Star Formation in Turbulent, Magnetized Clouds

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Properties of Molecular Clouds

- Supersonic turbulence

  molecular cloud is highly turbulent.

  linewidth δV is larger than Cs.

- Strong magnetic field

observed B field is close to a critical value.

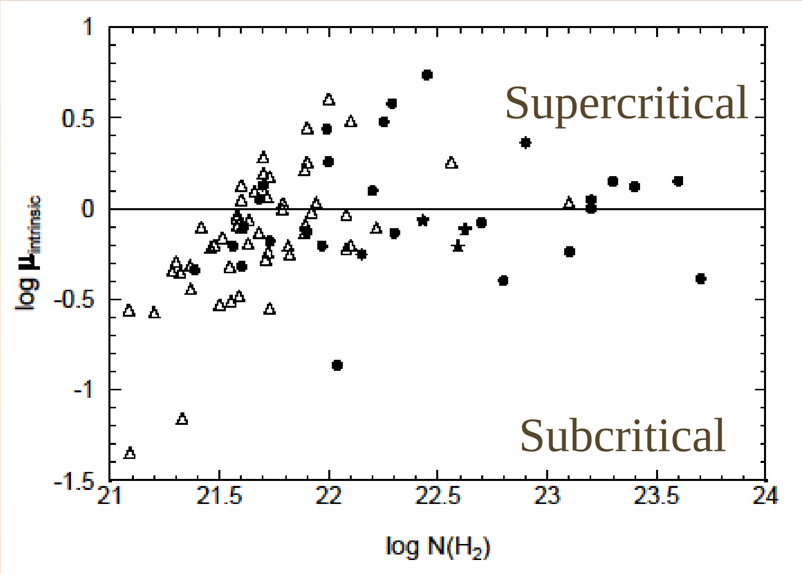
critical mass

$$M_{cr} = 0.13 \frac{\Phi}{G^{1/2}}, \quad \Phi = \text{magnetic flux}$$

supercritical vs. subcritical

$M > M_{cr}$ $\downarrow$ $M < M_{cr}$

quasi-static contraction due to ambipolar diffusion



Heiles & Crutcher 2002

1．Galactic Star Formation

Dispersed mode： low-mass stars Taurus

low SFE (a few %)

Magnetically-regulated model (ambipolar diffusion, inside-out) (Shu, Adams, Lizano 1987)

Turbulence-accelerated, magnetically regulated star formation (Li & Nakamura 2004; Nakamura & Li 2005)

Cluster mode： massive and low-mass stars Orion

high SFE (10-20%)

Strong supersonic turbulence

Strong magnetic field (Crutcher 2005)

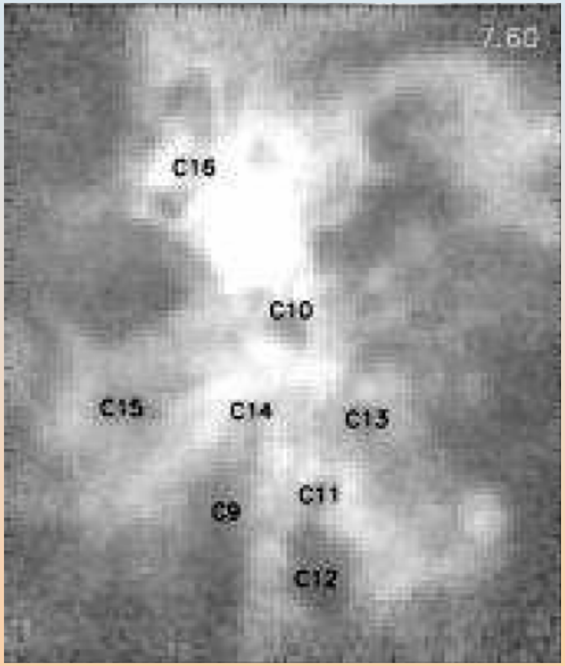
Feedback from young stars (Bally et al. 1999)

2．Turbulence simulations

- Observations of cluster forming regions

  Importance of protostellar outflows
  (Circinus complex Bally et al. 1999;
  NGC1333 Quillen et al. 2005;
  see also Norman & Silk 1980)

Effect of outflows
(NGC1333)



Quillen et al. (2005)

- HD Turbulent simulations

  (Klessen et al. 1998; Bate et al. 2003)

  Sink particle,
  but no protostellar outflows

- MHD Turbulent simulations

  Tilley & Pudritz 2005, Sugimoto & Hanawa 2004)

  prior to star formation

3. Our simulations

- Previous numerical simulations haven't taken into account the effect of stellar feedback.

- We include self-gravity, supersonic turbulence, magnetic field, and protostellar outflow.

3D MHD turbulent simulations

Questions

- What determines the efficiency of star formation?

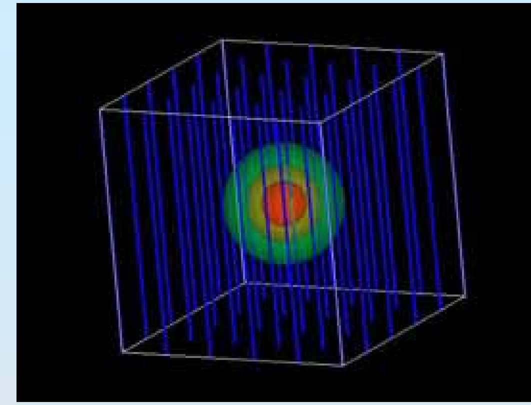
  magnetic field, protostellar outflow

- How is turbulence maintained in cluster forming clumps?

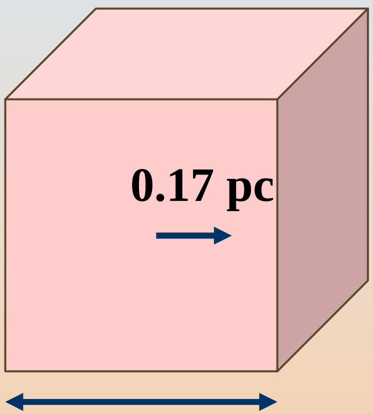
  protostellar outflow

4. Model

- Isothermal spherical cloud
- Uniform magnetic field (supercritical)
- Supersonic velocity field (Larson's law)



$$\left(E_k \propto k^{-n}\right)$$



$$n_{H2} = 6.1\times10^4 \left(\frac{T}{20K}\right)\left(\frac{0.11\mathrm{pc}}{L_J}\right) \ \mathrm{cm}^{-3}$$

$$L = 9L_J \approx 1 \left(\frac{L_J}{0.11\mathrm{pc}}\right) \ \mathrm{pc}$$

$$B_x = 71\,\alpha^{1/2}\left(\frac{T}{20K}\right)\left(\frac{0.11\mathrm{pc}}{L_J}\right) \ \mu\mathrm{G}$$

$$M = 626 M_\odot \left(\frac{T}{20K}\right)\left(\frac{L_J}{0.11\mathrm{pc}}\right)$$

$$B_x = 112\mu G \ \text{ for } \alpha = 2.5$$

1 pc = 9L_J
Effective radius = 1.5L_J
L_J= thermal Jeans length

- Star formation and protostelalr outflows

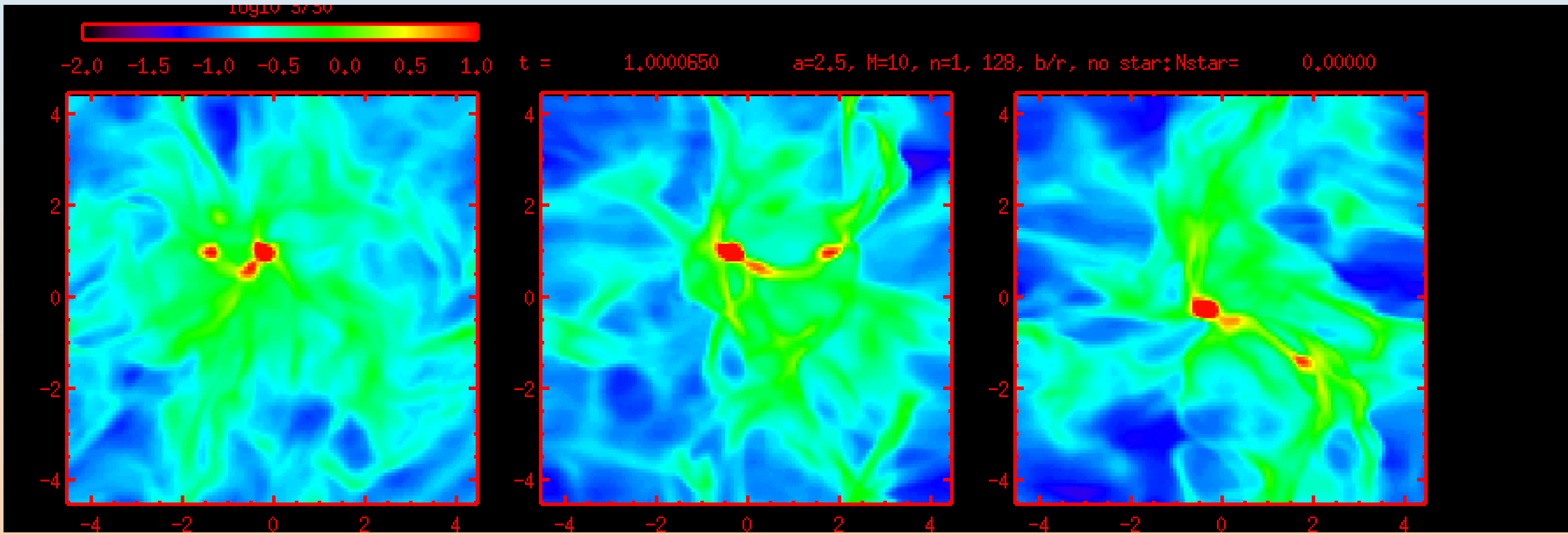
$$\rho_{cr} = 100\rho_0 \quad @128^3$$

5. Effect of Magnetic Field: No outflow

column density

- $\alpha = 2.5, M = 10$

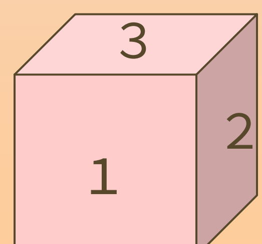
1 2 3



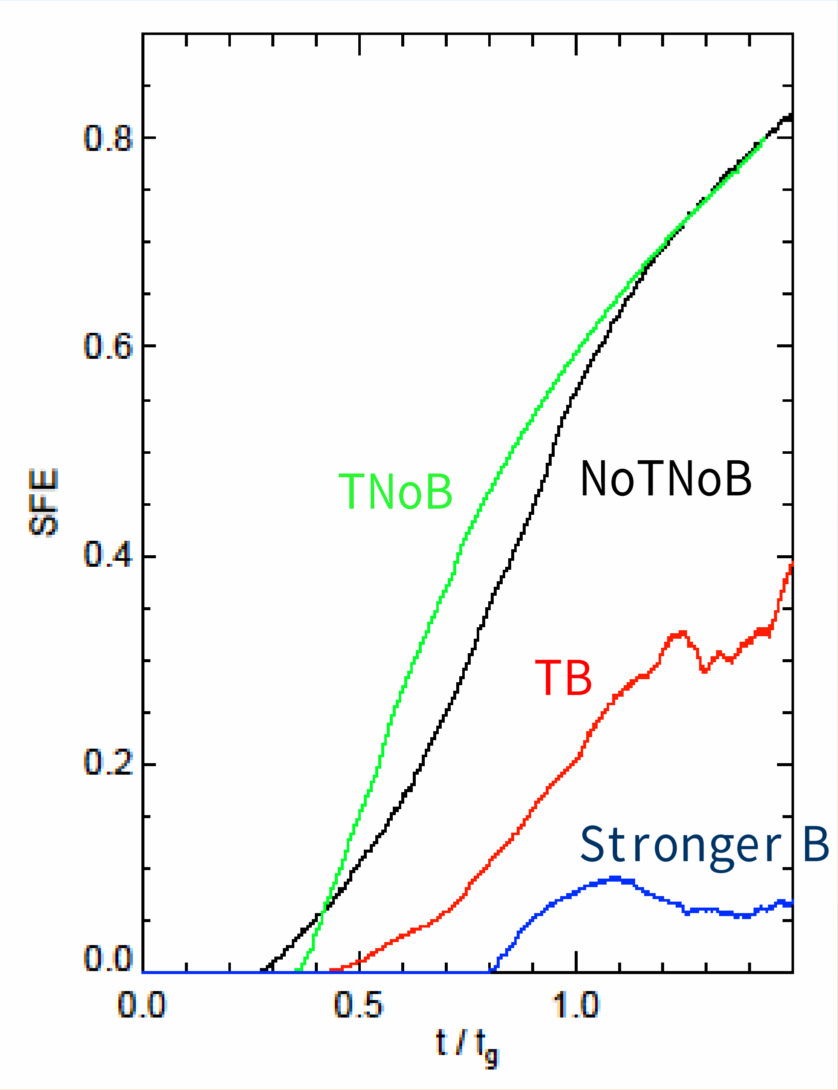
Direction of initial B field Direction of initial B field

$$n_{H2,0} = 6.1\times10^{4}\,\mathrm{cm}^{-3}, L = 0.99\ \mathrm{pc}$$

$$B_0 = 111\,\mu G,\ \ M = 626 M_{\odot},\ \ T = 20K$$



Star Formation Efficiency



- In the absence of magnetic field, the SFE becomes too high.
- Magnetic field can reduce the SFE.

$$SFE = \frac{M(\rho \geq \rho_{cr})}{M_{tot}}$$

$$\rho_{cr} = 100\rho_0$$

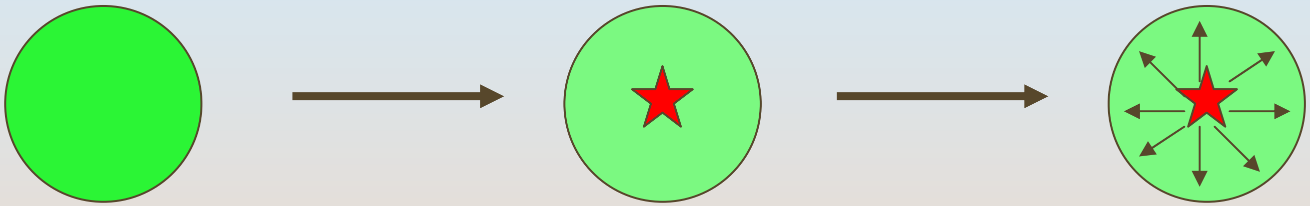
Summary 1

- The initial turbulence decays quickly. It is difficult to maintain supersonic turbulent motions.
- Magnetic field is needed to reduce the SFE that is consistent with observations (10 – 20 %).
- The cloud tends to collapse into a single dense core near the center.

6. Effect of Stellar Outflow

- **Creation of “stars”**

For $\rho > \rho_{cr} = 100\rho_0$ $\quad M_{star} = \varepsilon\, M_{core}$ $\qquad \varepsilon \approx 0.2$



- **Protostellar outflow**

(Matzner & McKee 2000; Nakamura & Li 2005)

$$P_{outflow} = \frac{M_W V_W}{M_{star}} = 100 f \ \mathrm{km\ s^{-1}}$$

f : outflow strength

★ Circinus complex f ∼ 0.3 (Bally et al. 1999)

★ L1551 IRS5 f = 0.23 ∼ 0.39

★ L1157 f ∼ 0.3

★ Matzner & McKee model f ∼ 0.4

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

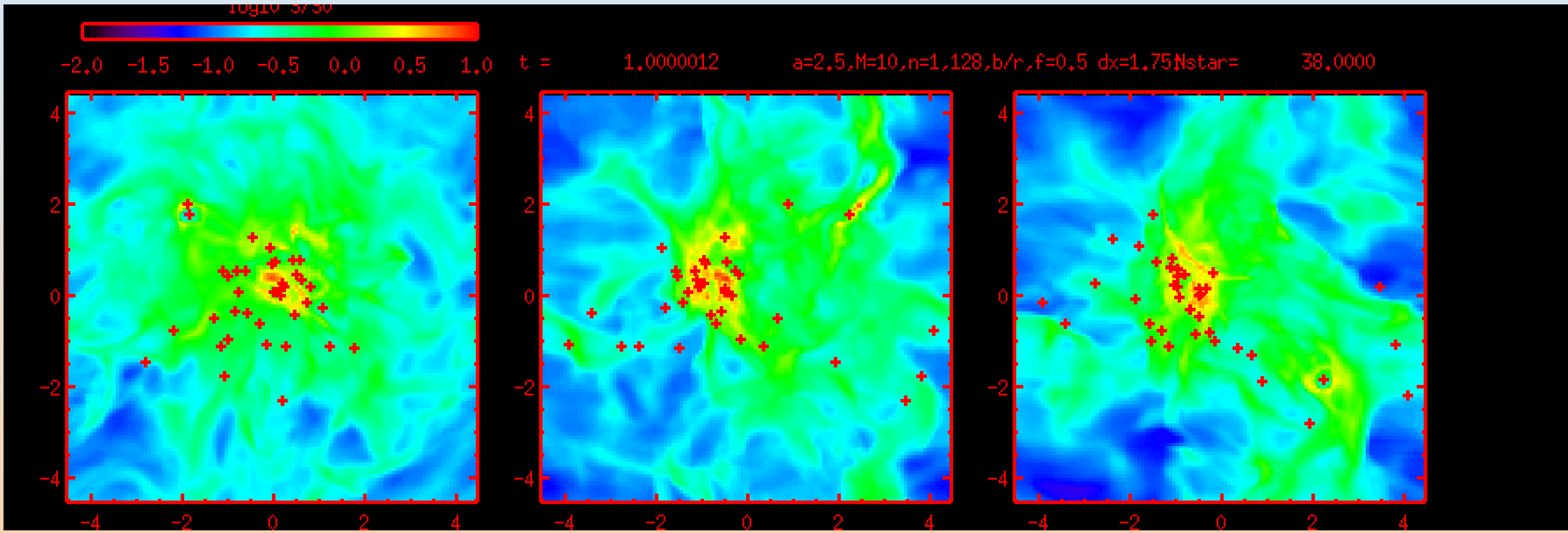
$$f \sim 0.3 - 0.4$$

Effect of Outflow

Column density

- $\alpha = 2.5, M = 10, f = 0.5$

1 2 3



Direction of initial B field Direction of initial B field

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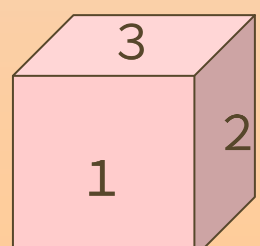
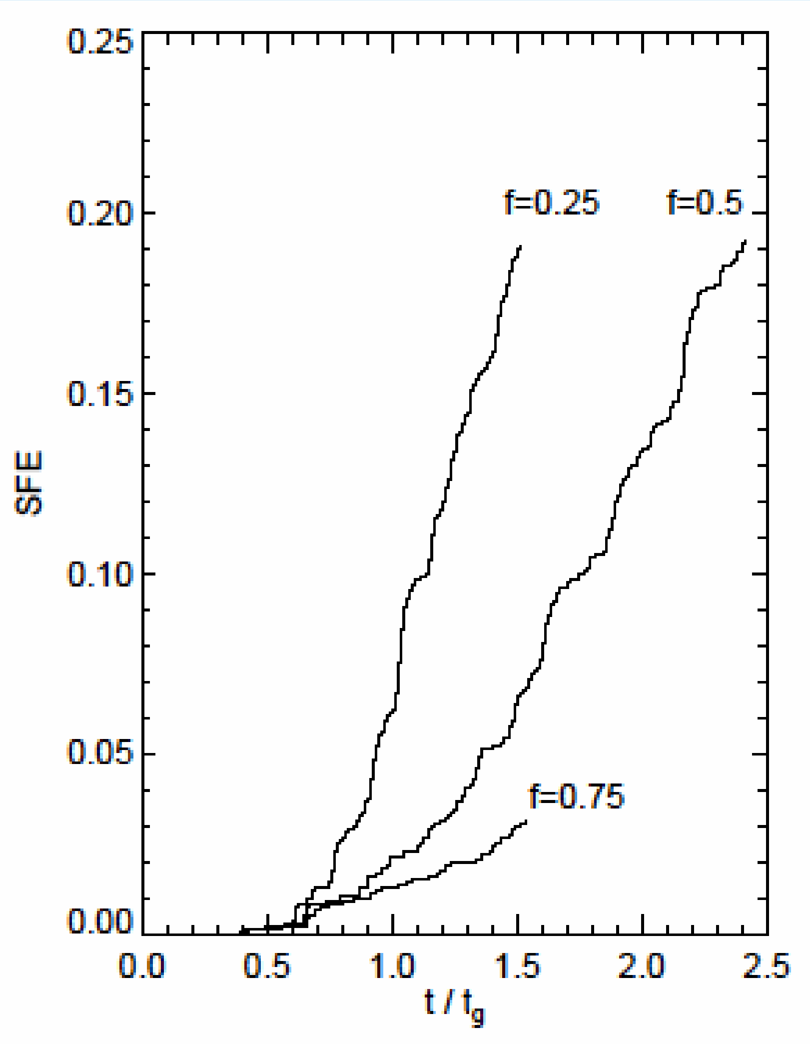
$B_0 = 111\ \mu G,\ \ M = 626 M_\odot,\ \ T = 20K$



$$P_{outflow} = \frac{M_W V_W}{M_{star}} = 100\,f\ \mathrm{km\ s^{-1}}$$

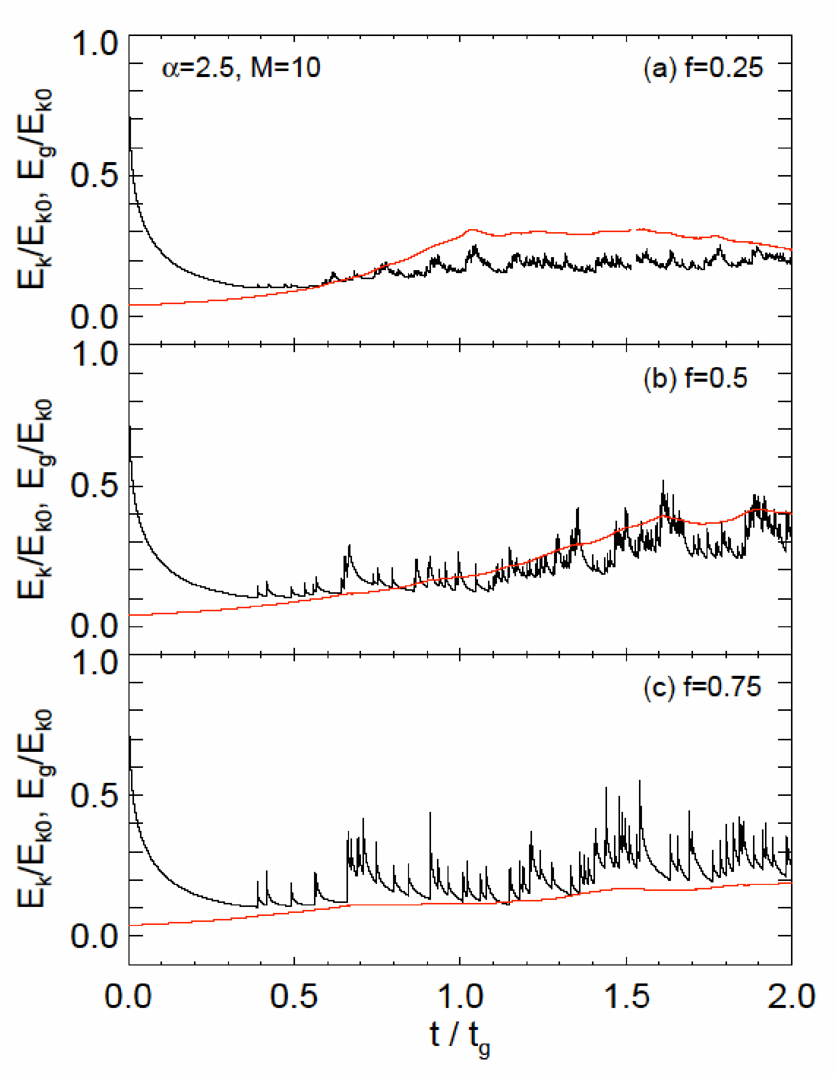
Star Formation Efficiency



- Outflow regulates SFEs.

$$P_{outflow} = \frac{M_W V_W}{M_{star}} = 100 f \ \mathrm{km\ s^{-1}}$$

7. Turbulence Generation



- Initial turbulence decays quickly.
- Outflows can generate and maintain turbulence at a level of Mach 5 (1 – 1.5 km s^{-1}).

8. Summary

- Both magnetic field and protostellar outflow are important in regulating star formation in cluster forming regions.

- Turbulence can be generated and maintained by protostellar outflows.
- The core mass function (the stellar IMF) may be determined by stars themselves through protostellar outflows, instead of initial turbulent field.

Padoan & Nordland (2002)