Collaborators

Many thanks to…

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- Andreas Burkert (Uni. München)
- Fabian Heitsch (Uni. München)
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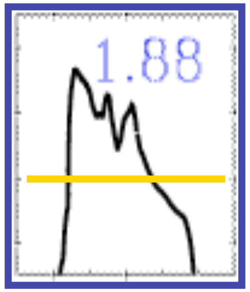
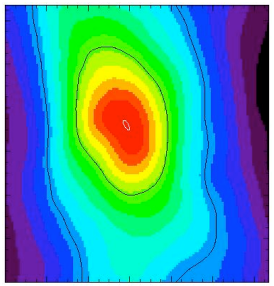
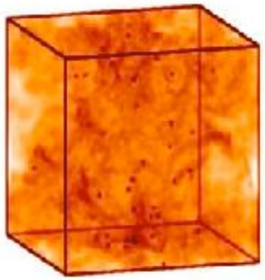
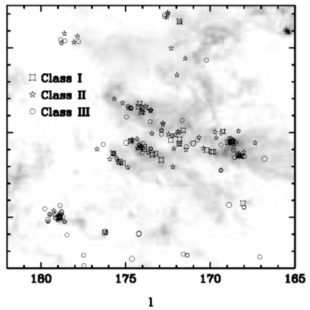
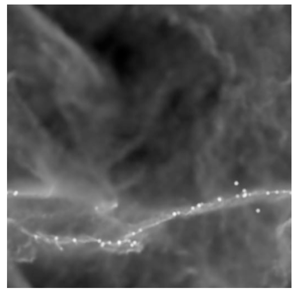
- Katharina Jappsen (AIP, Potsdam)
- Richard Larson (Yale University)
- Yuexing Li (Columbia University)
- Doug Lin (UC Santa Cruz)
- Mordecai-Mark Mac Low (AMNH, New York)
- Volker Ossenkopf (ESRON Gronigen)
- Stefan Schmeja (AIP, Potsdam)
- Michael Smith (Armagh University)
- Enrique Vazquez-Semadeni (UNAM, Morelia)
- Hans Zinnecker (AIP, Potsdam)

Gravoturbulent Star Formation







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AIP DFG

Würzburg, January 20, 2005

Structure

Motivation and Phenomenology

Historic Overview of Star Formation

Star form from ***gravoturbulent frag-mentation*** of molecular cloud material.

Star formation on galactic scales.

Why SF?

Why study star formation?

cosmology & galaxy formation
- relation between visible and dark matter
- formation of Pop III stars
- properties of high-z universe

planets
- initial conditions for planet formation
- diversity of planetary systems
- habitability (life)

galactic structure & evolution
- stars and star clusters are THE fundamental (visible) building blocks of galaxies
- stars probe galactic structure (e.g. GAIA)
- interrelation between SF and galactic structure

STAR FORMATION

stars
- IMF
- early evolution
- stars as members of culsters

star clusters
- chemical enrichment of galaxies
- probes of SF in the early universe (e.g. globular clusters)
- populate galactic field

ISM
- molecular cloud turbulence
- feedback from star formation
- initial conditions of SF

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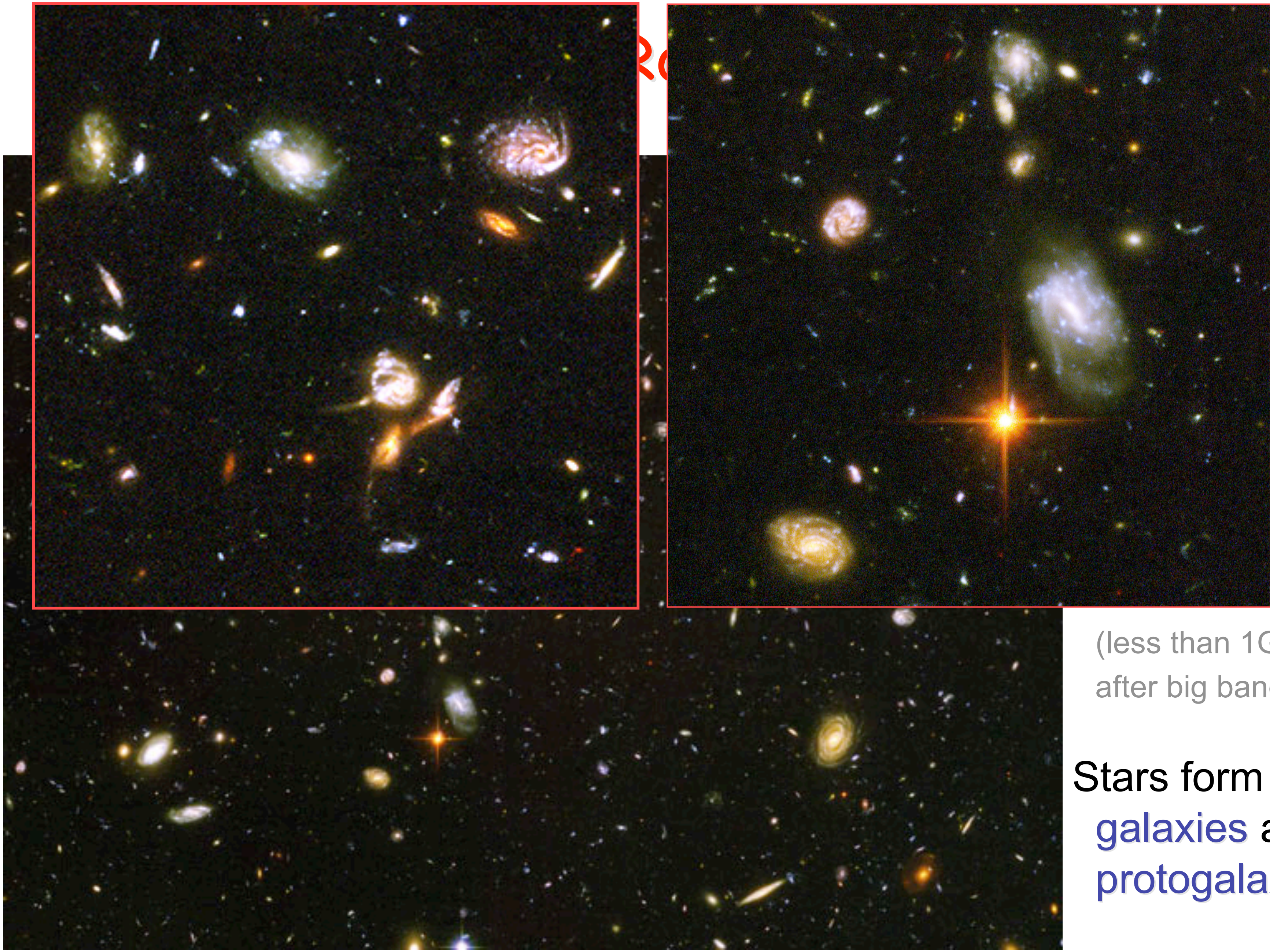
Star formation



tion
rly

(less than 1Gyr after big bangl)

Stars form in galaxies and protogalaxies

(Hubble Ultra-Deep Field, from HST Web site)

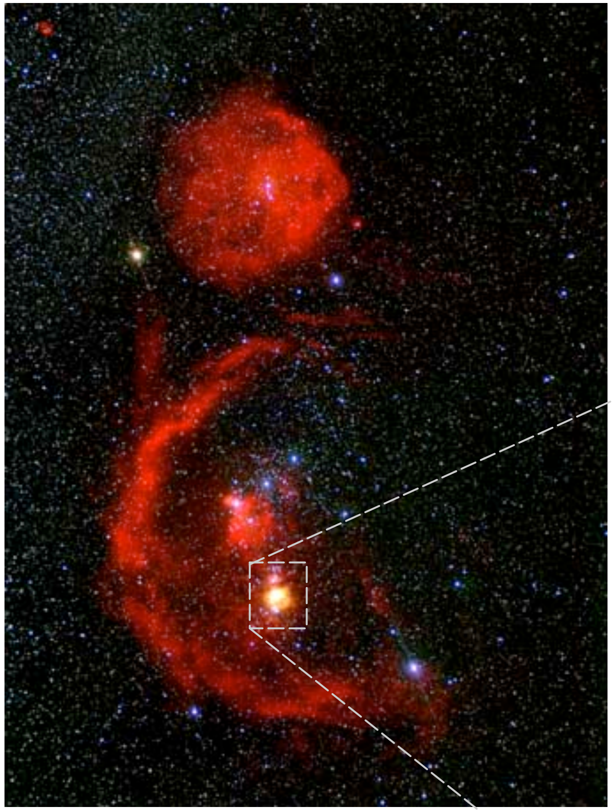
Star formation in "typical" spiral:

(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?

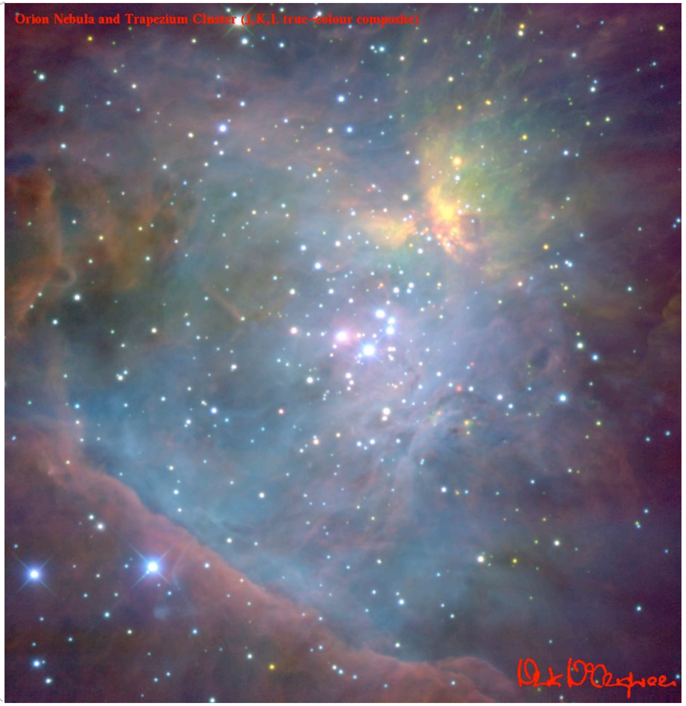
Local star forming region: The Trapezium Cluster in Orion



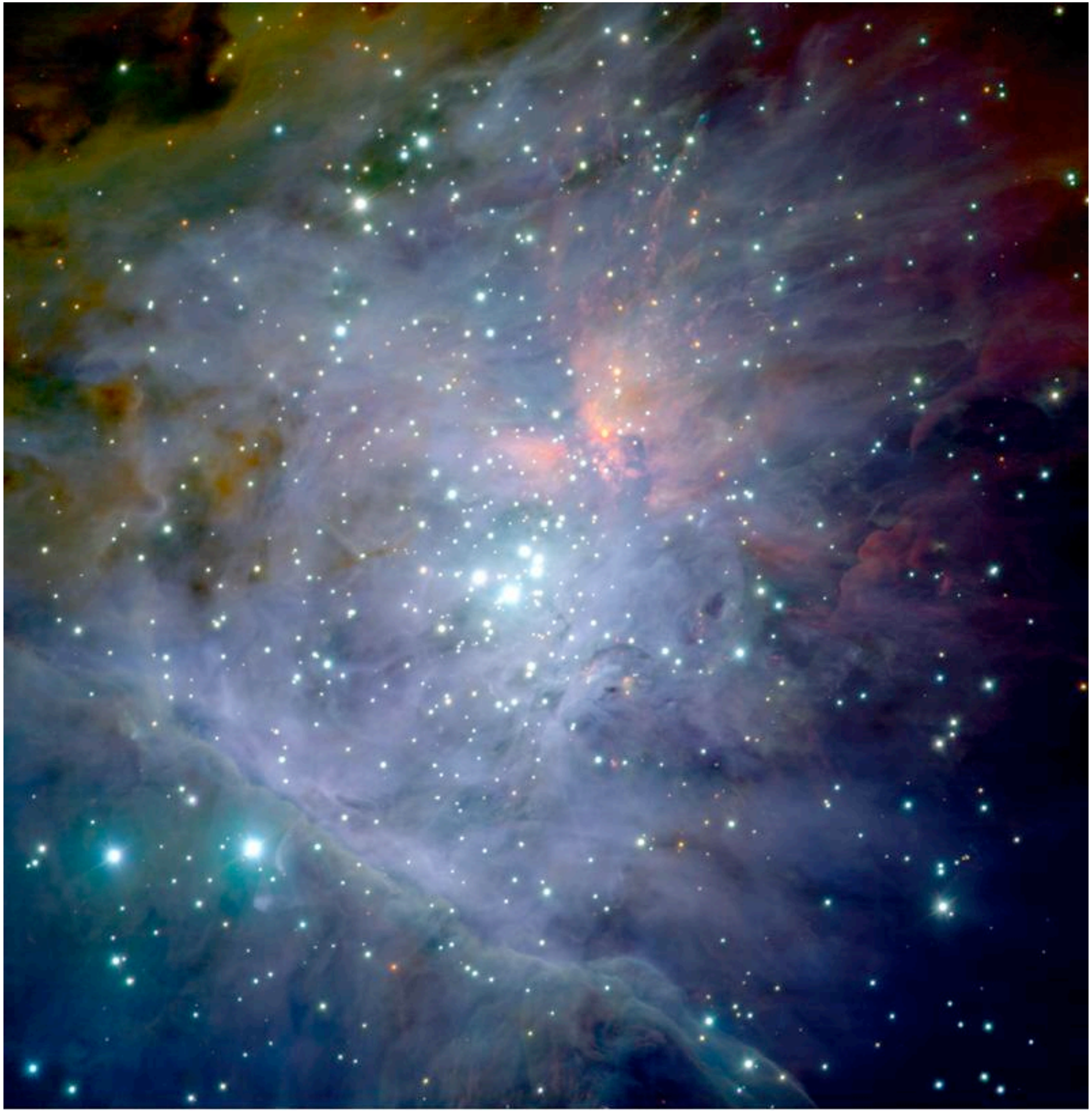
Orion molecular cloud

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.



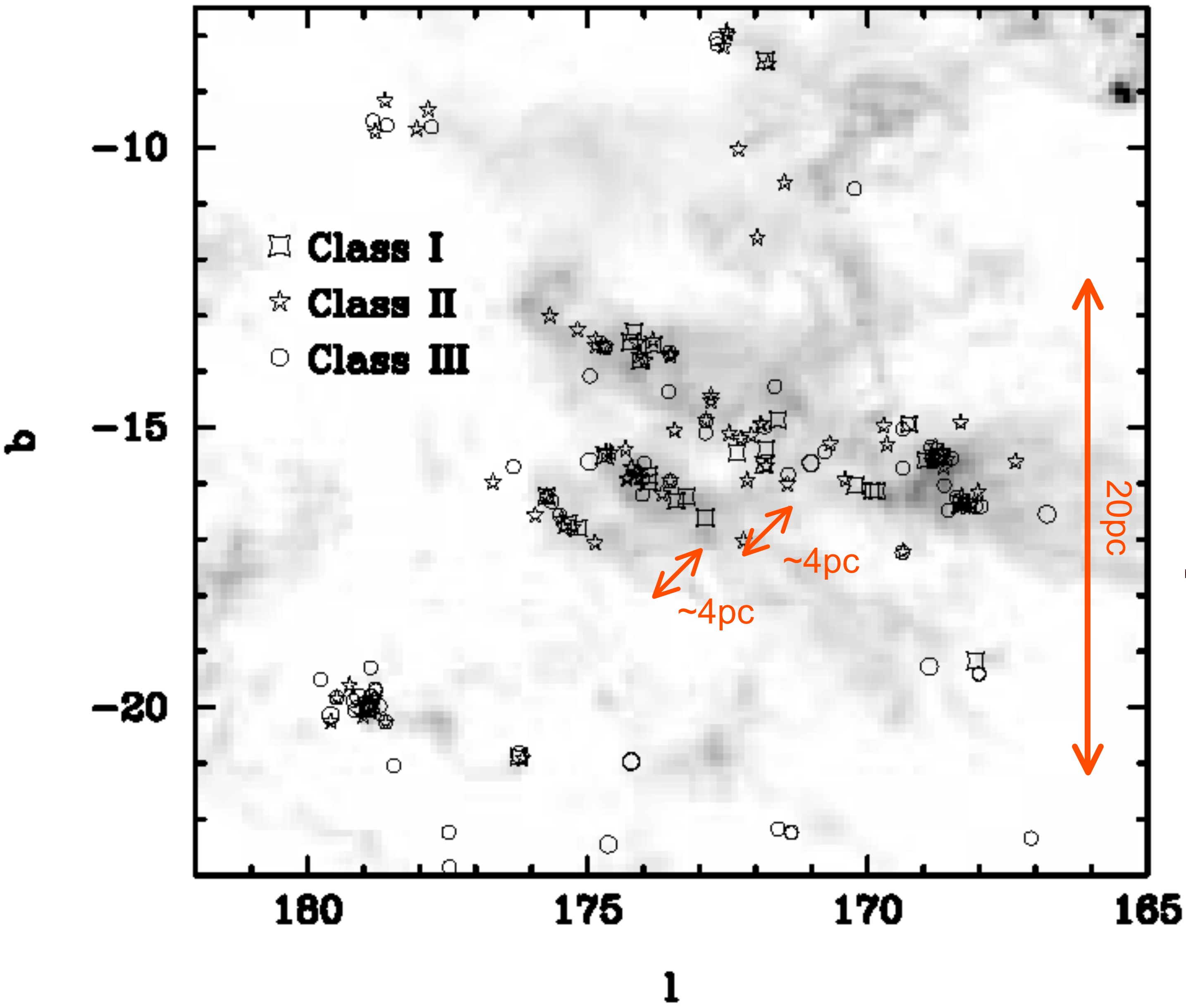
Trapezium cluster



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)



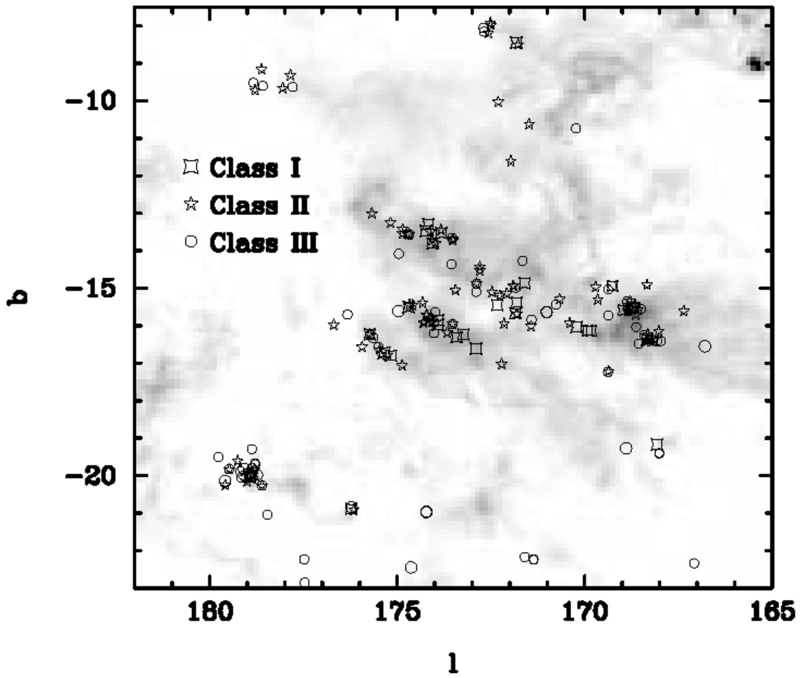
Taurus molecular cloud

star-forming filaments in the *Taurus* cloud

- Structure and dynamics of young star clusters is coupled to ***structure of mol. cloud***

(from Hartmann 2002)

Taurus molecular cloud

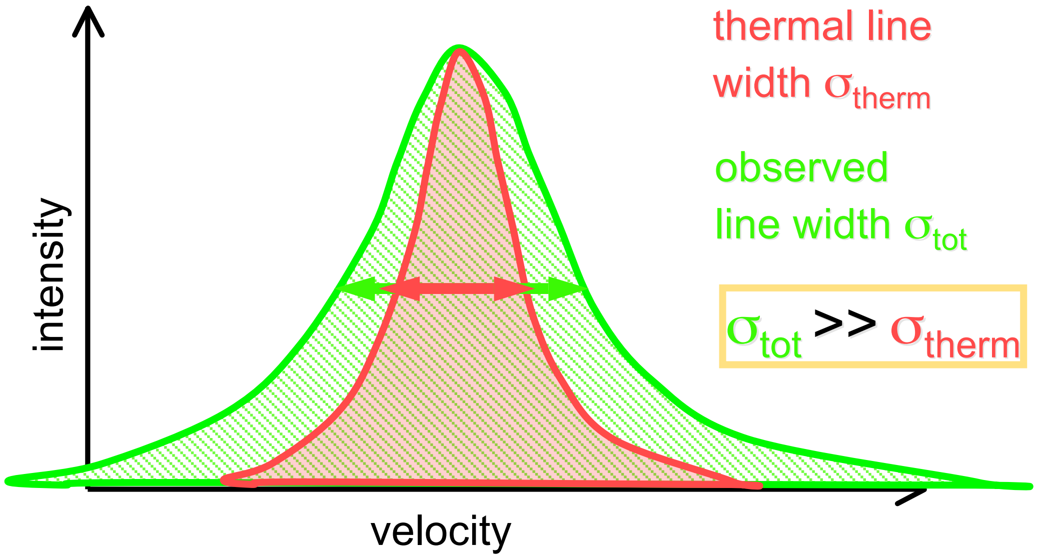


Star-forming filaments in *Taurus* cloud

(from Hartmann 2002)

- Strukture and dynamics of ***molekular cloud*** is determined by ***supersonic turbulence***

- Structure and dynamics of young star clusters is coupled to ***structure of molecular cloud***



HISTORY

Early dynamical theory

- *Jeans (1902):* Interplay between self-gravity and thermal pressure
  - stability of homogeneous spherical density enhancements against gravitational collapse
  - dispersion relation:

$$\omega^2 = c_s^2 k^2 - 4\pi G\rho_0$$

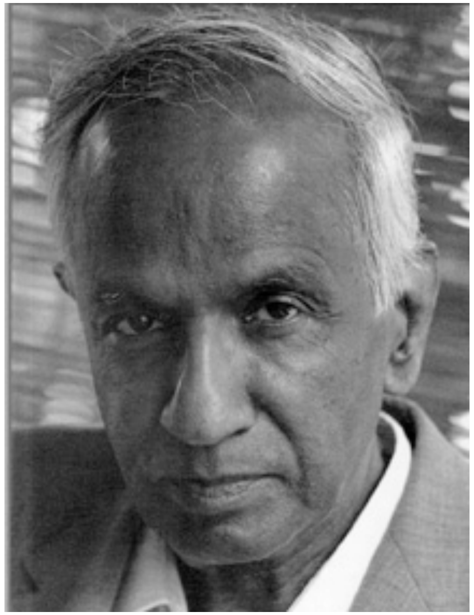
  - instability when $\omega^2 < 0$
  - minimal mass: $M_J = \frac{1}{6}\pi^{-5/2}G^{-3/2}\rho_0^{-1/2}c_s^3 \propto \rho_0^{-1/2}T^{3/2}$

Sir James Jeans, 1877 - 1946

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

First approach to turbulence

- *von Weizsäcker (1943, 1951)* and *Chandrasekhar (1951):* concept of **MICROTURBULENCE**
  - BASIC ASSUMPTION: separation of scales between dynamics and turbulence
    $\ell_{turb} \ll \ell_{dyn}$
  - then turbulent velocity dispersion contributes to effective soundspeed:
    $$c_c^2 \mapsto c_c^2 + \sigma_{rms}^2$$
  - → Larger effective Jeans masses → more stability
  - BUT: *(1) turbulence depends on k:* $\sigma_{rms}^2(k)$
    (2) supersonic turbulence → *usually* $\sigma_{rms}^2(k) >> c_s^2$


S. Chandrasekhar, 1910 - 1995

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

Problems of early dynamical theory

- Molecular clouds are *highly Jeans-unstable*
  Yet, they do *NOT* form stars at high rate
  and with high efficiency.
  (the observed global SFE in molecular clouds is *~5%*)
  → *something prevents large-scale collapse.*
- All throughout the early 1990's, molecular clouds had been thought to be long-lived quasi-equilitrium entities.
- Molecular clouds are *magnetized.*

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

Magnetic star formation

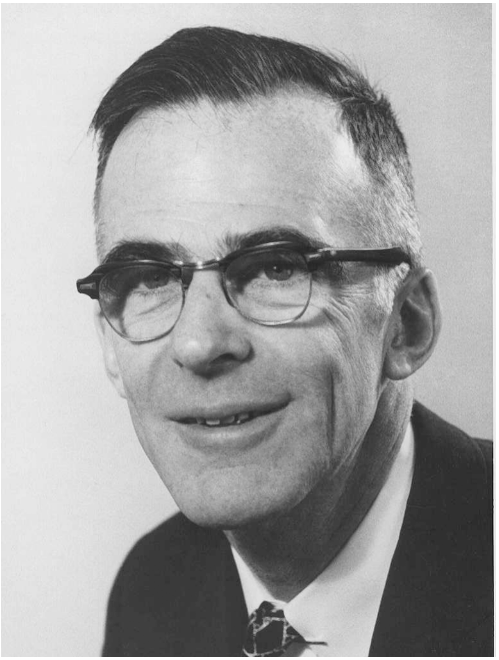
- *Mestel & Spitzer (1956):* Magnetic fields can prevent collapse!!!
  - Critical mass for gravitational collapse in presence of B-field

$$M_{cr} = \frac{5^{3/2}}{48\pi^2} \frac{B^3}{G^{3/2}\rho^2}$$

  - Critical mass-to-flux ratio (Mouschovias & Spitzer 1976)

$$\left[\frac{M}{\Phi}\right]_{cr} = \frac{\zeta}{3\pi}\left[\frac{5}{G}\right]^{1/2}$$

  - Ambipolar diffusion can initiate collapse

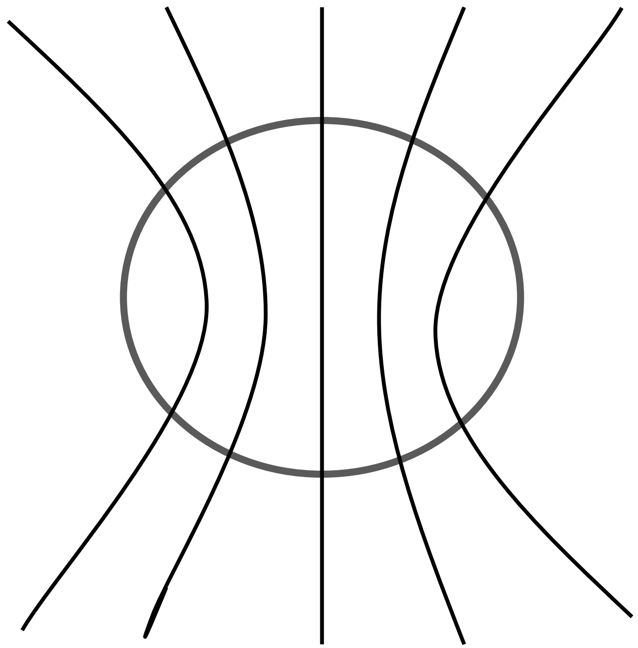


Lyman Spitzer, Jr., 1914 - 1997

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

The “standard theory” of star formation:

- BASIC ASSUMPTION: Stars form from magnetically highly subcritical cores
- Ambipolar diffusion slowly increases (M/Φ): $\tau_{AD} \approx 10\tau_{ff}$
- Once $(M/\Phi) > (M/\Phi)_{crit}$: dynamical collapse of SIS
  - Shu (1977) collapse solution
  - $dM/dt = 0.975\ c_s^3/G = const.$
- Was (in principle) only intended for isolated, low-mass stars



Problems of magnetic SF

- Observed B-fields are weak, at most marginally critical (Crutcher 1999, Bourke et al. 2001)
- Magnetic fields cannot prevent decay of turbulence
  (Mac Low et al. 1998, Stone et al. 1998, Padoan & Nordlund 1999)
- Structure of prestellar cores
  (Bacman et al. 2000, e.g. Barnard 68 from Alves et al. 2001)
- Strongly time varying dM/dt
  (e.g. Hendriksen et al. 1997, André et al. 2000)
- More extended infall motions than predicted by the standard model
  (Williams & Myers 2000, Myers et al. 2000)

Problems of magnetic SF

- As many prestellar cores as protostellar cores in SF regions (e.g. André et al 2002)
- Molecular cloud clumps seem to be chemically young
  (Bergin & Langer 1997, Pratap et al 1997, Aikawa et al 2001)
- Stellar age distribution small ($\tau_{ff} << \tau_{AD}$)
  (Ballesteros-Paredes et al. 1999, Elmegreen 2000, Hartmann 2001)
- Strong theoretical criticism of the SIS as starting condition for gravitational collapse
  (e.g. Whitworth et al 1996, Nakano 1998, as summarized in Klessen & Mac Low 2004)
- Most stars form as binaries

NEW THEORY

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

- New theory of 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)

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.
- *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)

In detail. . .

Molecular clouds

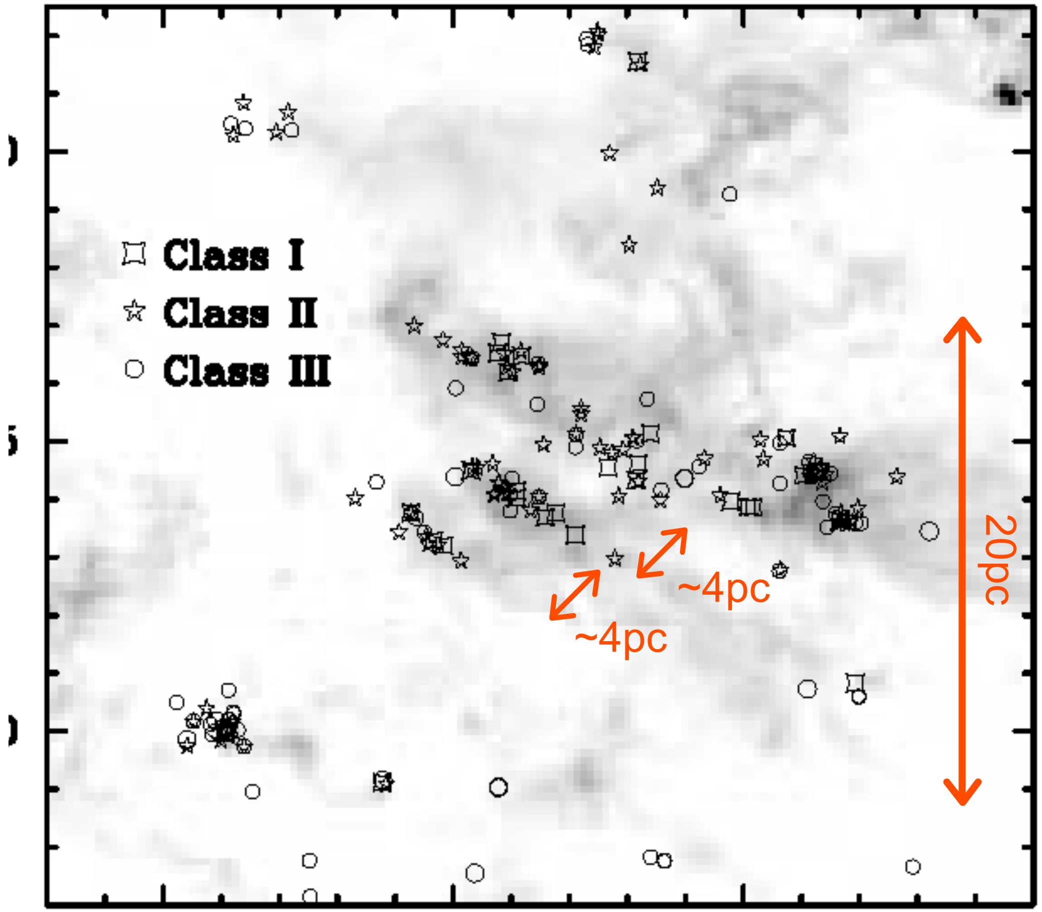
- MC's are *massive* ($M_{cloud} = 10^3 \ldots 10^6 M_\odot \leftrightarrow M_{Jeans} = 1 \ldots 100 M_\odot$)
- MC's are *cold* ($T_{cloud} = 10 \ldots 20$ K)
- MC's are *transient* (life time ≈ few τ_{cross} ≈ few τ_{ff} ≈ few 10^6 yr)
- MC structure is determined by *supersonic turbulence*
  (density and velocity structure dominated by large-scale modes)
- Energy budget: *Turbulent energy ≈ 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)
- ***Our group:*** Since 2000/1, 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.…

Gravoturbulent fragmentation



Map of Taurus: Hartmann 2002
Movie: a model for star formation in the Taurus cloud
from Klessen & Ballesteros Paredes, in preparation

Gravoturbulent fragmentation in molecular clouds:

- SPH model with 1.6×10^6 particles
- large-scale driven turbulence
- Mach number $\mathcal{M} = 6$
- periodic boundaries
- isothermal EOS
- total mass $M_{tot} = 120 \times M_J$
  (M_J = thermal Jeans mass)
- physical scaling:

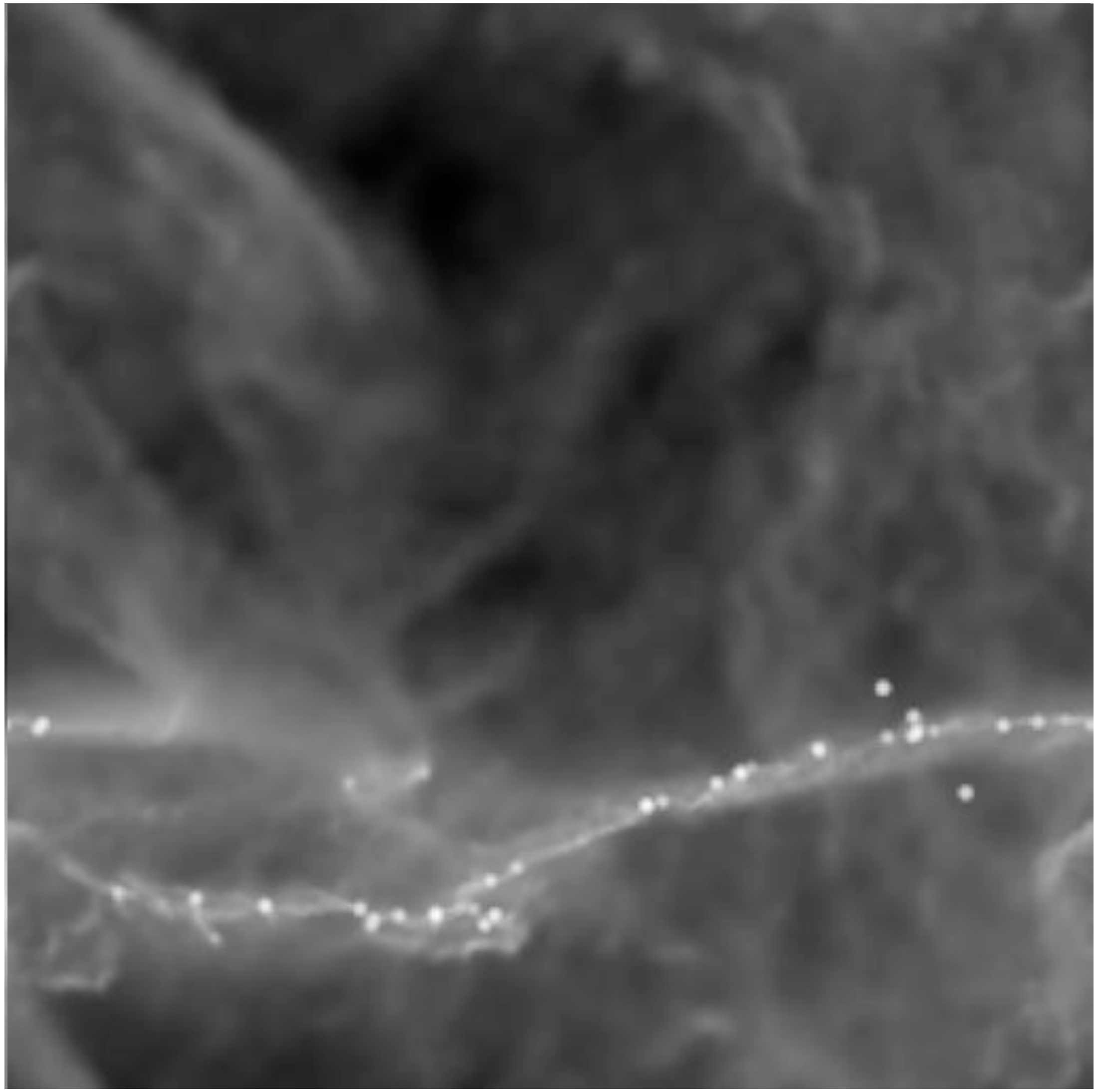
"Taurus":
→ density $n(H_2) \approx 10^2\, cm^{-3}$:
→ $L = 6\, pc, M = 5000\, M_\odot$

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



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- periodic boundaries
- physical scaling:

"Taurus":
→ density $n(H_2) \approx 10^2\, cm^{-3}$:
→ $L = 6\, pc$,
$M = 5000\, M_{\odot}$

NEXT STEPS: *differential rotation, chemical network (proper cooling function & $H \rightarrow H_2$), physical driving source*

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

weak driving

strong driving

k = 2

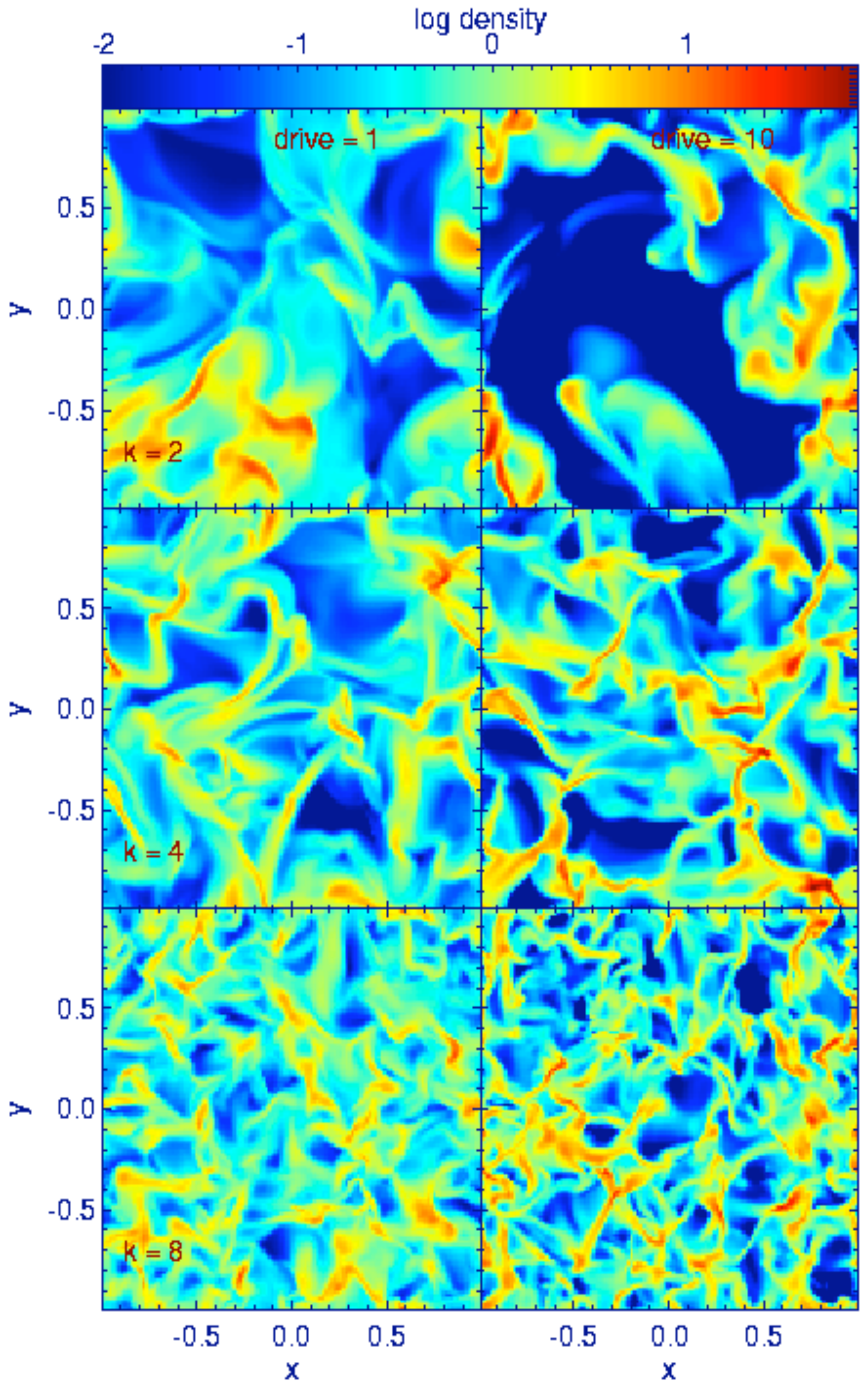
large-scale turbulence

k = 4

intermediate-scale turbulence

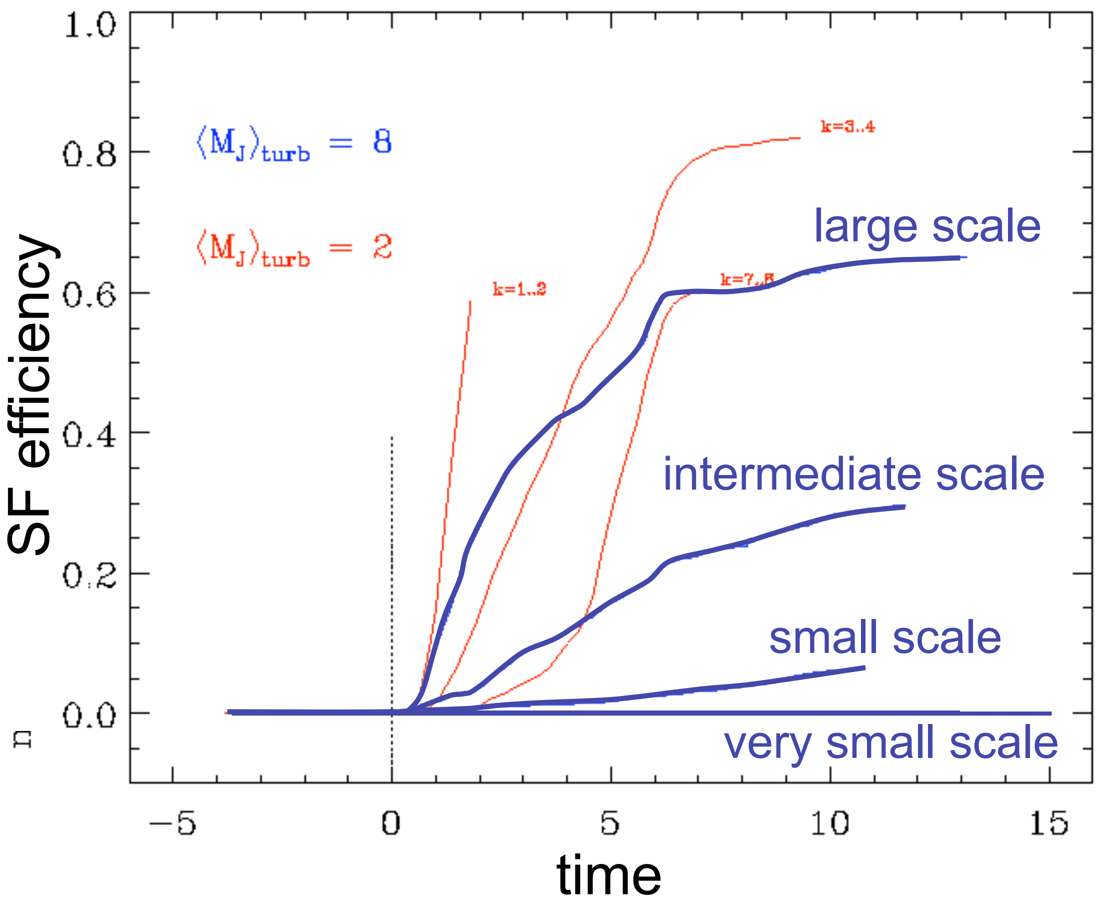
k = 8

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?

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

- *global properties* (statistical properties)
  - SF efficiency
  - SF time scale
  - IMF – formation of stellar clusters
  - description of self-gravitating turbulent systems (pdf's, Δ-*var.)*
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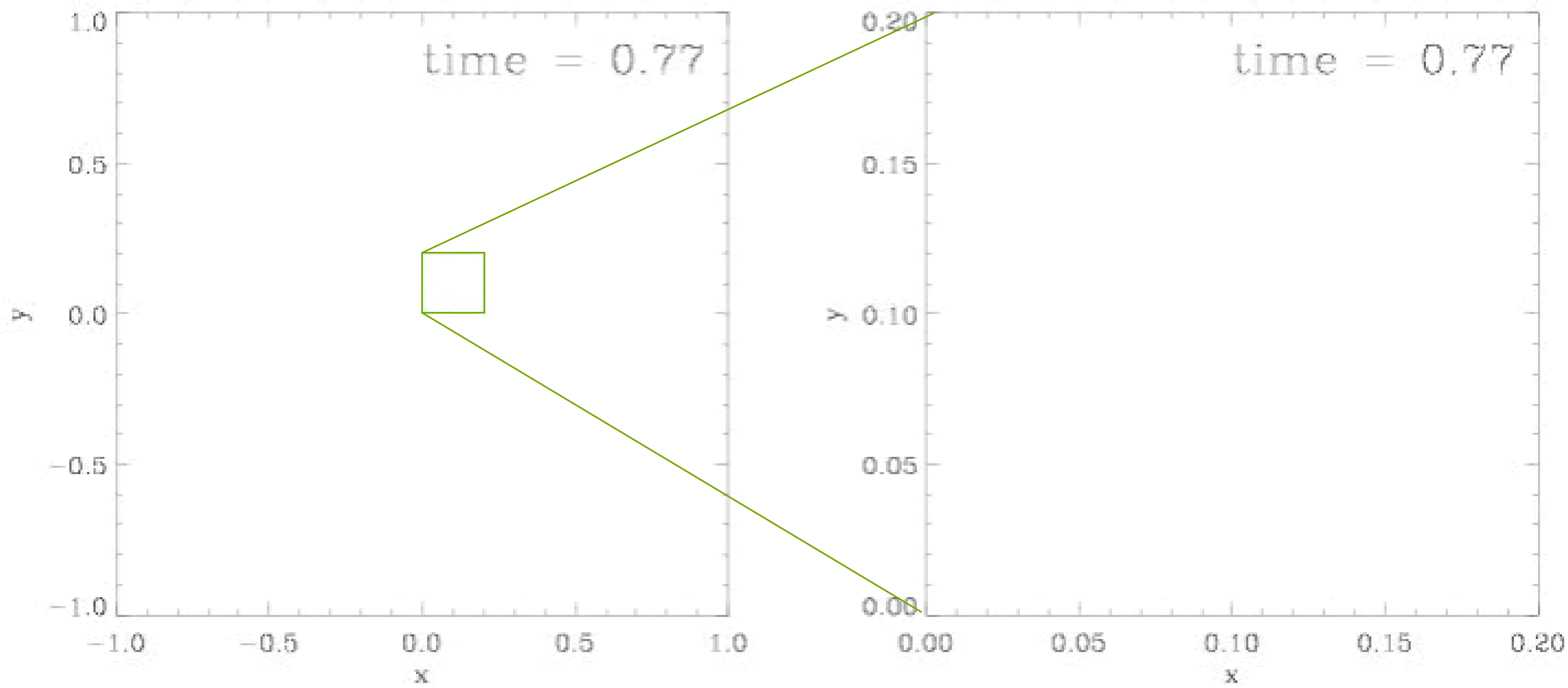
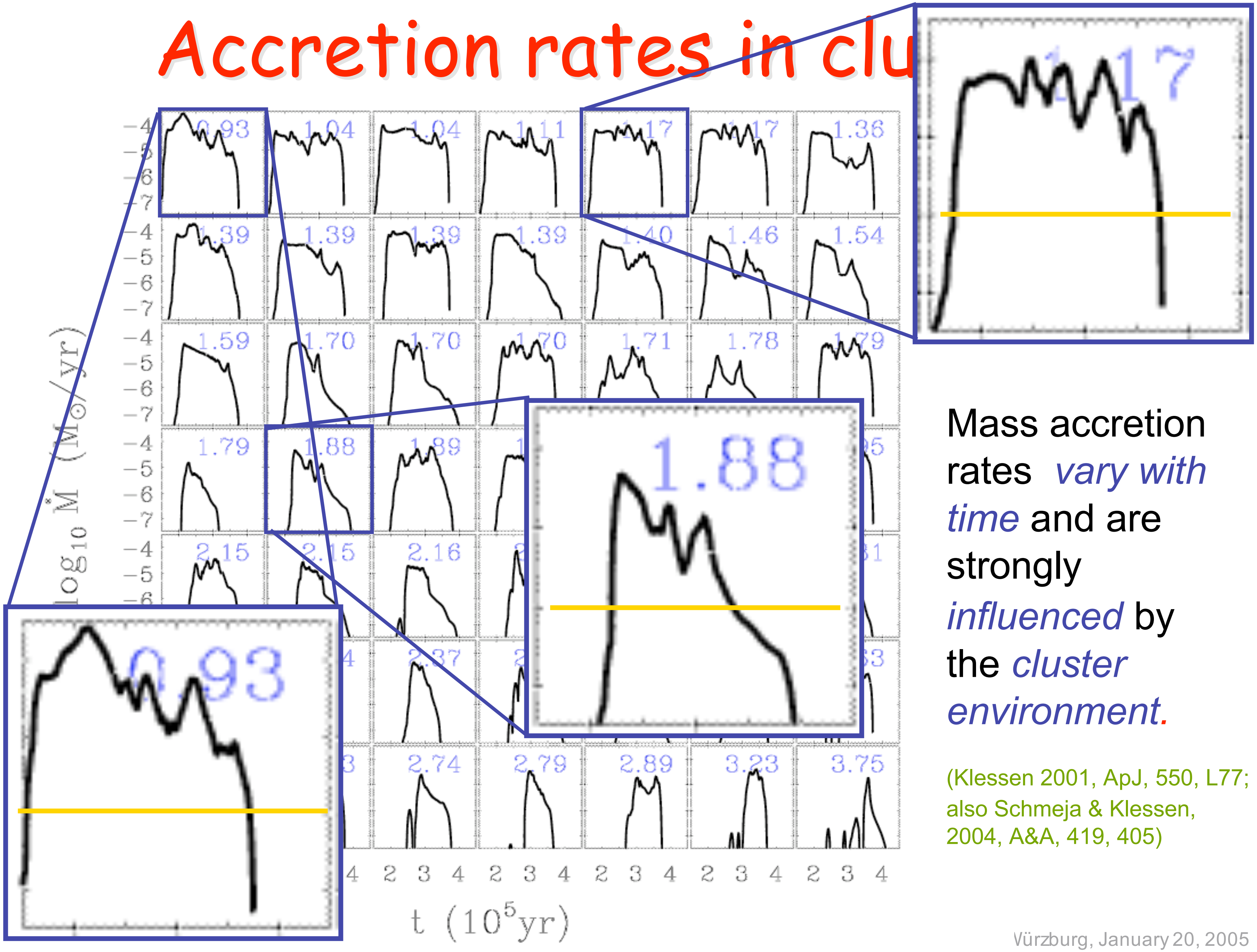
Star cluster formation

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

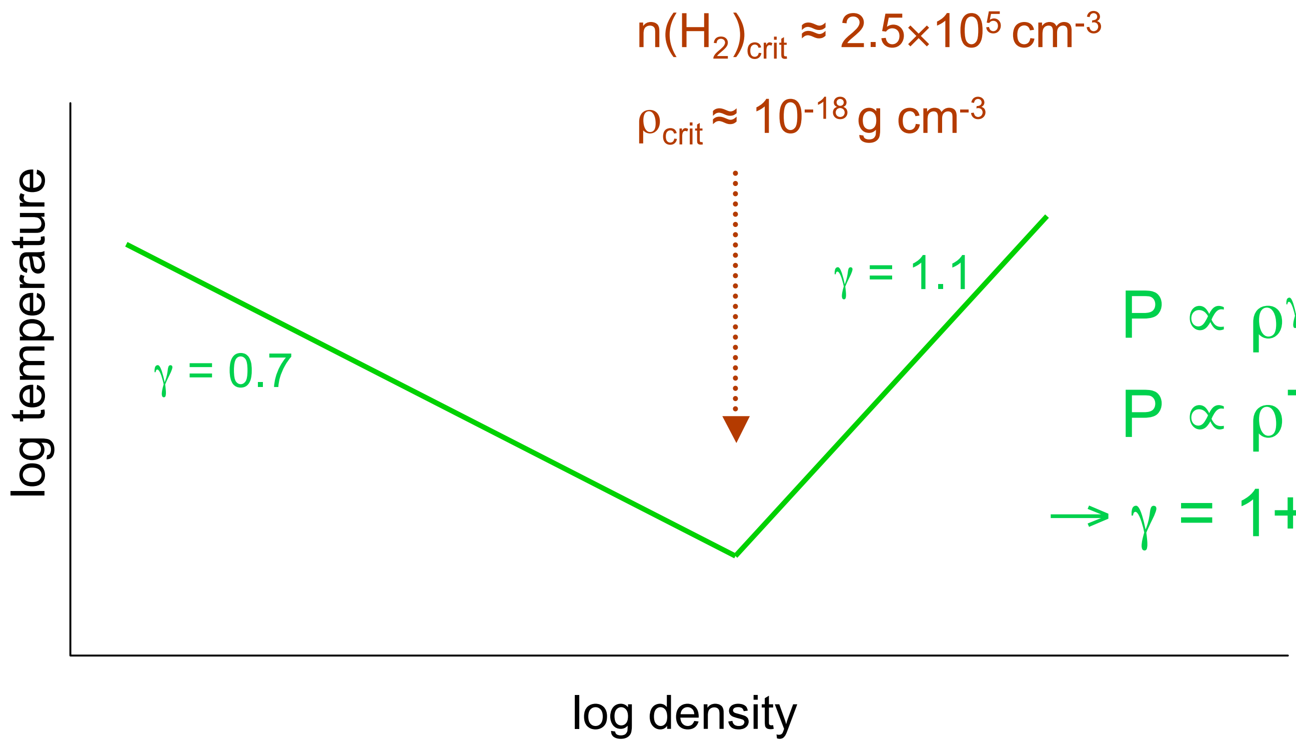


Mass accretion rates *vary with time* and are strongly *influenced* by the *cluster environment*.

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

Influence of EOS

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



$P \propto \rho^\gamma$

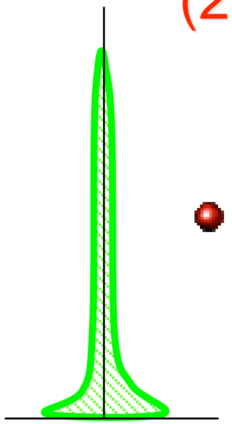
$P \propto \rho T$

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

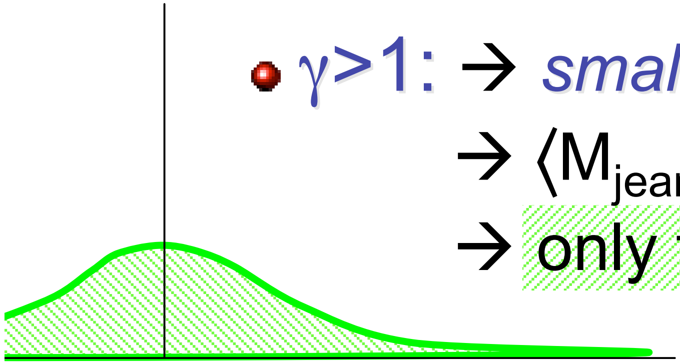
Influence of EOS

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

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

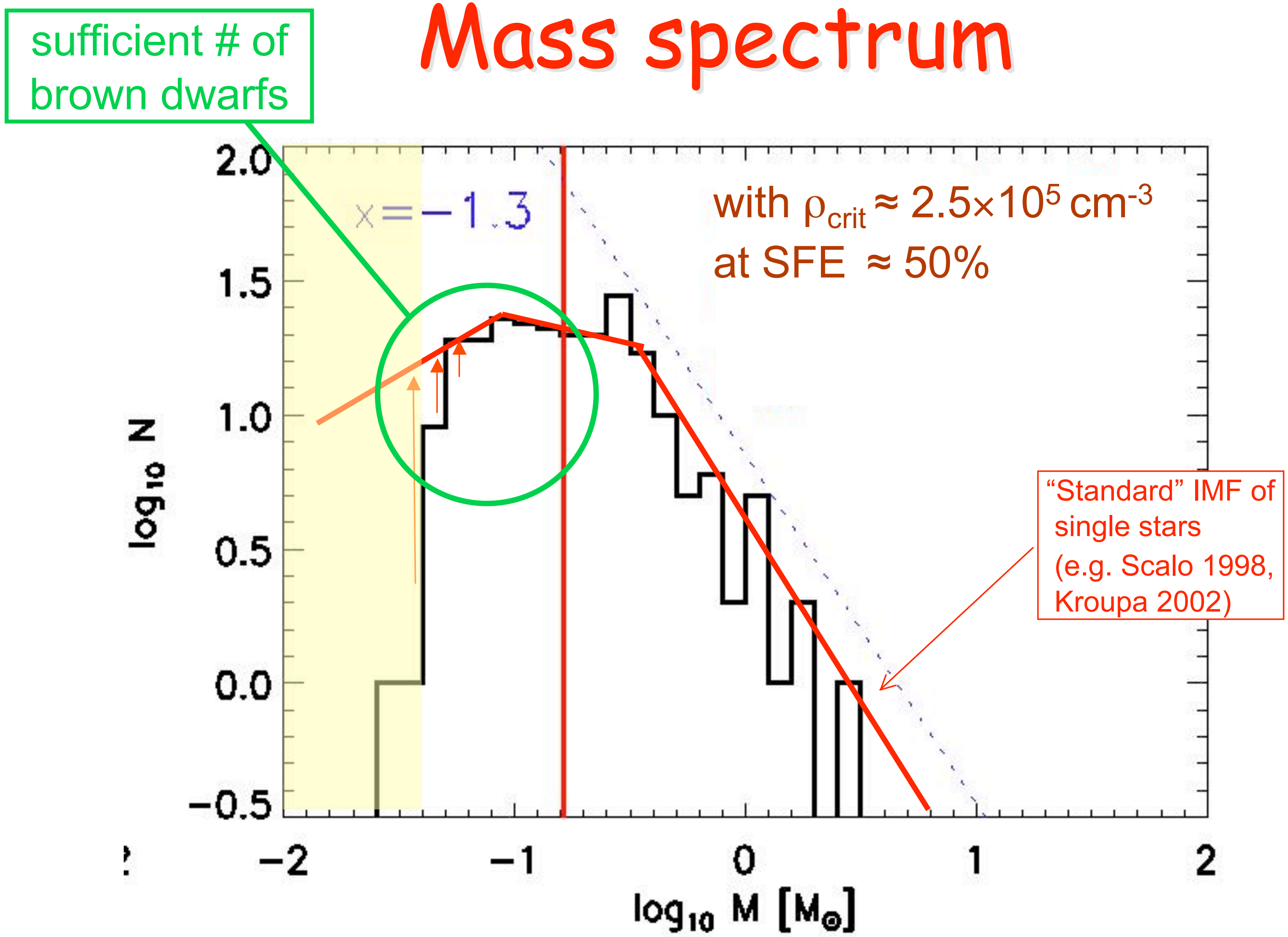


- $\gamma<1$: → *large* density excursion for given pressure
  → $\langle M_{jeans} \rangle$ becomes small
  → number of fluctuations with $M > M_{jeans}$ is large



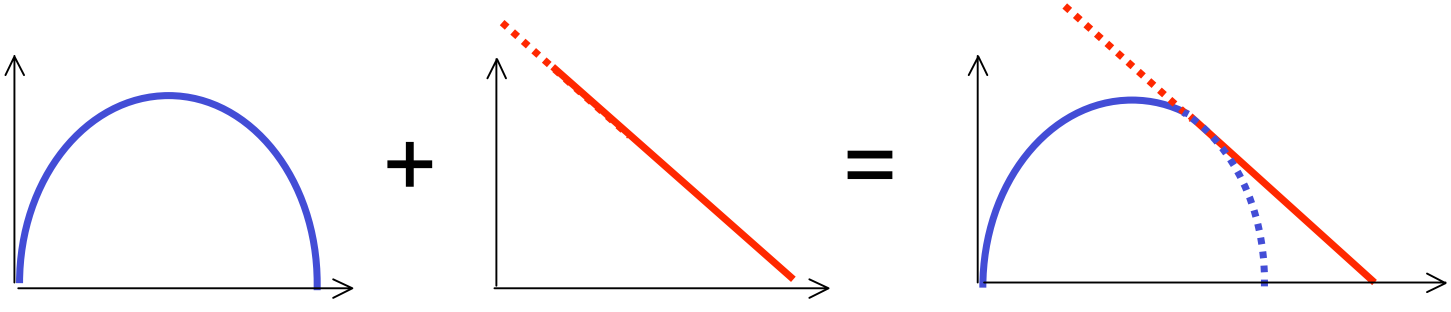
- $\gamma>1$: → *small* density excursion for given pressure
  → $\langle M_{jeans} \rangle$ is large
  → only few and massive clumps exceed M_{jeans}

Mass spectrum



(Jappsen, Klessen, Larson, Li, Mac Low, 2004, A&A submitted)

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*

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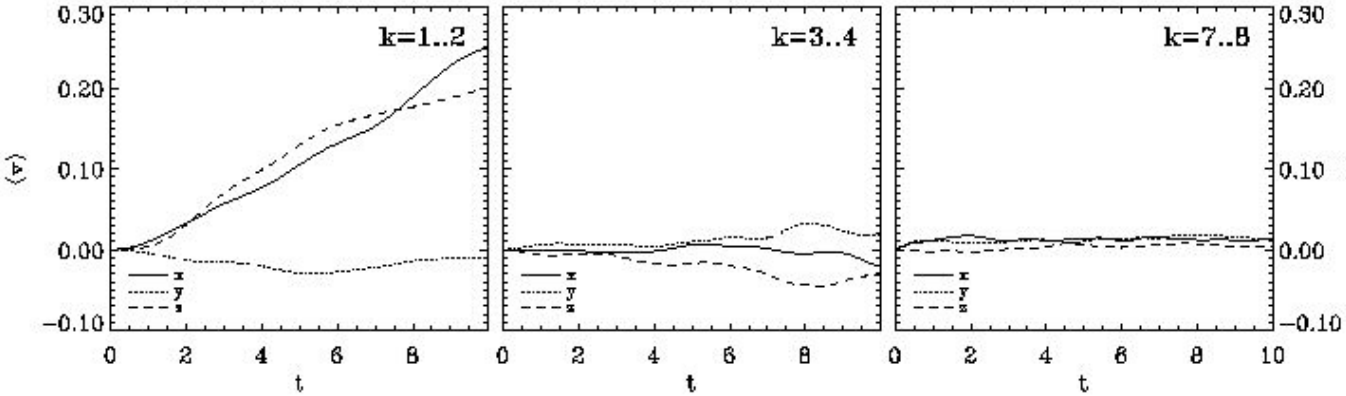
(details in review by Mac Low & Klessen, 2004, Rev. Mod. Phys., 76, 125-194)

Turbulent diffusion I

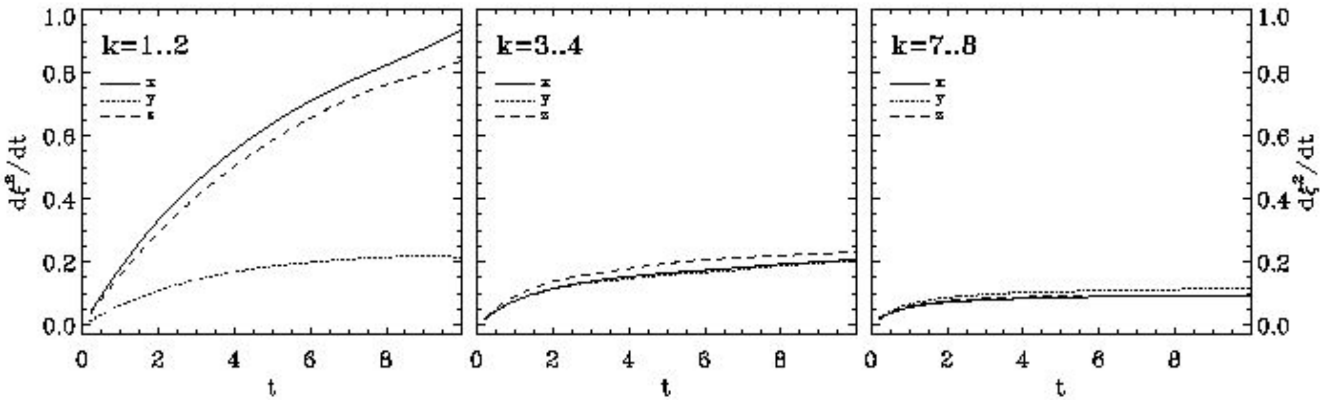
- Observations of young star clusters exhibit an enormous degree of *chemical homogeity* (e.g. in the Pleiades: Wilden et al. 2002)
- Star-forming gas must be *well mixed*.
- How does this constrain models of interstellar turbulence?
- → Study mixing in supersonic compressible turbulence….

Turbulent diffusion II

- Large-scale turbulence associated with bulk motion.



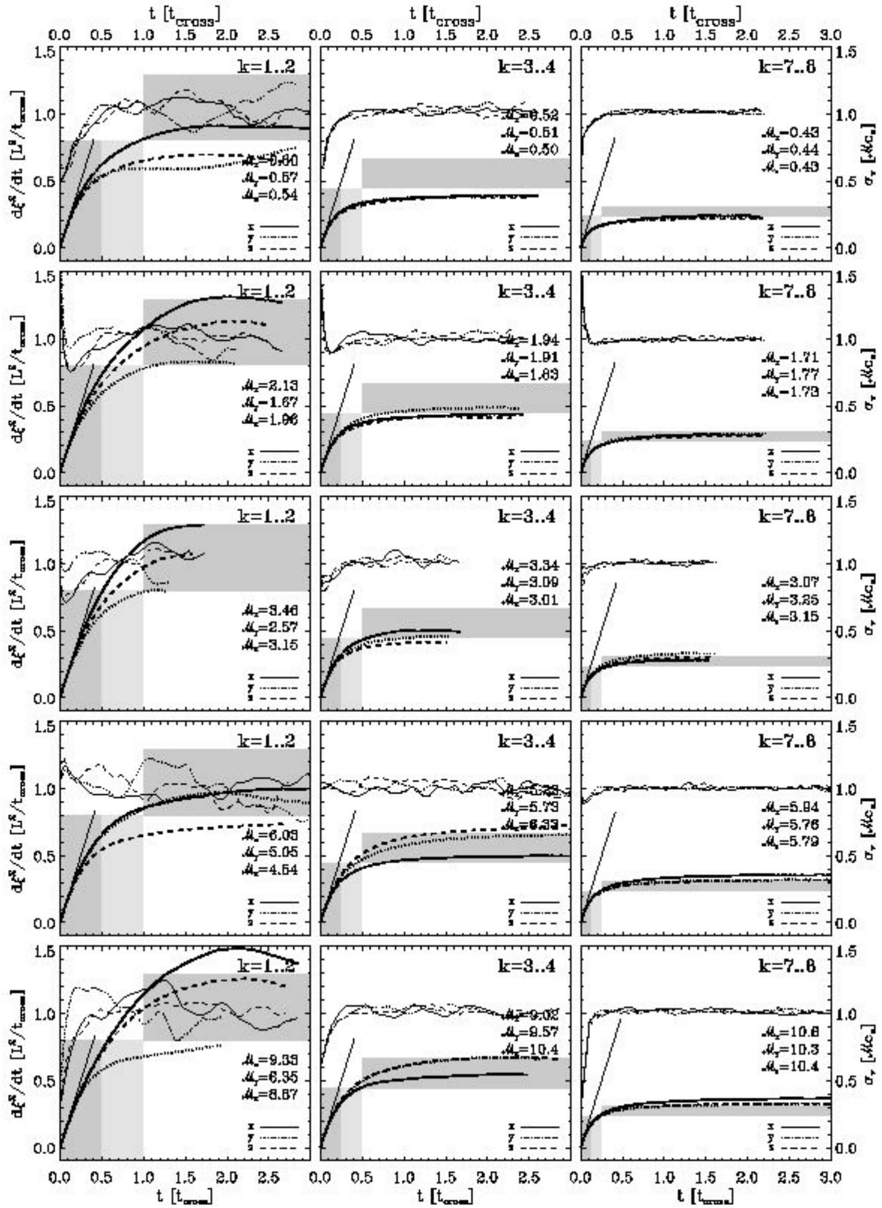
- Super-diffusive behavior.



(from Klessen & Lin 2003, PRE in press)

Turbulent diffusion III

- Mean-motion corrected diffusion
- Simple mixing-length approach:
  - $D(t) \approx v_{rms}{}^{2}\, t \qquad t<\tau$
  - $D(t) \approx v_{rms}{}^{2}\, \tau$
    $= v_{rms}\, \ell \qquad t>\tau$
  - With v_{rms} = rms velocity and ℓ = L/k = shock sep.



(from Klessen & Lin 2003, PRE, **67**, 046311)

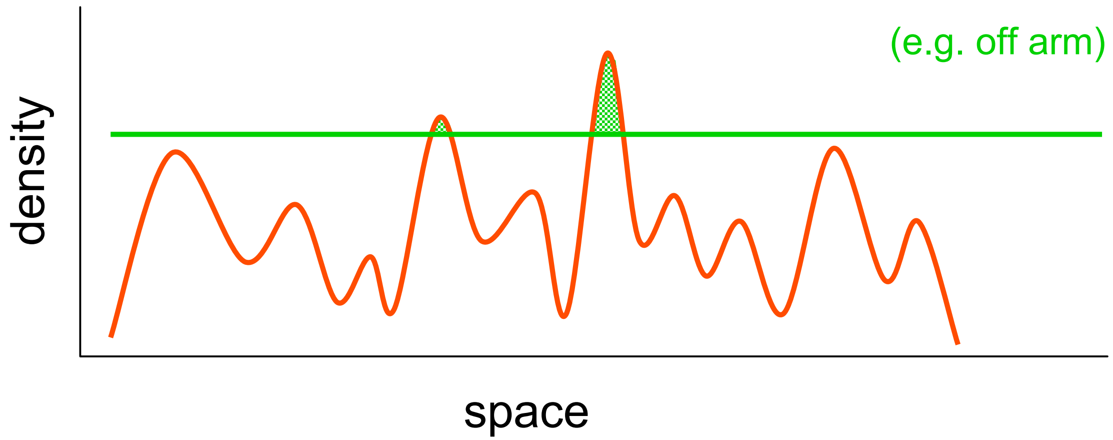
GALACTIC SCALE

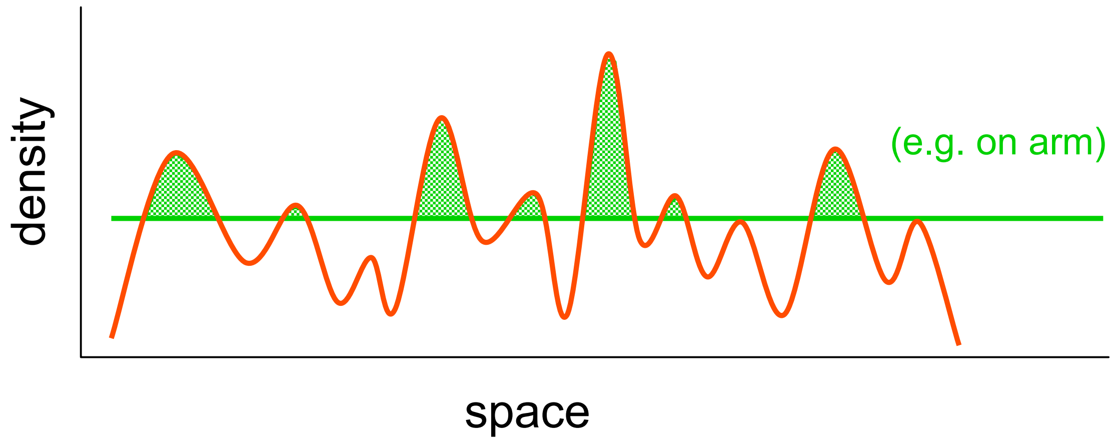
Würzburg, January 20, 2005

Star formation on *global* scales

- *SF on global scales* = *formation of molecular clouds* !
- MC's form at *stagnation points* of *convergent large-scale flows*
  (need ~0.5kpc^3 of gas) → high density → enhanced cooling → fast H_2 formation & gravitational instability → local collapse and star formation
- External perturbations *increase* the local likelihood of MC formation (e.g. in spiral density waves, galaxy interactions, etc.)

Star formation on *global* scales



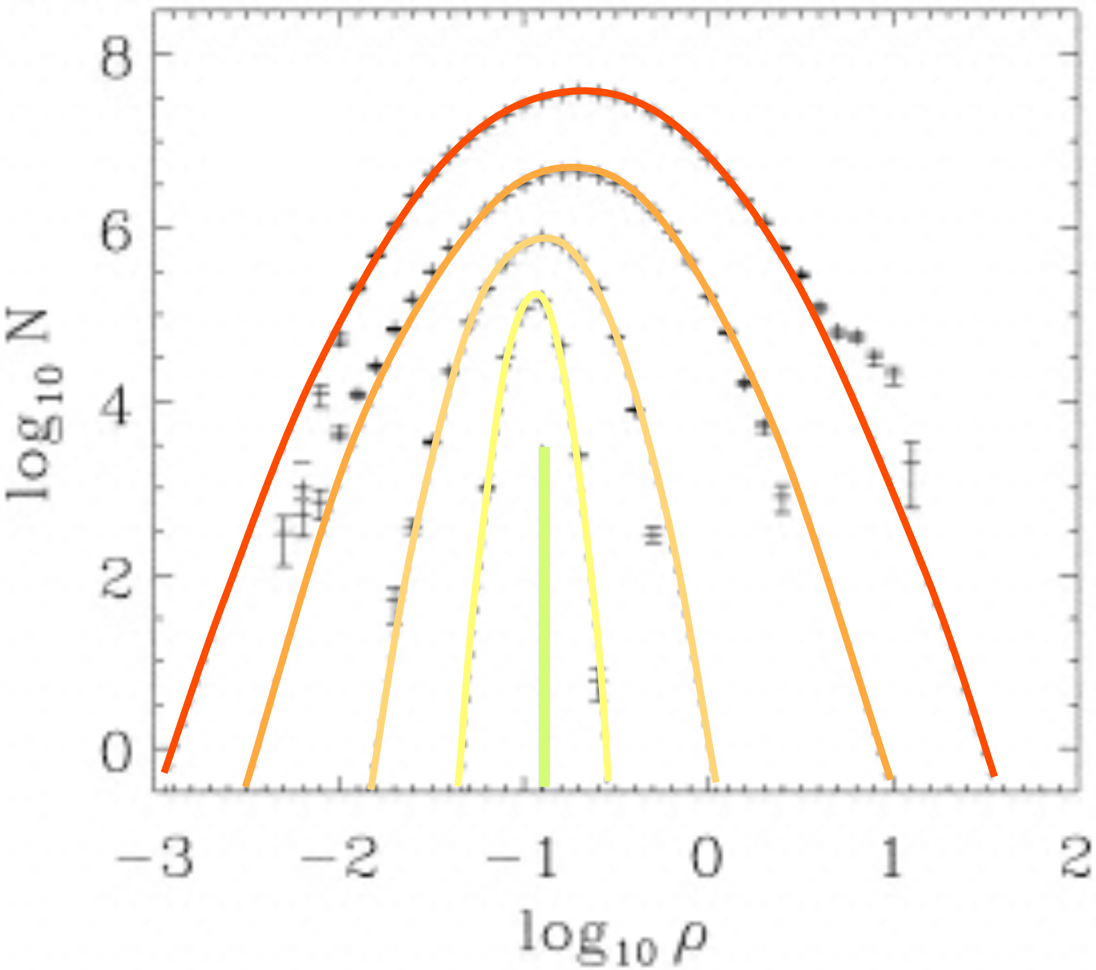


density fluctuations in warm atomar ISM caused by supersonic turbulence

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

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

Star formation on *global* scales



probability distribution function of density *(ρ-pdf)* for decaying supersonic turbulence

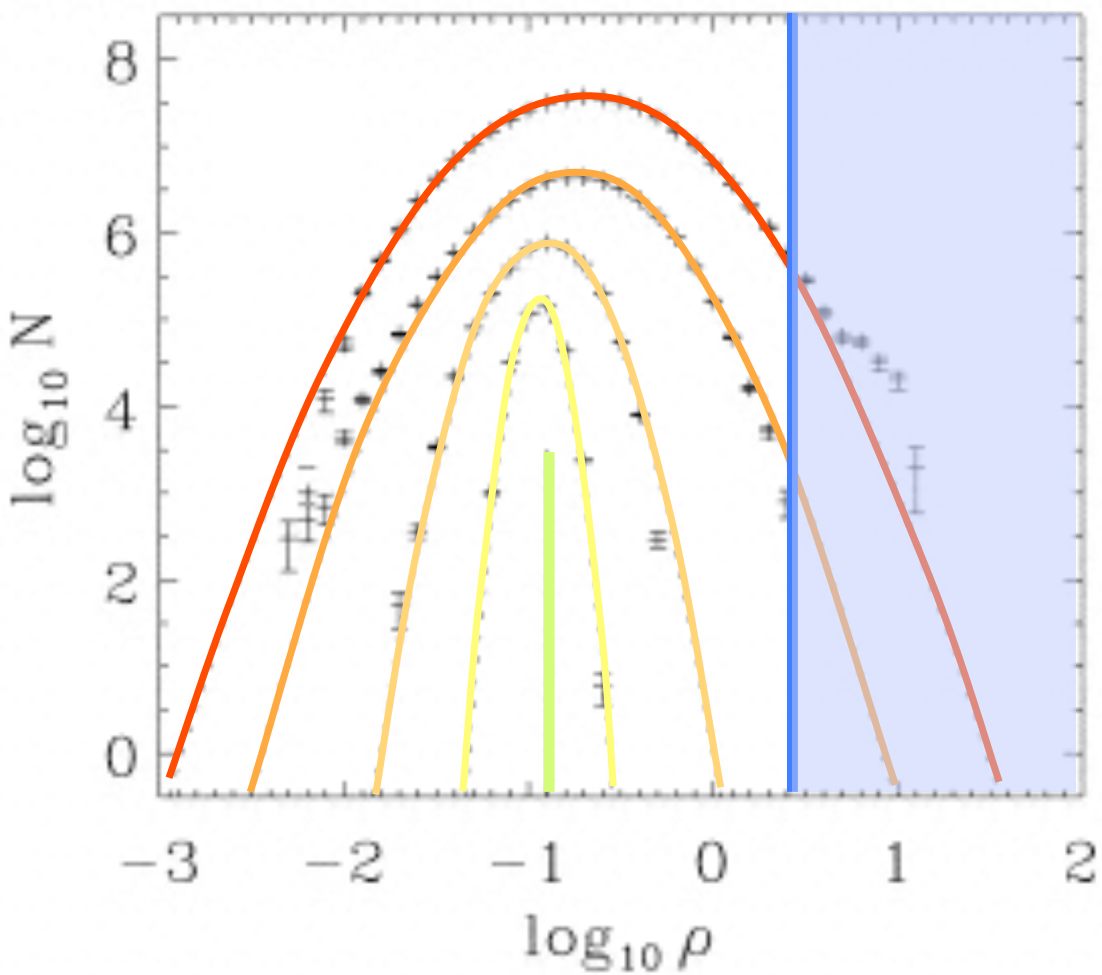
varying rms Mach numbers:

M1 > M2 > M3 > M4 > 0

mass weighted ρ-pdf, each shifted by ΔlogN=1

(from Klessen, 2001)

Star formation on *global* scales



mass weighted ρ-pdf, each shifted by ΔlogN=1

H_2 formation rate:

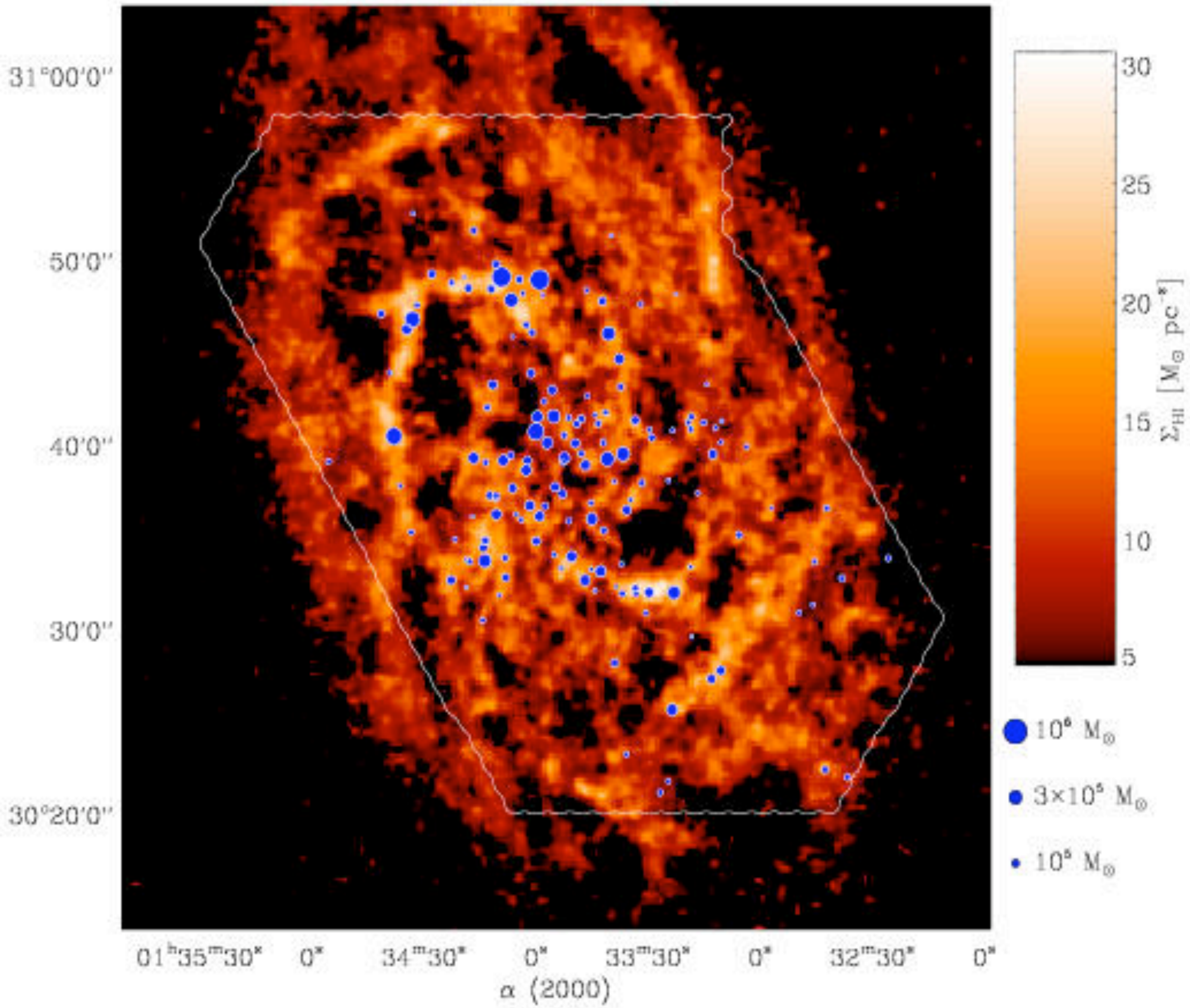
$$\tau_{H_2} \approx \frac{1.5\,\mathrm{Gyr}}{n_H / 1\mathrm{cm}^{-3}}$$

For $n_H \geq 100\ \mathrm{cm}^{-3}$, H_2 forms within 10Myr, this is about the lifetime of typical MC's.

What fraction of the galactic ISM reaches such densities?

(from Klessen, 2001; rate from Hollenback, Werner, & Salpeter 1971)

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)

Modeling galactic SF

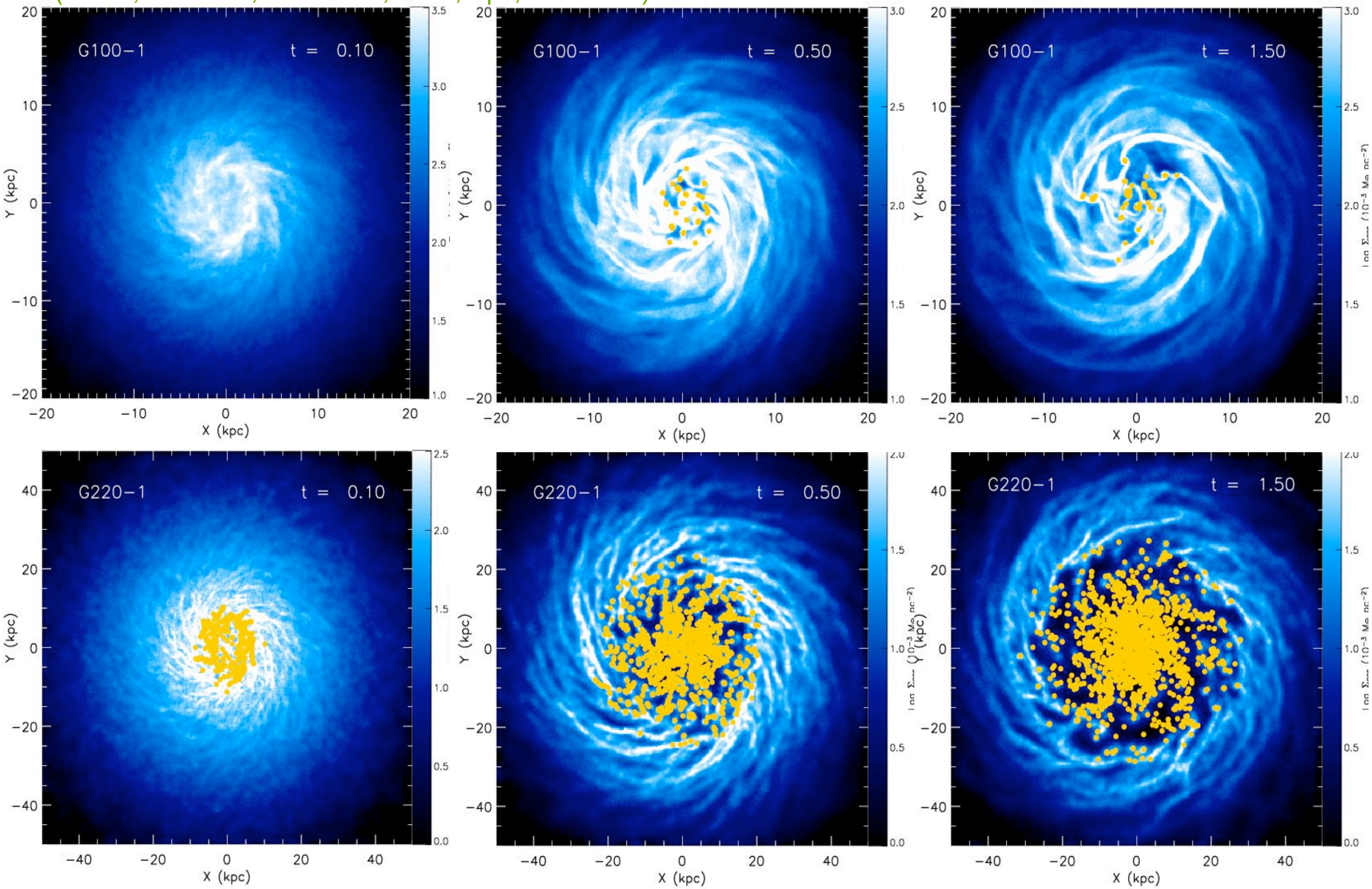
- Evolution of 42 isolated disk galaxies
  - DM halo, stellar disk & gas disk
  - SPH code GADGET with accretion particles
    (resolution: 5×10^5 to 3×10^6 gas particles)
  - $50\ \mathrm{km/s} \leq v_{circ} \leq 250\ \mathrm{km/s}$
  - fraction of disk mass: $m_d = 5\%$ - 10%
  - gas fraction in disk: $f_d = 20\%, 50\%,$ & 90%
  - total mass: $4.15\times10^{10}\ M_\odot \leq M_{200} \leq 357.14\times10^{10} M_\odot$

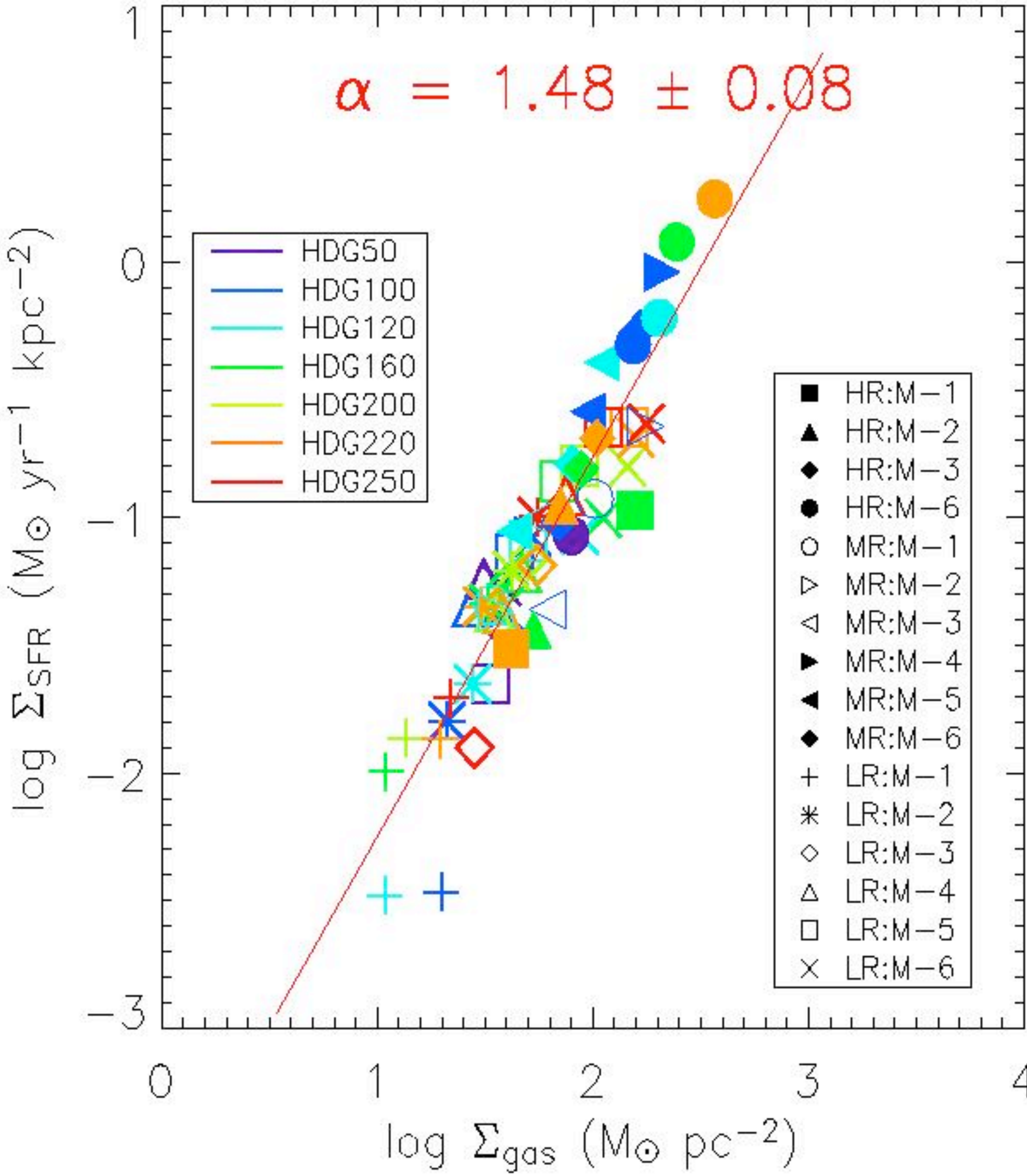
    (corresponds to mass resolution of $138\ M_\odot \leq M_{SPH} \leq 10^5\ M_\odot$ in models with $3\mathrm{x}10^6$ gas particles)

(Li, Mac Low, & Klessen, 2004a, ApJ, submitted)

Modeling galactic SF

(aus Li, Mac Low, & Klessen, 2004, ApJ, submitted)





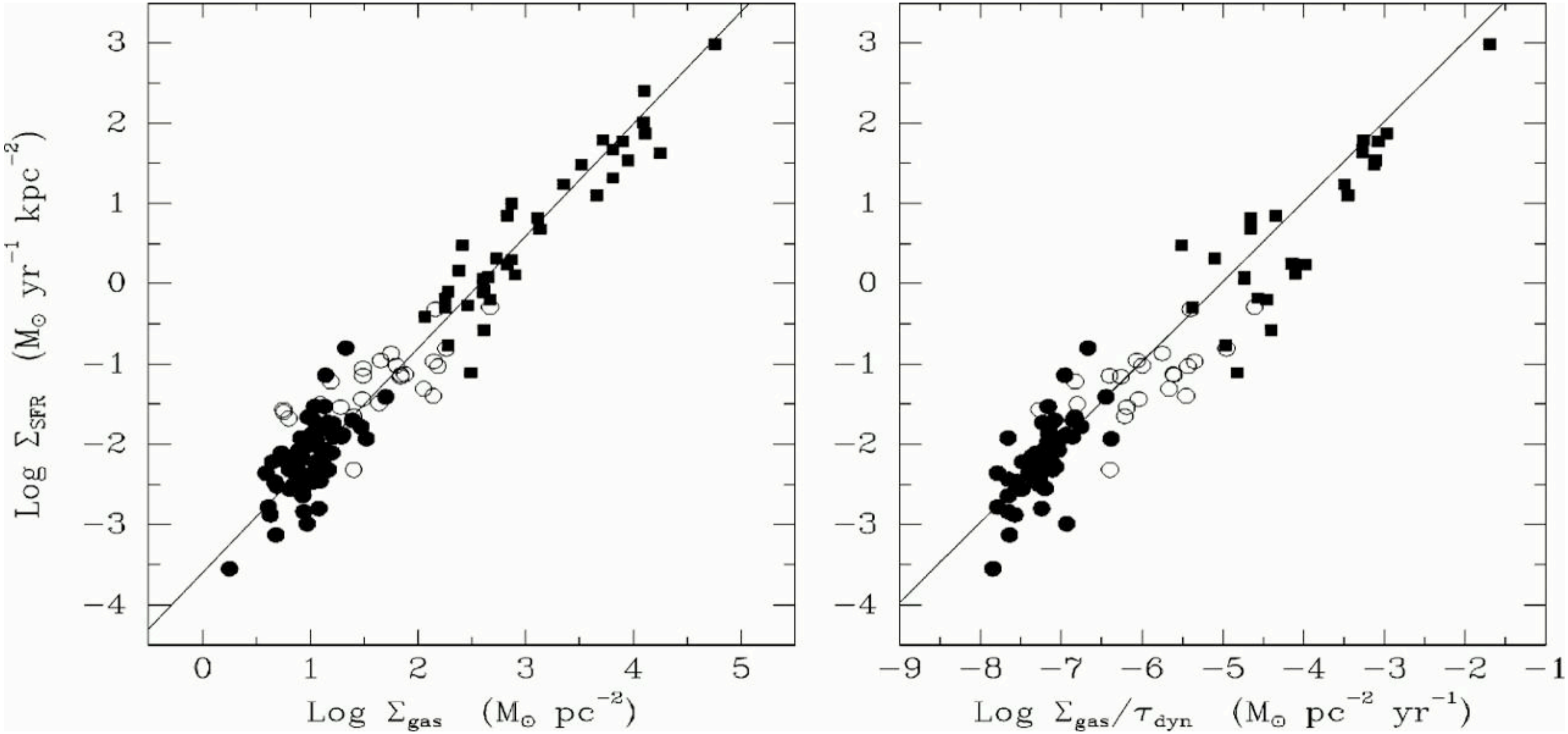
(Li, Mac Low, & Klessen, 2004, ApJ submitted)

We find correlation between *star formation rate* and *gas surface density:*

$$\Sigma_{SFR} \propto \Sigma_{gas}^{1.5}$$

global Schmidt law

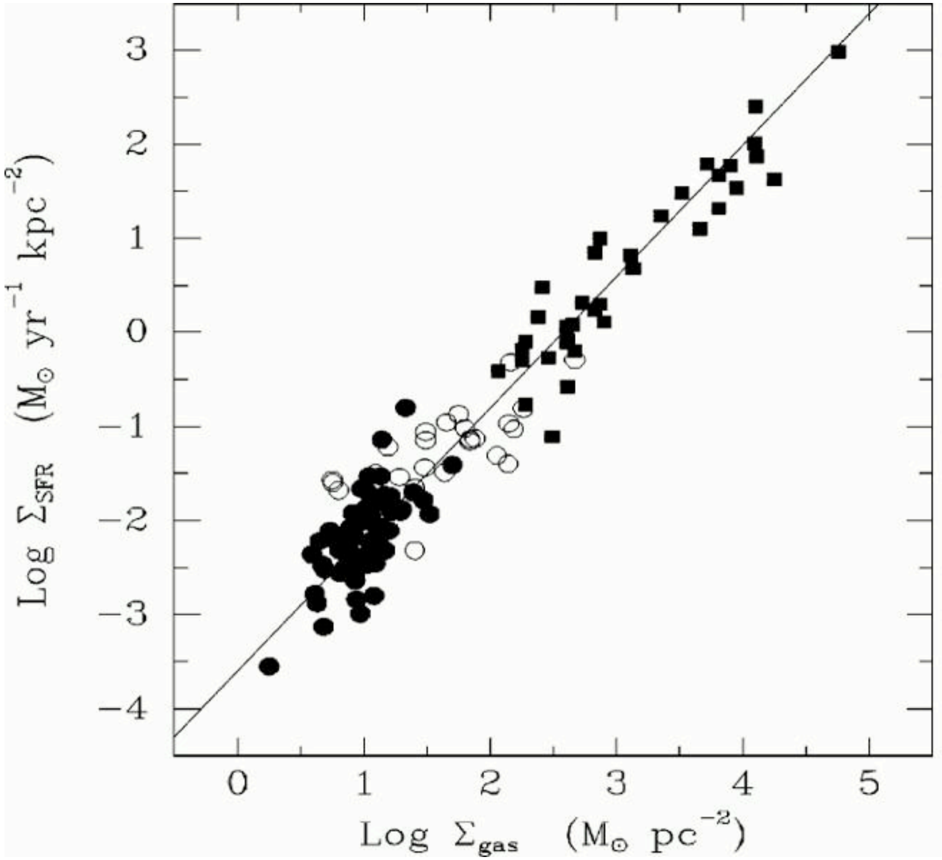
Observed Schmidt law

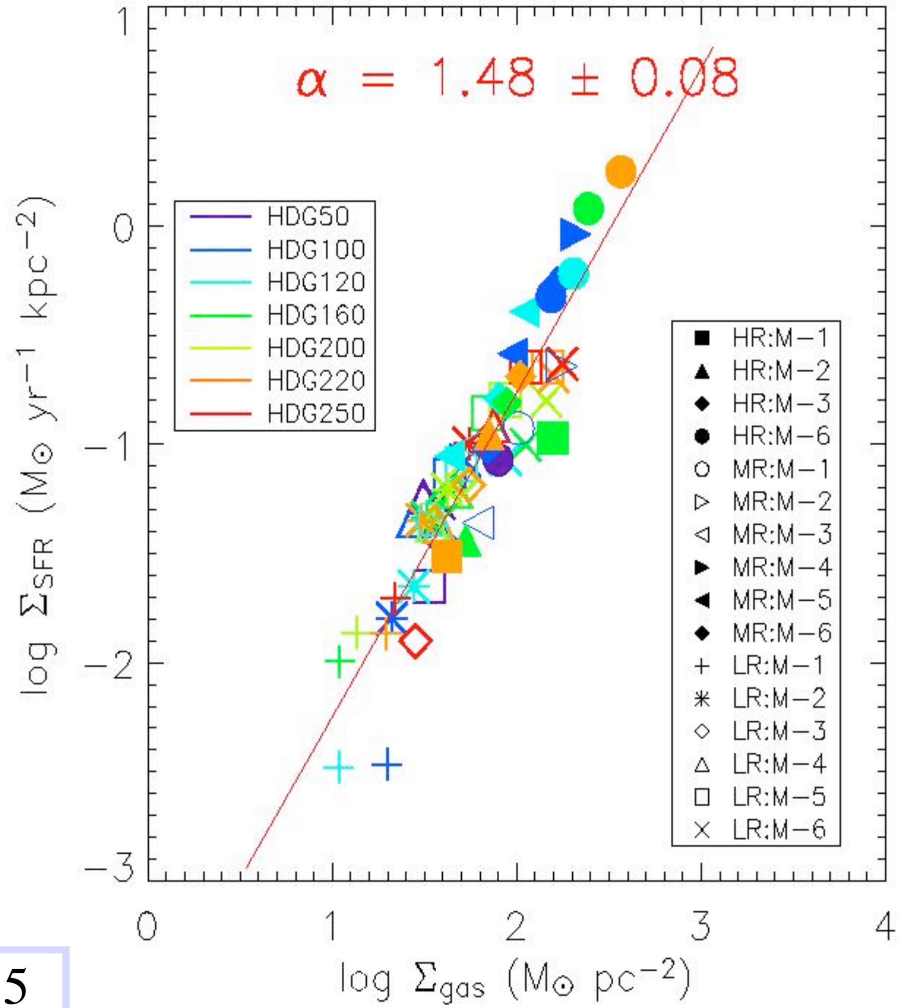


$$\Sigma_{SFR} = (2.5 \pm 0.7) \times 10^{-4} \left(\frac{\Sigma_{gas}}{1\ M_\odot\ \mathrm{pc}^{-2}} \right)^{1.4\pm0.15} M_\odot\ \mathrm{year}^{-1}\,\mathrm{kpc}^{-2},$$

(from Kennicutt 1998)

Observed Schmidt law





in both cases: $\Sigma_{SFR} \propto \Sigma_{gas}^{1.5}$

(from Kennicutt 1998)

Summary

Summary

- 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
  - microturbulent approach is *not valid* in astrophysics

Summary

- *Gravoturbulent star formation* can explain
  - structure and evolution of molecular clouds (structure functions, pdf's, Δ-variance, PCA,…)
  - chemical mixing properties of the ISM
  - timescale and efficiency of star formation in molecular clouds and on galactic scales
  - structure and evolution of pre- and protostellar cores
  - protostellar accretion rates
  - binary properties and frequencies

Summary

- *Gravoturbulent star formation* can explain
  - the *IMF:*
    - turbulence together with EOS determines density structure
    - gravity then selects fluctuations to collapse → *characteristic mass*
    - this interplay determines *PEAK* and *WIDTH* of IMF

Summary: theory of SF

- *Gravoturbulent star formation* can explain
  - Gravity overwhelms turbulence: *Star burst*
    (maybe triggered by interaction or global instability)
  - "Normal" *spiral galaxy:* approximate support by ISM turbulence, only local collapse
    (with intemediate to low SF rate)
  - *LSB galaxy:* strong turbulent support
    (turbulence generated by MRI or gas infall?)

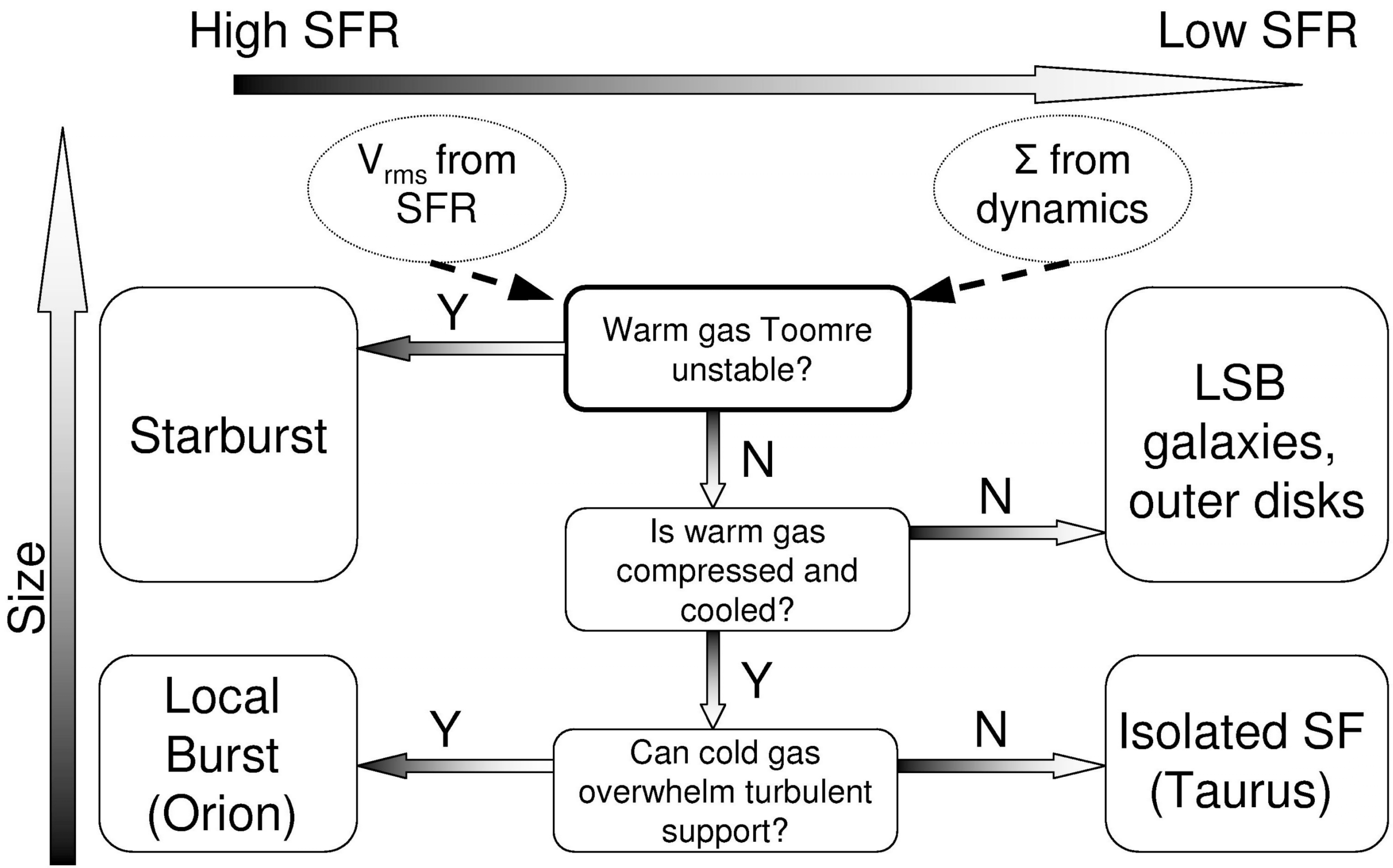
(from Mc Low & Klessen, 2004, Rev. Mod. Phys., 76, 125 - 194)

Open questions

- What's next?
  - Understand *protostellar feedback*…
  - Understand *what drives turbulence*…
    (and on what scales)
  - Understand *relation* between *large-scale dynamics* in the galaxy and *local build-up of stars*…
  - Understand *variations* of star formation with environemental conditions…
    (e.g. Pop III stars, star burst galaxies, etc.)
  - Understand *planet formation* in turbulent cloud context…

Thanks!

Summary



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

Literature

- Quasi-static “standard theory” of SF:
  - Shu, Adams, & Lizano (1986, ARAA)
- Dynamical gravoturbulent theory:
  - Larson (2003, Prog. Rep. Phys.)
  - Mac Low & Klessen (2004, Rev. Mod. Phys.)
  - Elmegreen & Scalo (2005, ARAA)
  - Scalo & Elmegreen (2005, ARAA)