Sternentstehung - Star Formation

Winter term 2022/2023

Henrik Beuther, Thomas Henning, & Jonathan Henshaw

18.10 - Introduction & overview (Beuther)
25.10 - Physical processes I (Beuther)
08.11 - Physical processes II (Beuther)
15.11 - Molecular clouds I: the birth places of stars (Henshaw)
22.11 - Molecular clouds II: Jeans analysis (Henshaw)
29.11 - Collapse models I (Beuther)
06.12 - Collapse models II (Henning)
13.12 - Protostellar evolution (Beuther)
20.12 - Pre-main sequence evolution & outflows/jets (Beuther)
10.01 - Accretion disks I (Henning)
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24.01 - High-mass star formation, clusters & the IMF (Henshaw)
31.01 - Extragalactic star formation (Henning)
07.02 - Planetarium @ HdA, outlook, questions
13.02 - Examination week, no star formation lecture

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

More information and the current lecture files: https://www2.mpia-hd.mpg.de/homes/beuther/lecture_ws2223.html

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Recap from the last lecture

- **Line profiles and a few applications for line emission**
  - Line broadening (natural, pressure, thermal, other++)
  - Outflow line "wings"
- **Magnetic field measurements (Zeeman and dust)**
  - OH molecule example
  - IR dust polarisation, grain alignment, polarisation (and therefore inferred orientation of B) depends on emission/extinction
  - Ambipolar diffusion
- **Maser emission**
  - Non-thermal emission
  - Proper motion measurements
  - Pumping mechanisms (collisional, radiative; e.g. shocks from protostellar jets) - very high density/temperature required
- **Dust properties**
  - Composition, size distribution, gas to dust mass ratio
  - Extinction vs emission
  - Heating (photoelectric effect) and cooling (CO at high density, and v. High density - cooling from dust)
  - Dust is porous - has important implications for grain growth, also surface chemistry
- **Physical distributions (Maxwell, Planck, Boltzmann, Saha)**
  - Equations governing energy: kinetic, level populations, photons, ionisation levels
  - Where are the limitations?

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Molecular clouds I: the birth places of stars

Today’s lecture

Learning outcomes:

- Molecular gas as a component of the interstellar medium
- Why are we interested in molecular gas/clouds?
- What *even is* a “molecular cloud”?
- What are the general properties of molecular clouds?
- The internal structure of molecular clouds

Useful resources:

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In depth look at the physical processes

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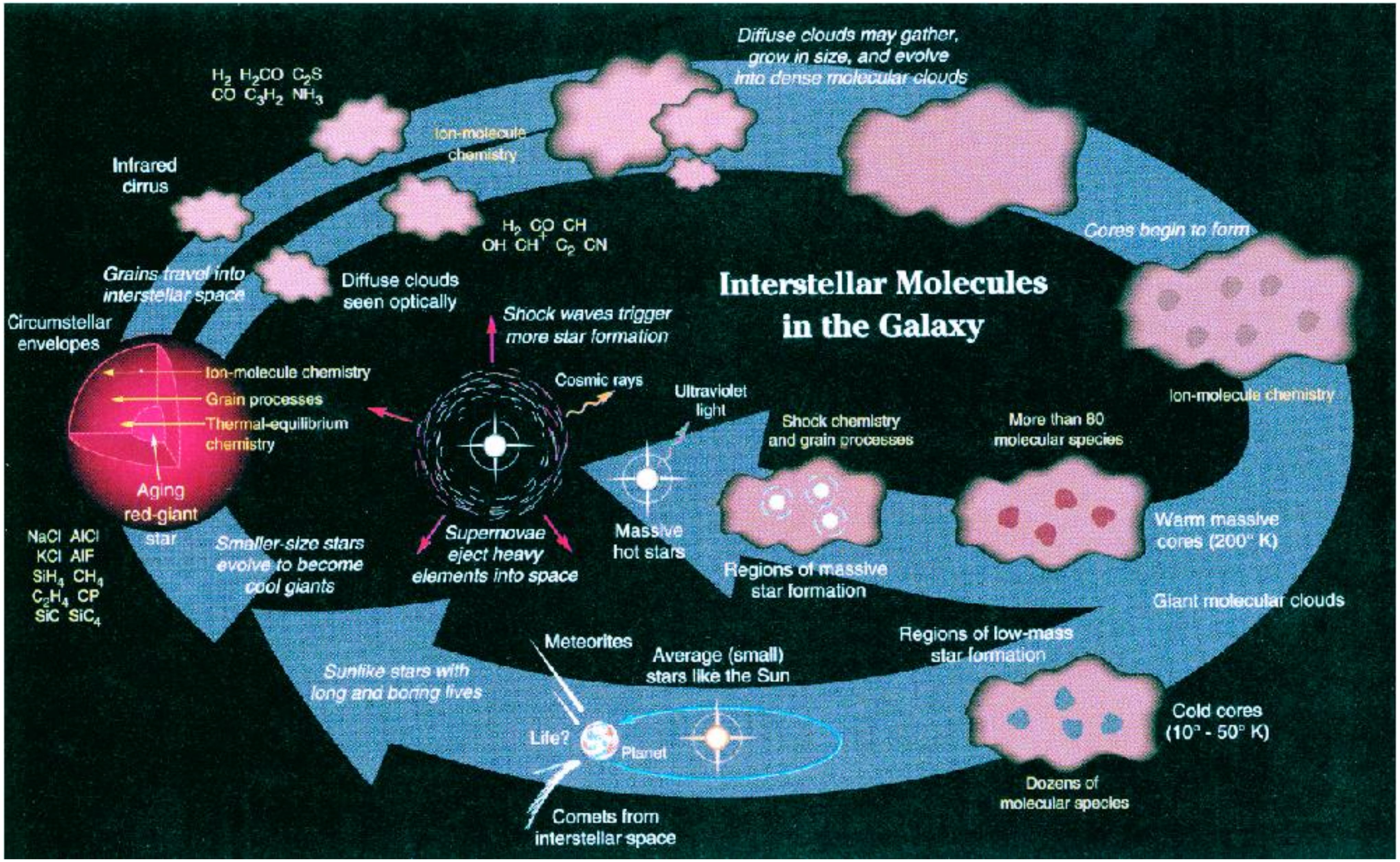
Molecular gas as a component of the interstellar medium



Baryons in the ISM of galaxies are found with a wide range of temperatures, densities, and ionisation fractions. Because the ISM is dynamic, all densities and temperatures within these ranges can be found *somewhere* in the ISM.

However, it is observed that most of the baryons have temperatures and densities that fall close to various characteristic states, or "*phases*".

Characterising these phases, and their interrelationship, is a major pursuit of ISM research.

Molecular gas as a component of the interstellar medium

ATOMIC GAS

Two-Phase model (Field et al. 1969)

Underlying idea: equilibrium — Heating rate, $\Gamma(n, T)$ = Cooling rate, $\Lambda(n, T)$

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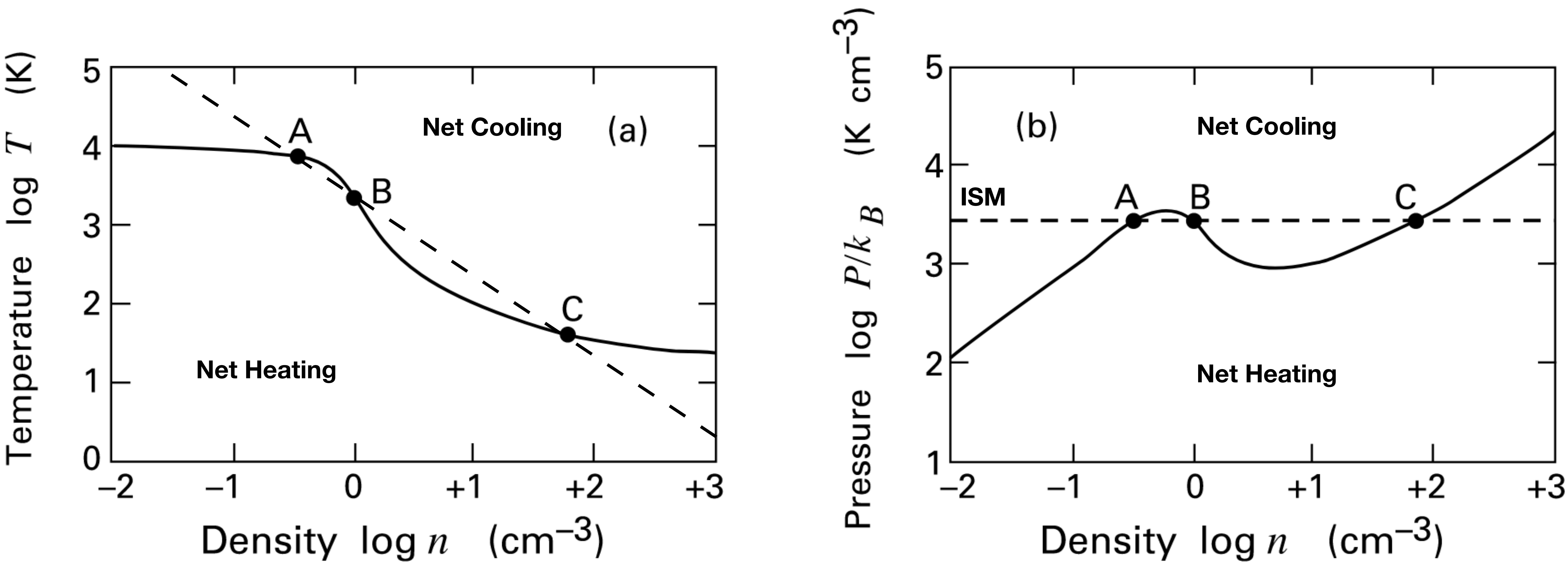

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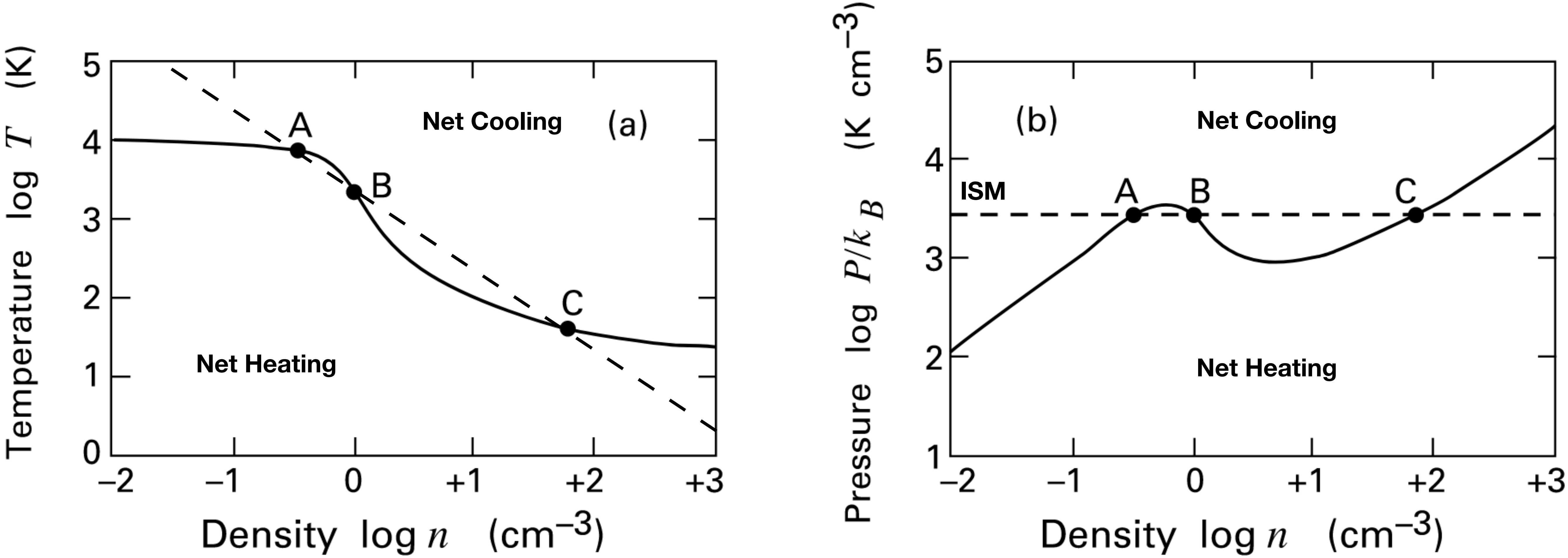

Lets consider the points that have pressure, $P/k_b = nT$, matching the known interstellar value…

Molecular gas as a component of the interstellar medium

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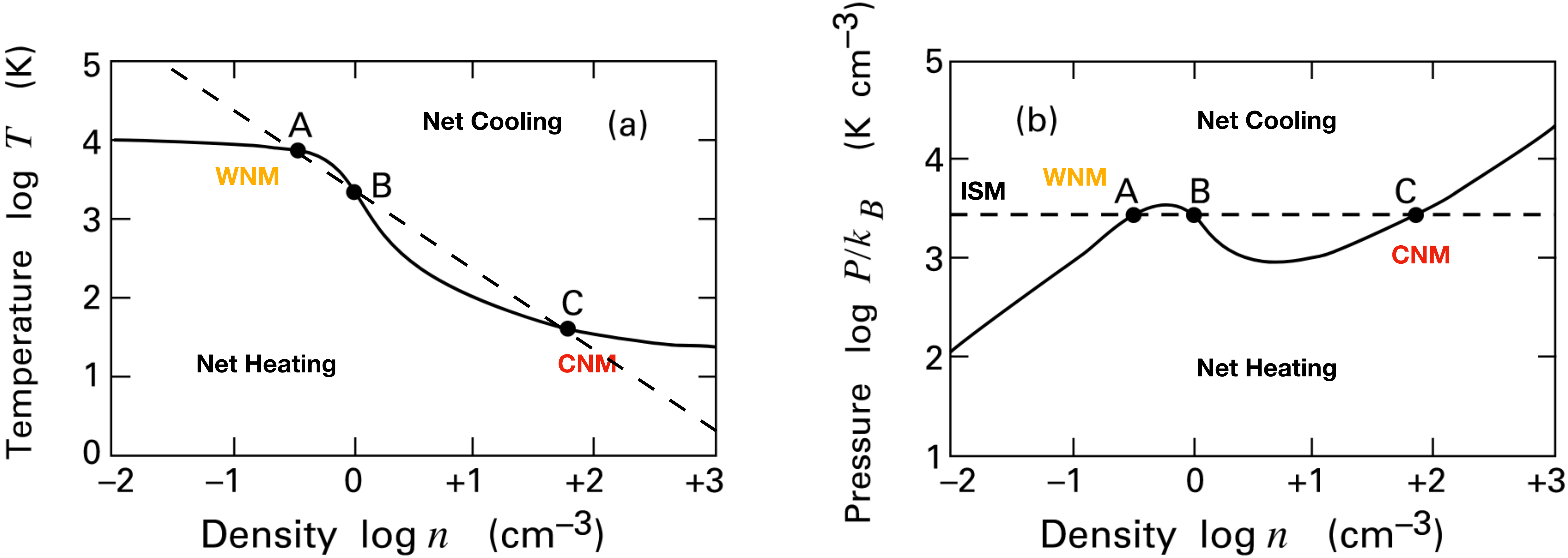
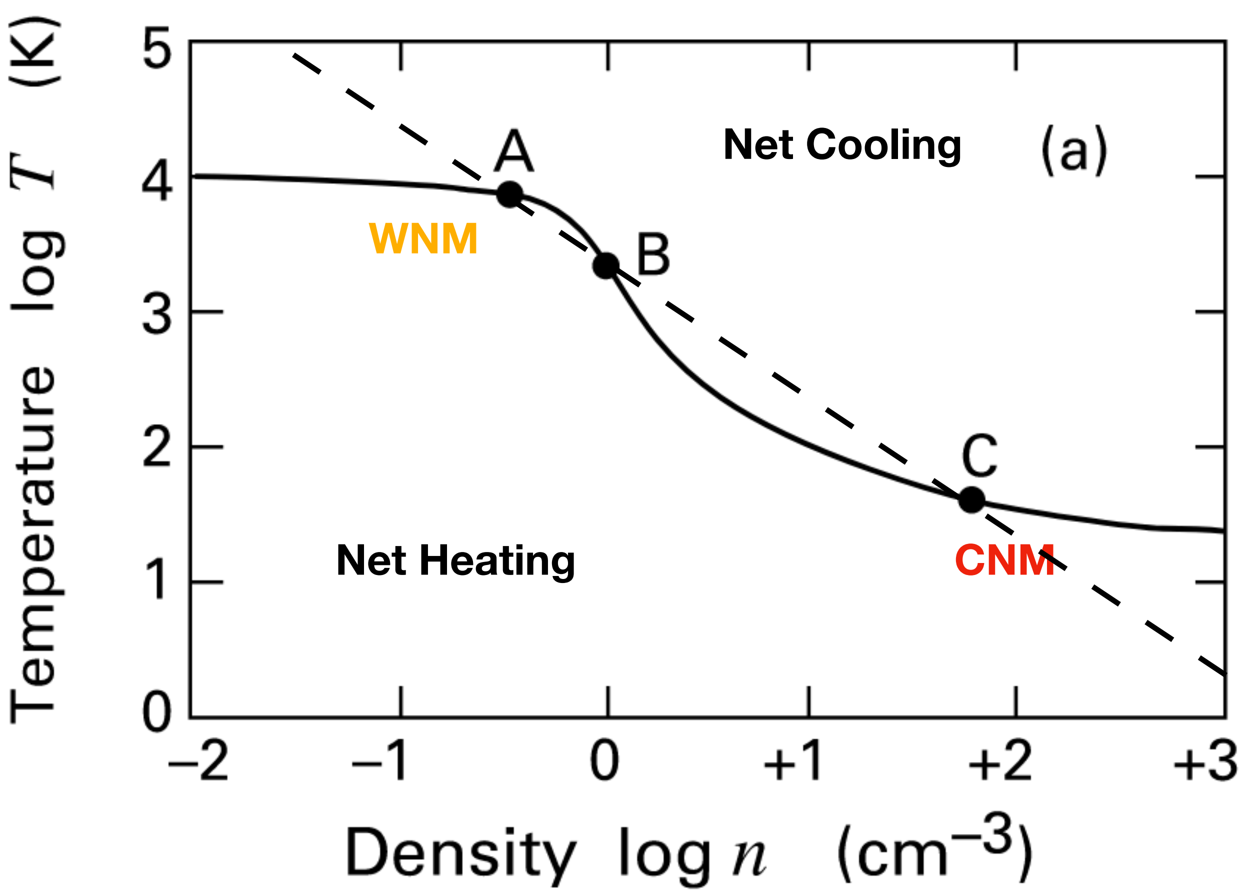


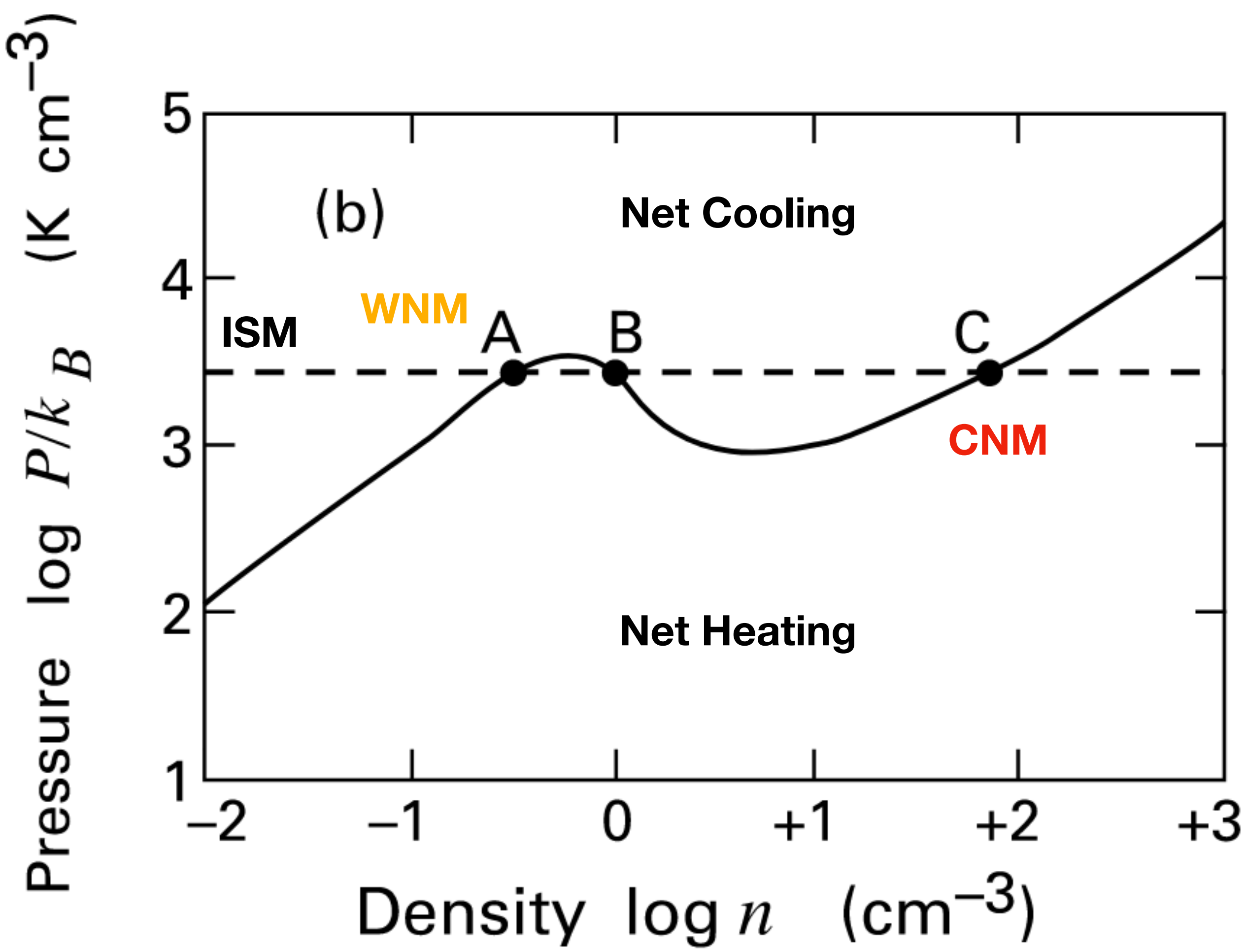
At low density, heating balances cooling at temperatures of around 8000 K, these are **warm neutral medium** conditions

At high density, heating balances cooling at temperatures of around 80 K, these are **cold neutral medium** conditions

At intermediate density, the gas is *thermally unstable*

Question time:





If we fix the pressure, $P/k_b = nT$, what happens at point A, B, and C when the density changes?

Molecular gas as a component of the interstellar medium

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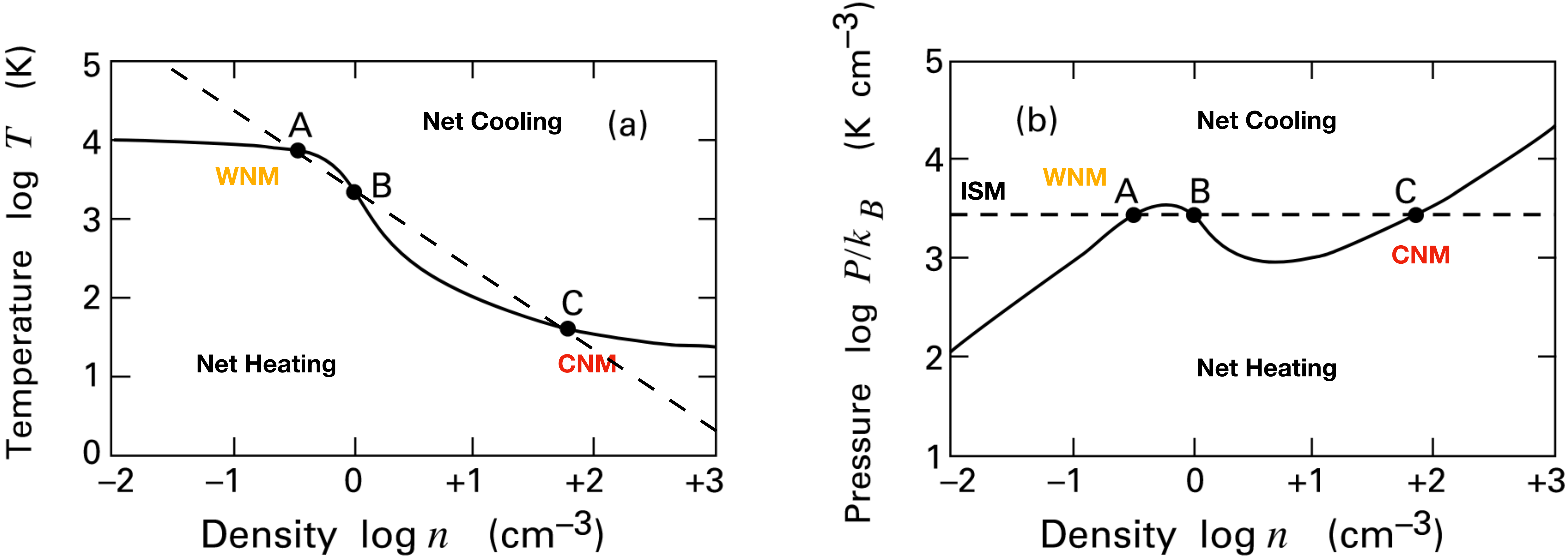

Gas at point B that is compressed to higher density while maintaining pressure equilibrium with its surroundings must cool until it reaches point C (the reverse is true if it expands).

Molecular gas as a component of the interstellar medium

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Atomic gas will naturally partition into cold neutral medium (HI clouds) and warm neutral medium which exist simultaneously as two *stable* phases of the ISM in pressure equilibrium

Molecular gas as a component of the interstellar medium

ATOMIC GAS

Two-Phase model (Field et al. 1969)

Shortcomings of the model:

1. Does not include hot gas with $T > 10^4\,\mathrm{K}$, though it is known to exist (detected in early 1970s via OVI absorption lines & diffuse X-ray background)
2. Doesn't account for the affects of supernovae, which must create very large volumes of hot, low-density gas that are very hard to destroy once created
3. Vertical scale height of WNM/CNM only explained if the material is turbulent - what is the energising agent for this motion?

Molecular gas as a component of the interstellar medium

Three-Phase model (Mckee & Ostriker 1977)

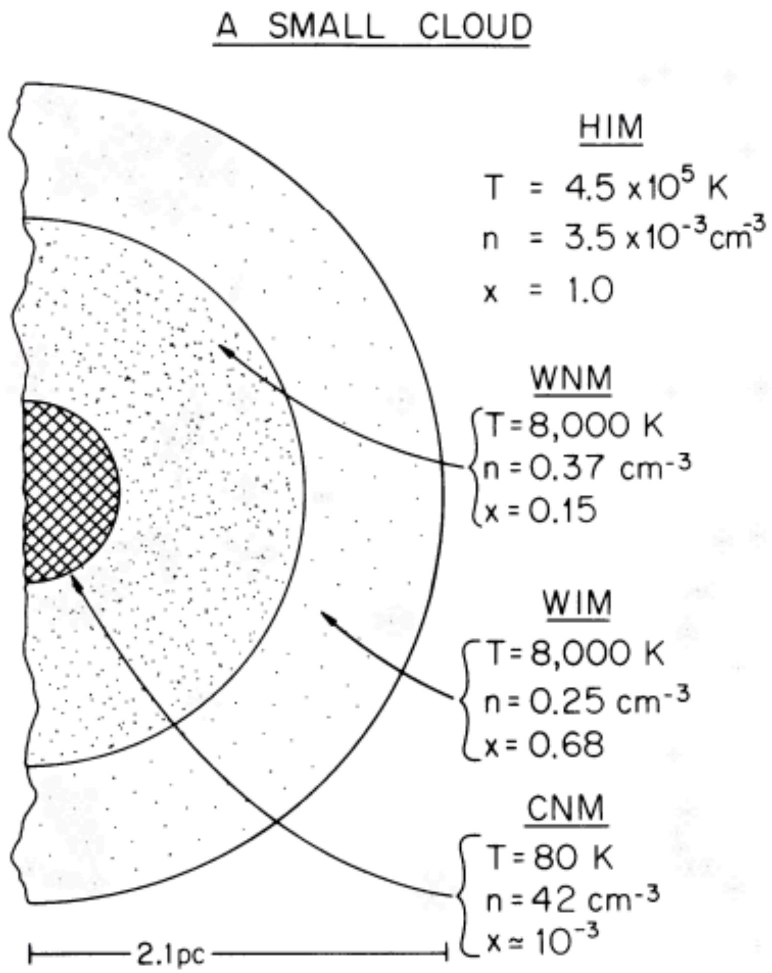


FIG. 1

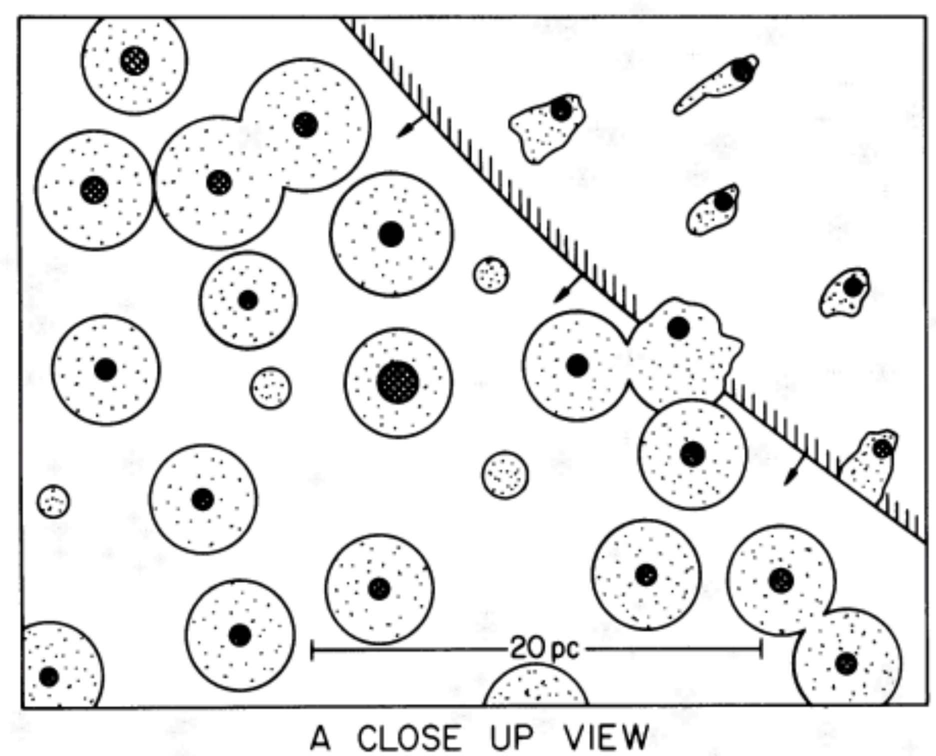
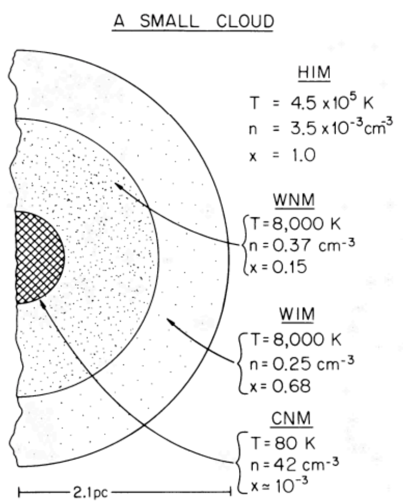


FIG. 2

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.

Three-Phase model (Mckee & Ostriker 1977)



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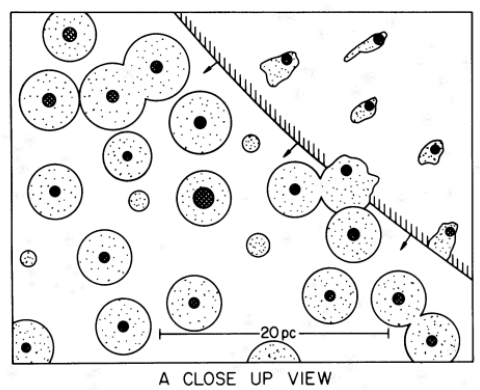

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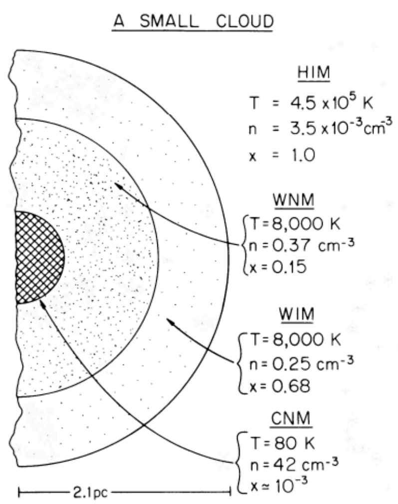
- CNM - $n \approx 50\,\mathrm{cm}^{-3}$ and $T \approx 80\,\mathrm{K}$
- The "intercloud phase" - subdivided into two components.
  - WIM: $n \approx 0.3\,\mathrm{cm}^{-3}$ and $T \approx 8000\,\mathrm{K}$
  - WNM: $n \approx 0.5\,\mathrm{cm}^{-3}$ and $T \approx 8000\,\mathrm{K}$
- HIM - the hot ionised medium - $n \approx 0.004\,\mathrm{cm}^{-3}$ and $T \approx 10^4\,\mathrm{K}$

Pressure equilibrium! $P/k_b = nT \approx 3000 - 4000\,\mathrm{cm}^{-3}\mathrm{K}$

Molecular gas as a component of the interstellar medium

Three-Phase model (Mckee & Ostriker 1977)



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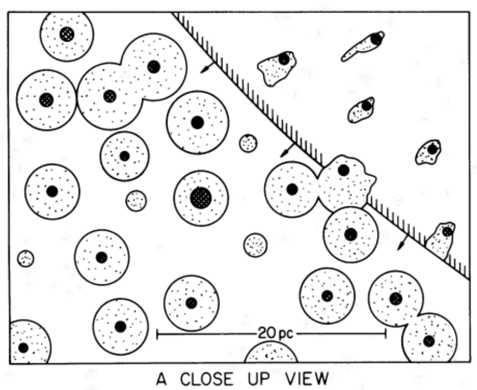

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Shortcomings of the model:

1. Clouds are not round and randomly distributed — they are layered, elongated and filamentary
2. SNe are also not randomly distributed, and the SN rate was overestimated
3. Observations show there is a considerable amount of warm HI gas that is evenly distributed and not associated with clouds

Molecular gas as a component of the interstellar medium

Fast Forward…

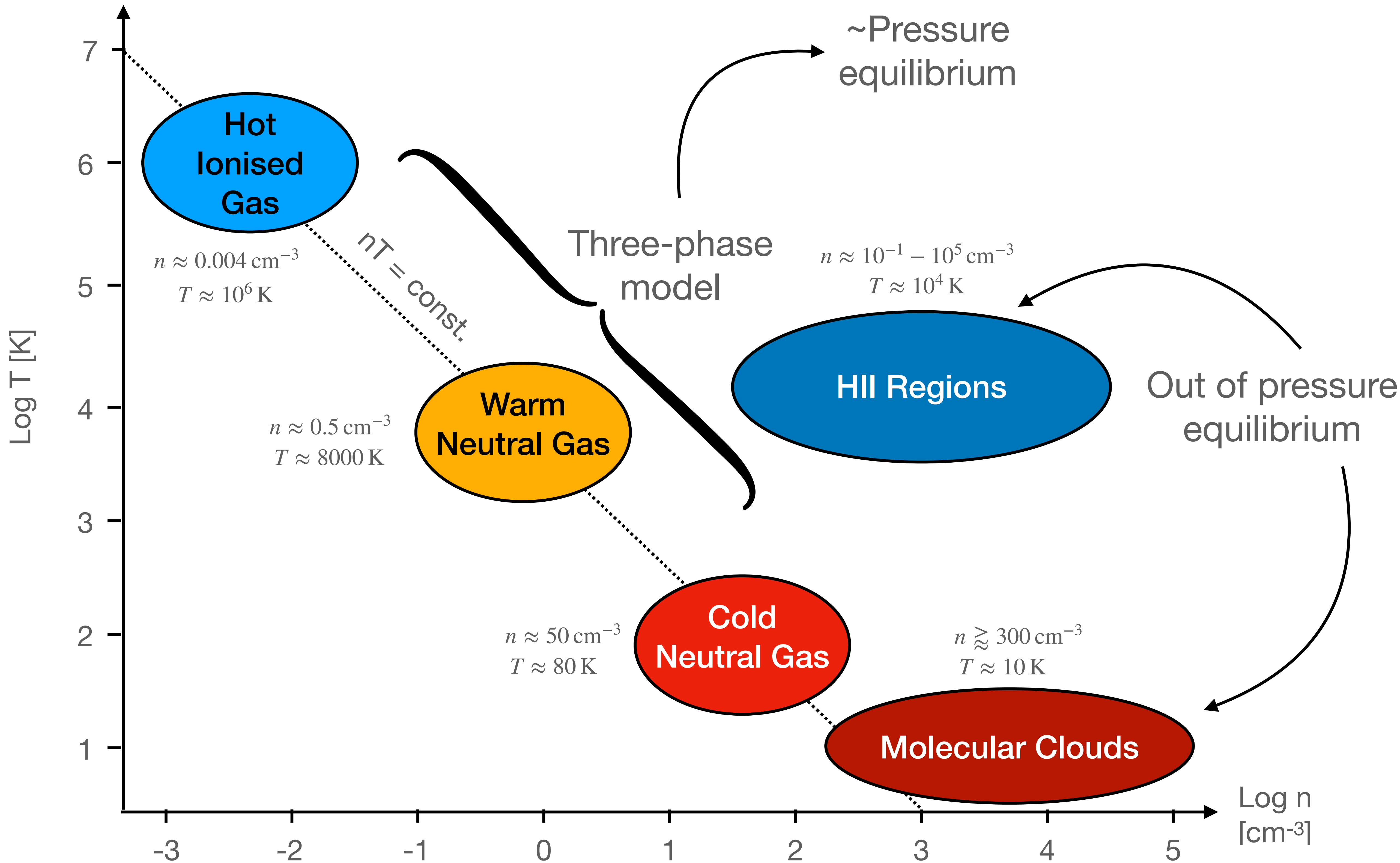
Phase	n [cm^{-3}]	T [K]	f	M [10^9 M_{sun}]
Hot ionised medium	0.004	10^6	0.5	0.1
Warm ionised medium	0.3	8000	0.1	1.0
Warm neutral medium	0.5	8000	0.4	1.4
Diffuse HI clouds	**50**	**80**	**-**	**2.5**
Molecular clouds	**>300**	**10**	**-**	**2.5**
HII regions	**0.1 – 10^5**	**10^4**	**-**	**0.05**

~Pressure equilibrium

f as volume filling factor regarding the Galactic disk

By mass in Milky Way (roughly): 20% ionised; 60% neutral; 20% molecular

Molecular gas as a component of the interstellar medium



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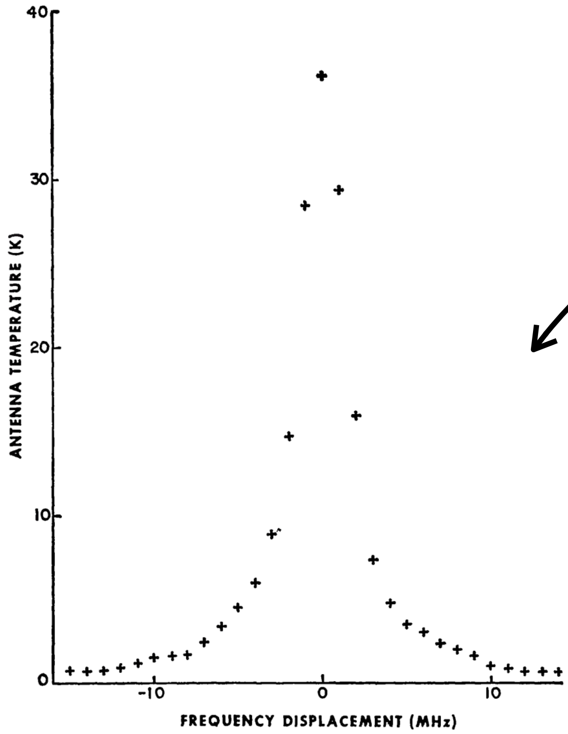
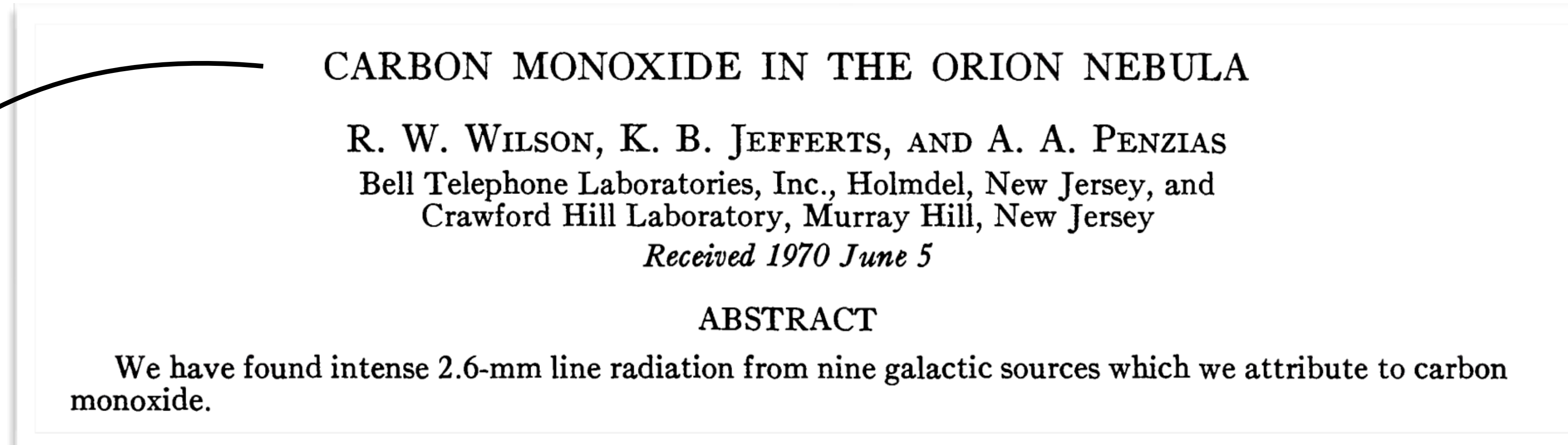



CARBON MONOXIDE IN THE ORION NEBULA

R. W. Wilson, K. B. Jefferts, and A. A. Penzias

Bell Telephone Laboratories, Inc., Holmdel, New Jersey, and
Crawford Hill Laboratory, Murray Hill, New Jersey

Received 1970 June 5

ABSTRACT

We have found intense 2.6-mm line radiation from nine galactic sources which we attribute to carbon monoxide.

1930s: Molecules in optical absorption (Swings and Rosenfeld 1937; McKellar 1940)

1960s: Molecules in radio emission (Weinreb+ 1963; Cheung+ 1968)

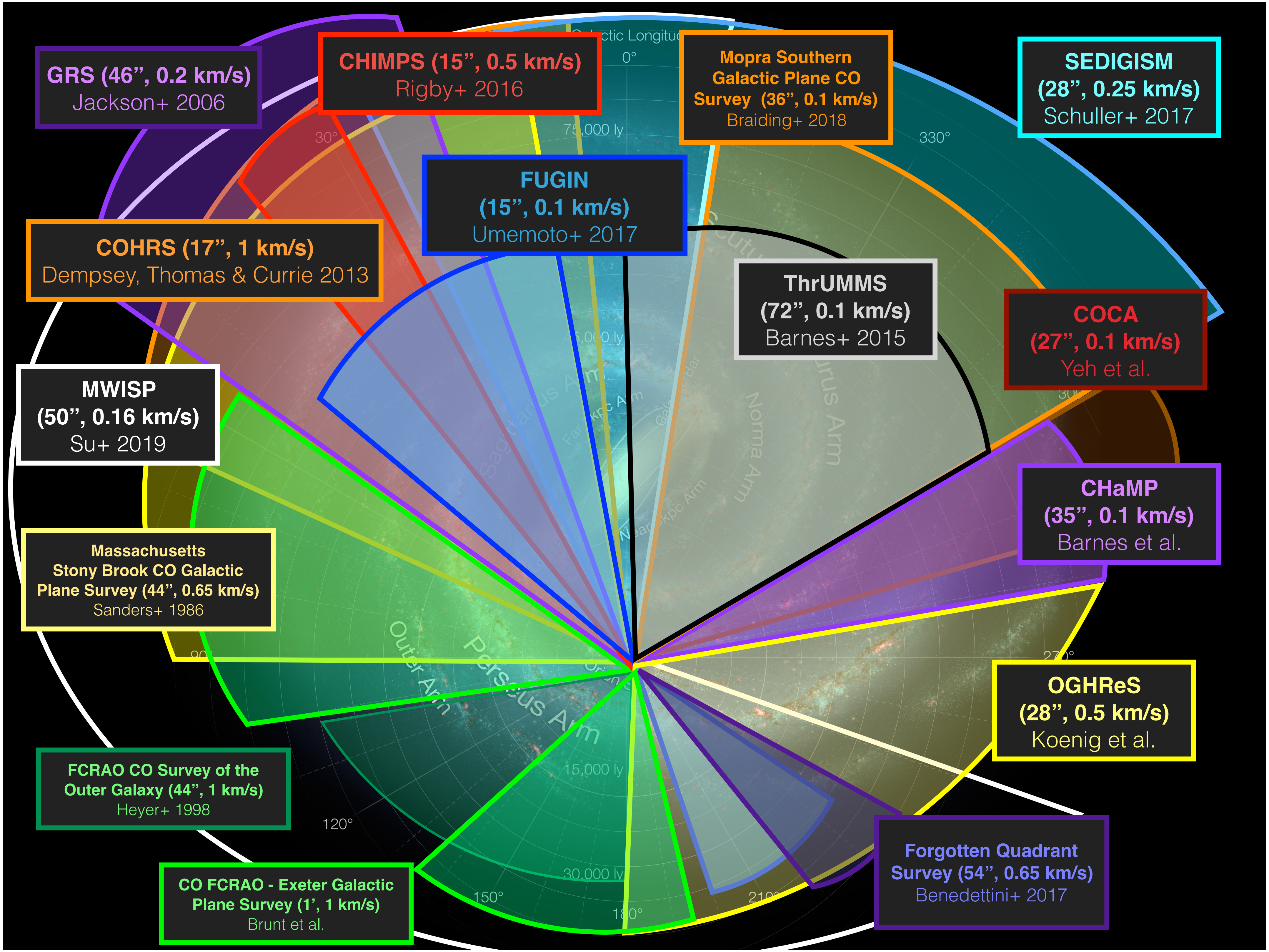
1970s: H_2 (Carruthers 1970); CO (Wilson+ 1970)

1980s: All-galaxy CO maps (Dame+ 1987), cloud catalogues (Solomon+ 1987, Scoville+ 1987), high-density gas tracers NH3, HCN, CS (Myers 1983, Snell+ 1984)

1990s: extragalactic GMCs, interferometer maps, sub-mm dust

Now: …

Why are we interested in molecular gas/clouds?



Dario Colombo

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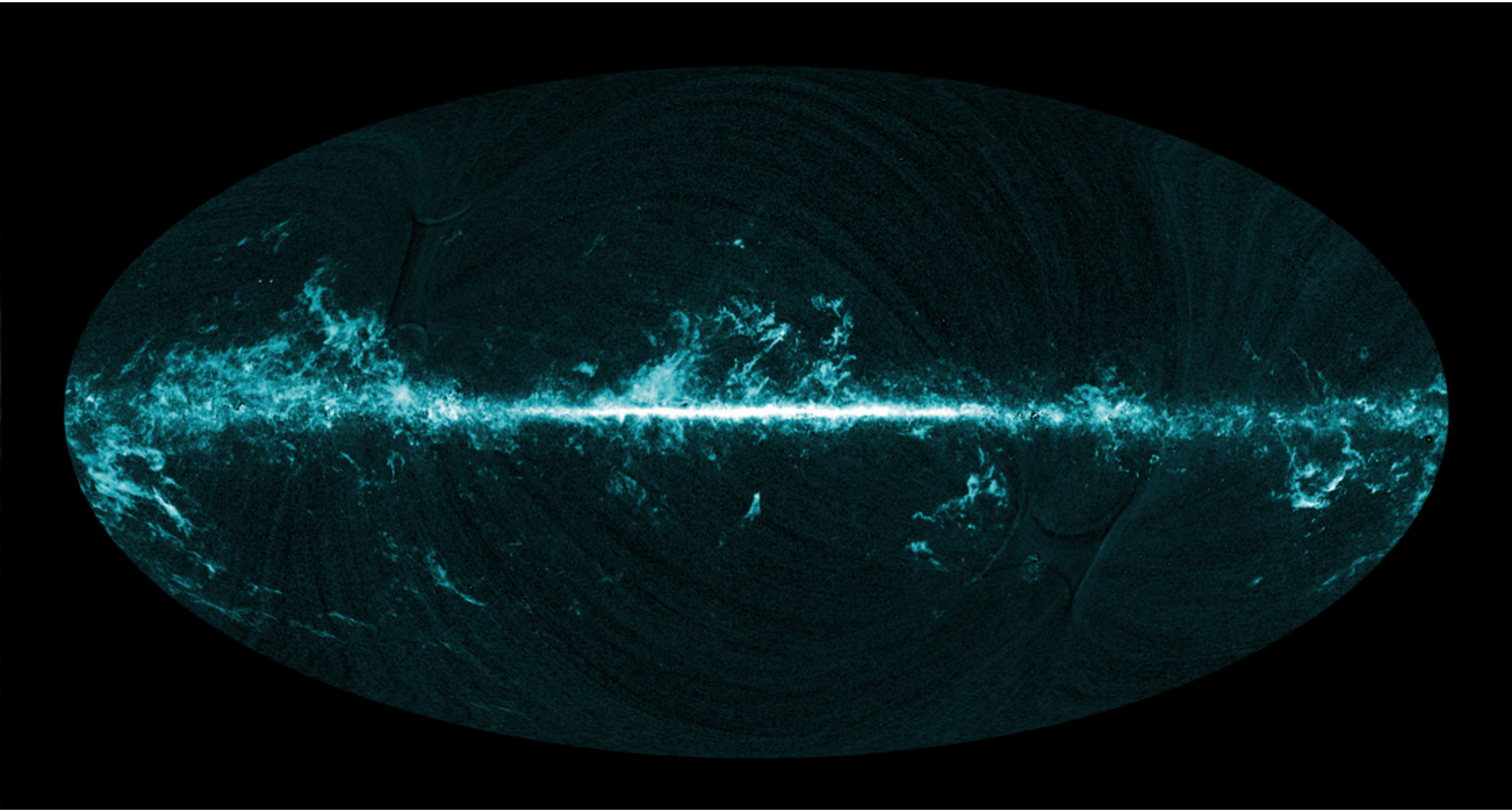
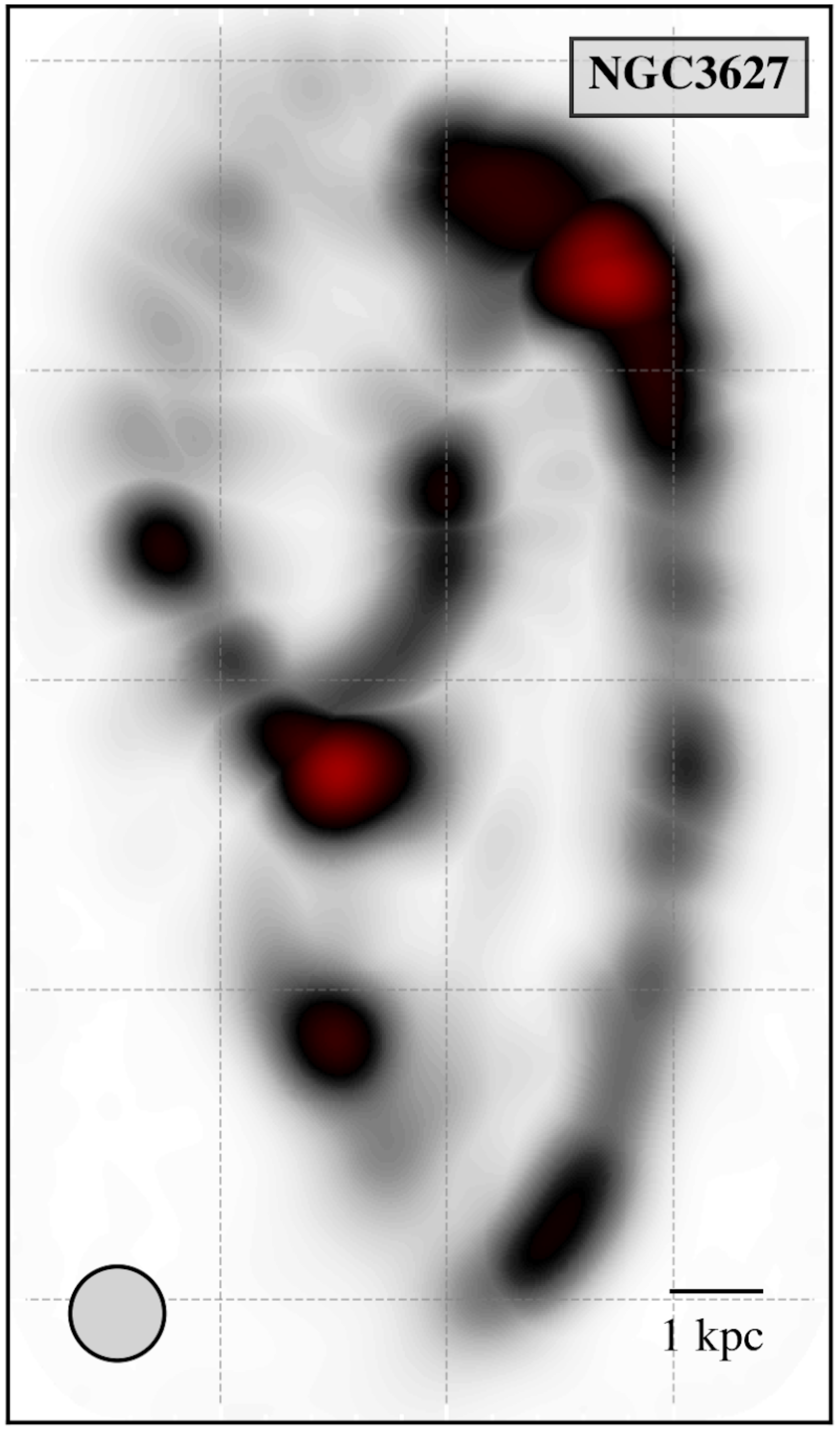


Planck collaboration CO map of the Milky Way — molecular gas across the whole sky

Why are we interested in molecular gas/clouds?



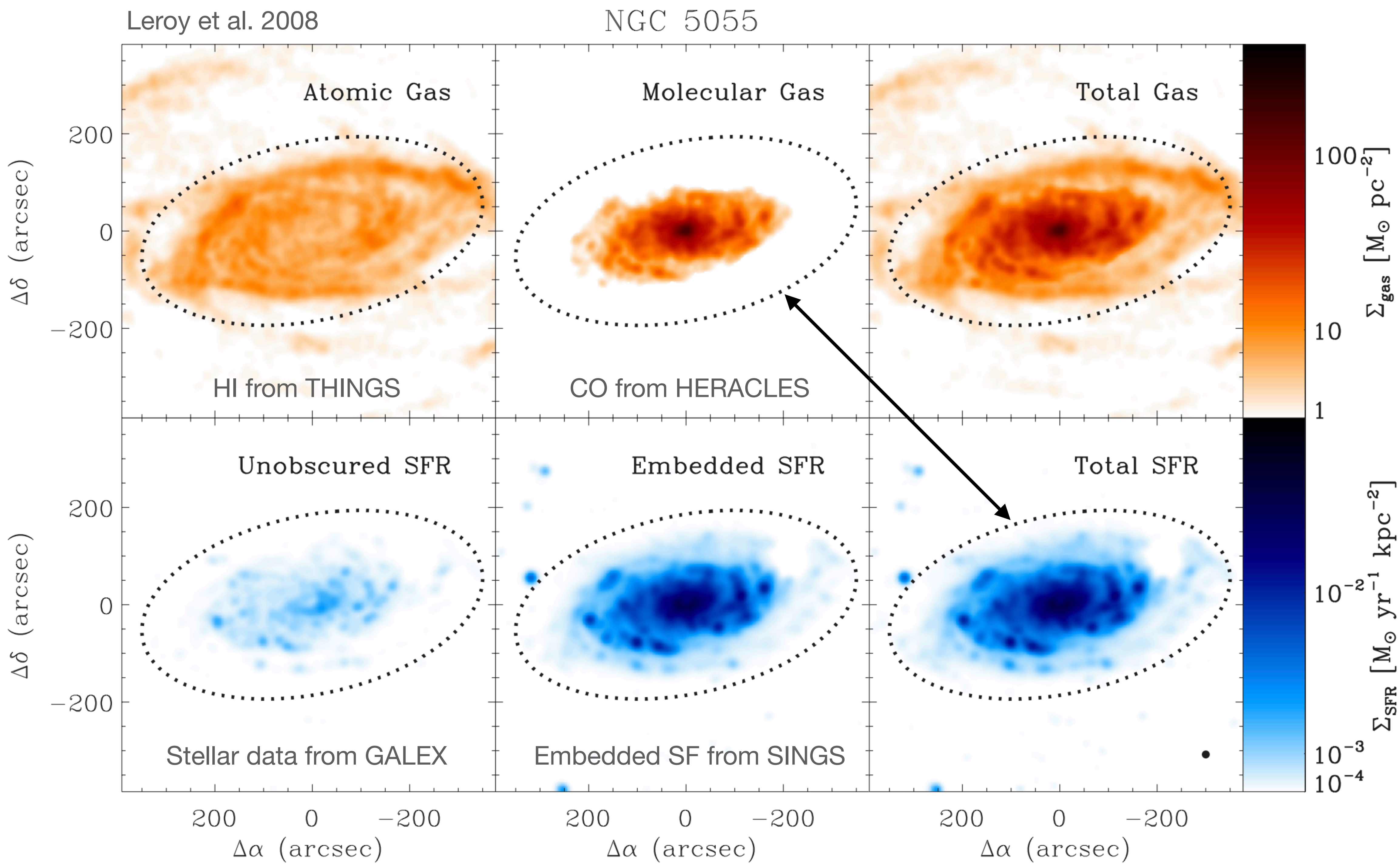
Adam Leroy courtesy of PHANGS

- Last 10-20 years has seen *billions of euros* investment in facilities designed to study the molecular interstellar medium
- We can now observe star-forming regions both in our own Milky Way and in nearby galaxies in unprecedented detail
- ALMA can now observe a whole nearby galaxy (<20 Mpc) in CO (2-1) at molecular cloud resolution in just a few hours — this is truly revolutionary!

Why are we interested in molecular gas/clouds?

All stars in all (z=0) galaxies are born in molecular gas.

Leroy et al. 2008



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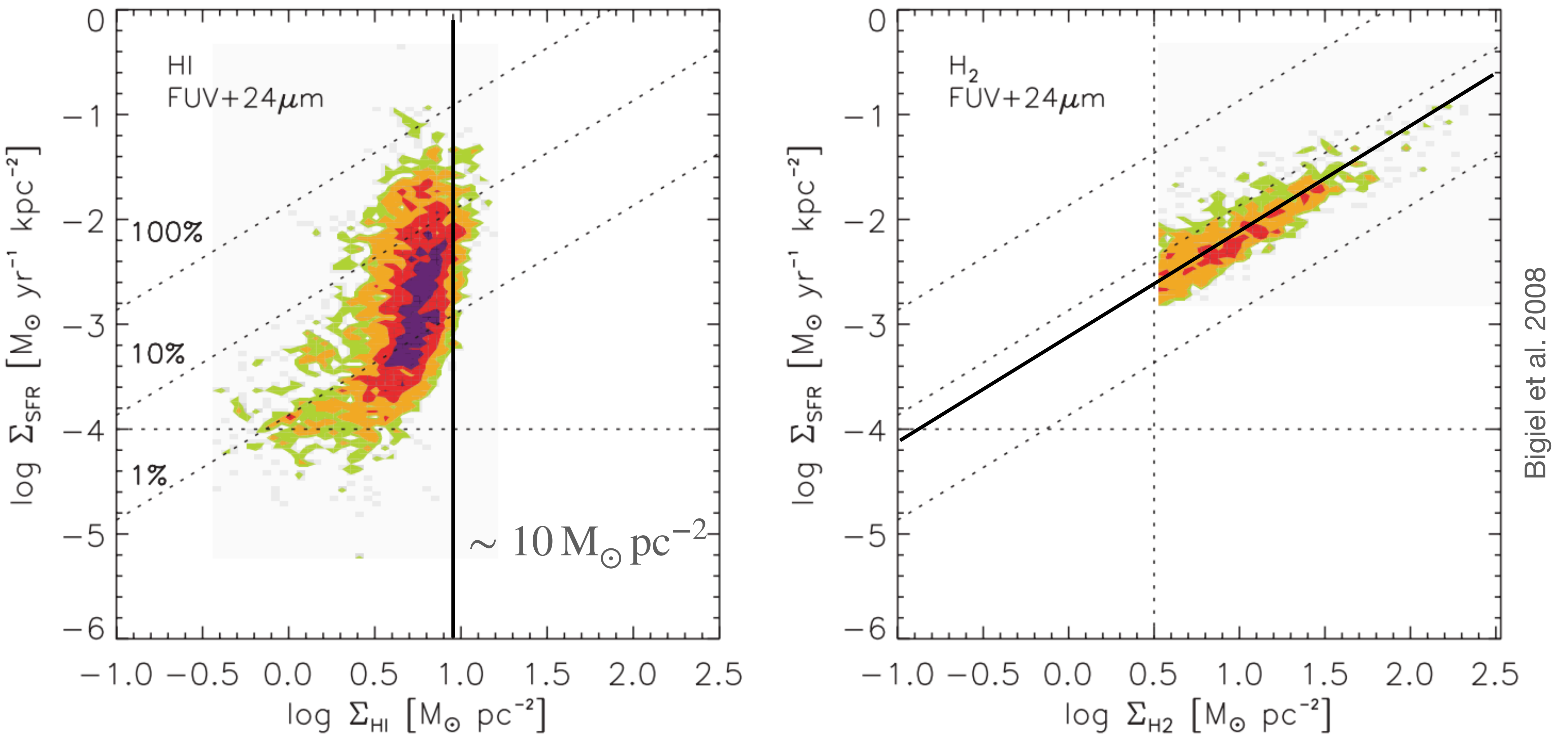

Bigiel et al. 2008

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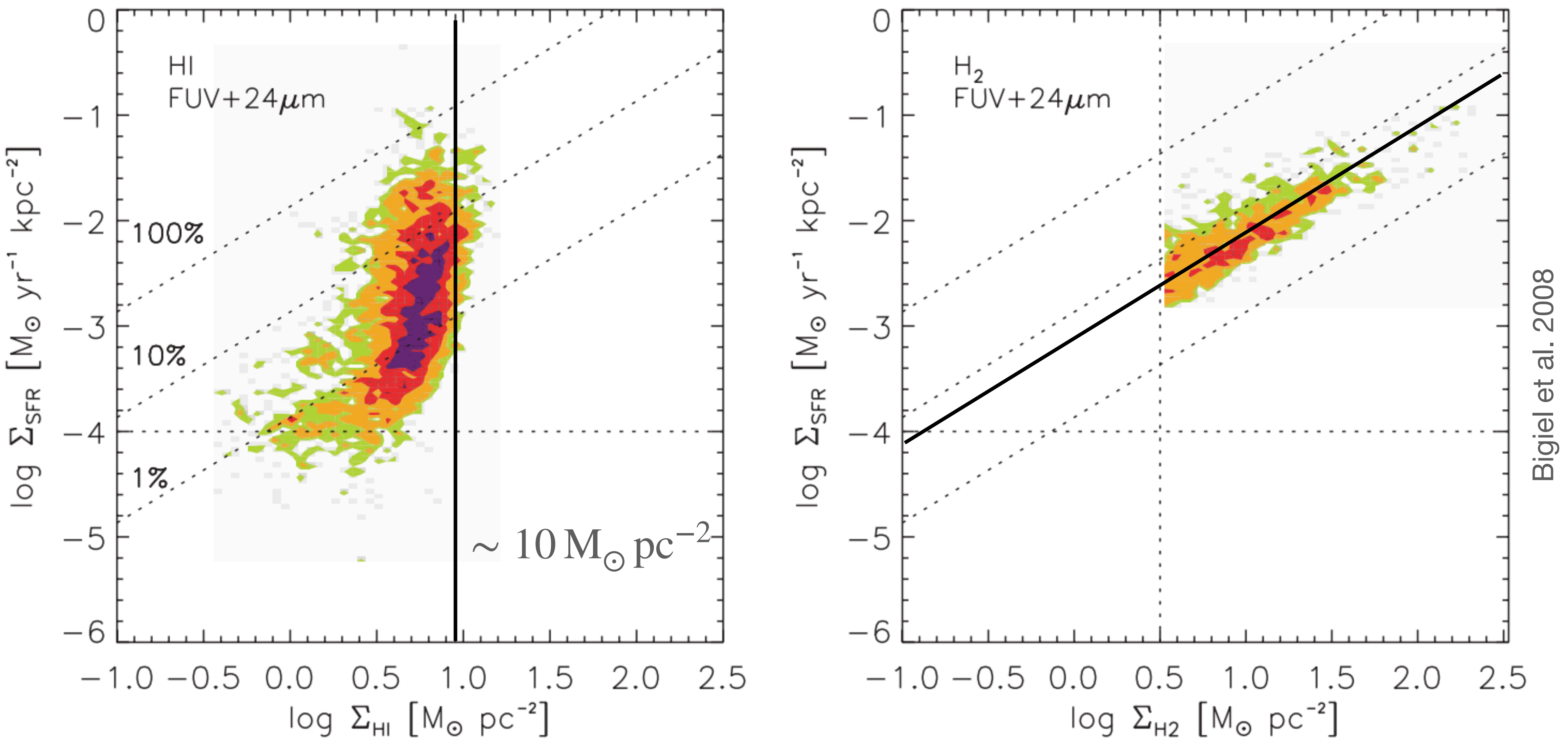

Bigiel et al. 2008

- SFR-HI correlation is steep and scattered - same surface density forms stars at many rates depending on different factors

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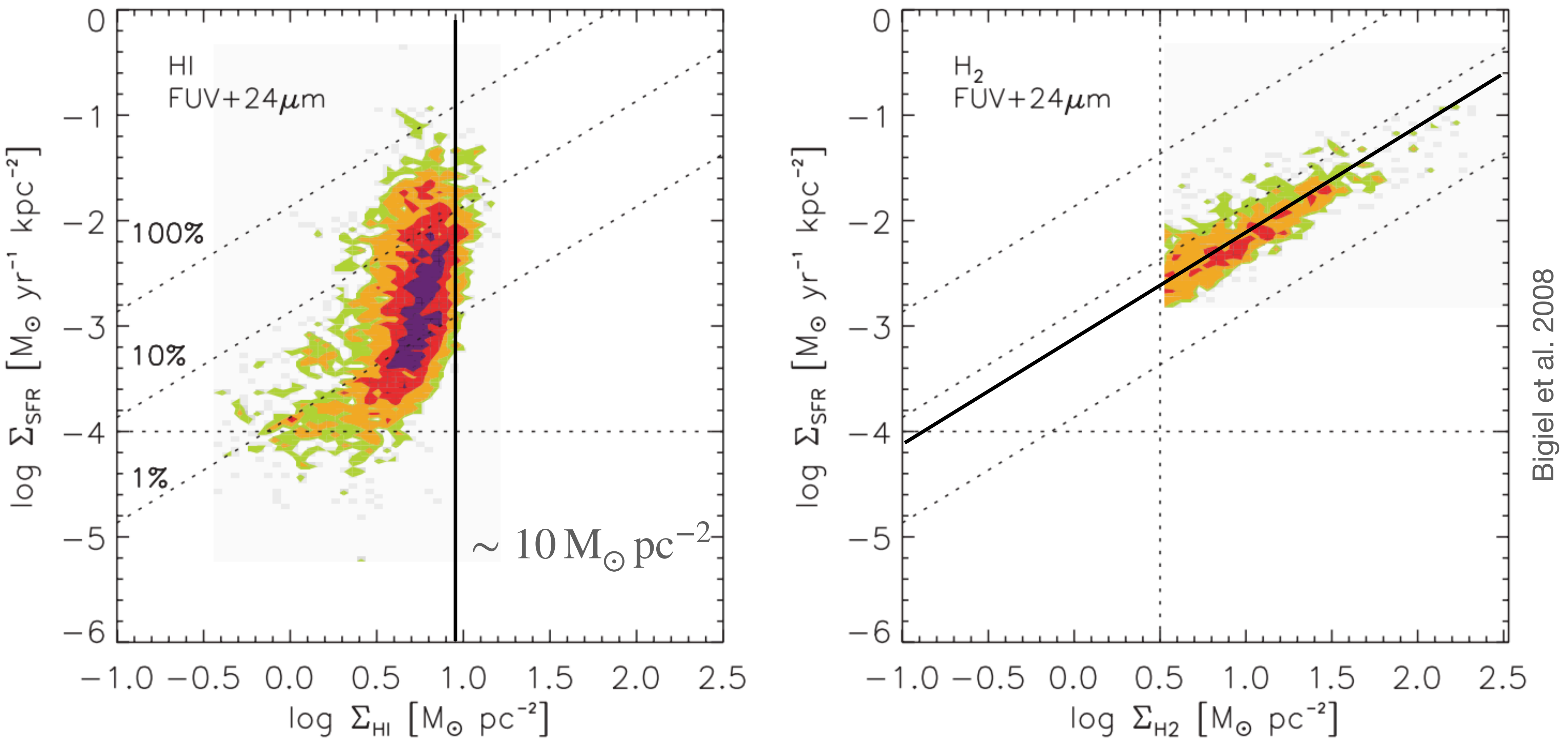

Bigiel et al. 2008

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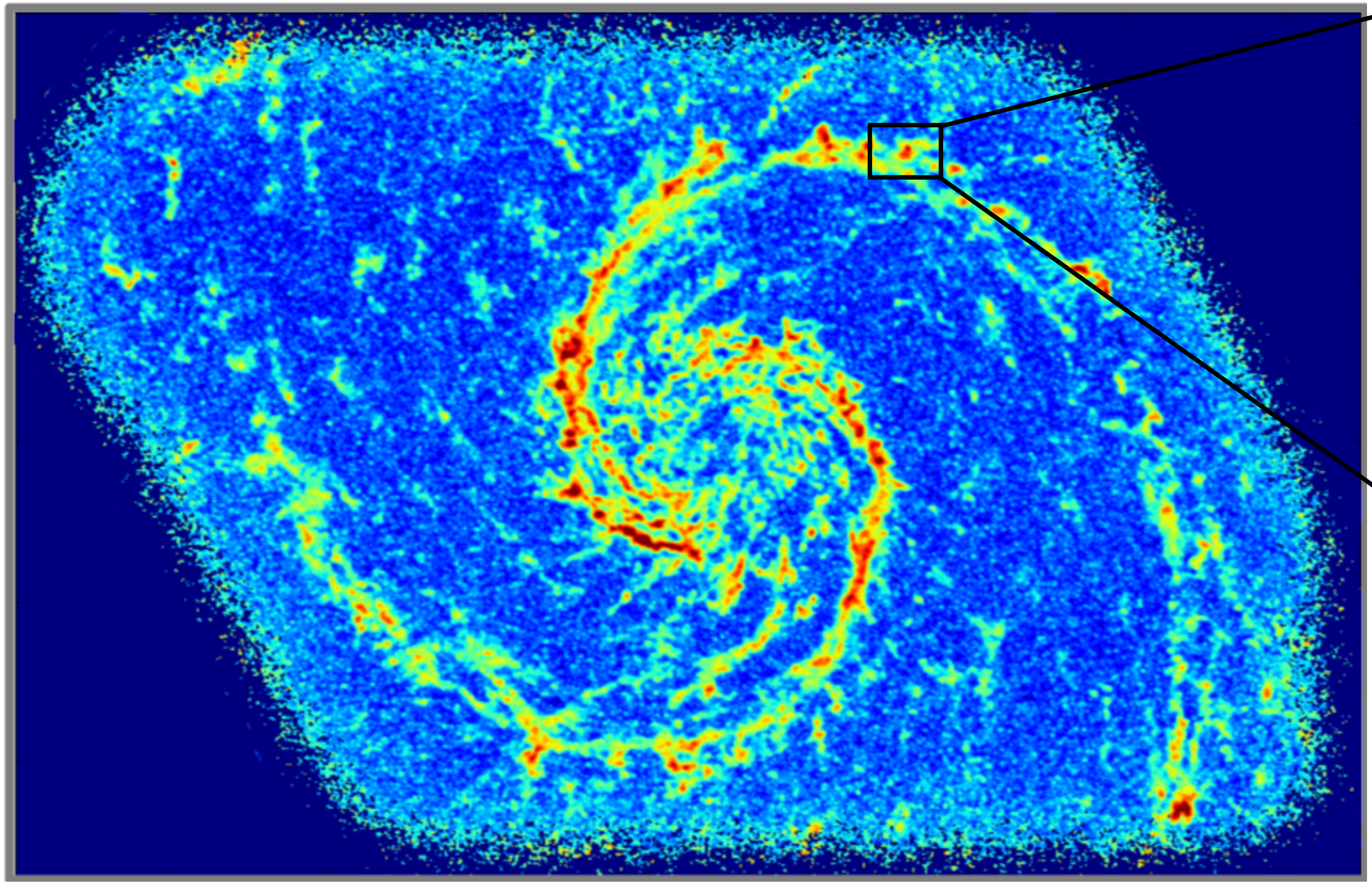
- SFR-H_2 (***H_2 as traced by CO!***) much tighter, index ~ 1

Why are we interested in molecular gas/clouds?



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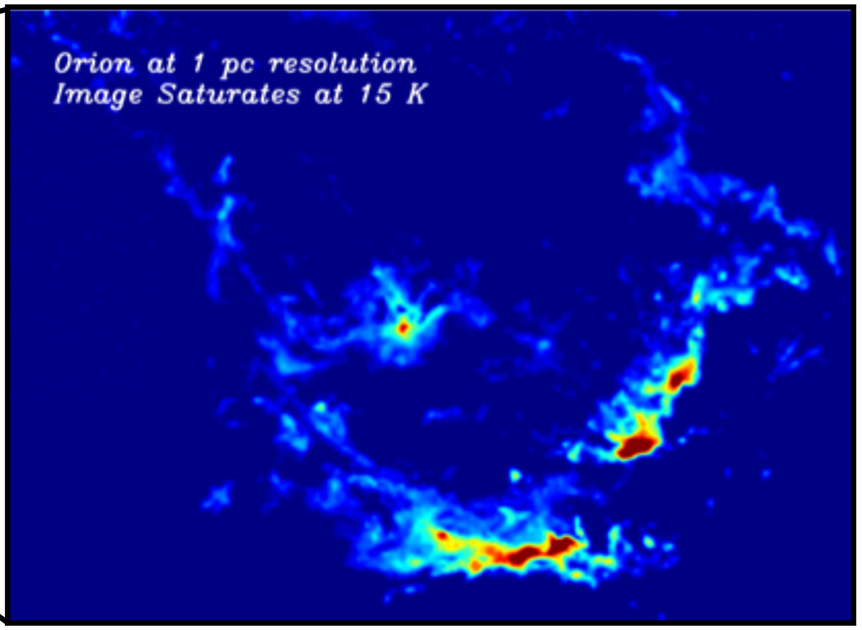

Orion

In the Milky Way, roughly ~20% by mass of the interstellar medium is in molecular form, and as far as we know, this gas is responsible for all Milky Way star formation.

The distribution of this gas is not smooth, it is organised into ***molecular clouds***

Today's lecture

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Question time:

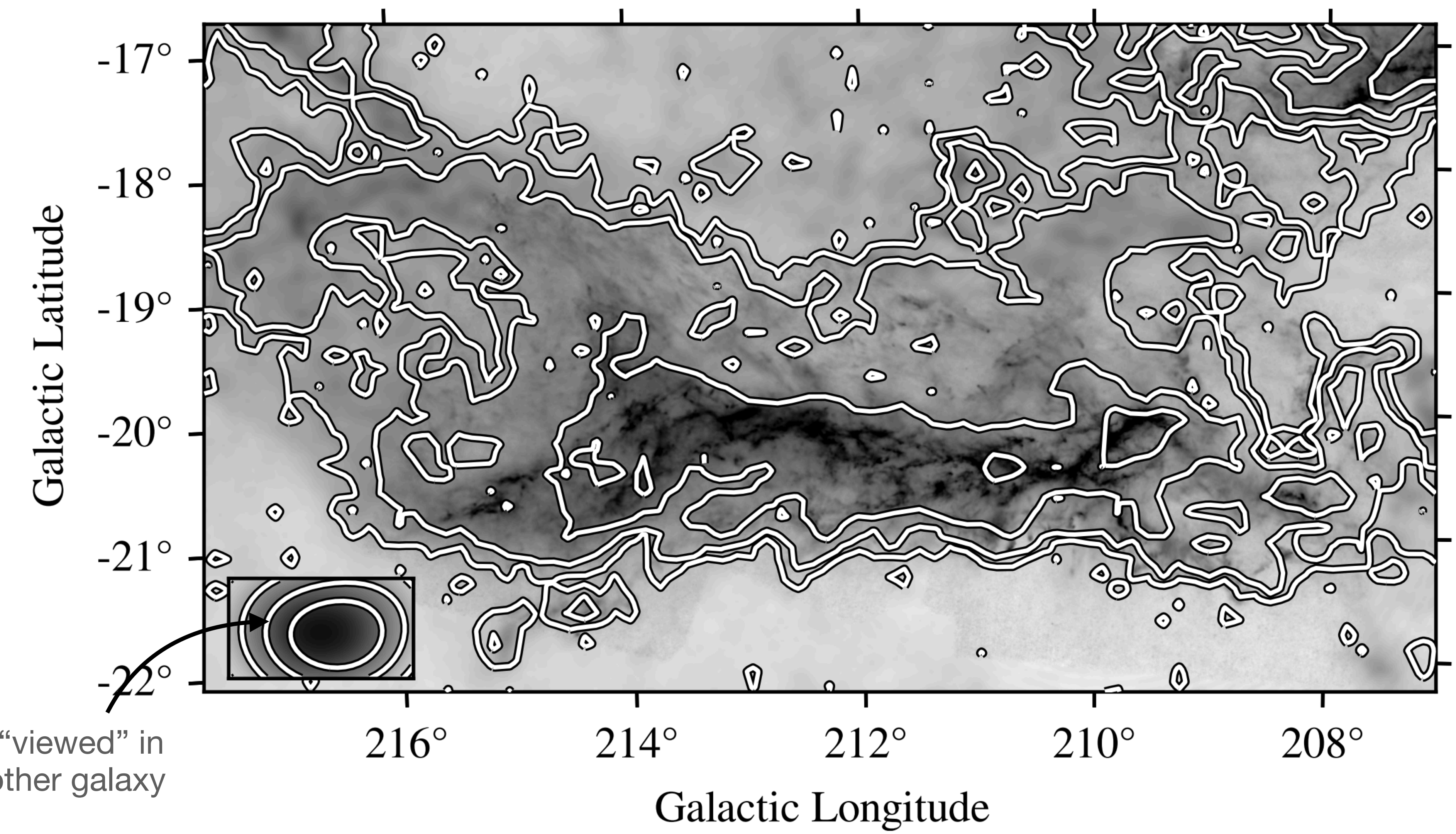
How would *you* define a “molecular <u>cloud</u>”?

Answers:

- cold
- High-density
-

What *even is* a “molecular cloud”?

Molecular clouds are *dynamic* — it is unclear whether there even is a physically motivated definition



As “viewed” in another galaxy

Orion A

Chevance et al. 2022

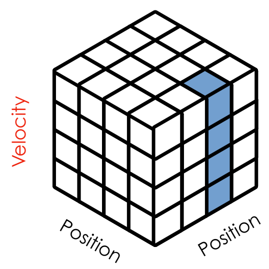
Background: Dust emission at 353micron with Herschel and Planck satellites

White contours: Molecular line emission from Carbon Monoxide from Harvard-Smithsonian 1.2m telescope

What *even is* a “molecular cloud”?

There are two main methods of cloud identification:

1. Molecular line observations



2. Dust emission/extinction

What *even is* a "molecular cloud"?

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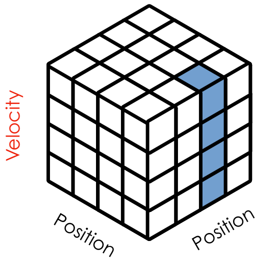
   - Various molecular lines used — CO (and isotopologues) most common
   - Method used in both Galactic and extragalactic observations
   - Get kinematic information for free



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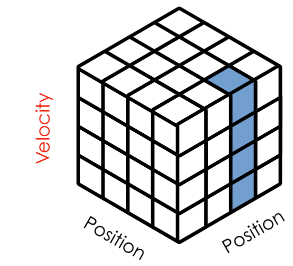
1. Molecular line observations
   - Various molecular lines used — CO (and isotopologues) most common
   - Method used in both Galactic and extragalactic observations
   - Get kinematic information for free
   - CO not a linear tracer of H2 throughout GMCs - “tip of the iceberg”
   - Position-position-velocity — velocity != position — emission regions well-separated in velocity may belong to the *same structure*, similarly, connected emission regions may belong to *different physical entities — challenging - particularly in MW*

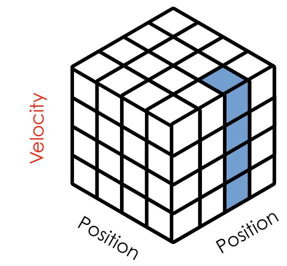


2. Dust emission/extinction

What *even is* a “molecular cloud”?

There are two main methods of cloud identification:

1. Molecular line observations



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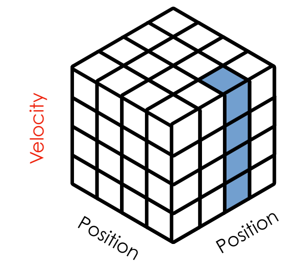

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2. Dust emission/extinction

- Combinations of wavelengths can be used to build a faithful tracer of the full column
- Detailed, high-angular resolution study of local clouds possible
- No kinematic information available
- Accuracy restricted to local clouds due to lack of background sources (extinction) and blending (emission) at large-distances

What *even is* a “molecular cloud”?

A working (observational) definition of a GMC:

Giant Molecular Clouds represent massive (a few 10^4 Msun), 10-100pc scale *over-densities* within the ISM, where conversion of the gas to molecular form readily occurs and in which gravitational collapse and star formation becomes possible

Chevance et al. 2022

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Chevance et al. 2022

*This is an observational definition and depends strongly on observations used

*Identification relative to local medium and boundaries of clouds are not well-defined

*Physically, clouds are not isolated from their surroundings - they are dynamic and evolving

Today’s lecture

Learning outcomes:

- Molecular gas as a component of the interstellar medium
- Why are we interested in molecular gas/clouds?
- What *even is* a “molecular cloud”?
- **What are the general properties of molecular clouds?**
- The internal structure of molecular clouds

Useful resources:

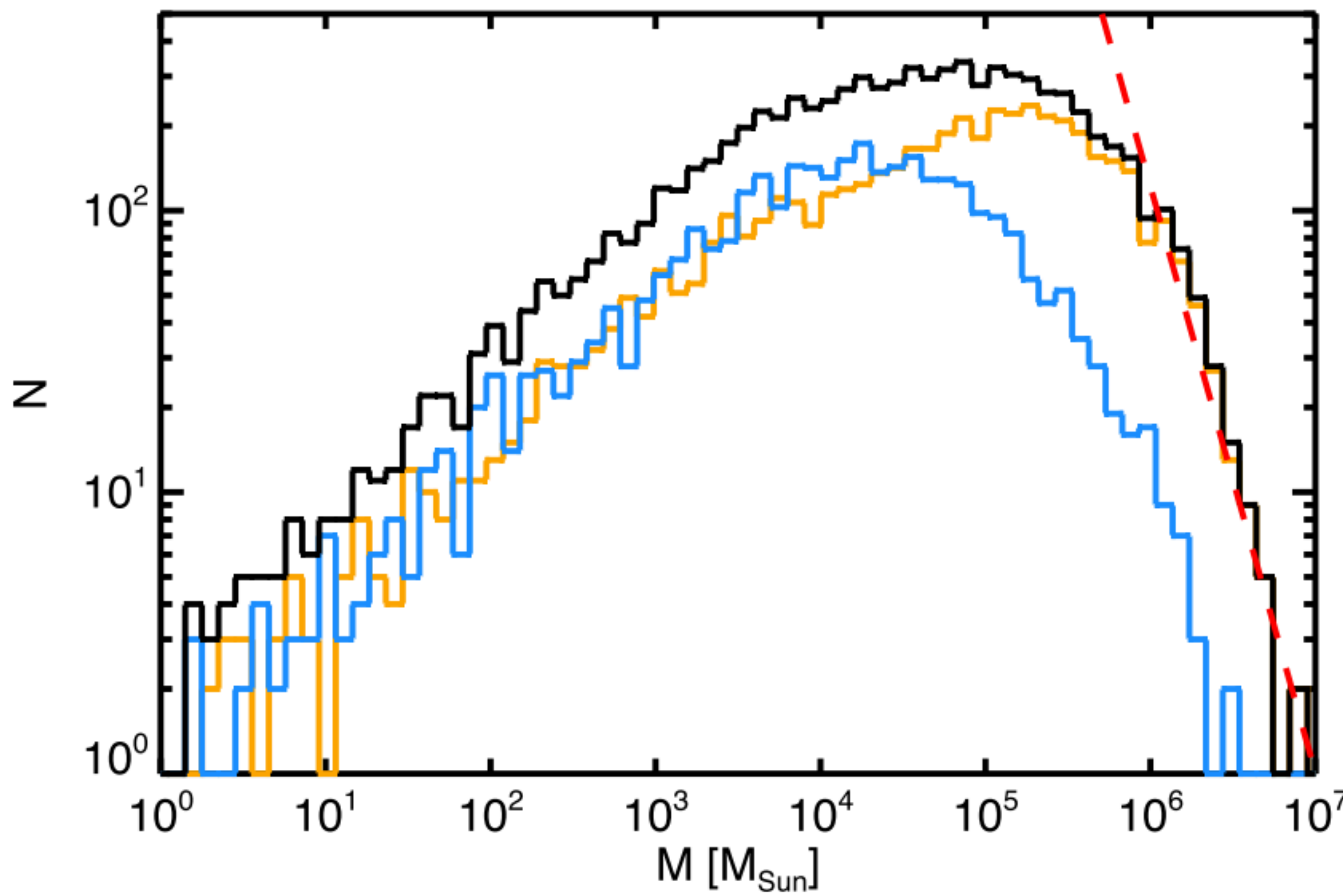
- Stahler & Palla 2004 - Chapters 2, 3, appendix D
- Draine 2011 - Chapters 30, 32
- Tielens 2005 - Chapters 8, 10

In depth look at the physical processes

- Chevance et al. 2022 (to appear in Protostars & Planets VII)
- Heyer & Dame 2015 (MW molecular clouds)
- Dobbs et al. 2014 (PPVI review)

What are the general properties of molecular clouds?

Most of the mass is in the most massive clouds



Miville-Deschenes et al. 2017

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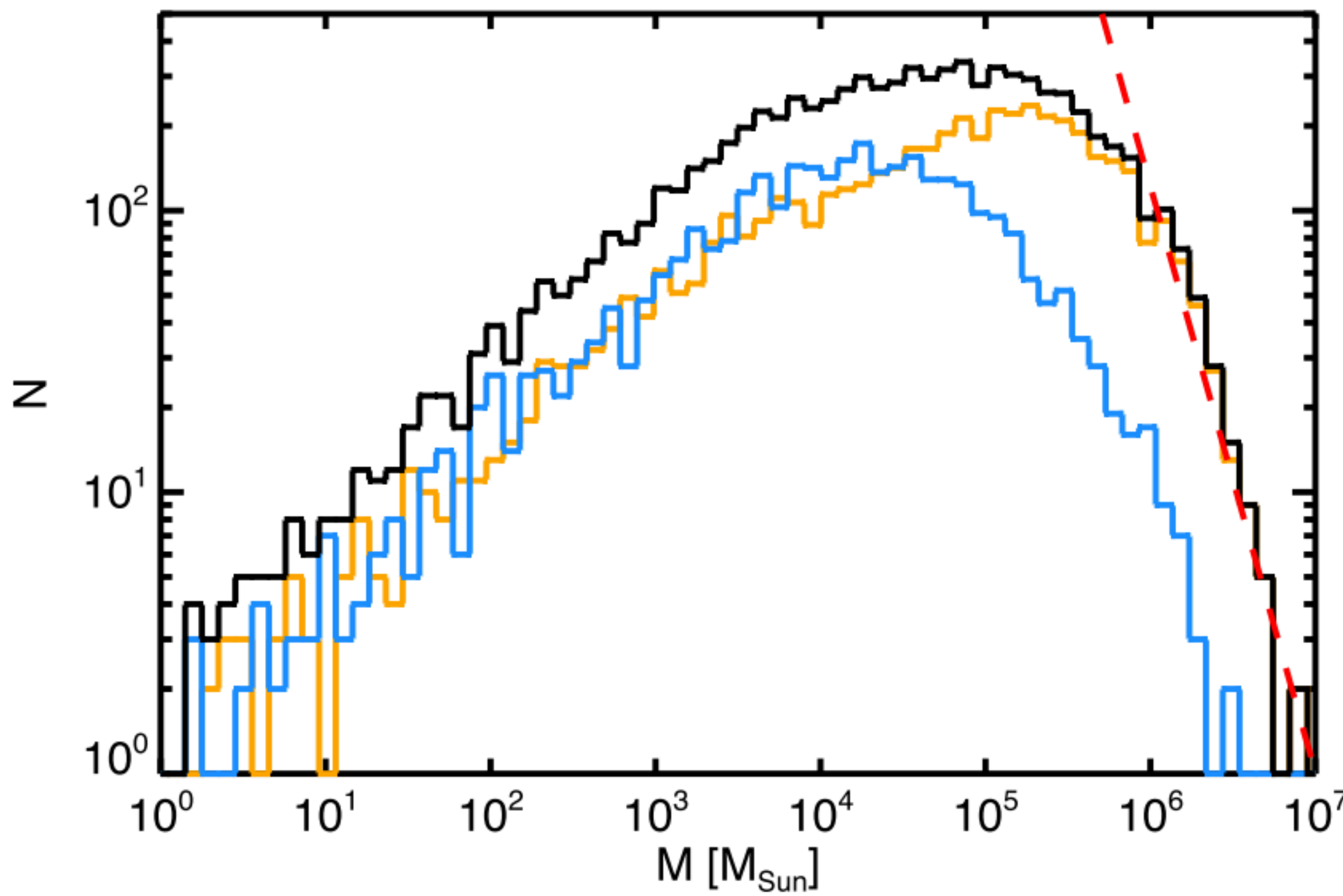

Miville-Deschenes et al. 2017

- Mass distribution fit by a power-law: $\dfrac{dN}{dM} \sim M^{-\gamma}$ (red dashed line)
- In the Milky Way, $\gamma = 1.5 - 1.8$ == most of the mass is in the most massive clouds
- In the MW - 24 of the most massive star forming complexes account for >50% of all present-day star formation

What are the general properties of molecular clouds?

Larson's *"Laws"* (Larson 1981)

Lets state them first, and then dig deeper…

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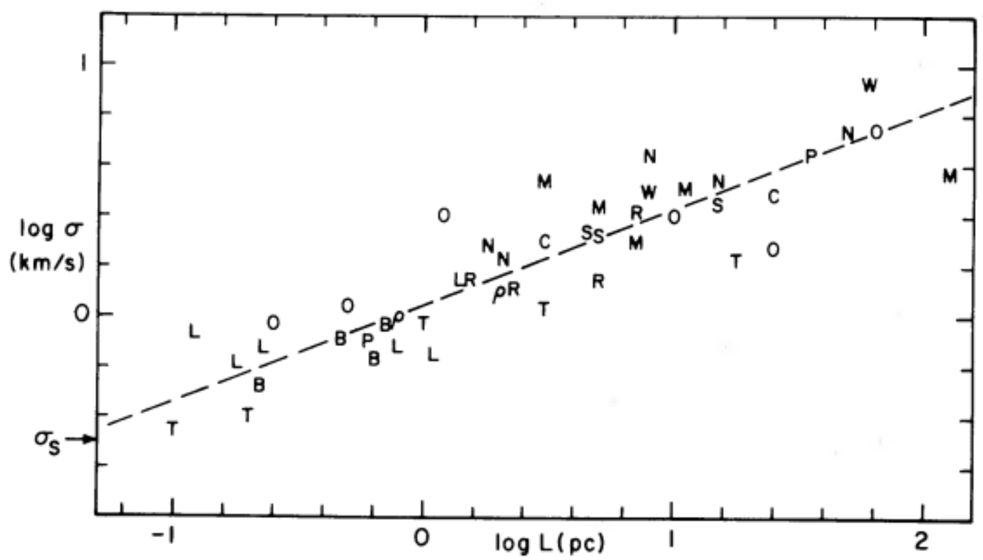

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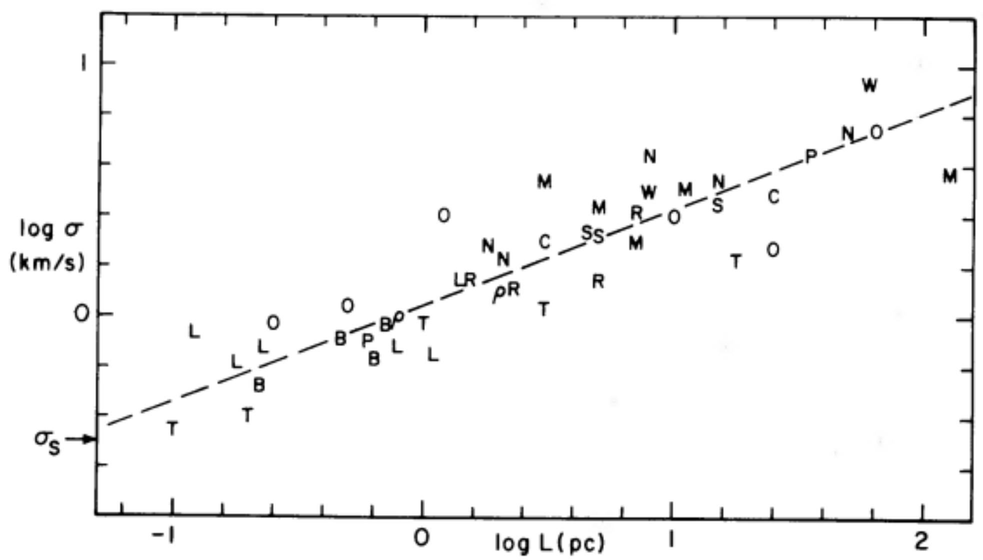

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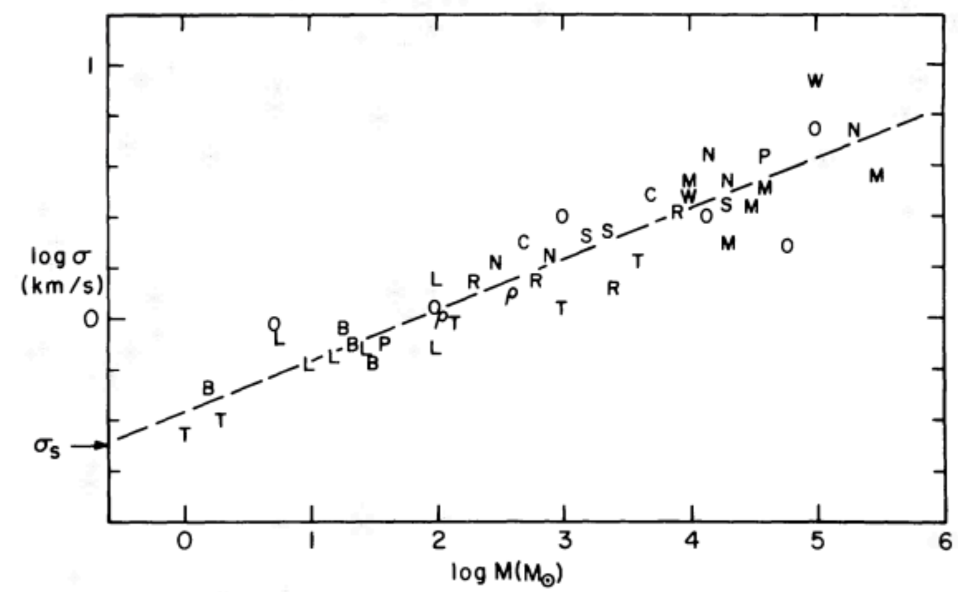

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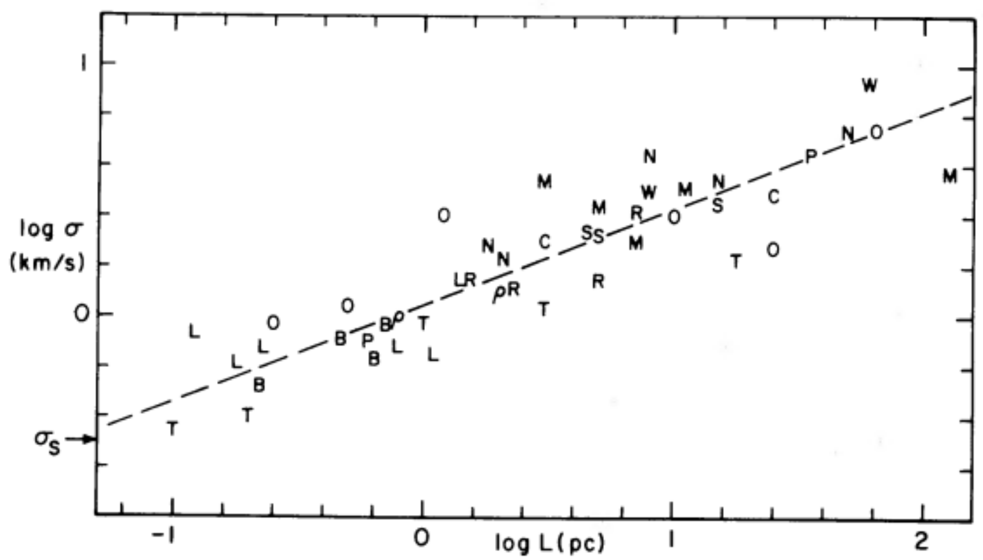

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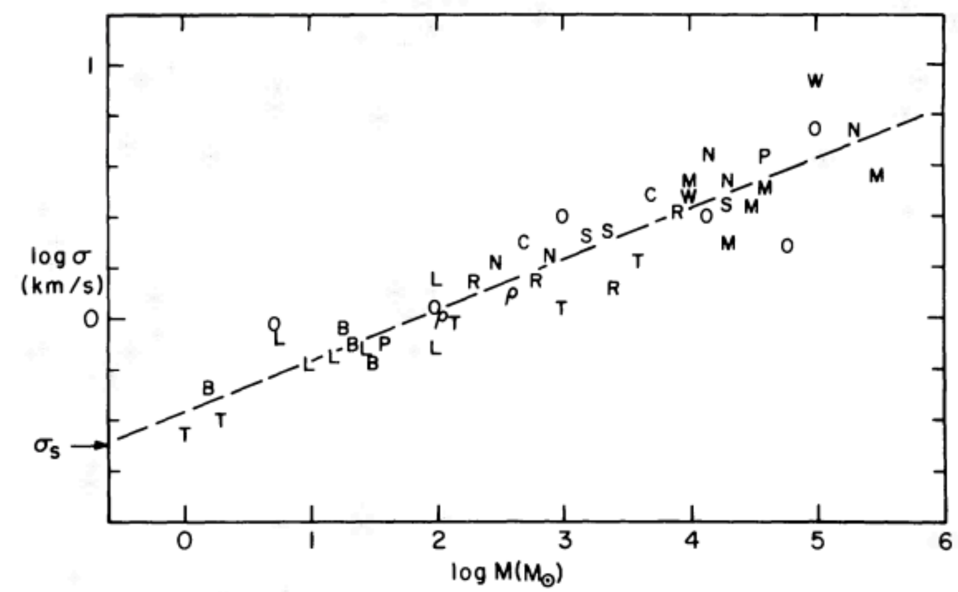

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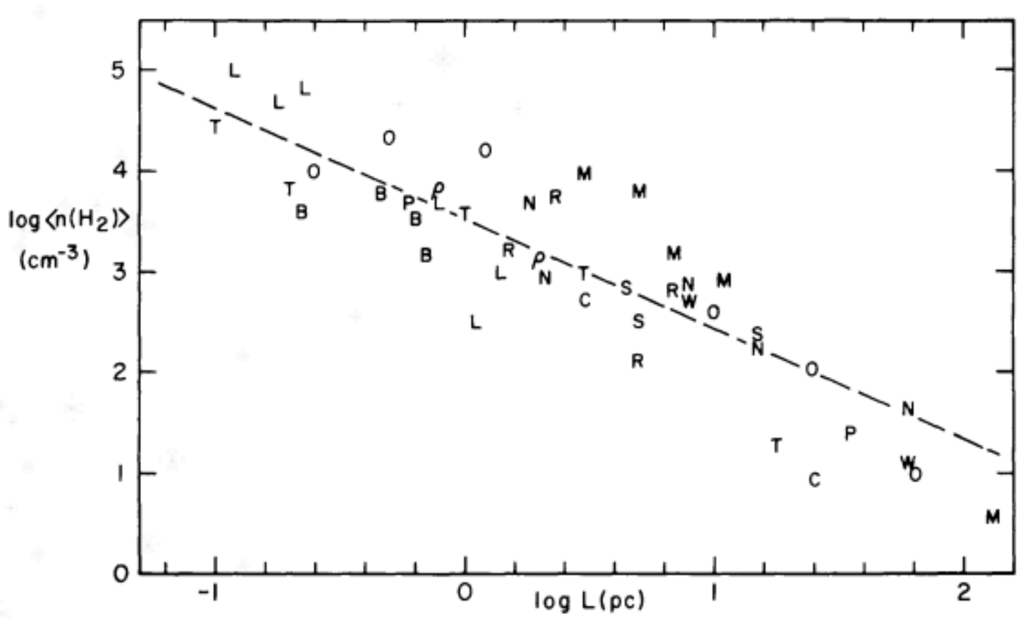

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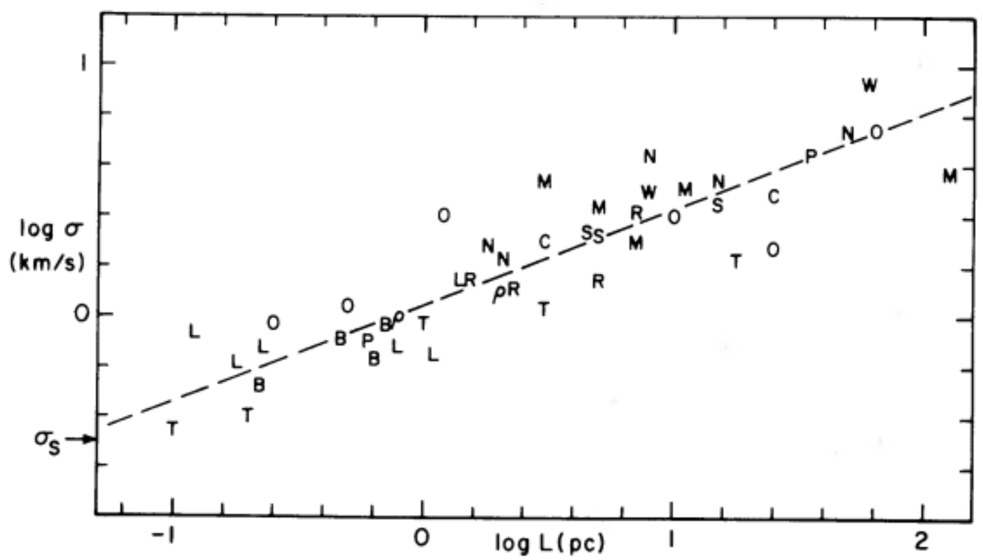

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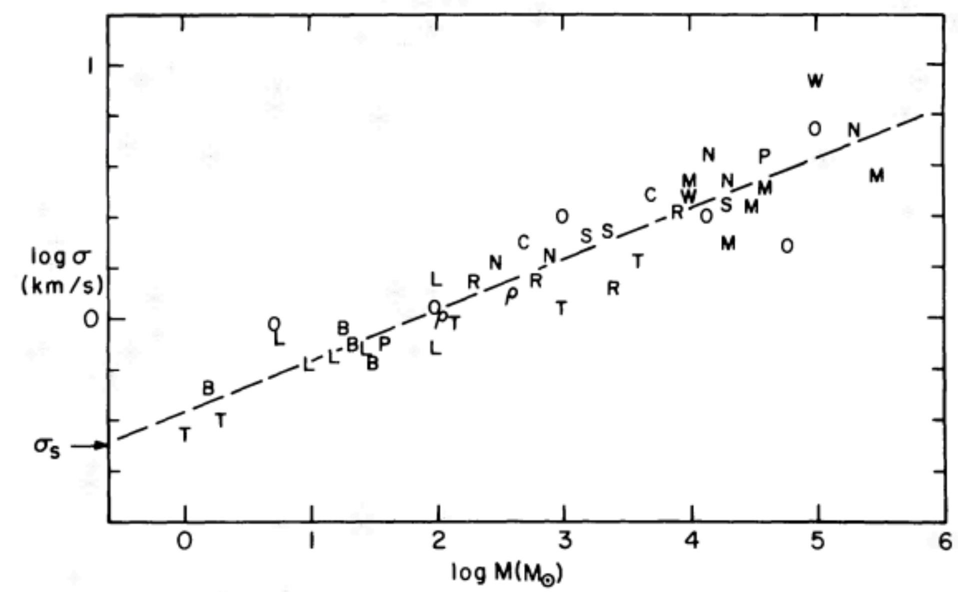

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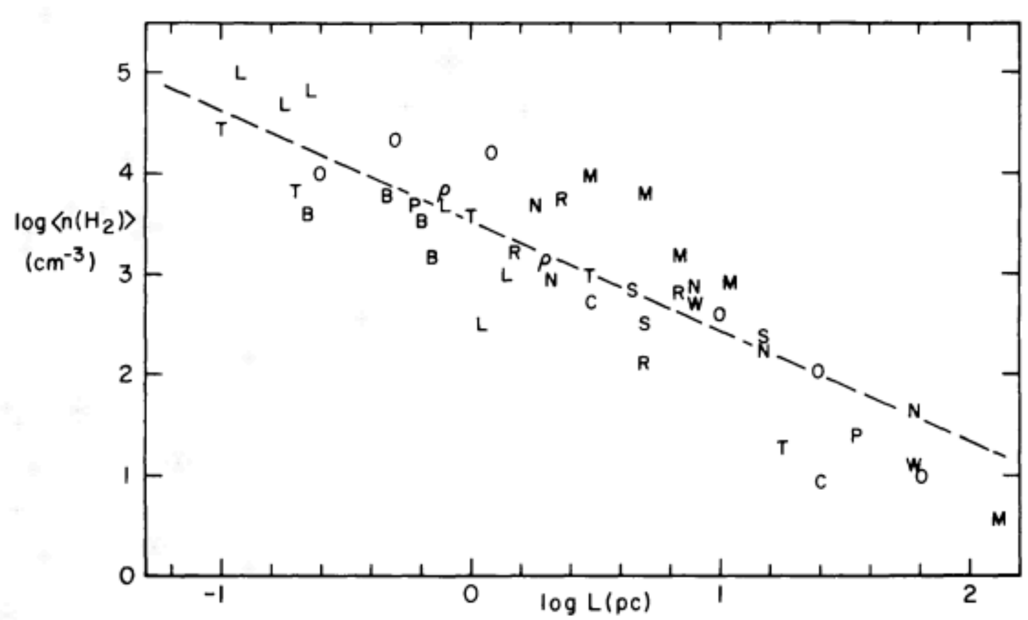

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Three relationships with important physical implications:

1. Molecular clouds are turbulent

2. An equipartition exists between gravitational and kinetic energy densities

3. The mass surface density does not vary significantly between clouds

What are the general properties of molecular clouds?

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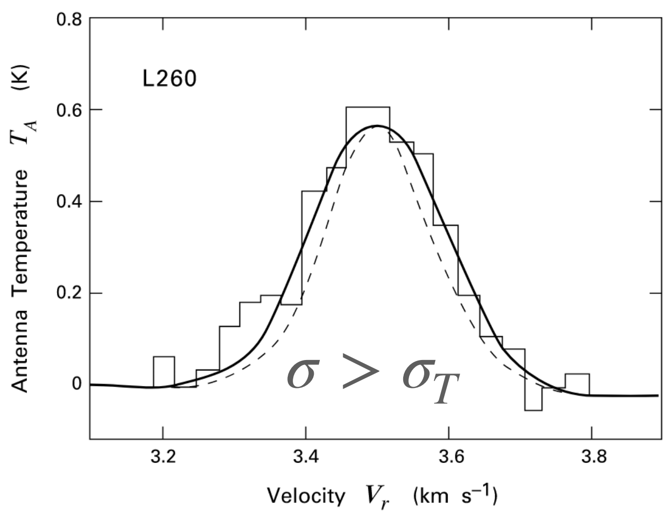
We know this already…



$$\sigma_T = \sqrt{\frac{K_B T}{m_{\mathrm{mol}}}}$$

For gas @ 10K:

$$\sigma_T = 0.07\,(\mathrm{km\,s^{-1}})$$

Also, Reynolds number: $R = Lv/\eta_{\mathrm{kin}}$; where L is the spatial size, v is the mean flow velocity, η_{kin} is the kinematic viscosity: Can be >10^8 under typical cloud conditions

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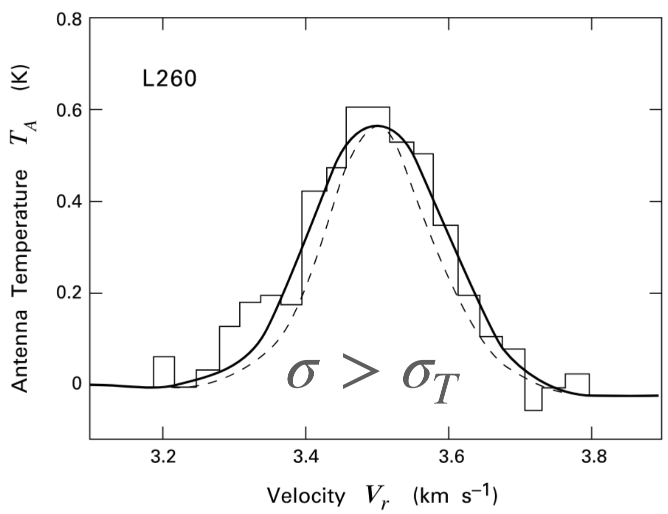

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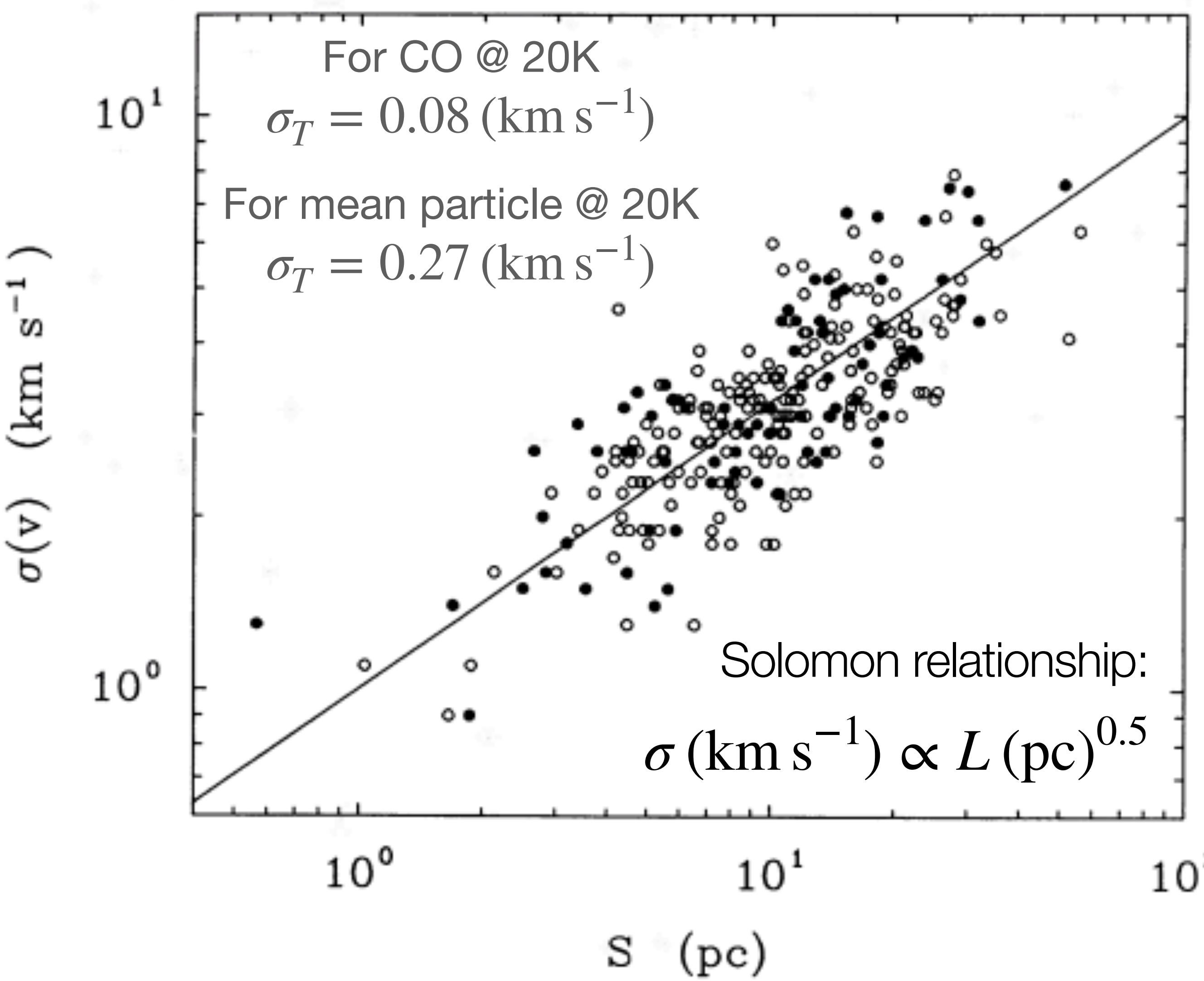

For CO @ 20K

$\sigma_T = 0.08\,(\mathrm{km\,s^{-1}})$

For mean particle @ 20K

$\sigma_T = 0.27\,(\mathrm{km\,s^{-1}})$

Solomon relationship:

$$\sigma\,(\mathrm{km\,s^{-1}}) \propto L\,(\mathrm{pc})^{0.5}$$

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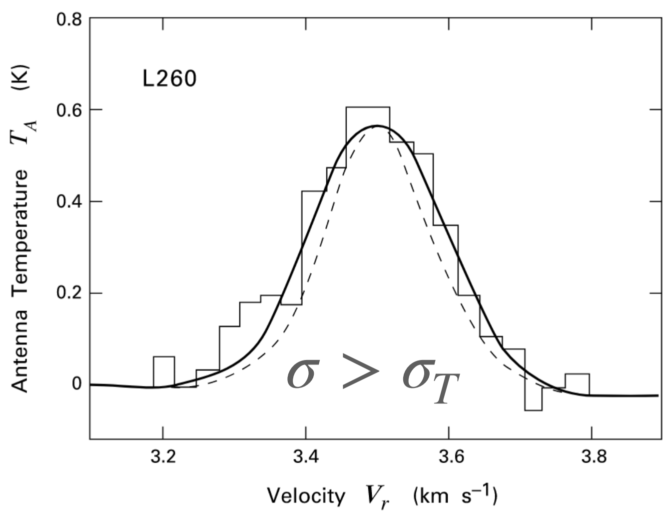

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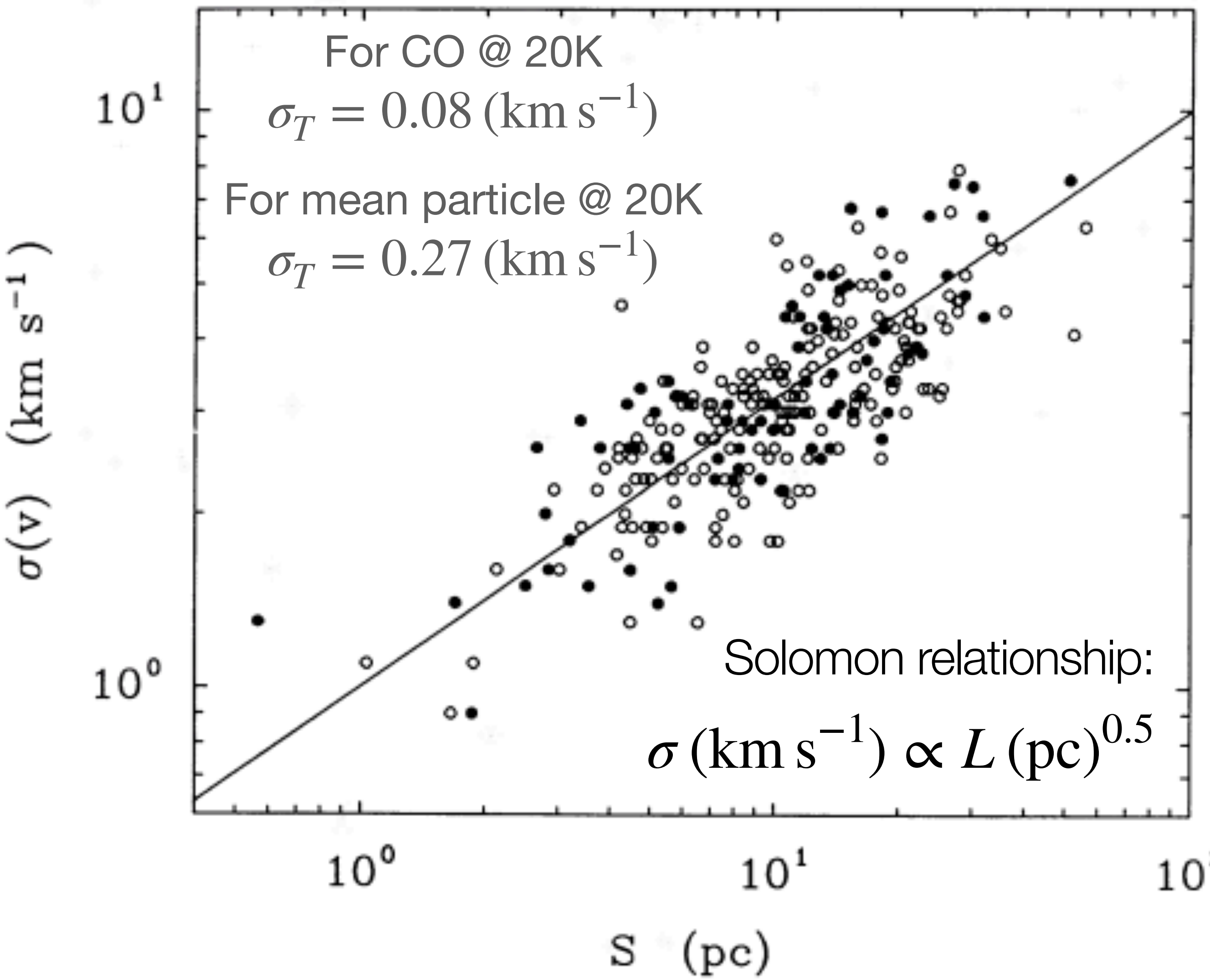

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- Larson pointed out that this scaling was very similar to that of subsonic, incompressible turbulent flows, which have a power-law dependence of eddy velocity on length scale that is the *Kolmogorov law*: $\sigma \propto L^{0.33}$
- However, on the scale of molecular clouds, turbulent motion is supersonic (Mach number, $\mathscr{M} = v/\sigma_{T,3\mathrm{D}} > 1$)
- More recent work suggests the scaling is closer to 0.5 — expected for compressible, shock dominated turbulence

What are the general properties of molecular clouds?

2. An equipartition exists between gravitational and kinetic energy densities

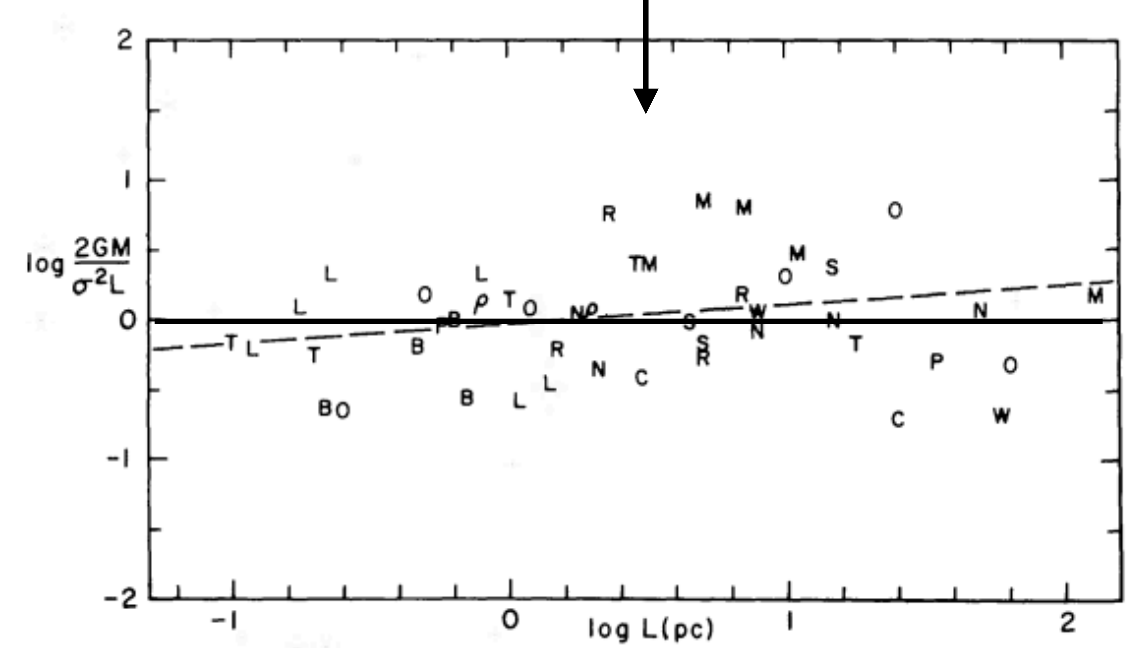
$$\sigma\,(\mathrm{km\,s^{-1}}) = 0.42\,M\,(\mathrm{M_\odot})^{0.2}$$

Positive correlation between dispersion and mass is expected for clouds in "virial equilibrium"

Kinetic energy: $\mathscr{T} = 0.5M\sigma^2$

Gravitational energy: $\mathscr{W} = GM^2/R$

$\dfrac{2\mathscr{T}}{|\mathscr{W}|} = 1$ implies $GM/\sigma^2 R = 1$



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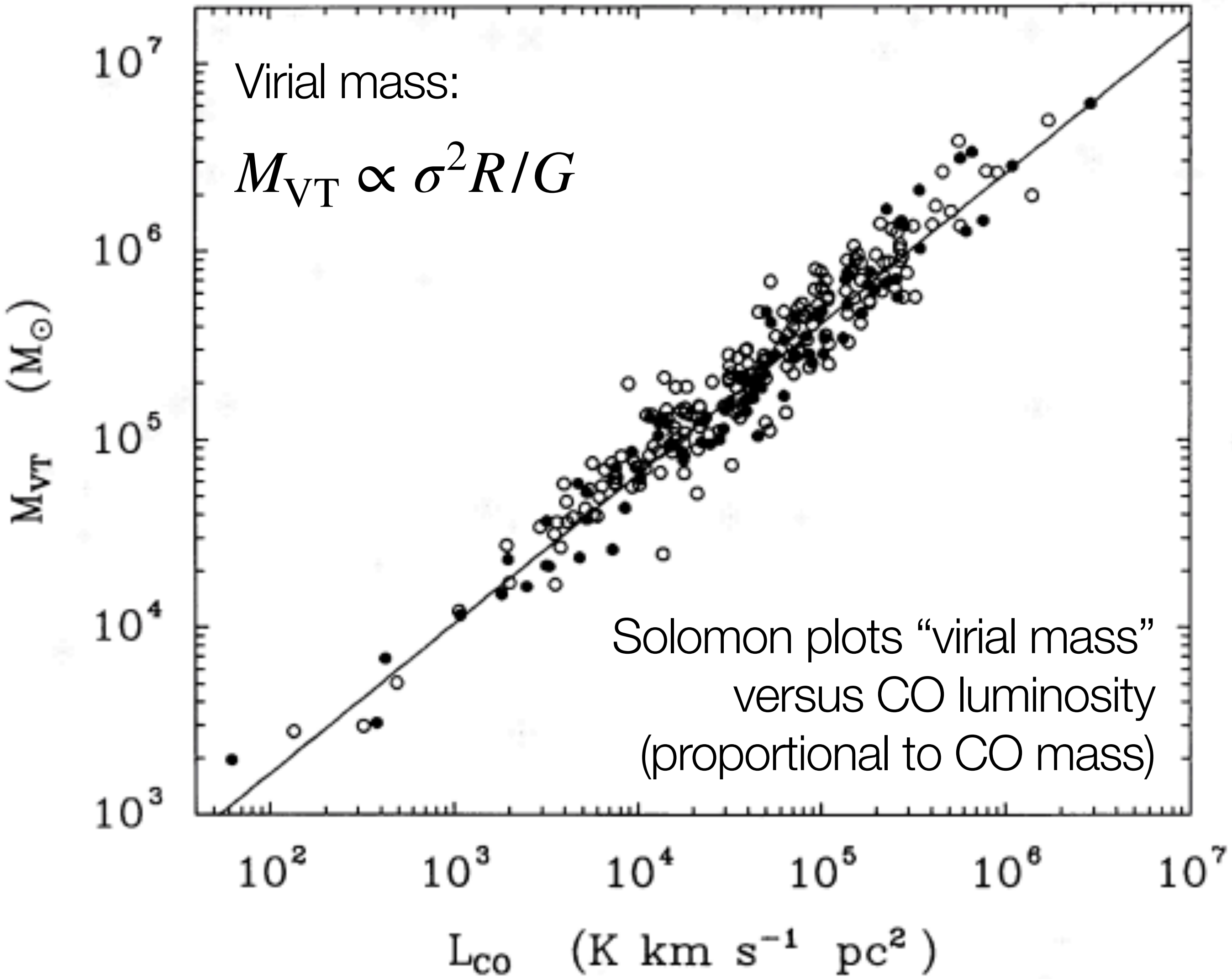

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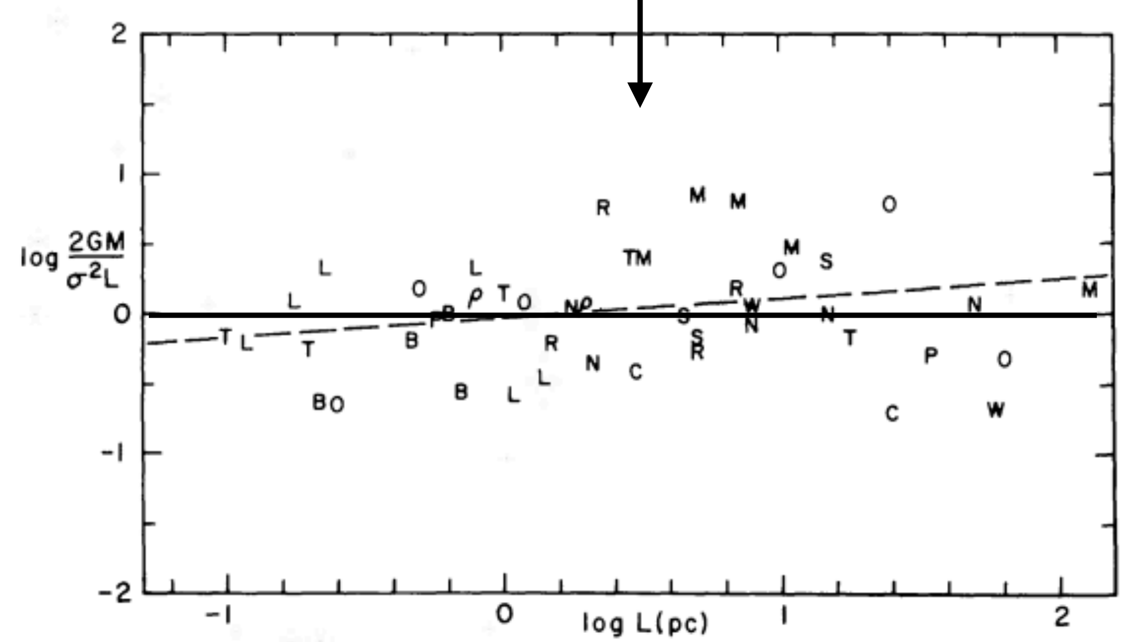

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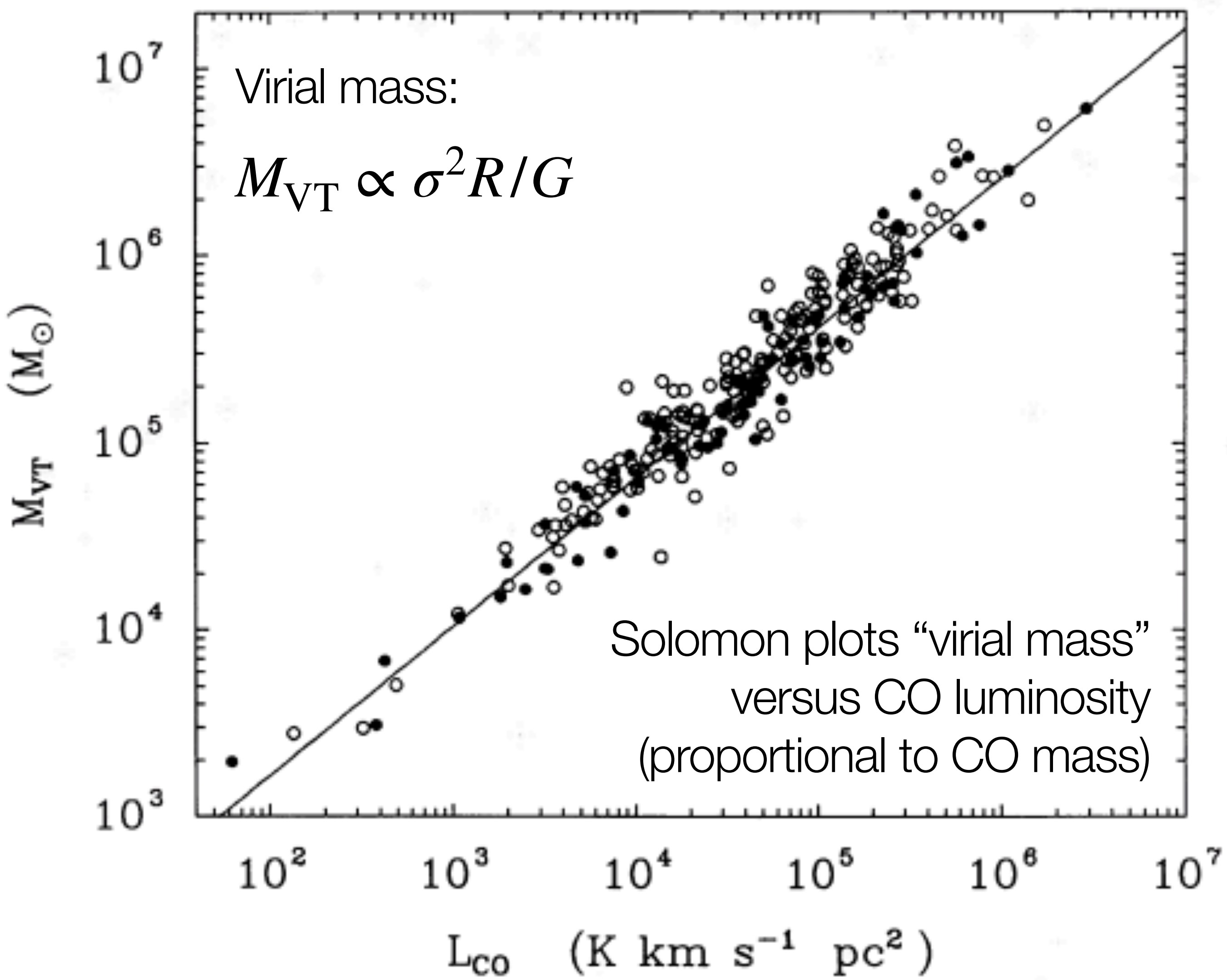

Virial mass:

$$M_{\rm VT} \propto \sigma^2 R/G$$

Solomon plots “virial mass” versus CO luminosity (proportional to CO mass)

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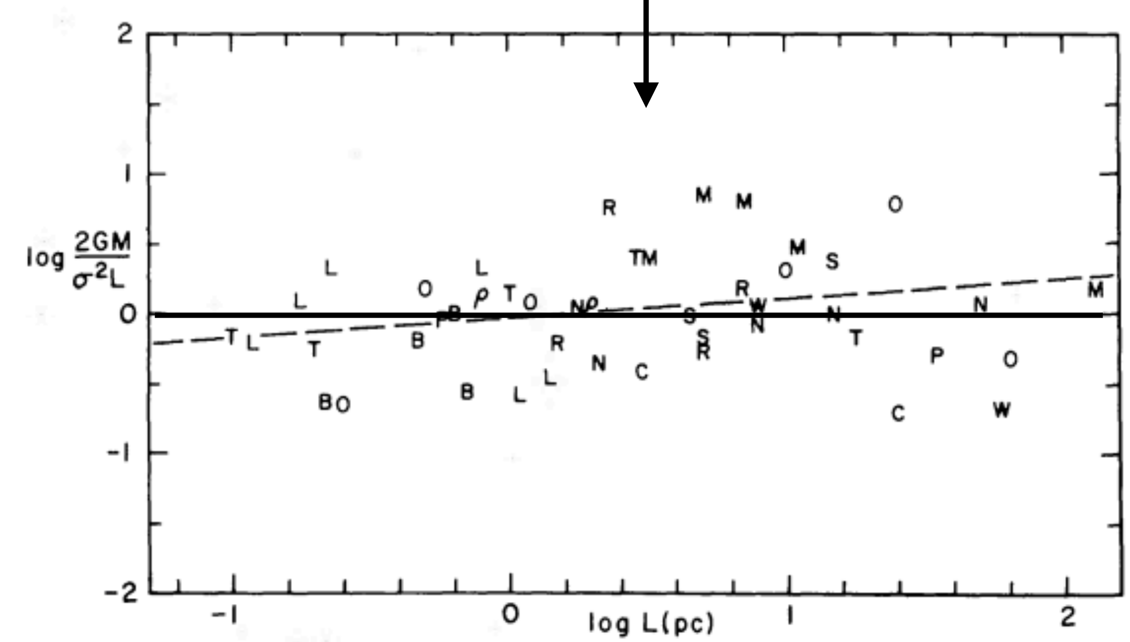

- Often the inference is that under typical conditions in the Galactic Disk, molecular clouds are gravitationally bound
- Note though that the physical interpretation of the motion is debated, as we shall see
- More on the virial theorem next week!

What are the general properties of molecular clouds?

3. The mass surface density does not vary significantly between clouds

Note that Larson's relations are not independent — the validity of any two of the relationships algebraically implies the third.

$$\sigma \propto R^{0.5}$$

$$GM/\sigma^2 R = 1$$

And so

$M/R^2 = \Sigma = \mathrm{const}$; implies $n \propto 1/R$

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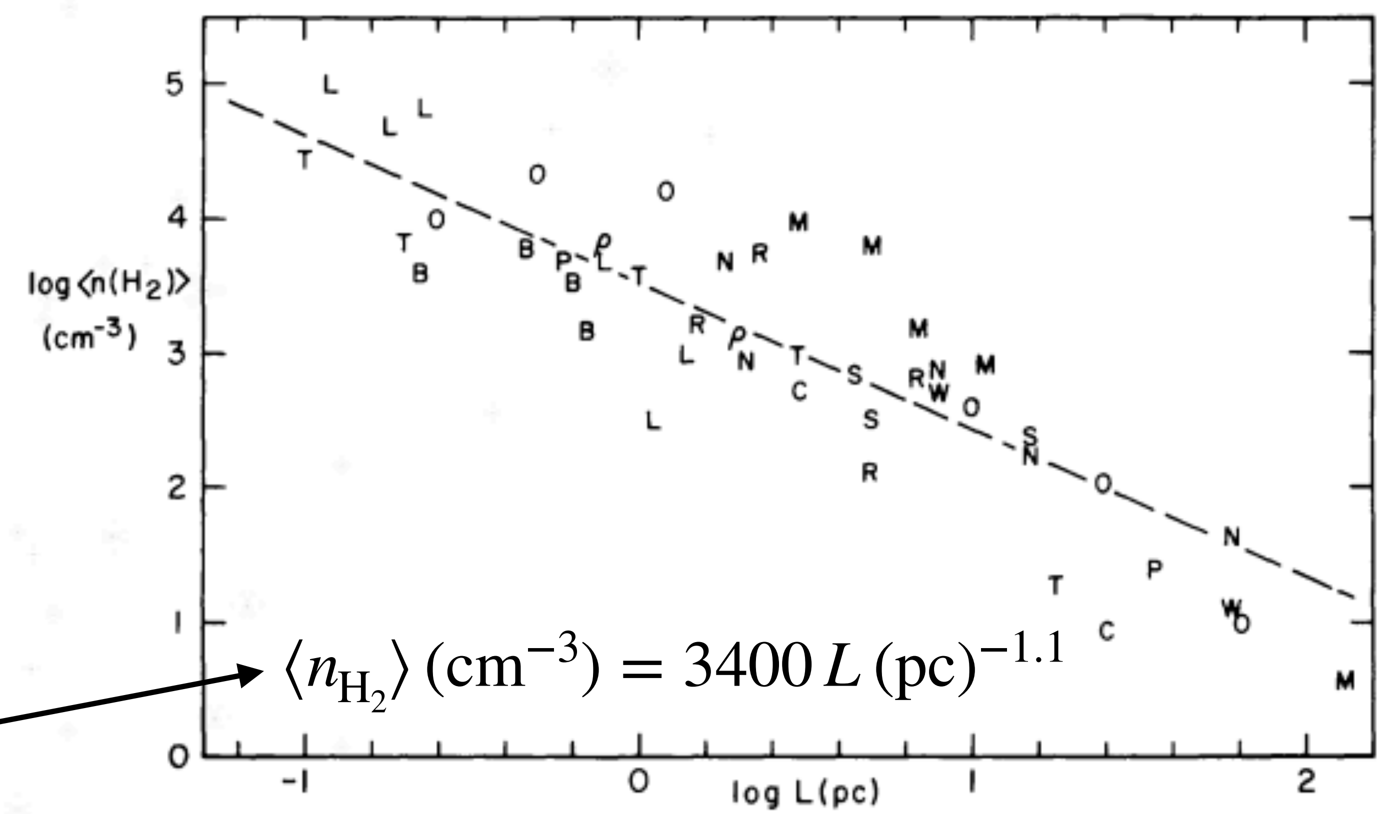

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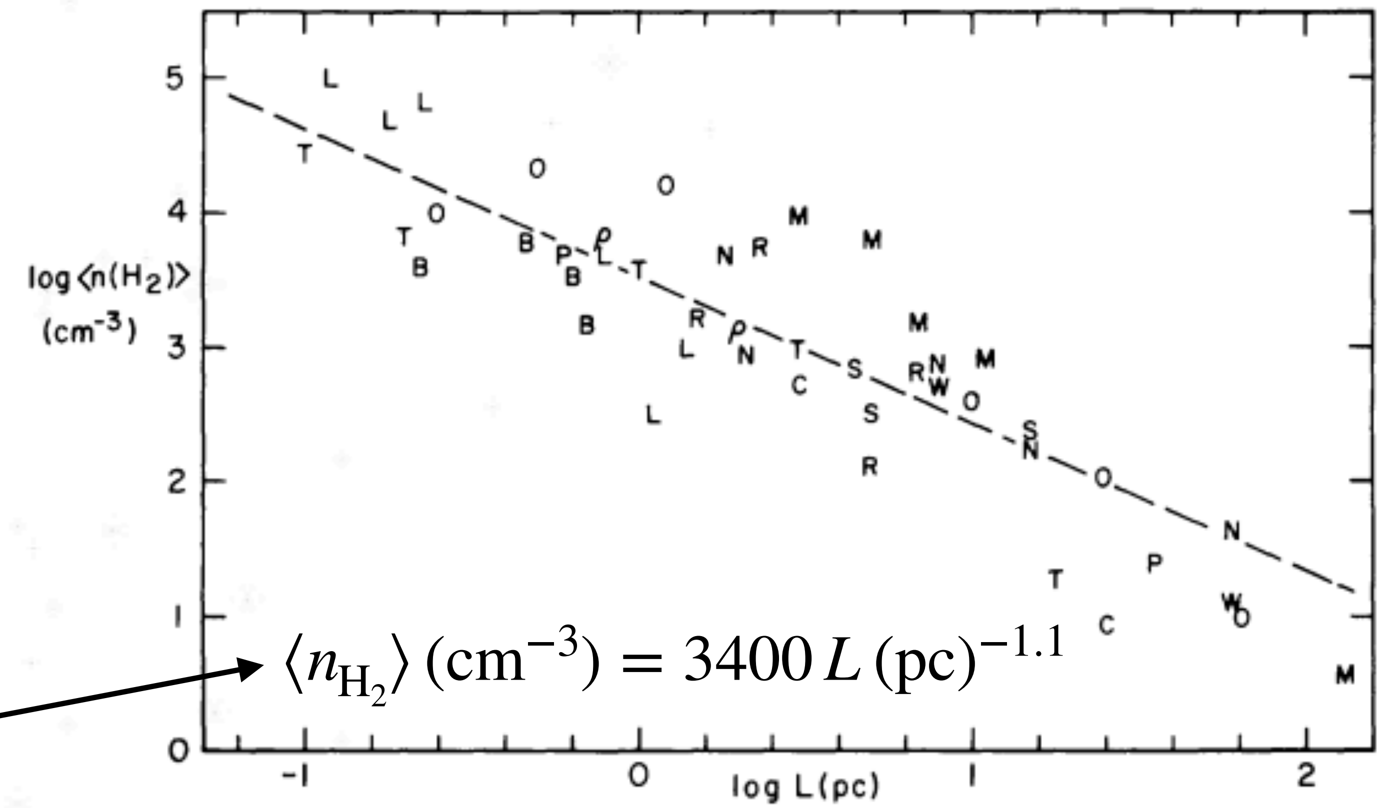

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- The Solomon+ 1987 sample of clouds has a mean surface density of the order $\Sigma \approx 200\,\mathrm{M_\odot\,pc^{-2}}$

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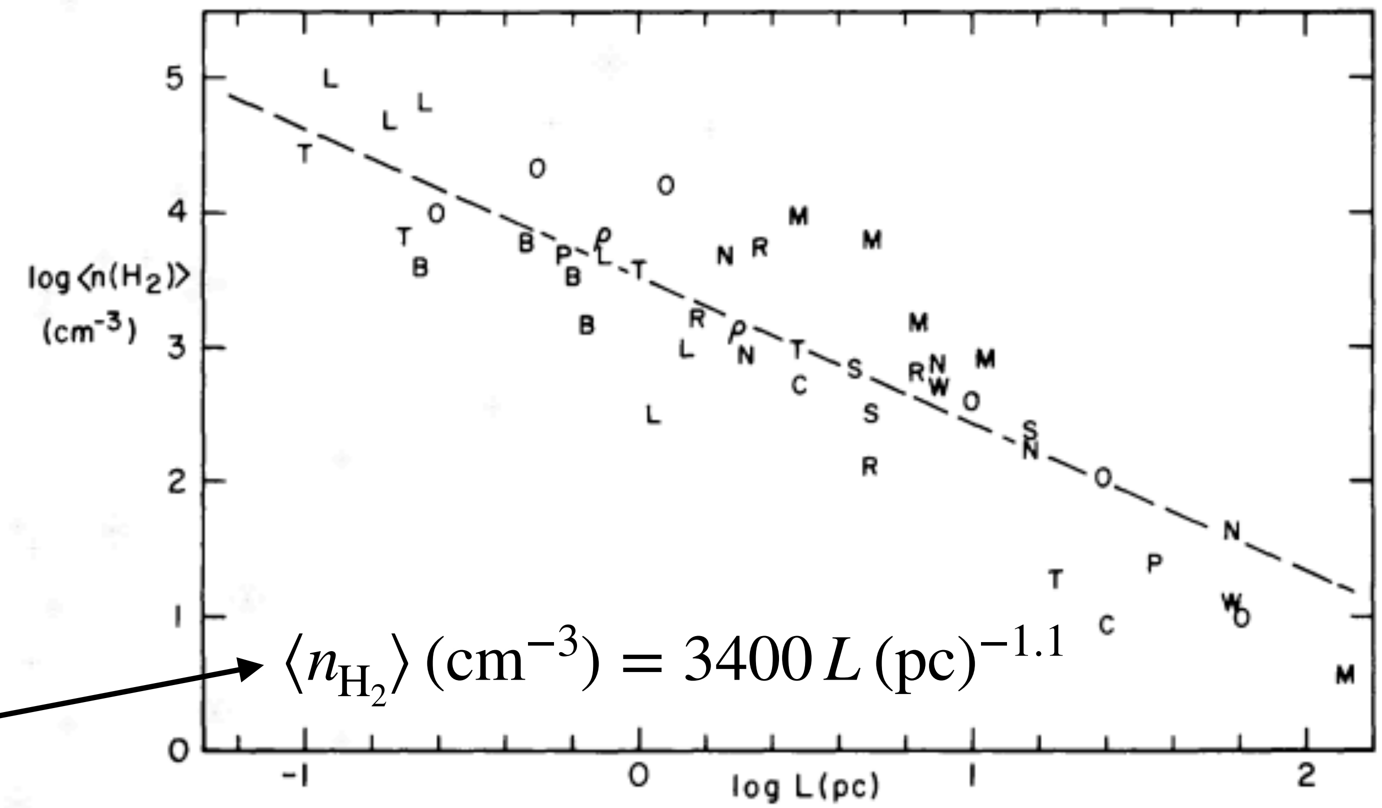

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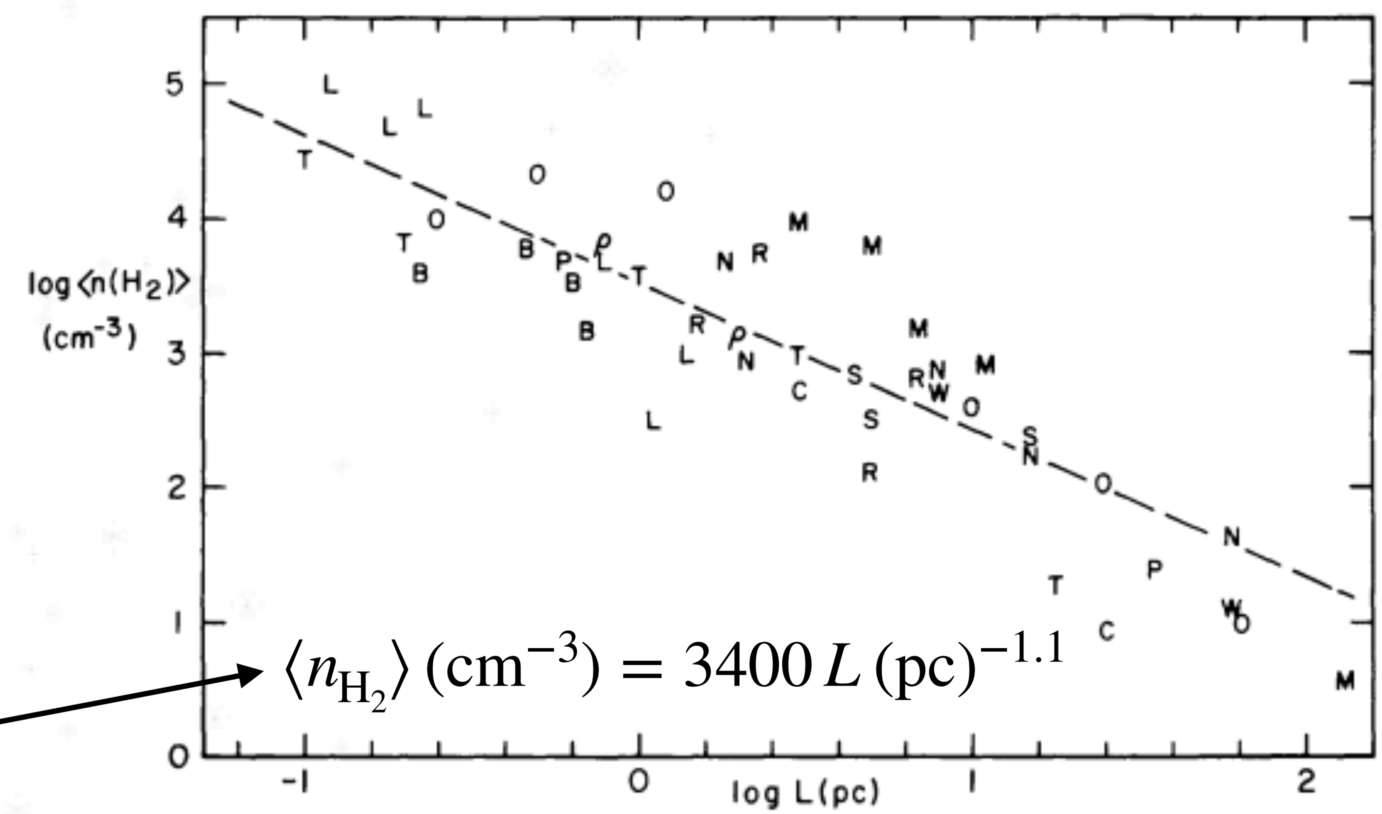

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But…

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If the surface density of clouds is a constant, then one recovers the linewidth-size scaling ($\sigma = v_0 R^{0.5}$), with the normalisation coefficient…

$$v_0 = (\pi G \Sigma / 5)^{1/2}$$

$$v_0 = 0.52 \left(\frac{\Sigma}{10^2\,\mathrm{M_\odot\,pc^{-2}}} \right)^{1/2} \mathrm{km\,s^{-1}\,pc^{-1}}$$

Given, $\sigma = (\pi G/5)^{1/2} R^{1/2} \Sigma^{1/2}$, absolute adherence to Universality and Larson's three relationships would mean a single point centred at $\sigma / R^{1/2} = (\pi G \Sigma / 5)^{1/2}$ for a constant value of Σ

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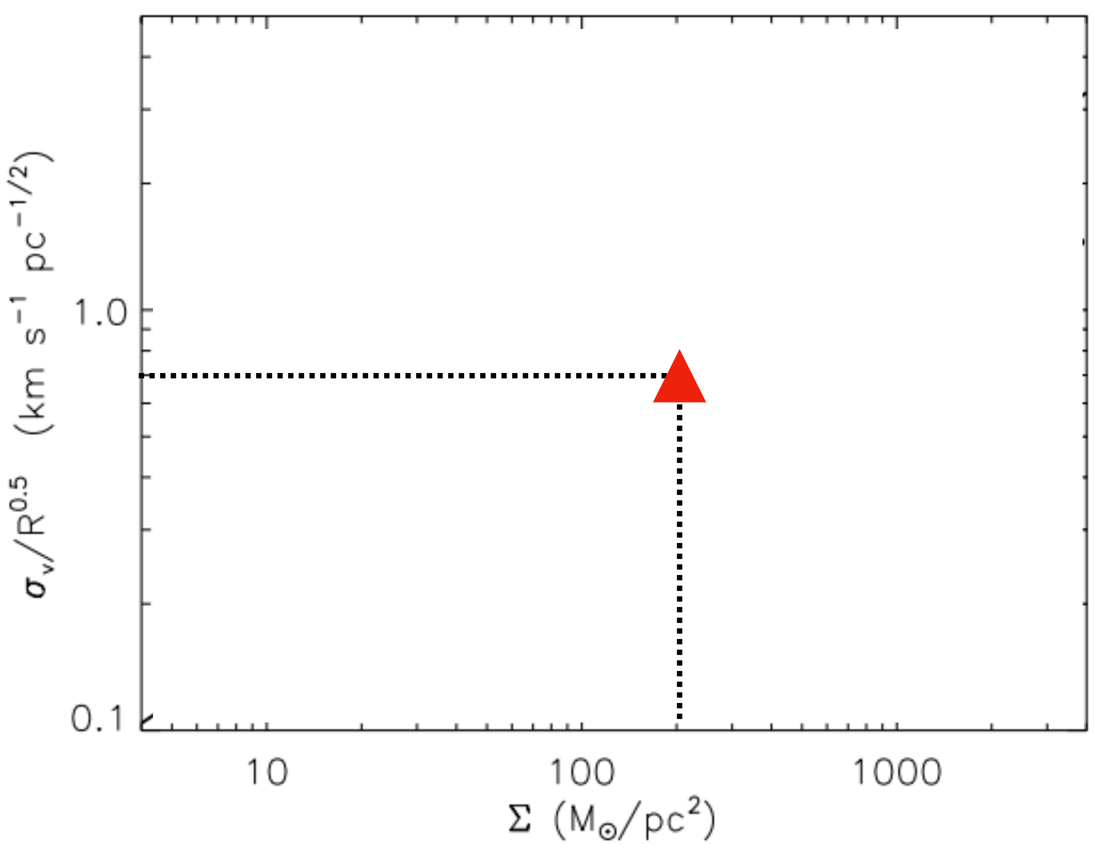

Heyer et al. 2009

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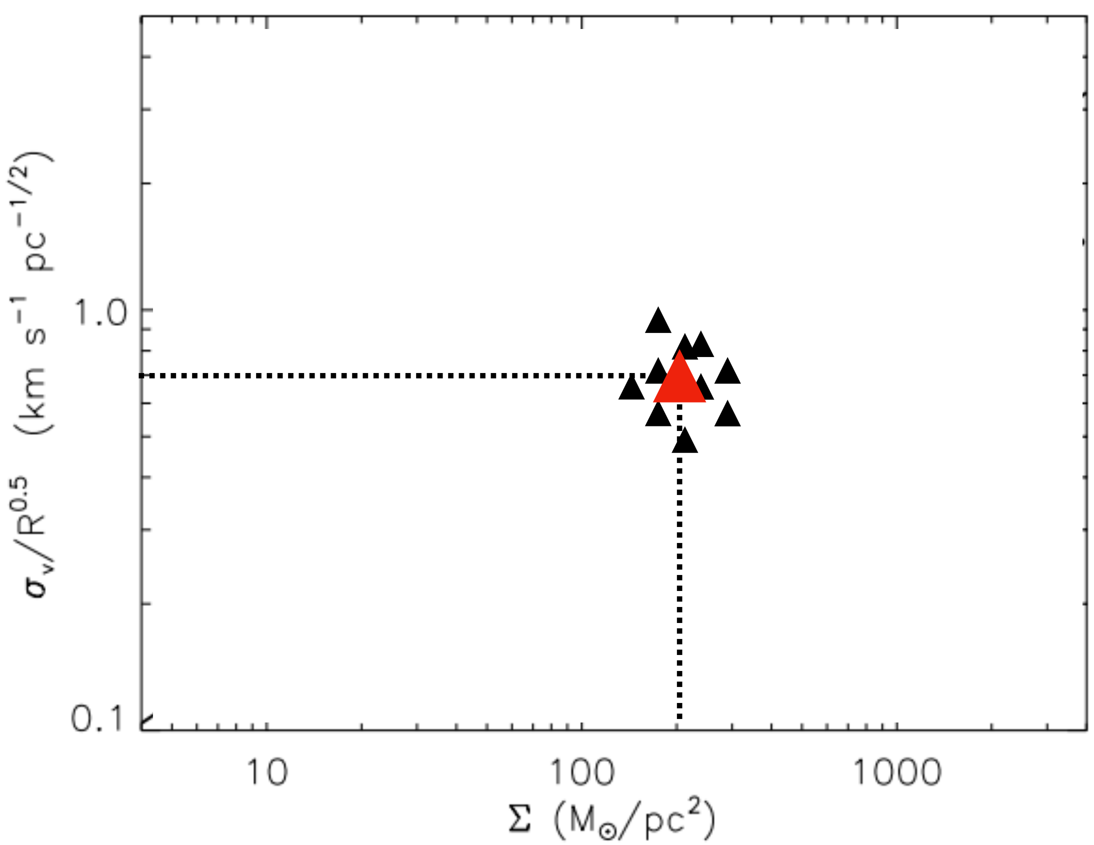

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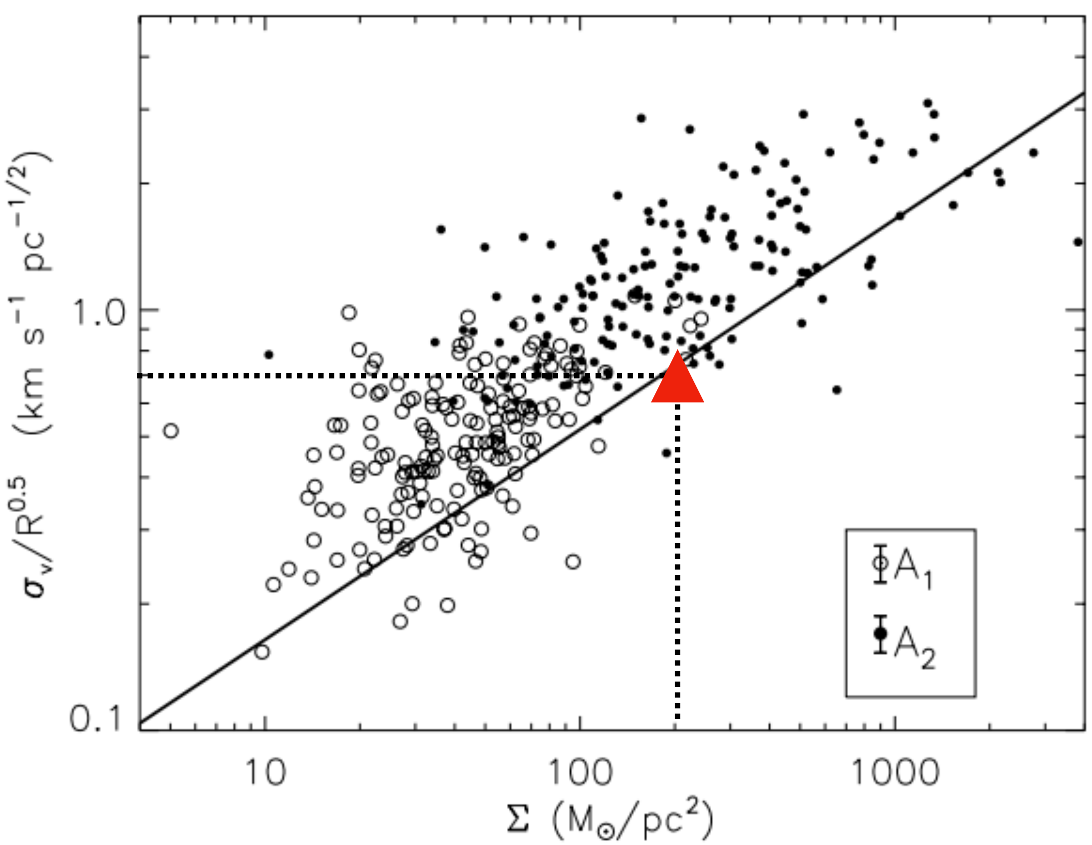
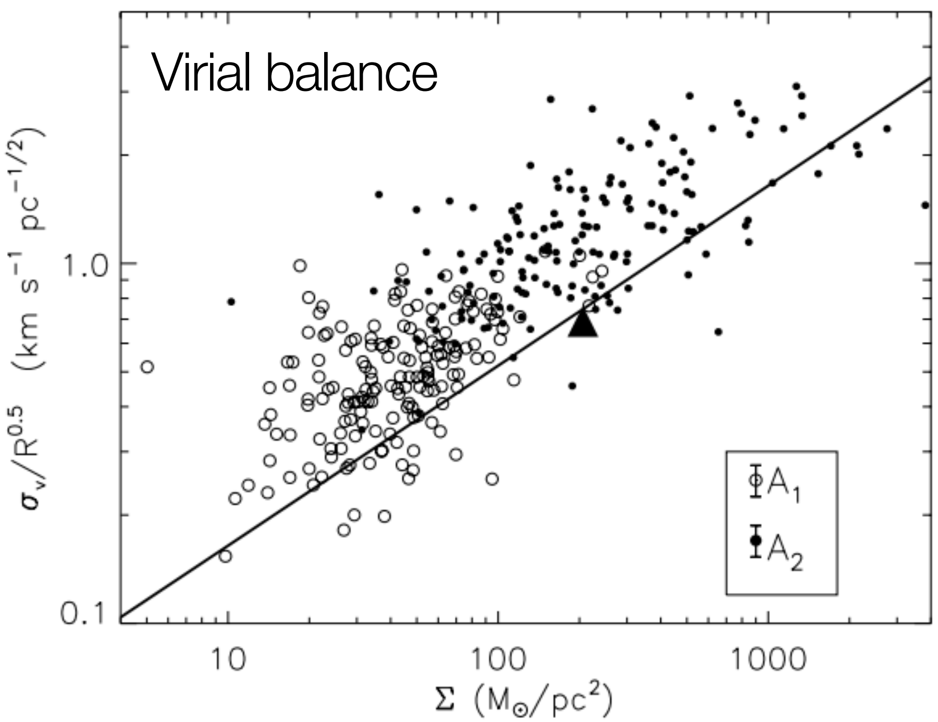


Heyer et al. 2009

- The surface density of molecular clouds varies throughout galaxies
- The dependency on surface density such that $\sigma \propto \Sigma^{1/2} R^{1/2}$, indicates that *a single linewidth-size relation does not describe all molecular clouds*
- The clouds lie above the solid line, which represents simple equipartition between the kinetic energy and gravitational energy

What are the general properties of molecular clouds?

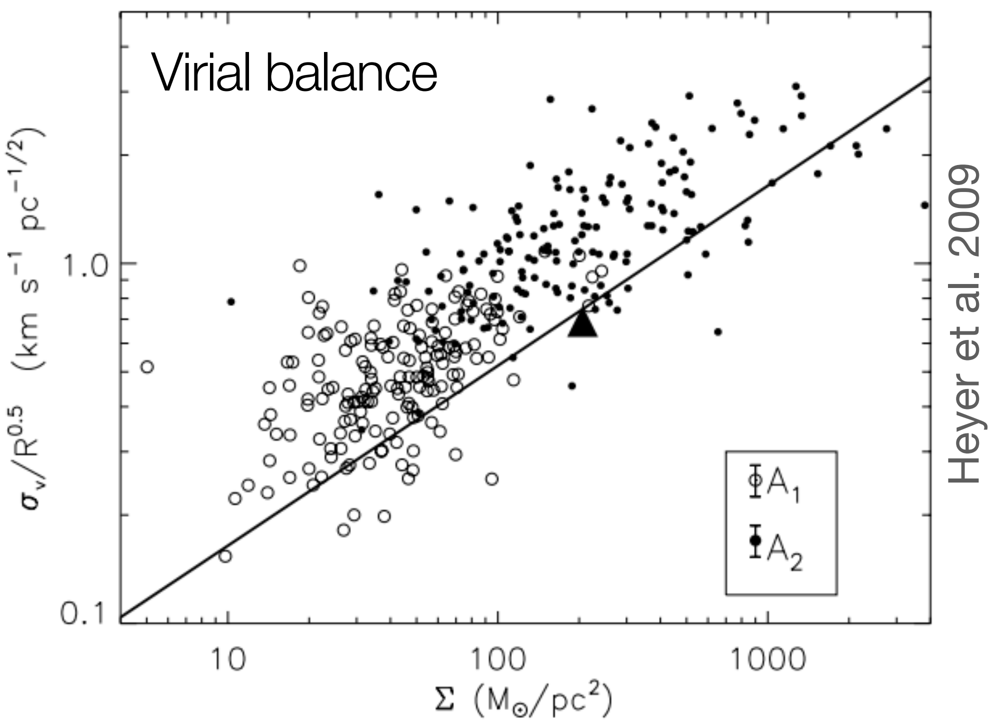
The physical meaning of velocity dispersions remains unclear

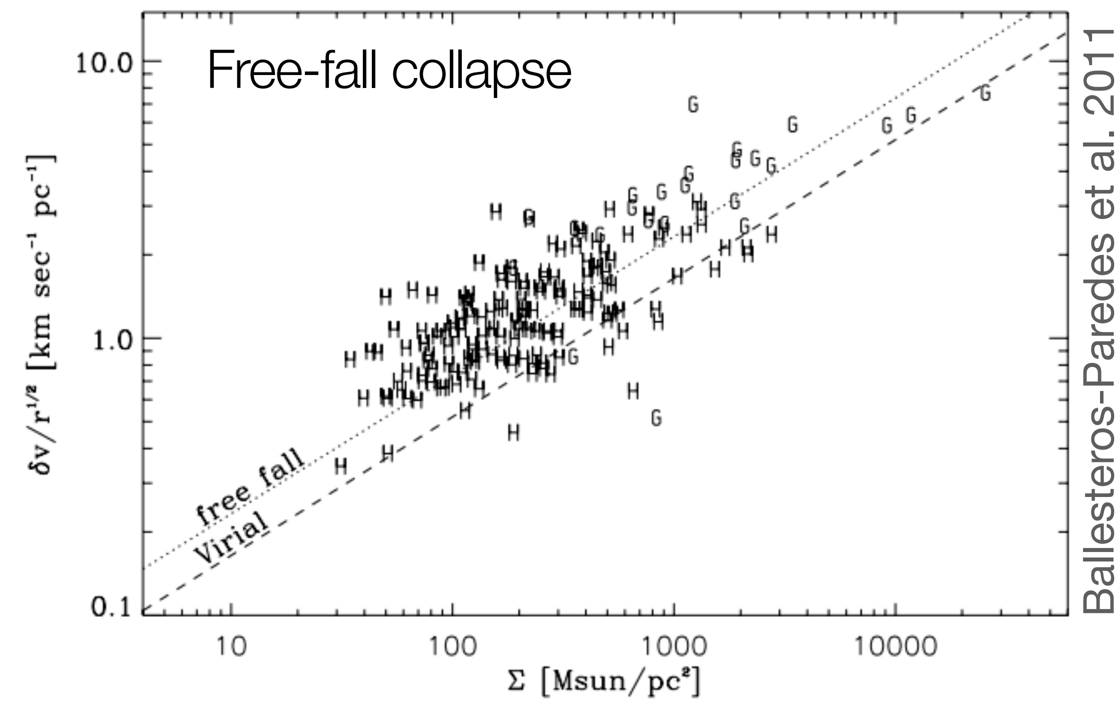


Heyer et al. 2009

What are the general properties of molecular clouds?

The physical meaning of velocity dispersions remains unclear





What are the general properties of molecular clouds?

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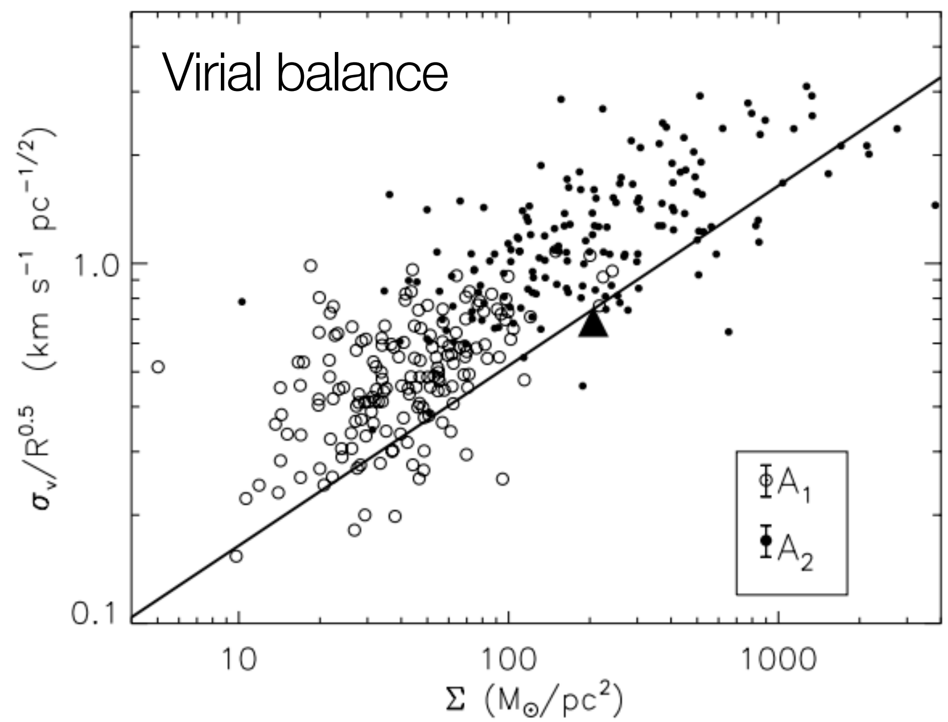
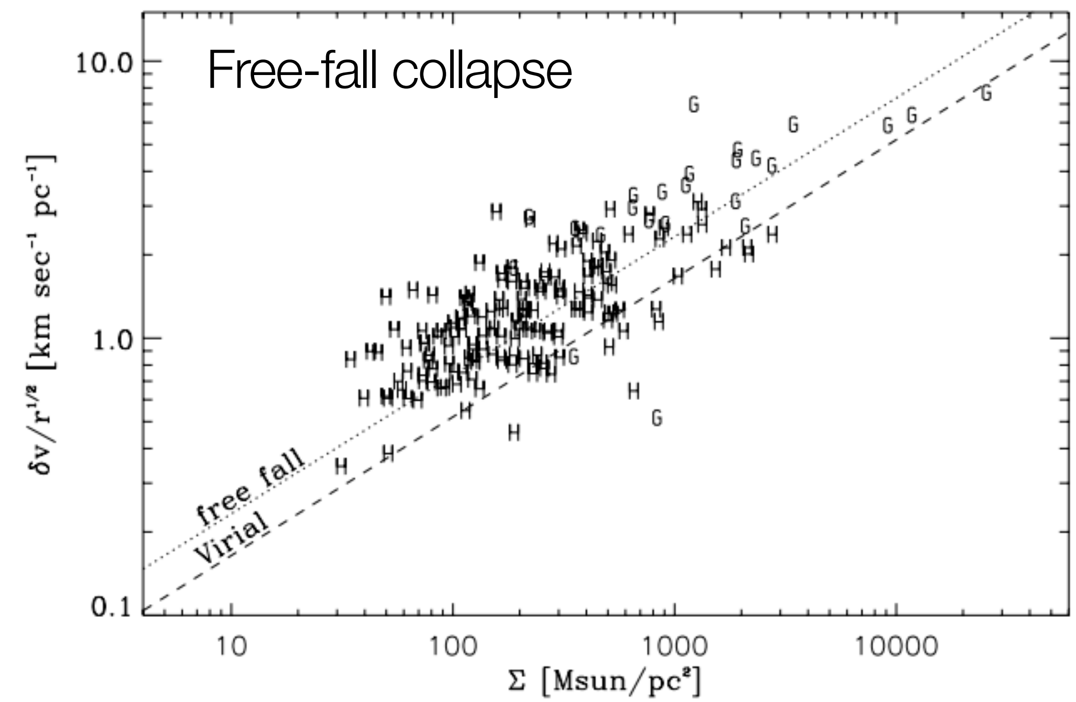


Heyer et al. 2009



Ballesteros-Paredes et al. 2011

- The fact that clouds are anywhere near equipartition tells us that the clouds can't be *too far away* from self-gravitating
- But the *exact* same data can lead to very different physical interpretations about what the clouds are doing
- The difference between these interpretations is $\sqrt{2}$ in the velocity dispersion

Today's lecture

Learning outcomes:

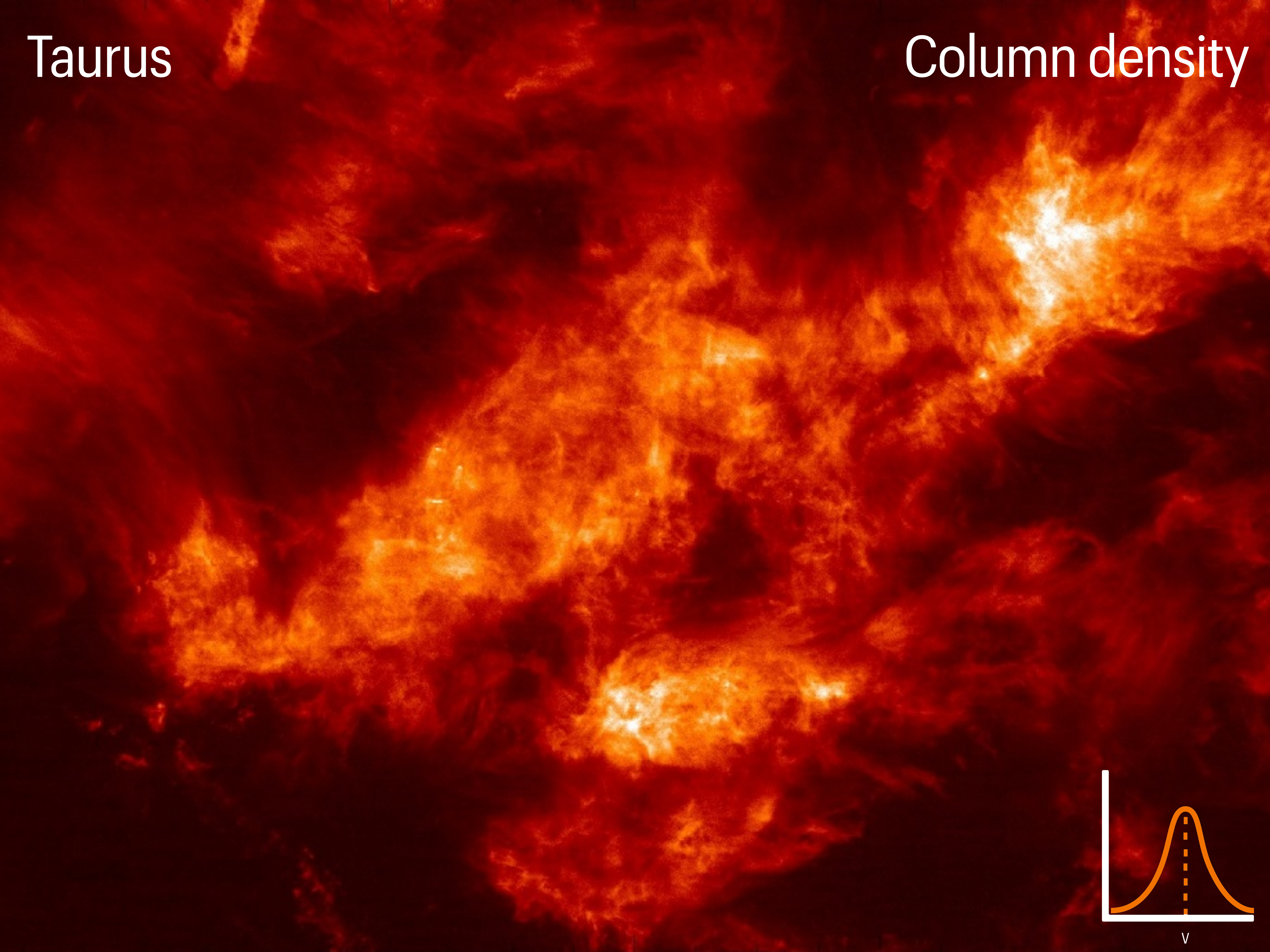
- Molecular gas as a component of the interstellar medium
- Why are we interested in molecular gas/clouds?
- What *even is* a "molecular cloud"?
- What are the general properties of molecular clouds?
- **The internal structure of molecular clouds**

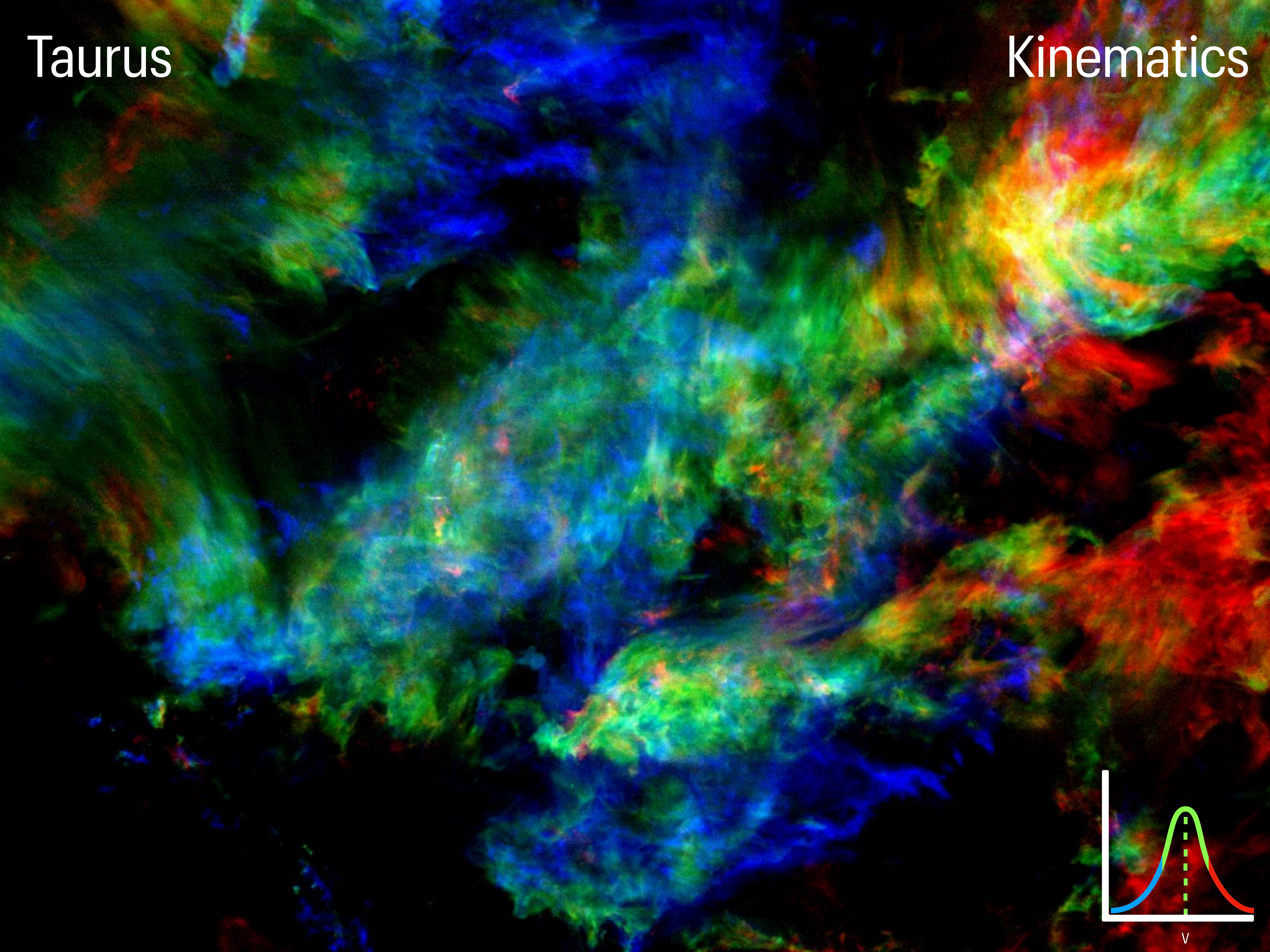
Useful resources:

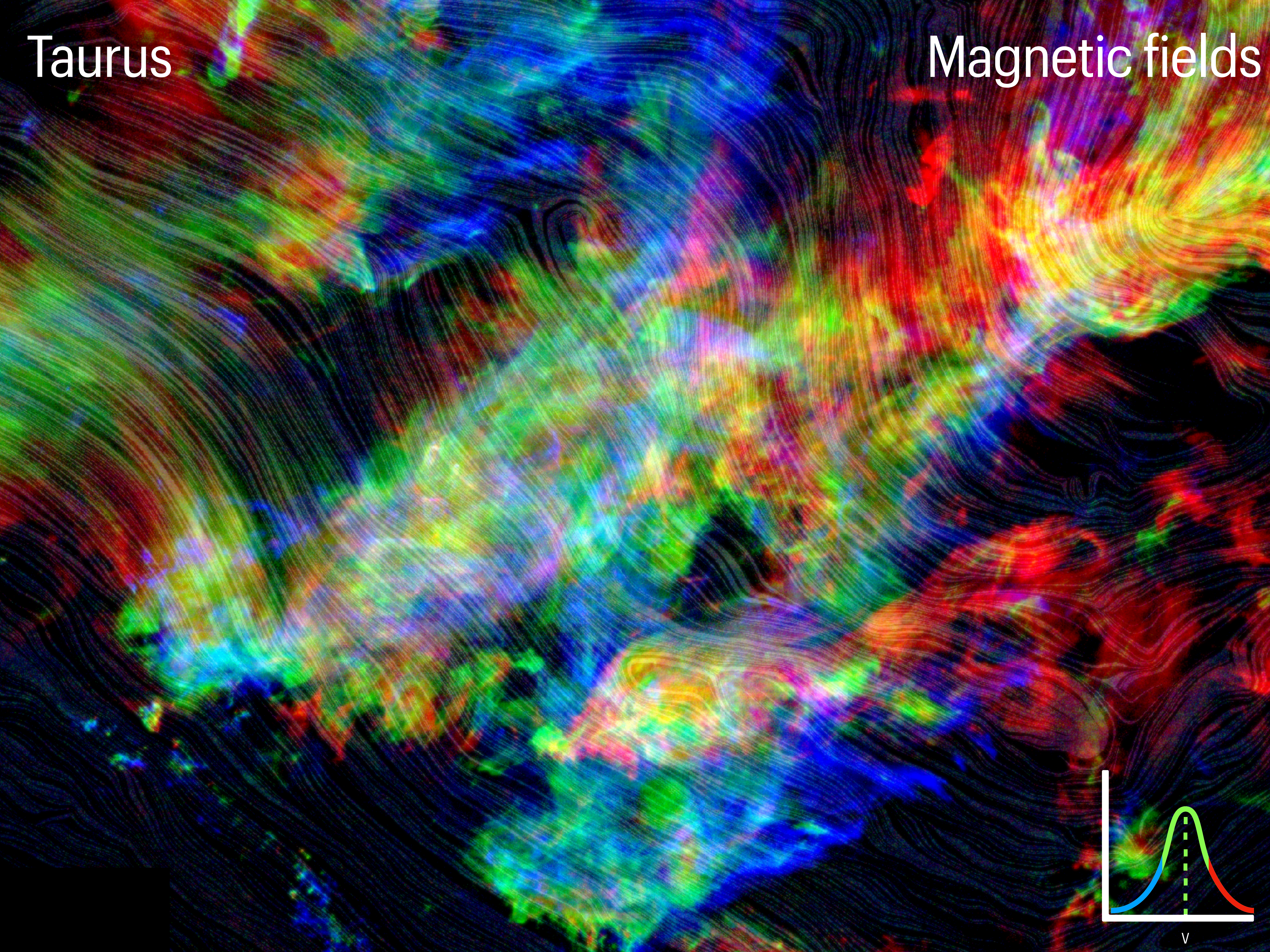
- Stahler & Palla 2004 - Chapters 2, 3, appendix D
- Draine 2011 - Chapters 30, 32
- Tielens 2005 - Chapters 8, 10

In depth look at the physical processes

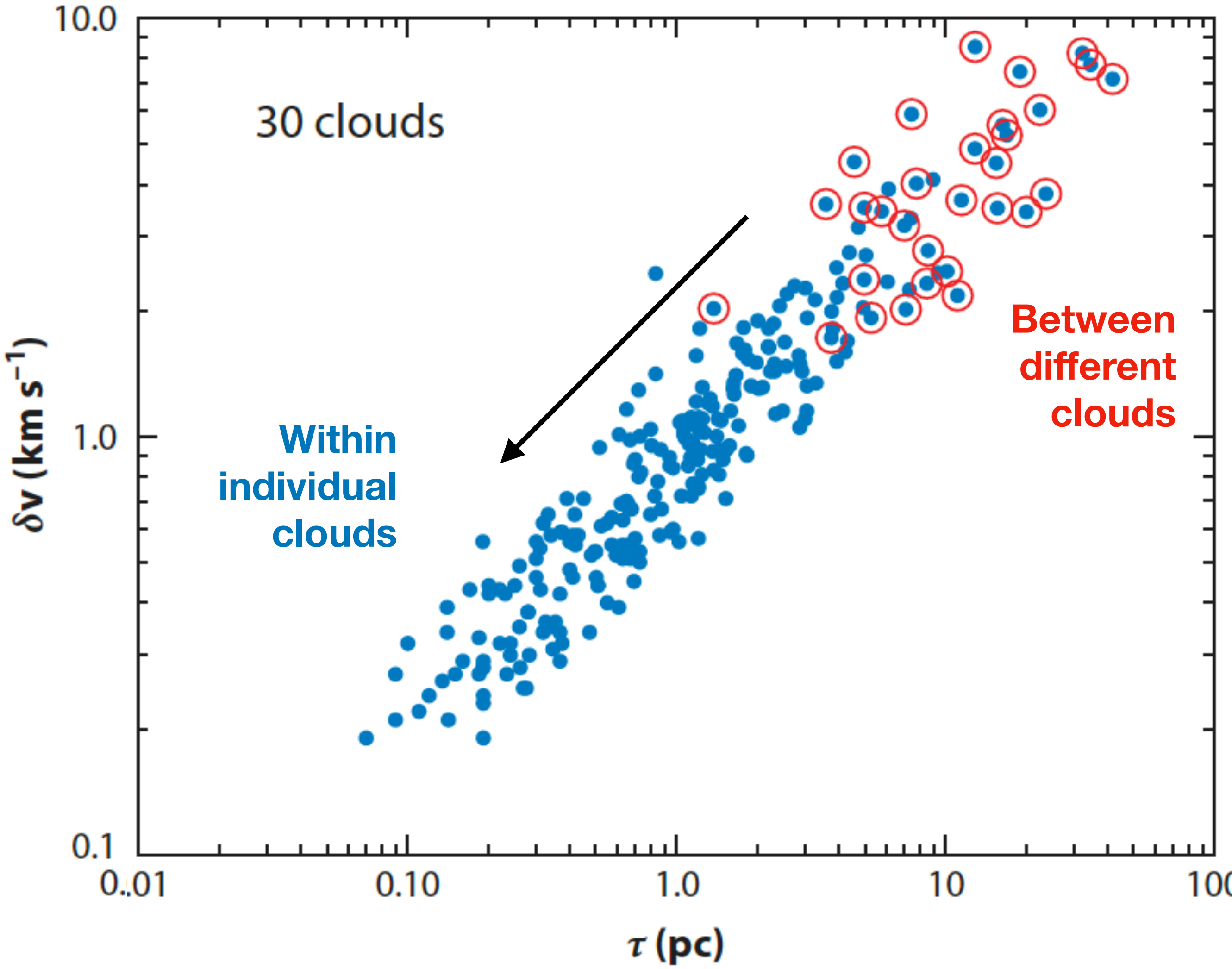
- Chevance et al. 2022 (to appear in Protostars & Planets VII)
- Heyer & Dame 2015 (MW molecular clouds)
- Dobbs et al. 2014 (PPVI review)


Taurus
Column density
V


Taurus
Kinematics
v

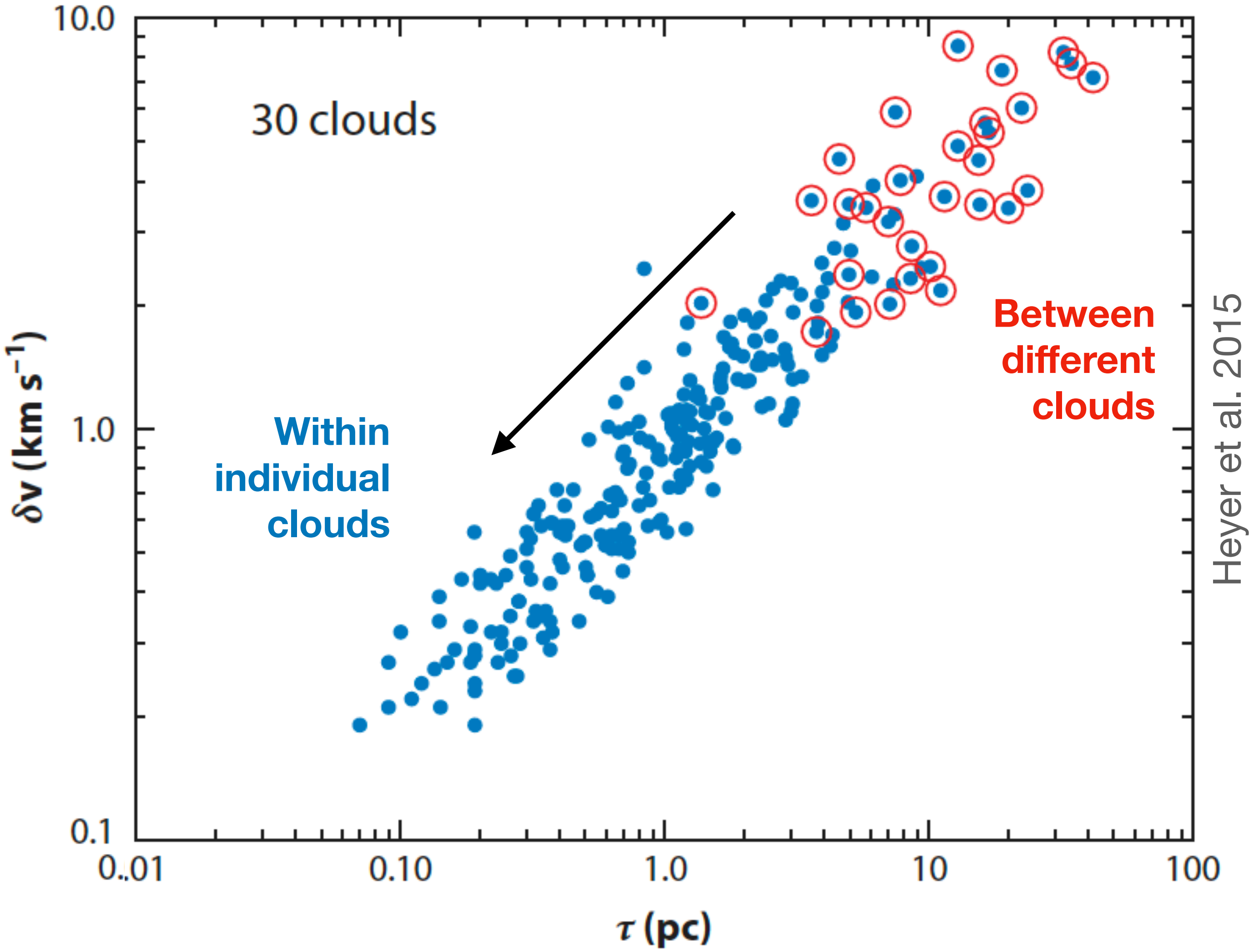

Taurus
Magnetic fields
v

The internal structure of molecular clouds



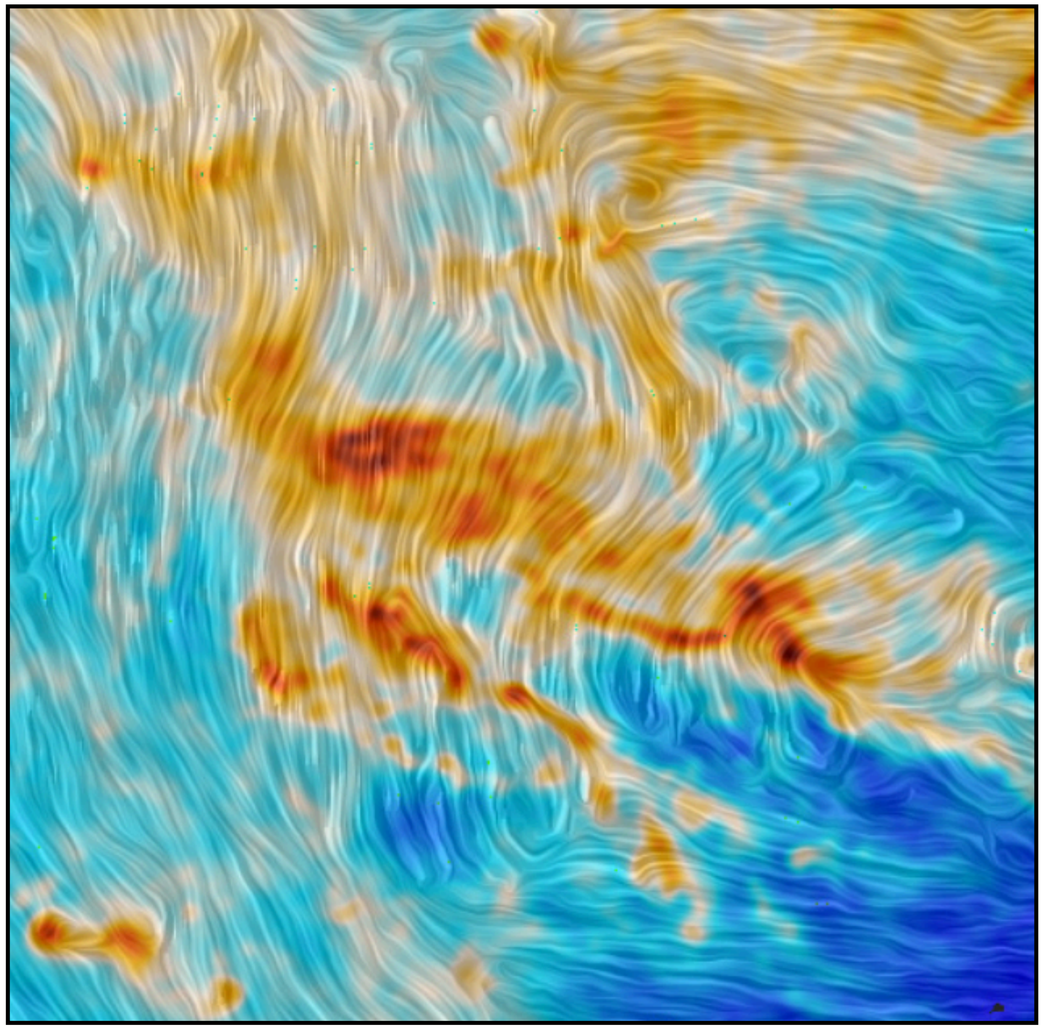
Heyer et al. 2015

The internal structure of molecular clouds

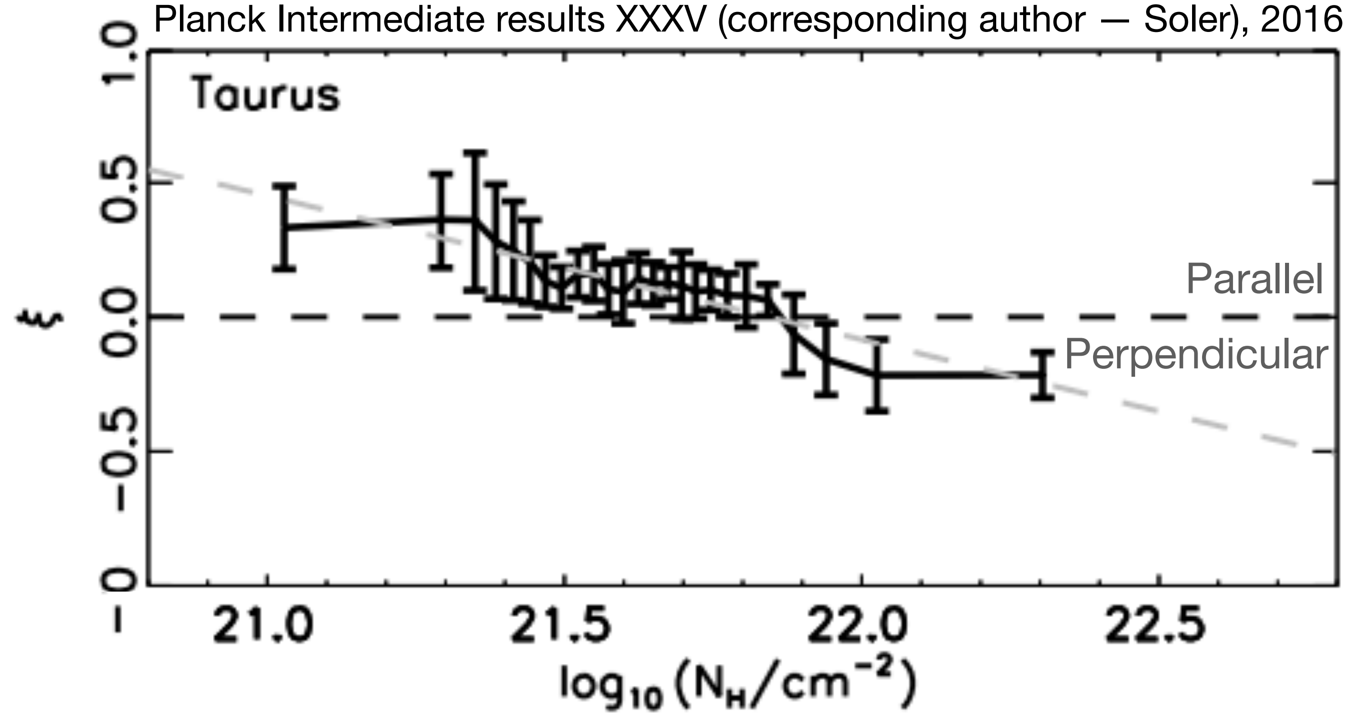


- For clouds with comparable mass surface density, the multi-cloud (e.g. Solomon+ 1987) linewidth-size relationship (red circles) converges to small scales with the internal velocity structure of individual clouds (blue circles)
- Clouds are turbulent — most power is on the largest scales and energy cascades to smaller scales
- Suggests a common formation mechanism from the atomic medium?

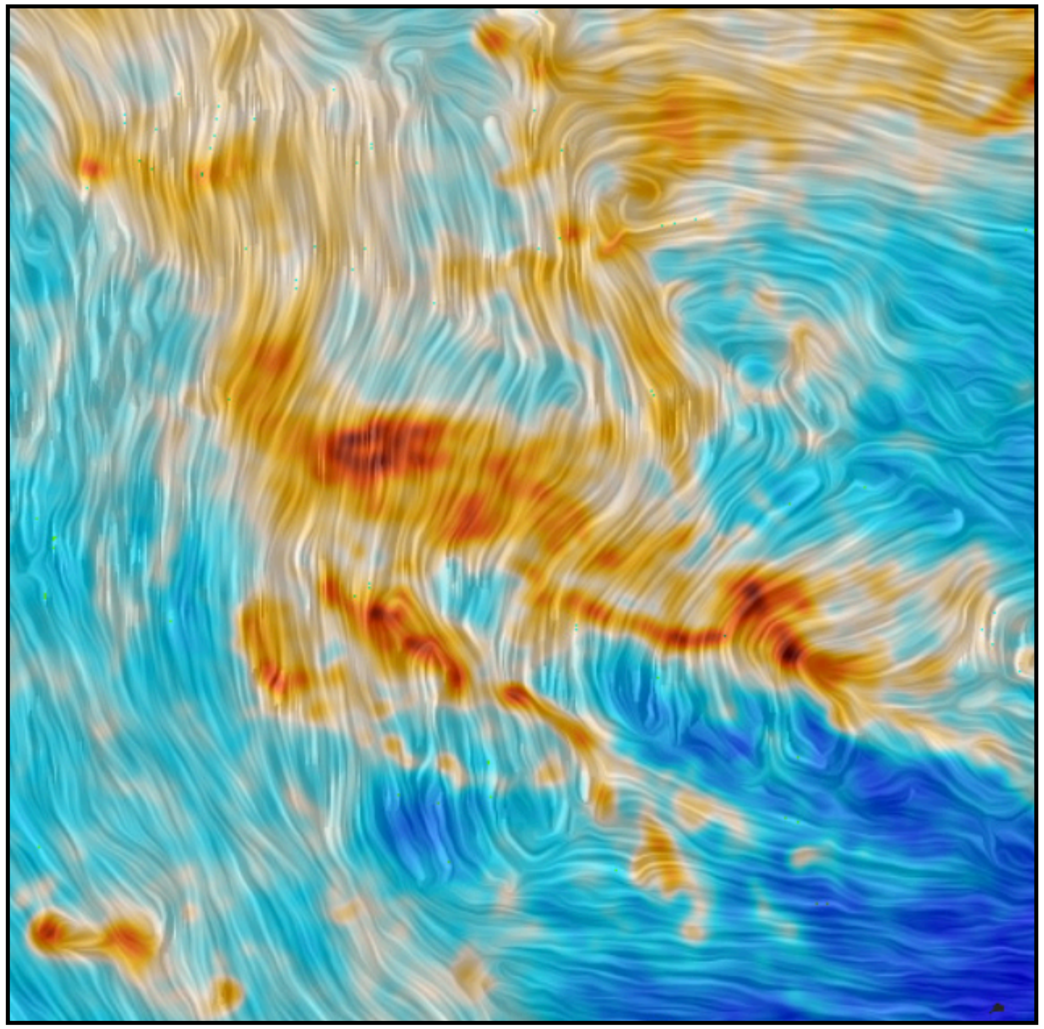
The internal structure of molecular clouds



Planck Intermediate results XXXV (corresponding author — Soler), 2016



The internal structure of molecular clouds



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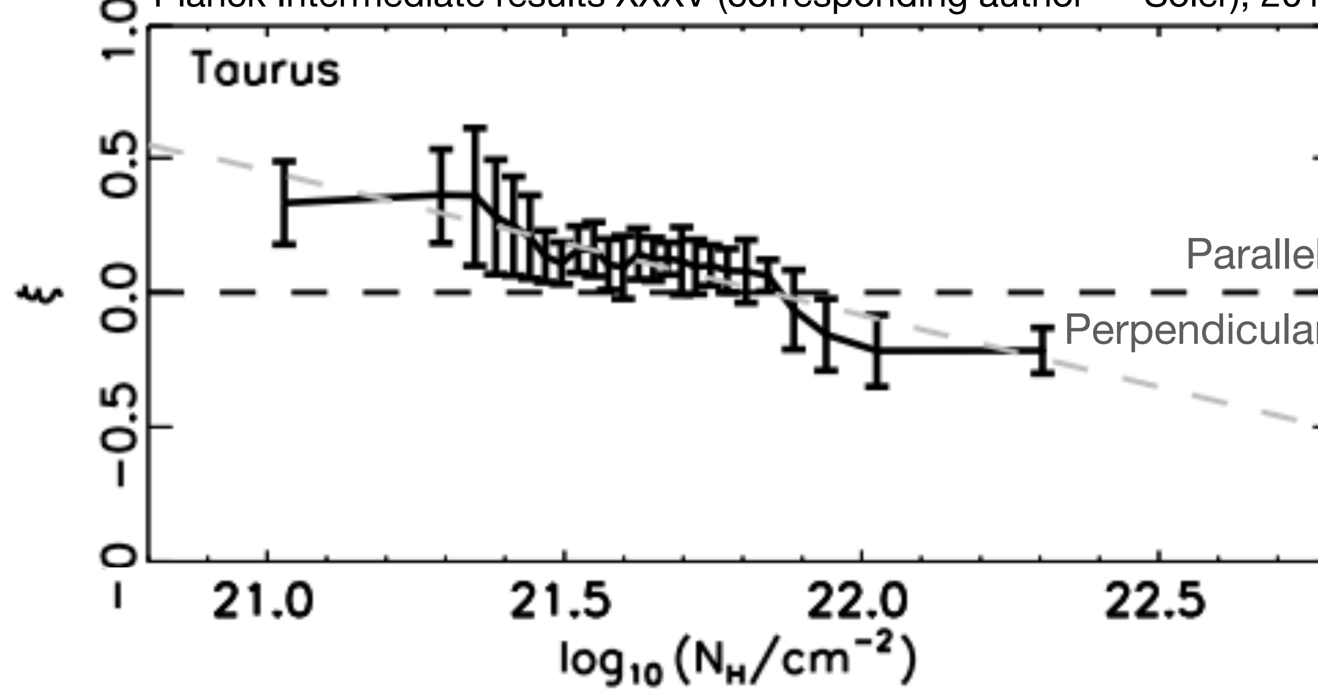
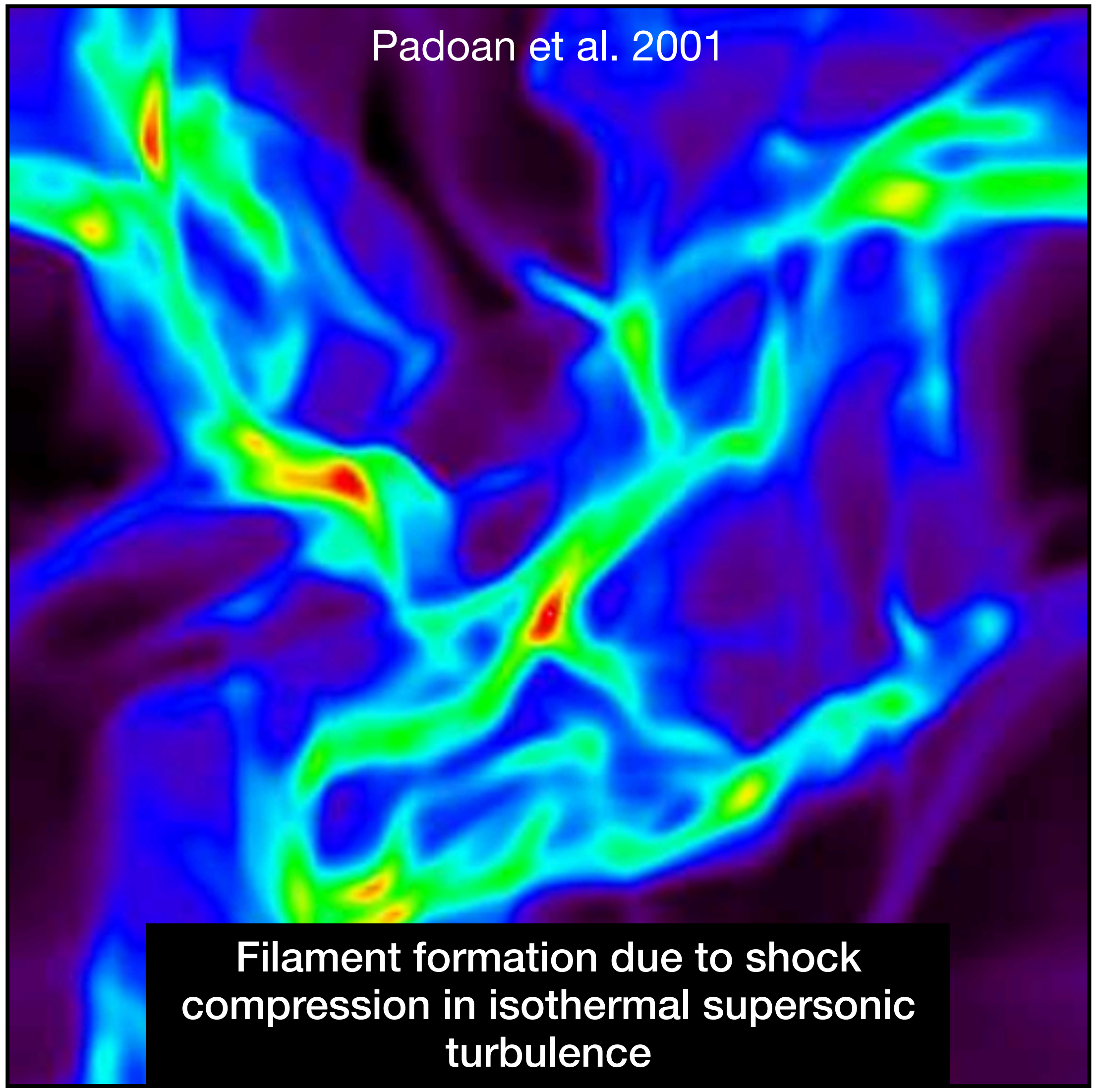
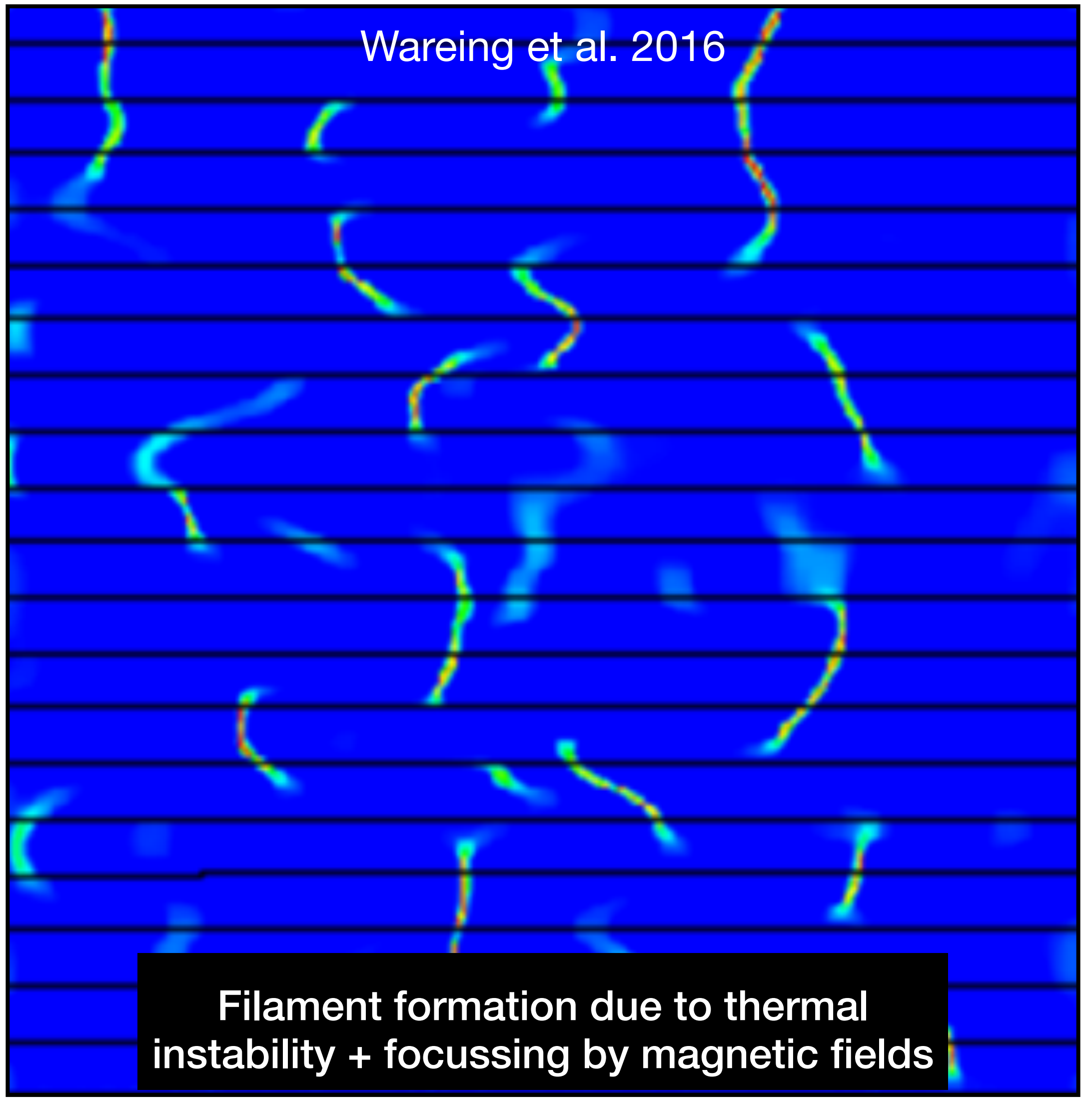


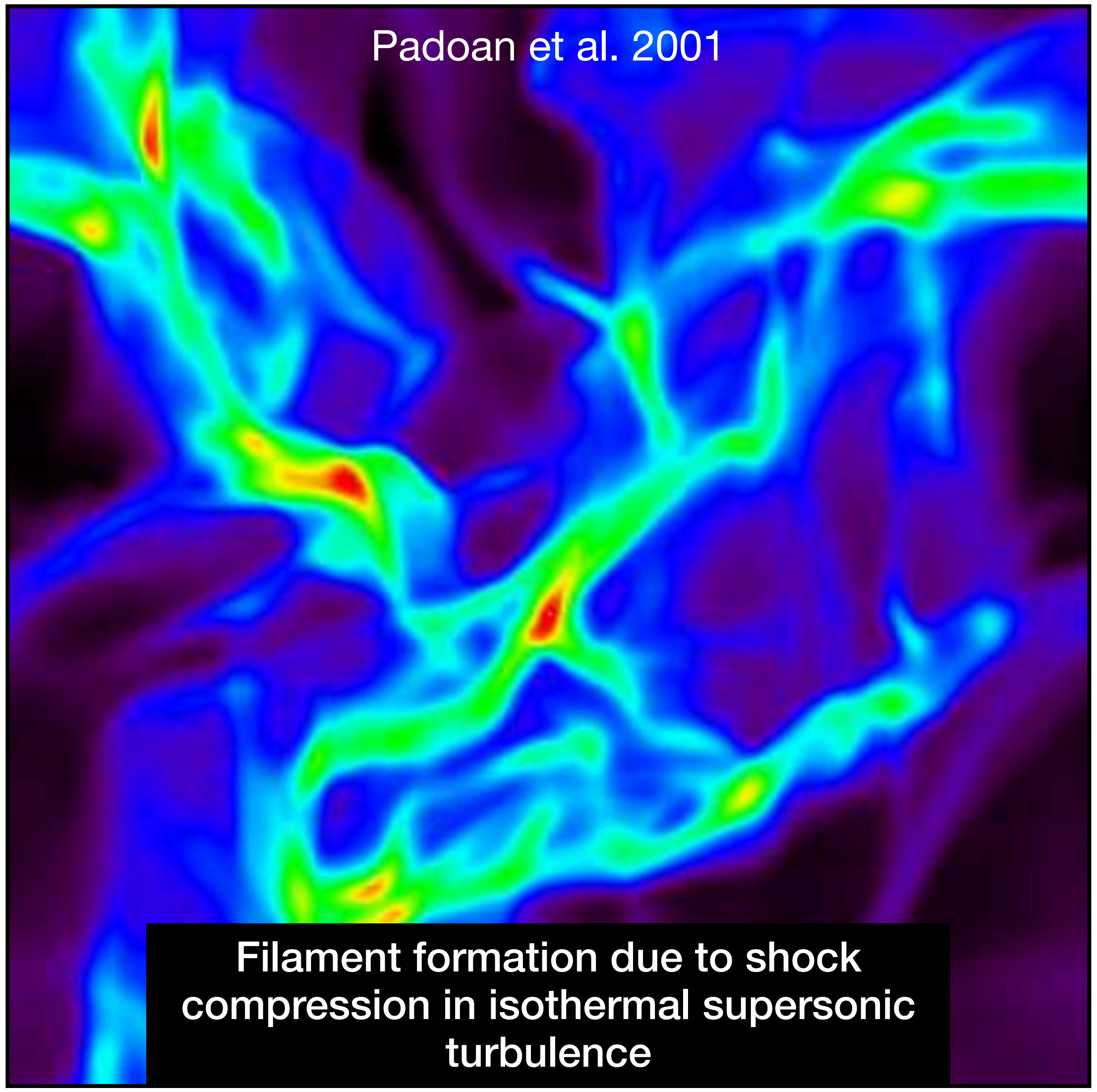
- Structures within molecular clouds are predominantly aligned parallel to magnetic field lines at low(er) column densities, and perpendicular at high(er) column densities
- Magnetic fields help to shape the internal structure of molecular clouds by allowing gas to flow along field lines

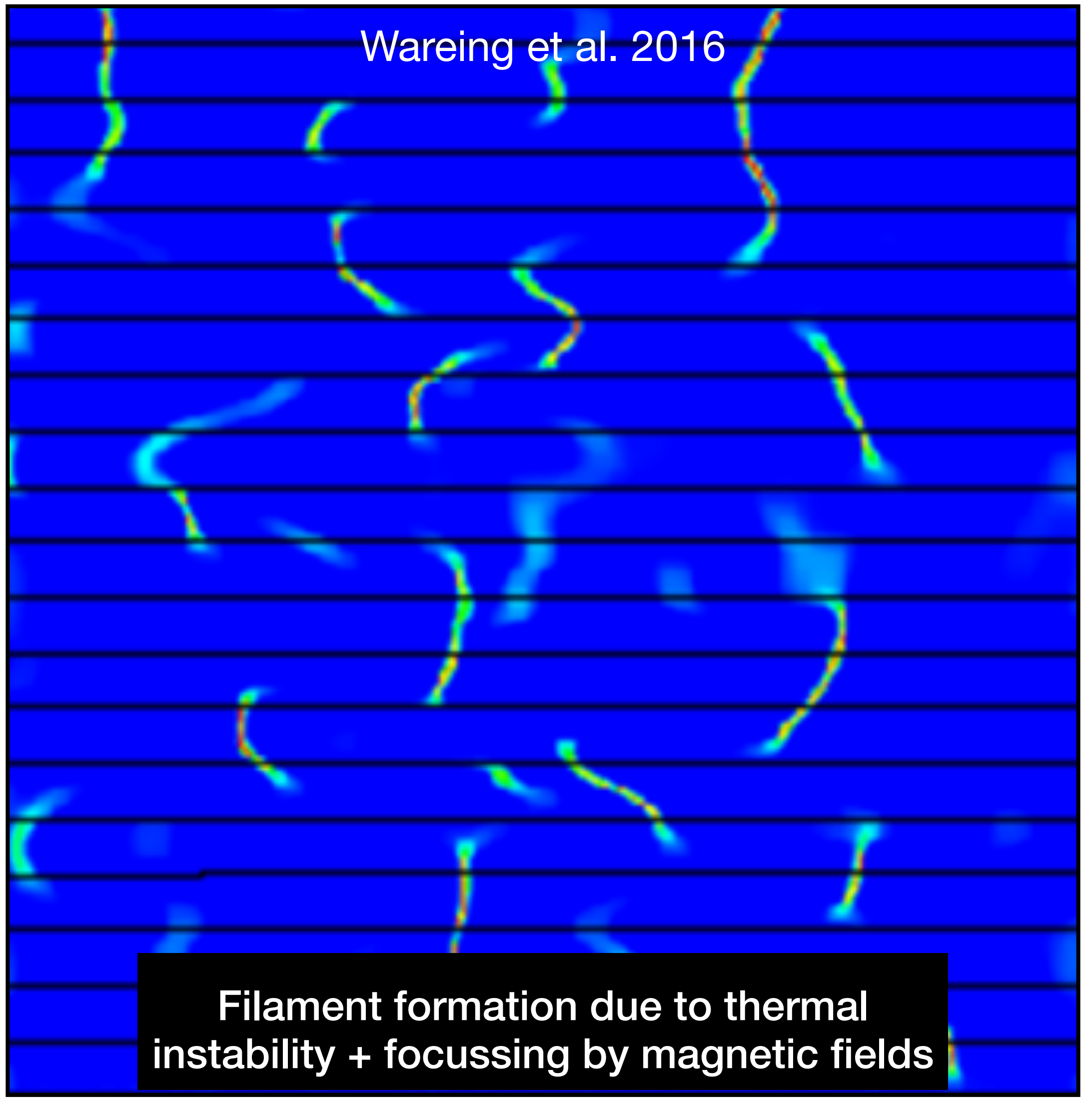
The internal structure of molecular clouds

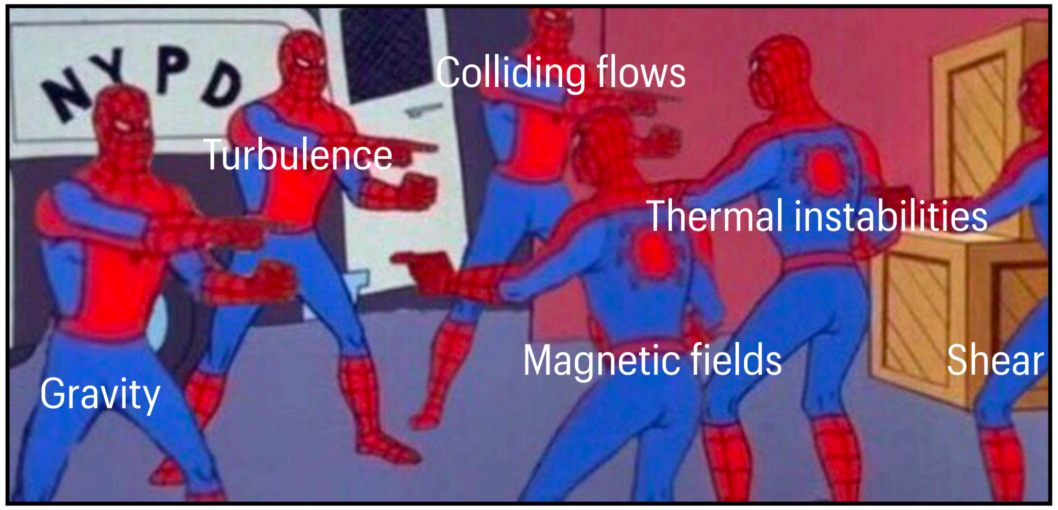




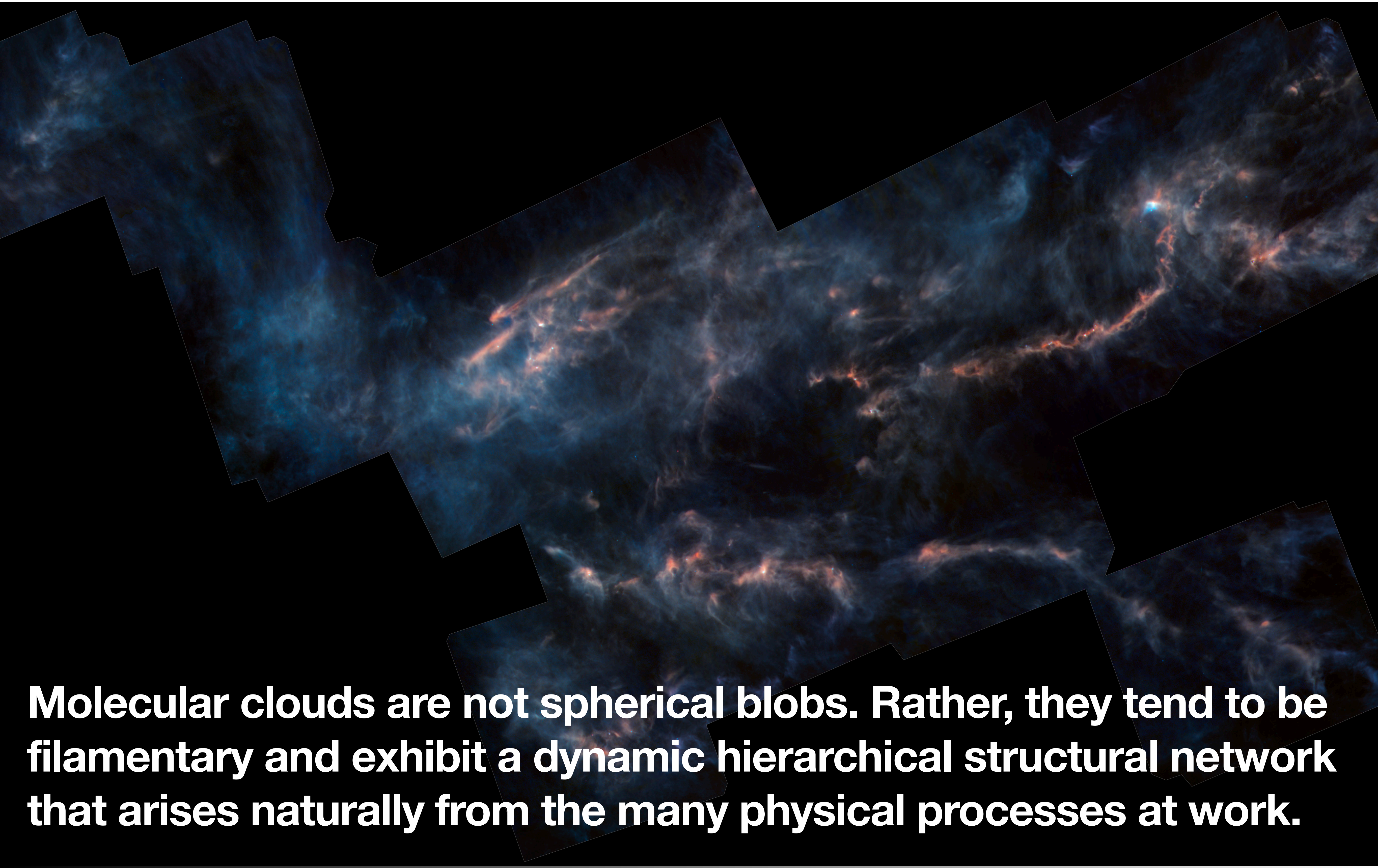
The internal structure of molecular clouds





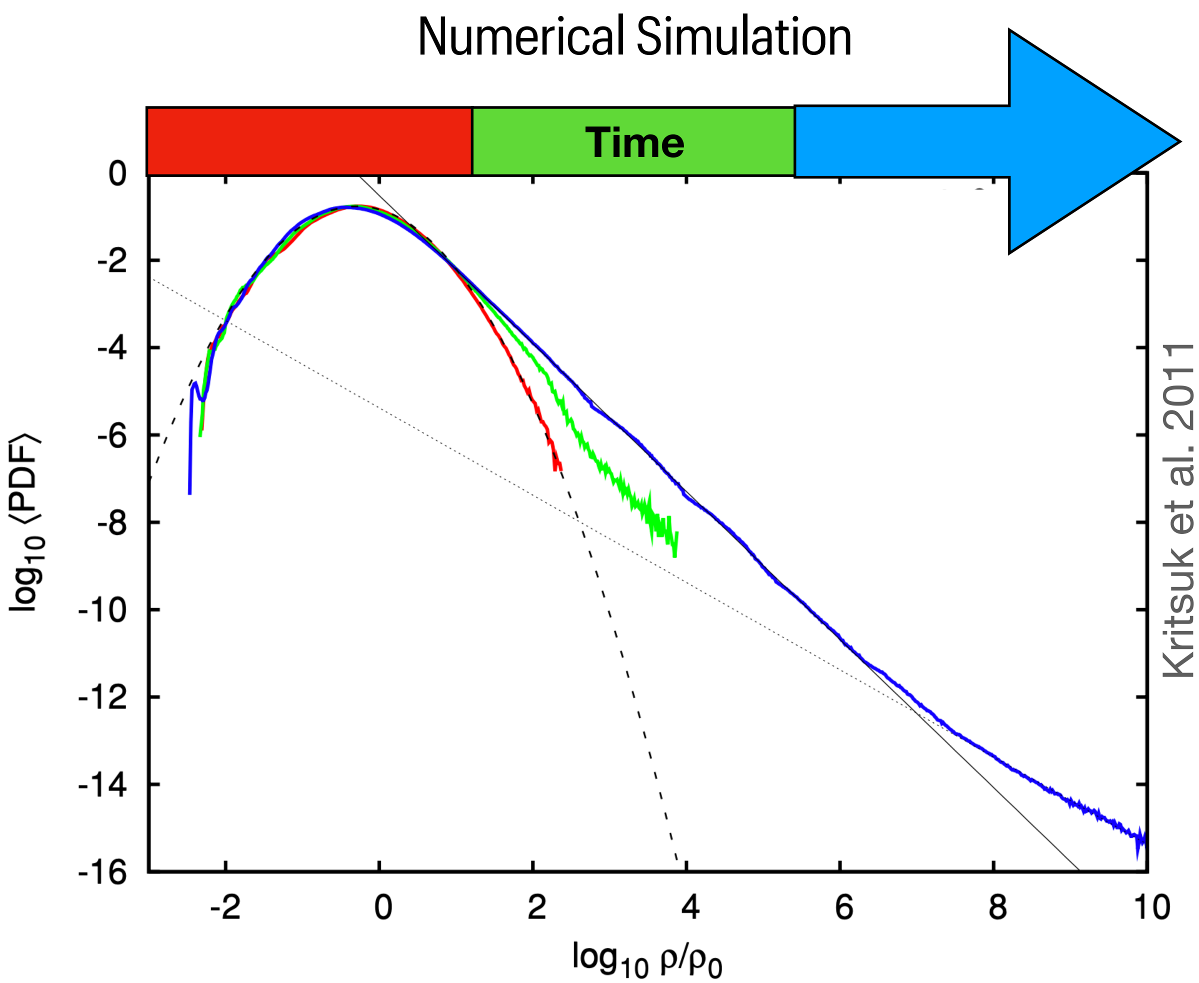


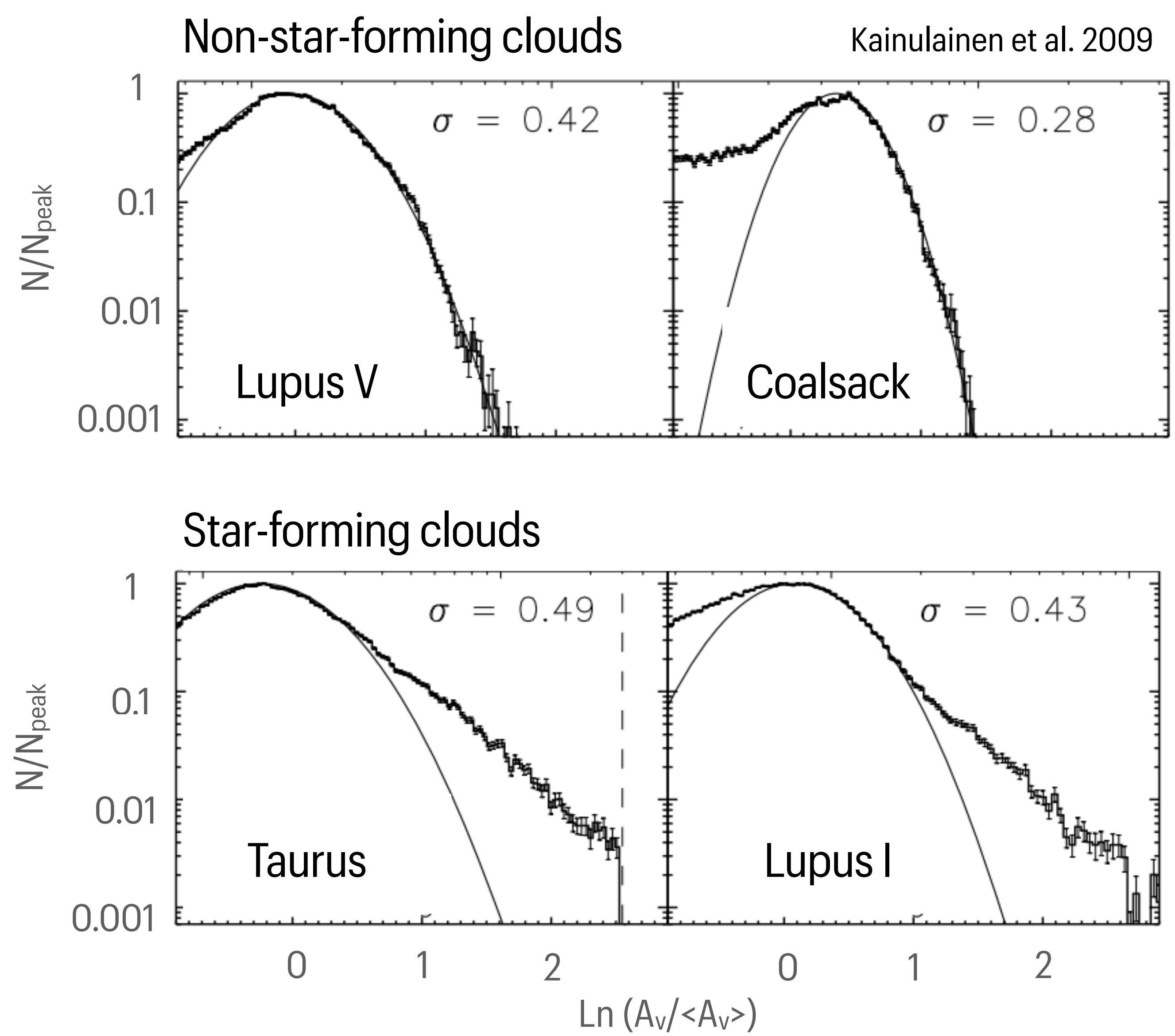
The internal structure of molecular clouds



Molecular clouds are not spherical blobs. Rather, they tend to be filamentary and exhibit a dynamic hierarchical structural network that arises naturally from the many physical processes at work.

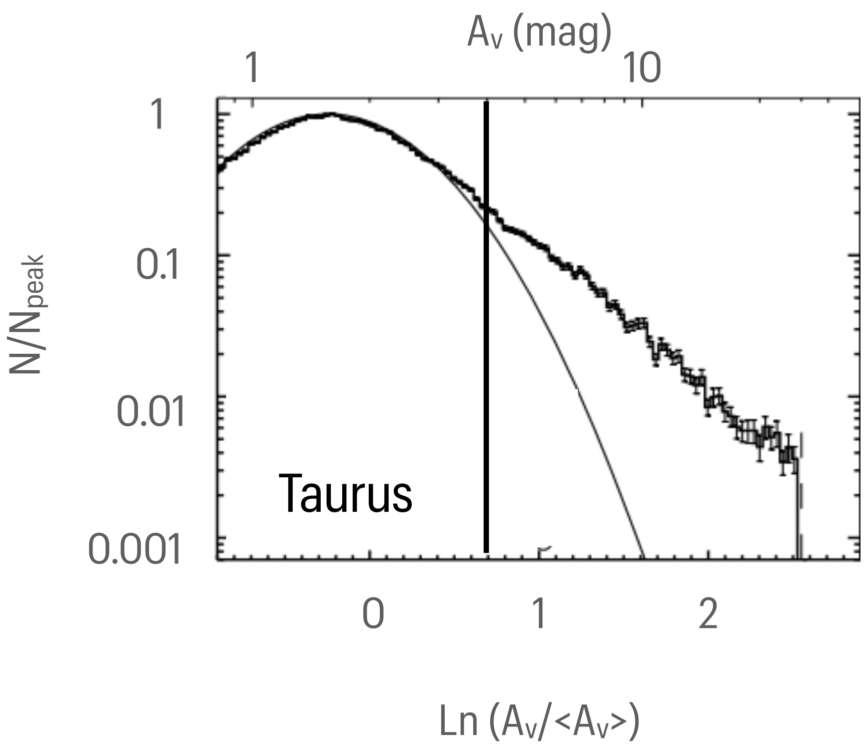
The internal structure of molecular clouds



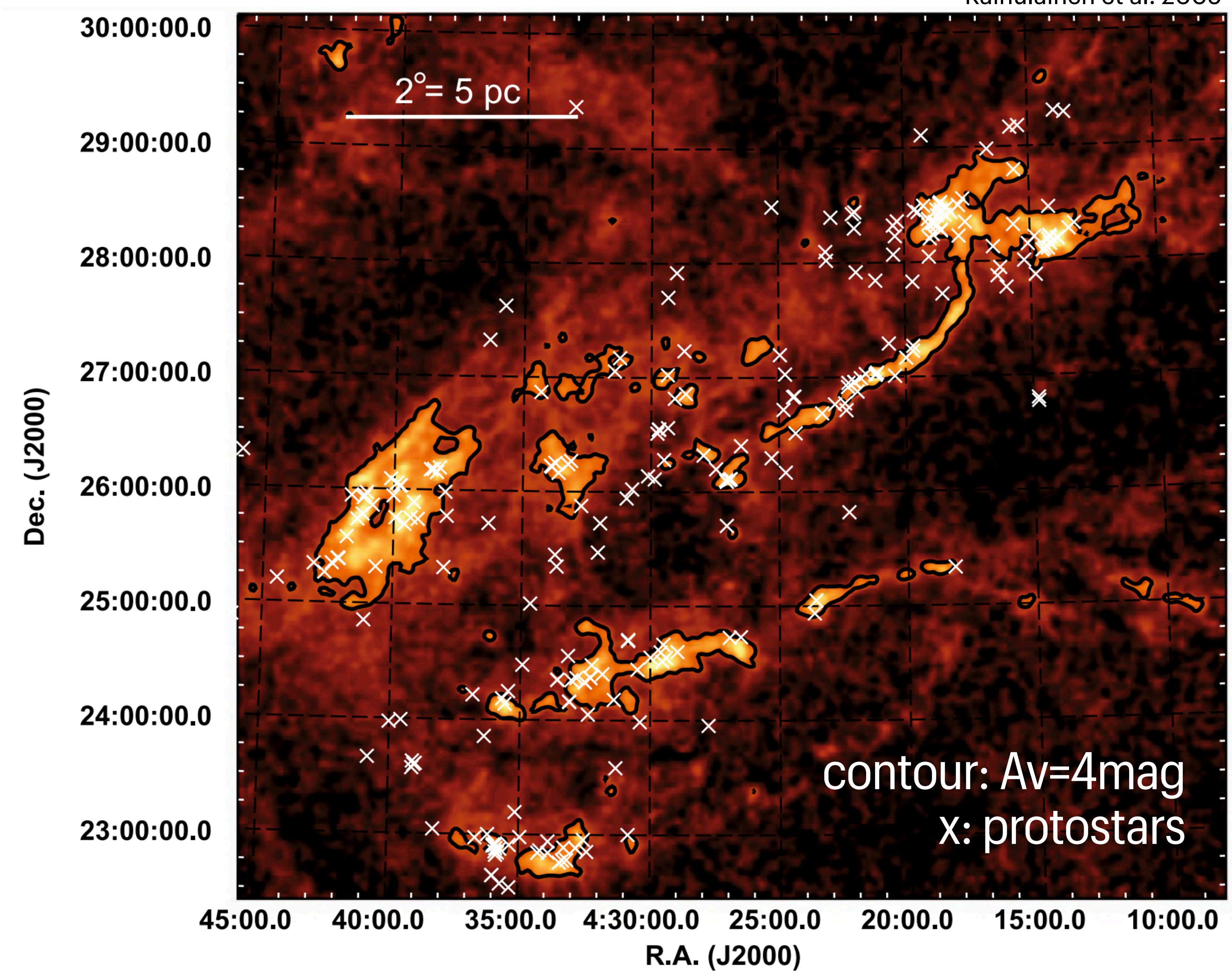


The density structure of the ISM determines where stars will form.

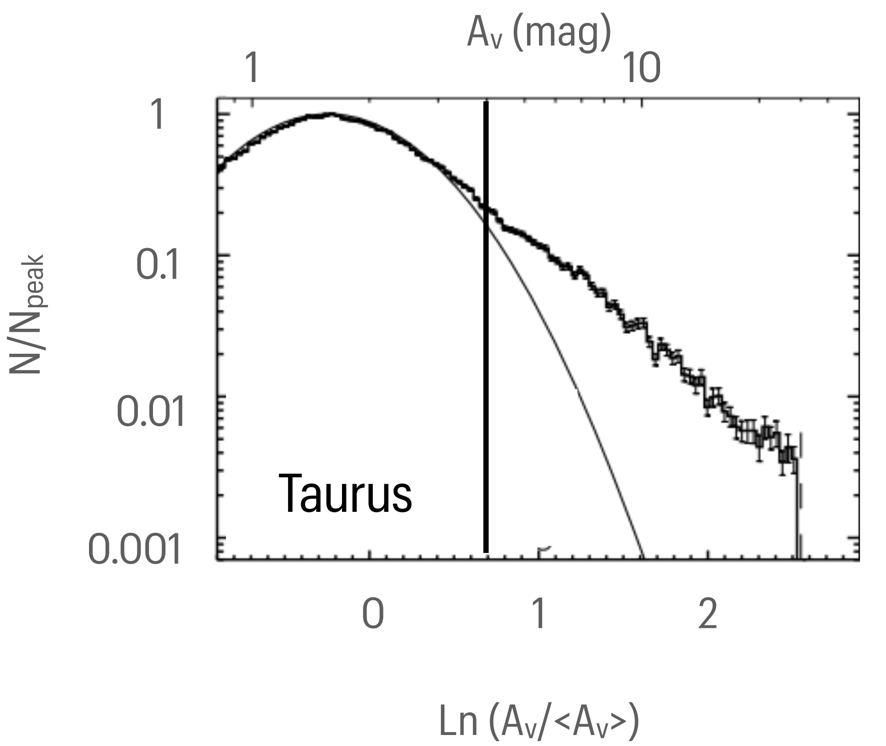
The internal structure of molecular clouds



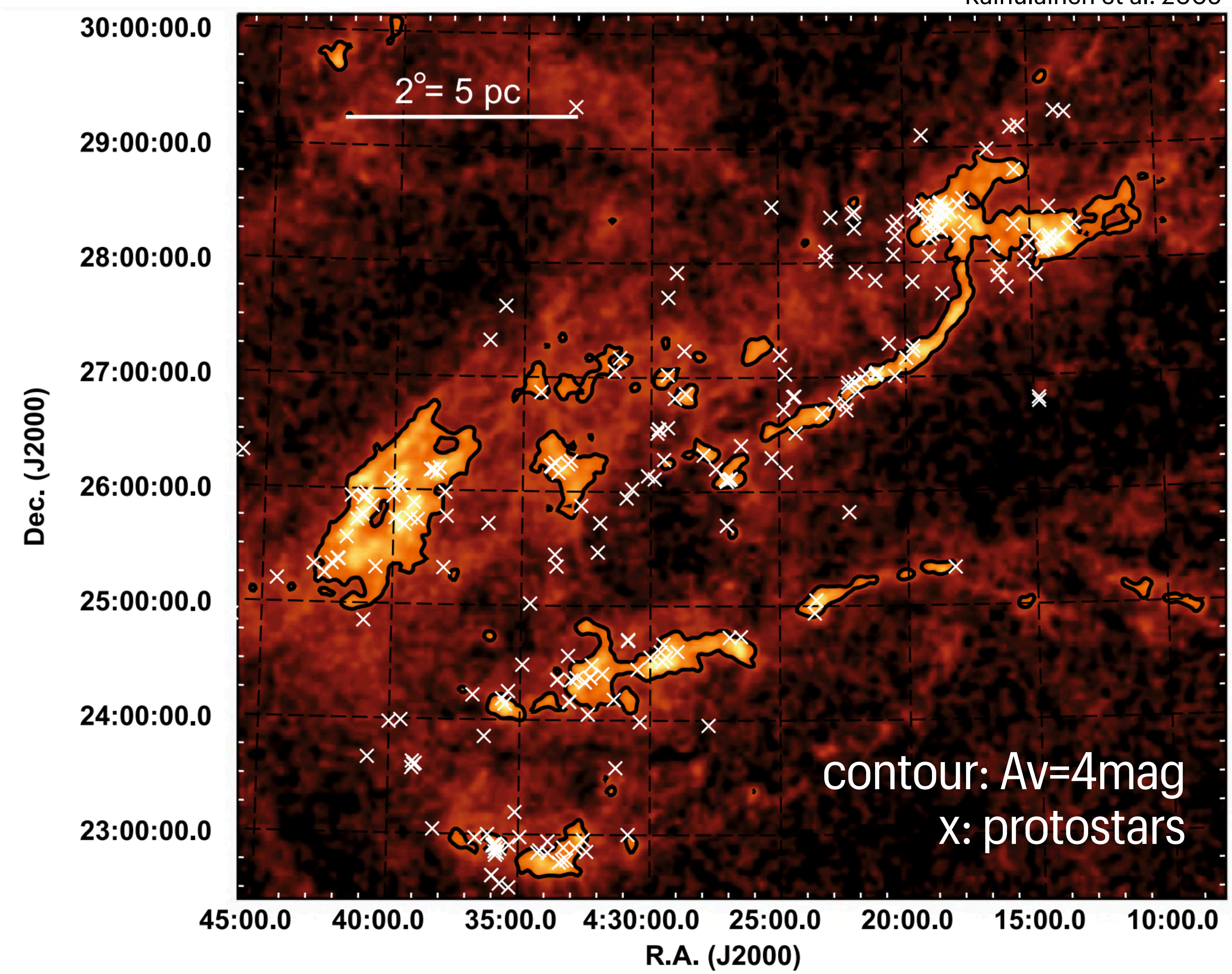
Kainulainen et al. 2009



The internal structure of molecular clouds



Kainulainen et al. 2009



- Most (>75%) of the cloud mass is at low to intermediate column densities (A_V ~ 3–7)
- A_V > 7: ~50-70% of the mass of gas contained within filaments; ~15-20% found in “cores”
- >75% of prestellar cores are located within filamentary structures of column density A_V > 7 mag

Summary

Learning outcomes:

- Molecular gas as a component of the interstellar medium
  - **~20% of the gas in the MW by mass is molecular**
- Why are we interested in molecular gas/clouds?
  - **All stars in all galaxies are born in molecular gas**
- What *even is* a “molecular cloud”?
  - **It turns out they are hard to define due to their dynamic nature — over densities in the ISM where gas is in molecular form and in which gravitational collapse and star formation possible**
- What are the general properties of molecular clouds?
  - **Most of mass is in most massive clouds, clouds have varying surface density, clouds are turbulent, unclear whether or not they are in virial equilibrium**
- The internal structure of molecular clouds
  - **Internal structure is filamentary - complex hierarchical structural network. Cores and stars tend to form in filaments.**

Sternentstehung - Star Formation

Winter term 2022/2023
Henrik Beuther, Thomas Henning, & Jonathan Henshaw

18.10 - Introduction & overview (Beuther)
25.10 - Physical processes I (Beuther)
08.11 - Physical processes II (Beuther)
15.11 - Molecular clouds I: the birth places of stars (Henshaw)
22.11 - Molecular clouds II: Jeans analysis (Henshaw)
29.11 - Collapse models I (Beuther)
06.12 - Collapse models II (Henning)
13.12 - Protostellar evolution (Beuther)
20.12 - Pre-main sequence evolution & outflows/jets (Beuther)
10.01 - Accretion disks I (Henning)
17.01 - Accretion disks II (Henning)
24.01 - High-mass star formation, clusters & the IMF (Henshaw)
31.01 - Extragalactic star formation (Henning)
07.02 - Planetarium @ HdA, outlook, questions
13.02 - Examination week, no star formation lecture

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

More information and the current lecture files: https://www2.mpia-hd.mpg.de/homes/beuther/lecture_ws2223.html
beuther@mpia.de, henning@mpia.de, henshaw@mpia.de

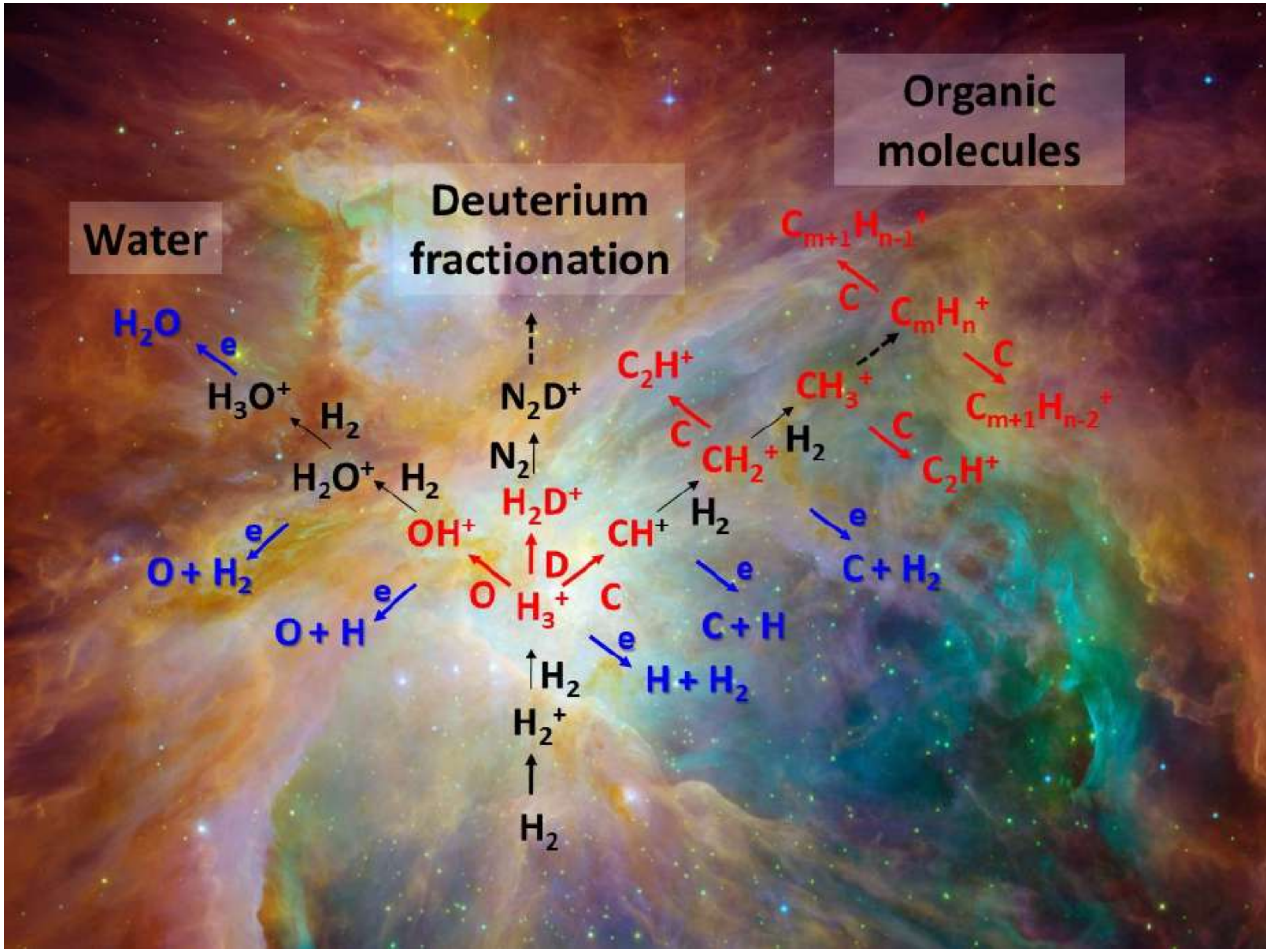
Heidelberg Joint Astronomical Colloquium

Winter Semester 2022 — Tuesday November 15th, 16:00

Main Lecture Theatre, Philosophenweg 12

Holger Kreckel (MPI Kernphysik, Heidelberg)

Molecular Astrophysics at the Cryogenic Storage Ring



Those unable to attend the colloquium in person are invited to participate online through Zoom.

More information is given on HePhySTO: https://www.physik.uni-heidelberg.de/hephysto/