

Protostellar turbulence in cluster forming regions of molecular clouds

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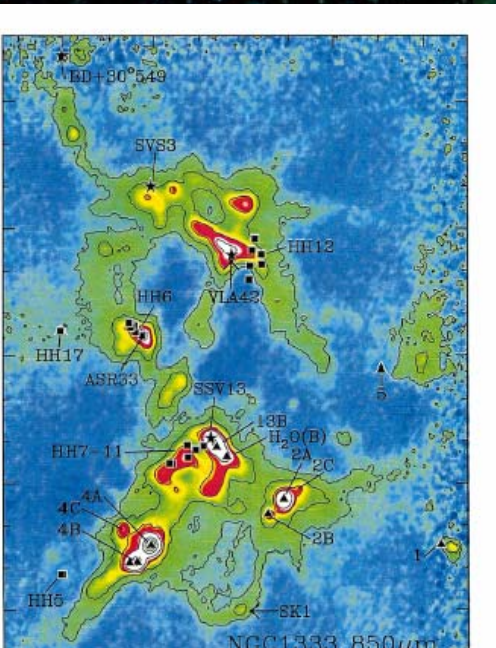
Zhi-Yun Li (Univ. of Virginia)

Cluster Forming Region NGC1333 (Spitzer)

NGC1333 (320 pc)

Embedded cluster
~ 150 stars already formed

Many outflows are observed.

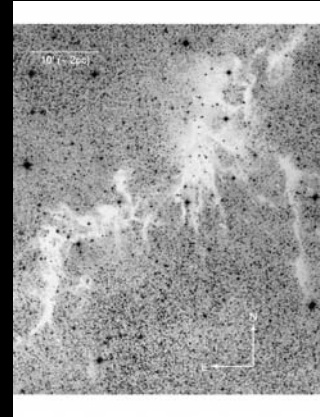


Protostellar Outflows and Star Formation

Observations

- Observations indicate that protostellar outflows play a significant role in cloud dynamics.

Circinus: Bally et al. 1999;
NGC1333: Quillen et al. 2005



Numerical Simulations

- No 3D turbulent simulations have taken into account effects of protostellar outflows. (e.g., Bonnell et al, Klessen et al.)
- MHD simulations have been limited to the stage prior to star formation. e.g., Vázquez-Semadeni et al. (2005); Tilley & Pudritz (2005)
- We perform 3D MHD simulations of turbulent magnetized clouds, including effects of protostellar outflows. (Li & Nakamura 2006; Nakamura & Li in prep.)

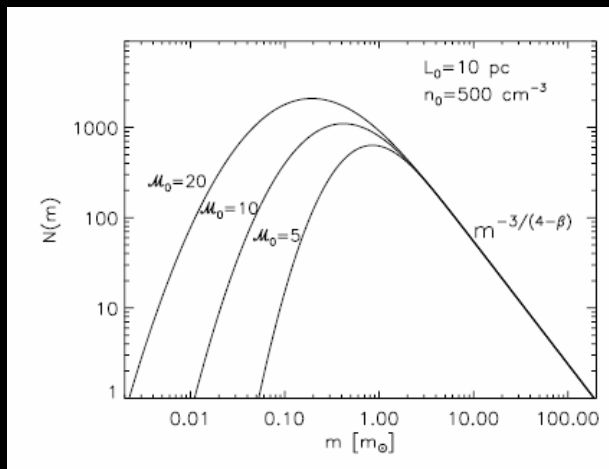
星の初期質量関数について

- 理論モデル turbulent fragmentation
(Padoan & Nordlund 2002)

$$E_k \propto k^{-\beta}$$



$$N(m)d \log m \propto m^{-3/(4-\beta)} \left[\int_0^m p(m_j) dm_j \right] d \log m .$$



Numerical Model

- Isothermal spherical cloud with uniform magnetic field
- We add supersonic velocity field that is consistent with the linewidth-size relation.
- **3D isothermal MHD calculation**

$$E_k \propto k^{-2}$$

$$n_{H_2} = 2.7 \times 10^4 \left(\frac{T}{20\text{K}} \right) \left(\frac{L_J}{0.17\text{pc}} \right) \text{cm}^{-3}$$

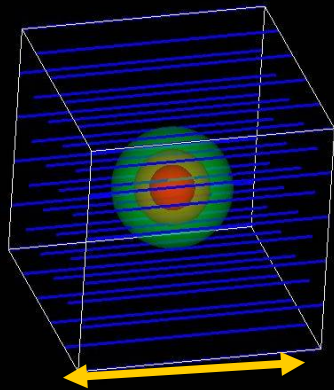
$$L = 9L_J = 1.5 \left(\frac{L_J}{0.17\text{pc}} \right) \text{pc}$$

$$M = 939 \left(\frac{T}{20\text{K}} \right) \left(\frac{L_J}{0.17\text{pc}} \right) M_\odot$$

$$B_0 = 47 \alpha^{1/2} \left(\frac{T}{20\text{K}} \right) \left(\frac{L_J}{0.17\text{pc}} \right)^{-1/2} \mu\text{G}$$

$$B_0 = 75 \mu\text{G} \quad @ \alpha = 2.5$$

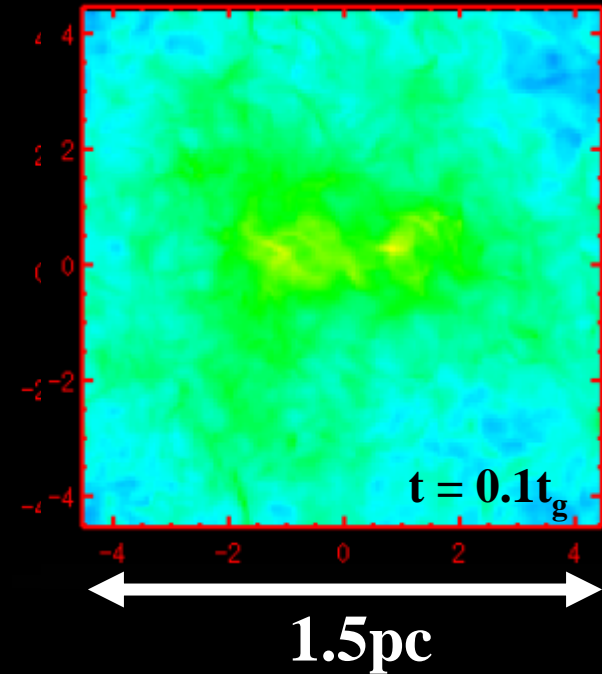
$$t_g = L_J / C_s = 0.6 \left(\frac{T}{20\text{K}} \right)^{-1/2} \left(\frac{L_J}{0.17\text{pc}} \right) \text{Myr}$$



1.5 pc = 9L_J

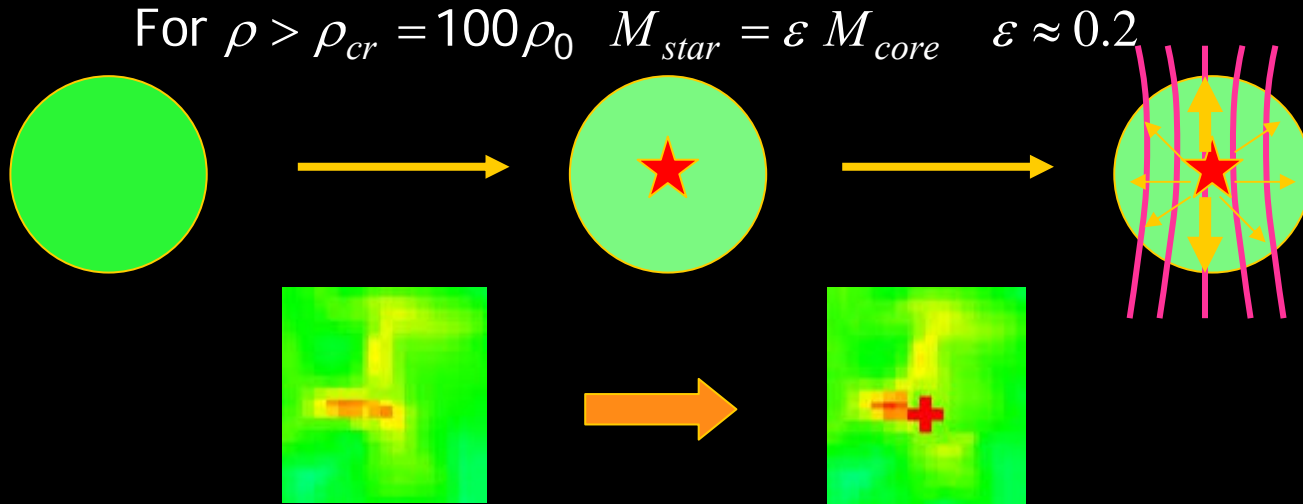
Effective radius = 1.5L_J
= 0.26 pc

L_J = thermal Jeans length



Numerical Model (Protostellar Outflow)

- Creation of “stars”



- Protostellar outflow

(Matzner & McKee 2000; Nakamura & Li 2005)

$$M_W V_W = 100 f M_{star} \left(M_{\odot} \text{ km s}^{-1} \right) \quad f : \text{outflow strength}$$

★Circinus cloud $f \sim 0.3$ (Bally et al. 1999)

★L1157 $f \sim 0.3$

★L1551 IRS5 $f = 0.23 \sim 0.39$

★X-wind model $f \sim 1/3$ (Shu et al. 2000)

★Matzner & McKee model $f \sim 0.4$

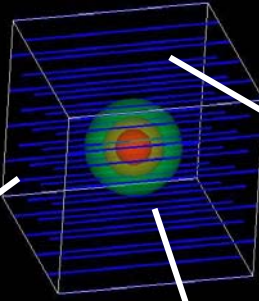
$f \sim 0.3 - 0.4$

Numerical Result: Effect of Outflow

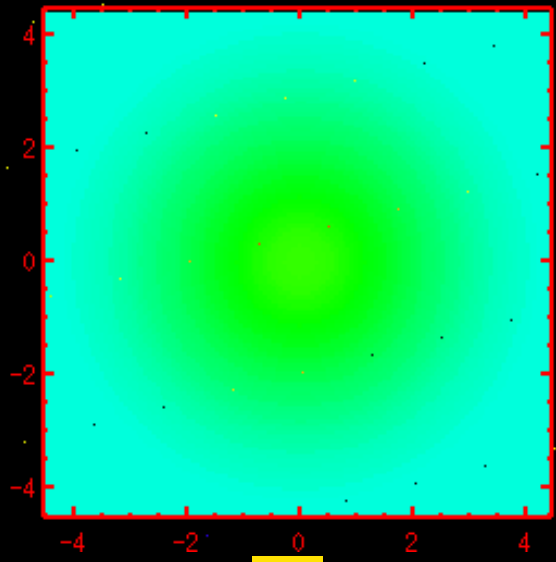


Column density distribution

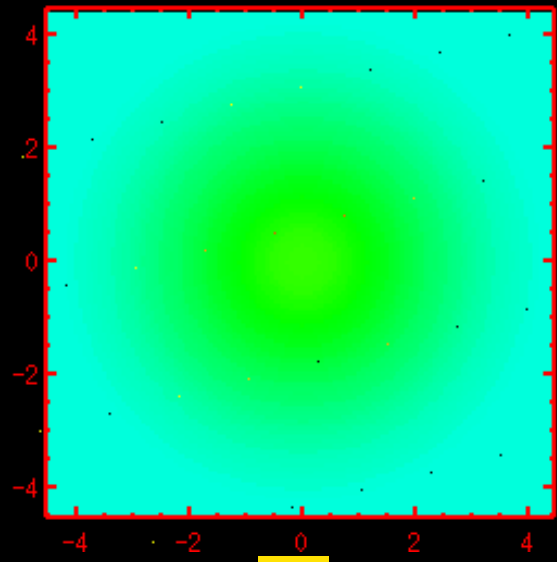
$M = 10, f = 0.5$



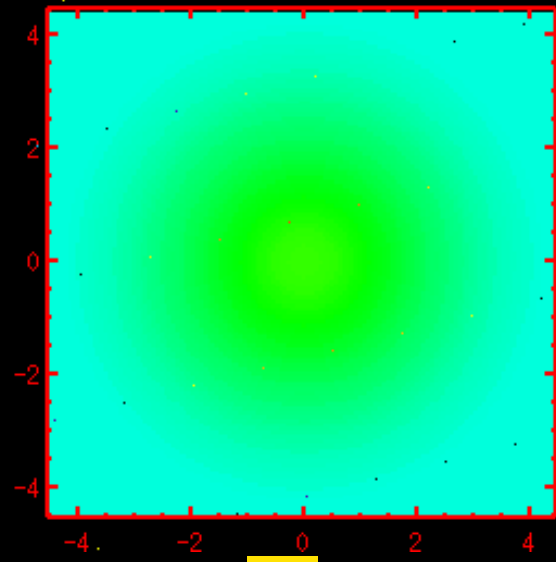
1.5 pc



1



2

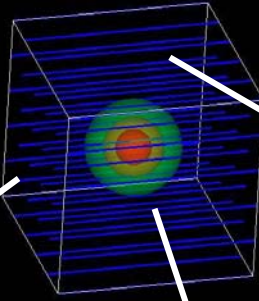


3

Numerical Result: Effect of Outflow

Column density distribution

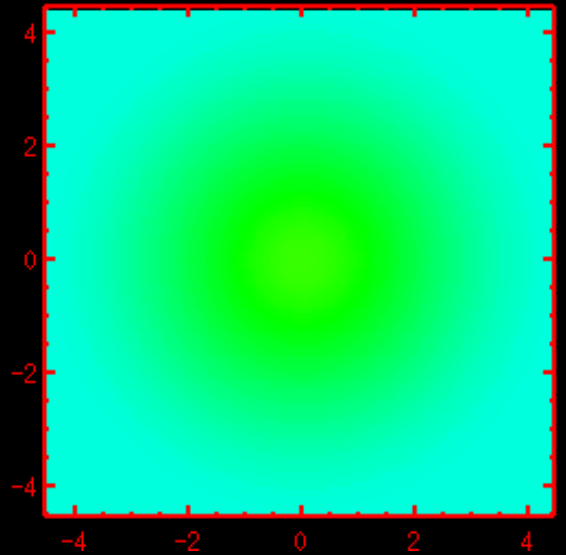
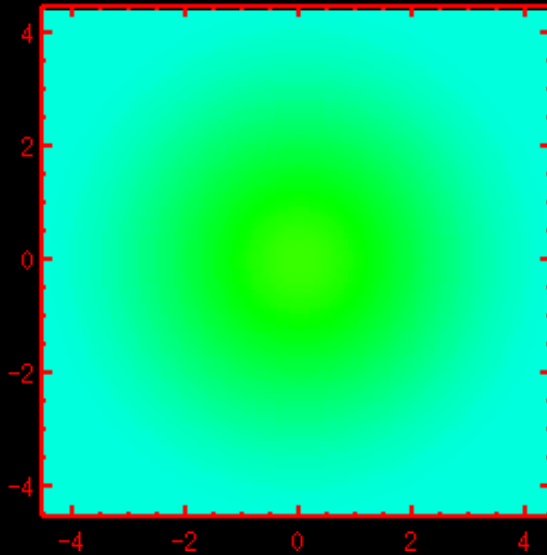
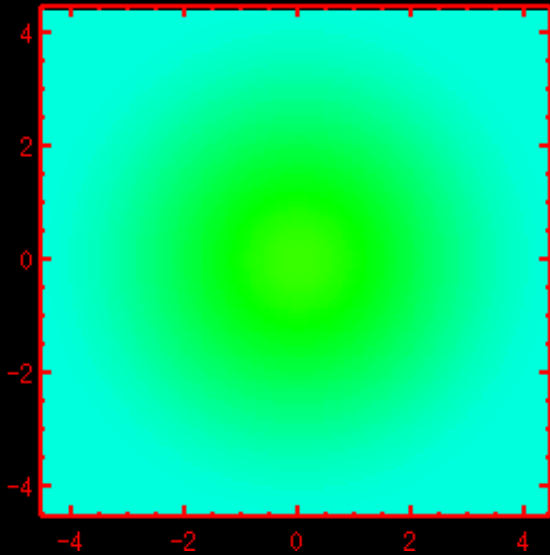
$M = 10, f = 0.5$



1.5 pc



-2.0 -1.5 -1.0 -0.5 0.0 0.5 1.0 $t = 0.0000000$ $a=2.5, M=10, n=1,128, b/r, f=0.5$ $dx=1.75 N_{stars} = 0.00000$



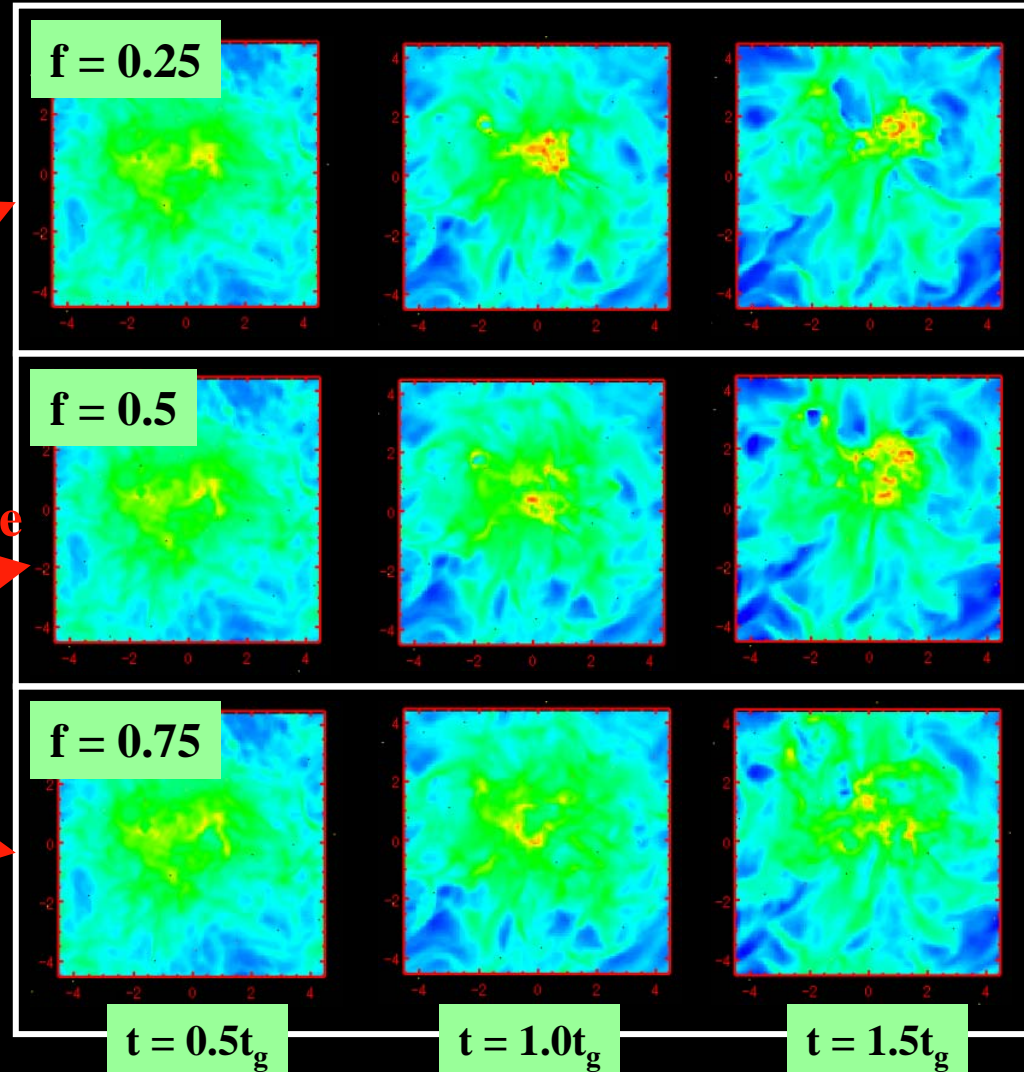
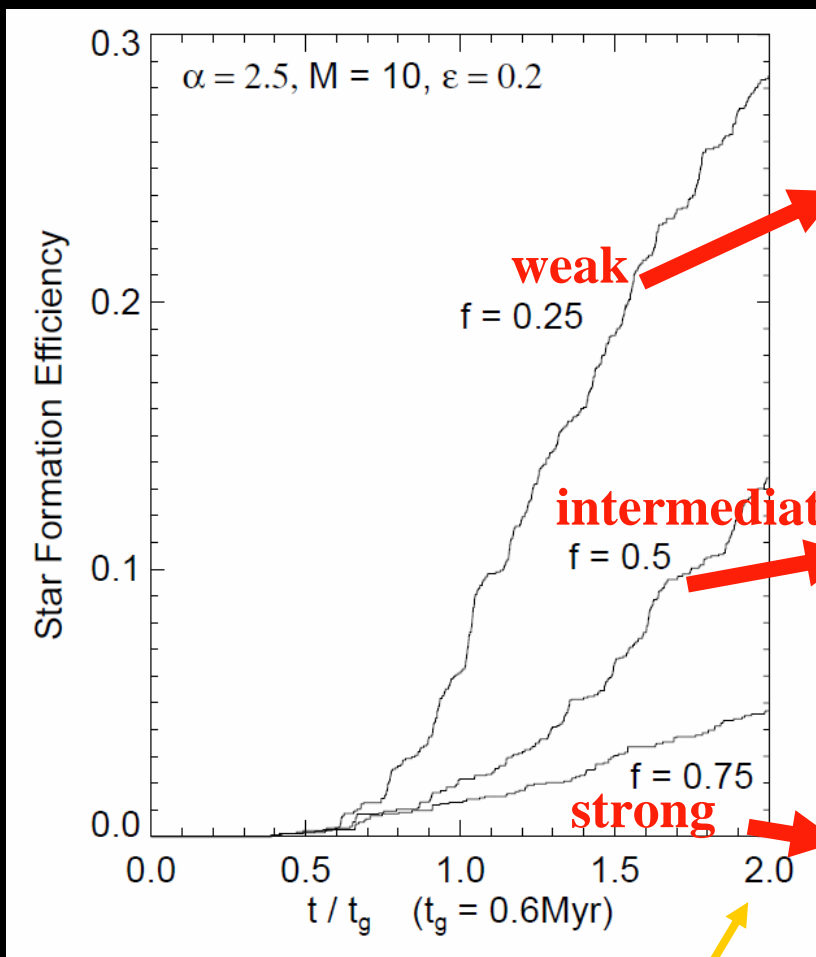
1

2

3

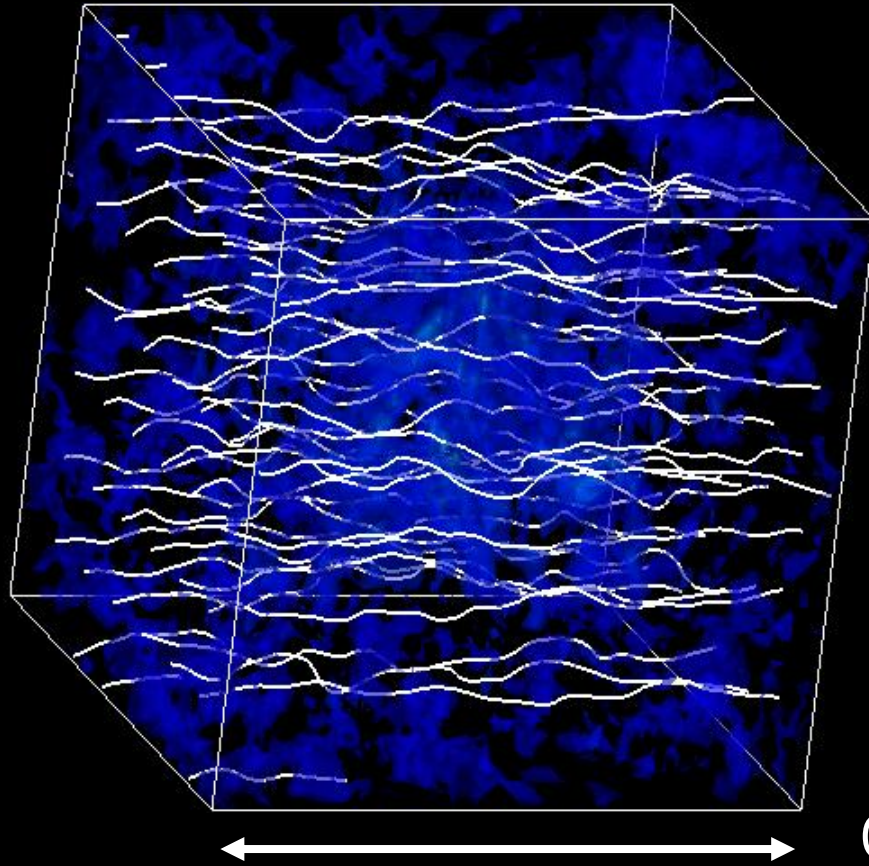


Star Formation Efficiency



- Global star formation is suppressed by outflows.

3D Density and Magnetic Structure

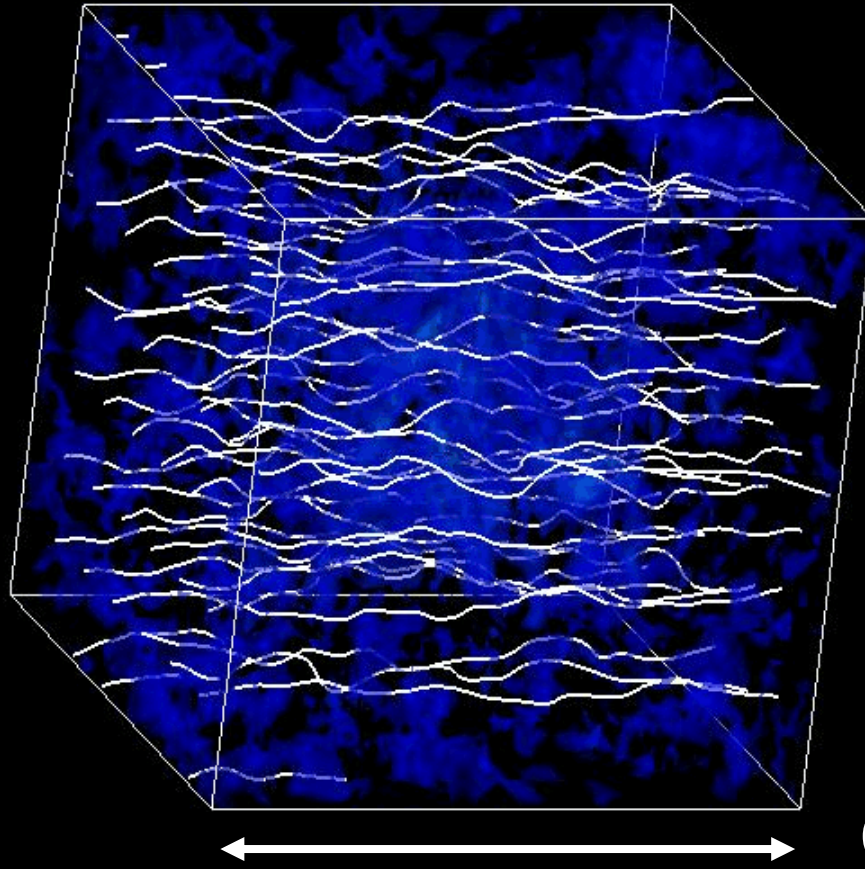


Red: $\rho > 10^6 \text{cm}^{-3}$

Blue: $\rho \sim 10^{4-5} \text{cm}^{-3}$

0.75 pc

3D Density and Magnetic Structure



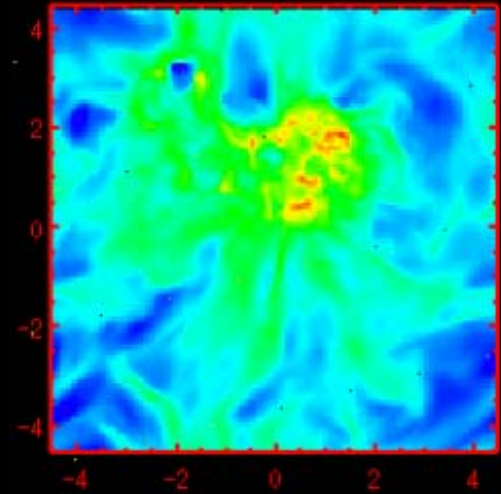
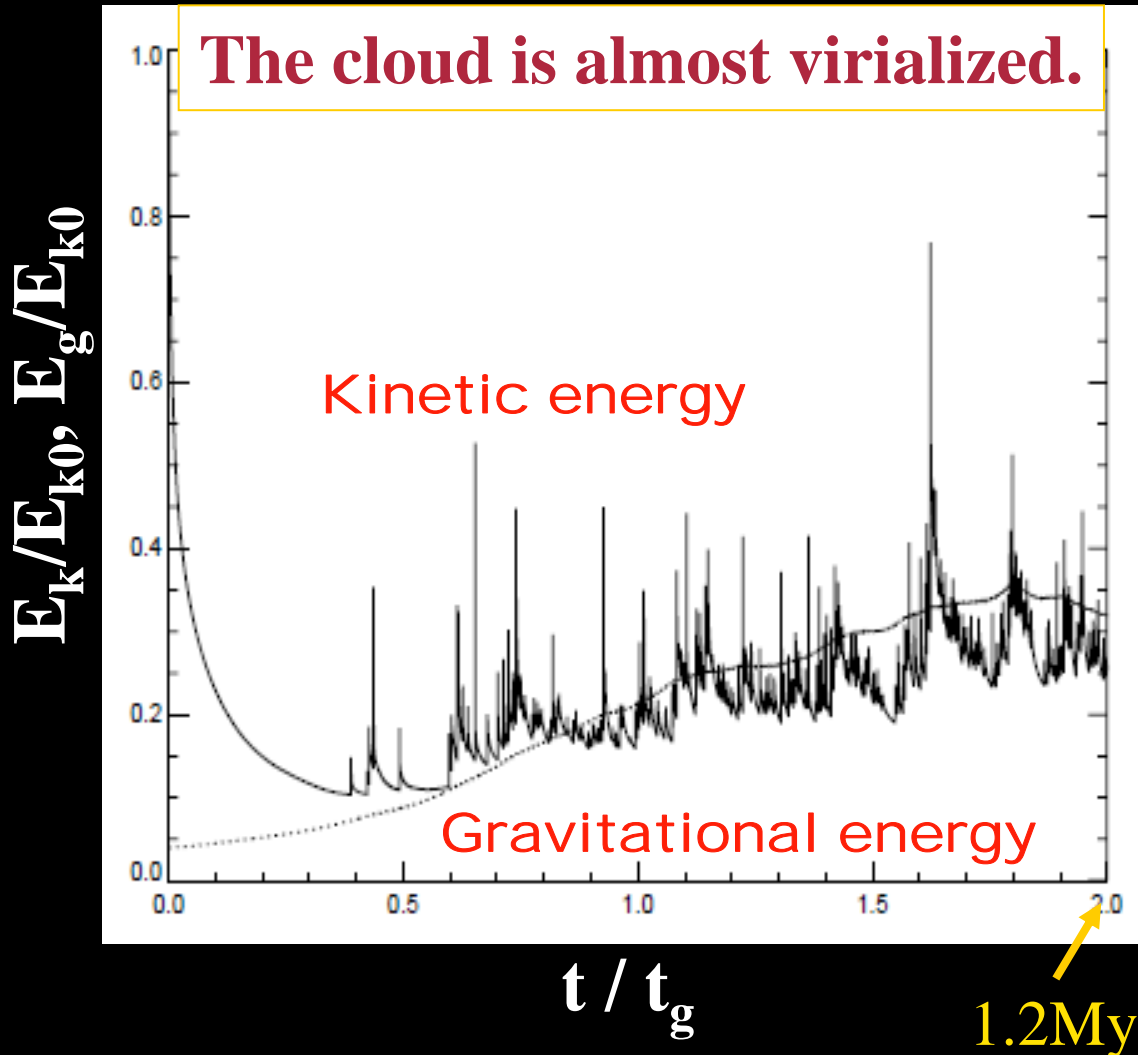
Red: $\rho > 10^6 \text{cm}^{-3}$

Blue: $\rho \sim 10^{4-5} \text{cm}^{-3}$

0.75 pc

Bipolar outflows generate large amplitude Alfvén and MHD waves, which transform outflow motions into turbulent motions efficiently.

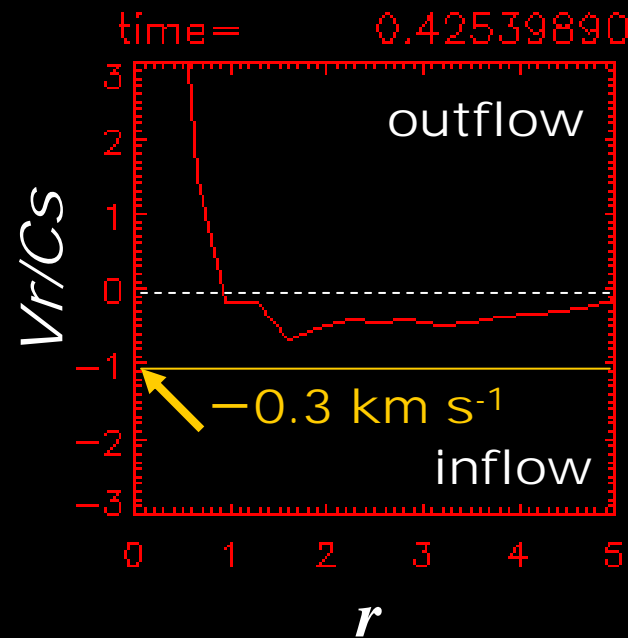
Dynamic State of Cluster Forming Clumps - Dynamic Equilibrium -



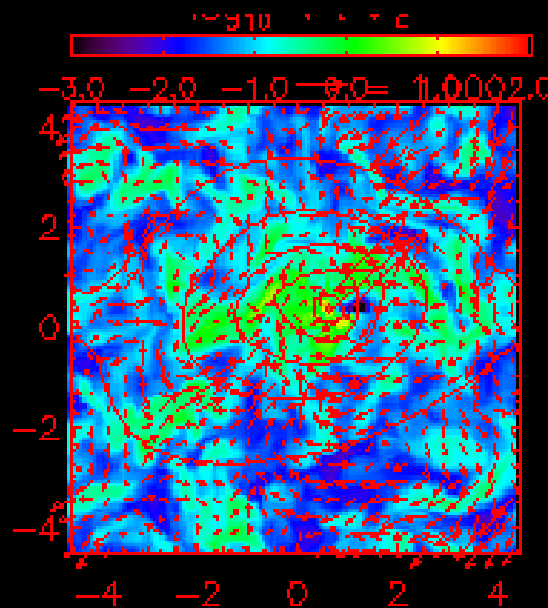
Mach ~ 5
 $\Delta V \sim 1.5 \text{ km s}^{-1}$
($T=20\text{K}$)

Infall Velocity and Density Profile in Cluster Forming Cores

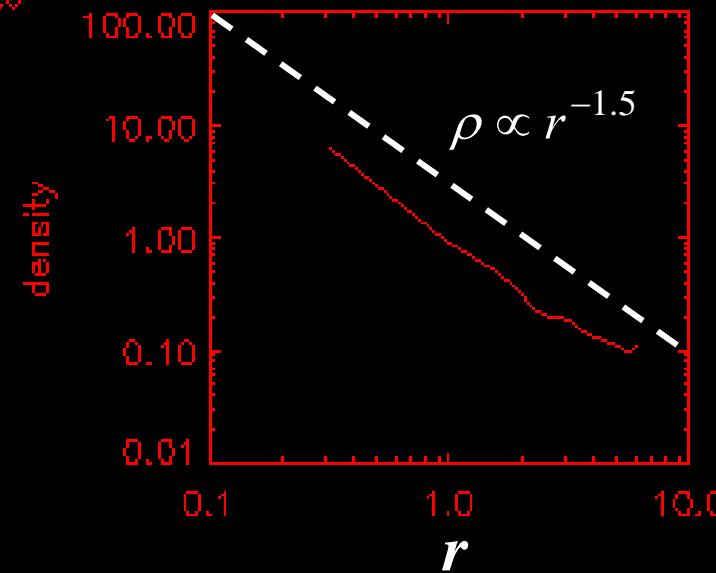
Net Radial velocity



yz plane (density)



Radial Density profile



- Radial speed is almost subsonic, indicating that the system is in quasi-equilibrium.
- Density profile is well approximated by $\rho \propto r^{-1.5}$.

乱流場のエネルギースペクトル

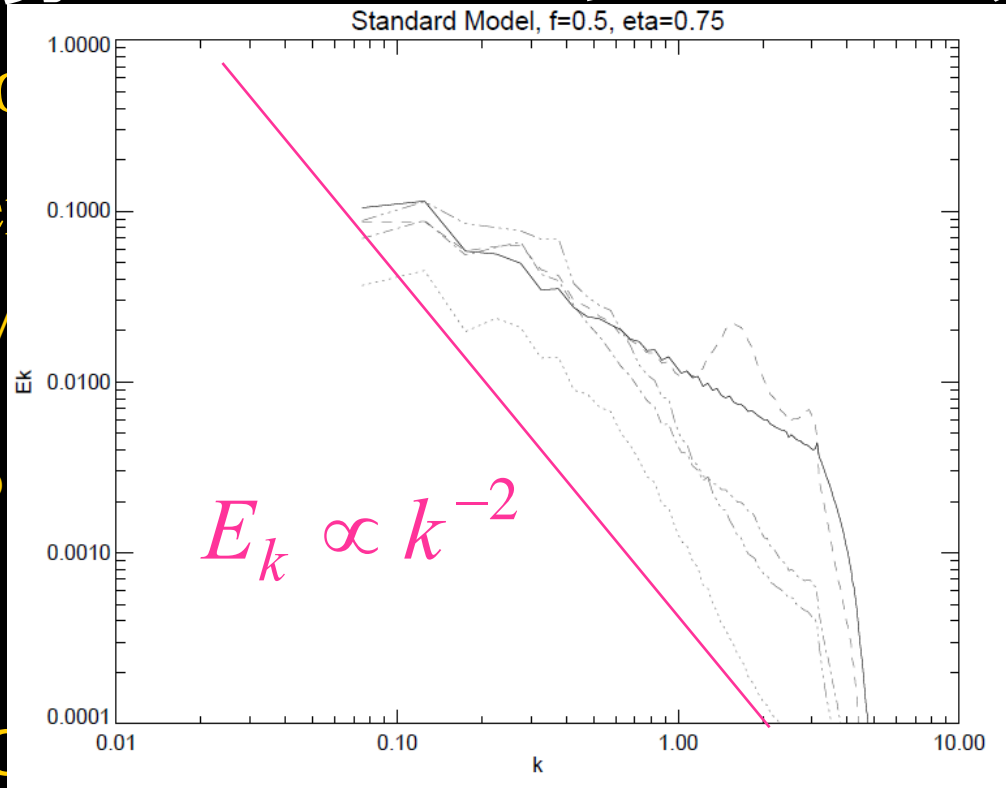
- Kolmogorov

- Burgers

Recent Model

Recent observations

Protocols



$$k^{-5/3}$$

$$\propto k^{-2}$$

(Low)

$$k^{-1.74}$$

& Heyer)

$$\beta \approx 2.17$$

$$E_k \propto k^{-2}$$

Summary

- Protostellar outflows can trigger local star formation, but, they suppress global star formation.
- Protostellar outflows can power supersonic turbulence at a level of 1.5 km s^{-1} .

(Protostellar turbulence)

- Protostellar outflows generate large amplitude Alfvén and MHD waves that transform the outflow motions into turbulent motions.
- The cloud reaches dynamic equilibrium.
(no significant infall motions, $\rho \propto r^{-1.5}$)

(cf. Krumholz & Tan 2006)