Sternentstehung - Star Formation

Winter term 2024/2025

Henrik Beuther, Thomas Henning & Caroline Gieser

15.10 Today: Introduction & Overview	*(Beuther)*
22.10 Physical processes I	*(Beuther)*
29.10 --	
05.11 Physcial processes II	*(Beuther)*
12.11 Molecular clouds as birth places of stars	**(Beuther)**
19.11 Molecular clouds (cont.), Jeans Analysis	(Henning)
26.11 Collapse models I	(Beuther)
03.12 Collapse models II	(Beuther)
10.12 Protostellar evolution	(Gieser)
17.12 Pre-main sequence evolution & outflows/jets	(Henning)
07.01 Accretion disks I	(Henning)
14.01 Accretion disks II	(Henning)
21.01 High-mass star formation, clusters and the IMF	(Gieser)
28.01 Extragalactic star formation	(Henning)
04.02 Planetarium@HdA, outlook, questions	
11.02 Examination week, no star formation lecture (Beuther, Gieser, Henning)	

Book: Stahler & Palla: The Formation of Stars, Wileys

More Information and the current lecture files: http://www.mpia.de/homes/beuther/lecture_ws2425.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.

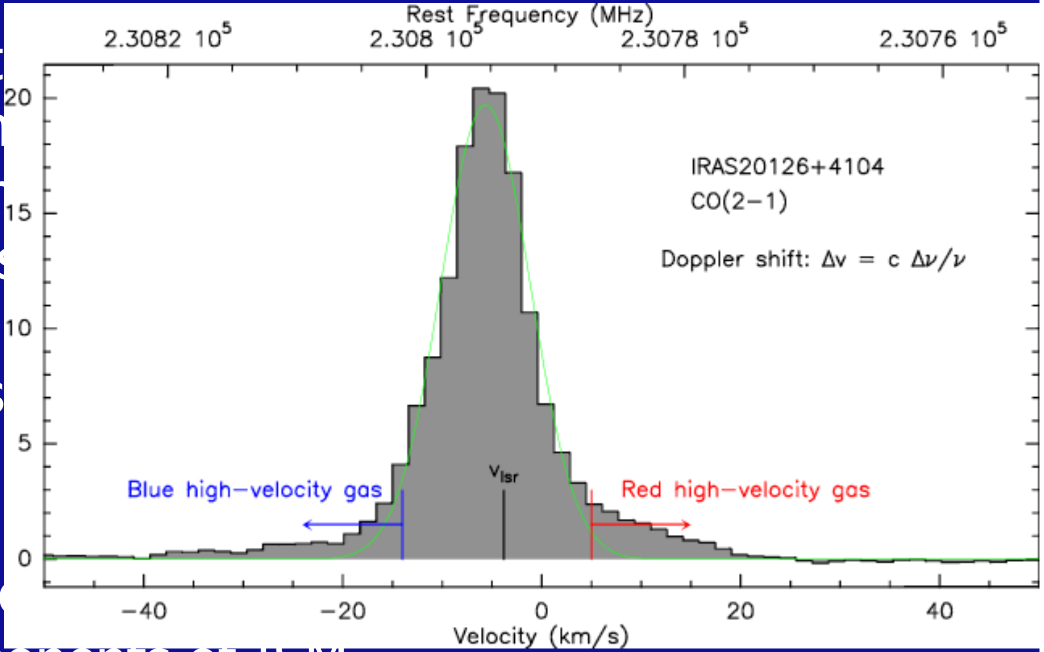
      (Other magnetic field measurements possible.)

- 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.

Last lecture

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



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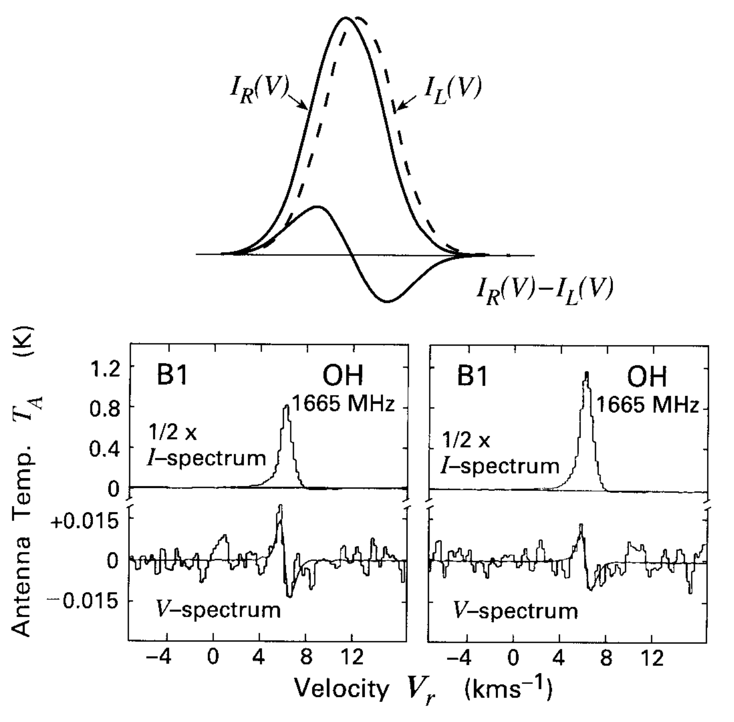

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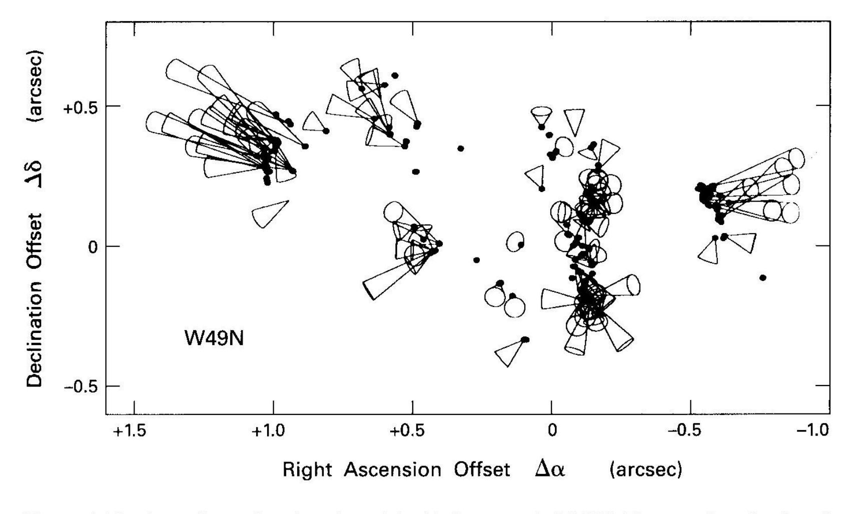

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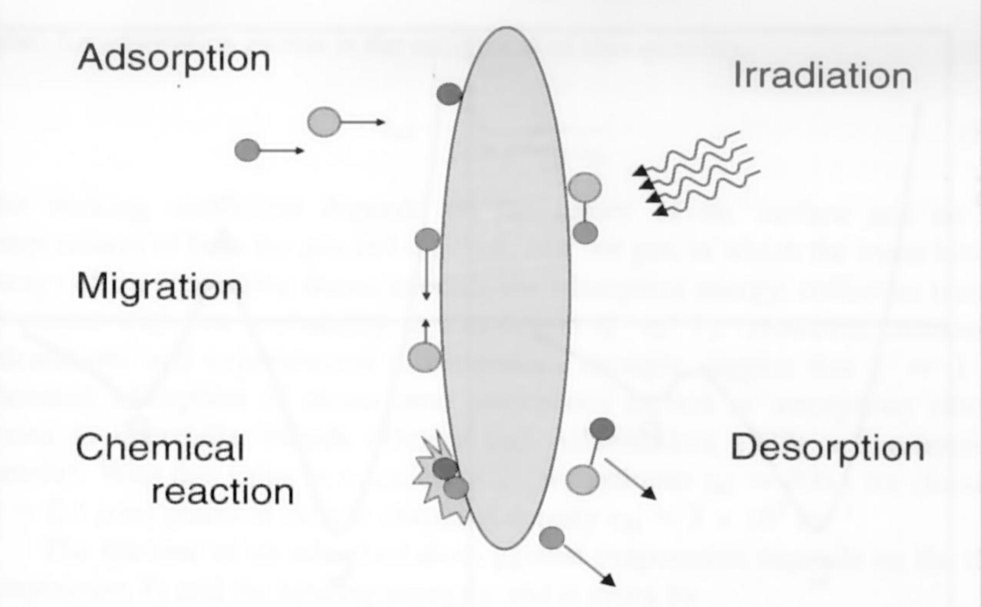

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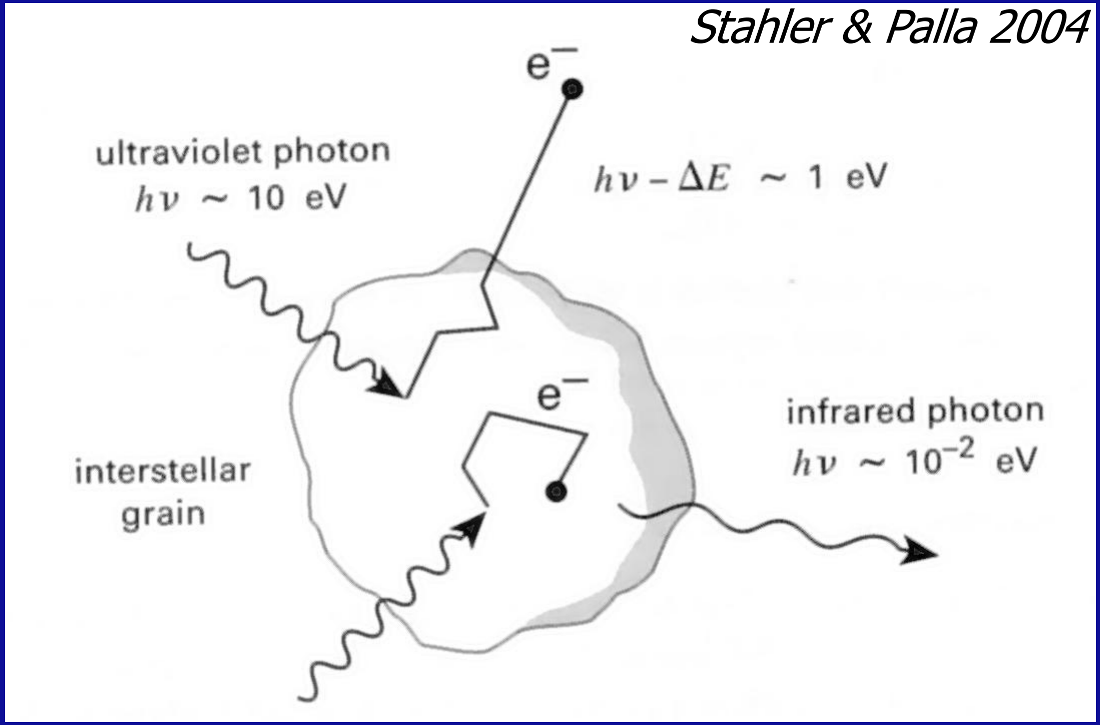
Dust action at longer wavelengths: Re-emission

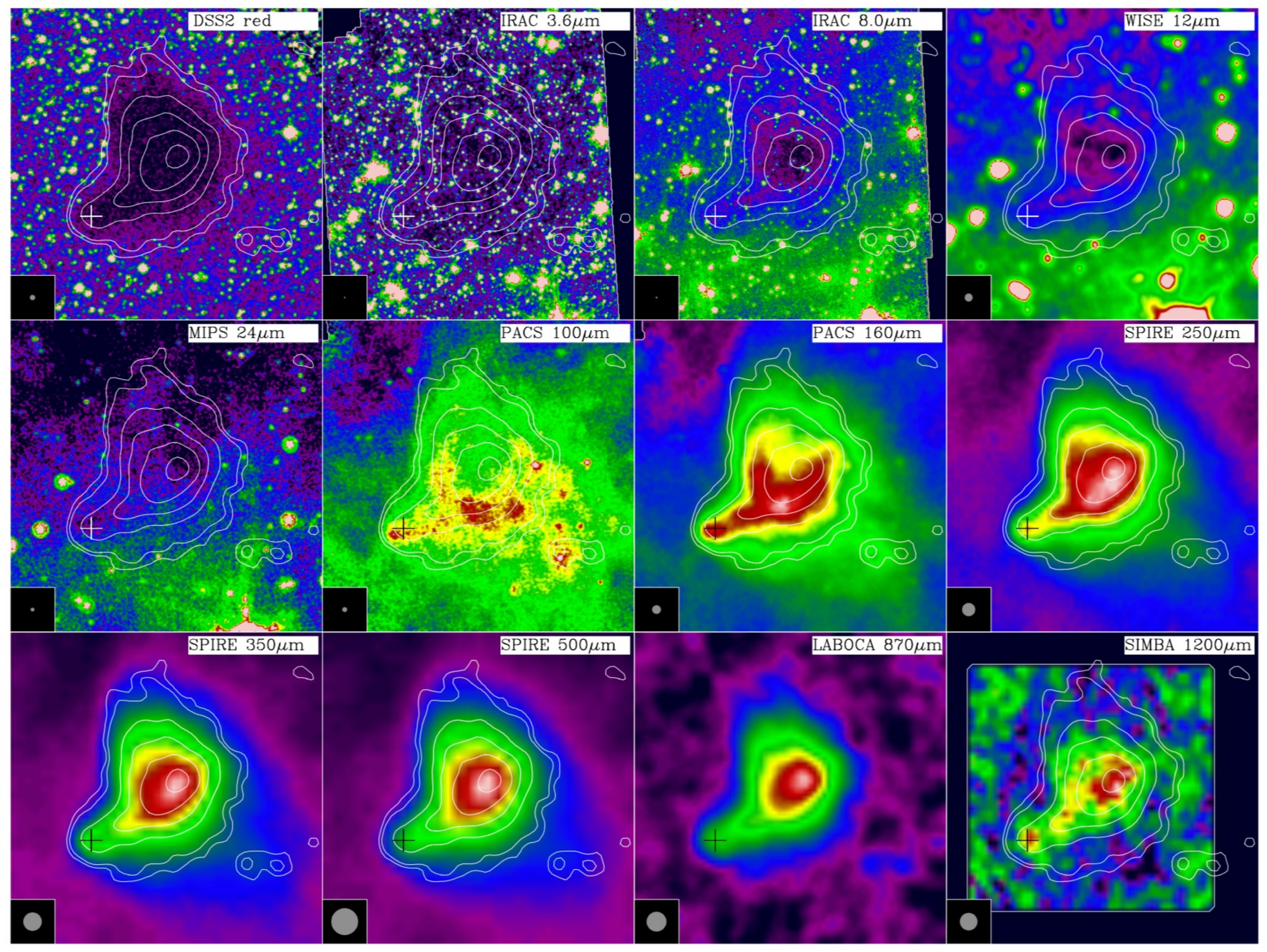


Dust grain hit by UV photon:

1) Photoelectrical effect → give energy to e^- → leaves grain and heats gas.

2) Excites lattice vibrations → transformed to (far)-IR photons and re-emitted.

Dust action at longer wavelengths: Re-emission



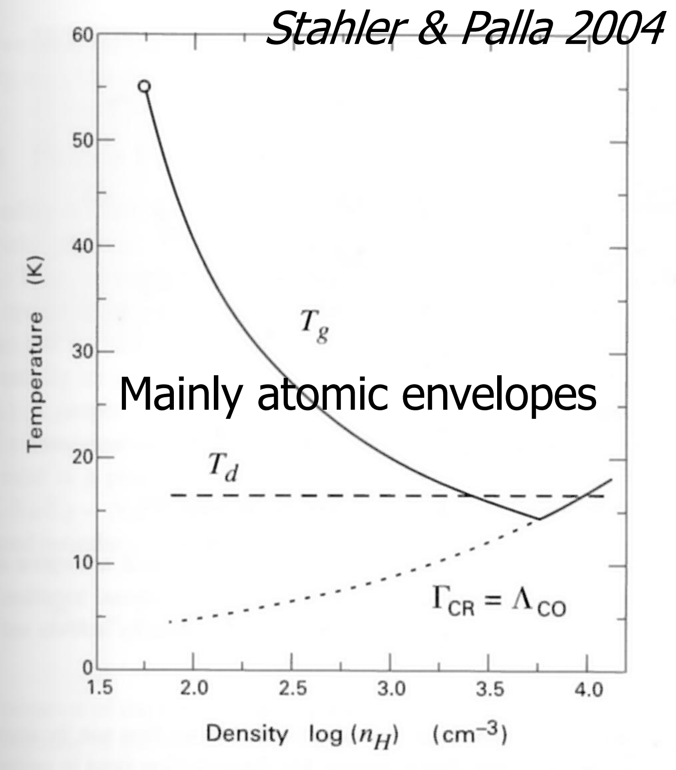
Dust g

1) Ph gas.

2) Ex emitted.

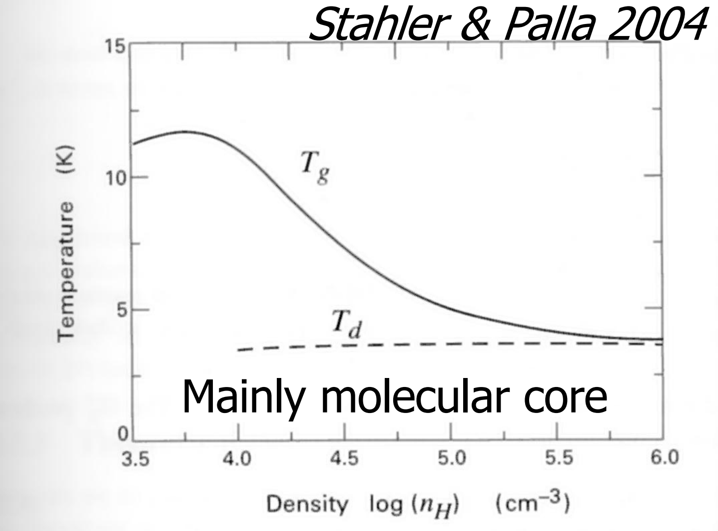
Nielbock et al. 2012, Contours 870μm

Dust and gas coupling


Stahler & Palla 2004

Mainly atomic envelopes

Cosmic ray heating more sensitive to density than CO cooling. Hence T_g rises again.


Stahler & Palla 2004

Mainly molecular core

simplified
model →
lowest obs.
T_d ~ 7-10K

Γ – heating rate Λ – Cooling rate

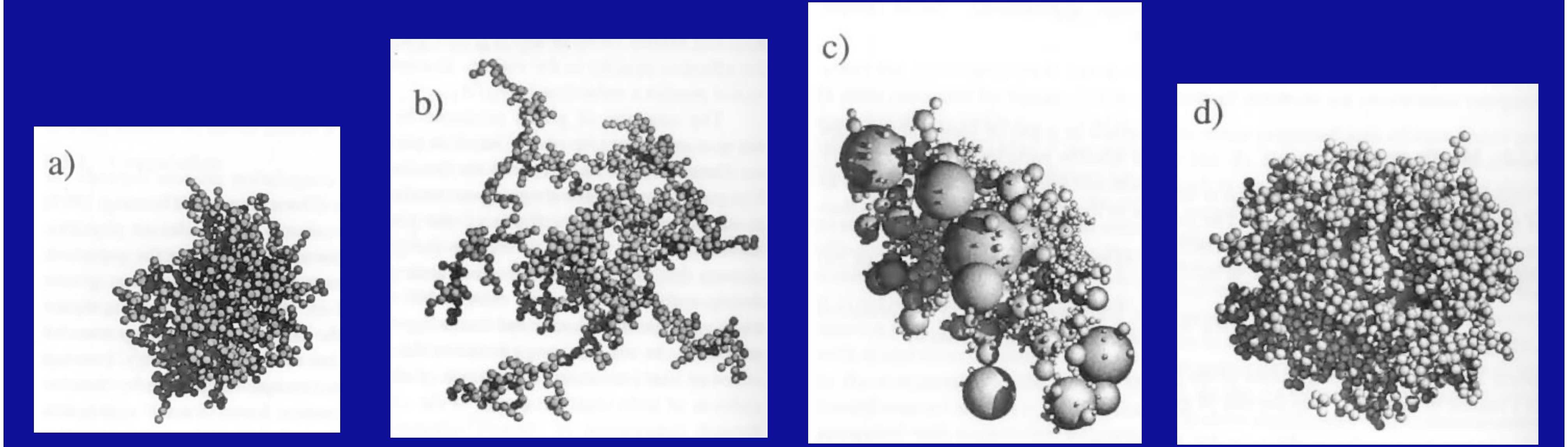
- Low densities: gas and dust de-coupled; at high densities coupled.

- Low densities gas cooling mainly CO; high densities via CO & dust.

- At very high densities gas and dust temperatures approach each other

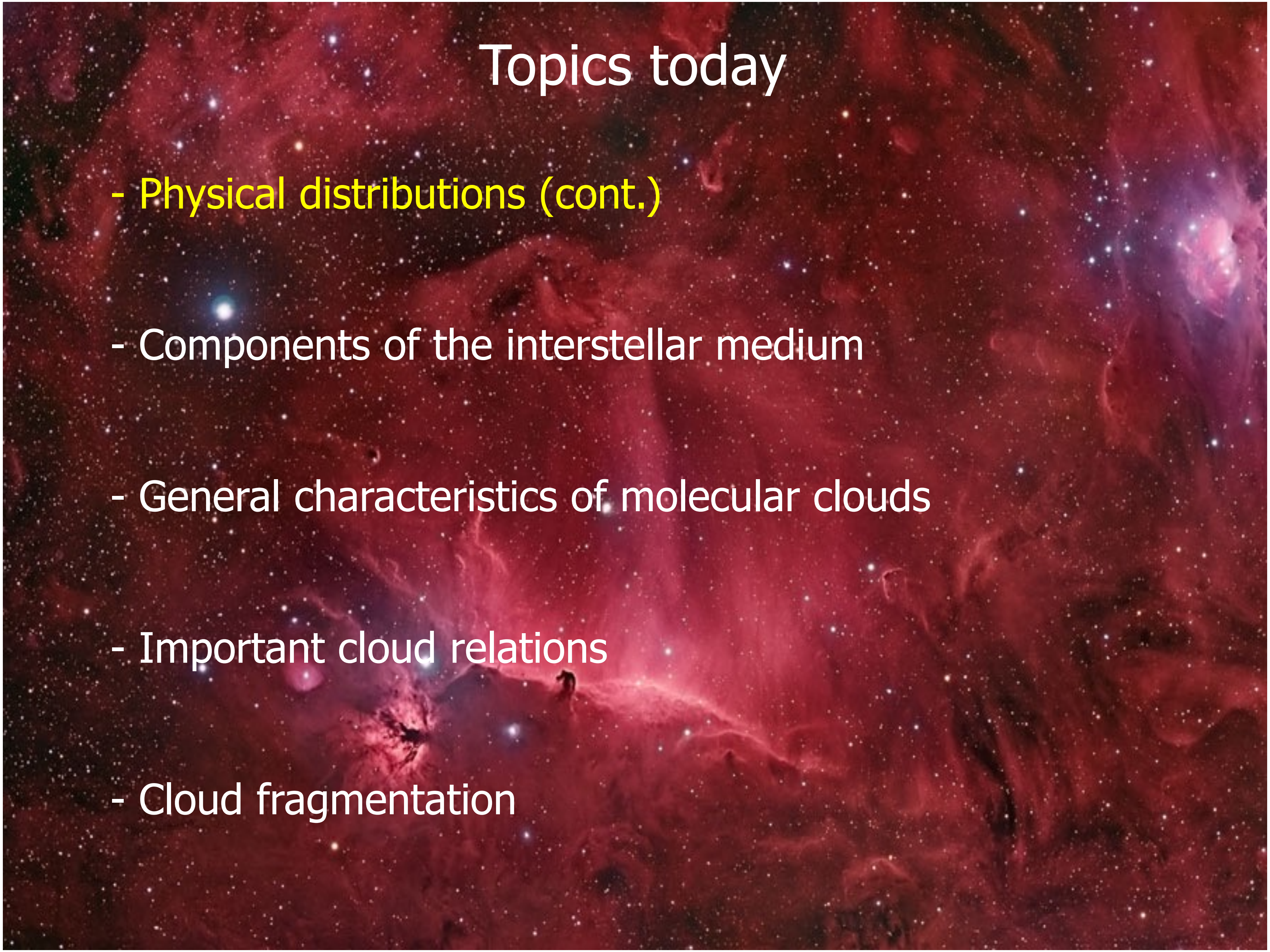
→ CO cooling becomes insignificant then!

Dust incarnations



Dust can grow and coagulate in very dense environments, e.g., disks.

Figures: Simulations of dust grain cluster growth for different initial parameters (gas and dust density, temperature, stickyness, grain charge, coagulation time …).
(From Dorschner & Henning 1995)



Topics today

- Physical distributions (cont.)

- Components of the interstellar medium

- General characteristics of molecular clouds

- Important cloud relations

- Cloud fragmentation

Physical conditions : Micro-Level

A medium in thermodynamic eq. can be described by 4 distribution laws:

1.) MAXWELL distribution of the particle velocity contributions (kinetic energy):

$$N(v;T) = 4\pi \left(\frac{m}{2kT} \right)^{3/2} v^2 \exp\left(-\frac{mv^2}{2kT} \right)$$

v: particle velocities

2.) BOLTZMANN distribution of the population numbers of the particle energy levels:

$$\frac{N_o}{N_u} = \frac{g_o}{g_u} \exp\left(-\frac{E_o - E_u}{kT} \right) \qquad \begin{array}{l} E_{o/u} \longrightarrow \\ g_{o/u} \longrightarrow \end{array}$$

Energies of the upper (o) and lower (u) levels

Corresponding statistical weights

3.) PLANCK radiation law (distribution of the photon energies):

$$B_\nu = \frac{2h\nu^3 / c^2}{\exp(h\nu / kT) - 1}$$

ν: photon frequencies

4.) SAHA equation (distribution of the ionisation levels in plasma):

$$\frac{N_{j+1} N_e}{N_j} = \frac{2\,U_{j+1}(T)}{U_j(T)} \left(\frac{2\pi m_e kT}{h^2} \right)^{3/2} \exp(-\chi_{j,j+1} / kT)$$

N_{j+1}, N_j - Number densities of (j+1)-fold and j-fold ionised particles

N_e - electron density

$\chi_{j,j+1}$ - ionisation energy needed to get from ionisation level j to $j+1$

U_{j+1}, U_j - partition function for both states

Physical conditions : Micro-Level

Are these distribution functions valid in the ISM?

General rule: time scale for processes leading to equilibrium short compared
to time scales of disturbing processes

1. Example : Collisions between H-atoms:

Consider:
T = 100 K → mean v ~ 1 km/s; cross section $\sigma = \pi R_H^2 \sim \pi\,(0.1\ \mathrm{nm})^2$

Probability for collision: $P = v\,\sigma\,n_H\,\tau_s$

→ average time τ_s between two collision for P=1: $\tau_s = (v\,\sigma\,n_H)^{-1}$
→ with HI density of 1 cm^{-3} → $\tau_s \sim 1000$ yrs

→ short compared to most interstellar processes (except shock fronts)

→ Maxwell distribution valid, introduction of kinetic temp. T_{kin} reasonable

Physical conditions : Micro-Level

2. Example: Balance for energy level population numbers for ISM:

Correction factor to Boltzmann: $\dfrac{1}{1 + (A_{21} / (n\,Q_{21}))}$

(Pure Boltzmann only if $(n\,Q_{21}) >> A_{21}$)

A_{21} [s^{-1}] Einstein coefficient for spontaneous radiative decay
Q_{21} [$m^3\,s^{-1}$] collision rate
n [m^{-3}] number density

- In thin ISM collision rate small (Example 1) → sub-thermal

- For dense cores: E.g. CO(1-0) at density $10^5 cm^{-3}$: $A_{21}=7.2x10^{-8}s^{-1}$,
$Q_{21}=3.3x10^{-11}\ cm^3s^{-1}$

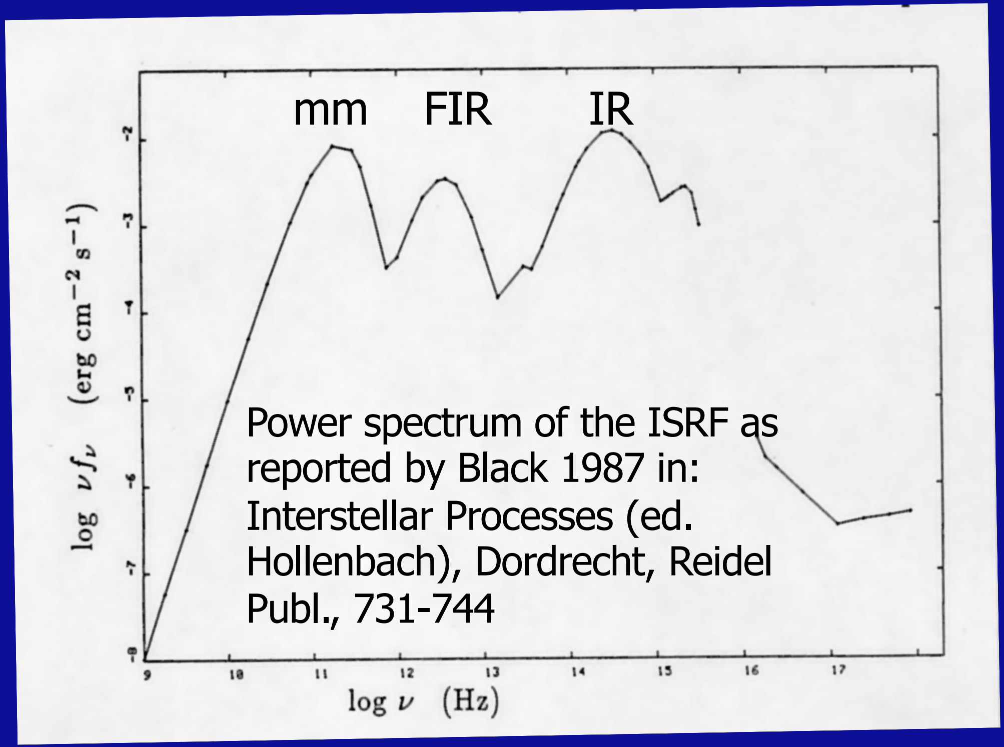
→ $A_{21} / (n\,Q_{21}) \sim 0.02$
→ Boltzmann distribution valid in dense cores!

Physical conditions : Micro-Level

3. Example : Interstellar radiation field (ISRF) :

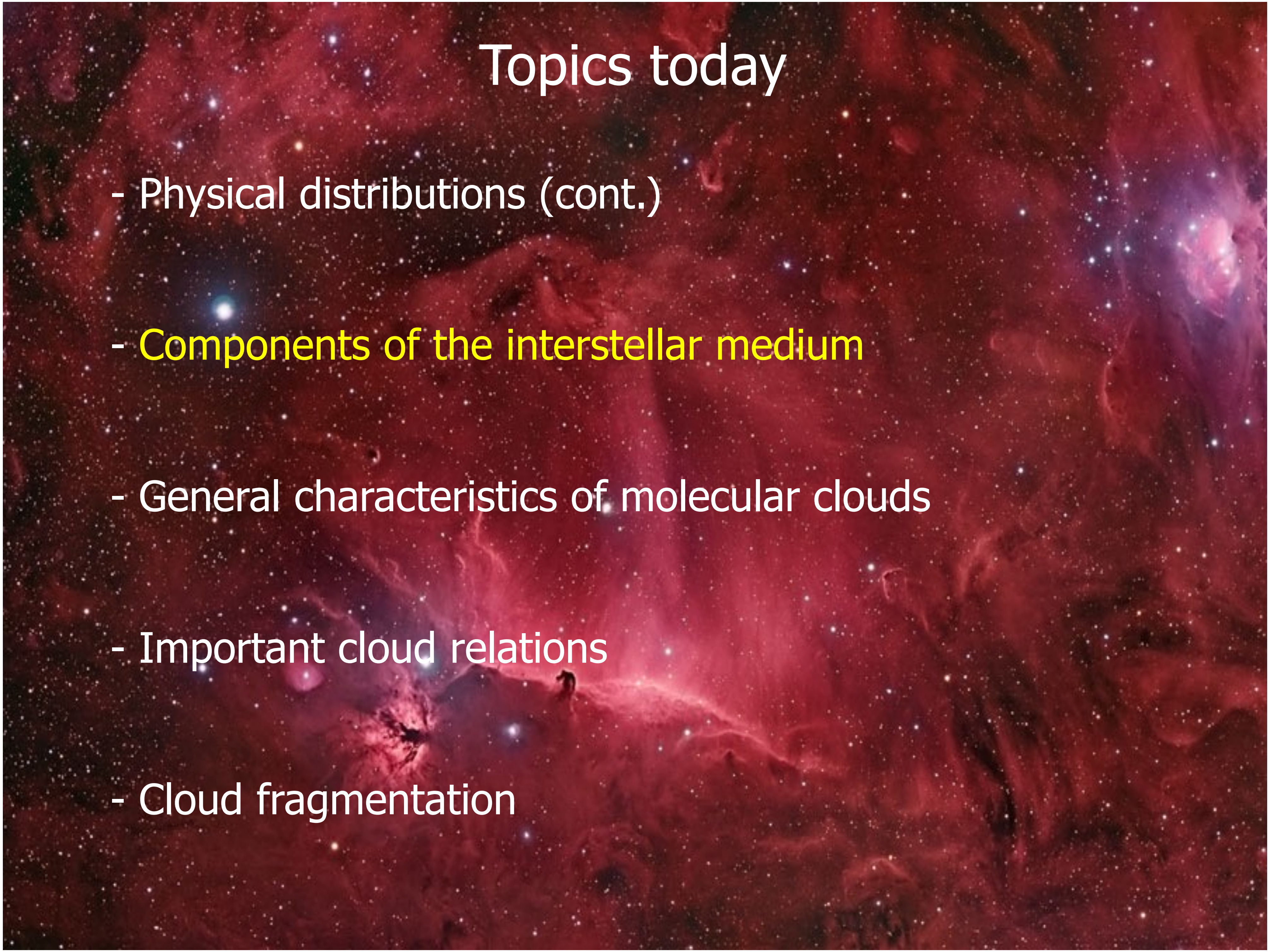
Sum of emission contributions from all emitting objects (stars, dust, gas) in the nearer and further vicinity of the gas cloud

ISRF cannot be approximated by a black body (i.e., Planck function not applicable)
ISRF hence far from thermodynamic equilibrium …



Power spectrum of the ISRF as reported by Black 1987 in: Interstellar Processes (ed. Hollenbach), Dordrecht, Reidel Publ., 731-744

However: Dense cores and stars can be fitted relatively well with single or multiple black body functions.



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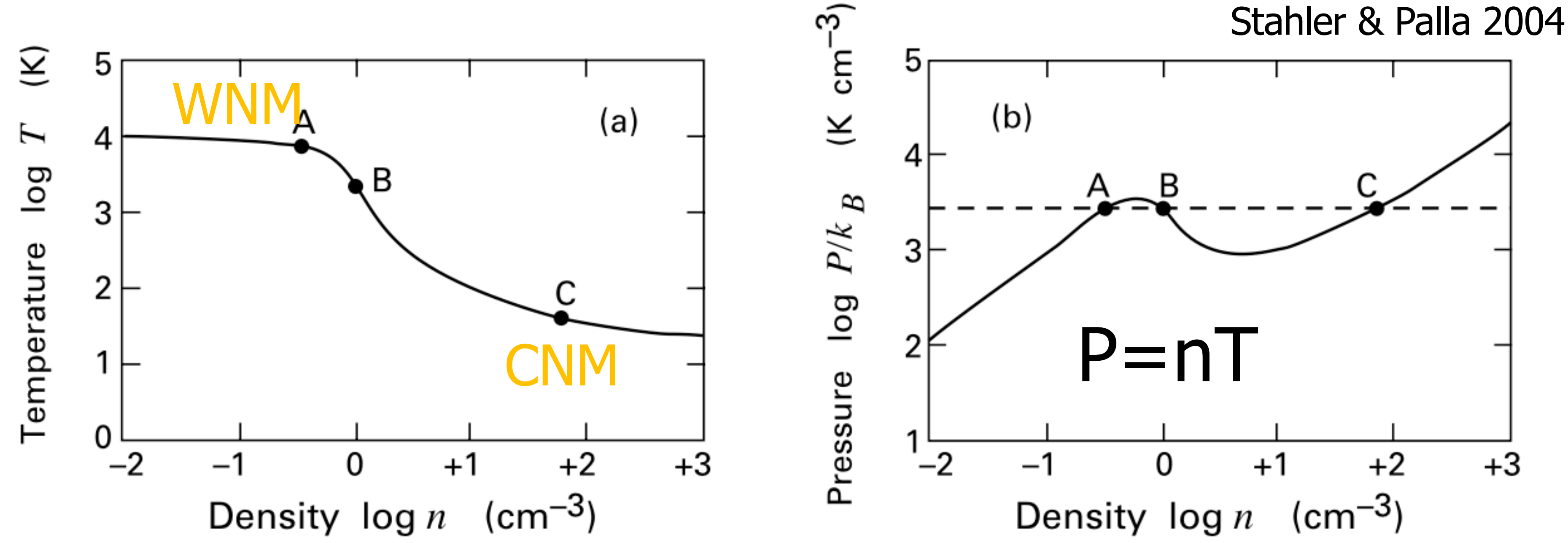
Historical Models of the ISM (I)

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

- Considering only the atomic gas

- Underlying idea: pressure equilibrium with environment



Stahler & Palla 2004

Shortcomings: does not account for hot ionized nor molecular medium

Historical Models of the ISM (II)

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

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

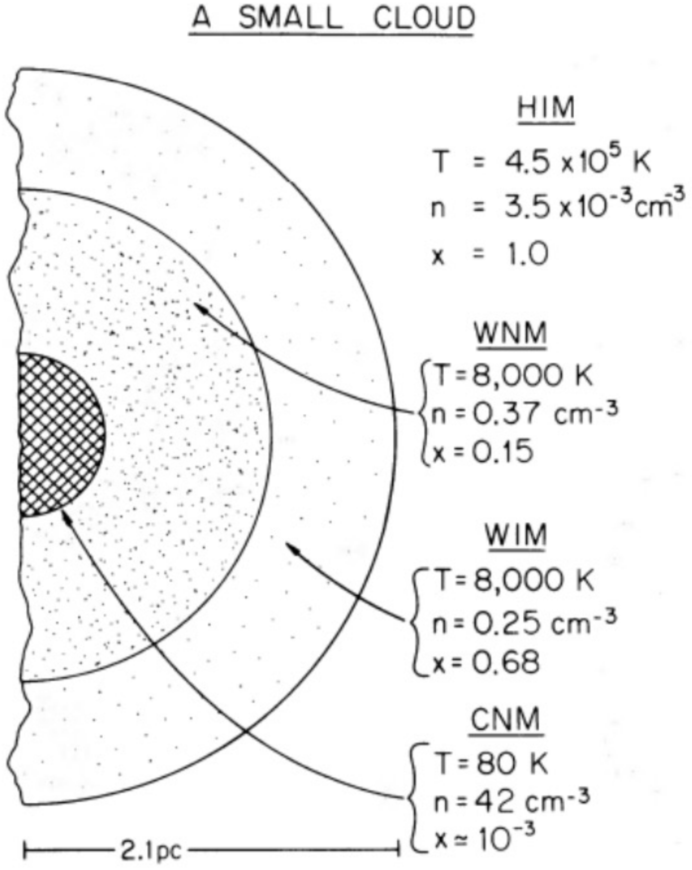


FIG. 1

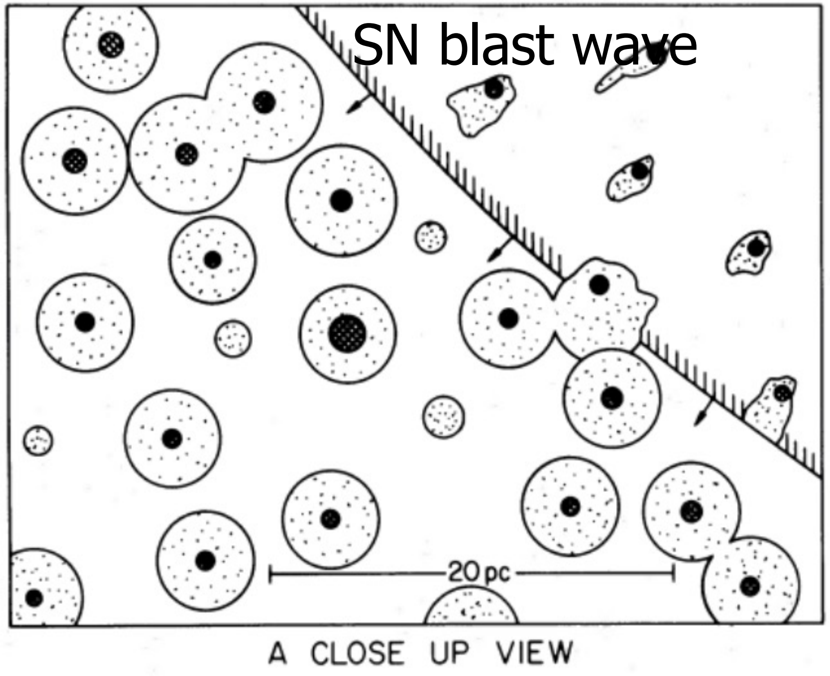


FIG. 2

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

- Observations indicate considerable amount of evenly distributed (i.e., not bound to clouds) warm HI gas

- 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 ⟶ molecular clouds ⟶ stars

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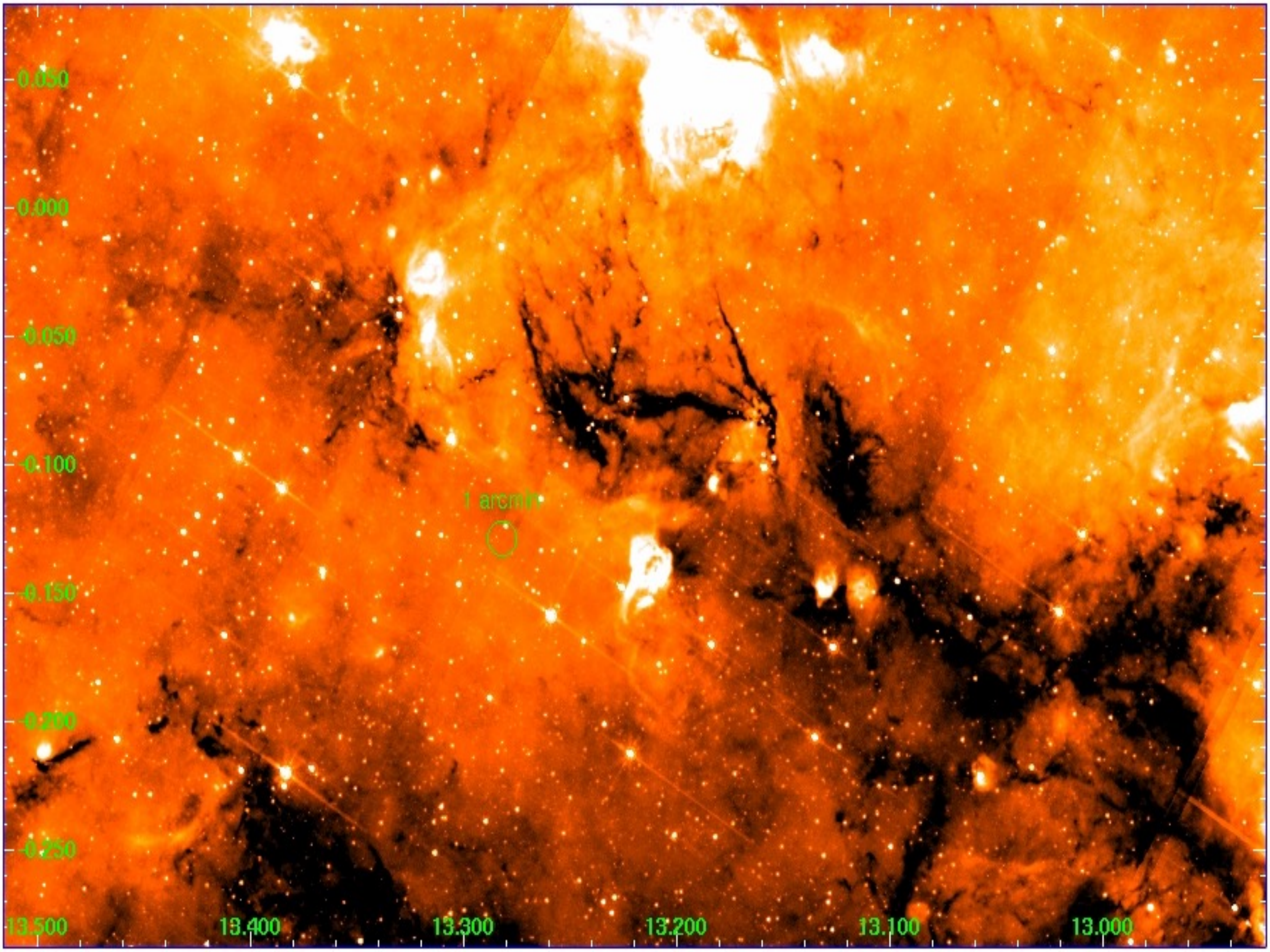


Phase transitions are possible (e.g., by heating and cooling)

Diffuse clouds ⟶ molecular clouds ⟶ stars

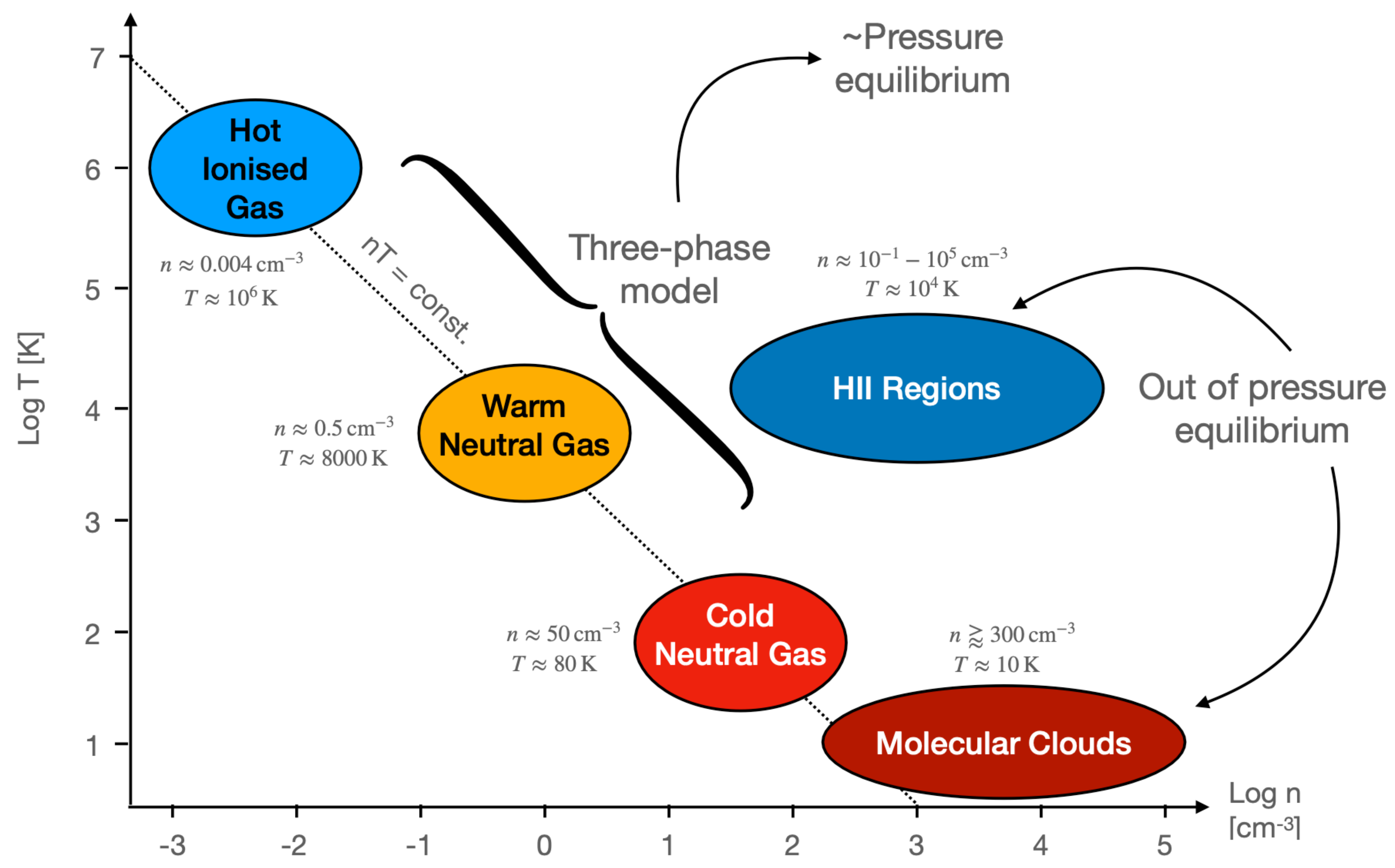
3.) Overview of the components

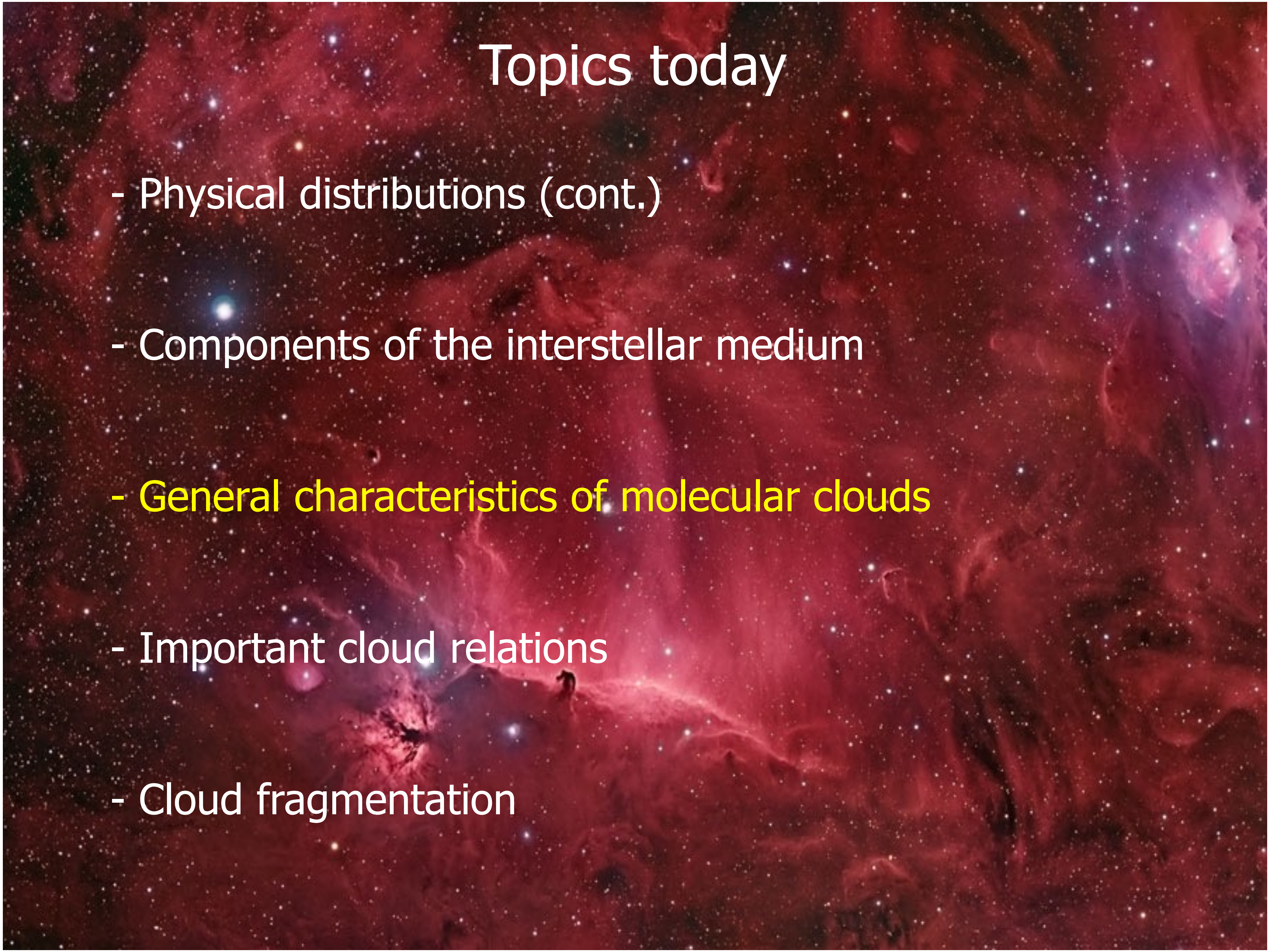
Phase	n [cm^{-3}]	T [K]	f	M [$10^9 M_\odot$]
Hot ionised medium	0.003	10^6	0.5	0.1
Warm ionised medium	0.3	8000	0.1	1.0
Warm neutral medium	0.5	8000	0.3…	1.4
Diffuse HI clouds	50	80	-	2.5
Molecular clouds	>300	10	-	2.5
HII regions	1 – 10^5	10^4	-	0.05

f as volume filling factor regarding the Galactic disk

By mass in Milky Way: ~20 ionized, 60% neutral, 20% molecular

3.) Overview of the components





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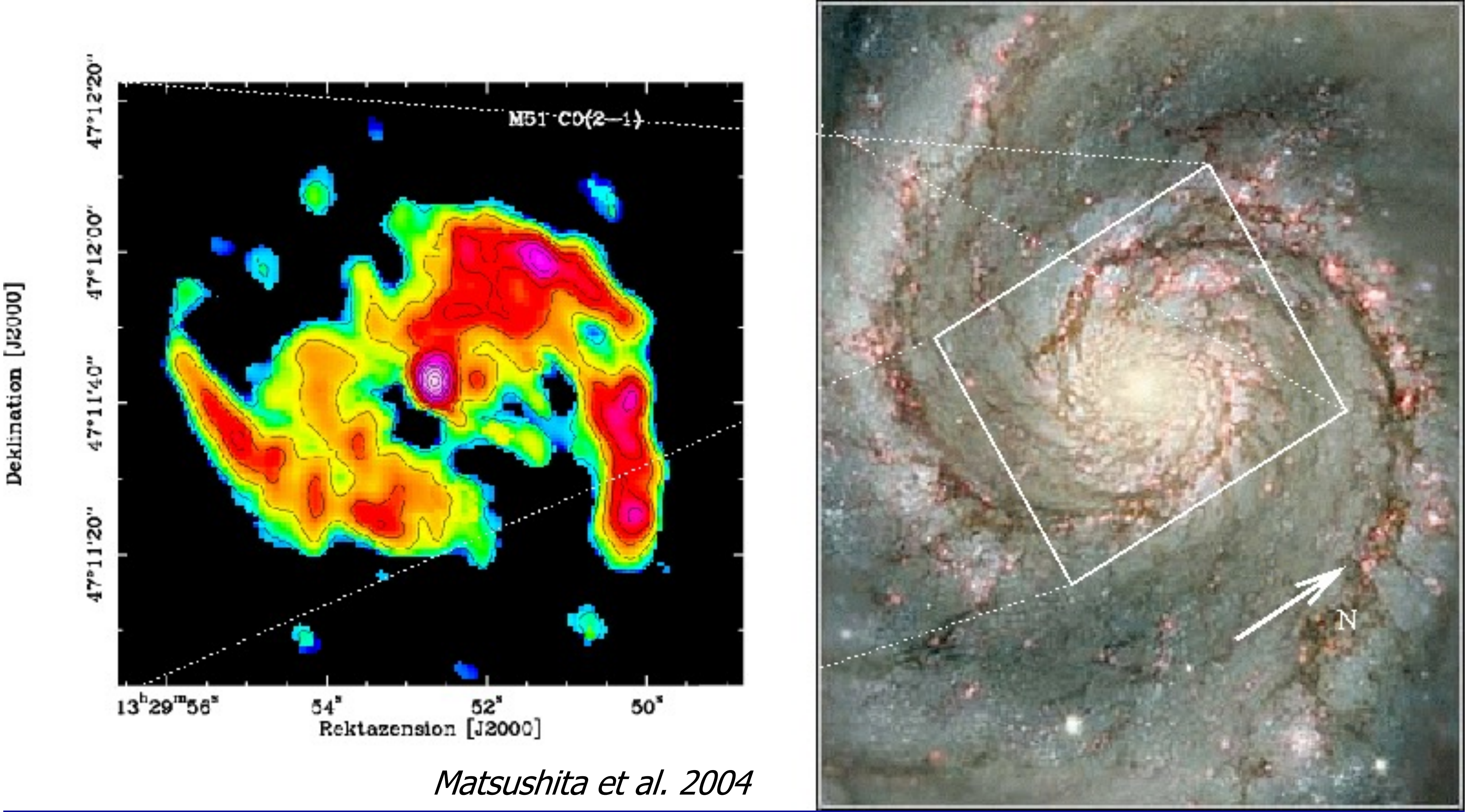
M51: The Whirlpool Galaxy



Matsushita et al. 2004

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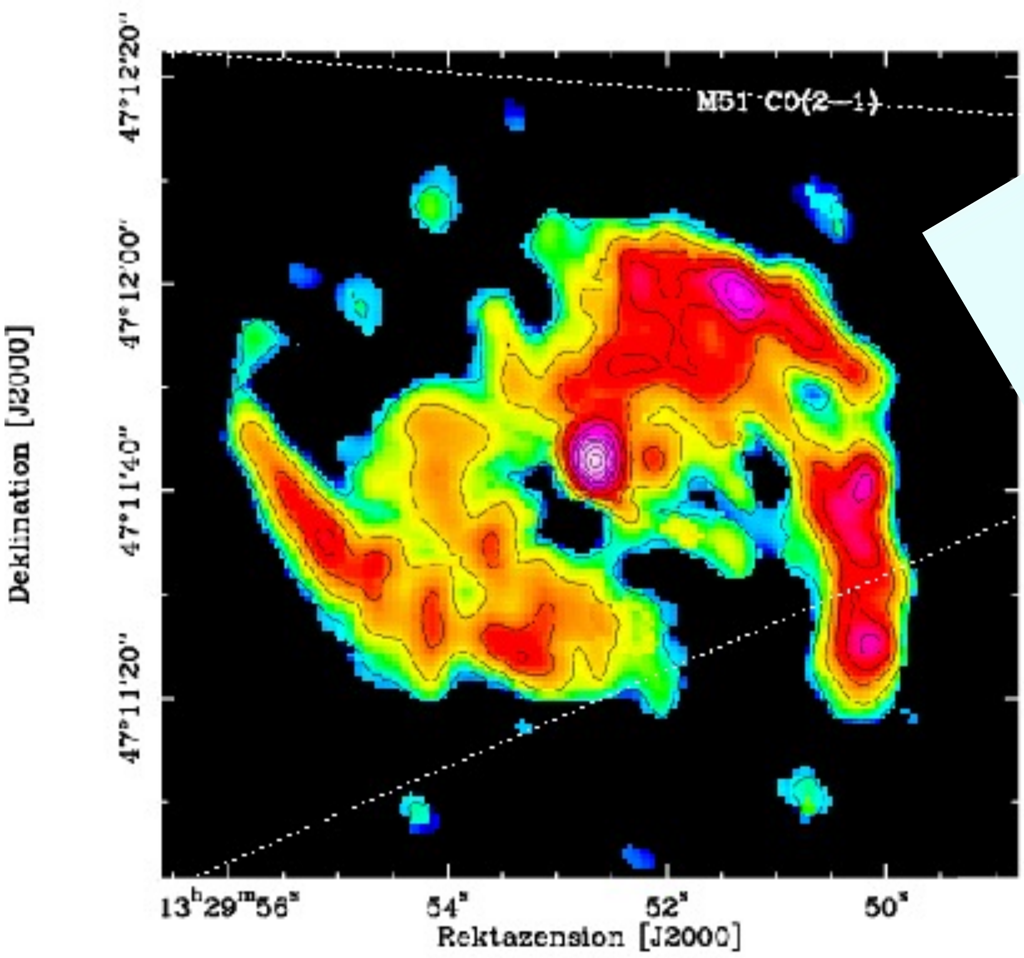

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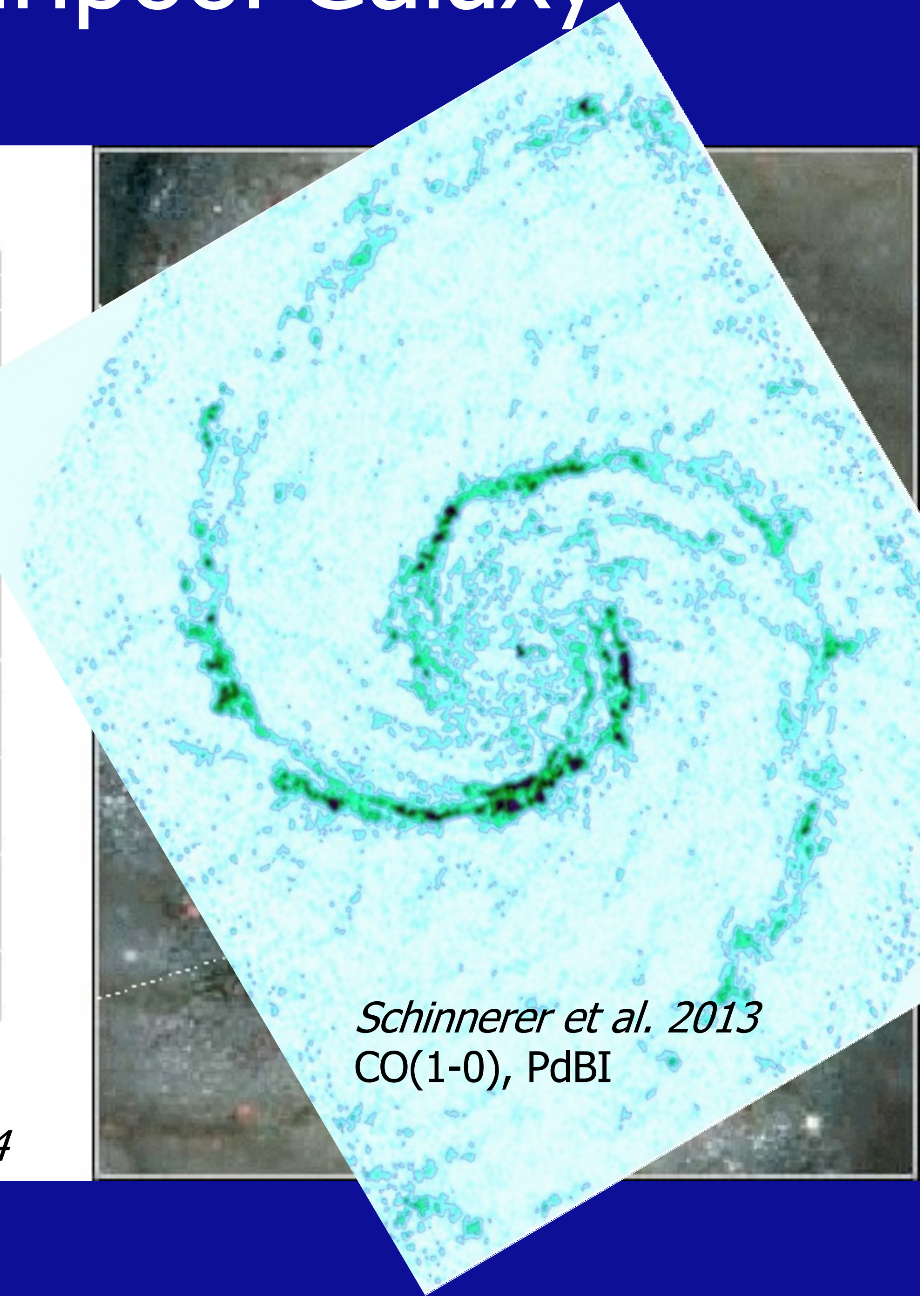
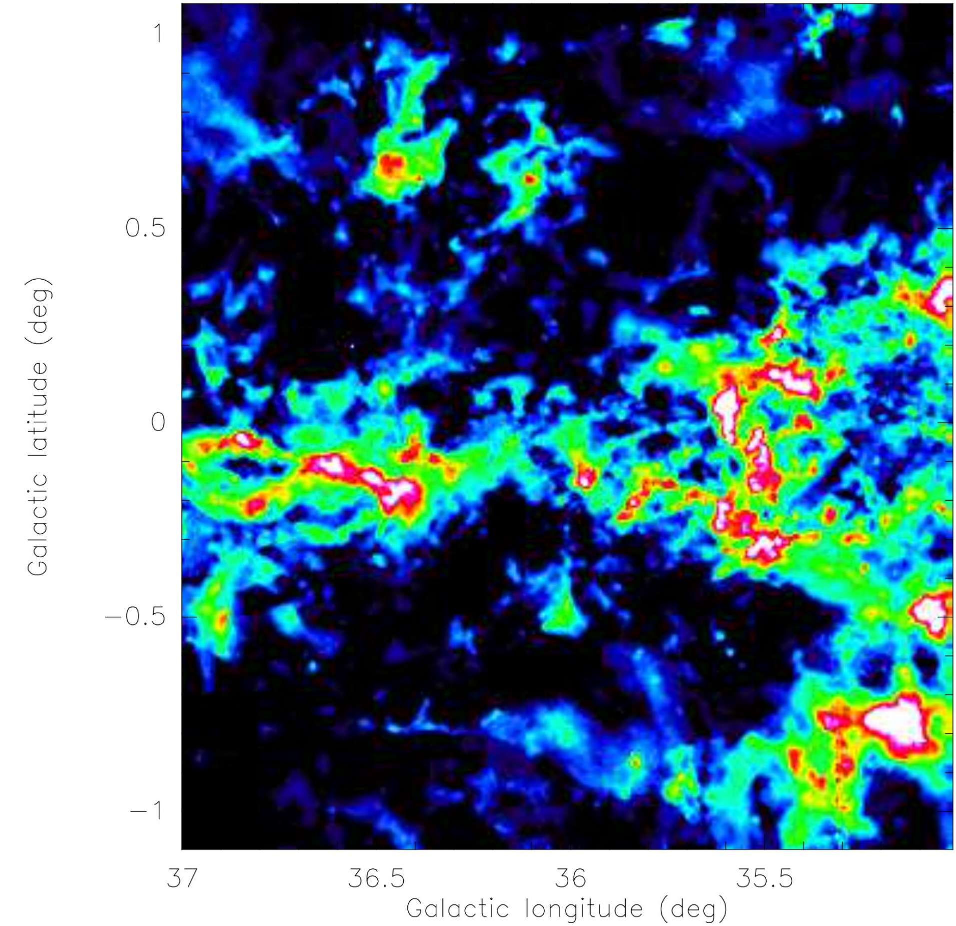


Schinnerer et al. 2013
CO(1-0), PdBI

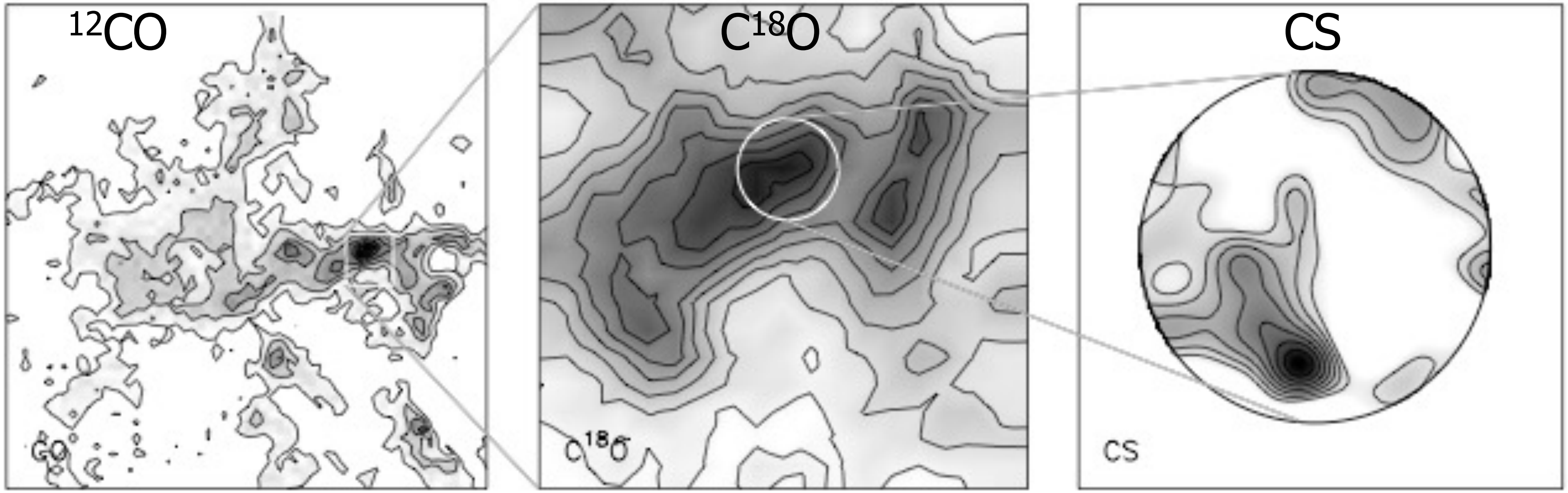
Giant Molecular Clouds



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 ~10^4cm^{-3}; Volume-averaged densities ~10^2cm^{-3}
--> highly clumped material

Hierarchical cloud structure

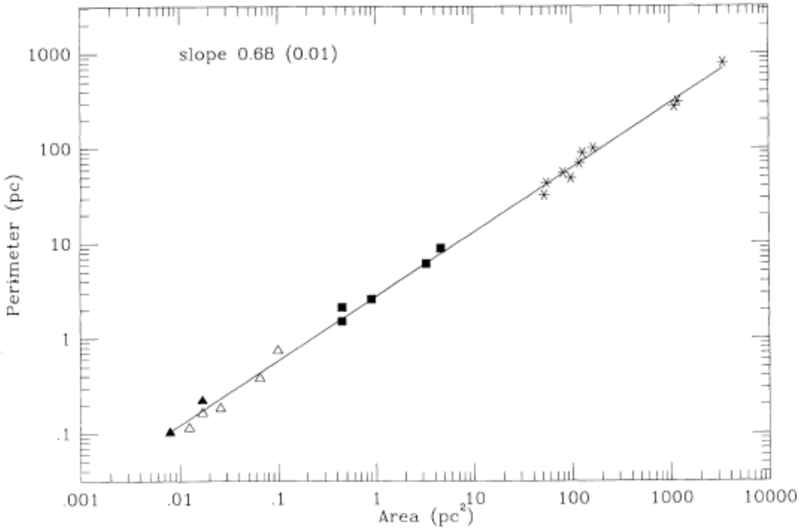


Rosette Molecular Cloud (Blitz & Williams 1999)

- Clouds fractal and self-similar from 100pc to 0.1pc

- Independent of star-forming or non-star-forming clouds

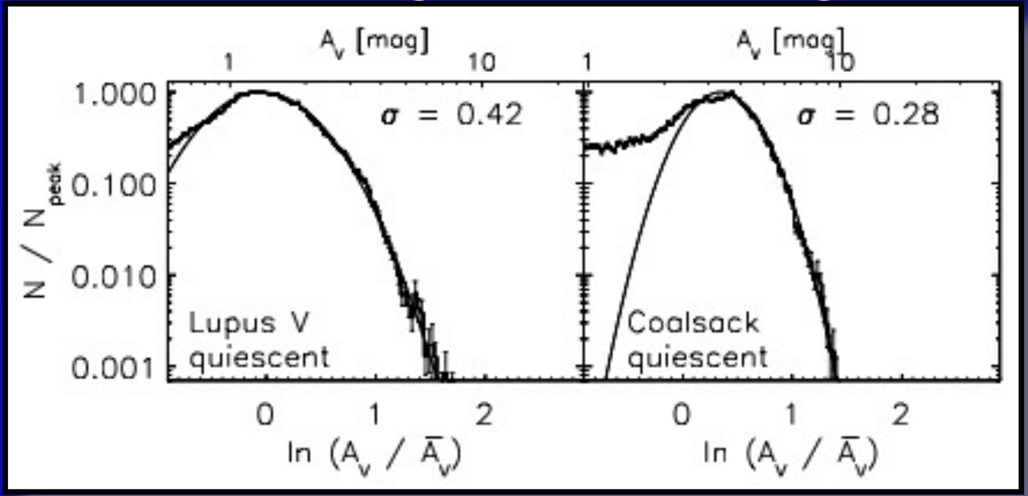
- Fractal dimension of perimeter P and area A: $P \sim A^{D/2}$ → $D \sim 1.4$

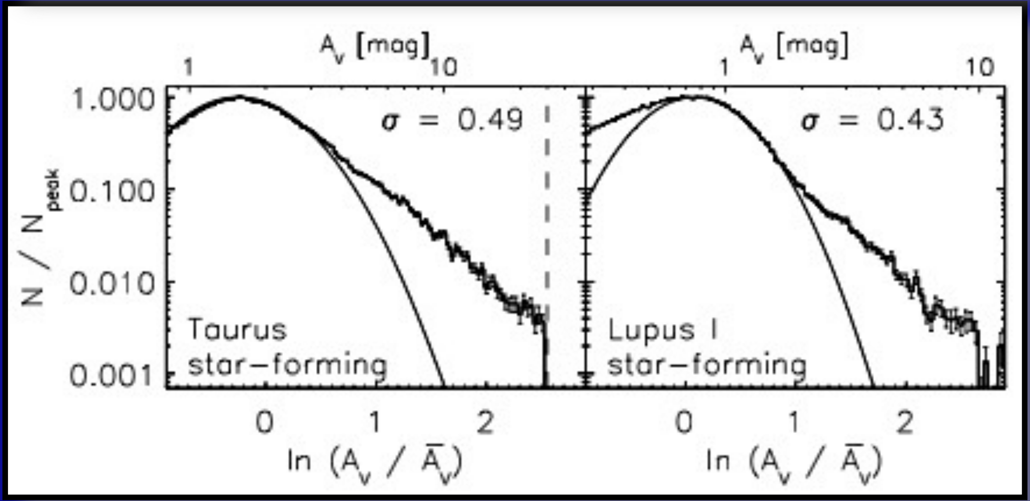


Probability density distributions (PDFs)

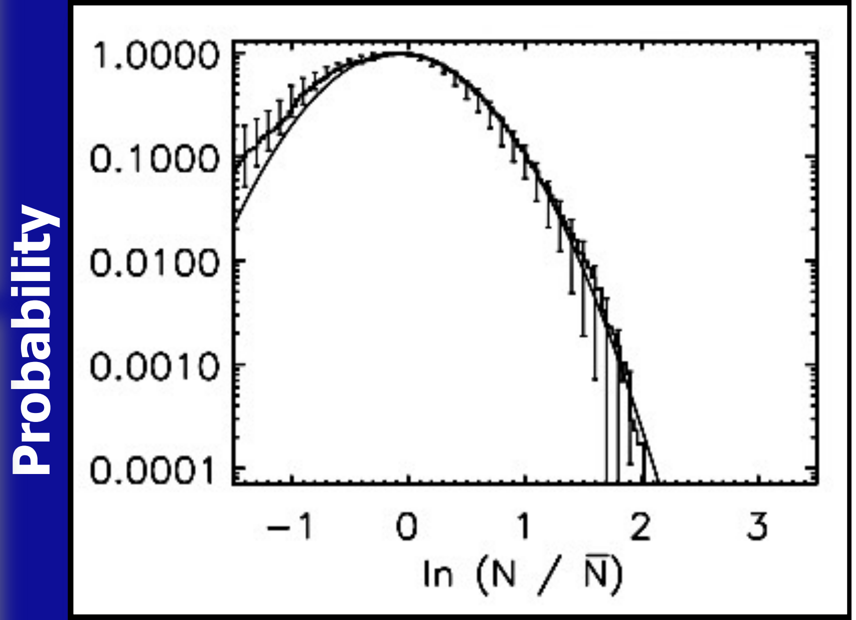
Observed distributions

Non-star-forming vs. star-forming clouds





Typical prediction for turbulent media

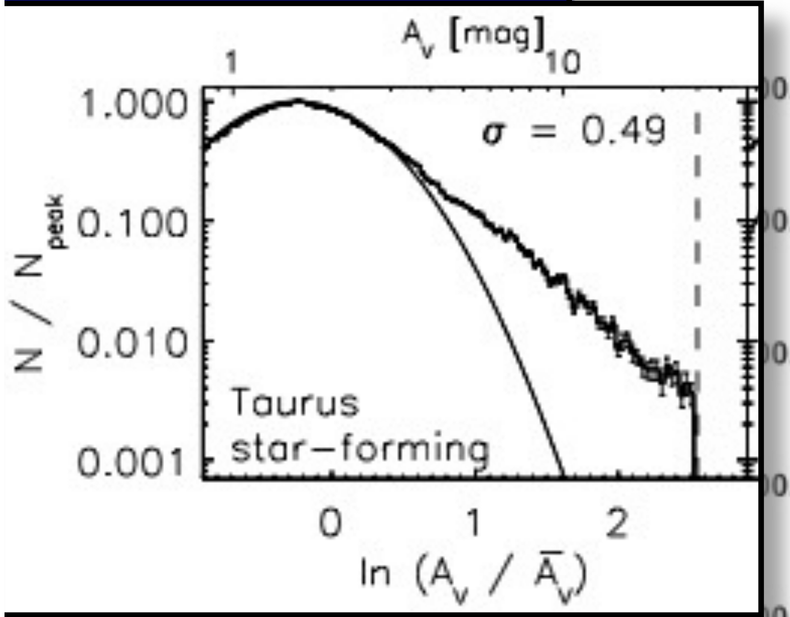


- non-star-forming: log-normal

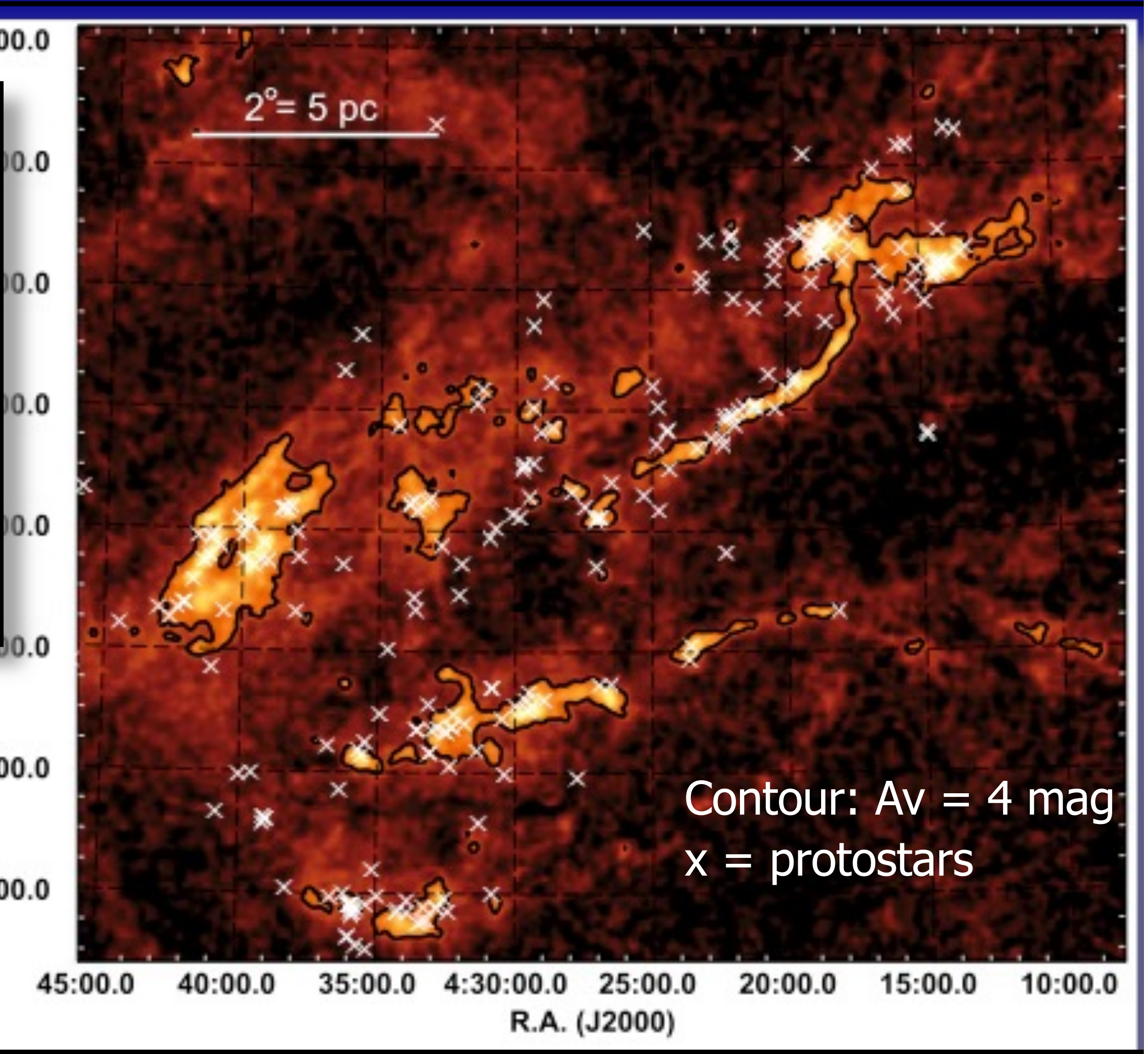
- star-forming: high column density excess

Kainulainen et al. 2009

Correlation of “tail” with star formation



Dust column density in Taurus, logarithmic color scale



Contour: Av = 4 mag

x = protostars

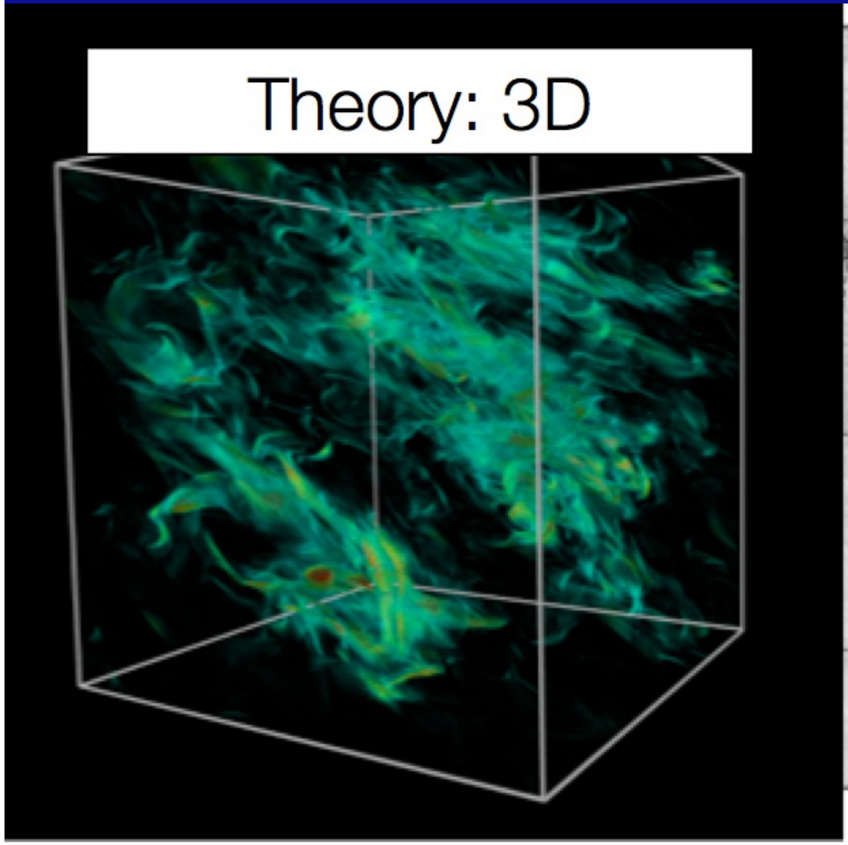
Excess tail can contain up to 50% of the mass

Kainulainen et al. 2009

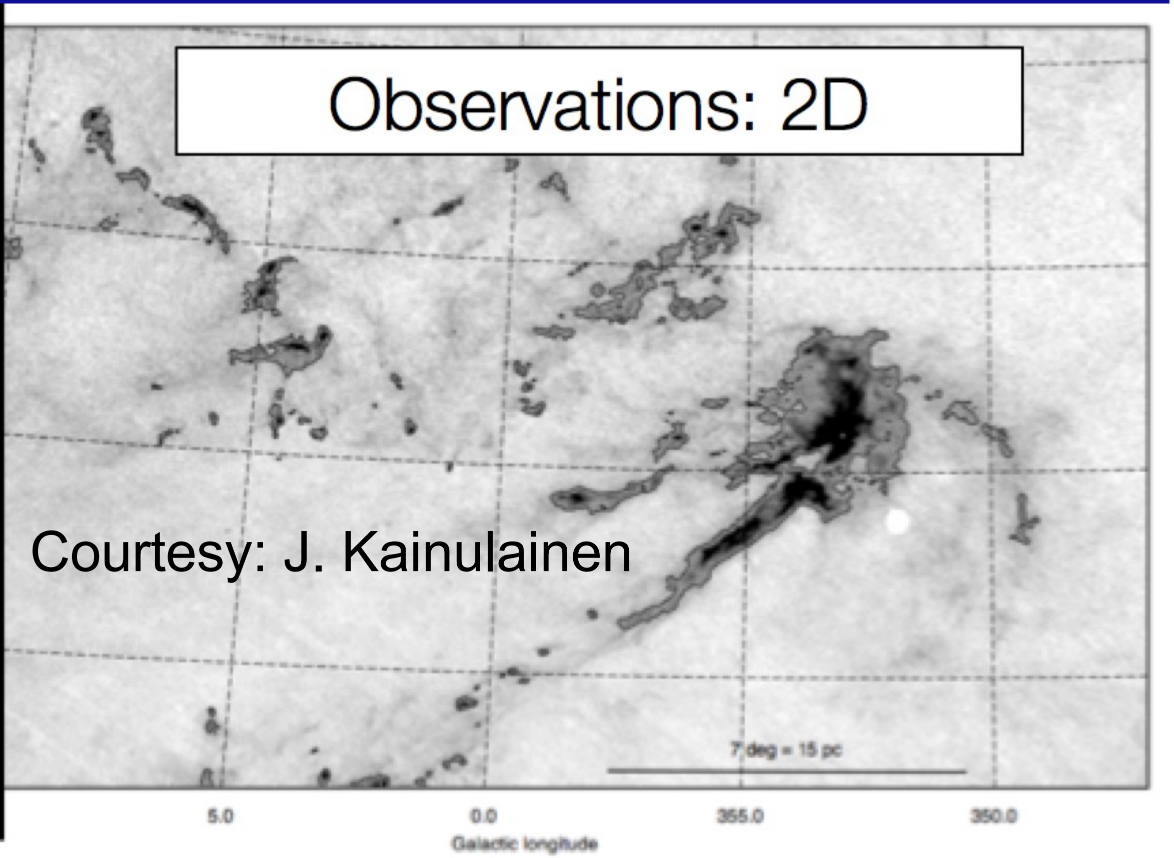
The 3D structure of molecular clouds?

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

- How to estimate the 3-dimensional structure?



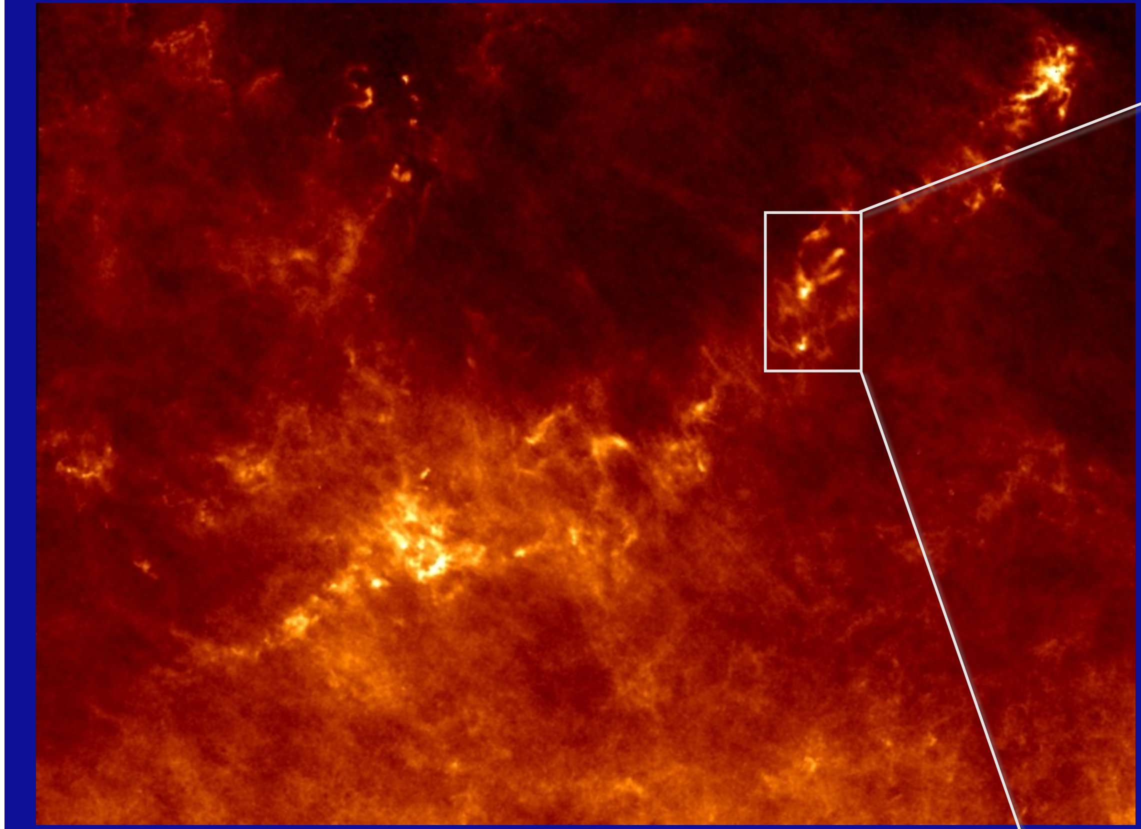
Theory: 3D



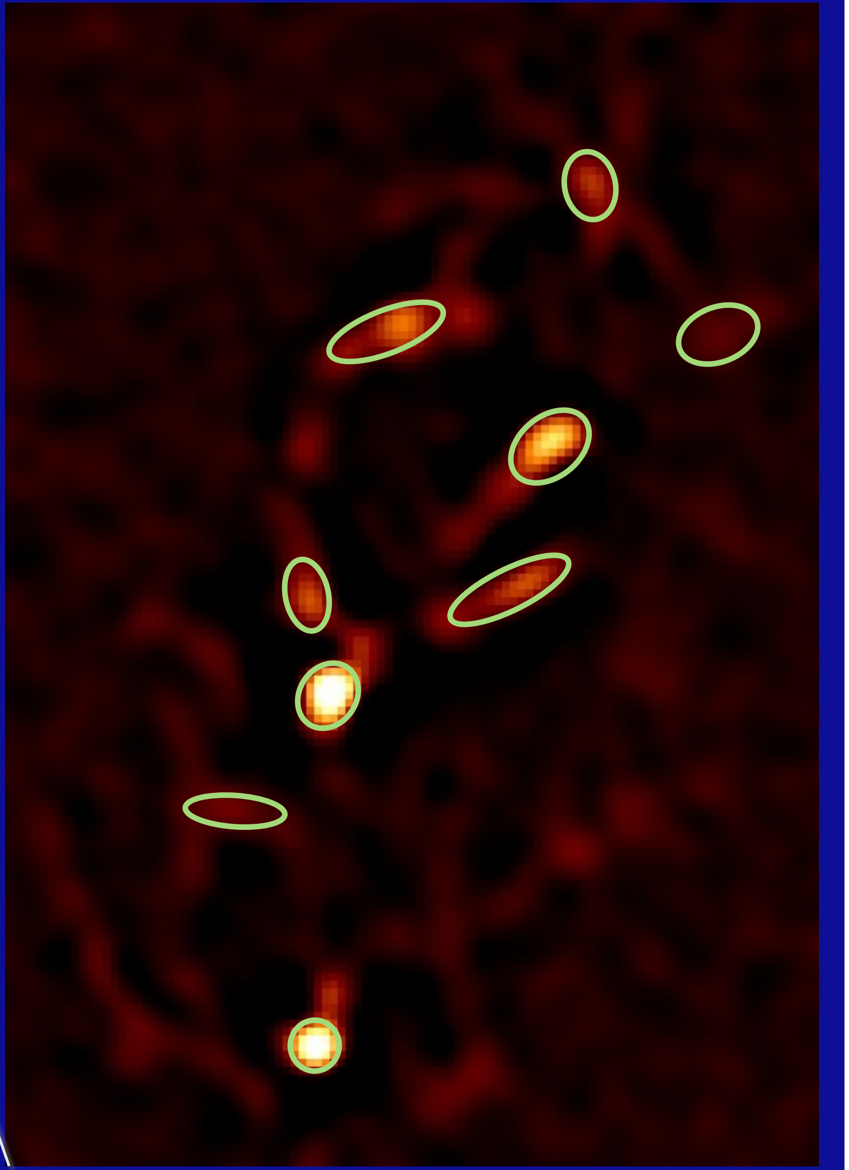
Observations: 2D

Courtesy: J. Kainulainen

The 3D structure of molecular clouds?



Column density map



Scale decomposition
and object recognition

Kainulainen et al. 2014

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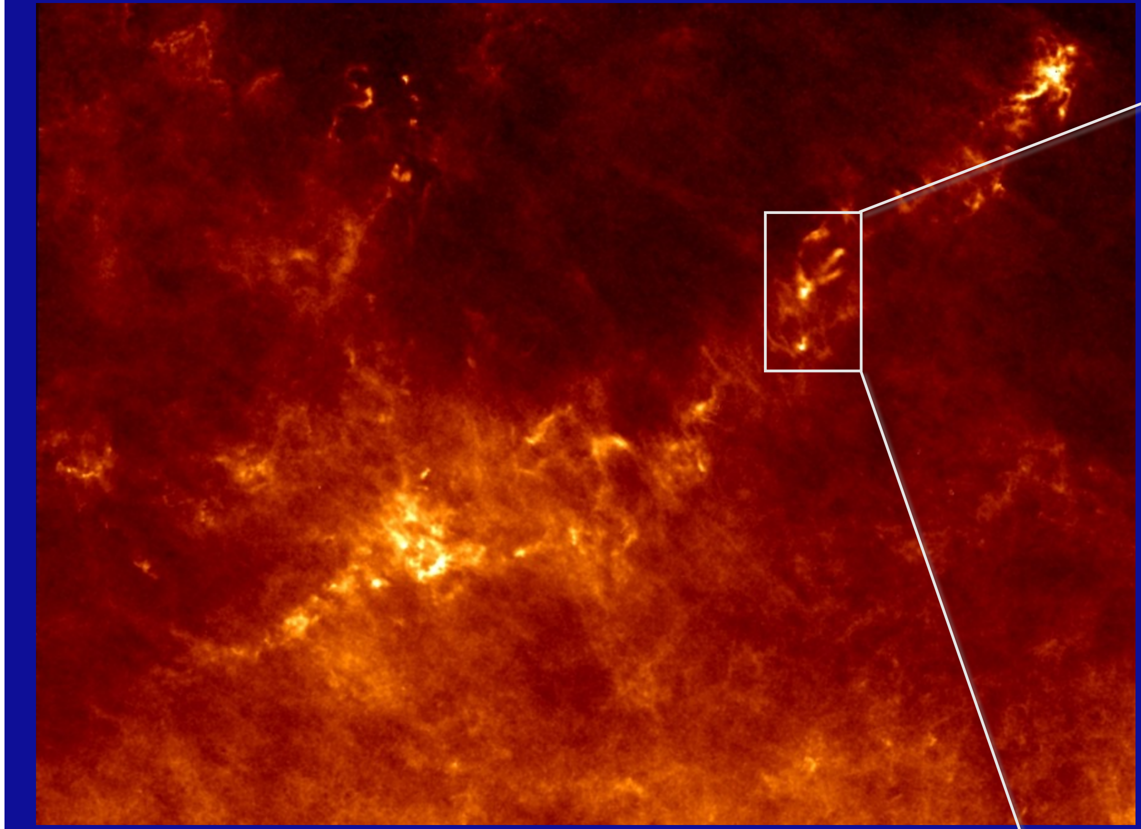

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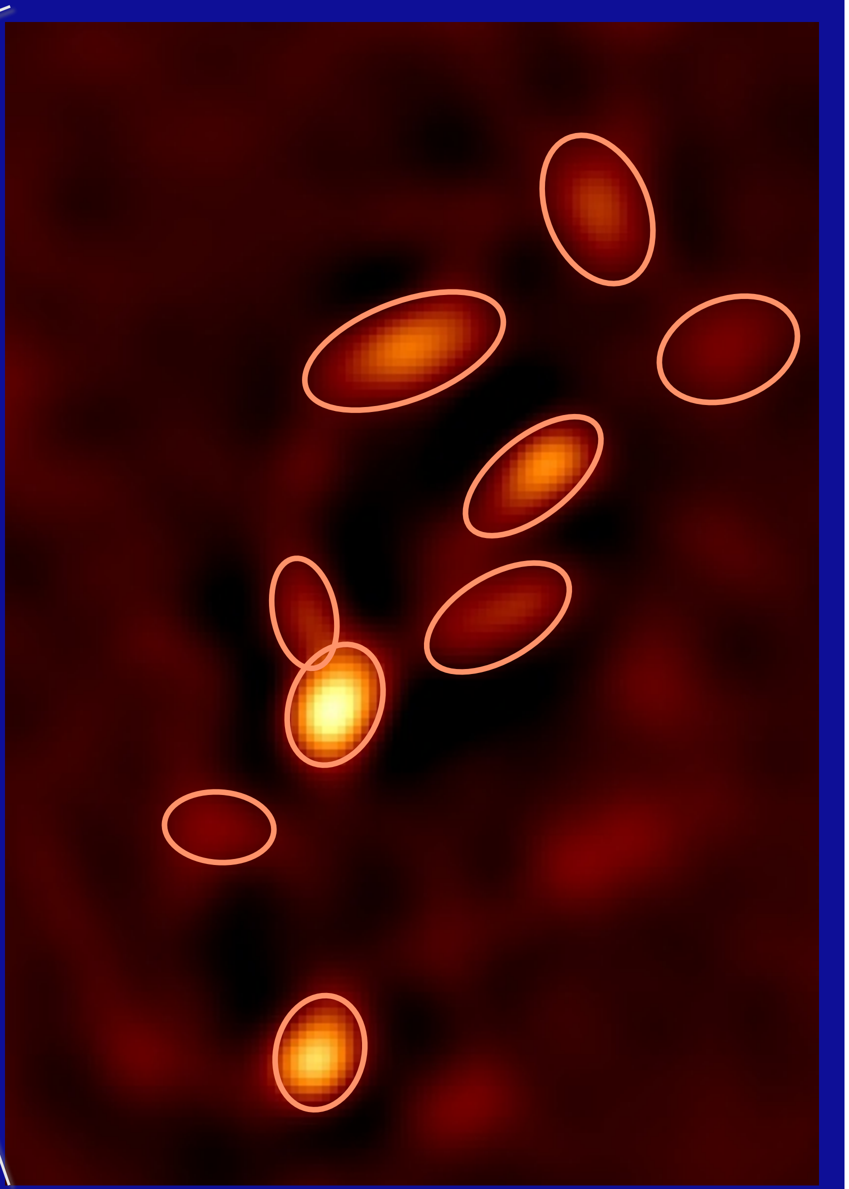

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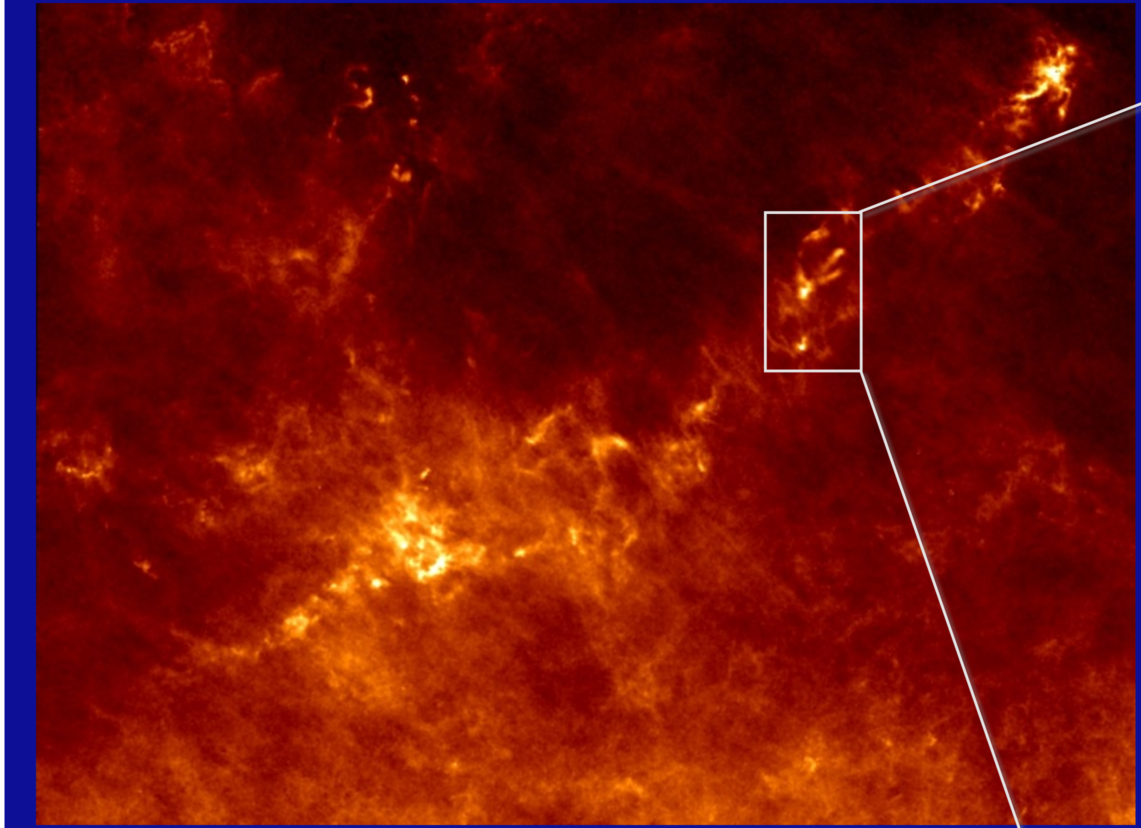

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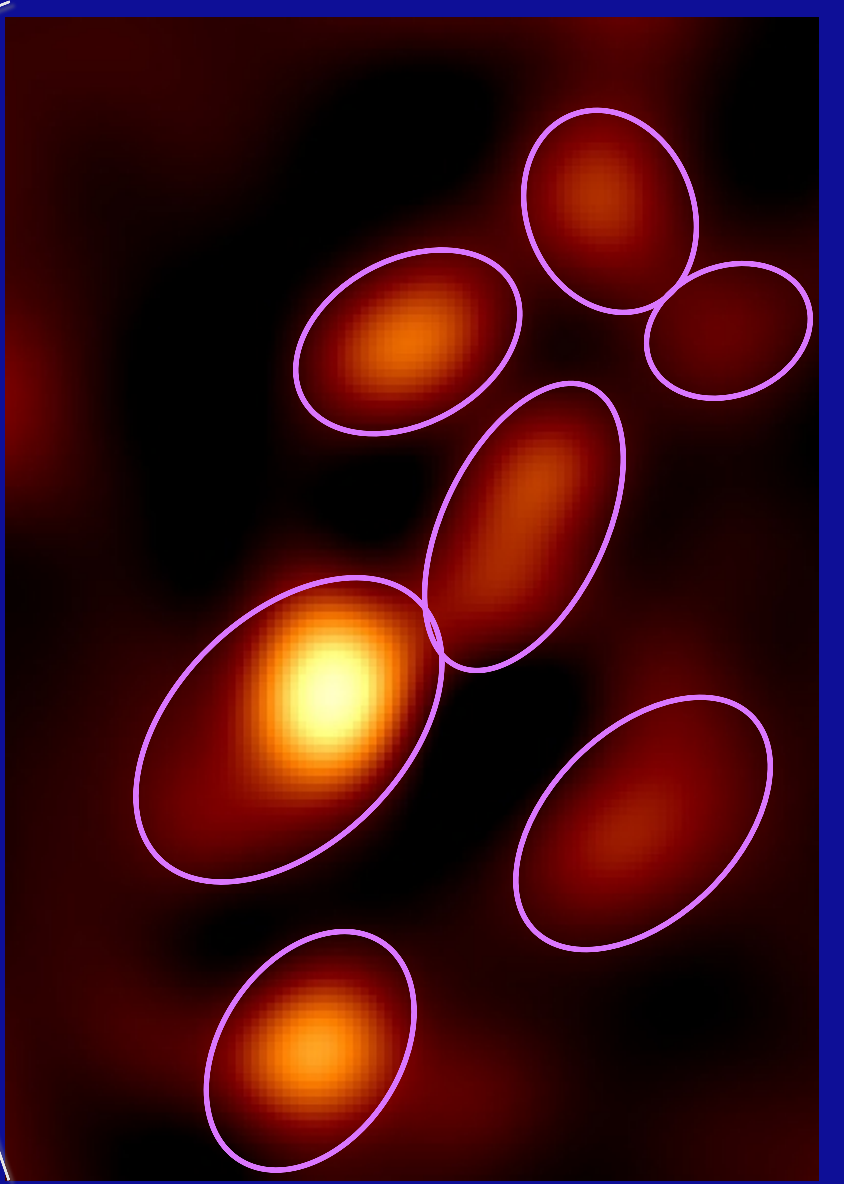

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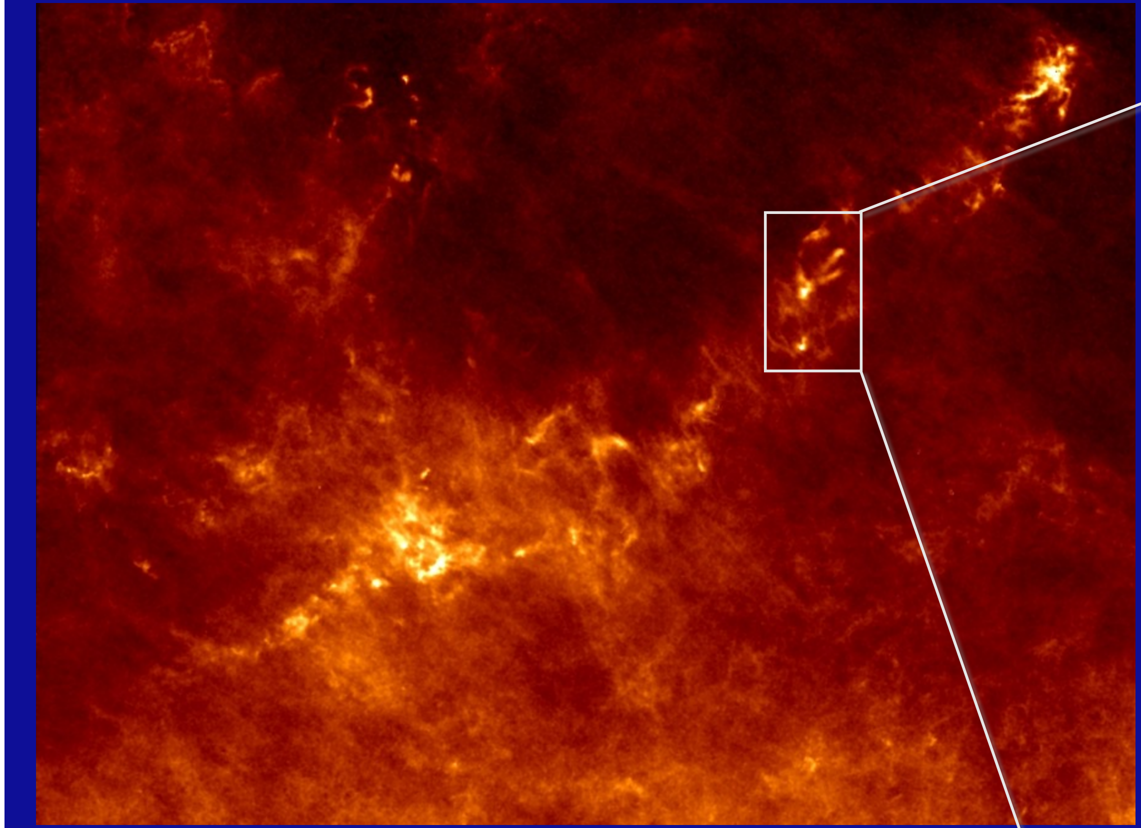

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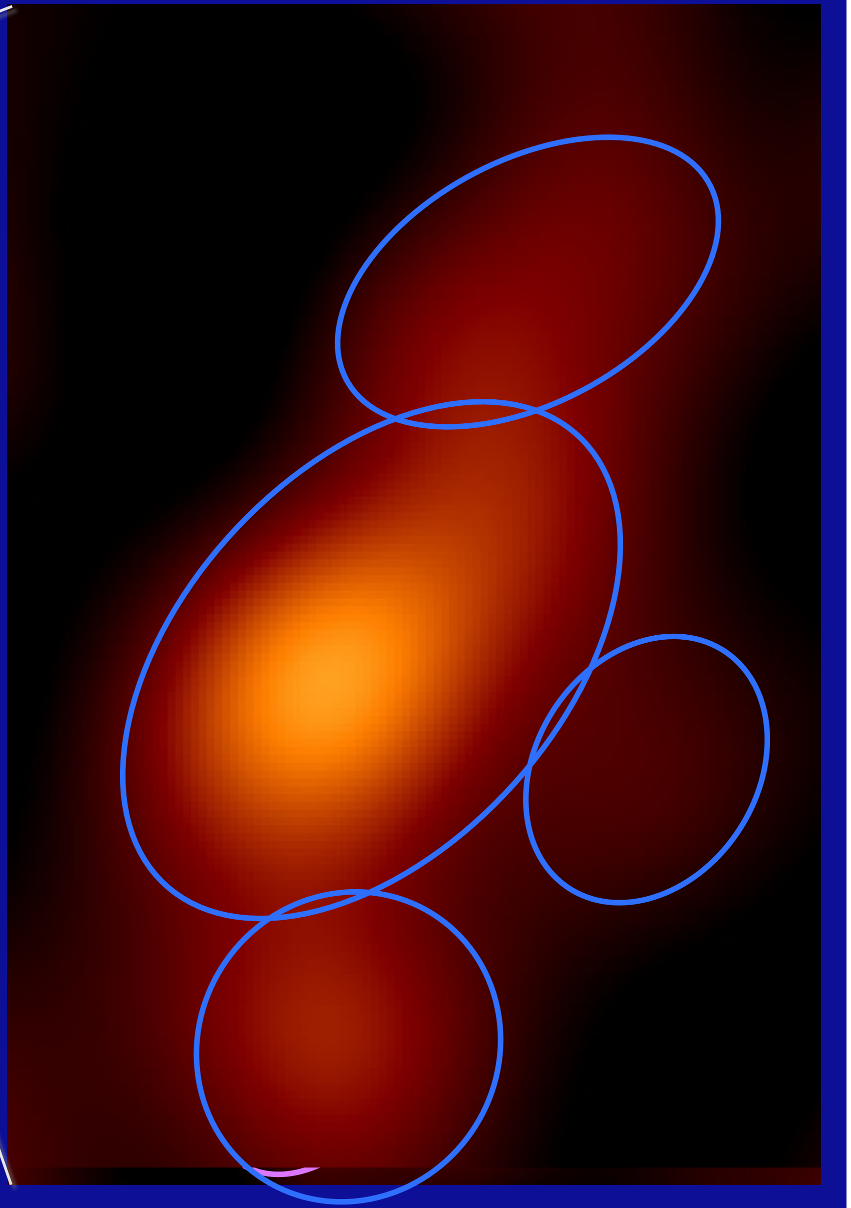

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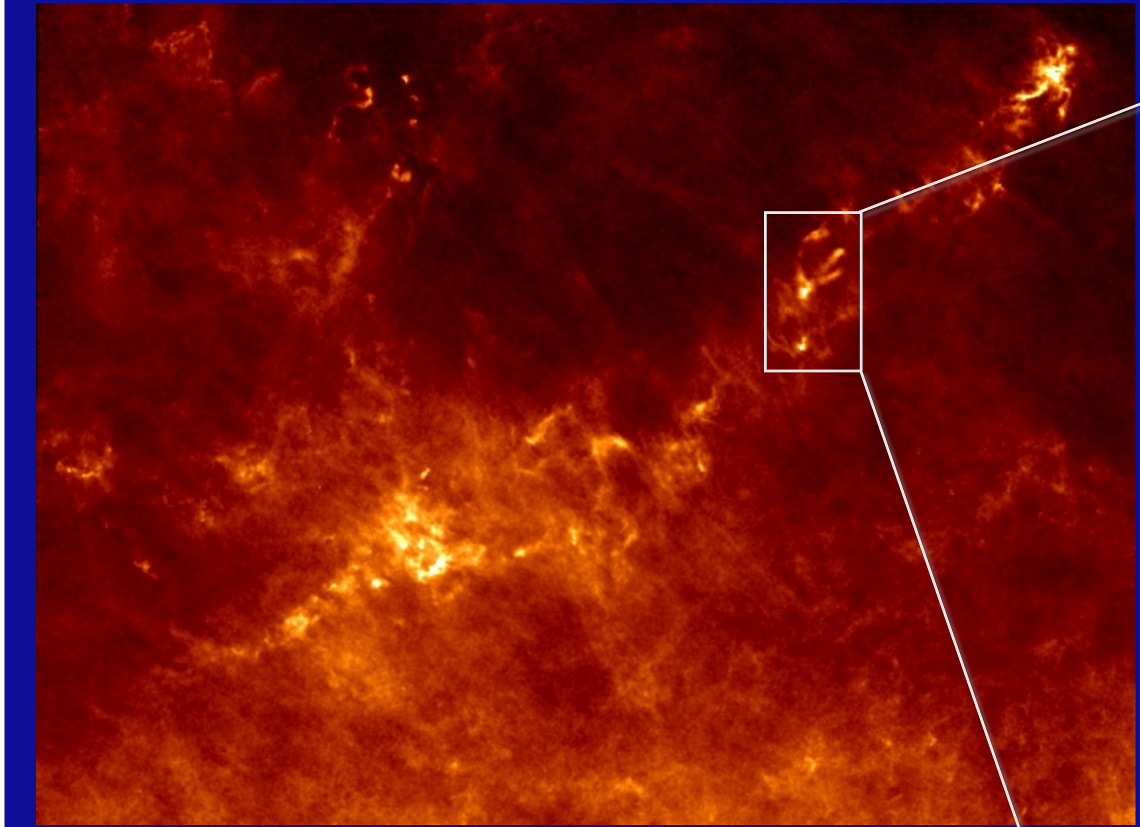

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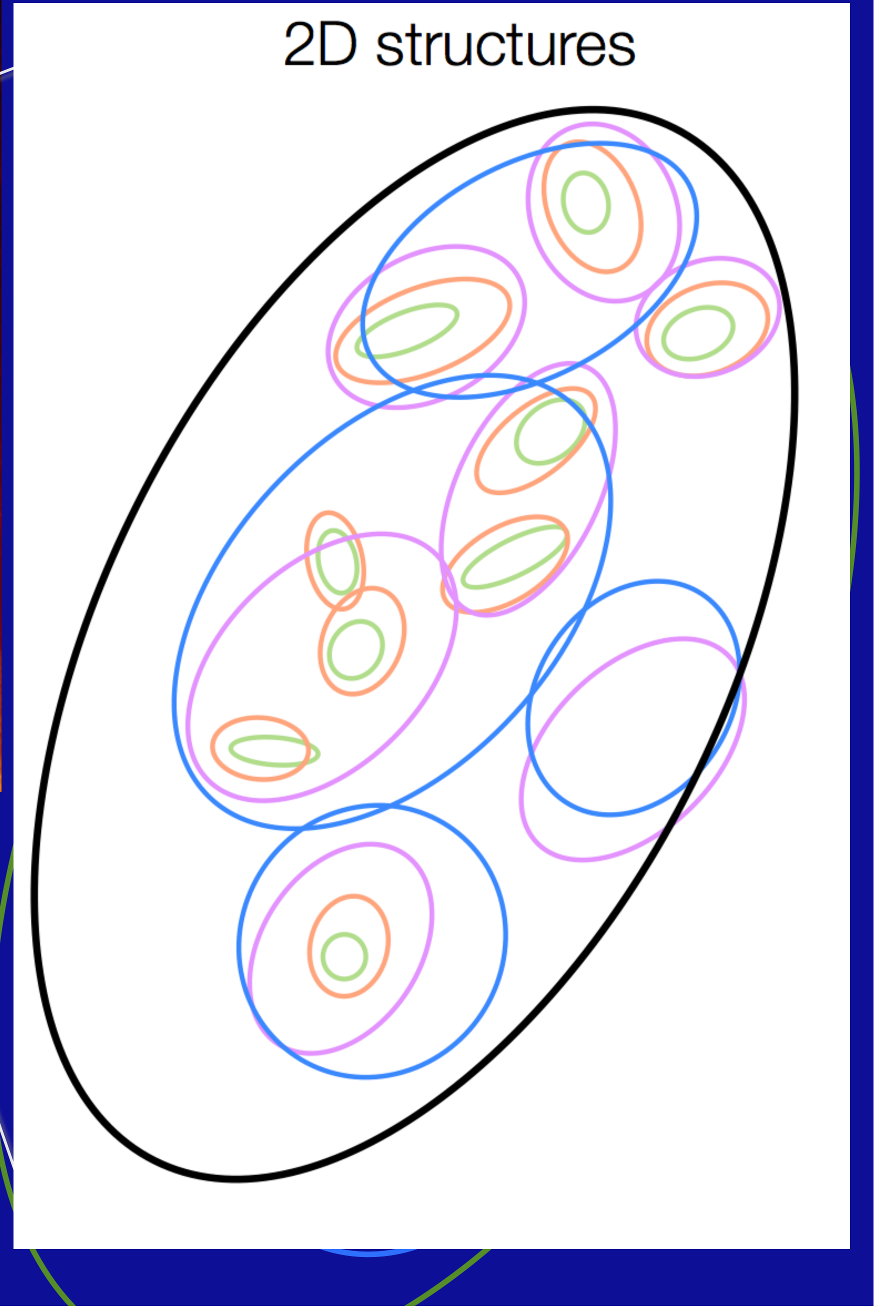

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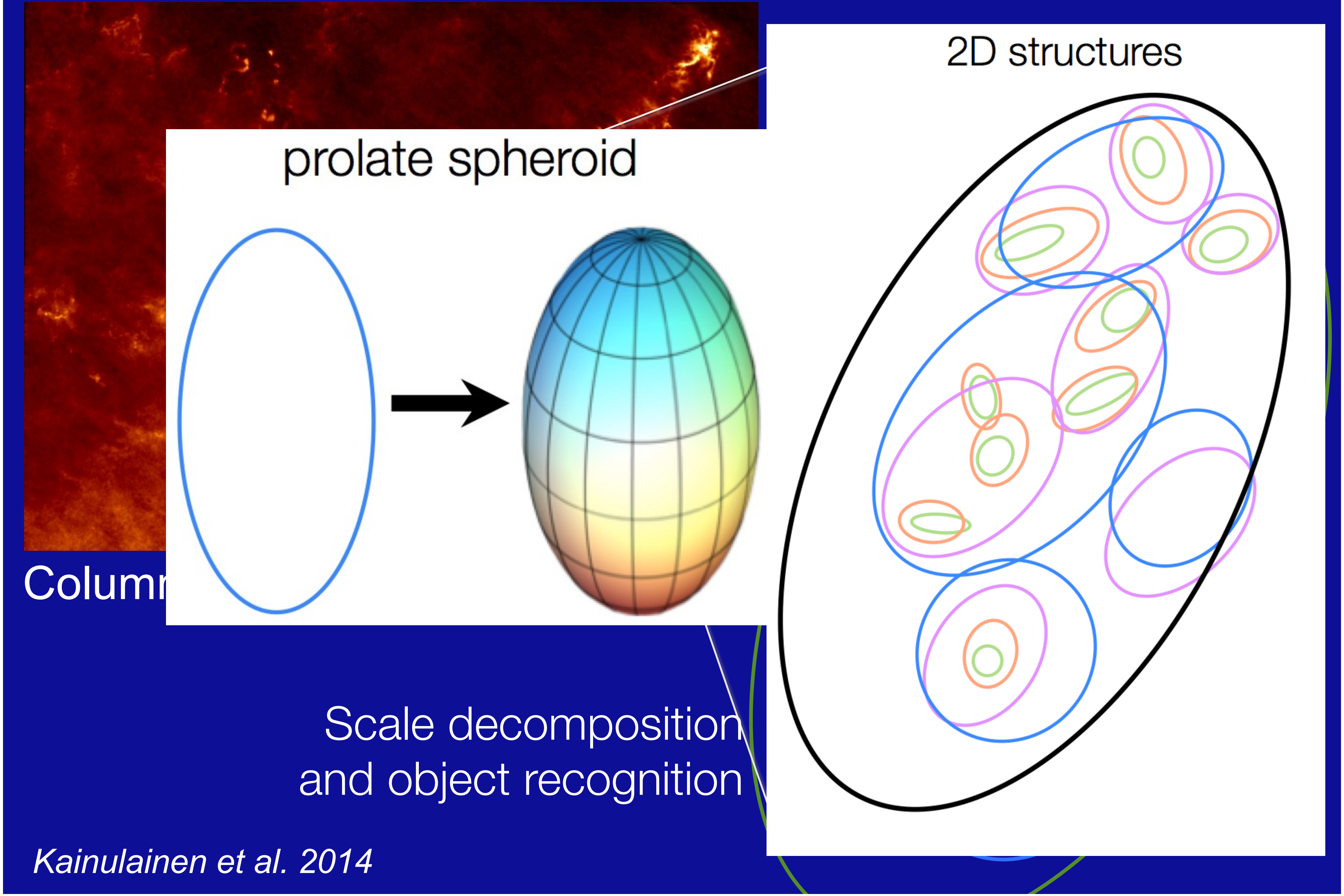
Kainulainen et al. 2014

The 3D structure of molecular clouds?



Colum

Scale decomposition
and object recognition

Kainulainen et al. 2014

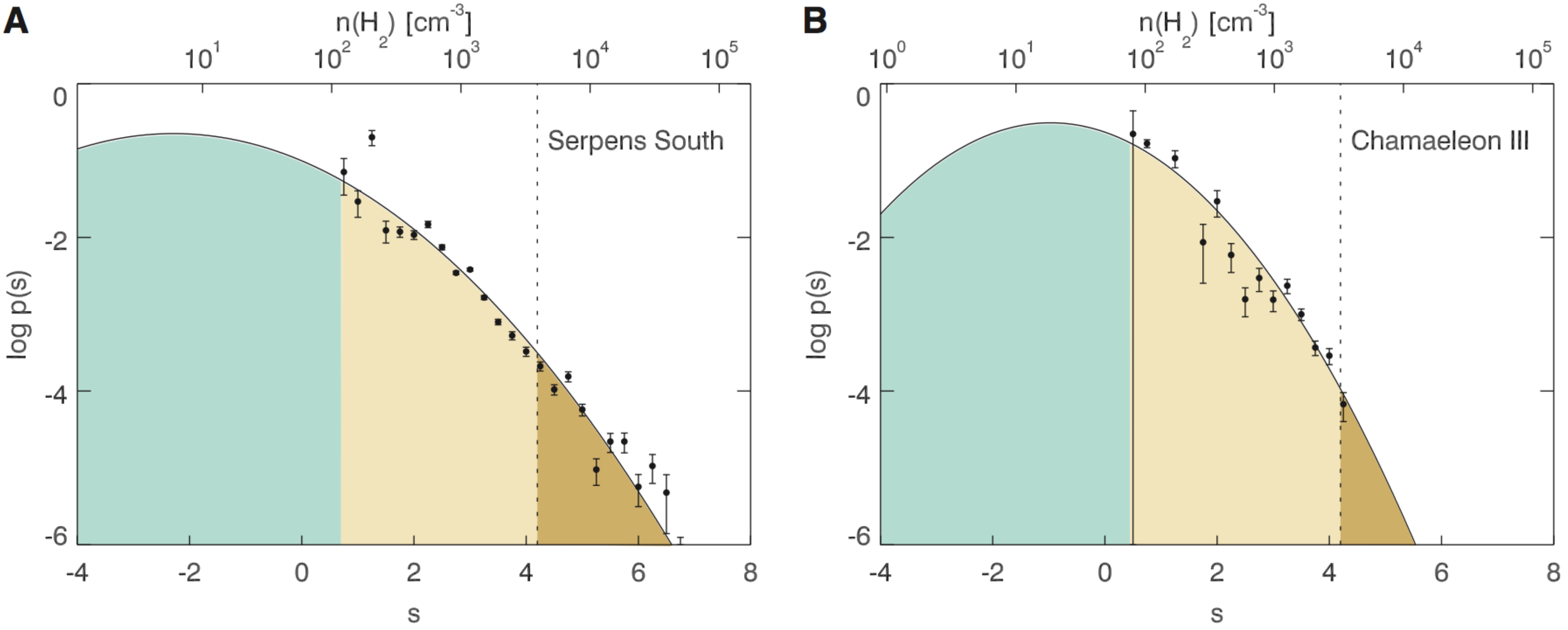
→ Density PDFs

Based on sample of Gould-Belt clouds

Dark brown: star-forming gas

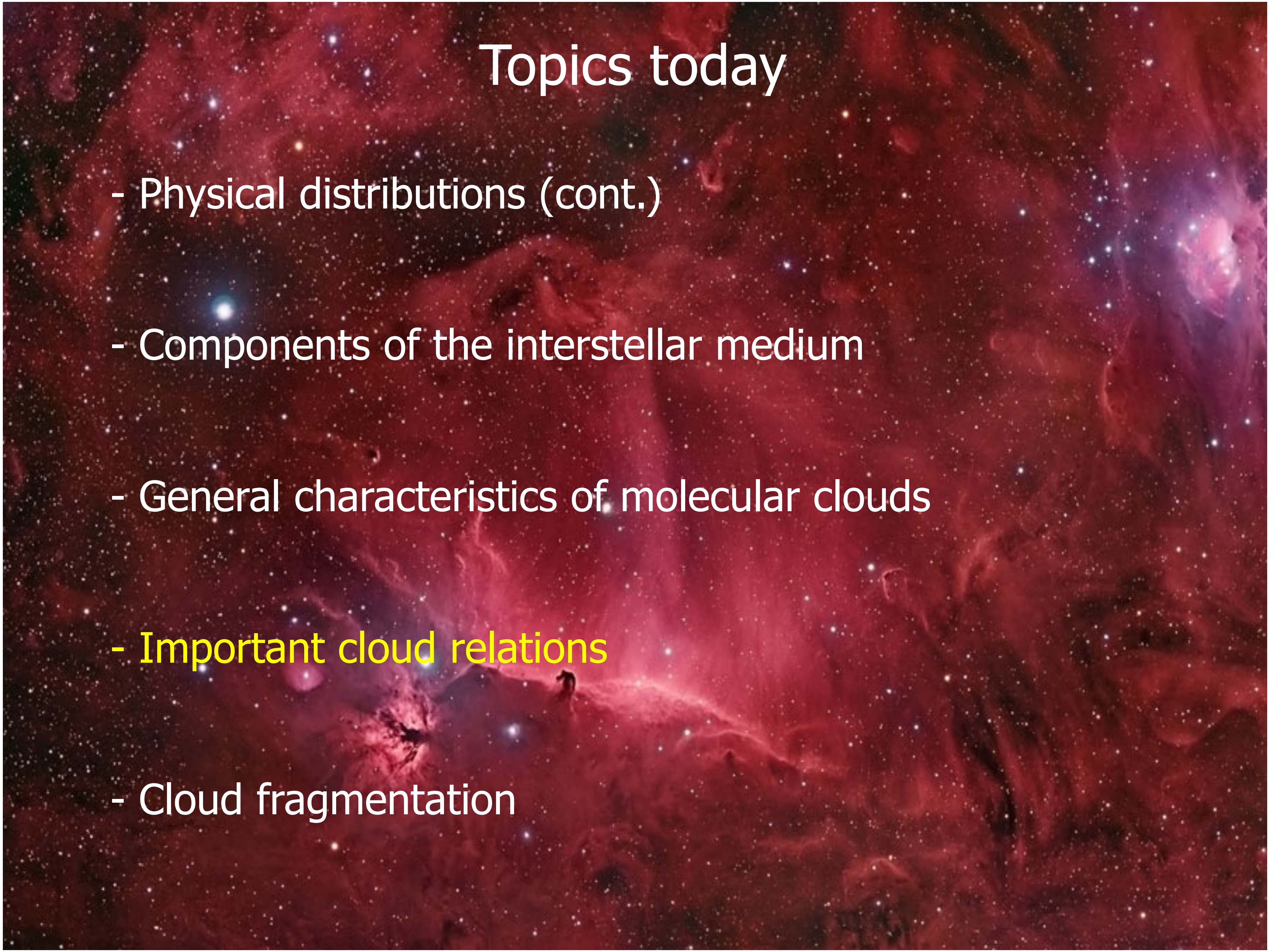
light brown: structures enveloping star-forming gas

Green: non-structured gas



- Direct comparison with theory
- Star formation density threshold → 5×10^{3}cm^{-3}

Kainulainen et al. 2014



Topics today

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

A GMC in viral 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: $m_{vir} = v^2 r/G$

Luminosity-mass relation

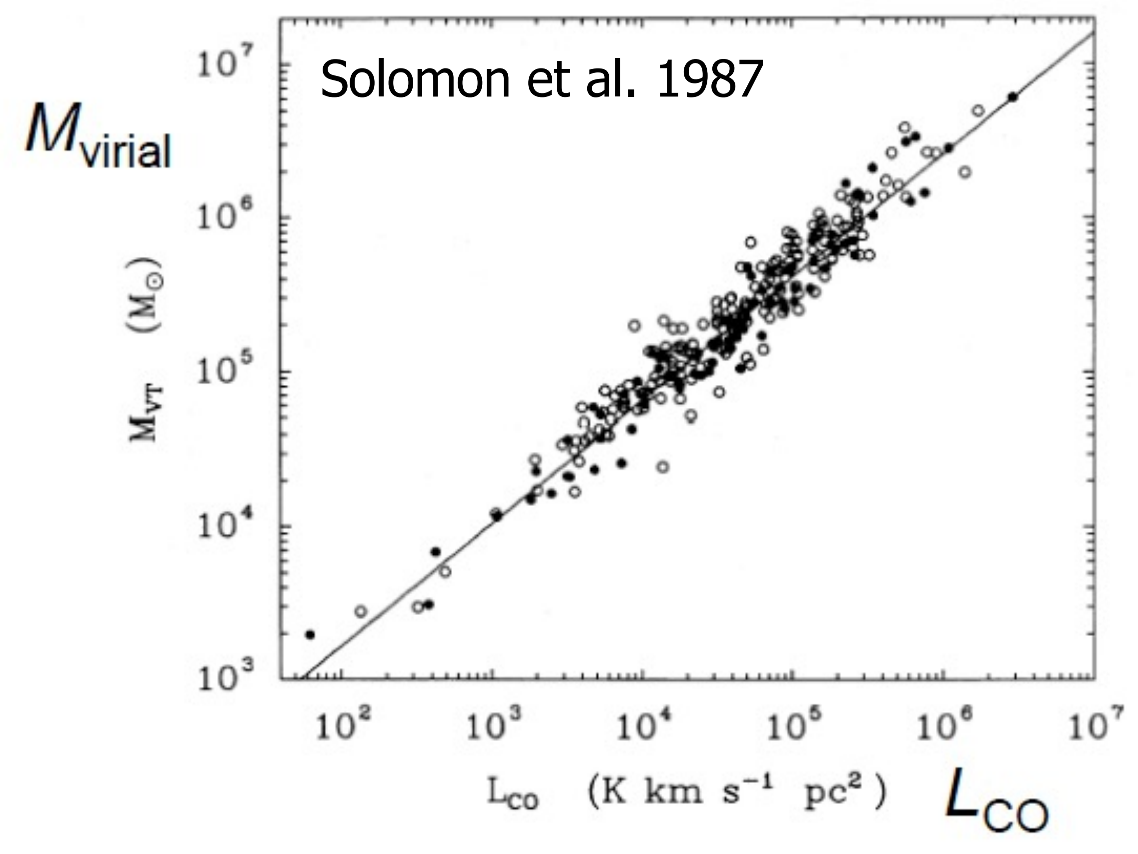
Integrated CO intensity: $I_{CO} = \int T(v)dv$

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 $m = 4/3\pi r^3\, \rho$

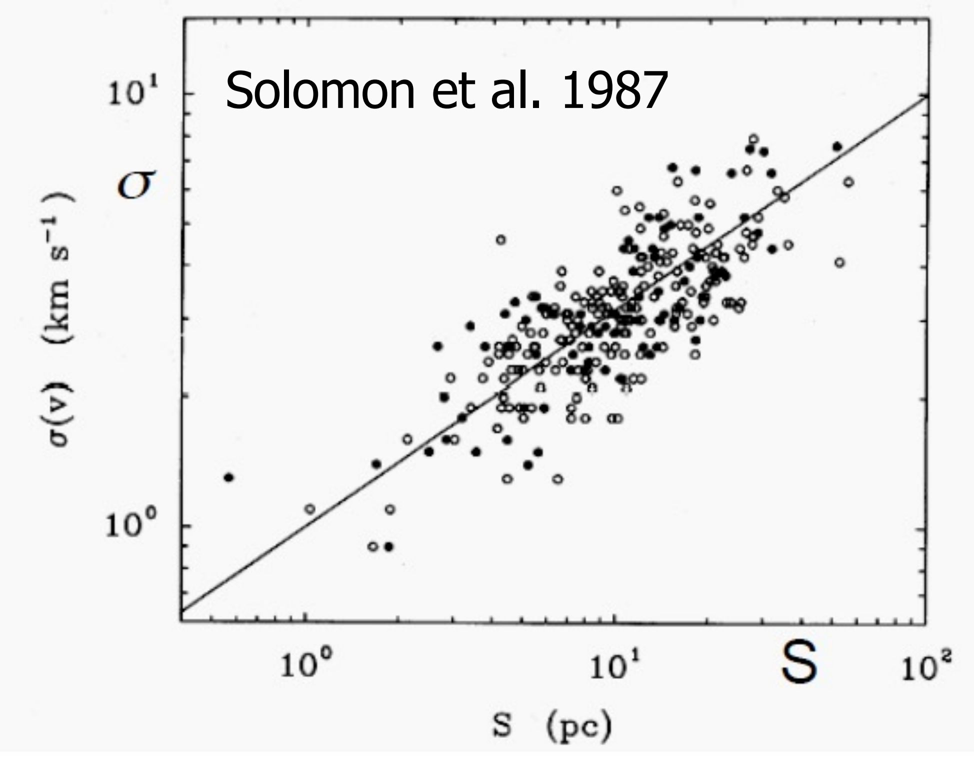
$\rightarrow L_{CO} = (3\pi G/(4\rho))^{1/2}\, T\, m$



Solomon et al. 1987

GMCs are roughly 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: $dv \approx r^{1/2}$
- Virial equilibrium: $dv \approx (Gm/r)^{1/2}$ → $m = dv^2 r/G$

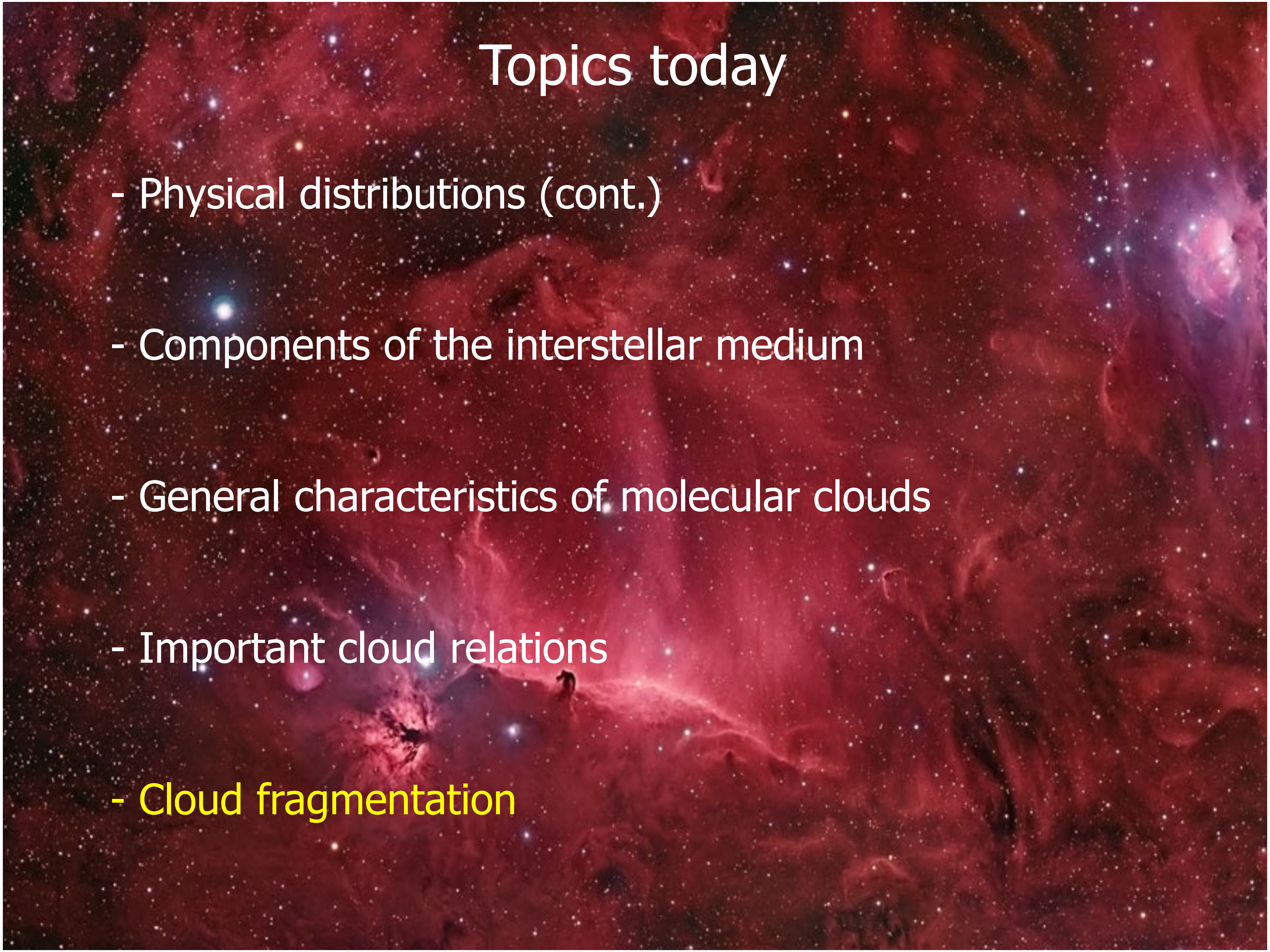
This leads to other relations:

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

→ $\rho \approx m/r^3 \approx dv^2/G * 1/r^2$

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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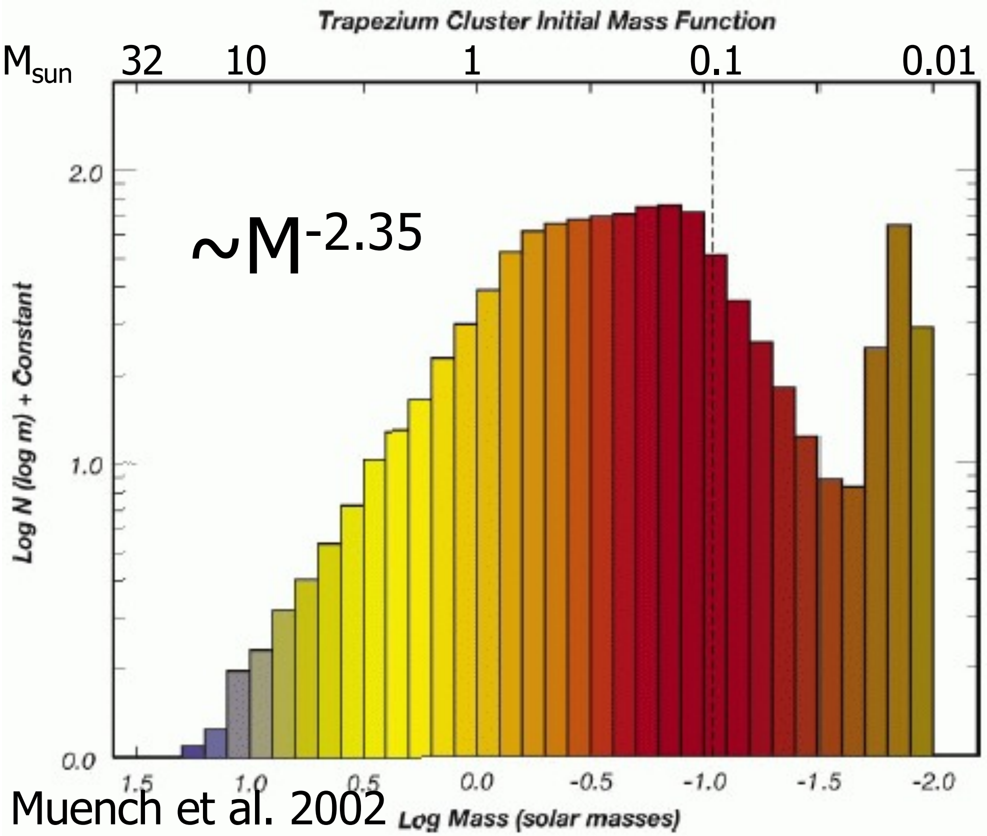
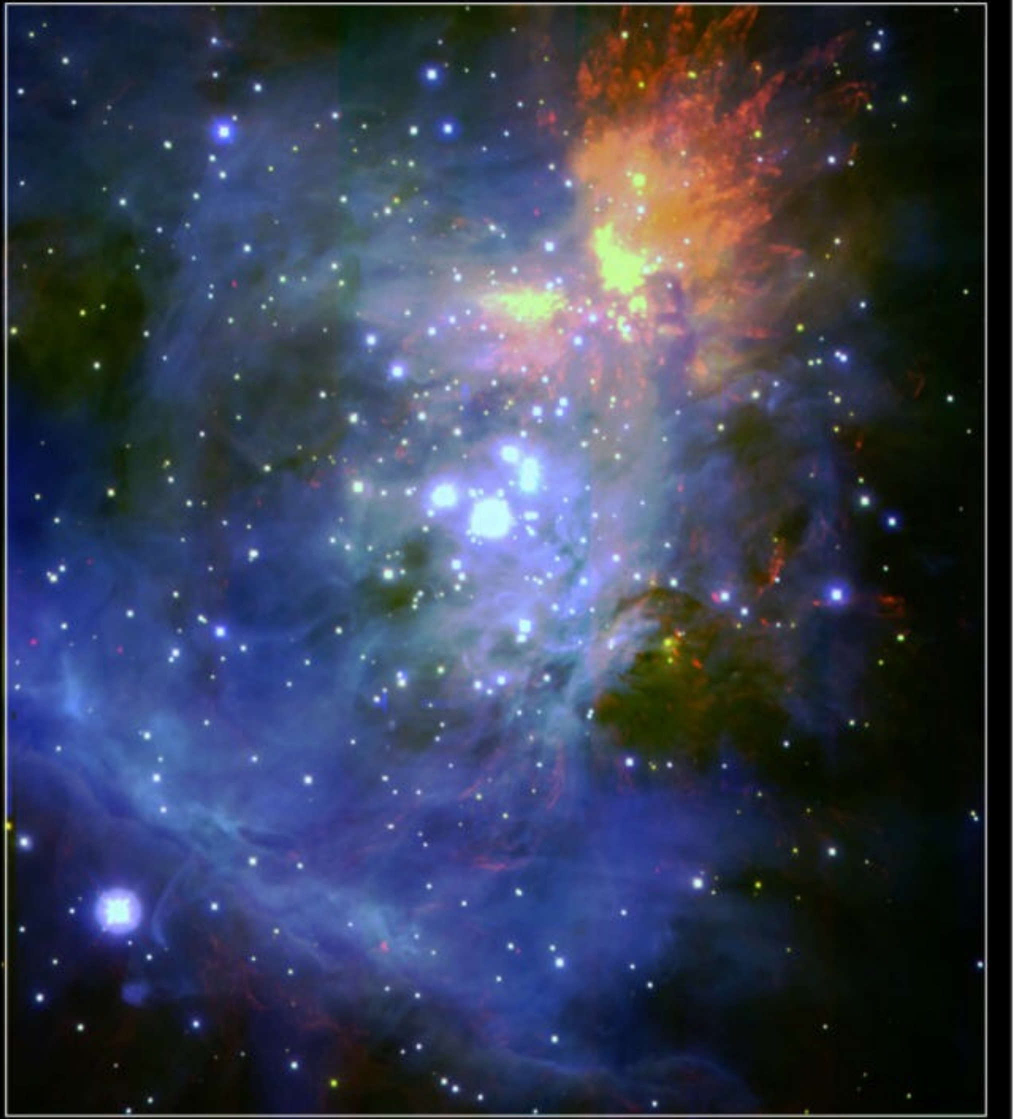
Clusters and the Initial Mass Function (IMF)



$\sim M^{-2.35}$

Muench et al. 2002



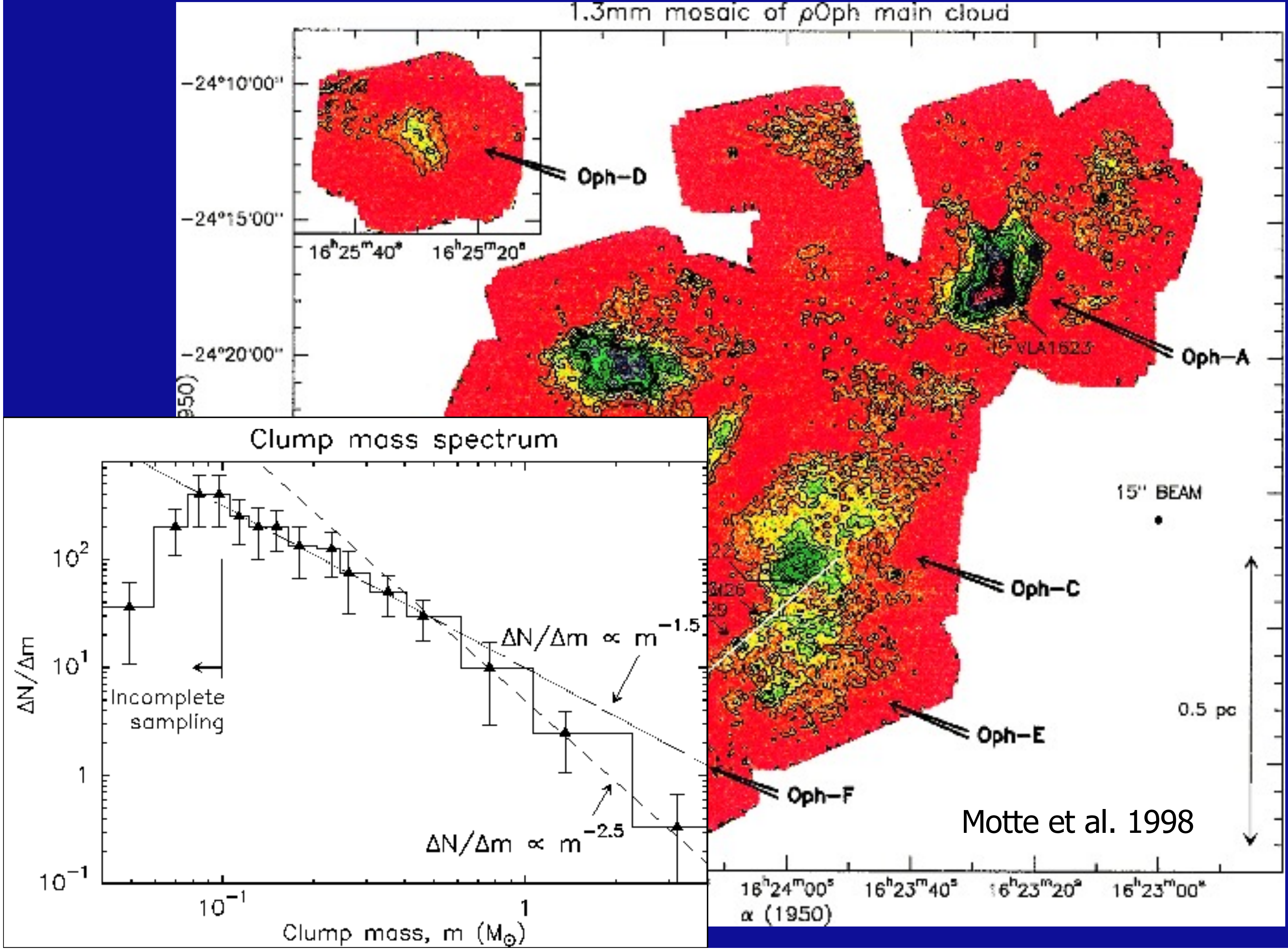
Orion Nebula

Subaru Telescope, National Astronomical Observatory of Japan

CISCO (J, K′ & H2 (v=1-0 S(1))

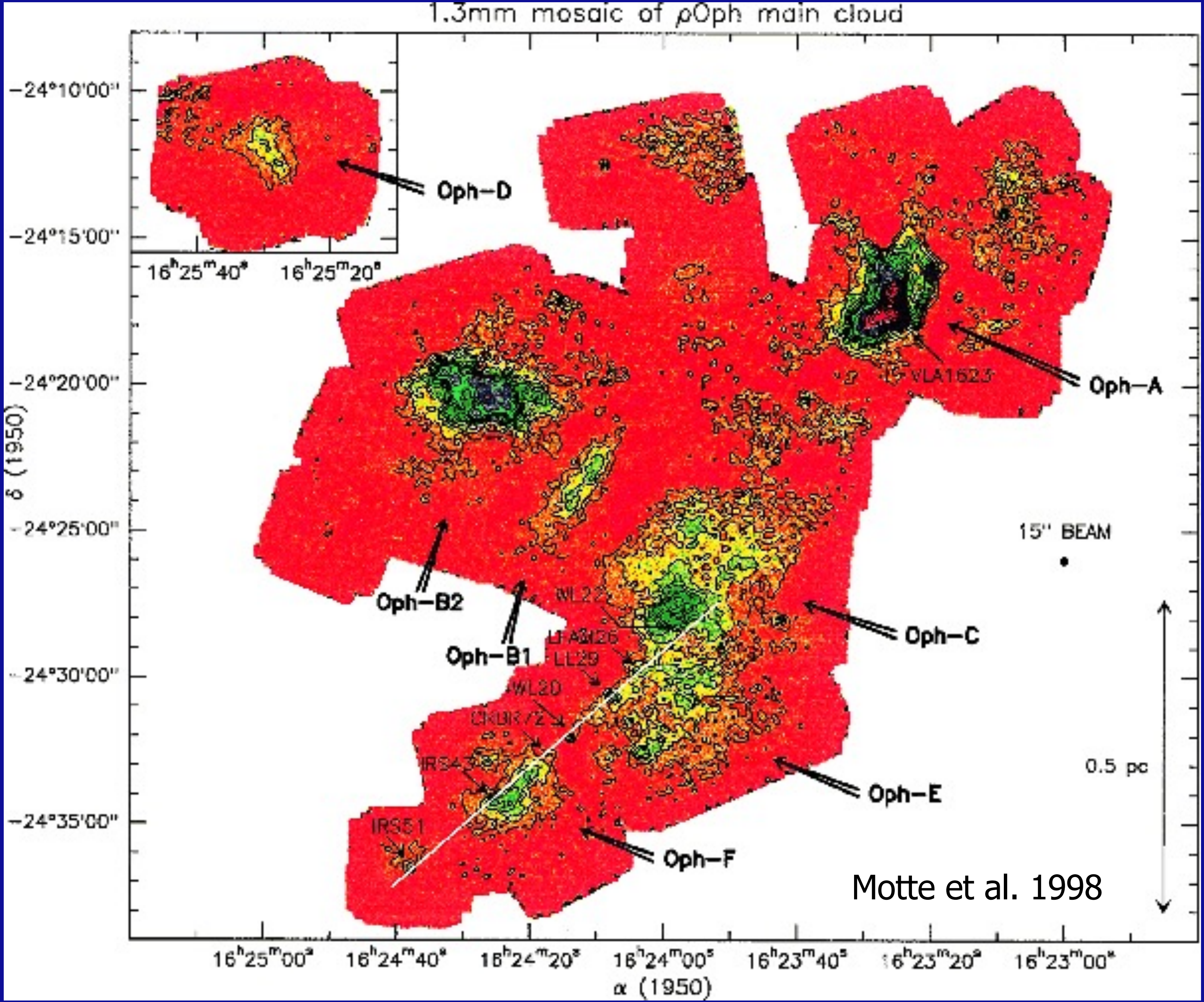
January 28, 1999

Pre-stellar core mass functions



Motte et al. 1998

Pre-stellar core mass functions

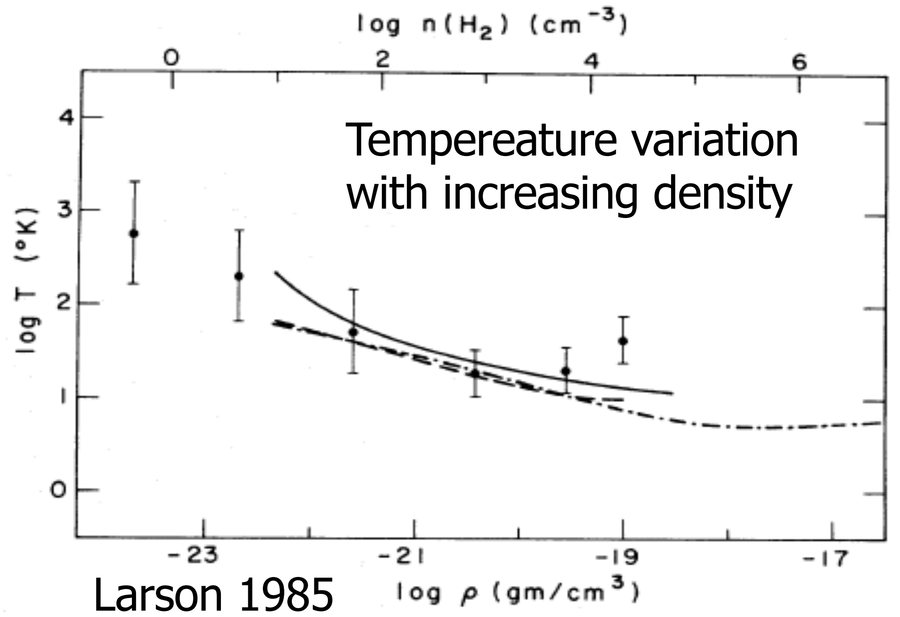


Motte et al. 1998

Characteristic mass defined by thermal physics

- Jeans mass depends on T:

$$M_J \sim a_t^3/\rho_0^{1/2} \sim T^{3/2}/\rho^{1/2}$$



Tempereature variation with increasing density

Larson 1985

- Low densities → T decreases with increasing ρ → regions cool efficiently
→ decreasing M_J suggests that fragmentation is favoured

- Further increasing ρ → gas thermally couples to dust and clouds, and become partially optically thick → Cannot cool well enough anymore
→ temperature slightly 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

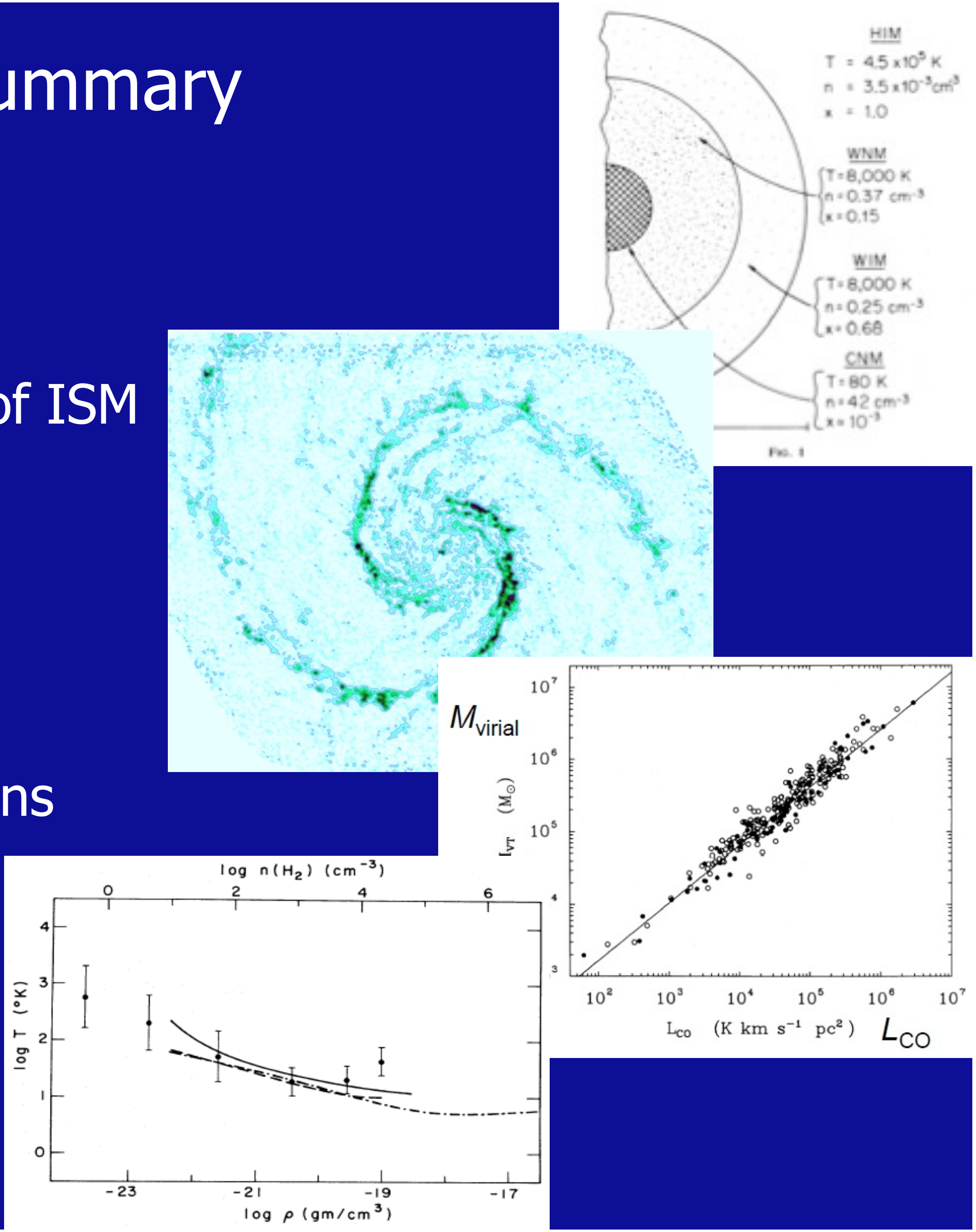
- Physical distribution

- Different components of ISM

- Basic characteristics

- Important cloud relations

- Cloud fragmentation



Sternentstehung - Star Formation

Winter term 2024/2025

Henrik Beuther, Thomas Henning & Caroline Gieser

15.10 Today: Introduction & Overview (Beuther)
22.10 Physical processes I (Beuther)
29.10 --
05.11 Physcial processes II (Beuther)
12.11 Molecular clouds as birth places of stars (Beuther)
19.11 Molecular clouds (cont.), Jeans Analysis (Henning)
26.11 Collapse models I (Beuther)
03.12 Collapse models II (Beuther)
10.12 Protostellar evolution (Gieser)
17.12 Pre-main sequence evolution & outflows/jets (Henning)
07.01 Accretion disks I (Henning)
14.01 Accretion disks II (Henning)
21.01 High-mass star formation, clusters and the IMF (Gieser)
28.01 Extragalactic star formation (Henning)
04.02 Planetarium@HdA, outlook, questions
11.02 Examination week, no star formation lecture (Beuther, Gieser, Henning)

Book: Stahler & Palla: The Formation of Stars, Wileys

More Information and the current lecture files: http://www.mpia.de/homes/beuther/lecture_ws2425.html
beuther@mpia.de, henning@mpia.de , gieser@mpia.de

Heidelberg Joint Astronomical Colloquium Winter Semester 2024/25

Tuesday November 12th Main Lecture Theatre, Philosophenweg 12, 16:30 CEST

Elena Pancino

(INAF – Osservatorio Astrofisico di Arcetri):

Stardance: The non-canonical evolution of stars in clusters

https://www.physik.uni-heidelberg.de/hephysto/

Host: Michela Mapelli (mapelli@uni-heidelberg.de)

Image Credit: Mark A. Garlick / University of Warwick