Gravoturbulent Fragmentation:

Effects of a Non-Isothermal EOS on Mass Spectra

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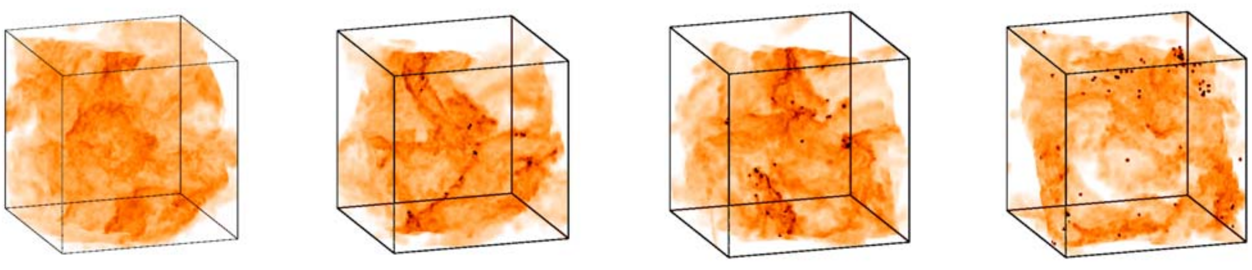

Collaborators

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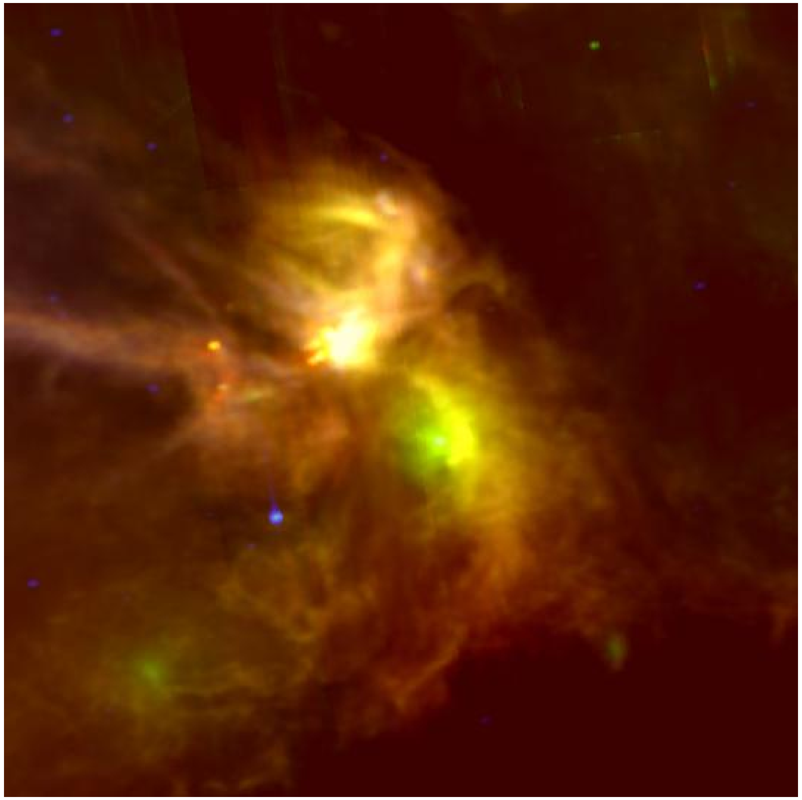
Yuexing Li - Columbia Univ., New York
Mordecai-Mark Mac Low - AMNH, New York

Born in Turbulent Times & Places



ρ Ophiuchi - IRAS

Orion Nebula - ESO

Turbulence

Evidence?

- transient clumpy nature of clouds
- linewidth of molecular emission lines (Blitz 93)

Characteristics?

- supersonic
- decays quickly

Driving Mechanisms?

- MRI, gravitational motions (e.g. collapse)
- stellar feedback (e.g. supernovae)

Turbulence + Gravity: Gravoturbulent Star Formation

- Dual role of turbulence:
  - stability on large scales
  - initiating collapse on small scales

- Supersonic turbulence
  → strong density fluctuations

- Gravity selects clumps to go into collapse
  → formation of stars and star clusters

(Mac Low & Klessen, 2004, Rev. Mod. Phys., 76, 125-194)

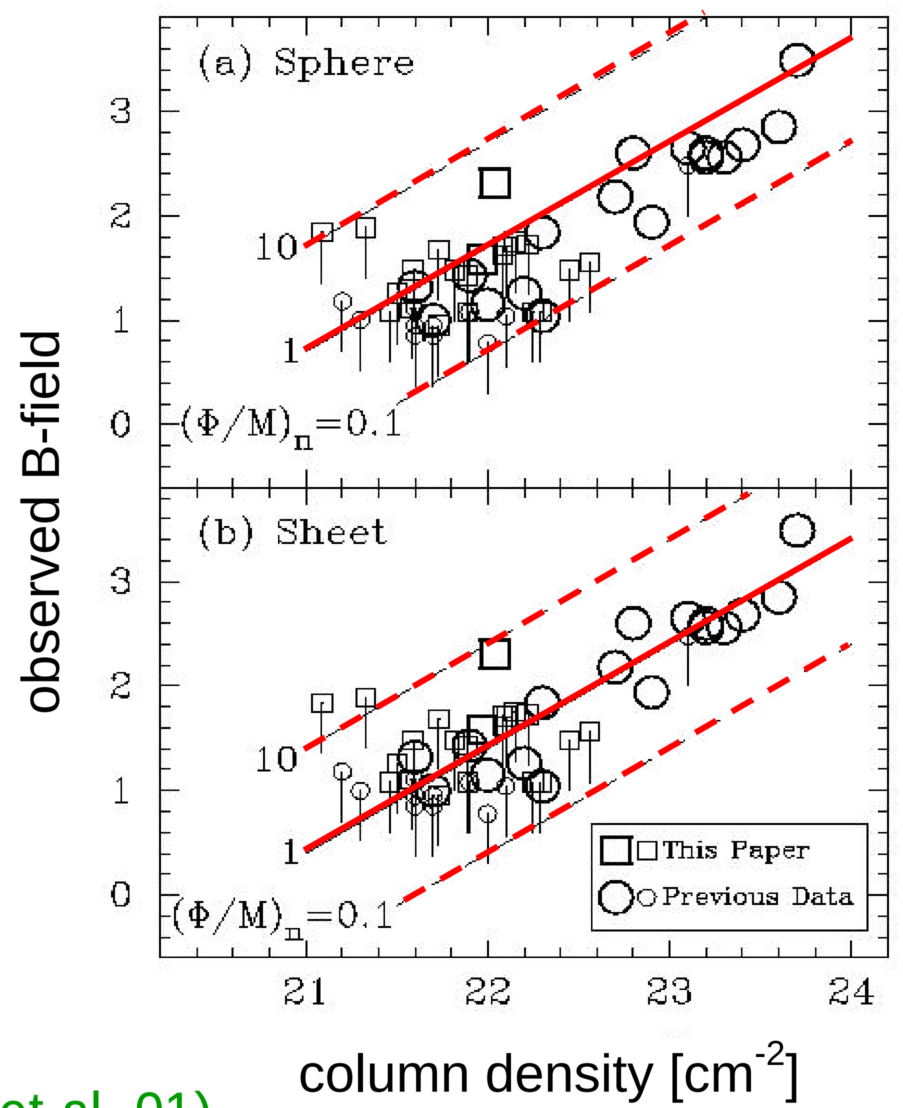
Magnetic Fields?

$(\Phi/M)_n > 1$ no collapse
$(\Phi/M)_n < 1$ collapse

- cloud cores
  magnetically supercritical

- B-fields too weak to prevent gravitational collapse

- B-fields cannot prevent decay of turbulence



(Bourke et al. 01)

What can we learn from models ?

- Global Properties:
  - SF efficiency and SF time scale
    - IMF
    - description of self-gravitating turbulent systems
    - chemical mixing properties

- Local Properties:
  - properties of individual clumps
    - accretion history of individual protostars
    - binary (proto)stars
    - SED's of individual protostars
    - dynamic PMS tracks: T_{bol}-L_{bol} evolution

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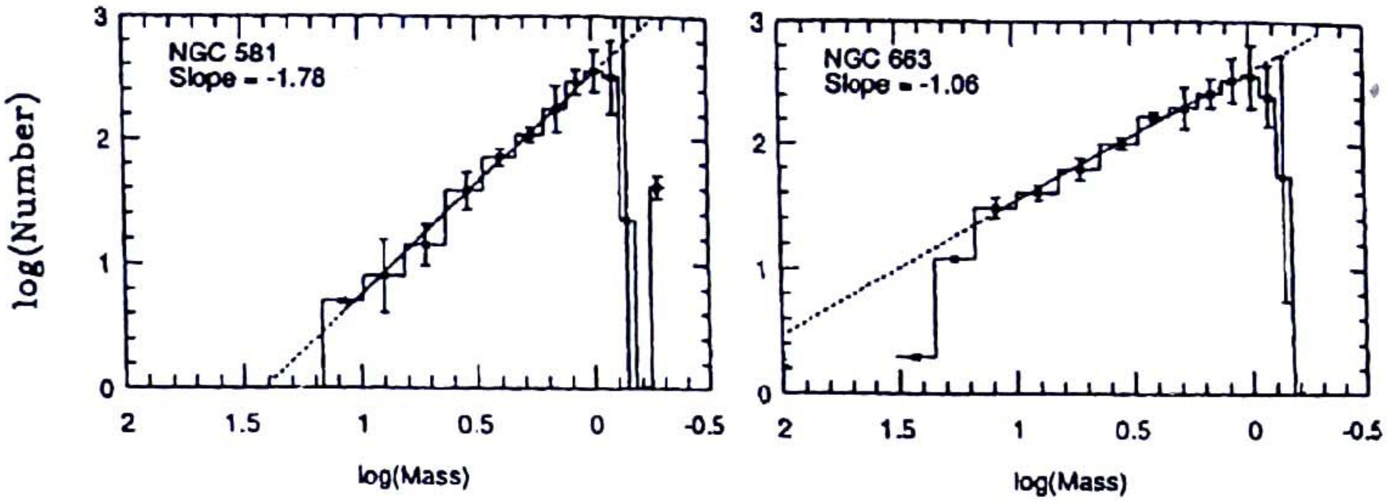
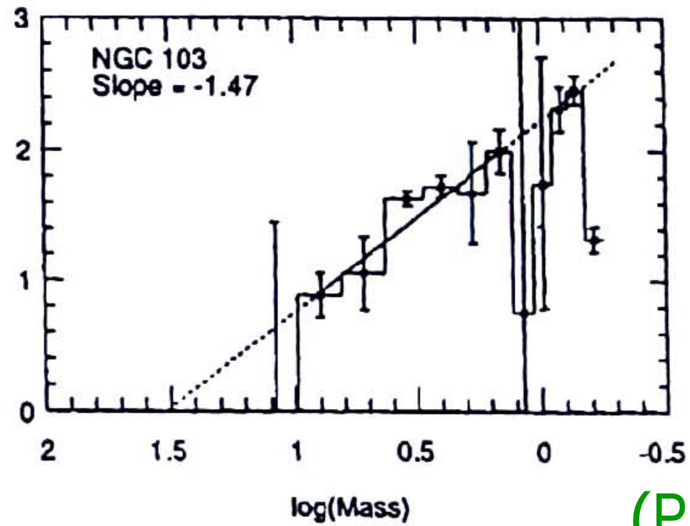
Characteristic Mass of the IMF



universal feature

universal cause?



(Phelps & Janes 93)

Thermal Properties of Star-Forming Clouds

Observations:

- balance: gravity and thermal pressure (Myers et al. 91)
- temperatures: 8 – 20 K
- heating and cooling processes

But in Simulations:

- isothermal approximation ($\gamma = 1.0$)
- temperature: ~ 10 K

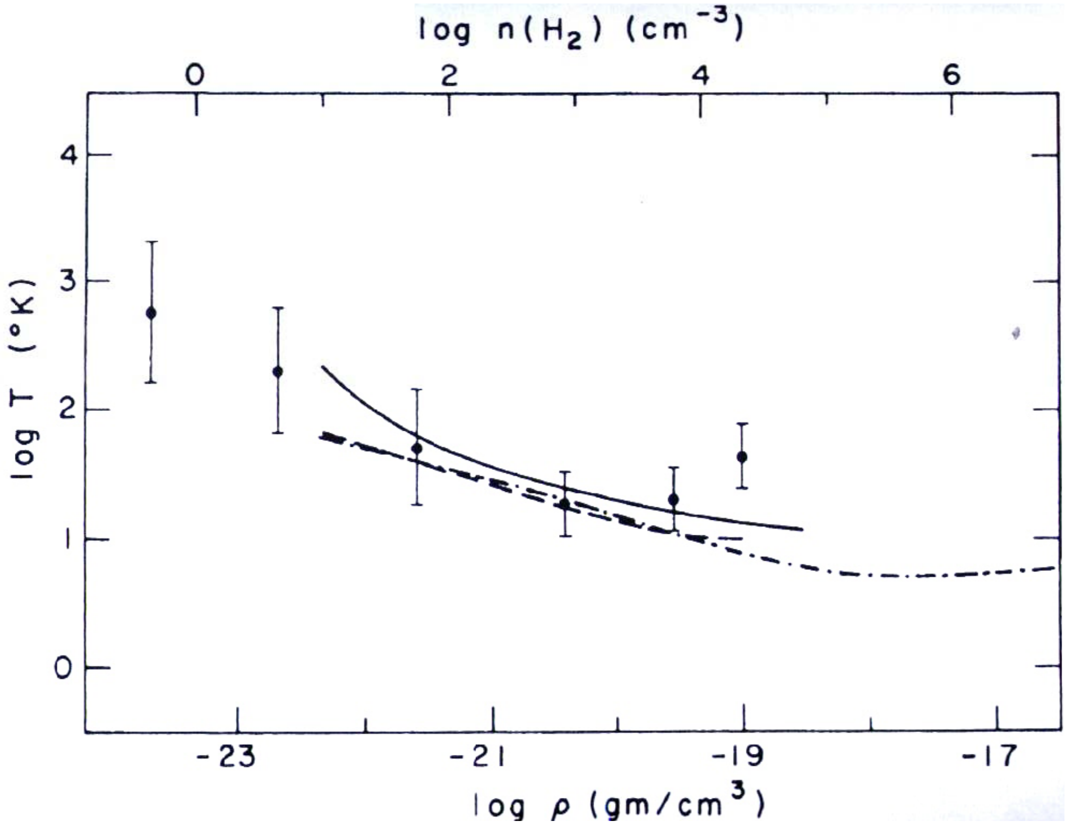
Fragmentation depends on Equation of State (EOS)

(Li et al. 03)

Beyond the Isothermal Approximation

below 10^{-18} gcm^{-3}: ρ ⬆ ⟹ T ⬇

above 10^{-18} gcm^{-3}: ρ ⬆ ⟹ T ⬆



(Larson 85)

Piecewise Polytropic Equation of State

$$P = K_1 \rho^{\gamma_1} \qquad \rho < \rho_{crit}$$

$$P = K_2 \rho^{\gamma_2} \qquad \rho > \rho_{crit}$$

$\gamma_1 = 0.7$

$\gamma_2 = 1.1$

$4 \times 10^4 \text{ cm}^{-3} < n_{crit} < 4 \times 10^7 \text{ cm}^{-3}$

Is there a connection between ρ_{crit} and a characteristic stellar mass ?

Numerical Method

- smoothed particle hydrodynamics
- parallel Gadget (Springel 01)

  + turbulent driving (Mac Low 99)
  + sink particles (Bate et al. 95)

- periodic boundaries
- polytropic EOS
- no magnetic fields

Turbulent Driving

- uniformly driven

- Gaussian random velocity fields

- characterized by:
  - mean value
  - standard deviation: power spectrum $P(k) = k^{-q}$

- random amplitude and phase

- const. energy input rate

Sink Particles

- replace gas core by single, non-gaseous, massive sink particle
- fixed radius – Jeans radius of core
- inherit masses, linear momenta, “spin“
- accrete gas particles
- boundary corrections

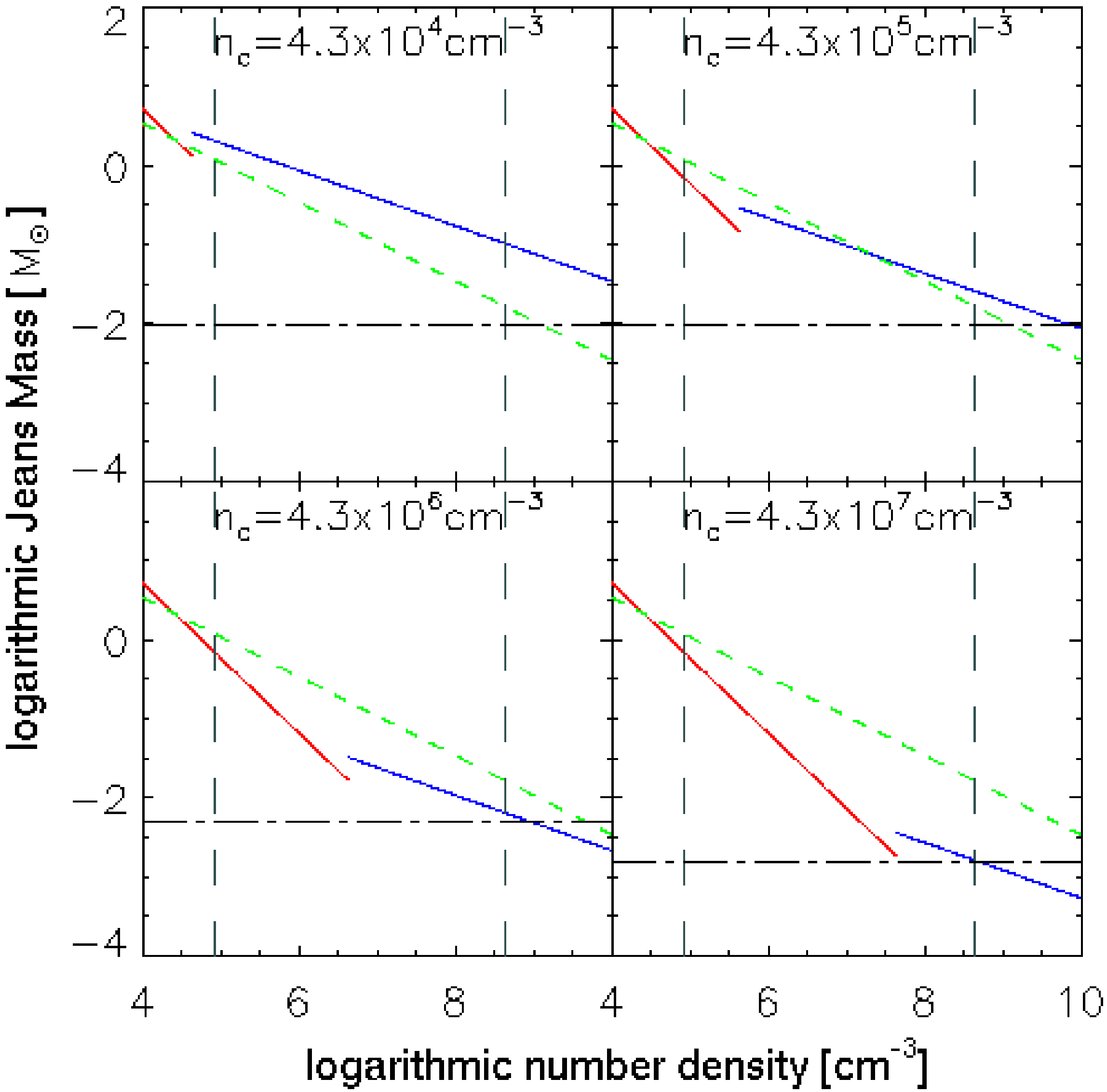
Model Parameter

- initial mean density: $n(H_2) = 10^5$ cm^{-3}
- volume: (0.3) pc^3
- initial temperature: 11.4 K
- contained mass: 120 M_{SUN}
- initial Jeans mass: 0.7 M_{SUN}
- number of gas particles: 10^6
- resolution limit: 0.01 M_{SUN}

- r_{SINK} = 310 AU
- free-fall time: 10^5 yrs
- $\mathcal{M}_{rms}$ = 3.2
- k_{drv} = 1..2

Jeans Mass as a Function of Density

- γ_1 = 0.7
- γ_2 = 1.1
- isothermal
- $M_J \sim \rho^{-0.95}$

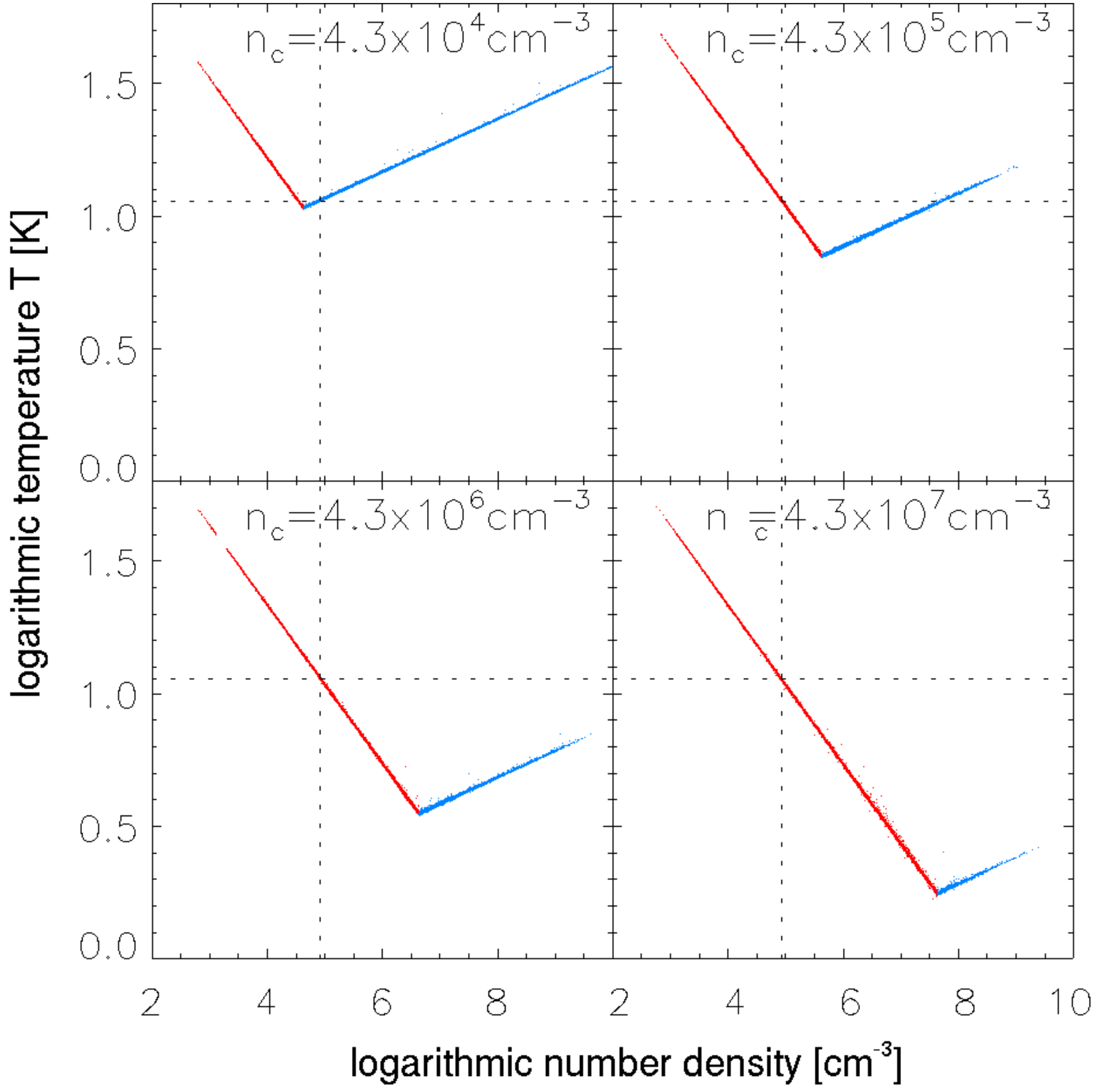


Temperature as a Function of Density

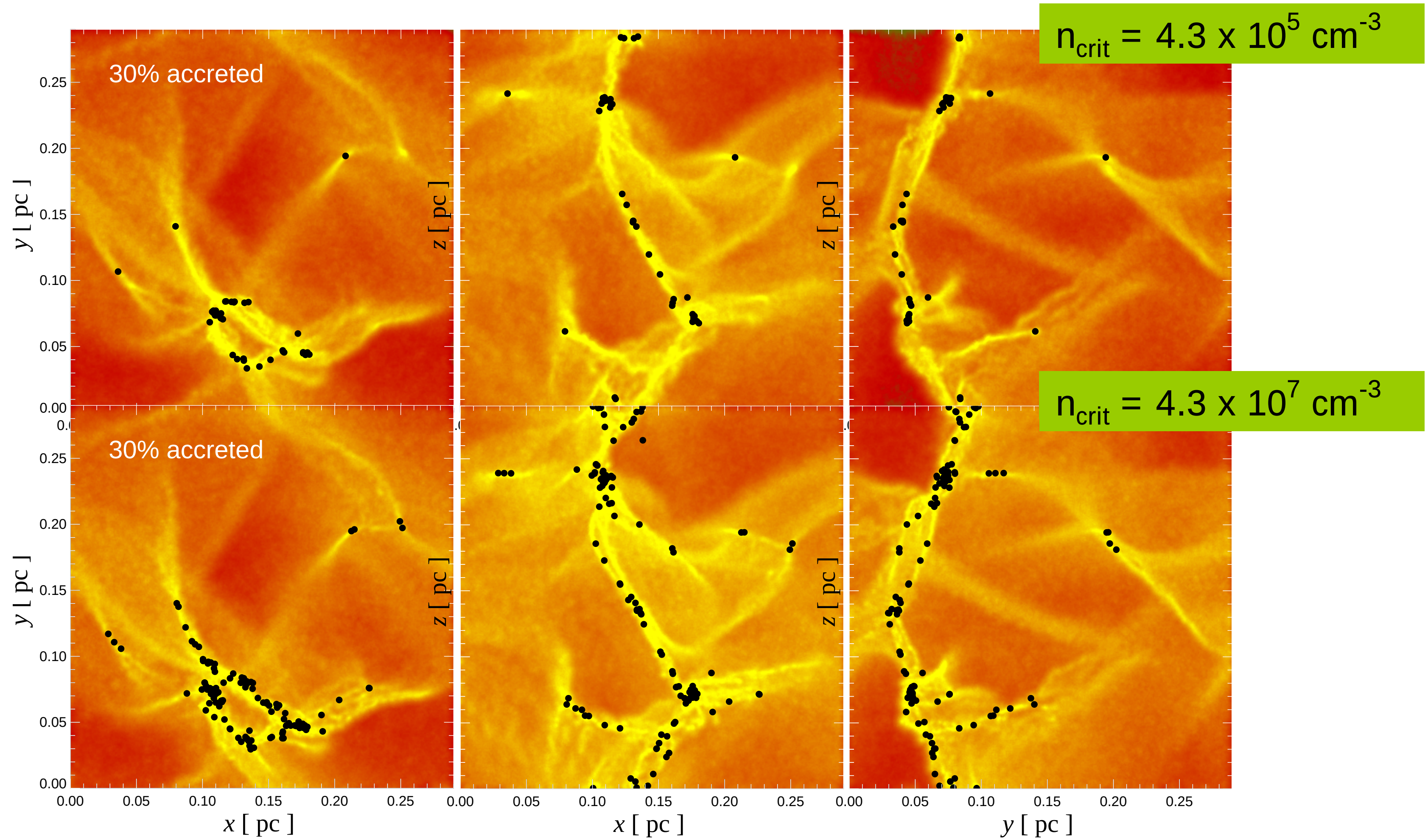
$\gamma_1 = 0.7$

$\gamma_2 = 1.1$

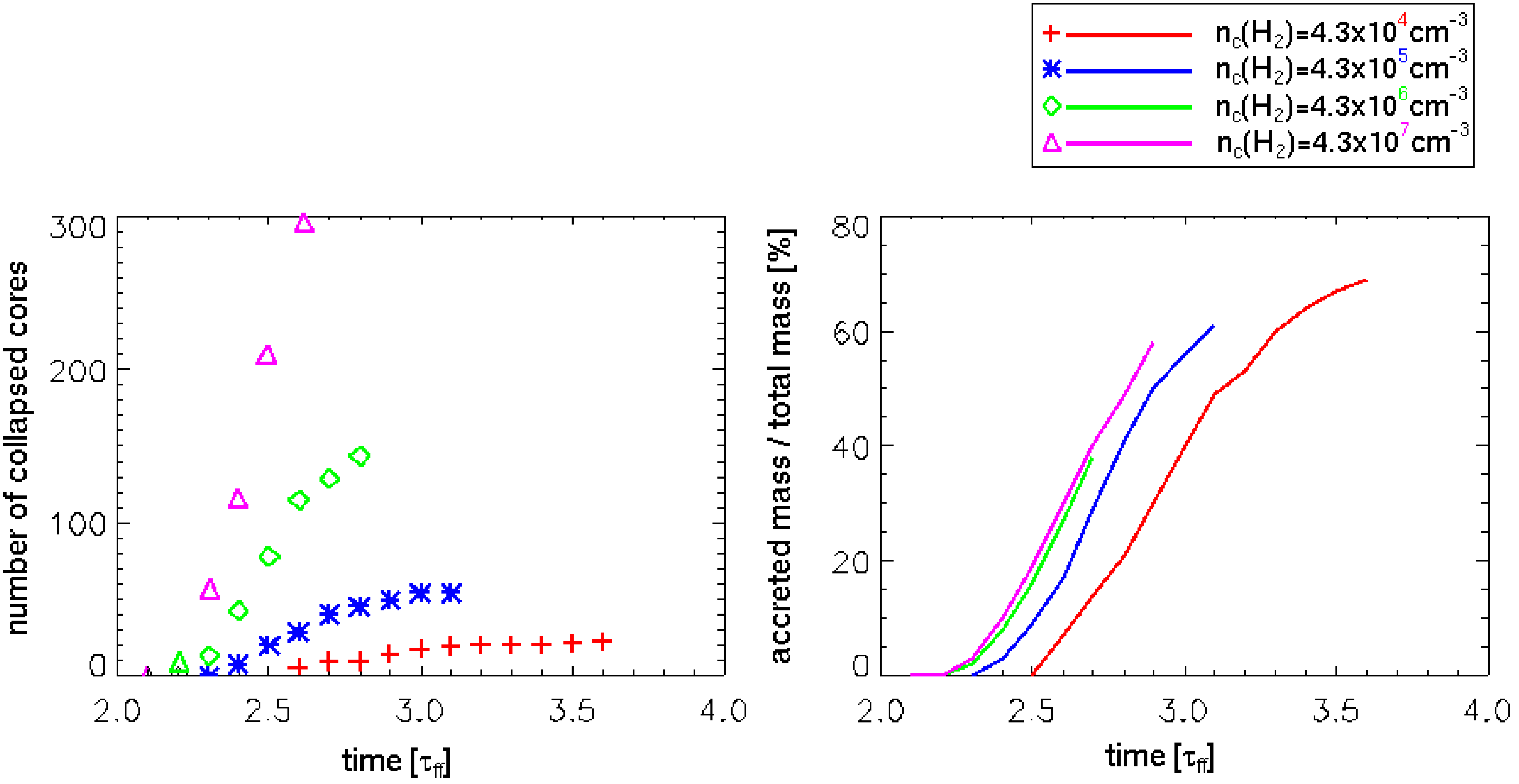
$$T \sim \rho^{\gamma - 1}$$



Density Distribution of the Gas

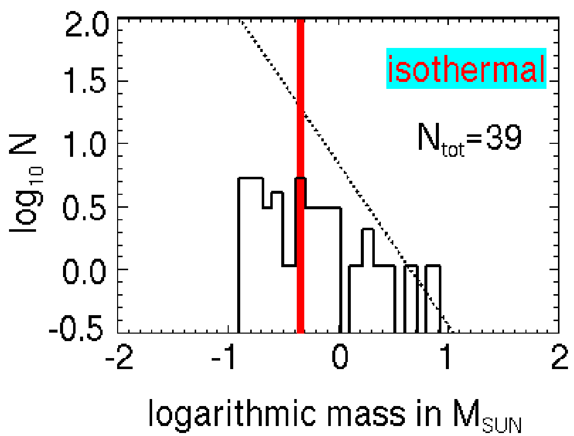


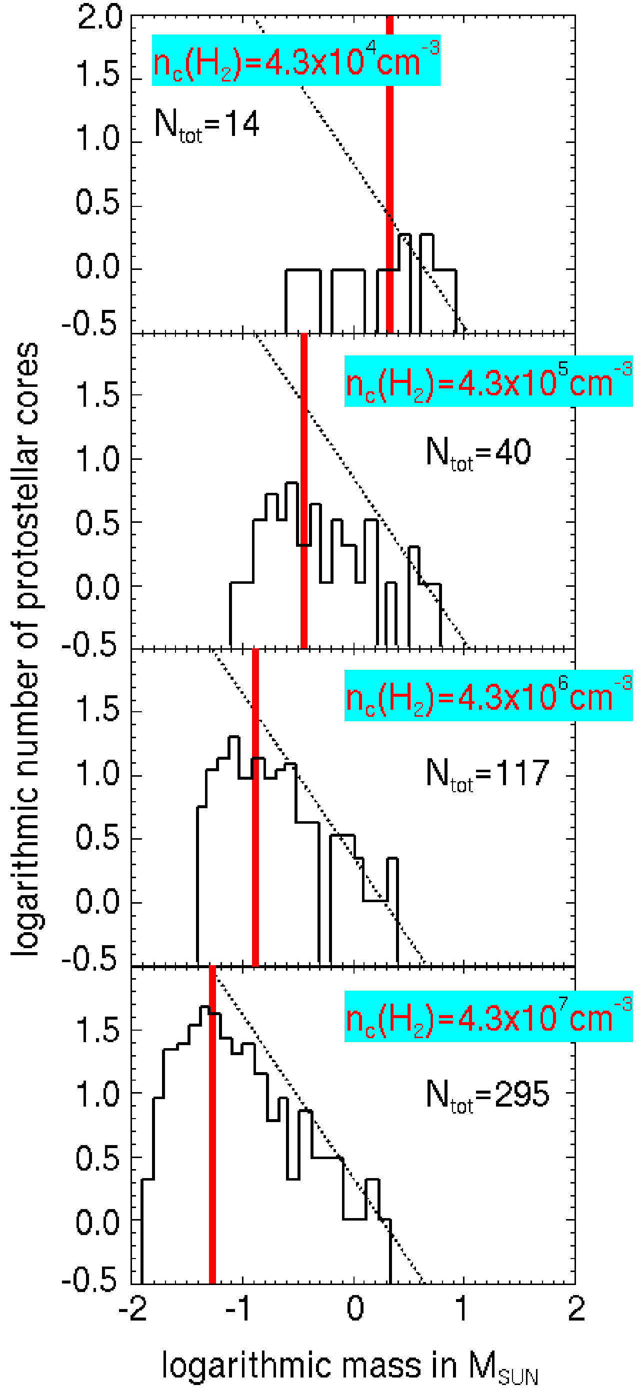
Temporal Evolution



Mass Spectra of Protostellar Cores

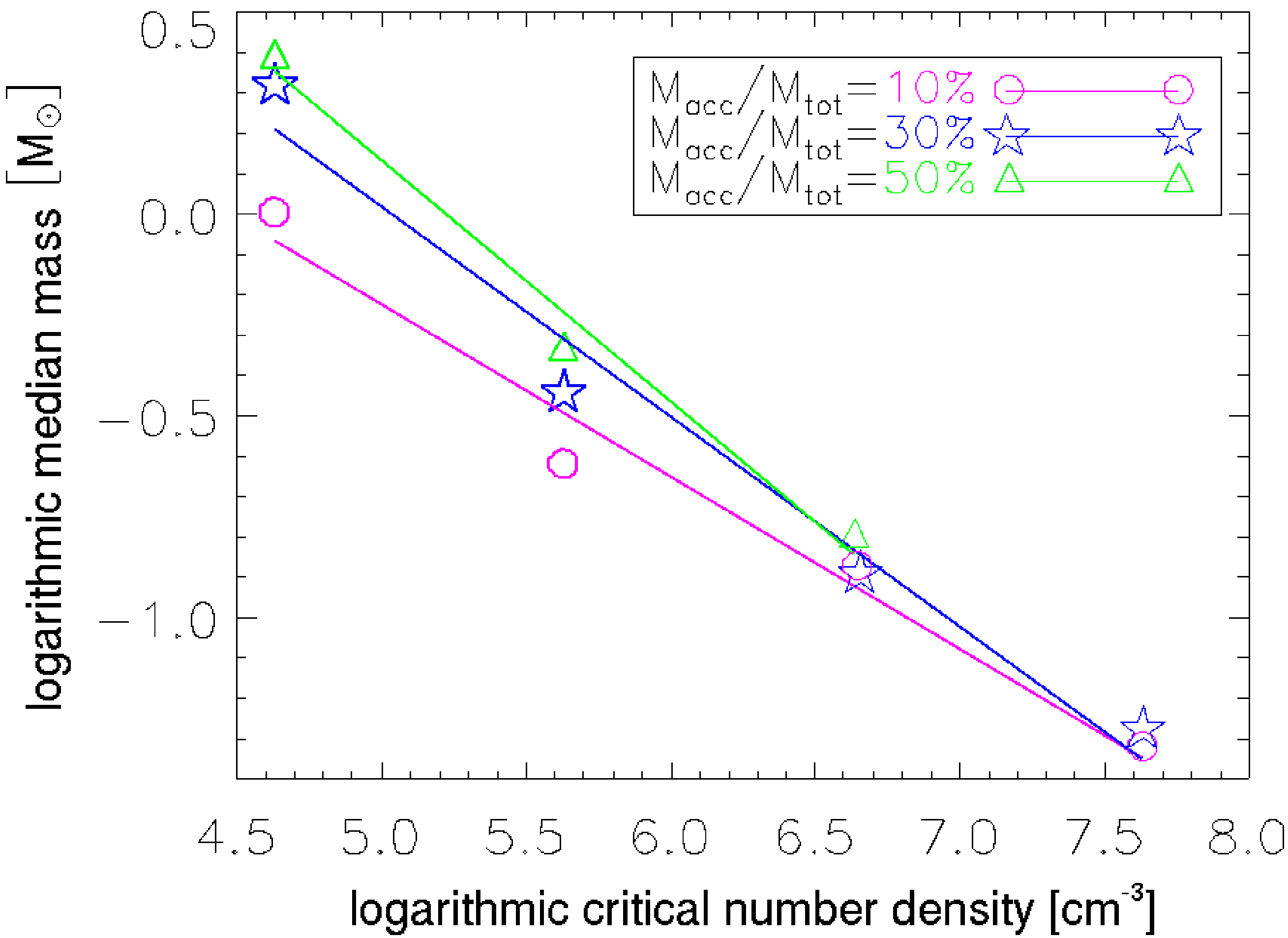
- 30% gas accreted
- median mass





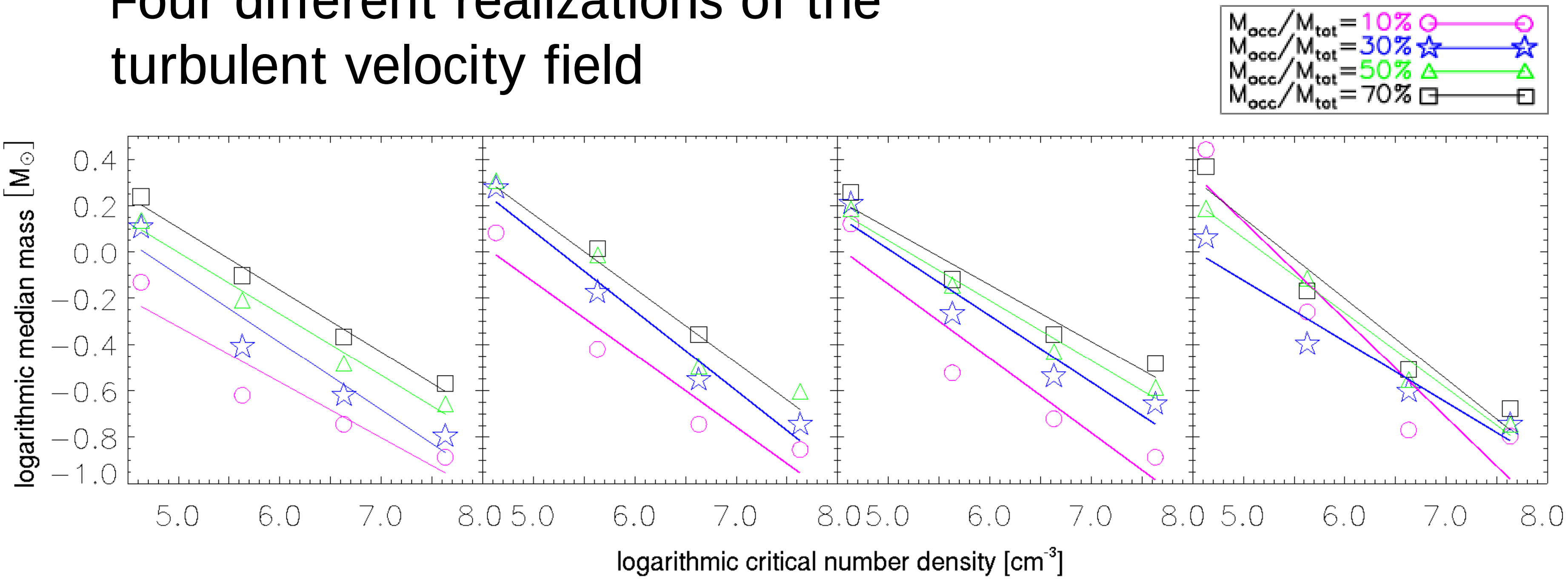
Median Mass over Critical Density

- critical density ⬆ ⇒ median mass ⬇



Changing the Turbulent Velocity Field

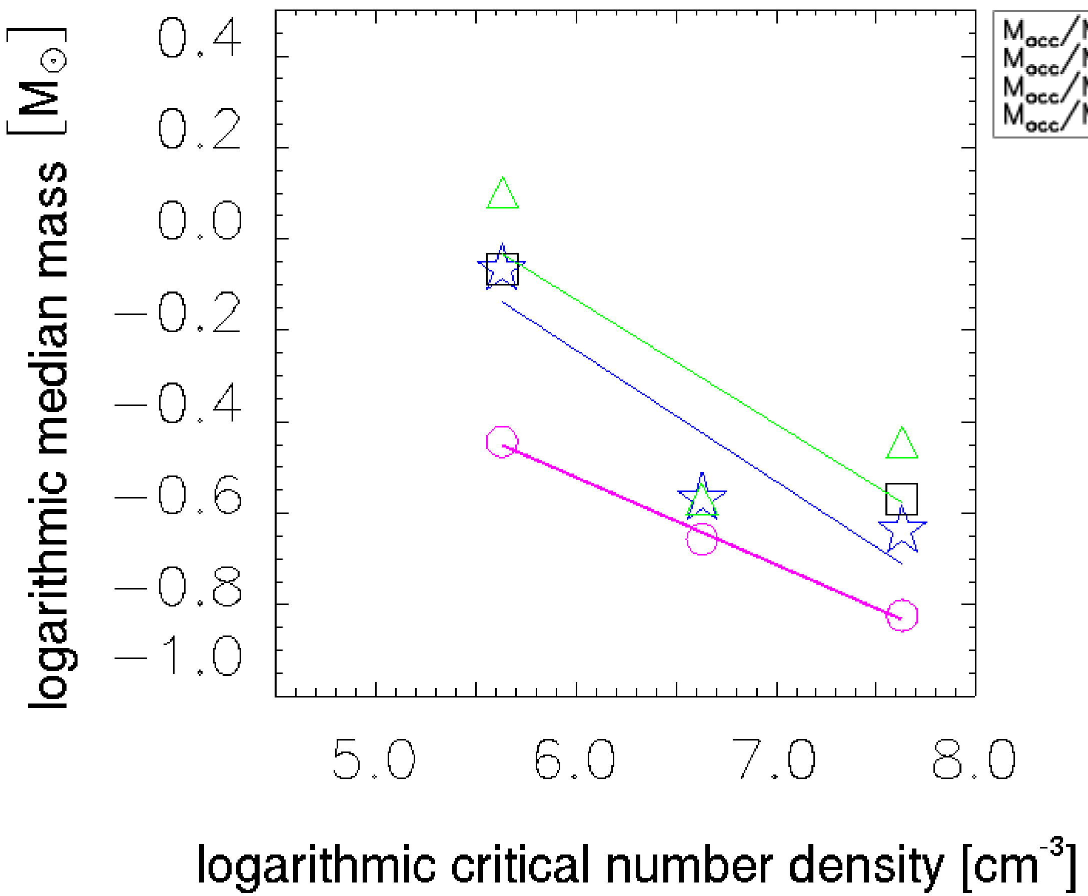
Four different realizations of the turbulent velocity field

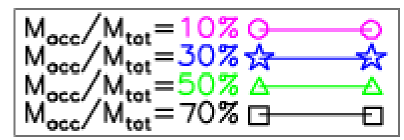


- slope < 0 but quantitatively -> differences
- star formation is a statistical process

Changing the Turbulent Driving Scale

k= 1..2 ⇨ k= 7..8





- less protostellar cores
- larger influence of local differences

Summary

- change in EOS selects characteristic mass scale

- dependence weaker than expected

- effect still present for:
    - different turbulent velocity fields
    - turbulent driving on smaller scales

- more work to be done:
    - which EOS represents thermal physics best?
    - further investigate influence of other parameters
    - better mass resolution
    - primordial gas $\underset{\gamma > 1.0}{\Longrightarrow}$ isolated, massive objects?