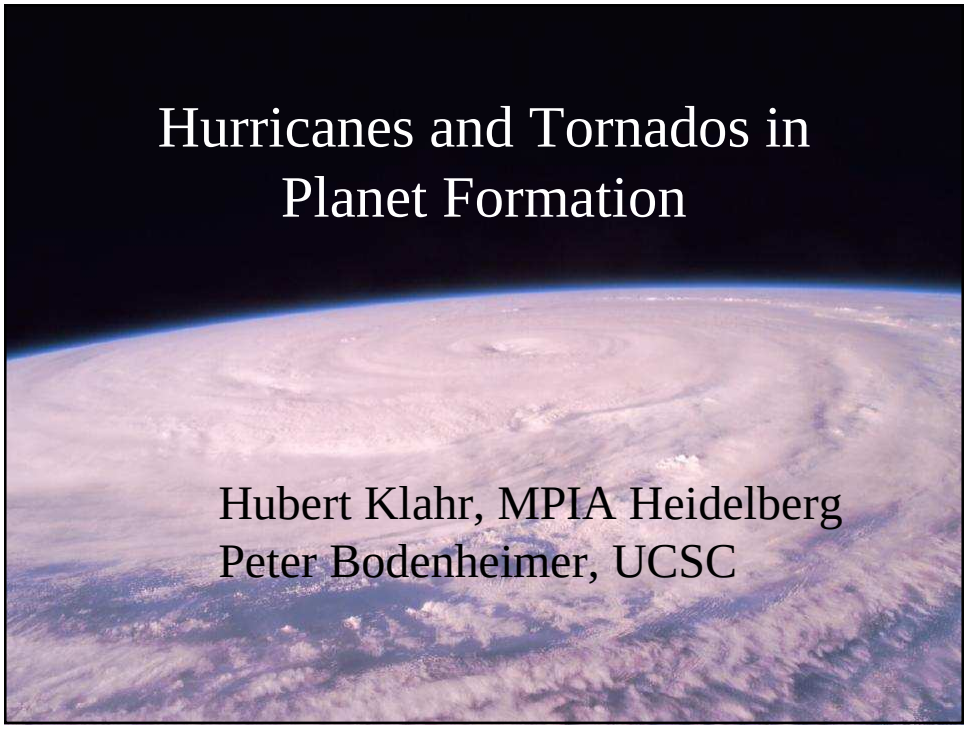
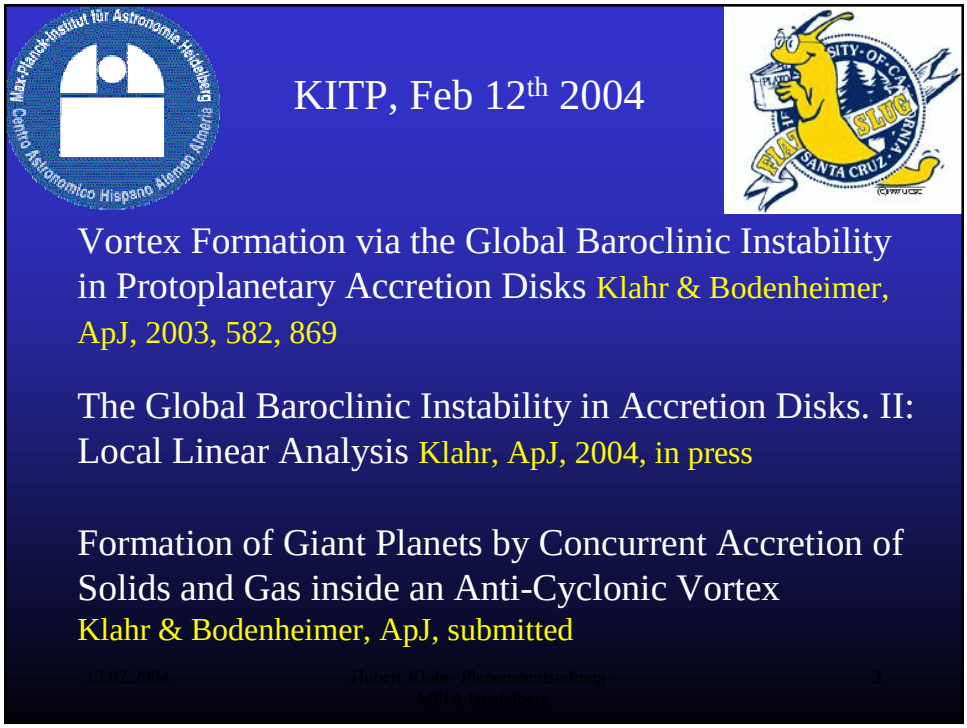

Hurricanes and Tornados in Planet Formation
Hubert Klahr, MPIA Heidelberg
Peter Bodenheimer, UCSC


Max-Planck-Institut für Astronomie Heidelberg
Centro Astronómico Hispano Aleman Almería
KITP, Feb 12th 2004
Vortex Formation via the Global Baroclinic Instability in Protoplanetary Accretion Disks Klahr & Bodenheimer, ApJ, 2003, 582, 869
The Global Baroclinic Instability in Accretion Disks. II: Local Linear Analysis Klahr, ApJ, 2004, in press
Formation of Giant Planets by Concurrent Accretion of Solids and Gas inside an Anti-Cyclonic Vortex
Klahr & Bodenheimer, ApJ, submitted
13.02.2004
Hubert Klahr - Planetenentstehung - MPIA Heidelberg
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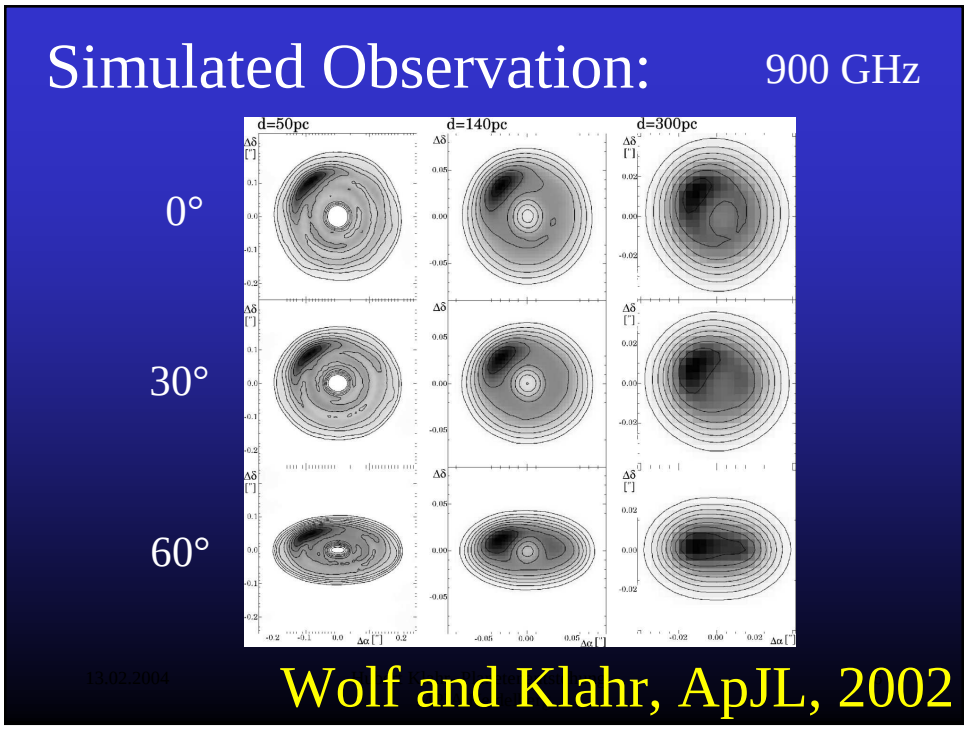
Things I will and things I will not talk about today, as this is an informal talk :

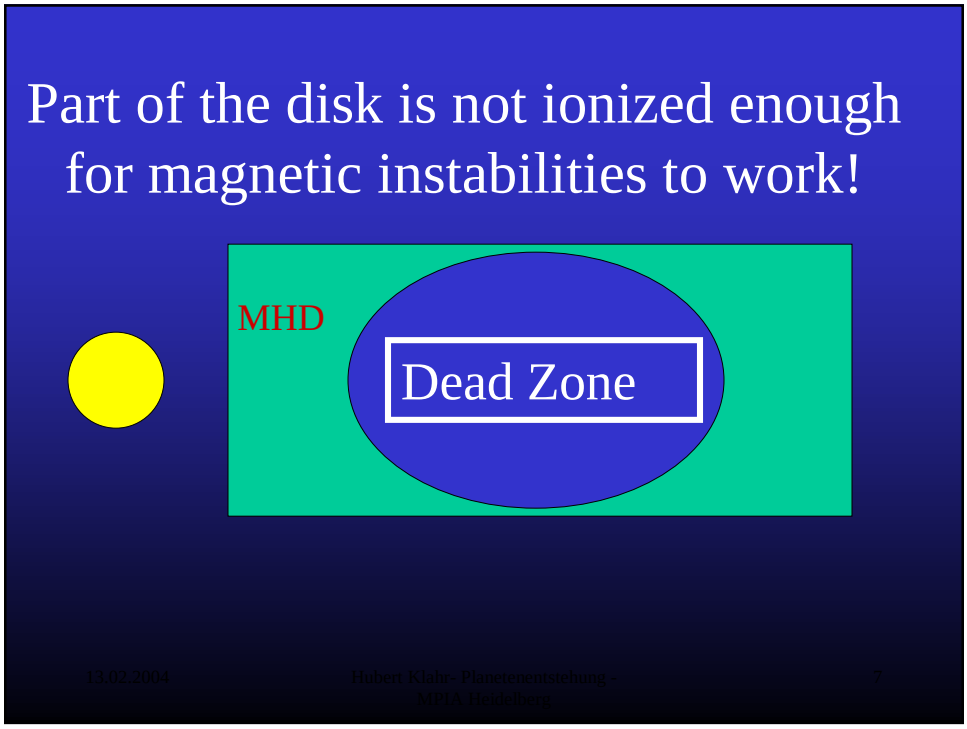
- Where do vortices come from?
- What is the lifetime of vortices?
- The 1m->1km Problem in Planet Formation!
- Vortices and the Core Accretion Model.

Where do vortices come from?

- Primordial: Barranco & Marcus 2000
- (MHD -) Turbulence in general:
- Rossby Wave Instability: Li et al. 2001
- Global Baroclinic Instability: Klahr & Bodenheimer 2003


Observation of Disks:
Protoplanetary Disks
Orion Nebula
HST · WFPC2
PRC95-45b · ST ScI OPO · November 20, 1995
M. J. McCaughrean (MPIA), C. R. O'Dell (Rice University), NASA


Simulated Observation:
900 GHz
0°
30°
60°
d=50pc
d=140pc
d=300pc
13.02.2004
Wolf and Klahr, ApJL, 2002


Part of the disk is not ionized enough for magnetic instabilities to work!
MHD
Dead Zone
13.02.2004
Hubert Klahr- Planetenentstehung - MPIA Heidelberg
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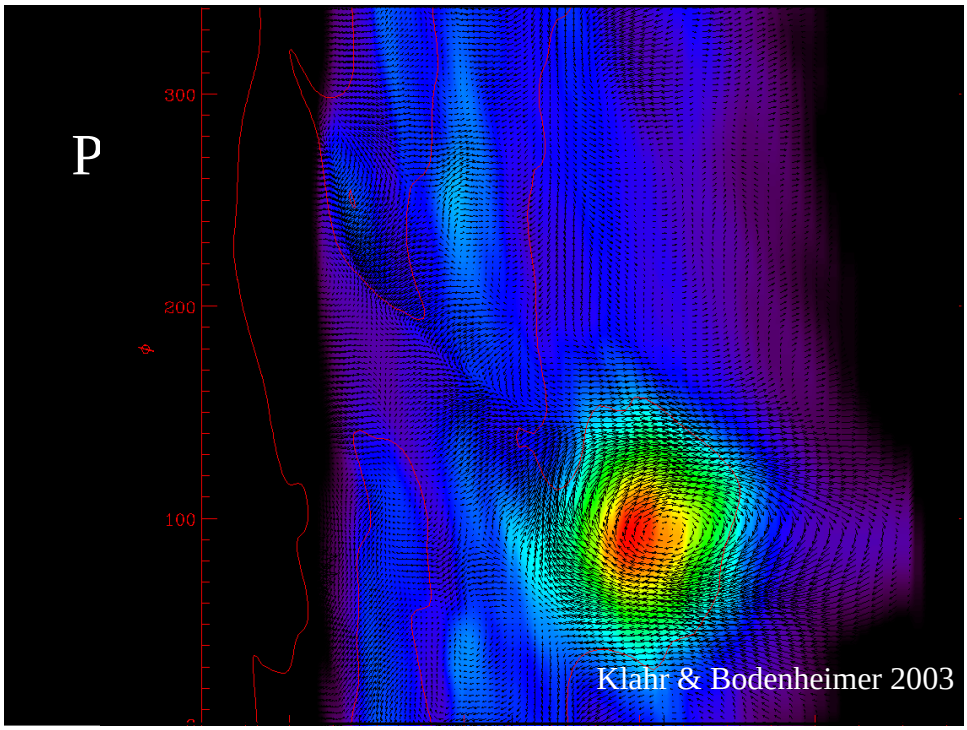
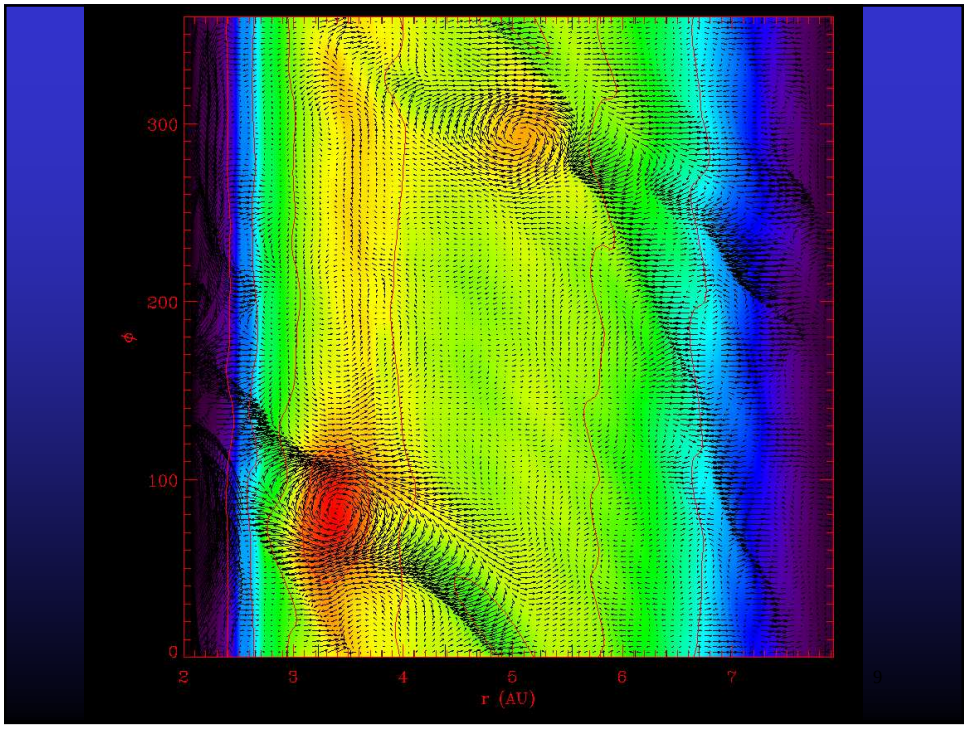
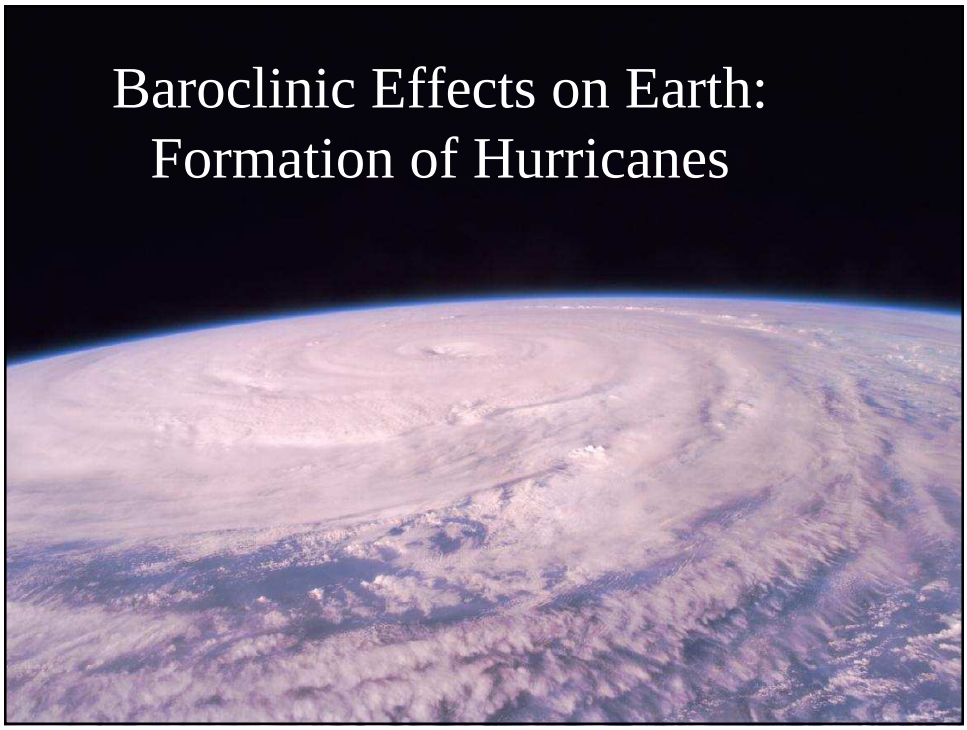

P
300
200
100
Klahr & Bodenheimer 2003


300
200
100
0
φ
2
3
4
5
6
7
r (AU)

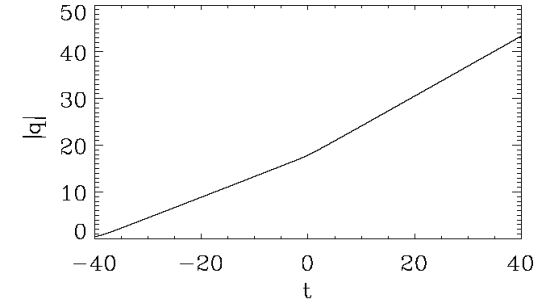

Baroclinic Effects on Earth:
Formation of Hurricanes

Buoyancy in the radial direction of a rotating system can lead to Rossby waves, which can break into vortices.

Klahr 2004 ApJ, in press

13.02.2004 Hubert Klahr- Planetenentstehung - MPIA Heidelberg 11

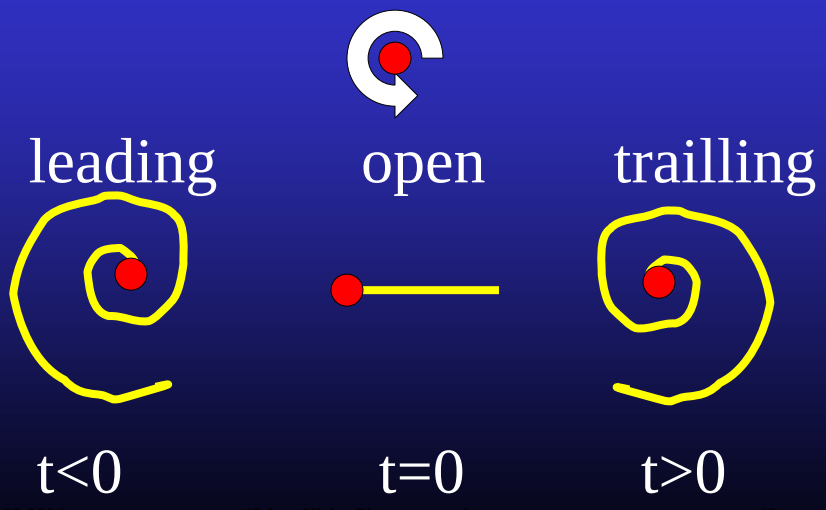
Potential Vorticity Generation



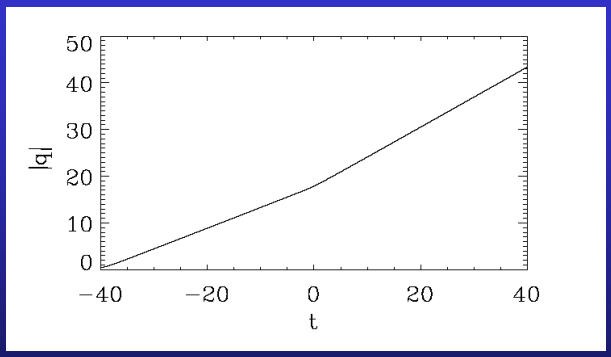
$$q(t) = \frac{\omega(t) + \frac{1}{2}\Omega}{\Sigma_0 + \Sigma_a(t)} - \frac{1}{2}\Omega$$

Klahr 2004, ApJ, in press

Eigenfunctions are spirals:



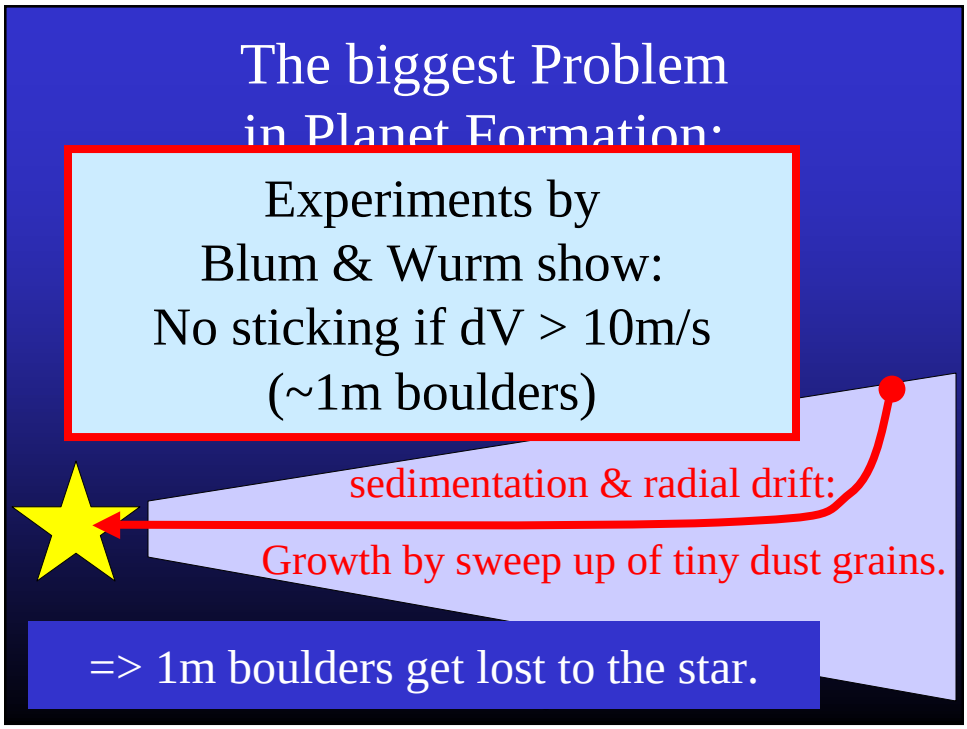
Potential Vorticity Generation

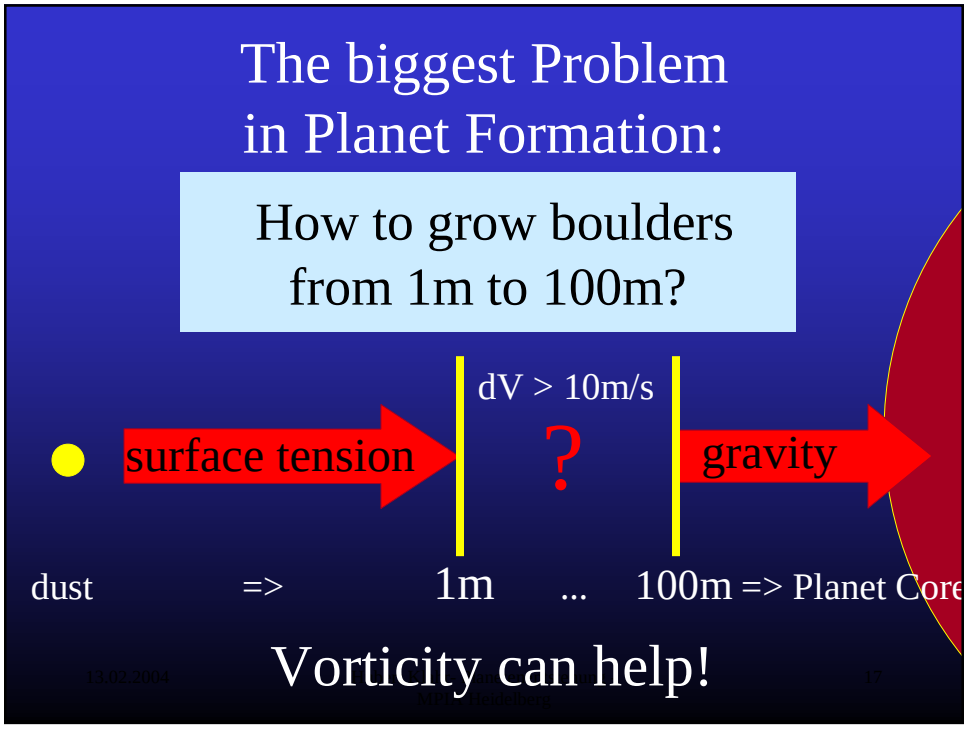


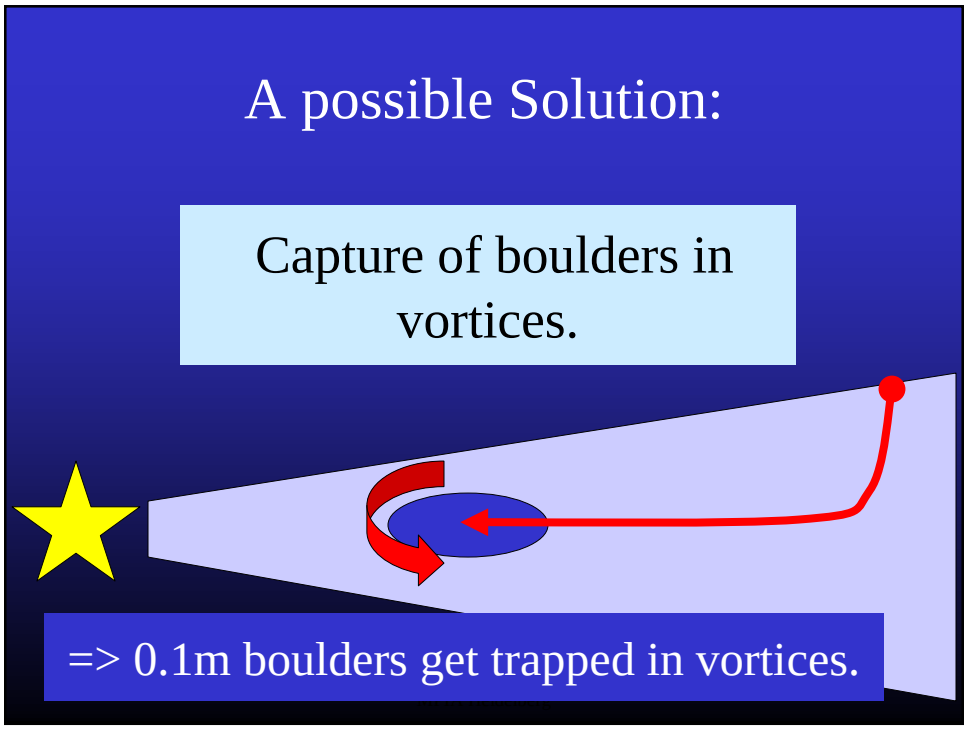
$$q(t) = \frac{\omega(t) + \frac{1}{2}\Omega}{\Sigma_0 + \Sigma_a(t)} - \frac{1}{2}\Omega$$

Klahr 2004, ApJ, in press


Are Vortices stable?
Some can be…
…numerical simulations
will have to tell!


The biggest Problem
in Planet Formation:
Experiments by
Blum & Wurm show:
No sticking if dV > 10m/s
(~1m boulders)
sedimentation & radial drift:
Growth by sweep up of tiny dust grains.
=> 1m boulders get lost to the star.

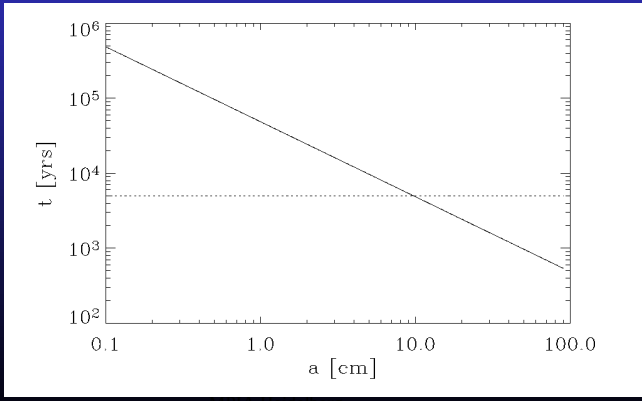

The biggest Problem
in Planet Formation:
How to grow boulders
from 1m to 100m?
dV > 10m/s
surface tension
?
gravity
dust
=>
1m
...
100m => Planet Core
Vorticity can help!


A possible Solution:
Capture of boulders in
vortices.
=> 0.1m boulders get trapped in vortices.

Core Accretion in Vortices

(Bodenheimer & Klahr submitted.)

Comparison between timescales for drift versus growth @ 7AU in minimum mass nebula:



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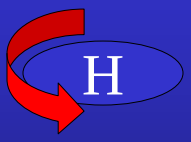
What makes a vortex so special? In contrast to the disk…



Pressure Maximum = Eye

… a vortex (Eye) moves at Keplerian rate!

… a vortex has no vertical shear.

… a vortex has a non turbulent Eye!

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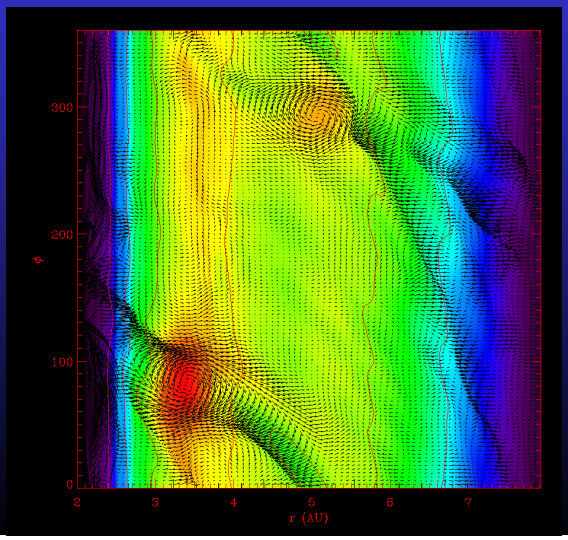
Anti Cyclonic Vortices are Dust Traps!

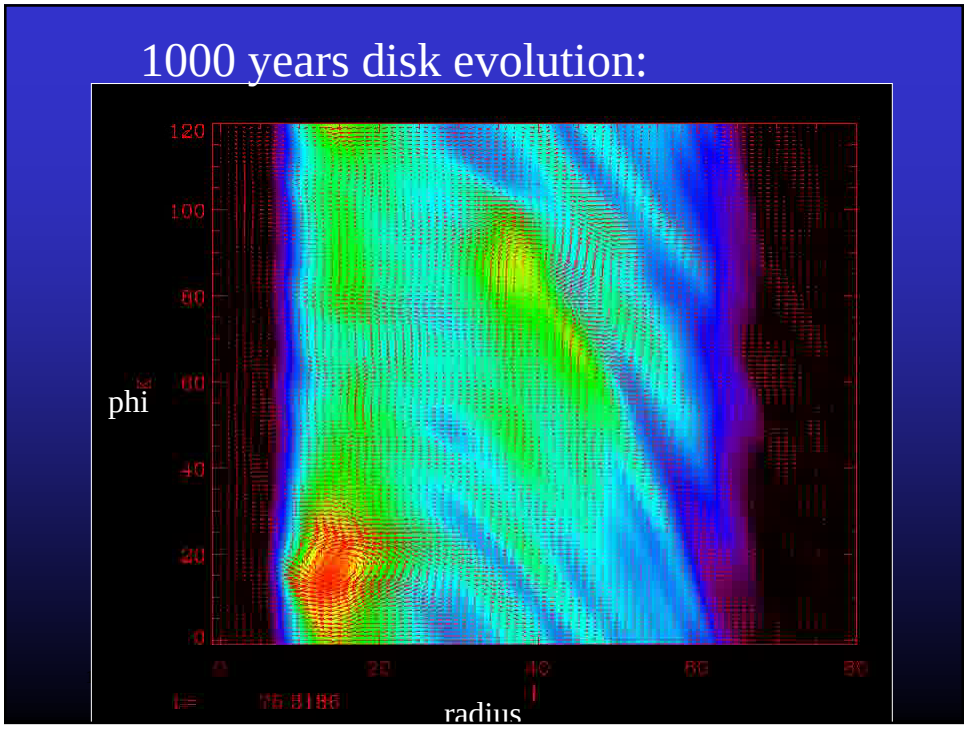
Balance between Centrifugal Forces, Gravity and Friction.

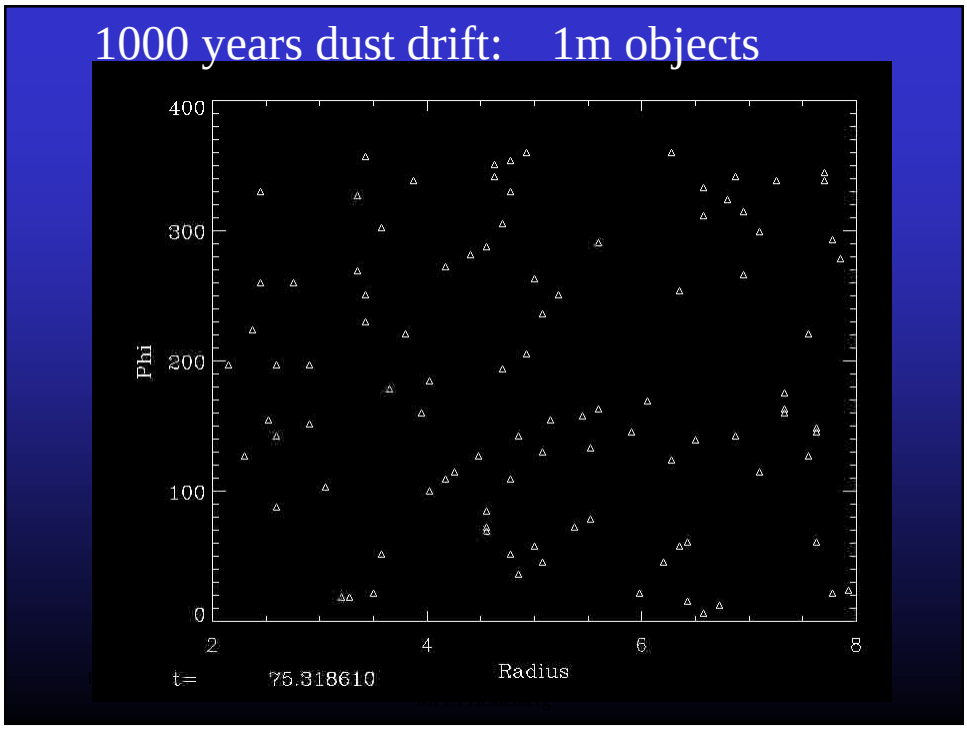
Inner side : Gas faster than Kepler!
Surplus of Centrifugal Acceleration:
⇒Drift of dust outward towards the vortex center
Analog: Outer side Drift inwards

Will boulders be concentrated in these vortices?

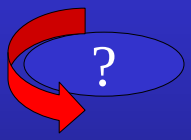


c.f. Barge & Sommeria 1995


1000 years disk evolution:
120
100
80
60
40
20
0
phi
radius


1000 years dust drift: 1m objects
400
300
200
100
0
Phi
2
4
6
8
Radius
t=
75.318610

What happens to the boulders inside the Vortex?



1. they accumulate to one large core.

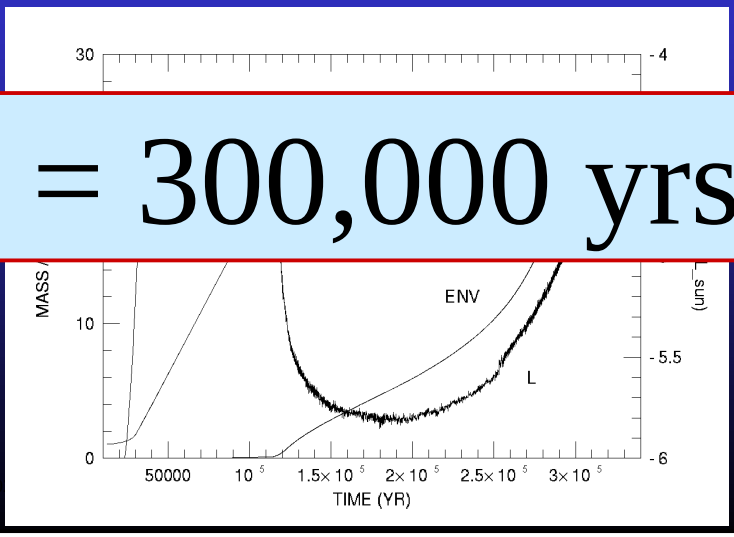
2. they enrich the gas until they undergo Gravitational Collaps. (Gurevich & Lebedinskii 1950, Safronov 1969, Goldreich & Ward 1973, etc.)

3. they accumulate to planetesimals and scatter (in part / at all) out of the vortex.

Core Accretion in Vortices

(Bodenheimer & Klahr submitted)

2.2E-4 M_{earth}/yr; 3g/cm^2; minimum Nebula!



t = 300,000 yrs

Core Accretion plus Vortices:

- Collision velocities for boulders
  dV < 10 m/s => no fragmentation
- No loss of 1m boulders into central object
- Fast buildup of cores from 0.1-1m boulders
- Minimum mass nebula and solar metalicity
- Accretion time for 12 Earth mass core < 10^5 yrs
- Formation time for Jupiter < 10^6 yrs

Summary:

An entropy gradient makes a disk hydro-dynamically unstable.

Entropy gradients generate vorticity in disks.

Vortices accelerate the core accretion for giant planets.


Three Phases of Planet Formation:
•Vortex Formation
•Dust Concentration
•Gas Accretion