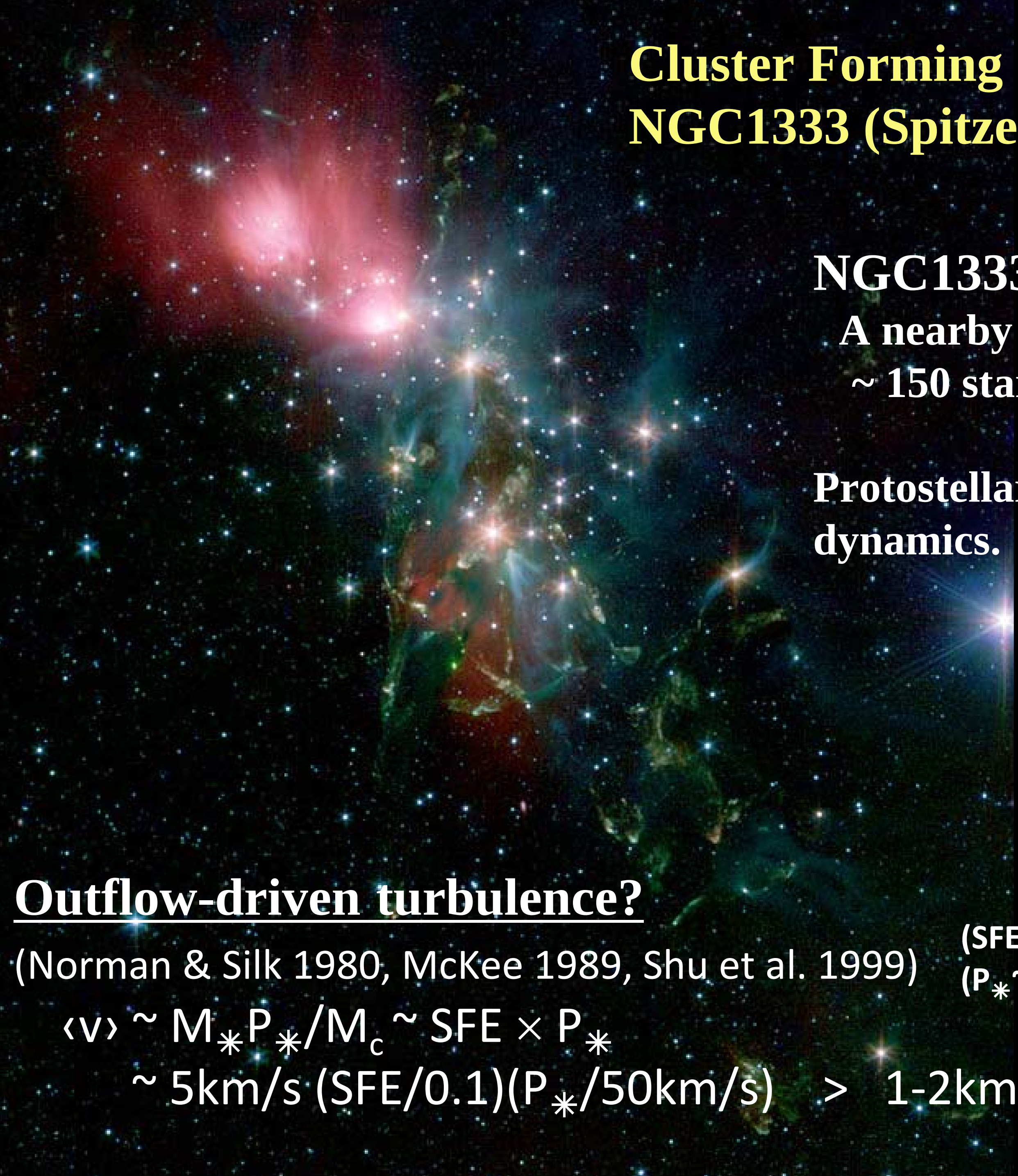
Protostellar Turbulence and Cluster Formation

Fumitaka Nakamura (Niigata Univ.)

Zhi-Yun Li (Univ. of Virginia)

Ref. Li & Nakamura, 2006, ApJL, 640, L187
Nakamura & Li, 2007, ApJ, 662, 395
+ latest results

Cluster Forming Clump
NGC1333 (Spitzer)



NGC1333

A nearby embedded cluster

~ 150 stars already formed.

Protostellar outflows influence cloud dynamics.

Outflow-driven turbulence?

(Norman & Silk 1980, McKee 1989, Shu et al. 1999)

(SFE~10% Lada & Lada 2000)

(P_*~40km/s, Matzner & McKee 2000)

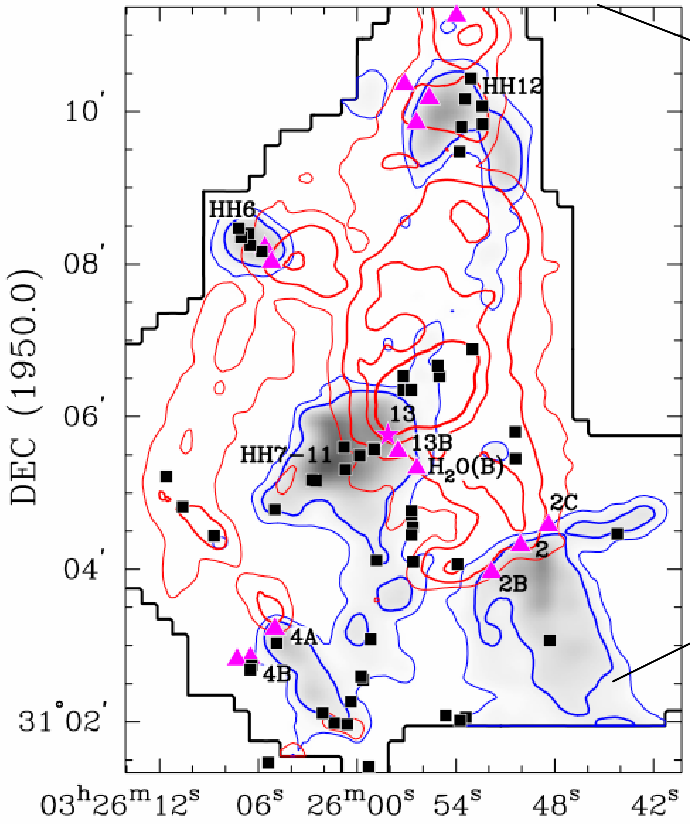
$$\langle v \rangle \sim M_* P_* / M_c \sim \mathrm{SFE} \times P_*$$

$$\sim 5\mathrm{km/s}\ (\mathrm{SFE}/0.1)(P_*/50\mathrm{km/s}) \quad > \quad 1\text{-}2\mathrm{km/s}$$

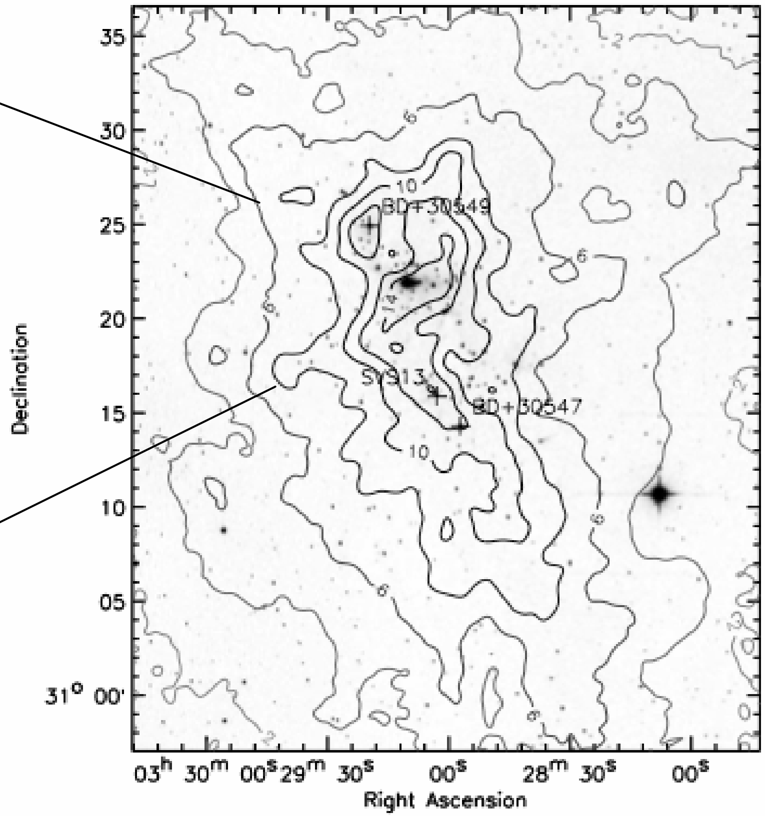
NGC1333 Cluster Forming Region in CO

multiple bipolar outflows

core + envelope



(Knee & Sandell 2000)



(Ridge et al. 2003)

- ●Molecular outflows are overlapping and interacting with themselves
- ●The envelope contains most of the mass in this system.

Cluster Formation in Parsec-Scale Dense Clumps: Global Issues

- What is the rate of star formation in cluster forming clumps?

  star formation rate per free fall time (Krumholz & McKee 2005)

  SFR_{ff}~1-5% for NGC 1333 (see also Krumholz & Tan 2007)

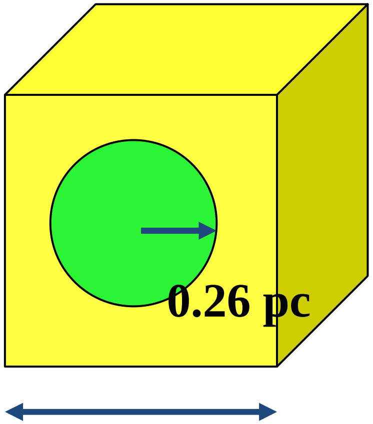
- Can outflows keep the cluster forming clumps close to a dynamical equilibrium?

  (Tan et al. 2006)

- Is there any unique characteristic of protostellar (outflow-driven) turbulence?

Numerical Model

- **Centrally condensed, isothermal spherical cloud with uniform magnetic field**
- **We superimpose supersonic velocity field of a Mach 10 turbulence in Fourier space.** $\left(v_k^2 \propto k^{-3}\right)$



1.5 pc = 9L$_J$

Effective radius = 1.5L$_J$

L$_J$= thermal Jeans length

$$n_{H2} = 2.7\times 10^{4}\left(\frac{T}{20\ \mathrm{K}}\right)\left(\frac{L_J}{0.17\ \mathrm{pc}}\right)\mathrm{cm}^{-3}$$

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

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

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

$$B_0 = 75\ \mu\mathrm{G}$$

Magnetically supercritical

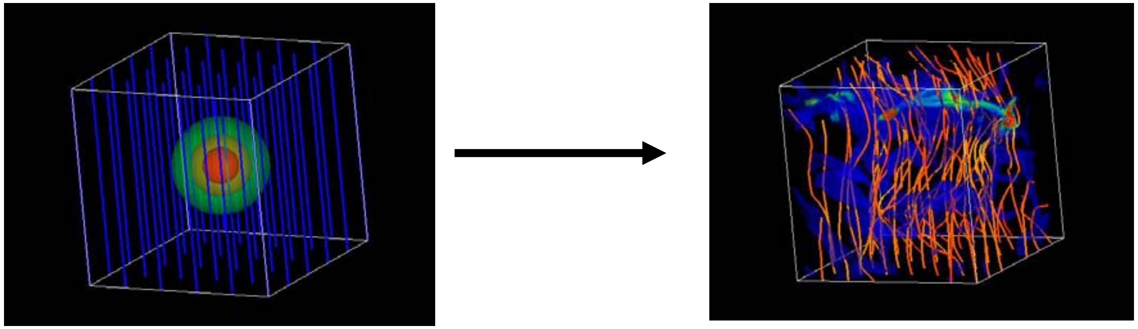
flux-to-mass ratio
20% the critical value at the center

50% the critical value as a whole

Gravitational collapse time

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

25% longer than global free-fall time

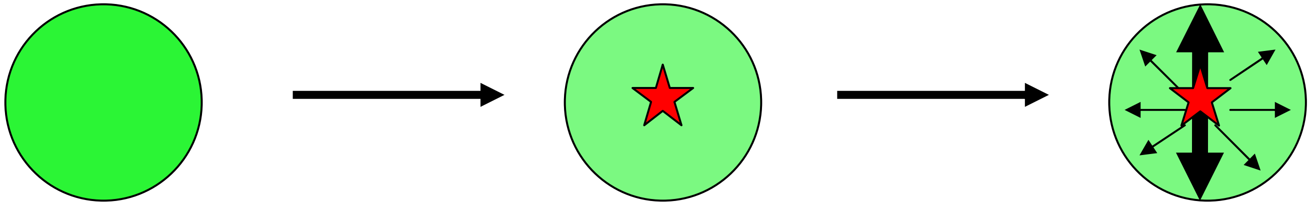


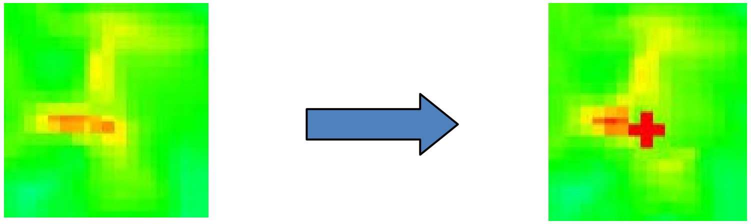
Numerical Model (Protostellar Outflow)

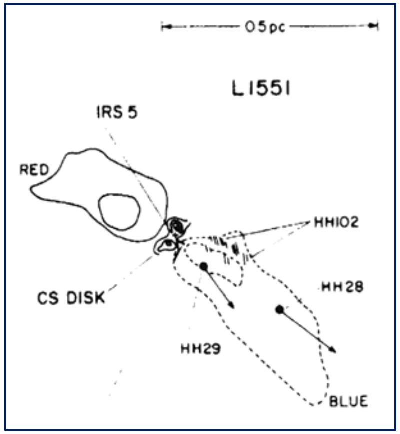
- **Star formation**

For $\rho > \rho_{cr} = 700\rho_{\mathrm{av}}$ $M_{star} = \varepsilon M_{core}$ $\varepsilon \approx 0.3$

CLUMPFIND







- **Protostellar outflow** **(jet + spherical components)**

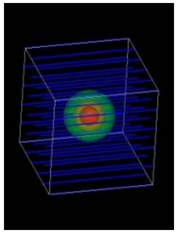
(Matzner & McKee 2000; Nakamura & Li 2005)

- a). strength parameterized by the outflow momentum per solar mass of star formed

P_*=50 km/s (P$_*$~40km/s, Matzner & McKee 2000)

- b). 75% of the momentum in a 30° “jets” around the local magnetic field direction and 25% of the momentum in a slower spherical component

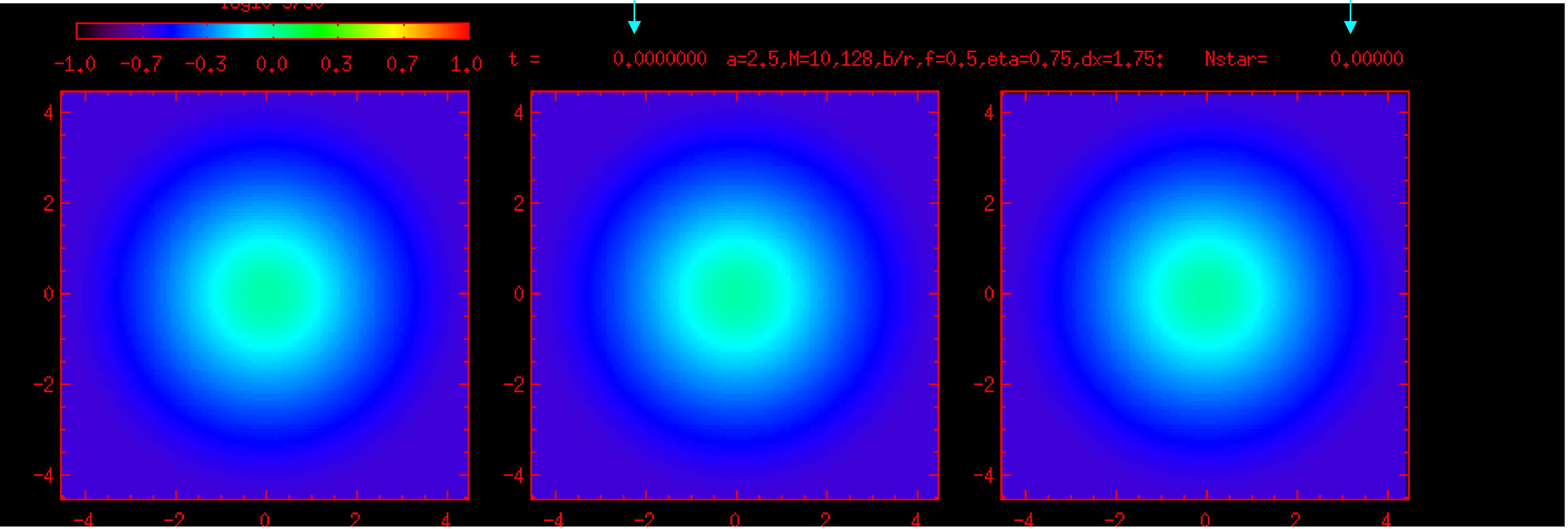
Column Density Movie of Clump Evolution



1.5 pc

$t_g = L_J/a = 0.6$ Myrs

number of stars

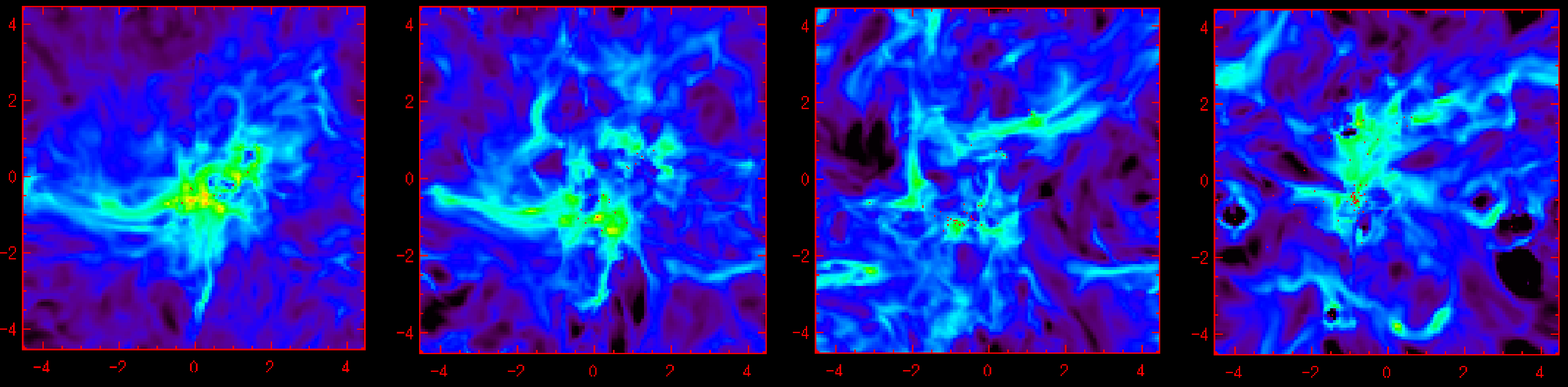


along x-axis (B field direction) y-axis z-axis (rotation axis)

- First star formed around t~0.4 t_g
- By t=1.5 t_g, 45 stars have formed, w/ star formation efficiency SFE ~ 6%

Column Density Evolution in Cluster Forming Clump

along x-axis (initial B field direction)



t =0.6 t_g (0.36Myr) t =0.8 t_g (0.5Myr) t =1.5t_g (0.9Myr) t =2t_g (1.2Myr)

centrally condensed

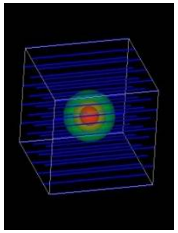
More extended,
Torn part by outflows

dispersing

accumulating

Oscillation around a dynamical equilibrium state?
(see also Matzner & McKee 1999)

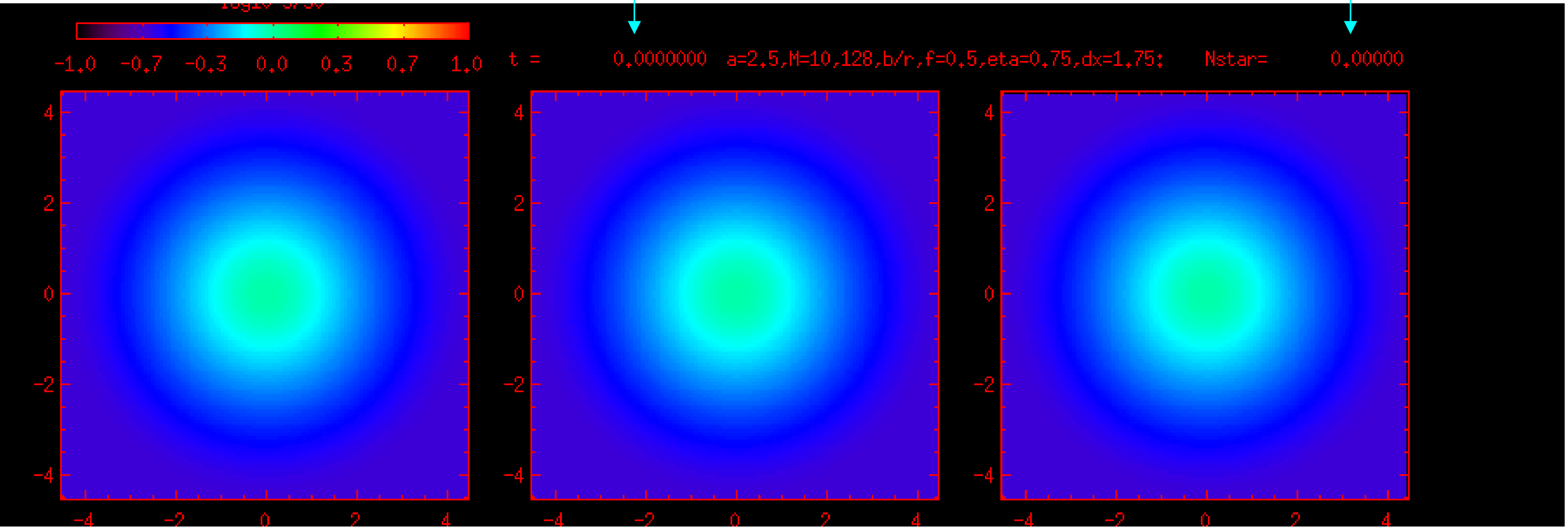
Column Density Movie of Clump Evolution



1.5 pc

$t_g = L_J/a = 0.6$ Myrs

number of stars



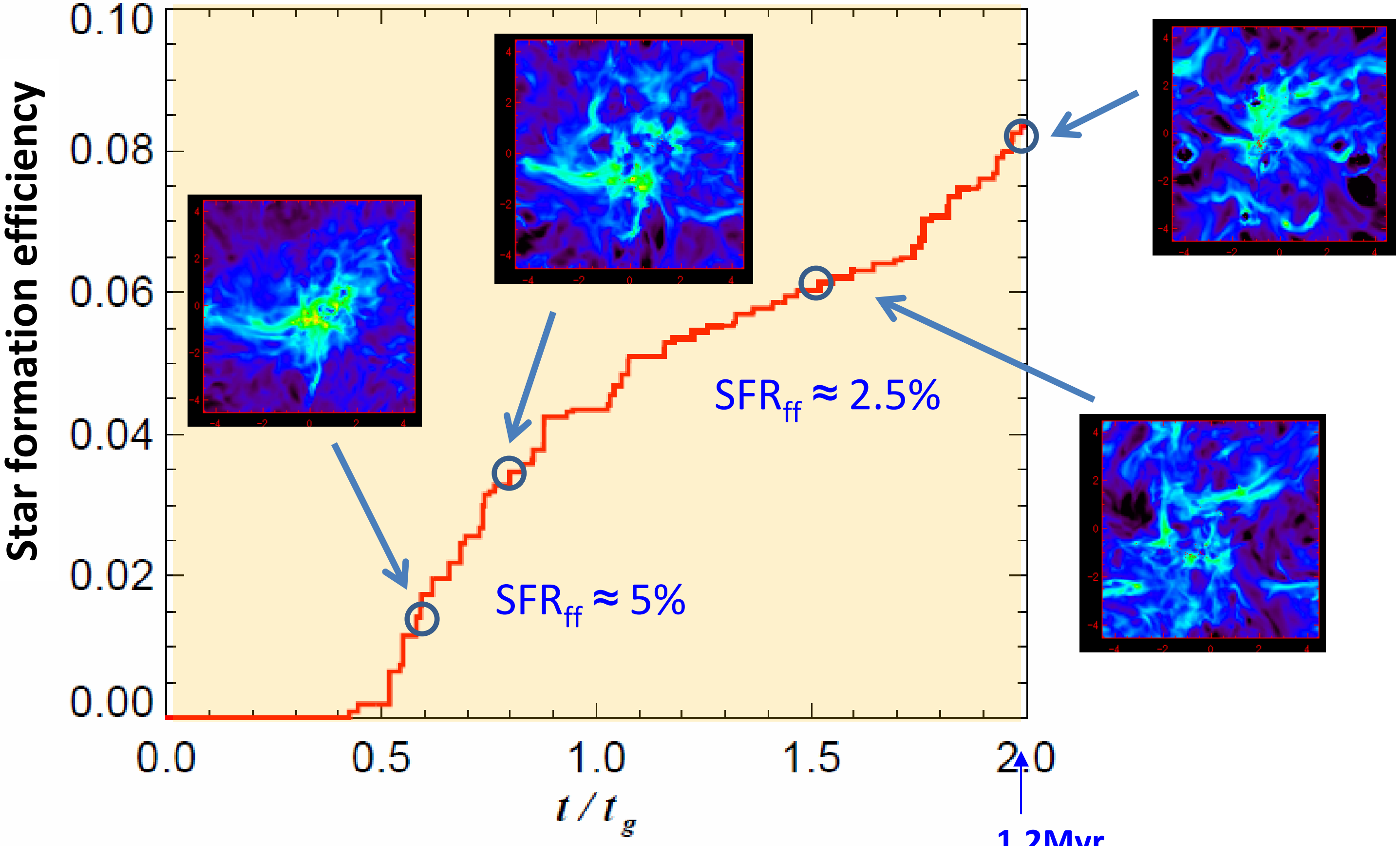
along x-axis (B field direction)

y-axis

z-axis (rotation axis)

- First star formed around t~0.4 t_g
- By t=1.5 t_g, 45 stars have formed, w/ star formation efficiency SFE ~ 6%

Evolution of Star Formation Efficiency



$SFR_{ff} \approx 5\%$

$SFR_{ff} \approx 2.5\%$

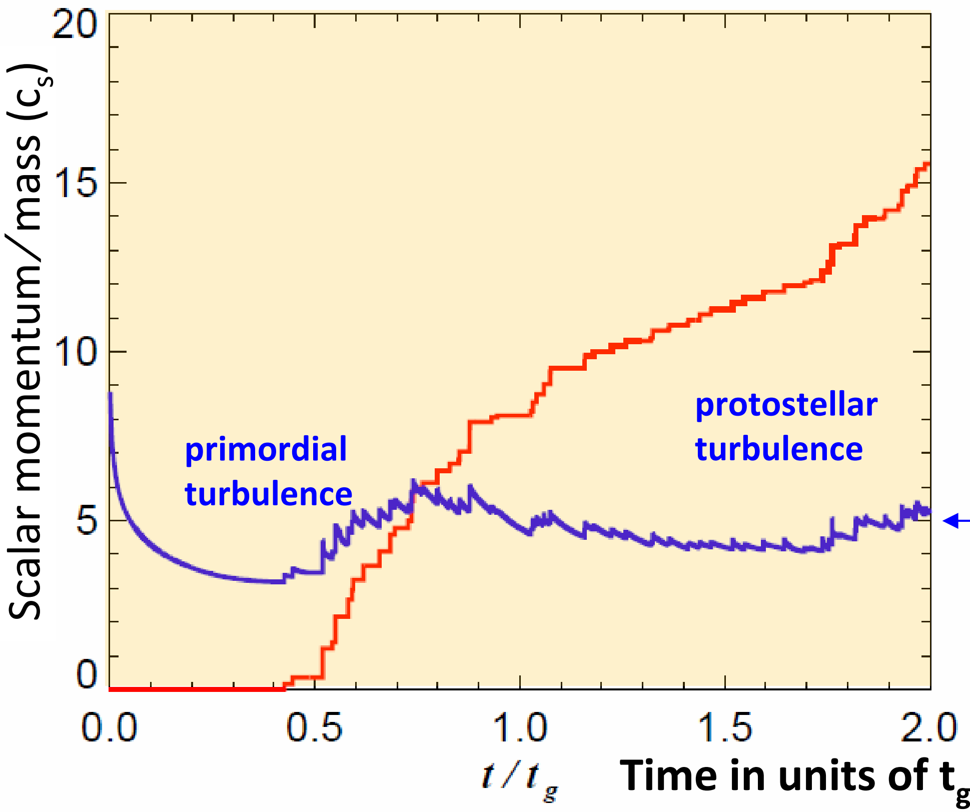
1.2Myr

Time in units of t_g=1.25t_{ff}= 0.6 Myrs

- About 8% of gas converted into stars in 1.6 t_g=2.1t_{ff}, yielding a rate

  $SFR_{ff} \approx 4$ % or depletion time ≈ 25 t_{ff}

Evolution of Scalar Momentum per unit Mass



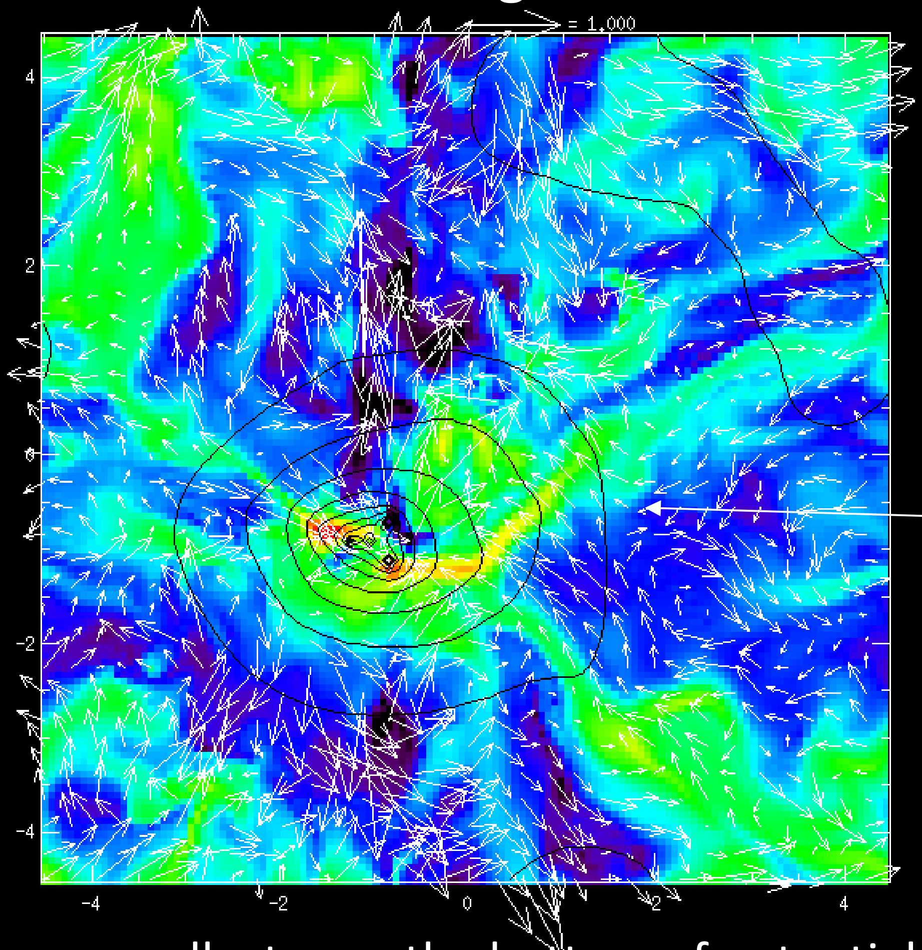
← 5 c_s=1.4 km/s

Time in units of t_g=1.25t_{ff}= 0.6 Myrs

- Initial turbulence decays quickly, controls first stars
- Majority of cluster members form in protostellar turbulence

protostellar turbulence more directly relevant to cluster formation

A Slice through Protostellar Turbulence



- Slices through the minimum of the gravitational potential

gravitational potential

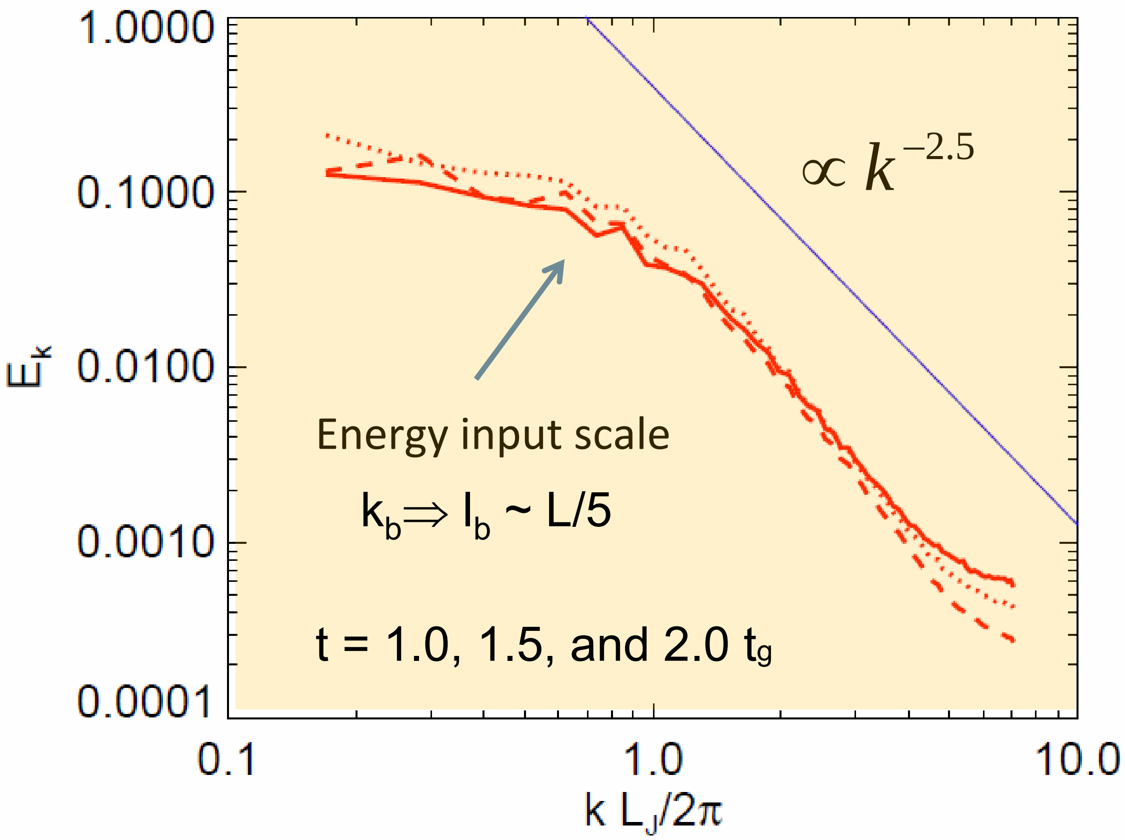
- Dense gas collect near the bottom of potential well, where most stars form
- Momentum injected into envelope, where most mass resides

  collimated outflows more efficient in supporting clump

- Gravity plays an important role, setting up a circulation of mass

  infall & outflow roughly balanced

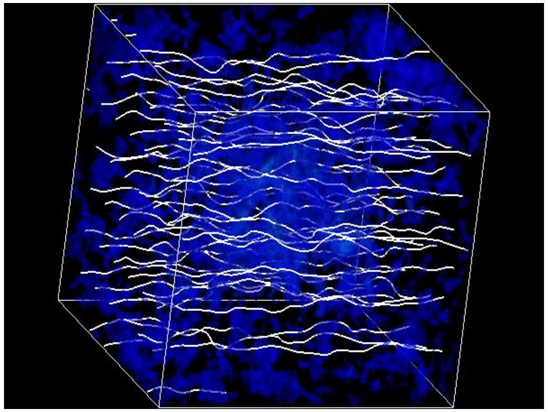
Power Spectrum of Protostellar Turbulence



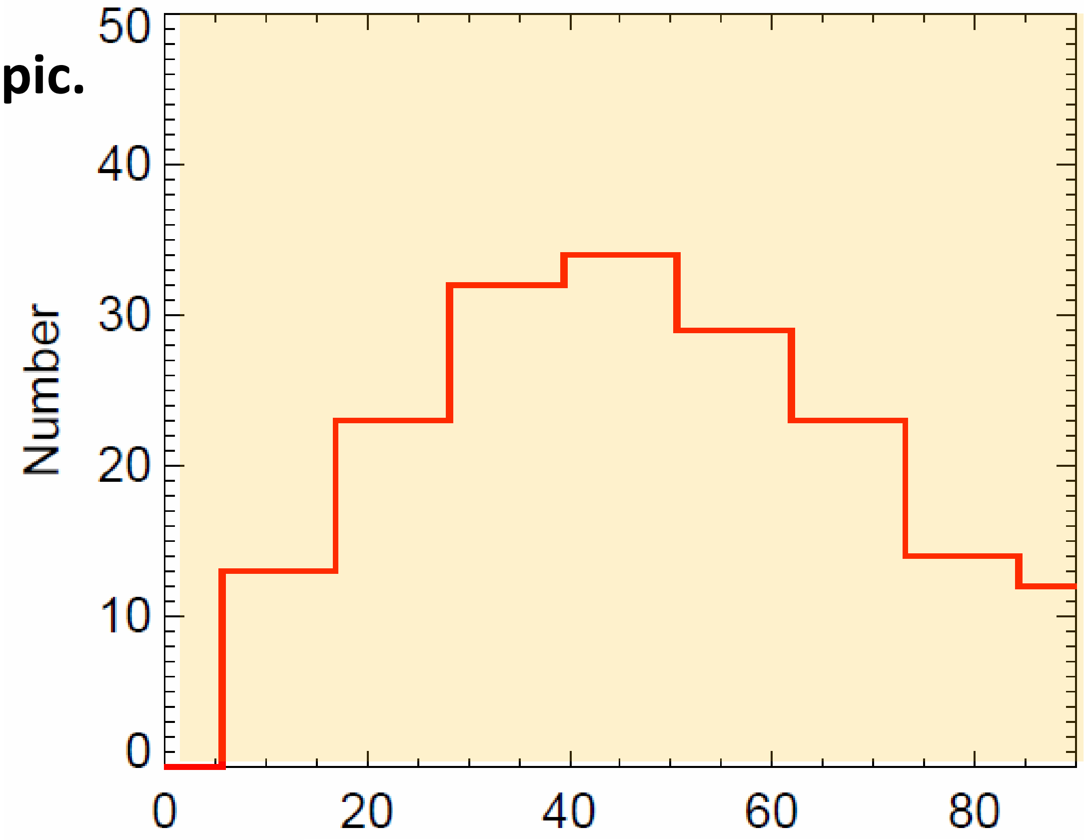
- Most power near the break
  characteristic scale ~ typical length of outflows (see also Matzner 2007)

Anisotropic Energy Input

Momentum input is anisotropic.

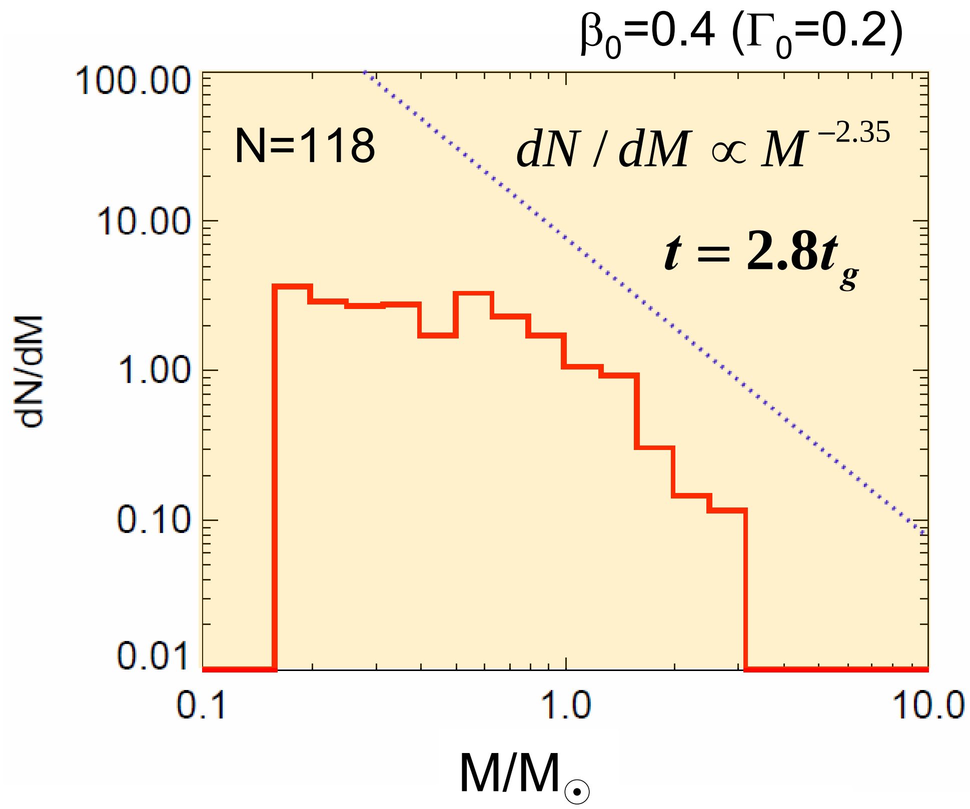


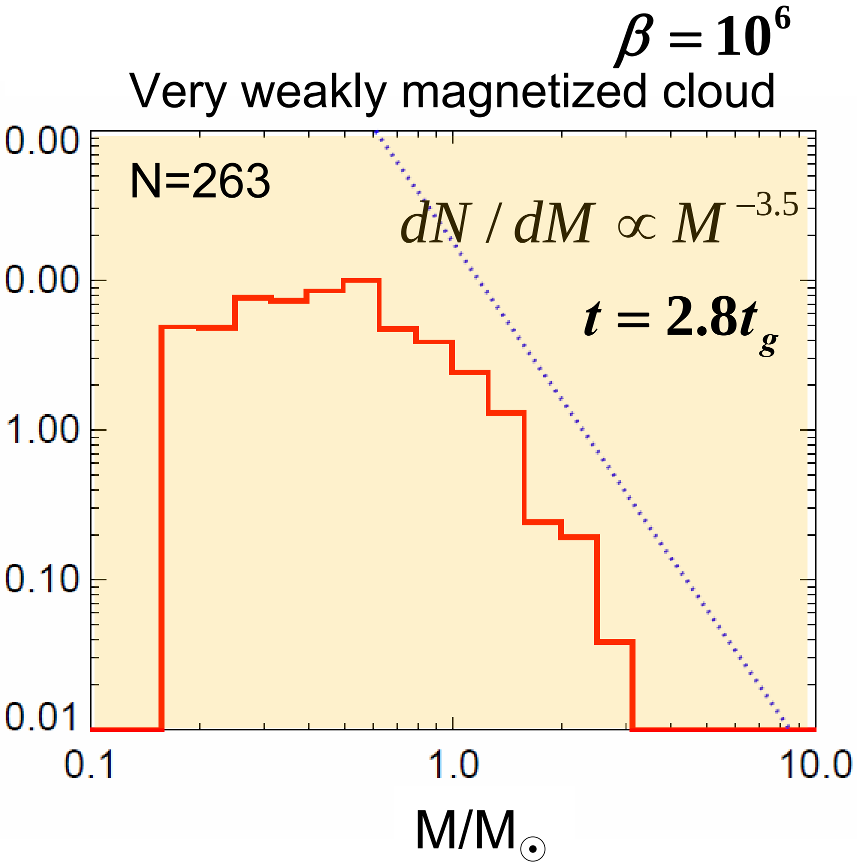
Number fraction of stars formed as a function of angle



Angle between outflow axis and initial magnetic field

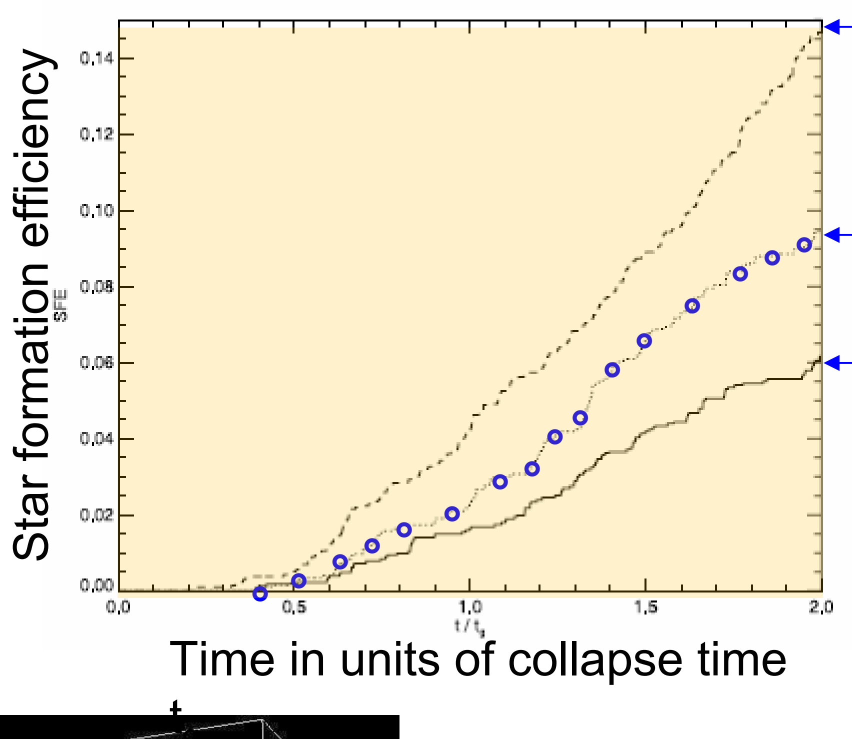
Initial Mass Function in Cluster Forming Clump





- The stellar IMF seems to be consistent with the Salpeter.
- For no magnetic field, the slope of the IMF tends to be steeper than the Salpeter.
- This trend appears to be consistent with the turbulent fragmentation model (Padoan & Nordlund 2000).

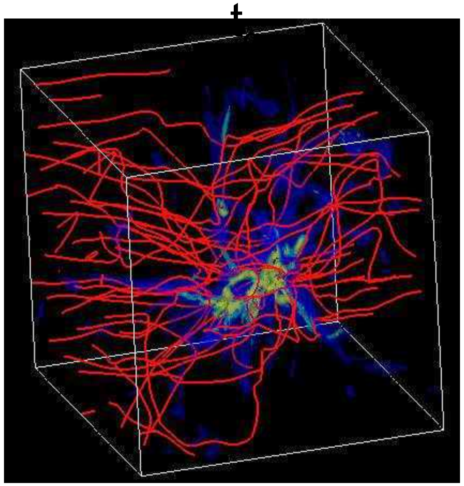
Role of Magnetic Fields in Cluster Formation



$\beta_0=10^6$, SFE ~ 15%

$\beta_0=2$, SFE ~ 9.5%

$\beta_0=0.4$ ($\Gamma_0=0.2$), SFE ~ 6%



- Moderately strong magnetic fields

slow down cluster formation by factor of a few

- Relatively weak magnetic fields

amplified to equipartition level

dynamically significant but secondary to outflows

Summary

1. Outflows of reasonable strength can replenish dissipated turbulence and keep the clump close to an equilibrium
2. Quasi-equilibrium maintained through low rate of star formation
3. Collimated outflows are more efficient for clump support (contrary to simplest expectation)
4. Prominent break in the velocity power spectrum
5. Energy and momentum injection is anisotropic
6. Majority of stars probably form in protostellar turbulence
7. Protostellar turbulence can reproduce the stellar IMF similar to Salpeter, in the presence of magnetic fields