Protostellar Outflows and Turbulence:

The Case for "Internal Driving"

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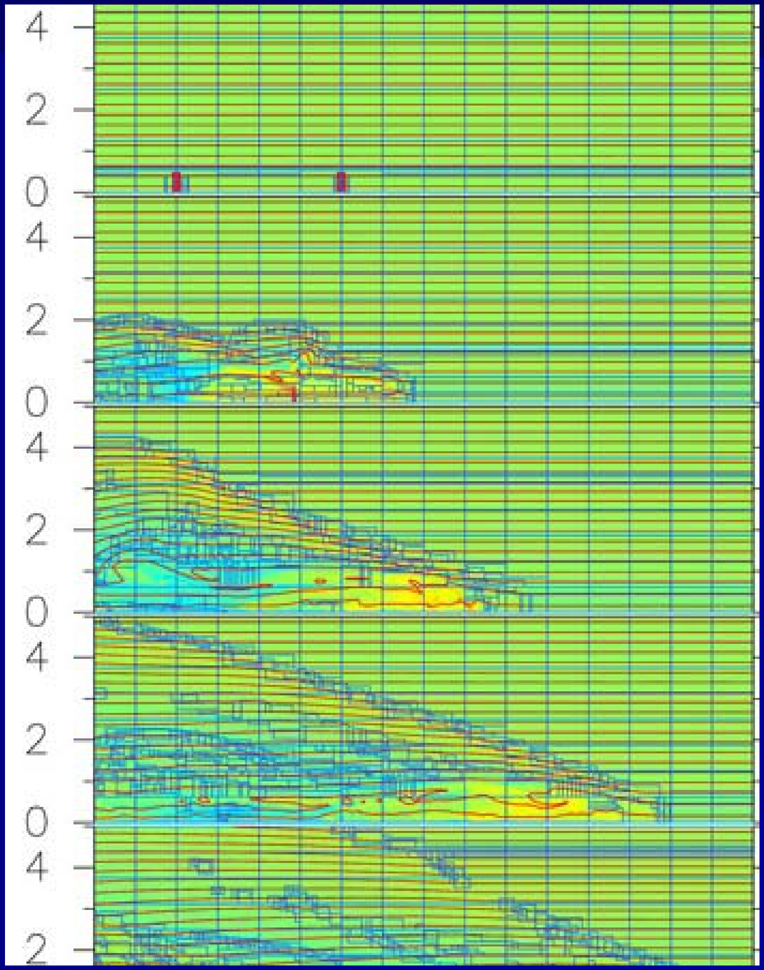
AstroBEAR MHD-AMR Code

Cunningham et al 2008

- Set of Riemann solvers: CTU Method (Gardiner & Stone)
- MHD divergence preserving: CT method.
- MHD DivB = 0 Prolongation-restriction.
- Built-in physics modules:
  - Time-dependent Ionization and H_2Chemistry
  - Real EOS
  - Elliptic Multi-grid solver (diffusion, self-gravity etc)
- Parallel – load balance and domain decomposition



Colliding MHD Clumps: Dennis et al 2008

Feedback Scales

- Microscopic = launch region

  L < 100 AU

- Mesoscopic = Individual outflow

  L < .1 pc

- Macroscopic = Cluster/pc-scale flow

  L > 1 pc

Turbulence and Molecular Clouds: 2 Issues

1. Star Formation Efficiency is low (0.1)

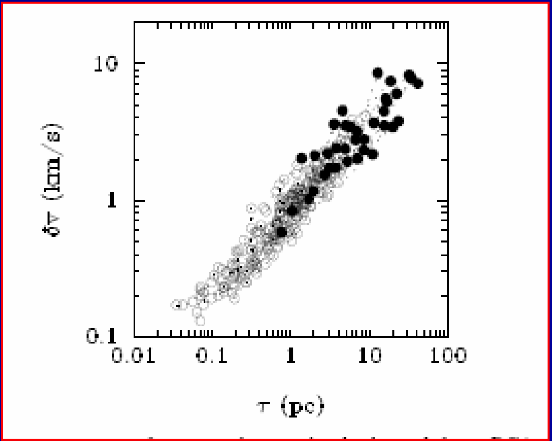
$$SFE = \frac{\dot{M}_* t_{ff}}{M_{cloud}}$$

2. Cloud Lifetimes
   – Clouds are long lived ($t_{cloud} > t_{ff}$)
   – Clouds are short lived ($t_{cloud} \sim t_{ff}$)

- Clouds are Turbulent (Larson's Law)

$$\boxed{\sigma = 0.7 R^{0.5} km / s}$$

   – Turbulence determines SFE
   – If $t_{cloud} > t_{ff}$ then turbulent support.



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What is Turbulence?

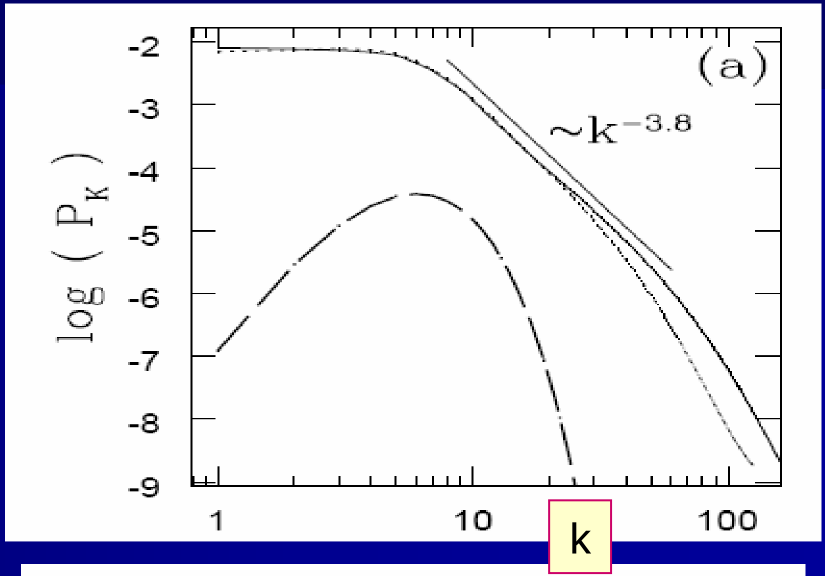
- Random but statistically steady motions.

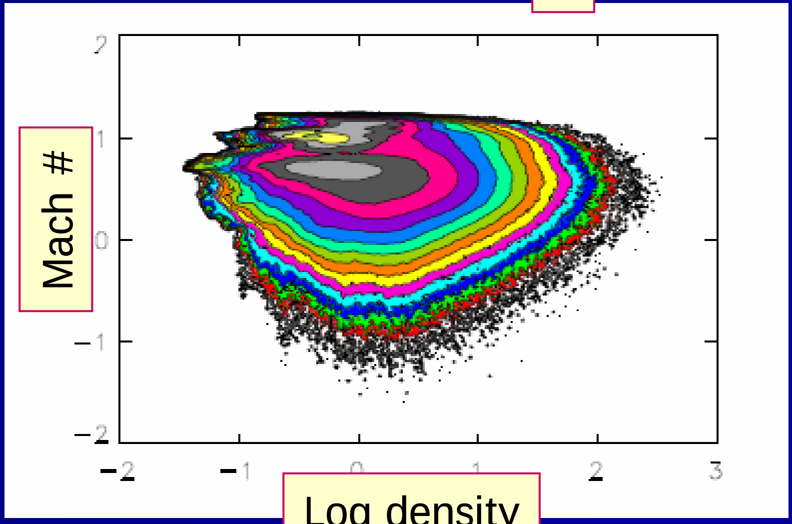
$$E(k) = |v(k)|^2 \propto k^{-n}$$

  - Kolmolgorov n= 5/3
  - Burgers n = 2
- Lognormal Density distribution

$$p(\ln\rho)d\ln\rho = \frac{1}{\sqrt{2\pi\sigma^2}} \times \exp\left[-\frac{1}{2}\left(\frac{\ln\rho - \overline{\ln\rho}}{\sigma}\right)^2\right] d\ln\rho,$$

Vestuto et al 03





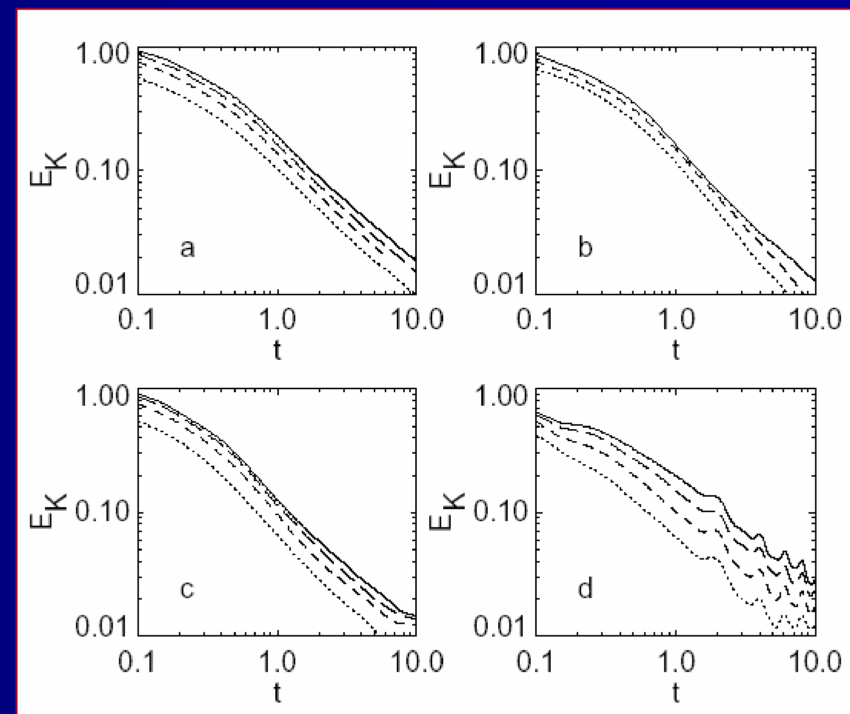
Krutsuk et al 07

The Problem: Turbulent Decay is fast

$$t_{diss} = \frac{E_{turb}}{\dot{E}_{turb}} = 0.5\frac{R}{\sigma}$$

McKee & Ostriker 07

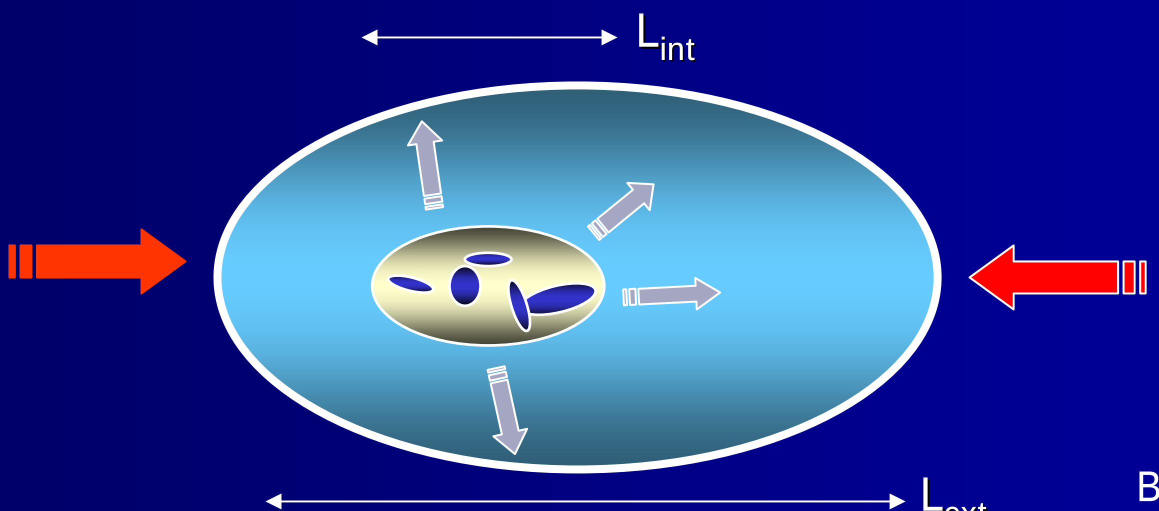
- $t_{diss} \sim t_{collapse}$
- Without continued energy injection (HD or MHD) turbulence decays rapidly (Stone, Ostriker, MacLow)



Kinetic energy vs time for 4 decaying turbulent sims (MacLow 02: Hydro, MHD, ZUES, SPH)

External vs. Internal Driving

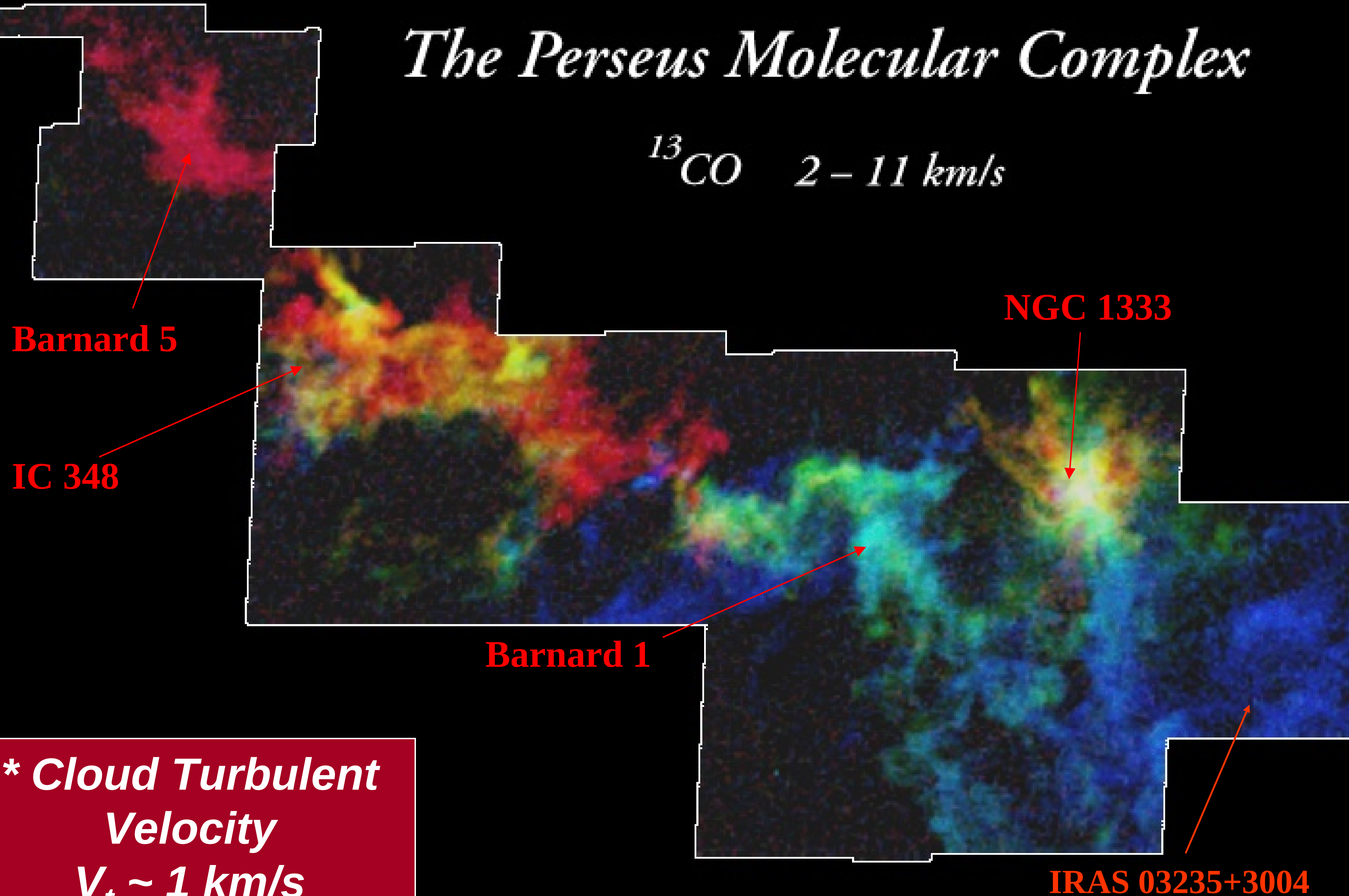
- Turbulent injection scale $L_0 \sim 1/k_0$
  – Cascade down to dissipation scales k_{diss}
- External Driving: $L_0 \sim R_{cloud}$
- Internal Driving: $L_0 \sim R_{cluster}$



Bally 06

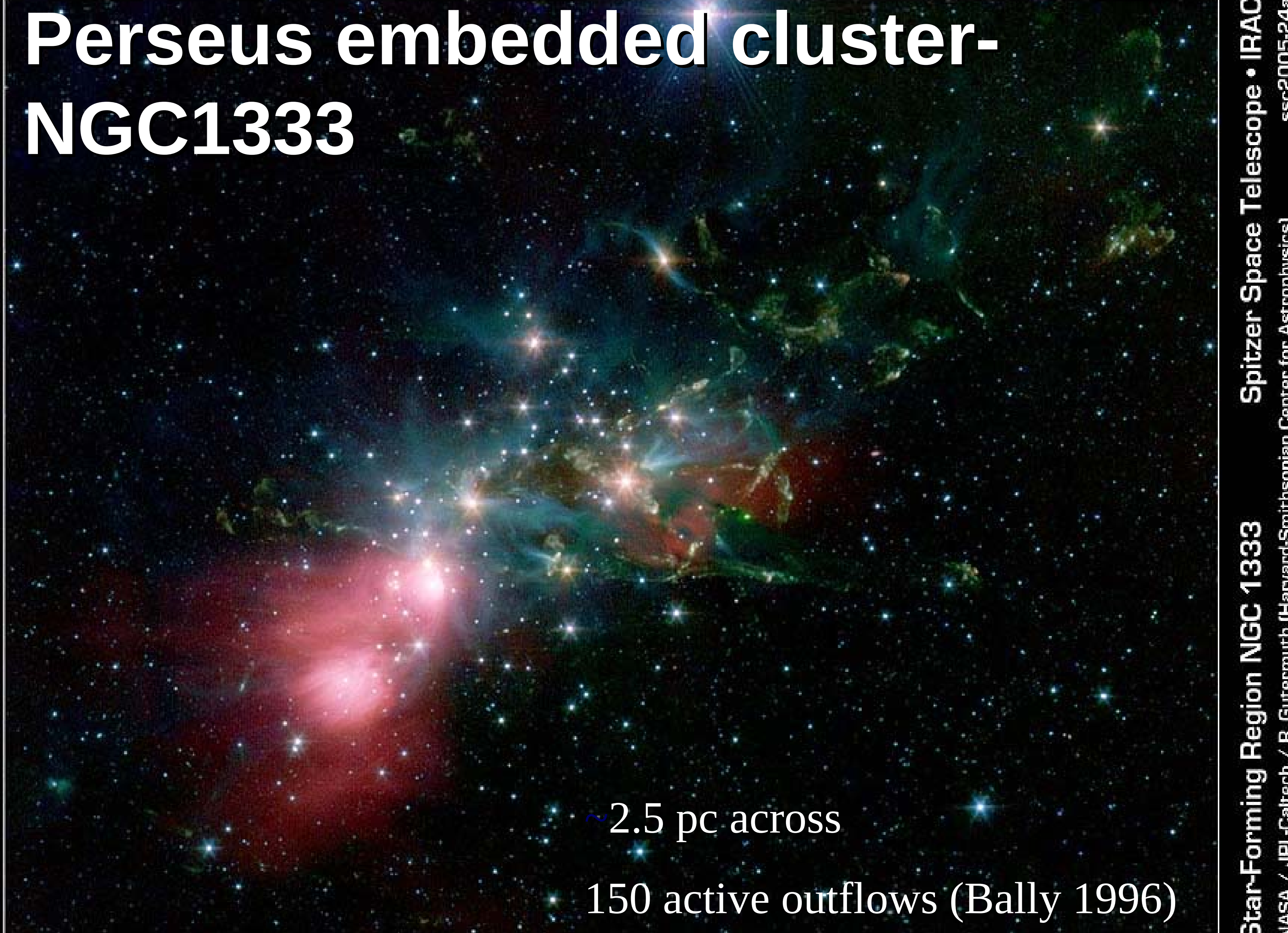
Sources of Turbulence

- Gravitational Collapse
- External SN
- Galactic Rotation
- HII Regions
- Internal SN
- ***<u>Proto-stellar Outflows</u>***



*** Cloud Turbulent Velocity $V_t \sim 1$ km/s**

Perseus embedded cluster- NGC1333



~2.5 pc across

150 active outflows (Bally 1996)

Macroscopic (Cluster) Scales: Outflow Feedback & Turbulence

- Can space-filling isotropic turbulence be driven by needles (jets), or balloons (outflows)?

- Explicate mechanisms.

- Connection with observational structures.

- Global Analytics – McKee, Matzner, Tan, Krumhotz
- Global sims – Maclow, Nakamura & Li, (poster Raga)
- ISM-Supernova Balsara et al, Dal Pino et al

- Resolution critical for jet sims : $R_j \sim 20$ zones.

The Storyline

- Cunningham et al 2006
  - Collision of active outflows
- Quillen et al 2005
  - Observations of turbulence & fossil outflows
- Cunningham et al 2007
  - Simulation of fossil outflows
- Cunningham et al 2008
  - Single fossil outflows in turbulent environments
- Carrol et al 2008
  - Multiple fossil outflows driving turbulent environments

Active Outflow Collisions

(Cunningham et al 06)

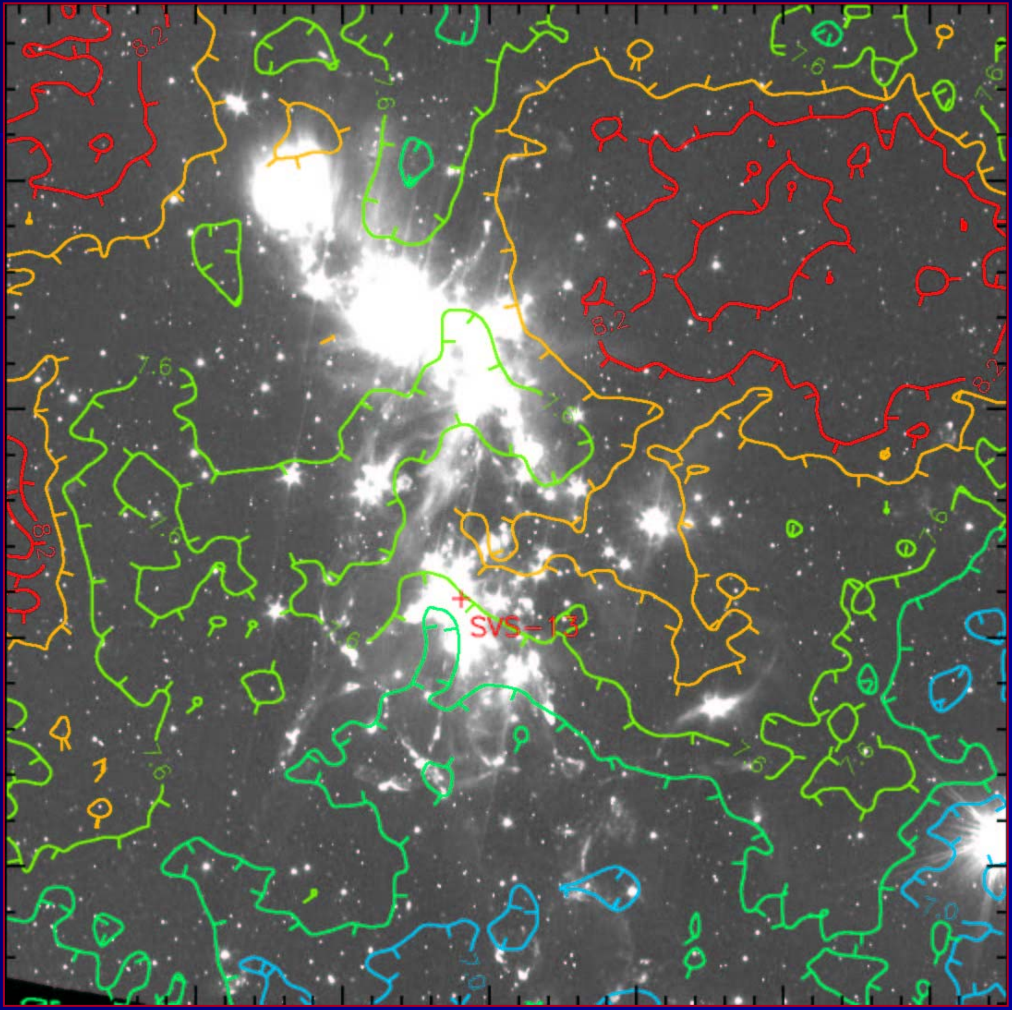
Conclusion # 1

Active Jets not good at driving Turbulence

What do Data Show: NGC 1333

Quillen et al 2005

- Explore High Rez ^{13}CO Data
  (Ridge et al 04)
- Correlate with Spitzer images + 2Mass data etc.

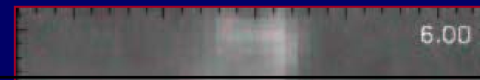


^{13}CO map + Spitzer 4.5 μ image

CO Data
.2 km/s contour spacing
.47 km/s gradient top to bottom

Spitzer data: SVS13 – center left
Many outflows visible

NGC 1333: Cavities



Conclusion # 2

Data show fossil cavities, not active jets, are smoking gun for protostellar outflow driven turbulence.

Does Fossil Cavity Scaling Work?

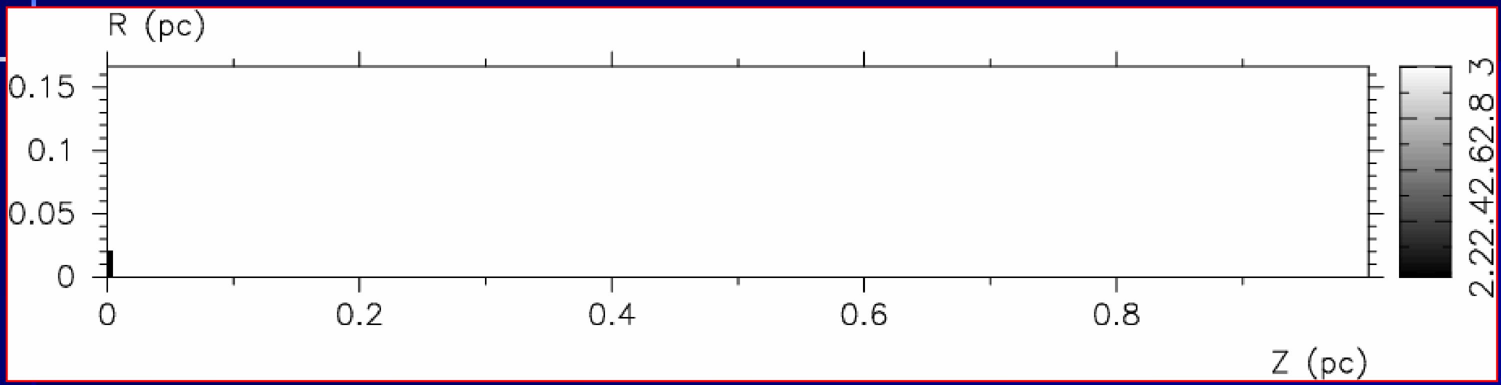
Cunningham et al 2006

- Explore time-decaying Jets/WAW outflow evolution (Bertout et al 96)

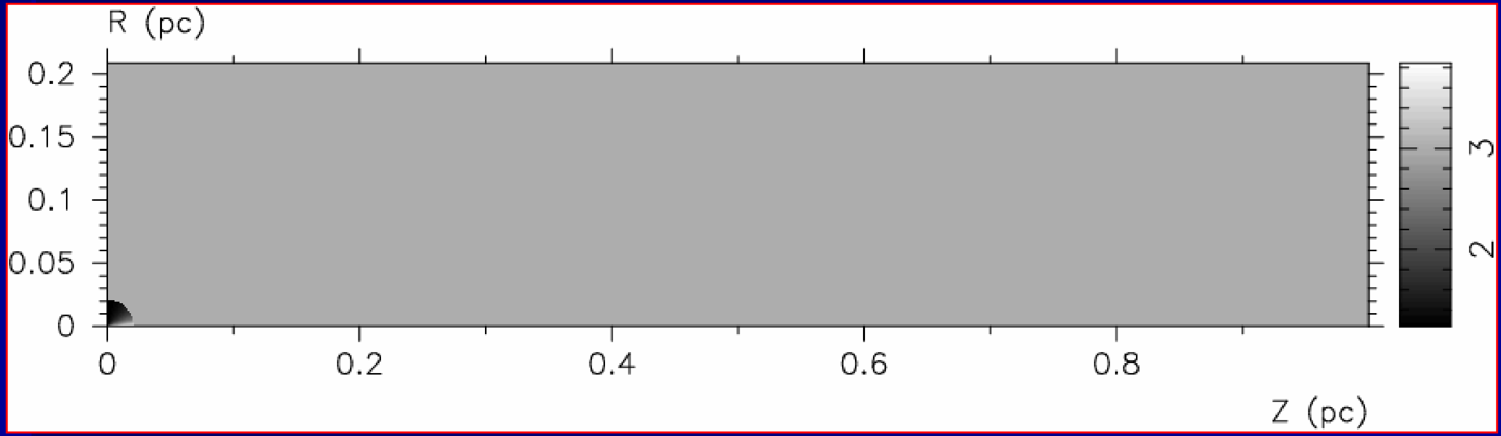
$$\dot{M} \approx \dot{M}_o e^{-\gamma t}$$

- Outflow power decays after 10^4 y.
- Simulation runs for 10^5 y
- Run to 0.5 pc scales
- Compare with scaling relations of *Quillen et al.*
- Compare with PV diagrams

Fossil Cavity Sims:
Jets and Wide Angle Winds



Collimated Jet



Wide Angle Wind (Matzner Class Sol)

- Strong deceleration
- Rarefactions backfill cavity

Fossil Cavity Sims: Results

Conclusion # 3

Fossil Cavities scaling from Quillen correct.

Fossil cavities “store” outflow momentum to transfer to turbulent motions

How Do Individual FCs Return Momentum to Turbulence?

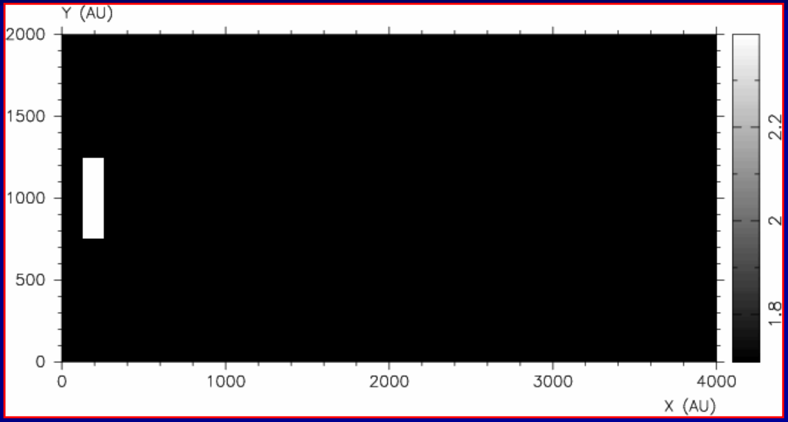
Cunningham et al 2008

- Background decaying turbulence

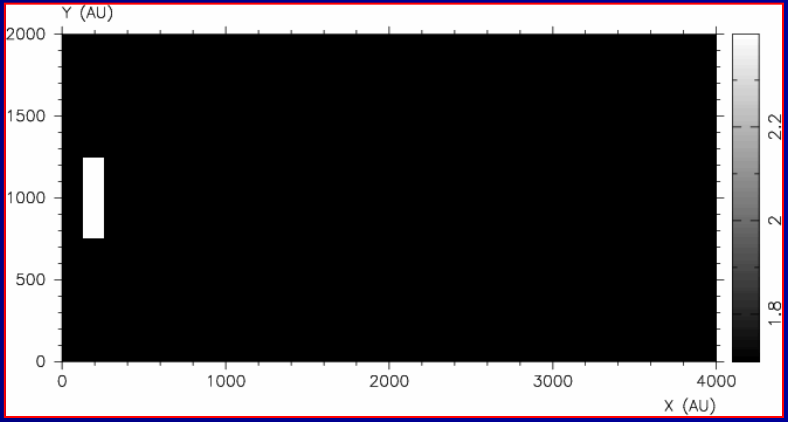
$$\begin{aligned} v_x(\mathbf{x}) &= \textstyle\sum_{i,j,k} A_{x\ i,j,k} \sin(\mathbf{k}_{i,j,k}\cdot \mathbf{x} + \phi_{x\ i,j,k}) \\ v_y(\mathbf{x}) &= \textstyle\sum_{i,j,k} A_{y\ i,j,k} \sin(\mathbf{k}_{i,j,k}\cdot \mathbf{y} + \phi_{y\ i,j,k}) \\ v_z(\mathbf{x}) &= \textstyle\sum_{i,j,k} A_{z\ i,j,k} \sin(\mathbf{k}_{i,j,k}\cdot \mathbf{z} + \phi_{z\ i,j,k}) \end{aligned}$$

- Vary jet duration τ_{jet}.
- Use $\tau_{jet} \sim \tau_{diss}$.
- Explore velocity power spectra

$$\int \mathcal{E}(k)\, dk = \frac{1}{V}\int_V \mathbf{u}(\mathbf{x})^2 d\mathbf{x} = \langle \mathbf{u}^2 \rangle$$



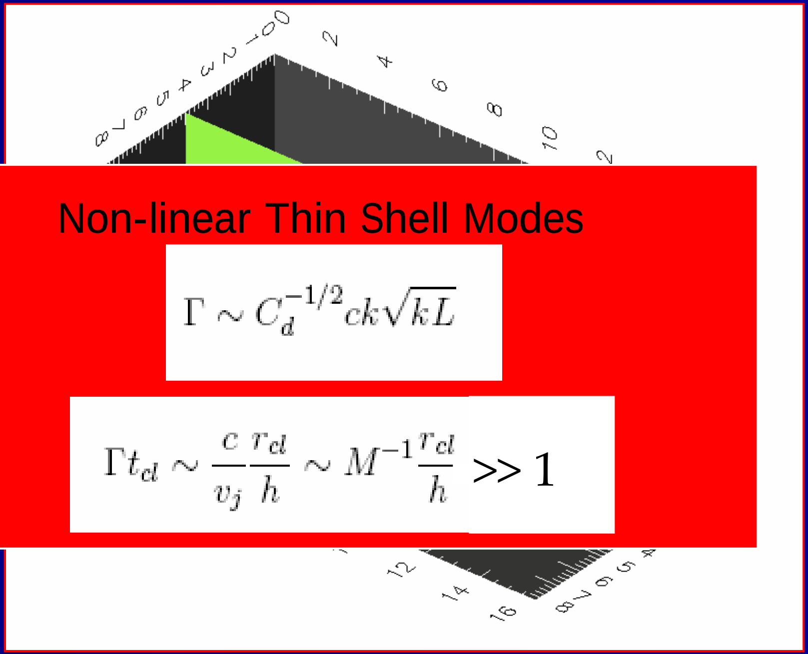
Long pulse jet



short pulse jet

Cavity Disruption Mechanism: Death by Instability

- New FC morphologies observed in turbulent environments!
- Why? Shells unstable to various modes.
- Turbulence seeds modes $k_{inj} < k < k_{dis}$
- Cavities disruption leads to turbulent resupply.

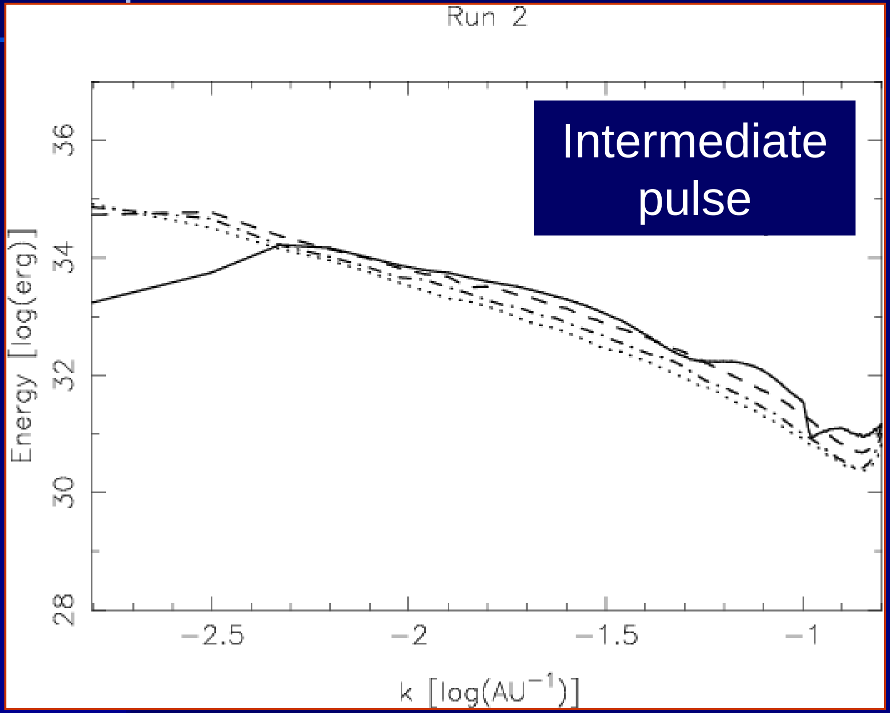


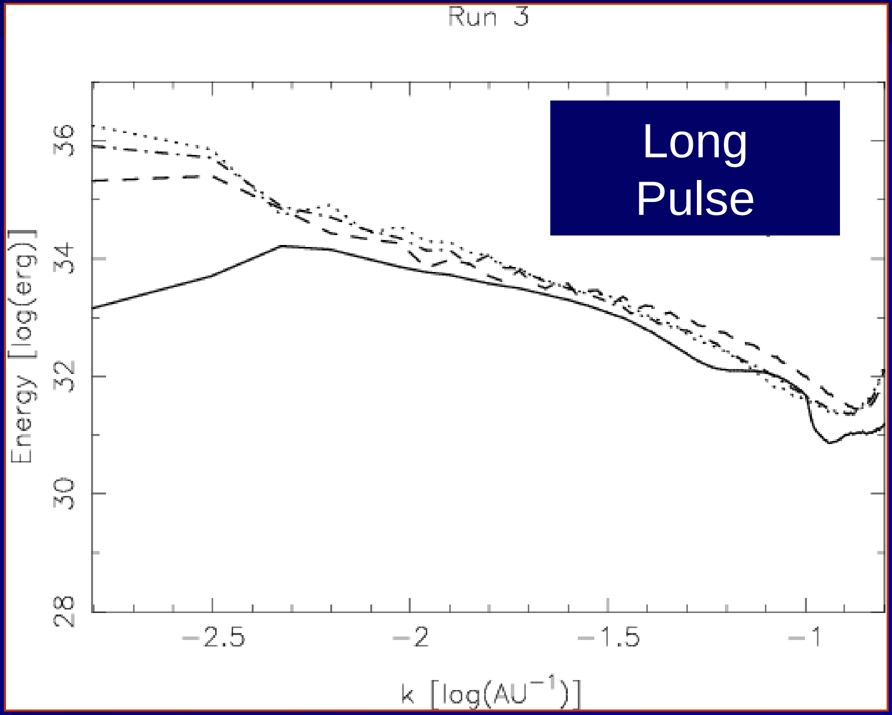
Non-linear Thin Shell Modes

$$\Gamma \sim C_d^{-1/2} ck\sqrt{kL}$$

$$\Gamma t_{cl} \sim \frac{c}{v_j}\frac{r_{cl}}{h} \sim M^{-1}\frac{r_{cl}}{h} >> 1$$

Power Spectra and Driving Scale





- Without jet, turbulence decays as expected.
- With jet, “turbulence” re-energized on all scales.
- With jet long “driving” scales energized which not previously present.

Cavity Disruption and

Conclusion # 4

Single Fossil Cavities in turbulent environment will be disrupted and subsumed.

FC bulk flow energy/momentum will be randomized and returned to the turbulent environment

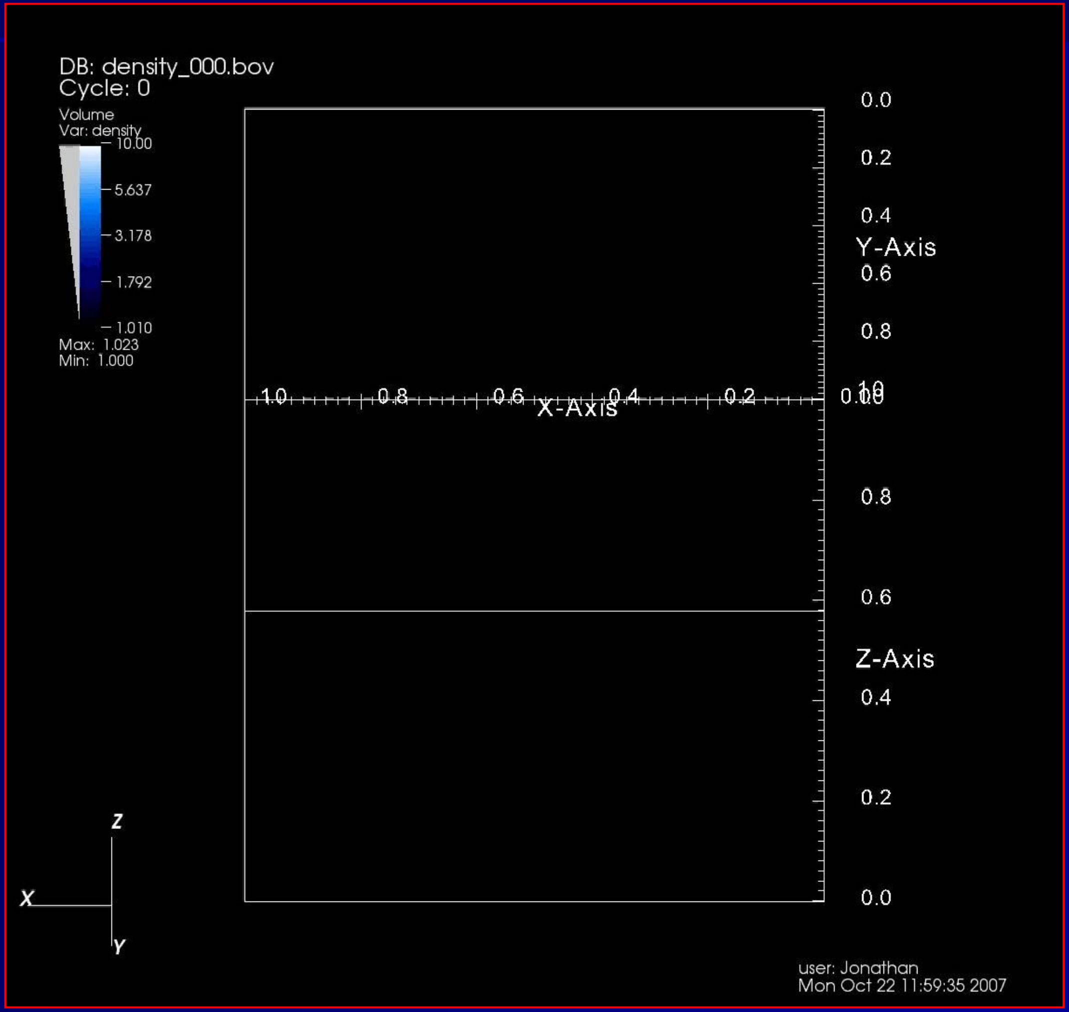
Outflow Driven Turbulence
Carroll et al. 2008

- Inputs: ρ_0, *I* = jet momentum, *S* = jet rate
- Use Matzner 2007 to define scales

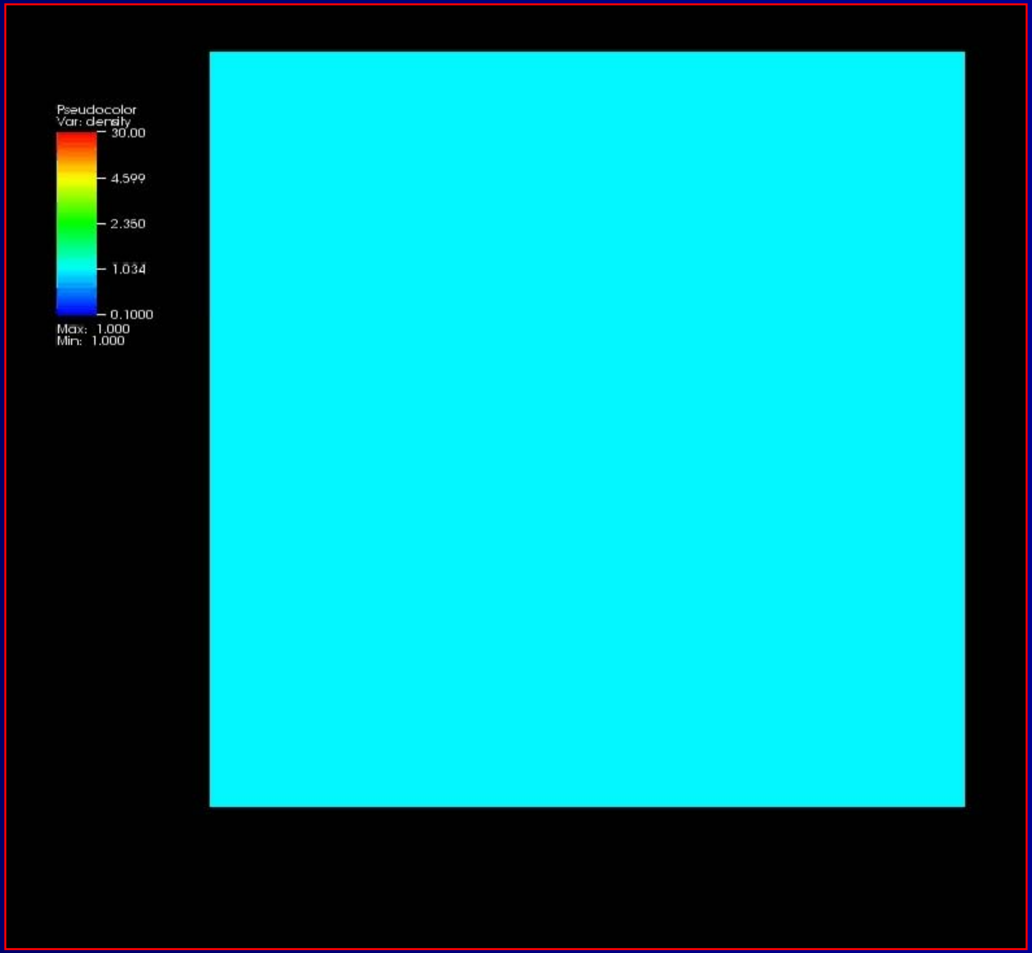
$$\mathcal{M} = \frac{\rho_0^{4/7}\mathcal{I}^{3/7}}{\mathcal{S}^{3/7}}, \mathcal{L} = \frac{\mathcal{I}^{1/7}}{\rho_0^{1/7}\mathcal{S}^{1/7}}, \mathcal{T} = \frac{\rho_0^{3/7}}{\mathcal{I}^{3/7}\mathcal{S}^{4/7}} \quad \mathcal{V} = \frac{\mathcal{L}}{\mathcal{T}} = \frac{\mathcal{I}^{4/7}\mathcal{S}^{3/7}}{\rho_0^{4/7}} = \frac{\mathcal{I}}{\rho_0\mathcal{L}^3}$$

- Run: t = 3*T* ~ 1My; l = 4*L* ~ 1 pc; N =136
- Jets: t ~ 10^4 y, R ~ 10^3 AU, Md = 10^{-4} Ms/y
- $N_{zones} = 256^3$;
- Control simulation: Driven turbulence $k = 4k_{box}$

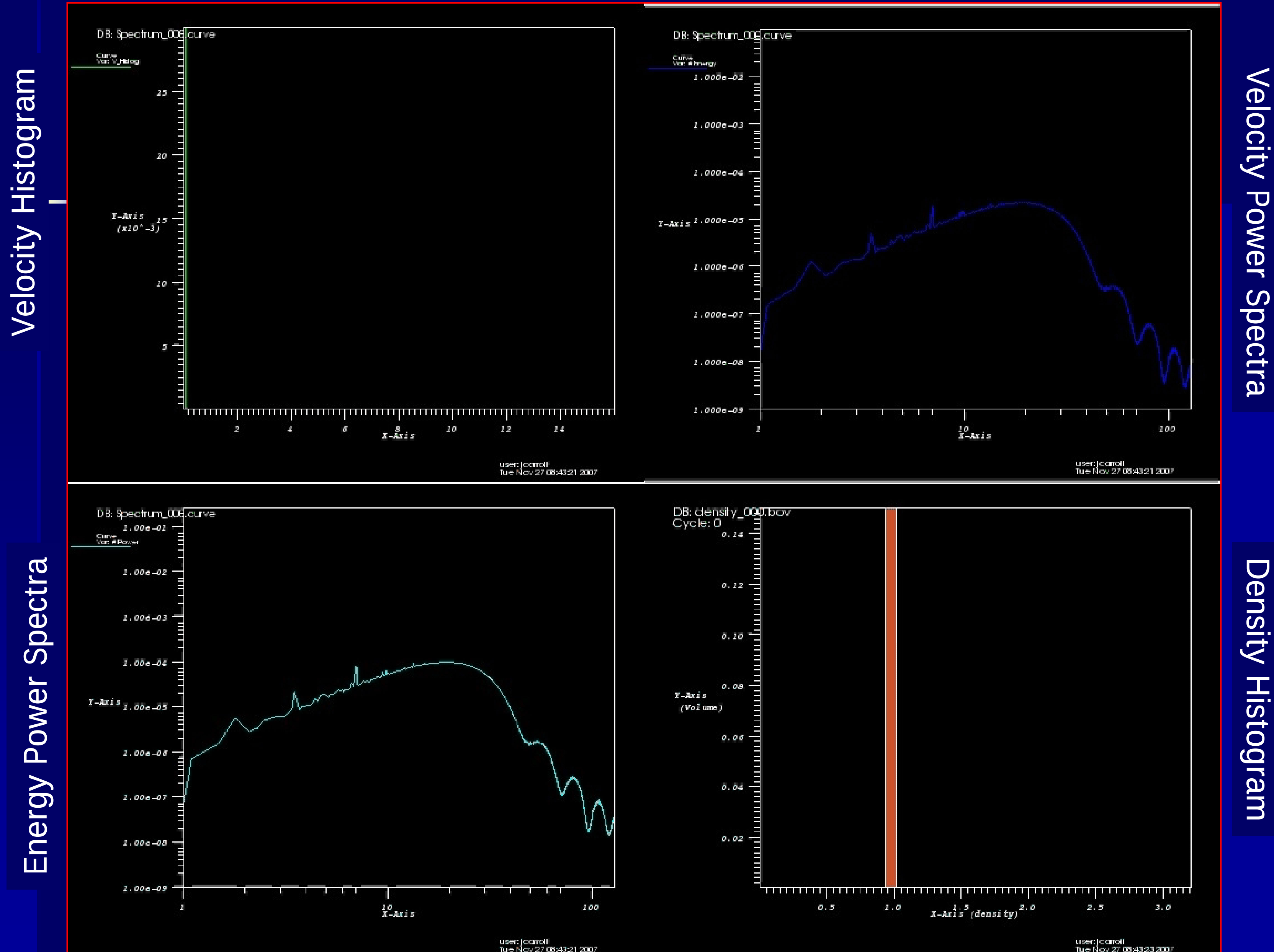
Jet-Driven Turbulence
Density Isosurfaces



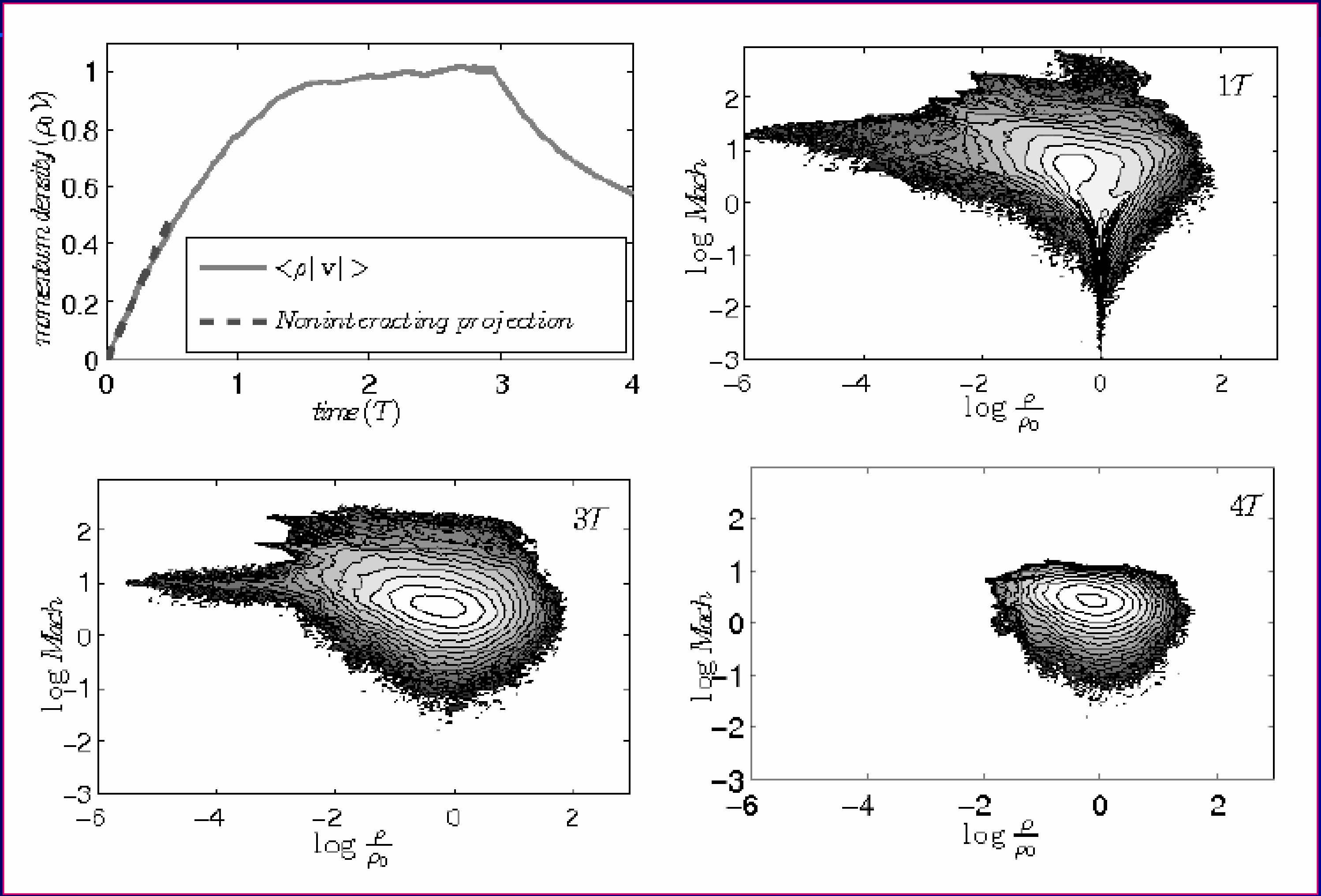
Jet-Driven Turbulence
Density Mid-plane



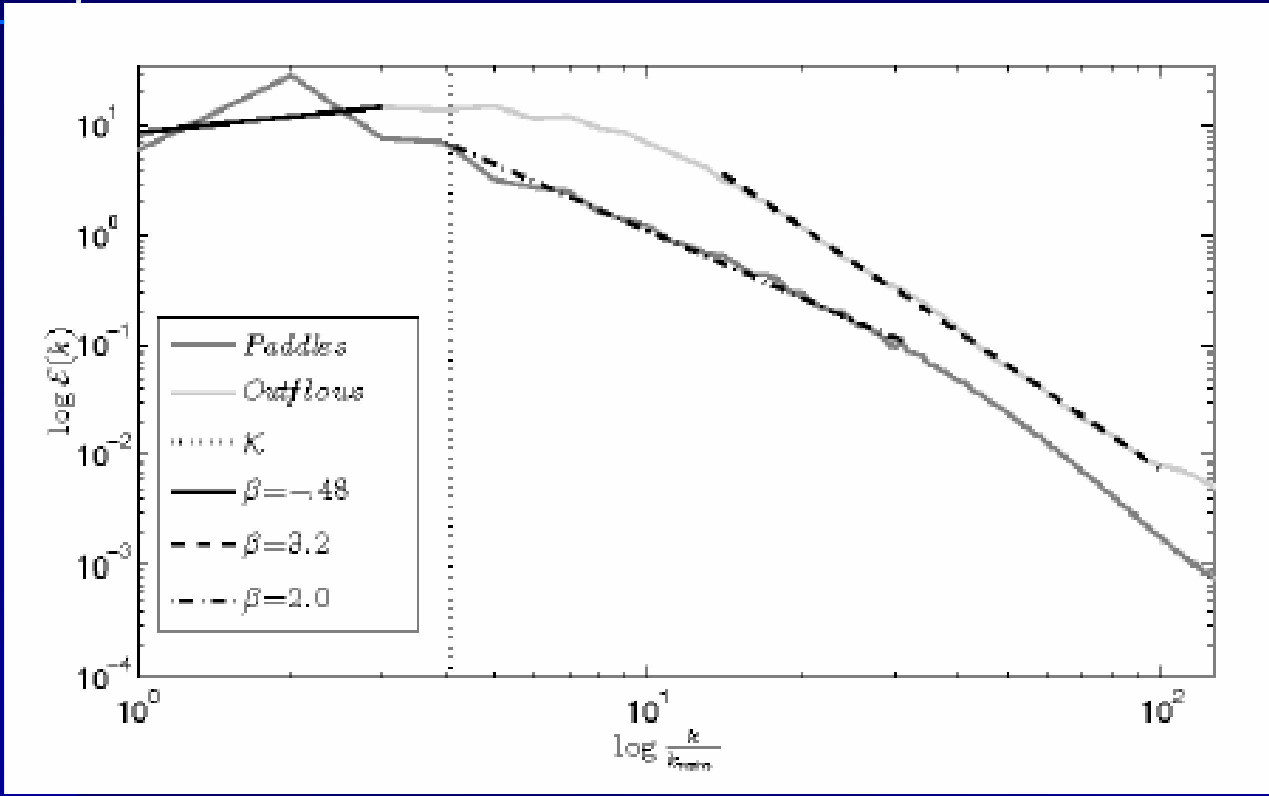
Evolution: Statistics of Turbulence



Statistics of Turbulence Probability Distribution Functions



Energy Spectra



$E(k) \sim k^{-n}$

Control Sim
n~2

Jet Sim
n~3

Injection Scale!
$K_{inj} \sim 1/L$

Cavities sweep up power (eddies) at smaller scale

Discreet vs. Continuous Forcing

- "Classic" Turbulence sims *assume* a forcing spectra: F_k.
- Jet driven sims use discreet forcing.
  - "back out" forcing spectrum.
- Assume:
  - $E(k) \sim k^{-n}$
  - $F(k) \sim k^{-\alpha}$
  - $\Pi(k) \sim v^2/t \sim k^{3/2(5/2-\alpha)}$

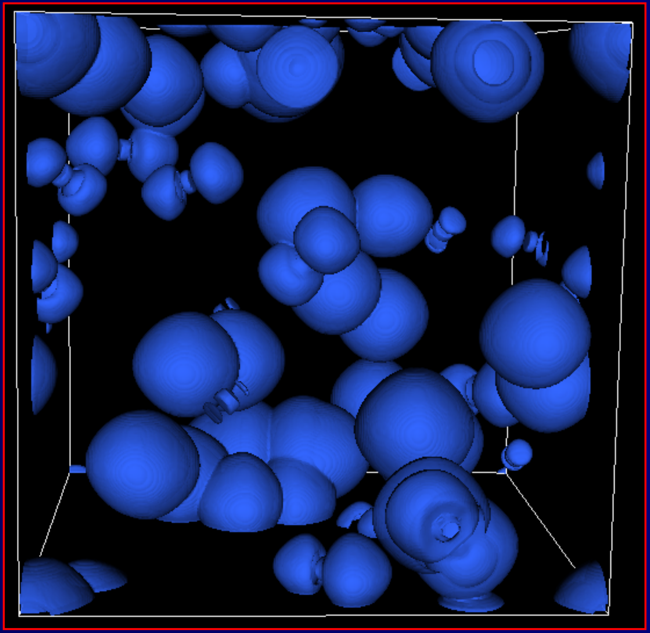
$$\frac{d\mathcal{E}_k}{dt} = \mathcal{F}_k - \frac{d}{dk}\Pi_k = 0$$

$$\alpha = \frac{3}{2}(1-n)$$

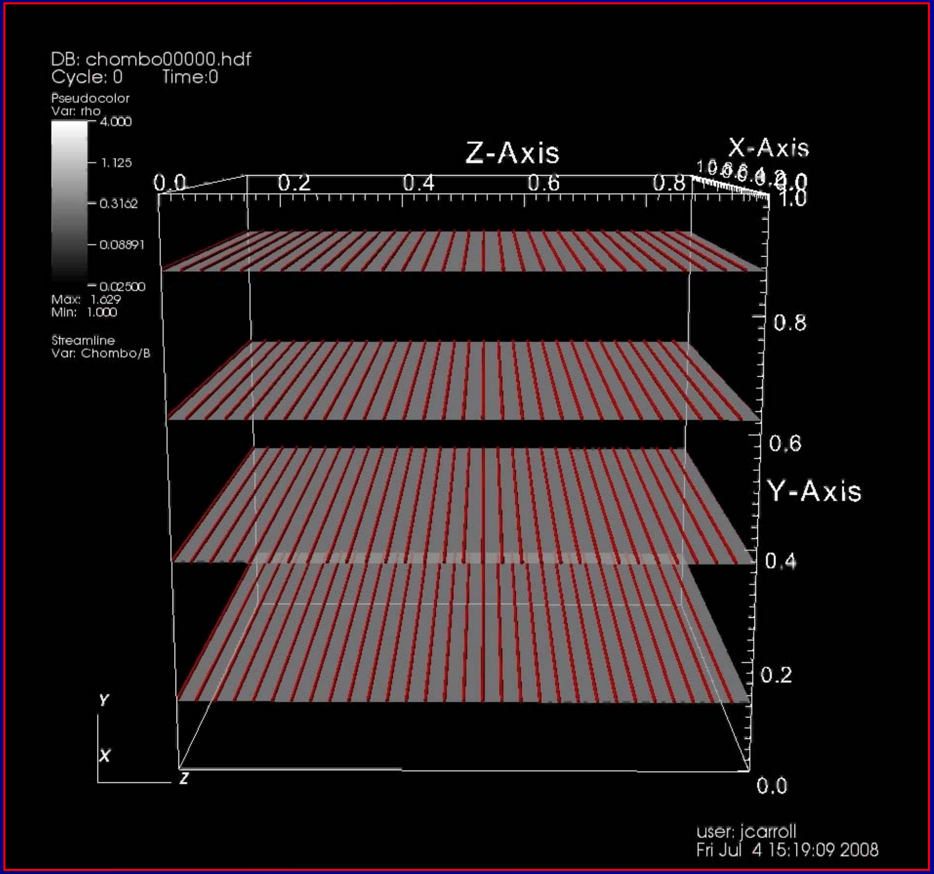
$$F \propto k^{2.2}$$

Magnetic Fields

Carroll et al 08



Density



So... (a 'la Banerjee et al 2007) Can Protostellar Jets Drive Turbulence?

- Definitively Yes.
- Yes even for moderately rich clusters $N_* \sim 100\ pc^3$

$$P = N_*^2 \pi R^2 L \frac{t_{out}}{t_{cloud}}$$

- Fossil Cavities re-energize existing E_{turb}
- Fossil Cavities drive E_{turb}

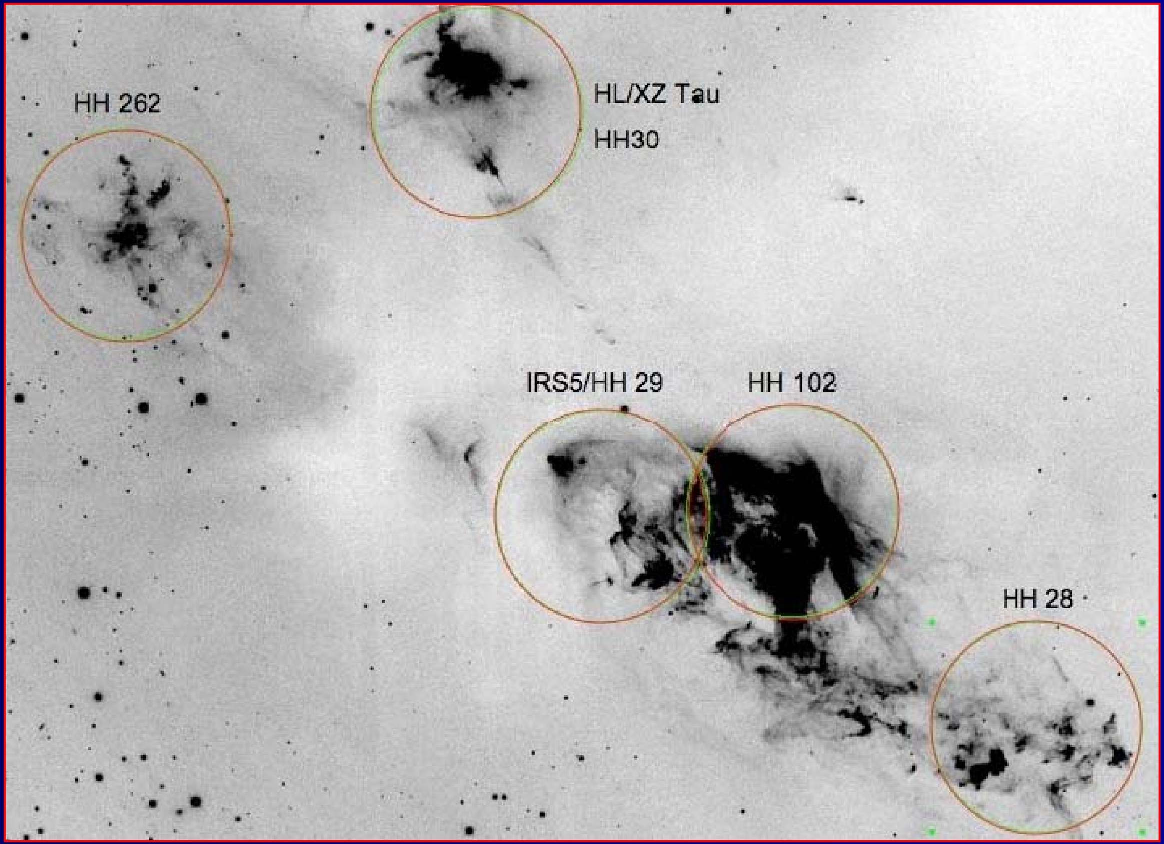
The Big Questions

- Effect of magnetic fields.
- Effect of collimation and jet power.
- Observational signatures.

- How does jet driven turbulence modify SFE?
- Beyond the cluster scale
  - Can jet driven turbulence power turbulence on cloud scales?
  - Produce MHD waves that cross cloud? (Raga, Lim, Basu etc)
- Self-consistent models: Self-gravity, Star Formation
- Massive stars vs. Low Mass stars.

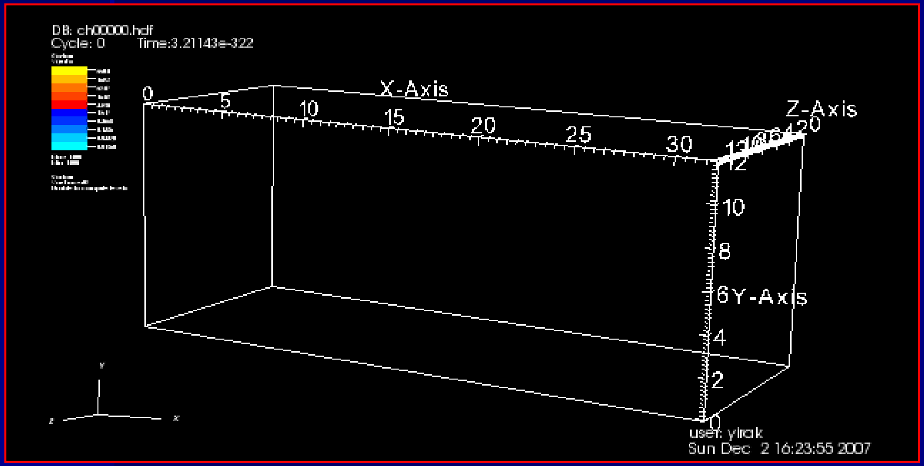
Future: Individual Objects L1551

Yirak, Carroll, Frank, Bally, Hartigan 2008*

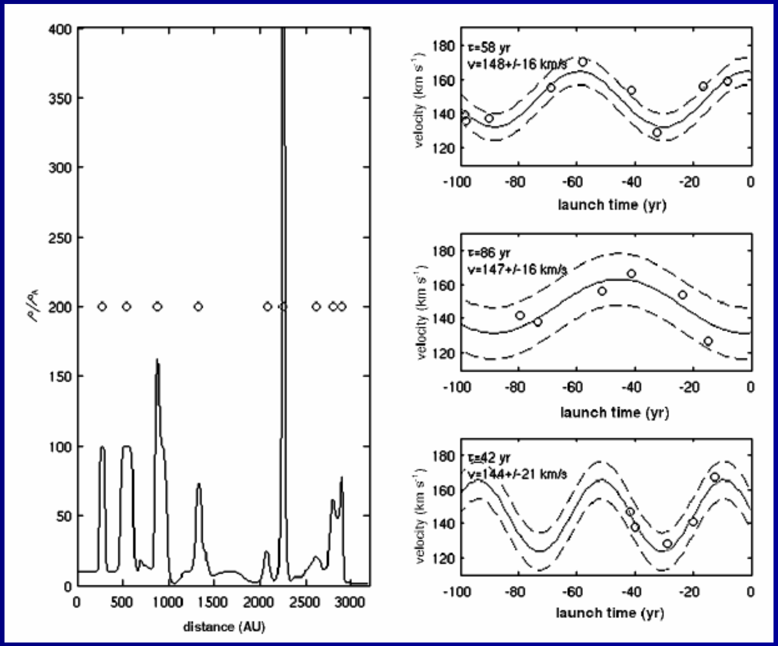


Are Jets Inherently Clumpy?

Yirak Frank & Cunningham 2008



Iso-density contours



Psuedo-periodicity