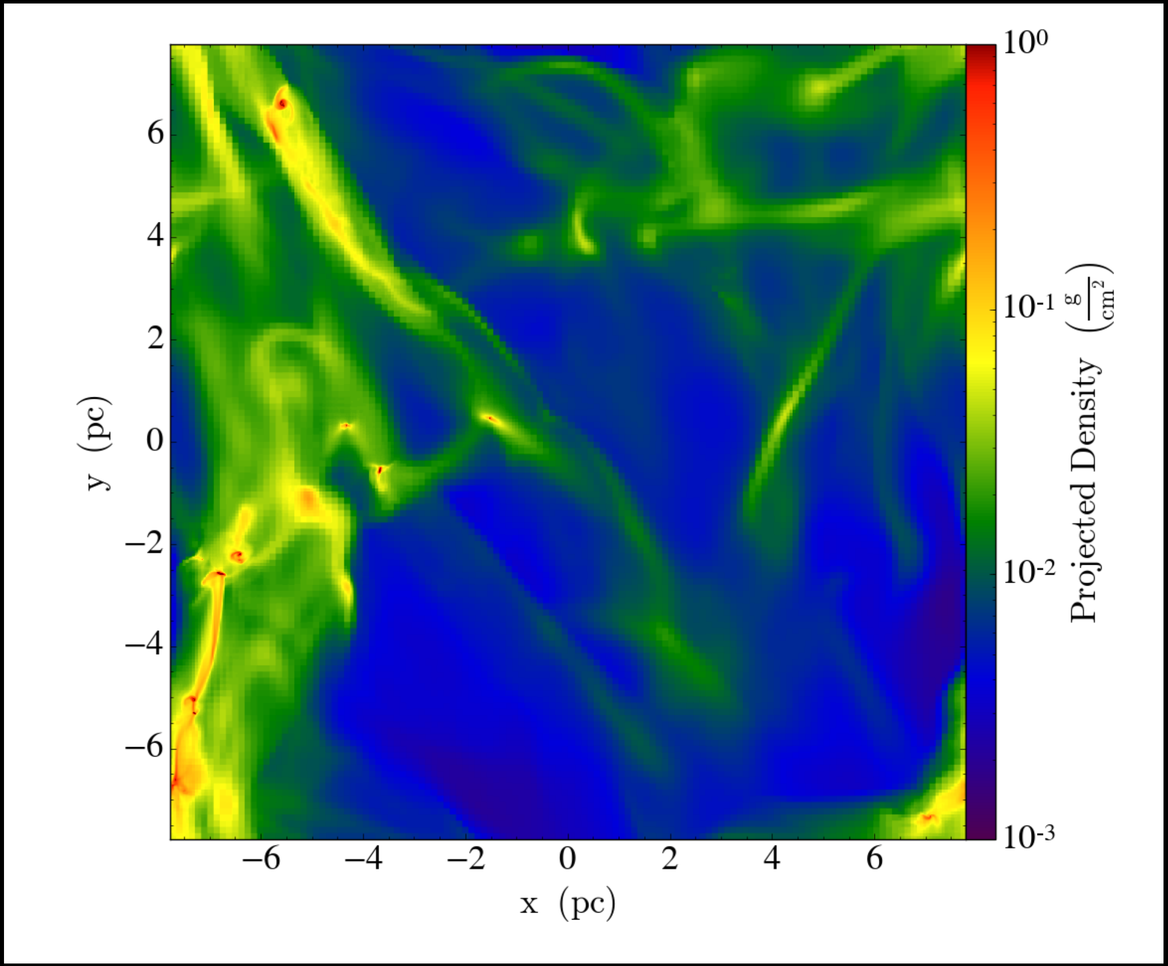


Turbulent Star Formation

Daniel Murray, Phil Chang

Cloud Size, Line-width Relation

Larson 1981

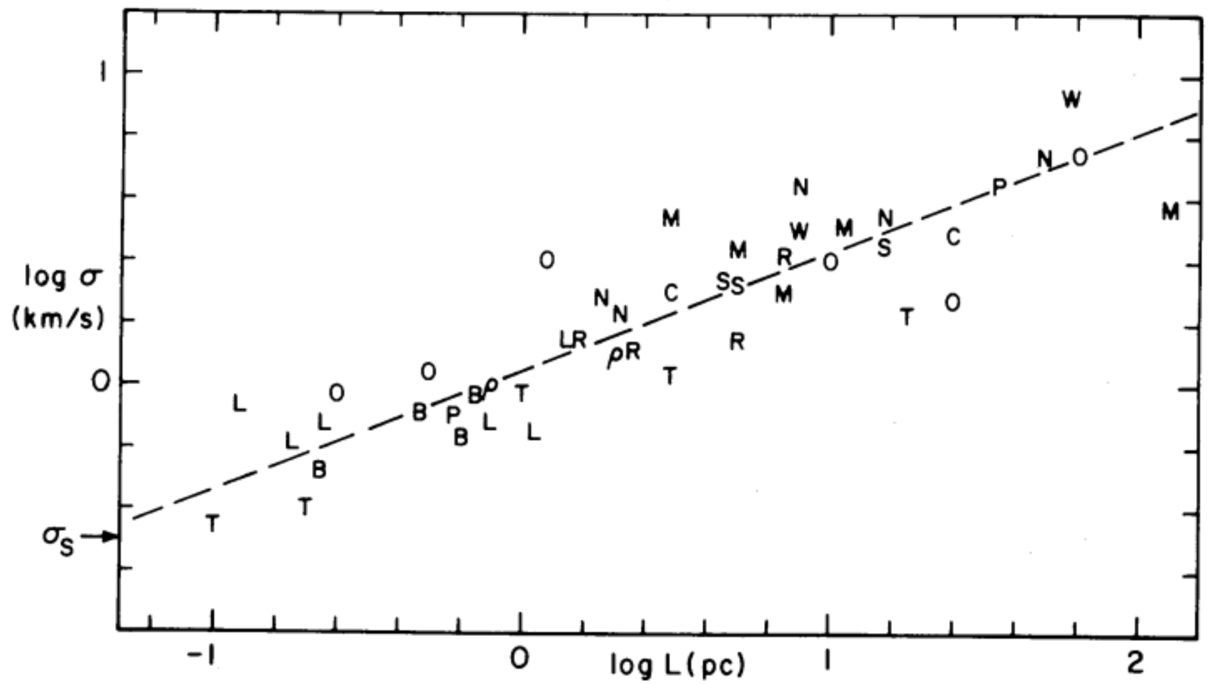
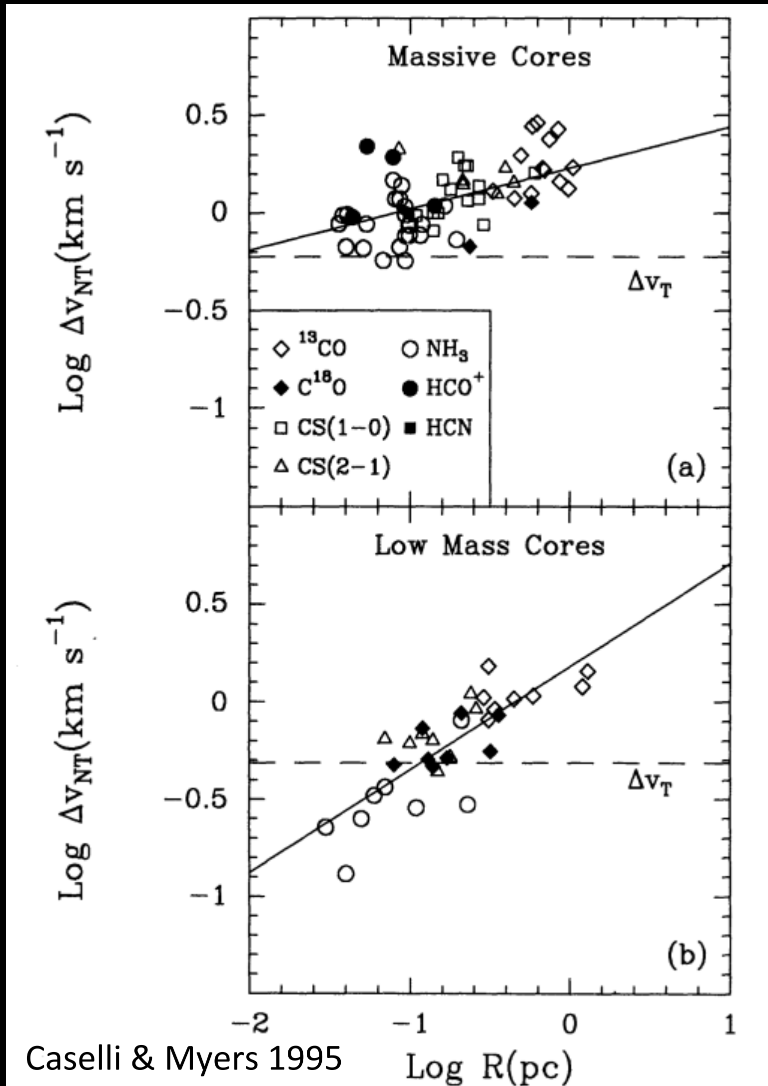


Figure 1. The three-dimensional internal velocity dispersion σ plotted versus the maximum linear dimension L of molecular clouds and condensations, based on data from Table 1; the symbols are identified in Table 1. The dashed line represents equation (1), and σ_S is the thermal velocity dispersion.

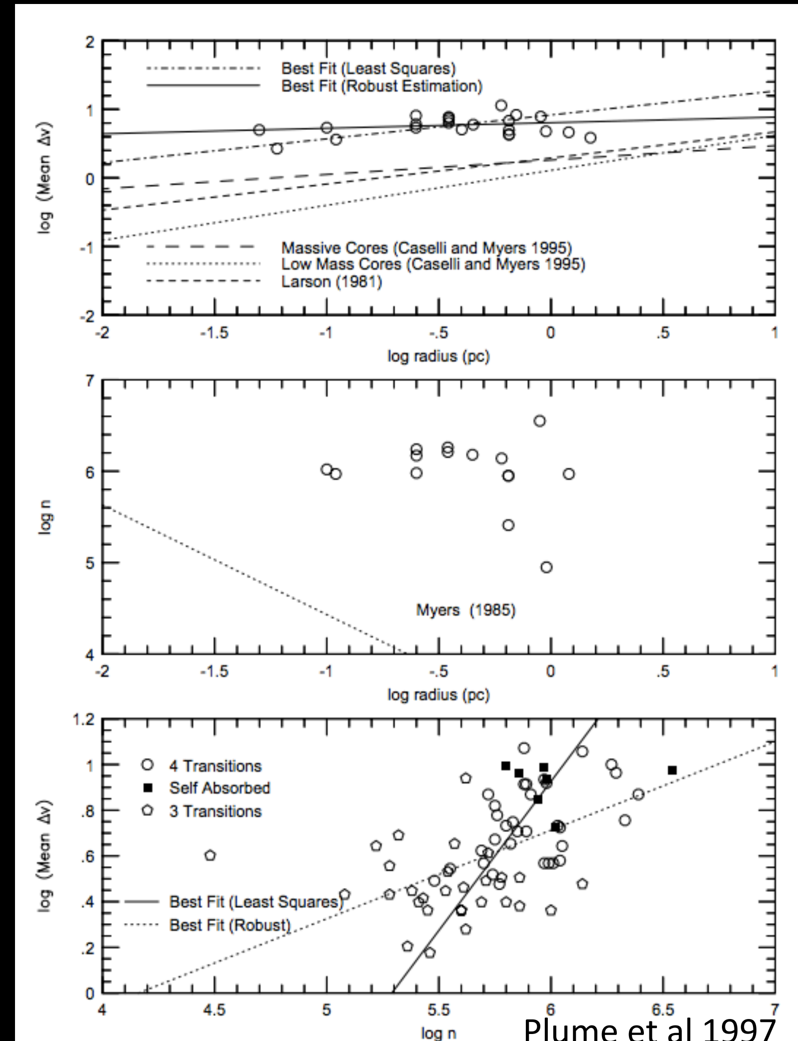
Scaling is: $\sigma \propto L^{1/2}$

Velocity dispersion   size

Deviations from Larsons Law



Caselli & Myers 1995



Plume et al 1997

Velocity is not given by Larson’s law for massive cores

Murray and Chang 15

- Turbulent closure model
  - Use mass, momentum conservation and:

$$\frac{\partial v_T}{\partial t} + u_r \frac{\partial v_T}{\partial r} + \left(1 + \eta \frac{v_T}{u_r}\right) \frac{v_T u_r}{r} = 0$$

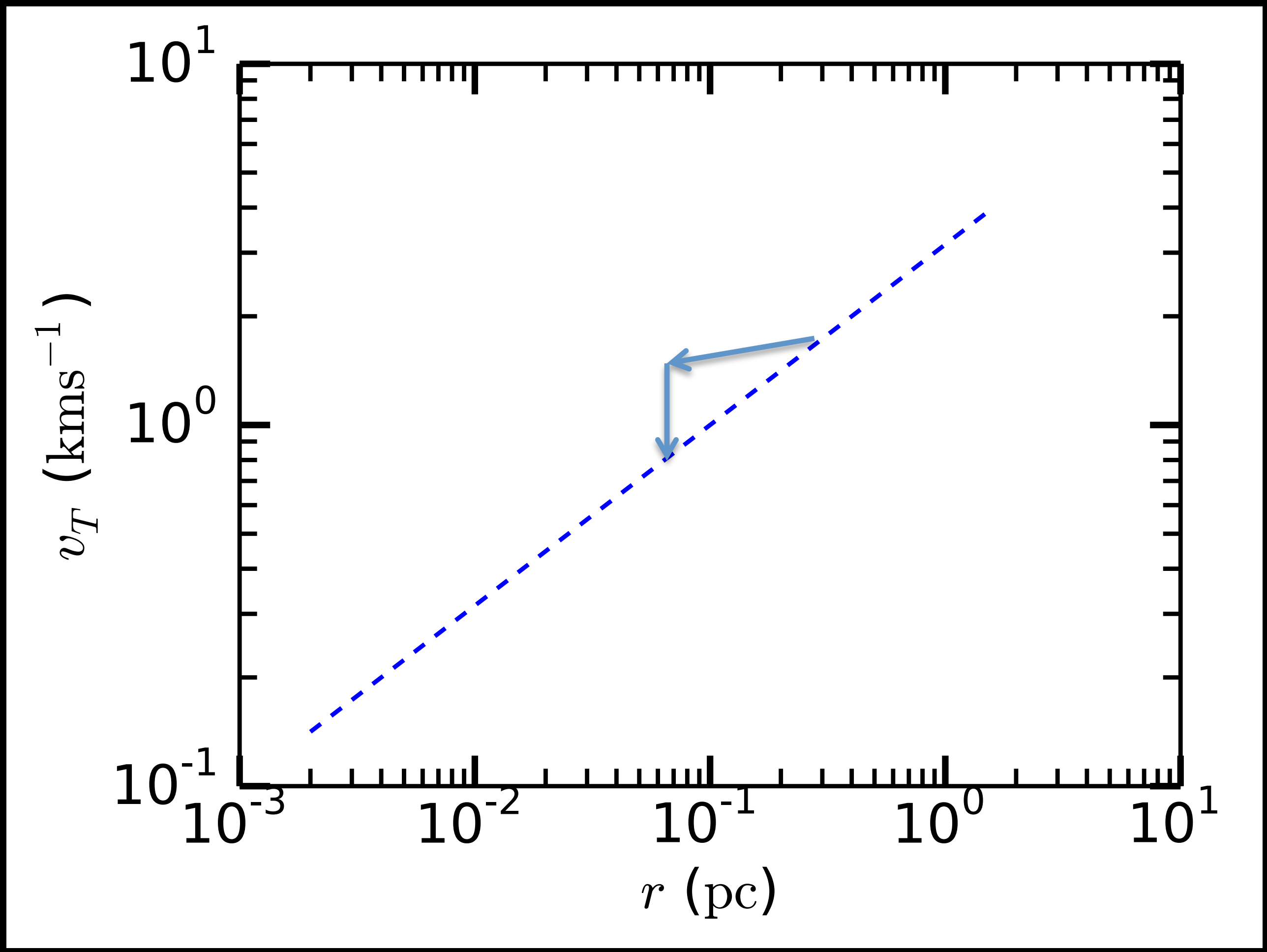
Robertson & Goldreich 2012

Essentially, it physically means: $v_T(r,t) \sim |u_r(r,t)|$

- Also define r_* to be a physical scale

$$M_*(t) \sim M_g(< r_*(t), t)$$

$$v_T(r,t) \sim |u_r(r,t)|$$

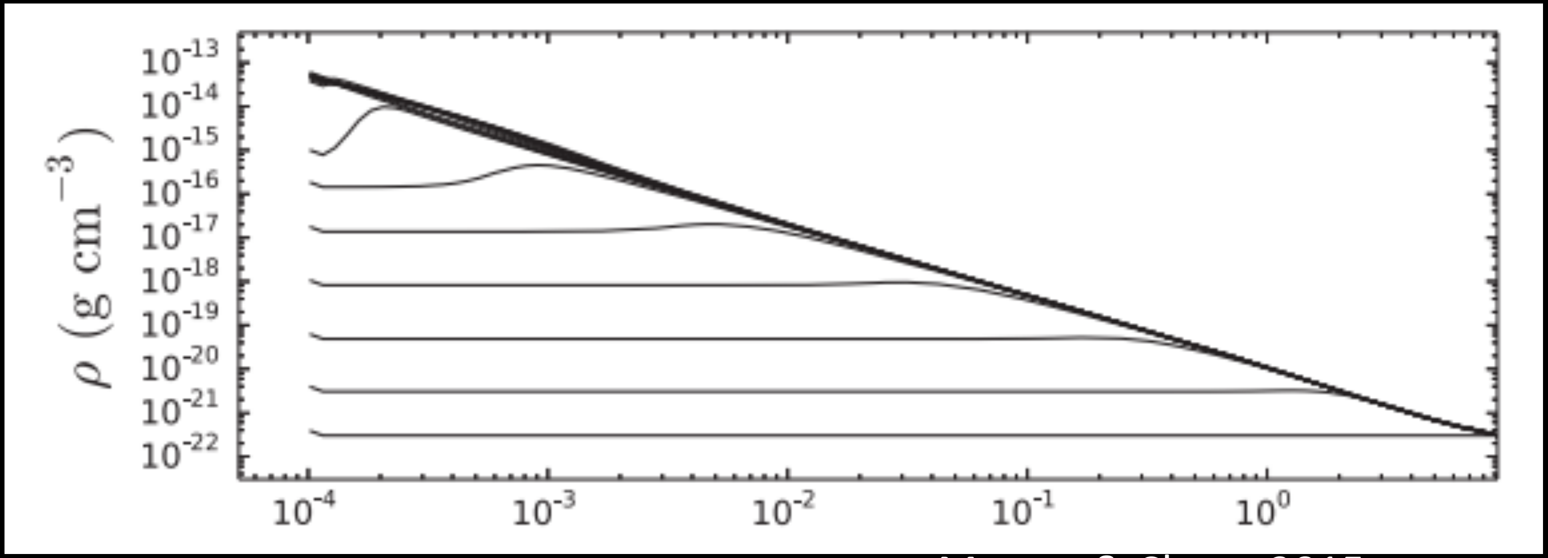


Predictions of Murray and Chang 15 I

- Density is an attractor solution for small r

$$\rho(r,t) = \rho(r_0)\left(\frac{r}{r_0}\right)^{-3/2} \quad \mathrm{for}\, r < r_*$$

$$\rho(r,t) = \rho(r_0,t)\left(\frac{r}{r_0}\right)^{-\kappa_\rho}, \kappa_\rho \approx 1.6 - 1.8\, \mathrm{for}\, r > r_*$$



Murray & Chang 2015

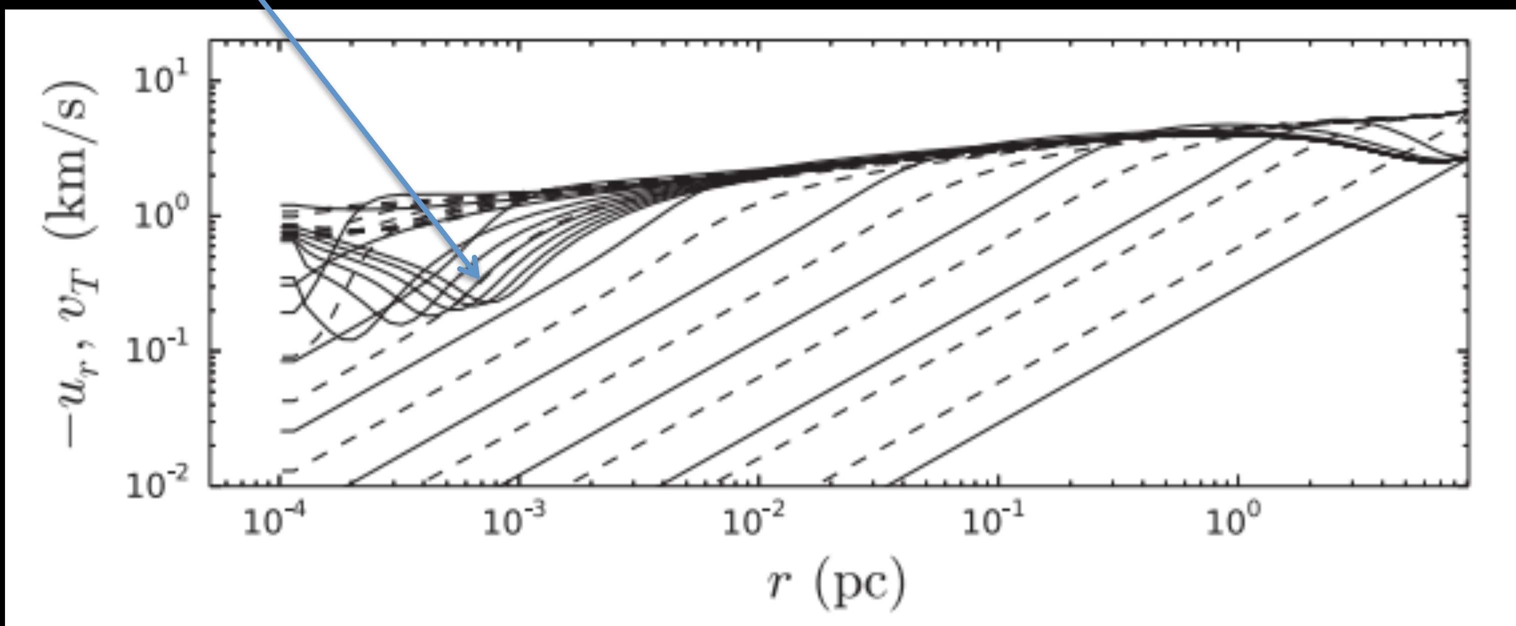
Predictions of Murray and Chang 15 II

- Velocity scaling for large and small r

$$u_r \propto r^{0.2}\,\mathrm{for}\,r > r_*$$

r_*

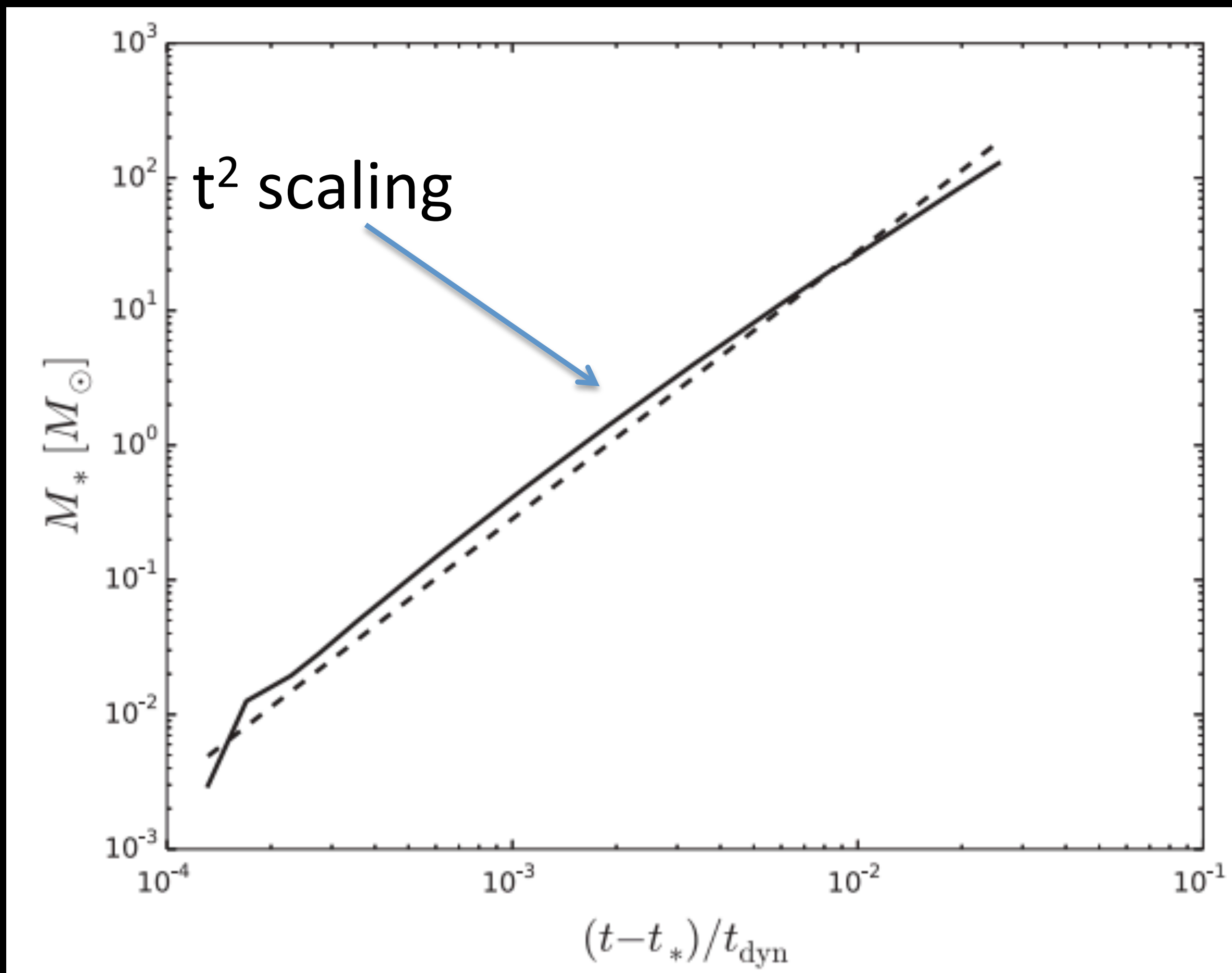
$$u_r \propto r^{-1/2}\,\mathrm{for}\,r < r_*$$



Murray & Chang 2015

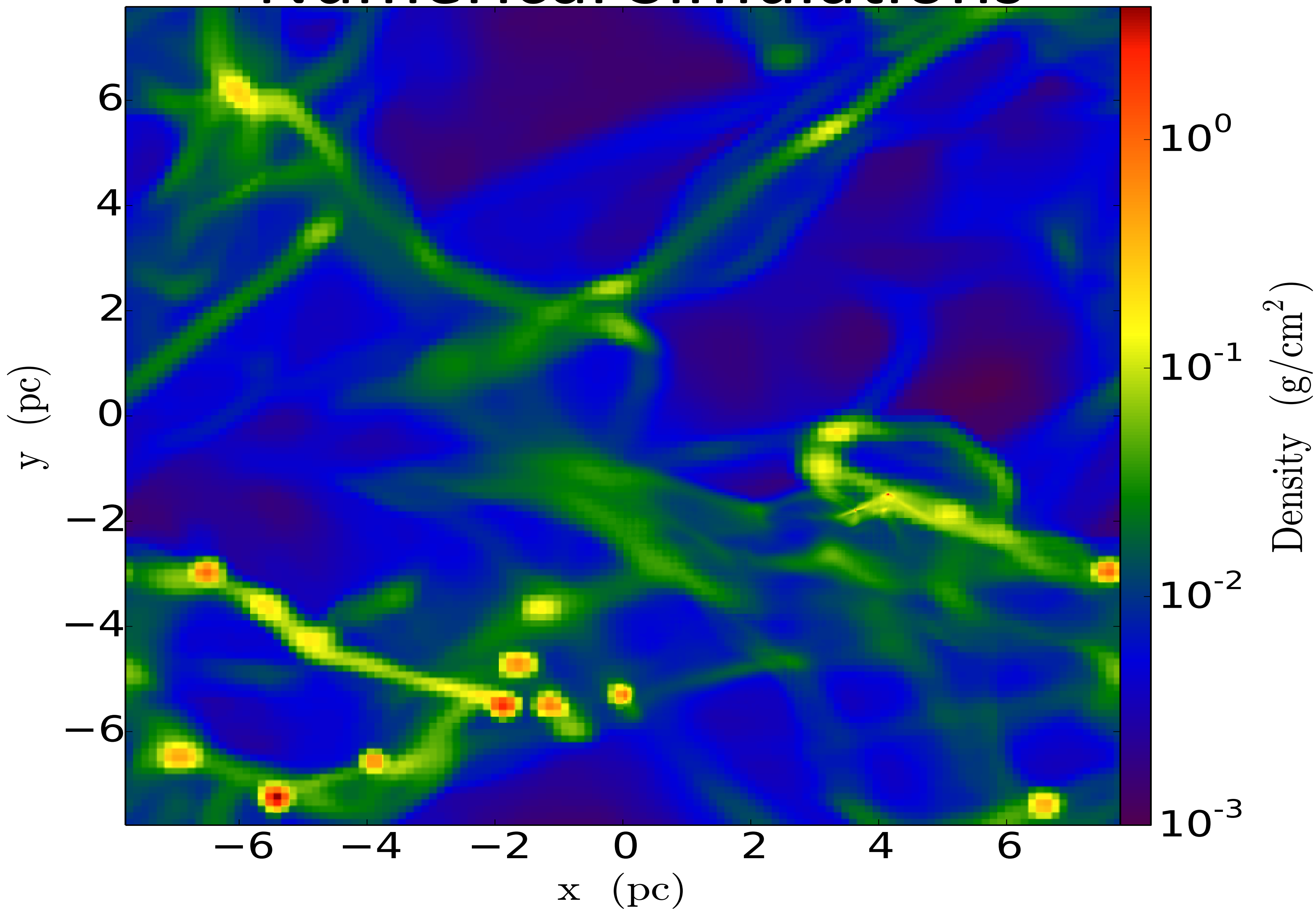
Predictions of Murray and Chang 15 III

- Mass in stars scales like t^2



Murray & Chang 2015

Numerical Simulations



MC15 Predictions

- Remember these predictions:
- Density is an attractor solution for small r:

$$\rho(r,t) \to \rho(r) \propto r^{-3/2}$$

- Velocity inverts at r_* :

$$u_r \propto r^{0.2} \,\mathrm{for}\, r > r_*$$
$$u_r \propto r^{-1/2} \,\mathrm{for}\, r < r_*$$

- Mass in stars scales like t^2

Results I

- Filamentary structure (an old result)
- (massive) star forming regions in the simulation are never in hydrostatic equilibrium
  - Does not look like Shu; Myers
- Recover Larson's size-linewidth relation, and deviations from it in collapsing regions
  - In other words, we see adiabatic heating of the turbulence

Results II

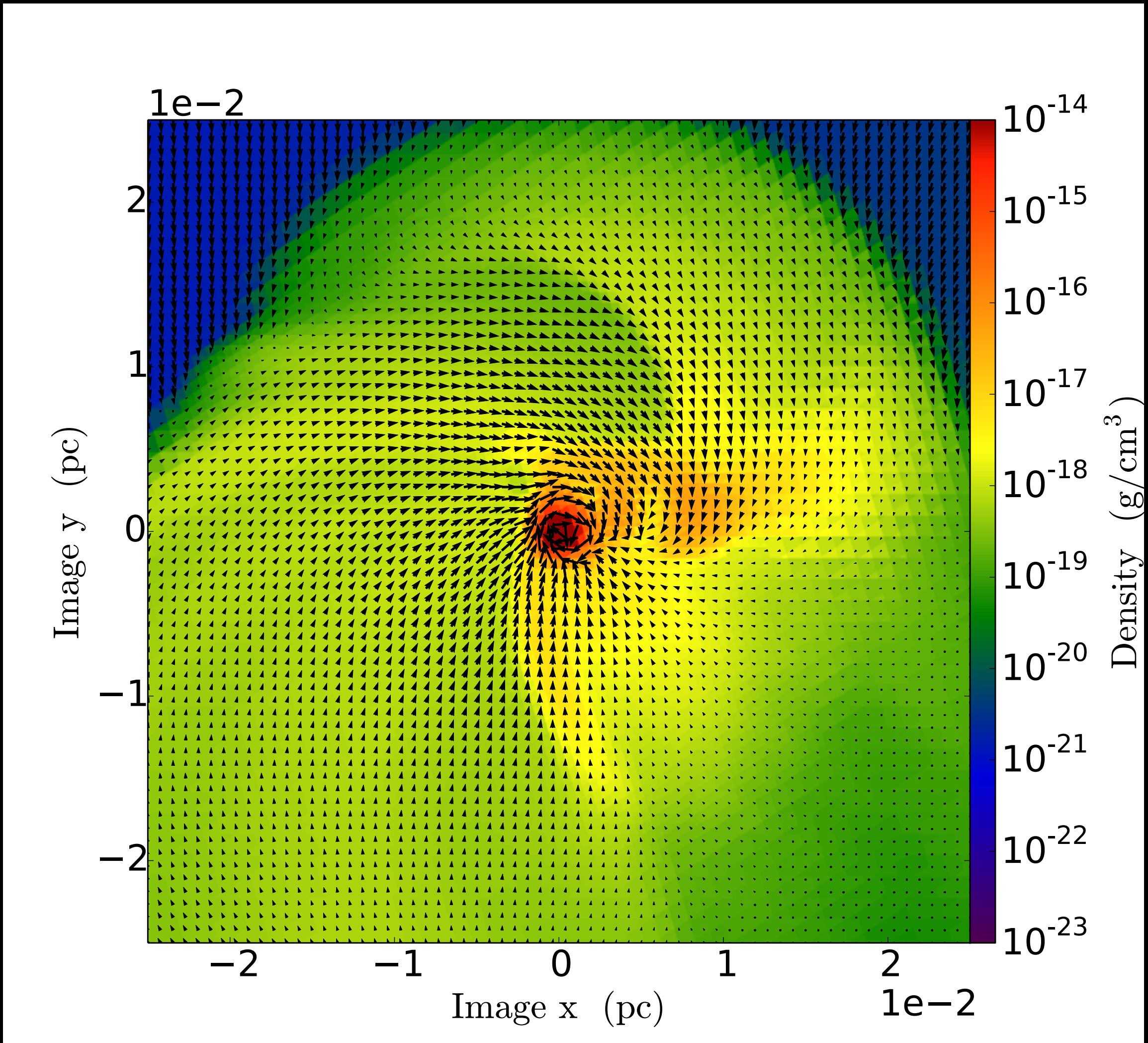
- Find an attractor for the density profile

$$\rho(r,t) \to \rho(r)\,\mathrm{for}\, r_d < r < r_*(t)$$

- $\dot{M}_*(r,t) \to \dot{M}_*(t)\,\mathrm{for}\, r < r_*$

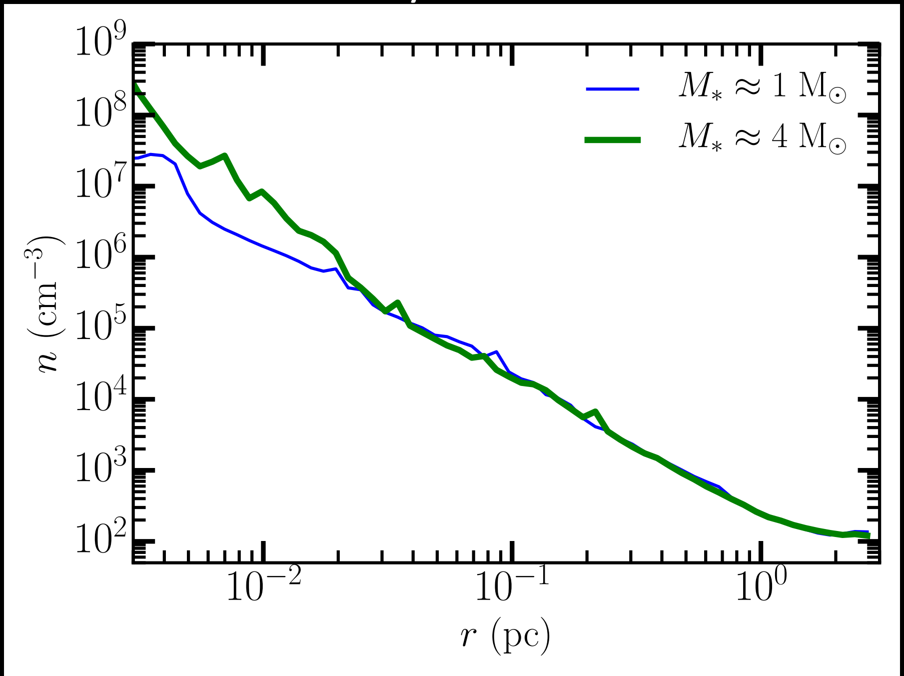
- Disks form first then stars form in the centers
  - Disks are around Q = 1, cycle around marginal stability over time

The Stellar Disk

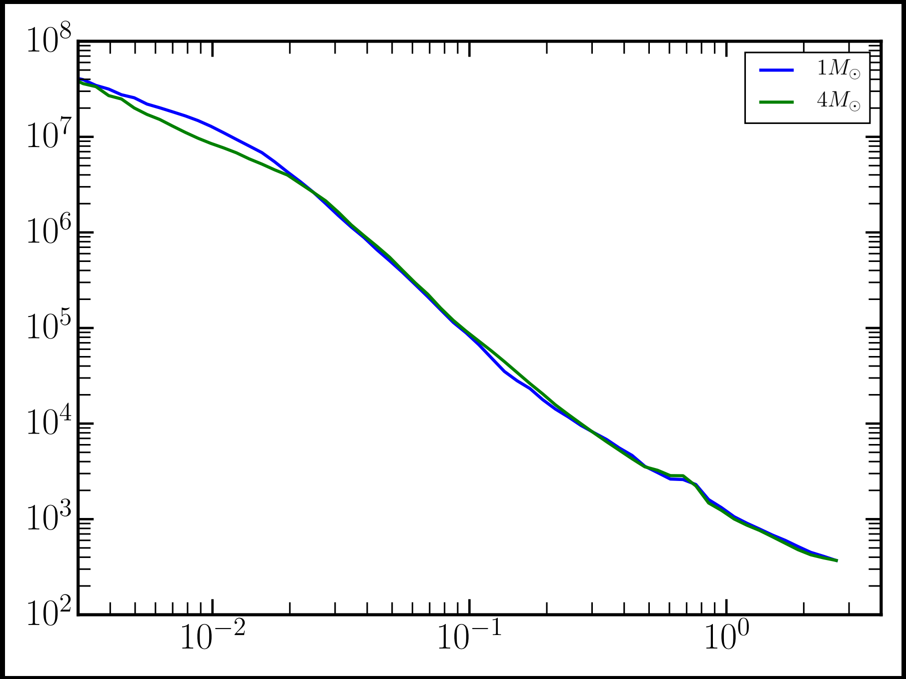


Density -> Attractor

Hydro



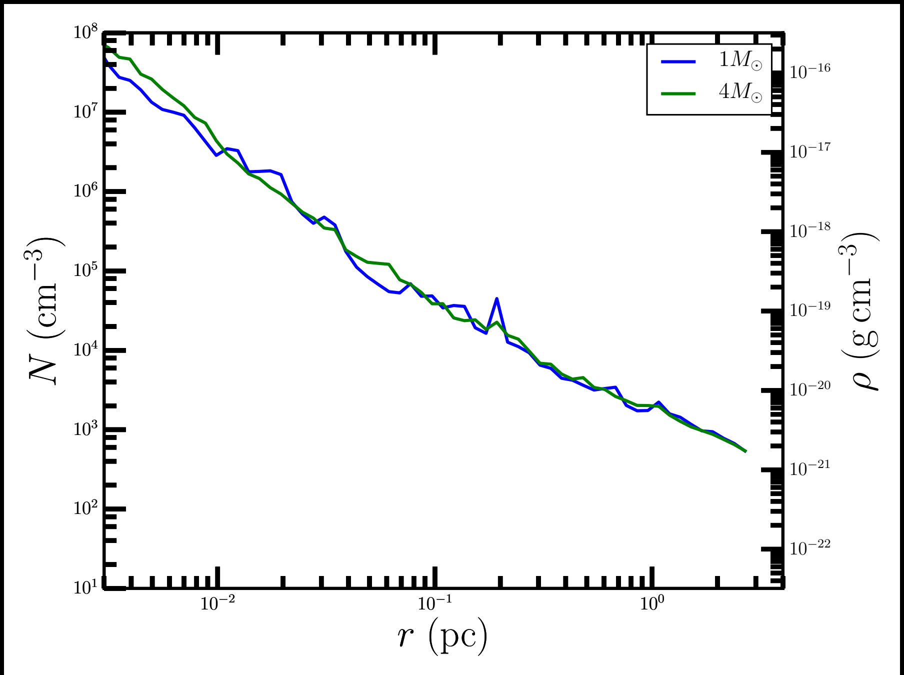
MHD



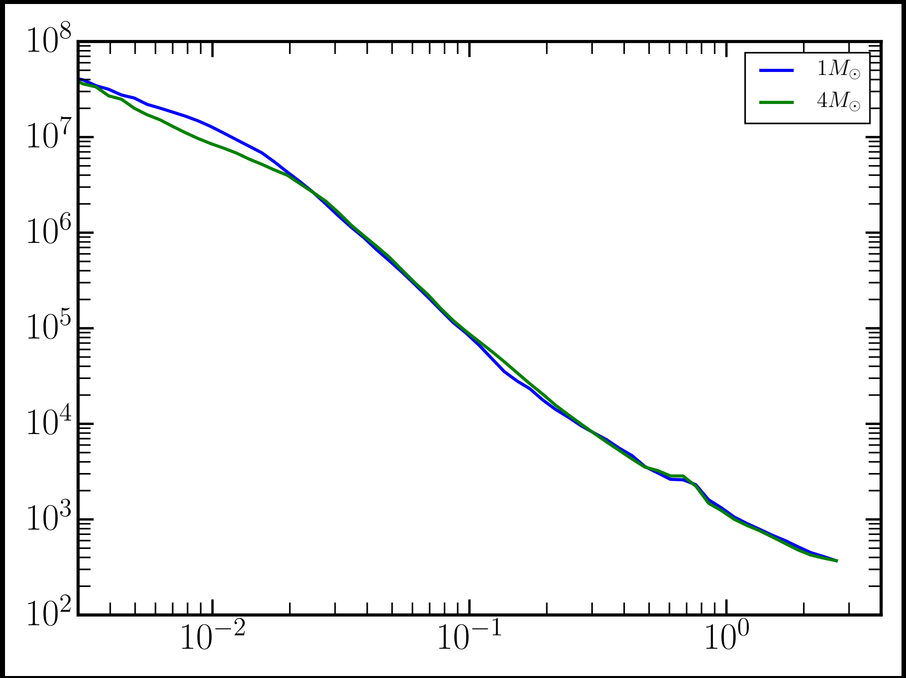
- Density is a power law: $\rho \propto r^{-1.9}$
- And independent of time -> attractor solution

Density -> Attractor

Hydro

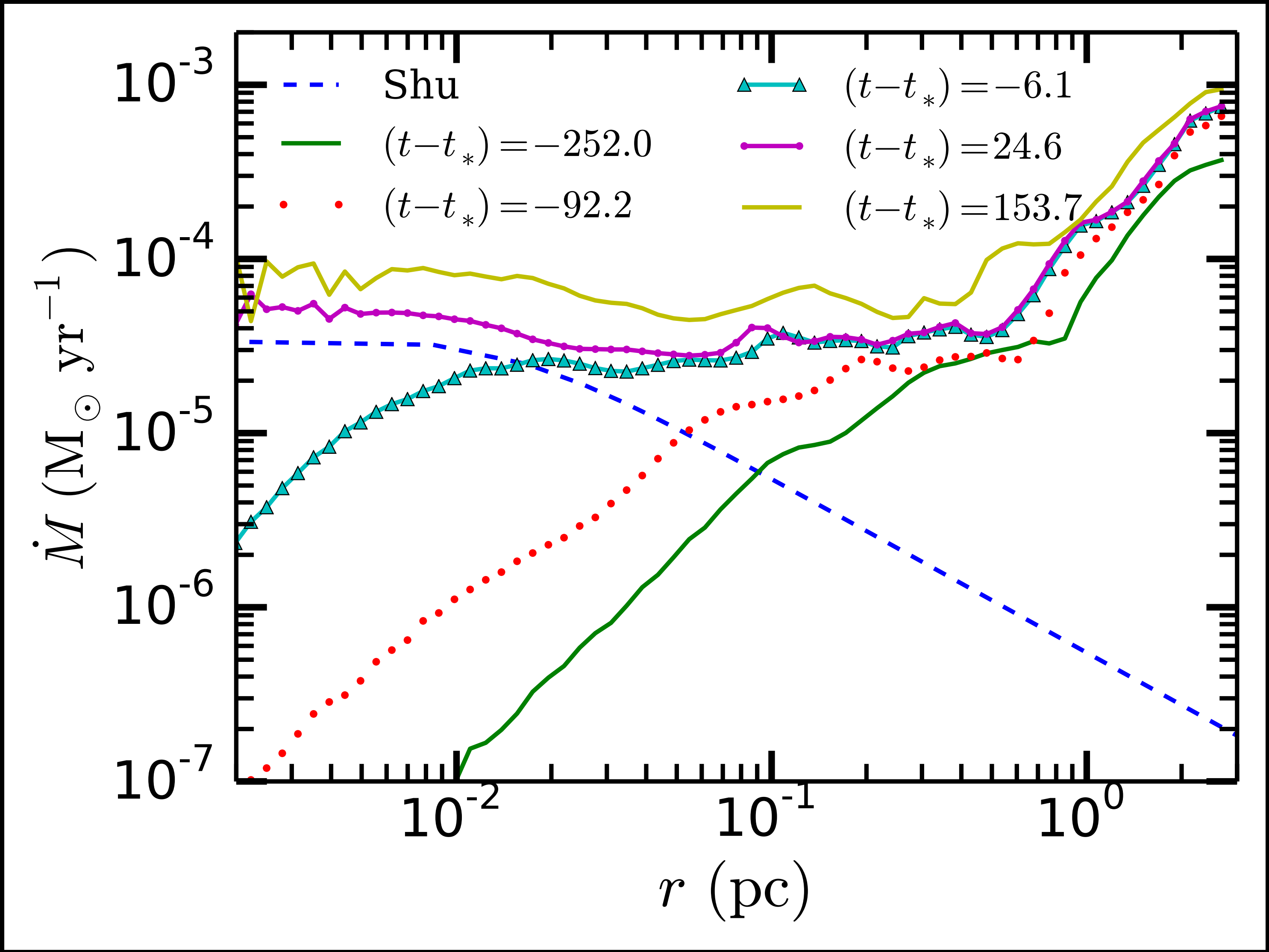


MHD



- Density is a power law: $\rho \propto r^{-1.9}$
- And independent of time -> attractor solution

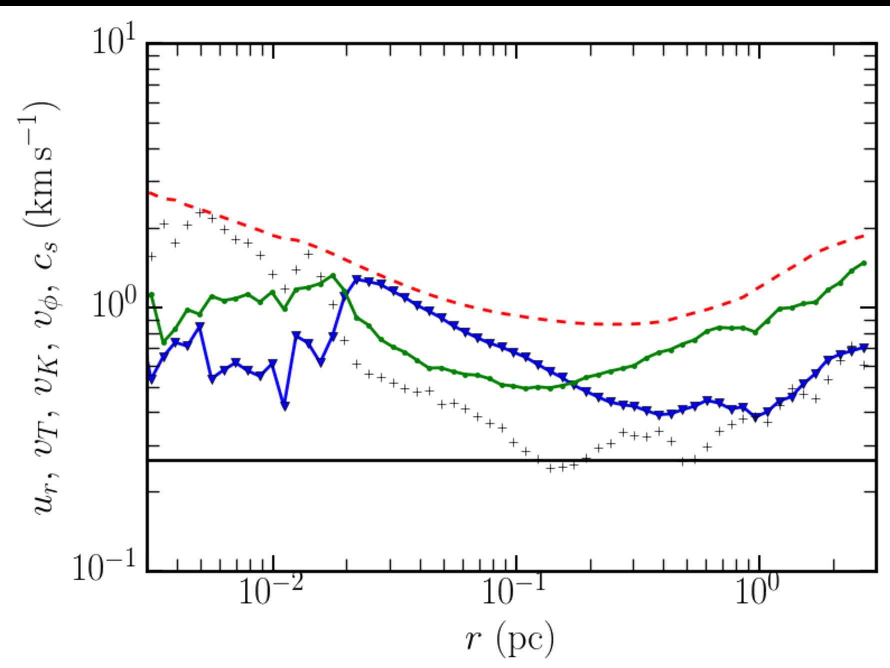
$\dot{M}_*(r,t)$



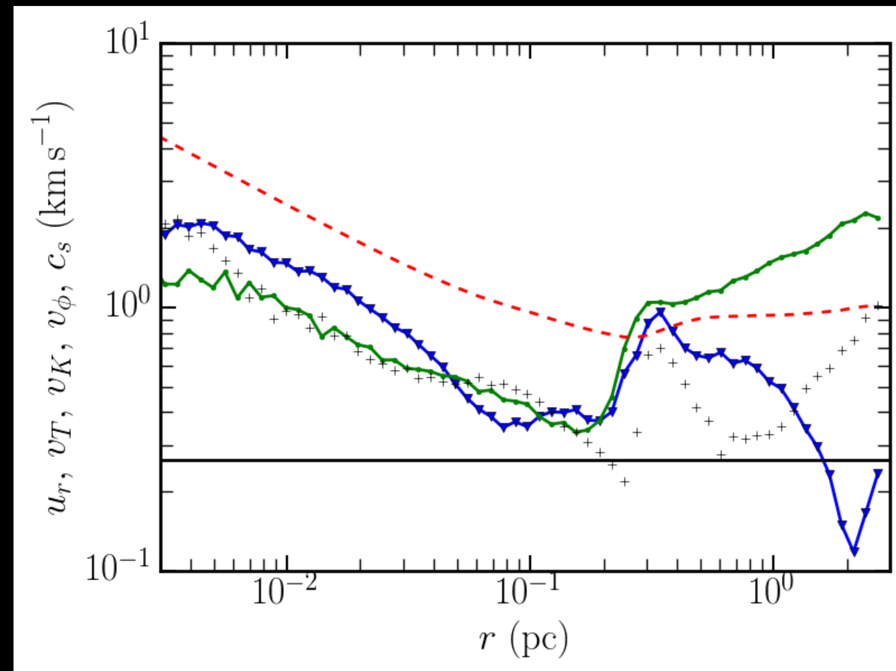
Shu
$(t-t_*)=-252.0$
$(t-t_*)=-92.2$
$(t-t_*)=-6.1$
$(t-t_*)=24.6$
$(t-t_*)=153.7$
$\dot{M}$ ($M_\odot$ yr^{-1})
r (pc)
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-2}
10^{-1}
10^{0}

Inversion of Velocity and R_*

Hydro



MHD



This Implies M(t) ≈ t²

- Density is an attractor solution at small r

$$\rho(r,t) \rightarrow \rho(r)$$

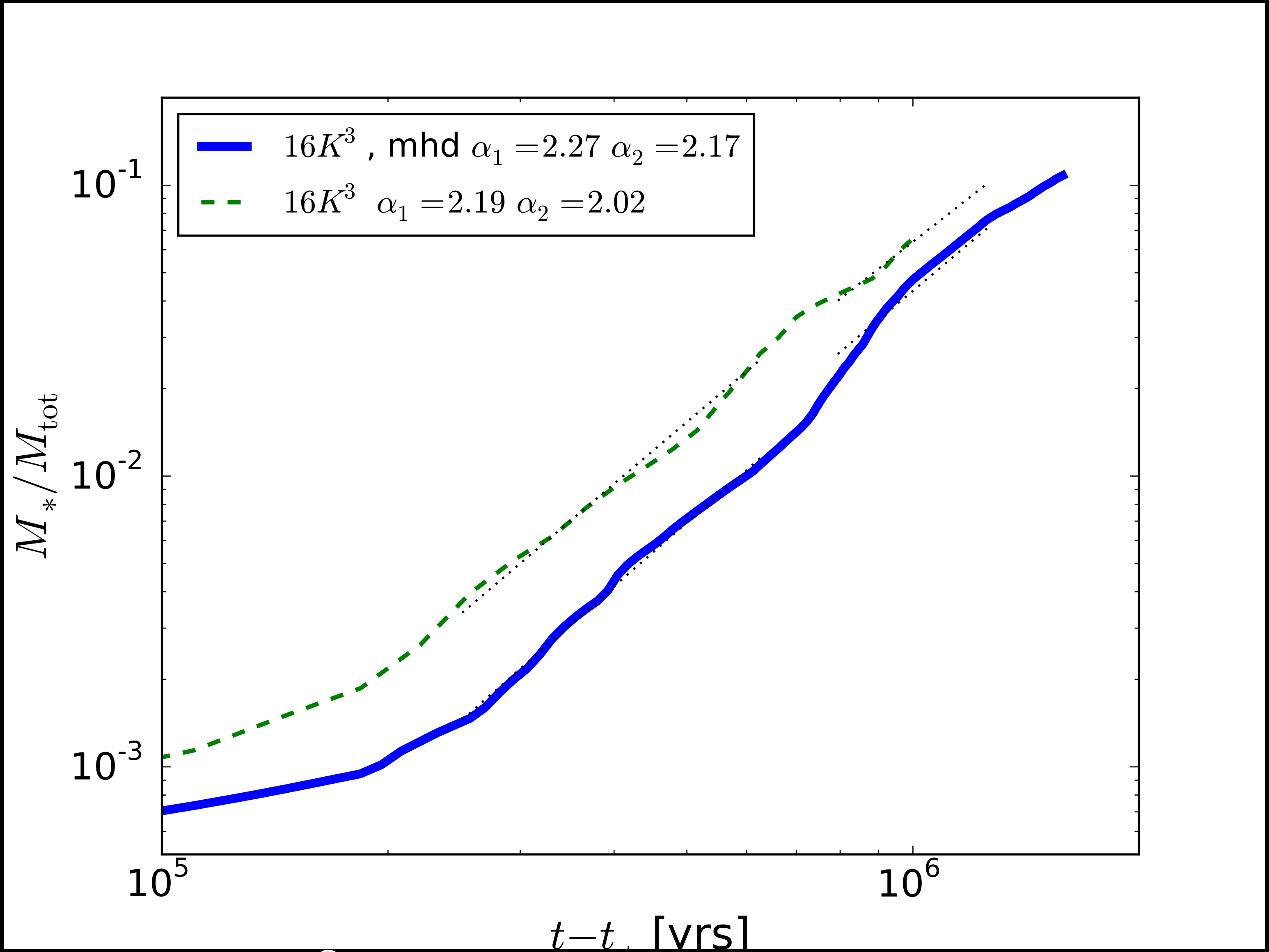
- Velocity scales with mass

$$u_r(r,t) \propto M_*^{1/2}(t) r^{-1/2}$$

- $\dot{M}_* = 4\pi r^2 u_r \rho \rightarrow \dot{M}_* \propto M_*^{1/2}$

- And so: $M_* \propto t^2$

Mass in Stars over time

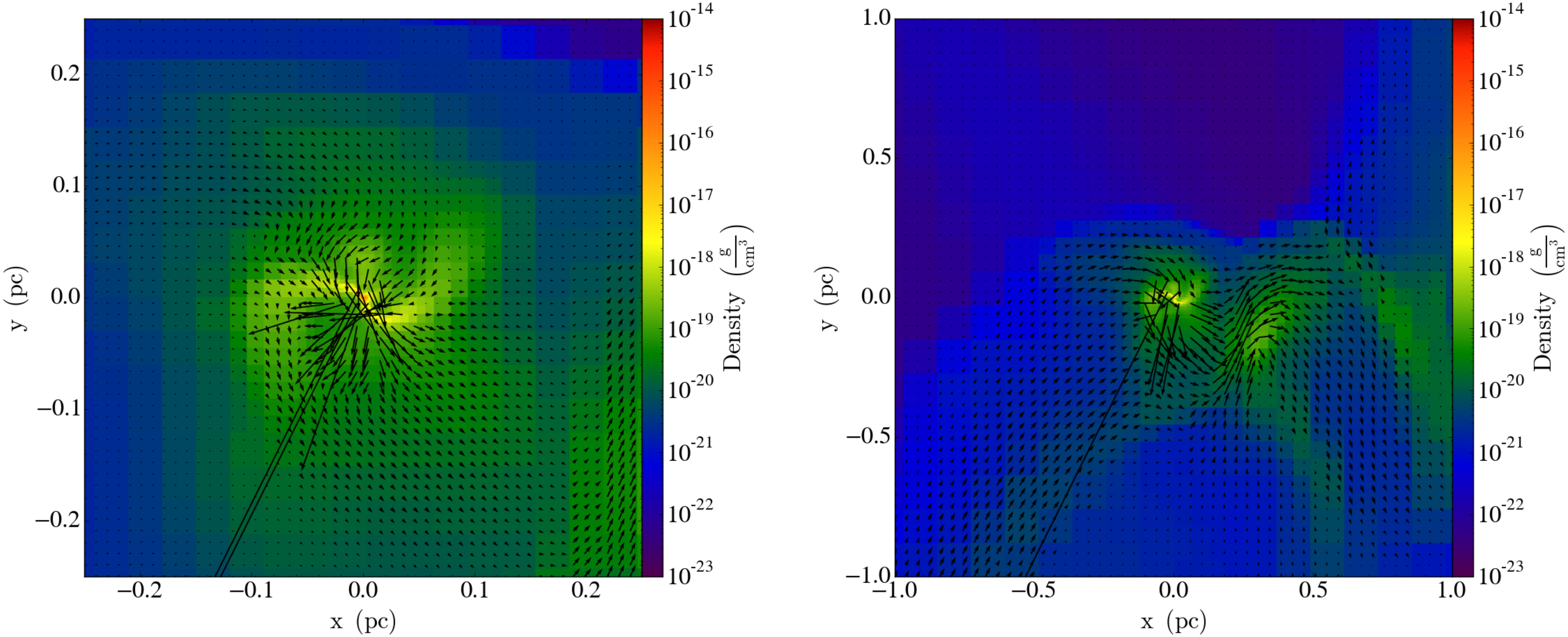


$$M_* \propto t^2 \text{ once } M_*/M_{GMC} \sim 0.001$$

Conclusions

- Density is attractor solution -> lifetime of the observed structures is not the same as the local dynamical time
- $M(t) \sim t^2$ -> large variation in SFE
- v(r,t) -> deviation from Larson @ small scales,
  - Explains observations of Plume et al, Caselli and Myers

Snapshot of MHD Sink



Future Work

- Numerically:
  - Inclusion of Magnetic fields
  - Feedback
    - Radiative transfer
    - Protostellar feedback
- Analytically:
  - Incorporate angular momentum into the theory of Murray & Chang (2015)

Velocity inversion – FLASH4

Additional Slides

- SFR starts slow but accelerates with time
- Density is attractor solution -> lifetime of the observed structures is not the same as the local dynamical time
- $M(t) \sim t^2$ -> large variation in SFE
- v(r,t) -> deviation from Larson @ small scales,
  - Explains observations of Plume et al, Caselli and Myers
- Disk arise spontaneously from turbulent fluctuations

Larson; Penston; Shu Solution eqns

$$\frac{\partial \rho}{\partial t} + \frac{1}{r^2}\frac{\partial}{\partial r}(r^2 \rho u_r) = 0$$

$$\frac{\partial u_r}{\partial t} + u_r \frac{\partial u_r}{\partial r} = -\frac{c_s^2}{\rho}\frac{\partial \rho}{\partial r} - \frac{GM_{gas}}{r^2}$$

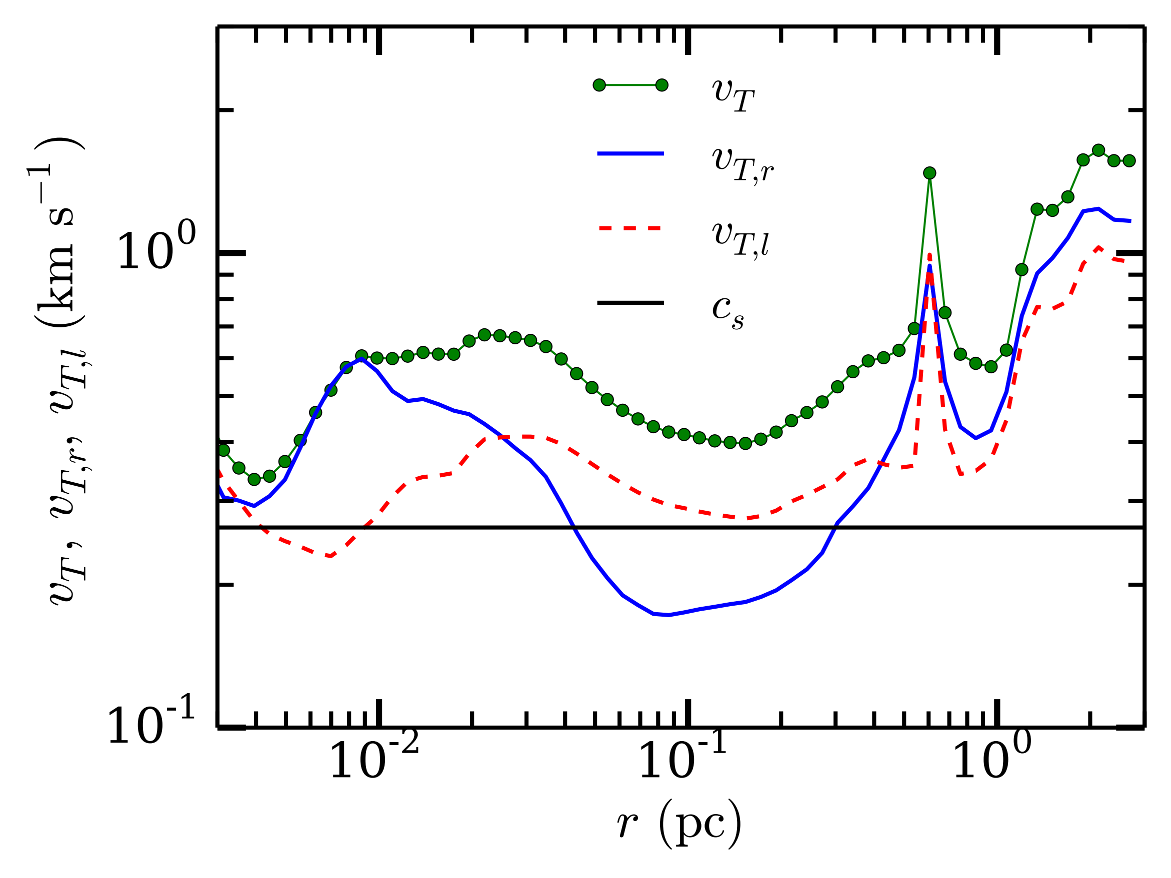
$$P = \rho c_s^2$$

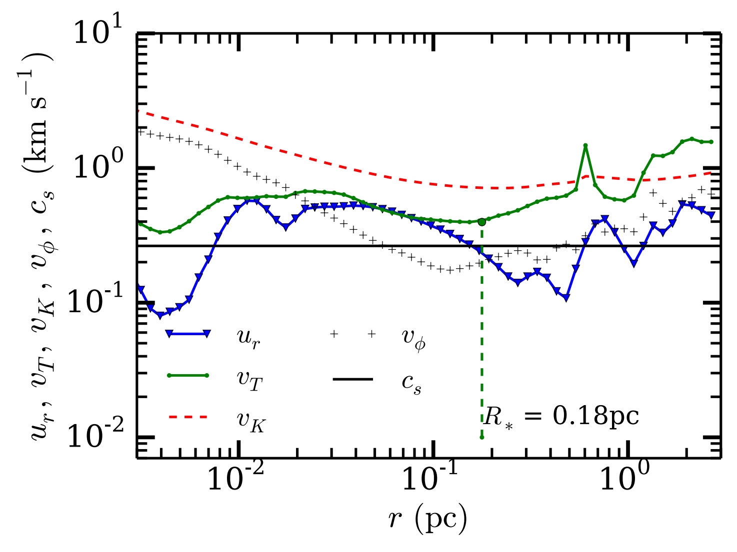
Myers & Fuller; McLaughlin & Pudritz; McKee & Tan Solution eqns

$$\frac{\partial \rho}{\partial t} + \frac{1}{r^2}\frac{\partial}{\partial r}(r^2 \rho u_r) = 0$$

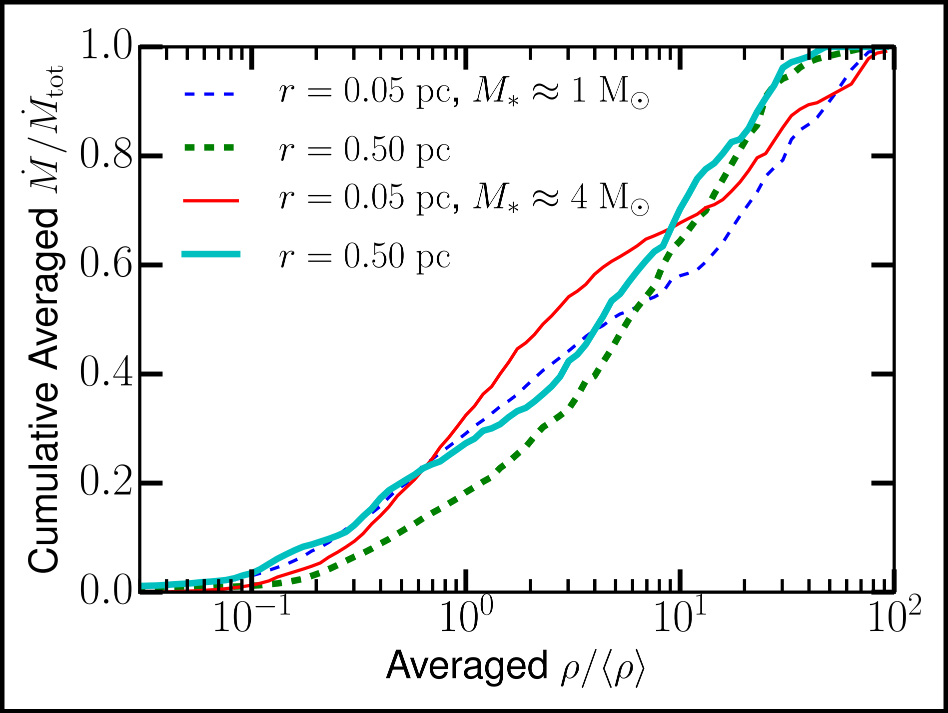
$$\frac{\partial u_r}{\partial t} + u_r \frac{\partial u_r}{\partial r} = -\frac{1}{\rho}\frac{\partial \rho v_T^2(r)}{\partial r} - \frac{GM(r)}{r^2}$$

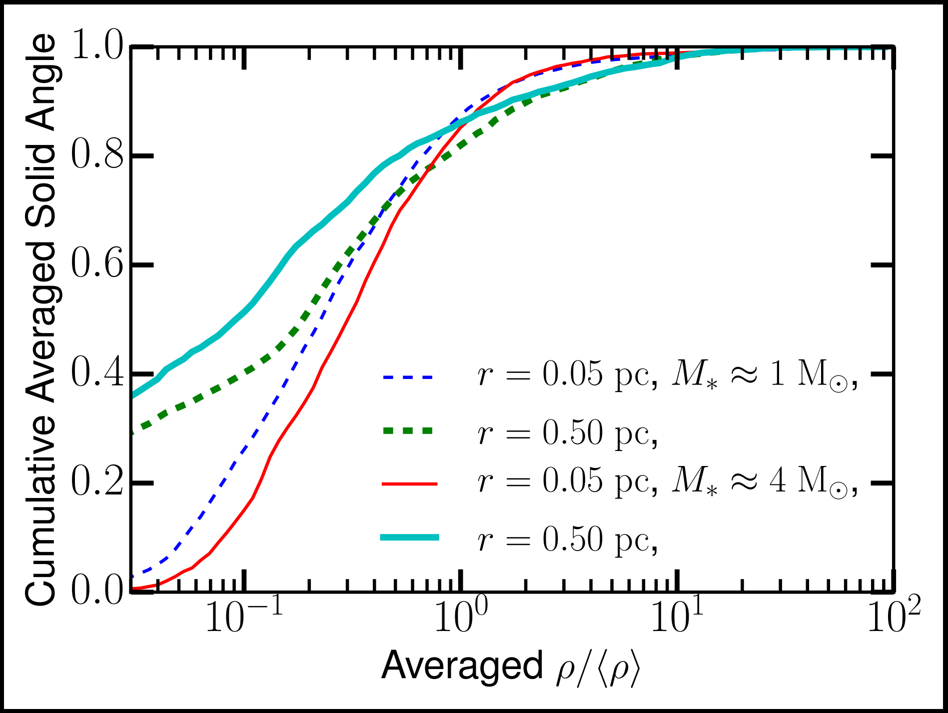
Breakup of Turbulent Velocity



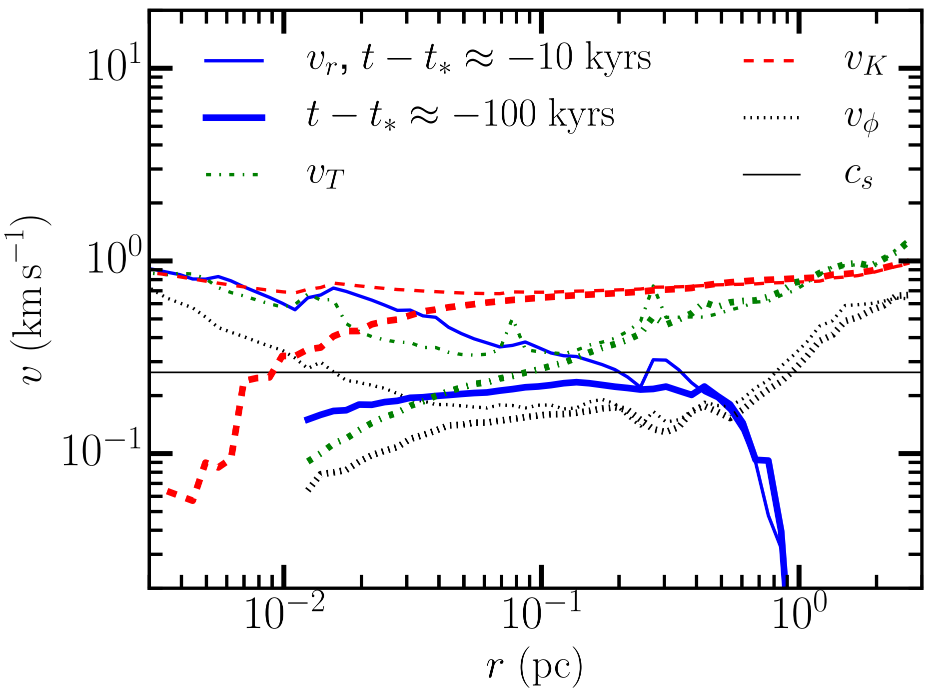


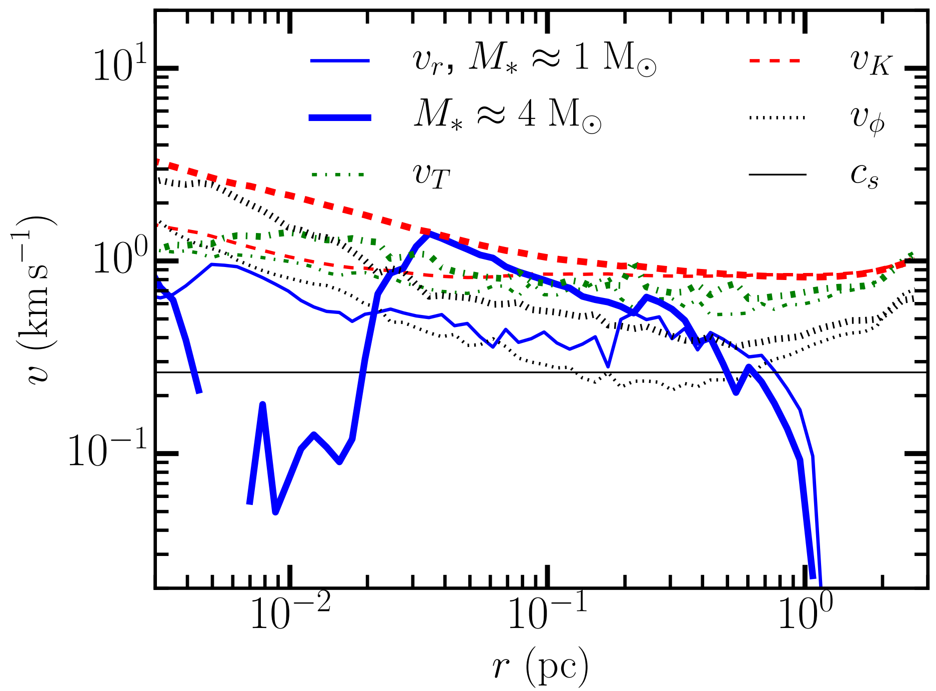
The Spherical Inflow Assumption



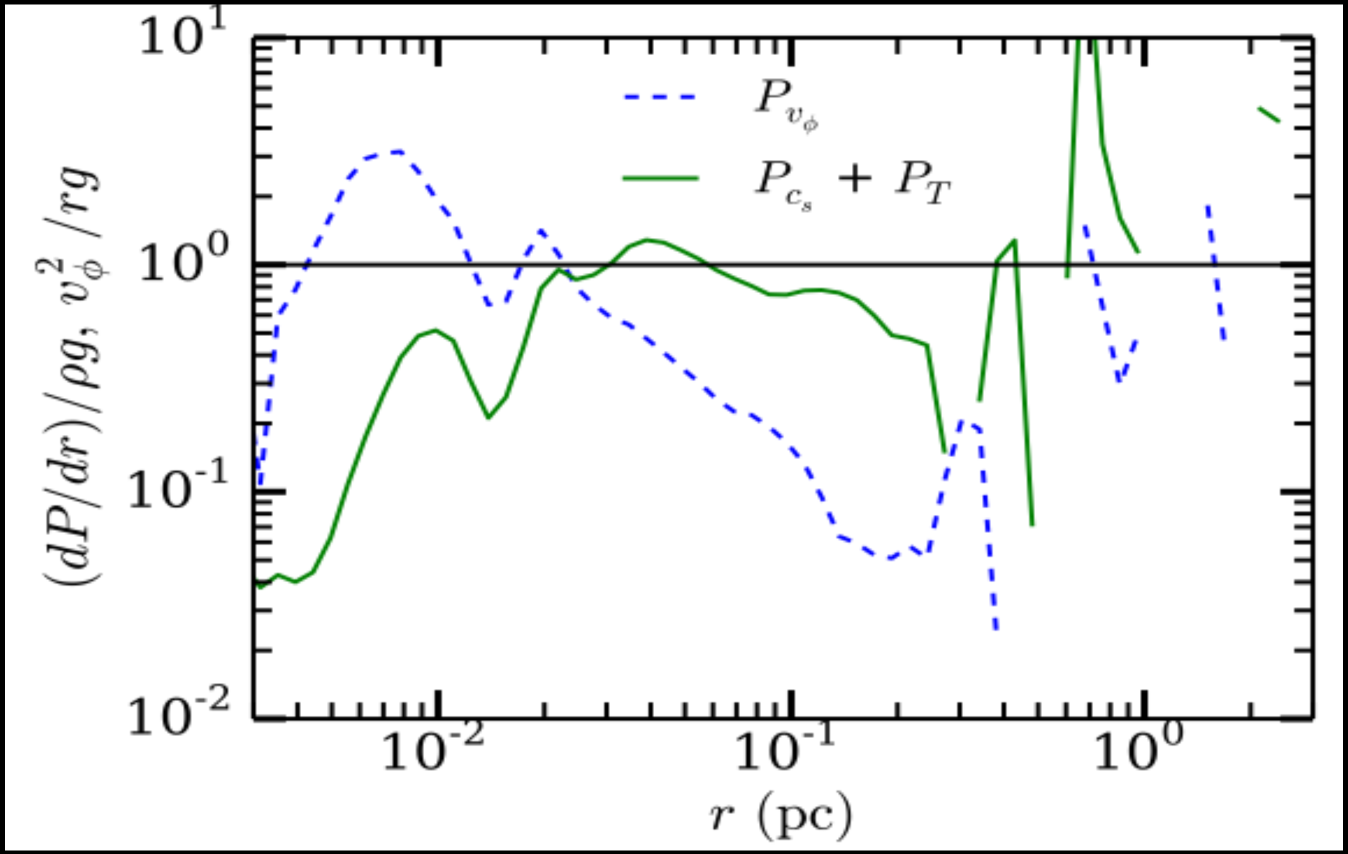


Velocity Profile Agregate



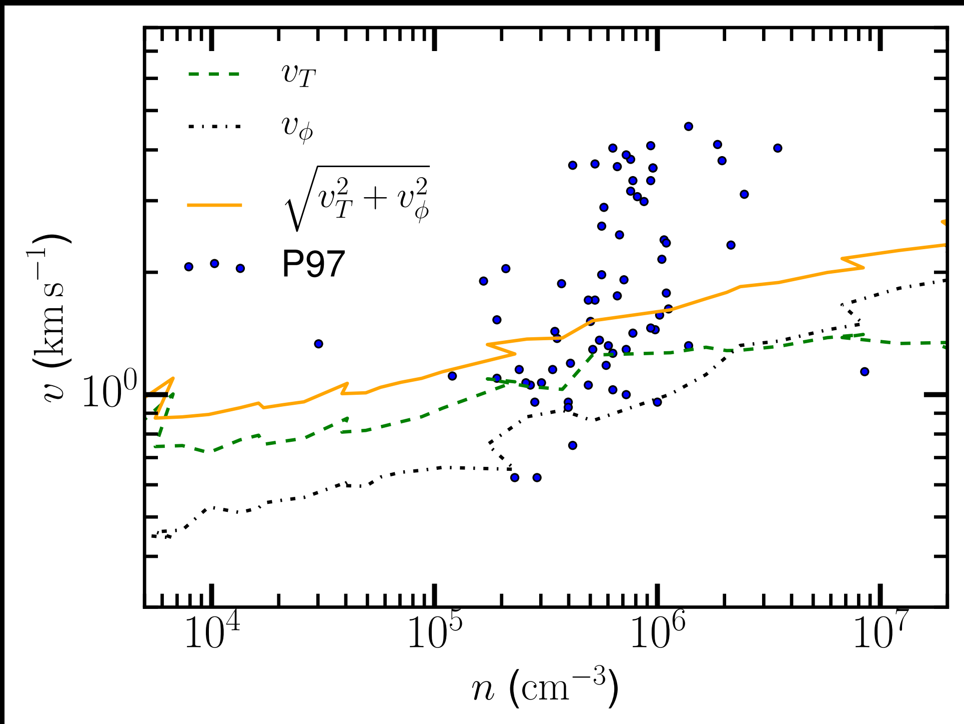


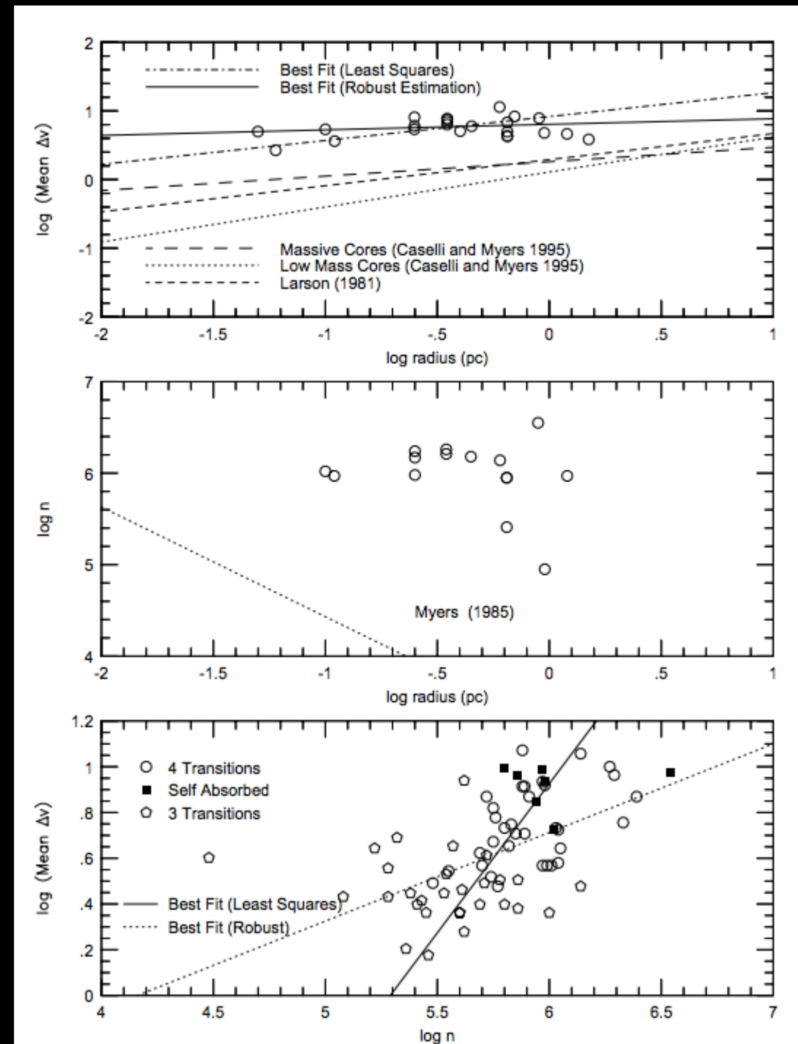
Pressure Gradient



The acceleration from the pressure gradient exceeds that from gravity for $r > r_*$; the reverse is true for $r < r_*$.

Comparison to Observations





Some evidence that v increases with density for star forming clumps