Initial Stages of Planet Formation in Protoplanetary Disks: Origin of Vortices

A. G. Tevzadze
Abastumani Astrophysical Observatory, Georgia
Tbilisi State University, Georgia

Collaboration

Abastumani Astrophysical Observatory, Georgia
George Chagelishvili
George Mamatsashvili
Revaz Chanishvili

Osservatorio Astronomico di Torino, Italy
Gianluigi Bodo
Andrea Mignone
Paola Rossi
Attillio Ferrari

Observatoir de Paris Meudon, France
Jean-Paul Zahn

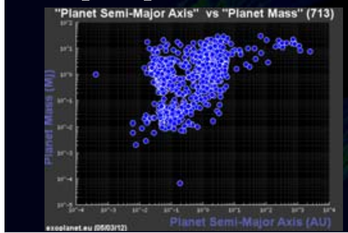
Plan

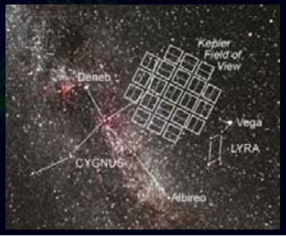
- **Planet Formation Theories**
- **Gravitational Fragmentation**
- **Core Accretion**
- **Initial Stages in Core Accretion: the role of vortices**
- **Generating Vortices**
- **Summary**

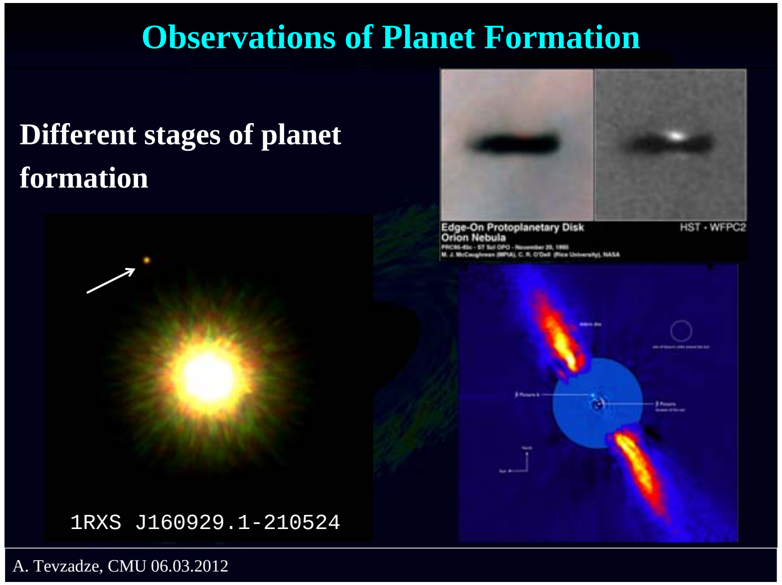
Exoplanets

New era for the planet formation theories

Exoplanets found:	760
Exoplanets in multiple systems:	129
Kepler planet candidates:	2326



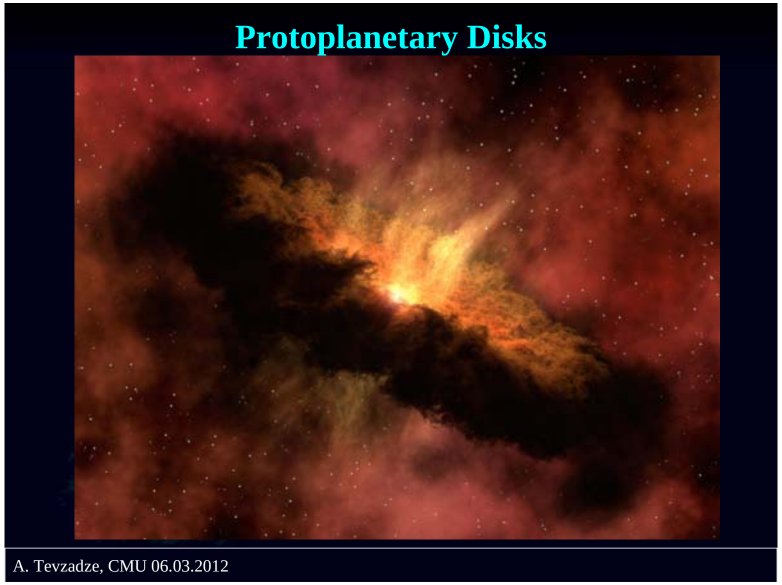




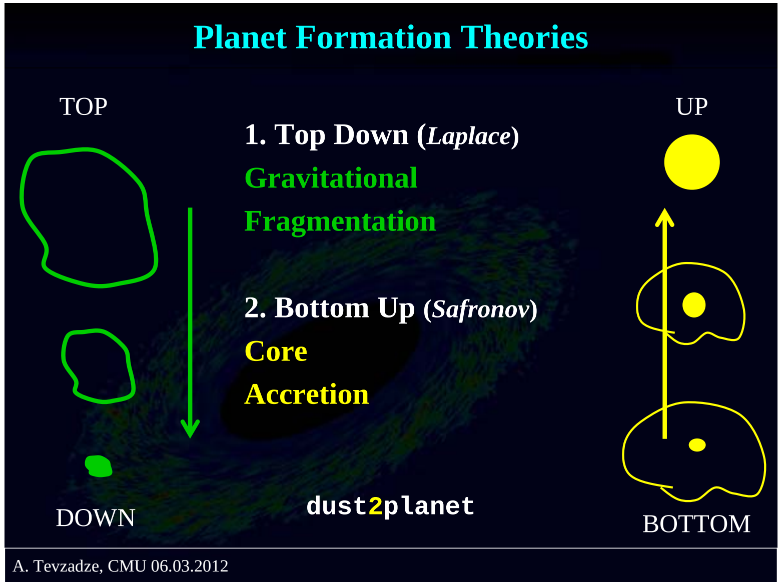
Observations of Planet Formation

Different stages of planet formation

1RXS J160929.1-210524



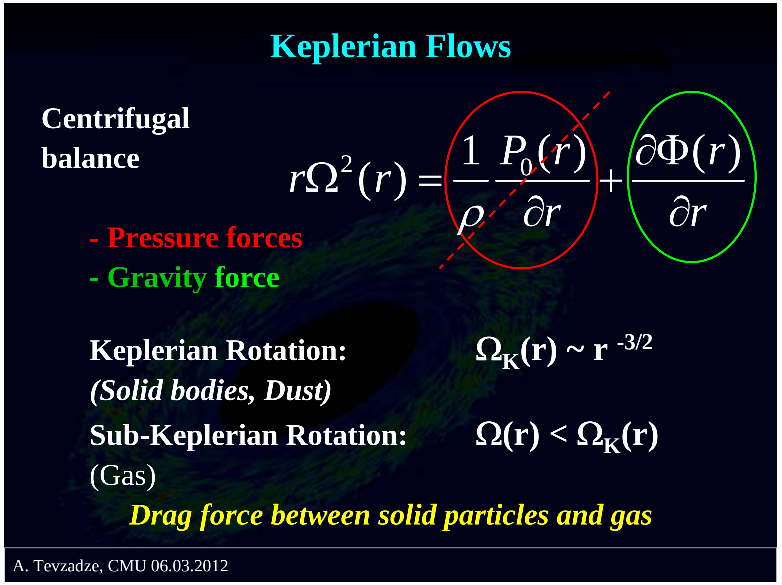
Protoplanetary Disks



Planet Formation Theories

1. **Top Down (*Laplace*)**
   Gravitational Fragmentation
2. **Bottom Up (*Safronov*)**
   Core Accretion

`dust2planet`



Keplerian Flows

Centrifugal balance

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

- Pressure forces

- Gravity force

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

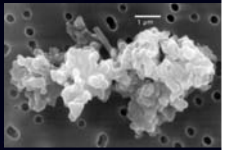
(Solid bodies, Dust)

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

(Gas)

Drag force between solid particles and gas

Dust Dynamics



Sub micro meter particles

growth by coagulation

Collisions: Sticking / Fragmentation
theory, simulations, experiment

Fast coagulation: micro meter – cm
Meter to kilometers? SLOW

1 METER SIZE BARRIER
Planetesimals: ~km size bodies

Radial Migration

Solid particle feel head wind (sub-Keplerian flows)

Solid bodies: spiral inward
Gas: drifts outward

Planetesimals: momentum exchange with disk gas (spiral waves)
Radial migration type I (II,III)

Mechanism to form planetesimals fast

Stopping migration: gap opening

Gravitational Instability

Self-gravity of disk matter dominates over centrifugal forces (gravity of central object)

Toomre’s parameter

$$Q = \frac{c_s \Omega}{\pi G \Sigma} < 1$$

Important factors
- Surface density (Σ)
- Temperature of gas (*Cs*)

Outer regions of massive protoplanetary disks (Ω)

Gravitational Instability

Goldreich & Ward (1973)
Gas Disk + Dust sub-disk

Dust sedimentetion to central plane:
gravitational instability

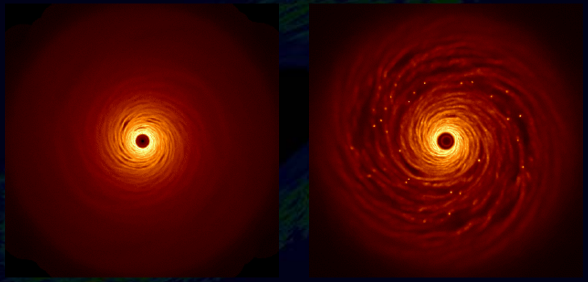
Direct formation mechanism

Triggering mechanism: Density-Spiral waves

Gravitational Instability

Fragmentation and formation of planetesimals

SPH simulations ***Rice et al. (2003)***



Gravitational Instability

Fragmentation: gas compression – heating

Instability: accelerated contraction due to self gravity;
Increasing temperature and pressure resists contraction;

Important parameters: thermal conduction, cooling

macroscopic behavior depends on microscopic physics

Gravitational Instability

Problems:

Self-gravity:	**High mass protoplanetary disks**
Result:	**Giant planets (earth?)**
Radia:	**>50AU**
Requriement:	**thermal conductivity - unrealistic**

Turbulence

Core Accretion

Three stage model

1. Formation of Planetesimals (>km-size)
(gas + dust)

2. Accretion of the Gas on the Core
(gas + planetesimals)

3. Oligarchic growth
(Oligarchs, embryos, protoplanets)

Core Accretion

Problem:

How to form planetesimals FAST without direct gravitational instability

- **Streaming Instability**
- **Vortex Model**

Streaming Instability

Linear Instability: Gas + particles (dust)

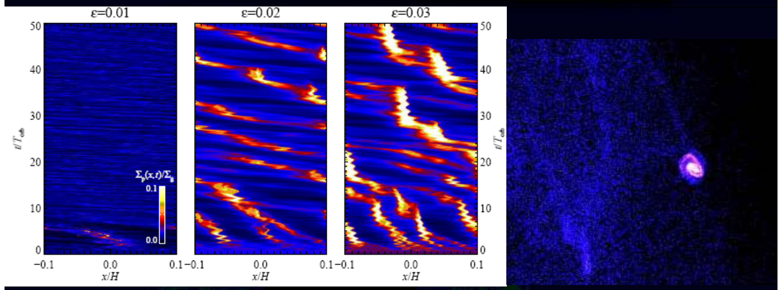
Goodman & Pindor 2001, Youdin & Goodman 2005

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**

Core Accretion: Vortex Model

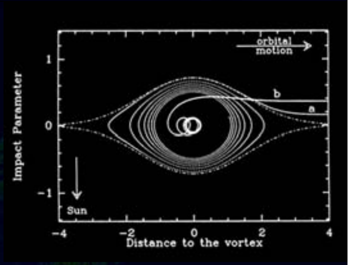
Problem building structure in Keplerian Flows:
Strong local velocity shear (differential rotation)

$$\Omega(r) \sim \Omega_0 (r/r_0)^{-3/2}$$

Shear Time-scale: $T_{shear} = 3/2 \ \Omega_0$

Building planets:
Linear Mechanisms – faster than T_{shear}
Nonlinear Processes – oppose Keplerian shearing
Nonlinear Vortices: safe heavens for planetesimals

Core Accretion: Vortex Model



Barge Sommeria (1995)

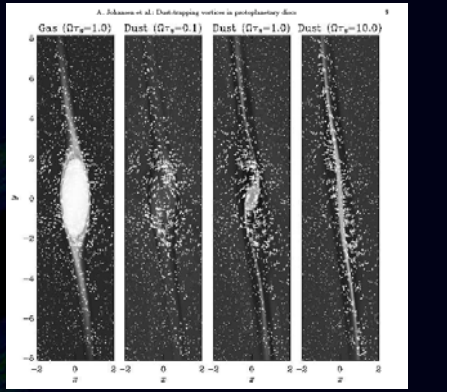
Dust capture by
long-lived vortices

- confirmed by numerical simulations

Long lived anticyclonic vortices can kinematically TRAP dust

Dust Capture

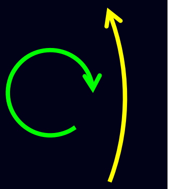
(Johansen 2004)

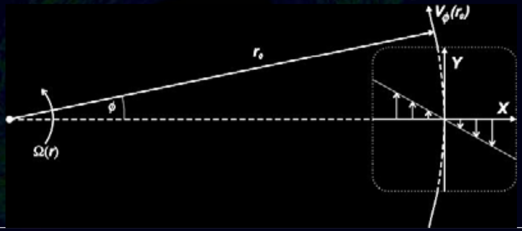


Anticyclonic Vortices

Stable vortex configuration in Keplerian flows

$V(r) \sim r^{-1/2}$
$d\,\Omega(r) / d\,r = -3/2\,\Omega(r)$
direction of vortex rotation is
opposite to global circulation





Anticyclonic Vortices

Keplerian flow: vortical

Potential vorticity – nonlinear invariant

$W = \mathrm{rot}\, V / \rho$

$\mathrm{rot}\, V_K < 0$

Anticyclonic vortex:
$\mathrm{rot}\, V_1 < 0$
$\rho 1 > 0$
Maximal density area in the vortex center

Vortices in Keplerian Flows

Long lived nonlinear compressible self-sustained Anticyclonic vortices

- Safe heavens for coherent structure formation
- Higher density in the center
- Large scale vortices
- Accelerated dust capture rate

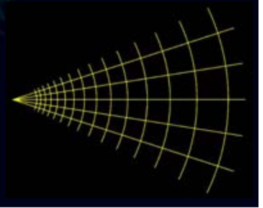
Accelerate planetesimal formation in the vortex centers

Vortex Stability Simulations

DNS of vortex dynamics in HD Keplerian disks

(Bodo et al. 2007)

```
code:    PLUTO (plutocode.to.astro.it)
solver:  Riemann/Godunov, HD, FARGO, (ppm)
grid:    Polar, [8192x1559]
```



- Global compressible model
- Radially inhomogeneous grid
- Shock capturing method

Vortex Stability Simulations

Initially imposed:

Cyclonic and anticyclonic vortices with different amplitudes and size

Non-equilibrium distribution of potential vorticity

Nonlinear developments:

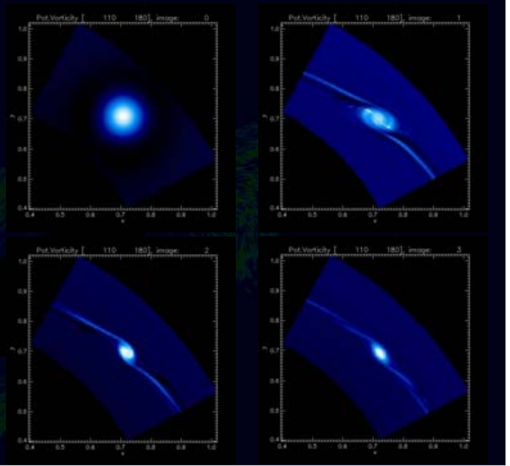
- Direct nonlinear adjustment to stable vortex;
- Stable vortex configuration
- Long time evolution (compressibility, dissipation)

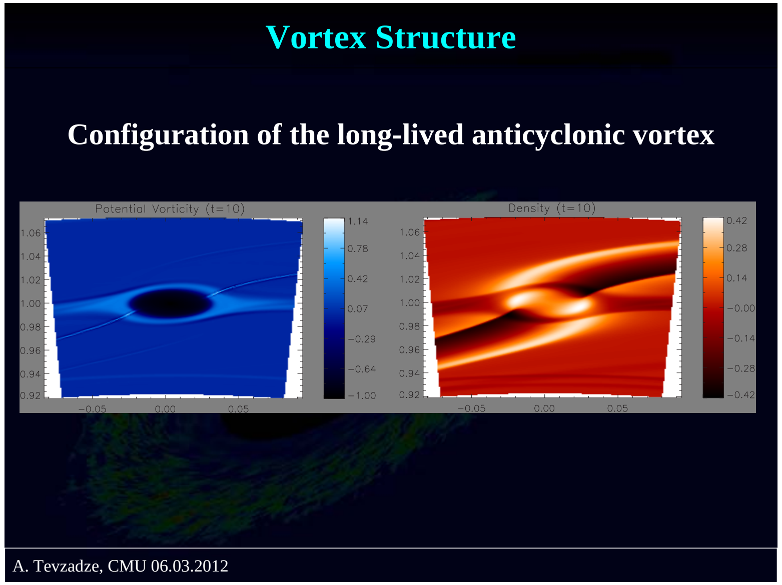
Vortex Adjustment

Adjustment of potential vorticity

Time scale:

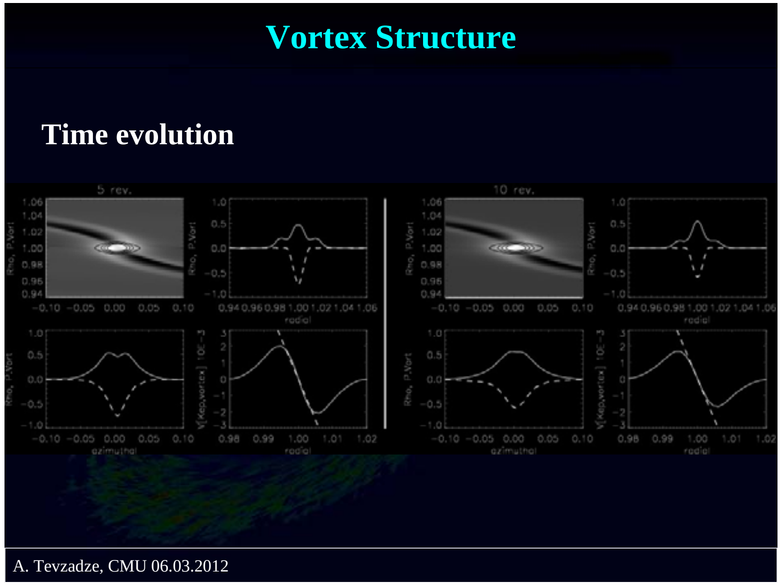
~3-5 Ω^{-1}





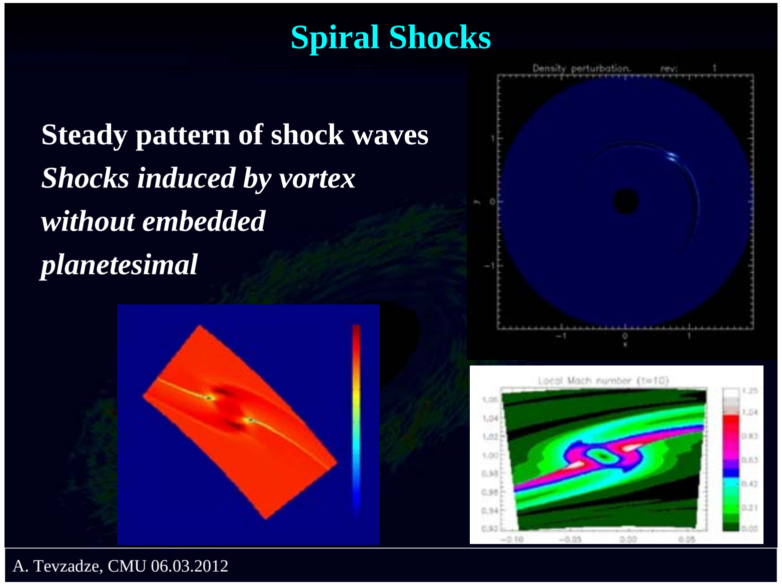
Vortex Structure

Configuration of the long-lived anticyclonic vortex



Vortex Structure

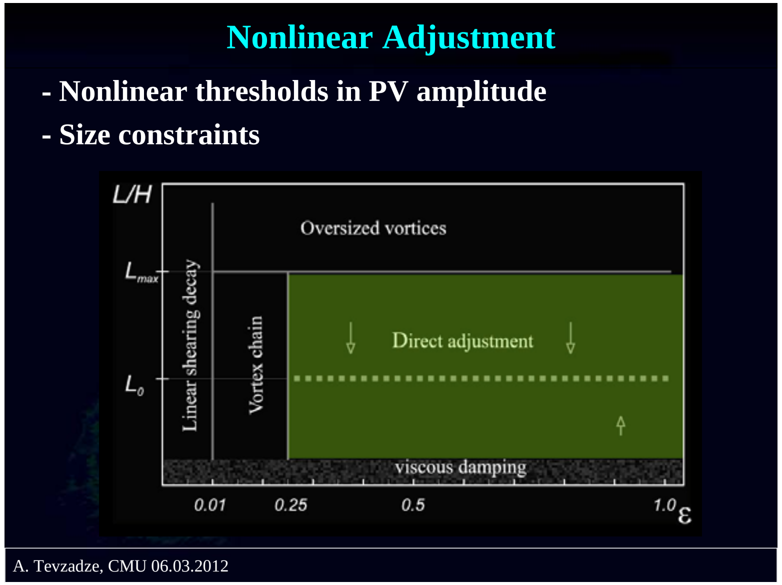
Time evolution



Spiral Shocks

Steady pattern of shock waves

Shocks induced by vortex without embedded planetesimal

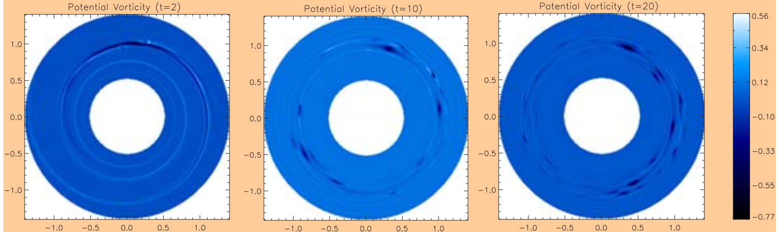


Nonlinear Adjustment

- **Nonlinear thresholds in PV amplitude**
- **Size constraints**

Oversized Vortices

Radial Spreading due to Rossby waves

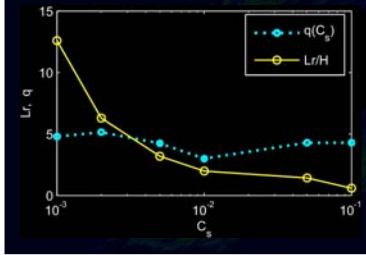


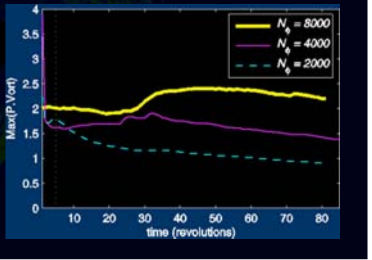
Equilibrium Vortices

Scaling relations of self-sustained vortex:

$a = f(Cs)$

$q=5$





Vortex Simulations

Challenges:

- **Global simulations (2π)**
- **High Resolution**
- **Compressibility**
- **Shock capturing and numerical dissipation**

3D Elliptic Instability

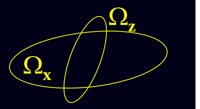
Bayly (1986), Pierrehumbert (1986)

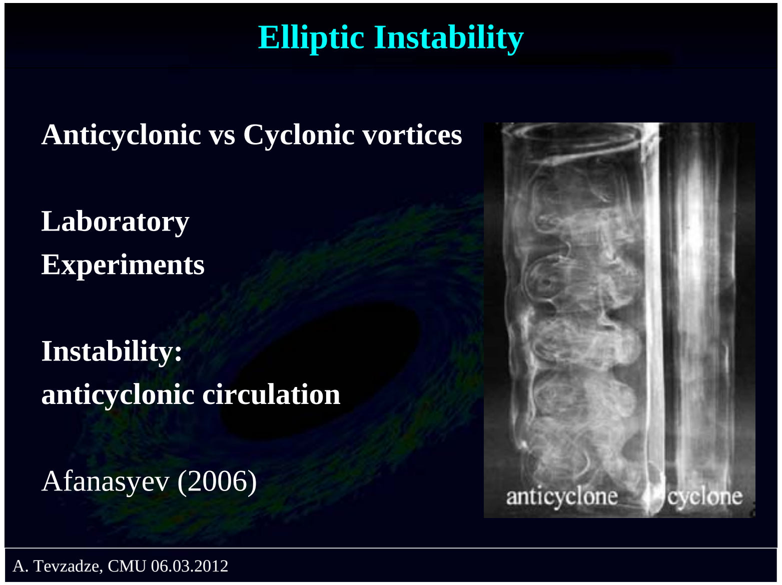
Instability of 3D vortices

Internal parametric resonance between vertical and horizontal circular motions

RESULT:

destruction of coherent structure





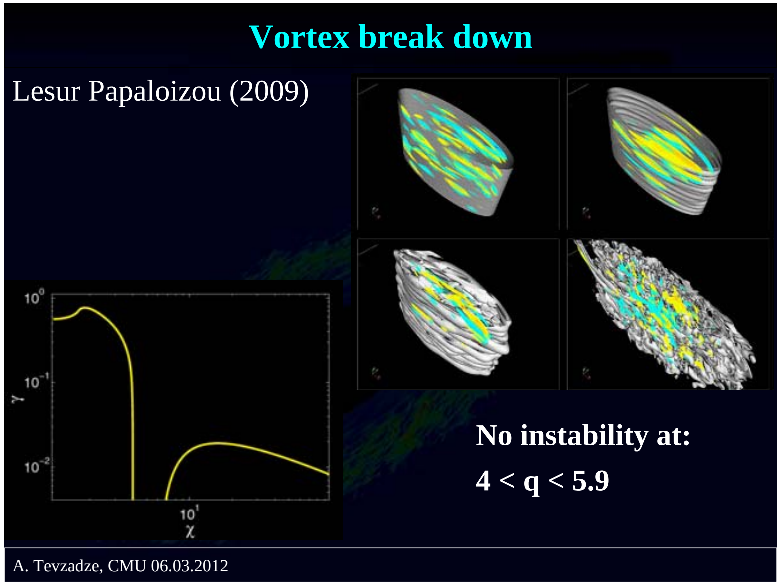
Elliptic Instability

Anticyclonic vs Cyclonic vortices

Laboratory
Experiments

Instability:
anticyclonic circulation

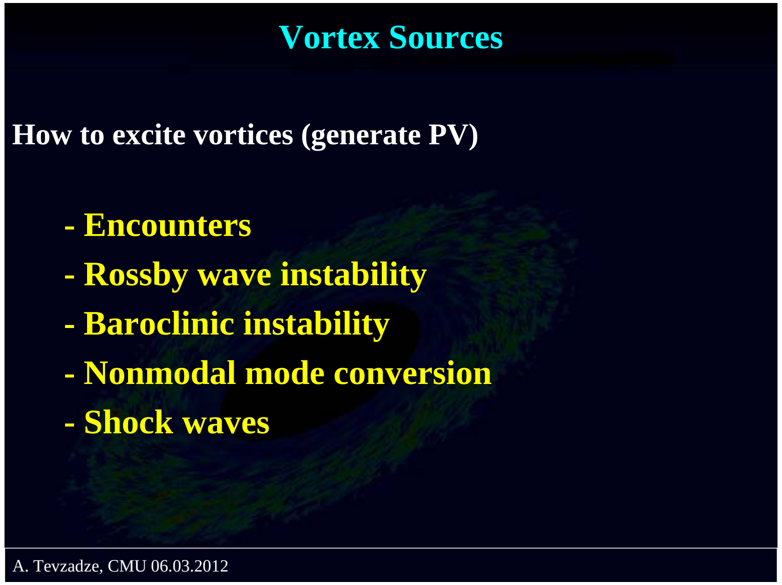
Afanasyev (2006)



Vortex break down

Lesur Papaloizou (2009)

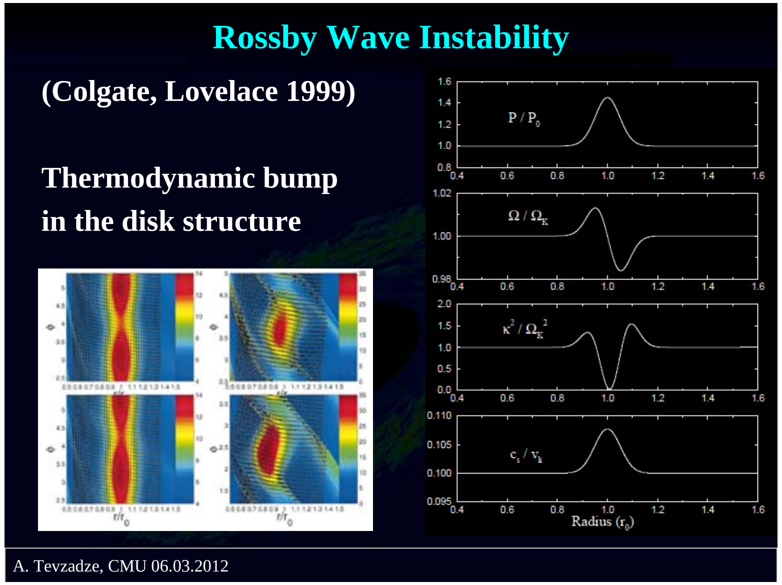
No instability at:
$4 < q < 5.9$



Vortex Sources

How to excite vortices (generate PV)

- **Encounters**
- **Rossby wave instability**
- **Baroclinic instability**
- **Nonmodal mode conversion**
- **Shock waves**



Rossby Wave Instability

(Colgate, Lovelace 1999)

Thermodynamic bump
in the disk structure

Baroclinic Instability

Barotropic disk: $\nabla P_0 \times \nabla \rho_0 = 0$

P = P(r), S = S(r)

Baroclinic perturbations: $\nabla P_1 \times \nabla \rho_1 \neq 0$

W ≠ constant

Potential vorticity production

Global baroclinic instability

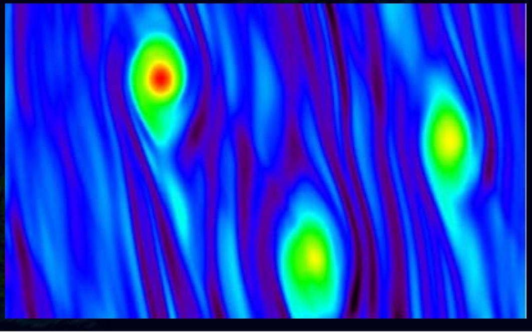
Global gradients;

Local perturbations;

Baroclinic Instability

(Klahr, Bodenheimer 2003)

Thermal perturbations lead to development of anticyclonic vortices in disks with global stratification



Baroclinic Instability

Radial stratification in protoplanetary disk

$$\bar{\Sigma}(r) = \Sigma_0 \left(\frac{r}{r_0}\right)^{-\beta_\Sigma}, \quad \bar{P}(r) = P_0 \left(\frac{r}{r_0}\right)^{-\beta_P}$$

Time-scale of the growth of baroclinic instability

$$T_{baro} \sim \gamma^2 / (\beta_P \beta_S)$$

Observations: $\beta_S < 1$

$T\Omega > 100$

Baroclinic growth is much slower than Keplerian shearing

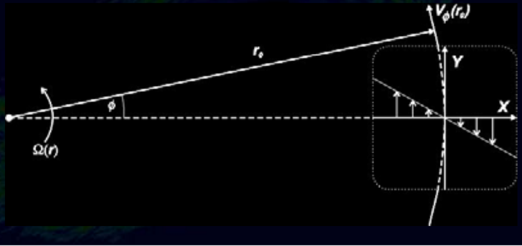
Shear Flow Analysis

Keplerian Differential Rotation in local frame:

Linear shear flow

Local linear analysis:

discard curvature, study shear flow effects



Shear Flow Non-normality

Linear shear of velocity: **V = (Ay, 0, 0)**

- Operators are not self-adjoint; (Trefethen 1993)

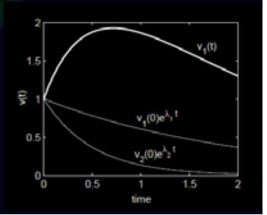
- Eigenfunctions are not orthogonal;

Non-normal system

Eigenvalue-eigenfunction analysis is not correct

Omitted: Eigenfunction interference

Nonmodal effect: transient growth



Shear Flow Non-normality

Shear flow analysis:

Shearing sheet transformation:

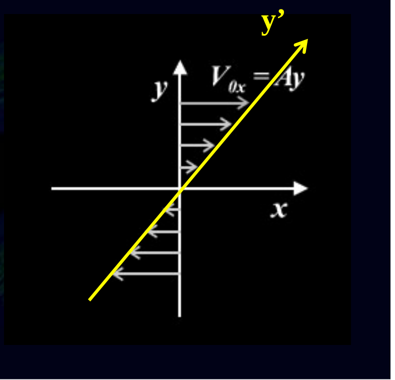
(x,y) / (x',y')

Spatial inhomogeneity

Temporal inhomogeneity

Initial value problem (SFH)

Kx(t) = Kx(0) – AKy t



Shear Flow Effects

Transient growth of vortices on shearing time scales

Energy exchange between different linear modes

- **Resonant mode transformations**
- **Nonresonant mode conversion (non-adiabatic)**

Vortex-wave mode conversion

Vortex – vorticity, pseudo acoustic perturbations;

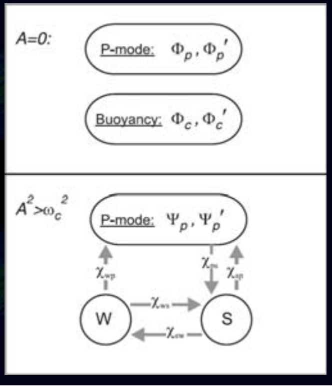
Wave – pressure, vortical sound;

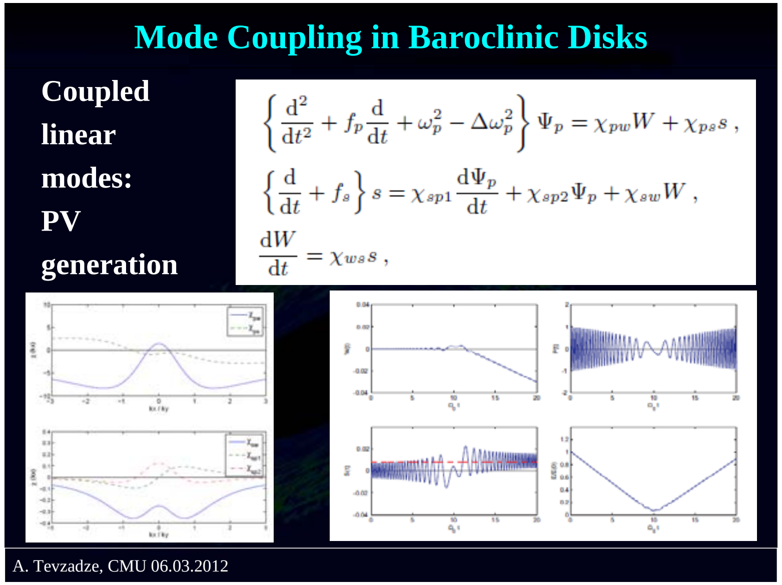
Mode Coupling in Baroclinic Disks

Local linear spectrum of radially stratified disks

(Tevzadze et al. 2010)

$T_{shear} \sim 3/2\ \Omega^{-1}$





Mode Coupling in Baroclinic Disks

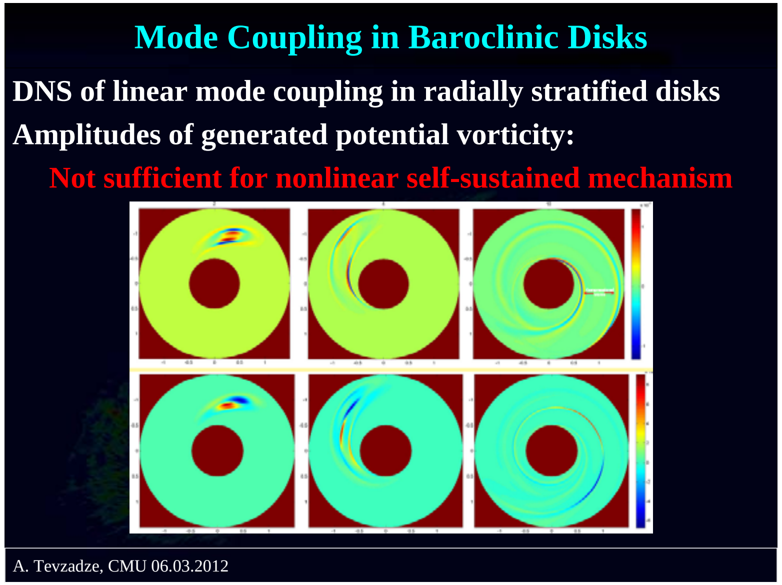
Coupled linear modes: PV generation

$$\left\{\frac{\mathrm{d}^2}{\mathrm{d}t^2}+f_p\frac{\mathrm{d}}{\mathrm{d}t}+\omega_p^2-\Delta\omega_p^2\right\}\Psi_p=\chi_{pw}W+\chi_{ps}s\,,$$

$$\left\{\frac{\mathrm{d}}{\mathrm{d}t}+f_s\right\}s=\chi_{sp1}\frac{\mathrm{d}\Psi_p}{\mathrm{d}t}+\chi_{sp2}\Psi_p+\chi_{sw}W\,,$$

$$\frac{\mathrm{d}W}{\mathrm{d}t}=\chi_{ws}s\,,$$

A. Tevzadze, CMU 06.03.2012



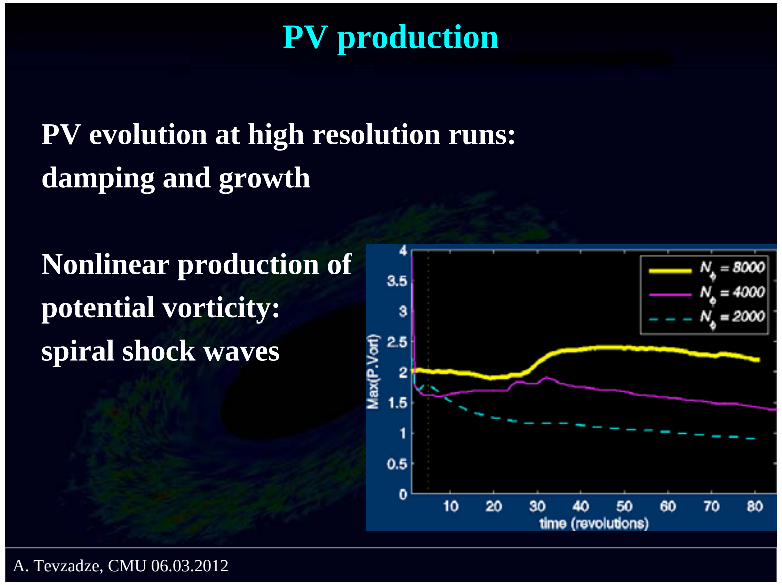
Mode Coupling in Baroclinic Disks

DNS of linear mode coupling in radially stratified disks

Amplitudes of generated potential vorticity:

Not sufficient for nonlinear self-sustained mechanism

A. Tevzadze, CMU 06.03.2012

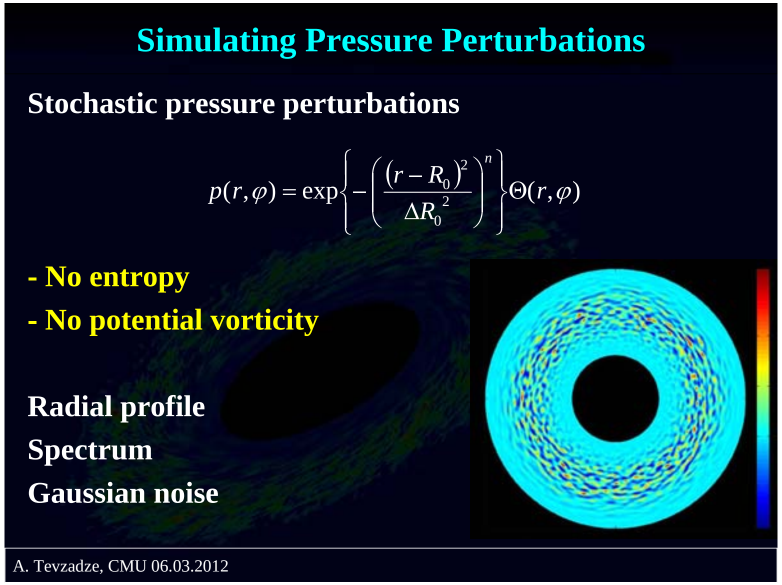


PV production

PV evolution at high resolution runs: damping and growth

Nonlinear production of potential vorticity: spiral shock waves

A. Tevzadze, CMU 06.03.2012



Simulating Pressure Perturbations

Stochastic pressure perturbations

$$p(r,\varphi)=\exp\left\{-\left(\frac{(r-R_0)^2}{\Delta R_0^{\;2}}\right)^n\right\}\Theta(r,\varphi)$$

- No entropy
- No potential vorticity

Radial profile

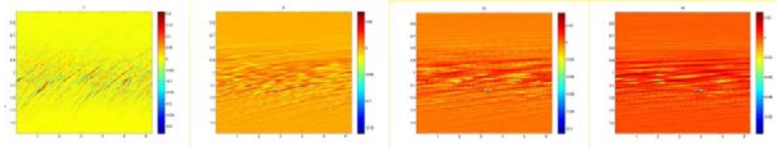
Spectrum

Gaussian noise

A. Tevzadze, CMU 06.03.2012

PV Shock Production

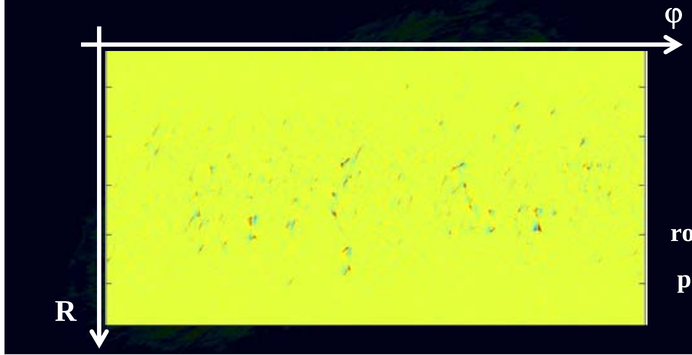
Shock waves (~ 1 local disk revolution)
Vorticity (~2 local disk revolutions)
Strong Anticyclonic vortices
(~5 local disk revolutions)



Numerical Simulations

Excitation of potential vorticity and development of stable anti-cyclonic vortices

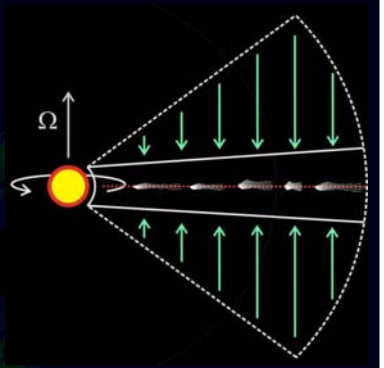
Global frame (2D Cartesian visualization)



20 rotation periods

Formation of Protoplanetary Disks

Disk flattering



middle layer:
+ compressible perturbations
+ Shock waves

Initial Heating
(Dullemond 2009)

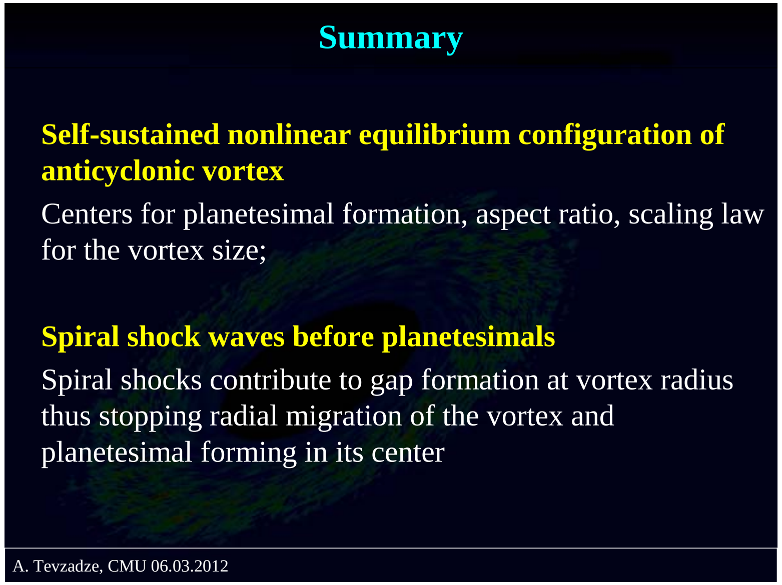
PV shock production

PV production on shearing time scales

Keplerian flow:
2-3 strong self-sustained anticyclonic vortices

Sub-Keplerian flows:
Radial stratification increases number of vortices that survive nonlinear developments

Remains to be clarified:
effects of vertical boundary conditions



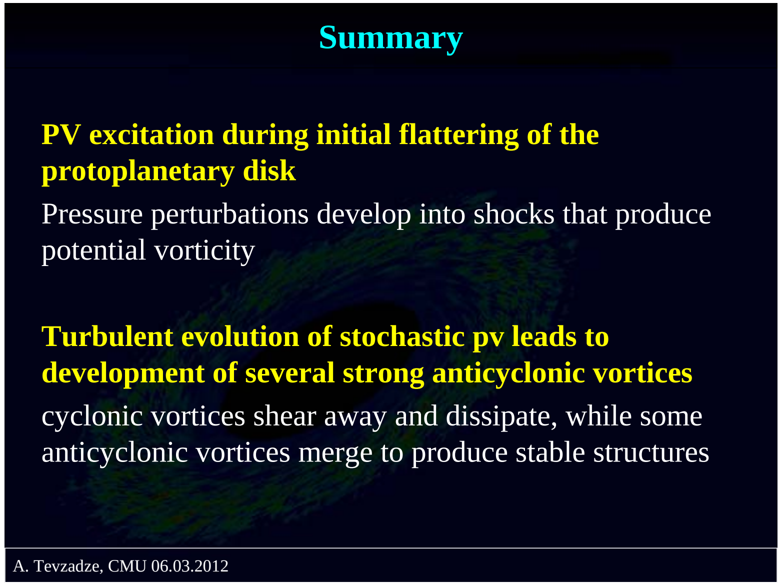
Summary

Self-sustained nonlinear equilibrium configuration of anticyclonic vortex

Centers for planetesimal formation, aspect ratio, scaling law for the vortex size;

Spiral shock waves before planetesimals

Spiral shocks contribute to gap formation at vortex radius thus stopping radial migration of the vortex and planetesimal forming in its center



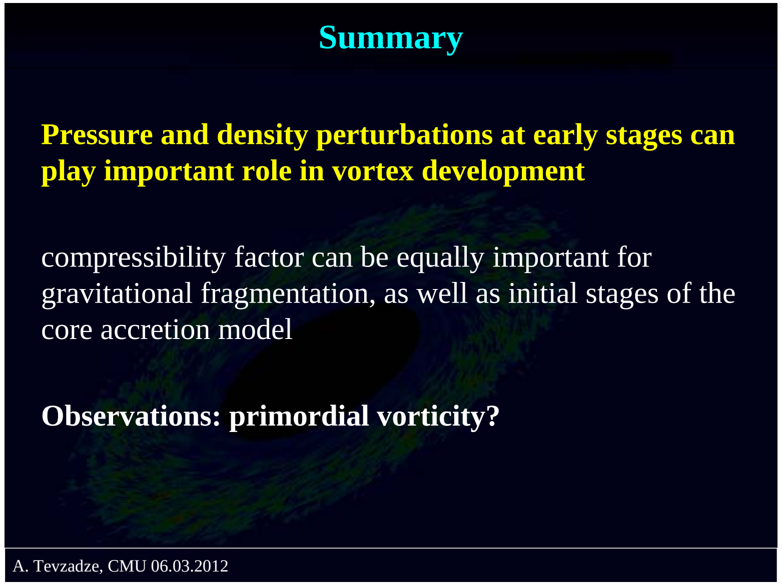
Summary

PV excitation during initial flattering of the protoplanetary disk

Pressure perturbations develop into shocks that produce potential vorticity

Turbulent evolution of stochastic pv leads to development of several strong anticyclonic vortices

cyclonic vortices shear away and dissipate, while some anticyclonic vortices merge to produce stable structures



Summary

Pressure and density perturbations at early stages can play important role in vortex development

compressibility factor can be equally important for gravitational fragmentation, as well as initial stages of the core accretion model

Observations: primordial vorticity?

THANK YOU

გმადლობთ