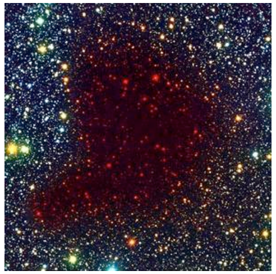
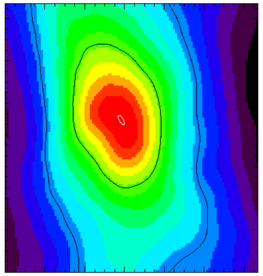
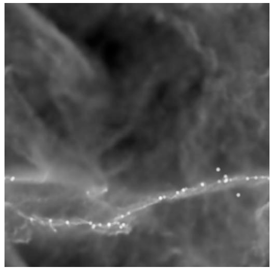
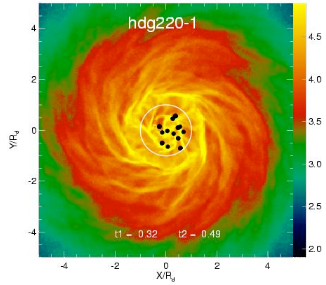
ISM Turbulence





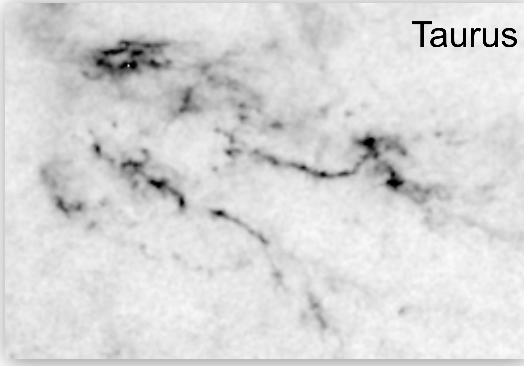
Ralf Klessen

Zentrum für Astronomie der Universität Heidelberg
Institut für Theoretische Astrophysik

Deutsche Forschungsgemeinschaft DFG
Emmy Noether-Programm
ASTRONET
LANDESSTIFTUNG Baden-Württemberg
HGSFP
IMPRS

Agenda

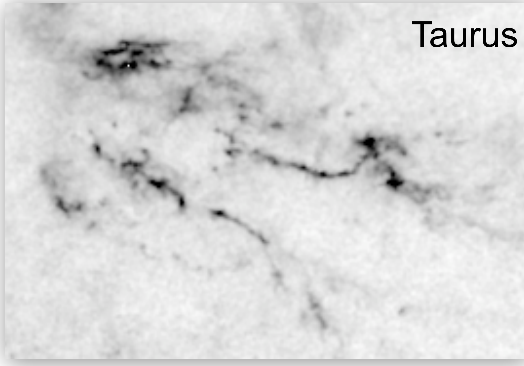
- some phenomenology
  - turbulence in the ISM
- a simple cartoon picture
  - relation between ISM turbulence and star formation
- some basic thoughts
  - accretion driven turbulence
  - the stellar mass function
  - formation first (strong) magnetic fields in the universe
  - mixing in supersonic turbulence
- summary



Interstellar Matter: ISM

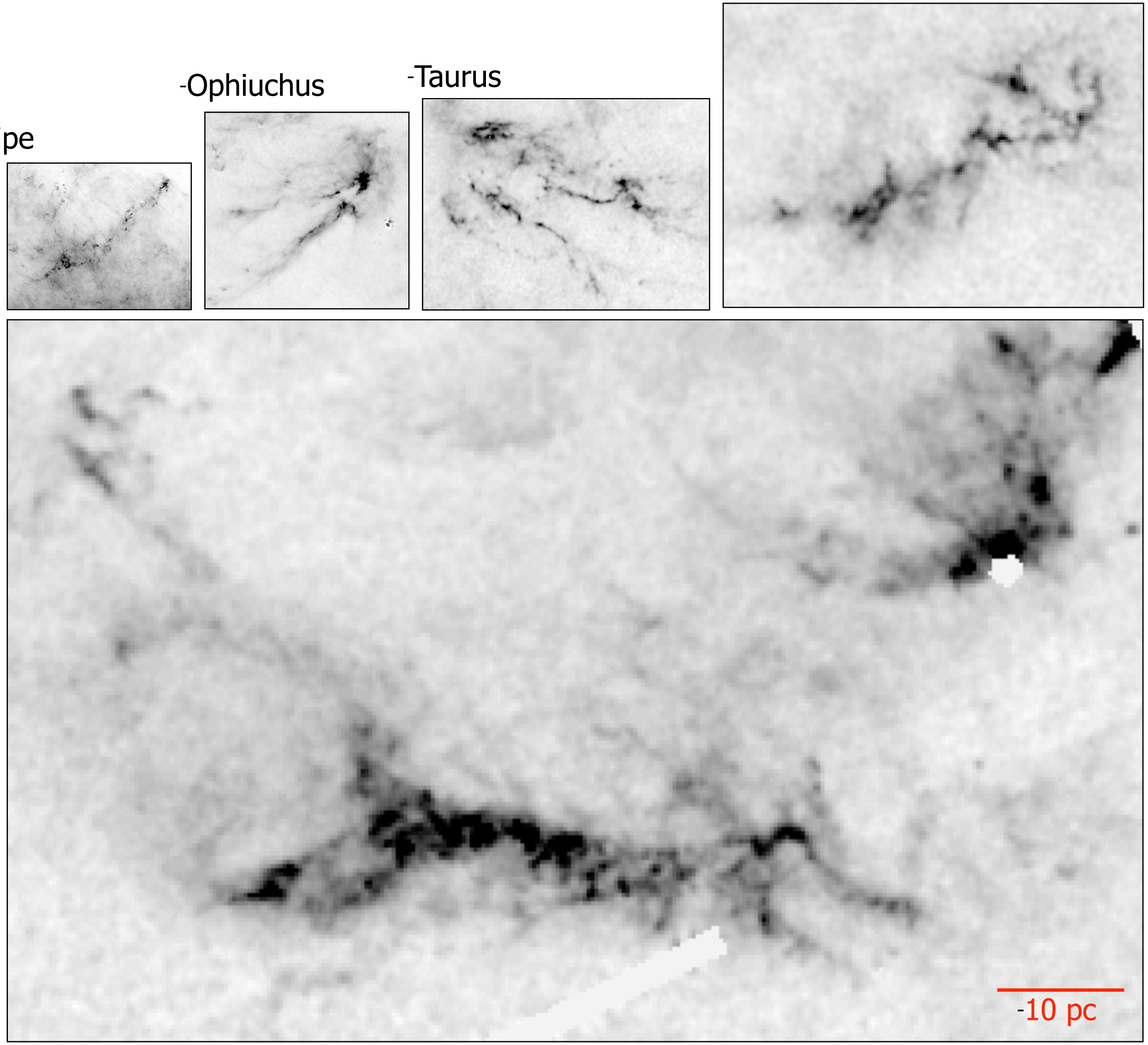
Abundances, scaled to 1.000.000 H atoms

element		atomic number	abundance
hydrogen	H	1	1.000.000
deuterium	${}_1H^2$	1	16
helium	He	2	68.000
carbon	C	6	420
nitrogen	N	7	90
oxygen	O	8	700
neon	Ne	10	100
sodium	Na	11	2
magnesium	Mg	12	40
aluminium	Al	13	3
silicium	Si	14	38
sulfur	S	16	20
calcium	Ca	20	2
iron	Fe	26	34
nickel	Ni	28	2

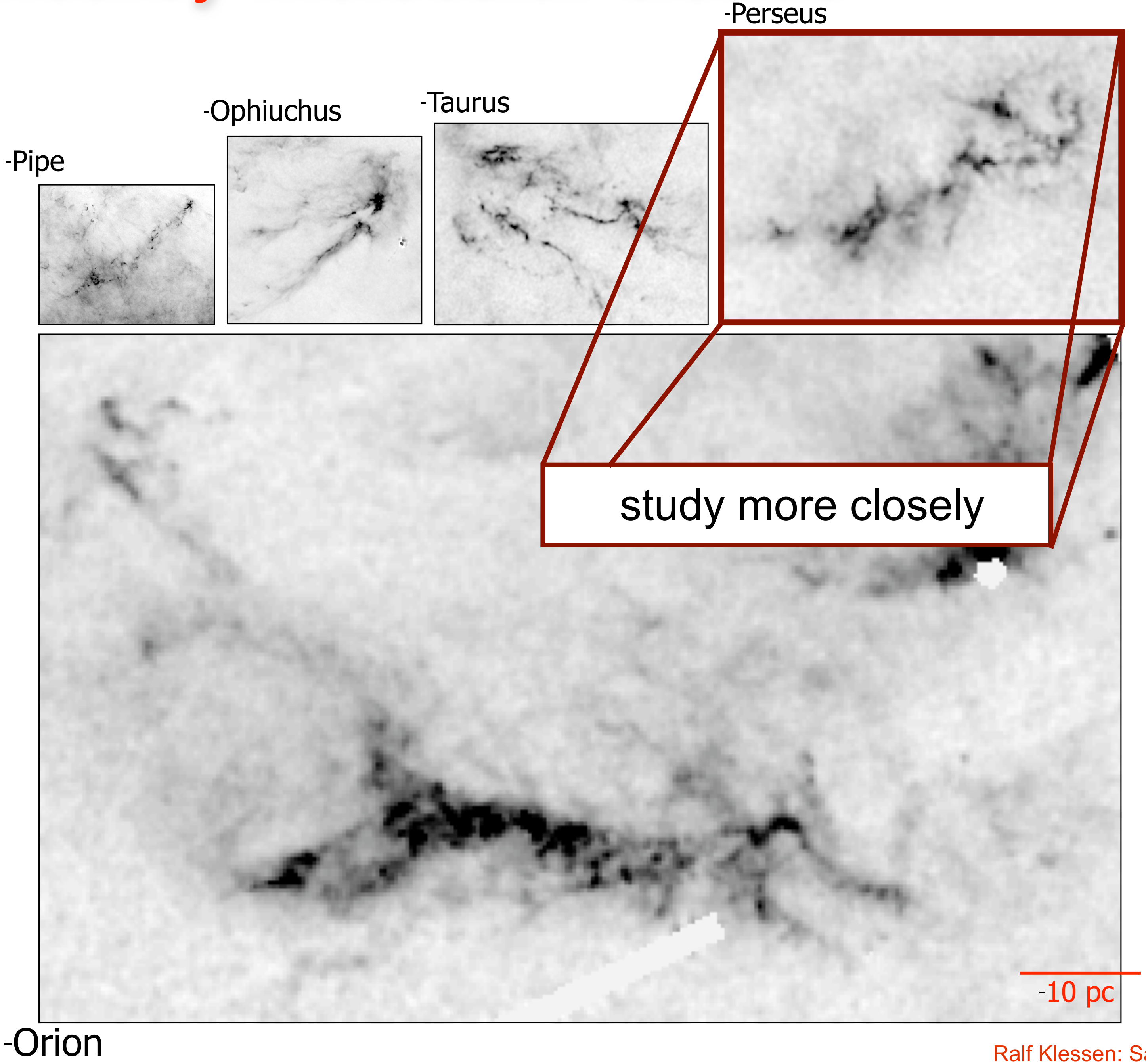


hydrogen is by far the most abundant element (more than 90% in number).

nearby molecular clouds



nearby molecular clouds



scales to same scale

(from A. Goodman)

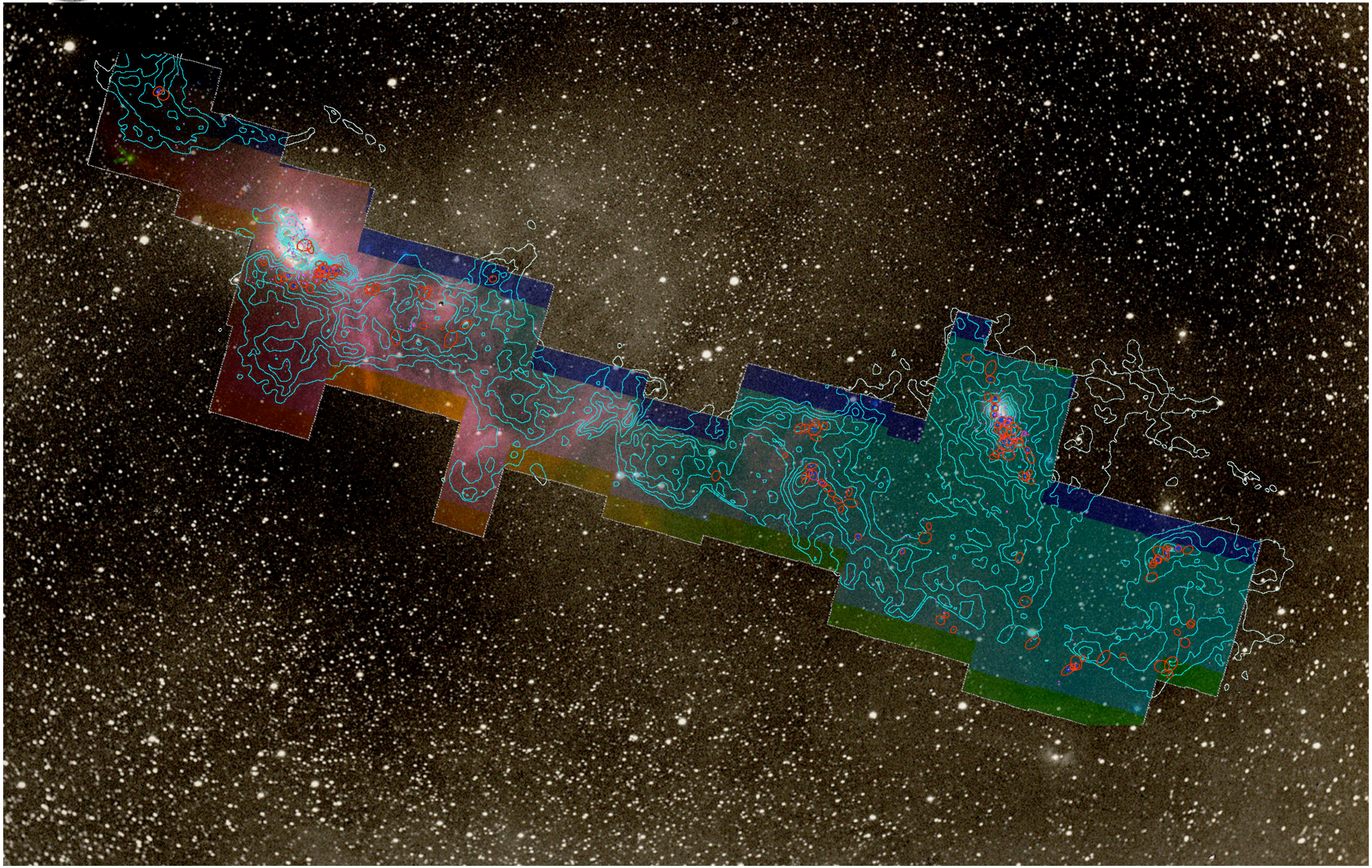
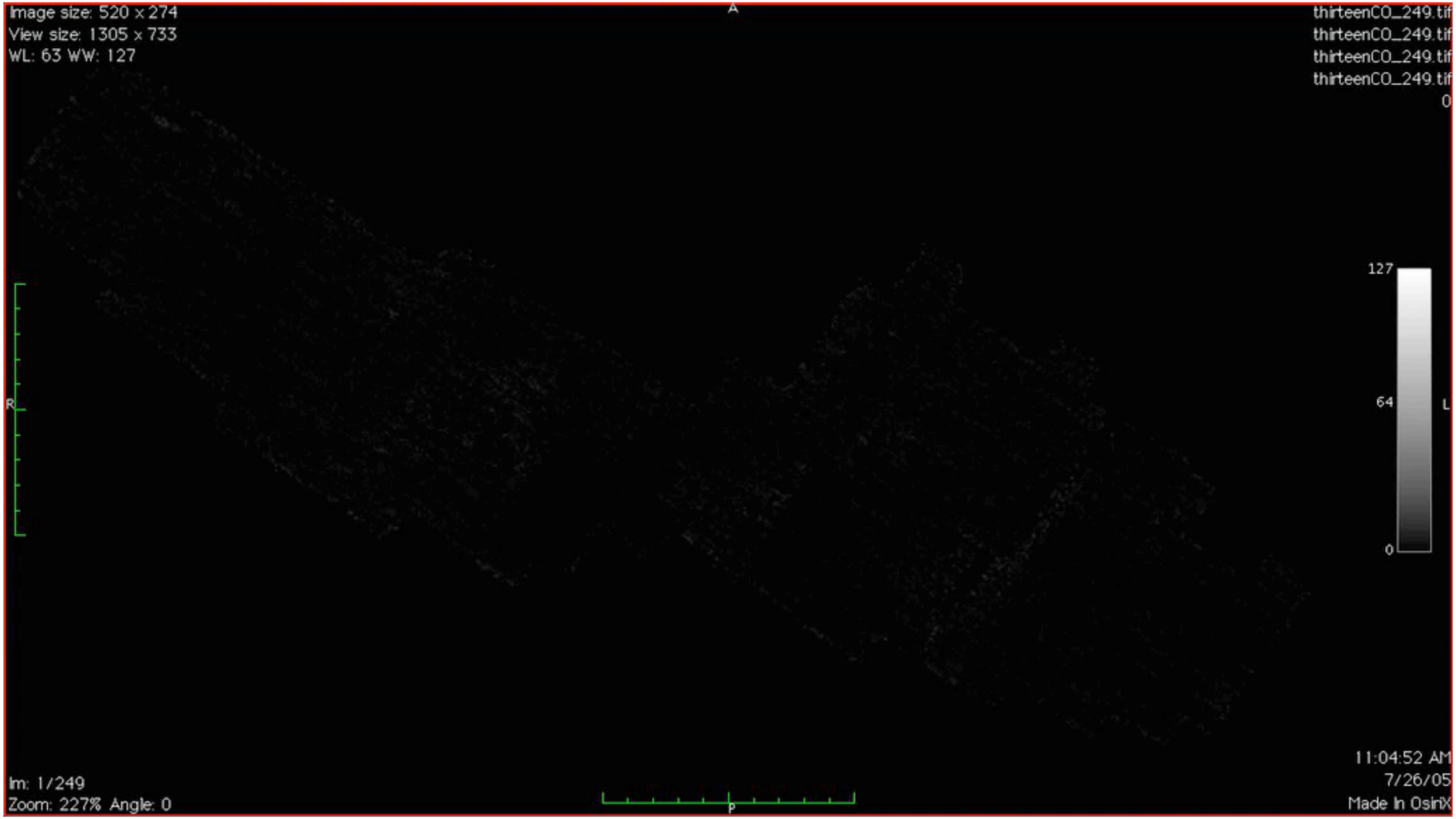


image from Alyssa Goodman: COMPLETE survey



velocity distribution in Perseus

velocity cube from Alyssa Goodman: COMPLETE survey

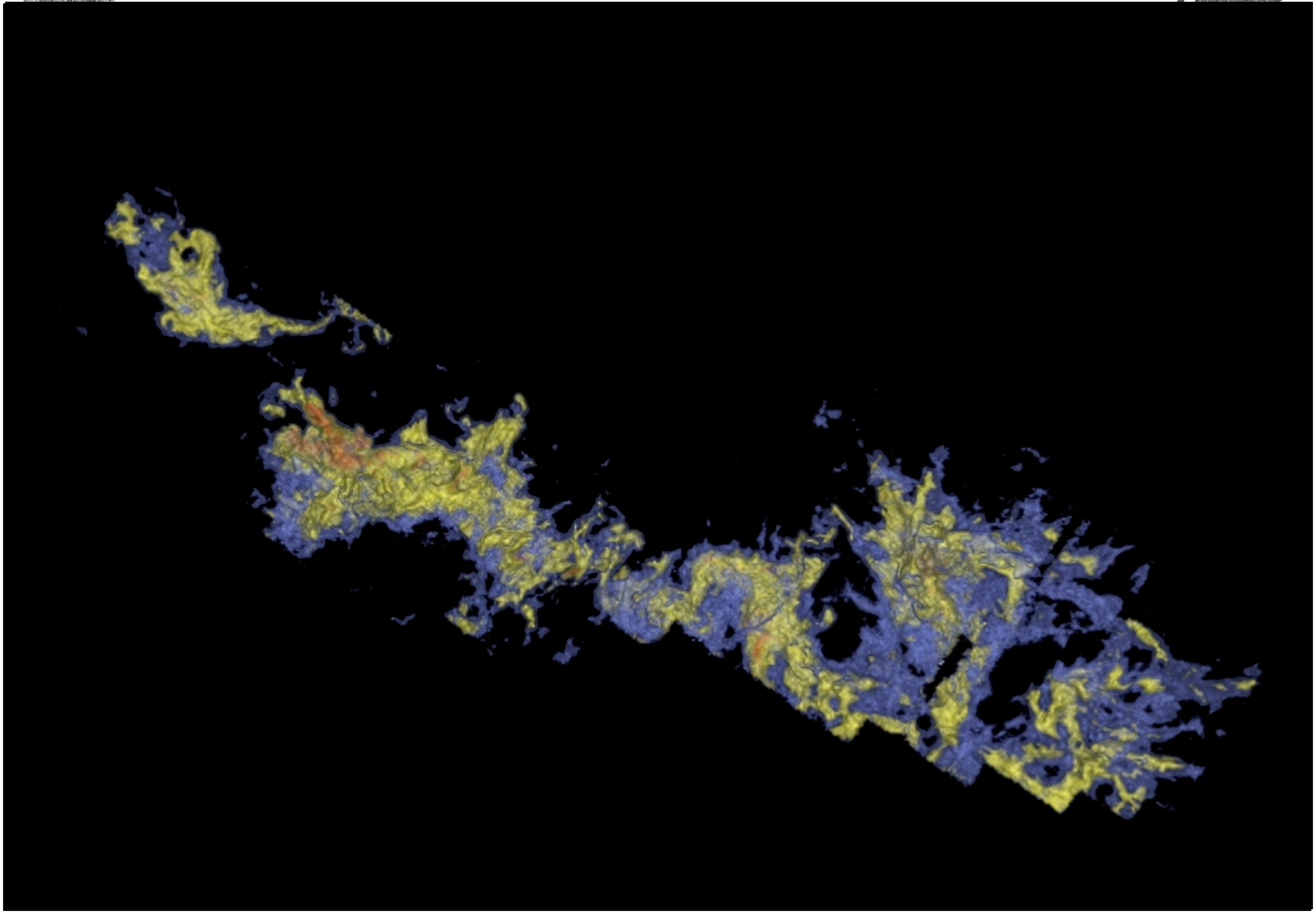
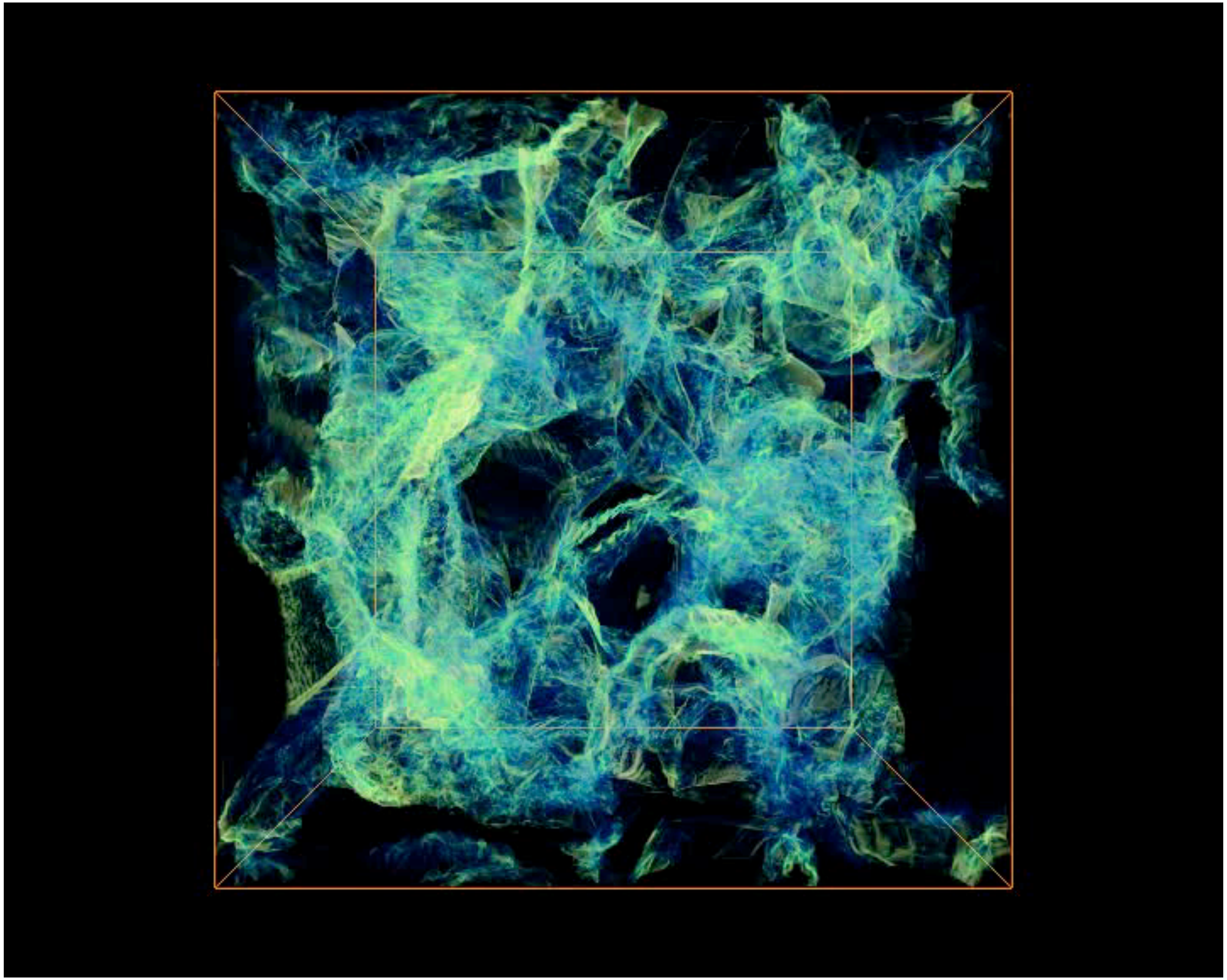


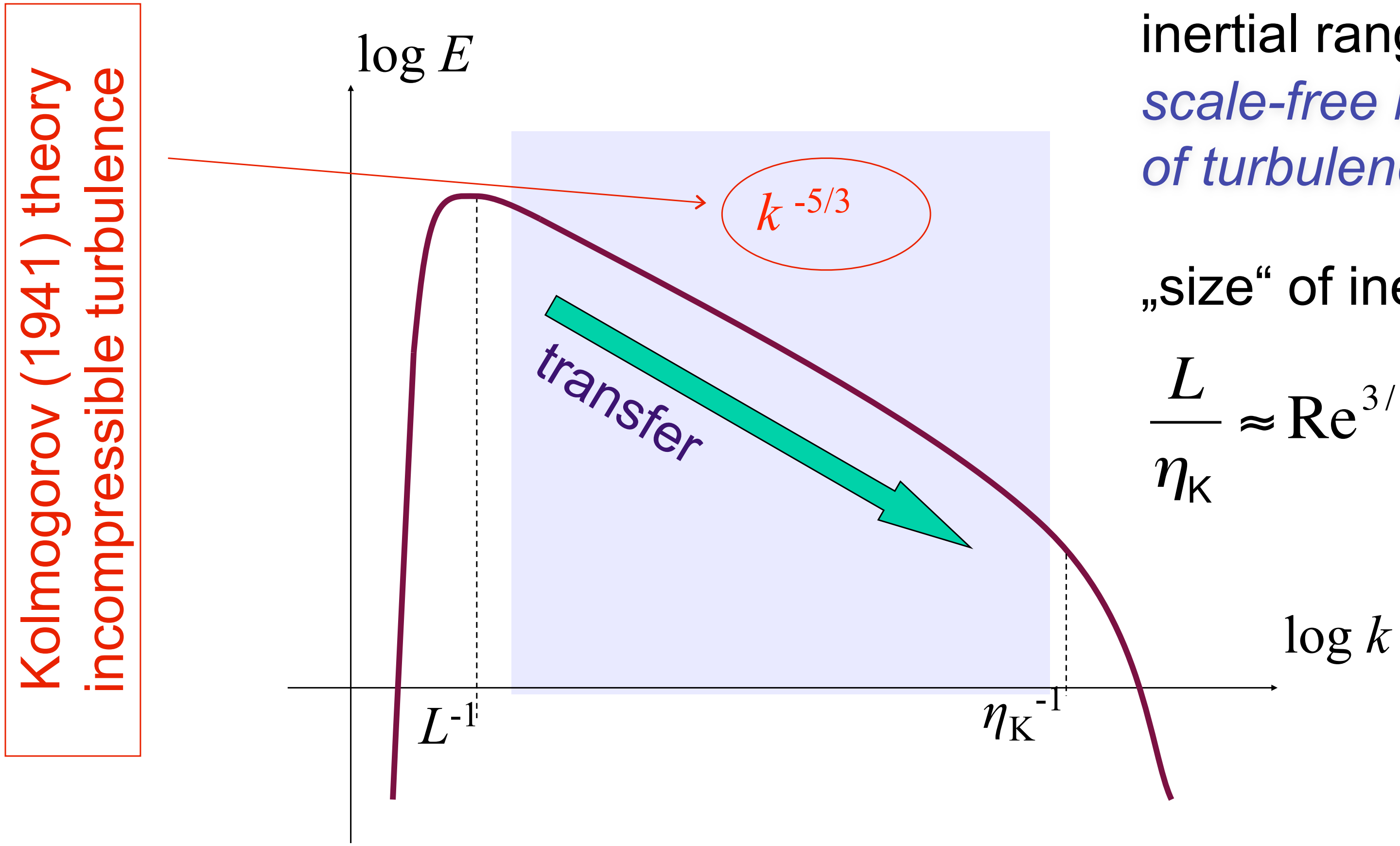
image from Alyssa Goodman: COMPLETE survey



(movie from Christoph Federrath)

turbulence

Turbulent cascade



energy input scale

energy dissipation scale

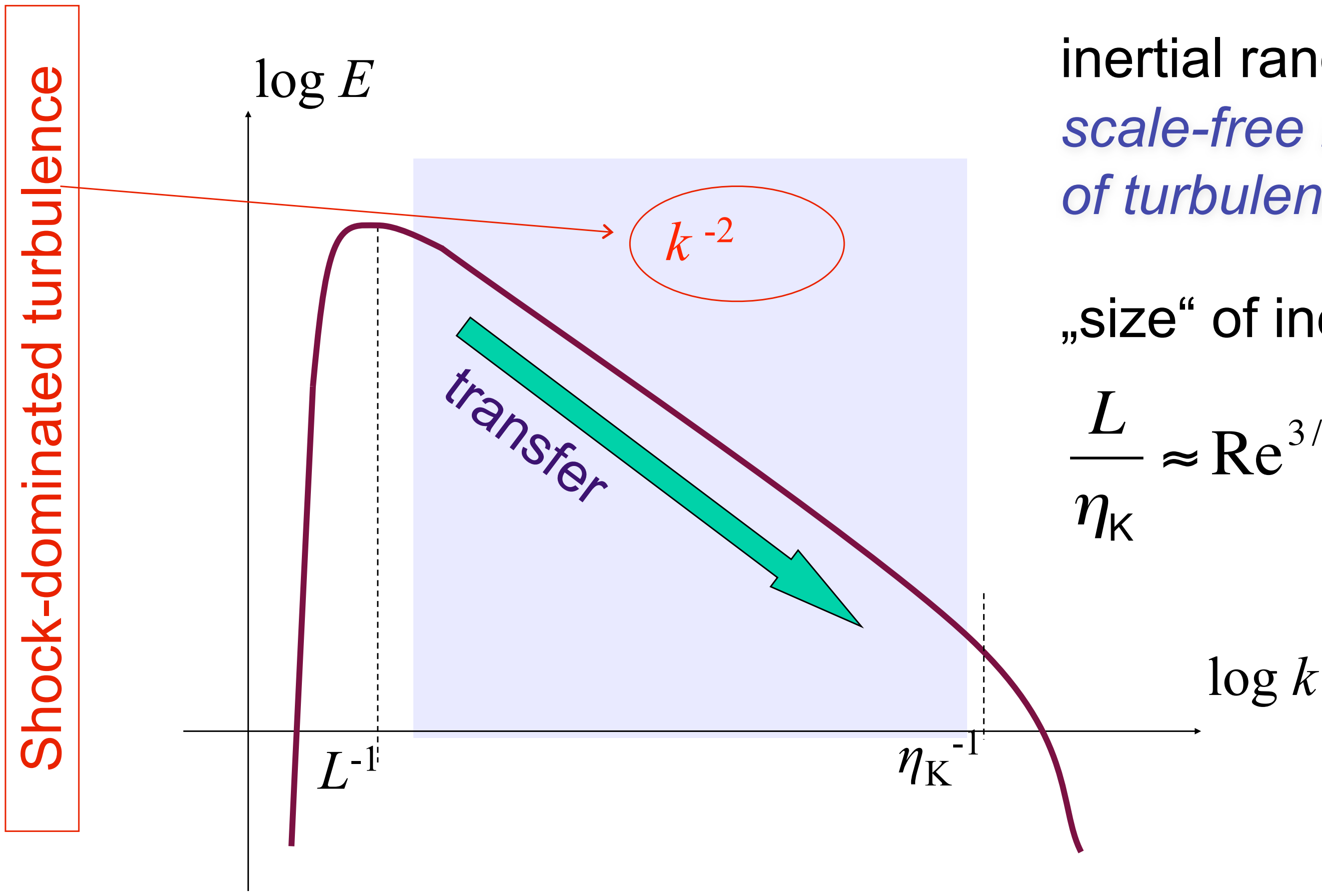
inertial range:

scale-free behavior of turbulence

„size“ of inertial range:

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

Turbulent cascade



energy
input
scale

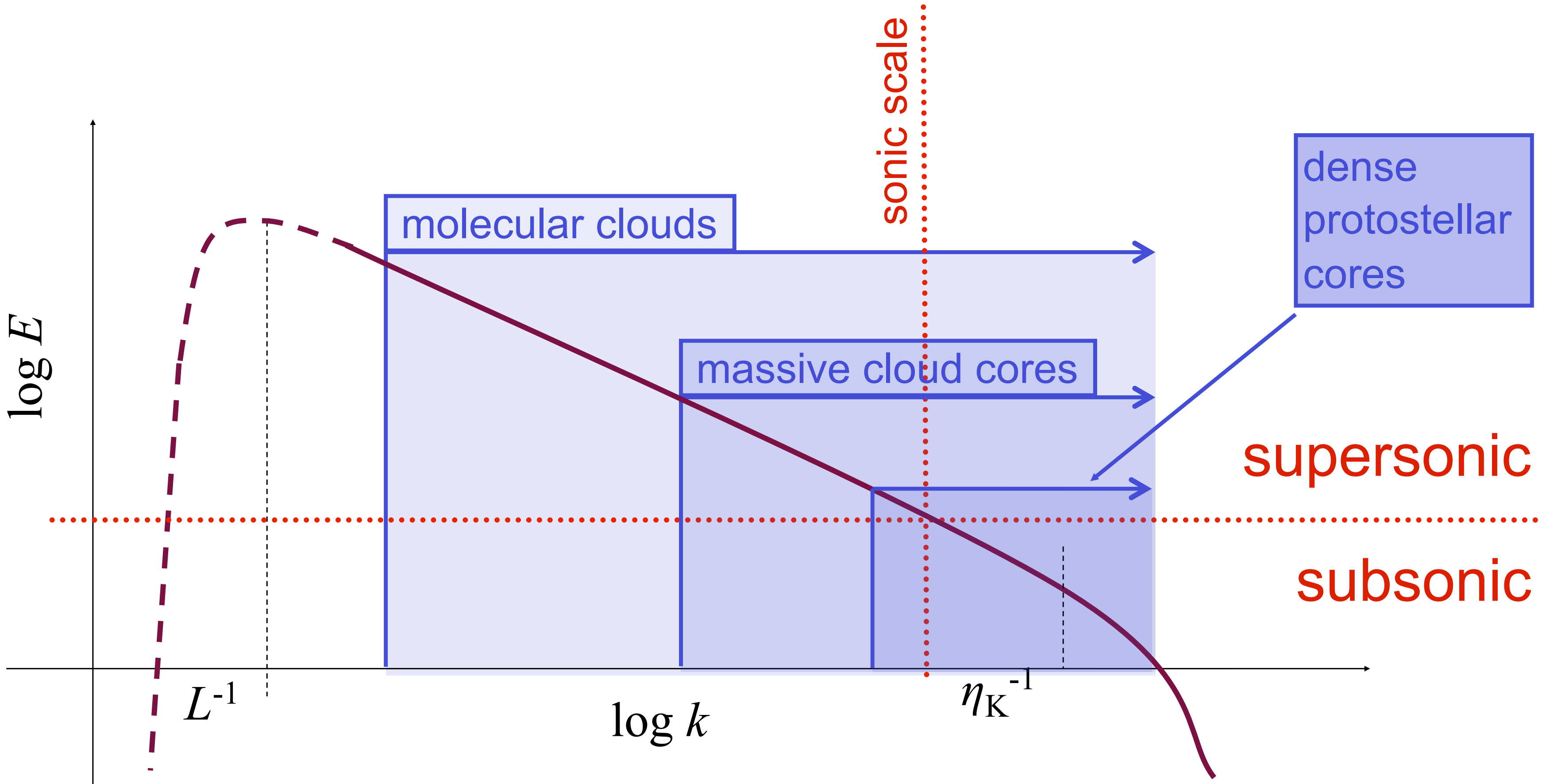
energy
dissipation
scale

inertial range:
scale-free behavior of turbulence

„size“ of inertial range:

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

Turbulent cascade in ISM



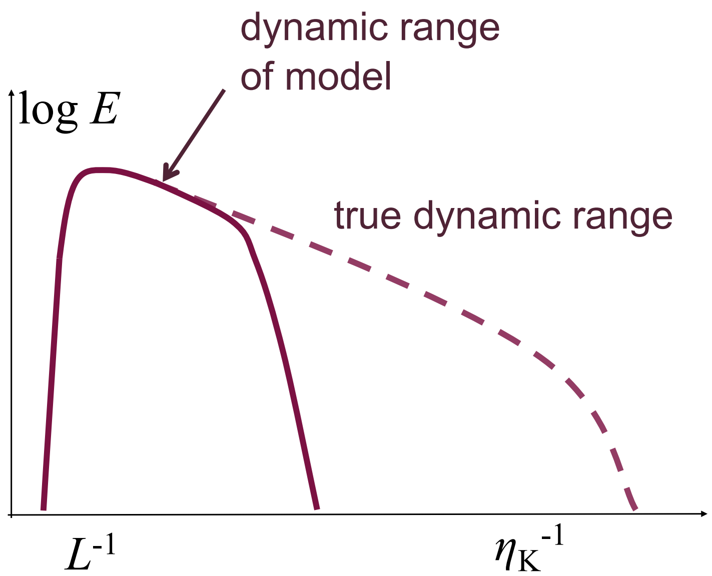
energy source & scale
NOT known
(supernovae, winds,
spiral density waves?)

σ_{rms} << 1 km/s
$M_{rms} \leq 1$
$L \approx 0.1$ pc

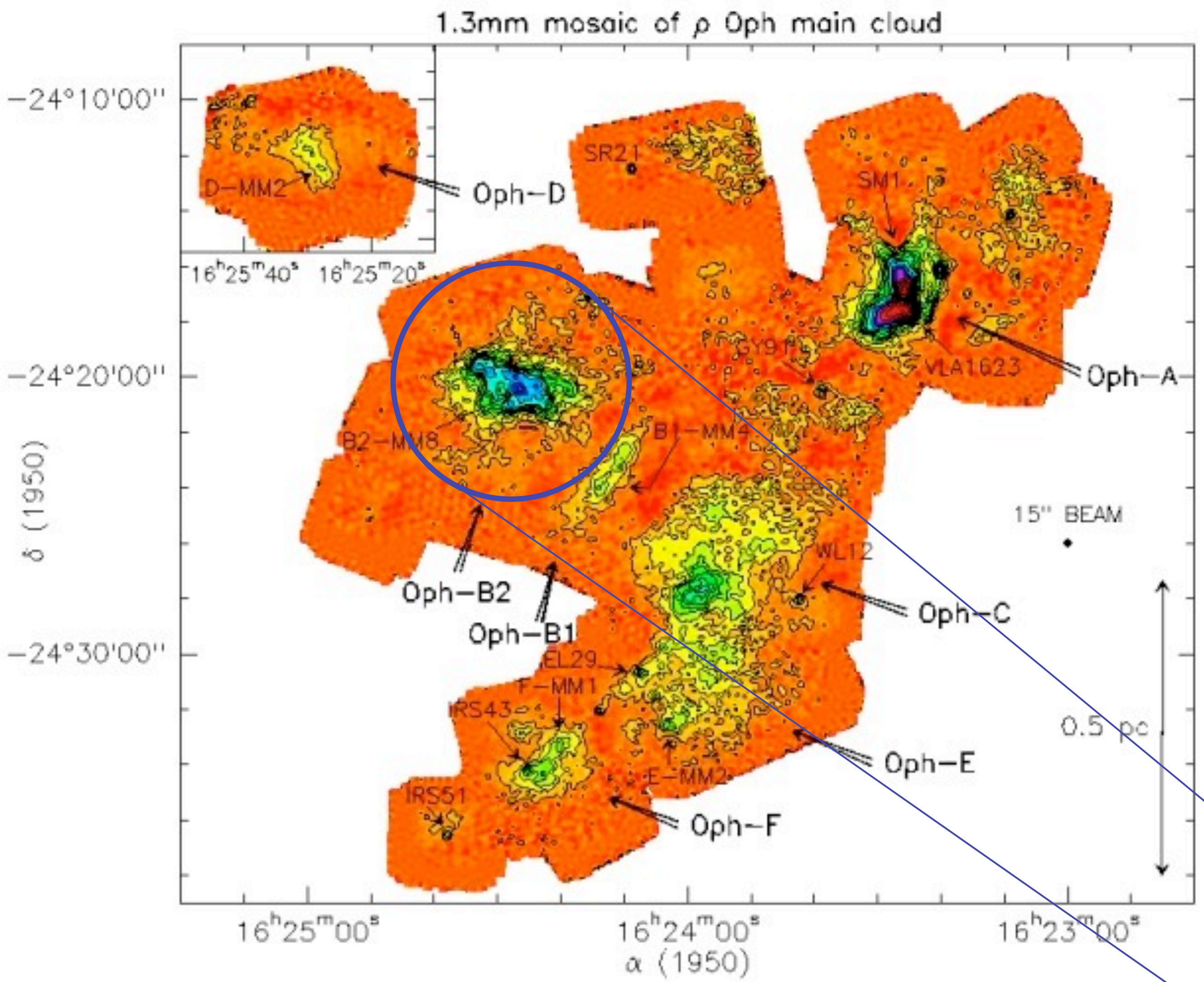
dissipation scale not known
(ambipolar diffusion,
molecular diffusion?)

Large-eddy simulations

- We use ***LES*** to model 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)
  - but what to do for more complex when processes on subgrid scale determine large-scale dynamics (chemical reactions, nuclear burning, etc)
  - Turbulence is "space filling" --> difficulty for AMR (don't know what criterion to use for refinement)
- How *large* a Reynolds number do we need to catch basic dynamics right?



Density structure of MC's



(Motte, André, & Neri 1998)

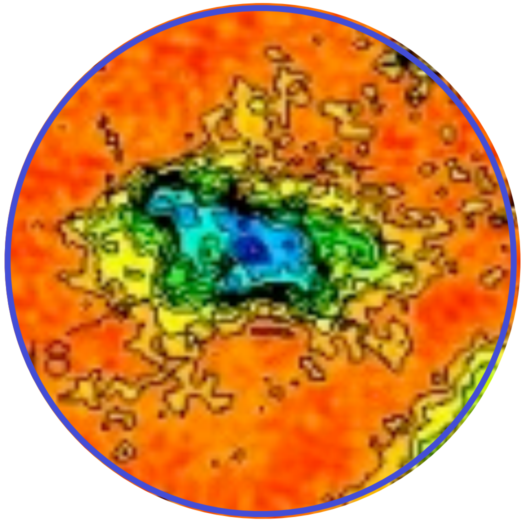
molecular clouds are highly inhomogeneous

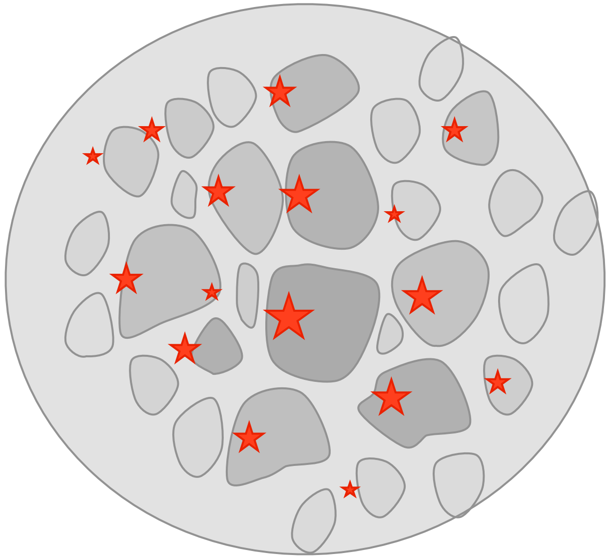
stars form in the densest and coldest parts of the cloud

ρ-Ophiuchus cloud seen in dust emission

let's focus on a cloud core like this one

Evolution of cloud cores





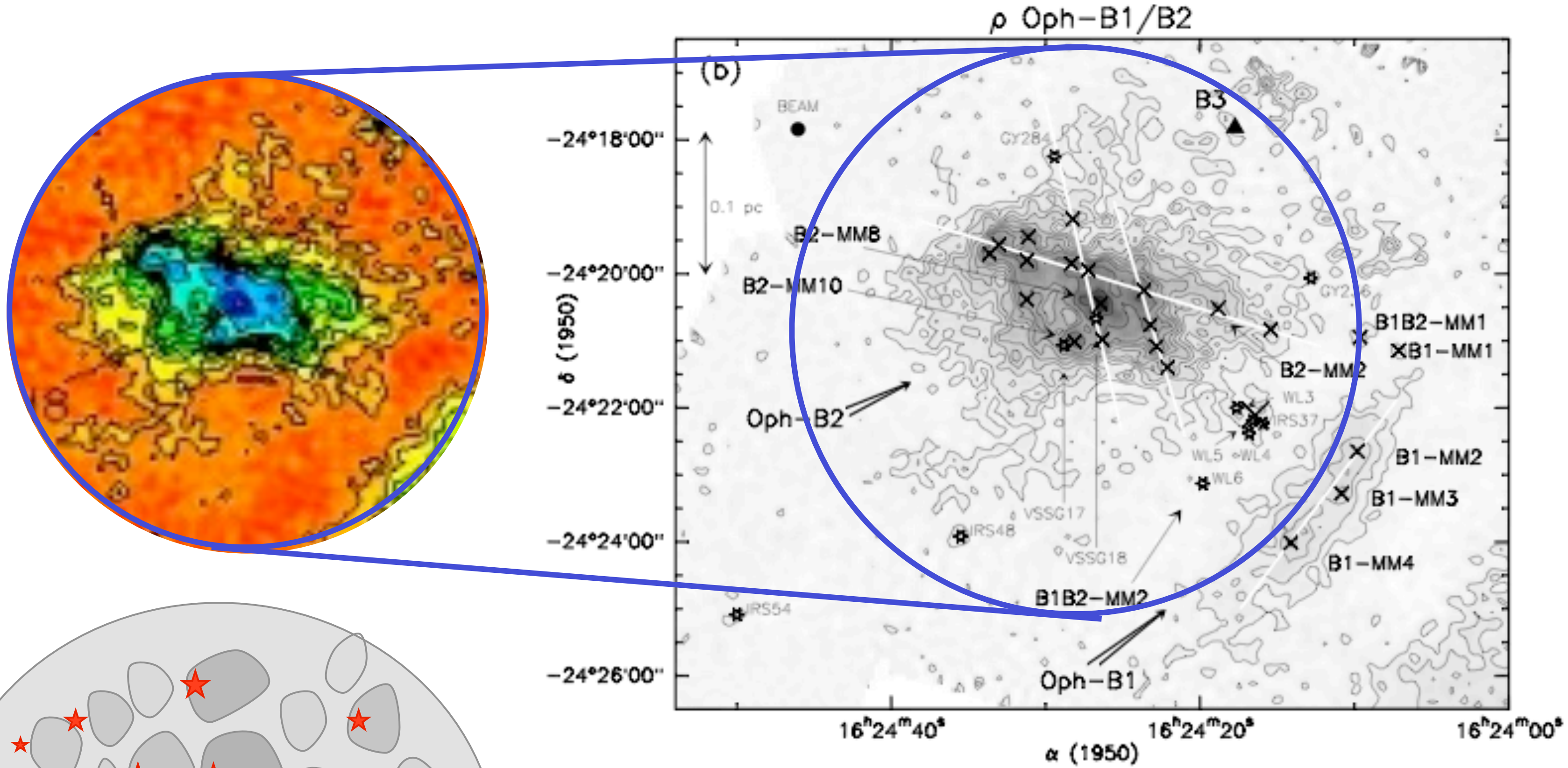
- How does this core evolve?
  Does it form one single massive star or cluster with mass distribution?

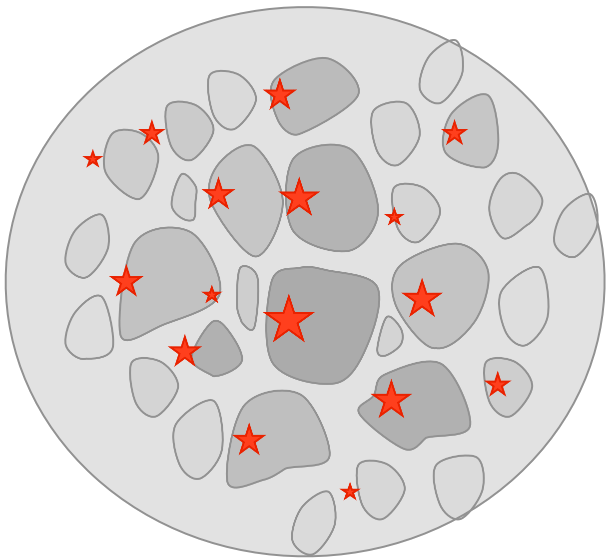
- Turbulent cascade „goes through“ cloud core
  --> NO *scale separation* possible
  --> NO *effective sound speed*
- Turbulence is supersonic!
  --> produces strong density contrasts:

  $$\delta\rho/\rho \approx \mathcal{M}^2$$

  --> with typical $\mathcal{M} \approx 10$ --> $\delta\rho/\rho \approx 100$!
- many of the shock-generated fluctuations are Jeans unstable and go into collapse
- --> expectation: *core breaks up and forms a cluster of stars*

Evolution of cloud cores



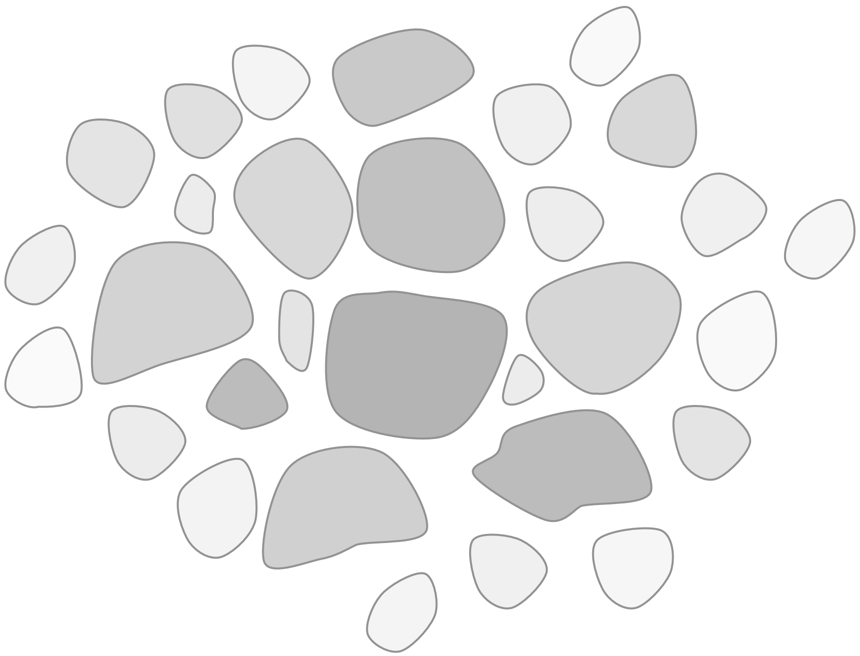


indeed ρ-Oph B1/2 contains several cores (“starless” cores are denoted by ×, cores with embedded protostars by ☆)

(Motte, André, & Neri 1998)

Formation and evolution of cores

What happens to distribution of cloud cores?



Two exteme cases:

(1) turbulence dominates energy budget:

$\alpha = E_{kin}/|E_{pot}| > 1$

--> individual cores do *not* interact

--> *collapse* of *individual* cores dominates *stellar mass growth*

--> *loose cluster of low-mass stars*

(2) turbulence decays, i.e. gravity dominates:

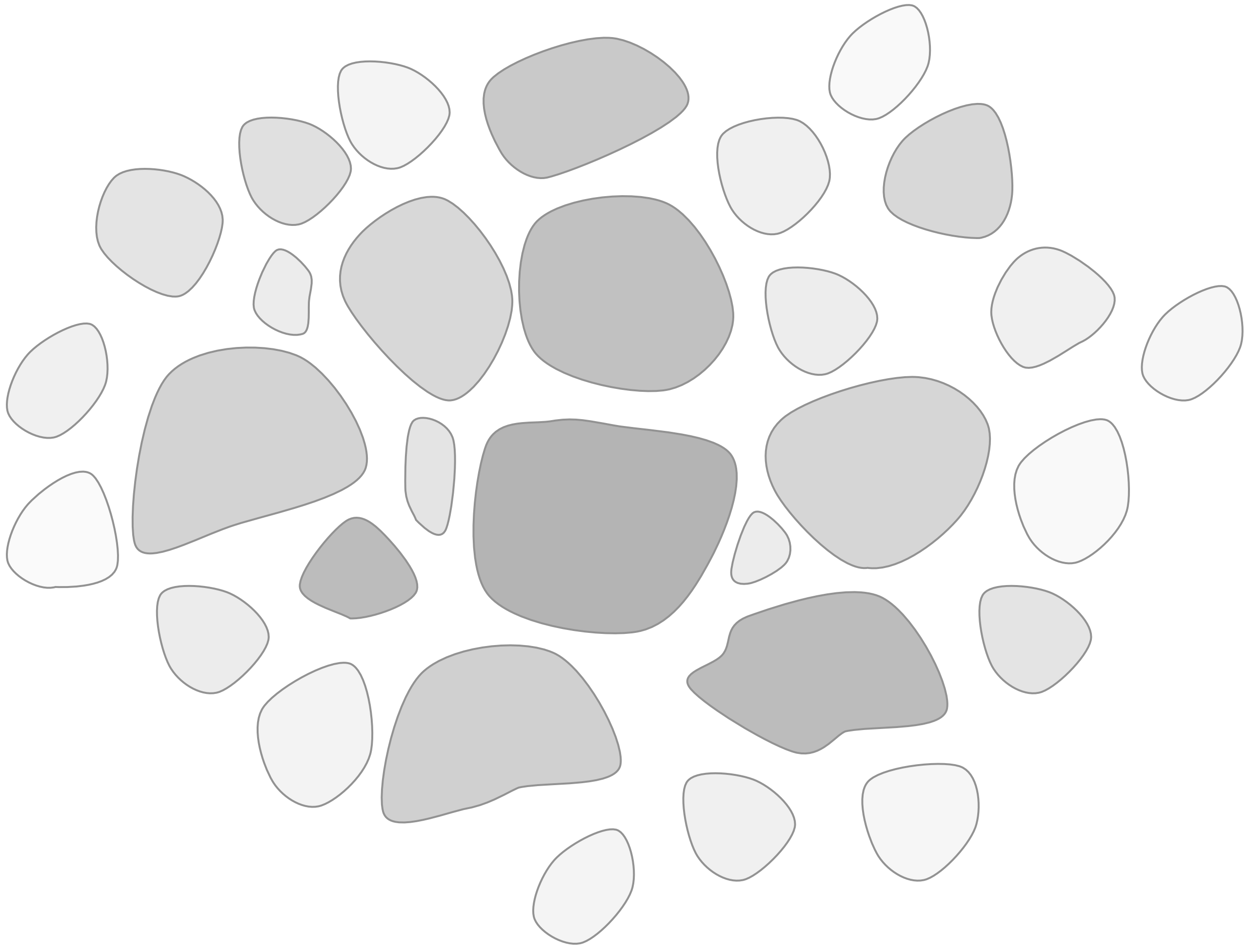
$\alpha = E_{kin}/|E_{pot}| < 1$

--> *global contraction*

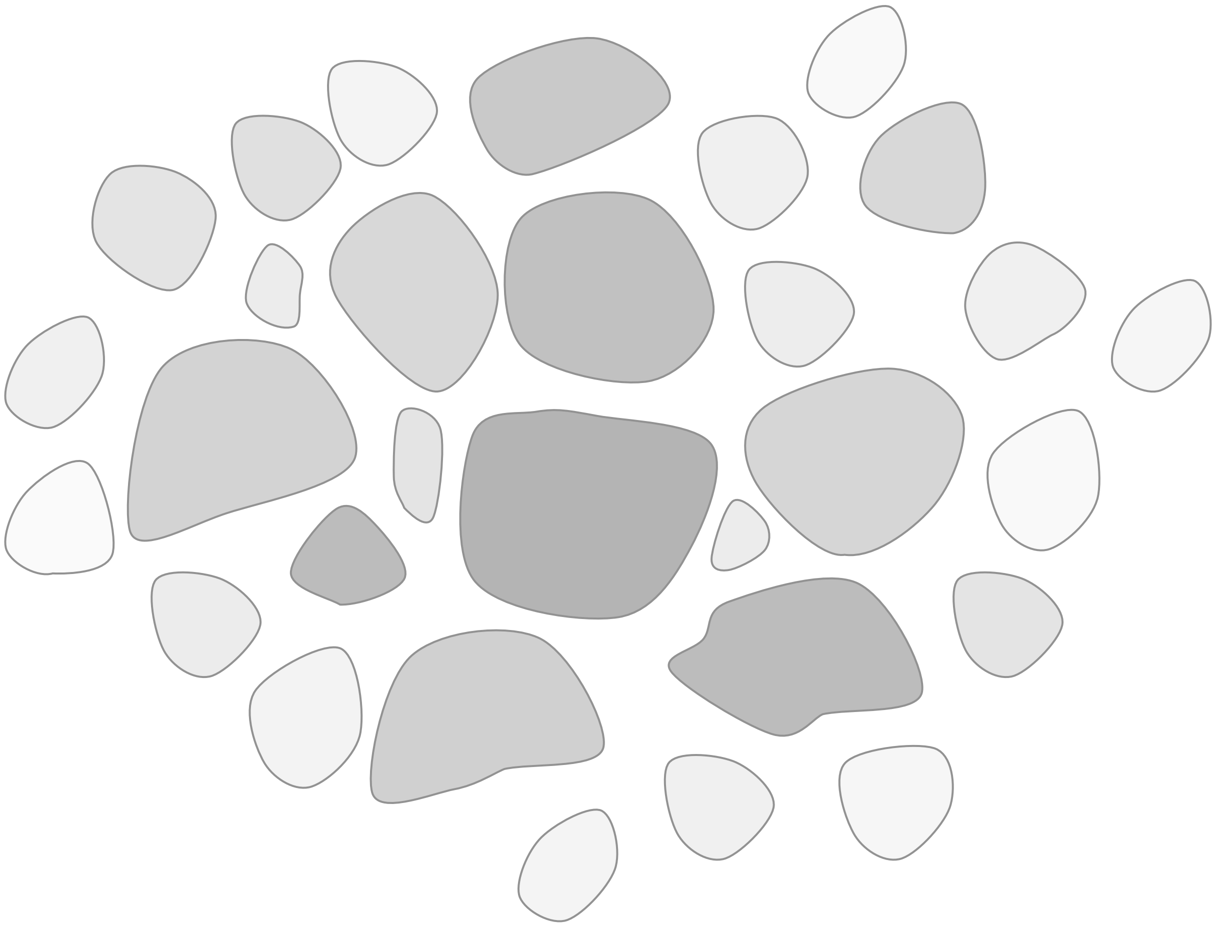
--> core do *interact* while collapsing

--> *competition* influences *mass growth*

--> *dense cluster with high-mass stars*

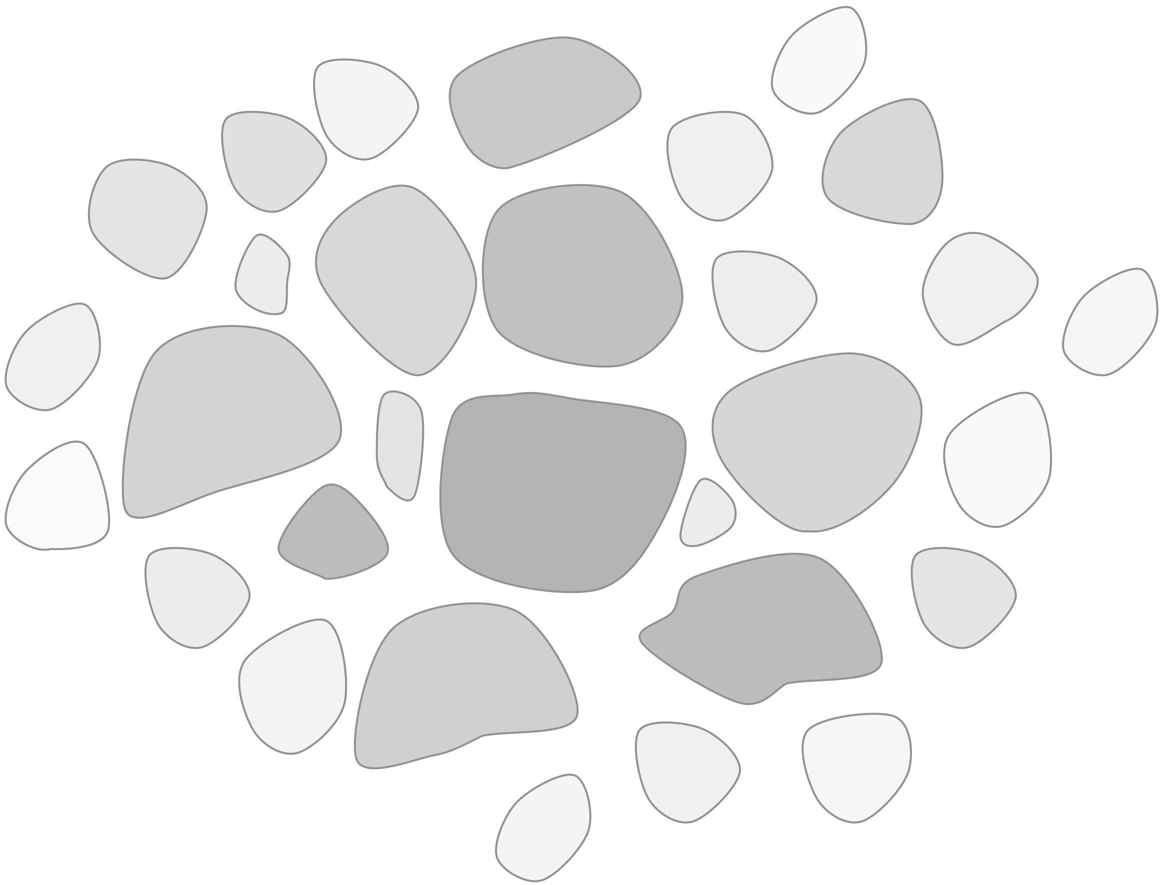


turbulence creates a hierarchy of clumps



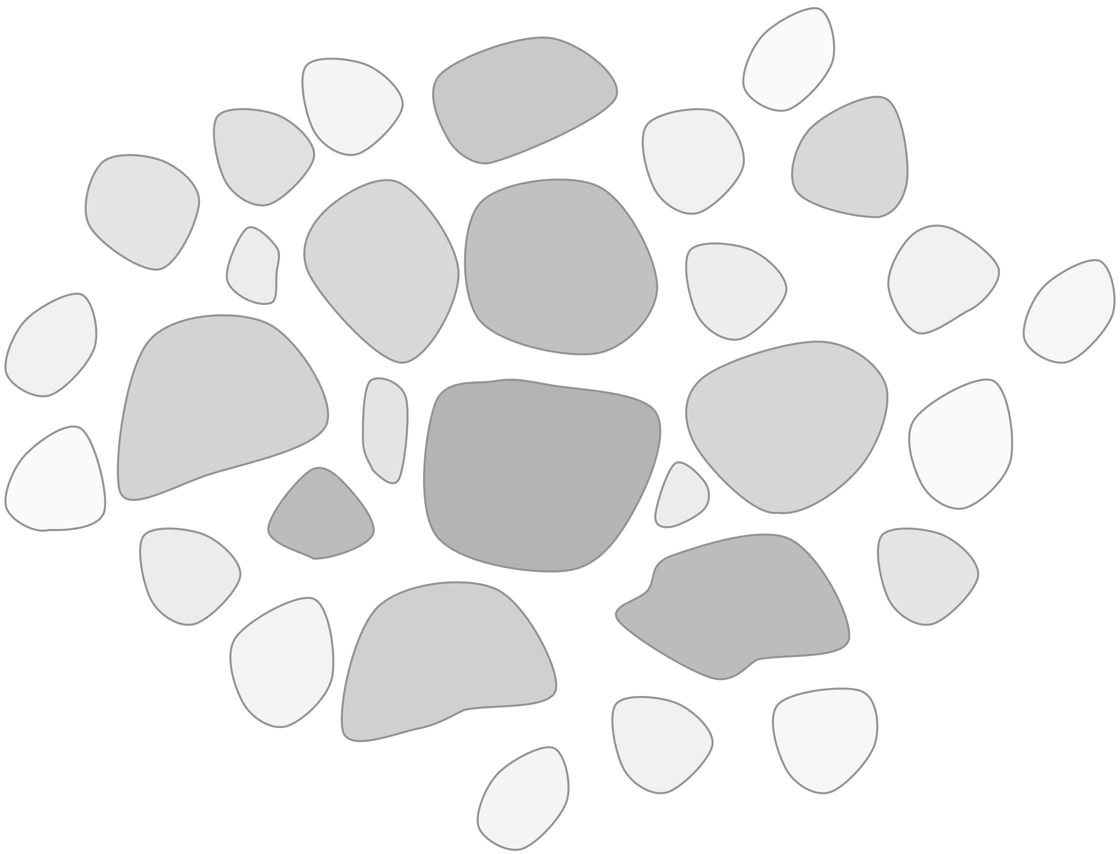
as turbulence decays locally, contraction sets in

Ralf Klessen: Santa Cruz, July 9.2010



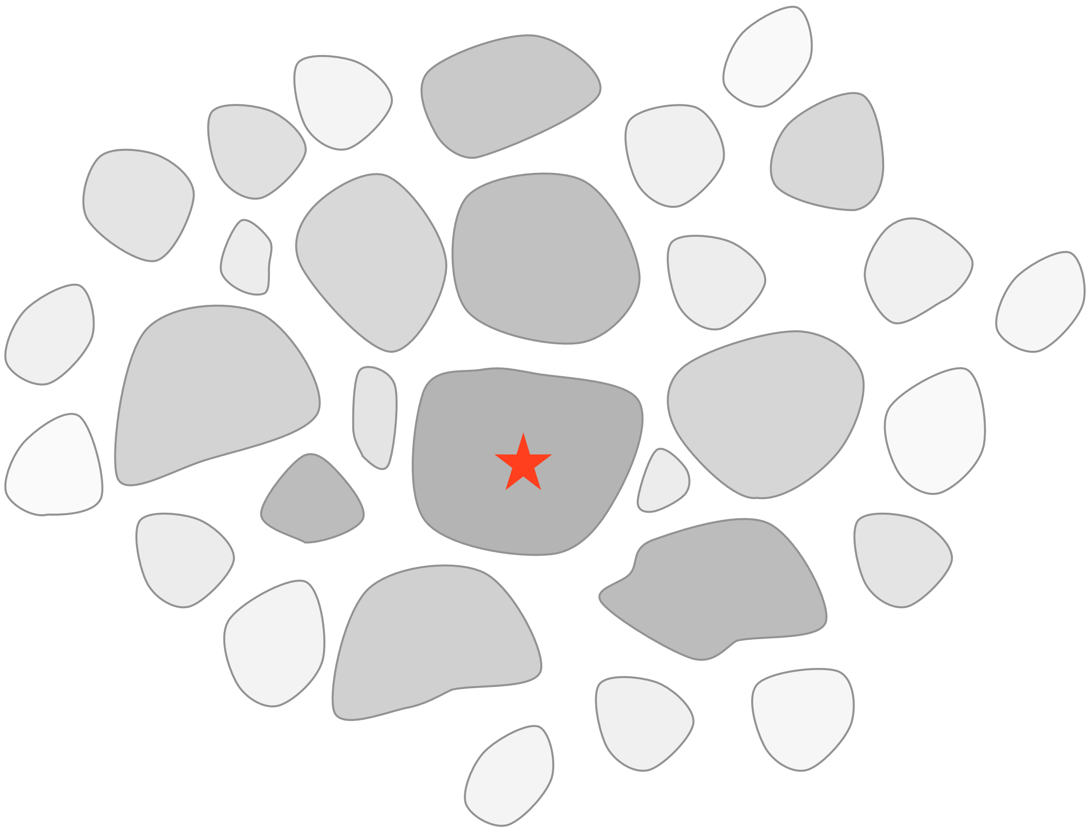
as turbulence decays locally, contraction sets in

Ralf Klessen: Santa Cruz, July 9.2010



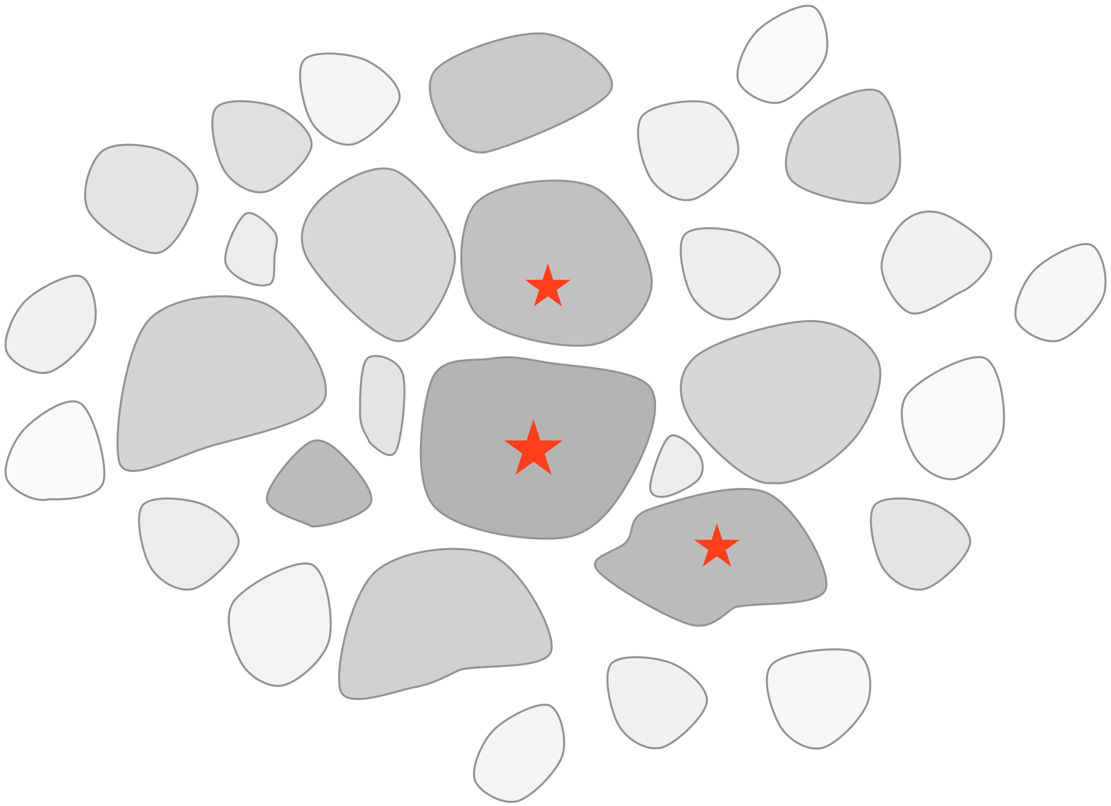
while region contracts, individual clumps collapse to form stars

Ralf Klessen: Santa Cruz, July 9.2010



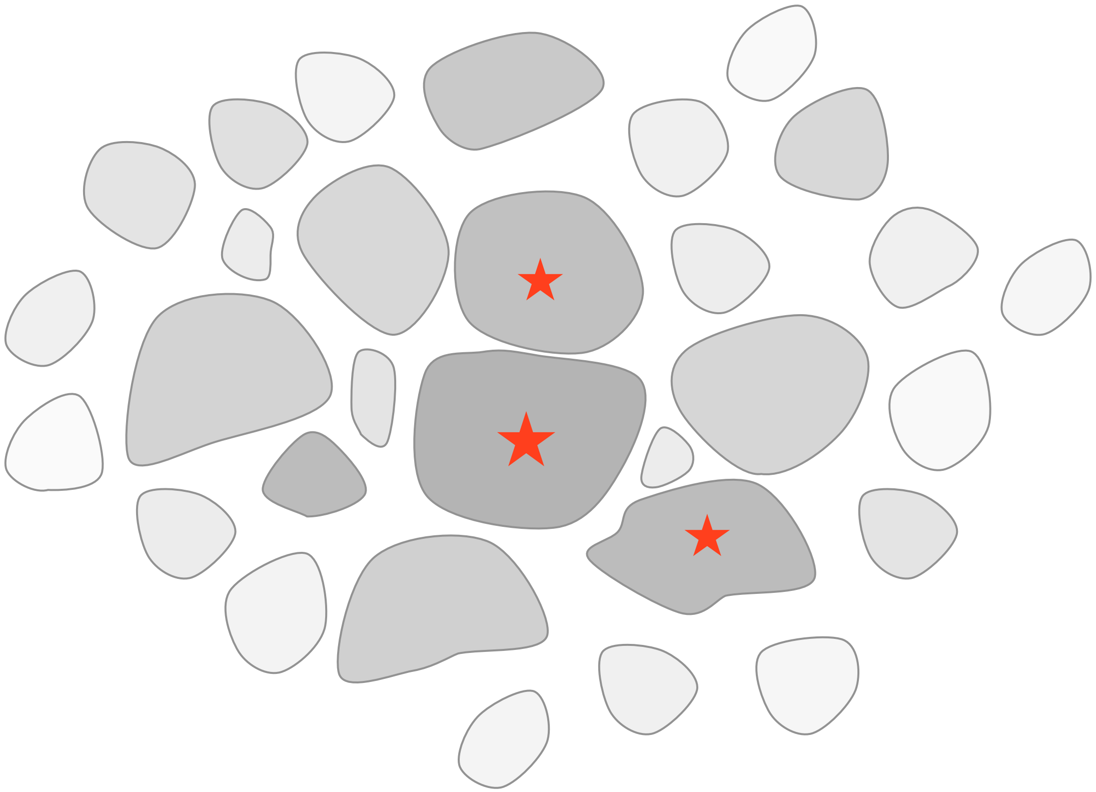
while region contracts, individual clumps collapse to form stars

Ralf Klessen: Santa Cruz, July 9.2010

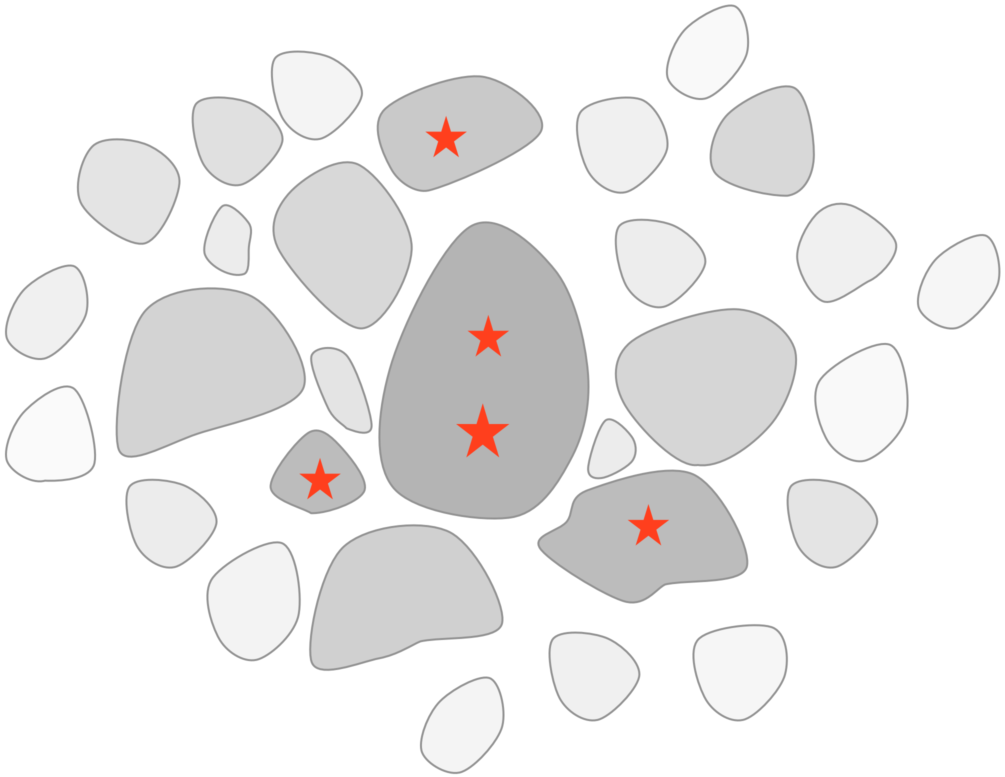


individual clumps collapse to form stars

Ralf Klessen: Santa Cruz, July 9.2010

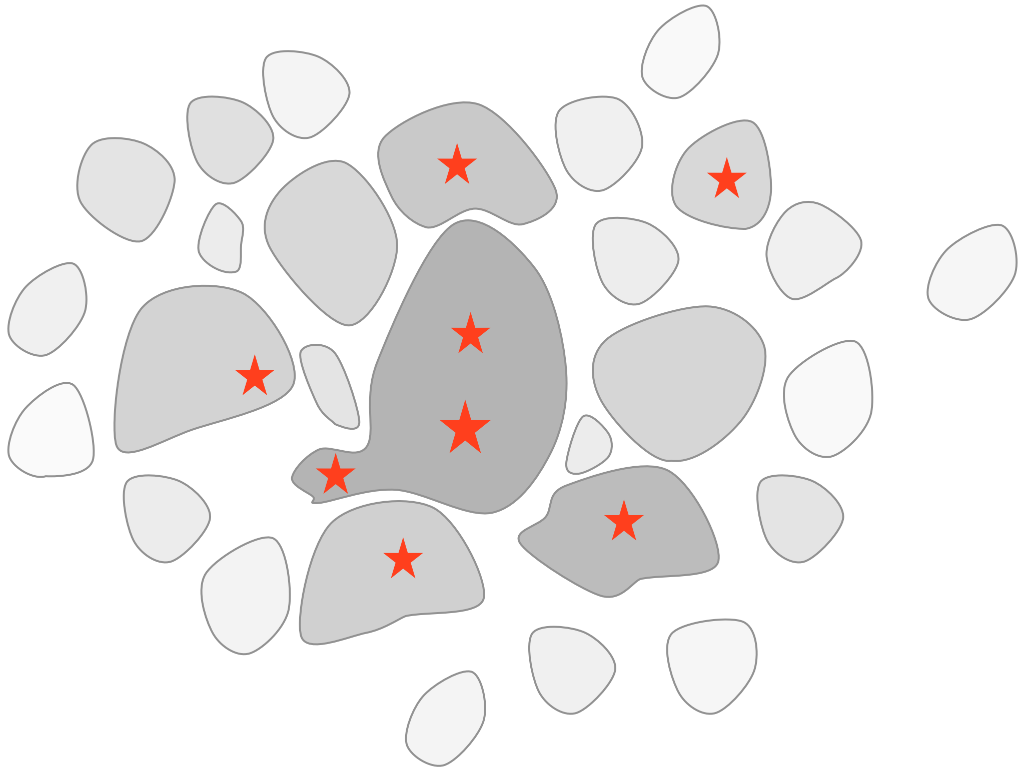


individual clumps collapse to form stars

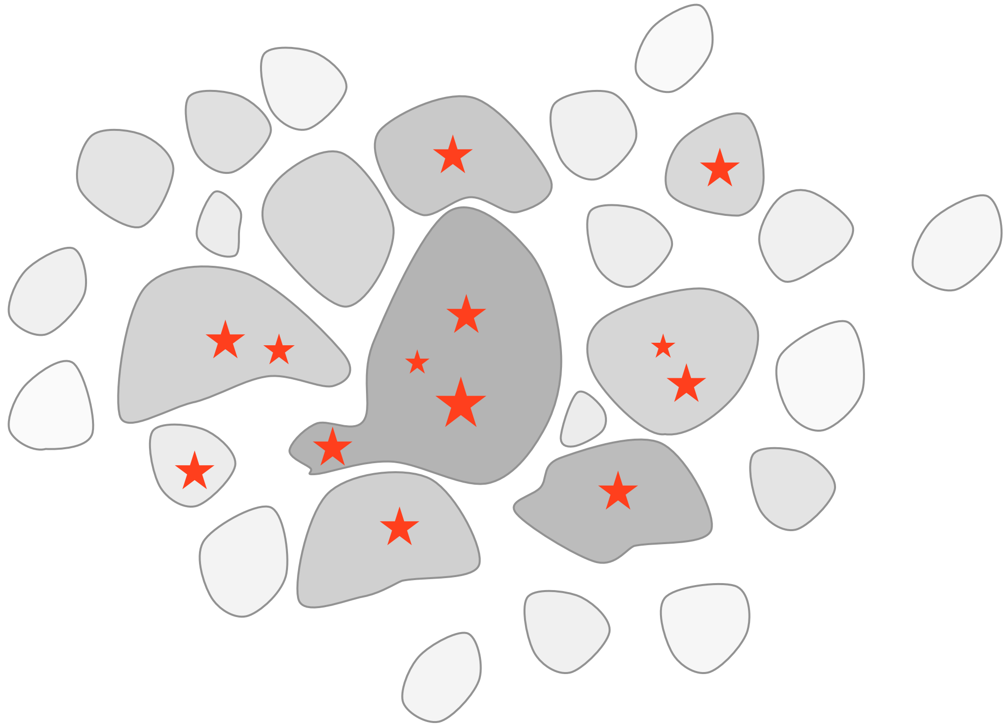


$\alpha = E_{kin}/|E_{pot}| < 1$

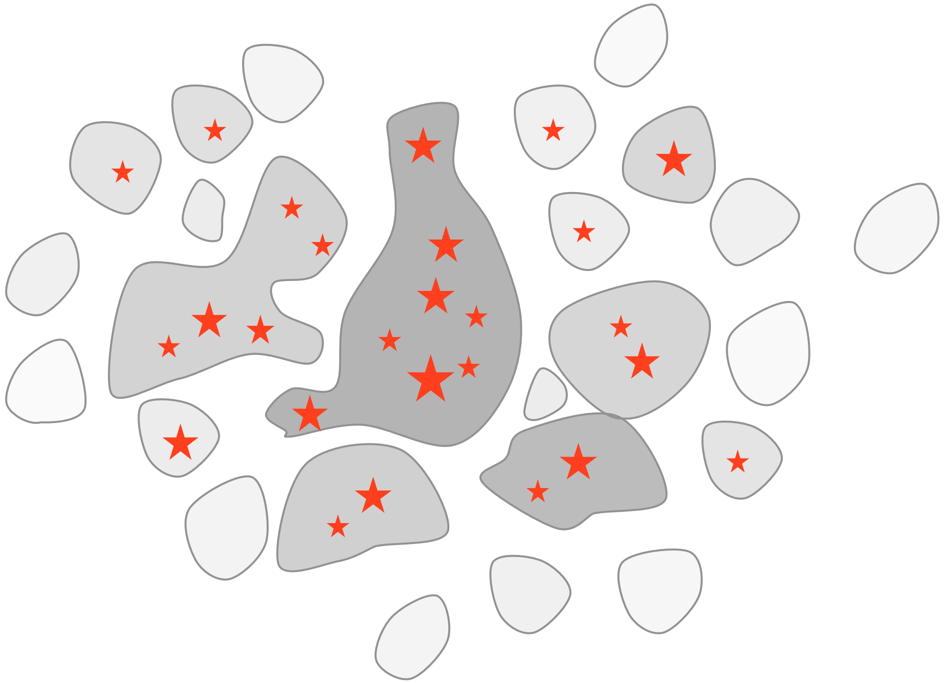
in *dense clusters*, clumps may merge while collapsing
--> then contain multiple protostars



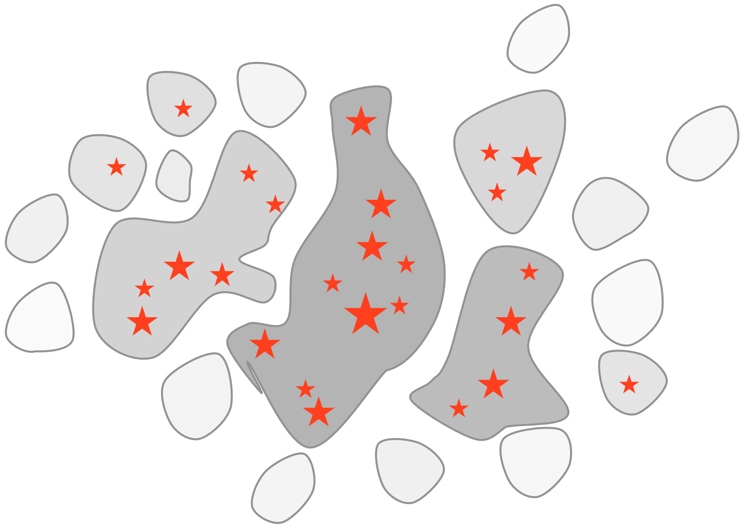
in *dense clusters*, clumps may merge while collapsing
--> then contain multiple protostars



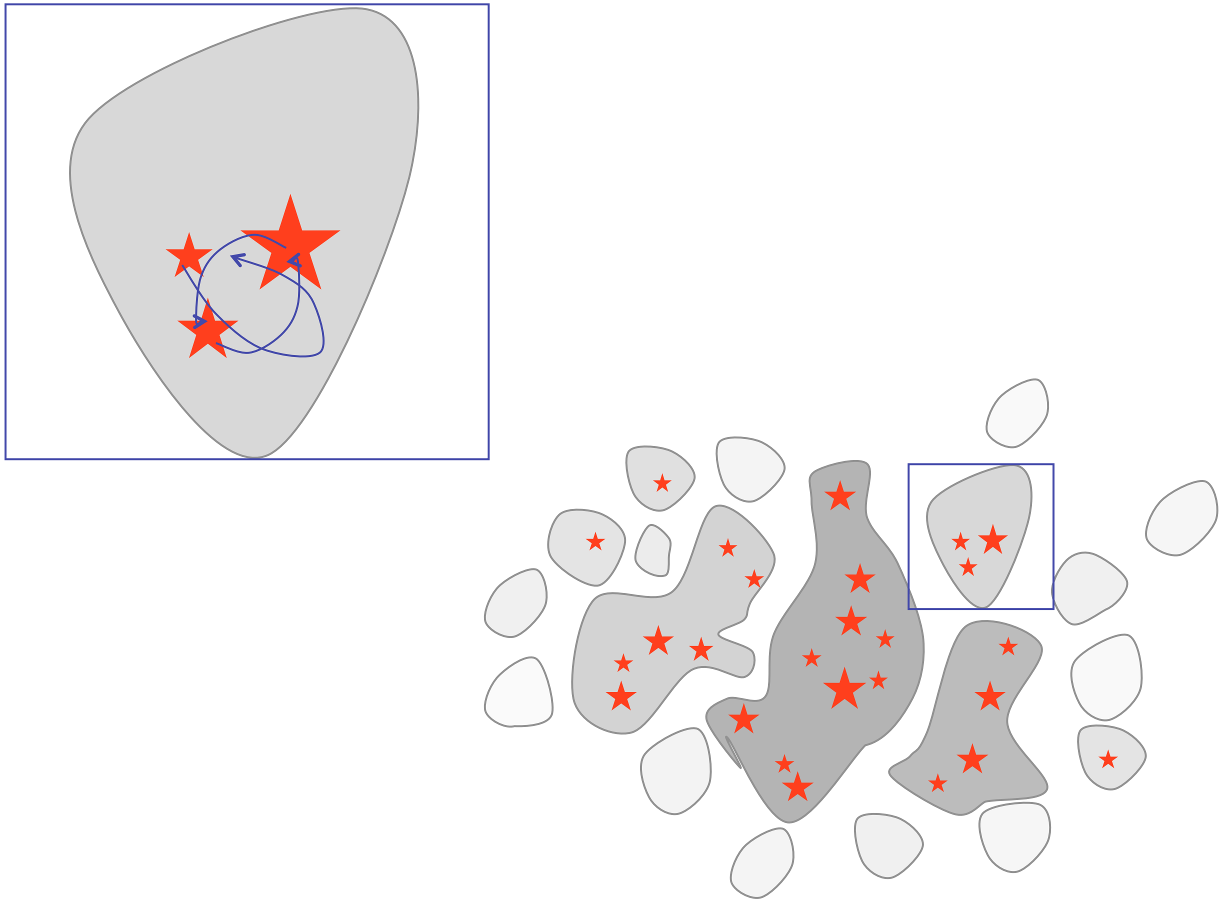
in *dense clusters*, clumps may merge while collapsing
--> then contain multiple protostars



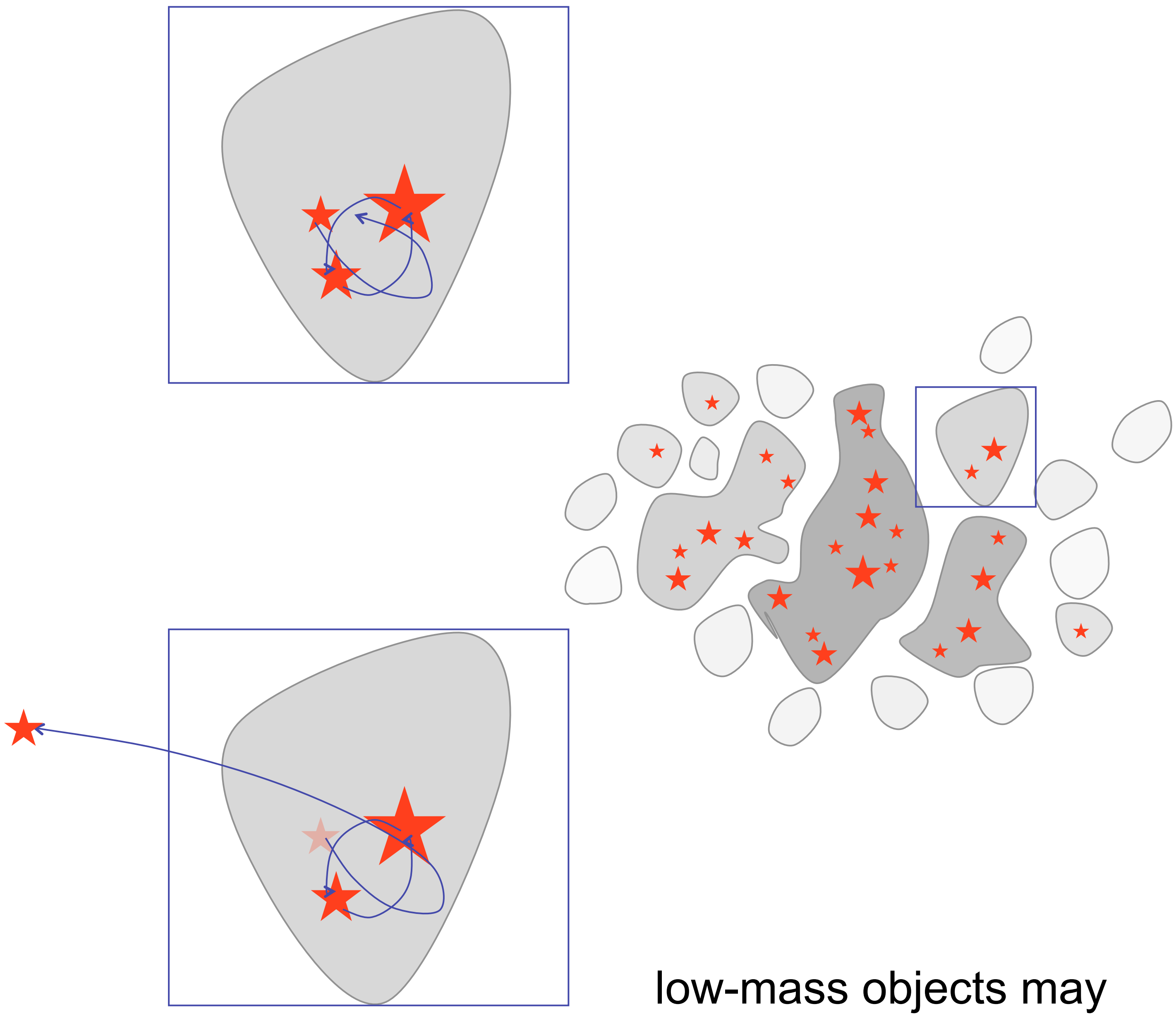
in *dense clusters*, competitive mass growth becomes important



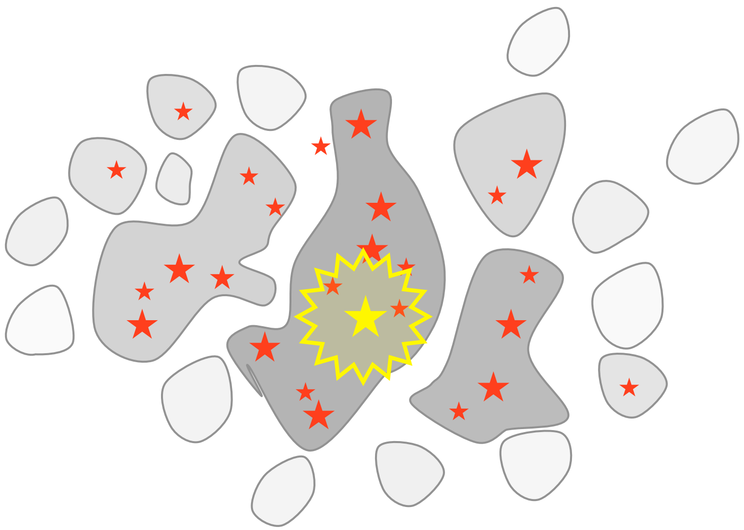
in *dense clusters*, competitive mass growth becomes important



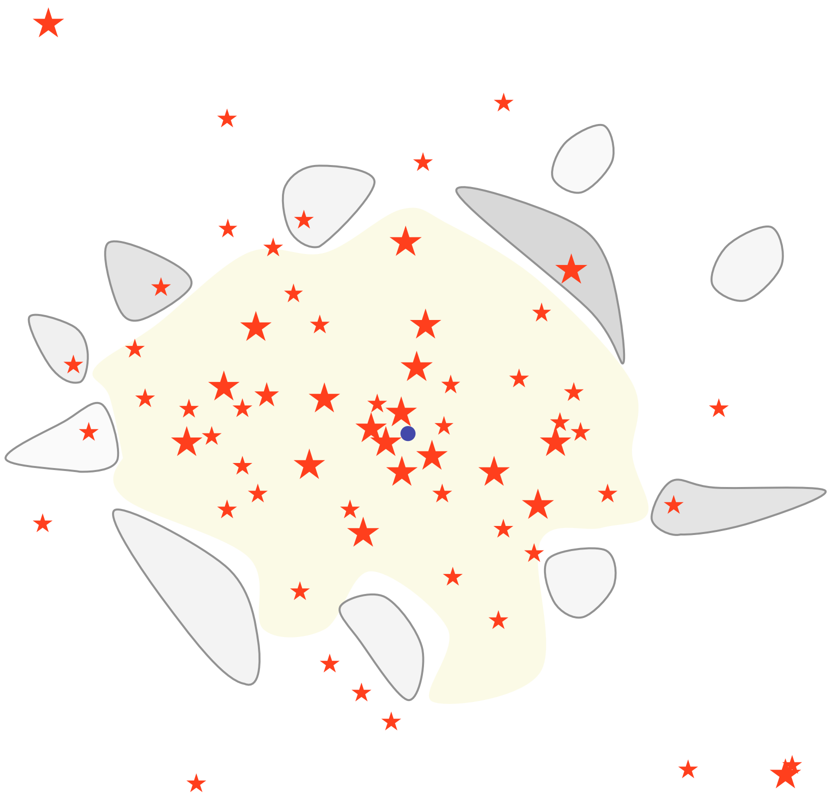
in *dense clusters*, *N*-body effects influence mass growth



low-mass objects may
become ejected --> accretion stops



feedback terminates star formation



result: *star cluster*, possibly with H II region

NGC 602 in the LMC: Hubble Heritage Image

result: *star cluster* with HII region

predictions

some details

- *what drives turbulence?*
  - accretion driven turbulence on ALL scales
    galaxies, molecular clouds, protostellar disks
- *stellar initial mass function (IMF)*
  - focus on effects of thermodynamics
- *formation of molecular cloud in the turbulent ISM*
  - combining MHD with time-dependent chemistry
- *the first (strong) B-fields in the universe*
  - the turbulent dynamo in action
- *diffusion in supersonic turbulence*
  - mixing length approach

accretion driven turbulence

- thesis:
  - astrophysical objects *form* by *accretion* of ambient material
  - the *kinetic energy* associated with this process is a key agent *driving internal turbulence*.
  - this works on *ALL* scales:
    - galaxies
    - molecular clouds
    - protostellar accretion disks

Klessen & Hennebelle (2010, A&A, in press)

concept

- turbulence decays on a crossing time

$$\tau_{\rm d} \approx \frac{L_{\rm d}}{\sigma}.$$

- energy decay rate

$$\dot{E}_{\rm decay} \approx \frac{E}{\tau_{\rm d}} = -\frac{1}{2}\frac{M\sigma^3}{L_{\rm d}}$$

- kinetic energy of infalling material

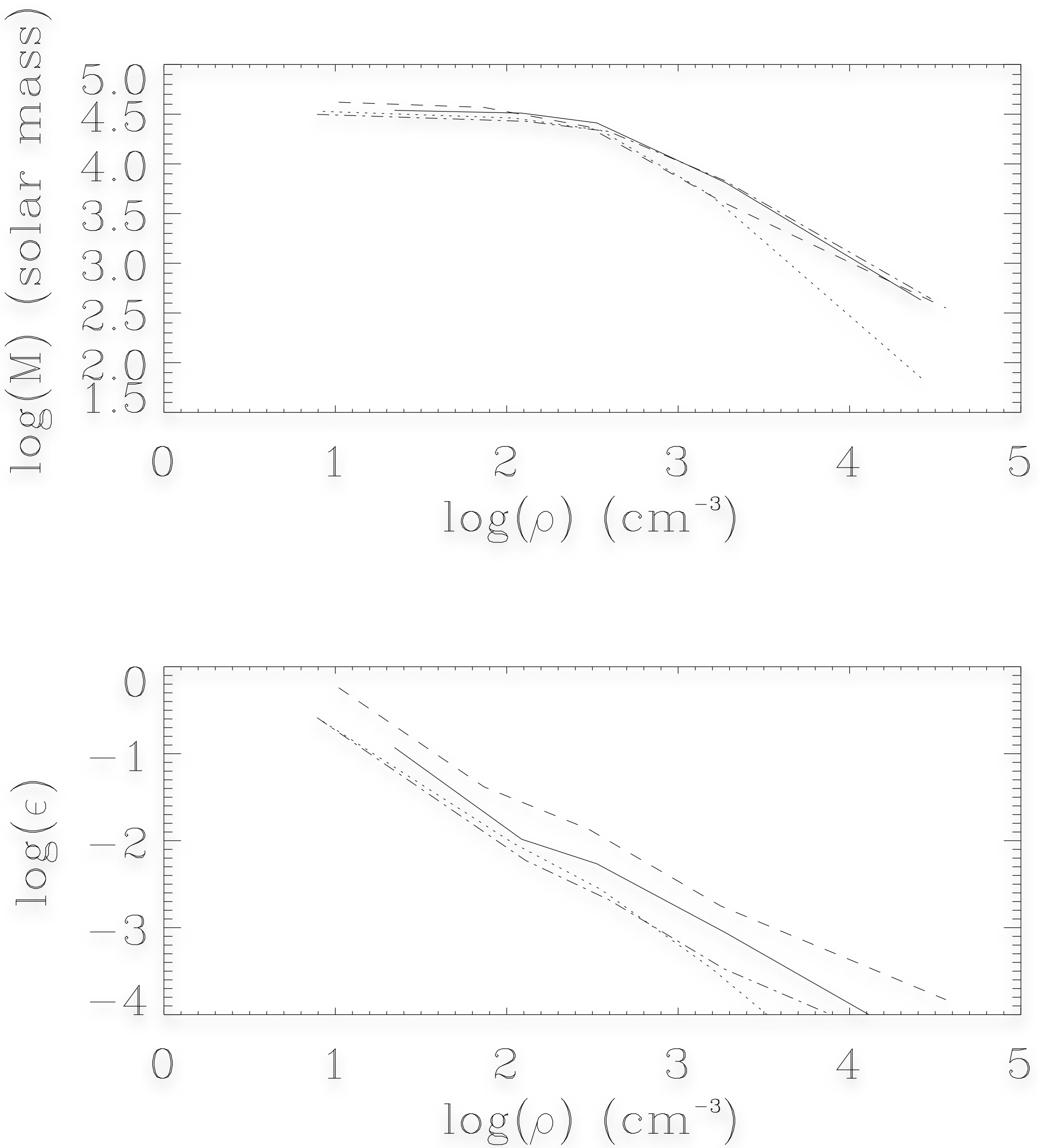
$$\dot{E}_{\rm in} = \frac{1}{2}\dot{M}_{\rm in}v_{\rm in}^2$$

- can both values match, modulo some efficiency?

$$\epsilon = \left|\frac{\dot{E}_{\rm decay}}{\dot{E}_{\rm in}}\right|$$

(Field et al.. 2008, MNRAS, 385, 181, Mac Low & Klessen 2004, RMP, 76, 125)

some estimates from convergent flow studies



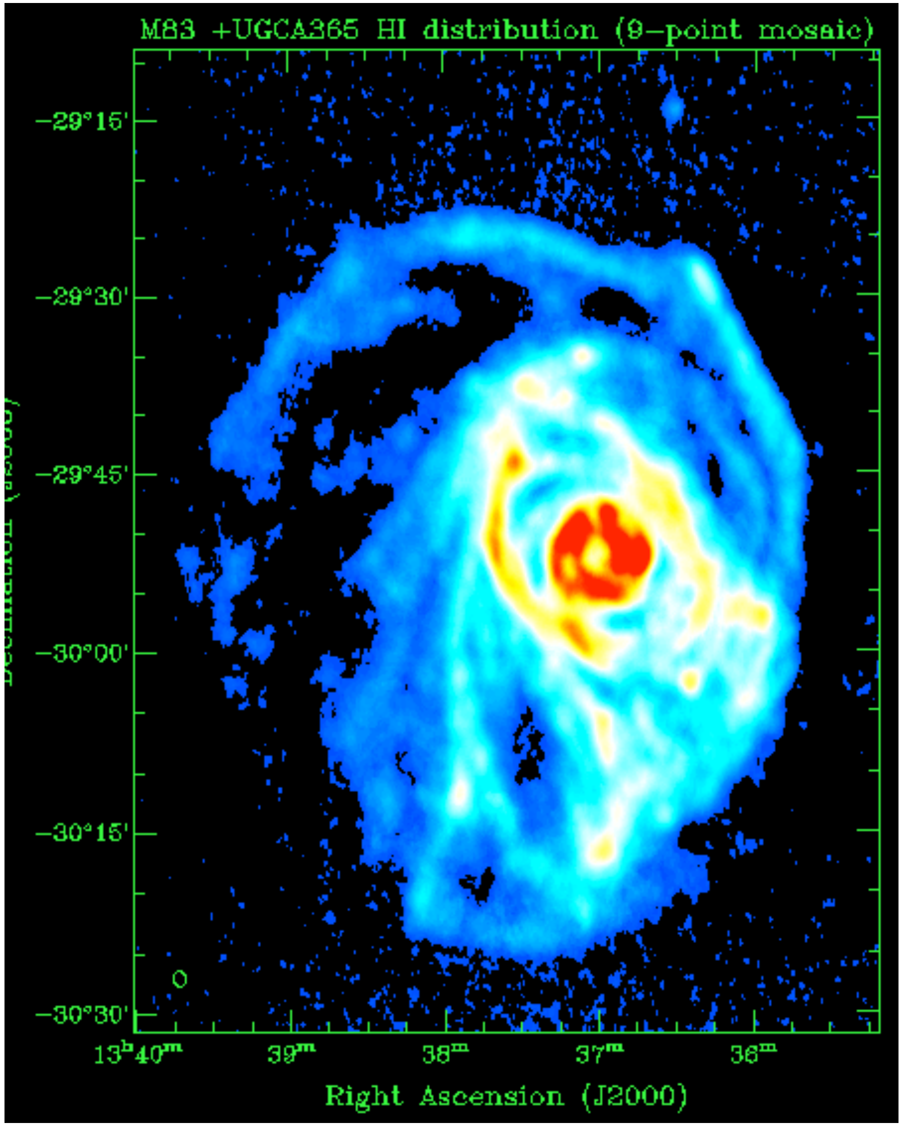
Klessen & Hennebelle (2010, A&A, in press)

application to galaxies

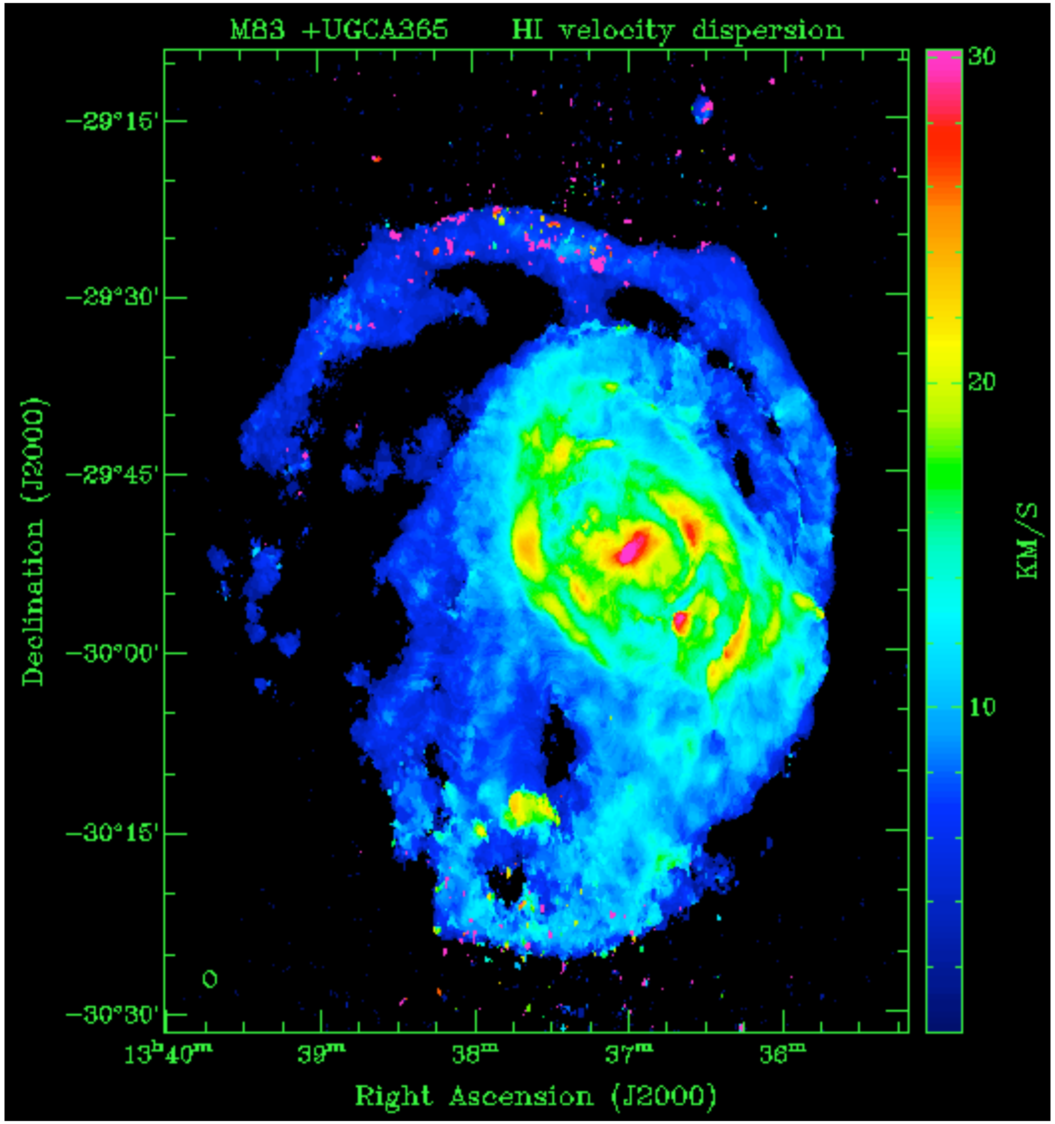
- underlying assumption
  - galaxy is in steady state
    ---> accretion rate equals star formation rate
  - what is the required efficiency for the method to work?
- study Milky Way and 11 THINGS
  - excellent observational data in HI:
    velocity dispersion, column density, rotation curve

Klessen & Hennebelle (2010, A&A, in press)

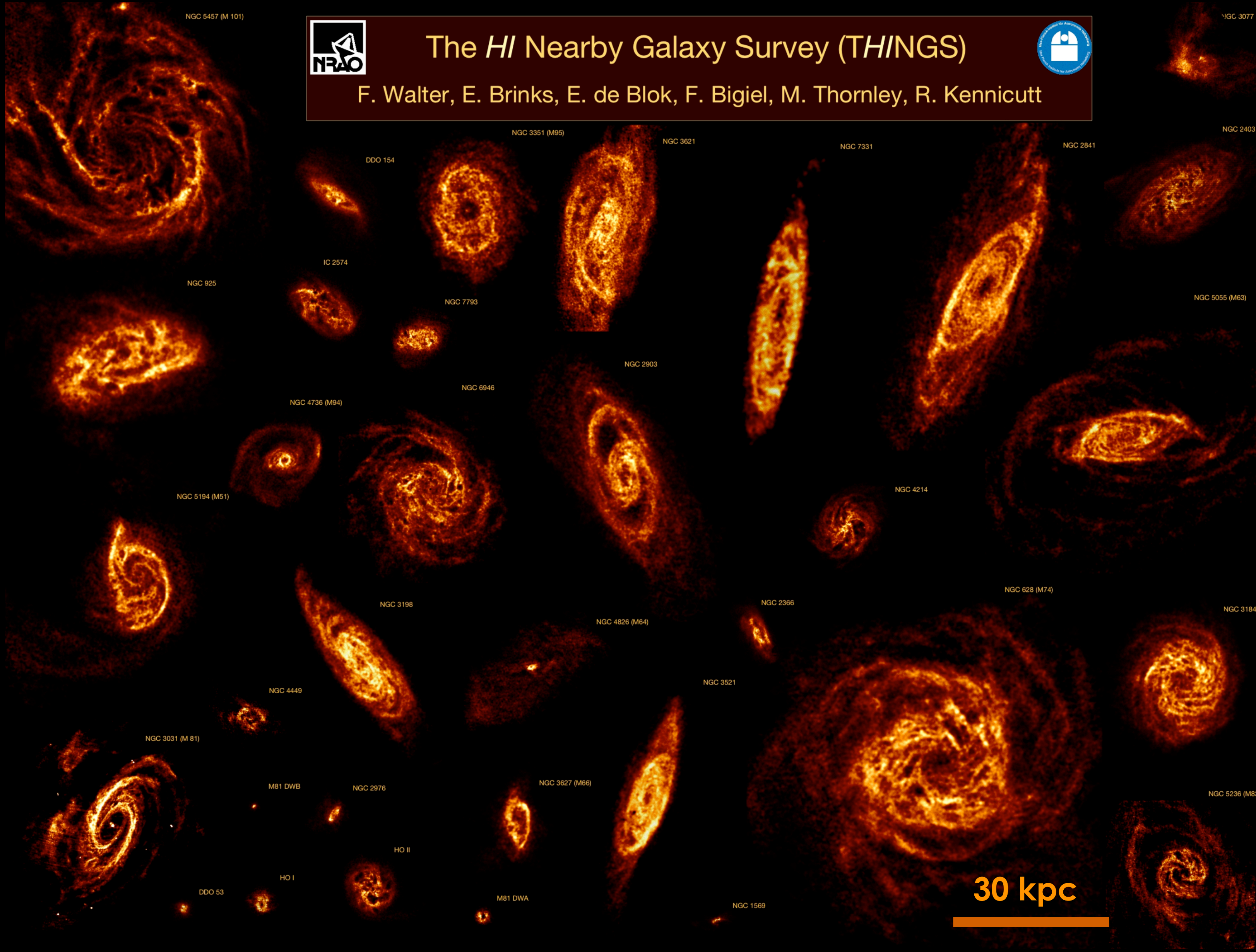
M83 HI column

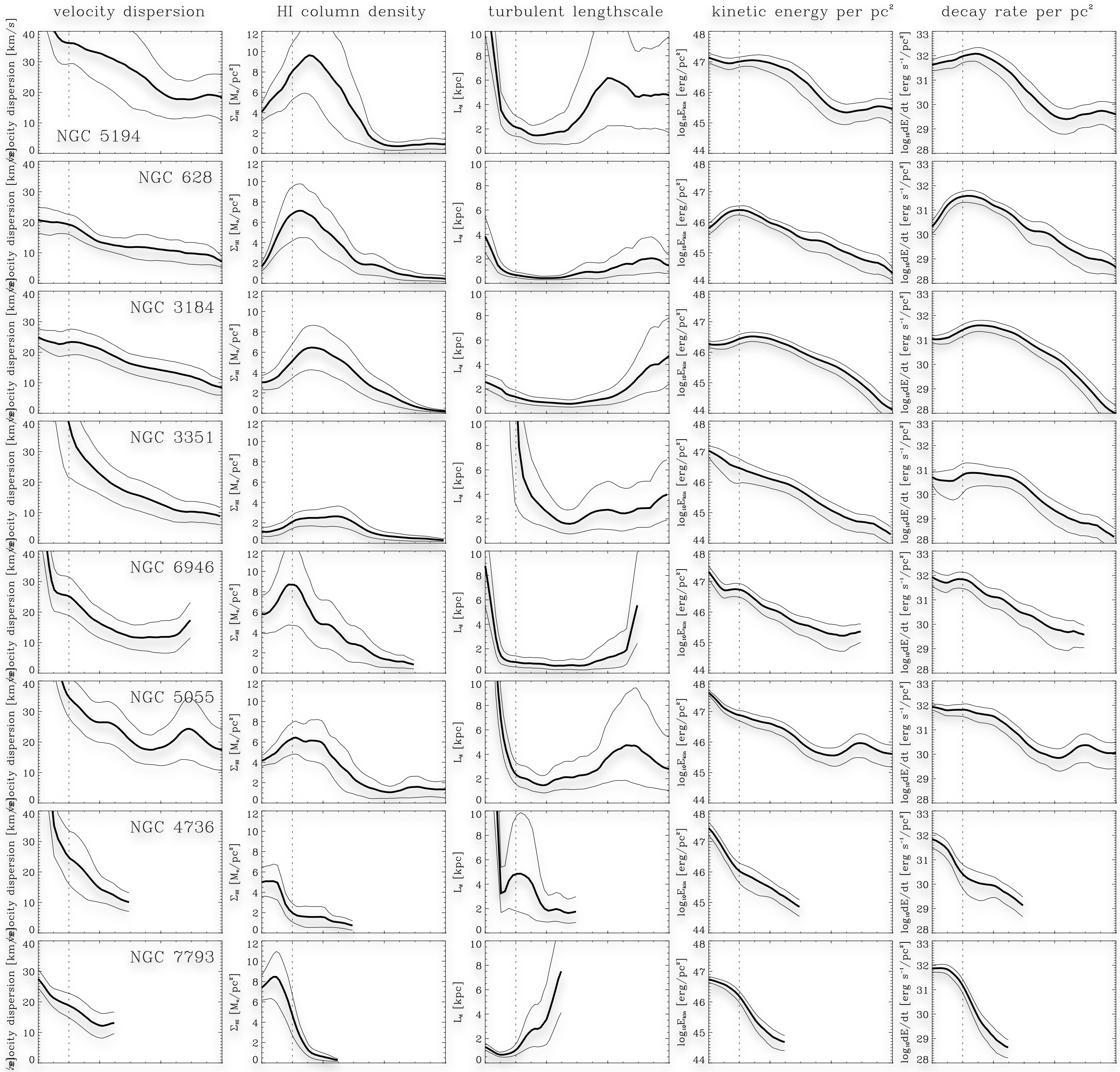


M83 HI velocity dispersion

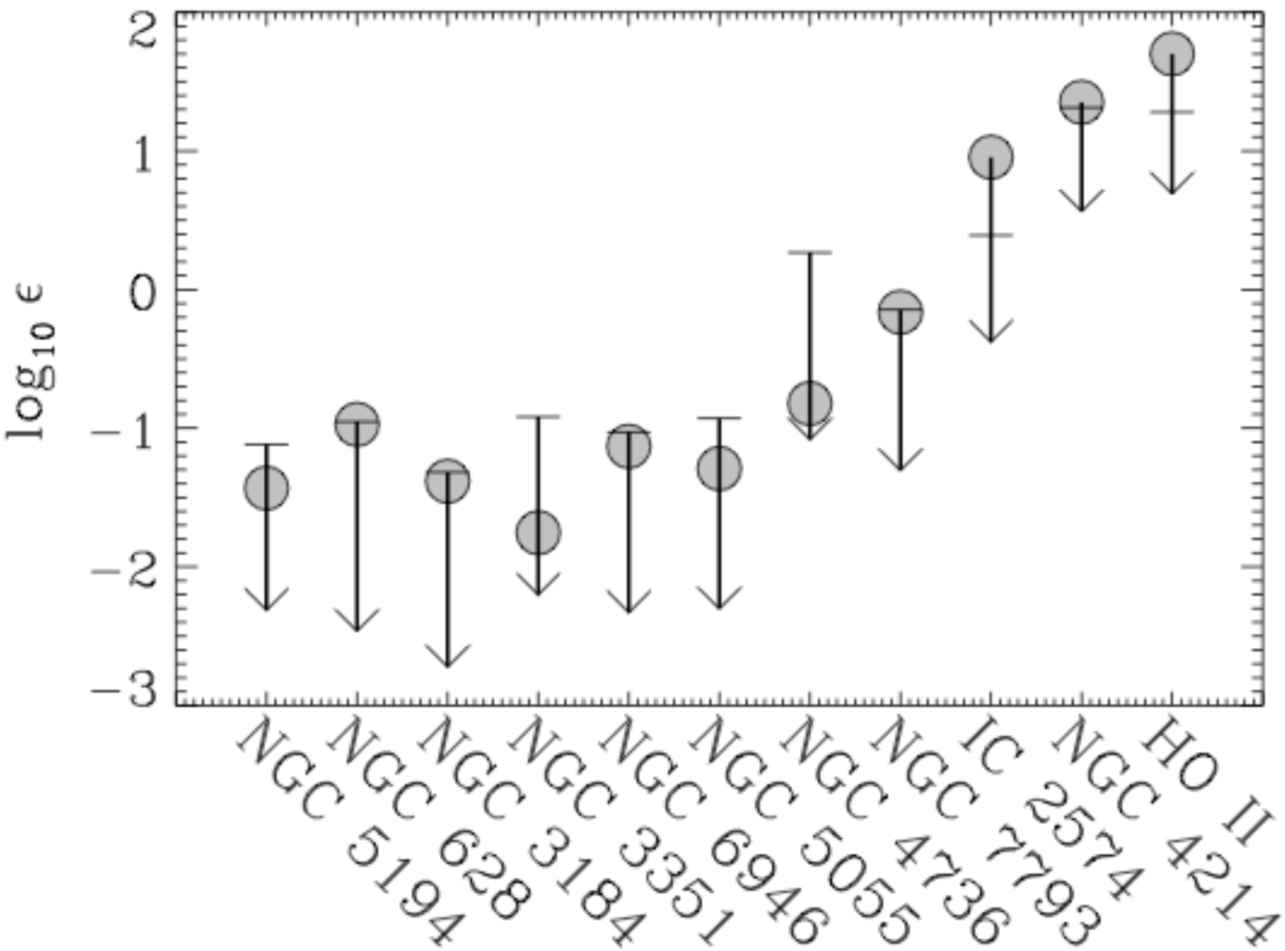


EveryTHINGS




velocity dispersion
HI column density
turbulent lengthscale
kinetic energy per pc²
decay rate per pc²
NGC 5194
NGC 628
NGC 3184
NGC 3351
NGC 6946
NGC 5055
NGC 4736
NGC 7793
velocity dispersion [km/s]
Σ_HI [M_⊙/pc²]
L_d [kpc]
log₁₀E_kin [erg/pc²]
log₁₀dE/dt [erg s⁻¹/pc²]

11 THINGS galaxies



Klessen & Hennebelle (2010, A&A, in press)

galactic disks

- method works for Milky Way type galaxies:
  - required efficiencies are ~1% only!
- relevant for outer disks (extended HI disks)
  - there are not other sources of turbulence (certainly not stellar sources, maybe MRI)
- works well for molecular clouds
  - example clouds in the LMC (Fukui et al.)
- potentially interesting for TTS
  - model reproduces dM/dt - M relation (e.g Natta et al. 2006, Muzerolle et al. 2005, Muhanty et al. 2005, Calvet et al. 2004, etc.)

Klessen & Hennebelle (2010, A&A, in press)

IMF

IMF

- distribution of stellar masses depends on
  - turbulent initial conditions
    --> mass spectrum of prestellar cloud cores
  - collapse and interaction of prestellar cores
    --> competitive accretion and *N*-body effects
  - thermodynamic properties of gas
    --> balance between heating and cooling
    --> EOS (determines which cores go into collapse)
  - (proto) stellar feedback terminates star formation
    ionizing radiation, bipolar outflows, winds, SN

(e.g. Larson 2003, Prog. Rep. Phys.; Mac Low & Klessen, 2004, Rev. Mod. Phys, 76, 125 - 194)

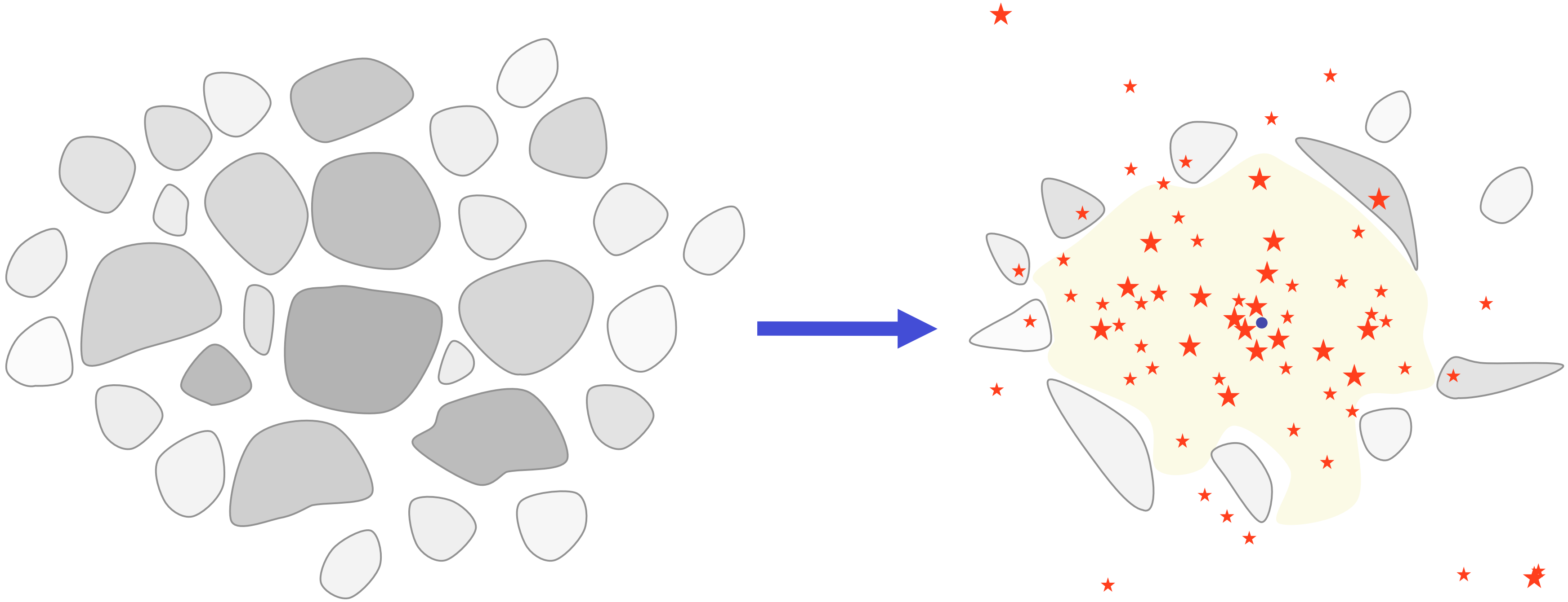
IMF

- distribution of stellar masses depends on
  - turbulent initial conditions
    --> mass spectrum of prestellar cloud cores
  - collapse and interaction of prestellar cores
    --> competitive accretion and *N*-body effects
  - thermodynamic properties of gas
    --> balance between heating and cooling
    --> EOS (determines which cores go into collapse)
  - (proto) stellar feedback terminates star formation
    ionizing radiation, bipolar outflows, winds, SN

(e.g. Larson 2003, Prog. Rep. Phys.; Mac Low & Klessen, 2004, Rev. Mod. Phys, 76, 125 - 194)

Star cluster formation

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



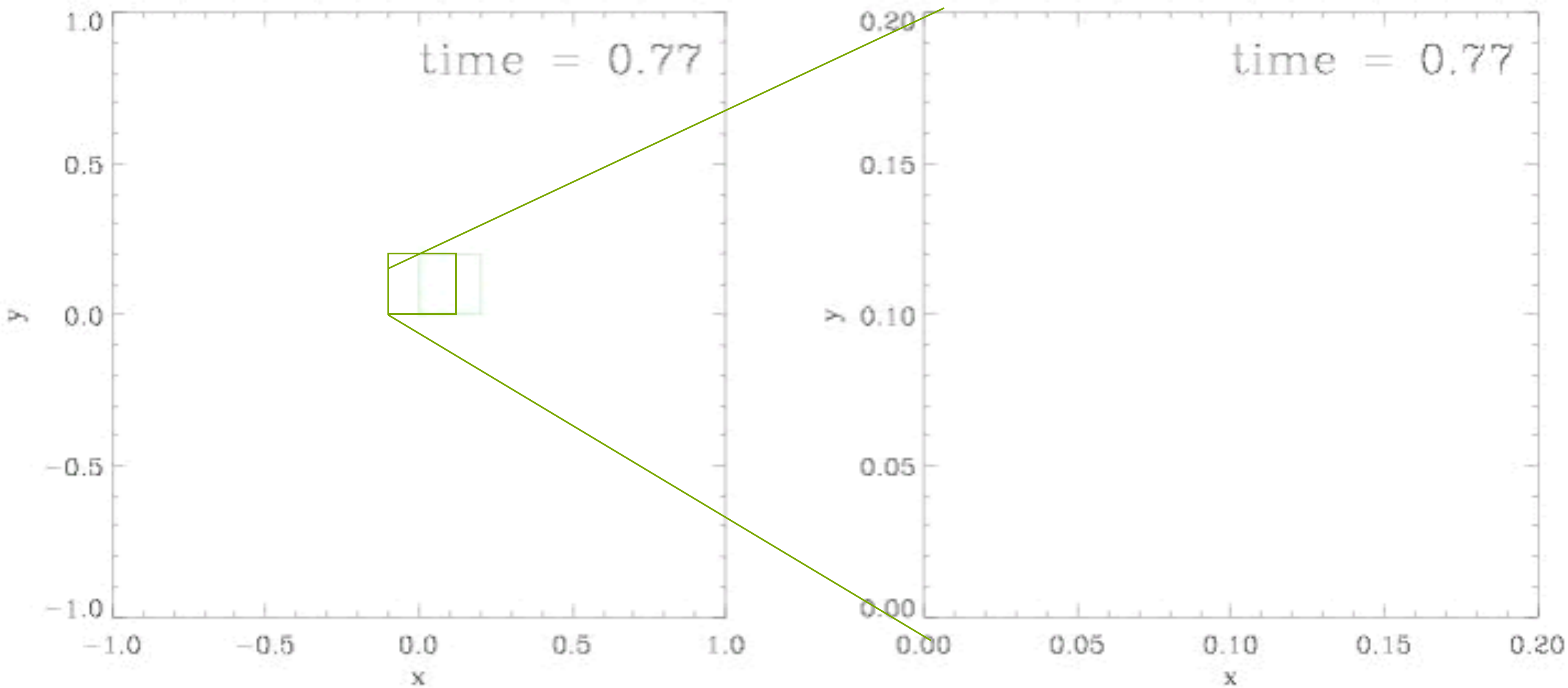
How to get from cloud cores to star clusters?

How do the stars acquire mass?

(e.g. Larson 2003, Prog. Rep. Phys.; Mac Low & Klessen, 2004, Rev. Mod. Phys, 76, 125 - 194)

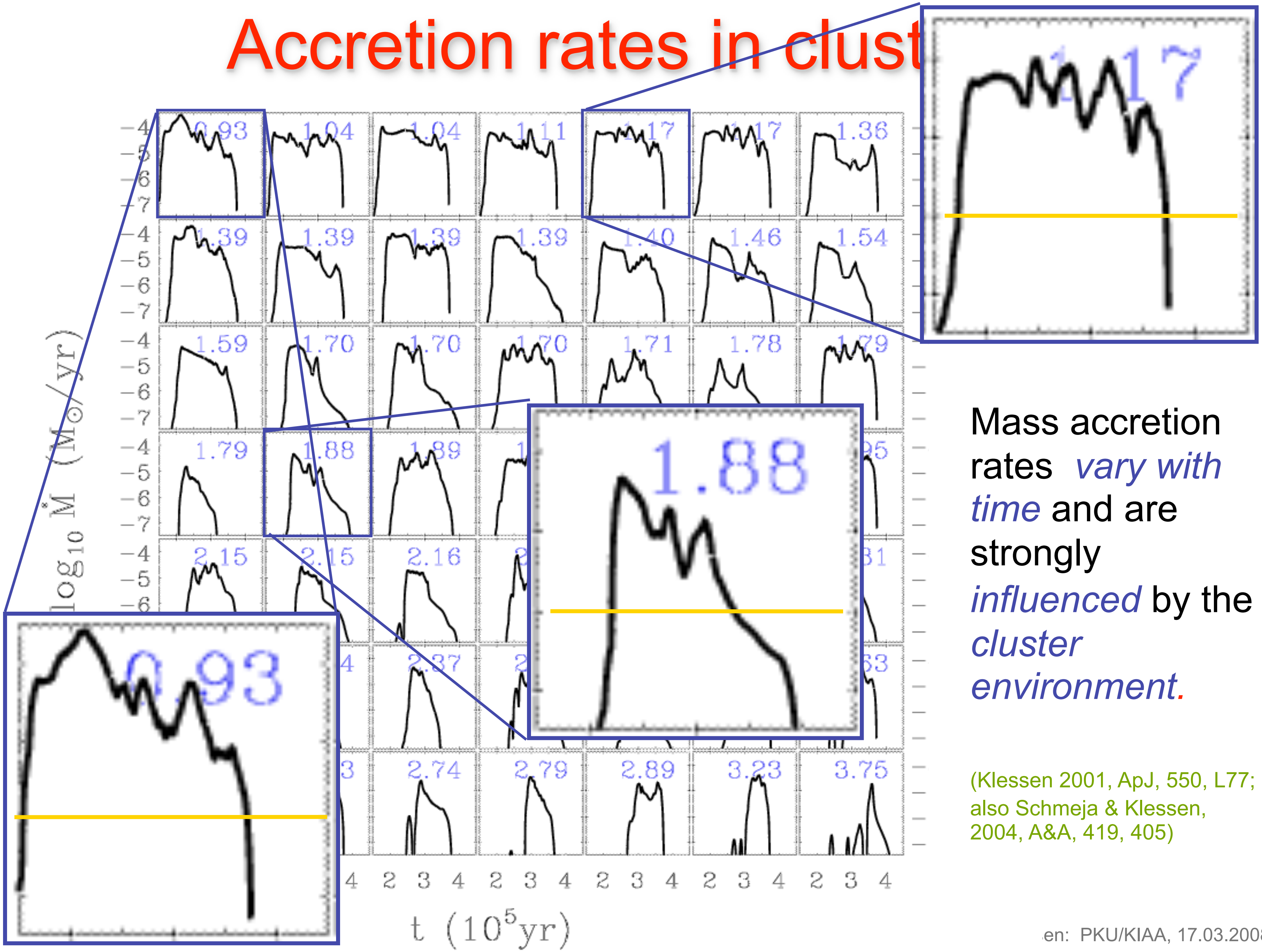
Dynamics of nascent star cluster

in dense clusters protostellar interaction may be come important!



Trajectories of protostars in a nascent dense cluster created by gravoturbulent fragmentation
(from Klessen & Burkert 2000, ApJS, 128, 287)

Accretion rates in clust



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)

IMF

- distribution of stellar masses depends on
  - turbulent initial conditions
    --> mass spectrum of prestellar cloud cores
  - collapse and interaction of prestellar cores
    --> competitive accretion and *N*-body effects
  - *thermodynamic properties of gas*
    --> balance between heating and cooling
    --> EOS (determines which cores go into collapse)
  - (proto) stellar feedback terminates star formation
    ionizing radiation, bipolar outflows, winds, SN

(e.g. Larson 2003, Prog. Rep. Phys.; Mac Low & Klessen, 2004, Rev. Mod. Phys, 76, 125 - 194)

dependency on EOS

- degree of fragmentation depends on *EOS!*

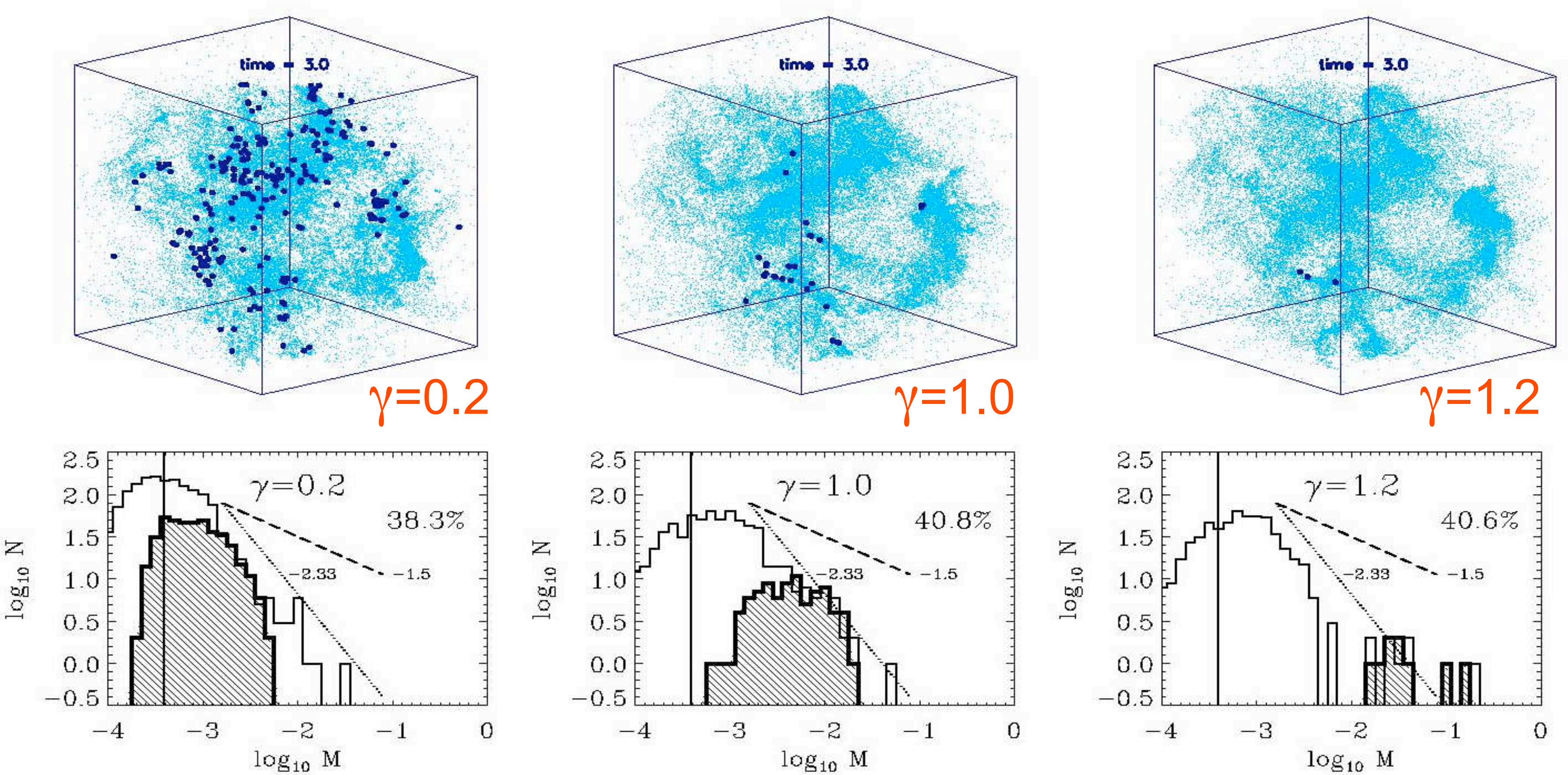
polytropic EOS: $\mathbf{p} \propto \rho^{\gamma}$

– $\gamma<1$: dense cluster of low-mass stars

– $\gamma>1$: isolated high-mass stars

(see Li, Klessen, & Mac Low 2003, ApJ, 592, 975; also Kawachi & Hanawa 1998, Larson 2003)

dependency on EOS



for γ<1 fragmentation is enhanced → *cluster of low-mass stars*

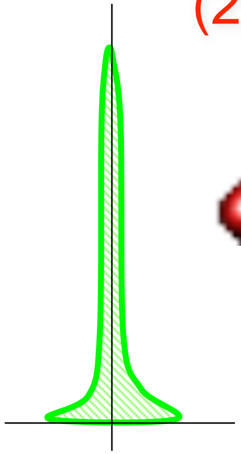
for γ>1 it is suppressed → formation of *isolated massive stars*

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

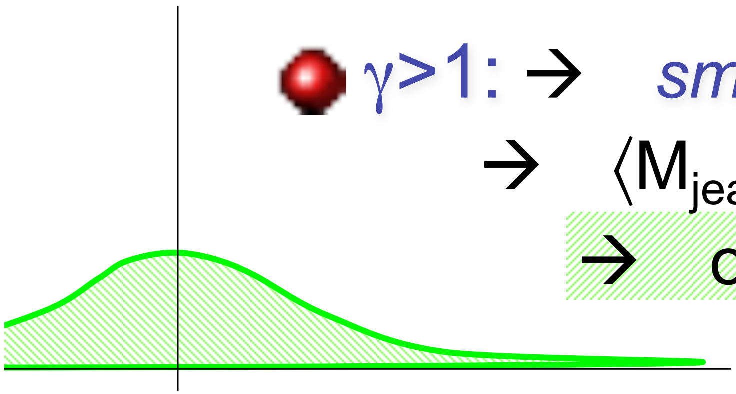
how does that work?

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

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



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

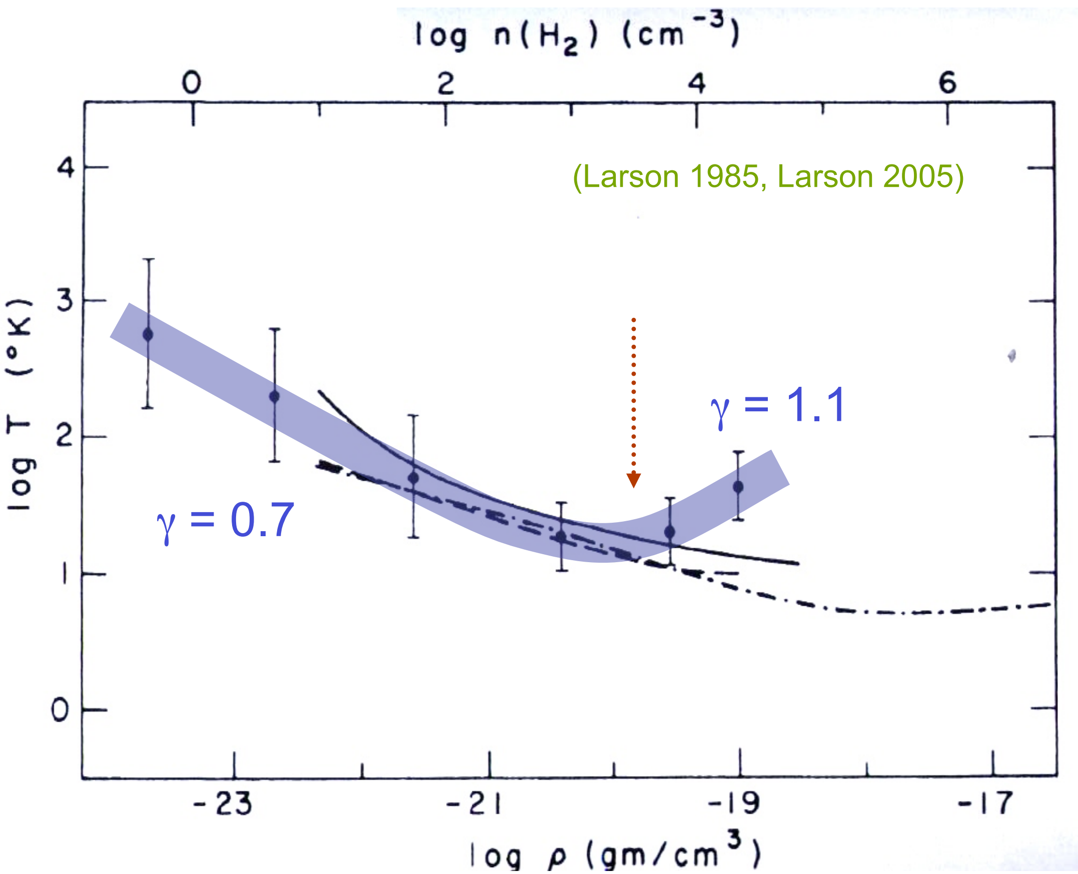


- $\gamma>1$: → *small* density excursion for given pressure
  → $\langle M_{jeans} \rangle$ is large
  → only few and massive clumps exceed M_{jeans}

EOS for solar neighborhood

below 10^{-18} gcm^{-3}: $\rho \uparrow \rightarrow T \downarrow$

above 10^{-18} gcm^{-3}: $\rho \uparrow \rightarrow T \uparrow$



$P \propto \rho^{\gamma}$

$P \propto \rho T$

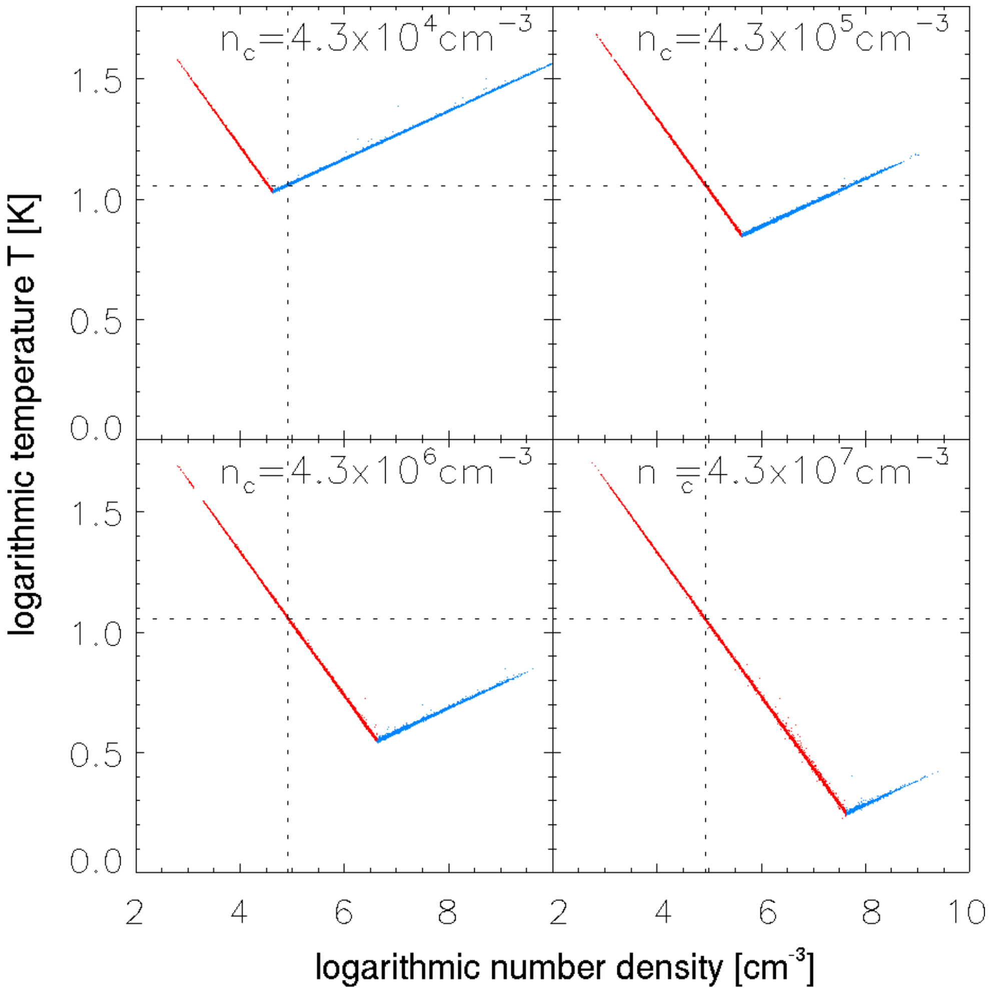
$\rightarrow \gamma = 1 + d\ln T / d\ln\rho$

IMF from simple piece-wise polytropic EOS

$\gamma_1 = 0.7$

$\gamma_2 = 1.1$

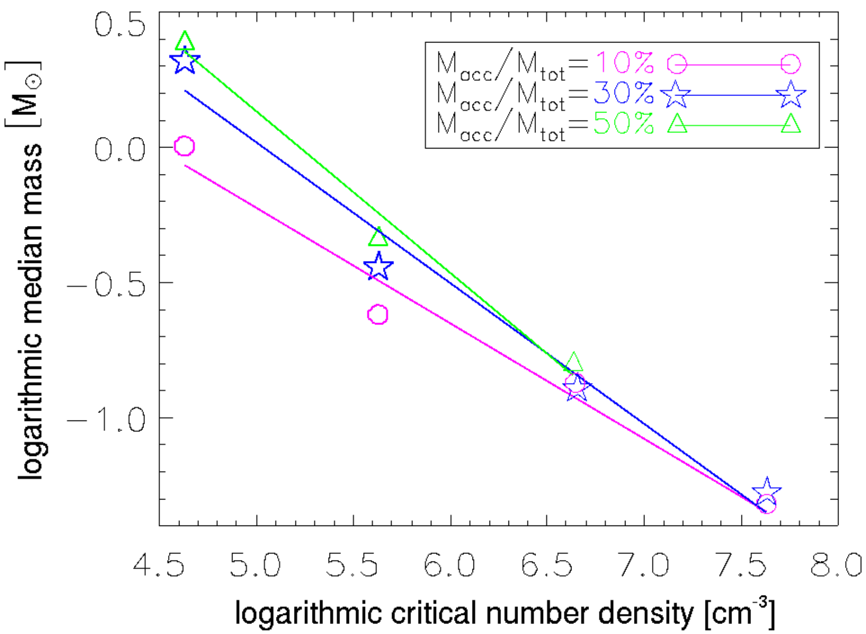
$T \sim \rho^{\gamma - 1}$

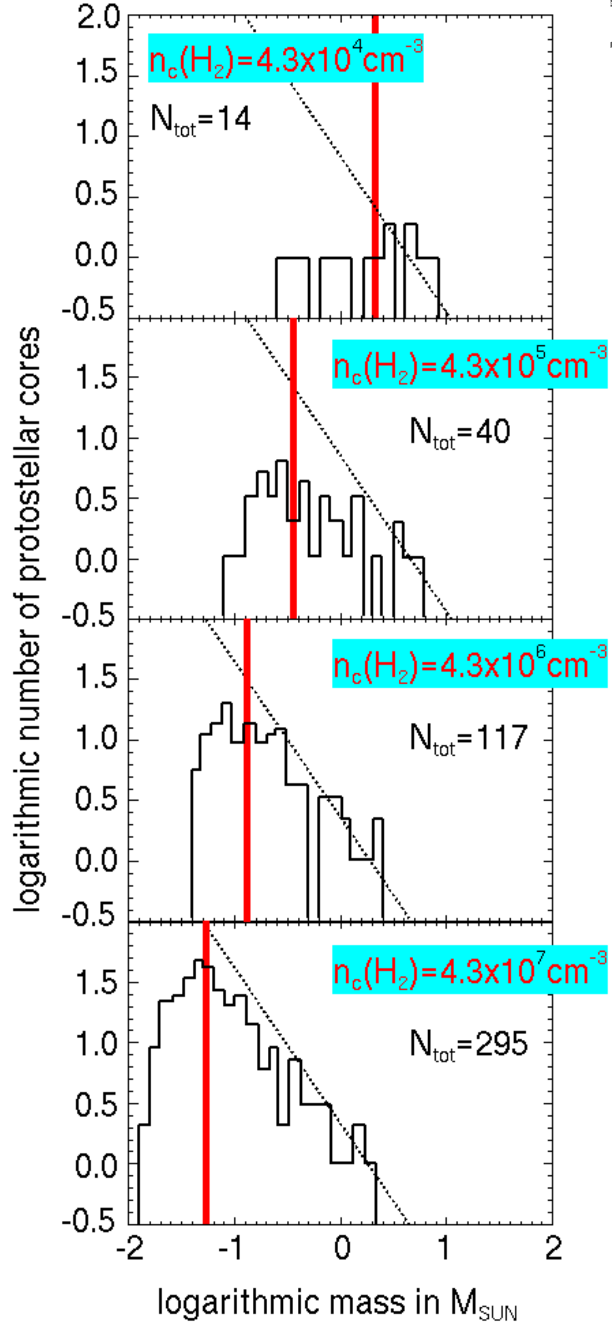


(Jappsen et al. 2005)

IMF from simple piece-wise EOS

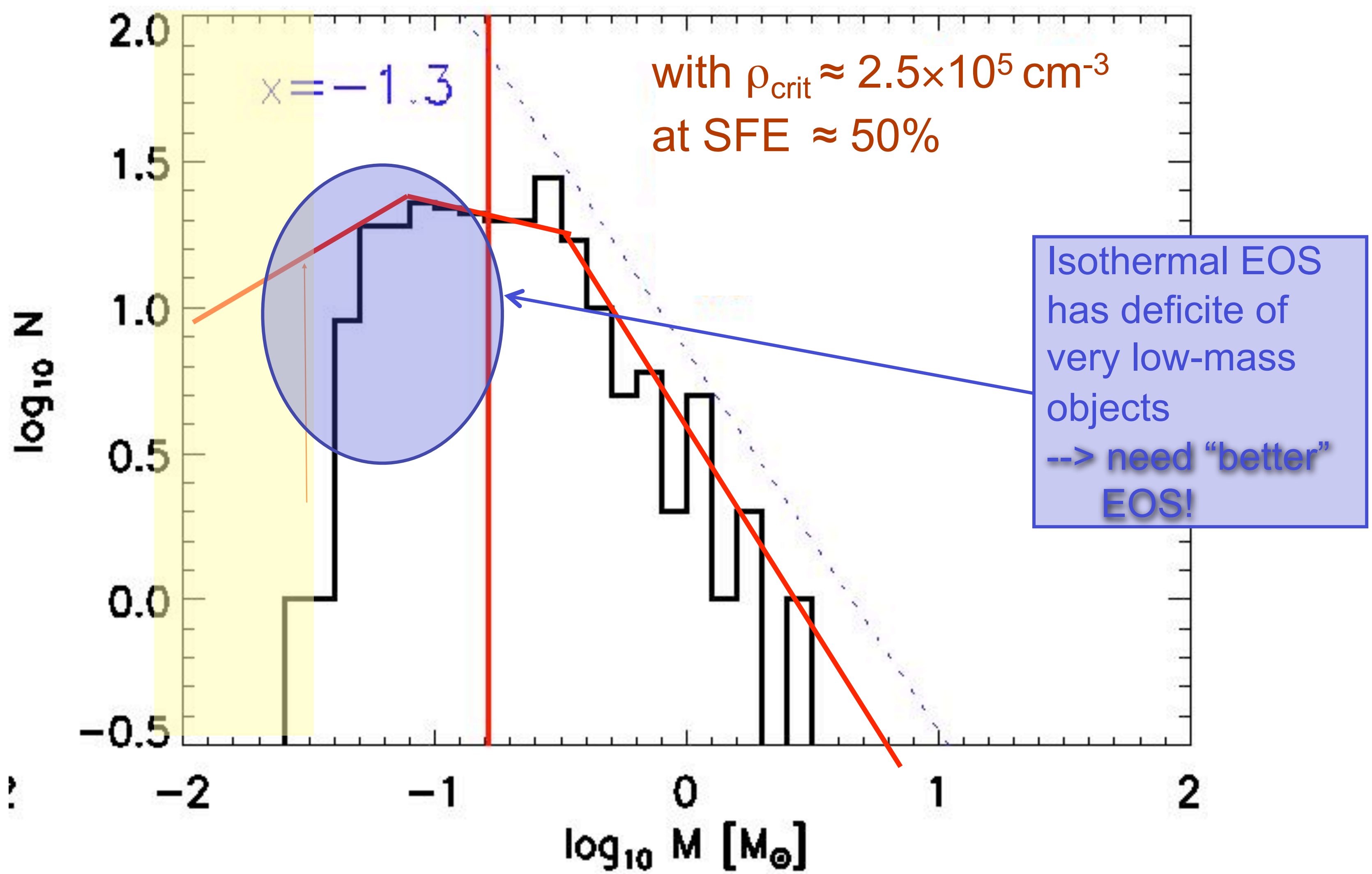
critical density ⬆ ⟹ median mass ⬇





(Jappsen et al. 2005)

IMF in nearby molecular clouds



(Jappsen et al. 2005, A&A, 435, 611)c

B-fields

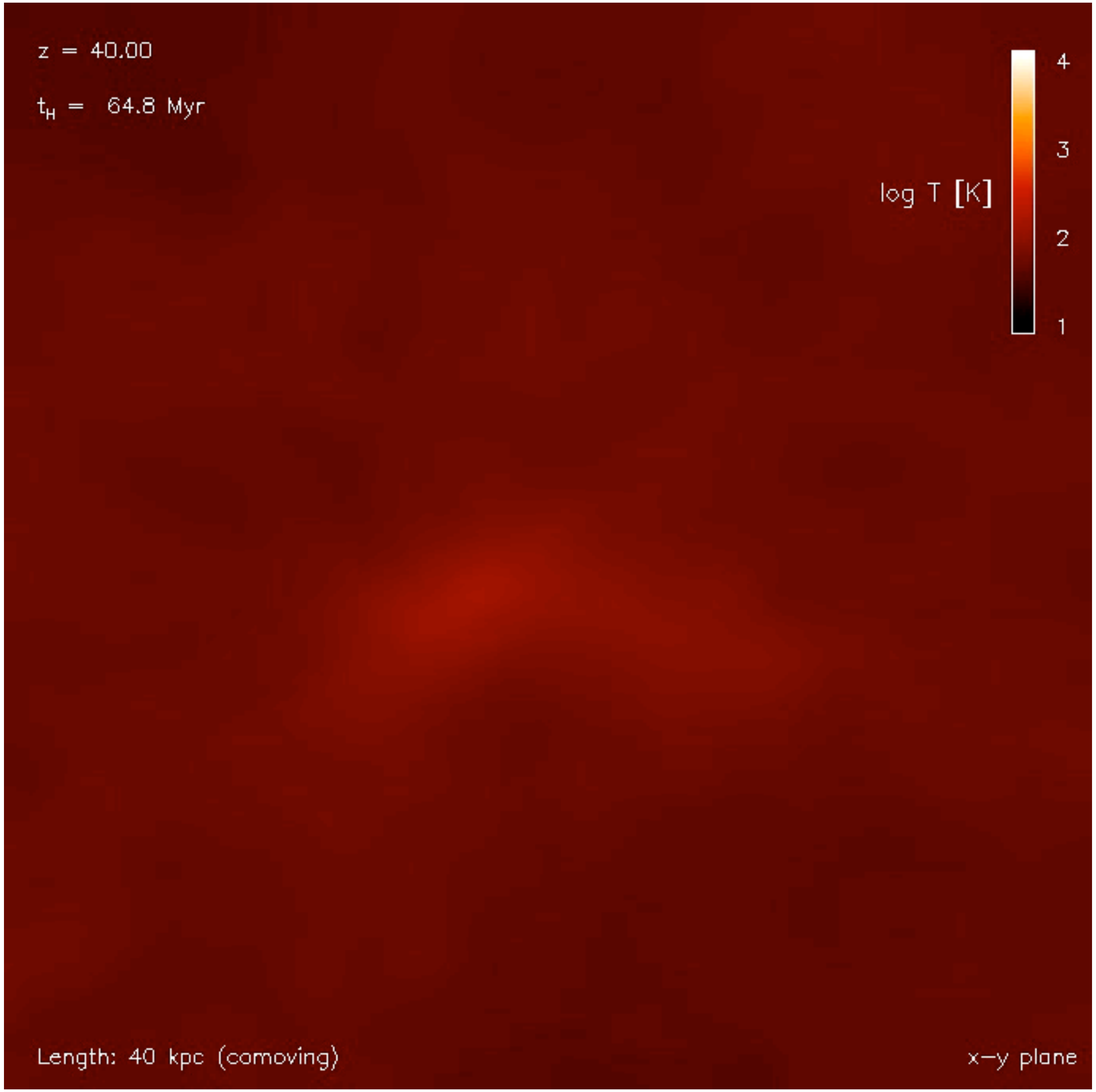
how to make strong B-fields

- we know the universe is magnetized (now)
- knowledge about B-fields in the high-redshift universe is extremely uncertain
  - inflation / QCD phase transition / Biermann battery / Weibel instability
- they are thought to be extremely small
- however, THIS MAY BE WRONG!

small-scale turbulent dynamo

- *idea:* the small-scale turbulent dynamo can generate strong magnetic fields from very small seed fields
- *approach:* model collapse of primordial gas ---> formation of the first stars in low-mass halo at redshift z ~ 20
- *method:* solve ideal MHD equations with very high resolution
  - grid-based AMR code FLASH
  - resolution up to 128^3 cells per Jeans volume (effective resolution 65536^3 cells)

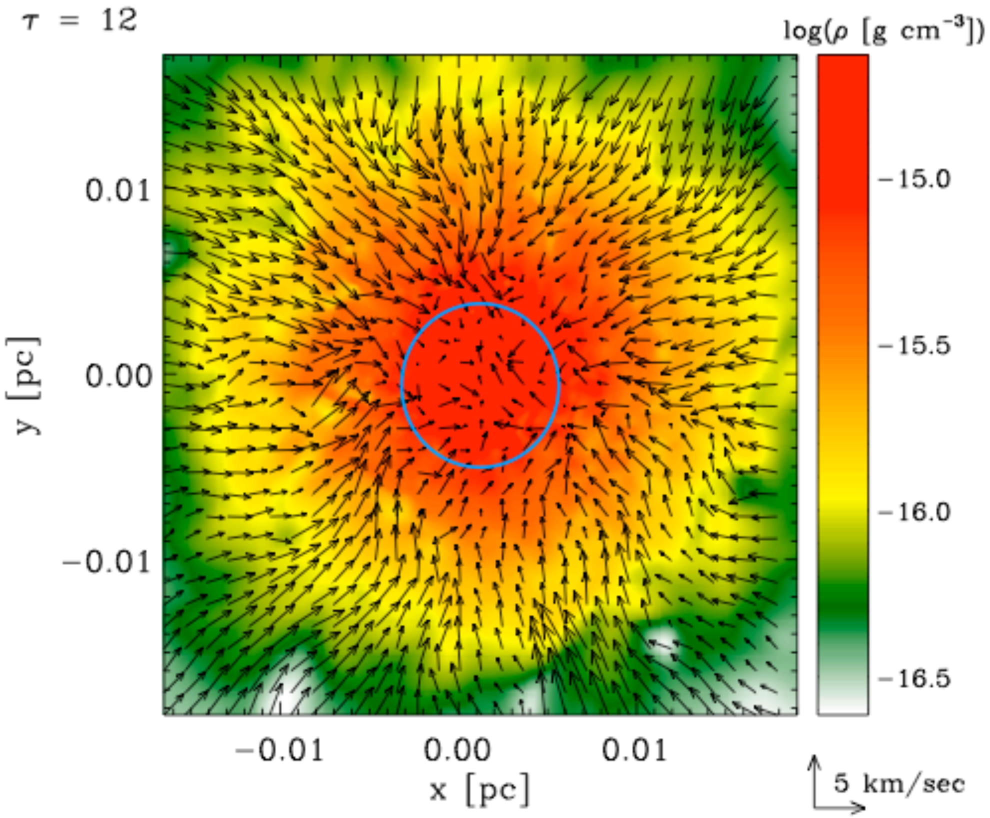
turbulence developing in an atomic cooling halo

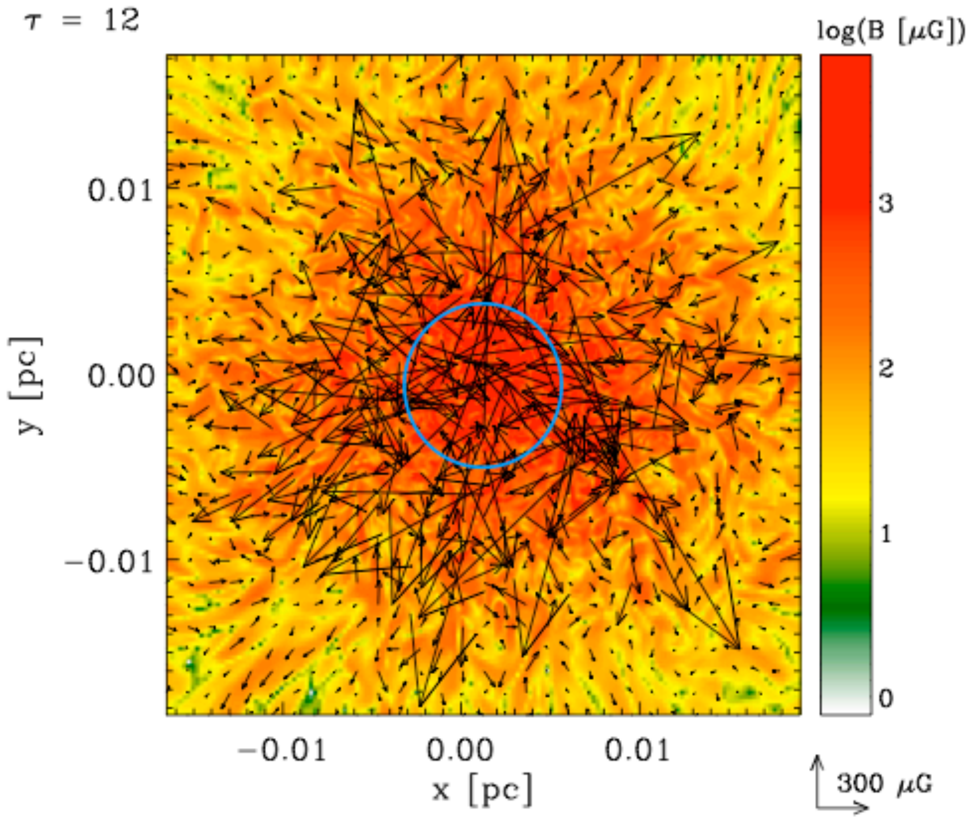


see also talk
by *Thomas Greif*

(Greif et al. 2008, MNRAS, 387, 1021, see also Wise & Abel 2007)

small-scale turbulent dynamo



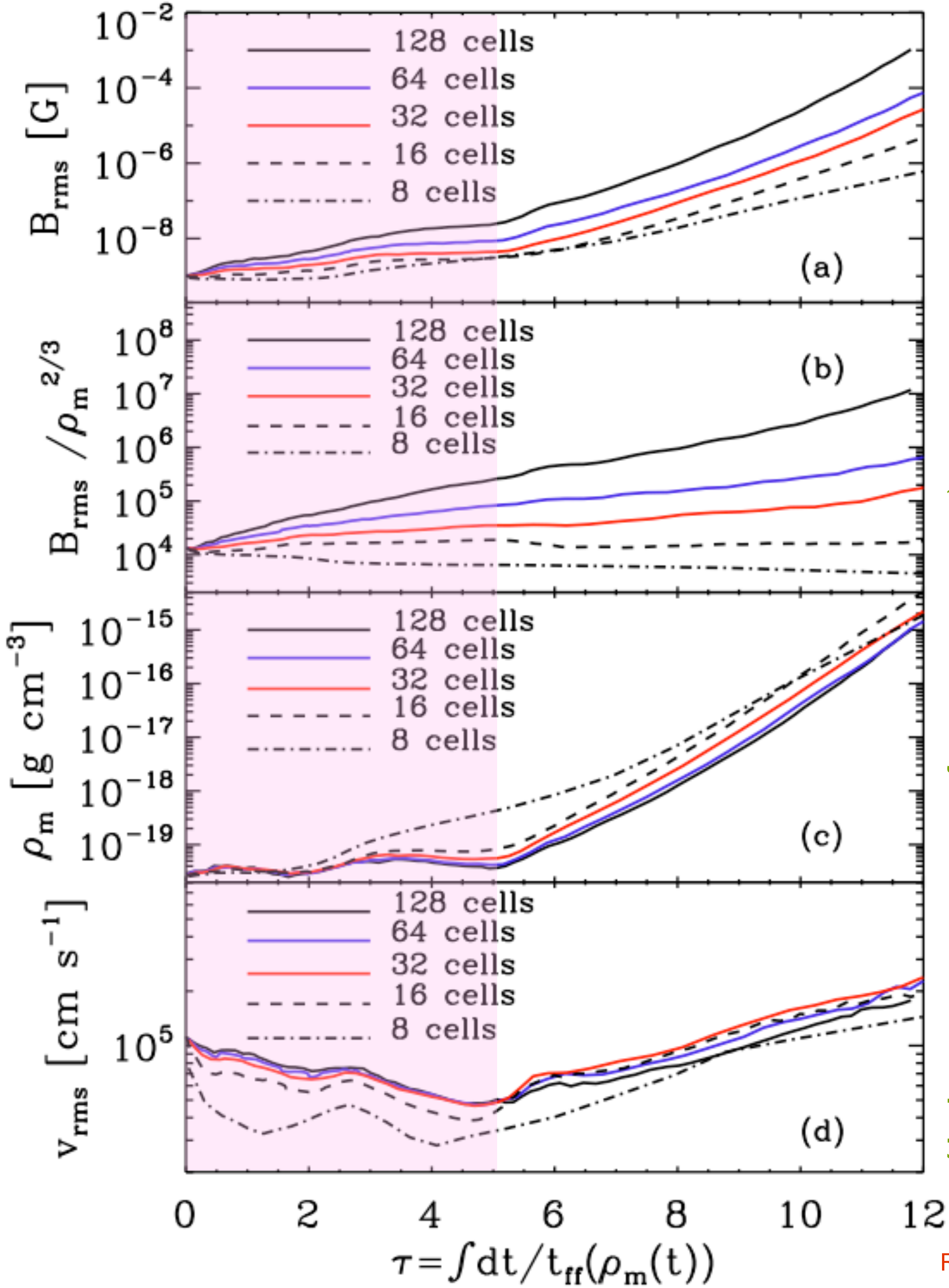


density, xy-velocity

B-field amplitude, xy-component

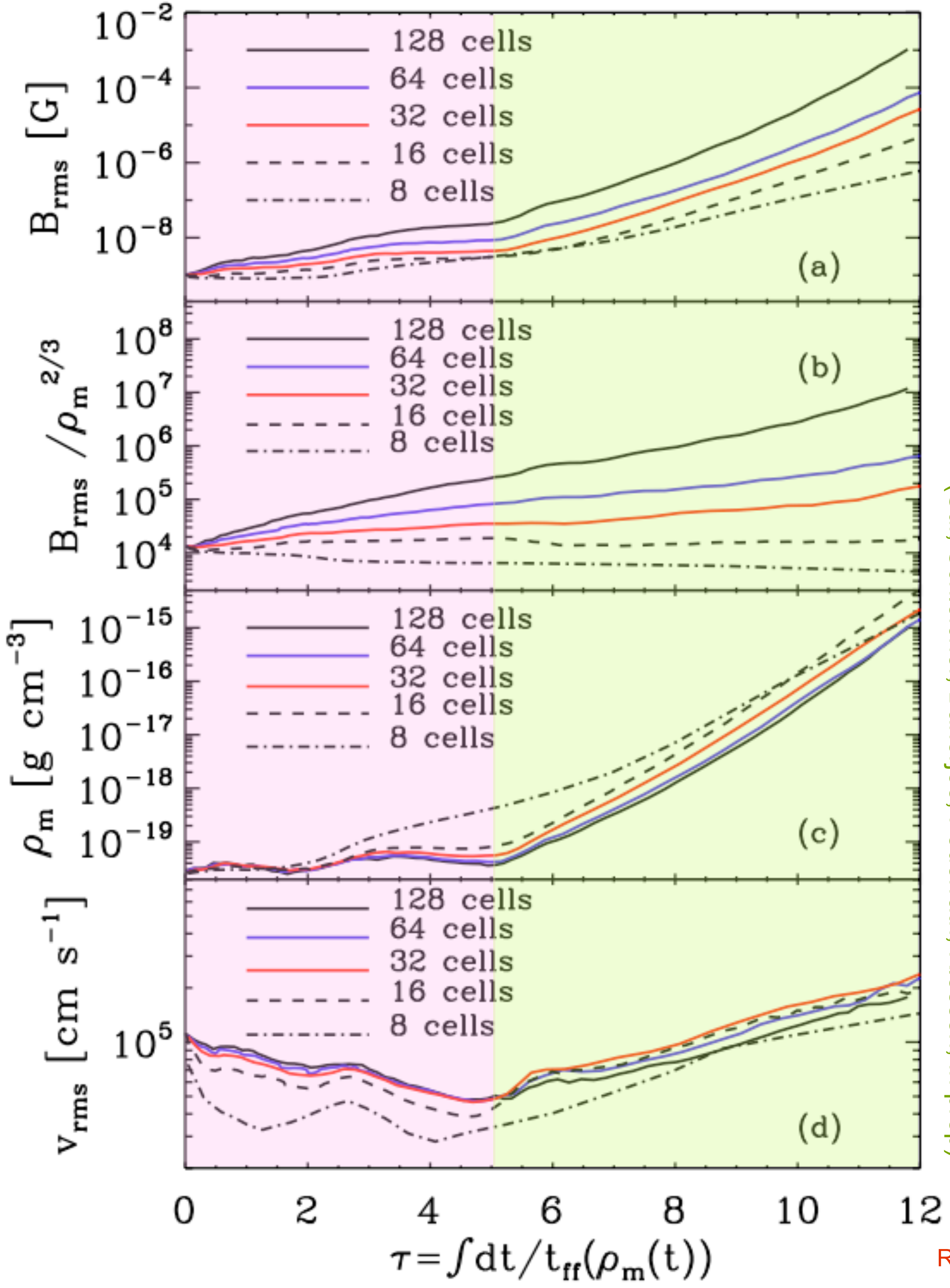
(Sur, Schleicher, Banerjee, Federrath, Klessen, in prep)

decay of turbulence



(*Sur, Schleicher, Banerjee, Federrath, Klessen, in prep)

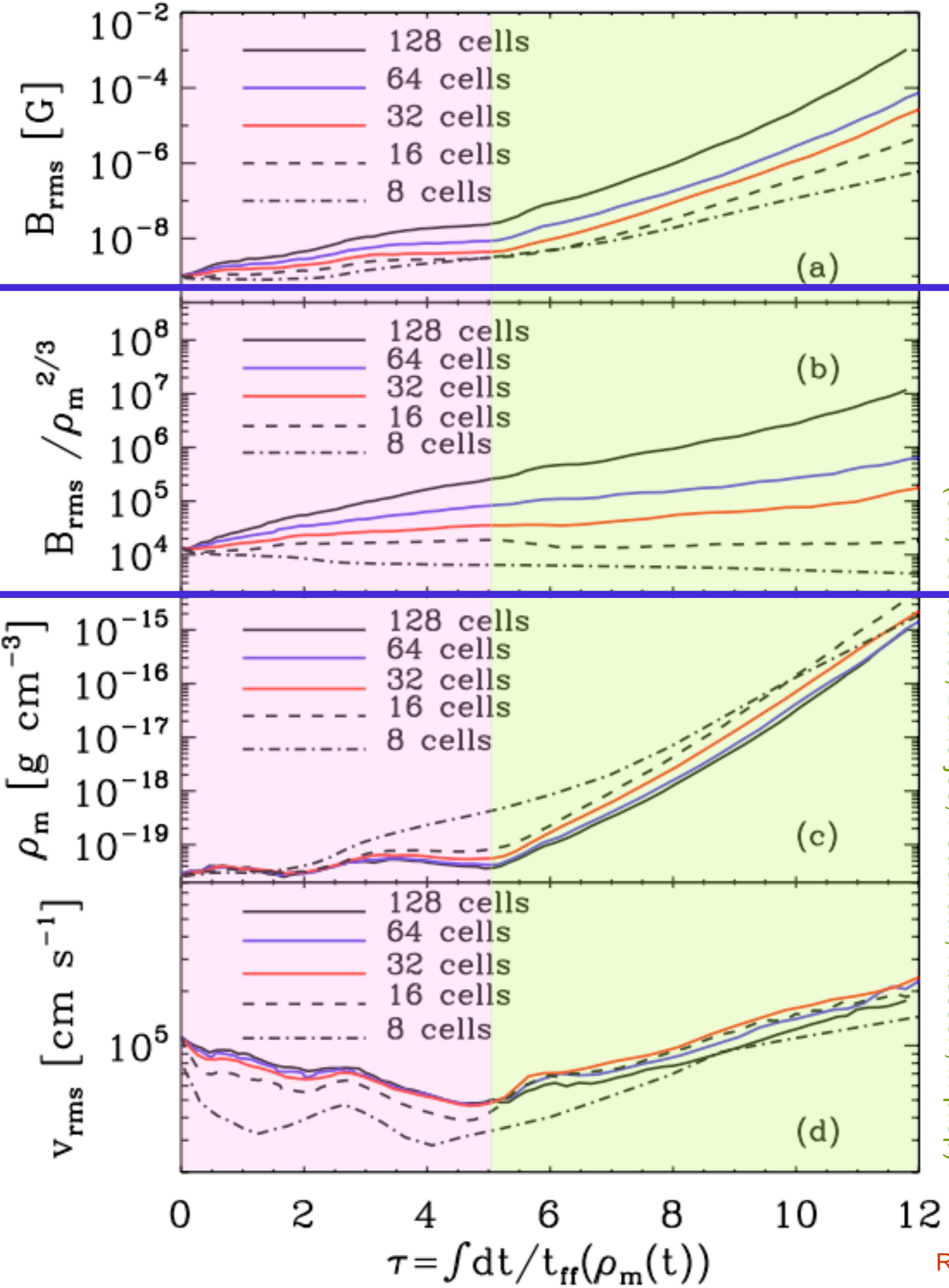
decay of turbulence



(Sur, Schleicher, Banerjee, Federrath, Klessen, in prep)

gravitational collapse,
accretion driven turbulence

decay of turbulence



(Sur, Schleicher, Banerjee, Federrath, Klessen, in prep)

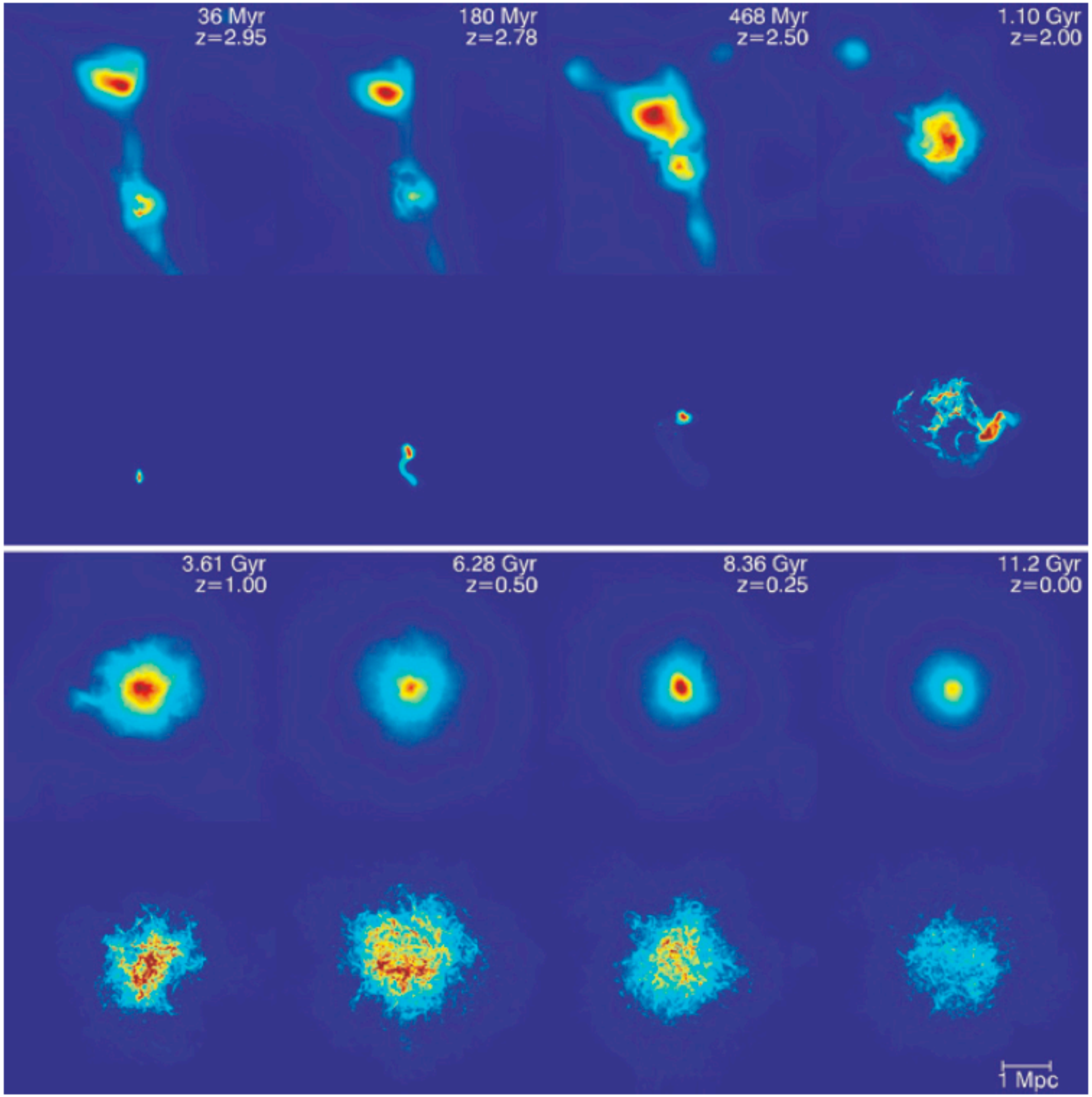
gravitational collapse,
accretion driven turbulence

small-scale turbulent dynamo

- small-scale turbulent dynamo can generate dynamically significant B-fields in the during first star formation!
- expected saturation level ~10% - 20% of equipartition value (Subramanian & Brandenburg 2005)
- needs very high resolution to be seen:

cells per Jeans length	max. refinement	max. effective resolution	min.cell size [cm]	mean growth rate Γ
8	10	4096	1.17×10^{16}	$--$
16	11	8192	5.86×10^{15}	0.021
32	12	16384	2.93×10^{15}	0.108
64	13	32768	1.46×10^{15}	0.188
128	14	65536	7.32×10^{14}	0.25

similar processes on scales of galaxy clusters



density

magnetic energy density

density

magnetic energy density

Xu et al. (2009)

diffusion

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….

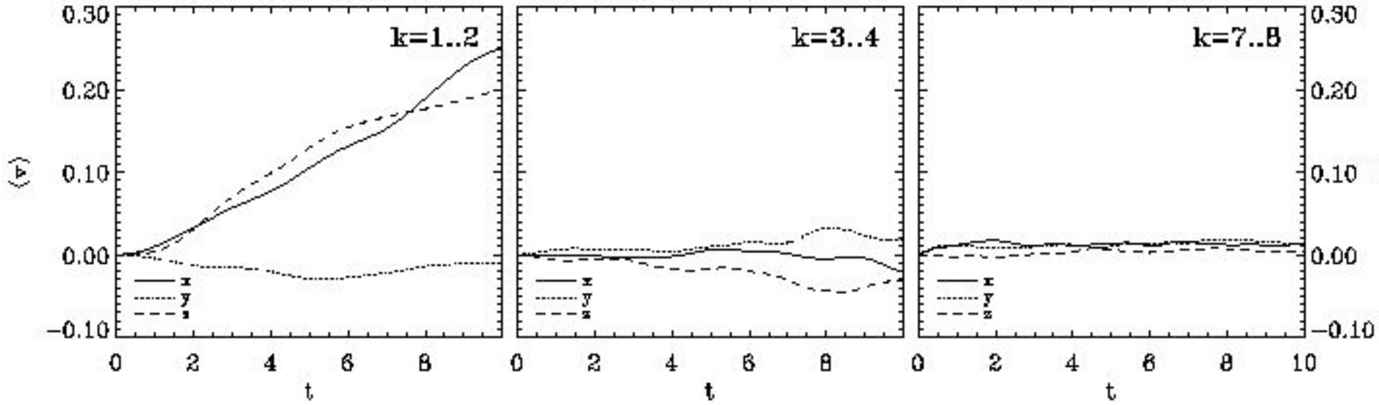
$$\xi_{\vec{r}}^2(t-t') = \langle [\vec{r}_i(t) - \vec{r}_i(t')]^2 \rangle_i$$

mean particle displacement for a given time interval

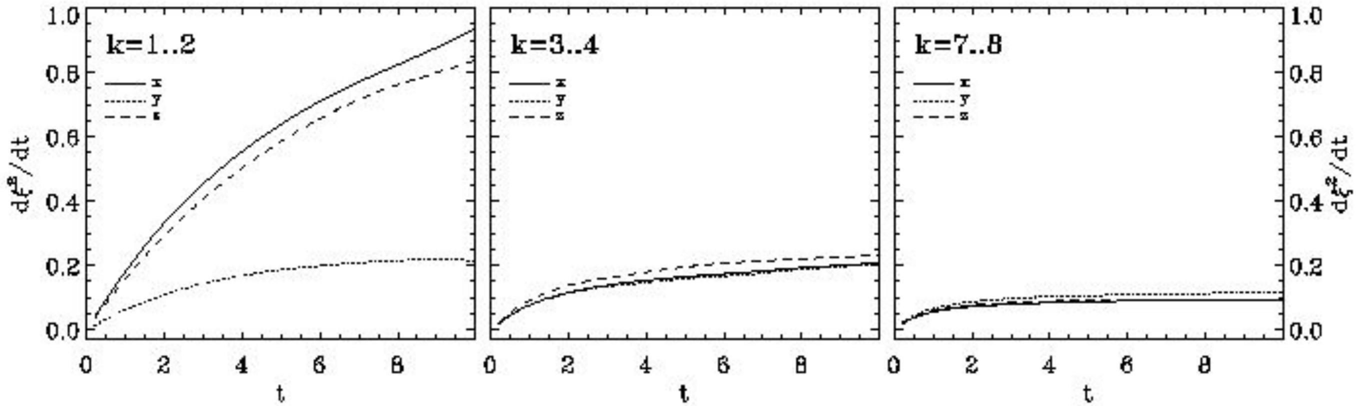
$$\frac{\partial n}{\partial t} = D\nabla^2 n \qquad D(t) = \frac{d\xi_{\vec{r}}^2(t)}{dt} = 2\langle \vec{r}_i(t)\cdot\vec{v}_i(t)\rangle_i$$

Turbulent diffusion II

- Large-scale turbulence associated with bulk motion.



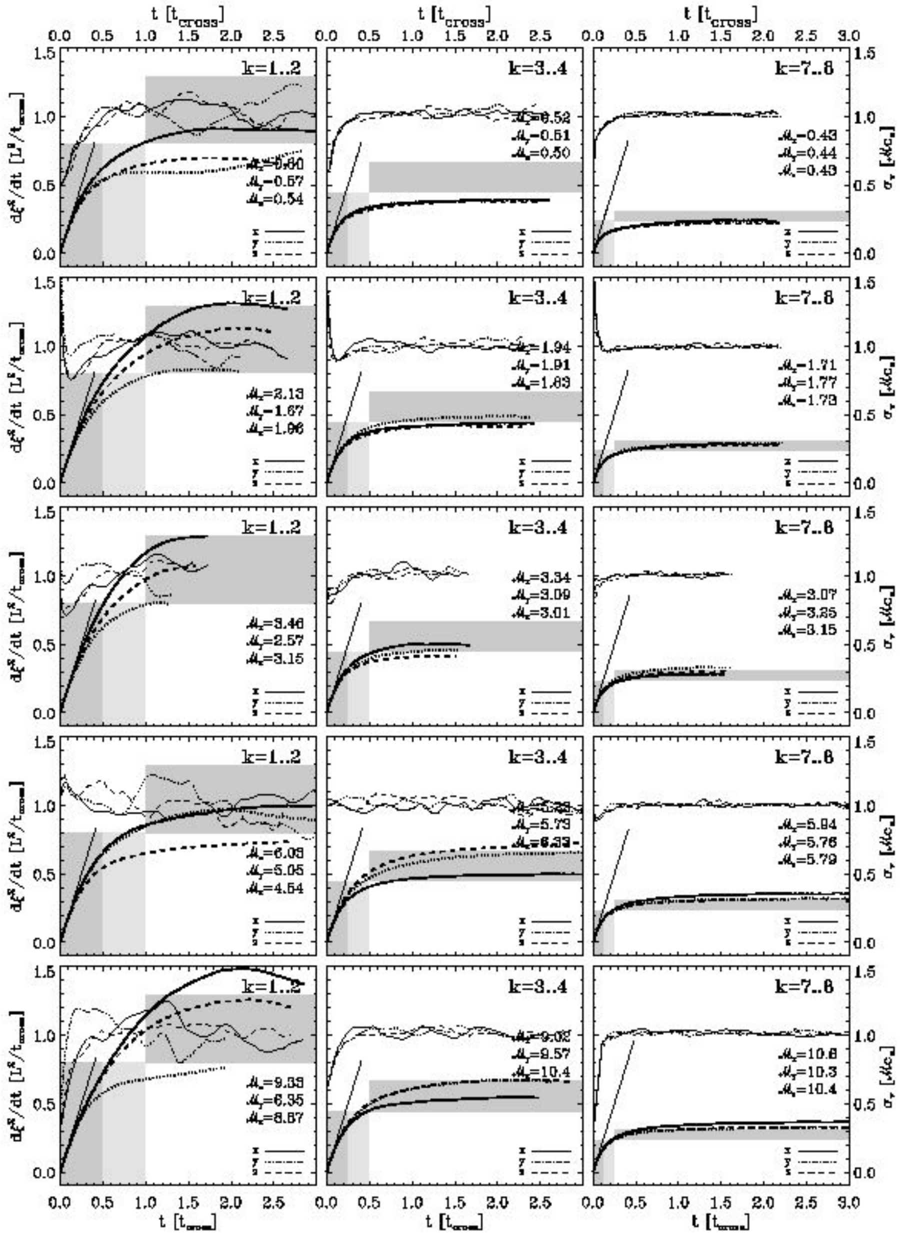
- Super-diffusive behavior.



(from Klessen & Lin 2003, PRE)

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 $\ell = L/k$ = shock sep.



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

summary

summary

- modeling ISM turbulence & star formation is feasable
  - more physics is needed (chemistry, radiation field, realistic sources of turbulence, etc.)
- caveat: all LES of ISM turbulence model "crude oil" not interstellar gas
- examples
  - stellar mass spectrum
  - molecular cloud formation
  - generation of the first dynamically significant magnetic fields in the universe
  - effective diffusivity in isotropic supersonic turbulence

thanks