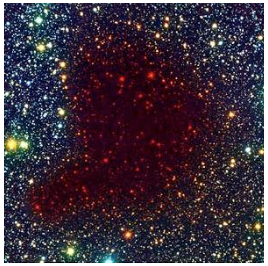
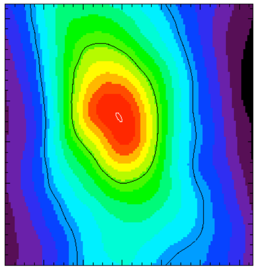
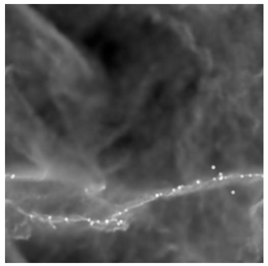
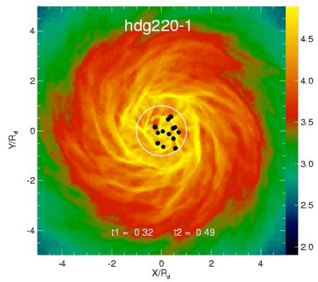
T H A N K S

What can we learn from present-day star formation about past star formation?









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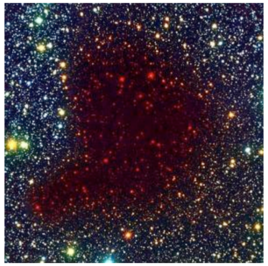
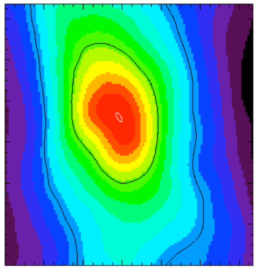
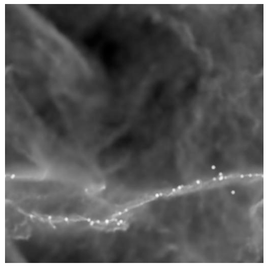
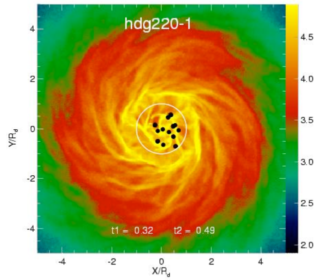
similarities between star formation now and then









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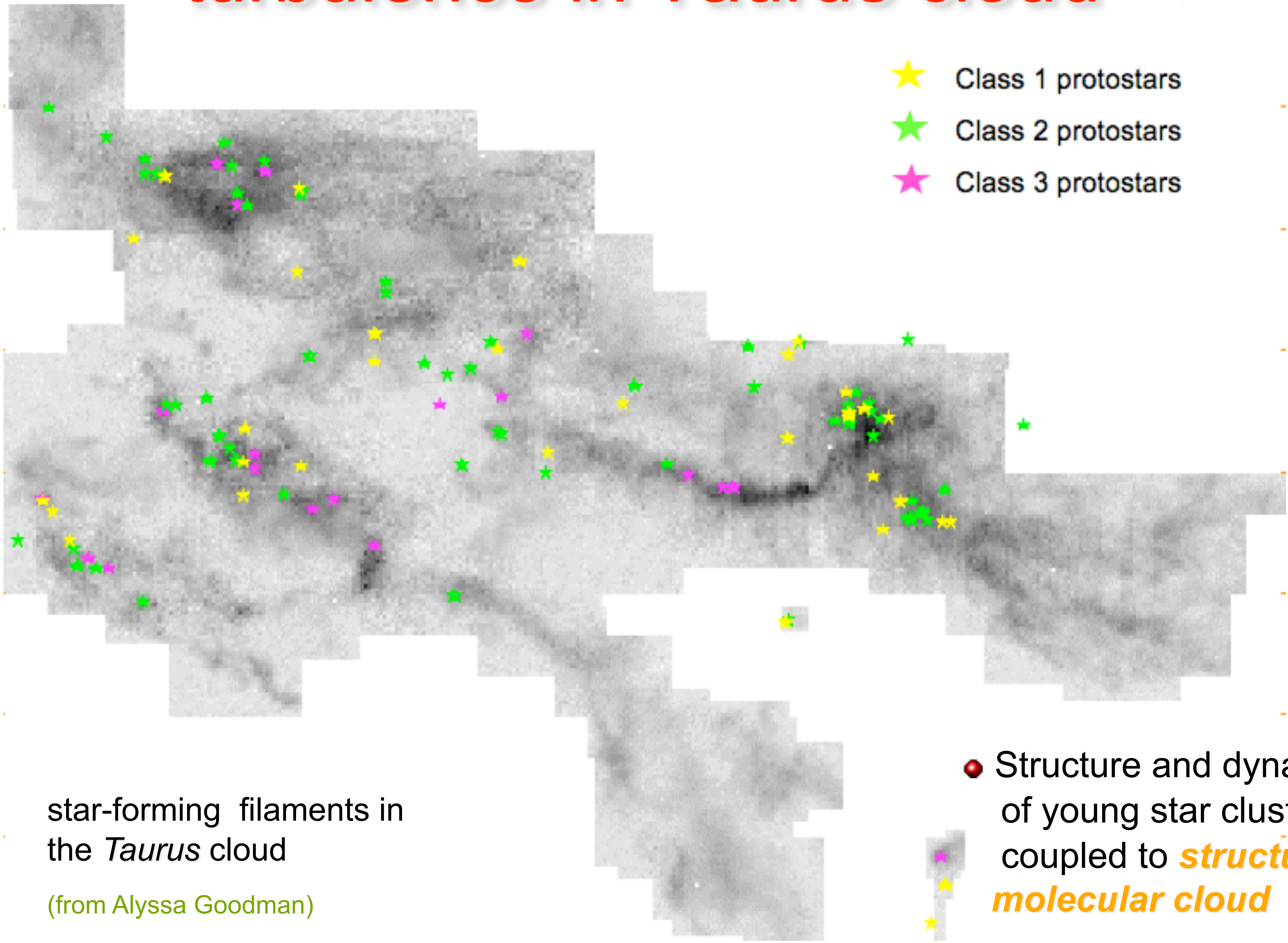
agenda

- turbulence
- cluster environment
- thermodynamics
- magnetic fields
- feedback

→ *influence on the stellar IMF*

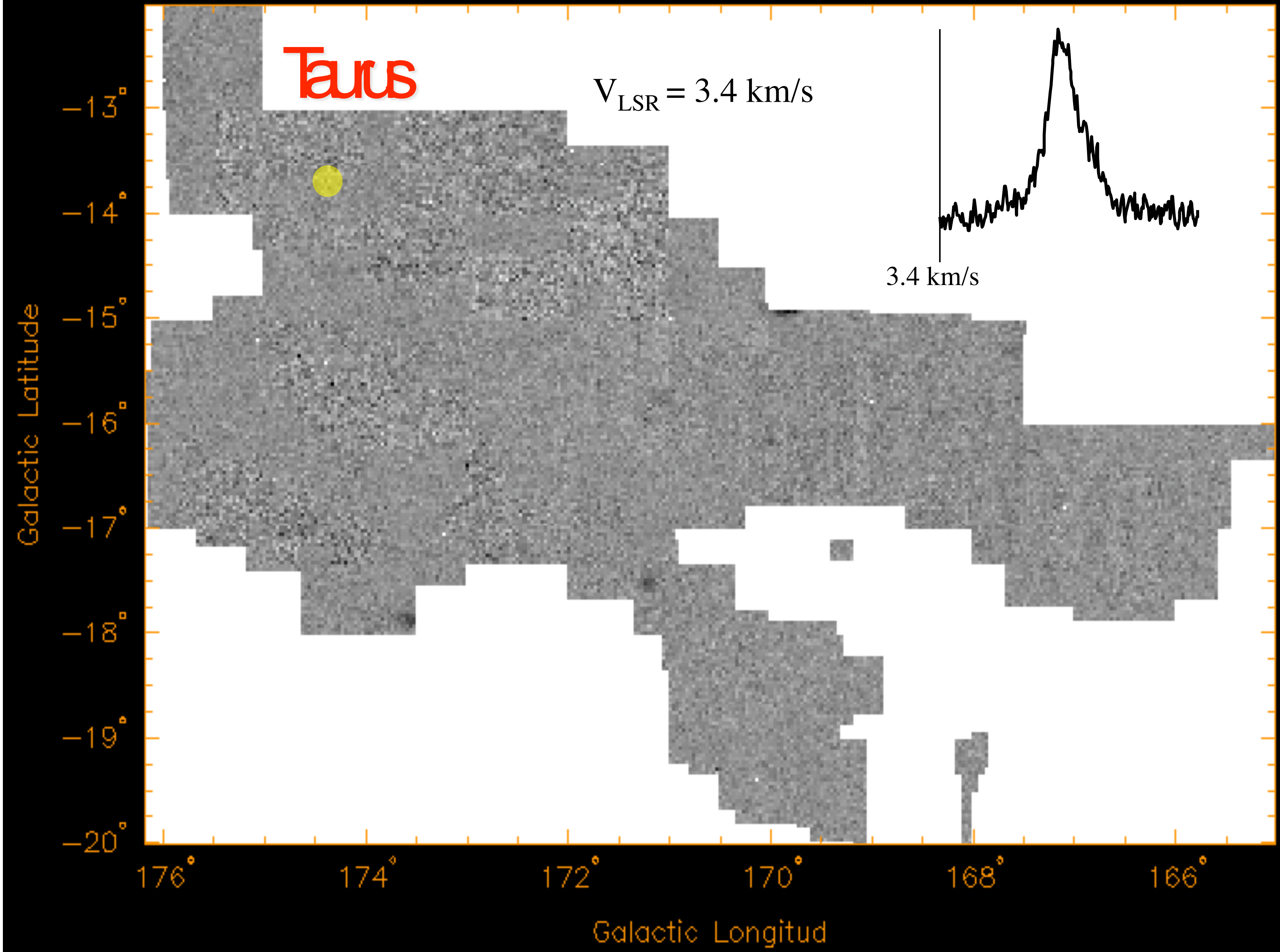
turbulence in Taurus cloud



star-forming filaments in the *Taurus* cloud

(from Alyssa Goodman)

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



Taurus
VLSR = 3.4 km/s
3.4 km/s
−13°
−14°
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Galactic Latitude
176°
174°
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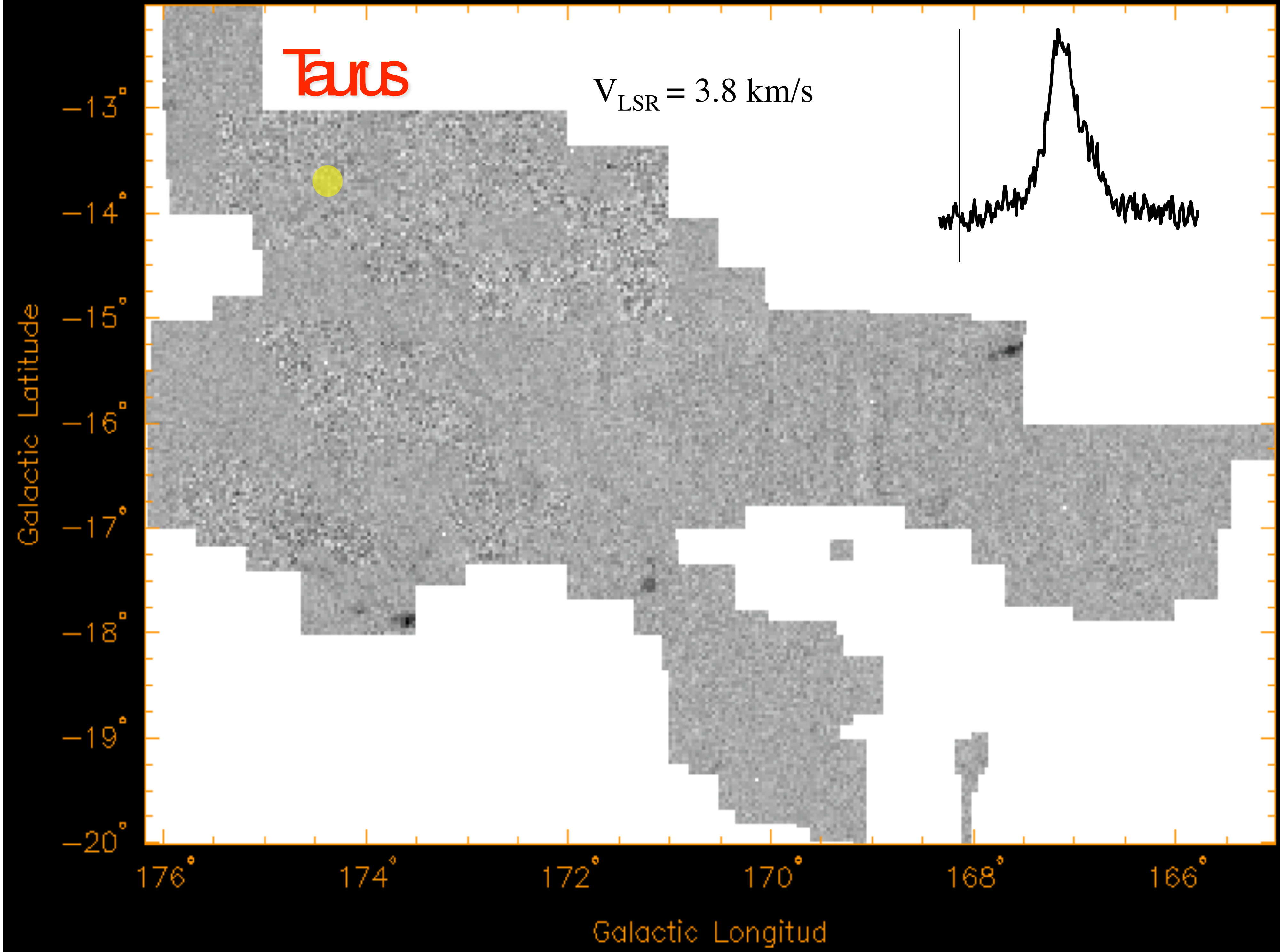
168°
166°
Galactic Longitud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V_LSR = 3.8 km/s
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Galactic Latitude
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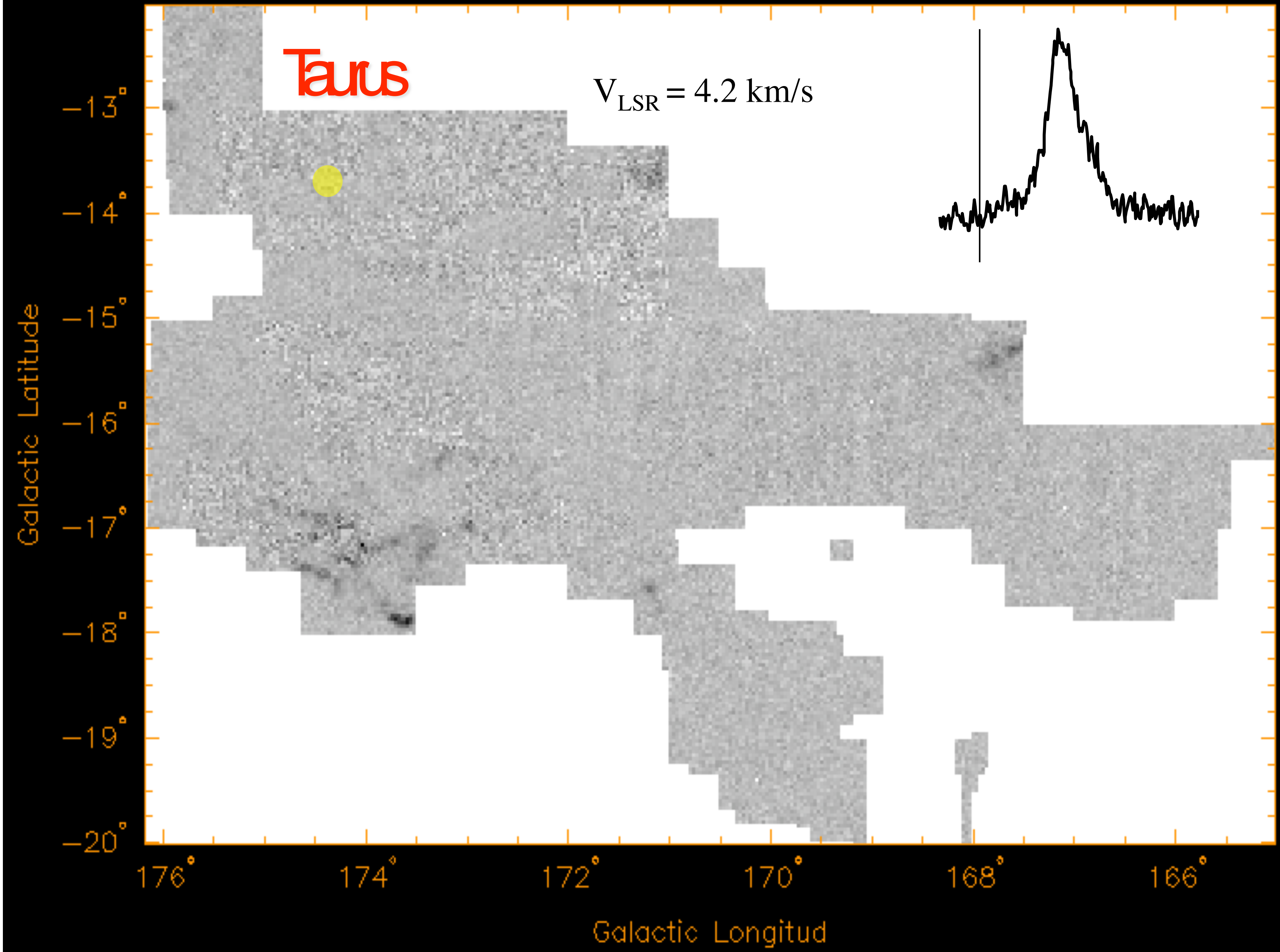
Galactic Longitud



Taurus
V_LSR = 4.2 km/s
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Galactic Latitude
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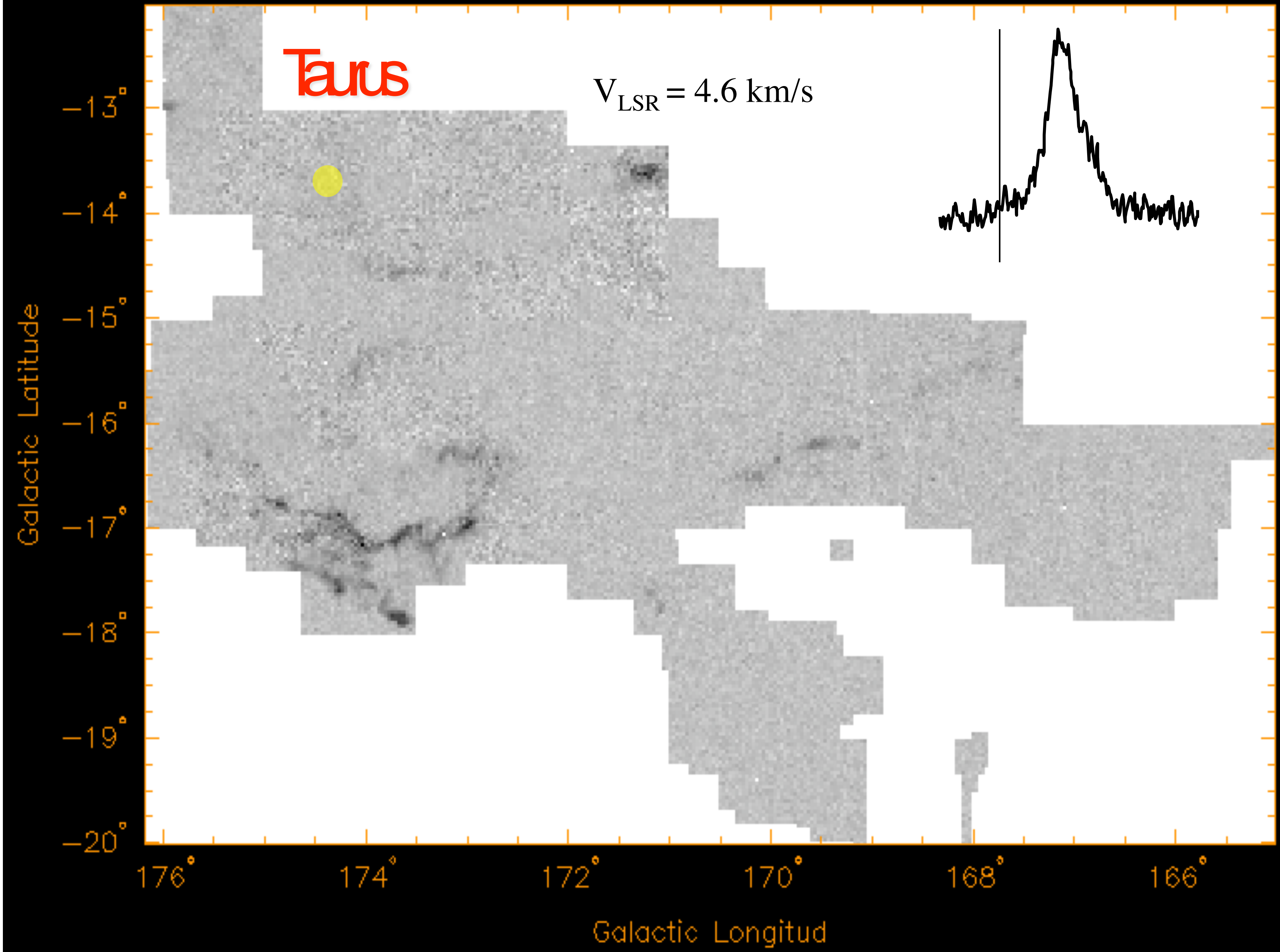
Galactic Longitud



Taurus
V_{LSR} = 4.6 km/s
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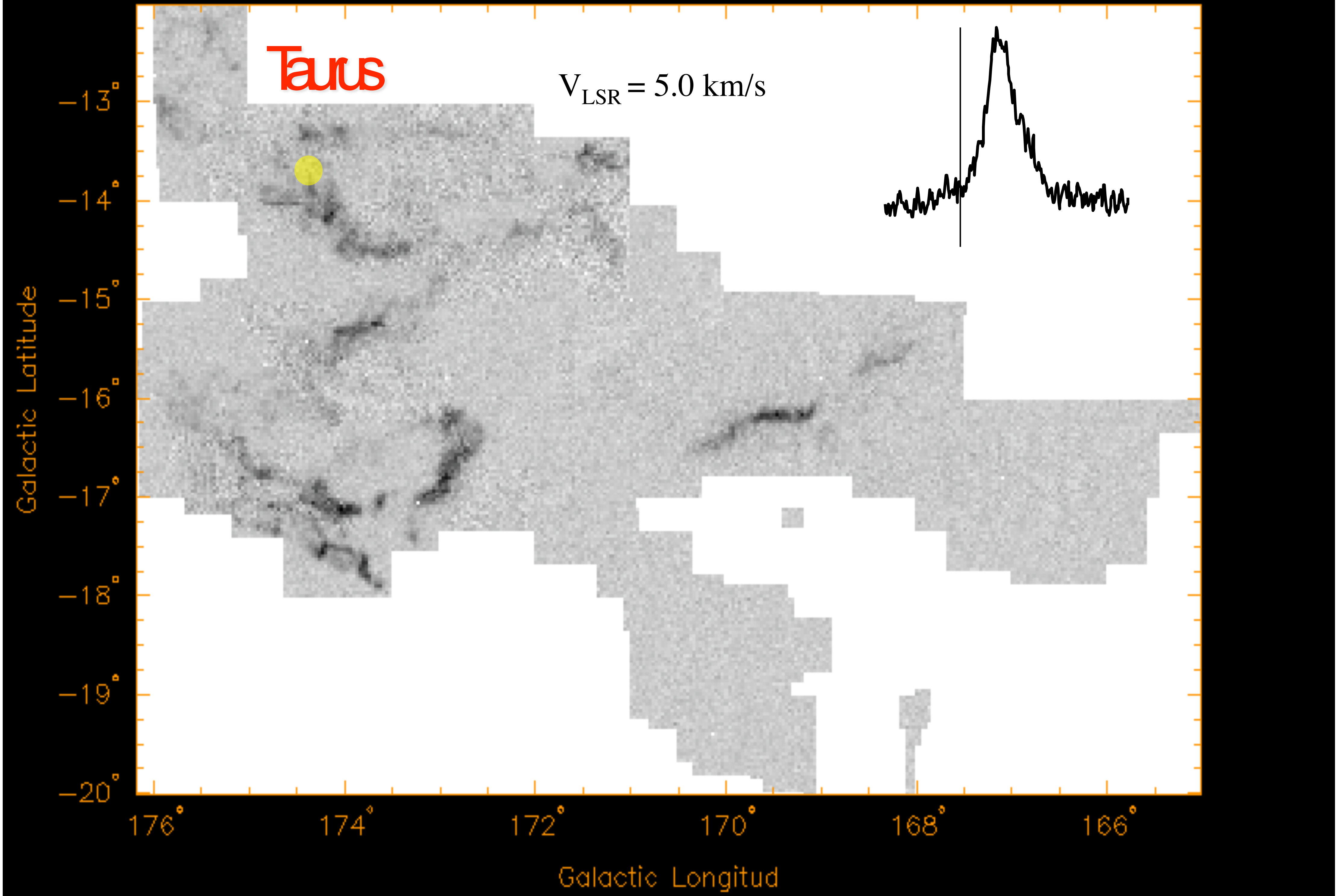
Galactic Longitud



Taurus
V_LSR = 5.0 km/s
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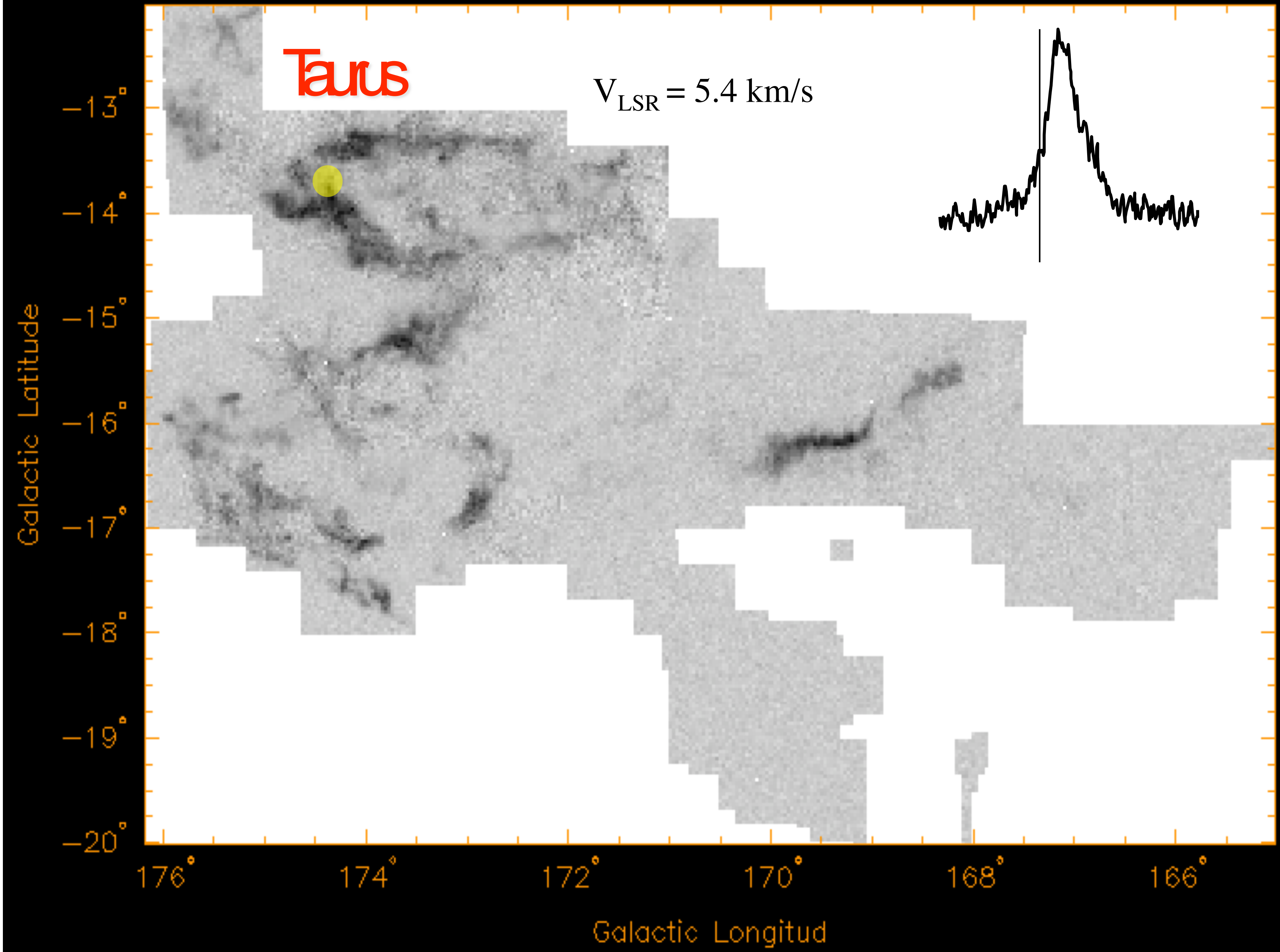
Galactic Longitud



Taurus
VLSR = 5.4 km/s
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Galactic Latitude
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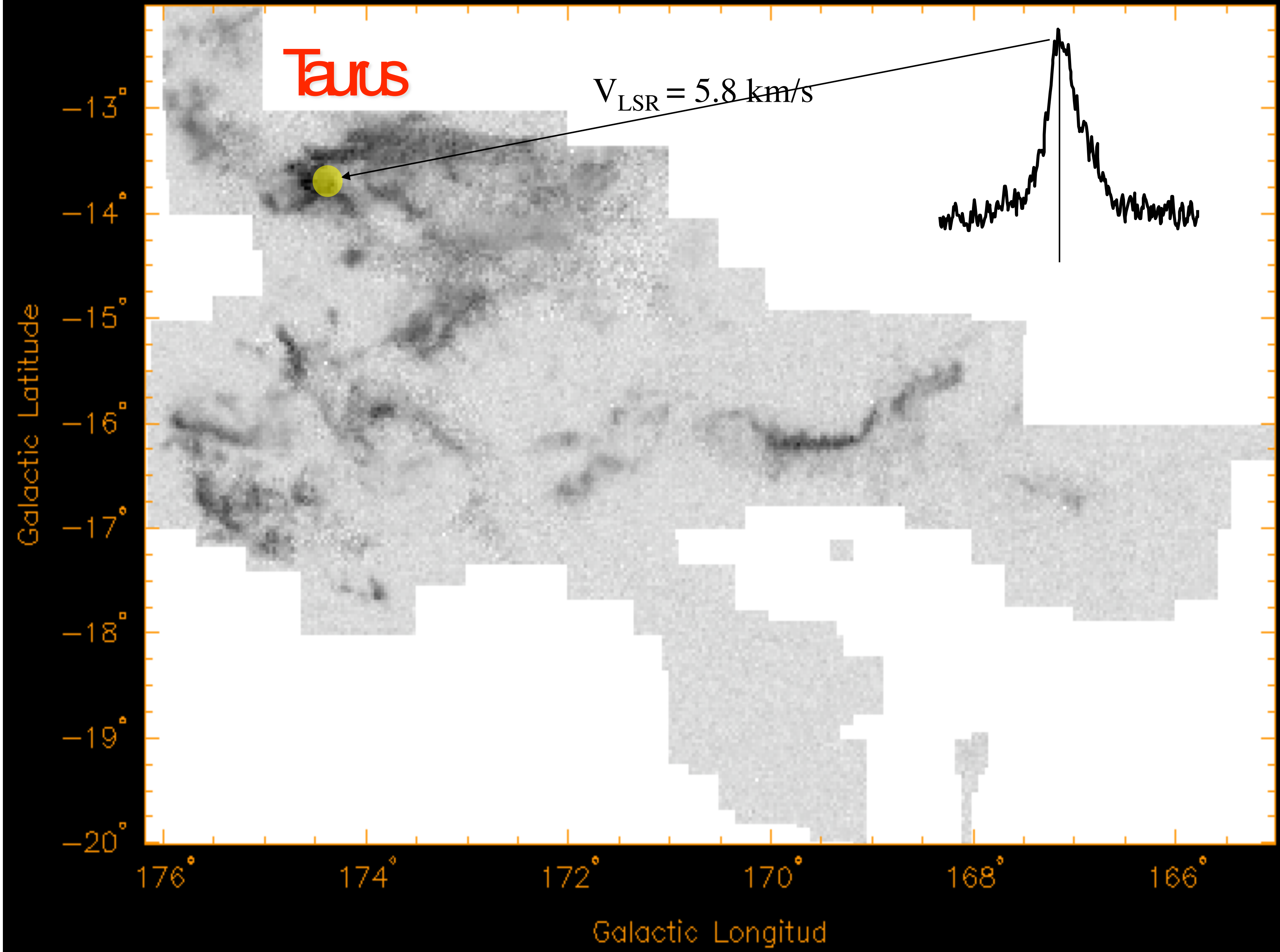
Galactic Longitud


Taurus
VLSR = 5.8 km/s
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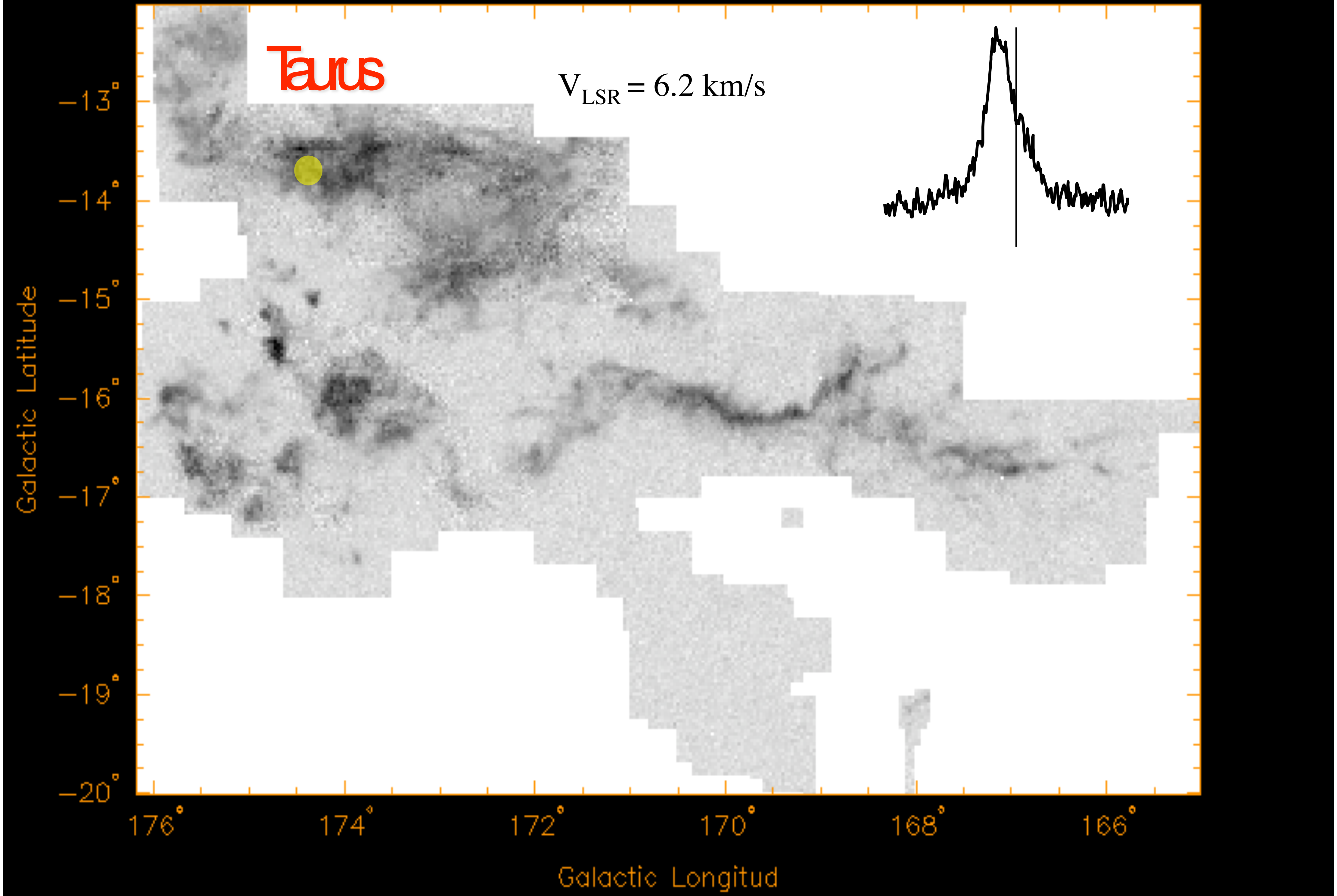
Galactic Longitud


Taurus
V_LSR = 6.2 km/s
Galactic Latitude
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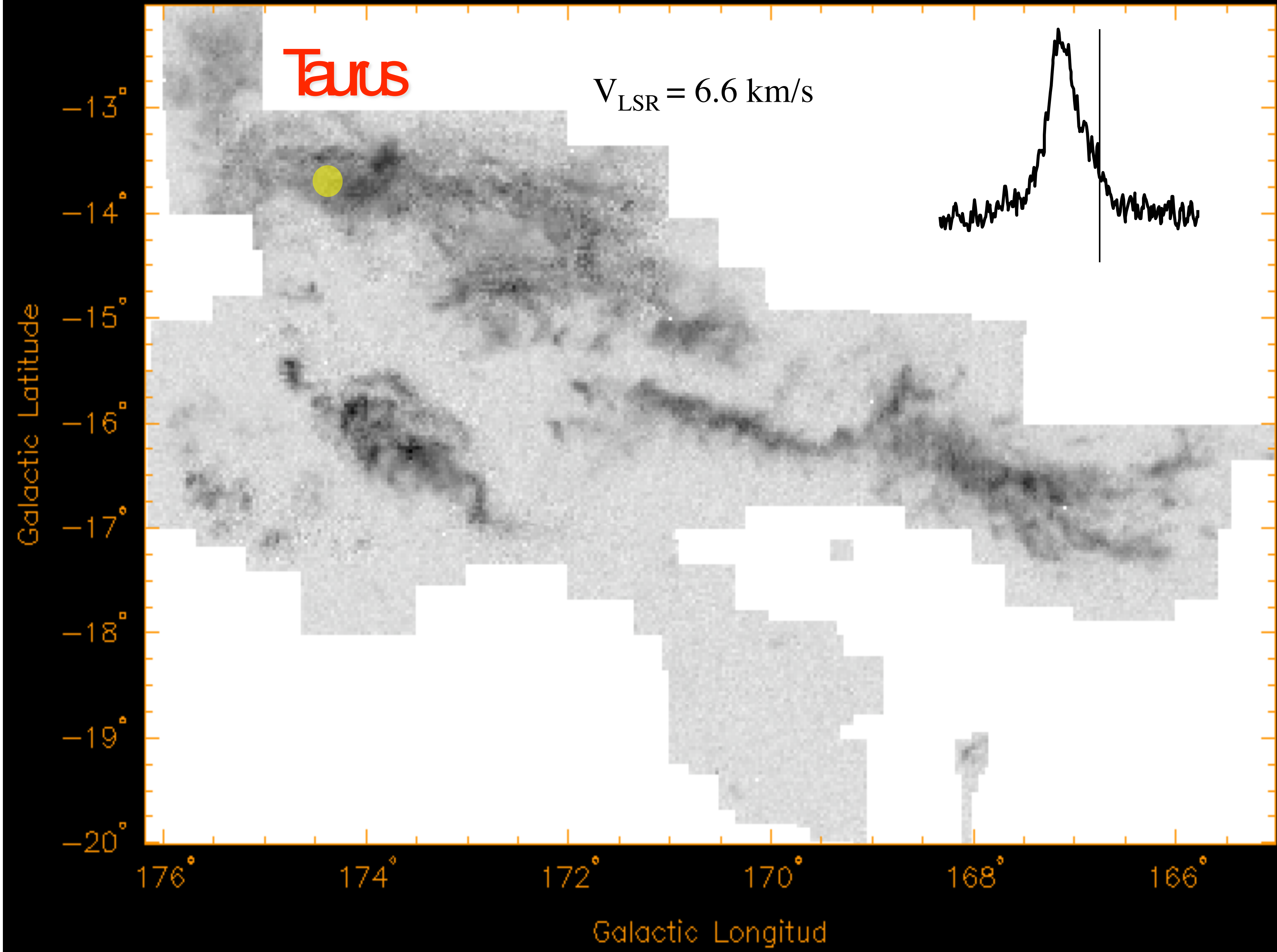
Galactic Longitud



Taurus
VLSR = 6.6 km/s
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Galactic Latitude
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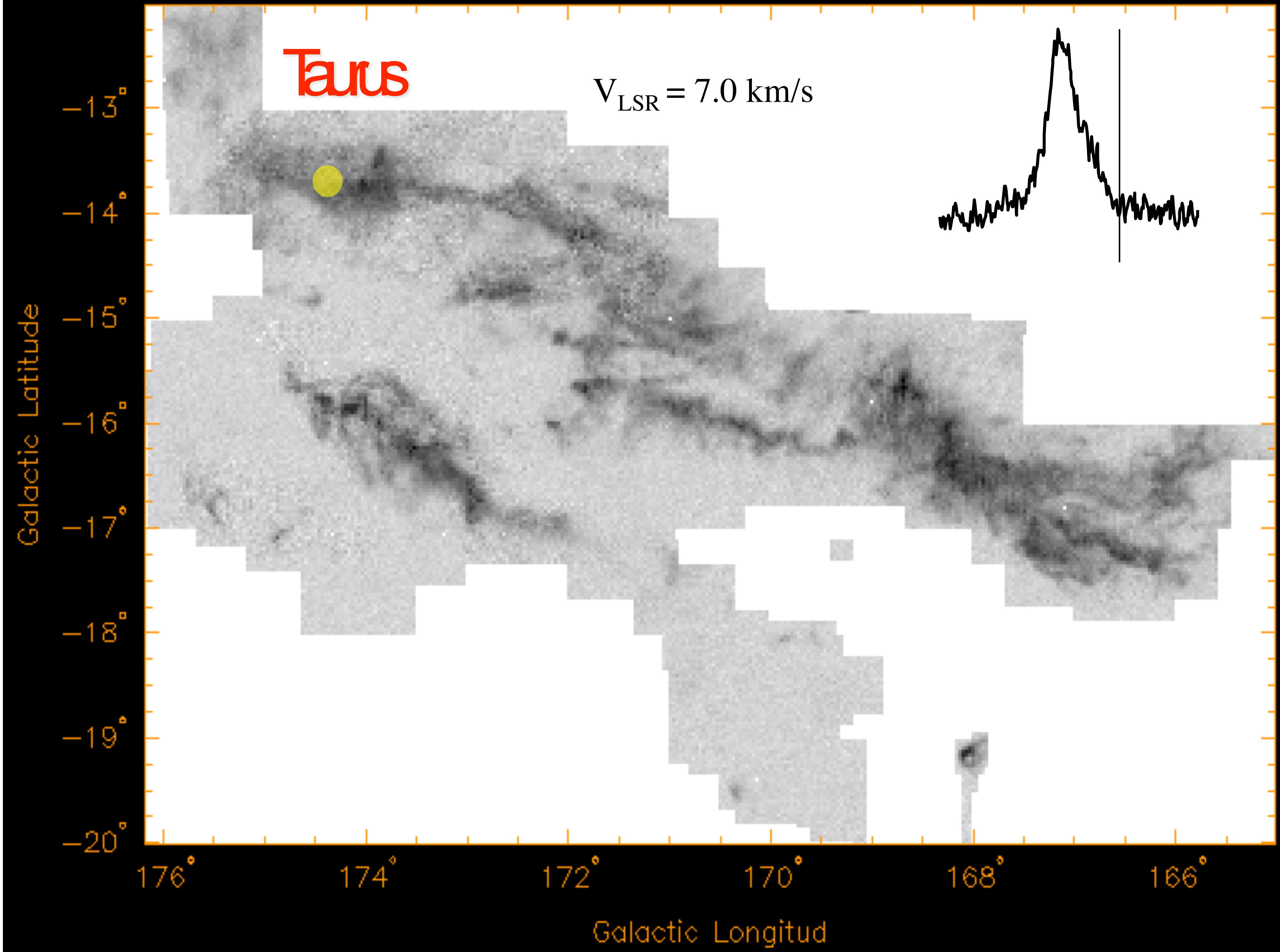
Galactic Longitud


Taurus
V_LSR = 7.0 km/s
−13°
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−15°
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Galactic Latitude
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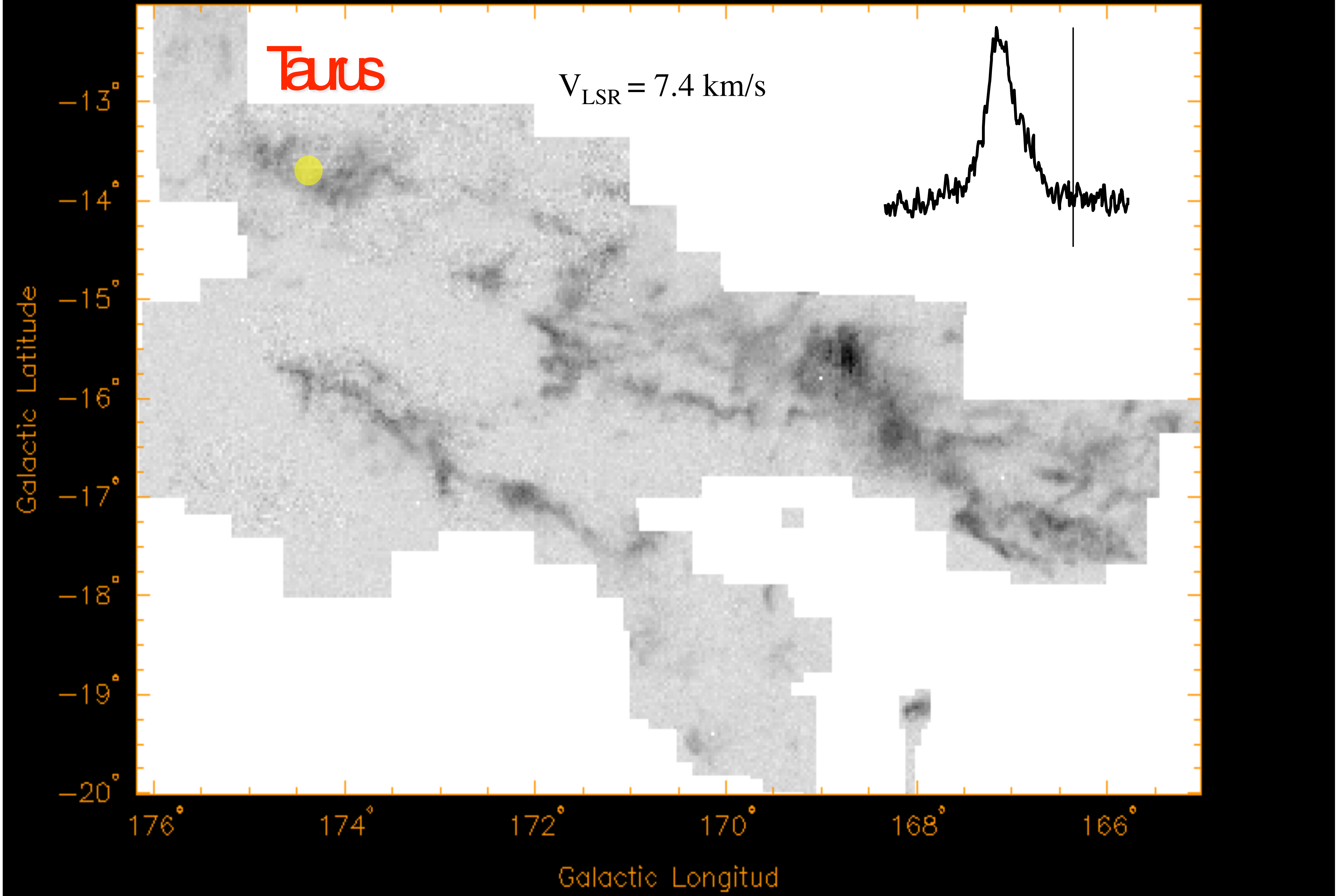
Galactic Longitud


Taurus
V_LSR = 7.4 km/s
Galactic Latitude
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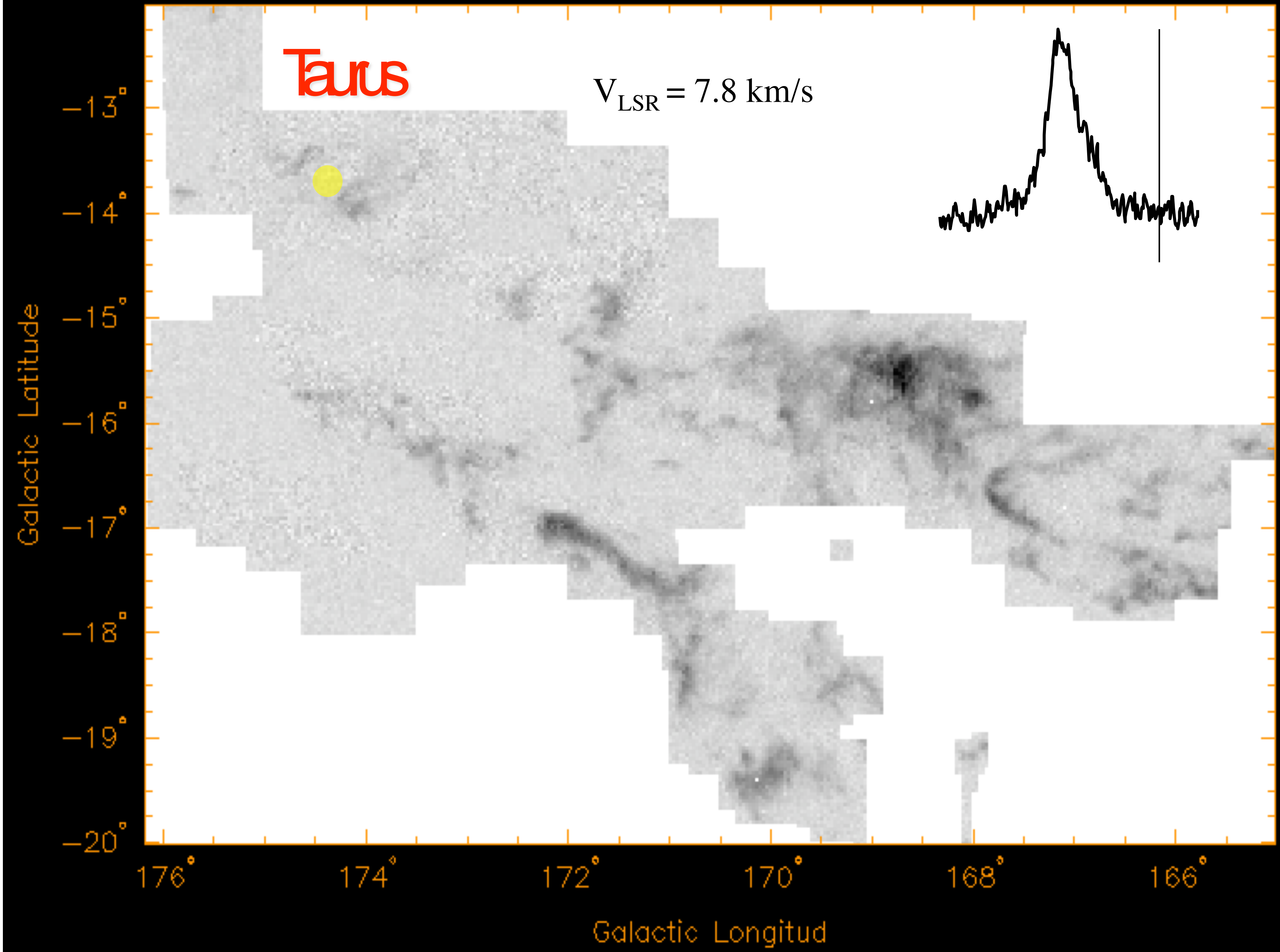
Galactic Longitud



Taurus
V_LSR = 7.8 km/s
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−15°
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Galactic Latitude
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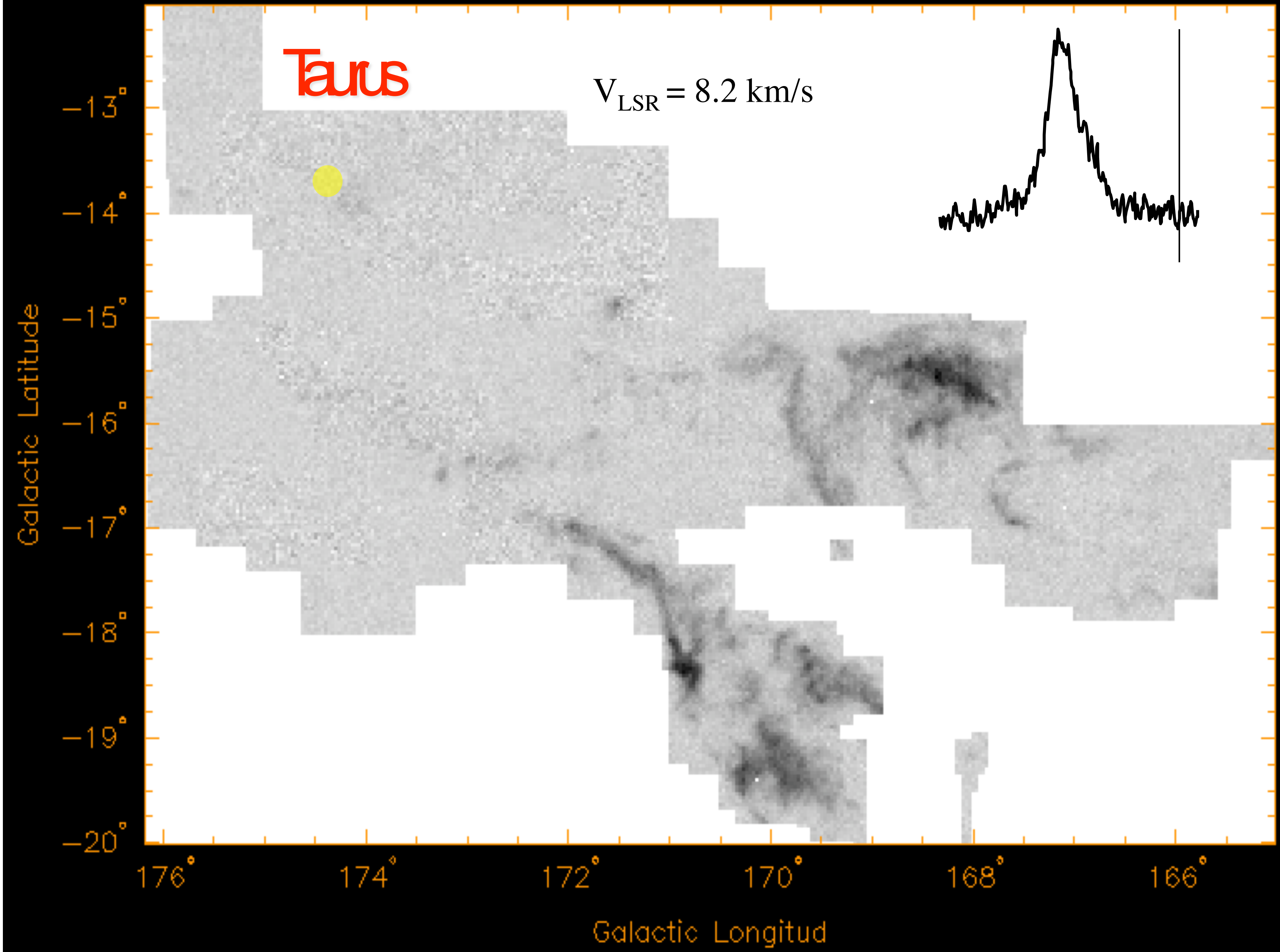
Galactic Longitud



Taurus
VLSR = 8.2 km/s
Galactic Latitude
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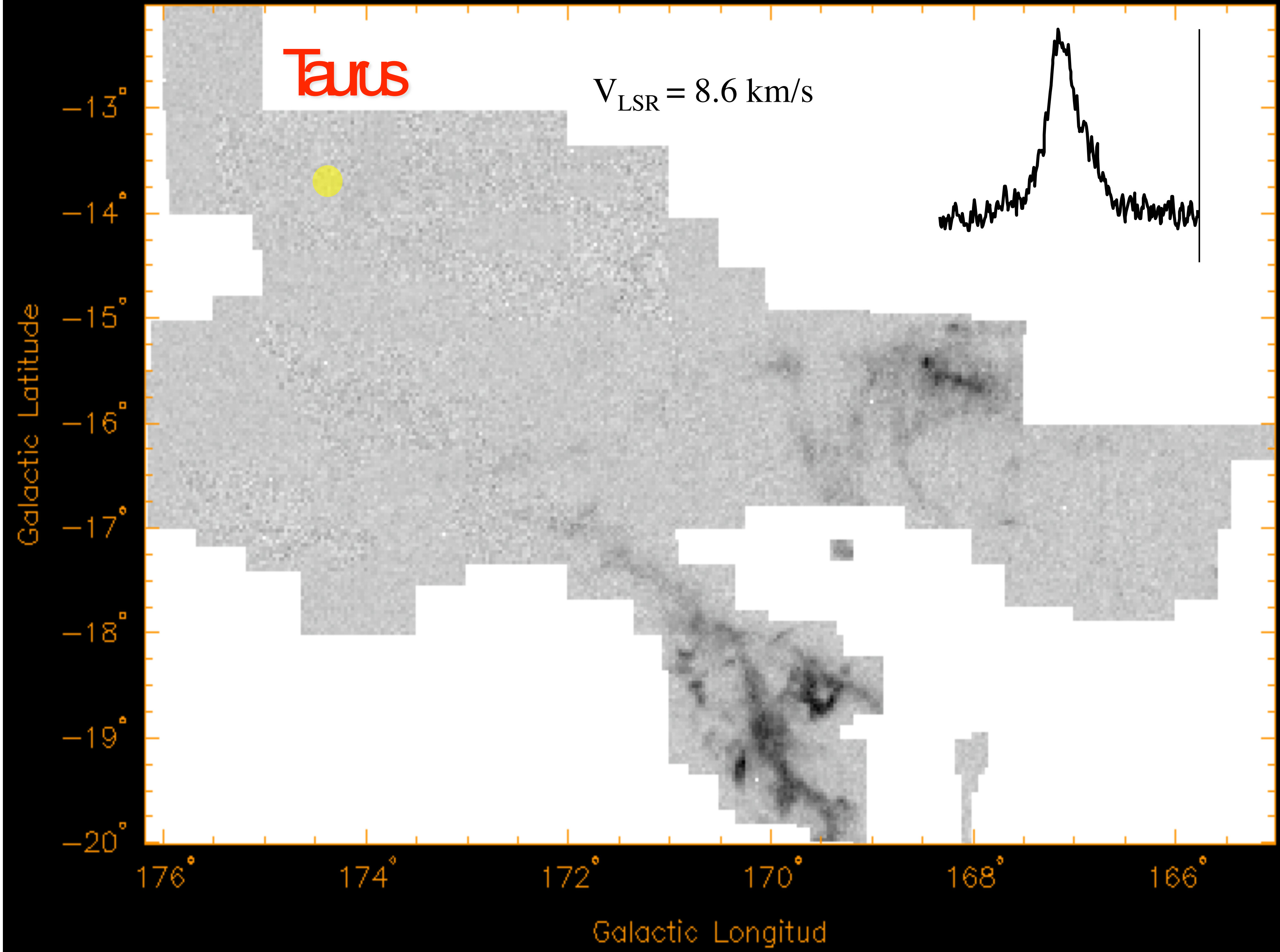
Galactic Longitud


Taurus
V_{LSR} = 8.6 km/s
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Galactic Latitude
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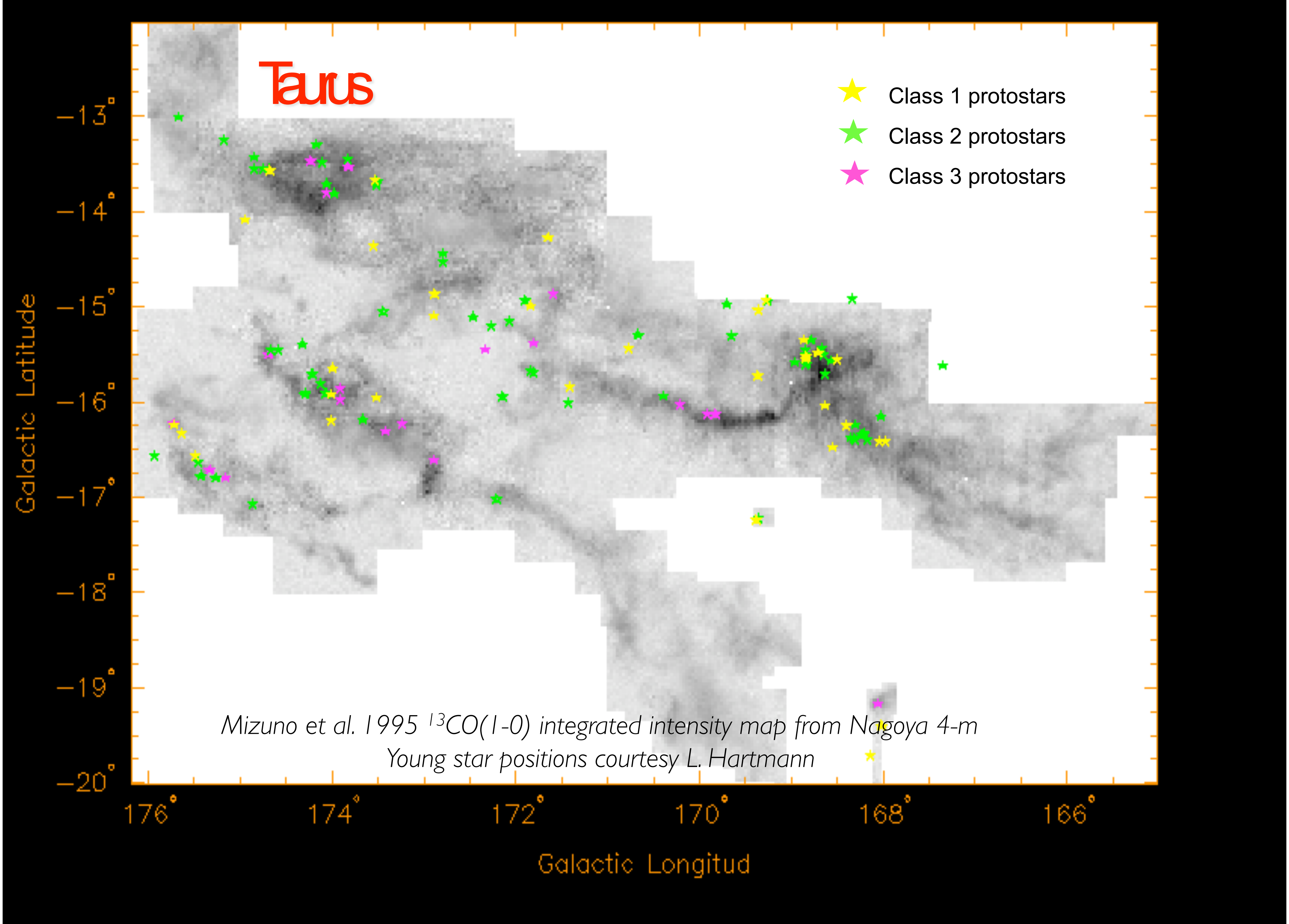
Galactic Longitud


Taurus
Class 1 protostars
Class 2 protostars
Class 3 protostars
Galactic Latitude
−13°
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−19°
−20°
176°
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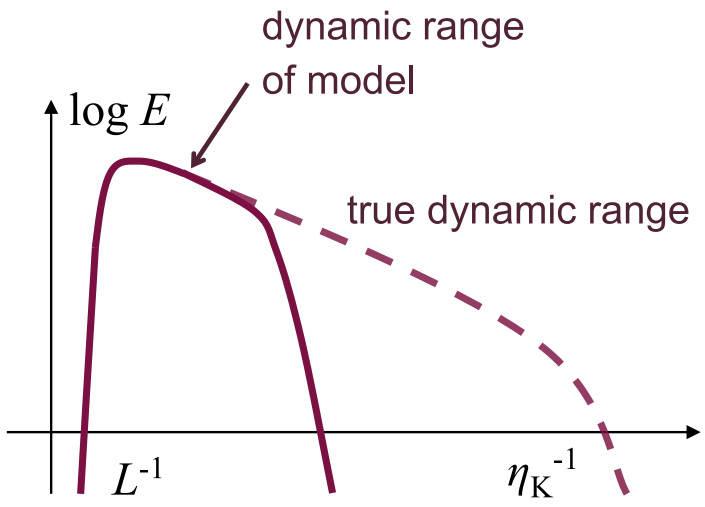
168°
166°
Galactic Longitud
Mizuno et al. 1995 13CO(1-0) integrated intensity map from Nagoya 4-m
Young star positions courtesy L. Hartmann

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?



gravoturbulent star formation

- Idea:

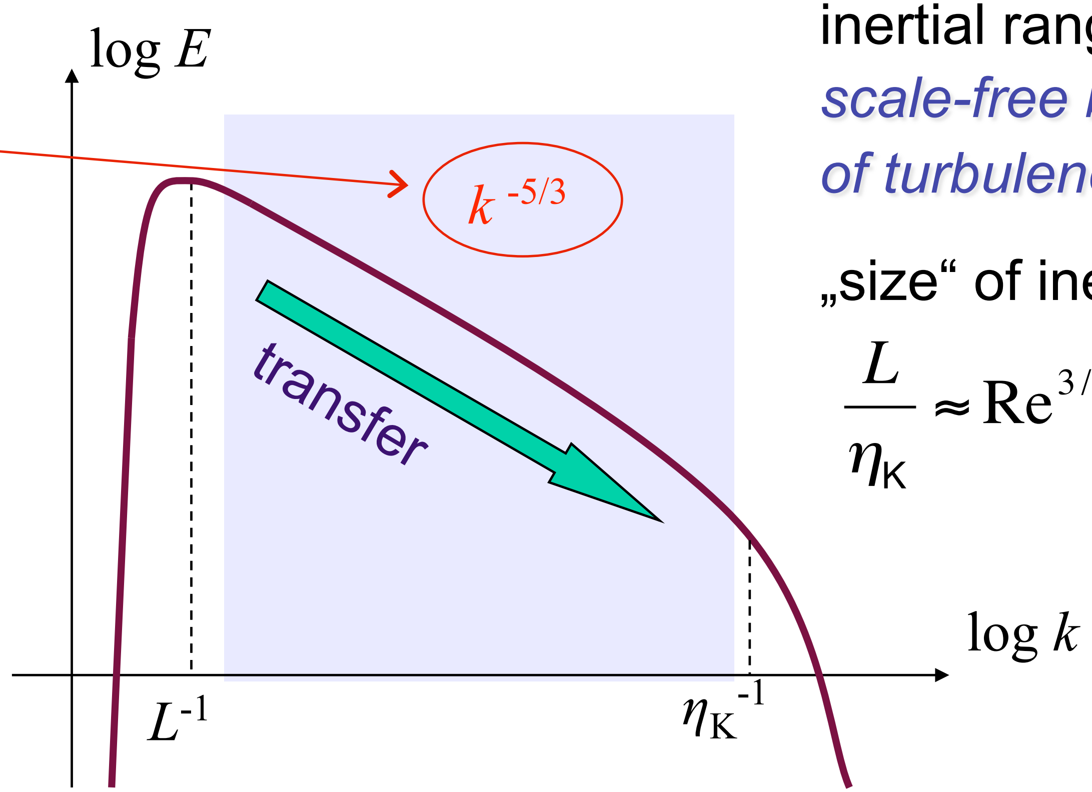
Star formation is controlled by interplay between gravity and supersonic turbulence!

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

(e.g., Larson, 2003, Rep. Prog. Phys, 66, 1651;
or Mac Low & Klessen, 2004, Rev. Mod. Phys., 76, 125)

turbulent cascade

Kolmogorov (1941) theory
incompressible turbulence



energy
input
scale

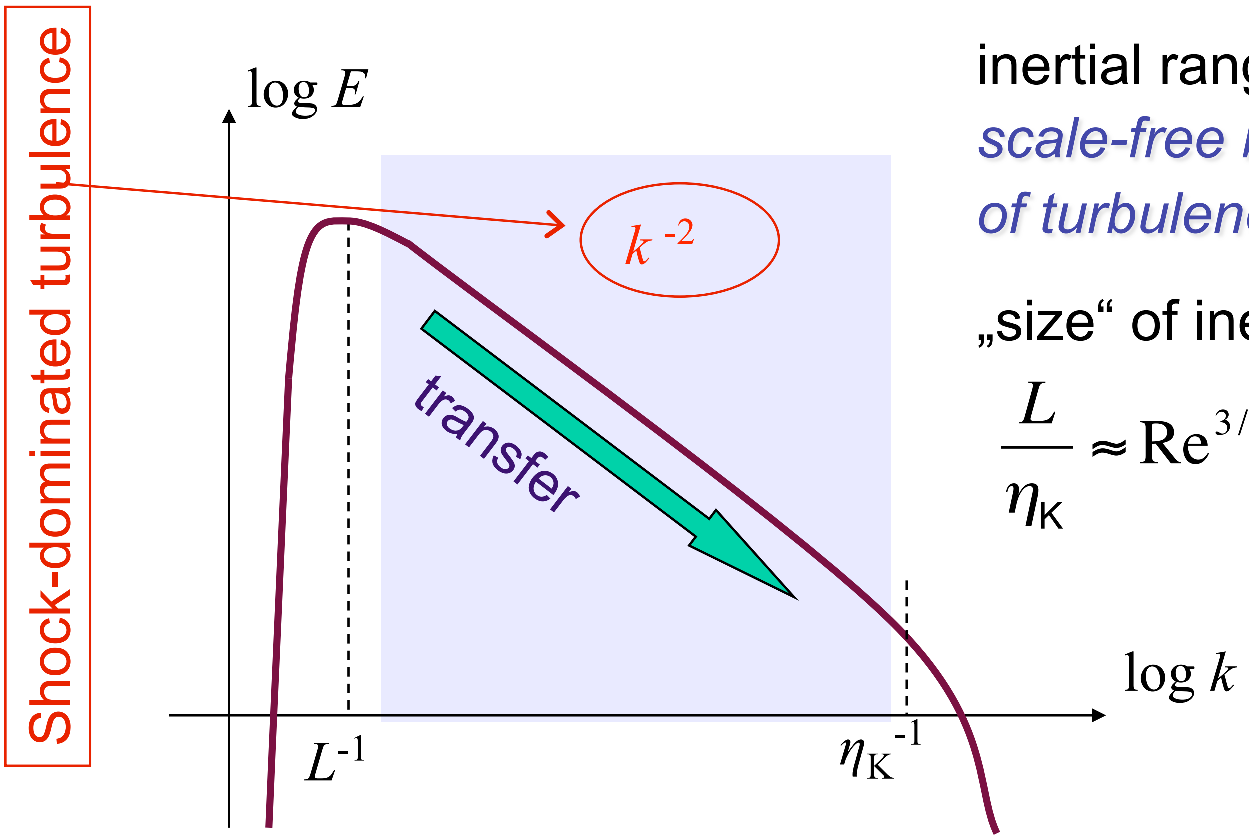
energy
dissipation
scale

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

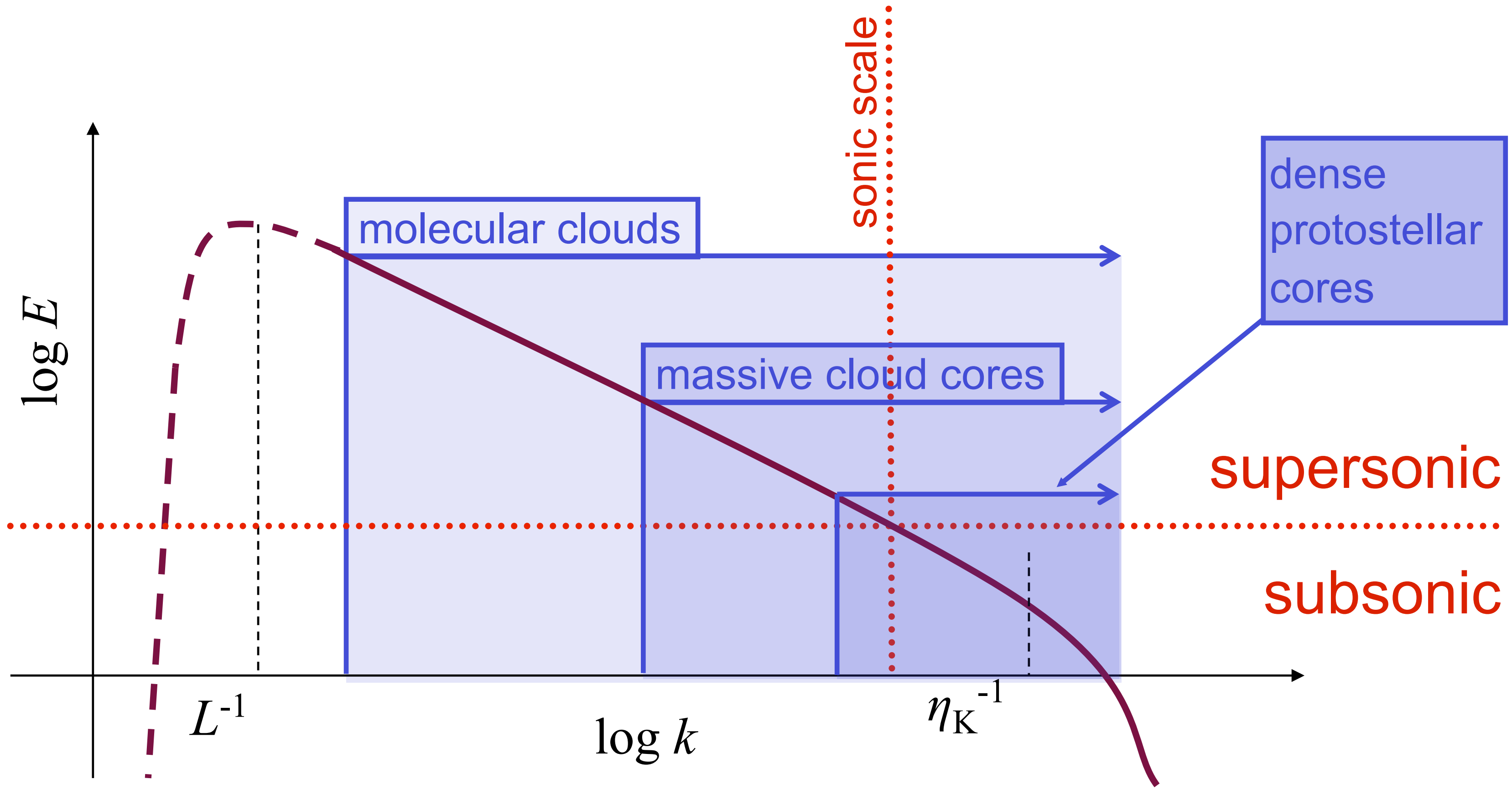
energy
dissipation
scale

inertial range:
scale-free behavior of turbulence

„size" of inertial range:

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

turbulent cascade in ISM



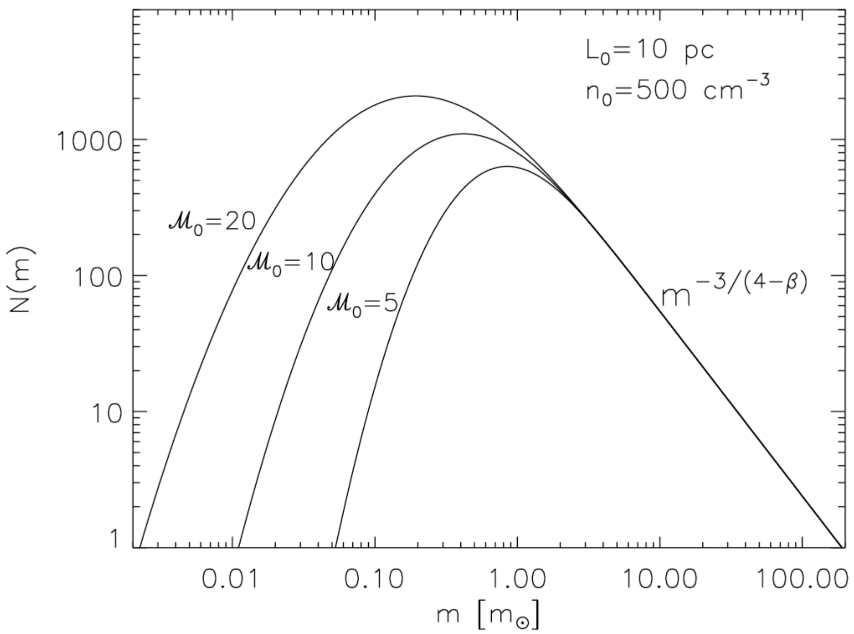
energy source & scale
NOT known
(supernovae, winds,
spiral density waves?)

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

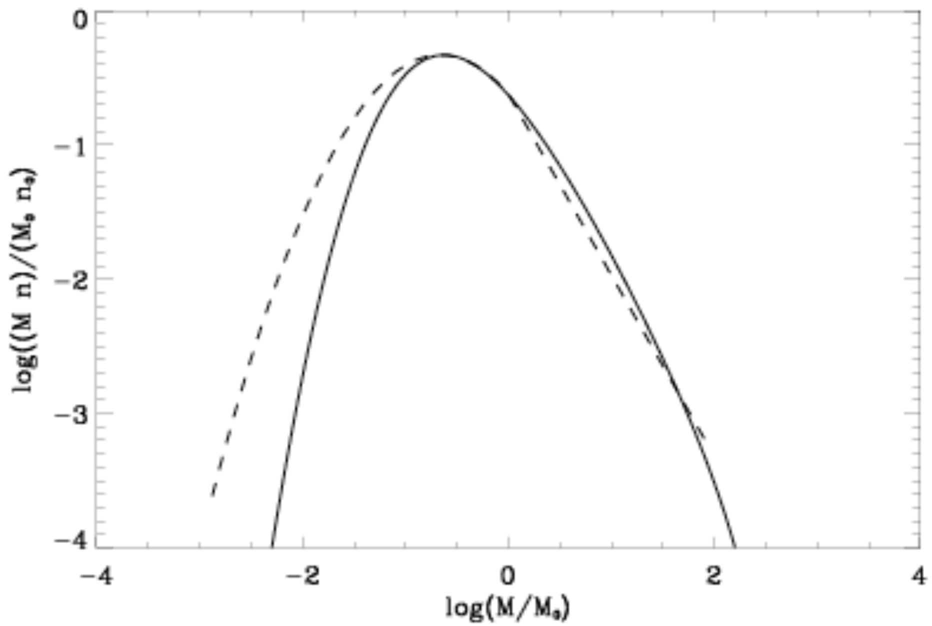
dissipation scale not known
(ambipolar diffusion,
molecular diffusion?)

gravotrbulent fragmentation

- *turbulence* sets power-law distribution of clumps, *gravity* then selects for collapse

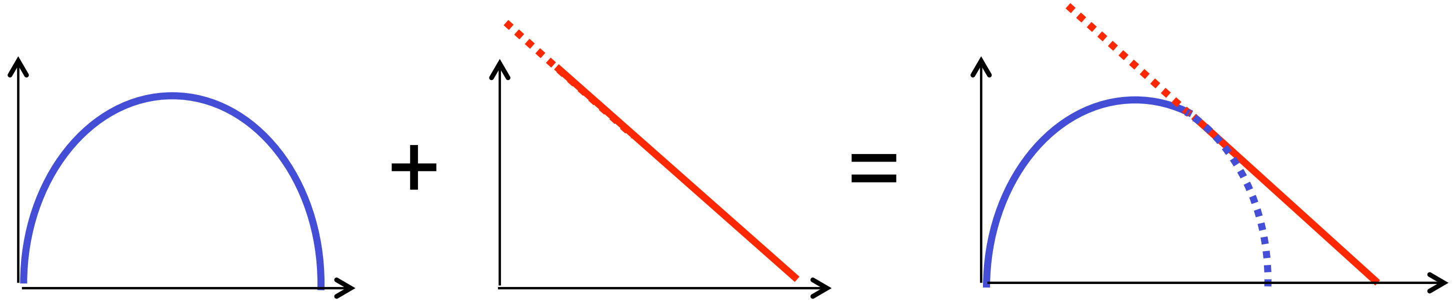


•Padoan & Nordlund (2002)



Hennebelle & Chabrier (2008)

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*

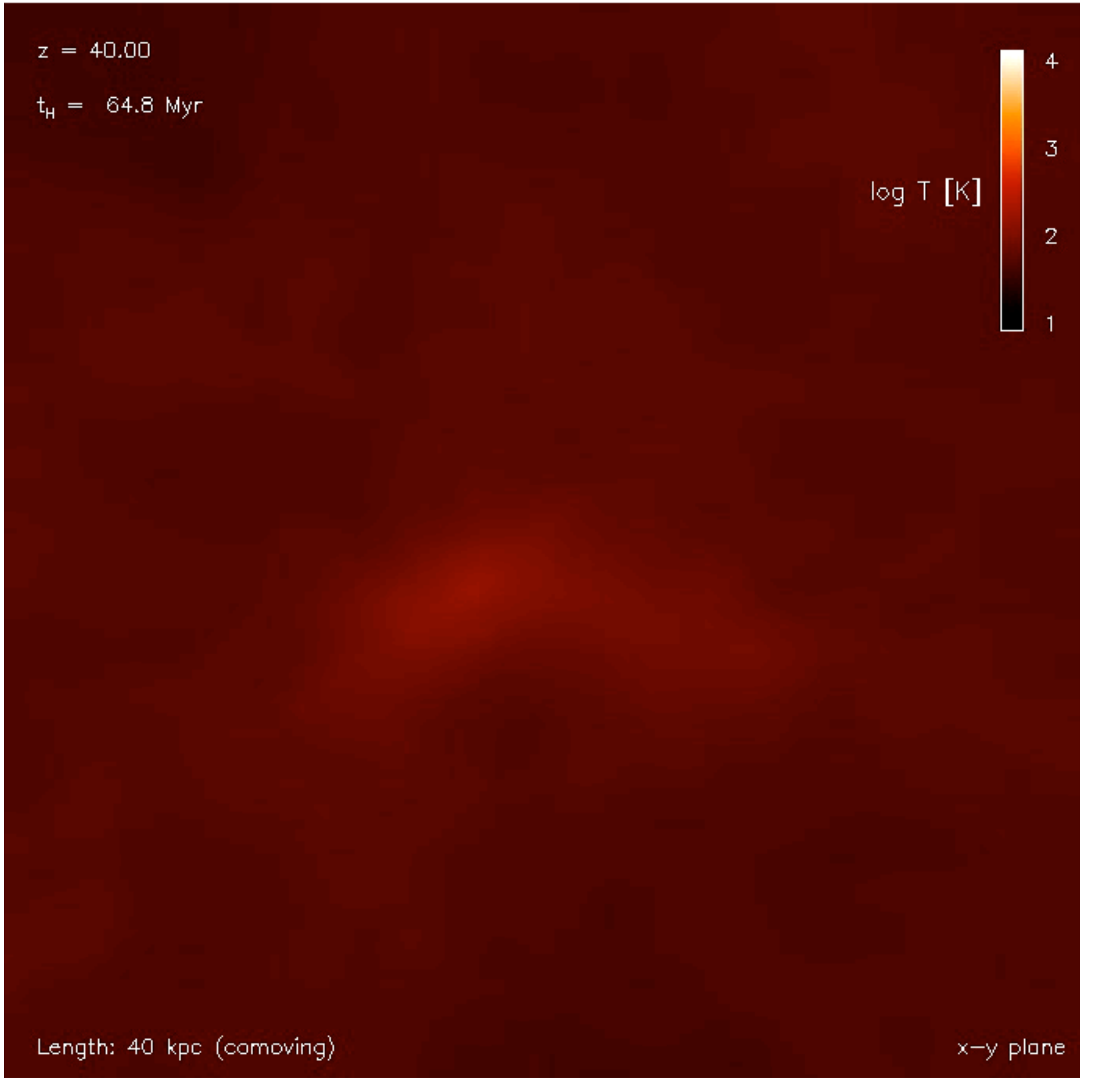
caveats

- mass spectrum depends on *scale of turbulence*
  → consistent IMF only for *large-scale turbulence* (Klessen 2001, ApJ, 556, 837)
  → dynamical effects are important
  (Bonnell et al., Clark et al.)
- result depends on *mechanism of turbulent driving*
  → *solenoidal* vs. *compressive driving*
  (Federrath, Klessen, Schmidt in prep.)

implications for Pop III

- star formation will depend on *degree of turbulence* in protogalactic halo
- speculation: *differences in stellar mass function*?
- speculation:
  - low-mass halos → low level of turbulence → relatively massive stars
  - high-mass halos (atomic cooling halos) → high degree of turbulence → wider mass spectrum with peak at lower-masses?

turbulence developing in an atomic cooling halo



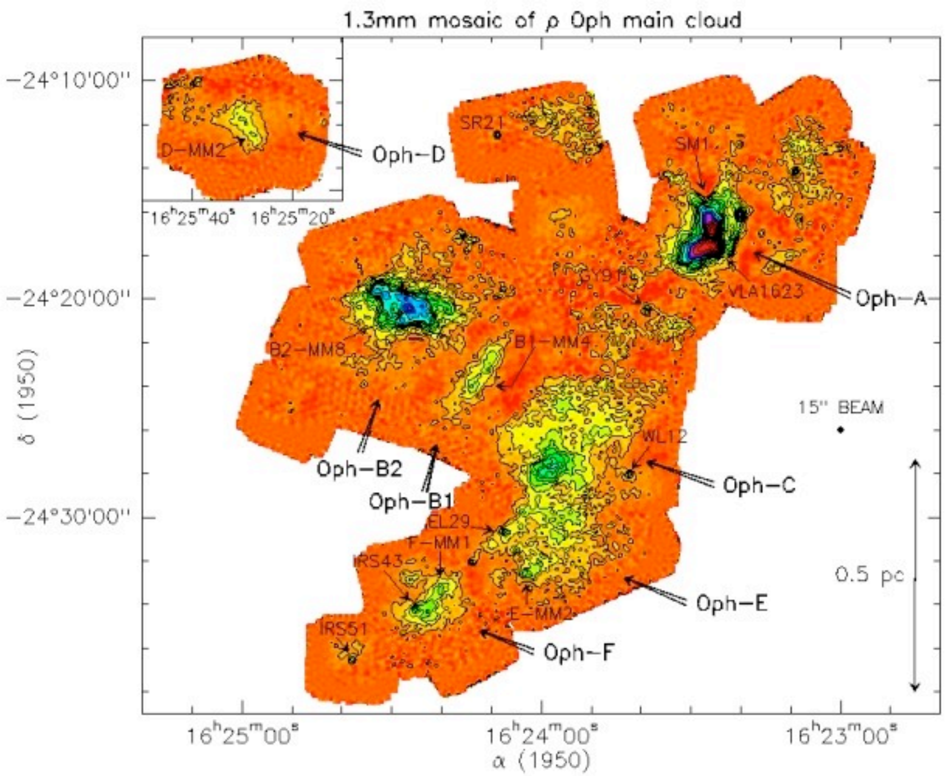
(Greif et al. 2008)

environment

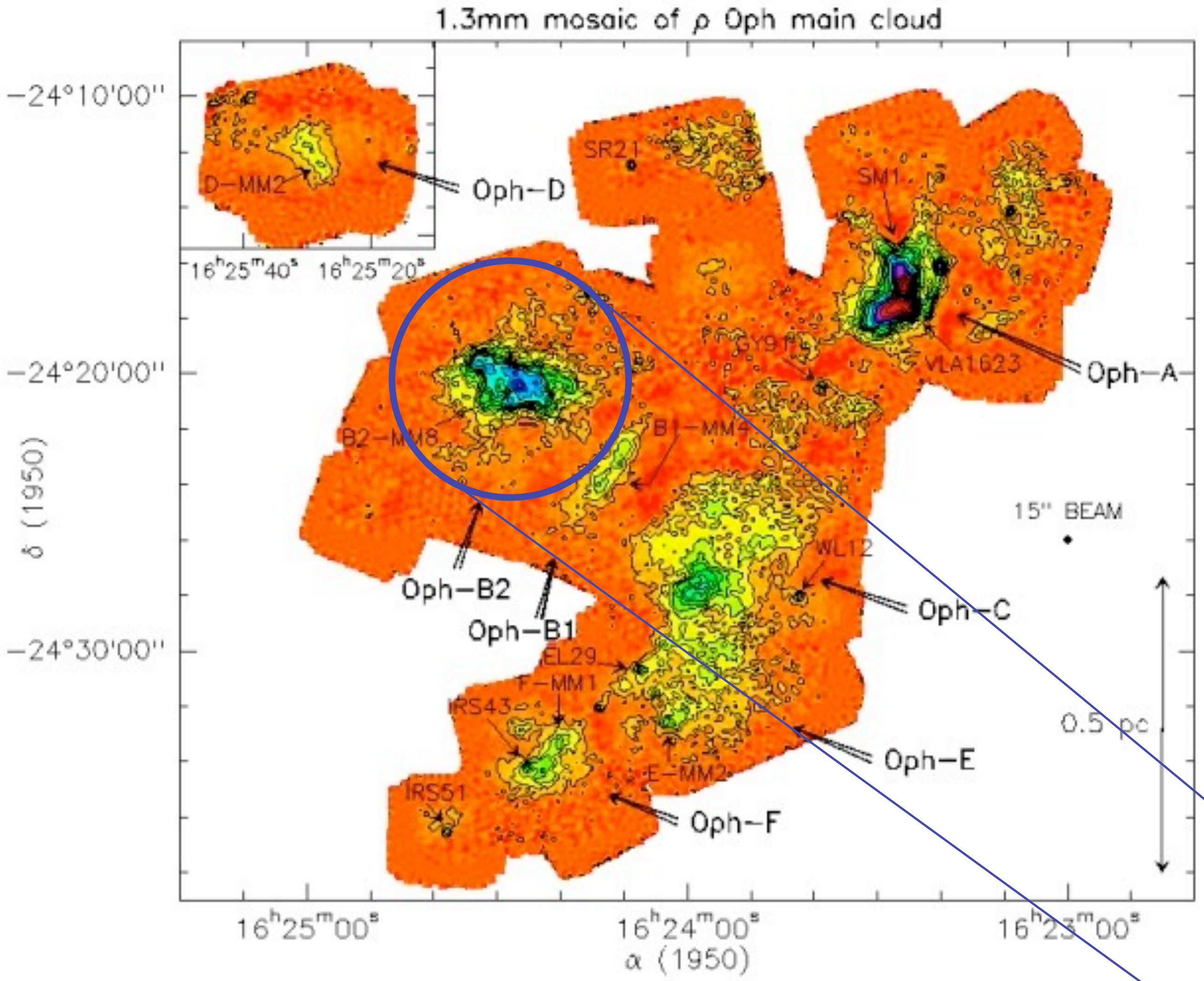
- also the environment (stellar density) will effect the stellar mass distribution

➘

competitive accretion vs. *simple collapse*



density structure of MC's



(Motte, André, & Neri 1998)

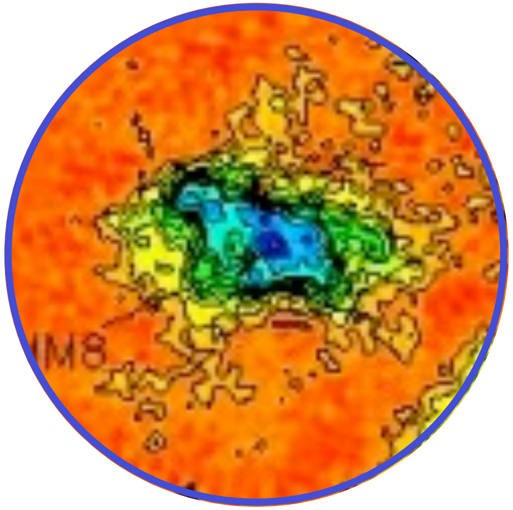
molecular clouds are highly inhomogeneous

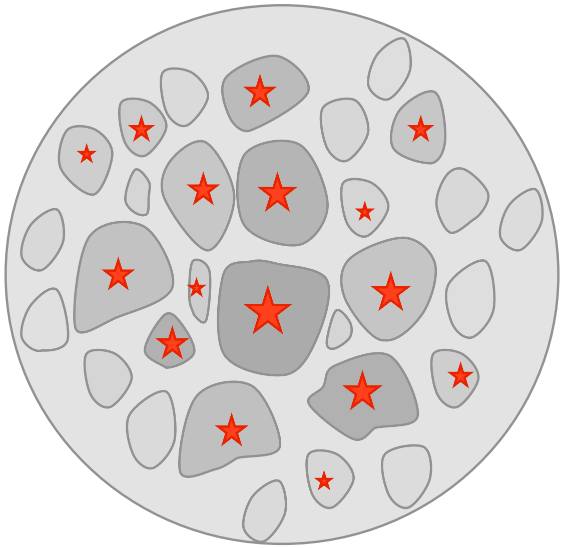
stars form in the densest and coldest parts of the cloud

ρ-Ophiuchus cloud seen in dust emission

let's focus on a cloud core like this one

evolution of cloud cores

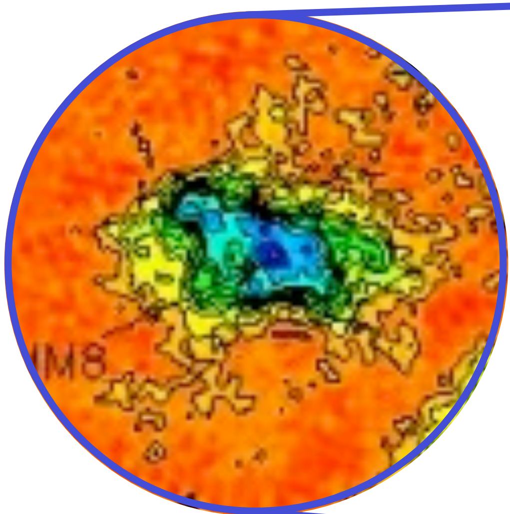


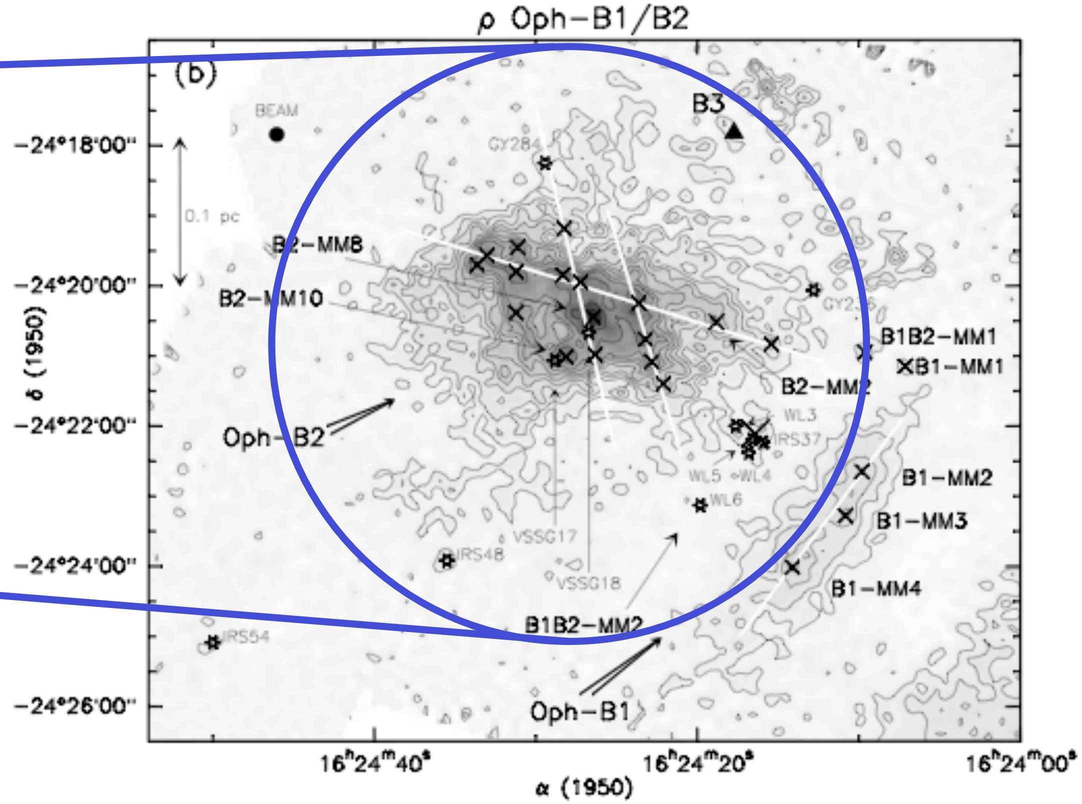


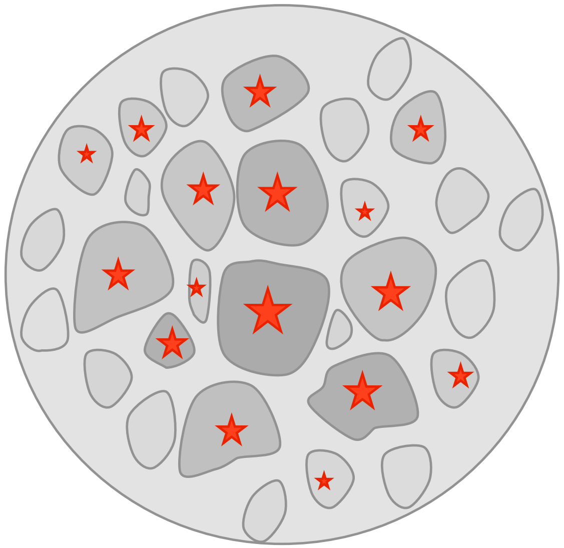
- How does this core evolve?
  Does it form one single massive star or cluster with mass distribution?

- Turbulent cascade „goes through“ cloud core
  --> NO *scale separation* possible
  --> NO *effective sound speed*
- Turbulence is supersonic!
  --> produces strong density contrasts:
  $\delta\rho/\rho \approx M^2$
  --> with typical $M \approx 10$ --> $\delta\rho/\rho \approx 100$!
- 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



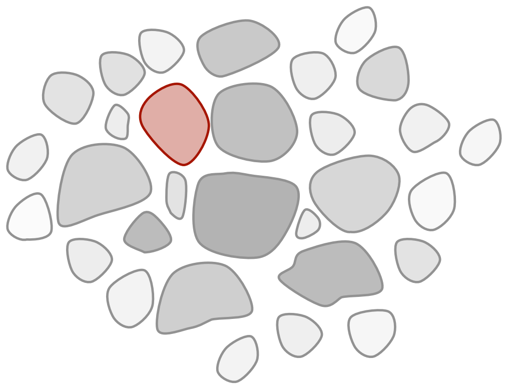




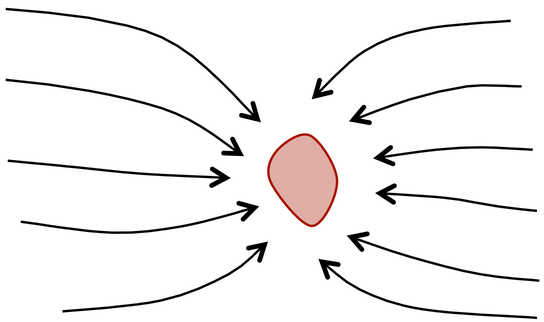
indeed ρ-Oph B1/2 contains several cores ("starless" cores are denoted by ×, cores with embedded protostars by ☆)

(Motte, André, & Neri 1998)

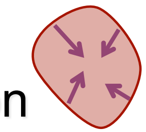
formation and evolution of cores



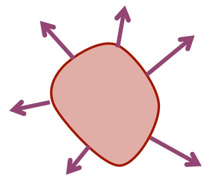
- protostellar cloud cores form at *stagnation point* in *convergent turbulent flows*



- if $M > M_{crit} \propto \rho^{-1/2}\, T^{3/2}$: collapse & star formation



- pf $M < M_{crit} \propto \rho^{-1/2}\, T^{3/2}$: reexpansion after end of external compression

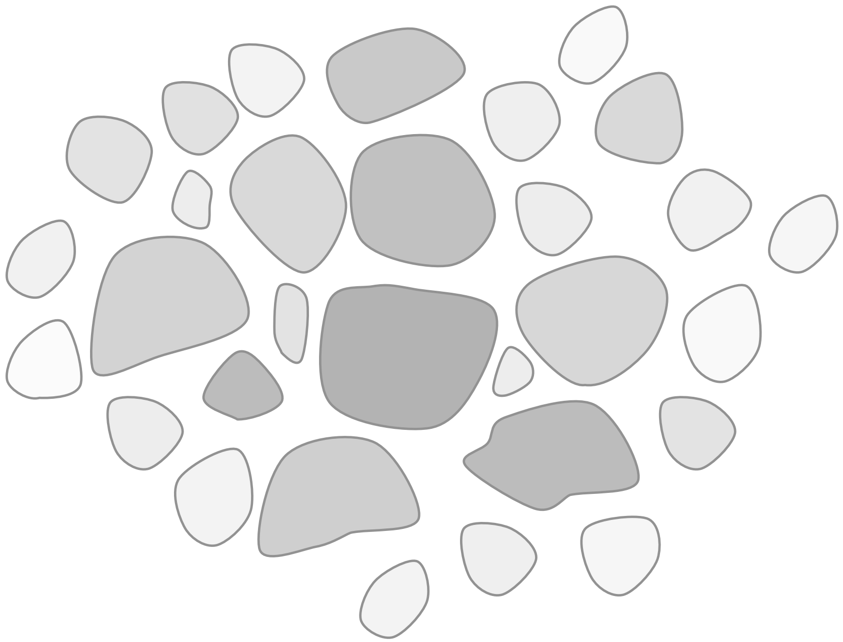


(e.g. Vazquez-Semadeni et al 2005)

- typical timescale: $t \approx 10^4 \ldots 10^5$ yr

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*

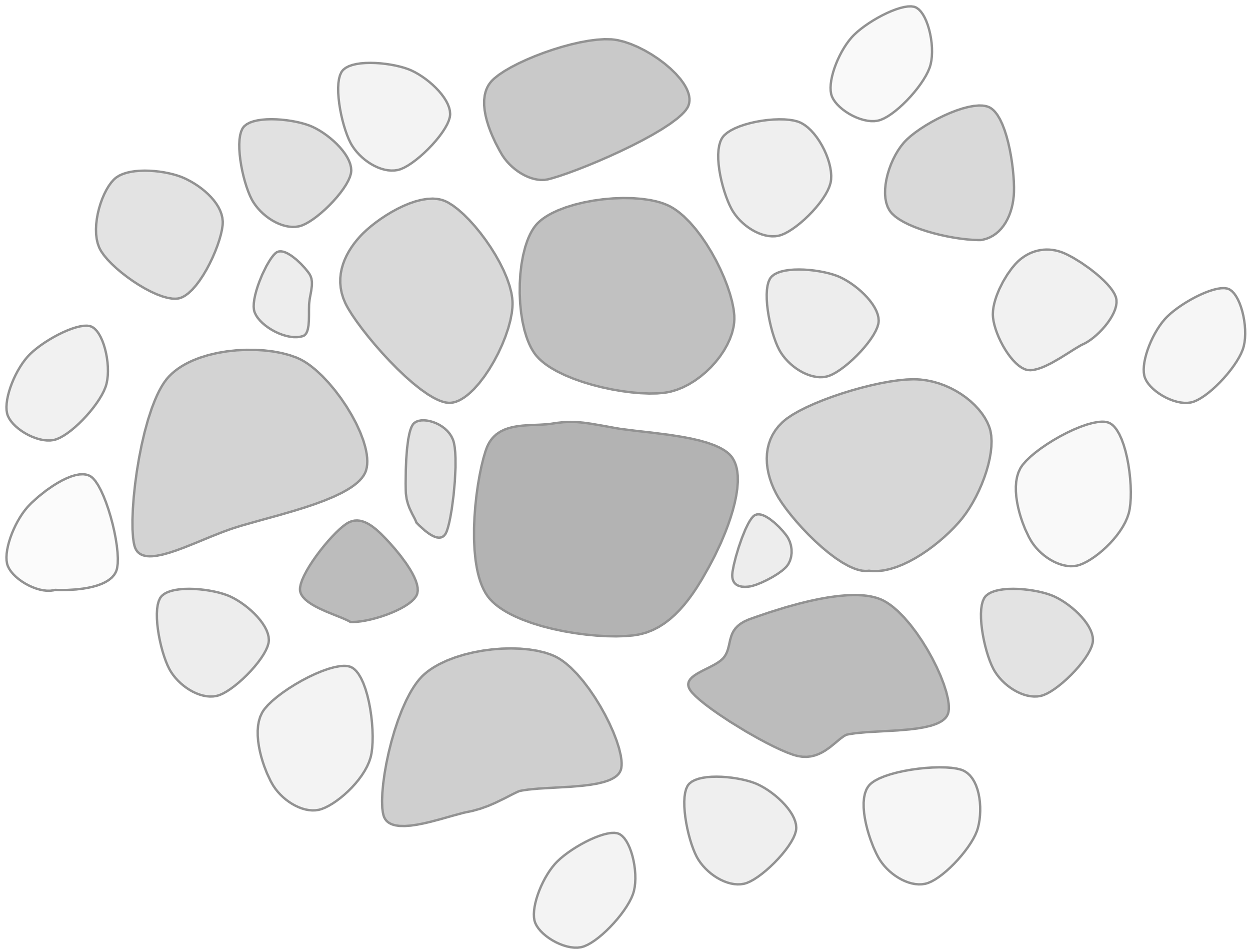
(2) turbulence decays, i.e. gravity dominates: $\alpha = E_{kin}/|E_{pot}| < 1$

--> *global contraction*

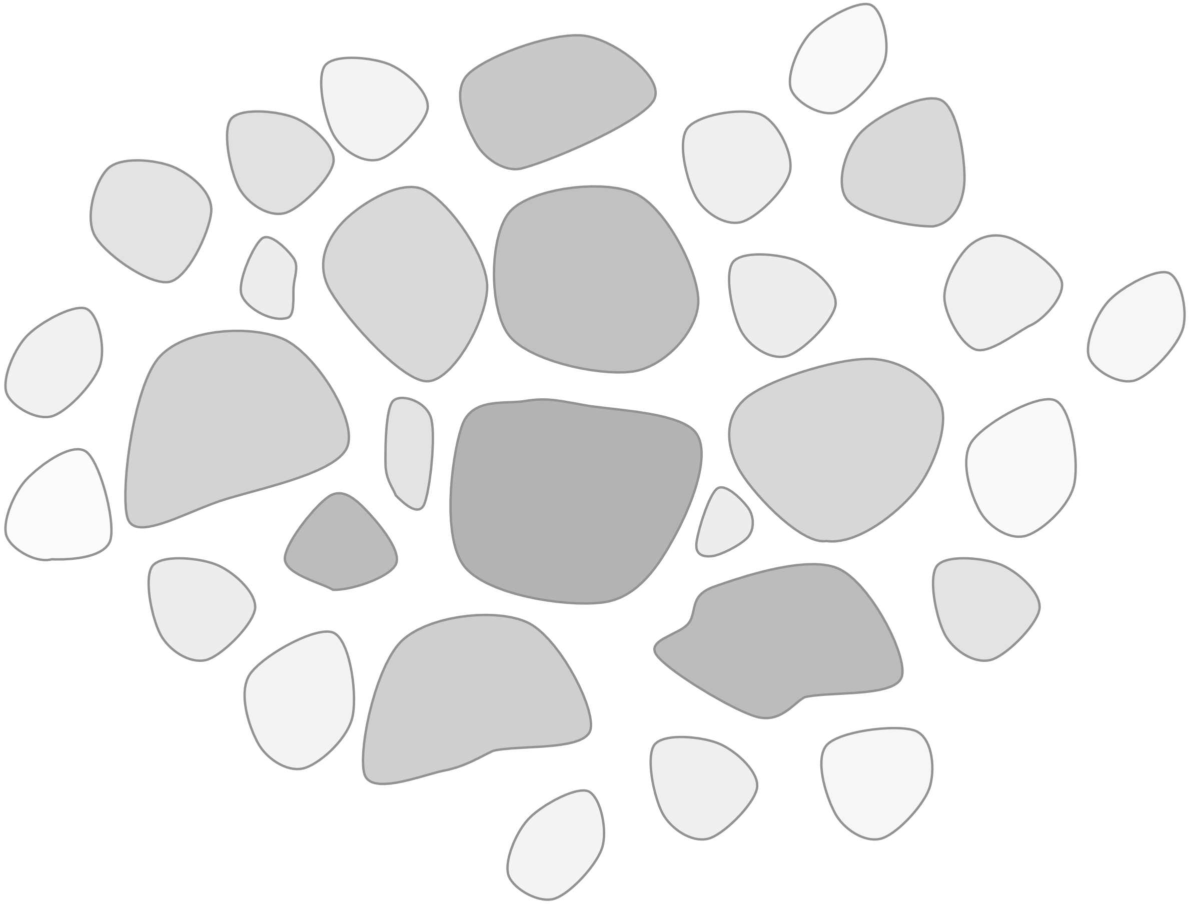
--> core do *interact* while collapsing

--> *competition* influences *mass growth*

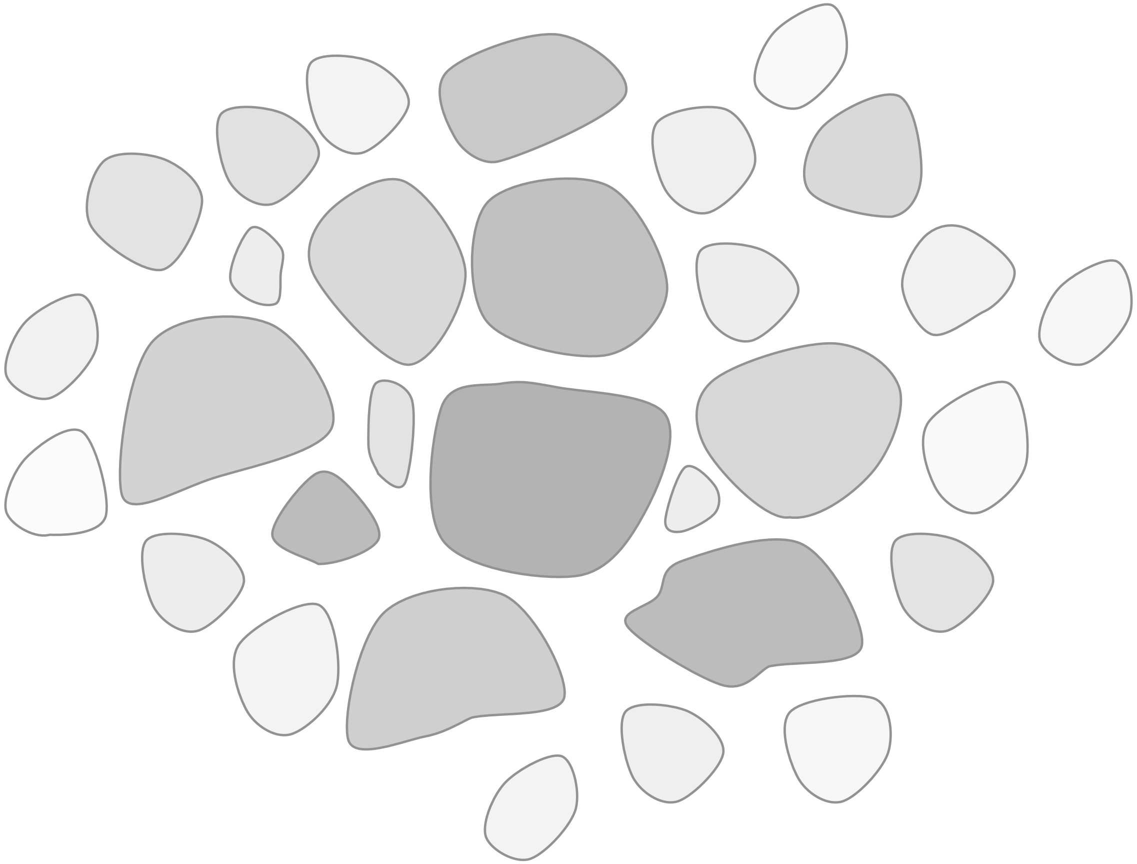
--> *dense cluster with high-mass stars*



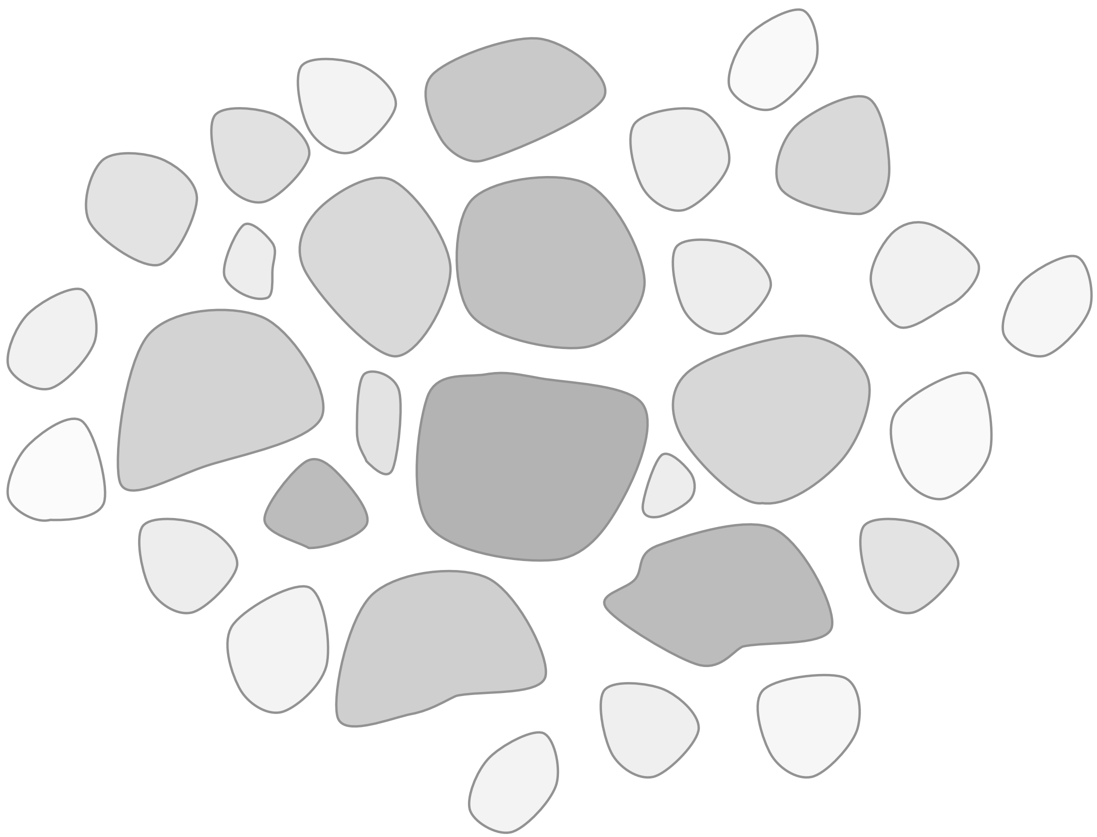
turbulence creates a hierarchy of clumps



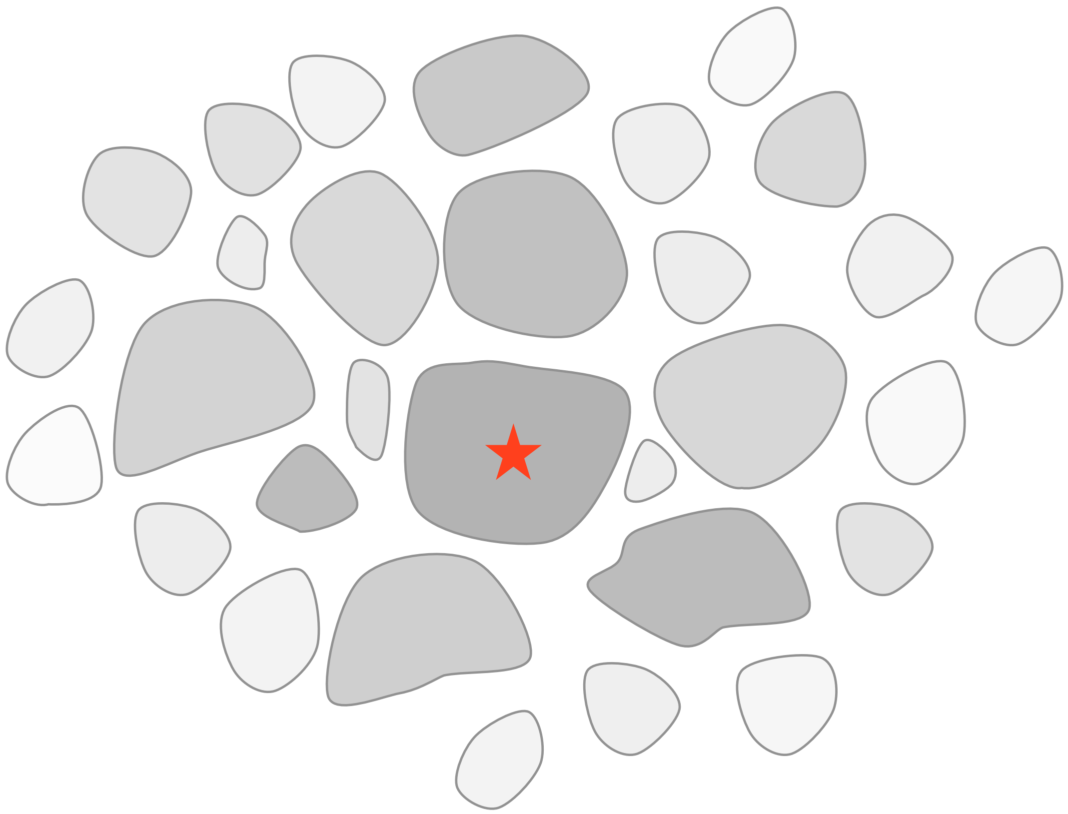
as turbulence decays locally, contraction sets in



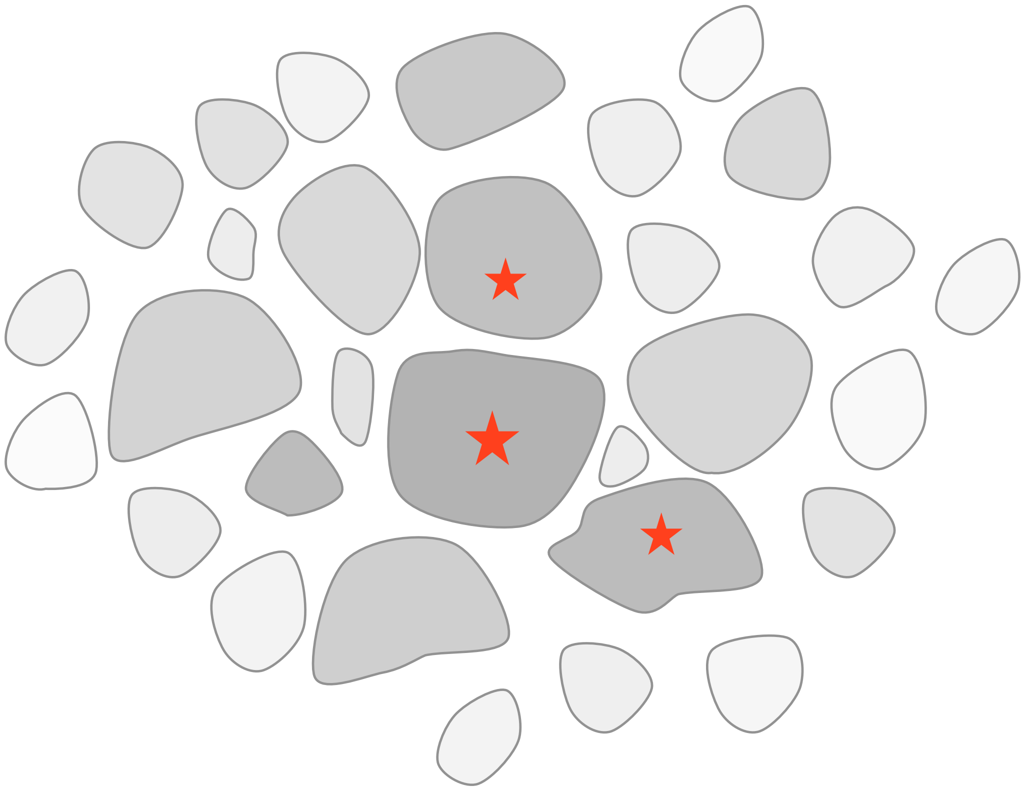
as turbulence decays locally, contraction sets in



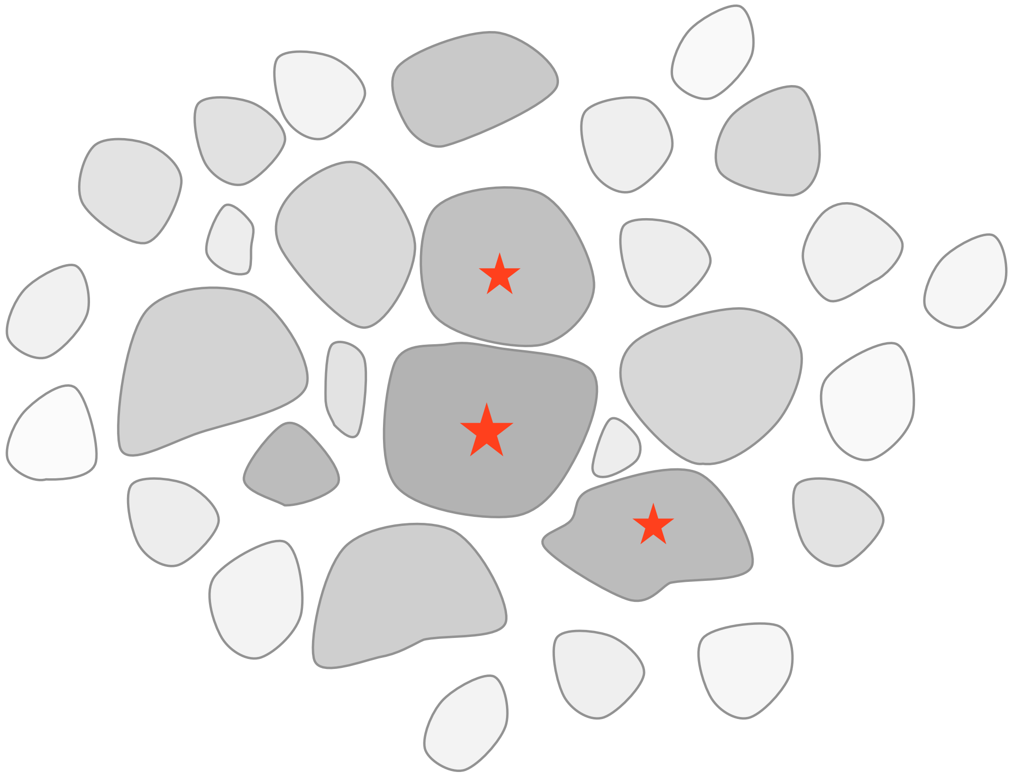
while region contracts, individual clumps collapse to form stars



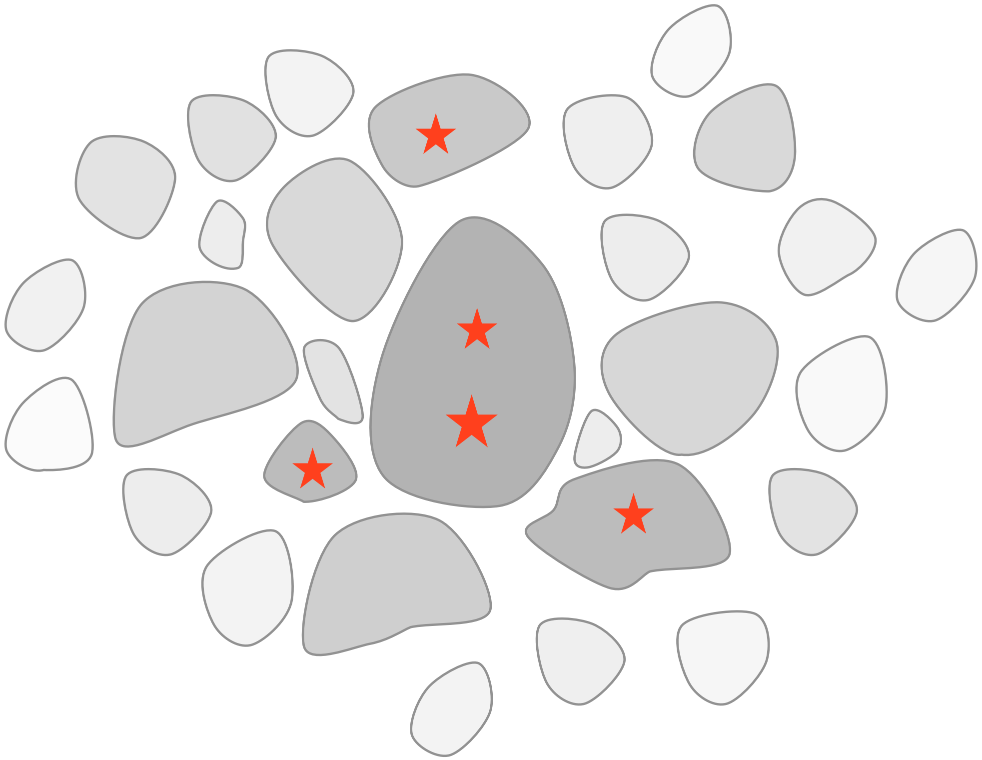
while region contracts, individual clumps collapse to form stars



individual clumps collapse to form stars

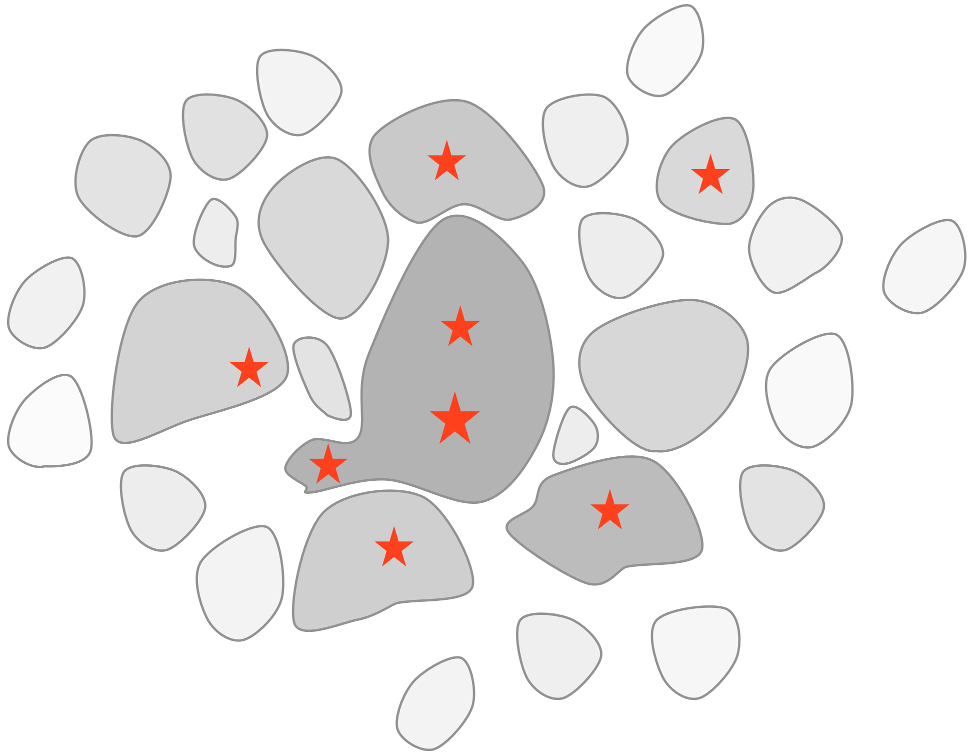


individual clumps collapse to form stars



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

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



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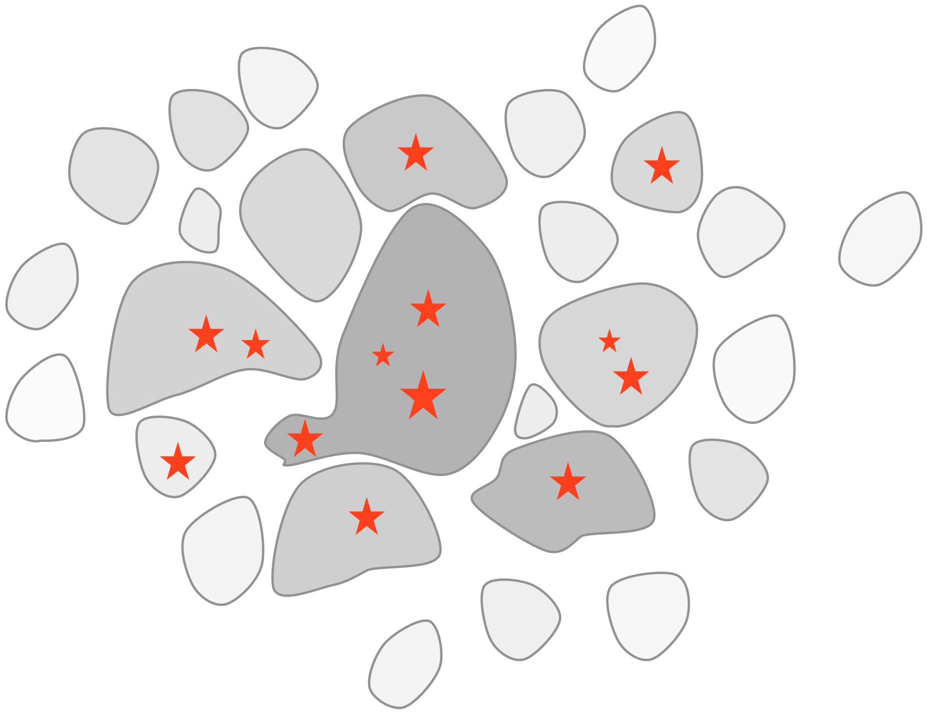

in *dense clusters*, clumps may merge while collapsing
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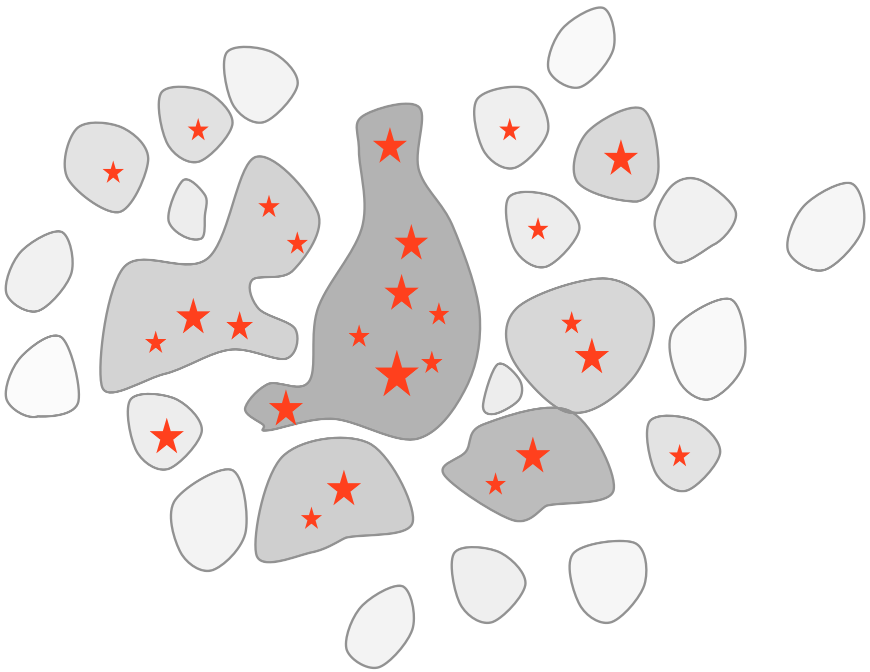
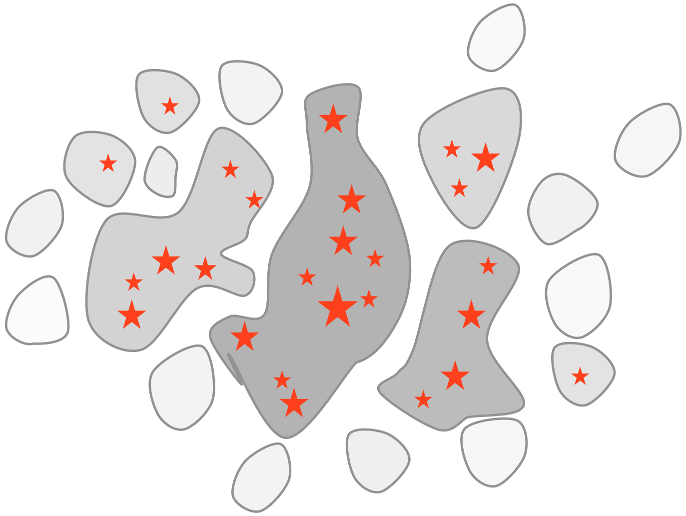
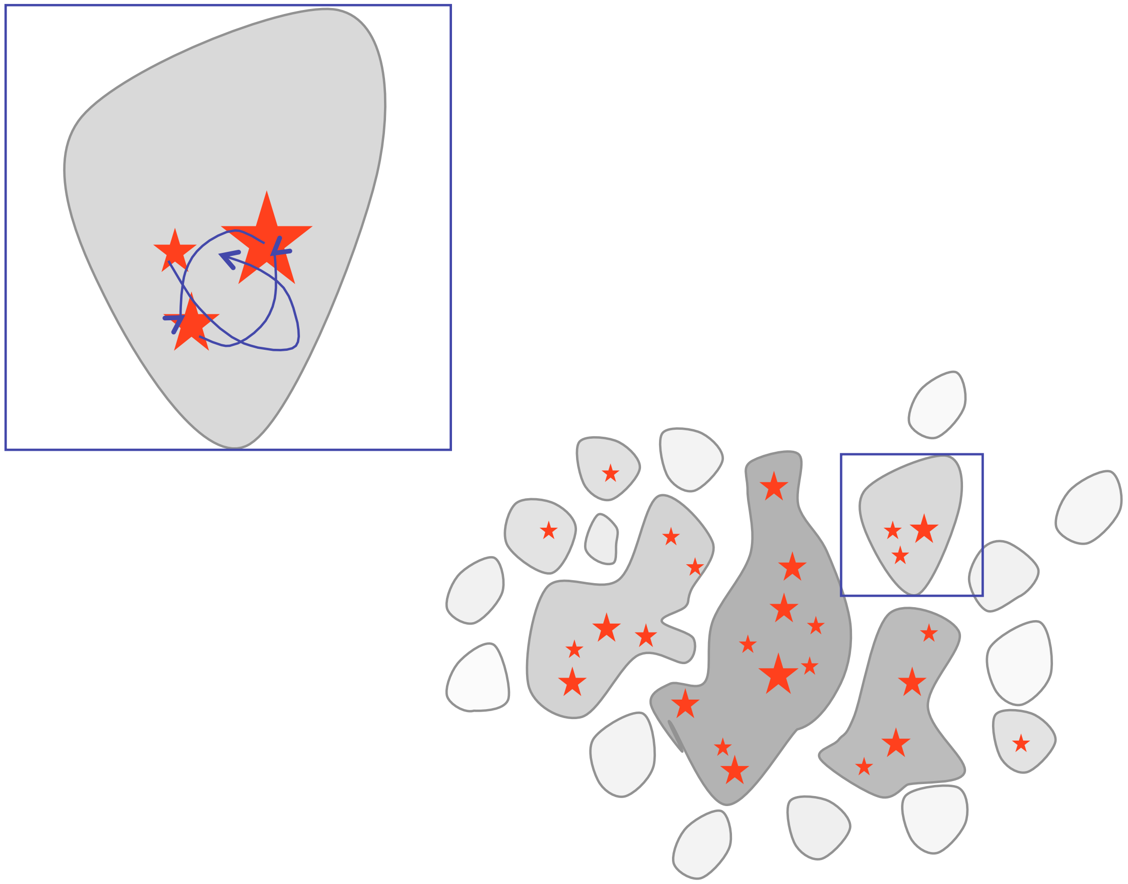


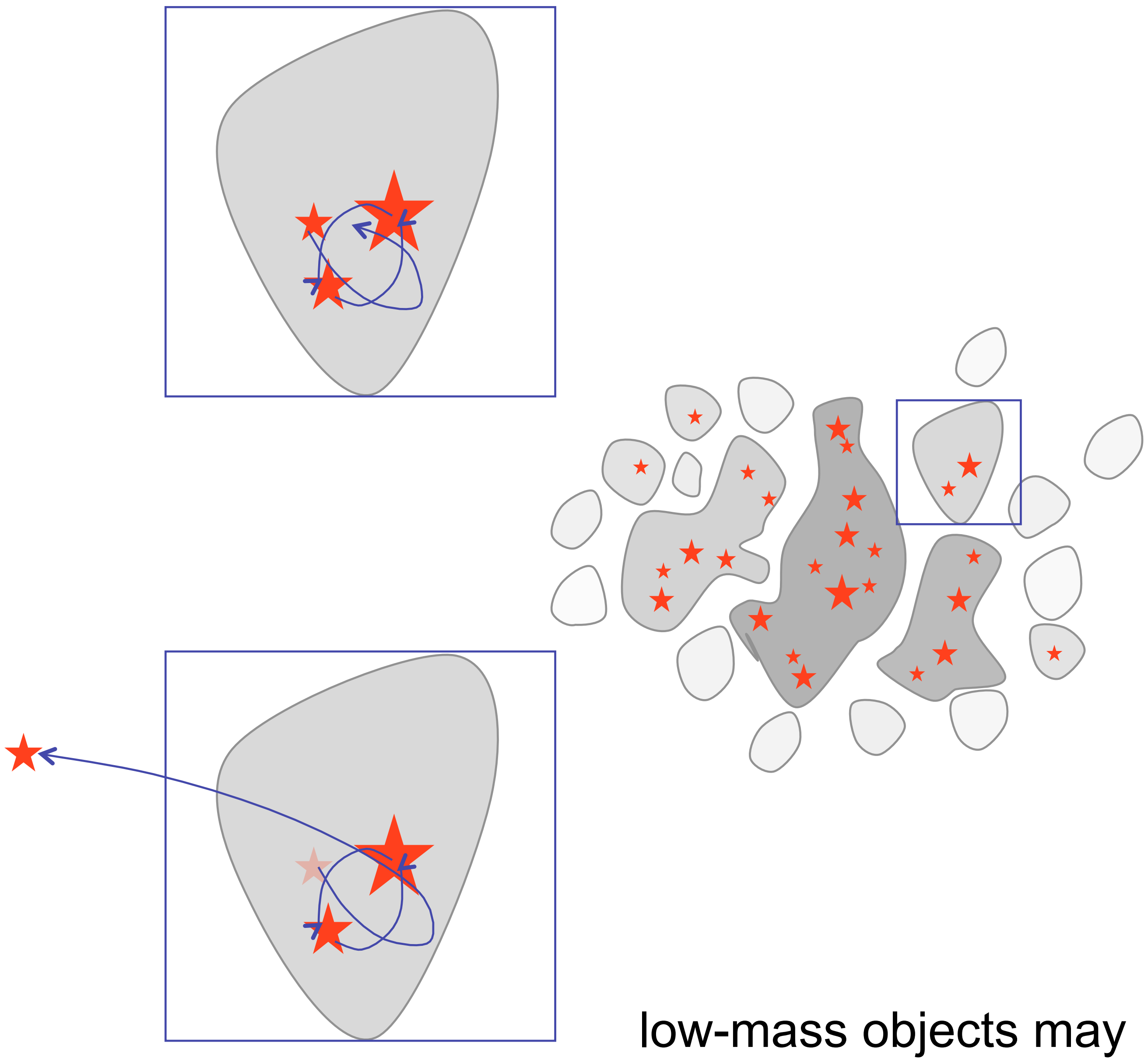
in *dense clusters*, competitive mass growth becomes important



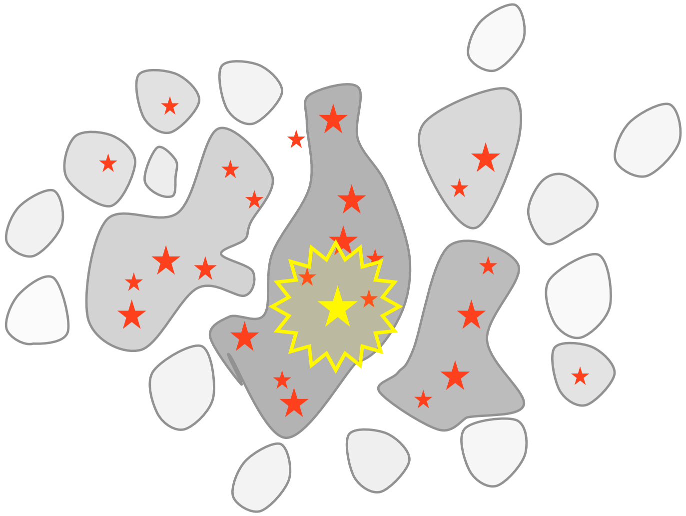
in *dense clusters*, competitive mass growth becomes important



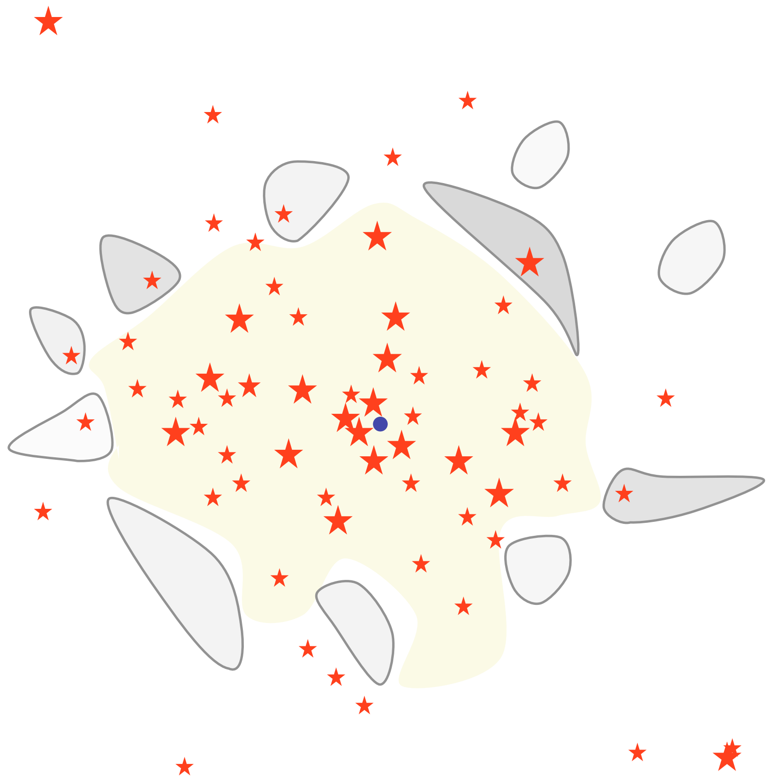
in *dense clusters*, *N*-body effects influence mass growth



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



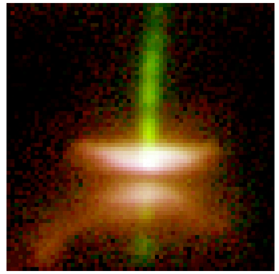
feedback terminates star formation

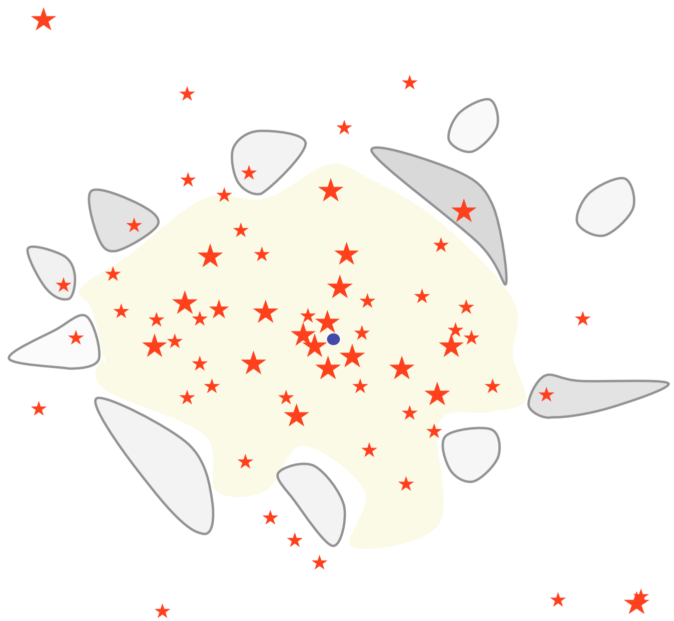


result: *star cluster*, possibly with HII region

Models of star cluster formation

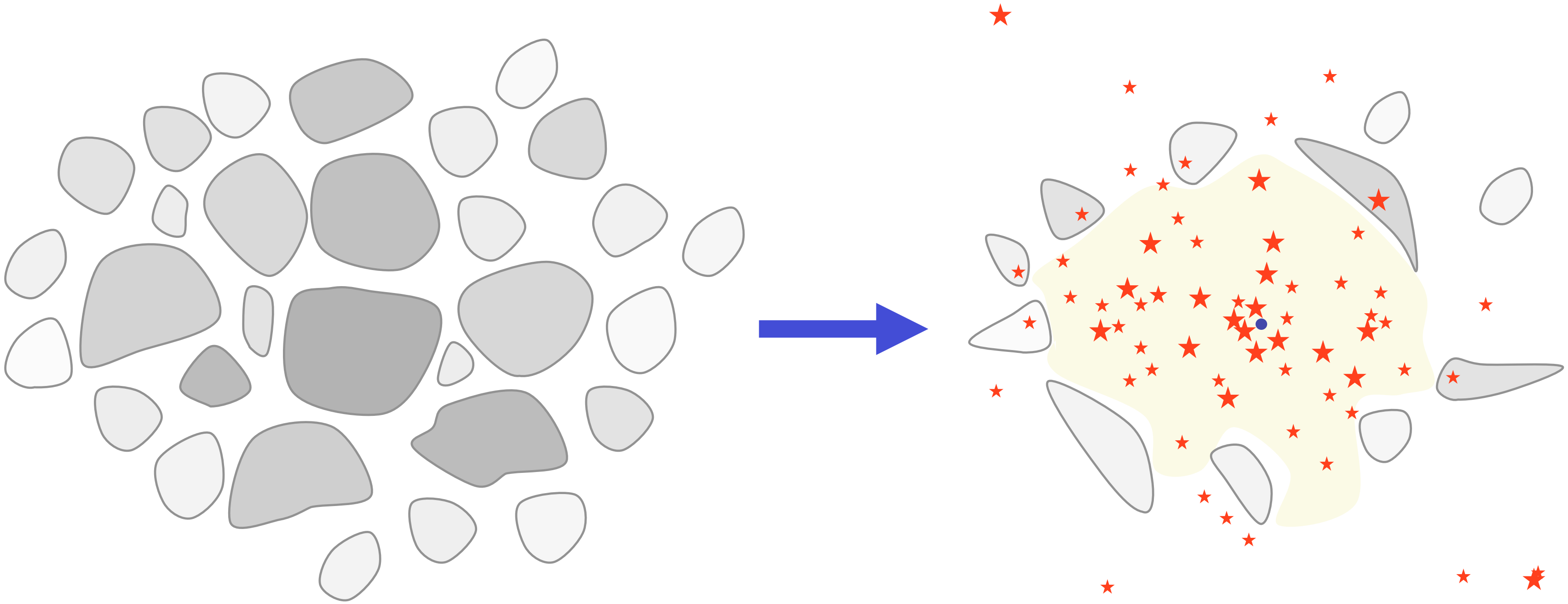
- dynamics:
  basic properties are probably okay
- BUT: no feedback
  (outflows, radiation, etc.)
- *how much detail are we missing?*
  - how does that change properties like *IMF, boundedness, efficiency*?





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)

example: model of Orion cloud

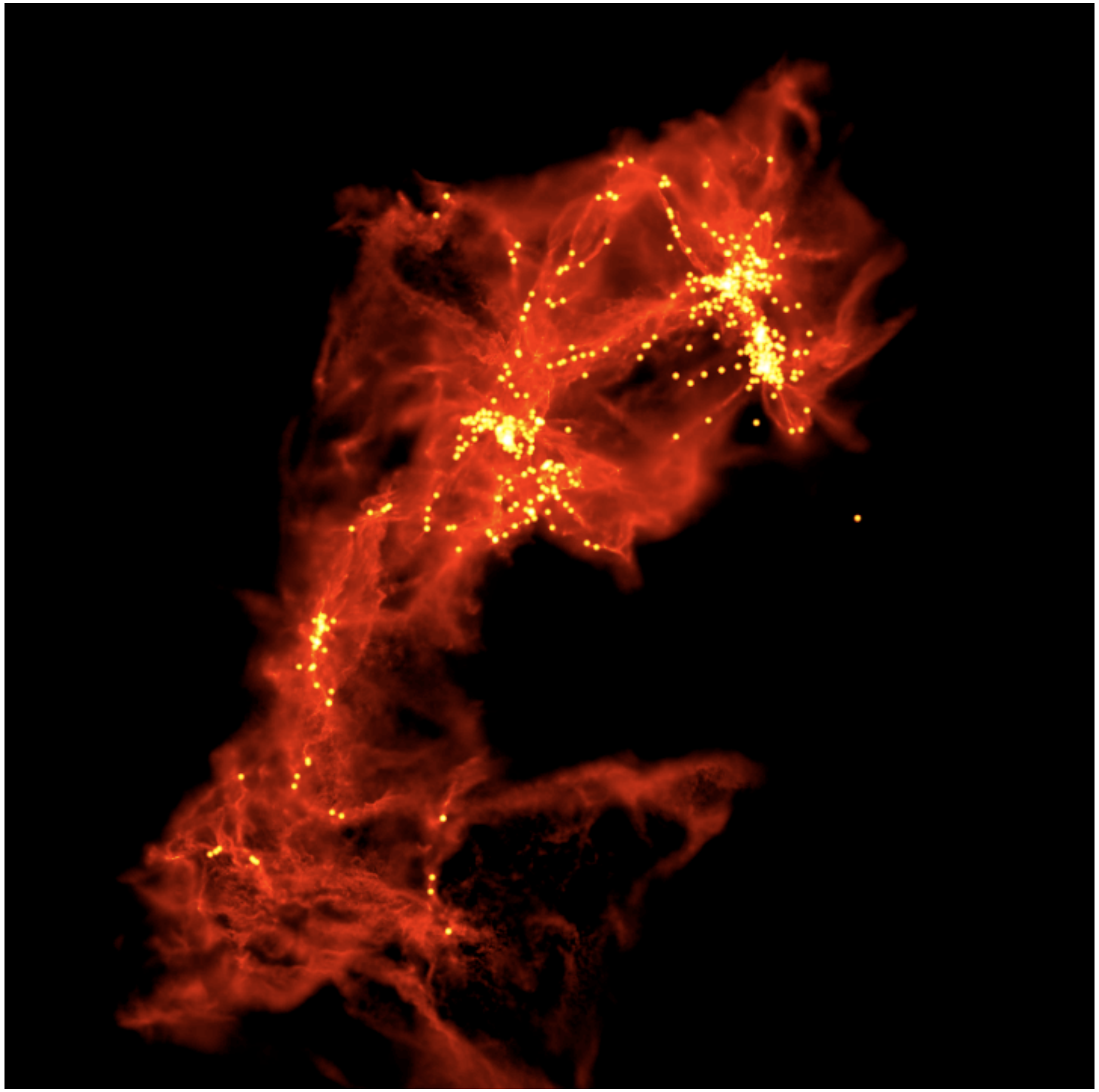
„model" of Orion cloud: 15.000.000 SPH particles, 10^4 M_{sun} in 10 pc, mass resolution 0,02 M_{sun}, forms ~2.500 „stars" (sink particles)

isothermal EOS, top bound, bottom unbound

has clustered as well as distributed „star" formation

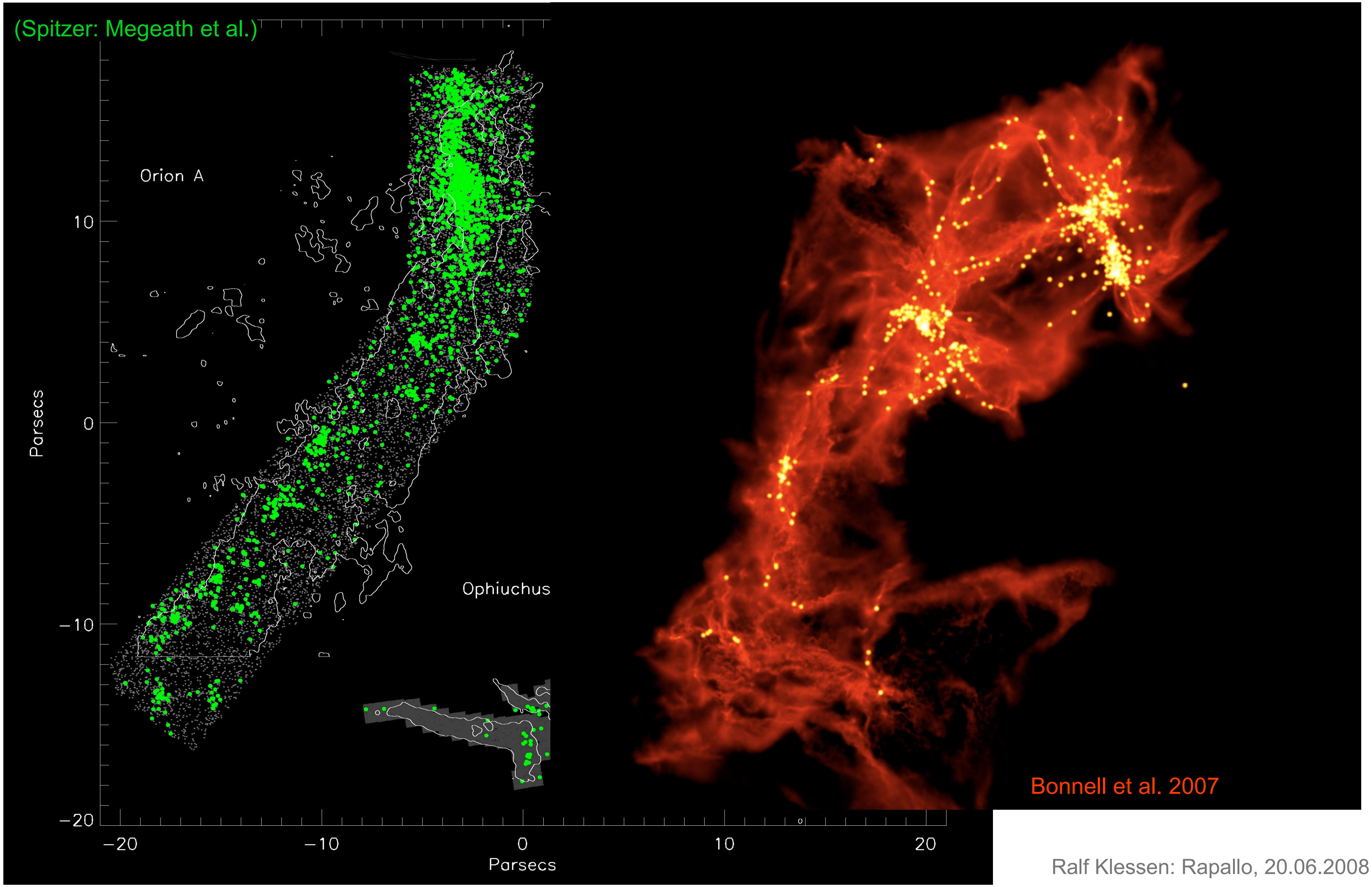
efficiency varies from 1% to 20%

develops full IMF
(distribution of sink particle masses)



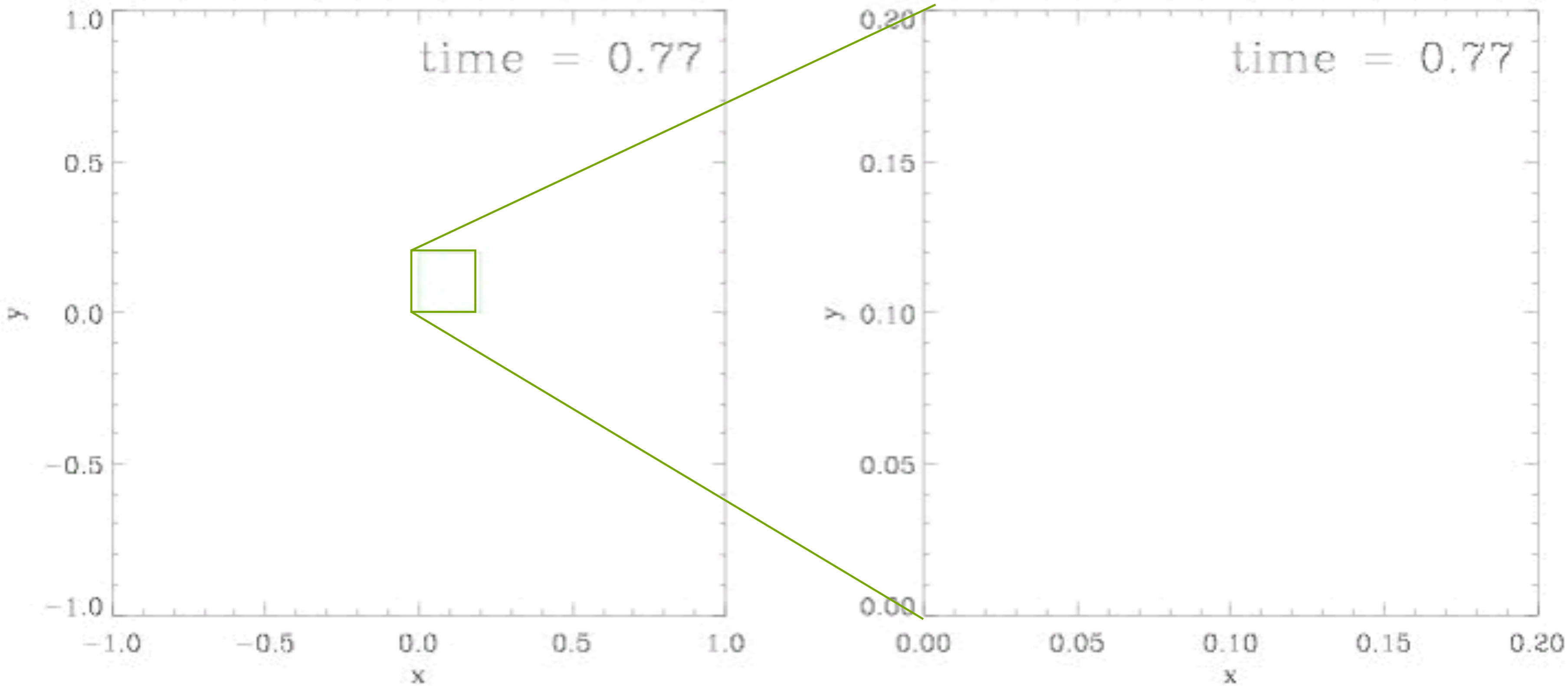
(Bonnell et al. 2007)

example: model of Orion cloud



Dynamics of nascent star cluster

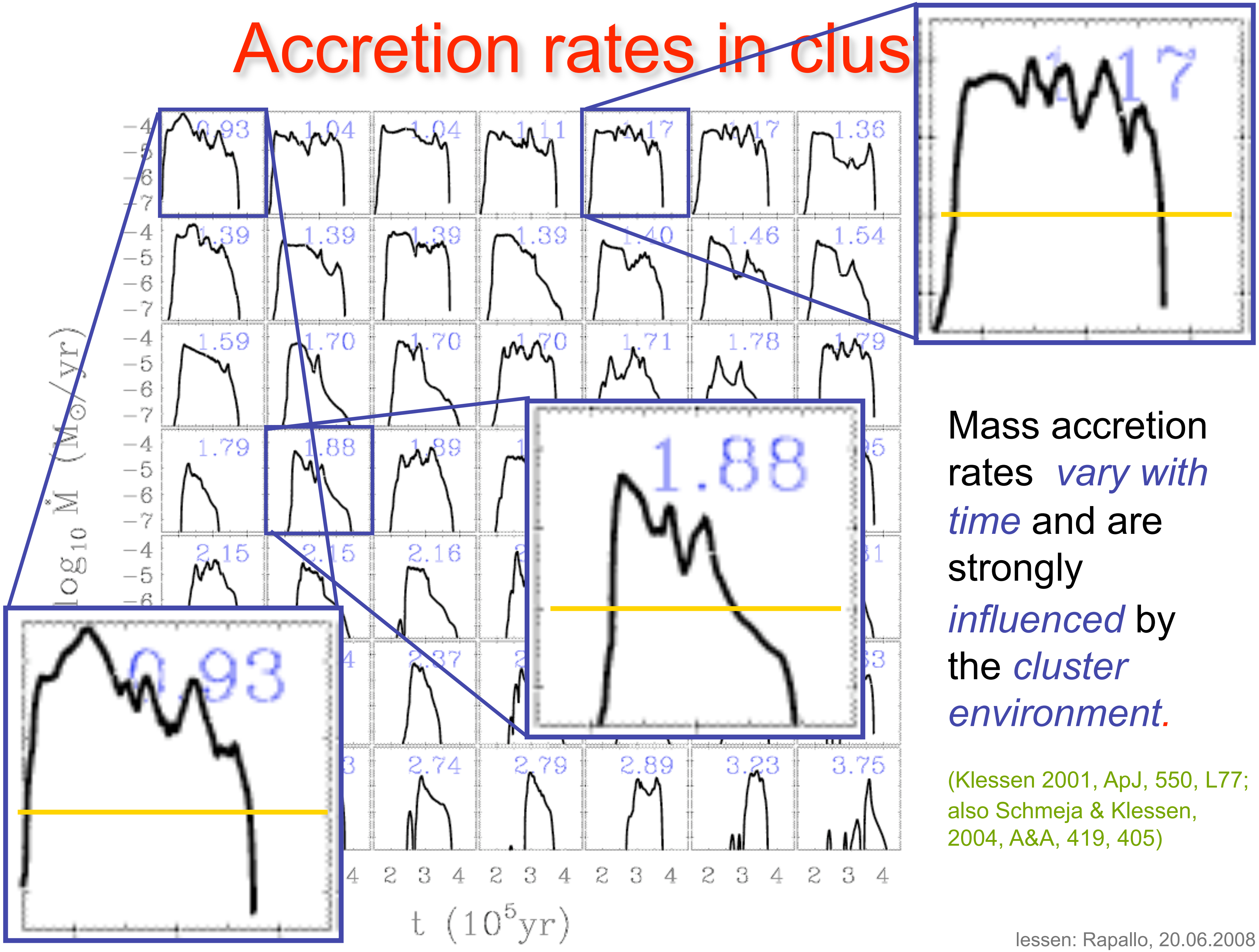
in dense clusters protostellar interaction may be come important!



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

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

Accretion rates in clus



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)

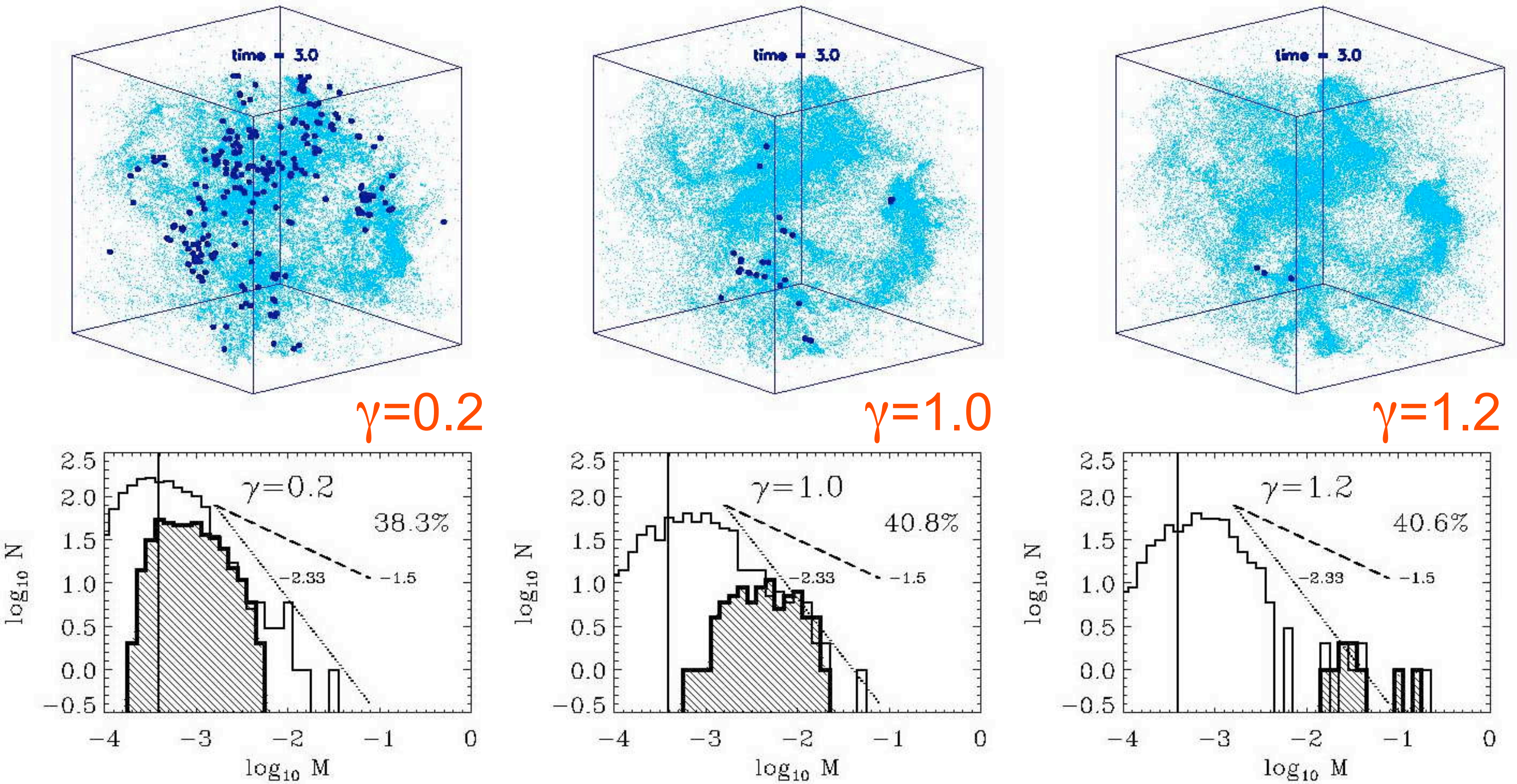
dependency on EOS

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

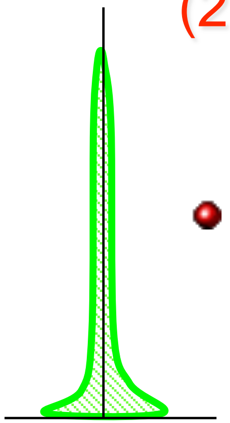
for $\gamma>1$ it is suppressed → formation of *isolated massive stars*

(from Li et al. 2003, ApJ, 592, 975)

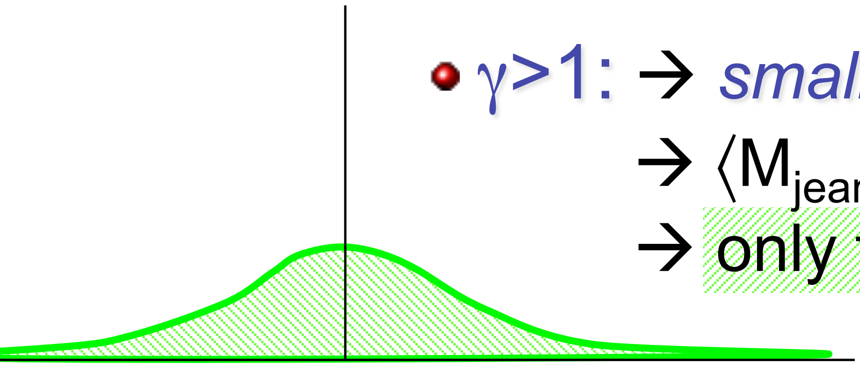
how does that work?

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

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



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

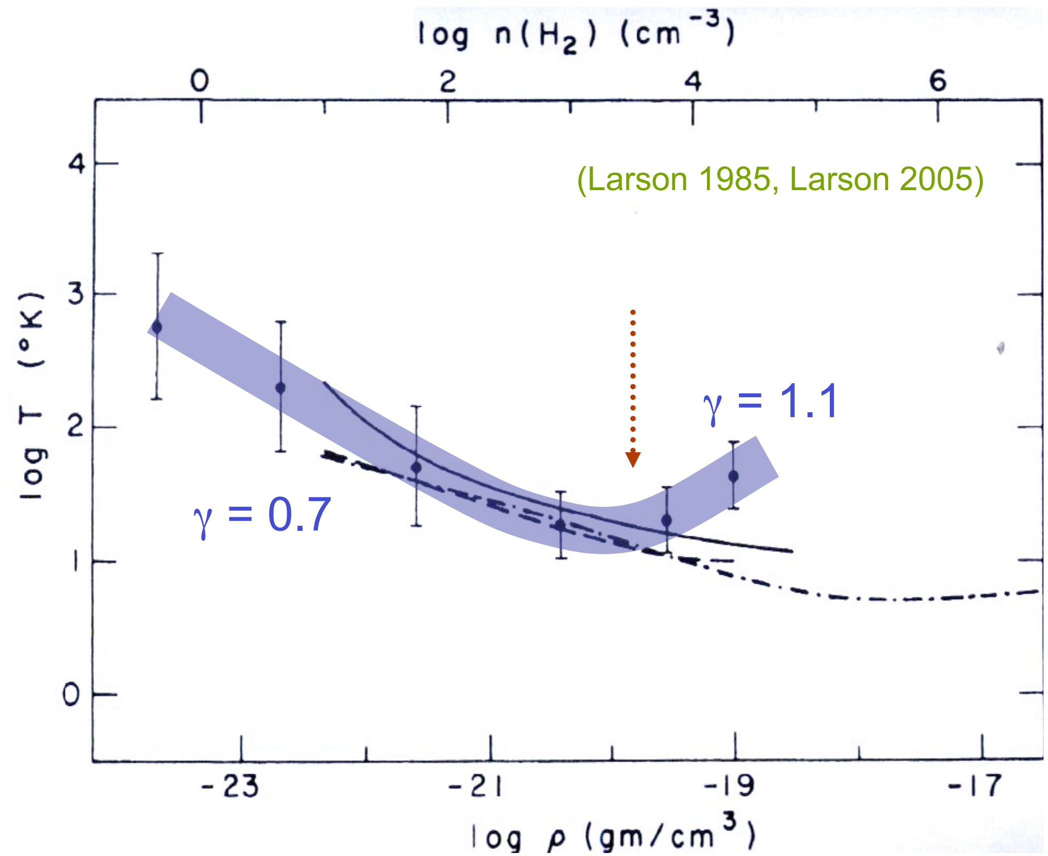


- $\gamma>1$: → *small* density excursion for given pressure
  → $\langle M_{jeans} \rangle$ is large
  → only few and massive clumps exceed M_{jeans}

EOS for solar neighborhood

below 10^{-18} gcm^{-3}: ρ ⬆ ⟹ T ⬇

above 10^{-18} gcm^{-3}: ρ ⬆ ⟹ T ⬆



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

$P \propto \rho T$

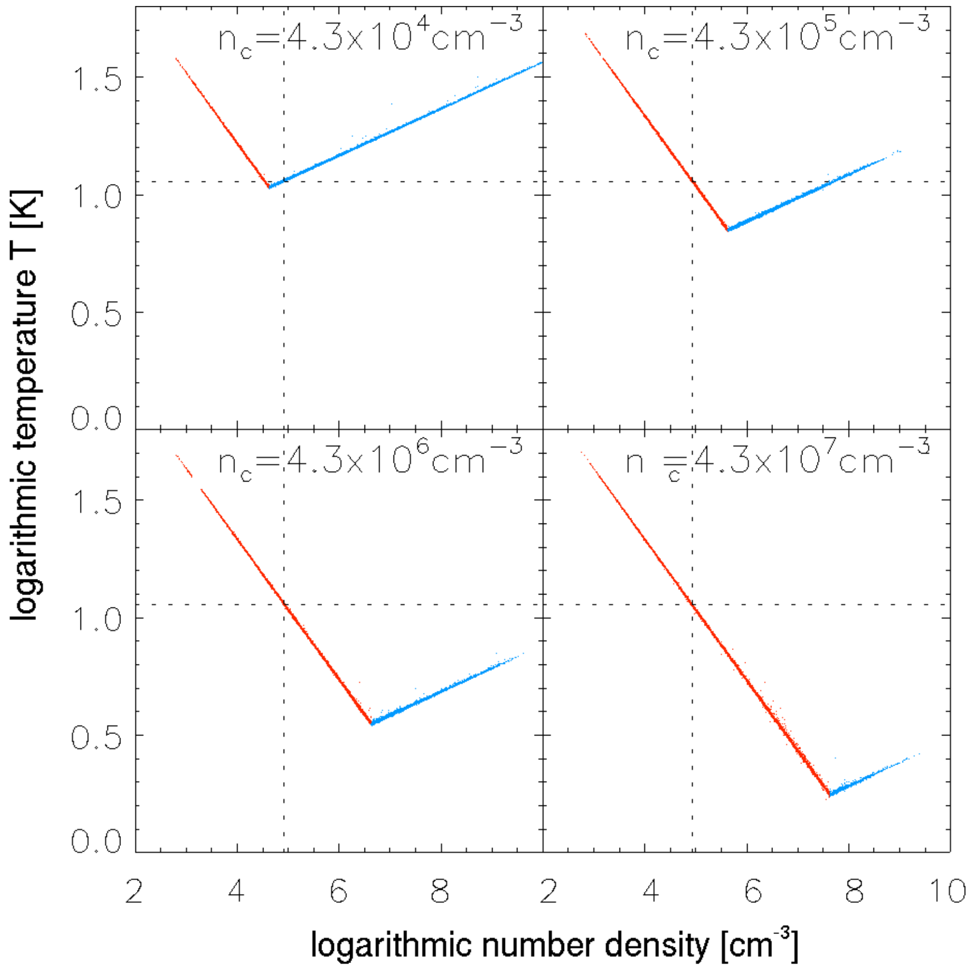
$\rightarrow \gamma = 1 + d\ln T / d\ln\rho$

IMF from simple piece-wise polytropic EOS

$\gamma_1 = 0.7$

$\gamma_2 = 1.1$

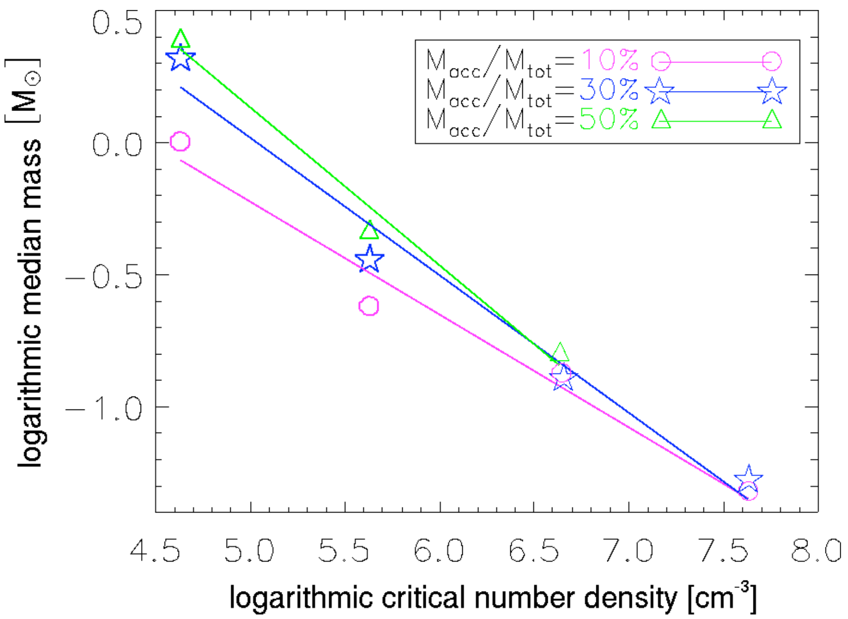
$T \sim \rho^{\gamma-1}$

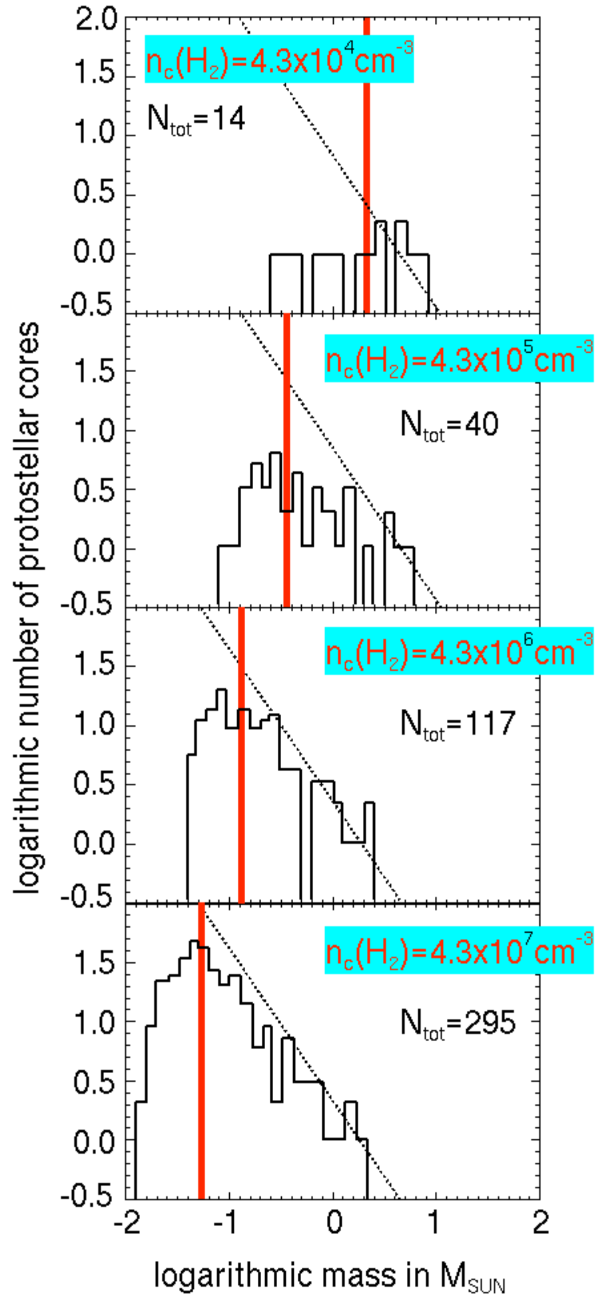


(Jappsen et al. 2005, A&A, 435, 611)

IMF from simple piece-wise polytropic EOS

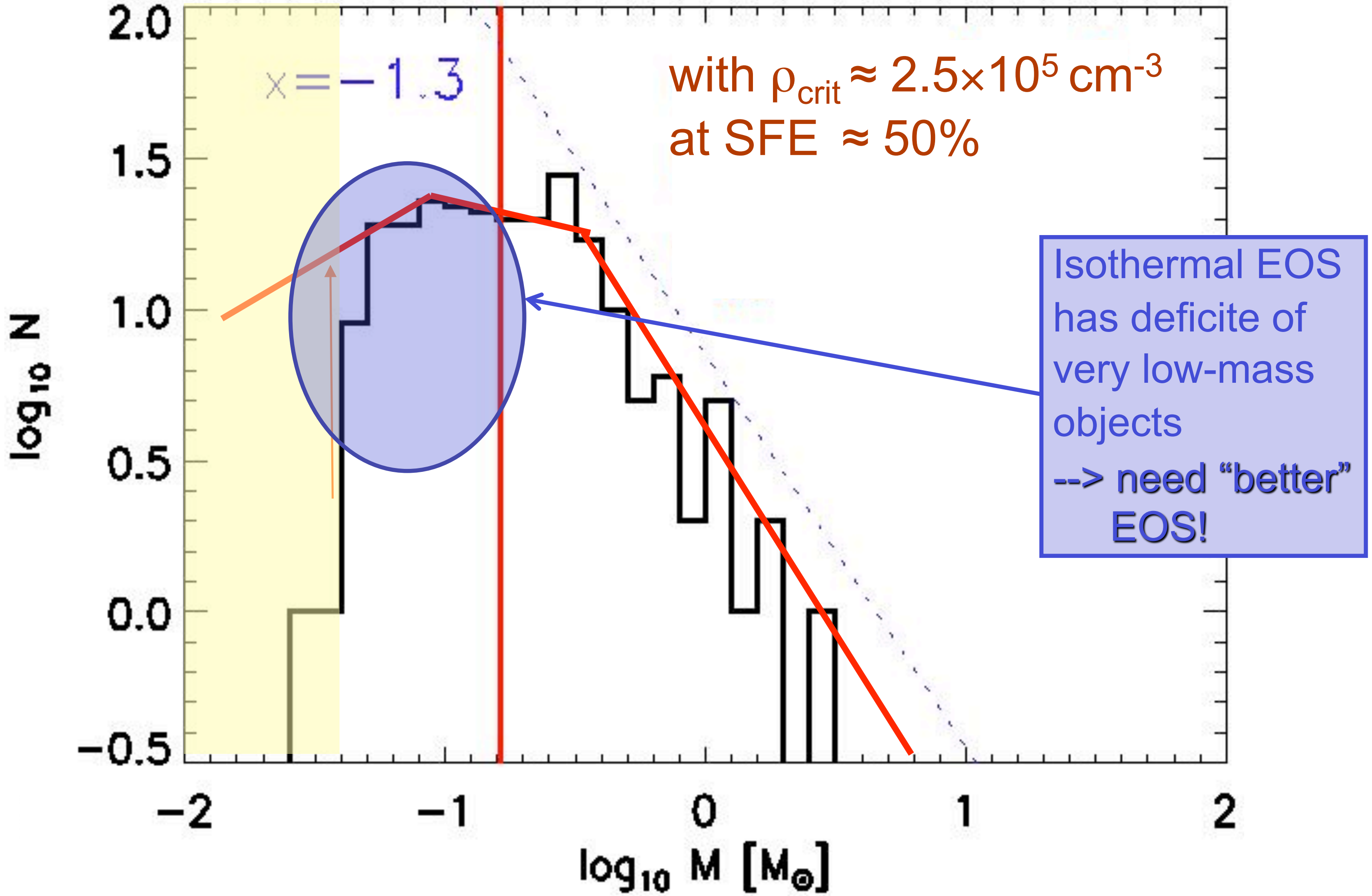
critical density ⬆ ⇨ median mass ⬇





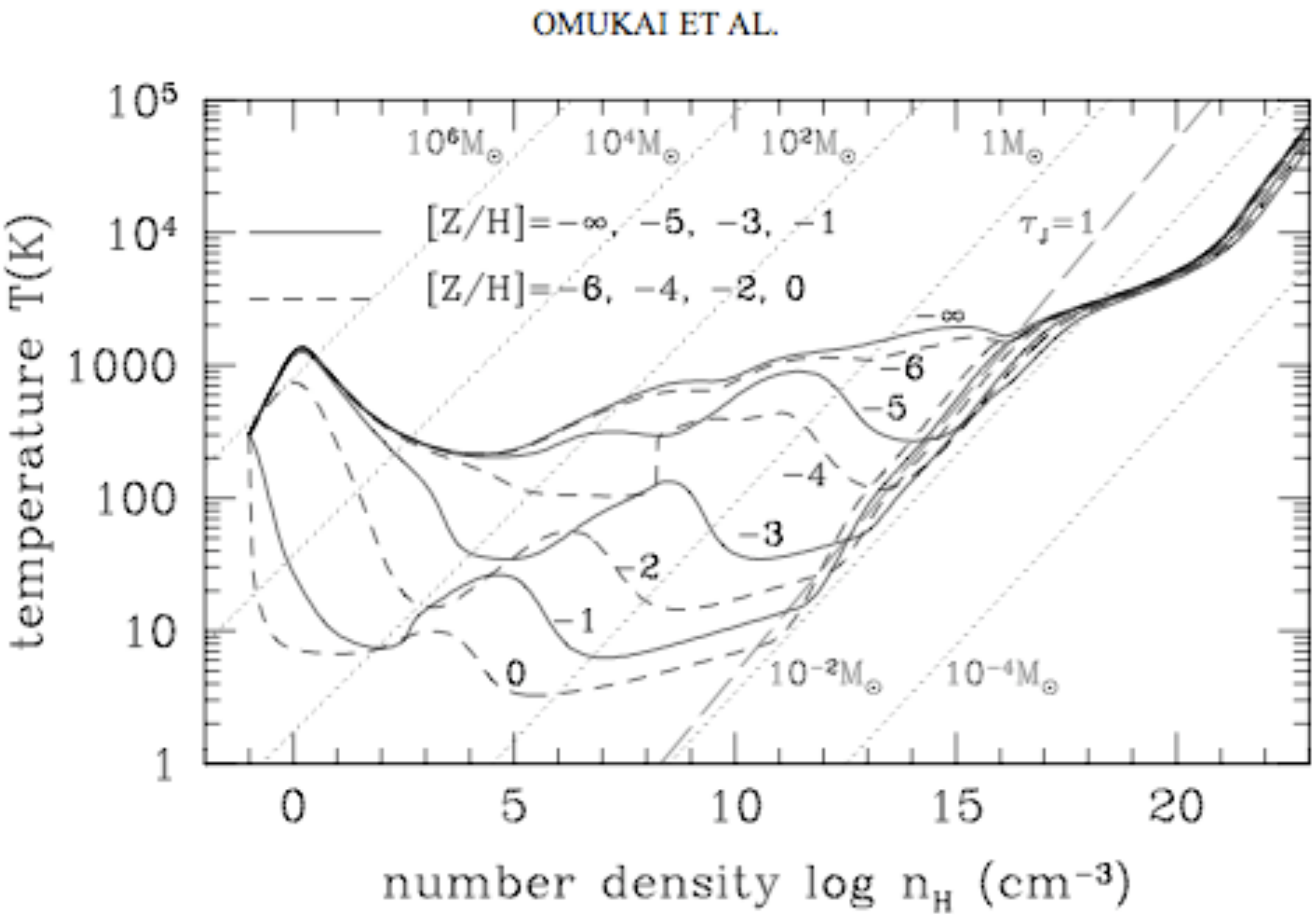
(Jappsen et al. 2005, A&A, 435, 611)

IMF in nearby molecular clouds



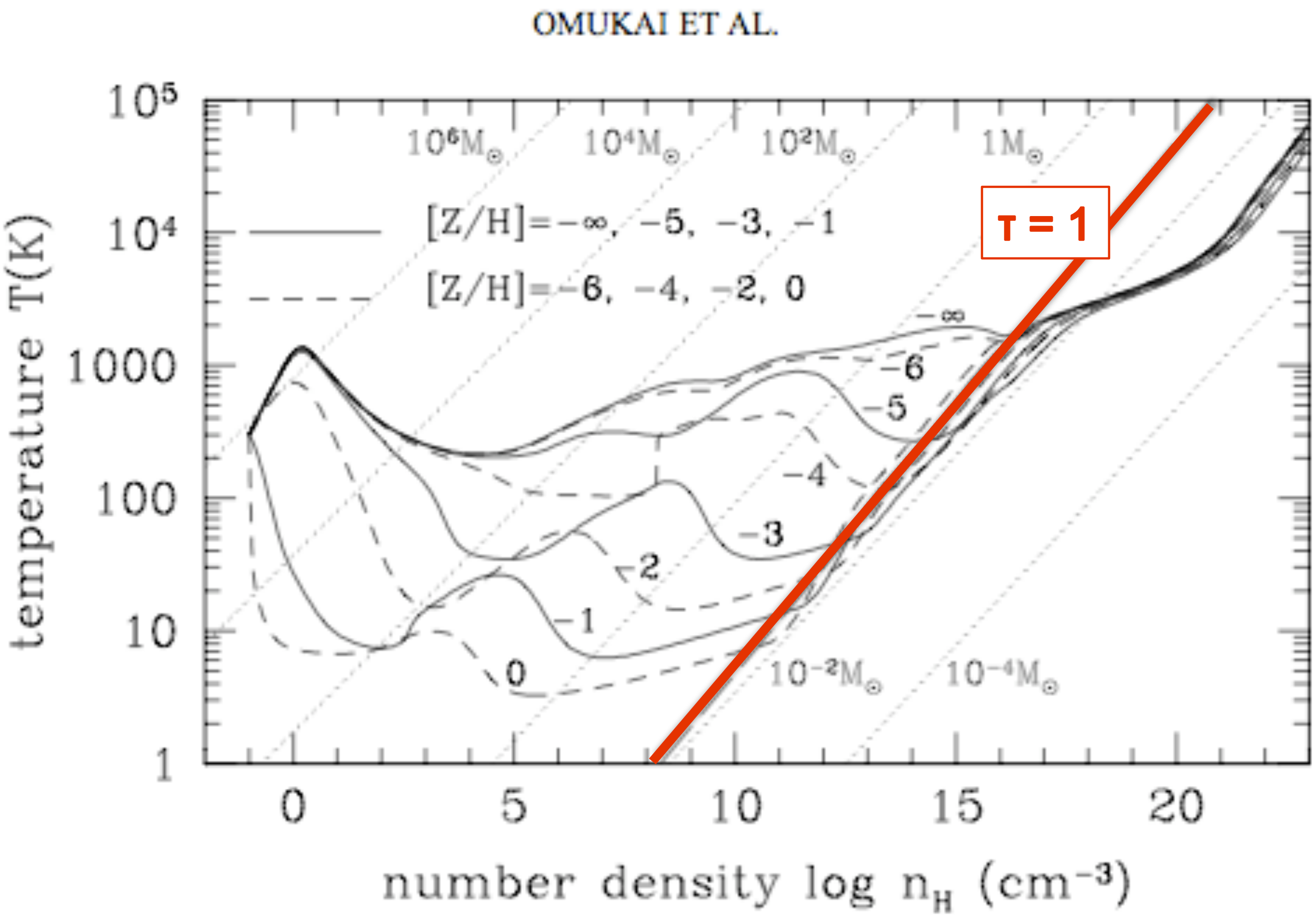
(Jappsen et al. 2005, A&A, 435, 611)

EOS as function of metallicity



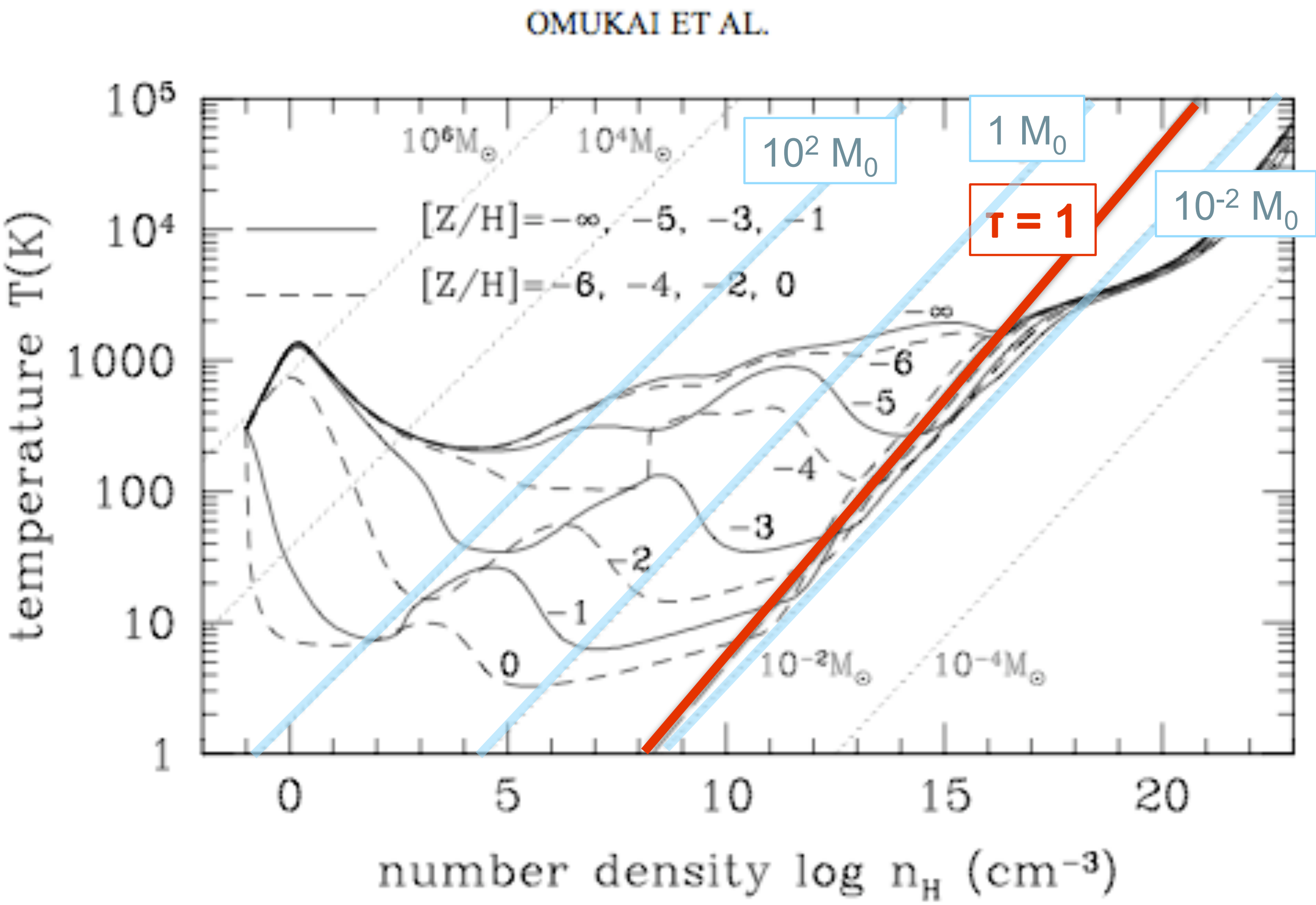
(Omukai et al. 2005)

EOS as function of metallicity



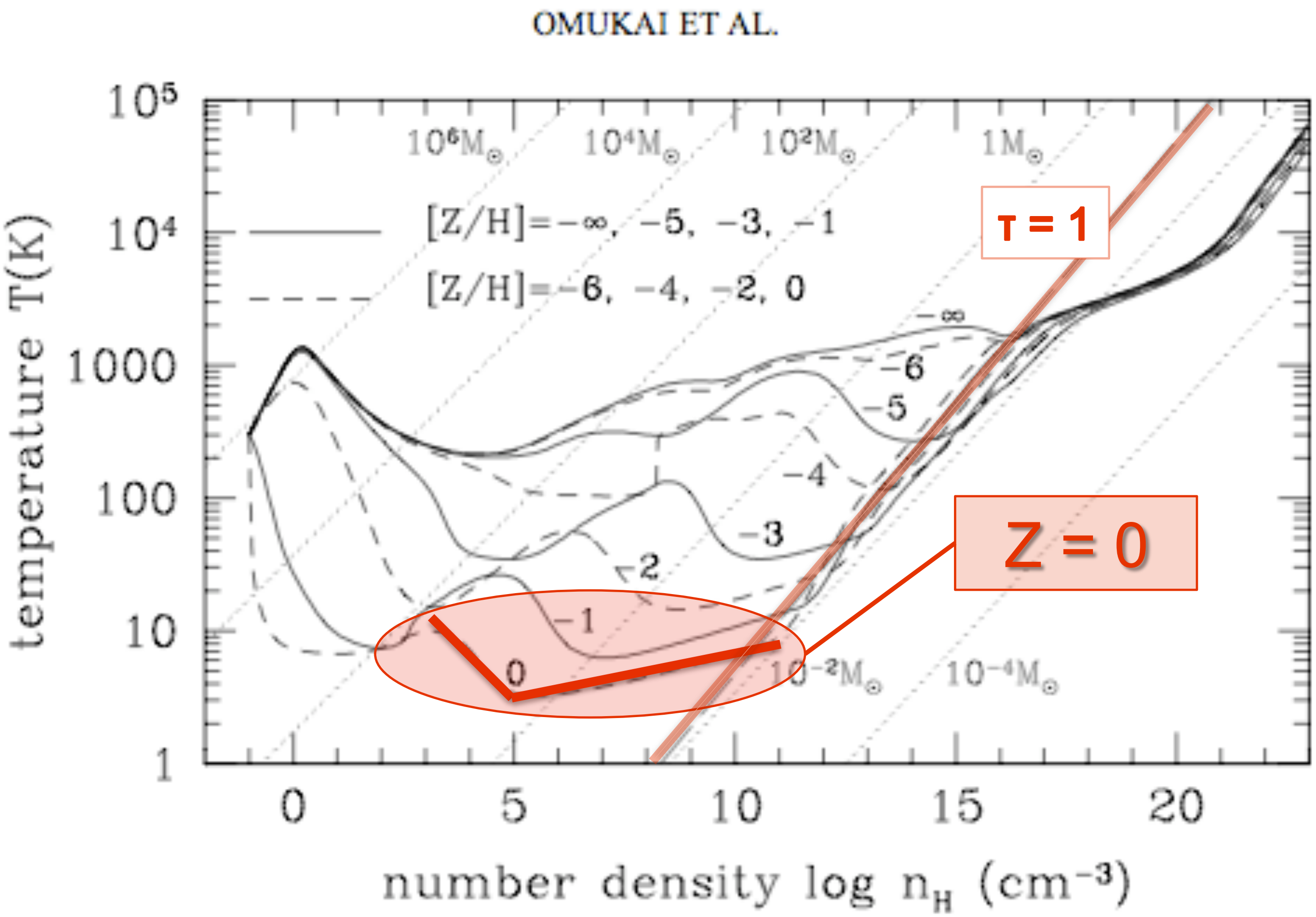
(Omukai et al. 2005)

EOS as function of metallicity



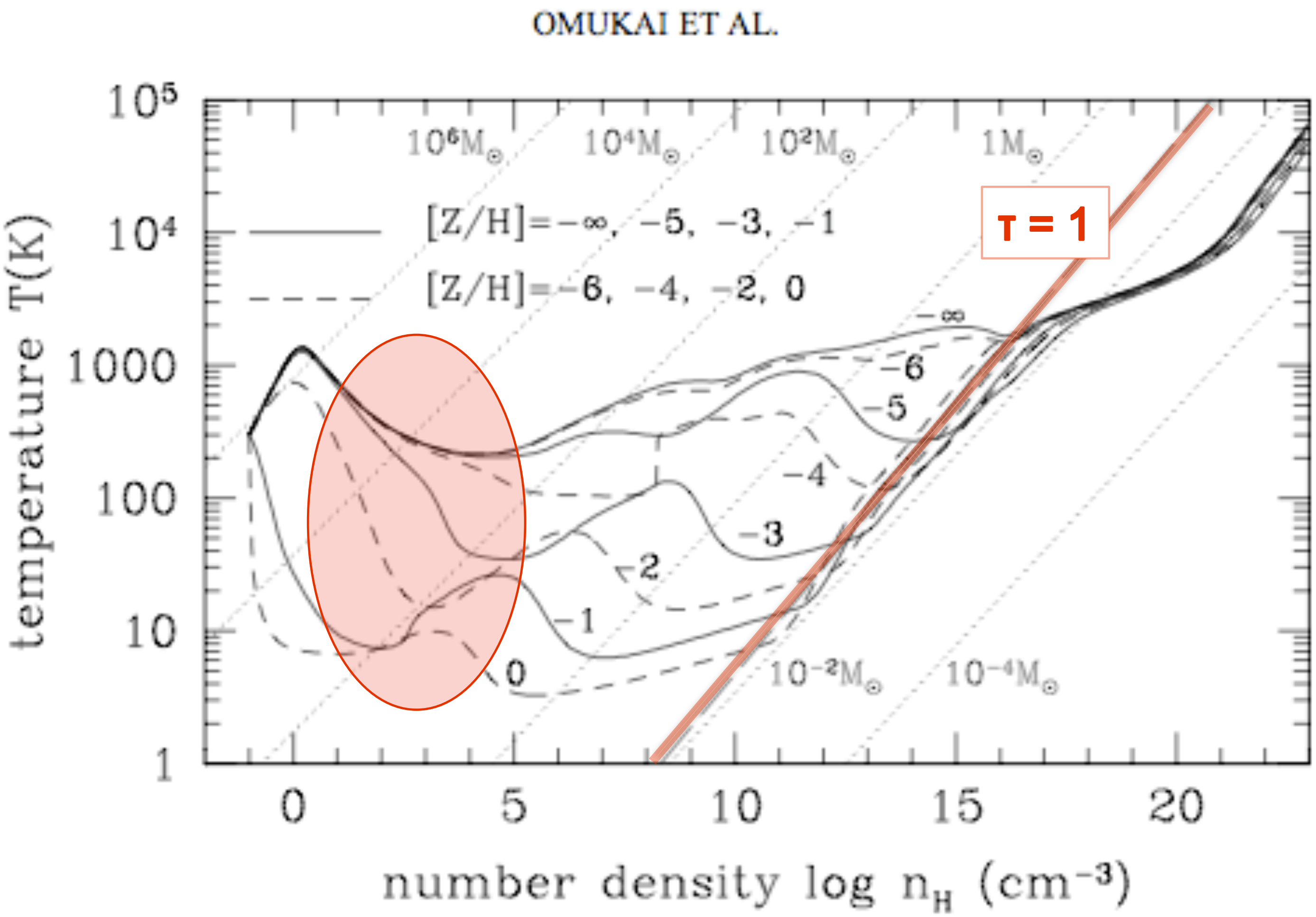
(Omukai et al. 2005)

present-day star formation



(Omukai et al. 2005)

dependence on Z at low density



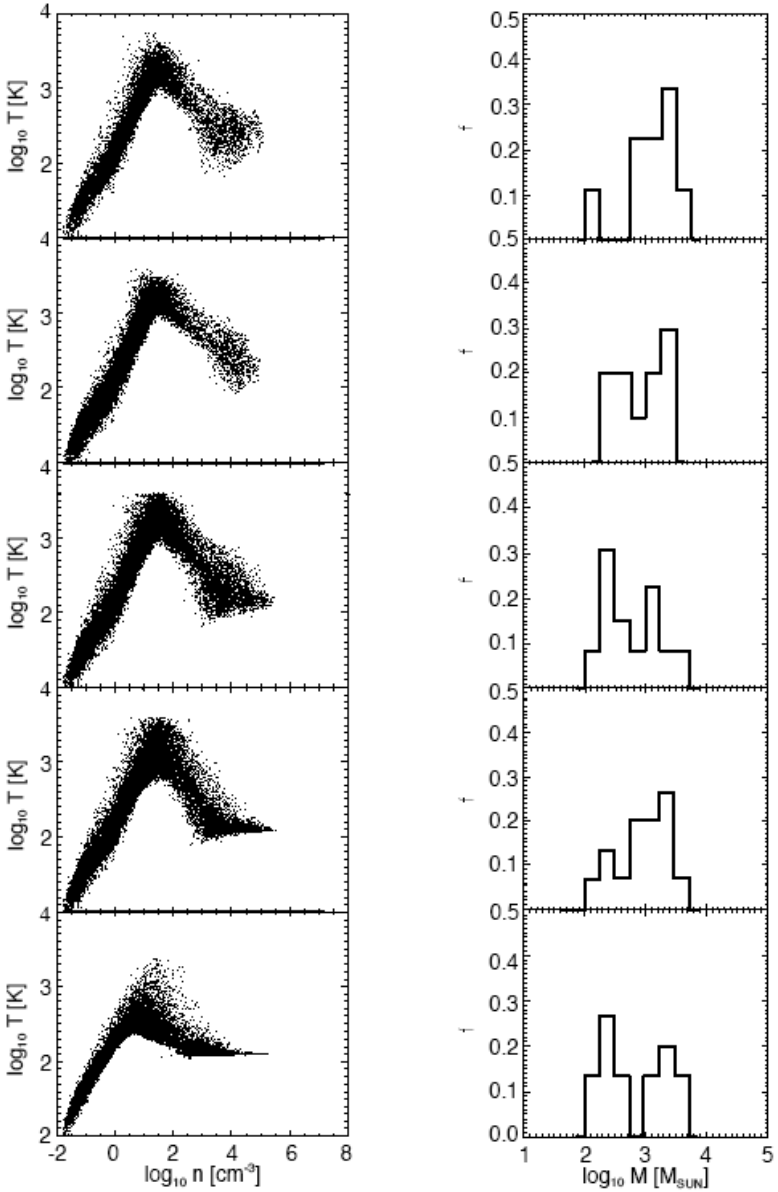
(Omukai et al. 2005)

dependence on Z at low density

- at densities below n ≈ 10^2 cm^{-3} *H_2 cooling* dominates the behavior. (Jappsen et al. 2007)
- fragmentation depends on *initial conditions then*
  - example: solid-body rotating top-hat initial conditions with dark matter fluctuations (a la Bromm et al. 1999) fragment no matter what metallicity you take (in regime n ≤ 10^6 cm^{-3}) → because unstable disk builds up

    (Jappsen et al. 2008a)

dependence on Z at low density



Z = 0

Z = -4

Z = -3

Z = -2

Z = -1

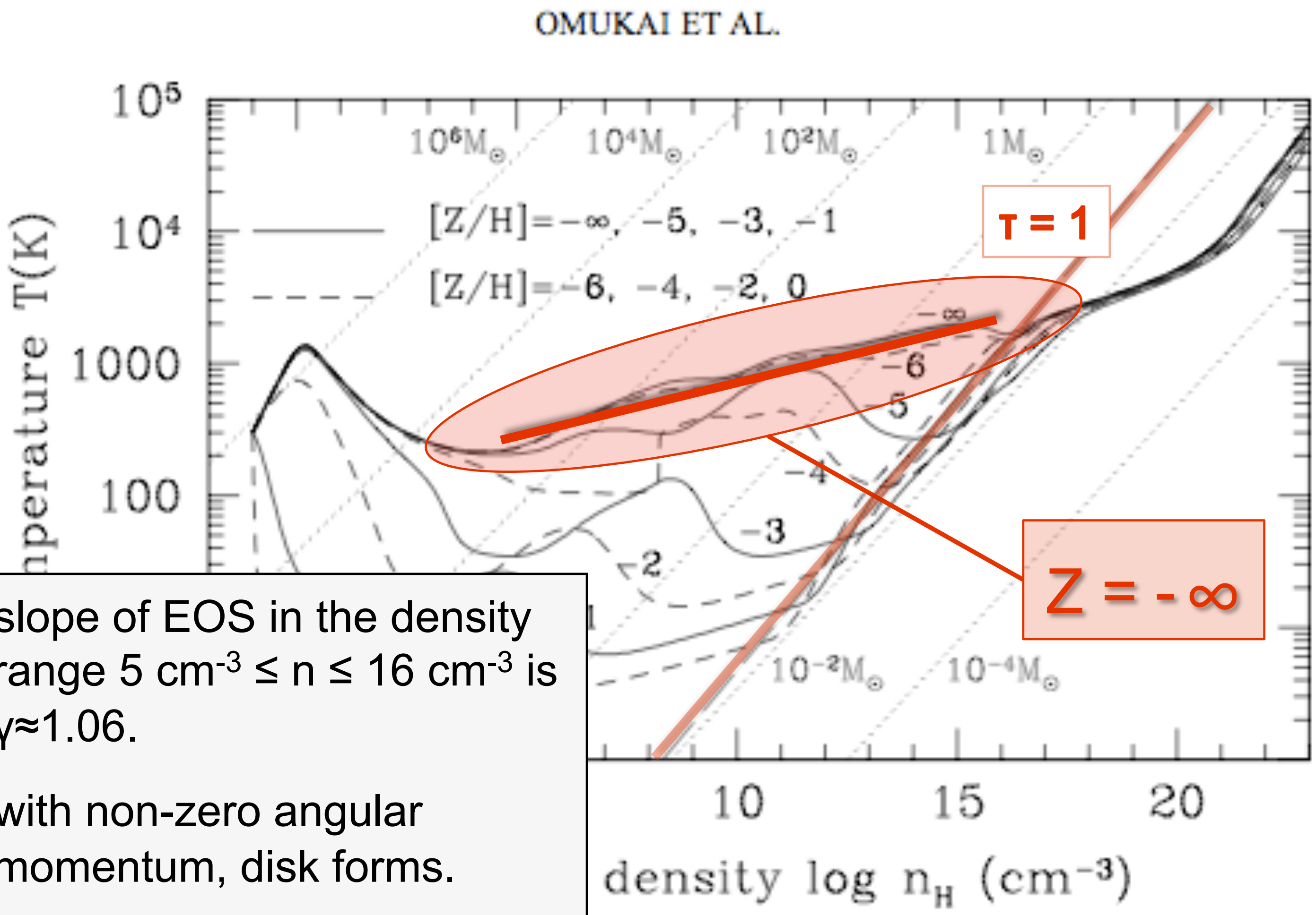
rotating top-hat with dark matter fluctuations fragments, no matter what

(Jappsen et al. 2008a, see poster by Jappsen et al, see also Clark et al. 2008)

dependence on Z at low density

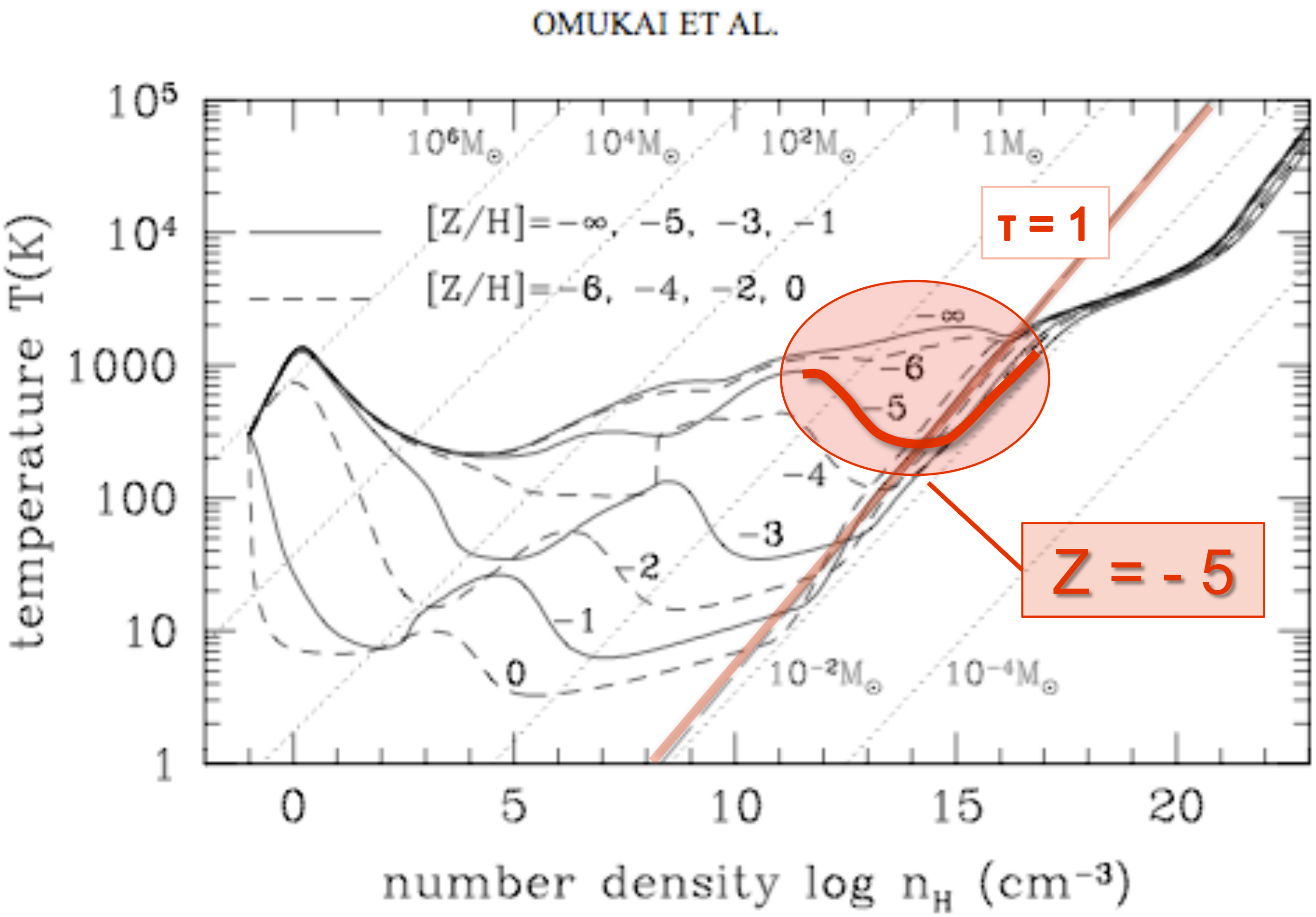
- fragmentation depends on *initial conditions then*
  - example: centrally concentrated halo does not fragment up to densities of n ≈ 10^6 cm^{-3} up to metallicities Z ≈ -1
    (Jappsen et al. 2008b)

metal-free star formation



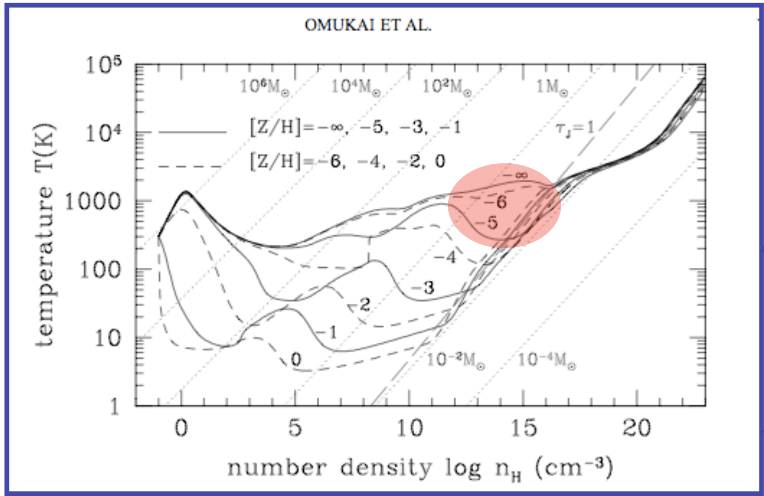
- slope of EOS in the density range 5 $cm^{-3} \leq n \leq 16$ cm^{-3} is $\gamma \approx 1.06$.
- with non-zero angular momentum, disk forms.
- this disk will be unstable against fragmentation

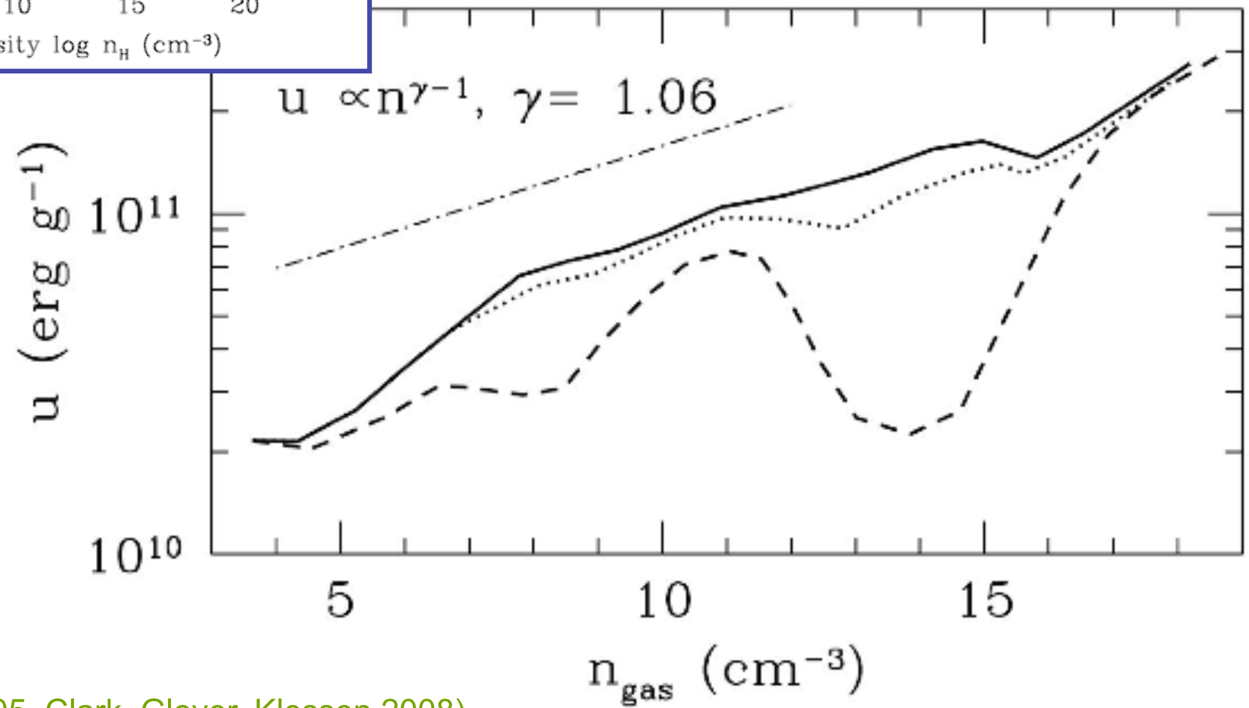
transition: Pop III to Pop II.5



(Omukai et al. 2005)

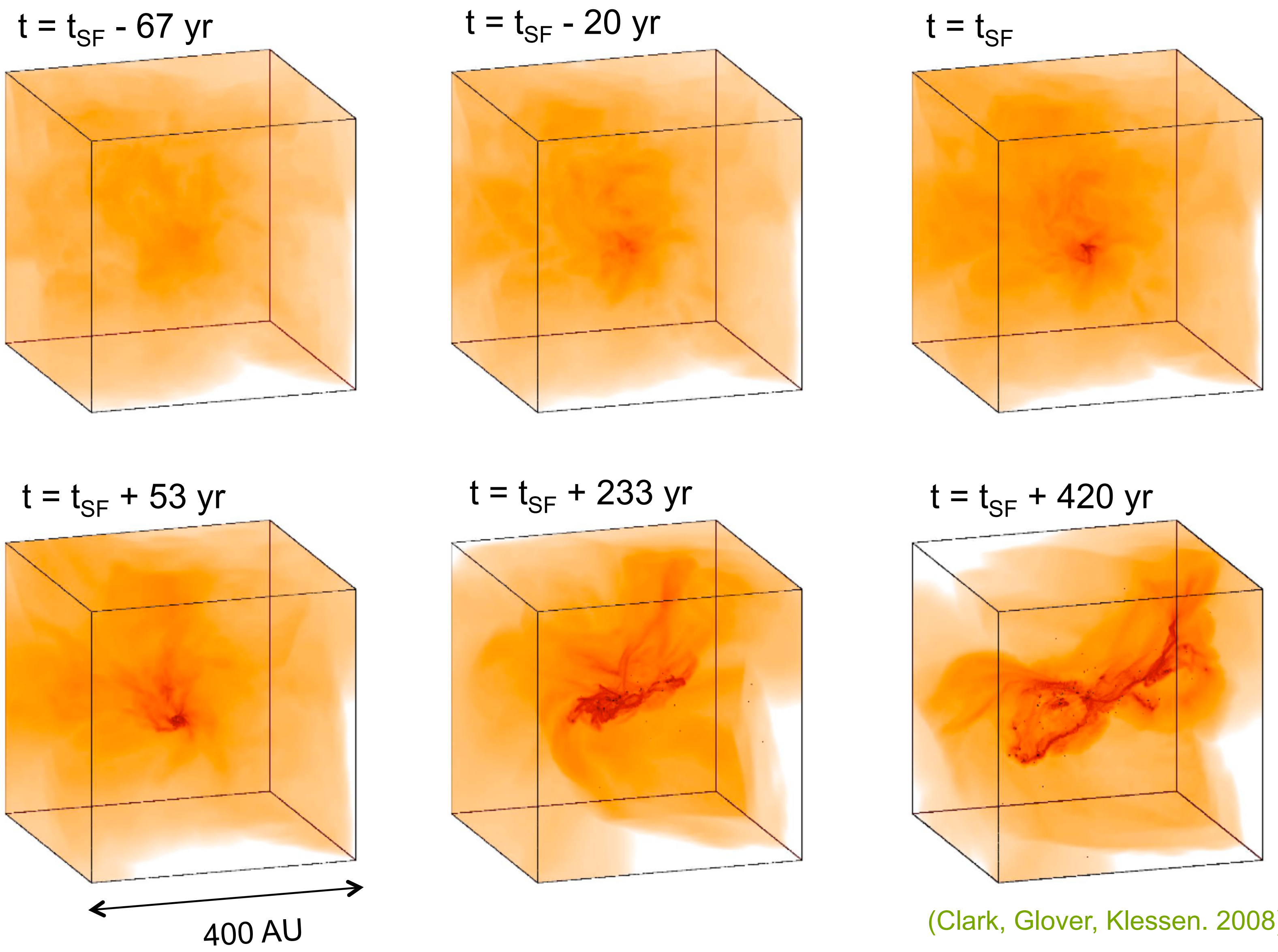
transition: Pop III to Pop II.5





(Omukai et al. 2005, Clark, Glover, Klessen 2008)

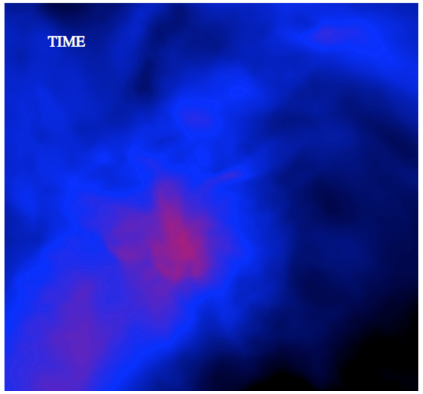
dust induced fragmentation at $Z=10^{-5}$



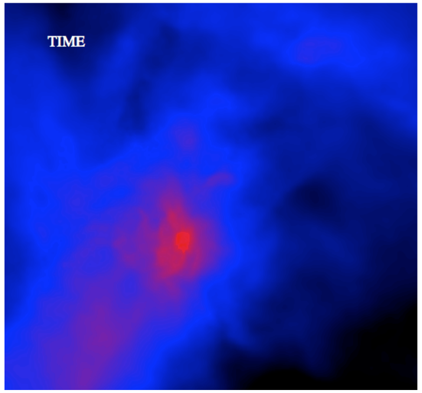
(Clark, Glover, Klessen. 2008)

dust induced fragmentation at $Z=10^{-5}$

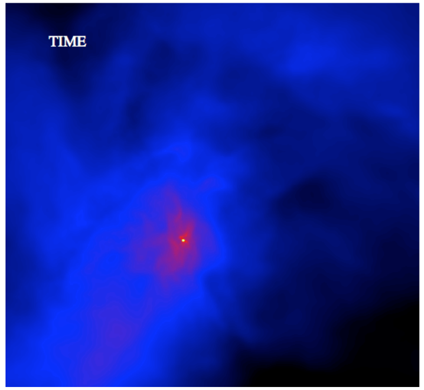
$t = t_{SF}$ - 67 yr



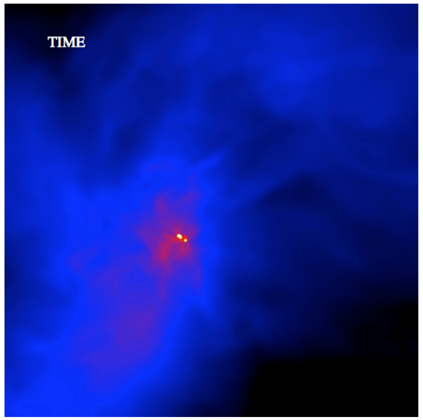
$t = t_{SF}$ - 20 yr



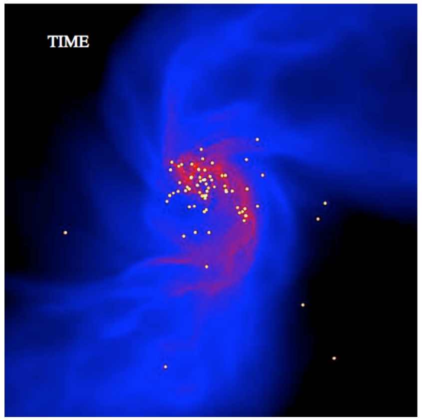
$t = t_{SF}$



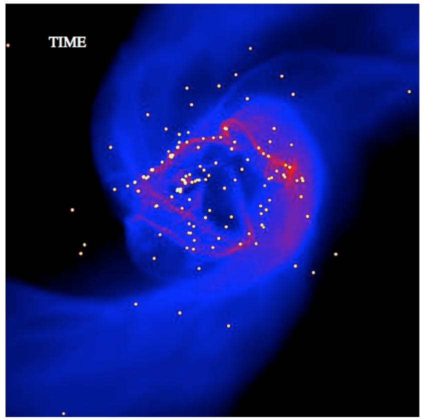
$t = t_{SF}$ + 53 yr



$t = t_{SF}$ + 233 yr

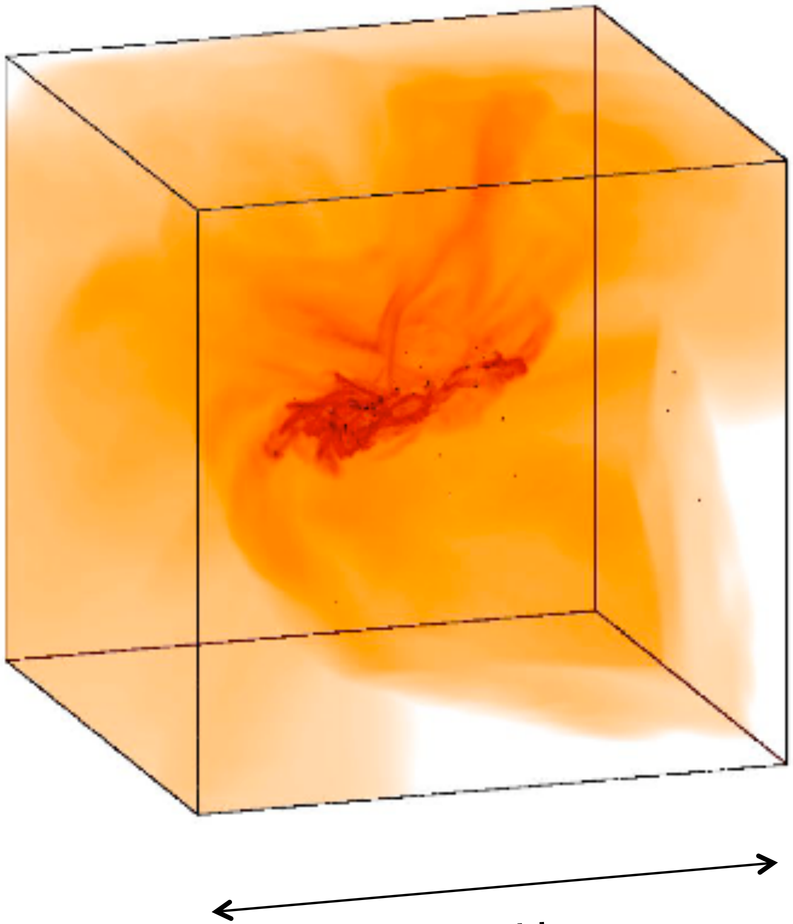


$t = t_{SF}$ + 420 yr



(Clark, Glover, Klessen 2008)

dust induced fragmentation at $Z=10^{-5}$

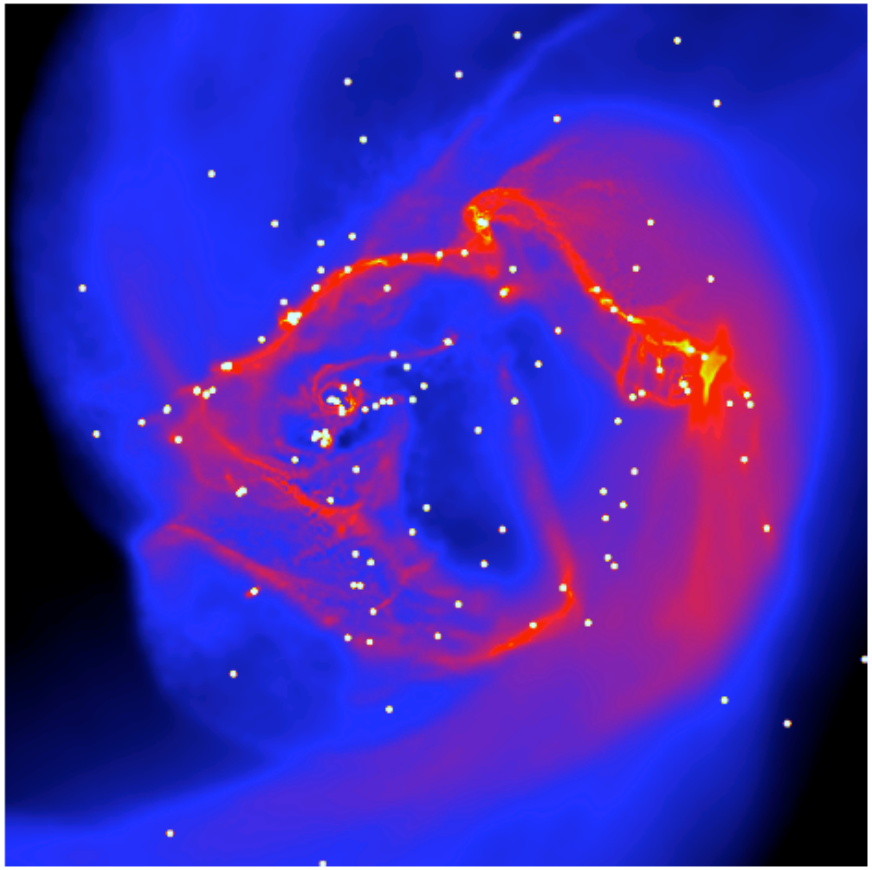


dense cluster of low-mass protostars builds up:

- mass spectrum peaks below 1 M_{sun}
- cluster VERY dense $n_{stars} = 2.5 \times 10^9\ pc^{-3}$
- fragmentation at density $n_{gas} = 10^{12} - 10^{13}\ cm^{-3}$

(Clark et al. 2008)

dust induced fragmentation at $Z=10^{-5}$



400 AU

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(Clark et al. 2008)

cluster build-up

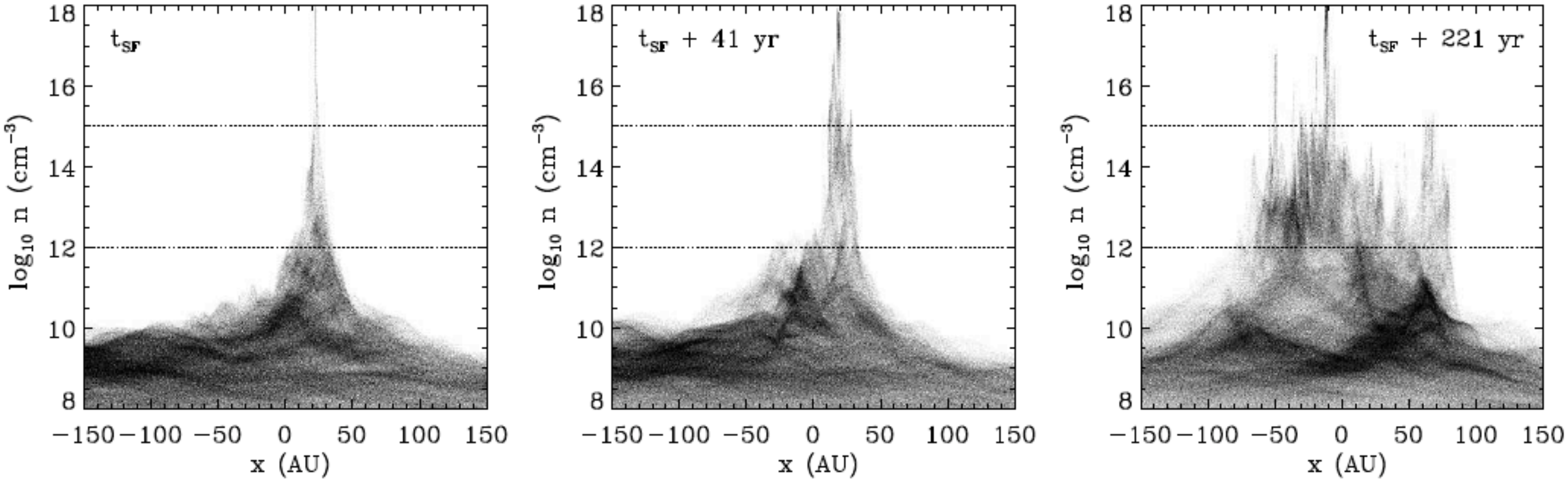
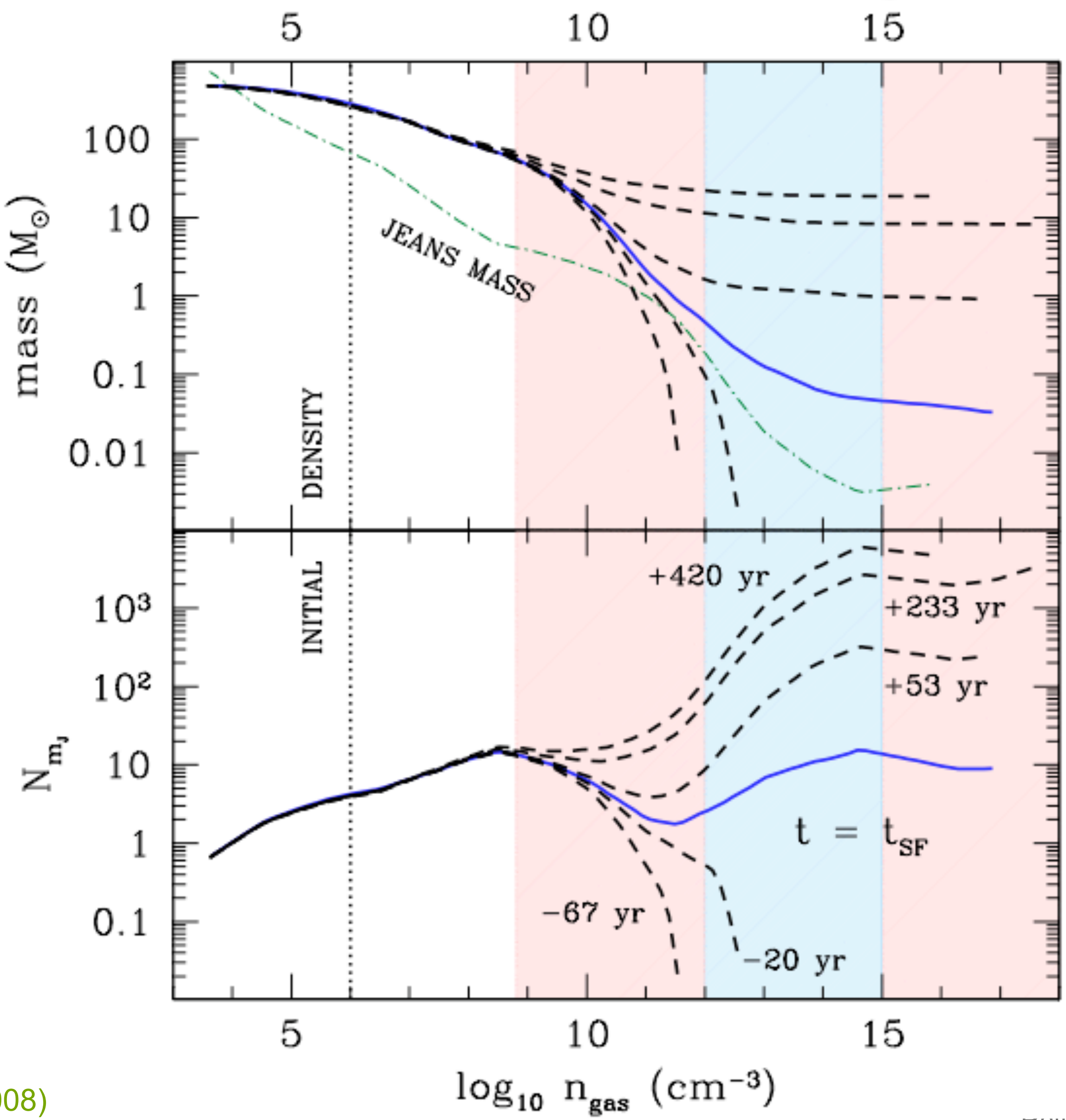
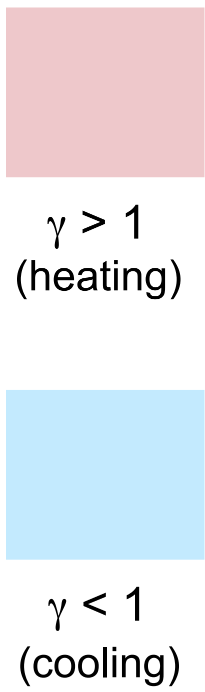


FIG. 3.— We illustrate the onset of the fragmentation process in the high resolution $Z = 10^{-5} Z_{\odot}$ simulation. The graphs show the densities of the particles, plotted as a function of their x-position. Note that for each plot, the particle data has been centered on the region of interest. We show here results at three different output times, ranging from the time that the first star forms (t_{sf}) to 221 years afterwards. The densities lying between the two horizontal dashed lines denote the range over which dust cooling lowers the gas temperature.

(Clark et al. 2008)

cluster build-up

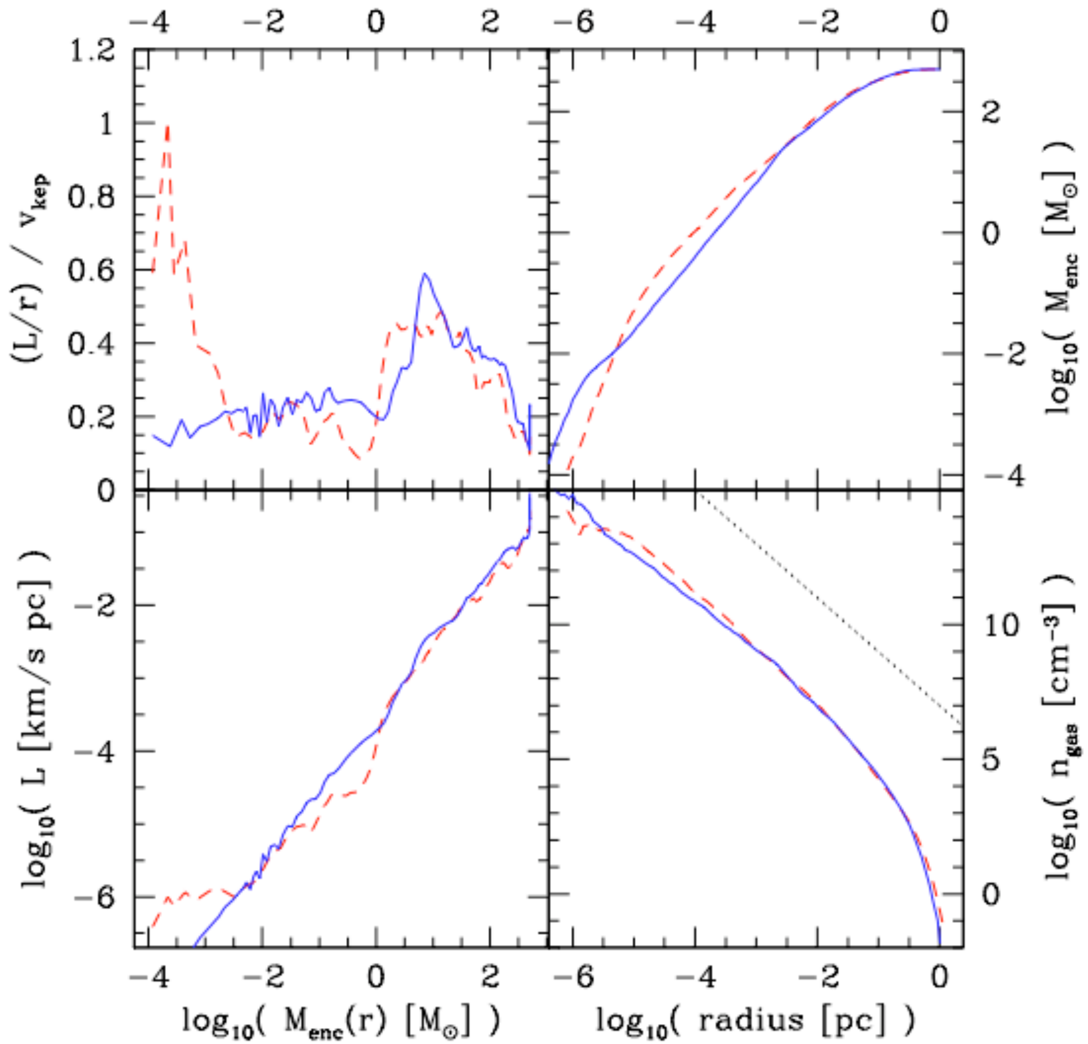




(Clark et al. 2008)

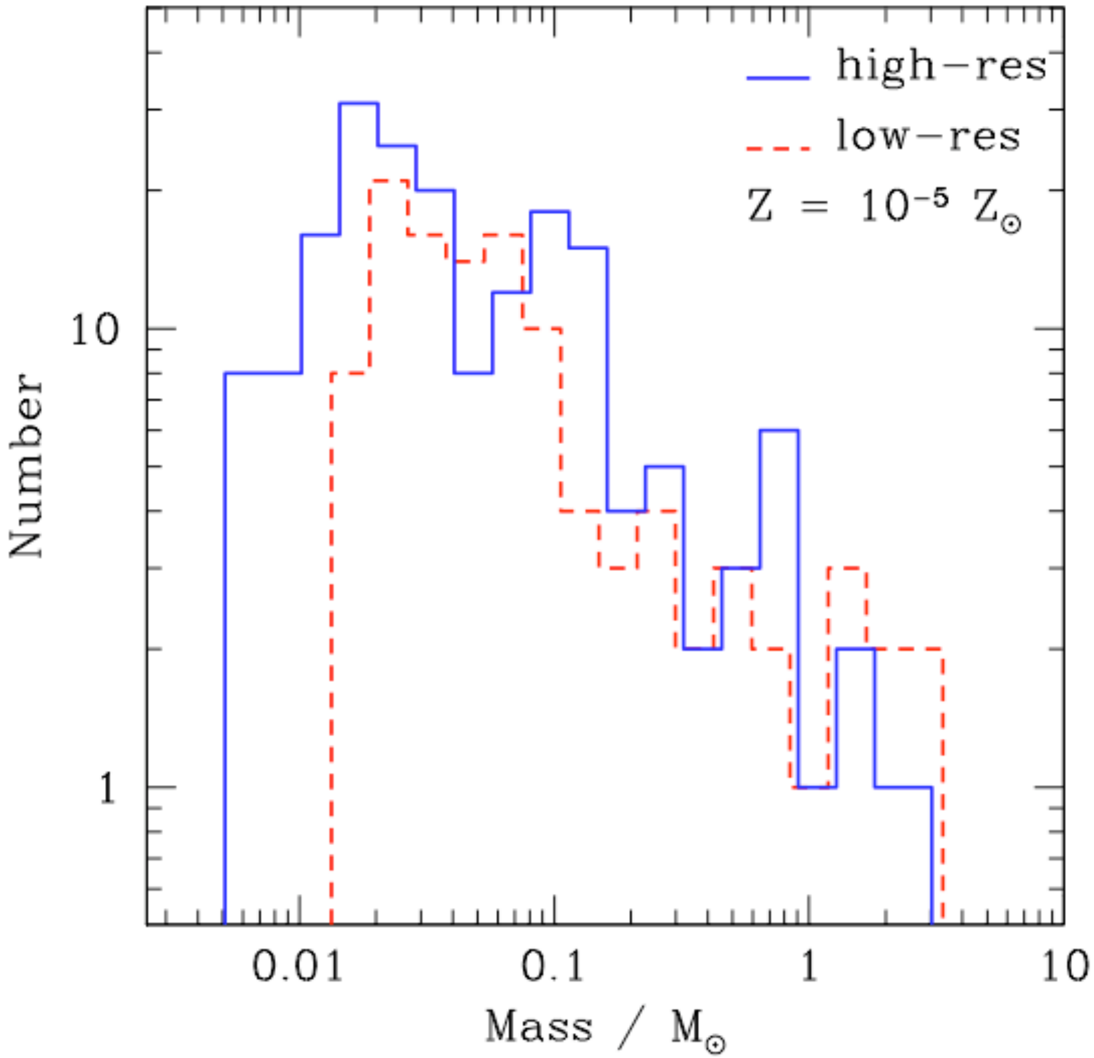
gas properties

gas properties at time when first star forms



(Clark et al. 2008)

dust induced fragmentation at $Z=10^{-5}$



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- cluster VERY dense $n_{stars} = 2.5 \times 10^9\ pc^{-3}$
- fragmentation at density $n_{gas} = 10^{12} - 10^{13}\ cm^{-3}$

(Clark et al. 2008)

comparison for different Z

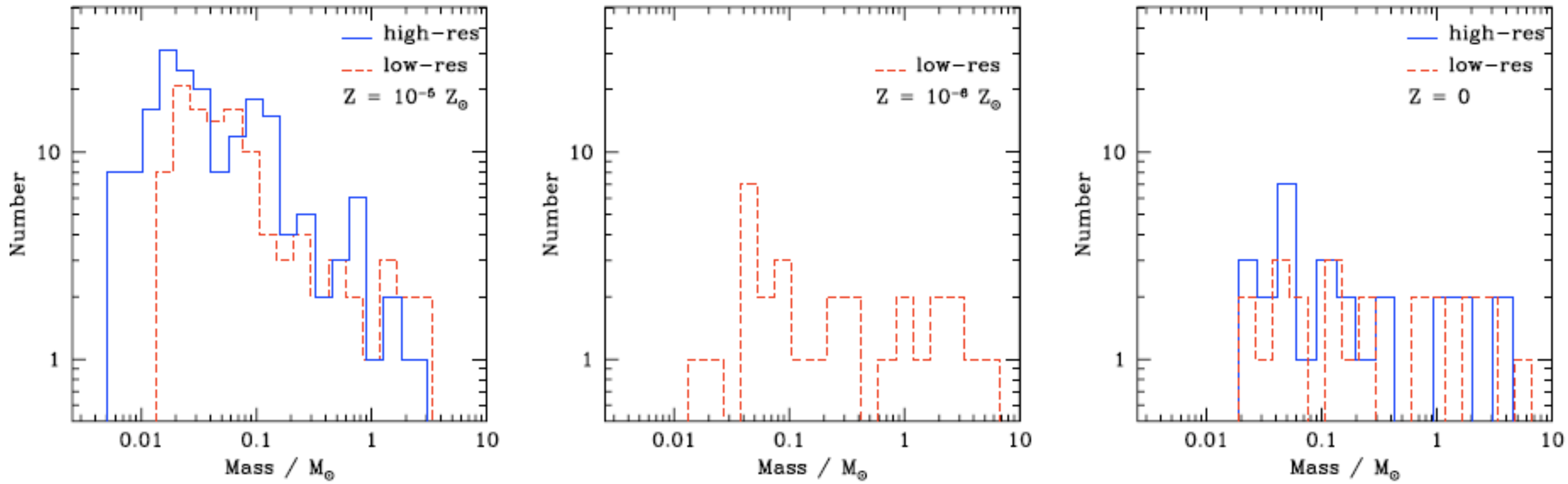

FIG. 4.— Mass functions resulting from simulations with metallicities $Z = 10^{-5}\ Z_\odot$ (left-hand panel), $Z = 10^{-6}\ Z_\odot$ (center panel), and $Z = 0$ (right-hand panel). The plots refer to the point in each simulation at which 19 $M_\odot$ of material has been accreted (which occurs at a slightly different time in each simulation). The mass resolutions are 0.002 $M_\odot$ and 0.025 $M_\odot$ for the high and low resolution simulations, respectively. Note the similarity between the results of the low-resolution and high-resolution simulations. The onset of dust-cooling in the $Z = 10^{-5}\ Z_\odot$ cloud results in a stellar cluster which has a mass function similar to that for present day stars, in that the majority of the mass resides in the lower-mass objects. This contrasts with the $Z = 10^{-6}\ Z_\odot$ and primordial clouds, in which the bulk of the cluster mass is in high-mass stars.

even zero-metallicity case fragments
(although much more weakly)

(Clark et al. 2008)

Summary

conclusions

- IMF 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

conclusions

- many of these processes will also be present in the early universe

  → *expect a wide range of stellar masses also for metal-free stars*

- features in EOS

  → *expect transition to lower masses at* $Z \approx 10^{-5}\, Z_{o}$

Thanks!