Planet Formation in Protoplanetary Disks: Origin of Planetesimals

A. G. Tevzadze

Abastumani Astrophysical Observatory, Georgia

Tbilisi State University, Georgia

Advances in Astrophysical Science, 20-22 September, Tbilisi 2010

- **Observations**
- **Planet Formation Theories**
- **Core Accretion**
- **Vortex Dynamics**
- **Summary**

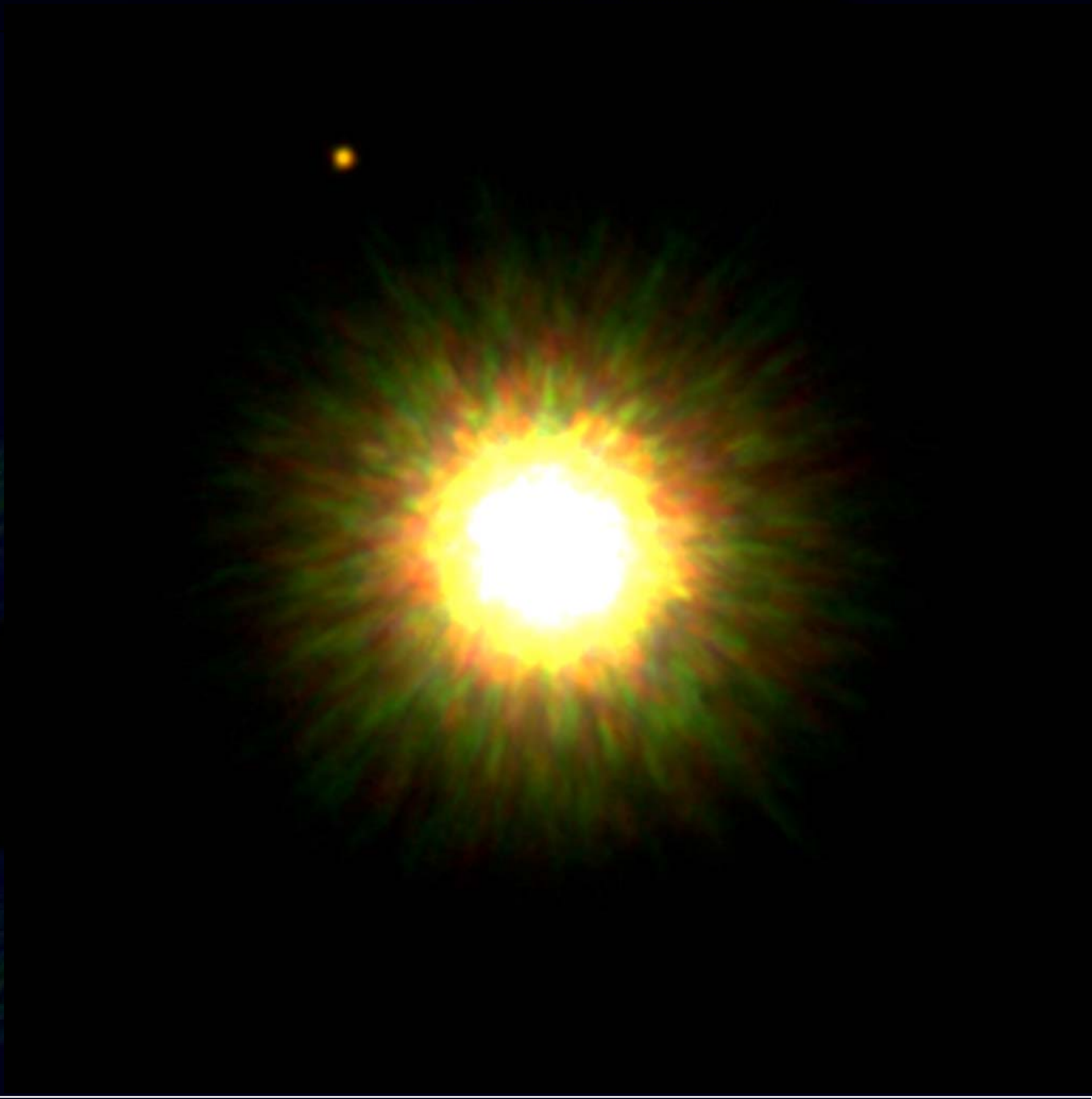
Exoplanet Observations

(1RSX J1609.1-210524)

Distance from Earth:
500 Light years

Mass: **$8M_J$**
S.M Axis: **330AU**

exoplanet spectrum
(2010)

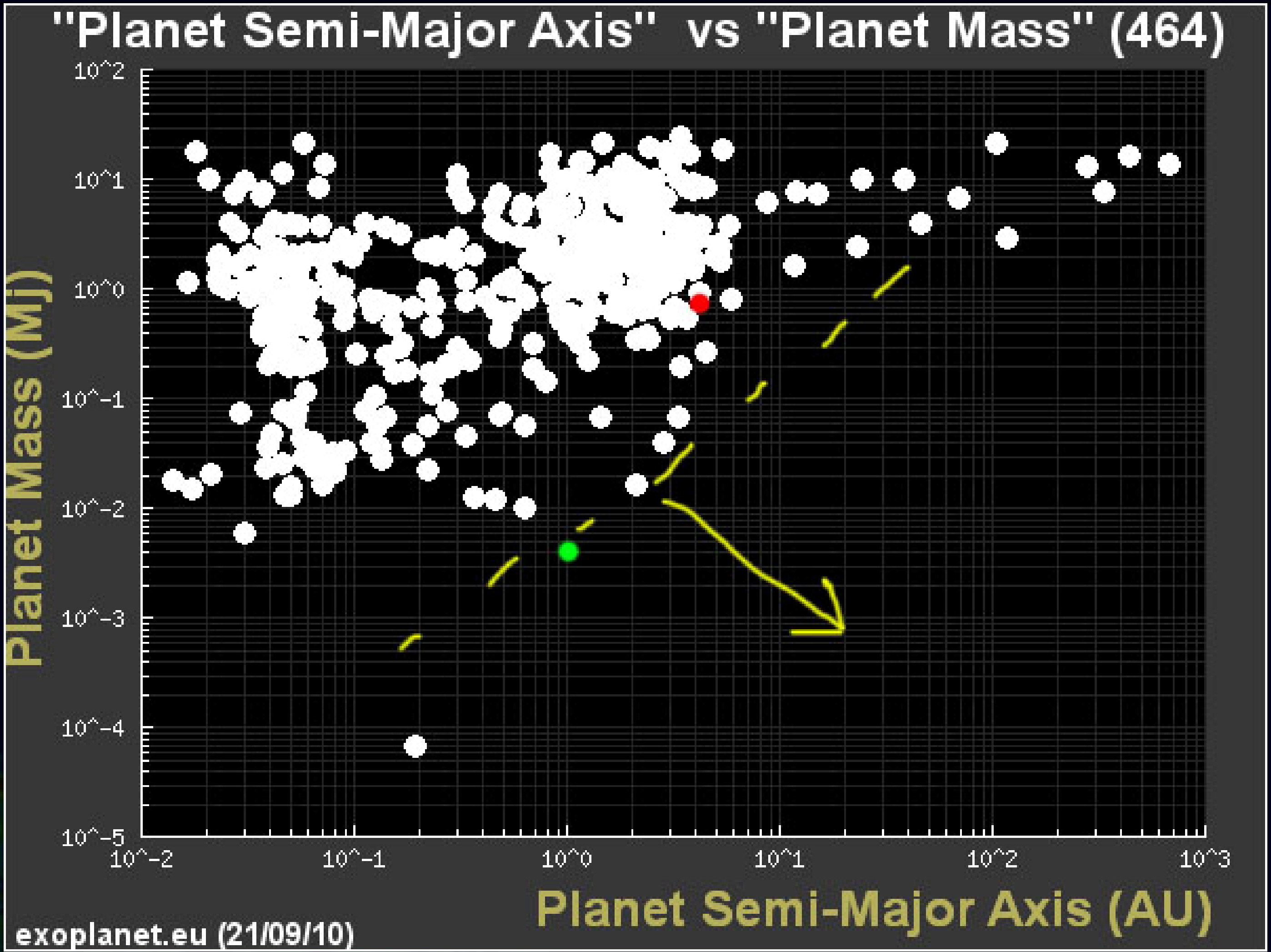


Exoplanet Observations

Exoplanets found (21.09.2010):	**490**
Candidates detected by radial velocity, astrometry or transits:	**488**
Microlensing:	**10**
Imaging:	**11**
Multiple Planet Systems:	**53**

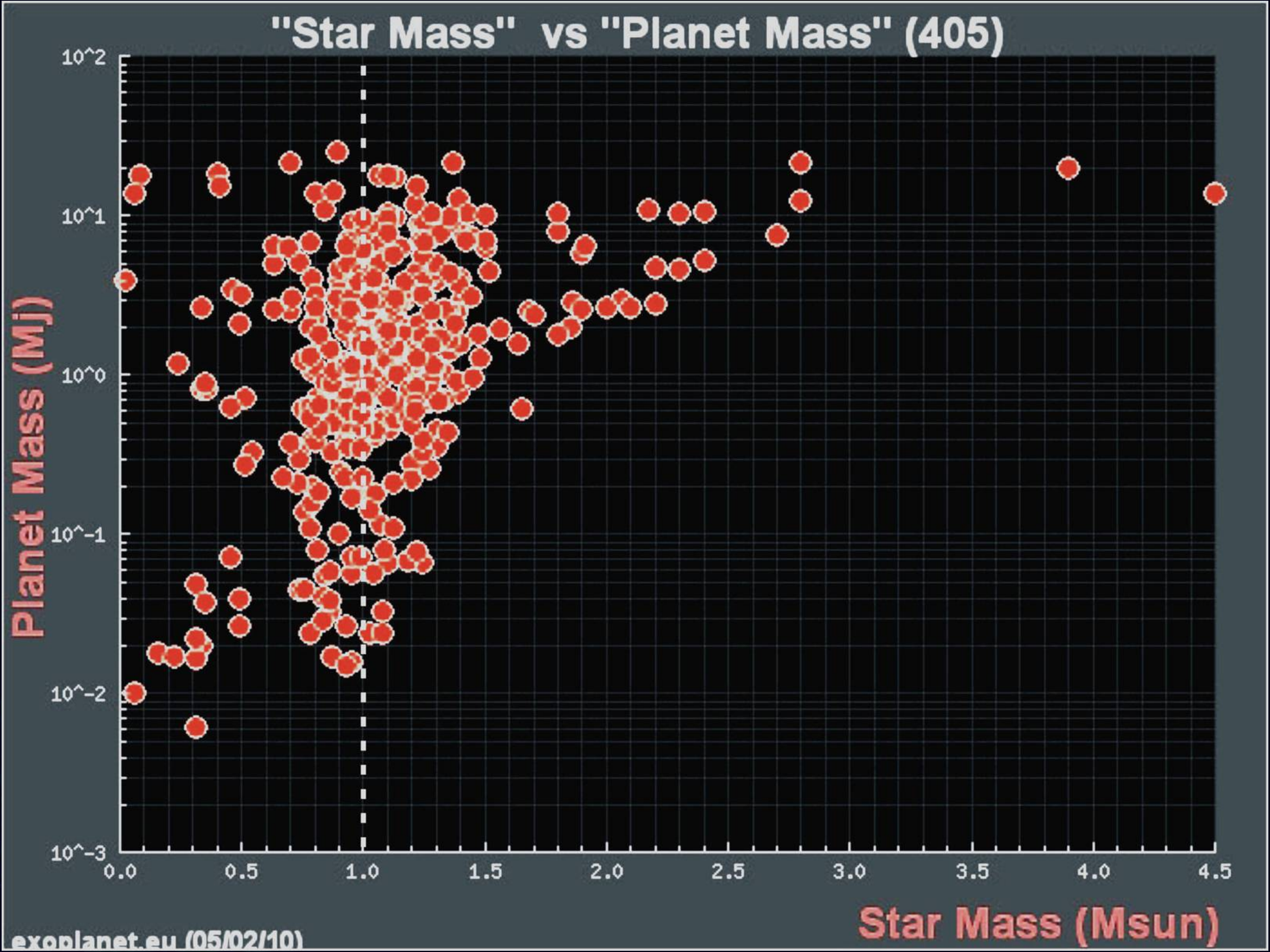
unconfirmed/controversial candidates

Exoplanets



Exoplanet groups: Giant planets, Hot Jupiters, Terrestrial?

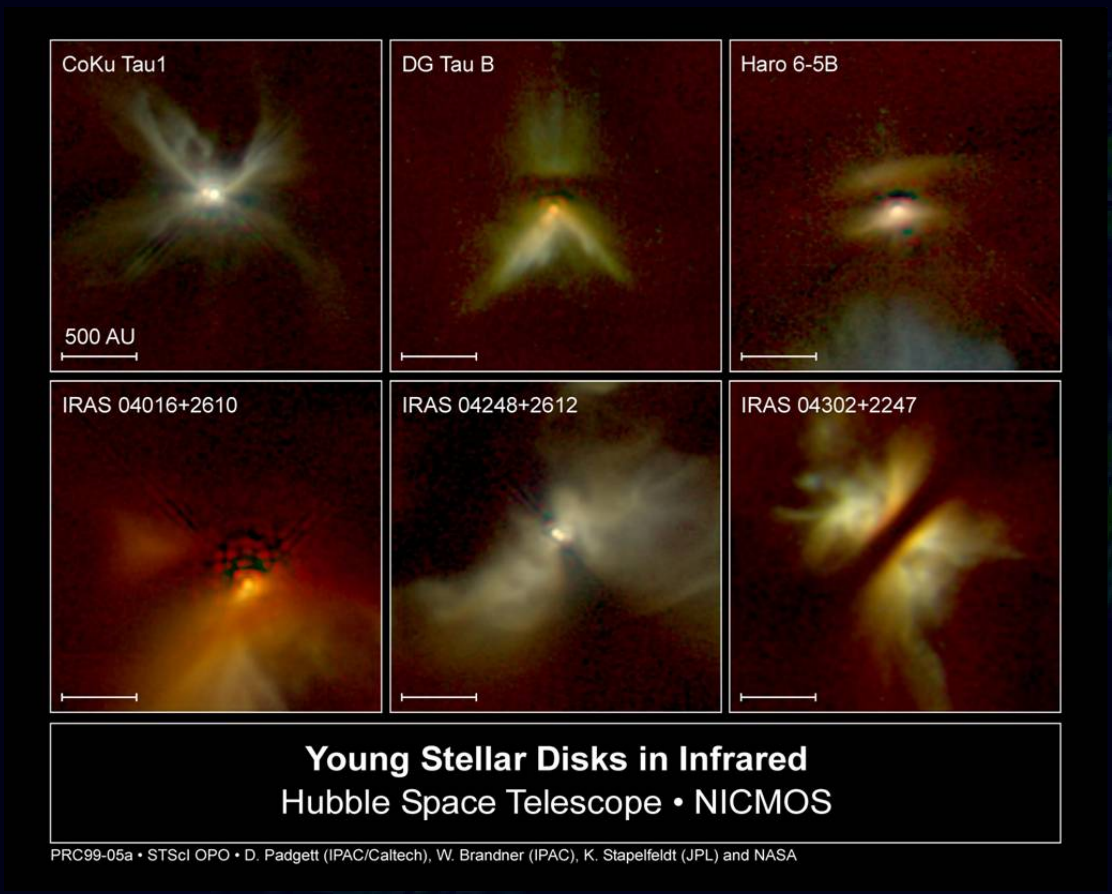
Exoplanets

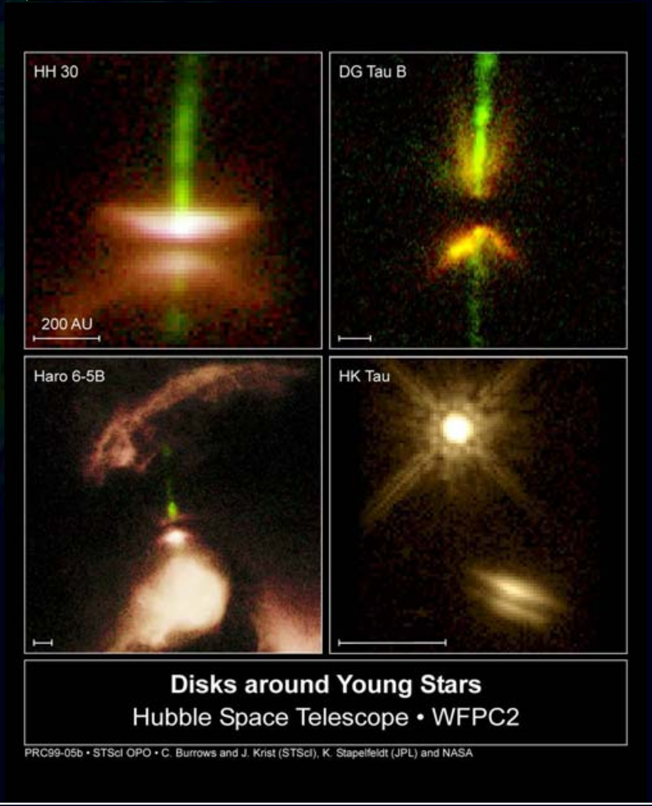


"Star Mass" vs "Planet Mass" (405)
Planet Mass (Mj)
10^2
10^1
10^0
10^-1
10^-2
10^-3
0.0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
4.0
4.5
Star Mass (Msun)
exoplanet.eu (05/02/10)

Protoplanetary Disk

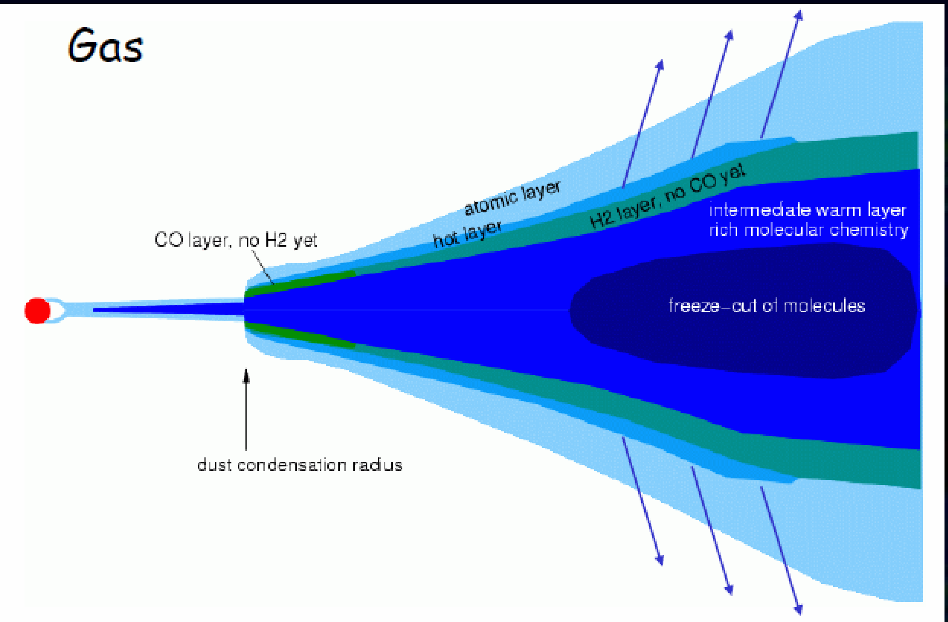
Early stages of planet formation process

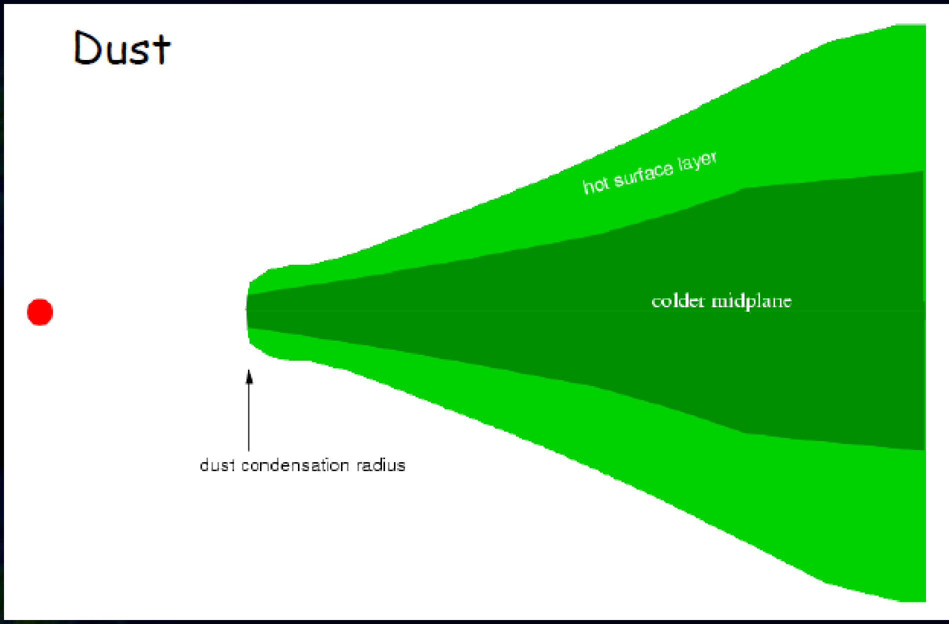




Protoplanetary Disks

Structure: Gas + Solid Particles





Dullemond et al. 2007

Infrared Interferometry

Planet Formation Theories

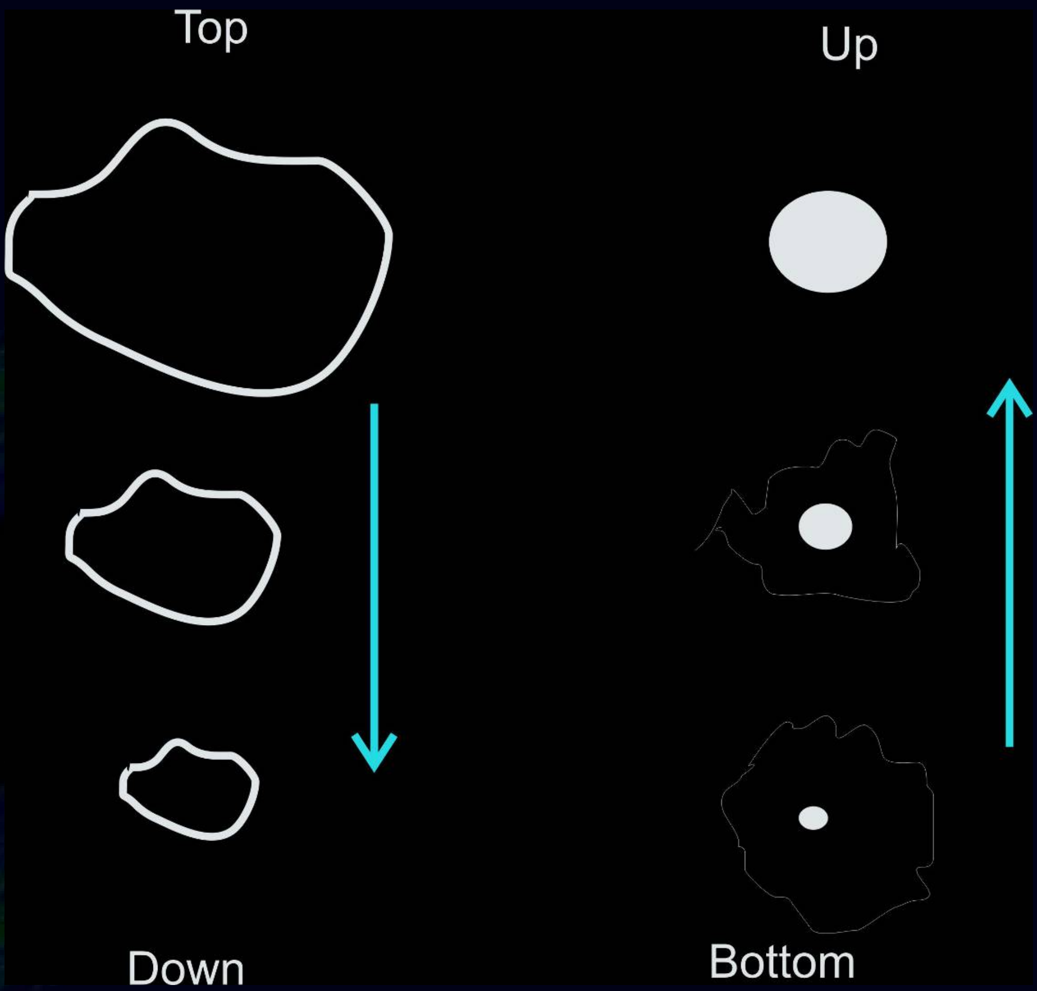
1. Top Down (*Laplace*)

Gravitational Fragmentation

2. Bottom Up (*Safronov*)

Core Accretion

dust2planet



Planet Formation: Major Aspects

Equilibrium state

$$r\Omega^2(r) = \frac{1}{\rho_0}\frac{\partial P_0(r)}{\partial r} + \frac{\partial \Phi(r)}{\partial r}$$

Gas Pressure

Gravity

Keplerian Rotation: $\Omega_K(r) \sim r^{-3/2}$

(Solid bodies, Dust)

Sub-Keplerian Rotation: $\Omega(r) < \Omega_K(r)$

Gas/Dust drag

Planet Formation: Major Aspects

Dust Coagulation

Micro meter solid particles

Dust types (compact, porous, fractal, linear)

Relative velocity + sticking property

dynamics: micro meter – cm

meter to kilometers? Possible? SLOW

1 METER SIZE BARRIER

Planet Formation: Major Aspects

Planetary Migration (Type I + II,III)

Solid particles feel head wind: sub-Keplerian rotation

Solid bodies: spiral inward
Gas: drifts outward

Time-Scale: 1m, 1AU: 100yr

Severe constraint on the planetesimal formation

Gravitational Fragmentation

Goldreich & Ward (1973)

Gas Disk + Dust sub-disk

dust sedimentetion to central plane:
gravitational instability

Direct Gas Fragmentation: Jeans instability

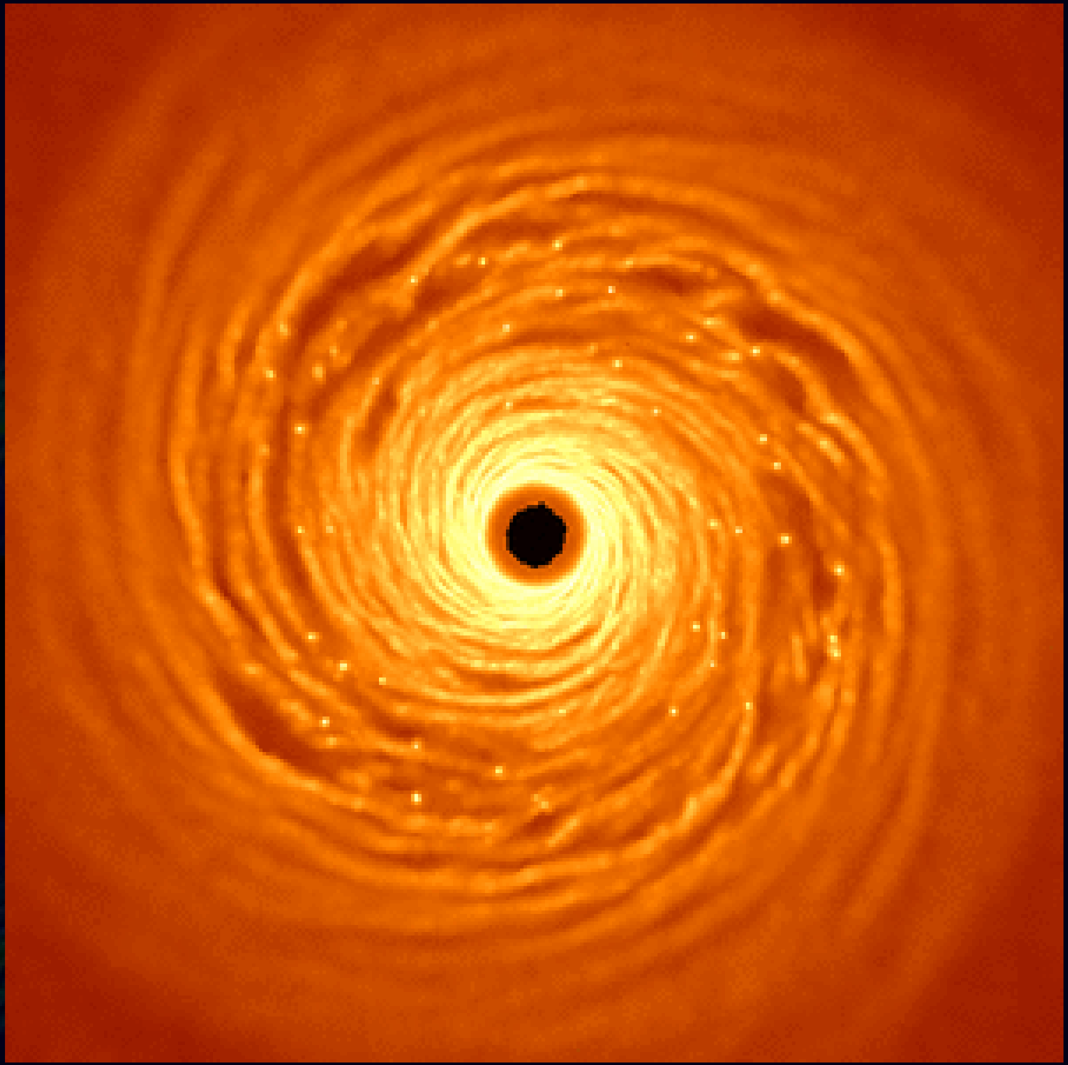
Triggering mechanism: Density-Spiral waves

Gravitational Fragmentation

Higly nonlinear process: numerical simulations

SPH

(*Rice et al.)*



Gravitational Fragmentation

Problems:

Self-gravity: **High mass protoplanetary disks**

Result: **Giant planets (earth?)**

Radia: **>50AU**

Requriement: **thermal conductivity - unrealistic**

Instability: accelerated contraction due to self gravity;

Increasing temperature and pressure resists contraction;

Turbulence

Core Accretion

Three stage model

1. Formation of Planetesimals (>km-size)
2. Accretion of the Gas on the Core
3. Oligarchic growth

Problem: How to form planetesimals FAST

- Streaming Instability
- Vortex Model

Streaming Instability

Linear Streaming Instability: Gas + particles (dust)

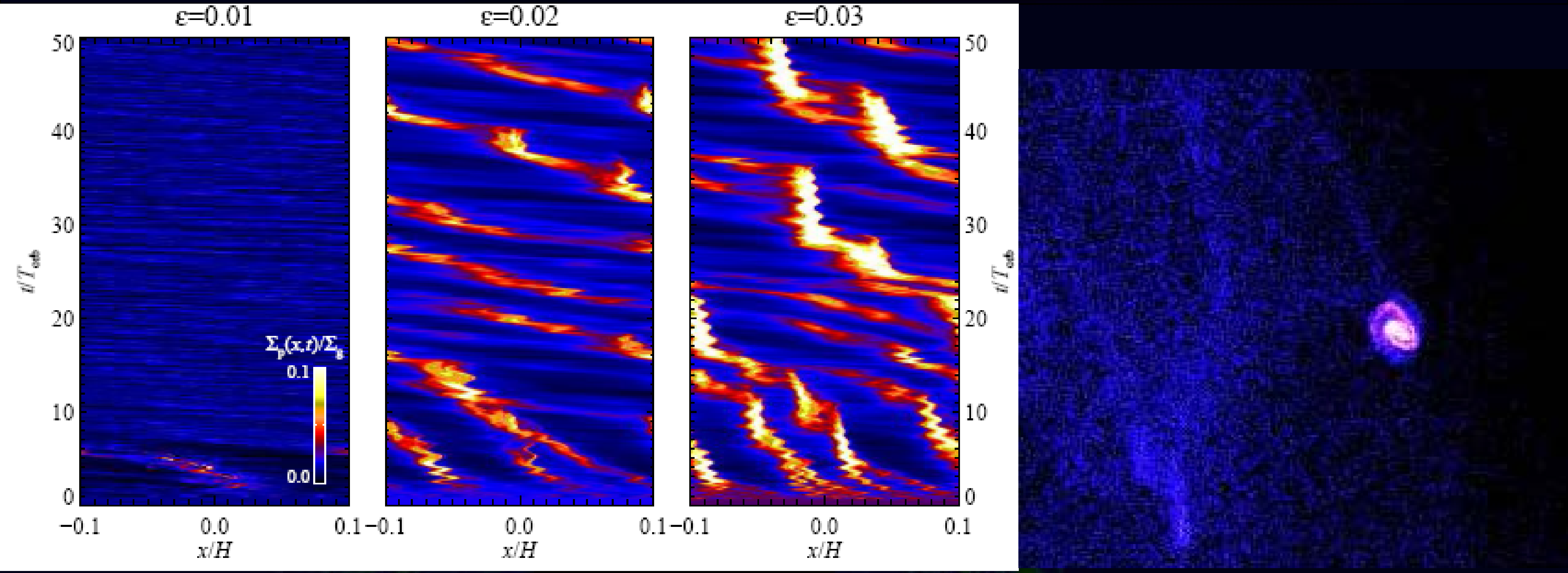
Goodman & Pindor 2001, Youdin & Goodman 2005

Momentum feedback from particles to the gas leads to a linear instability

Energy: radial pressure gradient

Nonlinear Development: Planetesimals?

Streaming Instability



Turbulence: **MRI?** ***Accelerates process (numerical)***

Problem: **Gas/Dust ratio ~ 1**

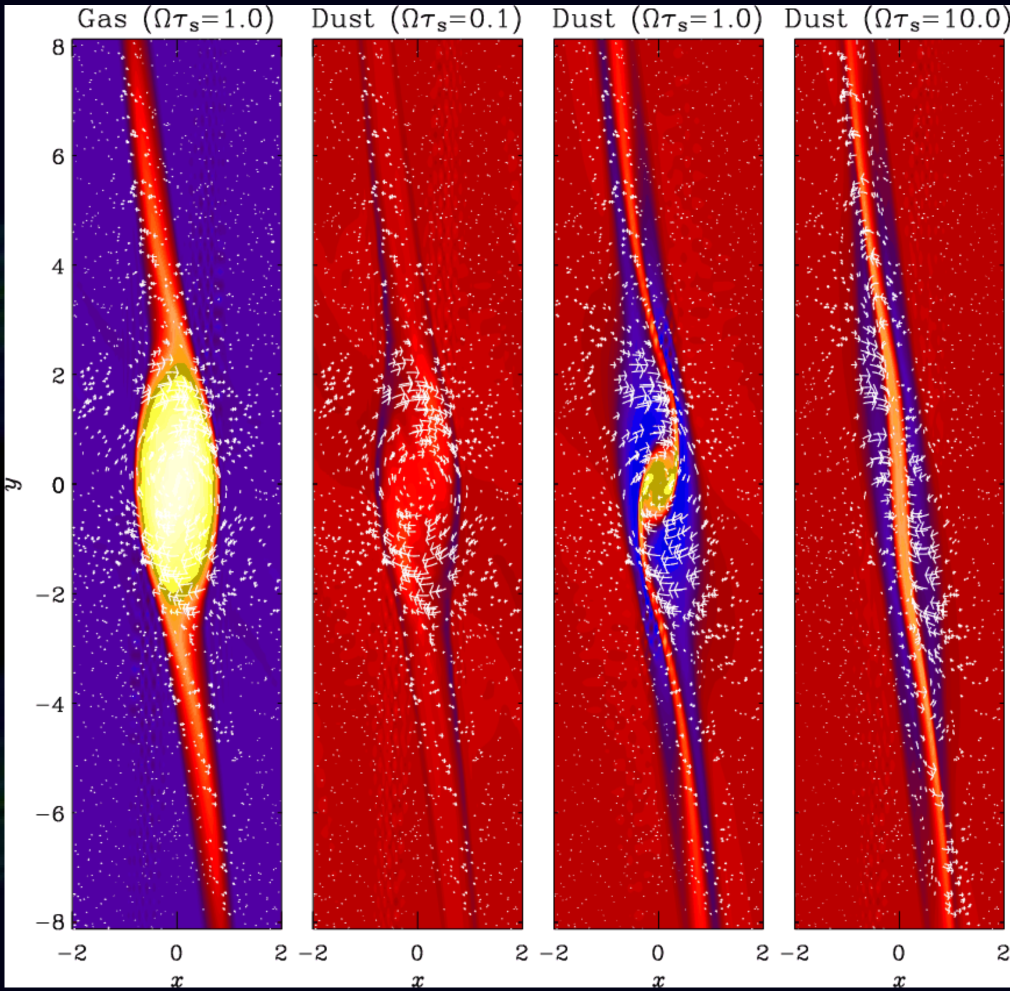
Core Accretion

Vortex Model

Barge, Sommeria (1995):

Particles captured by vortices

Long lived anticyclonic vortices can kinematically TRAP dust



Center: high density + dust

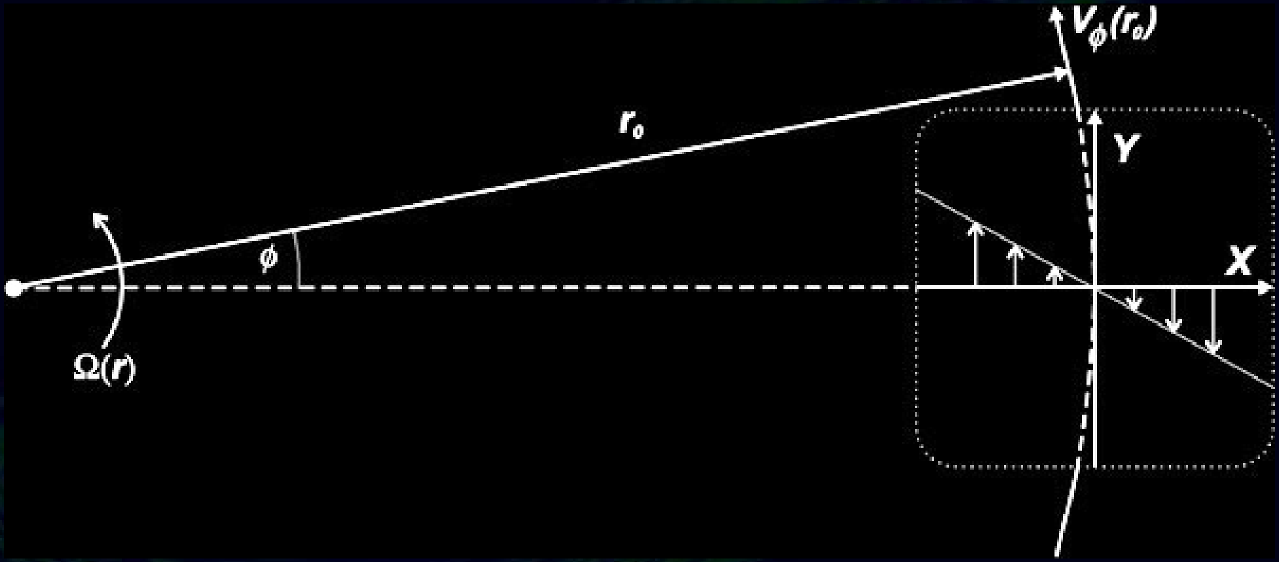
Triggering planetesimal formation

Vortices in Disks

Questions:

Differential rotation:

Linear shearing deformation of coherent structures;



Nonlinear evolution

Numerical Method

code: PLUTO `(plutocode.to.astro.it)`

solver: Riemann/Godunov, HD, FARGO, (ppm)

grid: Polar, [2048x326], [4096x652]

Equilibrium configuration:

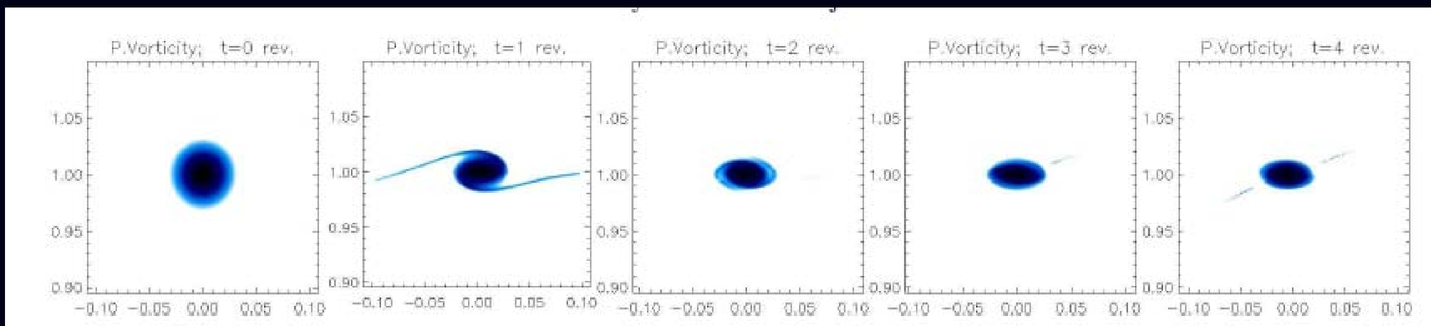
Radially stratified disk

Perturbations: pressure

Potential Vorticity, Entropy = 0.

Vortex Stability

Numerical simulations, 2D, global, compressible disk (Bodo et al. 2007): Nonlinear Adjustment



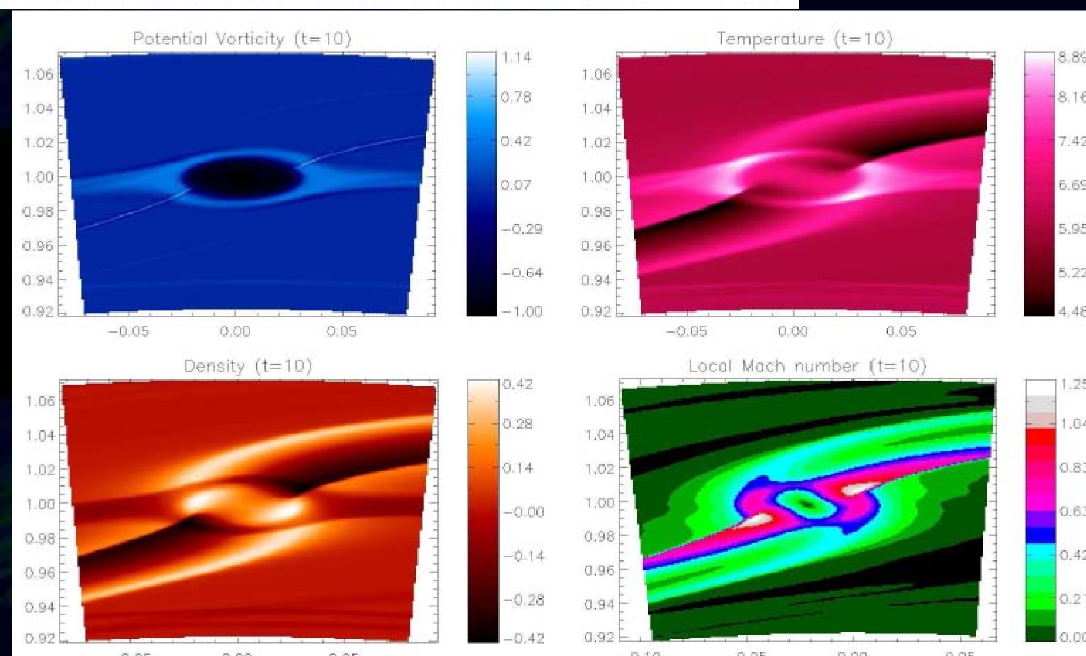
Stable

Anticyclonic

Structure

a = f(Cs)

q=5



Vortices in Disks

Vortex Source:

1. Rossby Wave Instability
(local entropy maxima)

2. Baroclinic Production of PV
(radial stratification)

3. Shock Waves

Vortex Sources

Linear Modes:

$$\bar{\omega}_p^2 = c_s^2 k^2 + 4\Omega_0^2 \, ,$$

$$\bar{\omega}_c^2 = - \frac{c_s^4 \eta k_y^2}{c_s^2 k^2 + 4\Omega_0^2} \, .$$

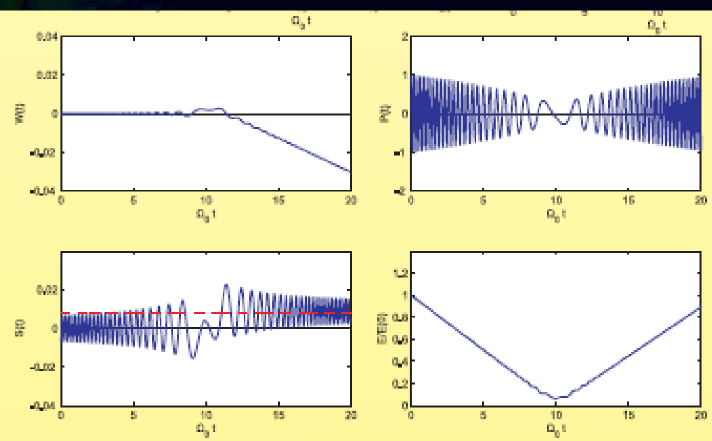
$$\eta = \frac{\beta_P \beta_S}{\gamma^2 r_0^2} \, .$$

Shear flow induced mode coupling

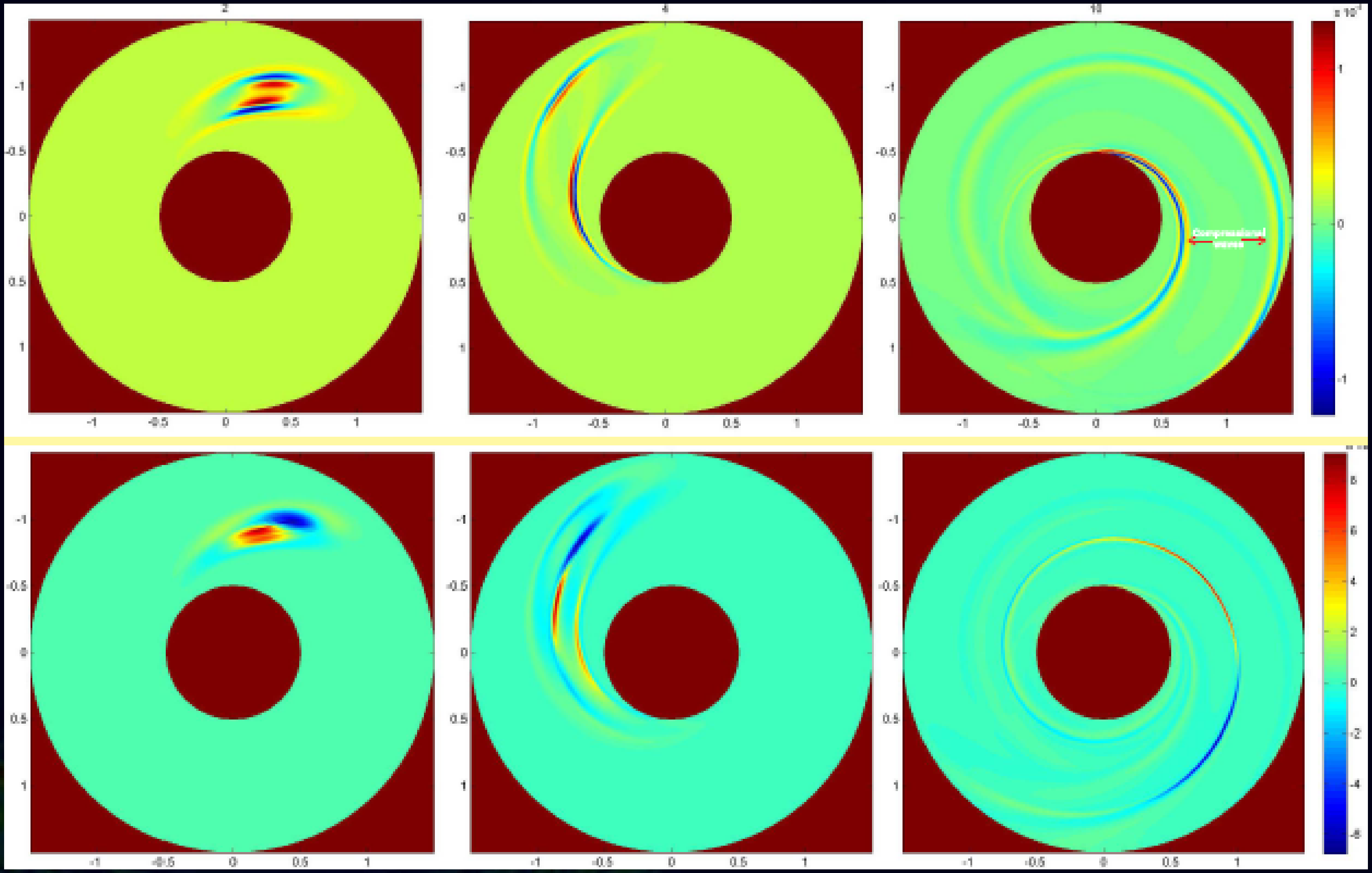
$$\bar{\omega}_c^2 \ll A^2 \ll \bar{\omega}_p^2$$

3 mode formalism

P ⟶ W, S



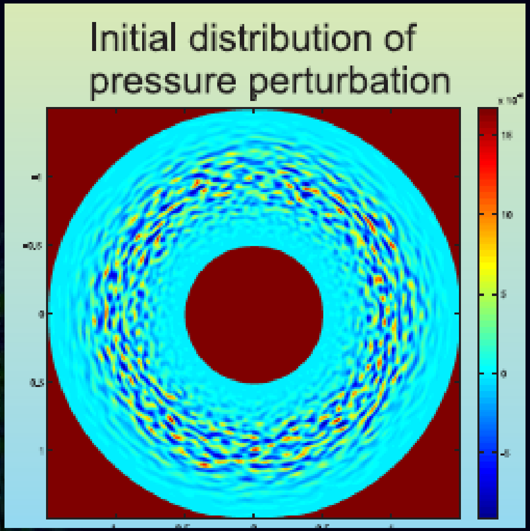
Vortex Sources



Nonlinear Evolution of mode coupling: *inneficient*

Vortex Sources

Vortex Production by Shock Waves

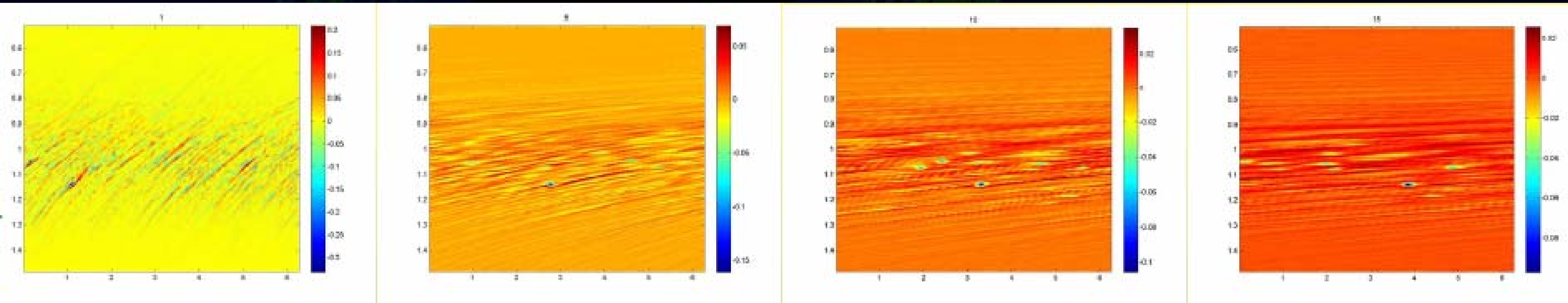


Kelperian Disk;

Random compressible perturbations;

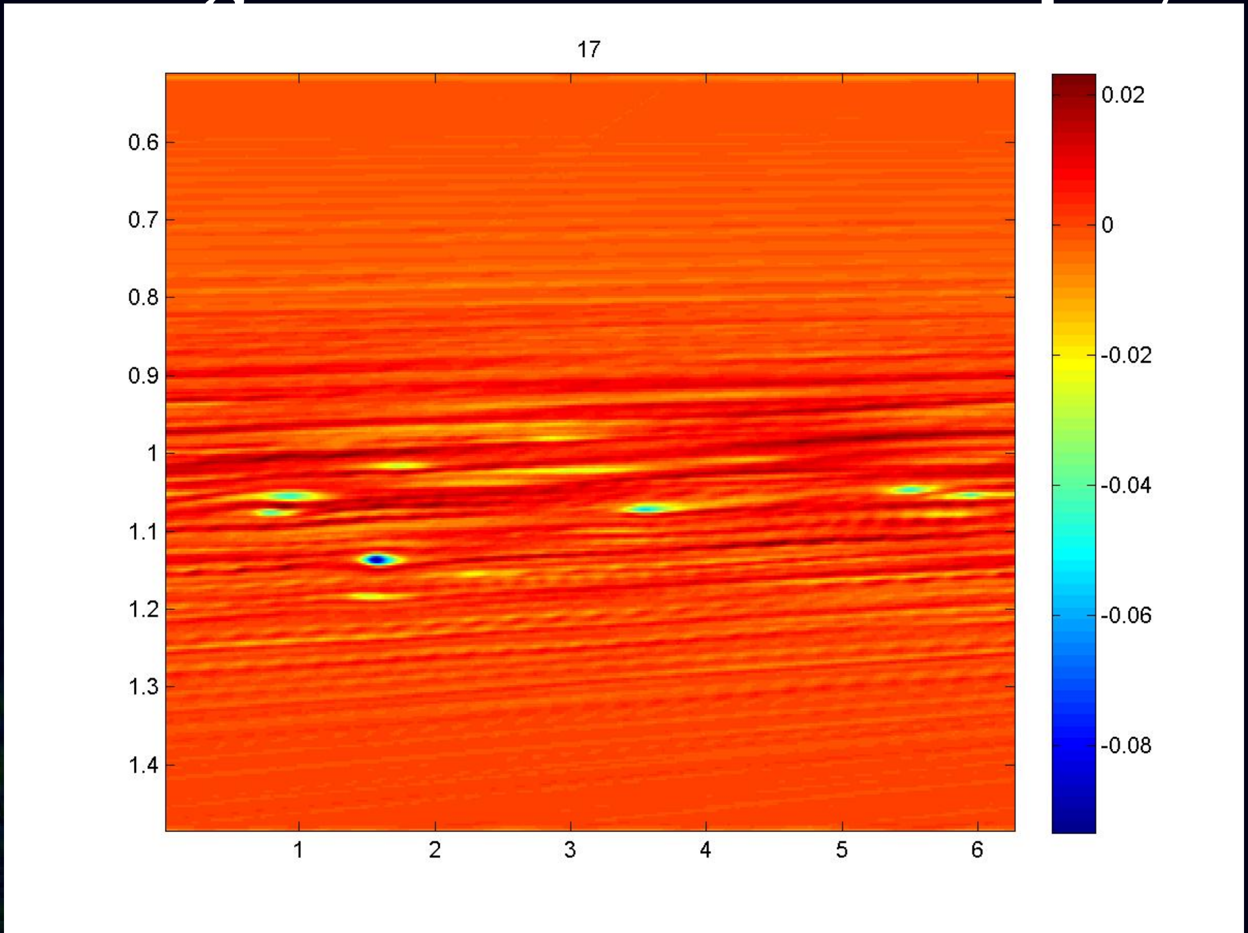
Development of shocks;

Generation of Coherent Vortices



Numerical Simulations

Vortex generation timescale: epicycle



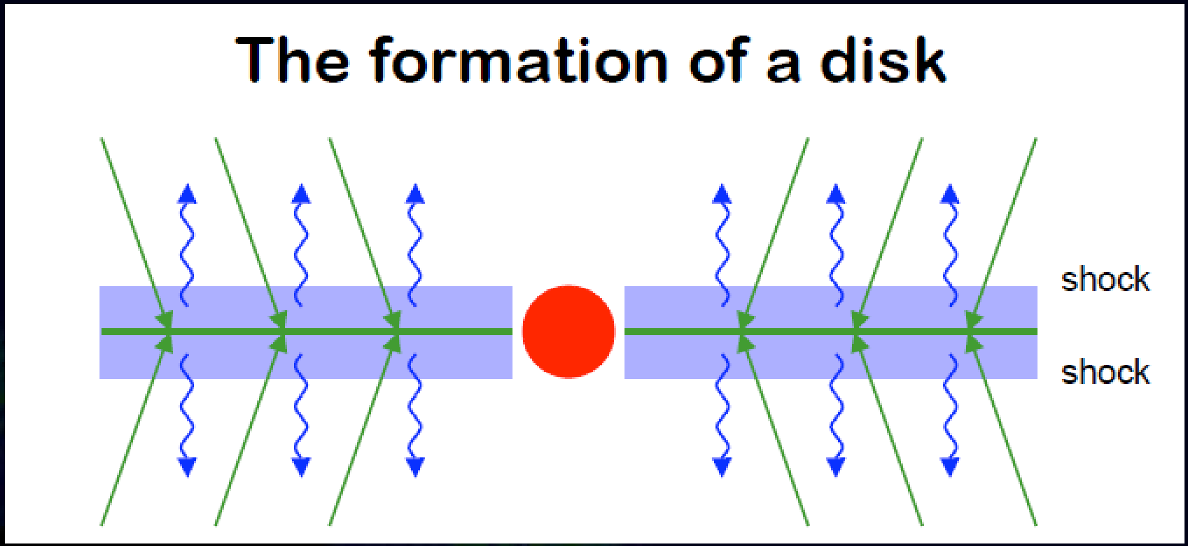
~1 year (!)

Source of Shocks?

Early stages of Protoplanetary disk formation

Dullemond (2009)

Initial heating



+ compressible perturbations;

+ shock waves;

Generation of Vortices together with Protoplanetary Disk

SUMMARY

- Long-live coherent structures resist shearing deformation in Keplerian flows;

-Accelerated formation of planetesimals inside anticyclonic vortices;

-Vorteices CAN be generated in flows with zero PV (compressible perturbations + shocks)

-Vortex mechanism: favorable process for the Core Accretion model of planet formation

გმადლობთ ყურადღებისათვის