Outflow Feedback in Cluster Formation

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1. Observational motivation

    distributed vs clustered star formation

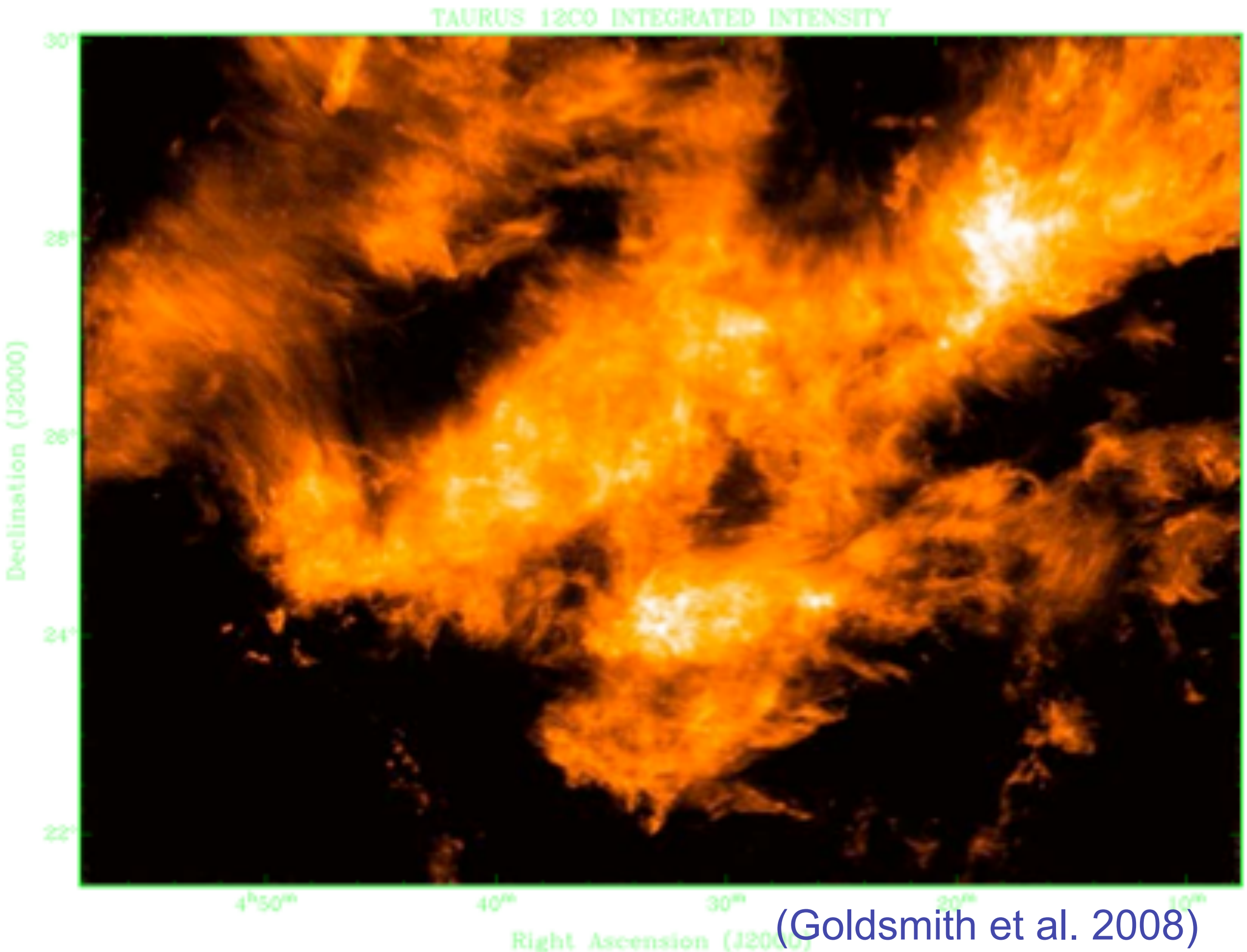
2. MHD simulations of cluster formation

    outflow-regulated star formation in dense clumps

3. Possible connection to massive star formation

1. Distributed vs Clustered Star Formation

distributed mode

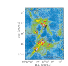


(Goldsmith et al. 2008)

30 pc

Taurus: ~$10^4 M_\odot$, ~200 stars, ~1% efficiency

clustered mode



NGC1333

~1pc

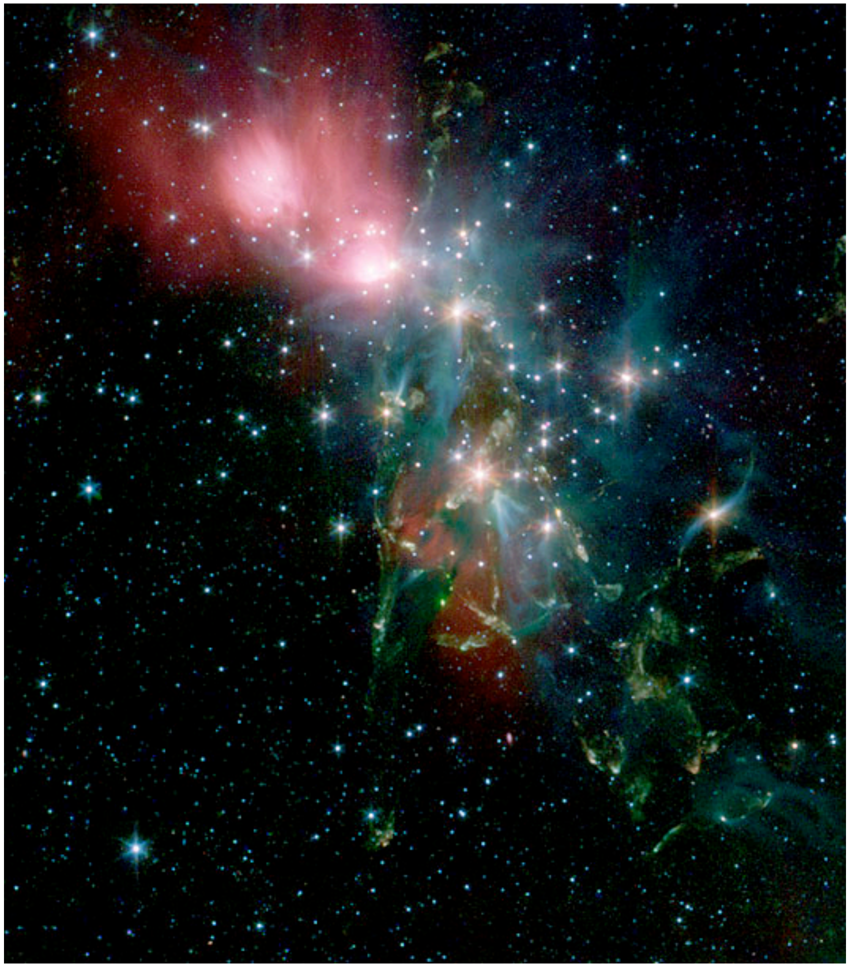
~$10^3 M_\odot$

~150 stars

~10% efficiency

Majority of stars form in clusters
(Lada & Lada 03, Allen et al. 07)

NGC 1333 Cluster-Forming Region by Spitzer



Gutermuth et al.

- Key ingredient

  outflows in close quarters
  interaction and feedback

- Outflow-driven turbulence?

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

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

  $\sim 5\mathrm{km/s}\ (\mathrm{SFE}/0.1)\ (P_*/50\mathrm{km/s})$

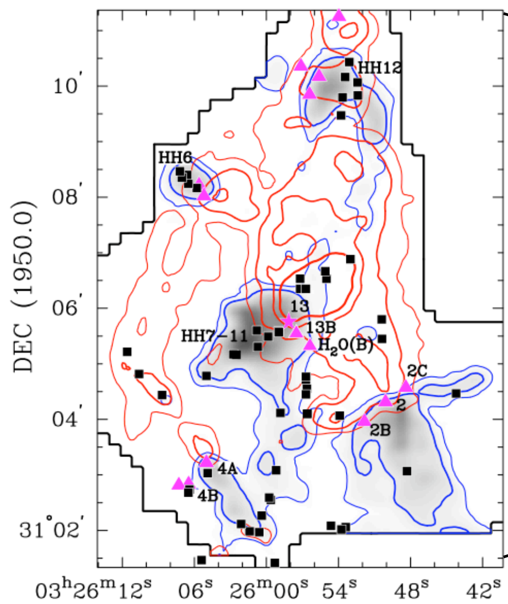
  $> 1\text{-}2\mathrm{km/s}$

- Multiple generations of stars?

  prestellar cores, Class 0-III objects

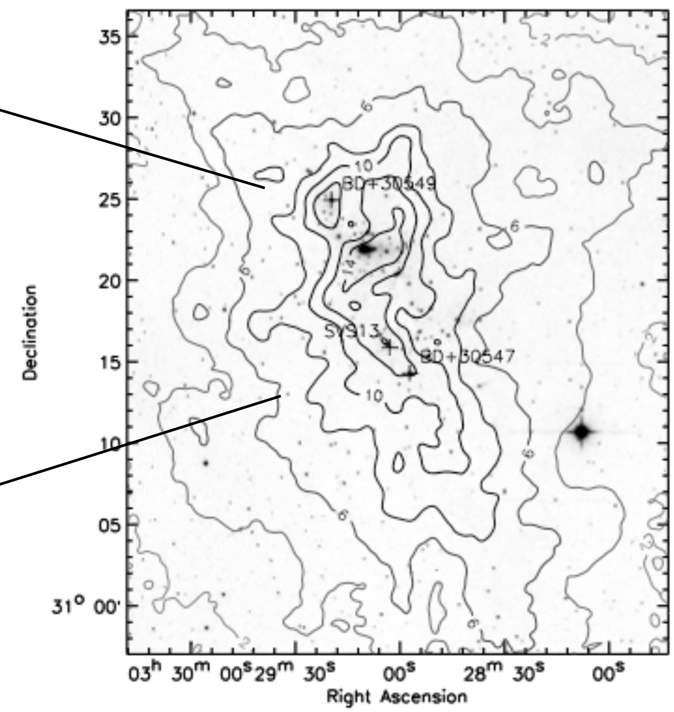
NGC 1333 Cluster-Forming Region in CO

multiple bipolar outflows



(Knee & Sandell 2000)

core + envelope



(Ridge et al. 2003)

2. Cluster Formation in Parsec-Scale Dense Clumps: Global Issues

1. Can outflows keep cluster-forming clumps near a quasi-equilibrium?

   (Tan et al. 2006)

2. What is the rate of star formation in clusters?

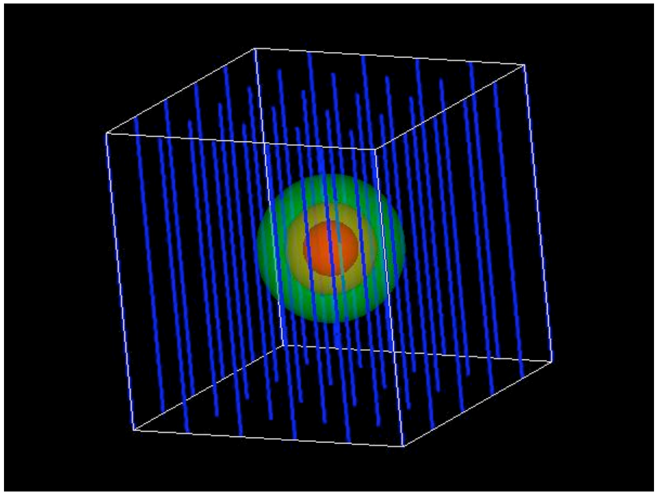
   star formation efficiency per free fall time (Krumholz & McKee 2005)

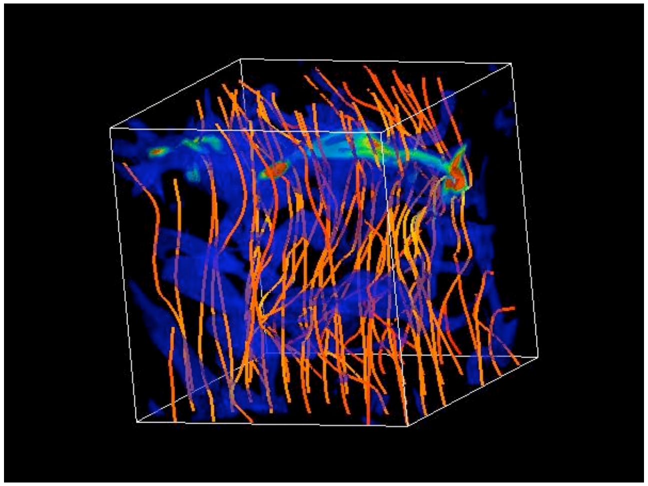
   SFR_{ff}~1-5% for NGC 1333 (see also Krumholz & Tan 2007)

3. What distinguishes protostellar (outflow-driven) turbulence?

Numerical Simulation Setup

(Li & Nakamura 2006, Nakamura & Li 2007, see also Mac Low 2000)





- Initially centrally condensed density distribution (center-to-edge contrast=10)
- Box size $L=9L_J$, plateau size $3L_J$, periodic boundary conditions
- Uniform B field - flux-to-mass ratio Γ=0.2 at center, 0.6 on average

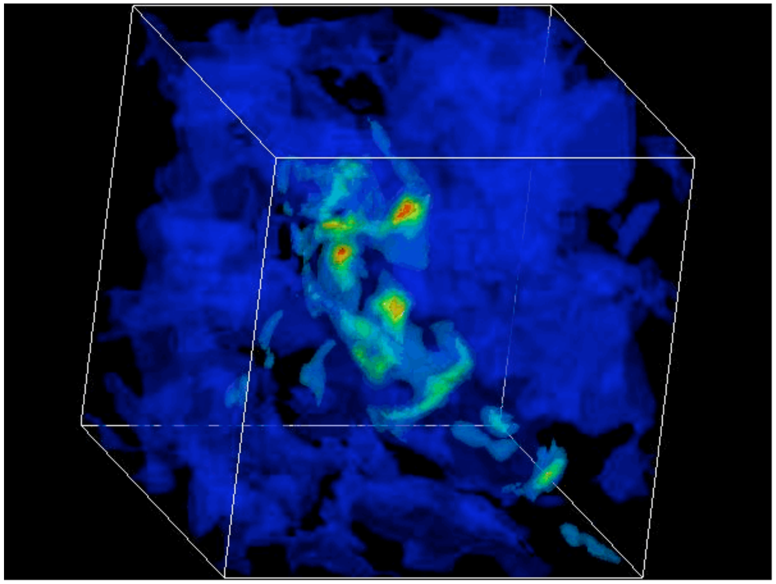
for T=20K (a=0.27km/s), L=1.5pc, max number density $2.7 \times 10^4 cm^{-3}$, total mass $939 M_\odot$

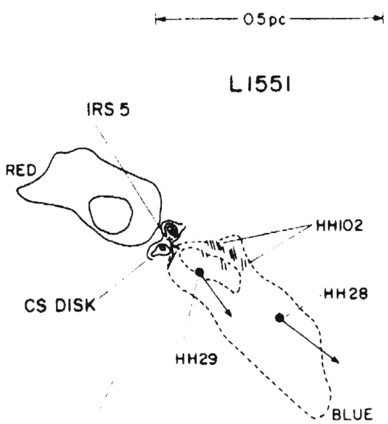
time unit $t_g = L_J/a$=0.6 Myr = 3.3 free-fall times at center = 1.25 ff times at average ρ

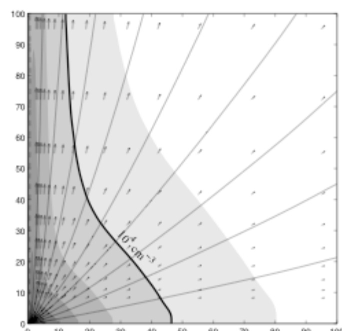
magnetic field strength = 75 μG

- Moderate rotation with axis perpendicular to field lines
- Stirred at t=0 by supersonic turbulence of rms Mach10 ($v^2_k \propto k^{-3}$)

Prescriptions for Star Formation and Outflows







(Krasnopolsky et al. 2003)

- Stellar mass

  a). probably determined by accretion and outflow

  (Matzner & McKee 2000, Shu et al. 2004)

  b). prescription - once peak density of a core exceeds $100\rho_0$~700 ρ_{av}, extract 20% mass from "inner core" and put in a "star"

  $M_\star \sim 0.5 M_\odot$

  c). Remaining material ejected in an outflow

- Outflow prescription

  a). $P_\star$ ~ 10 - 100 km/s estimated

  b). $P_\star$=50 km/s chosen (Matzner & McKee 2000)

  c). collimated momentum injection

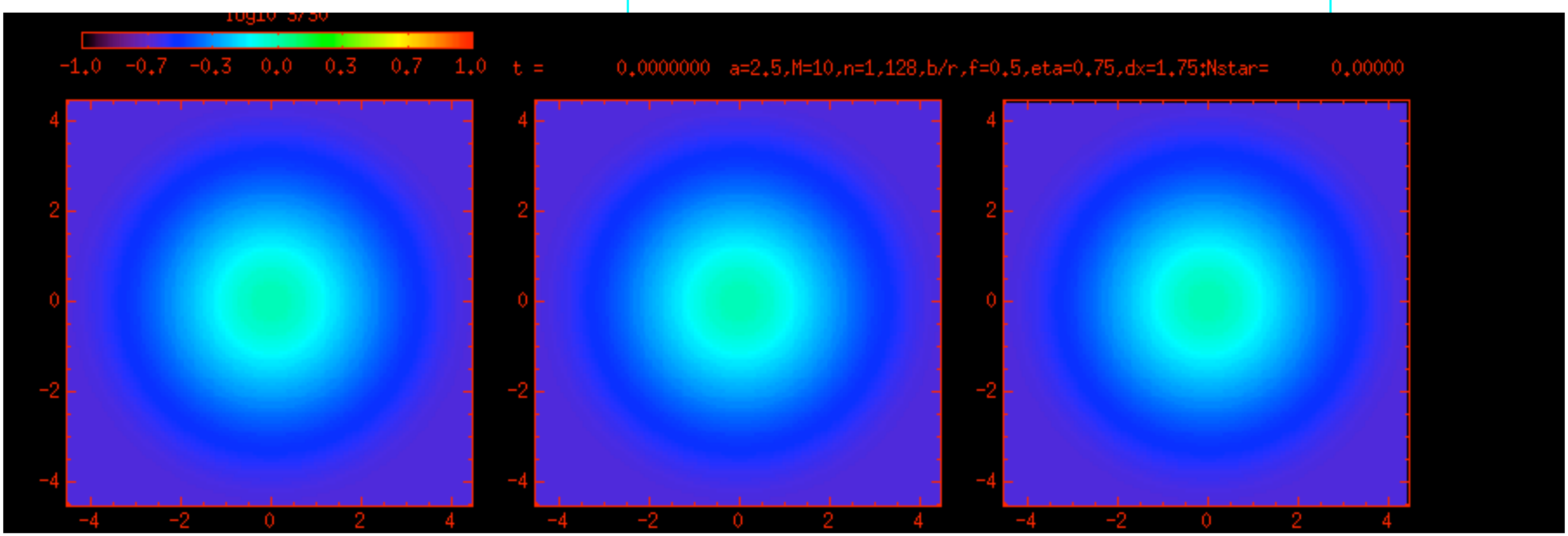
  75% momentum in 30° "jets"

  rest in spherical component

Column Density Movie of Clump Evolution

$t_g = L_J/a = 0.6$ Myrs

number of stars



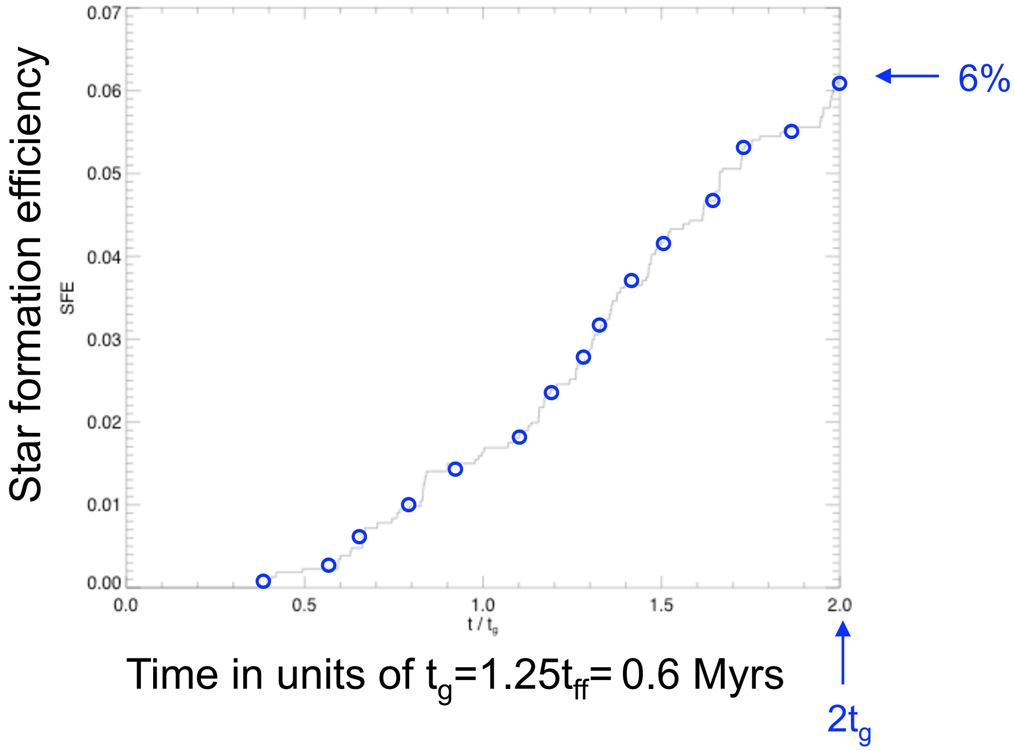
along x-axis (B field direction)

y-axis

z-axis (rotation axis)

- First star formed around $t \sim 0.4\ t_g$
- By $t=1.5\ t_g$, 80 stars have formed, with a star formation efficiency SFE ~ 4%

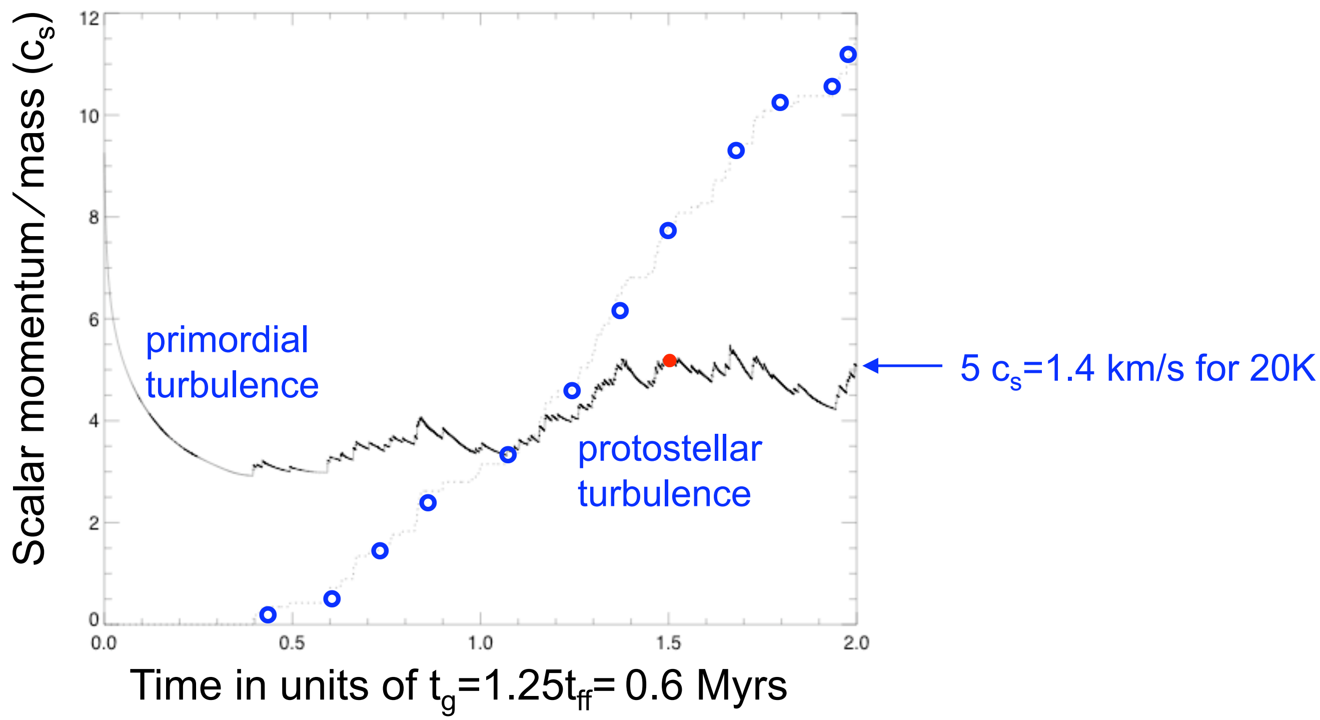
Evolution of Star Formation Efficiency



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

• About 6% of gas converted into stars in 1.6 t_g=2 t_{ff}, yielding a rate SFR_{ff} ≈ 3% or depletion time ≈ 33 t_{ff}

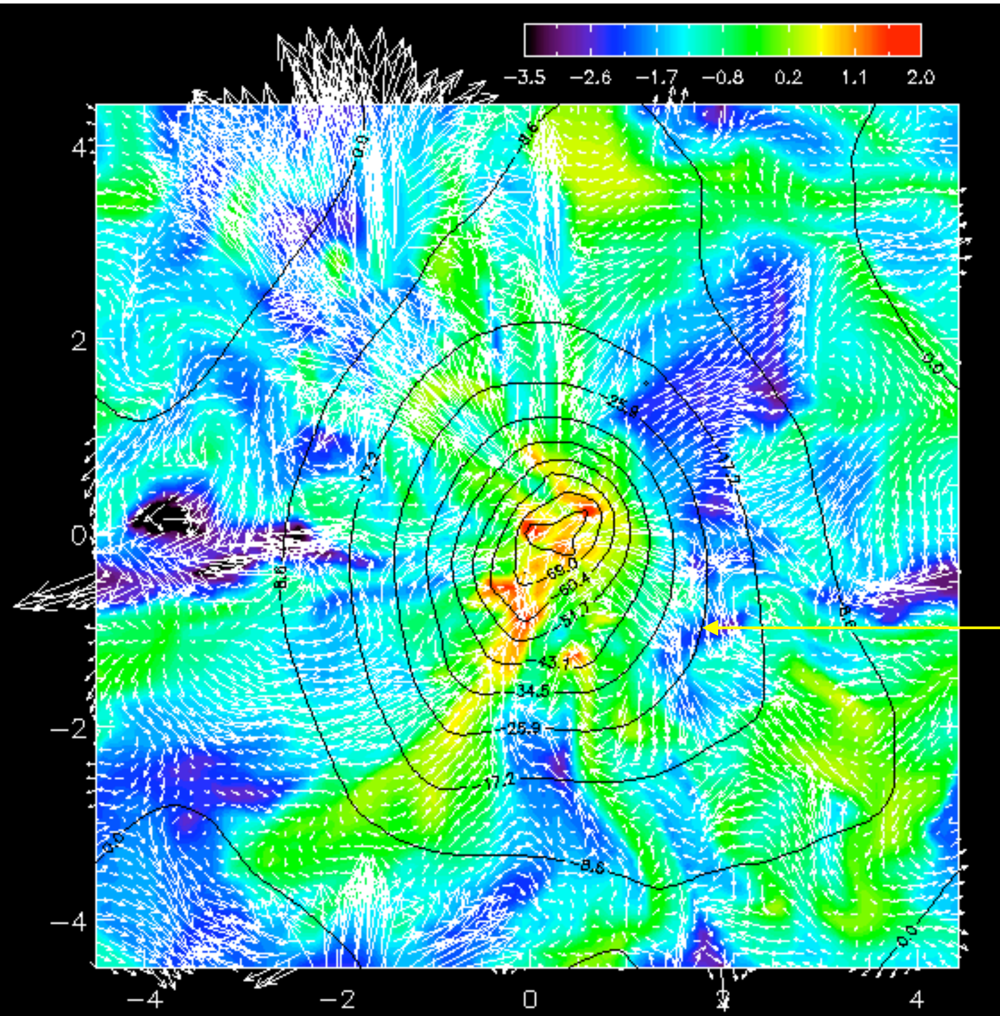
Evolution of Scalar Momentum per unit Mass



1. Initial turbulence decays quickly, controls first stars
2. Majority of cluster members form in protostellar turbulence

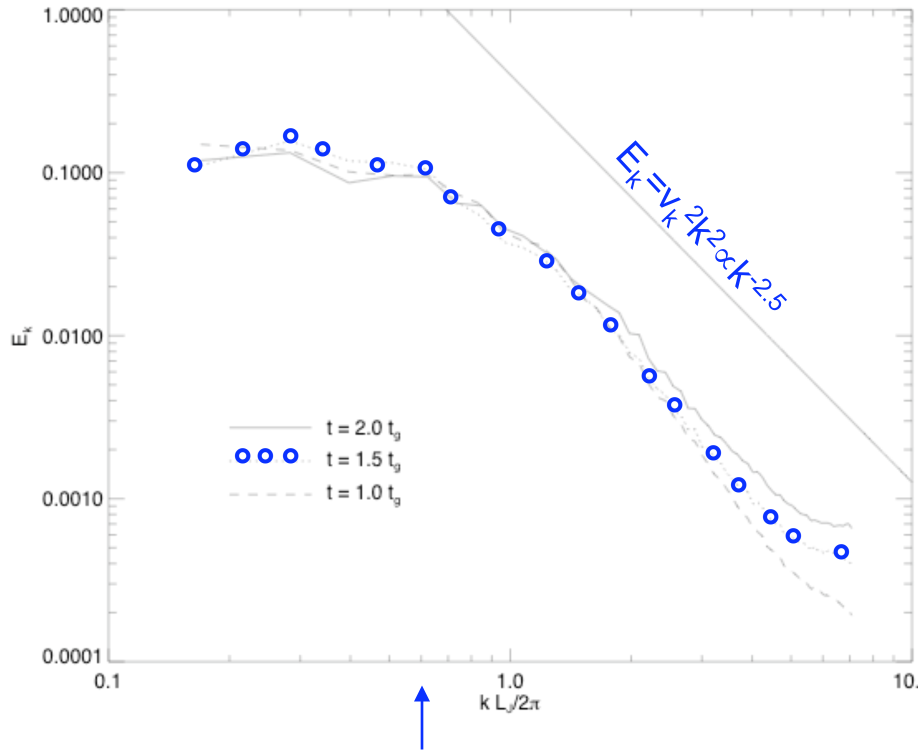
protostellar turbulence more directly relevant to cluster formation

3. Turbulence replenishment timescale ~ 1 t_{ff}



- Dense cores 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⇒quasi-equilibrium of slow star formation

Velocity Power Spectrum of Protostellar Outflow



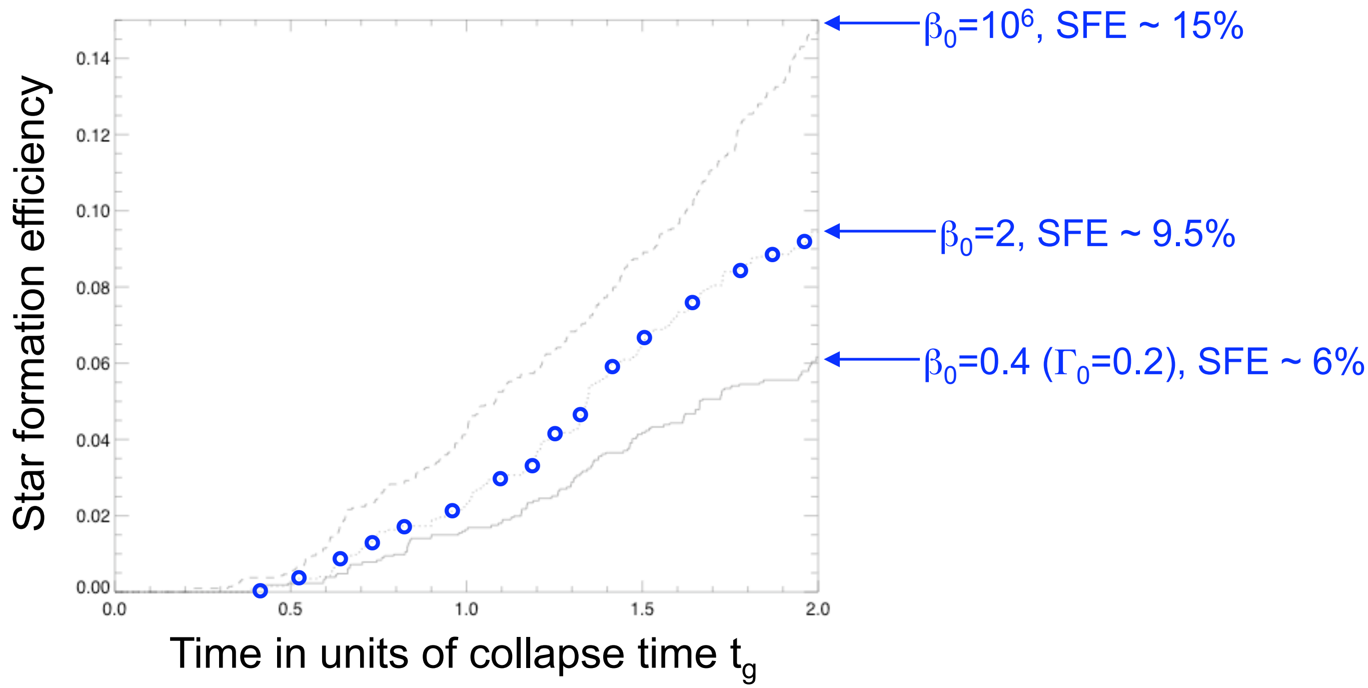
$k_b \Rightarrow \ell_b \sim L/5$

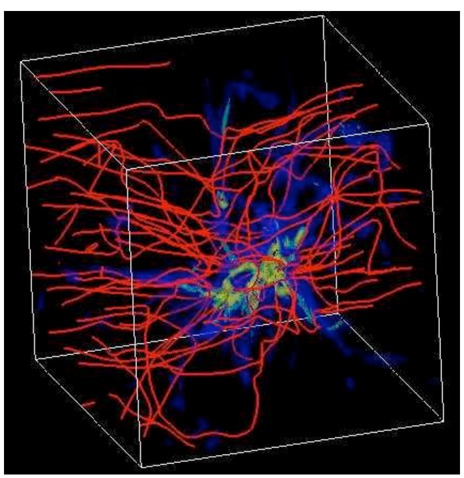
- Most power near the break

  characteristic scale ~ typical length of outflows (see also Matzner 2007)
- Implication:

power-law linewidth-size relation not strictly applicable inside cluster-forming clump

Role of Magnetic Fields in Cluster Formation





- 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

Conclusions

1. Outflows of reasonable strength can replenish dissipated turbulence

   & keep the clump close to an equilibrium (see also Matzner & McKee 2000)

2. Quasi-equilibrium maintained through low rate of star formation

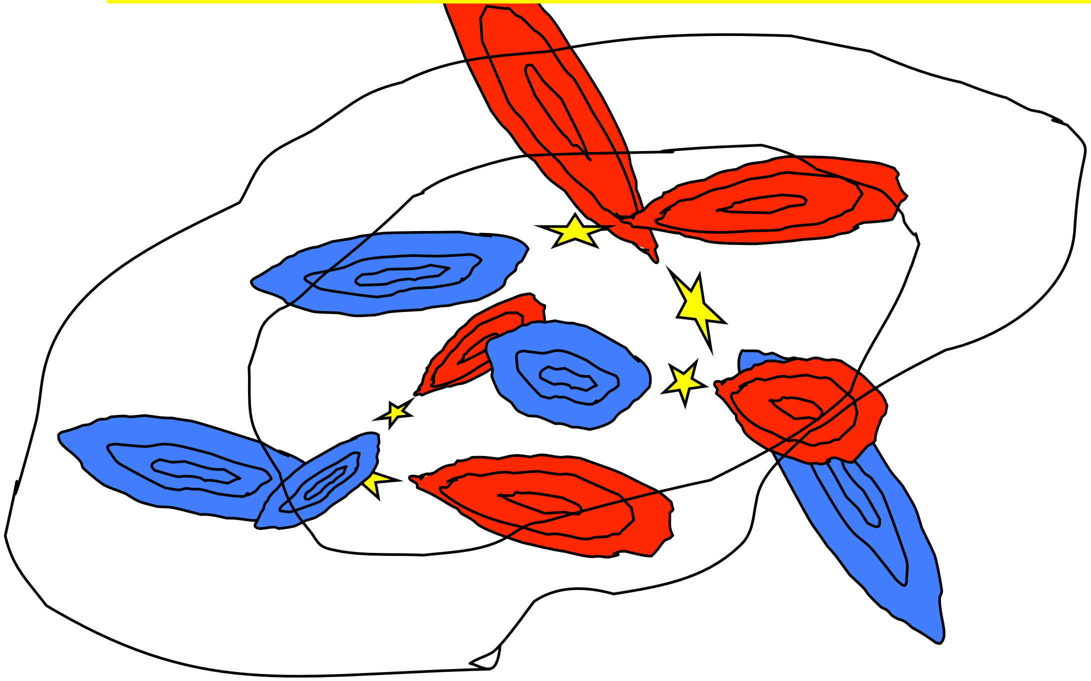
3. Collimated outflows are more efficient for clump support

4. Prominent break in the velocity power spectrum

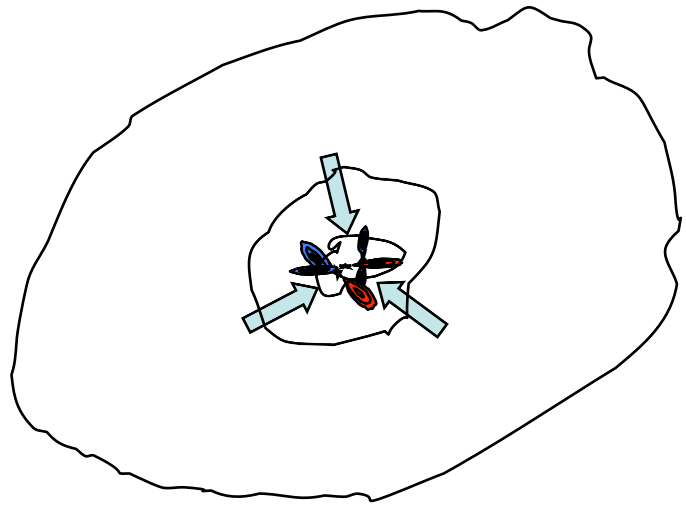
5. Majority of stars may form in protostellar turbulence

Systematic studies of outflows essential (e.g., Bontemps et al. 96, Shepherd & Churchwell 96)

3. Speculation on Protostellar Turbulence and Massive Star Formation



Easier to support at early times, with shallow potential well & large outflows



Clump condensation leads to outflow trapping, cutting off feedback into envelope, triggering rapid collapse? McKee-Tan core on the fly?

Failure of outflow feedback leads to global collapse and massive star formation??