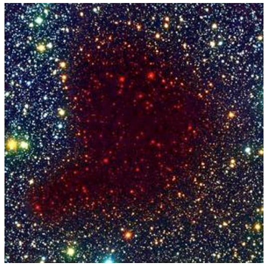
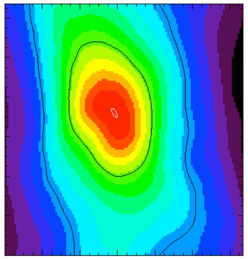
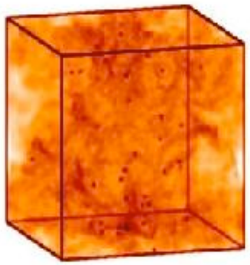
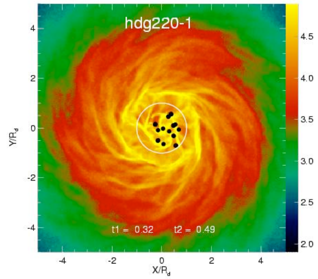
GRAVOTURBULENT STAR FORMATION





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Collaborators

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Overview

1. Physics of star formation

2. Numerical approach to star formation

Star formation

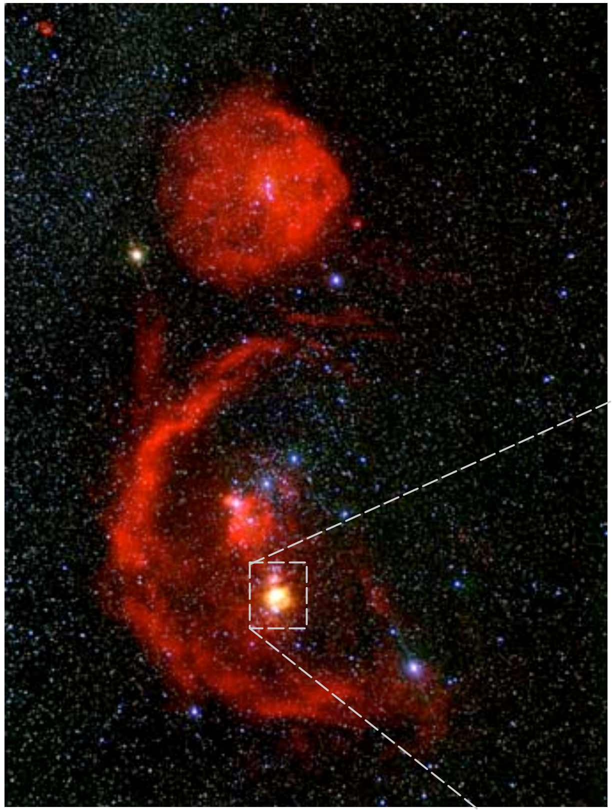
Star formation in “typical” spiral:

(from the Hubble Heritage Team)

NGC4622

- Star formation *always* is associated with *clouds of gas and dust*.
- Star formation is essentially a ***local phenomenon*** (on ~pc scale)
- HOW is star formation is *influenced* by ***global*** properties of the galaxy?

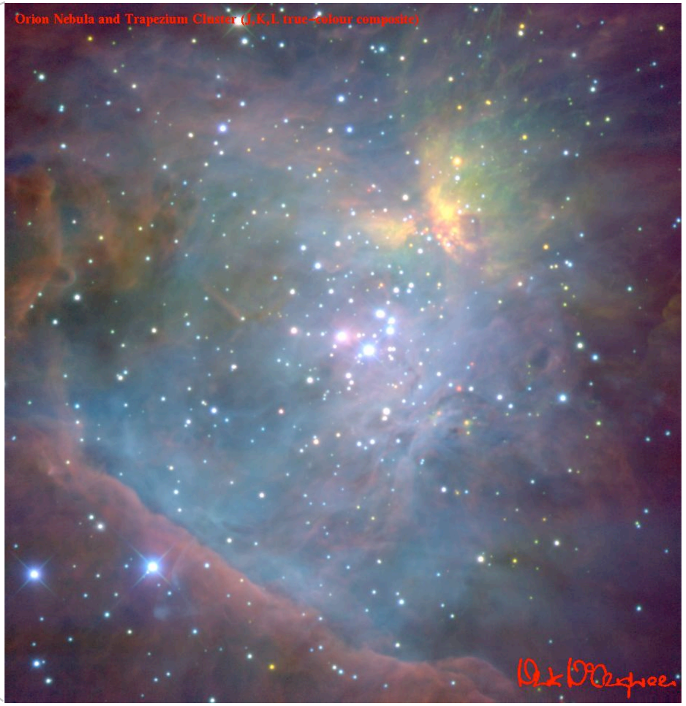
Local star forming region: The Trapezium Cluster in Orion



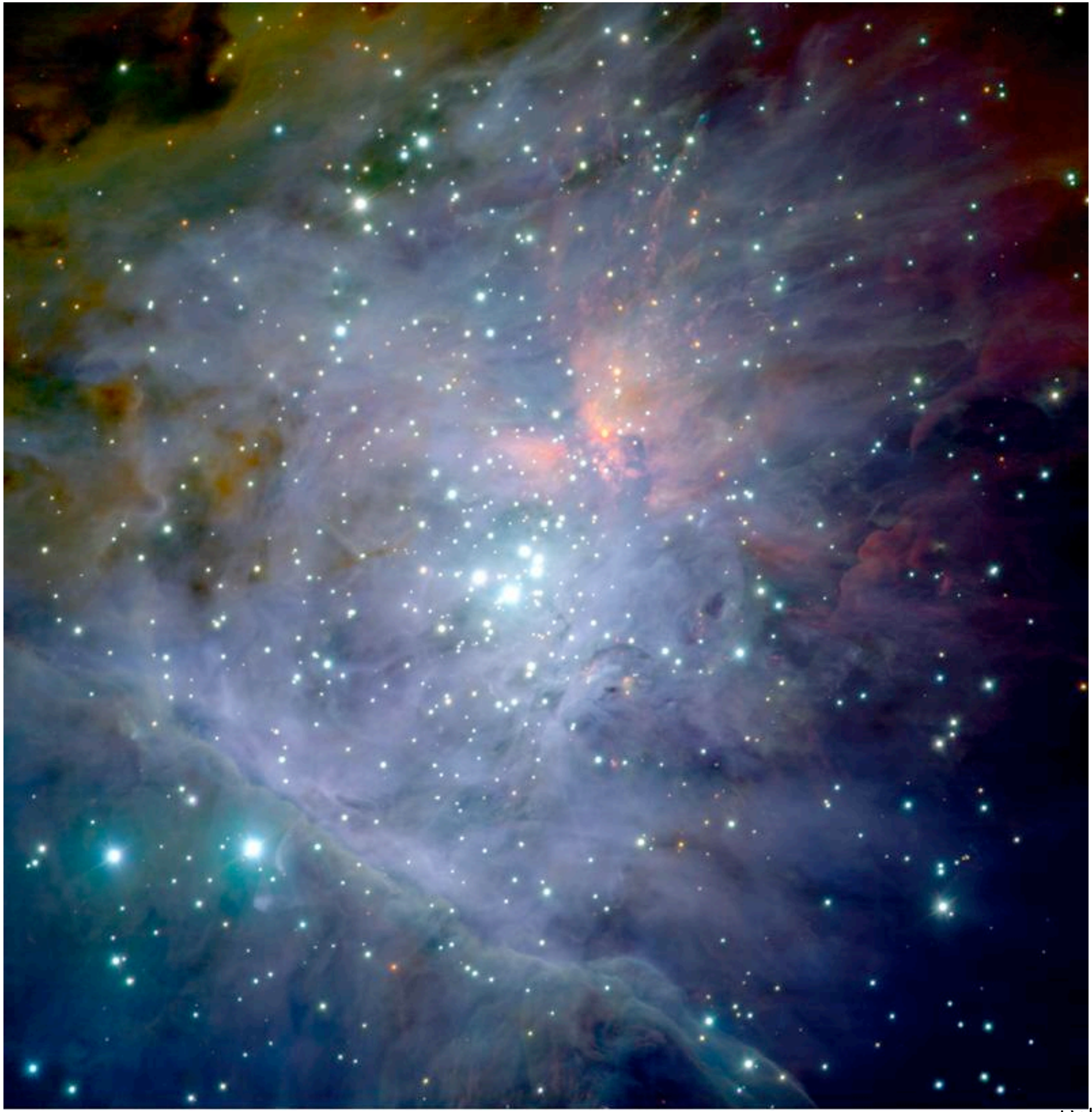
Orion molecular cloud

The Orion molecular cloud is the birth- place of several young embedded star clusters.

The Trapezium cluster is only visible in the IR and contains about 2000 newly born stars.



Trapezium cluster



Trapezium Cluster

(detail)

- stars form in clusters
- stars form in molecular clouds
- (proto)stellar feedback is important

(color composite J,H,K by M. McCaughrean, VLT, Paranal, Chile)

The star formation process

- *How* do stars form?
- What determines *when* and *where* stars form?
- What *regulates* the process and determines its *efficiency*?
- How do *global* properties of the galaxy influence star formation (a *local* process)?
- Are there different *modes* of SF?
  (Starburst galaxies vs. *LSBs*, *isolated* SF vs. *clustered* SF)

→ ***What physical processes initiate and control the formation of stars?***

Gravoturbulent star formation

- New theory of star formation:

Star formation is controlled by interplay between gravity and supersonic turbulence!

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

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

Gravoturbulent Star Formation

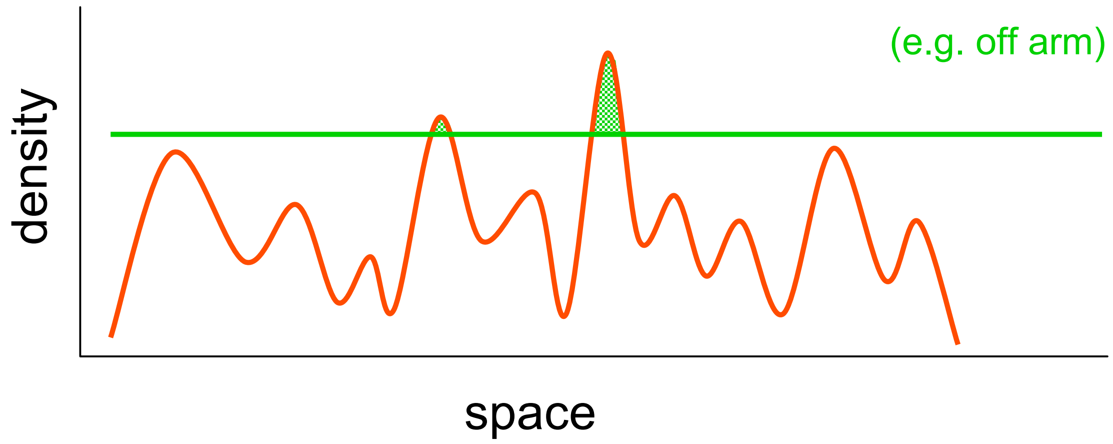
- *Supersonic turbulence* in the galactic disk creates strong density fluctuations (in shocks: $\delta\rho/\rho \approx \mathcal{M}^2$)
  - chemical phase transition: atomic → molecular
  - cooling instability
  - gravitational instability
- Cold *molecular clouds* form at the high-density peaks.
- *Turbulence* creates density structure, *gravity* selects for collapse

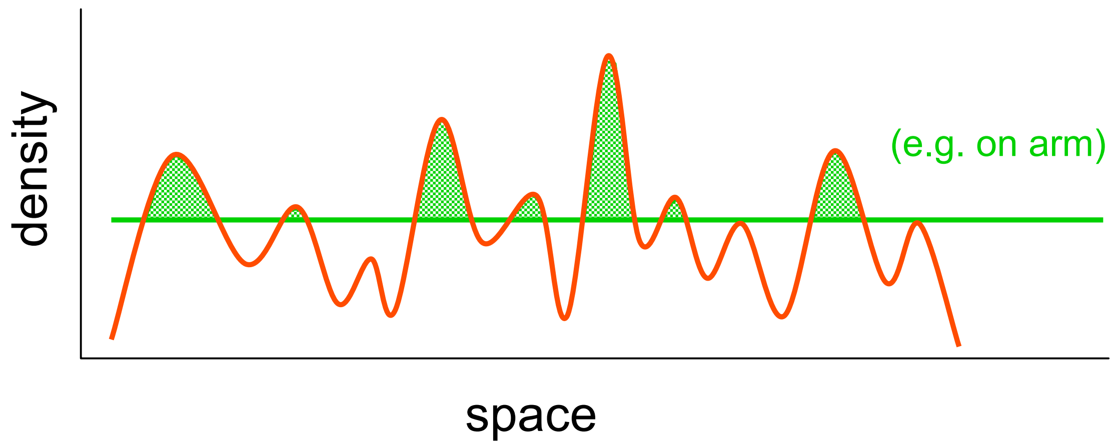
  ⟶ ***GRAVOTUBULENT FRAGMENTATION***

- *Turbulent cascade:* Local compression *within* a cloud provokes collapse → individual *stars* and *star clusters*

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

Star formation on *global* scales





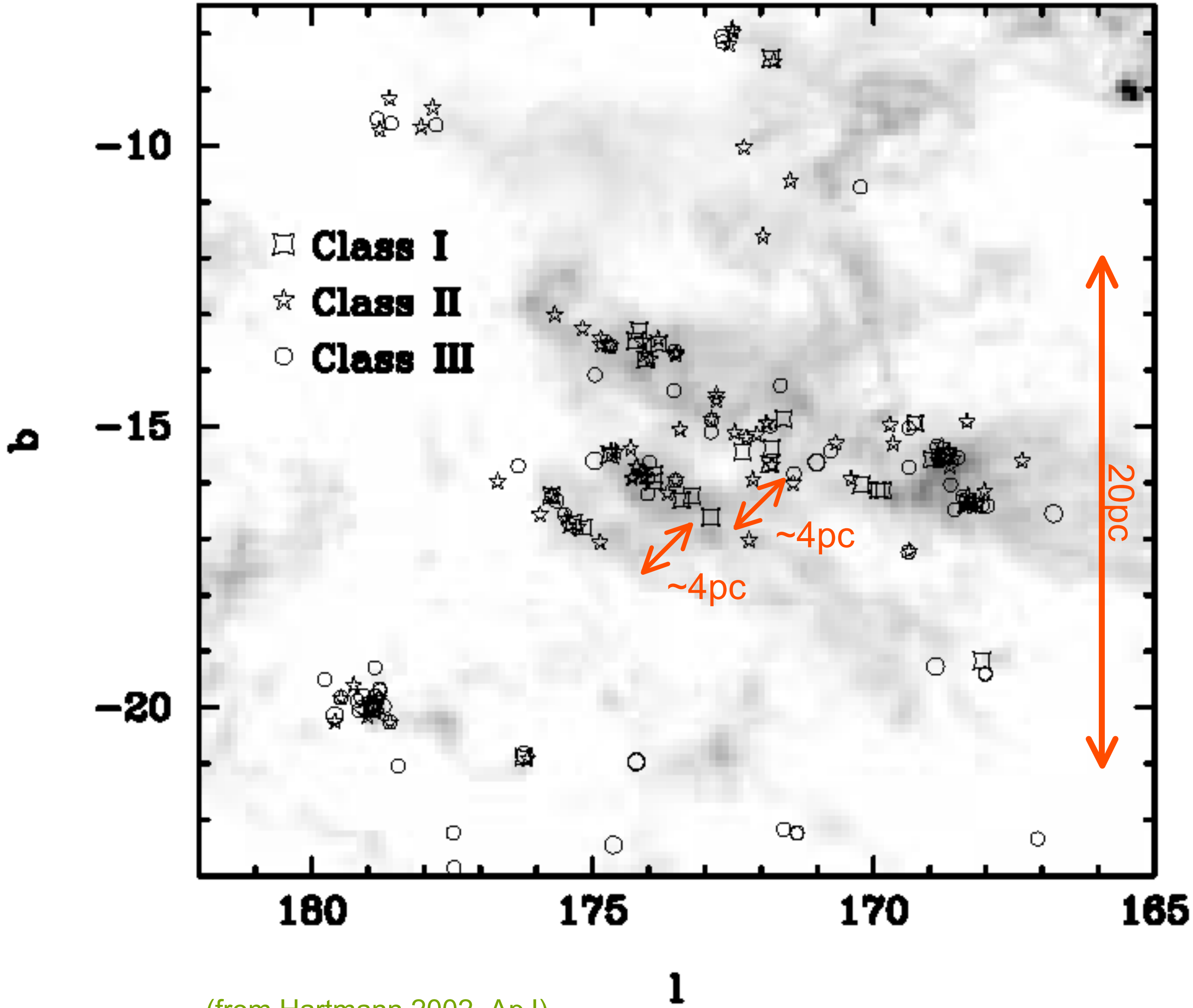
density fluctuations in warm atomar ISM caused by supersonic turbulence

some are dense enough
to form H2 within "reasonable timescale"
→molecular clouds

external perturbuations (i.e. potential changes) increase likelihood

Approaching the problem

Taurus SF cloud



(from Hartmann 2002, ApJ)

Star-forming filaments in the *Taurus* molecular cloud

Molecular clouds

- MC's are *massive* ($M_{cloud} = 10^3 \dots 10^6\ M_\odot \leftrightarrow M_{Jeans} = 1 \dots 100\ M_\odot$)
- MC's are *cold* ($T_{cloud} = 10 \dots 20$ K)
- MC's are *transient* (life time $\approx$ few $\tau_{cross} \approx$ few $\tau_{ff} \approx$ few 10^6 yr)
- MC structure is determined by *supersonic turbulence*
  (density and velocity structure dominated by large-scale modes)
- Energy budget: *Turbulent energy $\approx$ gravitational energy > magnetic energy*
- *BUT:* Turbulence *decays* rapidly ($\tau_{decay} \leq \tau_{ff} \approx 10^6$ yr)
  → need for certain degree of energy input
- Typical *SF efficiency ~5%*

Turbulent Jeans analysis

How do perturbations in self-gravitating supersonically turbulent gas evolve?

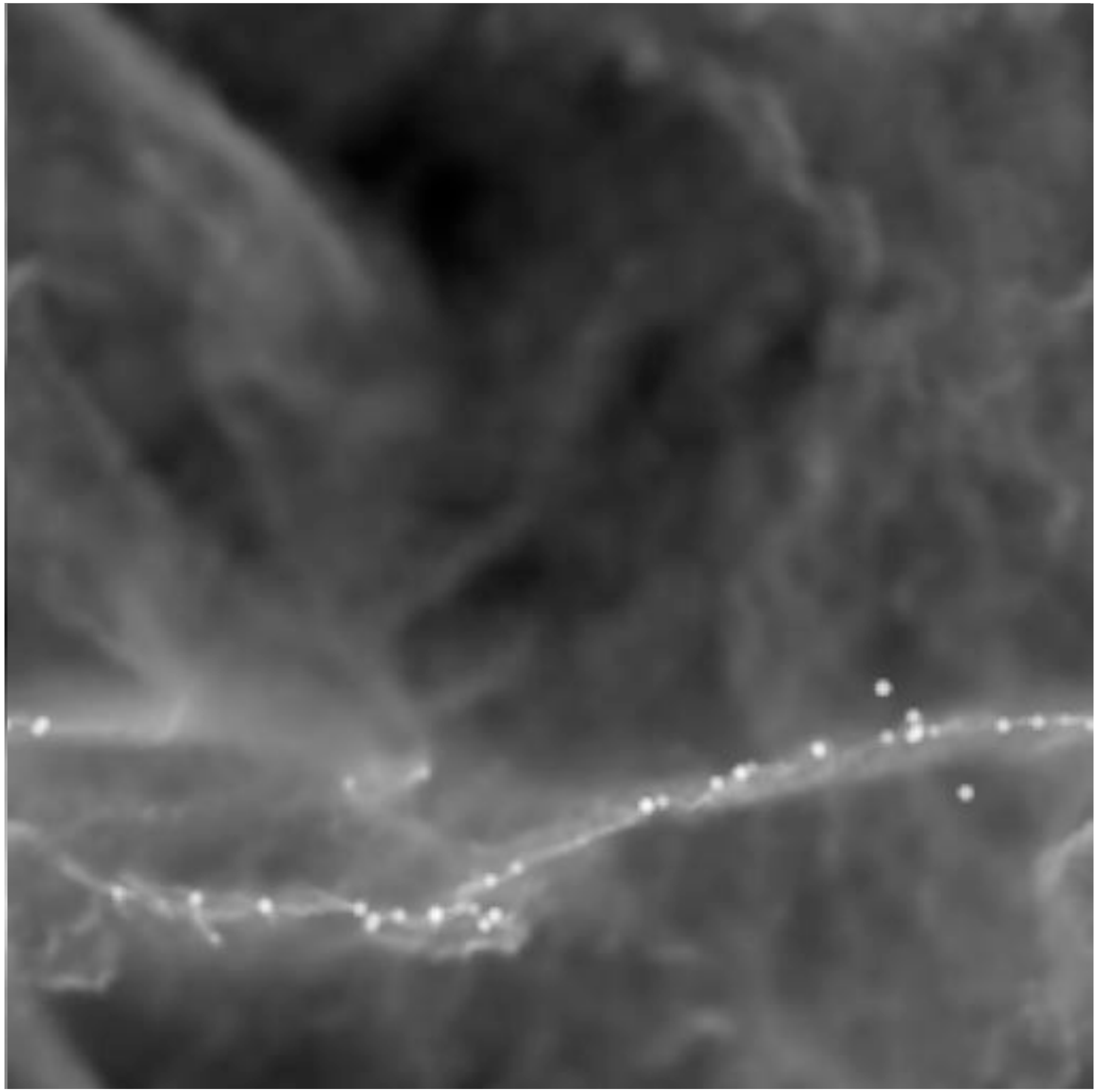
- Classical approach: ***dispersion relations***
  $\omega^2 - c_s^2 k^2 + 4\pi G\rho_0 = 0$ (Jeans 1921)
  to include turbulence: $c_s^2 \rightarrow c_s^2 + 1/3 \langle v^2 \rangle$ (Chandrasekhar 1951)
- Consider wavelength dependence: $c_s^2 \rightarrow c_s^2 + 1/3\, v^2(k)$
- For ***incompressible turbulence:*** support needs to act on wavelengths *below* the *thermal Jeans scale.* (Bonazzola et al. 1992)
- For ***compressible turbulence:*** 1D simulations show high-Mach number turbulence induces (local) collapse. (Gammie & Ostriker 1996)
- 2000/01: systematic 3D large-eddy simulations of (M)HD turbulence with SPH and ZEUS
  (Klessen, Heitsch, & Mac Low 2000 + Heitsch, Mac Low, & Klessen 2001)
- In the past 5-6 years: many studies with SPH, different finite difference schemes, spectral codes, BGK, etc.…

Model of gravoturbulent fragmentation

- SPH model with 1.6×10^6 particles
- large-scale driven turbulence
- Mach number $\mathcal{M} = 6$
- periodic boundaries
- physical scaling:

(from Klessen & Ballesteros, in preparaton)

Gravoturbulent fragmentation



Gravoturbulent fragmentation in molecular clouds:

- SPH model with 1.6×10^6 particles
- large-scale driven turbulence
- Mach number $\mathcal{M} = 6$
- periodic boundaries
- physical scaling:

"Taurus":

→ density $n(H_2) \approx 10^2\,cm^{-3}$

→ $L = 6\,pc$, $M = 5000\,M_\odot$

(from Ballesteros-Paredes & Klessen, in preparation)

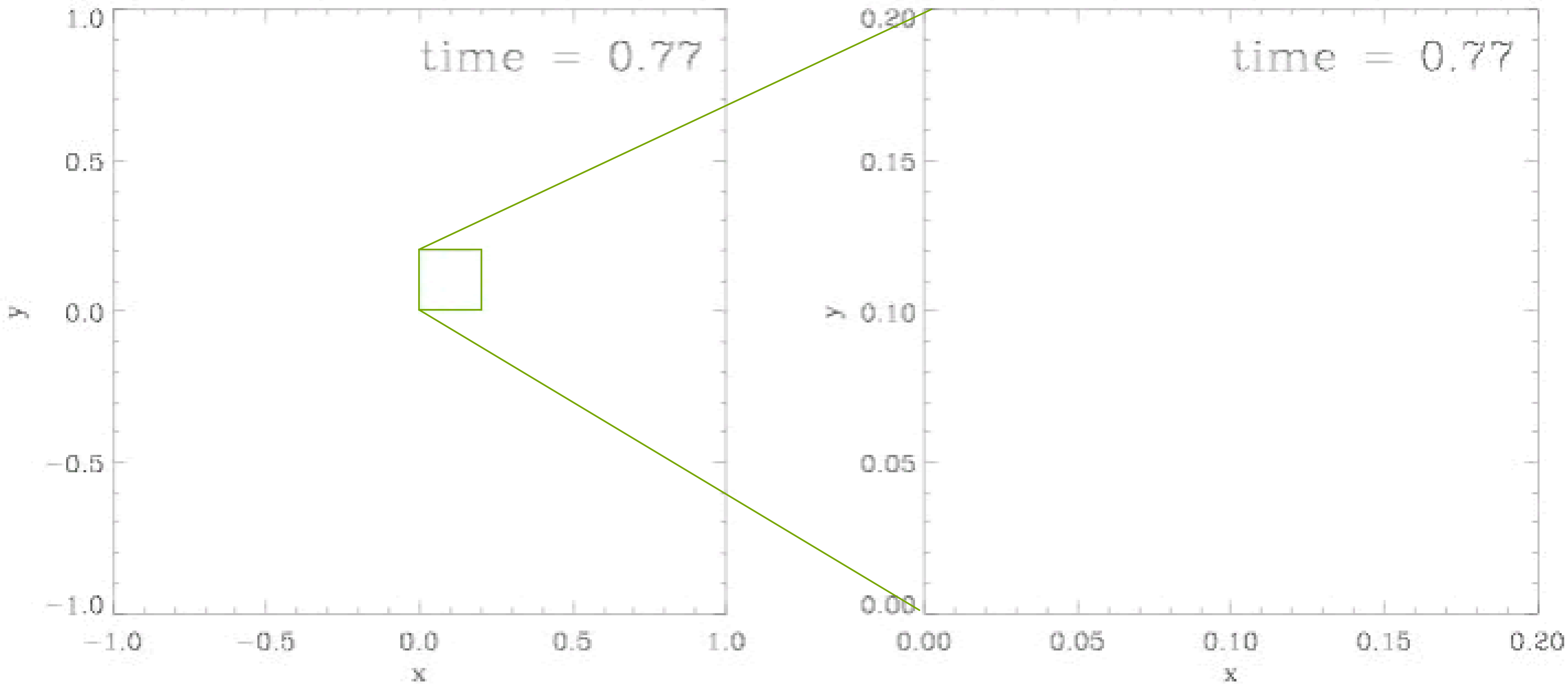
What can we learn from that?

- *global properties* (statistical properties)
  - SF efficiency
  - SF time scale
  - IMF – formation of stellar clusters
  - description of self-gravitating turbulent systems (pdf's, Δ-*var.)*
  - chemical mixing properties
- *local properties* (properties of individual objects)
  - properties of individual clumps (e.g. shape, radial profile)
  - accretion history of individual protostars (dM/dt vs. t, j vs. t)
  - binary (proto)stars (eccentricity, mass ratio, etc.)
  - SED's of individual protostars
  - dynamic PMS tracks: T_{bol}-L_{bol} evolution

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

Star cluster formation

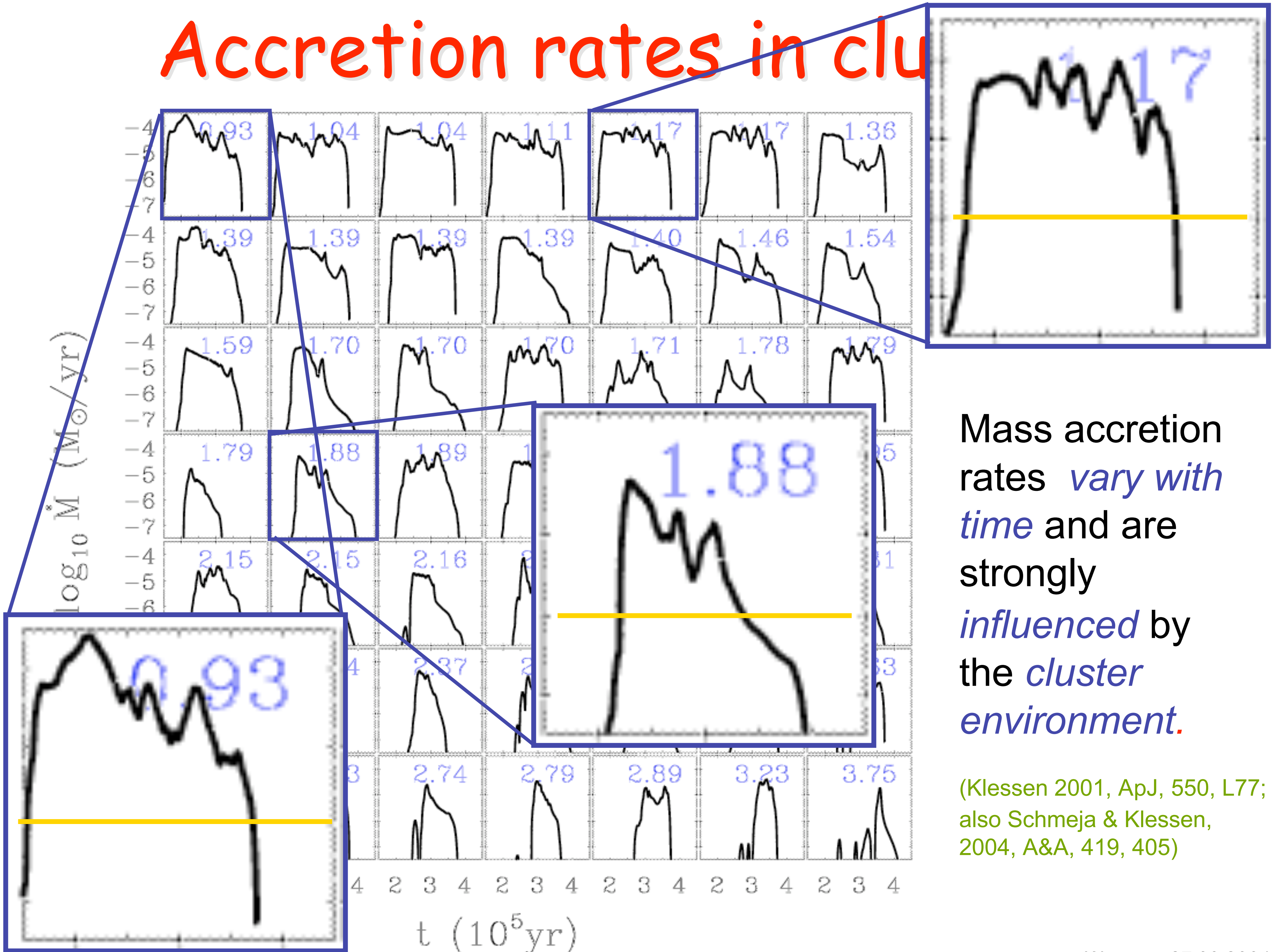
Most stars form in clusters → *star formation = cluster formation*



Trajectories of protostars in a nascent dense cluster created by gravoturbulent fragmentation

(from Klessen & Burkert 2000, ApJS, 128, 287)

Accretion rates in clu

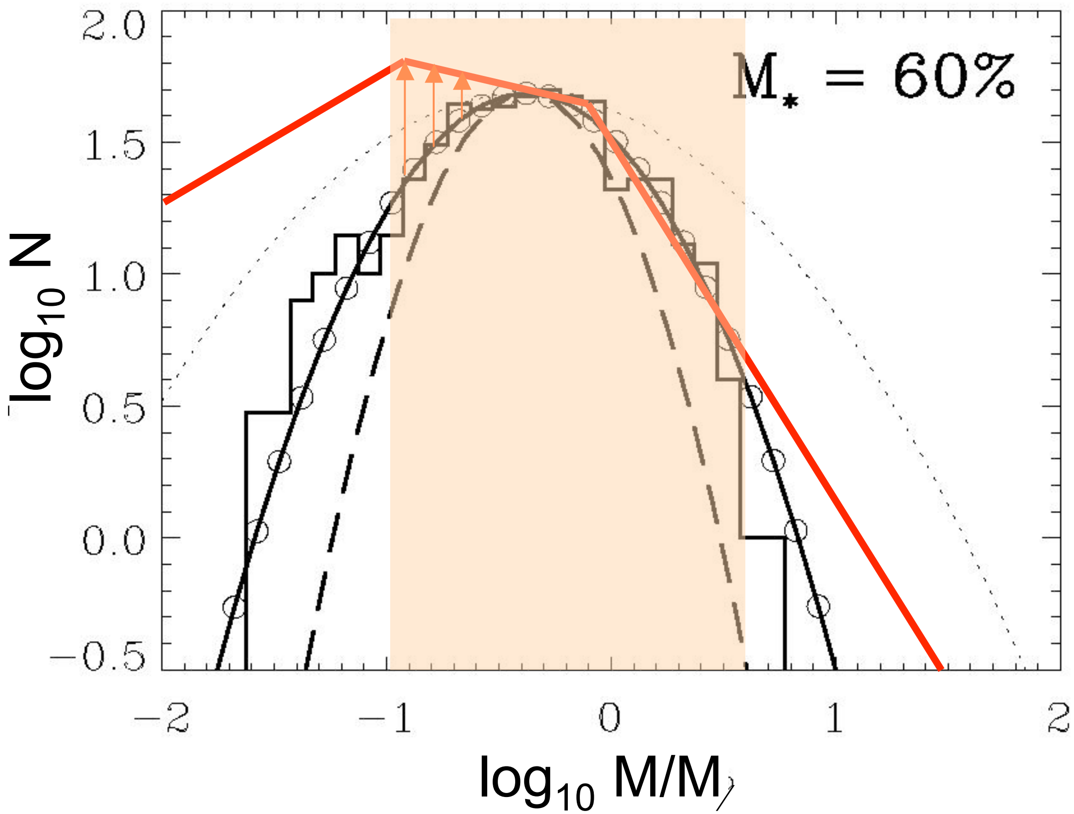


Mass accretion rates *vary with time* and are strongly *influenced* by the *cluster environment*.

(Klessen 2001, ApJ, 550, L77; also Schmeja & Klessen, 2004, A&A, 419, 405)

Protostellar mass spectra I

- gravoturbulent fragmentation of self-gravitating isothermal clouds gives mass spectra that come close to IMF



(from Klessen & Burkert 2000, ApJS, 128, 287)

Comparison with observed IMF (*no* binary correction)

Low statistics at *low-mass* and *high-mass* end.

BUT: Does ist really fit?
Ist there power-law slope?

Miller & Scalo (1979)
Kroupa, Tout, & Gilmore (1990)
"Standard" IMF of single stars (e.g. Scalo 1998, Kroupa 2002)

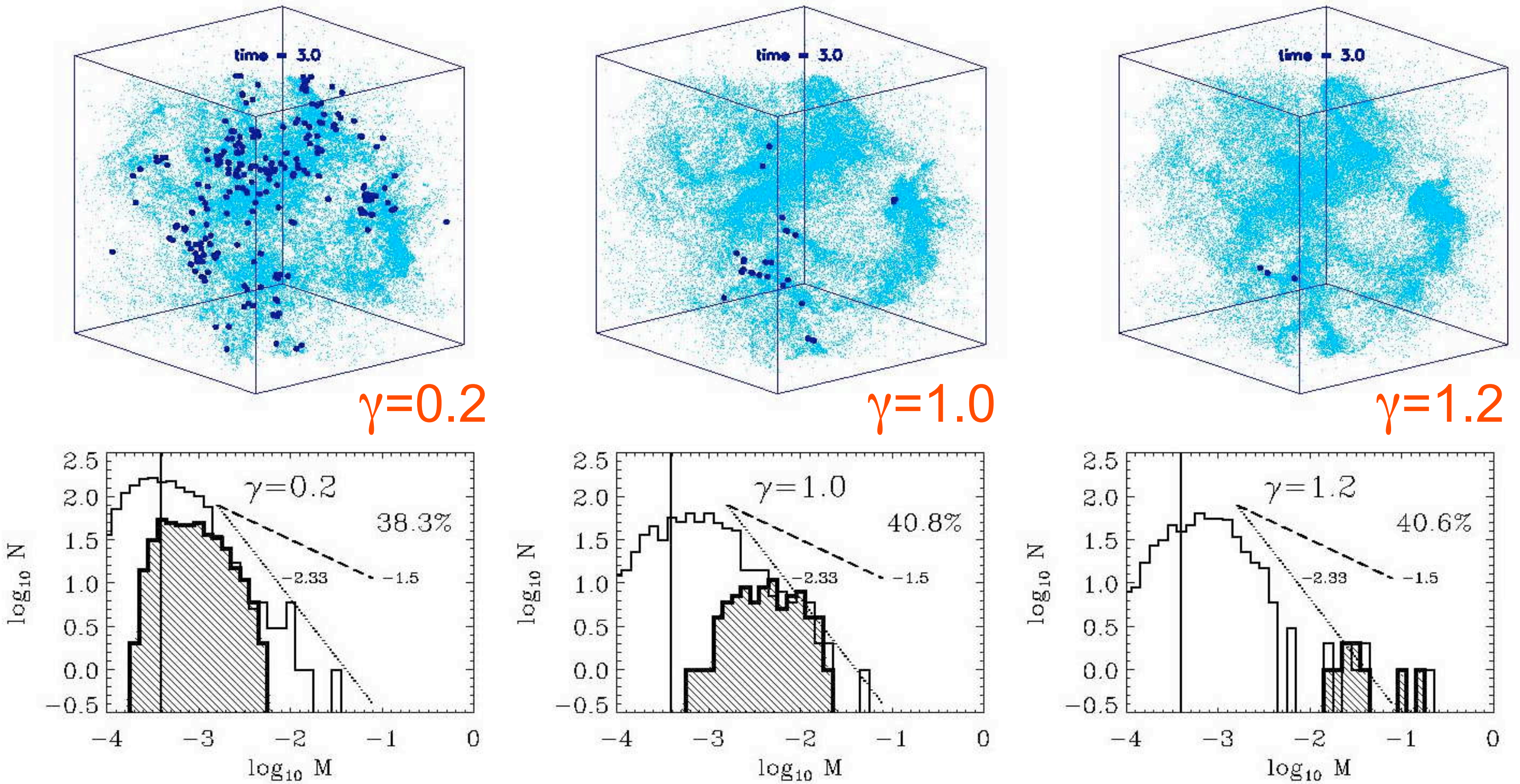
Dependency on EOS

- degree of fragmentation depends on *EOS!*

- polytropic EOS: $\mathbf{p} \propto \rho^{\gamma}$
- $\gamma<1$: dense cluster of low-mass stars
- $\gamma>1$: isolated high-mass stars

(see Li, Klessen, & Mac Low 2003, ApJ, 592, 975)

Dependency on EOS



for $\gamma<1$ fragmentation is enhanced → *cluster of low-mass stars*

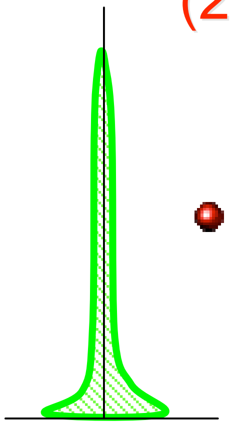
for $\gamma>1$ it is suppressed → formation of *isolated massive stars*

(from Li, Klessen, & Mac Low 2003, ApJ, 592, 975)

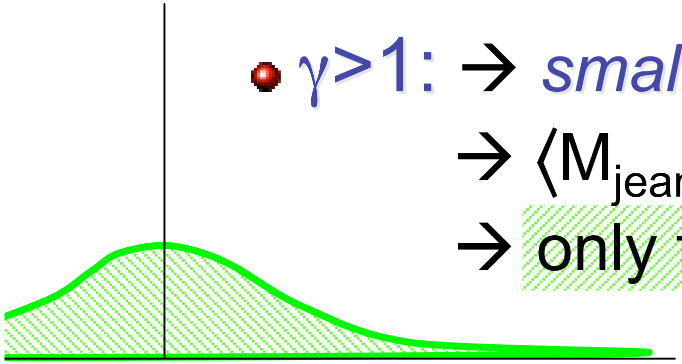
How does that work?

(1) $p \propto \rho^{\gamma} \rightarrow \rho \propto p^{1/\gamma}$

(2) $M_{jeans} \propto \gamma^{3/2} \rho^{(3\gamma-4)/2}$



- $\gamma<1$: → *large* density excursion for given pressure
  → $\langle M_{jeans} \rangle$ becomes small
  → number of fluctuations with $M > M_{jeans}$ is large



- $\gamma>1$: → *small* density excursion for given pressure
  → $\langle M_{jeans} \rangle$ is large
  → only few and massive clumps exceed M_{jeans}

Implications

- degree of fragmentation depends on *EOS!*

- polytropic EOS: $p \propto \rho^{\gamma}$
- $\gamma<1$: dense cluster of low-mass stars
- $\gamma>1$: isolated high-mass stars

- implications for very *metal-poor* stars
  (expect Pop III stars in the early universe
  to be massive and form in isolation)

  (see Li, Klessen, & Mac Low 2003, ApJ, 592, 975;
  also Jappsen, Klessen, Larson, Li, Mac Low,
  in preparation)

- Observational findings: isolated O stars in LMC (and M51)?

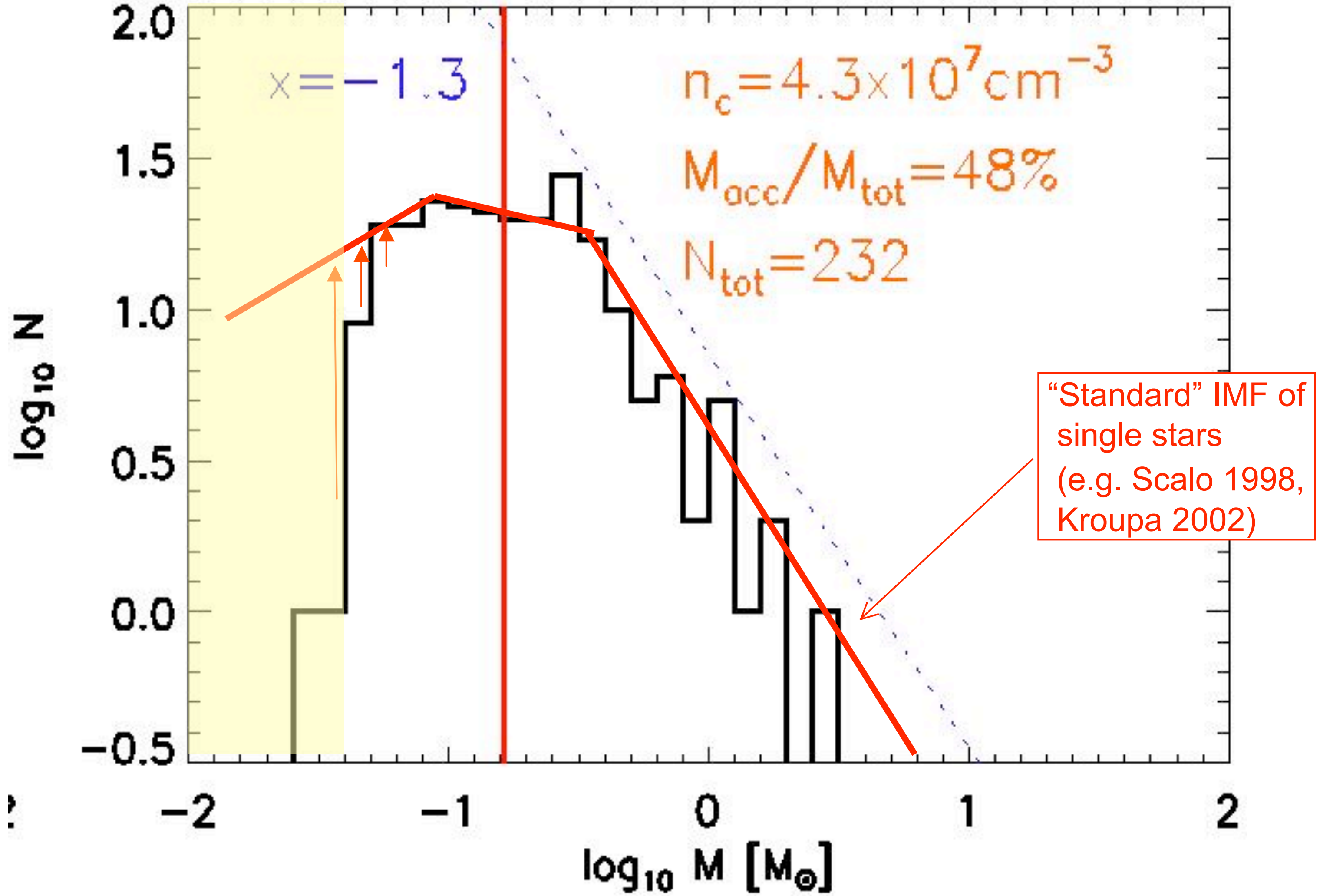
More realistic models

- But EOS depends on *chemical state*, on *balance* between *heating* and *cooling*

→ γ is function of ρ **!!!**

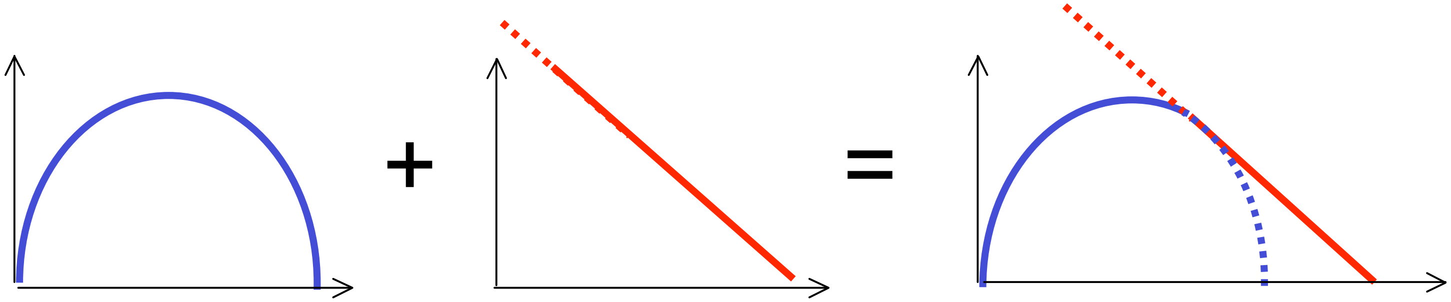
- New models with piecewise polytropic EOS:
  (Jappsen, Klessen, Larson, Li, Mac Low, in preparation)
- $\gamma = 0.7$ for $\rho < \rho_c$
- $\gamma = 1.1$ for $\rho \geq \rho_c$
- we vary ρ_c from 4.3×10^4 cm^{-3} to 4.3×10^8 cm^{-3}
- most realistic case for Galactic MC's: $\rho_c \approx 2\times10^6$ cm^{-3}
  (see, e.g., Spaans & Silk, 2000, ApJ, 538, 115)

Mass spectrum



(Jappsen, Klessen, Larson, Li, Mac Low, in preparation)

Plausibility argument for shape



- Supersonic turbulence is scale free process

  → *POWER LAW BEHAVIOR*

- *But also:* turbulence and fragmentation are highly stochastic processes → central limit theorem

  → *GAUSSIAN DISTRIBUTION*

Numerics

Numerical approach I

- Problem of star formation is very complex. It involves many scales (10^7 in length, and 10^{20} in density) and many physical processes → *NO* analytic solution
  → NUMERICAL APPROACH
- BUT, we need to…
  - solve the MHD equations in 3 dimensions
  - solve Poisson's equation (self-gravity)
  - follow the full turbulent cascade (in the ISM + in stellar interior)
  - include heating and cooling processes (EOS)
  - treat radiation transfer
  - describe energy production by nuclear burning processes

IMPOSSIBLE

Numerical approach II

- Simplify!
  Divide problem into little bits and pieces….
- **GRAVOTURBULENT CLOUD FRAGMENTATION**
- We try to…
  - solve the HD equations in 3 dimensions
  - solve Poisson's equation (self-gravity)
  - include a (humble) approach to supersonic turbulence
  - describe isothermal gas ("perfect" cooling)

LARGE-EDDY SIMULATIONS

Large-eddy simulations

- We use ***LES*** to models the large-scale dynamics
- Principal problem: only large scale flow properties
  - Reynolds number: Re = LV/ν ***(Re_{nature} >> Re_{model})***
  - dynamic range much smaller than true physical one
  - need ***subgrid model*** (in our case simple: only dissipation) more complex when processes (chemical reactions, nuclear burning, etc) on subgrid scale determine large-scale dynamics
- Also: stochasticity of the flow $\Rightarrow$ unpredictable when and where "interesting things" happen
  - occurance of localized collapse
  - location and strength of shock fronts
  - etc.

LES with SPH

- For self-gravitating gases SPH is probably okay …
  - fully Lagrangian (particles are free to move where needed)
  - good resolution in high-density regions (in collapse)
  - particle based --> good for transition from hydrodynamics to stellar dynamics
- BUT:
  - low resolution in low-density region
  - difficult to reach very high levels of refinement (however, particle splitting may be promising path)
  - dissipative and need for artificial viscosity
  - how to handle subgrid scales?

Gravoturbulent SF with SPH

- Comparison between particle-based and grid-based methods: SPH vs. ZEUS

  Klessen, Heitsch, Mac Low (2000)
  Heitsch, Mac Low, Klessen (2001)
  Ossenkopf, Klessen, Heitsch (2001)

- Both methods are complementary…

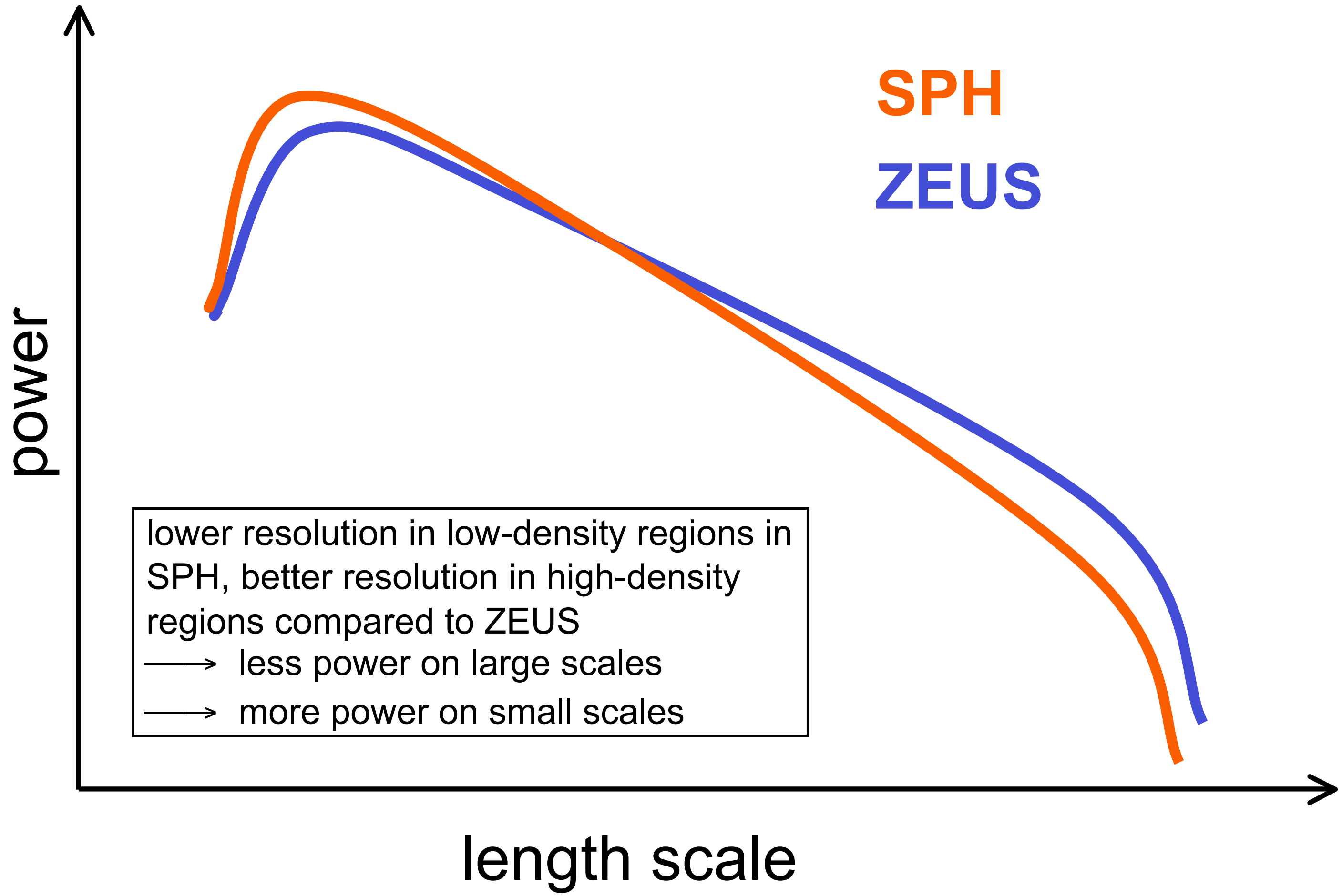
  ⟶ Bracketing reality!

- As a crude estimage:

  SPH is better in high-density regions

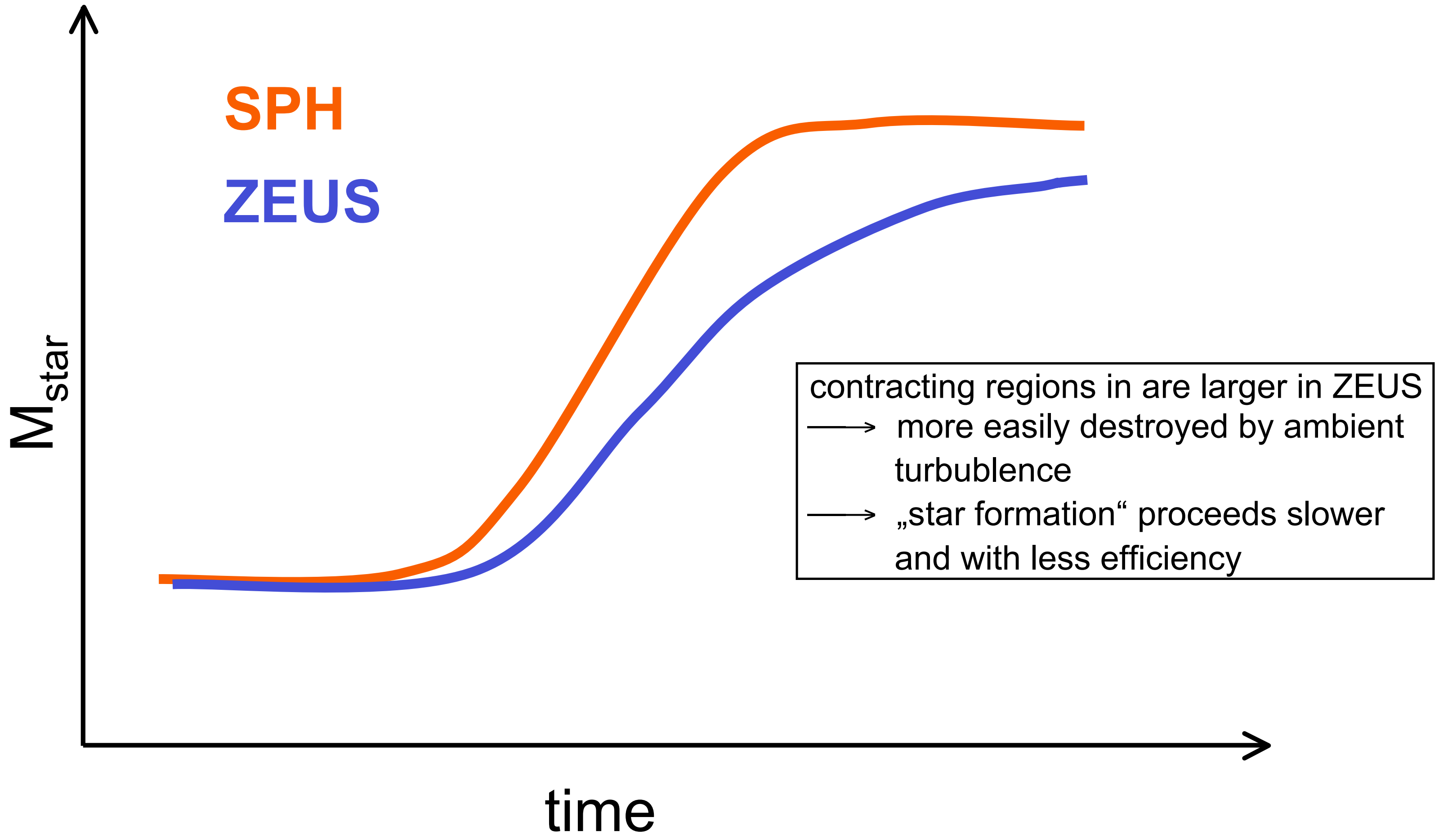
  ZEUS is better in low-density regions

SPH vs. ZEUS



(Ossenkopf, Klessen, Heitsch 2001)

SPH vs. ZEUS



(Ossenkopf, Klessen, Heitsch 2001)

Comments on SPH resolution

- Resolution study of „standard case“ of gravoturbulent SF shows convergence:

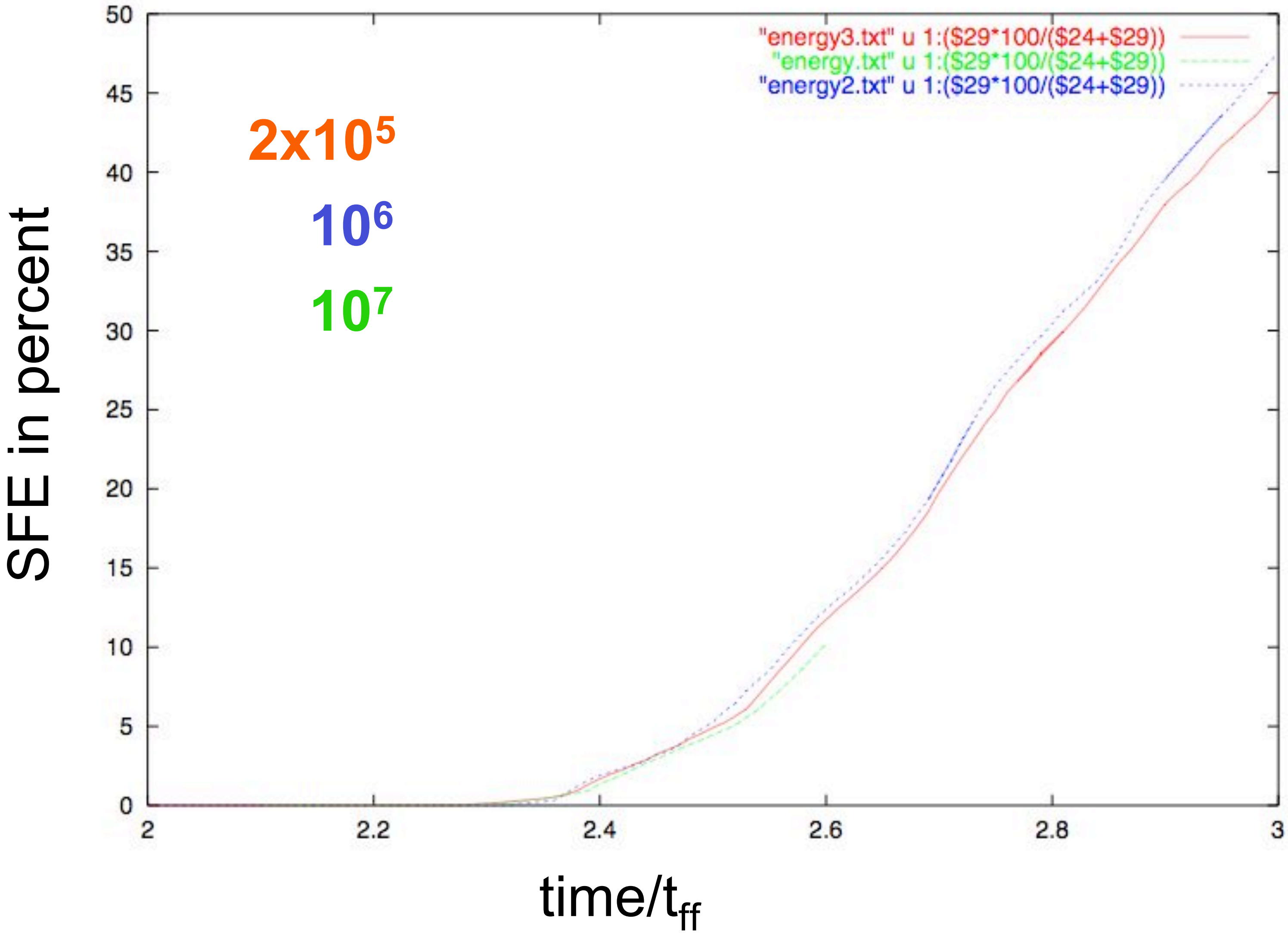
  SPH runs with 2×10^5, 10^6, and 10^7 particles show very little difference!

- Reason: Density fluctuations in molecular clouds are in the strongly NON-LINEAR regime ($\delta\rho/\rho \approx 10 \ldots 100$). Whether fluctuation collapses depends on the *detailed local balance* between pressure gradient and self-gravity in the numerical scheme.

- This differs from recent study by Fisher et al. who focus on fragmentation from quasi-equilibrium (rot. supported disk).

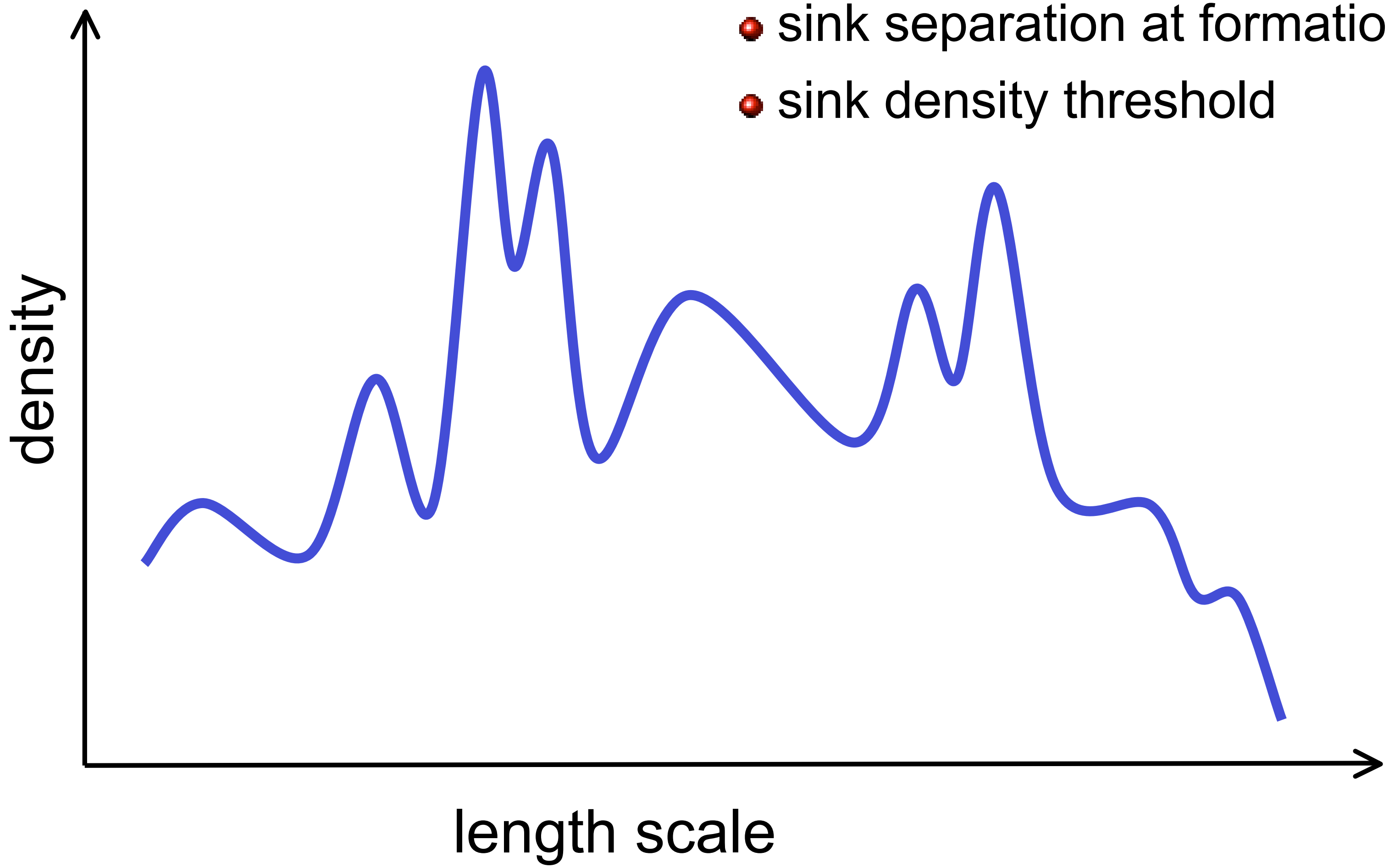
  See also recent studies by Pfalzner (2003, 2004) and Schäfer et al. (2004) on the evolution of self-gravitating disks.
  → Need several 10^5 SPH particles to resolve disk dynamics

SPH with $N=2x10^5$, 10^6 and 10^7



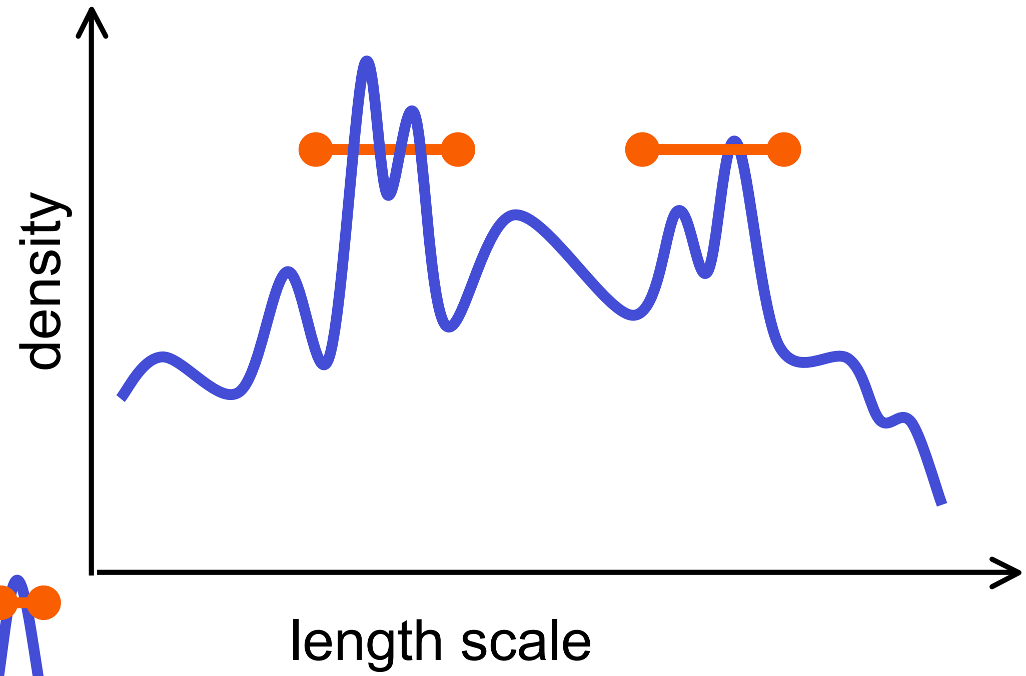
SPH with sink particles I

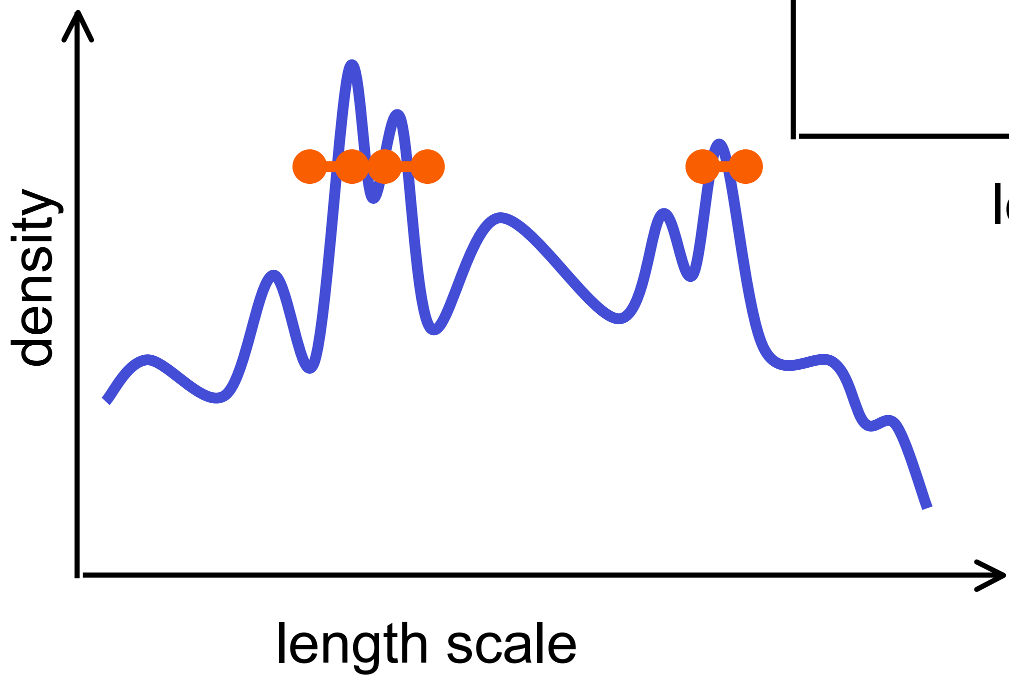
- sink particle diameter
- sink separation at formation
- sink density threshold



SPH with sink particles II

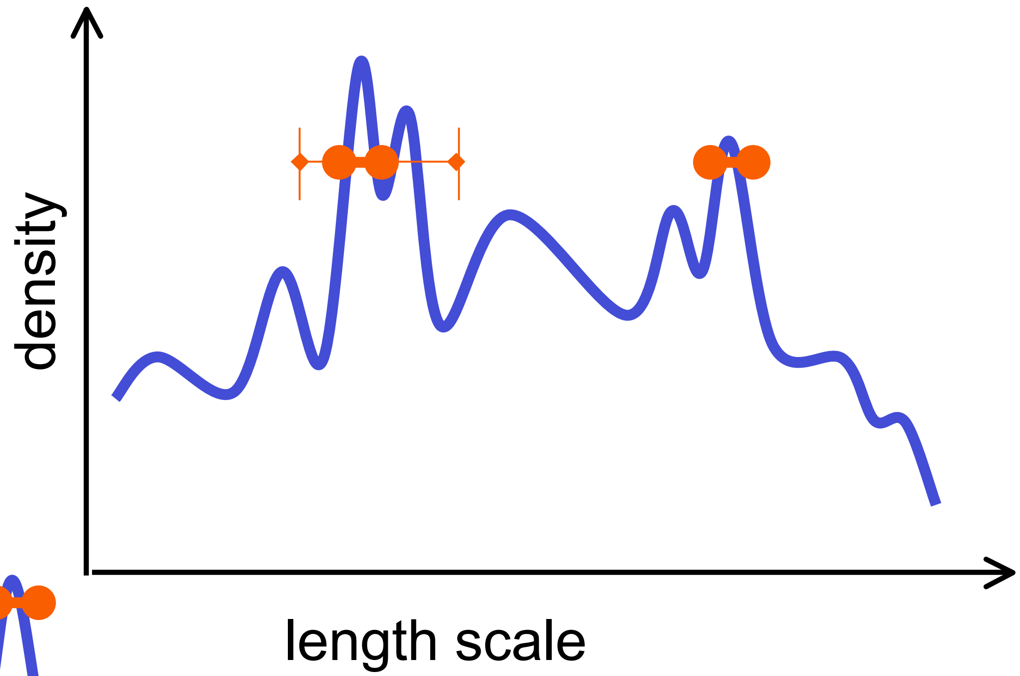
- sink particle diameter
- sink separation at formation
- sink density threshold

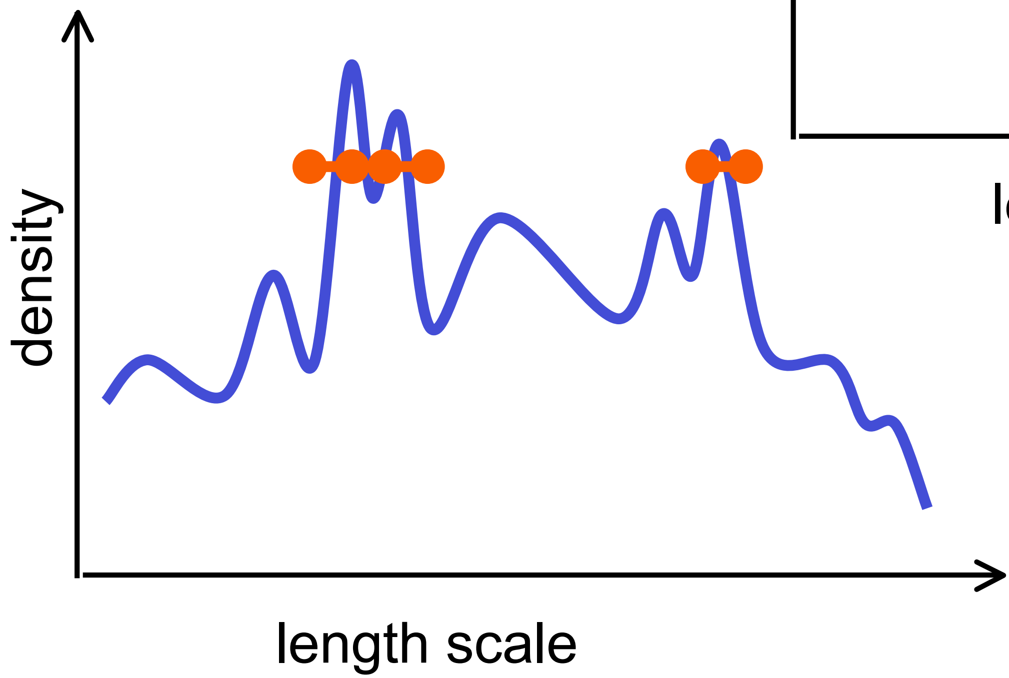




SPH with sink particles III

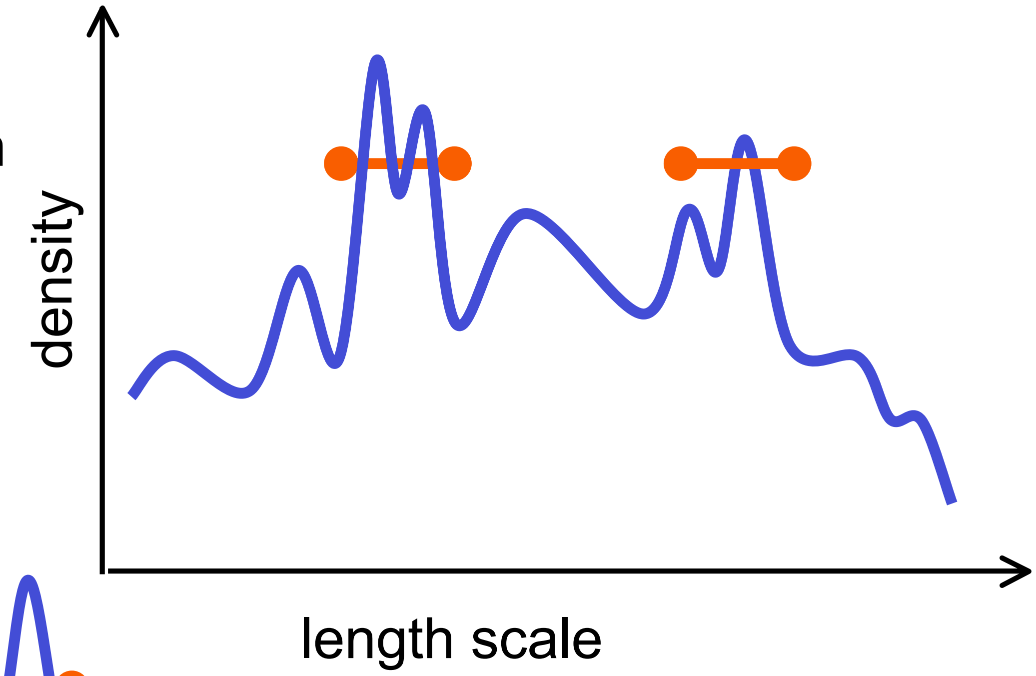
- sink particle diameter
- sink separation at formation
- sink density threshold

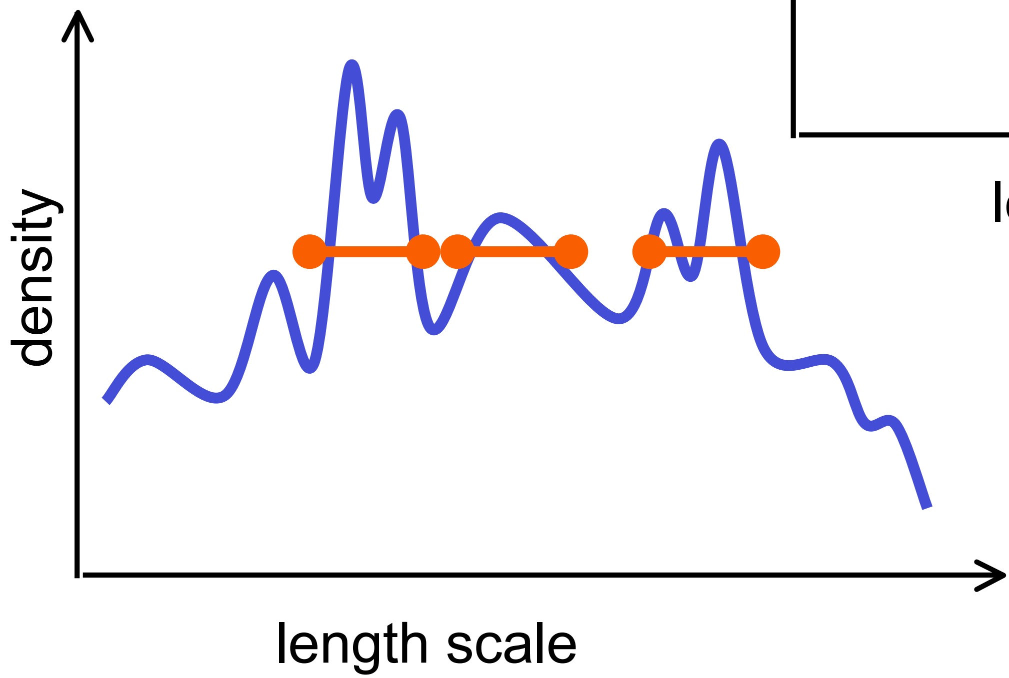




SPH with sink particles IV

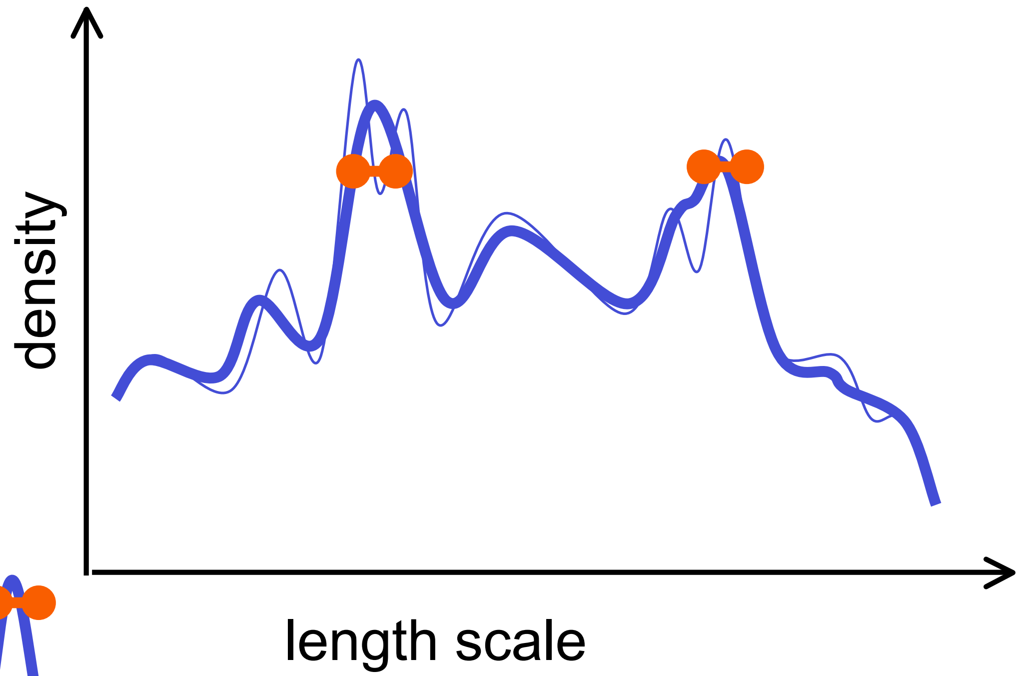
- sink particle diameter
- sink separation at formation
- sink density threshold

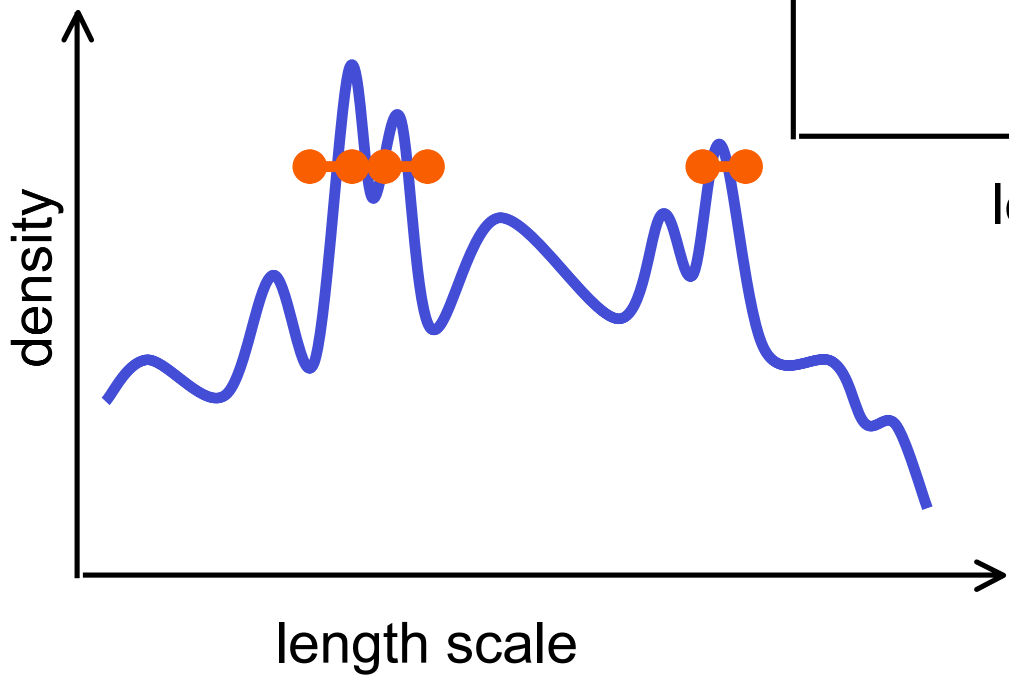




SPH with sink particles V

high-resolution runs vs.
low-resolution calculations





Some final questions…

- *SELF-GRAVITY:* How many particles do we *really* need to resolve collapse behavior (and not get spurious fragmentation)?
- *TURBULENCE:* How large Reynolds numbers do we need to catch at least the basic dynamical behavior?
  - How large Reynolds numbers can we actually model?
  - How serious is the discrepancy?
    Or differently speaking, how important are *subgrid* models and where do we need them?

Thanks