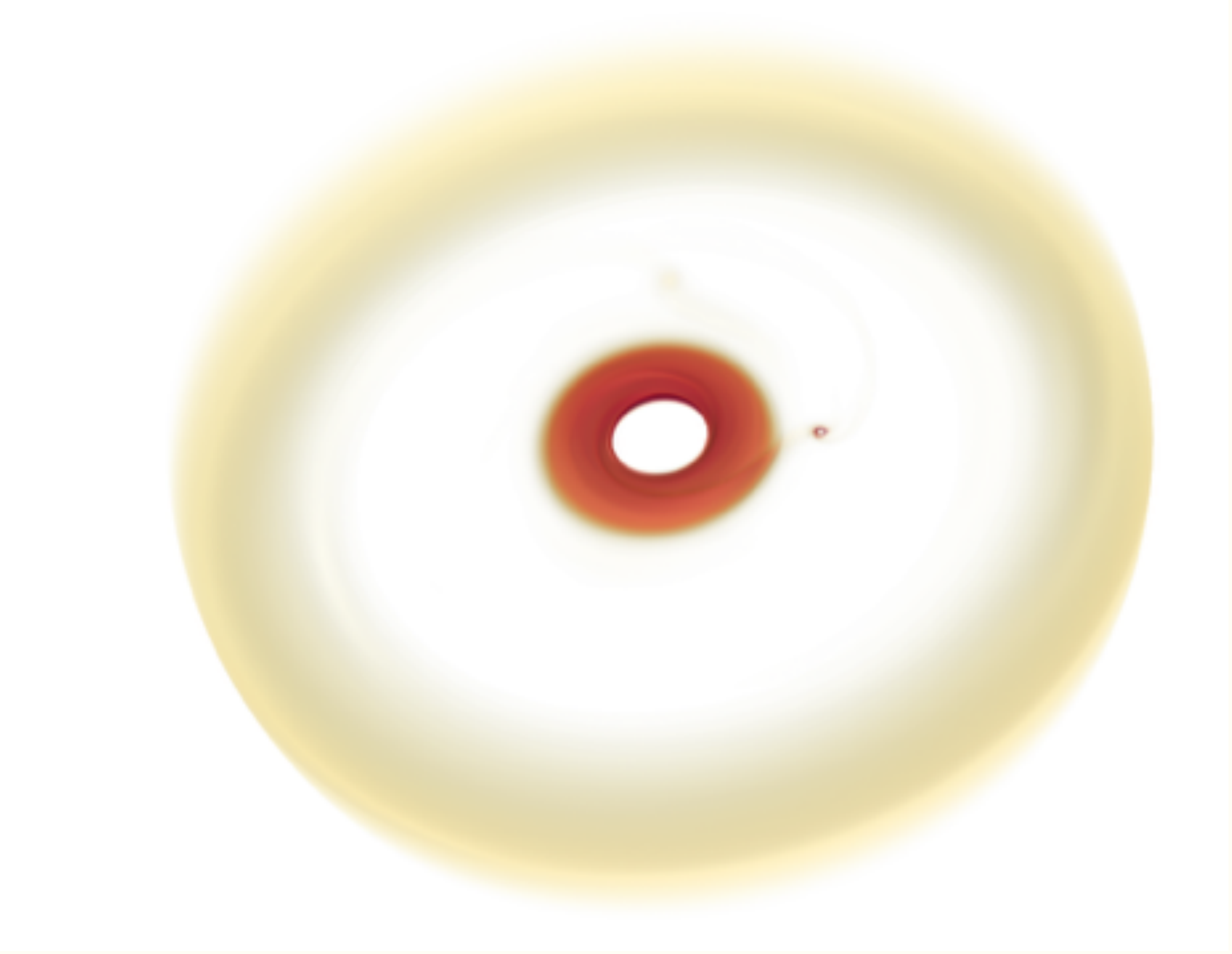
Young Planets in Protoplanetary Disks: Theory Confronts Observations

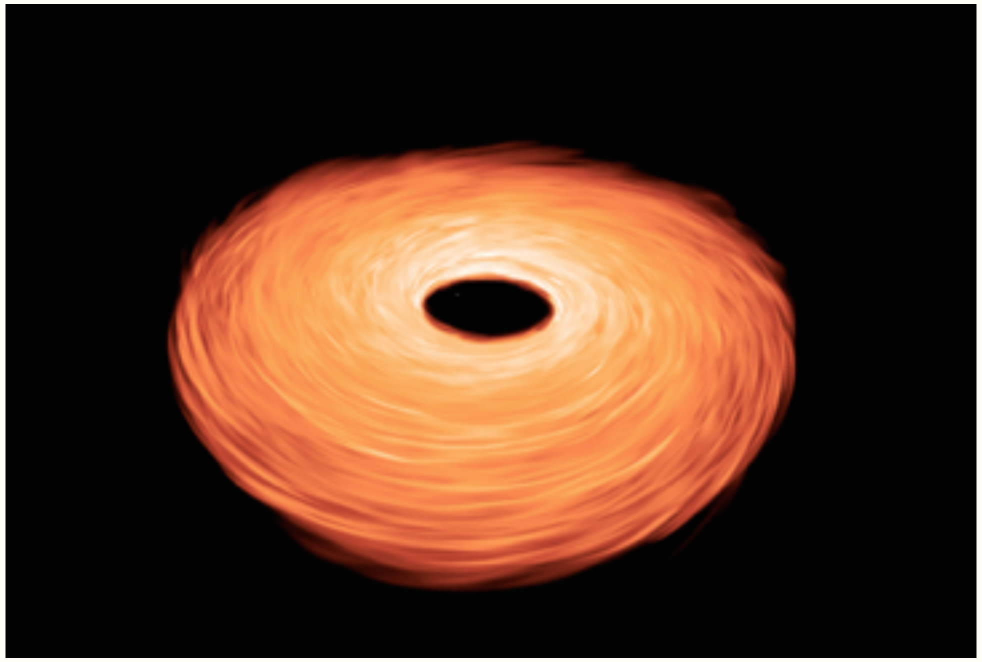
Zhaohuan Zhu
University of Nevada, Las Vegas

Collaborators: Jim Stone, Wenhua Ju (Princeton), Ruobing Dong (Arizona)



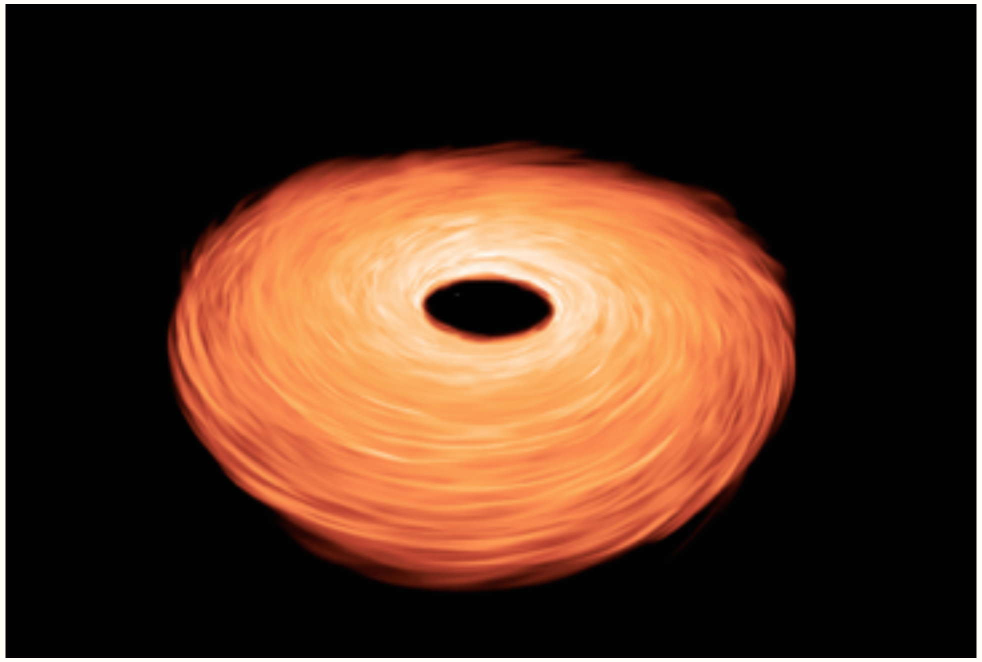
Disks, Dynamos, and Data: Confronting MHD Accretion Theory with Observations, KITP, Feb 7, 2017

Accretion process: complicated



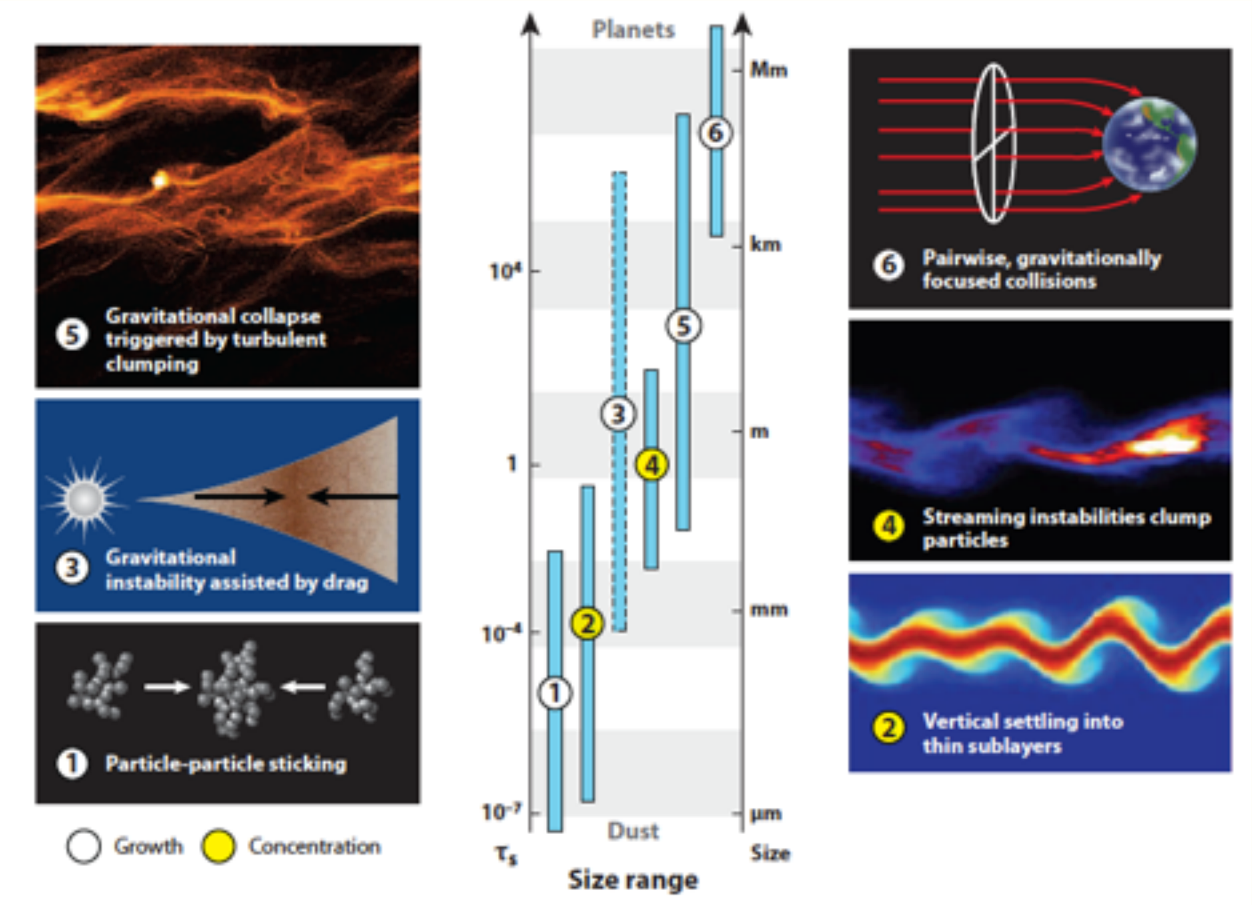
Flock

Accretion process: complicated



Flock

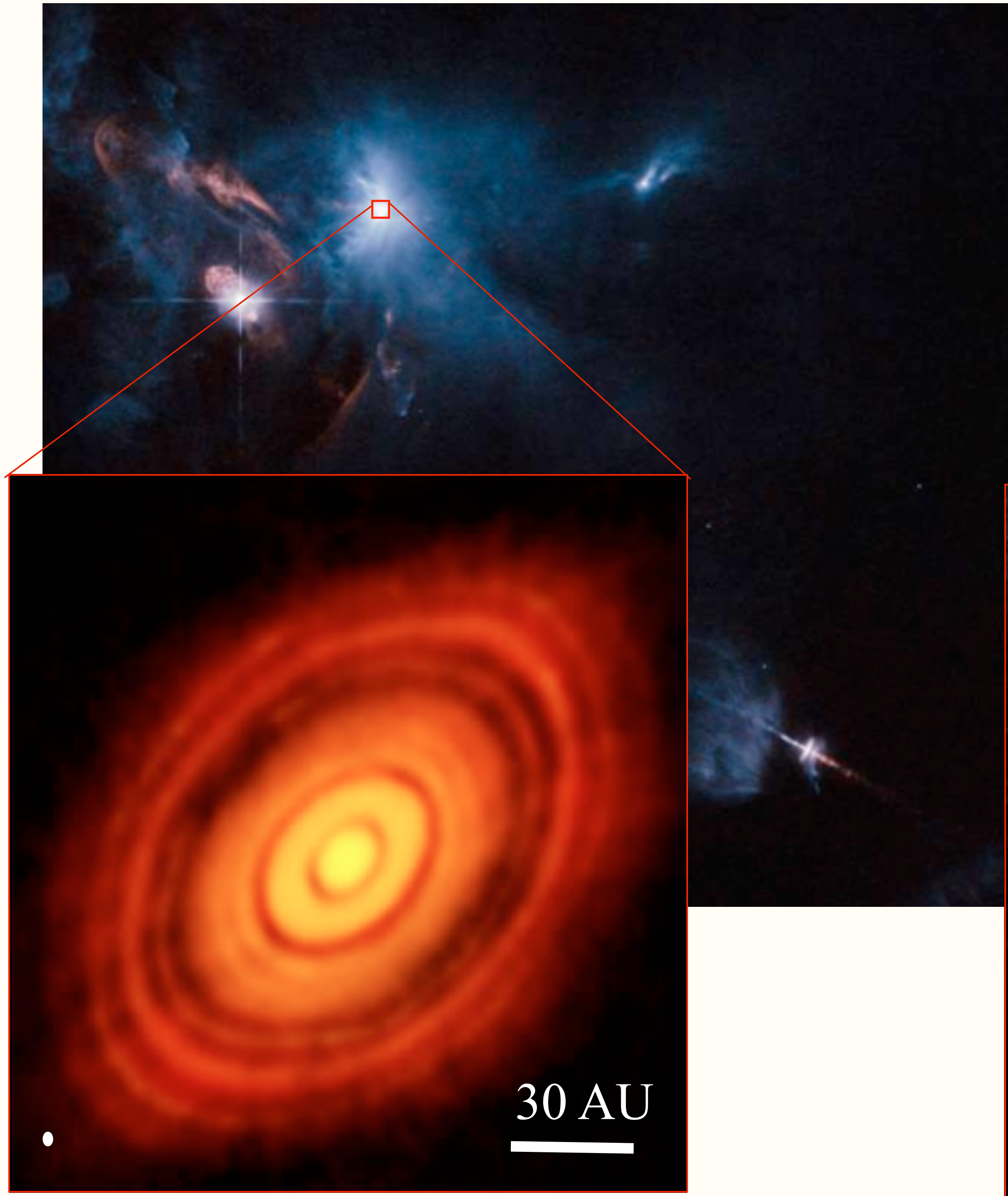
Planet formation: even more complicated



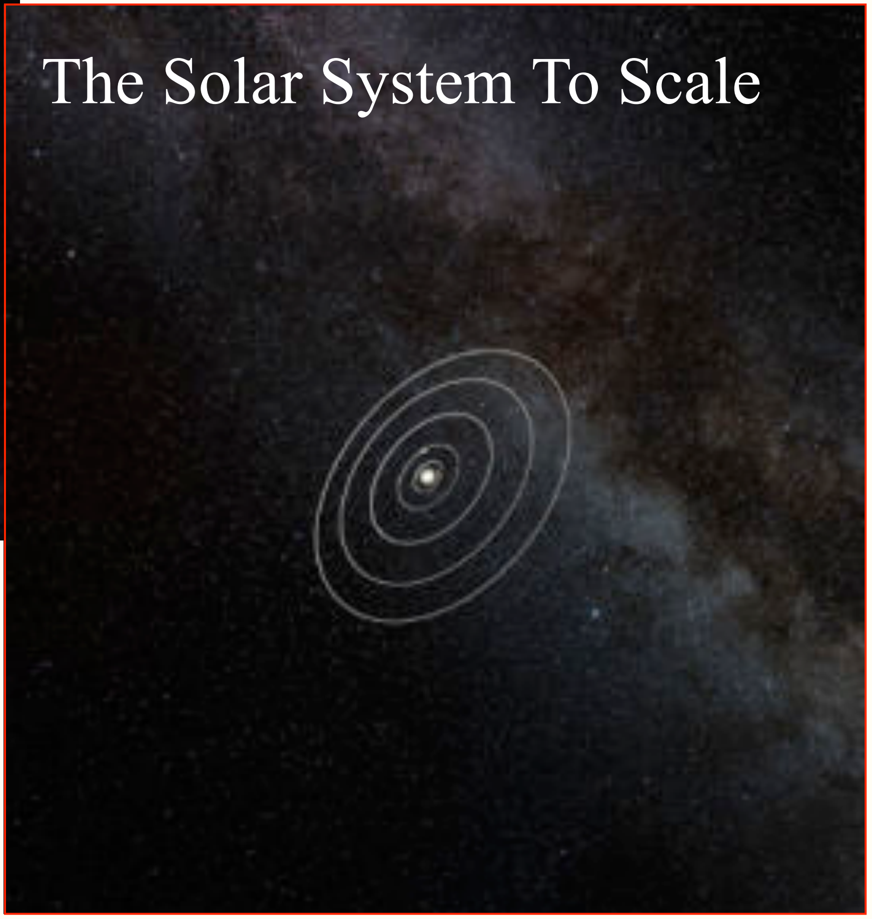
Chiang & Youdin (2010)

Need Observational Constraints

ALMA (0.03”): Planet Construction Zone

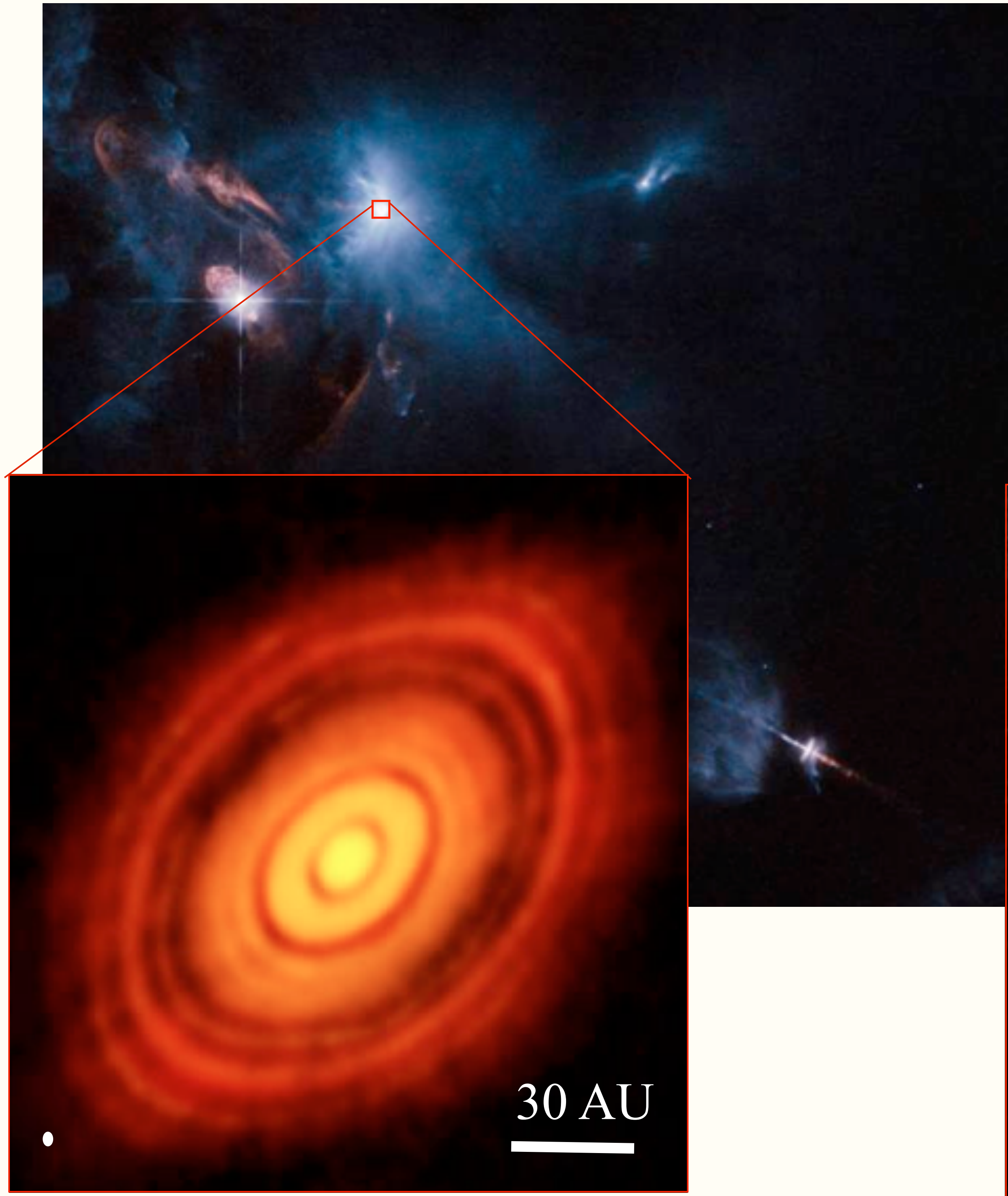


ALMA Partnership+ 2015

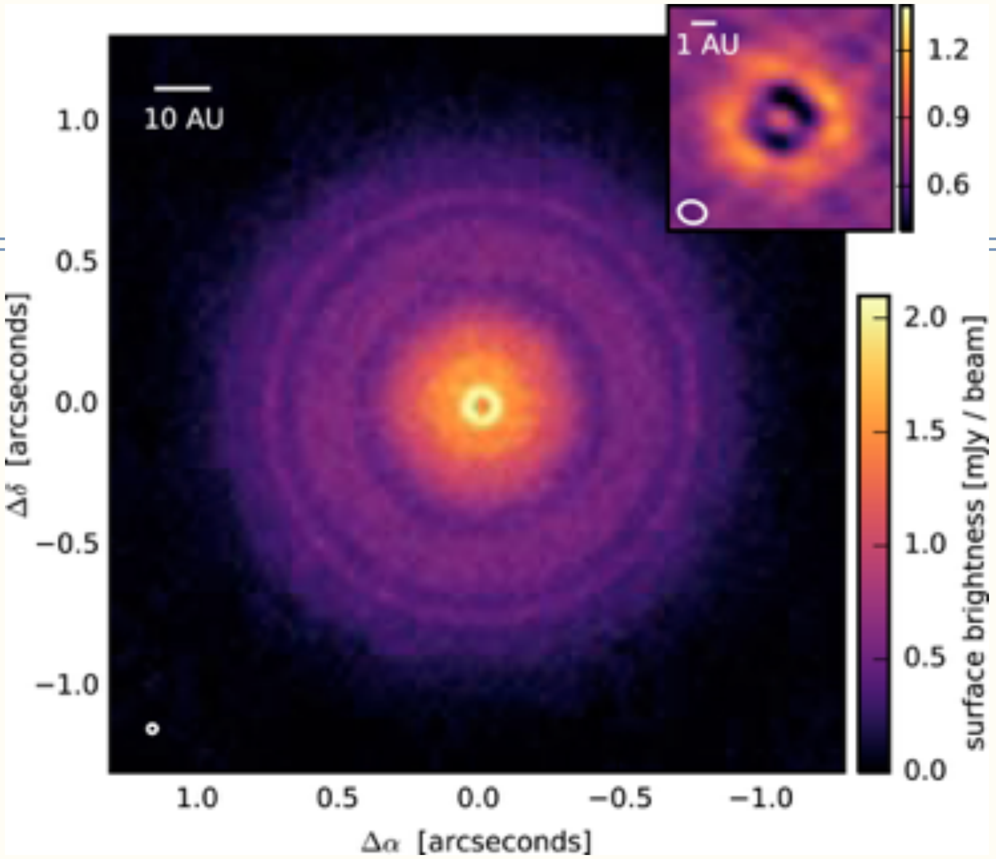


Need Observational Constraints

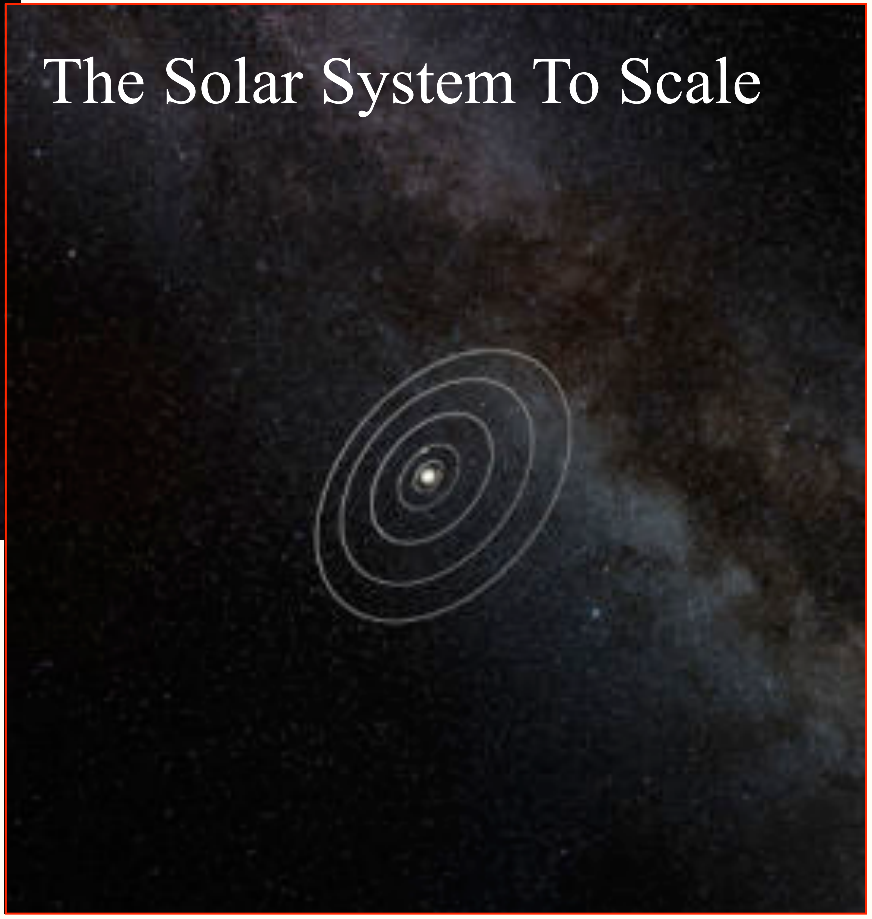
ALMA (0.03”): Planet Construction Zone



ALMA Partnership+ 2015



Andrews+ 2016
Tsukagoshi+ 2016



Disk Features

80 AU

Disk Features

80 AU

Axisymmetric

nonaxisymmetric

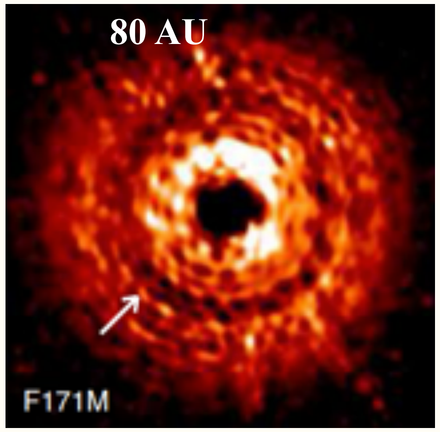
m=1

m=2

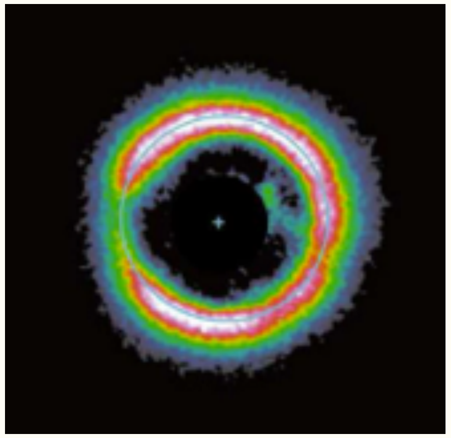
Disk Features

Optical/Near-IR

Axisymmetric



Debes+ 2013



Mayama+ 2012

nonaxisymmetric

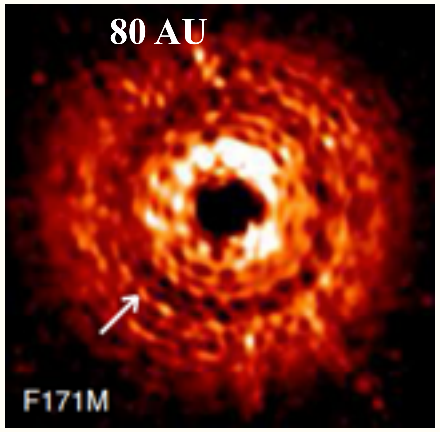
m=1

m=2

Disk Features

Optical/Near-IR

Axisymmetric



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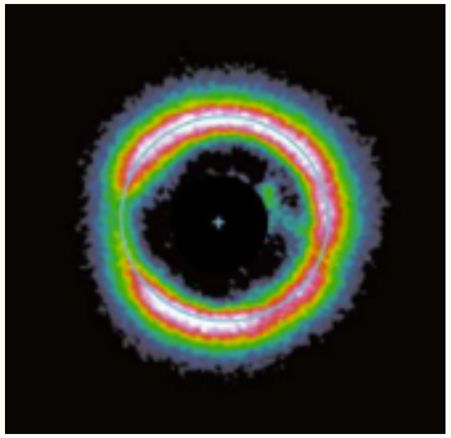

Mayama+ 2012

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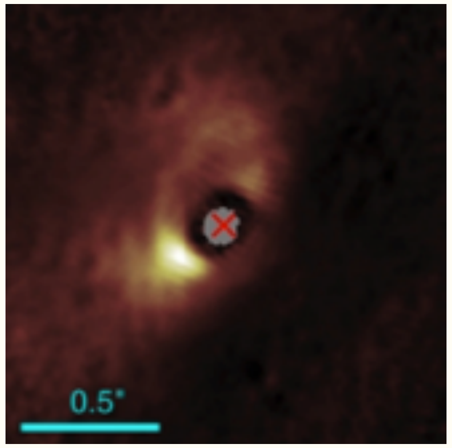
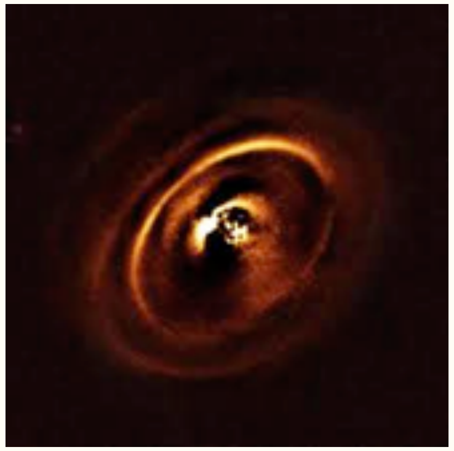
nonaxisymmetric

m=1



Avenhaus+ 2014



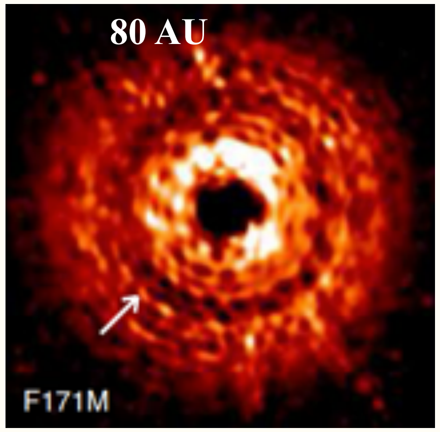
De Boer+ 2016

m=2

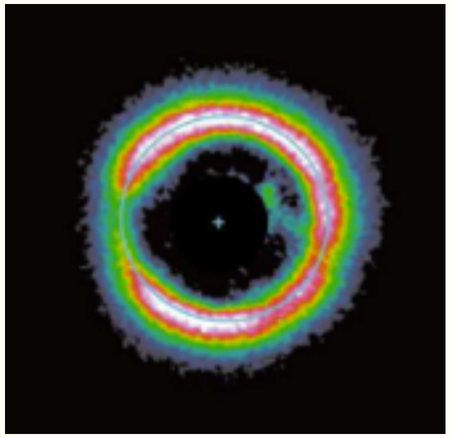
Disk Features

Optical/Near-IR

Axisymmetric



Debes+ 2013



Mayama+ 2012

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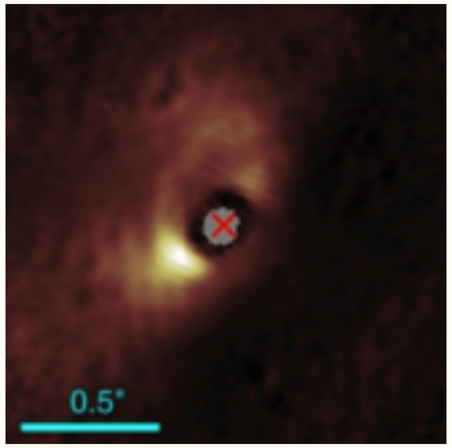
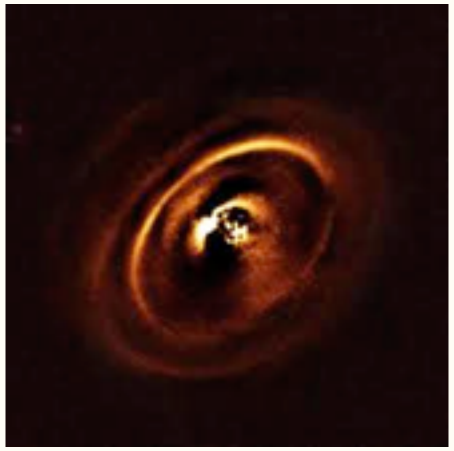
nonaxisymmetric

m=1

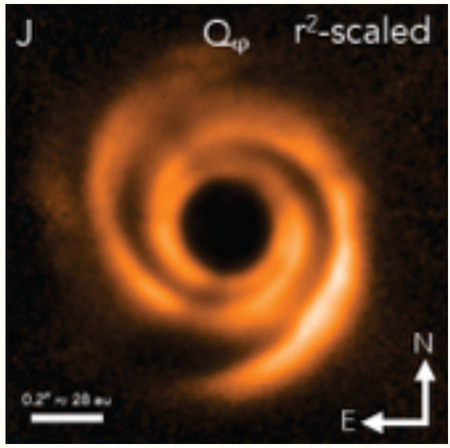


Avenhaus+ 2014

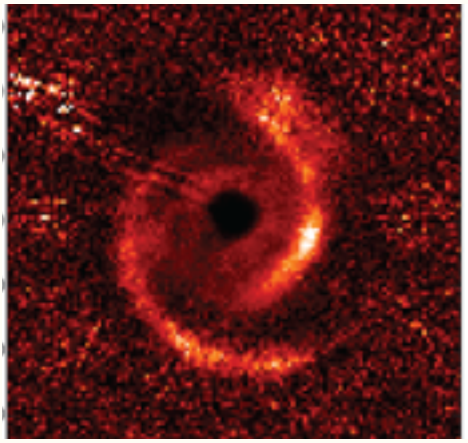


De Boer+ 2016

m=2



Garufi+ 2015



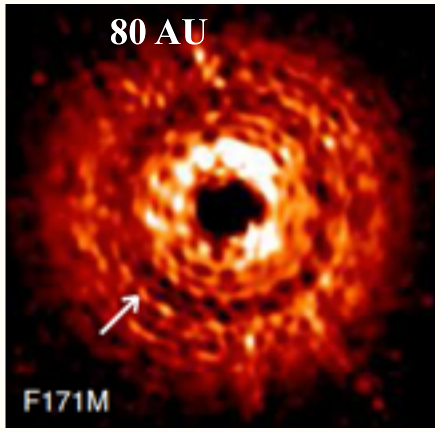
Benisty+ 2015

Disk Features

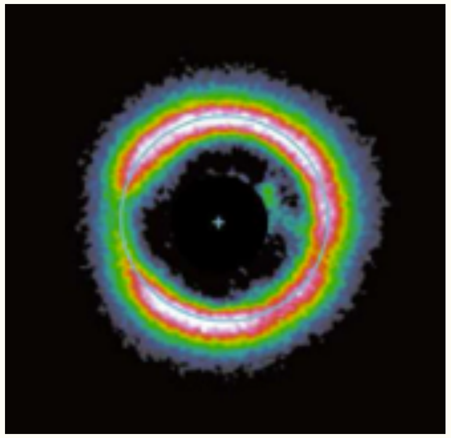
Optical/Near-IR

Radio

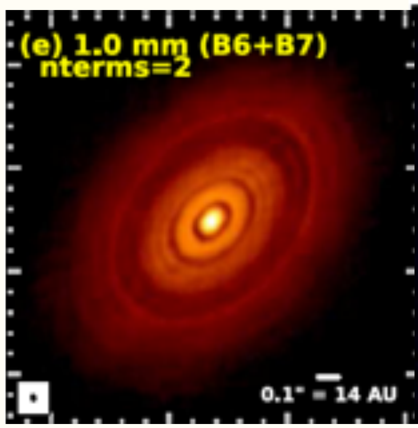
Axisymmetric



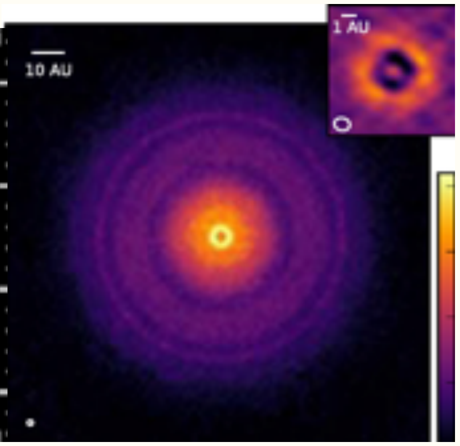
Debes+ 2013



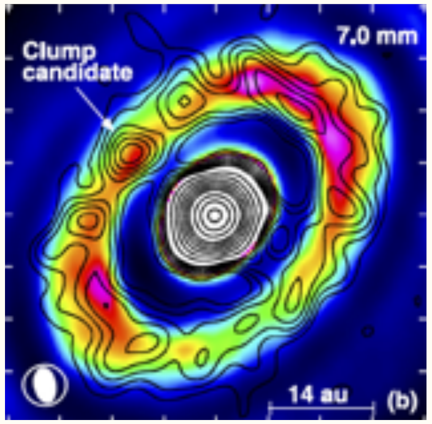
Mayama+ 2012



ALMA Partnership+ 2015



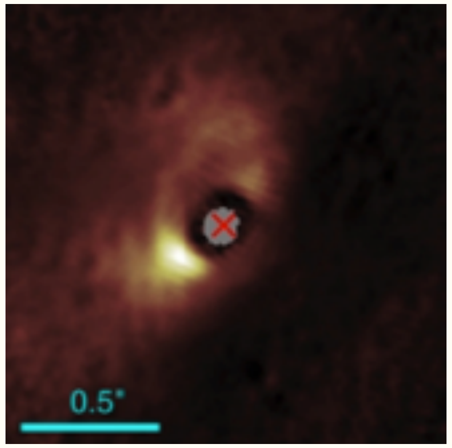
Andrews+ 2016



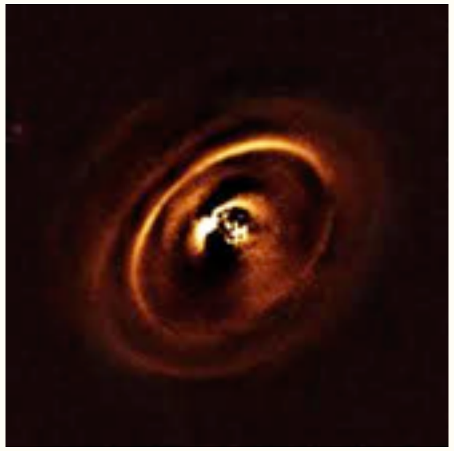
Carrasco-Gonzalez+ 2016

nonaxisymmetric

m=1

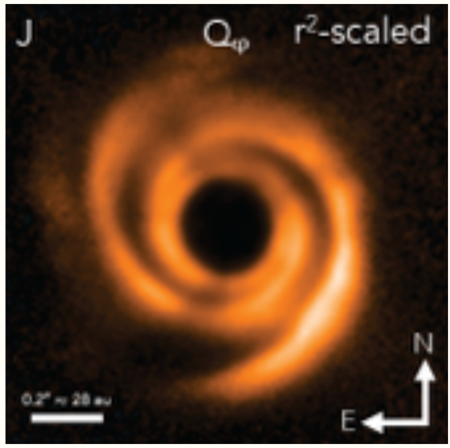


Avenhaus+ 2014

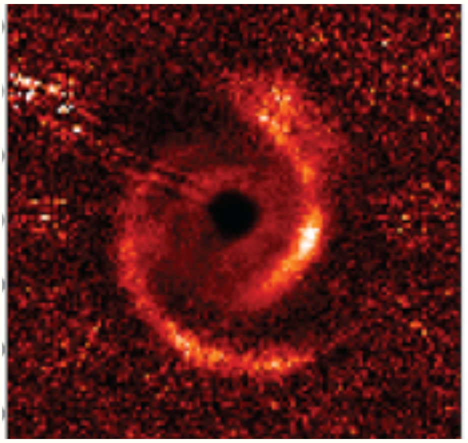


De Boer+ 2016

m=2



Garufi+ 2015



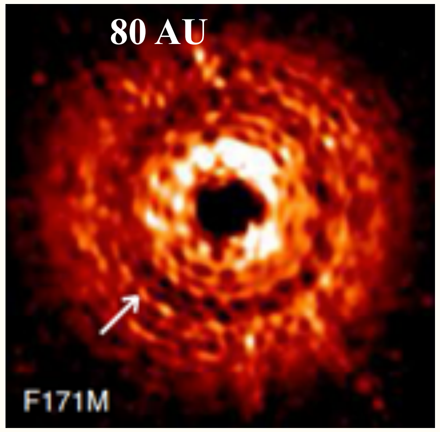
Benisty+ 2015

Disk Features

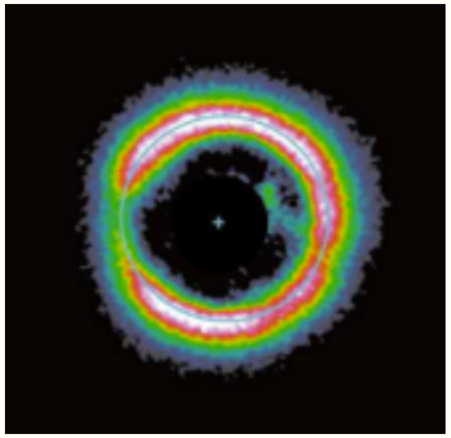
Optical/Near-IR

Radio

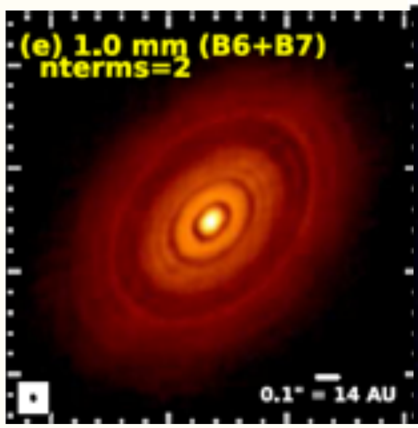
Axisymmetric



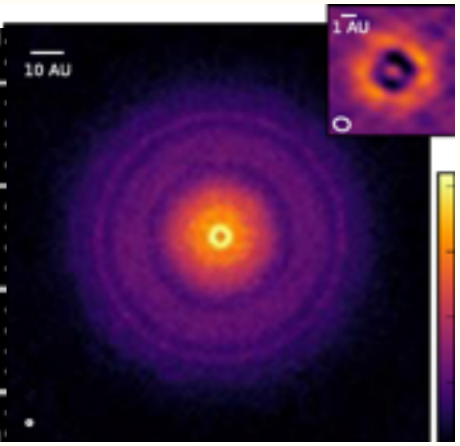
Debes+ 2013



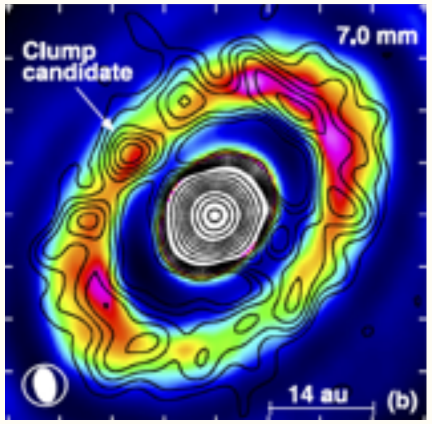
Mayama+ 2012



ALMA Partnership+ 2015



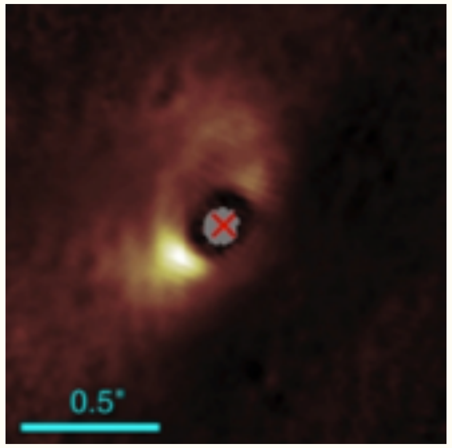
Andrews+ 2016



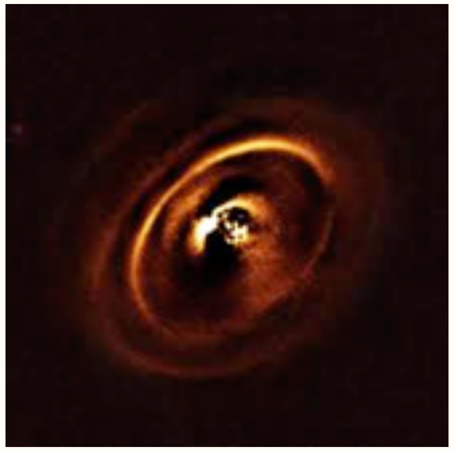
Carrasco-Gonzalez+ 2016

nonaxisymmetric

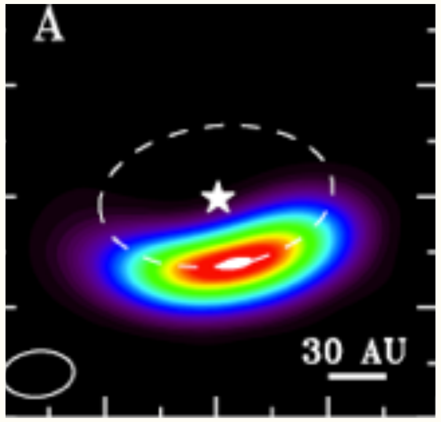
m=1



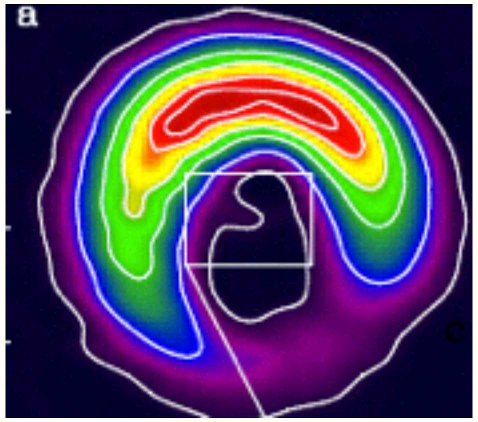
Avenhaus+ 2014



De Boer+ 2016

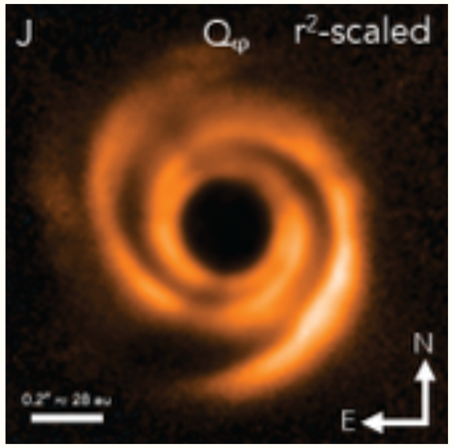


van der Marel+ 2013

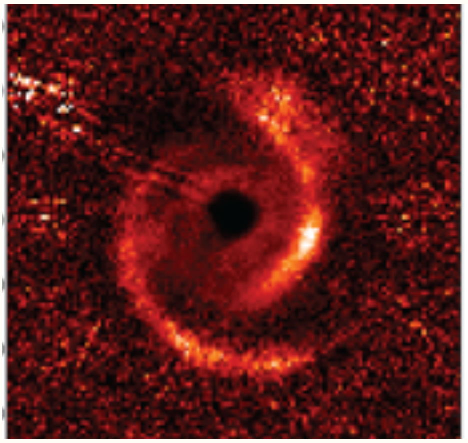


Casassus+ 2013

m=2



Garufi+ 2015



Benisty+ 2015

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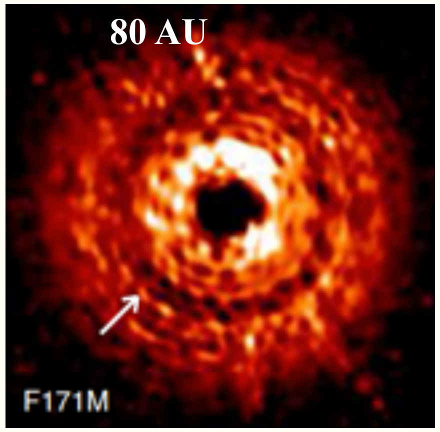
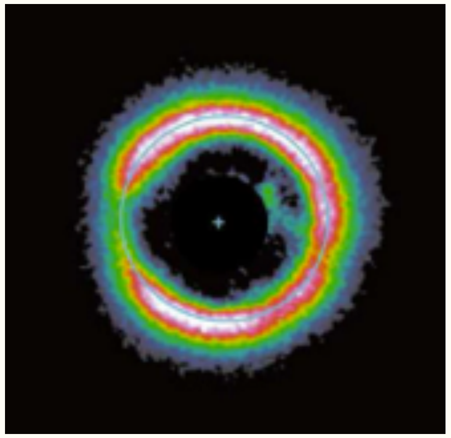
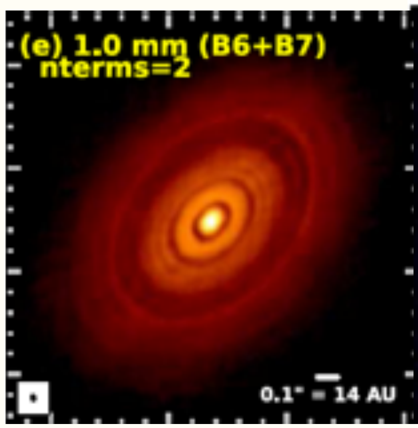
Axisymmetric



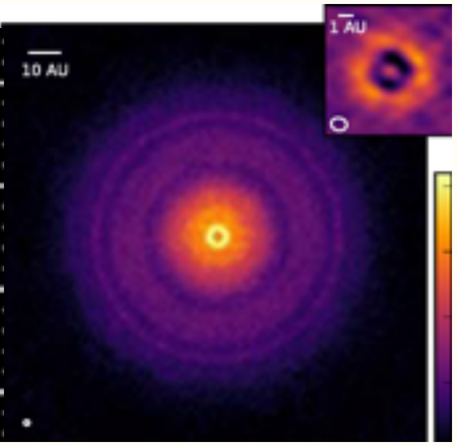
Debes+ 2013



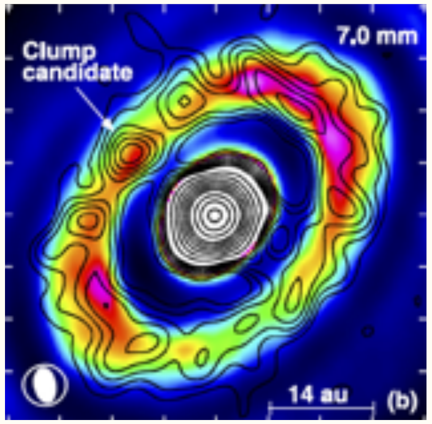
Mayama+ 2012



ALMA Partnership+ 2015



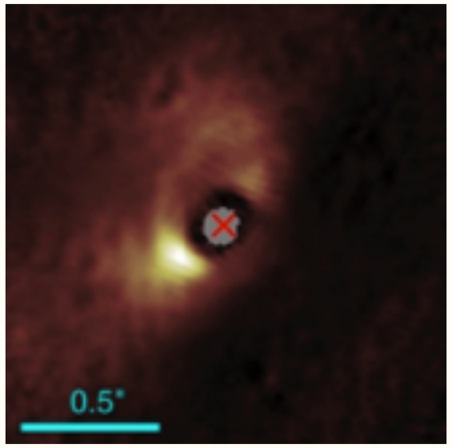
Andrews+ 2016



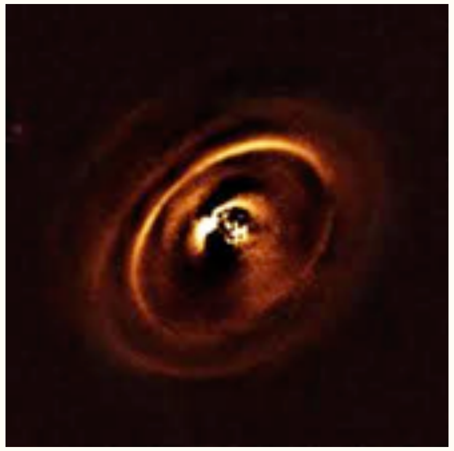
Carrasco-Gonzalez+ 2016

nonaxisymmetric

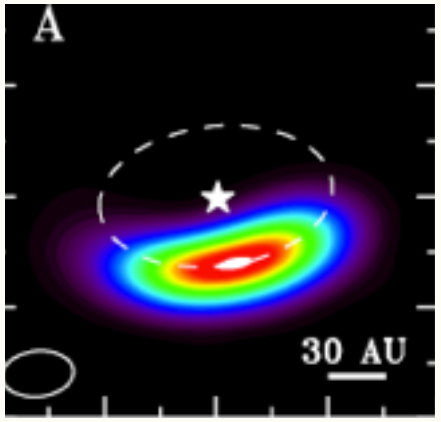
m=1



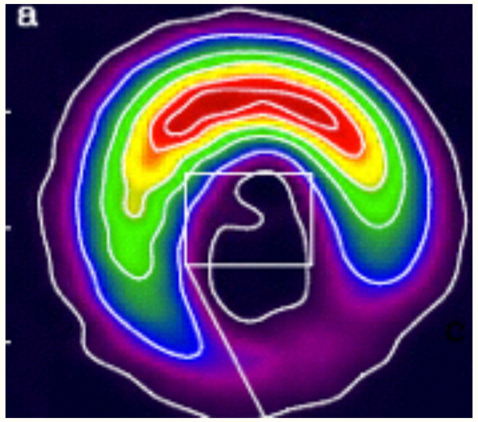
Avenhaus+ 2014



De Boer+ 2016

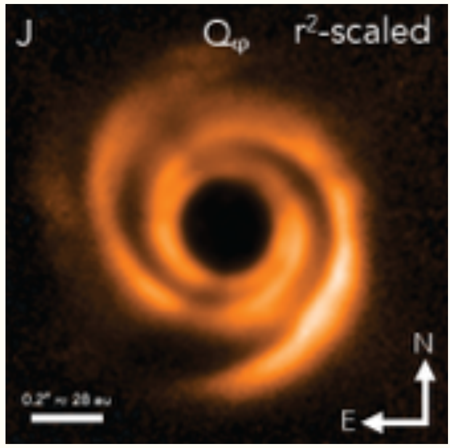


van der Marel+ 2013

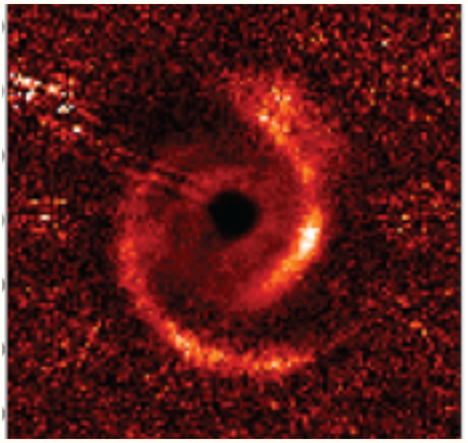


Casassus+ 2013

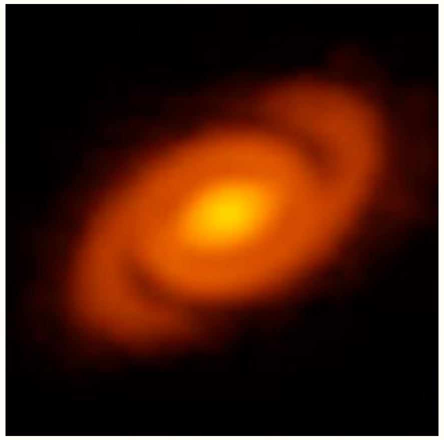
m=2



Garufi+ 2015



Benisty+ 2015



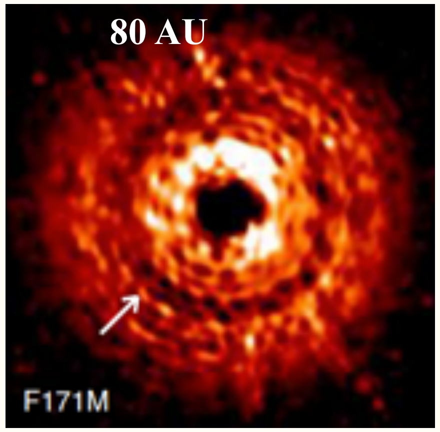
Pérez+ 2016

Disk Features

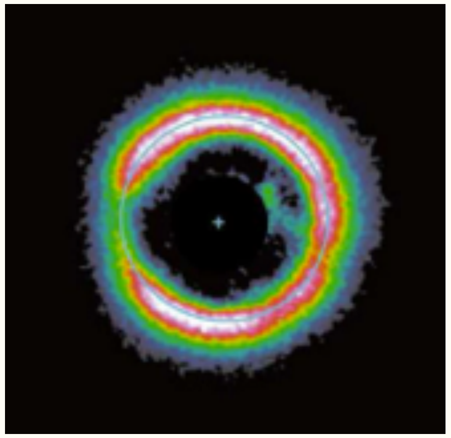
Optical/Near-IR

Radio

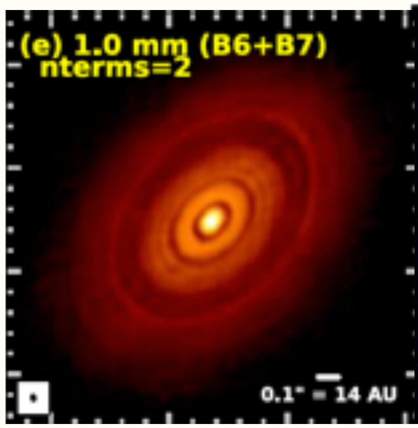
Axisymmetric



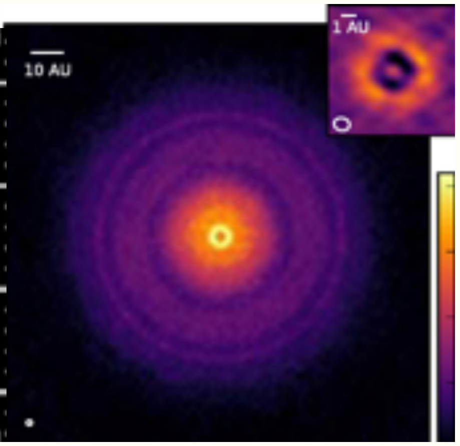
Debes+ 2013



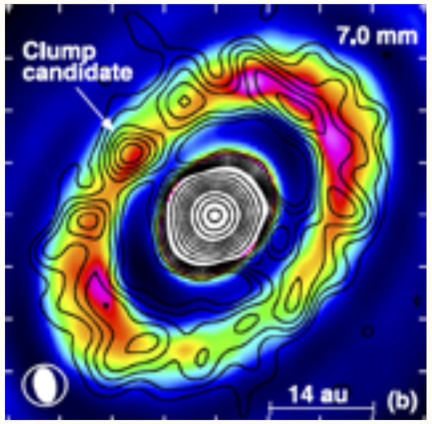
Mayama+ 2012



ALMA Partnership+ 2015



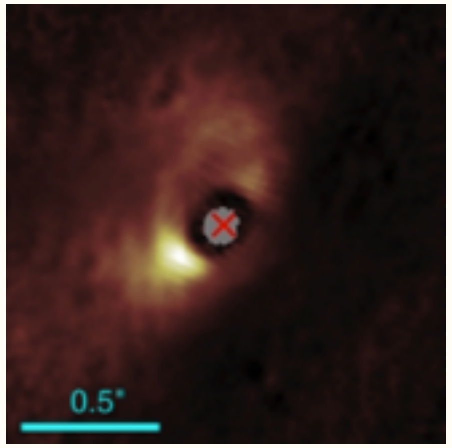
Andrews+ 2016



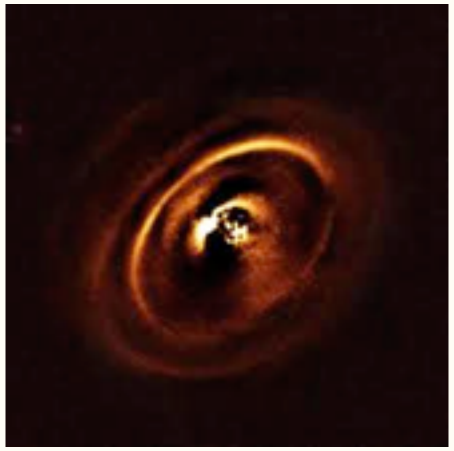
Carrasco-Gonzalez+ 2016

nonaxisymmetric

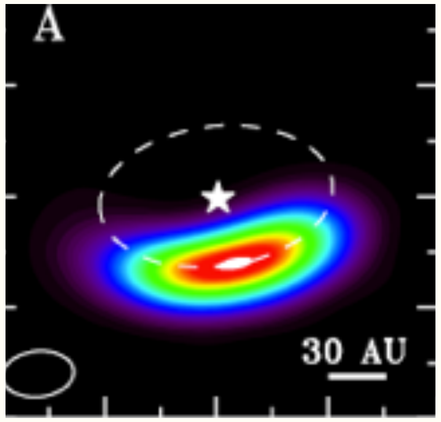
m=1



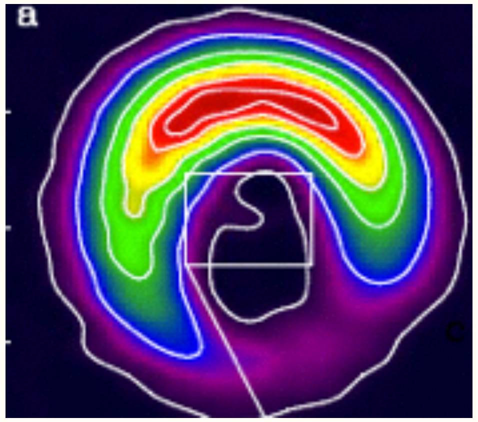
Avenhaus+ 2014



De Boer+ 2016

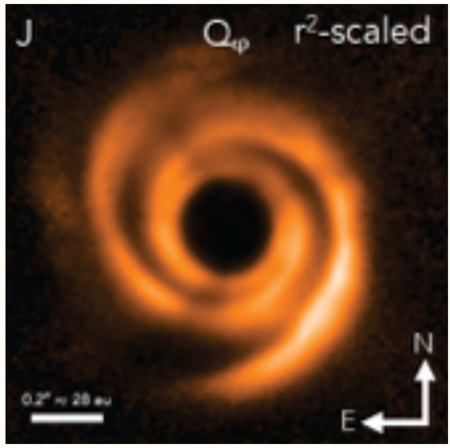


van der Marel+ 2013

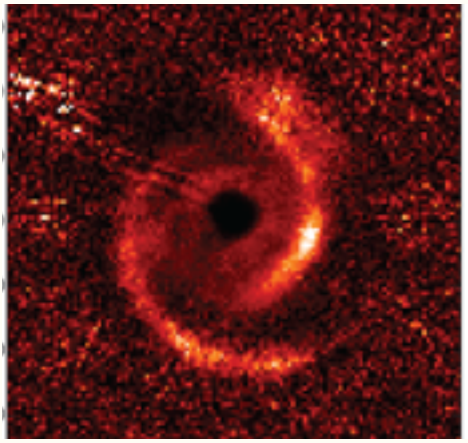


Casassus+ 2013

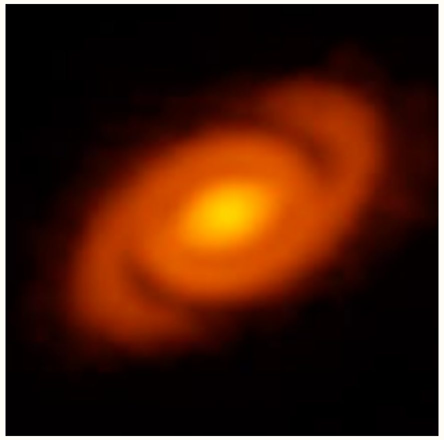
m=2



Garufi+ 2015

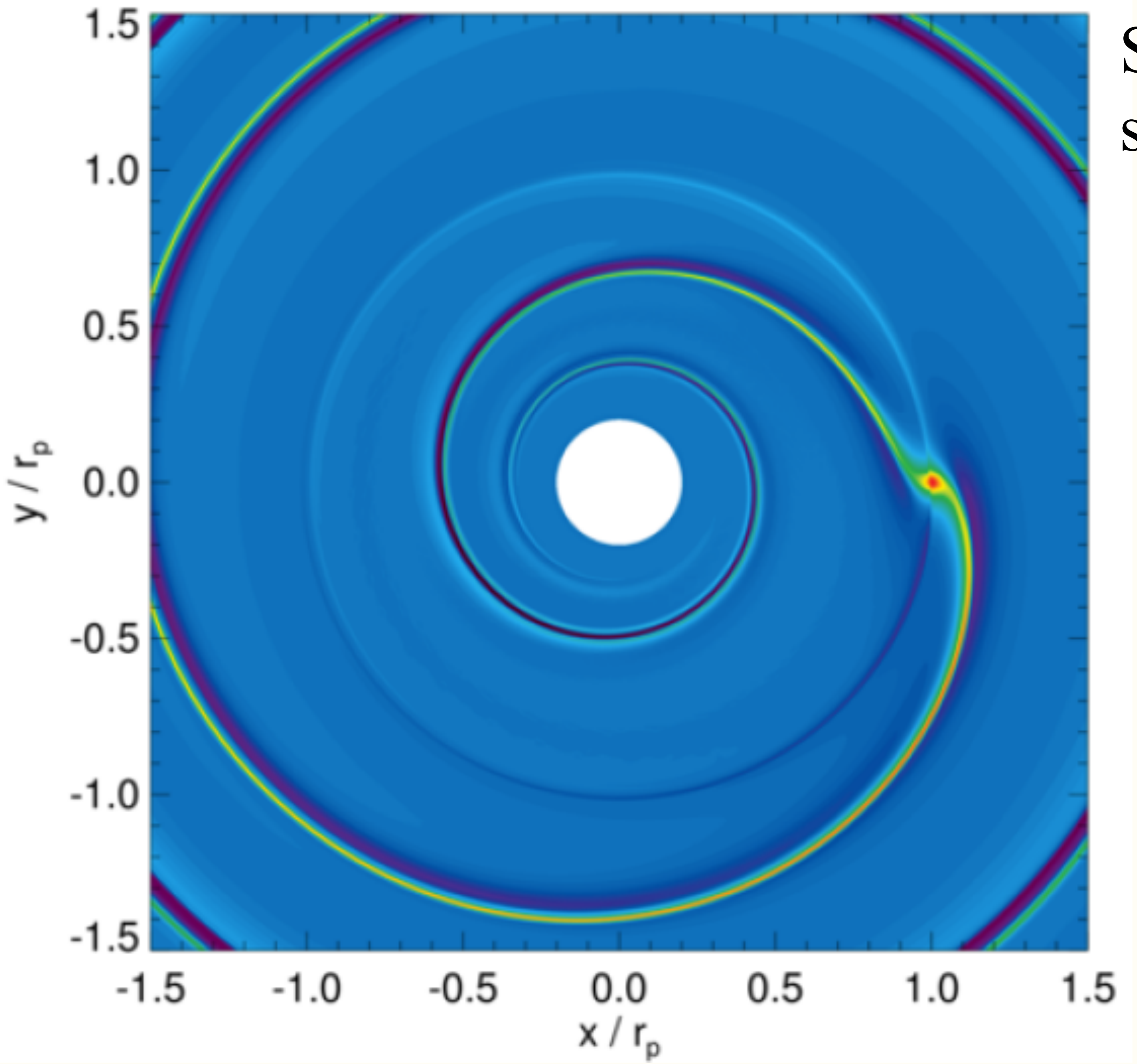


Benisty+ 2015

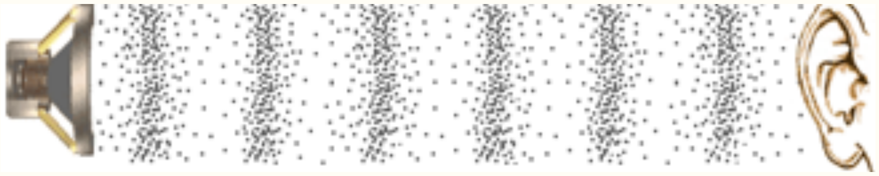


Pérez+ 2016

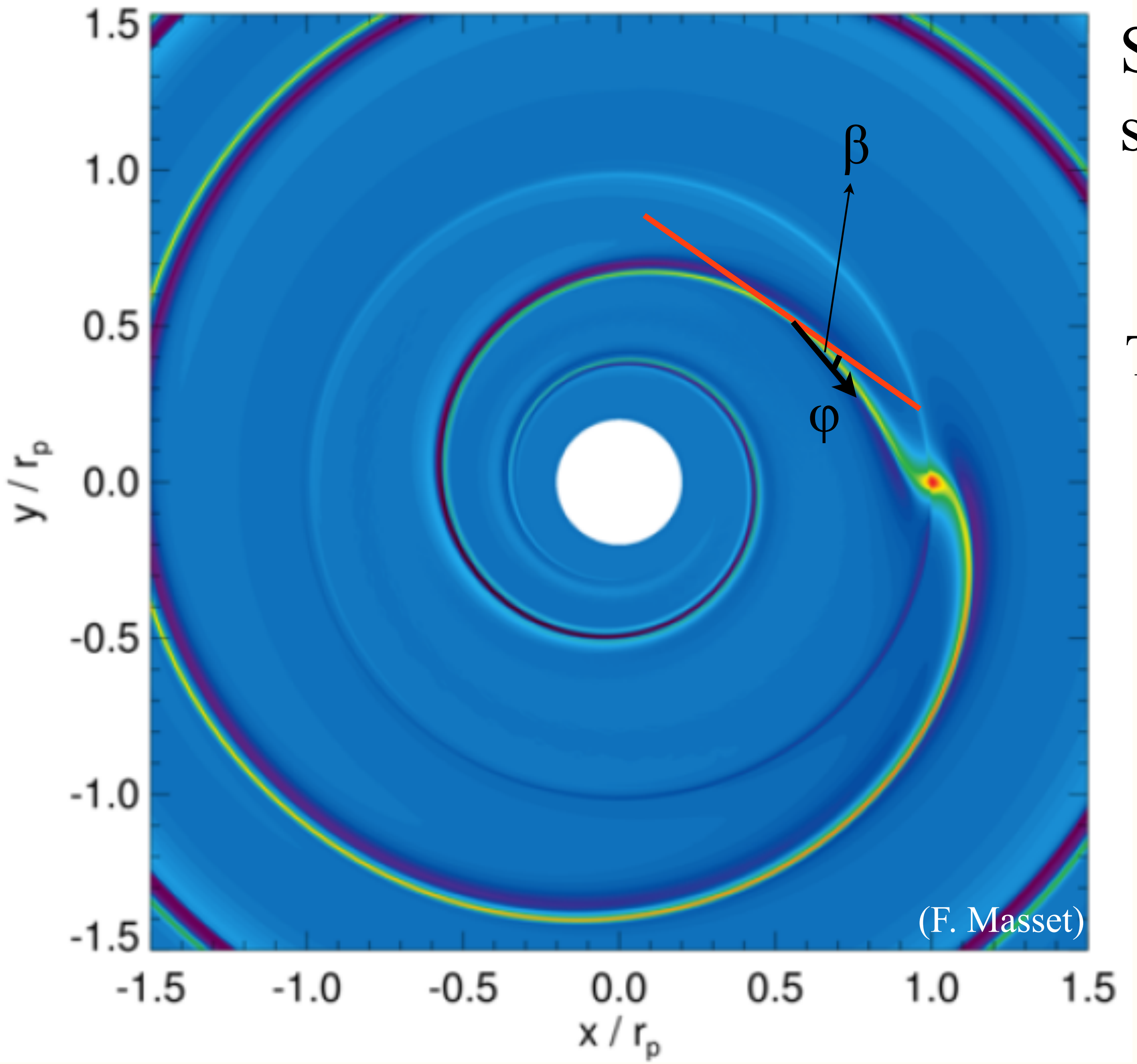
Spiral Arms



Spiral density waves are sound waves in disks

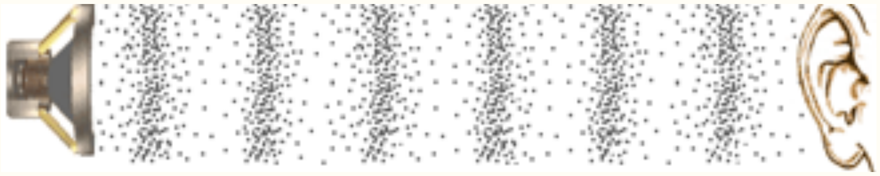


Spiral Arms



(F. Masset)

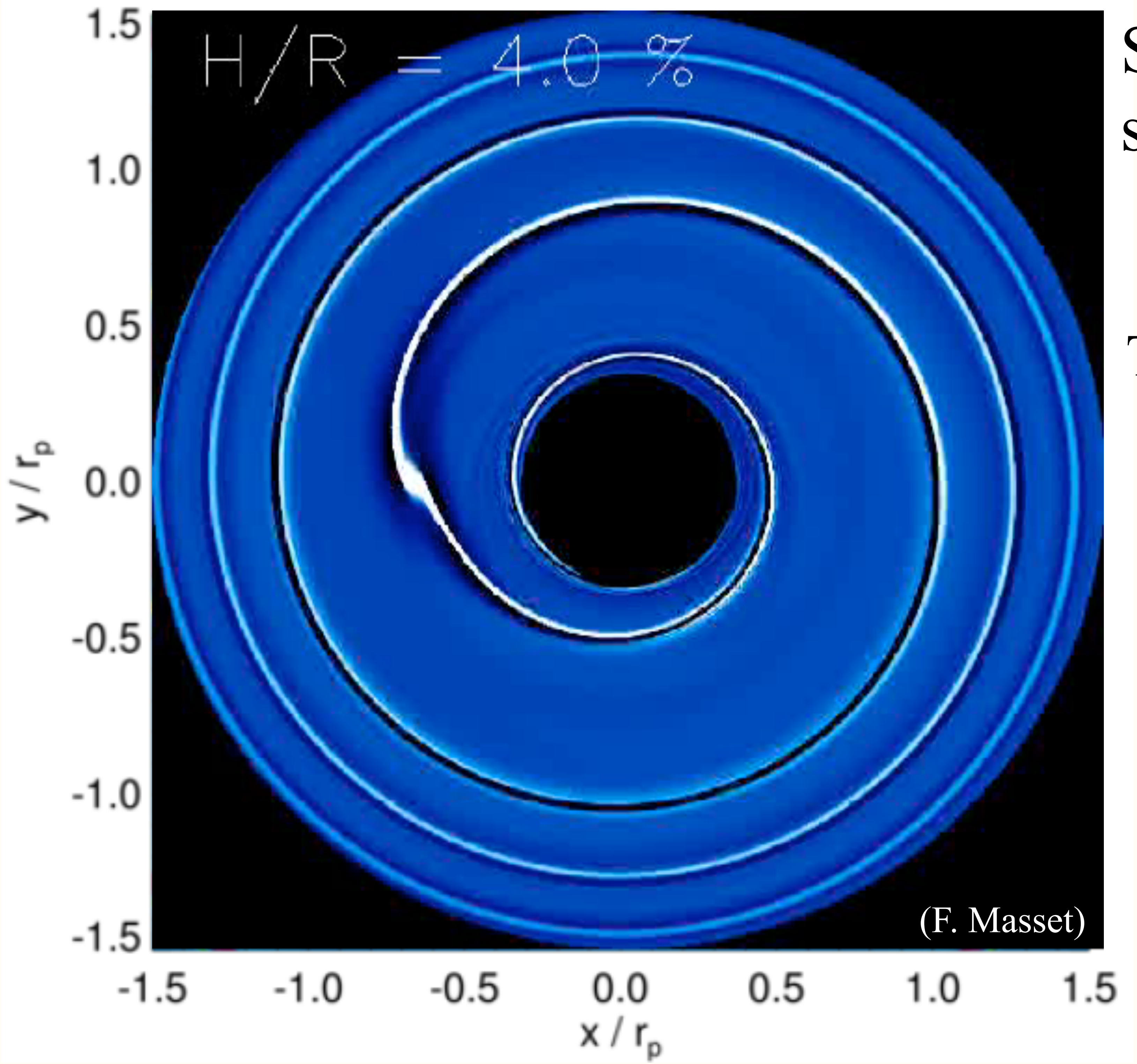
Spiral density waves are sound waves in disks



The pitch angle β

$$\tan \beta = \frac{c_s}{R\left|\Omega - \Omega_p\right|}$$

Spiral Arms



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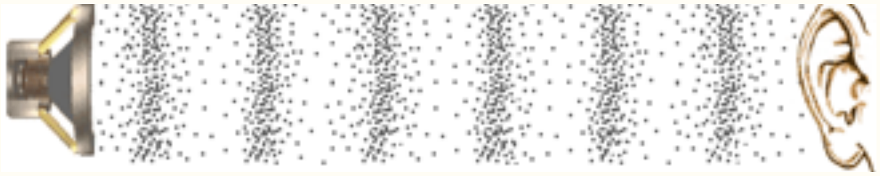

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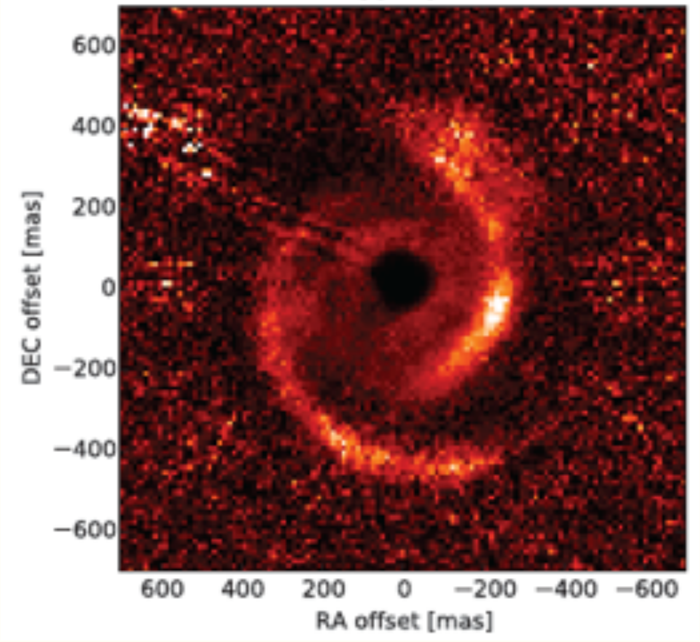
Are Spiral Arms Excited by Planets?

MWC 758



Benisty+ 2015

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Two difficulties:

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At 50 AU, T~300 K

CO lines suggest T~50 K

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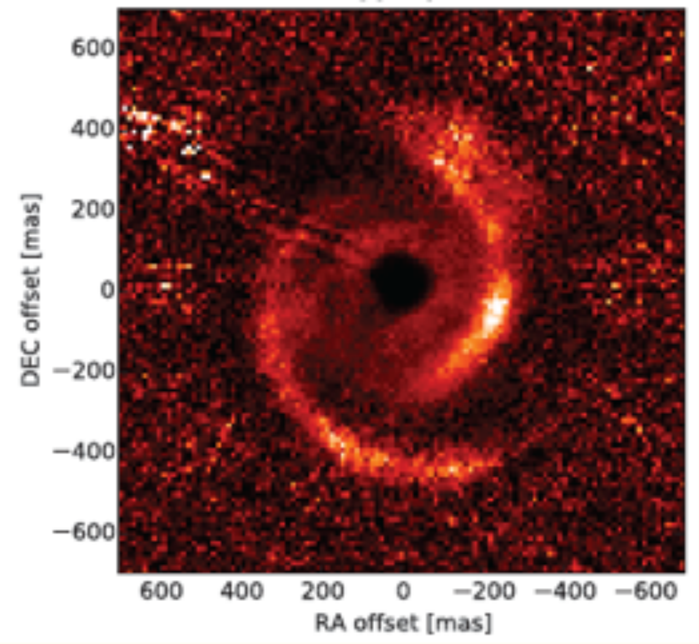

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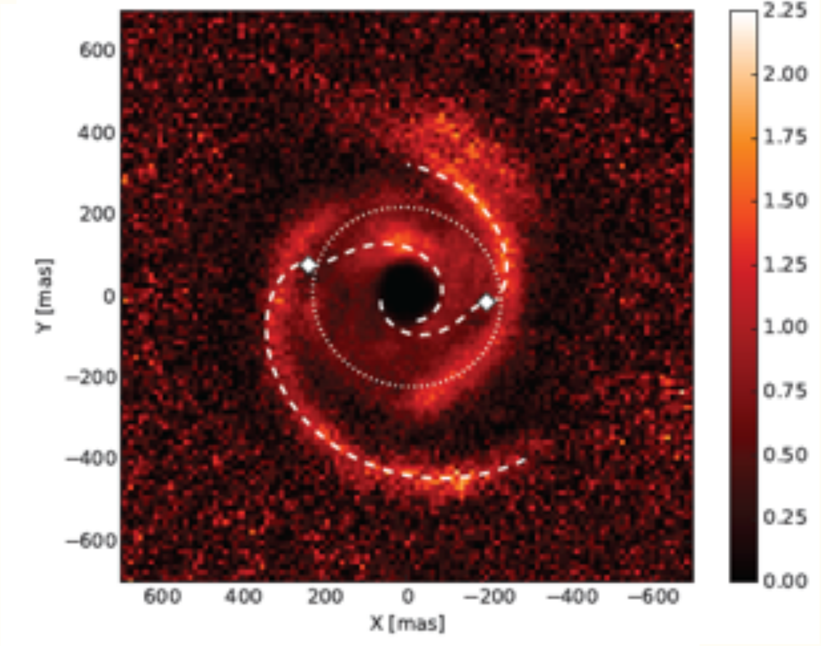

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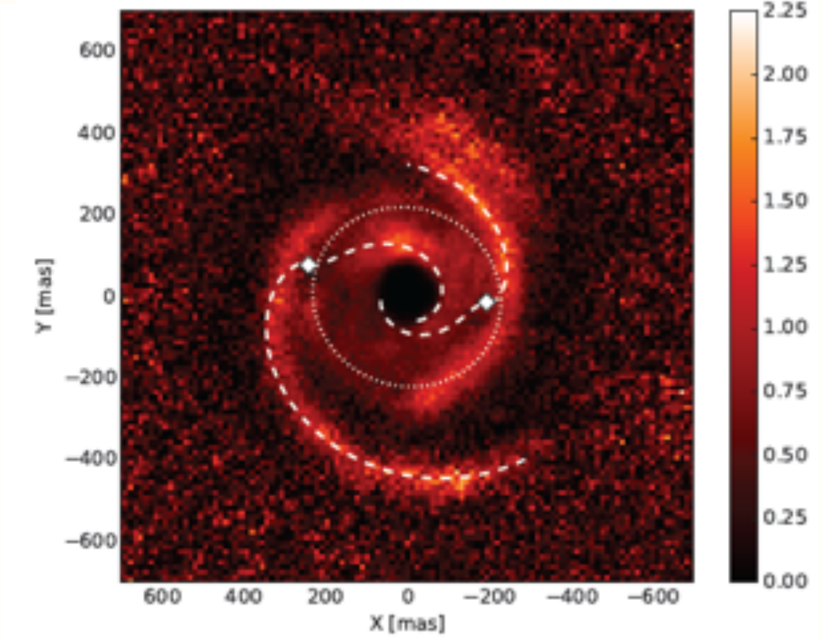

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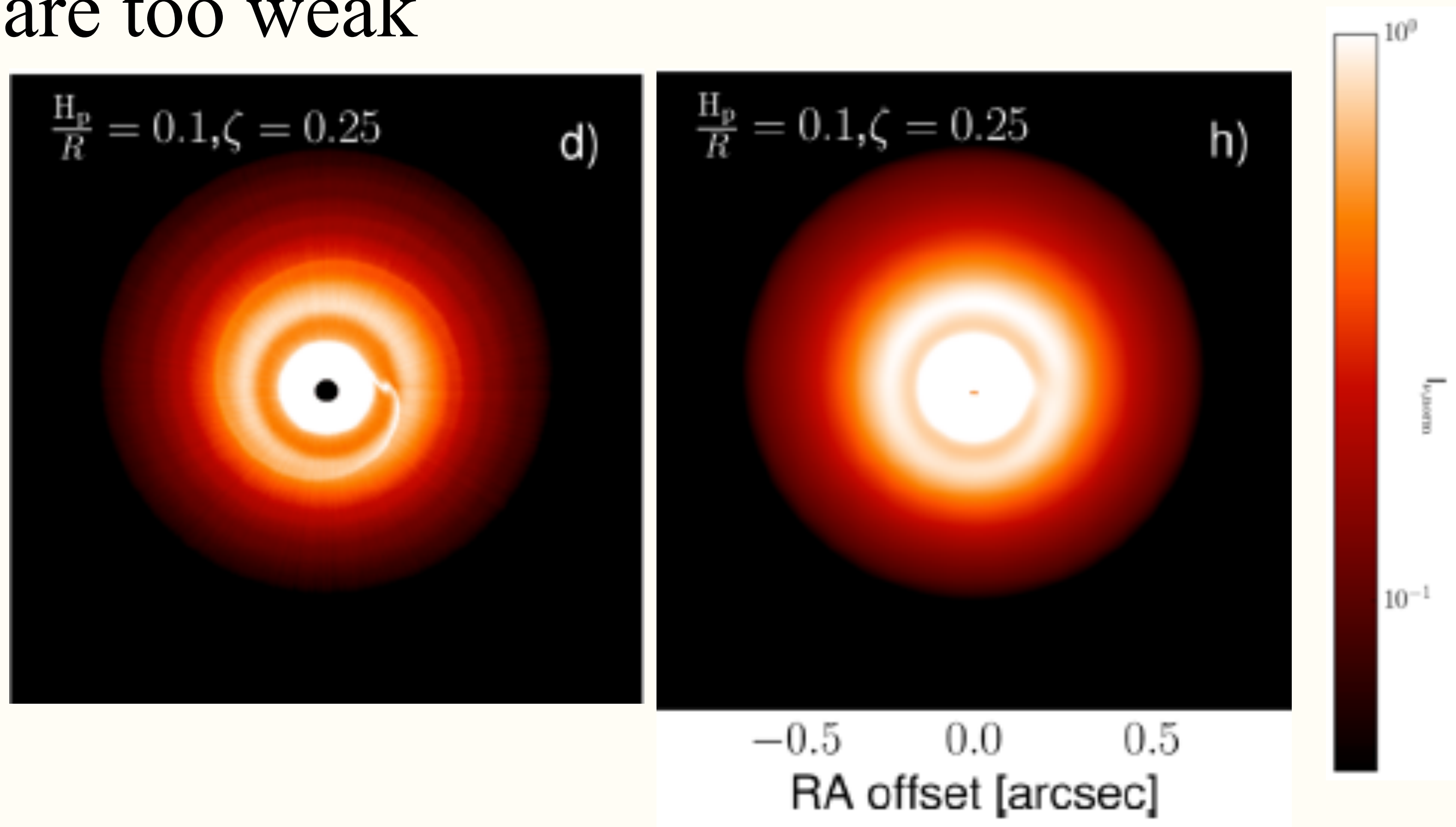

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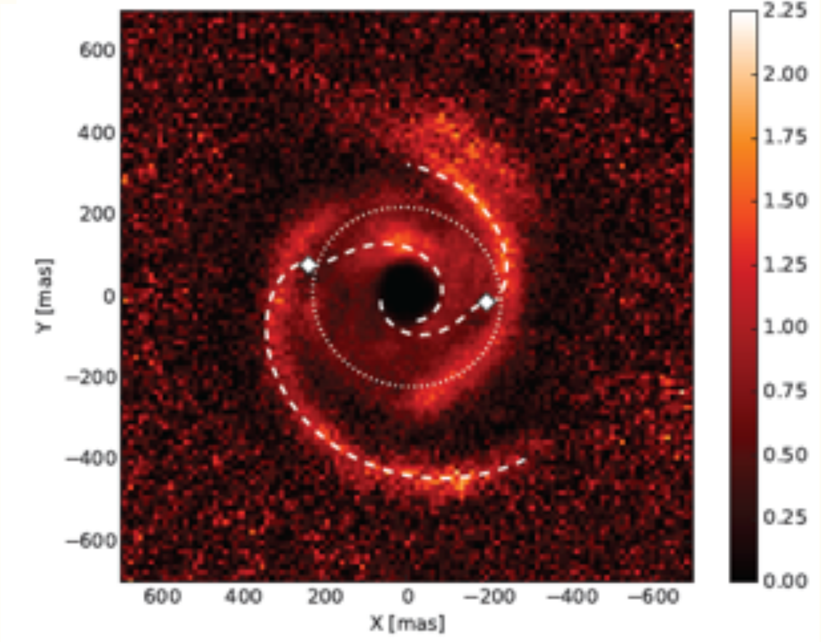

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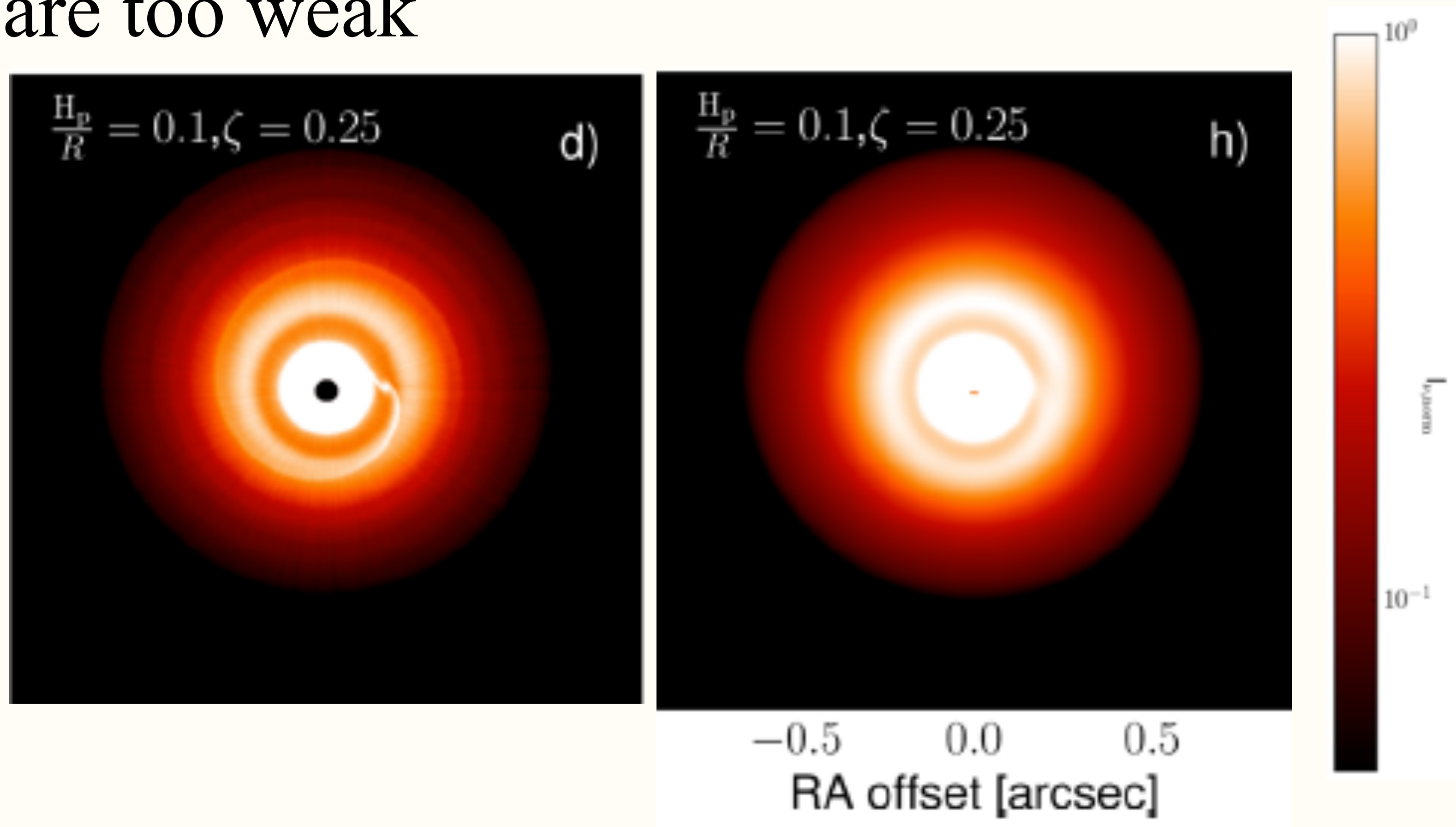

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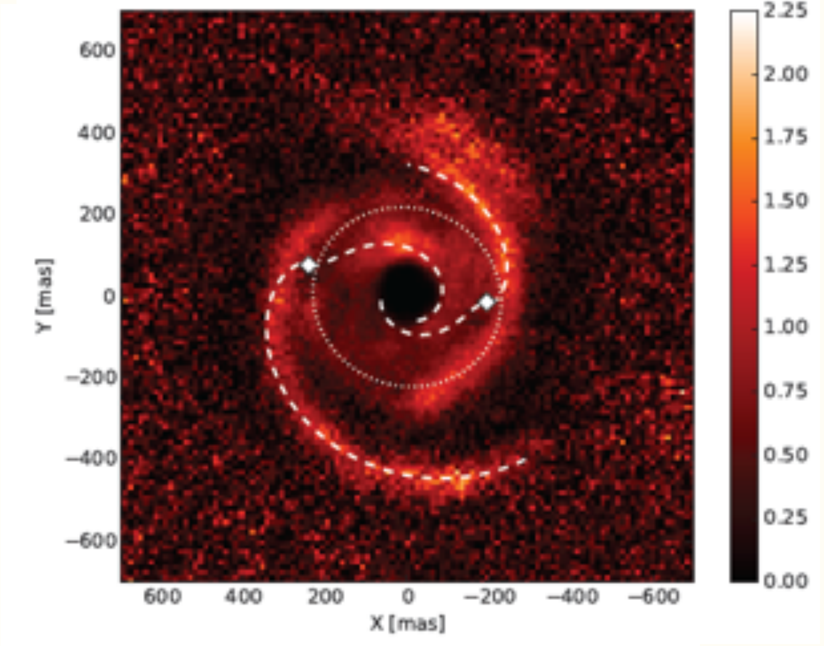

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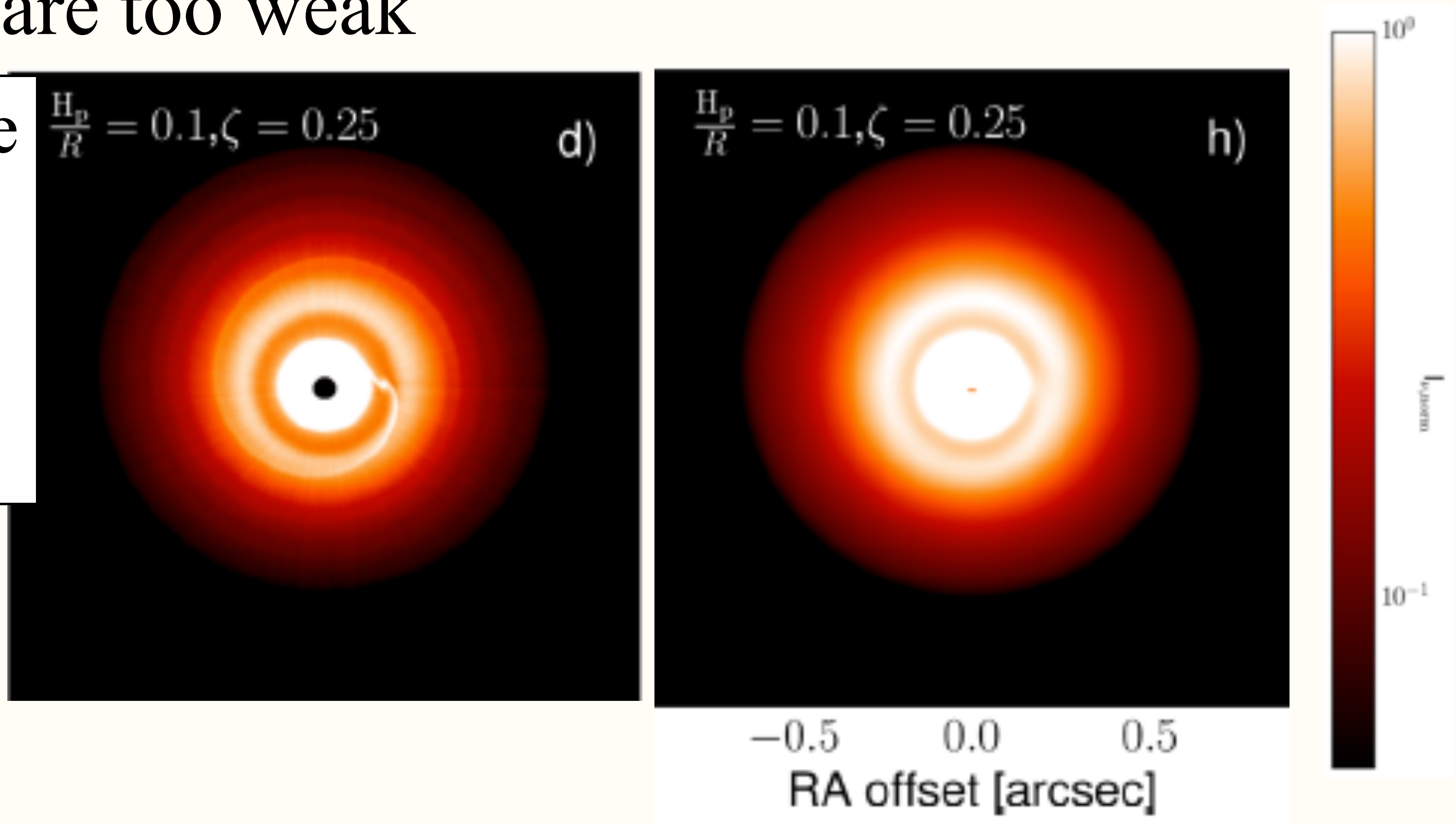
Near-IR observations only probe the disk surface.

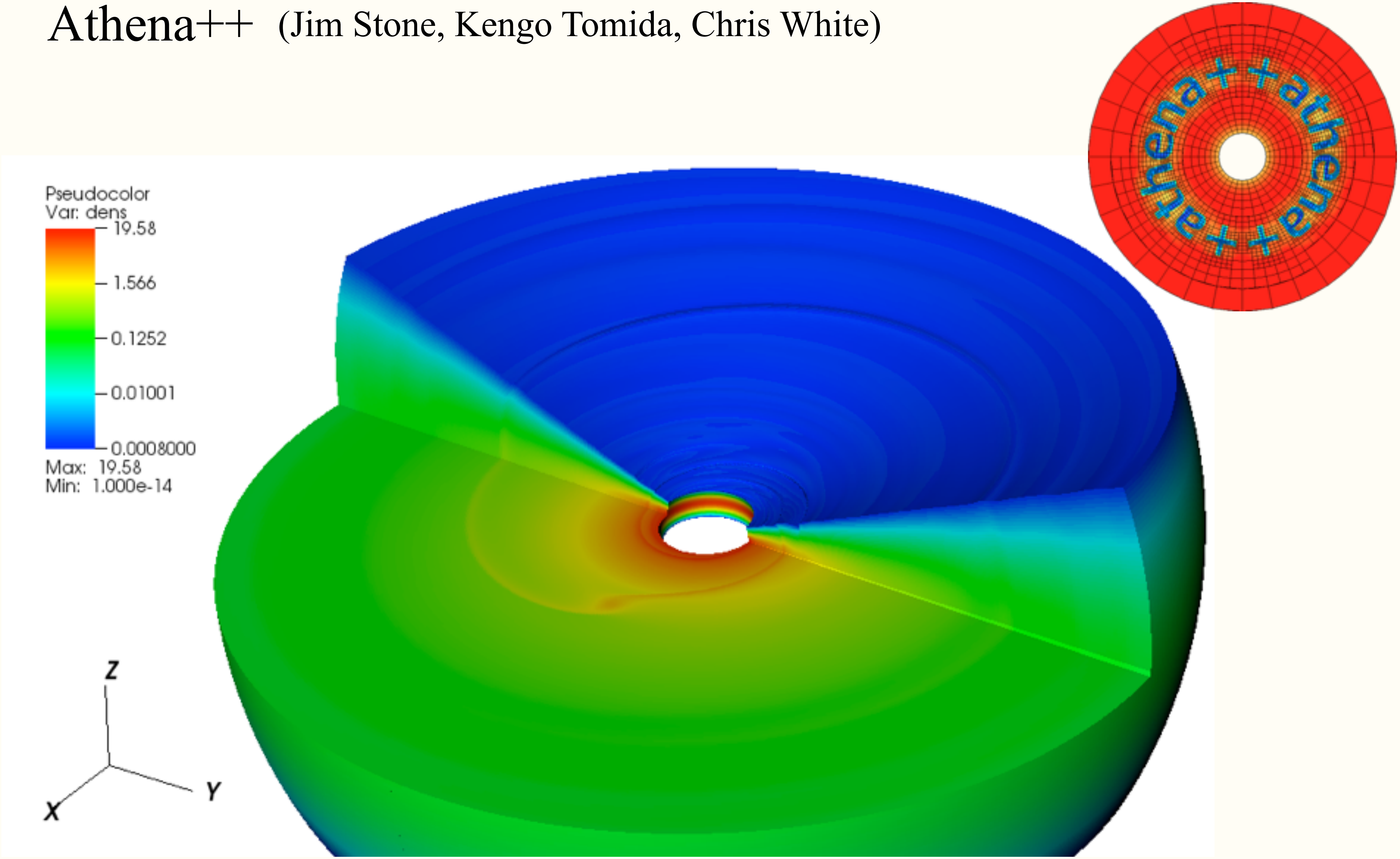
Shocks have 3-D structures

(Lubow & Ogilvie 1998)



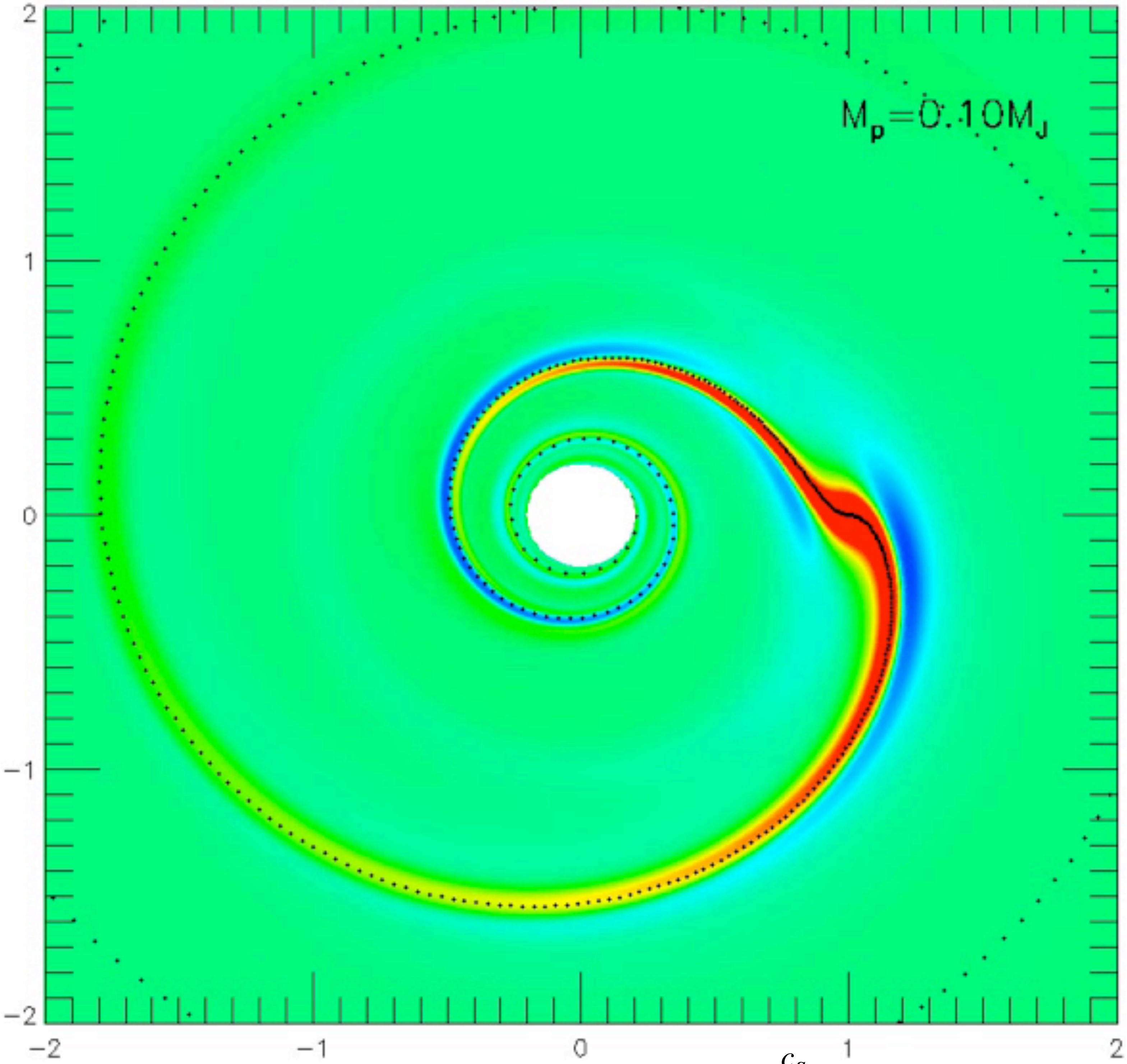
3-D Stratified Hydrodynamical Simulations

Athena++ (Jim Stone, Kengo Tomida, Chris White)



Zhu+ 2015

Surface density perturbation



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dotted curve: linear theory

$$\tan\beta = \frac{c_s}{R|\Omega - \Omega_p|}$$

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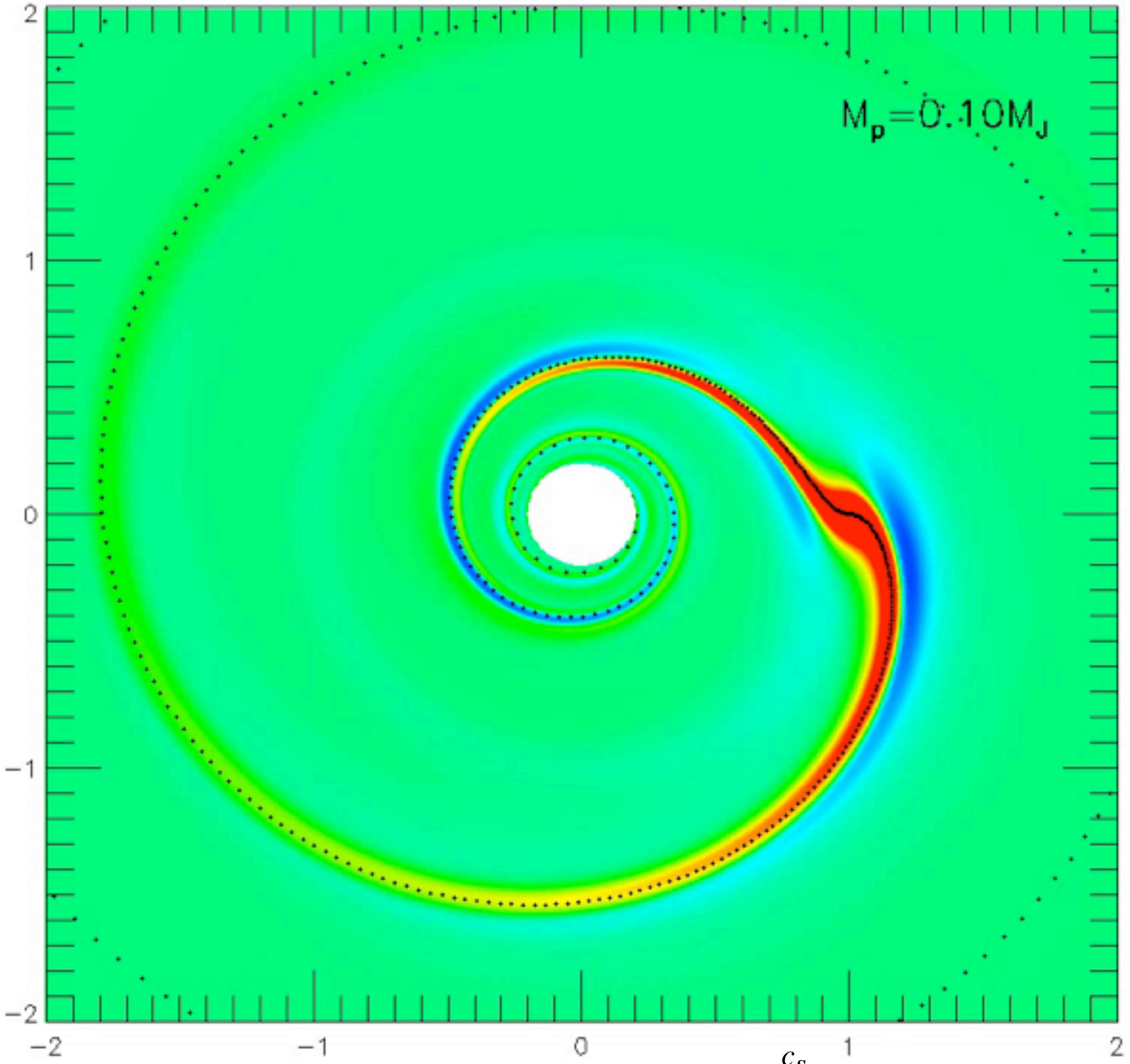

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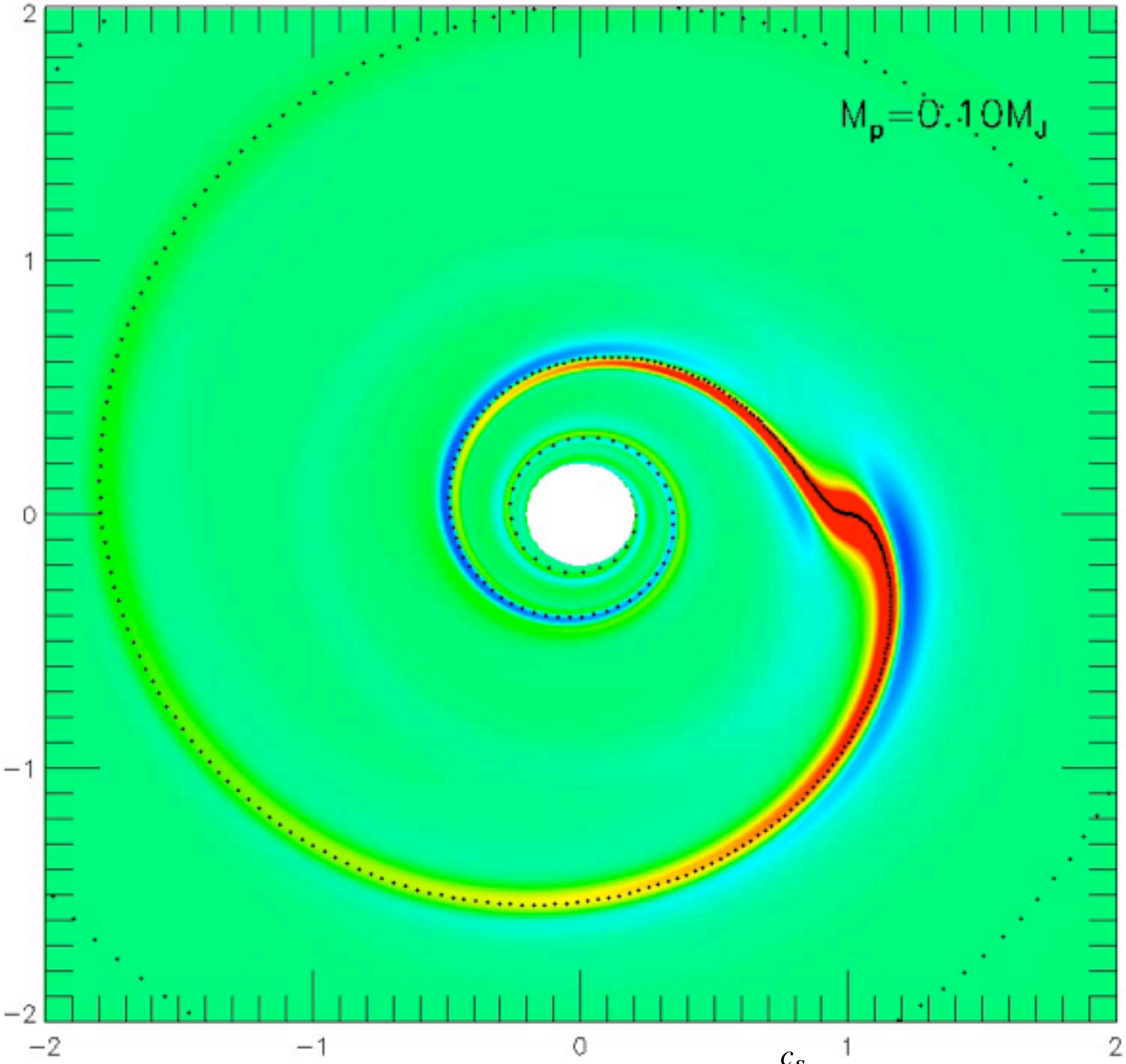


dotted curve: linear theory

$$\tan\beta = \frac{c_s}{R|\Omega - \Omega_p|}$$

When the planet mass increases:

- **The pitch angle increases**

Goodman & Rafikov 2001

- The secondary arm becomes apparent and **the separation between two arms increases**

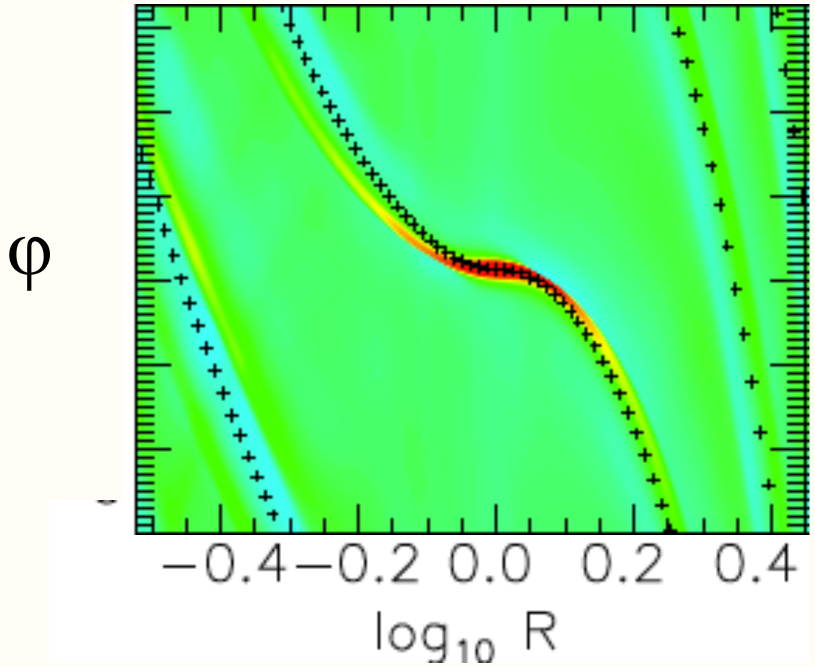
- **Amplitude of shocks becomes larger**

Zhu+ 2015

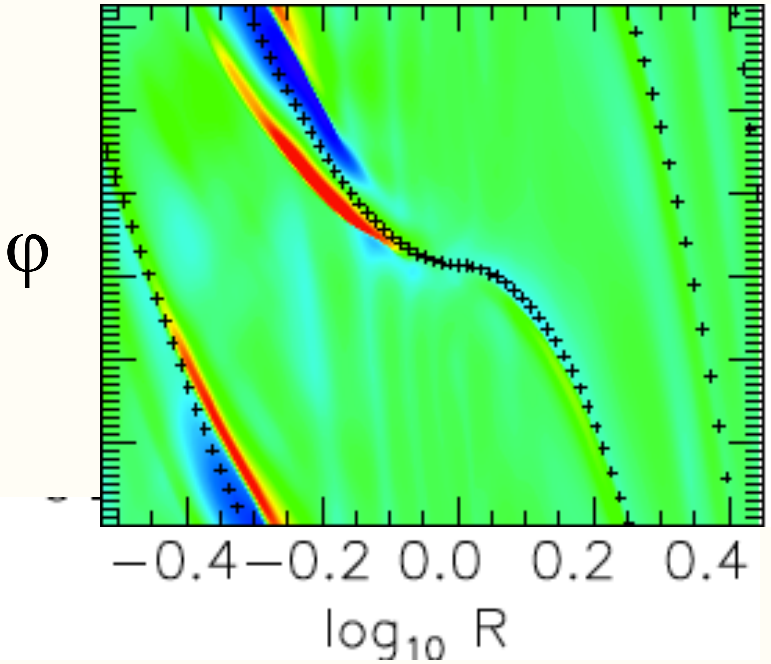
3-D Shock Structure

$\delta\rho/\rho$ at the disk midplane

M_J



$\delta\rho/\rho$ at disk surface (3 H)



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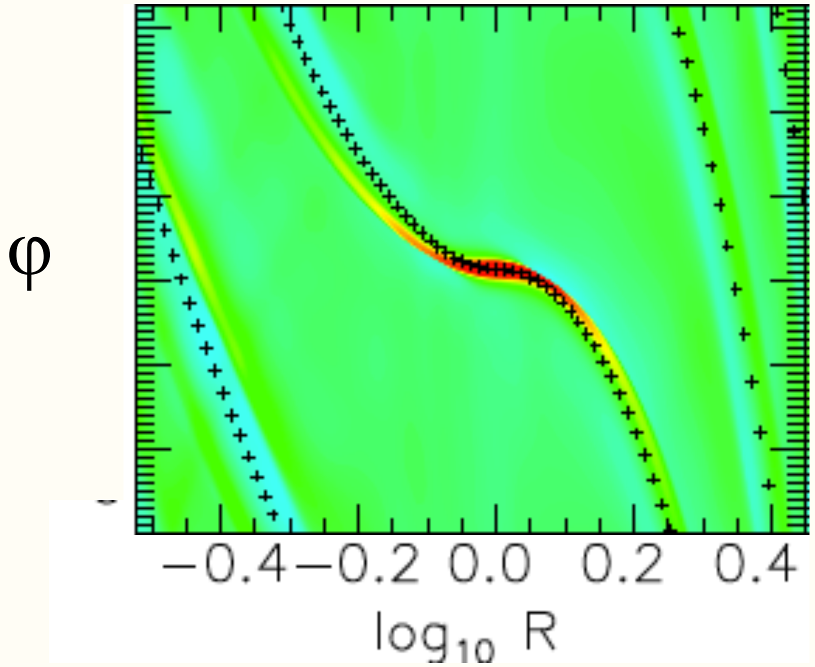

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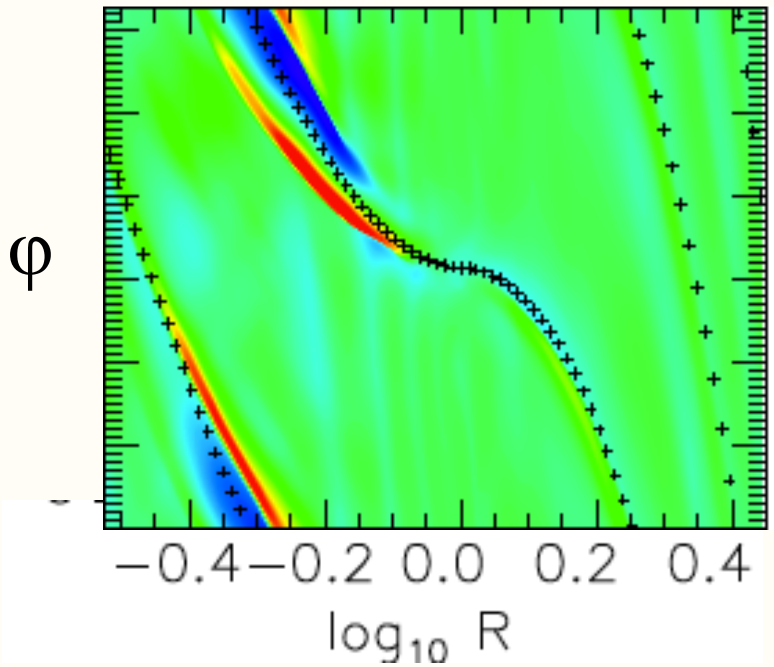
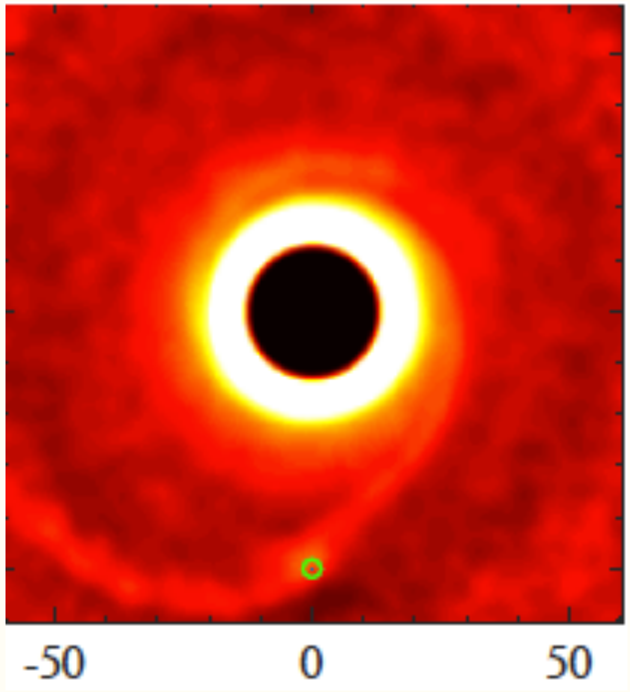
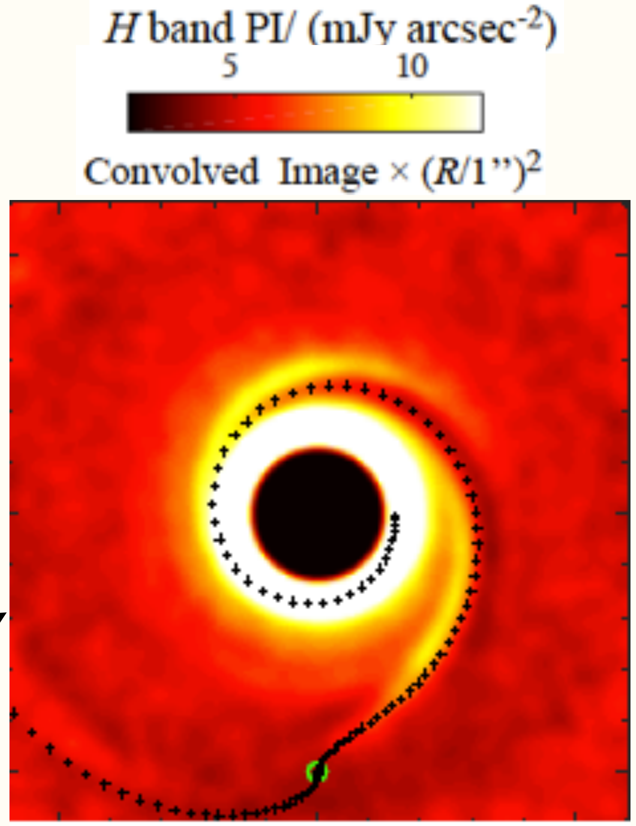


Post-processing simulation results with MCRT:



Similar to Juhasz+ 2015 puff from 2-D to 3-D

Directly using 3-D simulations

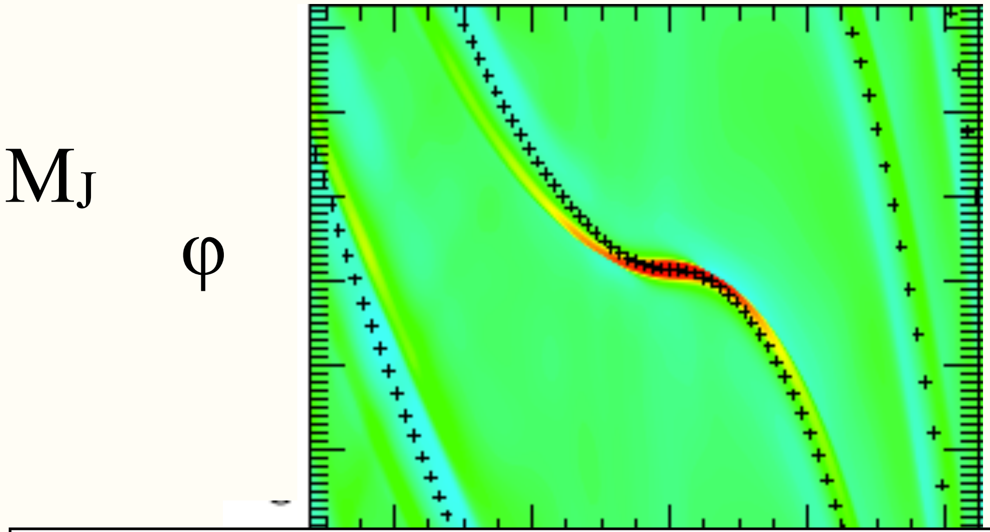


Zhu+ 2015

Also in Lyra+ 2016

3-D Shock Structure

δρ/ρ at the disk midplane



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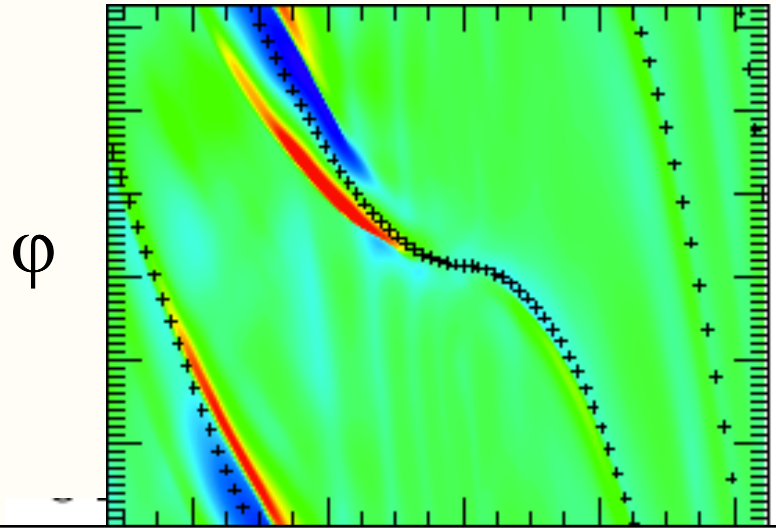
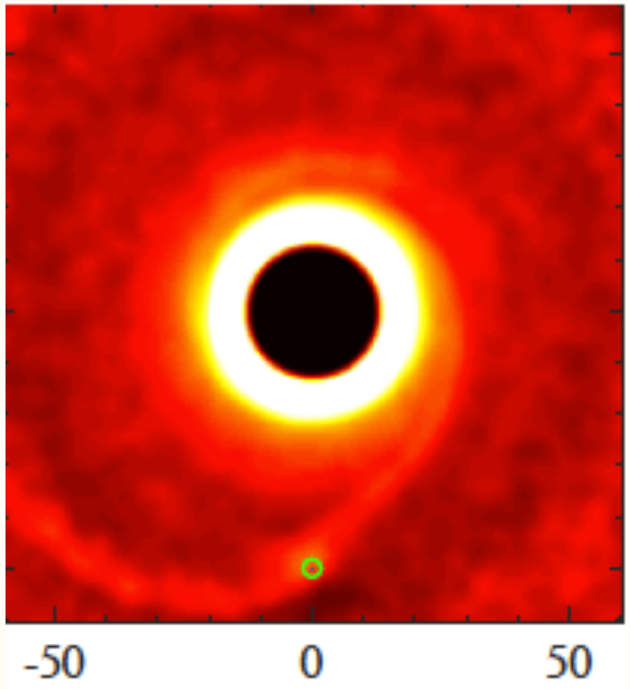


Use spiral arms to estimate the planet mass (nonlinear theory)



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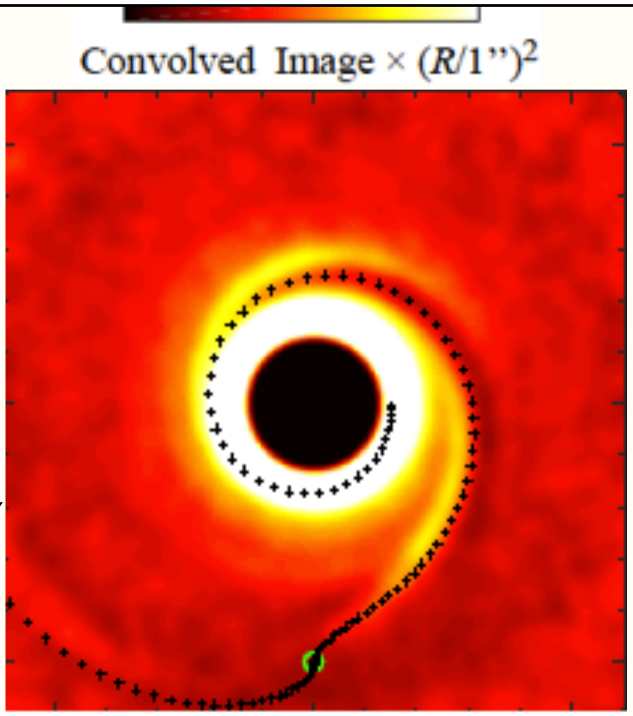

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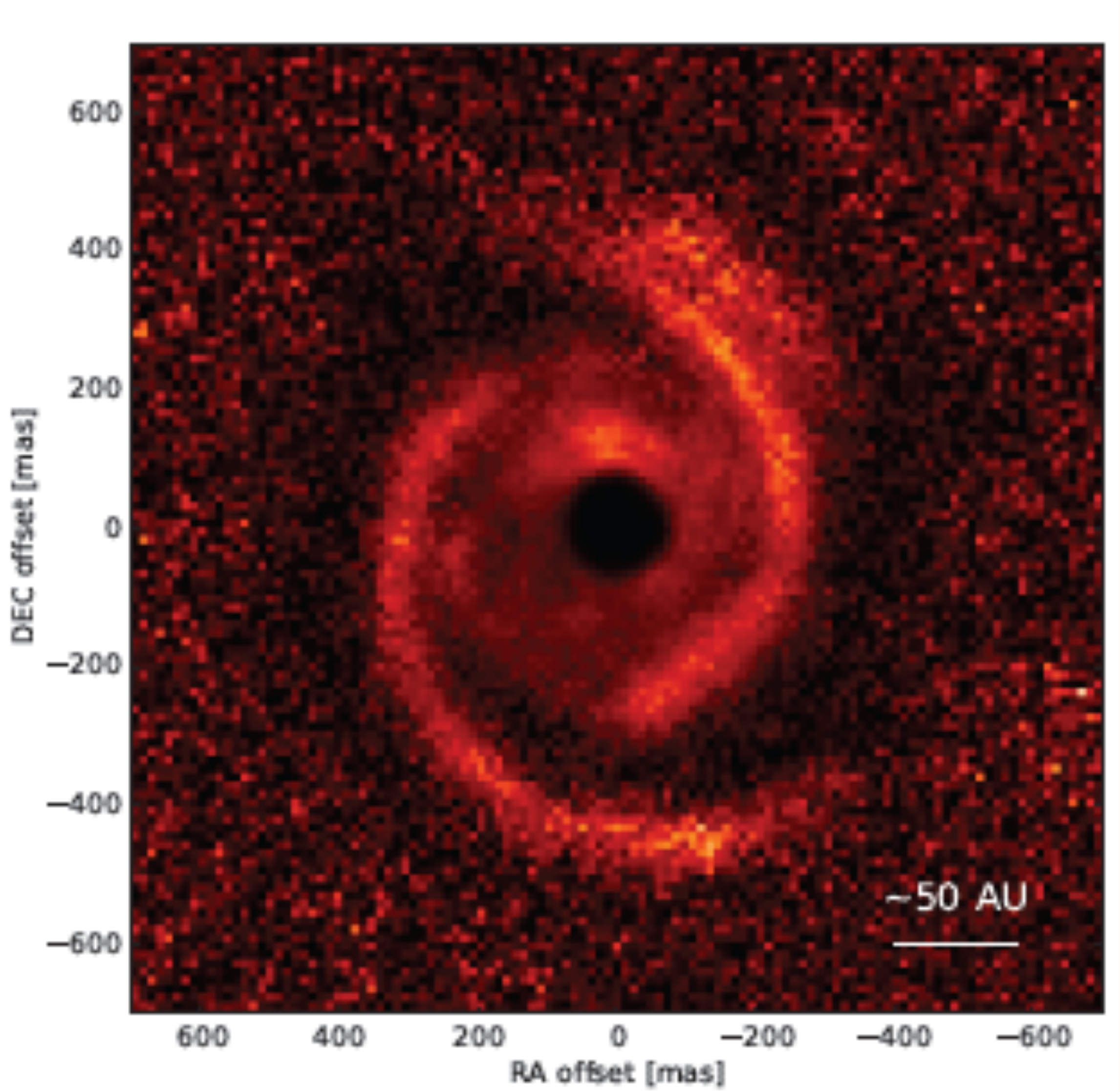
Comparison with Observations



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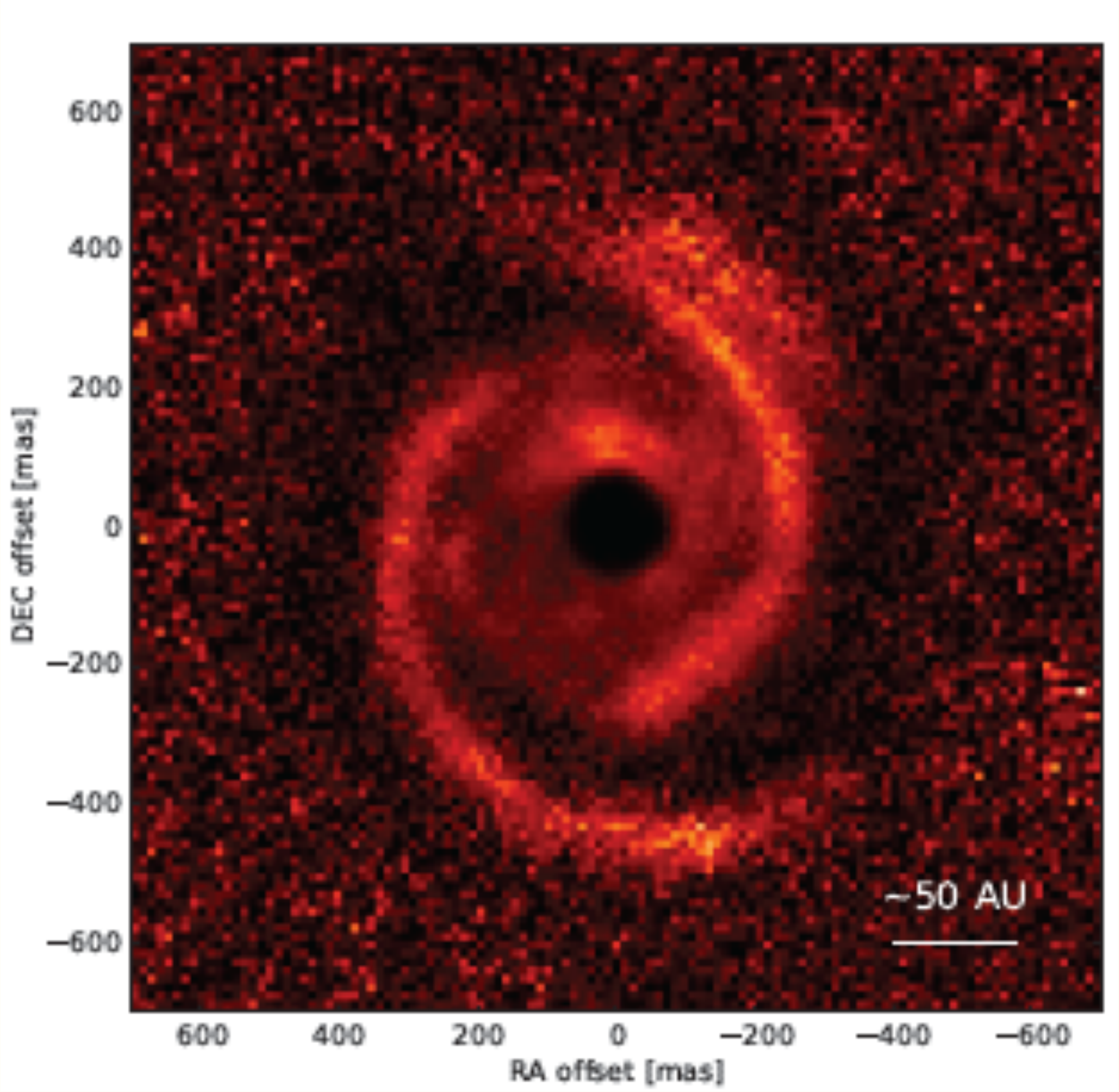
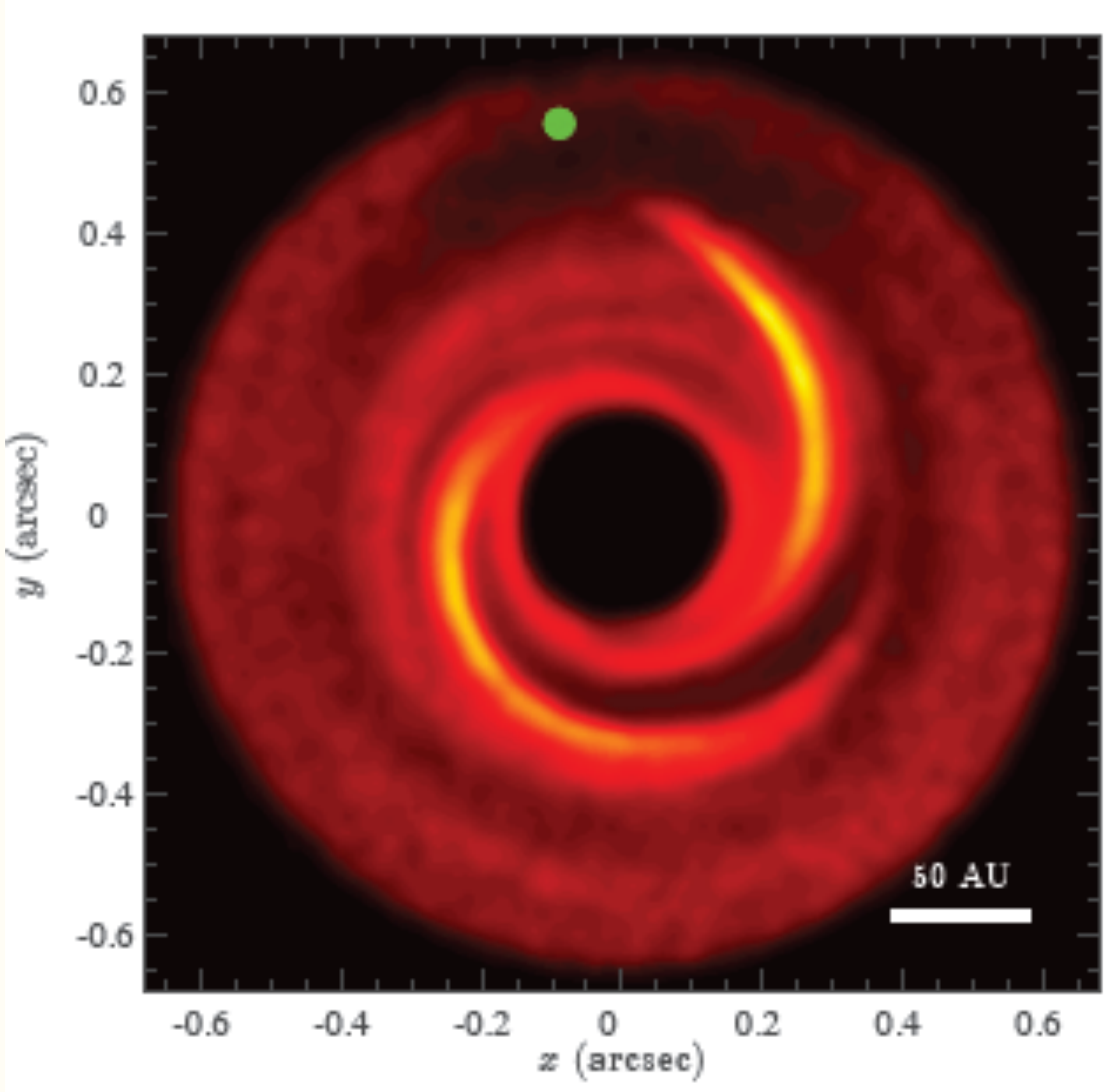


6 M_J planet



Dong+ (2015)

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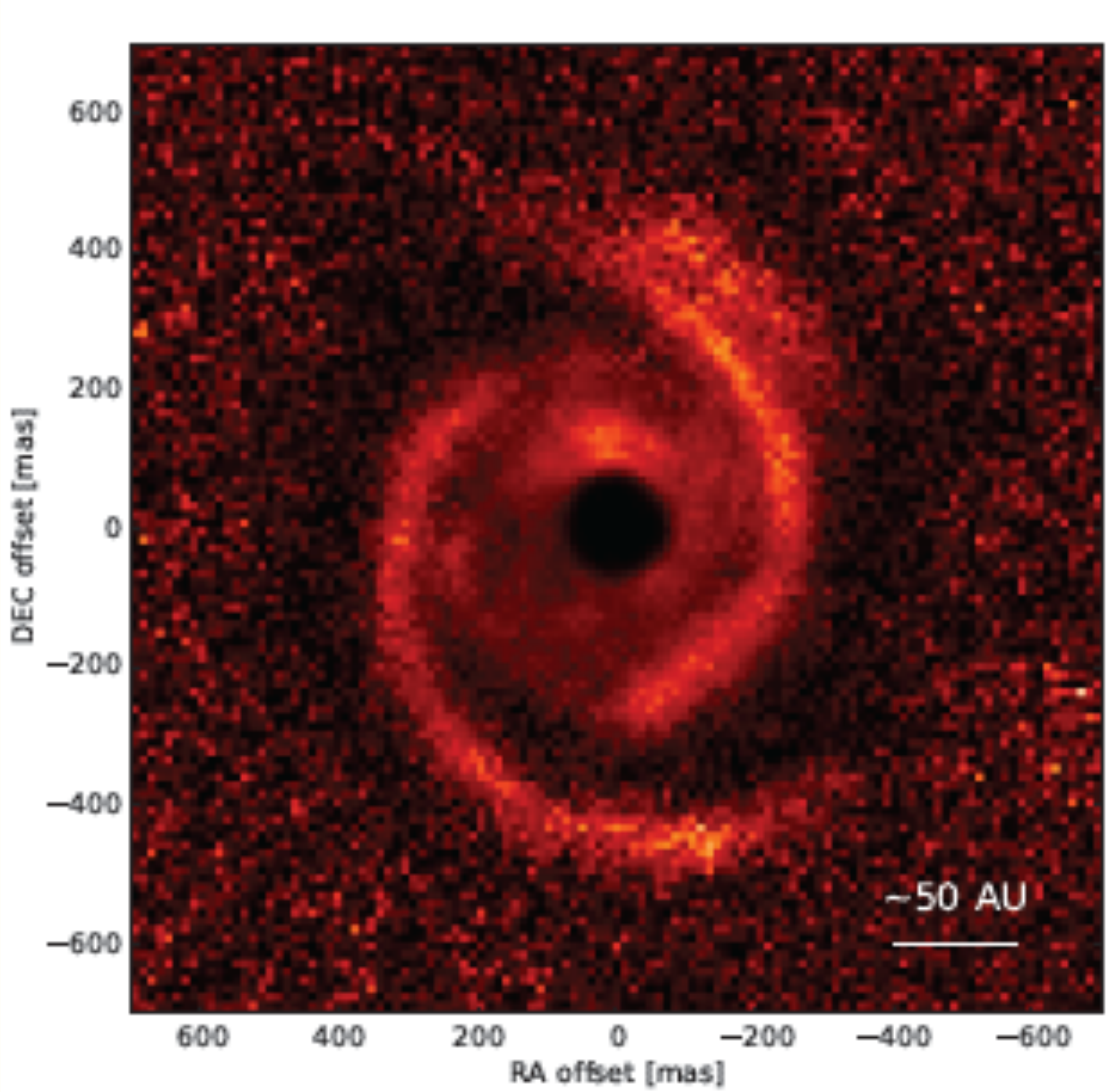

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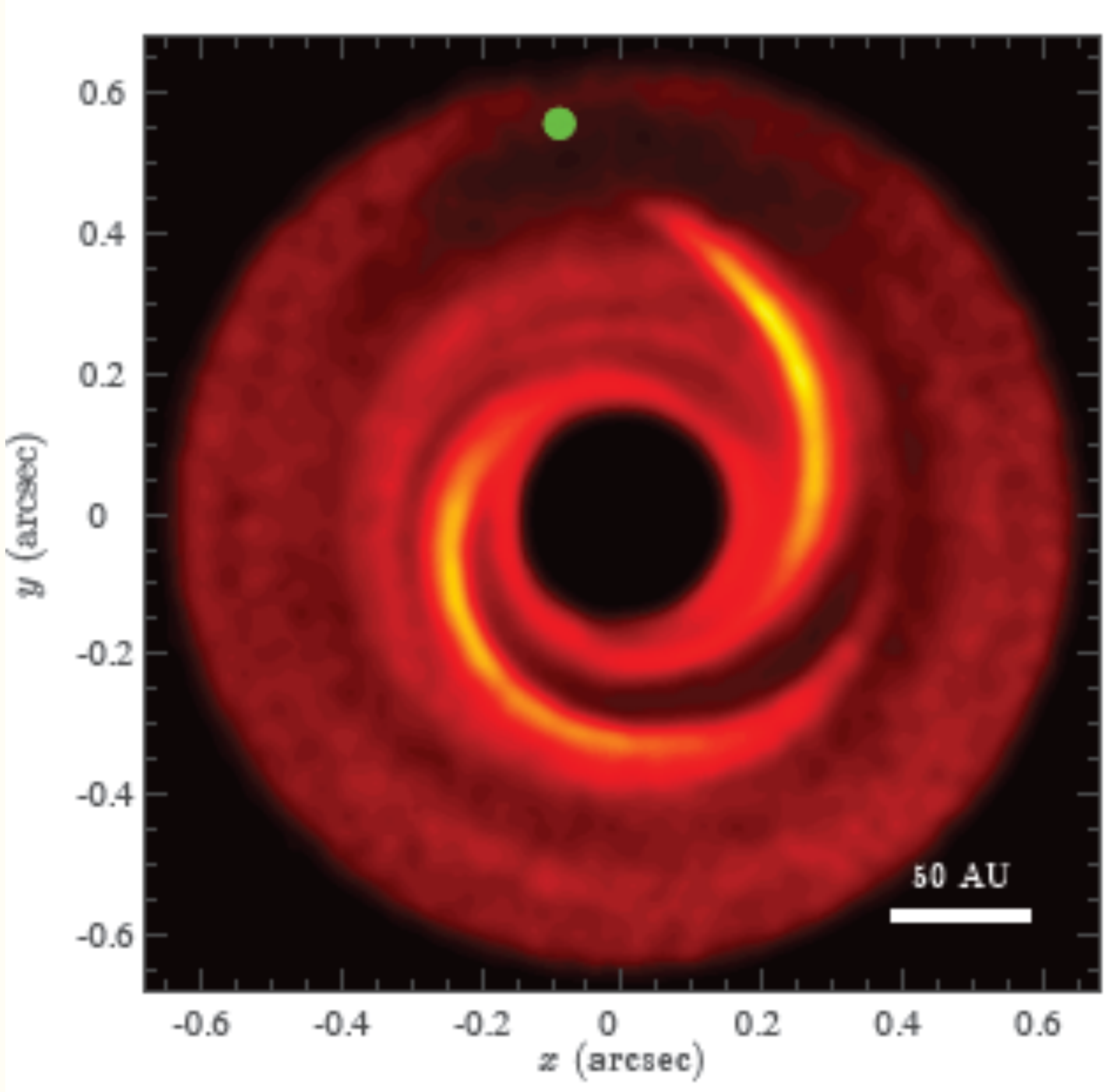

Planets at 30 AU, 10 years, rotates 30^{o}

Planets at 150 AU, 10 years, rotates 2.7^{o}

Dong+ (2015)

How to Directly Find Young Planets in Disks?

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Difficult!

$L_{Jupiter}=10^{-9}\ L_{sun}$

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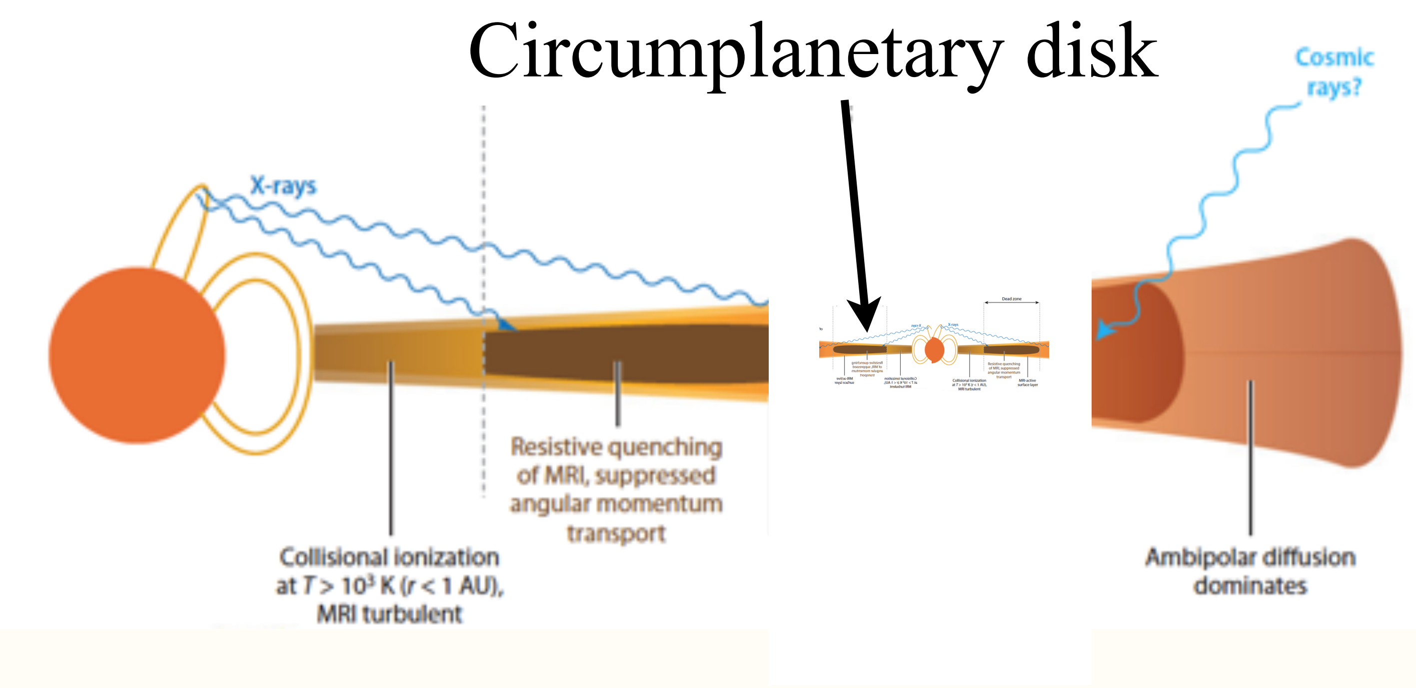

Circumplanetary disk

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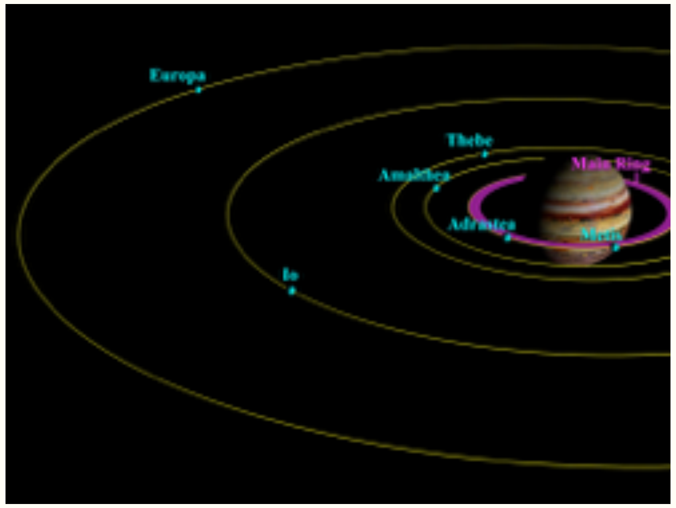

Canup & Ward 2002

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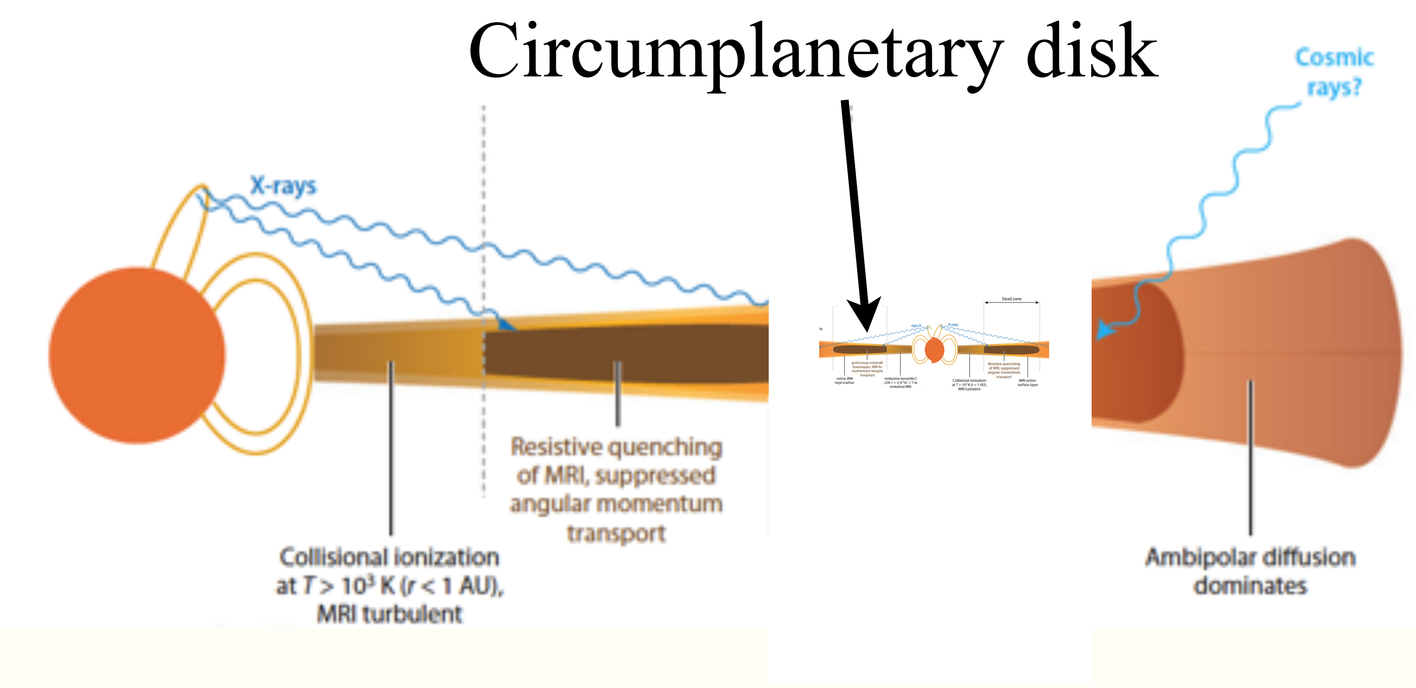

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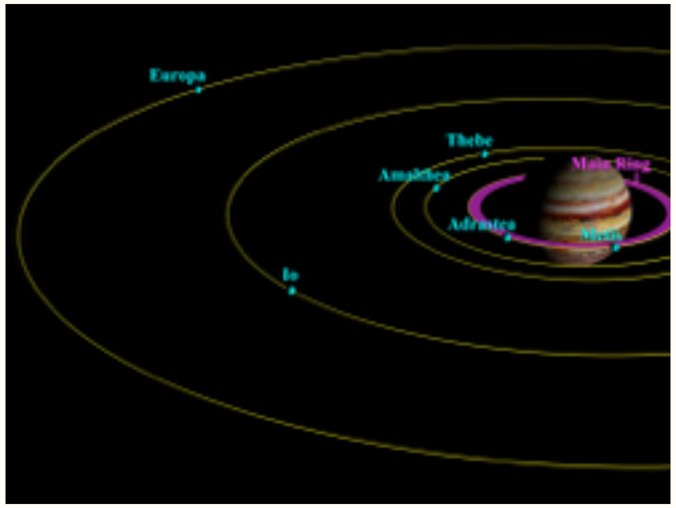

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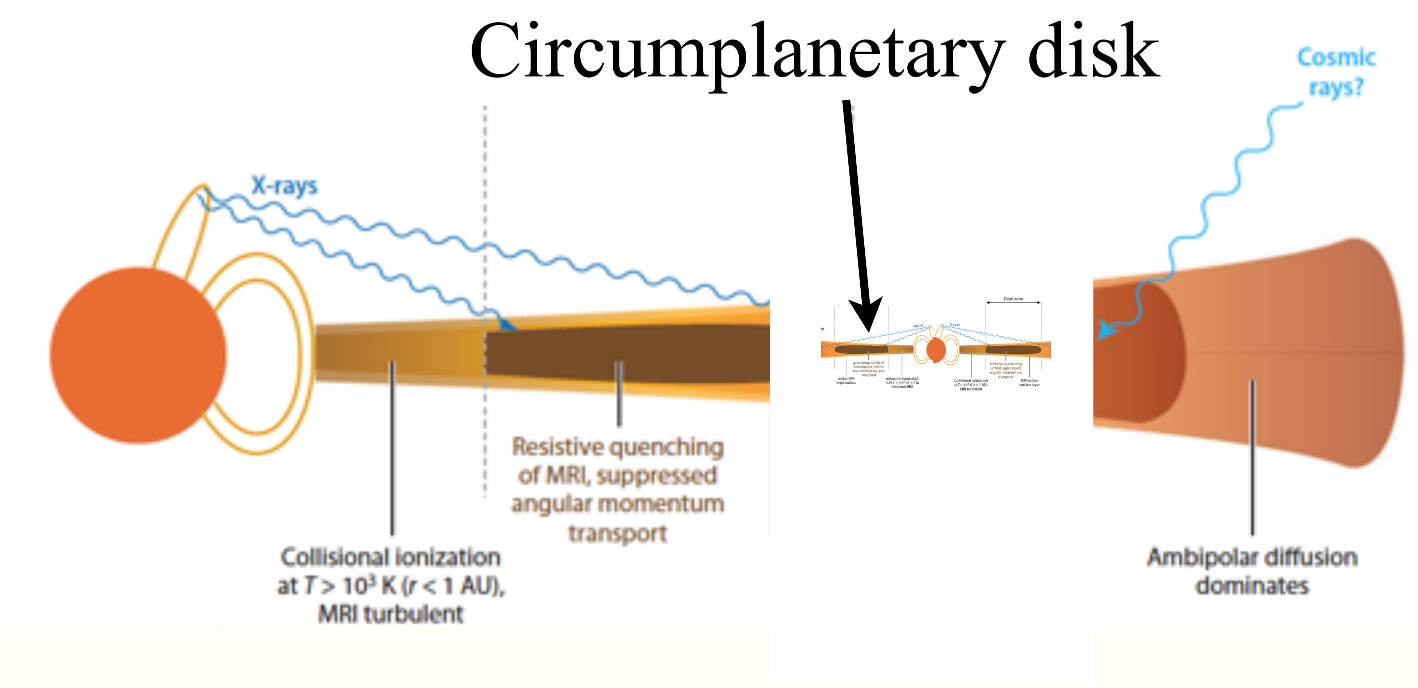
Circumplanetary disk

What if the circumplanetary disk is accreting?

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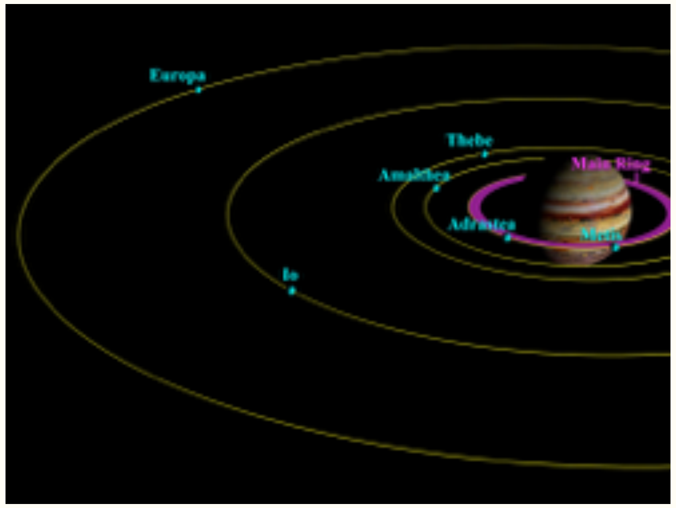

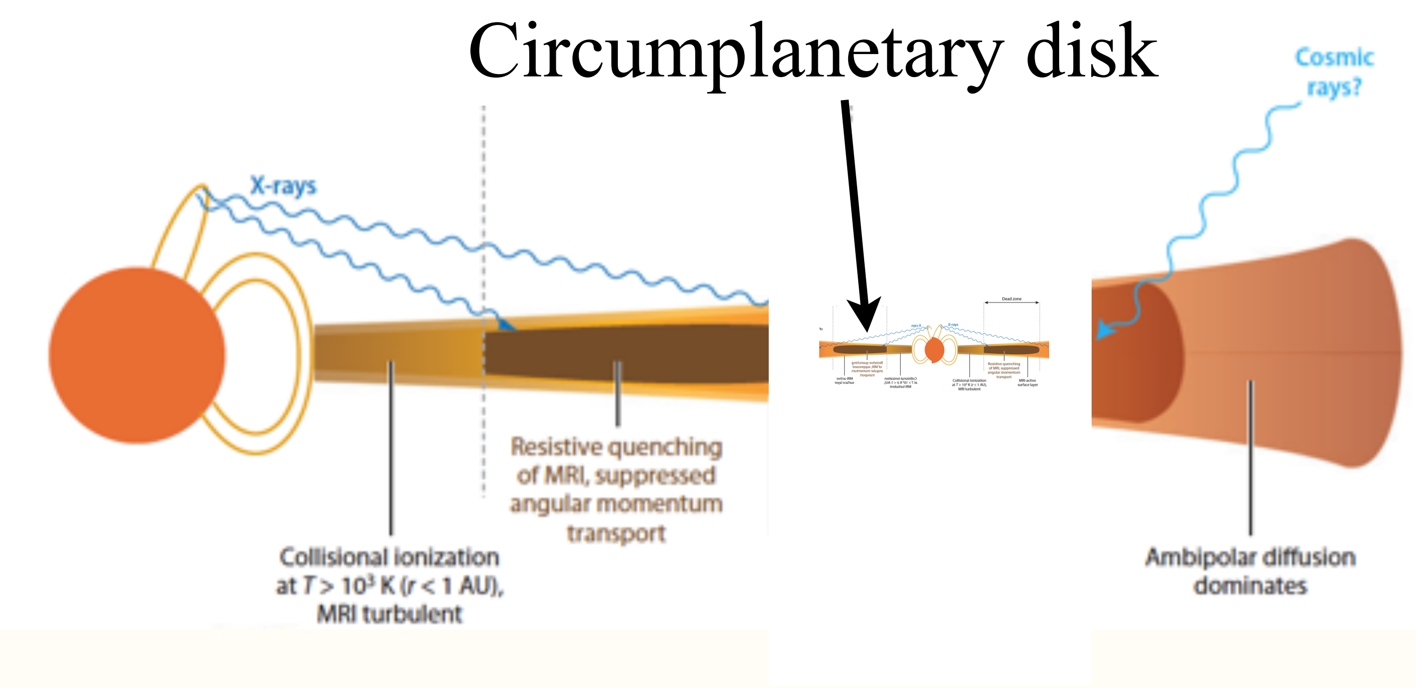

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If a Jupiter mass planet is accreting at $\dot{M}=10^{-5}\ M_{Jupiter}/yr$

$$L_{accretion}=0.5\ GM_{Jupiter}\dot{M}/R_{Jupiter}=1.5\times10^{-3}\ L_{sun}$$

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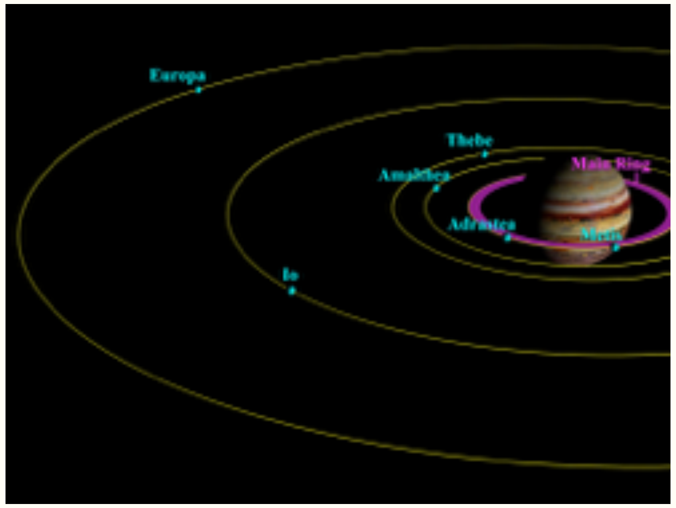

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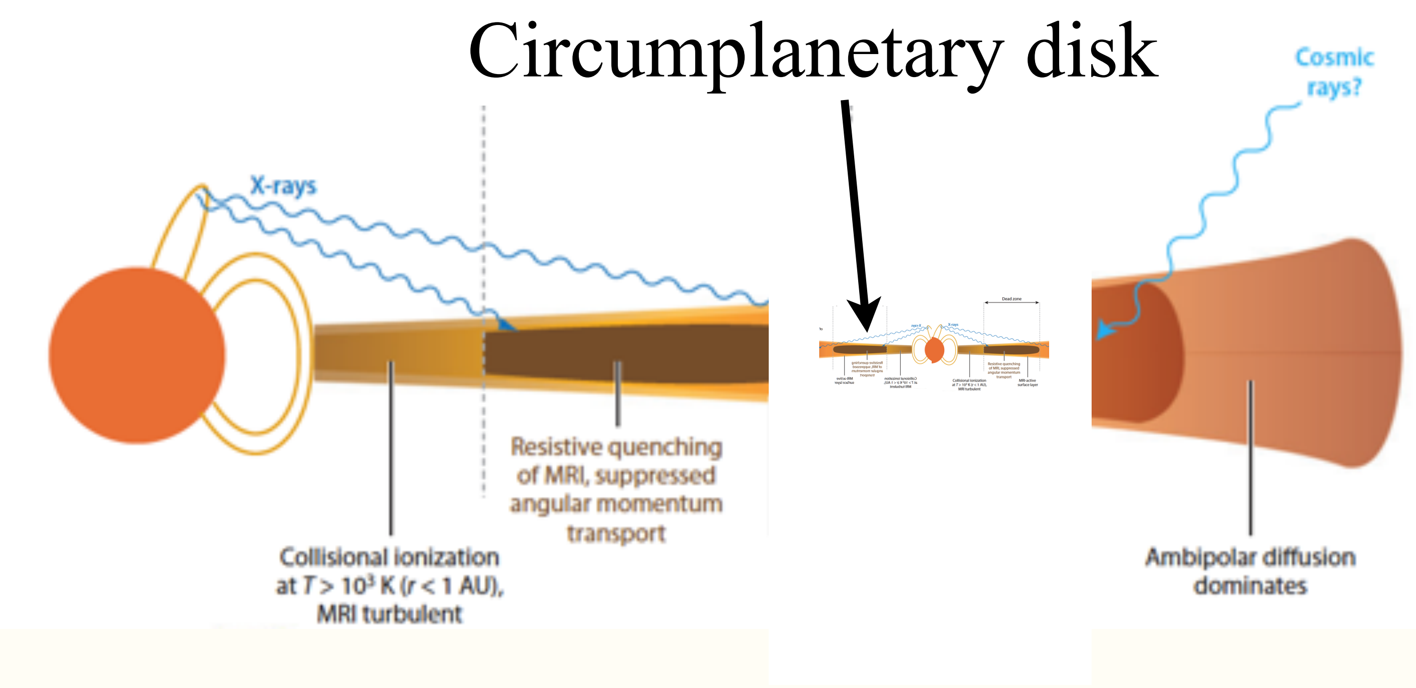

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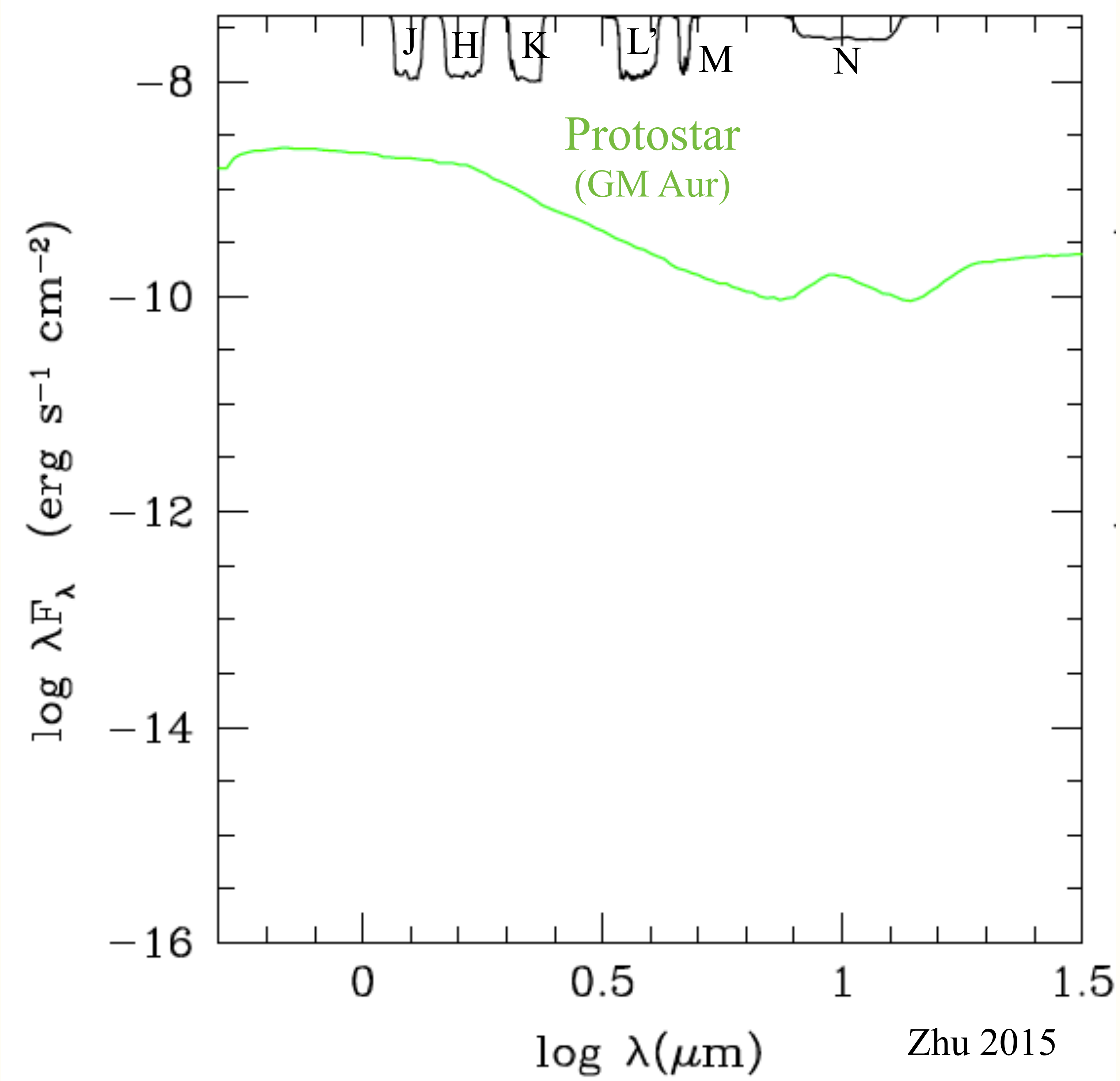
As bright as M type brown dwarfs!

Accreting Circumplanetary Disks (CPDs): SEDs



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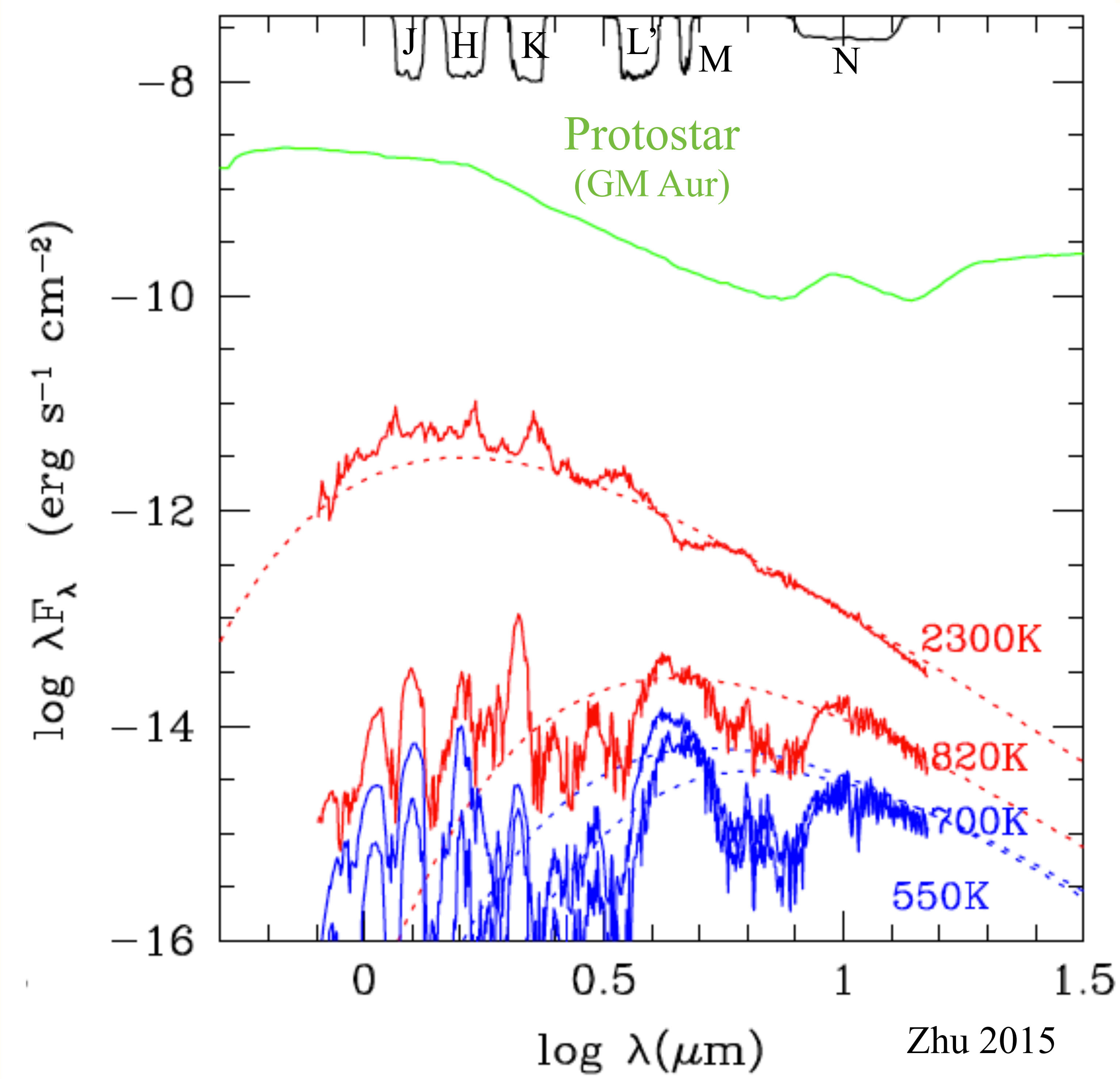

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Planet (Hot/Cold start)

Spiegel & Burrows 2012

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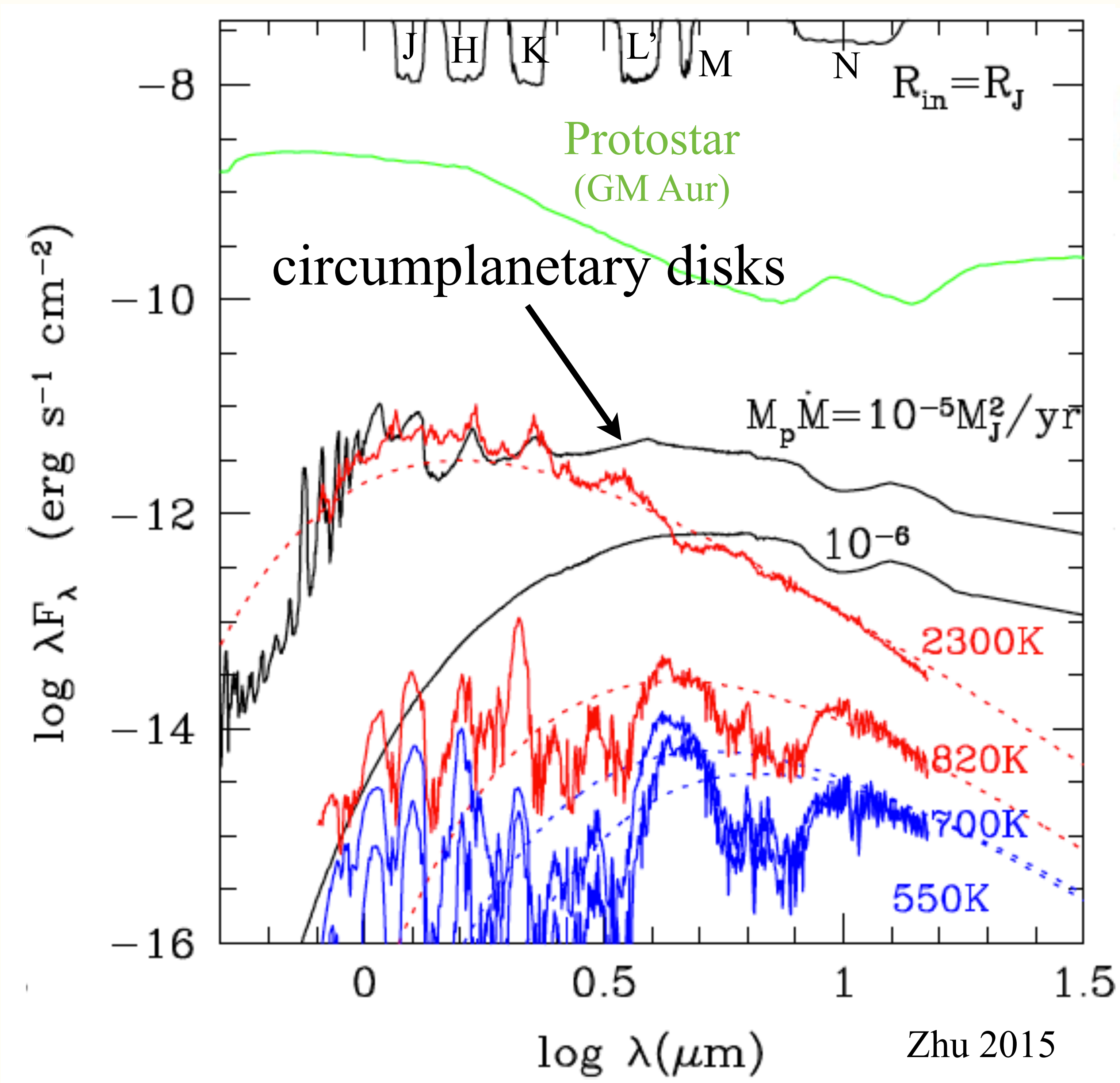

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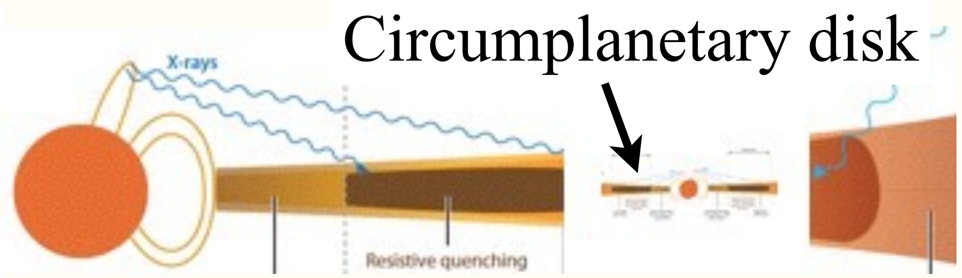

$$\sigma T_{\rm eff}^4 = \frac{3GM_p\dot{M}}{8\pi\sigma R^3}\left(1-\left(\frac{R_{\rm in}}{R}\right)^{1/2}\right)$$

Disk radiative transfer model

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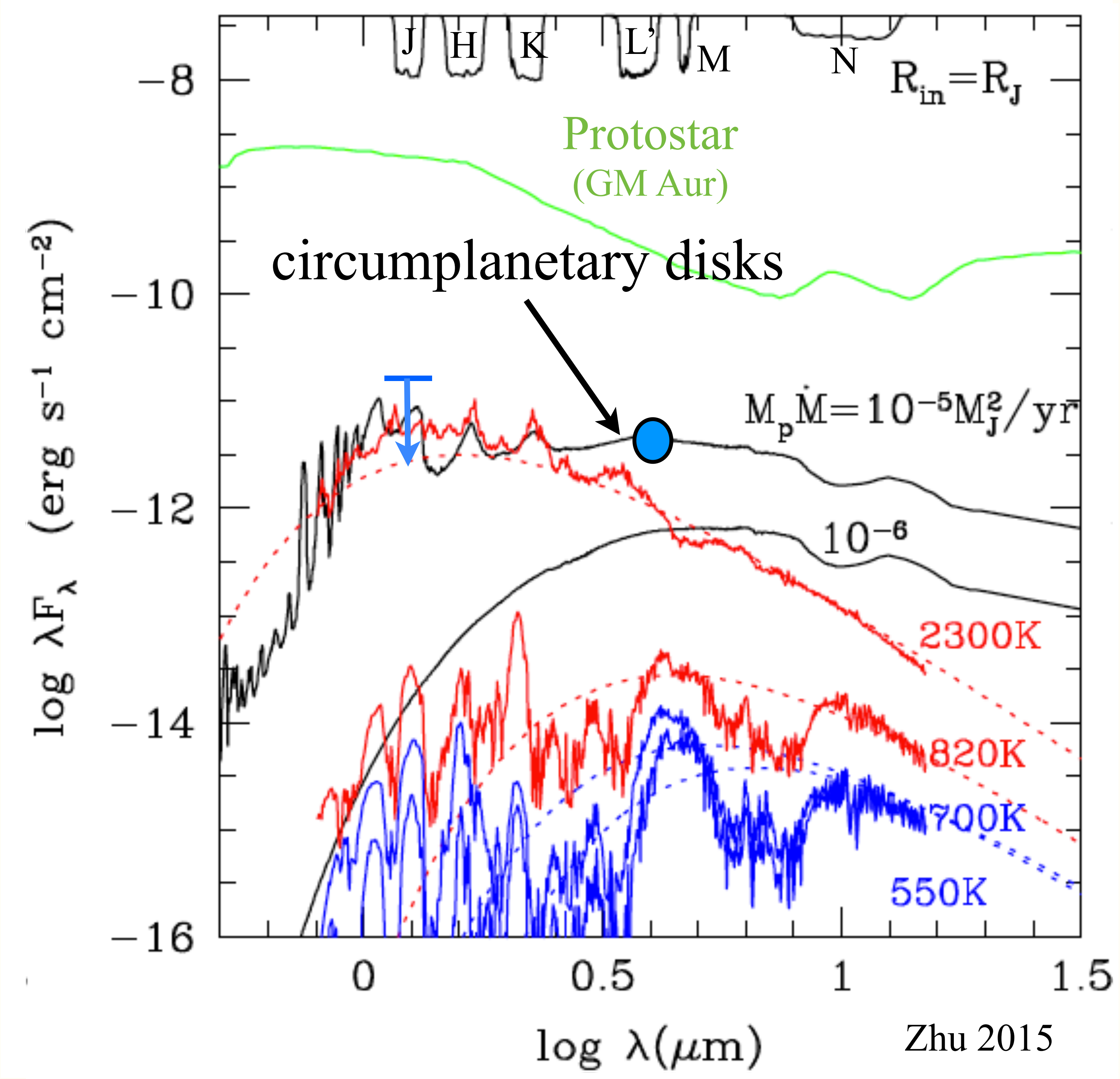

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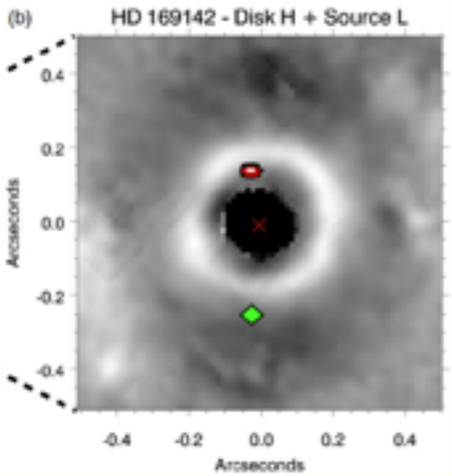

Reggiani et al. 2014
Biller et al. 2014

	Observations	Theory
HD 169142		
J band:	>13.8	15.1
L' band:	12.2±0.5	12.4
M band:	?	11.6
N band:	?	10.1

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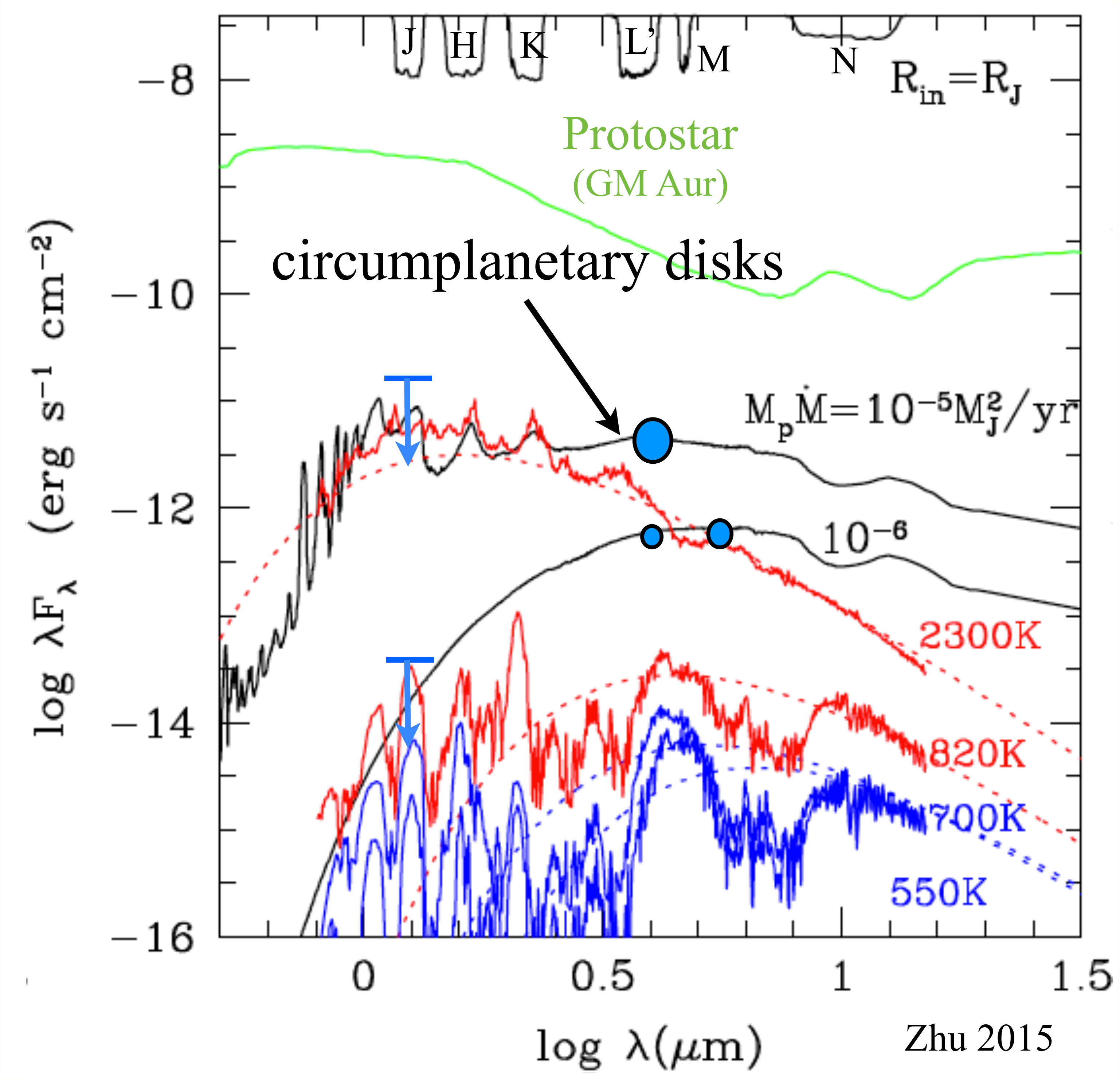

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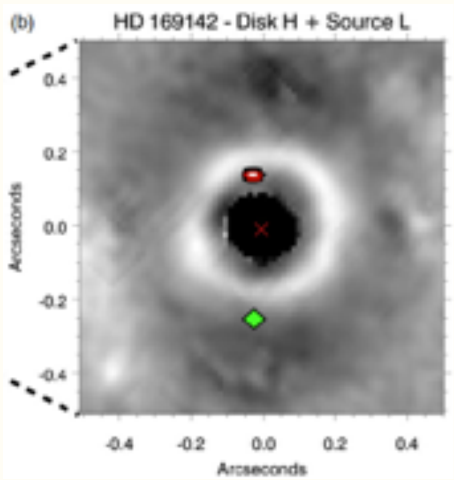

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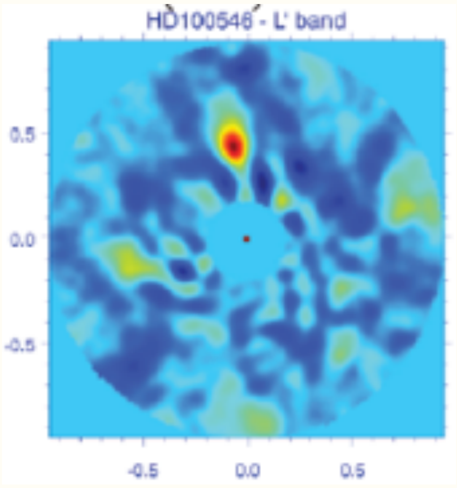

Currie et al. 2014
Quanz et al. 2014

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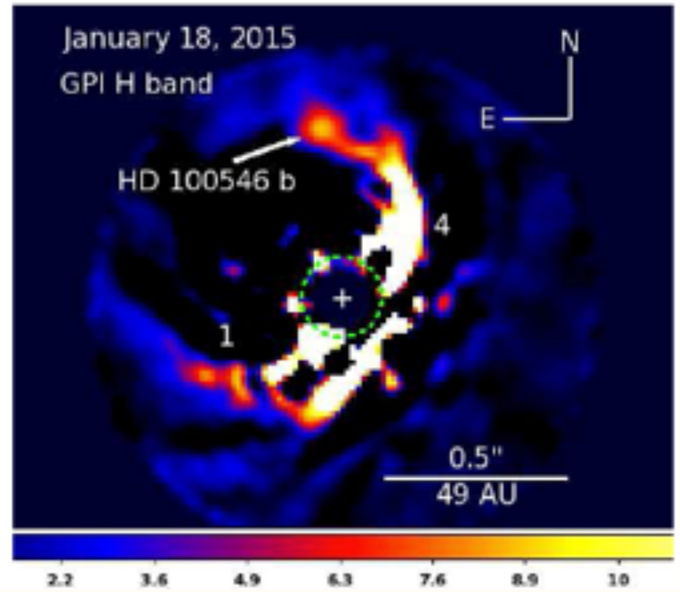
HD 100546		
Ks band:	>15.43±0.11	16.5
L' band:	13.92±0.10	13.9
M band:	13.33±0.16	13.1
N band:	?	11.4

Accreting Circumplanetary Disks: More Evidence

HD 100456



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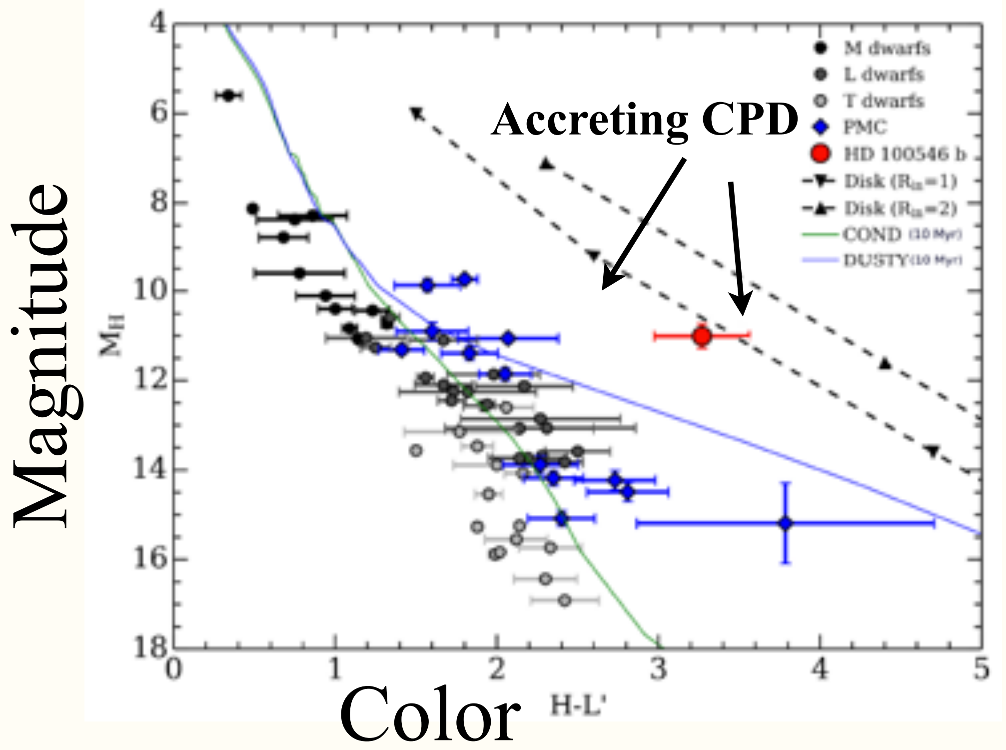

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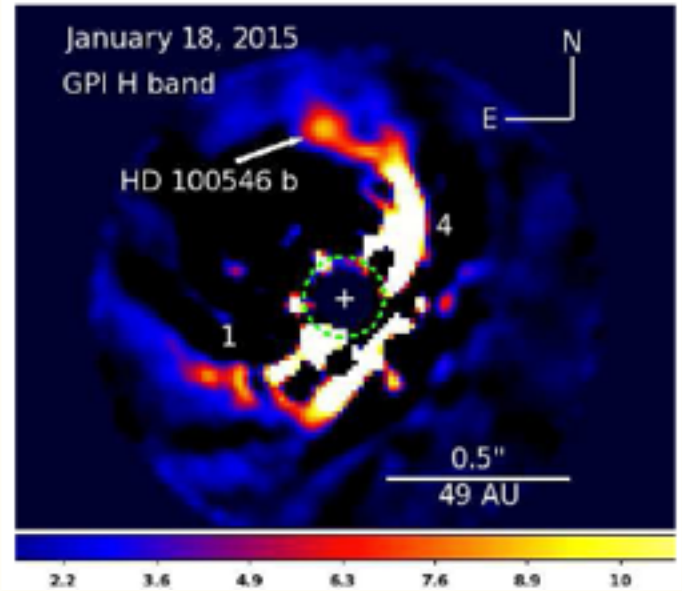

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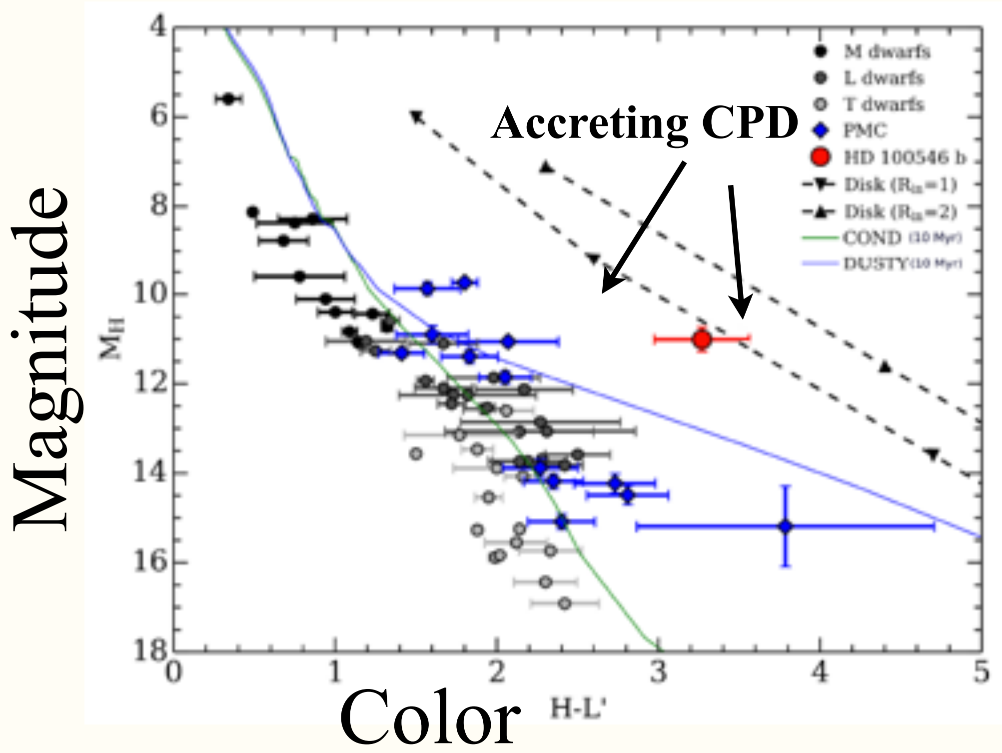
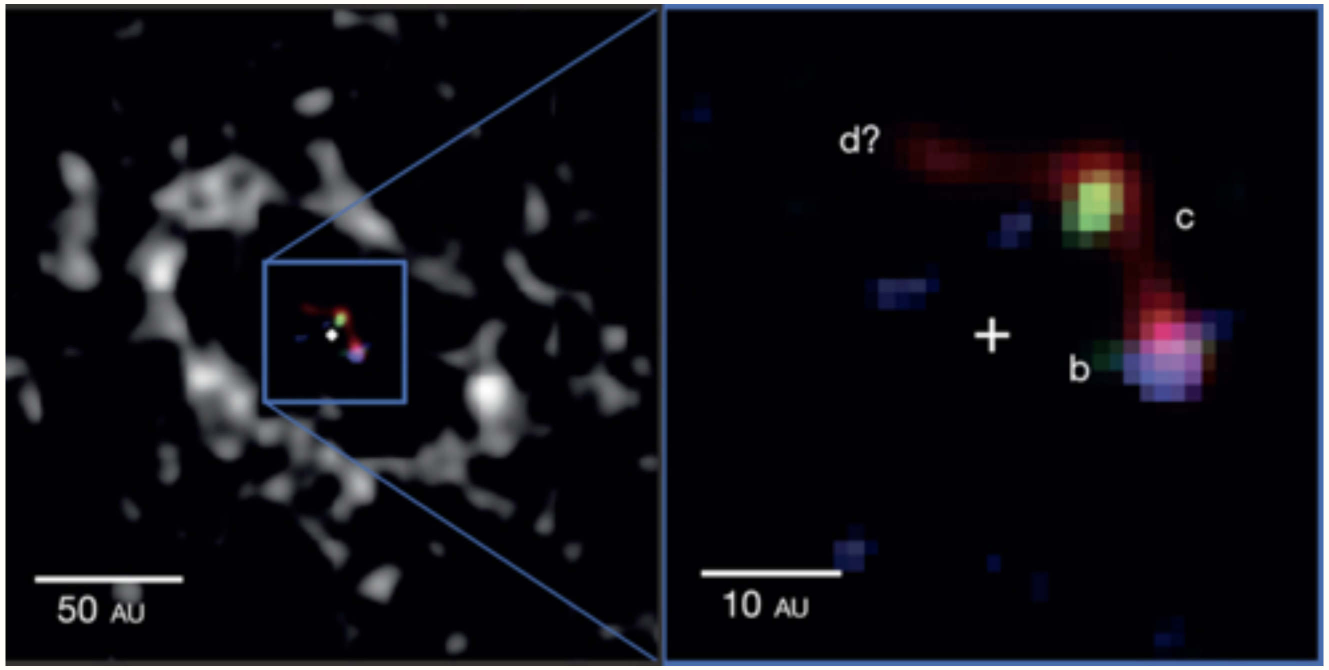


Accreting CPD

Magnitude

Color

Lk Ca 15



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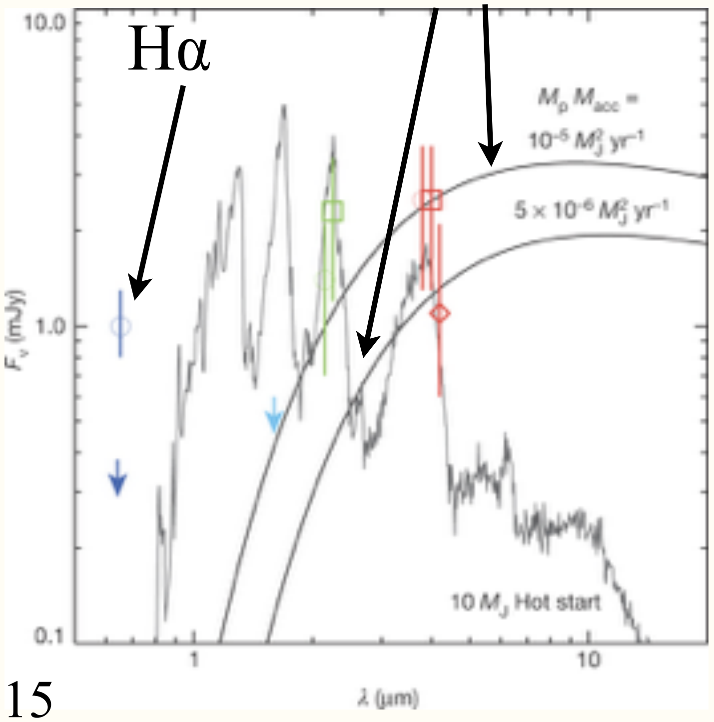

Hα

Sallum+ 2015

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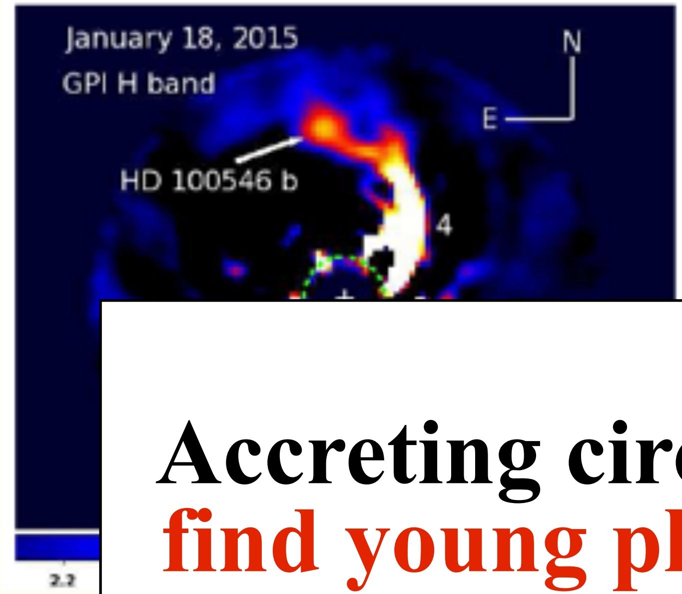
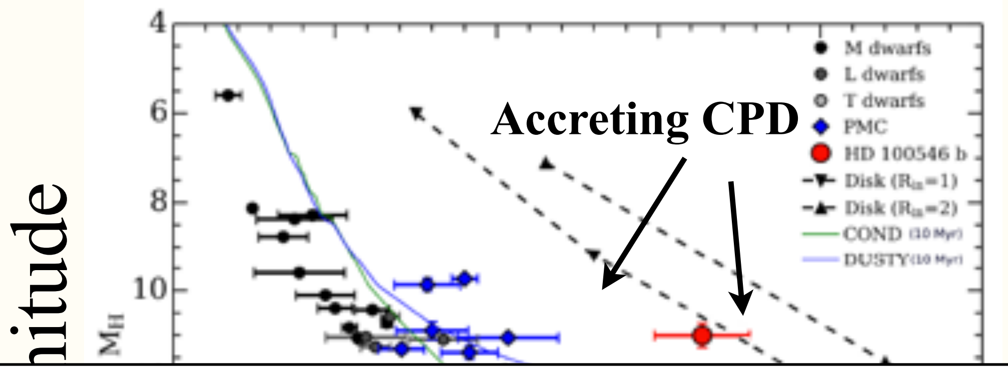
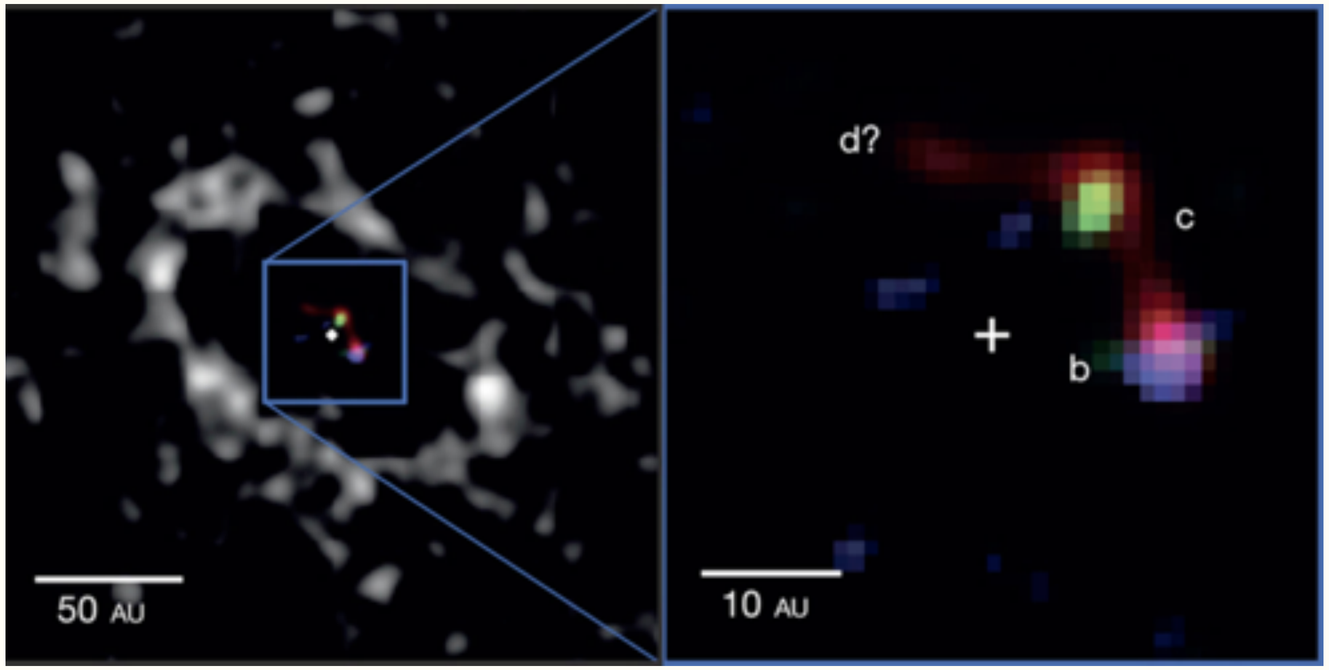




Accreting CPD

Accreting circumplanetary disks may be the key to find young planets directly.

Lk Ca 15



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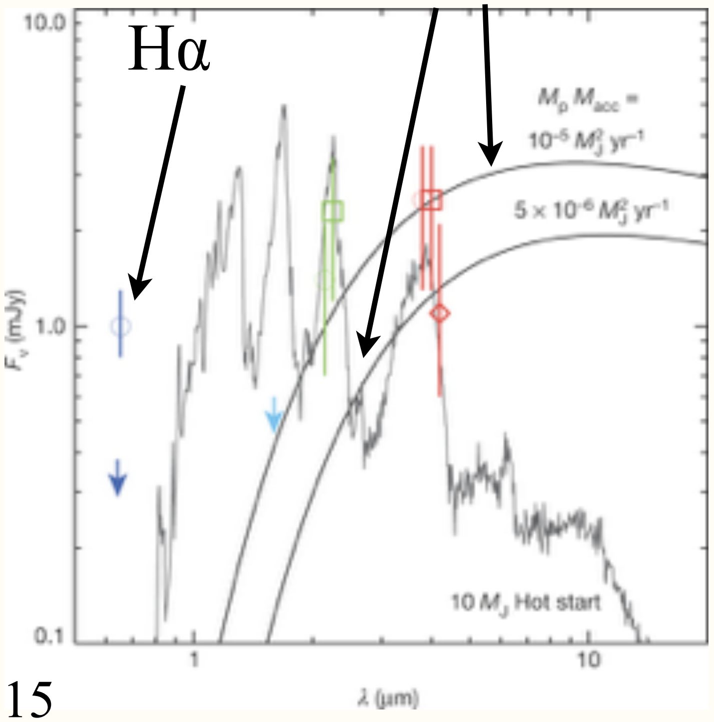

Sallum+ 2015

How CPDs accrete? Ideas from Circumstellar Disks

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- Turbulence (viscous model): Ayliffe & Bate 2009
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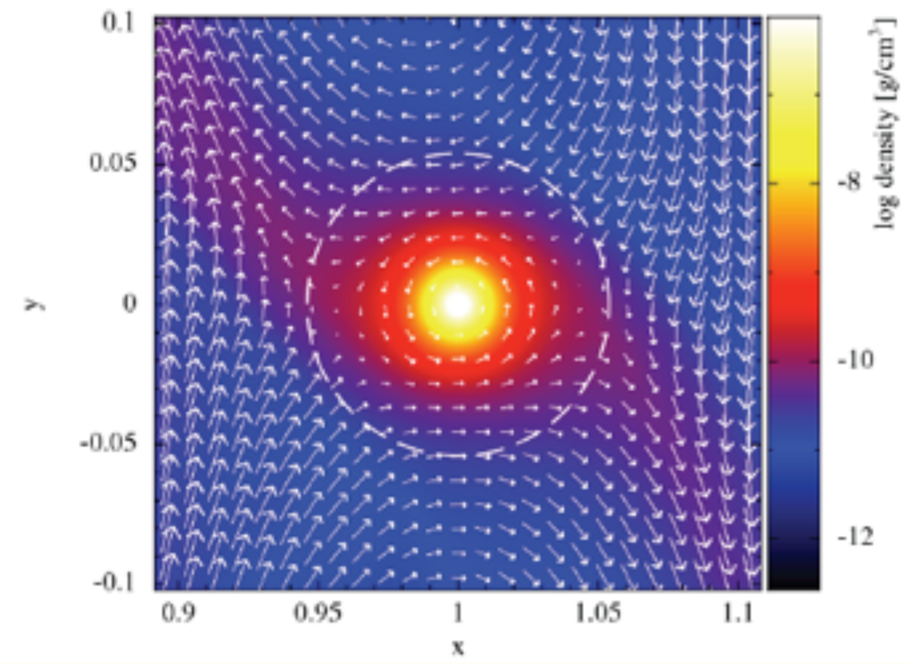

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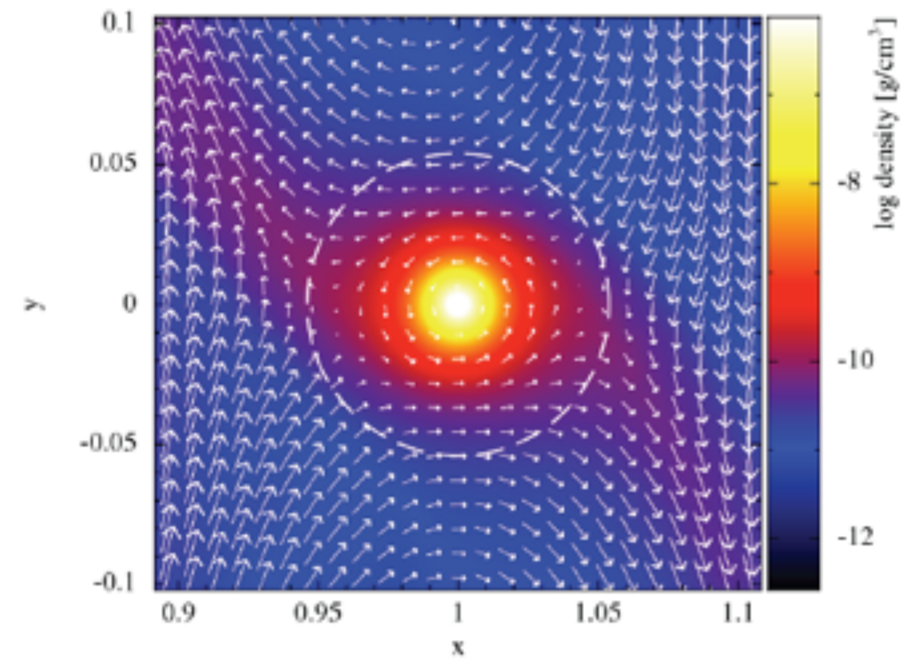

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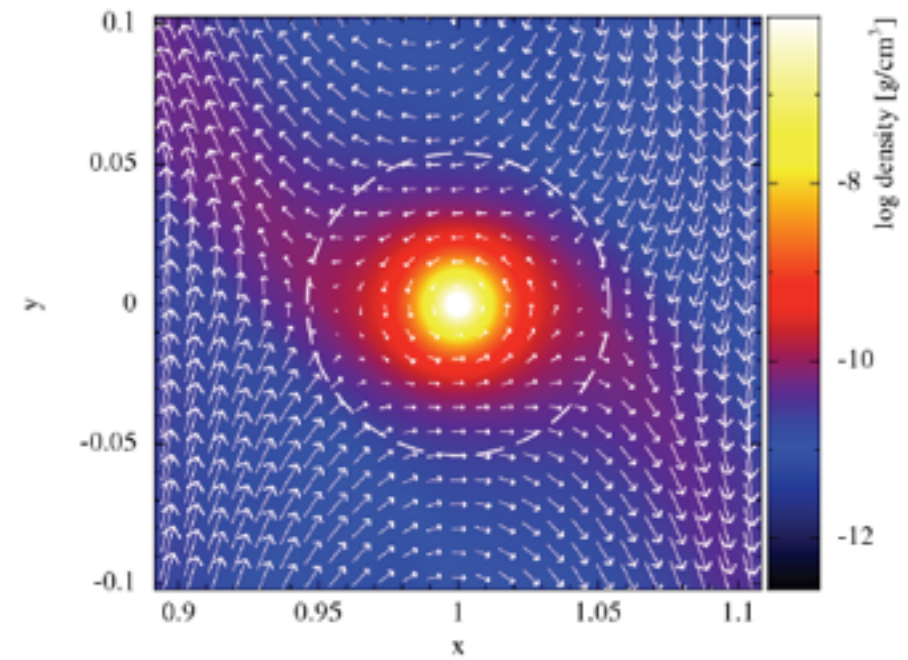
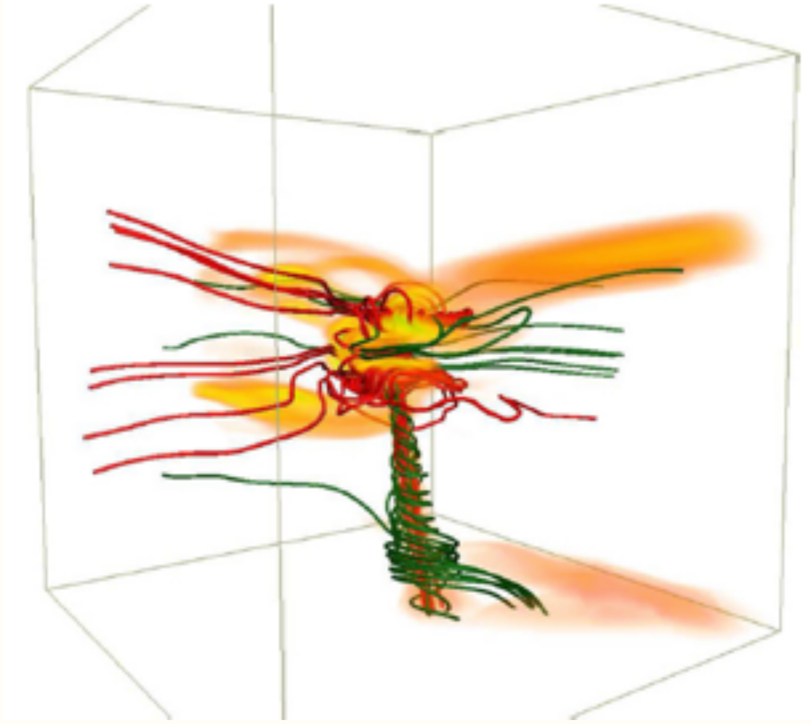


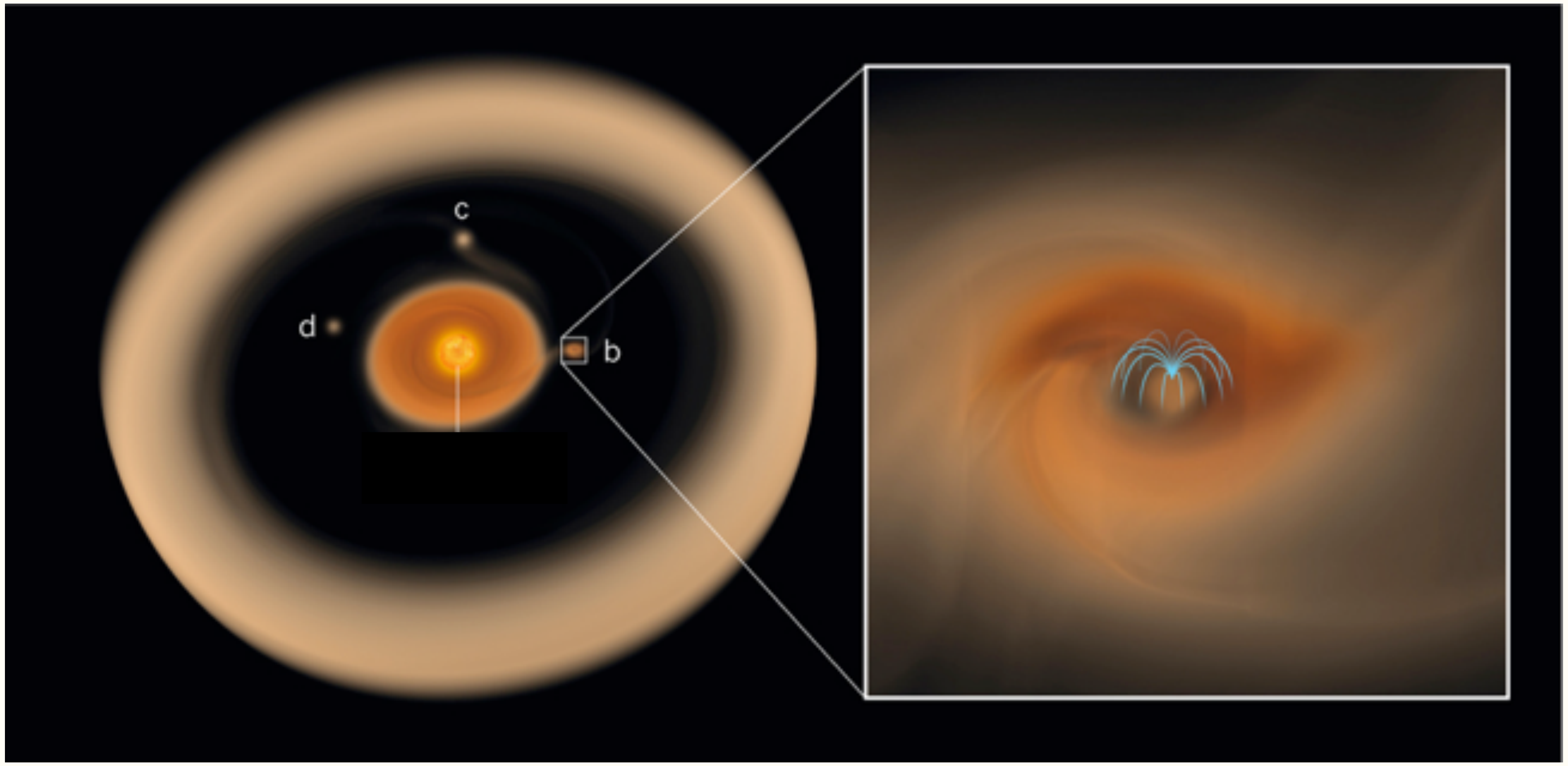
- Non-ideal MHD effects: Turner+ 2014, Fujii+ 2014, Keith & Wardle 2015

- Wind, outflow and jets:



Gressel+ 2015

How CPDs accrete? Ideas from Binaries



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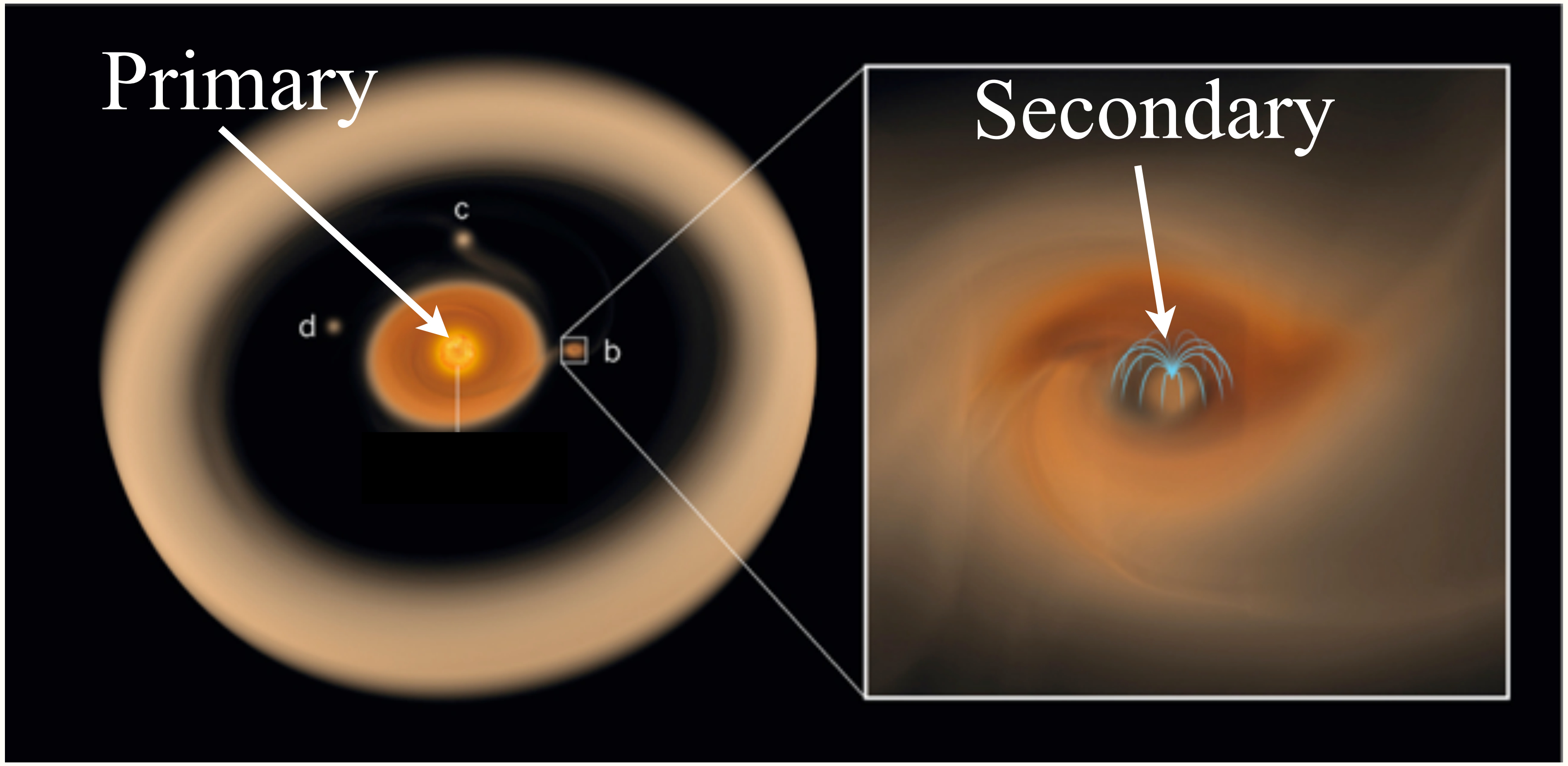

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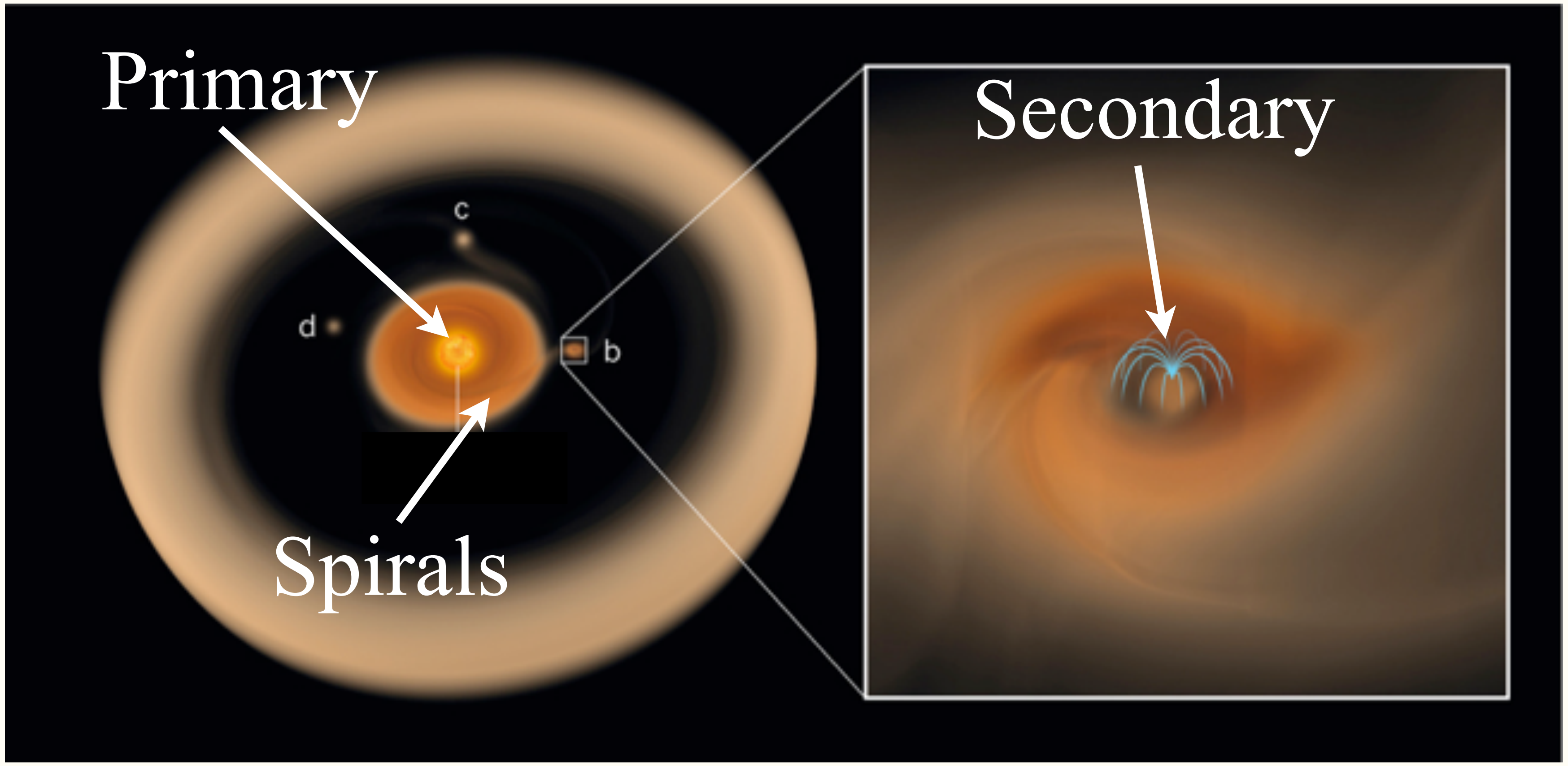

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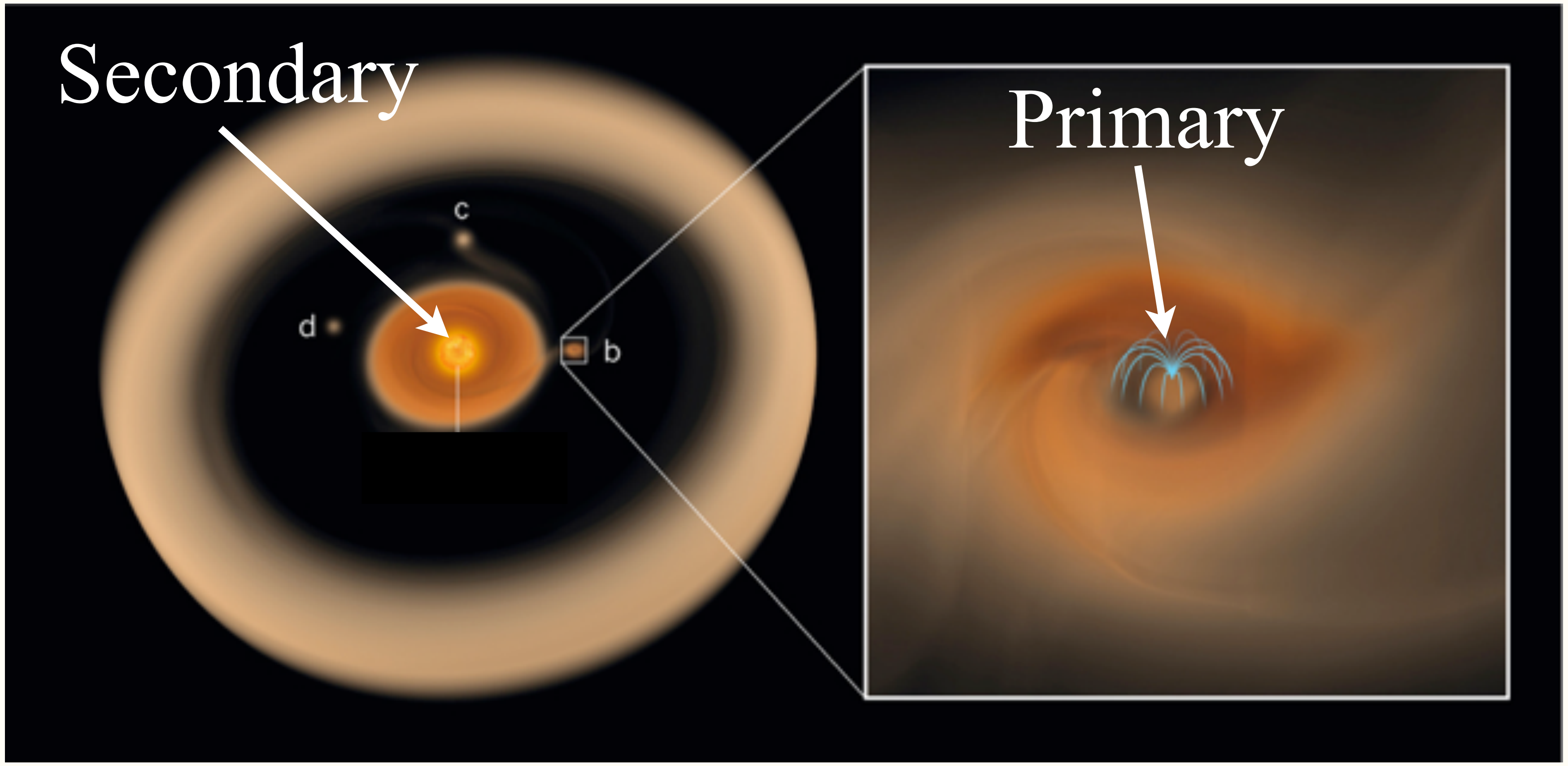

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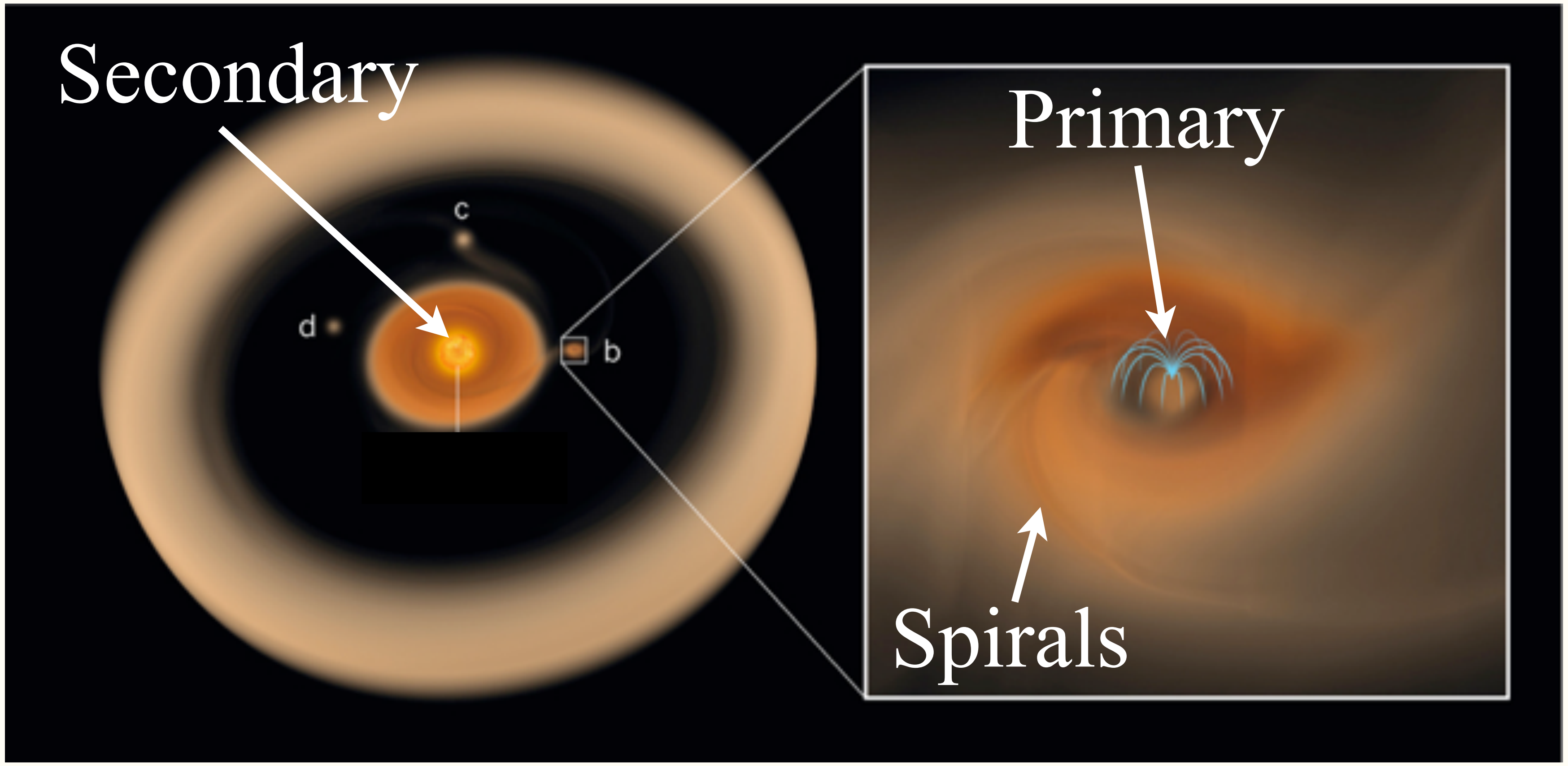

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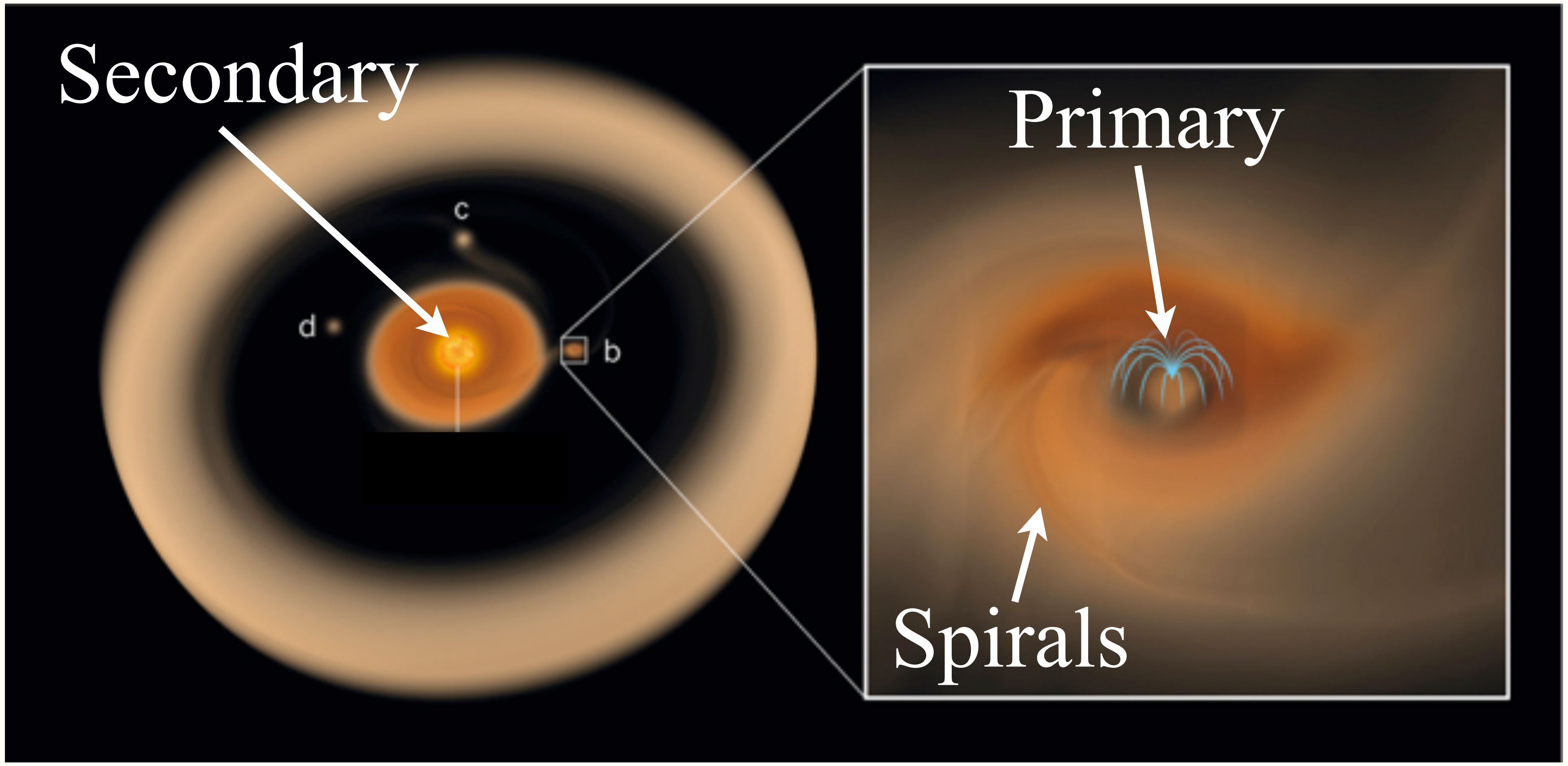

Spiral shocks excited by the star can transport angular momentum

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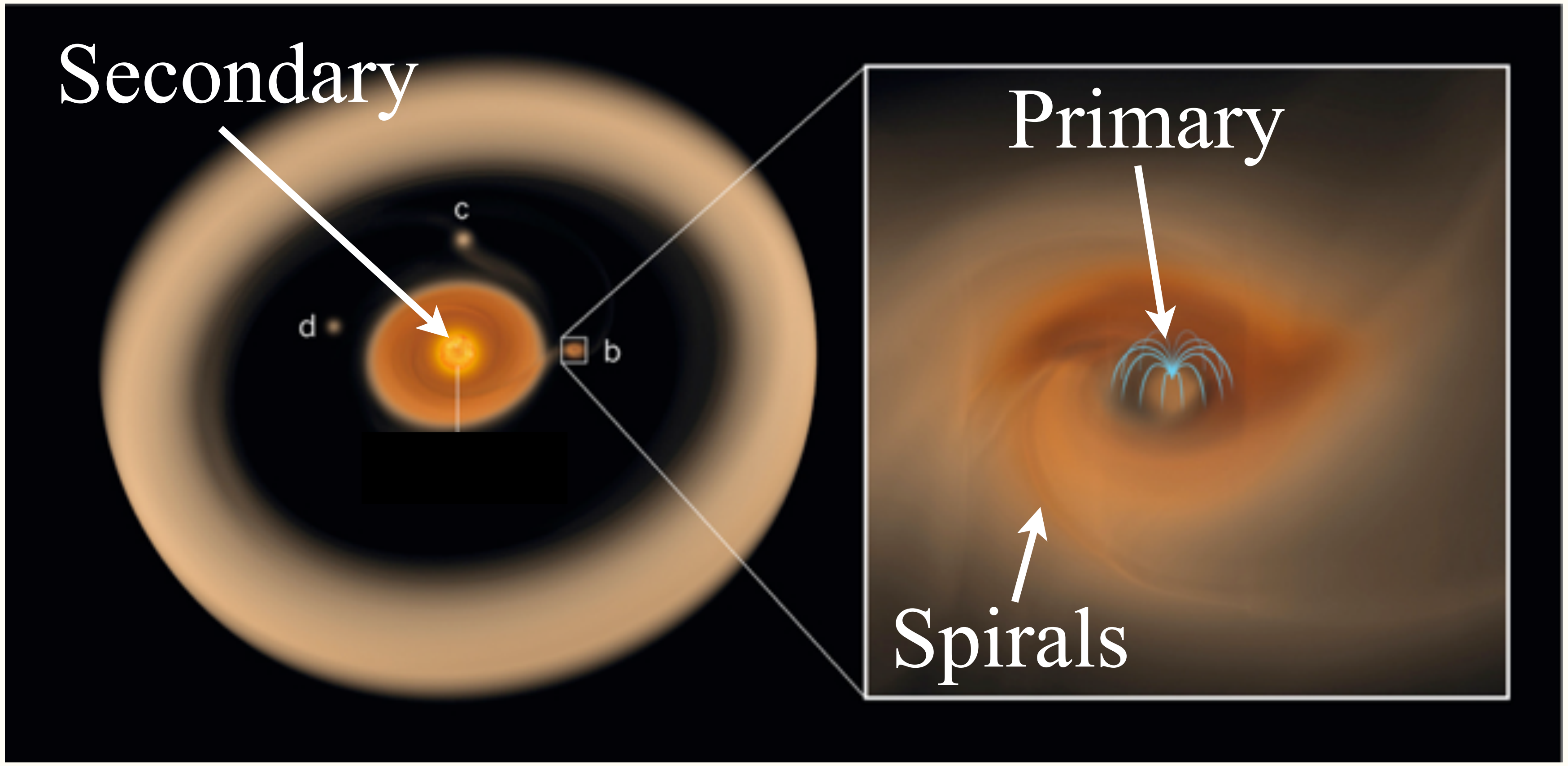

Spiral shocks excited by the star can transport angular momentum

Larson 1990: semi-analytically derived

$$\alpha \sim 0.013[(c_s/V)^3 + 0.08(c_s/V)^2]^{1/2}$$

(for a steady, self-similar shock)

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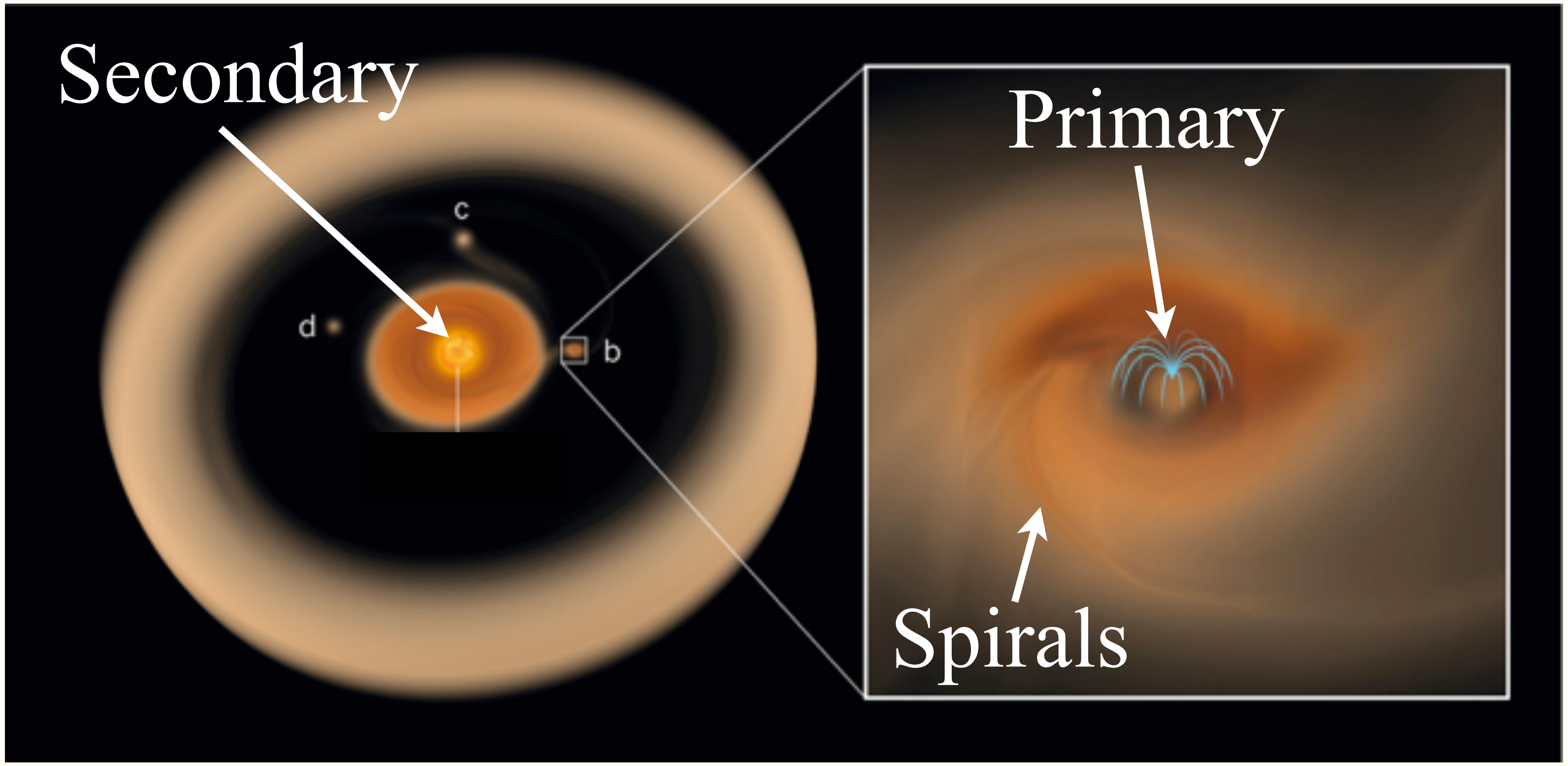

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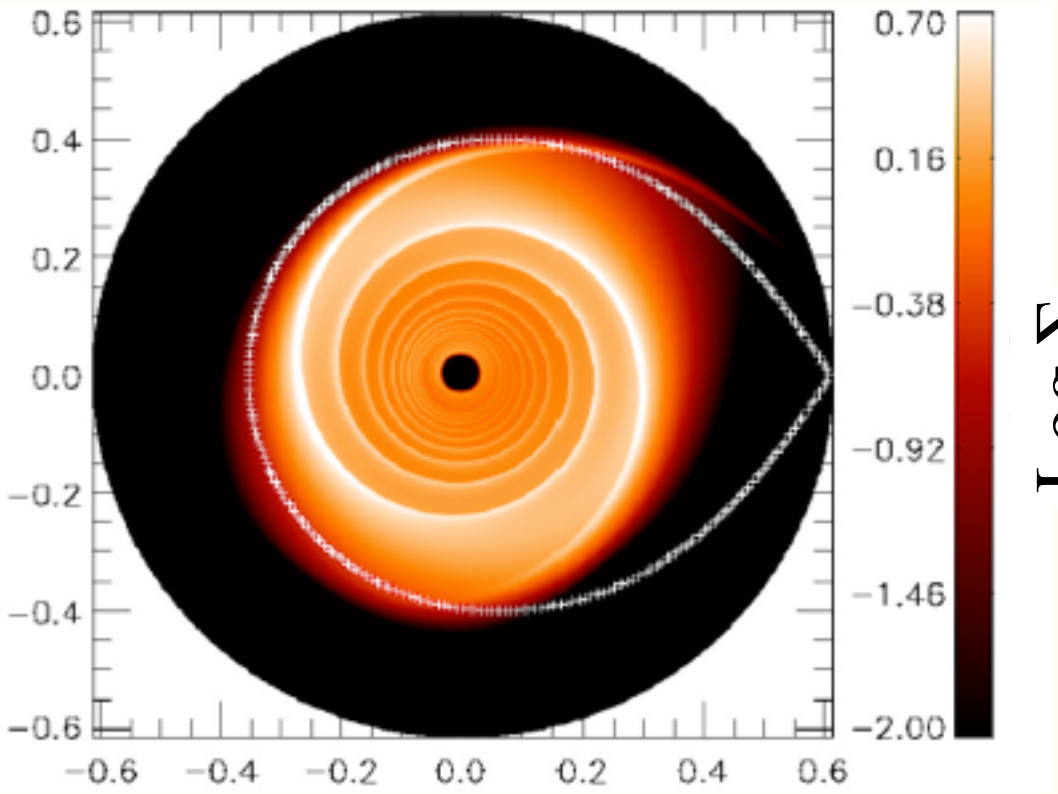
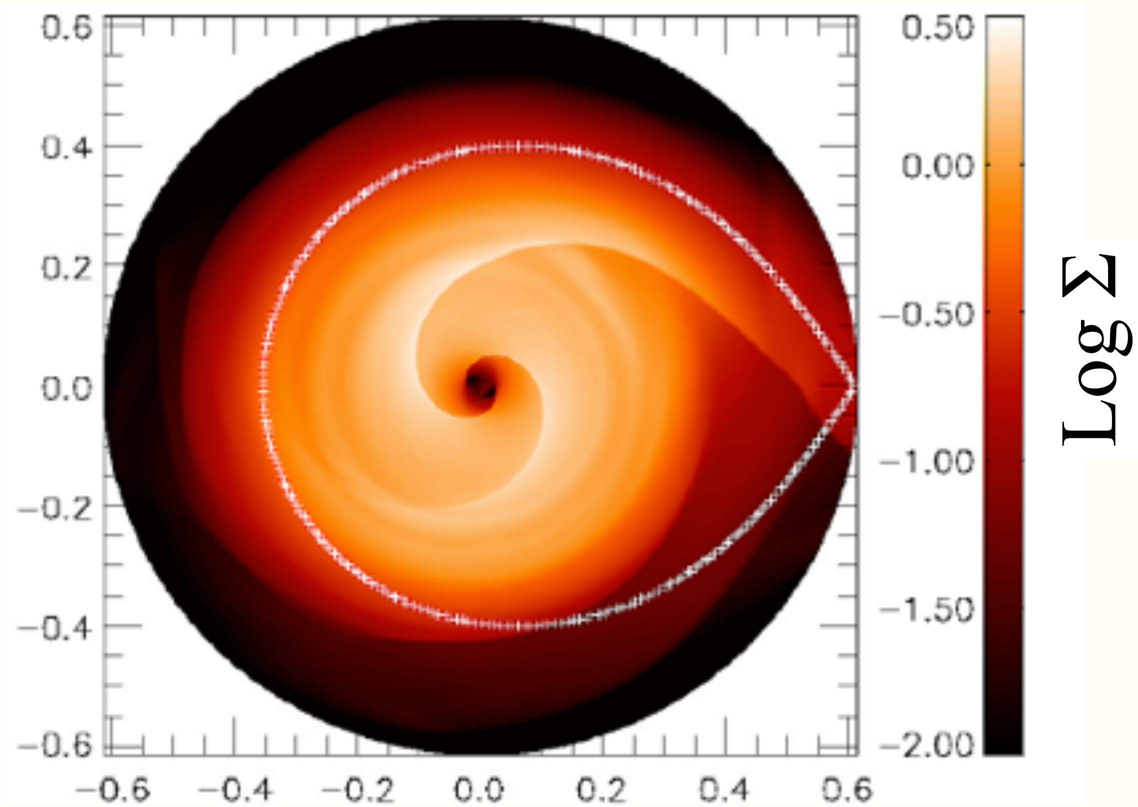
Shock-driven accretion can be efficient when the disk is hot

Accretion Depends on Disk Temperature

Cold (isothermal simulation)



Hot (adiabatic simulation)



Ju, Stone, Zhu 2016

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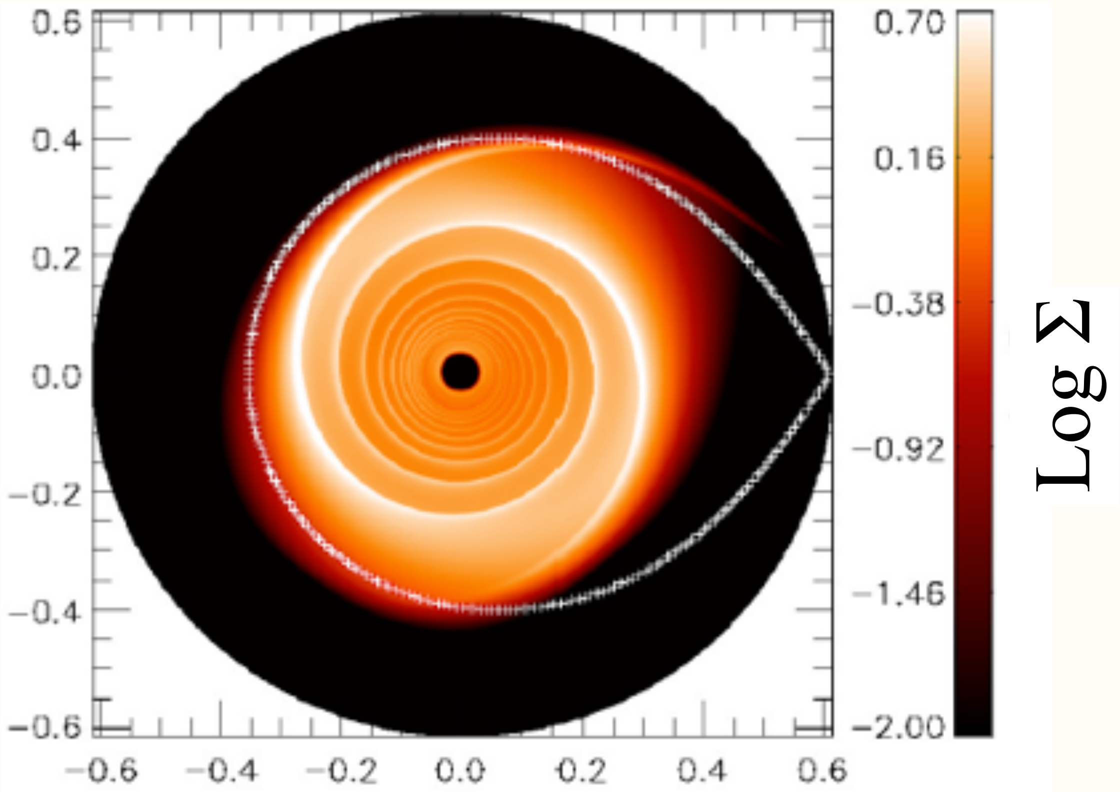

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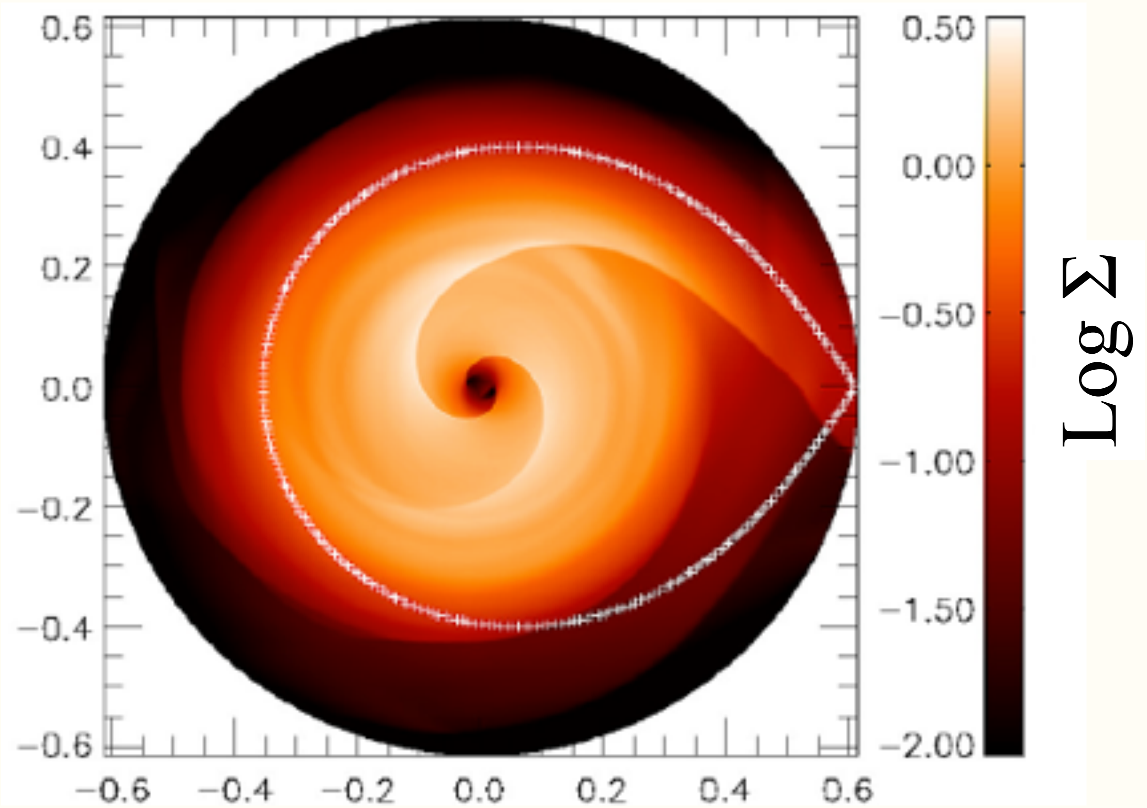

Ju, Stone, Zhu 2016

$$\tan\beta = \frac{c_s}{R|\Omega\text{-}\Omega_p|}$$

Tightly wound spiral arms
cannot transport mass globally

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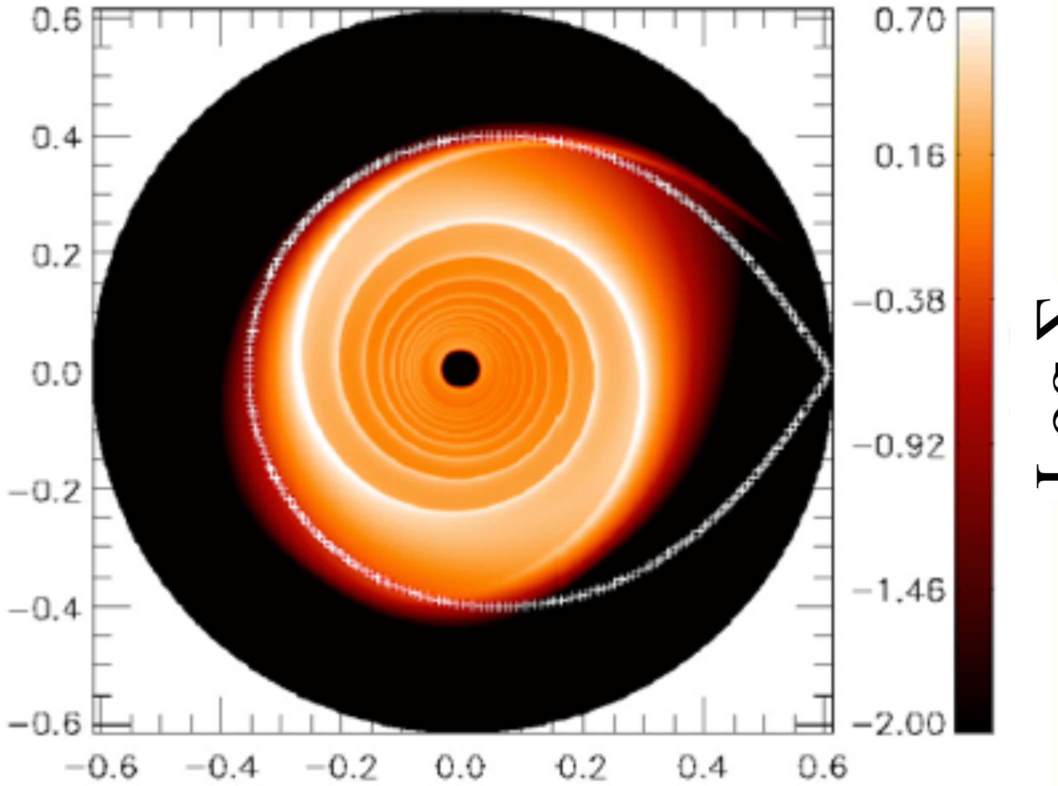

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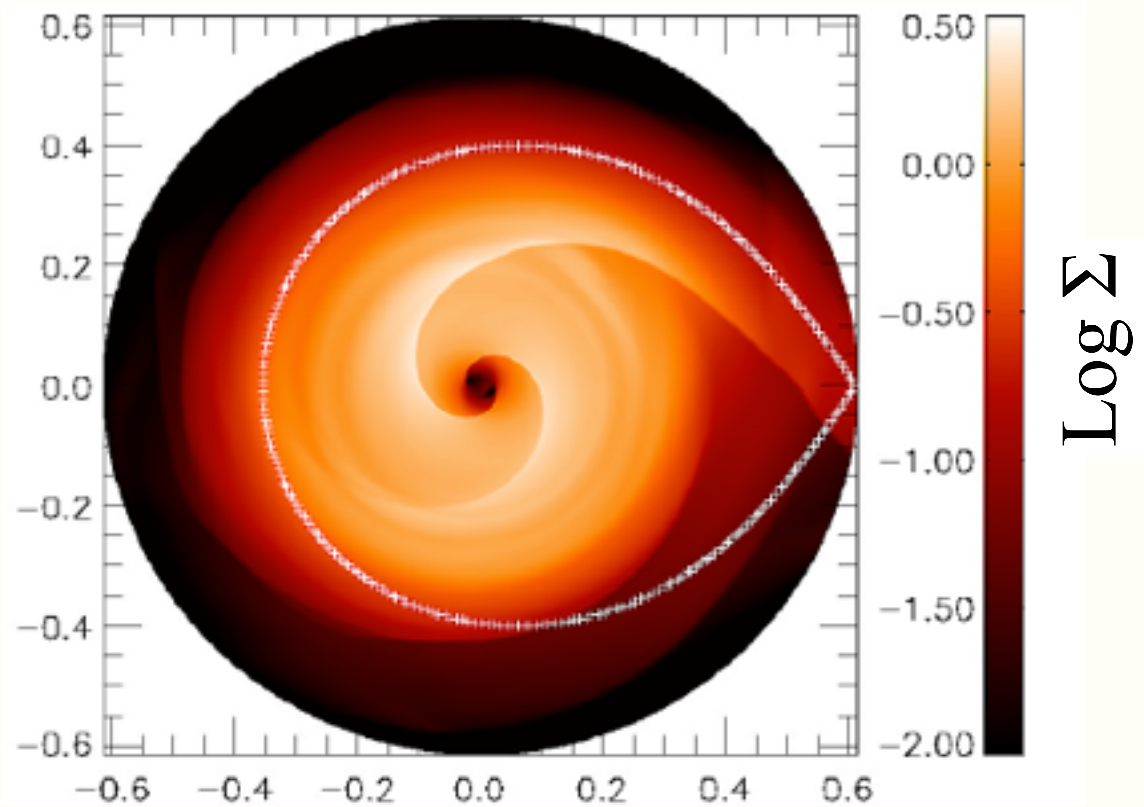

Ju, Stone, Zhu 2016

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Tightly wound spiral arms cannot transport mass globally

Open spiral arms, efficient angular momentum transport

Difficult to Simulate CPDs

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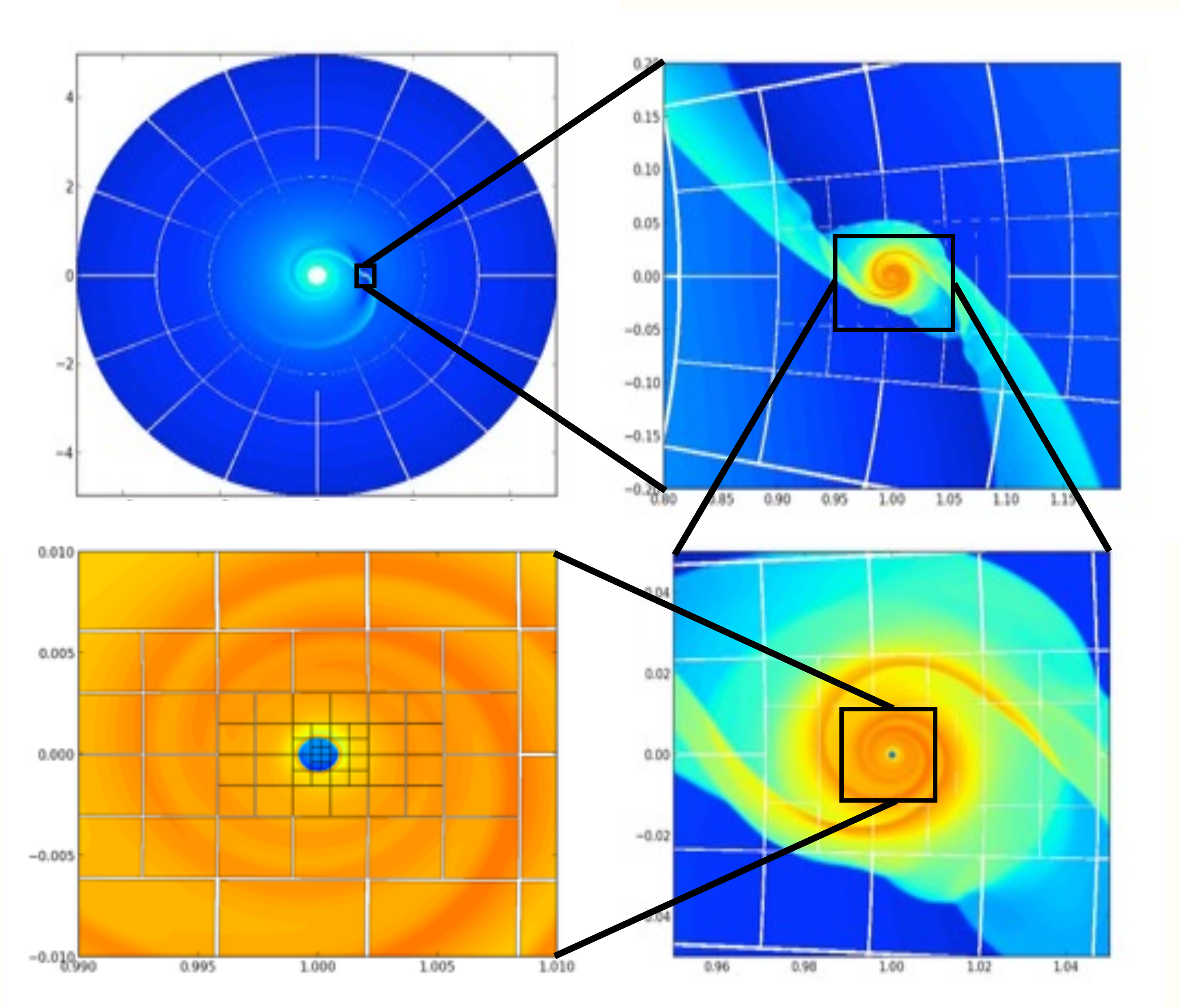

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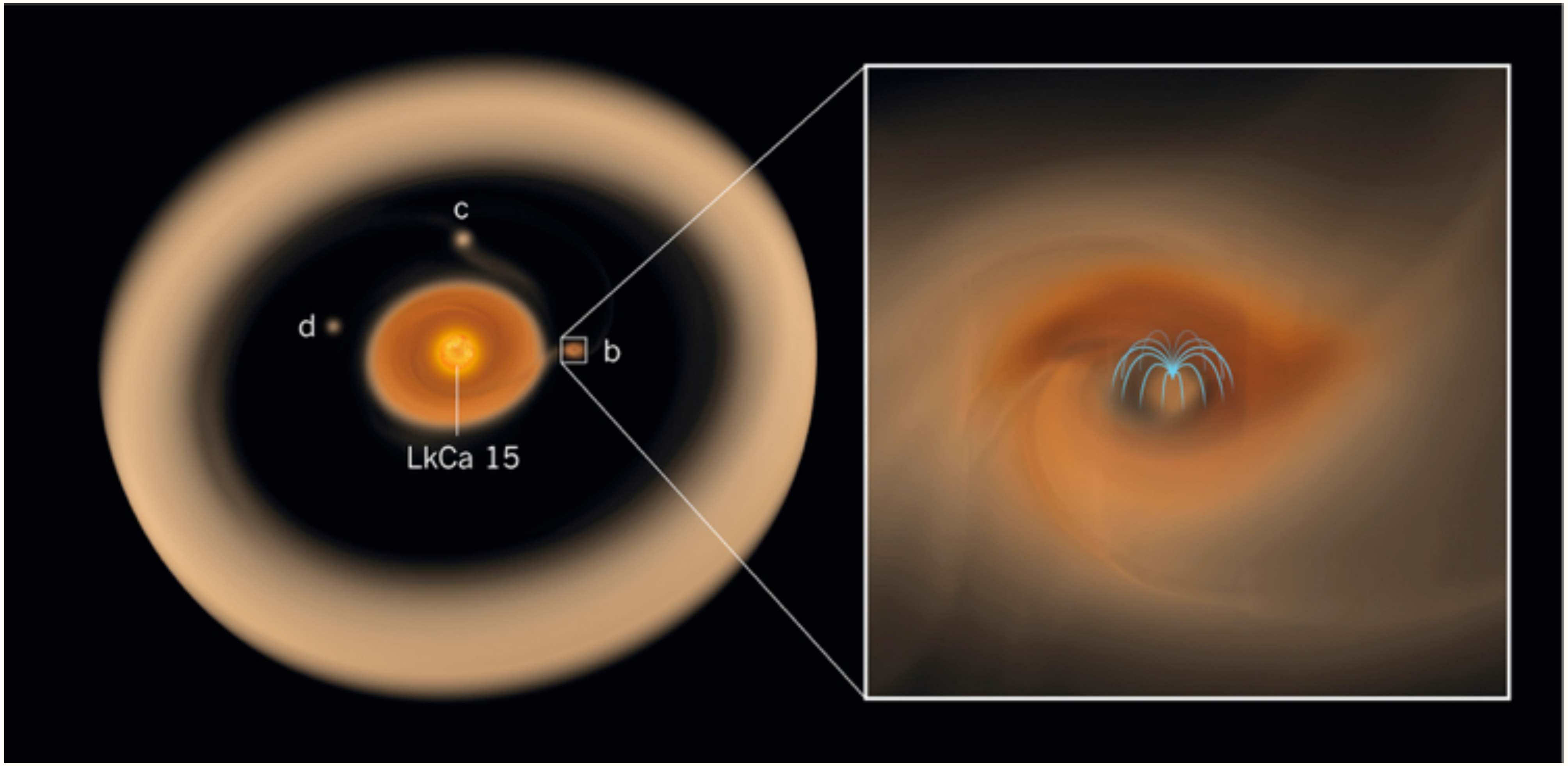
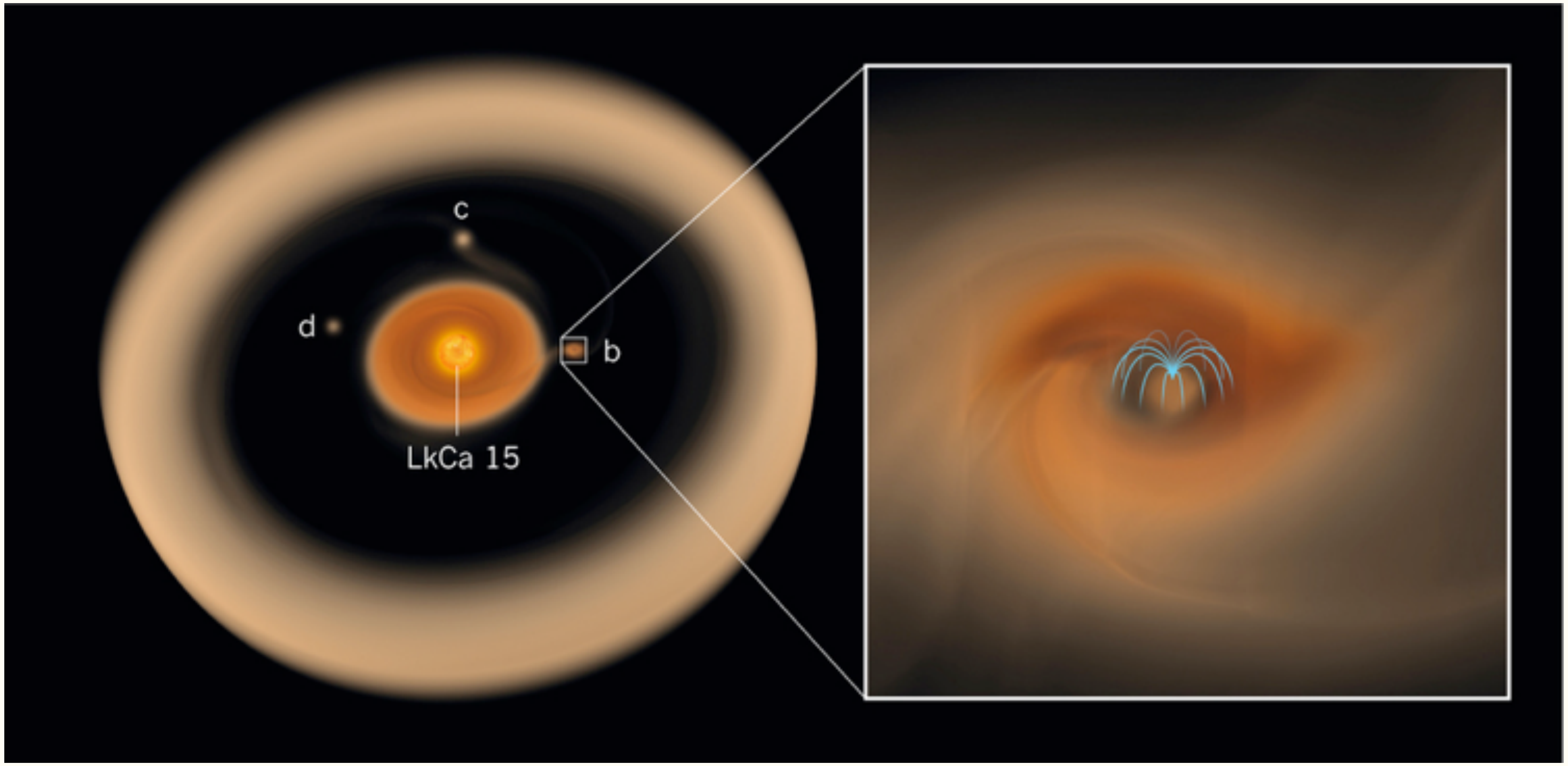


Difficult to Simulate CPDs

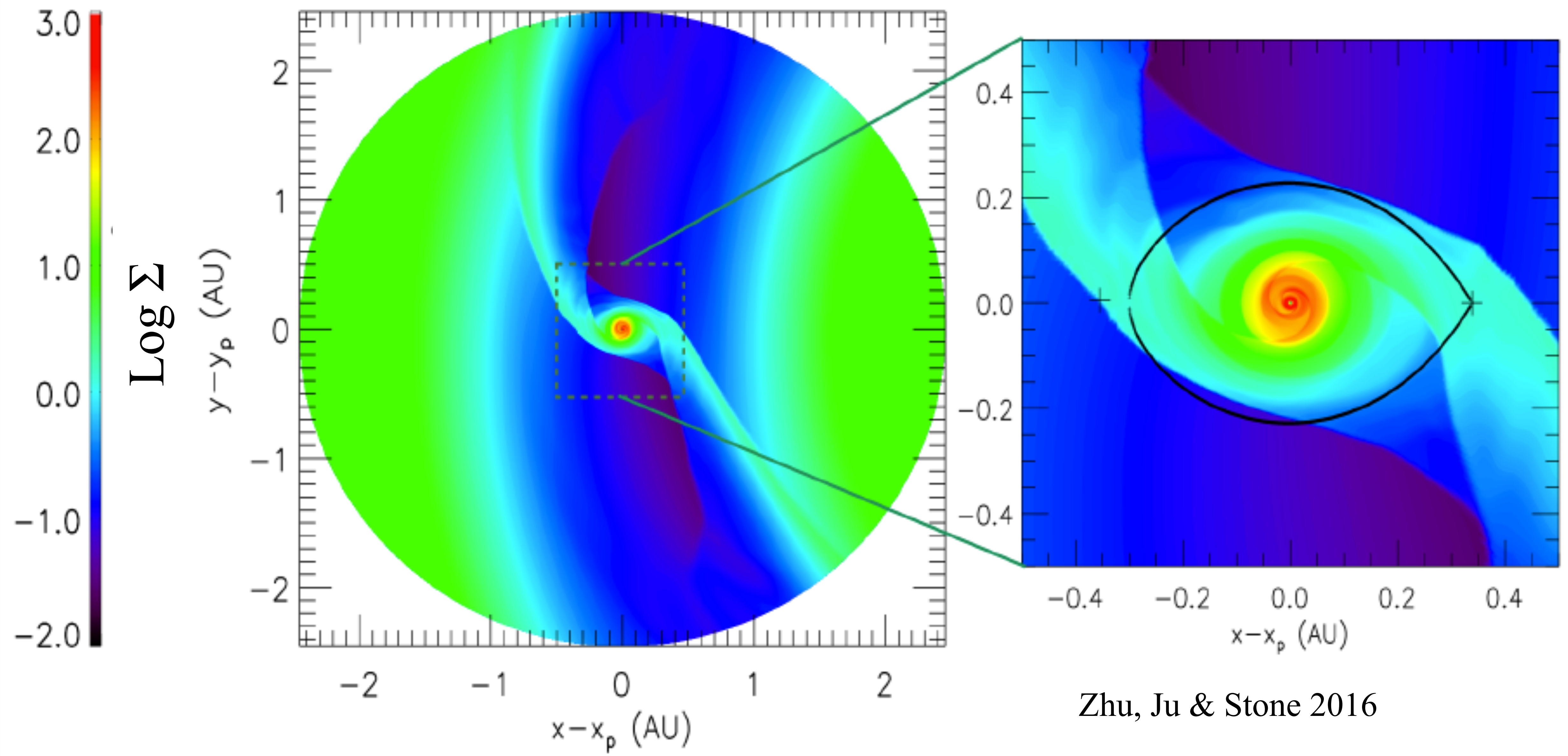
- Large Dynamical Range (4 orders of magnitude)
- Using Static Mesh Refinement (SMR) introduces grid noise
- Isothermal simulations show low accretion rate and are not numerically converged (Rivier+ 2012, Szulagyi+ 2014)



CPD 2-D Inviscid Hydrodynamical Simulations

Using Athena++

- centered at the planet



Zhu, Ju & Stone 2016

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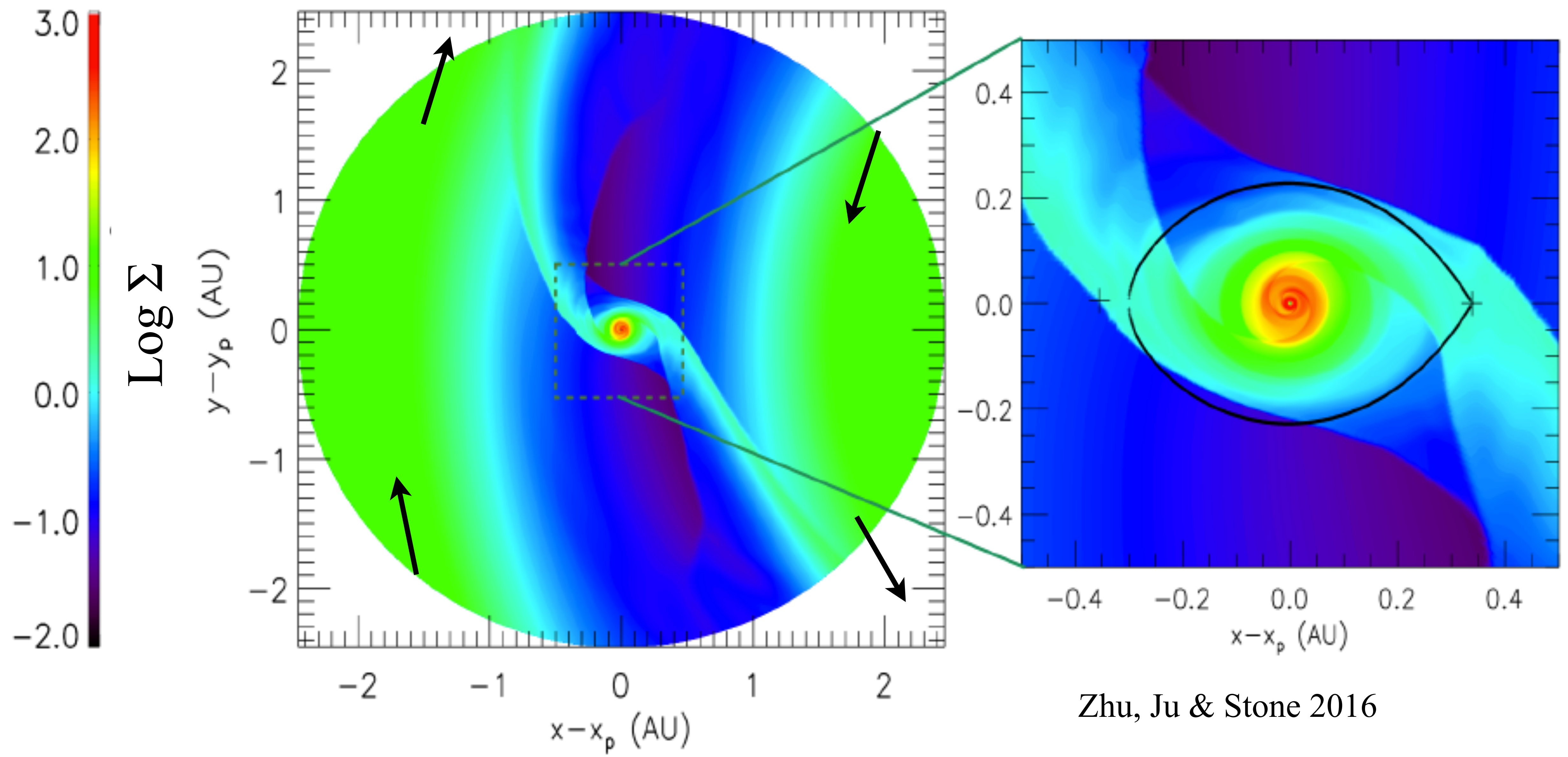

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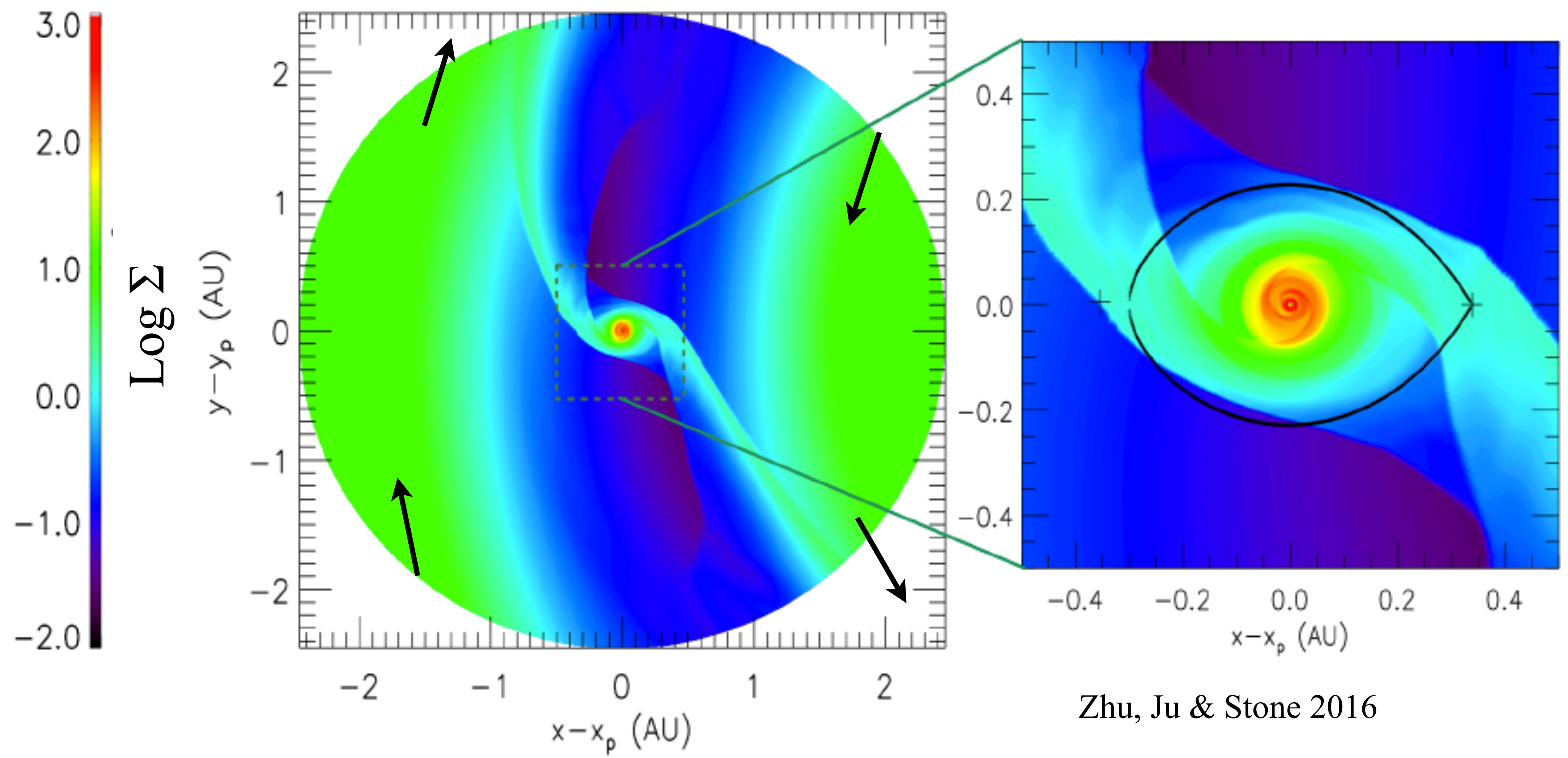
R_{out}/R_{in}=3000

3×10^5 inner orbits



Zhu, Ju & Stone 2016

CPD 2-D Inviscid Hydrodynamical Simulations

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3×10^5 inner orbits

Using Athena++

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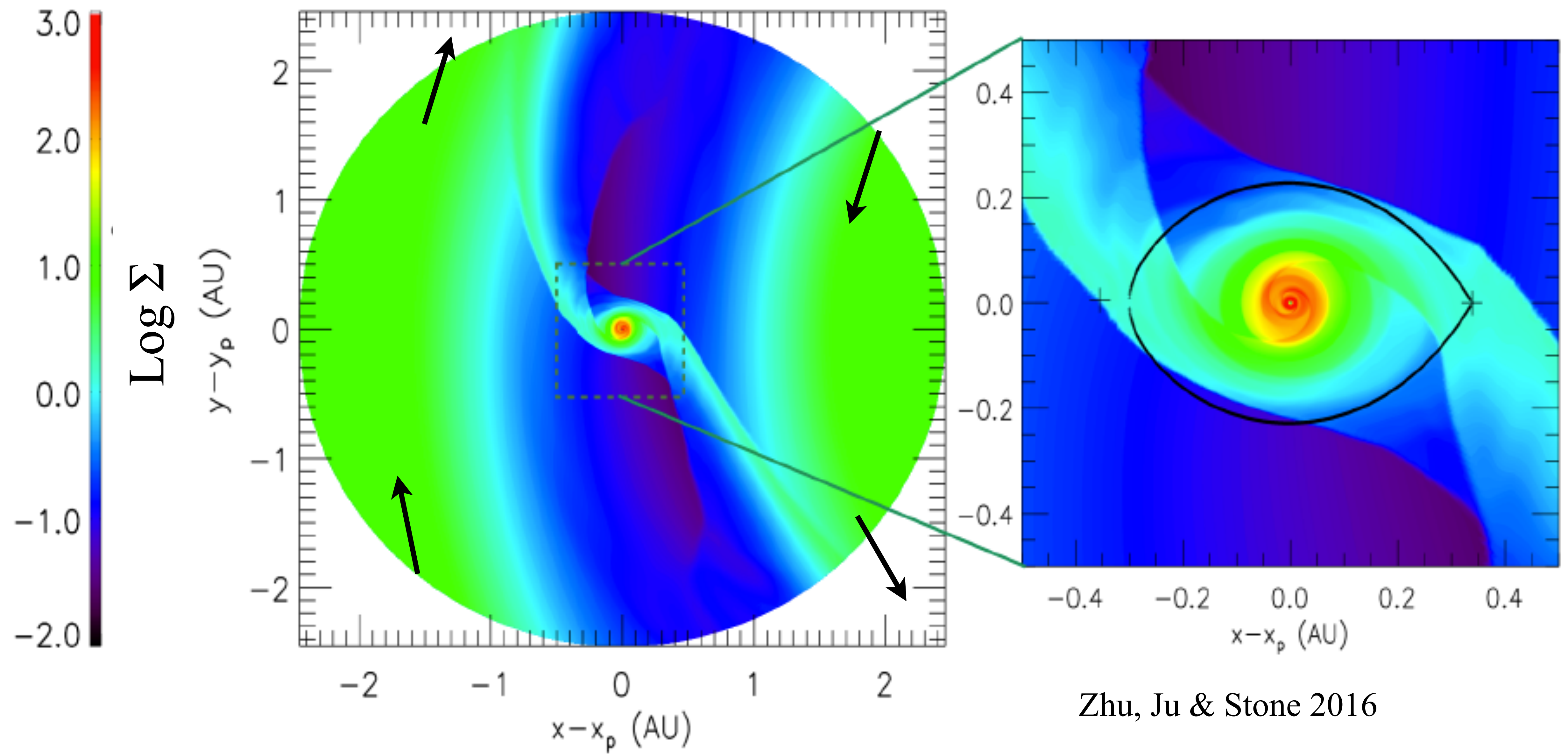
- radiative cooling $Q_c = \frac{16}{3}\sigma(T_c^4 - T_{\rm ext}^4)\frac{\tau}{1+\tau^2}$

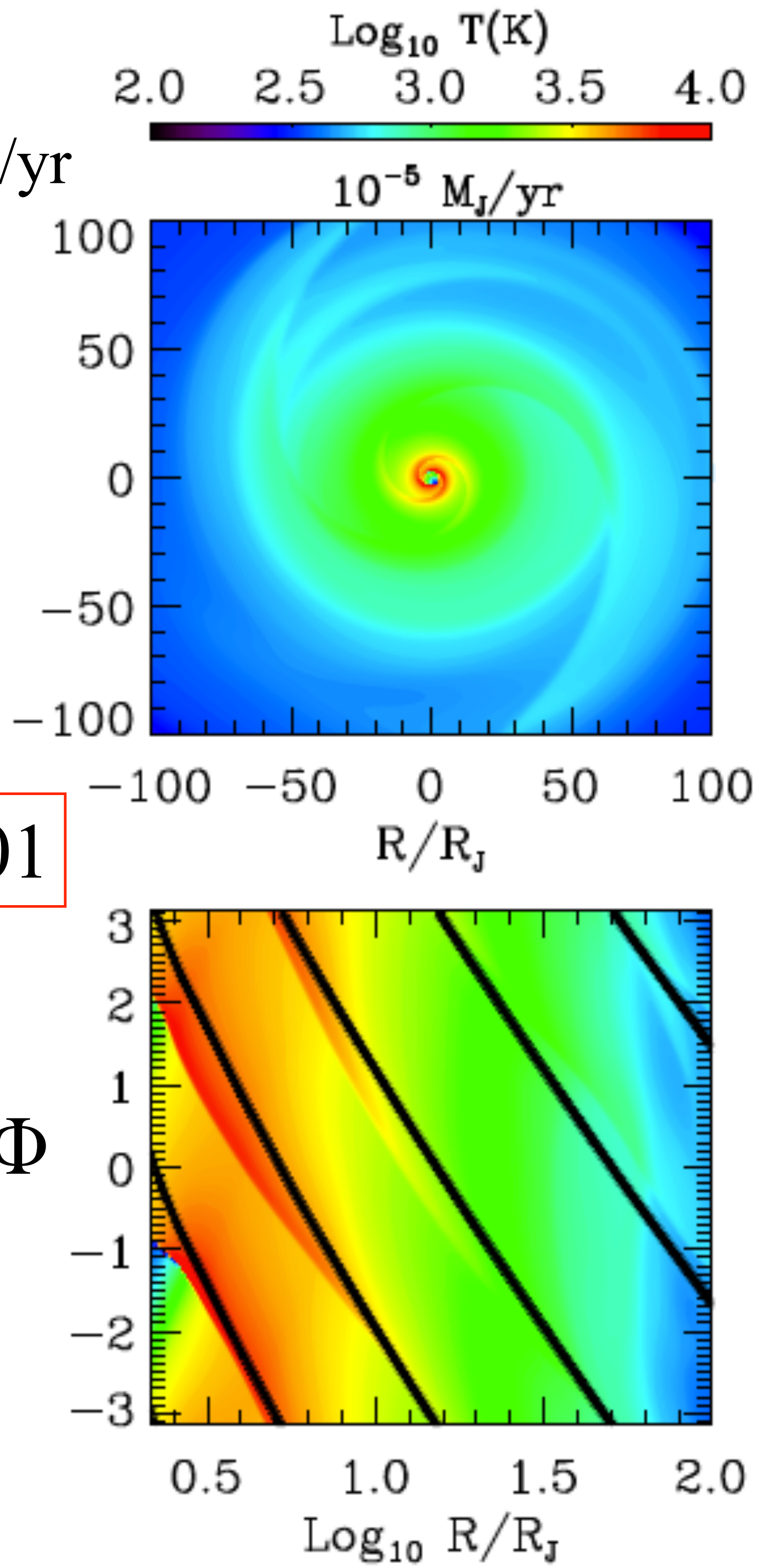


Zhu, Ju & Stone 2016

Spiral Shocks are efficient to transport mass in CPDs

$\dot{M}=10^{-5}$ M_J/yr

α=0.01



black curve: linear theory $\tan\beta = \frac{c_s}{R|\Omega - \Omega_p|}$

Zhu, Ju & Stone 2016

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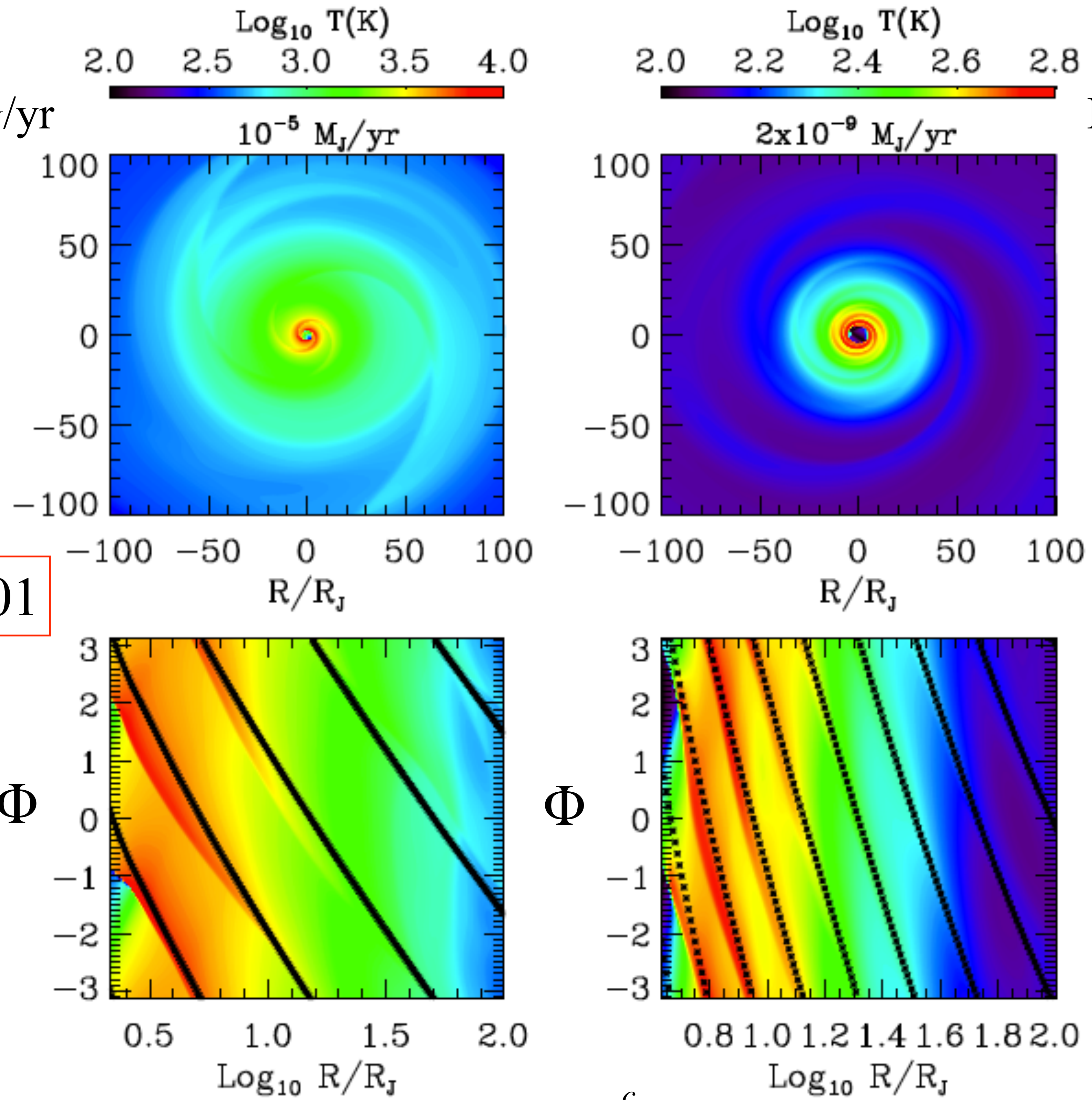

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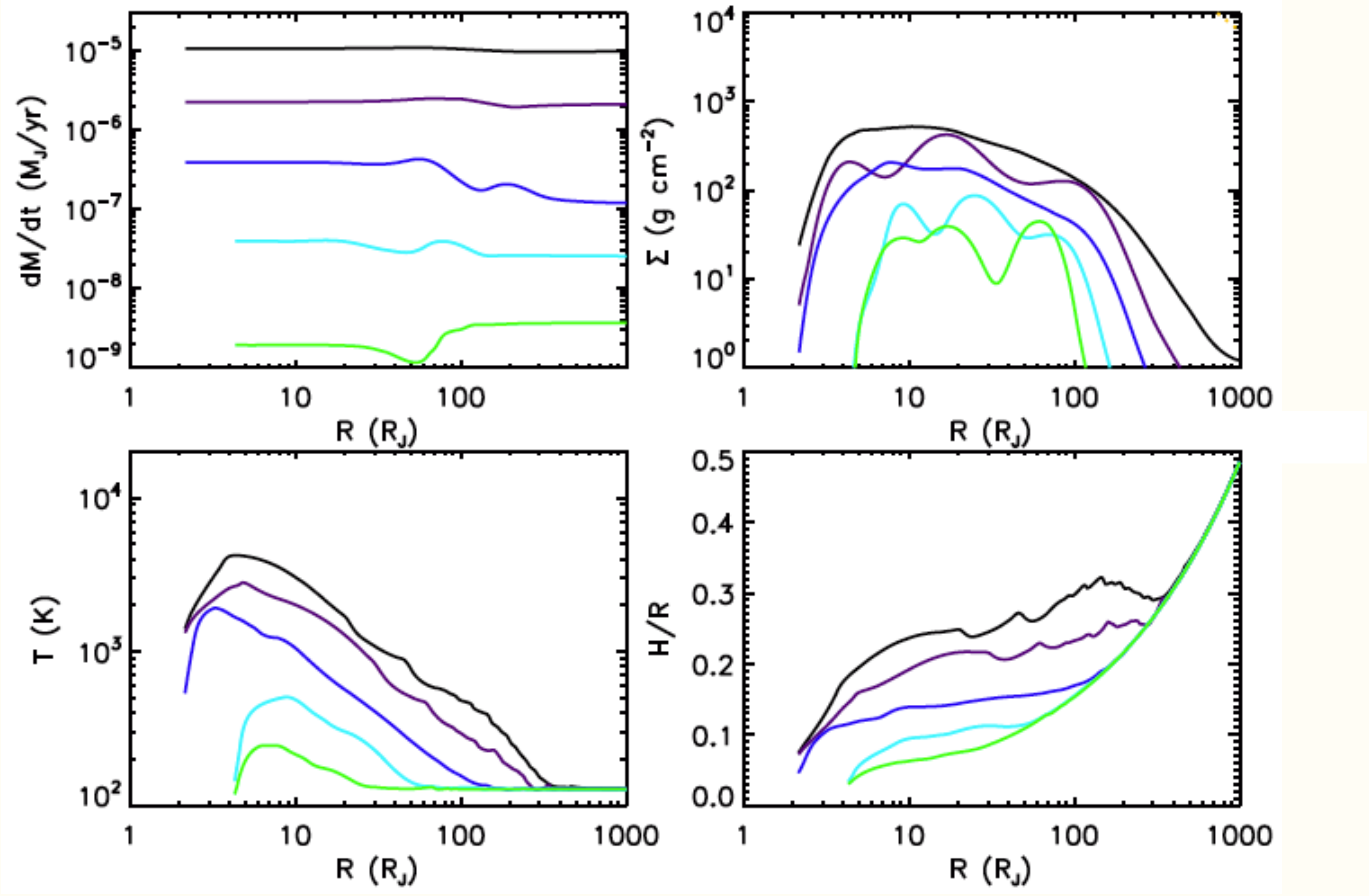
CPDs properties

Disk Accretion Rate



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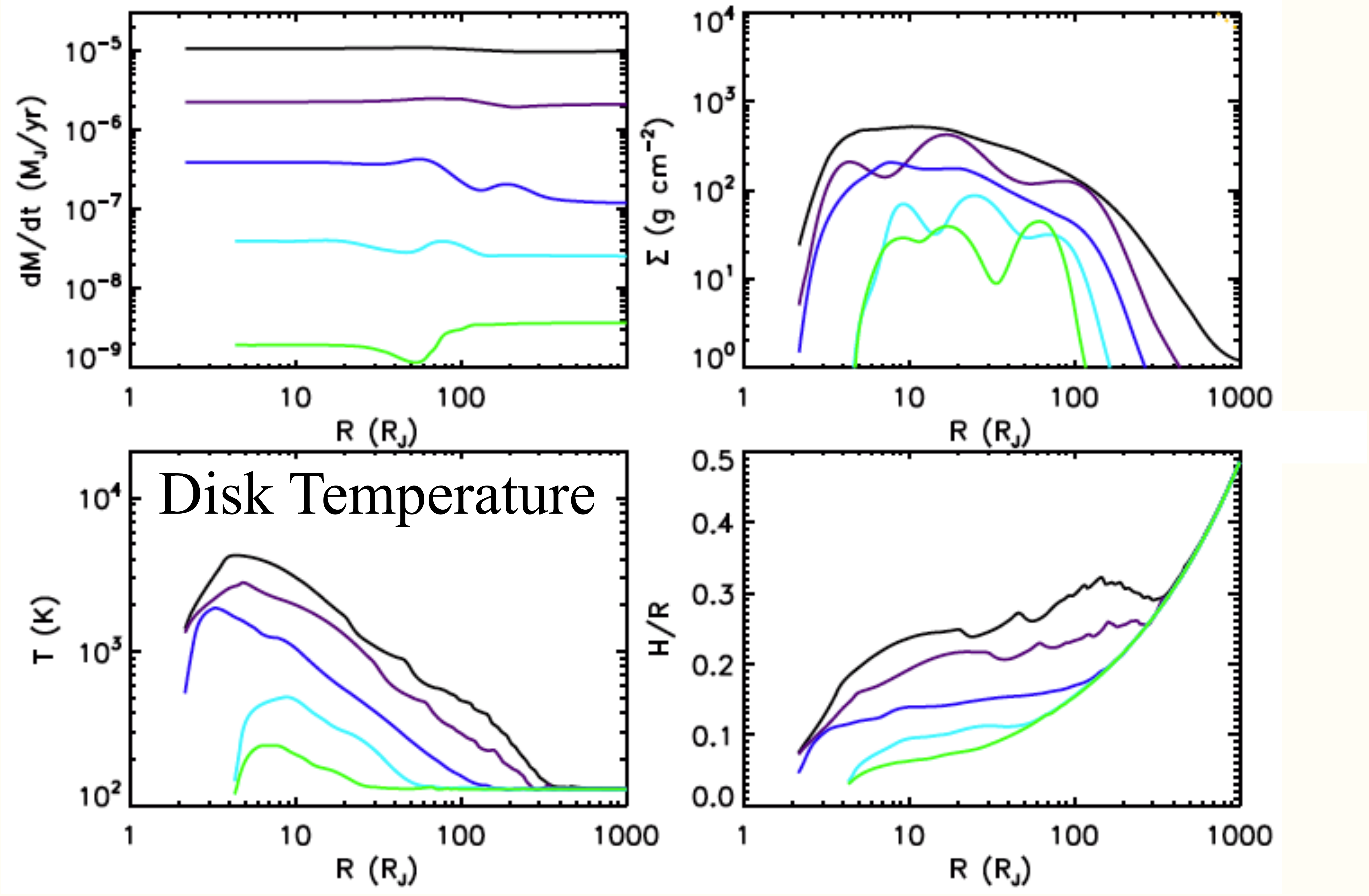
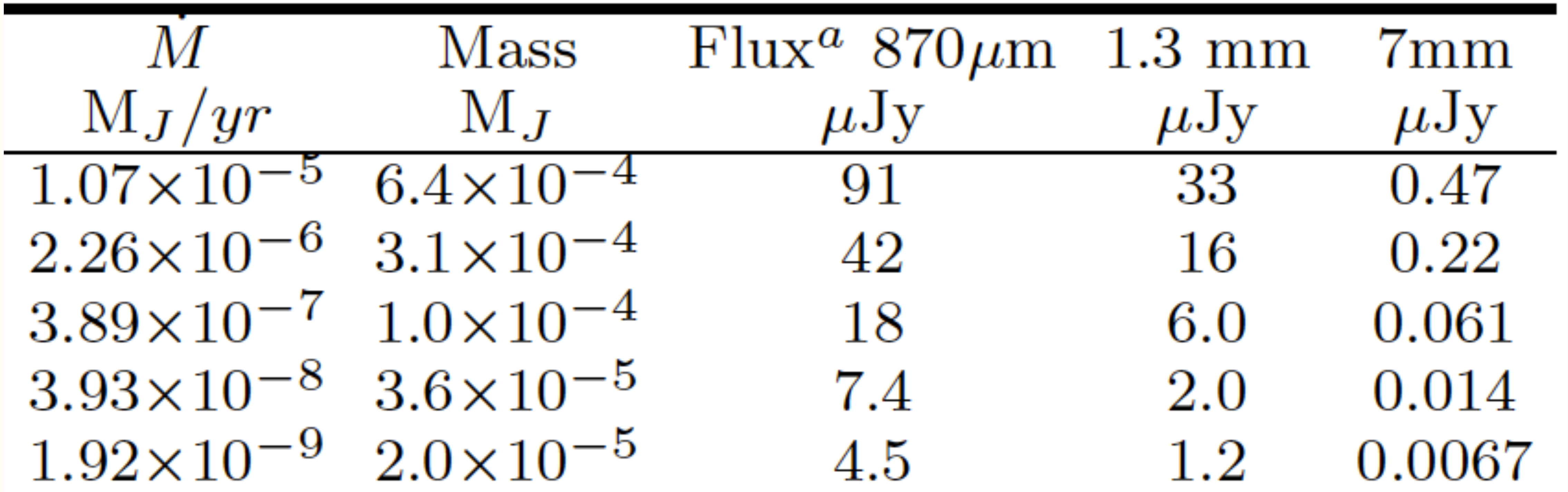
Disk Surface Density



Disk Temperature

Observational Signatures: Submm Flux of CPDs



$\dot{M}$ M_J/yr	Mass M_J	Flux^a 870μm μJy	1.3 mm μJy	7mm μJy
1.07×10^{-5}	6.4×10^{-4}	91	33	0.47
2.26×10^{-6}	3.1×10^{-4}	42	16	0.22
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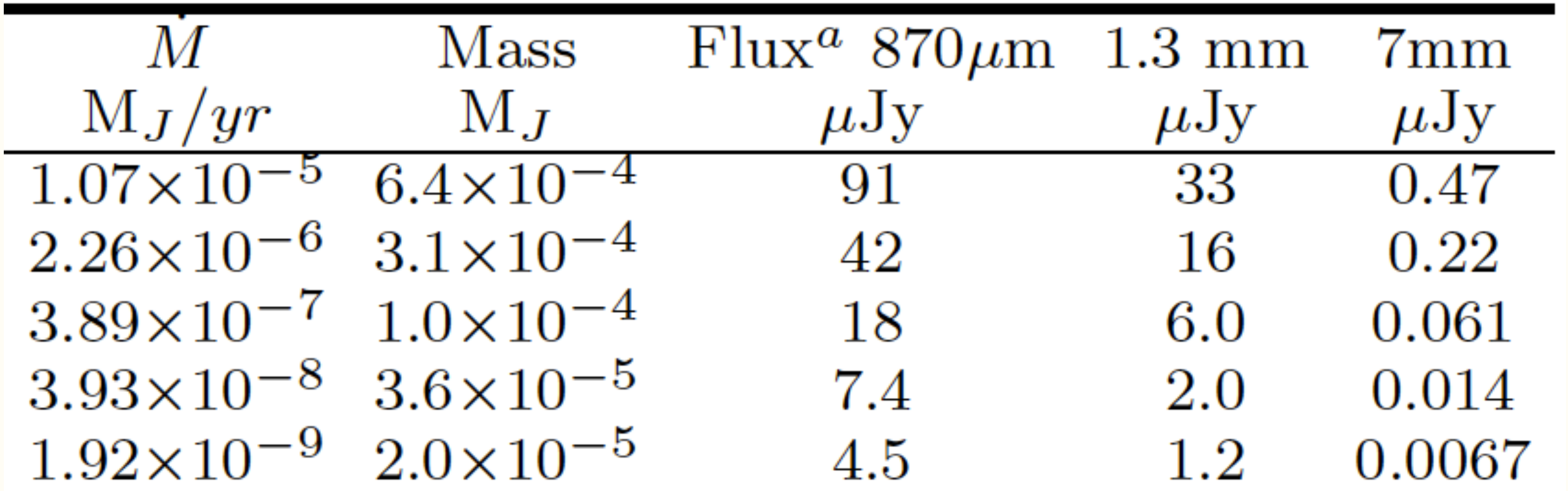

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100 µJy -1 mJy

Band 6

ALMA!!!

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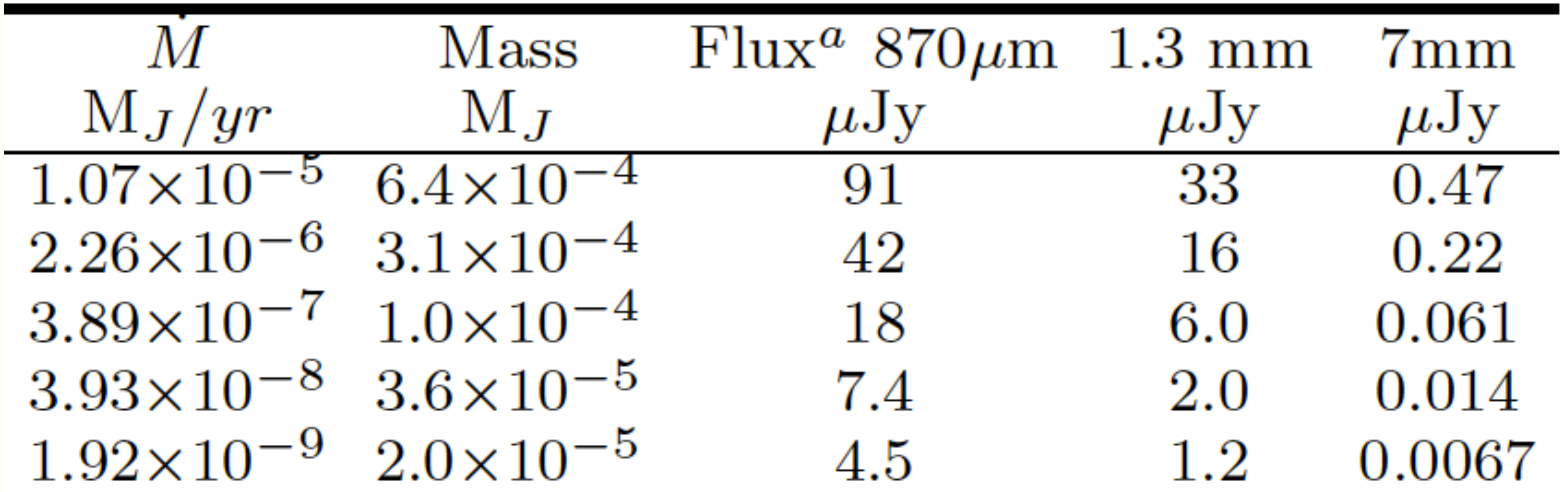

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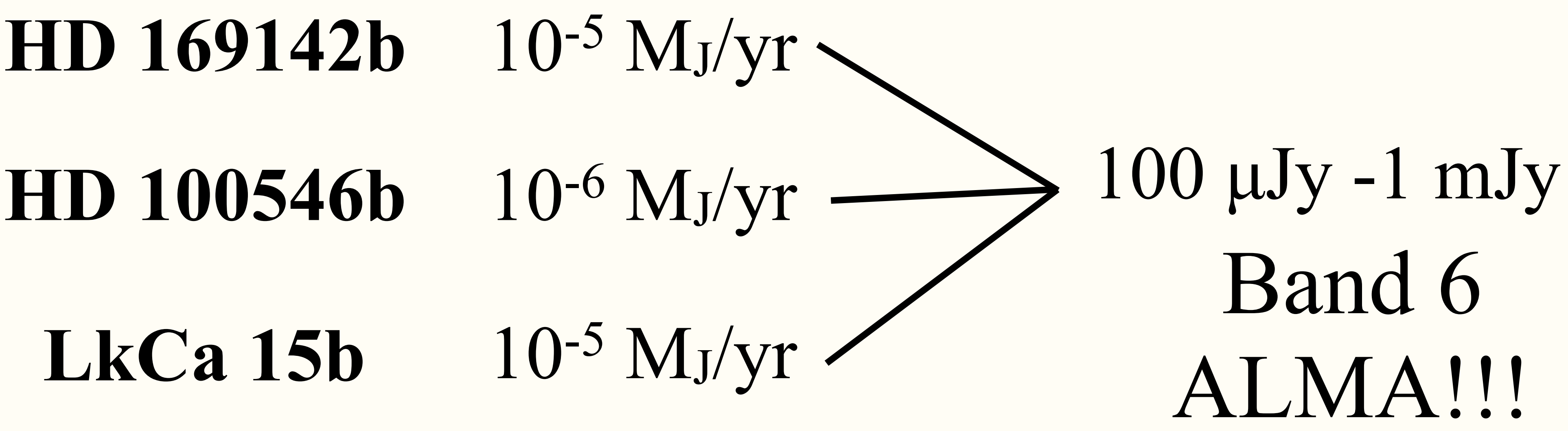

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Caveat: 3-D radiative transfer (Szulagyi+ 2016)

3-D instability (Bae+ 2016)

Outline

- Spirals excited by the planet

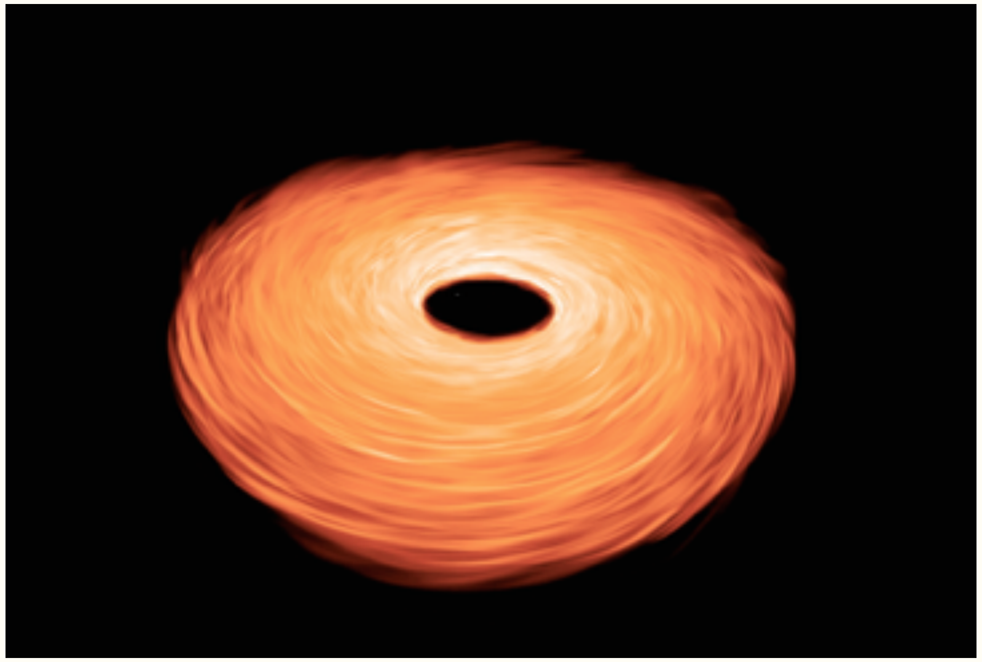
  Reveal the planet mass

- Spirals excited by the star

  Circumplanetary disk accretion

- Global MHD disk simulations

  Turbulence VS Wind



Accretion in disks with net vertical B-field

- Turbulence VS. Wind:

$$\dot{M}_{acc}\frac{\partial R v_k}{\partial R} = -2\pi\frac{\partial}{\partial R}\left(R^2\int\left(\langle\rho v_R \delta v_\phi\rangle - \langle B_R B_\phi\rangle\right)dz\right) - 2\pi R^2\left(\langle\rho v_z \delta v_\phi\rangle - \langle B_z B_\phi\rangle\right)\Big|_{z_{min}}^{z_{max}}$$

internal $T_{R\Phi}$ $T_{z\Phi}$ at the surface

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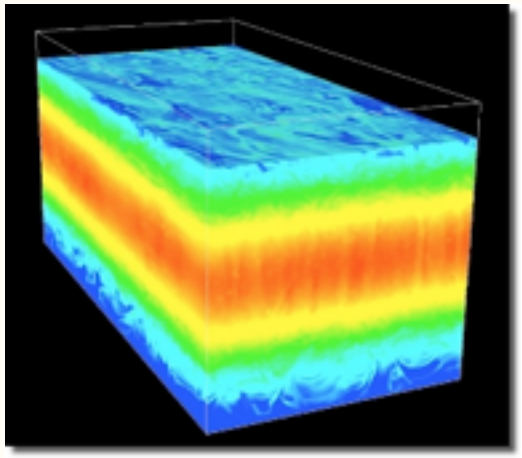
MRI (Balbus & Hawley 1991)



Simon+2012

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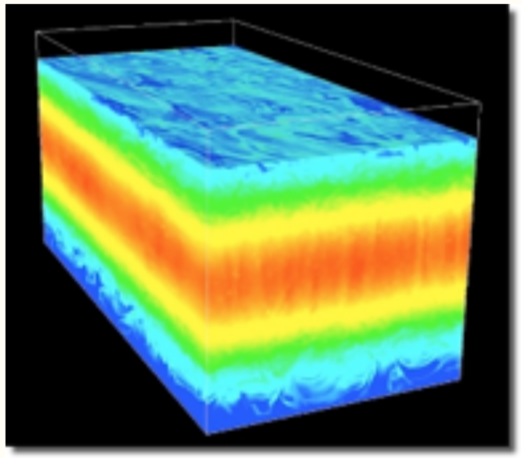

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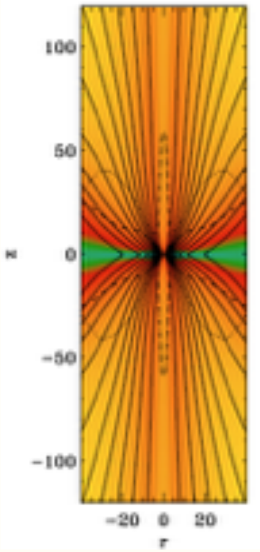

Zanni+2007

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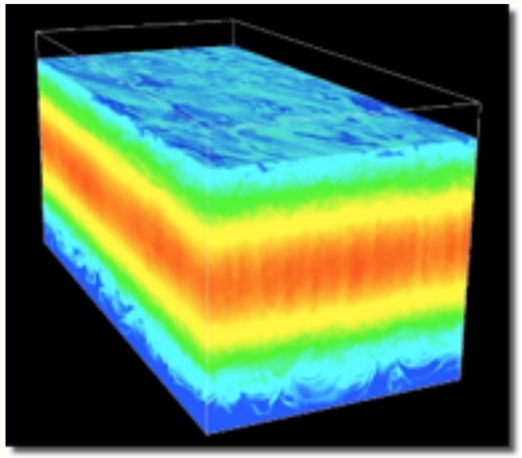

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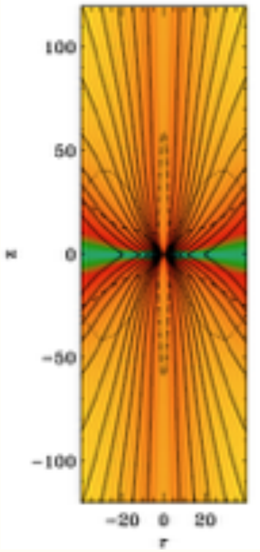

Zanni+2007

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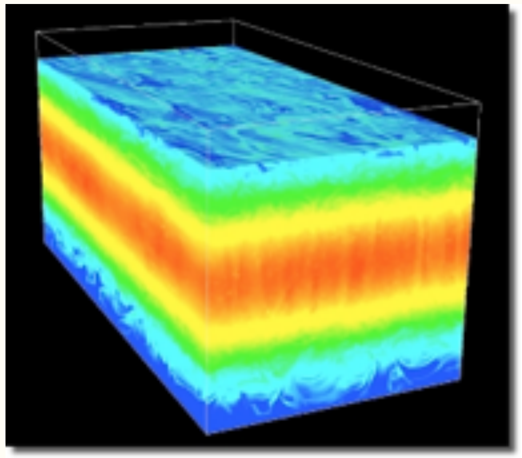

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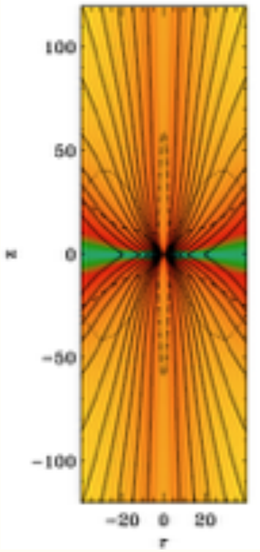

Zanni+2007

- Global field transport:

$$\partial_t A_\phi = -\, v_R B_z - \frac{\eta}{R}\partial_z B_R + \eta \partial_R B_z$$

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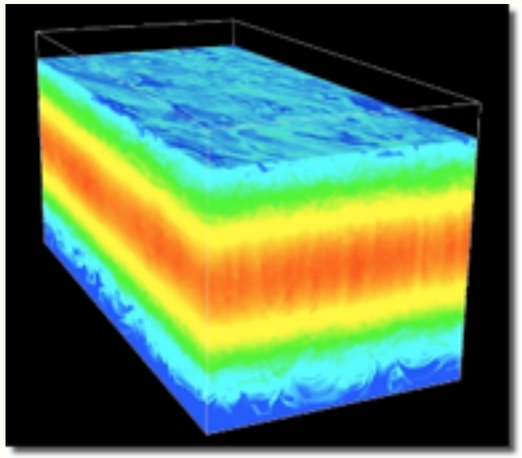
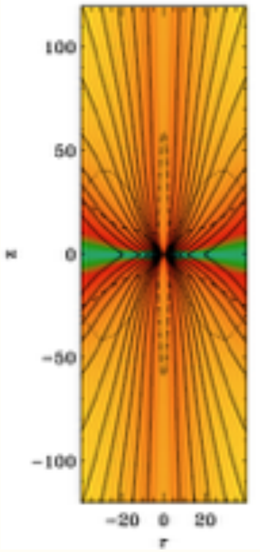
Net Vertical B-field



Simon+2012



Zanni+2007

- Global field transport:

$$\partial_t A_\phi = -\underbrace{v_R B_z}_{\nu B_z/R} - \underbrace{\frac{\eta}{R}\partial_z B_R}_{\eta B_z/H} + \underbrace{\eta\partial_R B_z}_{\eta B_z/R}$$

Accretion in disks with net vertical B-field

- Turbulence VS. Wind:

$$\dot{M}_{acc}\frac{\partial R v_k}{\partial R} = -2\pi\frac{\partial}{\partial R}\left(R^2\int\left(\langle\rho v_R\delta v_\phi\rangle - \langle B_R B_\phi\rangle\right)dz\right) - 2\pi R^2\left(\langle\rho v_z\delta v_\phi\rangle - \langle B_z B_\phi\rangle\right)\Big|_{z_{min}}^{z_{max}}$$

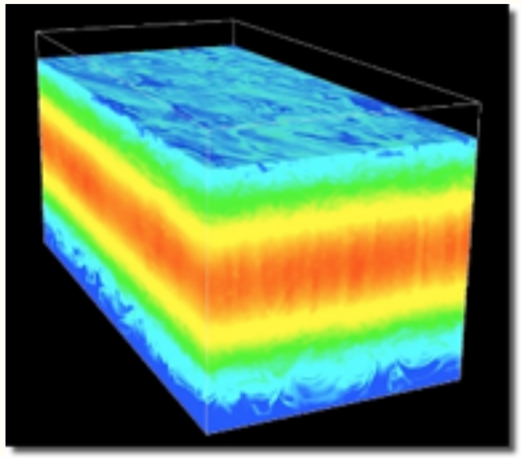
internal $T_{R\Phi}$

MRI (Balbus & Hawley 1991)

$T_{z\Phi}$ at the surface

Disk Wind (Blandford & Payne 1982)

Net Vertical B-field



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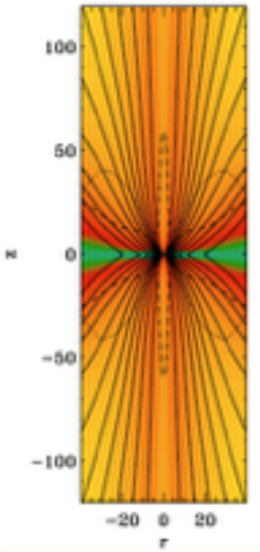

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If ν~η, diffusion is faster than advection by R/H

van Ballegooijen 1989

Accretion in disks with net vertical B-field

- Turbulence VS. Wind:

$\dot{M}_{acc}\frac{\partial R v_k}{\partial R} =$

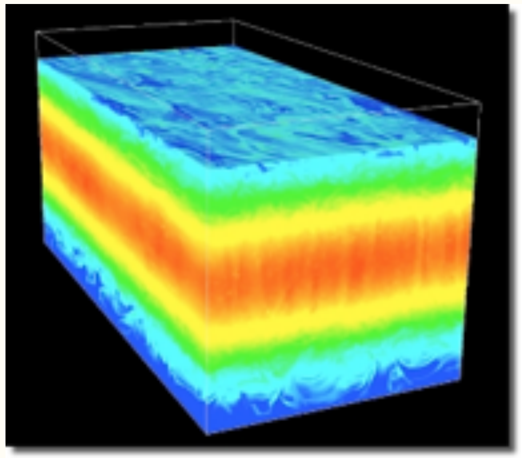
$B_z B_\phi\rangle)\Big|_{z_{min}}^{z_{max}}$

ace

Payne 1982)

High resolution global simulation
covering a large domain

Net Vertical
B-field



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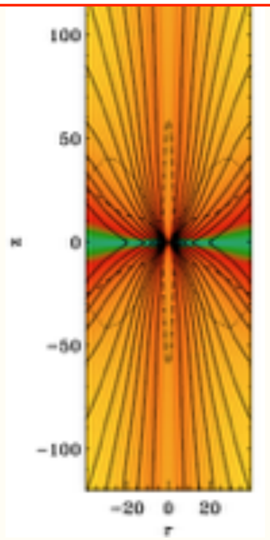

Zanni+2007

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Accretion in disks with net vertical B-field

- Turbulence VS. Wind:

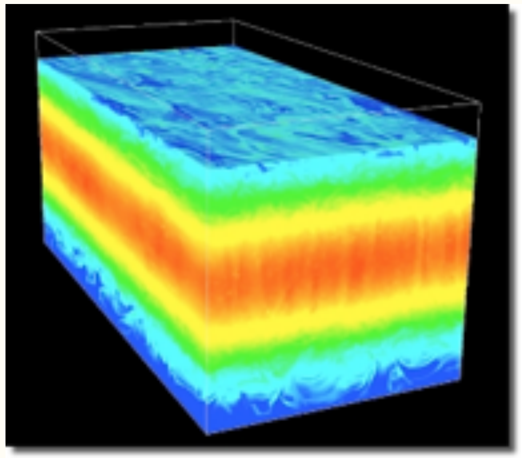
$\dot{M}_{acc}\frac{\partial R v_k}{\partial R} =$ … $B_z B_\phi\rangle)\Big|_{z_{min}}^{z_{max}}$

High resolution global simulation covering a large domain

ace

Payne 1982)

Net Vertical
B-field



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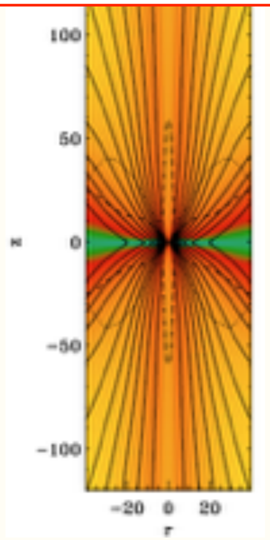


Zanni+2007

- Global field transport:

∂_t … η

Global Simulations conserve B flux

If ν~η, diffusion is faster than advection by R/H

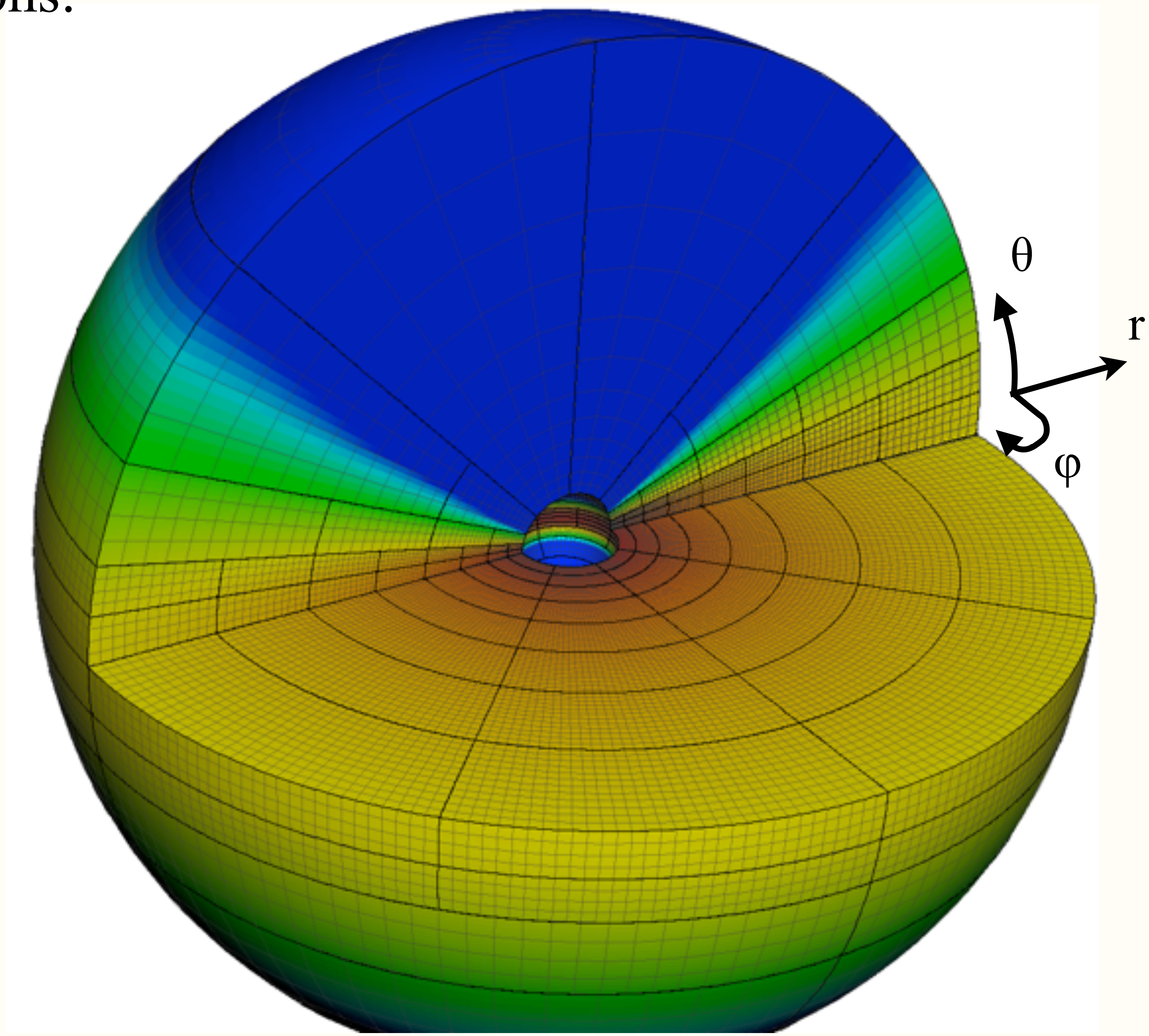
van Ballegooijen 1989

Global MHD Disk Models

3-D Ideal MHD Disk Simulations:

Athena++

- Mesh Refinement
- Including Polar Region



Zhu & Stone 2017 ArXiv

Global MHD Disk Models

3-D Ideal MHD Disk Simulations:

Athena++

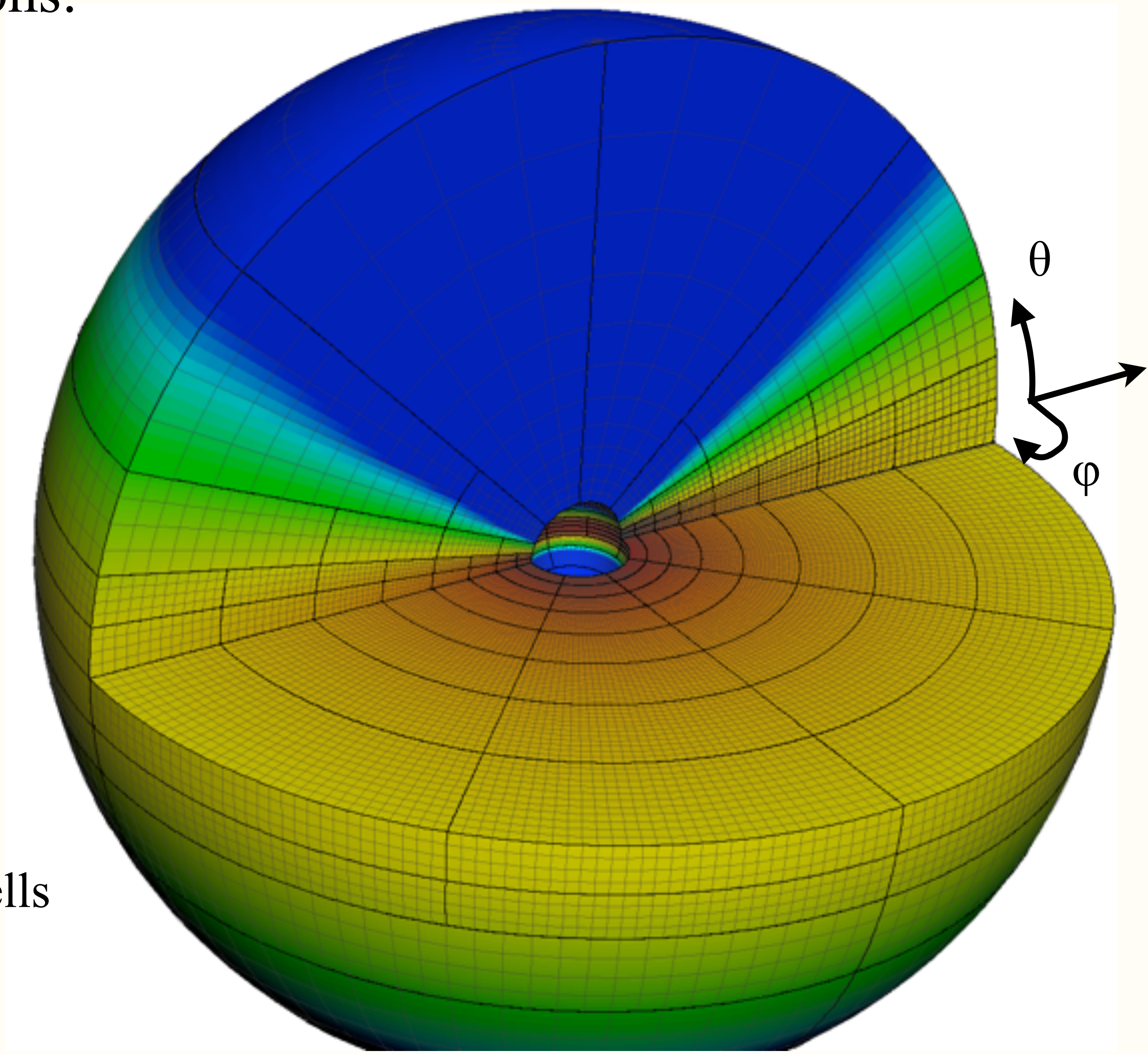
- Mesh Refinement
- Including Polar Region

Simulation Setup:

net vertical field, $\beta=10^3$, 10^4

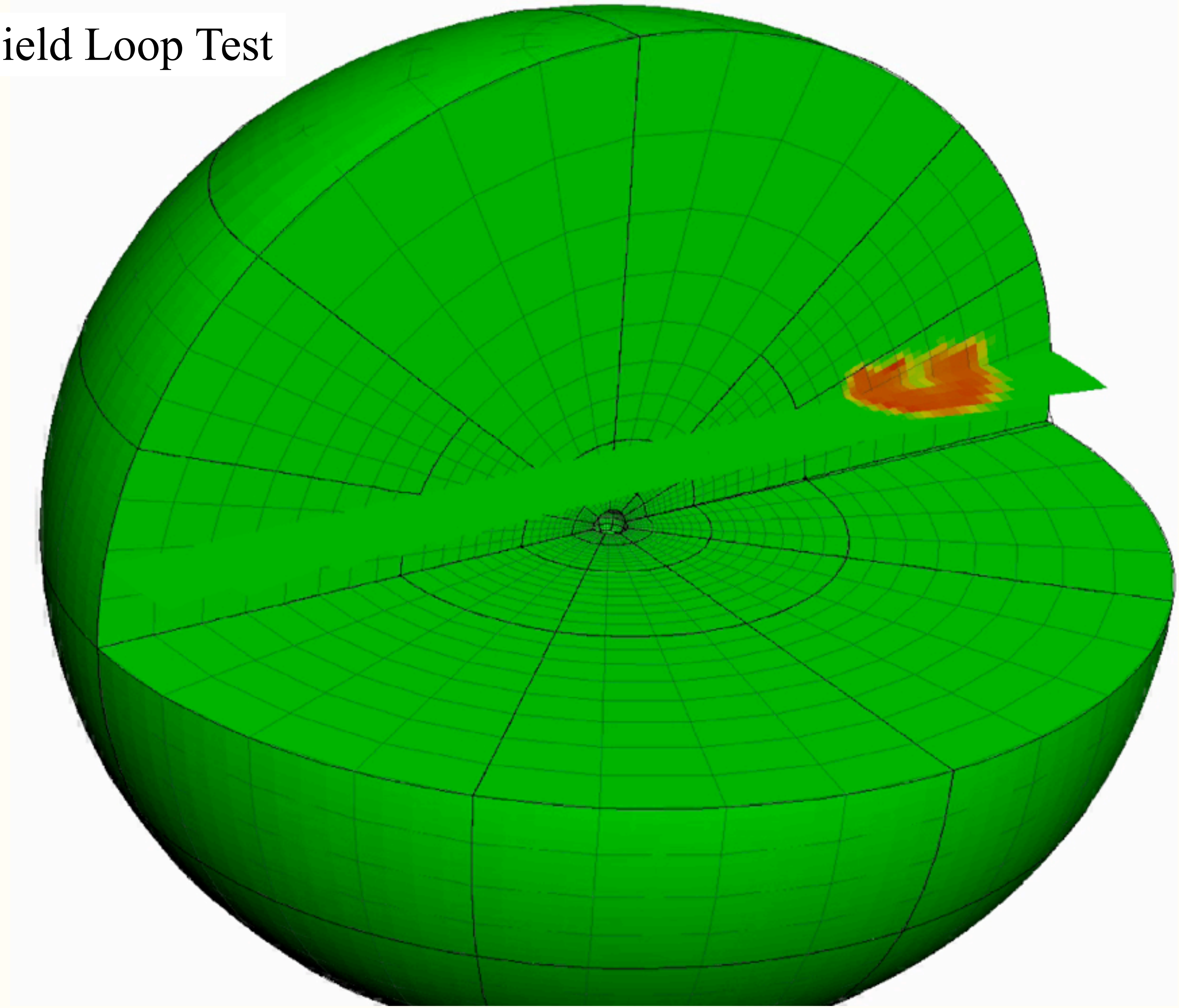
grids: logarithmic spacing
from r=0.1 to 100

3, 4 levels refinements in θ
1 H is resolved by 15 grid cells



Zhu & Stone 2017 ArXiv

Field Loop Test



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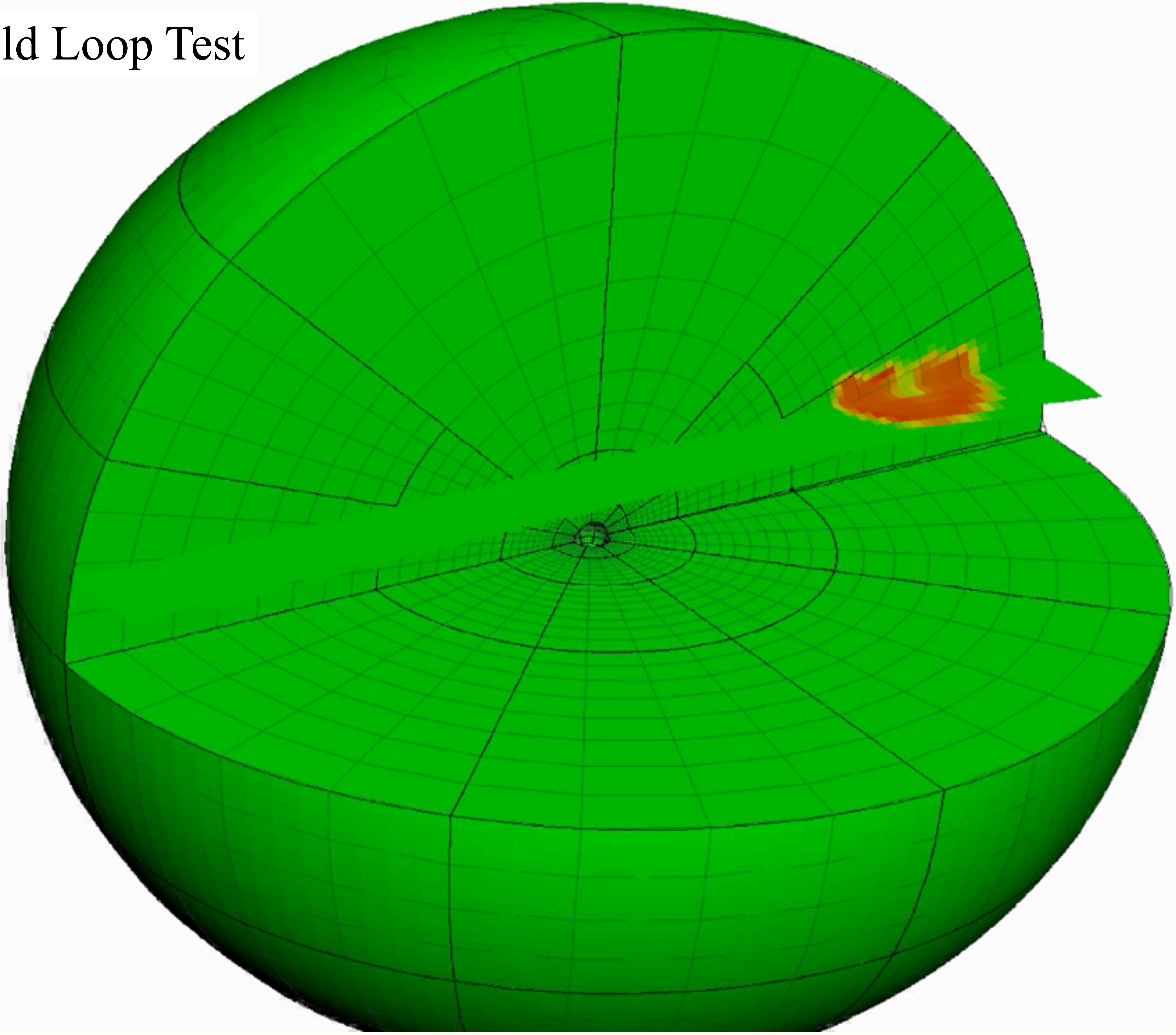
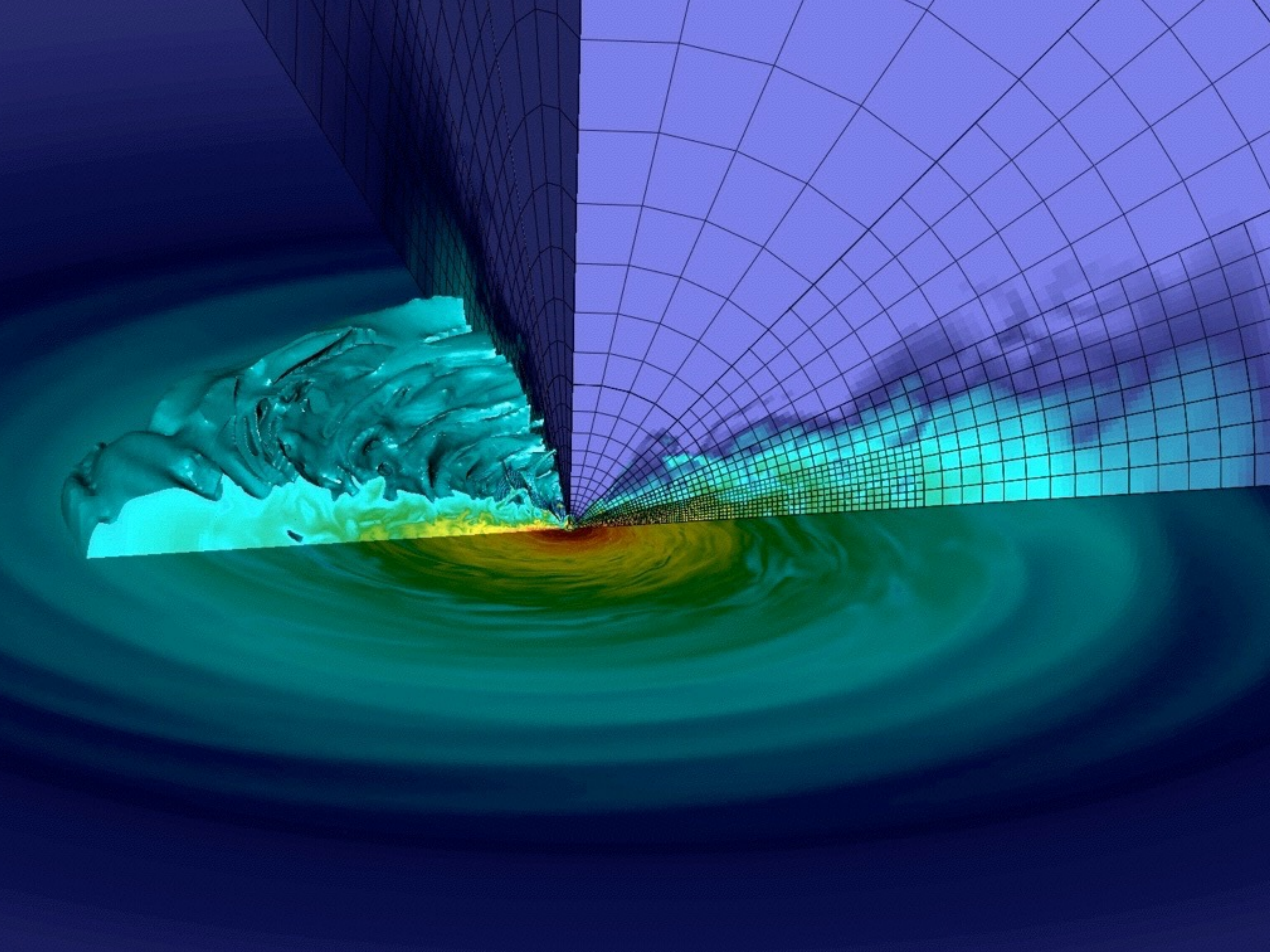
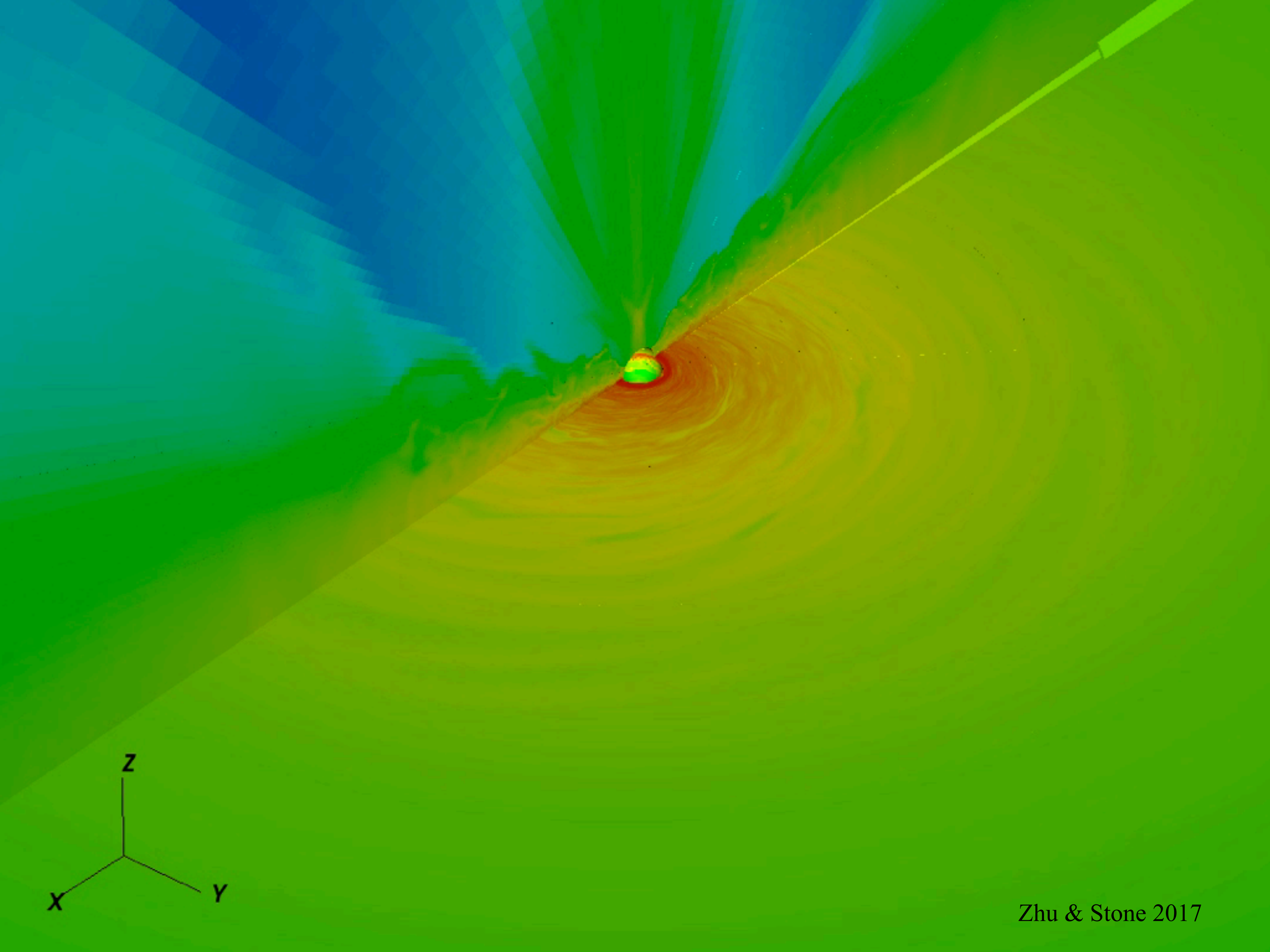
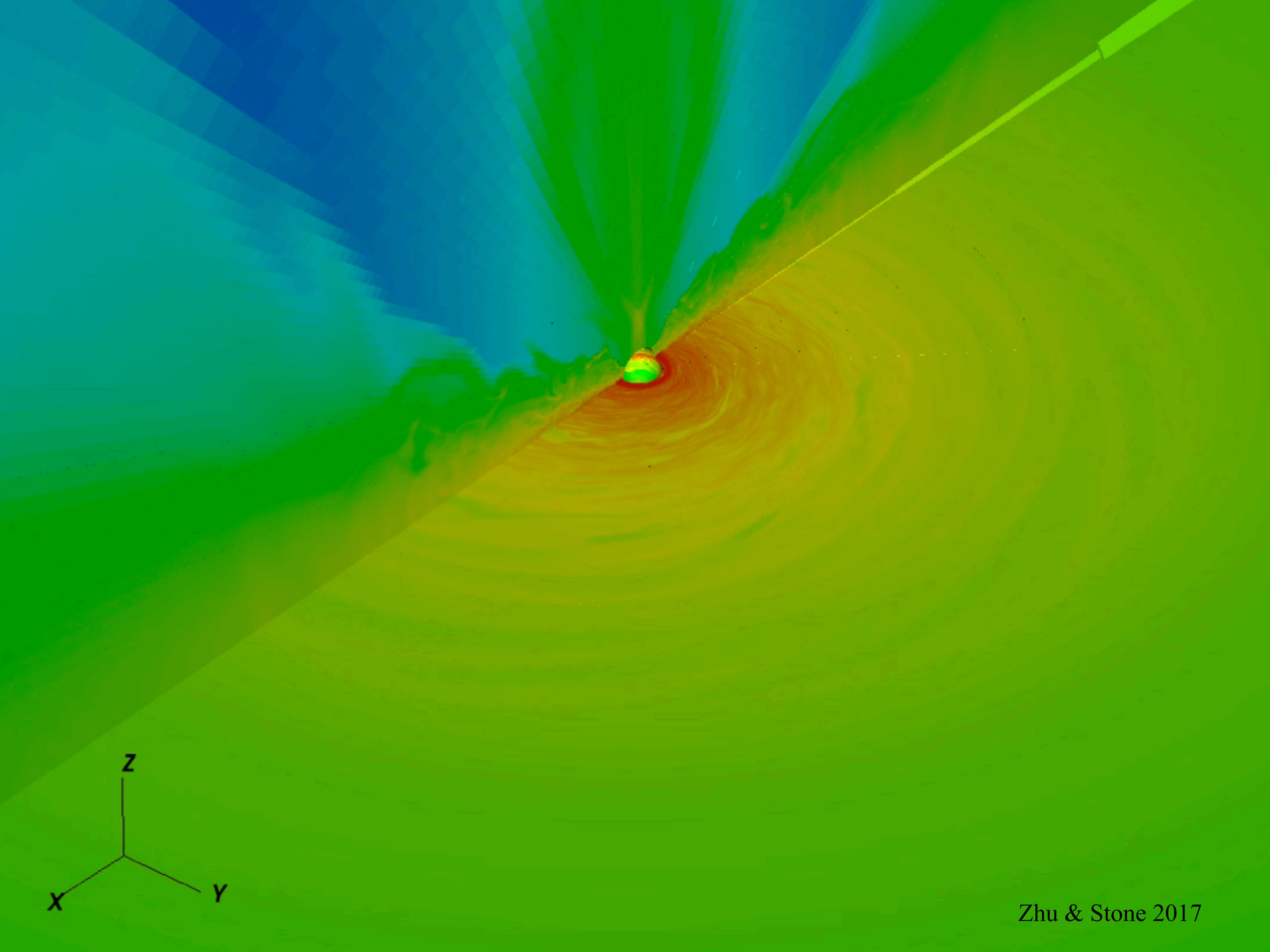


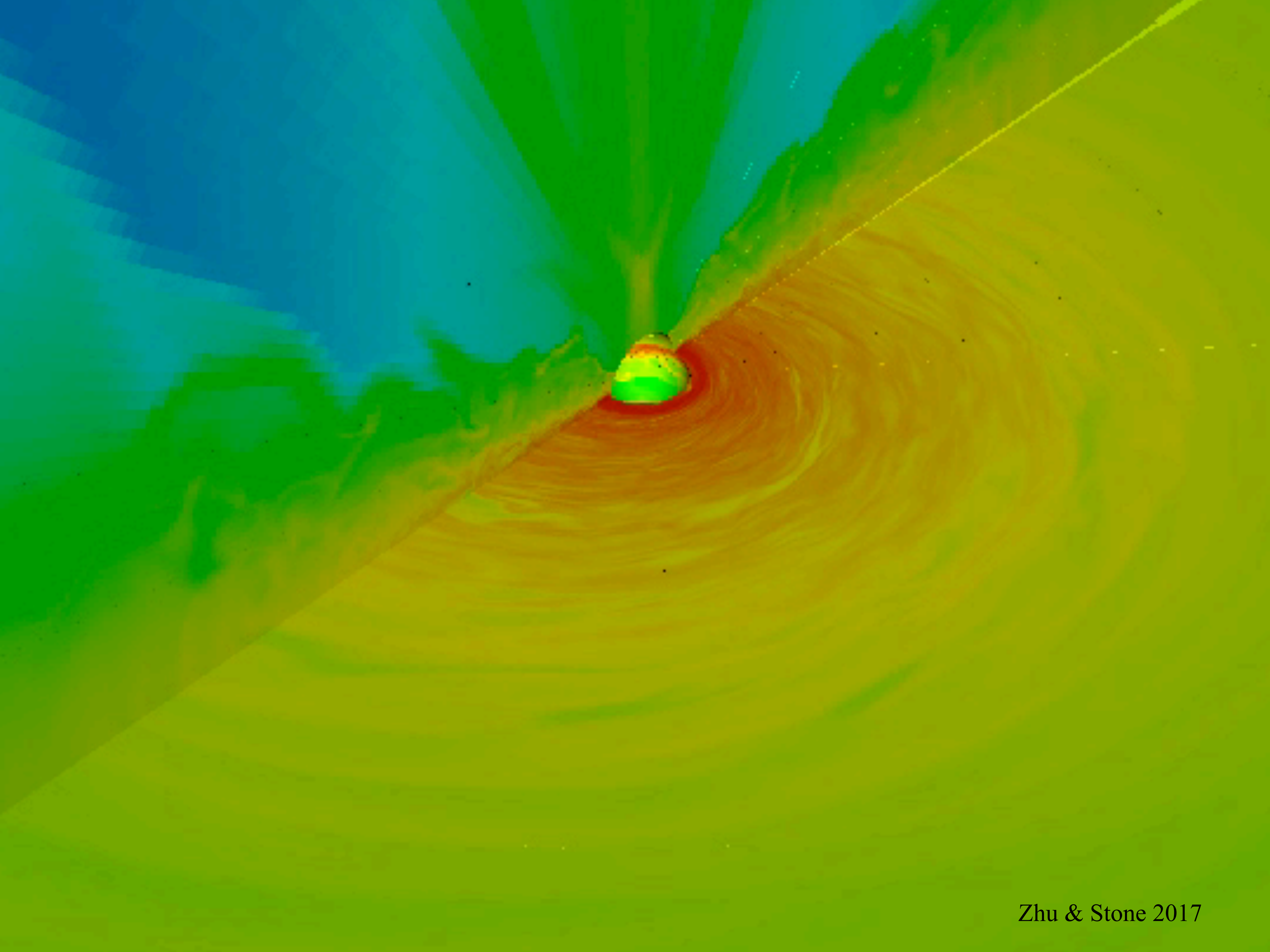




Zhu & Stone 2017



Zhu & Stone 2017



Zhu & Stone 2017

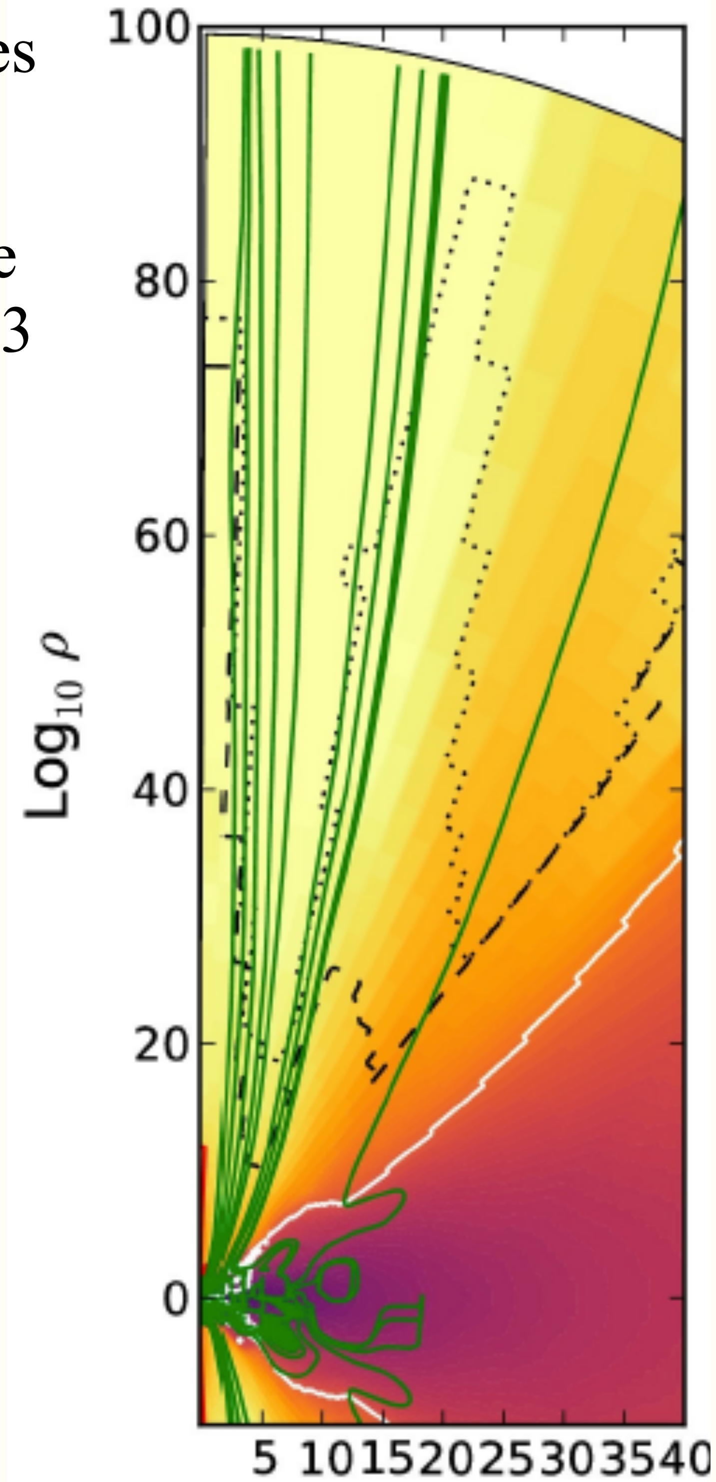
Accretion Structure

Green lines: velocity field lines

Dashed lines: alfven surface (R_A/R_0)~3

White lines: β=1

Azimuthally averaged density after 1400 inner orbits



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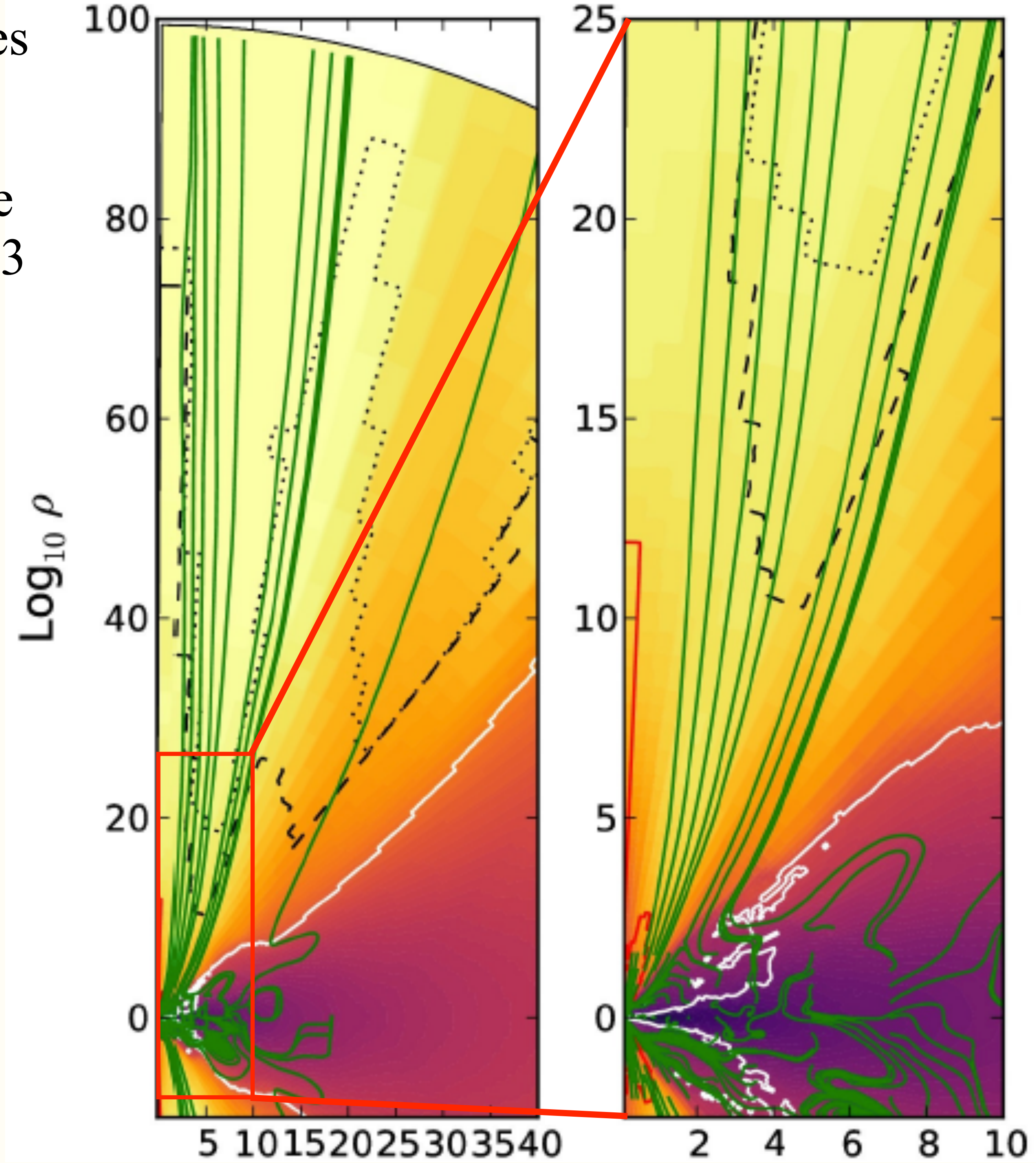

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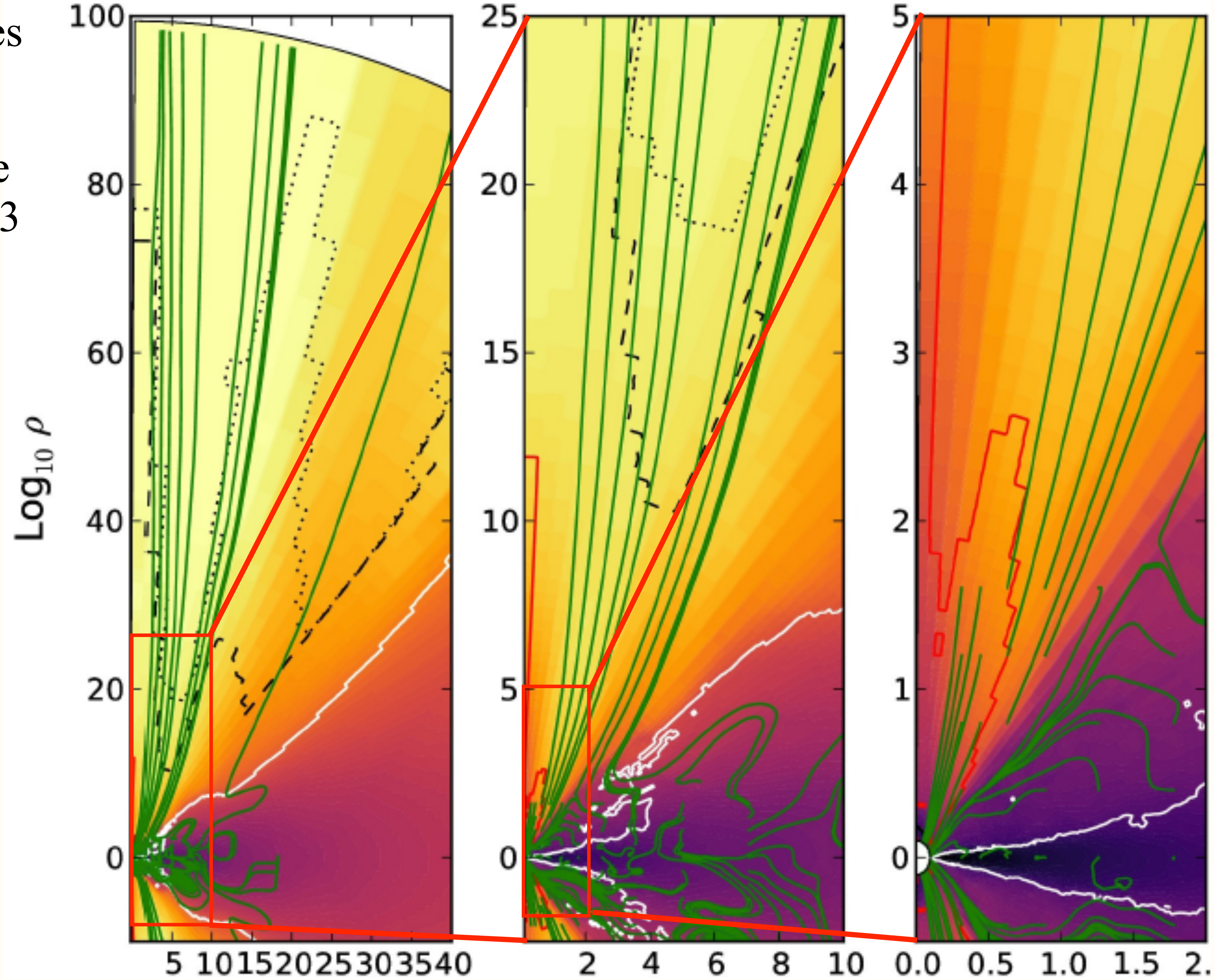


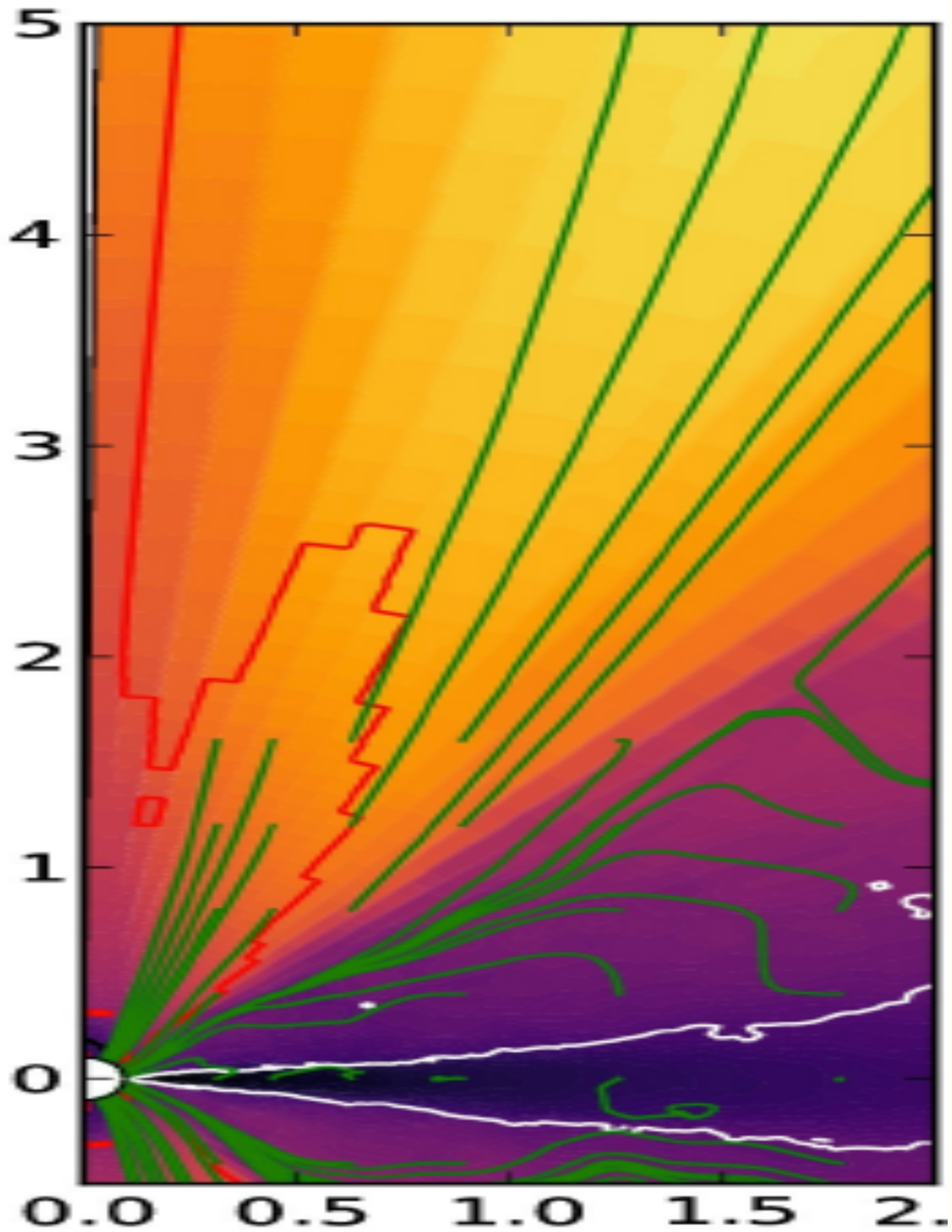
Corona Accretion

Green lines: velocity
field lines

Dashed lines: alfven
surface

White lines: β=1

Azimuthally averaged



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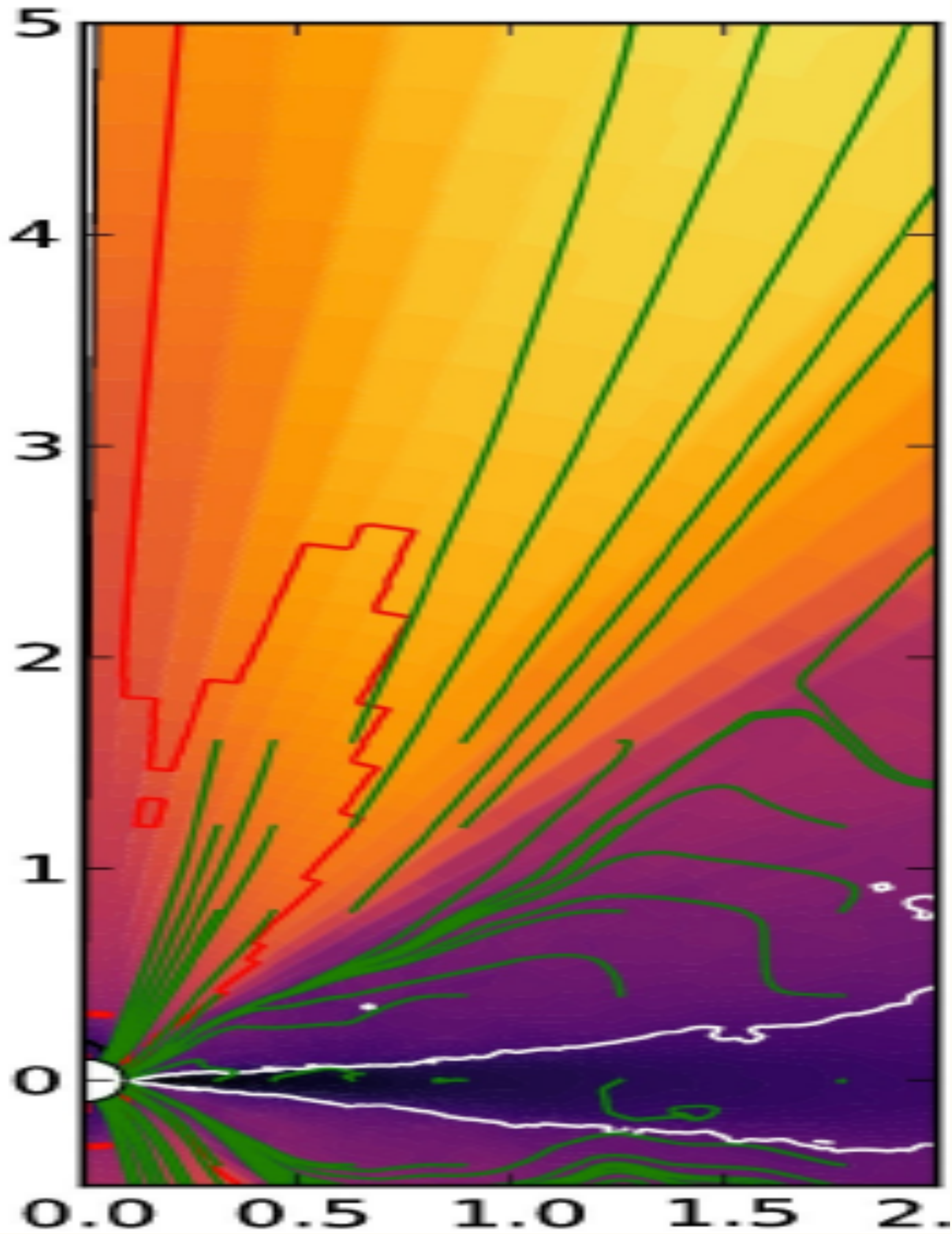

← MRI turbulent midplane

Corona Accretion

Green lines: velocity field lines

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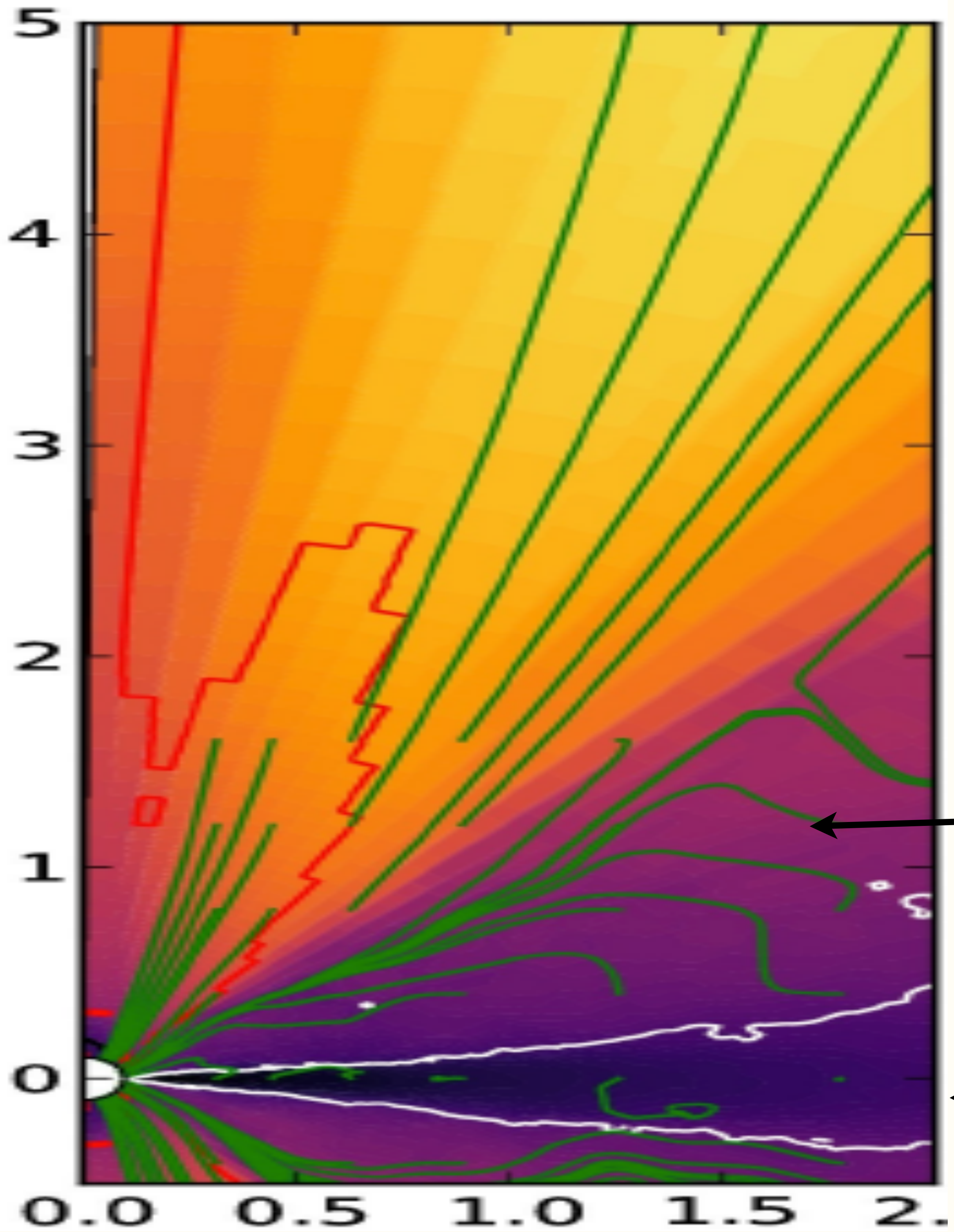
Azimuthally averaged



Fast corona accretion

Beckwith+ (2009)
Avara+ (2016)

MRI turbulent midplane

Corona Accretion

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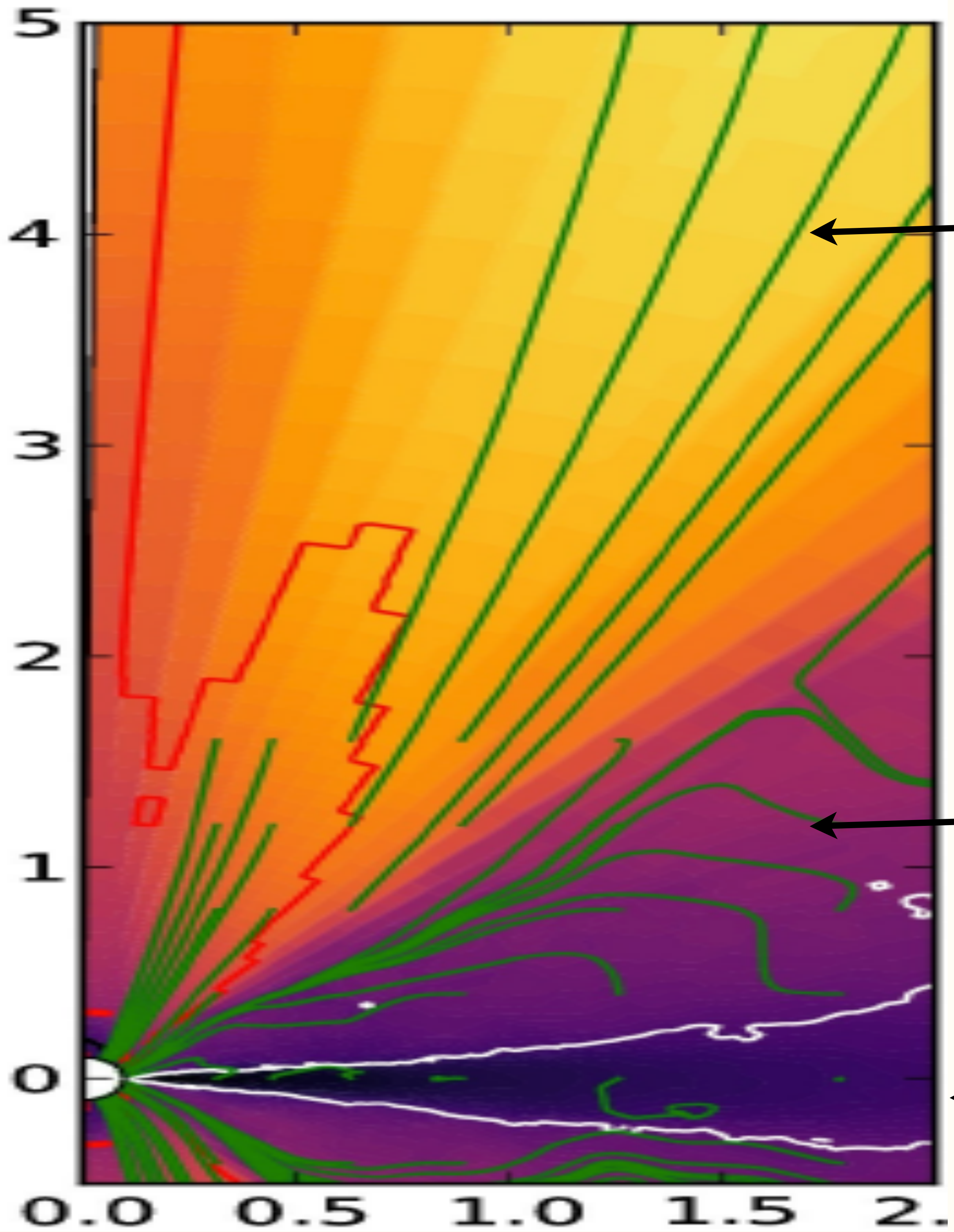


Wind region

Fast corona accretion
Beckwith+ (2009)
Avara+ (2016)

MRI turbulent midplane

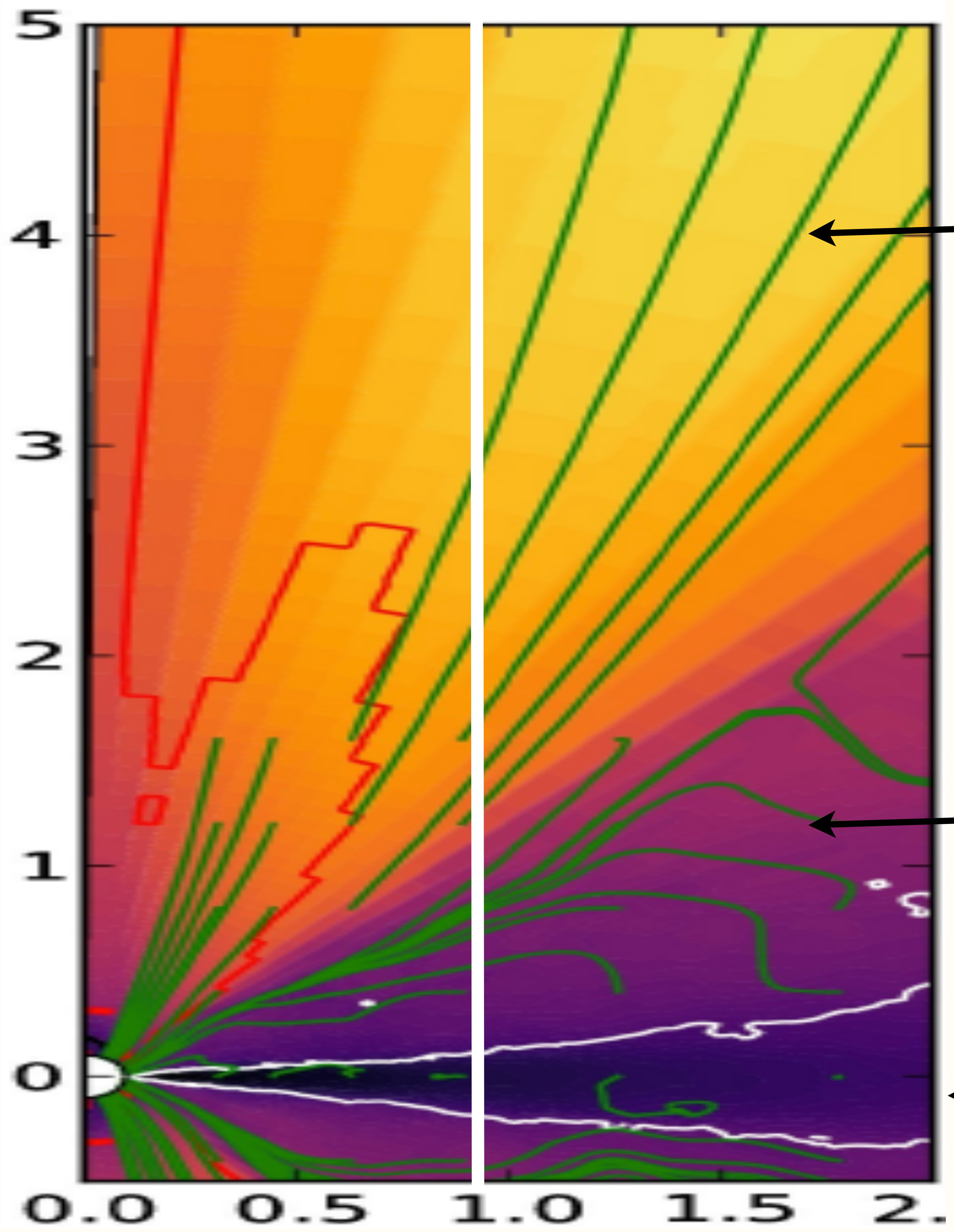
Corona Accretion

Green lines: velocity field lines

Dashed lines: alfven surface

White lines: β=1

Azimuthally averaged



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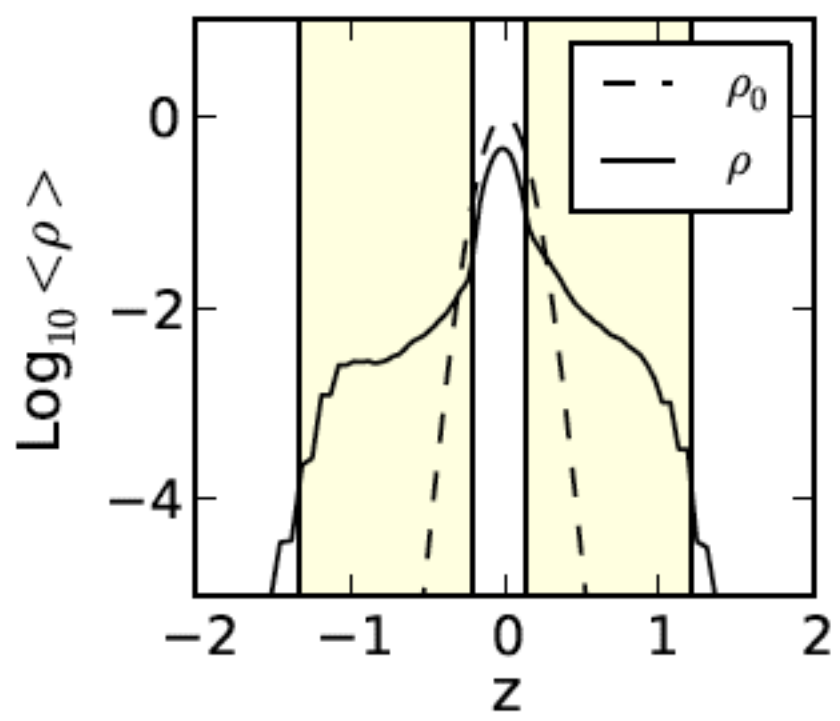
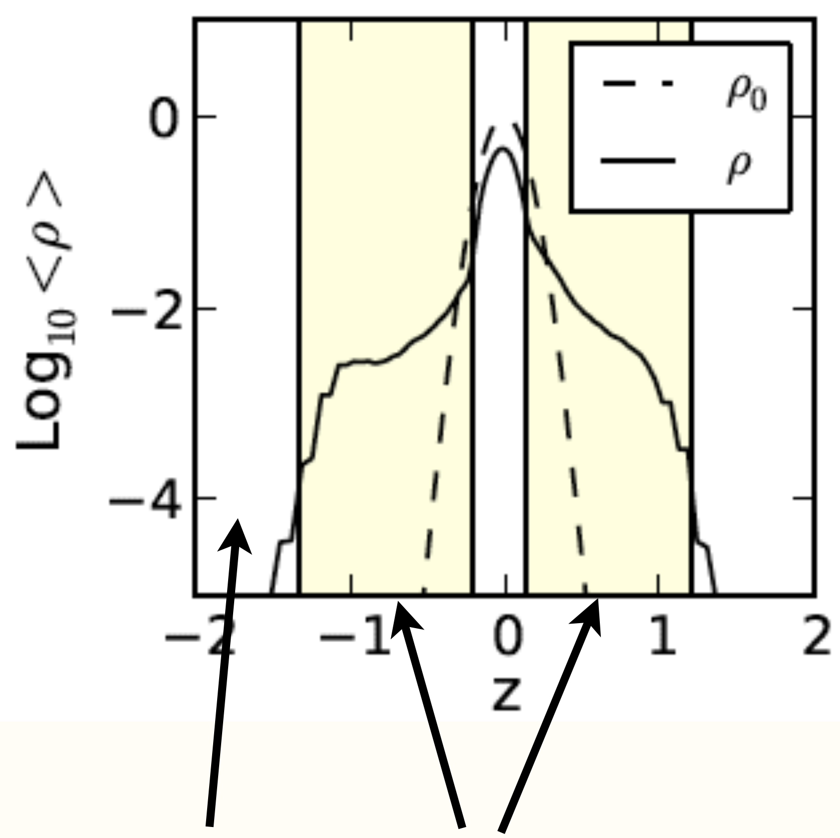
Turbulence VS. Wind

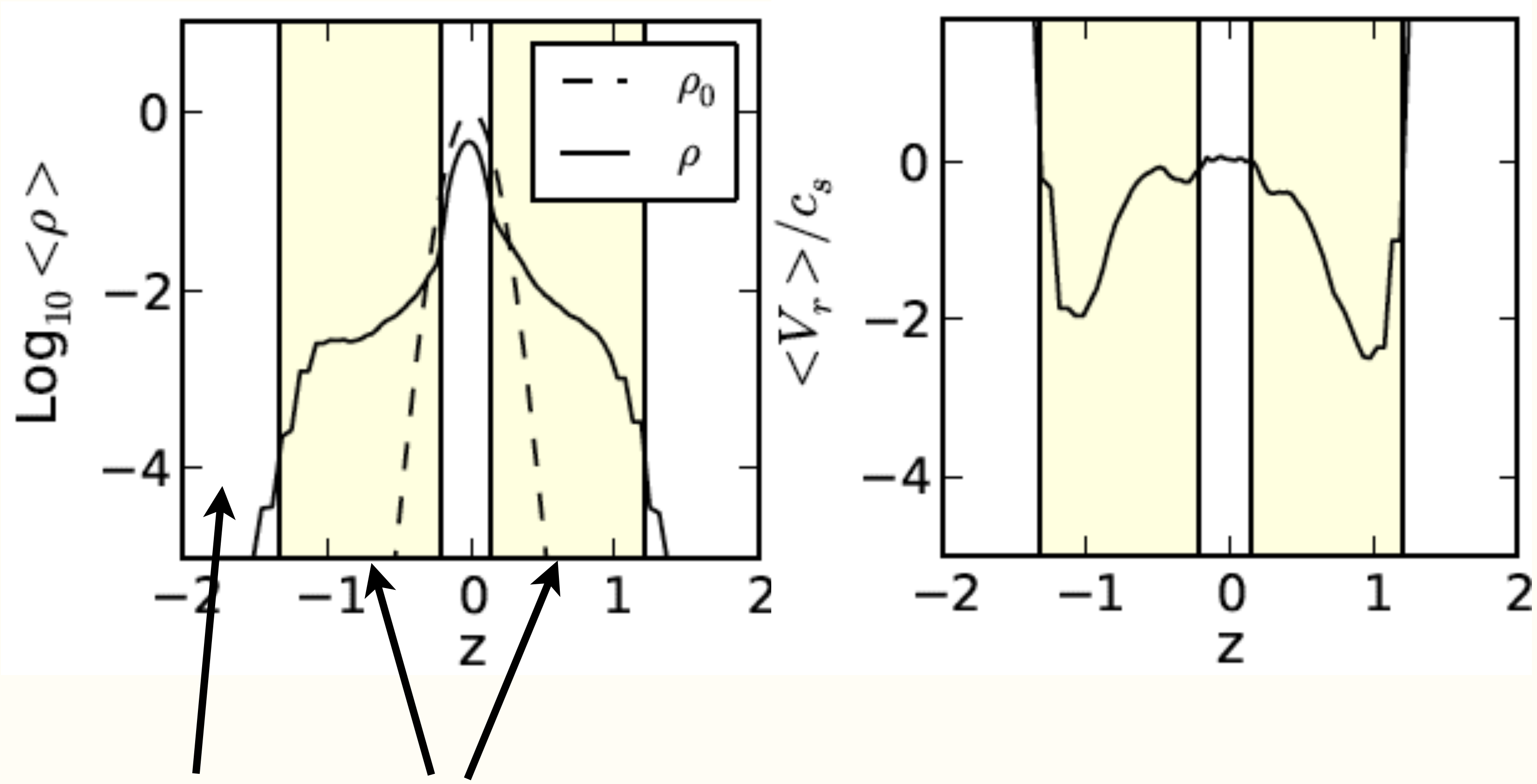


Turbulence VS. Wind



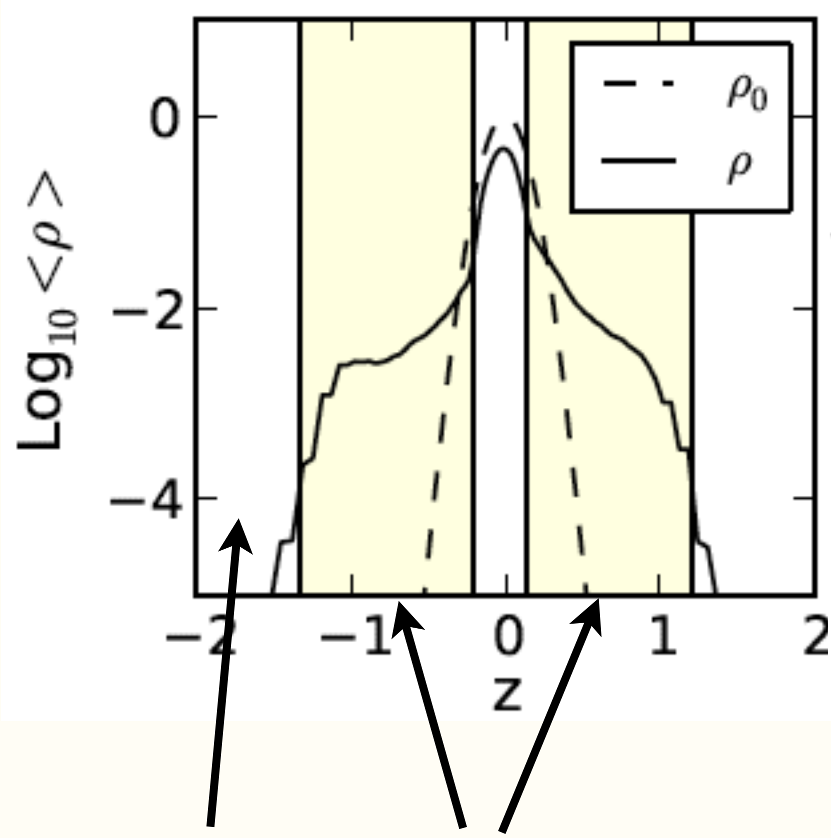
wind corona

Turbulence VS. Wind



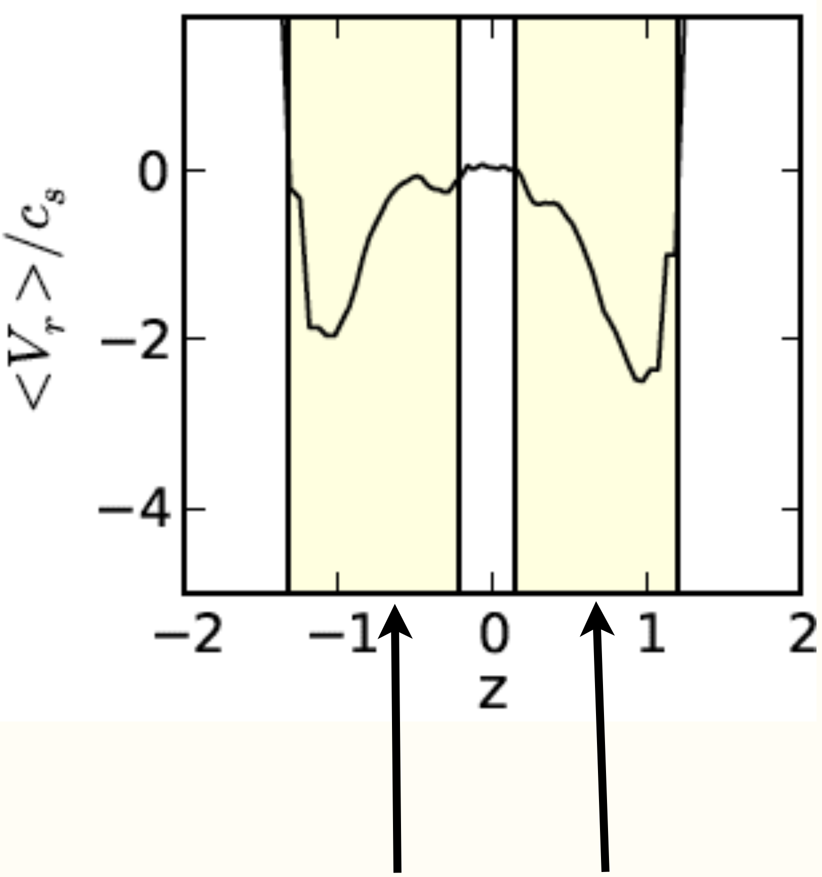
wind corona

Turbulence VS. Wind



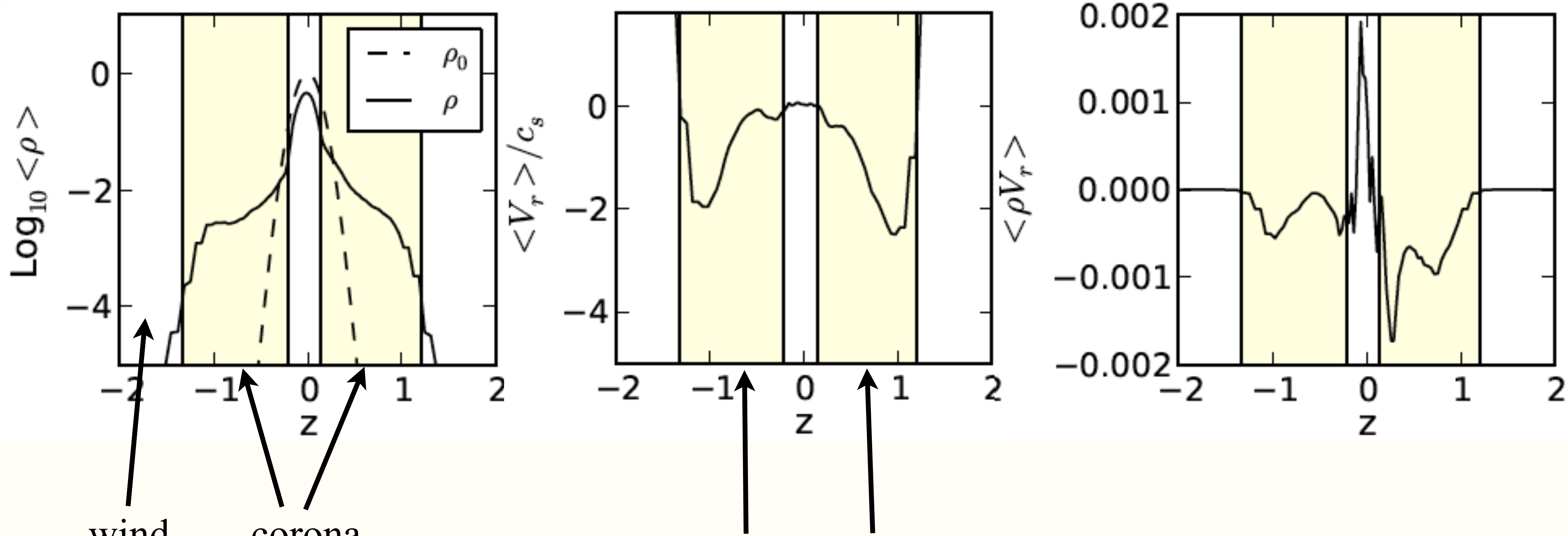
wind

corona



supersonic surface velocity

Turbulence VS. Wind

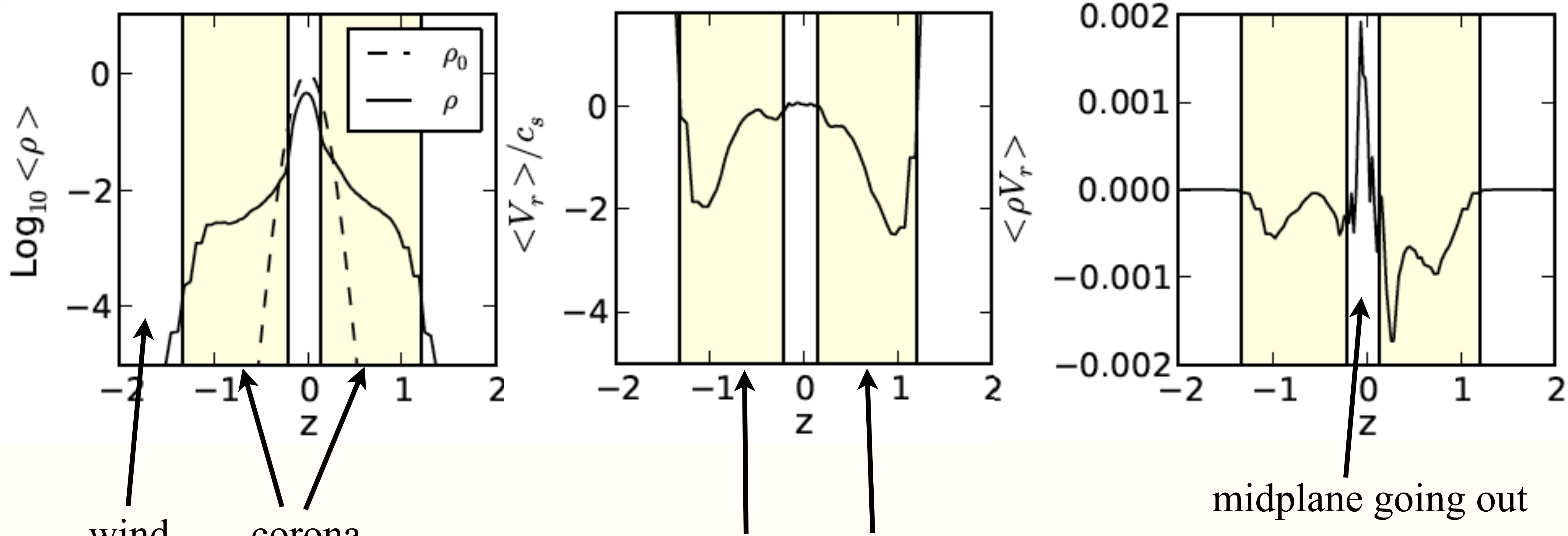


wind

corona

supersonic surface velocity

Turbulence VS. Wind



wind

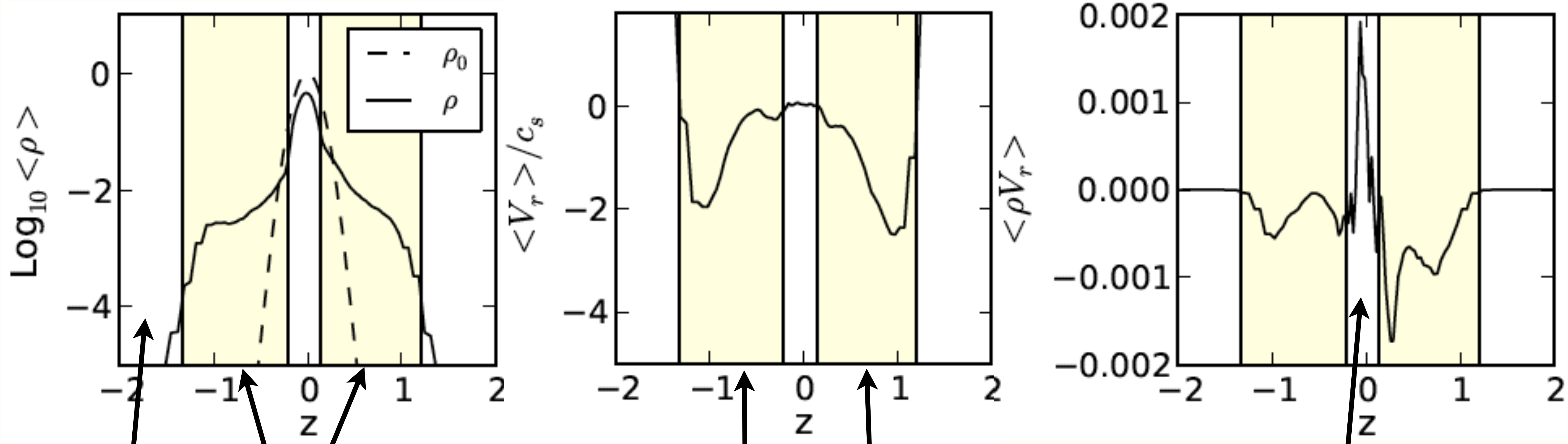
corona

supersonic surface velocity

midplane going out

Suzuki &Inutsuka 2014

Turbulence VS. Wind



wind

corona

supersonic surface velocity

midplane going out

Similar to
Meridian Circulation

Suzuki &Inutsuka 2014

Angular Momentum Budgets:

$$\frac{\partial\langle\rho\delta v_\phi\rangle}{\partial t}+\frac{1}{r^3}\frac{\partial(r^3\delta\langle M_{r\phi}\rangle)}{\partial r}+\frac{\langle\rho v_r\rangle}{r}\frac{\partial r v_K}{\partial r}+\frac{1}{r\mathrm{sin}\theta}\frac{\partial(\sin^2\theta\langle\delta M_{\theta\phi}\rangle)}{\partial\theta}+\frac{\langle\rho v_\theta\rangle}{r\mathrm{sin}\theta}\frac{\partial(\sin\theta v_K)}{\partial\theta}=0$$

— rφ stress

— θφ stress

— $\dot{m}_r$

— $\dot{m}_\theta$

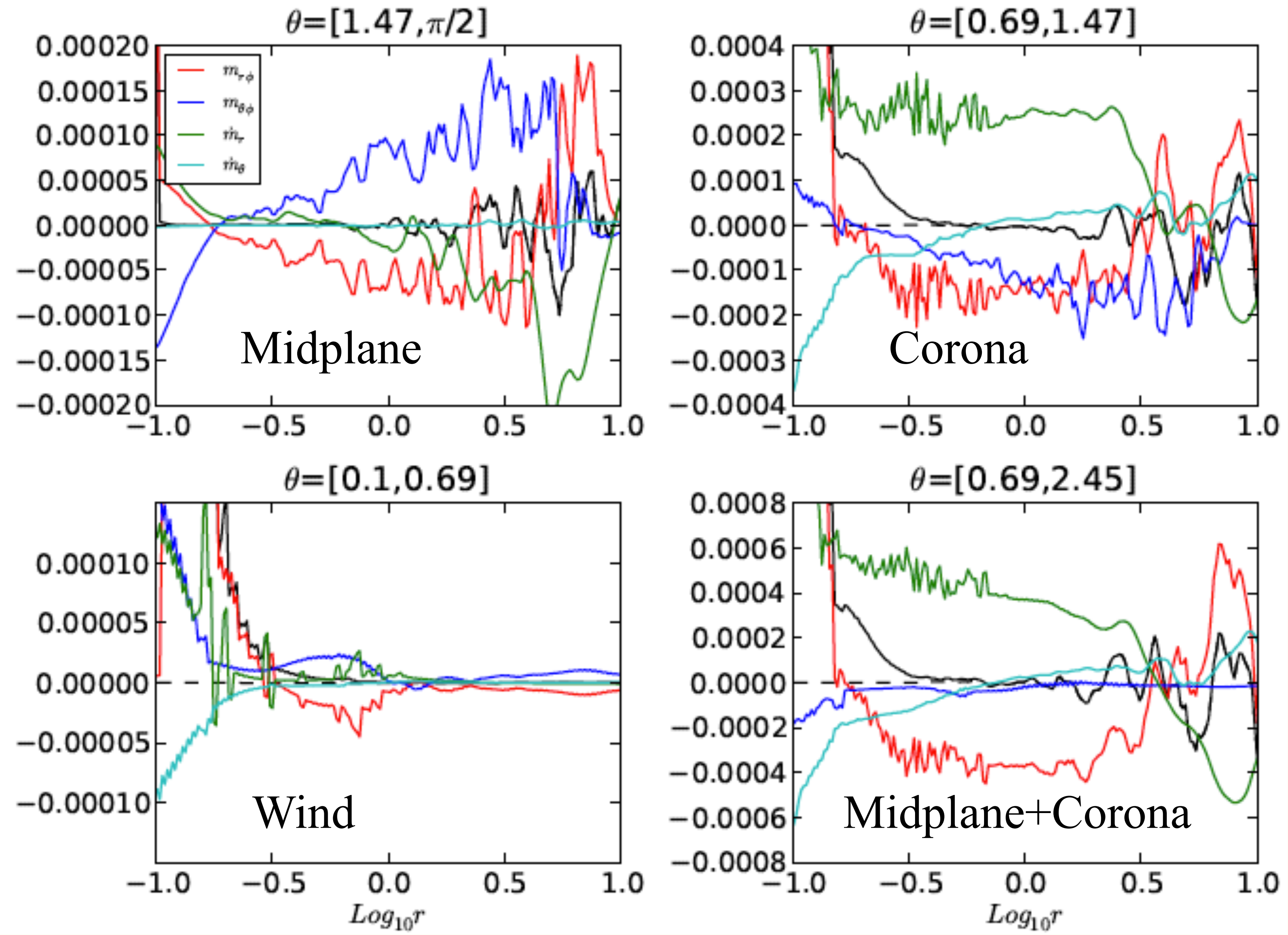
Wind

Angular Momentum Budgets:

$$\frac{\partial\langle\rho\delta v_\phi\rangle}{\partial t}+\frac{1}{r^3}\frac{\partial(r^3\delta\langle M_{r\phi}\rangle)}{\partial r}+\frac{\langle\rho v_r\rangle}{r}\frac{\partial r v_K}{\partial r}+\frac{1}{r\sin\theta}\frac{\partial(\sin^2\theta\langle\delta M_{\theta\phi}\rangle)}{\partial\theta}+\frac{\langle\rho v_\theta\rangle}{r\sin\theta}\frac{\partial(\sin\theta v_K)}{\partial\theta}=0$$

— rφ stress — θφ stress — $\dot{m}_r$ — $\dot{m}_\theta$

Wind



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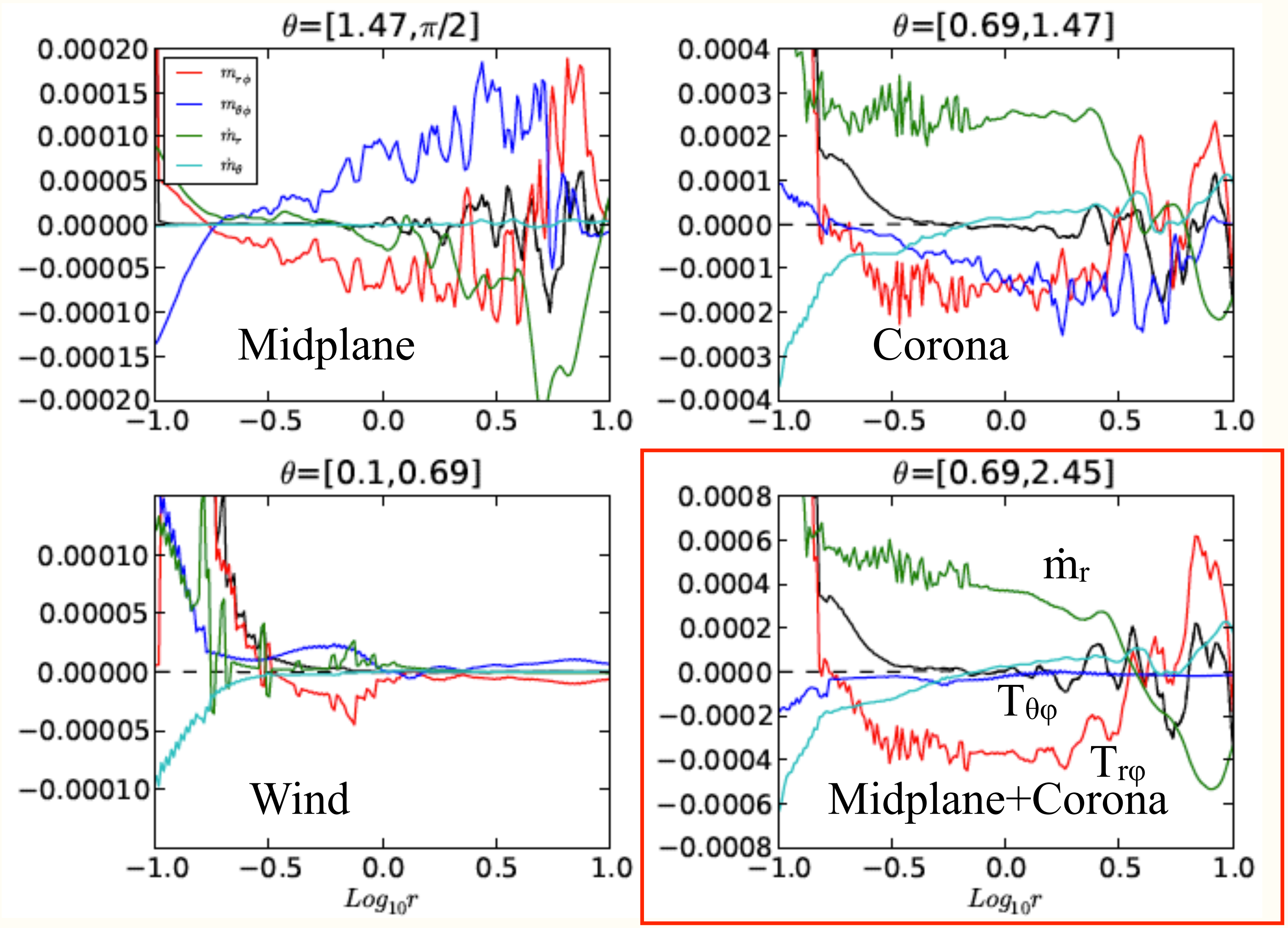
— rφ stress — θφ stress — $\dot{m}_r$ — $\dot{m}_\theta$

Wind



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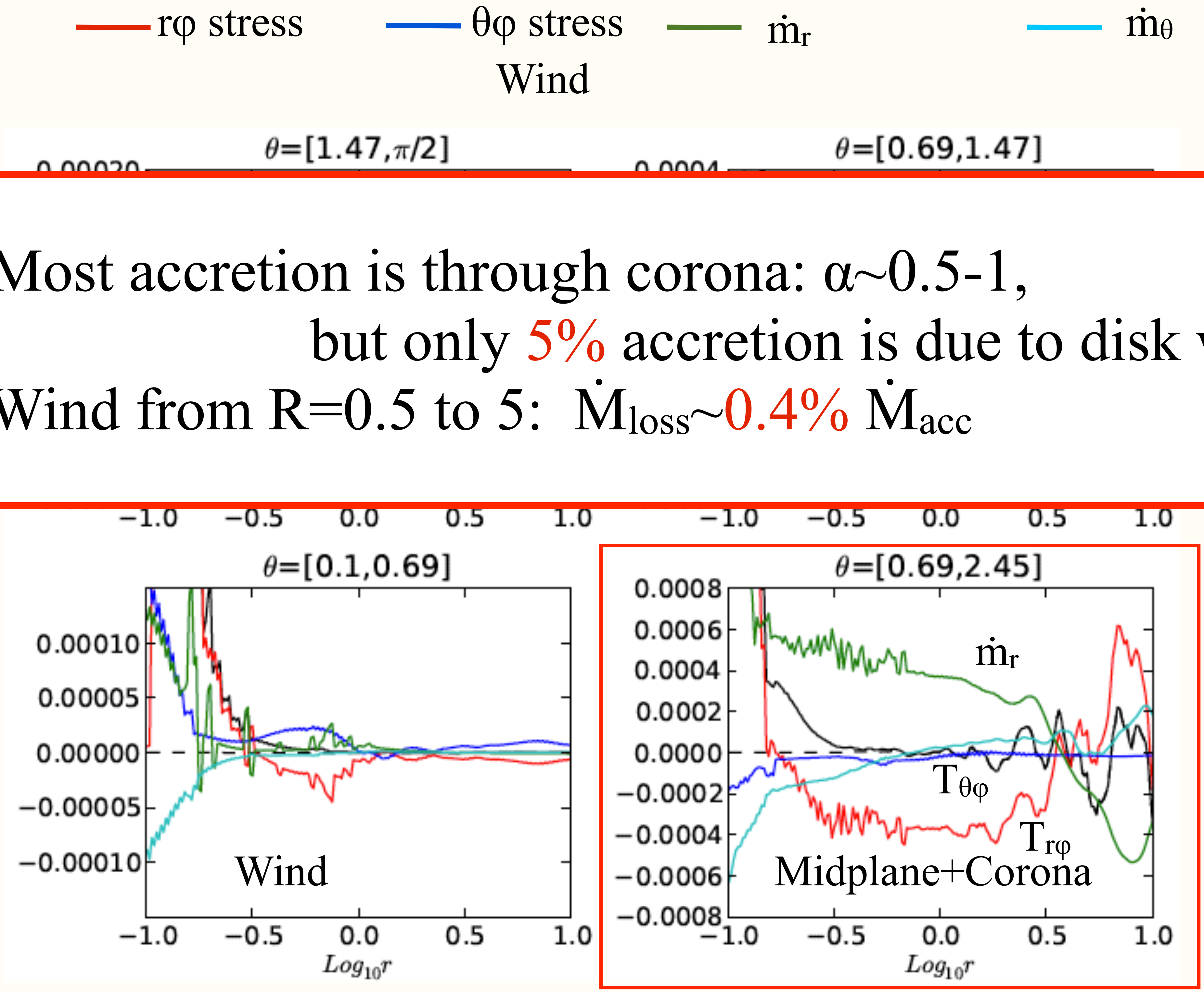
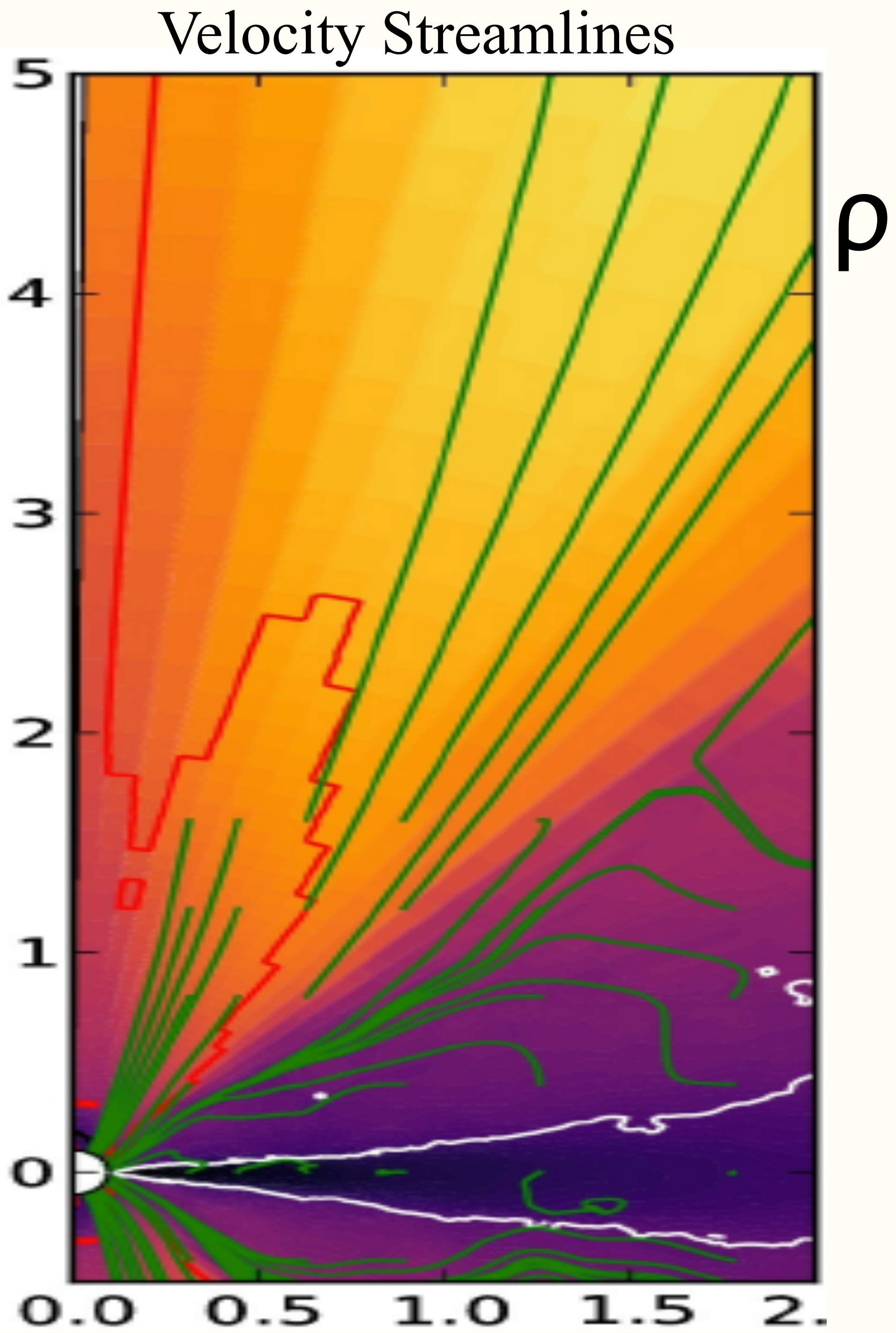
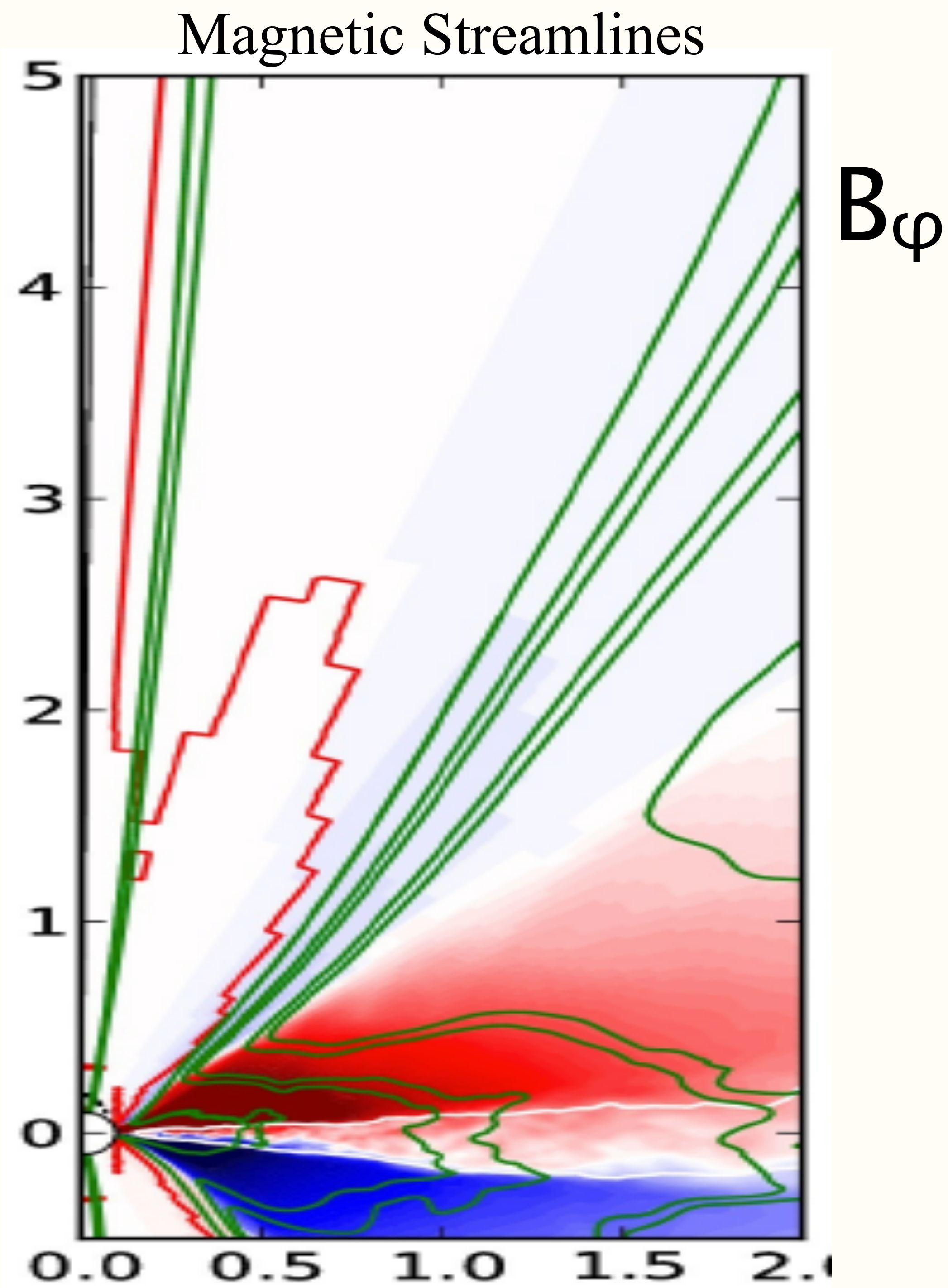


- Most accretion is through corona: α~0.5-1, but only 5% accretion is due to disk wind
- Wind from R=0.5 to 5: $\dot{M}_{loss}$~0.4% $\dot{M}_{acc}$

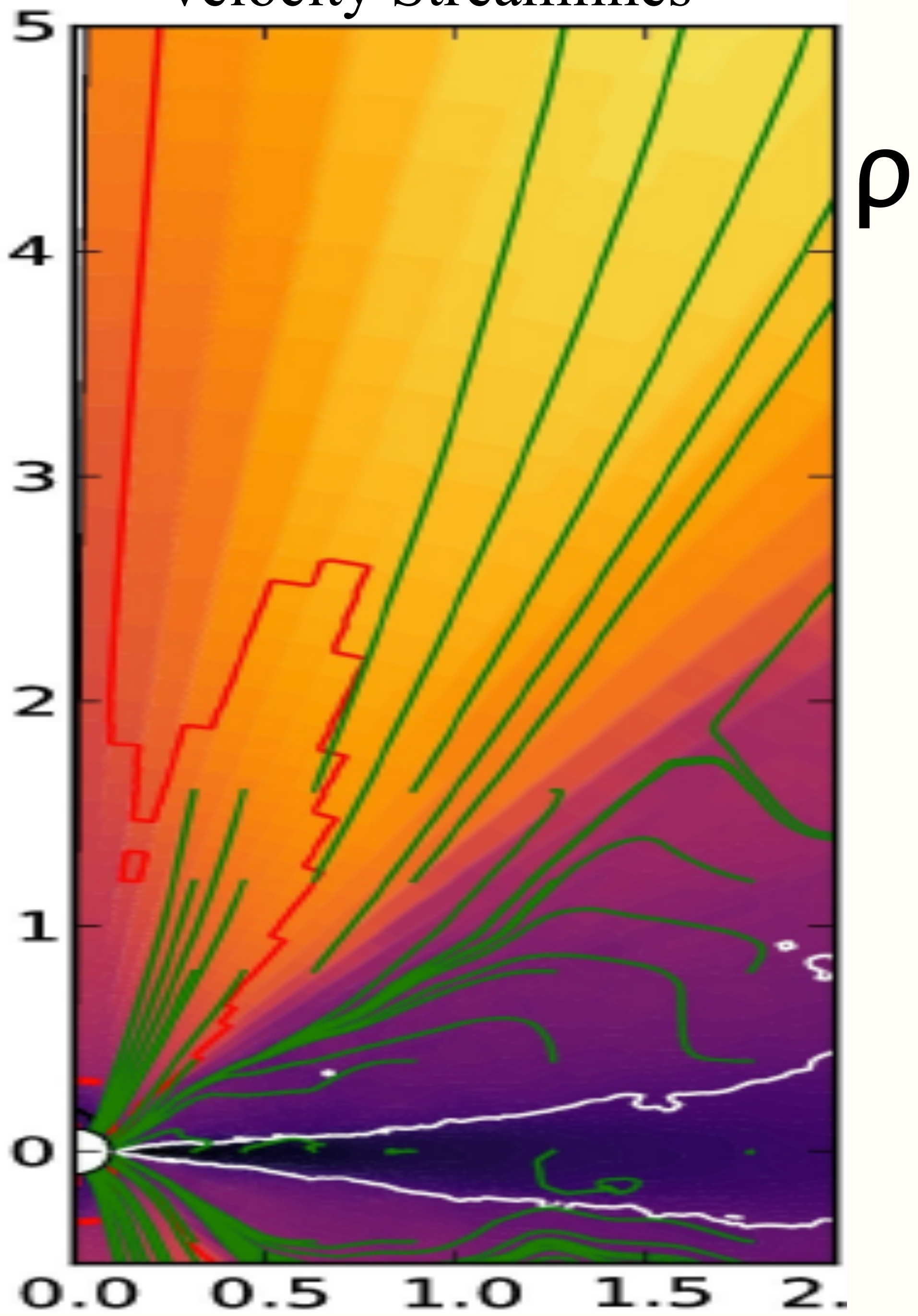
B-field Structure and Driving Mechanism



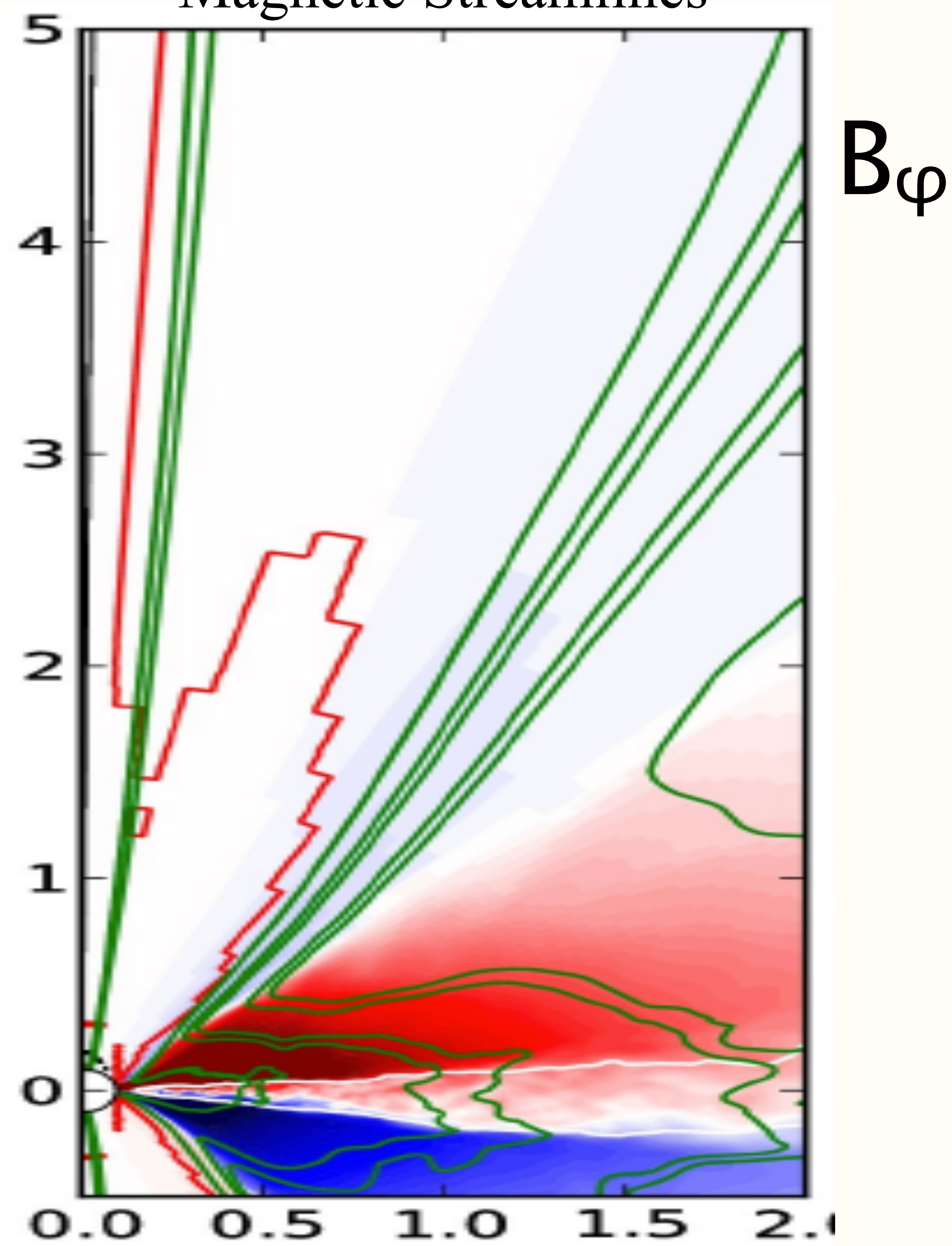


B-field Structure and Driving Mechanism

Velocity Streamlines



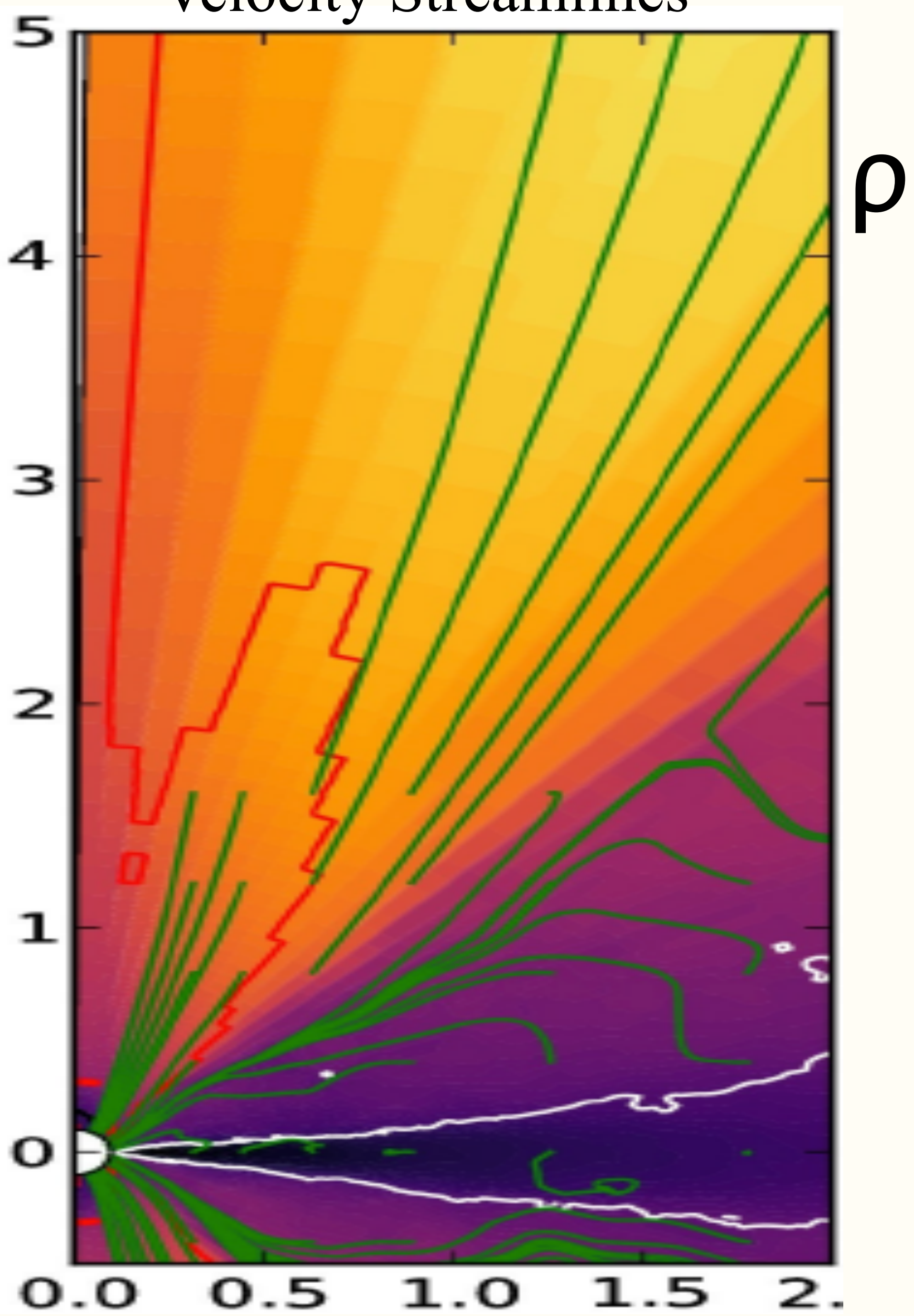
Magnetic Streamlines



Surface accretion drags **B** → Keplerian shear generates B_φ

B-field Structure and Driving Mechanism

Velocity Streamlines



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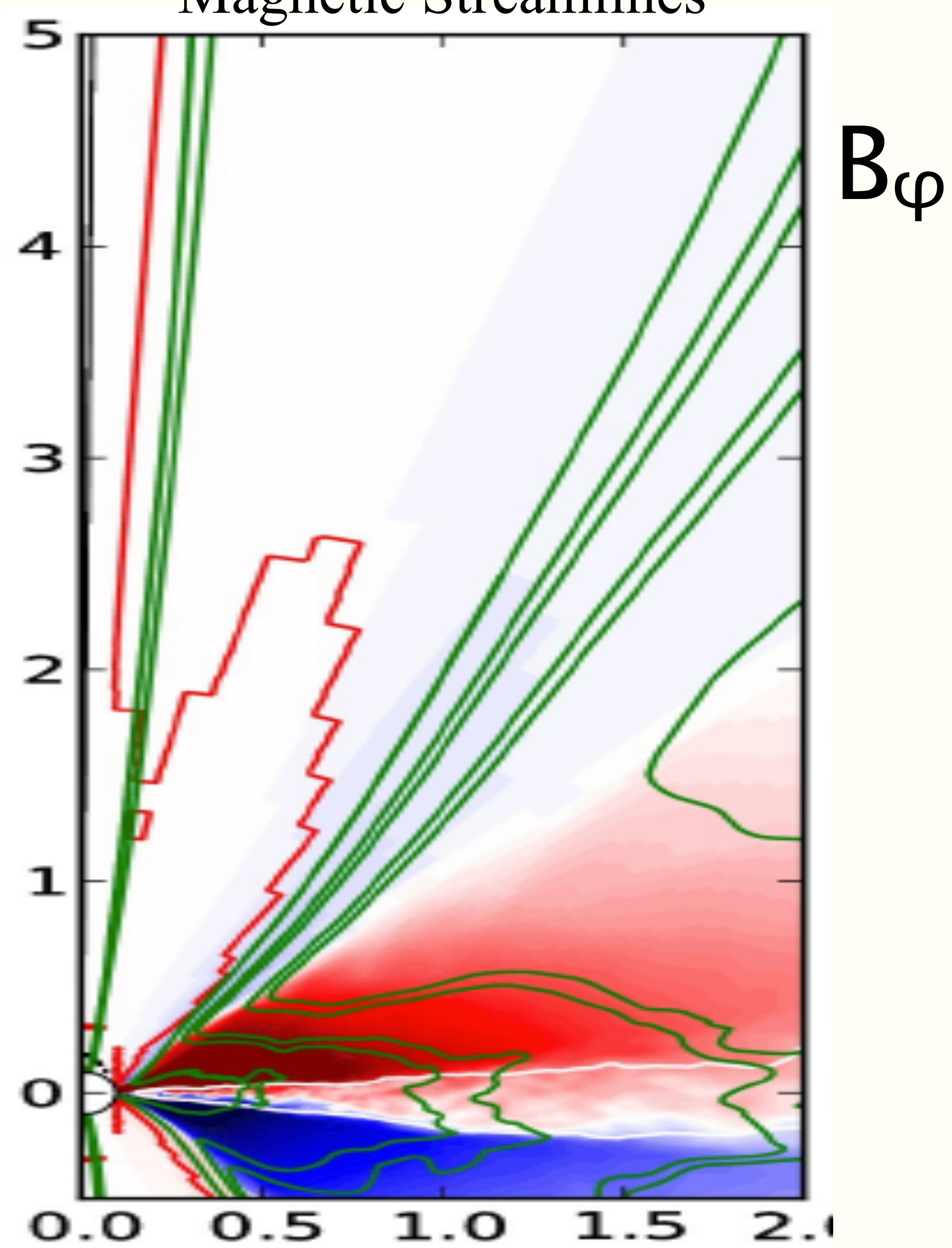
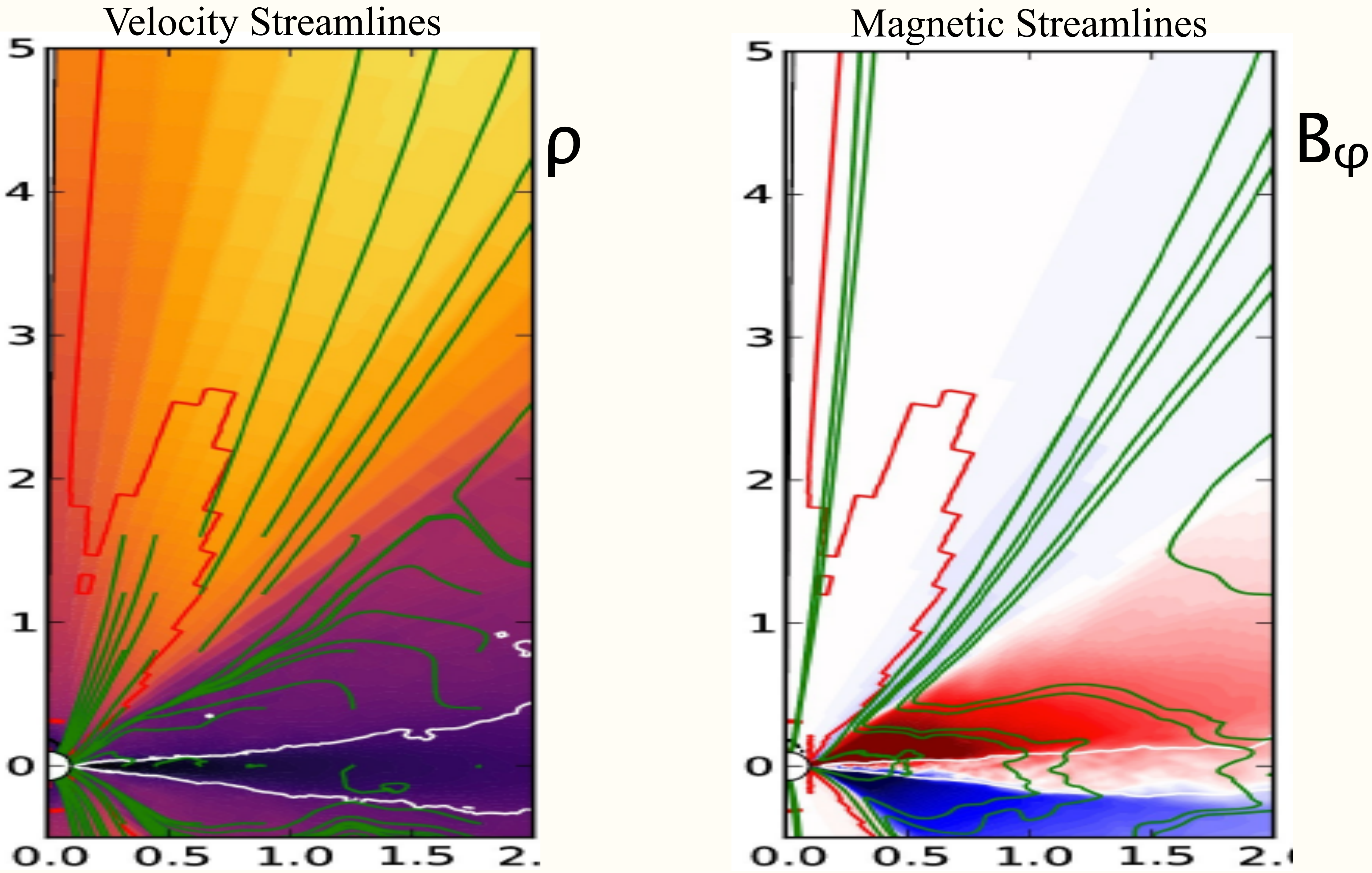


Surface accretion drags **B** → Keplerian shear generates B_φ → B_φ B_z leads to vertical shear B_φ B_R leads to overall accretion

B-field Structure and Driving Mechanism



Velocity Streamlines

Magnetic Streamlines

Surface accretion drags **B** → Keplerian shear generates B_φ → B_φ B_z leads to vertical shear

B_φ B_R leads to overall accretion

Maintain Global Fields

$$\frac{\partial A_\phi}{\partial t} = -v_R B_z + v_z B_R - \eta \frac{\partial B_R}{R \partial z} + \eta \frac{\partial B_z}{\partial R}$$

If η~ν, diffusion is larger than advection by R/H

Maintain Global Fields

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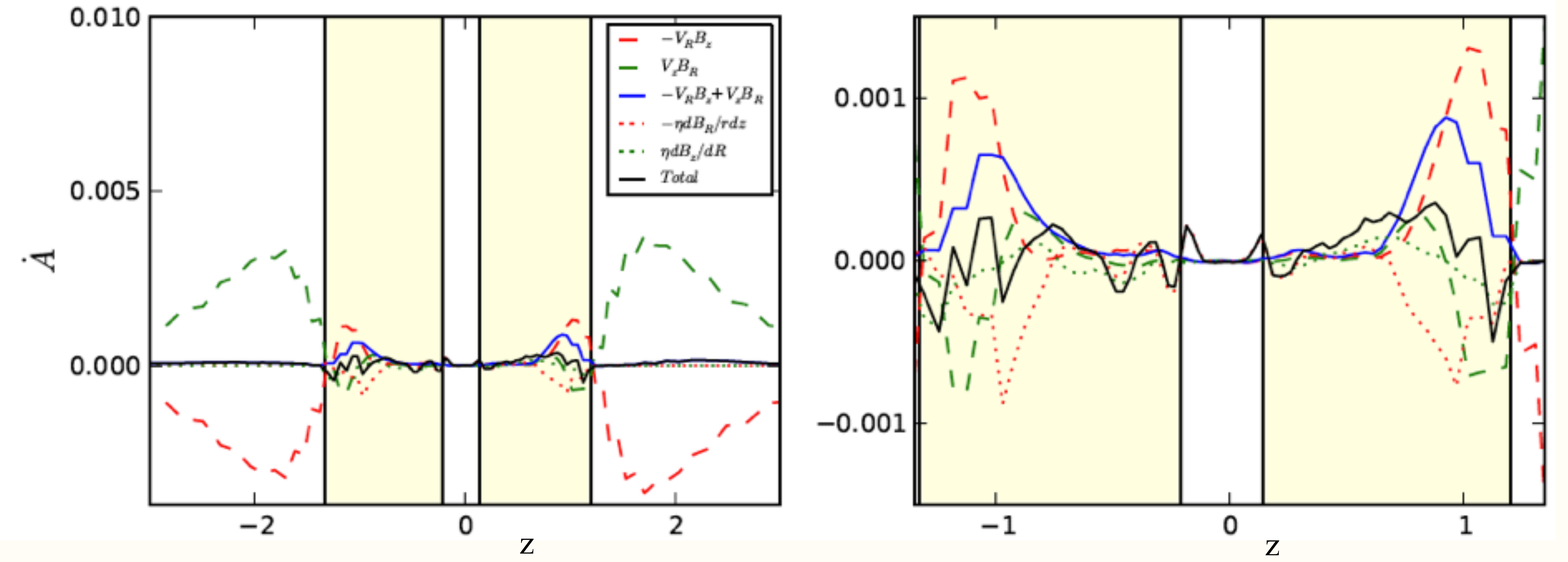
Using η~ν in our simulations (Guan &Gammie 2009, Lesur &Longaretti 2009, Fromang &Stone 2009)



Maintain Global Fields

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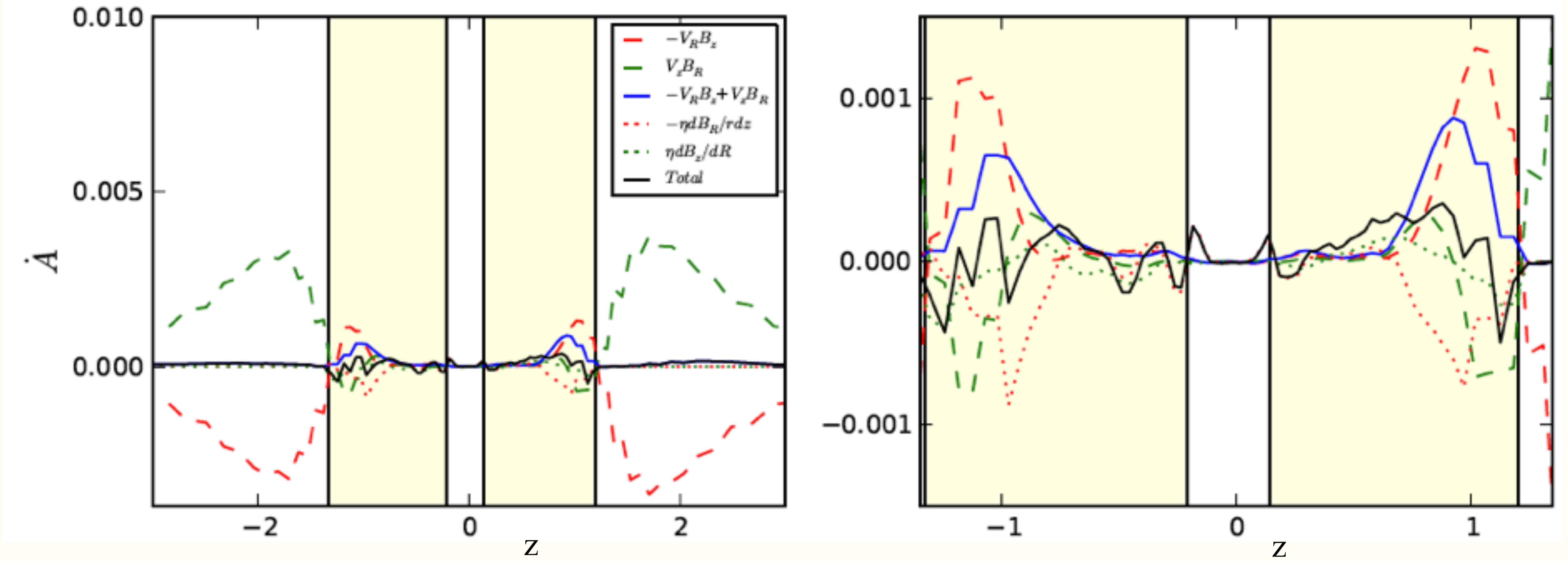

Why does the disk maintain global fields with η~ν?

- Fast coronal accretion increases the advection term
- The corona extends very high (z~R), and the scale height for B-field is ~R

Summary

- Spirals excited by the planet
  - constrain not only the position but also the mass of the perturber
- Spirals excited by the star
  - The circumplanetary disk: we may have some candidates, more with ALMA
  - Accretion is driven by spiral shocks induced by companion
- Global MHD disk simulations
  - Coronal Accretion, total $\alpha \sim 0.5$-1
  - Wind not important (leads to <5% of total accretion)
  - Global field is maintained with unity Prandtl number