Gaps, rings, and non-axisymmetric structures in protoplanetary disks

From simulations to ALMA observations.

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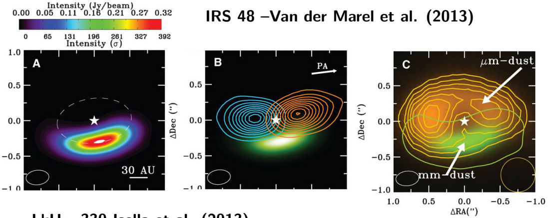
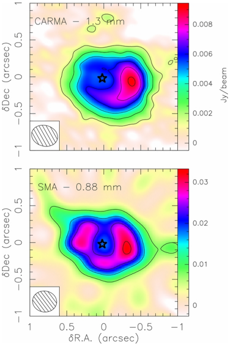
Sebastien Fromang, Sebastian Wolf, Thomas Henning, Hubert Klahr

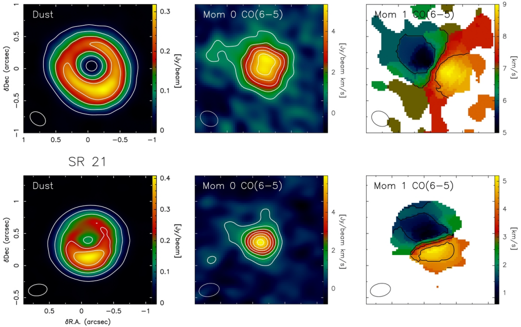
Planet Formation and Evolution 2014, Kiel, 8.9.2014

IRS 48 –Van der Marel et al. (2013)



LkHα 330 Isella et al. (2013)





Sao 206462, SR 21 Pérez et al. (2014)

Most used theory

$\rightarrow$ planet inside the disk $\rightarrow$ surface density bump at outer gap edge $\rightarrow$ vortex $\rightarrow$ concentration of particles $\rightarrow$ asymmetry

Most used theory

→ planet inside the disk → surface density bump at outer gap edge → vortex → concentration of particles → asymmetry

However

- planet size and position not always in agreement with planet population synthesis models
  core accretion timescale > disk lifetime (at R > 30 AU)

  difficult also for metal poor systems, Benz et al. (2014)
- GI ?

  Janson et al. 2012 < 10 % of the stars can form and retain a planet at 5-500 AU ?

How about another theory

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→ magneto-rotational instability (Balbus & Hawley 1991,92,98)

→ the turbulence drives accretion and mass flows (Shakura & Sunyaev 1973)

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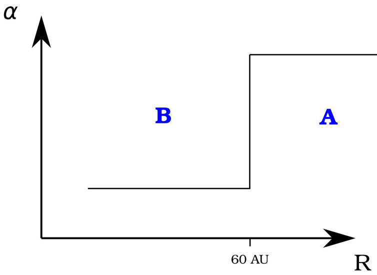

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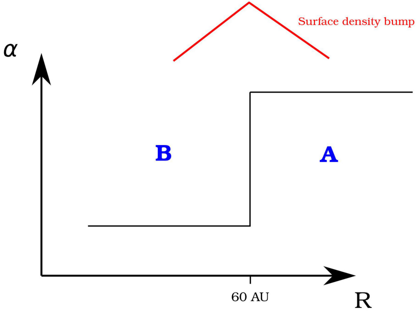

Varnière et al (2006)

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The transition is smooth (M. Wardle 2007, Dzyurkevich et al. 2013, Turner et al. 2014)

→ **no jump in surface density**

Let's try it ! Merge expertise !!

I Global 3D MHD simulations of accretion disks Flock et al. (2011,12)

II Parameterized disk model fitting high-angular resolution multi-wavelength observations of various circumstellar disks

Wolf et al. (2003)... Gräfe et al. (2013)

III Resistivity profile by dust chemistry Dzyurkevich et al. (2013)

Global model

PLUTO code Godunov type code, 2nd order in space and time, CT MHD.

Riemann solver HLLD (Miyoshi and Kusano 2005).

FARGO MHD optimized for MHD in fast rotating flows (Mignone et al. 2012).

Domain in spherical coordinates $\mathrm{r} = 20 - 100\mathrm{AU}$ $\Delta\theta = 0.72$ $\Delta\phi = 2\pi$ (256x128x512) (well resolved H/dx $>$ 20).

Magnetic field Vertical net-flux field
fields show $\sim 1/R$ Flock et al. 2011 and Suzuki et al. 2014
$\rightarrow$ set vertical field to $\sim 1/R$ (1 mGauss at 40 AU)
close to upper limit see Okuzumi et al. (2014)

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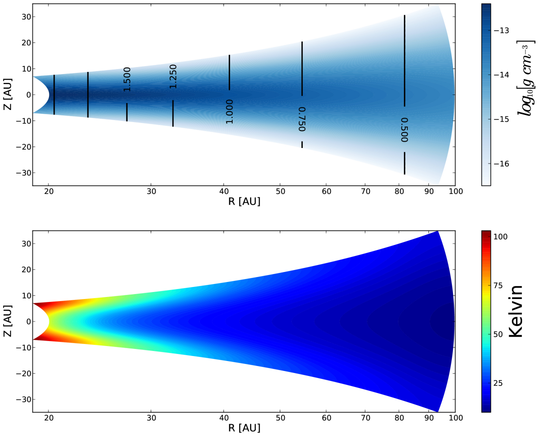
Disk model



$\Sigma = 5.94\ \mathrm{g\ cm^{-2}}\ \frac{R}{100AU}$

$T_* = 4000K$

$0.95\ L_\odot$

$M_* = 0.5M_\odot$

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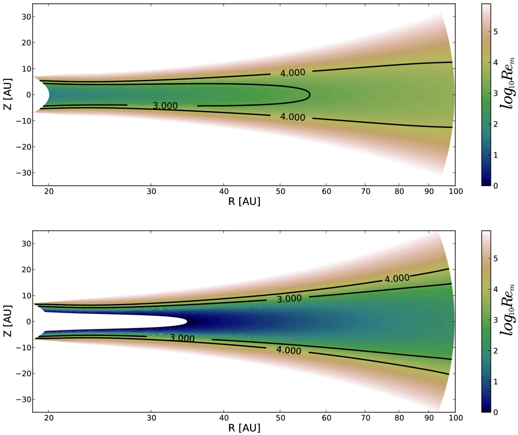
Resistivity



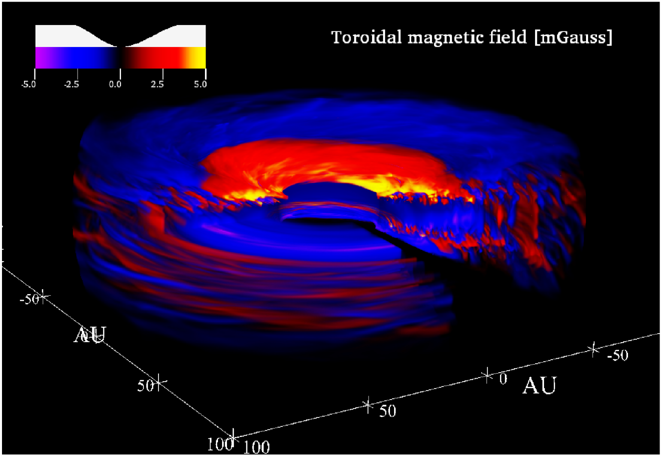
$\mathrm{Re_m} = \mathrm{c_s H}/\eta$
$\rho_d/\rho_g = 10^{-4}$ (**top**) and 10^{-2} (**bottom**)

- densities of charged species (I+, e-, Dust-) determined following Okuzumi 2009
- magnetic diffusivity calculation follows Wardle 2007
- method uses fractal dust aggregates with (2 μm) and 0.1 μm monomers.
- metals are frozen out, rep. ion HCO^+
- X-ray ionization rate following Bai & Goodman 2009.
- Cosmic ray ionizaten rate $5{\cdot}10^{-18}$ erg/s
- radio-nuclide is $7 \cdot 10^{19}$ (d2g /0.01)

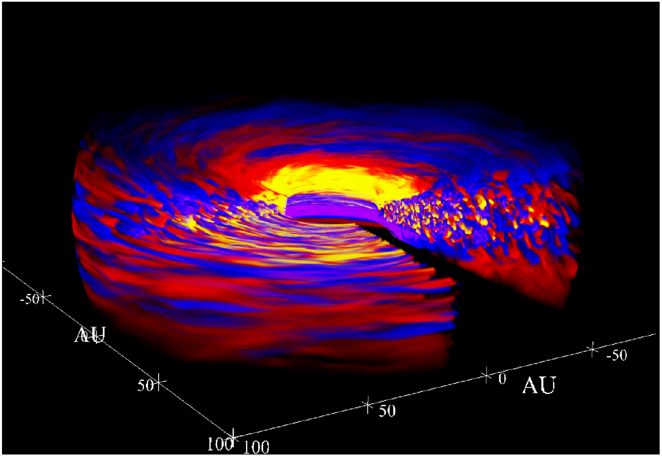
Turbulence and disk evolution

- Both models develop a turbulent state:
  - $\rho_d/\rho_g = 10^{-2} \rightarrow$ includes the dead-zone edge $\rightarrow$ less turbulent in total ($\alpha = 0.003$)
  - $\rho_d/\rho_g = 10^{-4} \rightarrow$ fully turbulent disk ($\alpha = 0.013$)

Turbulence and disk evolution



Turbulence and disk evolution



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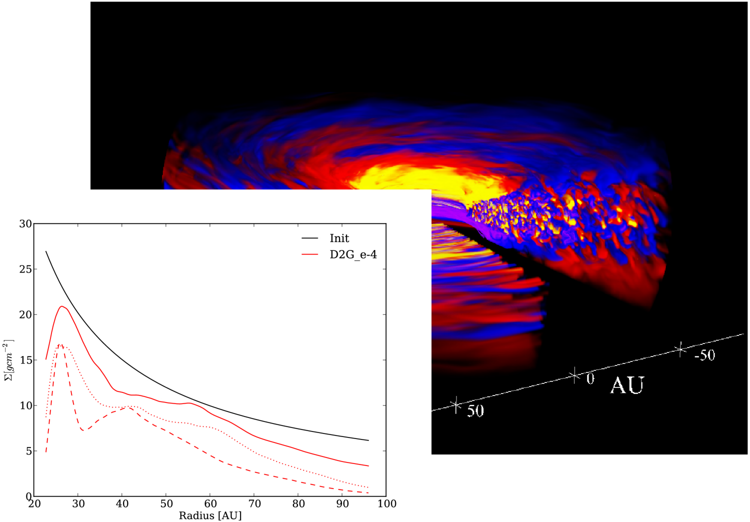

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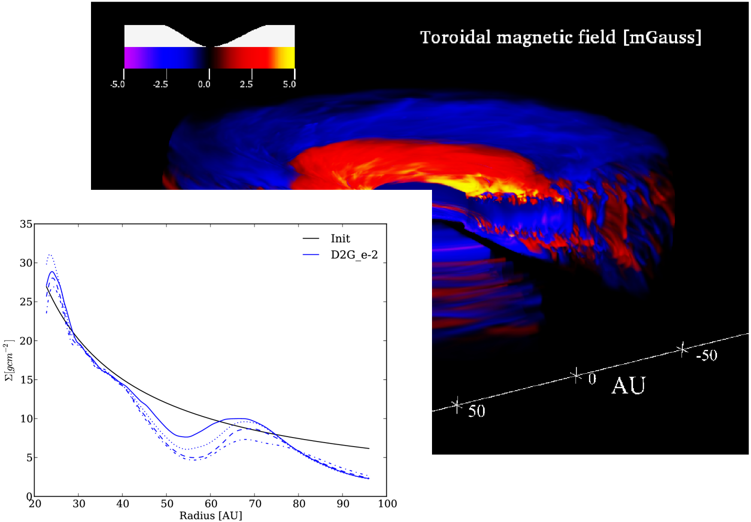
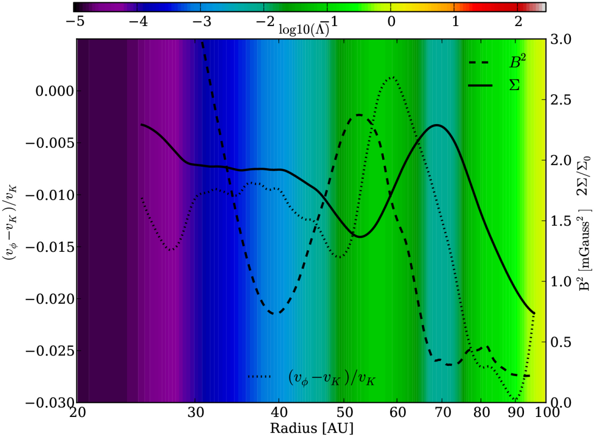


Elsasser number $\Lambda_z = B_z^2/(\rho\eta\Omega)$



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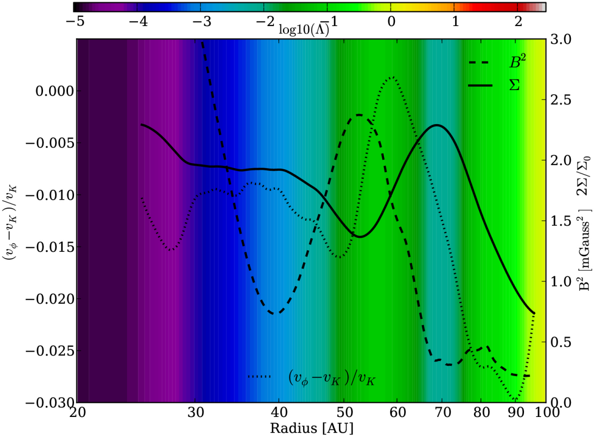
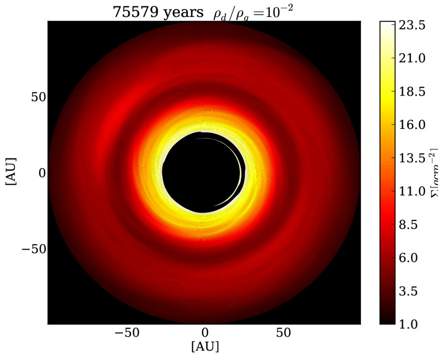
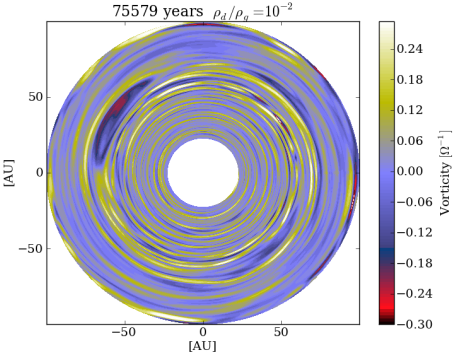


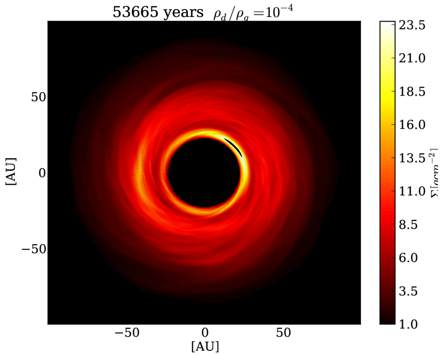
Similar as viscous instability in Johansen et al. 2011 (IAU Proceedings)

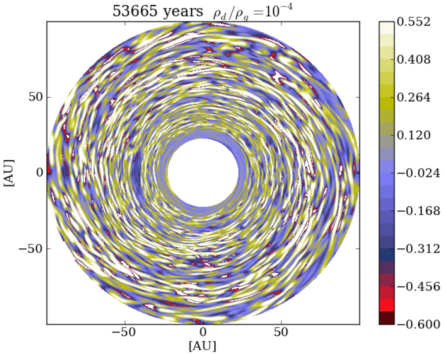
Surface density and vorticity





Surface density and vorticity - Part II





What do we observe with ALMA ?

- Use dataset in MC3D Monte Carlo Radiative Transfer !
- Calculate dust emission
- CASA 4.2 simulator (consider influence of thermal noise by water vapor) (75pc)

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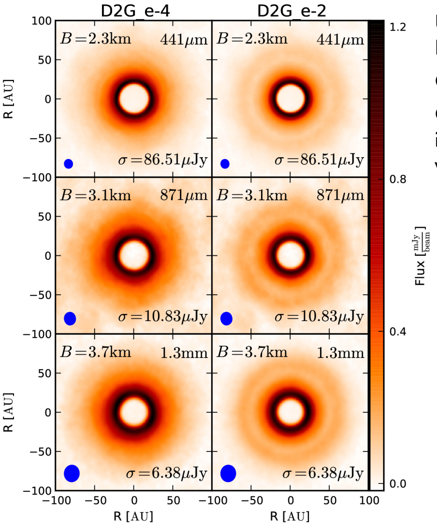

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Asymmetries without a planet

- Is there an alternative model which explains the observed asymmetries in protoplanetary disks ?
  - **A combination of dead-zone edge + zonal flow can trigger the RWI and form a vortex !**

Summary

- Formation of a large gap and bump structure in the surface density close to the dead-zone edge.
- Vortices are formed inside the ring by the Rossby wave instability with a lifetime of around 40 local orbits at a location of 60 AU (19000 years lifetime).
- The gap and ring structure produced by the MRI at the dead zone outer edge can be traced by ALMA
- Formation of a particle trap at the outer dead-zone edge.

Outlook

- Dust particles!
- Dynamical resistivity.
- More non-ideal MHD terms.