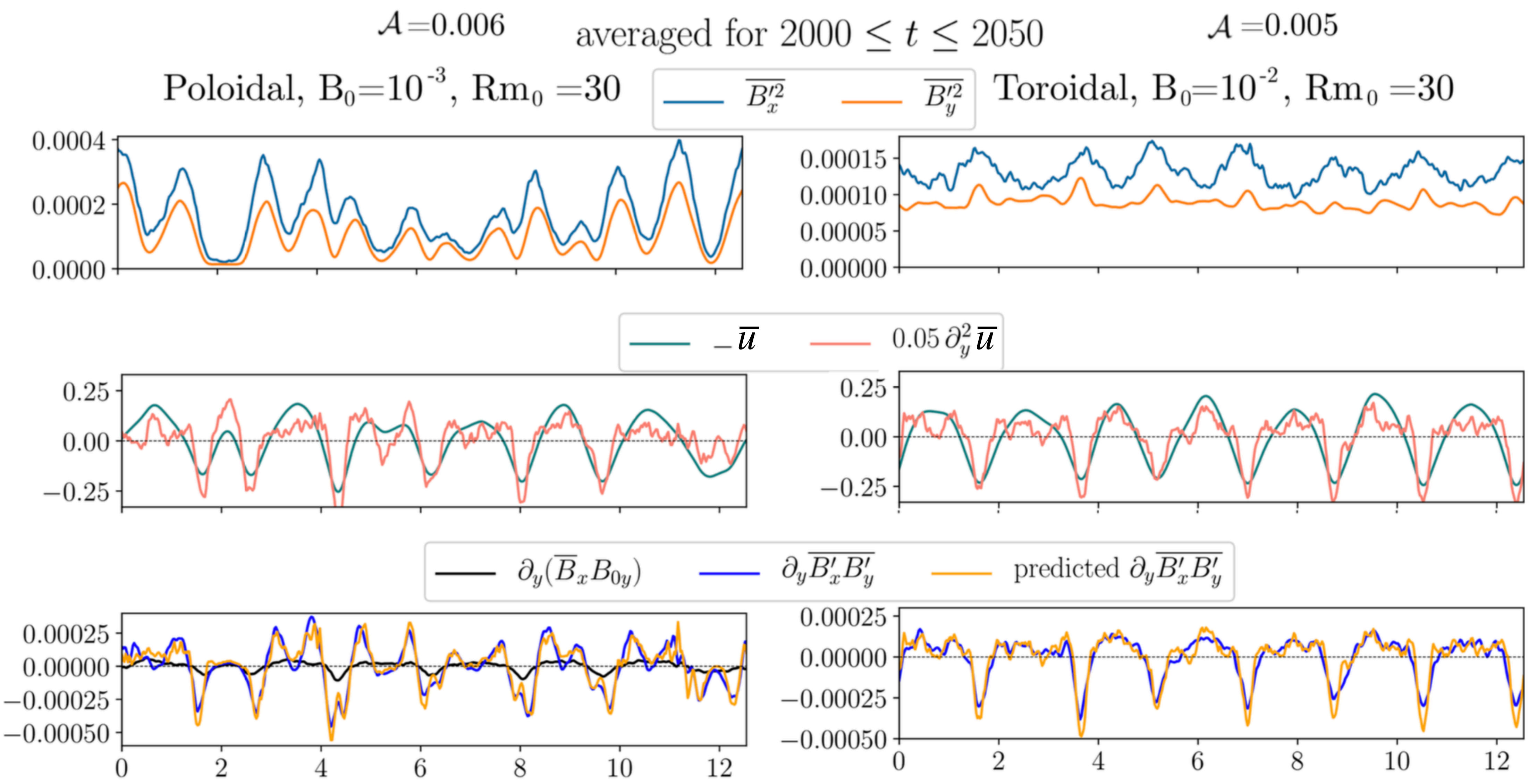
spacetime diagrams (Hovmollers) of zonal flow




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

# We verify magnetic viscosity in 2D magnetohydrodynamic simulations

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

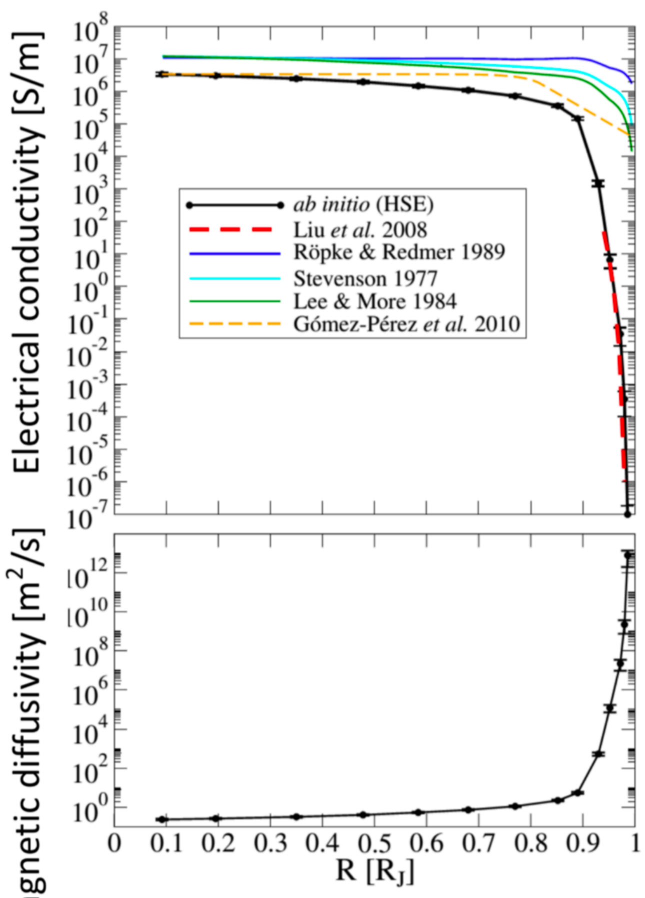



Parker & Constantinou, *Phys. Rev. Fluids*, 2019

# Ready for a leap of faith?

Use $$\frac{\partial \overline{\rho u}}{\partial t} = \frac{\partial}{\partial y}\left[\left(\alpha \frac{\overline{B_y^2}}{\mu_0} - \gamma \rho \overline{v^2}\right)\tau_{\mathrm{corr}} \frac{\partial \overline{u}}{\partial y}\right] + \ldots$$

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 $\eta$
- ➡ Use current internal structure models for each gas giant to compute the depth that corresponds to the $\eta_{\mathrm{crit}}$ value

We get: Jupiter 3500 km Saturn 8000 km

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

*σύμπτωση;*

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

# take home messages

Identified an MHD regime (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 provides a plausible explanation for the depth-extent of the zonal jets in Jupiter and Saturn

*ευχαριστώ*

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