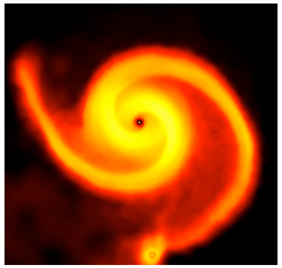
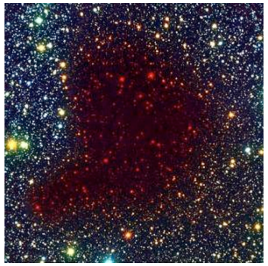
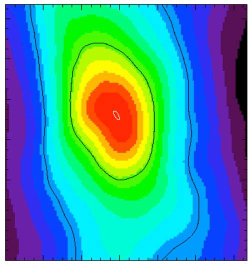
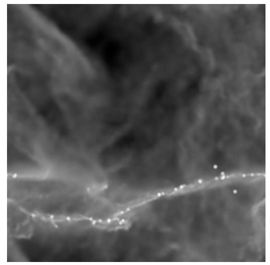
Formation and Evolution of Protostellar Disks in Star Clusters









Ralf Klessen

Zentrum für Astronomie der Universität Heidelberg
Institut für Theoretische Astrophysik

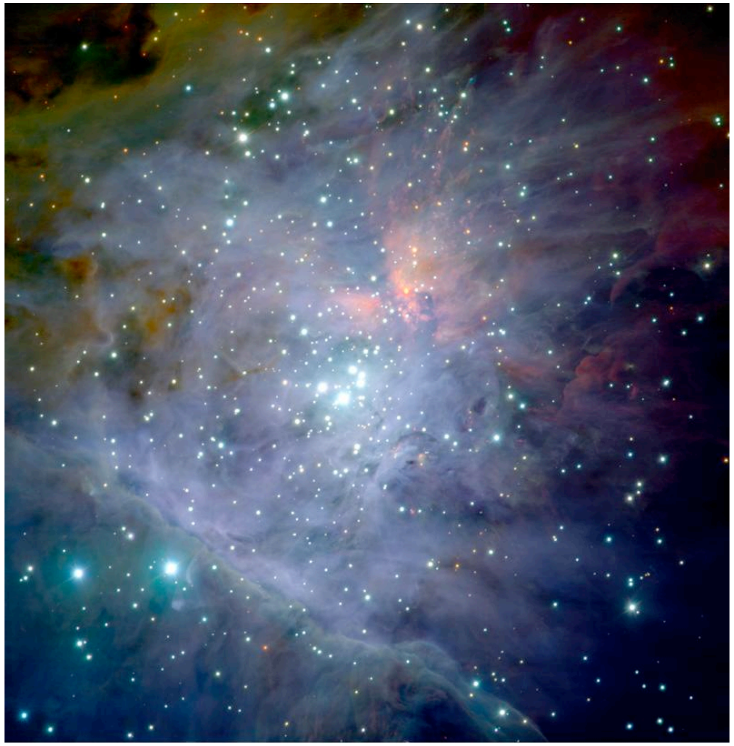
thanks to ...

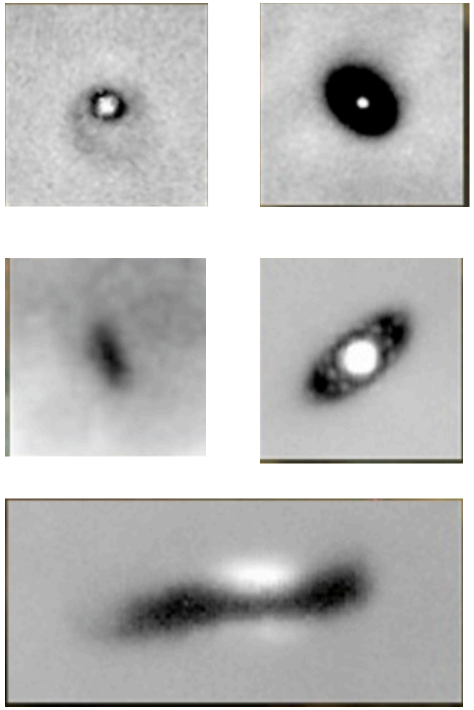
- many thanks to the members of the *star formation group* at the *Institute for Theoretical Astrophysics* at the *Center for Astronomy* of *Heidelberg University*

  - Robi Banerjee
  - Paul Clark
  - Christoph Federrath
  - Simon Glover
  - Milica Milosavljevic
  - Thomas Peters
  - Stefan Schmeja

  - and many guests:
    Ian Bonnell,
    Alyssa Goodman,
    Mordecai-Mark Mac

How do protostellar disks build-up and evolve in a forming star cluster?





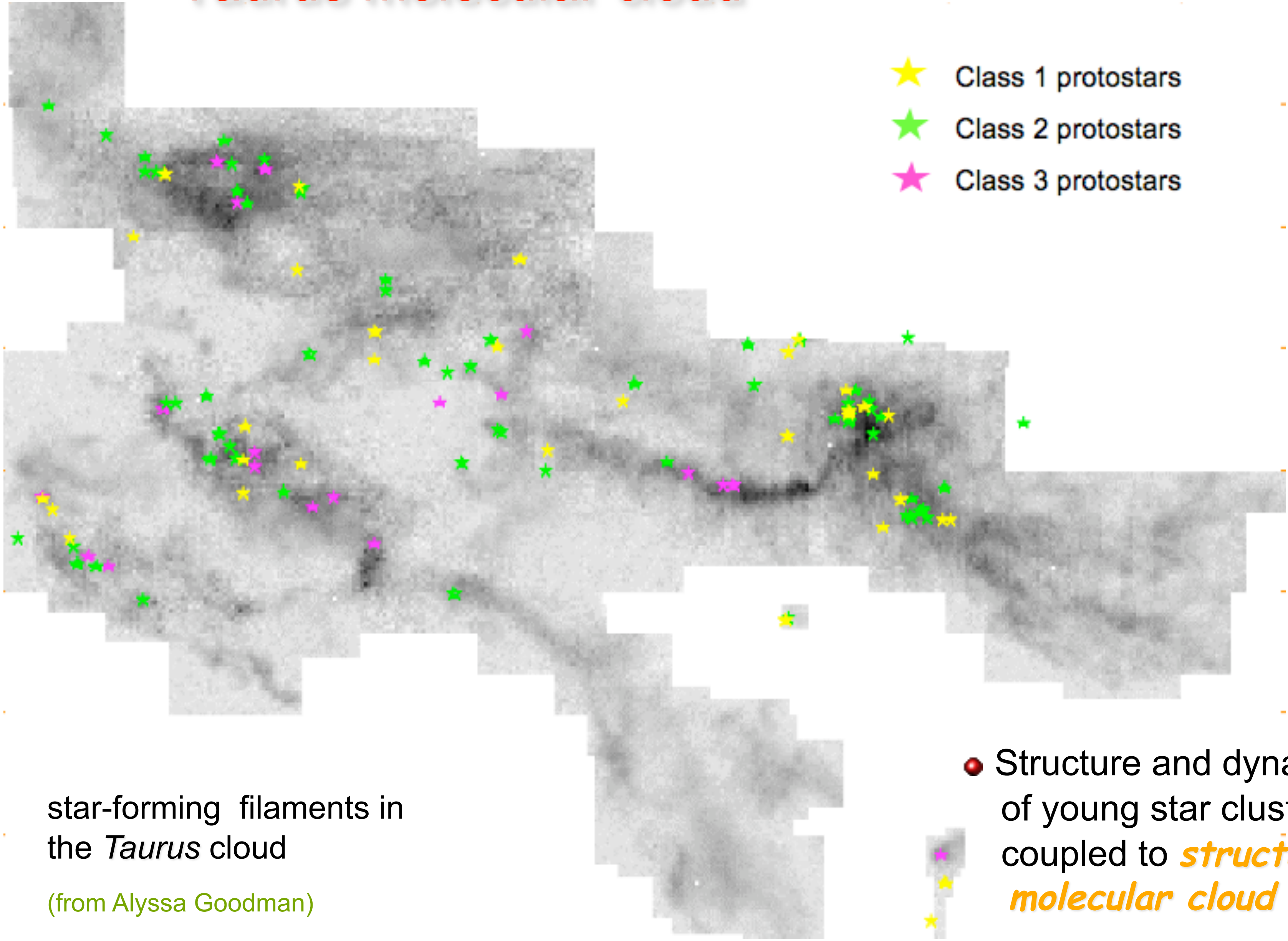
(data: Mark McCaughrean)

agenda

- turbulence in molecular clouds
- formation of star clusters
  - interplay between gravity and turbulence
- protostellar disks
  - formation and evolution
  - effects of environment
- what‘s next?

molecular clouds

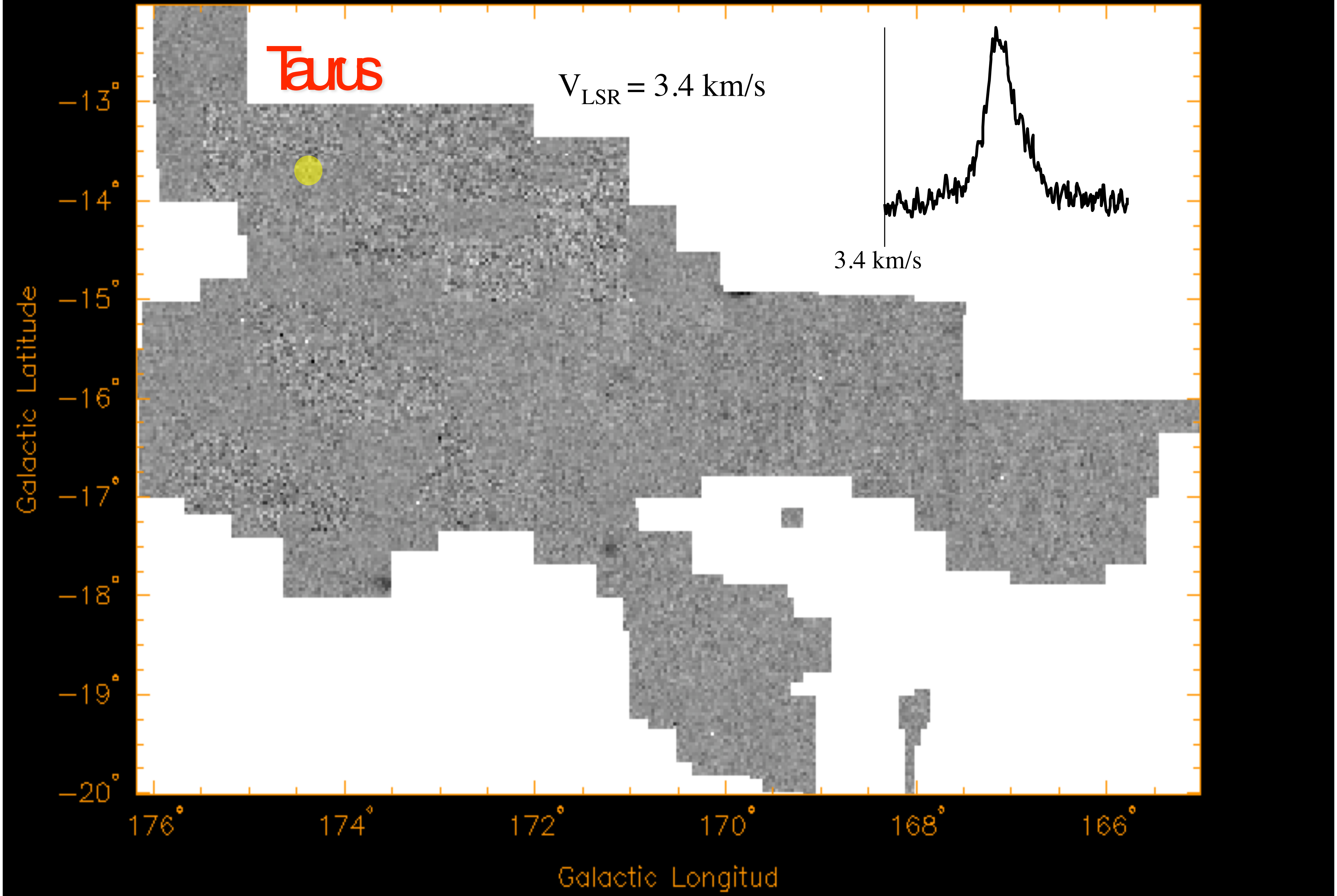
Taurus molecular cloud



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
V_{LSR} = 3.4 km/s
3.4 km/s
−13°
−14°
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Galactic Latitude
176°
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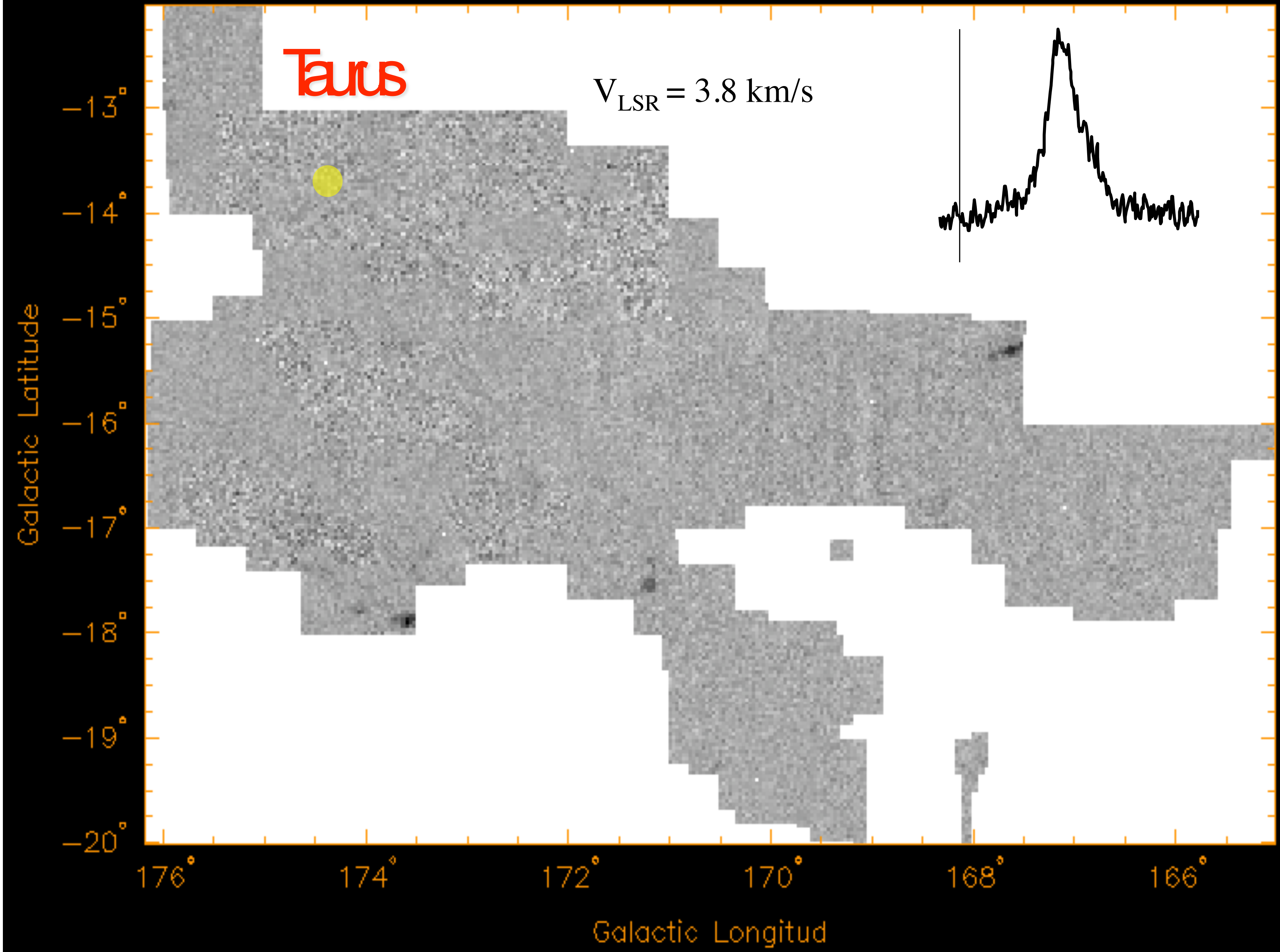
166°
Galactic Longitud



Taurus
V_{LSR} = 3.8 km/s
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Galactic Latitude
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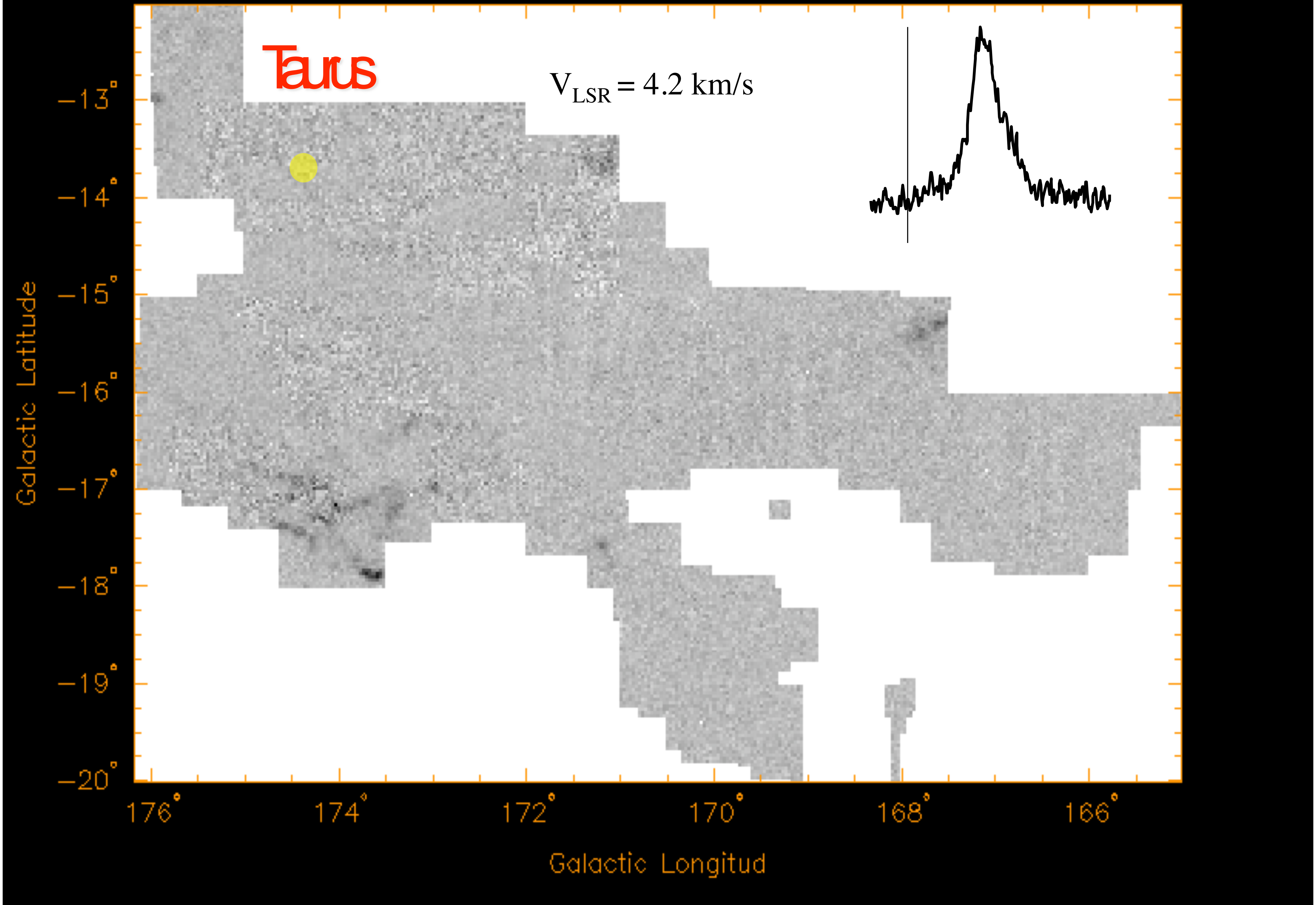
Galactic Longitud



Taurus
V_LSR = 4.2 km/s
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Galactic Latitude
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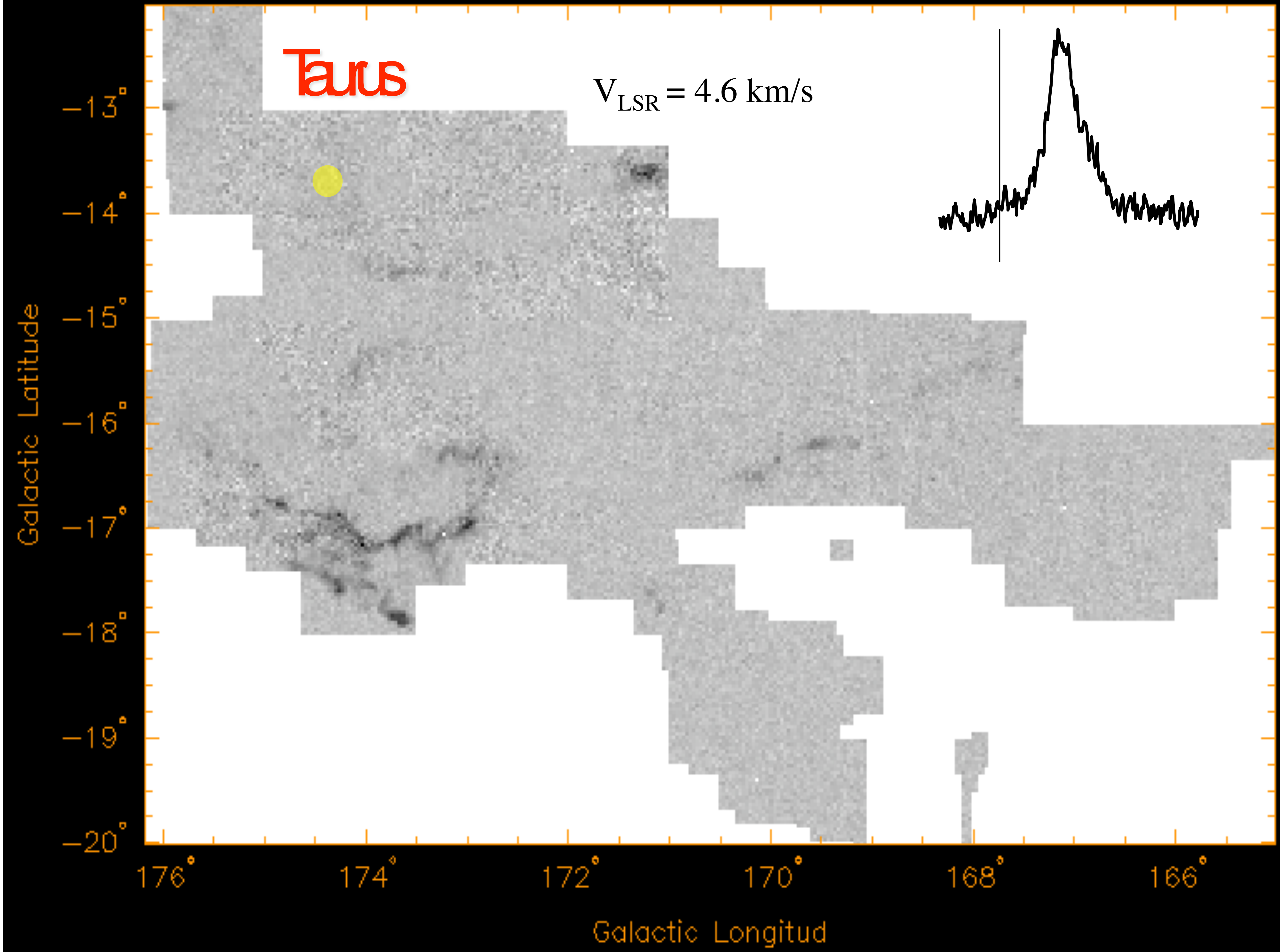
Galactic Longitud



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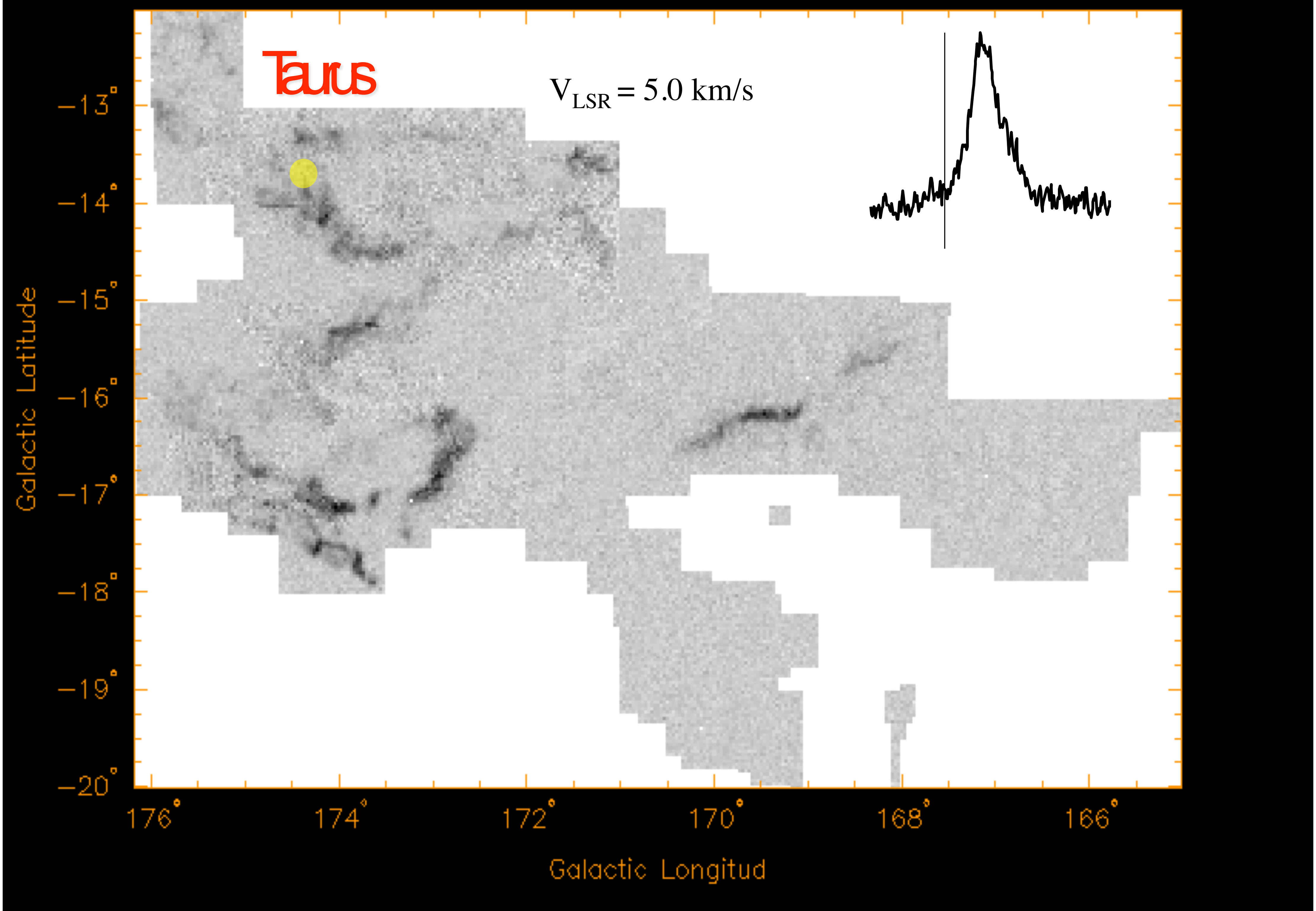
Galactic Longitud



Taurus
V_{LSR} = 5.0 km/s
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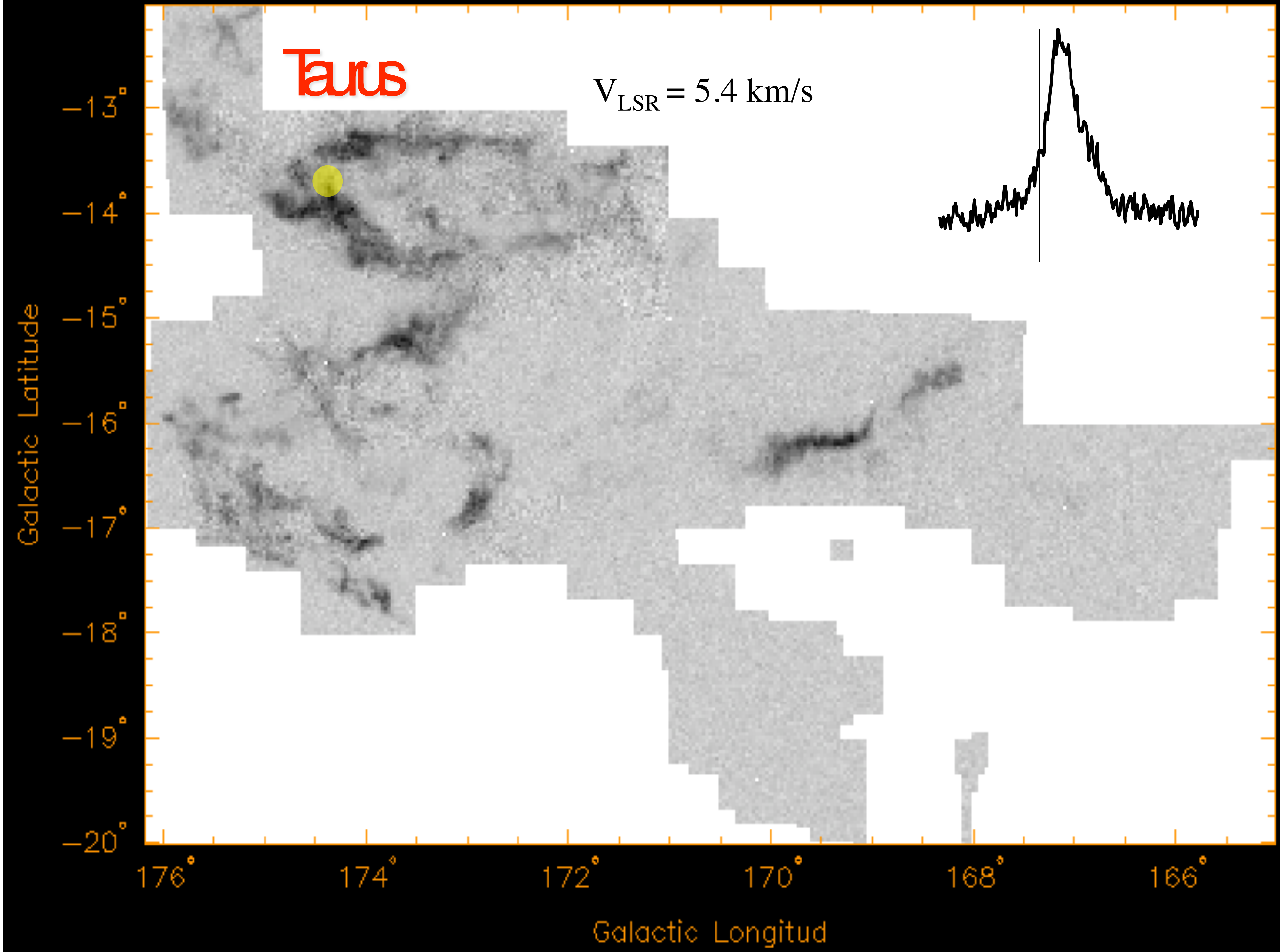
Galactic Longitud



Taurus
V_LSR = 5.4 km/s
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Galactic Latitude
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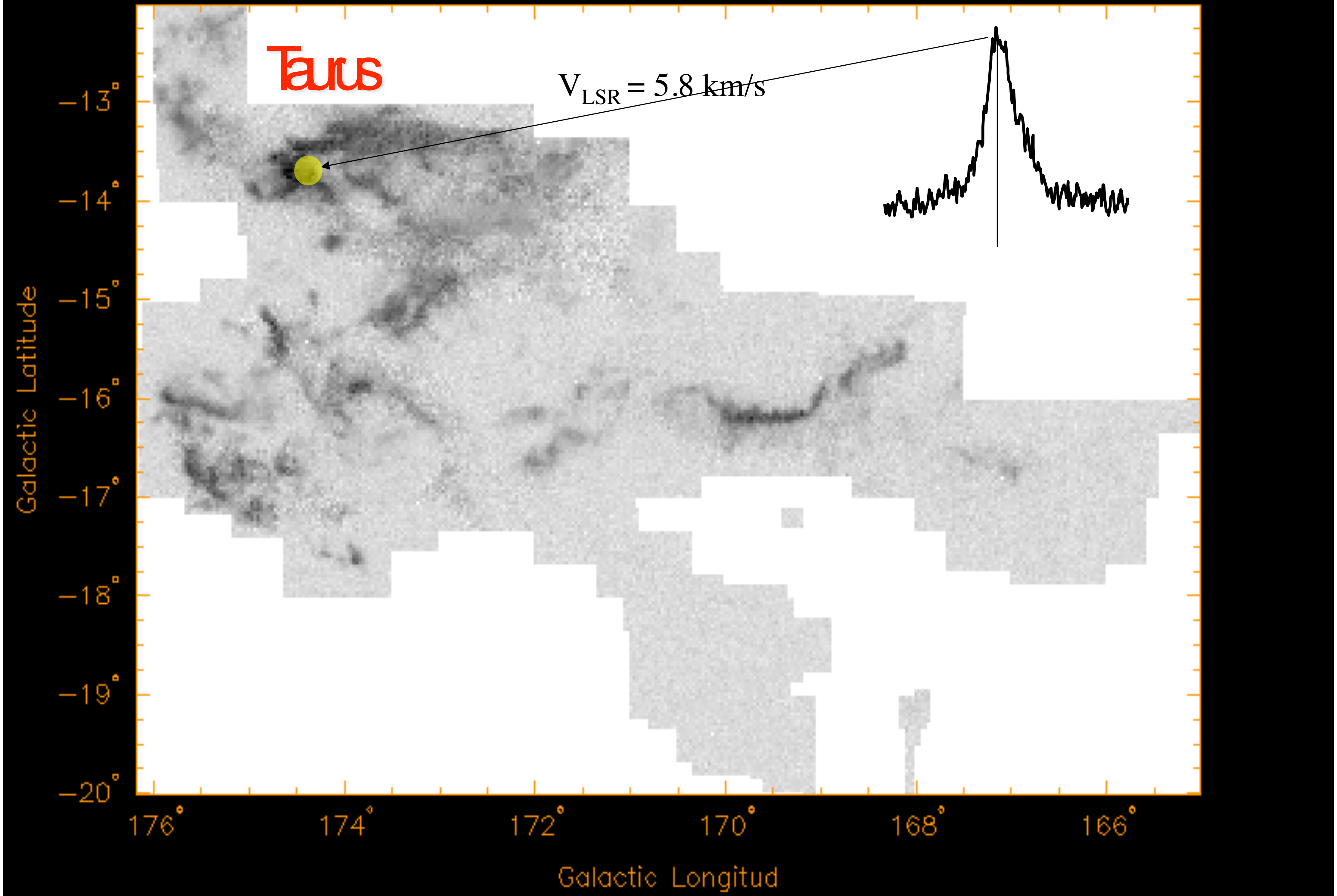
Galactic Longitud


Taurus
V_{LSR} = 5.8 km/s
Galactic Latitude
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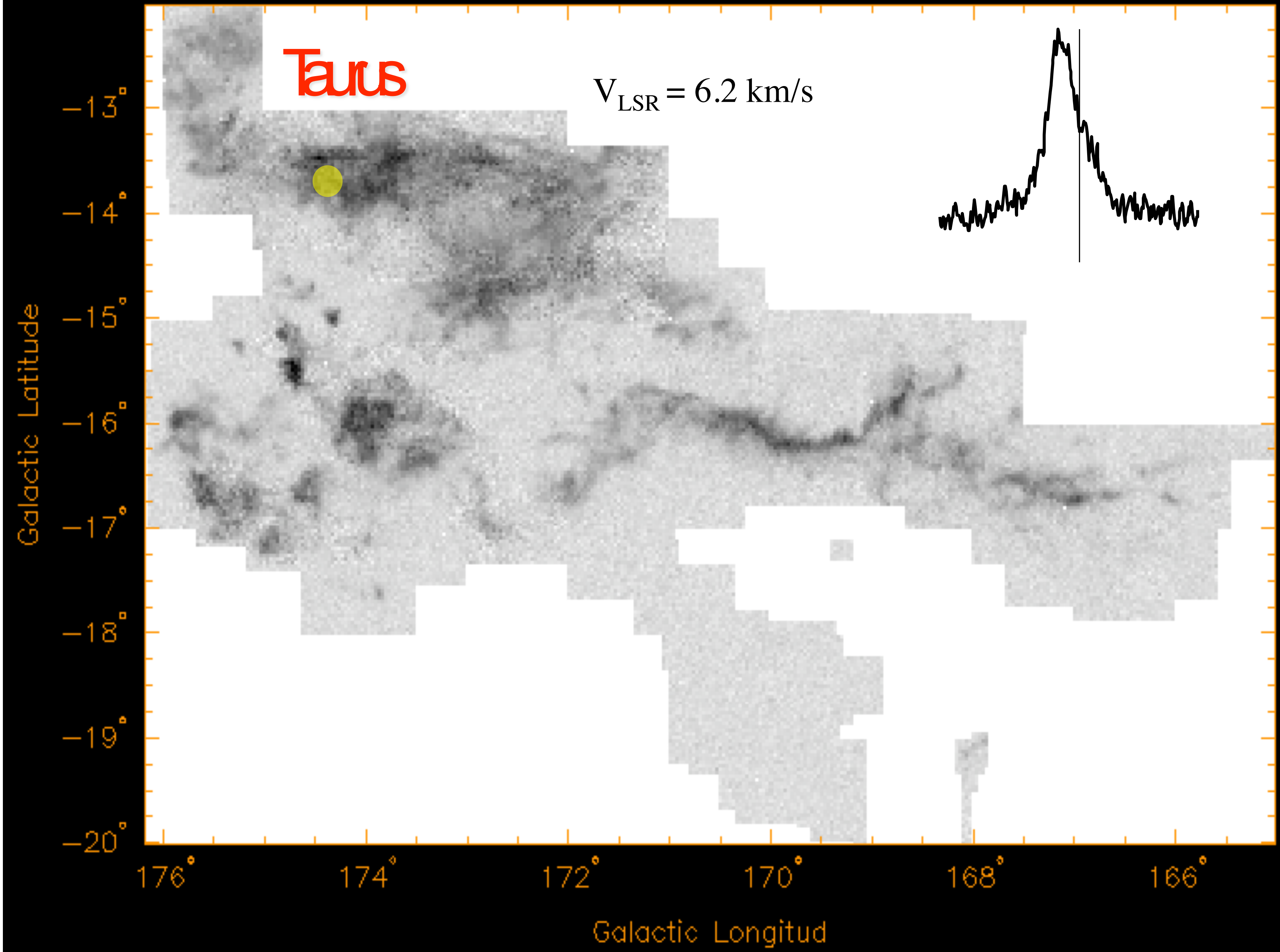
Galactic Longitud



Taurus
V_{LSR} = 6.2 km/s
Galactic Latitude
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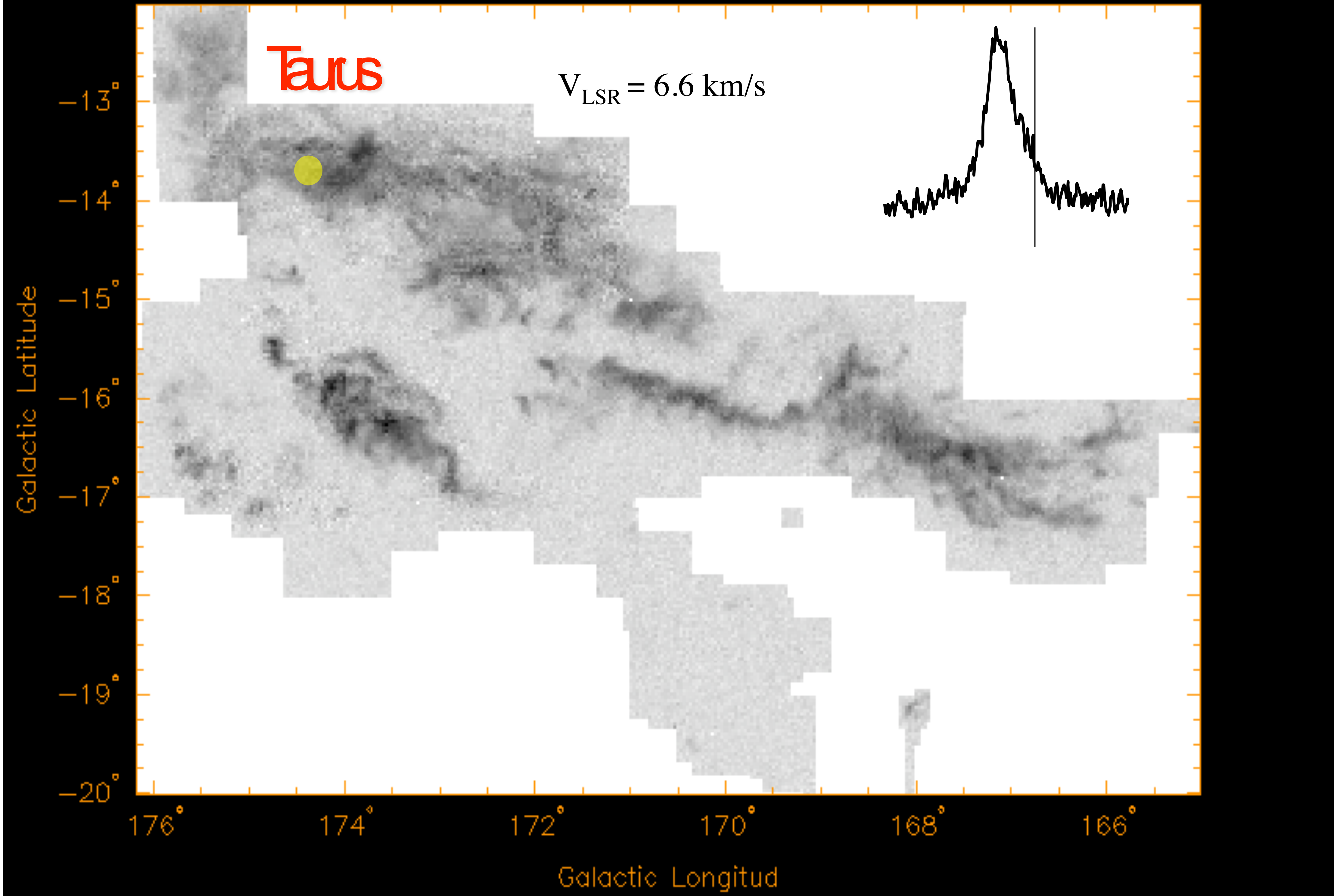
Galactic Longitud


Taurus
V_LSR = 6.6 km/s
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Galactic Latitude
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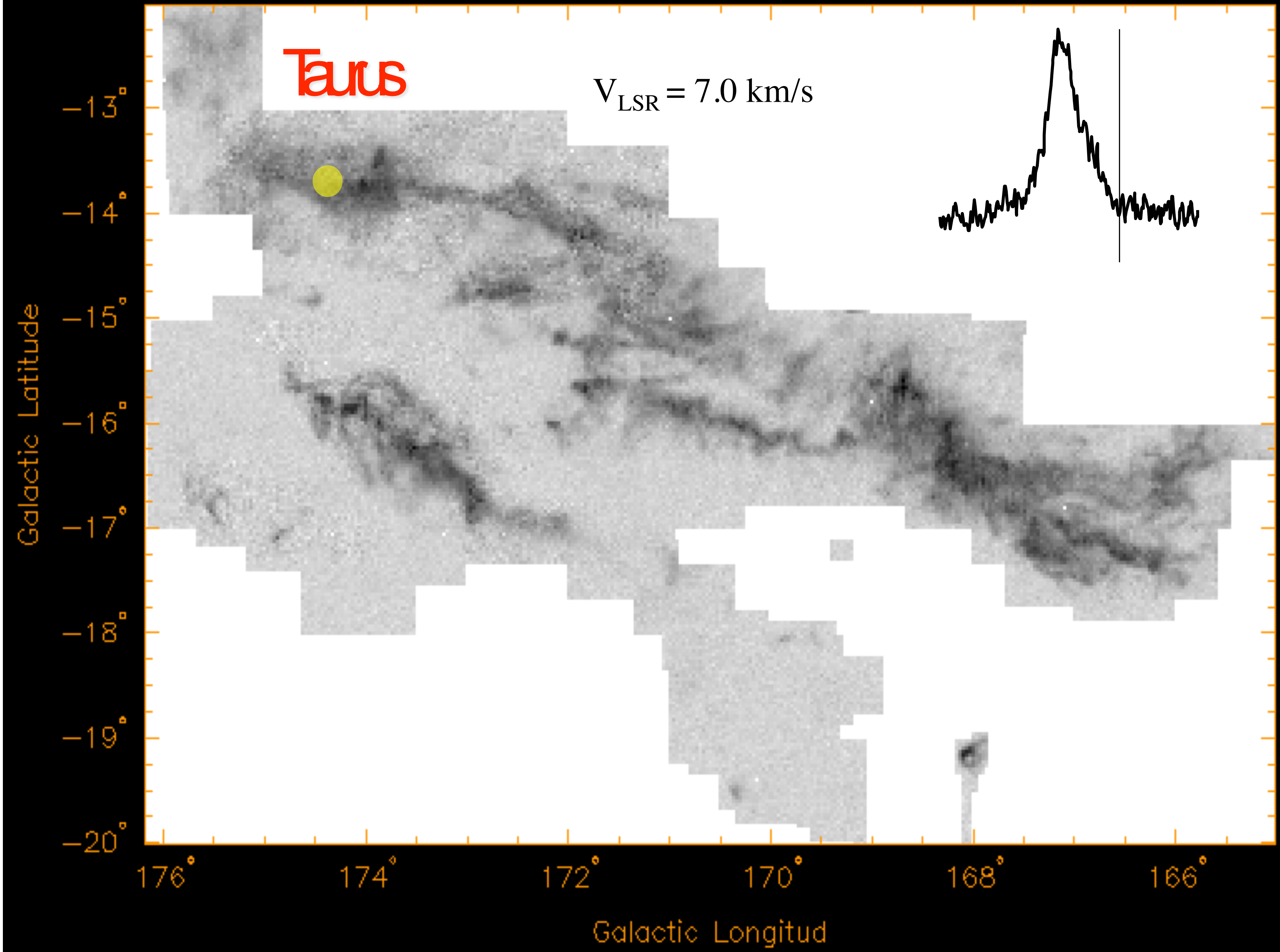
Galactic Longitud



Taurus
VLSR = 7.0 km/s
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Galactic Latitude
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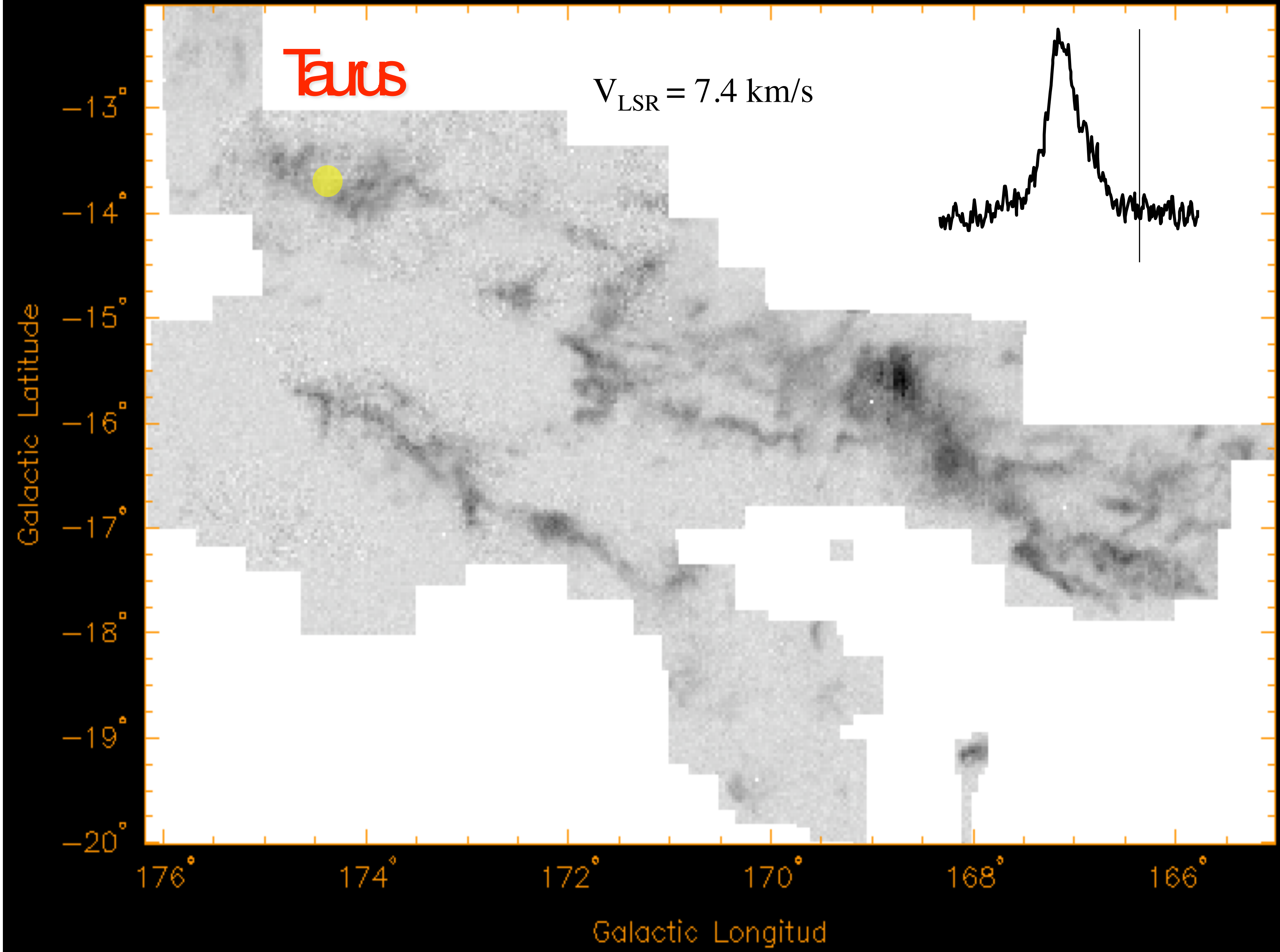
Galactic Longitud



Taurus
V_{LSR} = 7.4 km/s
Galactic Latitude
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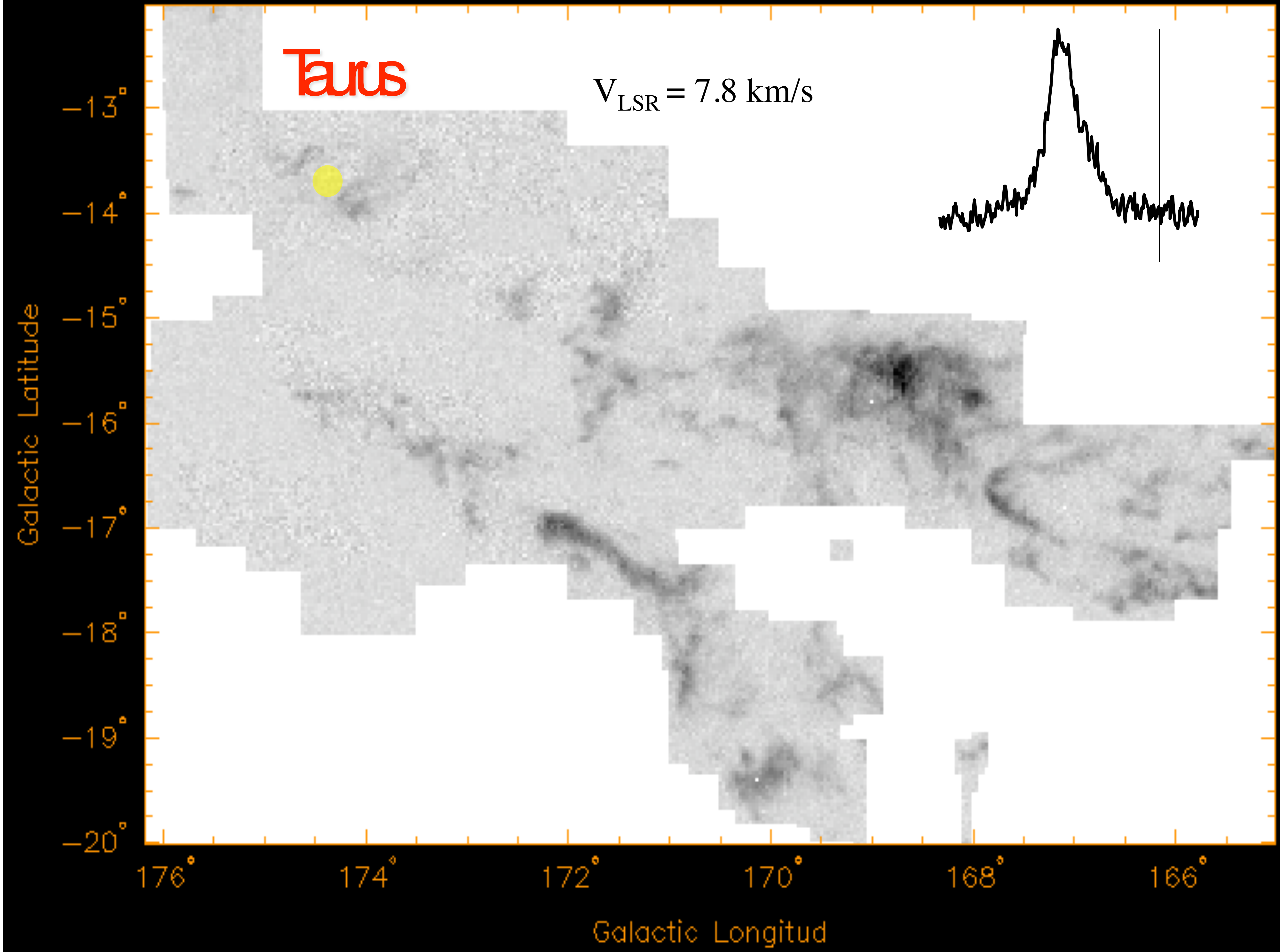
Galactic Longitud


Taurus
V_{LSR} = 7.8 km/s
Galactic Latitude
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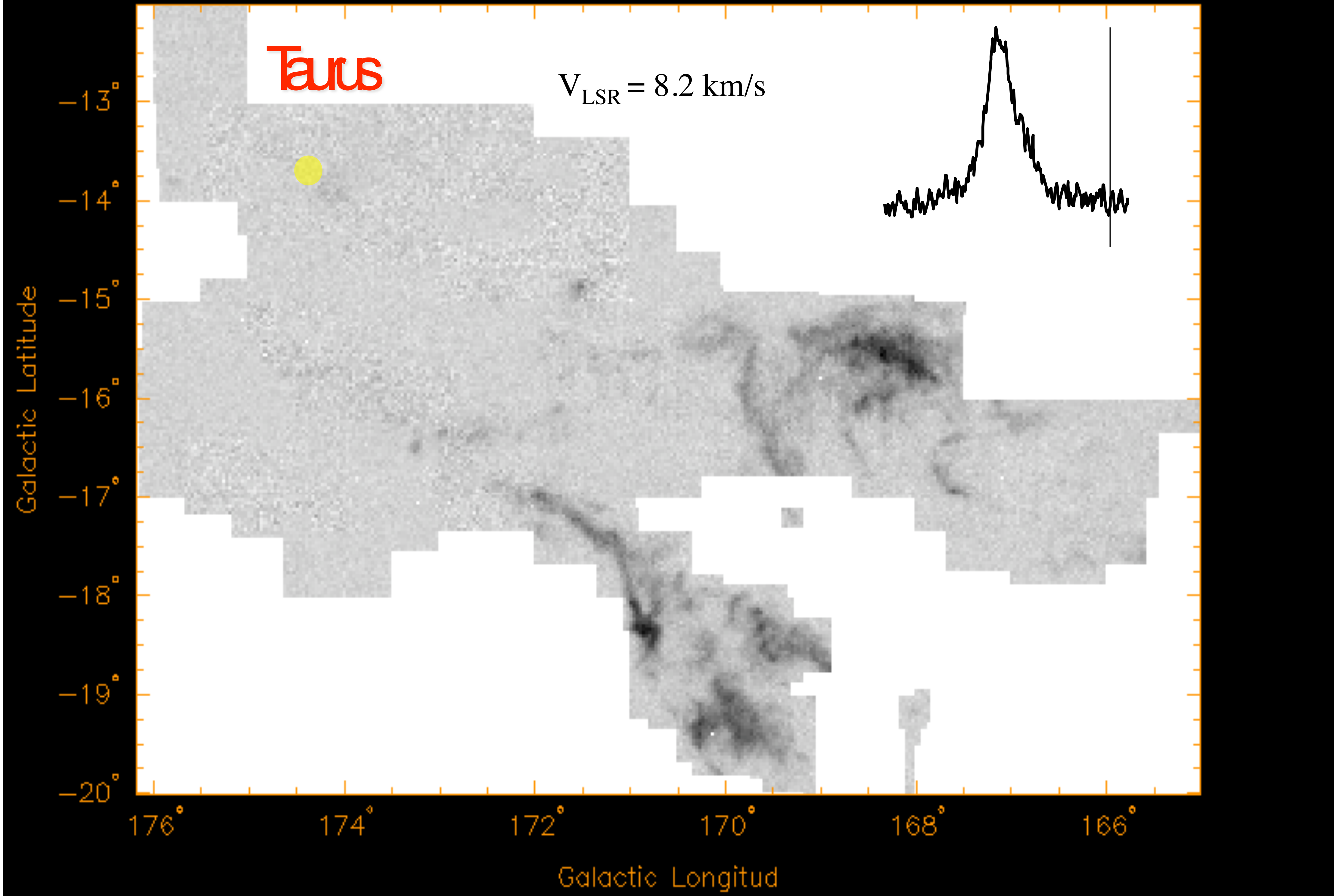
Galactic Longitud



Taurus
V_LSR = 8.2 km/s
Galactic Latitude
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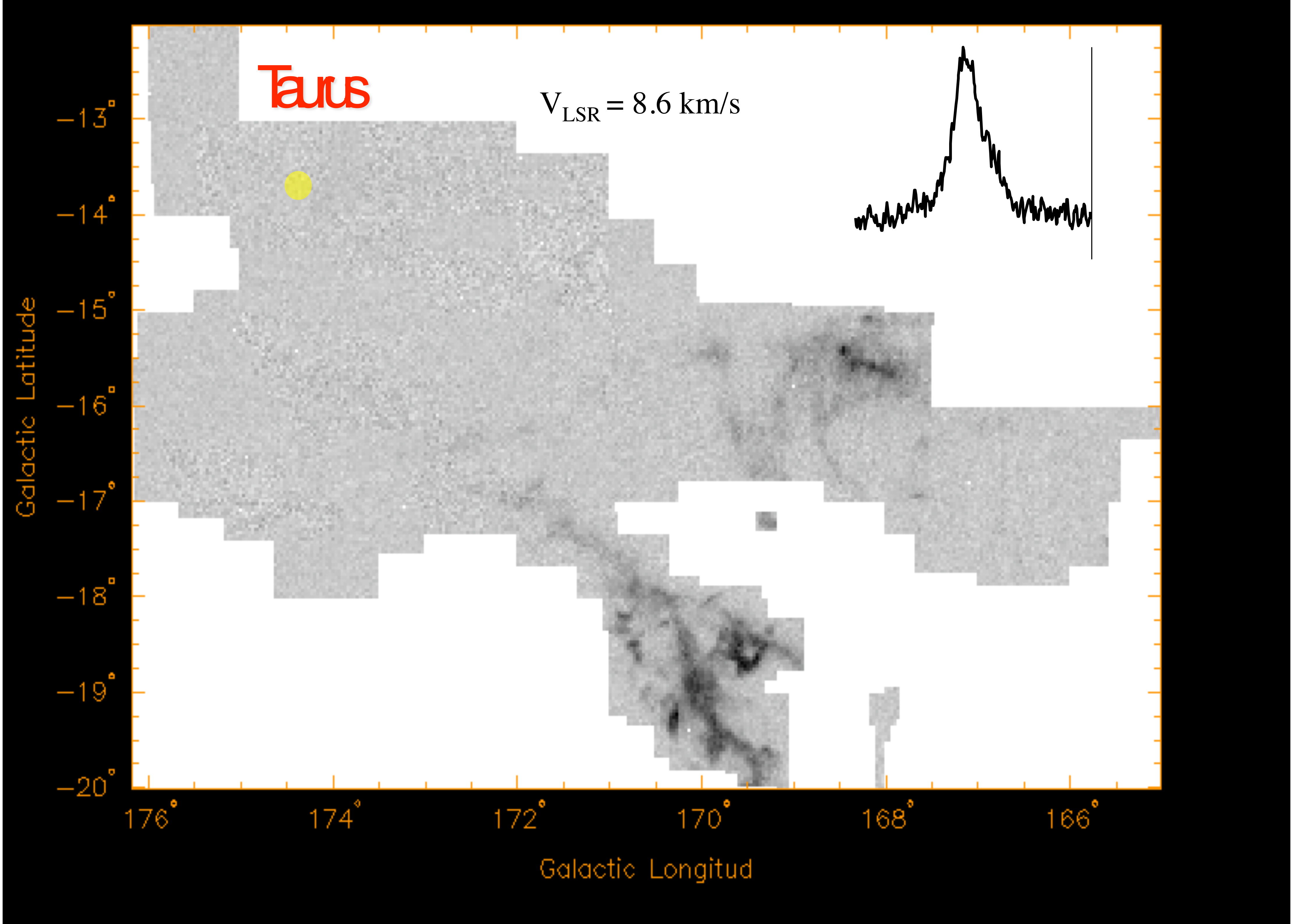
Galactic Longitud



Taurus
V_LSR = 8.6 km/s
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Galactic Latitude
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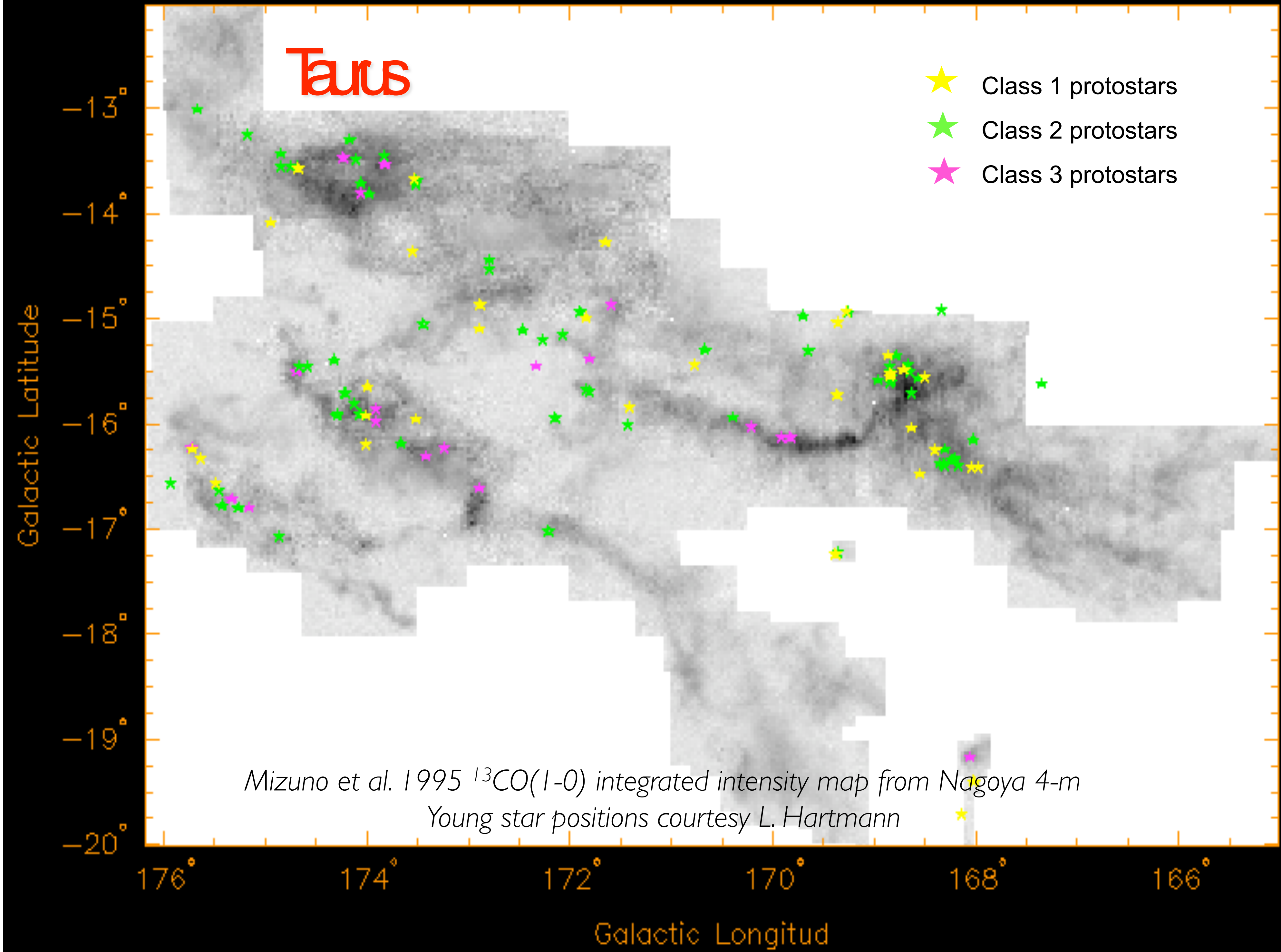
Galactic Longitud



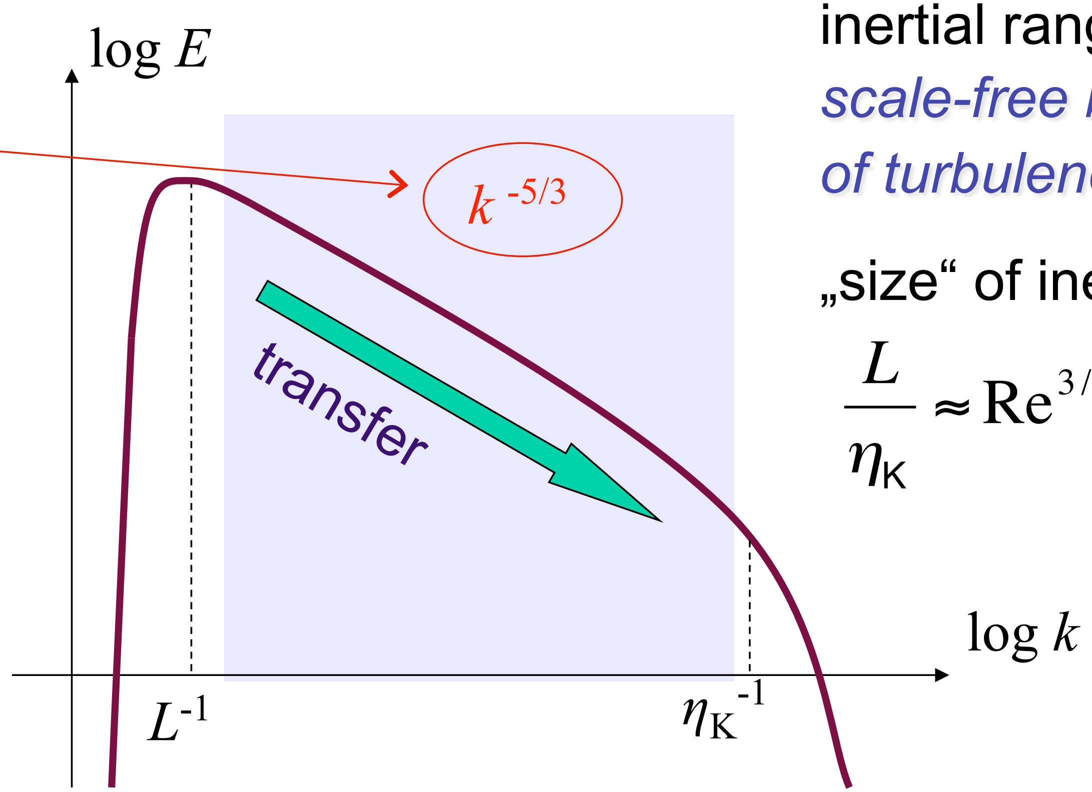
Mizuno et al. 1995 $^{13}CO(1\text{-}0)$ integrated intensity map from Nagoya 4-m

Young star positions courtesy L. Hartmann

turbulence & star clusters

Turbulent cascade

Kolmogorov (1941) theory
incompressible turbulence



energy
input
scale

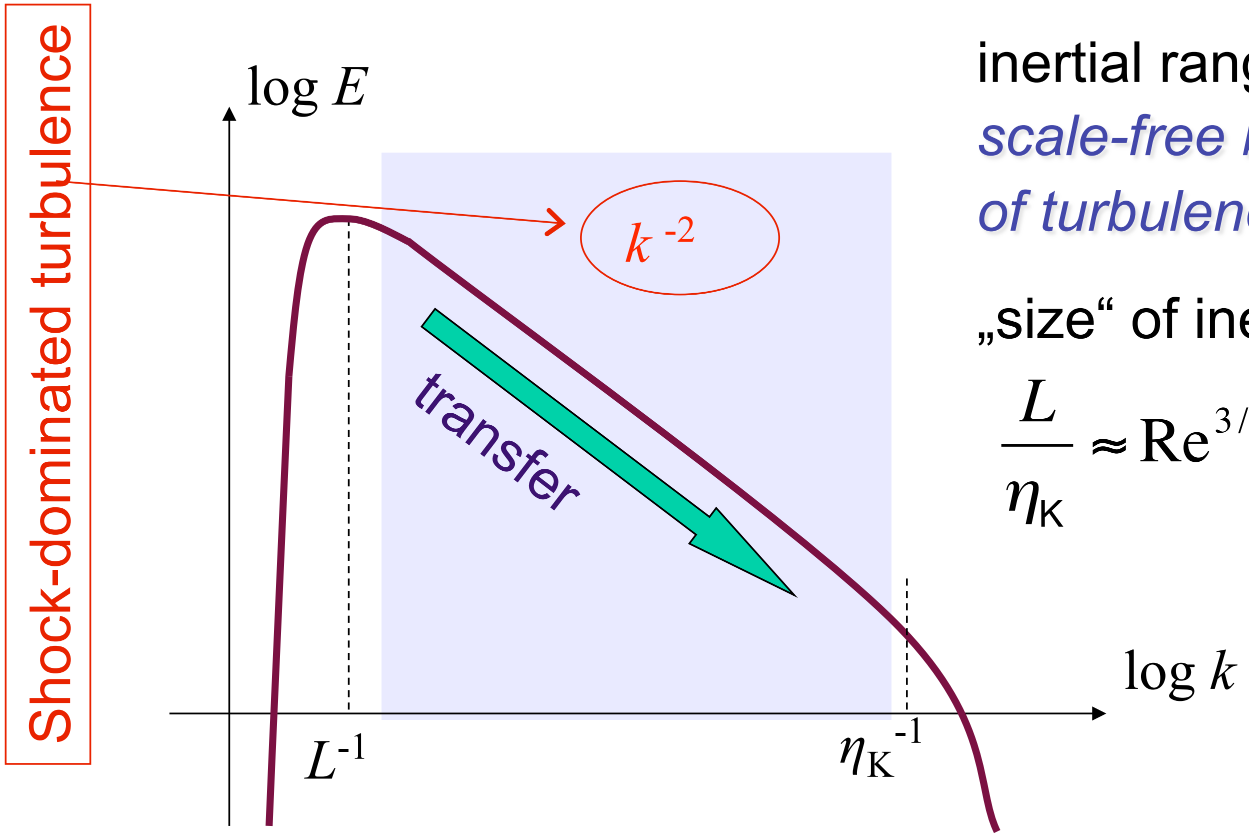
energy
dissipation
scale

inertial range:
scale-free behavior of turbulence

„size“ of inertial range:

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

Turbulent cascade



inertial range:

scale-free behavior of turbulence

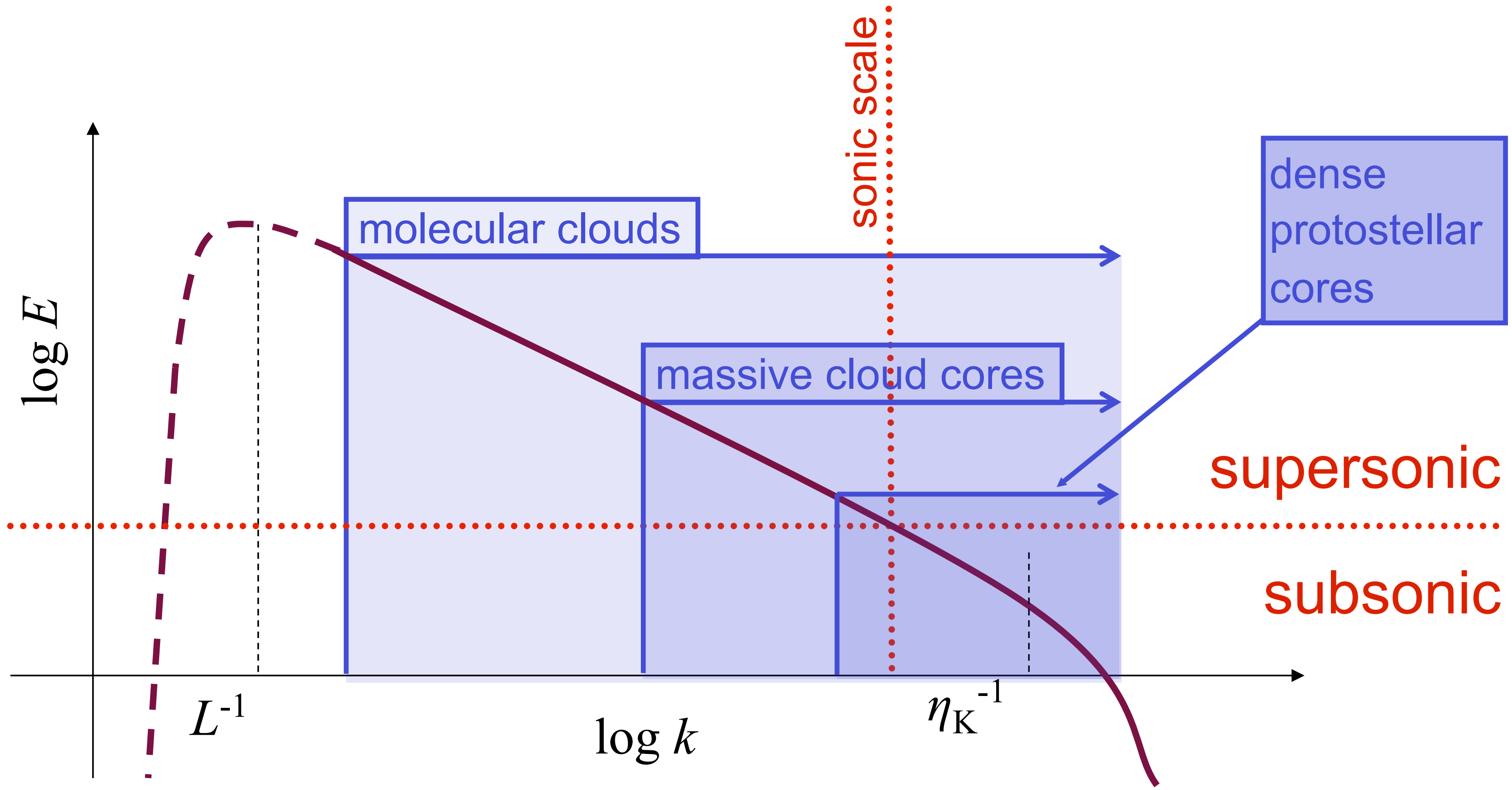
„size“ of inertial range:

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

energy input scale

energy dissipation scale

Turbulent cascade in ISM

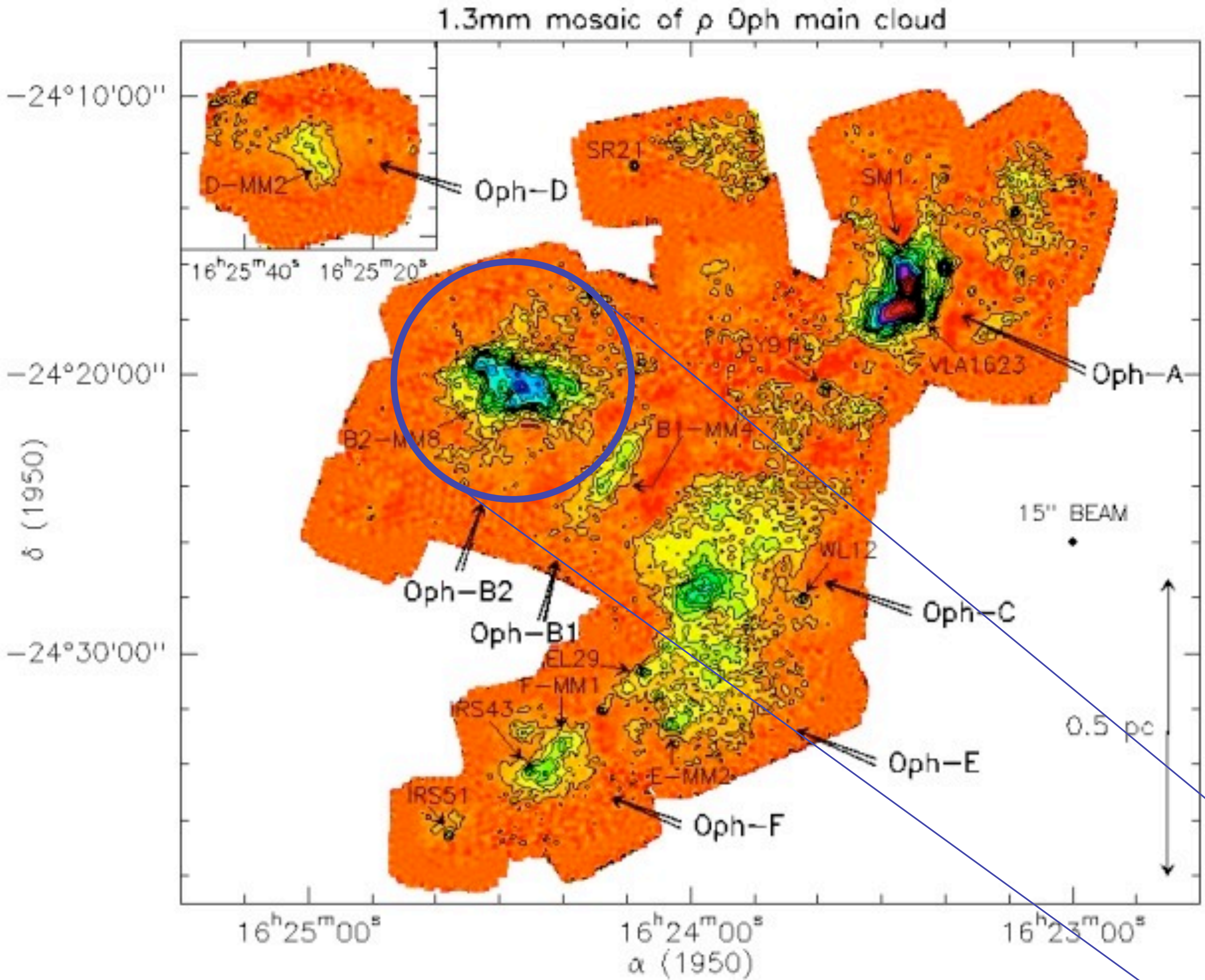


energy source & scale *NOT known* (supernovae, winds, spiral density waves?)

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

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

Density structure of MC's



(Motte, André, & Neri 1998)

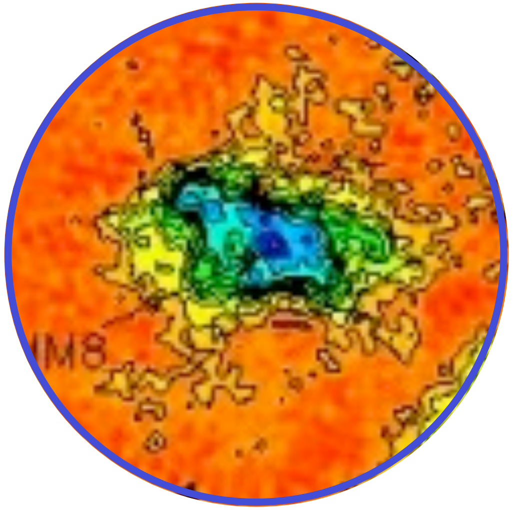
molecular clouds are highly inhomogeneous

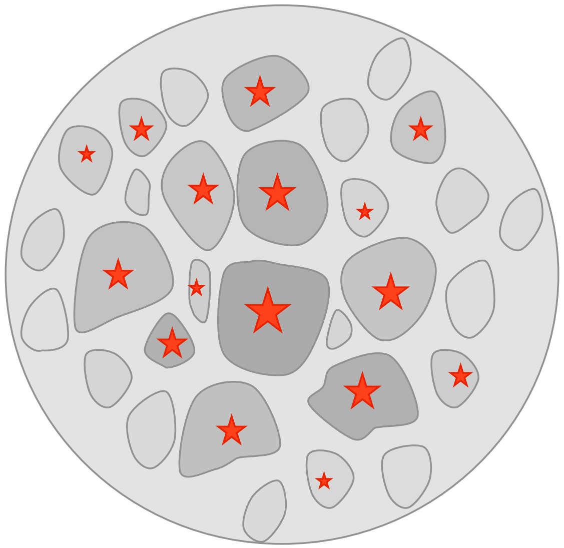
stars form in the densest and coldest parts of the cloud

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?

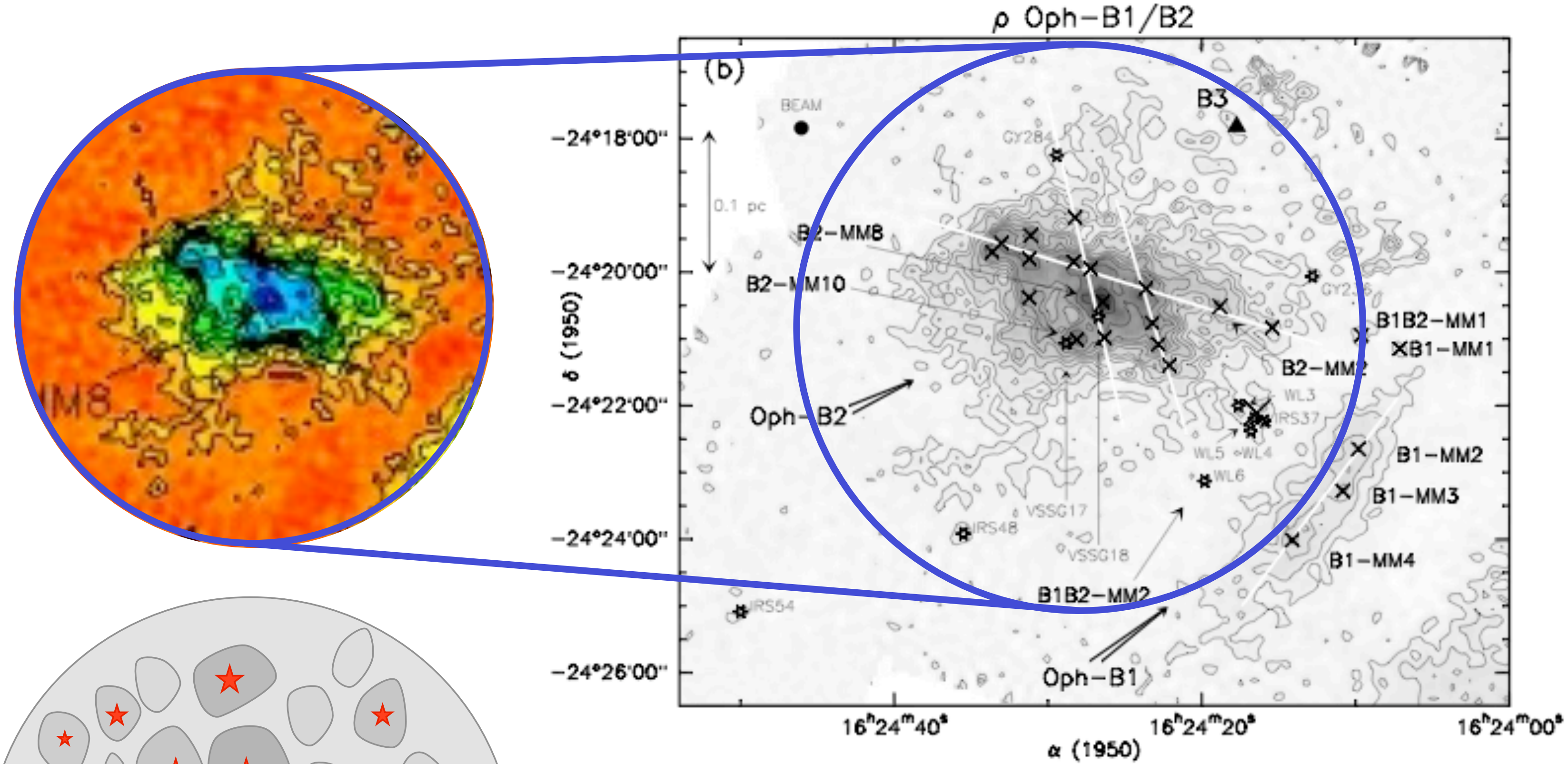
- Turbulent cascade „goes through" cloud core
  --> NO *scale separation* possible
  --> NO *effective sound speed*

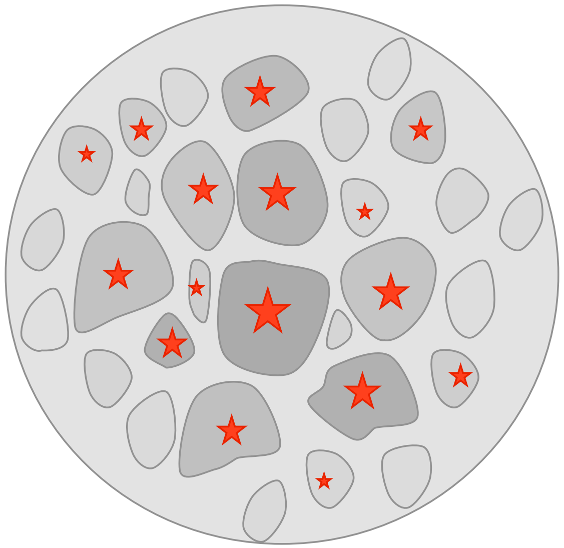
- Turbulence is supersonic!
  --> produces strong density contrasts:
  $\delta\rho/\rho \approx \mathcal{M}^2$
  --> with typical $\mathcal{M} \approx 10$ --> $\delta\rho/\rho \approx 100$!

- 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

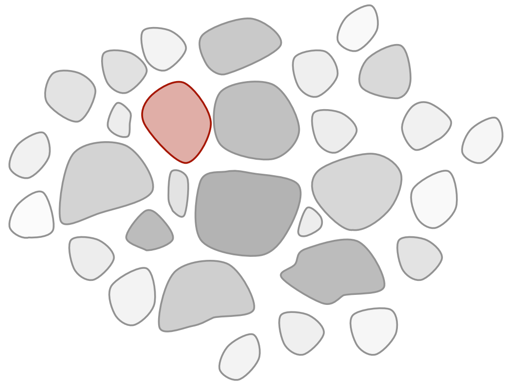




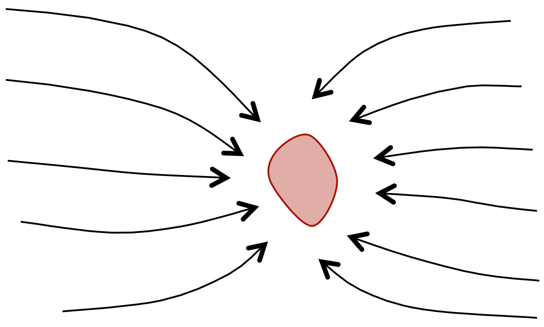
indeed ρ-Oph B1/2 contains several cores ("starless" cores are denoted by ×, cores with embedded protostars by ☆)

(Motte, André, & Neri 1998)

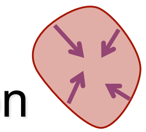
Formation and evolution of cores



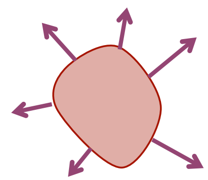
- protostellar cloud cores form at *stagnation point* in *convergent turbulent flows*



- 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

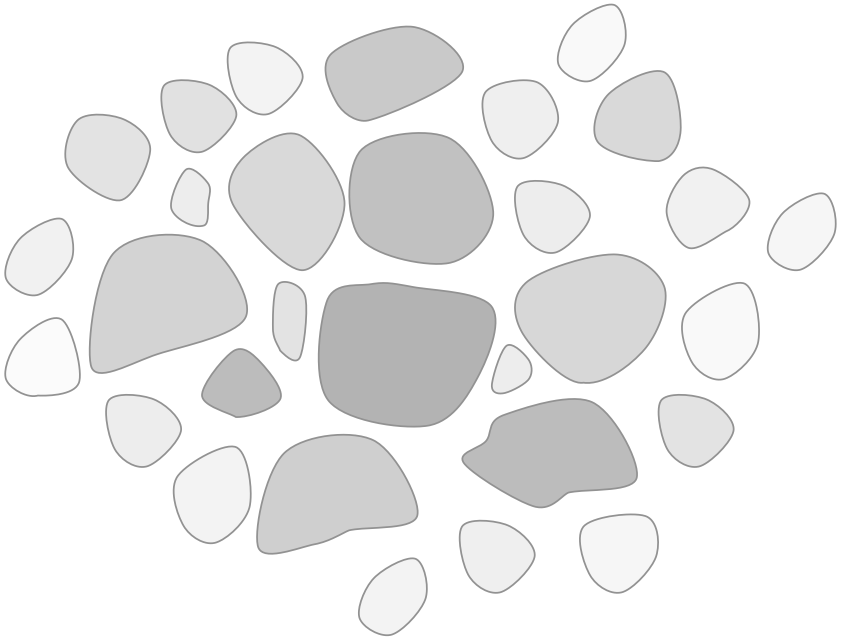


(e.g. Vazquez-Semadeni et al 2005)

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

Formation and evolution of cores

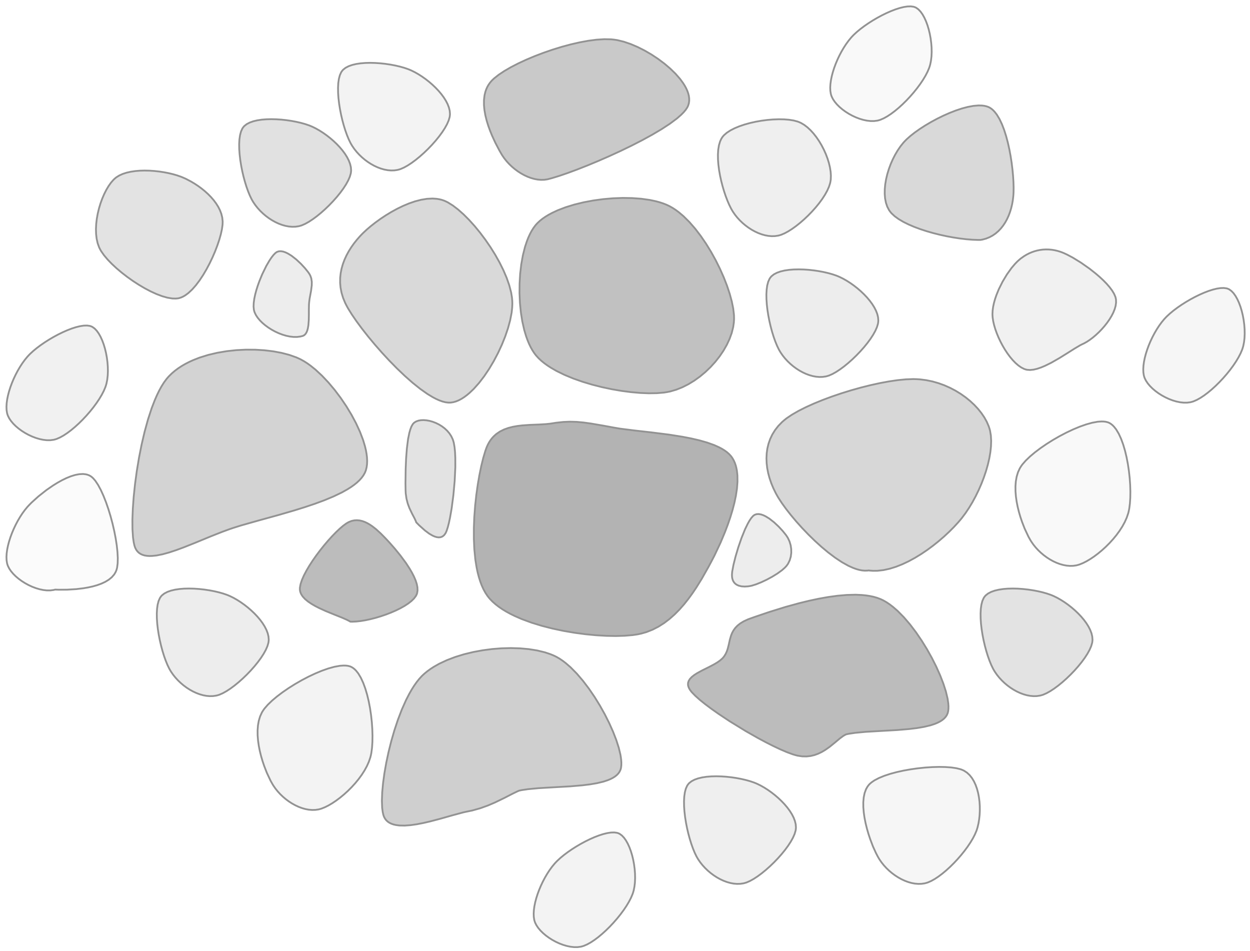
What happens to distribution of cloud cores?



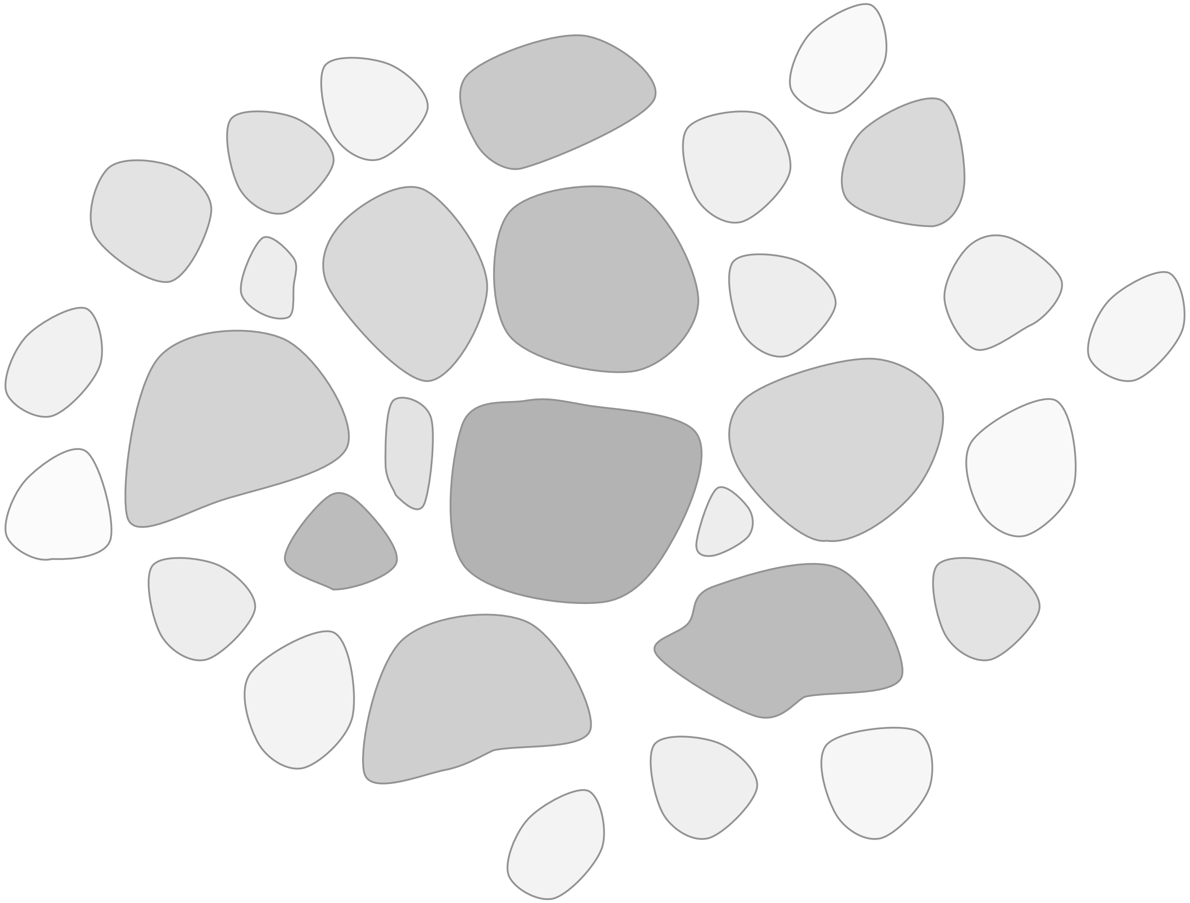
Two exteme cases:

(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*

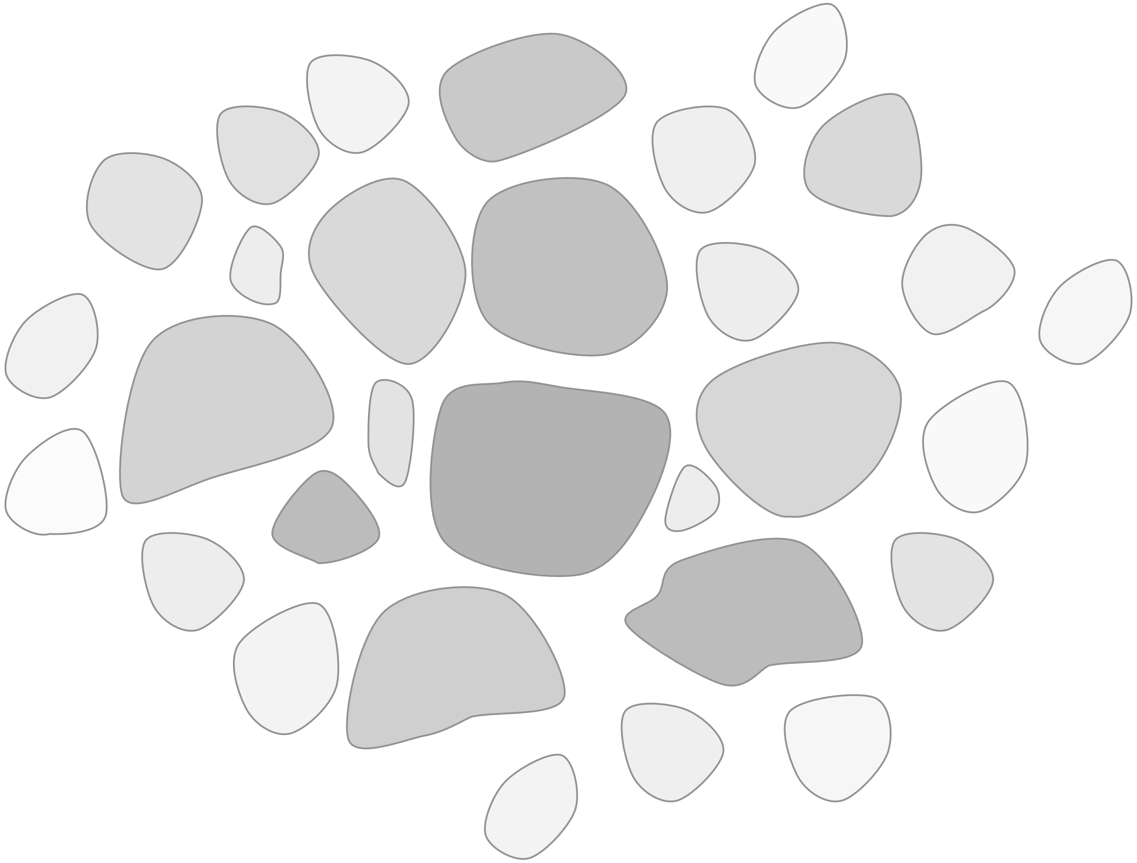
(2) turbulence decays, i.e. gravity dominates: $\alpha = E_{kin}/|E_{pot}| < 1$
--> *global contraction*
--> core do *interact* while collapsing
--> *competition* influences *mass growth*
--> *dense cluster with high-mass stars*



turbulence creates a hierarchy of clumps



as turbulence decays locally, contraction sets in



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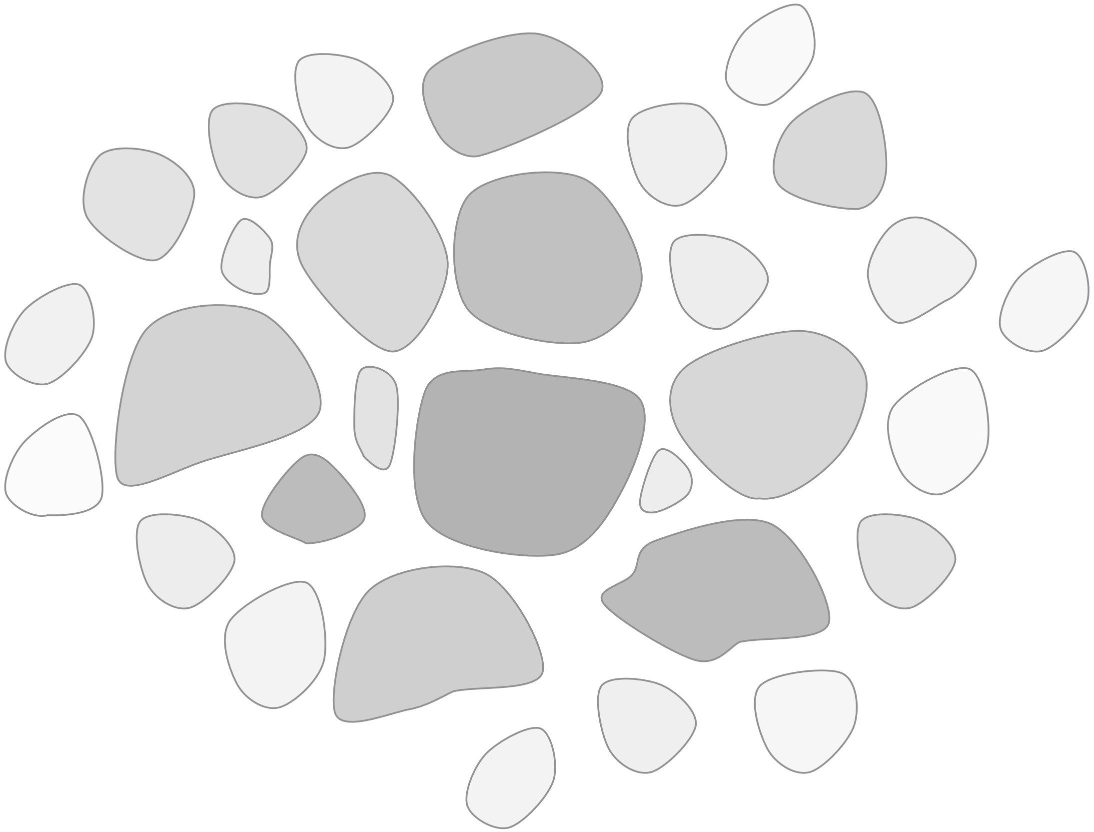
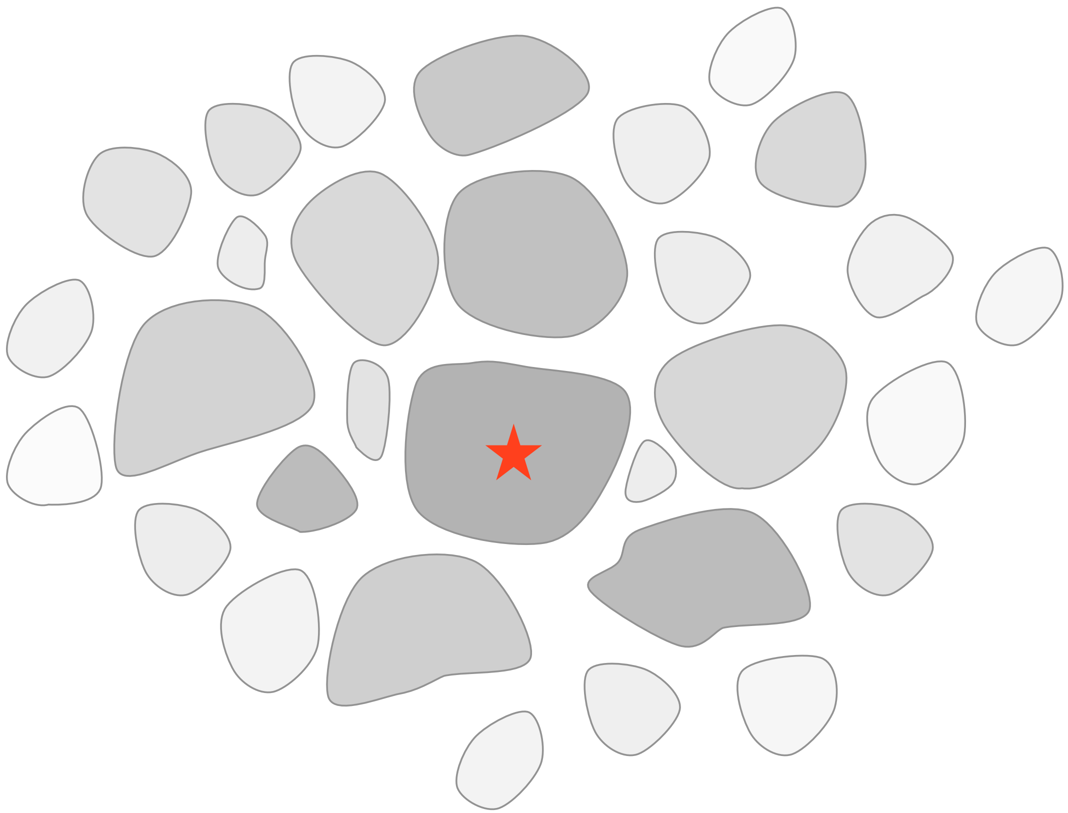


while region contracts, individual clumps collapse to form stars



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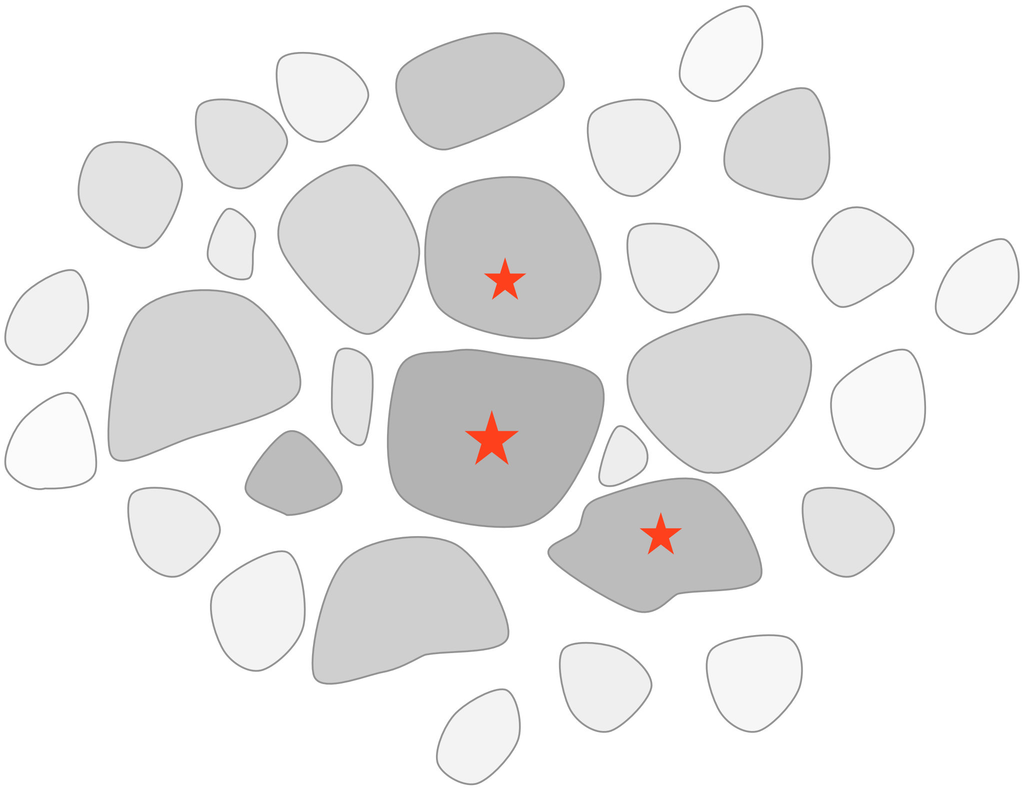
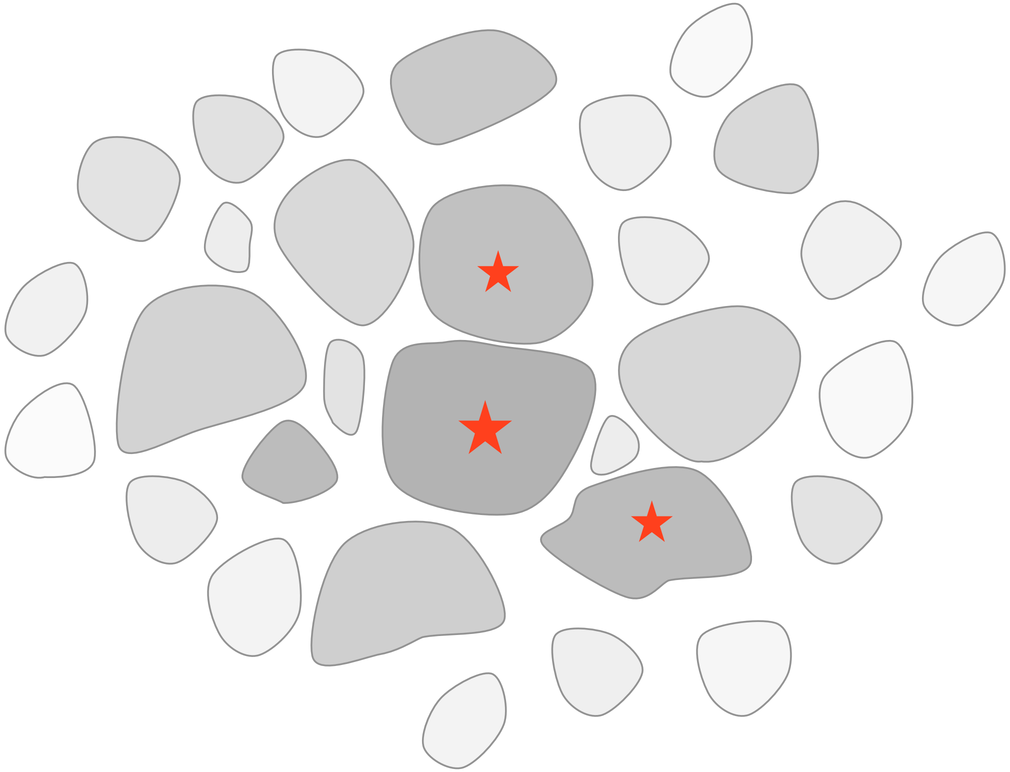
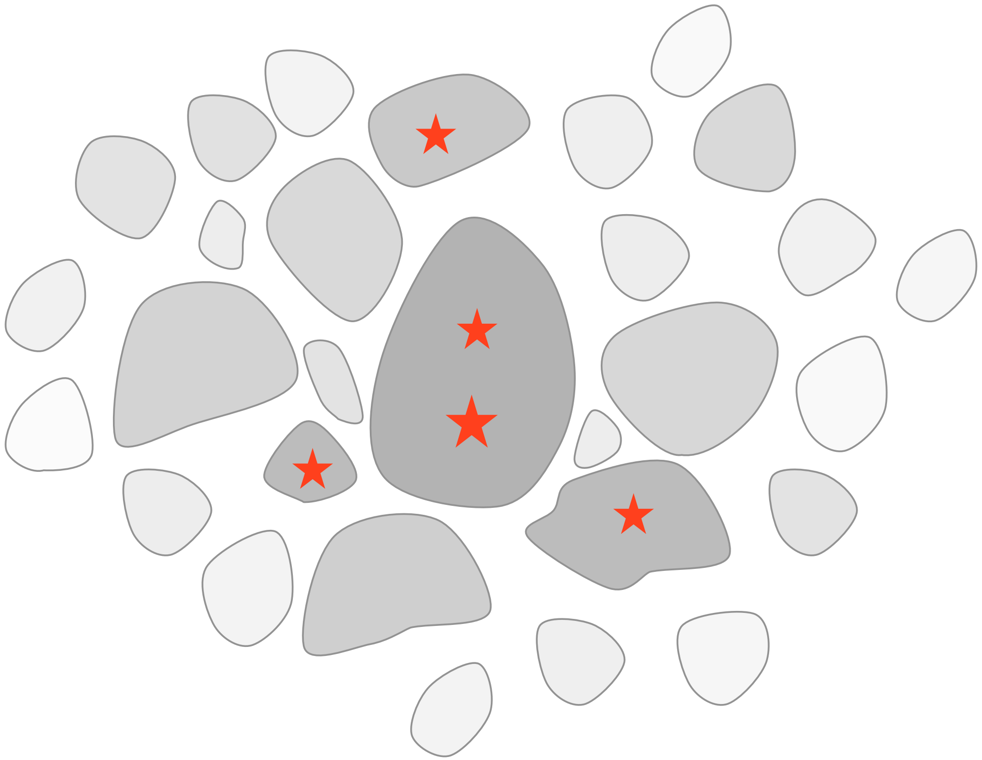


individual clumps collapse to form stars

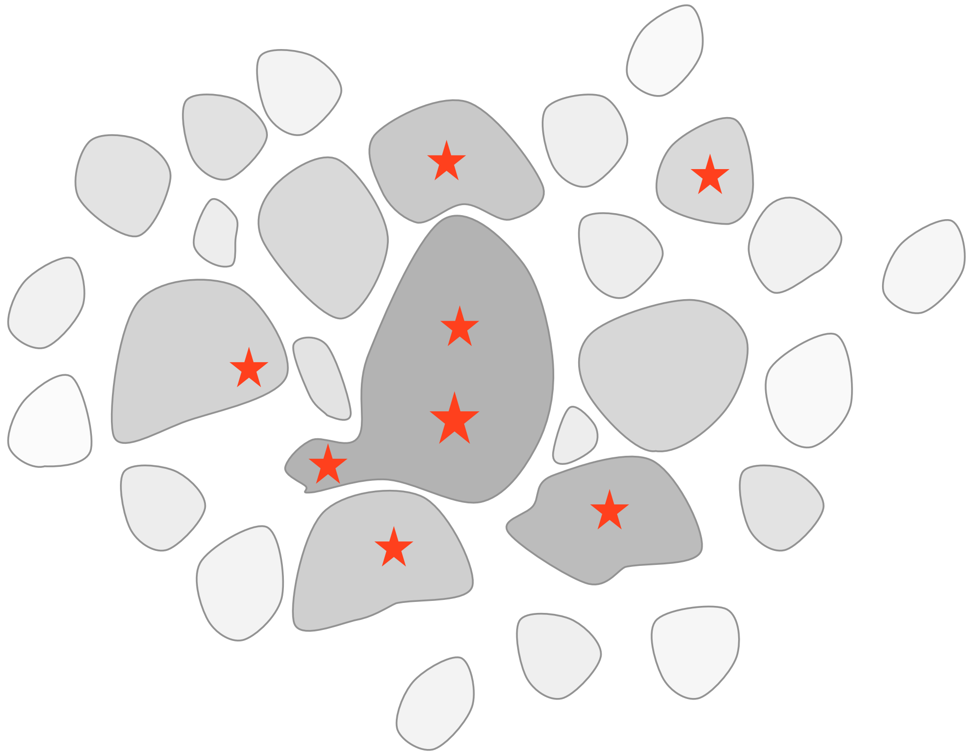


individual clumps collapse to form stars

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



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



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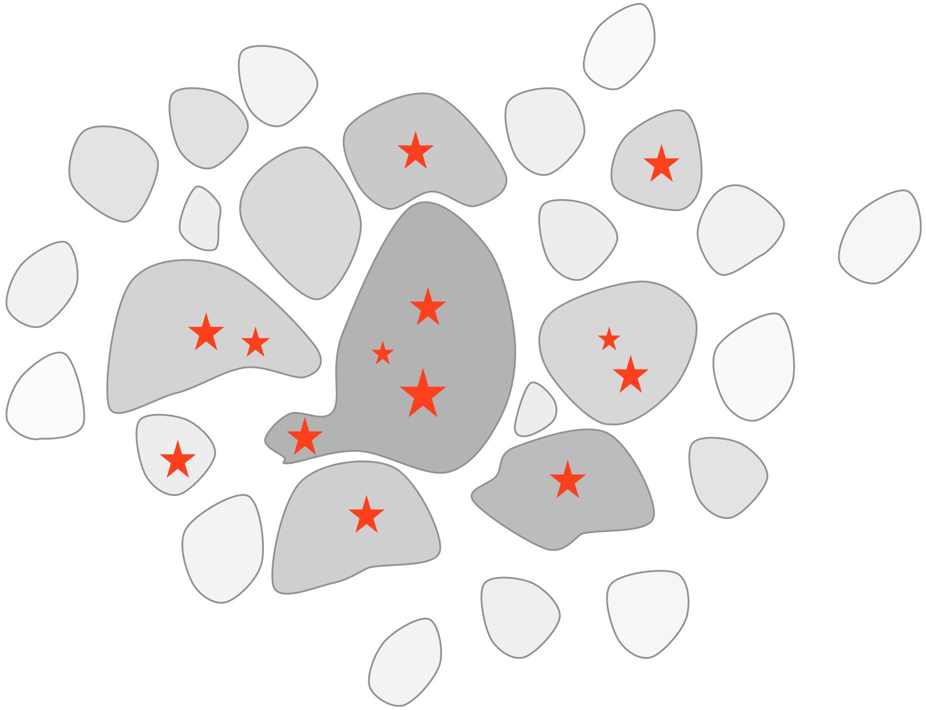

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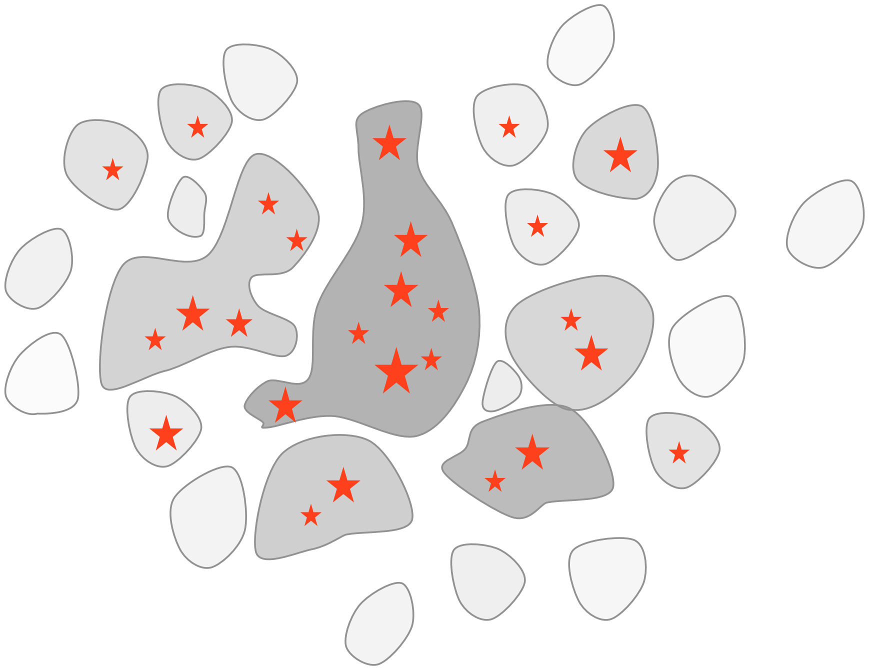
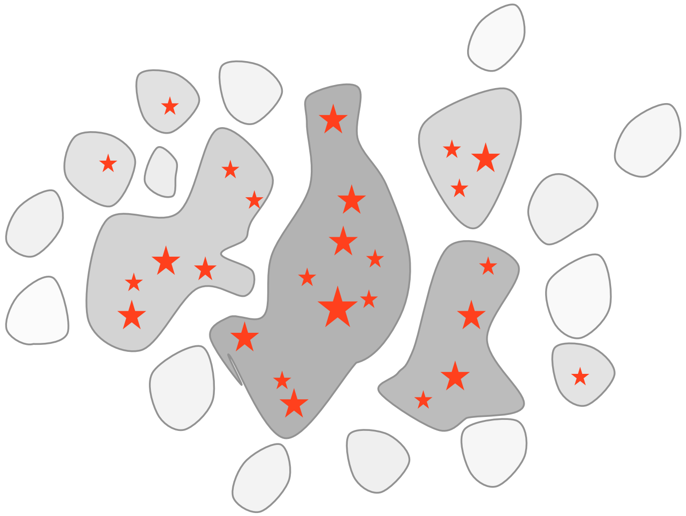
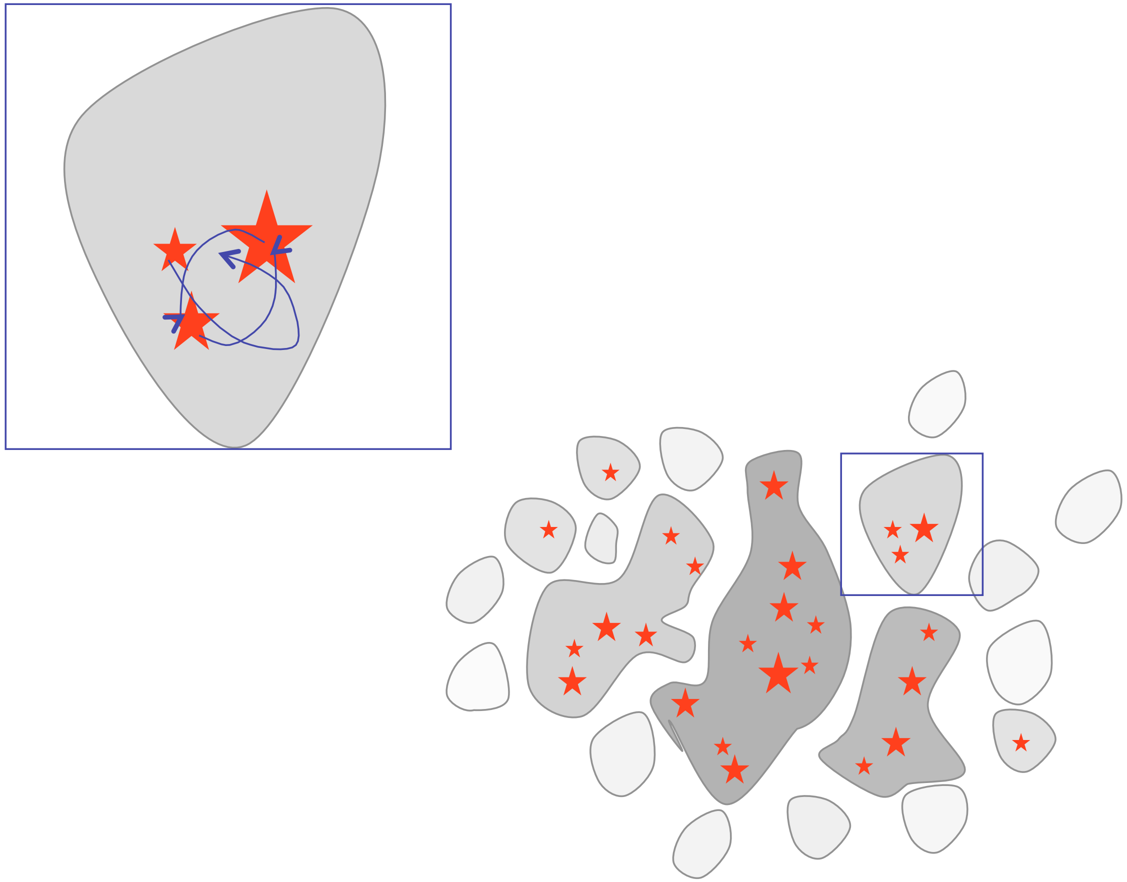


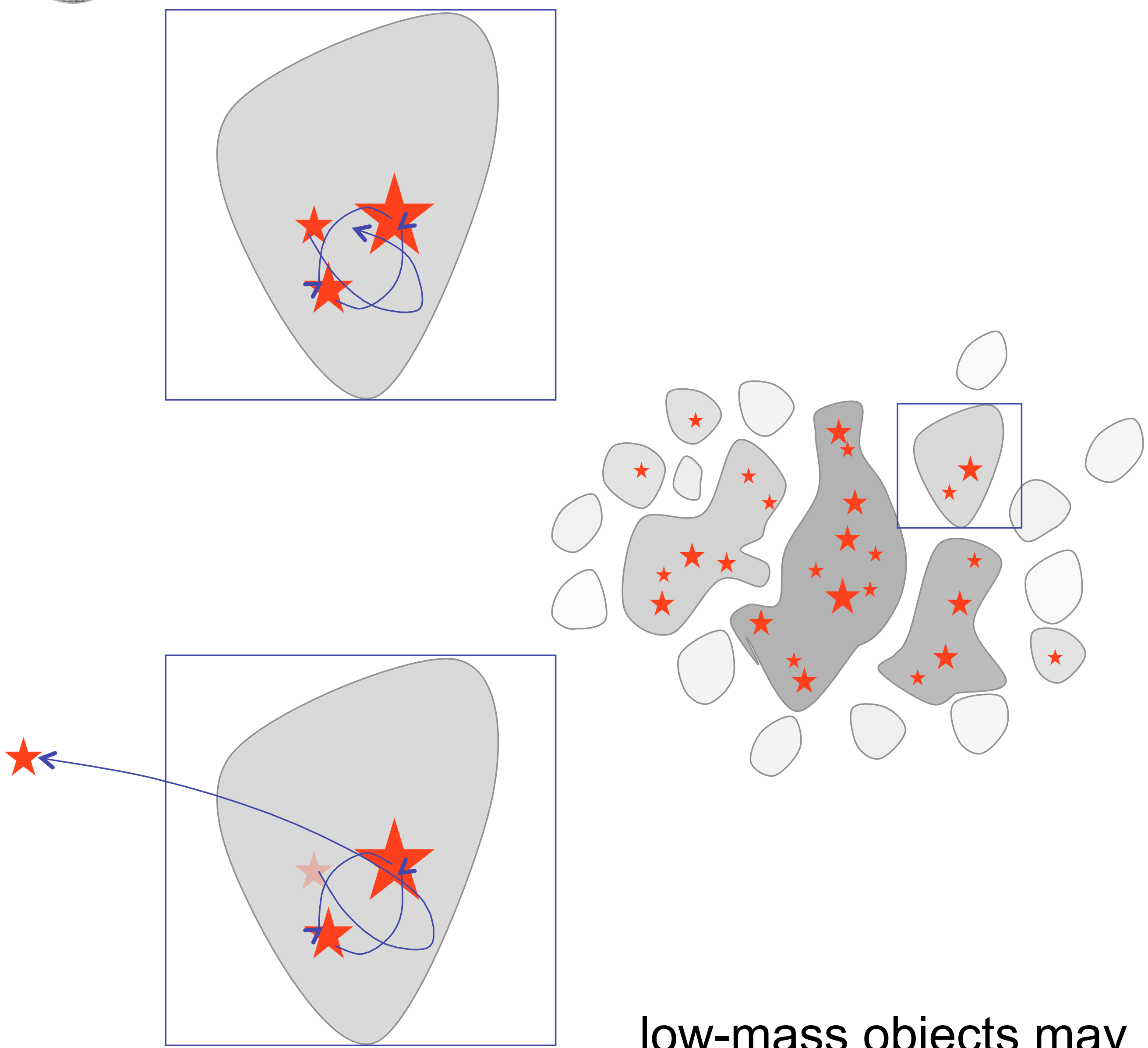
in *dense clusters*, competitive mass growth becomes important



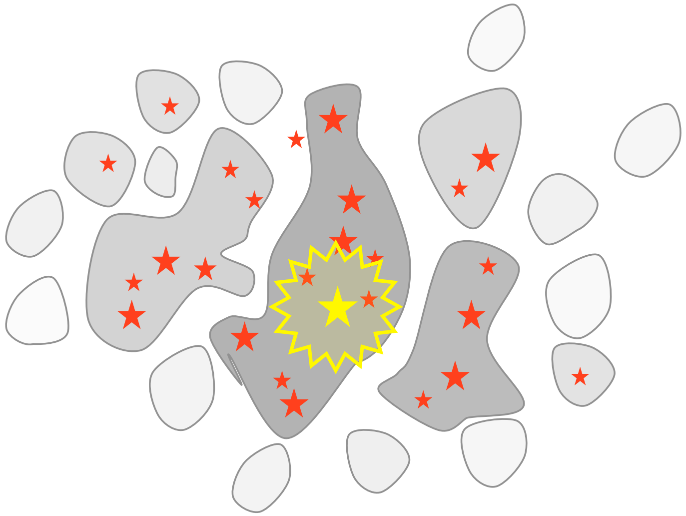
in *dense clusters*, competitive mass growth becomes important



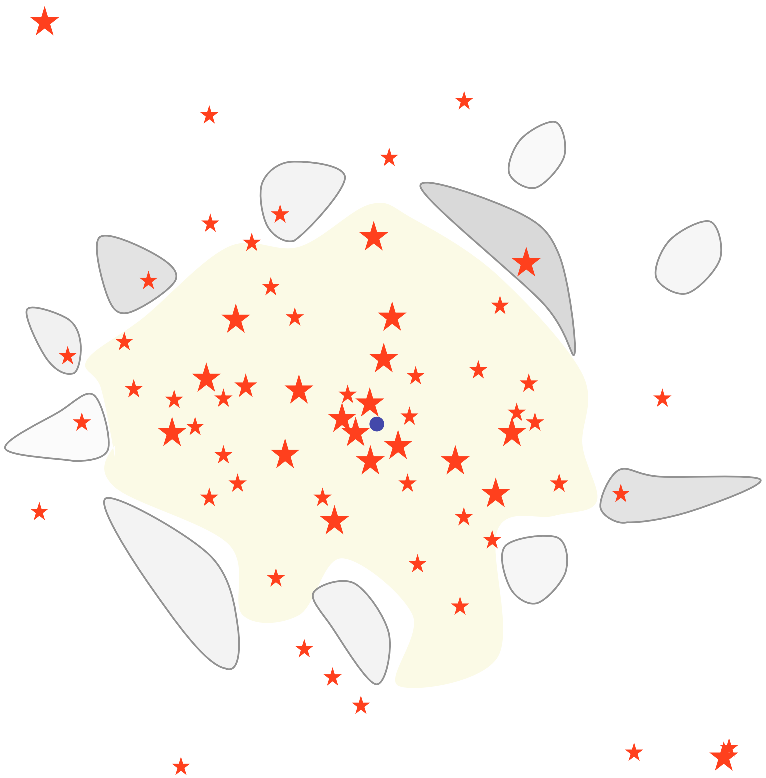
in *dense clusters*, *N*-body effects influence mass growth



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



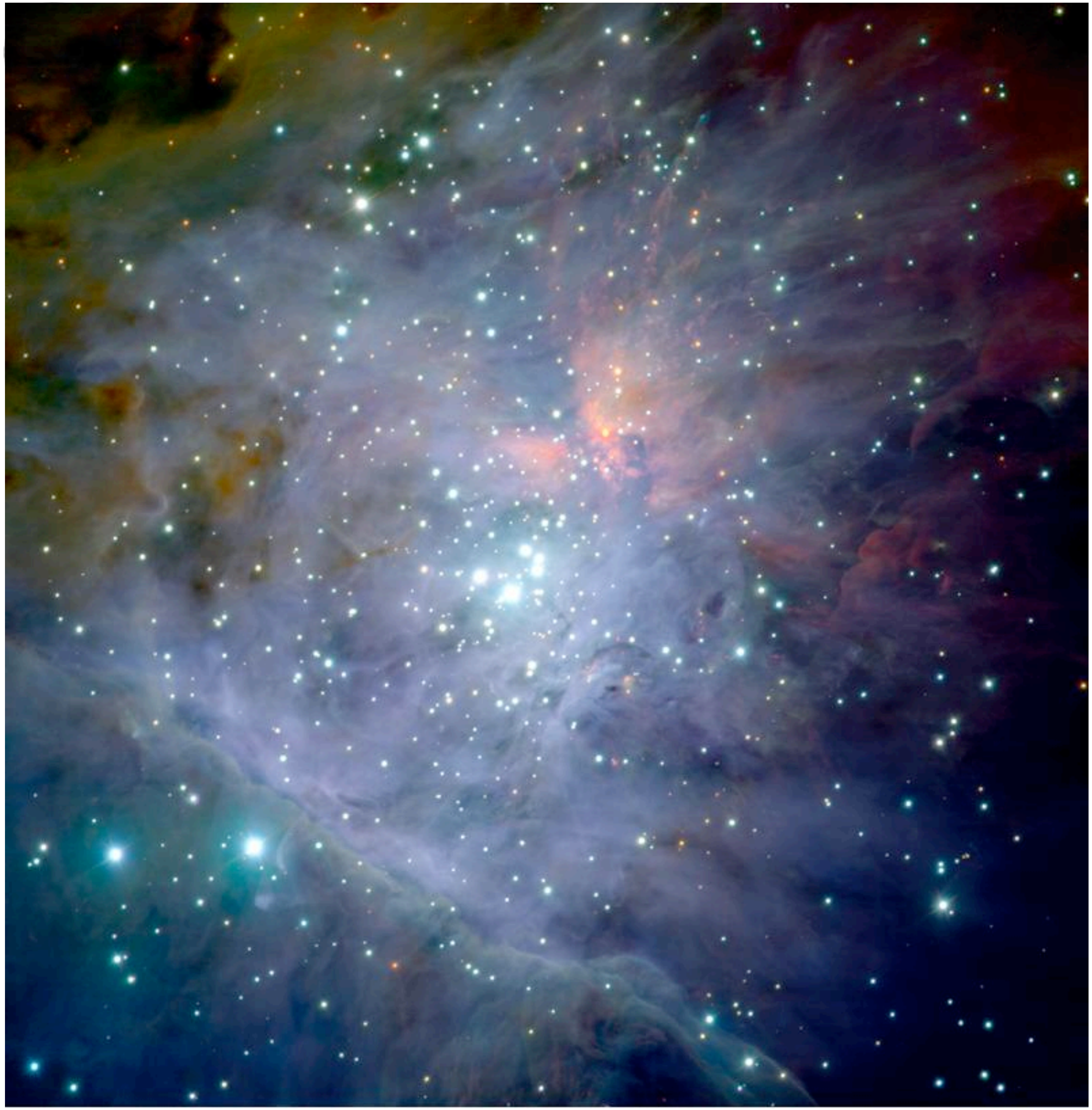
feedback terminates star formation



result: *star cluster*, possibly with HII region

NGC 602 in the LMC: Hubble Heritage Image

result: *star cluster* with HII region



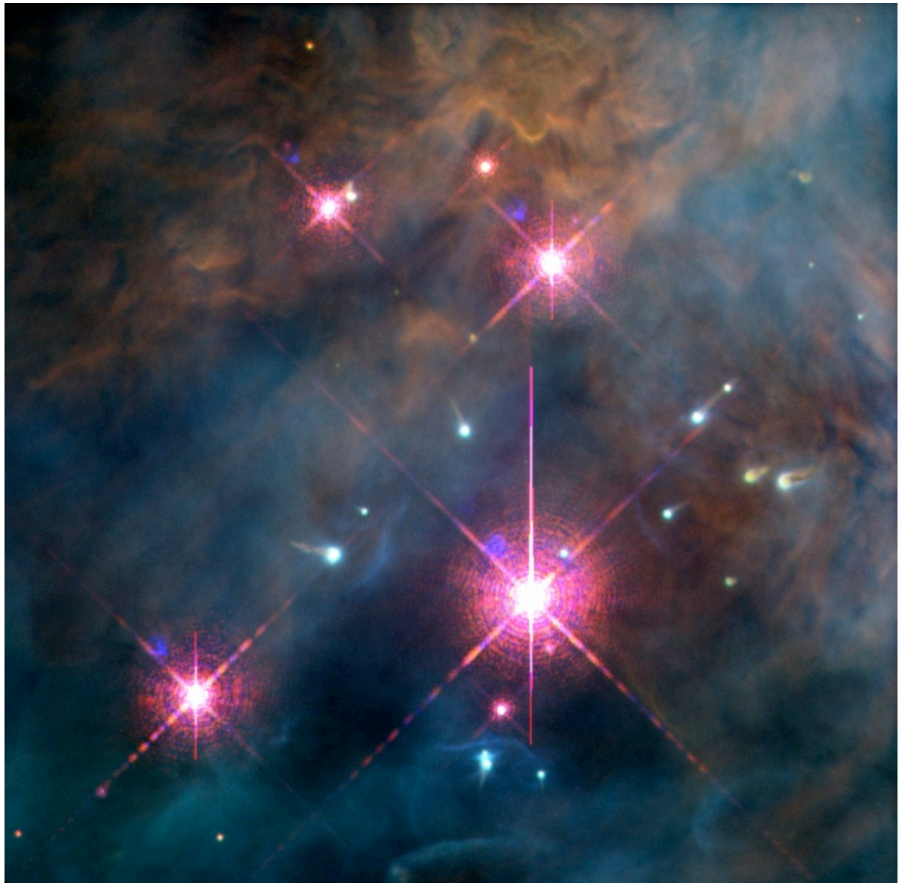
Trapezium Cluster

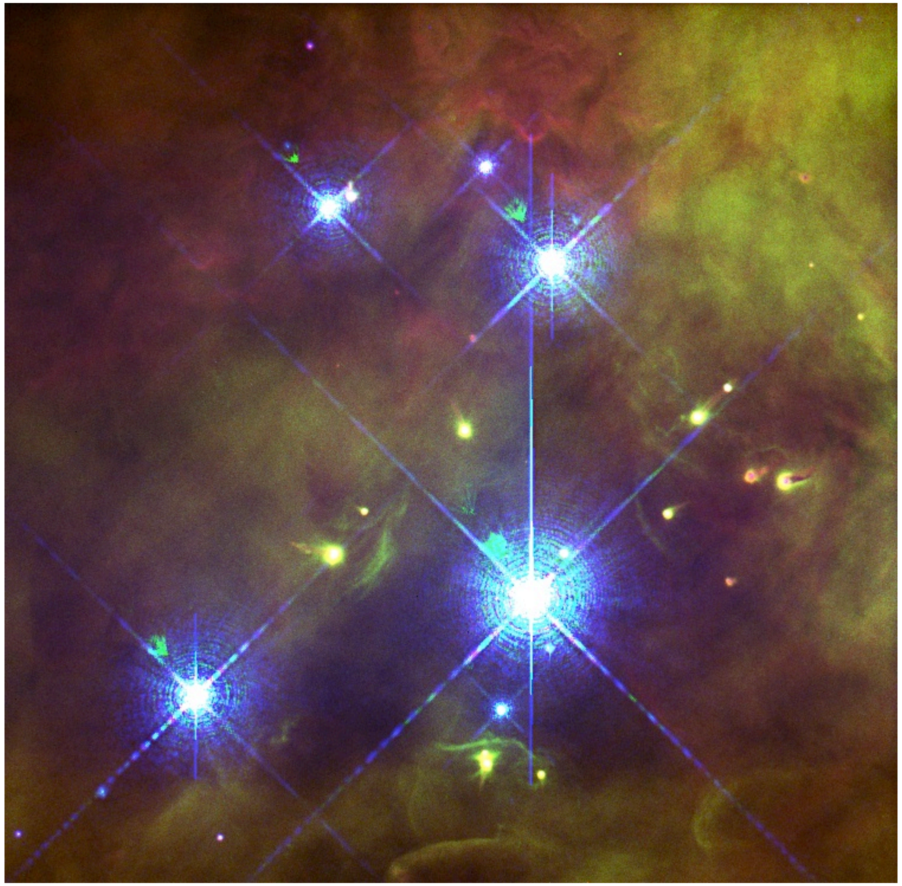
(detail)

- 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)

Trapezium Cluster: Central Region



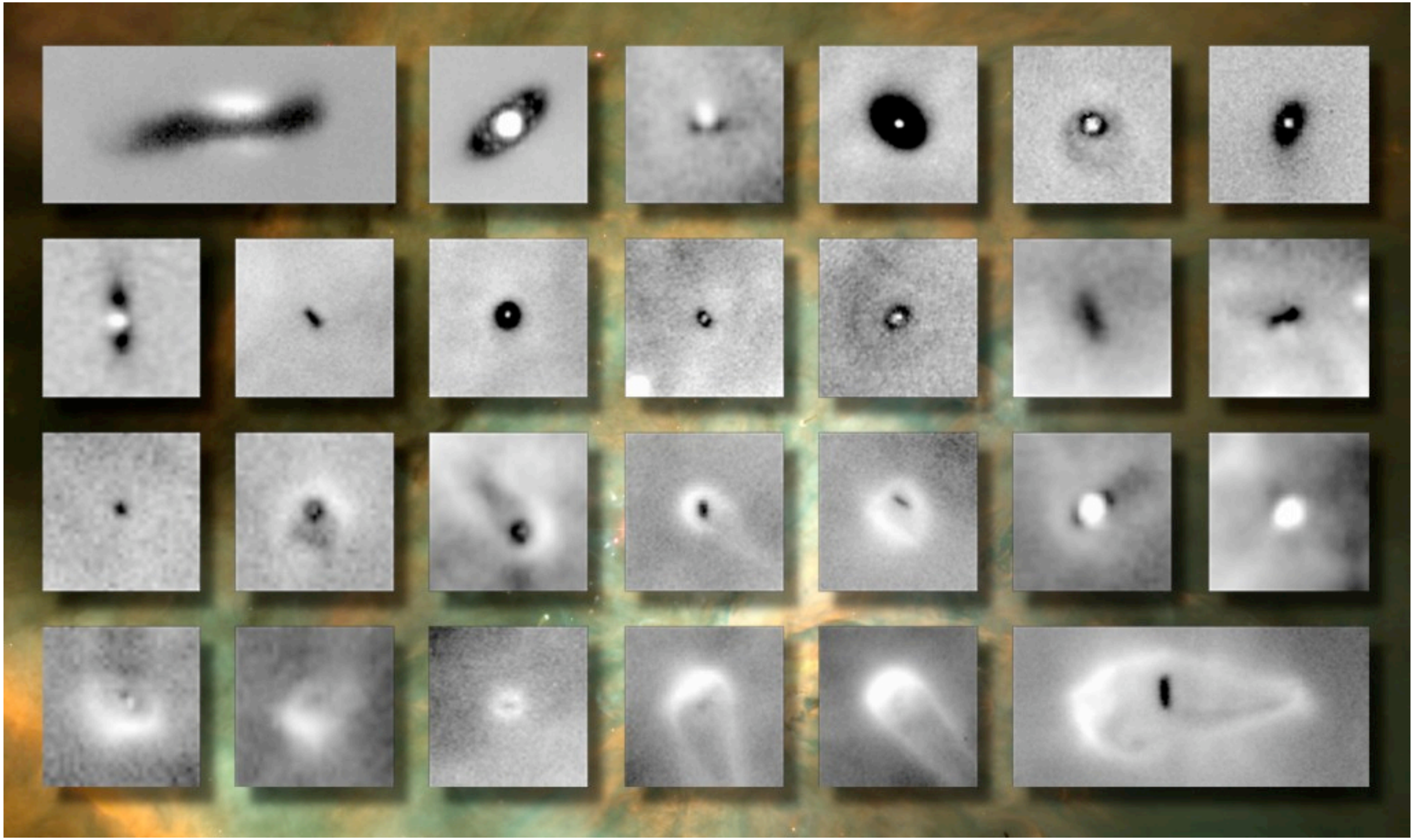


Ionizing radiation from central star
Θ1C Orionis

Proplyds: Evaporating ``protoplanetary´´ disks around young low-mass protostars

(images: Doug Johnstone et al.)

Futher Details: Siluette Disks in Orion

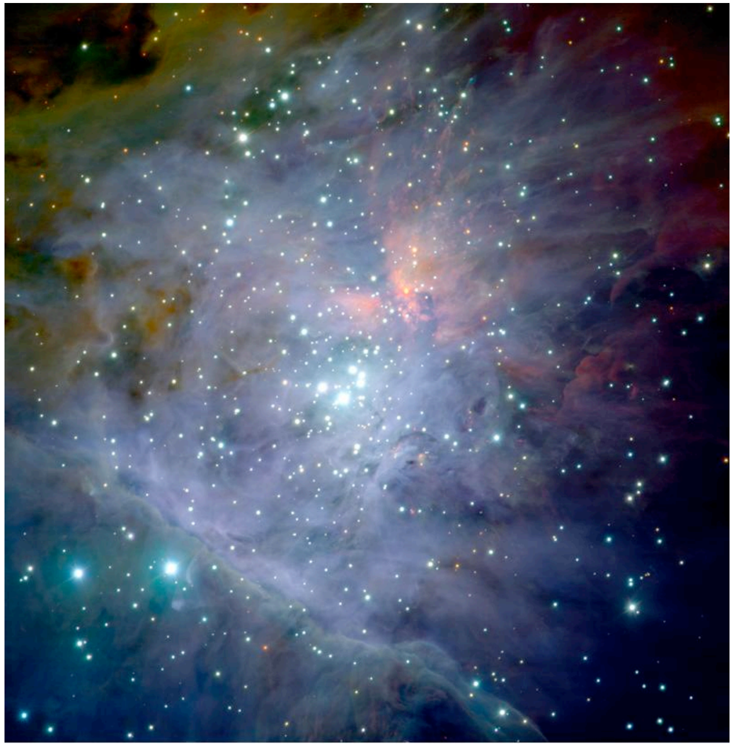


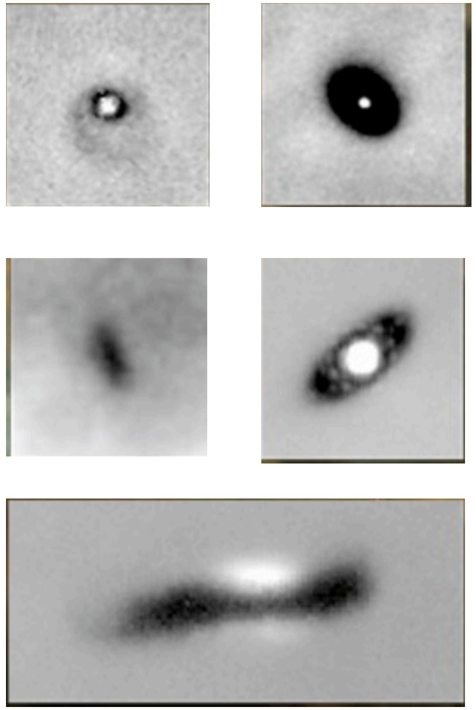
protostellar disks: dark shades in front of the photodissociation region in the background. Each image is 750 AU x 750 AU.

(data: Mark McCaughrean)

disks in clusters

MAIN QUESTION: how do protostellar disks build-up and evolve in a forming star cluster?





(data: Mark McCaughrean)

protostellar disks in clusters

- what is the difference between isolated disks and disks that form in (dense) clusters?
  - dense environment → perturbations
    - tidal distortions (ang mom. transport → binarity?)
    - disk truncation (life times, mass loss)
  - feedback from massive stars
    - evaporation (disk lifetimes, morphology, stability)

protostellar disks in clusters

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  - dense environment → perturbations
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    - disk truncation (life times, mass loss)
  - feedback from massive stars
    - evaporation (disk lifetimes, morphology, stability)
- *comment:* need cluster environment to get IMF → distribution of disk masses is set by environment!

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

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

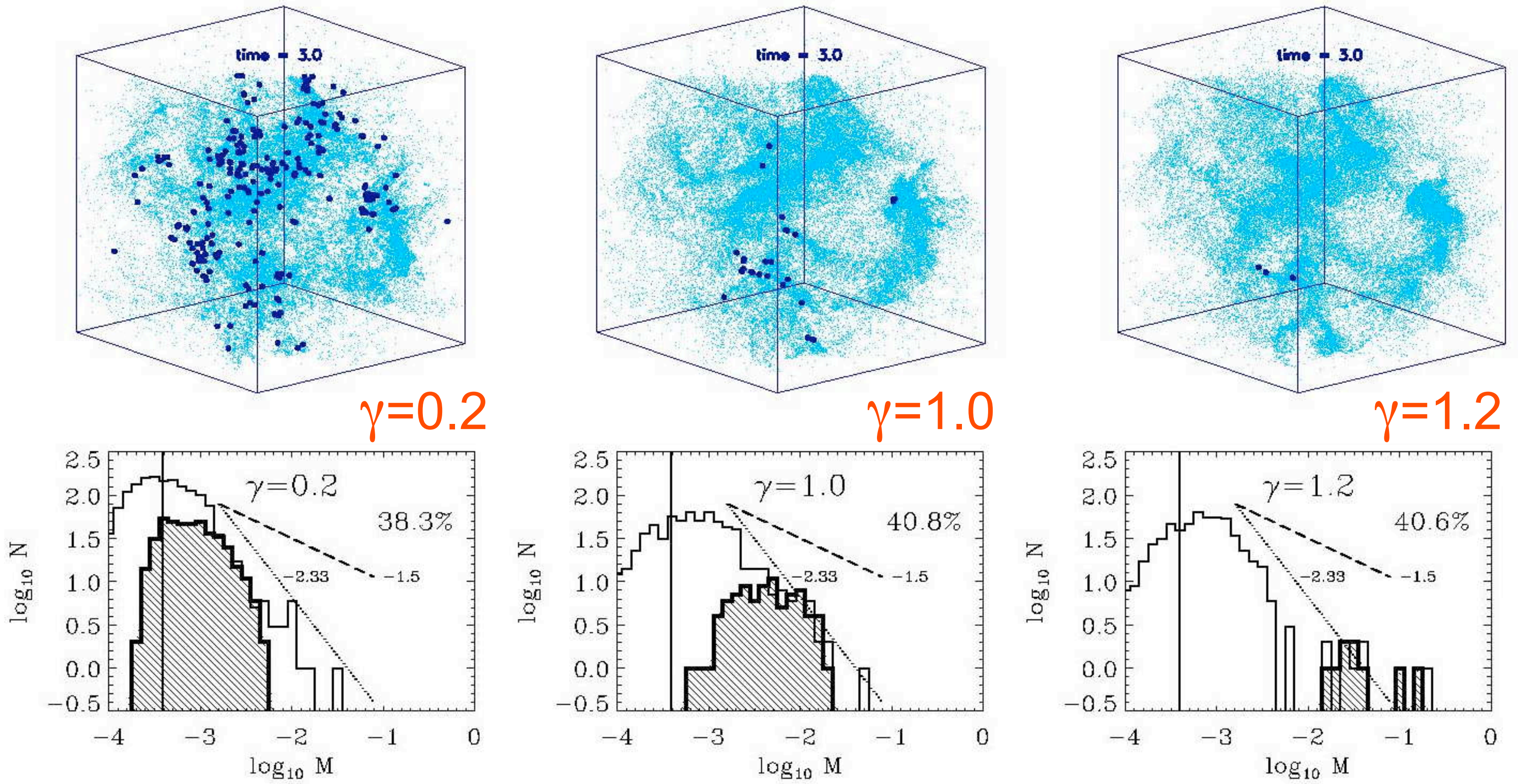
dependency on EOS

- 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*

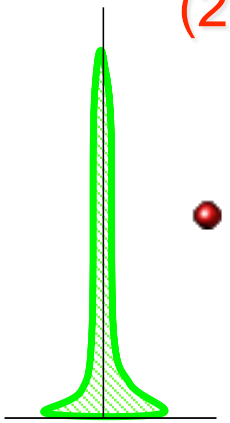
for $\gamma>1$ it is suppressed → formation of *isolated massive stars*

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

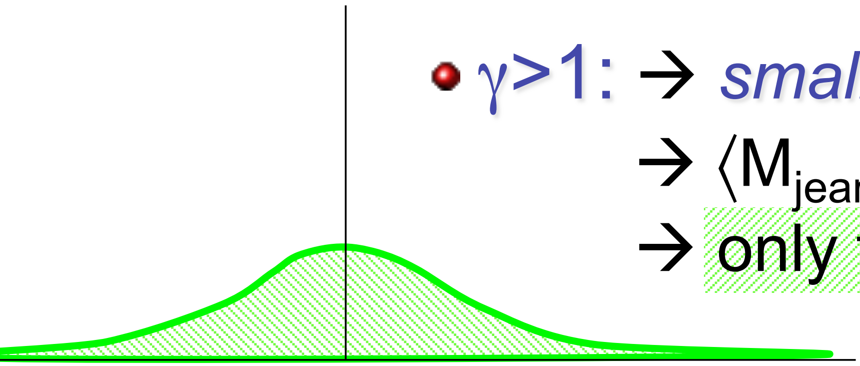
how does that work?

(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

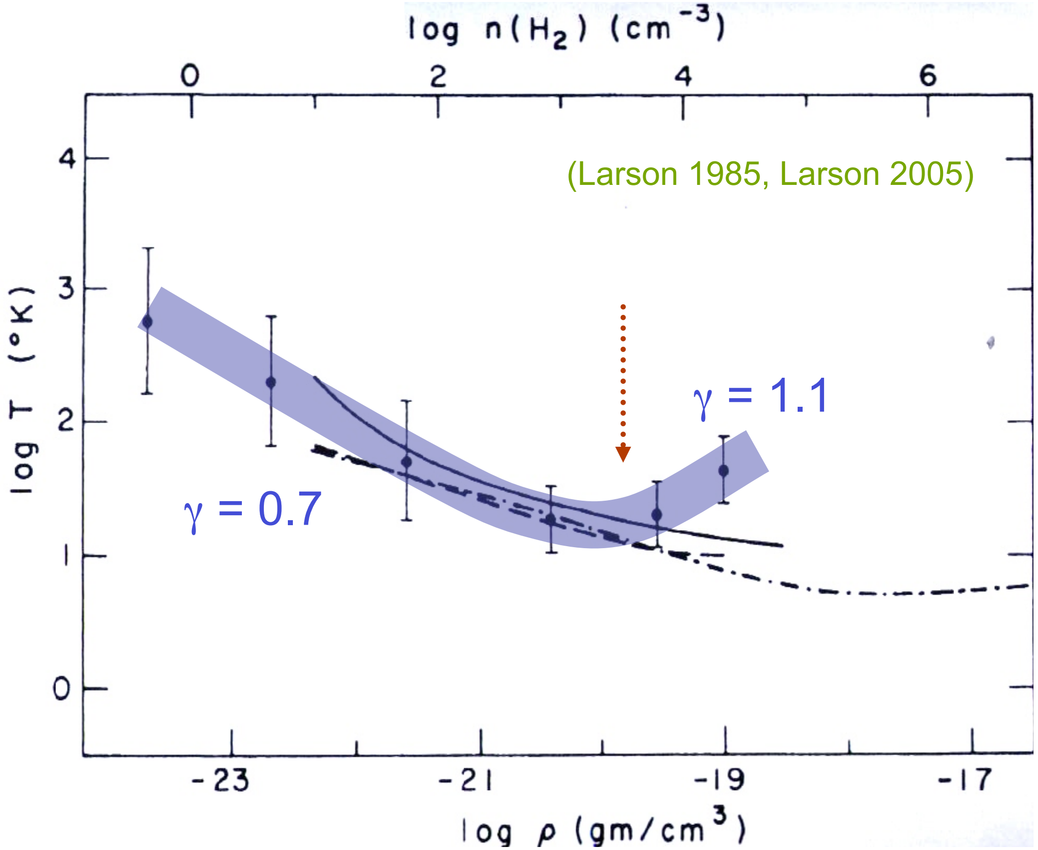


- $\gamma>1$: → *small* density excursion for given pressure
  → $\langle M_{jeans} \rangle$ is large
  → only few and massive clumps exceed M_{jeans}

EOS for solar neighborhood

below 10^{-18} gcm^{-3}: ρ ⬆ ⟹ T ⬇

above 10^{-18} gcm^{-3}: ρ ⬆ ⟹ T ⬆



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

$P \propto \rho T$

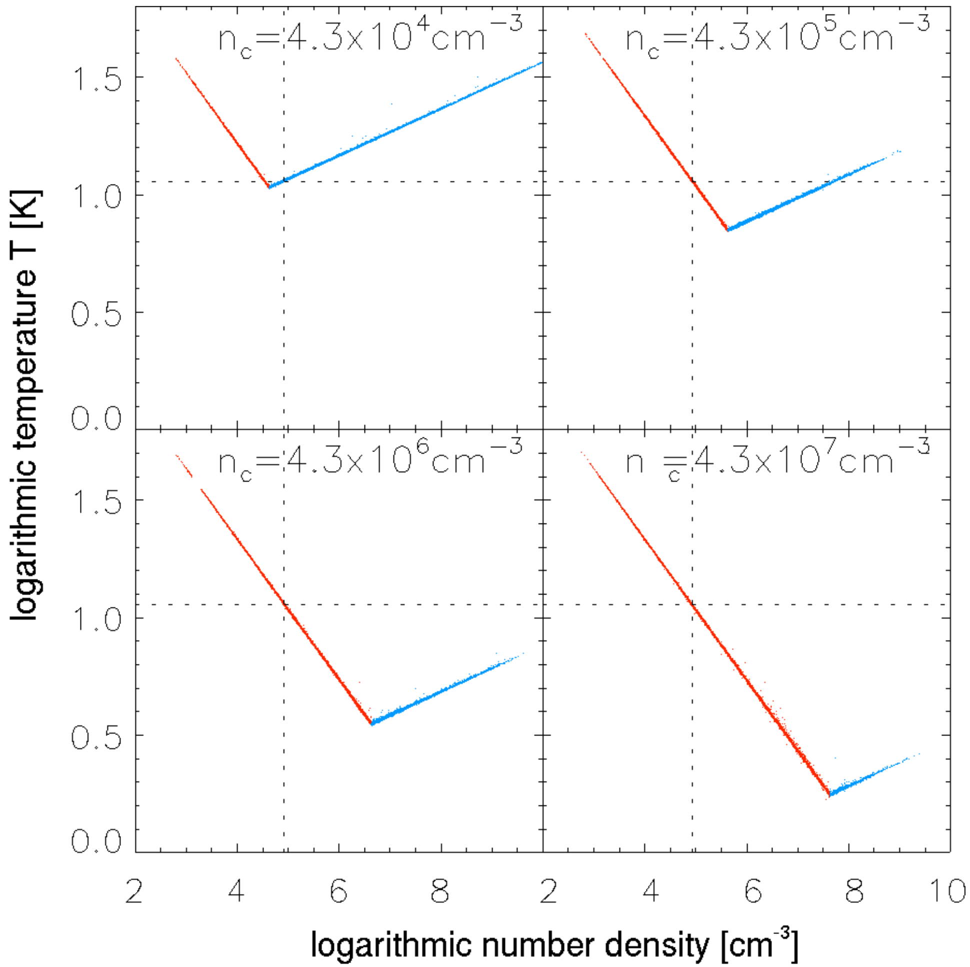
$\rightarrow \gamma = 1 + d\ln T / d\ln \rho$

IMF from simple piece-wise polytropic EOS

$\gamma_1 = 0.7$

$\gamma_2 = 1.1$

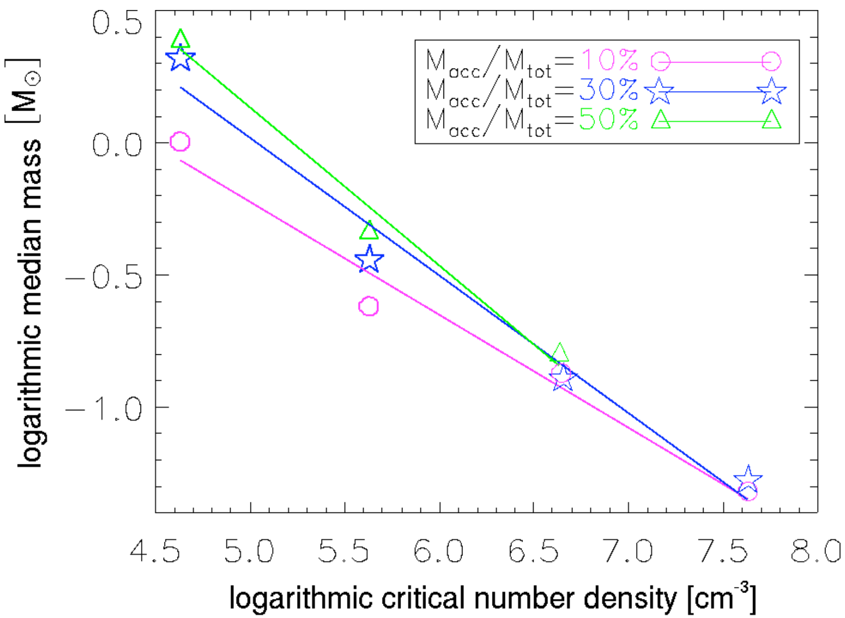
$T \sim \rho^{\gamma-1}$

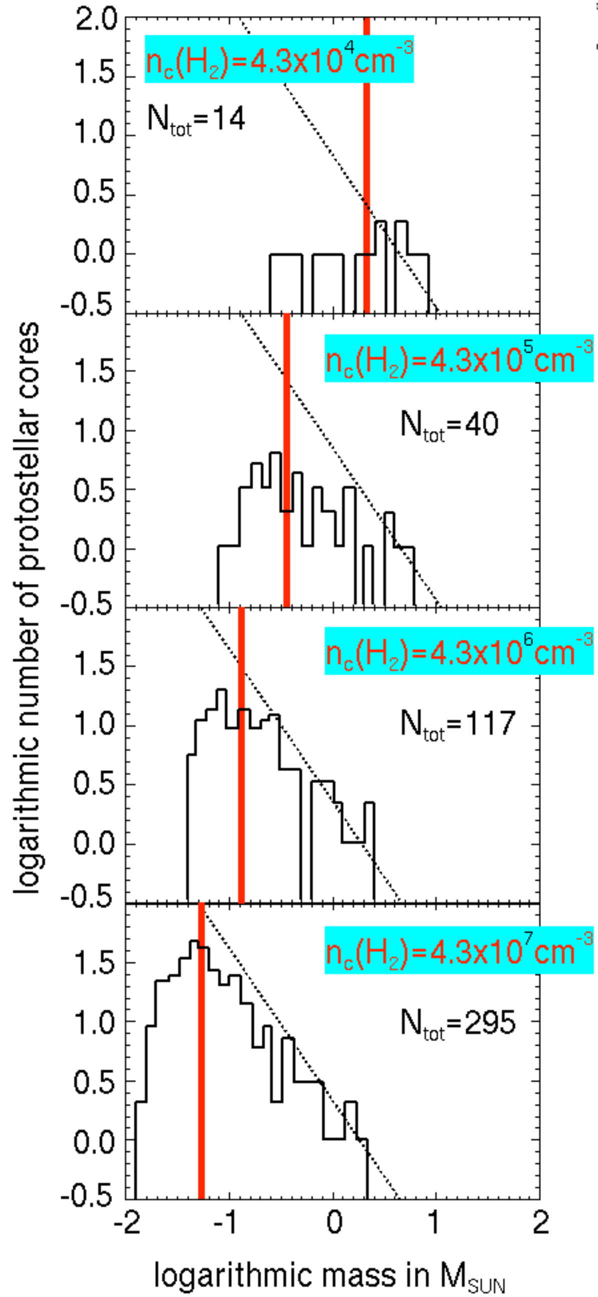


(Jappsen et al. 2005)

IMF from simple piece-wise polytropic EOS

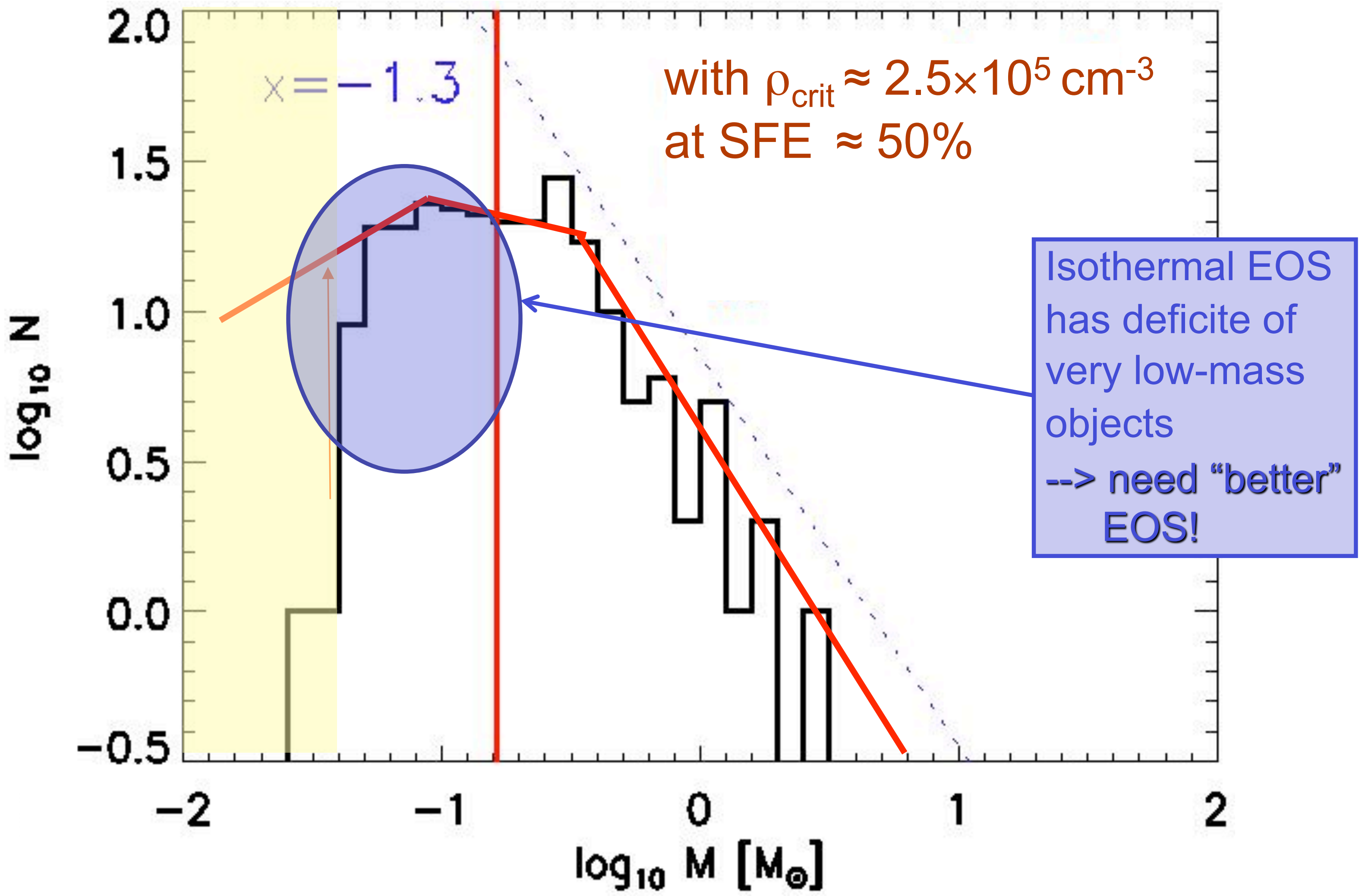
critical density ⬆ ⇨ median mass ⬇





(Jappsen et al. 2005)

IMF in nearby molecular clouds



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

caveats

- mass spectrum depends on *scale of turbulence*
  → consistent IMF only for *large-scale turbulence*

  (Klessen 2001)

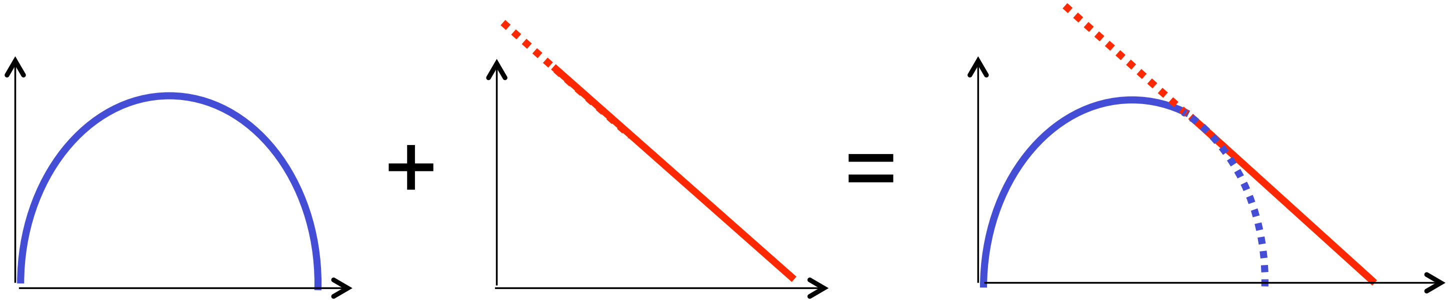
  → dynamical effects are important
  (Bonnell et al., Clark et al.)

- result depends on *mechanism of turbulent driving*
  → *solenoidal* vs. *compressive driving*
  (Federrath et al. 2008)

initial mass function

- what is the relation between molecular cloud fragmentation and the distribution of stars?
- important quantity: *IMF*
- BUT: “everyone” gets the right IMF
  → better look for secondary indicators
  - *stellar multiplicity* (see focus group lead by H. Zinnecker)
  - protostellar *spin* (including disk)
  - *spatial distribution* + *kinematics* in young clusters
  - *magnetic field strength* and *orientation*
    (see focus group lead by R. Crutcher)

Plausibility argument for shape



- Supersonic turbulence is scale free process

  → *POWER LAW BEHAVIOR*

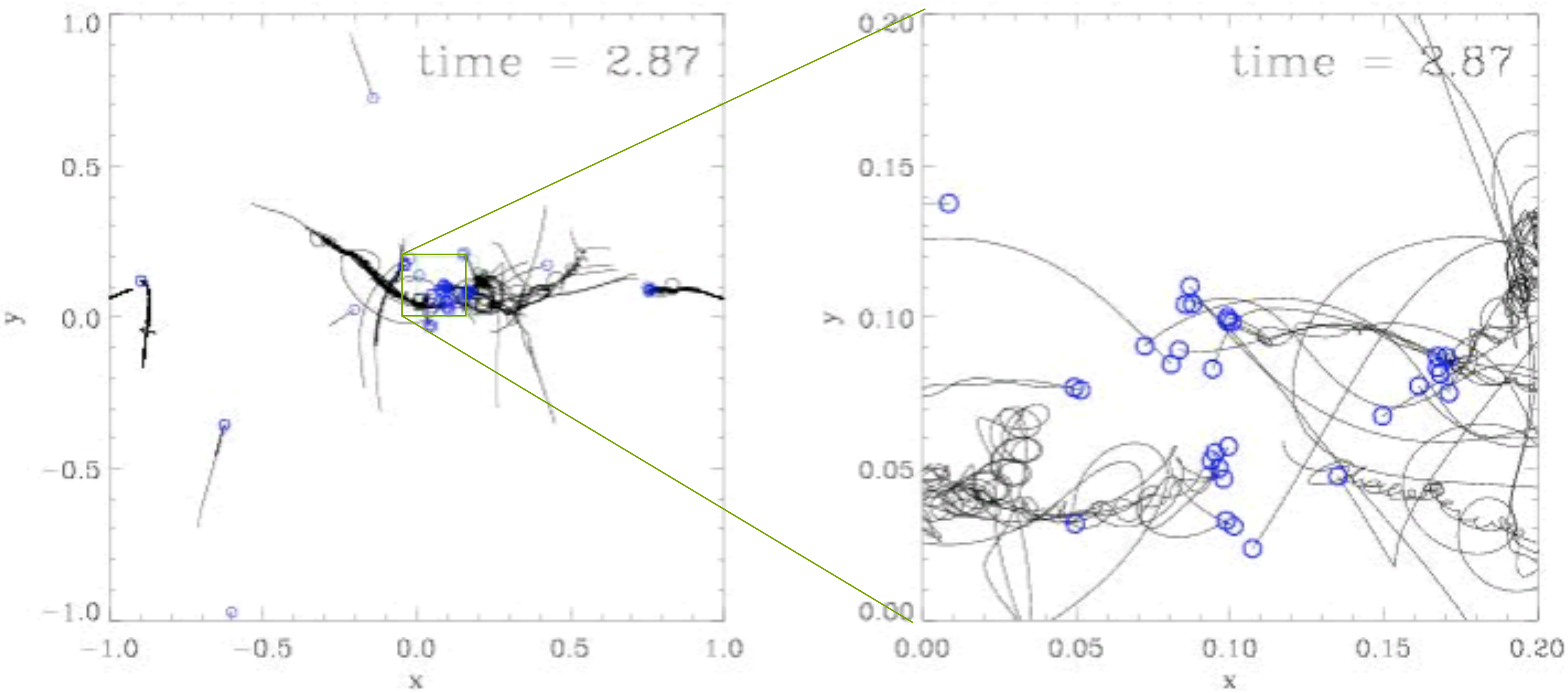
- *But also:* turbulence and fragmentation are highly stochastic processes → central limit theorem

  → *GAUSSIAN DISTRIBUTION*

effects of dynamics

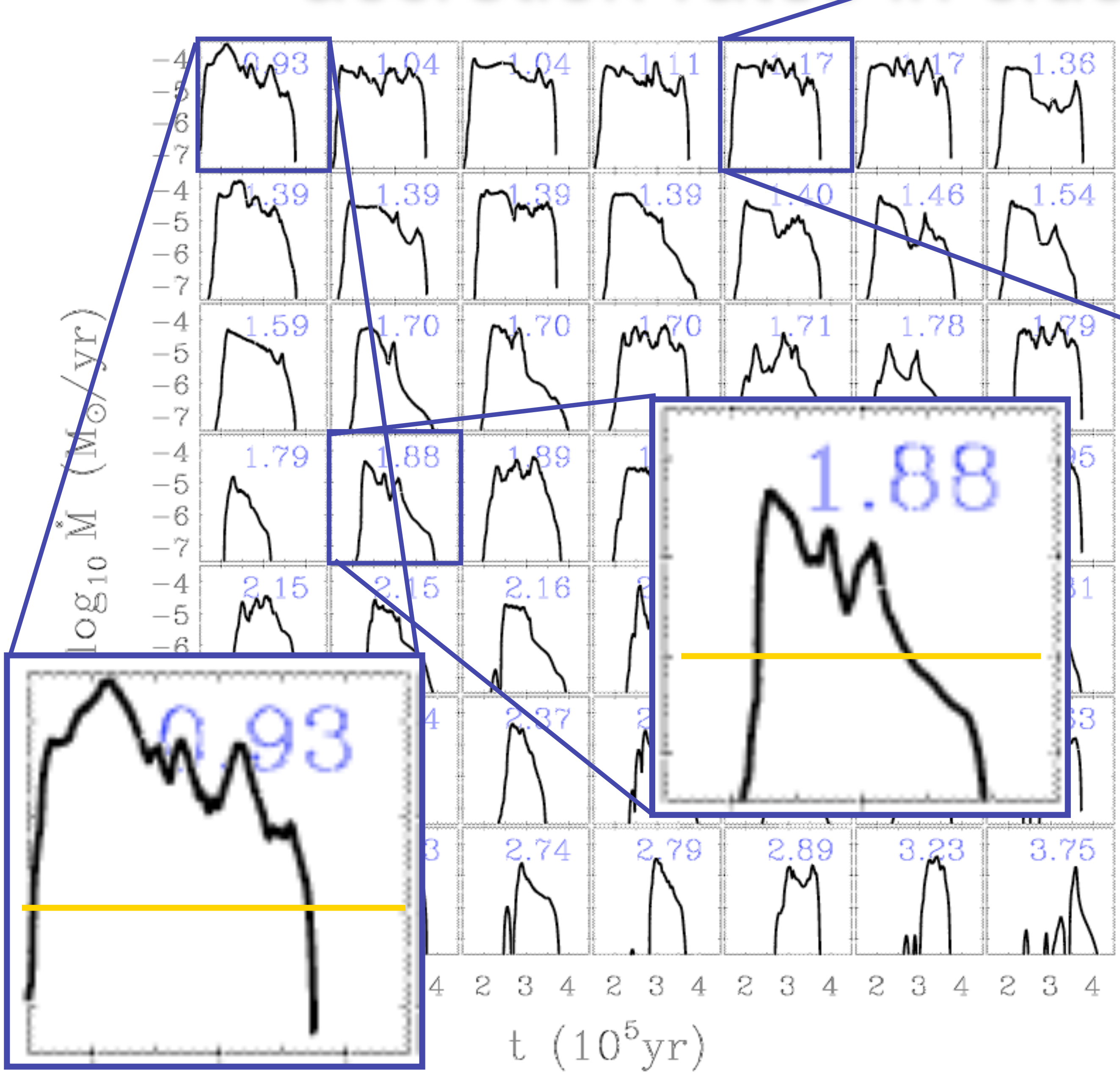
Star cluster formation

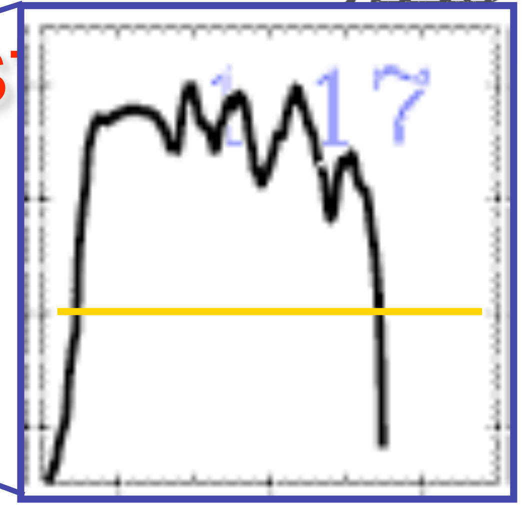
Most stars form in clusters → *star formation = cluster formation*



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

accretion rates in clust

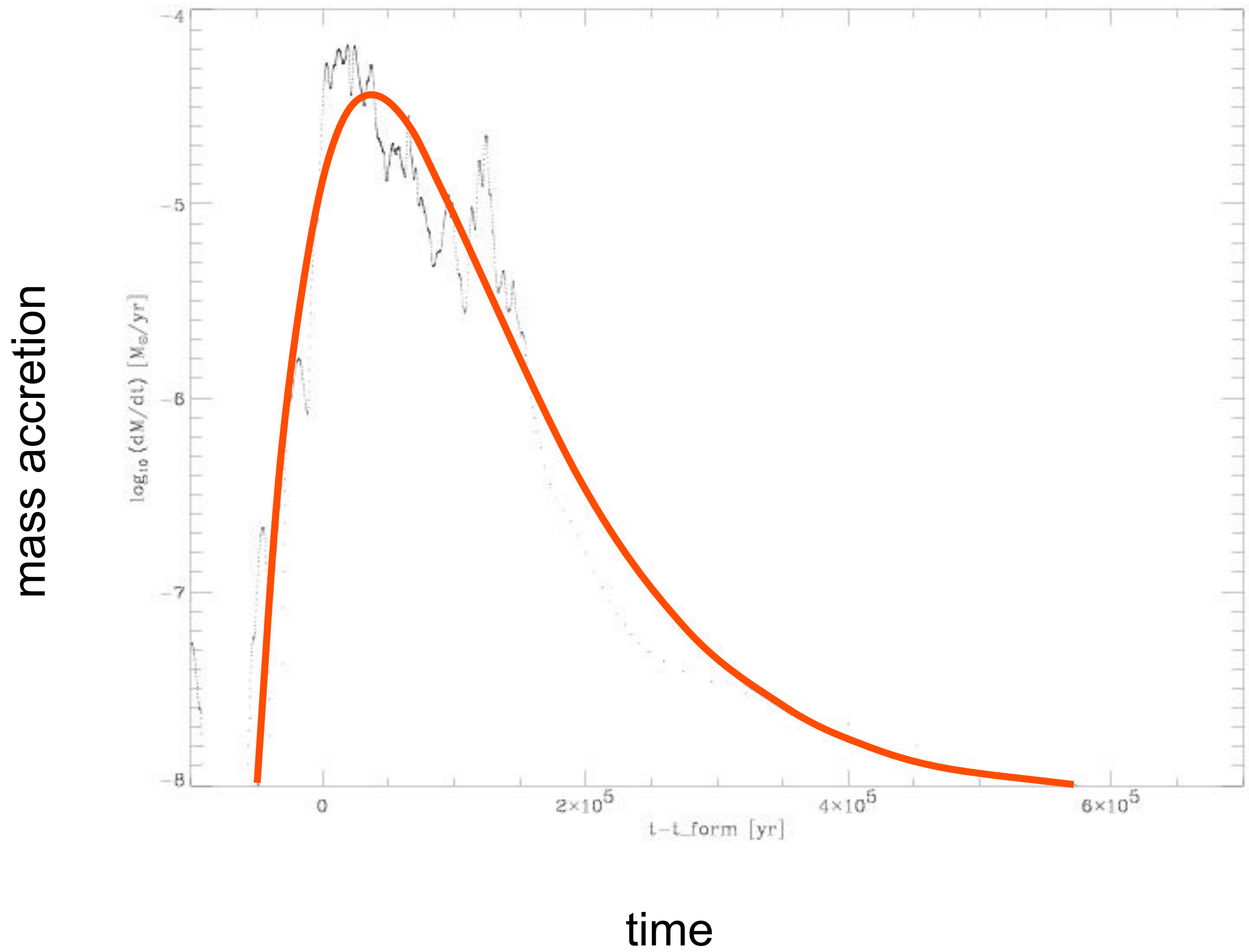




Mass accretion rates *vary with time* and are strongly *influenced* by the *cluster environment*.

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

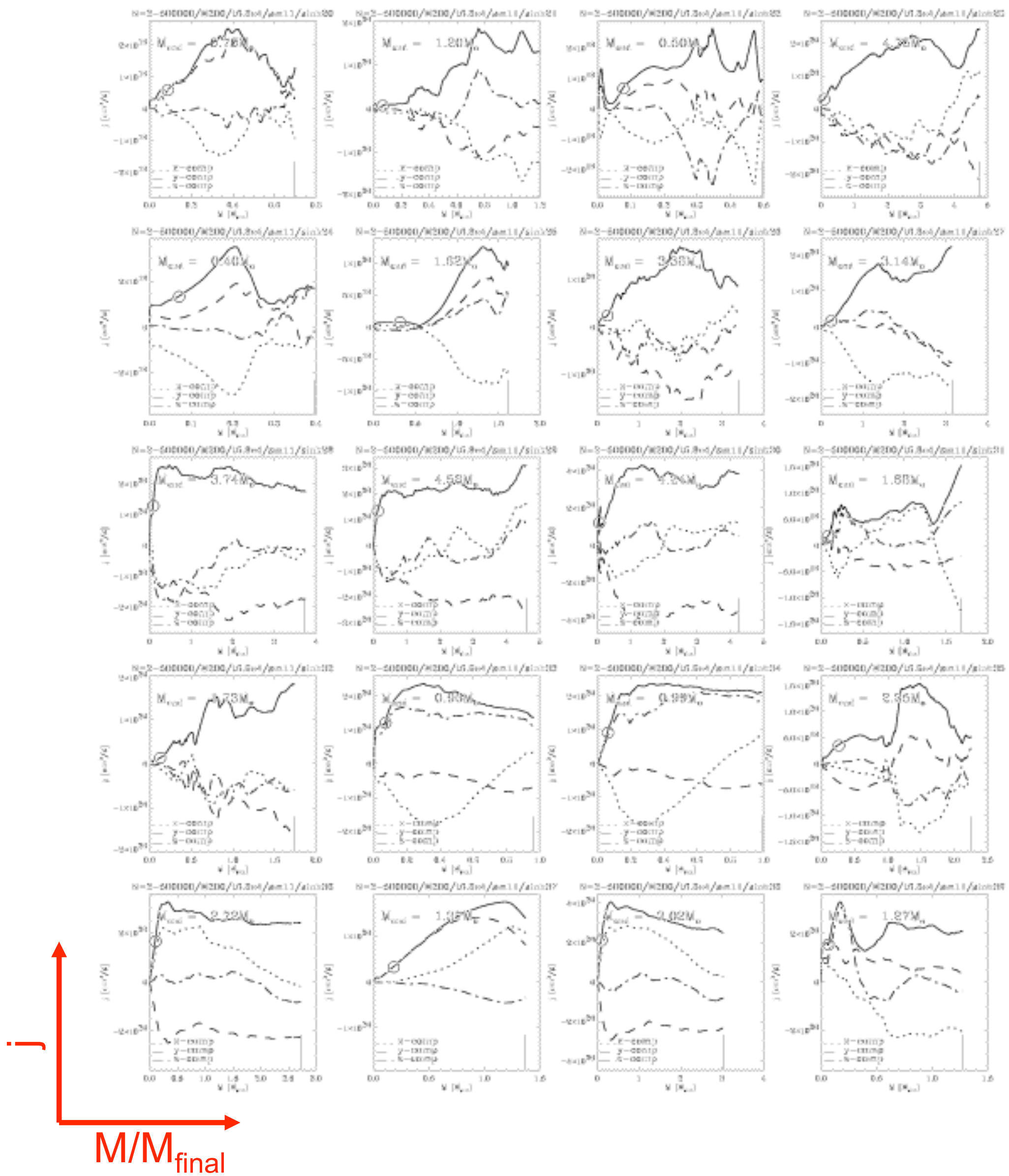
“Empirical” mass accretion law



Simple analytic formula for individual mass accretion rates: $dM/dt = At \cdot \exp(-t/\tau)$

(Schmeja & Klessen, 2004 -- A&A, 419, 405 - 417)

Angular momentum evolution I

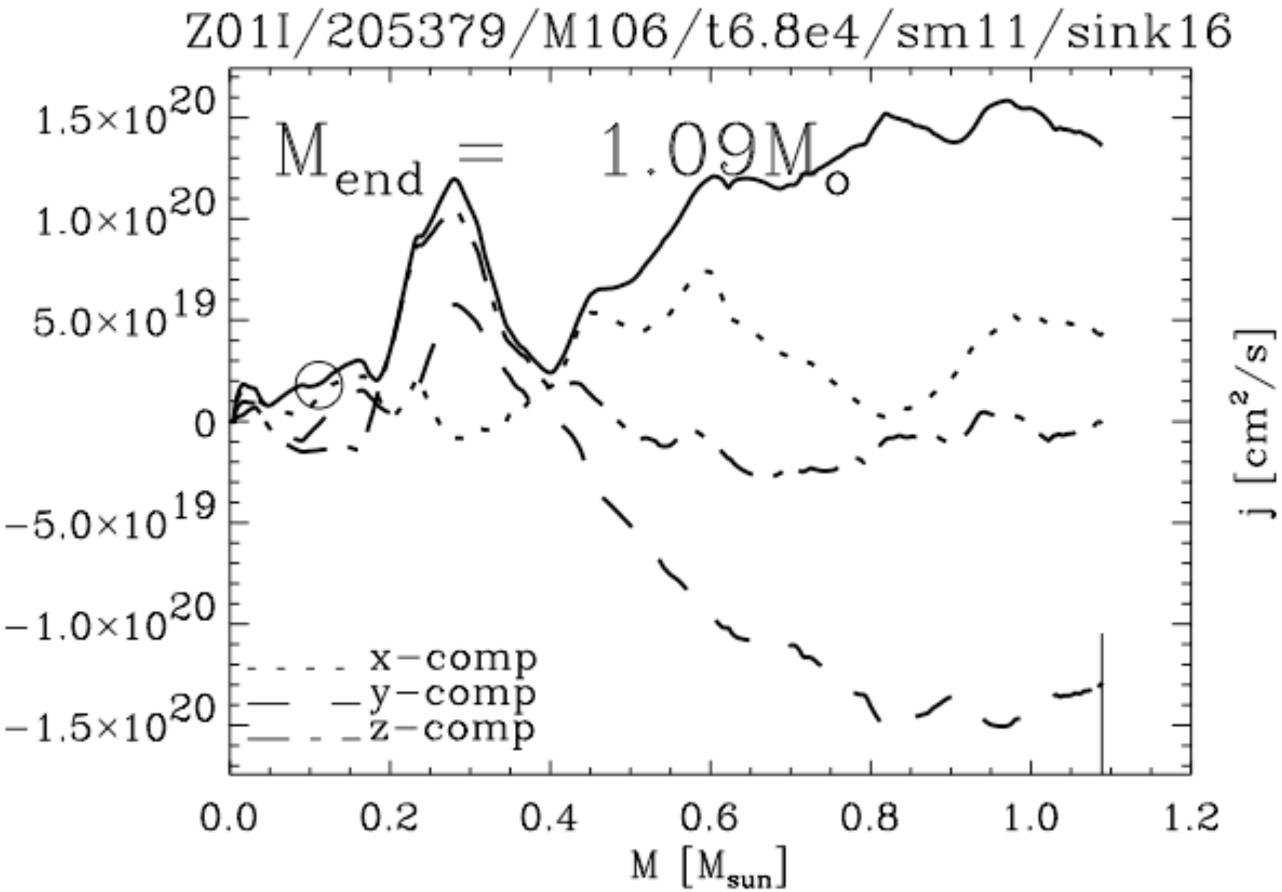


- *Angular momentum evolution* during protostellar collapse determines *disk sizes* (and possible *binary fraction*)

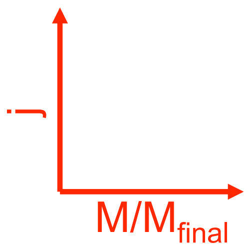
Examples of the time evolution of *j*

(Jappsen & Klessen, 2004, A&A, 423, 1)

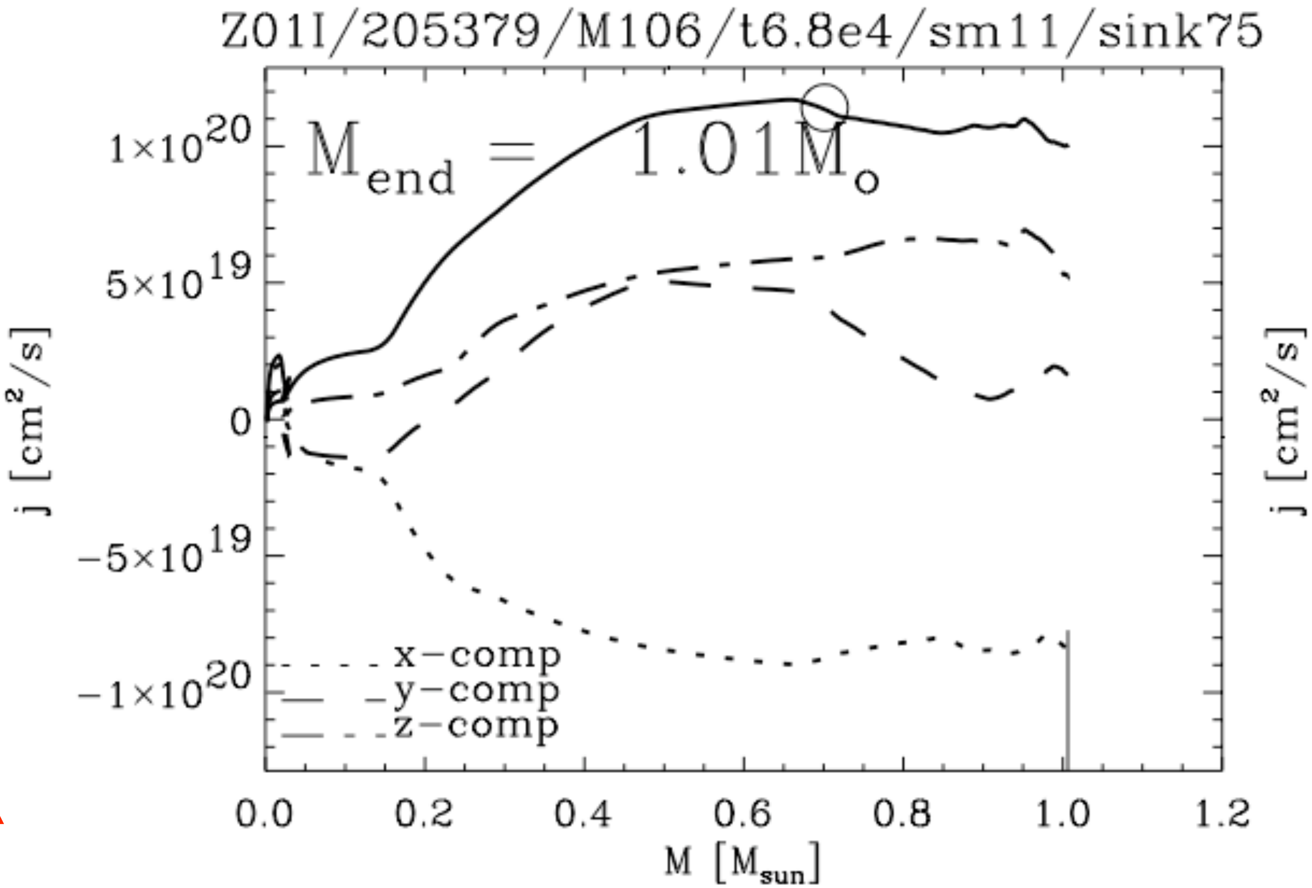
Angular momentum evolution Ib



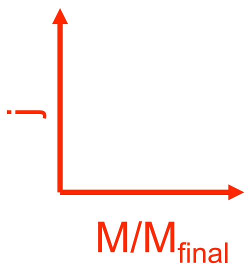
details of the time evolution of *j*



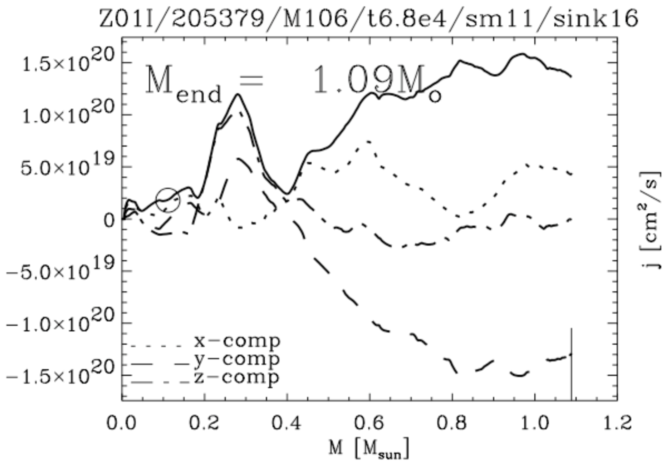
Angular momentum evolution Ic

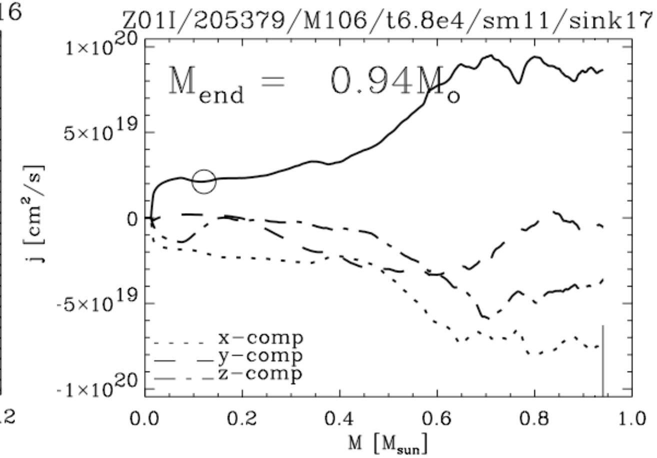


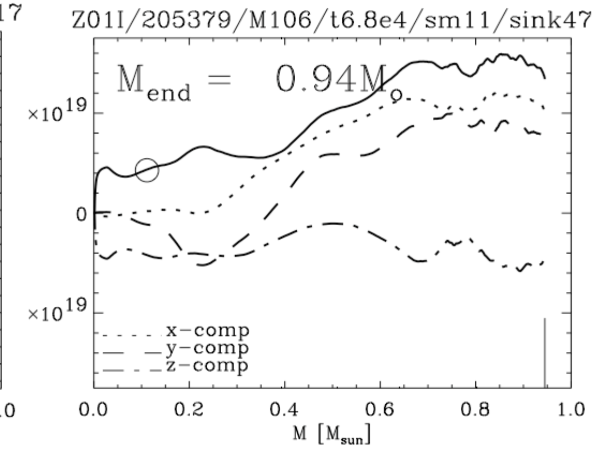
details of the time evolution of *j*

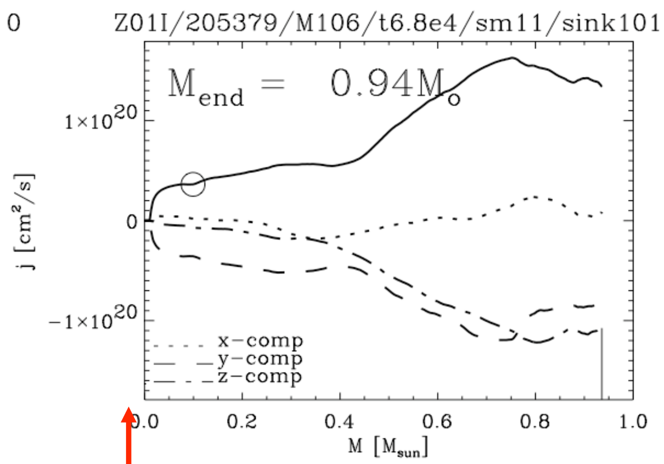


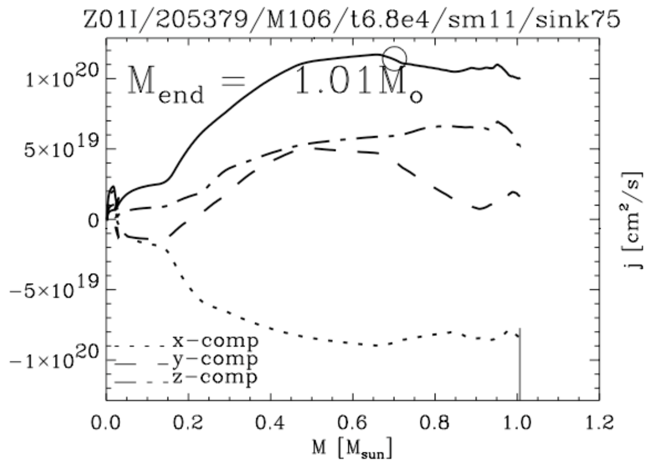
Angular momentum evolution Id

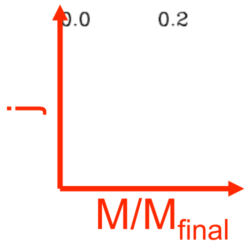












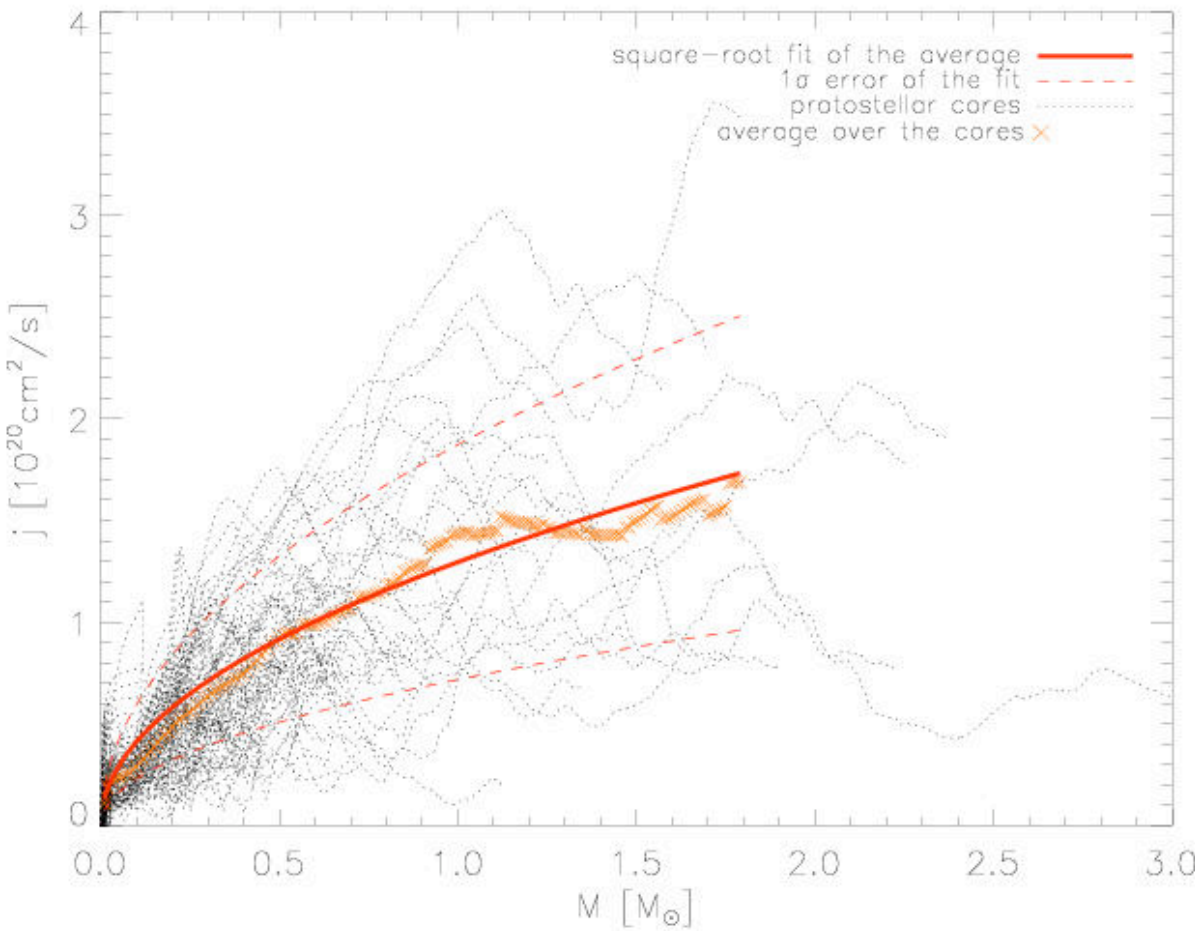
detailes of the time evolution of *j*

3 of these 5 disks become unstable and may form binary

(Bodenheimer & Klessen, not published)

Angular momentum evolution II

- Statistical dependence of *ang. mom.* on *mass*



$j \propto M^{2/3}$

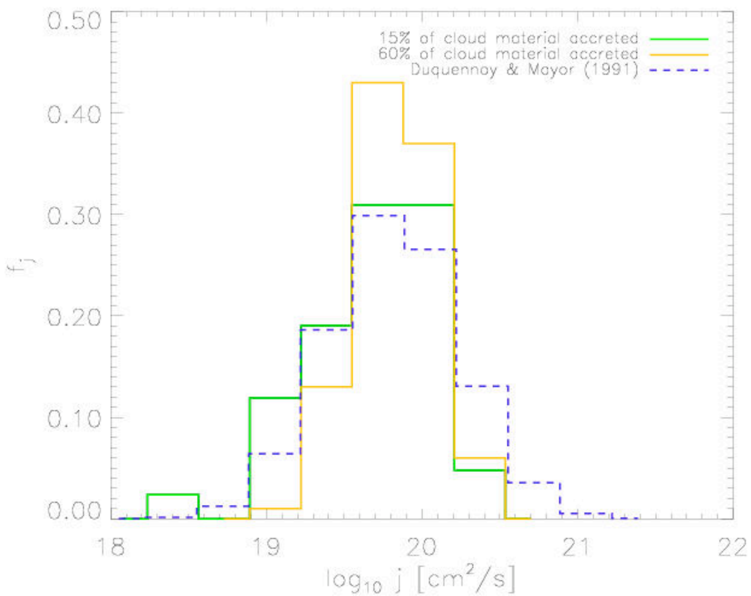
β = constant

R = constant

ρ = contant (initially)

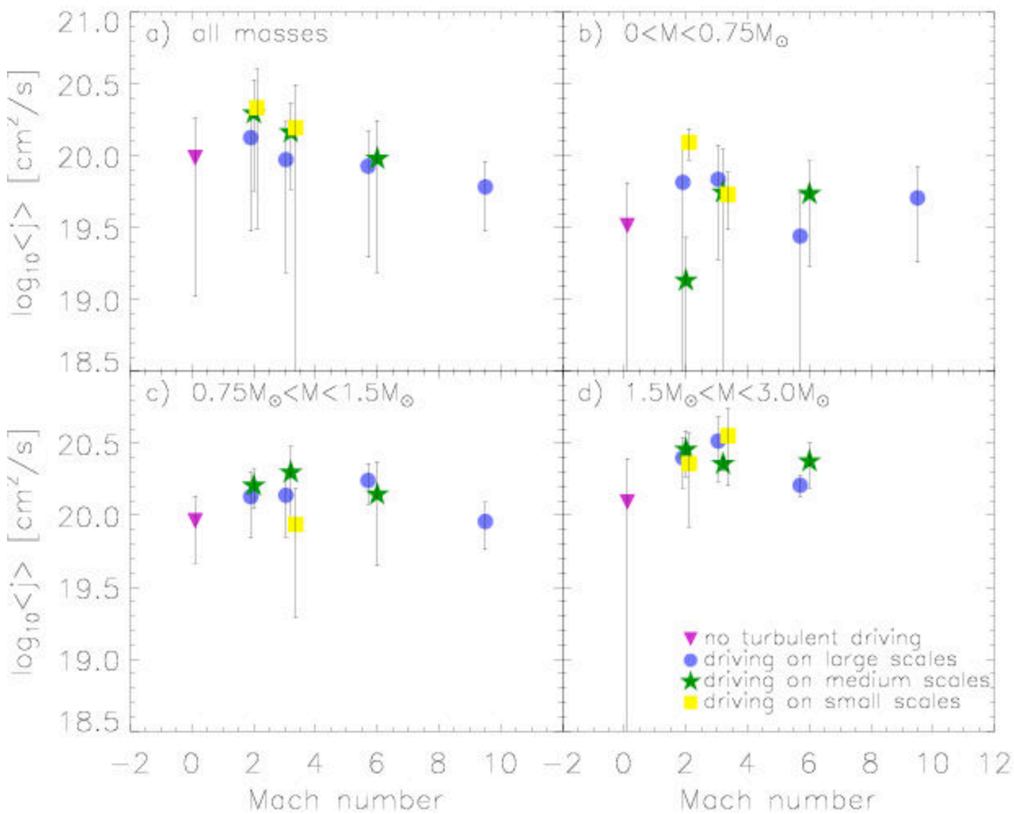
(Jappsen & Klessen, 2004, A&A, 423, 1)

Angular momentum evoluton III



Distribution of *j* similar to that of observed G-dwarf binaries

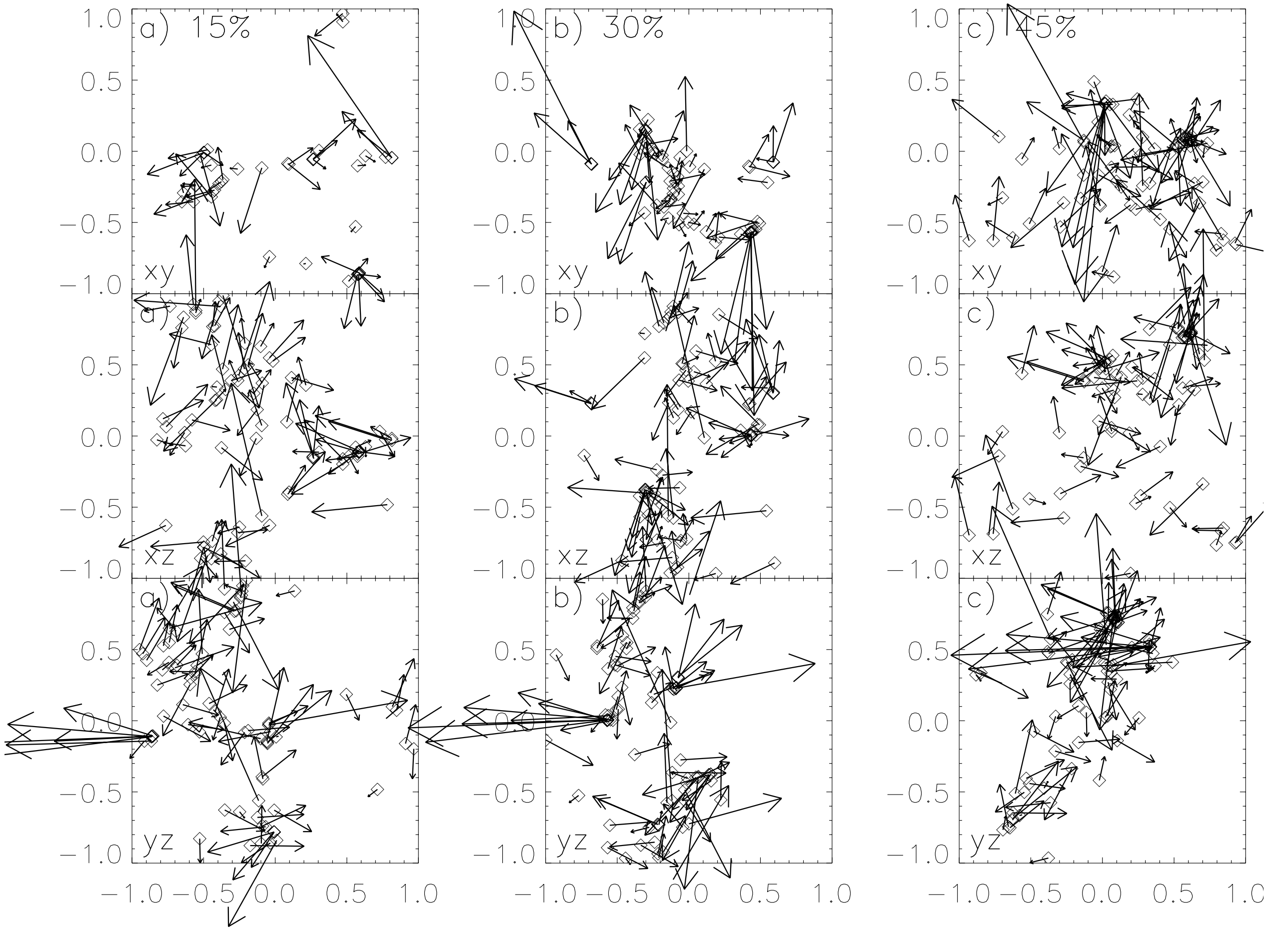
Angular momentum loss by gravitational torques in turbulent environment



Weak dependency of *j* on Mach number

(Jappsen & Klessen, 2004, A&A, 423, 1)

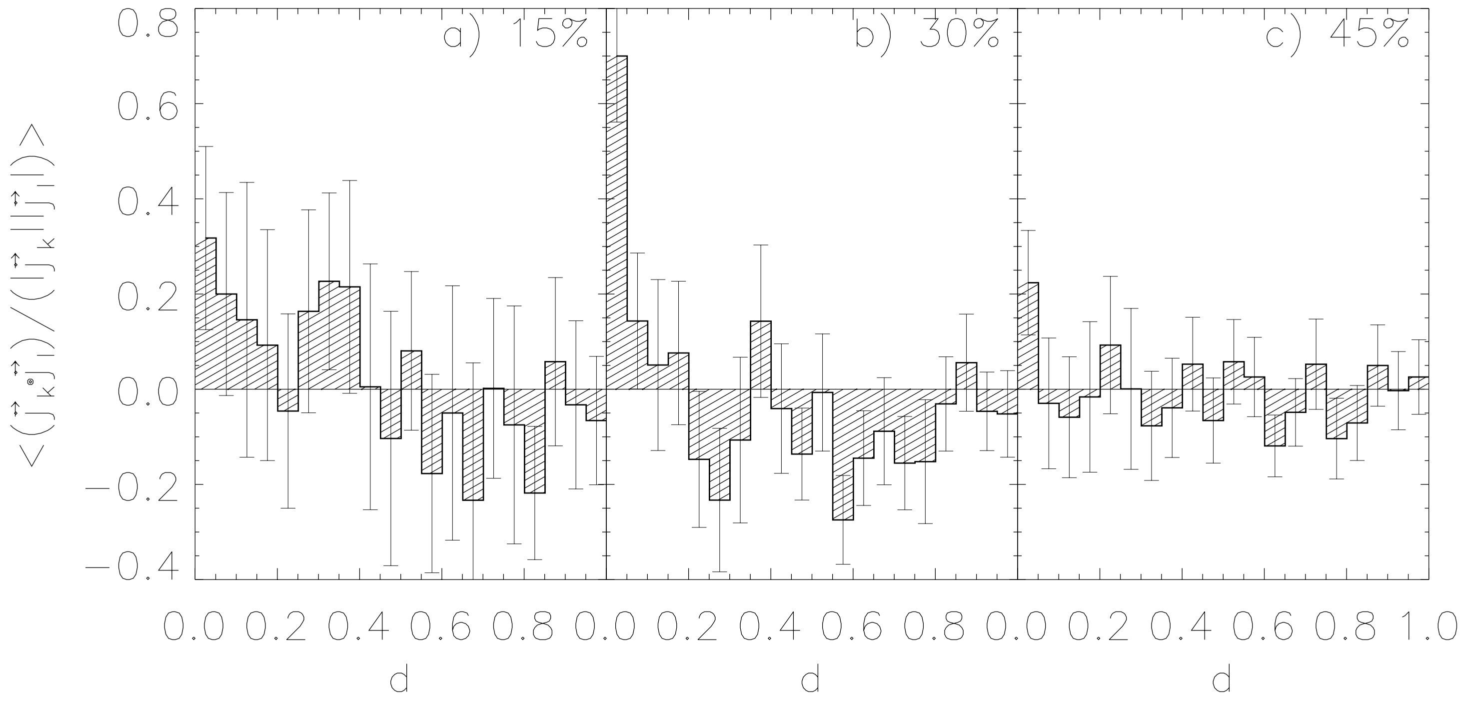
Angular momentum IV



orientation of disk axes as function of time...

(Jappsen & Klessen, 2004, A&A, 423, 1)

Angular momentum V



correlation of disk axis orientation as function of time...

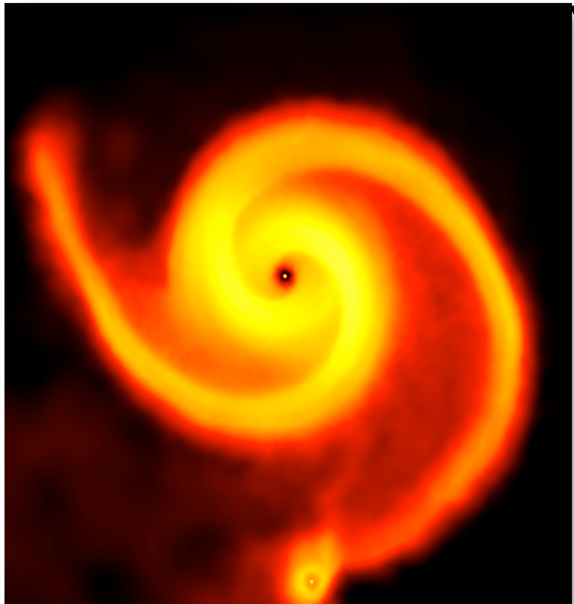
(Jappsen & Klessen, 2004, A&A, 423, 1)

modeling disks in clusters

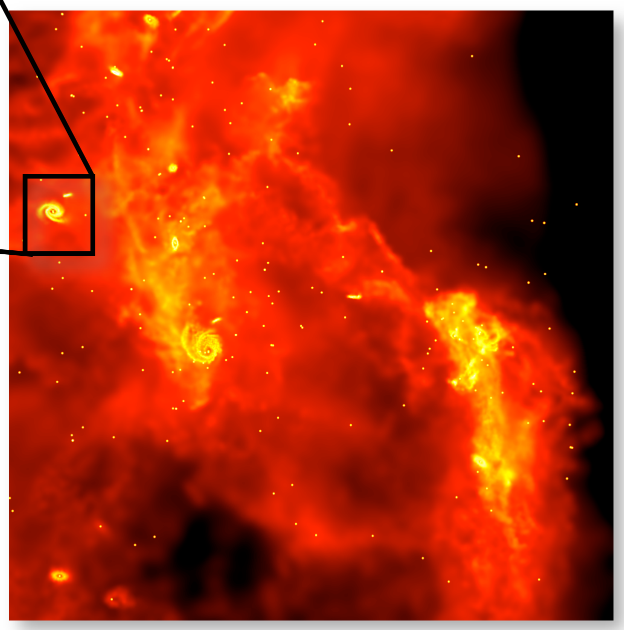
numerical difficulties

- Resolving discs such that numerical viscosity doesn't dominate requires high resolution... e.g. for SPH:
  - I) Lodato & Rice (2004) -> $\alpha_{art} = (1/8)\alpha_{SPH}\ (h/H)$
  - II) Rice, Lodato, Stamatellos, etc typically employ > 200,000 particles...
- Today, this is easy for disc/star system, OK for an isolated core, impossible for a whole cluster simulation:
  - 0.1 $M_{\odot}$ disc requires particle mass ~$1\times10^{-6}\ M_{\odot}$
  - 1000 $M_{\odot}$ cluster then need *> 10^9 particles*
  - (that's a lot)

possible solution?



Use large-scale simulations as a input for detailed small-scale simulations



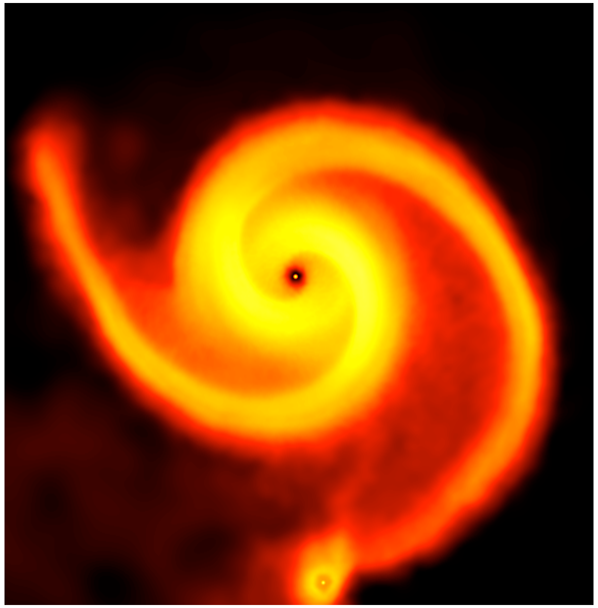
Problem: still difficult to study global disk properties as cluster evolves.

(from Clark et al. in preparation)

how to define a disk in cluster simul.?

Combine the sinks into systems:

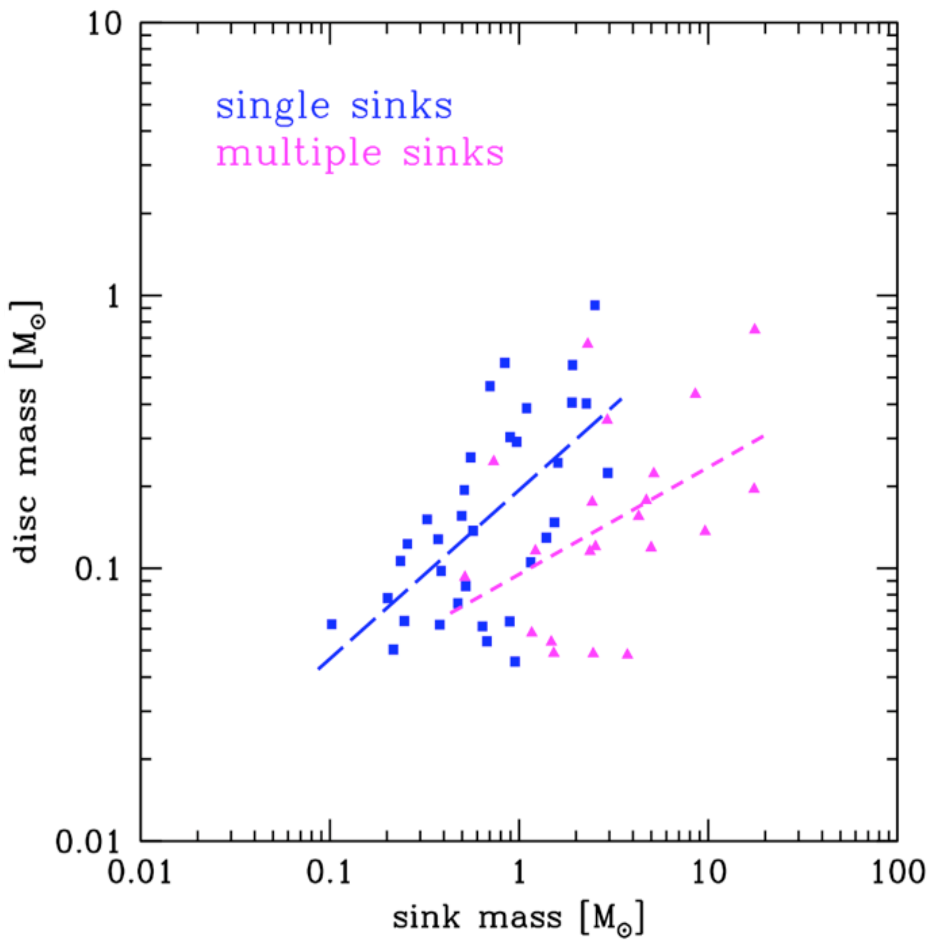
- $20 < a < 500$ au
- material needs to be bound
- must sit in potential well associated with sink/system
- $v_{rot} > v_{rad}$
- density threshold
- coherent object! (well, at least radially)



Roughly 50% of the systems have 'resolvable' disks.

(from Clark et al. in preparation)

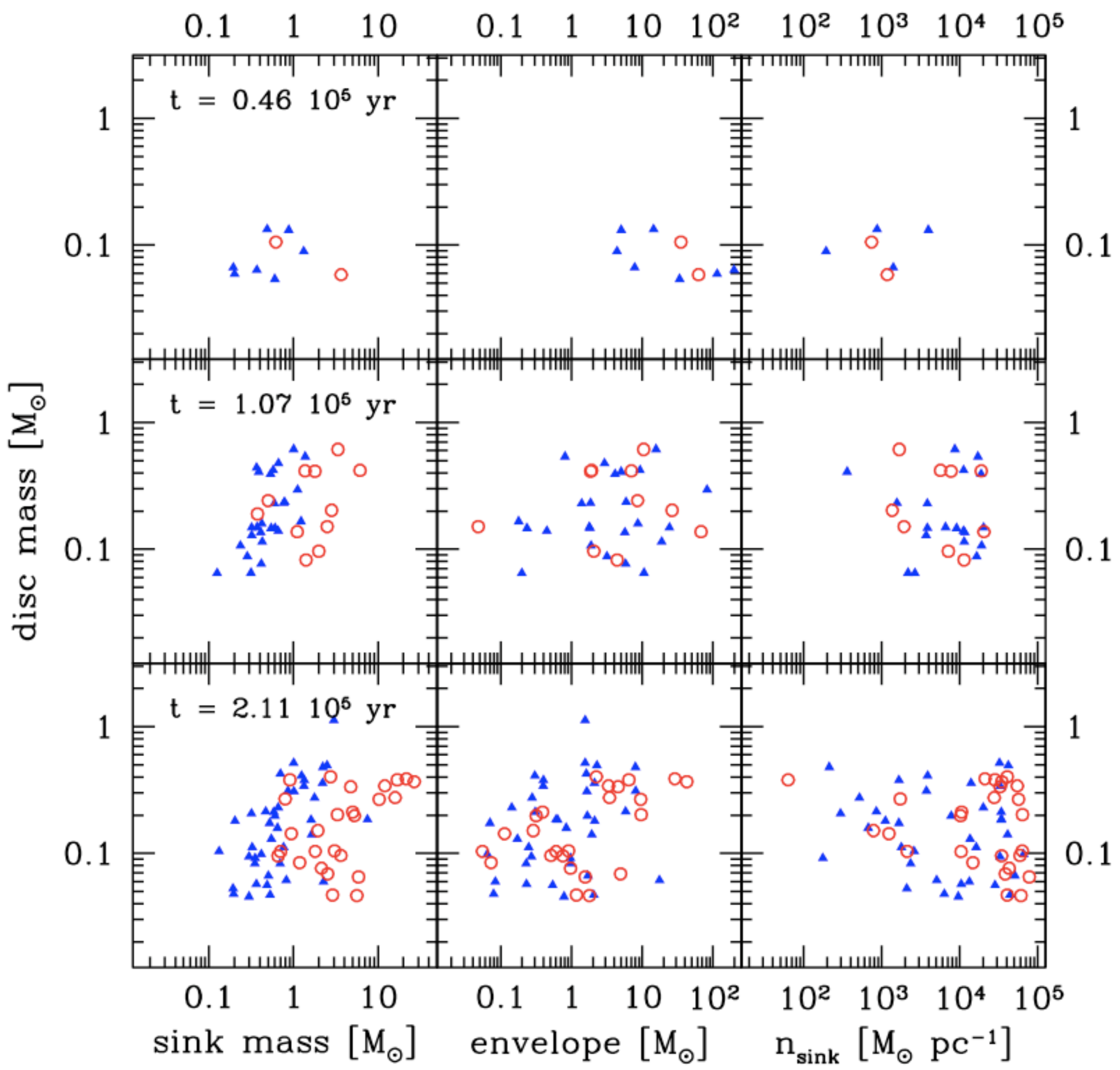
disk masses



- (very) broad trend with mass of sink system.
- M_{disc}/M_* often larger than 0.1
- would expect these discs to be self-gravitating (e.g. Lodato & Rice 2004, 2005).
- is this a feature of accretion in cluster environment (interactions, irregular dM/dt and dj/dt?)?
- sinks in systems occupy a different region from isolated sinks.

note that these are lower limits to the mass ...

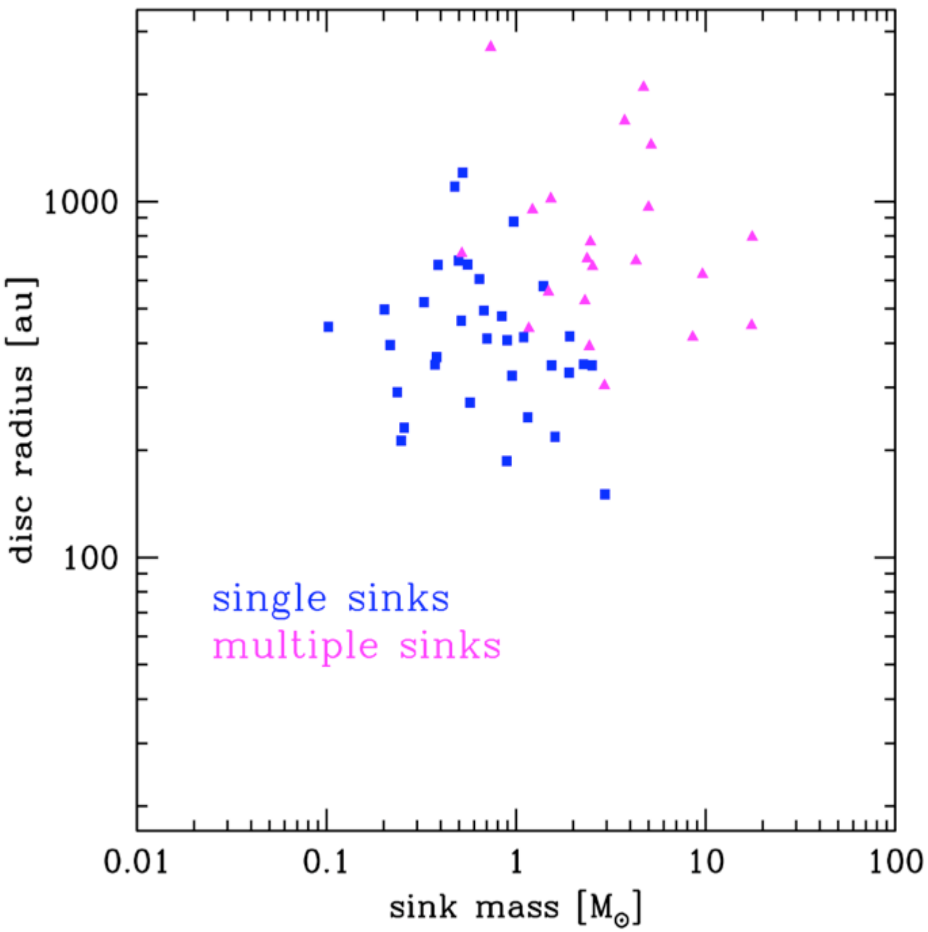
(from Clark et al. in preparation)



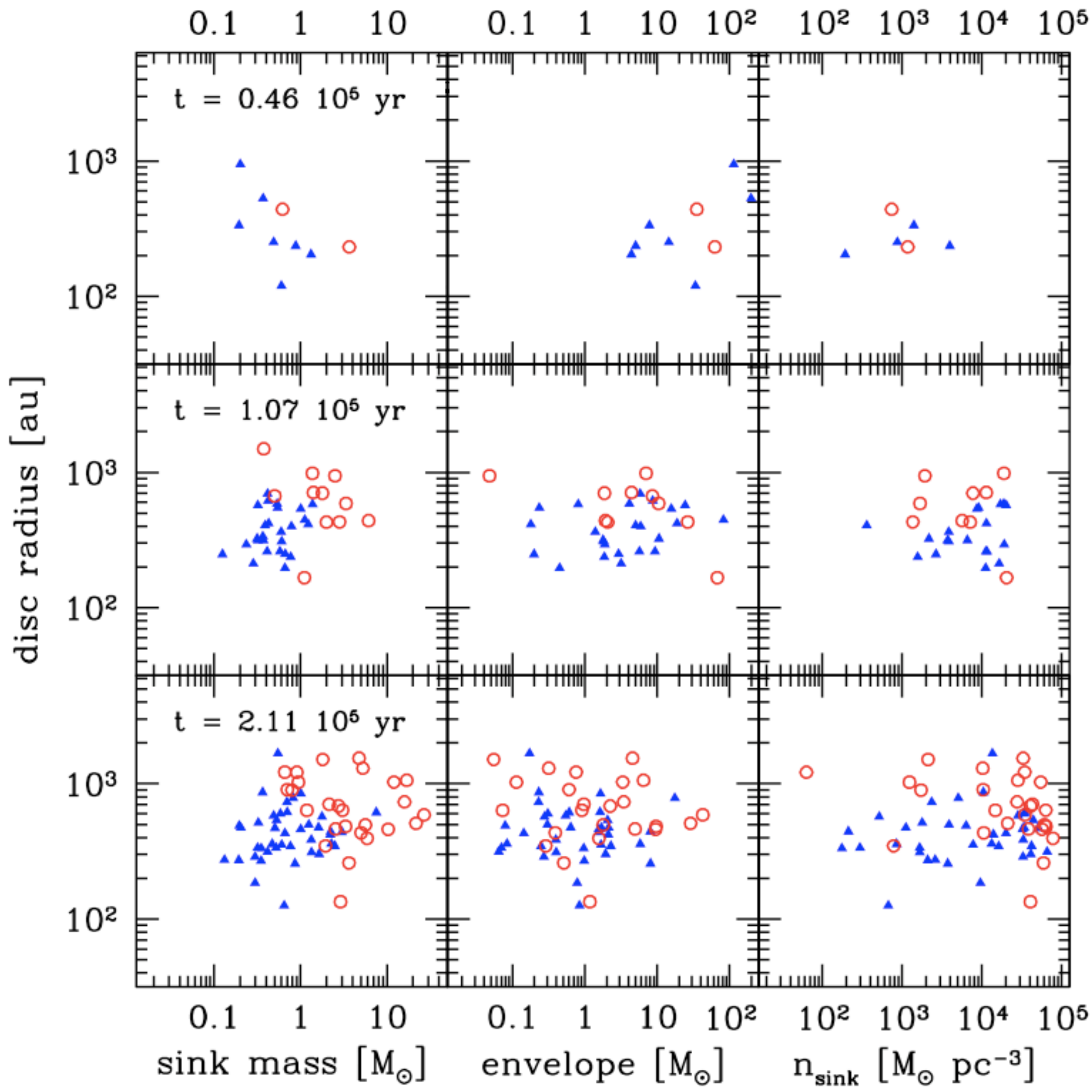
(from Clark et al. in preparation)

disk radii

- again a broad trend with sink-system mass.
- disks around systems are larger that those around individual sinks (makes sense, given that they must surround larger objects).



(from Clark et al. in preparation)



(from Clark et al. in preparation)

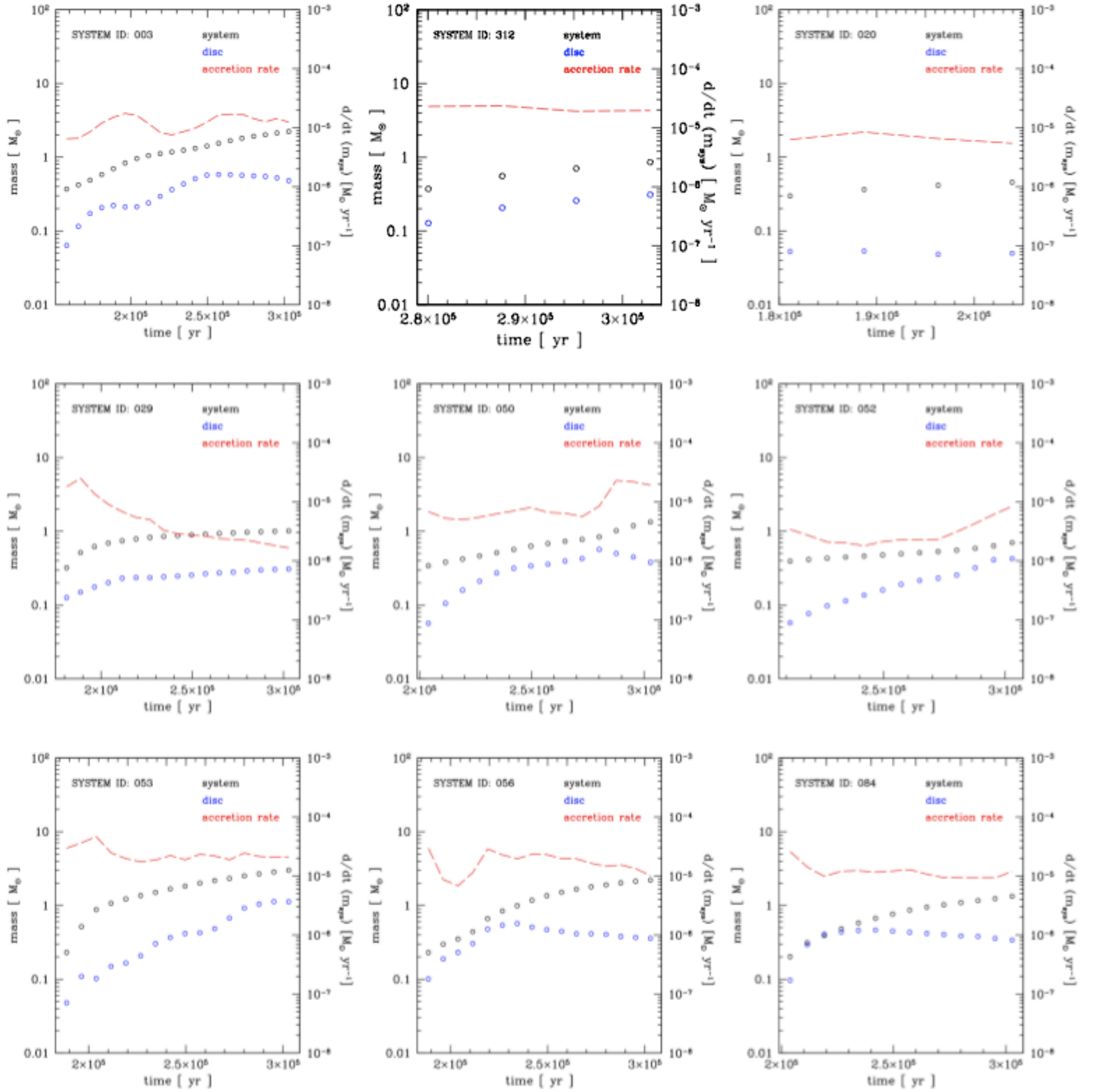


FIG. 7.— This plot is the same as the previous, but this time all the evolution tracks are for discs around sinks which remain isolated (i.e. single sinks).

(from Clark et al. in preparation)

disk evolution in cluster

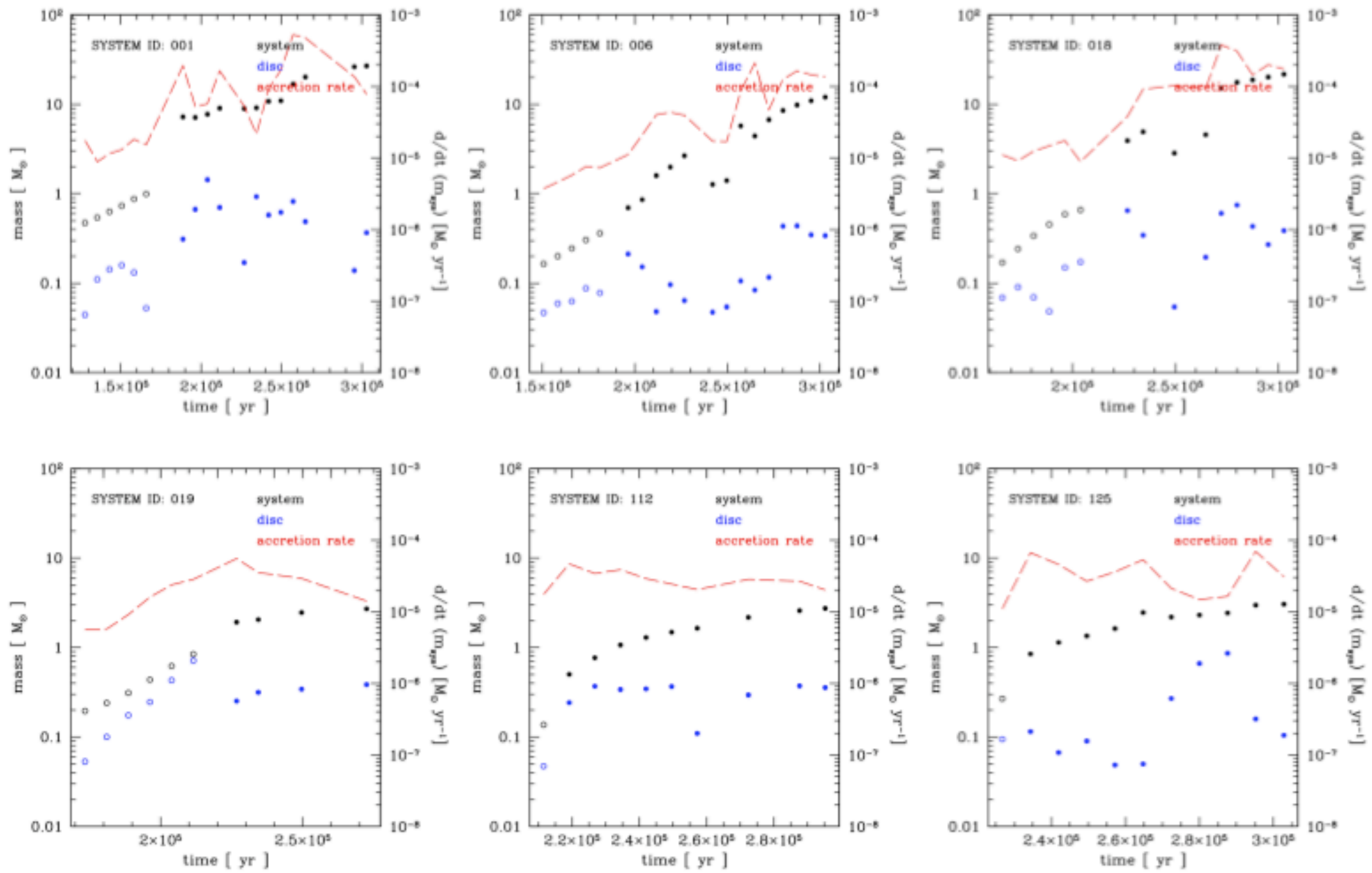
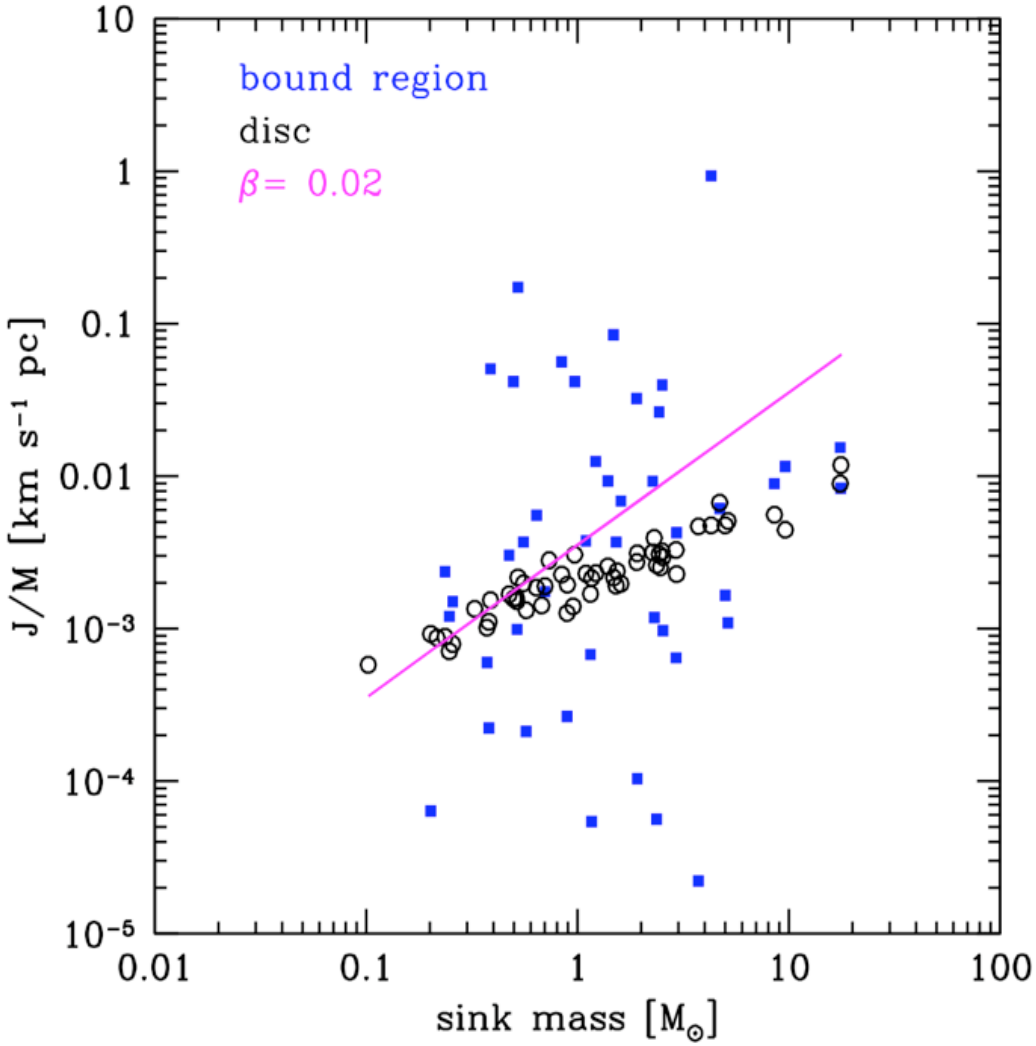


FIG. 6.— The time evolution of several discs along with their host sinks, for the case where the sinks enter a multiple system. Points in the evolution in which the disc orbits a single sink are given as open circles, while the filled circles denote times when the disc is orbiting a system of sinks. The accretion rate, denoted by the dashed line, is that of the sink or sink-system.

(from Clark et al. in preparation)

angular momentum

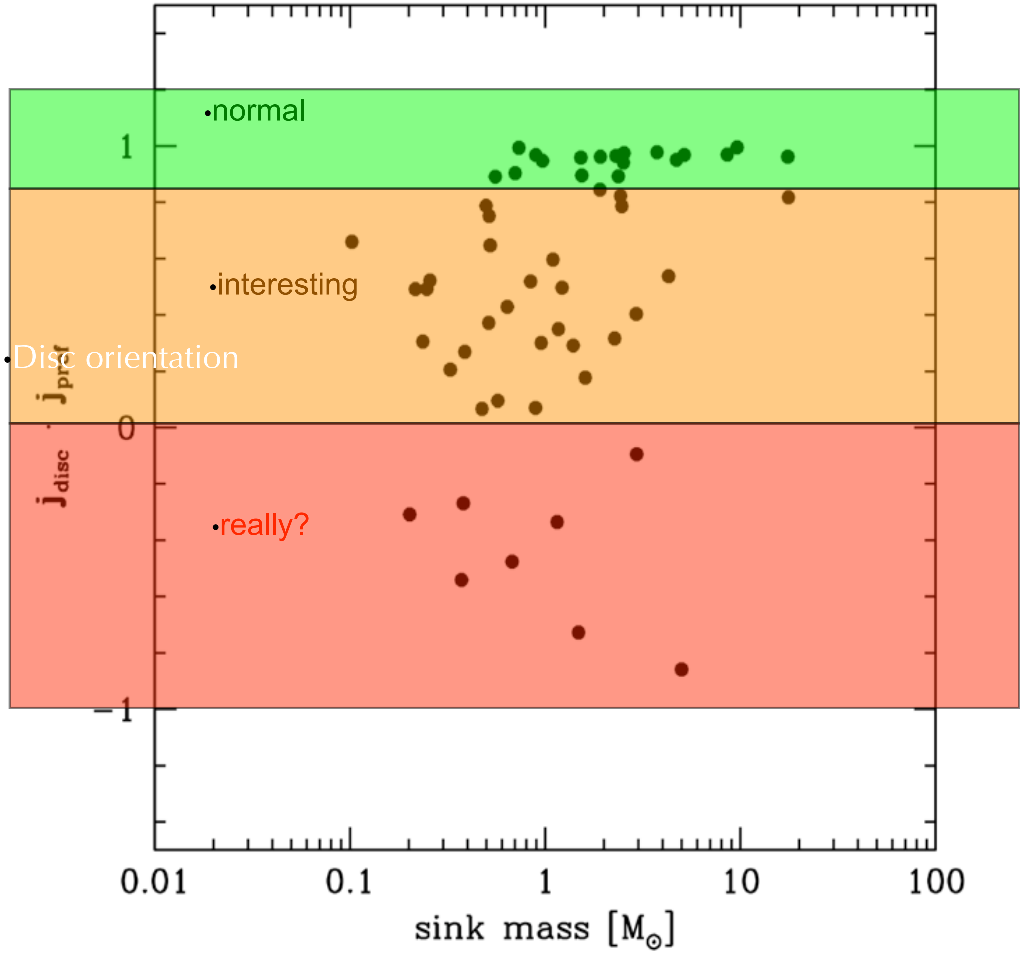


(from Clark et al. in preparation)

disk orientation

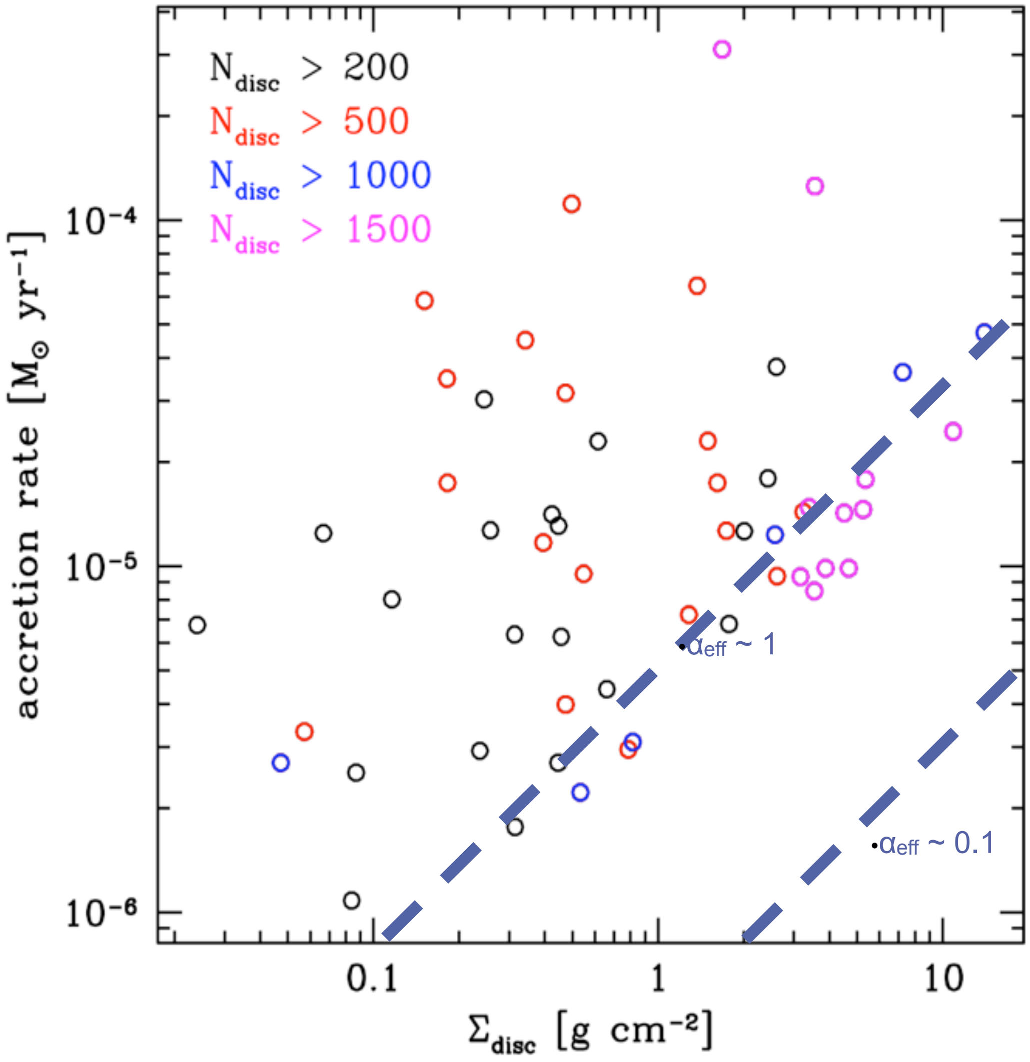
- How does the plane of the disc compare to the preferred plane in the incoming bound material?

•jdisc• jregion



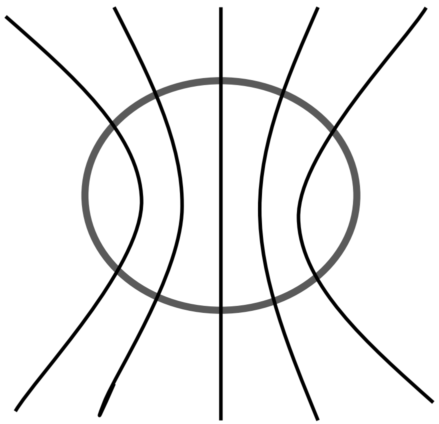
(from Clark et al. in preparation)

accretion through disk ...



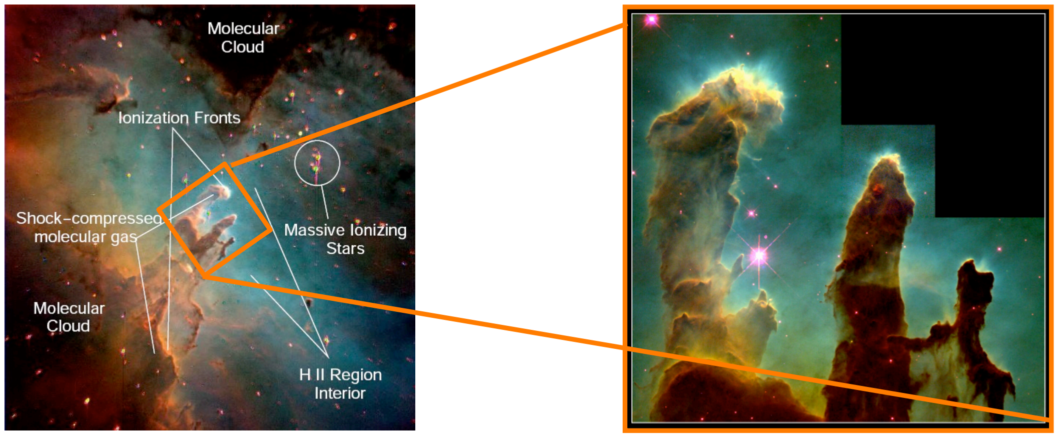
caveats

- magnetic fields
  - ideal MHD → effective angular mom. transport
    - → small disks, no binaries
    - → is there a fragmentation crisis?
  - need non-ideal MHD
    - → ambipol. diffusion to remove field?
    - → but on what scales?



caveats

- radiative feedback
  - rich clusters form O/B stars
    → ionizing radiation can quench subsent star formation
    → how does this influence disks (morphology, life times, stability)



summary

conclusions

- the whole problem of disks in clusters is currently not numerically tractable!
- can use a multi-scale approach to study initial stage of the disks (but still costly!).
- lower-res simulations of a full cluster can provide useful limits and trends.
- disks in the early stages of accretion are (probably) dominated by gravitational angular momentum transport.
- no obvious differences between discs in the competitive accretion picture and the isolated star formation model.
- even low levels of angular momentum can provoke fragmentation in the while the disc is accreting.

thanks