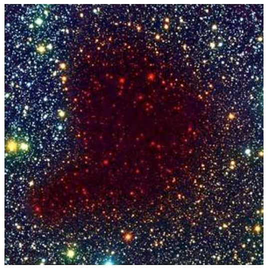
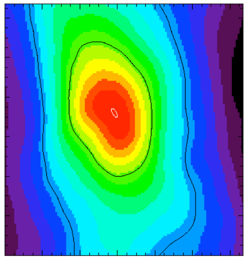
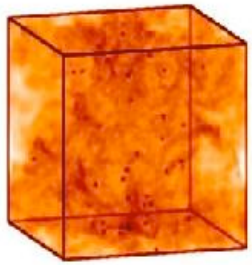
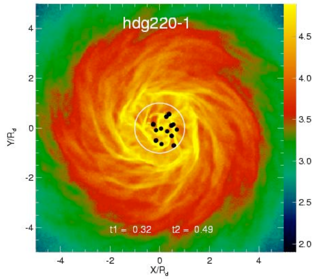
Massive Stars from Gravoturbulent Fragmentation









Ralf Klessen

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Astrophysikalisches Institut Potsdam

IAU Symposium 227, Acireale, May 19, 2005

Literature

- Recent reviews on dynamic star formation and interstellar turbulence:
  - *Elmegreen & Scalo (2004), Ann. Rev. Astron. Astrophys., 42, 211*
  - *Larson (2003), Prog. Rep. Physics, 66, 1651*
  - *Mac Low & Klessen (2004), Rev. Mod. Physics, 76, 125*
  - *Scalo & Elmegreen (2004), Ann. Rev. Astron. Astrophys., 42, 275*
- Magnetically mediated star formation:
  - *Shu, Adams, & Lizano (1987), Ann. Rev. Astron. Astrophys., 25, 23*
- General turbulence:
  - *Lesieur (1997), "Turbulence in Fluids" (Kluwer, Dordrecht), 3rd edition*

The questions in star formation

- *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?
  (do high-mass stars *always* form in *clusters*, or are there *isolated* high-mass stars?)

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

Gravoturbulent star formation

- Dynamic approach to 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

- Dynamic approach to star formation:

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

- Validity:

This hold on *all* scales and applies to build-up of stars and star clusters within molecular clouds as well as to the formation of molecular clouds in galactic disk.

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

Overview

- Some comments on supersonic turbulence

GRAVOTURBULENT FRAGMENTATION

- Application to formation of stars and star clusters within molecular clouds

  → *formation of stars and star clusters*
  (when and where do massive stars form)

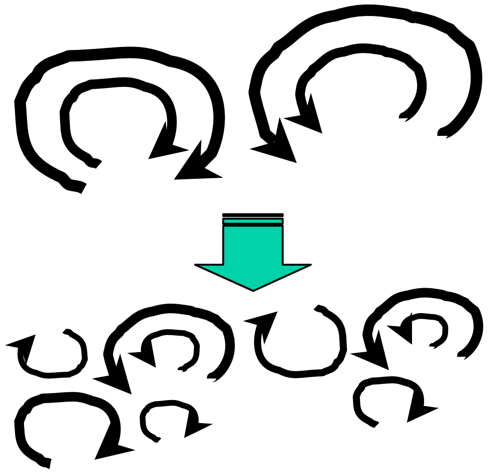
  → *importance of stochasticity*

  → *importance of thermodynamic state of gas*

  (implications for the IMF)

turbulence

Properties of turbulence



- laminar flows turn *turbulent* at *high* *Reynolds* numbers

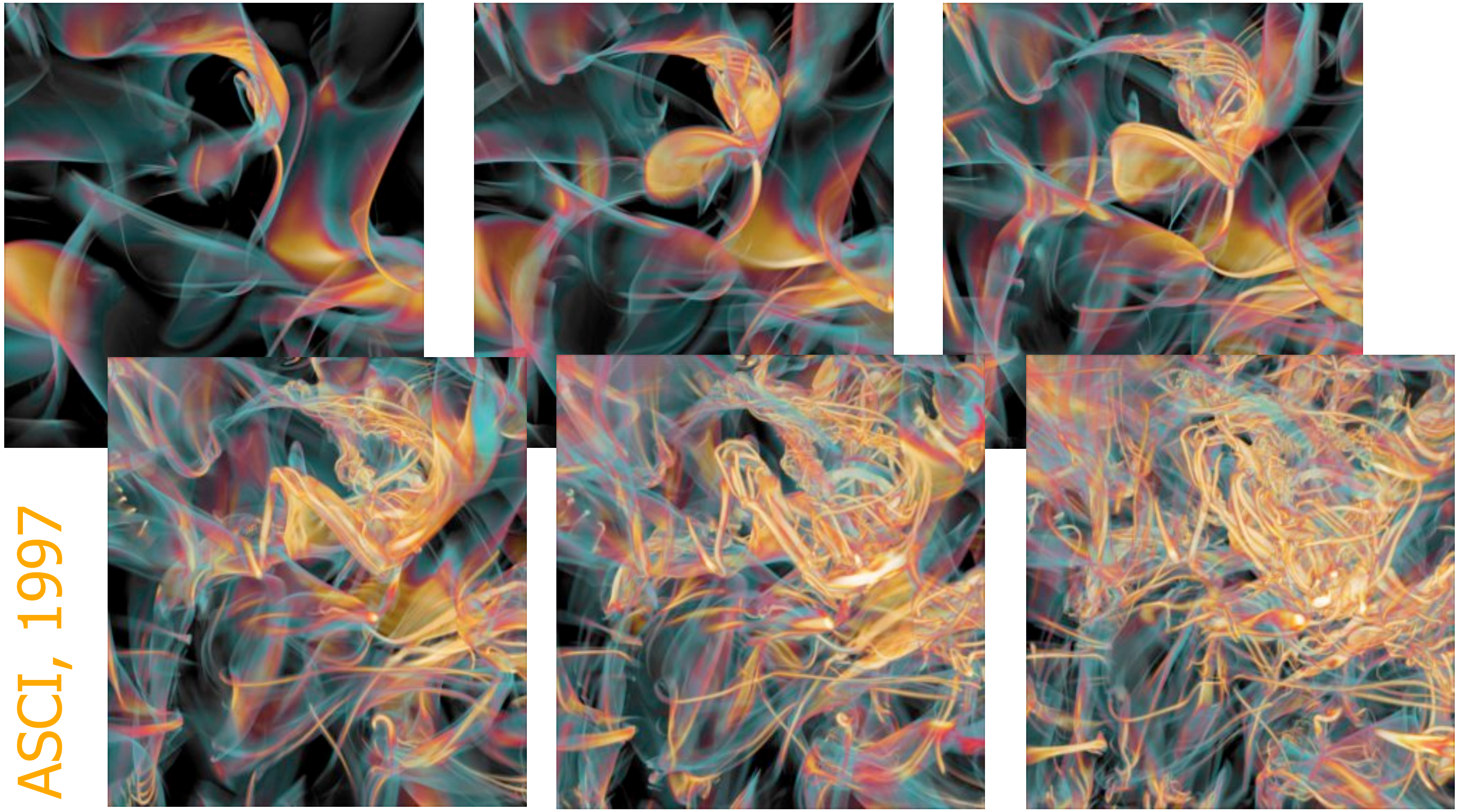
$$\boxed{\mathrm{Re} = \frac{\text{advection}}{\text{dissipation}} = \frac{VL}{\nu}}$$

V= typical velocity on scale L, ν = viscosity, Re > 1000

- *vortex streching* --> turbulence is *intrinsically* *anisotropic*
  (only on large scales you *may* get homogeneity & isotropy in a statistical sense;
  see Landau & Lifschitz, Chandrasekhar, Taylor, etc.)

  (ISM turbulence: shocks & B-field cause additional inhomogeneity)

Vortex Formation

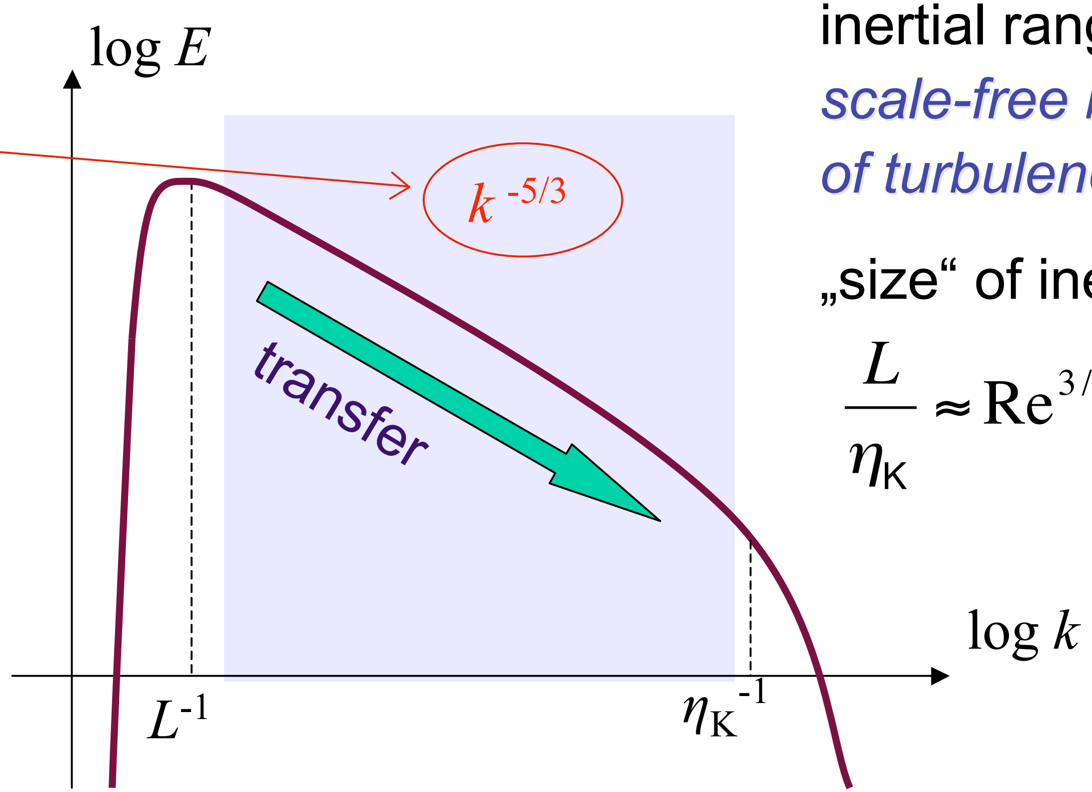


Porter et al.
ASCI, 1997

Vortices are streched and folded in three dimensions

Turbulent cascade

Kolmogorov (1941) theory
incompressible turbulence



energy
input
scale

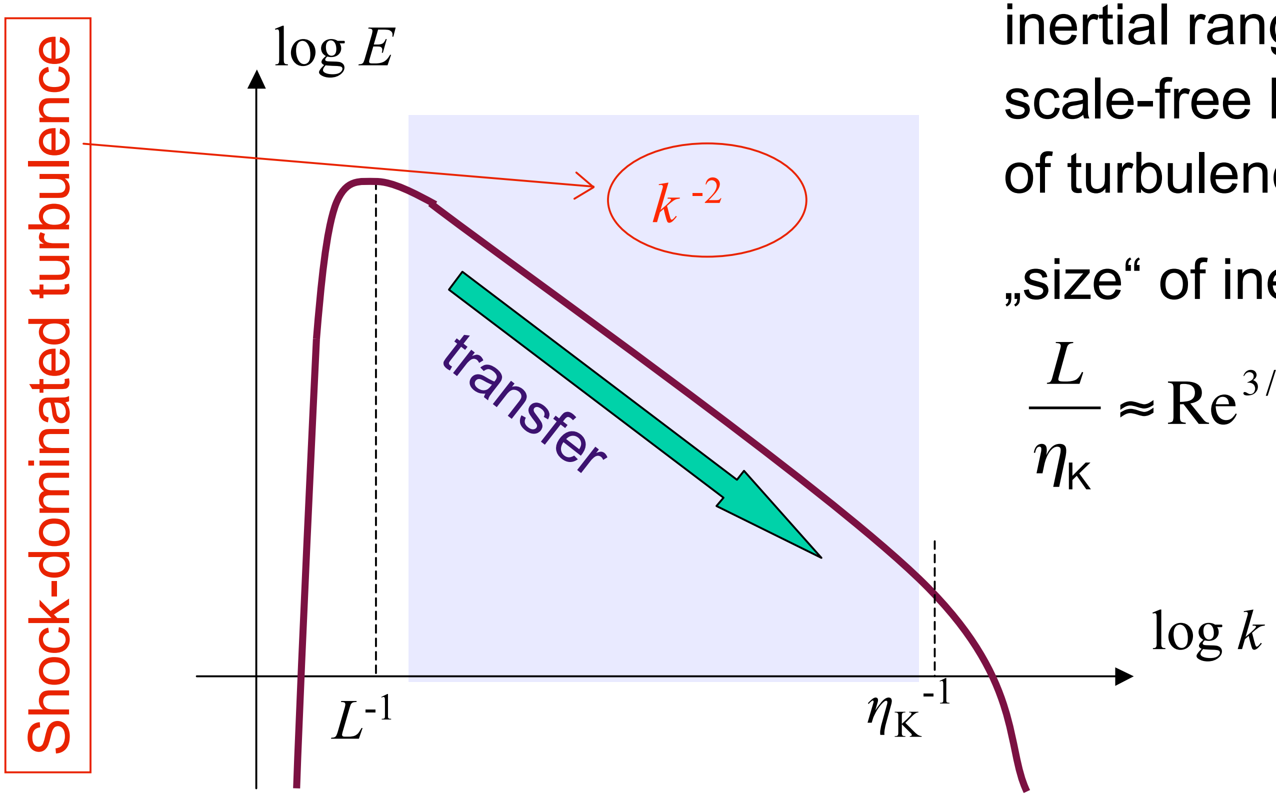
energy
dissipation
scale

inertial range:
scale-free behavior of turbulence

„size“ of inertial range:

$$\frac{L}{\eta_K} \approx \mathrm{Re}^{3/4}$$

Turbulent cascade



energy
input
scale

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inertial range:
scale-free behavior
of turbulence

„size“ of inertial range:

$$\frac{L}{\eta_K} \approx \mathrm{Re}^{3/4}$$

Properties of IMS turbulence

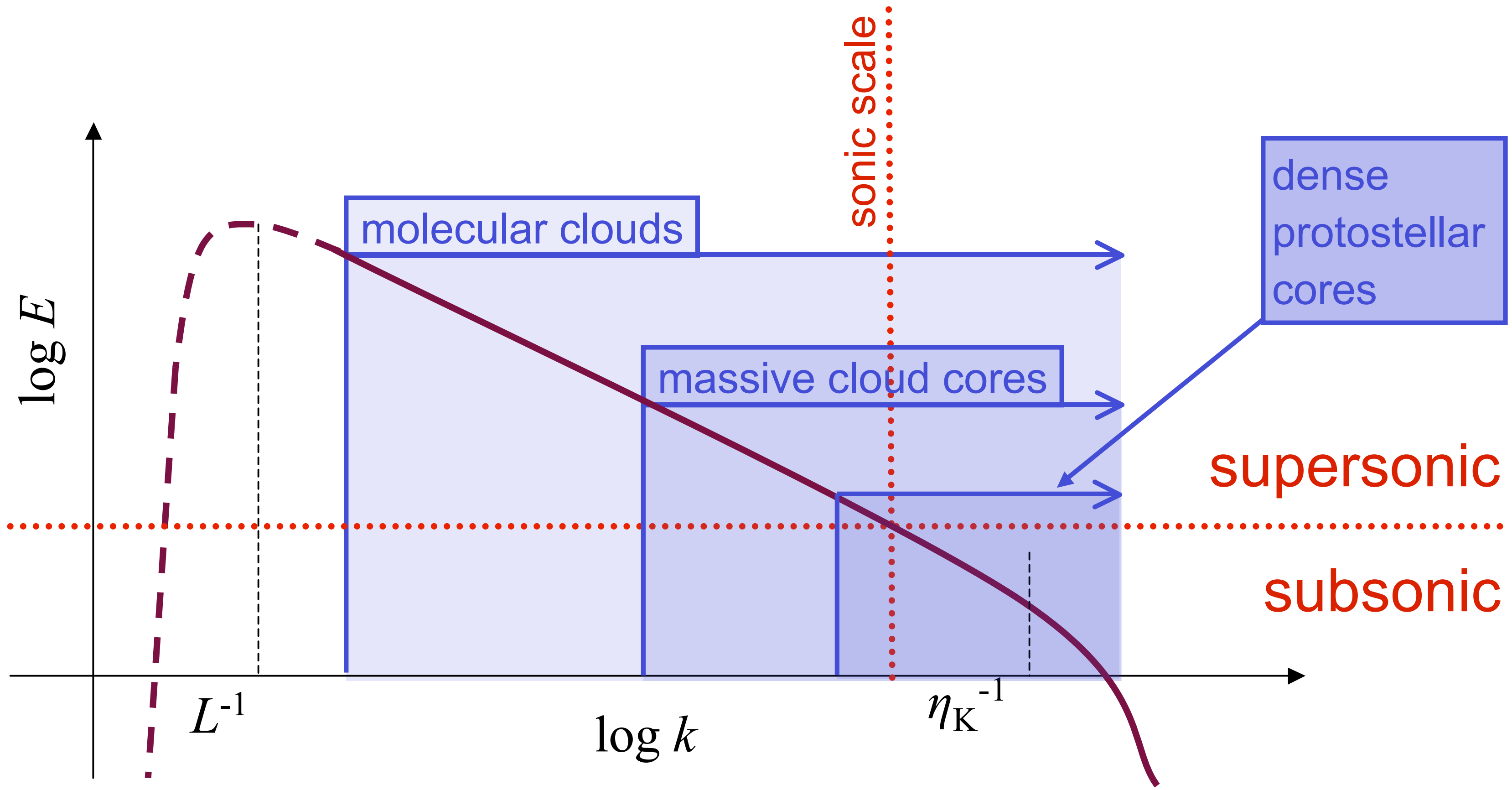
ISM turbulence is:

- Supersonic (rms velocity dispersion >> sound speed)
- Anisotropic (shocks & magnetic field)
- Driven on large scales (power in mol. clouds always dominated by largest-scale modes)

Microturbulent approach is NOT valid in ISM

- No closed analytical/statistical formulation known --> necessity for numerical modeling

Turbulent cascade in ISM



energy source & scale *NOT known* (supernovae, winds, spiral density waves?)

σ_{rms} << 1 km/s

dissipation scale not known (ambipolar diffusion, molecular diffusion?)

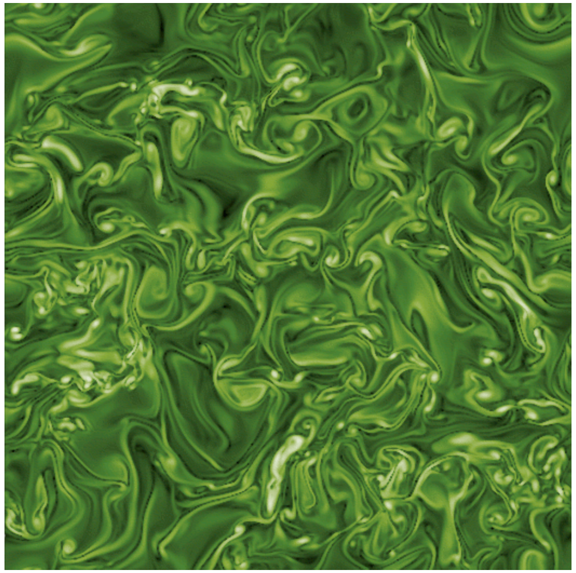
Comments on MICROturbulence

- *von Weizsäcker (1943, 1951)* and *Chandrasekhar (1951):* concept of MICROTURBULENCE
  - BASIC ASSUMPTION: separation of scales between dynamics and turbulence
    $\ell_{\rm turb} \ll \ell_{\rm dyn}$
  - then turbulent velocity dispersion contributes to effective soundspeed:

$$\boxed{c_c^2 \mapsto c_c^2 + \sigma_{rms}^2}$$

  - → Larger effective Jeans masses → more stability
  - BUT: *(1) turbulence depends on k:* $\sigma_{rms}^2(k)$

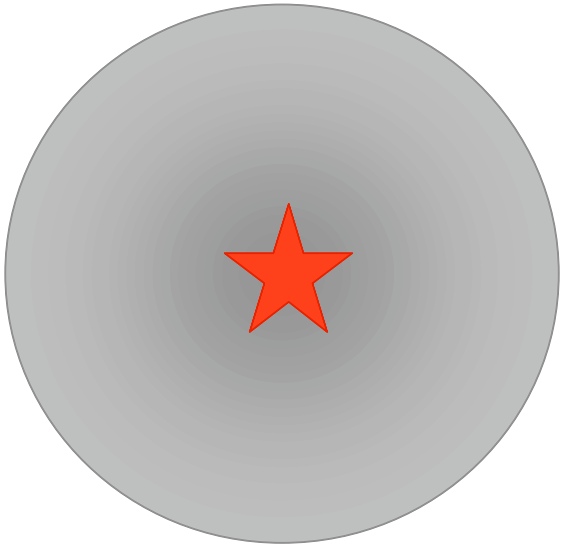
    (2) supersonic turbulence → *usually* $\sigma_{rms}^2(k) >> c_s^2$

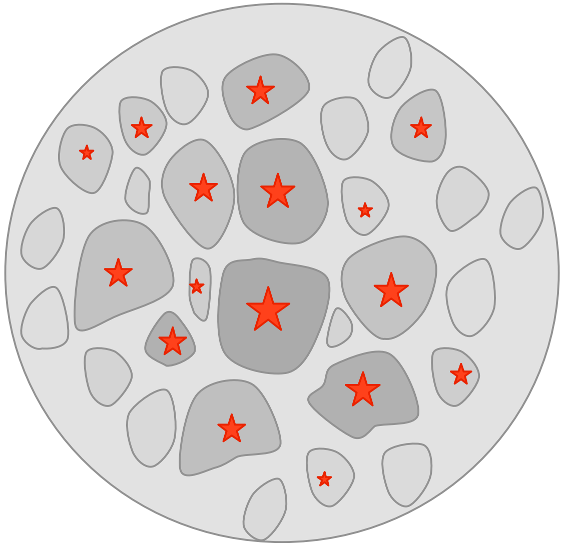


Driven turbulence, from Schmidt et al

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

Comments on MICROturbulence





- Turbulence is driven on LARGE scales.
  --> no scale separation possible
- Turbulence is supersonic!
- produces strong density contrasts:
  $\delta\rho/\rho \approx \mathcal{M}^2$
  --> with typical $\mathcal{M} \approx 10$ --> $\delta\rho/\rho \approx 100$!

Microturbulence is not valid in ISM

- **Example:** High-mass star formation MORE complicated than using „effective" soundspeed (c_s^2 --> $c_s^2 + \sigma_{rms}^2$) to increase Jeans mass ($M_J \propto \rho^{-1/2} c_s^3$)
- --> instead of forming one single high-mass star system will form cluster of lower-mass stars.

star

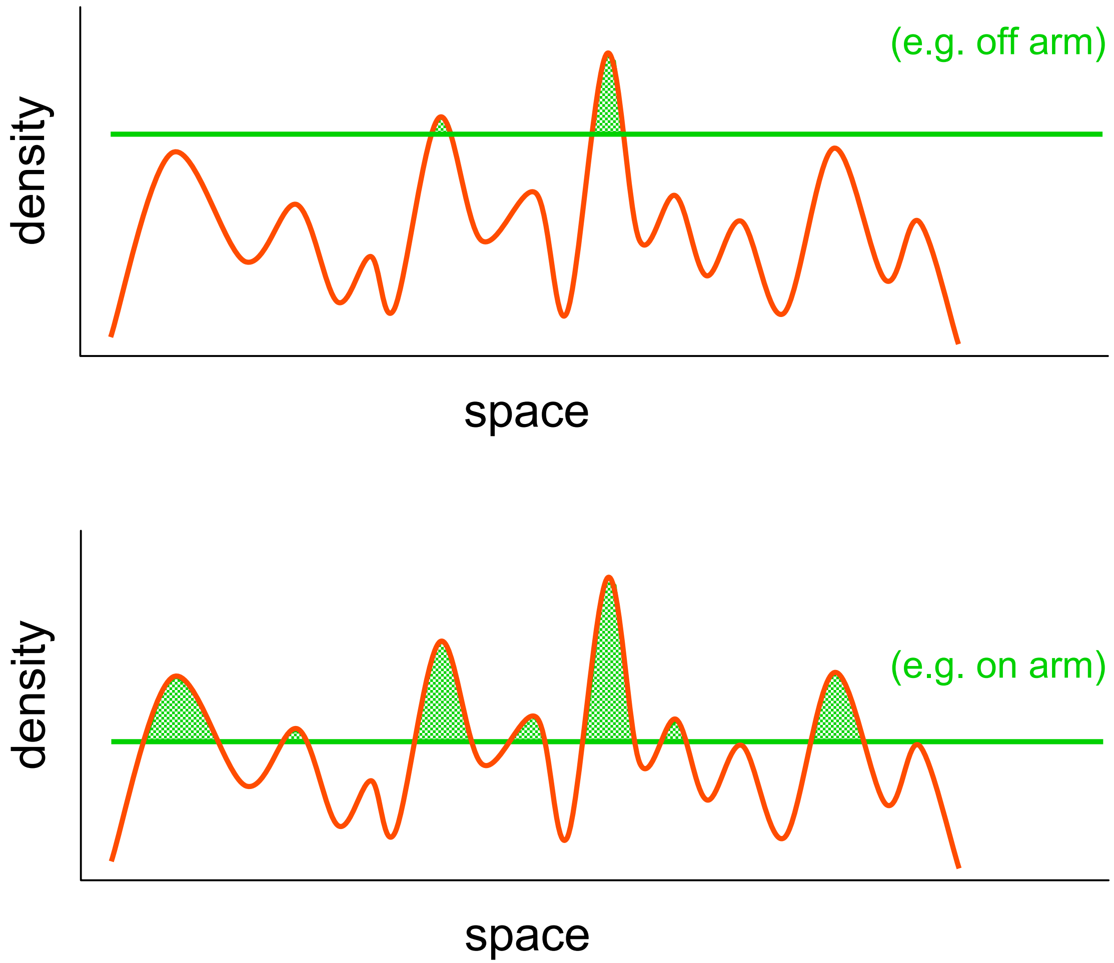
formation

Gravoturbulent Star Formation

- *Supersonic turbulence* in the galactic disk creates strong density fluctuations (in shocks: $\delta\rho/\rho \propto M^2$)
  - chemical phase transition: atomic → molecular
  - cooling instability
  - gravitational instability
- Cold *molecular clouds* form at the high-density peaks.
  - The process is *modulated* by large-scale *dynamics* in the galaxy

(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

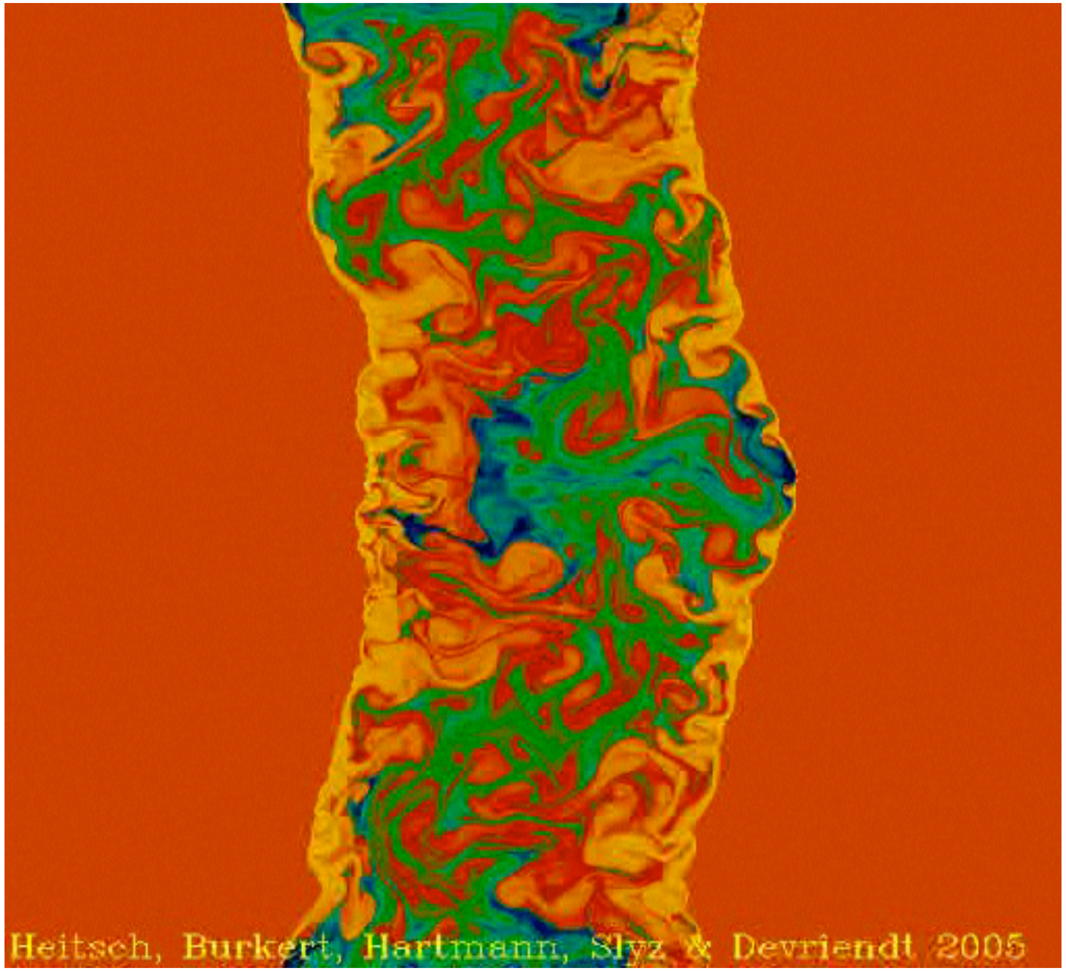
external perturbuations (i.e. potential changes) increase likelihood

Molecular cloud formation

... in *convergent large-scale flows*

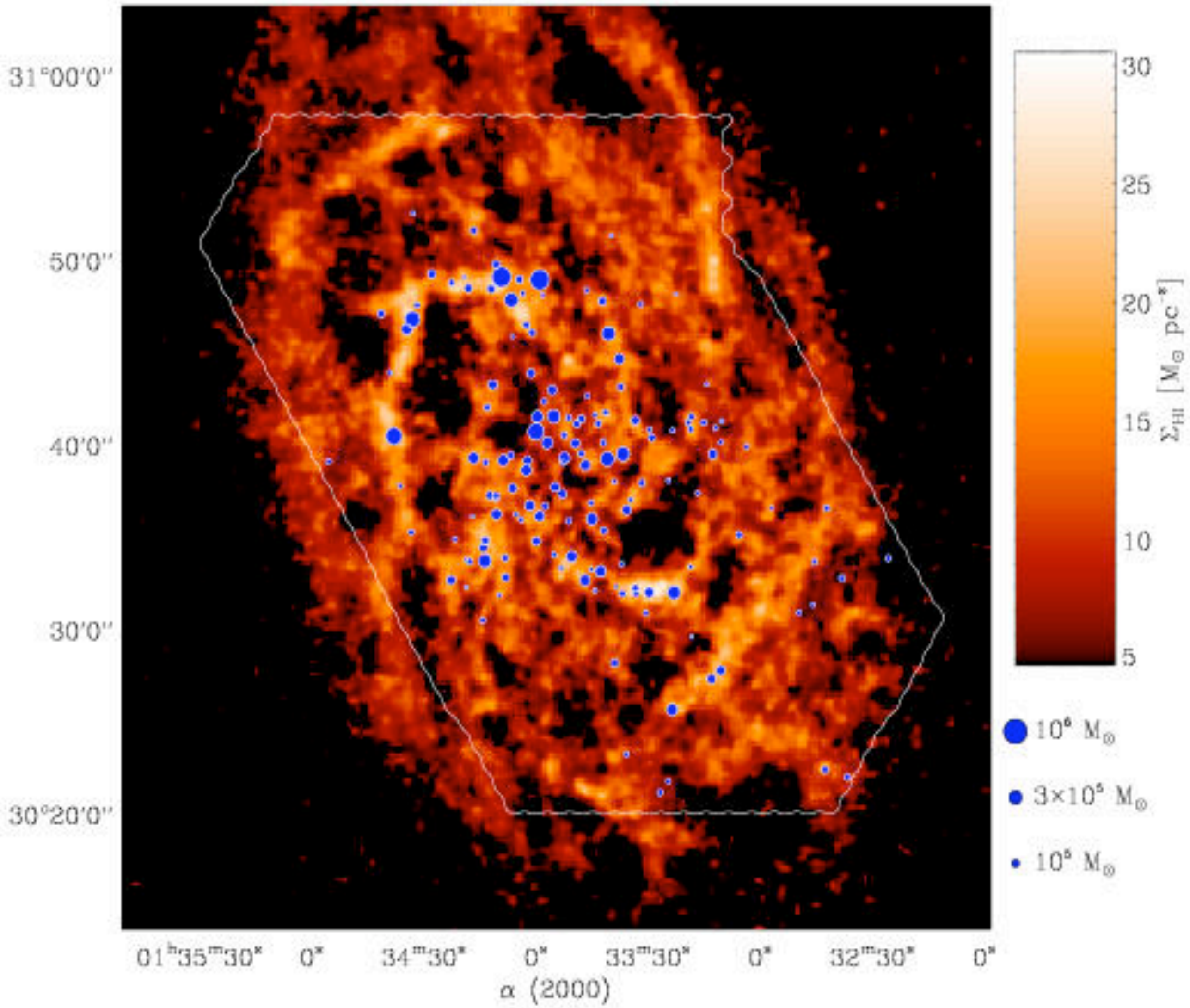
... setting up the *turbulent cascade*

- colliding Mach 3 flows
- Vishniac instability + thermal instability
- compressed sheet breaks up and builds up cold, high-density „blobs“ of gas
- --> molecular cloud formation
- clouds have internal supersonic turbulence



(Heitsch et al., in preparation --> see Poster 59)

Correlation between H_2 and HI



Compare H_2 - HI in M33:

- H_2: BIMA-SONG Survey, see Blitz et al.
- HI: Observations with Westerbork Radio T.

H_2 clouds are seen in regions of high HI density (in spiral arms and filaments)

(Deul & van der Hulst 1987, Blitz et al. 2004)

Gravoturbulent Star Formation

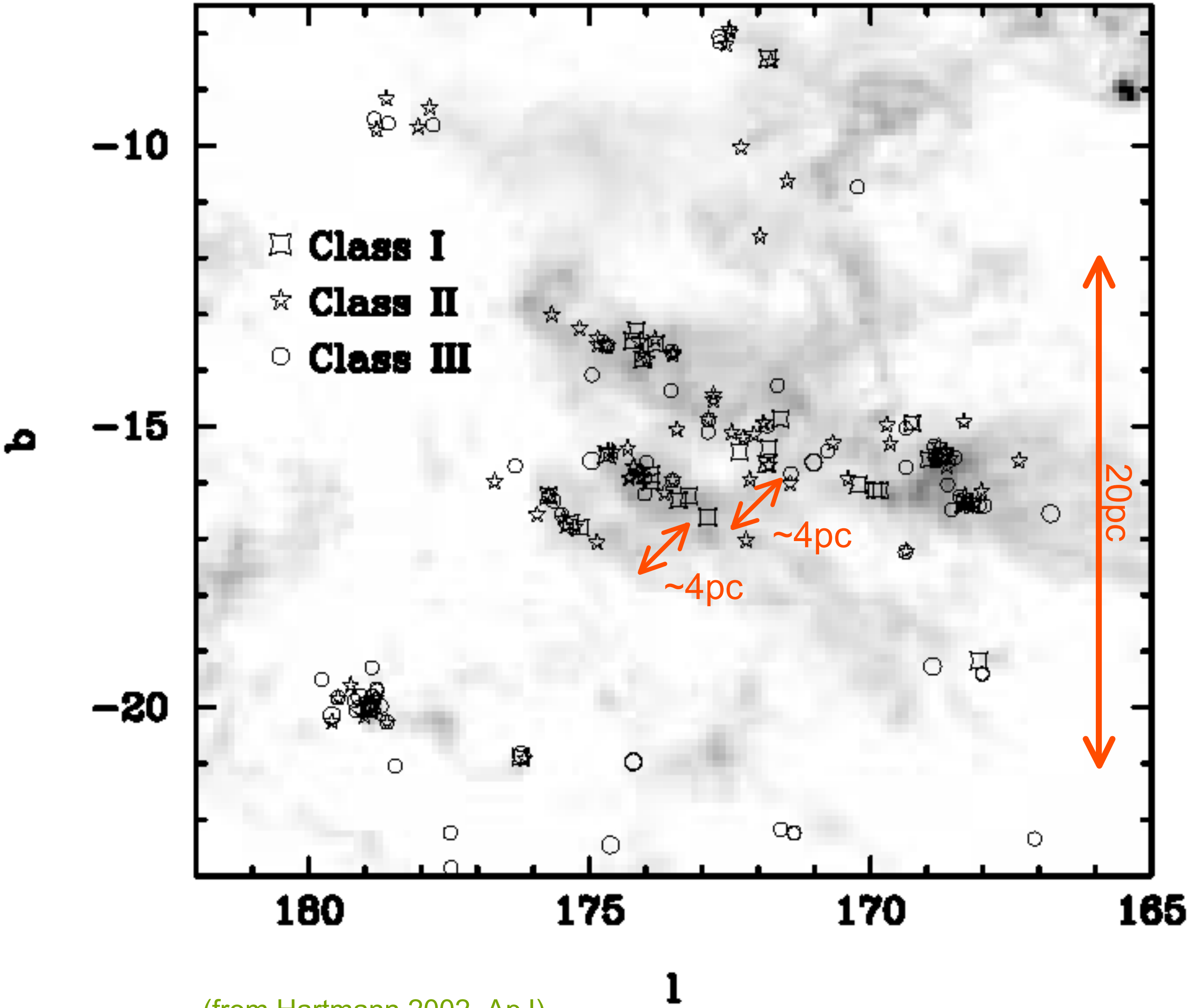
- *Supersonic turbulence* in the galactic disk creates strong density fluctuations (in shocks: $\delta\rho/\rho \approx \mathcal{M}^2$)
  - chemical phase transition: atomic → molecular
  - cooling instability
  - gravitational instability
- Cold *molecular clouds* form at the high-density peaks.
- *Turbulence*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

  ⟶ ***GRAVOTUBULENT FRAGMENTATION***

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

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

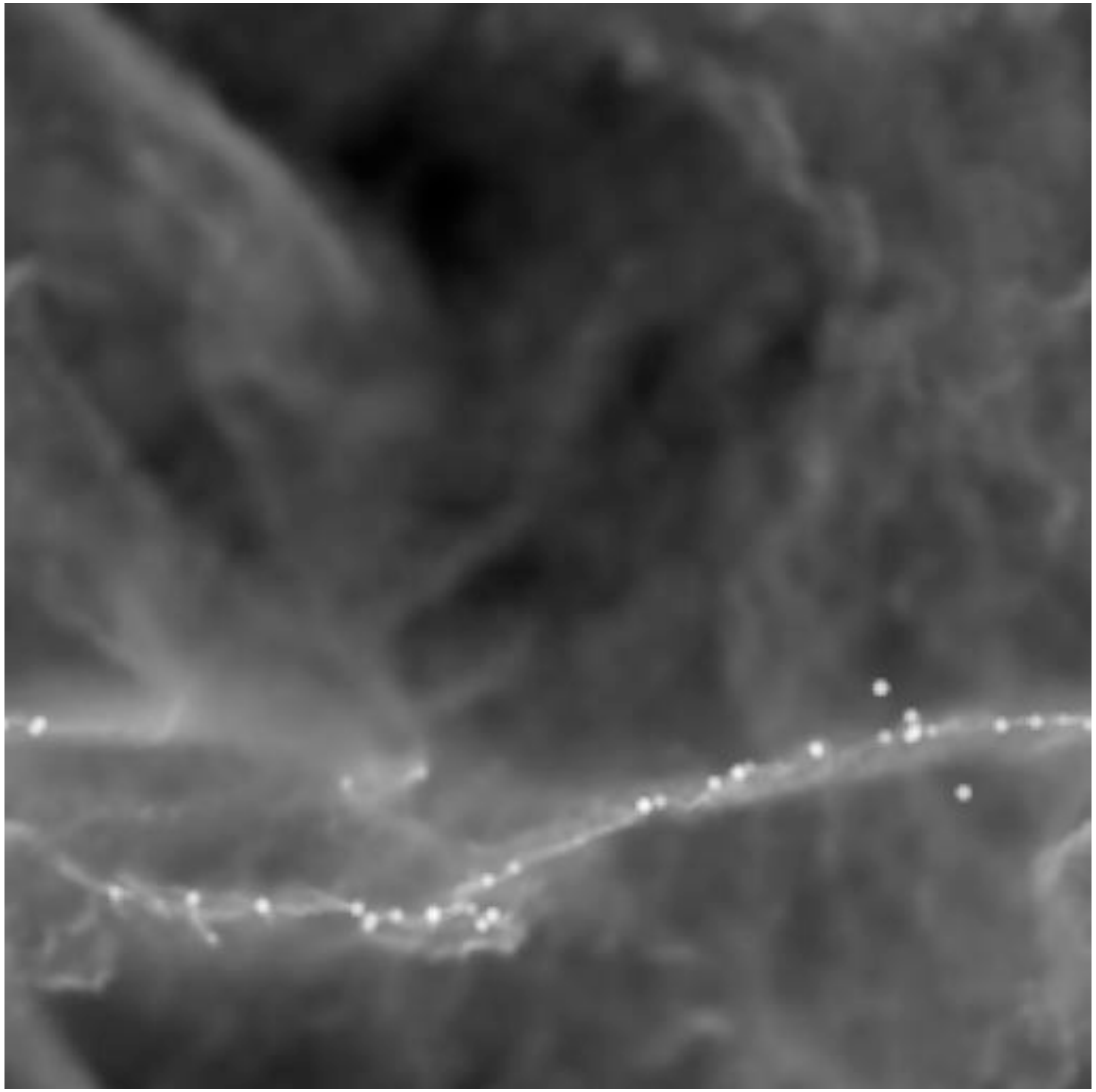
Taurus SF cloud



(from Hartmann 2002, ApJ)

Star-forming filaments in the *Taurus* molecular cloud

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
  - 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)

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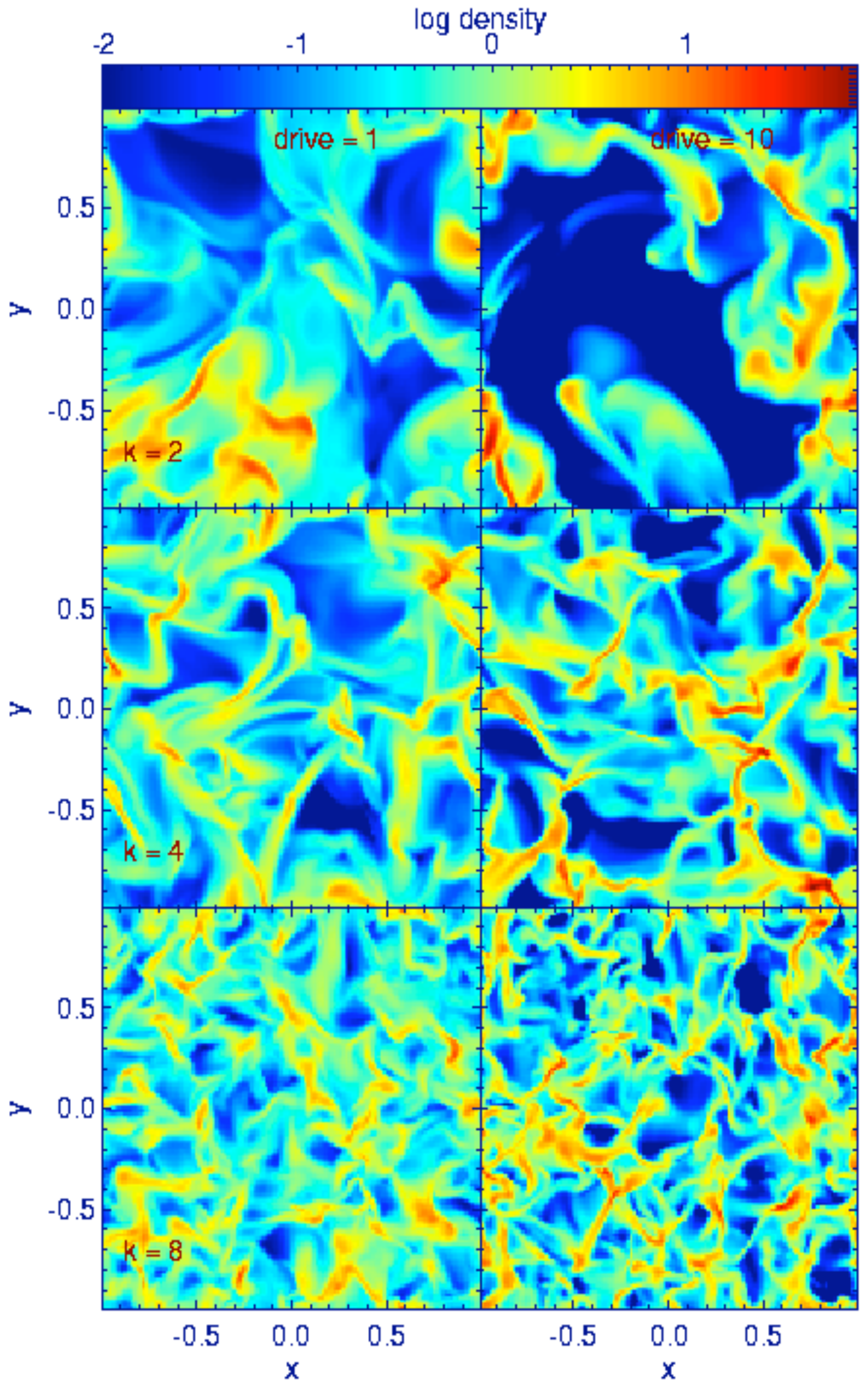
weak driving

strong driving

$k = 2$

$k = 4$

$k = 8$



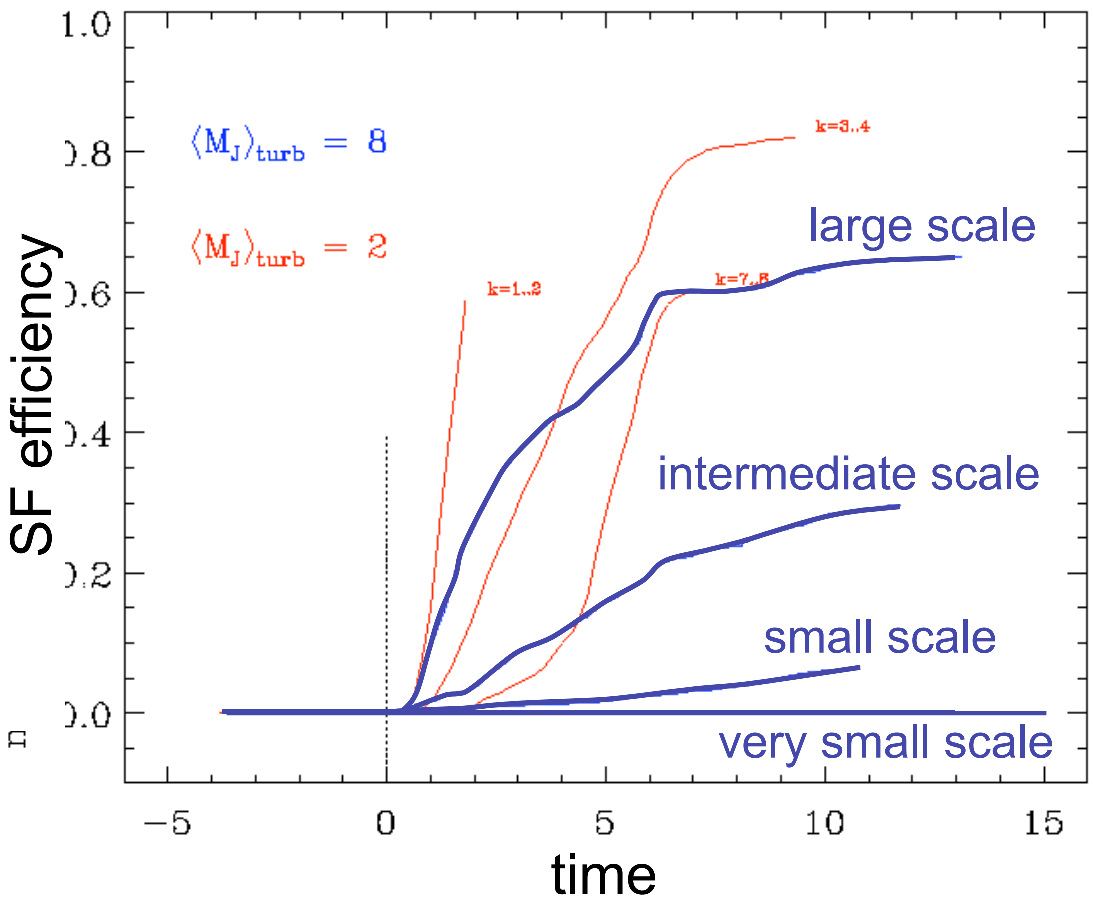
large-scale turbulence

intermediate-scale turbulence

small-scale turbulence

(from Mac Low 1999, ApJ)

Efficiency of star formation



Star formation efficiency is high for *large-scale turbulence* and low if most energy resides on *small scales.*

Efficiency *decreases* with *increasing* turbulent kinetic energy.

Local collapse can only be *prevented* completely if turbulence is driven on scales *below* the Jeans length. ← this is unrealistic

→ It is very difficult prevent star formation in molecular clouds.

(see Klessen, Heitsch & Mac Low 2000, ApJ or Vazquez-Semadeni, Ballesteros-Paredes, & Klessen 2003, ApJ)

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)
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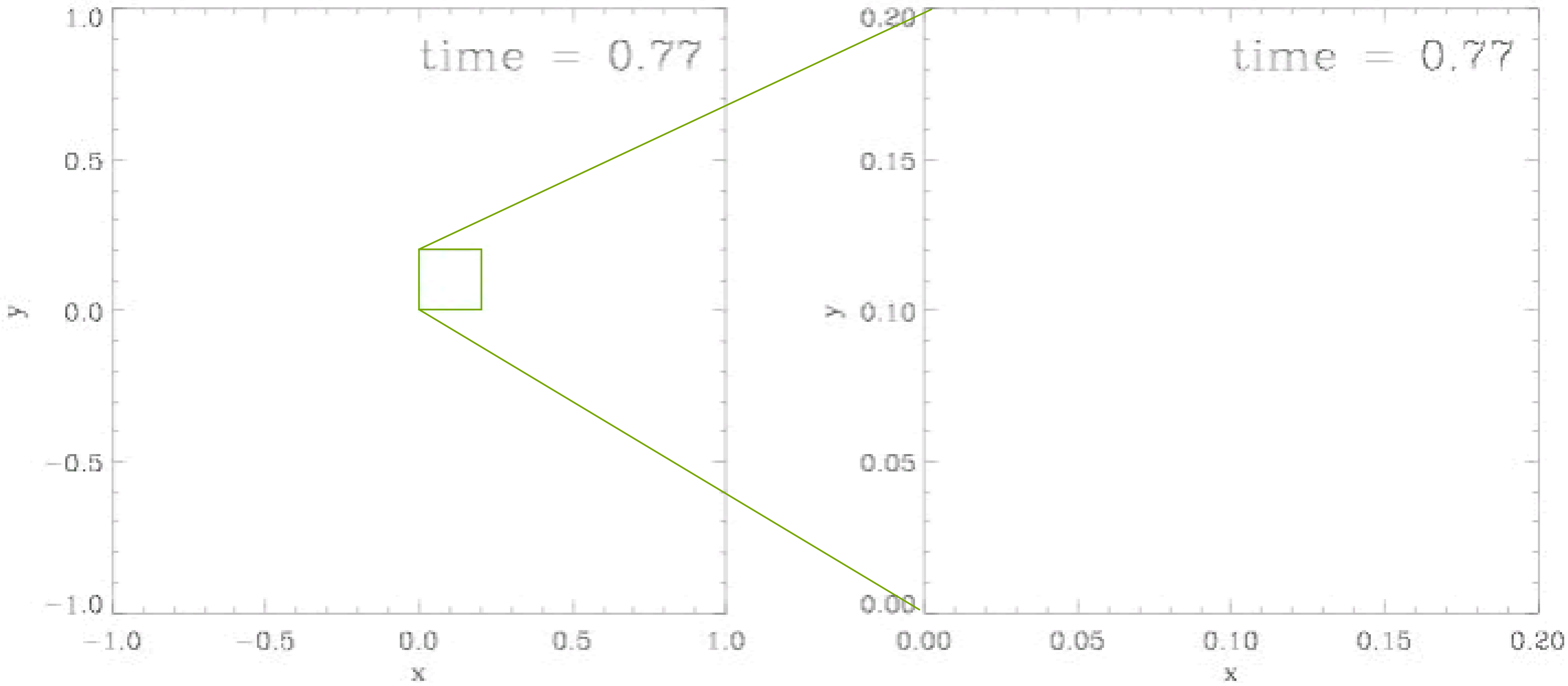
  - SED's of individual protostars
  - dynamic PMS tracks: T_{bol}-L_{bol} evolution

(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)

Star cluster formation

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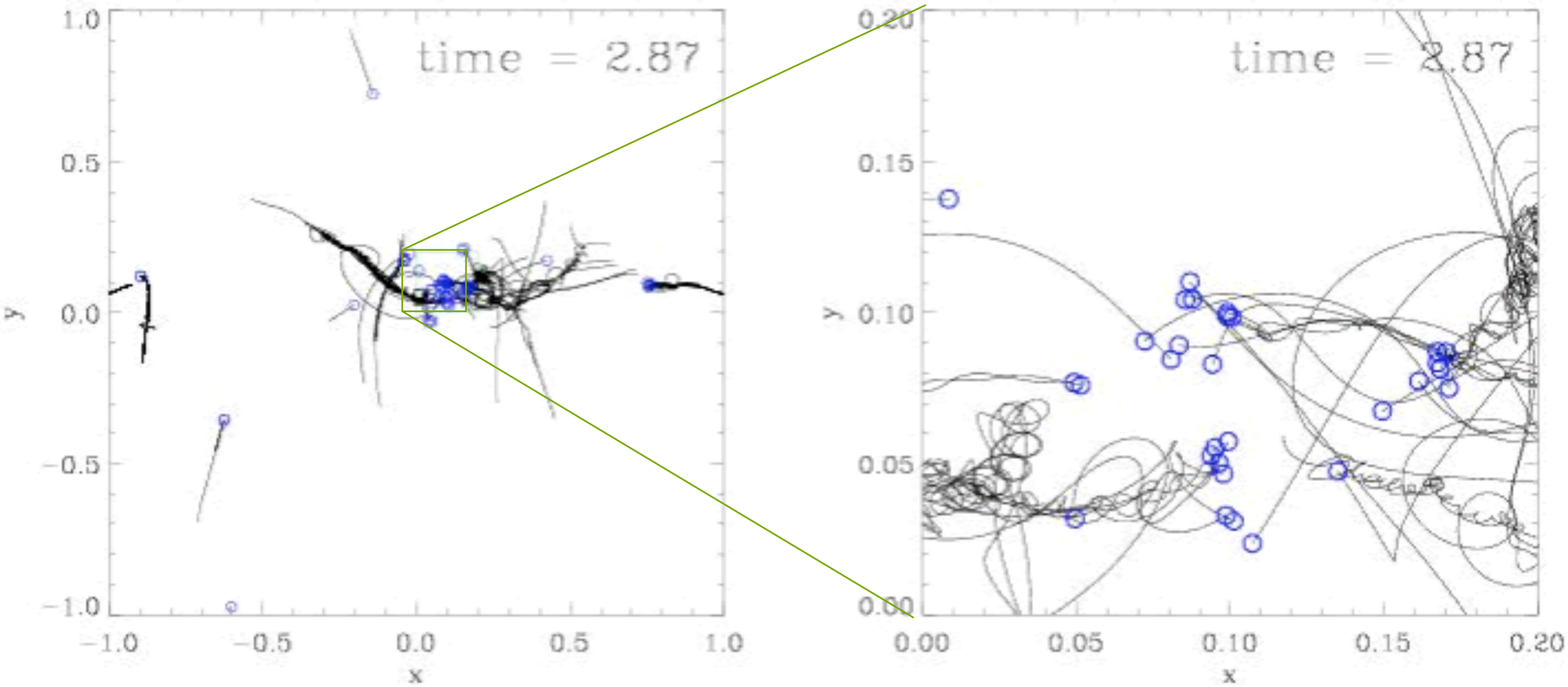

Trajectories of protostars in a nascent dense cluster created by gravoturbulent fragmentation

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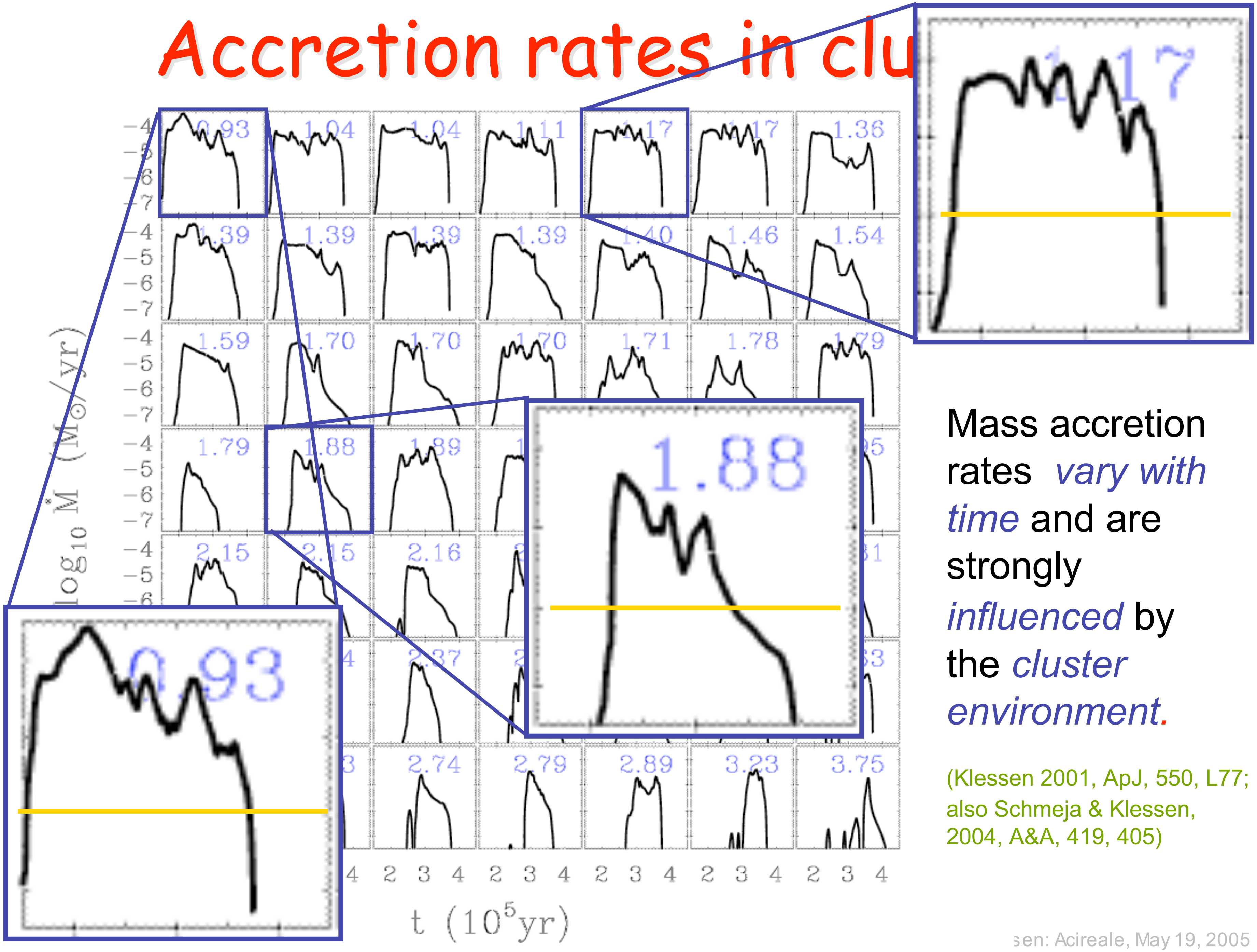
Accretion rates in clu

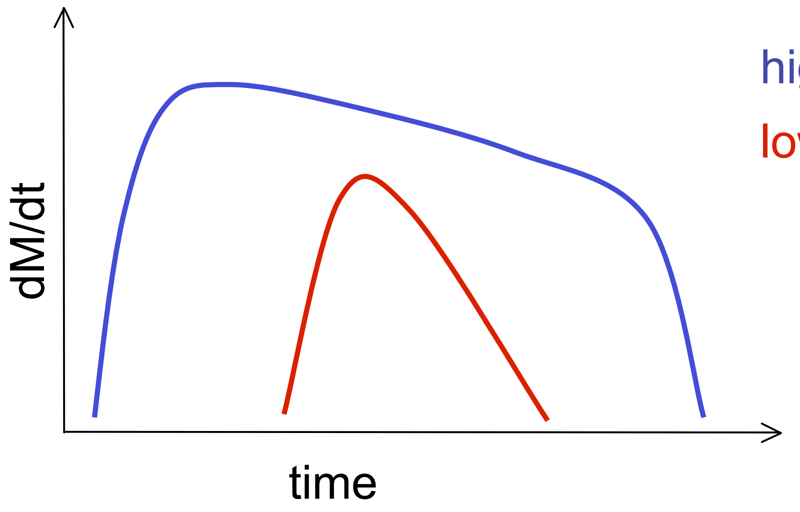


Mass accretion rates *vary with time* and are strongly *influenced* by the *cluster environment*.

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

High-mass vs. low-mass stars

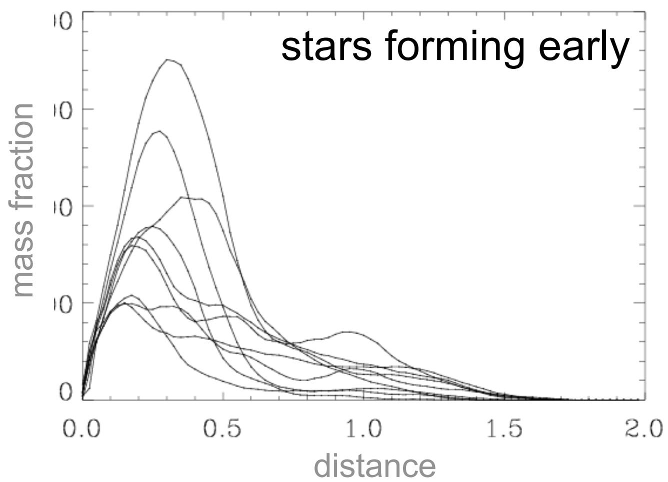
- High-mass stars build-up in central regions of the nascent cluster --> *initial mass segregation*
- High-mass stars *begin* to form *early*, but *end* to form *last*.
  They can maintain high accretion rates, because they sit in cluster center.

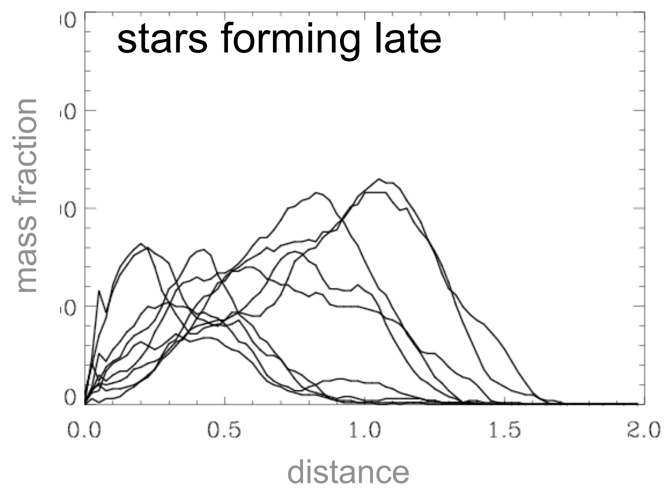


(see Bonnell talk; also Klessen 2001, Schmeja & Klessen 2004)

High-mass vs. low-mass stars

- High-mass stars build-up in central regions of the nascent cluster --> *initial mass segregation*
- High-mass stars *begin* to form *early*, but *end* to form *last*.
  They can maintain high accretion rates, because they sit in cluster center.
- Stars that form *first* tend to gain mass from their *near surrounding*, gas that goes into collapse *later* is *well mixed* by turbulence (gas comes from larger distances)

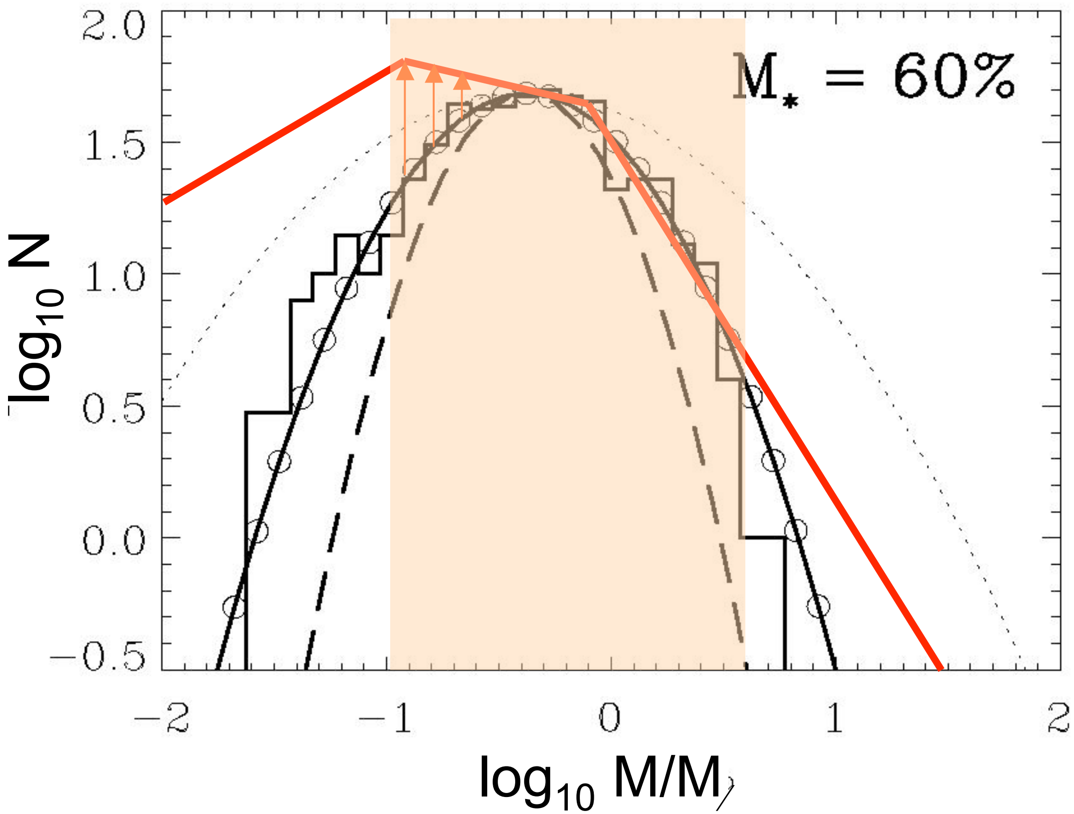




(from Klessen & Burkert 2000, ApJS, 128, 287)

Protostellar mass spectra I

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



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)

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

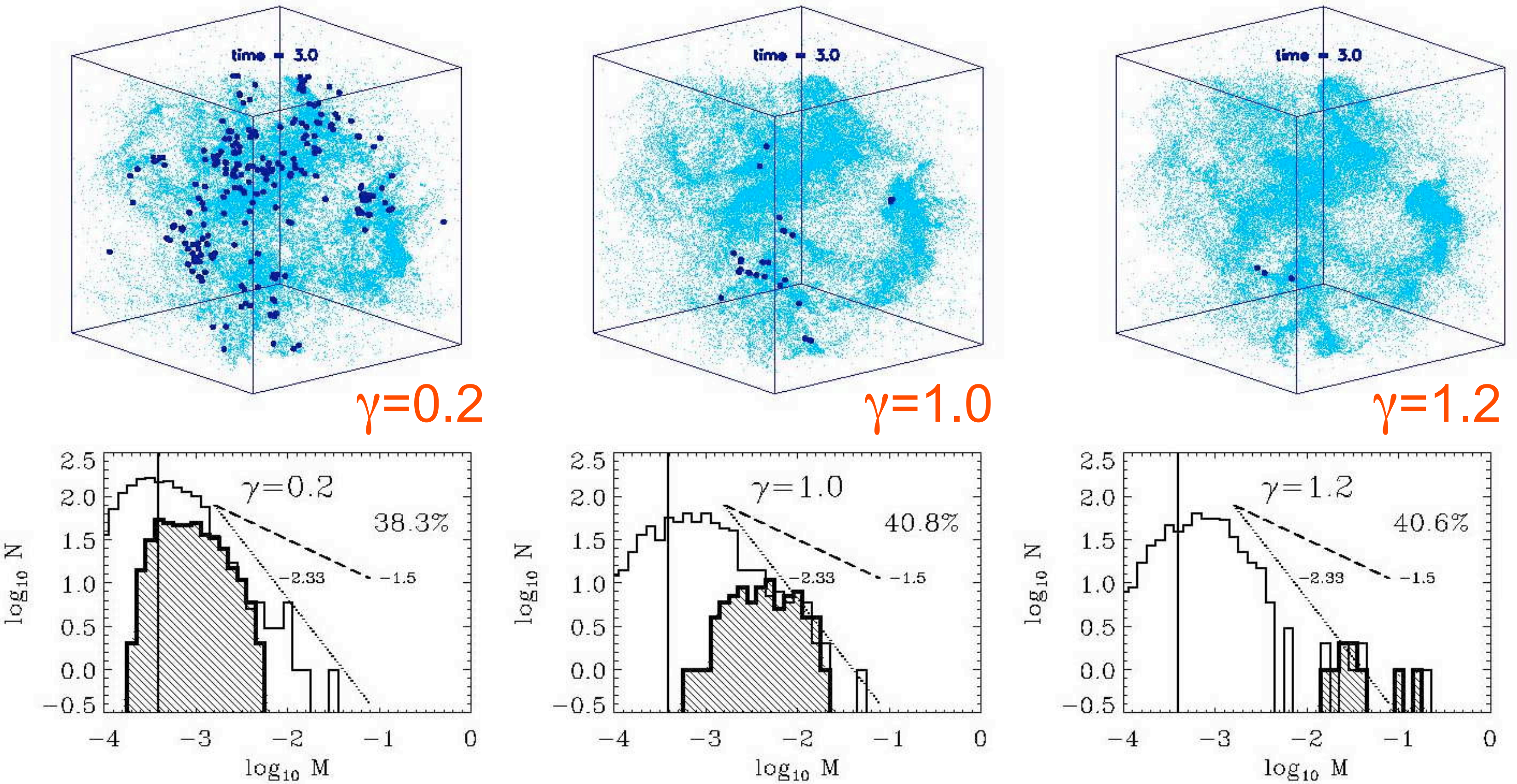
Dependency on EOS

- 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

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

Dependency on EOS



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

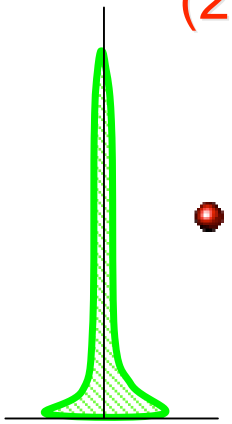
for $\gamma>1$ it is suppressed → formation of *isolated massive stars*

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

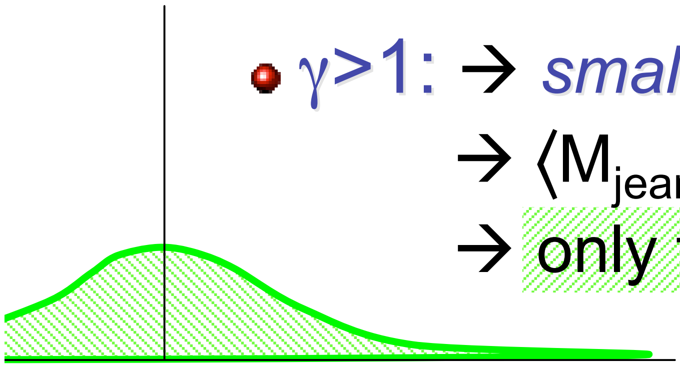
How does that work?

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

(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

  (see Li, Klessen, & Mac Low 2003, ApJ, 592, 975;
  also Jappsen, Klessen, Larson, Li, Mac Low, 2005, 435, 611)

- implications for very *metal-poor* stars

  (expect Pop III stars in the early universe
  to be massive and form in isolation)

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

  (talk by H. Lamers; Lamers et al. 2002, Massey 2002; see however, de Witt et al. 2005 for Galaxy)

More realistic models

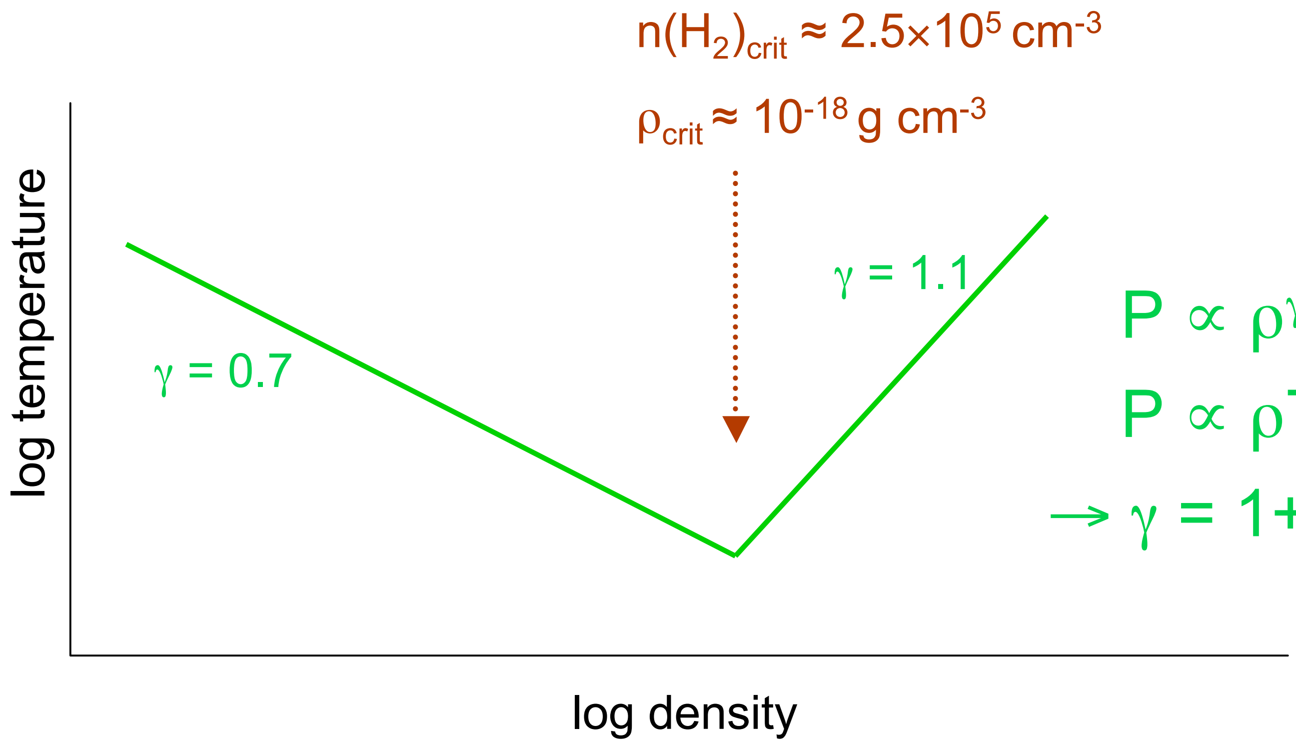
- But EOS depends on *chemical state*, on *balance* between *heating* and *cooling*

→ γ is function of ρ !!!

- Next step: models with piecewise polytropic EOS:
  (Jappsen, Klessen, Larson, Li, Mac Low, 2004, A&A submitted)
- $\gamma = 0.7$ 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: $\rho_c \approx 2\times10^5$ cm^{-3}
  (see, e.g., Spaans & Silk, 2000, ApJ, 538, 115, Larson 2005)

Influence of EOS

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



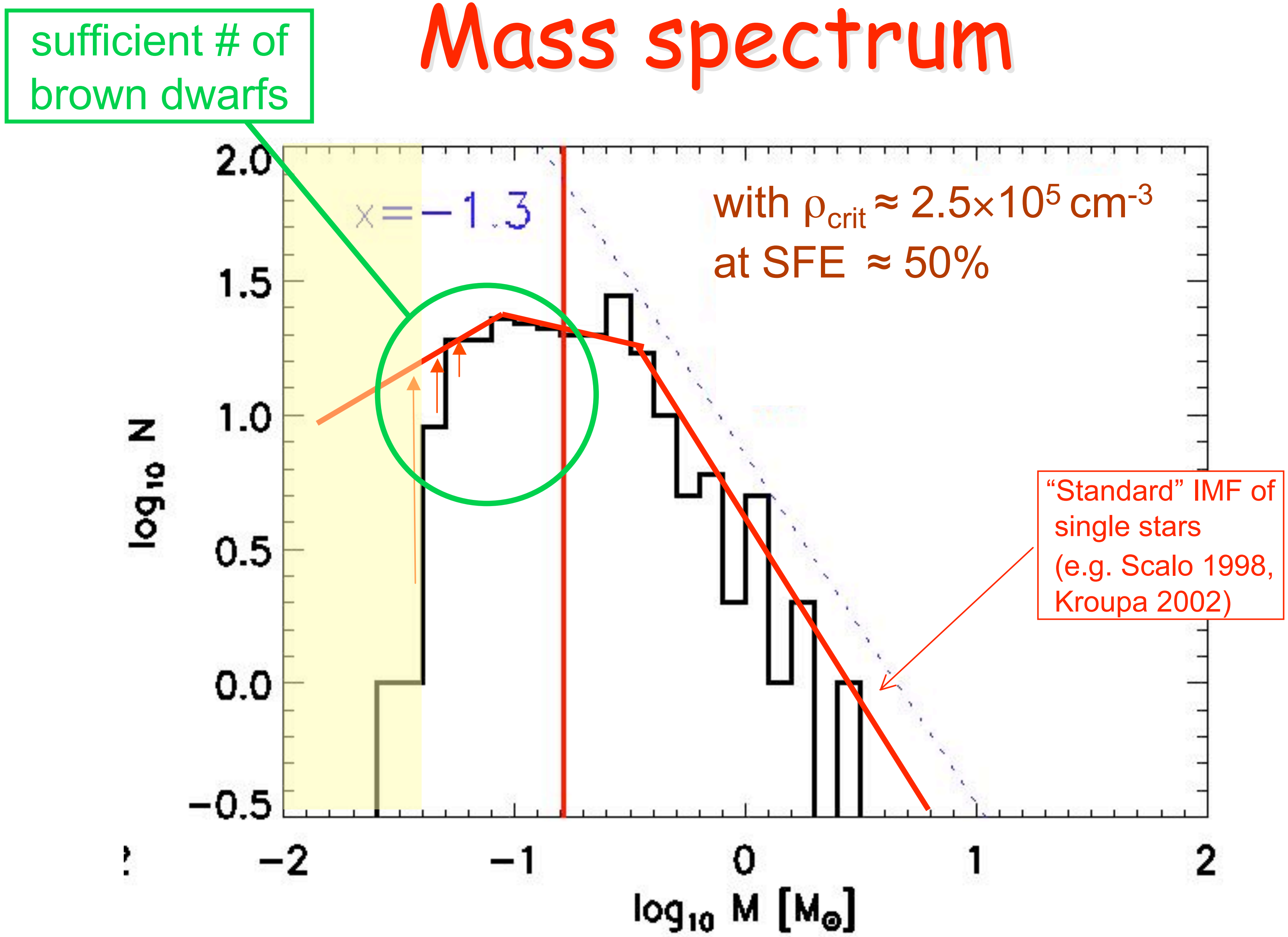
$P \propto \rho^\gamma$

$P \propto \rho T$

$\rightarrow \gamma = 1 + d\log T / d\log\rho$

(Larson 2005)

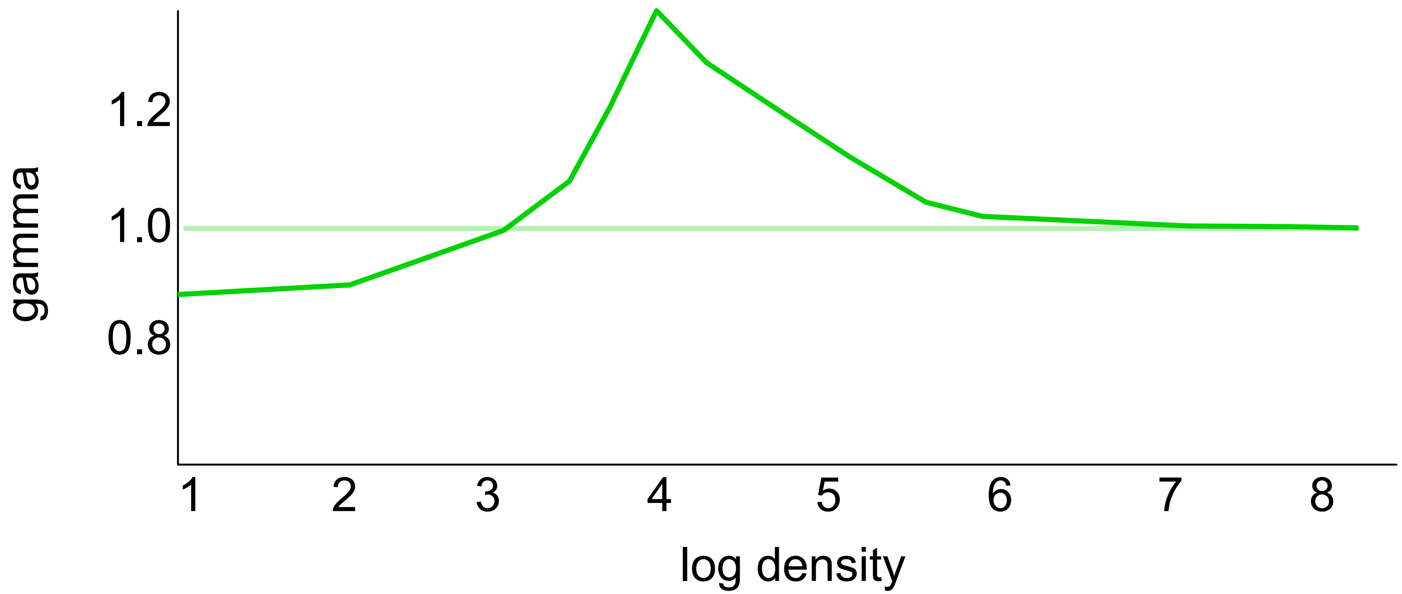
Mass spectrum



(Jappsen, Klessen, Larson, Li, Mac Low, 2005, A&A, 435, 611)

IMF in starburst galaxies

- Nuclear regions of starburst galaxies are extreme:
  - hot dust, large densities, strong radiation, etc.
- Thermodynamic properties of star-forming gas differ from Milky Way --> Different EOS!
  (see Spaans & Silk 2005)



IMF in starburst galaxies

Does it differ from
„local“ star formation ?

Is there observational evidence?

Is there theoretical evidence?

Summary

Summary

- *Dynamic approach of star formation:*
- Stars form from complex *interplay* between *gravity* and *supersonic turbulence*

  → *GRAVOTURBULENT STAR FORMATION*

- Supersonic turbulence plays a *dual role:*
  - on large scales: supersonic turbulence carries sufficient energy to prevent global collapse
  - on small scales: turbulence provokes collapse by creating high-density peaks

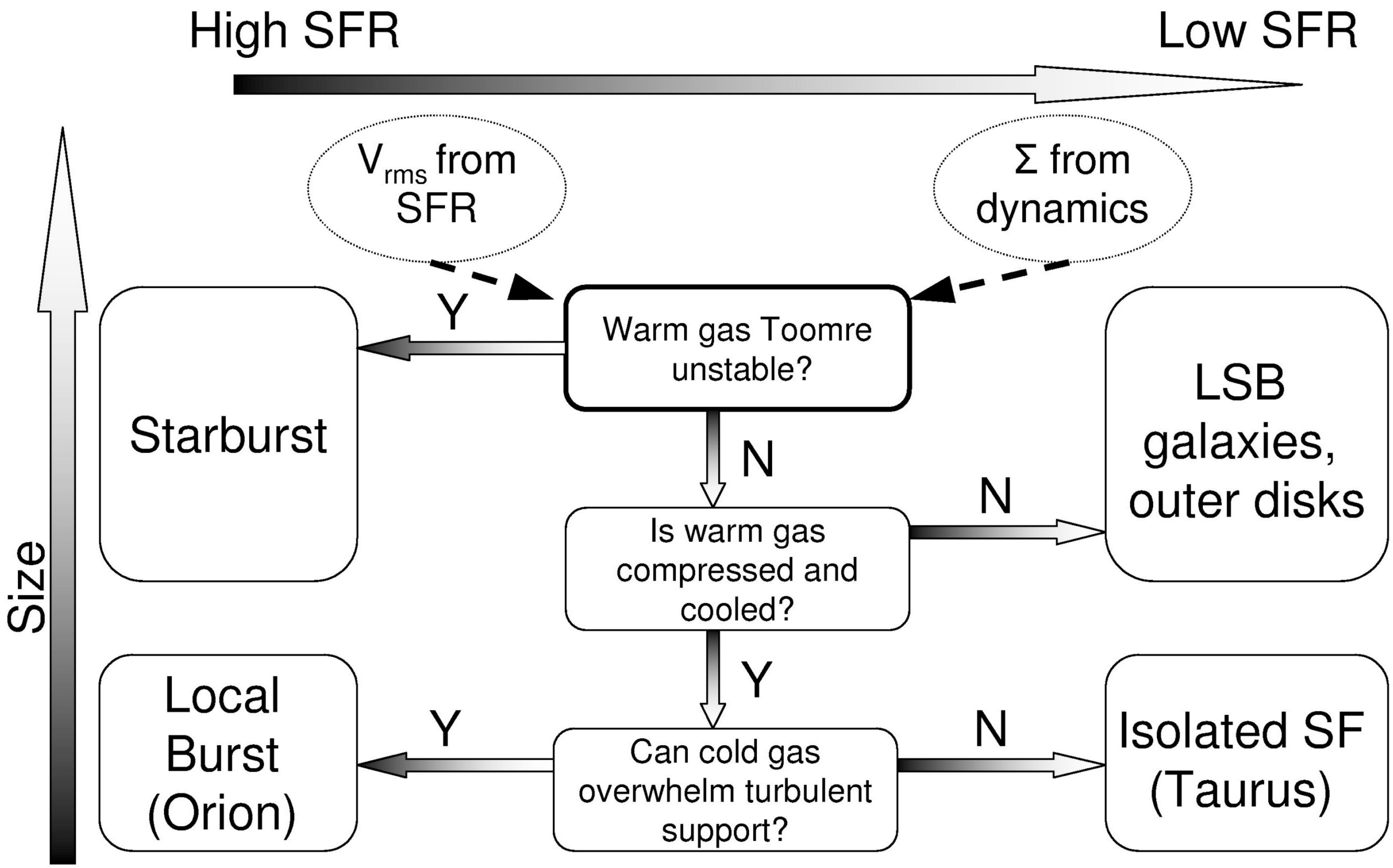
(from Mc Low & Klessen, 2004, Rev. Mod. Phys., 76, 125 - 194)

Summary

- *Gravoturbulent star formation* can explain
  - all basic properties of star-forming regions on *local* (within molecular clouds) as well as on *global* (galactic) *scales*
  - the *IMF:*
    - *turbulence* together with *EOS* determines density structure
    - *gravity* then selects fluctuations to collapse → *characteristic mass*
    - this interplay determines *PEAK* and *WIDTH* and *SLOPE* of IMF
    - top-heavy IMF may form in extreme environment

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

Summary



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