Sternentstehung - Star Formation

Winter term 2017/2018

Henrik Beuther & Thomas Henning

17.10.	Introduction & Overview	(H.B.)
24.10.	Physical processes I	(H.B.)
31.10.	no Lecture – Reformationstag	(M.L.)
07.11.	Physcial processes II	(H.B.)
14.11.	**Molecular clouds as birth places of stars**	**(H.L.)**
21.11.	Molecular clouds (cont.), Jeans Analysis	(H.B.)
28.11.	Collapse models I	(H.B.)
05.12.	Collapse models II	(T.H.)
12.12.	Protostellar evolution	(T.H.)
19.12.	Pre-main sequence evolution & outflows/jets	(T.H.)
09.01.	Accretion disks I	(T.H.)
16.01.	Accretion disks II	(T.H.)
23.01.	High-mass star formation, clusters and the IMF	(H.B.)
30.01.	Planet formation	(T.H.)
06.02.	Examination week, no star formation lecture	

Book: Palla & Stahler (2004) The Formation of Stars, Wileys

More Information and the current lecture files: http://www.mpia.de/homes/beuther/lecture_ws1718.html

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Last lecture

- Line profiles (thermal and kinematic broadening) and some applications

- Magnetic fields are very important but difficult to measure:
  - Zeeman effect traces **B** component along line of sight.
  - Dust polarication traces **B** in plane of the sky.

    (Other magnetic field measurements possible.)

- Masers are non-thermal processes. Good for high spatial accuracy and proper motion studies.

- Dust important from many points of view:
  - Traces warm and cold components of ISM.
  - Important coolant at high densities.
  - Traces magnetic field.
  - Chemical catalyst.

- Physical distributions and their applicability to the ISM.

  (Maxwell, Boltzmann, Planck, Saha)

Last lecture

- oadening) and some applications
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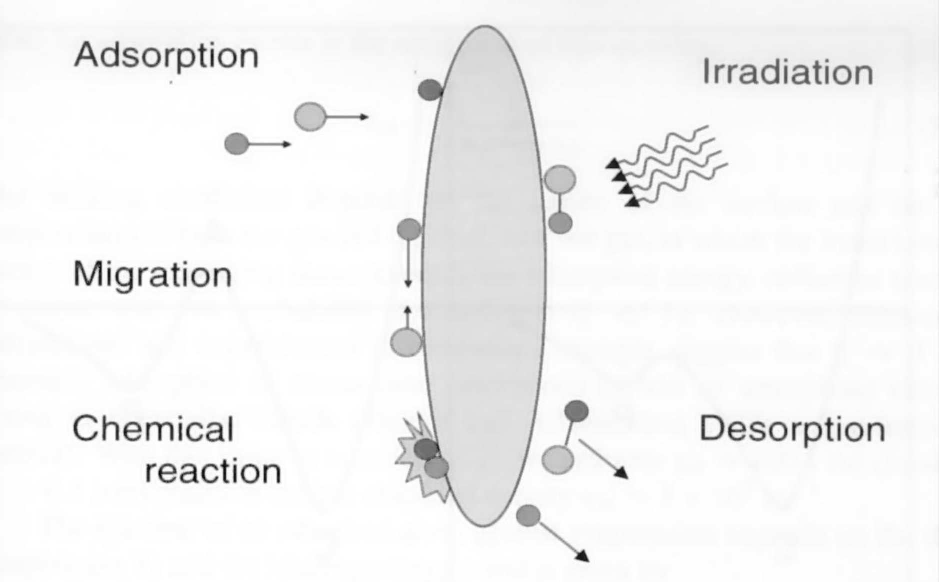

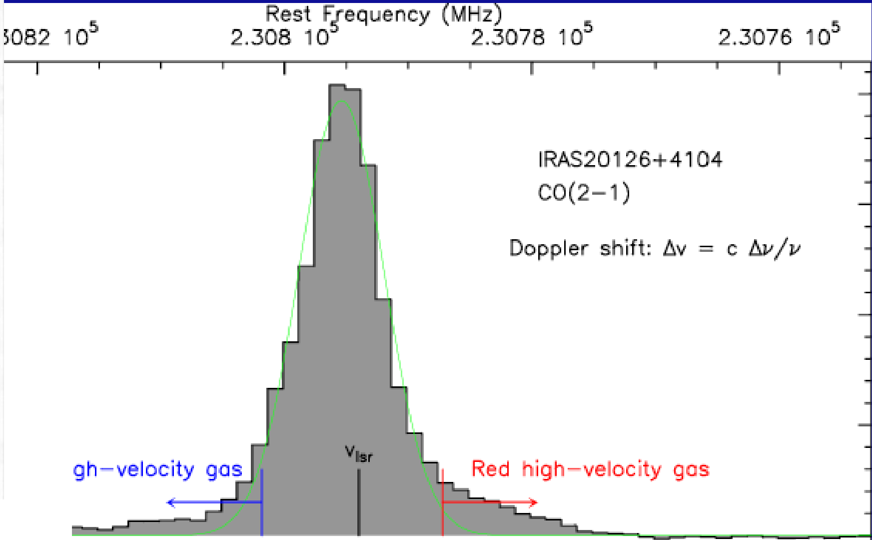

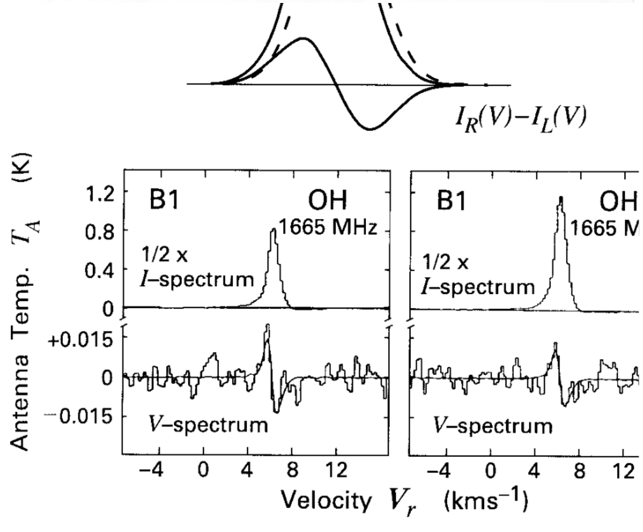

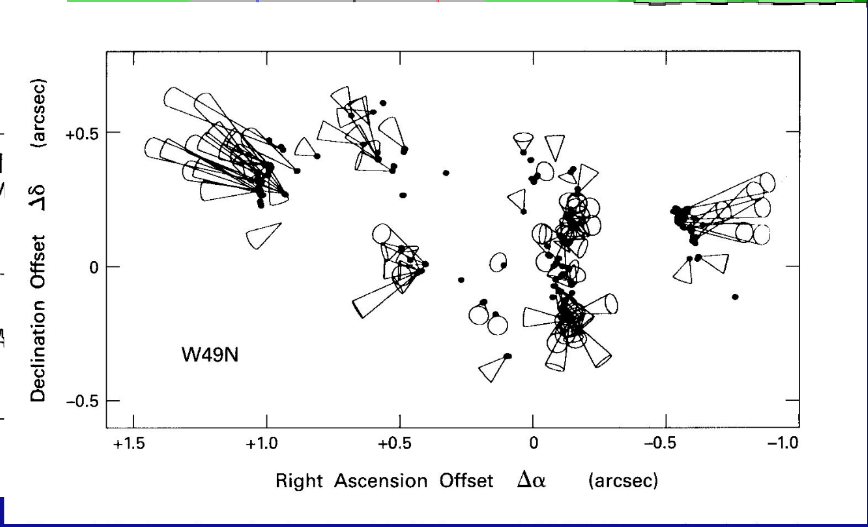

- Dust importa
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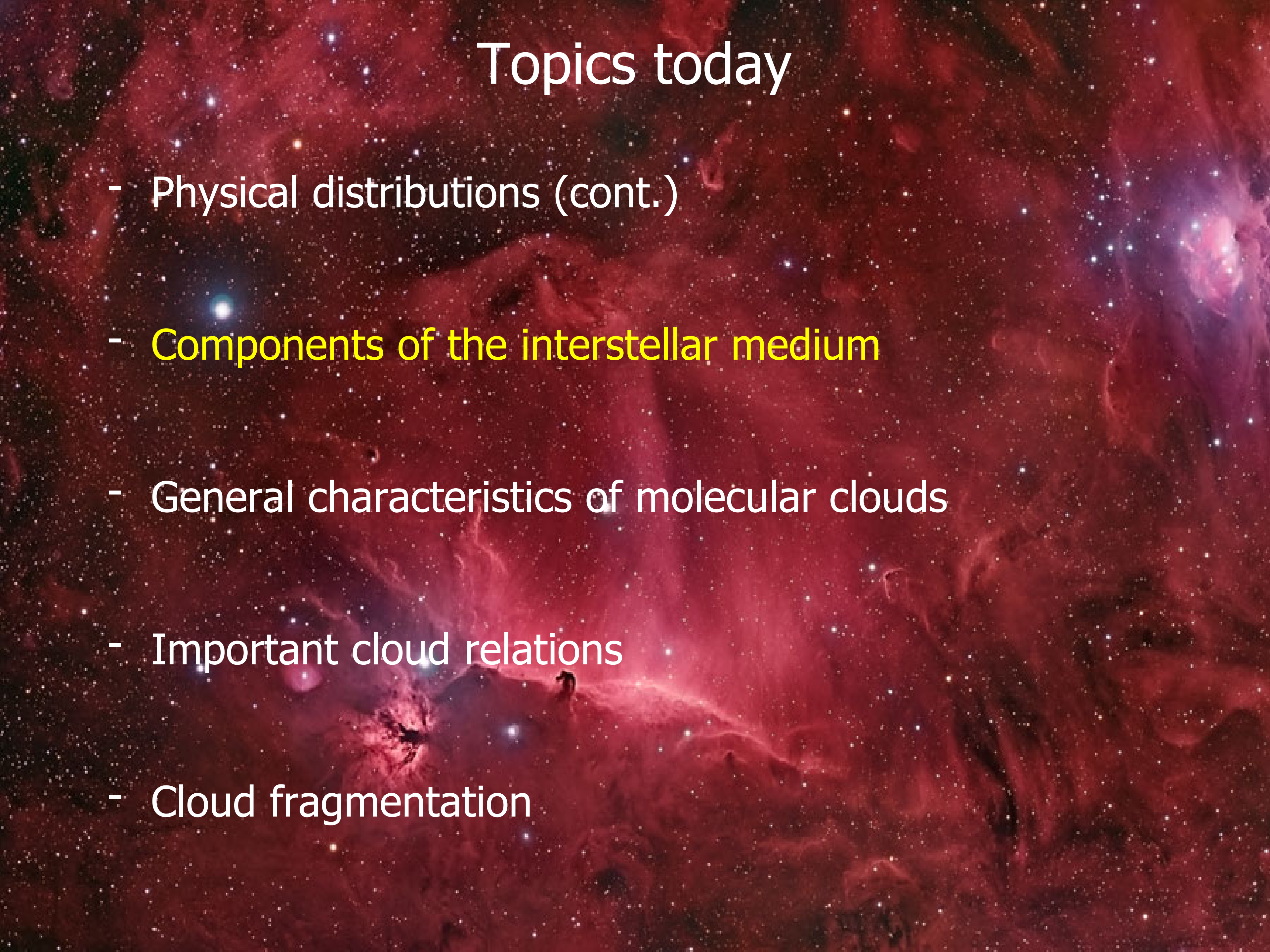
    - Chemi
- Physical dist

(Maxwell, Boltzm)



Topics today

- Physical distributions (cont.)
- Components of the interstellar medium
- General characteristics of molecular clouds
- Important cloud relations
- Cloud fragmentation

Historical Models of the ISM (I)

1.) Simple Two-Phase Model (Field et al. 1969)

- Underlying idea: equilibrium: heating rate $\Gamma(n,T)$ = cooling rate $\Lambda(n,T)$

- Stationary condition → equation of state between dens. *n* and temp. *T*

- Pressure equilibrium → several combinations of (n,T) are possible (remember ideal gas: $p = n\,k\,T$)

- Only certain combinations thermally stable (different dependence of $\Gamma(n,T)$ and $\Lambda(n,T)$ on the density) …

- Two phases: a.) $n < 0.3$ cm^{-3}, $T \approx 5000 - 10000$ K (thin, warm, ionised)
  b.) $n \approx 50$ cm^{-3}, $T \approx 80 - 100$ K (dense, cold, neutral)

BUT: maintaining 80 – 100 K in dense gas with cosmic-ray heating difficult
needed ionisation rate: 10^{-15} s^{-1},observed (Copernicus UV satellite):10^{-17} s^{-1}

warm (inter-cloud) gas not observed in this way …

Historical Models of the ISM (II)

2.) Three-Phase Model (McKee & Ostriker 1977)

Takes into account hot component of ISM and supernova blast waves. Model is more dynamical and coupled to the formation (and death) of massive stars

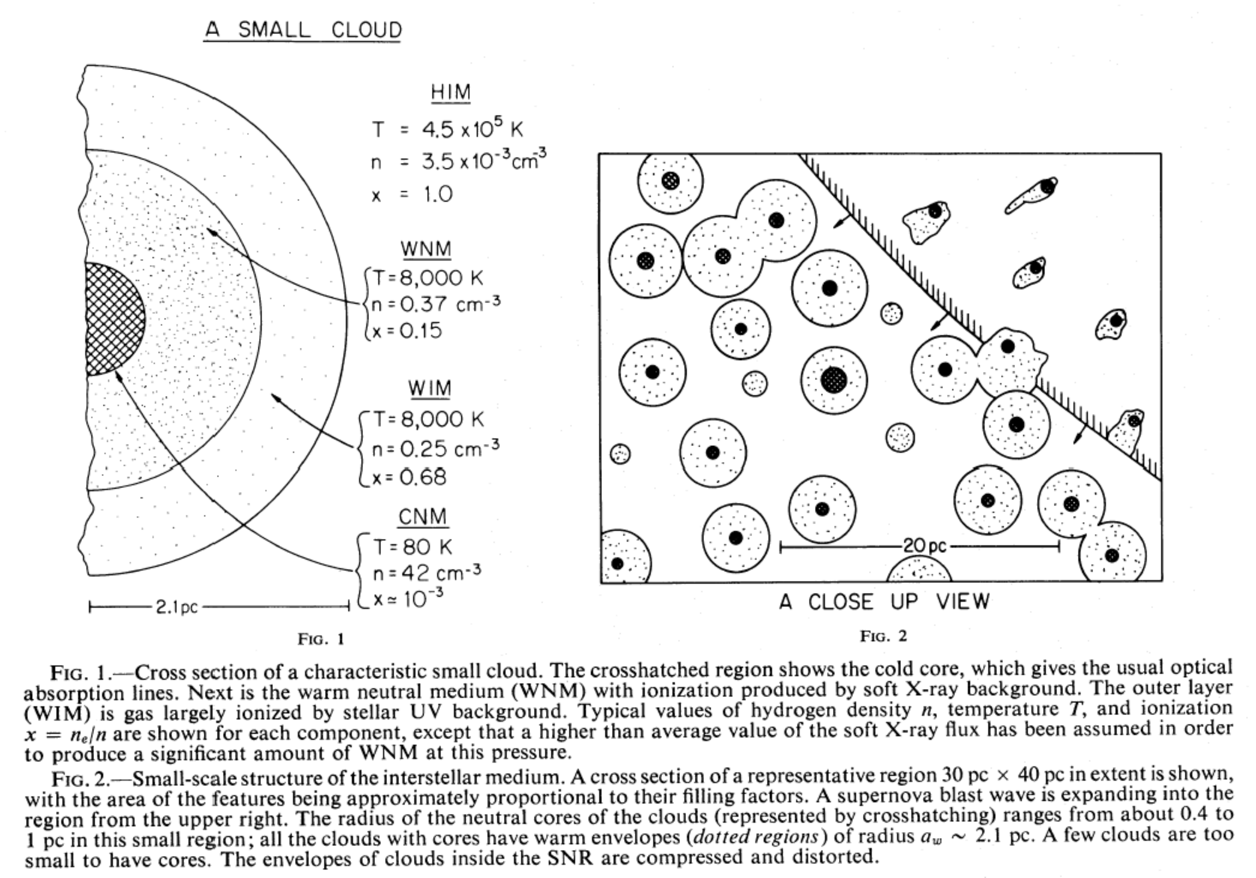


FIG. 1

FIG. 2

FIG. 1.—Cross section of a characteristic small cloud. The crosshatched region shows the cold core, which gives the usual optical absorption lines. Next is the warm neutral medium (WNM) with ionization produced by soft X-ray background. The outer layer (WIM) is gas largely ionized by stellar UV background. Typical values of hydrogen density n, temperature T, and ionization $x = n_e/n$ are shown for each component, except that a higher than average value of the soft X-ray flux has been assumed in order to produce a significant amount of WNM at this pressure.

FIG. 2.—Small-scale structure of the interstellar medium. A cross section of a representative region 30 pc × 40 pc in extent is shown, with the area of the features being approximately proportional to their filling factors. A supernova blast wave is expanding into the region from the upper right. The radius of the neutral cores of the clouds (represented by crosshatching) ranges from about 0.4 to 1 pc in this small region; all the clouds with cores have warm envelopes (*dotted regions*) of radius $a_w \sim 2.1$ pc. A few clouds are too small to have cores. The envelopes of clouds inside the SNR are compressed and distorted.

Historical Models of the ISM (III)

2.) Three-Phase Model (McKee & Ostriker 1977)

Shortcomings in the original model:

- SN rate and SN “luminosity” overestimated, SNe not arbitrarily distributed
- Clouds are not round, but mostly elongated, layered and filamentary
- Observations indicate considerable amount of evenly distributed (i.e., not bound to clouds) warm HI gas

General comments:

- Model still assumes global pressure equilibrium between the phases
- One very important component still missing: **molecular clouds !!**

($T \approx 10$ K, $n > 300$ cm^{-3})

Phase transitions are possible (e.g., by heating and cooling)

Diffuse clouds $\longrightarrow$ molecular clouds $\longrightarrow$ stars

Historical Models of the ISM (III)

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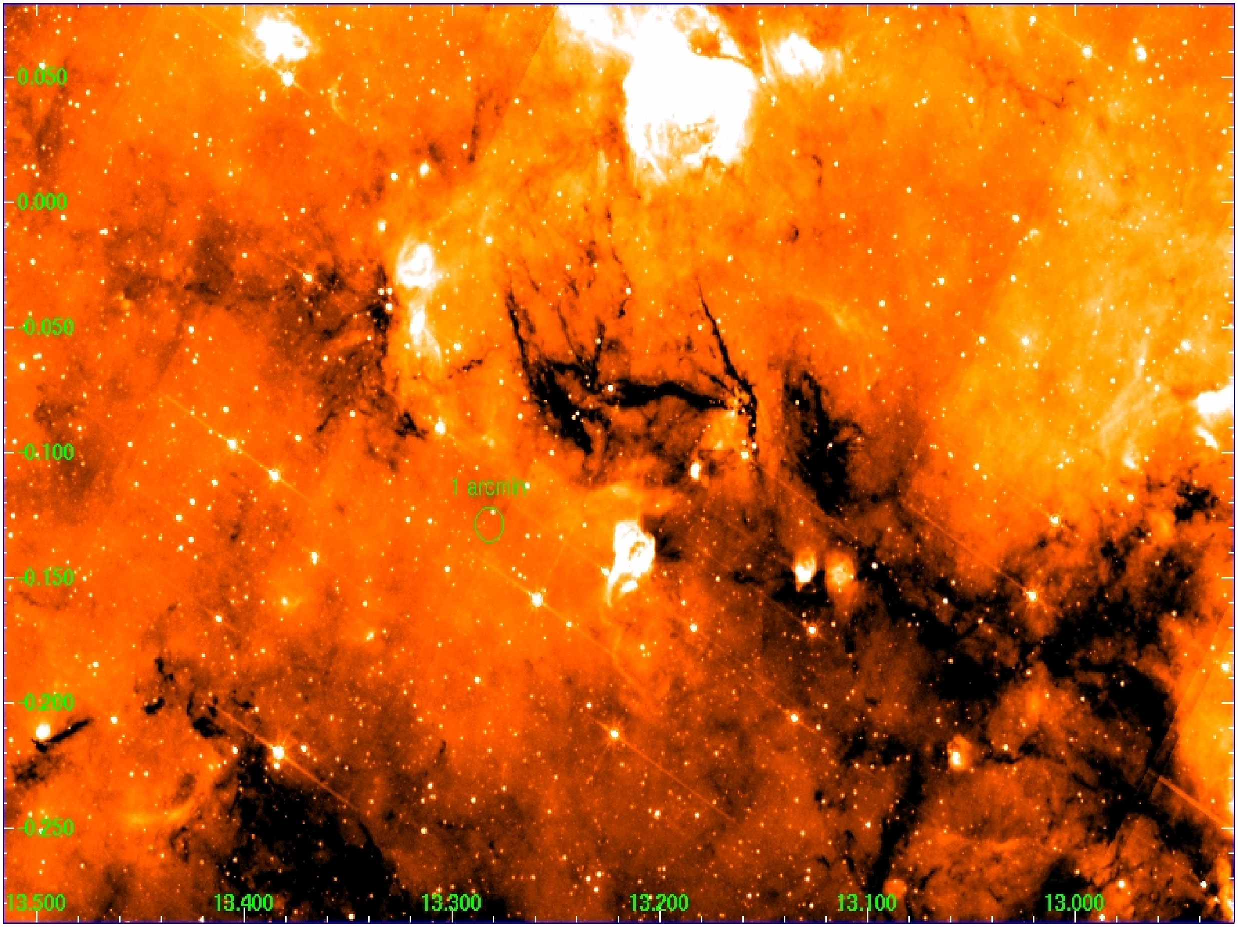


Phase transitions are possible (e.g., by heating and cooling)

Diffuse clouds ⟶ molecular clouds ⟶ stars

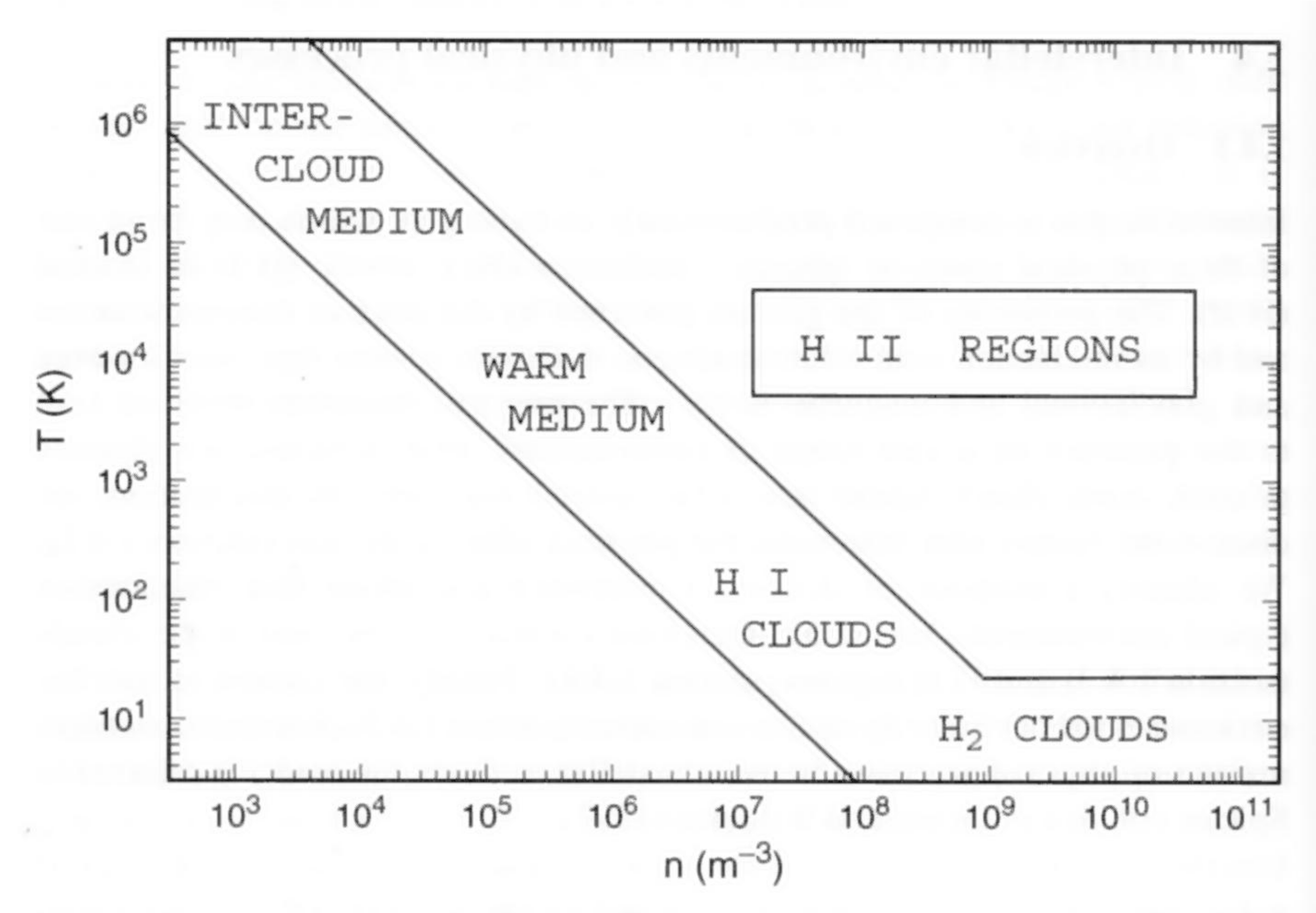
3.) Overview of the components

Phase	n [cm^{-3}]	T [K]	f	M [$10^9\ M_\odot$]
Hot ionised medium	0.003	10^6	0.5	0.1
Warm neutral medium	0.5	8000	0.4	1.4
Warm ionised medium	0.3	8000	0.1	1.0
Diffuse HI clouds	**50**	**80**	**-**	**2.5**
Molecular clouds	**>300**	**10**	**-**	**2.5**
HII regions	**$1 - 10^5$**	**10^4**	**-**	**0.05**

f as volume filling factor regarding the Galactic disk

3.) Overview of the components

Phase	n [cm^{-3}]	T [K]	f	M [10^9 $M_\odot$]
Hot ion				
Warm				
Warm i				
Diffuse				
Molecu				
HII reg				



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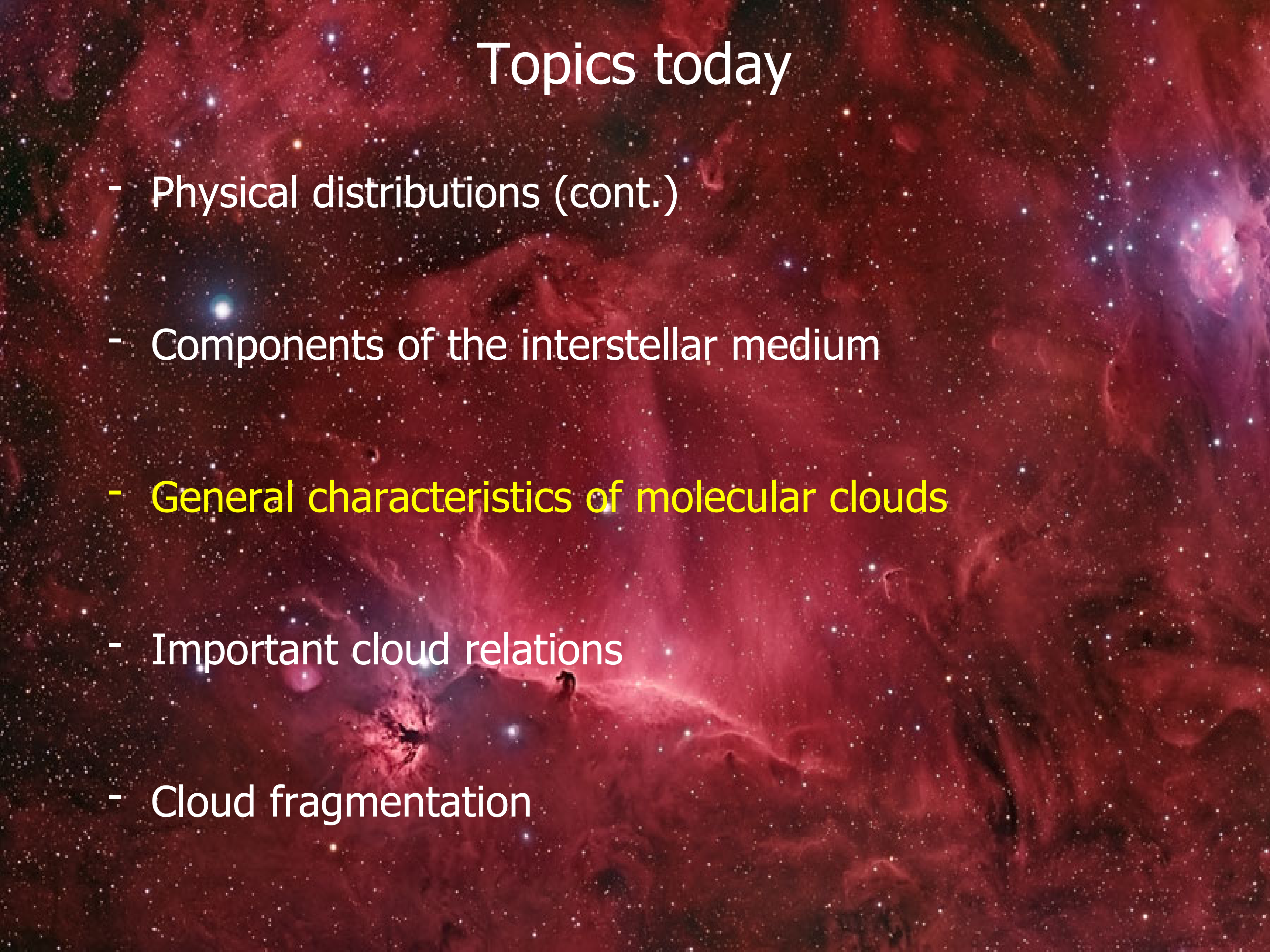
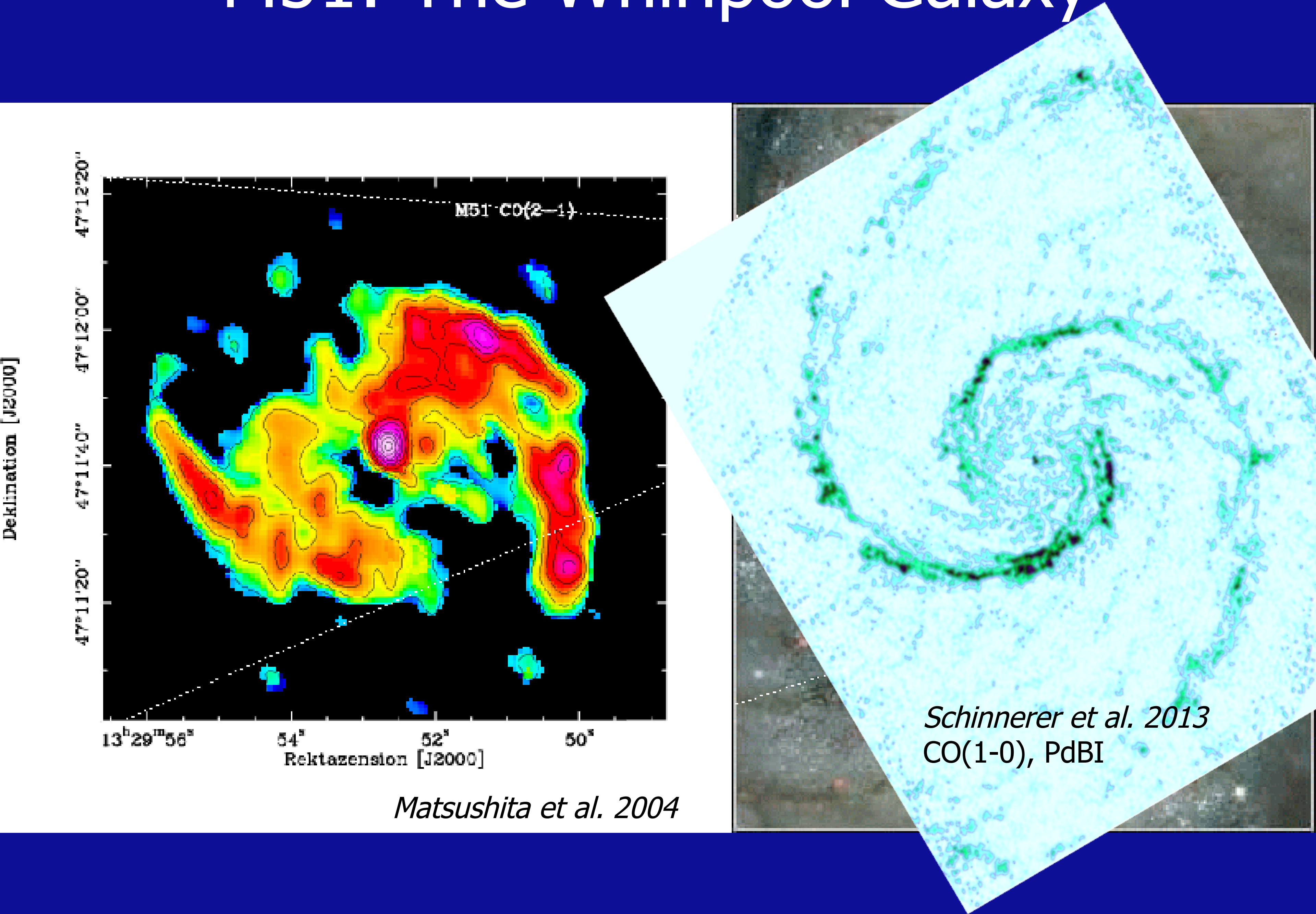


Topics today

- Physical distributions (cont.)
- Components of the interstellar medium
- General characteristics of molecular clouds
- Important cloud relations
- Cloud fragmentation

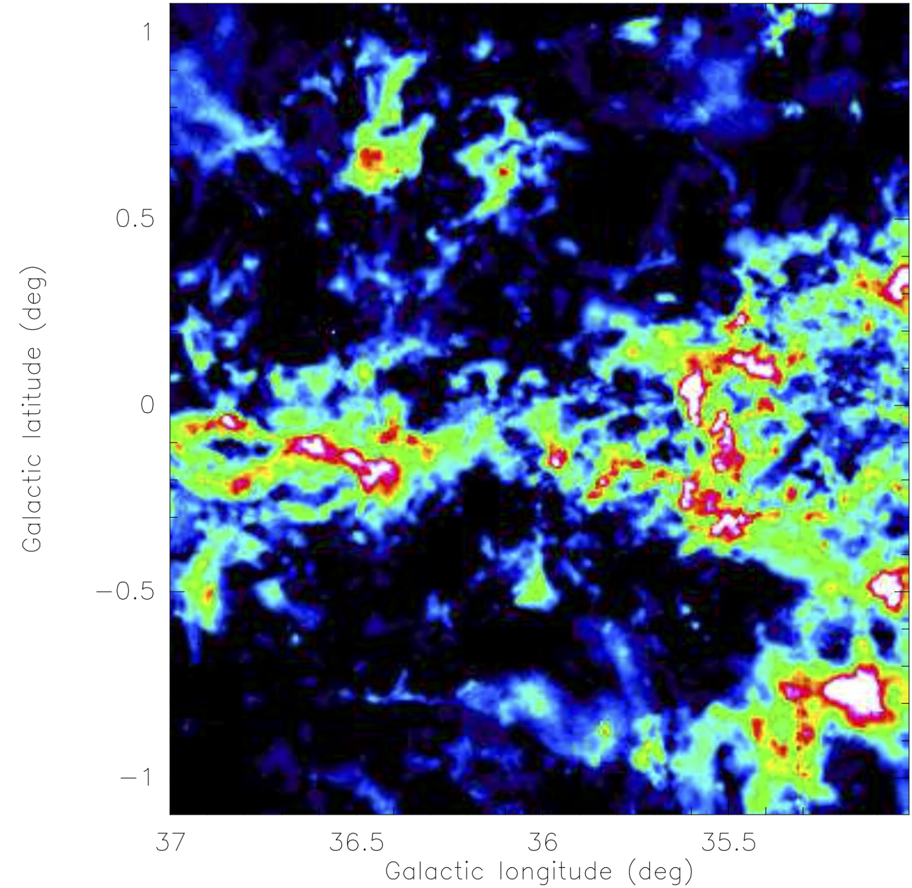
M51: The Whirlpool Galaxy



Matsushita et al. 2004

Schinnerer et al. 2013
CO(1-0), PdBI

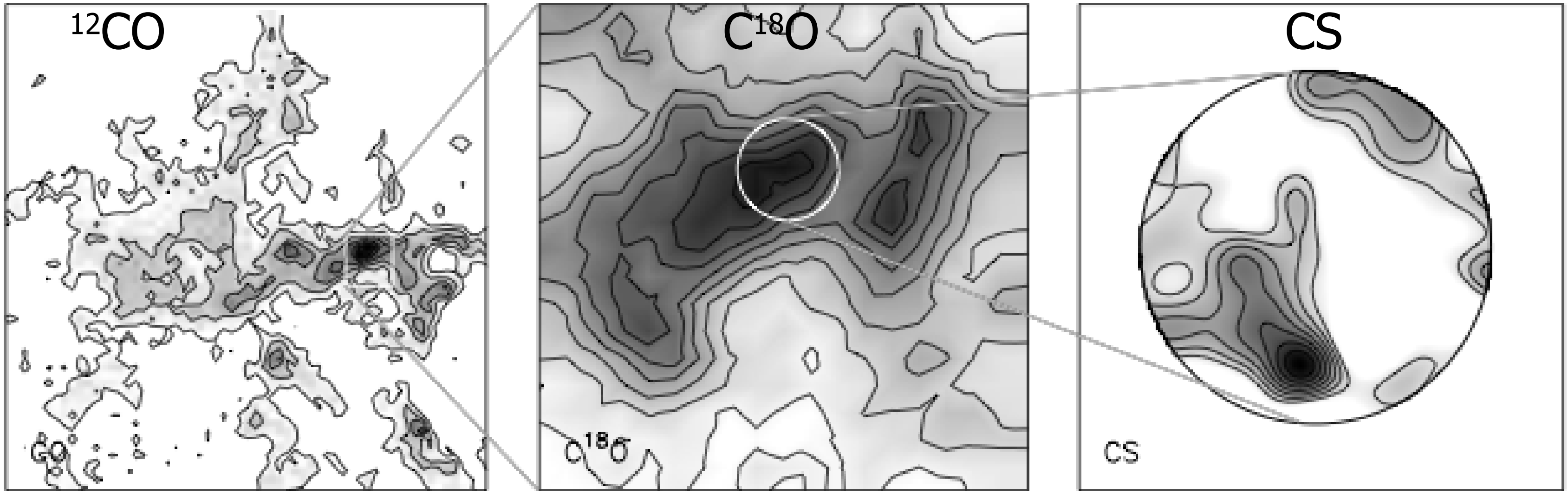
Giant Molecular Clouds



Galactic Ring survey
$^{13}CO(2\text{-}1)$
Jackson et al. 2006

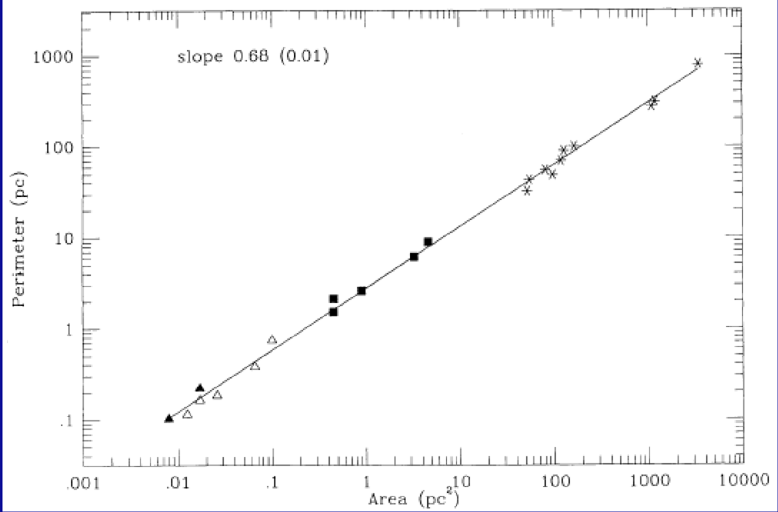
Sizes: 20 to 100pc; Masses: 10^4 to 10^6 M_{sun}; Temperatures: 10 to 20K
Supersonic velocity dispersion ~2-3 km/s mainly due to turbulence
Magnetic field strengths on the order of 10μG
Average local densities $\sim 10^4 cm^{-3}$; Volume-averaged densities $\sim 10^2 cm^{-3}$
--> highly clumped material

Hierarchical cloud structure



Rosette Molecular Cloud (Blitz & Williams 1999)

- Clouds are fractal and self-similar over many orders of magnitude in spatial scale (from 100pc to 0.1pc, Falagarone et al. 1991)
- Also independent of star-forming or non-star-forming clouds
- Remember predominantly used nomenclature: Clouds → Clumps → Cores (e.g., Williams, Blitz & McKee 2000, PPIV)
- Fractal dimension of perimeter P and area A: $P \sim A^{D/2}$ → D~1.4



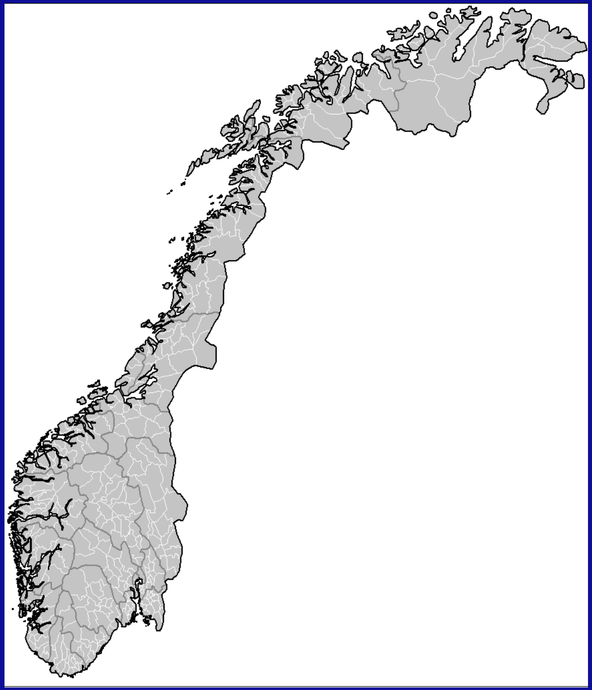
Fine-structure of Molecular clouds

- Fractal dimension $P \sim A^{D/2}$ → $D \sim 1.4$ for some molecular clouds

Ireland

East coast: $D = 1.10$
West coast: $D = 1.26$
Average: $D = 1.22$

Norway

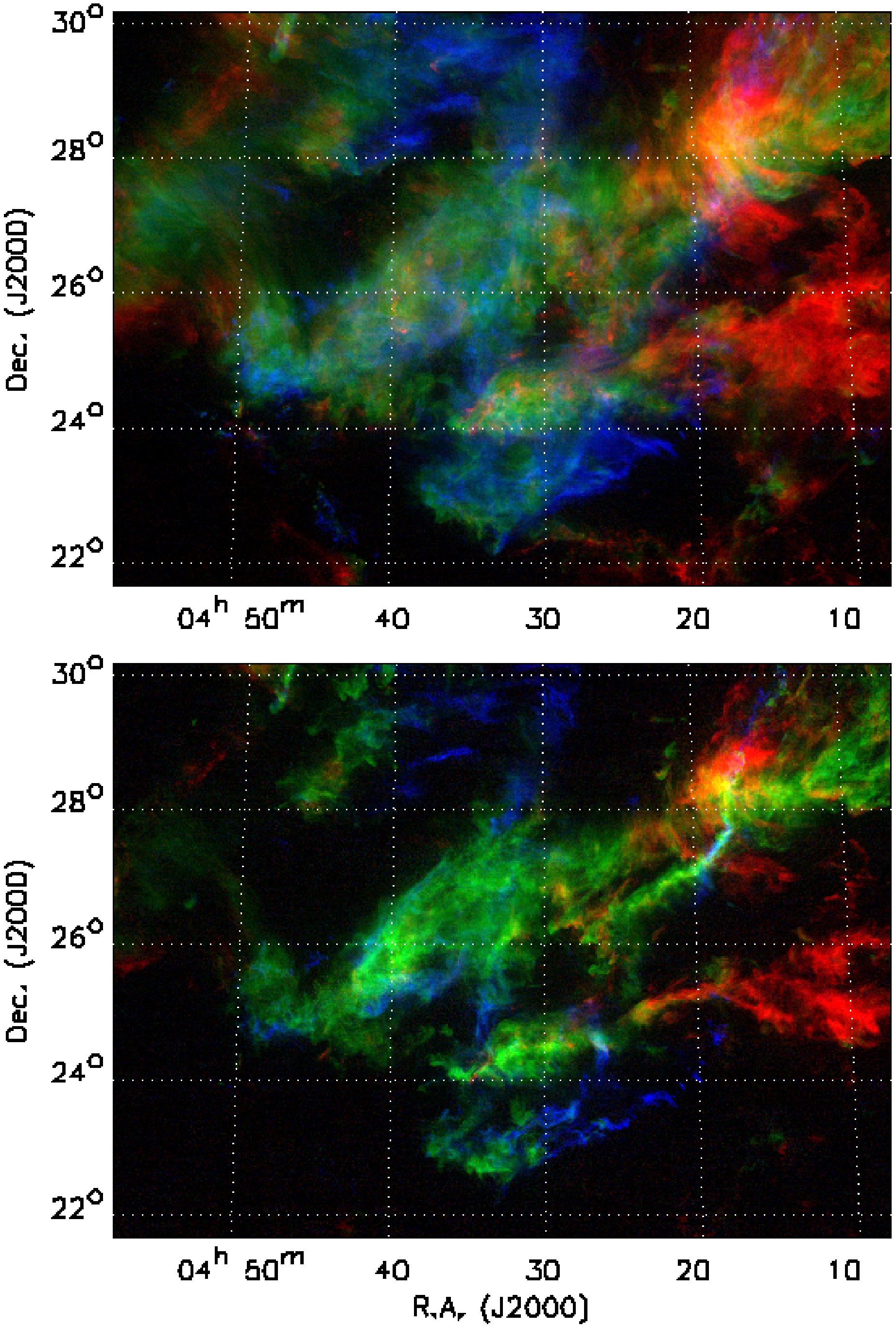


Average: $D = 1.52$

Source: Wikipedia – Fractals – Hausdorff dimension

Fine-structure

- Fractal dimension P ~ $A^{D/2}$
→ D~1.4 for some molecular clouds … probably quite dependent on observational capabilities



Shown is the Taurus molecular Cloud. M ~ 2.4 x 10^4 M_{sun}

Top: ^{12}CO (1-0) with three distinct velocity components (in blue, green, red)

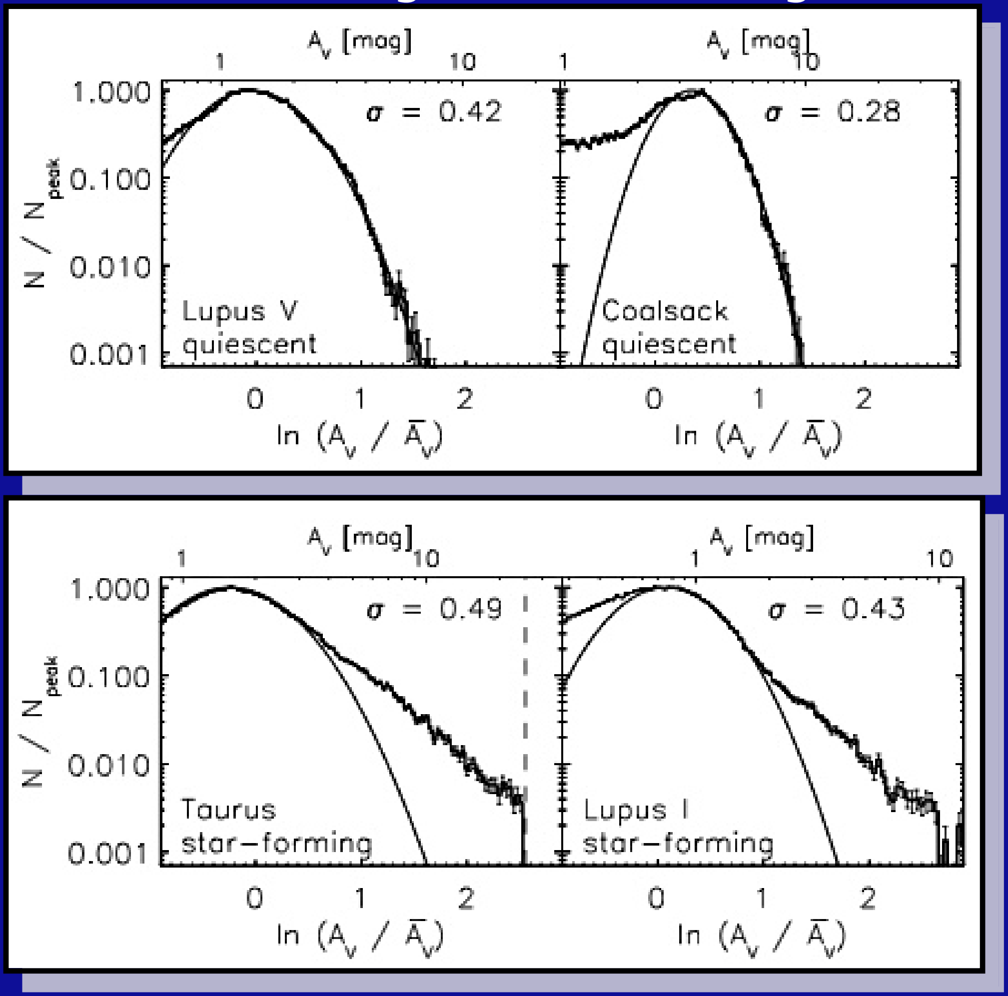
Down: The same in ^{13}CO(1-0)

Source: Goldsmith et al. 2008,
ApJ 680, 428

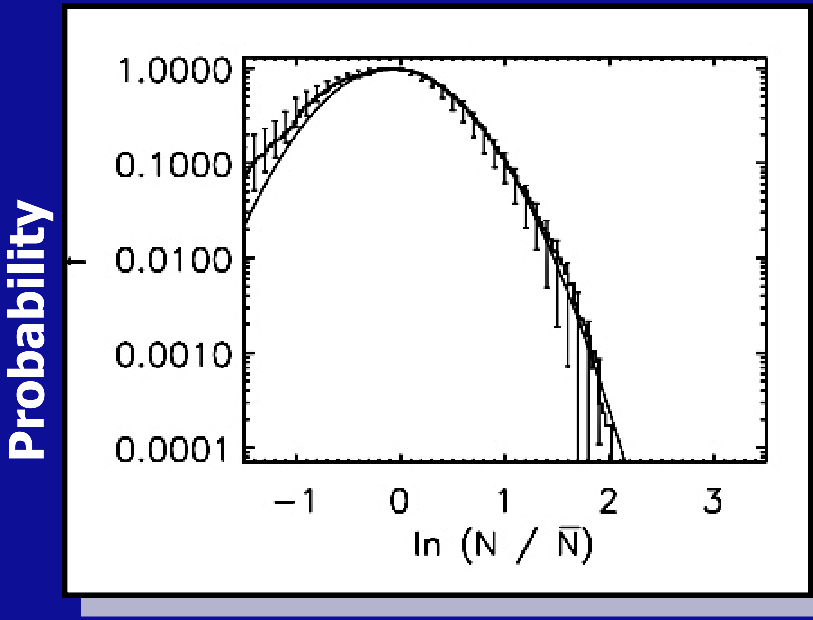
Probability density distributions (PDFs)

Observed distributions

Non-star-forming vs. star-forming clouds



Typical prediction for turbulent media



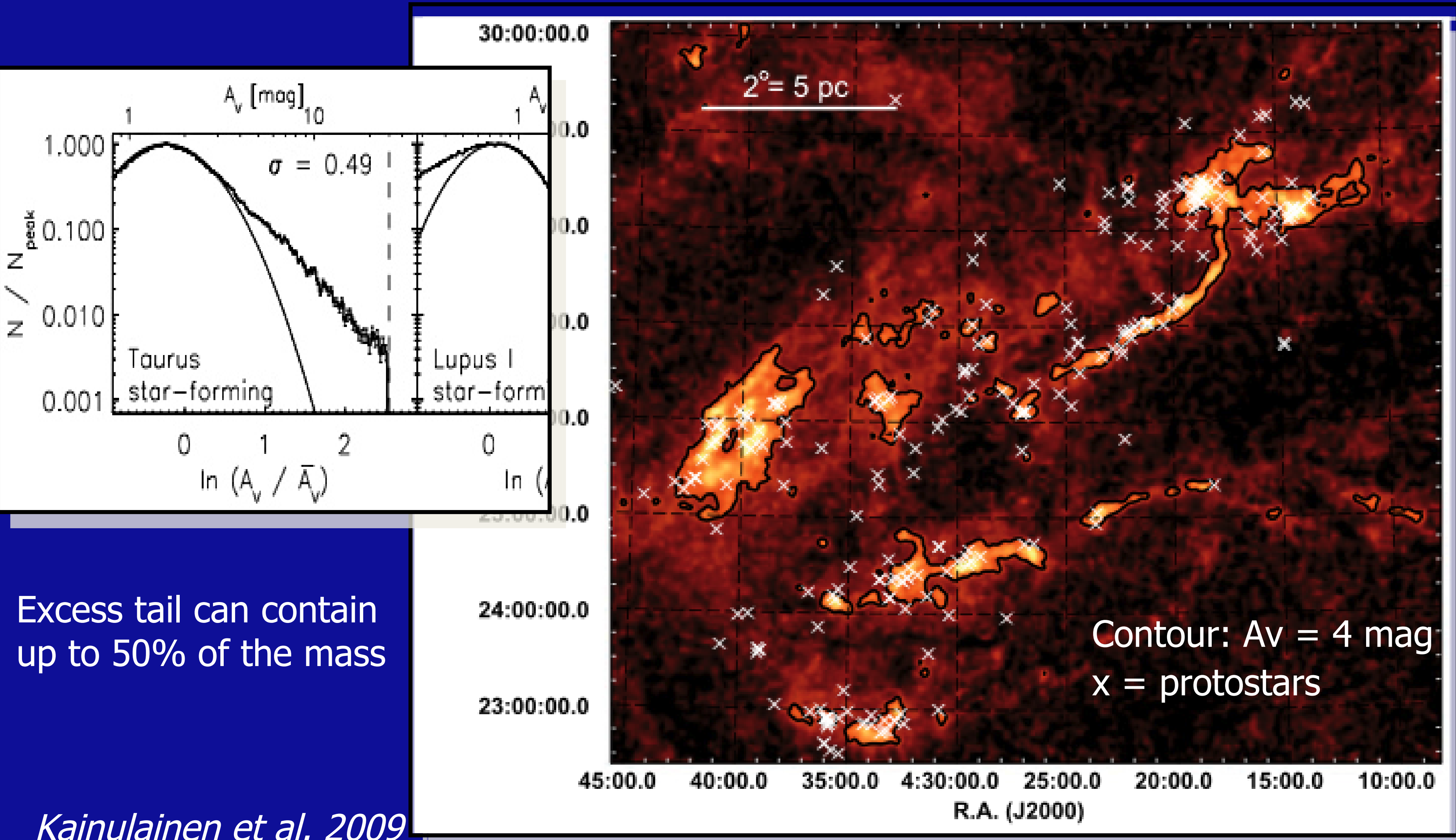
- non-star-forming: log-normal

- star-forming: high column density excess

Kainulainen et al. 2009

Correlation of “tail” with star formation

Dust column density in Taurus, logarithmic color scale



Contour: Av = 4 mag

x = protostars

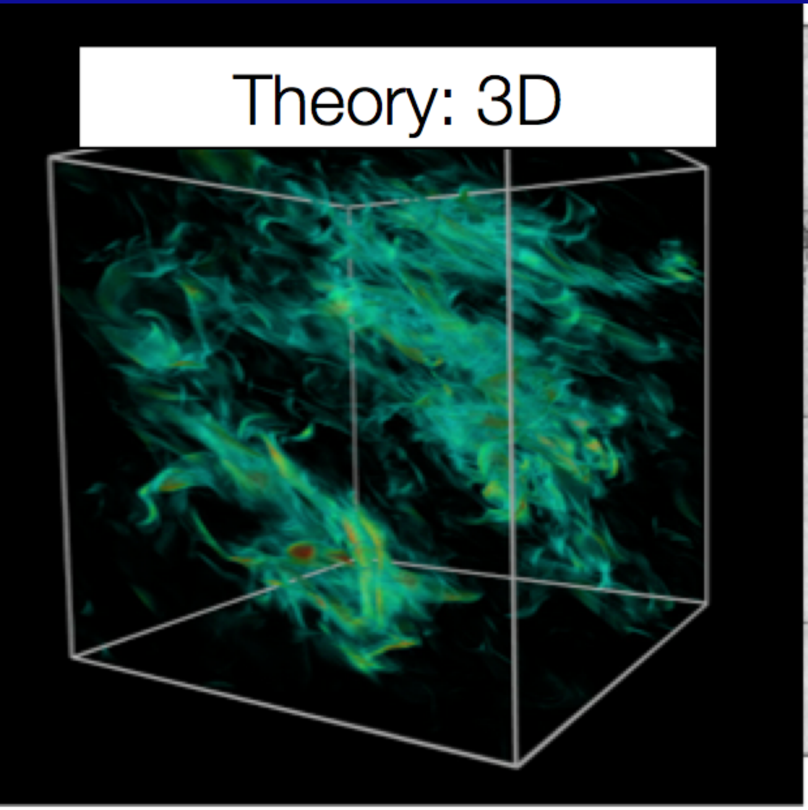
Excess tail can contain up to 50% of the mass

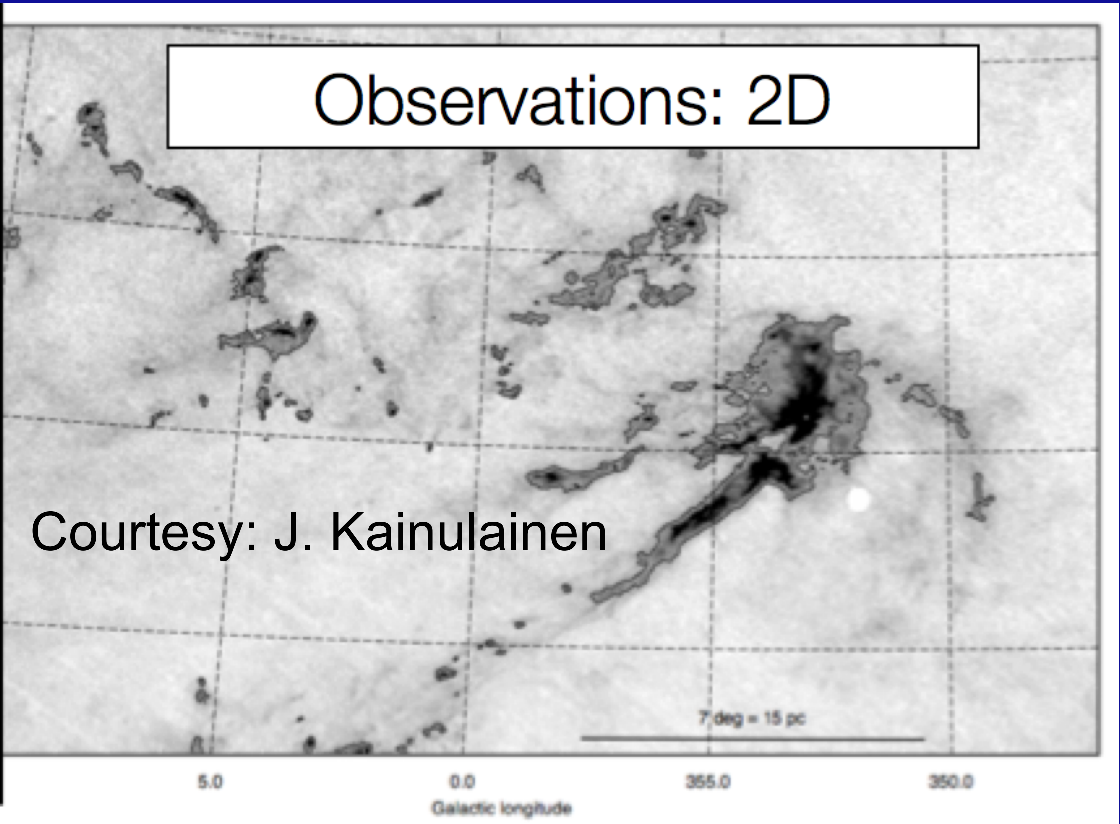
Kainulainen et al. 2009

The 3D structure of molecular clouds?

- Observations only probe *column* densities,
  but theories deal with *volume* densities.

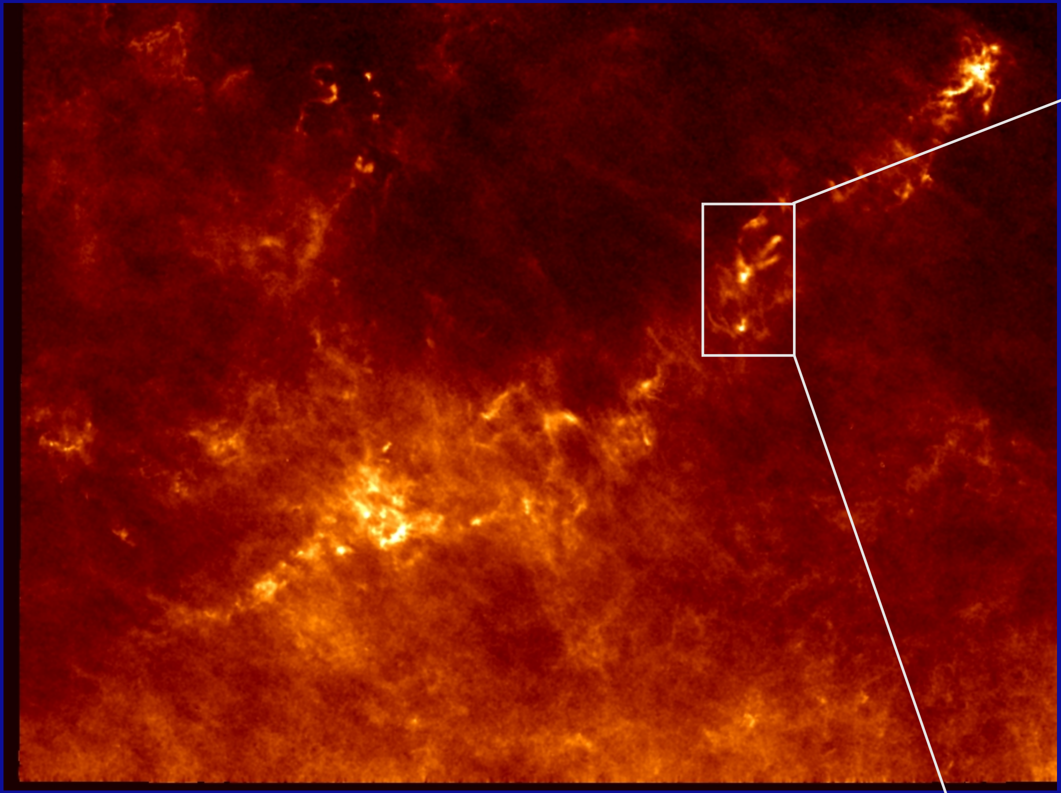
- How to estimate the 3-dimensional structure?



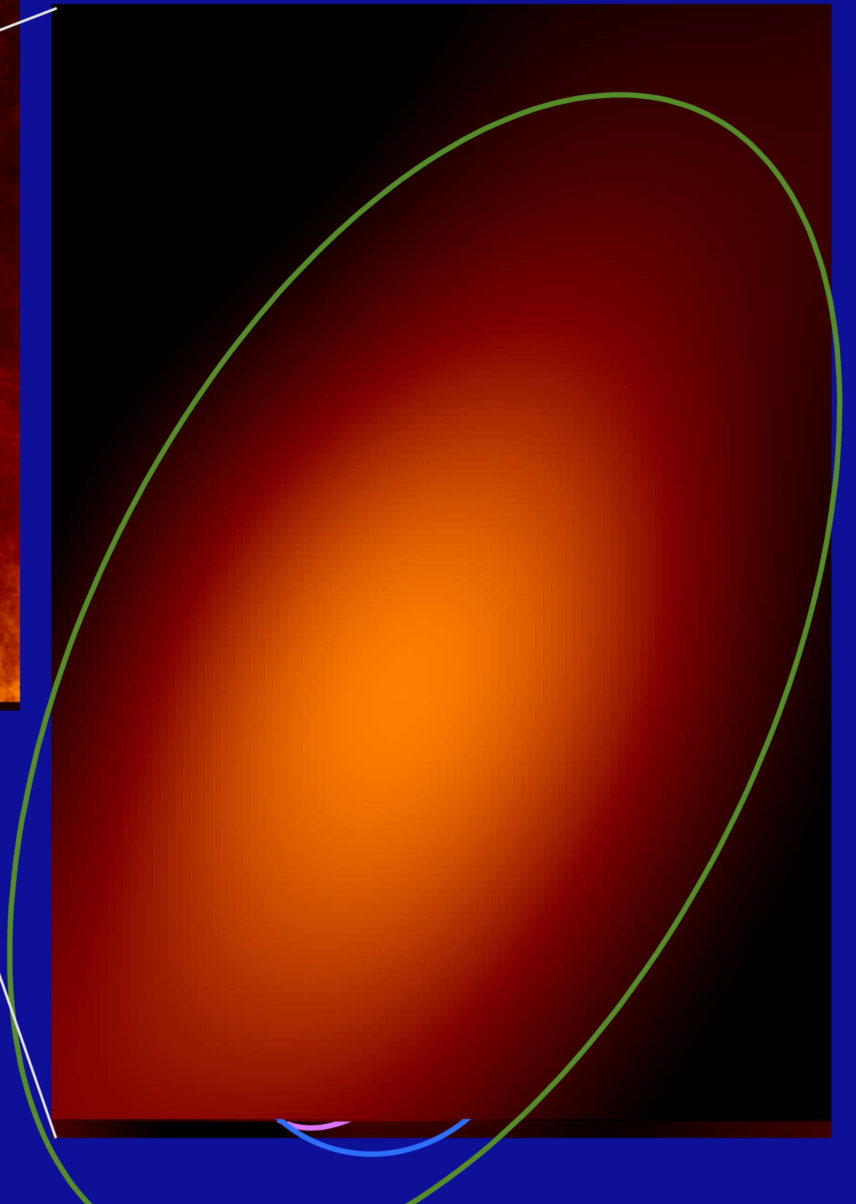


Courtesy: J. Kainulainen

The 3D structure of molecular clouds?



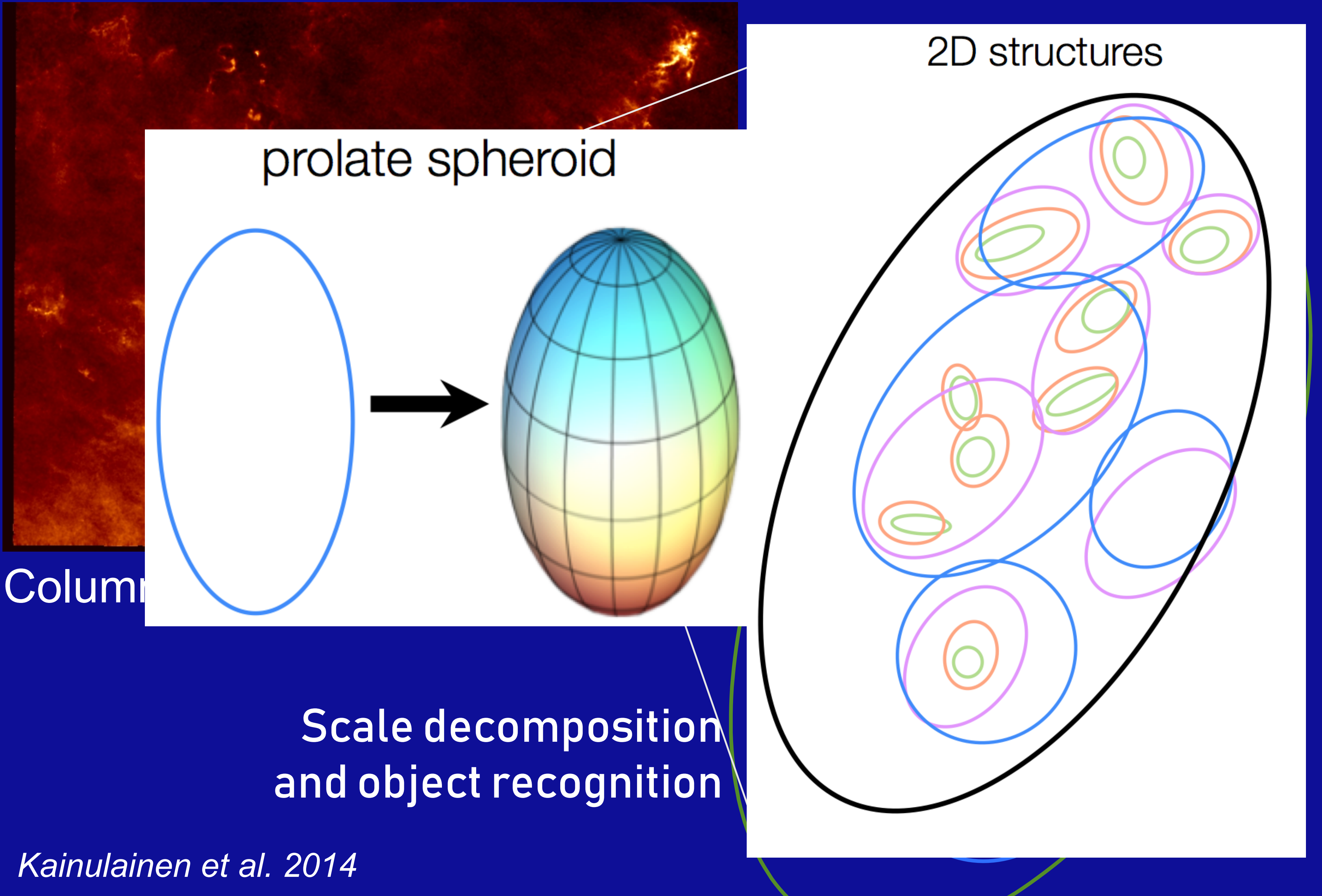
Column density map



Scale decomposition
and object recognition

Kainulainen et al. 2014

The 3D structure of molecular clouds?



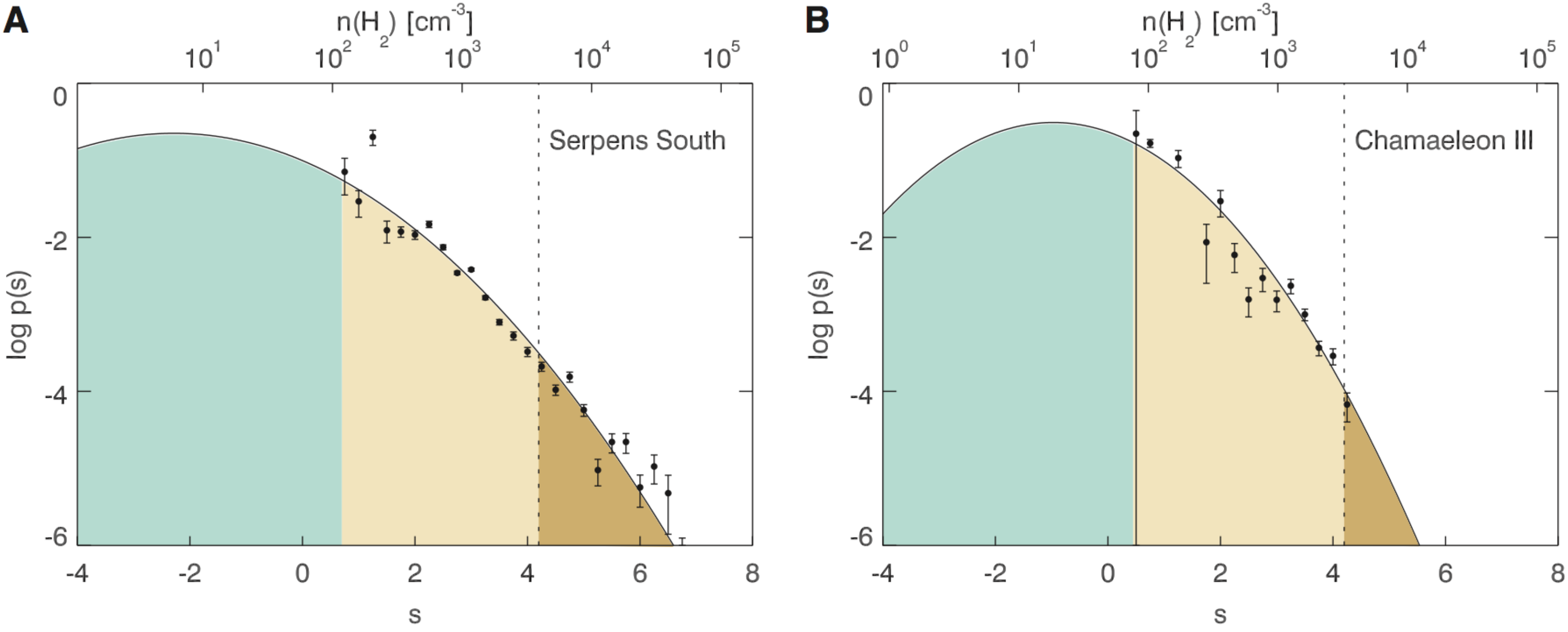
Colum

Scale decomposition
and object recognition

Kainulainen et al. 2014

→ Density PDFs

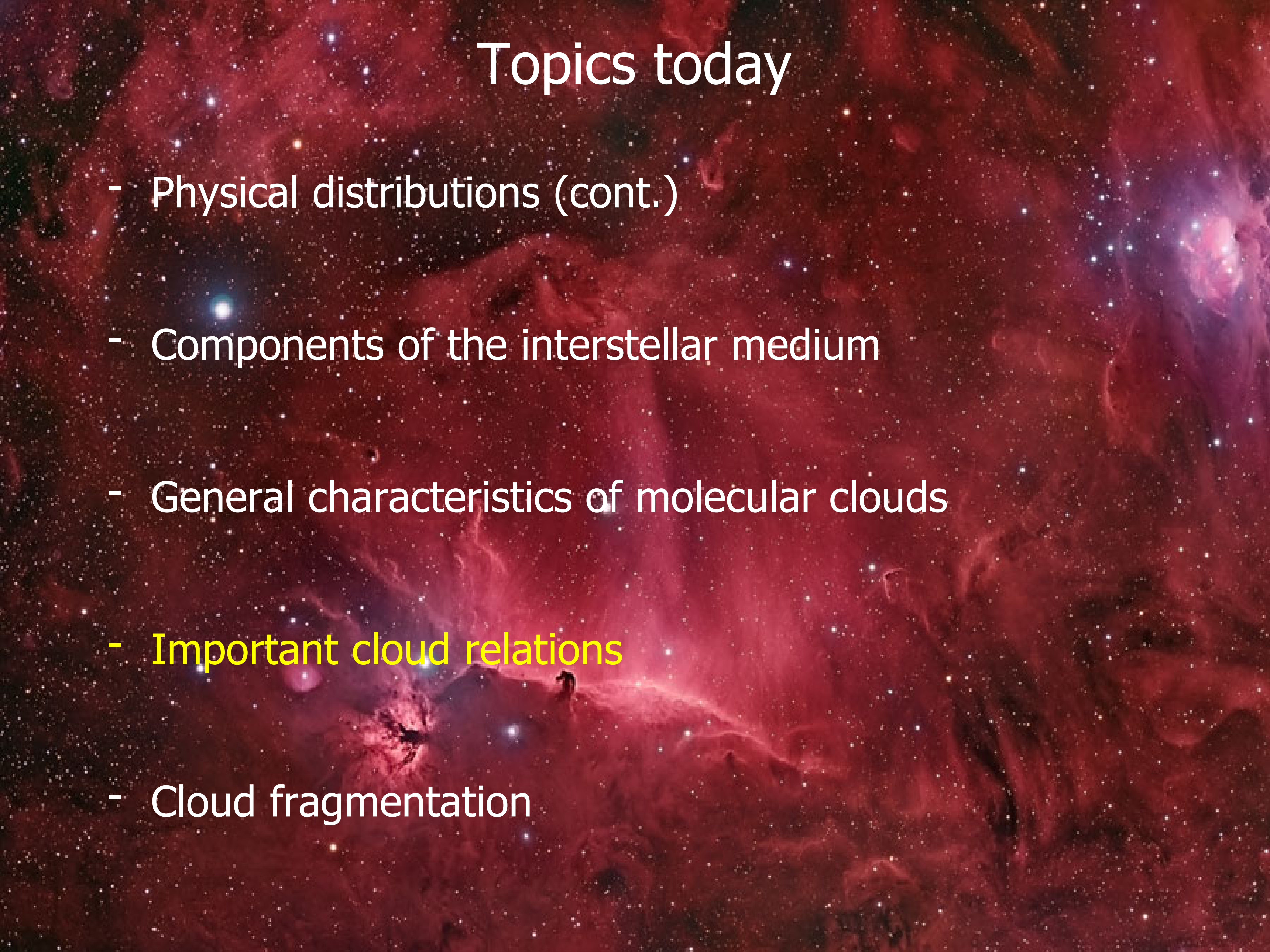
Based on sample of Gould-Belt clouds
Dark brown: star-forming gas
light brown: structures enveloping star-forming gas
Green: non-structured gas



- Direct comparison with theory

- Star formation density threshold → 5×10^3cm^{-3}

Kainulainen et al. 2014



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- Components of the interstellar medium
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A GMC in virial equilibrium

Shortest version of virial theorem (next week): $2T = -W$

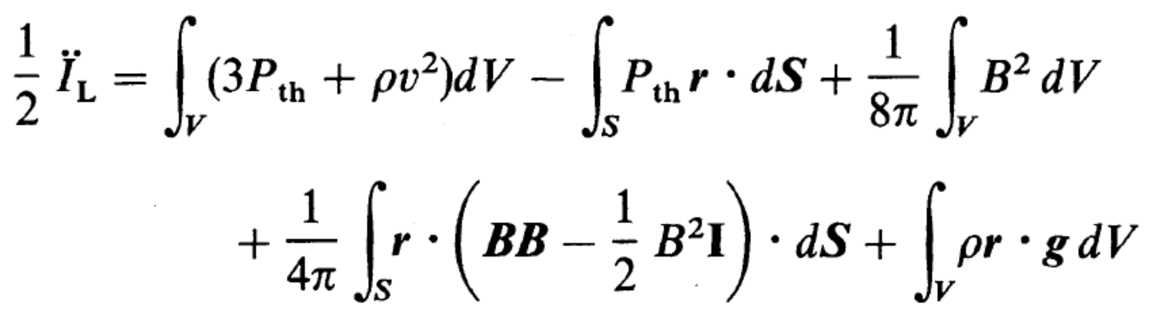
(T kinetic energy, W gravitational energy)

$$2T = 2*(1/2 m \Delta v^2) = -W = Gm^2/r$$

→ virial velocity: $v_{vir} = (Gm/r)^{1/2}$

→ or virial mass: $m_{vir} = v^2 r/G$

Keep in mind that this version of the virial theorem is a strong simplification and only valid if no magnetic energy is important, and if the cloud is in isolation (without important surface terms). In its full(er) glory, the virial theorem would be like:



$$\frac{1}{2}\ddot{I}_{\mathrm{L}} = \int_V (3P_{\mathrm{th}} + \rho v^2)\,dV - \int_S P_{\mathrm{th}}\,\boldsymbol{r}\cdot d\boldsymbol{S} + \frac{1}{8\pi}\int_V B^2\,dV + \frac{1}{4\pi}\int_S \boldsymbol{r}\cdot\left(\boldsymbol{BB} - \frac{1}{2}B^2\mathbf{I}\right)\cdot d\boldsymbol{S} + \int_V \rho\boldsymbol{r}\cdot\boldsymbol{g}\,dV$$

From: McKee
& Zweibel 1992,
ApJ 399, 551

Luminosity-mass relation

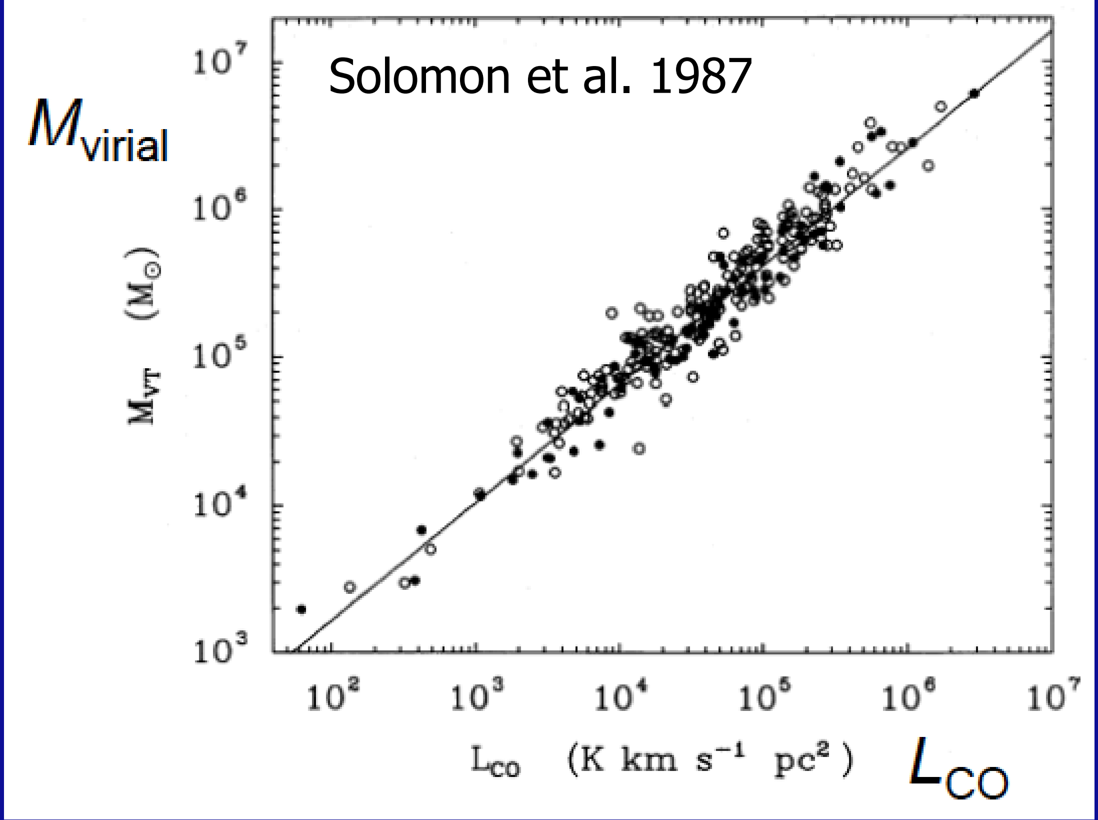
Integrated CO intensity: $I_{CO} = \int T(v)dv$

CO luminosity $L_{CO} = T\Delta v \, \pi r^2$

(T brightness temperature, Δv linewidth, r cloud radius)

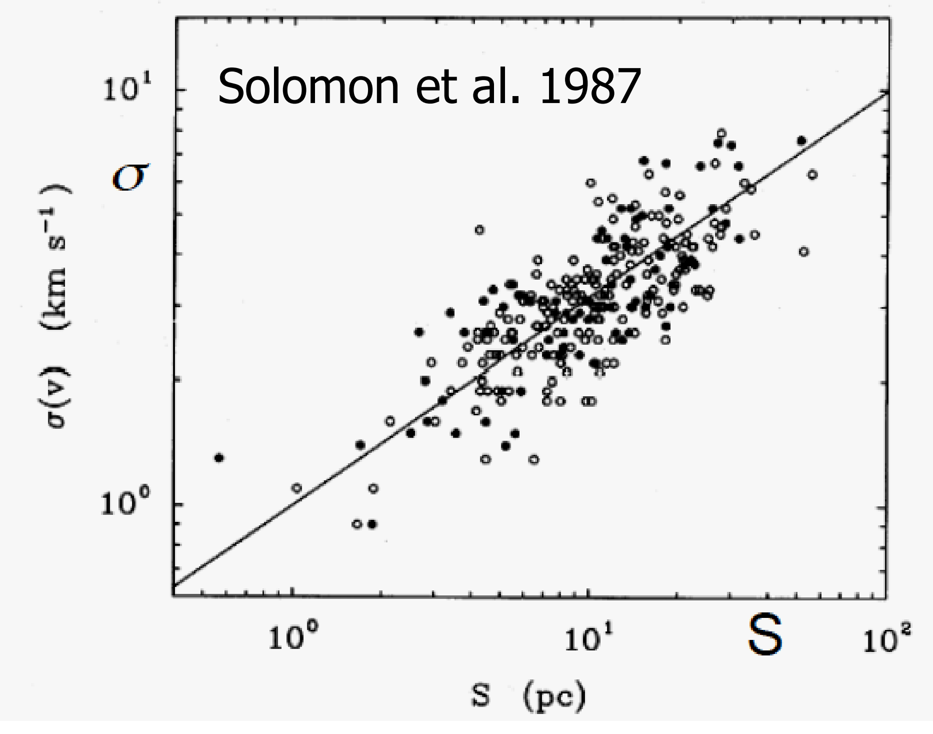
Substituting $v = (Gm/r)^{1/2}$ and mass $m = 4/3\pi r^3 \rho$

→ $L_{CO} = (3\pi G/(4\rho))^{1/2}\, T\, m$



Supports assessment that GMCs are in virial equilibrium.

The linewidth-size relation



- Linewidth-size relation first found by Larson 1981 (Thermal CO linewidth at 20K only ≈0.1km/s)

- Approximate relation: linewidth ≈ √size

- Extends over many orders of magnitude in size but not down to cores

- Implies strong turbulent contribution to the ISM

Additional relations

- Linewidth-size relation: $\Delta v \approx r^{1/2}$
- Virial equilibrium: $\Delta v \approx (Gm/r)^{1/2} \rightarrow m = (\Delta v)^2 r/G$

This leads to other relations:

$\rightarrow m = r^2/G \rightarrow m/r^2 = \text{constant} \rightarrow$ approximate constant column density N in GMCs

$\rightarrow \rho \approx m/r^3 \approx (\Delta v)^2/G * 1/r^2$

Some average empirical values for GMCs:

$N \approx 1.5 \times 10^{22}\ \text{cm}^{-2}$

$A_V \approx 10\text{mag}$

$\Sigma \approx 150\ M_{sun}\text{pc}^{-2}$

Topics today

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- Components of the interstellar medium
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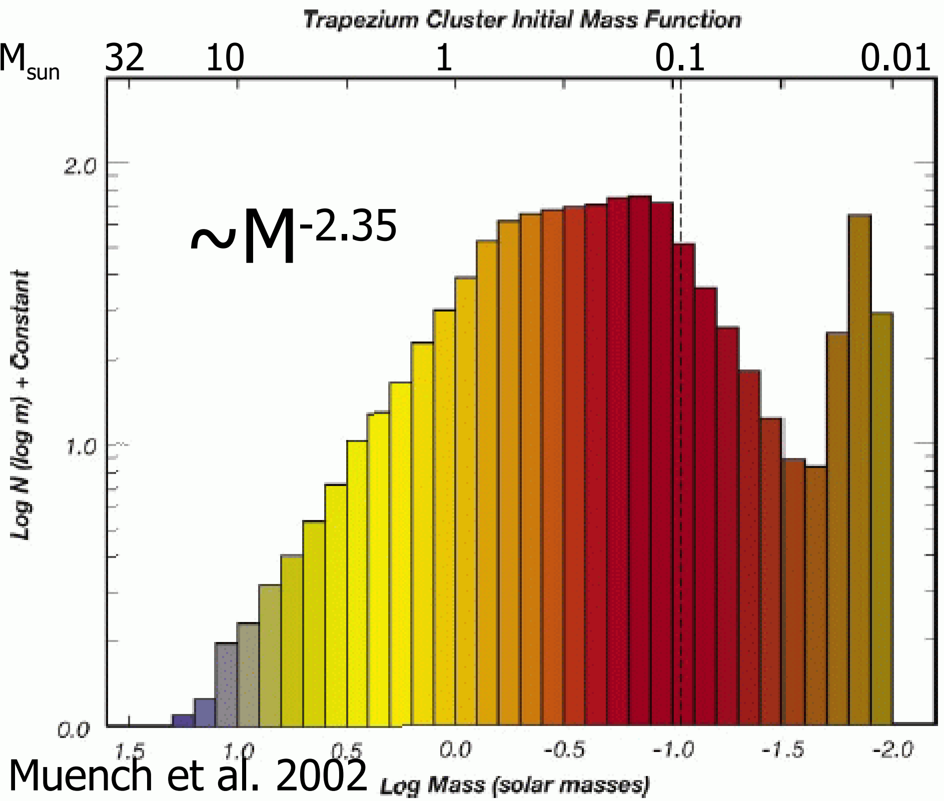
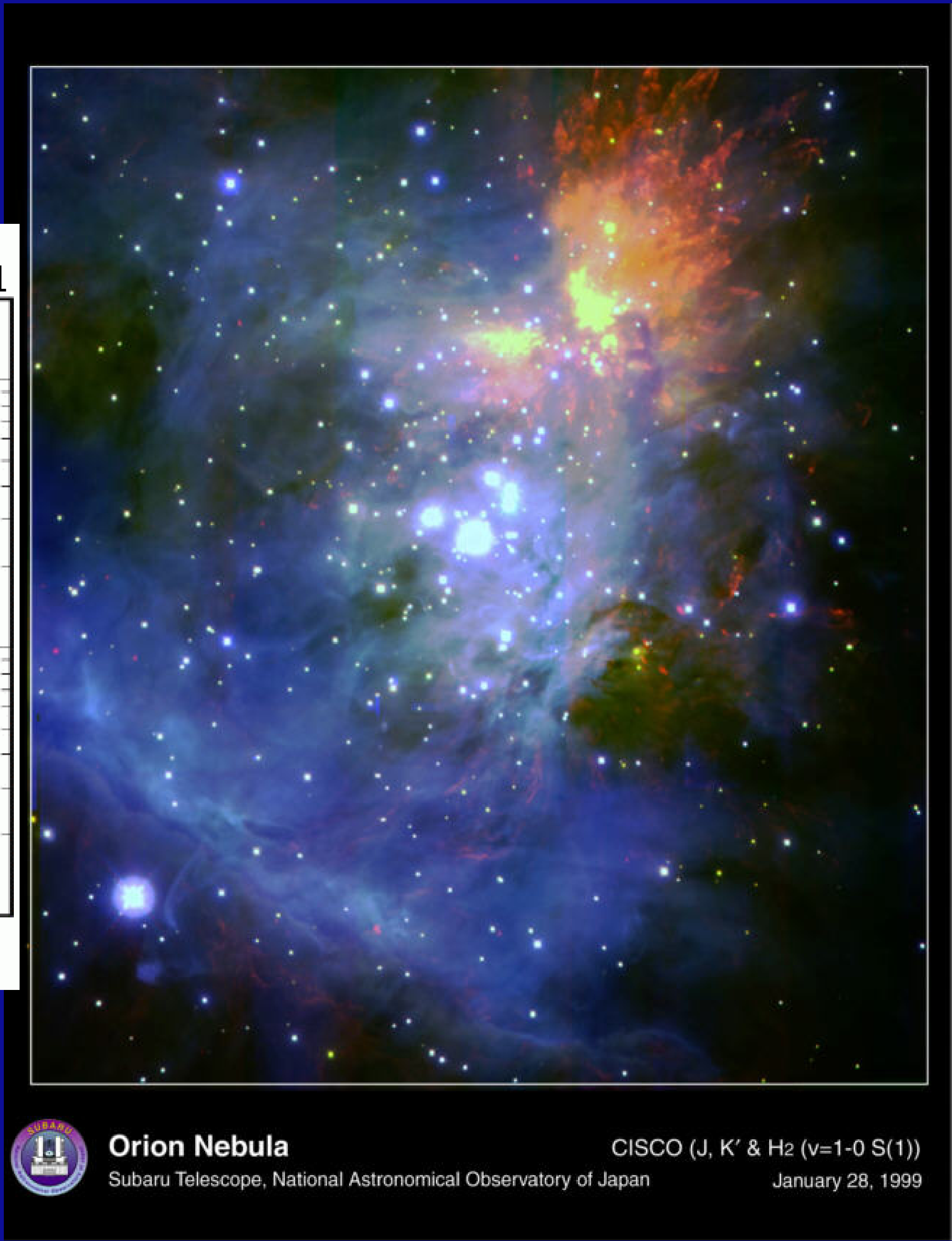
Clusters and the Initial Mass Function (IMF)



Muench et al. 2002



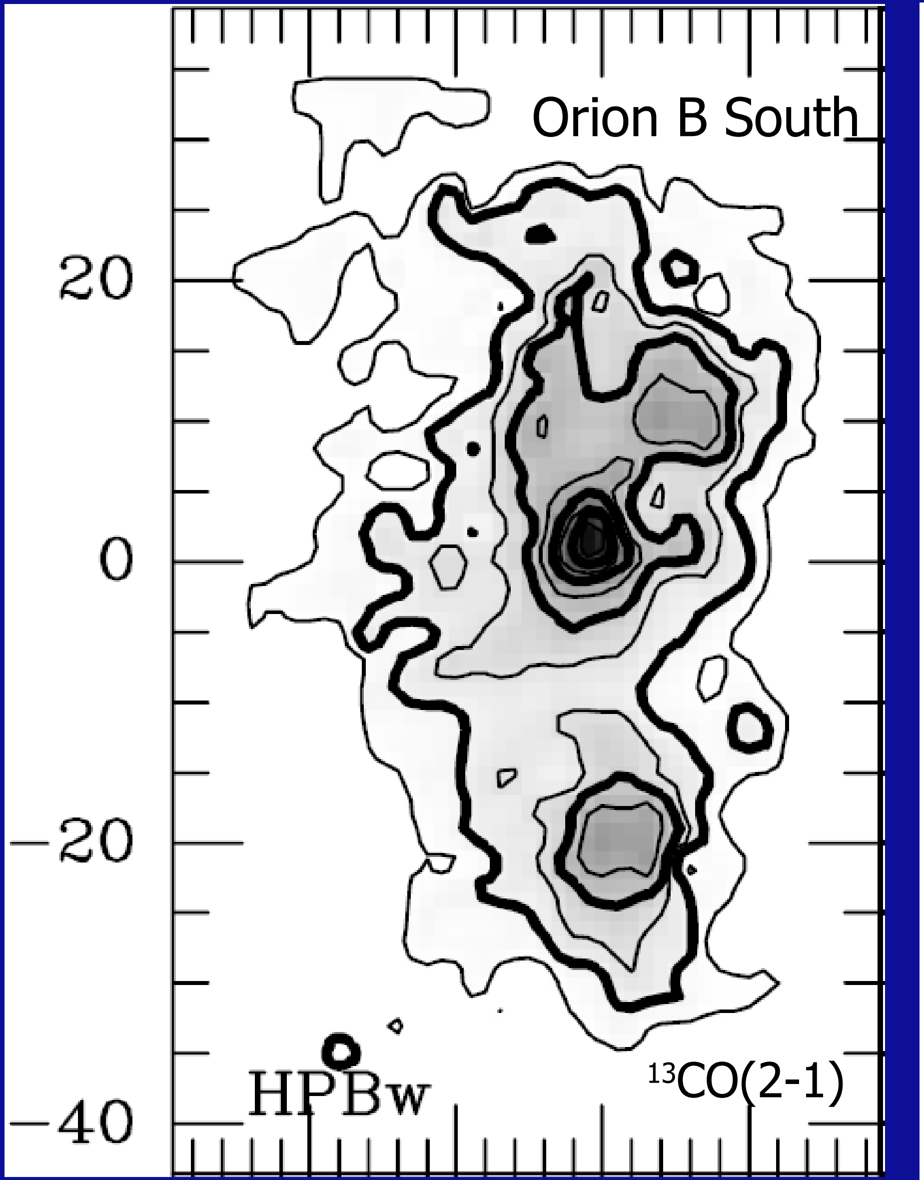
Orion Nebula

Subaru Telescope, National Astronomical Observatory of Japan

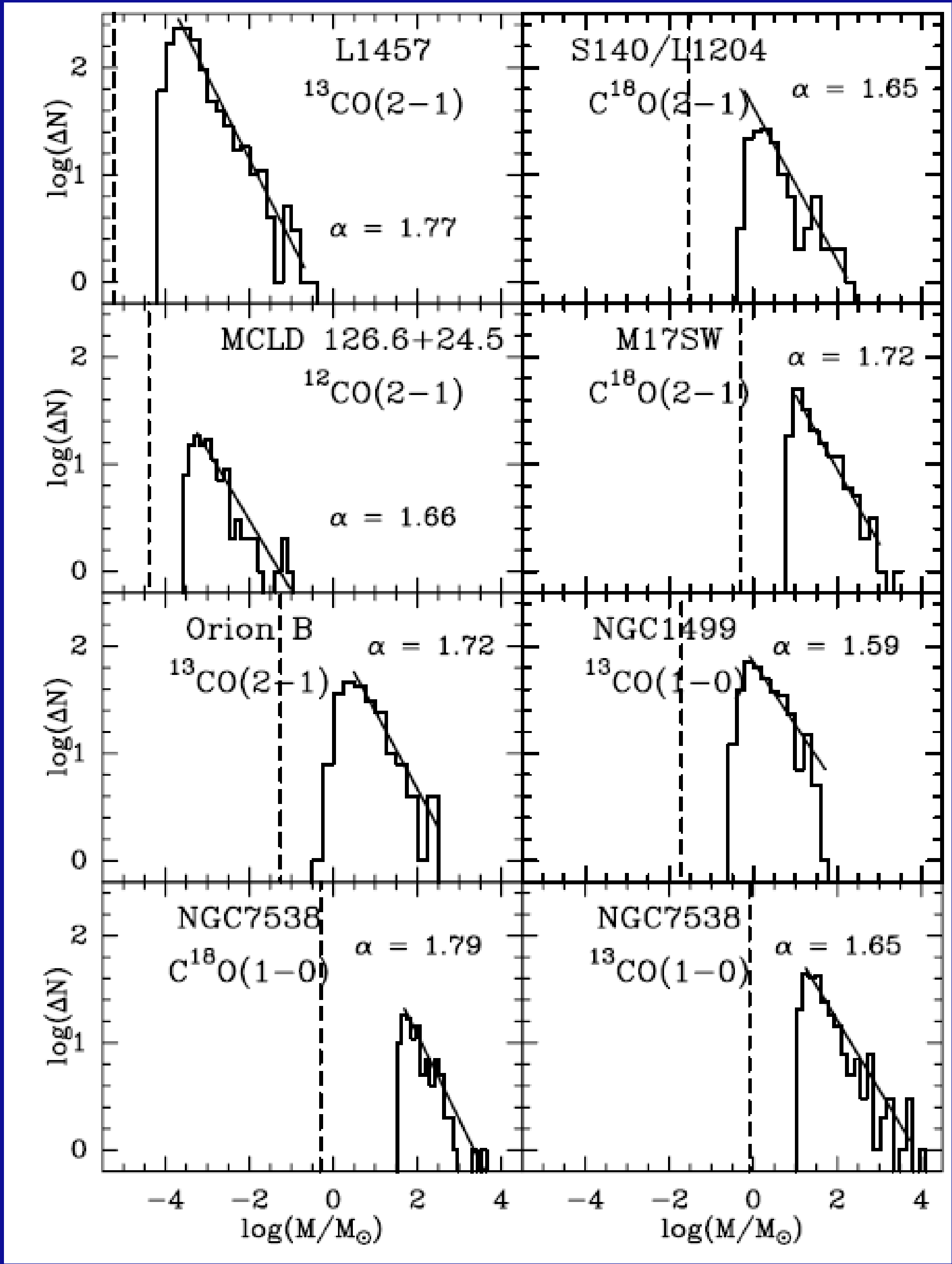
CISCO (J, K′ & H_2 (v=1-0 S(1))

January 28, 1999

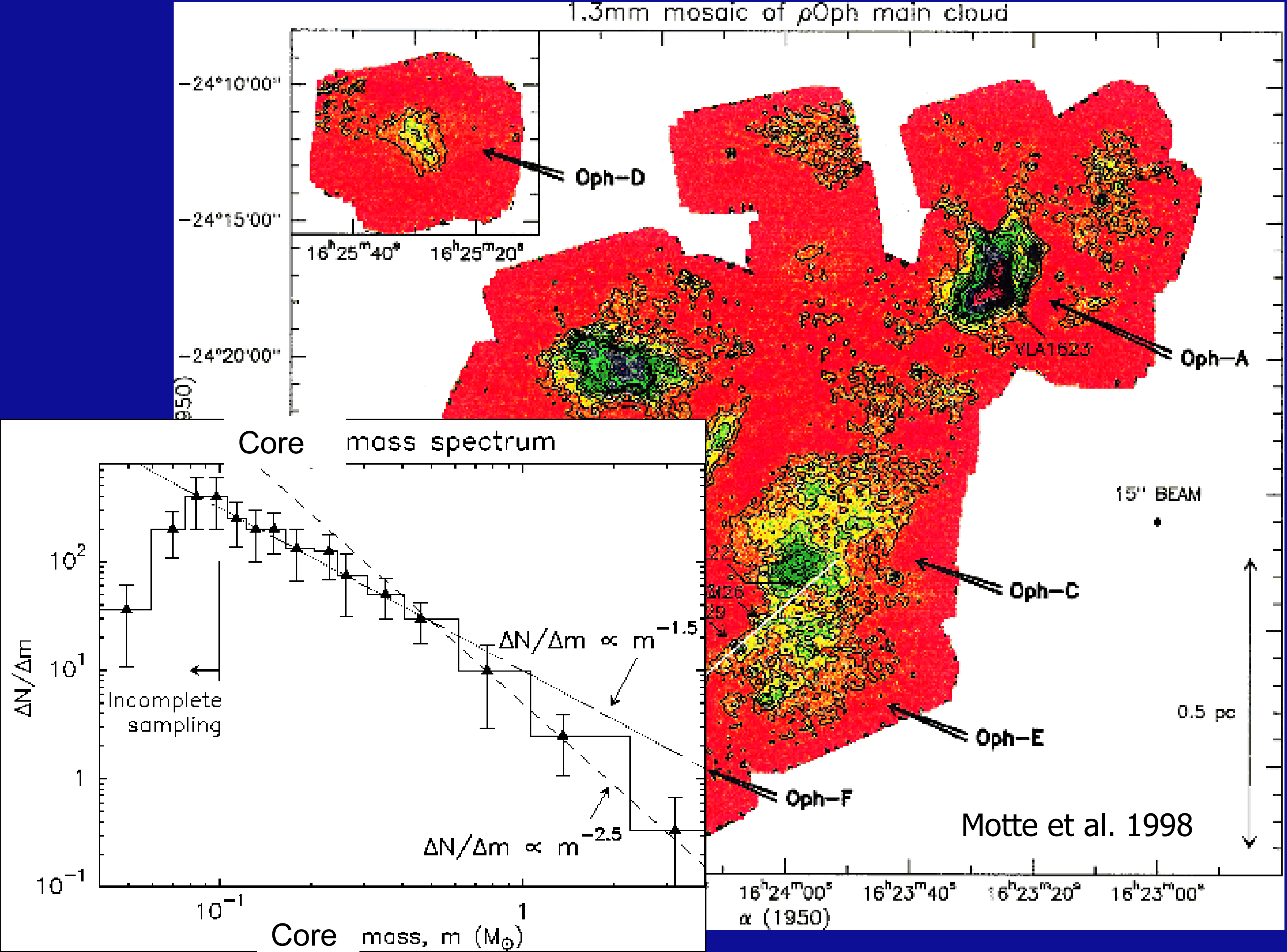
Cloud mass distributions



Kramer et al. 1996

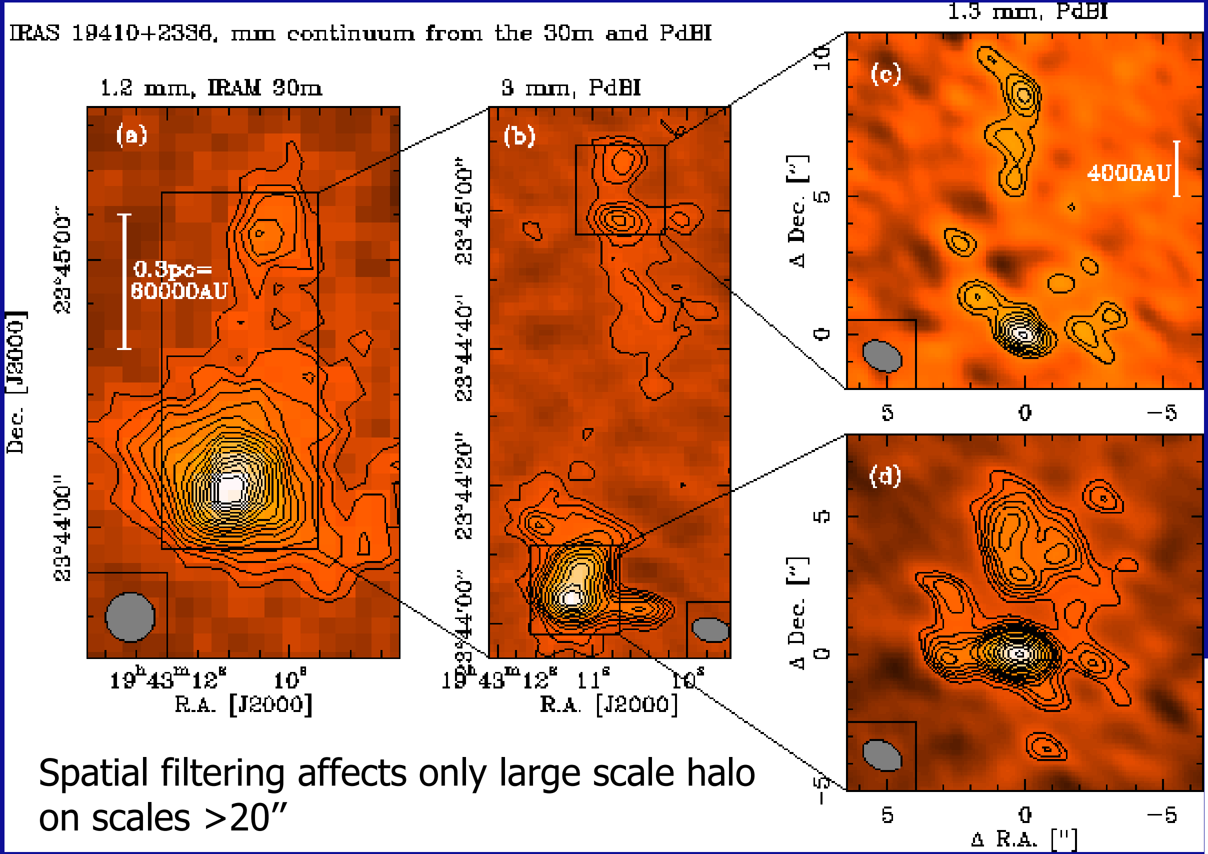


Pre-stellar core mass functions



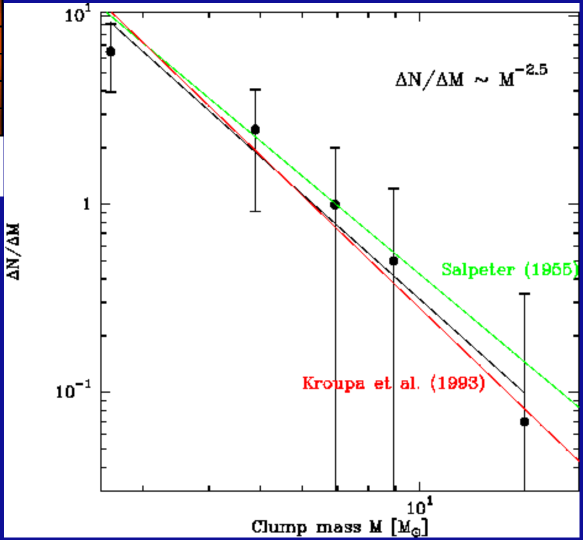
Motte et al. 1998

Fragmentation of a massive protocluster



Spatial filtering affects only large scale halo on scales >20"

- 12 clumps within each core
- Integrated masses
  98M$_{sun}$ (south)
  42M$_{sun}$ (north)
  --> 80 to 90% of the gas in halo
- Clump masses 1.7M$_{sun}$ to 25M$_{sun}$
- Column densities



(Assumptions: - All emission peaks of protostellar nature
- Same temperature for all clumps (46K, IRAS))

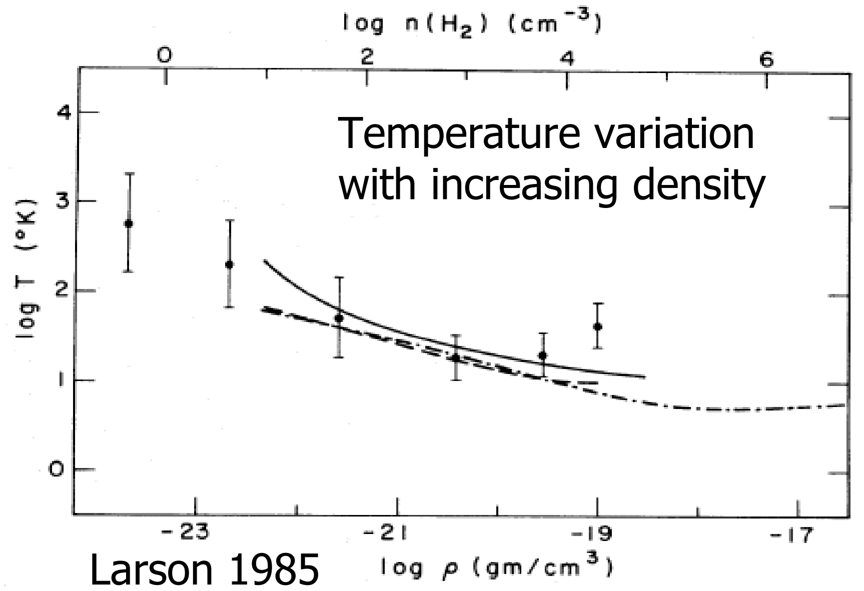
Beuther & Schilke 2004

Characteristic mass defined by thermal physics

- Jeans mass depends on T:

$$M_J = \text{constant} * a_t^3 / (\rho_0^{1/2}\ G^{3/2})$$

$$= 1.0 M_{sun}\ (T/(10K))^{3/2}\ (n_{H2}/(10^4 cm^{-3})^{-1/2}$$



Temperature variation with increasing density

Larson 1985

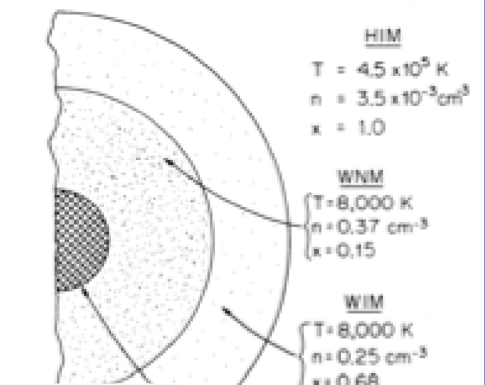
- Low densities → T decreases with increasing ρ → regions cool efficiently
  → decreasing M_J suggests that fragmentation may be favoured there.

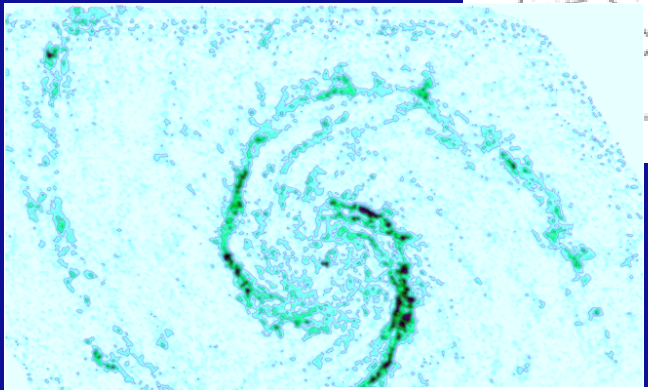
- Further increasing ρ → gas thermally couples to dust and clouds, and become partially optically thick → Cannot cool well enough anymore
  → temperature increases again.
  → M_J decreases slower, inhibiting much further fragmentation.

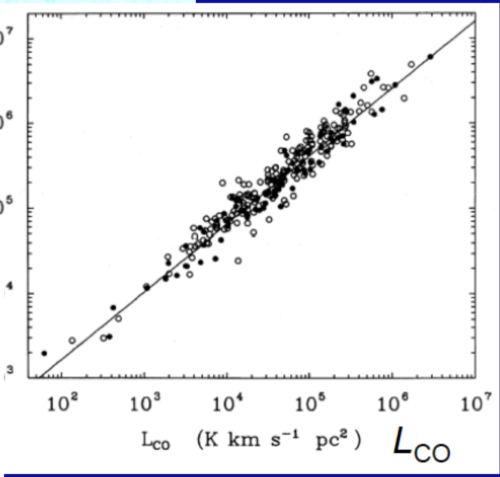
→ Regime with lowest T should correspond to preferred fragmentation scale
→ The Jeans mass at this point is about 0.5 M_{sun}.

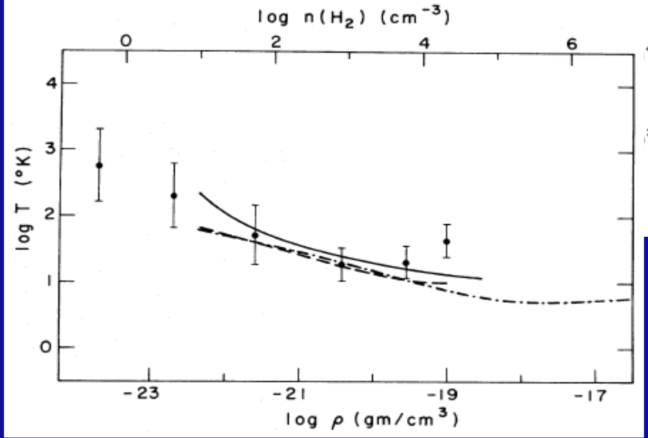
Summary

- Physical distribution
- Different components of ISM
- Basic characteristics
- Important cloud relations
- Cloud fragmentation









Sternentstehung - Star Formation

Winter term 2017/2018

Henrik Beuther & Thomas Henning

17.10.	Introduction & Overview	(H.B.)
24.10.	Physical processes I	(H.B.)
31.10.	no Lecture – Reformationstag	(M.L.)
07.11.	Physcial processes II	(H.B.)
14.11.	Molecular clouds as birth places of stars	(H.L.)
21.11.	**Molecular clouds (cont.), Jeans Analysis**	**(H.B.)**
28.11.	Collapse models I	(H.B.)
05.12.	Collapse models II	(T.H.)
12.12.	Protostellar evolution	(T.H.)
19.12.	Pre-main sequence evolution & outflows/jets	(T.H.)
09.01.	Accretion disks I	(T.H.)
16.01.	Accretion disks II	(T.H.)
23.01.	High-mass star formation, clusters and the IMF	(H.B.)
30.01.	Planet formation	(T.H.)
06.02.	Examination week, no star formation lecture	

Book: Palla & Stahler (2004) The Formation of Stars, Wileys

More Information and the current lecture files: http://www.mpia.de/homes/beuther/lecture_ws1718.html

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