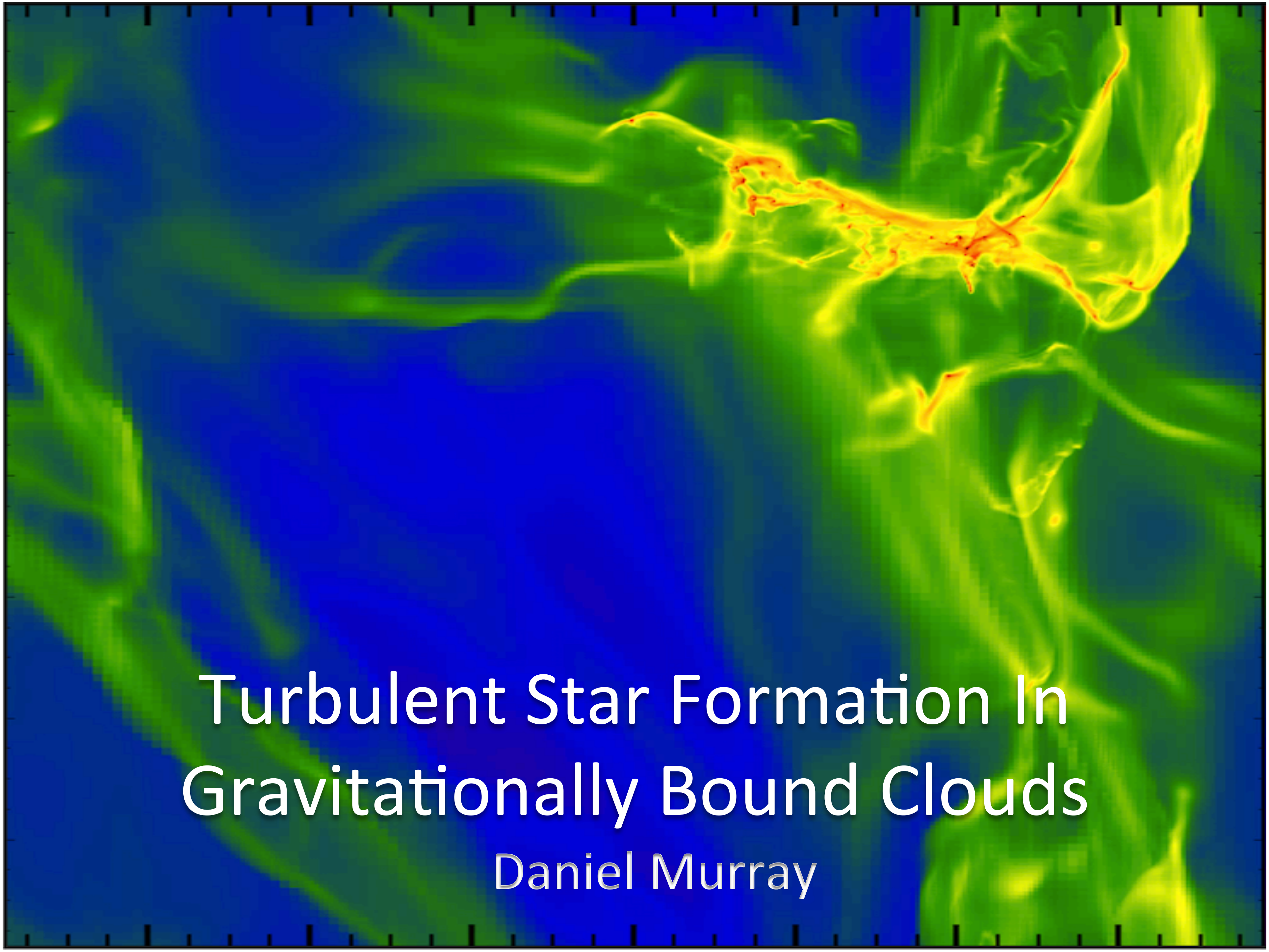


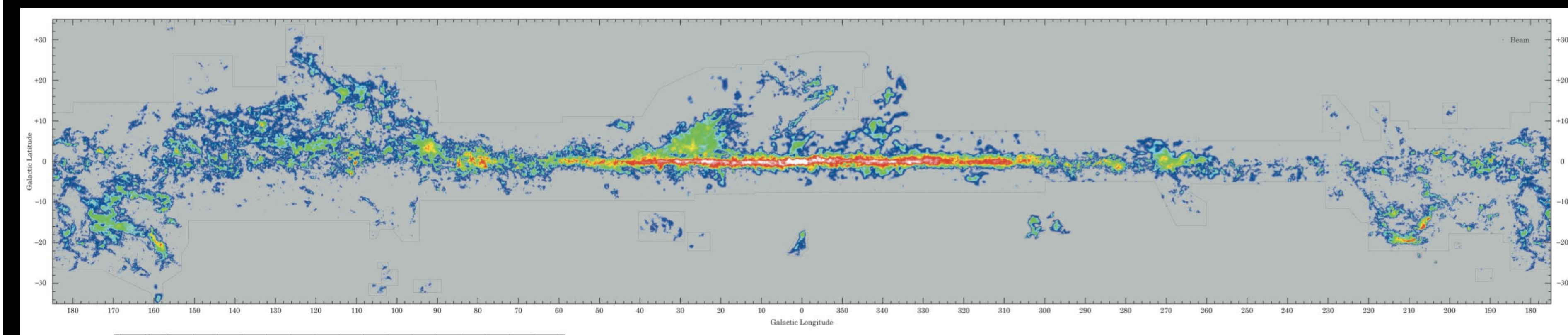
Turbulent Star Formation In Gravitationally Bound Clouds

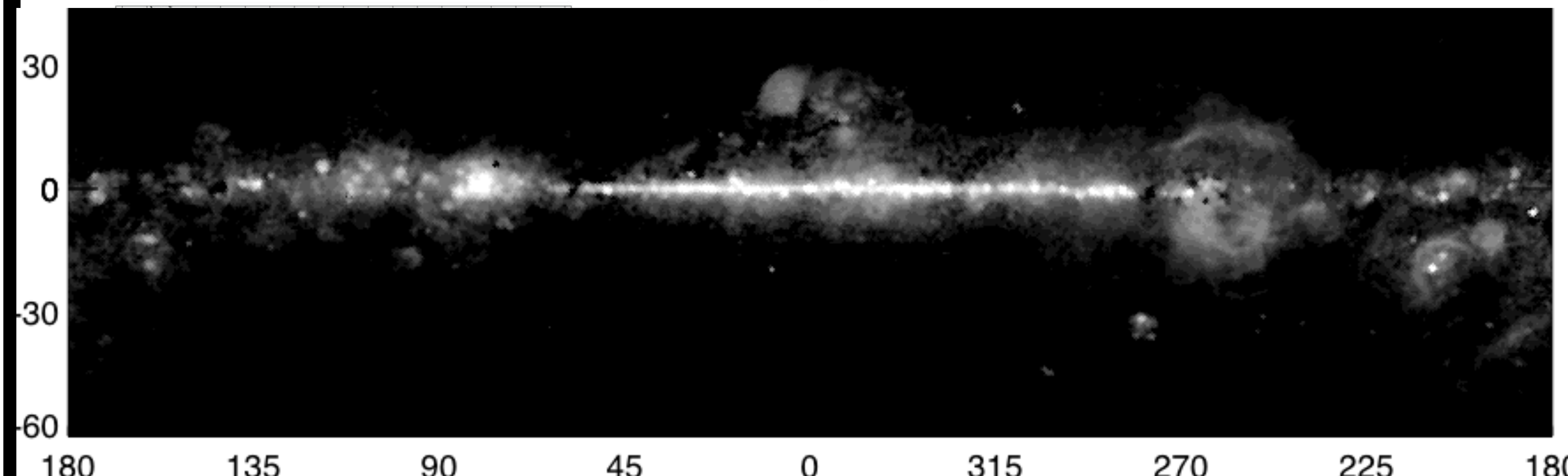
Daniel Murray

Outline

- Phenomenology of Star Formation
- Analytic Theories of Star Formation
- Numerical Simulations and Results
- Conclusions

Where do Stars form?





Stars form in Giant Molecular Clouds

- Milky Way Galaxy is ~50-50 atomic to molecular gas
- Stars have only been seen forming in molecular gas
- Most stars form in the most massive clouds
- Giant Molecular Clouds have virial parameters of order unity (gravitationally bound)
- The gas in these clouds is seen to have highly supersonic turbulence: Mach 10 – 20 (e.g. Liszt et al. 74)
- Relation between Cloud size and line-width: attributed to turbulence (Larson 81)

Carina Nebula

Cloud Size, Line-width Relation

Larson 1981

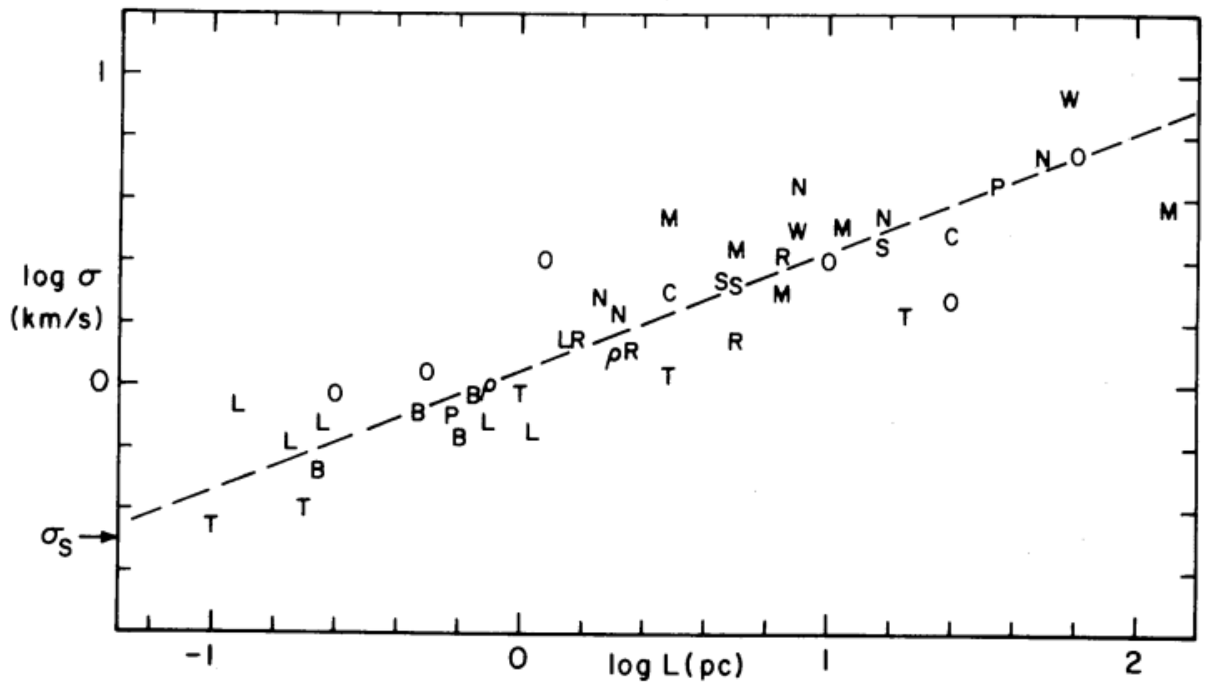
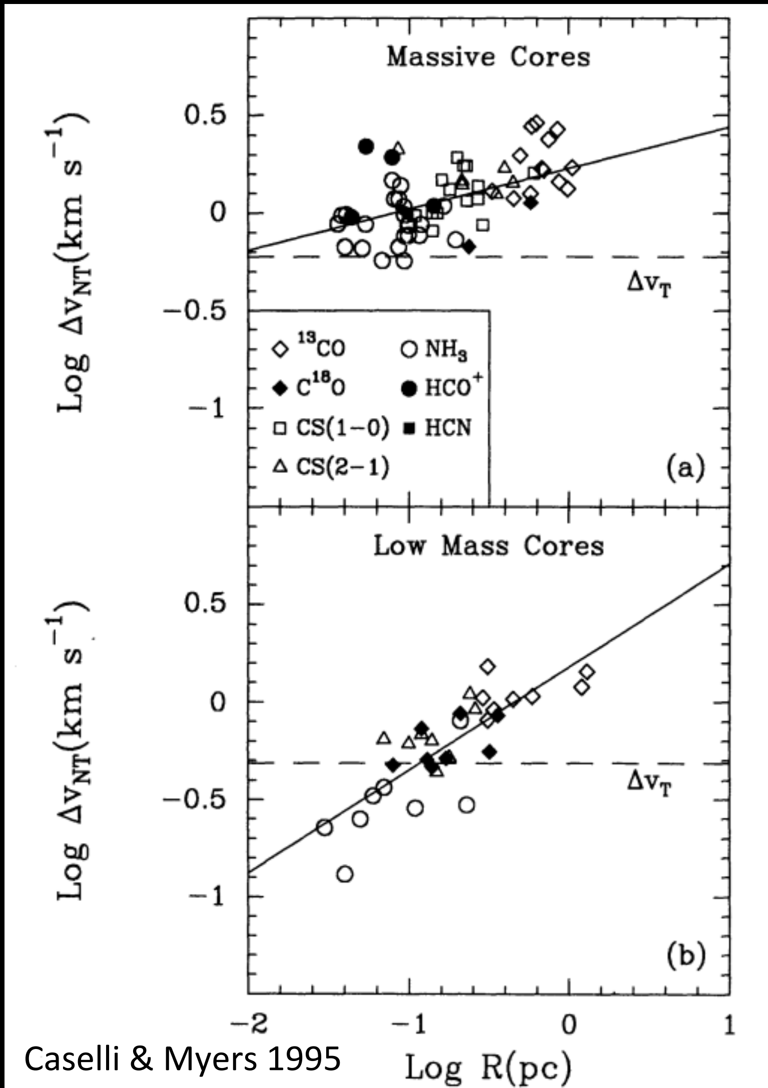


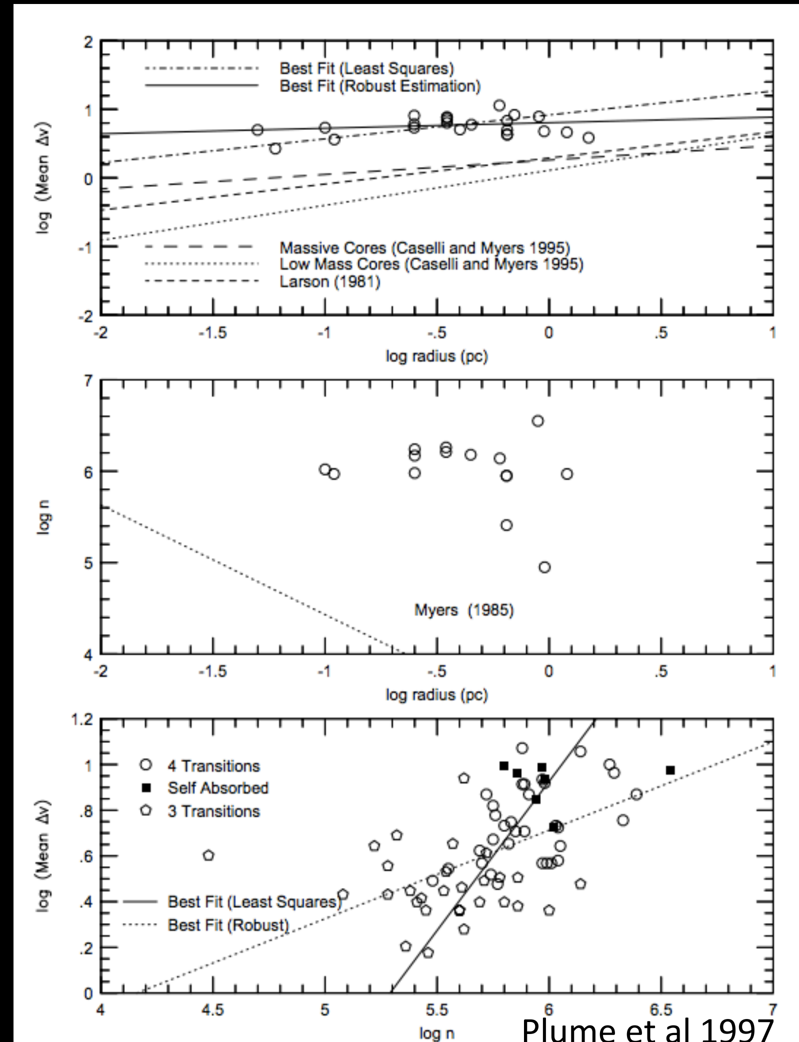
Figure 1. The three-dimensional internal velocity dispersion σ plotted versus the maximum linear dimension L of molecular clouds and condensations, based on data from Table 1; the symbols are identified in Table 1. The dashed line represents equation (1), and σ_S is the thermal velocity dispersion.

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

Velocity dispersion size

Deviations from Larsons Law





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

How fast do stars form?

Given by Kennicutt-Schmidt law on galaxy scales

- Naively $t_{collapse} \approx t_{ff}$

$$t_{ff} = \sqrt{\frac{3\pi}{32G\rho}}$$

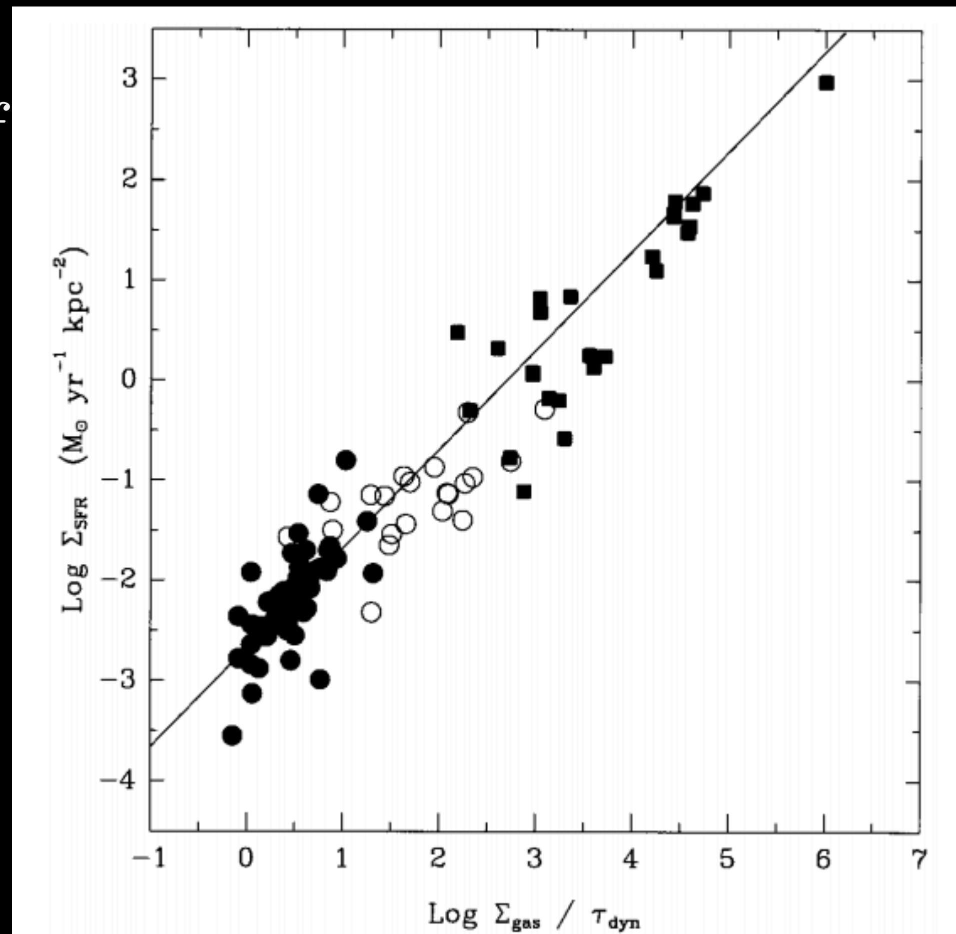
$$\dot{\Sigma}_* = \epsilon \Sigma_g t_{ff}^{-1}$$

Where: $\epsilon = 1$

Instead: $\epsilon \approx 0.017$

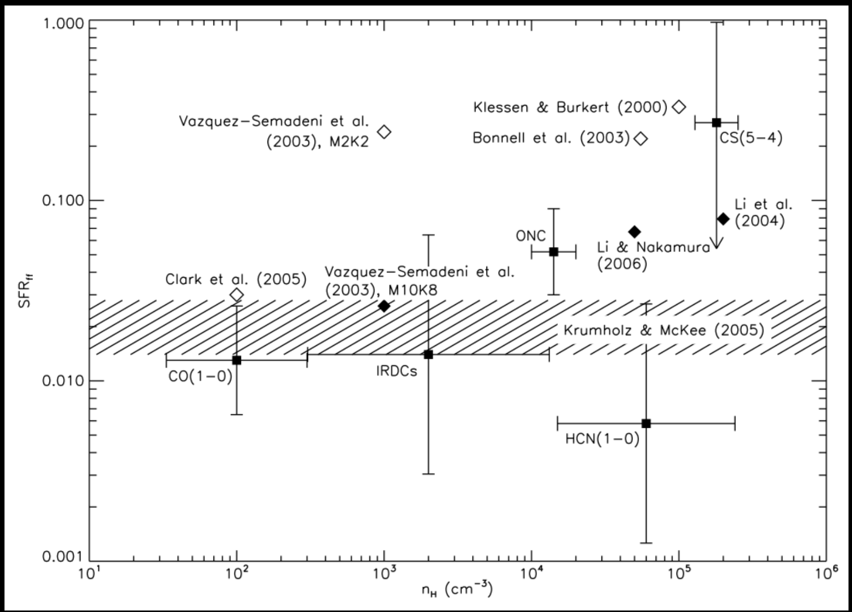
$$t_{collapse} \approx 50 t_{ff}$$

Star formation is slow !

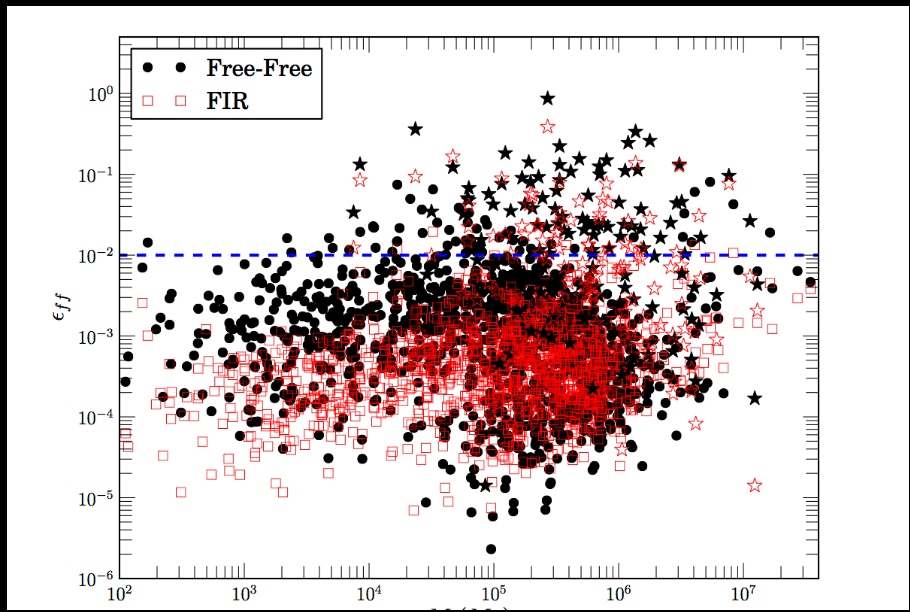


Kennicutt 1998

Is star formation slow on GMC or smaller scales?



Krumholz & Tan (2007) ApJ 654 304



Mivelles-Deschene, Murray, & Lee (2016)

- SFE independent of density
- Claim little scatter in SFE

- Large scatter in SFE vs GMC mass

Why is Star Formation so slow?

- Thermal pressure support HSE (Larson 69; Penston 69; Shu 77)
- Magnetic pressure support
- Turbulent pressure support HSE (Myers; McLaughlin; McKee & Tan)
- Turbulence (Padoan & Nordlund; Krumholz & McKee)
- Stellar Feedback

Early analytic theories of star formation

- Larson 69; Penston 69
  - 2 equations Mass and Momentum conservation
  - Energy eqn replaced by isothermality $P = \rho c_s^2$
  - BC's $u_r = 0$ at $r = 0$ and $u_r = \infty$ at $r = \infty$
- Shu 77
  - BC's $u_r = \infty$ at $r = 0$ and $u_r = 0$ at $r = \infty$

$$M_*(t) \approx \frac{c_s^3 t}{G} \quad \dot{M}_*(t) \approx 4 \times 10^{-6} M_\odot yr^{-1}$$

  - Cannot form the most massive stars

Myers & Fuller 92; McLaughlin & Pudritz 97; McKee & Tan 03

- Turbulent Core Model
  - The sound speed c_s -> turbulent velocity v_T

$$P = \rho v_T^2(r)$$

  - Allow for faster propagation on information -> faster accretion rate -> can form massive stars.
  - Turbulent velocity is fixed as function of r.

Murray and Chang 15

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

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

Robertson & Goldreich 2012

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

- Also define r_* to be a physical scale

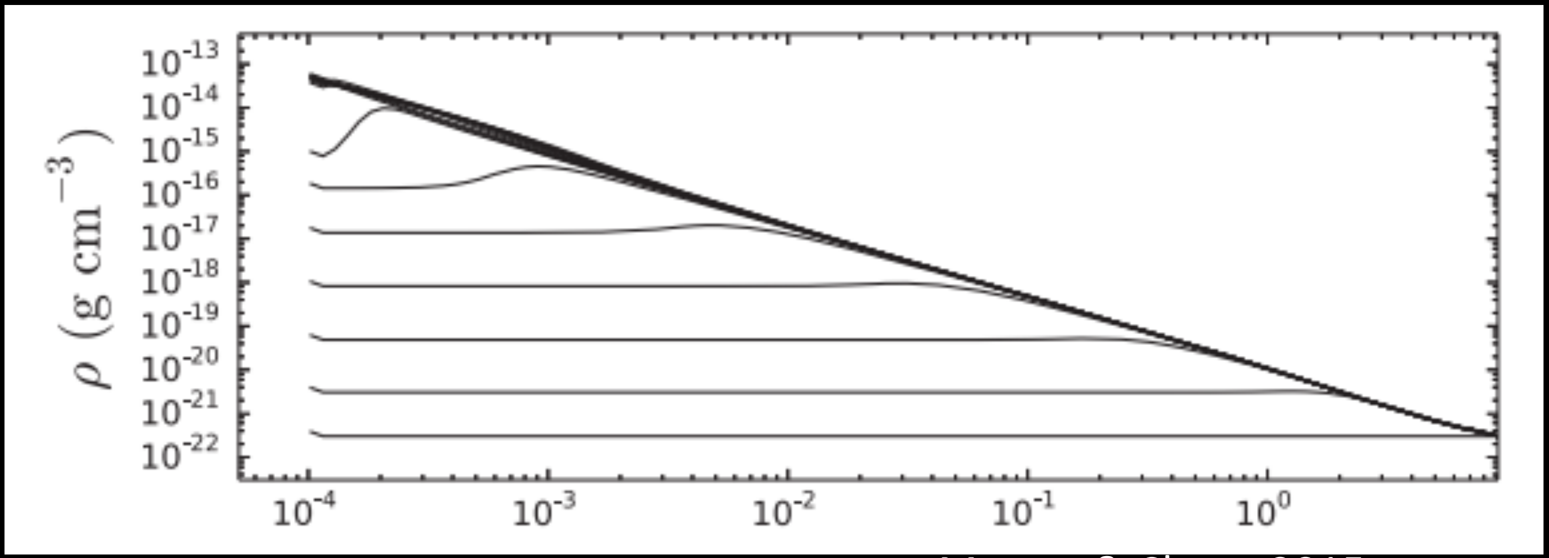
$$M_*(t) \sim M_g(< r_*(t), t)$$

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

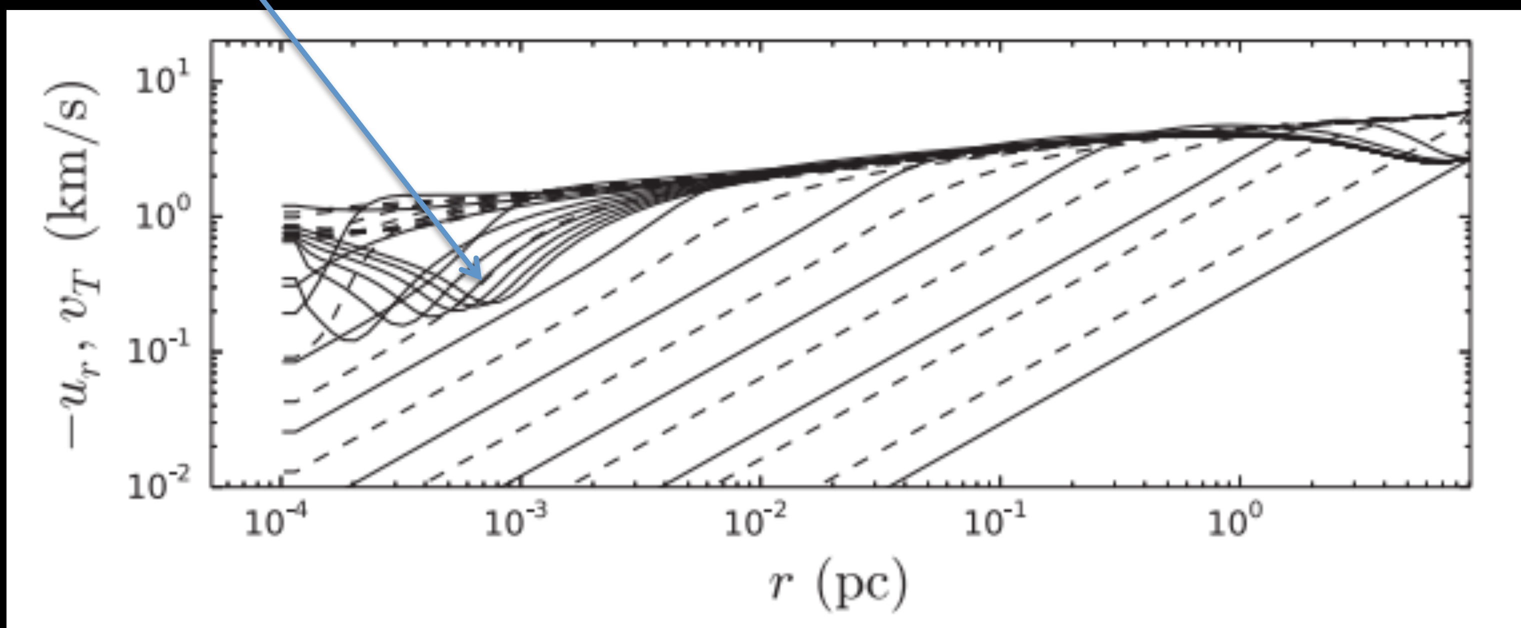
Predictions of Murray and Chang 15 II

- Velocity scaling for large and small r

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

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

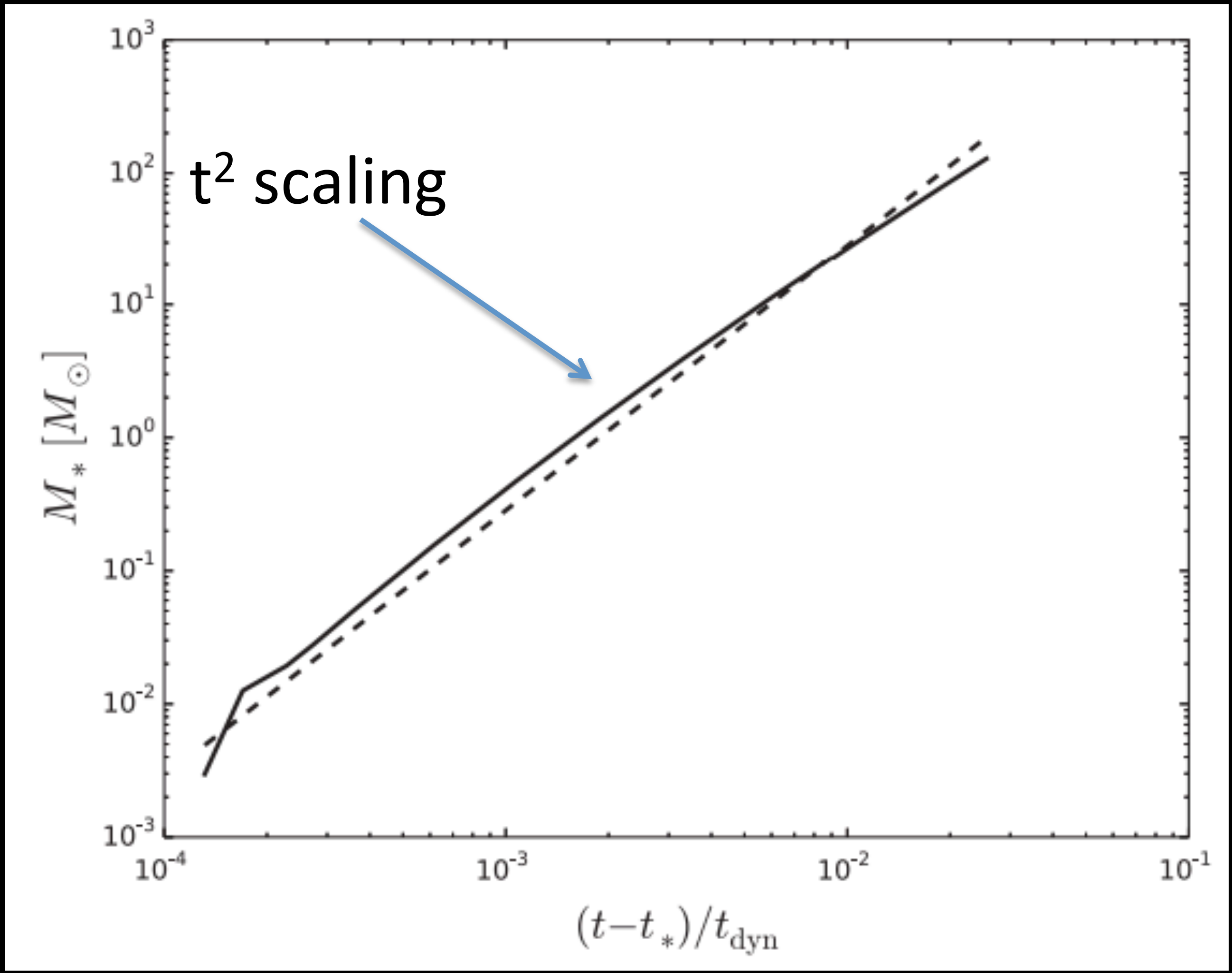
r_*



Murray & Chang 2015

Predictions of Murray and Chang 15 III

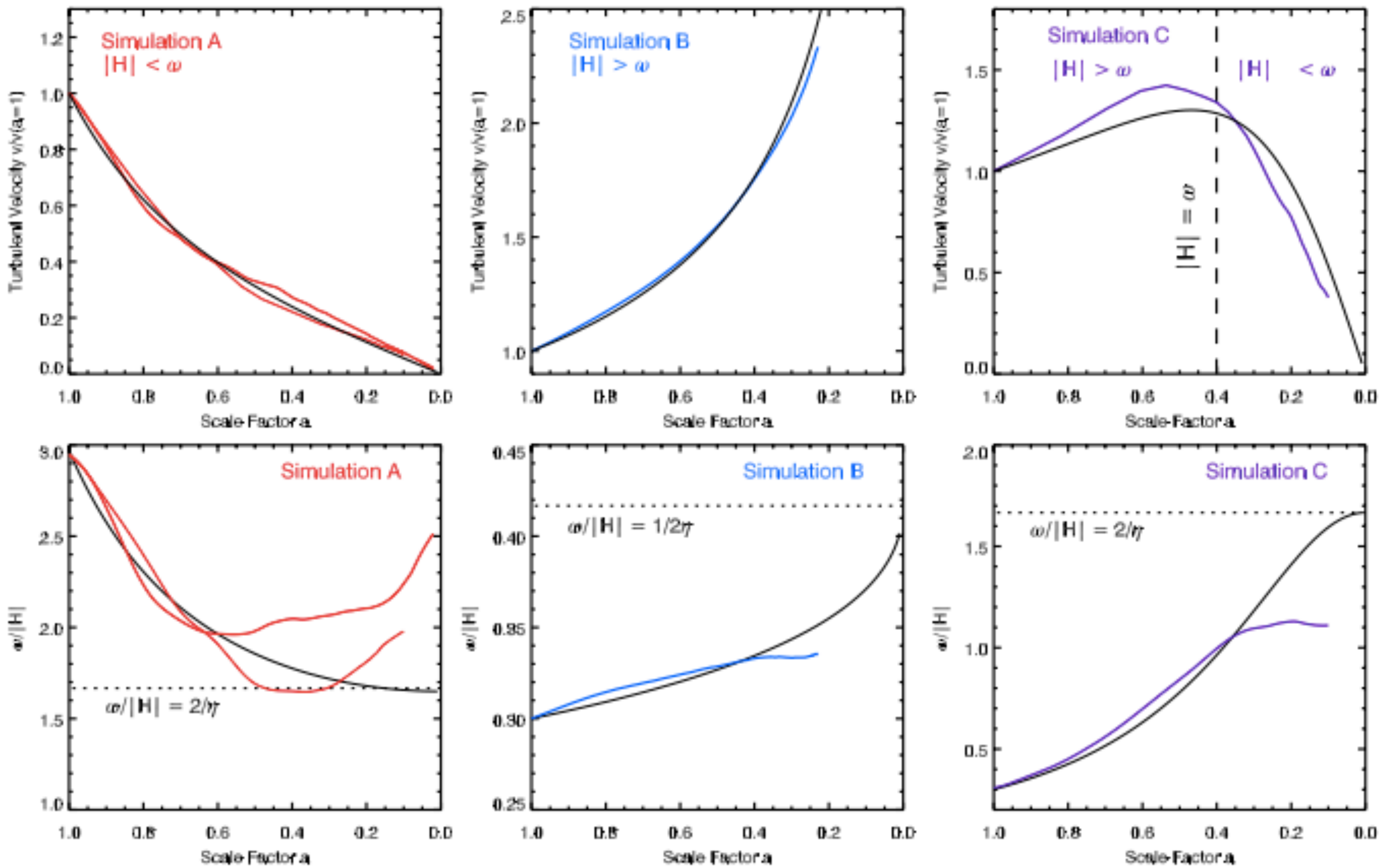
- Mass in stars scales like t^2

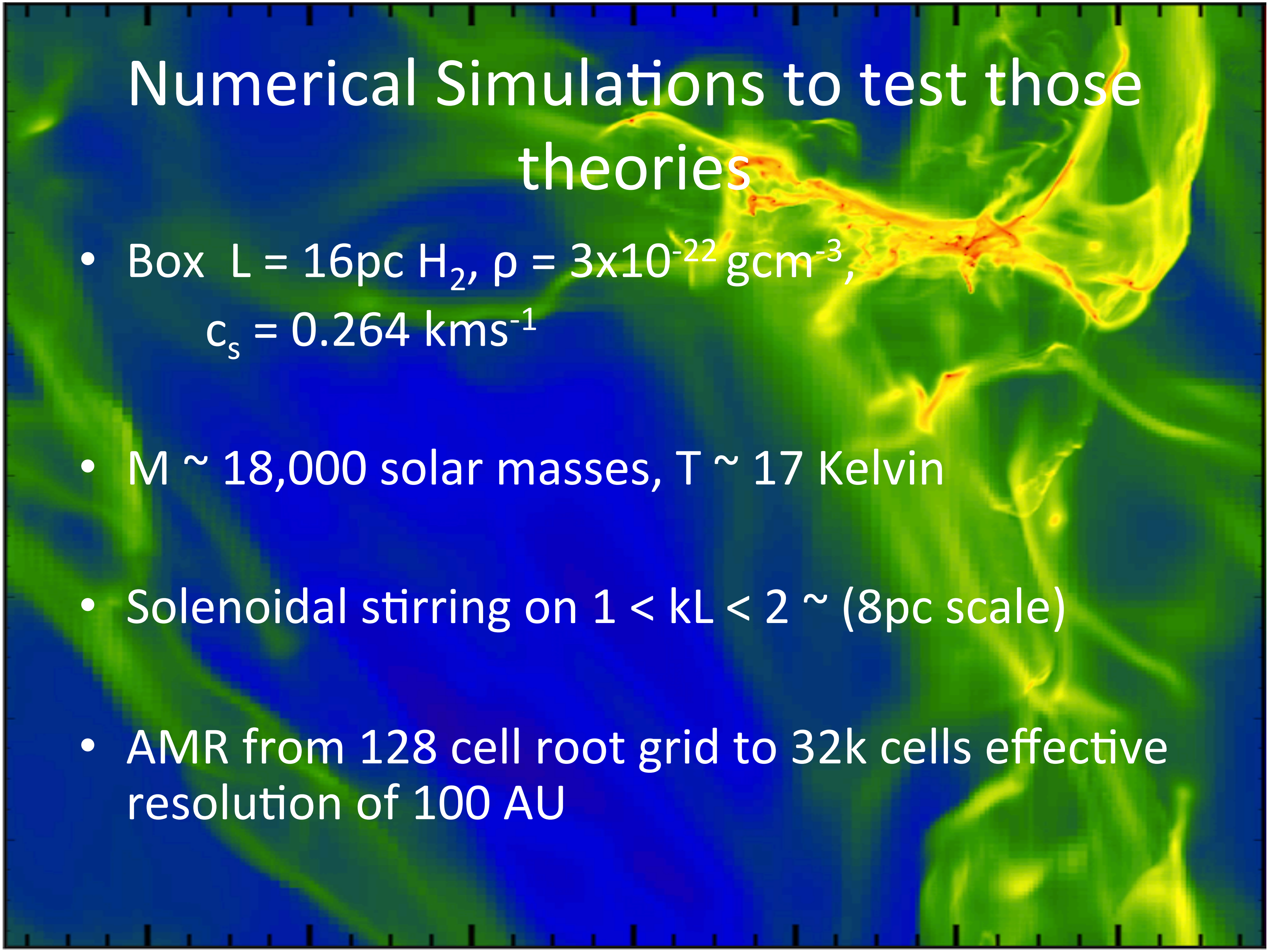


Murray & Chang 2015

Robertson & Goldreich 2012

Adiabatic Heating in Turbulence



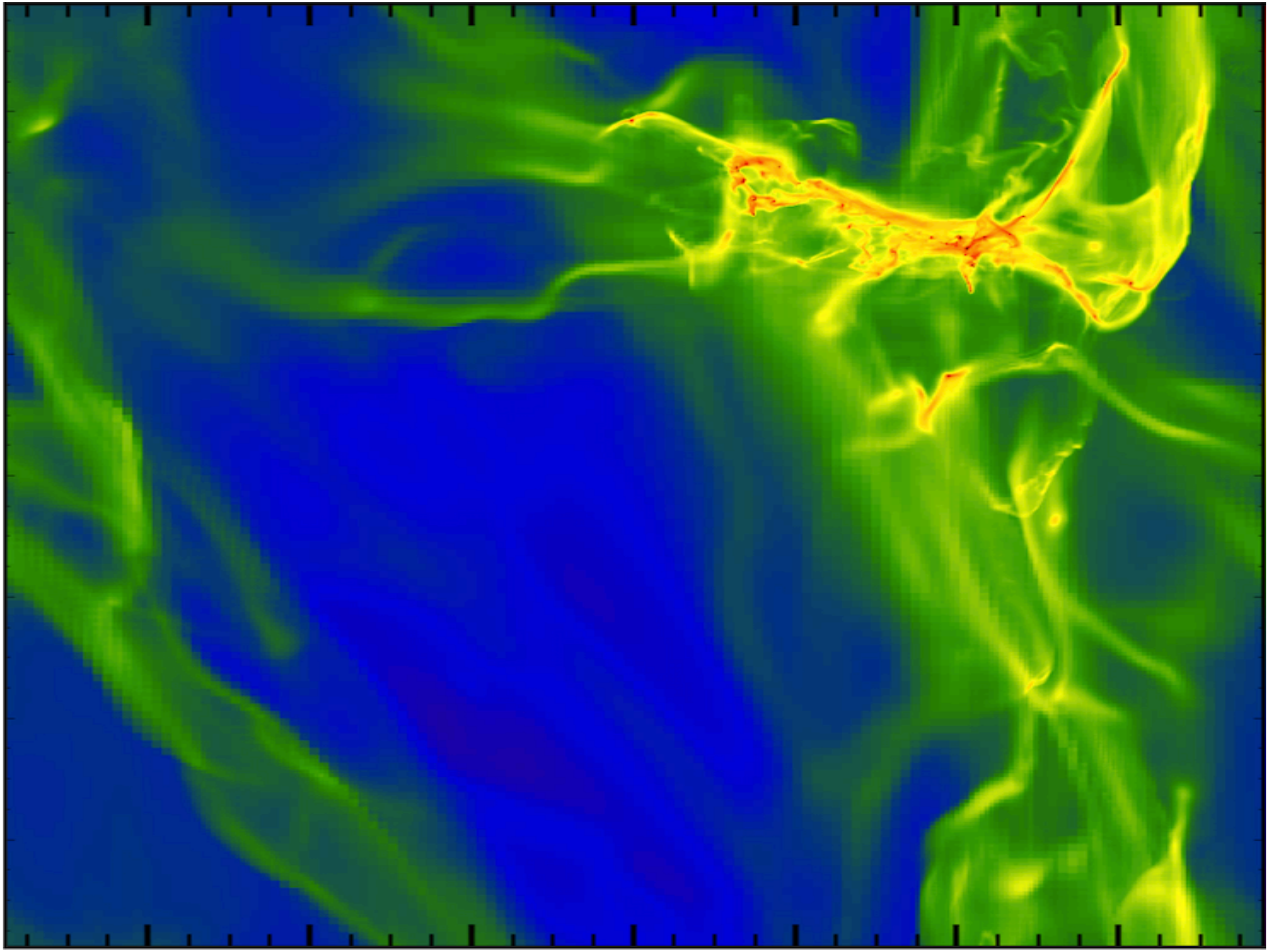


Numerical Simulations to test those theories

- Box L = 16pc H_2, $\rho = 3 \times 10^{-22}\ \mathrm{g cm^{-3}}$,
  $c_s = 0.264\ \mathrm{kms^{-1}}$
- M ~ 18,000 solar masses, T ~ 17 Kelvin
- Solenoidal stirring on 1 < kL < 2 ~ (8pc scale)
- AMR from 128 cell root grid to 32k cells effective resolution of 100 AU

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



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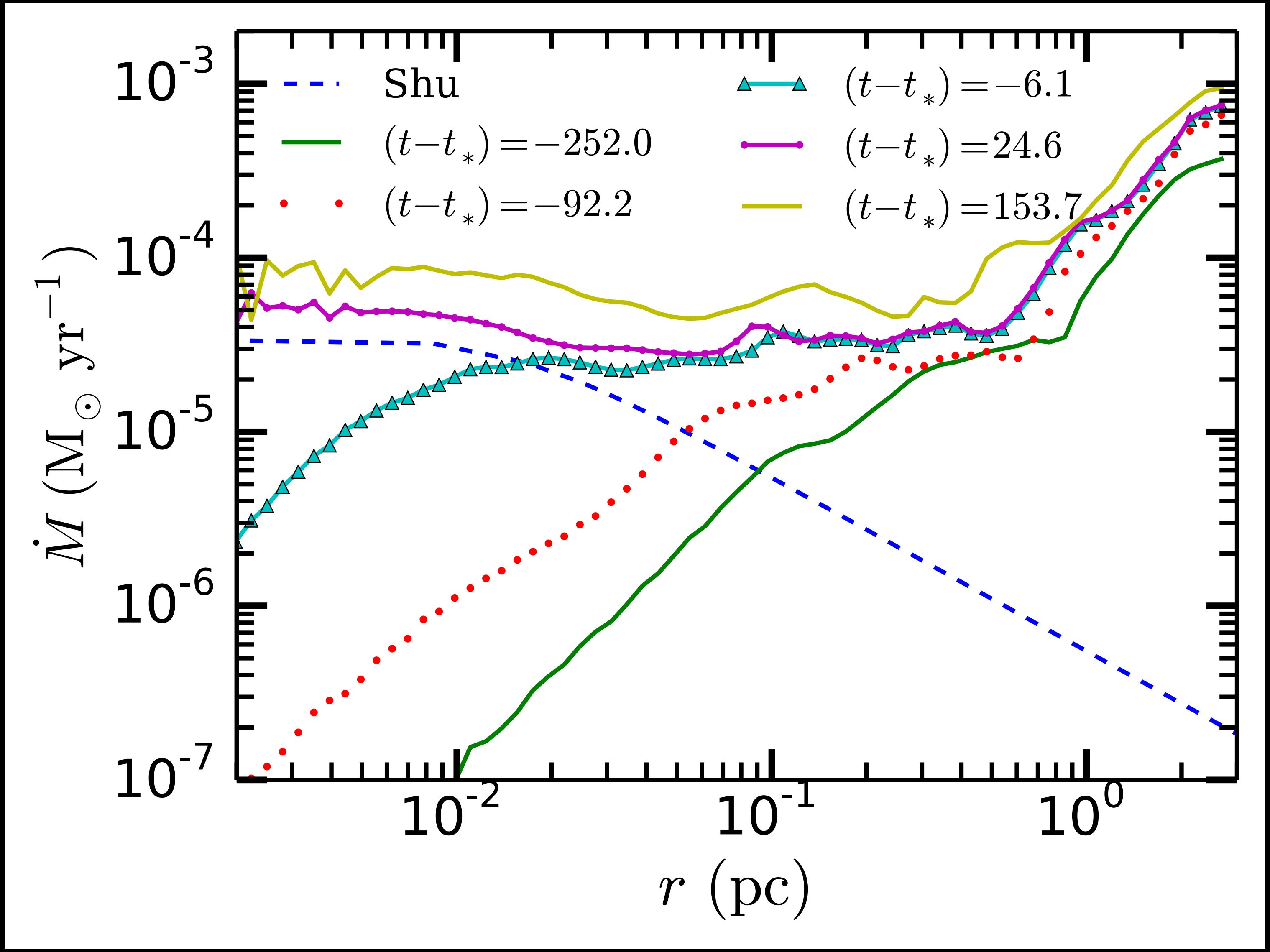
Hydro – $\dot{M}(r)$



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})
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-2}
10^{-1}
10^{0}
r (pc)

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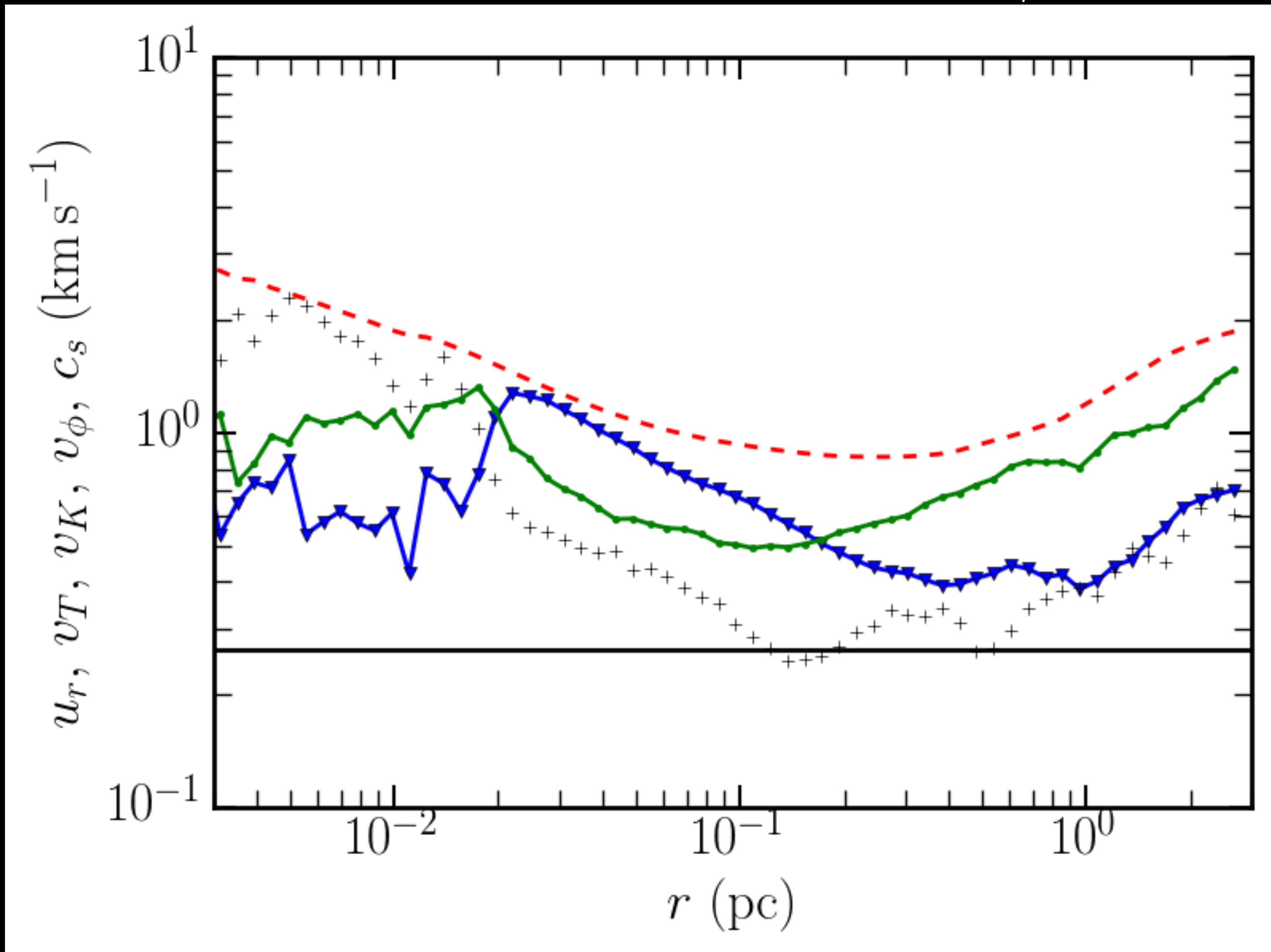
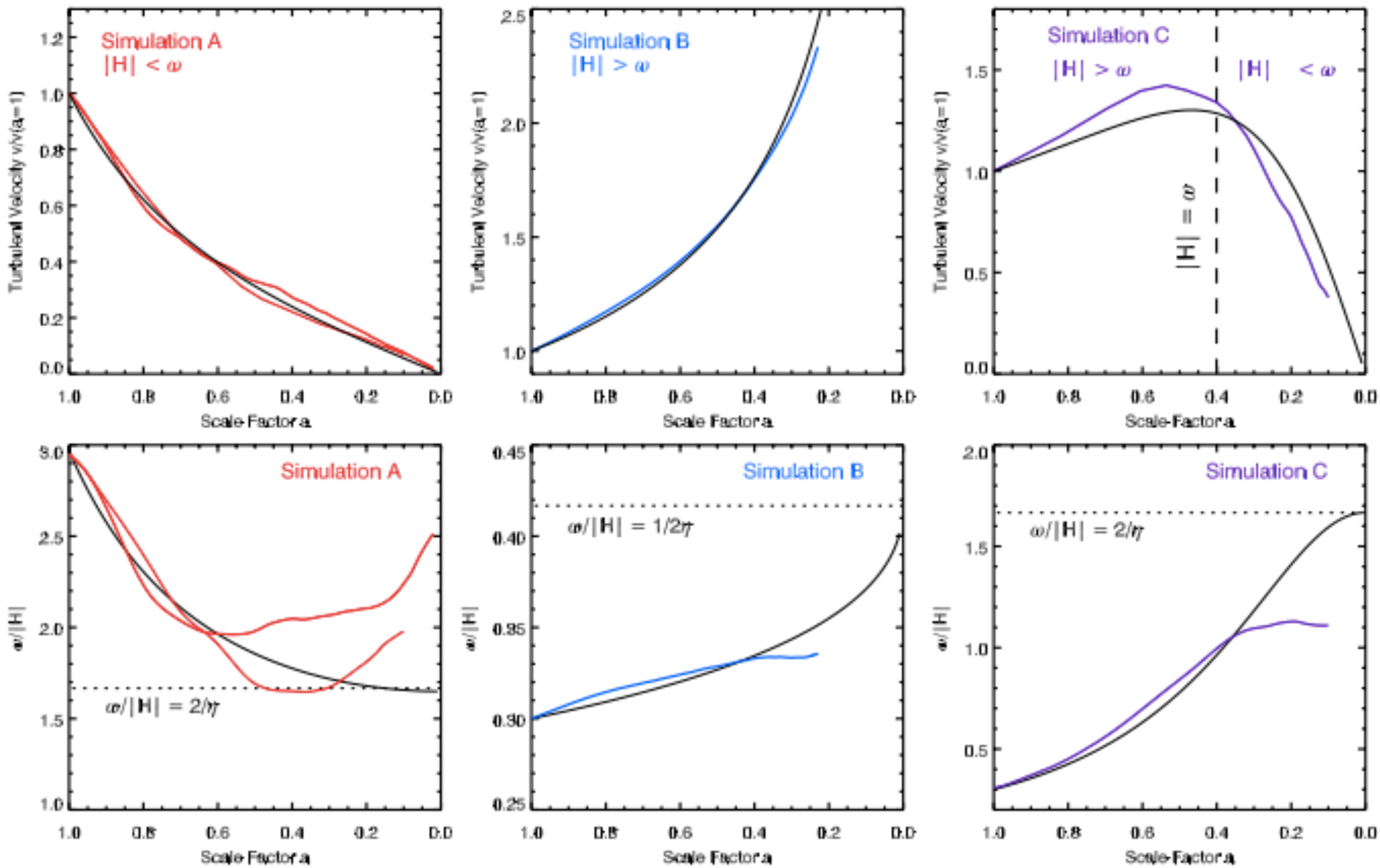
Hydro – $|u_r|$, v_T, v_ϕ

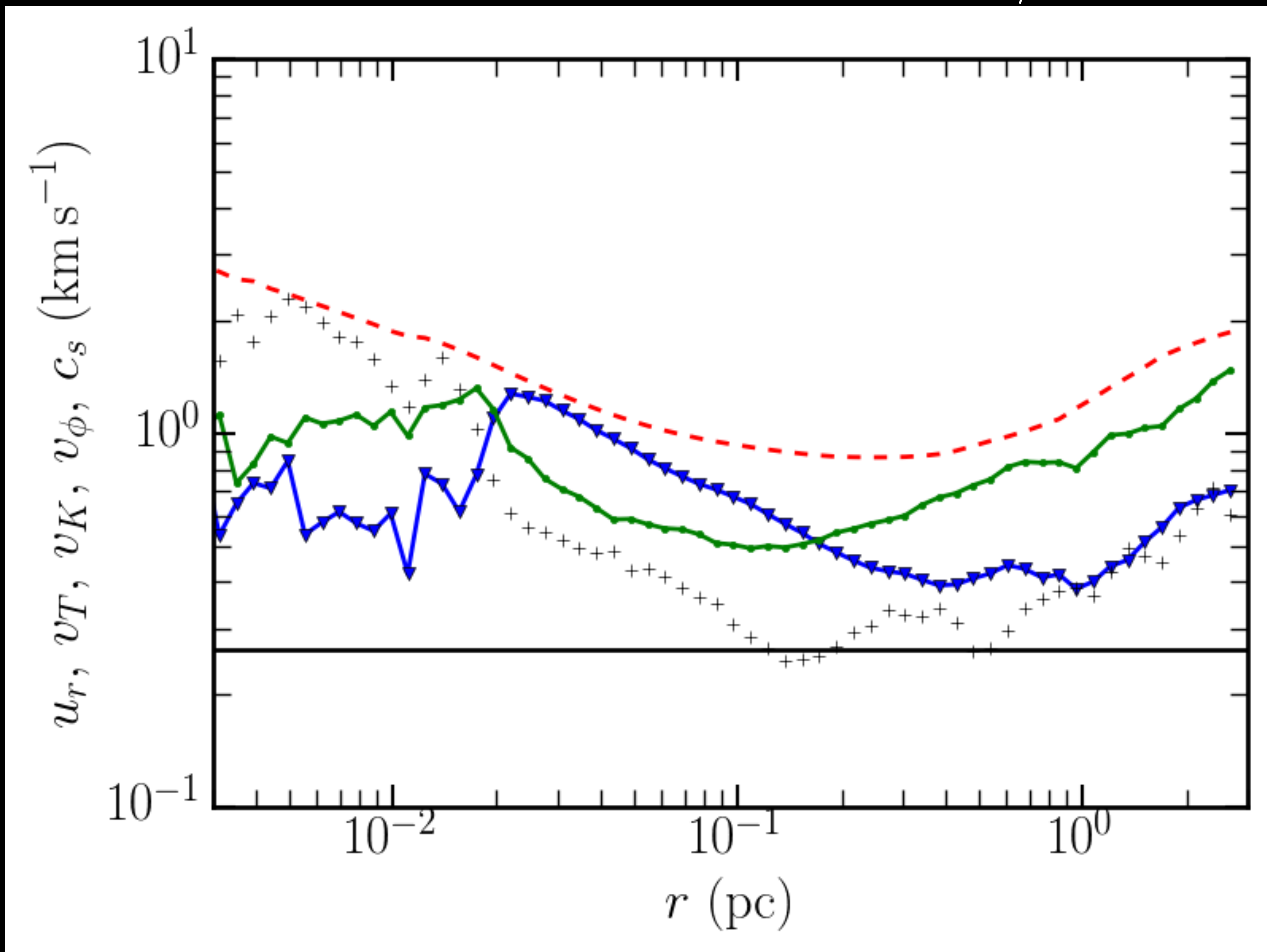


Robertson & Goldreich 2012

Adiabatic Heating in Turbulence



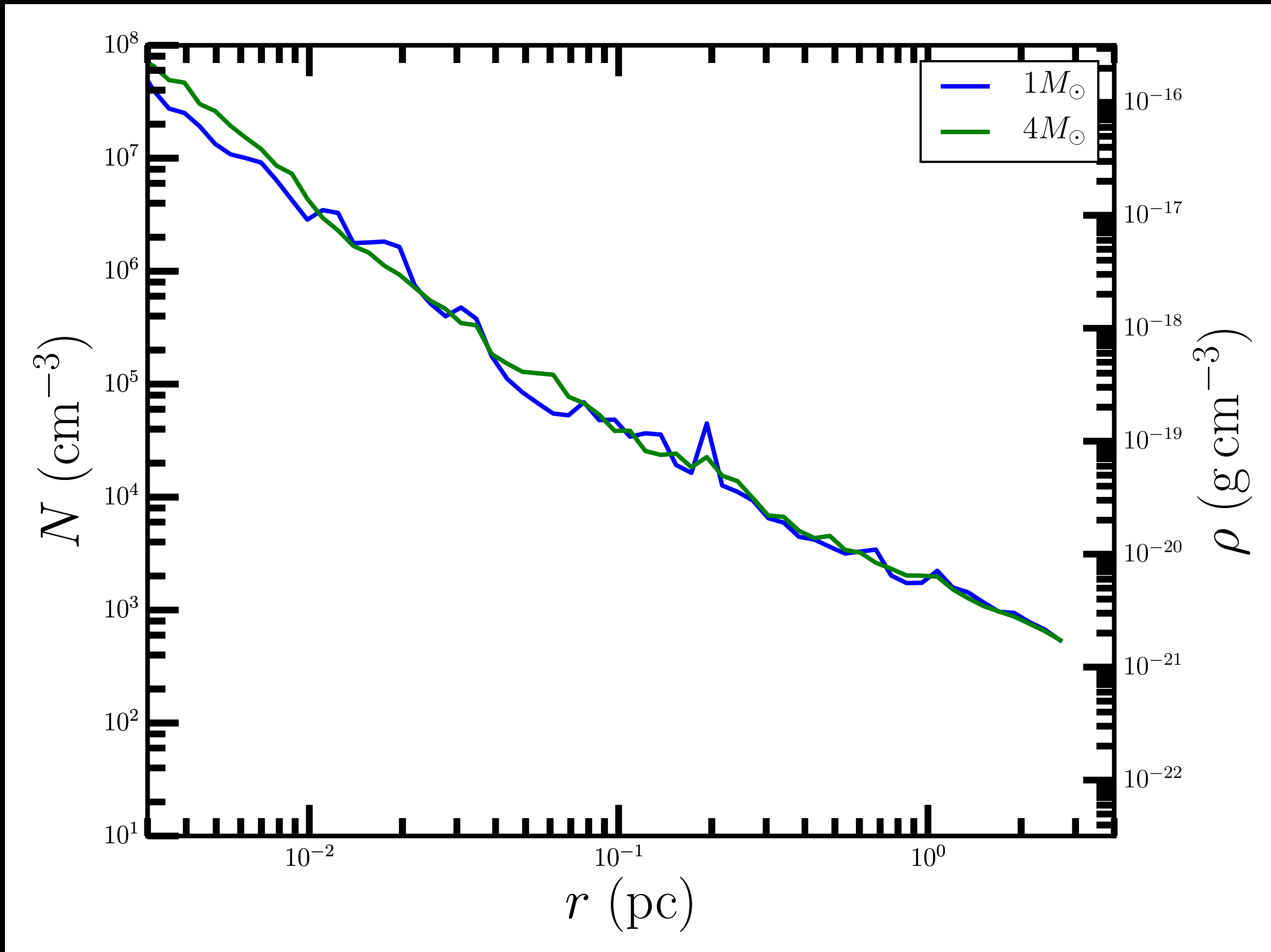
Hydro – $|u_r|$, v_T, v_ϕ



Results II

- Find an attractor for the density profile $\rho(r,t) \rightarrow \rho(r)$ for $r_d<r<r_*(t)$
- Disks form first then stars
  - Disks are around $Q = 1$, cycle around marginal stability over time

Hydro – $\rho(r)$



$1M_\odot$
$4M_\odot$
$N\ (\mathrm{cm}^{-3})$
$\rho\ (\mathrm{g\ cm}^{-3})$
r (pc)
10^{1}
10^{2}
10^{3}
10^{4}
10^{5}
10^{6}
10^{7}
10^{8}
10^{-2}
10^{-1}
10^{0}
10^{-16}
10^{-17}
10^{-18}
10^{-19}
10^{-20}
10^{-21}
10^{-22}

Results II

- Find an attractor for the density profile $\rho(r,t) \rightarrow \rho(r)$ for $r_d<r<r_*(t)$
- Disks form first then stars
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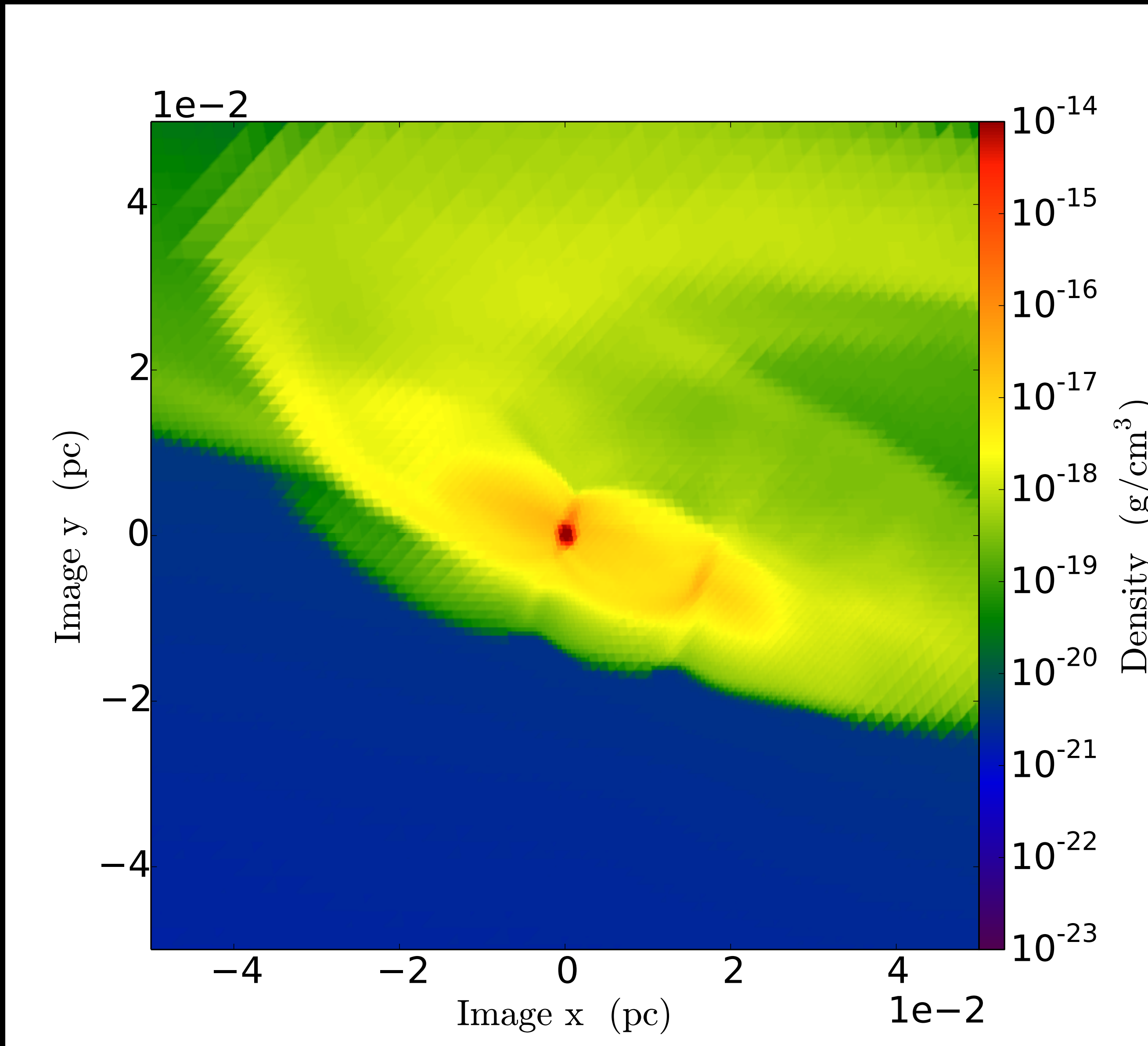
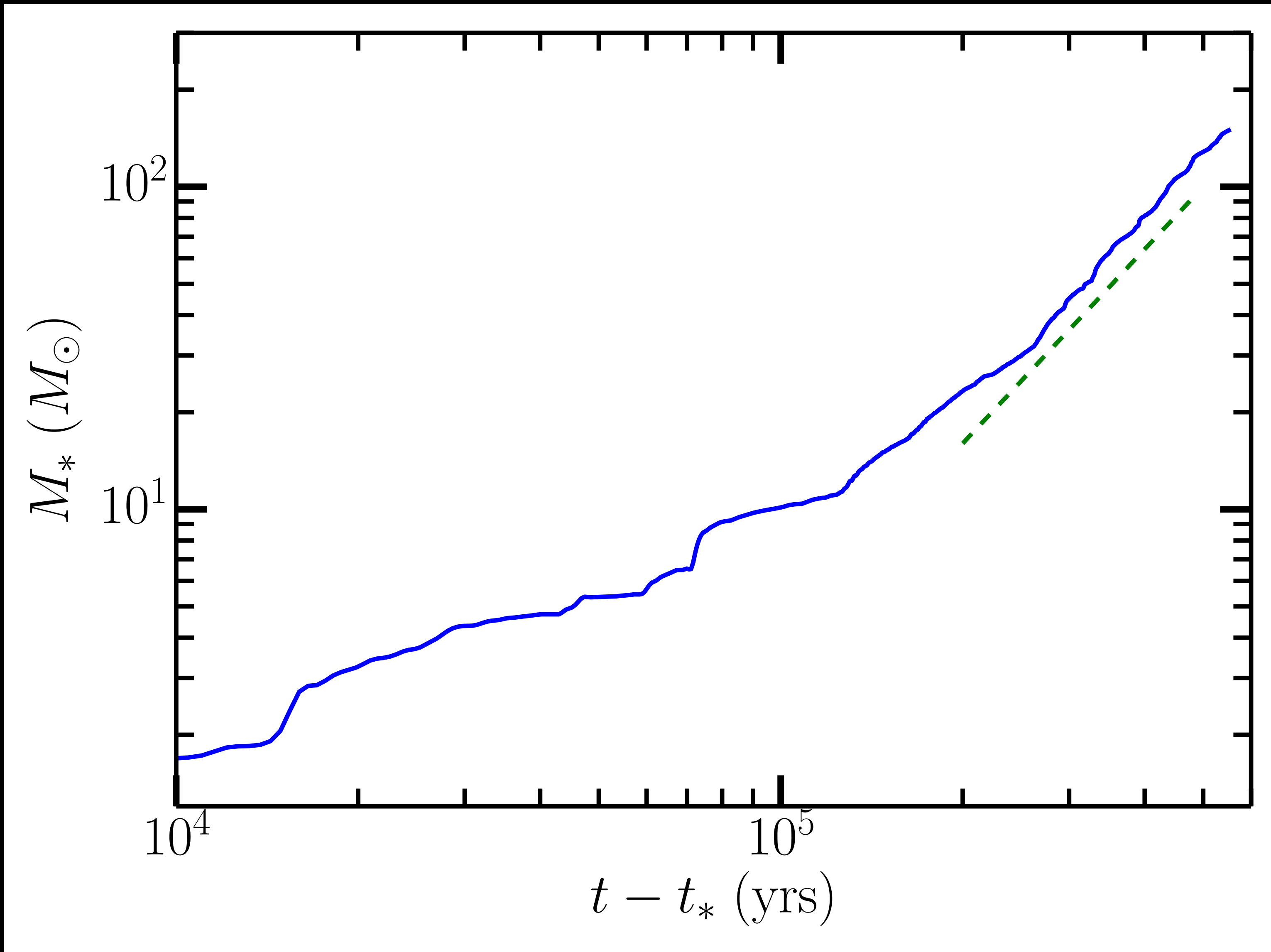
The Stellar Disk



Hydro - SFE



Why does M(t) ≈ t²?

- Density is constant (independent of time) at small r

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

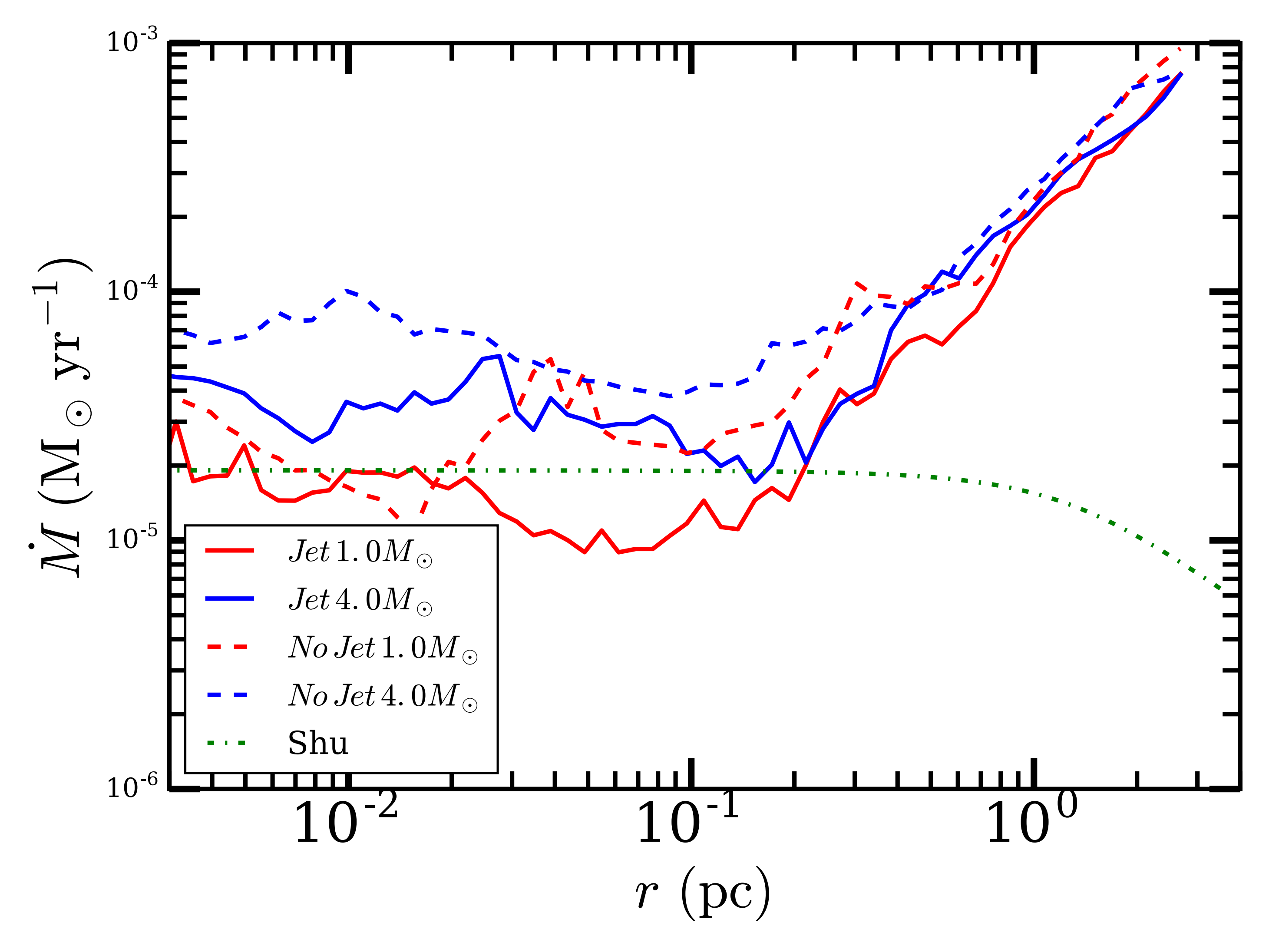
- Infall velocity scales with mass

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

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

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

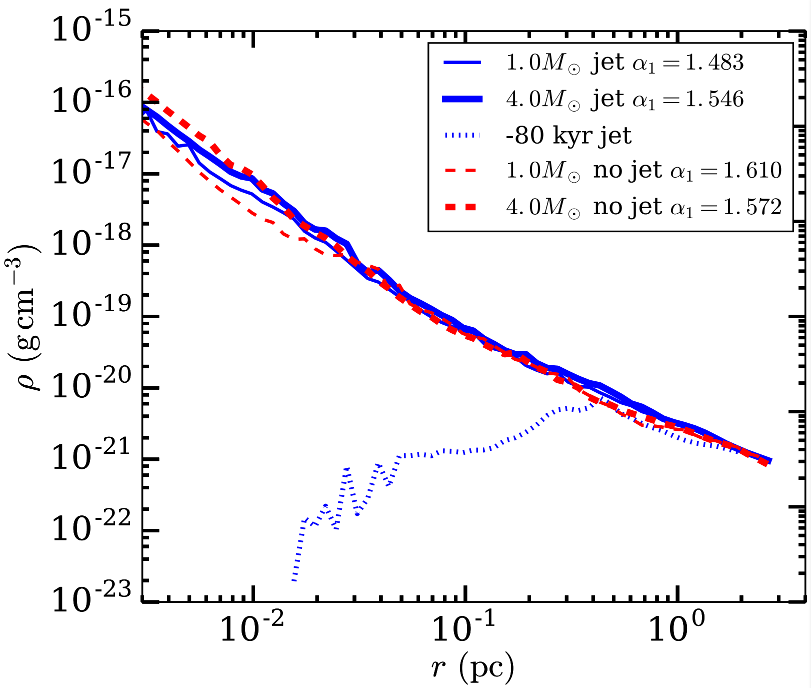
Jet − $\dot{M}\,(r)$



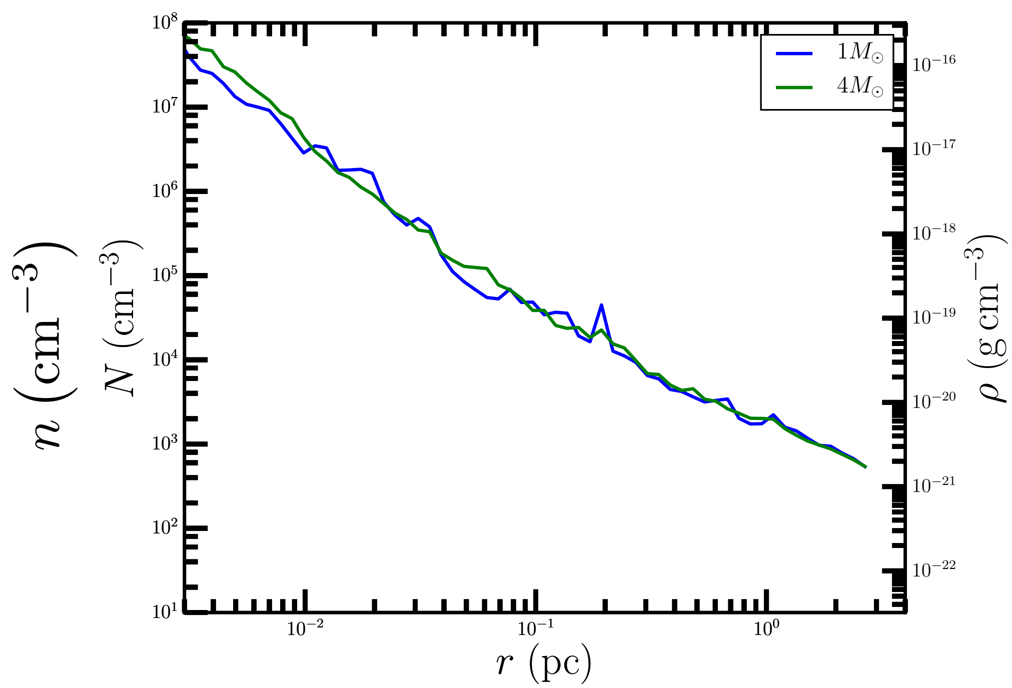
10^{-3}
10^{-4}
10^{-5}
10^{-6}
$\dot{M}$ ($M_\odot$ yr^{-1})
10^{-2}
10^{-1}
10^{0}
r (pc)
$Jet\,1.0M_\odot$
$Jet\,4.0M_\odot$
$No\,Jet\,1.0M_\odot$
$No\,Jet\,4.0M_\odot$
Shu

Protostellar Feedback & Hydro - Density

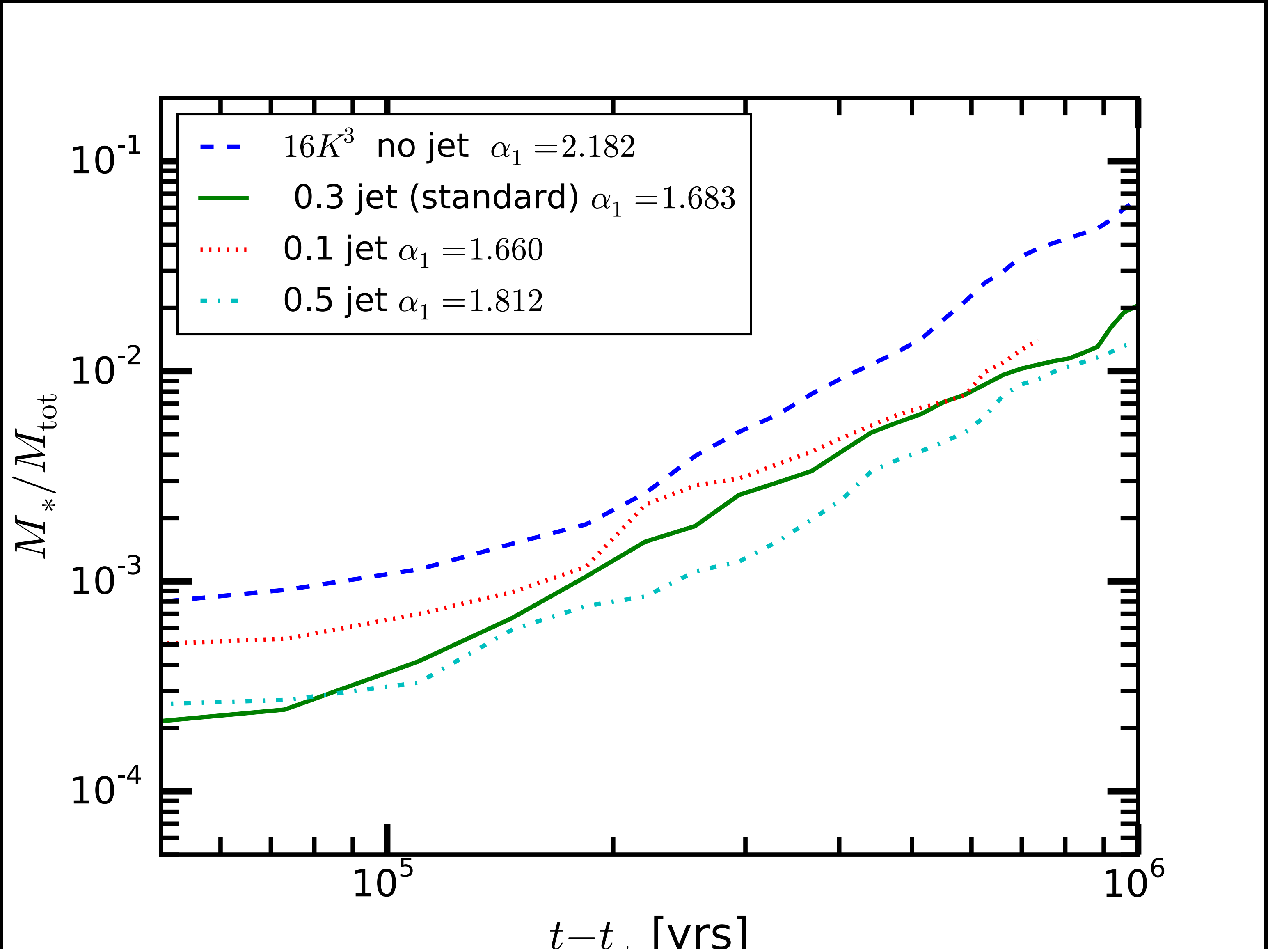
Protostellar jet feedback



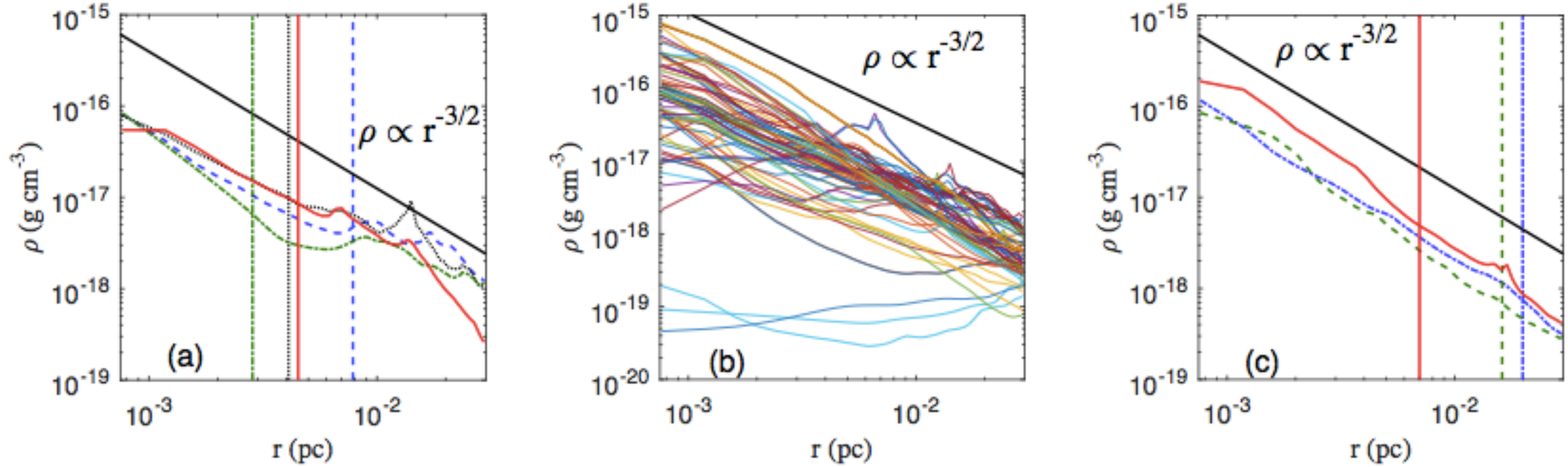
HD



Jet SFE vs m_jet

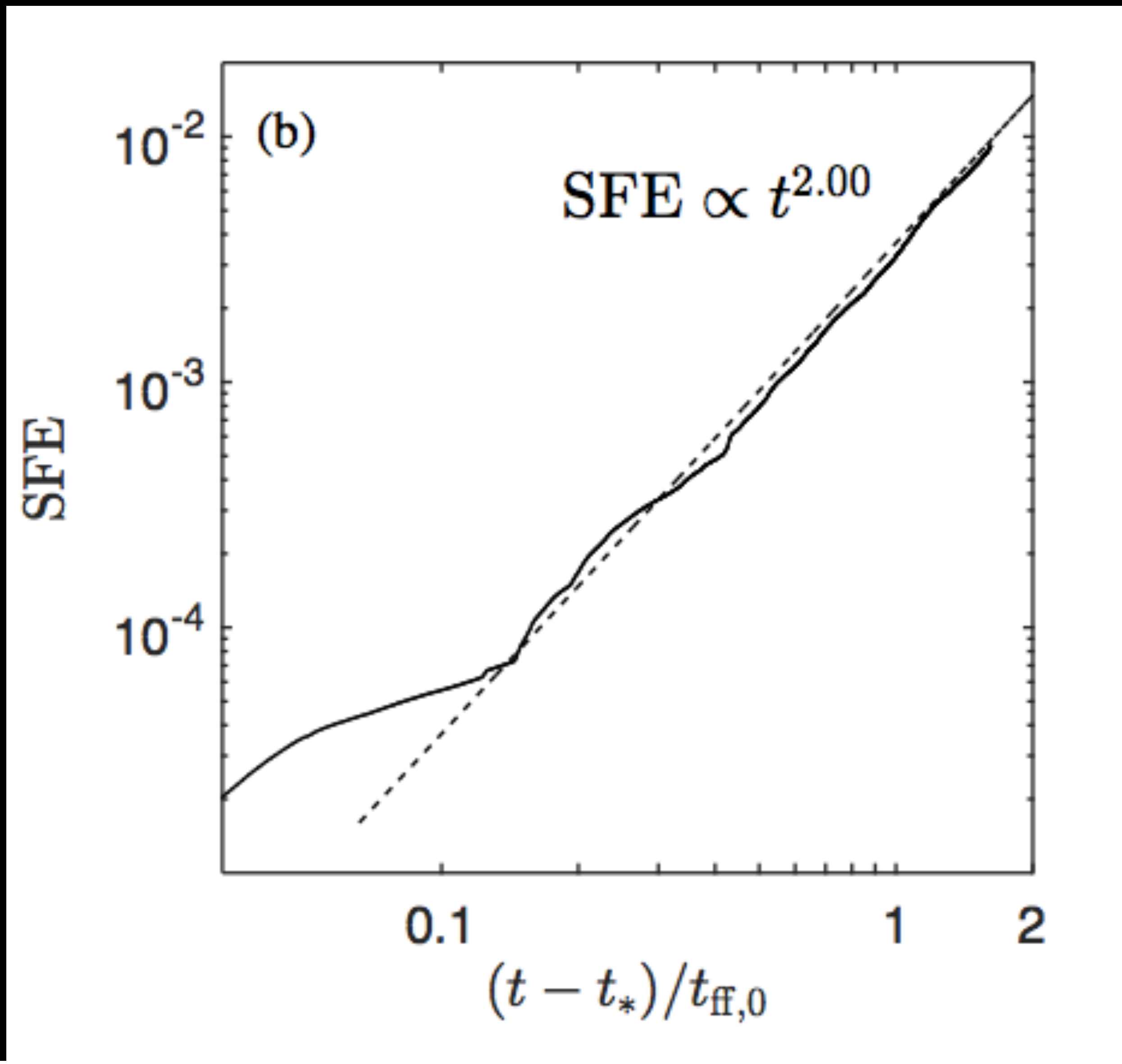


Li et al. 2017 – $\rho\,(r)$



Li et al. 2017

Li et al. 2017



Implications

- 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
  - Also observable with ALMA.
- Disk arise spontaneously from turbulent fluctuations

Conclusion I

- v(r,t) -> deviation from Larson @ small scales,
  - Explains observations of Plume et al, Caselli and Myers
- Disks arise spontaneously from turbulent fluctuations

Conclusion II

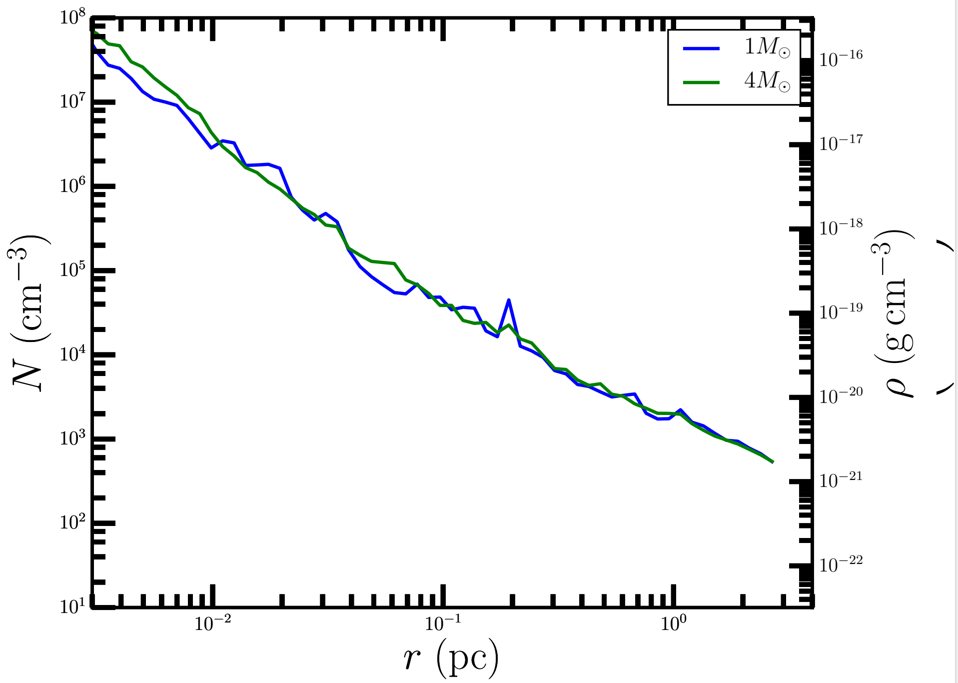
- Density is attractor solution -> lifetime of the observed structures is not the same as the local free-fall time
- $u_r\,(r,t) \propto M_*^{1/2}(t) r^{-1/2}$
- M(t) ~ t^2 -> large variation in SFE
- SFR starts slow but accelerates with time

Future Work

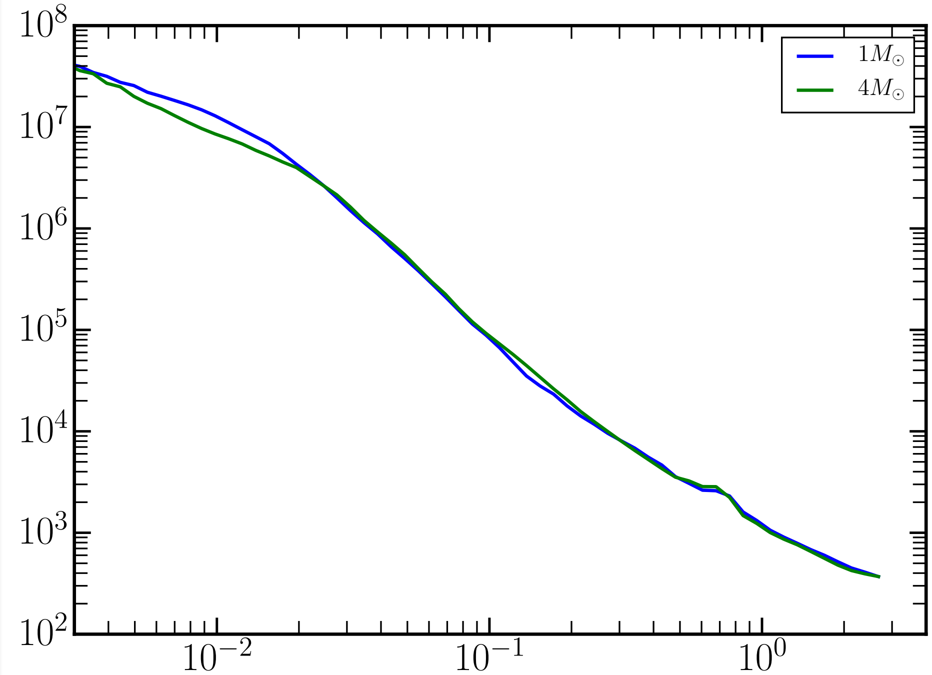
- Numerically:
  - Inclusion of Magnetic fields
  - Feedback
    - Radiative transfer
- Analytically:
  - Incorporate angular momentum into the theory of Murray & Chang (2015)

Run of Density with Magnetic Fields

HD

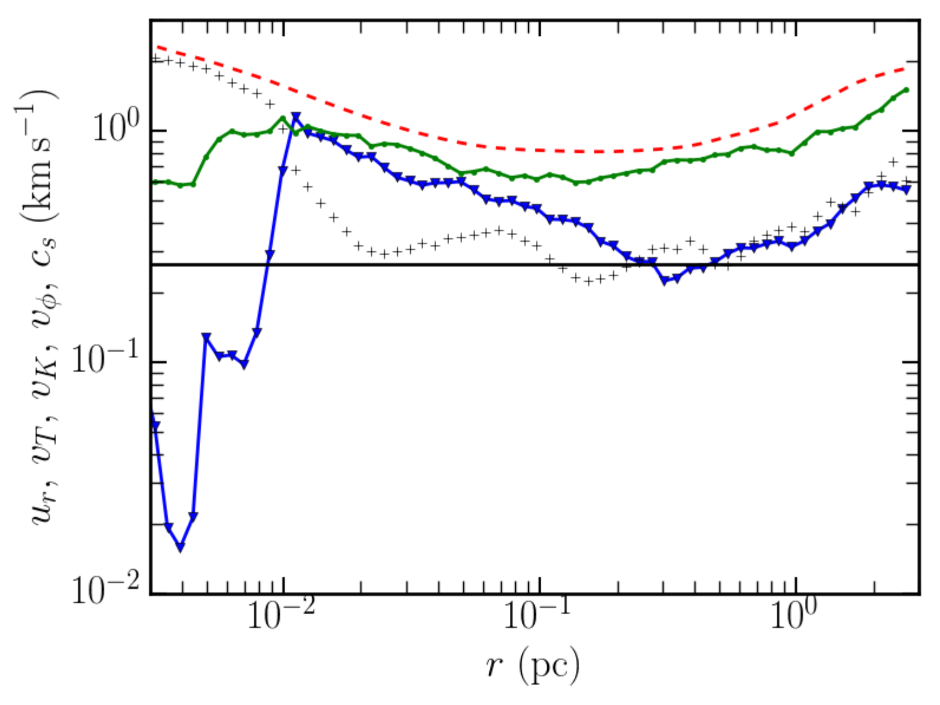


MHD

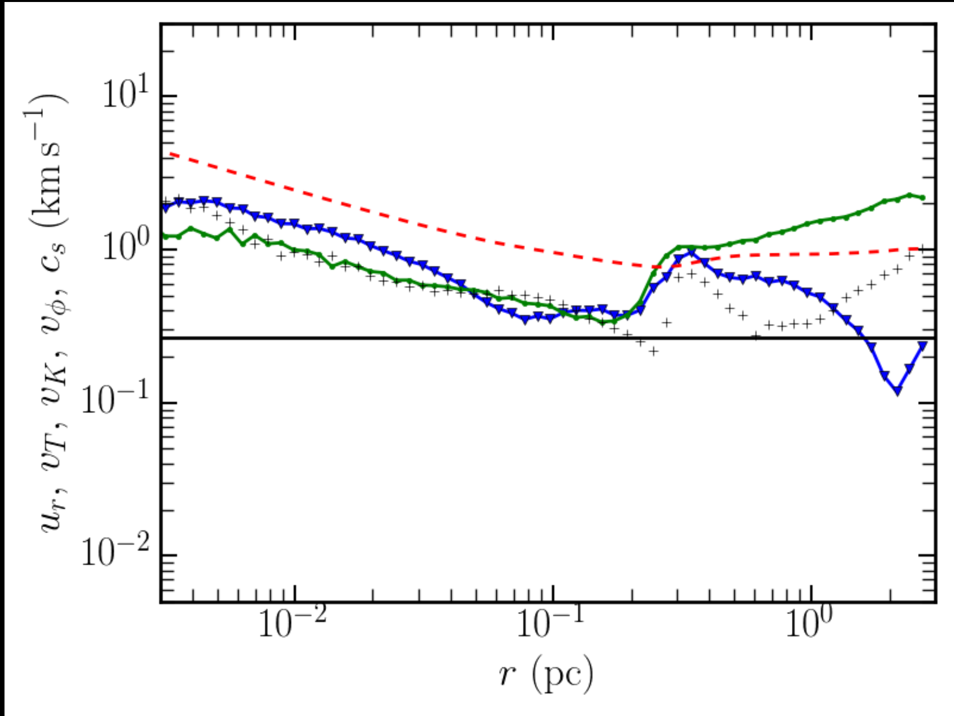


Velocities

Protostellar jet feedback

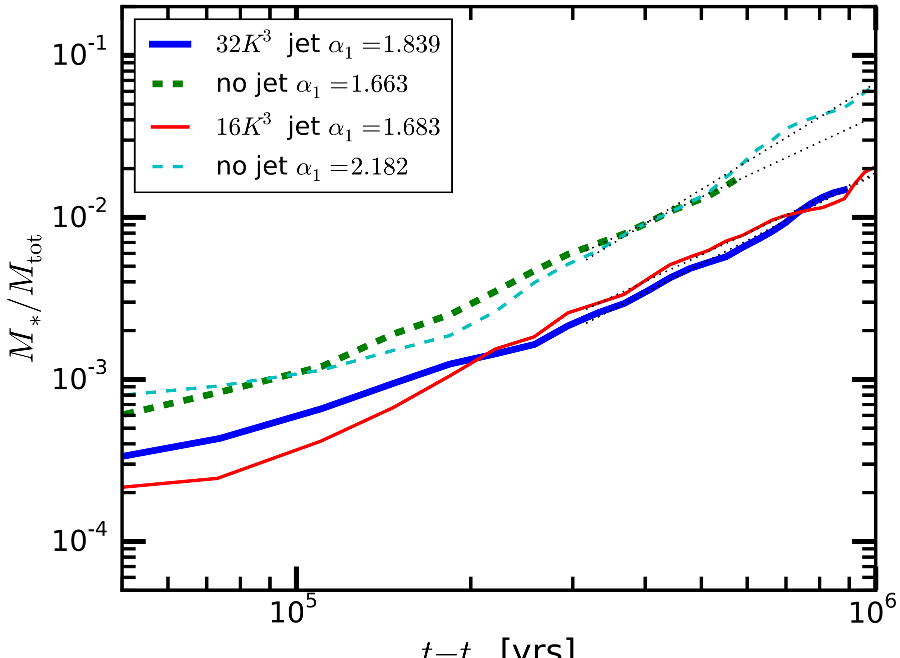


MHD

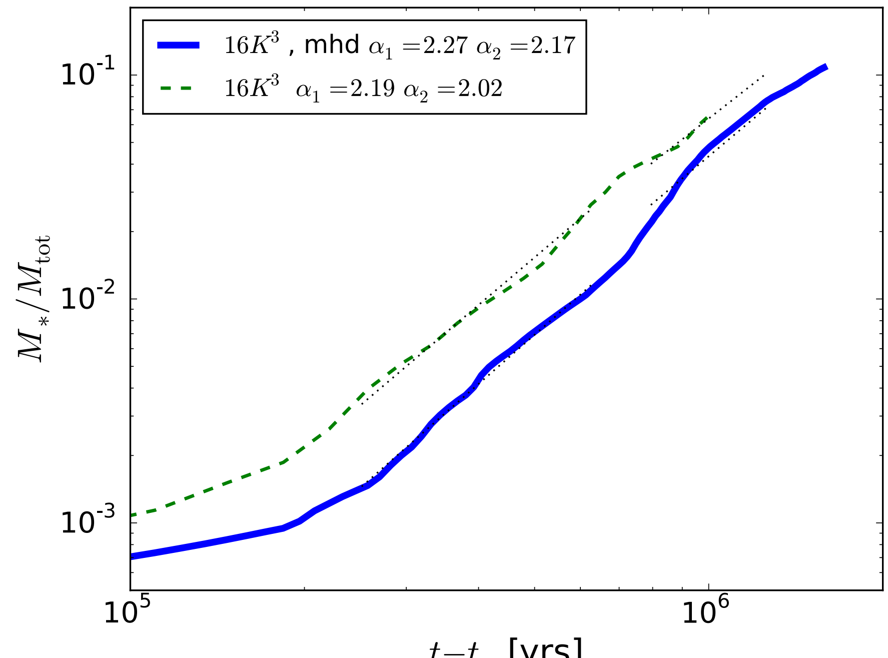


SFE

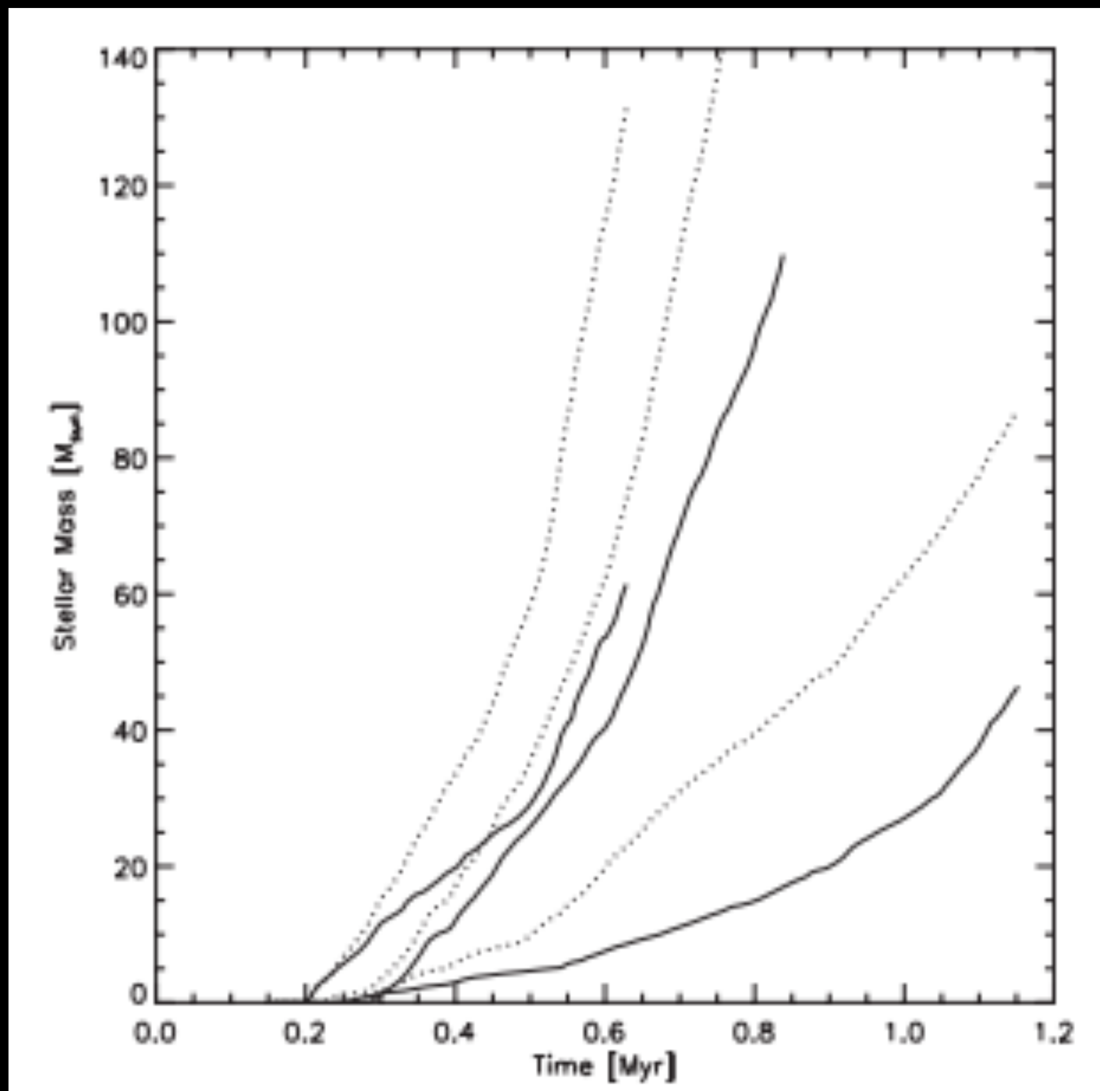
Protostellar jet feedback



MHD



Wang et al. 2010



Larson; Penston; Shu Solution eqns

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

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

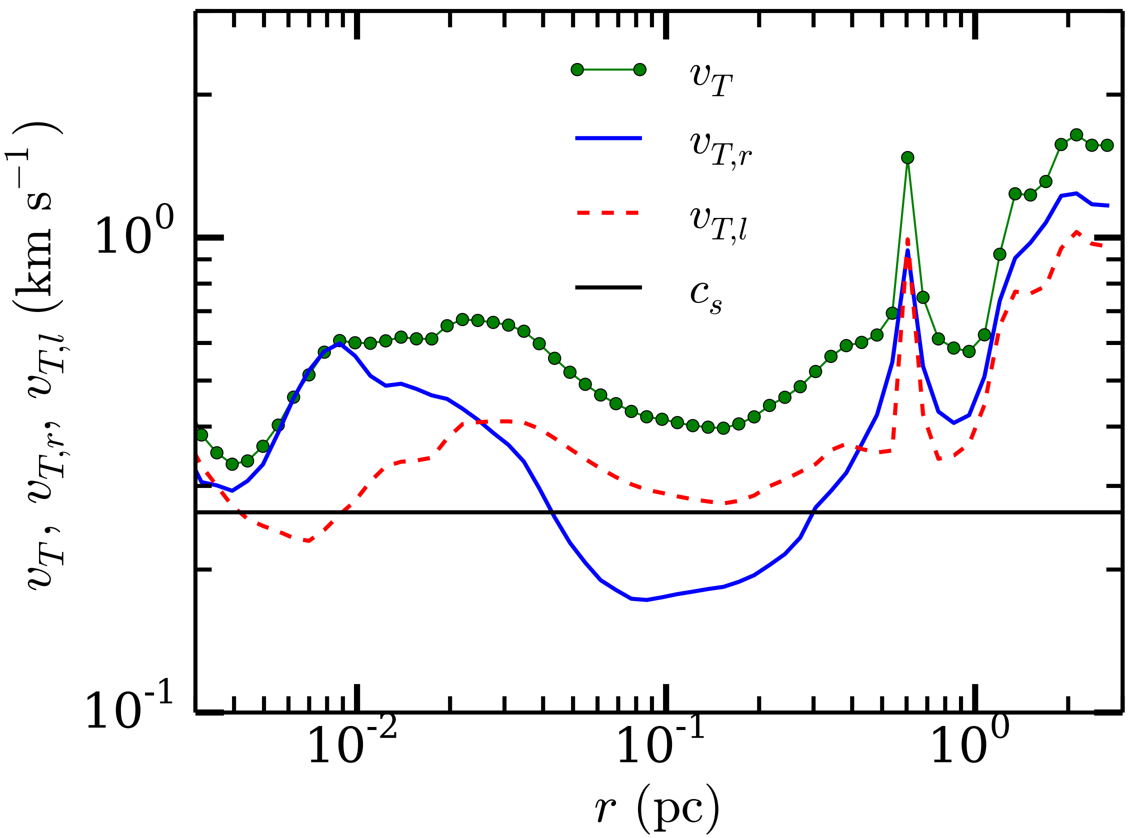
$$P = \rho c_s^2$$

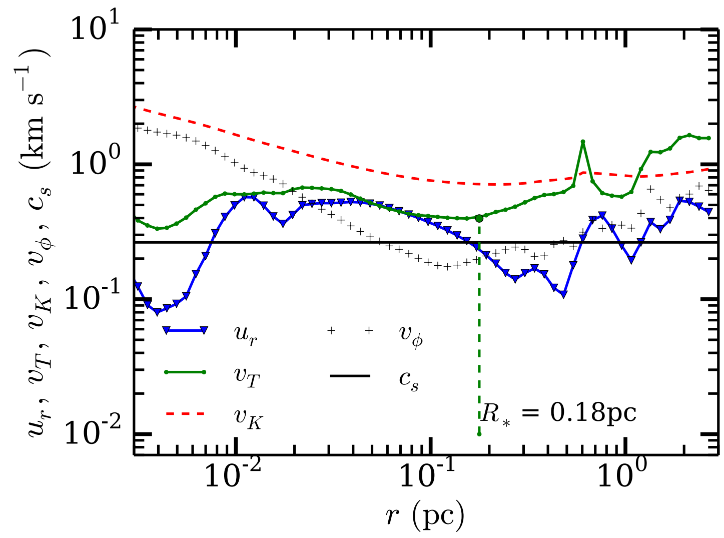
Myers & Fuller; McLaughlin & Pudritz; McKee & Tan Solution eqns

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

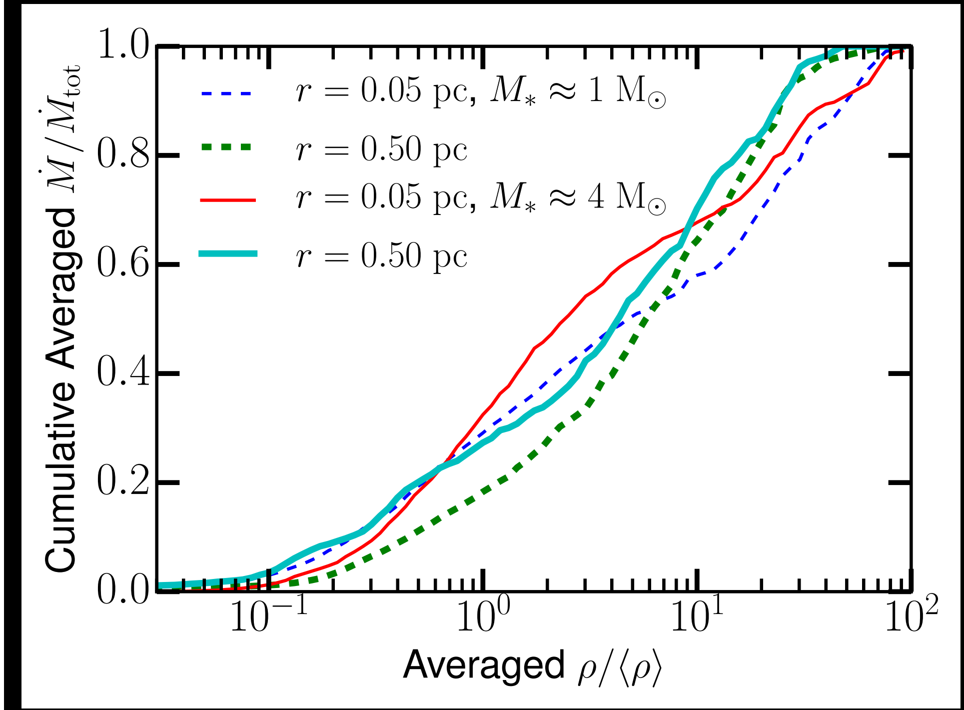
$$\frac{\partial u_r}{\partial t} + u_r \frac{\partial u_r}{\partial r} = -\frac{1}{\rho}\frac{\partial \rho v_T^2(r)}{\partial r} - \frac{GM(r)}{r^2}$$

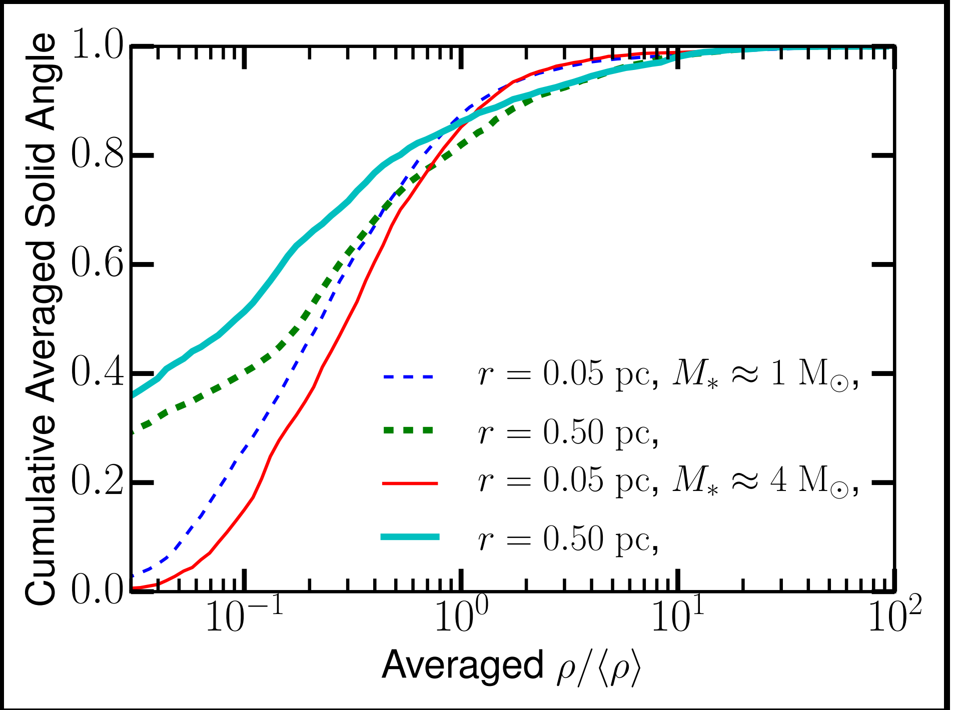
Breakup of Turbulent Velocity





The Spherical Inflow Assumption





Velocity Profile Agregate